Physics Beyond the Standard Model

— Signals at Colliders

Tao Han
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CTEQ Summer School, Puebla, Mexico
(May 26, 27, 2005)

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Our "Theory Bank"
New Physics Signals at Hadron Colliders

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The Standard Model and the Need For Going Beyond
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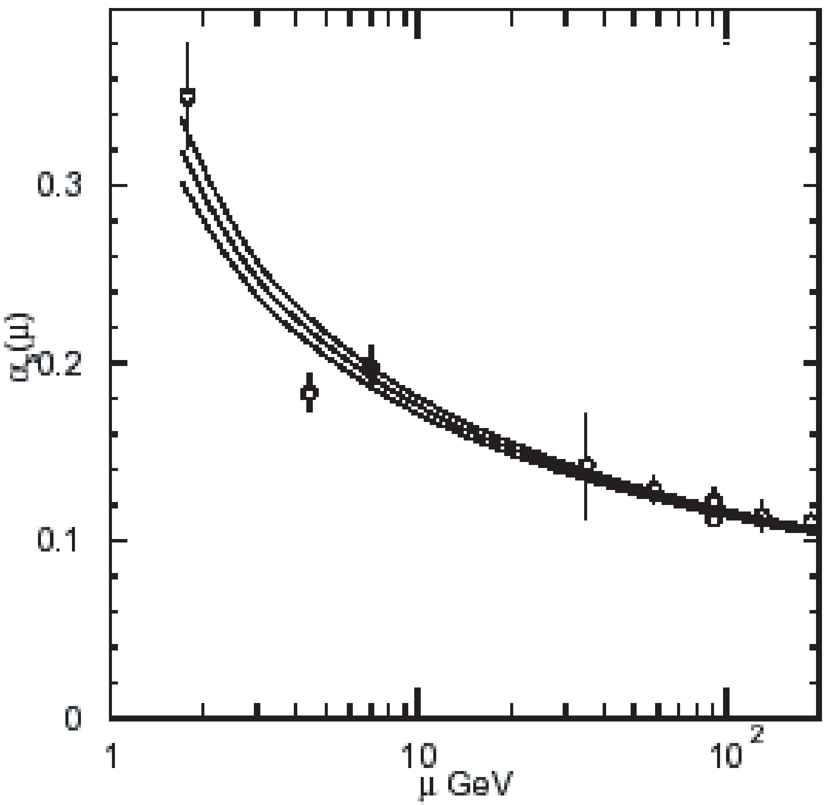
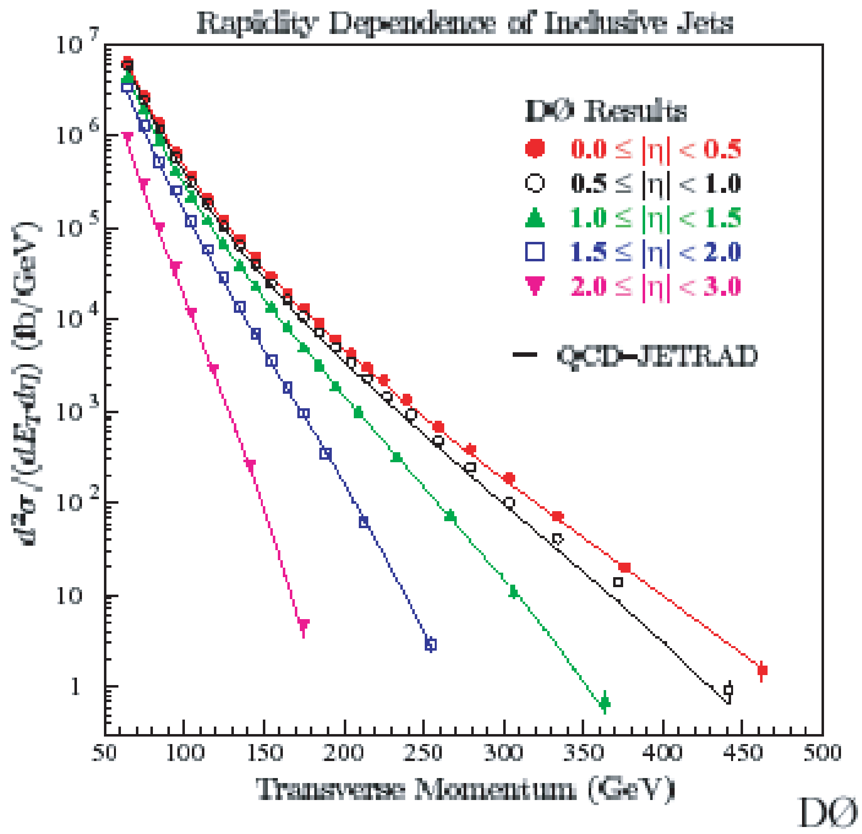
New Physics Signals at Hadron Colliders

- Higgs bosons
- SUSY particles
- New gauge bosons
- New heavy fermions
- Extra dimensions

The Standard Model
as a Low-Energy Effective Theory

- $SU_c(3)$ QCD as the theory of strong interactions:





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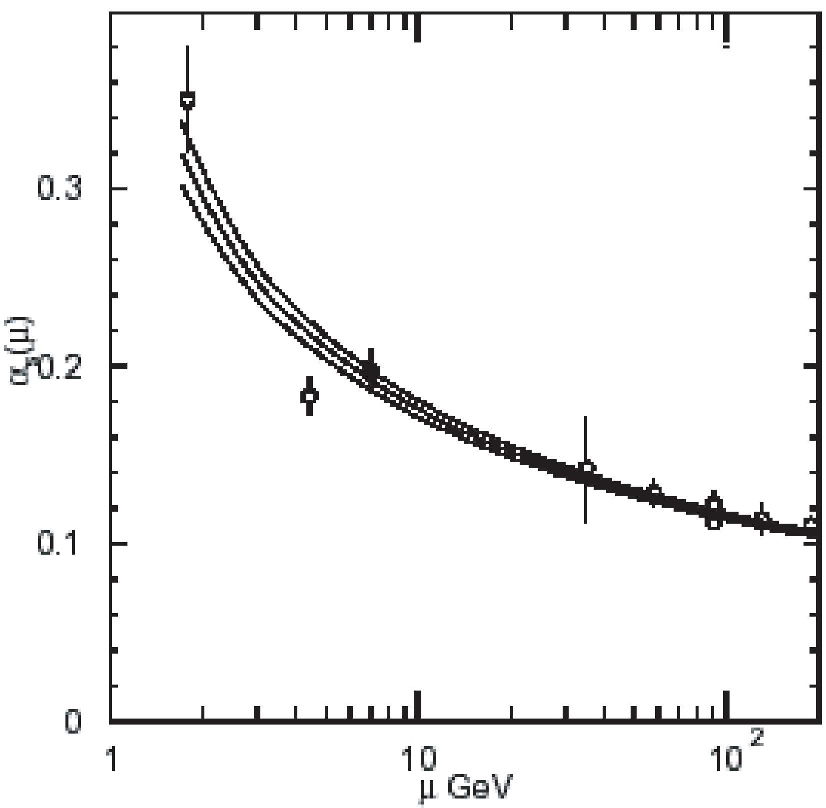
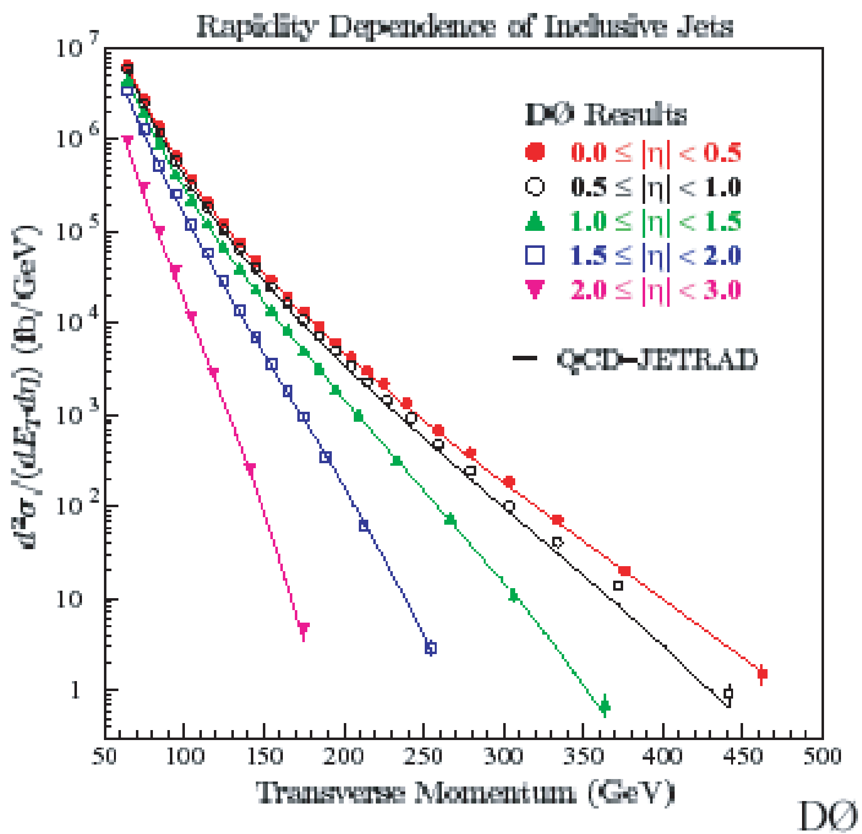


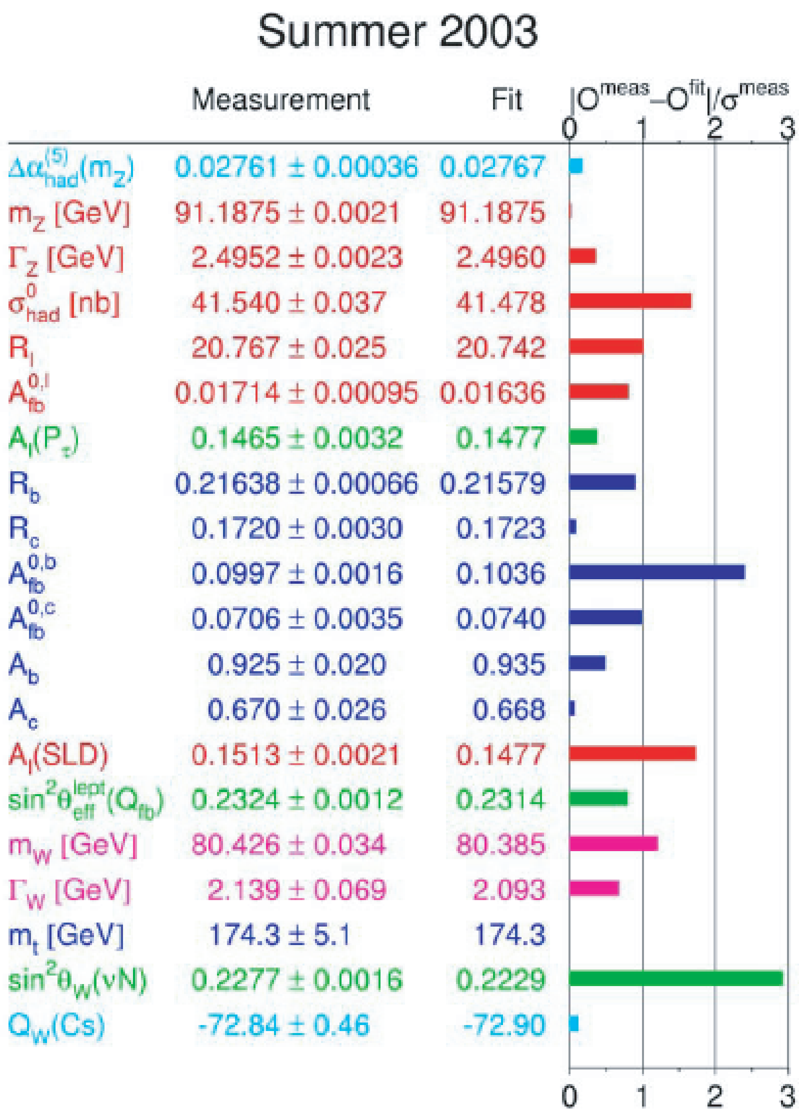


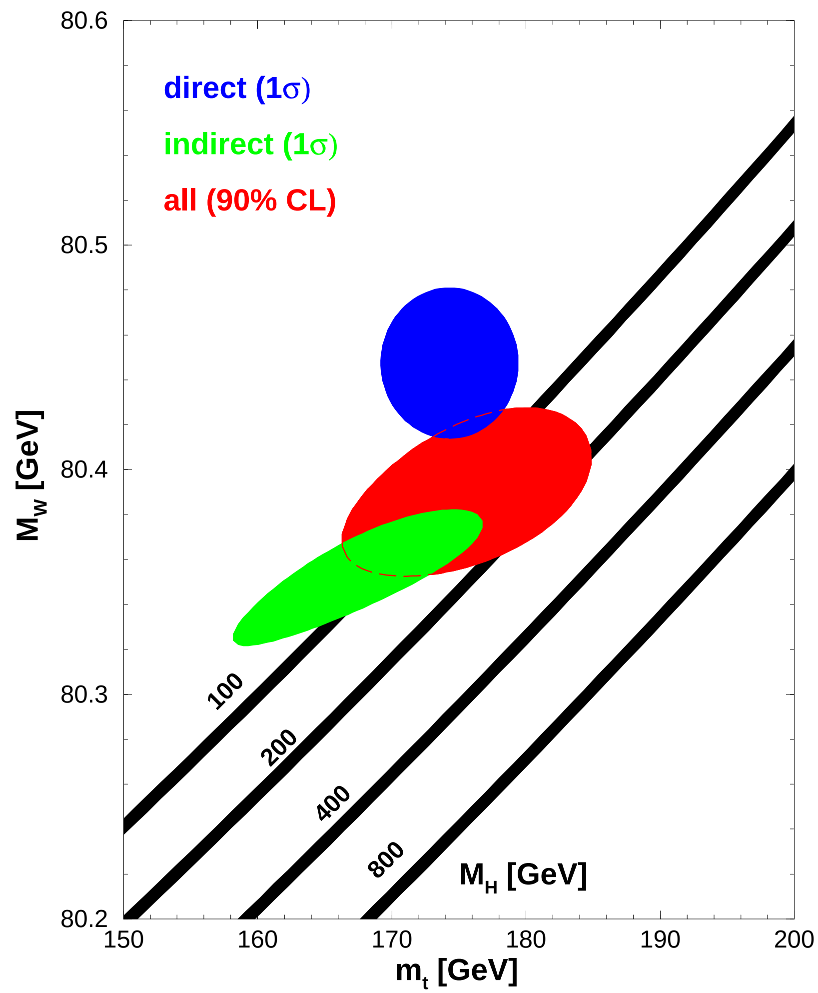
QCD remarkably successfful:

Perturbative QCD well tested and formed foundation for HEP;

Significant progress in lattice gauge calculatioins.

- $SU_L(2) \otimes U_Y(1)$ EW theory and precision measurements:





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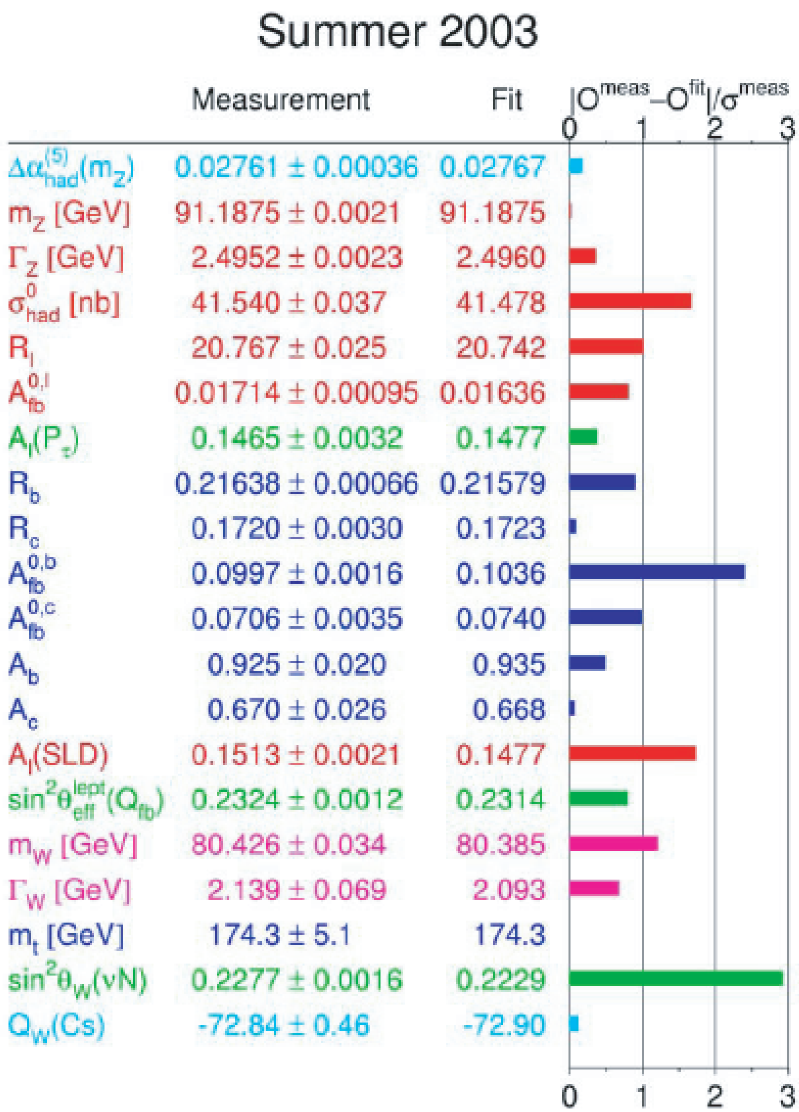
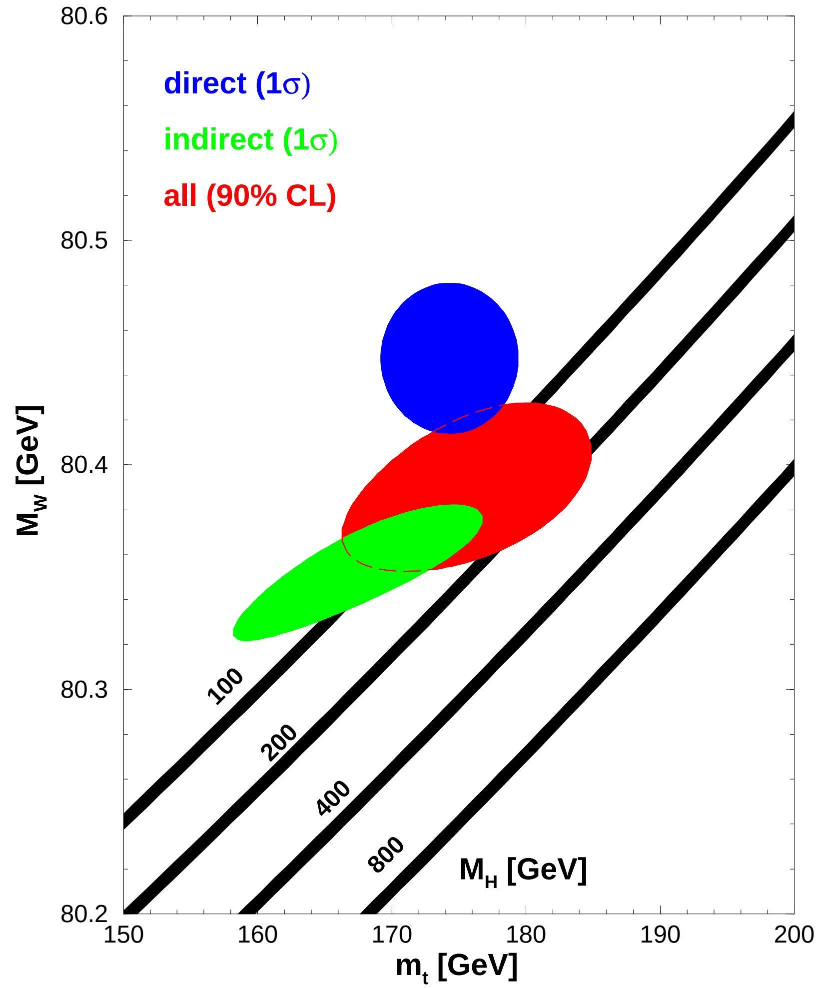


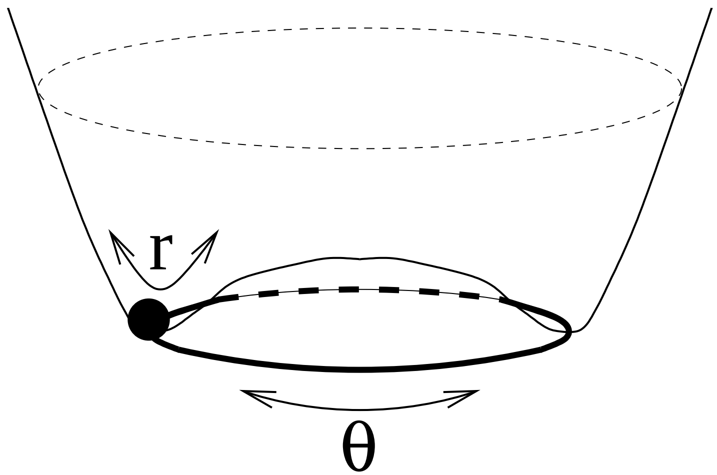


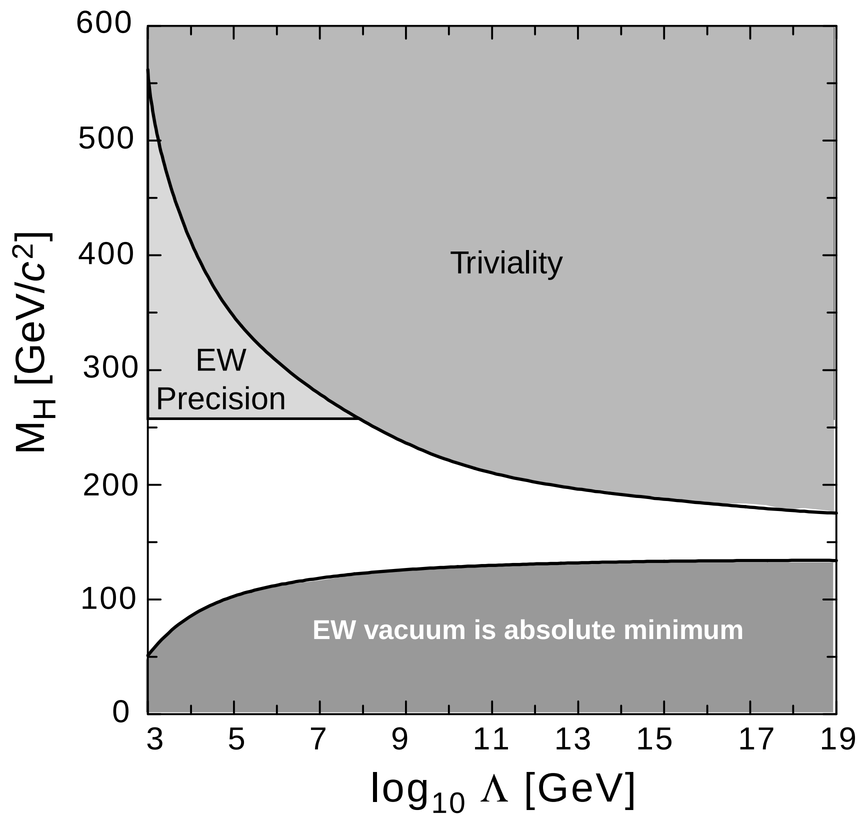
EW precision data: $m_H < 251$ GeV at 95% CL with $m_t = 178$ GeV.

• SM as an effective theory ?

$$V = -\mu^2\Phi^2 + \lambda\Phi^4, \quad <\Phi>= \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{2\lambda}}, \quad v^{-2} = \sqrt{2}\ G_F$$

$$m_H = \sqrt{2\lambda}\ v$$





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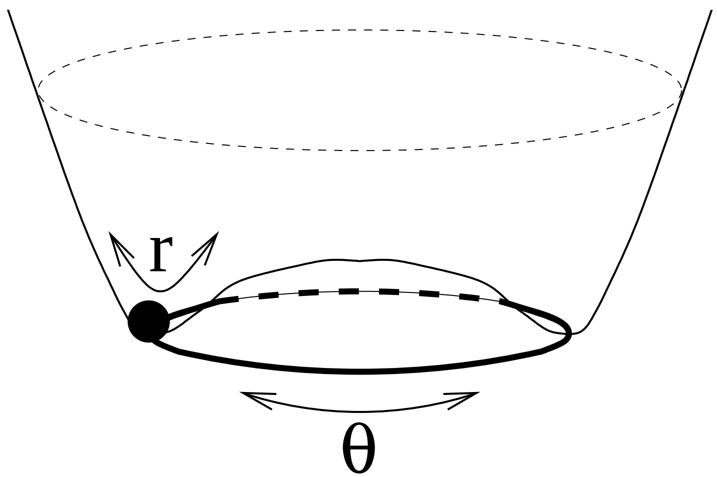
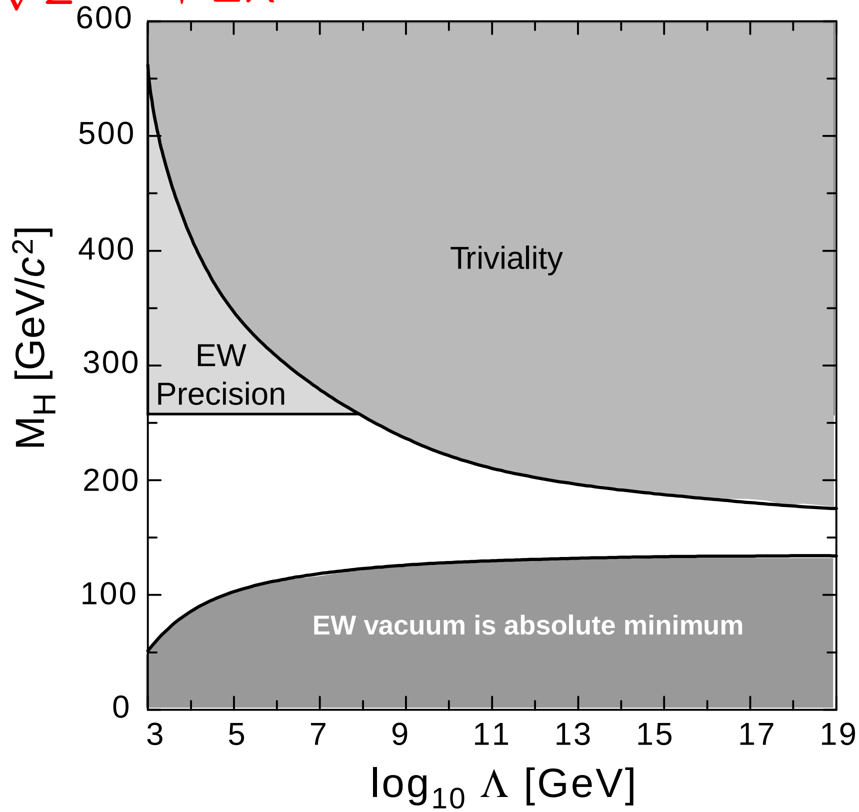




All couplings $g_{2,3}$, $\sin^2\theta_W$, g_f and masses $\sim g_i v$ are in place.
SM with a light H could be an *effective theory* to $\Lambda \sim M_{pl}$.

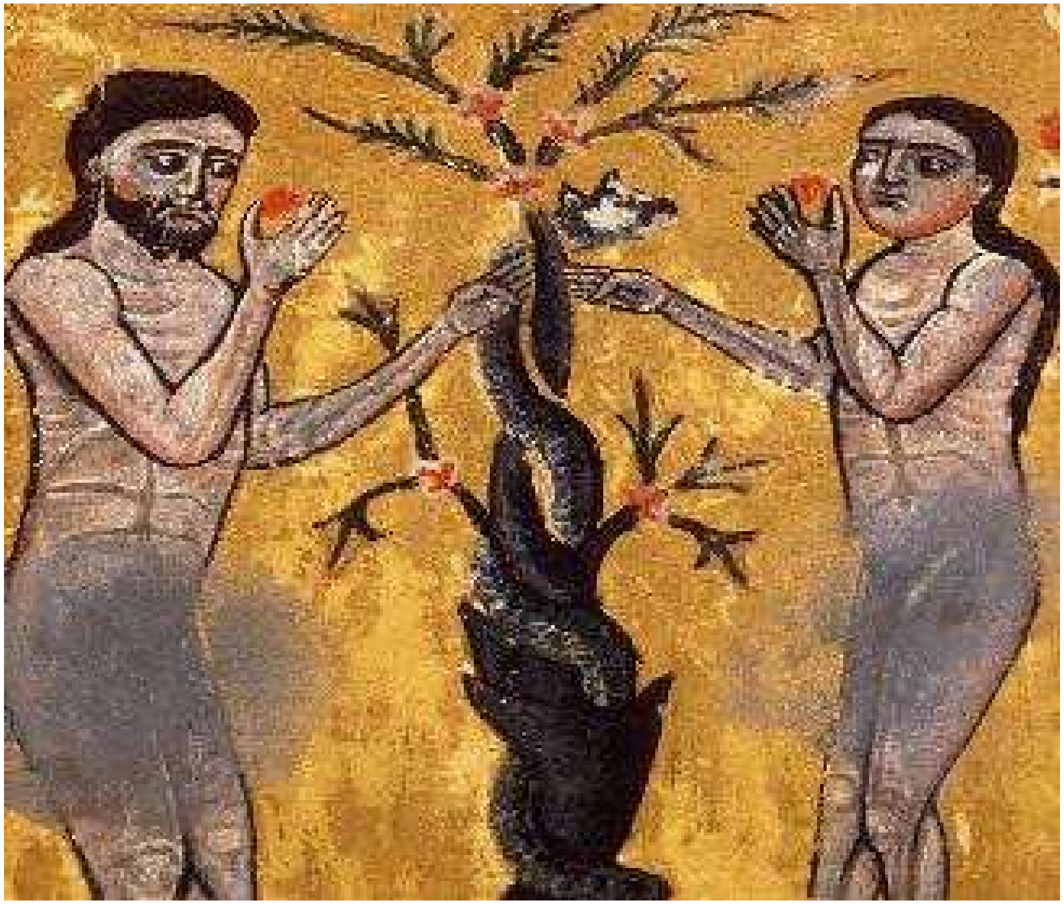
a stable vacuum;

non-trivial interactions;

renormalizability ...

Q: Would you need physics beyond the Standard Model?

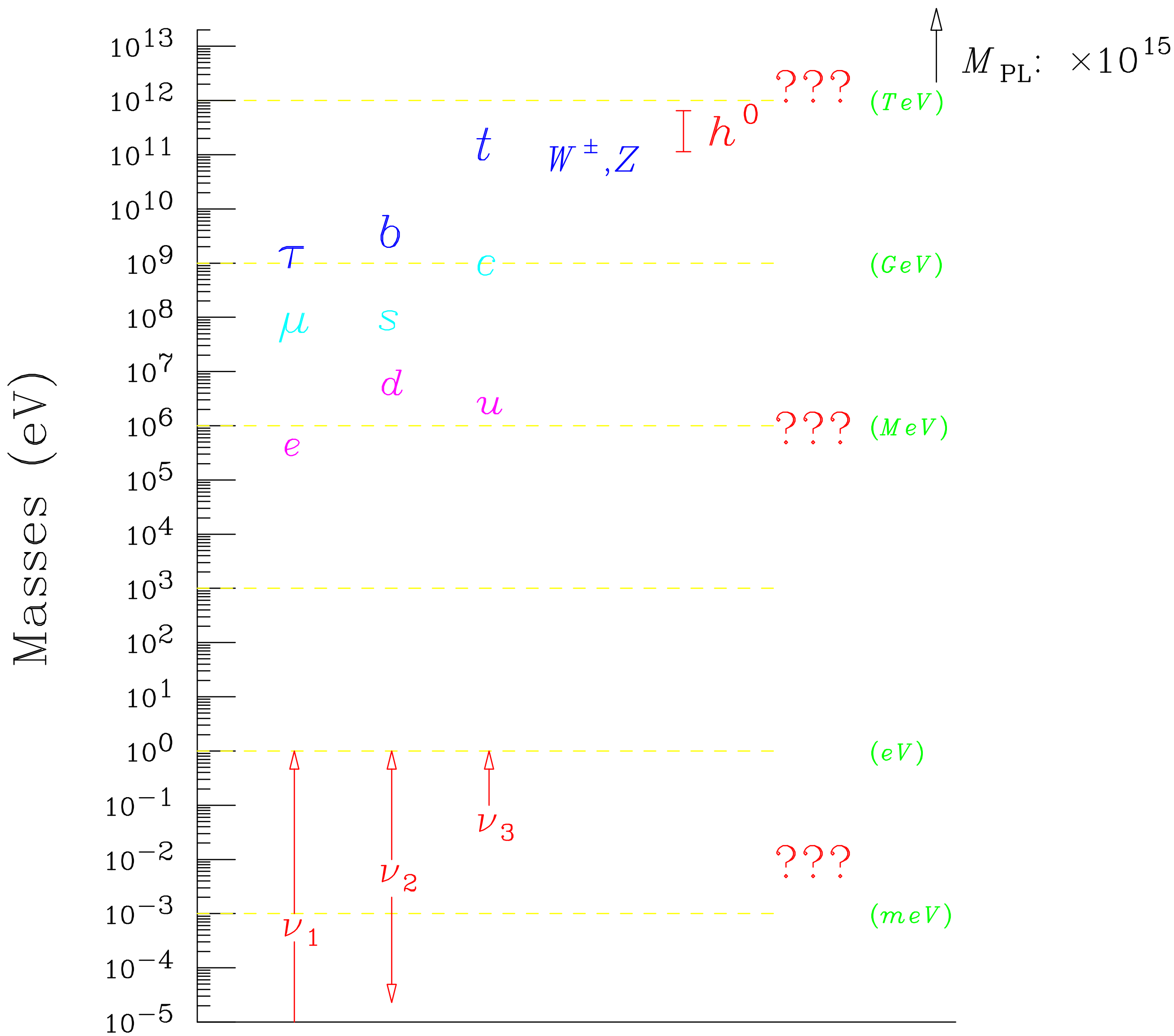
A: ... ...



(The Garden of Aden)

The Need For Going Beyond SM ?

Mass Spectrum in a Wide Range:



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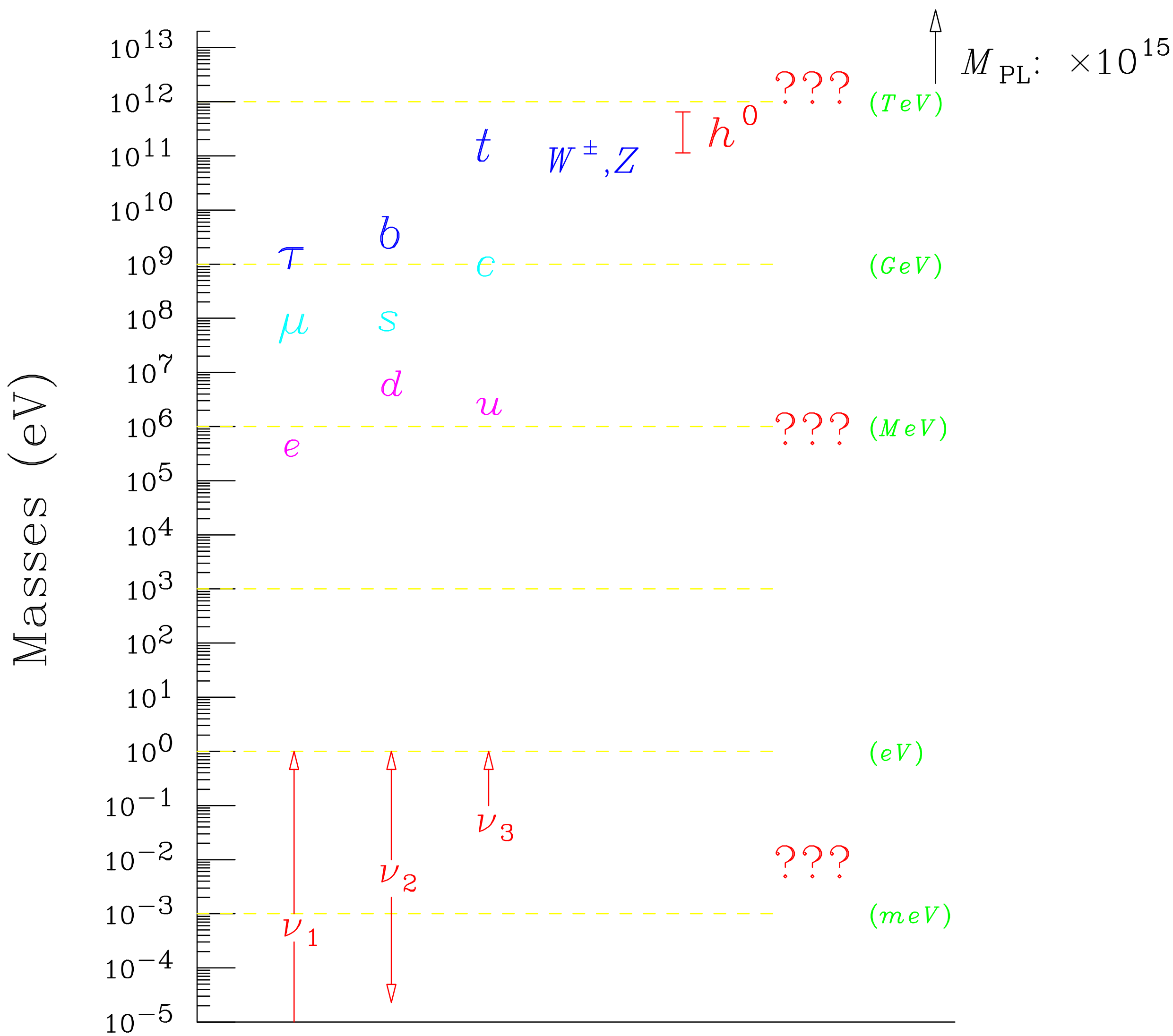

EW scale: $v \approx \mathcal{O}(1$ TeV); $m_\nu : 10^{-15}$ down ? $M_{pl} : 10^{15}$ up ?.

Vastly Separated Scales for Fundamental Interactions:

- QCD condensate: f_π

  At the scale Λ_{QCD}, the interaction becomes non-perturbative:

$$\alpha_s(Q^2) = \frac{1}{b\,\ln(Q^2/\Lambda^2)} \;\Rightarrow\; \Lambda_{QCD} \sim \Lambda\ \exp(-\frac{1}{2b\alpha_s}),$$

$$f_\pi \propto \langle \bar{q}_L q_R \rangle_0^{1/3} \sim 100\ \text{MeV}.$$

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  Empirically (Fermi's weak interaction) and theoretically (EWSB):

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- Quantum Gravity?

$$M_{Pl} = \hbar c/\sqrt{G_N} \approx 10^{19} \text{ GeV}.$$

  We have NO clue about it ...

Nontrivial fermion pattern: (observed)

Three fermion generations;
Quark small mixing;
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CP violation...

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Gravitation and cosmology: (observation)

Gravity and Planck scale physics;
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$\Longrightarrow$ All indicate the need for physics beyond the SM.

Our "theory bank"

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(A). Supersymmetry:

Weak scale SUSY stabilizes the hierarchy $M_W - M_{pl}$

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\frac{\lambda_f^2}{16\pi^2}\ln\left(\frac{\Lambda}{M_{SUSY}}\right).$$

if the "soft-SUSY breaking": $M_{SUSY} \sim \mathcal{O}(M_{SM})$.

Predict TeV scale new physics:
light Higgs bosons $H^0,\ A^0,\ H^\pm$;
SUSY partners $\tilde{W}^\pm ...,\ \tilde{g},\ \tilde{q},\ \tilde{l}^\pm ...$

Lead to rich physics at the electroweak scale at colliders;
Accommodate SUSY GUTs $M_{GUT} \sim 5 \times 10^{16}$ GeV.

(B). Dynamical approach for mass generation:

- Technicolor and alike: a lesson from QCD

  SU(N_{TC}) gauge theory, TC fermions $Q = U, D, ...$

  EWSB by TC-fermion condendation at Λ_{TC}:

  $$v \sim \langle \overline{Q_L} Q_R \rangle^{1/3} \sim 246 \text{ GeV}.$$

  Predicts new strong dynamics at the TeV scale: $\pi_T,\ \eta_T,\ \rho_T,\ \omega_T ...$

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- "Topcolor/Top-seesaw": Top quark special ?

  $$m_t \approx v/\sqrt{2} = 174 \text{ GeV}.$$

Introducing an additional fermion pair $\chi_L,\ \chi_R$

to generate the condensation $H \sim (\bar{\chi}_R t_L,\ \bar{\chi}_R b_L)$

Lead to a heavy Higgs $m_H \sim 1$ TeV,

a SM t, and a heavy state χ, $M_\chi \approx 4$ TeV.

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- A less ambitious approach: Little Higgs Models

  Accept the existence of a light Higgs;

  keep the Higgs boson "naturally" light (at 1-loop level).

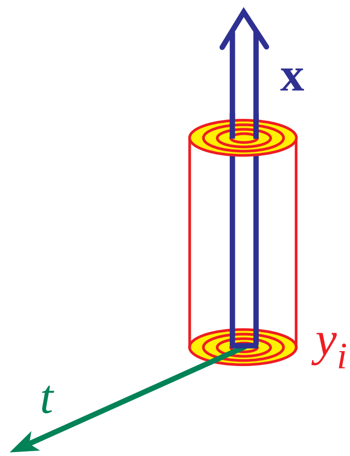
  Predicts new "partner particles":

  $$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(C). Extra-dimensions:
A new approach to the hierarchy problem

- Large Extra-dimension Scenario; ADD*

In a world with $D = 4 + n$ dimensions, n of them compactified,



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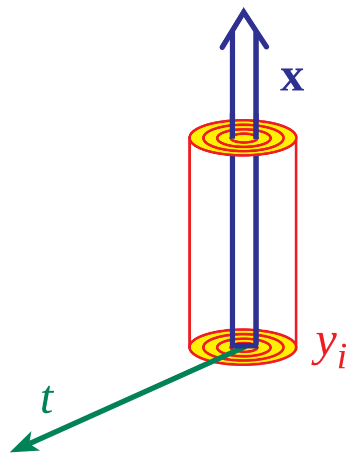

the 4-dim Planck scale is related to the D-dim one M_D as

$$M_{PL}^2 \sim M_D^{n+2} \int dx^n = M_D^{n+2} V_n.$$

Thus the fundamental scale in the theory:

$$M_D \sim (M_{pl}^2 / V_n)^{1/n+2} \longrightarrow \mathcal{O}(1 \text{ TeV}).$$

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• Extra dimensions and KK particles:

If an extra dimension y becomes compact (a circle of radius R), then all fields (gravitational, electromagnetic etc.) in y-dimension are periodic functions :

$$F(x, y) = \sum_{n=-\infty}^{\infty} F^n(x)\ e^{in \cdot y/R}.$$

Equation of motion:

$$(\partial^\mu \partial_\mu - \partial^y \partial_y) F(x, y) \Rightarrow (\partial^\mu \partial_\mu + \frac{n^2}{R^2}) F^n(x)$$

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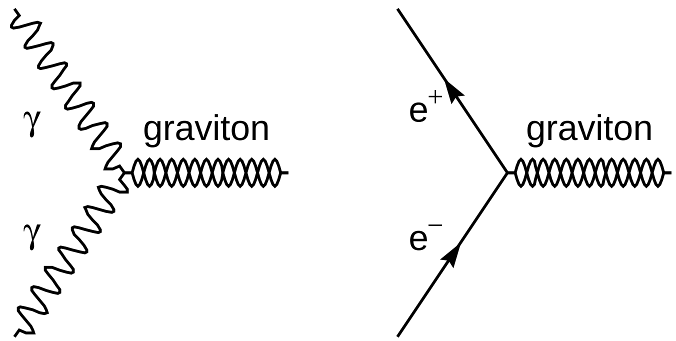
$$\Delta M_{KK} = 1/R.$$

No γ_{KK}, e^-_{KK}, ... found $\Rightarrow$ R^{-1} large; or γ, e^- ... don't go there.

• Graviton Interactions With SM Fields:

The rule: gravitons couple to ANYTHING

(attach it on any legs or vertices in the SM)



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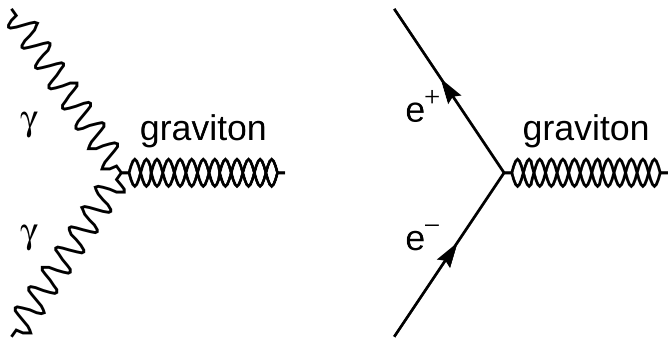

Although each graviton couples gravitationally $\kappa^2 \sim G_N$*,*
the high-degeneracy leads to

$$\kappa^2 \rho(m) dm^2 \sim \kappa^2 R^n m^{n-2} dm^2 \sim E^n / M_S^{n+2}$$

Effective coupling $\kappa^2 \sim \frac{1}{M_{pl}^2} \rightarrow \frac{1}{M_S^2}$!

- The Randall-Sundrum Scenario

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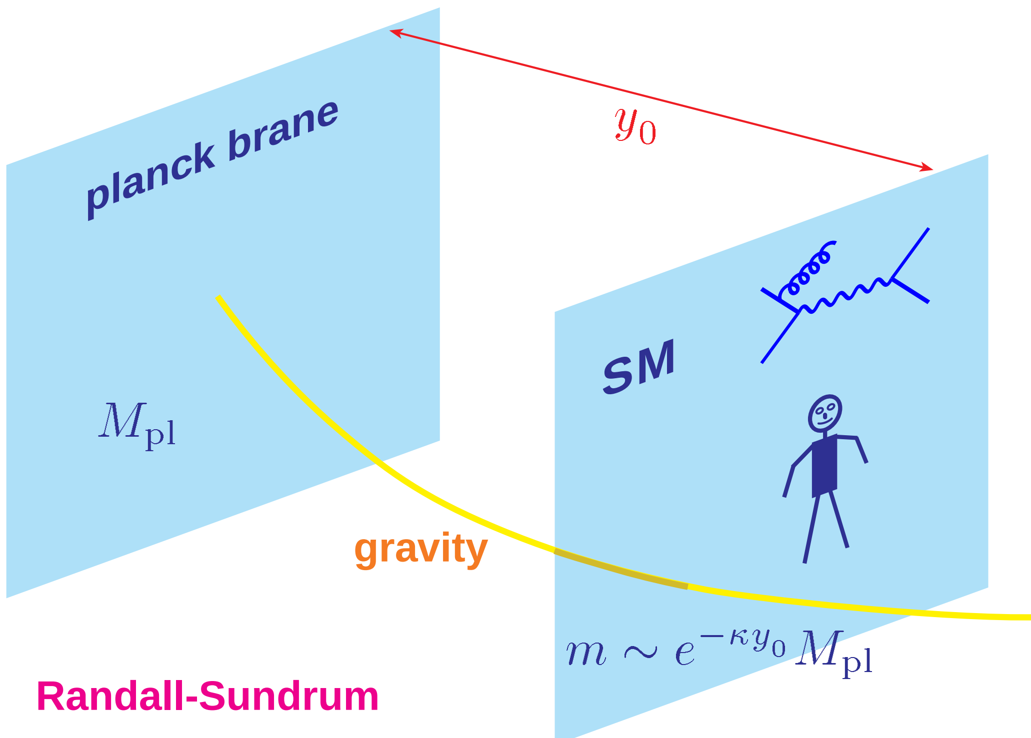
The extra dimension y is "warped":

$$ds^2 = e^{2A(y)}\ \eta_{\mu\nu}\ dx^\mu dx^\nu - dy^2,$$

where the "warp" factor $A(y) = -ky$,
with k the curvature scale in the 5^{th}-dim.



So the masses of the KK states are *not* equally-spaced.

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Electroweak precision constraints;

K/B rare decays and CP violation: $B \to X_s\gamma$; $J/\psi K_S$, ϕK_S, $\eta' K_S$...;

Neutrino masses and mixing;

muon $g-2$; $\mu \to e\gamma$...; neutron/electron EDMs;

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Yet more to come:

Tevatron: ($p\bar{p}$ at 1.96 TeV, current)

EW, top sector, new particle searches, Higgs (?) ...

LHC: (pp at 14 TeV, 2007)

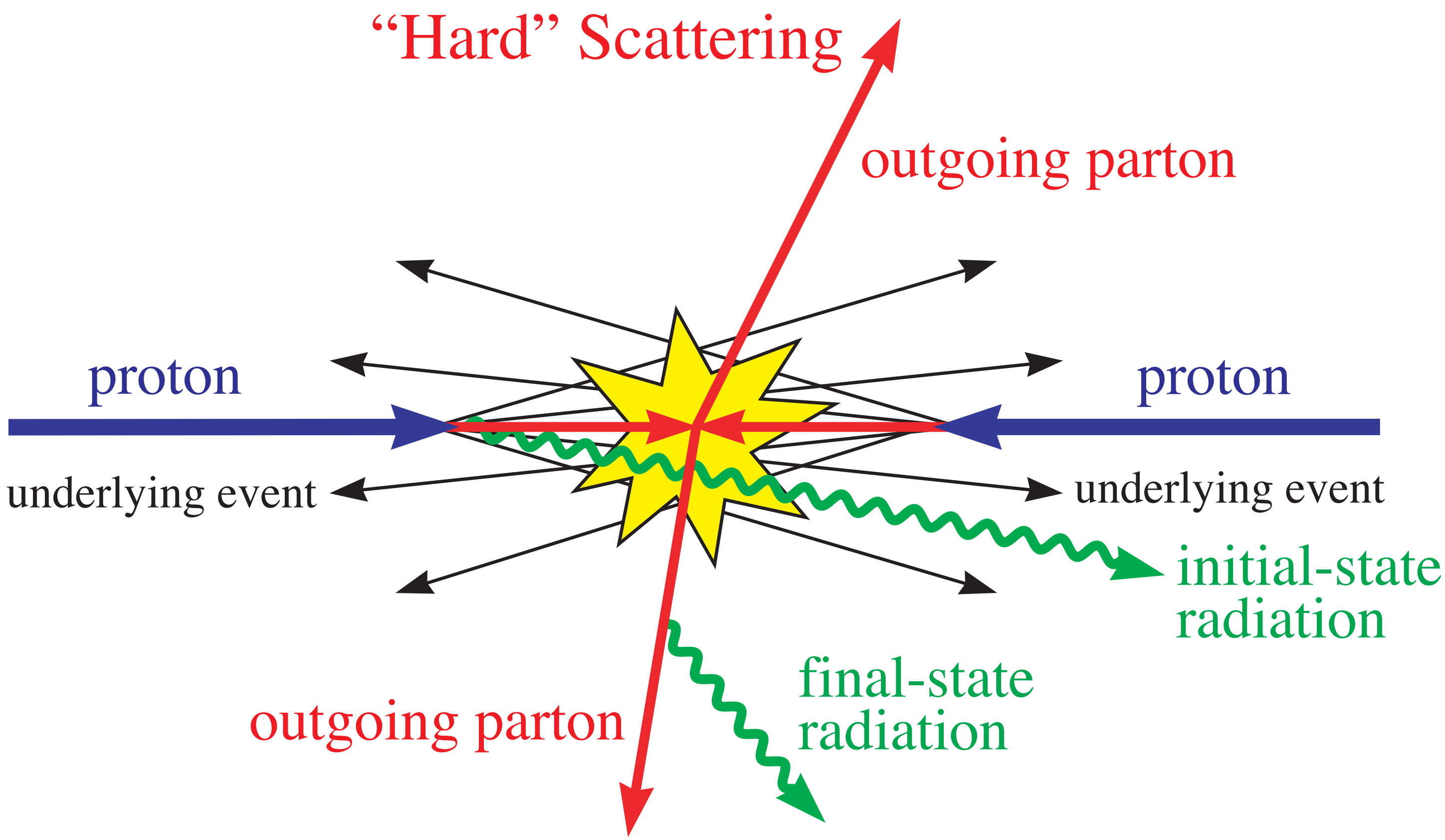
comprehensive Higgs studies, extensive new particle searches...

ILC: (e^+e^- at 500 GeV – 1 TeV ?)

more on top sector, precision Higgs and new light particles...

New Physics Search at Hadron Colliders

In high-energy hadron collisions,



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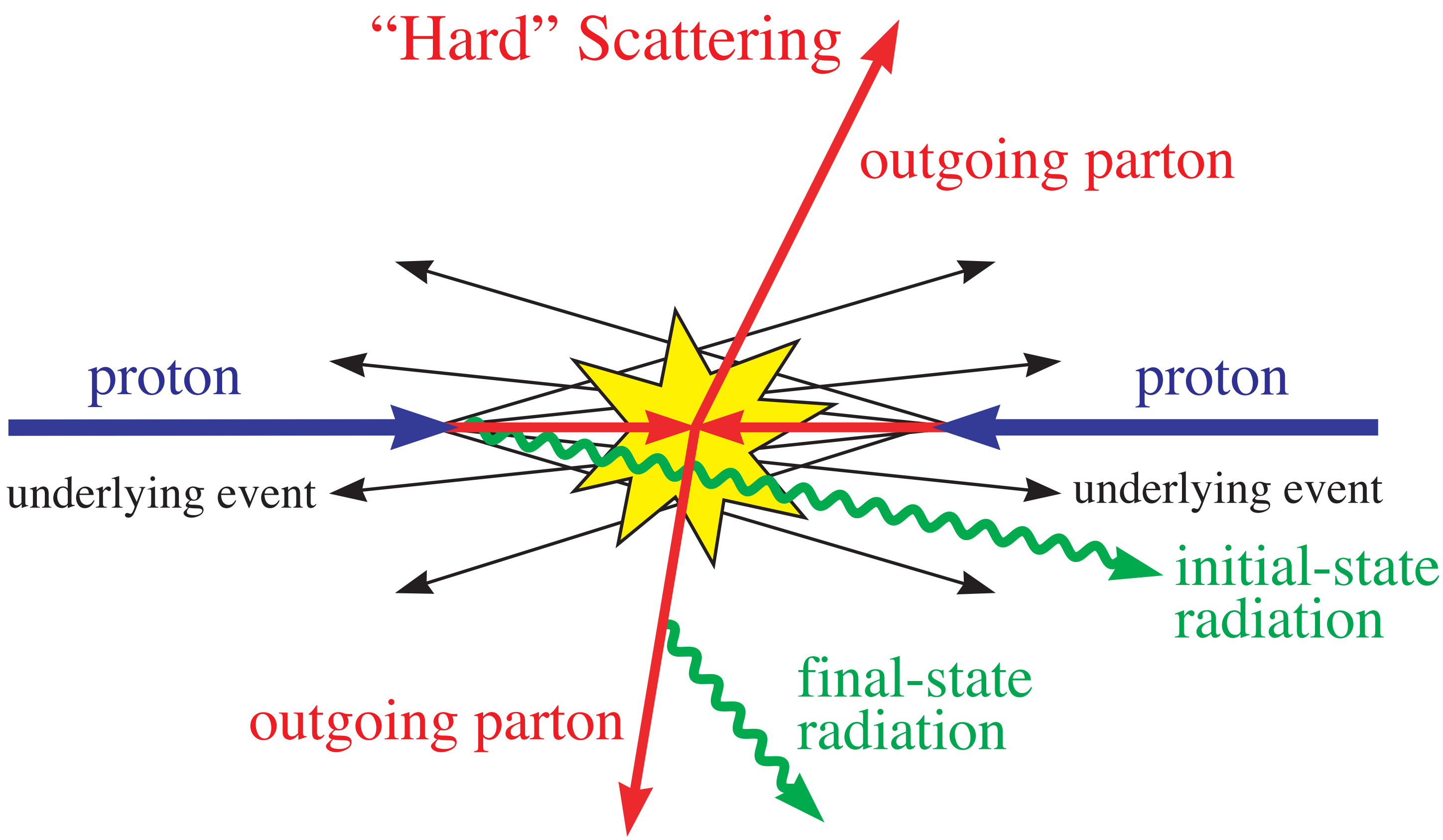
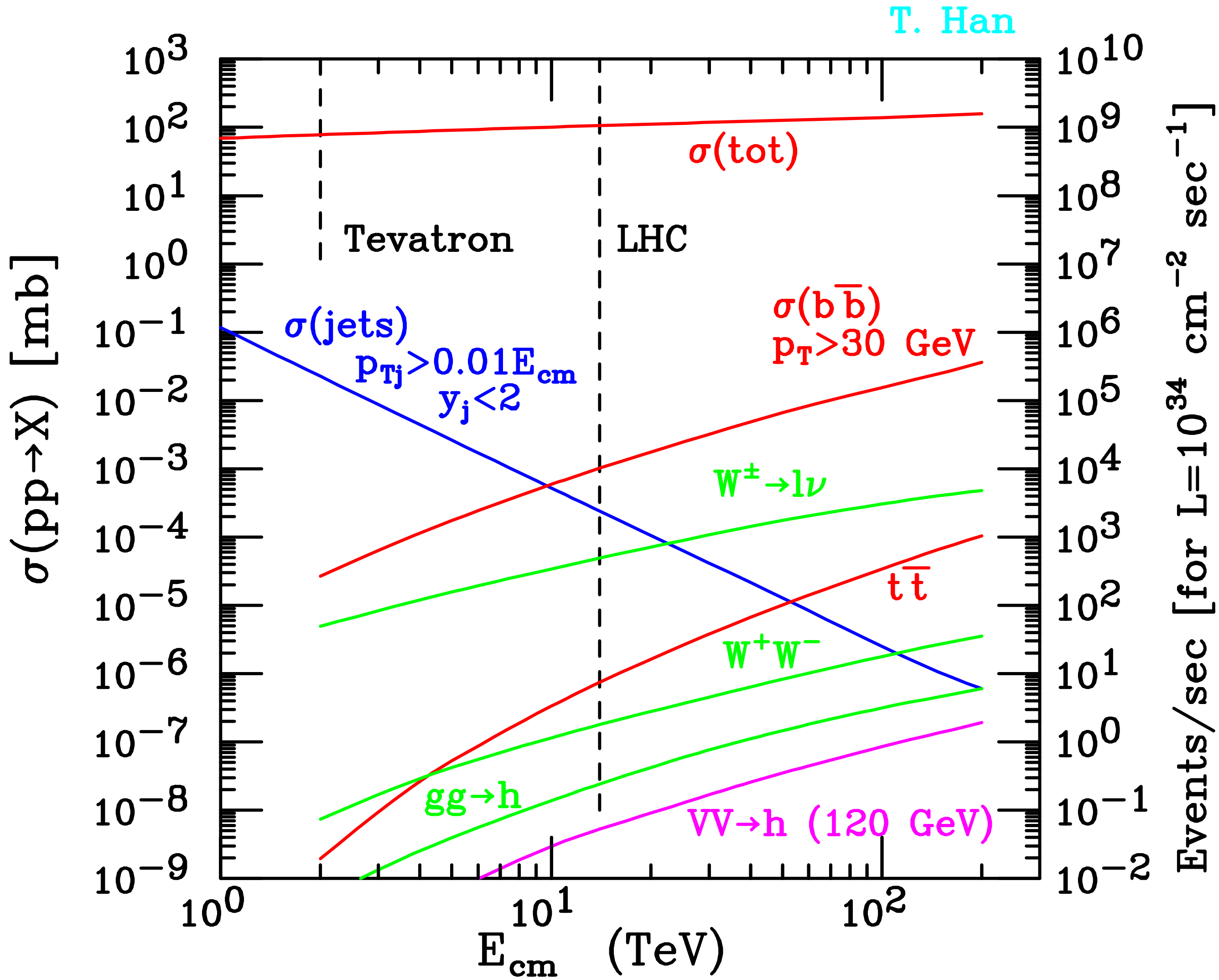


- Higher energy threshold: $M_{new} \sim \sqrt{s}$.
- multiple (strong, electroweak) channels: $q\bar{q},\ gg,\ qg,\ b\bar{b},\ WW\ ...$

Scattering cross sections for various SM processes:



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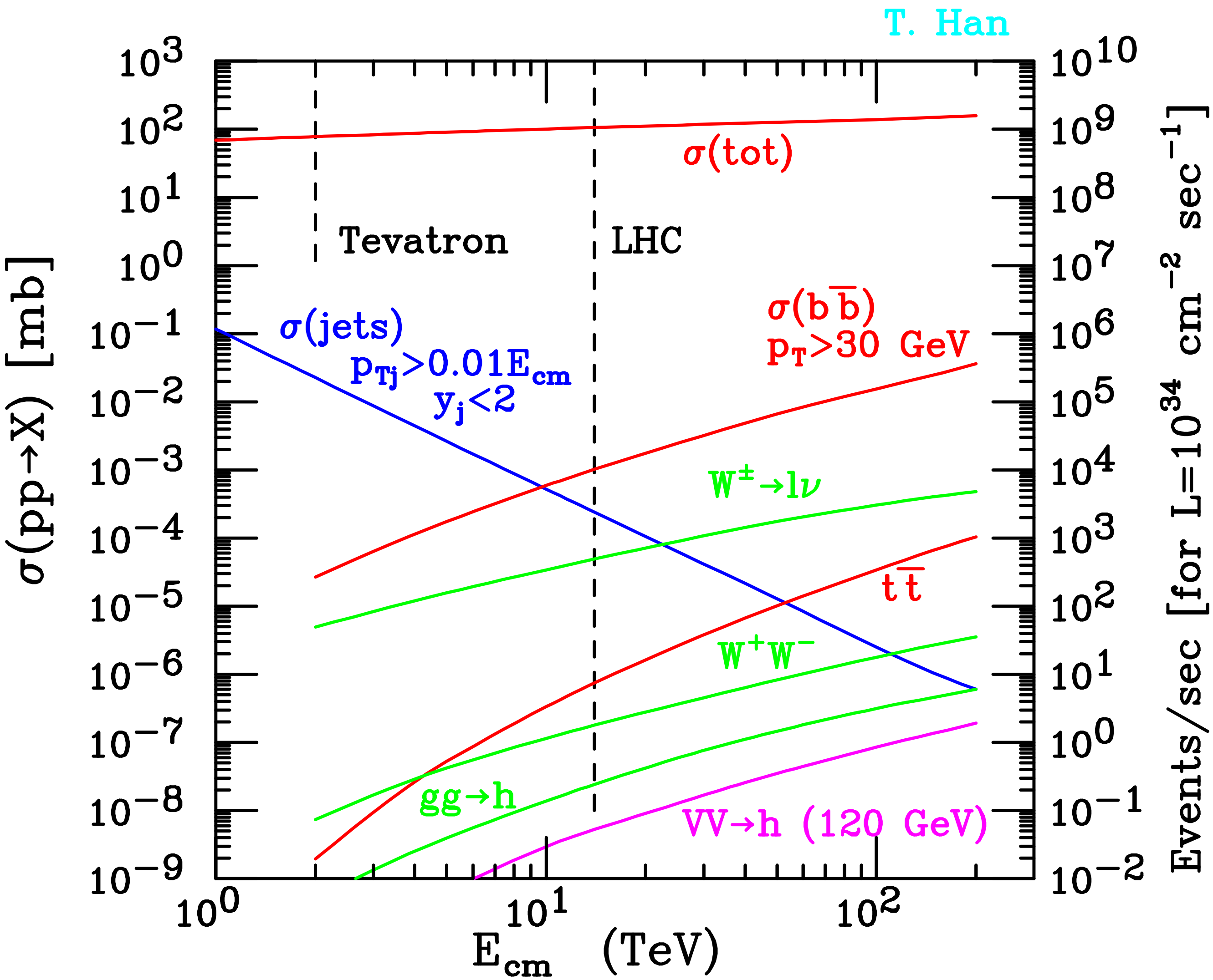

- Rare events: once every 1,000,000, there may be one interesting ...
- challenge to dig signals out of the backgrounds...

How to search for new particles?

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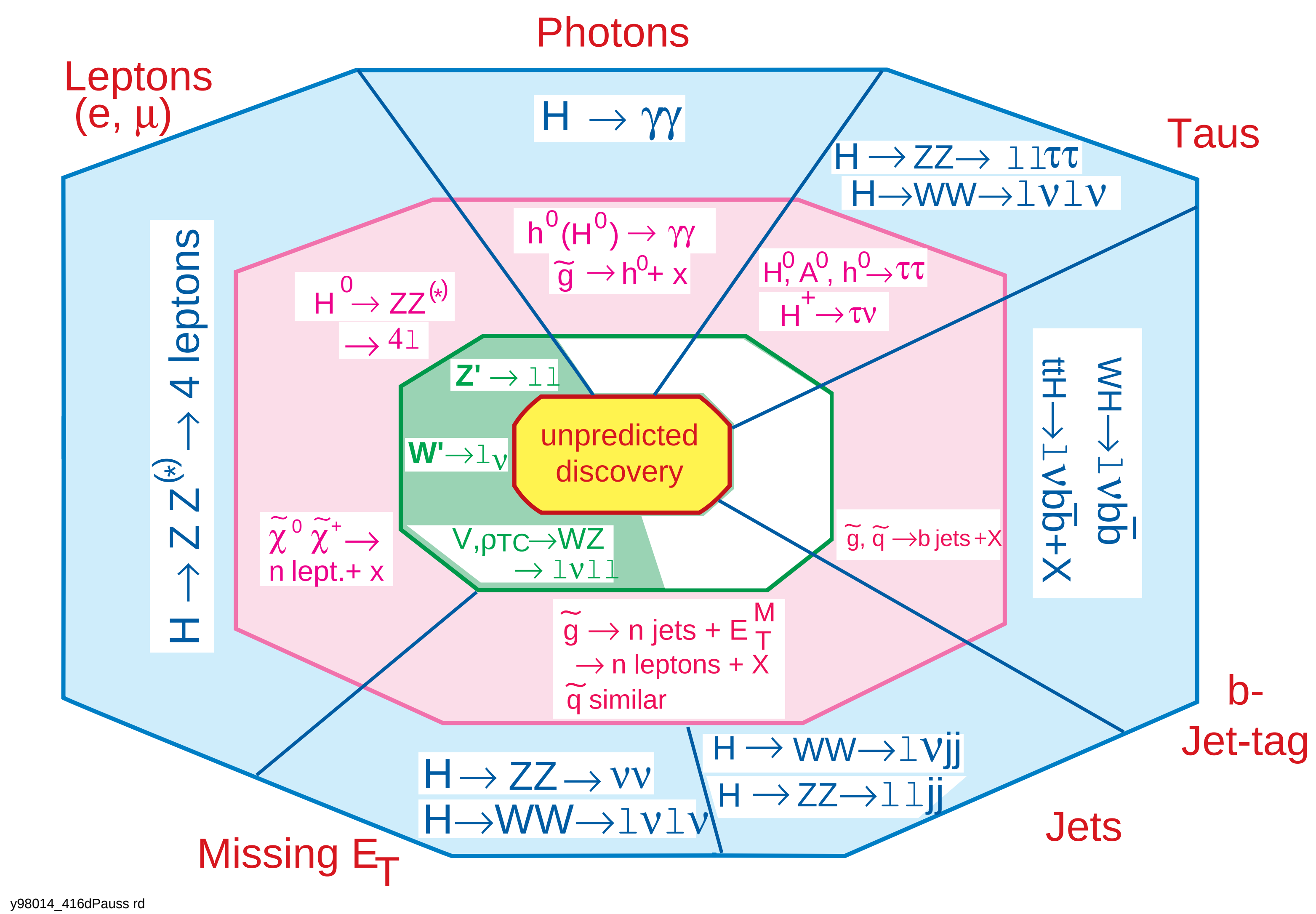
Distinctive decay products: (in high p_T)



Kinematical features:

- invariant mass of two-body $R \to ab:\ m_{ab}^2 = (p_a + p_b)^2 = M_R^2.$

  Jacobian peak in transverse momentum:

$$\frac{d\sigma(R \to ab)}{dp_T^2} \propto \frac{1}{(m_{ab}^2 - 4p_T^2)^{1/2}}.$$

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- cluster transverse mass of multi-body $H^0 \to W^+W^- \to e^+\nu_e\ e^-\bar{\nu}_e$:

$$\begin{aligned} m_{WW\ T}^2 &= (E_{e1T} + E_{e2T} + E_{\nu 1T} + E_{\nu 2T})^2 - (\vec{p}_{e1T} + \vec{p}_{e2T} + \vec{p}_{\nu 1T} + \vec{p}_{\nu 2T})^2 \\ &= (E_{e1T} + E_{e2T} + E_T^{miss})^2 - (\vec{p}_{e1T} + \vec{p}_{e2T} + \vec{p}_T^{\,miss})^2 \leq M_H^2. \end{aligned}$$

where $\vec{p}_T^{\,miss} = -\sum_{obs} \vec{p}_T^{\,obs}$.

Kinematical features:

- invariant mass of two-body $R \to ab$: $m_{ab}^2 = (p_a + p_b)^2 = M_R^2$.

  Jacobian peak in transverse momentum:

$$\frac{d\sigma(R \to ab)}{dp_T^2} \propto \frac{1}{(m_{ab}^2 - 4p_T^2)^{1/2}}.$$

- "transverse" mass of two-body $W^- \to e^- \bar{\nu}_e$:

$$\begin{aligned} m_{e\nu\ T}^2 &= (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \\ &= 2E_{eT}E_{\nu T}(1 - \cos\phi) \leq M_W^2. \end{aligned}$$

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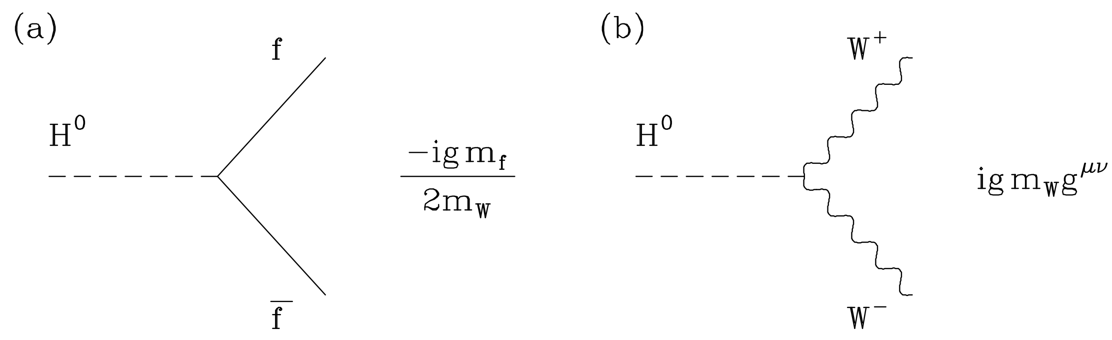
where $\vec{p}_T^{\ miss} = -\sum_{obs} \vec{p}_T^{\ obs}$.

YOU design an appropriate variable/observable for the search.

Higgs Searches at the Tevatron and the LHC:

The crucial features: Couplings proportional to masses.



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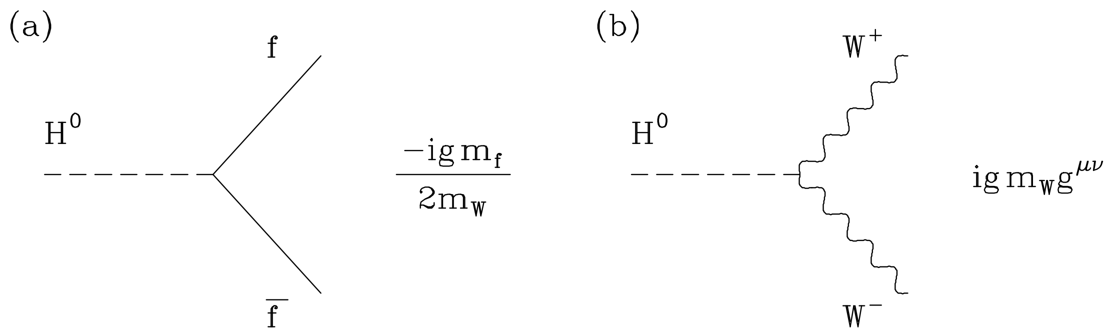
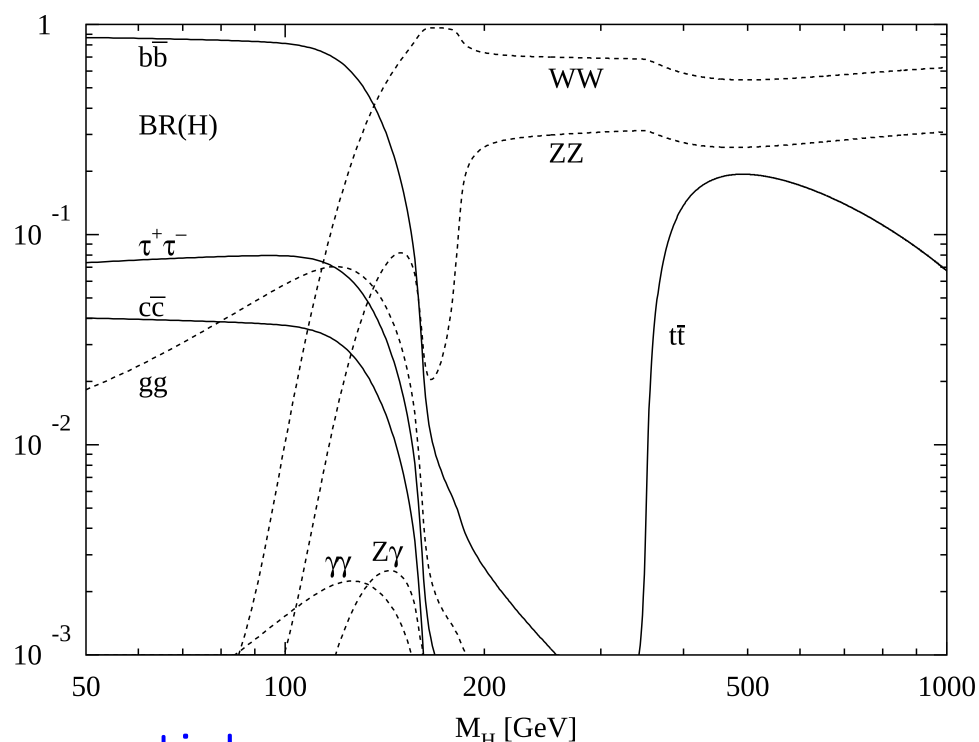
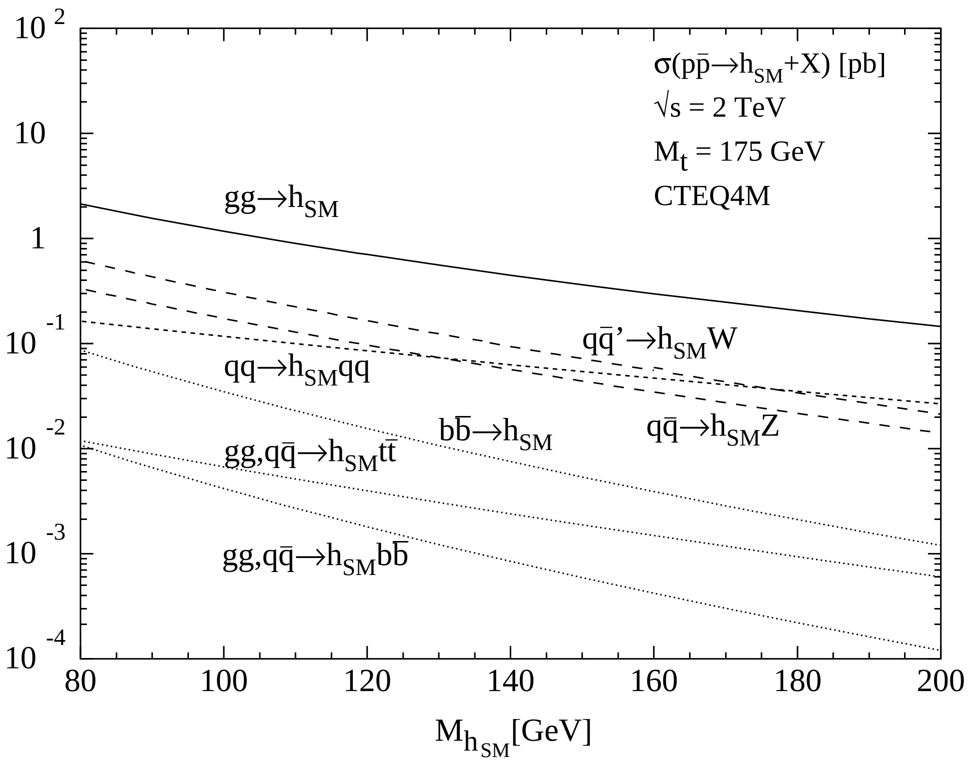


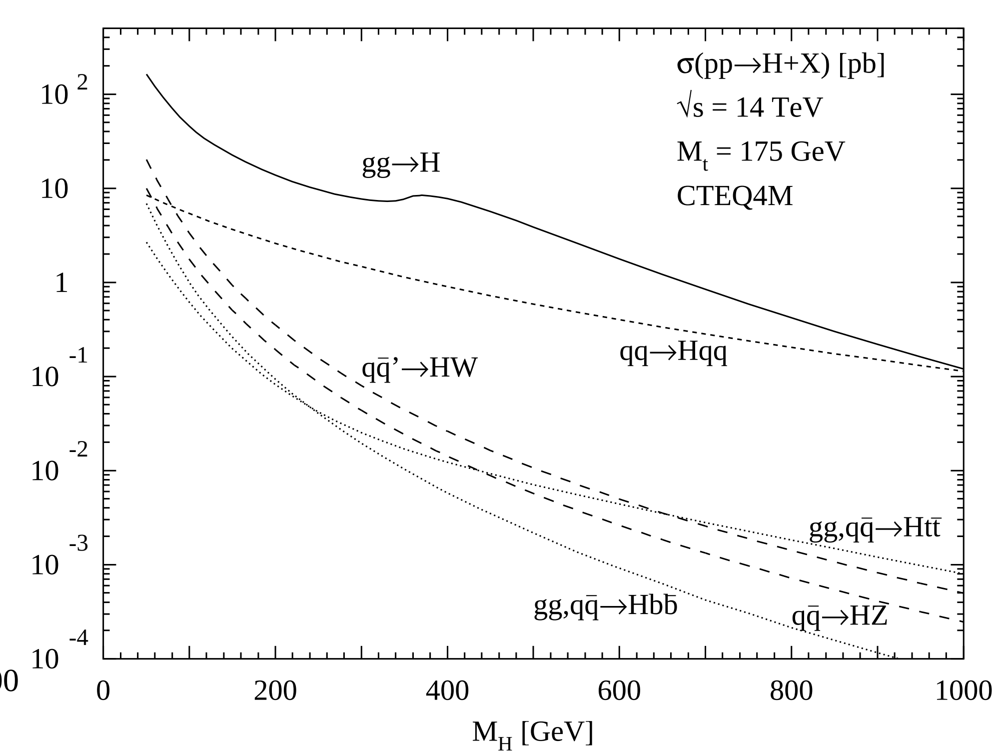
SM Higgs boson decay branching fractions:



preferably to heavier particles.

SM Higgs boson production rates:





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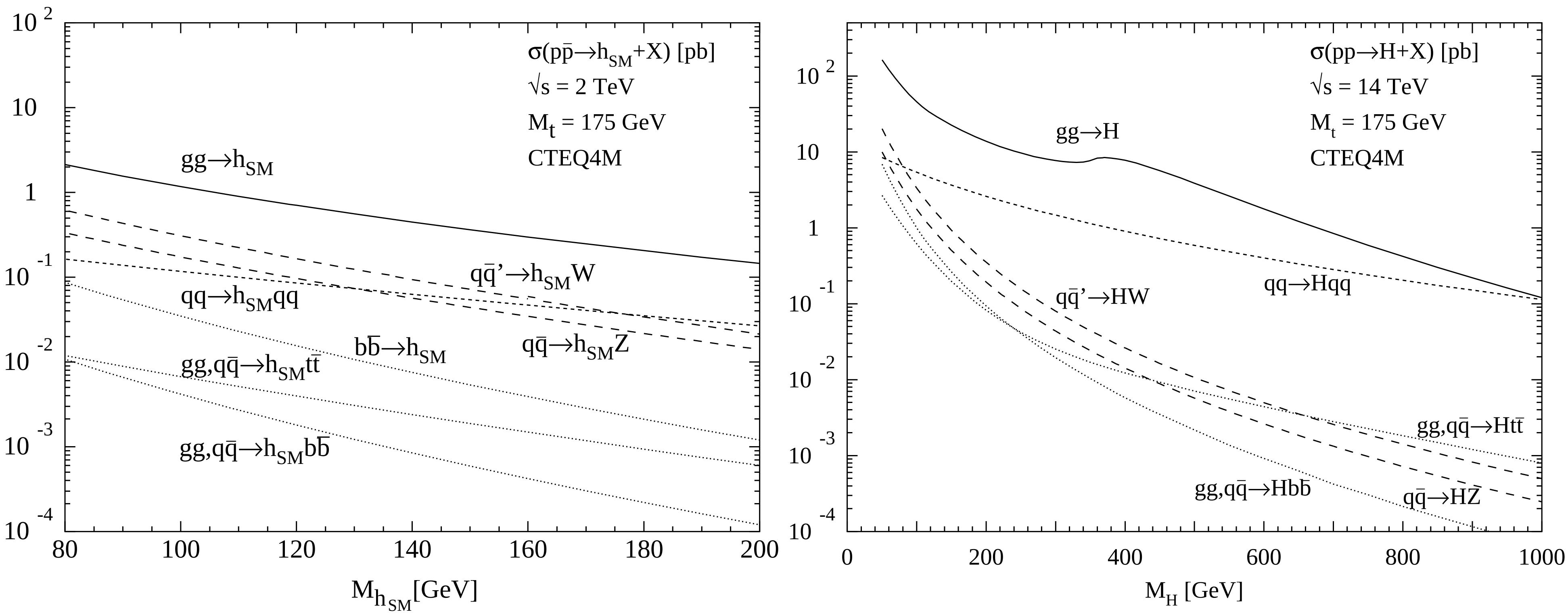
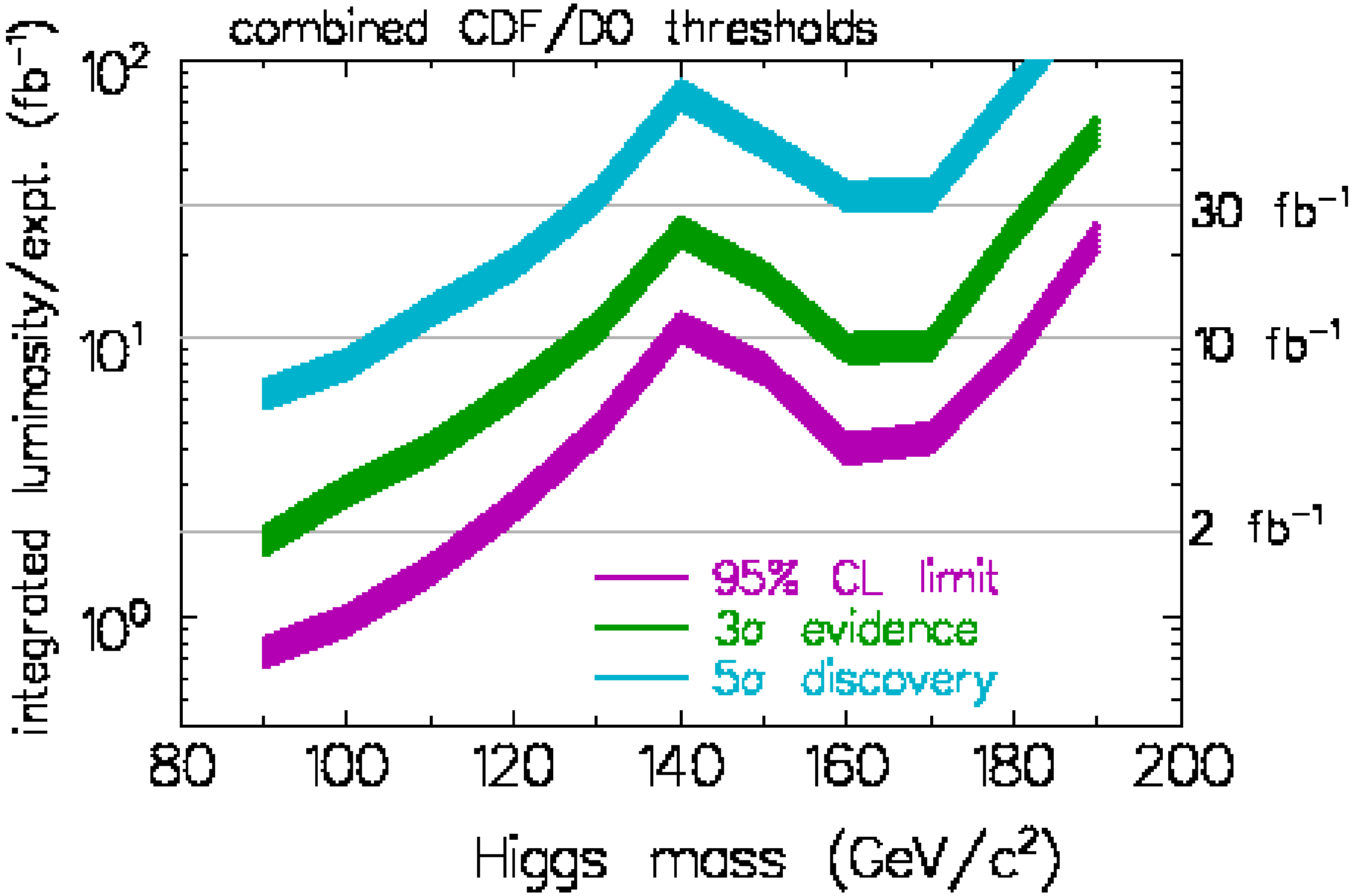


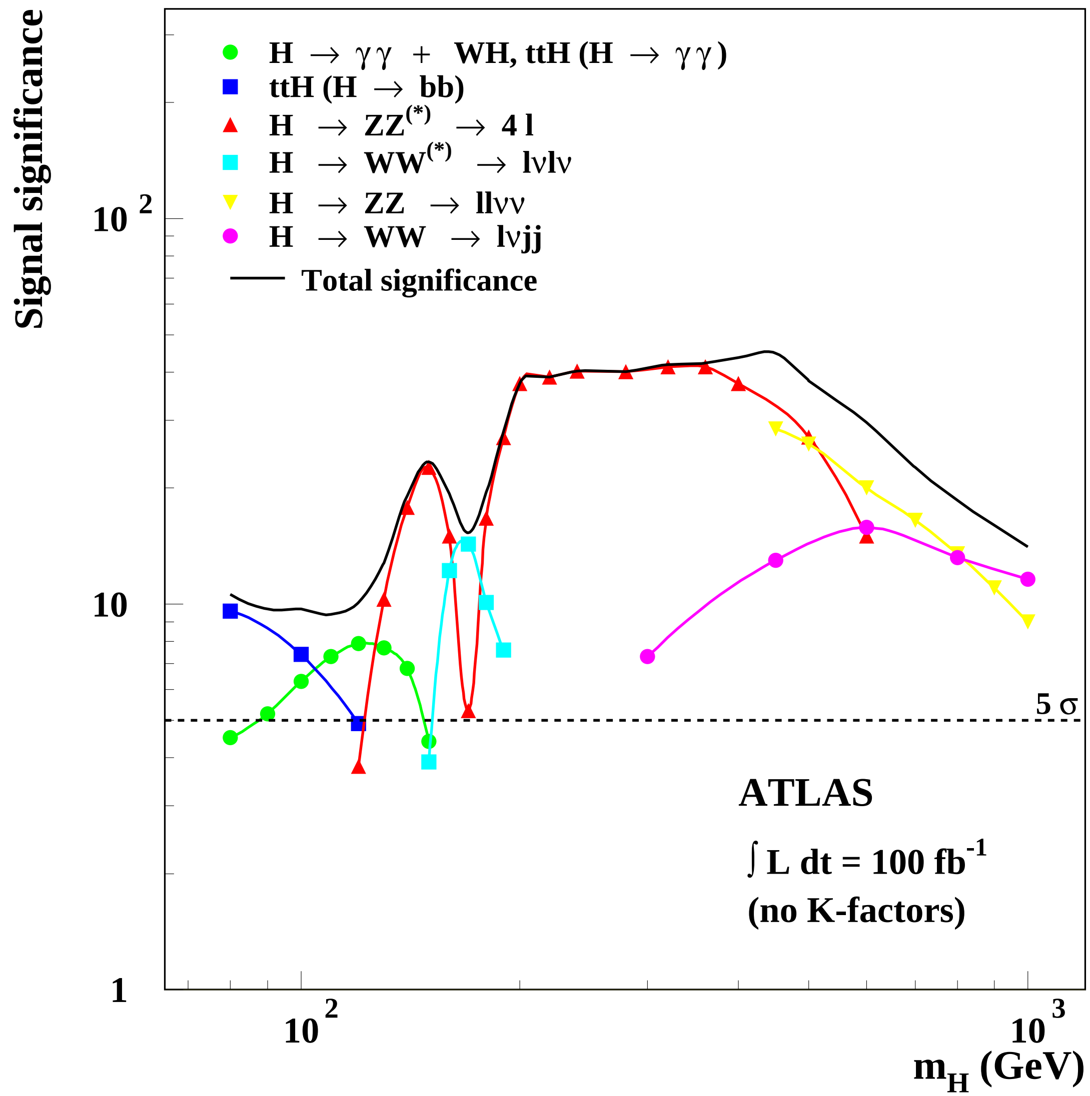
- At the Tevatron: hundreds of Higgs bosons may have been produced,
  for $m_h \lesssim 200$ GeV, 500 pb^{-1}.
- At the LHC: hundreds of thousand may be produce,
  for $m_h \lesssim 700$ GeV, 100 fb^{-1}.

- Higgs first shot at the Tevatron:

$$q\bar{q}' \to Wh,\ Zh, \quad h \to b\bar{b}$$
$$gg \to h, \quad h \to WW^*,\ ZZ^*,\ \tau^+\tau^-$$

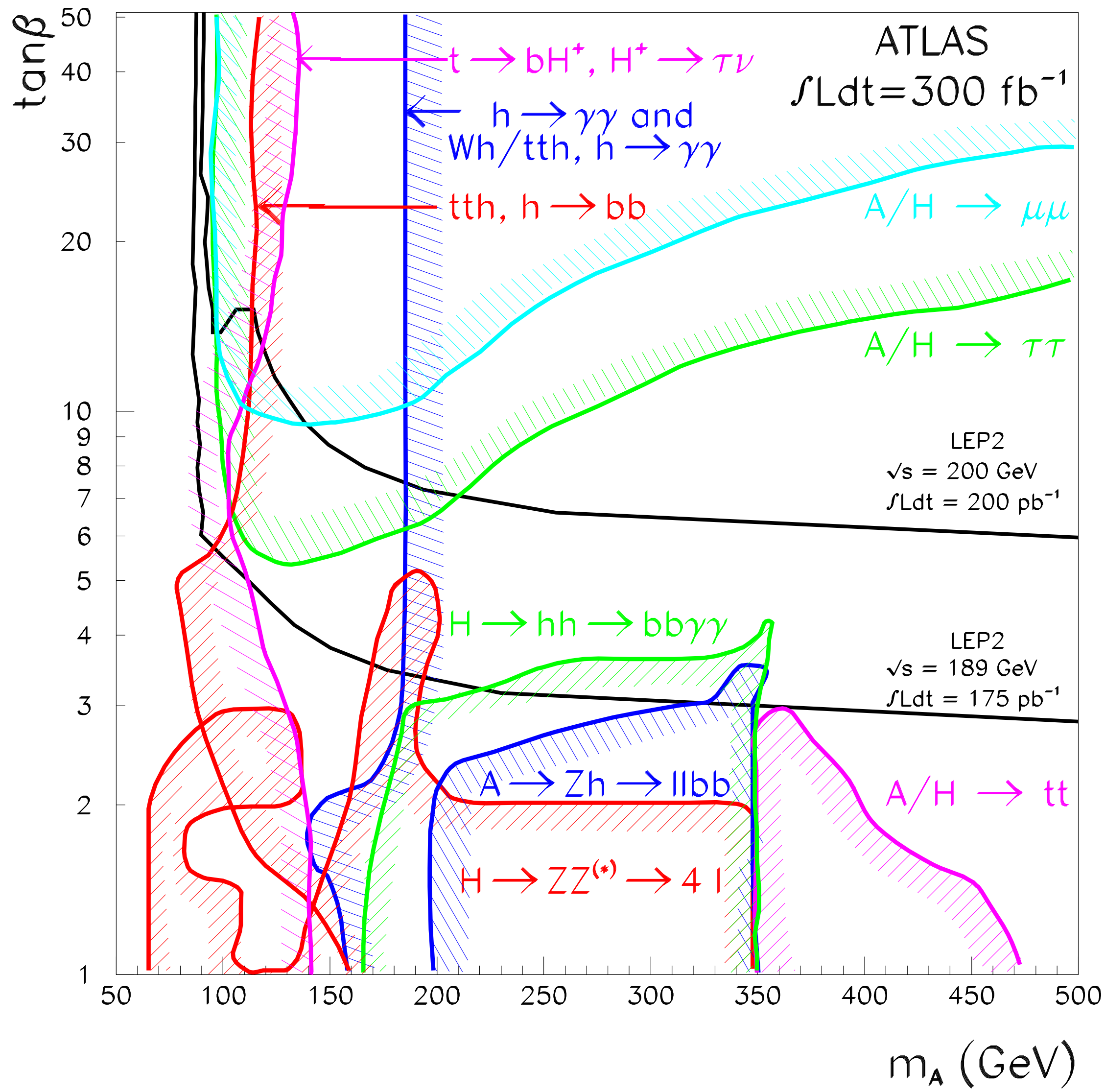


- SM Higgs fully covered at the LHC:



ATLAS report: combining multiple channels, 10σ observation achievable.

- SUSY Higgs fully covered at the LHC:



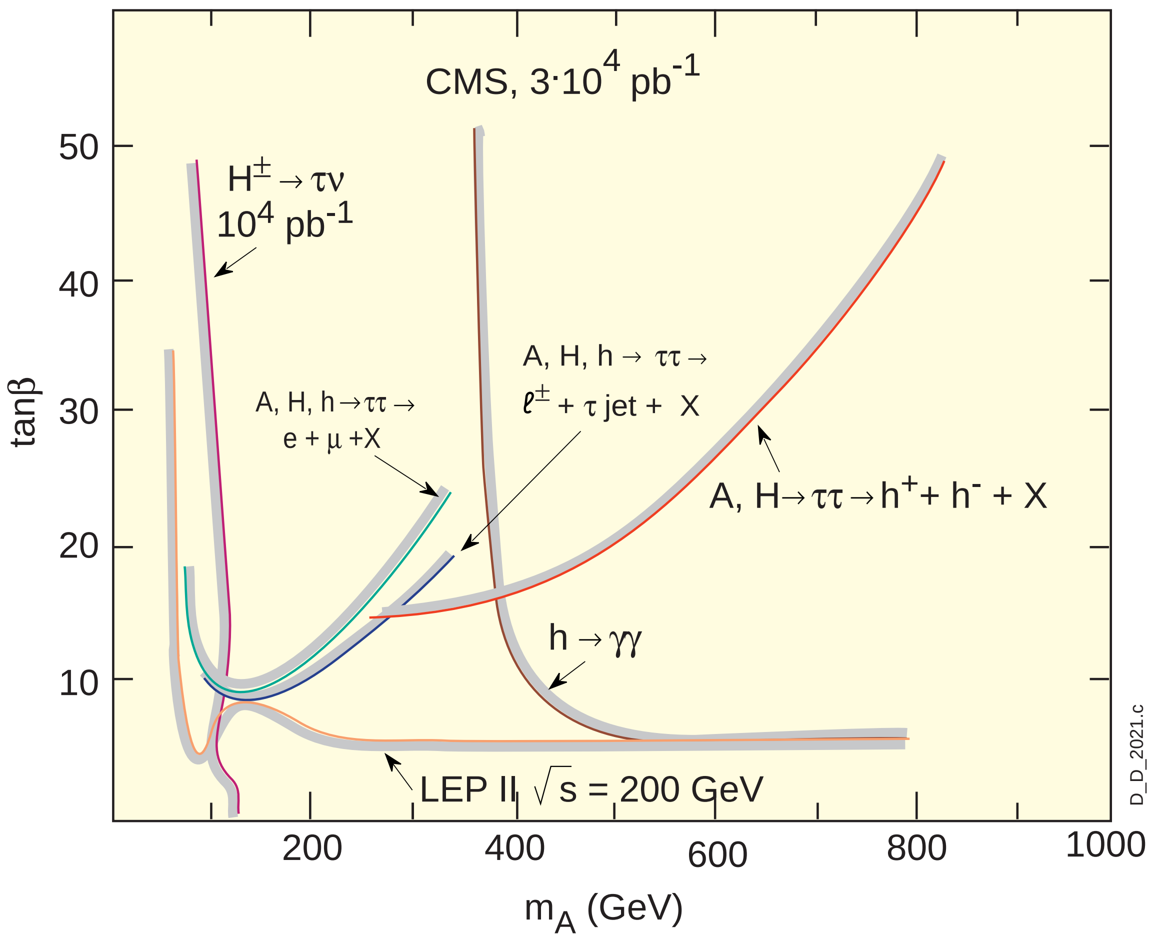
In MSSM, 5 Higgs bosons: h^0, H^0, A^0, $H^{\pm}$,

two independent parameters: $\tan\beta - M_A$.

Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

- 5 σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1 TeV, no stop mixing ;



Weak Scale Supersymmetry

- SUSY partners

particles	symbol	spin	mass param.
gluino	$\tilde{g}$	1/2	M_3
charginos	$\tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm}$	1/2	M_2
neutralinos	$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$	1/2	$M_1,\ \mu,\ B$ $m_{H_u}^2,\ m_{H_d}^2$
sleptons	$\tilde{e}_L,\ \tilde{\nu}_{e_L},\ \tilde{e}_R$ $\tilde{\mu}_L,\ \tilde{\nu}_{\mu_L},\ \tilde{\mu}_R$ $\tilde{\tau}_1, \tilde{\tau}_2,\ \tilde{\nu}_{\tau_L}$	0 0 0	$m_{\ell L}^2$ $m_{\ell R}^2$
squarks	$\tilde{u}_L,\ \tilde{d}_L,\ \tilde{u}_R, \tilde{d}_R$ $\tilde{c}_L, \tilde{s}_L,\ \tilde{c}_R, \tilde{s}_R$ $\tilde{t}_1,\ \tilde{t}_2,\ \tilde{b}_1, \tilde{b}_2$	0 0 0	$m_{q_L}^2$ $m_{q_R}^2$
Higgs	$h^0,\ H^0,\ A^0,\ H^{\pm}$	0	m_A^2, tan β

But where do they get their masses?

$\Rightarrow$ "soft" SUSY breaking

(many parameters put in by hand)

Also general Yukawa couplings

$A_{u,d,\ell}$, that lead to Sfermion mixings; CP phases etc.

R-parity violation couplings ...

- Parameter count in the SM and MSSM

model	masses and mixing ang.	CP-viol. phases	TOTAL
SM	17	2	19
MSSM	79	45	124
$(\mathrm{MSSM})_{BV}$	97	62	159
$(\mathrm{MSSM})_{LV}$	157	122	279
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Guidance and Assumptions:

Based on observation:

* Proton stability:

$\Rightarrow$ R-parity conservation; or B, L not broken simultaneously (in $1^{st}, 2^{nd}$ generations).

* No large CP-violation/FCNC:

$\Rightarrow$ no (or small) phases; sfermion mass degenerate (or heavy).

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Pure theoretical considerations:

* Gauge-coupling/Yukawa Unification:

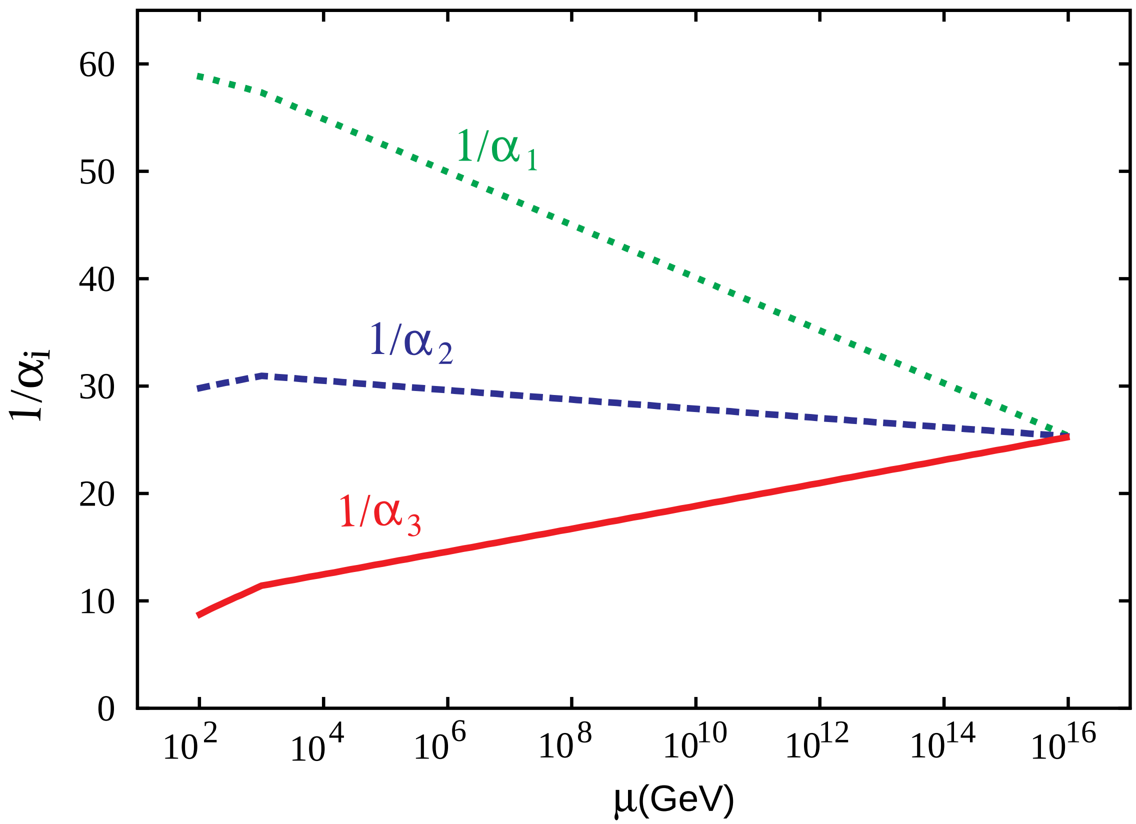
$\Rightarrow$ universal masses at the GUT scale

* radiative E.W.S.B.;

* LSP cold dark matter; ...

- Gauge coupling unification

$$\alpha_1 = \alpha_2 = \alpha_3 = \alpha_G \text{ at } \mathcal{O}(10^{16} \text{ GeV})$$

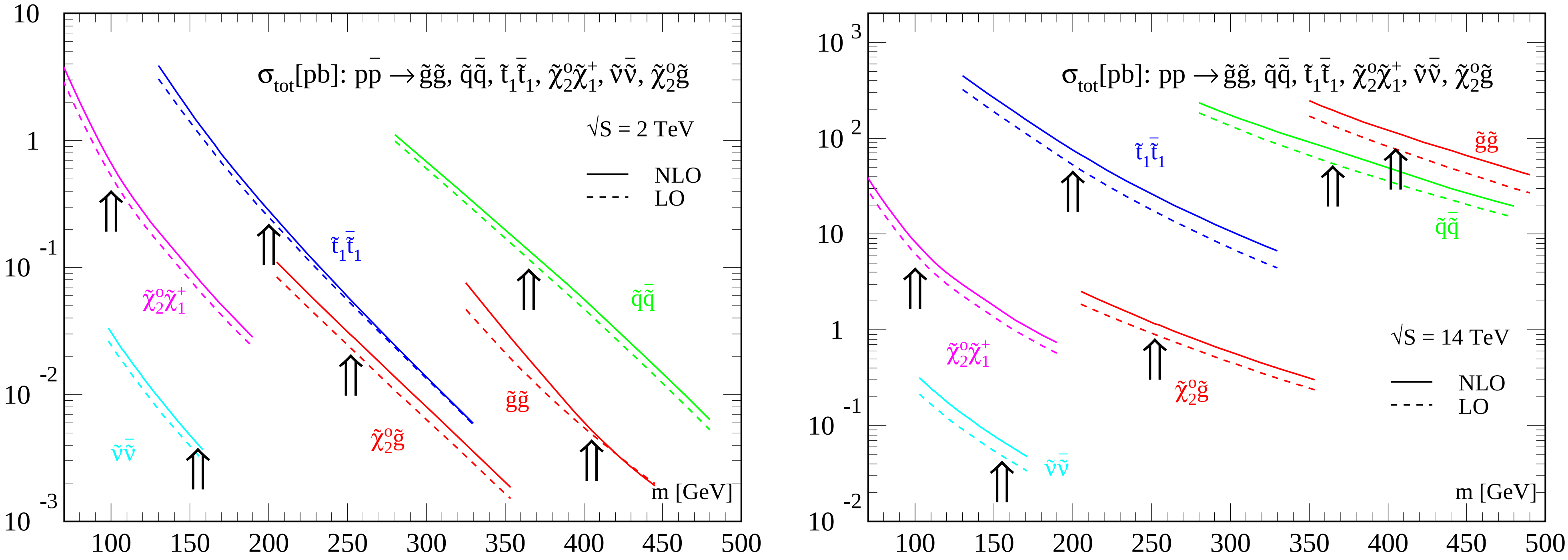


need the help of weak-scale SUSY threshold.

Hadron colliders can be a S-particle factory:

QCD production: $q\bar{q},\ gq,\ gg \to \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}.$

E.W. production: $q\bar{q} \to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^0,\ \tilde{\chi}_1^\pm\tilde{\chi}_2^0.$



Typically,

$$\sigma(Tevatron) \approx \mathcal{O}(0.1 - 1\text{ pb});\quad \sigma(LHC) \approx \mathcal{O}(10 - 100\text{ pb}).$$

New ball-game for signal searches:

The lightest SUSY particle (LSP $\tilde{\chi}_1^0$) is stable (R-parity), and nearly non-interacting (in detectors),

$\Rightarrow$ large missing energy is the characteristics;
difficult to reconstruct a mass peak for the sparticle.

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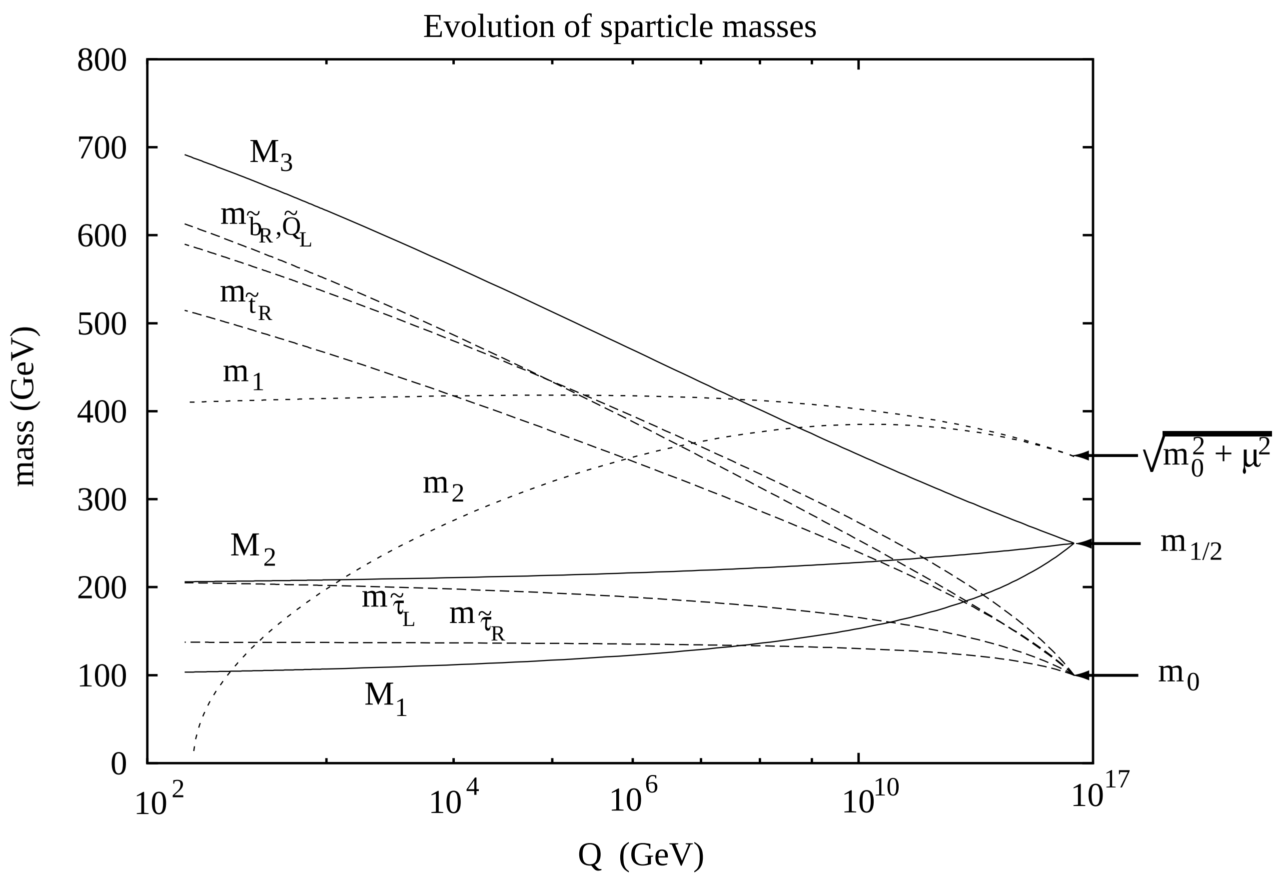
Details depend on the model...

- mSUGRA scenario: SUSY breaking near M_{GUT}.

Supergravity as messenger to transmit SUSY breaking effects.

$$m_0,\ m_{1/2},\ A,\ \tan\beta,\ \text{and}\ sign(\mu)$$



Sparticle decays:

$$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu, \quad \tilde{\chi}_1^0 q \bar{q}'$$

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-, \quad \tilde{\chi}_1^0 q\bar{q}$$

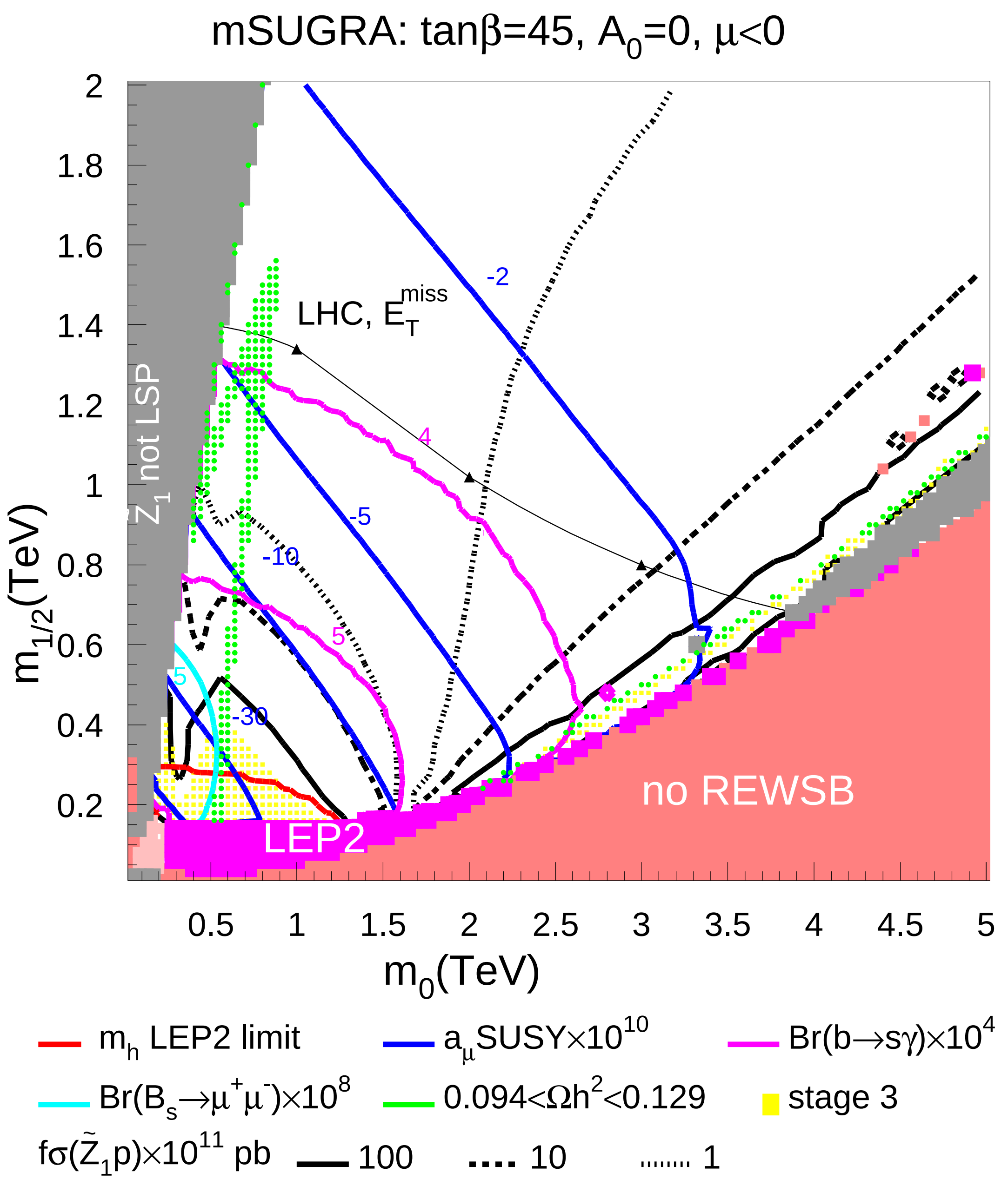
$$\tilde{g} \to \tilde{\chi}_2^0 q\bar{q}, \quad \tilde{g} \to \tilde{\chi}_1^+ \bar{q} q, \quad \tilde{g} \to \tilde{q}\bar{q},$$
$$\tilde{t}_1 \to \tilde{\chi}_1^0 t, \quad \tilde{t}_1 \to \tilde{\chi}_2^0 t, \quad \tilde{t}_1 \to \tilde{\chi}_1^+ b.$$

Generically, $\tilde{\chi}_1^0$ leads to missing energy signal:

"missing $\not\!\!E_T$ plus jets": $\not\!\!E_T$+jets

"dilepton plus missing $\not\!\!E_T$" $\ell\ell + \not\!\!E_T \quad (\pm\pm \ \ or \ \ +-)$

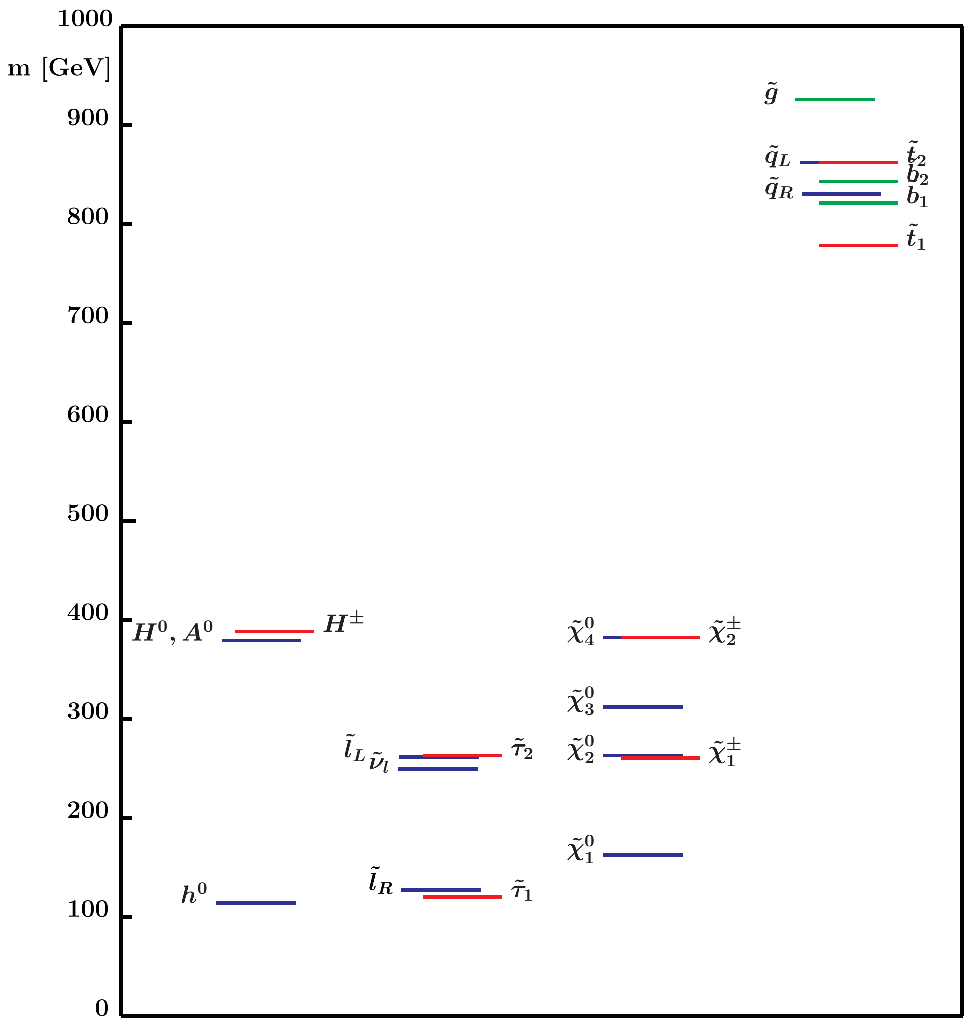
"trilepton plus missing $\not\!\!E_T$" $\ell\ell\ell + \not\!\!E_T$



LHC: $m_0 > 4000$ GeV, $m_{1/2} > 1400$ GeV, $\tan\beta \gtrsim 45$.

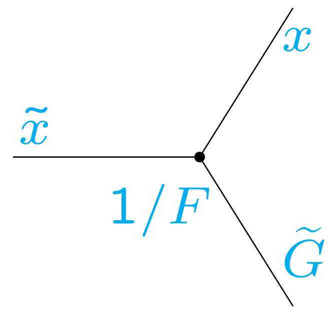
- Gauge mediation scenario: SUSY breaking at $\Lambda \sim 10 - 100$ TeV, Gauge interactions as messengers to mediate SUSY breaking effects.

Λ, M, $\tan\beta$, and N_M



Squarks and gluinos are typically heavier; Gravitino $\widetilde{G}$ LSP.

The NLSP dominates phenomenology:



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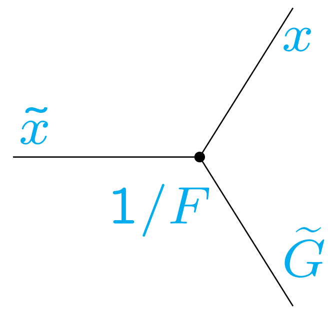
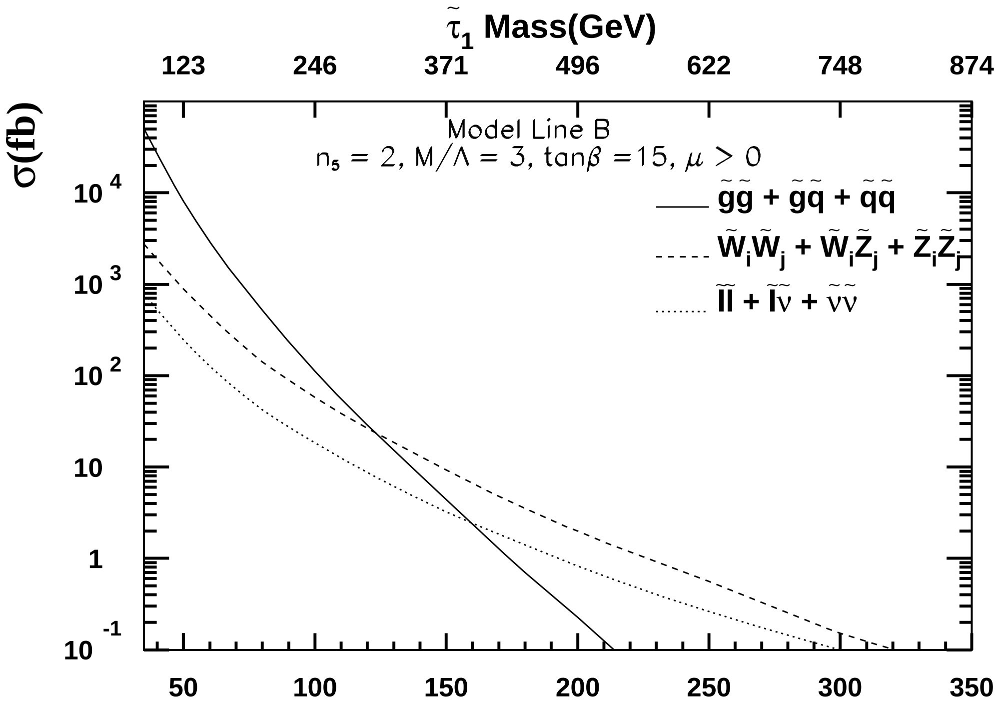


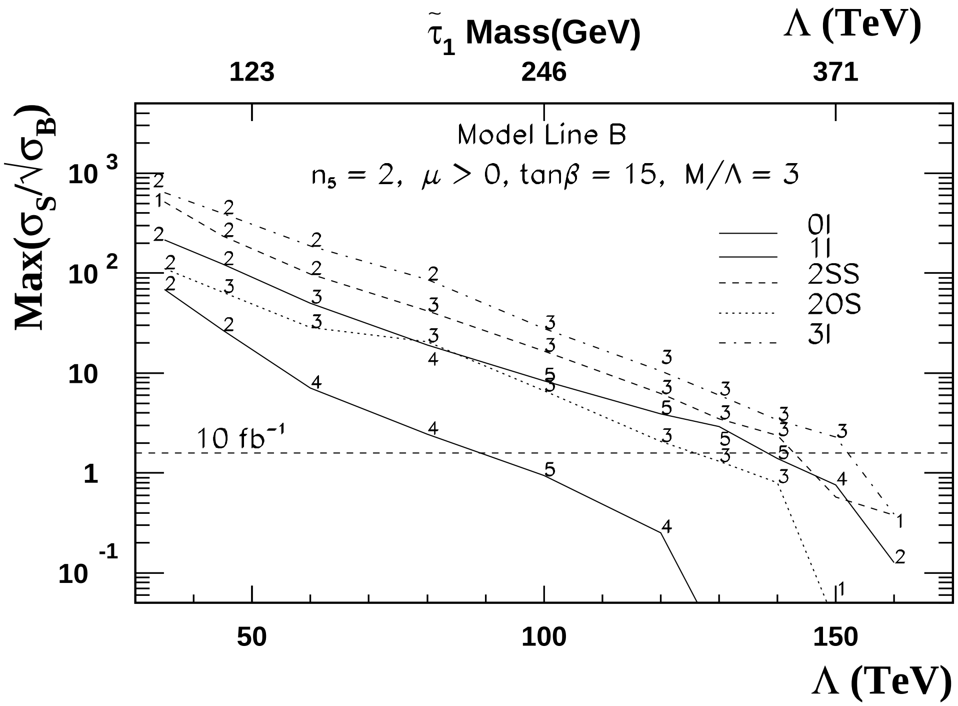
NLSP	Decay to the $\widetilde{G}$
Bino-like Neutralino	$\tilde{\chi}^0_1 \to \gamma\ \widetilde{G}$
Higgsino-like Neutralino	$\tilde{\chi}^0_1 \to (h, Z, \gamma)\ \widetilde{G}$
Stau	$\tilde{\tau} \to \tau\ \widetilde{G}$
Slepton Co-NLSP	$\tilde{\ell} \to \ell\ \widetilde{G}$
Squark	$\tilde{q} \to (q, q'W)\ \widetilde{G}$
Gluino	$\tilde{g} \to g\ \widetilde{G}$

$$c\tau(\tilde{x} \to x\widetilde{G}) \approx 100\ \mu\text{m} \left(\frac{100\ \text{GeV}}{m_{\tilde{x}}}\right)^5 \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4 .$$

could lead to a displaced vertex in decay, or quasi-stable charged track.

LHC reach:


$\tilde{\tau}_1$ Mass(GeV)
123
246
371
496
622
748
874
σ(fb)
Model Line B
n_5 = 2, M/Λ = 3, tanβ =15, μ > 0
$\tilde{g}\tilde{g} + \tilde{g}\tilde{q} + \tilde{q}\tilde{q}$
$\tilde{W}_i\tilde{W}_j + \tilde{W}_i\tilde{Z}_j + \tilde{Z}_i\tilde{Z}_j$
$\tilde{l}\tilde{l} + \tilde{l}\tilde{\nu} + \tilde{\nu}\tilde{\nu}$
10^4
10^3
10^2
10
1
10^{-1}
50
100
150
200
250
300
350
Λ (TeV)


$\tilde{\tau}_1$ Mass(GeV)
123
246
371
$Max(\sigma_S/\sqrt{\sigma_B})$
Model Line B
n_5 = 2, μ > 0, tanβ = 15, M/Λ = 3
0l
1l
2SS
2OS
3l
10 fb^{-1}
10^3
10^2
10
1
10^{-1}
50
100
150
Λ (TeV)

New gauge bosons and heavy fermions

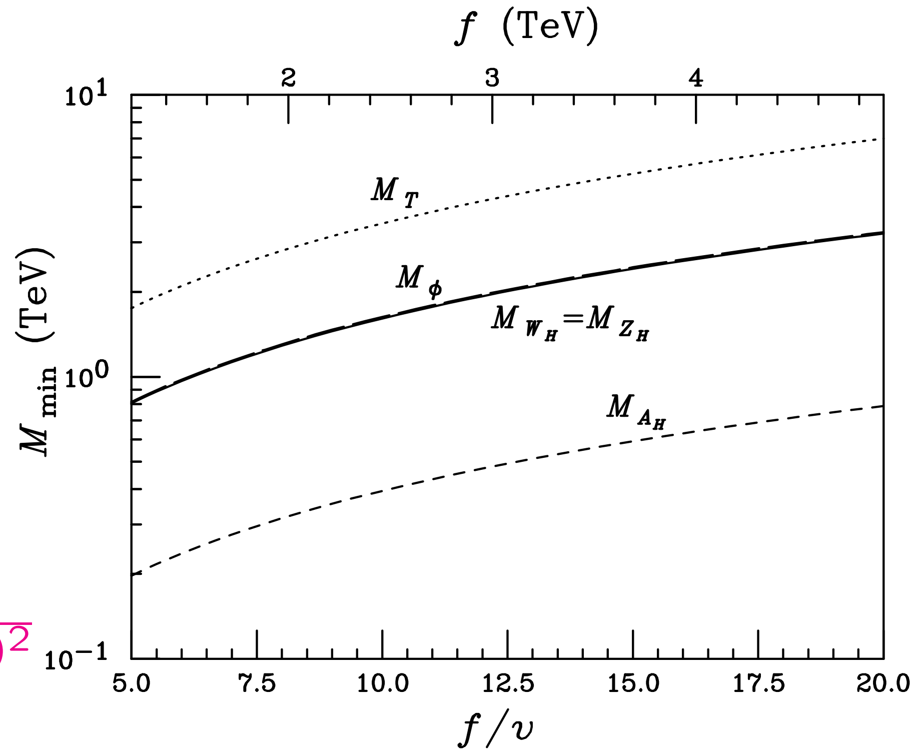
New gauge bosons and heavy fermions

Little Higgs models as an example

In the Littlest Higgs model:*

Heavy particles	Mass
A_H	$m_z^2 s_W^2 \frac{f^2}{5s'^2c'^2v^2}$
Z_H	$m_W^2 \frac{f^2}{s^2c^2v^2}$
W_H	$m_W^2 \frac{f^2}{s^2c^2v^2}$
$\phi^{0,\ \pm,\ \pm\pm}$	$\frac{2m_H^2 f^2}{v^2} \frac{1}{1-(4v'f/v^2)^2}$
T	$\sqrt{\lambda_1^2+\lambda_2^2}\ f$

(where $m_W = gv/2$.)

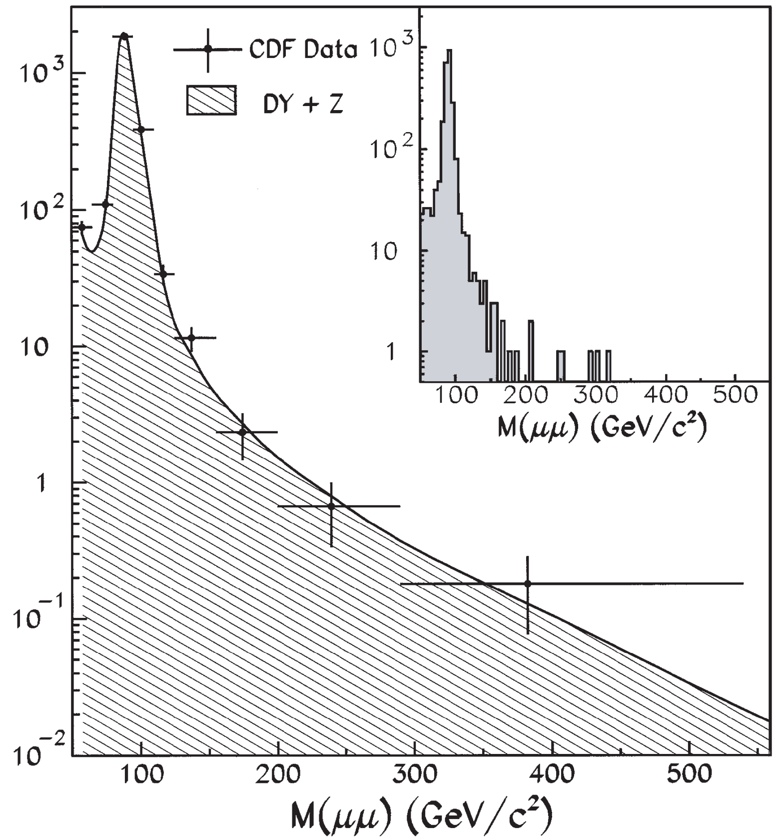


*Arkani-Hamed, Cohen, Katz, Nelson, hep-ph/0206021.

$\tan\theta = \frac{s}{c} = \frac{g_2}{g_1}$	New $SU(2)$ gauge coupling (or equivalently mixing angle θ)
$\tan\theta' = \frac{s'}{c'} = \frac{g'_2}{g'_1}$	New $U(1)$ gauge coupling (or equivalently mixing angle θ')
f	Symmetry breaking scale $\mathcal{O}$(TeV)
v'	Triplet ϕ vacuum expectation value, $v'/v \lesssim v/4f$
m_H	Regular SM Higgs mass
M_T	Heavy vector top mass, we trade λ_2 for M_T

• New gauge bosons in DY process:

Recall CDF searches for a $Z' \to \mu^+\mu^-$: [PRL 79, (1997)]



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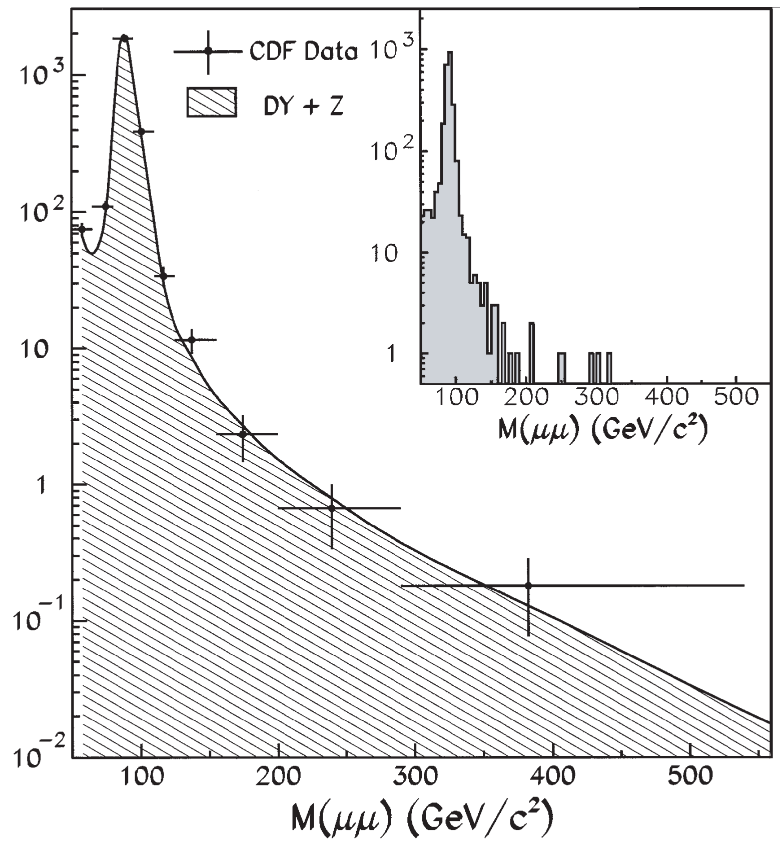

including:

$$p\bar{p} \to Z, \gamma \to \mu^+\mu^- X,$$
$$p\bar{p} \to W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu X,$$
$$p\bar{p} \to b\bar{b} \to \mu^+\mu^- + hadrons + X,$$
$$p\bar{p} \to t\bar{t} \to W^+b\ W^-\bar{b} \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu b\bar{b}\ X.$$

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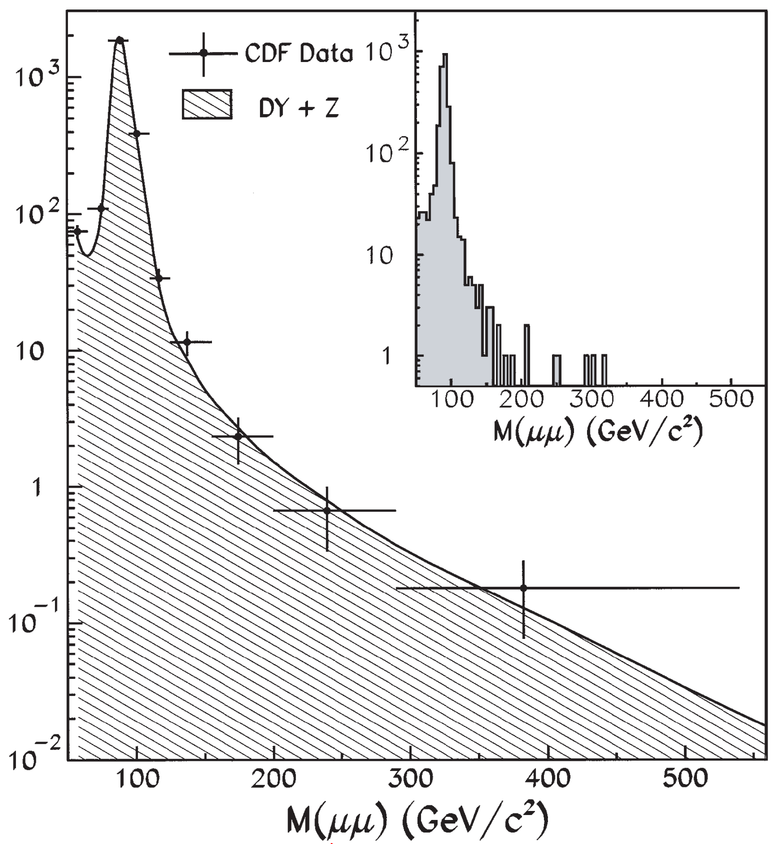

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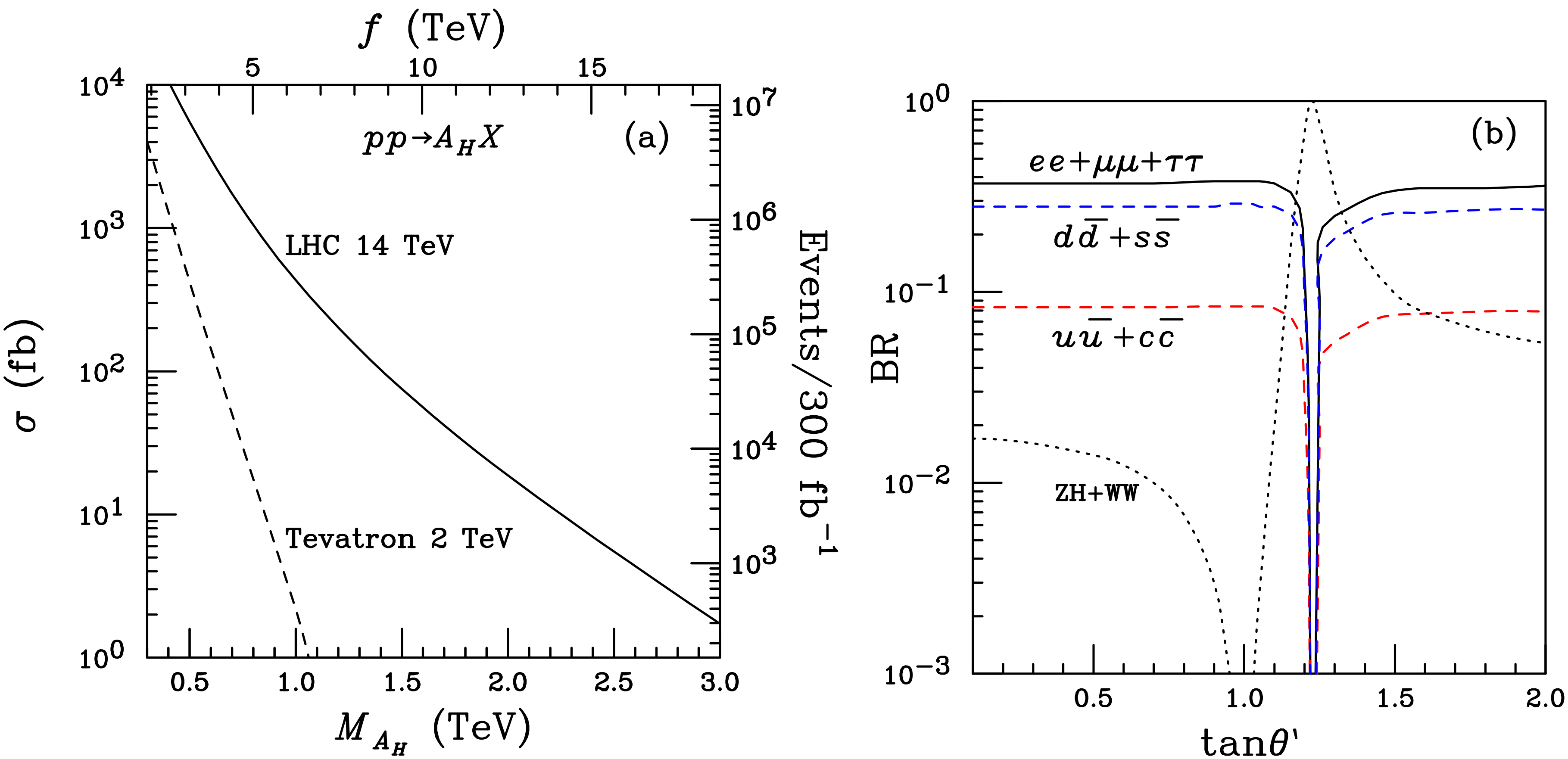
$\sigma <$ 40 fb $\Rightarrow$ $M_{Z'} >$ 600 GeV.

- A_H should be the lightest new state;
- large DY production $A_H \to \ell^+\ell^-$ $(\ell = e, \mu)$



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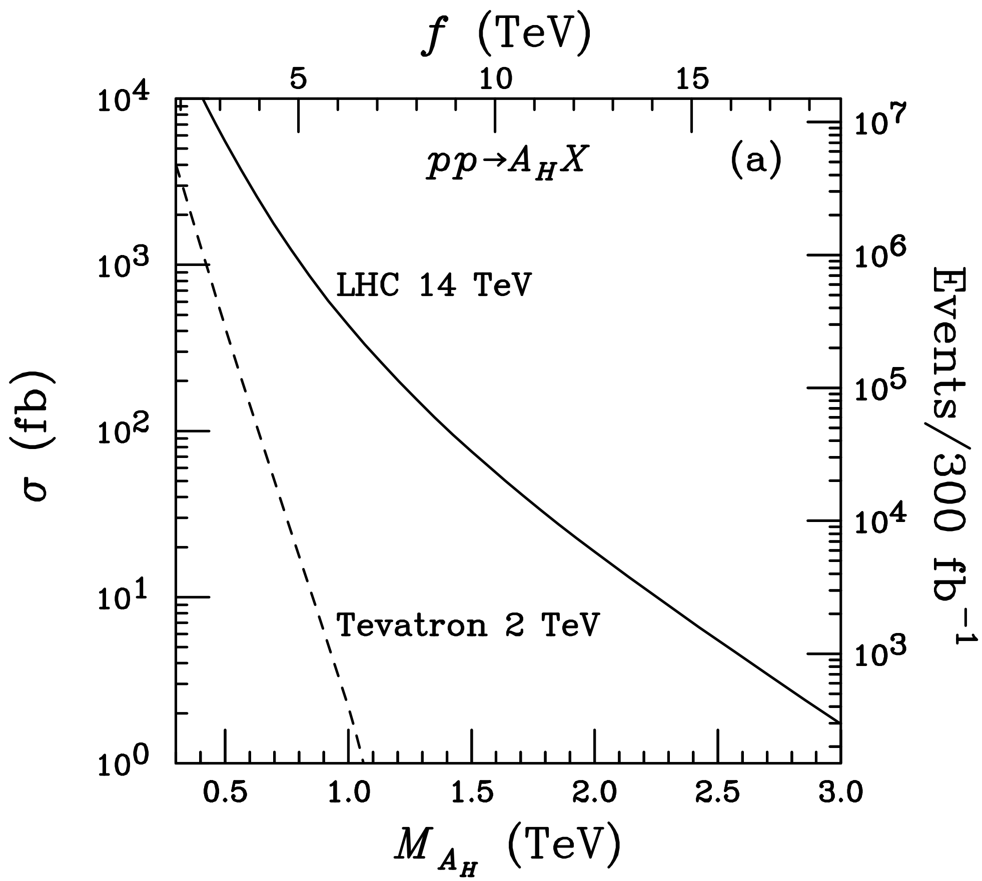
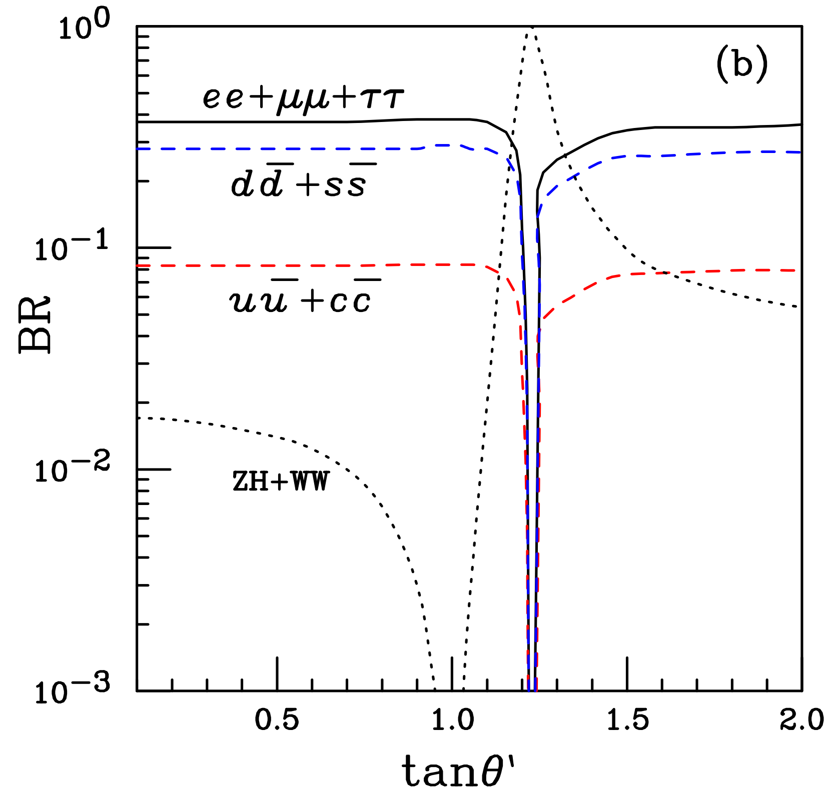
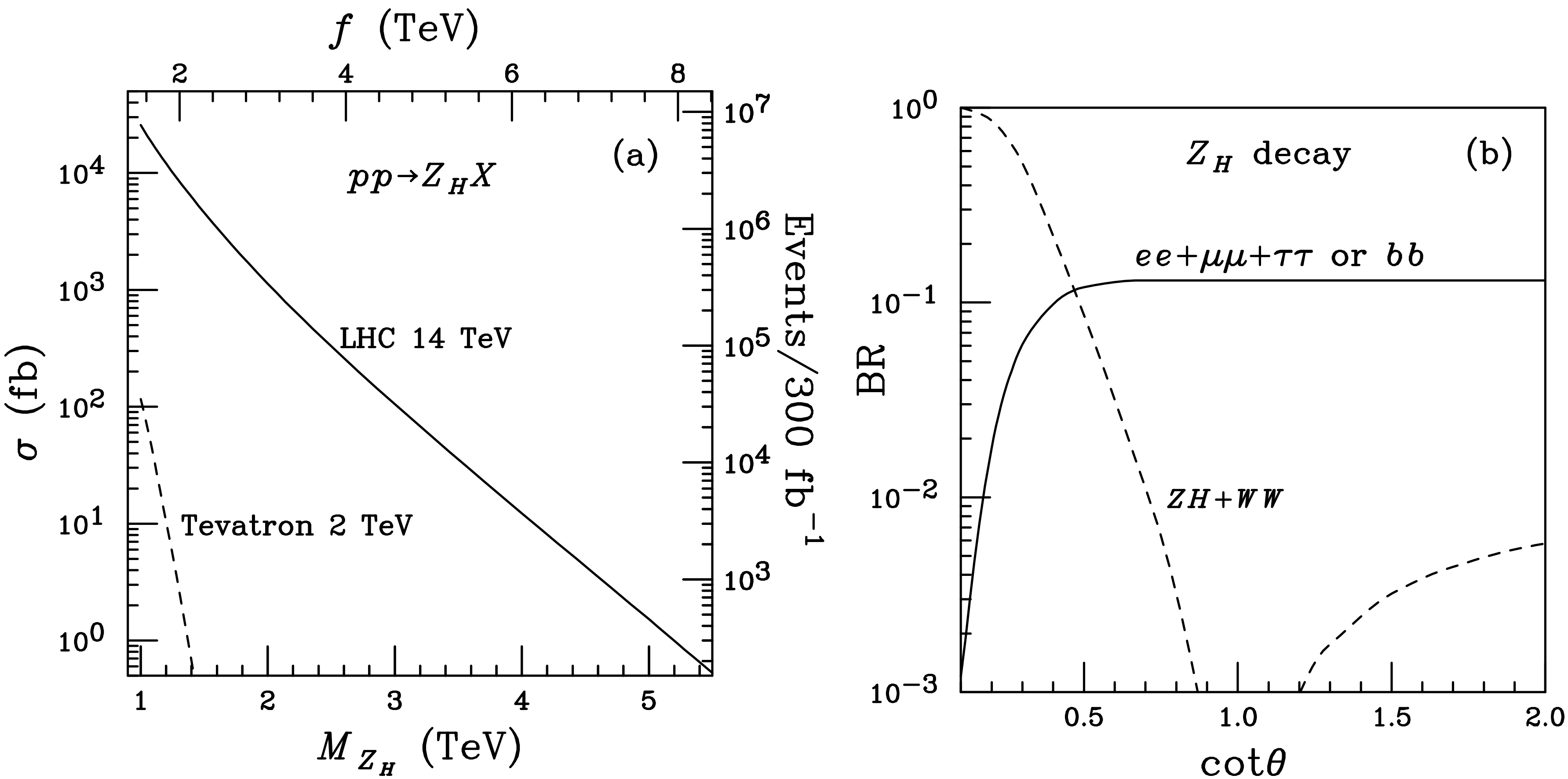




Tevatron: $M_{A_H} > 0.5$ TeV or $f > 3$ TeV;

LHC: $M_{A_H} \sim 3$ TeV or $f \sim 18$ TeV.

- Z_H/W_H rebust new state
- DY production rate large



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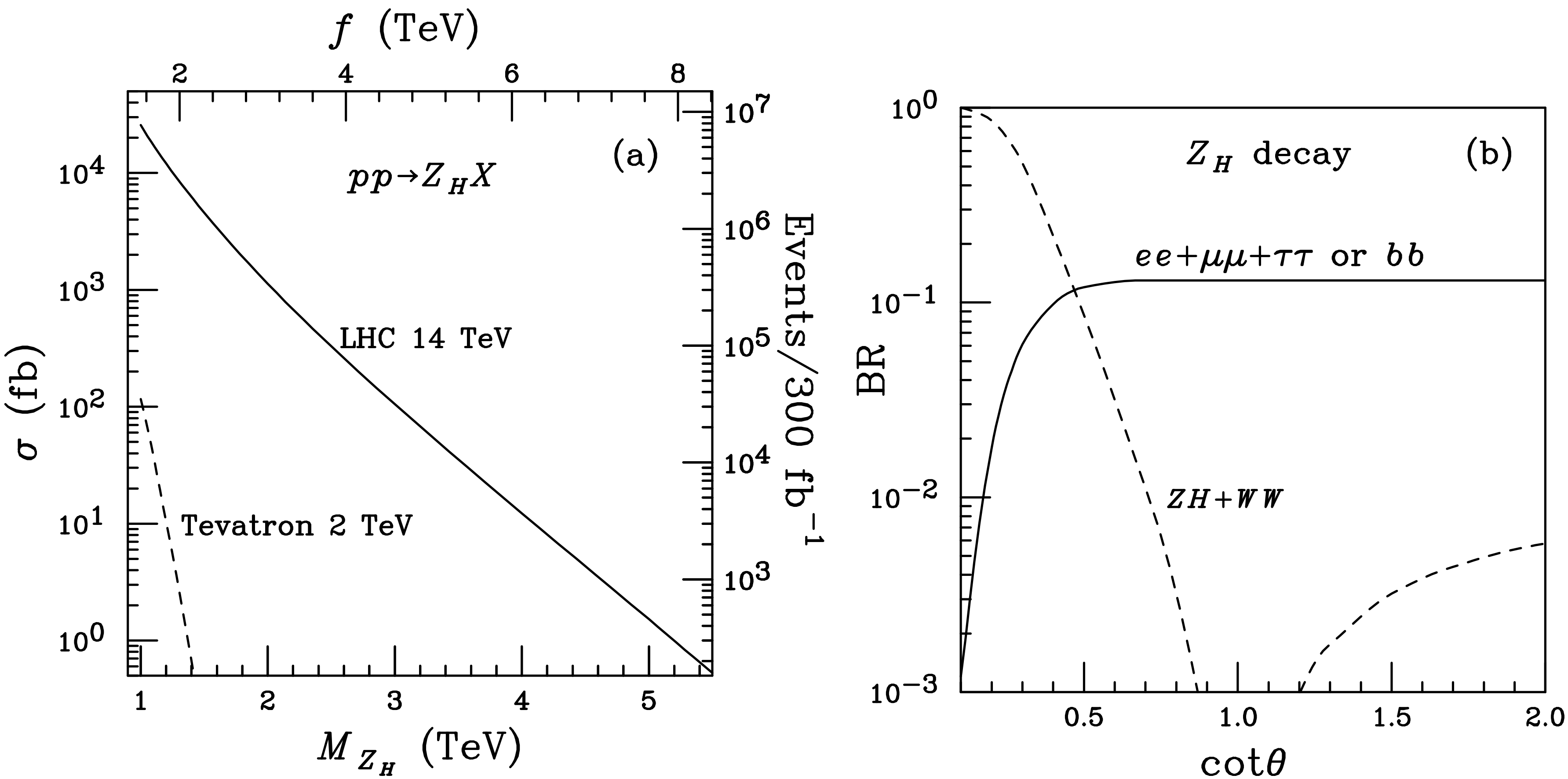
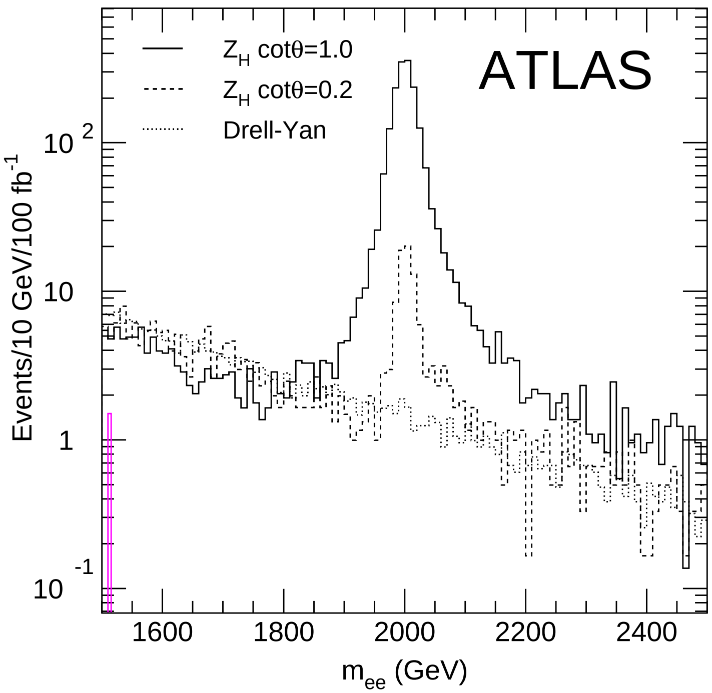
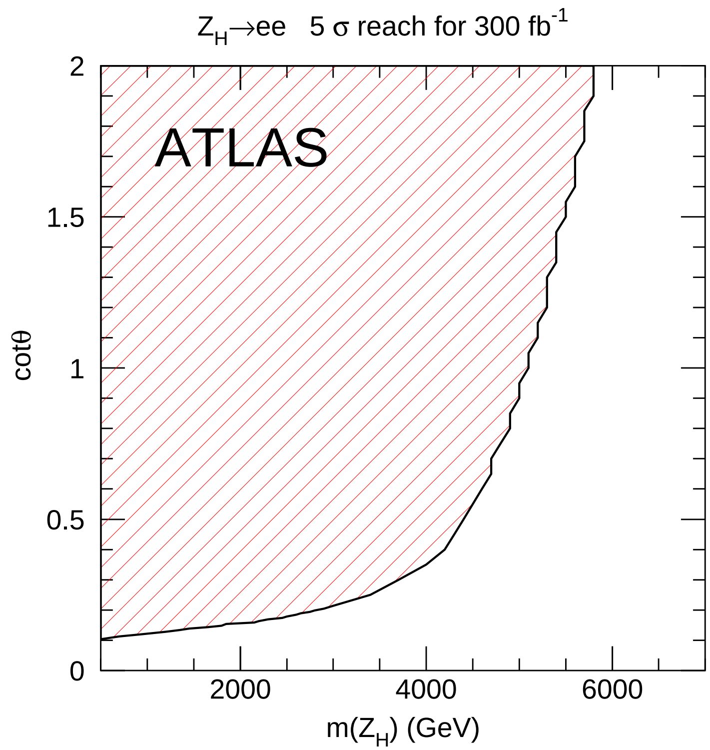


Tevatron: not quite accessible (except for A_H);
LHC: $M_{Z_H} \sim 5$ TeV or $f \sim 8$ TeV.

ATLAS simulations for $Z \rightarrow \ell^+\ell^-$:





Reach $M_{Z_H} \sim$ several TeV for $\cot\theta > 0.1$:

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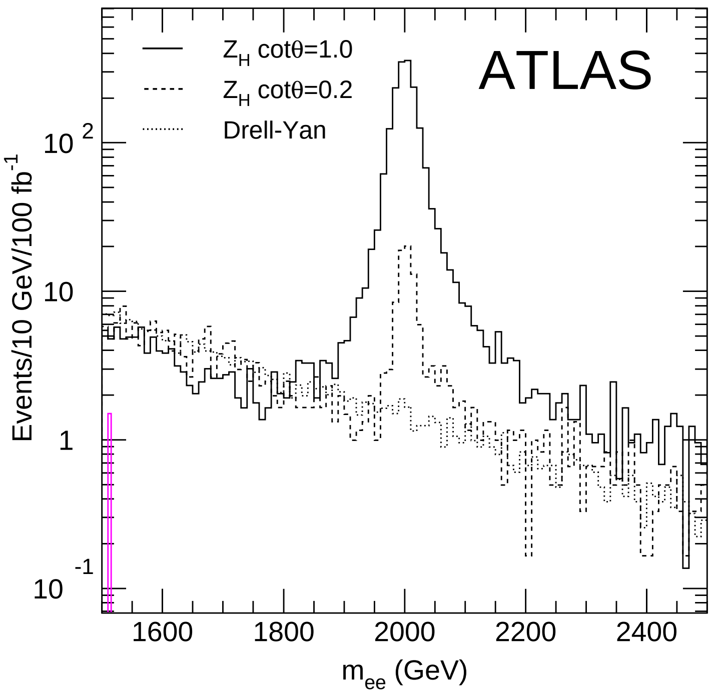
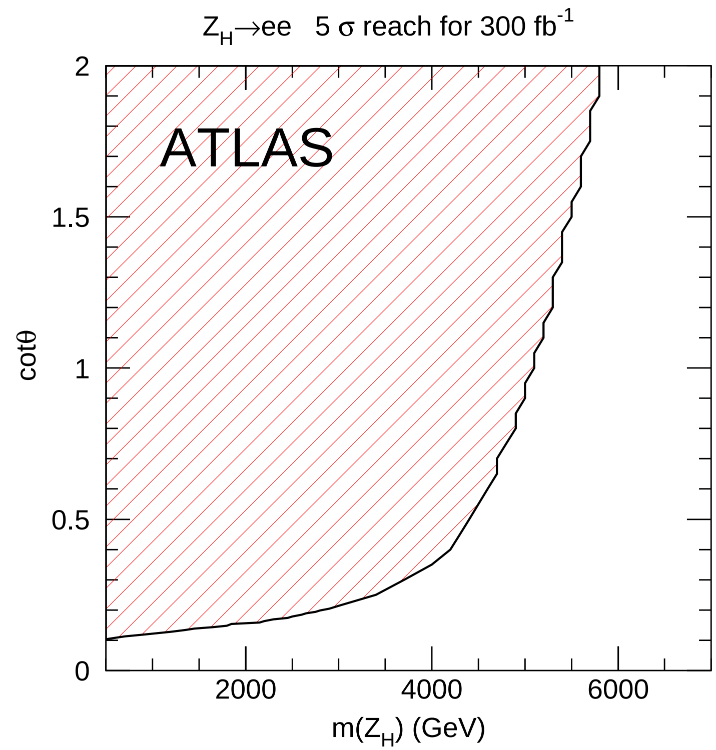


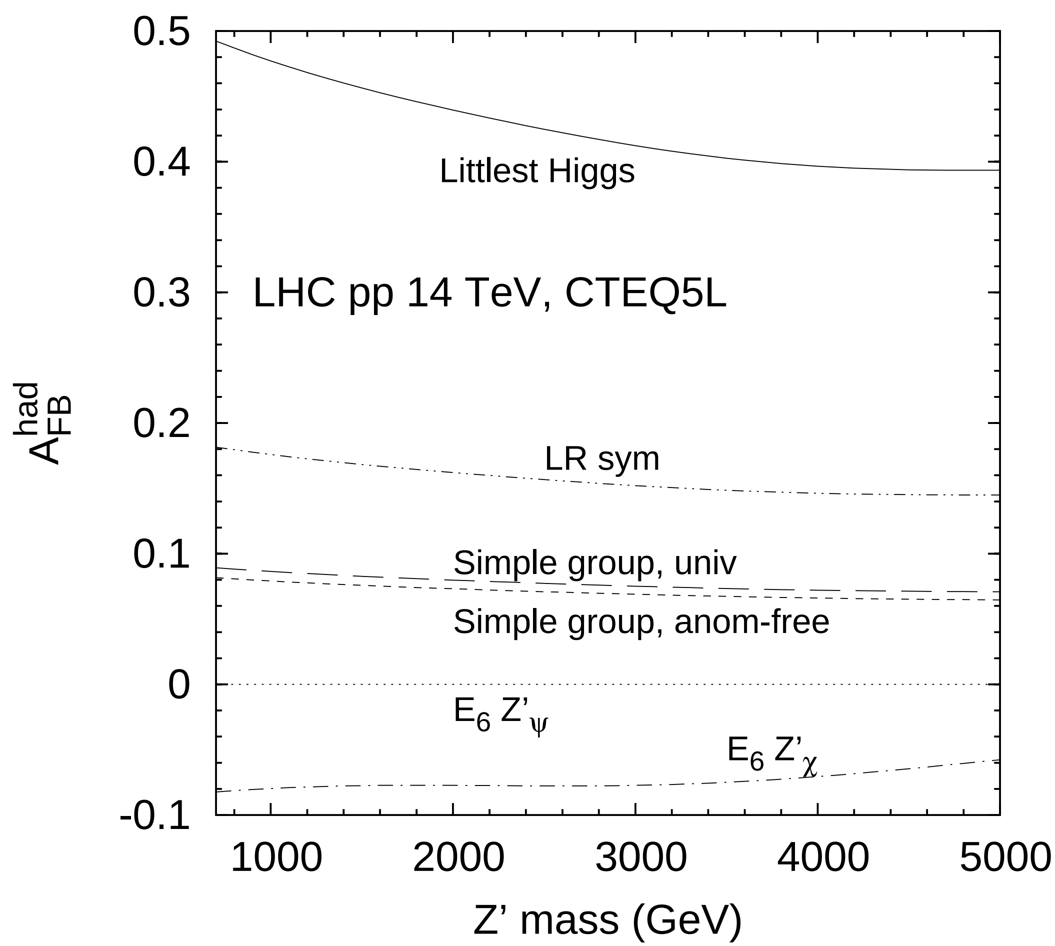


Reach $M_{Z_H} \sim$ several TeV for $\cot\theta > 0.1$:
Cross-sectiions measure $\cot\theta$: $N(\ell^+\ell^-)$ versus $N(Zh)$.
Mass peak M_{Z_H} determines f.

Significant differences for FB asymmetry among Z's:

$$A_{FB}^{i,f} = \frac{3}{4} A_i A_f, \quad A_i = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}.$$

$$A_{FB}^{\mathrm{had}} = \frac{\int dx_1 \sum_{q=u,d} A_{FB}^{qe} \left(F_q(x_1) F_{\bar{q}}(x_2) - F_{\bar{q}}(x_1) F_q(x_2)\right) \mathrm{sign}(x_1 - x_2)}{\int dx_1 \sum_{q=u,d,s,c} \left(F_q(x_1) F_{\bar{q}}(x_2) + F_{\bar{q}}(x_1) F_q(x_2)\right)},$$



• Heavy quark signals:

Recall the top-quark searches at hadron colliders

The leading production channels:

$$q\bar{q} \to t\bar{t}, \quad \text{Tevatron 90\%; LHC 10\%}$$
$$gg \to t\bar{t}, \quad \text{Tevatron 10\%; LHC 90\%}$$
$$\text{with } t\bar{t} \to W^+ b\ W^- \bar{b} \to ...$$

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$qb \to q'W^{*}b \to q'\ t$ 1/3 of QCD.

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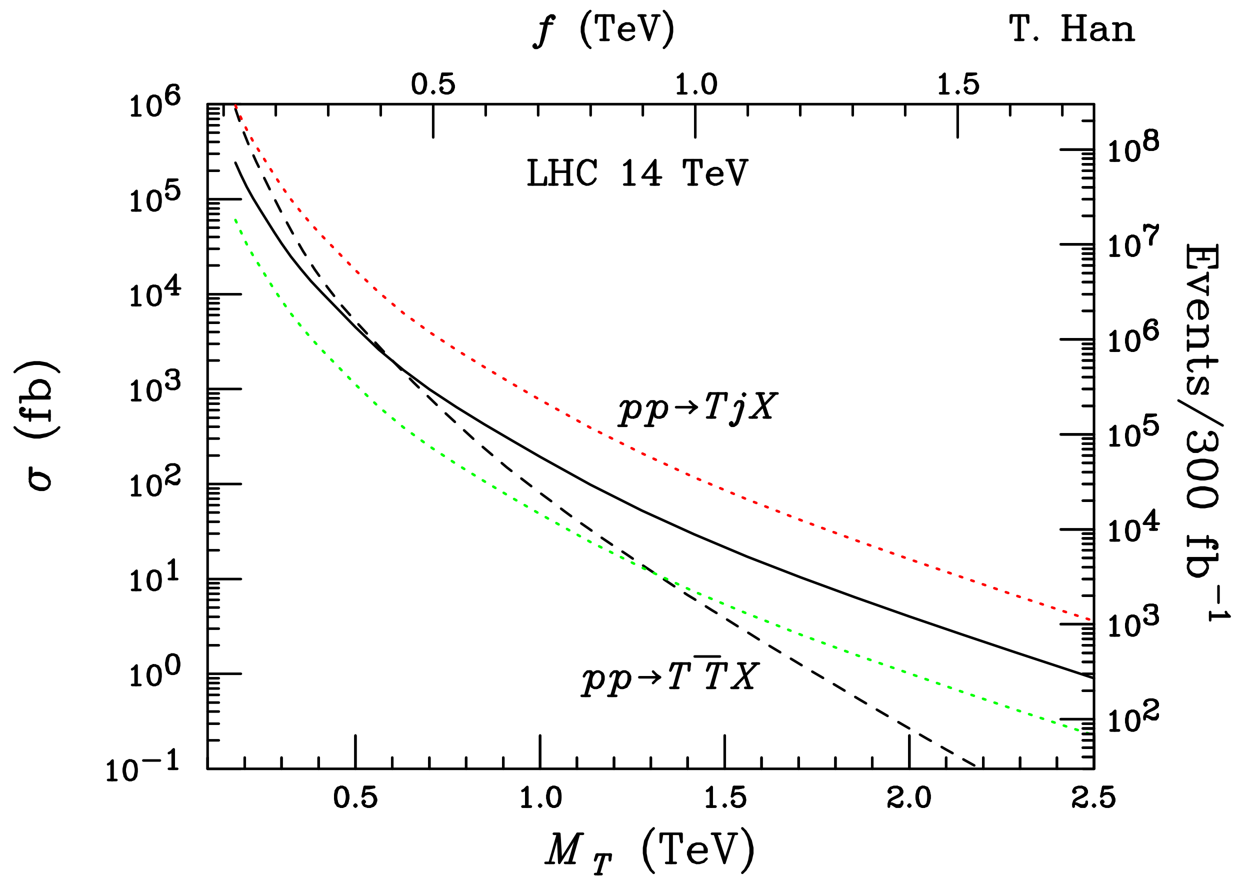
$$qb \to q'W^{*}b \to q'\ t \quad 1/3 \text{ of QCD.}$$

measure V_{tb} and test tbW_L coupling $\Leftarrow$ surely new at the Tevatron.

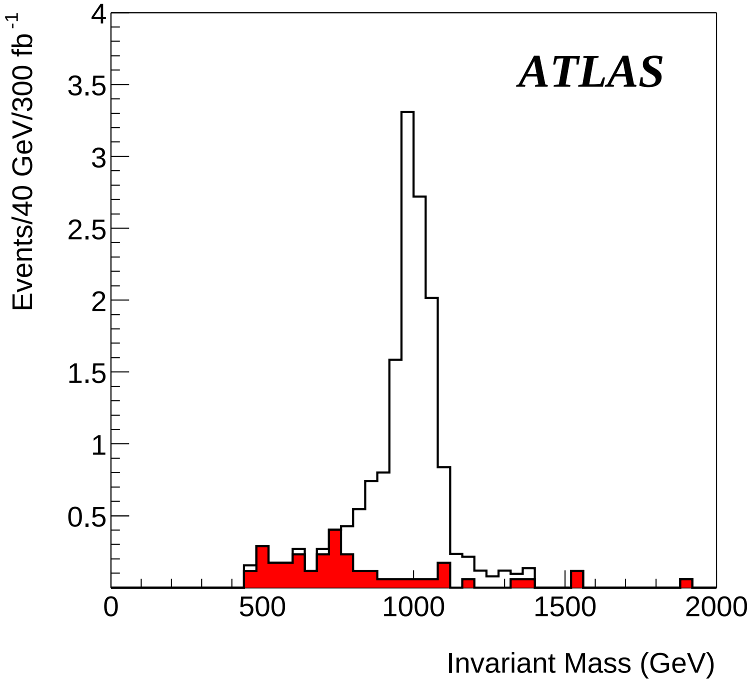
The heavy T signal at the LHC

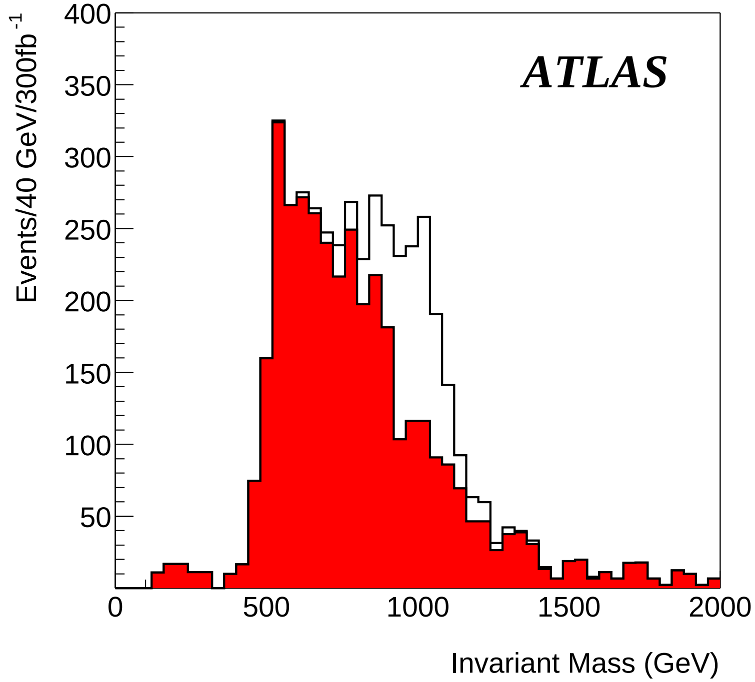


$gg \to T\bar{T}$ phase-space suppression;

$qb \to q'T$ via t-channel $W_L b \to T$.

ATLAS simulations for $T \to tZ,\ bW$:





Reach $M_T \sim 1\ (2)$ TeV for $x_\lambda = 1\ (2)$.

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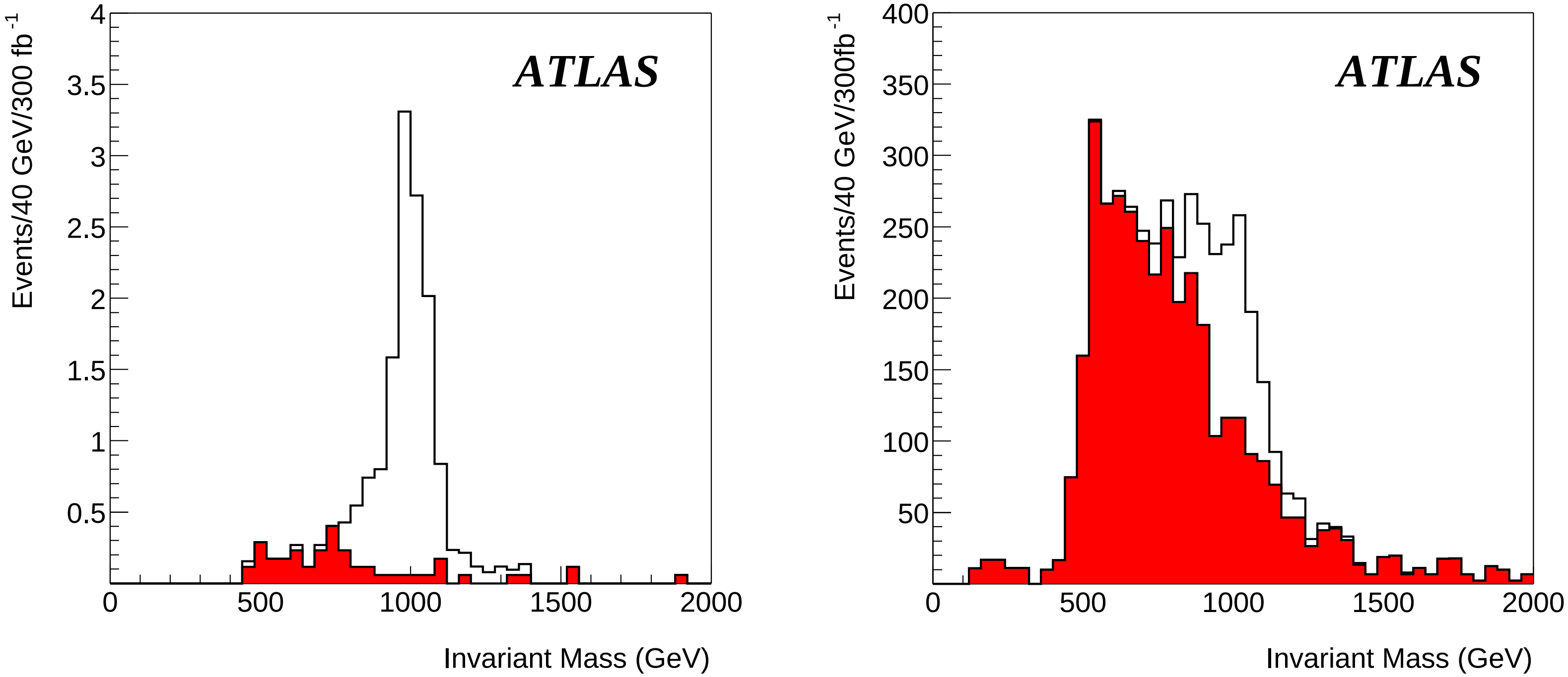


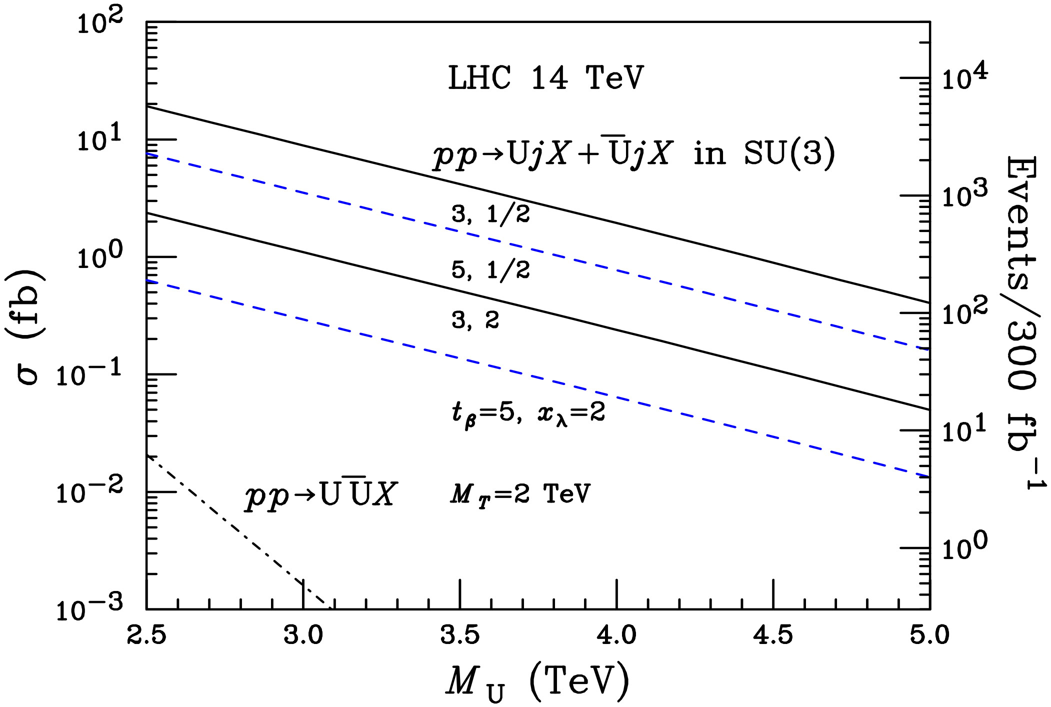
Reach $M_T \sim 1$ (2) TeV for $x_\lambda = 1$ (2).

Cross-sectiions measure coupling x_λ.

Mass peak M_T determines $f:\ v/f = m_t/M_T(x_\lambda + x_\lambda^{-1})$

$\Longrightarrow$ check consistency with f from M_{Z_H}.

If there is either a U-type or D-type heavy quark, must observe $W^+ d \to U$ or $W^- u \to D$:



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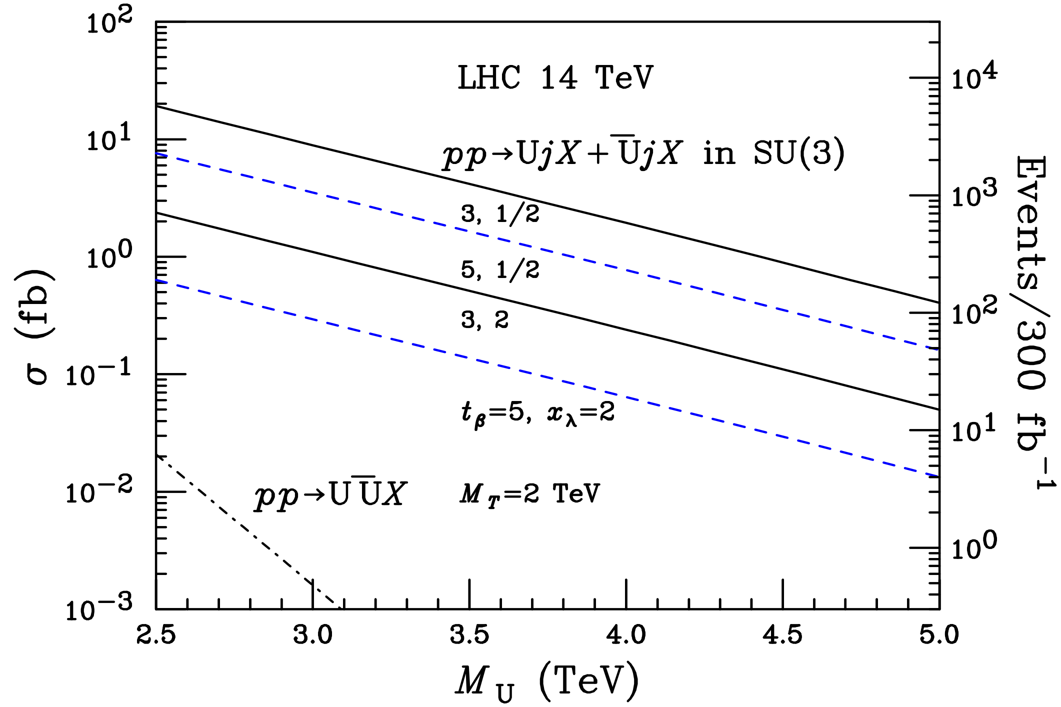

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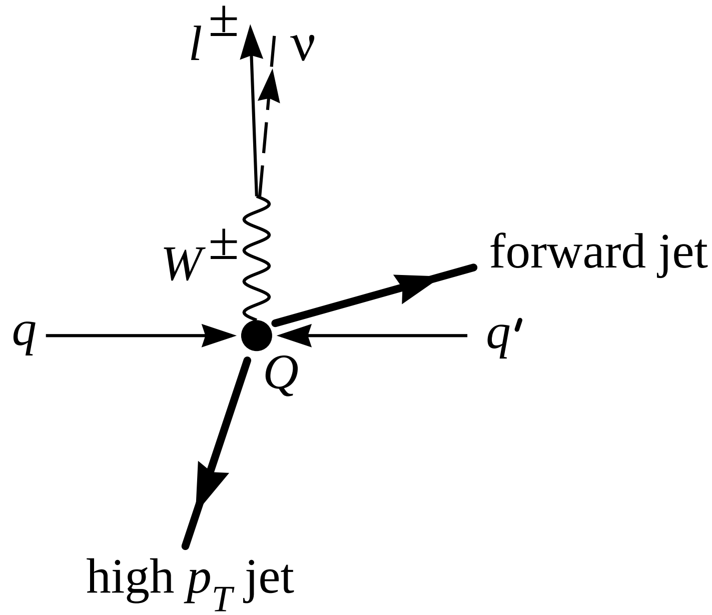
Interesting to note:

- $\sigma_U \approx 10\sigma_{\bar{U}}; \quad \sigma_D \approx 10\sigma_{\bar{D}}$;
- $U \to d\ell^+\nu \Rightarrow$ sequential fermion embedding;
  $D \to u\ell^-\bar{\nu} \Rightarrow$ anomaly-free fermion embedding.

Kinematical features: $W^+d \to U \to \ell^+\nu j$:



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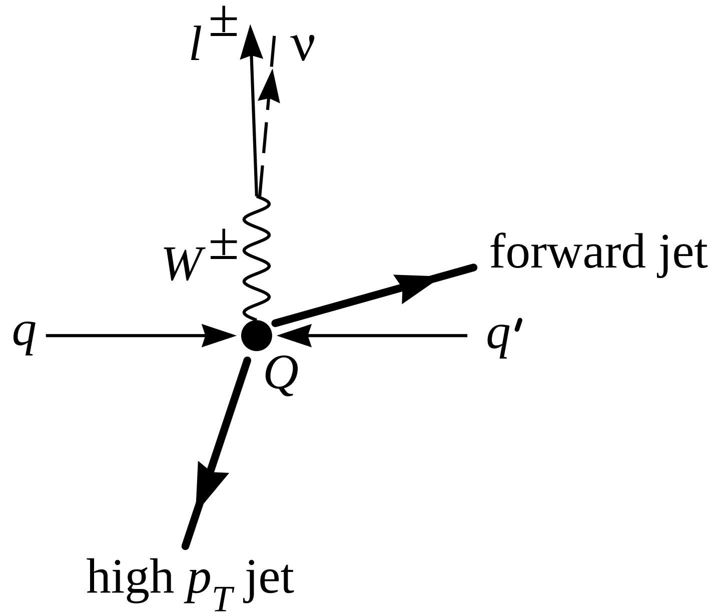

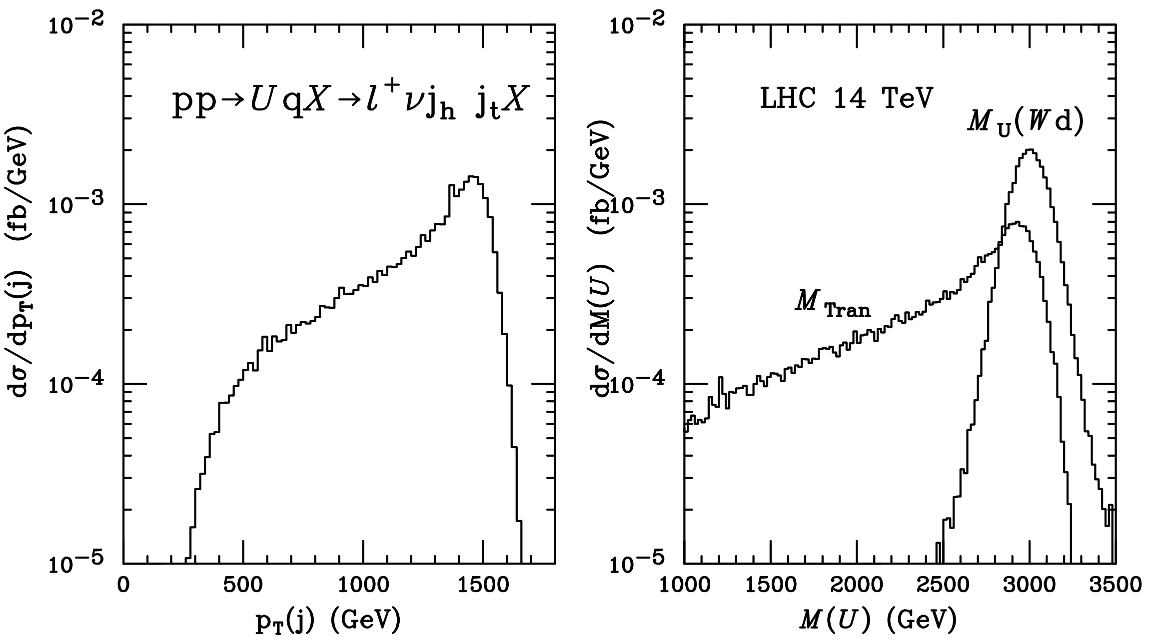

Deep into extra-dimensions at the LHC:

- Observable signatures for extra-dim models:

▷ At "low" energies

† "very low": $E \ll 1/R,\ M_D$:

4d effective theory: as the Standard Model; weak effects from gravity.

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▷ Intermediate energy regime $E \sim M_D$: stringy states significant: s-channel poles as resonances:

$$\mathcal{M}(s,t) \sim \frac{t}{s - M_n^2}, \quad M_n = \sqrt{n} M_S.$$

▷ At "trans Planckian" energies $E > M_D, M_S$:
$(4+n)$−dim physics directly probed;
gravity dominant: black hole production*

$$\sqrt{s} = M_{BH} > M_D \text{ for } b < r_{bh}.$$

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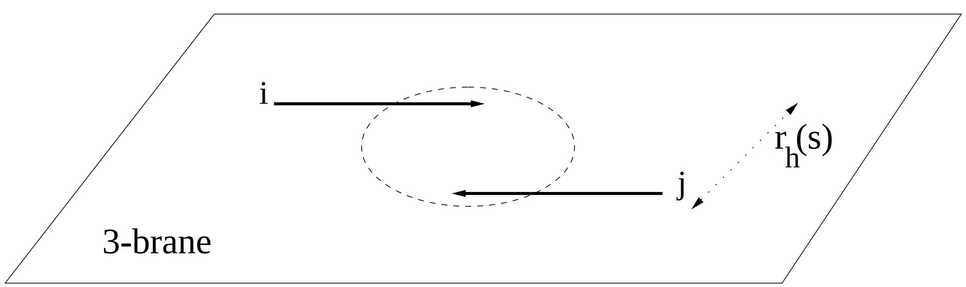
$$r_{bh} = \frac{1}{\sqrt{\pi} M_D}\left[\frac{M_{BH}}{M_D}\left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)\right]^{\frac{1}{n+1}} \rightarrow M_{BH}/M_{pl}^2 \text{ in 4d}$$

$$\sigma = \pi r_{bh}^2.$$



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- Collider Searches for Extra Dimensions:

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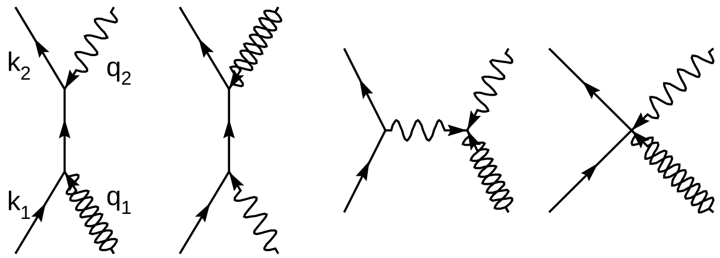
Real KK Emission: Missing Energy Signature

a. $e^+e^- \rightarrow \gamma + KK$ (γ+missing energy)



n − dim :	at LEP2
$n = 4$	$M_S > 730$ (GeV)
$n = 6$	$M_S > 520$ (GeV)

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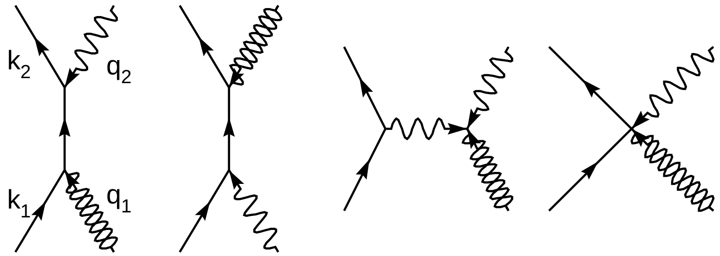

n − dim :	at LEP2
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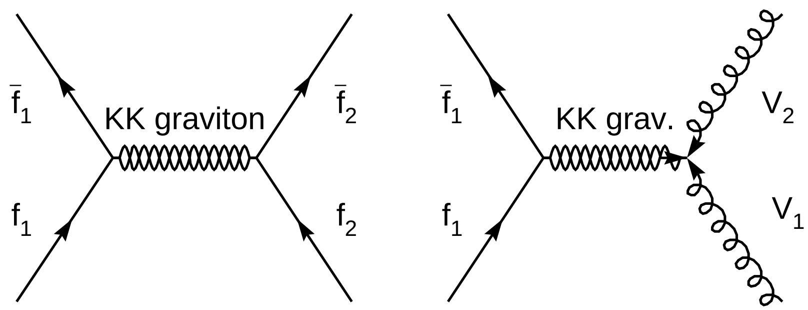
b. $p\bar{p} \to jet + KK$ (mono-jet+missing energy)

n − dim :	at Tevatron	at LHC
$n = 4$	$M_S >$ 900 (GeV)	3400
$n = 6$	$M_S >$ 810 (GeV)	3300

B. Collider Signals II (ADD)

Virtual KK Graviton Effects

On four-particle contact interactions:

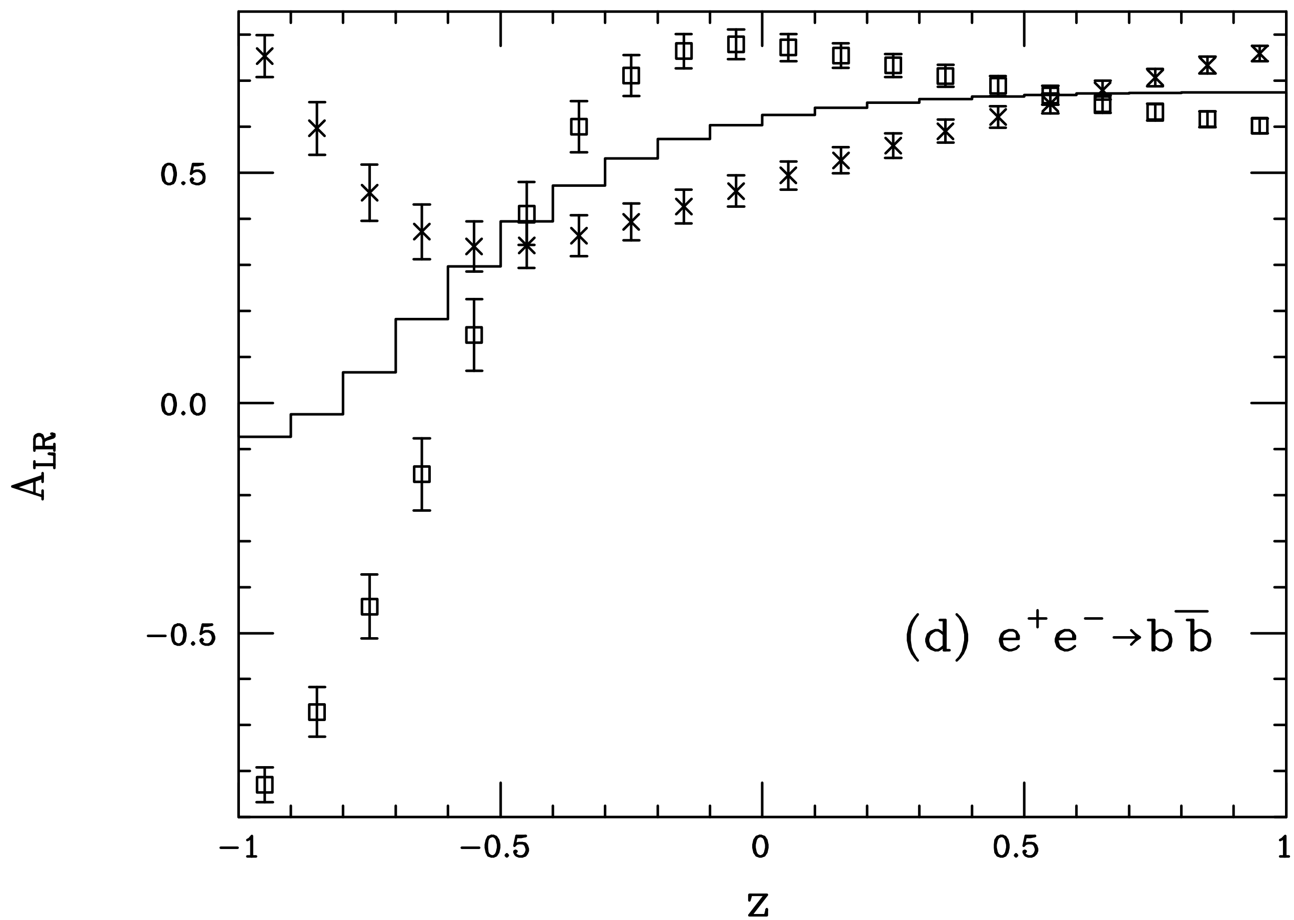


Sum over virtual KK exchanges:

$$
\begin{aligned}
i\mathcal{M} &\sim \bar{f}\mathcal{O}_i f\ \bar{f}\mathcal{O}_j f \int_0^\infty \frac{dm_{\vec{n}}^2\ \kappa^2 \rho(m_{\vec{n}})}{s - m_{\vec{n}}^2 + i\epsilon} \\
&\sim \frac{s^2}{M_S^4}\ \bar{f}\mathcal{O}_i f\ \bar{f}\mathcal{O}_j f.
\end{aligned}
$$

Again, effective coupling $\kappa^2 \sim \frac{1}{M_{pl}^2} \to \frac{1}{M_S^2}$!

Qualitative differences for signal/background distributions, due to the spin-2 exchange:



LR asymmetry for $e^+e^- \to b\bar{b}$ at $\sqrt{s} = 500$ GeV.
Solid: SM; "data" points for $\lambda = \pm 1$ with $= 75\ fb^{-1}$.

C. KK Resonant States at Colliders: (RS)

If the SM fields (photons, electrons, Z, W, H^0...) also propagate in extra dimensions, then they have KK excitations.

Direct search bounds:

$$M^*_{\gamma,Z,W} \sim \frac{1}{R} > 4 \text{ TeV}.$$

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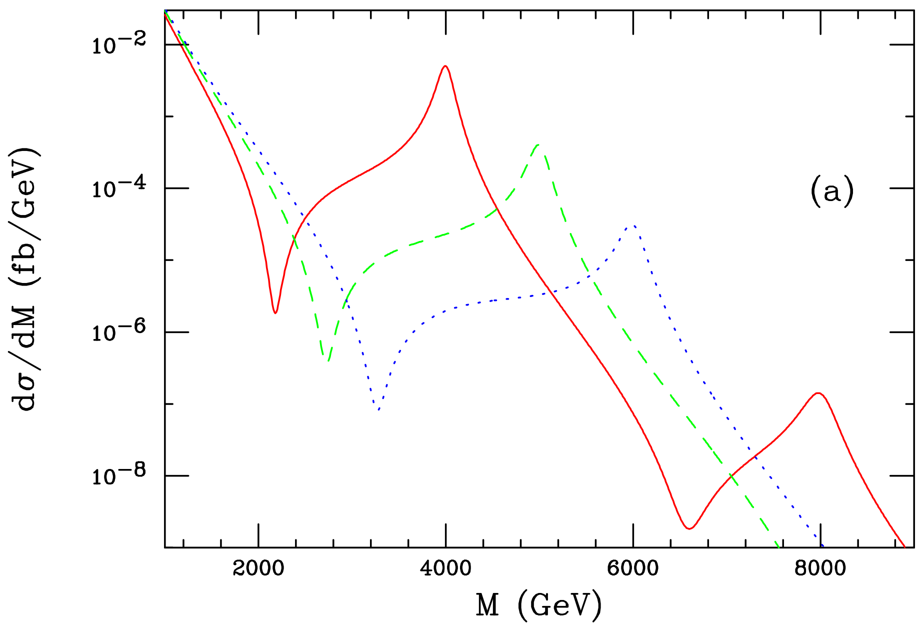
Resonant production at the LHC:



D. Stringy States at Colliders

Future colliders may reach the TeV string threshold thus directly produce the "stringy" resonant states.

Amplitude factor near the resonance

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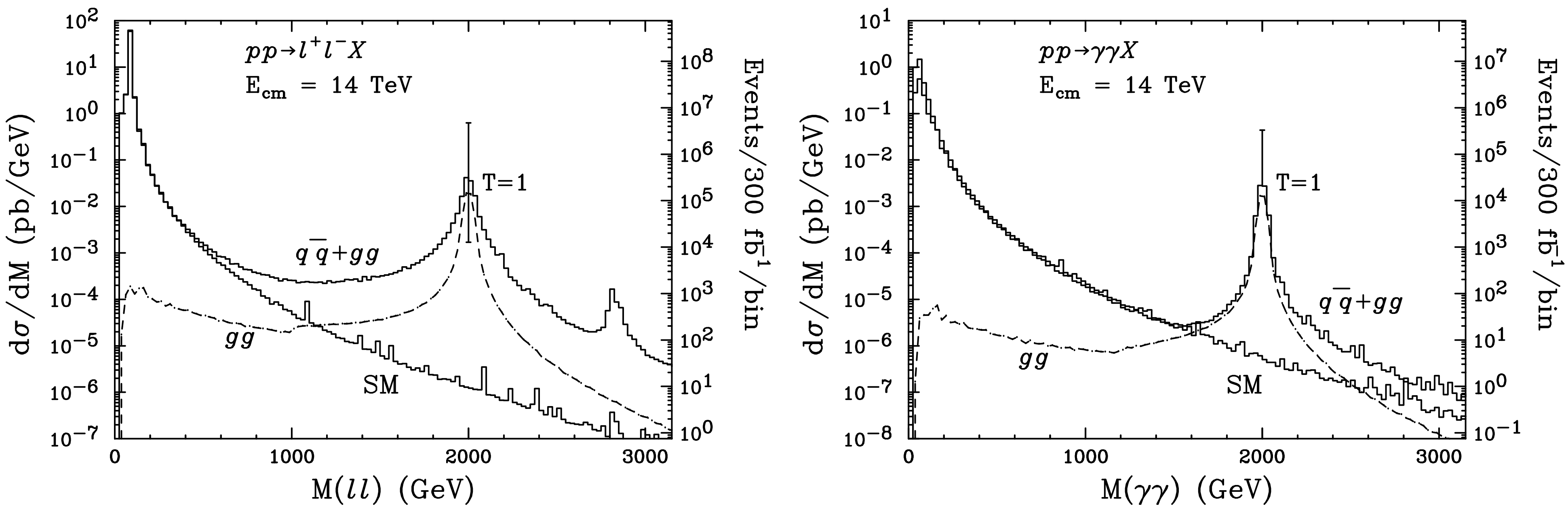
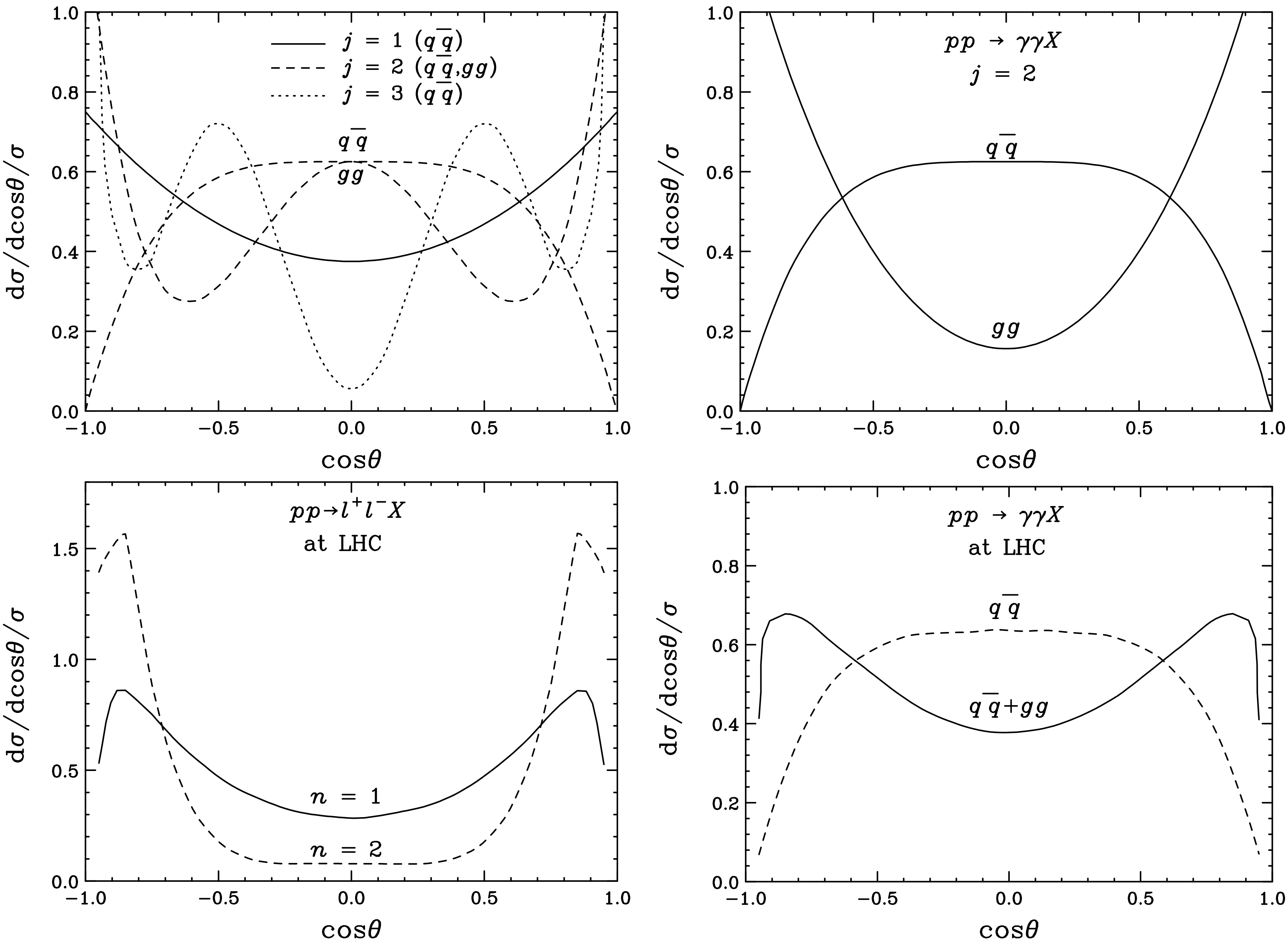
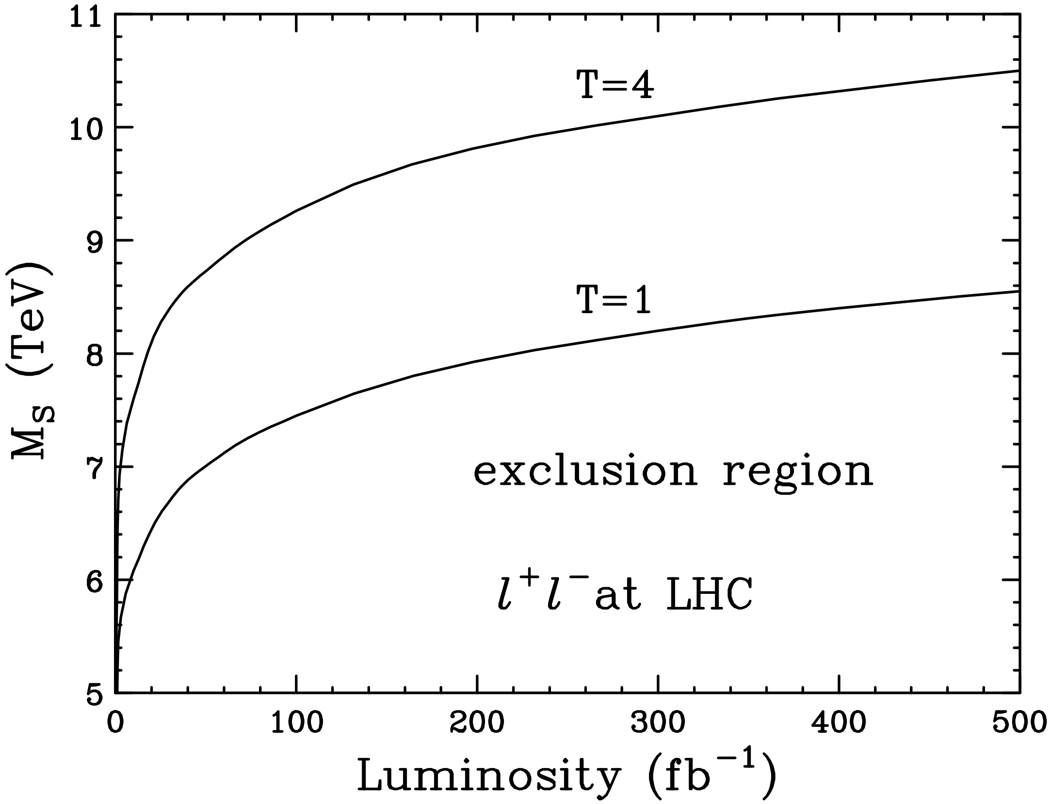


where T is an unkown gauge factor (Chan-Simon factor), typically $1-4$.

Very rich structure of angular distributions:



LHC 95% C.L. sensitivity from $\ell^+\ell^-$ mode:



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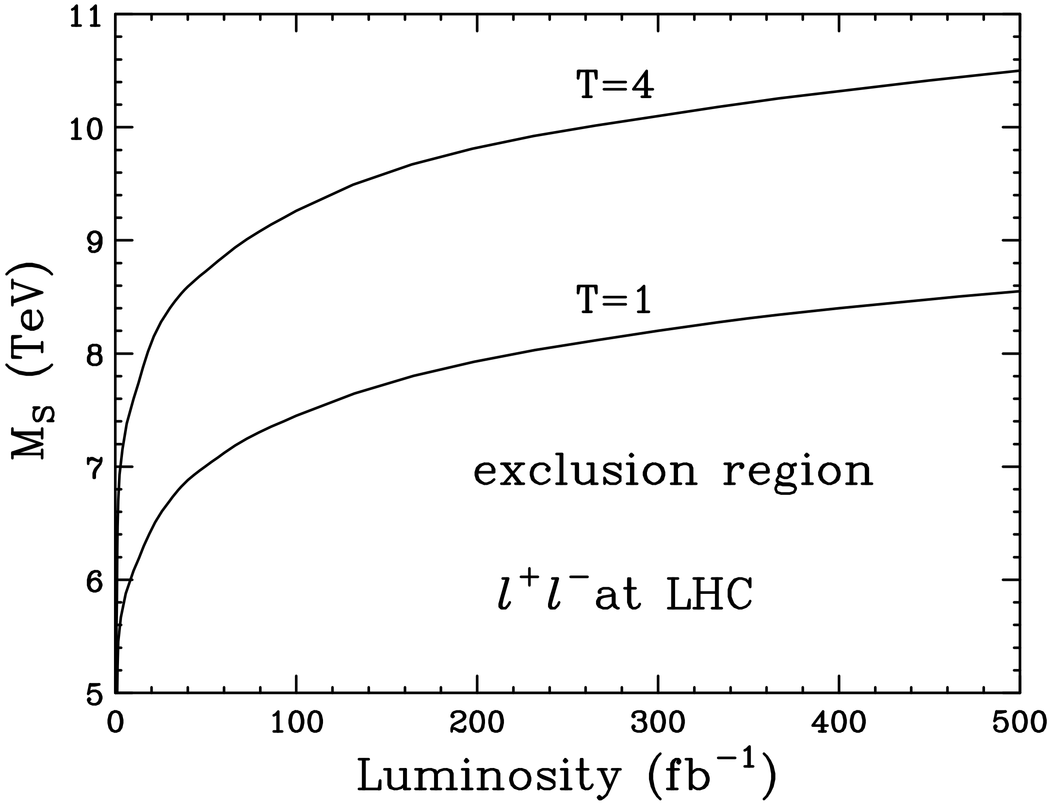

With 300 fb^{-1}, if no signal seen, we expect to reach bounds for

$$M_S > 8\ (10)\ \text{TeV for } T = 1 - 4.$$

E. Black Hole Production at Colliders

For a black hole of mass M_{BH}, its size is

$$r_{bh} \approx \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}} \rightarrow \frac{M_{BH}}{M_{pl}^2} \text{ in 4d.}$$

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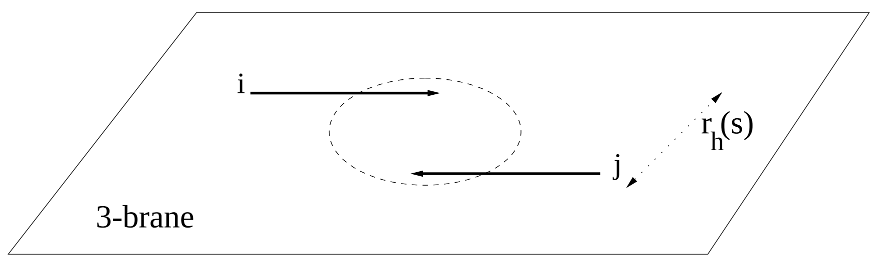
At higher energies and shorter distances (impact parameter)

$$E_{cm} > M_{BH} > M_D, \quad b_{impact} < r_{bh},$$

black holes formation is the dominant quantum gravity phenomena.



Black holes copiously produced at the LHC energies,

M_{BH}	$n = 4$	$n = 6$
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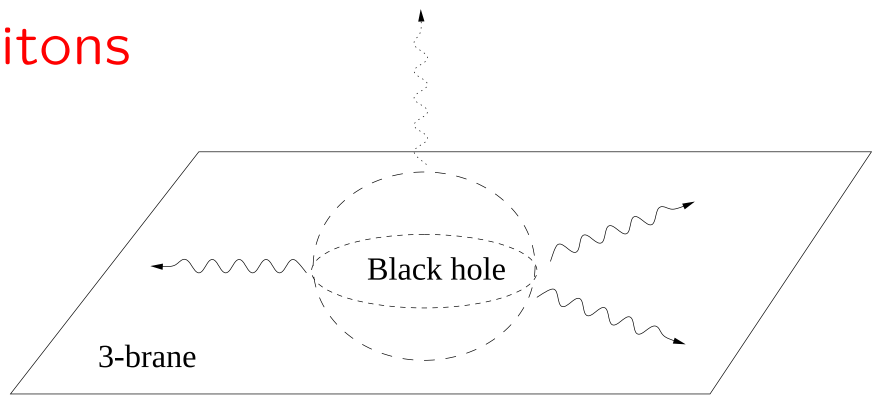
Black holes "decay" via Hawking radiation:

$\gamma,\ \nu,\ e^{\pm},\ hadrons, \ldots\ W^{\pm},\ Z \ldots,$ gravitons



Spectacular events:

- very luminous in the detector!
- lepton-number/baryon-number violation (?)
- spherical/angular momentum orientation (?) ... ...

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Realize the Tevatron potential, go for the LHC!
Major breakthrough ahead of us!