Physics at the LHC

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Outline

- Introduction: LHC and (high-P_T) pp experiments
- Electroweak Symmetry Breaking
- Supersymmetry
- Other (possible) new physics (extra dims, etc.)
- LHC++
- Summary

Thoughts on the Standard Model

- **It's beautiful, logically consistent**
  - It's relatively low cost: it needs (with respect to today) only one new particle – the Higgs boson.
- **Of course, it doesn't tell us many things:**
  - why three generations
  - anything about gravity
  - why masses are what they are (it blames the couplings…)
  - and many, many other things (Cosmological Constant etc)
    - It is "only" an effective theory (but a very effective one indeed)
- **Nevertheless, it is, with the possible exception of adding supersymmetry, the most powerful theory we have today**
  - But we need to find the Higgs; and theory does NOT provide (precise) information on its mass
  - Alternatively, we still need to understand why $M_Z >> M_\gamma$

Pending issues/questions (and LHC)

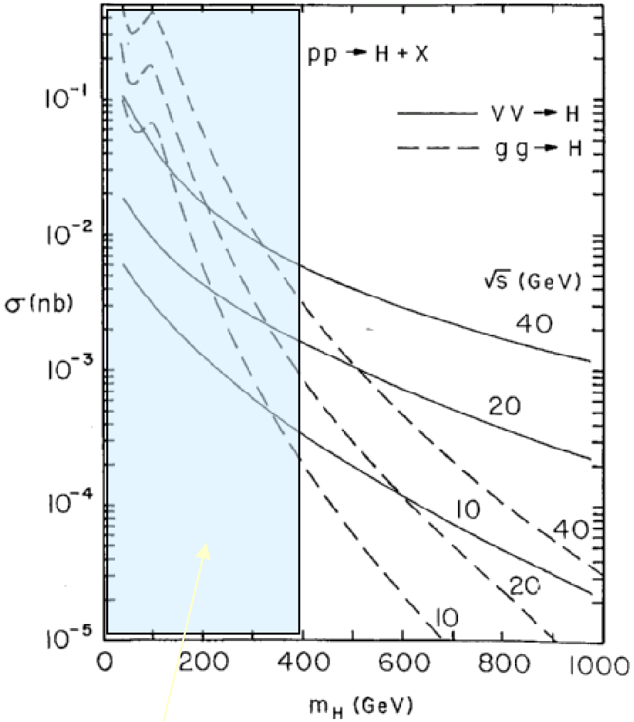
- **Too many parameters (19→26)**
  - 3 couplings (g_1, g_2, g_3 or α, Θ_W, Λ_{QCD})
  - 2 parameters from the Higgs potential (υ, λ or M_Z, M_H)
  - 9 (12) fermion masses: e, μ, τ, u, c, t, d, s, b; ν_e, ν_μ, ν_τ
  - 3 mixing angles + 1 phase in CKM matrix (+ 3+1 for leptons…)
  - Vacuum parameter of QCD, Θ_{QCD}.
- **Naturalness of mass scale υ.**
  - Or, why it is so much smaller than $(G_N)^{-1/2}$
    - Why does υ have the specific value
    - Is this value a stable one?

$$\delta m^2 \sim g^2 \int_0^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \sim O(\alpha^2)\Lambda^2$$

→ Ways out: no Higgs, e.g. dynamical symmetry breaking; and supersymmetry

A machine for EWK Symmetry Breaking

- **Superconducting SuperCollider (SSC)**
  - **THE machine to do this job; history…**
- **Large Hadron Collider**
  - **Use existing LEP tunnel**

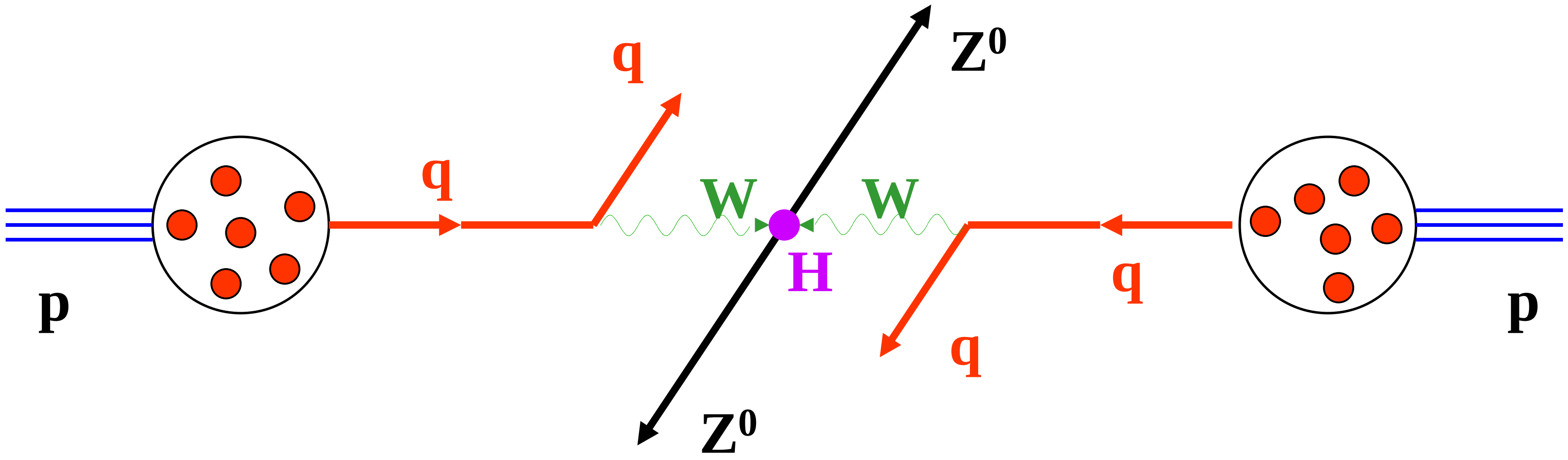


D.Dicus, S. Willenbrock

Phys.Rev.D32:1642,1985

Need to probe the physics of ~ 1 TeV

Higgs Production in pp Collisions



$M_H \sim 1000$ GeV

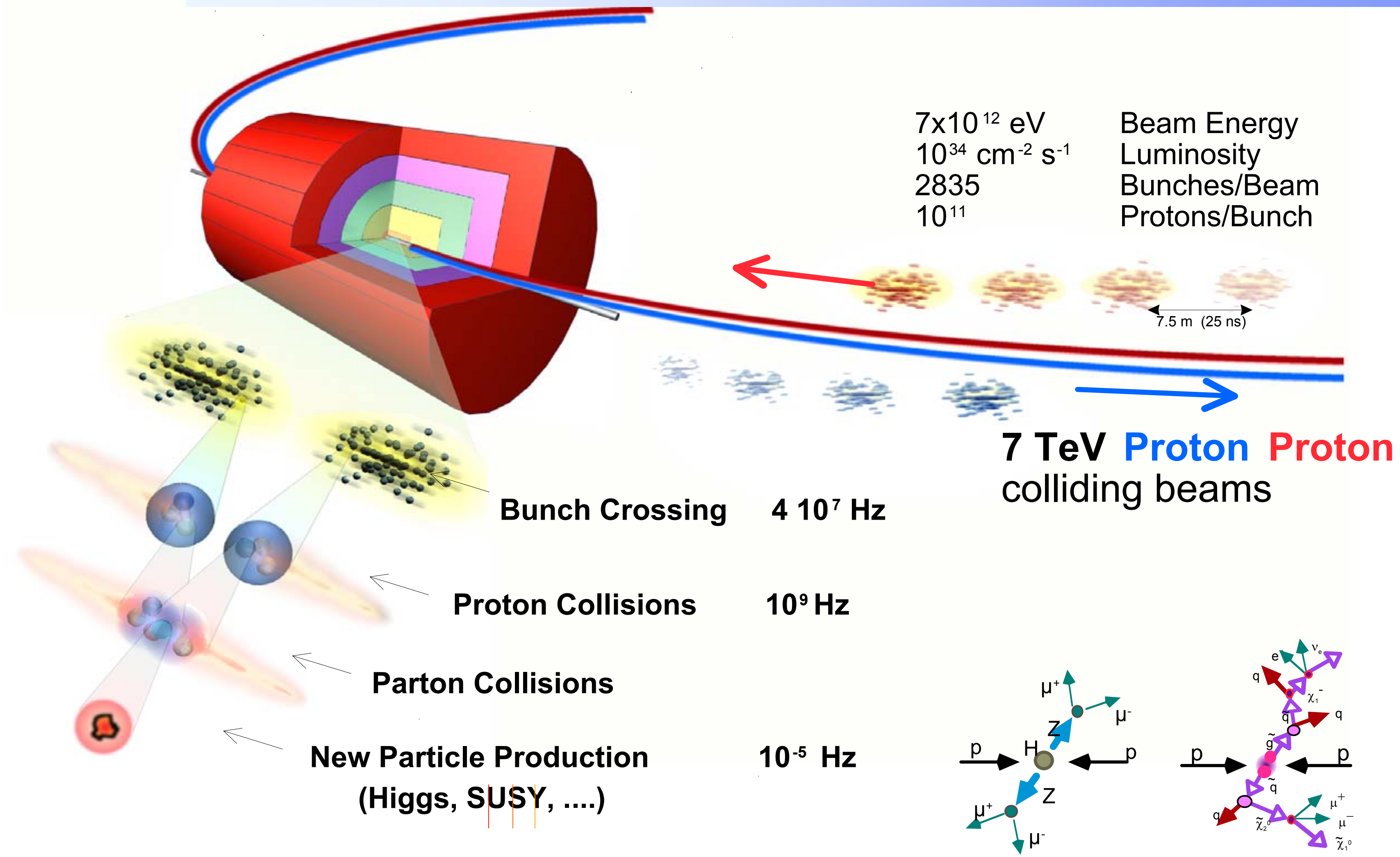
$E_W \geq 500$ GeV

$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

→ Proton Proton Collider with $E_p \geq 7$ TeV

Collisions at the LHC: summary

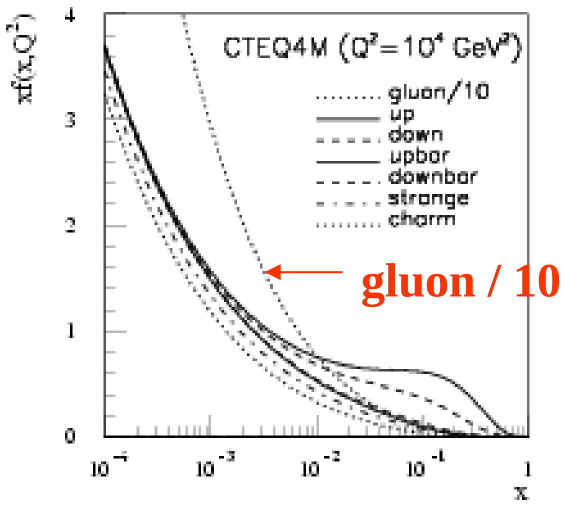


Selection of 1 event in 10,000,000,000,000

Further conditions

- **LHC: make up for the lower production cross section**
  - **Normally, $\sigma \sim 1/s$, so a factor x in c.m. energy needs a factor x^2 in luminosity (for the same number of events; $N=\sigma L$)**
    - **Not true at a hadron-hadron collider:**

$$\sigma = \frac{1}{s} \sum_{a,b} \int_{x_a x_b = m^2/s}^{1} \hat{\sigma}_{ab}\, dx_a\, dx_b\, F_a(x_a, Q^2)\, F_b(x_b, Q^2)$$

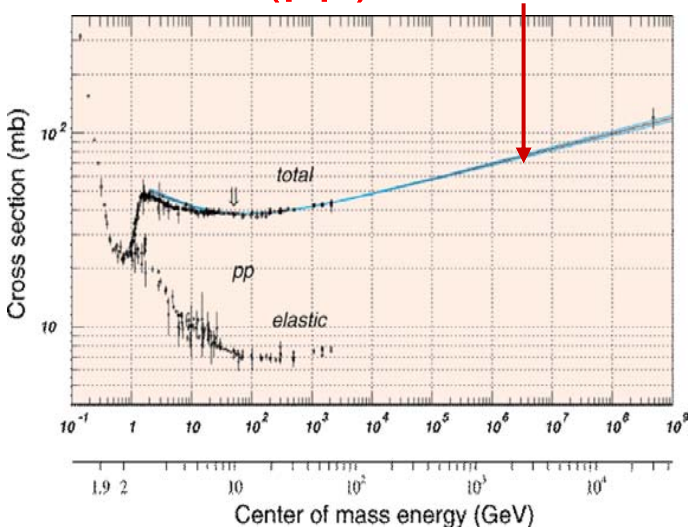


    - **Very rapid increase of structure functions at low x**
      - ➔ **Very significant increase in σ as s increases**
  - **Rough rule of thumb: a factor 2 in s is equivalent to a factor ~10 in luminosity**
  - **LHC must run at a higher luminosity (than the SSC would)**
    - **Full "design" luminosity: 10^{34} cm^{-2}s^{-1}**
    - **"Low", luminosity: 10^{33}cm^{-2}s^{-1}**

pp cross section and min. bias

- **# of interactions/crossing:**
  - **Interactions/s:**
    - **Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}$Hz**
    - **σ(pp) = 70 mb**
    - **Interaction Rate, R = 7×10^8 Hz**
  - **Events/beam crossing:**
    - **Δt = 25 ns = 2.5×10^{-8} s**
    - **Interactions/crossing=17.5**
  - **Not all p bunches are full**
    - **2835 out of 3564 only**
    - **Interactions/"active" crossing = 17.5 x 3564/2835 = 23**

σ(pp)≈70 mb



Operating conditions (summary):
1) A "good" event containing a Higgs decay +
2) ≈ 20 extra "bad" (minimum bias) interactions

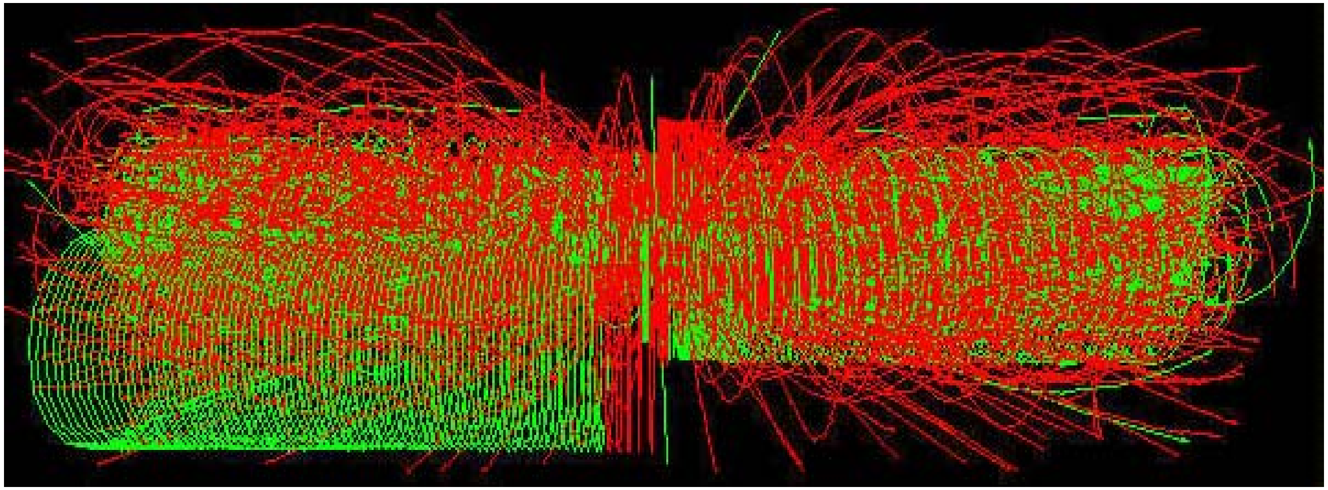
pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

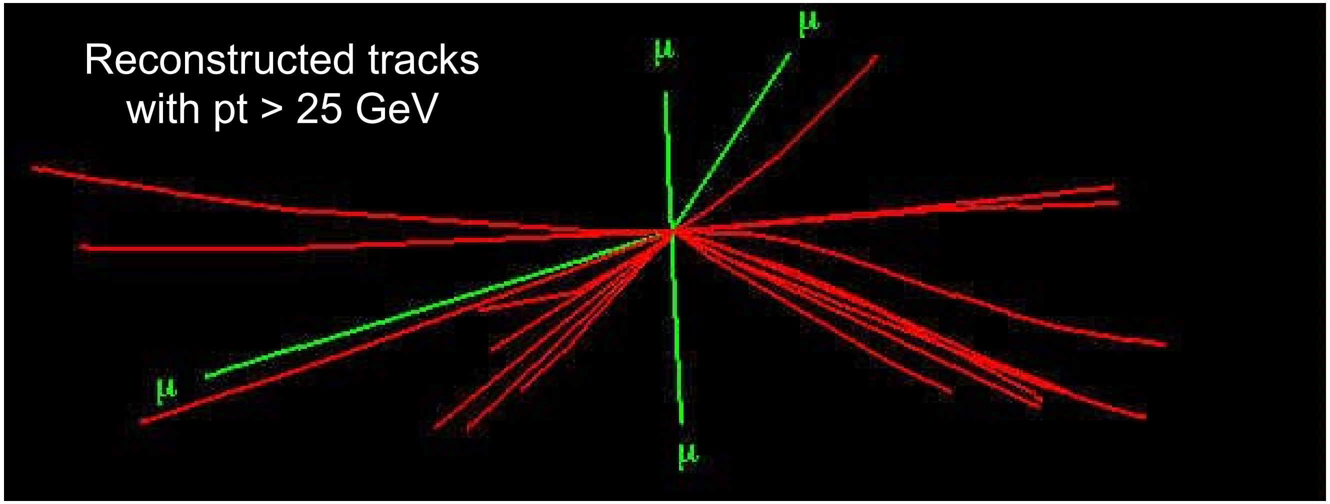
- 20 min bias events overlap
- $H \rightarrow ZZ$

$Z \rightarrow \mu\mu$

H→ 4 muons: the cleanest ("golden") signature

And this (not the H though…) repeats every 25 ns…





Impact on detector design

- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns

    → integrate over 1-2 bunch crossings → pile-up of 25-50 min-bias

    → very challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \to \gamma\gamma$ decays)

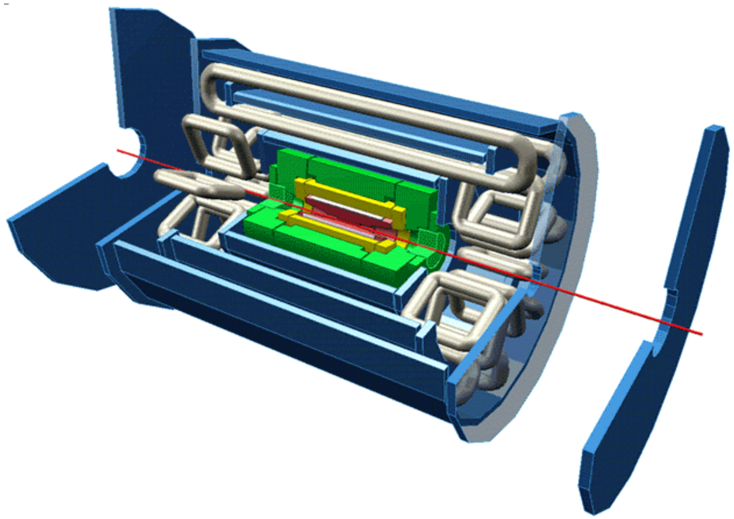
    → large number of electronic channels

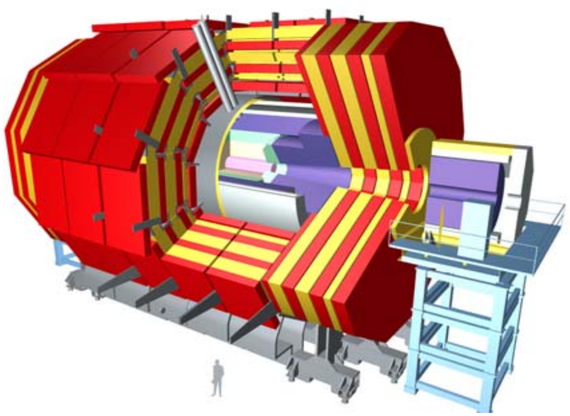
    → high cost
- **LHC detectors must be radiation resistant:**
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

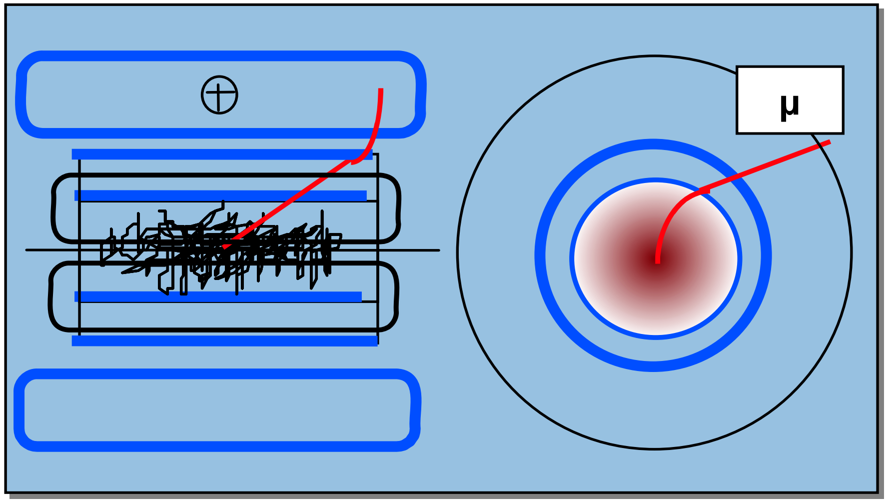
LHC: pp experiments

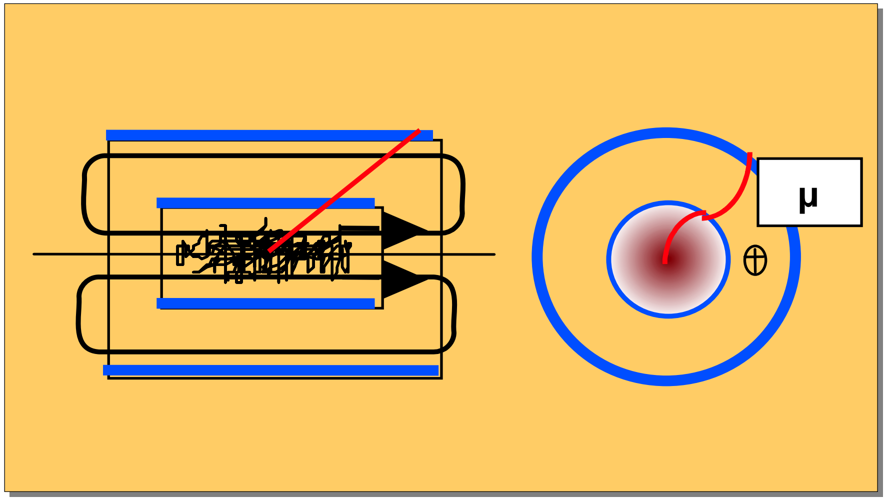
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid



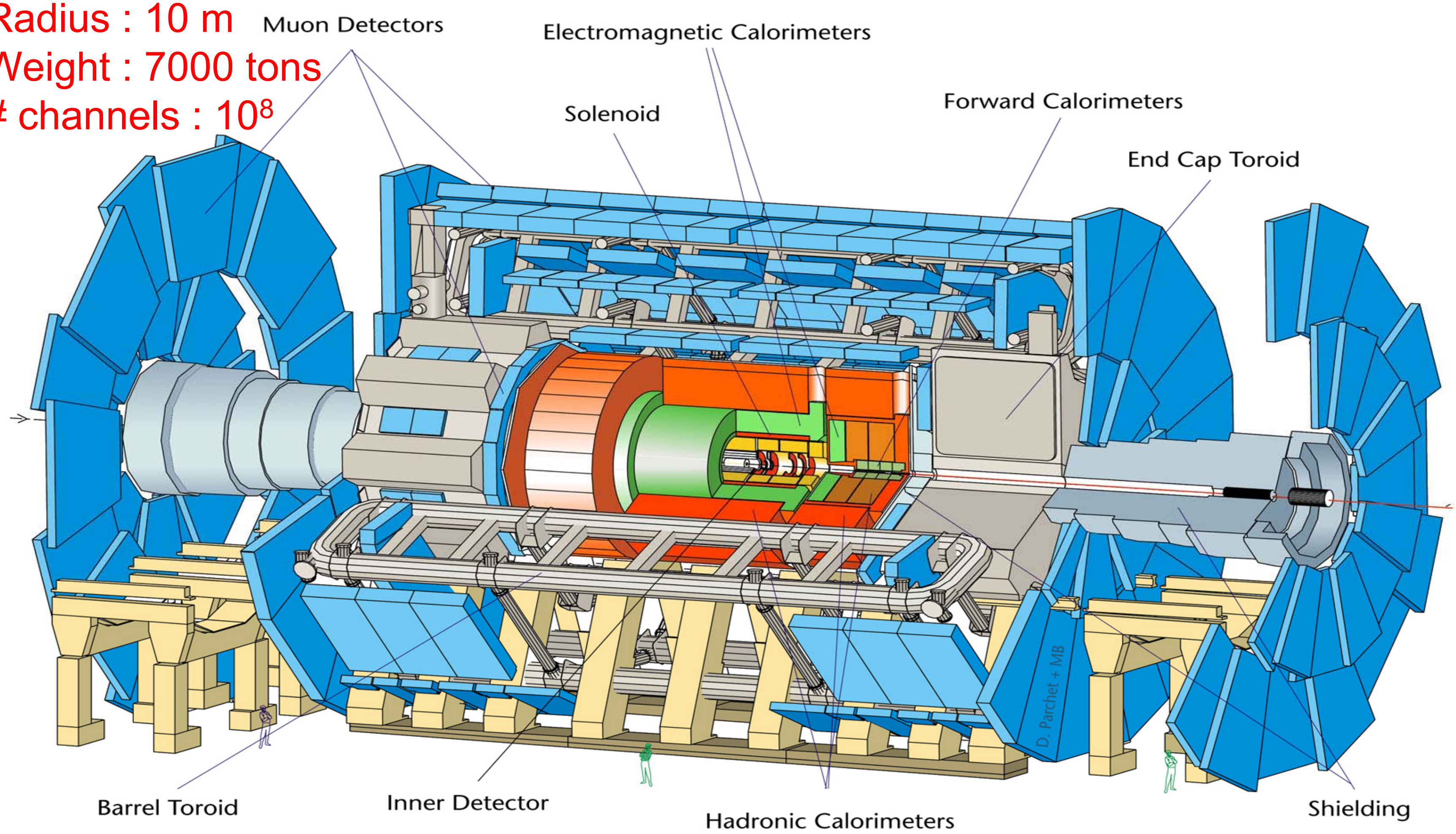




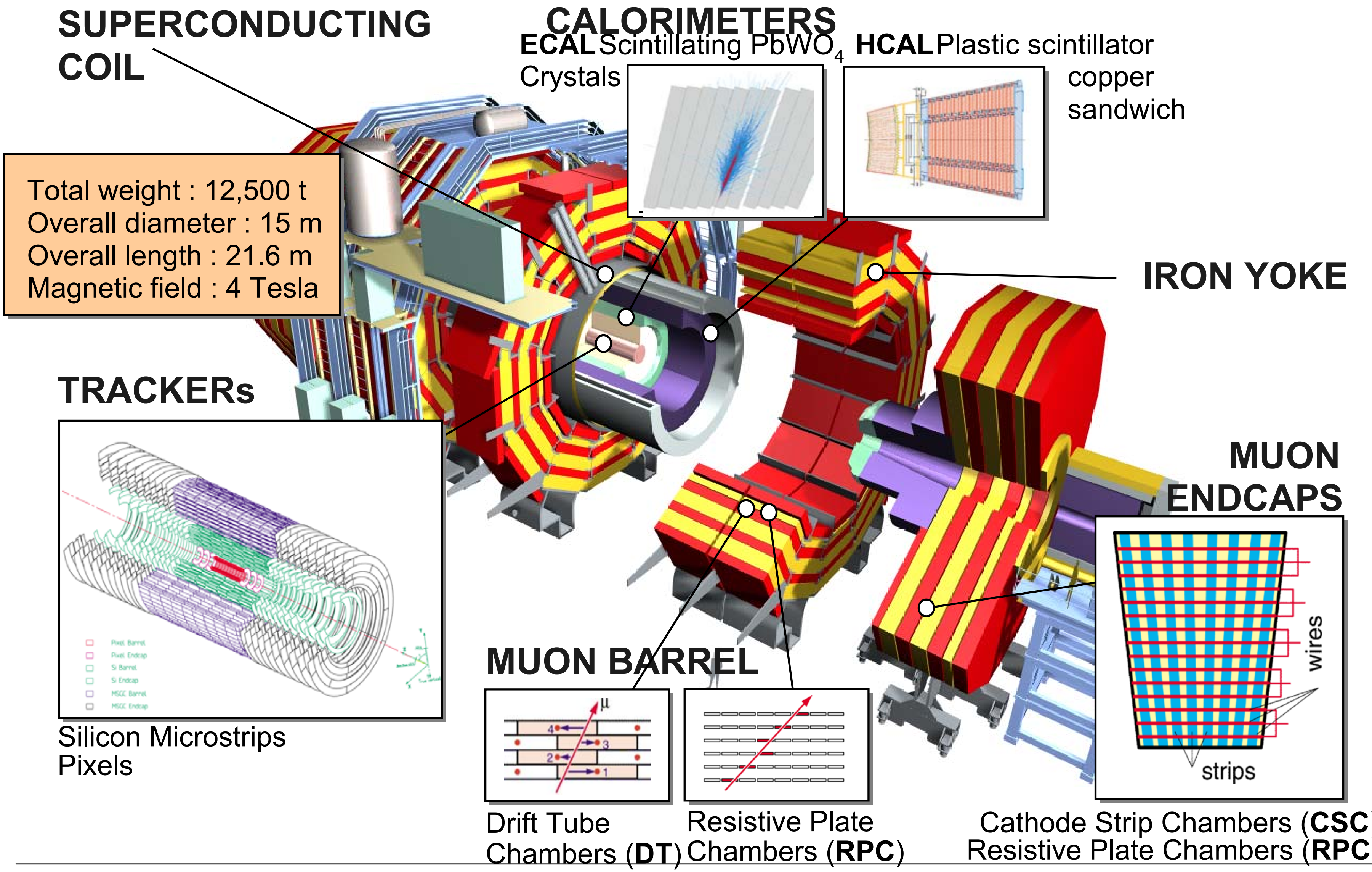


ATLAS

Length : 40 m
Radius : 10 m
Weight : 7000 tons
channels : 10^8

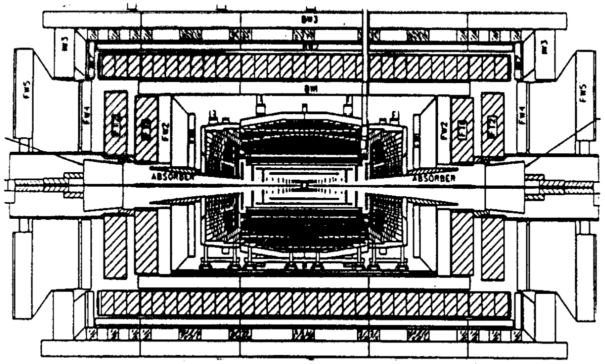


The Compact Muon Solenoid (CMS)



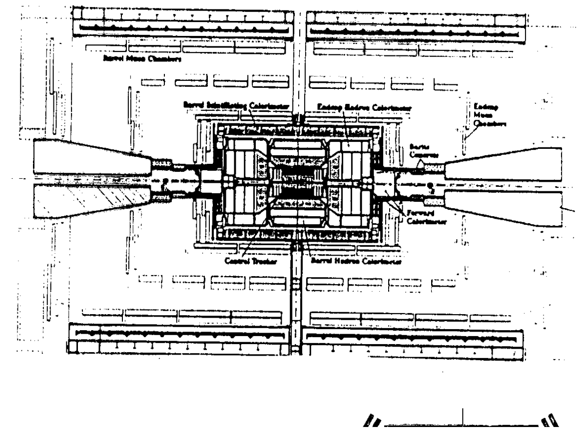
Designs of Various Detectors

SDC



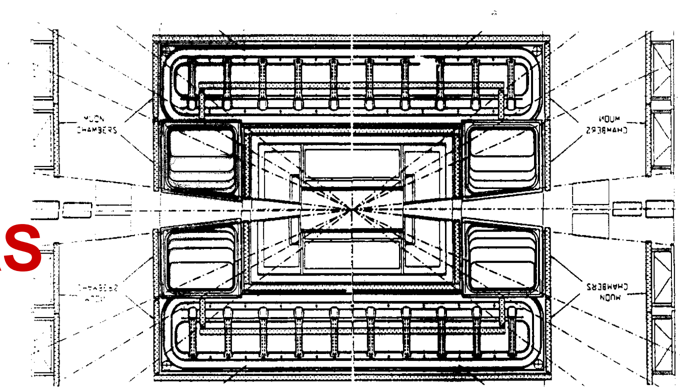
L=40m, ϕ=22m, Solenoid R=1.7m, B=2T
Fe Toroid 6.75m < R < 8.25 m, B=1.8T

GEM



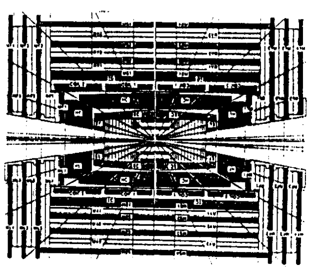
L=38m, ϕ=24m, Solenoid R=9m, B=0.8T

ATLAS



L=40m, ϕ=20m, Solenoid R=1.1.5m, B=2T
Air Toroid 5m < R < 10 m, B=0.6T

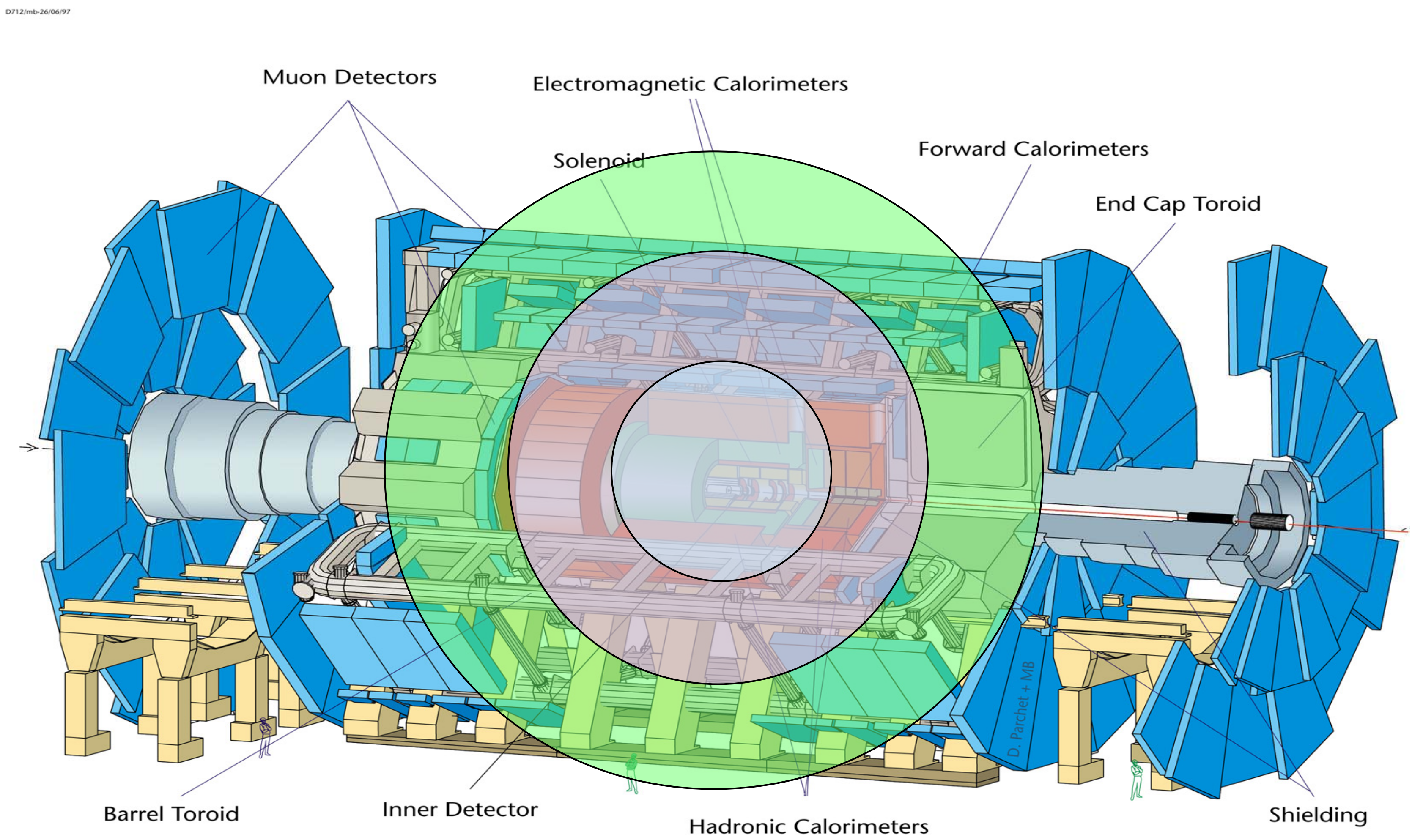
CMS



L=20m, ϕ=13m, Solenoid R=3, B=4T

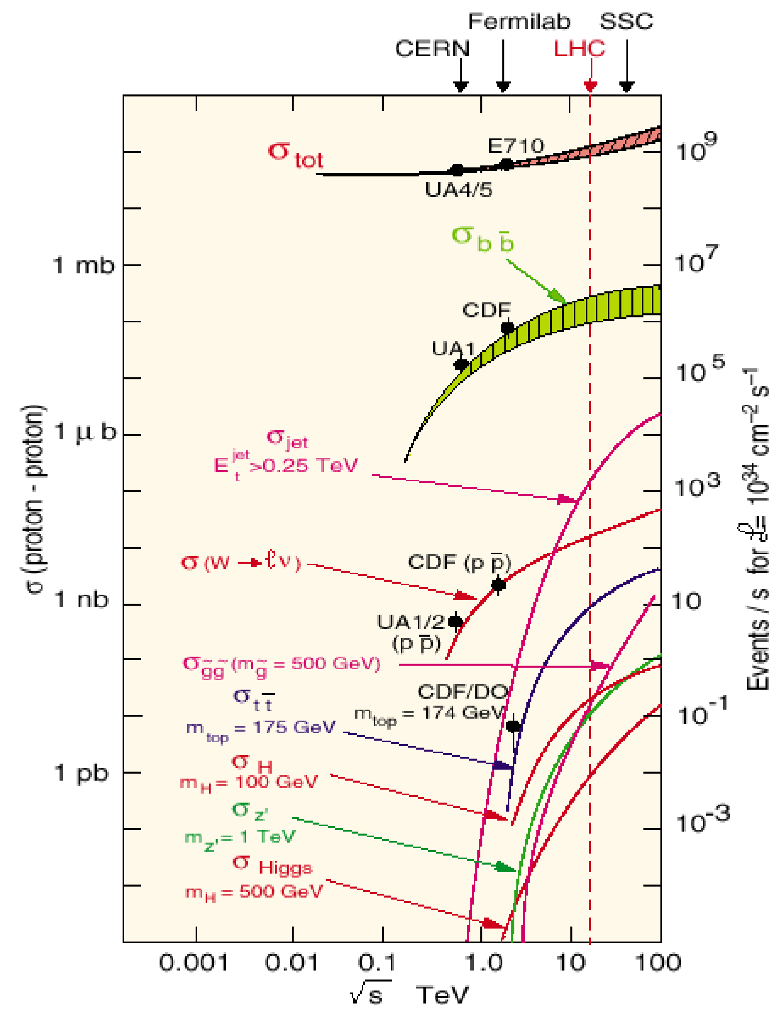
Time of Flight

c=30cm/ns; in 25ns, s=7.5m

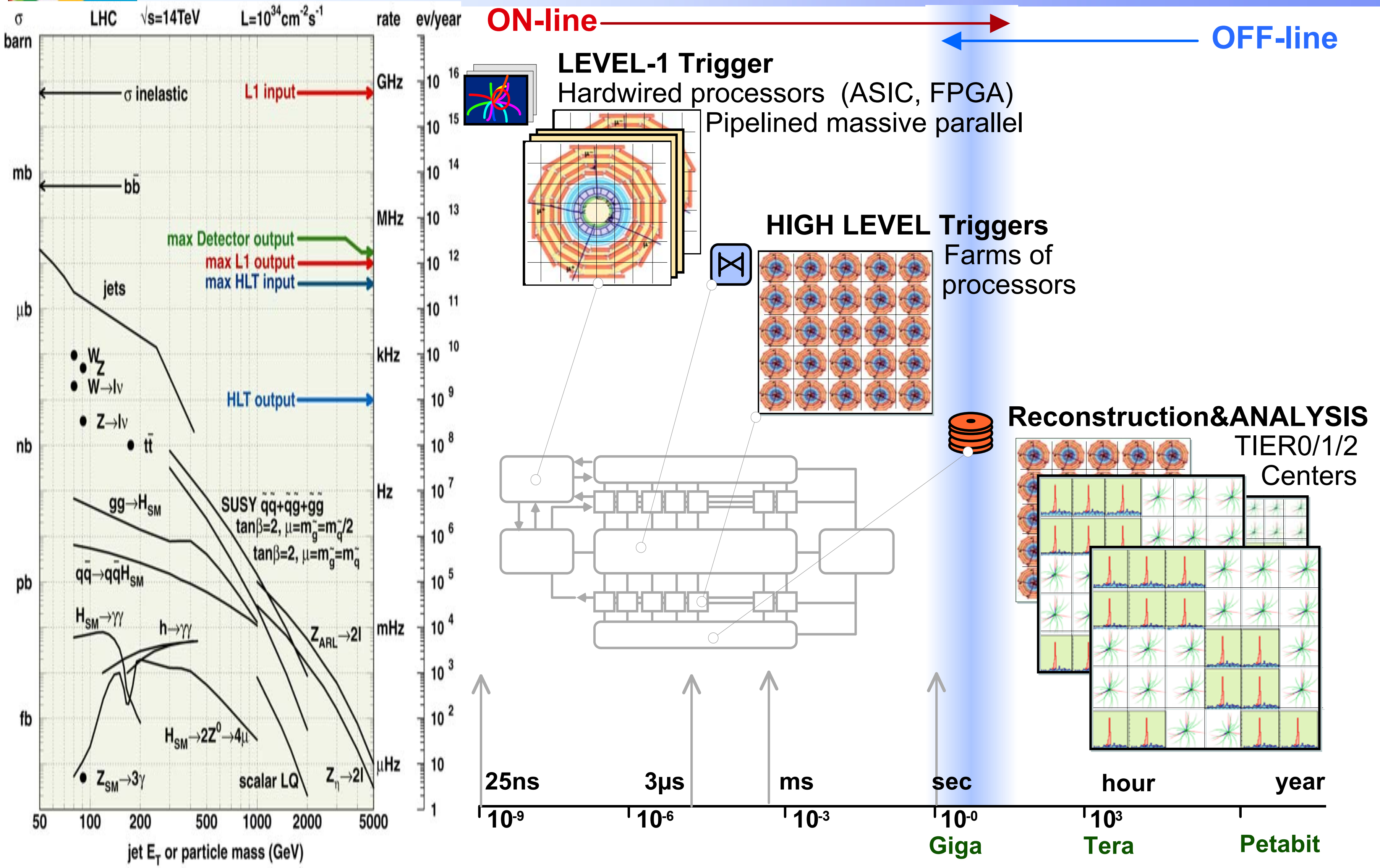


Selectivity: the physics

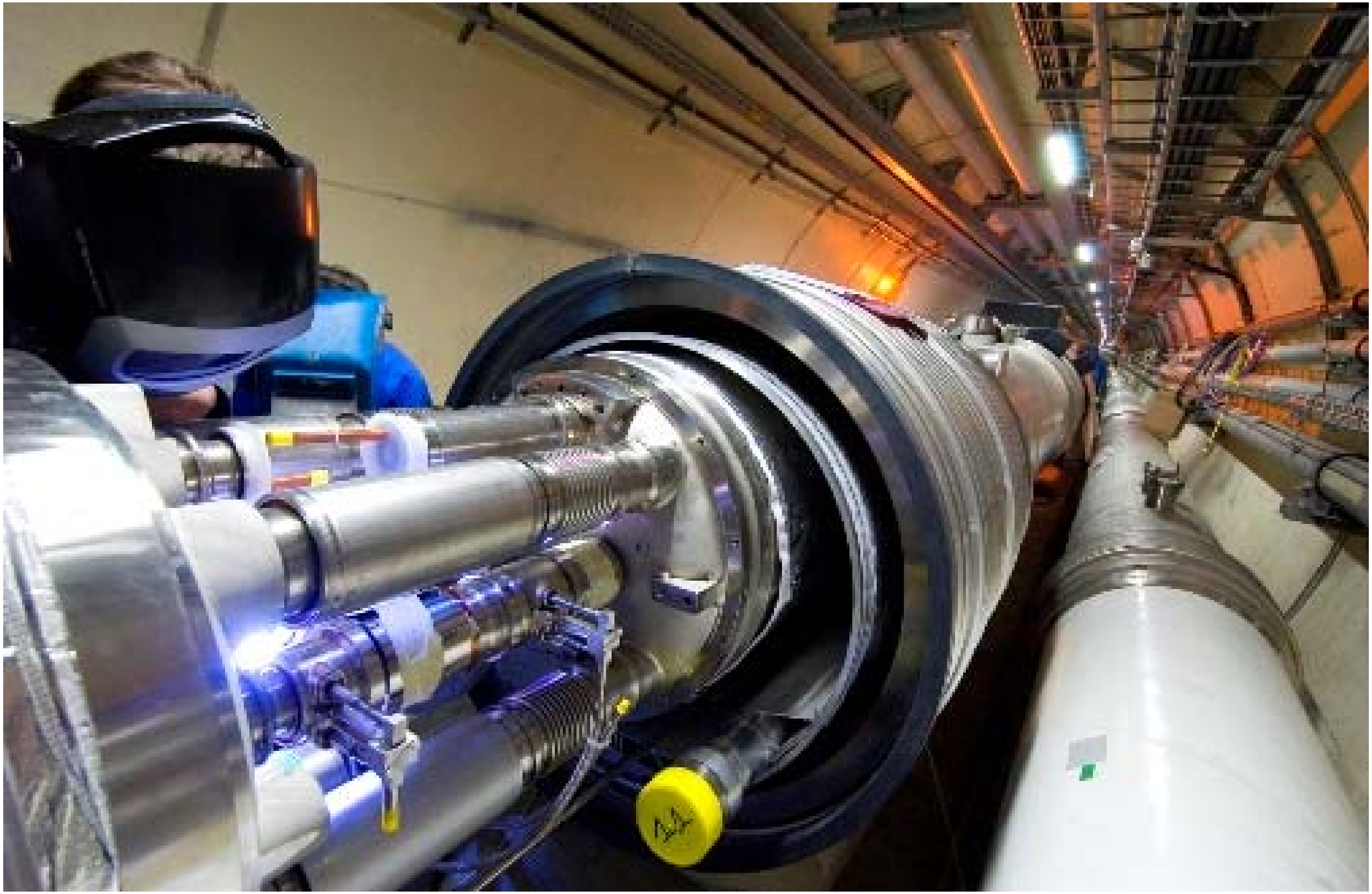
- **Cross sections for various physics processes vary over many orders of magnitude**
  - Inelastic: 10^9 Hz
  - $W \rightarrow \ell\,\nu$: 10^2 Hz
  - t t production: 10 Hz
  - Higgs (100 GeV/c^2): 0.1 Hz
  - Higgs (600 GeV/c^2): 10^{-2} Hz
- **Selection needed: 1:10^{10-11}**
  - Before branching fractions...



Physics selection at the LHC

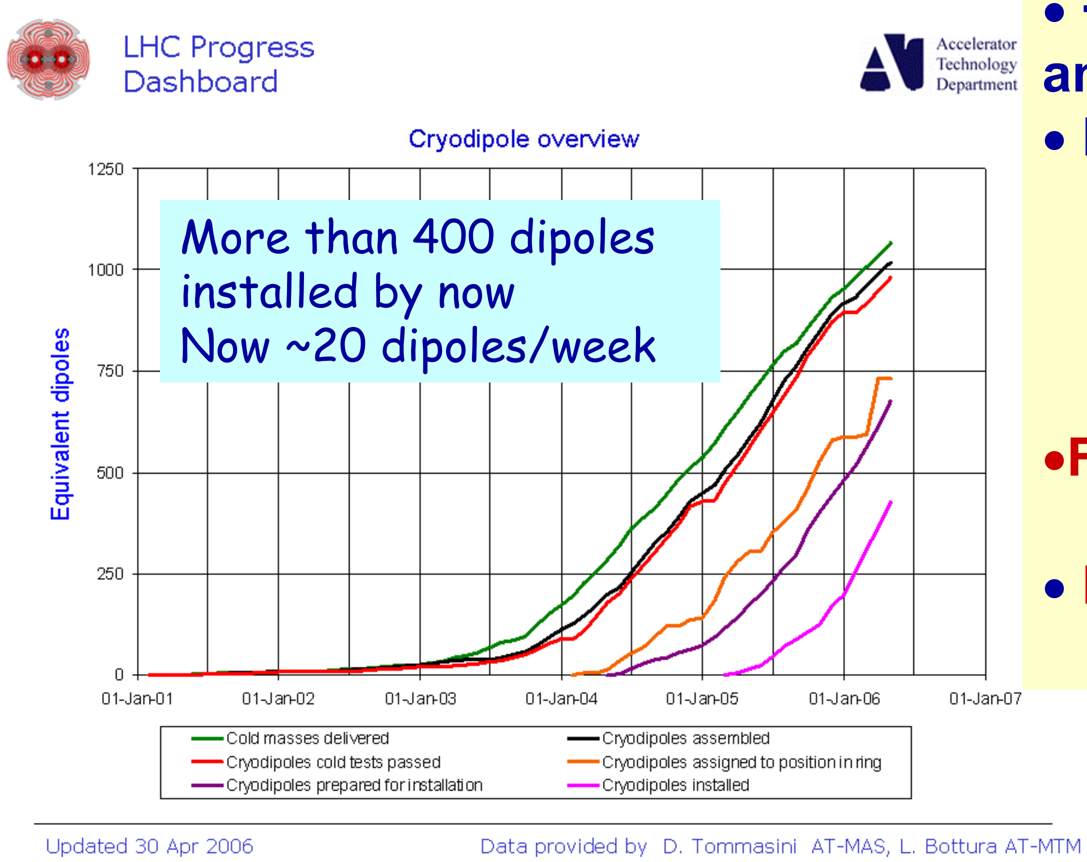


The LHC is coming!



The LHC is coming!

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



More than 400 dipoles installed by now
Now ~20 dipoles/week

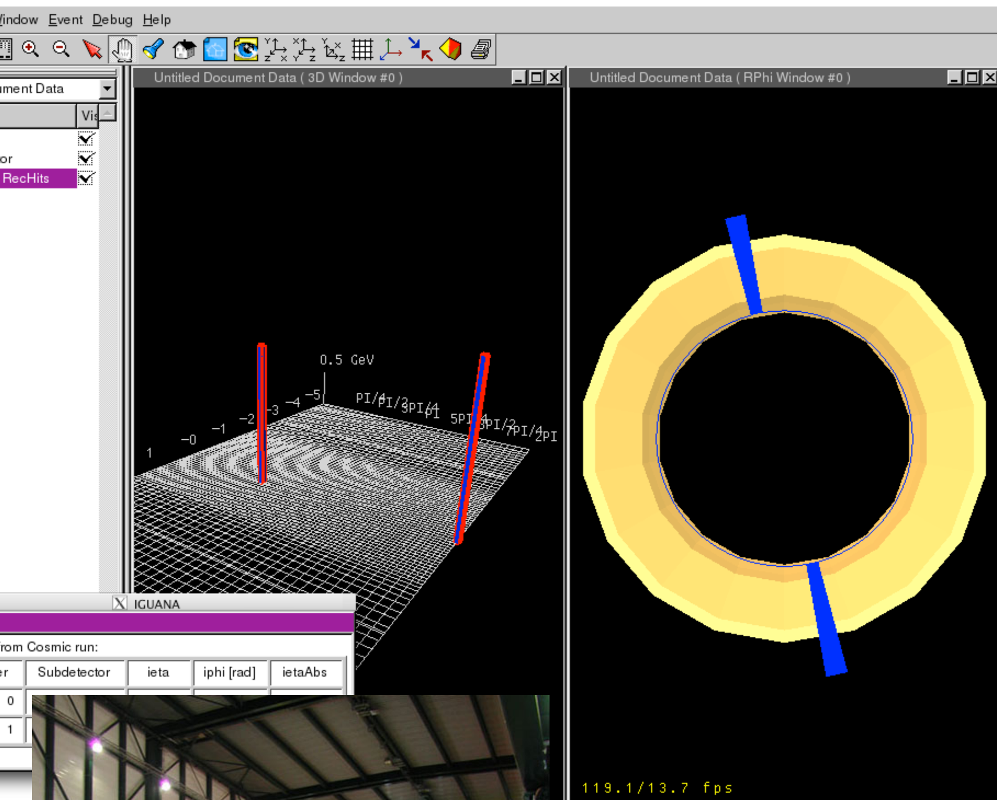
LHC Schedule(*)

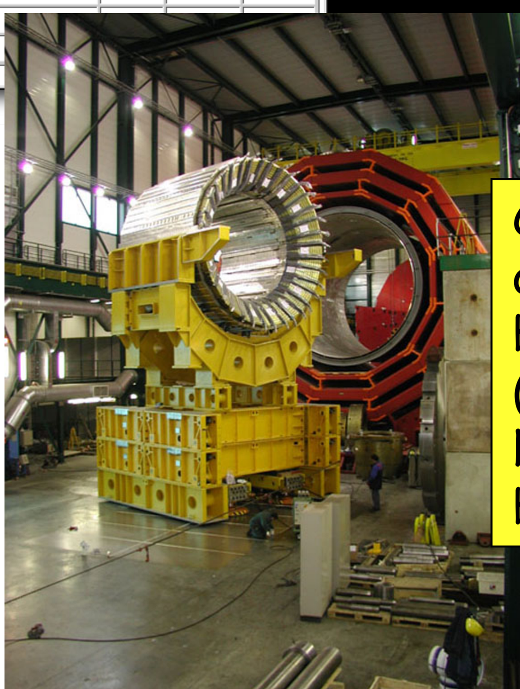
- **Expts ready to for LHC closed and set up for beam: Aug 31 07**
- **+6 wks ~mid Oct: expts closed and ready for collisions**
- **First collisions ~ in Nov 07**
  - **New plan: 900 GeV**
  - **Short pilot run**
  - **O(10) pb^{-1} ? 100?**
  - **Discussions on higher s…**
- **First physics run in 2008**
  - **one to a few fb^{-1}?**
- **Physics run in 2009 +…**
  - **10-20 fb^{-1}/year $\Rightarrow$100 fb^{-1}/yr**

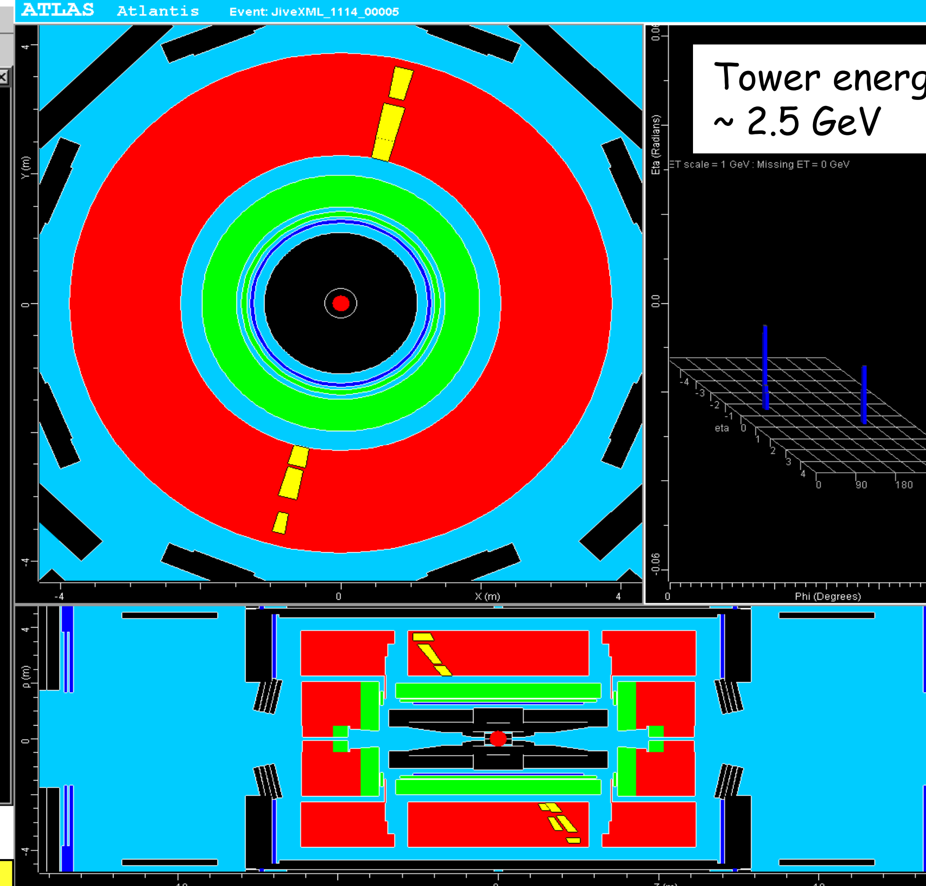
(*) eg. M. Lamont et al, April 2005.
Achtung! Lumi estimates are mine, not from the machine
Update in ~July 2006

The experiments are coming!

- Construction finishing for many sub-detectors
- ATLAS has been installing for over two years now
  - Big parts of CMS installation on surface
- Toroids, solenoid tests
  - Big CMS magnet test scheduled in mid-July 2006
- Turning to commissioning
  - Taking cosmics, debugging readout, etc





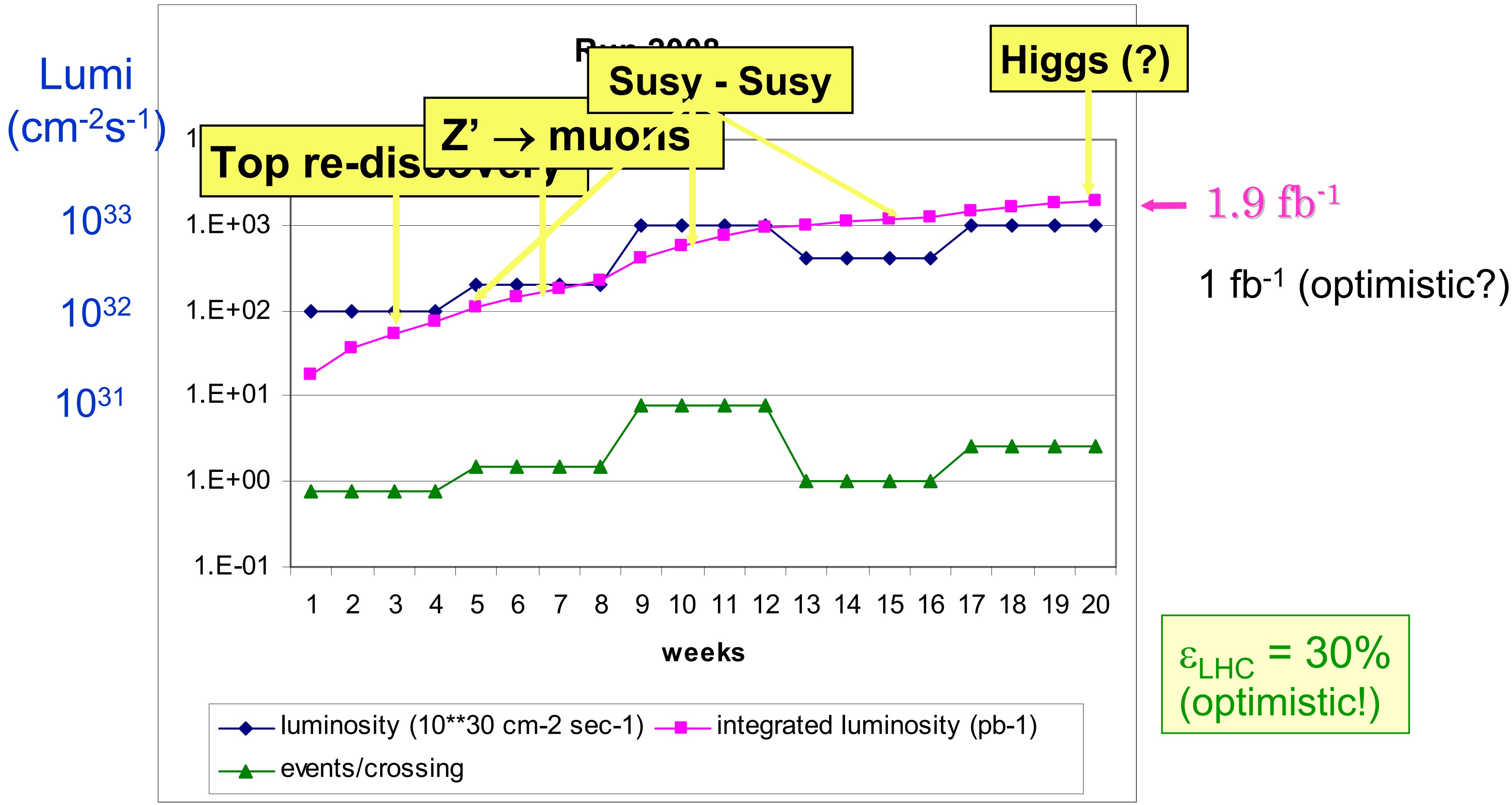


Cosmic muons observed by CMS at IP5 (recorded by hadron barrel calorimeter)

Cosmic muons observed by ATLAS in the pit (recorded by hadron Tilecal calorimeter)

LHC startup: CMS/ATLAS

- **Integrated luminosity with the current LHC plans**



ε_{LHC} = 30% (optimistic!)

EWK Symmetry Breaking

Standard Model Higgs search

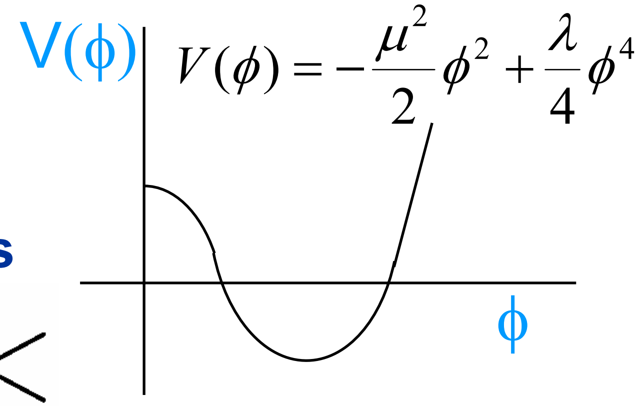
Strong EWK interaction

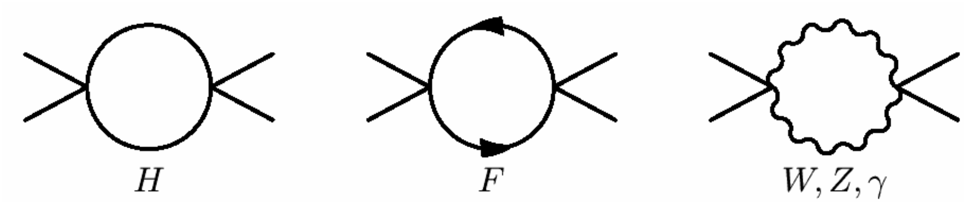
Higgs mechanism in SUSY – the MSSM Higgs bosons

SUSY Higgs search

Limits on M_H (I): EWK vaccum stability

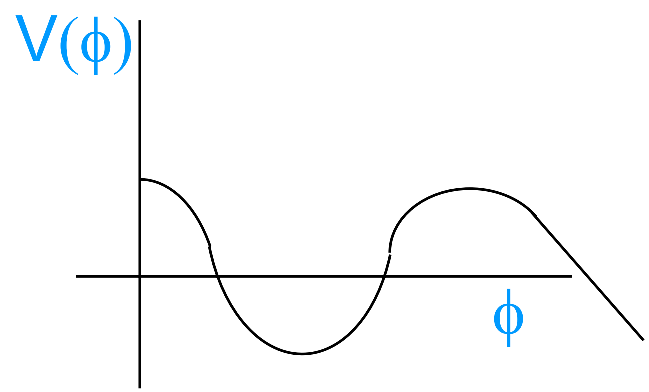
- **Central to the Higgs mechanism: that point with vev≠0 is stable (genuine minimum)**
  - **Radiative corrections can change this**





$$\Delta V \sim \frac{1}{v^4}\left(M_H{}^4 + 6M_W{}^4 + 3M_Z{}^4 - 12m_t{}^4\right)H^4 \log\left(H^2/v^2\right)$$

- For large top masses, potential can curve back down; two terms fighting:
- $\lambda\phi^4$ vs ~ - $(m_t/v)^4$
- And since $M_H^2 \sim \lambda v^2$, get a lower bound on M_H (~ 130 GeV)



Limits on M_H (II): triviality bound

- **From previous discussion: need a high value of λ (i.e. self-coupling) to protect the vacuum**
  - However, the running of the coupling results in an increase with Q^2:

$$\lambda(Q^2) = \frac{\lambda(Q_0^{\ 2})}{1 - \lambda(Q_0^{\ 2})/16\pi^2 \log(Q^2/Q_0^{\ 2})}$$

  - So, as $Q^2 \to \infty$, $\lambda \to \infty$
  - Alternative: if λ is normalized to a finite value at the pole then it must vanish at low Q^2. Theory is non-interacting → "trivial"
  - Way out: assume that analysis breaks down at some scale Λ (clearly, when gravity gets added, things will change)

$$\Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

Information (limits) on M_H: summary

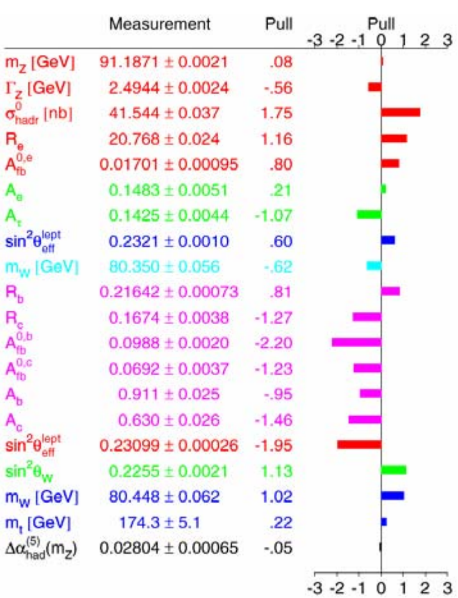
- **Triviality bound**
  - $<\phi_0>\neq 0$

$$\Lambda \leq M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

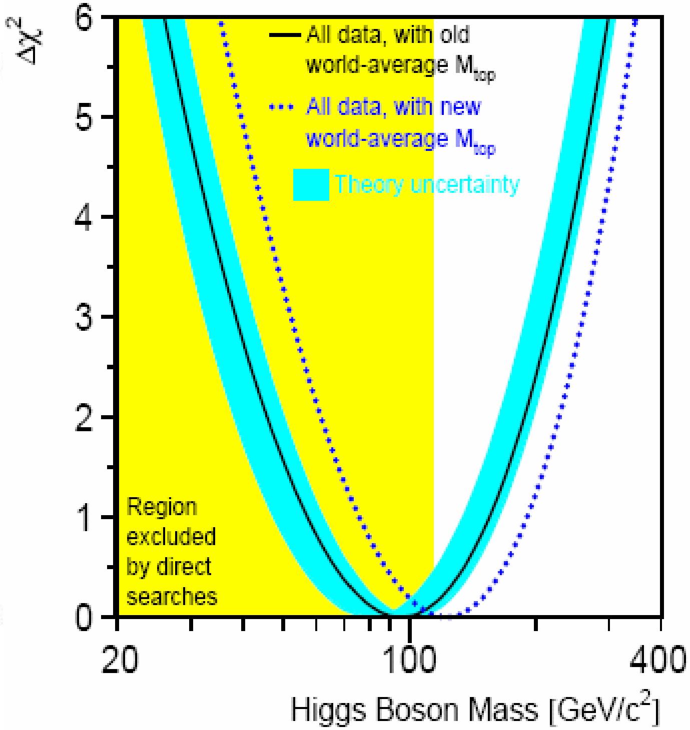
- **Vacuum stability**

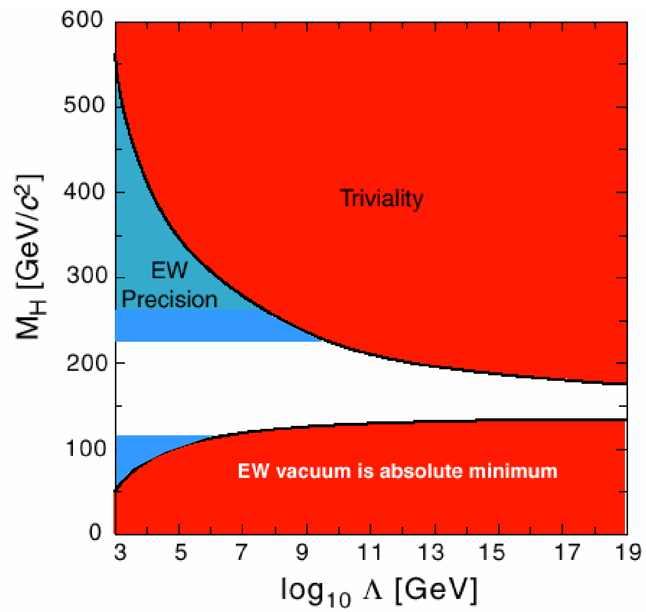
$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$$

- **Precision EWK measurements**



	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A_{fb}^{0,e}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A_{fb}^{0,b}$	0.0988 ± 0.0020	-2.20
$A_{fb}^{0,c}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05

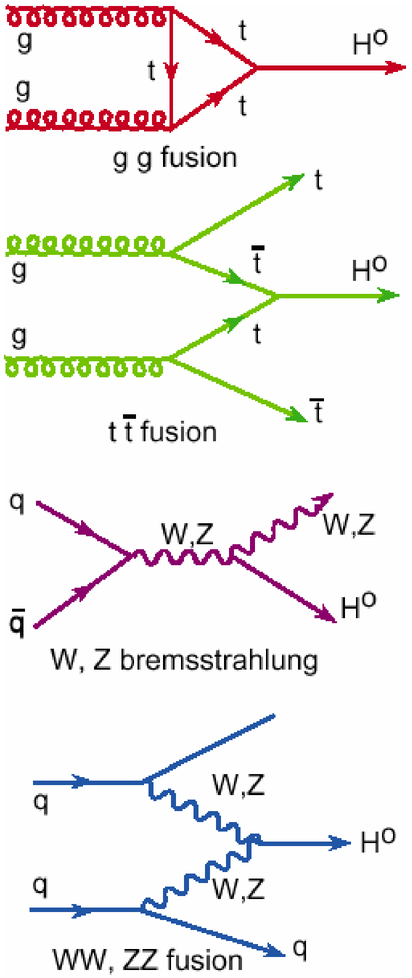


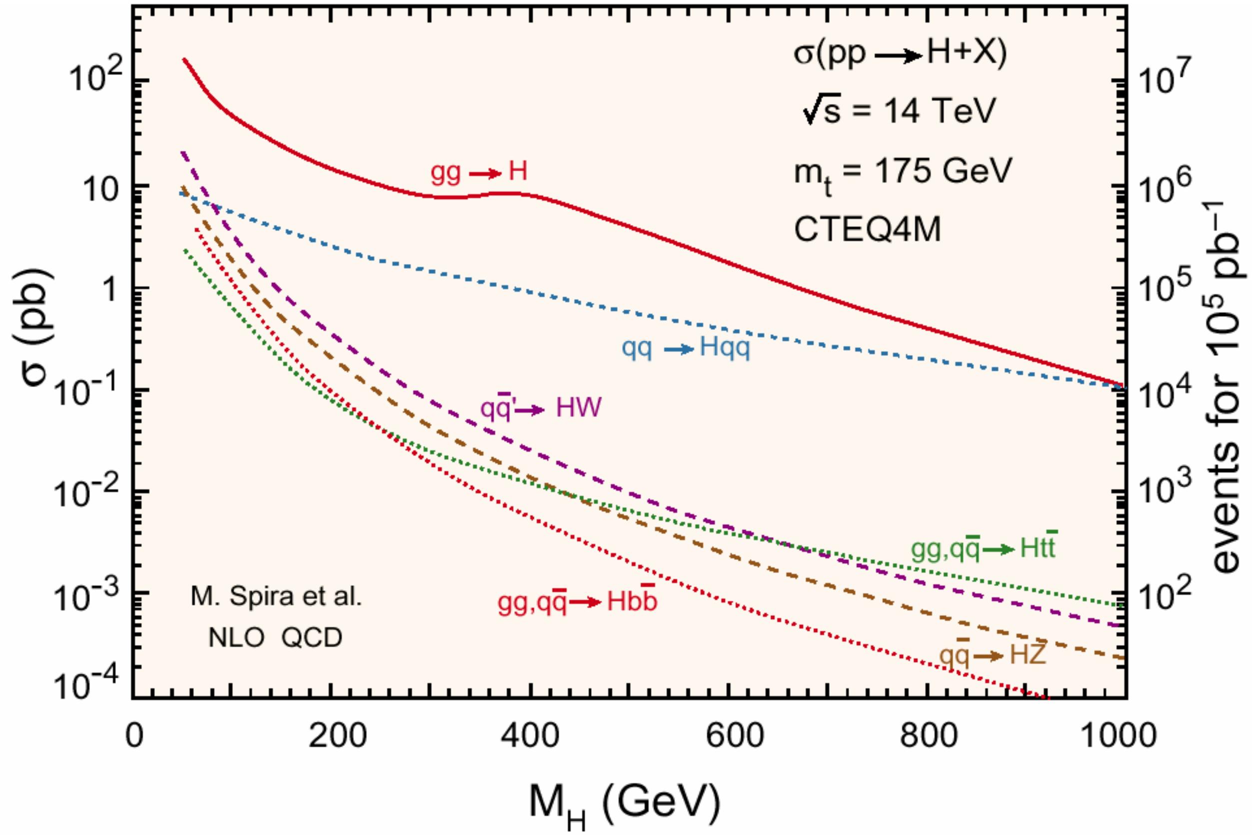


LEP direct search: M_H>114 GeV/c^2

SM Higgs (I)

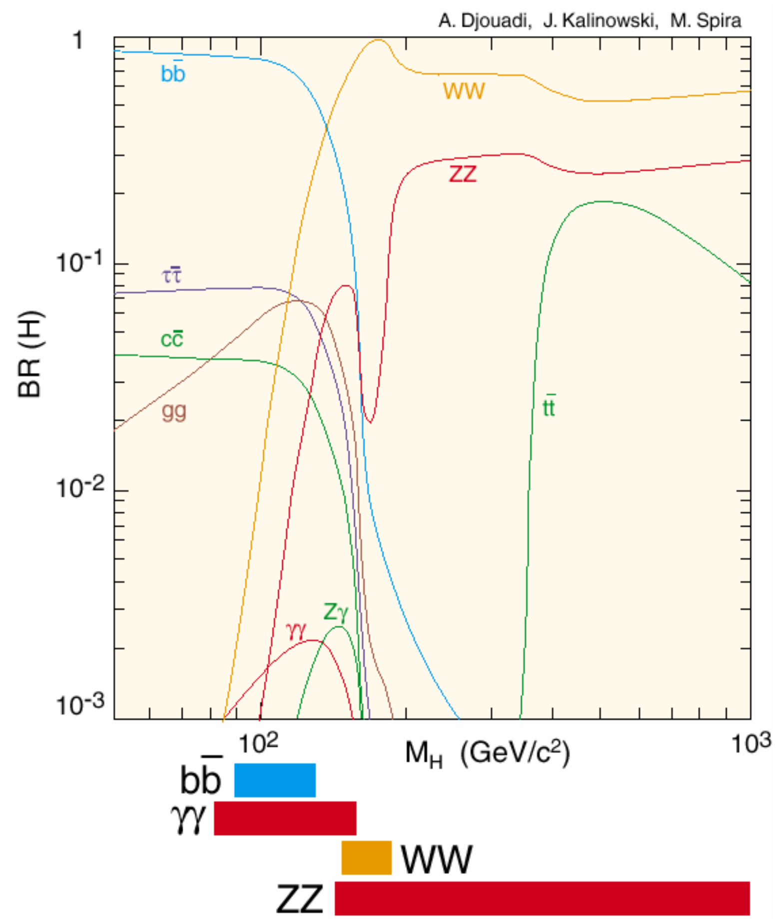
- **Production mechanisms & cross section**





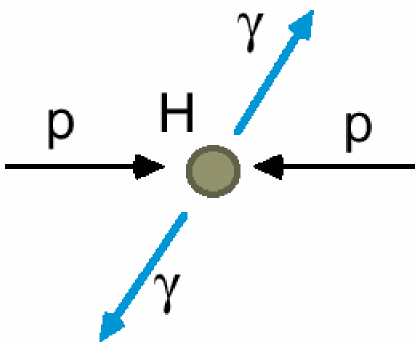
SM Higgs (II)

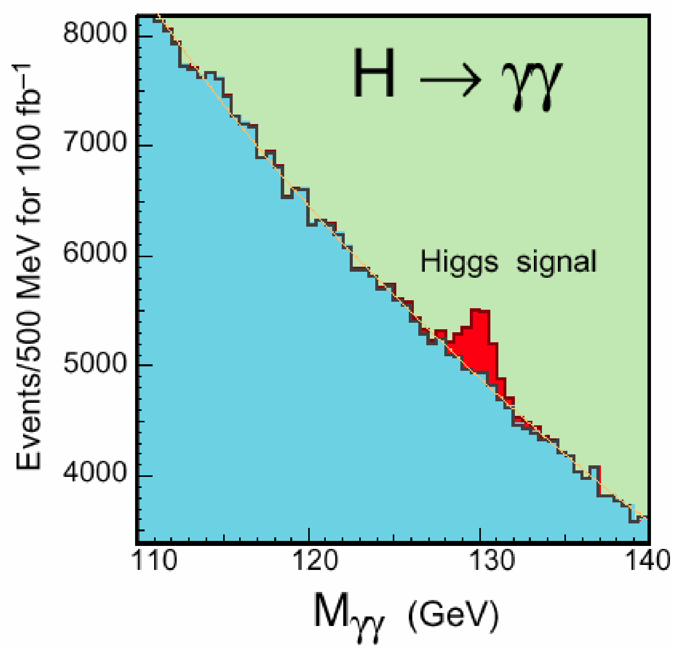
- **Decays & discovery channels**
  - Higgs couples to m_f^2
    - Heaviest available fermion (b quark) always dominates
    - Until WW, ZZ thresholds open
  - Low mass: b quarks → jets; resolution ~ 15%
    - Only chance is EM energy (use $\gamma\gamma$ decay mode)
  - Once $M_H > 2M_Z$, use this
    - W decays to jets or lepton+neutrino (E_T^{miss})

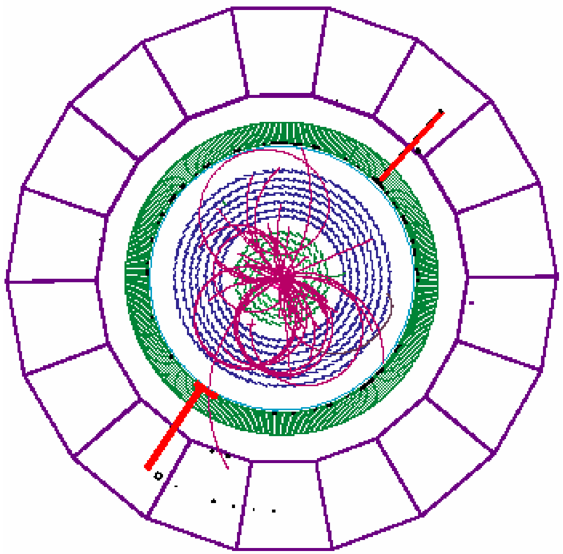


Low mass Higgs (M_H<140 GeV/c^2)

- **H→γγ: decay is rare (B~10^{-3})**
  - **But with good resolution, one gets a mass peak**
  - **Motivation for LAr/$PbWO_4$ calorimeters**
  - **CMS: at 100 GeV, σ≈1GeV**
    - **S/B ≈ 1:20**

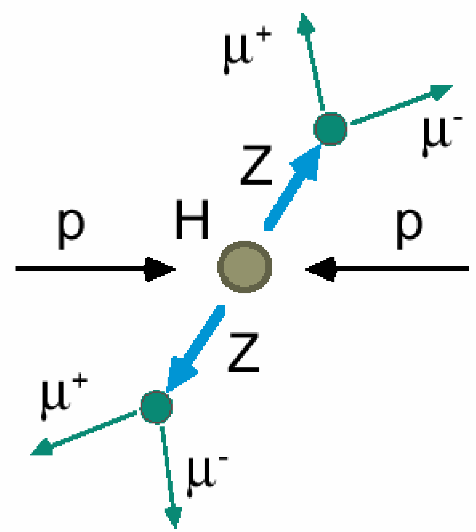


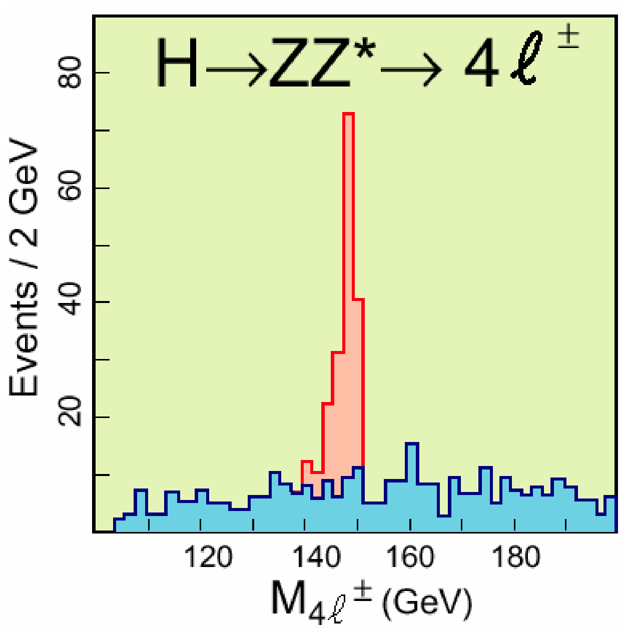


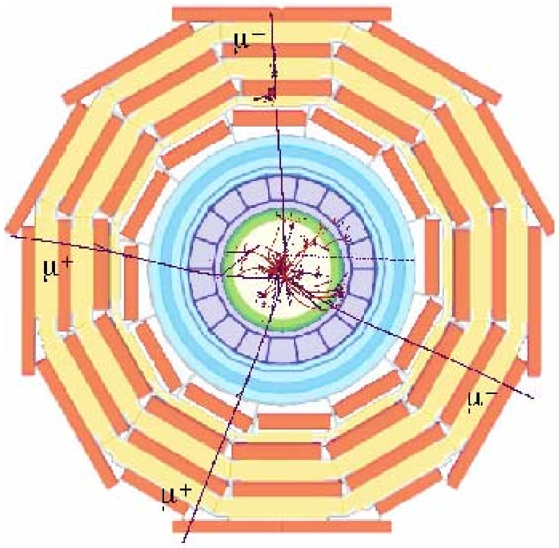


Intermediate mass Higgs

- $H \to ZZ \to \ell^+\ell^- \ \ell^+\ell^-$ (ℓ =e,μ)
  - Very clean
    - Resolution: better than 1 GeV (around 100 GeV mass)
  - Valid for the mass range $130 < M_H < 500$ GeV/c^2

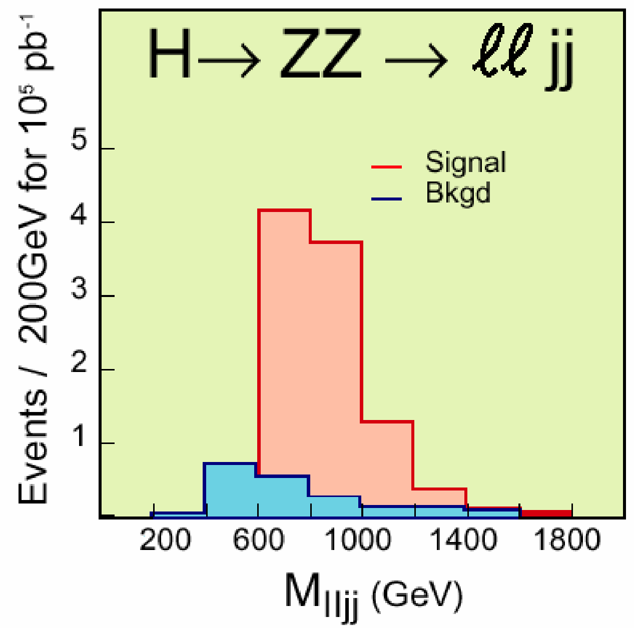


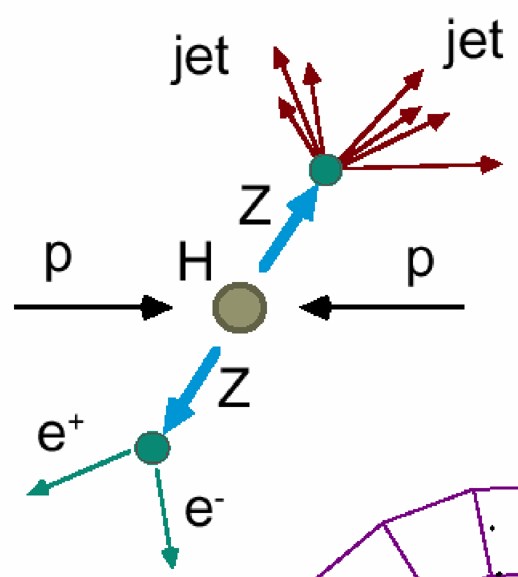


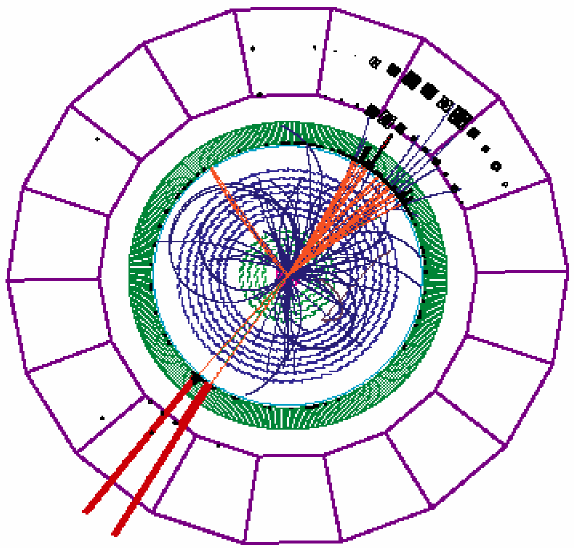


High mass Higgs

- **$H \to ZZ \to \ell^+\ell^-$ jet jet**
  - **Need higher Branching fraction (also $\nu\nu$ for the highest masses ~ 800 GeV/c^2)**
  - **At the limit of statistics**

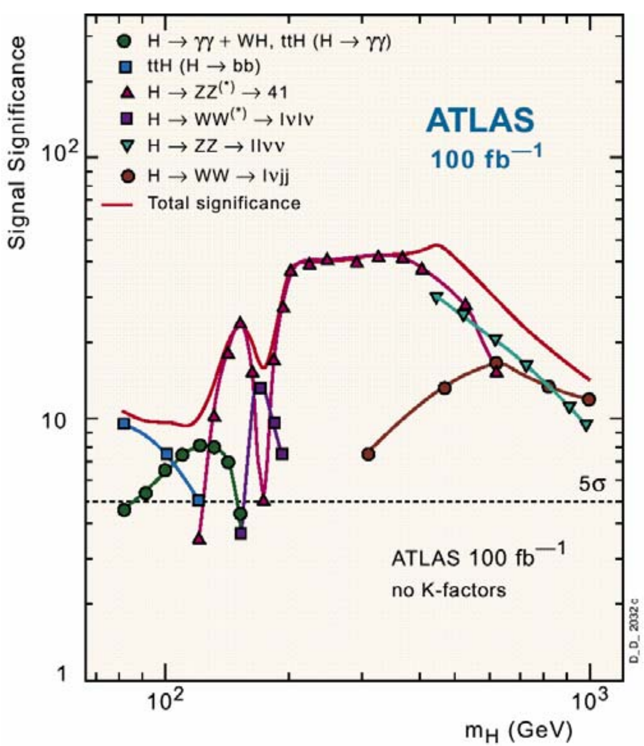


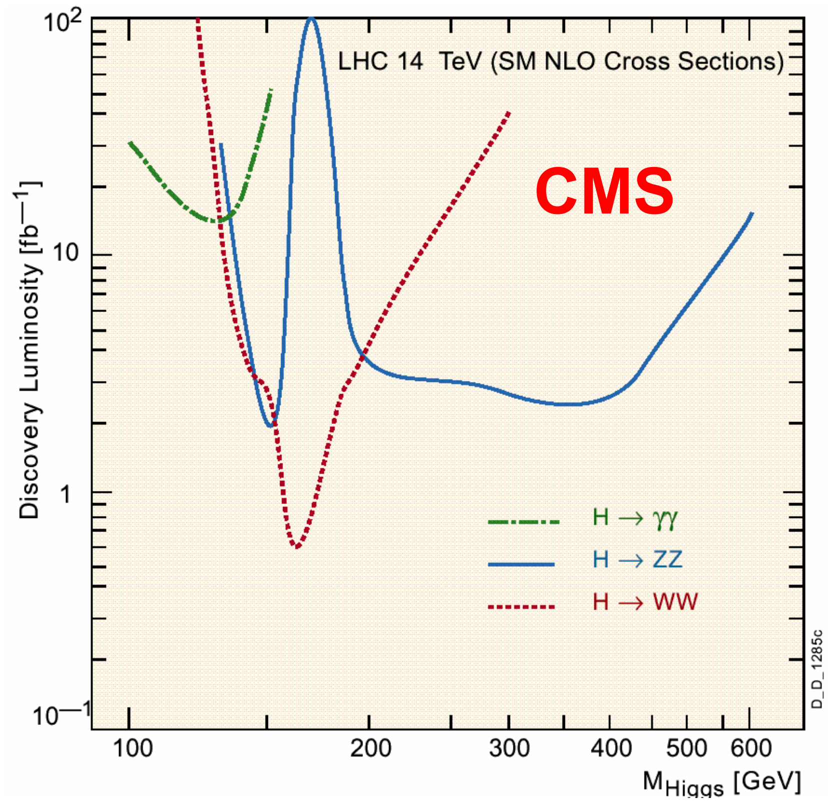




Higgs discovery prospects @ LHC

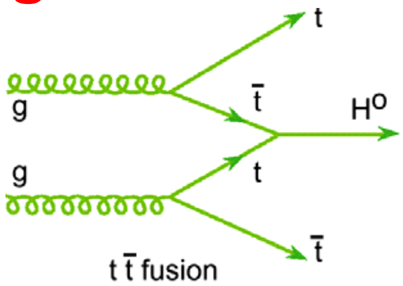
- **The LHC can probe the entire set of "allowed" Higgs mass values;**
  - **in most cases a few months at low luminosity are adequate for a 5σ observation**



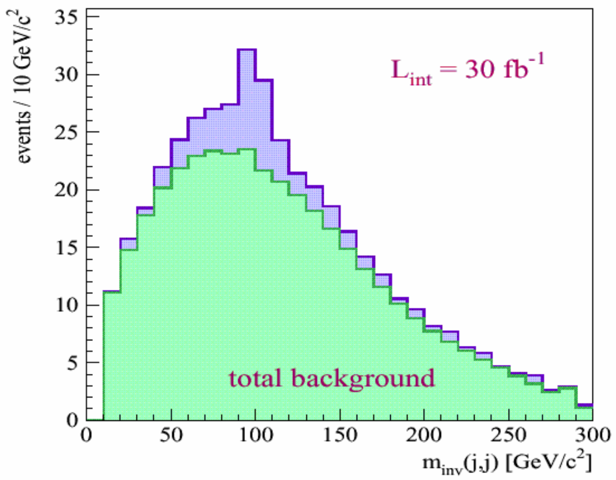


Other channels: $H \rightarrow b\bar{b}$ (I)

- **Low mass Higgs; useful for coupling measurement**
  - $H \rightarrow b\bar{b}$ in $t\bar{t}H$ production
    - σ.Br=300 fb
    - Backgrounds:
      - → Wjjjj, $Wjjb\bar{b}$
      - → $t\bar{t}jj$
      - → Signal (combinatorics)
    - Tagging the t quarks helps a lot
      - → Trigger: $t \rightarrow b(e/\mu)\nu$
      - → Reconstruct both t quarks
    - In mass region 90GeV<$M(b\bar{b})$<130GeV, S/B =0.3



$t\bar{t}H^0$: $S + B$ $(100\ GeV)$

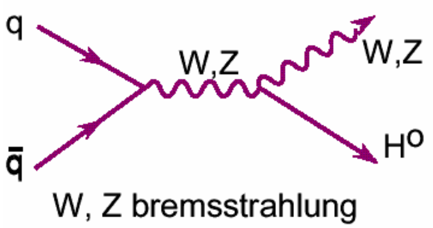


Recent from CMS: systematics make this very difficult

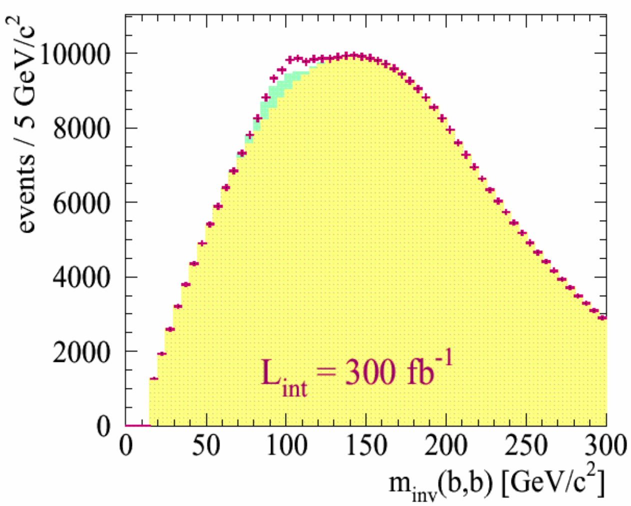
Other channels: $H \rightarrow b\bar{b}$ (II)

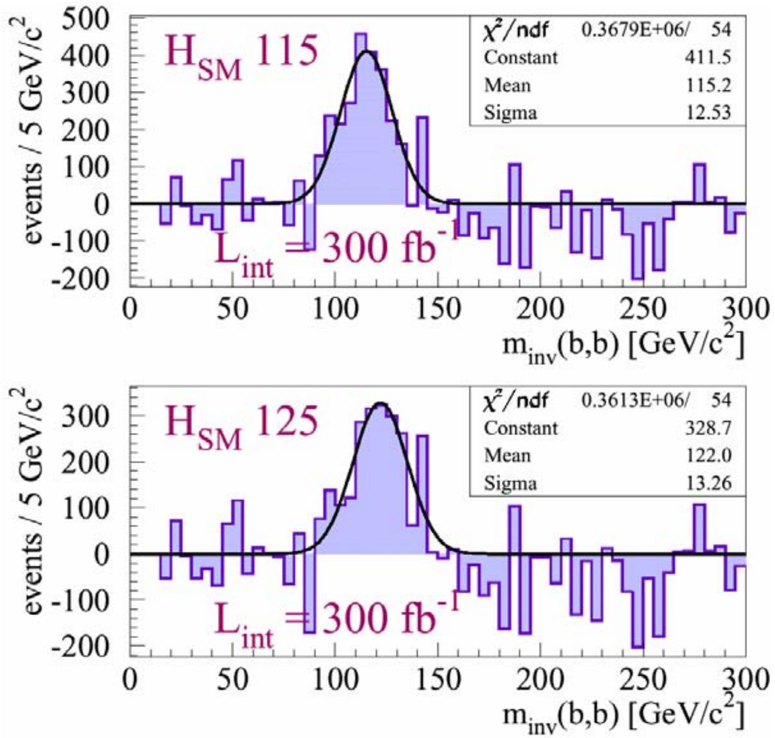
- $H \rightarrow b\bar{b}$ in WH production
  - Big background subtraction
    - Mainly: Wjj, $t\bar{t}$ (smaller: tX,WZ)
    - Example (below) at 105:

      → in mass region 88GeV<M($b\bar{b}$)<121GeV, S/B =0.03



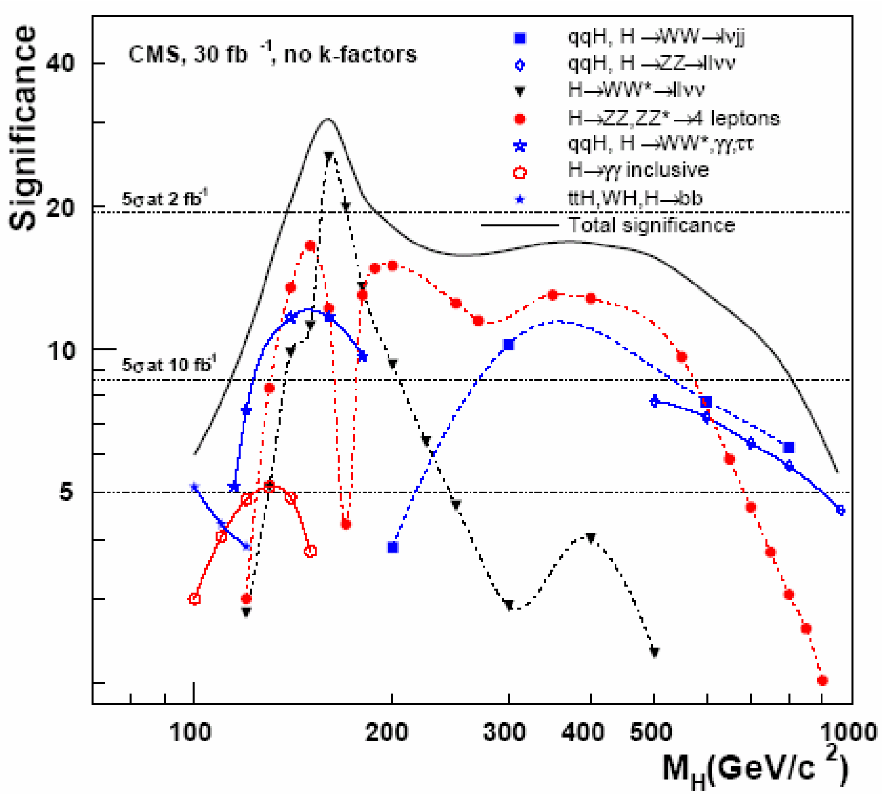
After bkg subtraction



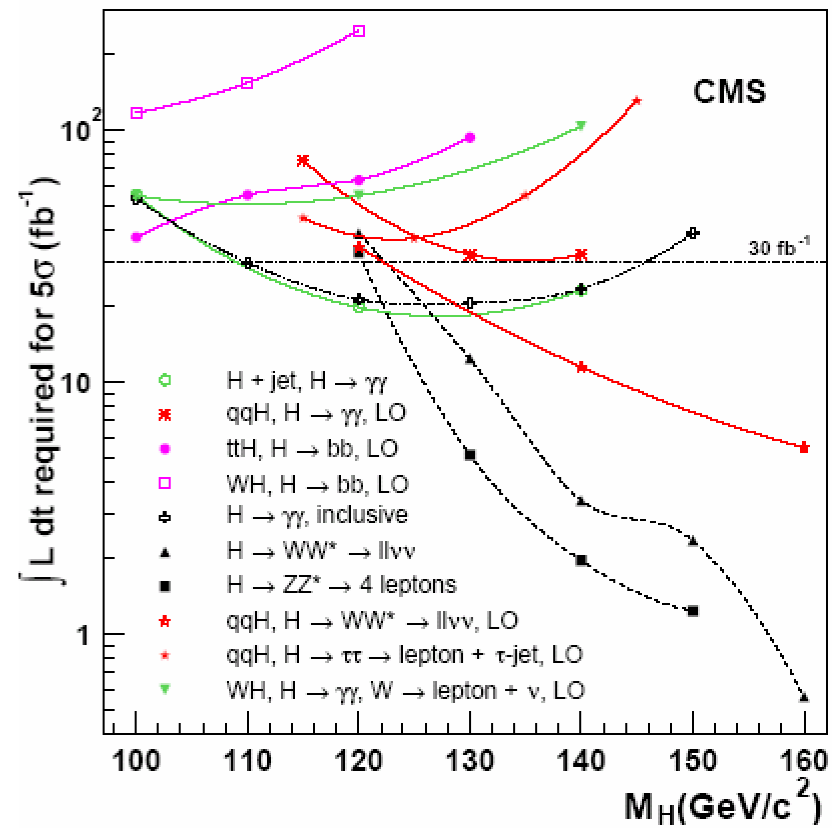


Other Higgs channels

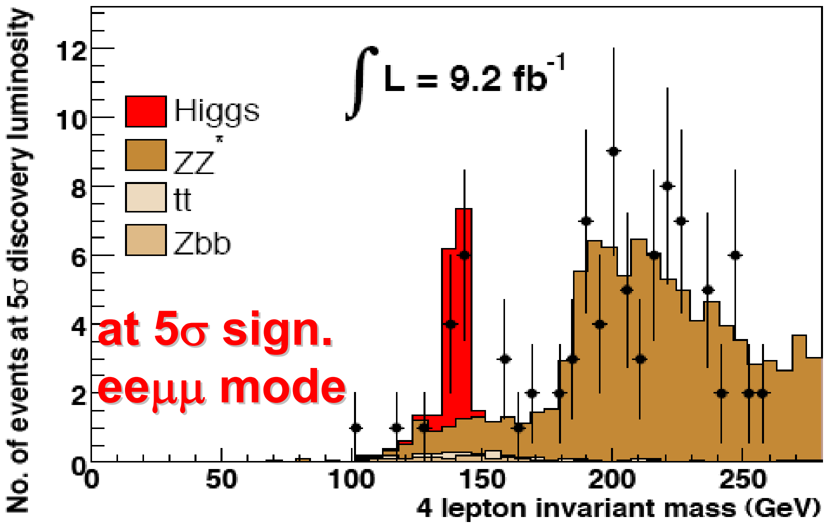
- **Significance**

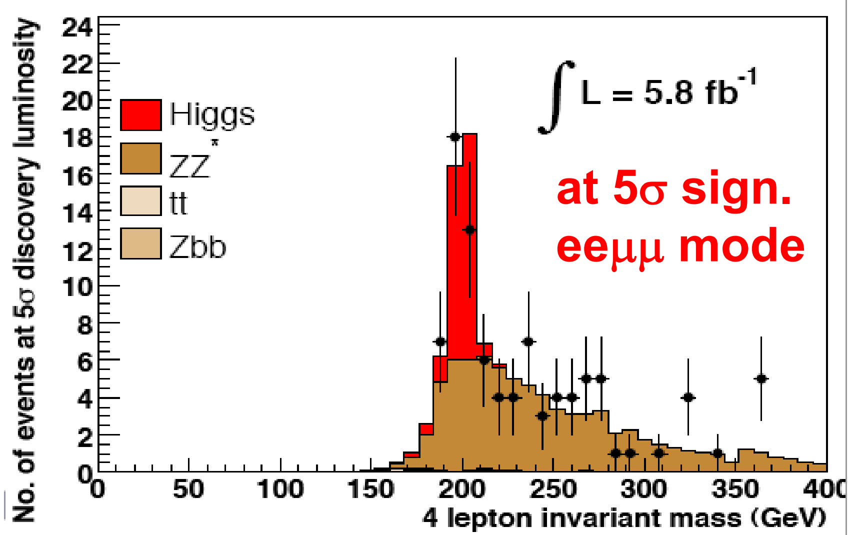


- **Luminosity required (low mass)**

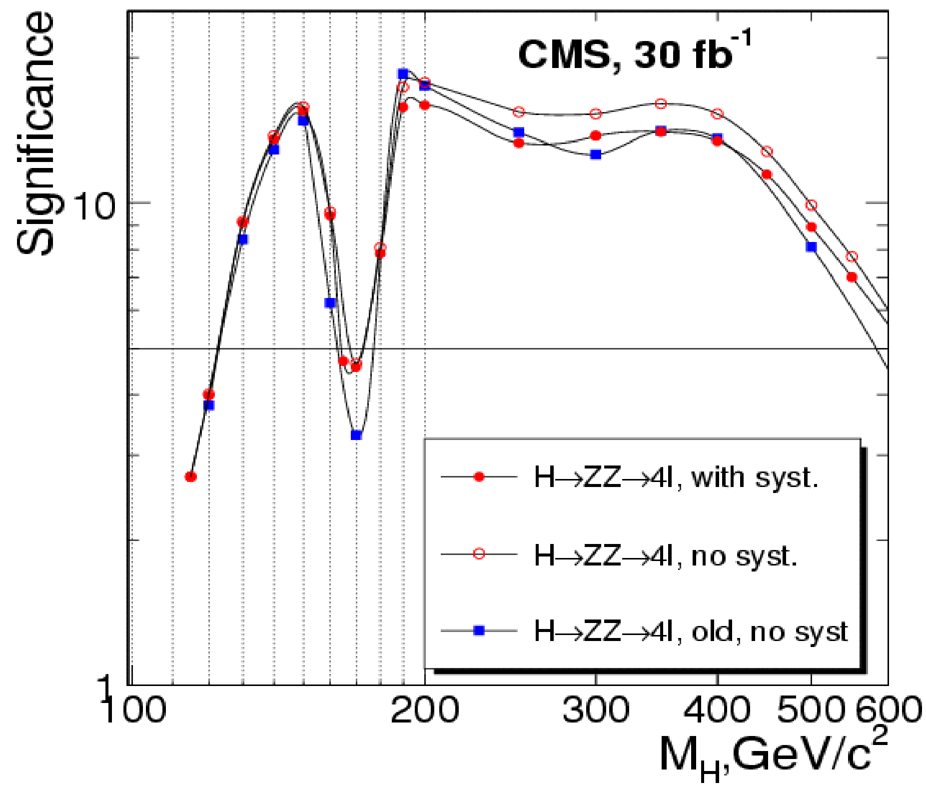


More recent work (I)

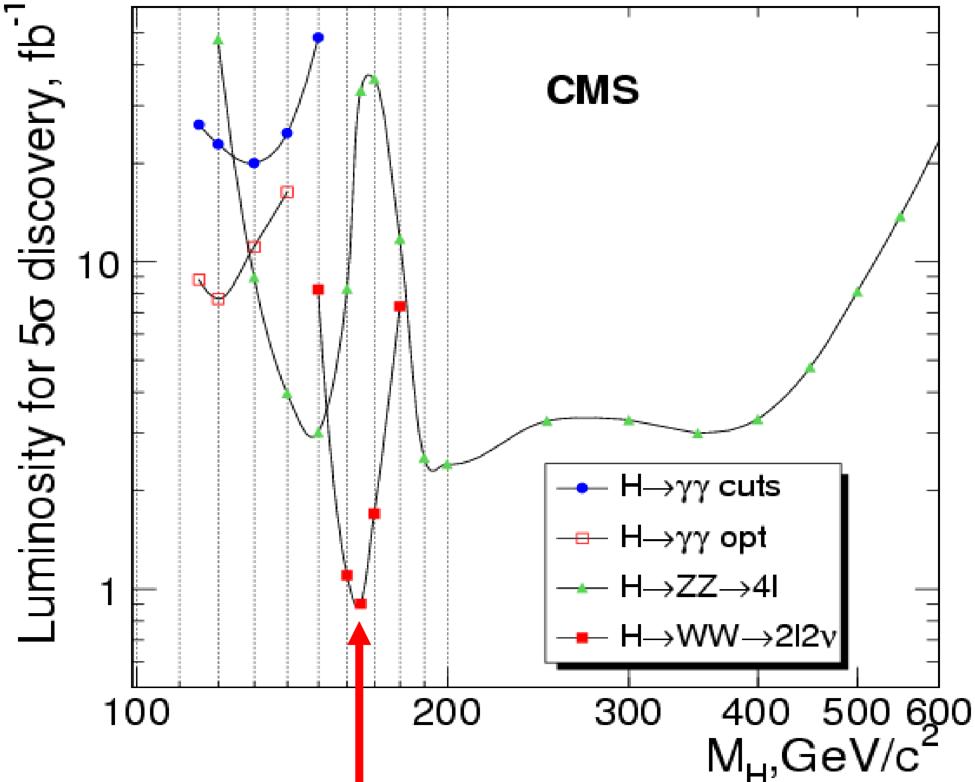




Combined 4μ, 4e, eeμμ signal significance

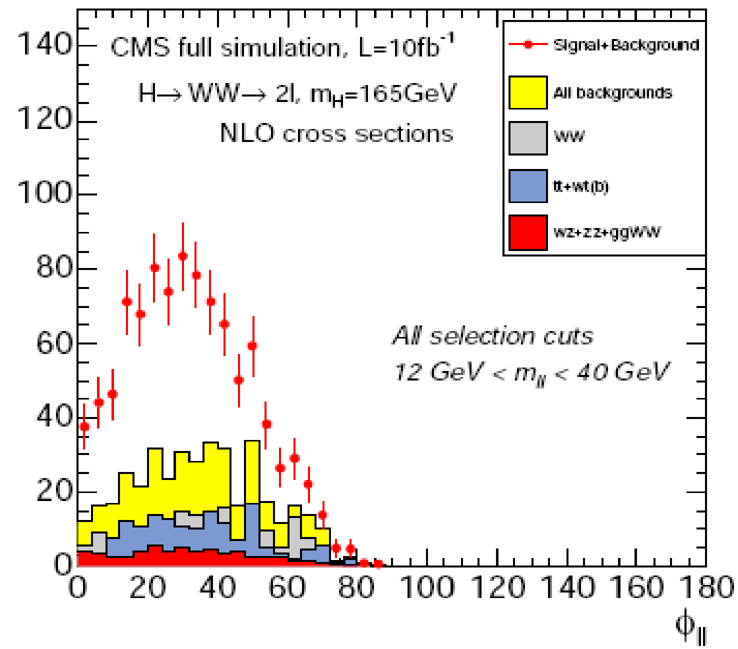


More recent work (II)



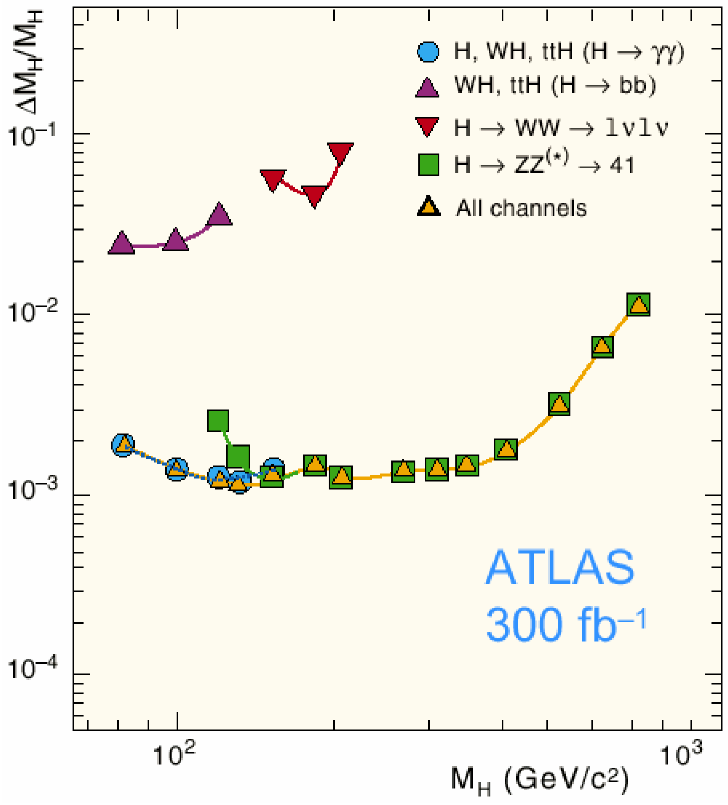
Discovery with ~1 fb-1

Very detailed studies
on SM backgrounds
and related systematics



SM Higgs properties (I): mass

- **Mass measurement**
  - Limited by absolute energy scale
    - leptons & photons: 0.1% (with Z calibration)
    - Jets: 1%
  - Resolutions:
    - For $\gamma\gamma$ & $4\ell \approx 1.5$ GeV/c^2
    - For bb ≈ 15 GeV/c^2
  - At large masses: decreasing precision due to large Γ_H
  - CMS ≈ ATLAS



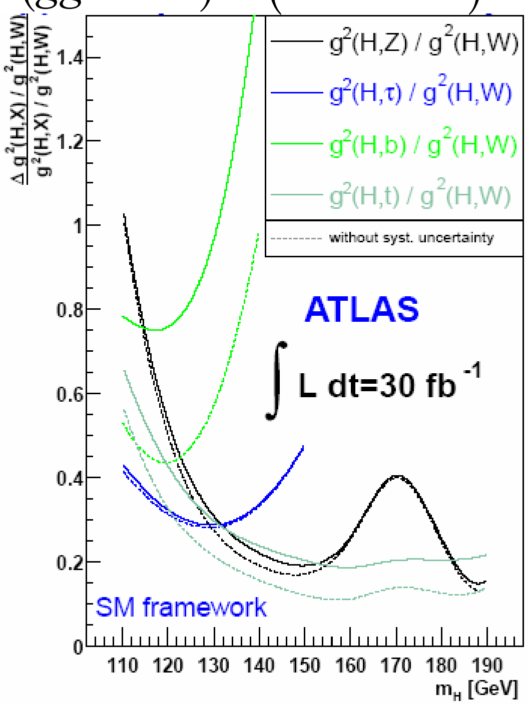
Higgs properties (II): couplings

$$\frac{\sigma(gg\to H)\cdot B(H\to WW)}{\sigma(gg\to H)\cdot B(H\to ZZ)}=\frac{\Gamma_W}{\Gamma_Z}$$

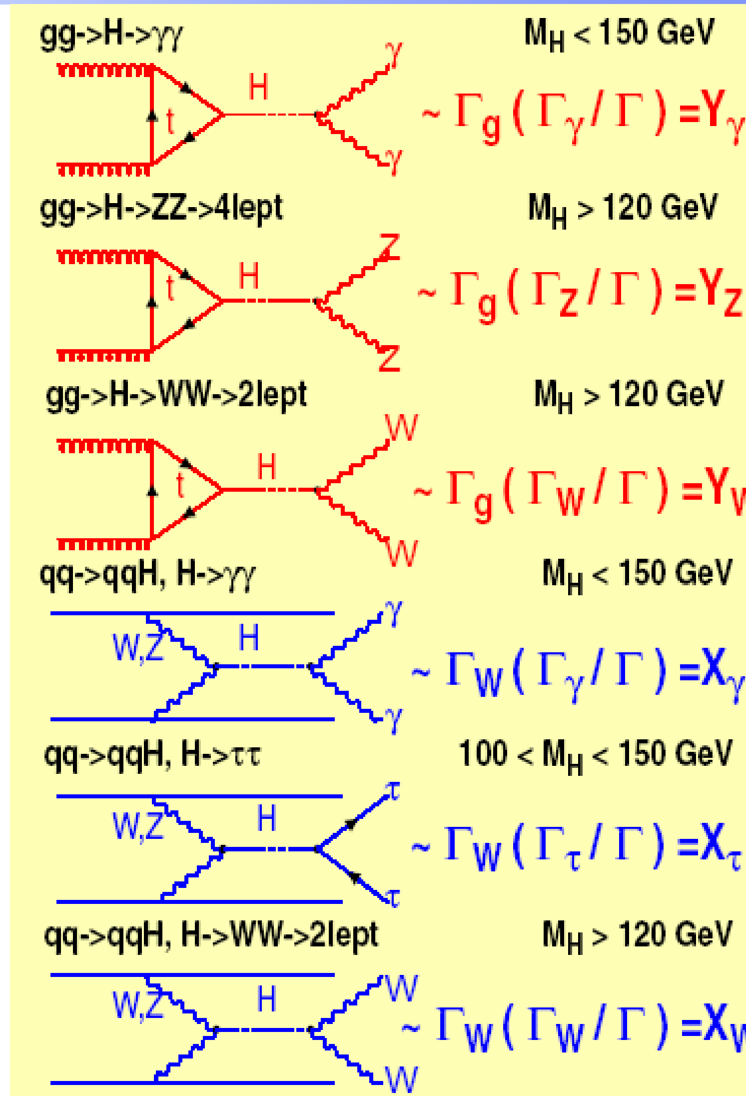
Th-err: ~4%

$$\frac{\sigma(gg\to H)\cdot B(H\to \gamma\gamma)}{\sigma(gg\to H)\cdot B(H\to ZZ)}=\frac{\Gamma_\gamma}{\Gamma_Z}\propto\frac{\Gamma_W}{\Gamma_Z}$$

$$\frac{\sigma(qq\to qqH)\cdot B(H\to WW^*)}{\sigma(gg\to H)\cdot B(H\to ZZ^*)}=F_{QCD}\frac{\Gamma_W}{\Gamma_Z}$$

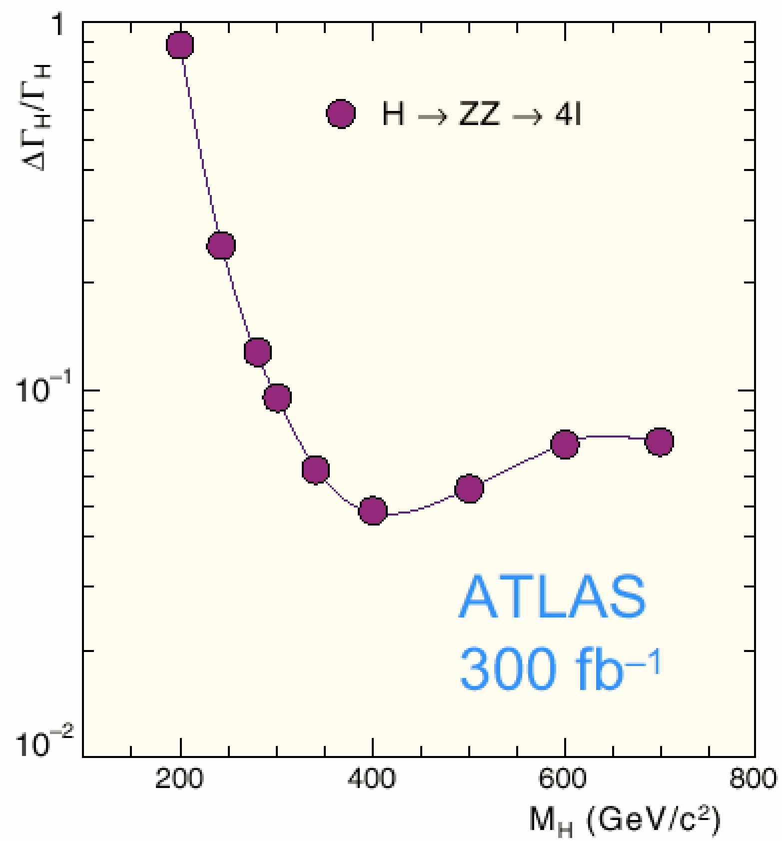


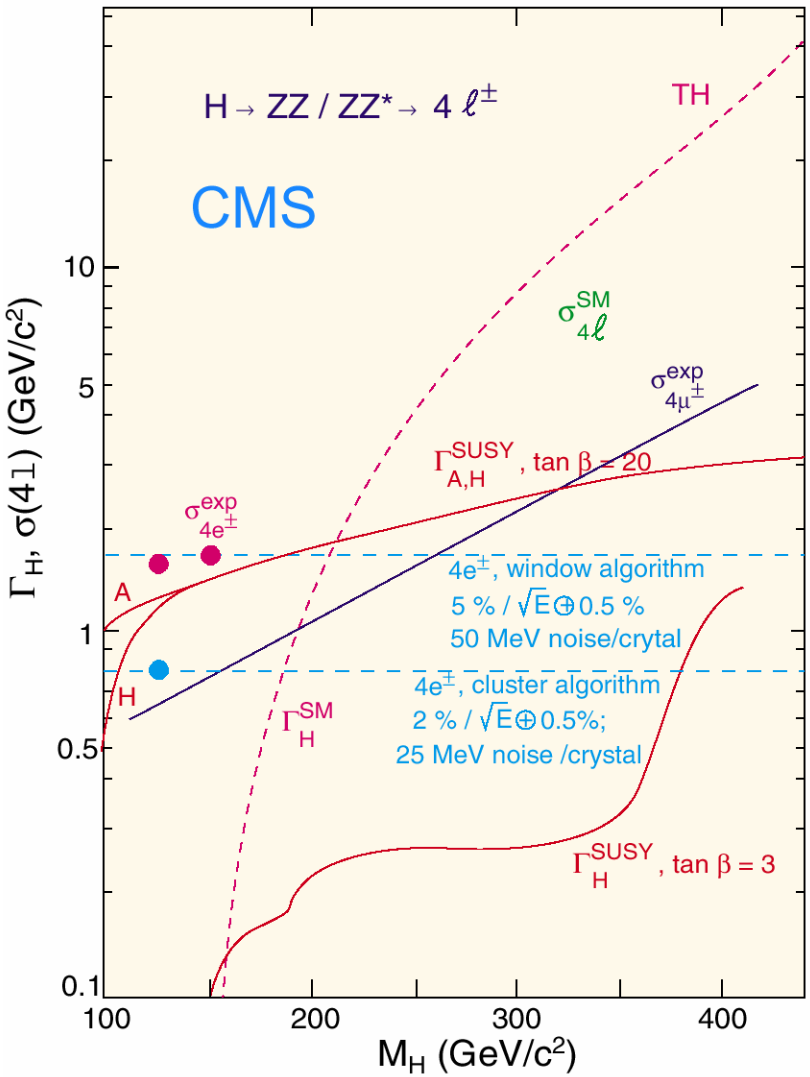
Th-err: ~20%



SM Higgs properties (II): width

- **Width; limitation:**
  - Possible for M_H>200
    - Using golden mode (4ℓ)

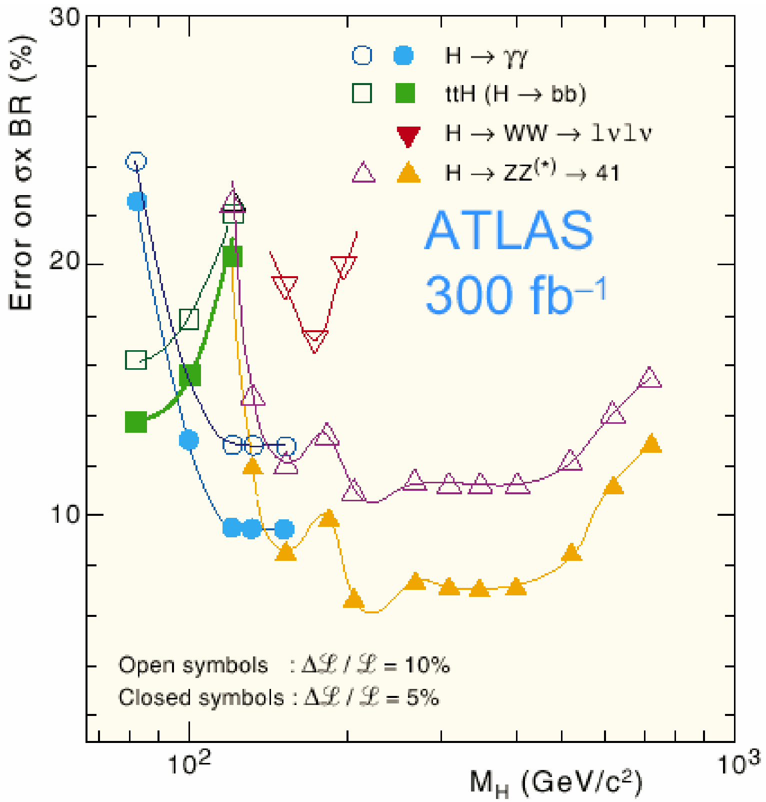




SM Higgs properties (III)

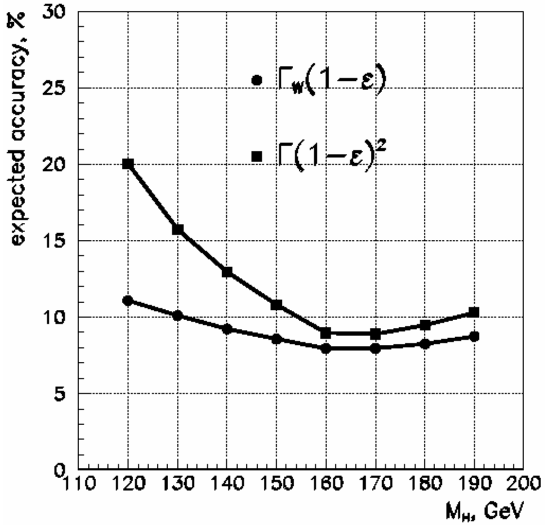
- **Biggest uncertainty (5-10%): Luminosity**
  - **Relative couplings statistically limited**
    - **Small overlap regions**

Measure	Error	M_H range
$\frac{B(H\to\gamma\gamma)}{B(H\to b\bar{b})}$	30%	80–120
$\frac{B(H\to\gamma\gamma)}{B(H\to ZZ^*)}$	15%	125–155
$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$	25%	80–130
$\frac{B(H\to WW^{(*)})}{B(H\to ZZ^{(*)})}$	30%	160–180



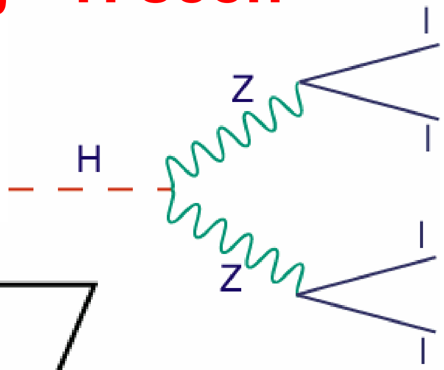
SM Higgs properties (III); width for $M_H<2M_Z$

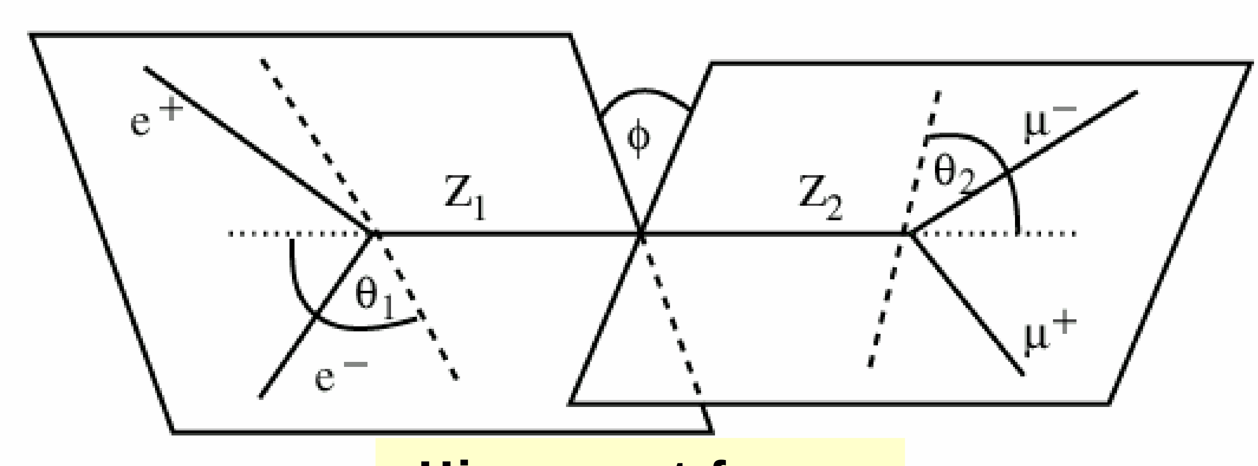
- **Basic idea: use $qq \to qqH$ production (two forward jets+veto on central jets)**
  - Can measure the following: $X_j = \Gamma_W\Gamma_j/\Gamma$ from $qq \to qqH \to qqjj$
    - Here: $j = \gamma, \tau$, W(W*); precision~10-30%
  - One can also measure $Y_j = \Gamma_g\Gamma_j/\Gamma$ from $gg \to H \to jj$
    - Here: $j = \gamma$, W(W*), Z(Z*); precision~10-30%
  - Clearly, ratios of X_j and Y_j (~10-20%) $\to$ couplings
  - But also interesting, if Γ_W is known:
    - $\Gamma = (\Gamma_W)^2/X_W$
    - Need to measure $H \to WW^*$
    - $\varepsilon=1-(B_b+B_\tau+B_W+B_Z+B_g+B_\gamma)<<1$
    - $(1-\varepsilon)\Gamma_W= X_\tau(1+y)+X_W(1+z)+X_\gamma+X_g$
    - $z= \Gamma_W/\Gamma_Z$; $y= \Gamma_b/\Gamma_\tau=3\eta_{QCD}(m_b/m_\tau)^2$



SM Higgs properties (IV): J^{CP}

- **Spin-1 assignment excluded if $H \rightarrow \gamma\gamma$ or $gg \rightarrow H$ seen**
- **Higgs decay products correlations**
  - In analogy with "textbook" $\pi^0 \rightarrow \gamma\gamma \rightarrow eeee$ case





Higgs rest frame

- **Two observables:**
  - Angle between decay planes in Higgs rest-frame
  - Angle between leptons and Z-momentum the Z rest-frame (Gottfried-Jackson angle).

EWK Symmetry Breaking

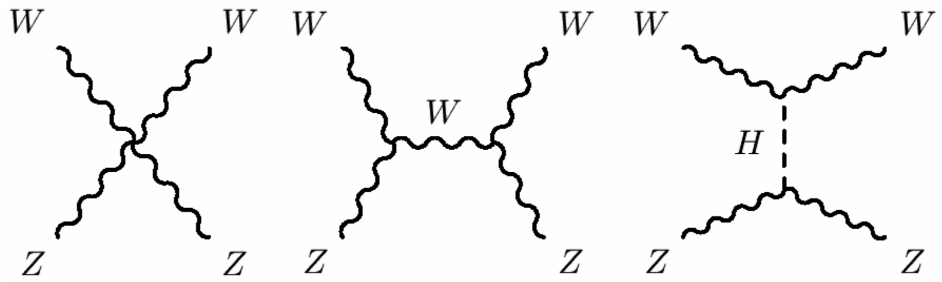
Standard Model Higgs

Strong EWK interaction

SUSY Higgs search

Strong boson-boson scattering

- **Example: $W_L Z_L$ scattering**
  - W, Z polarization vector ε^μ satisfies: $\varepsilon^\mu p_\mu=0$;
    - for $p_\mu=(E,0,0,p)$, $\varepsilon^\mu=1/M_V(p,0,0,E) \approx P^\mu/M_V+O(M_V/E)$
  - Scattering amplitude ~ $(p_1/M_W)\,(p_2/M_Z)\,(p_3/M_W)\,(p_4/M_Z)$, i.e. $\sigma \sim s^2/M_W^2 M_Z^2$

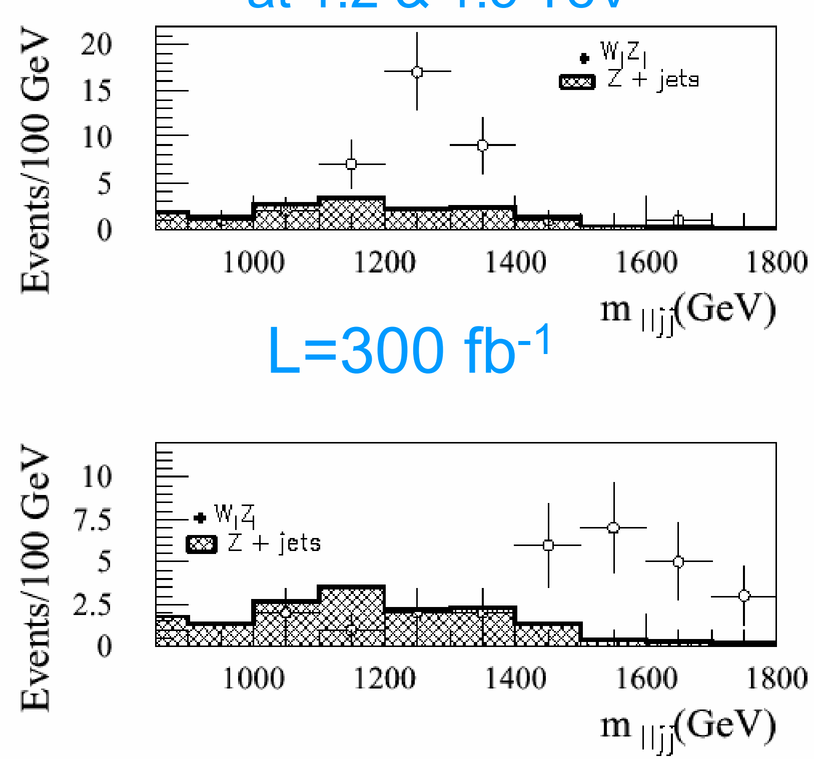


  - Taking $M_H \to \infty$ the H diagram goes to zero (~ $1/M_H^2$)
  - Technicalities: diagrams are gauge invariant, can take out one factor of s
    - but the second always remains (non-abelian group)
  - Conclusion: to preserve unitarity, one must switch on the H at some mass
    - Currently: $M_H \leq 800$ GeV

The no Higgs case: $V_L V_L$ scattering

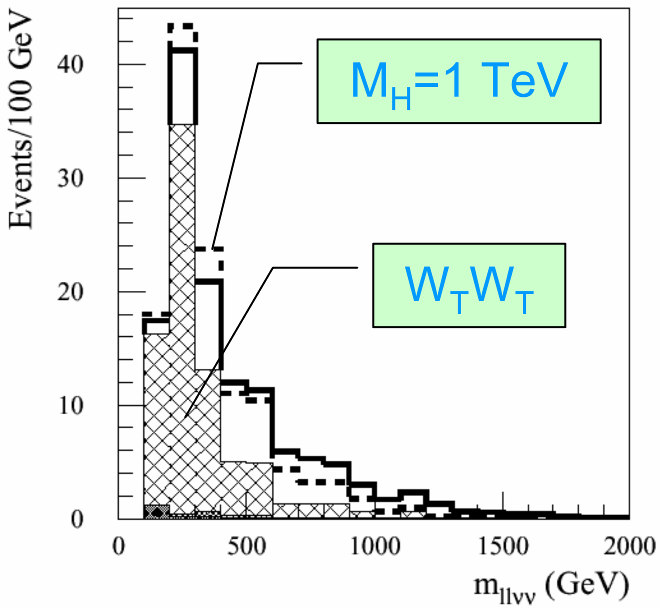
- **Biggest background is Standard Model VV scattering**
  - **Analyses are difficult and limited by statistics**

Resonant WZ scattering at 1.2 & 1.5 TeV



$L=300\ fb^{-1}$

Non-resonant W^+W^+ scattering



Technicolor basics (I)

- **Basic idea: there exists a new strong interaction, whose charge is called "technicolor". And is felt by "technifermions".**
  - **the Higgs is a condensate of two techni-fermions (techni-pion), just like the pion is a bound state of two quarks.**
- **The decay constant is, then, the vacuum energy of the technifermion pair.**
  - **In analogy with QCD, then, if Λ_{TC} is the Λ technicolor parameter**

$$\langle \bar{f}f \rangle \sim \Lambda^3_{TC} \qquad \langle \bar{q}q \rangle \sim \Lambda^3_{QCD}$$

  - **Vaccum expectation value:**

$$v \rightarrow f_\pi \Rightarrow M_W = g f_{\pi_T}/2 \Rightarrow f_{\pi_T} \sim 500\,\mathrm{GeV}$$

- **Questions: how do fermions get mass?**
  - **Via four-fermion coupling (the condensate and the fermion)**

Technicolor basics (II)

- **Fermions: four-fermion coupling**

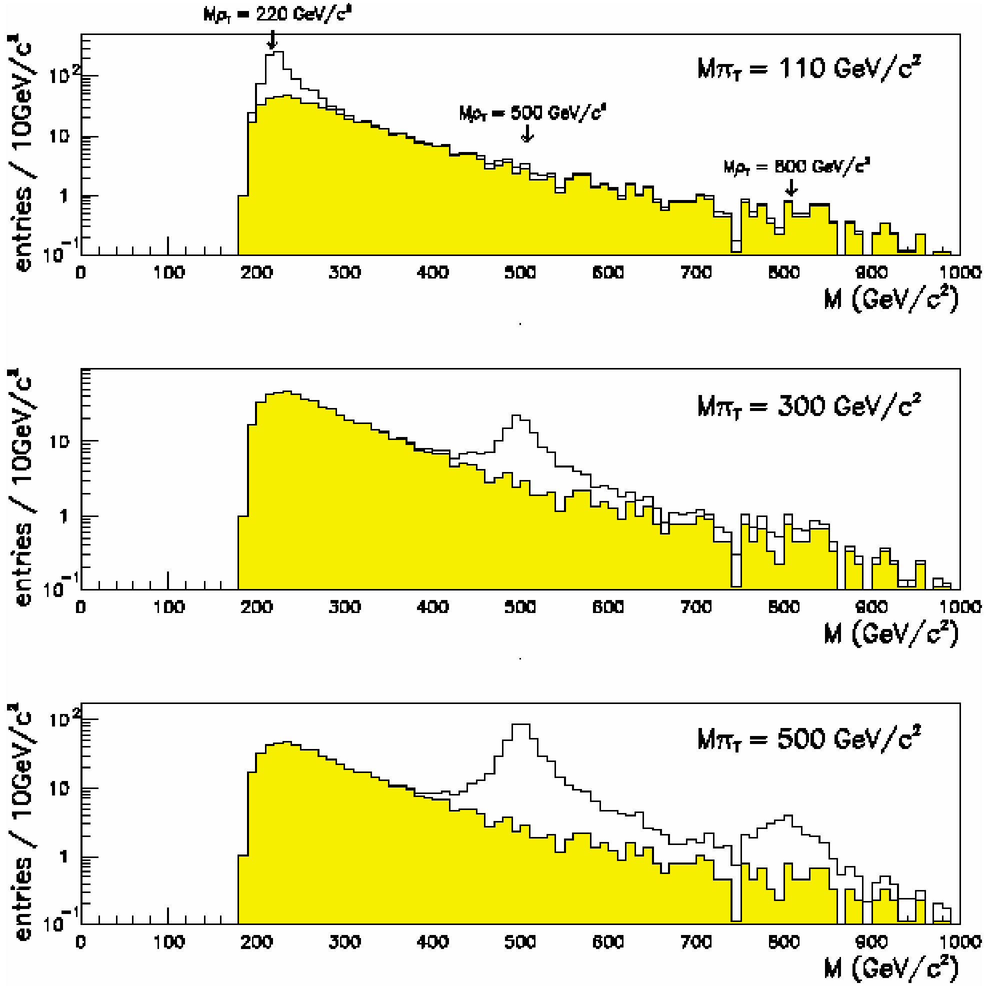
$$L_{\text{int}} = \lambda Q\overline{Q}f\overline{f} \Rightarrow [\lambda] = -2 \Rightarrow \lambda \sim (1/M_{ETC})^2 \Rightarrow m_f \sim \frac{\Lambda_{TC}{}^3}{M^2{}_{ETC}}$$

- **In other words, bosons that transmit (extended) technicolor (ETC)**
- **And ETC must be broken (since boson has M_{ETC})**
  - Moreover, this mass must be high
    - To avoid FCNC limits from experiment: M>500 GeV
    - Which implies very small fermion masses
      - → Walking ETC, large N_{TC}, … topcolor…
- **Phenomenology: techni-pion and techni-rho resonances decaying to (among others) W, Z.**
  - Direct decays to jets more difficult due to jet-energy resolution
  - W, Z to leptons: clean, striking, directly attacks VB "scattering"

Technicolor

- **Technicolor; many possibilities**
  - **Example: $\rho_T^{\pm} \to W^{\pm}Z^0 \to \ell^{\pm}\nu\ell^{+}\ell^{-}$ (cleanest channel…)**
  - **Many other signals (bb, tt resonances, etc…)**
  - **Wide range of observability**

ATLAS; 30 fb^{-1}



EWK Symmetry Breaking

Standard Model Higgs

Strong EWK interaction

SUSY Higgs search

MSSM Higgs(es)

- **Complex analysis; 5 Higgses ($\Phi \equiv H^{\pm}; H^0, h^0, A^0$)**
  - At tree level, all masses & couplings depend on only two parameters; tradition says take M_A & $\tan\beta$
  - Modifications to tree-level mainly from top loops
    - Important ones; e.g. at tree-level, $M_h < M_z \cos\beta$, $M_A < M_H$; $M_W < M_{H^+}$; radiative corrections push this to 135 GeV.
  - Important branch 1: SUSY particle masses
    - (a) M>1 TeV (i.e. no Φ decays to them); well-studied
    - (b) M<1 TeV (i.e. allows Φ decays); "on-going"
  - Important branch 2: stop mixing; value of $\tan\beta$
    - (a) Maximal–No mixing
    - (b) Low (1.5) and high (≈30) values of $\tan\beta$

Higgs mechanism in SUSY (I)

- **Higgs physics (MSSM)**
  - **Two independent Higgs doublets (H_u, H_d) required.**
    - **Technicalities: cannot put complex conjugate of Φ in super-potential (analytic function), so cannot use the same trick as in SM ($\iota\tau_2\Phi^*$) to give masses to up-like quarks. Also, anomaly cancellation (Φ has isospin).**
  - **Symmetry-breaking: both roll to minima, with different isospin – to give mass to corresponding fermion**

$$\left.\begin{aligned} \mathrm{H}_u &= \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \xrightarrow{V\,\min} \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_u \end{pmatrix} \\ \mathrm{H}_d &= \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \xrightarrow{V\,\min} \frac{1}{\sqrt{2}}\begin{pmatrix} v_d \\ 0 \end{pmatrix} \end{aligned}\right\} \text{with} \quad \begin{aligned} \tan\beta &= \frac{v_u}{v_d} = \text{free parameter} \\ v_d^2 + v_u^2 &= v^2 = (246\,\mathrm{GeV})^2 \end{aligned}$$

Higgs mechanism in SUSY (II)

- **2 Complex doublets = 2x2x2 = 8 dofs**
  - **Symmetry-breaking, lose three dofs to additional (longitudinal) polarizations of $W^{\pm}$, Z**
    - **5 physical states h^0, H^0 (CP-even), A^0 (CP-odd), $H^{\pm}$**
- **Next: obtain mass matrices, find eigenvectors and eigenvalues (to obtain these physical states)**
  - **6 parameters - 4 masses, tanβ, α (mixing parameter in CP-even mass matrix). Only two independent ones; "tradition": m_A, tanβ**

$$M_{H,h}^2 = \frac{1}{2}\left\{\left(M_A^2 + M_Z^2\right) \pm \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right\}$$

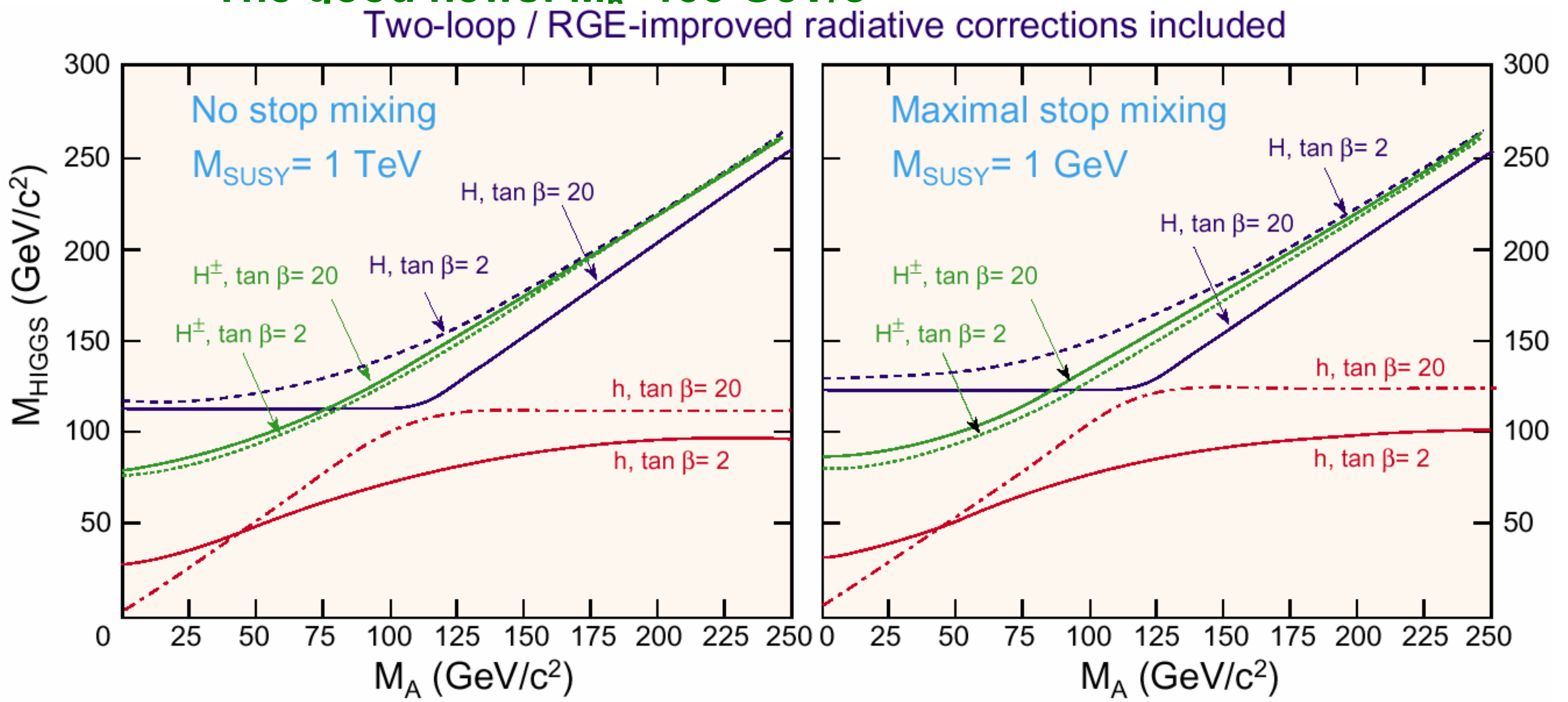
$$M_{H^{\pm}}^2 = M_A^2 + M_W^2$$

$$\cos^2(\beta - \alpha) = \frac{M_h^2\left(M_Z^2 - M_h^2\right)}{M_A^2\left(M_H^2 - M_h^2\right)}$$

$$M_h^2 \leq M_Z^2 \cos^2 2\beta$$

MSSM Higgses: masses

- **Mass spectra for M_{SUSY}>1TeV**
  - **Radiative corrections introduce more parameters**
    - **Incomplete top-stop loop cancellation most important**
      - ➔ ~ $M_{top}^4 \log(M_{stop}/M_{top})$, stop mixing
    - **The good news: M_h<135 GeV/c²**

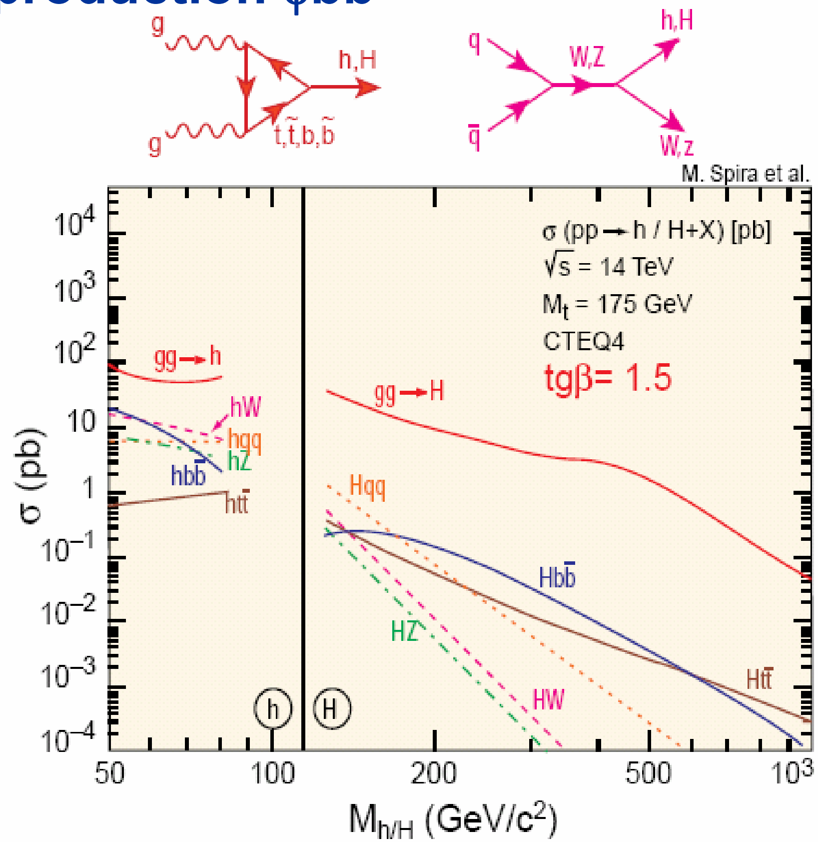


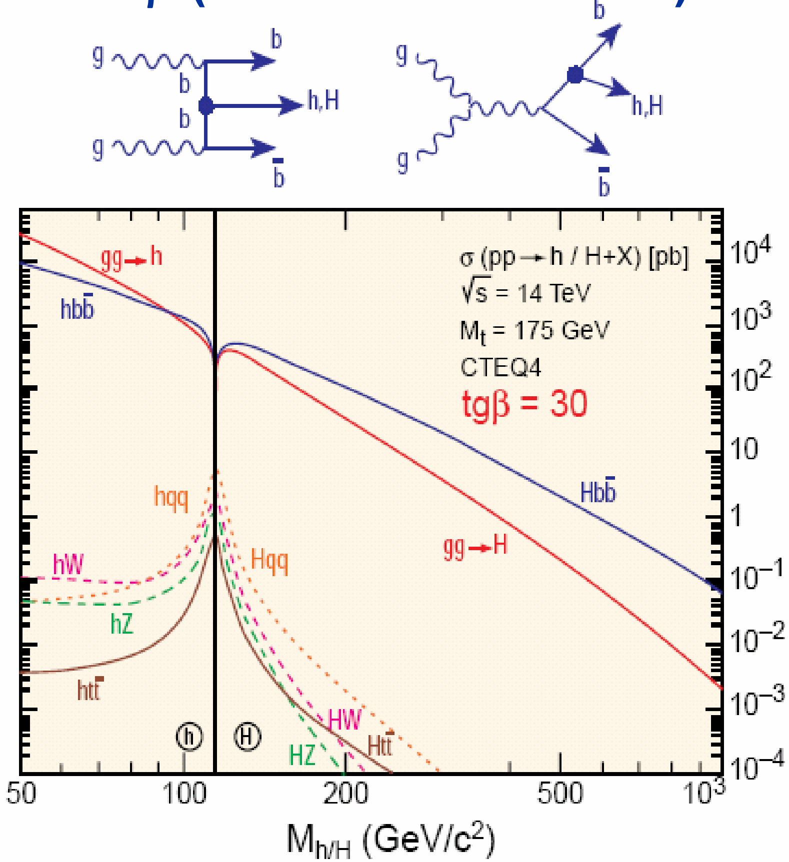
Production of MSSM Higgses: h, H

- **Largest branch: tanβ**

Large tanβ: ϕbb coupling important ⇒ gg → ϕ, associated production ϕbb

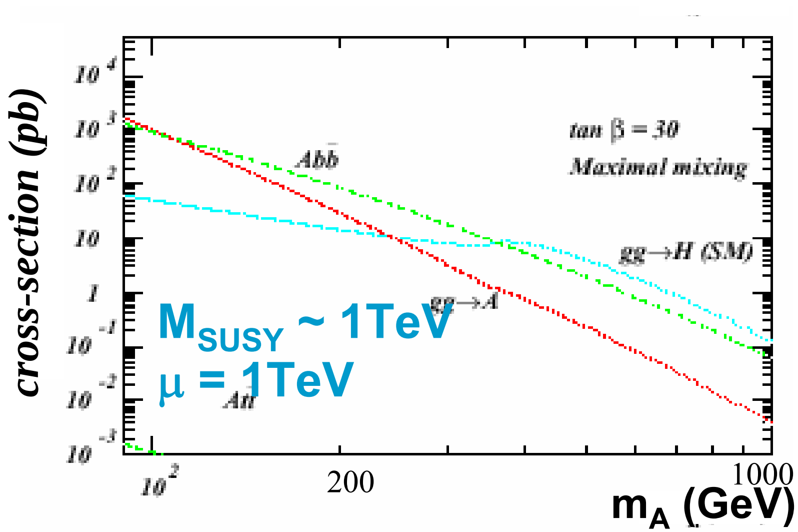
H^0VV couplings ∝ cos(β–α) ⇒ suppressed for large tanβ. VBF production low for H^0 at large tanβ (also no VBF for A^0)

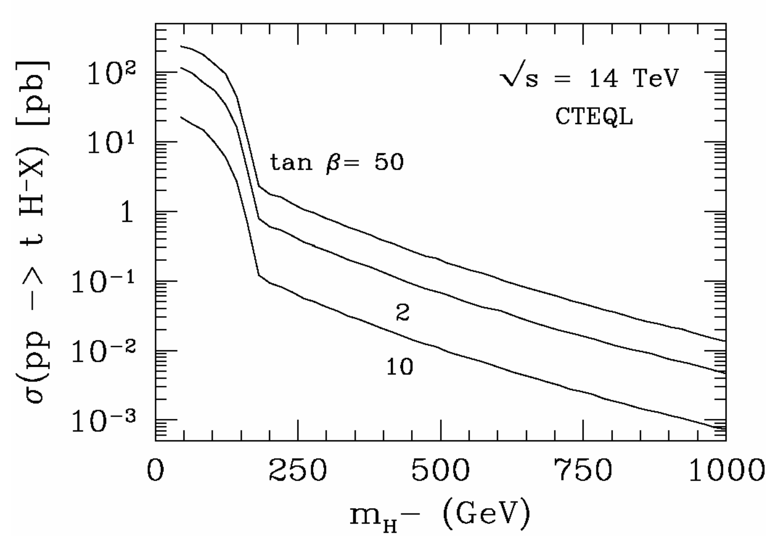




Production of MSSM Higgses : $A^0, H^{\pm}$

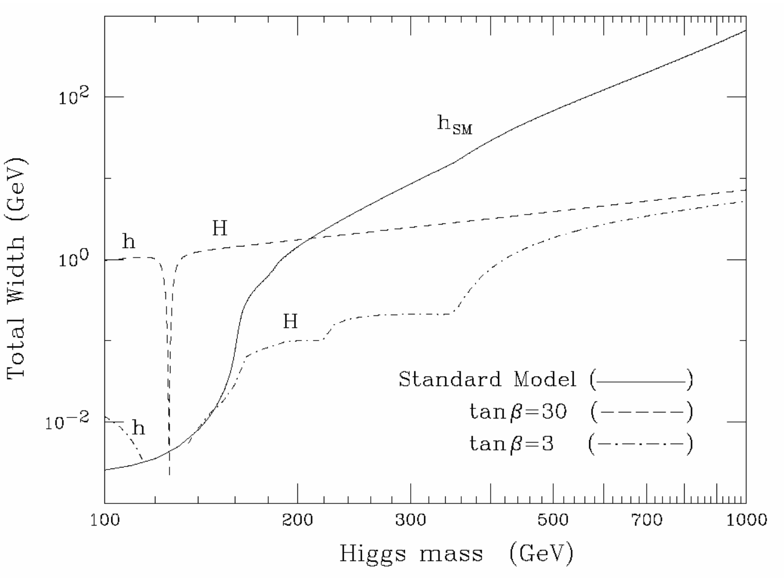
- **A^0 production:**
  - A^0 does not couple to W/Z (tree level) no VBF prodn
  - Large tanb: A^0bb coupling very important.
    - Affects both gg $\rightarrow A^0$, and associated production A^0bb
- **Case 1: $M_{H+} < M_t - M_b$**
  - $t \rightarrow bH^+$ competes with SM
  - $t \rightarrow Wb$ produced in tt production followed by t decay
- **Case 2: $M_{H+} > M_t$**
  - gg, qq $\rightarrow$ tbH$^-$, gb $\rightarrow$ tH$^{\pm}$
  - Radiation off 3rd-generation quark





MSSM Higgs: decays (I)

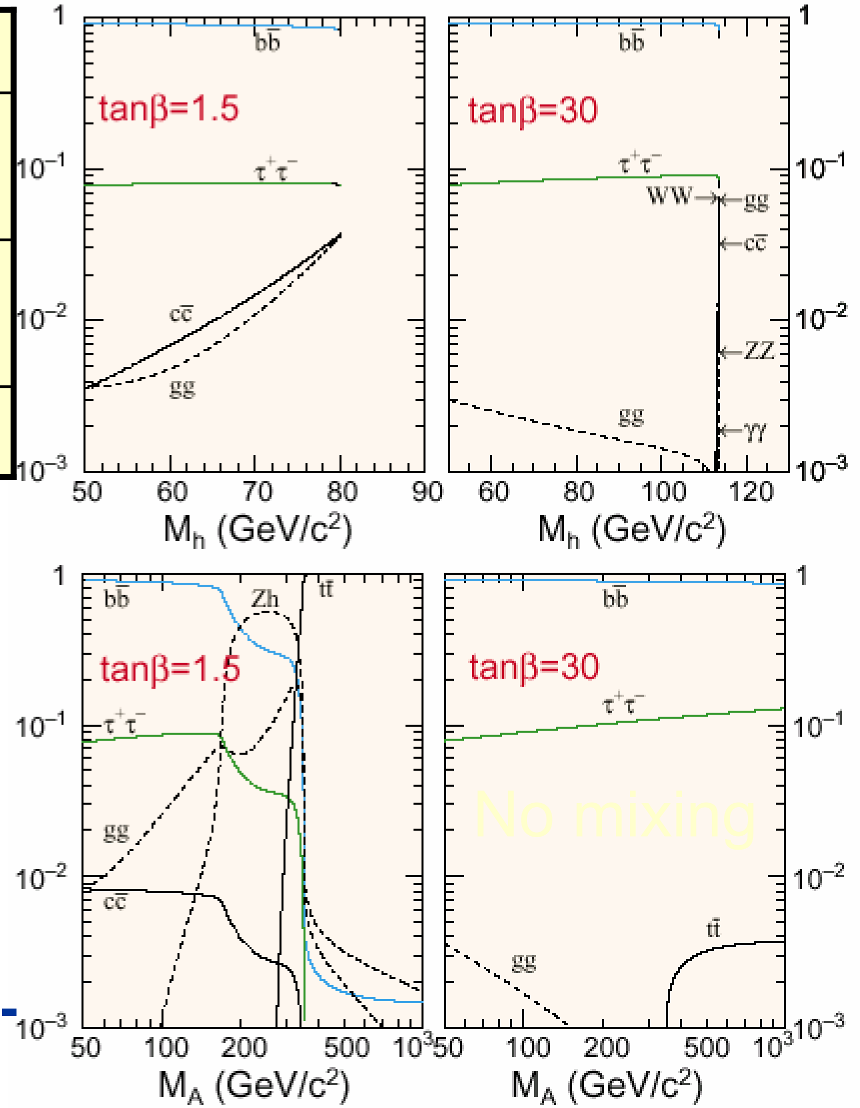
- **Decay pattern depends on region of parameter space and SUSY parameters**
  - **$M_A >> M_Z$ (decoupling limit)**
    - **MSUSY large (~1TeV); $h \rightarrow h_{SM}$**
    - **MSUSY light (e.g. 200GeV) modified. Direct to SUSY + contributions to 1-loop decay rate $h^0 \rightarrow \gamma\gamma$, gg possible.**
    - **In both cases H^0, A^0, $H^\pm$ ~ mass degenerate BR ~ tan β.**
  - **M_A< 150 GeV, tanβ > 10-30 (Intense coupling regime.)**
    - **All higgs masses 100-150 GeV. All H produced in many channels. Signal for one bkg for another**



Suppression of HVV coupling results in smaller widths than SM.

MSSM Higgs: decays (II)

Φ	$g(\Phi uu)$	$g(\Phi dd)$	$g(\Phi VV)$
h	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\sin\alpha/\sin\beta \to 1/\tan\beta$	$\cos\alpha/\cos\beta \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0



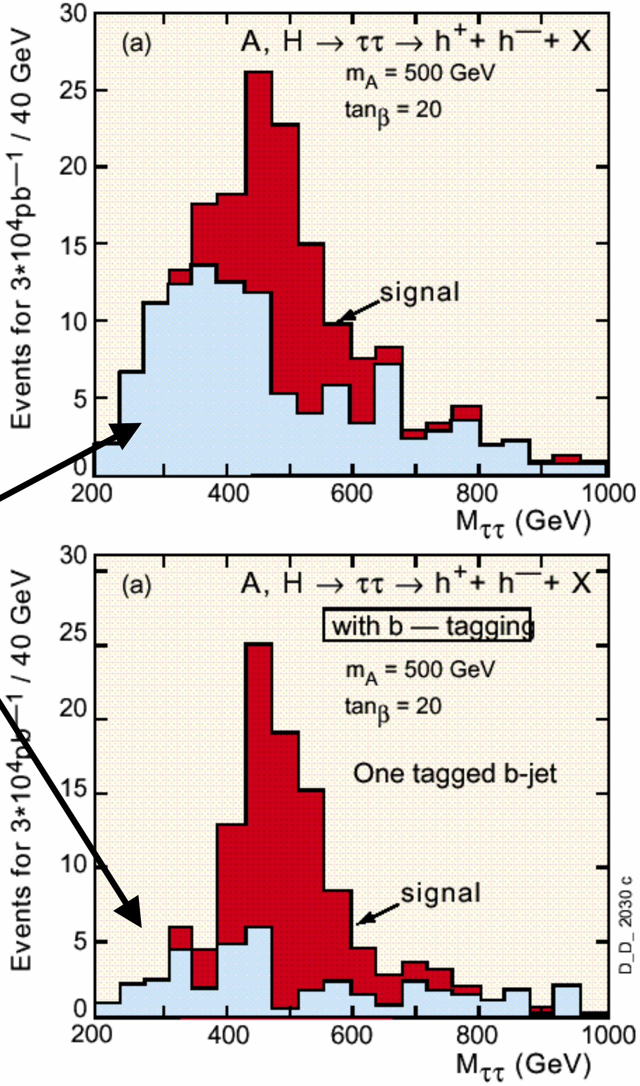
- **h is light**
  - Decays to bb (90%) & $\tau\tau$ (8%)
    - cc, gg decays suppressed
- **H/A "heavy"**
  - Decays to top open (low $\tan\beta$)
  - Otherwise still to bb & $\tau\tau$
  - But: WW/ZZ channels suppressed; lose golden modes for H

Higgs channels considered (examples)

- **Channels currently being investigated:**
  - H, h→$\gamma\gamma$, $b\bar{b}$ (H→$b\bar{b}$ in WH, $t\bar{t}$H) — (very) important and hopeful
  - h→$\gamma\gamma$ in WH, $t\bar{t}$h → $\ell\gamma\gamma$
  - h, H → ZZ*, ZZ → 4 ℓ
  - h, H, A→ $\tau^+\tau^-$ → $(e/\mu)^+ + h^- + E_T^{miss}$
    → $e^+ + \mu^- + E_T^{miss}$
    → $h^+ + h^- + E_T^{miss}$
    } inclusively and in $b\bar{b}H_{SUSY}$
  - $H^+ \to \tau^+ \nu$ from $t\bar{t}$
  - $H^+ \to \tau^+ \nu$ and $H^+ \to t\bar{b}$ for $M_H > M_{top}$
  - A → Zh with h →$b\bar{b}$; A →$\gamma\gamma$
  - H, A → $\tilde{\chi}^0_2\tilde{\chi}^0_2$, $\tilde{\chi}^0_i\tilde{\chi}^0_j$, $\tilde{\chi}^+_i\tilde{\chi}^-_j$
  - $H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$
    } promising
  - qq →qqH with H →$\tau^+\tau^-$
  - H →$\tau\tau$, in WH, $t\bar{t}$H

H,A→ττ; the gen-3 lepton at the LHC

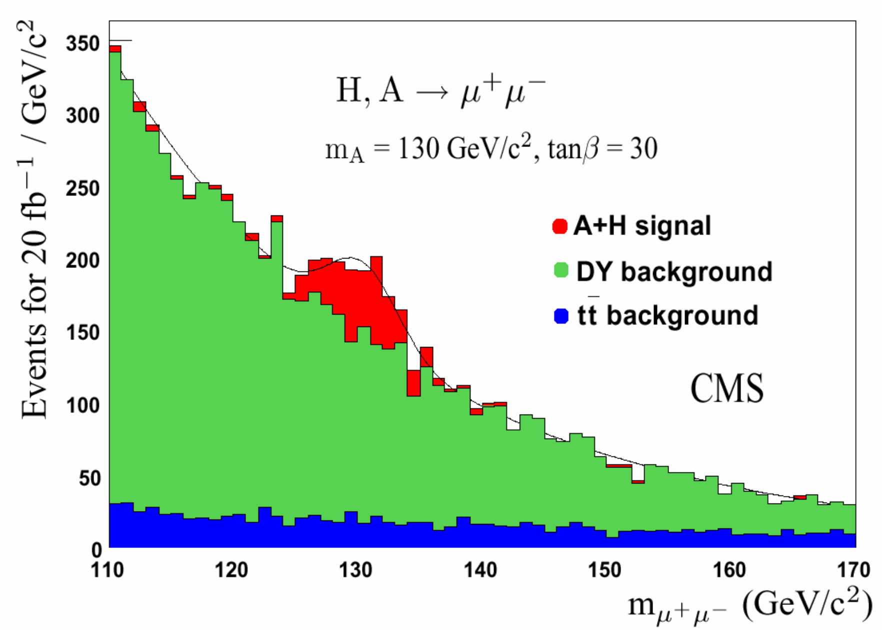
- **Best reach for large tanβ**
  - **All channels: ττ→ℓ+ℓ , ℓ+jet, jet+jet**
  - **All-hadronic channel: main reason for hadronic tau-trigger**
    - **Backgrounds: QCD (fake τ); Z/γ*→ττ; tt; W+jet, W →τν**
    - **tau-id: a tau-jet (1- and 3-prong) plus lifetime info**
    - **b-tagging: essential to reduce bkg**
    - **potential bkg from SUSY decays ($\tau,\chi^2_0,\chi_1^{\pm}$) negligible**
- **Decay offers measurement of tanβ, albeit with external input needed**



- **QCD rejection ~ 10^6**
- **Mass resolution ~ 15%**

H,A→μμ

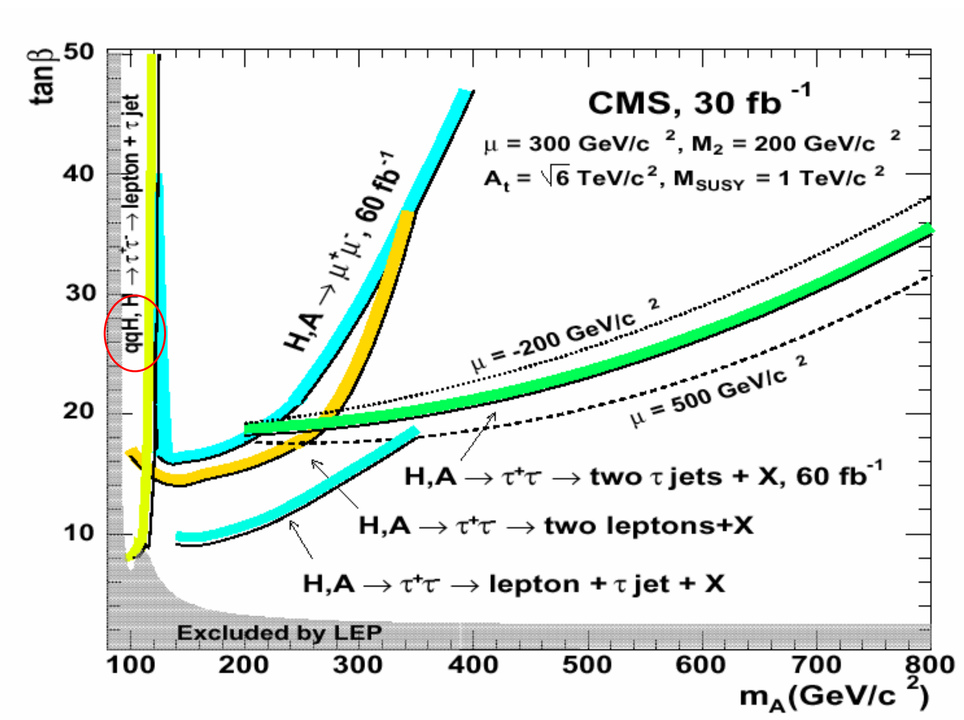
- **Enhanced $b\bar{b}$(H/A) production at high tanβ: also this channel possible**
  - **Smaller rate (than tau channel) but far better resolution**
  - **Backgrounds:**
    - **Z,γ* → μμ;   reject using b-tagging**
    - **$t\bar{t}$ → Wb, W → μν reject using central jet veto**

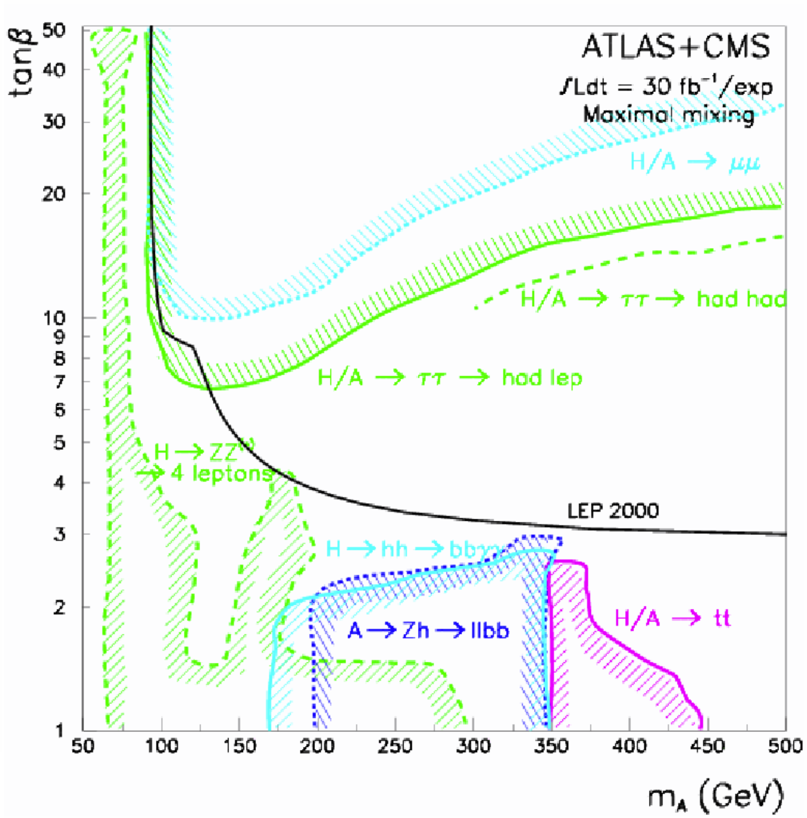


Cannot resolve A and H peaks.
Δm ~ 1%
Example shown:
$|m_H - m_A|$ ~ 2GeV

H, A reach via μ,τ decays

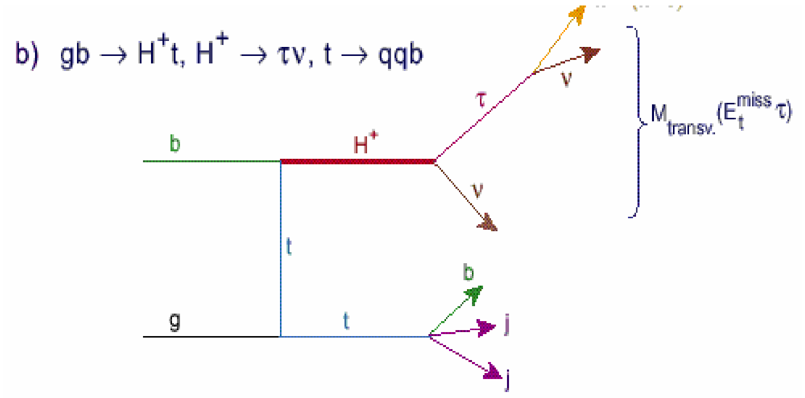
5σ reach





H^+ detection

- **Associated top-H^+ production:**
  - **Use all-hadronic decays of the top (leave one "neutrino")**
  - **H decay looks like W decay → Jacobian peak for τ-E_T^{miss}**

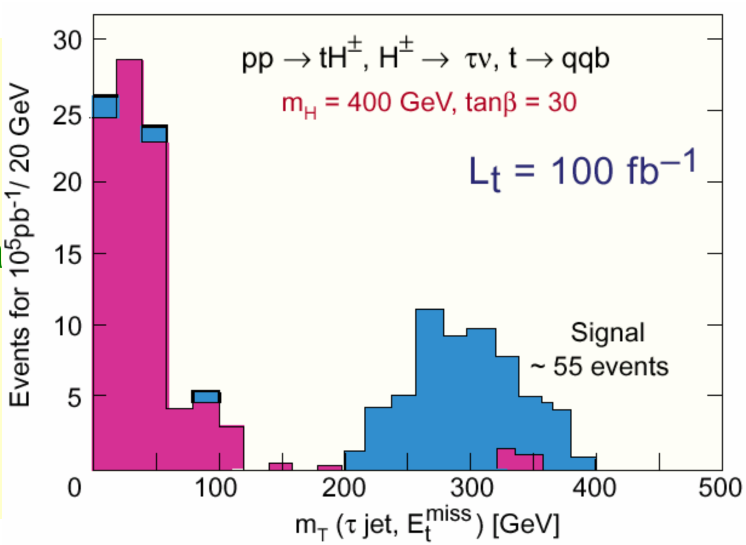


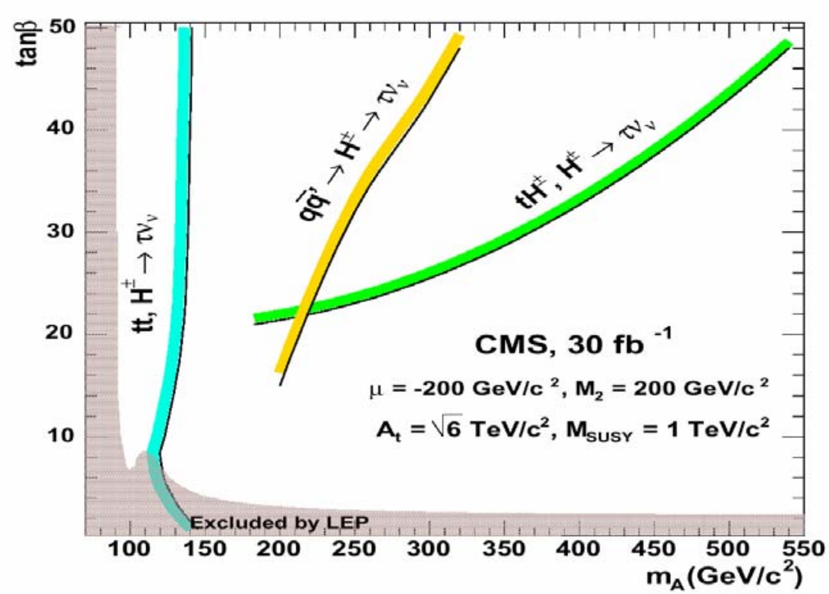
E_T(jet)>40

|η|<2.4

Veto on extra jet, and on second top

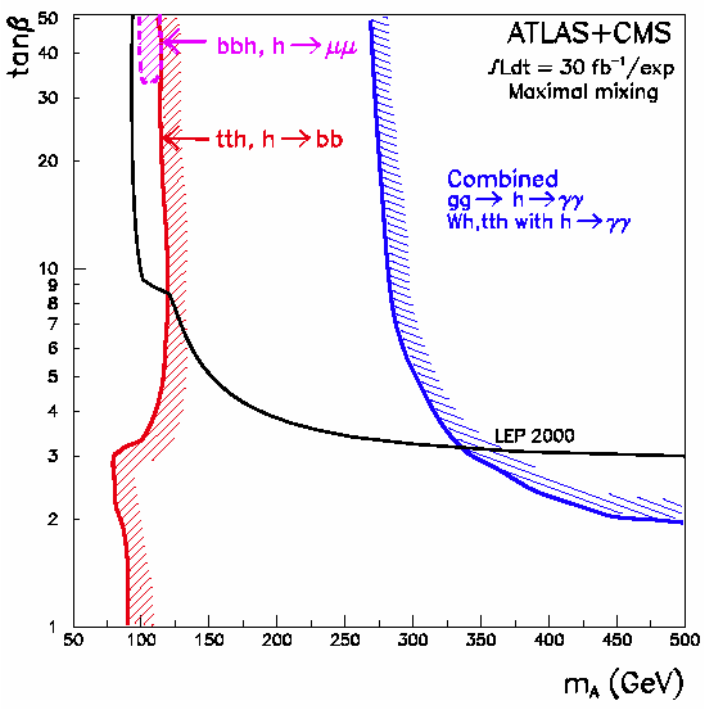
Bkg: $t\bar{t}H$

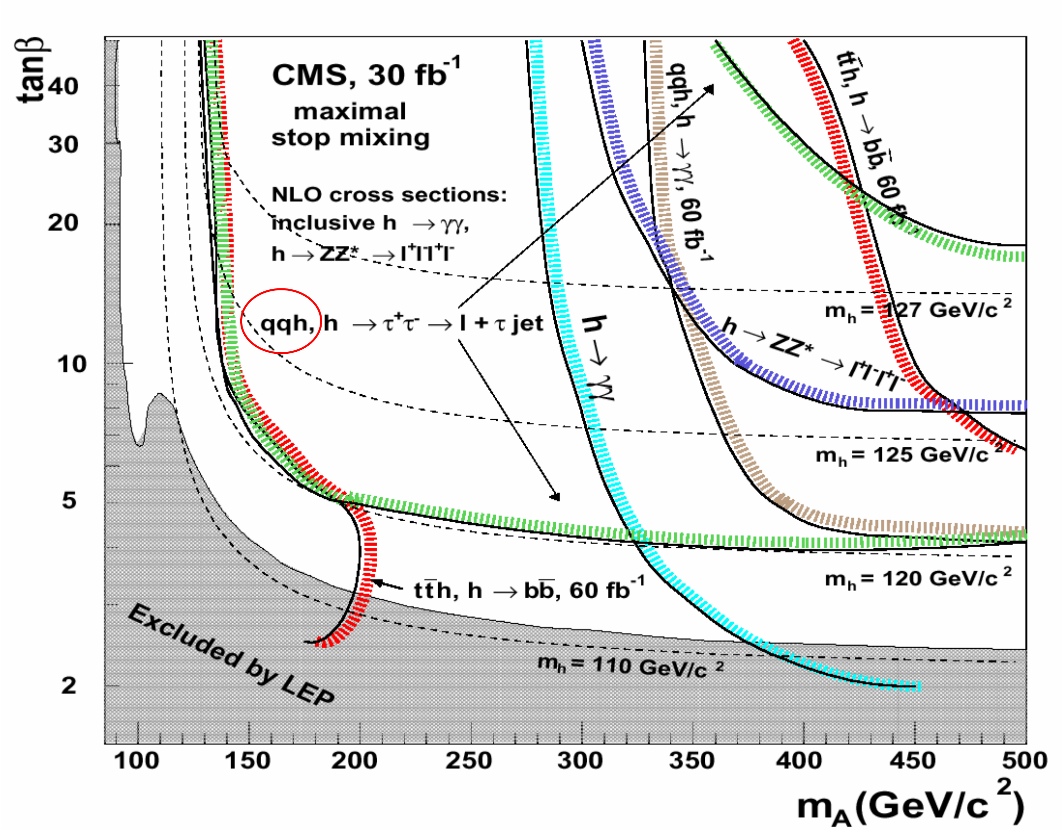




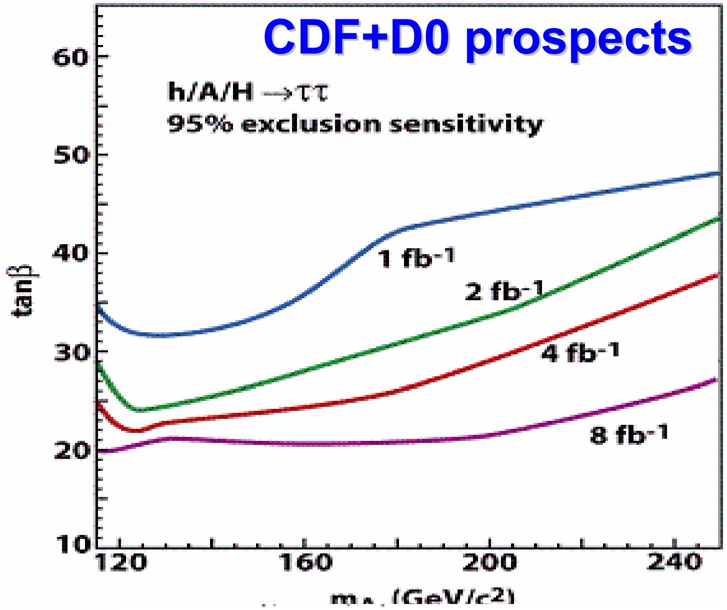
h^0 reach

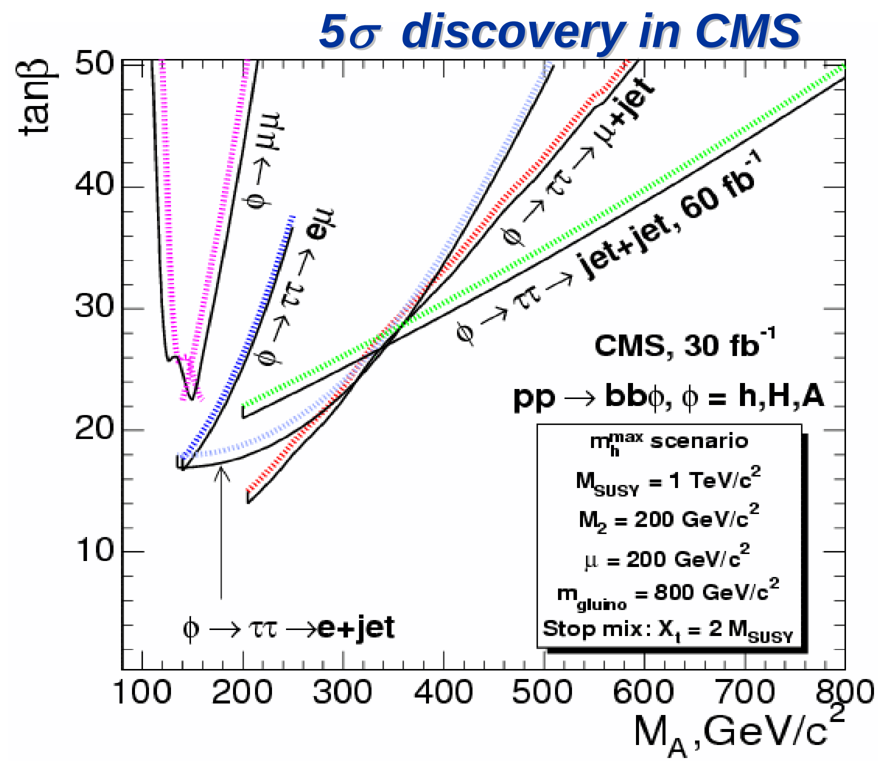
- **Search for in SM-like channels.**
  - **VBF channels very useful, e.g. qqh, $h \to \tau\tau$**

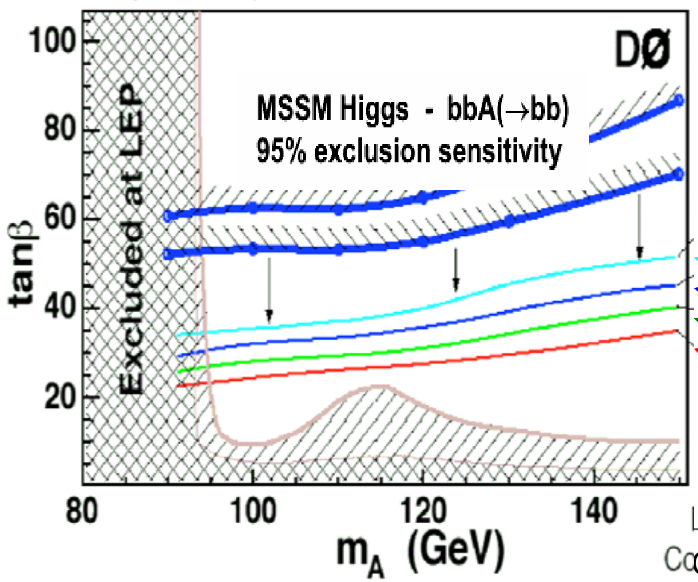




MSSM Higgs: Tevatron vs LHC







CDF+D0 prospects for exclusion

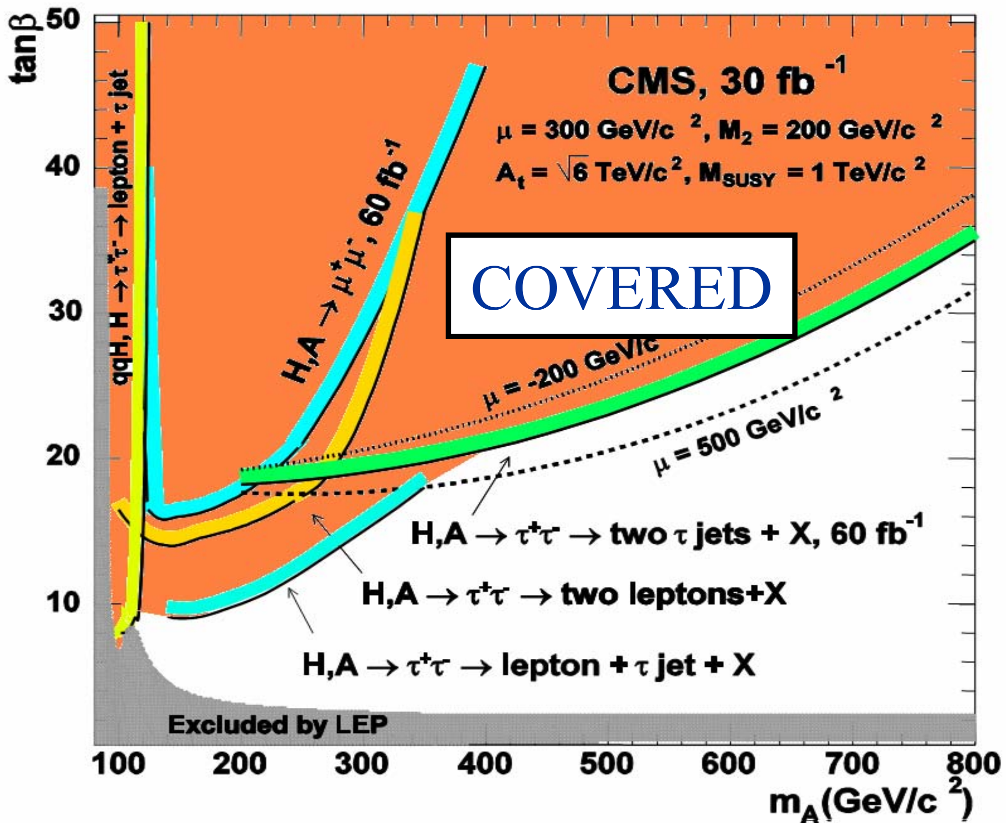
1 fb^{-1}

2 fb^{-1}

4 fb^{-1}

8 fb^{-1}

Discovery search: summary

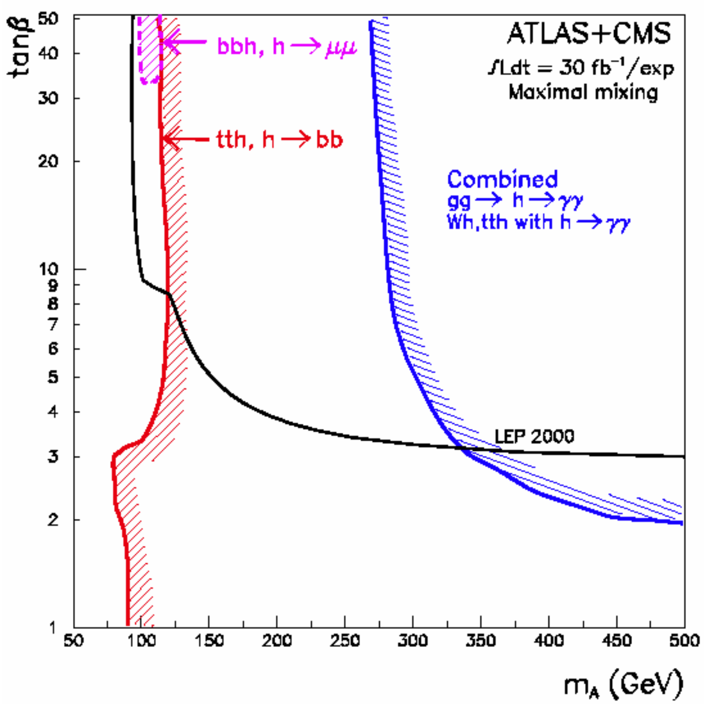


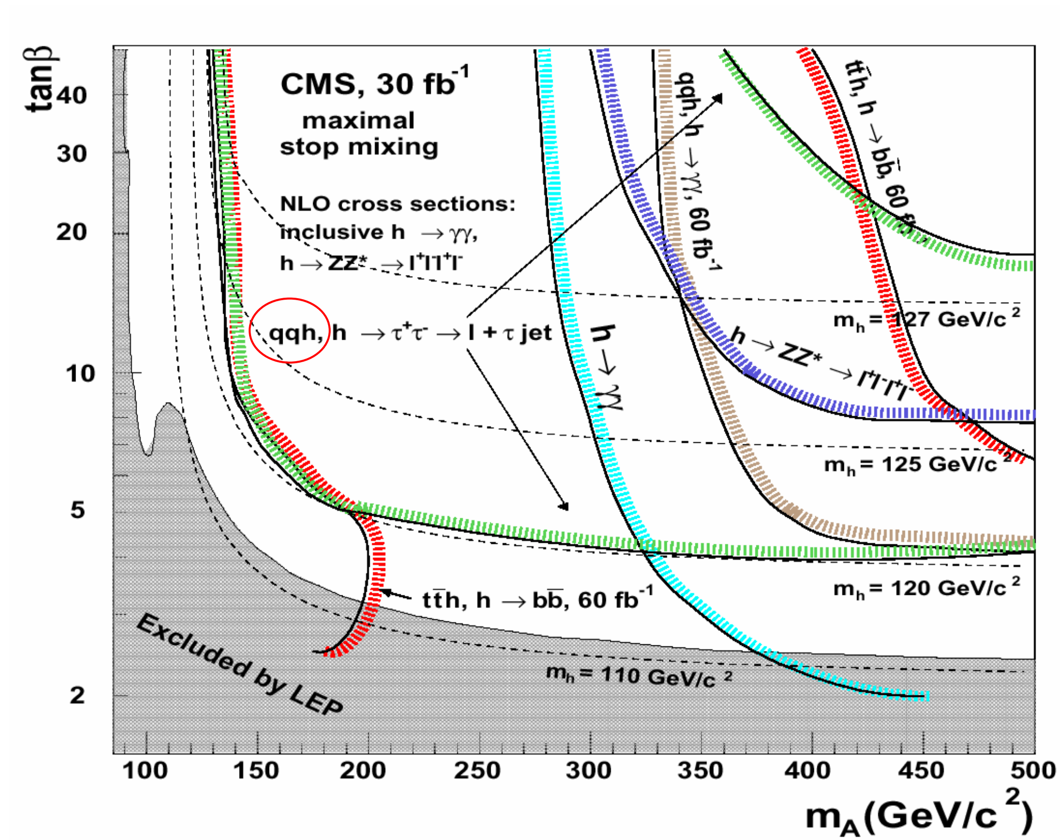
- The light Higgs, h^{0}, is always visible (a no-lose "theorem" for the LHC)
- Reach for heavy MSSM Higgses limited to upper-left part of M_A – $\tan\beta$ plot
  - reason: production mechanism (e.g. bbA^0,H^0) significant only with $\tan\beta$ enhancement

Need new channels to cover SUSY plane in the low-to-intermediate $\tan\beta$ - and high M_A region …

h^0 reach

- **Search for in SM-like channels.**
  - **VBF channels very useful, e.g. qqh, $h \rightarrow \tau\tau$**





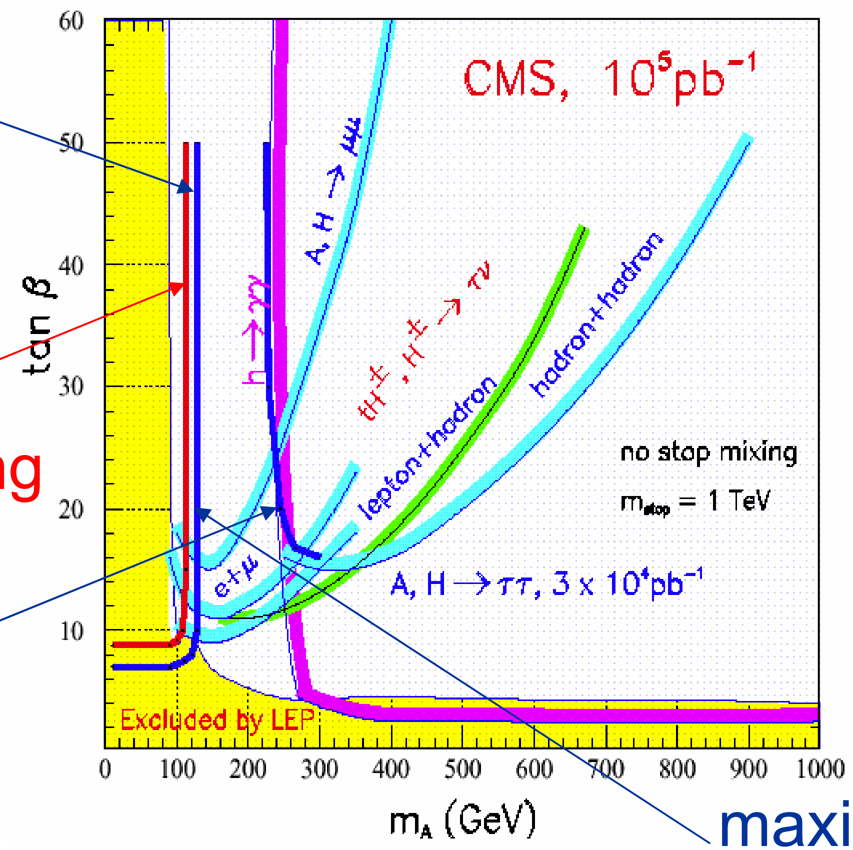
SUSY reach on tanβ-M_A plane

- **Adding $b\bar{b}$ on the τ modes can "close" the plane**

(W-tt)h → (e/μ)ν, $b\bar{b}$

No stop mixing

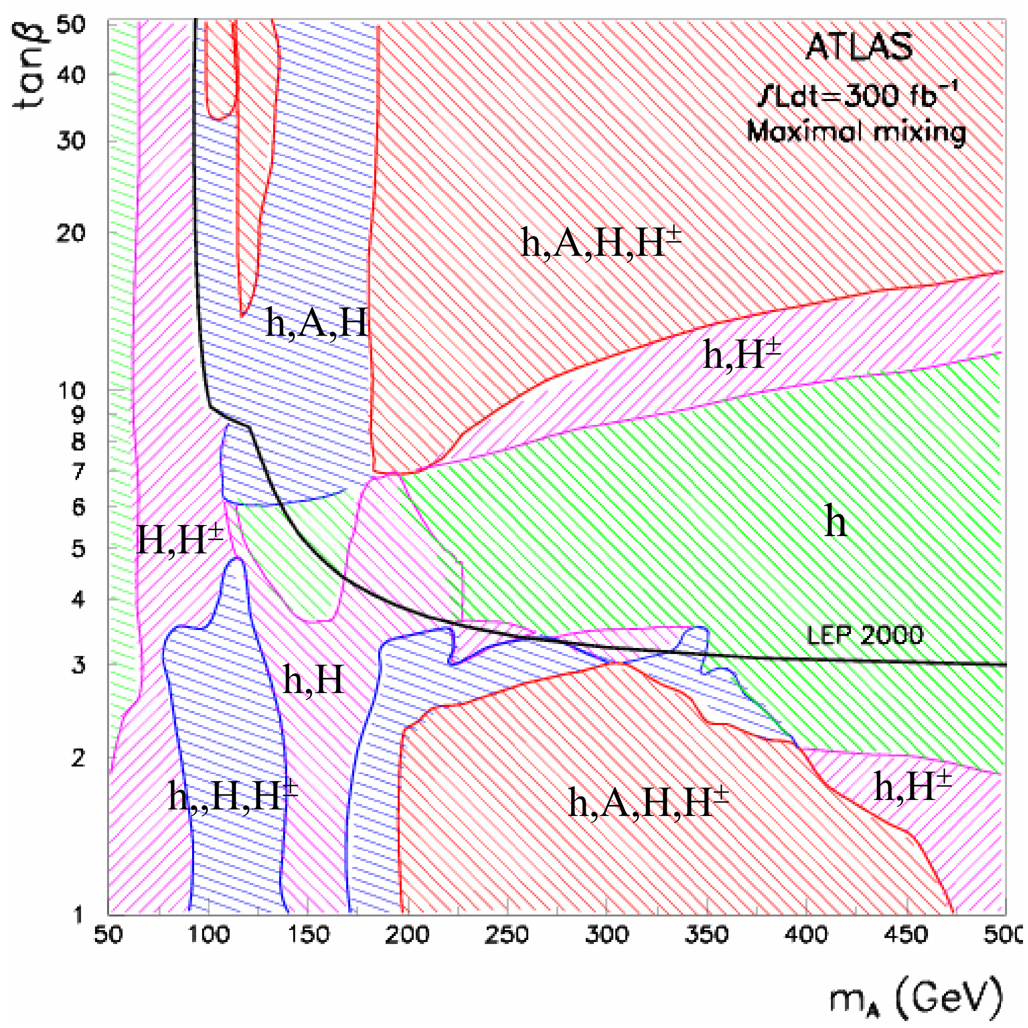
maximal stop mixing with 30 fb^{-1}



maximal stop mixing with 300 fb^{-1}

Observability of MSSM Higgses

MSSM Higgs bosons



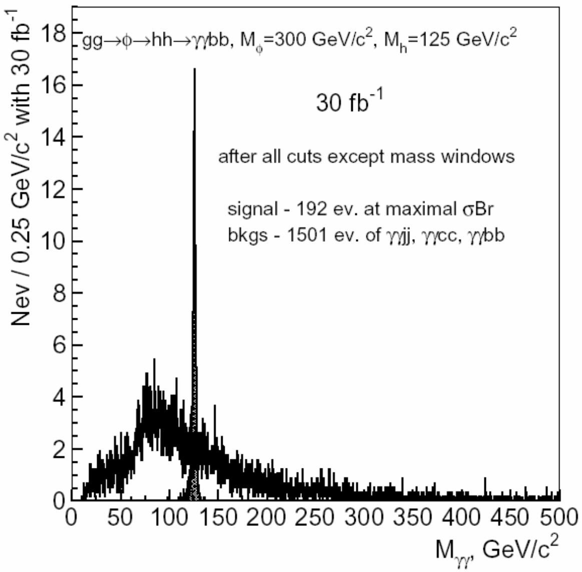
- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

5σ contours

Assuming decays to SM particles only

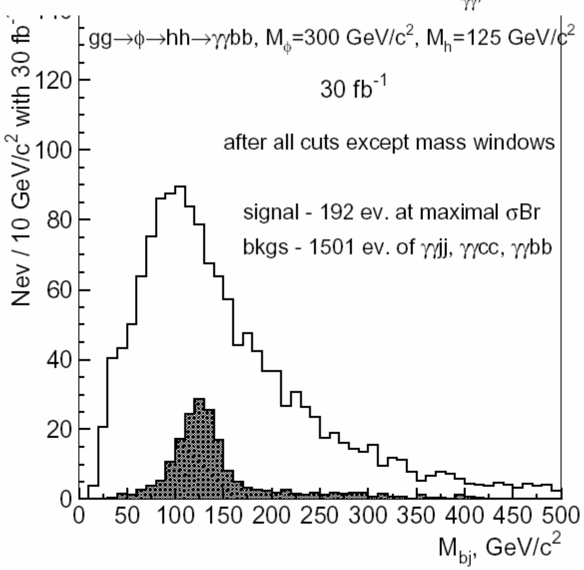
Extras

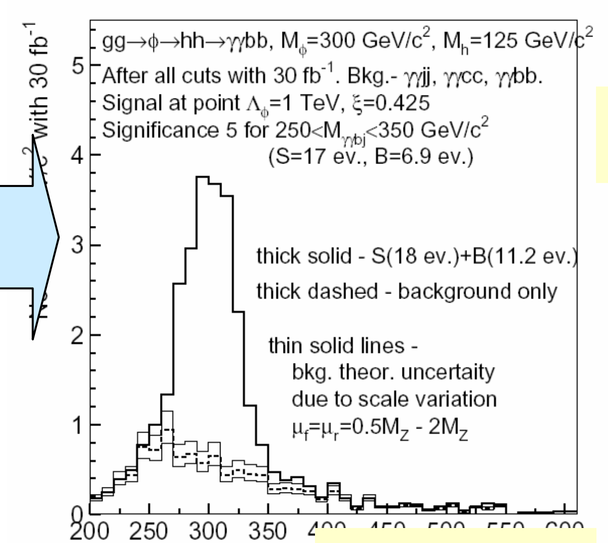
Radions… $\phi \to hh \to \gamma\gamma bb$



the field between the two (RS) branes

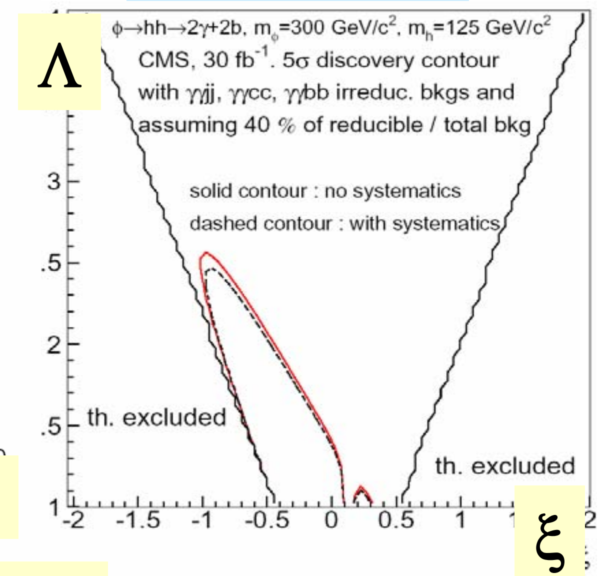
Di-photon selection + at least one b-jet
photon vertex from jets…





M(radion)

CMS, 30 fb^{-1}

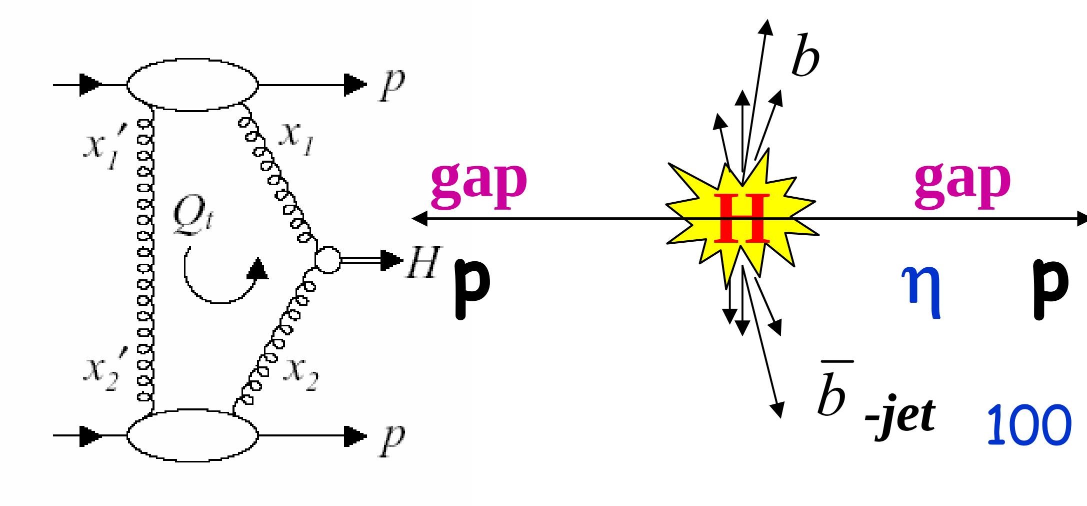


Also doable: $\phi \to hh \to \tau\tau bb$;
4b channel very difficult

bkg systematics included

Diffractive Higgs production

SM Higgs: ($30fb^{-1}$)
11 signal vs 12 bkg events
MSSM: σ ~ x10 larger ($\tan\beta$)



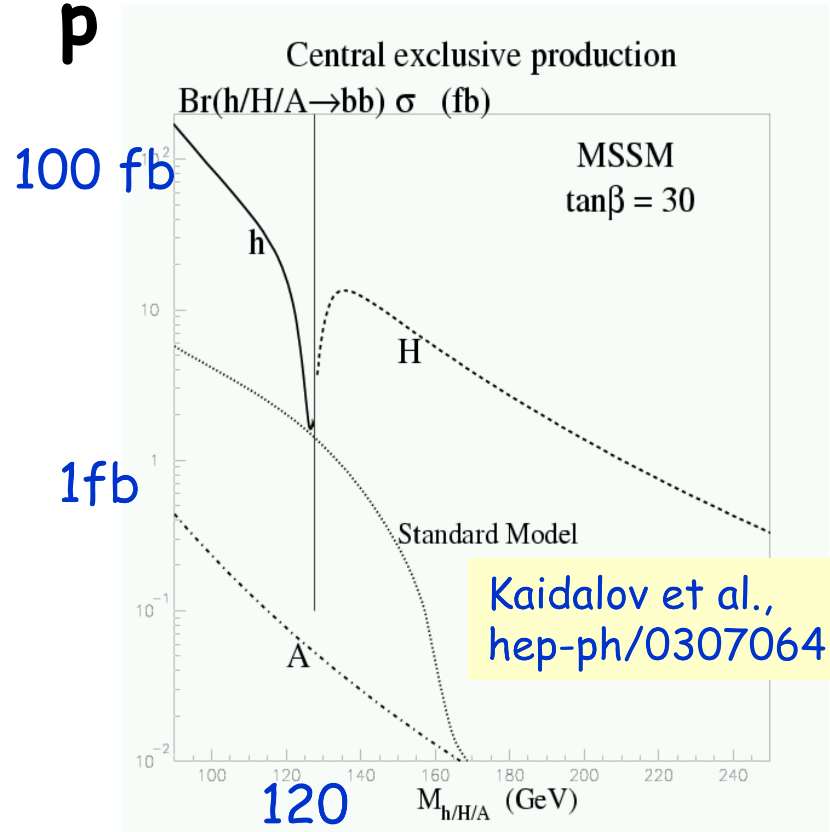
Exclusive production:

- **J_z=0 suppression of gg→bb bkg**
- **Higgs mass via missing mass**

$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

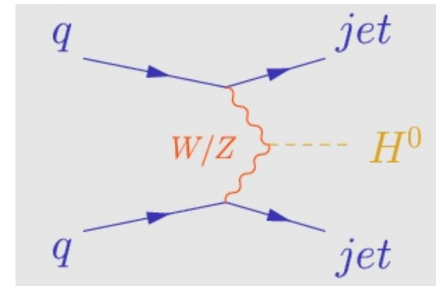
$\Delta M = O(1.0 - 2.0)$ GeV

- **Of course, need Roman pots**

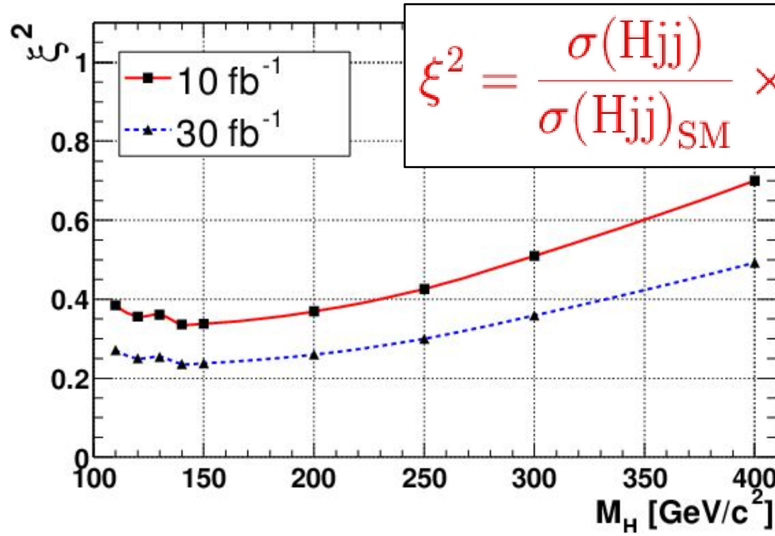


Invisible Higgs…

- **H $\rightarrow$ LSP decays possible.**
  - **Use production channels like VBF (Hqq), WH, ZH, ttH**
  - **VBF signal: forward and backward jets + large missing pt in central region.**
  - **Requires dedicated jets+E_T^{miss} trigger**



- **Backgrounds:**
  - **Z jet jet, Z $\rightarrow\nu\nu$; W jet jet, W $\rightarrow\ell\nu$ (miss ℓ) , QCD jets + escaping particles**
  - **Selection:**
    - **F & B jets**
    - **Missing E_T**
    - **Central jet veto**
    - **Lepton veto**



$$\xi^2 = \frac{\sigma(\mathrm{Hjj})}{\sigma(\mathrm{Hjj})_{\mathrm{SM}}} \times \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{inv})$$

End of Lecture 1

Other Higgs stories

- **CP-violating scenario**
  - Physical states mixture of CP eigenstates
  - Couplings depend on phases of complex parameters (e.g. X_t)
  - Huge effect on all previously shown plots/results
- **Benchmark scenarios "at the edge"**
  - X-phobic scenarios (gluo-phobic, fermio-phobic, etc)
    - But in general Y-friendly scenario helps
  - small-α_{eff} scenario
- **Higgs self-coupling**
  - At the limit with LHC++

Other case: SUSY particles accessible

- **If SUSY kinematically accessible**
  - **Higgses can decay directly to or come from decays of SUSY particles**
  - **Light SUSY particles suppress or enhance loop induced production or decays**
- **Sparticle decay modes can compete with SM modes**

$$\mathrm{H/A} \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4\ell^{\pm} X$$

$$\mathrm{H}^{\pm} \rightarrow \chi_2^0 \chi_1^{\pm} \rightarrow 3\ell^{\pm} X$$

Also possible $h^0 \rightarrow$ LSP, invisible for R parity conservation

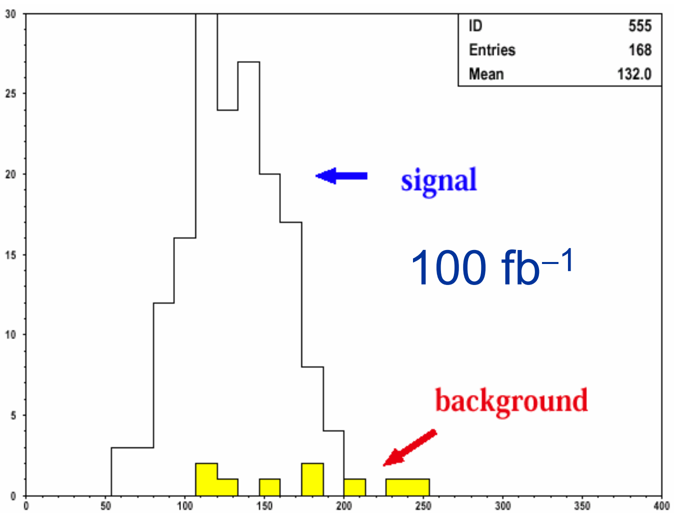
- **Further source of Higges from cascade decays of heavy SUSY particles**

$$\chi_2^0, \chi_1^{\pm} \rightarrow \chi_1^0 + \Phi \qquad \text{"little cascade"}$$

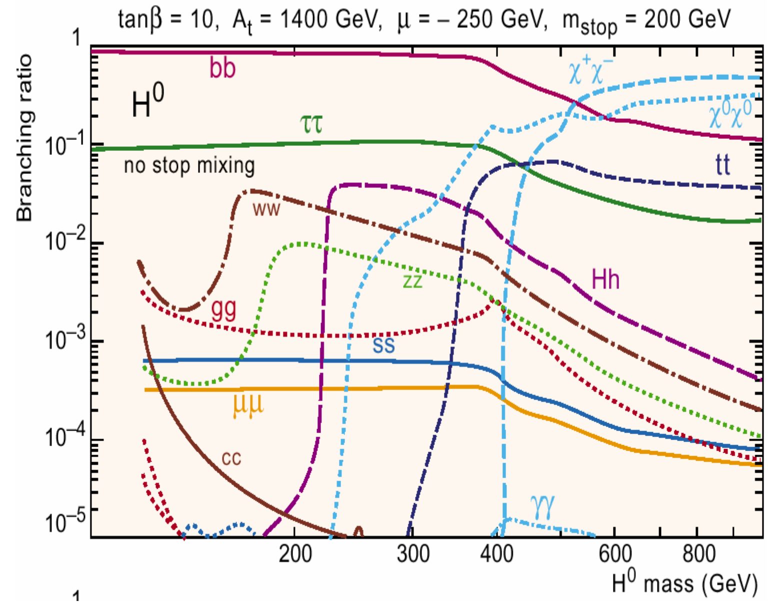
$$\chi_{3,4}^0, \chi_2^{\pm} \rightarrow \chi_{1,2}^0, \chi_1^{\pm} + \Phi \qquad \text{"big cascade"}$$

If SUSY charg(neutral)inos < 1 TeV (I)

- **Decays $H^0 \to \tilde{\chi}^0_2\tilde{\chi}^0_2$, $\tilde{\chi}^+_i\tilde{\chi}^-_j$ become important**
  - **Recall that $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+\ell^-$ has spectacular edge on the dilepton mass distribution**
  - **Example: $\tilde{\chi}^0_2\tilde{\chi}^0_2$. Four (!) leptons (isolated); plus two edges**



Four-lepton mass



Central point in MSSM parameter space :

$M_{A,H} = 350$ GeV $\tan\beta = 5$

$M_{\tilde{l}} = 250$ GeV $\mu = -500$ GeV

$M_{\tilde{\chi}^0_1} = 60$ GeV $M_{\tilde{\chi}^0_2} = 110$ GeV

$M_{\tilde{q}} = M_{\tilde{g}} = 1$ TeV

If SUSY charg(neutral)inos < 1 TeV (II)

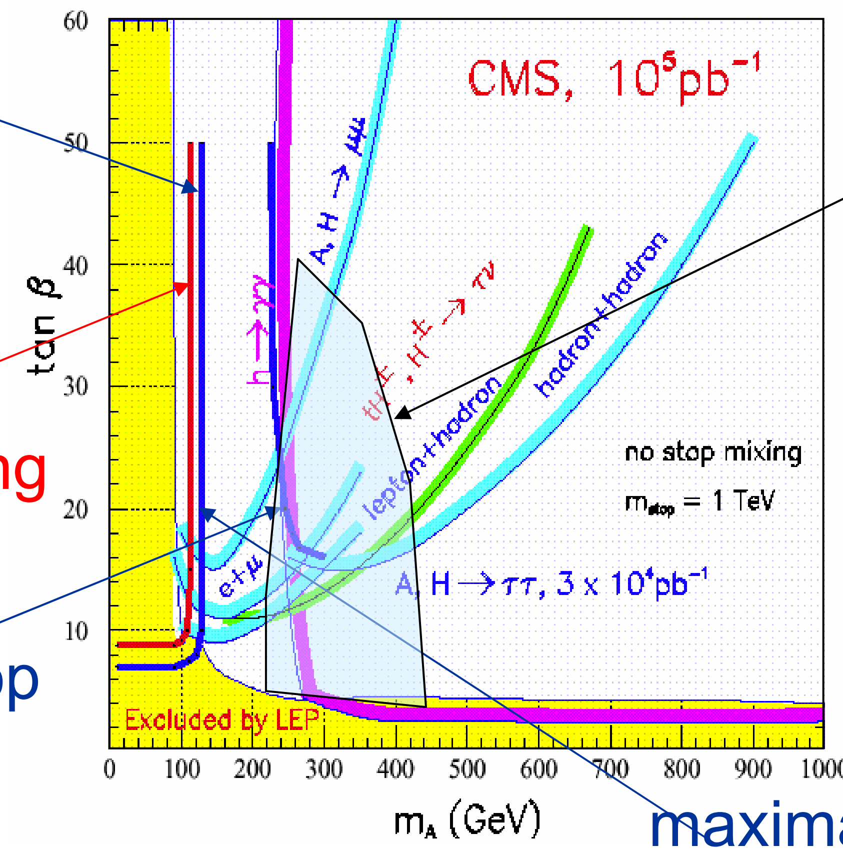
- **Helps fill up the "hole"**

Wh

$(e/\mu)\nu$ $b\bar{b}$

No stop mixing

maximal stop mixing with 30 fb^{-1}



Area covered by $H^0 \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2$, $\rightarrow 4\ell$eptons 100 fb^{-1}

maximal stop mixing with 300 fb^{-1}

Another branch: cascades

- **Alternative to other decay modes**
  - **Alternative production mechanisms**
- **Exploit MSSM Higgs boson production in cascades of SUSY particles**

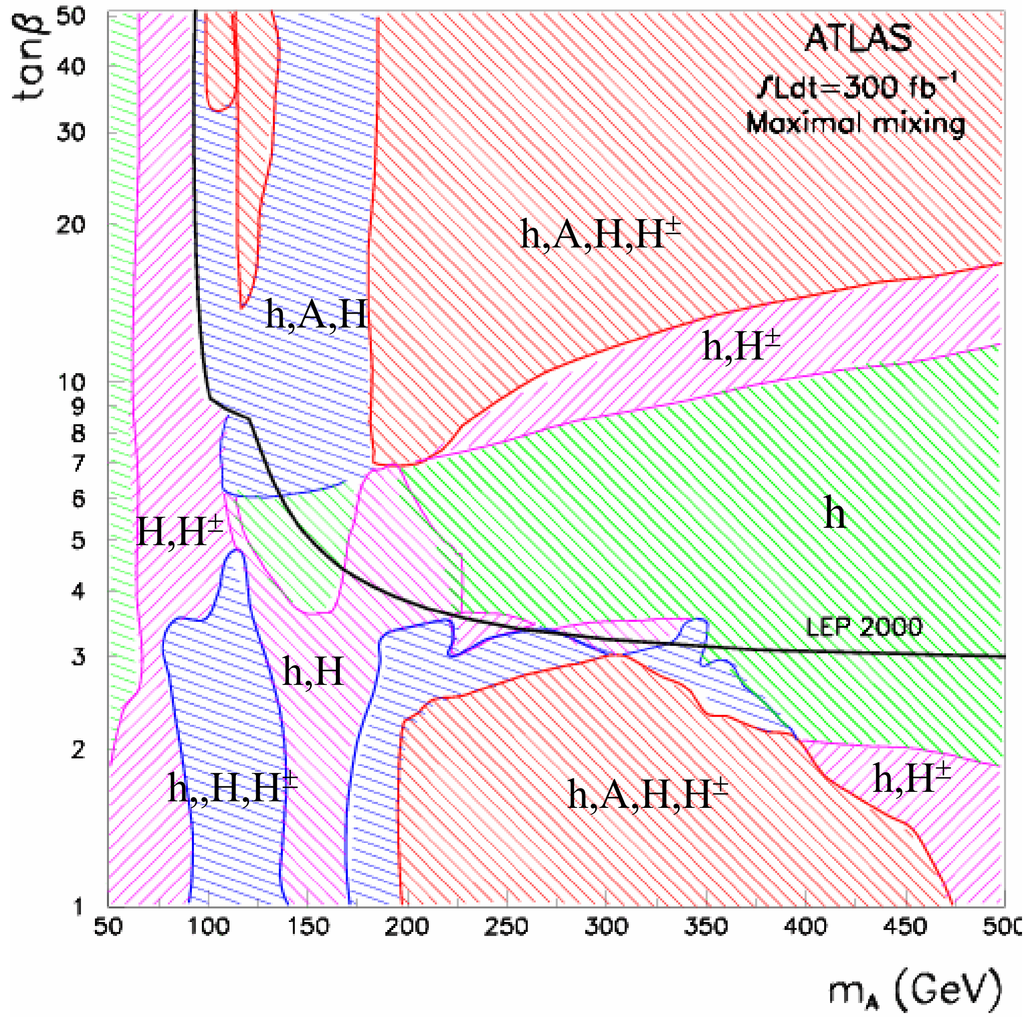
$$\tilde{g} \rightarrow qq^{(\prime)} \; \chi_3^0, \chi_4^0, \chi_2^{\pm} \rightarrow \chi_1^0, \chi_2^0, \chi_1^{\pm} \; A, H$$

A. Datta (Uni. Florida), A. Djouadi (Uni. Montpellier),
M. Guchait (TIFR Mumbay), F. Moortgat (CERN),

Lecture 2

Observability of MSSM Higgses

MSSM Higgs bosons



- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

5σ contours

Assuming decays to SM particles only

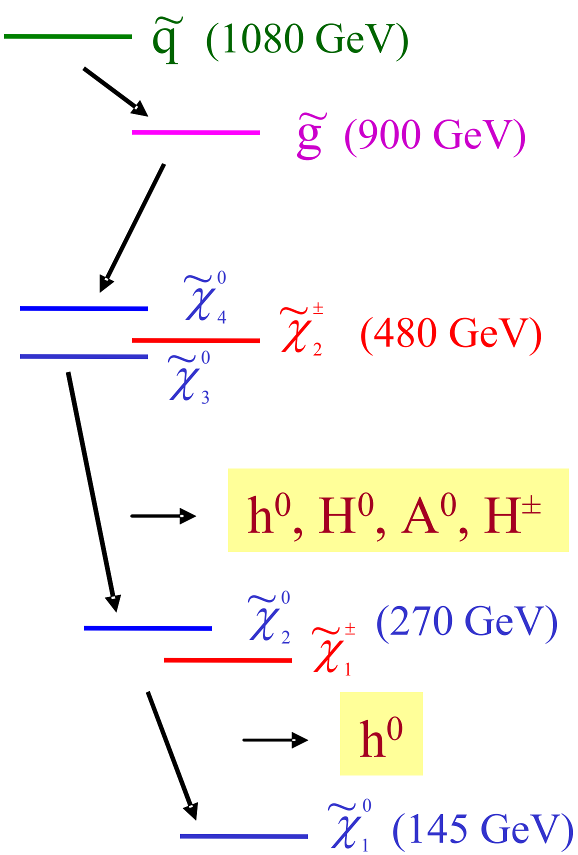
MSSM: Higgs summary

- **At least one ϕ will be found in the entire M_A-$\tan\beta$ plane**
  - latter (almost) entirely covered by the various signatures
  - Full exploration requires 100 fb^{-1}
  - Difficult region: $3<\tan\beta<10$ and $120<M_A<220$; will need:
    - > 100 fb^{-1} or $h\rightarrow bb$ decays
    - Further improvements on τ identification?
  - Intermediate $\tan\beta$ region: difficult to disentangle SM and MSSM Higgses (only h is detectable)
- **Potential caveats (not favored)**
  - Sterile (or "invisible") Higgs
    - Excess visible, but it'll tough to "prove" what it is…

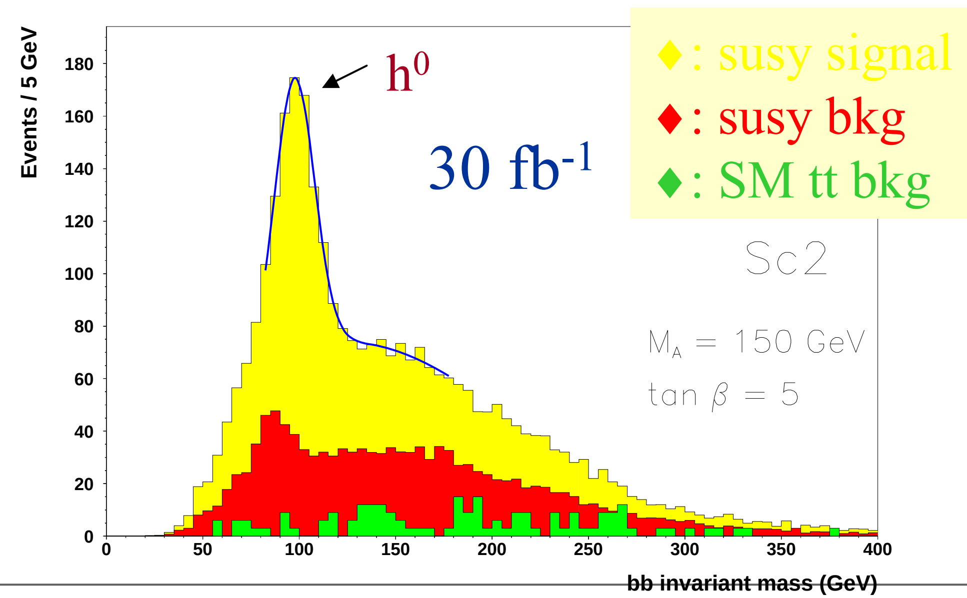
Cascade scenarios (I)

Little + big cascades

$$\tilde{g} \rightarrow qq^{(')}\ \chi_3^0, \chi_4^0, \chi_2^\pm \rightarrow \chi_1^0, \chi_2^0, \chi_1^\pm\ A, H$$



- At least 5 jets; One jet with E_T >300 GeV
- E_T^{miss} > 150 GeV
- Effective mass $E_T^{total} = \sum_{jets} E_T + E_T^{miss}$ >1.2TeV
- At least two *b*-tagged jets, with 45 GeV < E_T < 120 GeV



Invisible Higgs

- **H $\rightarrow$ LSP decays possible.**
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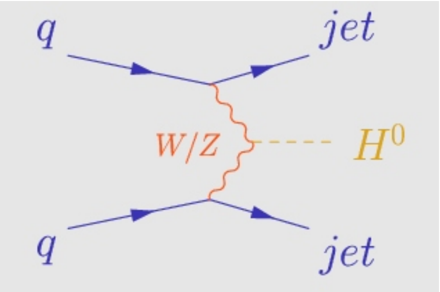
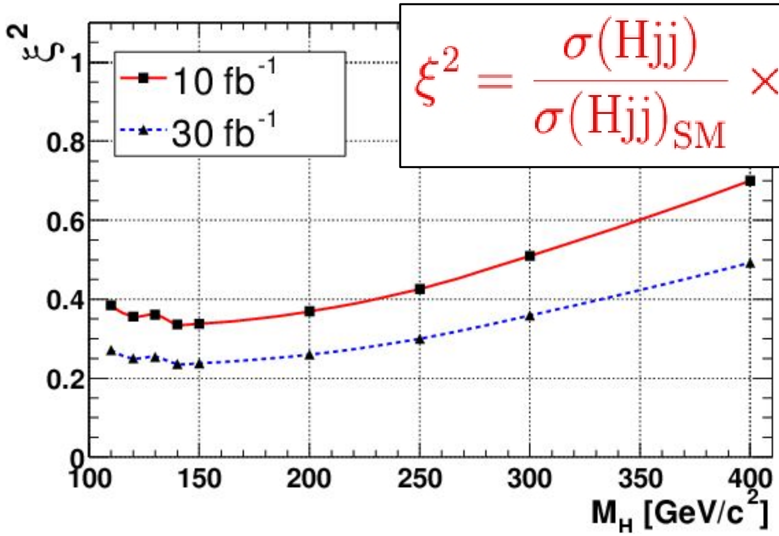
  - VBF signal: forward and backward jets + large missing pt in central region.
  - Requires dedicated jets+E_T^{miss} trigger



- **Backgrounds:**
  - Z jet jet, Z $\rightarrow \nu\nu$; W jet jet, W $\rightarrow \ell\nu$ (miss ℓ) , QCD jets + escaping particles
  - Selection:
    - F & B jets
    - Missing E_T
    - Central jet veto
    - Lepton veto

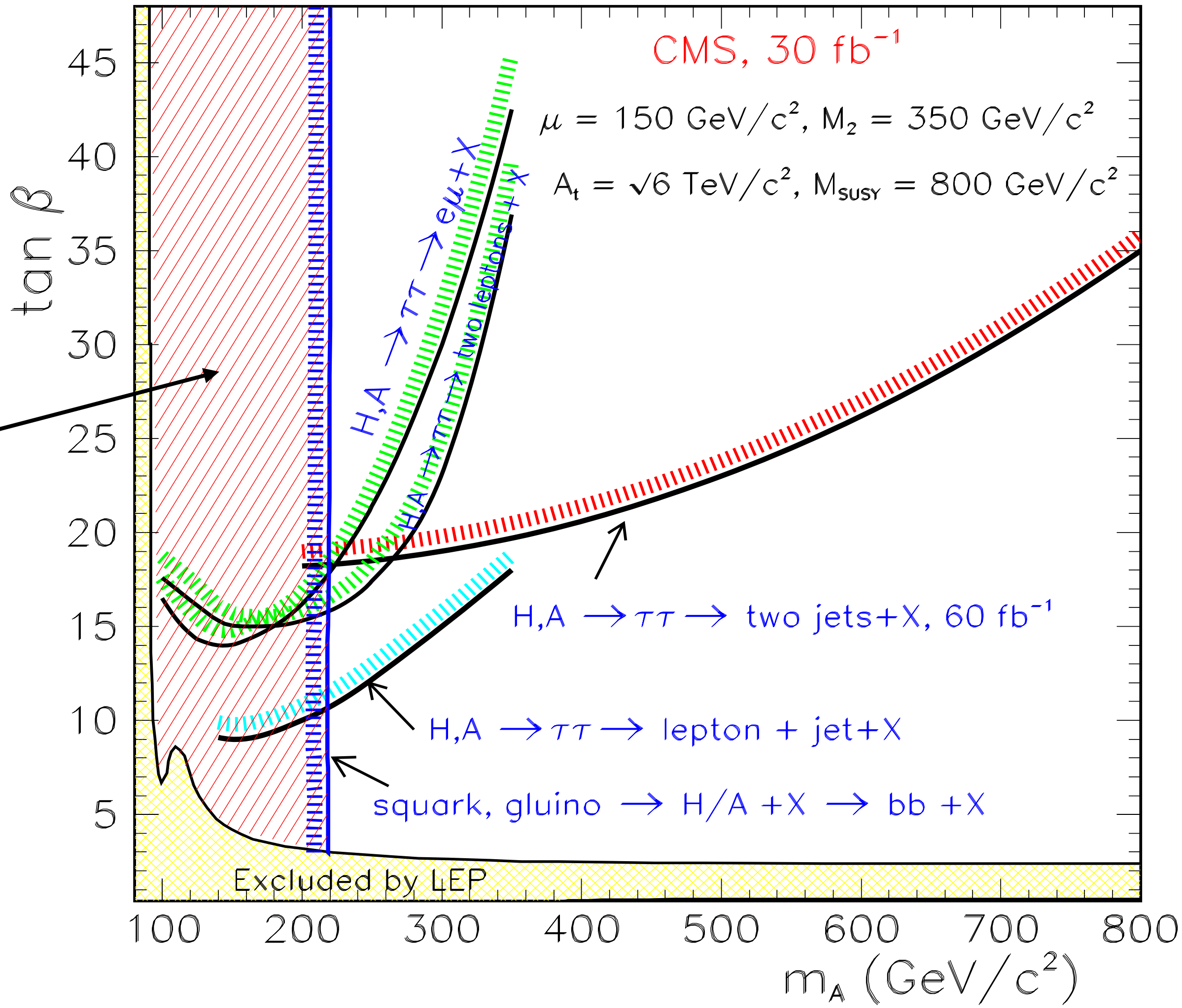


$$\xi^2 = \frac{\sigma(\mathrm{Hjj})}{\sigma(\mathrm{Hjj})_{\mathrm{SM}}} \times \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{inv})$$

Discovery reach at $30fb^{-1}$

- **Recall: h^0 can be found in the entire plane**

region where H^0 and A^0 can be found in SUSY cascade decays



Scenario 3

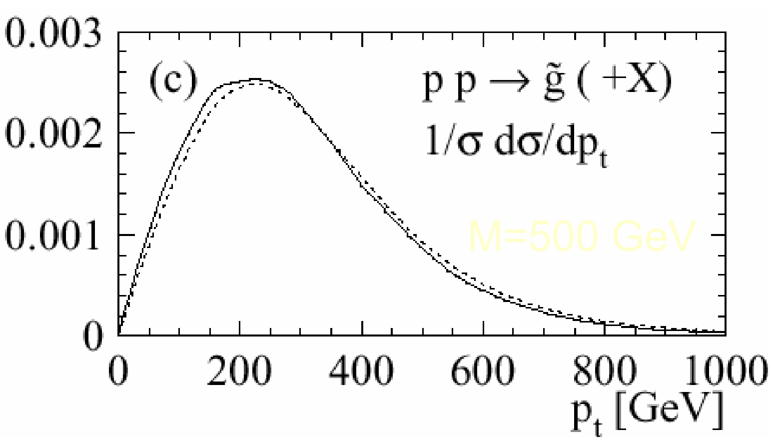
Supersymmetry

Sparticles

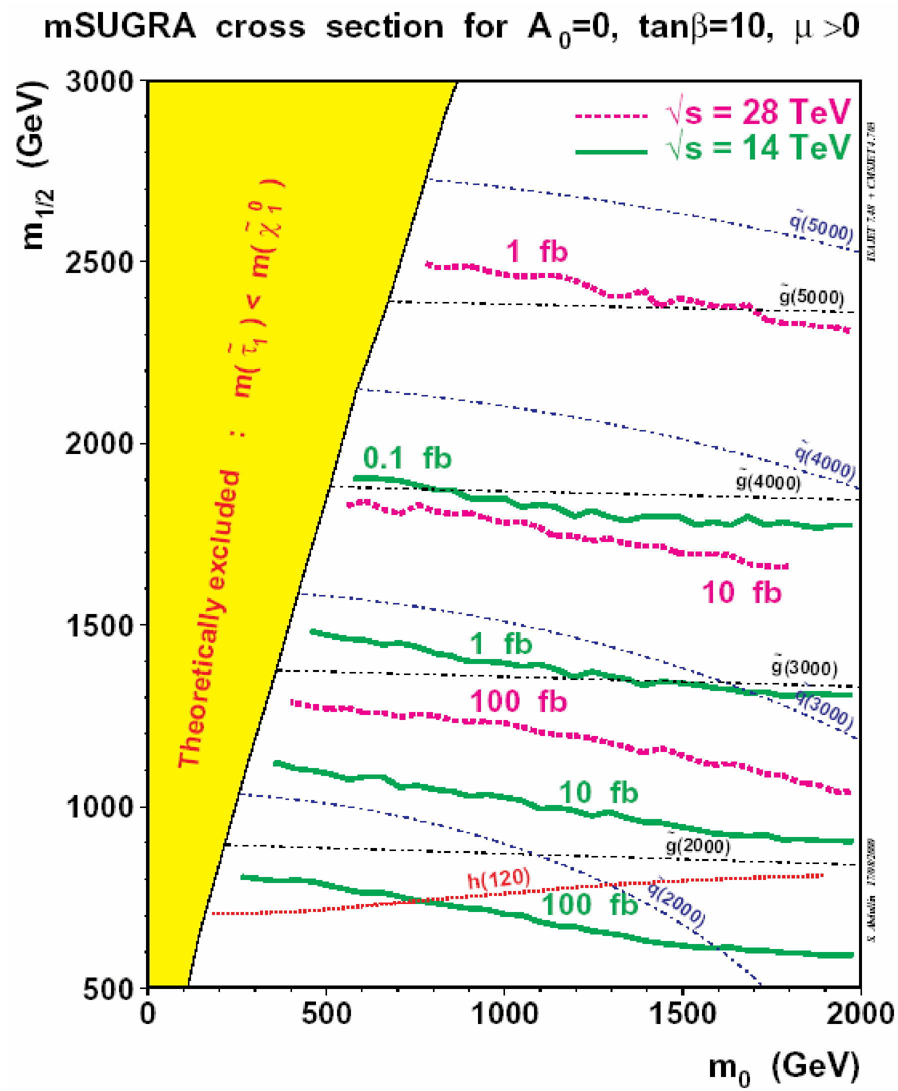
SUSY @ LHC

- **Simplest SUSY**
  - **A SUSY factory**

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

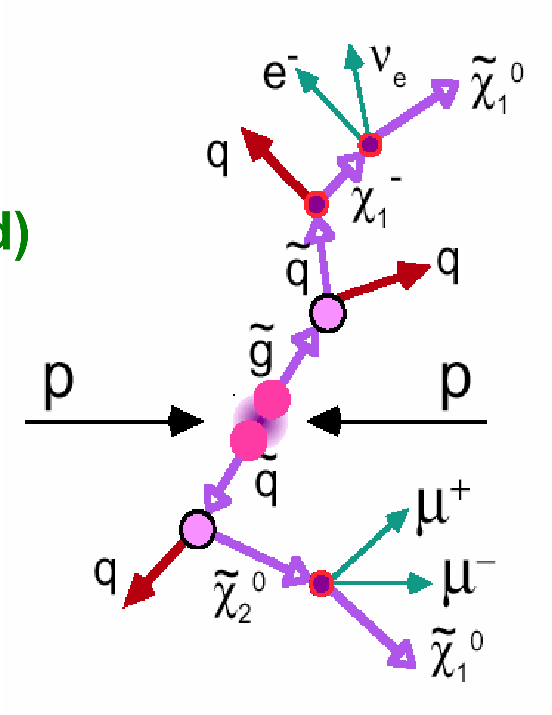


  - **Gauginos produced in their decay; example: $q_L \rightarrow \chi_2^0 q_L$**



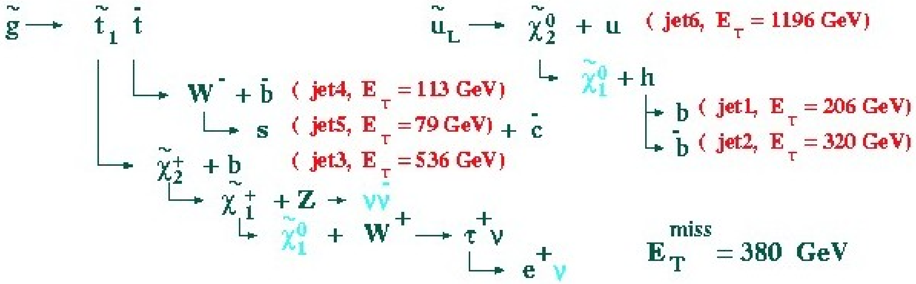
SUSY decays

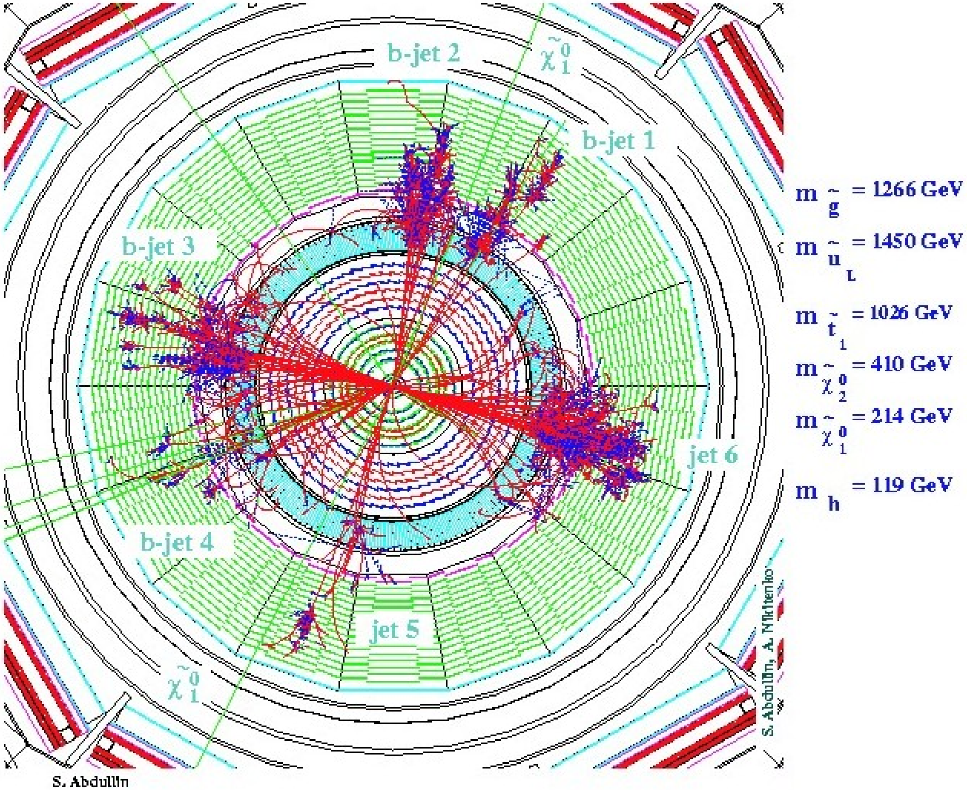
- **Squarks & gluinos produced together with high σ**
  - **Gauginos produced in their decays; examples:**
    - $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 \tilde{q}_L$ (SUGRA P5)
    - $\tilde{q} \rightarrow \tilde{g}\, q \rightarrow \tilde{\chi}_2^0 \tilde{q}\bar{q}$ (GMSB G1a)
  - **Two "generic" options with $\tilde{\chi}^0$:**
    - (1) $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ (~ dominates if allowed)
    - (2) $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+\ell^-$ or $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^+\ell^-$
  - **Charginos more difficult**
    - Decay has ν or light q jet
  - **Options:**
    - Look for higgs (to $b\bar{b}$)
    - Isolated (multi)-leptons



SUSY signature(s)

- Many hard Jets
- Large missing energy
  - 2 LSPs
  - Many neutrinos
- Many leptons
- In a word:
  - Spectacular!

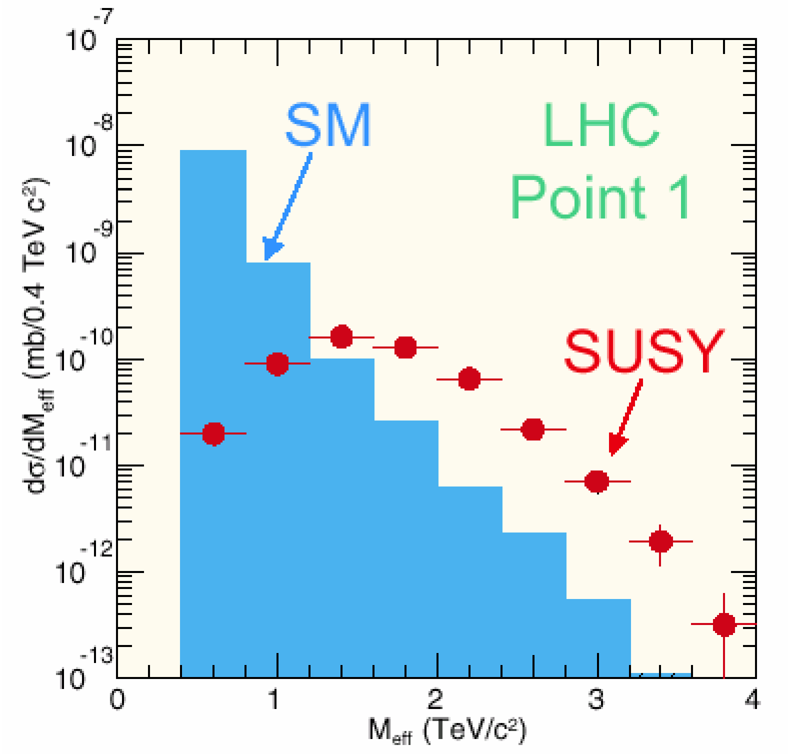




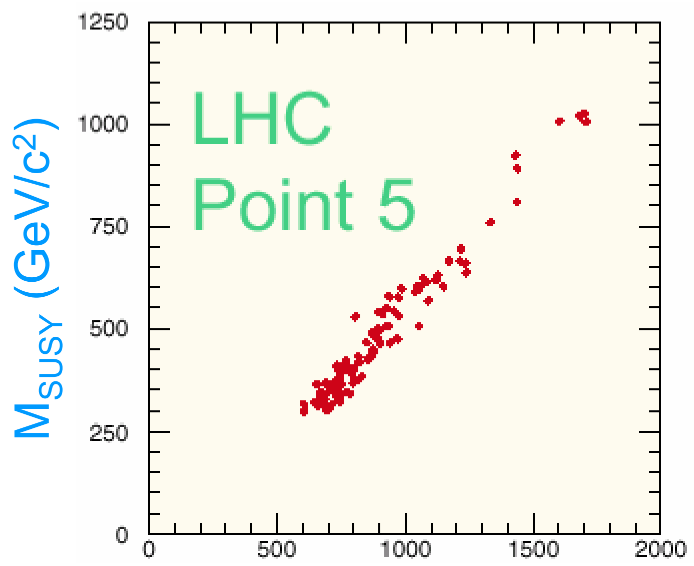
SUSY mass scale

- **Events with ≥ 4jets + E_T^{miss}**
  - **Clean: S/B~10 at high M_{eff}**
  - **Establish SUSY scale (σ ≈ 20%)**

$$M_{\mathrm{eff}} = \sum_{j=1}^{4} P_{\mathrm{T},j} + E_{\mathrm{T}}^{\mathrm{miss}}$$

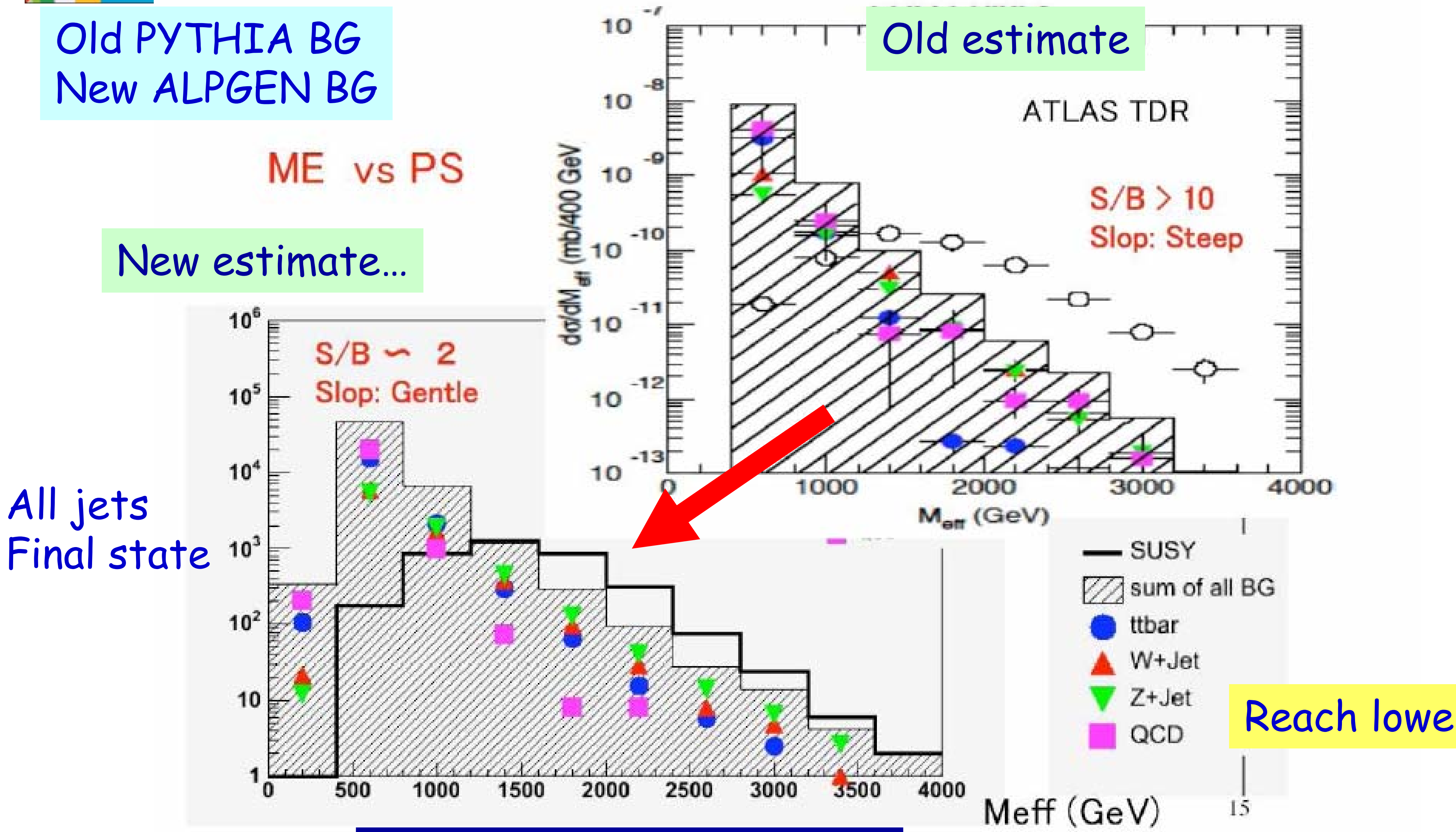


Effective mass "tracks" SUSY scale well



Effective mass: example

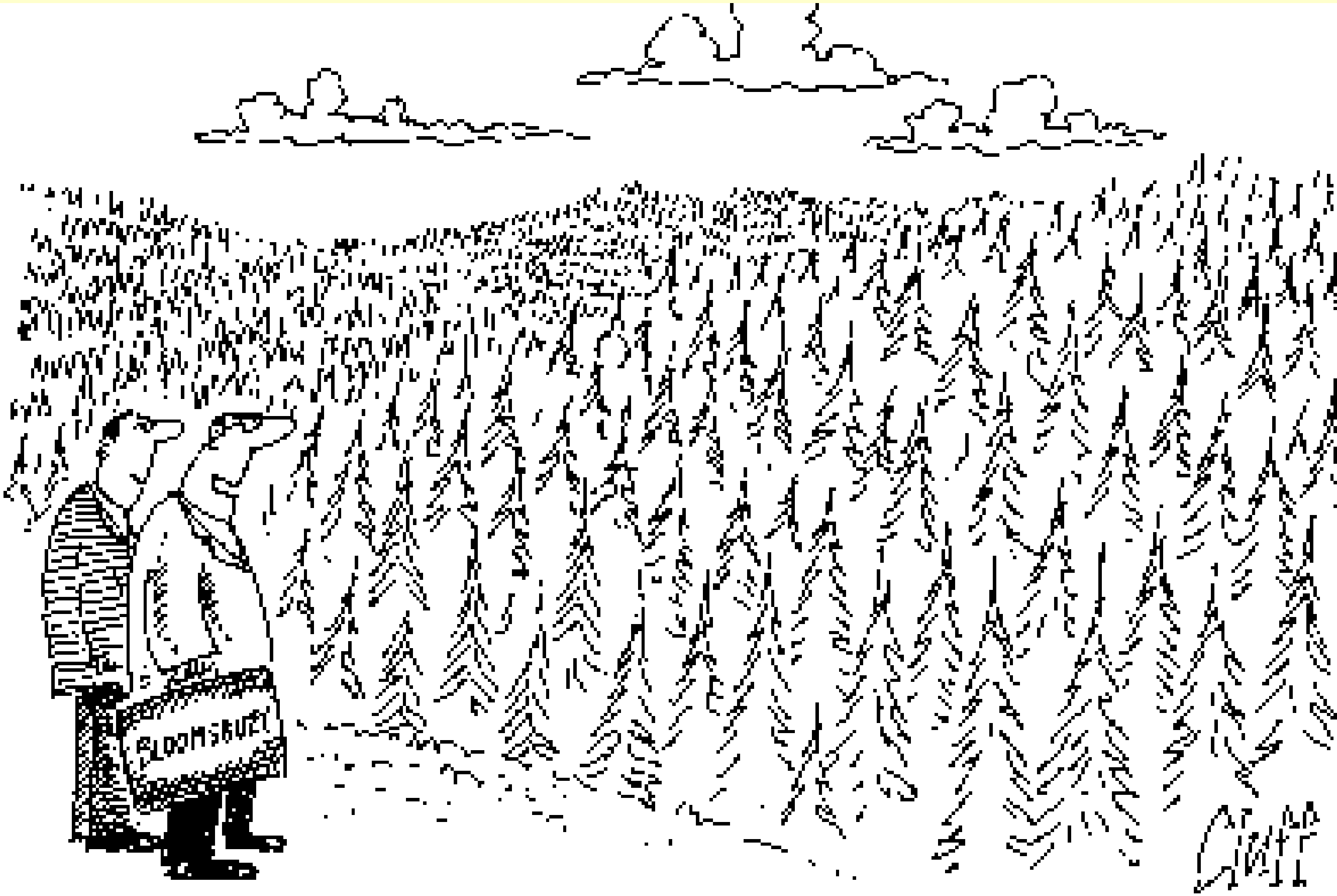
Old PYTHIA BG
New ALPGEN BG



$$M_{\text{eff}} = \Sigma_i \left| p_{T(i)} \right| + \not{E}_T$$

SUSY space is huge; aka many models

"One day, all of these will be SUSY phenomenology papers."



SUSY

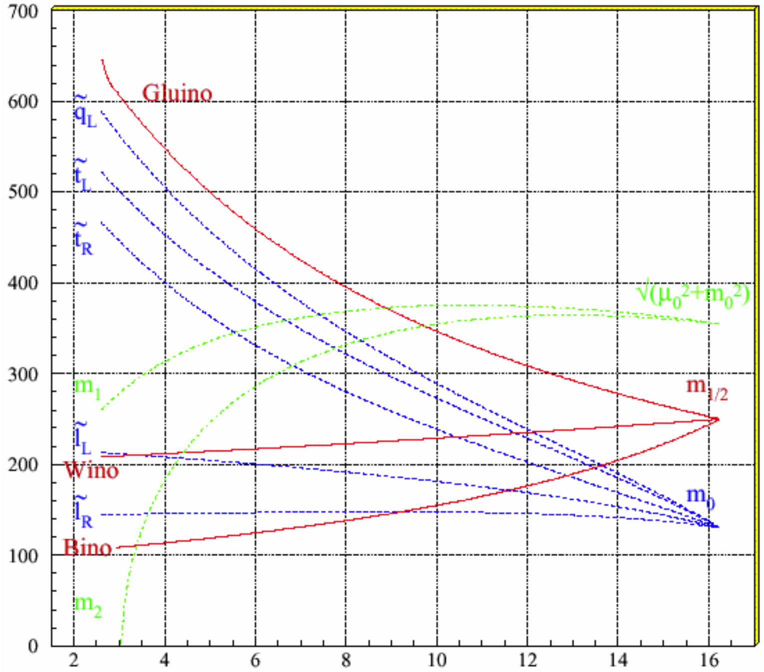
- **Huge number of theoretical models**
  - Very complex analysis; MSSM-124
  - Very hard work to study particular scenario
    - assuming it is available in an event generator
  - To reduce complexity we have to choose some "reasonable", "typical" models; use a theory of dynamical SYSY breaking
    - mSUGRA
    - GMSB
    - AMSB (studied in less detail)
  - Model determines full phenomenology (masses, decays, signals)

SUGRA

- **Five parameters**
  - All scalar masses same (m_0) at GUT scale
  - All gaugino masses same ($m_{1/2}$) at GUT scale
  - $\tan\beta$ and sign(μ)
  - All tri-linear Higgs-sfermion-sfermion couplings common value A_0 (at GUT scale)
- **Full "particle table" predictable**
  - 26 RGE's solved iteratively
  - Branches: R parity (non)conservation
  - Extensions: relax GUT assumptions (add parameters)

SUGRA spectroscopy

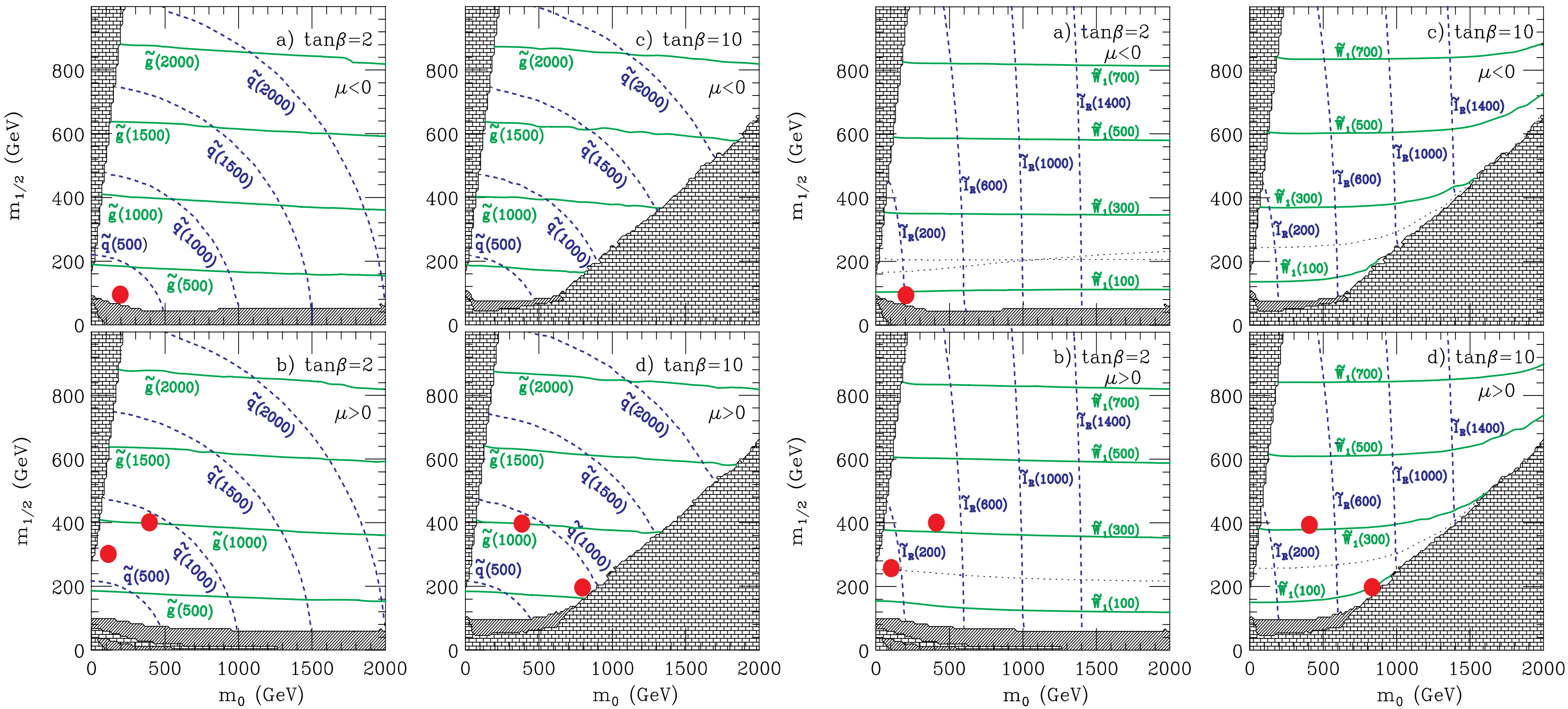
- **Basic assumption: mass universality**
  - Scalar masses: m_0;
  - gaugino masses: $m_{1/2}$;
  - Higgs masses: $(m_0^2+\mu^2)^{1/2}$
- **RGE: run masses down to EWK scale**
  - M(squark): large Increase (due to α_3)
  - M(slepton): small increase (due to α_1, α_2)
  - Gauginos: gluino is fast-rising; B-ino, W-ino mass decreases
  - Mixing leads to charginos (2) and neutralinos (4)



- **Higgs: strong top coupling drives $\mu^2<0$; Symmetry Breaking mechanism arises naturally in mSUGRA(!)**

Sparticles in SUGRA

- **Contours of fixed $\tilde{g}/\tilde{q}$ and $\tilde{\chi}/\tilde{\ell}$ mass**



$$m(\tilde{g}) \approx 3m_{1/2}$$

$$m(\tilde{q}) \approx \sqrt{m_0^2 + 6m_{1/2}^2}$$

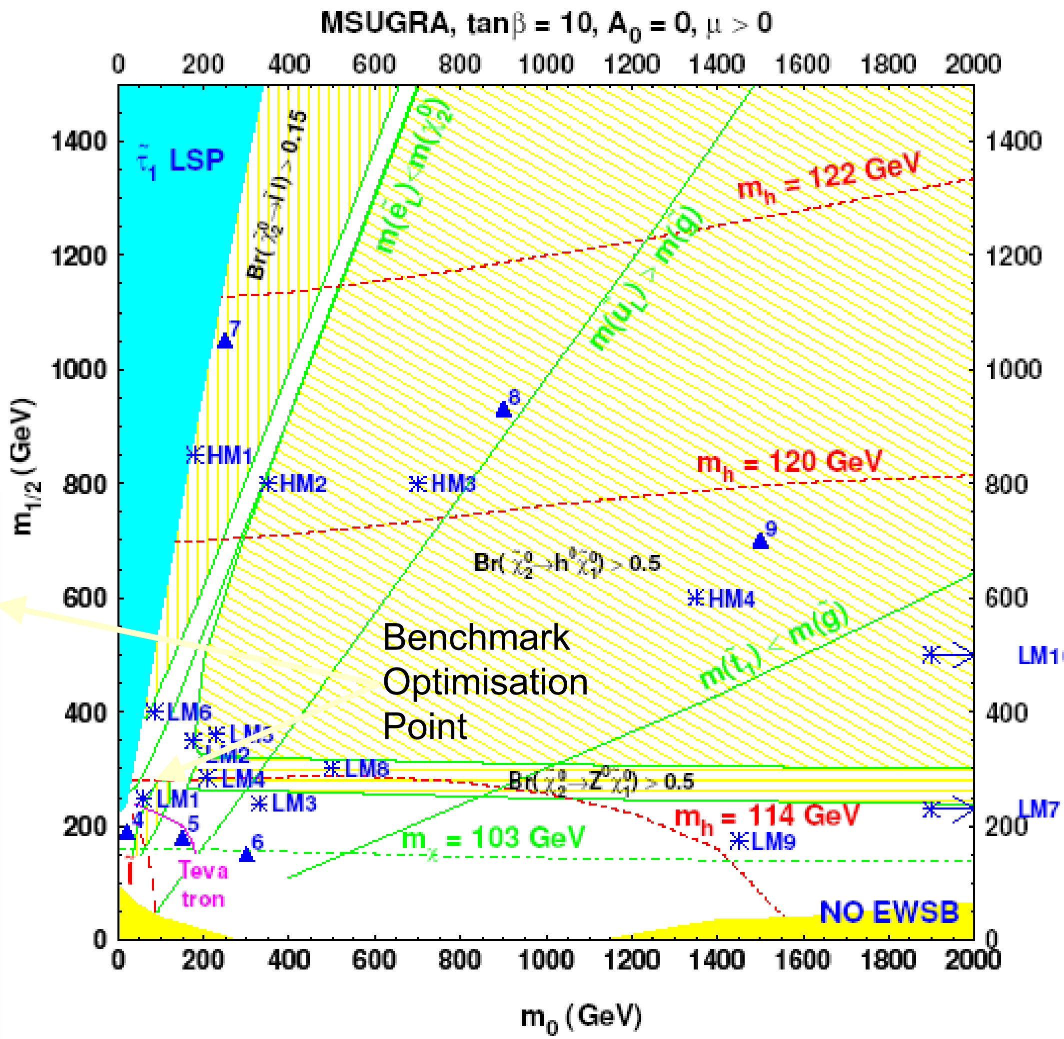
$$m(\tilde{\chi}_1^0) \approx m_{1/2}/2; m(\tilde{\chi}_2^0, \tilde{\chi}^{\pm}) \approx m_{1/2};$$

$$m(\tilde{\ell}_L^{\pm}, \tilde{\ell}_R^{\pm}) \approx \sqrt{m_0^2 + (0.5, 0.15)m_{1/2}^2}$$

Benchmark Test Points

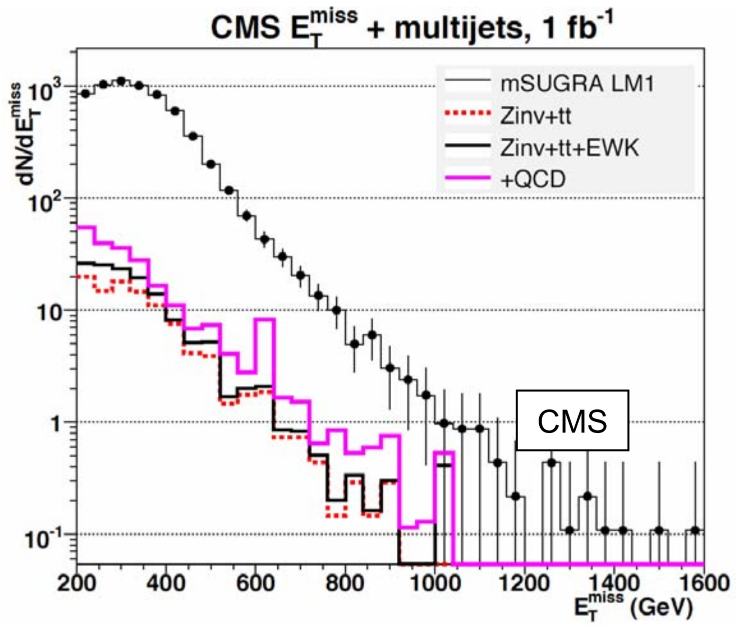
- Low mass points for early LHC running but outside Tevatron reach
- High mass points for ultimate LHC reach
- Indirect constraints from WMAP for strict mSUGRA exclude most except LM1, 2, 6, 9

Point	m_0	$m_{1/2}$	$\tan\beta$	sgn(μ)	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0



Inclusive search

- **Selection Criteria**
  - MET>200 GeV + Clean-up
  - ≥ 3 jets:
    - E_T> 180, 110, 30 GeV
  - Indirect lepton veto
  - Cuts on $\Delta\phi$ between jets and MET
  - $H_T/M_{eff}=E_{T1}+E_{T2}+E_{T3}$+MET>500 GeV
- **Results:**
  - LM1 efficiency is 13%, S/B ~ 26 : Number of events (below) for 1 fb^{-1}

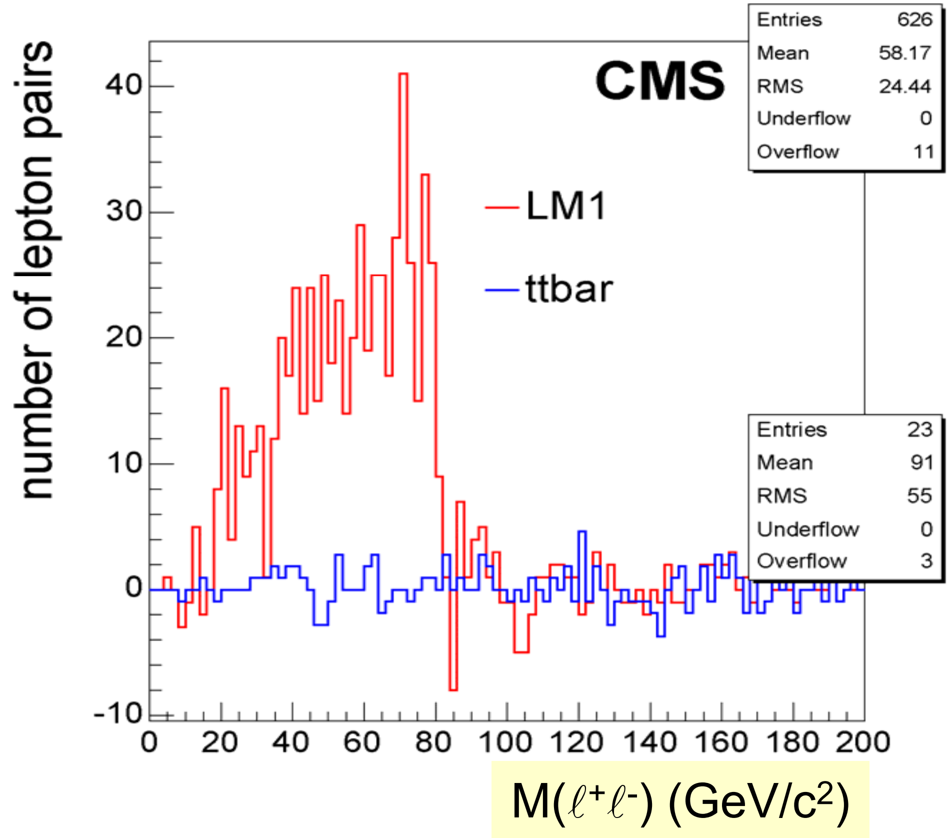


Signal	$t\bar{t}$	single t	$Z(\to \nu\bar{\nu})$+ jets	$(W/Z,WW/ZZ/ZW)$ + jets	QCD
6319	53.9	2.6	48	33	107

  - ~6 pb^{-1} for 5σ discovery
- **Lower jet multiplicity requirement reduces sensitivity to higher-order QCD corrections**

Dilepton search

- "Prototype": $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$
- Cuts (optimize @ LM1):
  - 2 OS SF isolated leptons (e,μ)
    - p_T > 10 GeV
  - MET > 200 GeV
  - ≥2 jets:
    - E_T^1>100 GeV
    - E_T^2>60 GeV
    - |η| < 3
- Background (1 fb^{-1})
  - 200 events, mostly t-tbar
  - Systematic uncertainty 20%
- LM1 Signal (1 fb^{-1})
  - 850 events



ΔM measurement easy

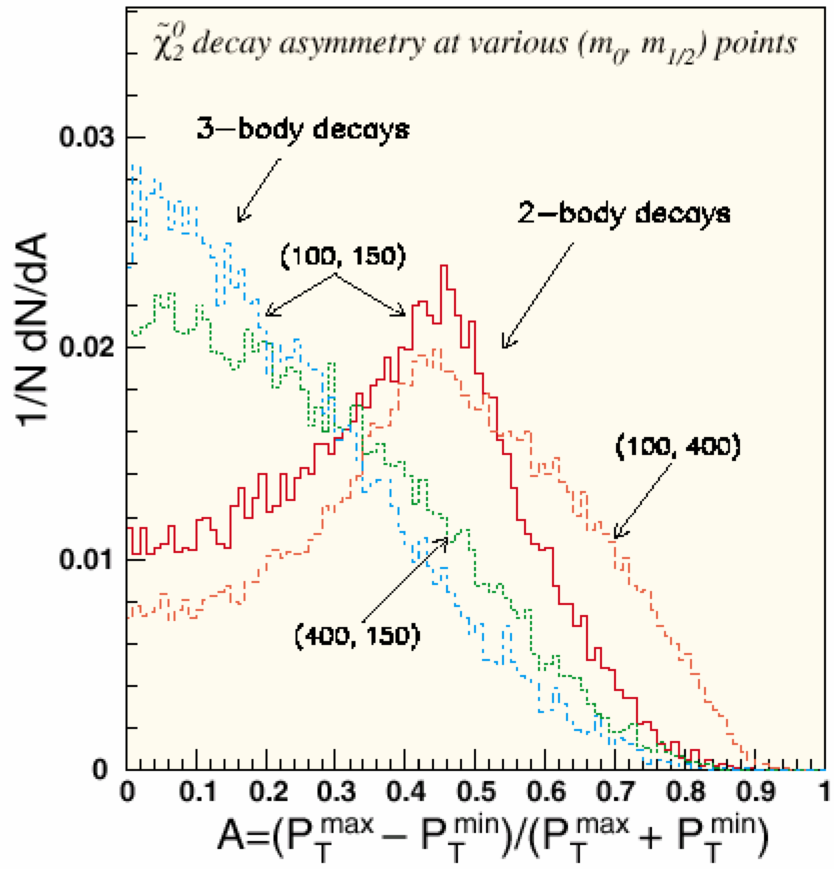
Position of edge; accurate

Distinguishing 2 & 3-body decays

- **Two scenarios can be disentangled directly**
  - **From asymmetry of two leptons:**

$$A = \frac{P_T^{\max} - P_T^{\min}}{P_T^{\max} + P_T^{\min}}$$

  - **In analogy with τ decays**



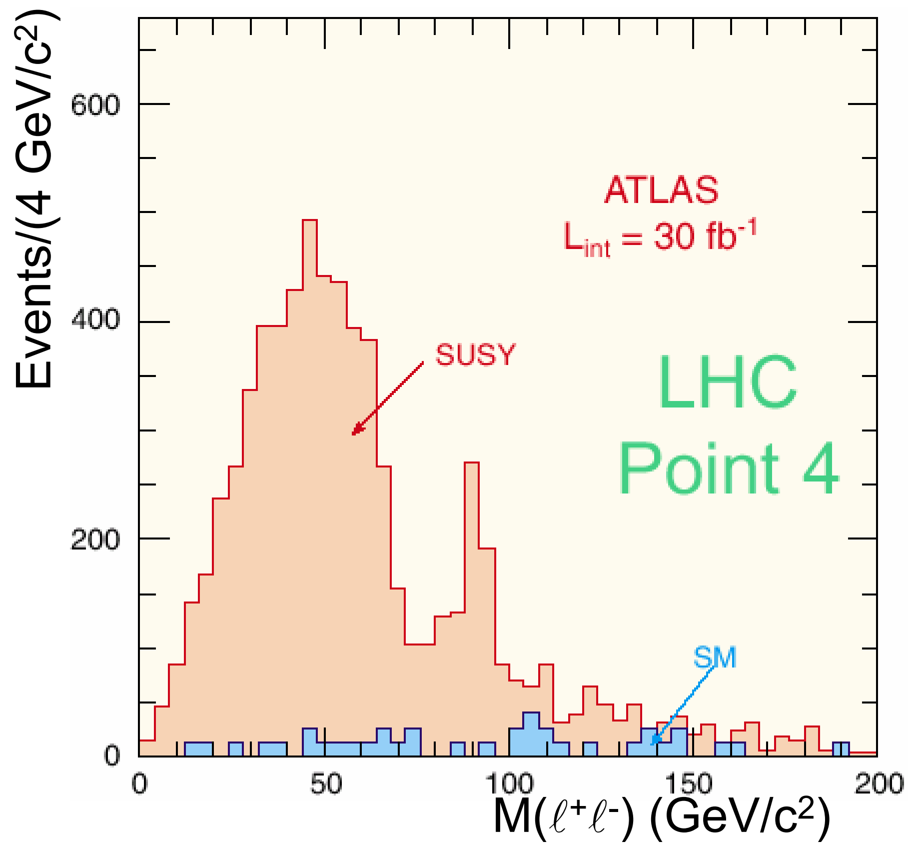
Dileptons @ other points

- **Multi-observations**
  - Main peak from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+\ell^-$
    - Measure Δm as before
  - Also peak from Z^0 through $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^0$
    - Due to heavier gauginos
    - P4 at "edge" of SB

      → small μ^2 →

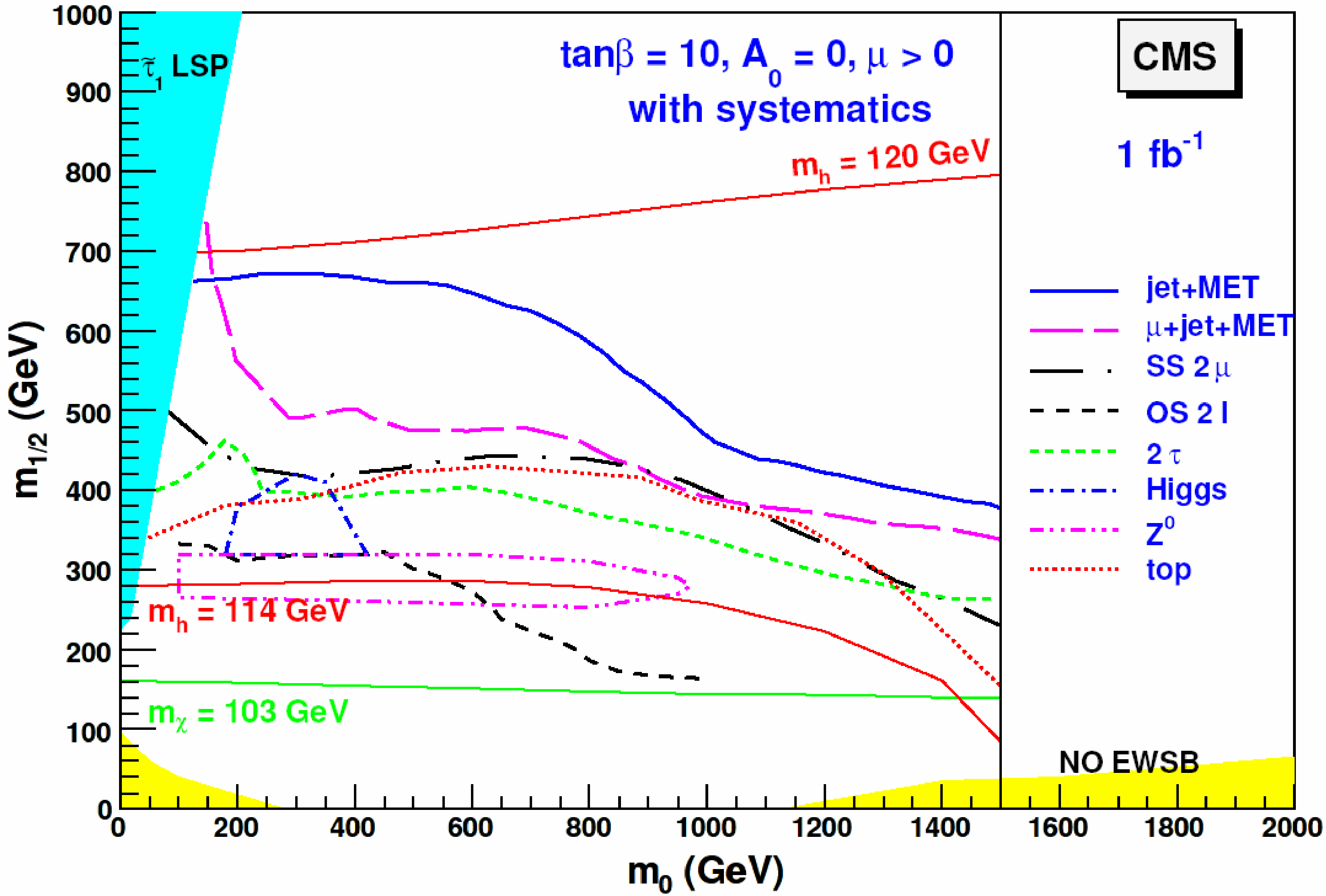
      (a) $\tilde{\chi}^\pm$ and $\tilde{\chi}^0$ are light

      (b) strong mixing between gauginos and Higgsinos

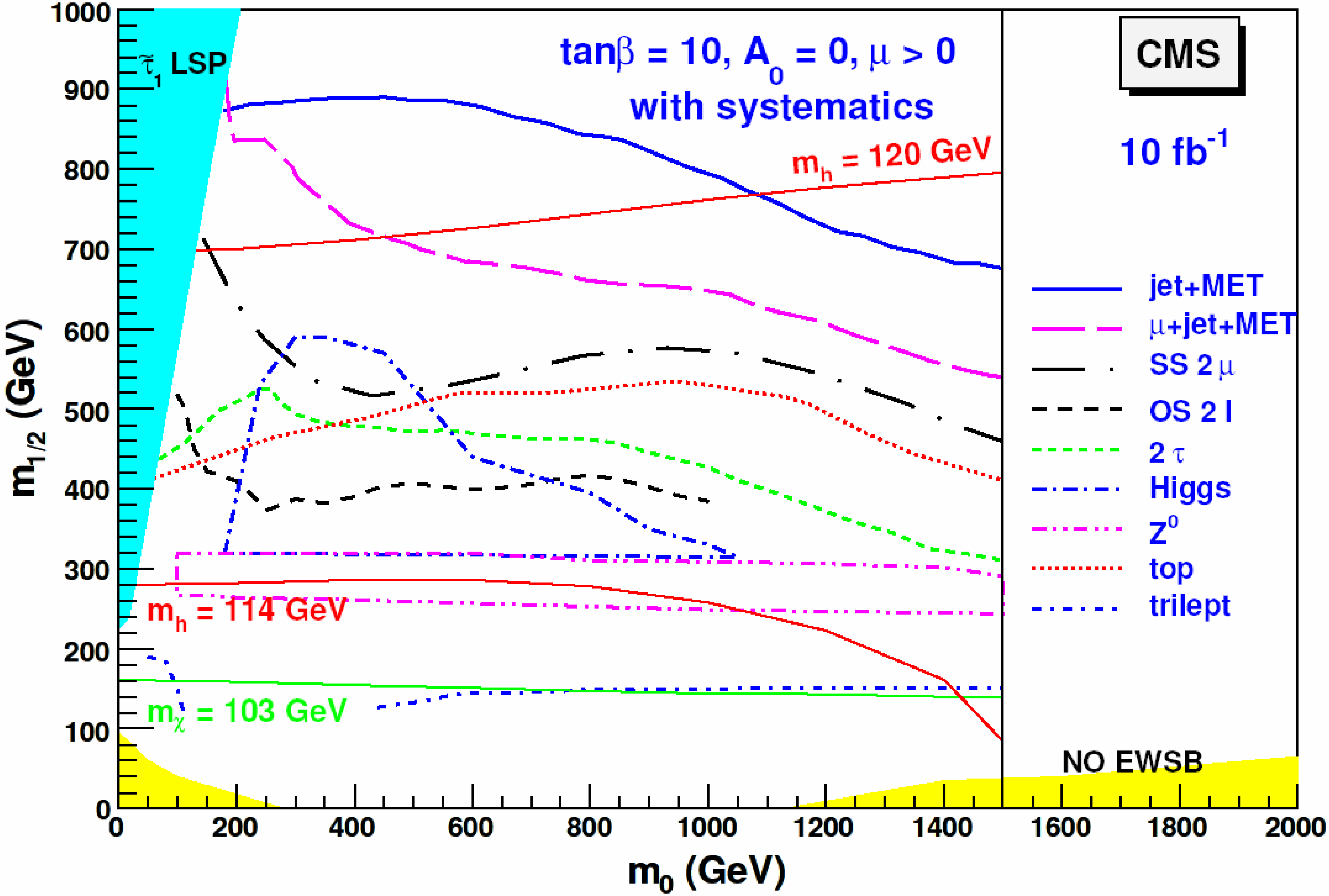


- At P4 large Branching fractions to Z decays:
  - e.g. $B(\tilde{\chi}_3 \rightarrow \tilde{\chi}_{1,2} Z^0) \approx 1/3$; size of peak/$P_T(Z)$→info on masses and mixing of heavier gauginos (model-dependent)

Reach with 1fb^{-1}

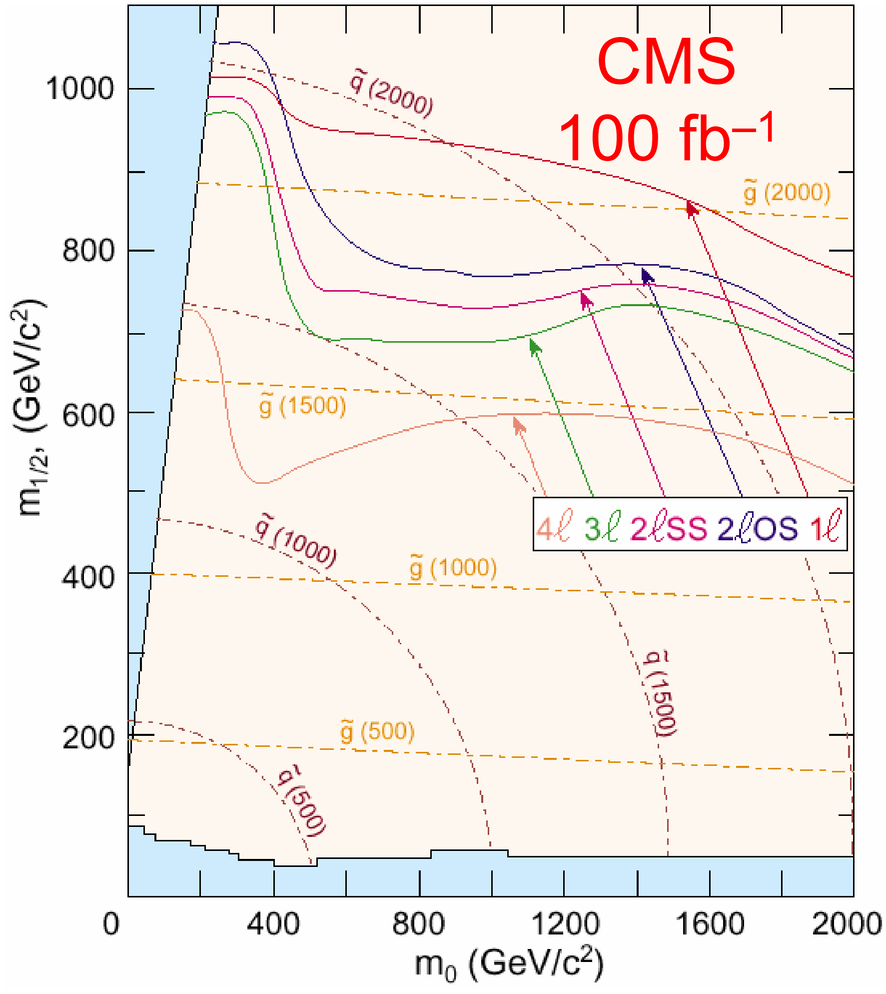


Reach with $10 fb^{-1}$



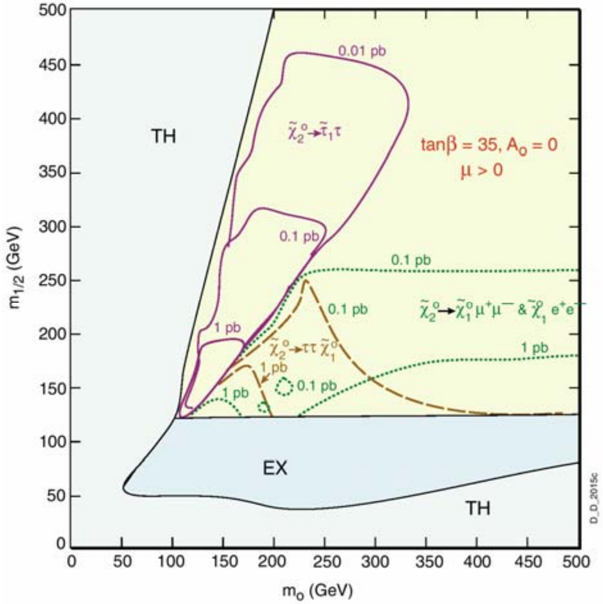
SUGRA "asymptotic" reach

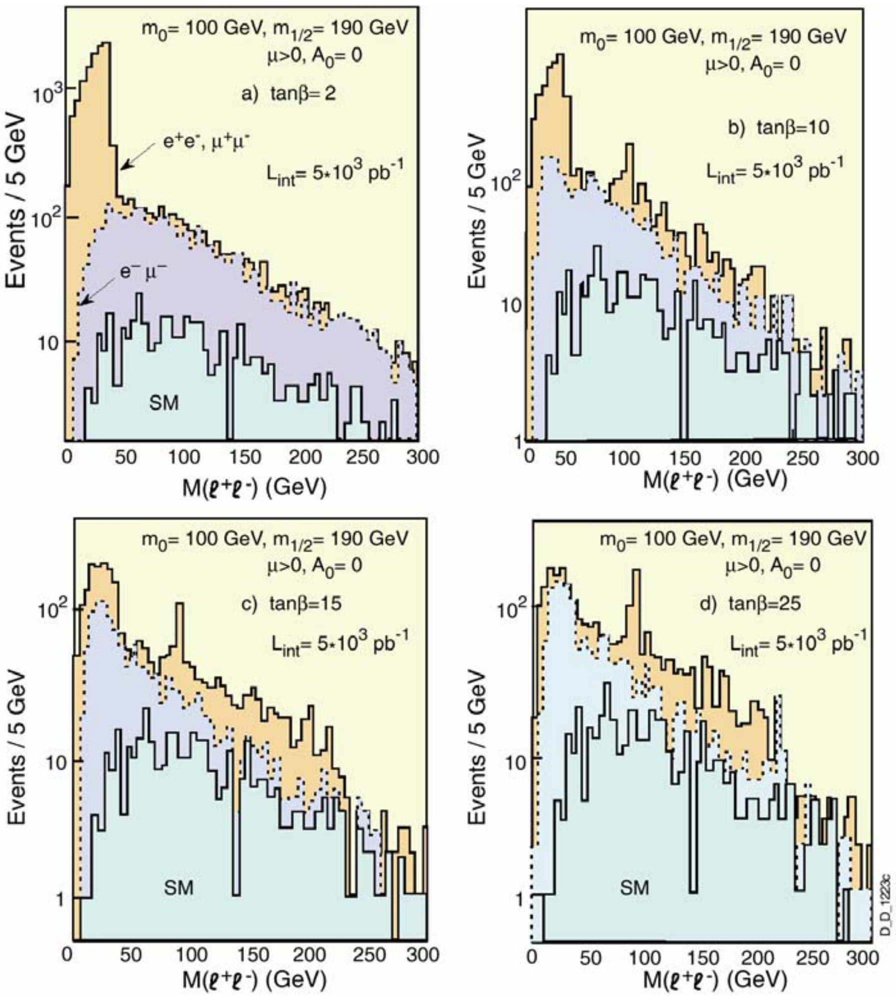
- **Using all signatures**
  - **$\tan\beta=2; A_0=0; \mathrm{sign}(\mu)=-$**
  - **But look at entire m_0-$m_{1/2}$ plane**
  - **Example signature:**
    - **N (isolated) leptons + ≥ 2 jets + E_T^{miss}**
    - **5σ (σ=significance) contours**
- **Essentially reach is ~2 (1) TeV/c^2 for the m_0 ($m_{1/2}$) plane**



Varying tanβ

- τ modes eventually become important



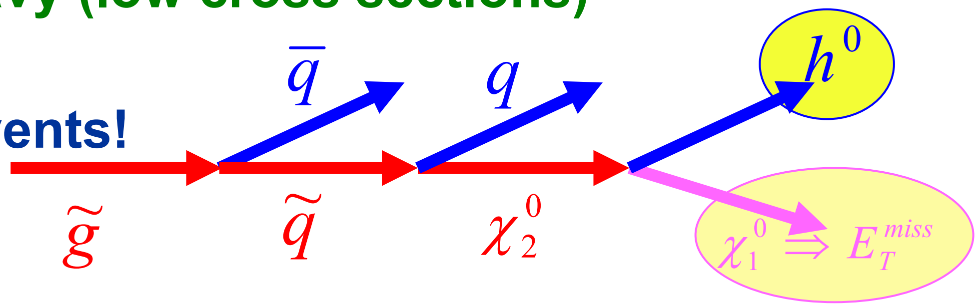


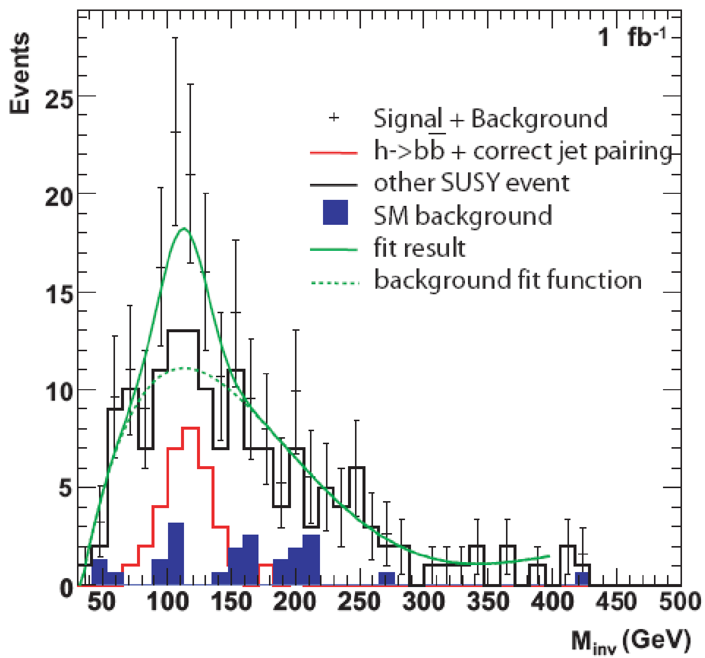
  - At tanβ>>1 only 2-body $\tilde{\chi}_2^0$ decays (may be): $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau \to \tau\tau\tilde{\chi}_1^0$

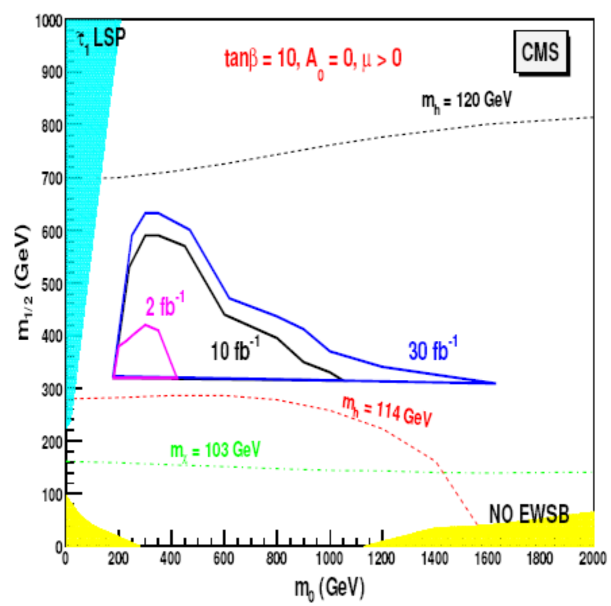
- Visible eμ excess over SM; for dilepton edge: need ττ mass

The other scenario: $\chi_2^0 \rightarrow \chi_1^0 h$

- **Followed by $h \rightarrow b\bar{b}$: h discovery at LHC**
  - E.g. at Point 1, ≈20% of SUSY events have $h \rightarrow b\bar{b}$
    - But squarks/gluinos heavy (low cross sections)
  - b-jets are hard and central
  - Largest bkg: other SUSY events!

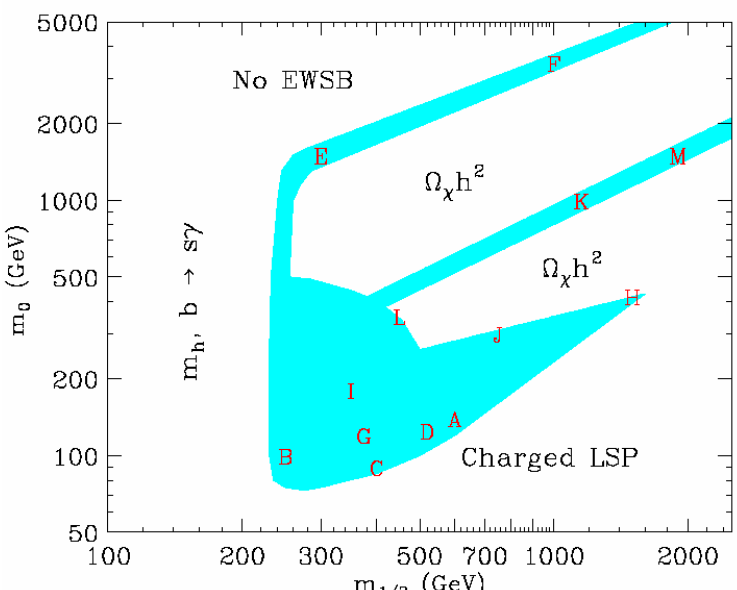


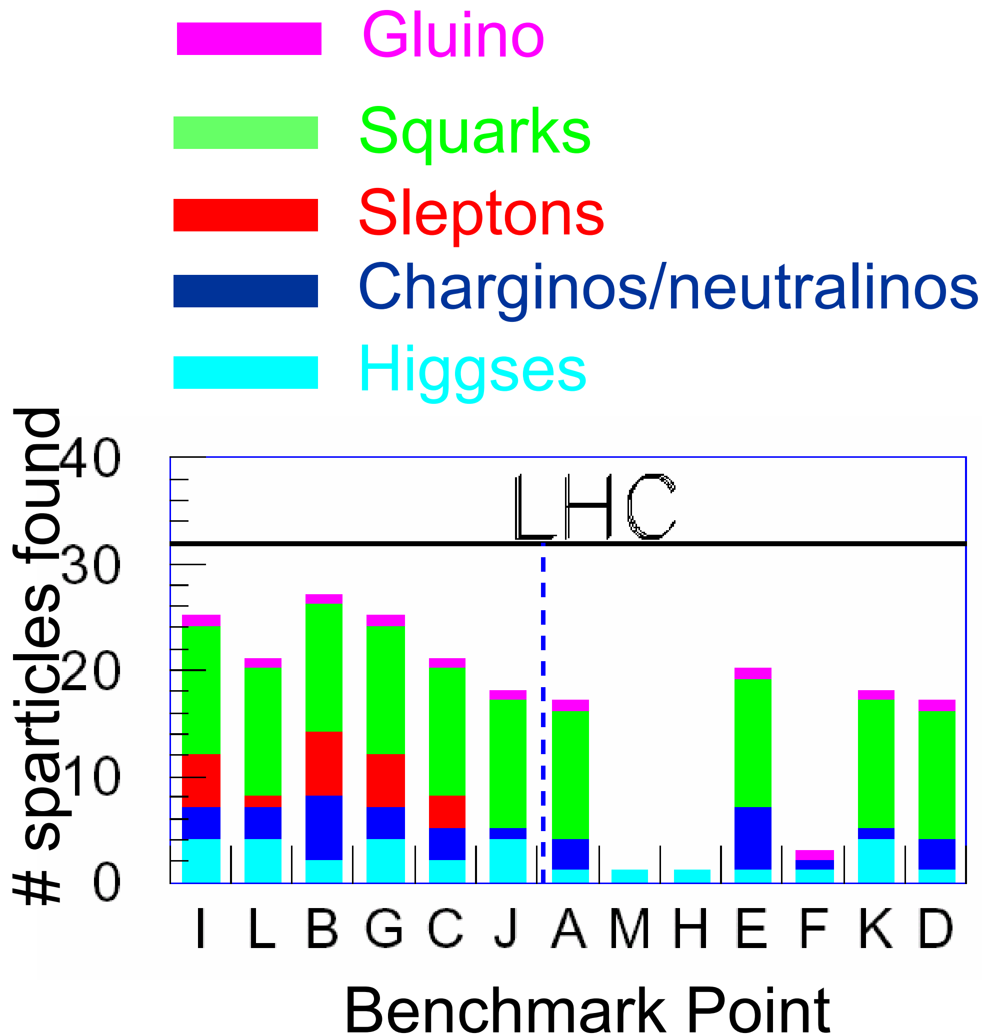




Overall reach

- **New set of benchmarks currently in use**
  - **Account for LEP, $b \rightarrow s\gamma, g_\mu - 2$ and cosmology**
  - **Example: "BDEGMOPW"**
    (Battaglia et al. hep-ph/0112013)





  - **Recent: Snowmass points & slopes; working on updates**

SUSY parameters; SUGRA

Point/Lumi	m_0 (GeV)	$m_{1/2}$ (TeV)	$\tan\beta$	$s(\mu)$
P1 @100fb^{-1}	400±100	400±8	2.00±0.08	ok
P2 @100fb^{-1}	400±100	400±8	10±2	ok
P4 @100fb^{-1}	800±50	200±2	10±2	ok
P5 @10fb^{-1}	100±4	300±3	±0.1	ok

Essentially no information on A_0

(A_{heavy} evolve to fixed point independent A_0)

GMSB

- **Model assumes SUSY broken at scale $F^{1/2}$ in sector containing non-SM (heavy) particles**
  - This sector couples to SM via "messengers" of mass M
  - Loops involving messengers $\rightarrow$ mass to s-partners
    - Advantage of model; mass from gauge interactions $\rightarrow$ no FCNC (which can cause problems in SUGRA)
- **Phenomenology: lightest SP is gravitino ($\tilde{G}$)**
  - SUGRA: M($\tilde{G}$)~O(1)TeV, phenomenologically irrelevant
  - GMSB: NSLP decays to $\tilde{G}$; unstable $\rightarrow$ NLSP can be charged
    - Lifetime of NLSP "free": $O(\mu m) < c\tau < O(km)$
  - Neutral NLSP: lightest combination of higgsinos and gauginos $\rightarrow$ behaves like SUGRA LSP (except for its decay…)
  - Charged NLSP: $\tilde{\ell}_R$; low tanβ: degenerate $\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$; high tanβ: $\tilde{\tau}_R$ is lightest slepton, others decay to it

GMSB parameters

- **SUSY breaking scale: Λ=F/M**
  - **N_5: # messenger fields**
  - **tanβ (ratio of Higgs vev's)**
  - **s(μ) (|μ| fixed from M(Z))**
  - **C_{grav} ($\tilde{G}$ mass scale factor)**
    - **$\tau_{NLSP} \sim (C_{grav})^2$**
- **GMSB "points"***
  - **G1: NLSP is $\tilde{\chi}_1^0$**
    - **G1a: cτ is short (1.2mm)**
    - **G1b: cτ is long (1km)**
  - **G2: NLSP is $\tilde{\tau}_1$**
    - **G2a: $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_1$ short-lived**
    - **G2b: long-lived (all)**

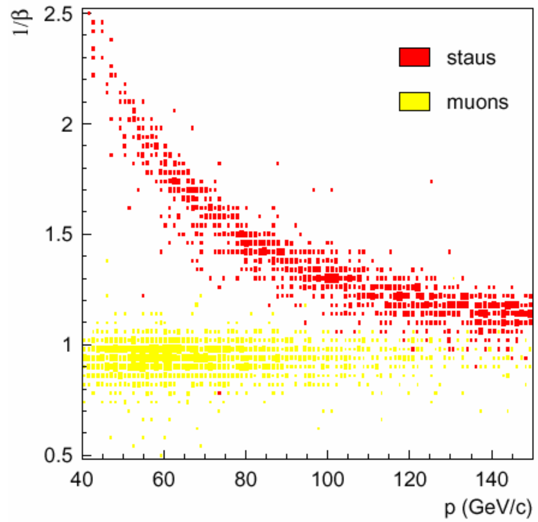
P	*Λ (TeV)*	*M_m (TeV)*	*N_5*	*C_{grav}*
G1a	90	500	1	1.0
G1b	90	500	1	10^3
G2a	30	250	3	1.0
G2b	30	250	3	5×10^3

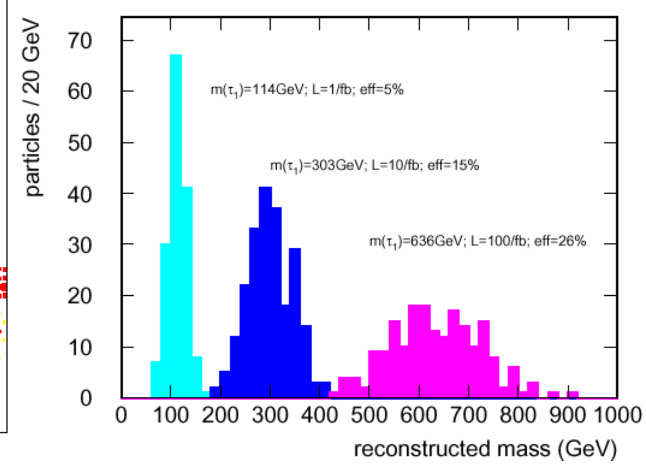
tanβ: 5.0; s(μ)=+

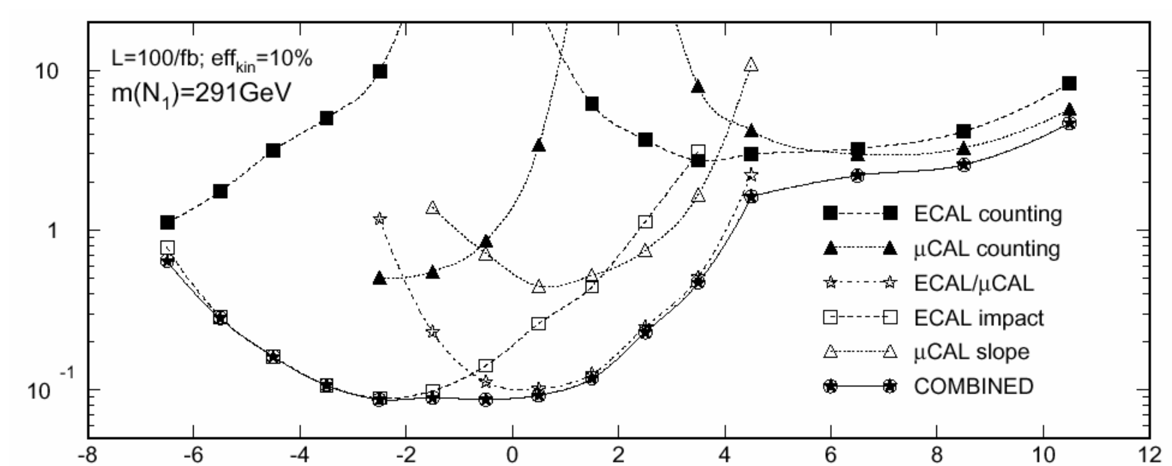
* Hinchliffe & Paige, Phys.Rev. D60 (1999) 095002; hep-ph/9812233

GMSB: NLSP and χ_1^0 lifetime

- **If NLSP=τ_1, use TOF (σ~1ns) (good for high lifetimes)**
- **Detecting the $\chi_1^0 \to \tilde{G}\tilde{\gamma}$ decay**
  - **Off-pointing photons + χ_1^0 decays in muon chambers**







SUSY Summary

- **SUSY discovery (should be) easy and fast**
  - Expect very large yield of events in clean signatures (dilepton, diphoton).
    - Establishing mass scale is also easy (M_{eff})
- **Squarks and gluinos can be discovered over very large range in SUGRA space (M_0,$M_{1/2}$)~(2,1)TeV**
  - Discovery of charginos/neutralinos depends on model
  - Sleptons difficult if mass > 300 GeV
  - Evaluation of new benchmarks (given LEP, cosmology etc) in progress
- **Measurements: mass differences from edges, squark and gluino masses from combinatorics**
- **Can extract SYSY parameters with ~(1-10)% accuracy**

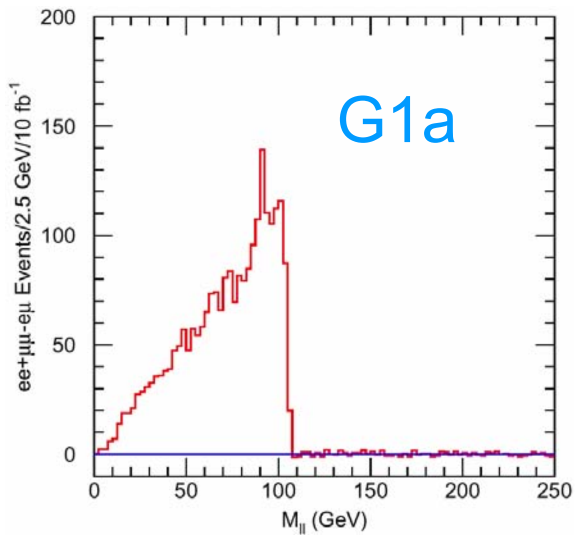
SUSY: precision measurements

GMSB observation

- **Example: G1a; same dilepton edge**
  - **Decay observed:**

$$\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\, \ell^{\pm}\ell^{\mp} \to \tilde{G}\gamma\ell^+\ell^-$$

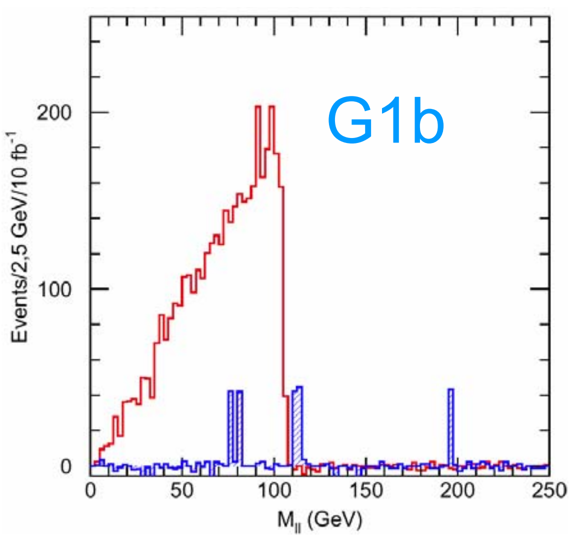
  - **Selection is simple:**
    - M_{eff}>400 GeV
    - $E_T^{miss}>0.1M_{eff}$
    - Demand same-flavor leptons
    - Form $e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$



- **G2b: very similar to SUGRA**
  - χ_1^0 is long-lived, escapes
  - **Decay observed:**

$$\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\, \ell^+\ell^-$$

  - M_{eff}>1 TeV; rest of selection as in G1a



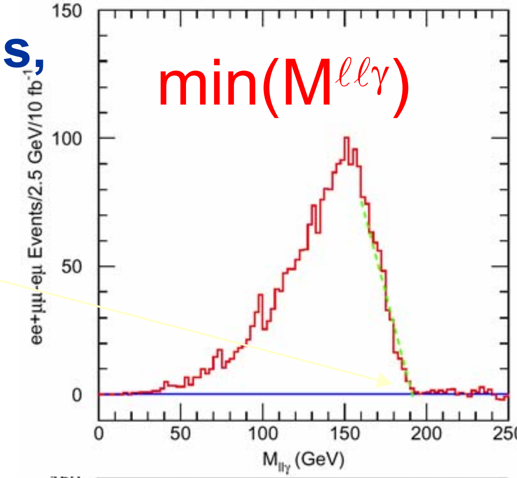
SUSY parameter measurements (G1a)

- **G1a: endpoint in M($\ell\ell$) → 3 parameters**

$$M_{\max}^{\ell^+\ell^-} = M(\tilde{\chi}_2^0)\sqrt{1-\left(\frac{M(\tilde{\ell}_R)}{M(\tilde{\chi}_2^0)}\right)^2}\sqrt{1-\left(\frac{M(\tilde{\chi}_1^0)}{M(\tilde{\ell}_R)}\right)^2}$$

- **Events with two leptons and two photons, plot min(M($\ell\ell\gamma$)) yields second relation:**

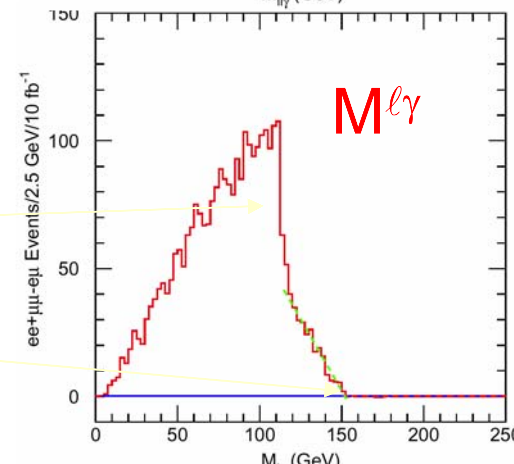
$$M_{\max}^{\ell^+\ell^-\gamma} = \sqrt{M^2(\tilde{\chi}_2^0) - M^2(\tilde{\chi}_1^0)}$$



- **Next: evts with only one M($\ell\ell\gamma$) smaller than endpoint mass**
  - **Unambiguous id of χ_2^0 decay**
  - **Plot lepton-photon mass, two more structures:**

$$\sqrt{M^2(\tilde{\ell}_R) - M^2(\tilde{\chi}_1^0)} = 112.7\,\text{GeV}$$

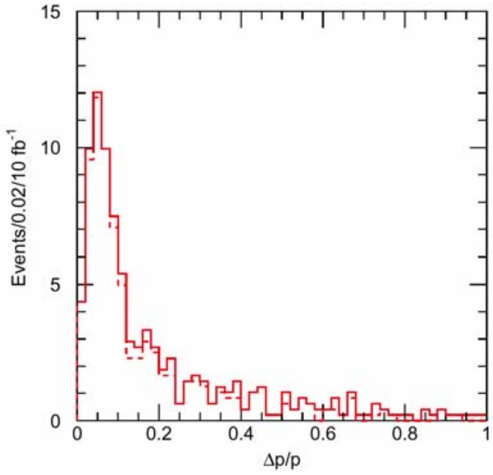
$$\sqrt{M^2(\tilde{\chi}_2^0) - M^2(\tilde{\ell}_R)} = 152.6\,\text{GeV}$$



SUSY mass measurements (G1a)

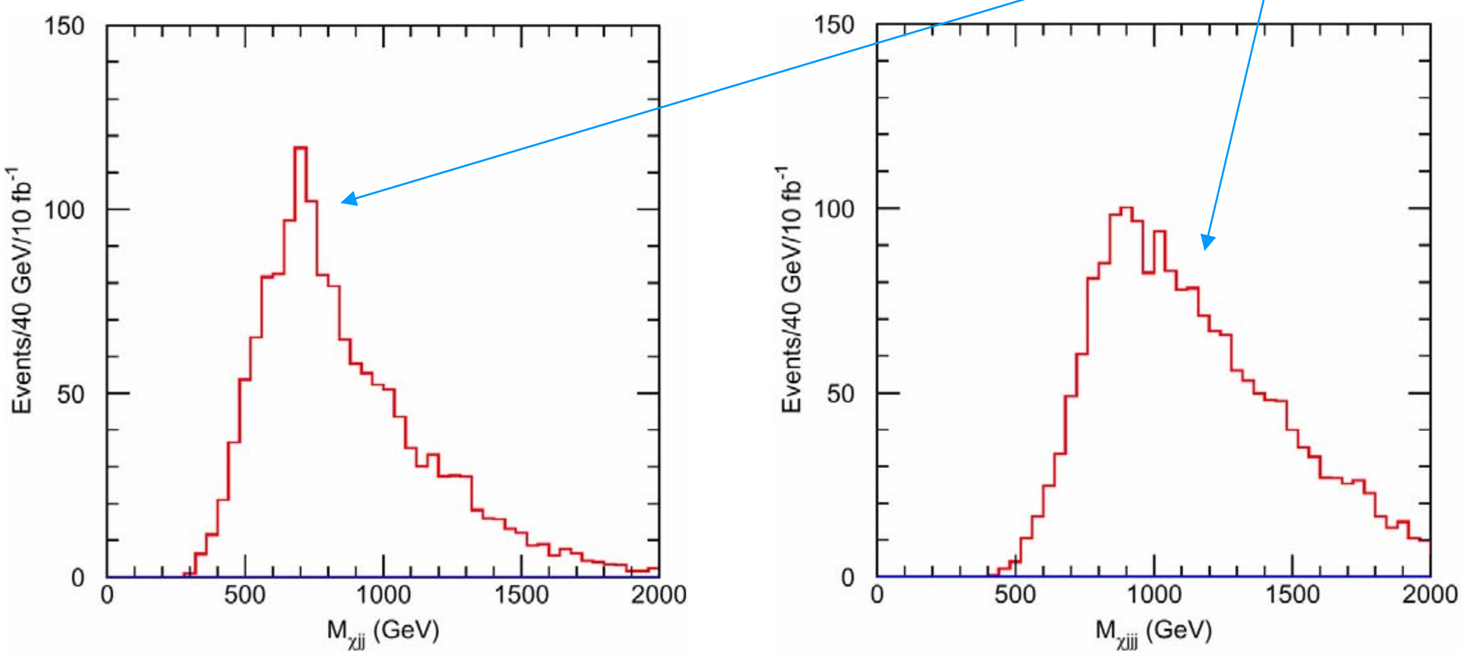
- **Measurement of edge positions: very accurate**
  - Worse resolution on linear fit (e.g. min(M($\ell\ell\gamma$)) $\rightarrow$
    - Low luminosity: ±0.5 GeV; High lumi: ±0.2 GeV (syst).
  - One can extract masses of $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$, $\tilde{\ell}_R$
    - Model-independent (except for decay, rate and interpretation of slepton mass as mass of $\tilde{\ell}_R$)
- **Next step: reconstruct G momentum**
  - Motivation: can then build on $\tilde{\chi}_2^0$ to reconstruct M_q and M_g
    - 0C fit to $\tilde{\chi}_2^0 \rightarrow \tilde{G}\gamma\ell^+\ell^-$ (with $M_{\tilde{G}}=0$)
      - ➔ Momentum to 4-fold ambiguity
    - Use evts with 4 leptons + 2 photons
      - ➔ E_T^{miss} fit to resolve solns: min(χ^2):

$$\chi^2 = \left(\frac{E_x^{miss} - P_{1x} - P_{2x}}{\Delta E_x^{miss}} \right)^2 + \left(\frac{E_y^{miss} - P_{1y} - P_{2y}}{\Delta E_y^{miss}} \right)^2$$



G1a: masses of squarks and gluinos (I)

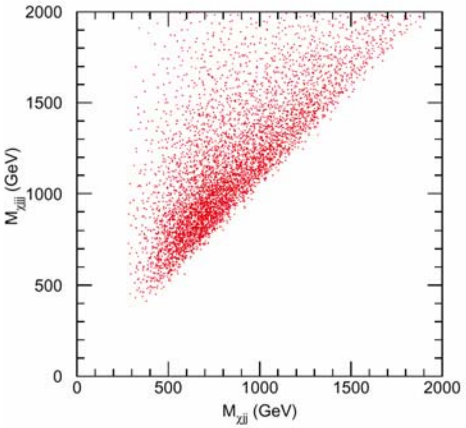
- **Decay sought: $\tilde{q} \to g\tilde{q} \to \tilde{\chi}_2^0 q q \bar{q}$**
  - Select evts with ≥ 4 jets (P_T>75)
  - Combine each fully-reconstructed $\tilde{\chi}_2^0$ with 2 and 3 jets



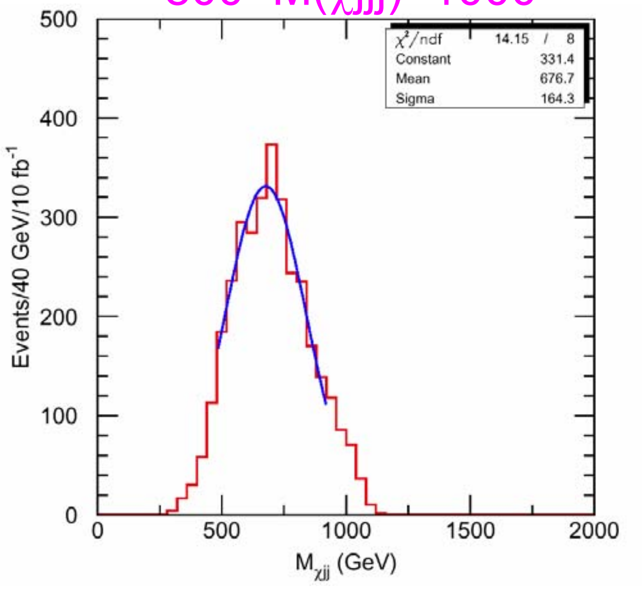
  - This yields peaks at gluino and squark mass (direct)
    - Peak position not a function of jet cut…

G1a: masses of squarks and gluinos (II)

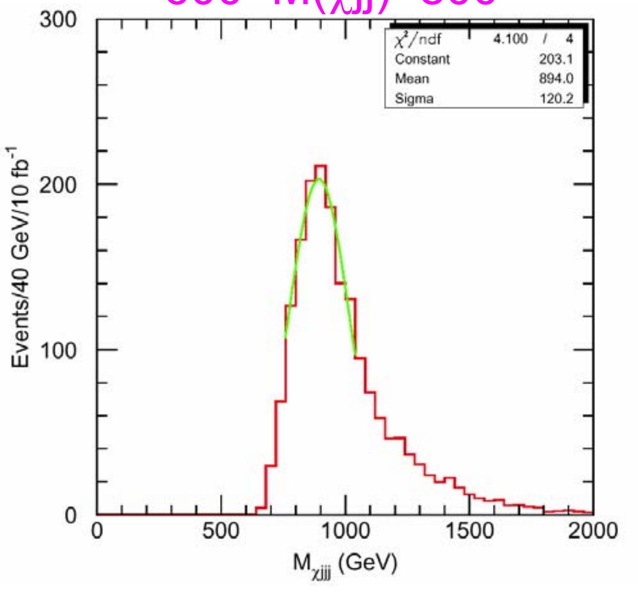
- **Mass distributions can be sharpened**
  - **Use correlations in M(χjj) vs M(χjjj)**
  - **Statistical errors small**
    - **Expect syst. dominance (jet energy scale)**



800<M(χjjj)<1000



600<M(χjj)<800



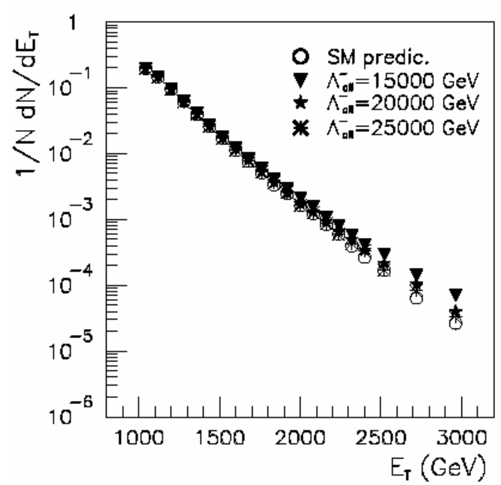
Other new Physics BSM

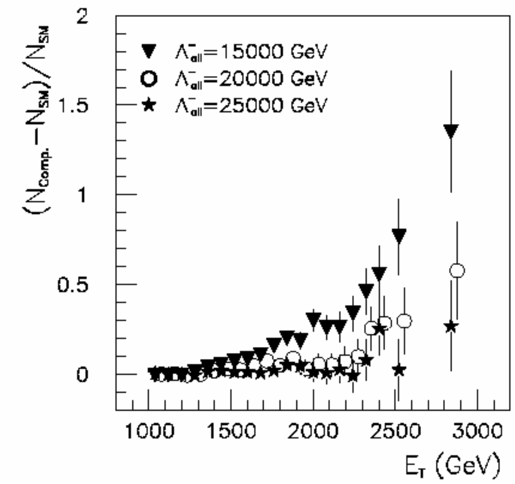
Compositeness

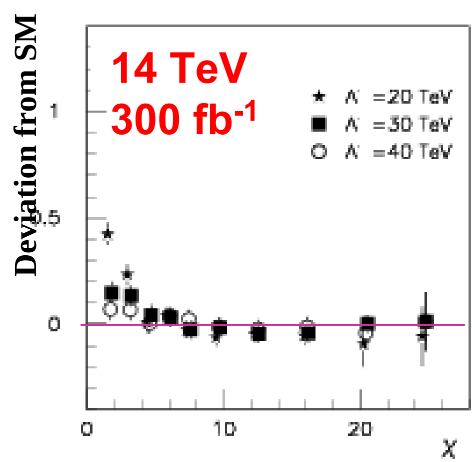
- **Usual excess @ high P_T(jet) expected**
  - **Tricky issue:** calorimeter (non)linearity
  - **Analysis proceeds via angular distribution**

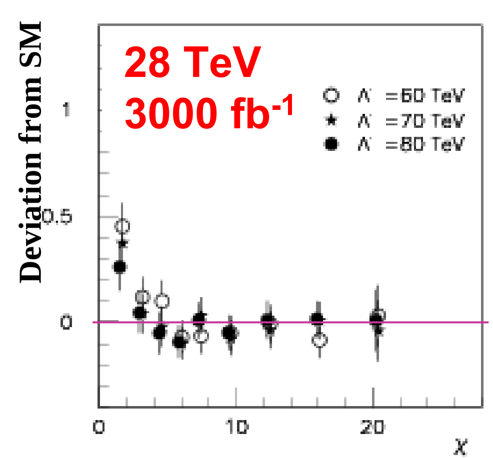
$$\chi = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

  - **Ultimate reach:** Λ_{comp} ~ 40 TeV (depends on understanding non-linearity @ 1-2% level)



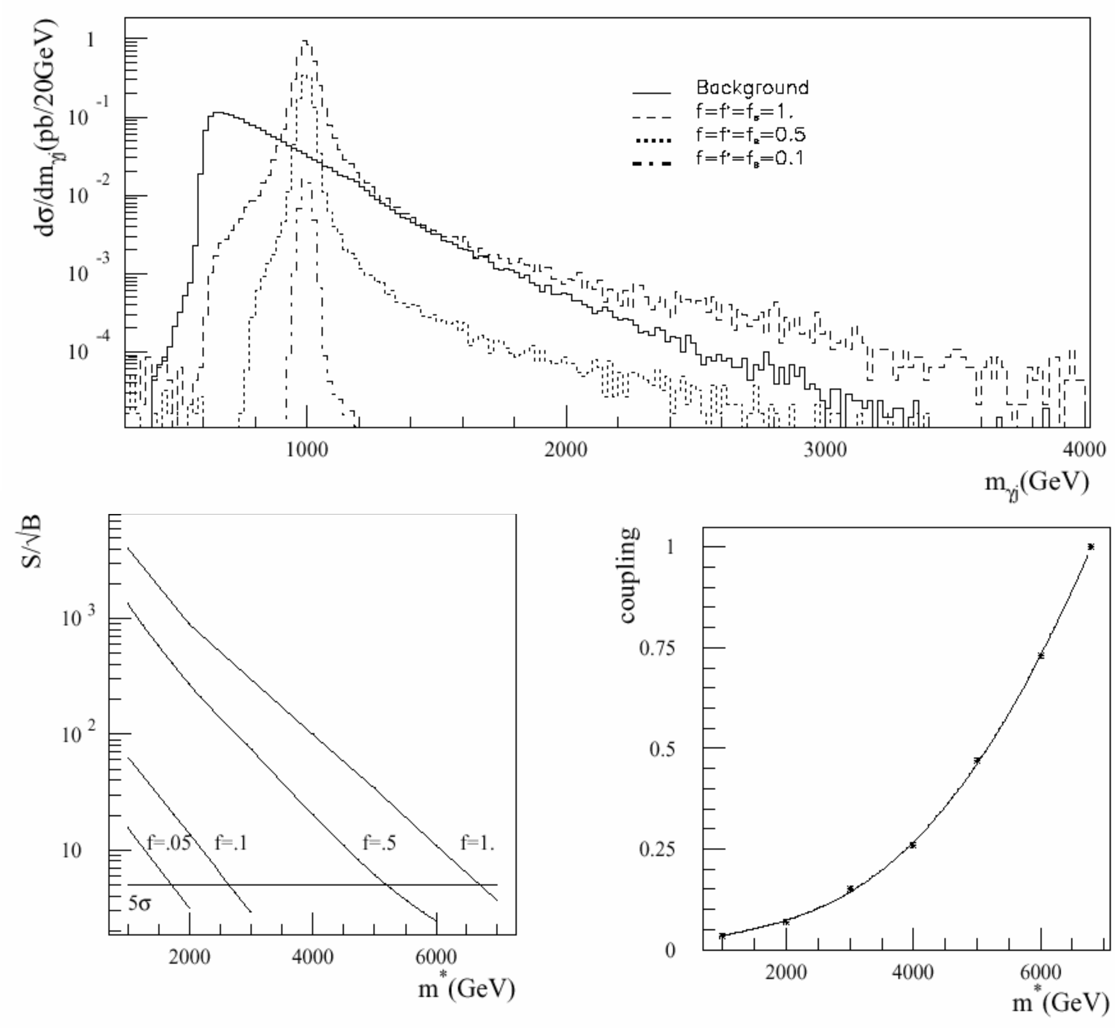






Excited quarks

- **Search for $q^* \to q\gamma$**



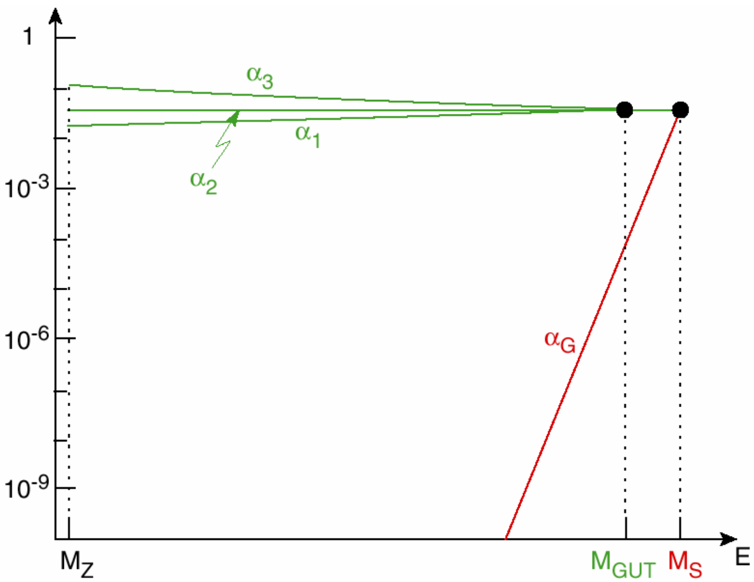
TeV-scale gravity

Naturalness

- **SUSY: the mass protector**
  - $\delta M_W^2 \sim (\alpha/\pi)\Lambda^2 >> (M_W)^2$; But with SUSY $\delta M_W^2 \sim (\alpha/\pi)|M_{SP} - M_P|^2$
    - The pro-LHC argument: correction small$\rightarrow M_{SP} \sim 1$TeV
    - Lots of positive side-effects:
      - → LSP a great dark-matter candidate;
      - → unification easier;
      - → poetic justice: why would nature miss this transformation? (complete transforms in the Poincaré group – only SUSY escapes Coleman-Mandula no-go theorem)
- **SUSY does not answer why $G_F \sim (M_W)^{-2} >> (M_{PL})^{-2} \sim G_N$**
  - But it (at least) allows it

TeV-scale gravity

- **The idea of our times: that the scale of gravity is actually not given by M_{PL} but by M_W**
  - Strings live in >4 dimensions. Compactification → 4D "SM". $M_{PL\text{-}4}$ related to $M_{PL\text{-}(4+d)}$ via volume of xtra dimensions:
    - $M_{PL\text{-}4}^2 \sim V_d\, M_{PL\text{-}(4+d)}^{2+d}$
  - Conventional compactification: very small curled up dims, $M_{PL\text{-}4} \sim M_{PL\text{-}(4+d)}$
    - $V_d \sim (M_{PL\text{-}4})^{-d}$



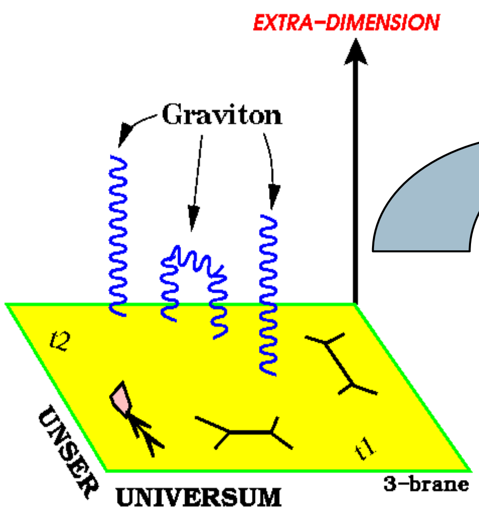
Alternative: volume is large; large enough that $V_d >> (M_{PL\text{-}(4+d)})^{-d}$

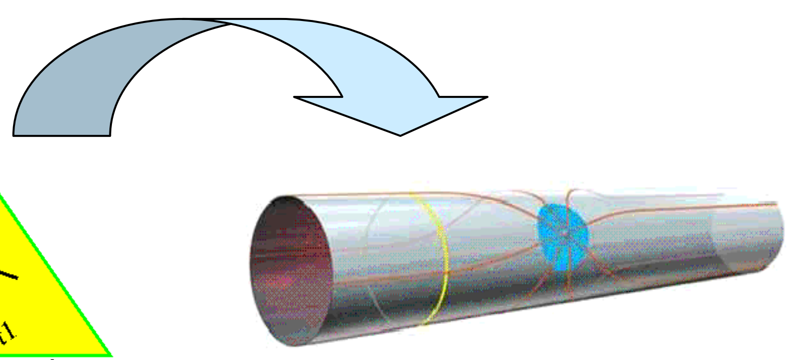
Then $M_{PL\text{-}(4+d)}$ can be ~ TeV (!) – thus the name

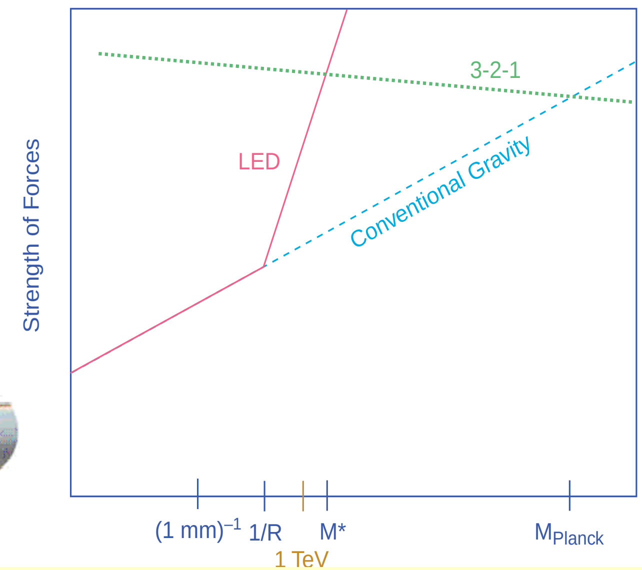
Two ways: by hand; warp factor.

Getting MP_{L-4}~1TeV. Method I

- **By hand: "Large extra dimensions"**
  - (Arkani-Hamed, Dimopoulos, Dvali)
  - Size of xtra dimensions from ~mm for δ=2 to ~fm for d=6
  - But gauge interactions tested to ~100 GeV
    - Confine SM to propagate on a brane (from string theory)
  - Rich phenomenology



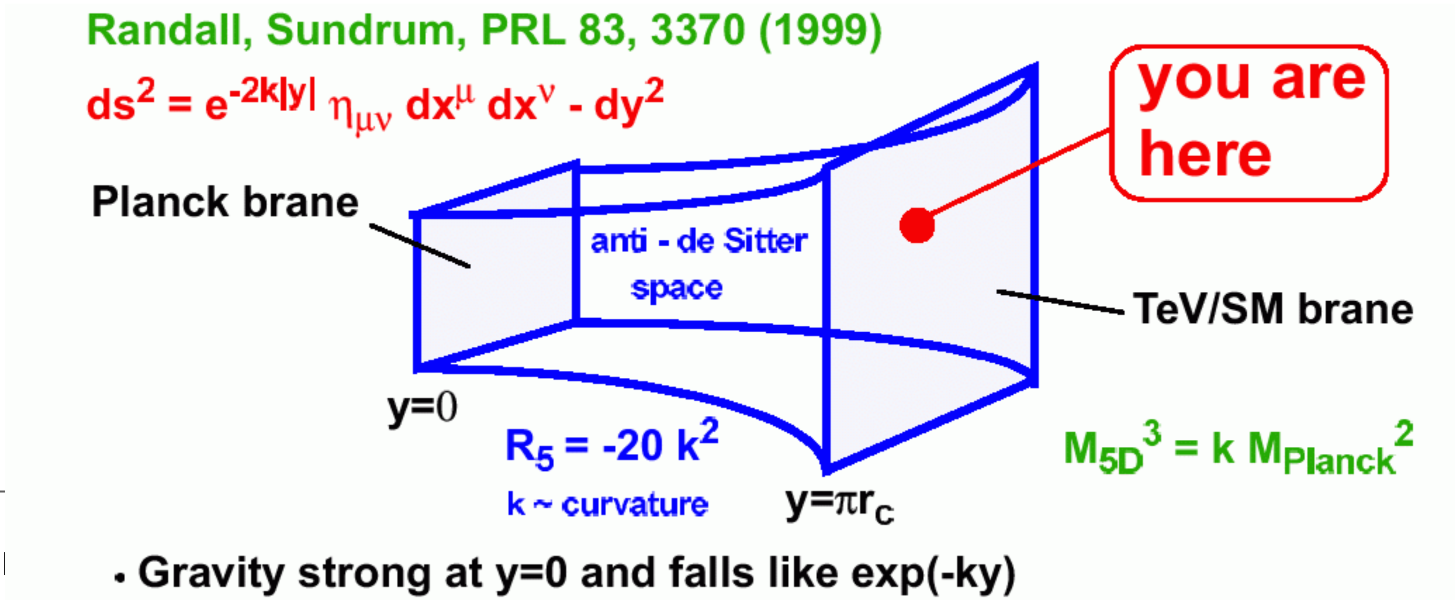




"our" Planck mass at log(Λ)~19: an artifact of the extrapolation

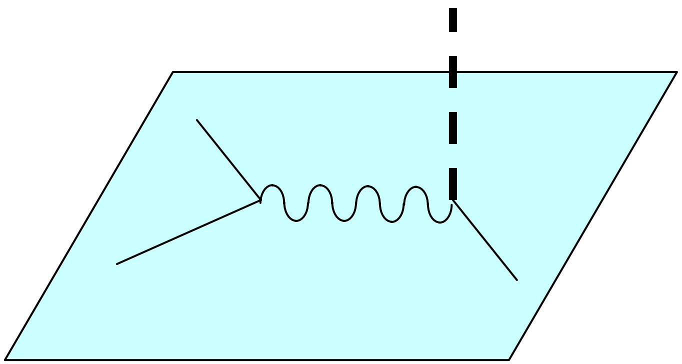
Getting MP_{L-4}~1TeV. Method II

- **Via a warp factor (Randall-Sundrum)**
  - $ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}(y) dy^m dy^n$
    - (x: SM coordinates; y: d xtra ones)
  - Generalize: dependence on location in xtra dimension
  - $ds^2 = e^{2A(y)}\, g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}(y) dy^m dy^n$
    - Large exp(A(y)) also results in large V_d
    - Example: RS model; two 4-D branes, one for SM, one for gravity, "cover" a 5-D space – with an extra dim in between

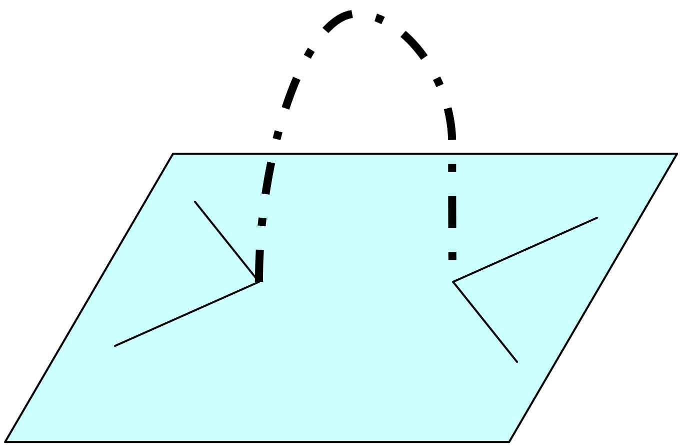


Extra (large) dimensions

- **Different models, different signatures:**
  - **Channels with missing E_T: E_T^{miss}+(jet/γ) (back-to-back)**
  - **Direct reconstruction of KK modes**
    - **Essentially a W', Z' search**
  - **Warped extra dimensions (graviton excitations)**



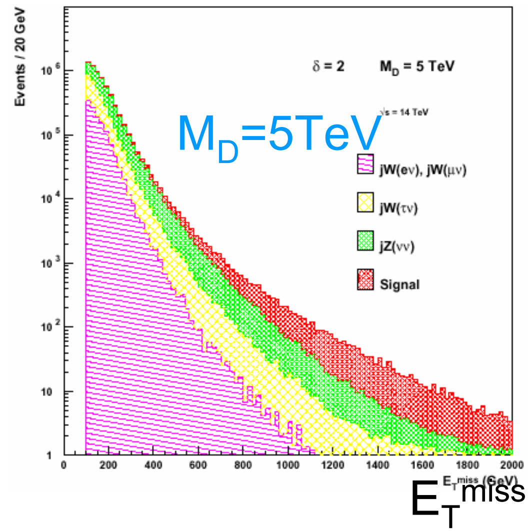
Giudice, Ratazzi, Wells (hep-ph/9811291)

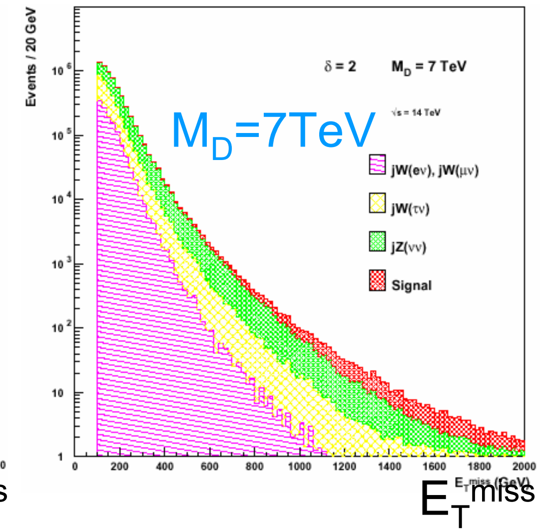


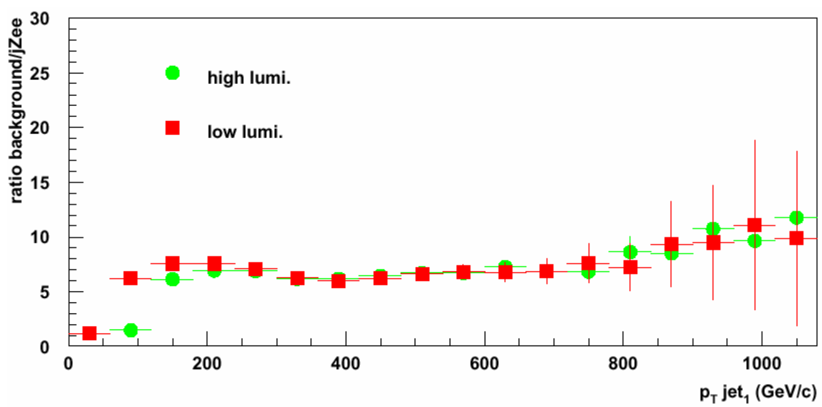
Hewett (hep-ph/9811356)

Extra dimensions (I): E_T^{miss}+Jet

- **Issue: signal & bkg topologies same; must know shape of bkg vs e.g. E_T^{miss}**
  - **Bkg: jet+W/Z; $Z \rightarrow \nu\nu$; $W \rightarrow \ell\nu$.**
  - **Bkg normalized through jet+Z, $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events**







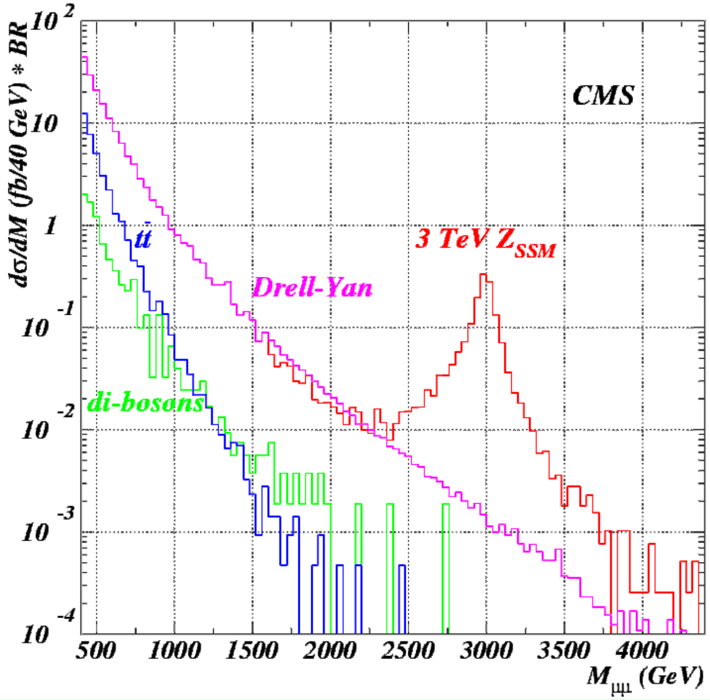
Reach @ 5σ

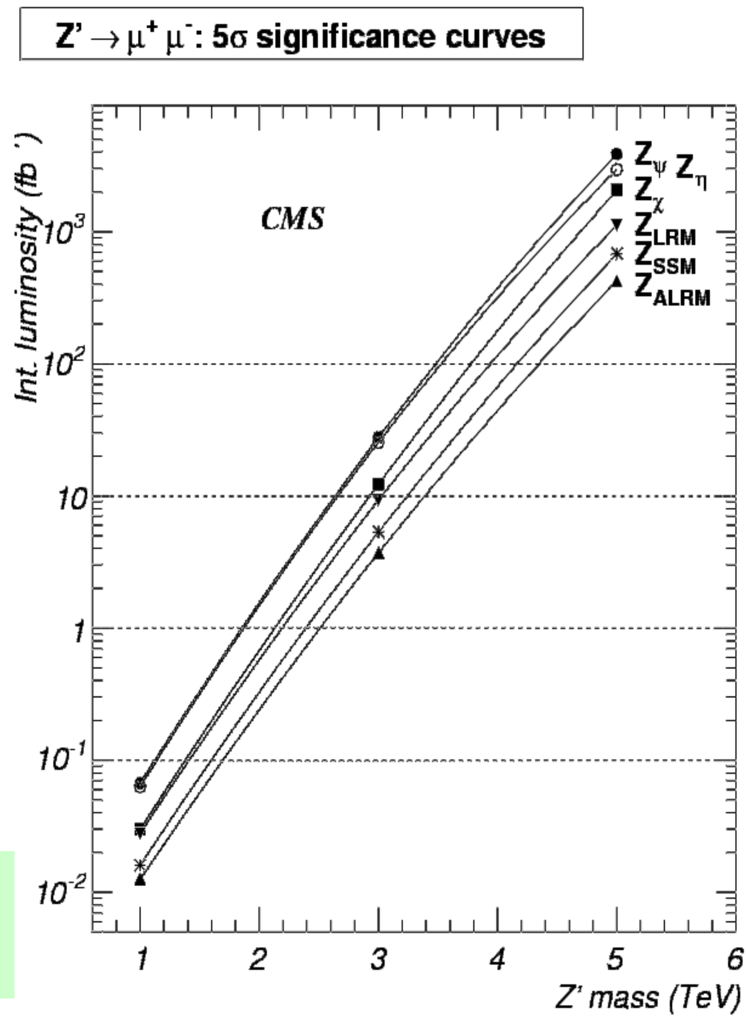
δ	M_D (TeV)	R_D
2	7.5	10 μm
3	5.9	200 pm
4	5.3	1 pm

- **Also $E_T^{miss}+\gamma$; M_D reach smaller**

Z' Discovery Studies

Z'→μμ production
No systematics included yet





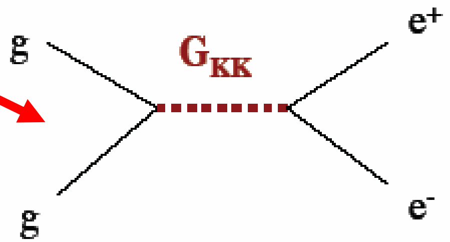
Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible, beyond Tevatron II
High lumi 100 fb^{-1}: extend range to 3.4-4.3 TeV

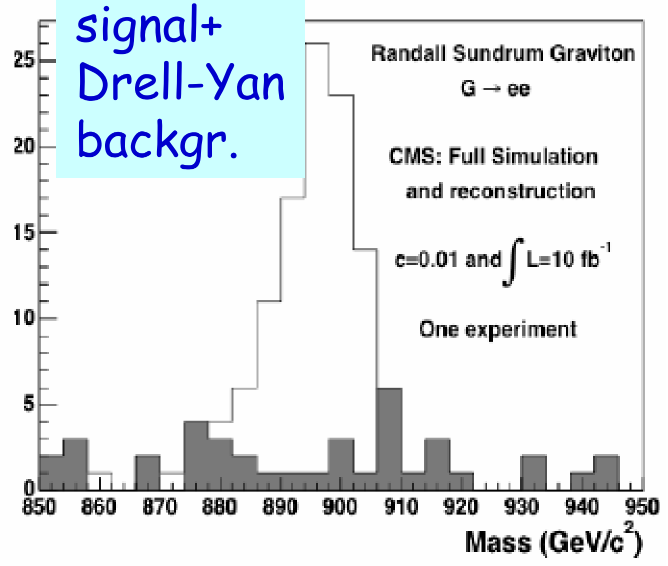
Curved Space: RS Extra Dimensions

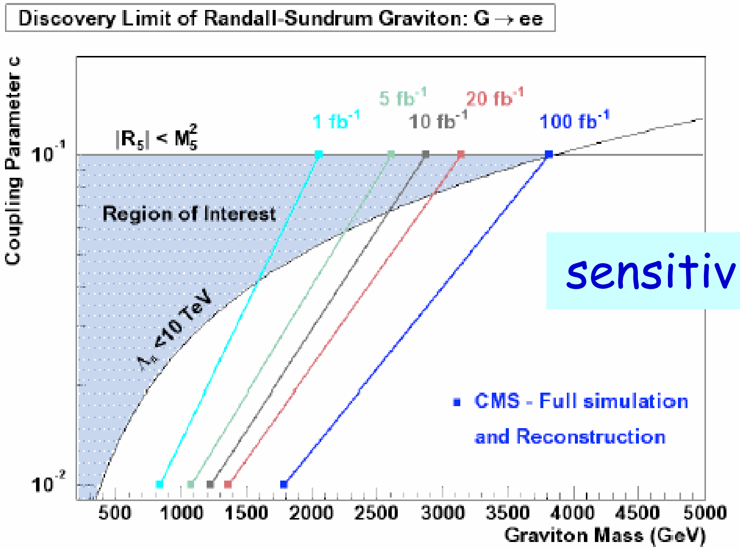
Study the channel pp→Graviton→ e+e-

phenomenology



signal+ Drell-Yan backgr.



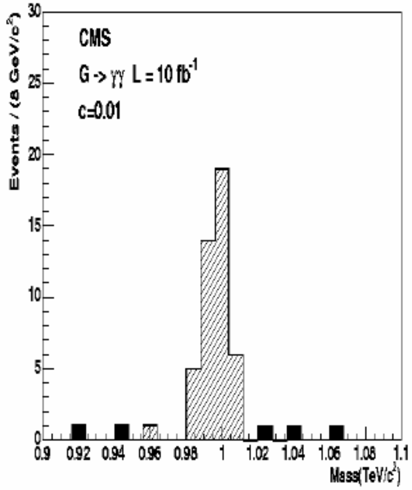


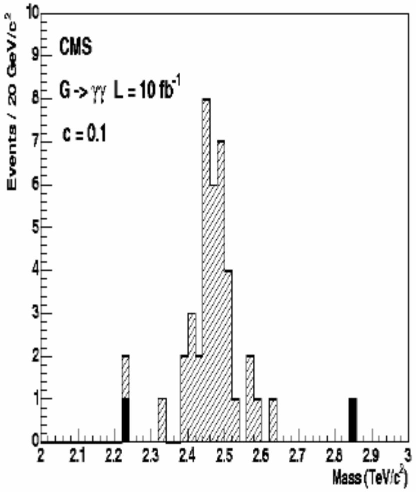
sensitivity

TeV-scale Gravity; Randall Sundrum G→γγ

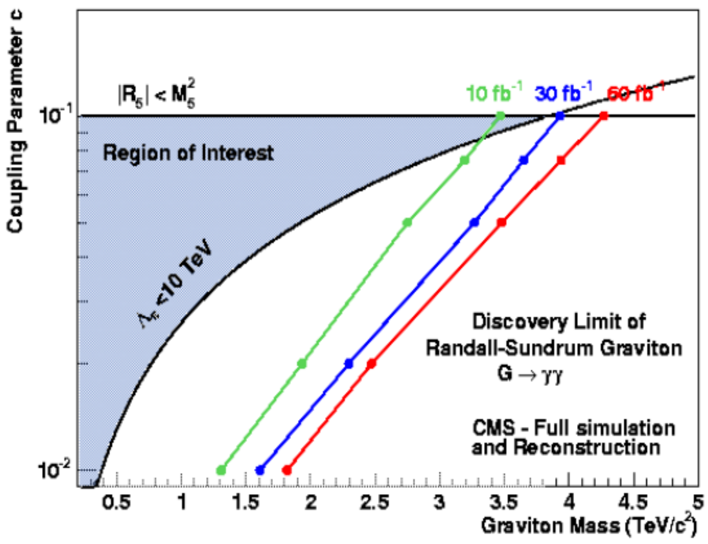
New:
Study RS decays into 2 photons

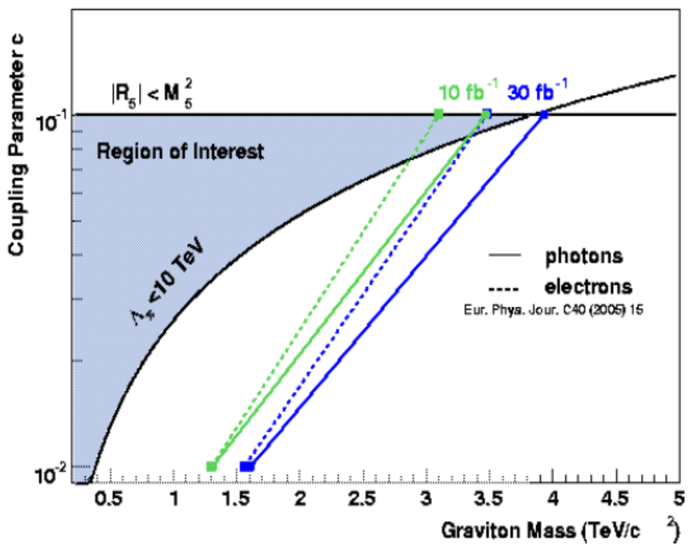
K factors for signal?
P. Mathews et al.





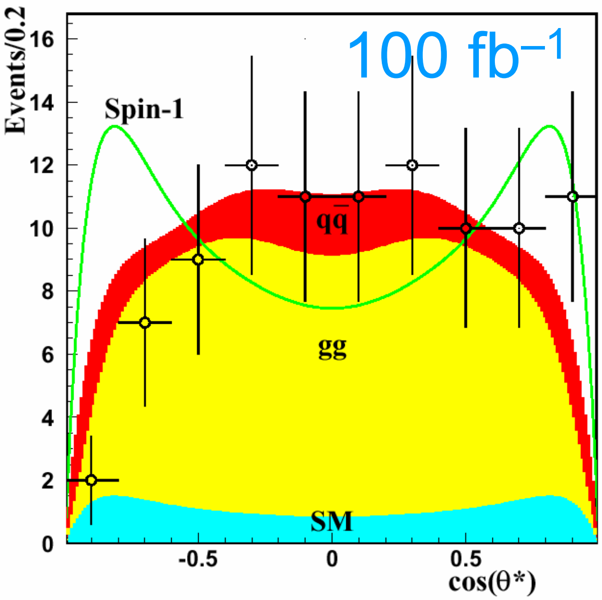
Signal + Background for 10 pb^{-1}

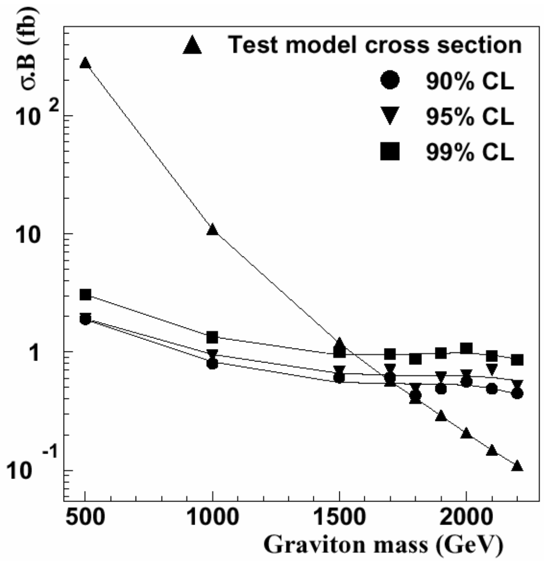




KK resonances + angular analysis

- **If graviton excitations present, essentially a Z' search.**
  - **Added bonus: spin-2 (instead of spin-1 for Z)**
    - **Case shown*: $G \to e^+e^-$ for M(G)=1.5 TeV**
    - **Extract minimum σ.B for which spin-w hypothesis is favored (at 90-95%CL)**





* B.Allanach,K.Odagiri,M.Parker,B.Webber JHEP09 (2000)019

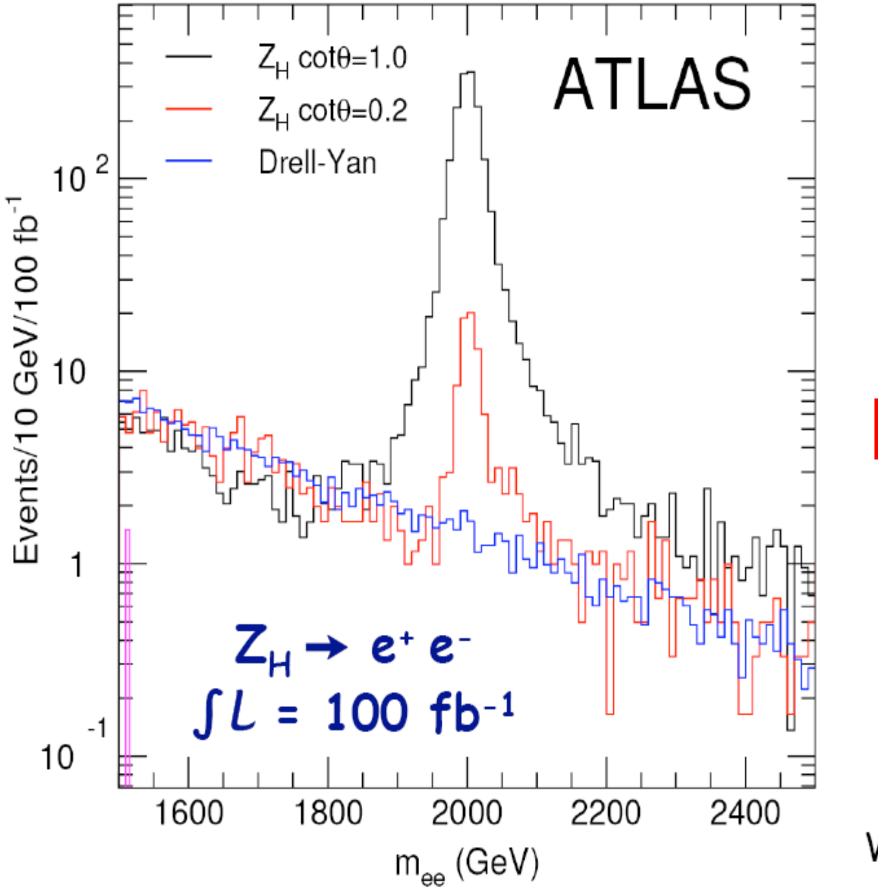
En passant

- **TeV-scale gravity is attracting a lot of interest/work**
  - Much is recent, even more is evolving
  - Turning to new issues, like deciding whether a new dilepton resonance is a Z' or a KK excitation of a gauge boson
    - In the latter case we know photon, Z excitations nearly degenerate
      - ➔ One way would be to use W' (should also be degenerate, decays into lepton+neutrino)

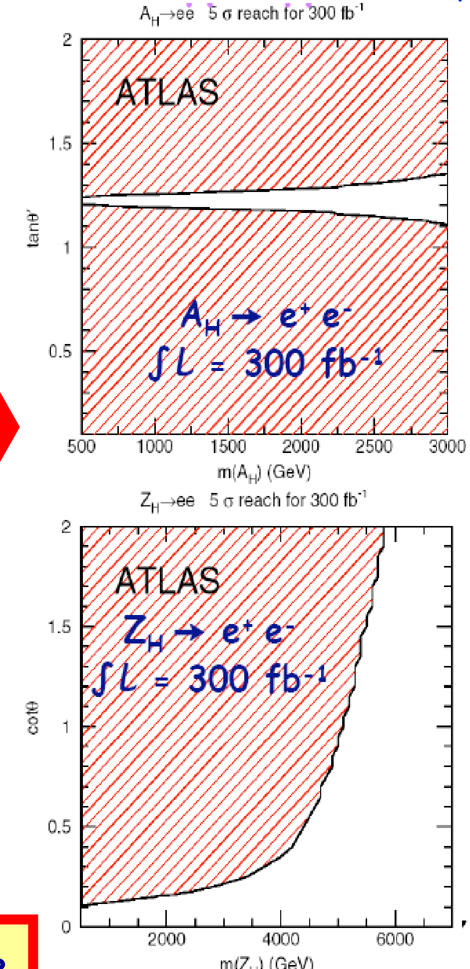
        But this is also the case for additional bosons…
  - Example: radion phenomenology
    - Radion: field that stabilizes the brane distance in the RS scenario. Similar to Higgs. Recent work suggests it can even mix with the Higgs.
      - ➔ Can affect things a lot
  - Stay tuned, for this is an exciting area

Little Higgs Model A_H and Z_H

Signal : di-lepton resonance



Littlest Higgs Model
Arkani-Hamed et al., Han et al.



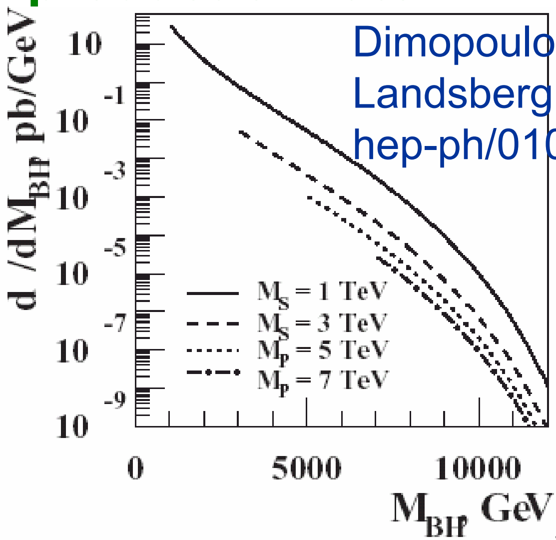
Reach up to 5.7 TeV depending on the θ angle

Black Holes at the LHC (?) (I)

- **Always within context of "TeV-scale gravity"**
  - **Semi-classical argument: two partons approaching with impact parameter < Schwarzschild radius, $R_S \rightarrow$ black hole**
    - **$R_S \sim 1/M_P\ (M_{BH}/M_P)^{(1/d+1)}$** **(Myers & Perry; Ann. Phys 172, 304 (1996)**
  - **From dimensions: $\sigma(M_{BH}) \sim \pi R_S^2$; $M_P \sim 1$TeV $\rightarrow \sigma \sim 400$ pb (!!!)**
    - **Absence of small coupling like α**
  - **LHC, if above threshold, will be a Black Hole Factory:**
    - **At minimum mass of 5 TeV: 1Hz production rate**

Giddings & Thomas
hep-ph/0106219

Dimopoulos & Landsberg
hep-ph/0106295

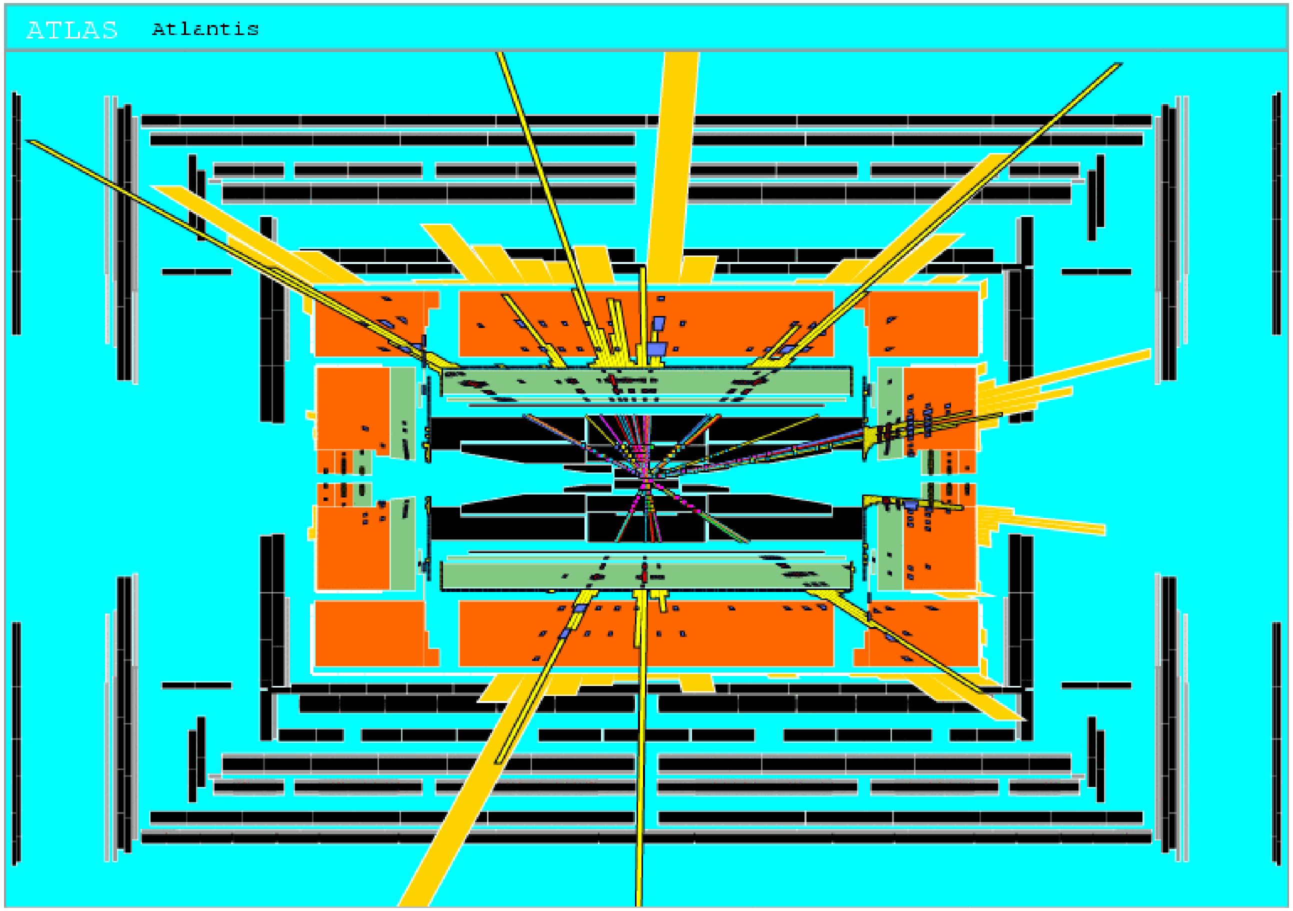


Assumptions:

$M_{BH} >> M_P$; in order to avoid true quantum gravity effects… clearly not the case at the LHC – so caution

Black-hold production

- Simulation of BH event with M_{BH} ~ 8 TeV in ATLAS



M_D ~ 1 TeV
n=6

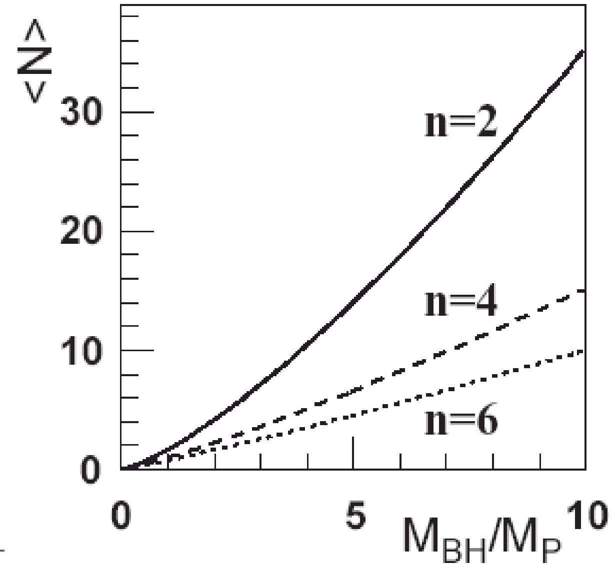
Black Holes at the LHC (II)

- **Decay would be spectacular**
  - Determined by Hawking temperature, $T_H \propto 1/R_S \sim M_P(M_P/M_{BH})^{(1/n+1)}$
    - Note: wavelength of Hawking T_H $(2\pi/T_H) > R_S$
      - → BH a point radiator emitting s-waves
  - Thermal decay, high mass, large number of decay products
    - Implies democracy among particles on the SM brane
      - → Contested (number of KK modes in the bulk large)

Picture ignores time evolution

…as BH decays, it becomes lighter, hotter, and decay accelerates (expect: start from asymmetric horizon →symmetric, rotating BH with no hair →spin down →Schwarz-schild BH, radiate until $M_{BH} \sim M_P$. Then? Few quanta with $E \sim M_P$?

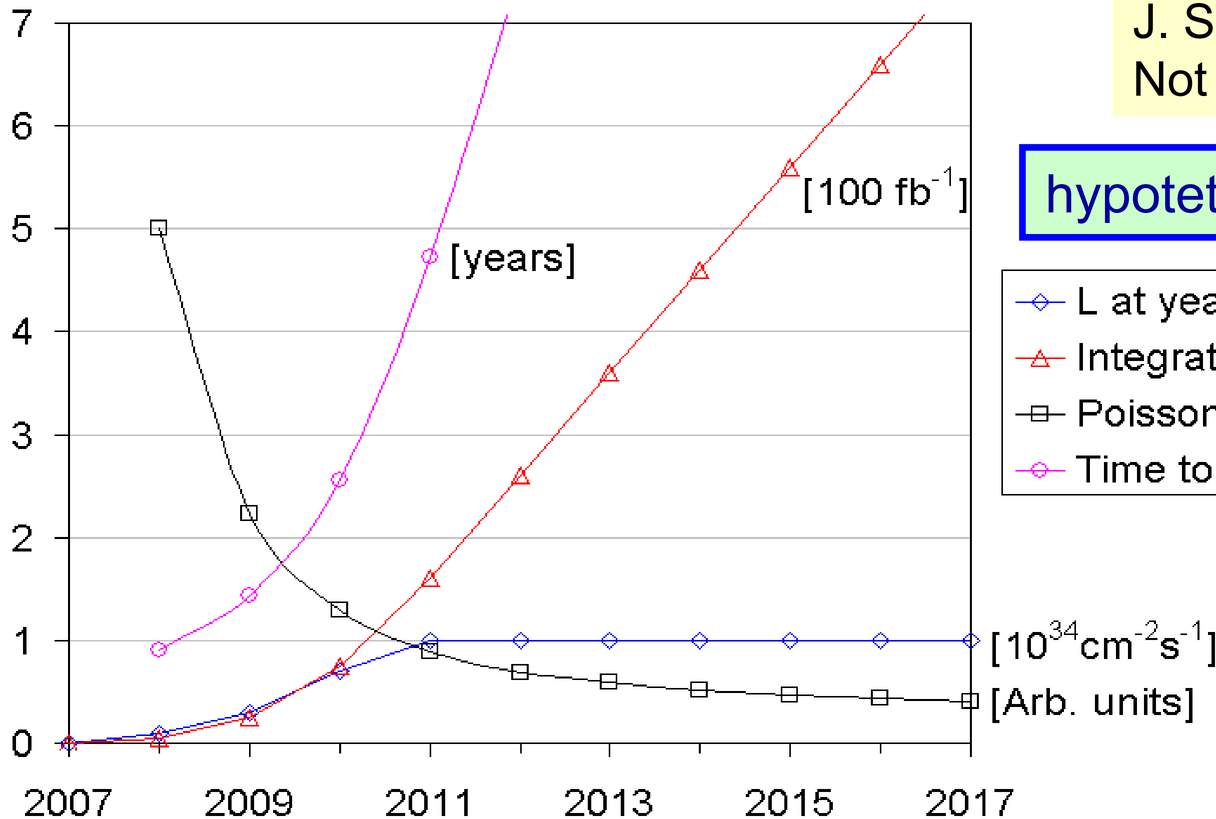
More generally: "transplackian physics"; see: Giudice, Ratazzi&Wells, hep-ph0112161



Beyond the LHC

LHC++

LHC upgrade



J. Strait 2003:
Not an "official" LHC plot

hypotethical lumi scenario

If startup as good as (optimistically) assumed here (10^{34} $cm^{-2}s^{-1}$ in 2011 already)

⇒After ~3 years the simple continuation becomes less exciting

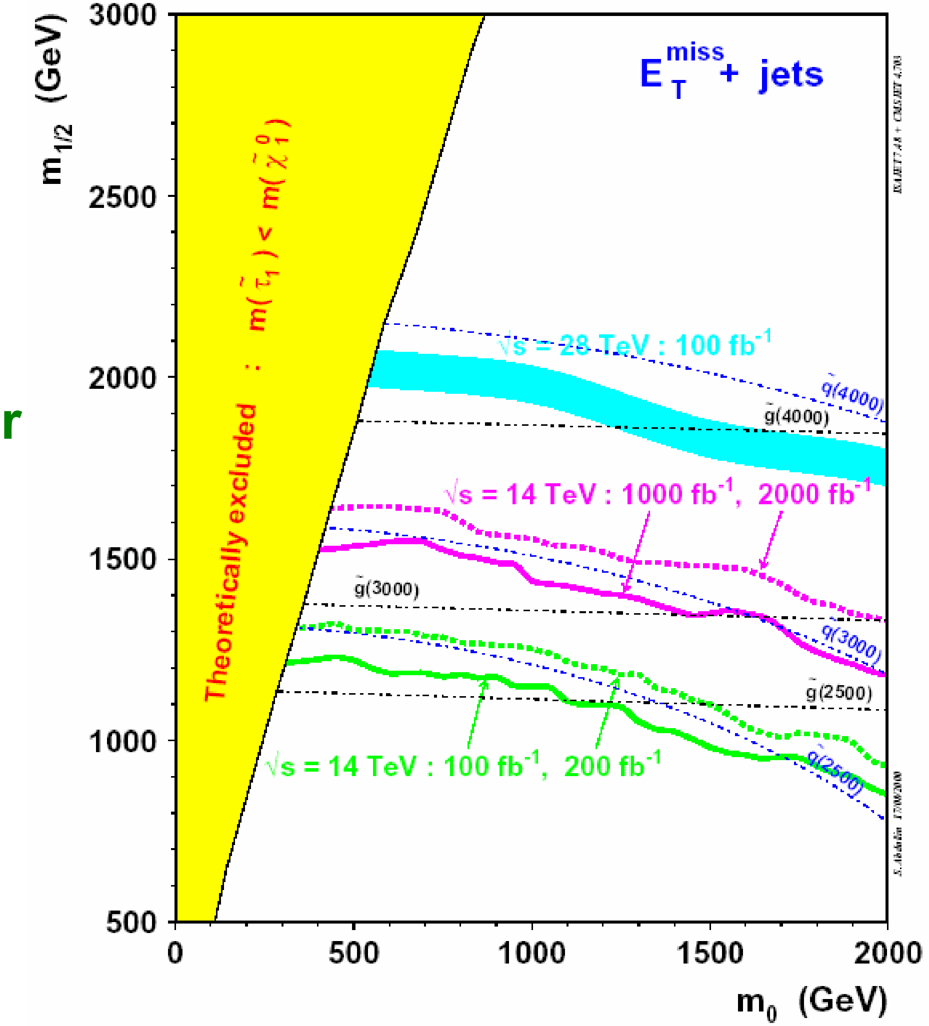
⇒Time for an upgrade?

Beyond LHC; LHC++?

- Clearly, a Linear Collider is a complementary machine to the LHC
  - Will narrow in on much of what the LHC cannot probe
- As for LHC, a very preliminary investigation of
  - LHC at 10^{35}cm^{-2}s^{-1}; LHC at 28 TeV; LHC with both upgrades
  - First look at effect of these upgrades
    - Triple Gauge Couplings
    - Higgs rare decays; self-couplings;
    - Extra large dimensions
    - New resonances (Z')
    - SUSY
    - Strong VV scattering
  - Clearly, energy is better than luminosity
    - Detector status at 10^{35} needs careful evaluation

Supersymmetry reach @ LHC++

- **mSUGRA scenario**
  - Assume R_P conservation
  - Generic E_T^{miss}+Jets
  - Cuts are optimized to get best $S^2_{SUSY}/(S_{SUSY}+B_{SM})$
    - In some cases 0-2 leptons could be better
  - Shown: reach given
    - $A_0 = 0$; $\tan\beta=10$; $\mu>0$
  - For 28 TeV @ $10^{34}cm^{-2}s^{-1}$ probe squarks & gluinos up to ~ 4 TeV/c^2
  - For 14 TeV @ $10^{35}cm^{-2}s^{-1}$ reach is ~ 3 TeV/c^2

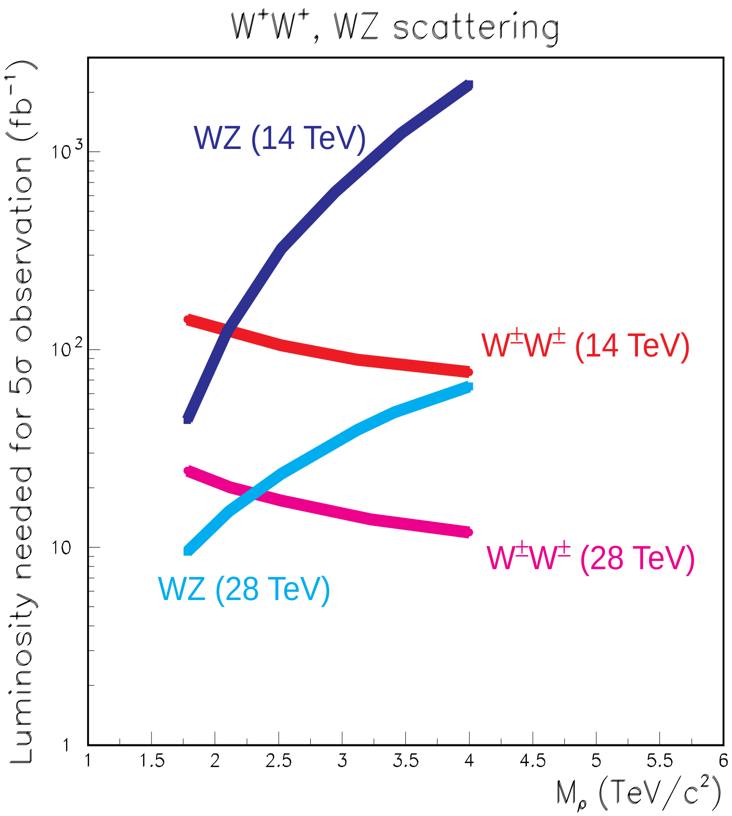


Strong WW/WZ scattering

- **"Golden modes" considered (leptonic decays; e/μ only)**
  - **Numerous channels (WW, WZ, ZZ). Worst-case (signal vs backgrounds) channel is WZ**
  - **Only $L=10^{34}cm^{-2}s^{-1}$ considered because analysis requires:**
    - **forward tagging jets and**
    - **central jet vetoes**

    large effect from pileup at $L=10^{35}cm^{-2}s^{-1}$

- **Like-sign WW & WZ:**
  - **luminosity needed for 5σ observation**



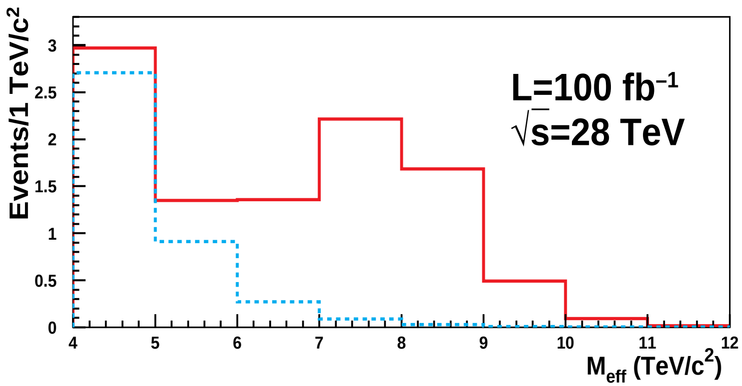
Z' reach in LHC++

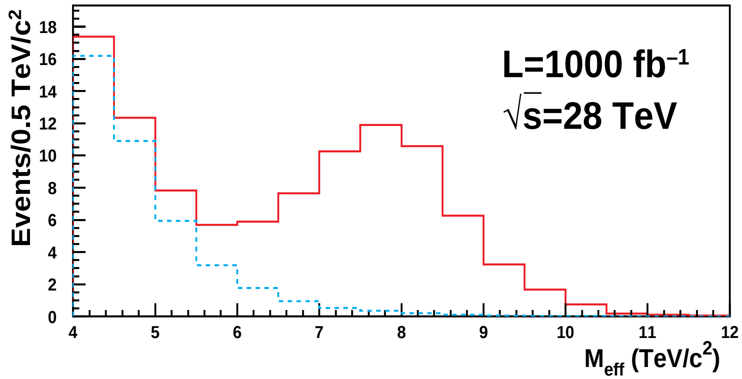
Only $Z' \to \mu^+\mu^-$ considered

$M(Z')=8$ TeV/c^2

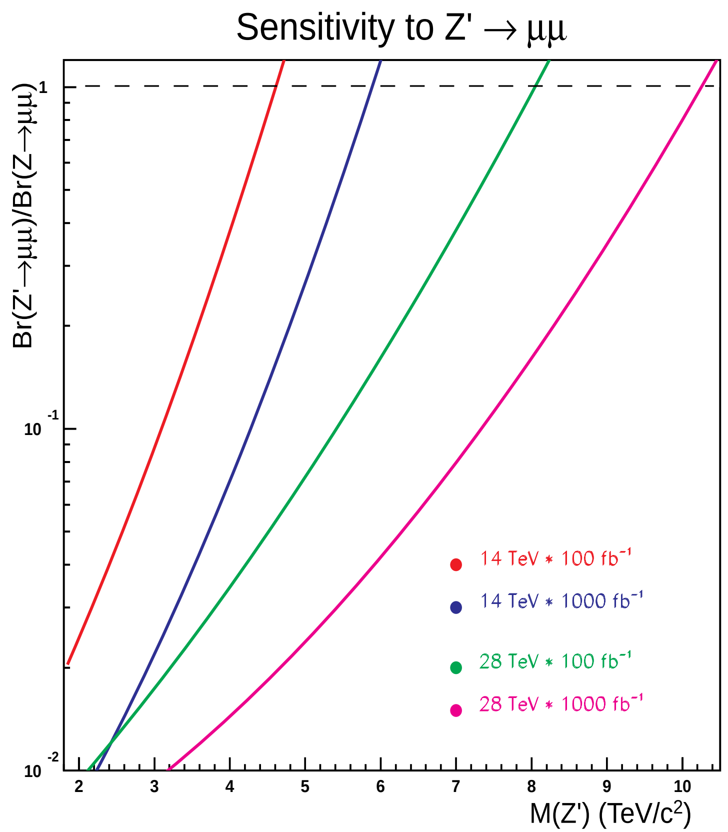
signal vs Drell-Yan background

Example: with Standard Model Br



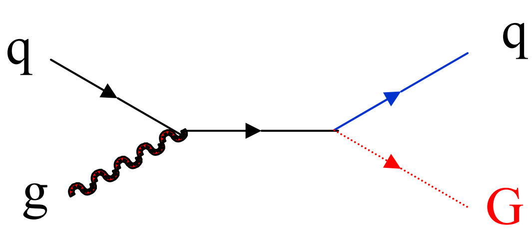


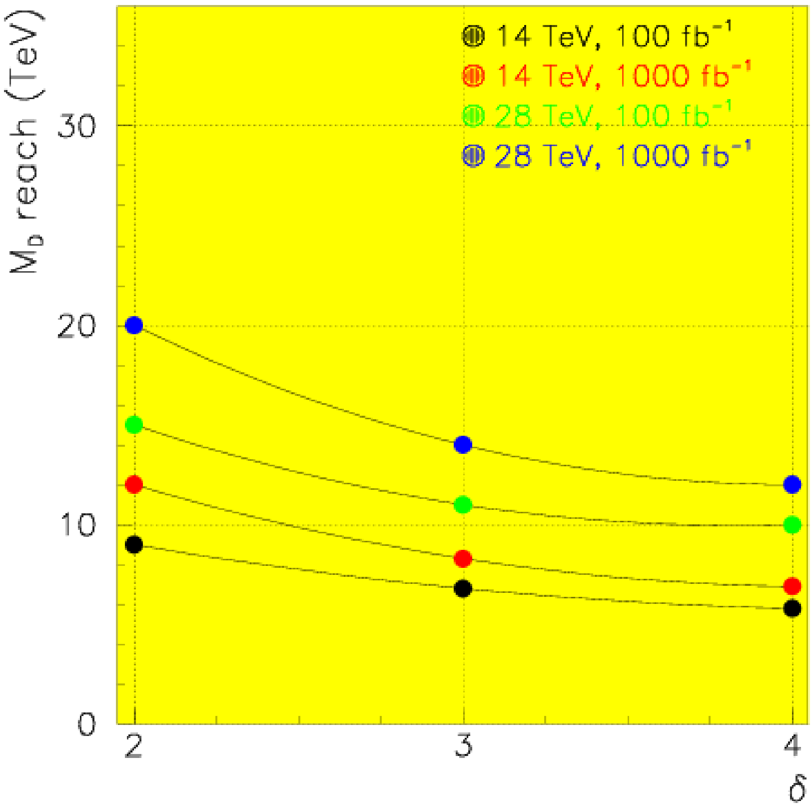
Reach in M(Z') is a function of $Br(Z' \to \mu\mu)$



Extra (large) dimensions @ LHC++

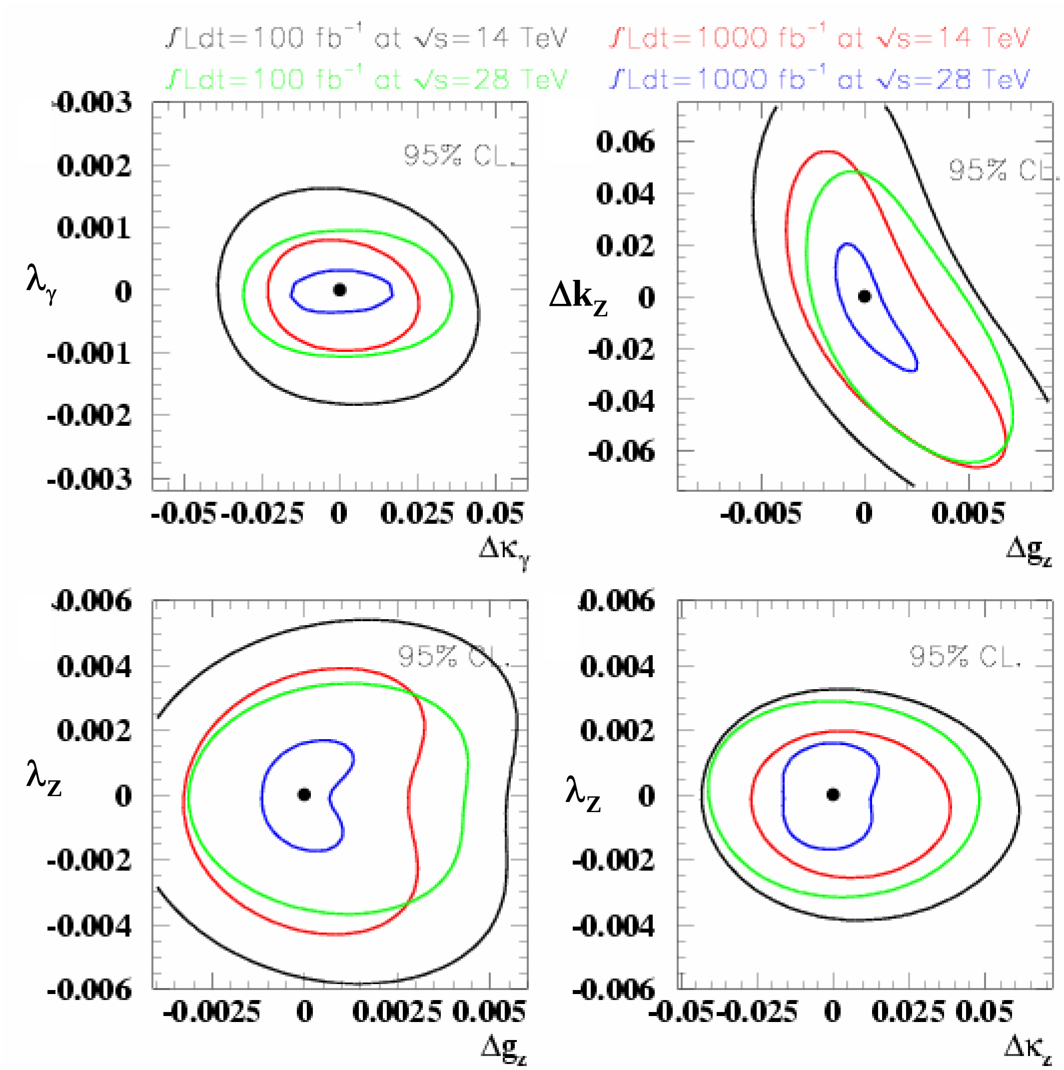
- **Signatures: the same**
  - **Bonus: can extract M_D and δ from σ(28 TeV) / σ(14 TeV) (since $\sigma \sim M_D^{-(\delta+2)}$)**





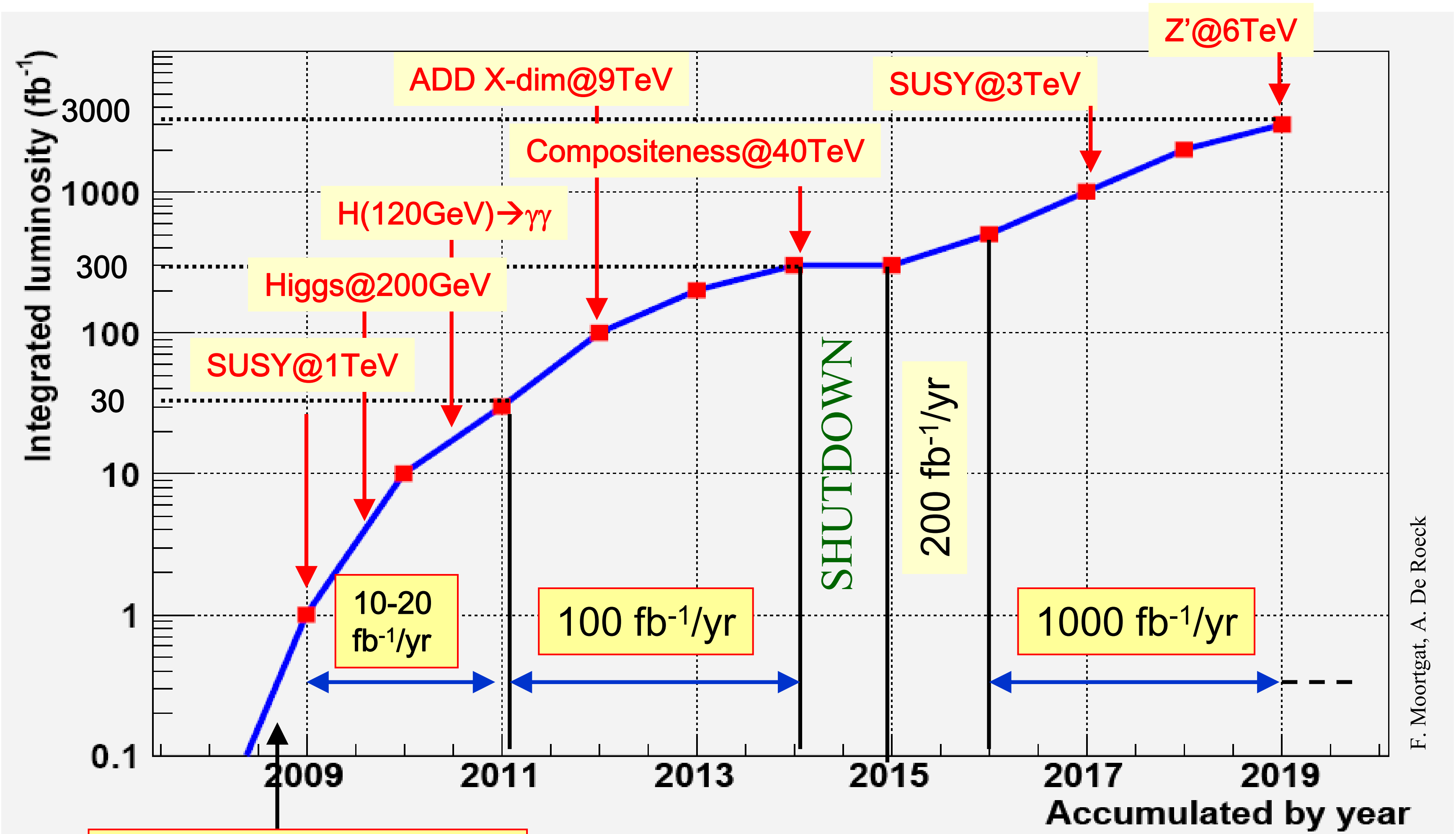
  - **Topology used here: Jet+missing E_T**

Triple Gauge Couplings @ LHC++



Machine Energy/Lum	Δk_Z x10^{-3}	λ_Z x10^{-3}
NLC 0.5 TeV 500 fb^{-1}	1.6	1.3
LHC 14 TeV 100 fb^{-1}	40	1.4
LHC 14 TeV 1000 fb^{-1}	34	0.6
LHC 28 TeV 1000 fb^{-1}	13	0.2

LHC Luminosity/Sensitivity with time



First physics run: O(1fb^{-1})

Summary

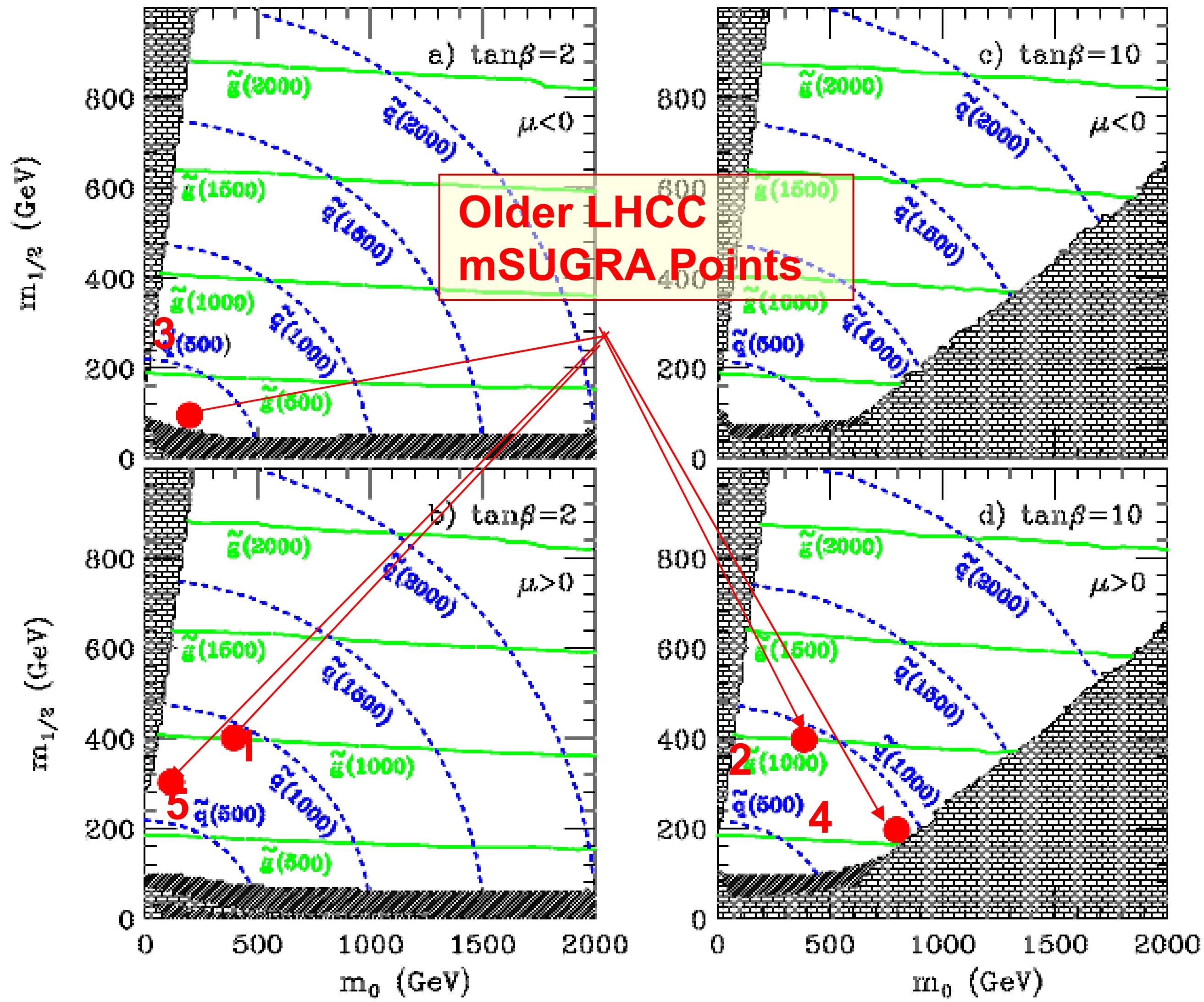
- **The LHC and its experiments on track for first collisions in 2007 and physics runs starting from 2008 onwards**
  - Challenge: commissioning of machine and detectors of unprecedented complexity, technology and performance
- **The LHC should be decisive in revealing the Electro Weak Symmetry Breaking mechanism in the SM (Higgs/no Higgs)**
- **The LHC will break new ground in exploring the TeV scale and hunt for new physics.**
  - Could be easy; could also take more time and ingenuity before we can claim a discovery
  - 1-3 TeV can be covered already with $<10fb^{-1}$

(Grand) summary

- **If no unexpected bad surprises happen**
  - LHC will come

  - and will discover or exclude the SM Higgs by the year 2010
  - discover low energy SUSY if it exists,
  - and cover a mass range of 1-3 TeV for many other scenarios
    - Large com energy: new thresholds
      - ➔ TeV-scale gravity? Large extra dimensions? Black Hole production? The end of small-distance physics? And of course, compositeness, new bosons, excited quarks…
  - There might be a few physics channels that could benefit from more luminosity… LHC++?

SUGRA points

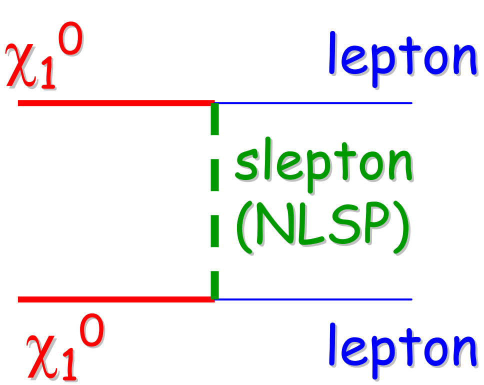


A cosmological interlude

$$0.0094 < \Omega_m h^2 = n_{LSP} \times m_{LSP} < 0.129$$

ρ_{LSP} = Relic LSP Density × LSP mass

Relic LSP Density decreases when the LSP annihilation cross section in the early universe increases



$$\sigma(\chi\chi \rightarrow f f) \propto m_\chi^2 / (m_\chi^2 + m_{\tilde{f}}^2)^2$$

$$\rho_{LSP} \propto (m_\chi^2 + m_f^2)^2 / m_\chi$$
$$\approx m_\chi^3$$

Cosmological interlude (II)

$$0.0094 < \rho_{LSP} < 0.129$$

+

$$m_\chi \approx 0.4 m_{1/2}$$

+

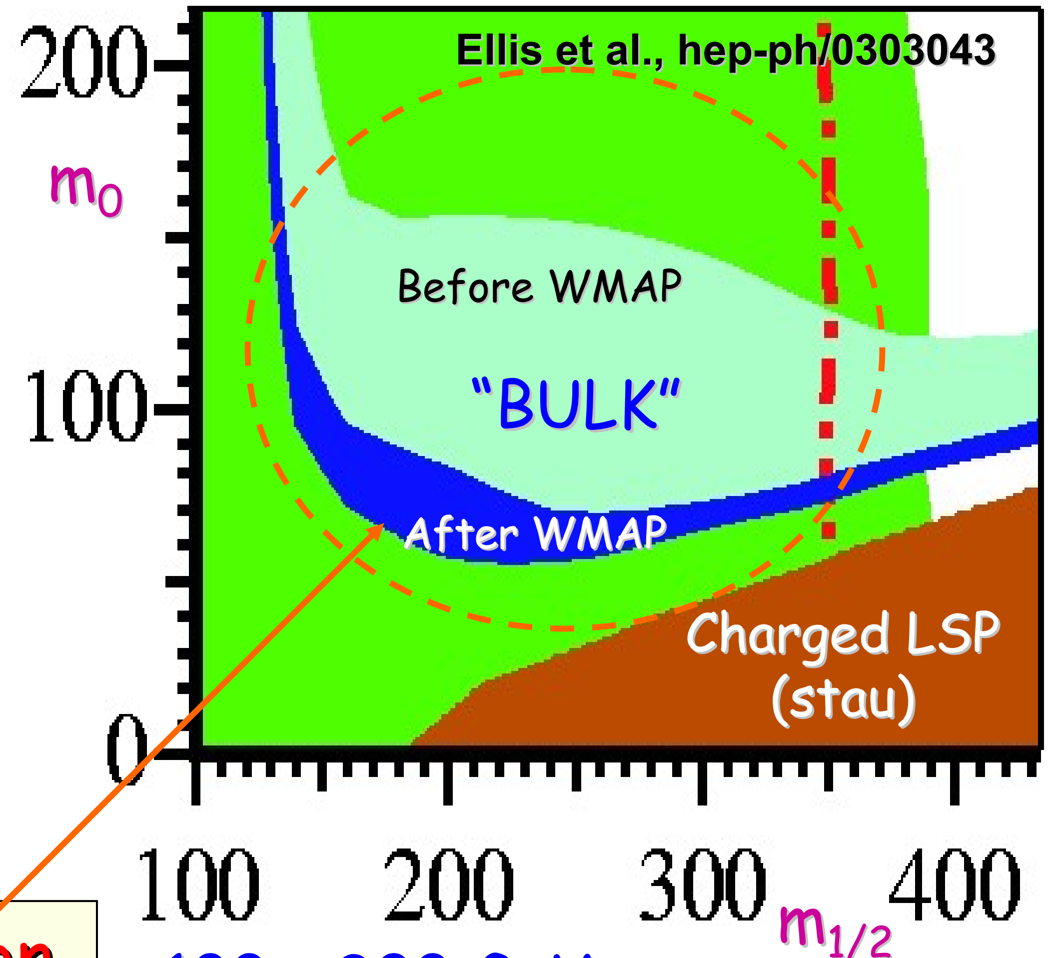
$$m^2_{\tilde{\ell}_R} = m_0^2 + 0.15 m_{1/2}^2 + \cdots$$

$$m^2_{\tilde{\ell}_L,\tilde{\nu}} = m_0^2 + 0.5\, m_{1/2}^2 + \cdots$$

$$m^2_{\tilde{q}_{R,L}} = m_0^2 + 6\, m_{1/2}^2 + \cdots$$

=

Upper and lower limits on m_0 , $m_{1/2}$ and m_χ



100 - 300 GeV

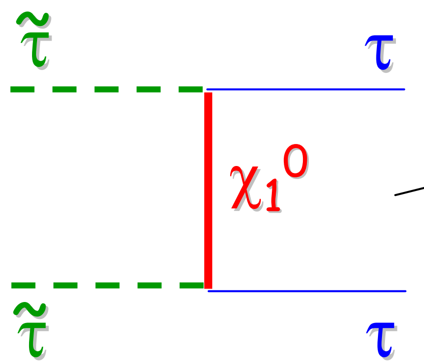
LIGHT !

A cosmo-interlude (III)

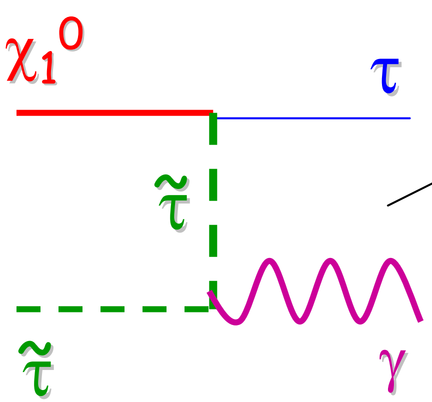
Co-annihilation tail : **LSP and NLSP almost degenerate:**

e.g., $m_{\tilde{\tau}} - m_\chi < m_\tau$ (no direct decay to $\tau\chi_1^0$).

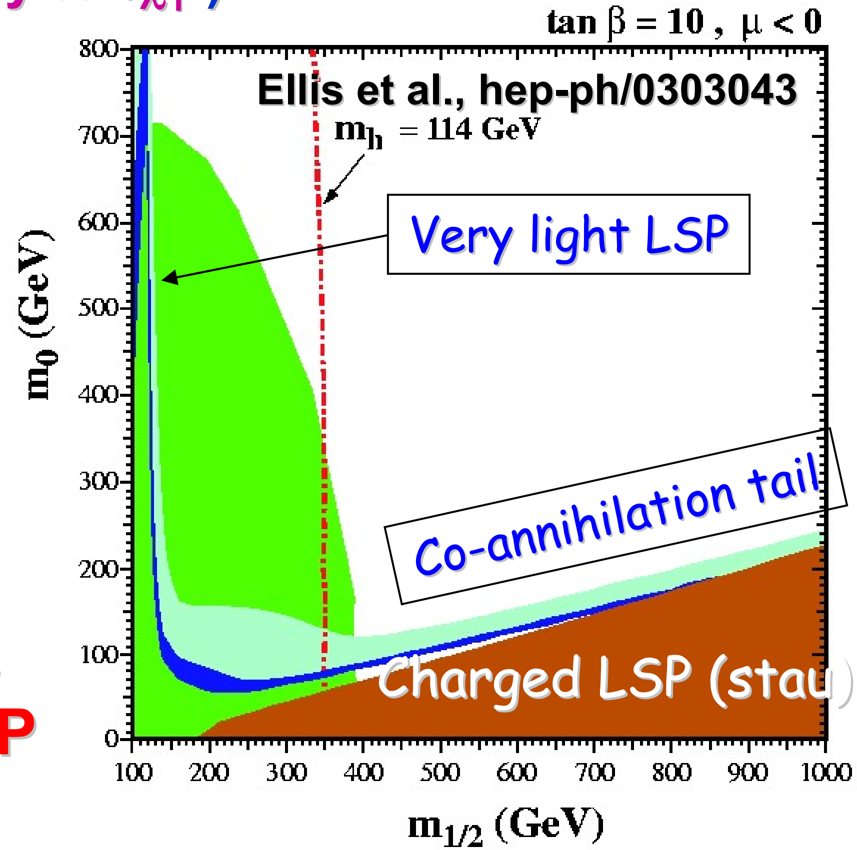
Dominant processes:



The stau disappears slowly



The LSP co-annihilates with the NLSP

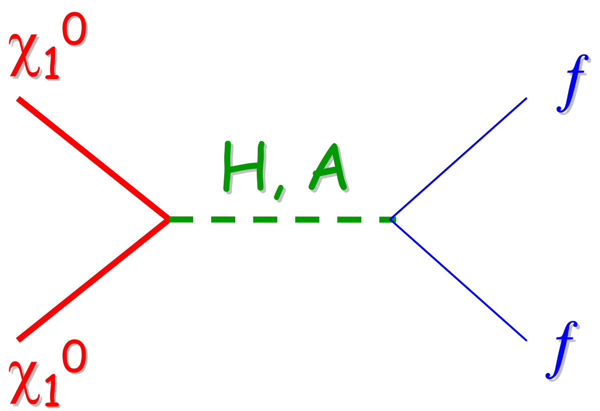


Smaller relic density ⇒ larger m_χ possible…

A cosminterlude (IV)

Rapid annihilation : At large tanβ, and for $m_0 \approx m_{1/2}$, the LSP mass is about half the heavy Higgs boson mass (A and H)

Dominant process:



Annihilation is too rapid if LSP mass is exactly half the Higgs-boson mass
⇒ two allowed lines on the plot