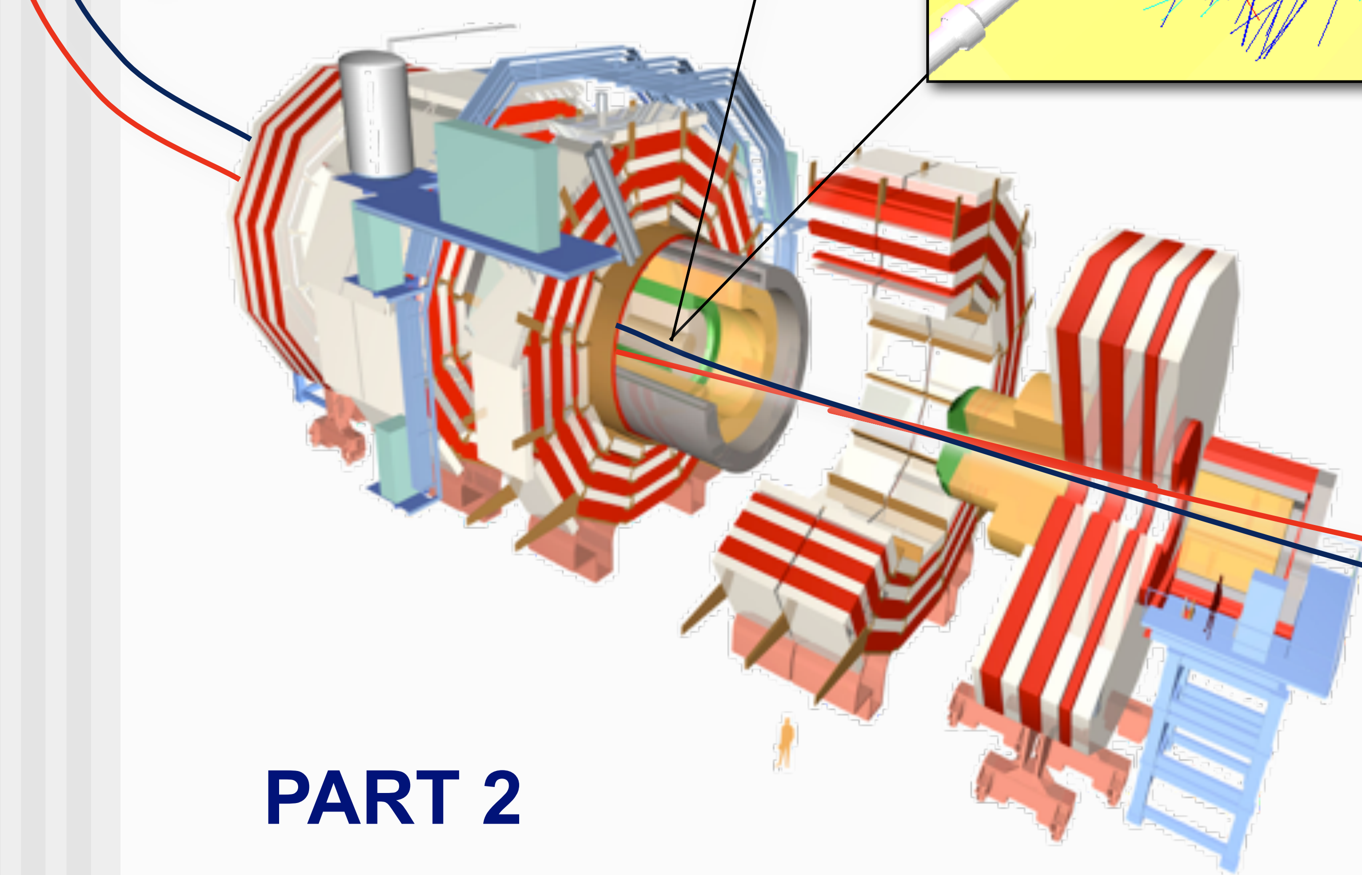
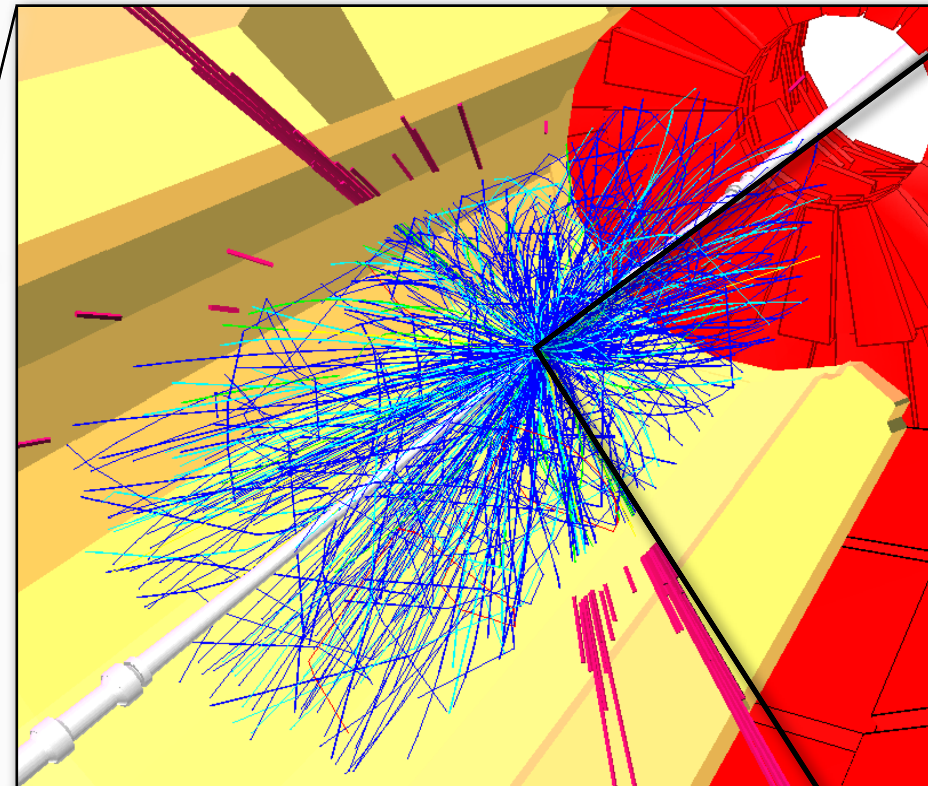
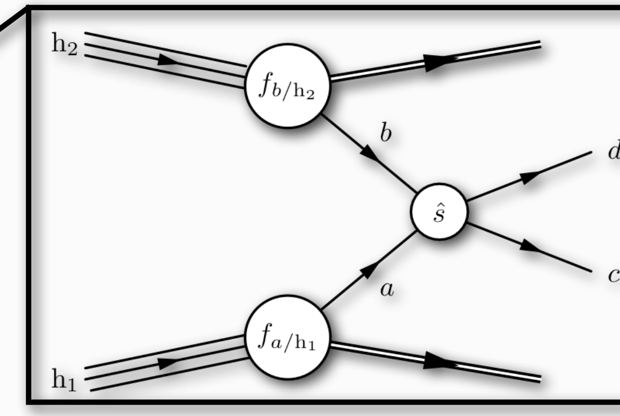
# Experimental Results from CMS

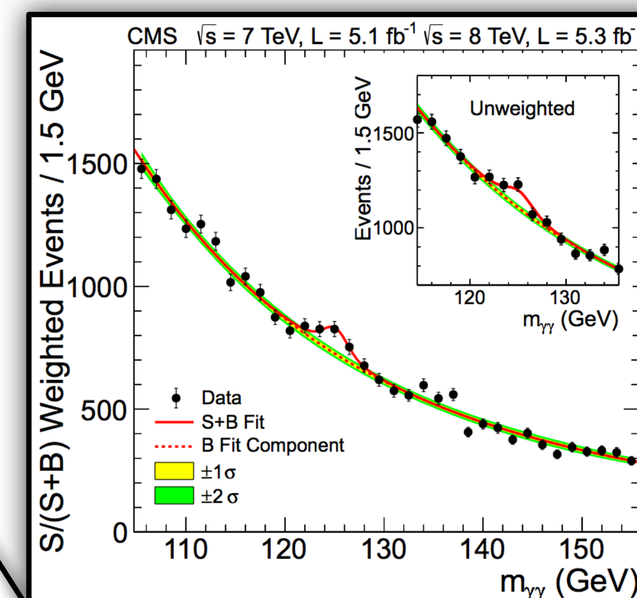

**Günther Dissertori**

**ETH Zürich**



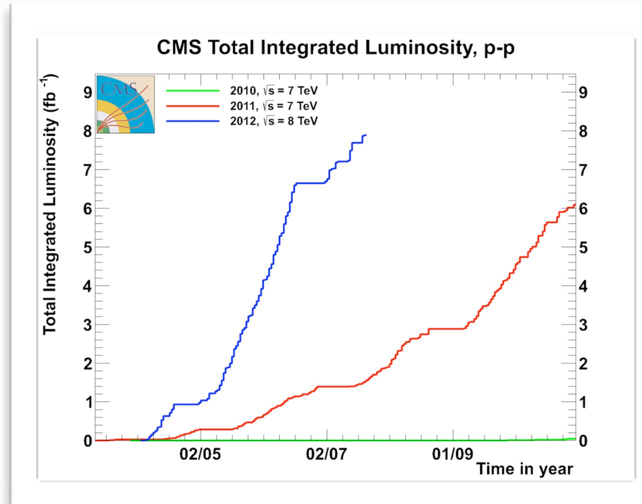


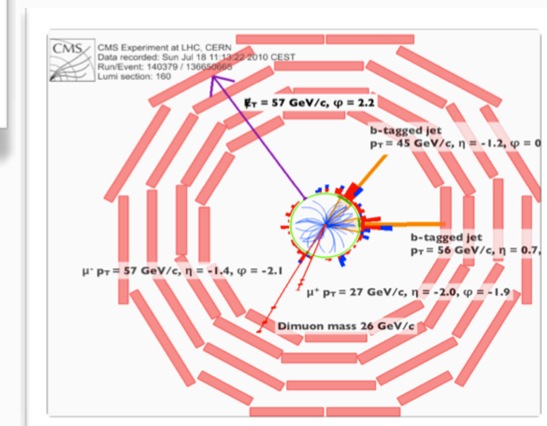



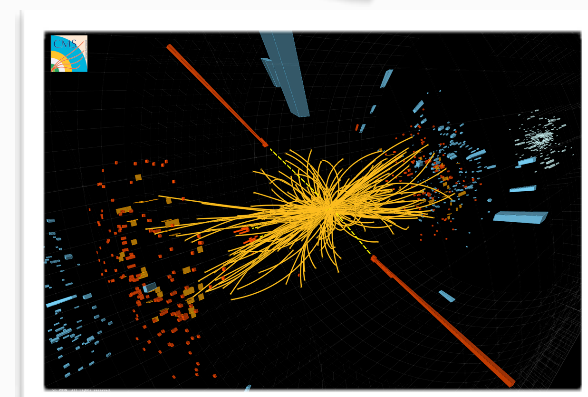

## PART 2

# Overall Outline

- Introduction
  - CMS, Lumi, performance
- SM Physics
  - QCD, EWK, TOP
- BSM Physics
  - some Exotica and SUSY searches
- Searches for the Higgs
- Bonus Material (only in backup)
  - Machine
  - Physics expectations,requirements
  - Tools/Methods





Disclaimer 1 : Many introductory and theoretical aspects covered in the other lectures

Disclaimer 2 : For complete list of results: see https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Disclaimer 3 : Some slides or slide content taken from seminars/lectures/write-ups of other colleagues or previous lectures of mine

# Some thoughts about BSM searches

“LHC is most powerful street lamp in history”

J. Wells, ICHEP2010

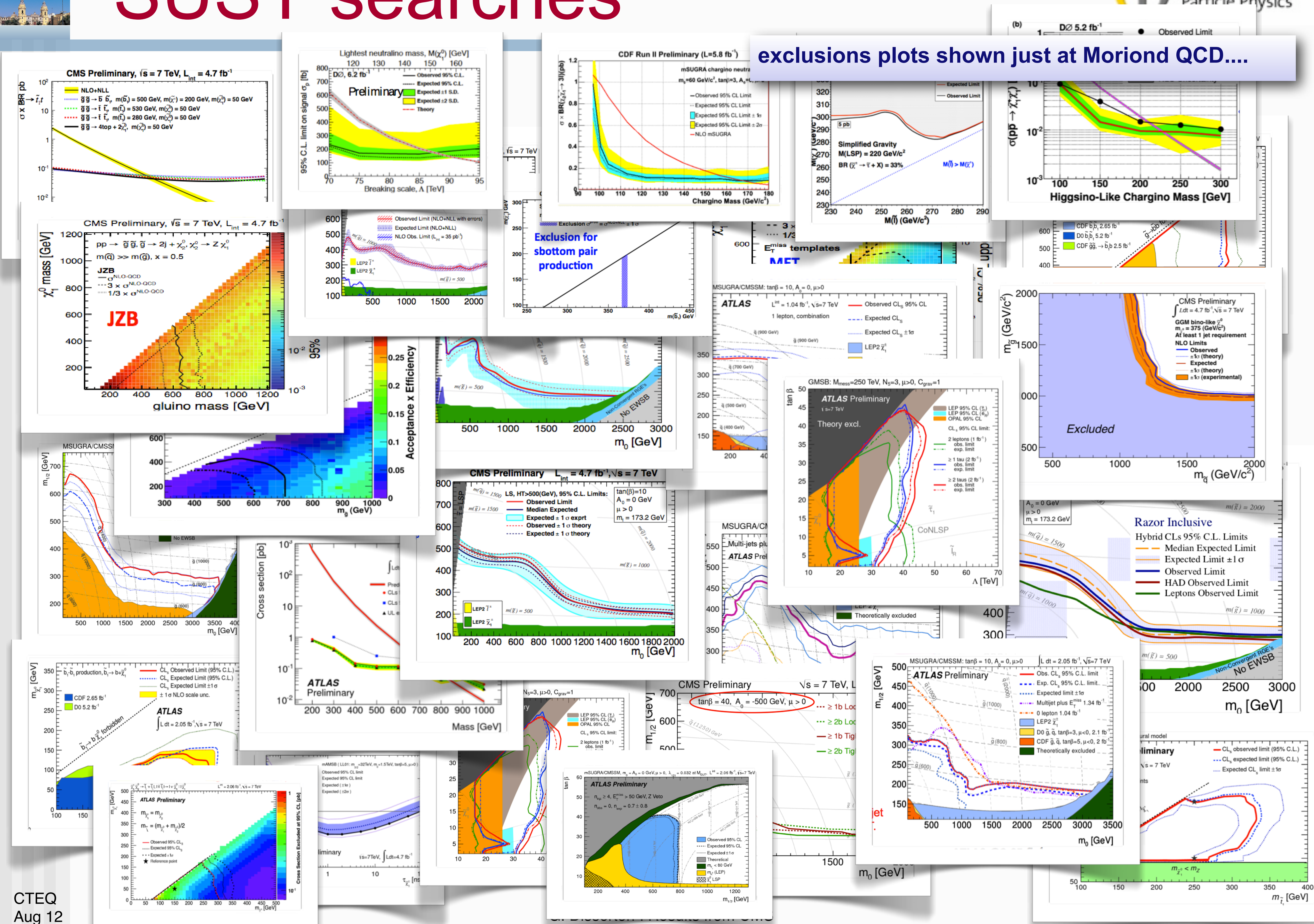
ETH Institute for Particle Physics

# Some remarks

- In the following I will not go through the, roughly infinite, list of models, with how much lumi they can be detected (or not), what are the ~14356 limits obtained so far, etc etc
- Motivations for why and how of BSM models are given in other lectures
- I rather try to make some "general" observations...
- ... and talk about "tools", ie. useful variables and data-driven background estimates
- *I can't wait for the moment when exclusion plots will mostly disappear from BSM talks....*

# SUSY searches

**exclusions plots shown just at Moriond QCD....**



# The zoo...

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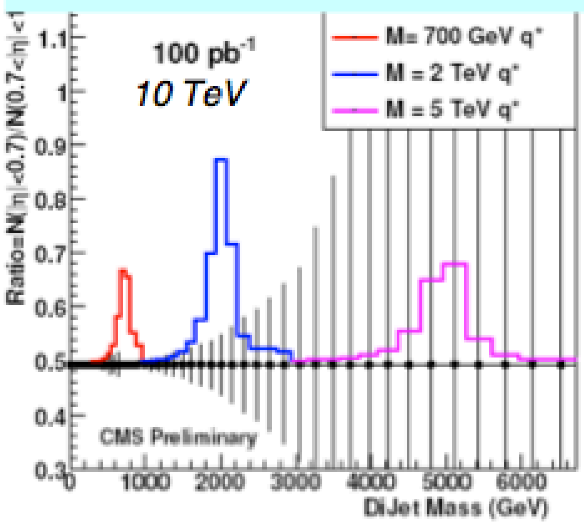
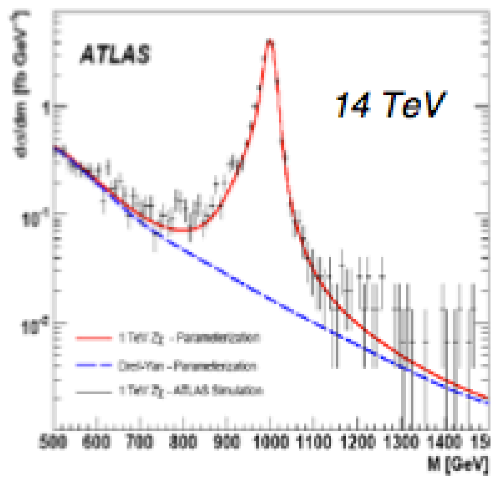
## *From the Possible to the Unexpected*

*Large zoo of models that predict different incarnations of New Physics at the LHC*

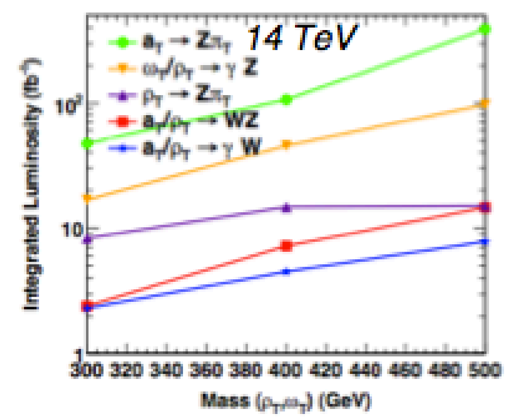
Contact Interaction /Excited Quarks?



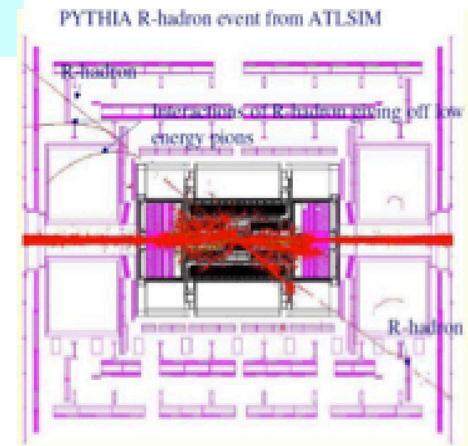

New Gauge Bosons?



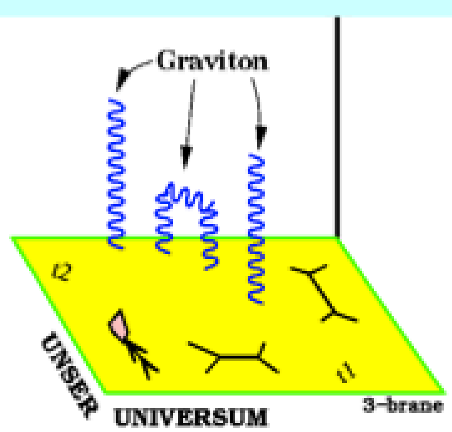

Technicolour?



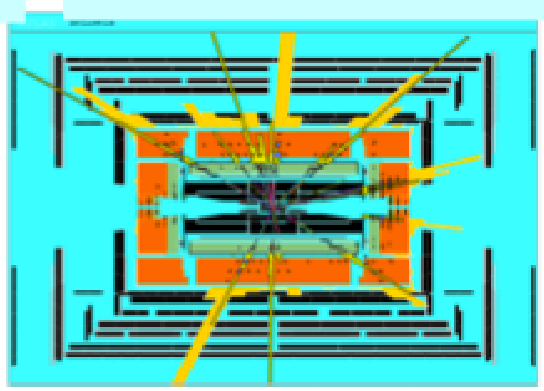

Split Susy?



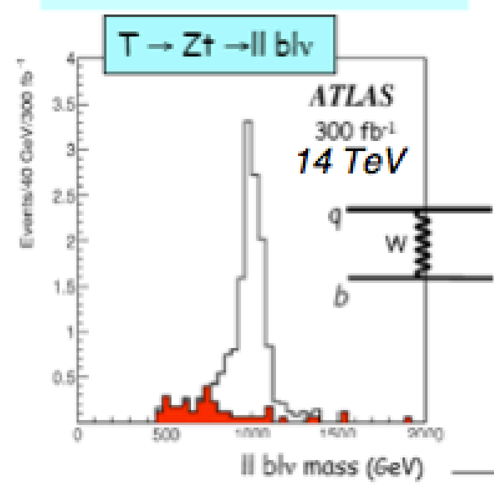

Extra Dimensions?



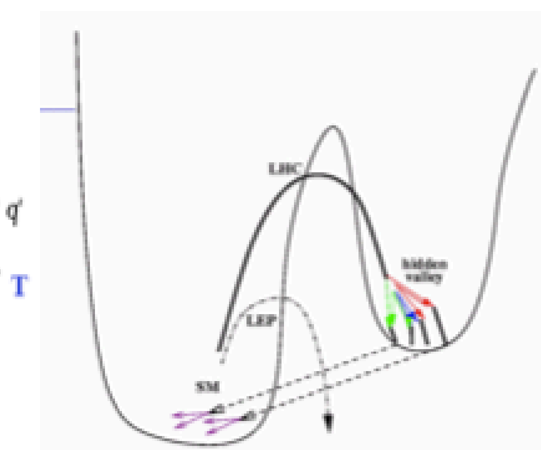

Black Holes???



Little Higgs?




Hidden Valley??



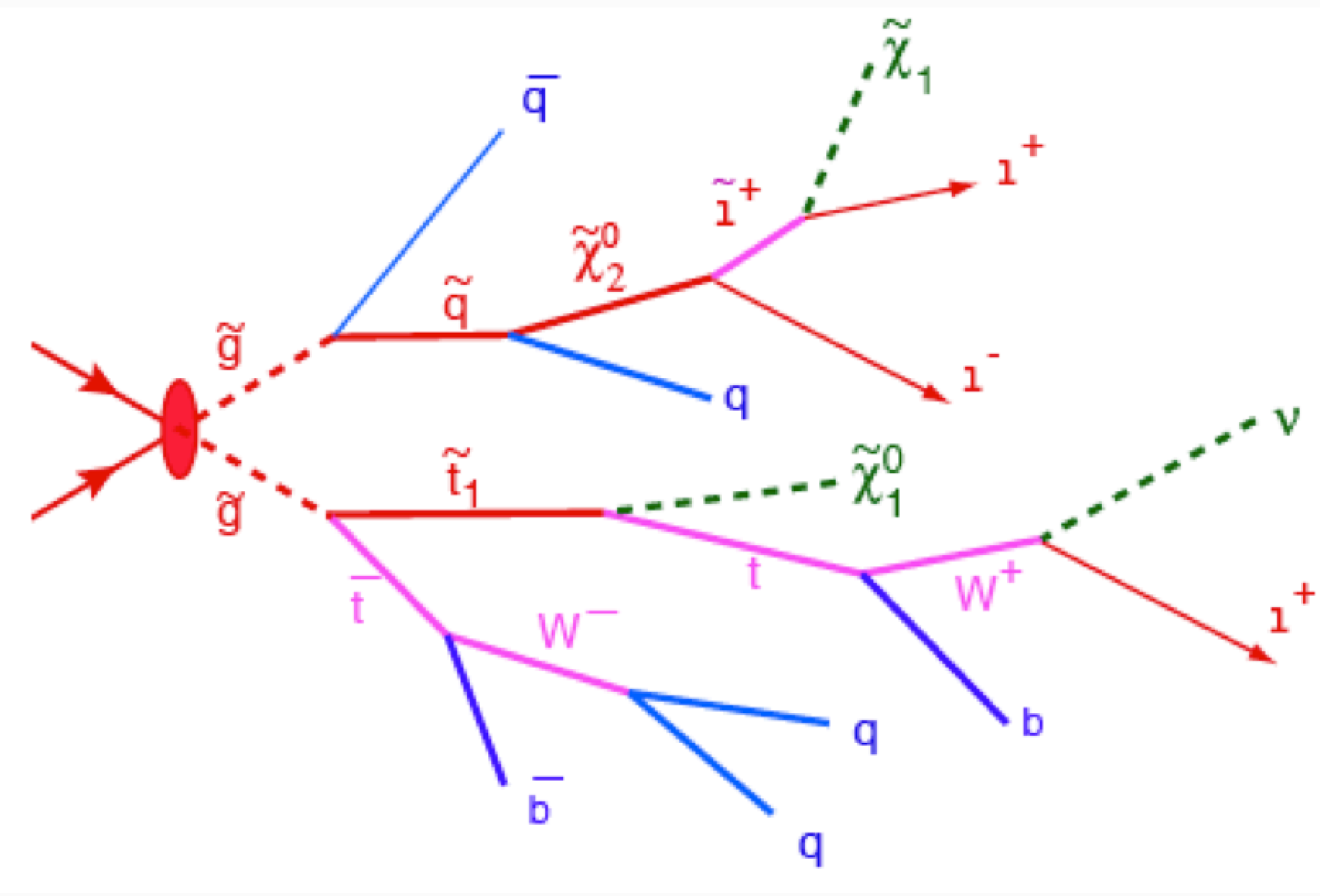

5/05/2010 LHCC/A101 O. Buchmüller (ICL) *Non exhaustive list (by far)* 21

original slide by A. de Roeck

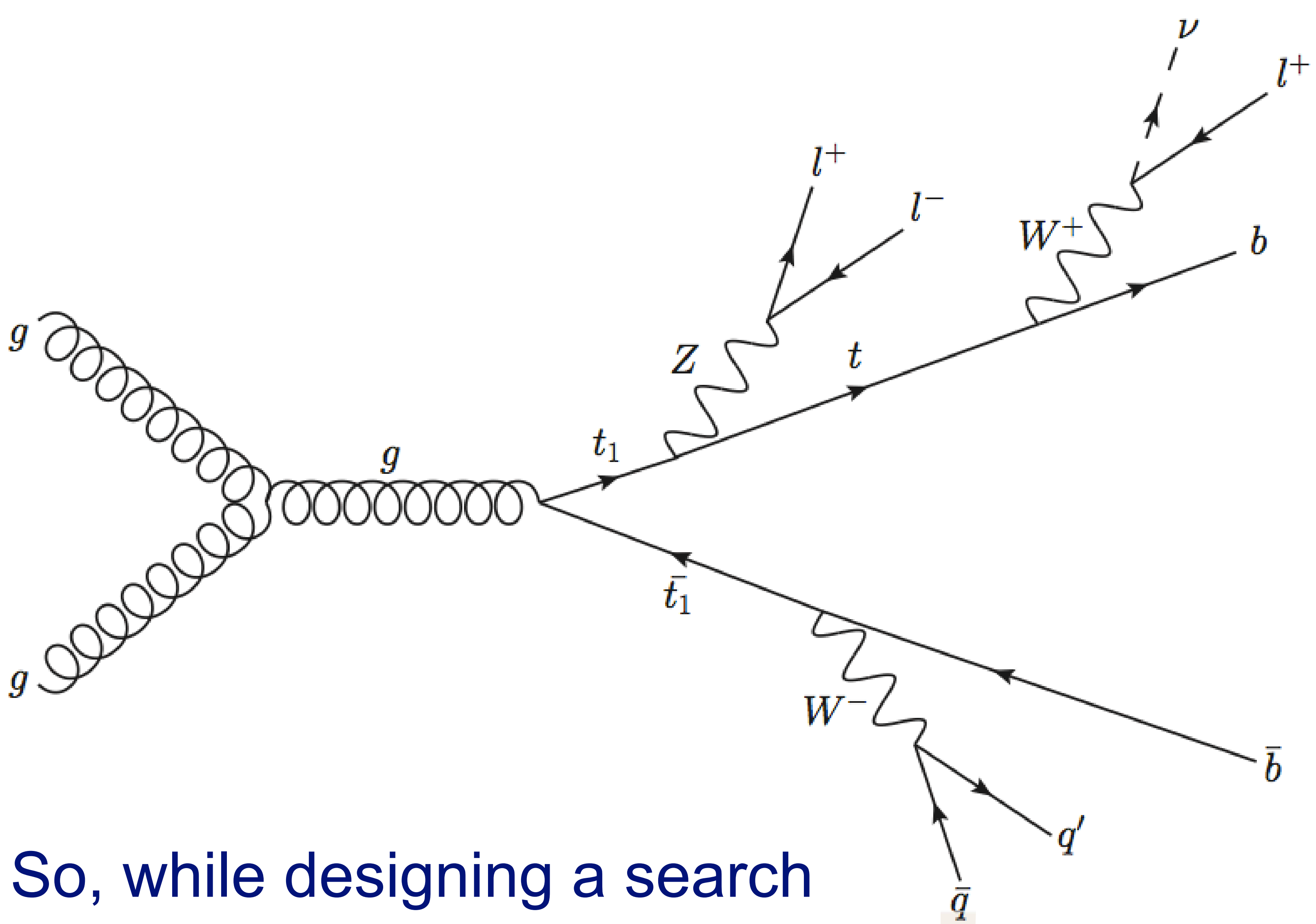
# Topologies

ETH Institute for Particle Physics

- **A fundamental problem**: most of the models depend on many (!) parameters, which influence production and decay modes. Many topologies to look for!
- To make life a bit easier, people chose some benchmark points/models, and studied those in more detail
- However, some "generic features" very often apply
- Take example of a "typical" SUSY mode (gluino/squark production and decay):
  - Production via strong interactions ie. large cross section
  - decay details depend on model parameters
  - However, once the heavy state is produced, it will decay to jets, leptons/photons and MET
  - Most of the jets and leptons have "relatively large $p_T$", leptons are isolated, considerable MET and large $H_T$ = sum over $p_T$s



# Topologies, another example




4th generation

Heavy quarks

t'

Composite Higgs models

New vector-like quark states, ....

- So, while designing a search
  - focus on robust and "simple" signatures, be "topology-oriented"
  - in this way, hopefully you can cover a wide variety of models/parameters
  - let the SM backgrounds decide on the feasibility, not the models
  - if you see "something", you have the pleasant problem to understand what it is: the "LHC" inverse problem"
- Then data came, and the experiments basically tried to follow this approach....

# Signatures (not at all complete!!)

| Signature | class of model | important backgrounds | issues |
|---|---|---|---|
| Resonances<br>-di-jets<br>-di-leptons/photons | Z', W',<br>excited quarks<br>ED | falling QCD or DY spectrum | - Jet Energy Scale and resolution<br>- leptons : alignment, momentum resolution, calorimeter saturation |
| Multi-jets + MET | SUSY<br>New heavy quarks, composite models | QCD<br>ttbar<br>V+jets | - data-driven bckg. estimation<br>- MET modeling, jet fluctuations<br>- choice of clever variables ($H_T$, alpha$_T$, Razor, $m_{T2}$, ... ) |
| leptons + jets + MET | SUSY<br>New heavy quarks,<br>t', b', ... | QCD<br>ttbar<br>V+jets | - like above<br>- jets faking leptons, lepton isolation<br>- lepton charge mis-ID (for same-sign lepton searches) |
| photons + MET | SUSY<br>Extra Dimensions | QCD | - jets faking photons<br>- MET modeling |

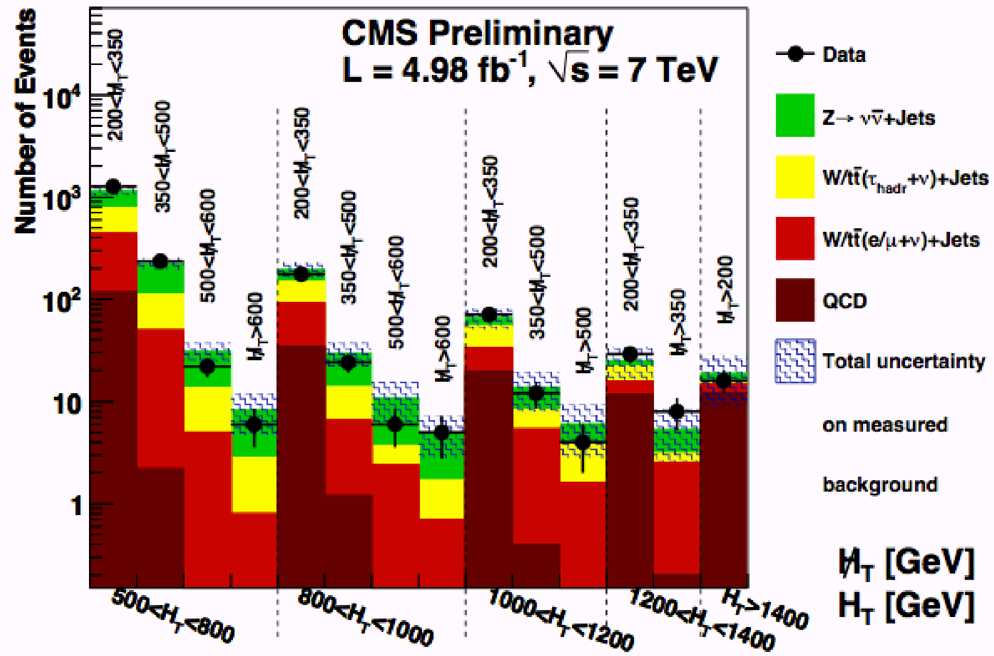
# Examples of variables

slide adapted from M. Dünser

## Kind of classical one: $H_T$ + $MH_T$

**selection:**

- -> **#jets ≥ 3** with **$p_T$ > 50 GeV** and **|eta| < 2.5**
- -> $H_T$ = scalar sum of these jets $p_T$'s
  - --> **$H_T$ > 500 GeV**
- -> $MH_T$ = negative vectorial sum of jets $p_T$'s
  - --> jet **$p_T$ > 30 GeV** and **|eta| < 5.0**
  - --> **$MH_T$ > 200 GeV**
- -> **Δφ(jet, $MH_T$) > 0.5 (0.3)** for 1., 2., (3.) jet
  - --> suppresses QCD mis-measurement




**backgrounds:**

- -> **Z to νν** : **data-driven** estimate
- -> **lost-lepton (W,ttbar)** : **data-driven**
- -> **hadronic τ decays** : data validated **MC**
- -> **QCD** : **data-driven**

## Others

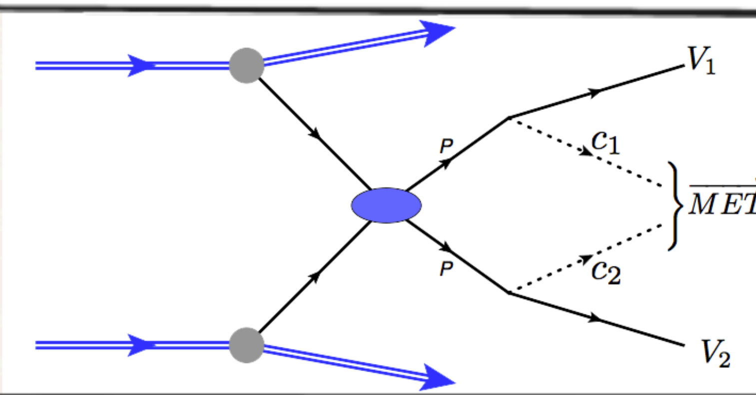
$$\alpha_T = \frac{E_T^{j_2}}{M_T}$$

**peaks at 0.5 for QCD!**

$$M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2}.$$

$$M_{T2}(m_c) = \min_{p_T^{c(1)}+p_T^{c(2)}=p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$

- in case the mass of the unobserved child $m_c$ were known, the endpoint of $M_{T2}$ would correspond to the parent mass $m_p$.




$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$R = \frac{M_T^R}{M_R}$$

- -> $M_R$ ~ scale of the event
- -> R very small for QCD, large for signal
  - --> **analysis in $M_R$ vs. $R^2$ plane**

**Most of the experience shows:**

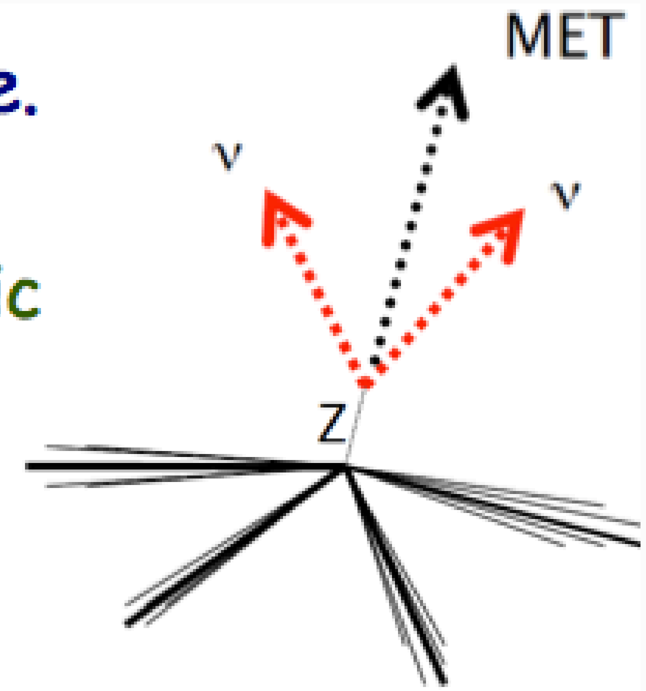
also using other approaches (alpha$_T$, MT2, Razor):

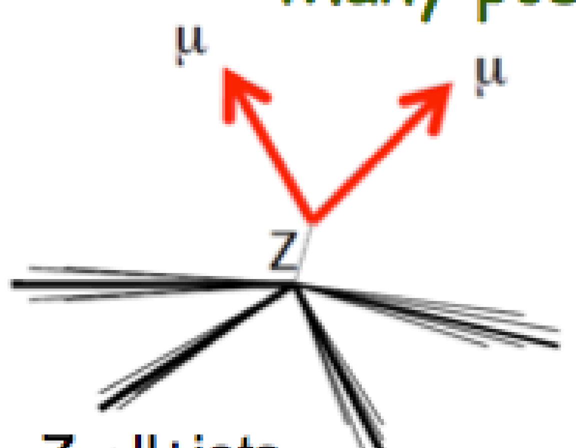
QCD can be pretty well controlled

A lot of work has to go into control of EWK backgrounds with real MET

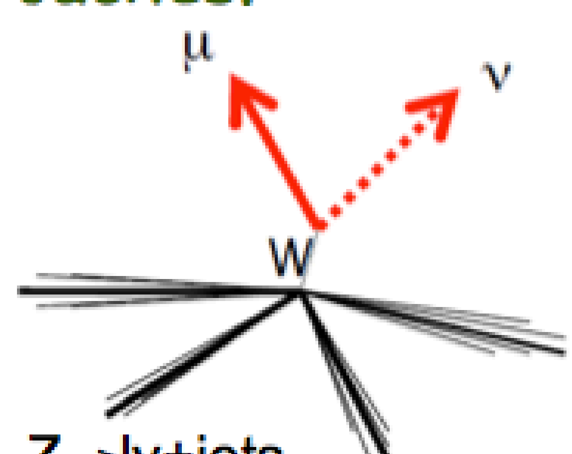
# Background estimates

- Data driven background estimates. An example.
  $Z \rightarrow \nu\nu$+jets
  - Irreducible background for the fully hadronic searches, at any jet multiplicity.
  - Use similar signatures to estimate in SM dominated regions and project in search region.
  - Many possible approaches.

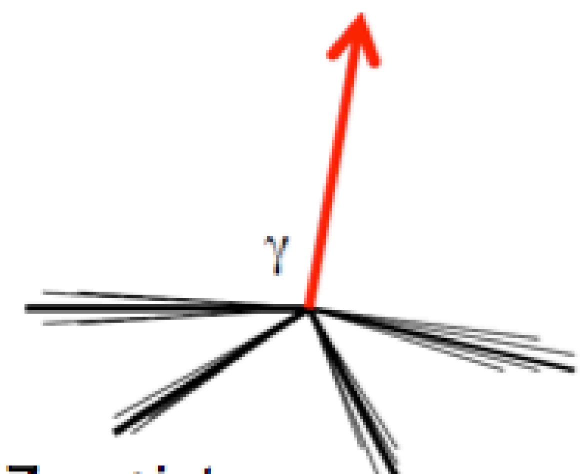



$Z \rightarrow ll$+jets
Pros: Clean and direct
Cons: Low statistics




$Z \rightarrow l\nu$+jets
Pros: Larger stat
Cons: backgrounds from SM and BSM




$Z \rightarrow \gamma$+jets
Pros: large stat, clean at high $E_T$
Cons: backgrounds at low $E_T$, theoretical error

Will pursue them all. Redundancy is good.

17/07/2010 Blois R. Rossin

CMS PAS SUS-08-002

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Indeed, most or all of them have been pursued!

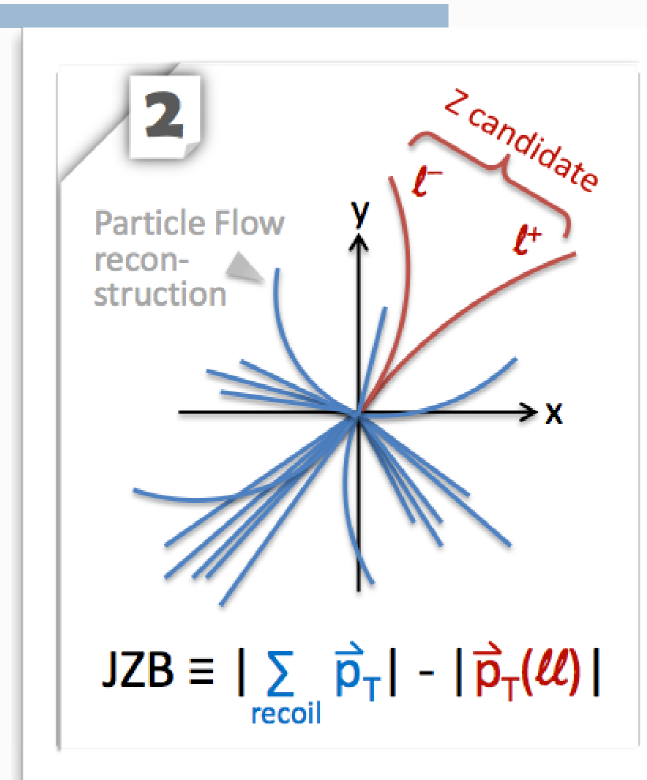
# Example of variable : JZB (fully data-driven)

ETH Institute for Particle Physics

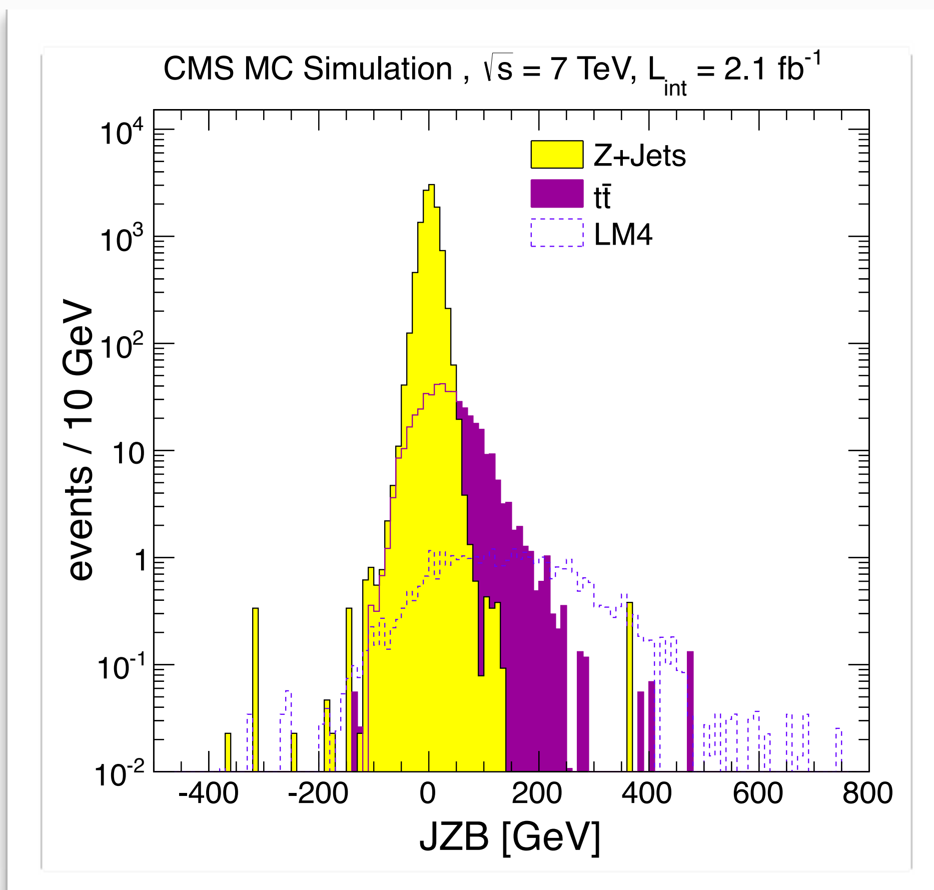
## Search for topologies with jets, MET, Z :

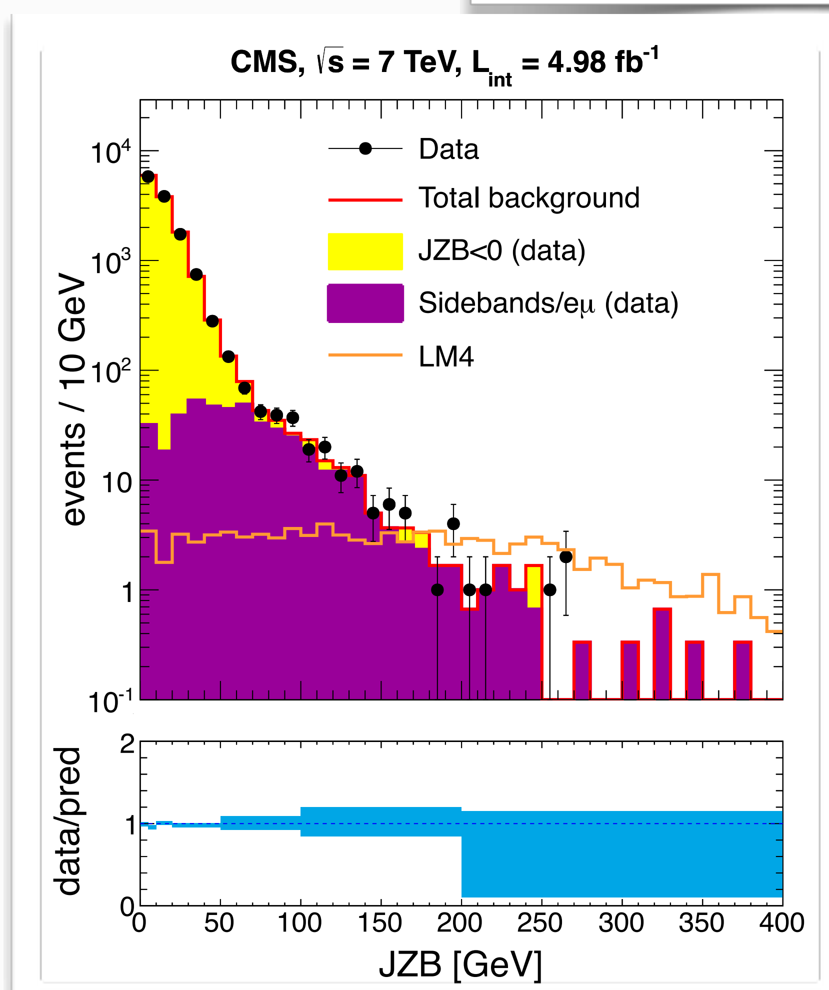
**1 Event selection:**

- ≥3 jets ($p_T$ > 30 GeV, central)
- Two $p_T$ > 20 GeV, opposite-sign, same flavor isolated leptons (e or μ).
- Dilepton invariant mass within 20 GeV of nominal Z mass.



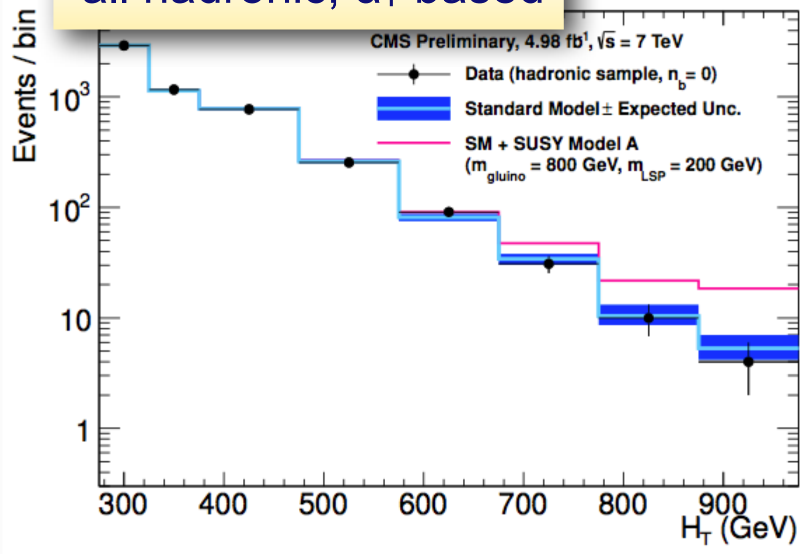

- JZB : Jet- Z - Balance
- MET in Z+jets events: fake, from jet mis-measurements
- Z+jets bkg on positive JZB: from negative JZB part
- top backg : use opposite-flavour events



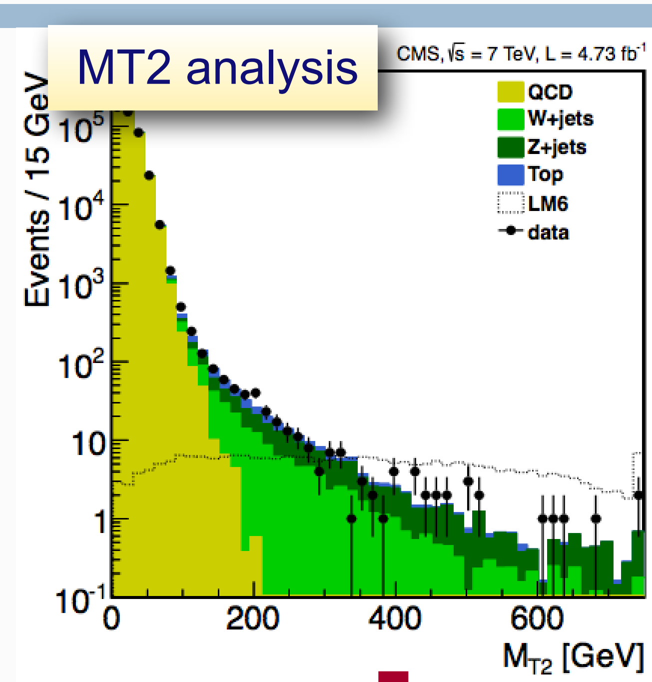




arXiv:1204.3774

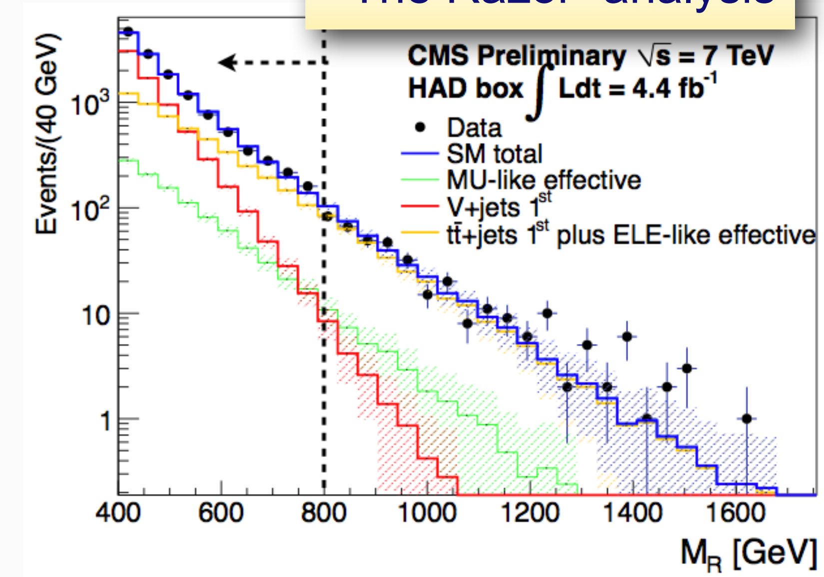
all hadronic, $\alpha_T$ based




MT2 analysis

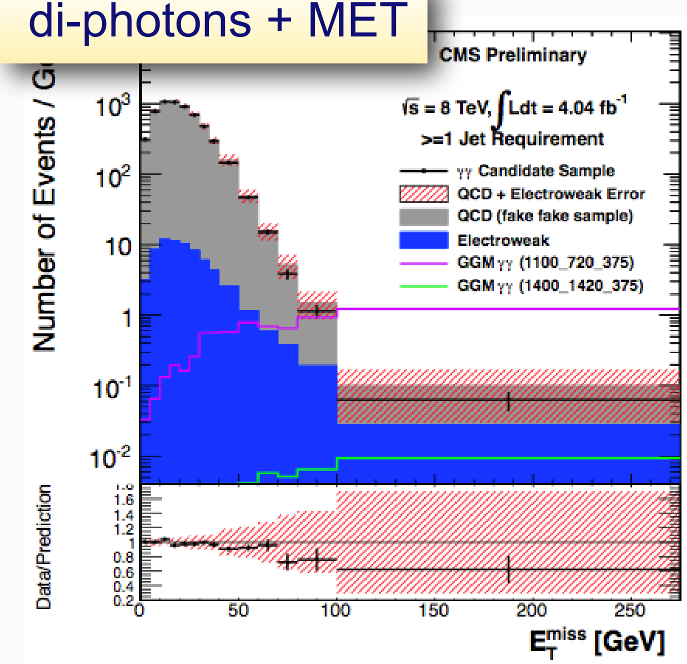



"The Razor" analysis

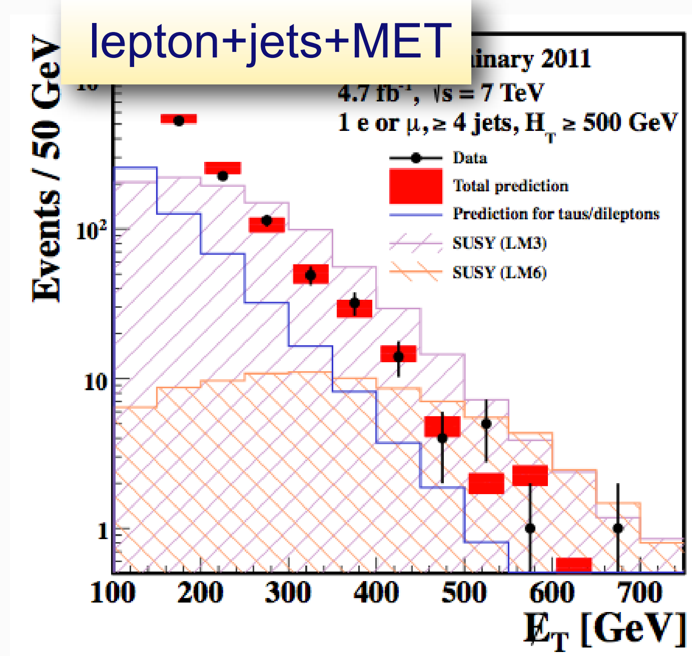



# Searches for Supersymmetry

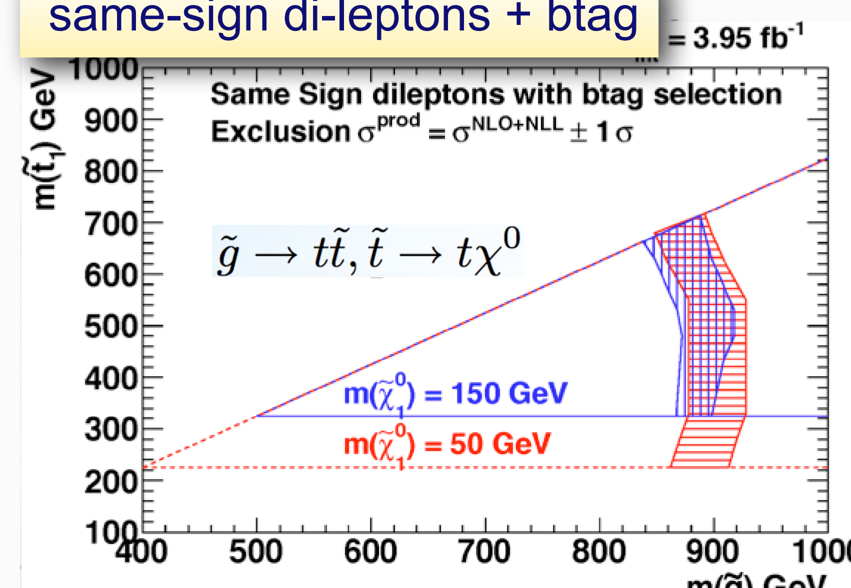
di-photons + MET




lepton+jets+MET




same-sign di-leptons + btag



# Example of the CMS strategy



| 0-leptons | 1-lepton | OSDL | SSDL | ≥3 leptons | 2-photons | γ+lepton |
|---|---|---|---|---|---|---|
| Jets + MET | Single lepton + Jets + MET | Opposite-sign di-lepton + jets + MET | Same-sign di-lepton + jets + MET | Multi-lepton | Di-photon + jet + MET | Photon + lepton + MET |

**Large** SM backgrounds **Low**

sensitivity to strongly produced SUSY

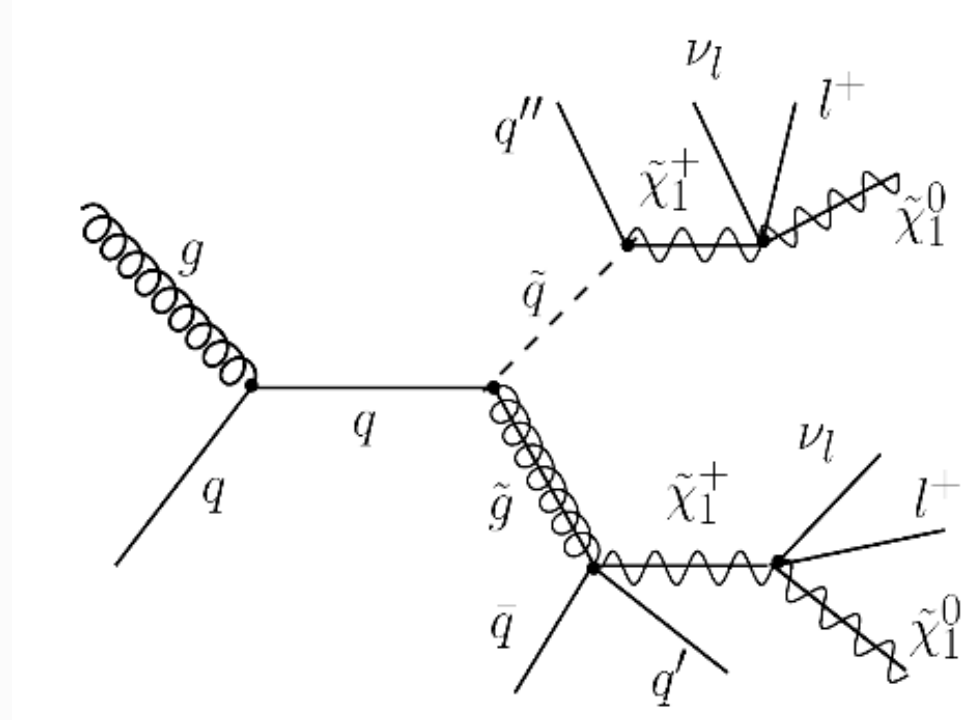
sensitivity to gauge-mediated SUSY

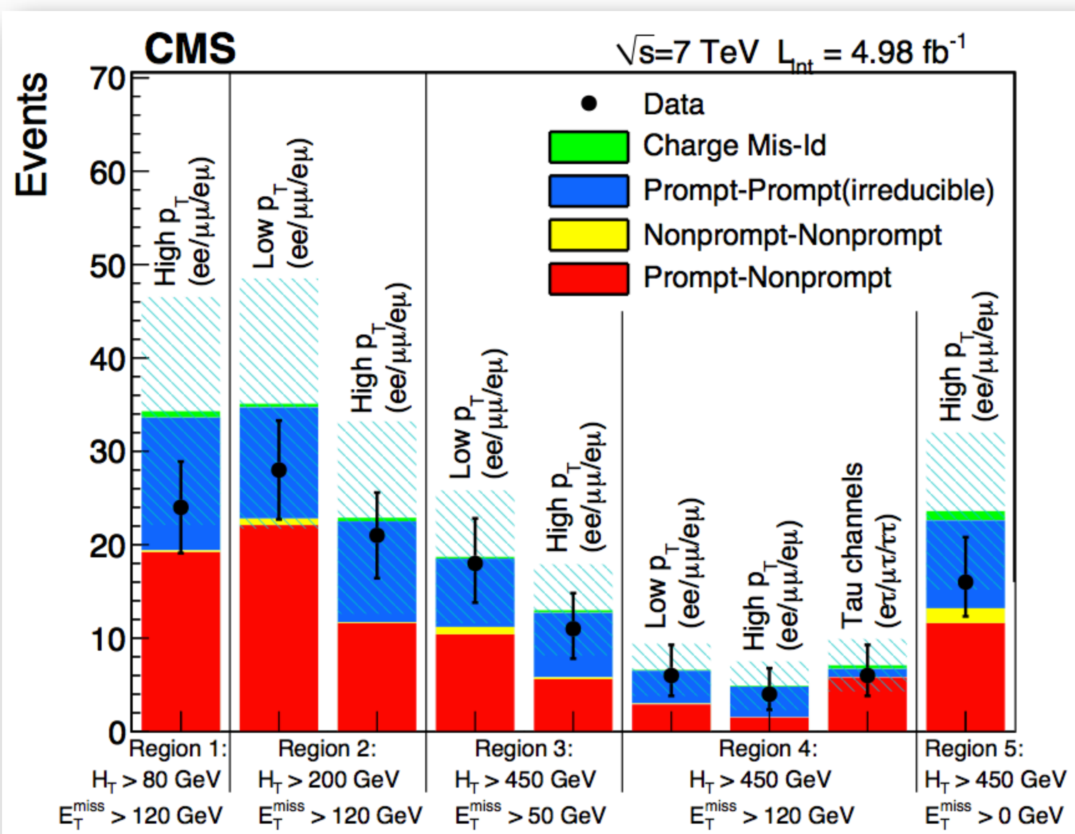
- **Focus on signatures (topologies)**, use different approaches/observables
  - alpha_T, "Razor", MT2, HT, MHT, ...
  - more recently: add b-tags to enhance sensitivity to 3rd gen. squarks, and design dedicated, "high-precision" 3rd gen. searches
- Established many different **data-driven techniques** to derive backgrounds
  - jet smearing and re-balancing, ABCD, fakeable-object technique to estimate fake lepton rates, generic properties of lepton $p_T$ spectra, generic properties of falling SM spectra
- Different trigger paths (all hadronic HT-based, leptonic)
- Not necessarily optimized for best excl. limits, but sharpened tools for discovery!
- **cross check, cross check, cross check....**

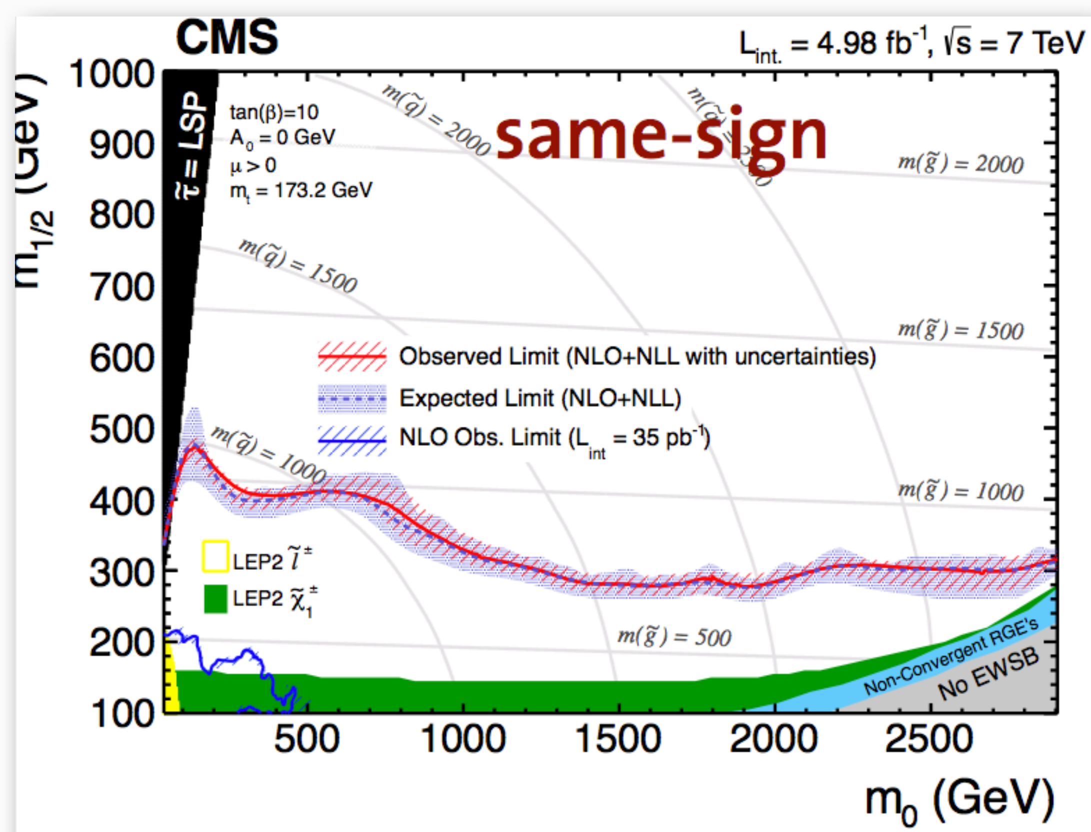
# Example: same-sign dileptons +MET



- Very low SM backgrounds
- Name of the game: fake-rate estimates
  - estimated from data
- Baseline selection
  - Define different search regions, based on lepton $p_T$, $H_T$, MET



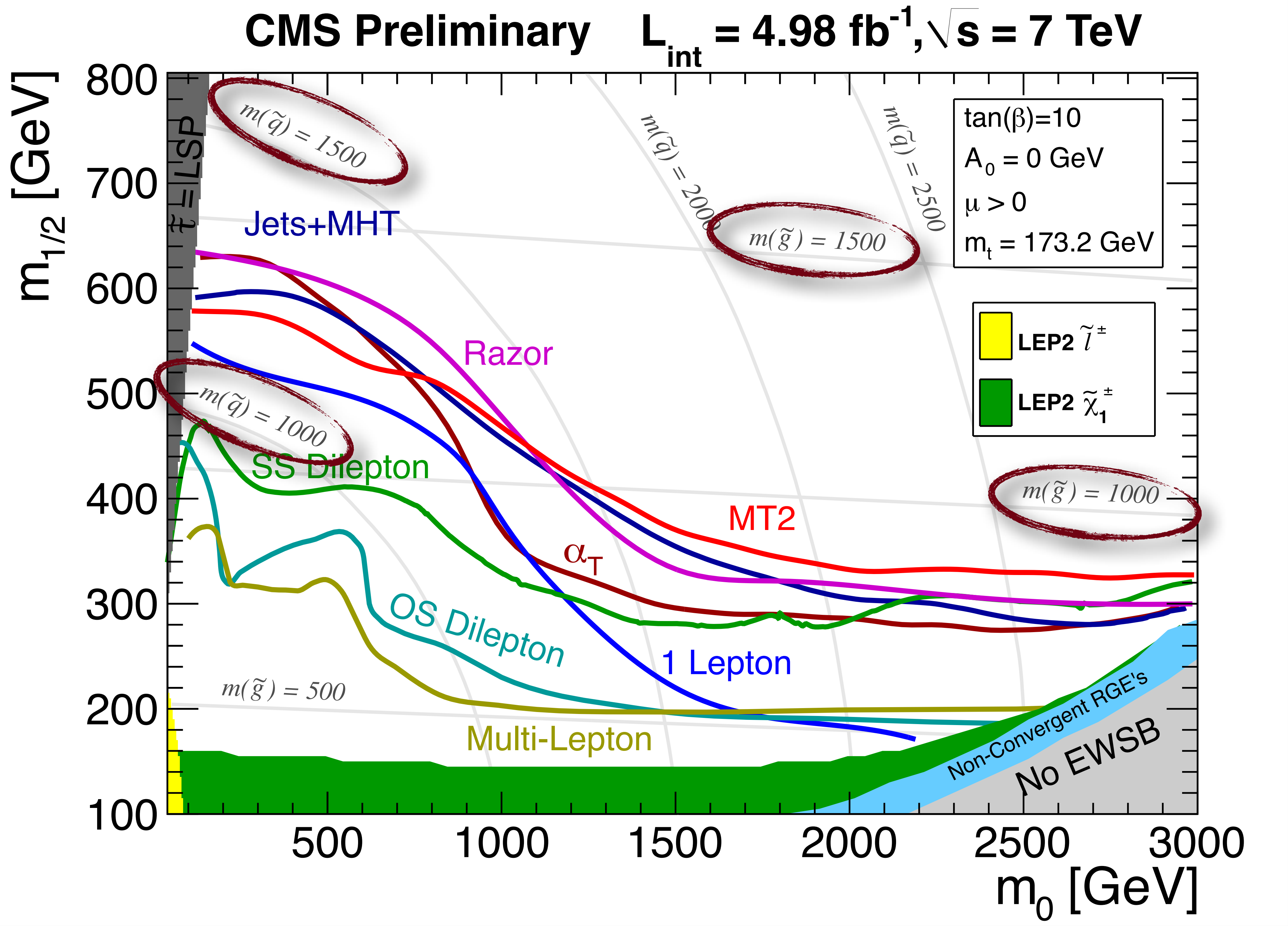




arXiv:1205.6615

# And the results are...

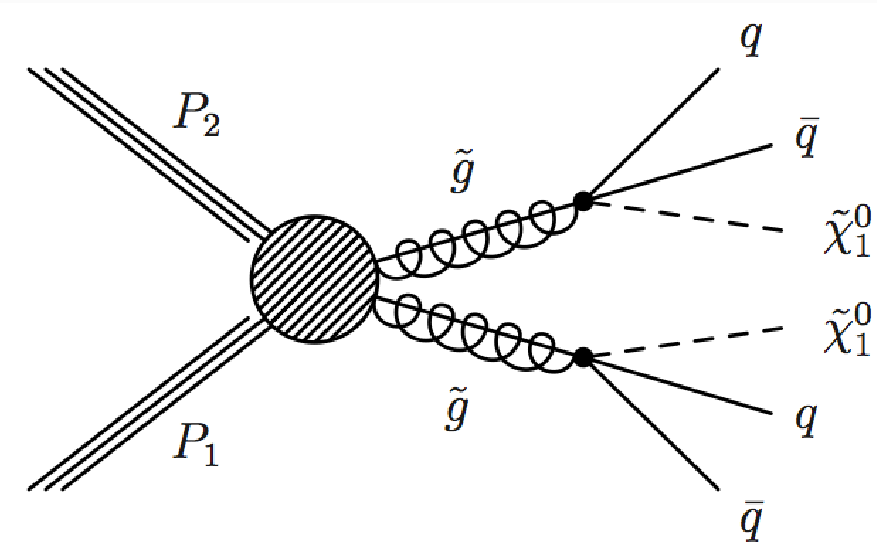
- in the context of the cMSSM

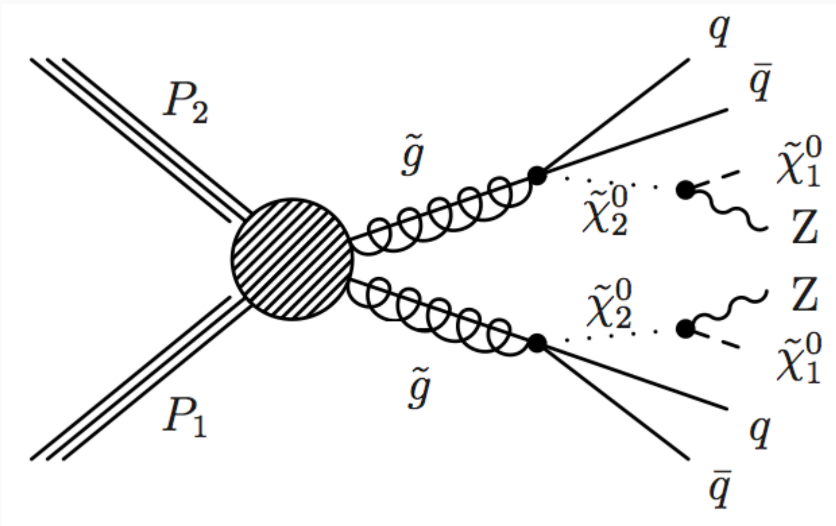


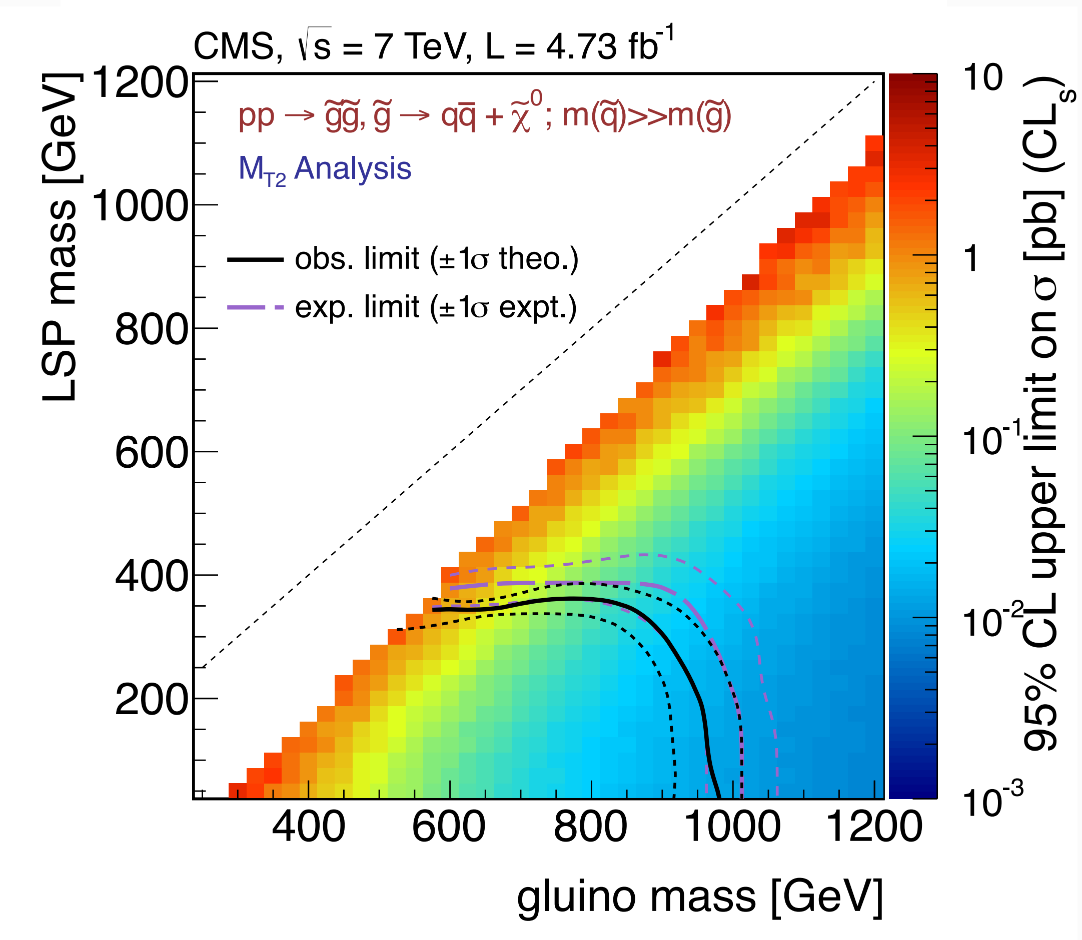
# Interpretation: Simplified models

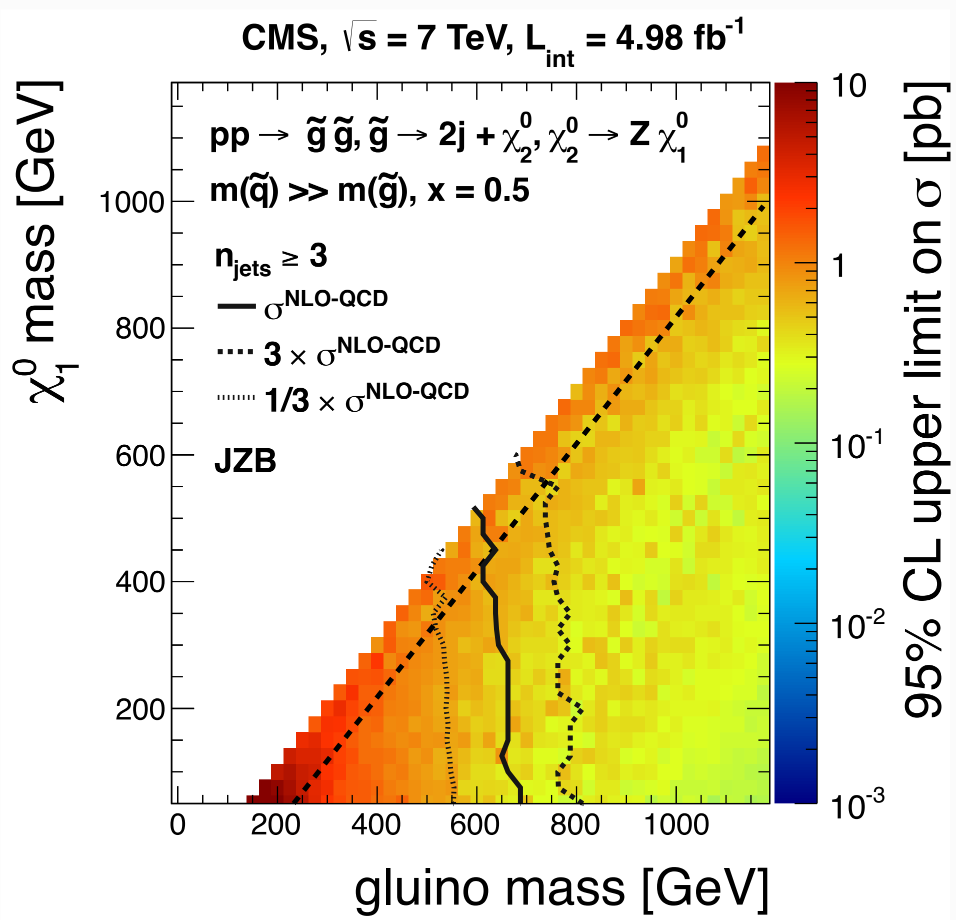
ETH Institute for Particle Physics

Models proposed at: http://www.lhcnewphysics.org



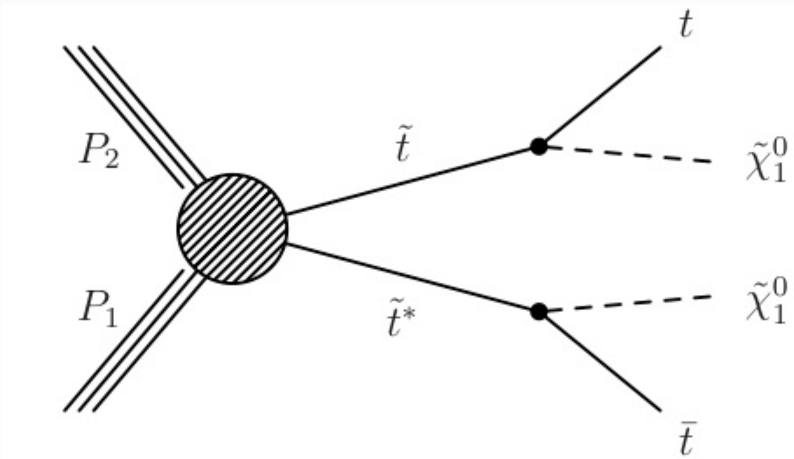

**ie. re-interpret existing searches and provide information to model builders in this generic form**

**Watch out regarding (simple) assumptions made, eg. about branching ratios**

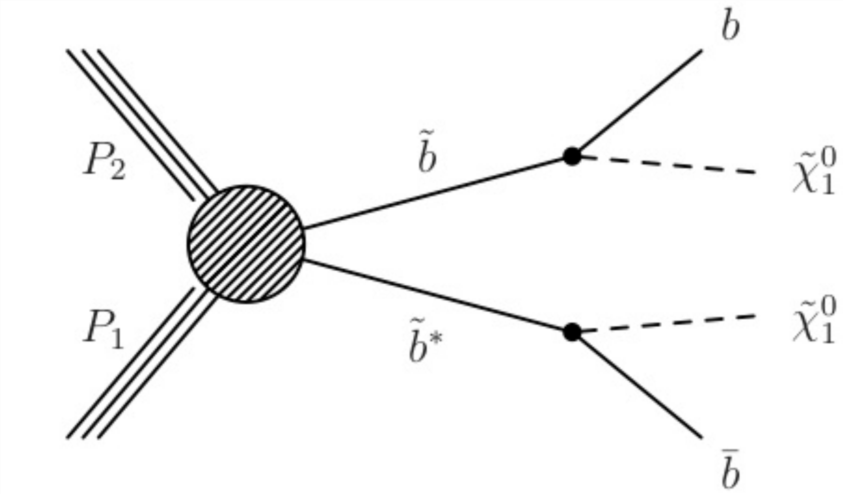
# Interpretation: Simplified models

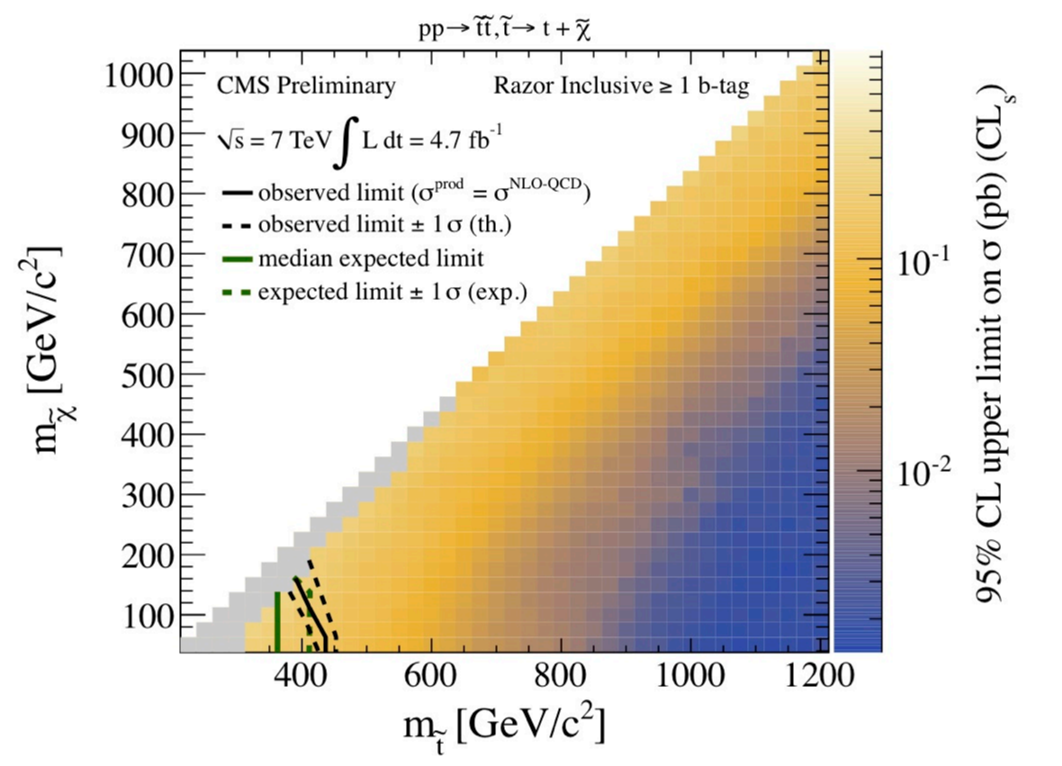
**example of a 3rd generation search, for direct stop / sbottom production**

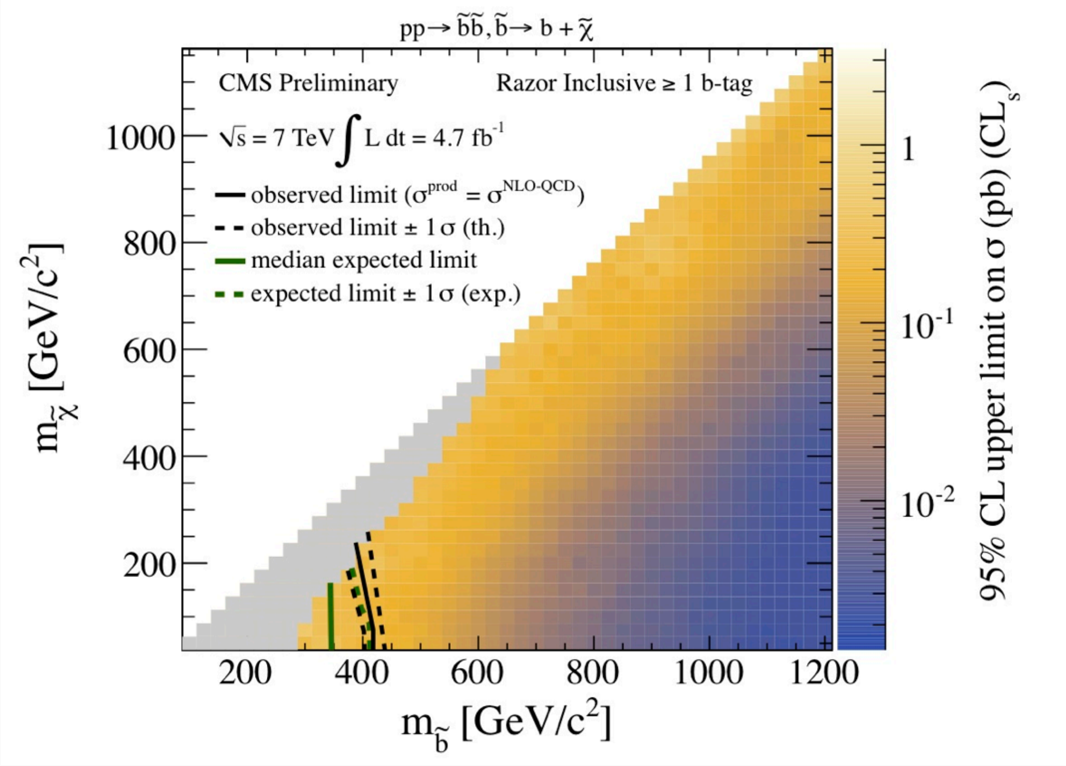
T2tt - Di-stop production resulting in 2 top quarks + MET final states



T2bb - Di-sbottom production resulting in 2 b quarks + MET final states

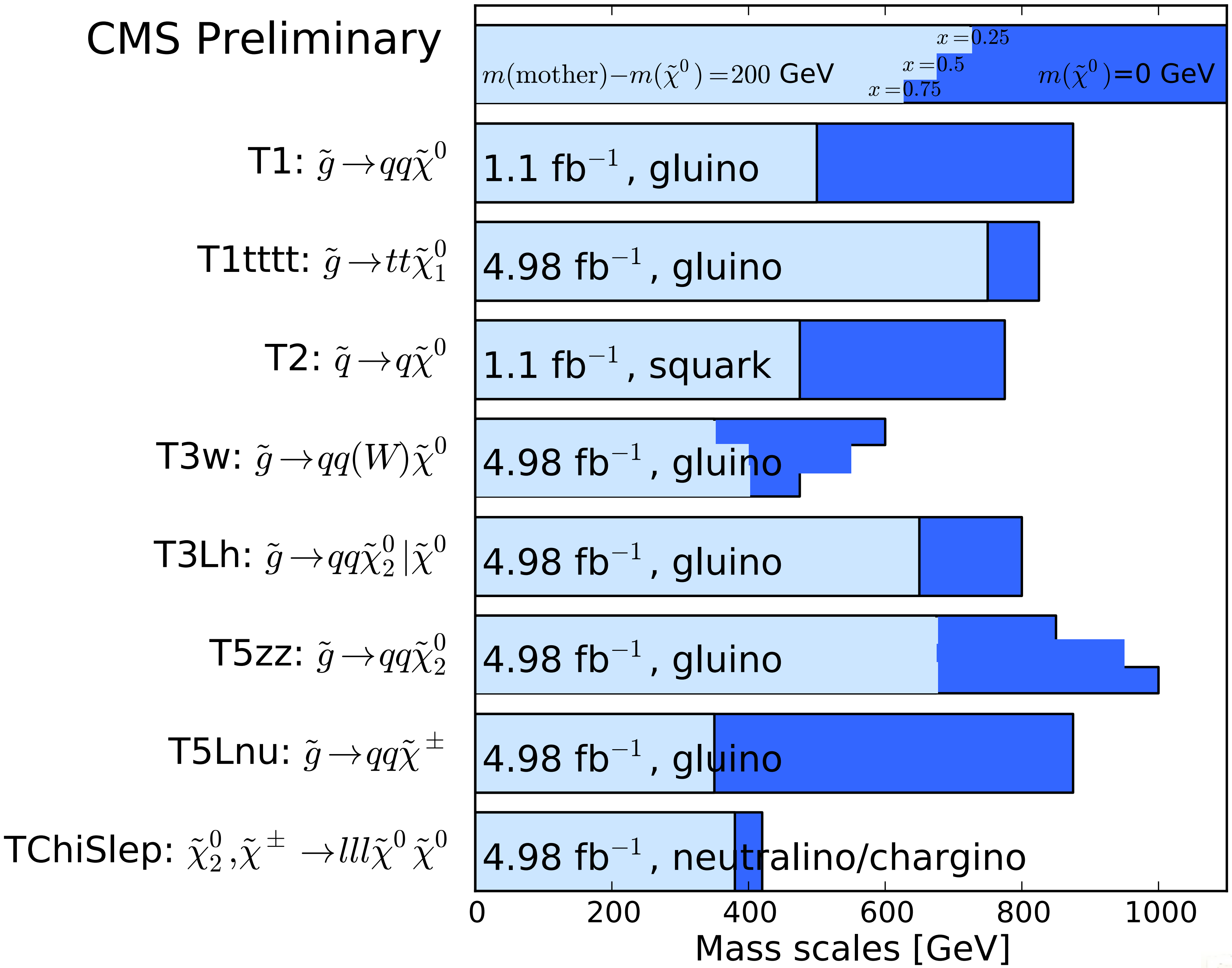





CMS-SUS-11-024

# Simplified models




For limits on $m(\tilde{g}),m(\tilde{q})>>m(\tilde{g})$ (and vice versa). $\sigma^{\text{prod}}=\sigma^{\text{NLO-QCD}}$.

$m(\tilde{\chi}^{\pm}),m(\tilde{\chi}^0_2)\equiv\frac{m(\tilde{g})+m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ is varied from 0 GeV$/c^2$ (dark blue) to $m(\tilde{g})-200$ GeV$/c^2$ (light blue).

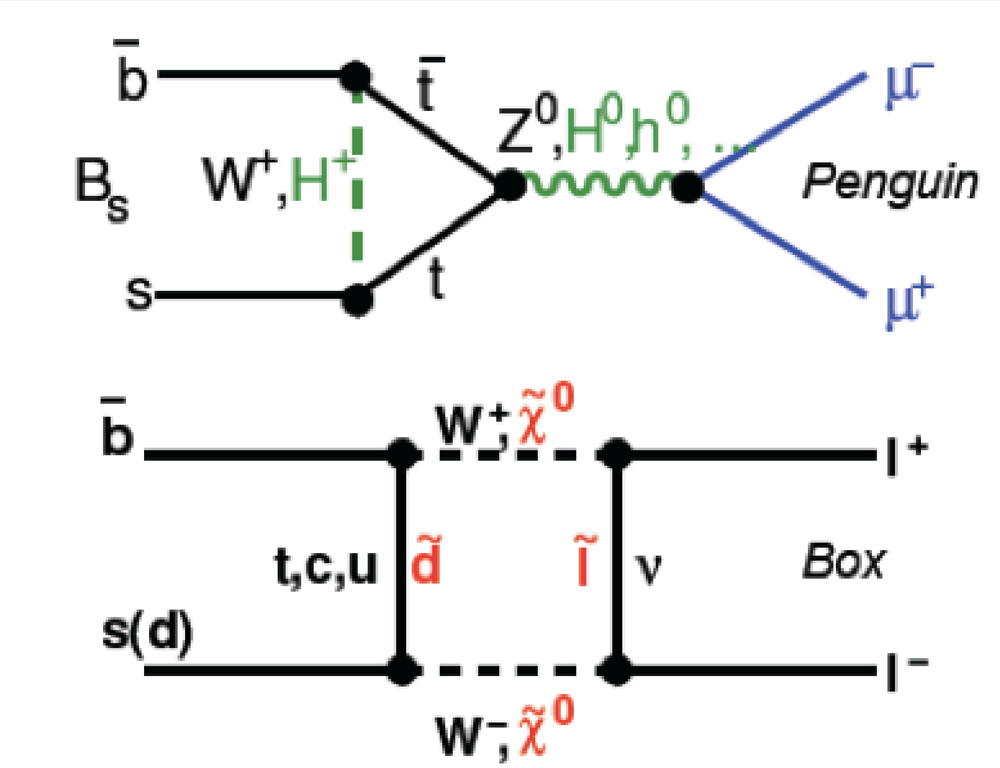
Note the fine print: Limits get weaker and weaker for heavier neutralinos (less mass splitting, less MET). Also, 100% BR assumed!

# And finally, not to forget...



## Why searching for $B_{s,d} \to \mu^+\mu^-$ ?

- **Decays highly suppressed in SM**
  - Forbidden at tree level
  - $b \to s(d)$ FCNC transition only through penguin and box diagrams
  - Helicity suppressed by factors of $(m_\mu/m_B)^2$



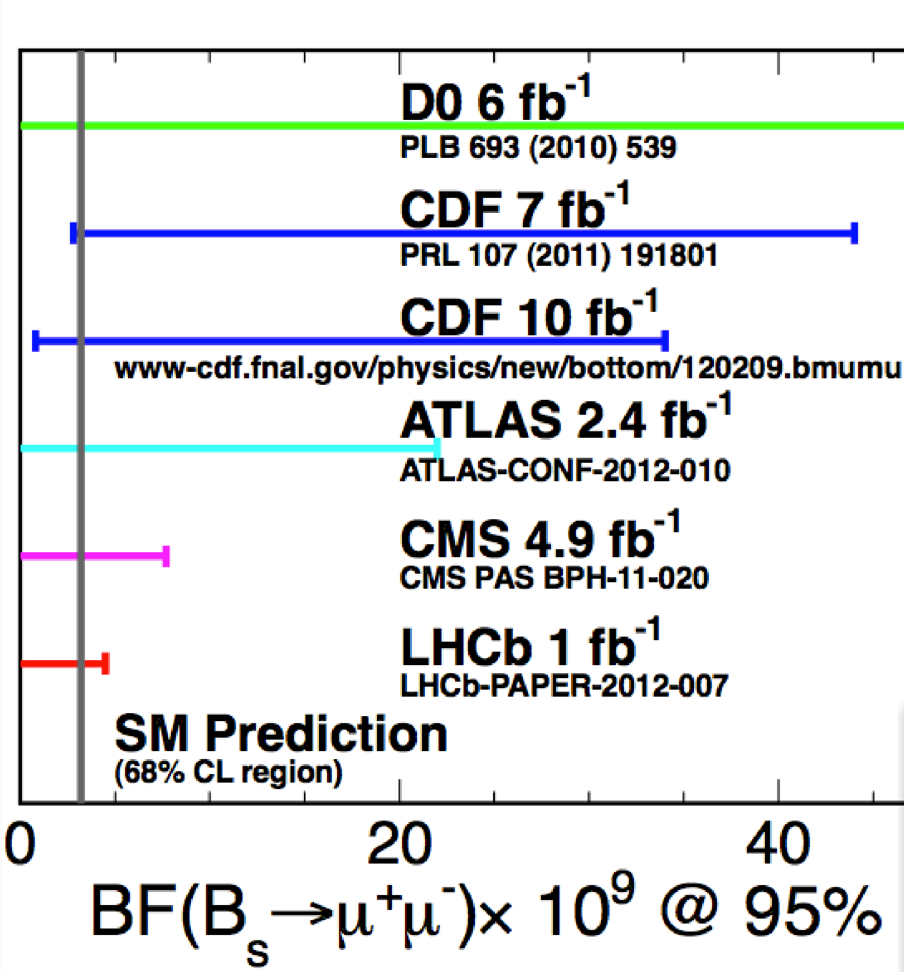

- **Standard Model Predictions**
  - $Bs \to \mu\mu = (3.2 \pm 0.2)\ 10^{-9}$
  - $Bd \to \mu\mu = (1.0 \pm 0.1)\ 10^{-10}$

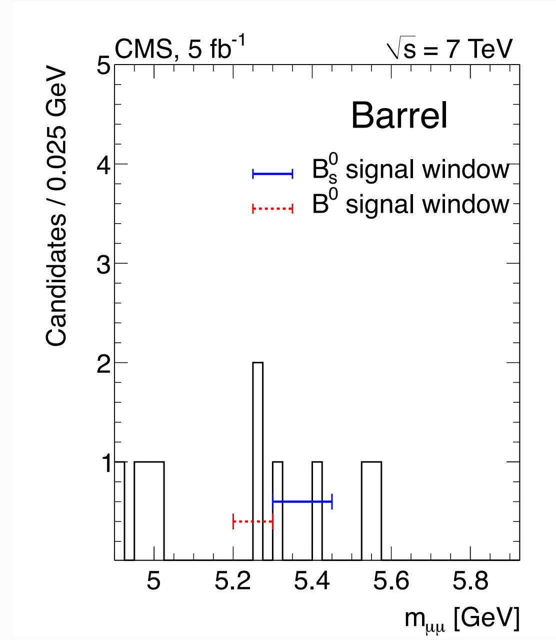
- **Sensitivity to New Physics**
  - BR in MSSM proportional to $\tan\beta^6$

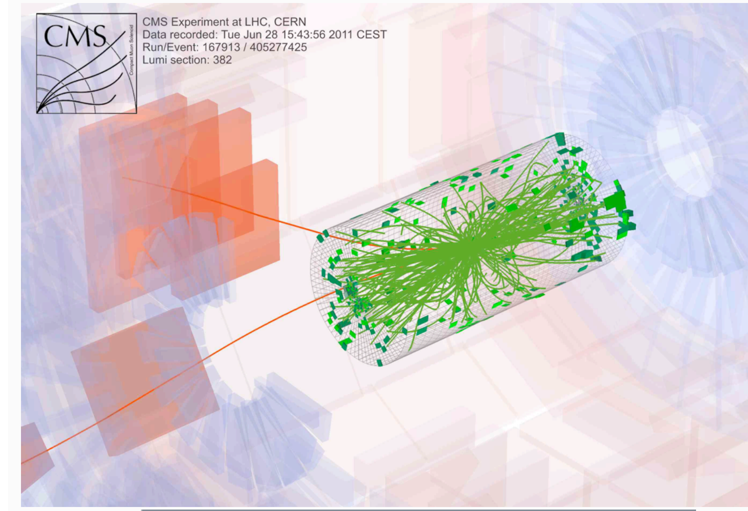
Wien
26/11/11 gigi.rolandi@cern.ch CMS Status and Physics 10 /52

# A very rare decay



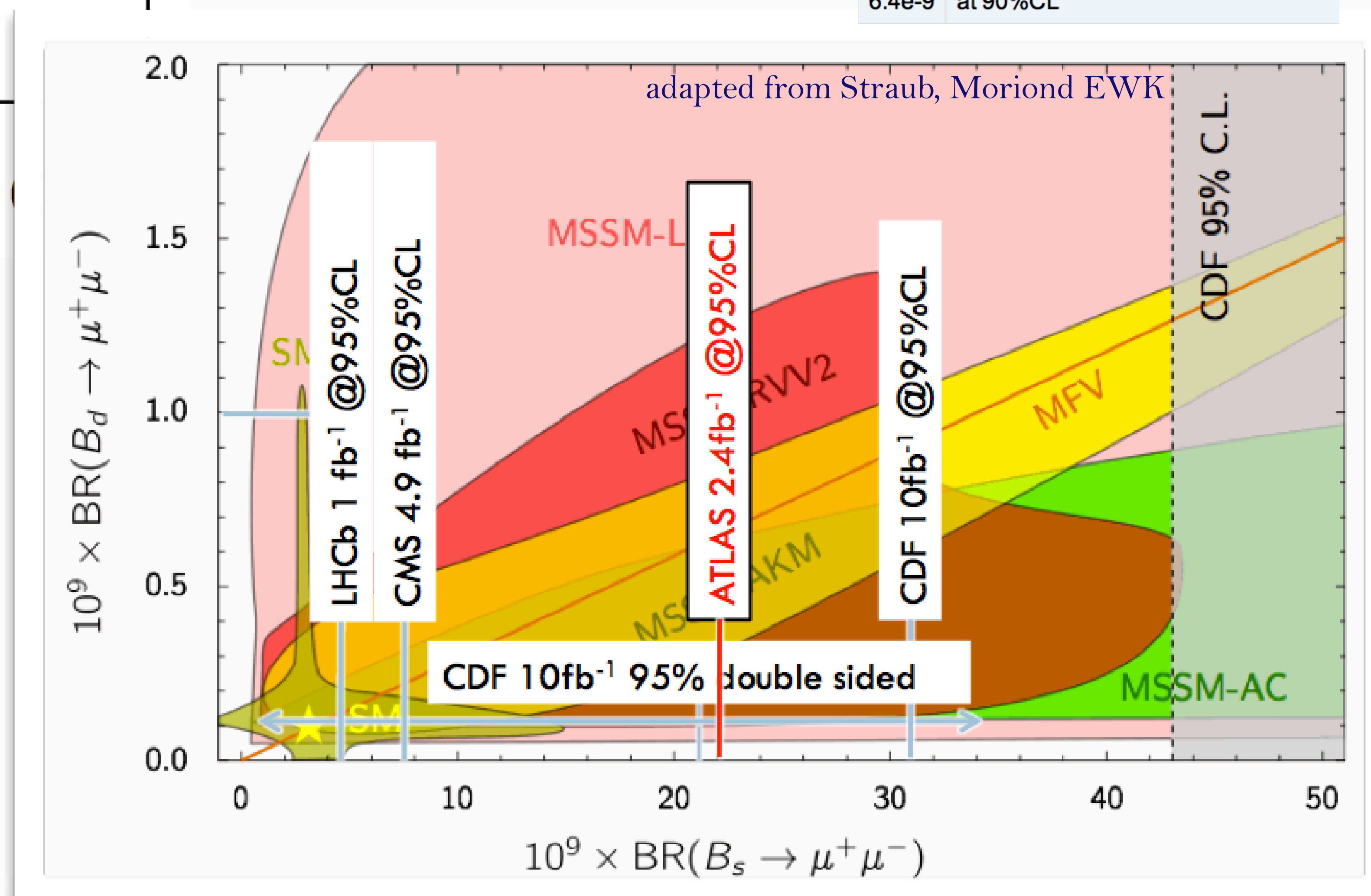


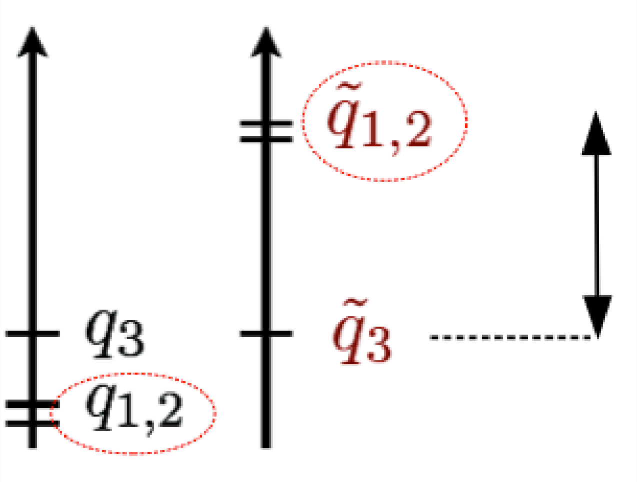

| Observed upper limit on BF(Bs -> mu mu) | |
|---|---|
| 7.7e-9 | at 95%CL |
| 6.4e-9 | at 90%CL |

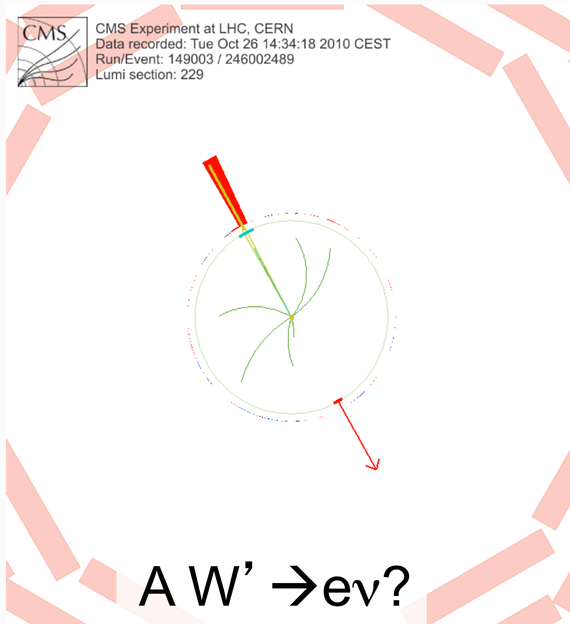
**Examples of implications:**



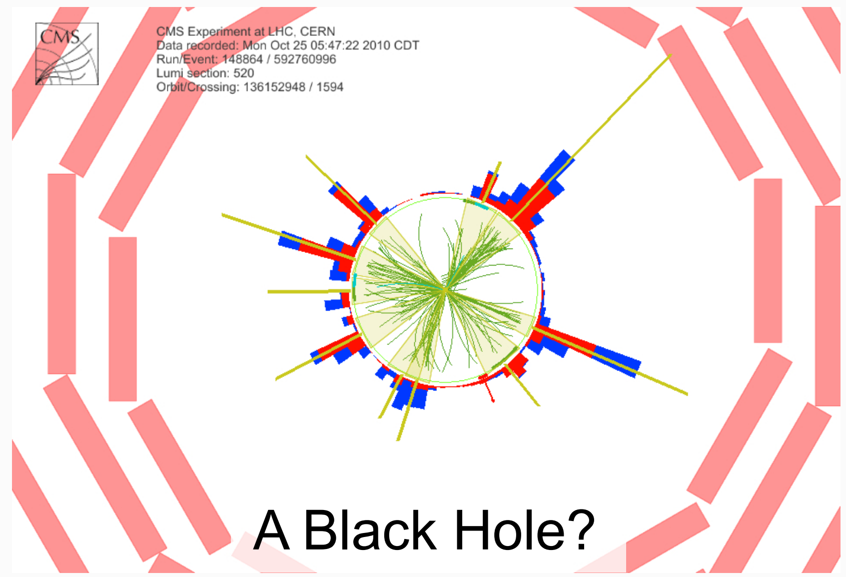
# So....

- CMSSM is being cornered
  - very much so, also because of recent Higgs results
  - “Vanilla SUSY searches” at the LHC exclude gluinos and light squarks at and beyond O(1) TeV by now, much weaker limits for all other parts of the SUSY spectrum, eg.
    - 3rd gen. squarks below ~300-400 GeV
    - “EWKinos”, eg. from direct chargino-neutralino production: ~ O(100) GeV
  - In developing **data-driven methods**, actually there are often **interesting side-products**, in terms of probing SM processes in challenging regions, eg. **gamma+njets/Z+njets**
- Naturalness to be given up?
- However, remember:
  - in the beginning we have been running for the low-lying fruits
  - they are not hanging where we hoped for
  - Only “simple” SUSY models being squeezed
  - Now, a lot of effort going into searches for “light” 3rd generation partners (eg. previous searches plus b-tags),
    first results on stop and bottom searches appearing....
  - and thinking how to tackle difficult phase space regions,
    eg. with (close to) degenerate states

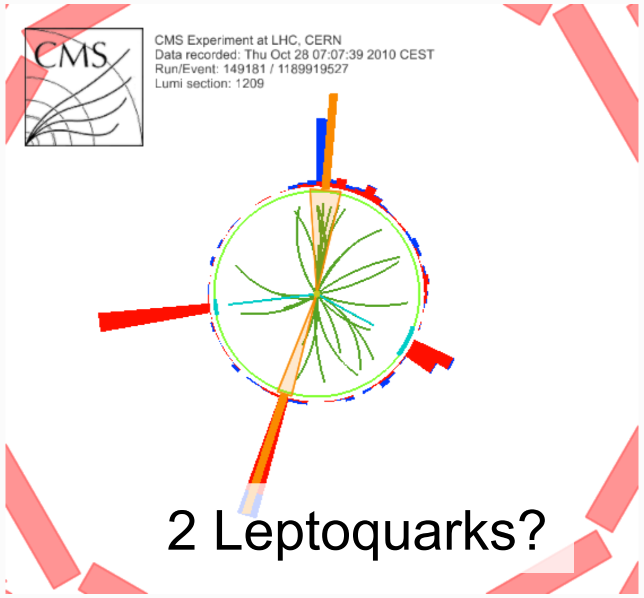





A W' →eν?

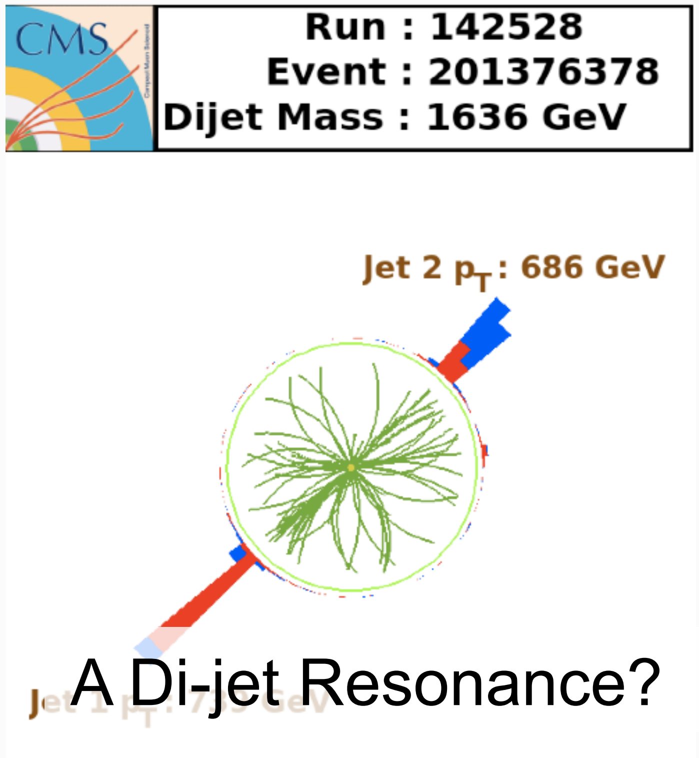



A Black Hole?

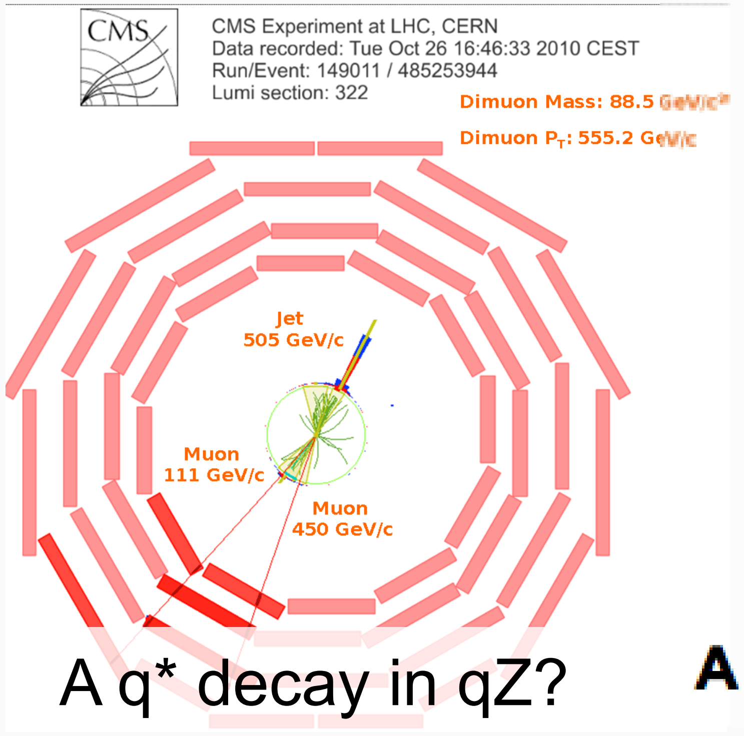



2 Leptoquarks?

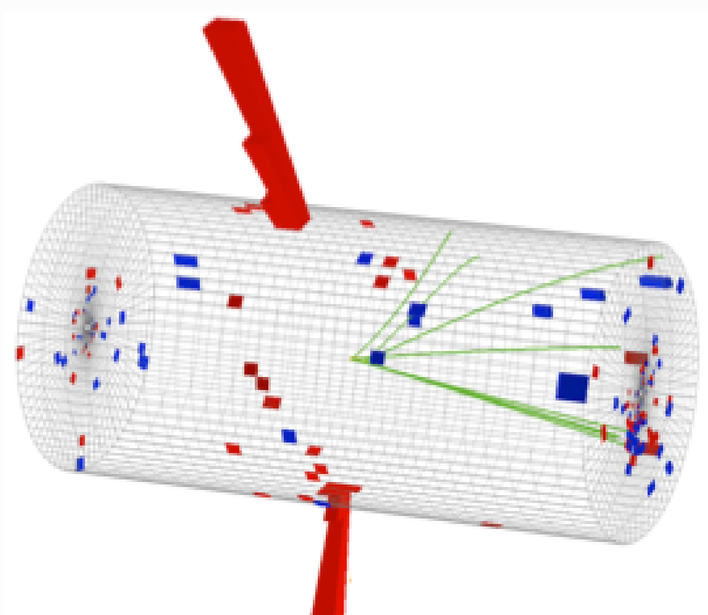
# Exotic signatures




A Di-jet Resonance?




A q* decay in qZ?



A graviton decay in γγ?

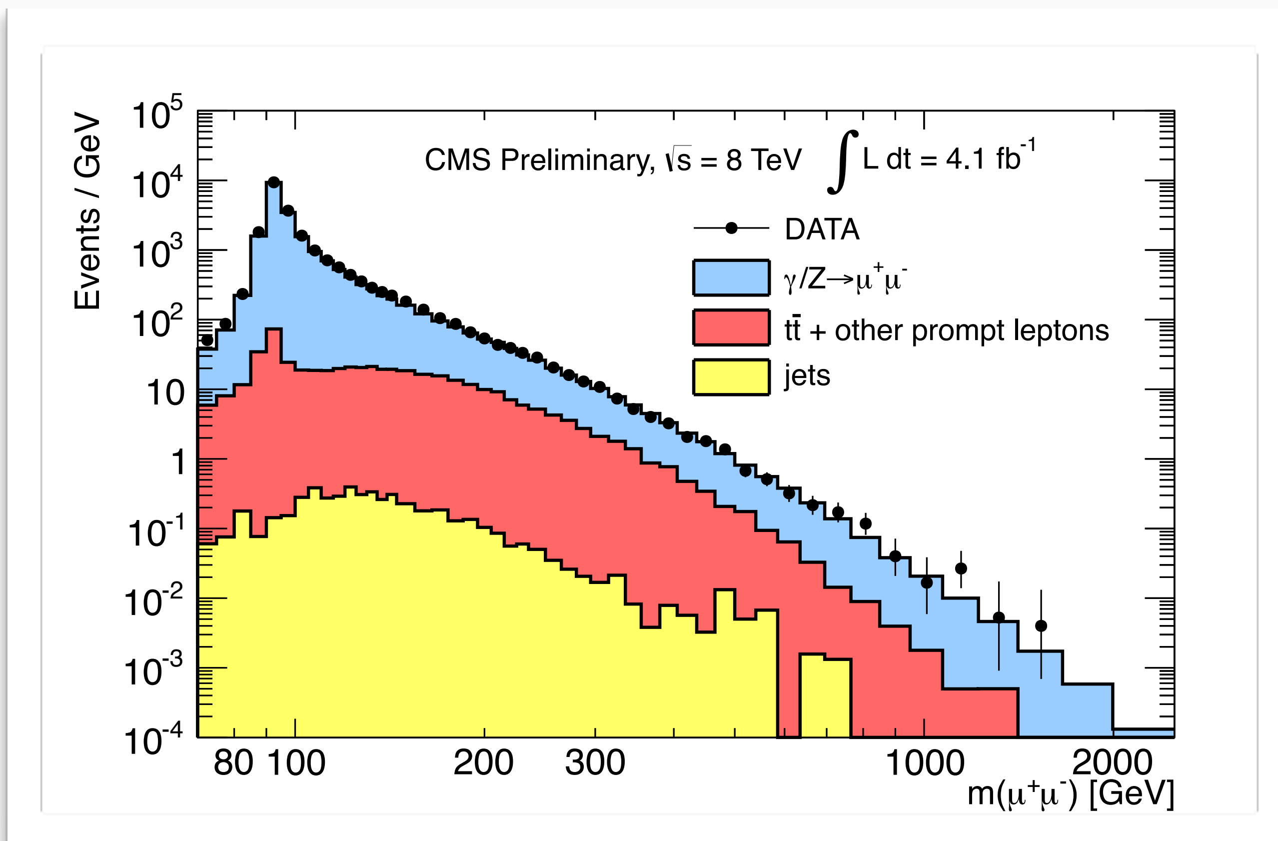
CTEQ

# Leptons (+ $E_{Tmiss}$)

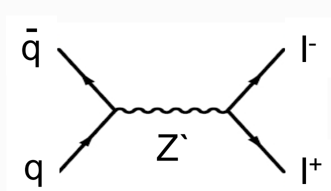
ETH Institute for Particle Physics

## Search for heavy resonances decaying to lepton pairs

- Bump hunt in M(ee, μμ) spectrum
- no deviations observed

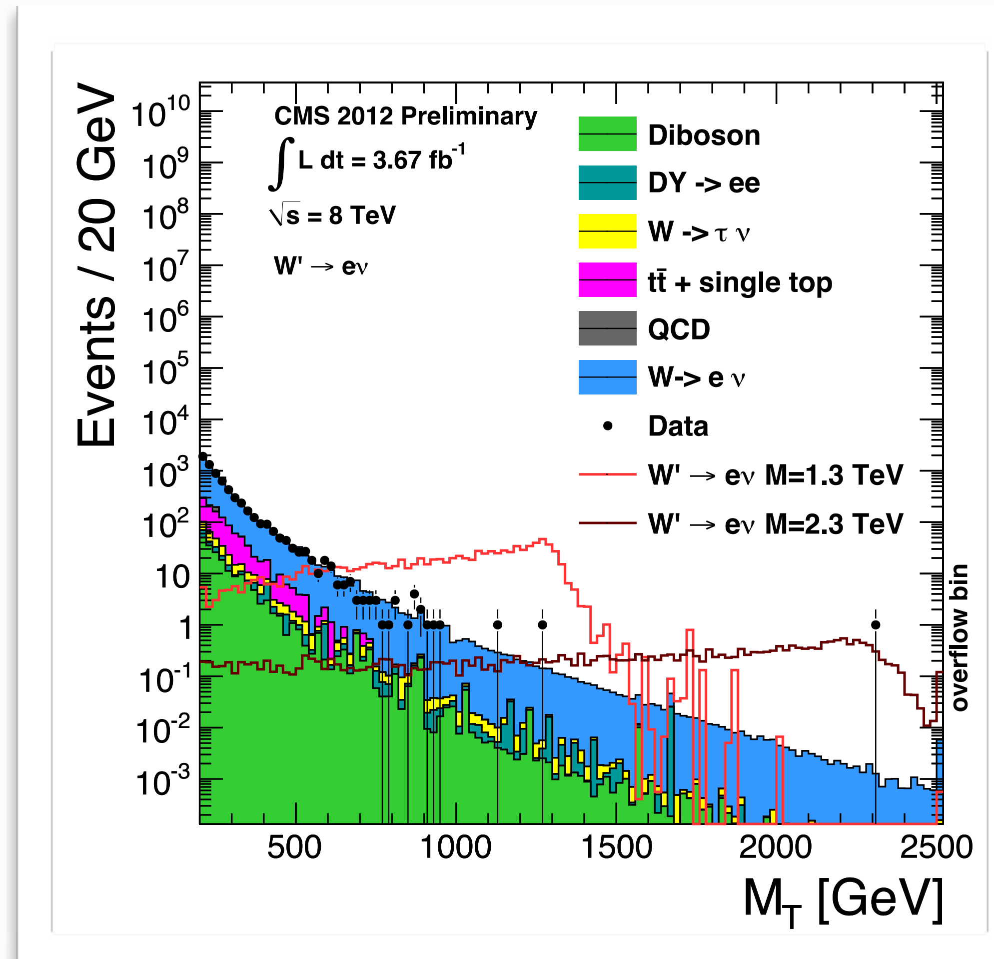



CMS-PAS-EXO-12-015

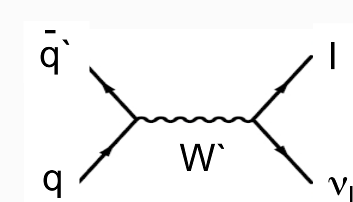



- Z’ with SM-like couplings **< 2590 GeV**

- Bump hunt in $M_T$(lν) spectrum
- no deviations observed




CMS-PAS-EXO-12-010

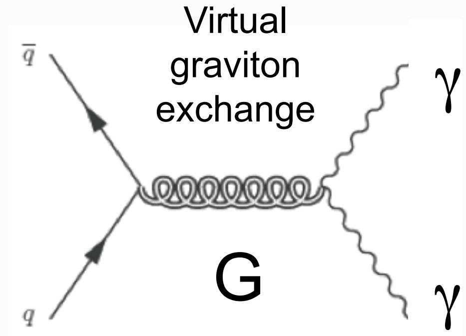


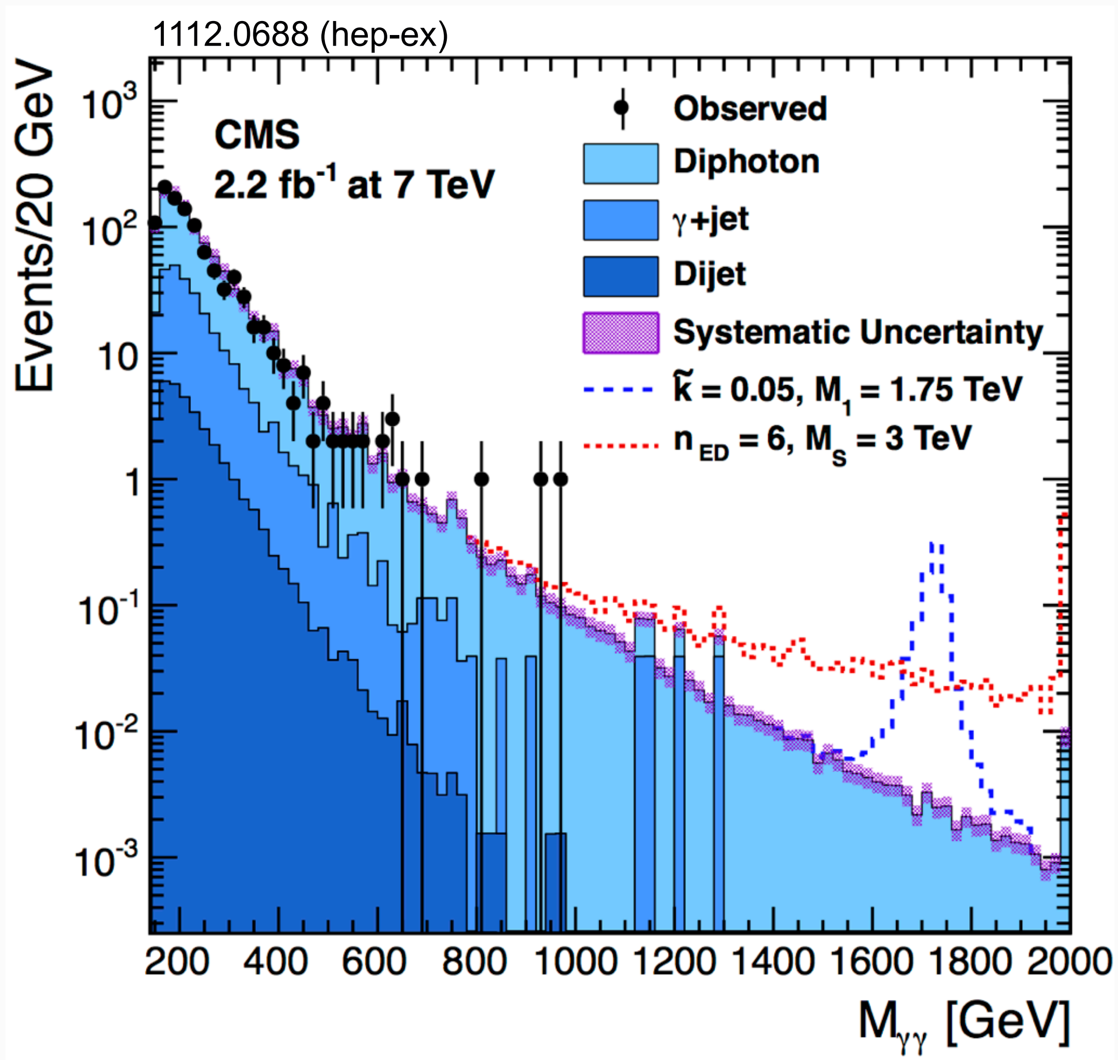

- W’ with SM-like couplings **< 2.85 TeV**

# Photons and Tops in the final state

ETH Institute for Particle Physics

**Search for LED via**



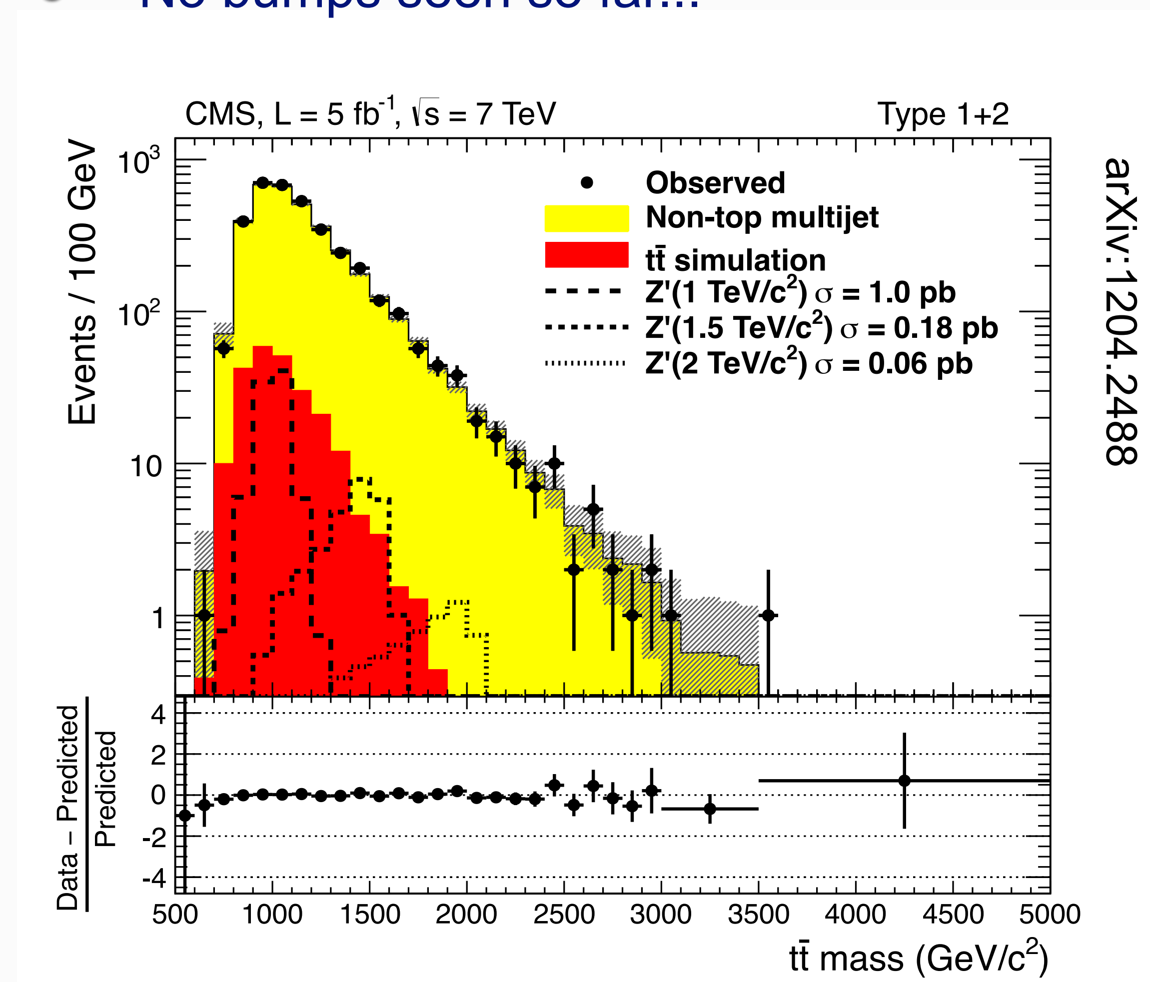



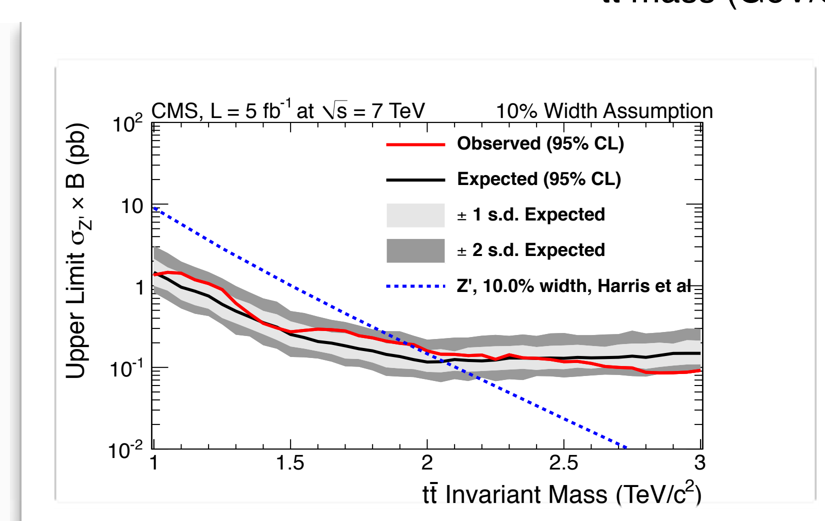

Photons in ECAL barrel, $E_T$> 70 GeV

Upper limit on σxBRxA < 3 fb for $M_{\gamma\gamma}$>900 GeV

lower limits on eff. Planck scale of 2.3 - 3.8 TeV !

- **Search for massive neutral bosons**
- Bump hunt in M(ttbar) spectrum
- Reconstructing boosted tops
- No bumps seen so far...

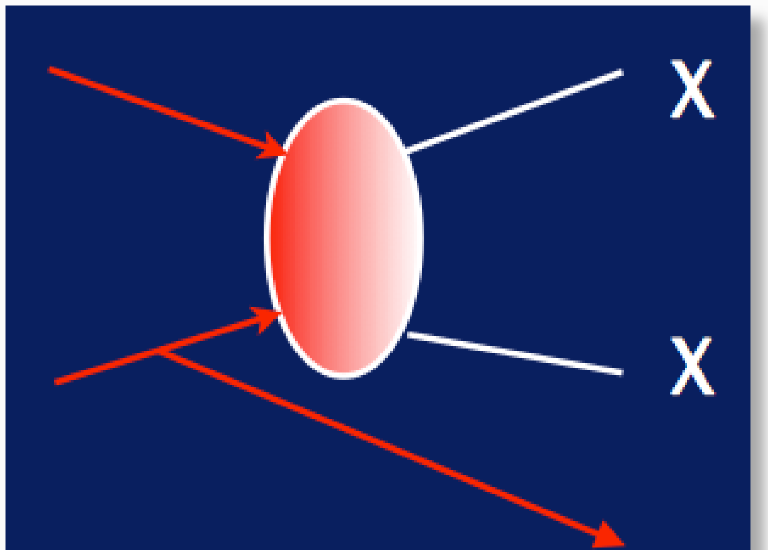


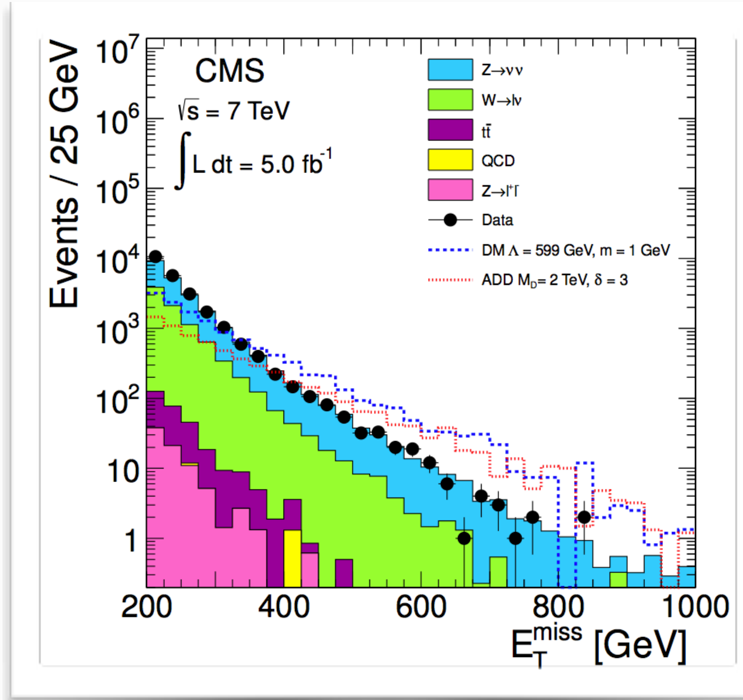



# Complementarity is always nice



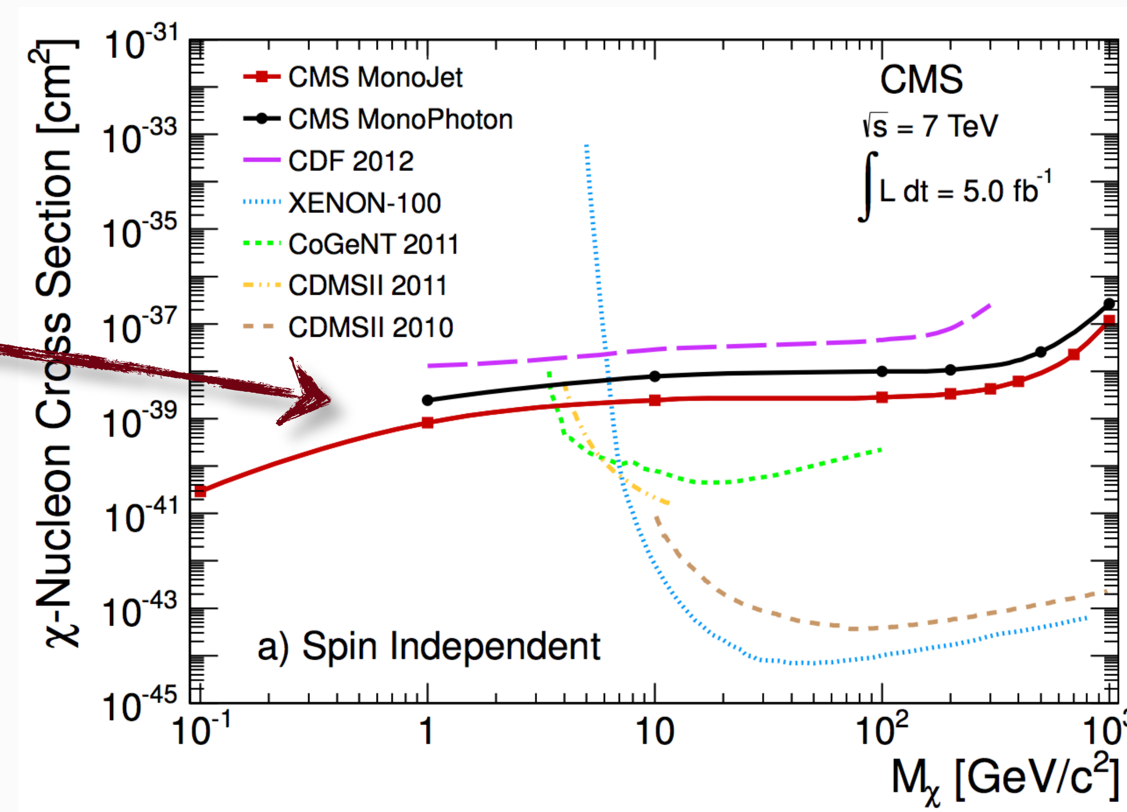
- Interesting complementarity of collider exps and direct DM detection
  - monojets, photons+MET



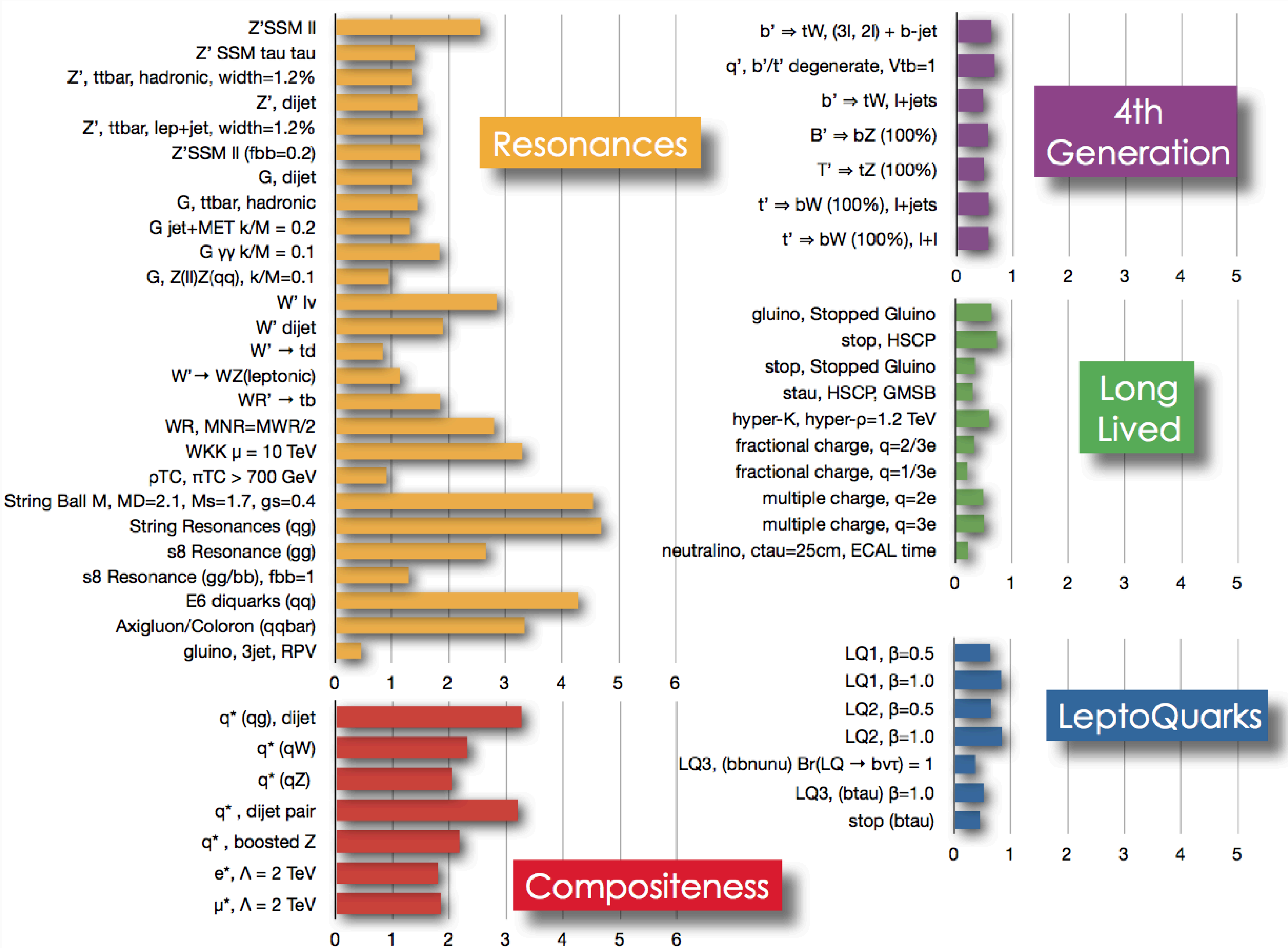




arXiv:1204.0821

**At colliders we probe parton-DM couplings, whereas in DDM it is the coherent nucleon-DM scattering. Collider exps can cover much lower masses and also very high cross sections not accessible by underground direct DM (DDM) detectors.**



# And many, many more...



# Grand Summary of Searches

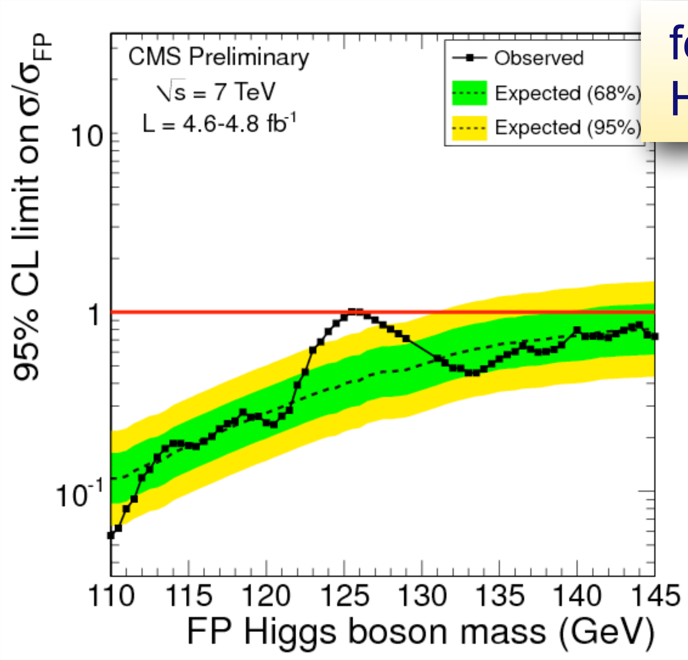
- In (too?) simple terms:

## LHC Search Summary

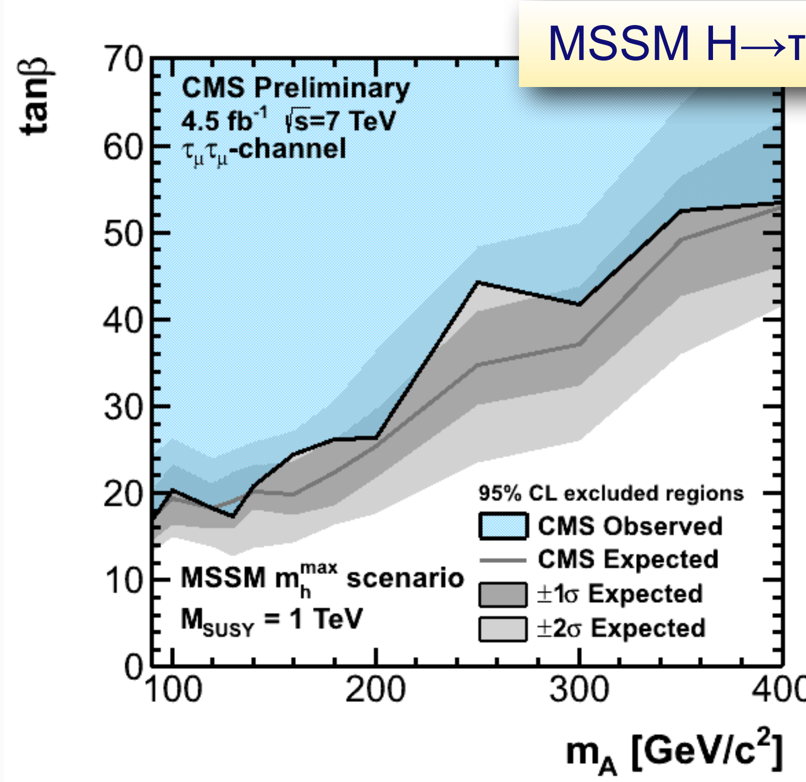
No signatures for new physics yet
→ Simple Summary (LP11: H. Bachacou)

| | Lower Limit (95% C.L.) |
|---|---|
| CMSSM ~~SUSY~~ ($m_{\tilde{q}} = m_{\tilde{g}}$) | 1 - 1.2 TeV |
| Gauge bosons (SSM) | 2 - 3 TeV |
| Excited quark | 3 TeV |

A. de Roeck, Sep11

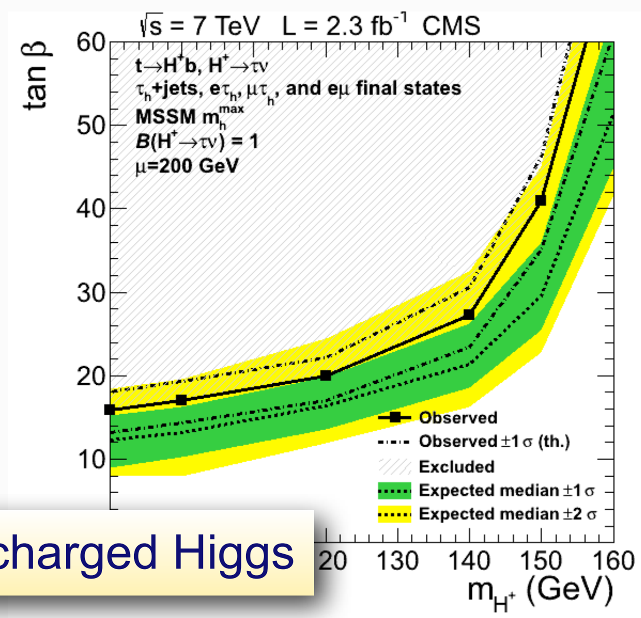



fermiophobic Higgs



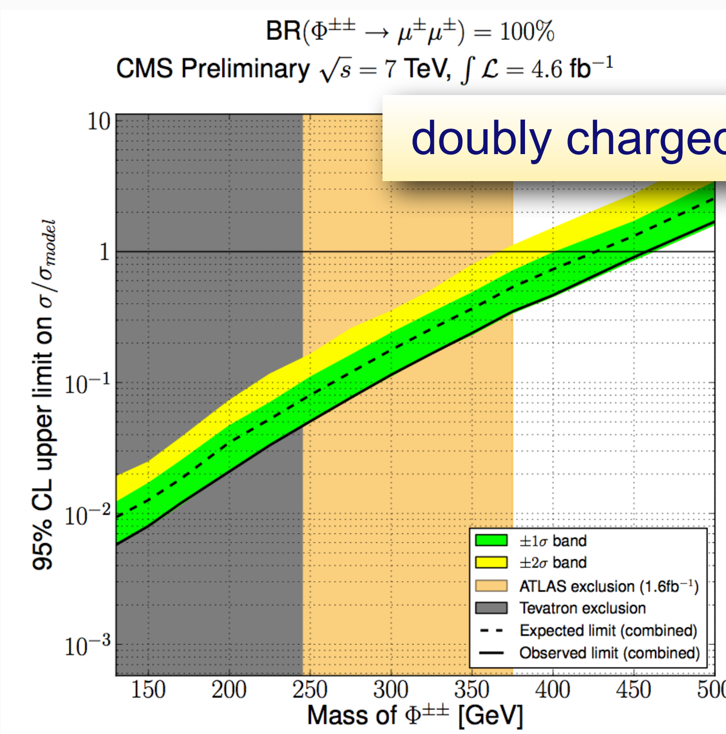

MSSM H→ττ

# Higgs searches




charged Higgs

**in the following:**
**concentrating on SM Higgs,**
**low mass range,**
**most sensitive channels**



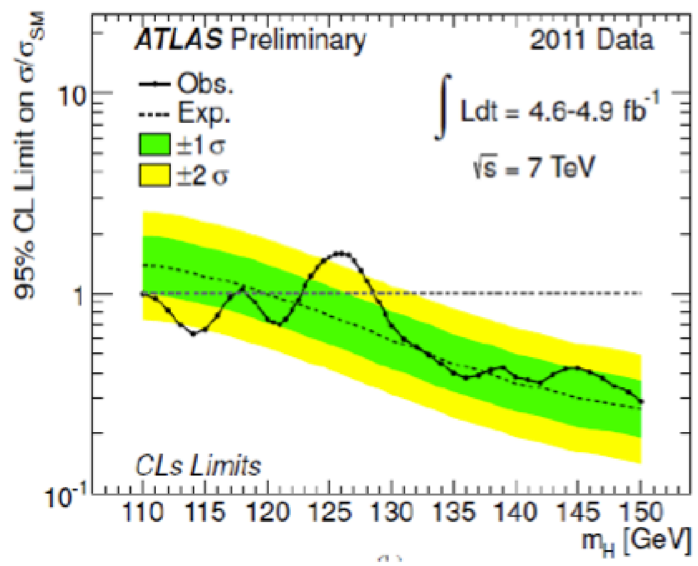

doubly charged Higgs

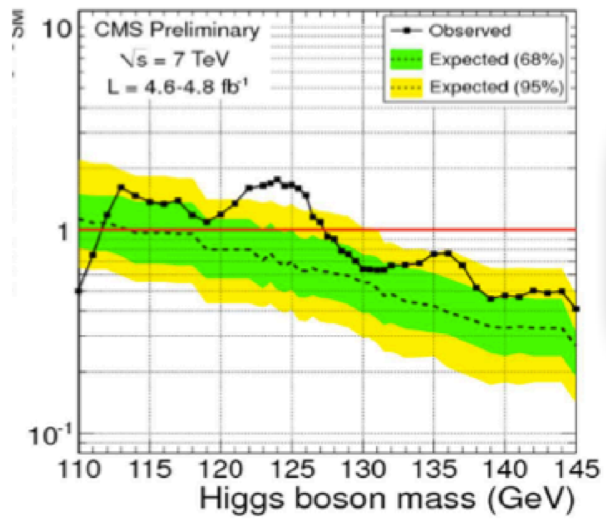
# Executive summary

*at the time of Moriond 2012*

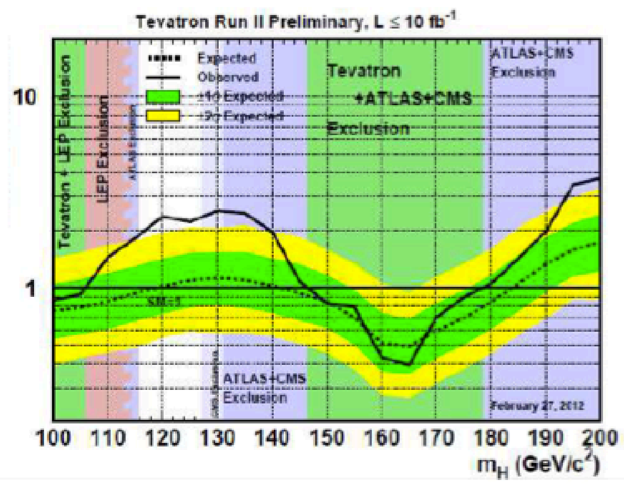
## The Higgs

*G. Altarelli*



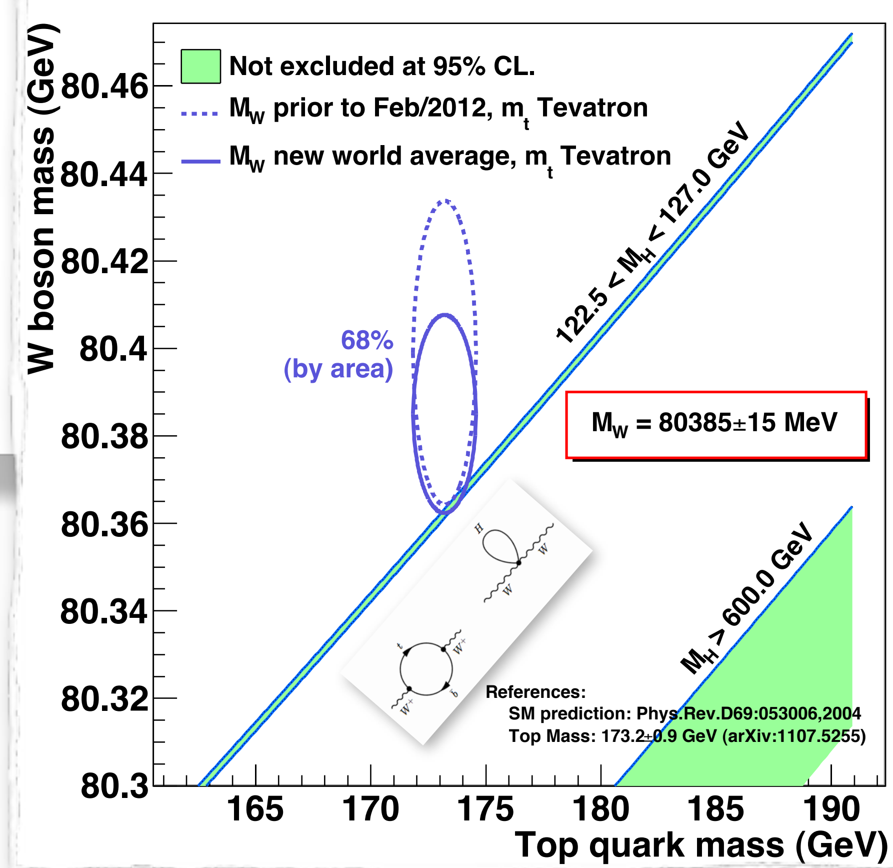

dashed line (plus errors, indicated by bands): what you'd expect in the case of background only




95% exclusion
ATLAS:
110-117.5, 118.5-122.5, 129-539 GeV
CMS:
127.5- 600 GeV

All experiments see some excess at ~ 122 - 128 GeV

*see R. Lopez de Sa, Moriond QCD*




- after March analyses were blinded
- re-optimization only using simulation
- analyses validated in control regions

New (preliminary) indirect Higgs mass determination

$M_H = 94^{+29}_{-24}\,GeV$ (was $M_H = 92^{+34}_{-26}\,GeV$ before)

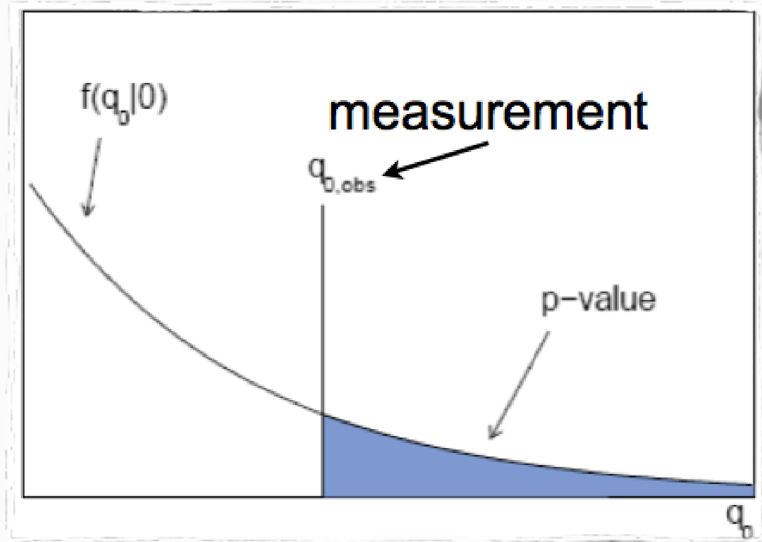
# The statistics behind all this

- oh boy....
- something for the discussion session ;-)

$$\mathcal{L}(\,\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,) = \mathcal{P}\,(\,\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot p(\tilde{\theta}|\theta)$$

$$q_\mu \;=\; -2\ln\frac{\mathcal{L}(\text{data}\,|\,\mu\cdot s(\hat{\theta}_\mu)+b(\hat{\theta}_\mu)\,)}{\mathcal{L}(\text{data}\,|\,\hat{\mu}\cdot s(\hat{\theta})+b(\hat{\theta})\,)}$$

$$p_0 = P\left(q_0 \geq q_0^{obs}\,|\,b\right)$$

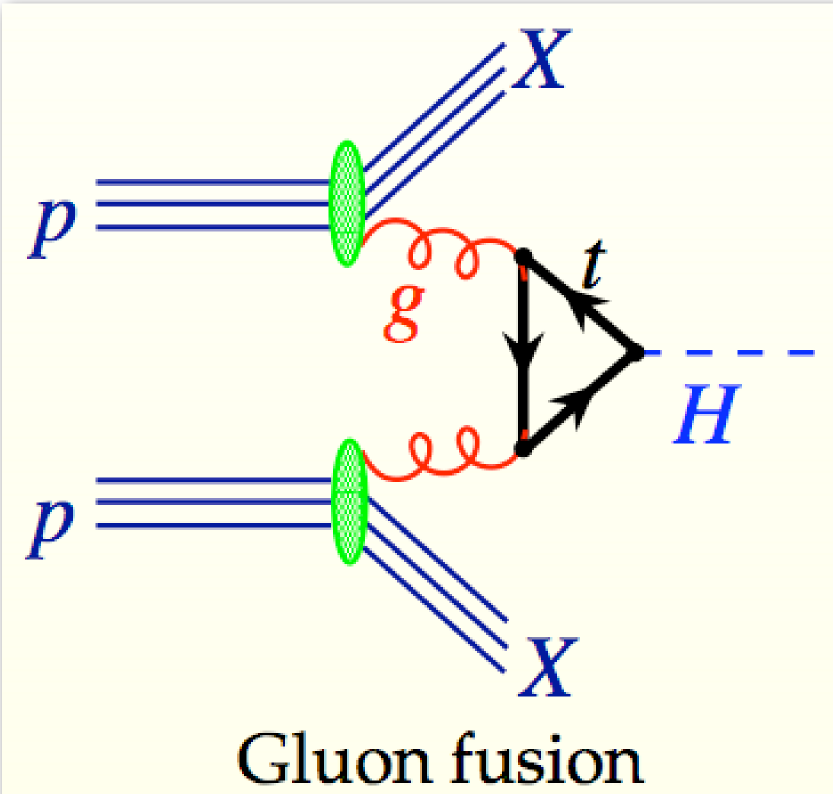


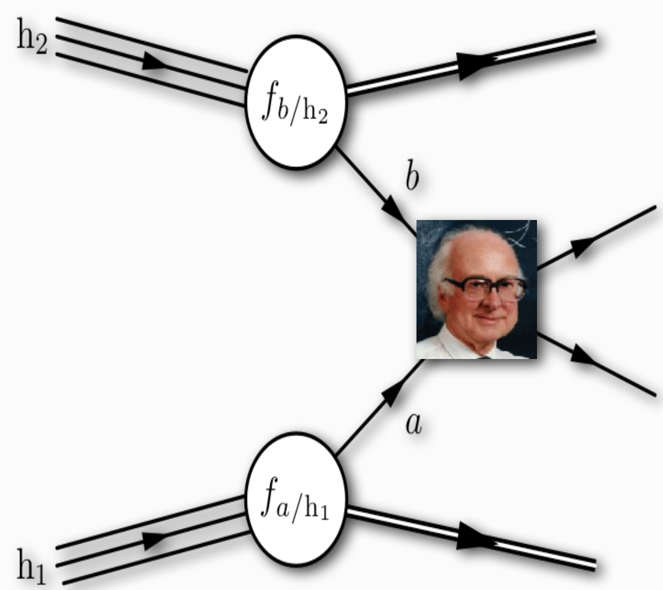

$$\mathrm{CL_{s+b}} = P\left(q_\mu \geq q_\mu^{obs}\,|\,\mu\cdot s+b\right)$$

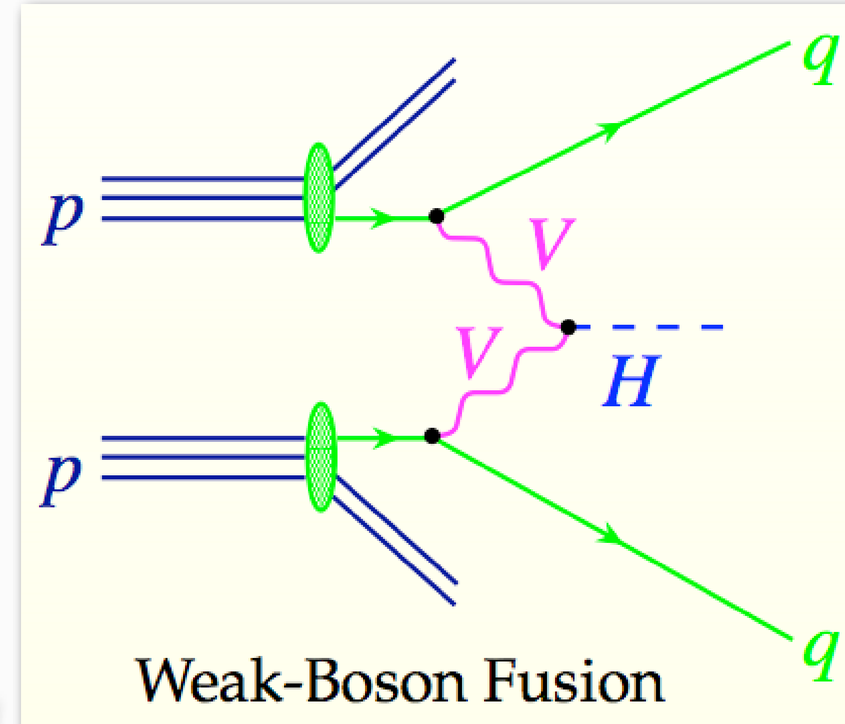
$$\mathrm{CL_b} = P\left(q_\mu \geq q_\mu^{obs}\,|\,b\right),$$

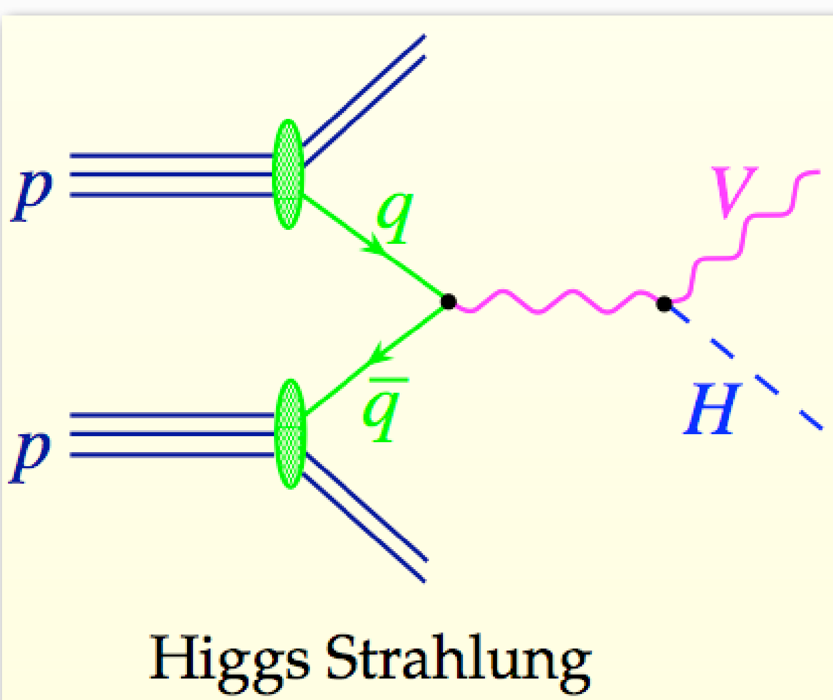
$$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}}$$

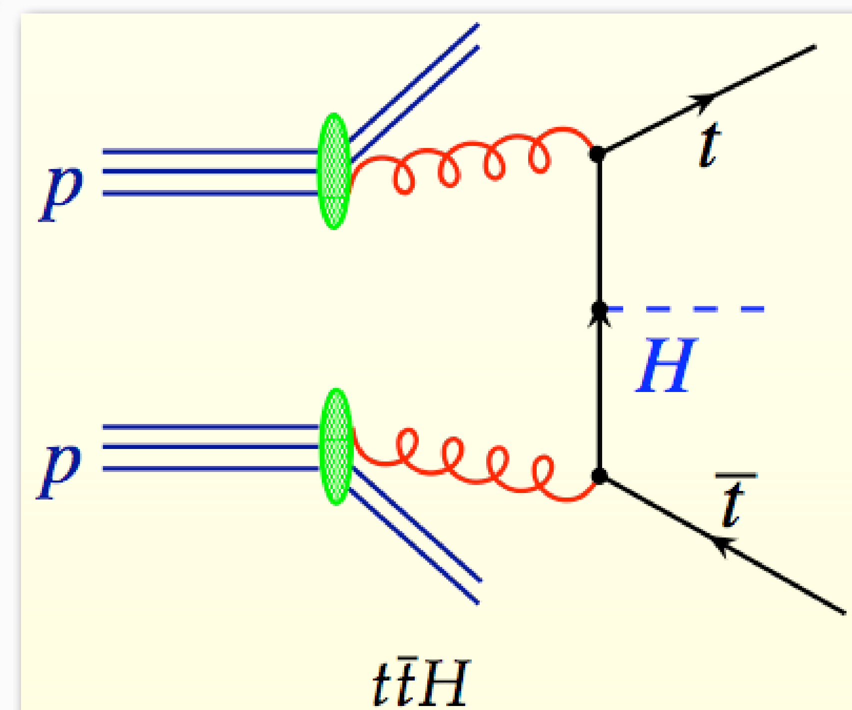
# Higgs production



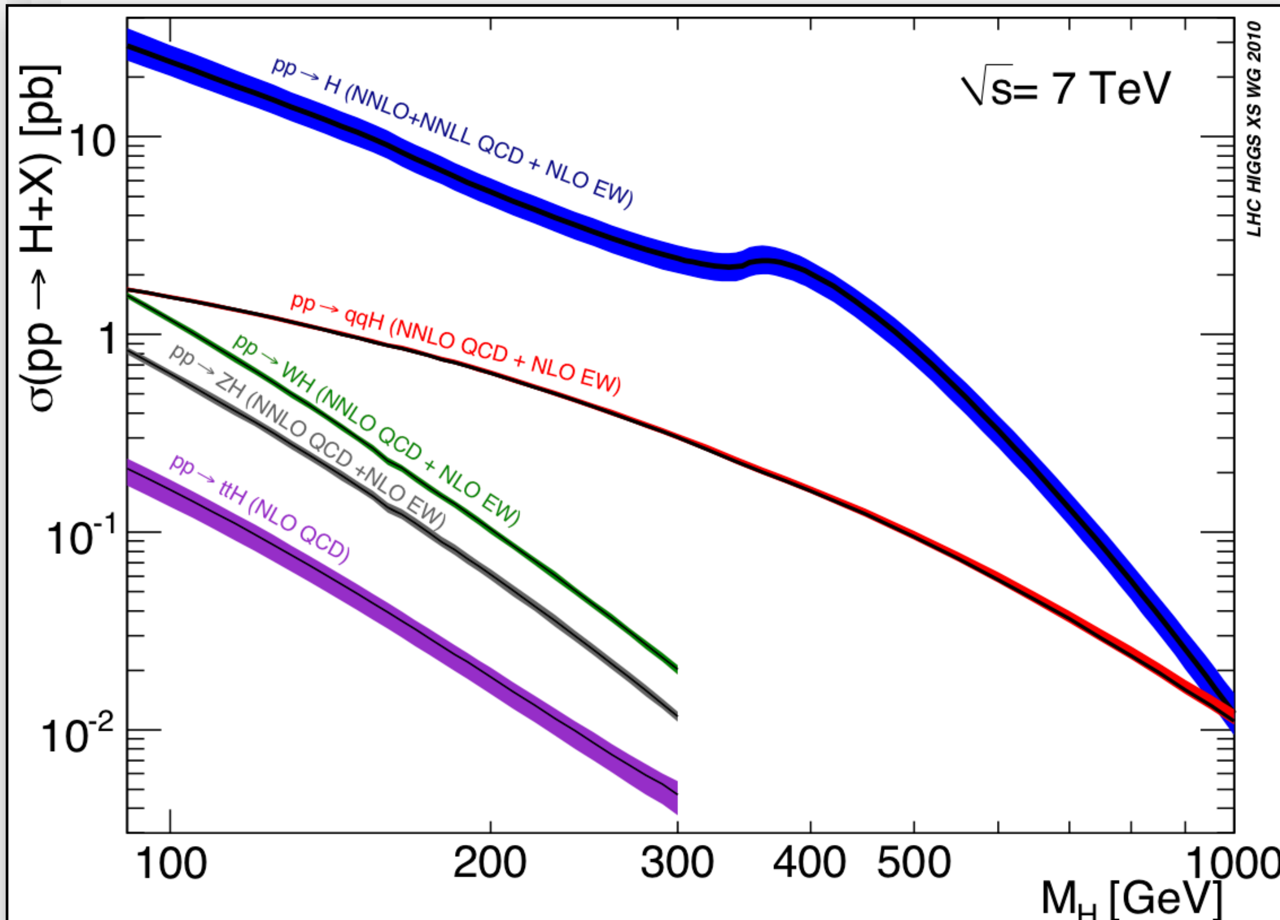



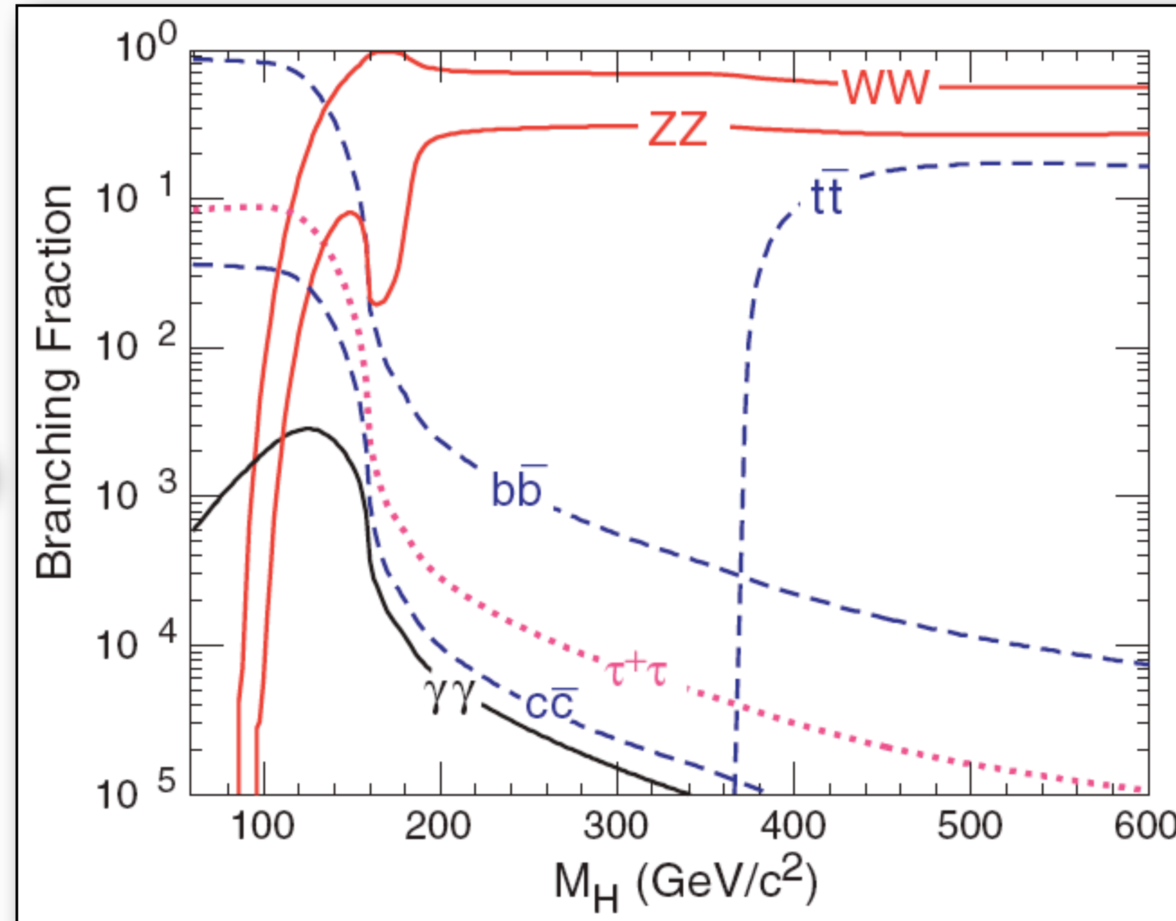



# Production and Decay



# Signatures/Channels

- 2-photon final states
  - excellent detector / mass resolution (1-3 %), isolation, background fit
- lepton final states ( μ, e or tau )
  - isolation, momentum resolution, tau identification
  - for electrons and muons: excellent mass resolution (1-2 %) at low mass
- lepton + neutrino final states
  - lepton identification, WW, tt and W+jets bkg rejection, MET resolution
- associated Higgs production (VHbb, ttH)
  - b-tagging, jet resolution and energy scale, V+c,b and ttjj backgrounds
- Higgs production via Vector Boson Fusion
  - very forward jet tagging

# Classes of Final States

- Mass can be fully reconstructed ($\gamma\gamma$, 4 leptons, bb)
  - background from sidebands and/or fits, on data
  - for hadronic final state: need excellent jet $E_T$ resolution

- Neutrinos in final state,
  no exact mass reconstruction possible

  eg. $H \rightarrow WW \rightarrow l\nu l\nu$ or $H/A \rightarrow \tau\tau$

  - Jacobian peaks
  - background from 'sidebands' if possible
  - background from MC
  - extrapolation of background from non-signal region using data and MC (shape)
  - extrapolation of background using data and theory (ratio of cross sections)

CTEQ

# Overview and expected sensitivity

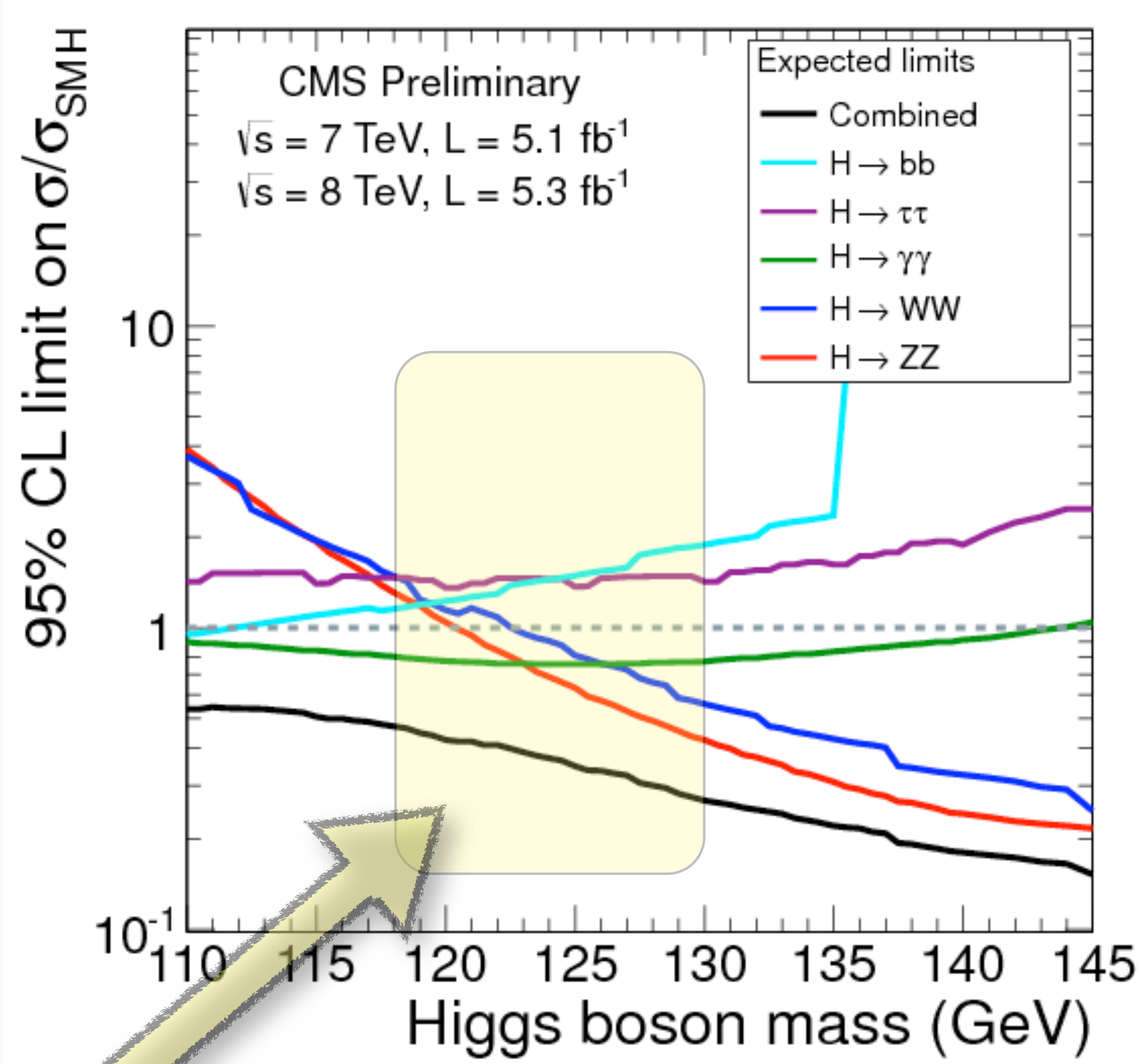
ETH Institute for Particle Physics

slide adapted from P. Meridiani

- main CMS search strategy (main channels)

| mode | signature | S/B | Mass Resol. | N events in 10fb$^{-1}$ | Good For |
|---|---|---|---|---|---|
| **H→bb** | two b-jets, Z or W, bb inv. mass | low O(0.1) | 10% | ~$10^5$ ~30 (sel) | couplings to fermions |
| **H→ττ** | had tau, leptons, MET | low O(0.1) | 15% | ~$10^4$ ~20 (sel) | couplings to fermions |
| **H→WW** | two leptons with opposite charge MET | medium O(1) | - | ~$10^3$ ~60 (sel) | cross section, BR, couplings to V |
| **H→γγ** | two photons peak in inv. mass | low O(0.1) | 2% | 400 ~200 (sel) | H mass, couplings $C_V C_F$, discovery |
| **H→ZZ** | four leptons with right charge peaks in inv. mass ($Z_1$ and Higgs) | high >1 | 1-2% | 20 ~6 (sel) | H mass, discovery |

from CMS-HIG-12-020



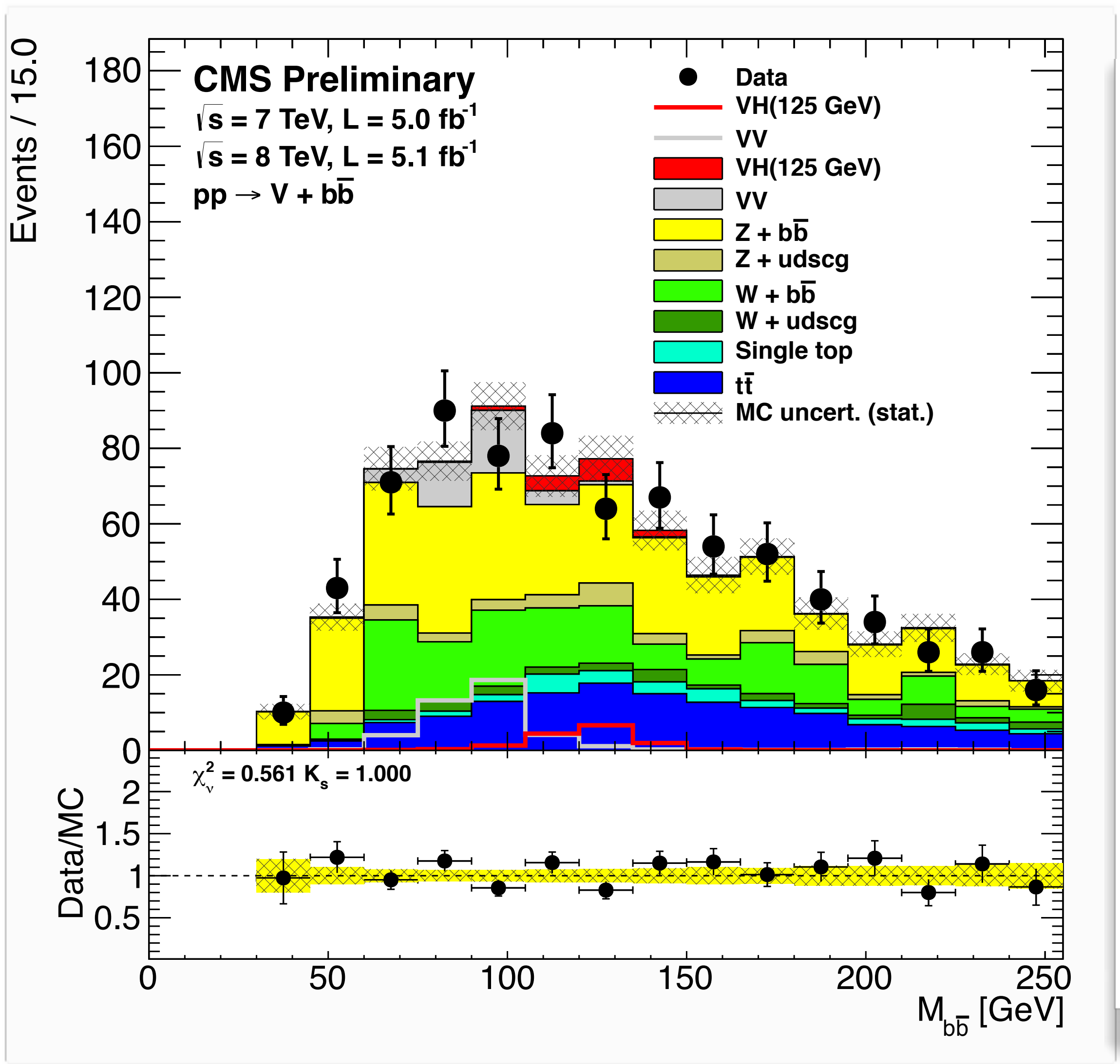

- at 125 GeV, all analyses show good expected sensitivity
- redundant measurements, addressing different production and decay modes
- excellent mass range for studying Higgs properties
- **Side remark**: Always look at **expected sensitivities**, when judging performance of an experiment!!

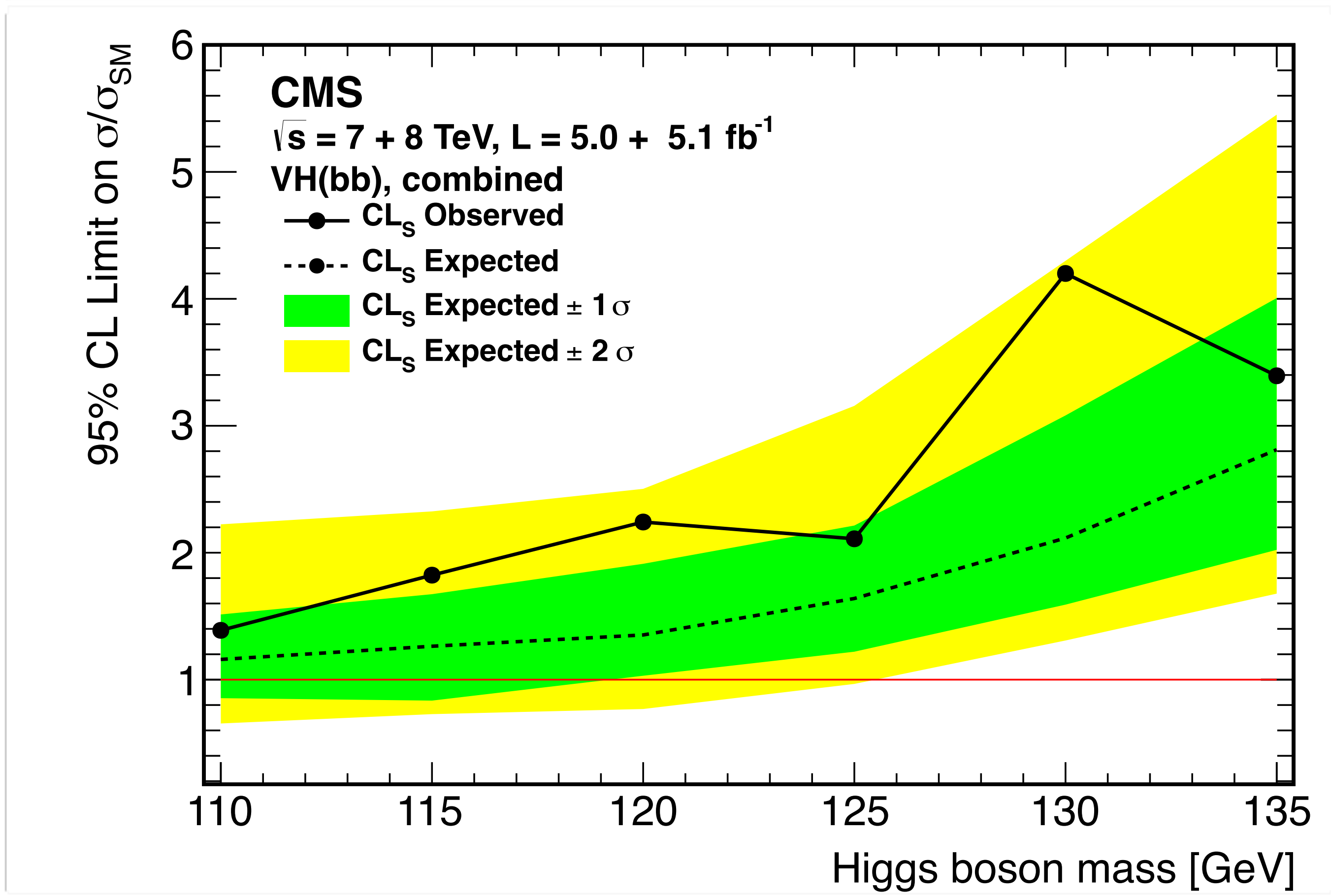
# H→bb

CMS-HIG-12-019

see also arXiv:1207.7235

- in associated production mode (VH)
  - reduced background when asking for a W or Z (with leptonic and invisible decays)
- two b-jets with high $p_T$
- Analysis improvements wrt 2011: ~50% in sensitivity
- **Result**: **broad excess compatible with presence of 1xSM Higgs boson**



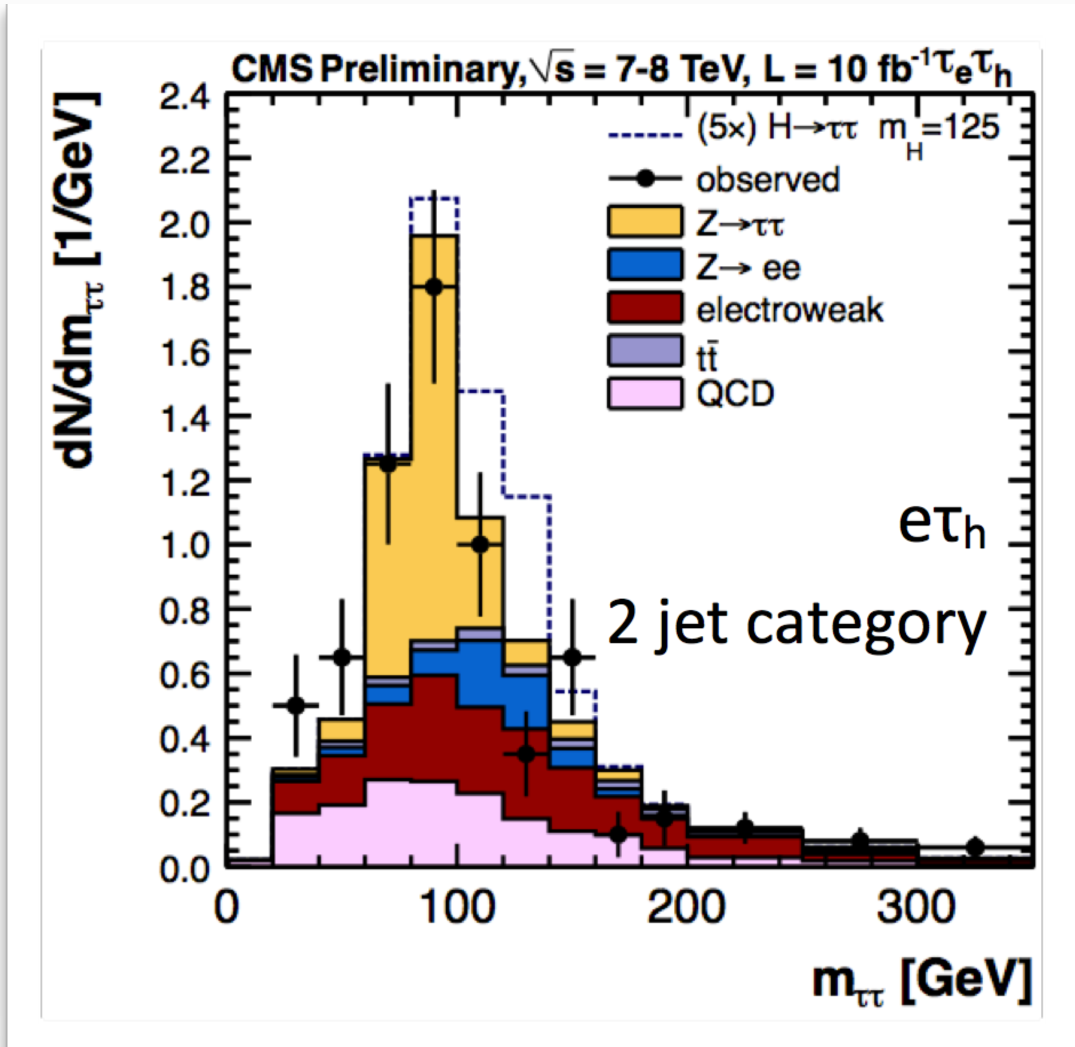



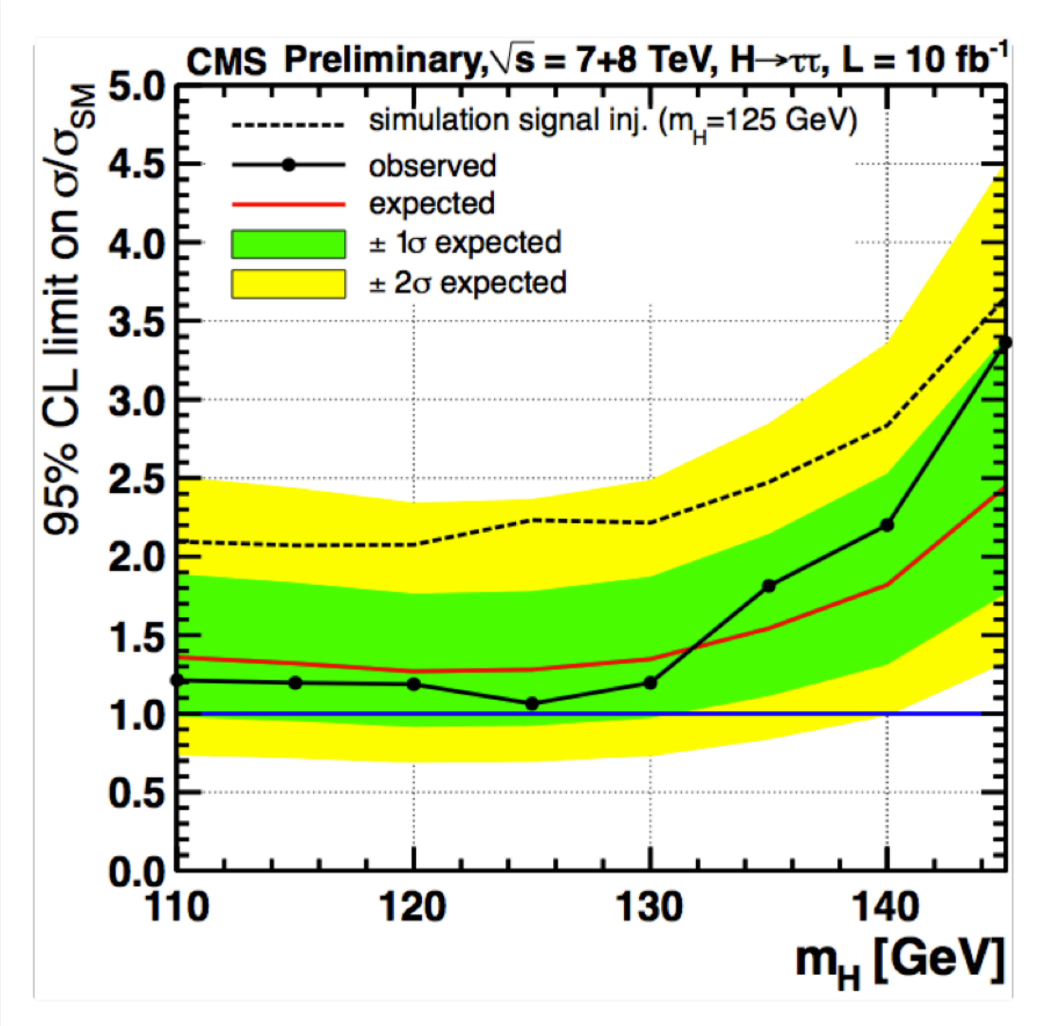
# H→ττ

CMS-HIG-12-018

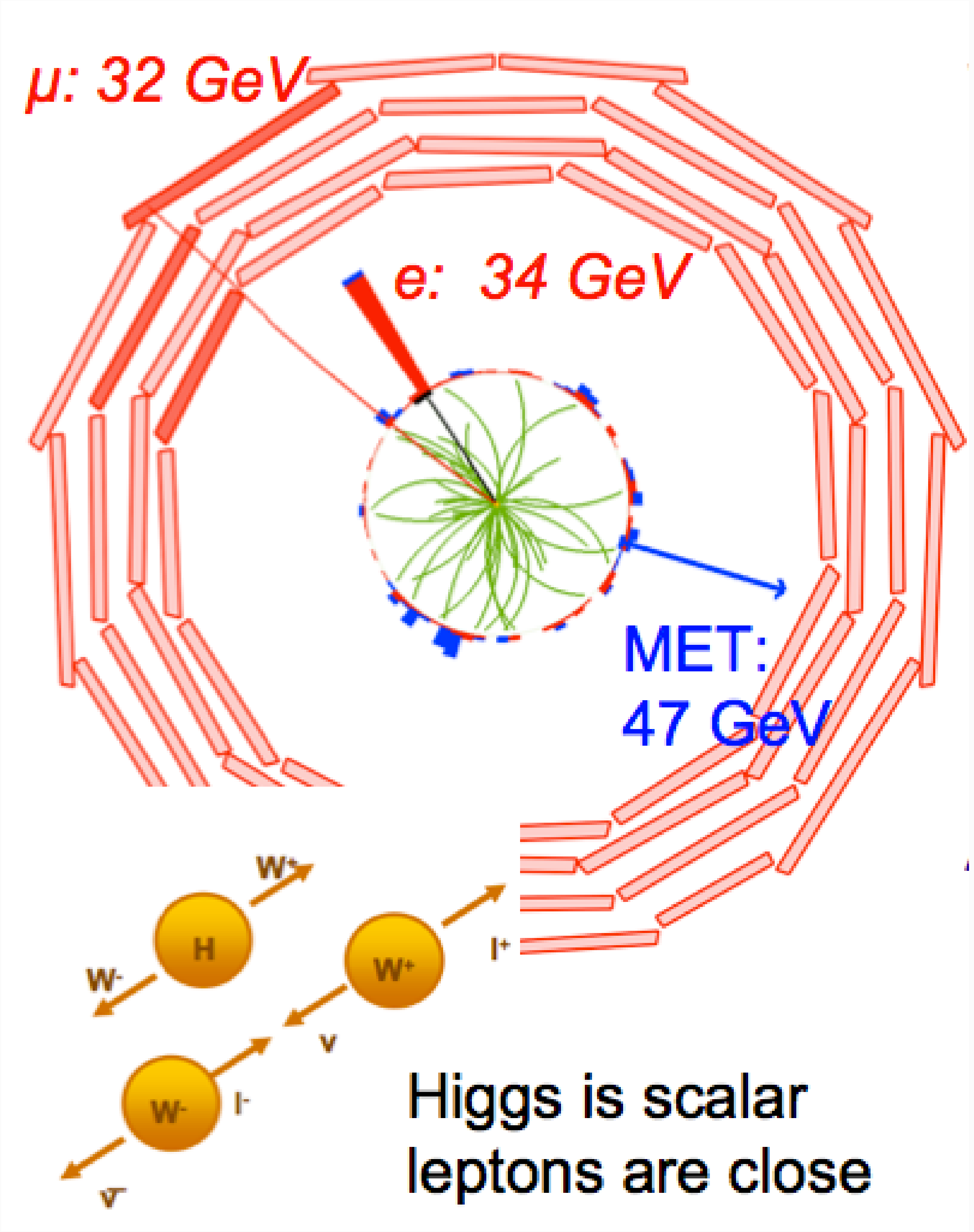
see also arXiv:1207.7235

- Channels used: e-mu, e-had, mu-had, mu-mu
- VBF / boosted / 0-jet
- Backgrounds: top, EWK, DY (irreducible)
- **No significant excess** wrt SM background
  - with very broad excess expected
- **Sensitivity close to 1xSM Higgs** (improved by ~70% wrt 2011)



# HWW




- Signature
  - 2 opposite charged leptons (leptons only e, μ)
  - 2 neutrinos == missing transverse energy (MET)
- no Higgs mass peak
- enhance sensitivity by subdividing into + (0,1,2) jets
- Kinematic variables to reject backgrounds: most discriminant: delta-phi and inv. mass of the two leptons
- Analysis challenges
  - understand backgrounds
  - normalize to control regions
  - backgrounds: WW, top, W+jets, DY

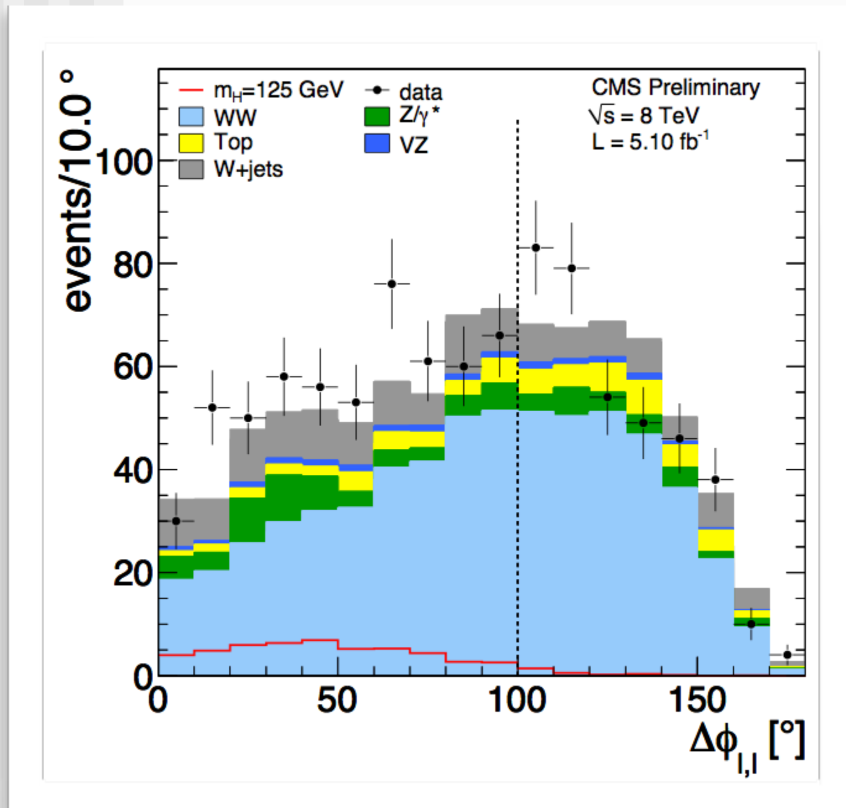
# HWW: results

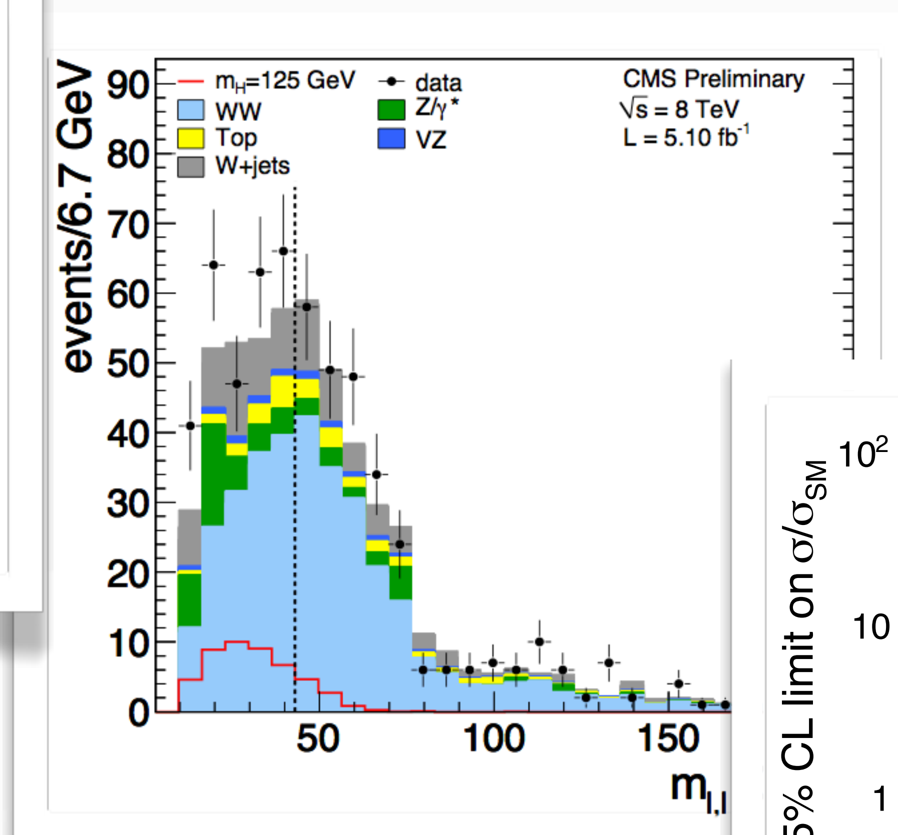
CMS-HIG-12-017

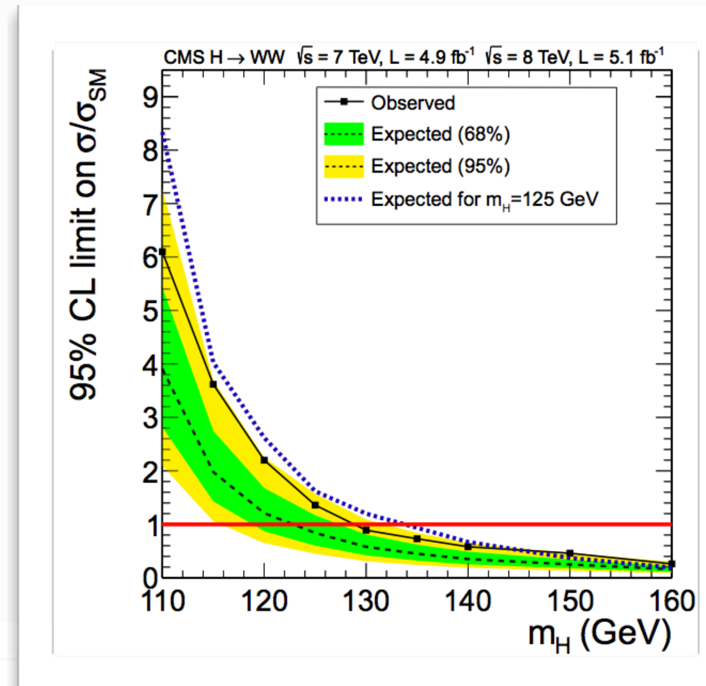
see also arXiv:1207.7235

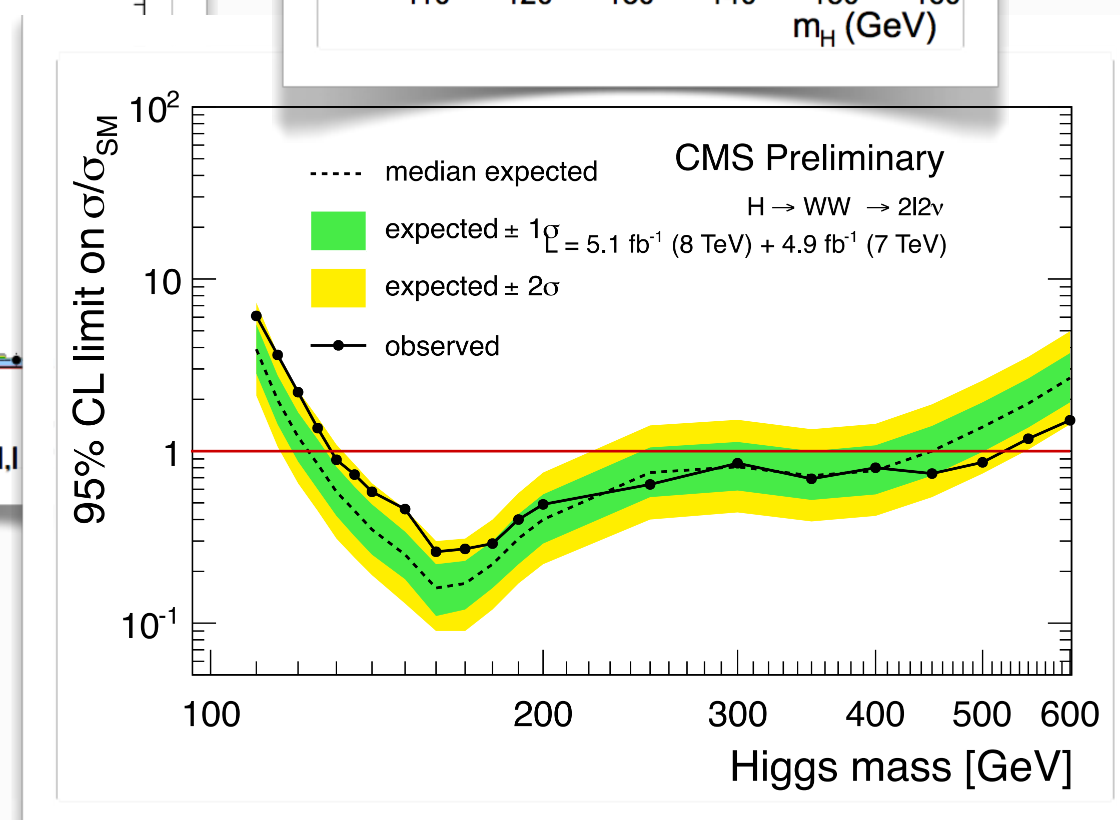
- 2011 analysis had BDT and cut-and-count approaches
- in 2012: so far only the cut-and count results available
- **Result**: **broad excess compatible with presence of 1xSM Higgs**

at final selection level, 0-jet bin

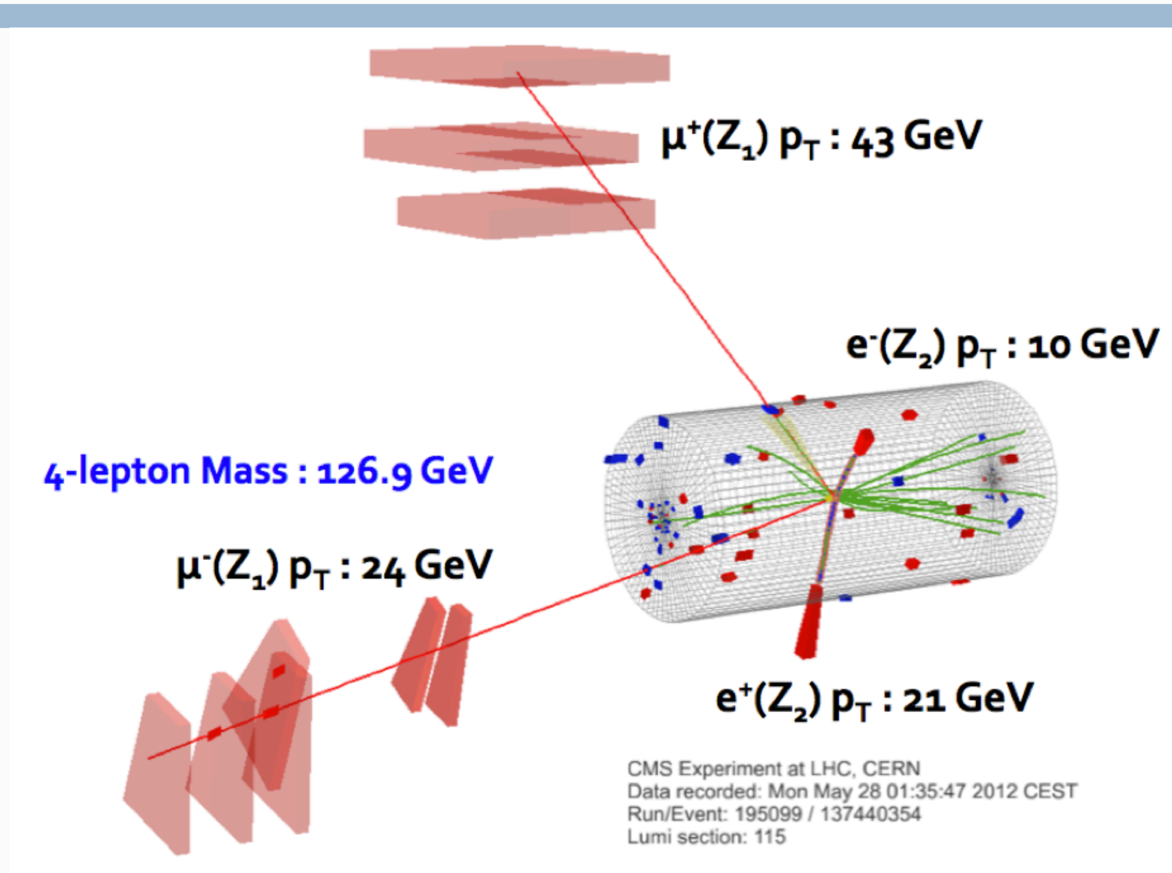


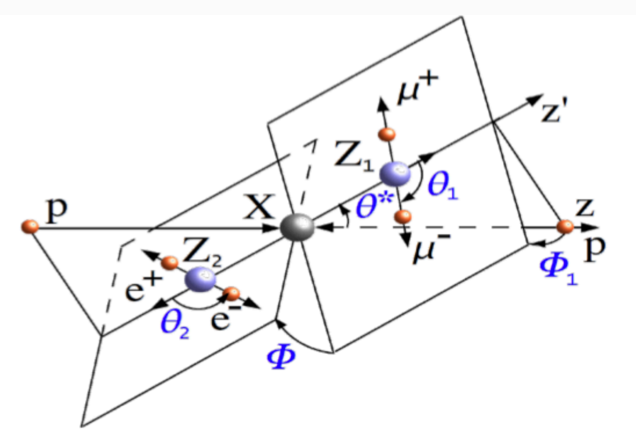



# The 4-lepton channel : The golden mode



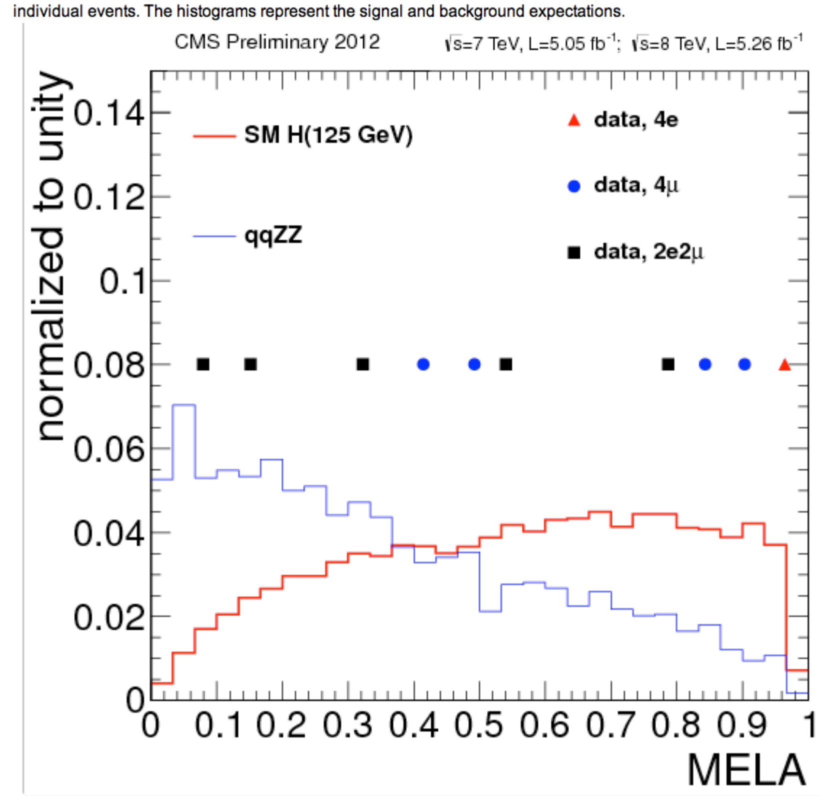

- 4 isolated high $p_T$ leptons
  - consistent with Z decays
  - from same vertex
  - fit mass peak with resolution: 2-3 GeV
  - little background, main comes from non-resonant ZZ production, irreducible
  - also Zbb and top (2l2nu2b)
- **Modes**: eeee, eemumu, 4mu

- **>20% improvement** wrt. 2011 analysis
- **New**: inclusion of angular information using a matrix-element likelihood analysis (MELA)




$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

Distribution of the MELA KD in the four-lepton reconstructed mass range [121-131] GeV. The points representing the individual events. The histograms represent the signal and background expectations.

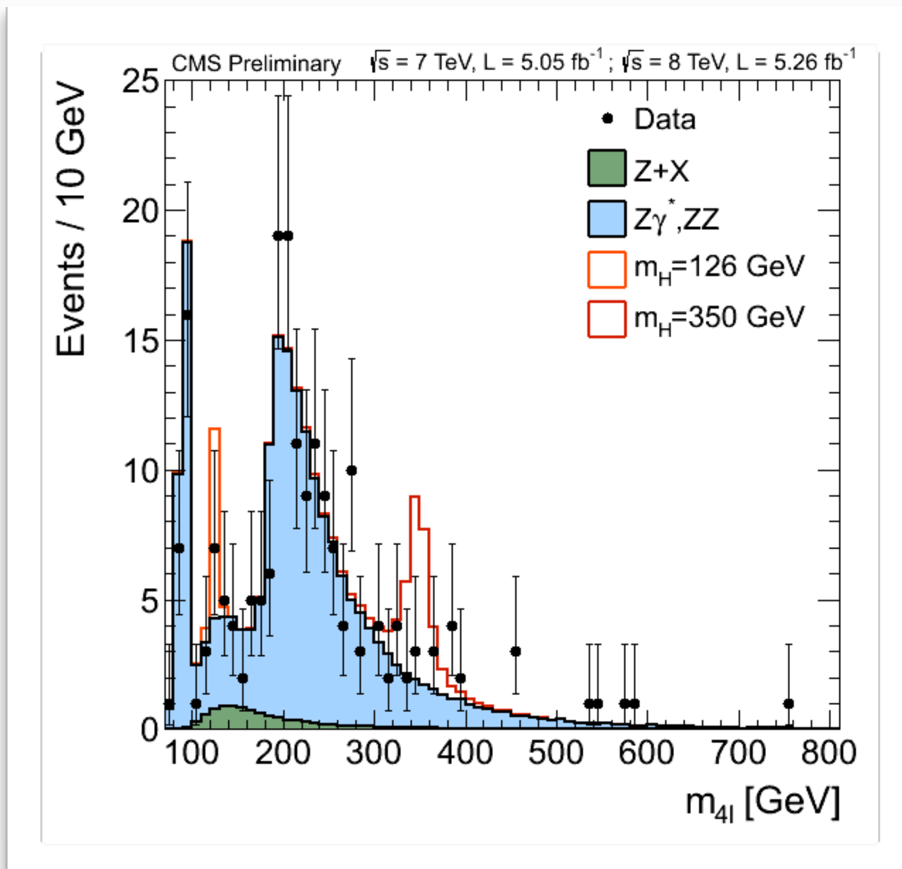


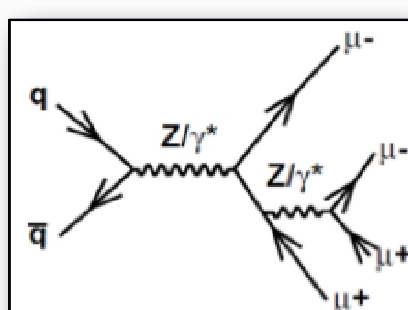
# HZZ: results

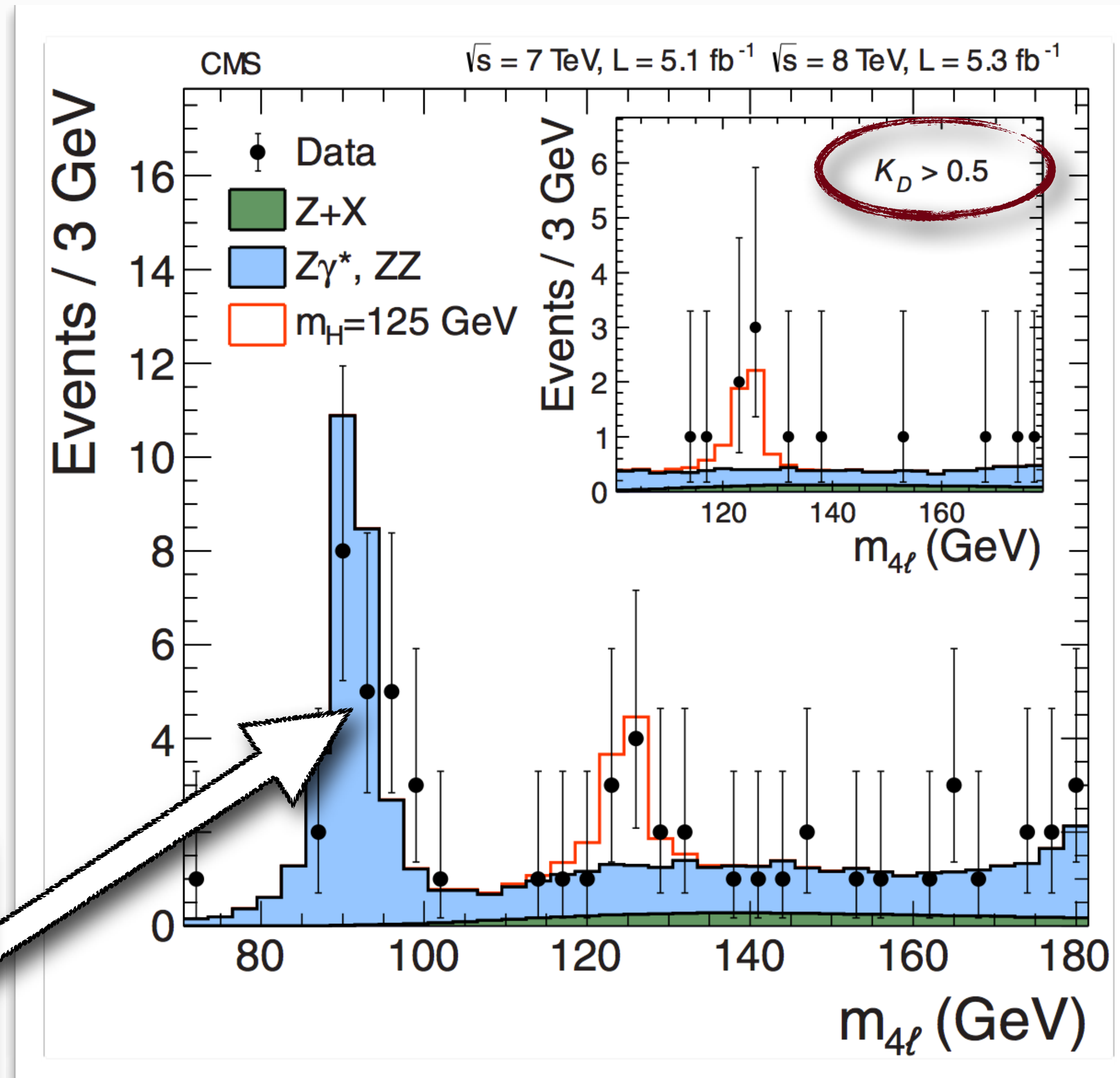
CMS-HIG-12-016

see also arXiv:1207.7235

- Normalization and background shape ok
  Remember: ZZ xsec in agreement with NLO pred.
- **Result**: **excess at ~125 GeV**



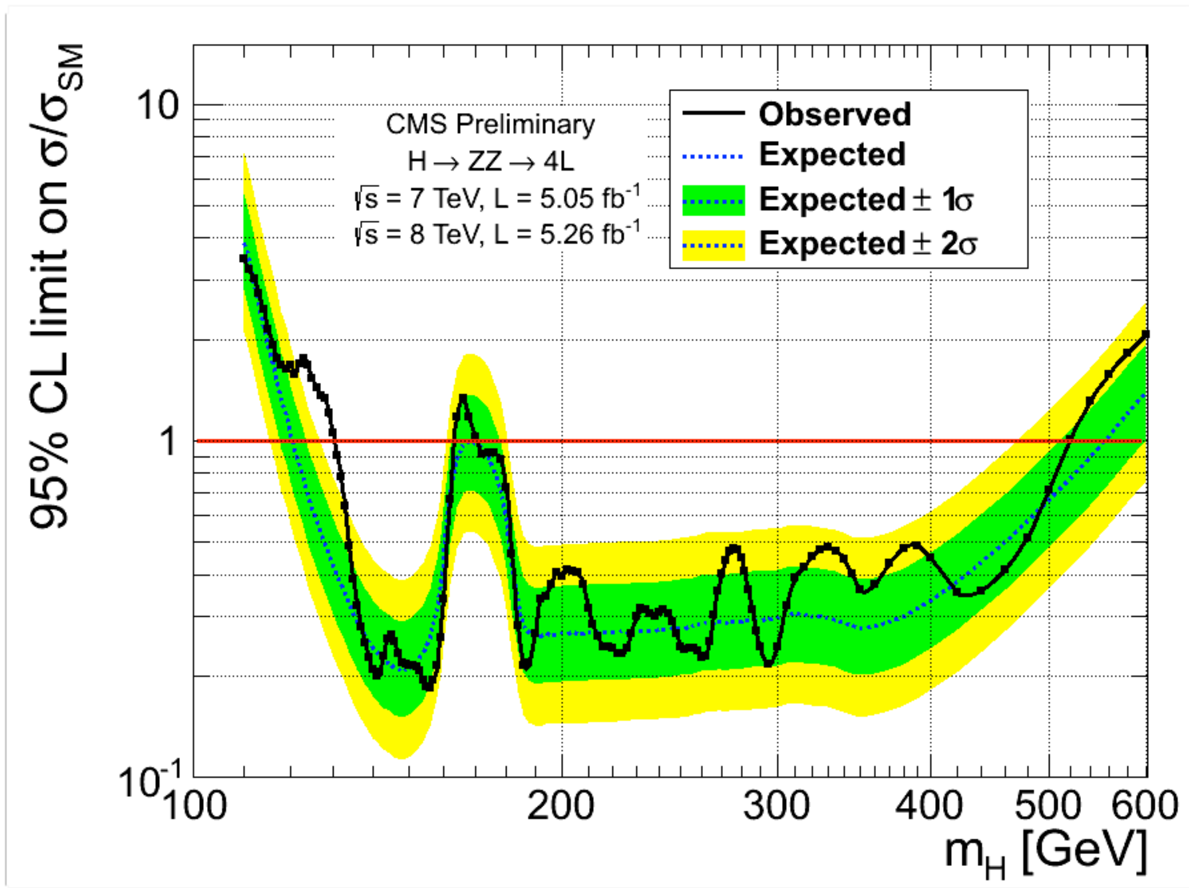



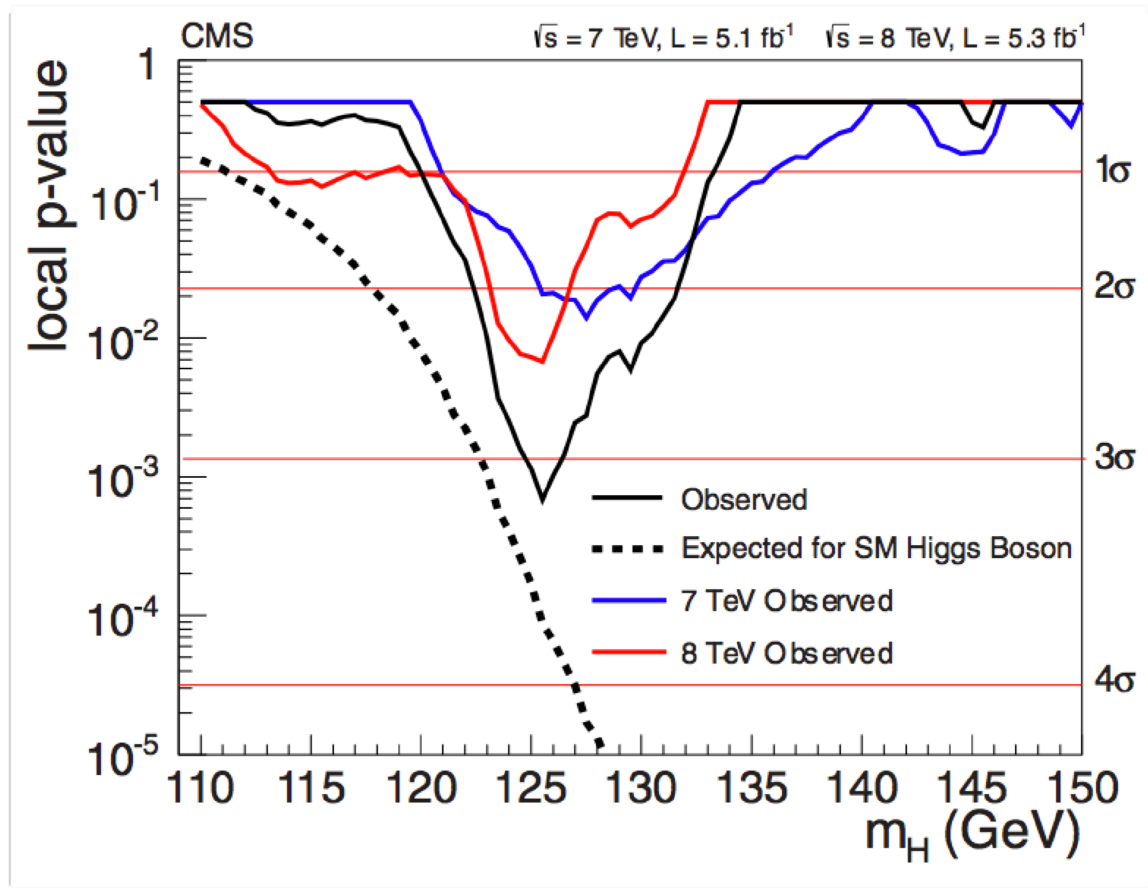
# HZZ: results

CMS-HIG-12-016

see also arXiv:1207.7235

- **Excess at ~125.6 GeV**
  - observed 3.2σ, expected 3.8σ
- **Resulting strength at 125.6 GeV:** $\mu = \sigma/\sigma_{SM} \sim 0.7$
- ZZ alone excludes almost full mass region



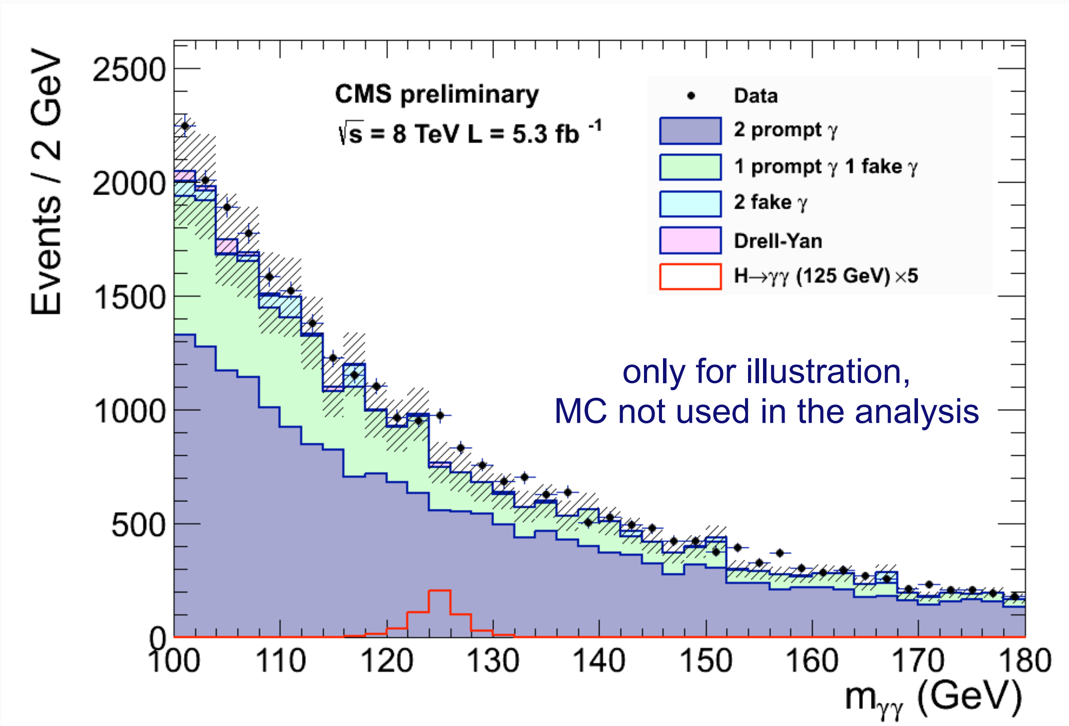



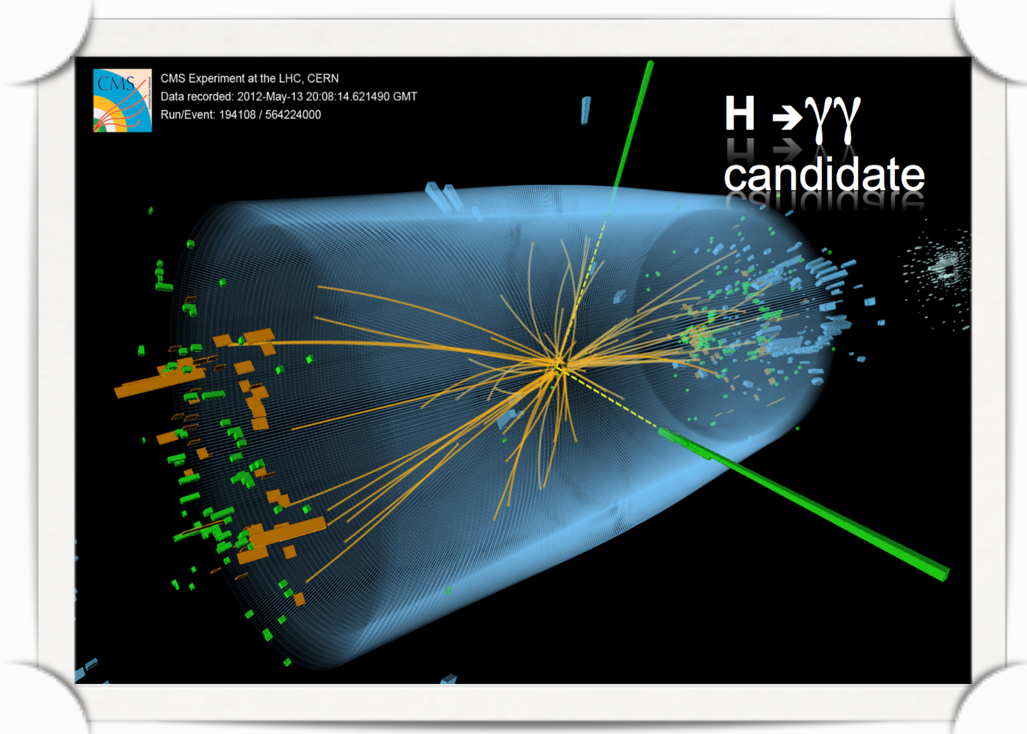
# The di-photon channel

CMS-HIG-12-015

see also arXiv:1207.7235

- It's (almost) all about mass resolution!




**Expected signal and estimated background**

| Event classes | | SM Higgs boson expected signal ($m_H$=125 GeV) Total | ggH | VBF | VH | ttH | $\sigma_{eff}$ (GeV) | FWHM/2.35 (GeV) | Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV) |
|---|---|---|---|---|---|---|---|---|---|
| 7 TeV 5.1 fb$^{-1}$ | Untagged 0 | 3.2 | 61% | 17% | 19% | 3% | 1.21 | 1.14 | 3.3 ± 0.4 |
| | Untagged 1 | 16.3 | 88% | 6% | 6% | 1% | 1.26 | 1.08 | 37.5 ± 1.3 |
| | Untagged 2 | 21.5 | 91% | 4% | 4% | – | 1.59 | 1.32 | 74.8 ± 1.9 |
| | Untagged 3 | 32.8 | 91% | 4% | 4% | – | 2.47 | 2.07 | 193.6 ± 3.0 |
| | Dijet tag | 2.9 | 27% | 73% | 1% | – | 1.73 | 1.37 | 1.7 ± 0.2 |
| 8 TeV 5.3 fb$^{-1}$ | Untagged 0 | 6.1 | 68% | 12% | 16% | 4% | 1.38 | 1.23 | 7.4 ± 0.6 |
| | Untagged 1 | 21.0 | 88% | 6% | 6% | 1% | 1.53 | 1.31 | 54.7 ± 1.5 |
| | Untagged 2 | 30.2 | 92% | 4% | 3% | – | 1.94 | 1.55 | 115.2 ± 2.3 |
| | Untagged 3 | 40.0 | 92% | 4% | 4% | – | 2.86 | 2.35 | 256.5 ± 3.4 |
| | Dijet tight | 2.6 | 23% | 77% | – | – | 2.06 | 1.57 | 1.3 ± 0.2 |
| | Dijet loose | 3.0 | 53% | 45% | 2% | – | 1.95 | 1.48 | 3.7 ± 0.4 |

# The di-photon channel

CMS-HIG-12-015



slide adapted from P. Meridiani

**Analysis very advanced: makes use of several multivariate techniques to enhance the small S/B signal**

| STEP | CRITICAL ISSUES |
|---|---|
| **1) two isolated photons with large transverse momentum** | • isolation to reject γ+jet and QCD background |
| **2) di-photon mass reconstruction** $m_H^2 = 2E_1E_2(1 - cos\theta)$ | • vertex determination in presence of multiple interactions pile-up (PU)<br>• energy scale and resolution |
| **3) signal extraction** | • event categories to maximize sensitivity: MVA categories + di-jet (VBF enriched)<br>• background shape |

# The di-photon channel

CMS-HIG-12-015



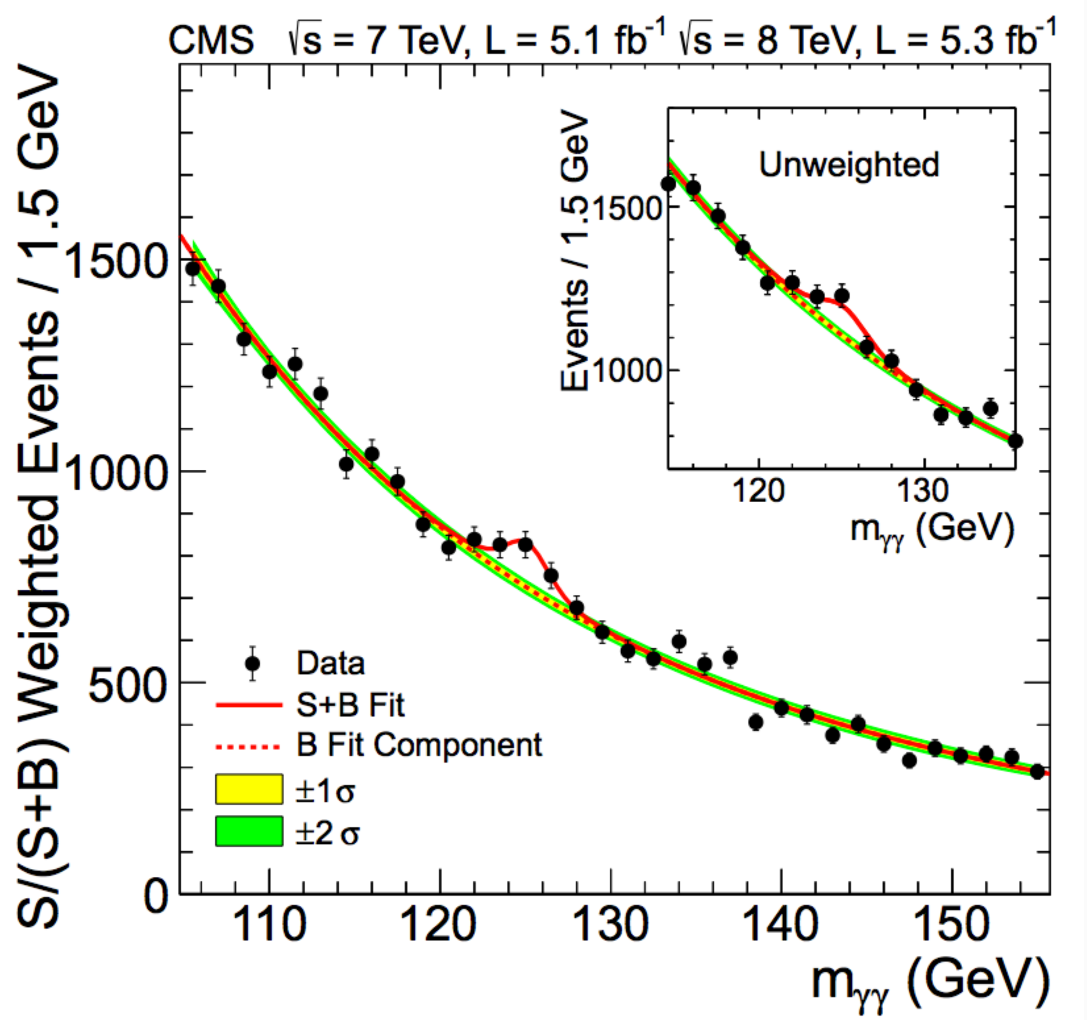
slide adapted from P. Meridiani

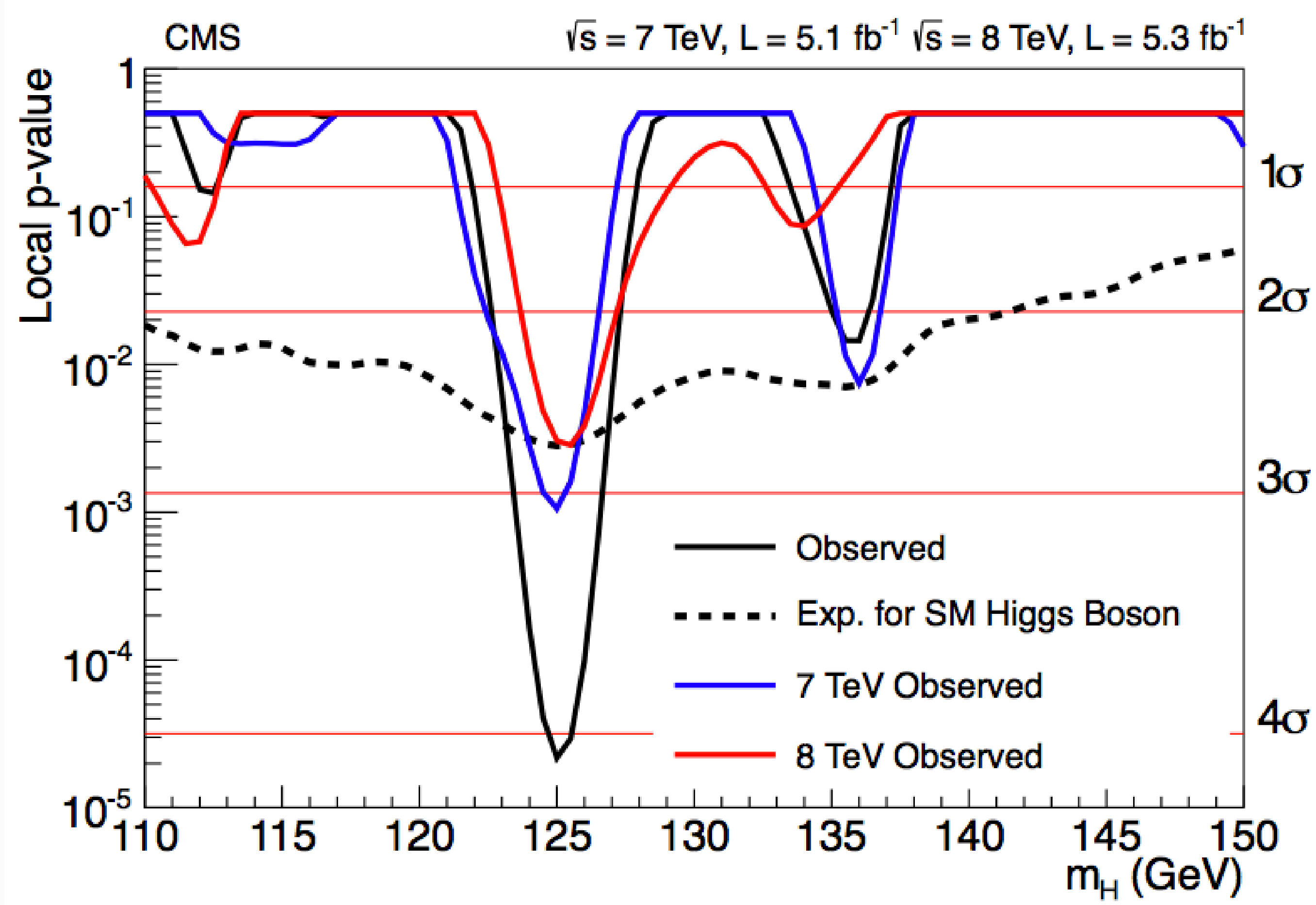
## Result:

- **4.1 σ** excess at **125 GeV**
- **Very consistent between 2011 and 2012**
- Cross-checked with two alternative analyses (including fully cut based). Compatible results

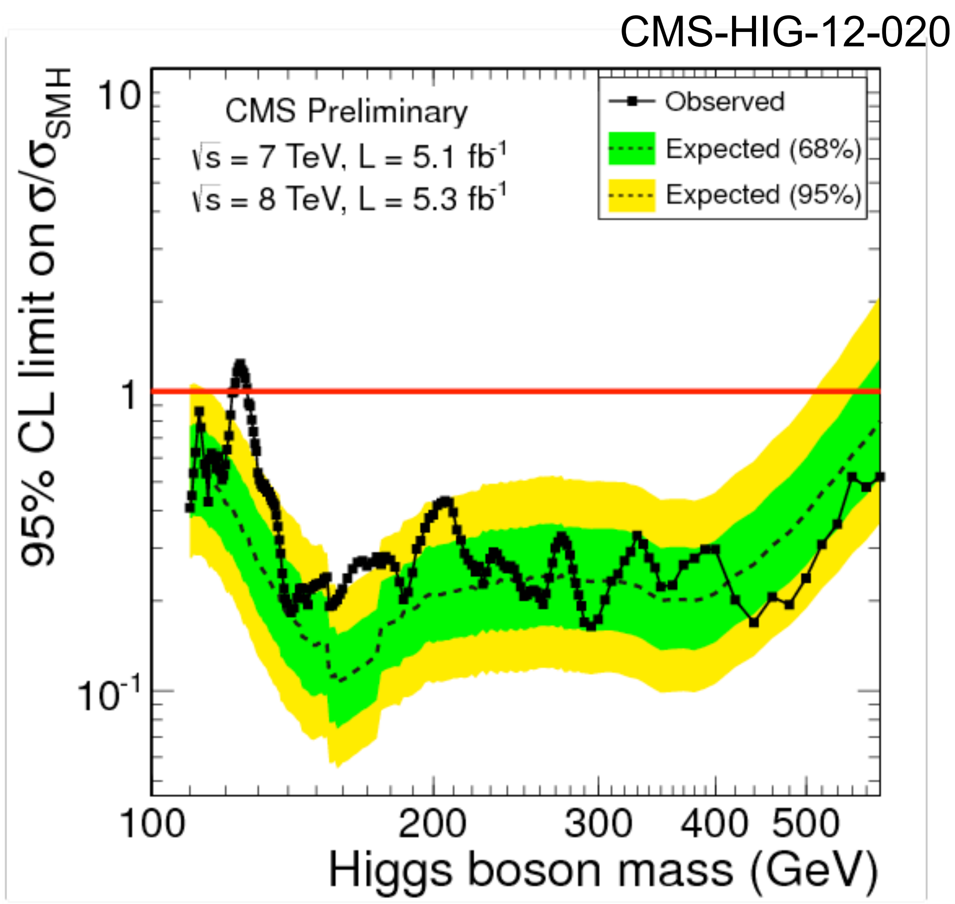
see also arXiv:1207.7235

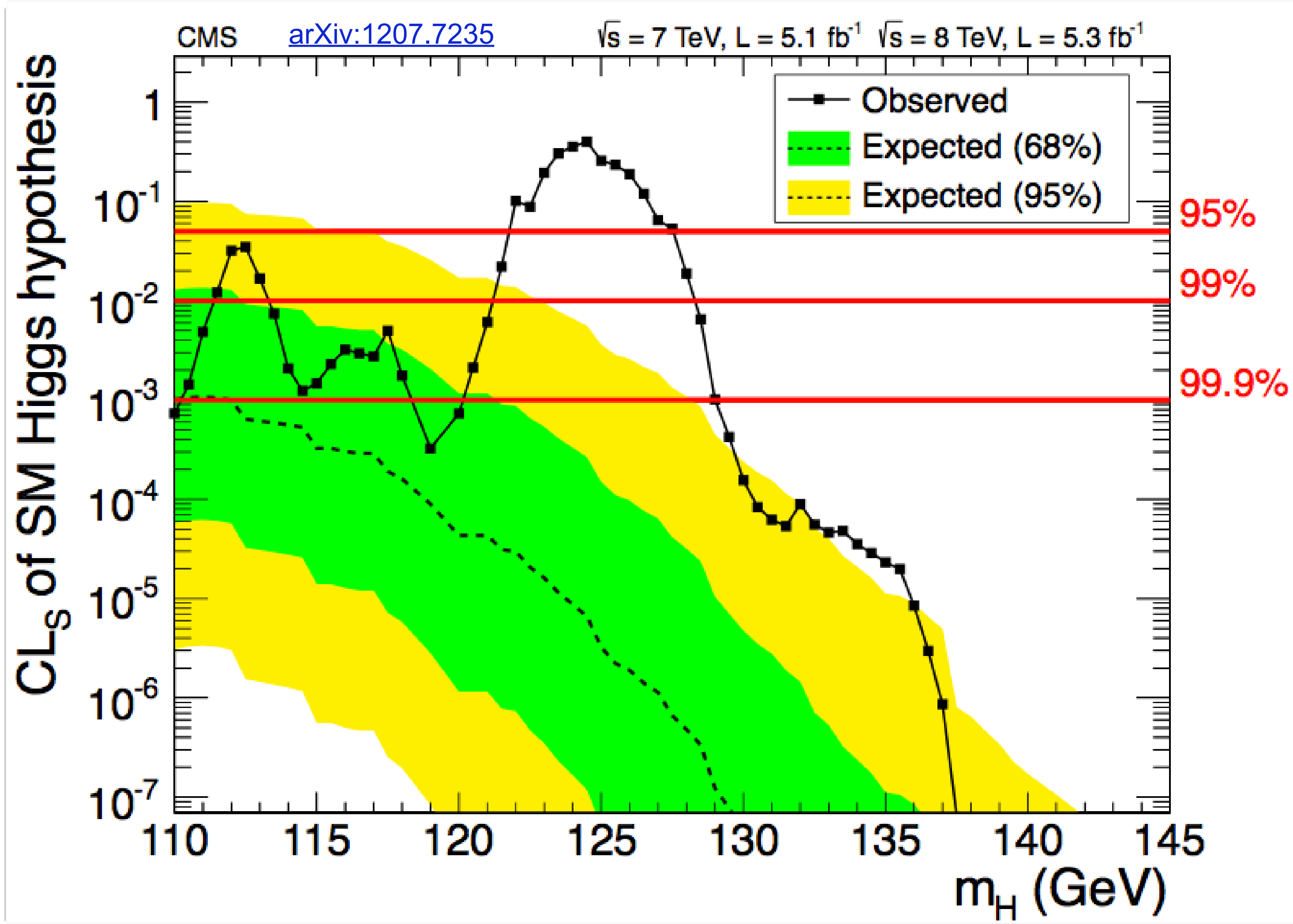
**events weighted by expected S/(S+B)**



# Results - all combined




Note: at ICHEP all these channels were used in the combination

| Decay | Prod. Topology | Luminosity |
|---|---|---|
| H→bb | WH, ZH | 5+5 fb-1 at 7+8 TeV |
| H→bb | ttH | 5 at fb-1 at 7 TeV |
| H→ ττ | Inclusive + VBF | 5+5 fb-1 at 7+8 TeV |
| H→ ττ | WH, ZH | 5 at fb-1 at 7 TeV |
| H → γγ | Inclusive + VBF | 5+5 fb-1 at 7+8 TeV |
| H → WW | 0/1 jet + VBF | 5+5 fb-1 at 7+8 TeV |
| H → WW | WH, ZH | 5 at fb-1 at 7 TeV |
| H → ZZ | Inclusive | 5+5 fb-1 at 7+8 TeV |

Now, for the paper:

| Decay mode | Production tagging | No. of subchannels | $m_H$ range (GeV) | Int. Lum. ($fb^{-1}$) 7 TeV | 8 TeV |
|---|---|---|---|---|---|
| $\gamma\gamma$ | untagged<br>dijet (VBF) | 4<br>1 or 2 | 110–150 | 5.1 | 5.3 |
| ZZ | untagged | 3 | 110–600 | 5.1 | 5.3 |
| WW | untagged<br>dijet (VBF) | 4<br>1 or 2 | 110–600 | 4.9 | 5.1 |
| $\tau\tau$ | untagged<br>dijet (VBF) | 16<br>4 | 110–145 | 4.9 | 5.1 |
| bb | lepton, $E_T^{miss}$ (VH) | 10 | 110–135 | 5.0 | 5.1 |

# Questions on the excess:

Is it statistically significant?
Is it a boson?
What is its mass?
Is it “the” SM Higgs boson?
Is it “a” Higgs boson?

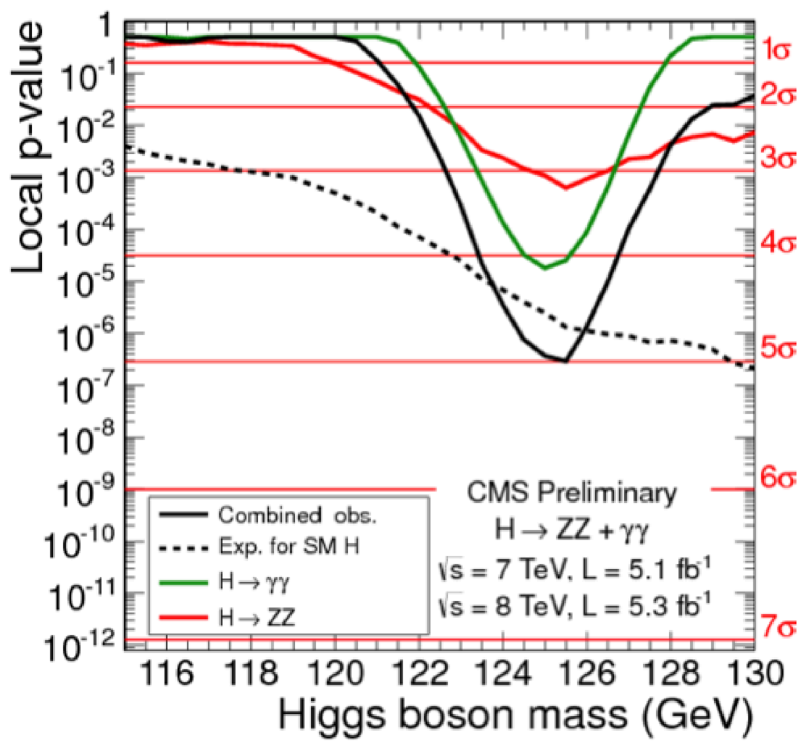
# Results - all combined

CMS-HIG-12-020

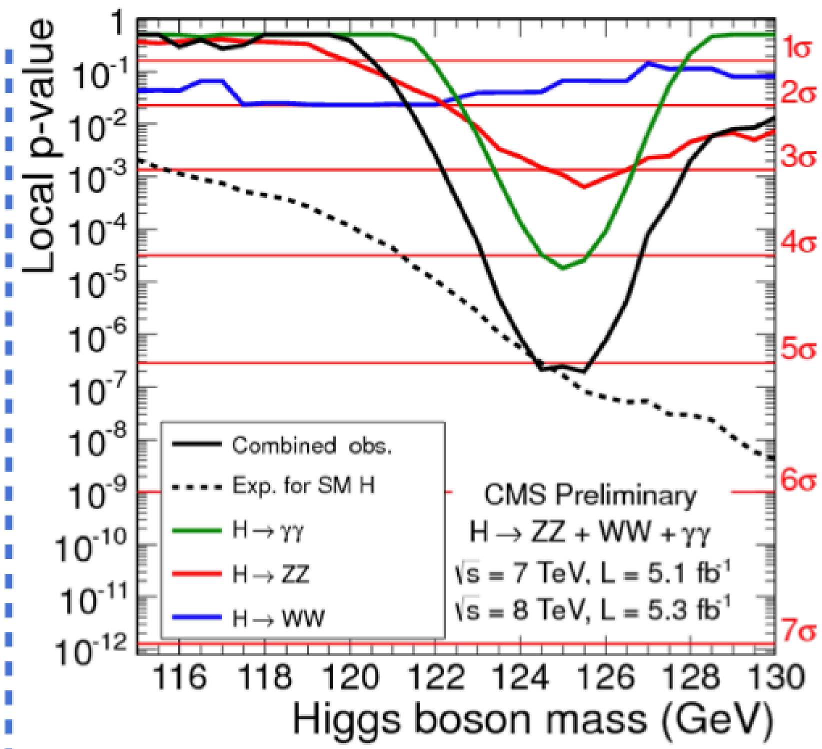
ETH Institute for Particle Physics

slide adapted from P. Meridiani

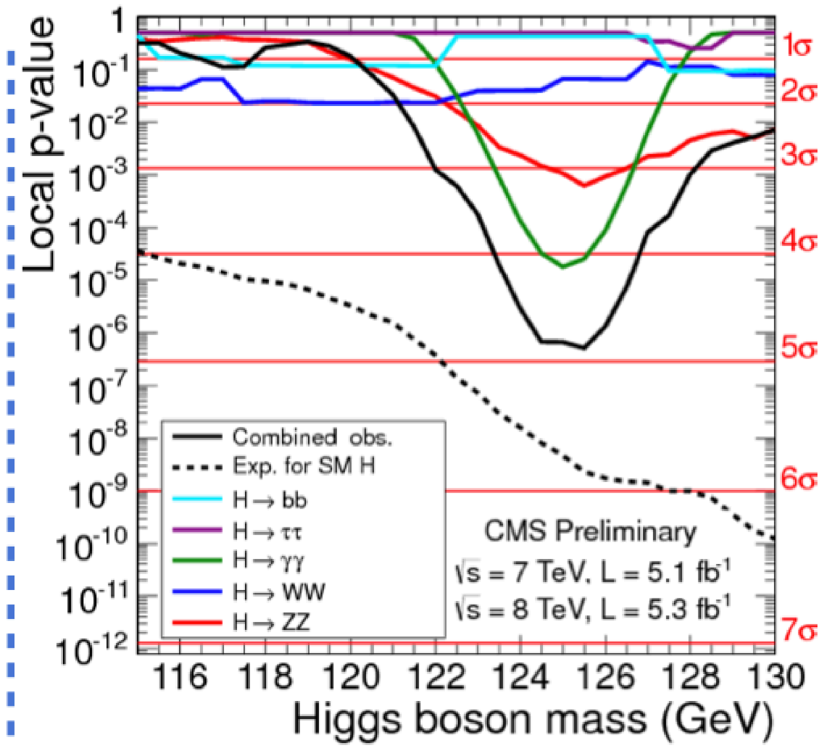
- Evolution of p-values, adding modes (**ICHEP combination**):




- **γγ and ZZ combo only**
- 5σ excess (exp. 4.7σ)
- Is it a boson?
  - Yes, for instance significance from di-photon channel




- **adding WW**
- 5.1σ excess (exp. 5.2σ)




- **all channels together**
- 4.9σ excess (exp. 5.9σ)

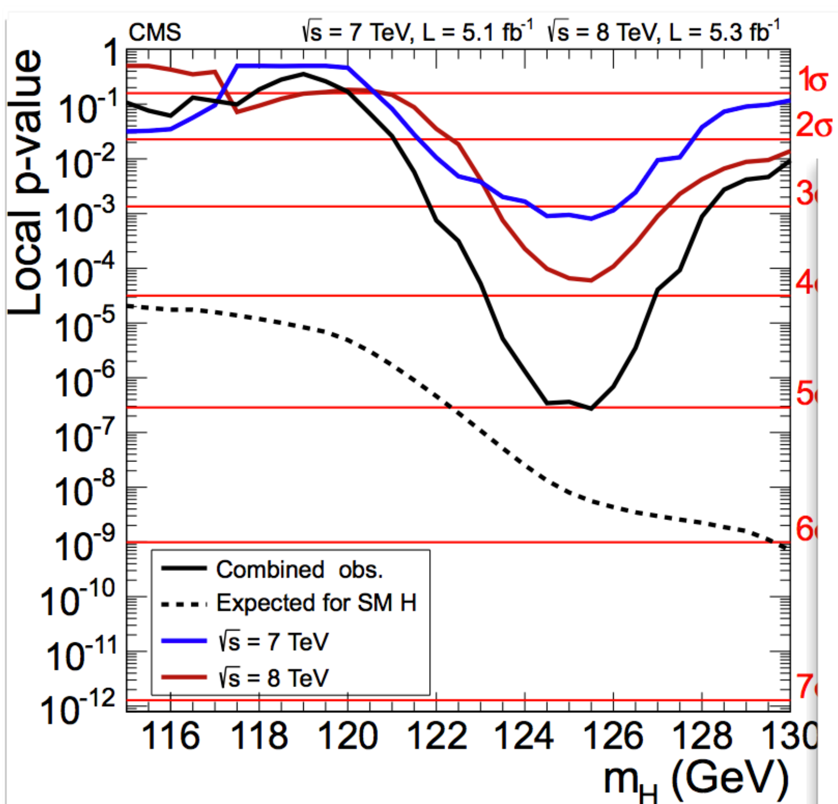
CTEQ

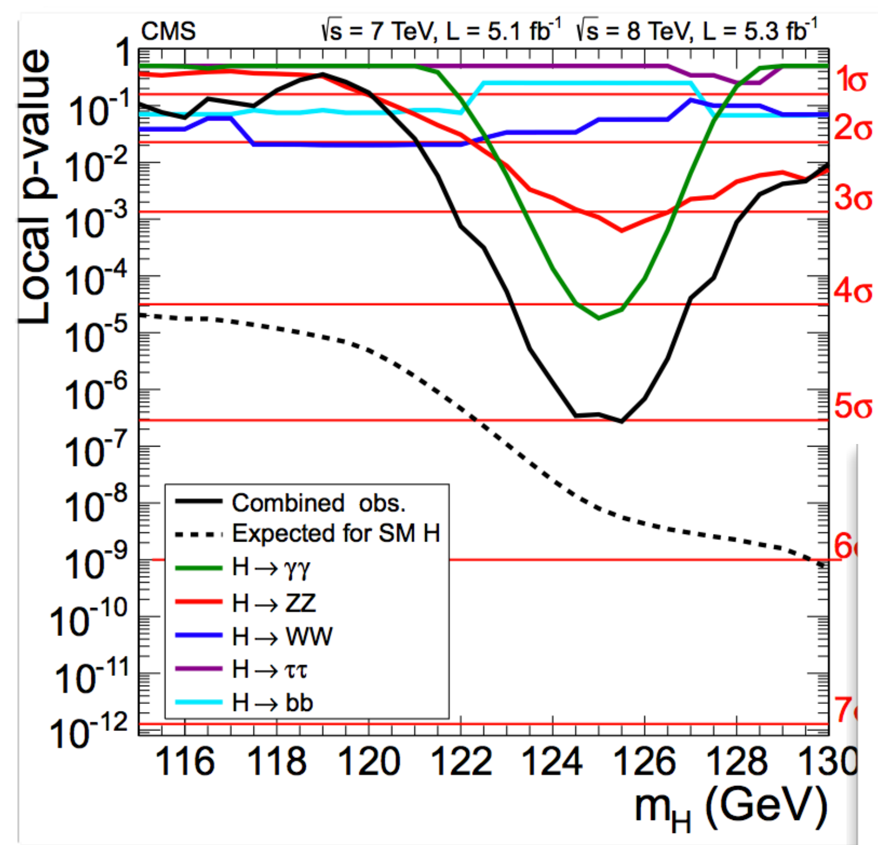
# Results - all combined

ETH Institute for Particle Physics

arXiv:1207.7235

- Combination as shown in the **paper**:




EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2012-220
2012/08/01

CMS-HIG-12-028

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

arXiv:1207.7235v1 [hep-ex] 31 Jul 2012

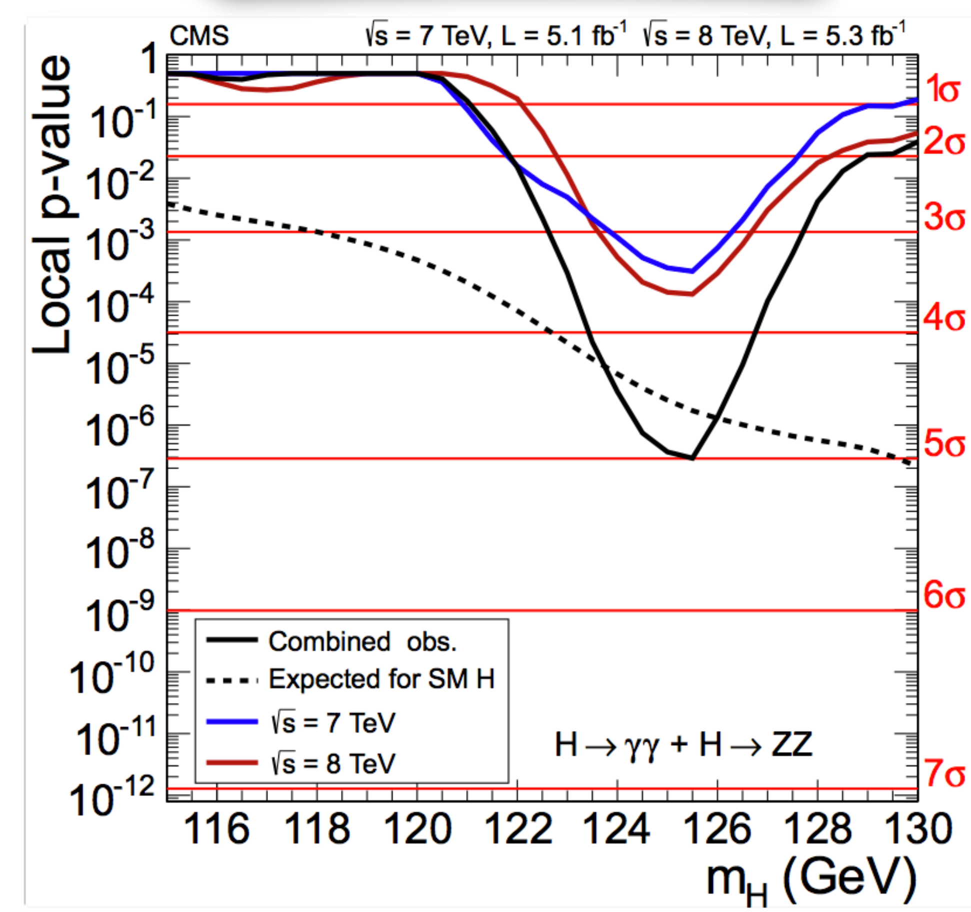
Abstract


Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s}$ = 7 and 8 TeV in the CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb$^{-1}$ at 7 TeV and 5.3 fb$^{-1}$ at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and bb. An excess of events is observed above the expected background, a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.


*This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away.*

*In recognition of their many contributions to the achievement of this observation.*

*Submitted to Physics Letters B*




## Abstract

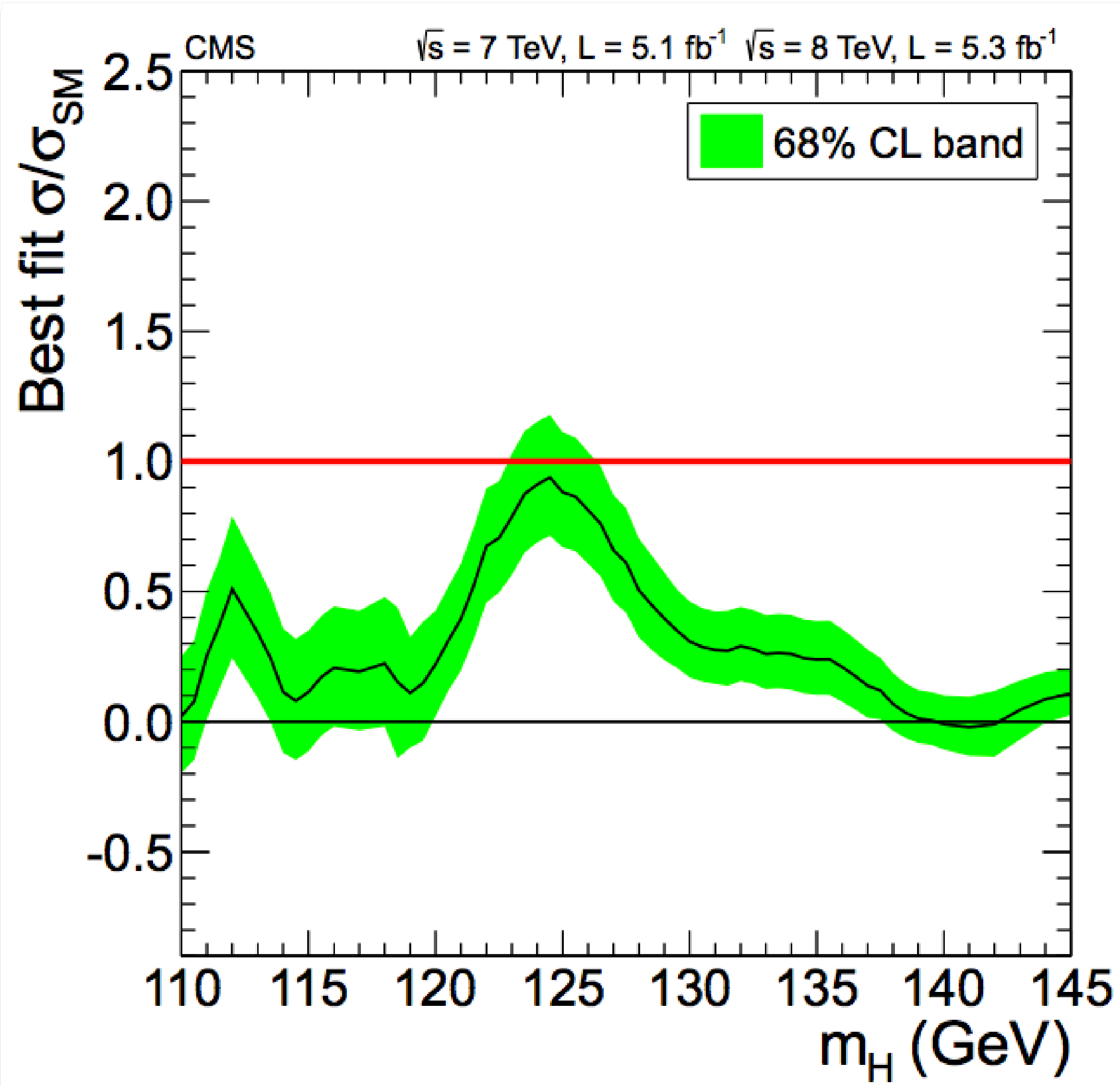
Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s}$ = 7 and 8 TeV in the CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb$^{-1}$ at 7 TeV and 5.3 fb$^{-1}$ at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and bb. An excess of events is observed above the expected background, a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

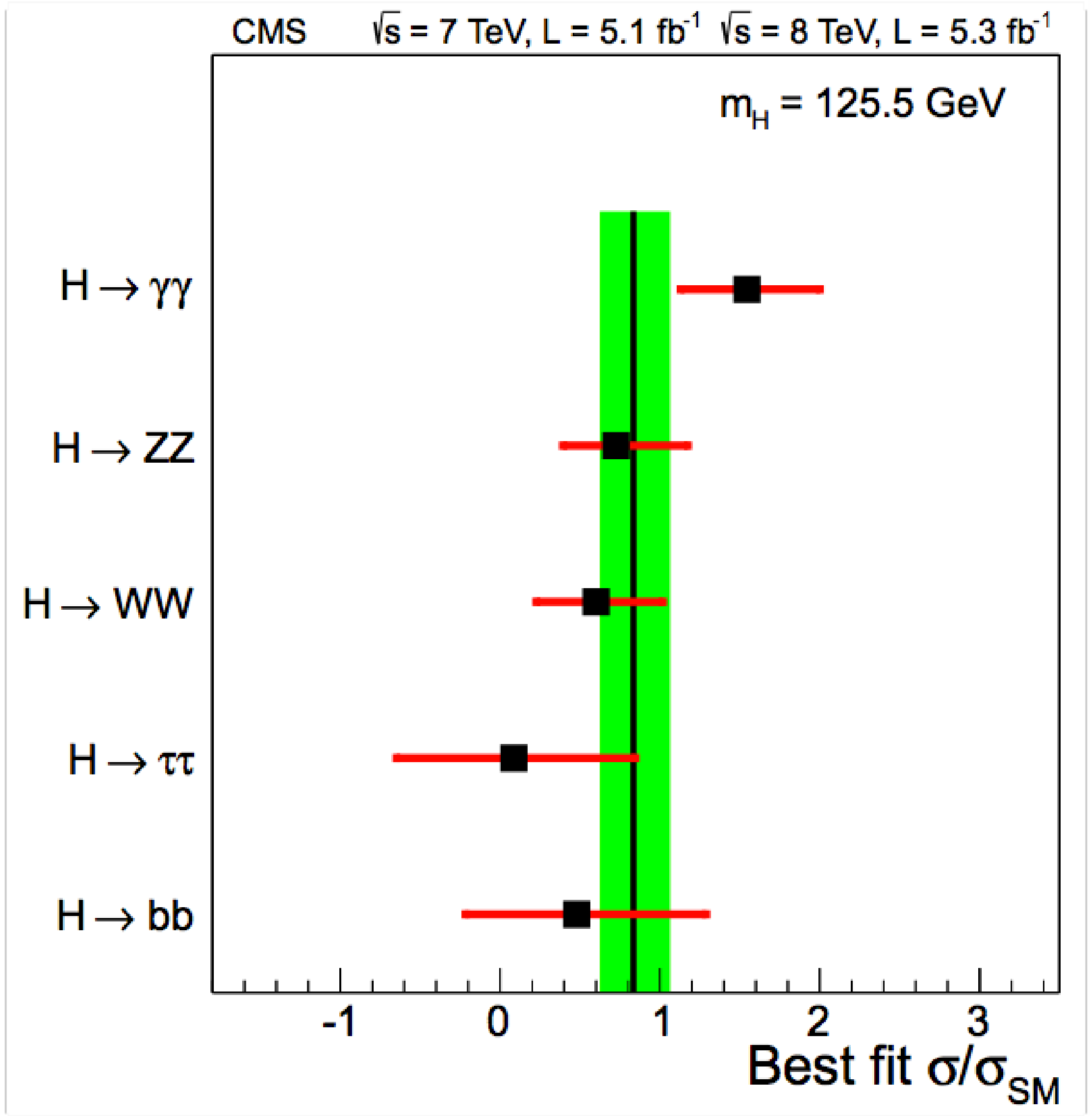
# Compatibility with SM Higgs

arXiv:1207.7235

slide adapted from P. Meridiani

- Best fit SM **strength at 125GeV:** $\mu = \sigma/\sigma_{SM} = 0.87 \pm 0.23$
- **Good agreement among modes**
  - **exceptions**: ττ (small), γγ (large, about 1.6xSM)



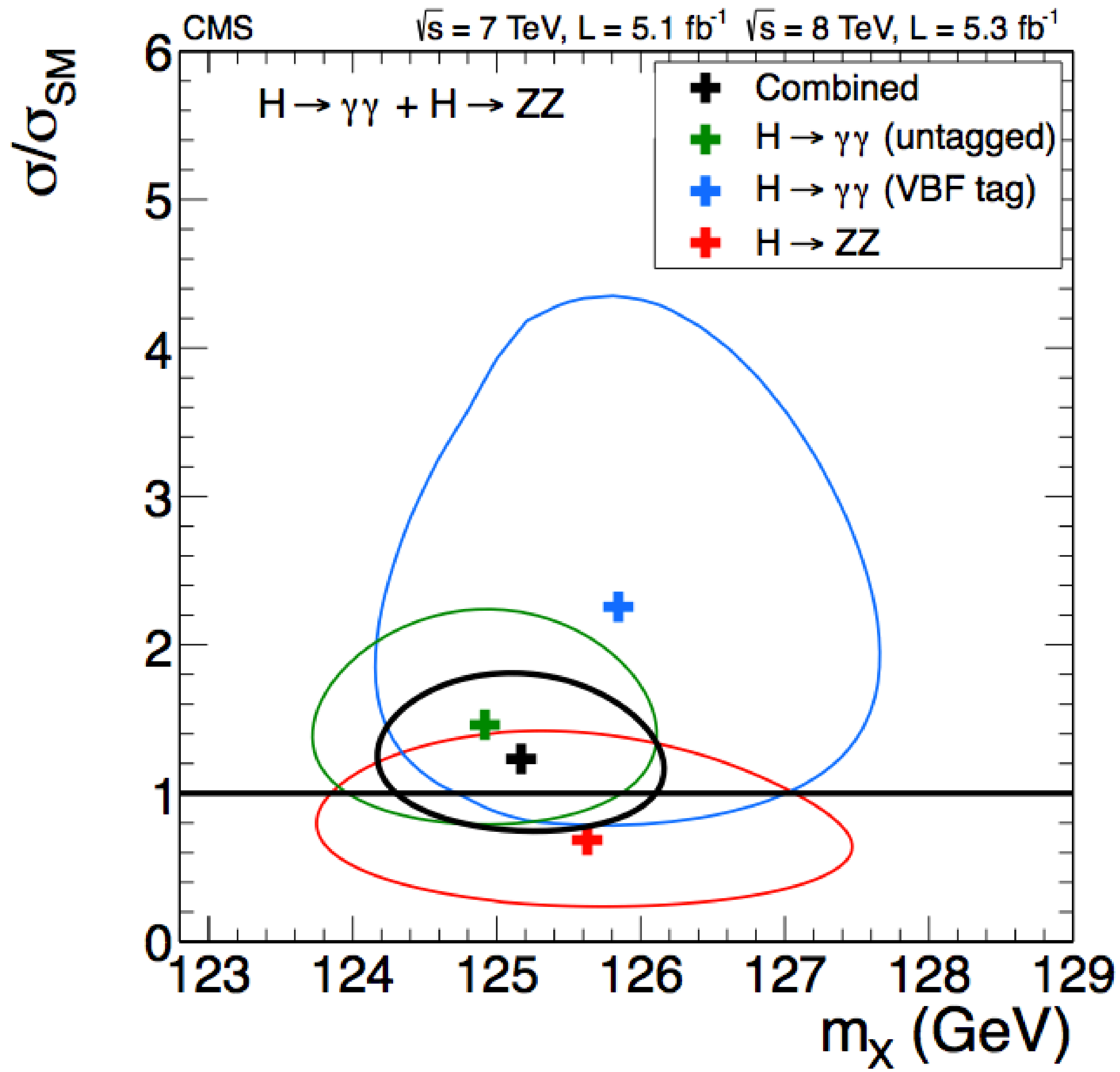



# First measured property: Mass

arXiv:1207.7235

slide adapted from P. Meridiani

- Mass derived from **most sensitive channels** (best resolution)
  - $H\rightarrow\gamma\gamma$
  - $H\rightarrow\gamma\gamma$ dijet (VBF enriched)
  - $H\rightarrow ZZ$
- Likelihood scan (mass vs σ)
- Systematics mainly from **ECAL energy scale**




**m = 125.3 ± 0.4 (stat) ±0.5 (syst) GeV**

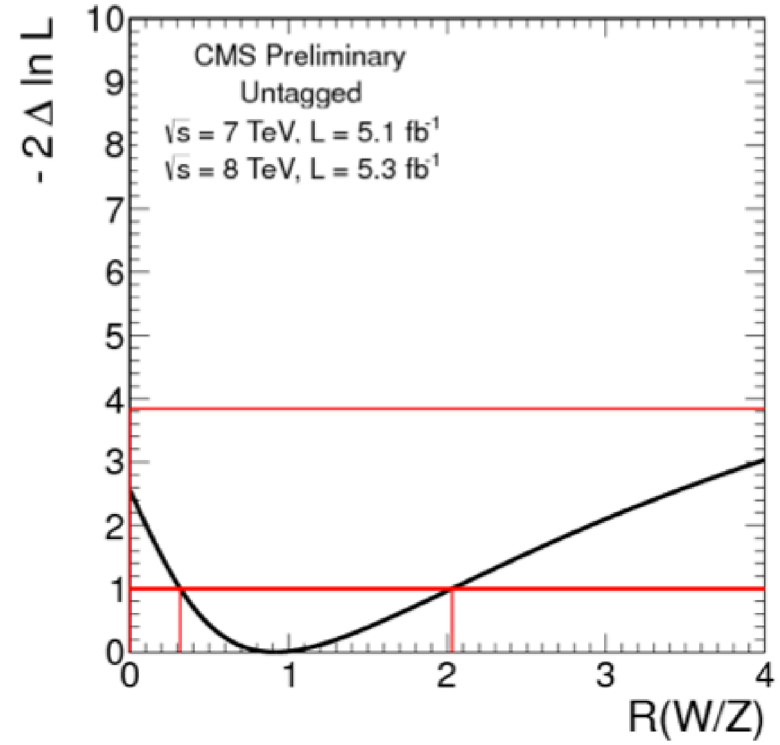
# Is it the SM Higgs?

CMS-HIG-12-020

slide adapted from P. Meridiani

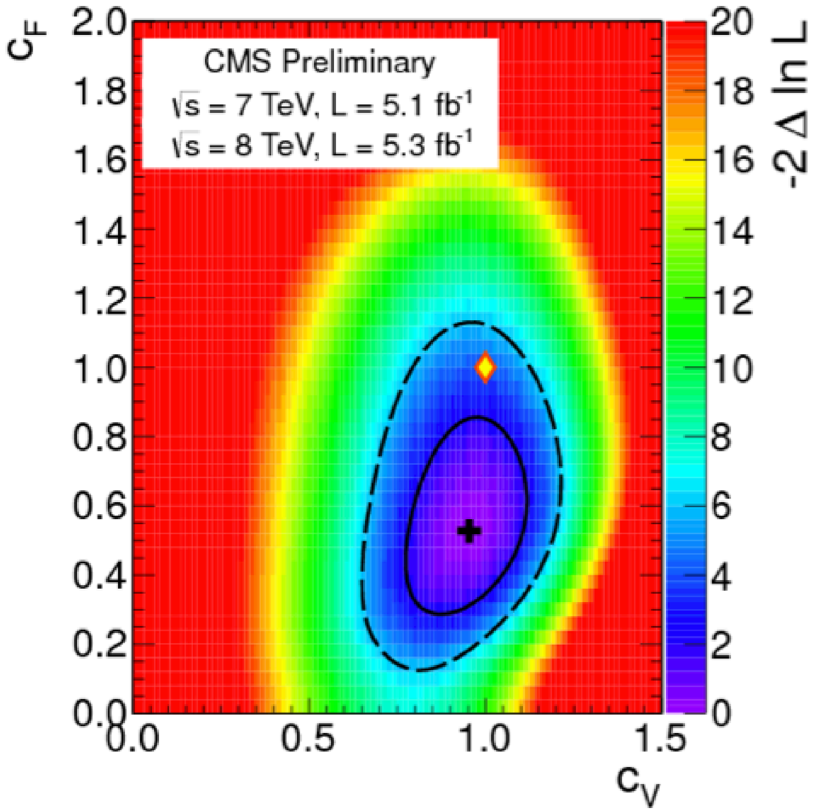
**Ratio sensitive to coupling to W and Z bosons** ($g_{HWW}/g_{HZZ}$) protected by gauge custodial symmetry

$$R_{WZ} = \mu_{WW}/\mu_{ZZ} = 0.9^{+1.1}_{-0.6}$$



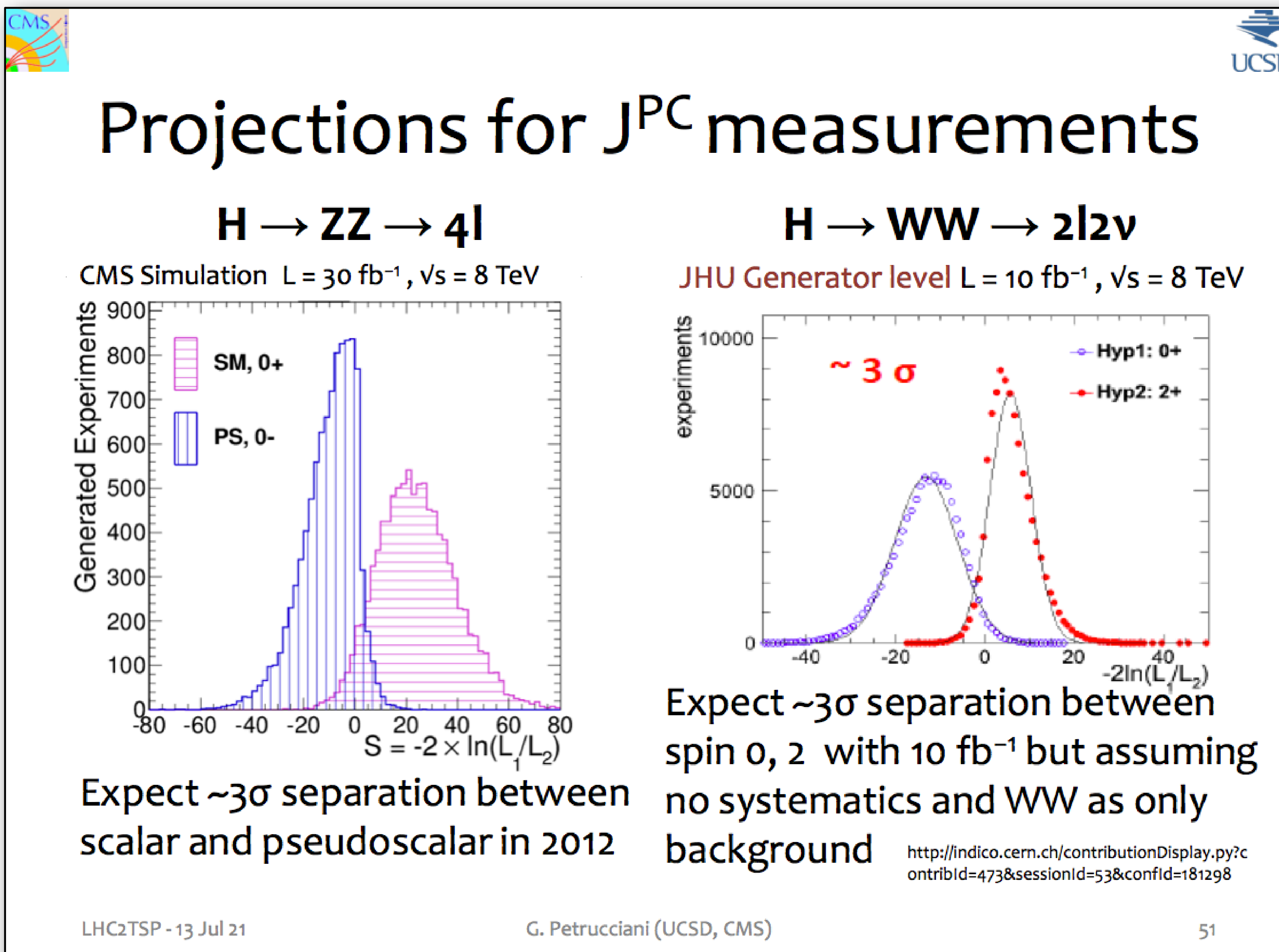

**Another exercise: group couplings in fermionic and vectorial ones ($C_F$, $C_V$)**

- Use LO prediction for loops in H→γγ and H→gg couplings
- In **agreement with SM within 95% CL**
- **Some tension** to be studied with more exclusive channels and data



# What next?

- By the end of this year's run:
  - might have collected 20-30/fb
- further input for the big questions mentioned before, e.g.



# The consequence

ETH Institute for Particle Physics


'Yes, I'm serious. Three posh blokes on camels wanting to meet the God particle'

*To order a copy of The Best of Mac 2011, priced £9.99, call the Mailshop Bookstore on 0843 382 0000 or visit mailshop.co.uk/books*

# Grand Summary

# Summary 1

- **So many things I couldn't cover :(**
  - Heavy Ion results (extremely rich!)
  - lot's of low-$p_T$ physics
  - forward physics, diffraction
  - more BPH, QCD, EWK, TOP results
  - many, many search results
- my god, too much...
- **Note**: CMS has already produced **~155 papers**, on collision data!

# Summary 2

- I guess, by now you must be pretty tired
- I am...

- But there is a good reason for that ;-)
  - in these two years only, CMS has produced such a wealth of high-quality results, that it is just mind-boggling when scanning through all of it
- **And now, we have this new boson!!!**

- So the best is only to come!

thus, this is not the

ETH Institute for Particle Physics

# Backup

# Higgs couplings

- parametrizations

| Production | Decay | LO SM | |
|---|---|---|---|
| VH | $H \to bb$ | $\sim \frac{C_V^2 \times C_F^2}{C_F^2}$ | $\sim C_V^2$ |
| ttH | $H \to bb$ | $\sim \frac{C_F^2 \times C_F^2}{C_F^2}$ | $\sim C_F^2$ |
| VBF | $H \to \tau\tau$ | $\sim \frac{C_V^2 \times C_F^2}{C_F^2}$ | $\sim C_V^2$ |
| ggH | $H \to \tau\tau$ | $\sim \frac{C_F^2 \times C_F^2}{C_F^2}$ | $\sim C_F^2$ |
| ggH | $H \to ZZ$ | $\sim \frac{C_F^2 \times C_V^2}{C_F^2}$ | $\sim C_V^2$ |
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| VBF | $H \to WW$ | $\sim \frac{C_V^2 \times C_V^2}{C_F^2}$ | $\sim C_V^4 / C_F^2$ |
| ggH | $H \to \gamma\gamma$ | $\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$ | $\sim C_V^2$ |
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# Higgs couplings

## Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters (**$c_V$, $c_F$**) modifying the expected signal yields in each mode through

| Production | Decay | LO SM | |
|---|---|---|---|
| VH | $H \to bb$ | $\sim \frac{C_V^2 \times C_F^2}{C_F^2}$ | $\sim C_V^2$ |
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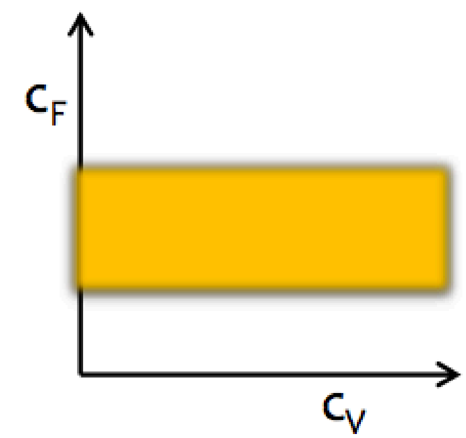

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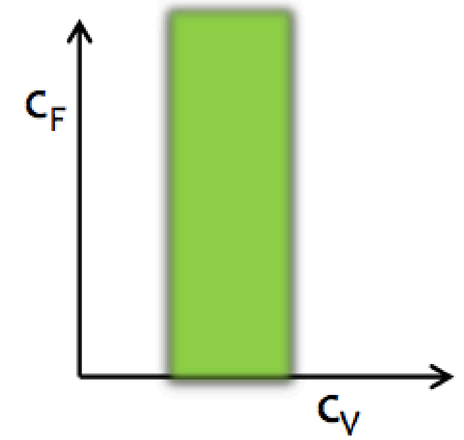


LHC2TSP - 13 Jul 21 G. Petrucciani (UCSD, CMS) 46

# Higgs couplings

## Is it a SM Higgs boson?

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| VBF | $H \to WW$ | $\sim \frac{C_V^2 \times C_V^2}{C_F^2}$ | $\sim C_V^4 / C_F^2$ |
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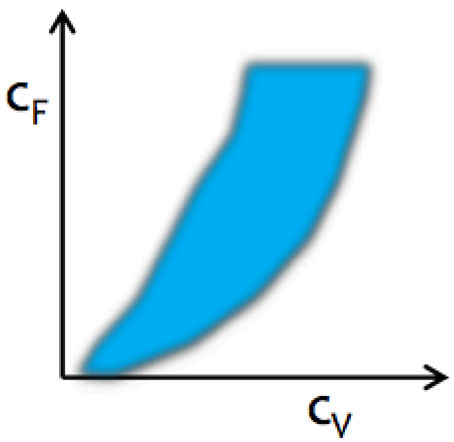
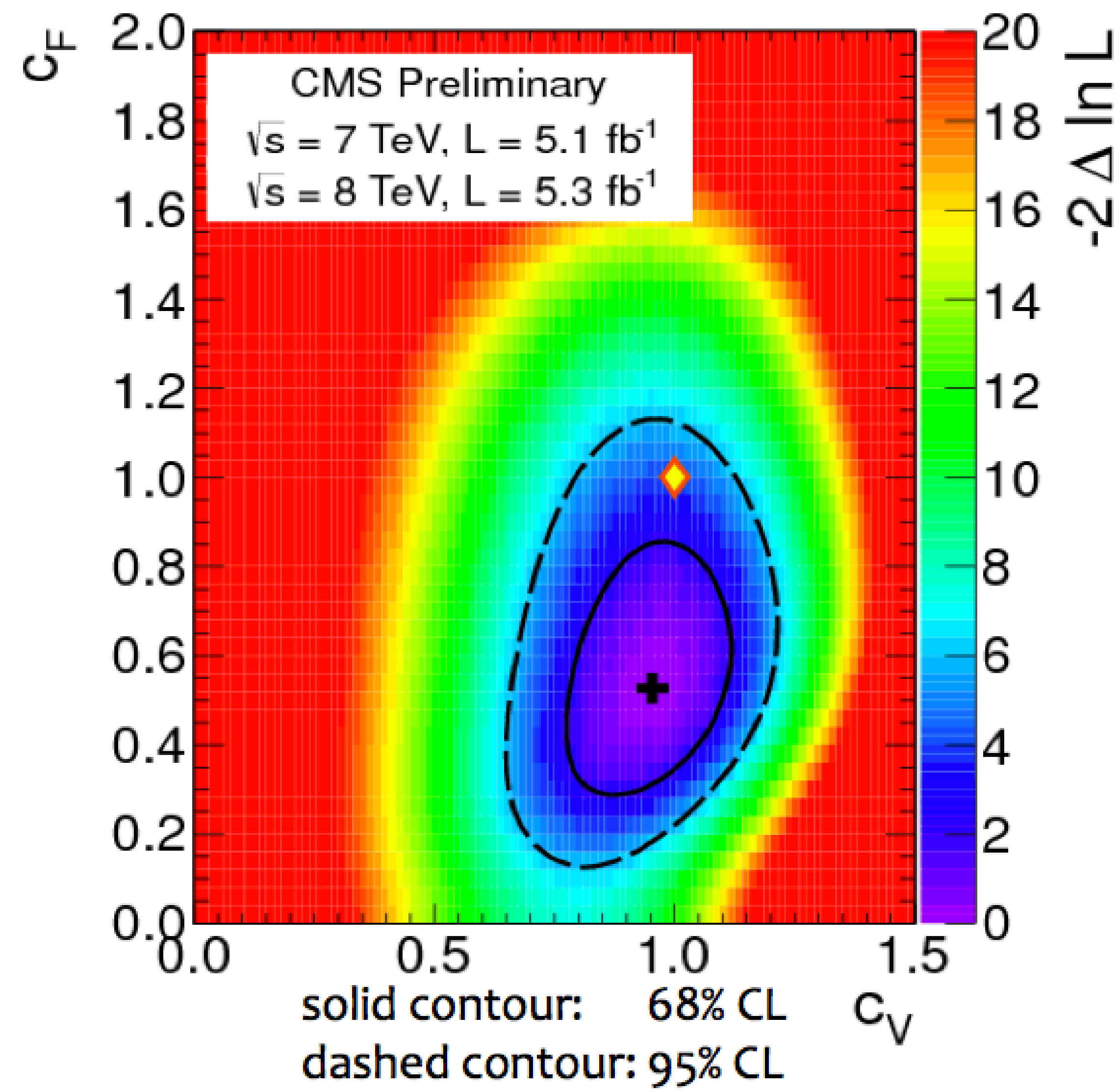


# Higgs couplings

## Is it a SM Higgs boson?

- **CMS data compatible with SM prediction at 95% C.L.**
- Best fit $c_F$ driven to low values by VBF γγ excess and ττ deficit.
- **More data needed to draw any definite conclusion.**
- LHC Cross Section WG also converging on an improved models for these kinds of fits.

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# Higgs couplings

- parametrizations

| Production | Decay | LO SM | |
|---|---|---|---|
| VH | $H \to bb$ | $\sim \frac{C_V^2 \times C_F^2}{C_F^2}$ | $\sim C_V^2$ |
| ttH | $H \to bb$ | $\sim \frac{C_F^2 \times C_F^2}{C_F^2}$ | $\sim C_F^2$ |
| VBF | $H \to \tau\tau$ | $\sim \frac{C_V^2 \times C_F^2}{C_F^2}$ | $\sim C_V^2$ |
| ggH | $H \to \tau\tau$ | $\sim \frac{C_F^2 \times C_F^2}{C_F^2}$ | $\sim C_F^2$ |
| ggH | $H \to ZZ$ | $\sim \frac{C_F^2 \times C_V^2}{C_F^2}$ | $\sim C_V^2$ |
| ggH | $H \to WW$ | $\sim \frac{C_F^2 \times C_V^2}{C_F^2}$ | $\sim C_V^2$ |
| VBF | $H \to WW$ | $\sim \frac{C_V^2 \times C_V^2}{C_F^2}$ | $\sim C_V^4 / C_F^2$ |
| ggH | $H \to \gamma\gamma$ | $\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$ | $\sim C_V^2$ |
| VBF | $H \to \gamma\gamma$ | $\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$ | $\sim C_V^4 / C_F^2$ |

# An extrapolation

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CMS

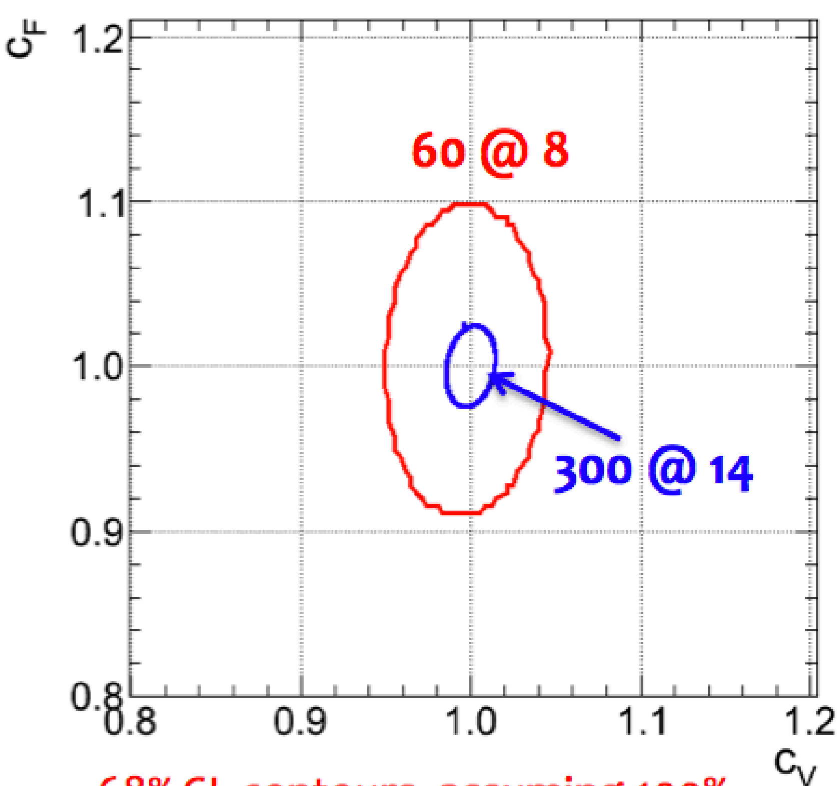
UCSD

## The road goes ever on…

Naïve rescaling of uncertainties on σ  BR with √(σ  L),

**NOT AN OFFICIAL CMS PROJECTION**

| Decay | Prod. | 60fb⁻¹ @ 8 TeV | 300fb⁻¹ @ 14 TeV |
|---|---|---|---|
| H→bb | VH | 30% | |
| H→bb | ttH | 60% | |
| H→ ττ | ggH | 40% | |
| H→ ττ | qqH | 40% | |
| H → γγ | ggH | 20% | |
| H → γγ | | 40% | |
| H → WW | ggH | 16% | |
| H → WW | qqH | 60% | |
| H → ZZ | ggH | 16% | |




68% CL contours, assuming 100% signal purity and no correlations

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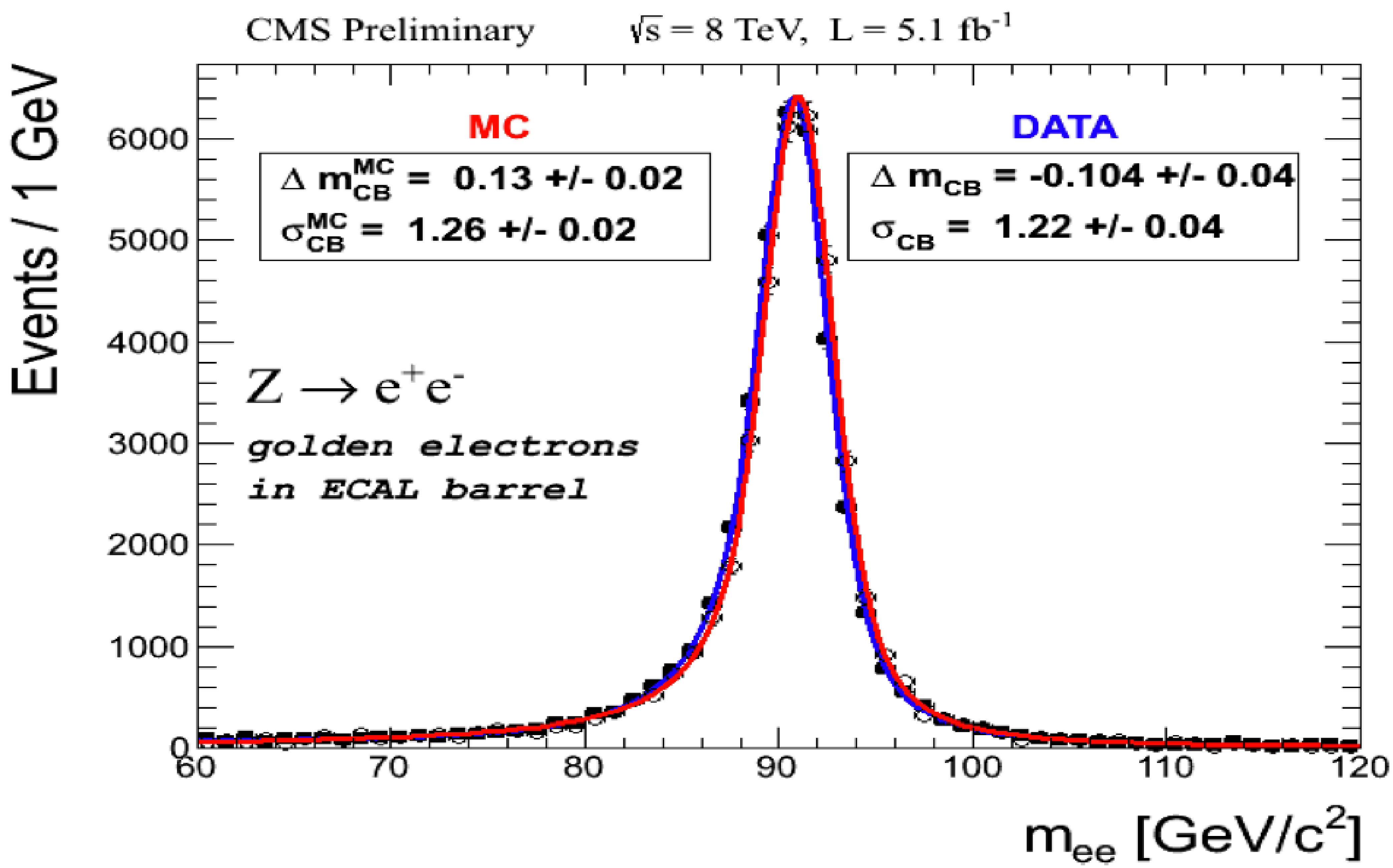
# Resolution, E-scale

## Electron energy scale: golden barrel



# Some Stat.

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slide adapted from M. Donega

Playing with Poisson: (s = #expected signal; b= #expected background events)

$$P(n|b) = \frac{b^n}{n!}e^{-b} \qquad P(n|s+b) = \frac{(s+b)^n}{n!}e^{-(s+b)}$$

We have n events for which we measure all sorts of variables **x.**
We can write the likelihoods for $H_0$ and $H_1$.

background only

$$L_b = \frac{b^n}{n!}e^{-b}\prod_{i=1}^{n} f(\mathbf{x}_i|\mathrm{b})$$

$\pi_s$ = s/(s+b)
$\pi_b$ = b/(s+b)

signal + background

$$L_{s+b} = \frac{(s+b)^n}{n!}e^{-(s+b)}\prod_{i=1}^{n}\left(\pi_{\mathrm{s}} f(\mathbf{x}_i|\mathrm{s}) + \pi_{\mathrm{b}} f(\mathbf{x}_i|\mathrm{b})\right)$$

**see also, eg.**:
Tom Junk at ETH Pauli lectures 2012, http://www-cdf.fnal.gov/~trj/
Glen Cowan: CERN academic lectures on statistics 2012 https://indico.cern.ch/conferenceDisplay.py?confId=173726

# Some Stat.



slide adapted from M. Donega

Typically (for numerical reasons take the ln, the -2 is conventional) one defines a test statistics Q as:

-2 ln converges to a χ2 for large samples

$$Q = -2\ln\frac{L_{s+b}}{L_b} = -s + \sum_{i=1}^{n} \ln\left(1 + \frac{s}{b}\frac{f(\mathbf{x}_i|\mathrm{s})}{f(\mathbf{x}_i|\mathrm{b})}\right)$$

constant it shifts the distributions but it doesn't affect the separation, so you usually drop it

Neyman-Person Lemma tells the LR is the best test statistics in the bkg only hp and has the biggest power relative to the S+B hp (you have both hp in the defintion)

To compute the p-value (for H0 reject the bkg only or H1 reject a signal model) we need the pdf for Q under the different hp: f(Q|b) and f(Q|s+b)
You do it with MC (toy). You build f(Q|b) generating pseudo-data on the background only hp and for each pseudo-experiment you compute Q. (same with s+b).

# Some Stat.

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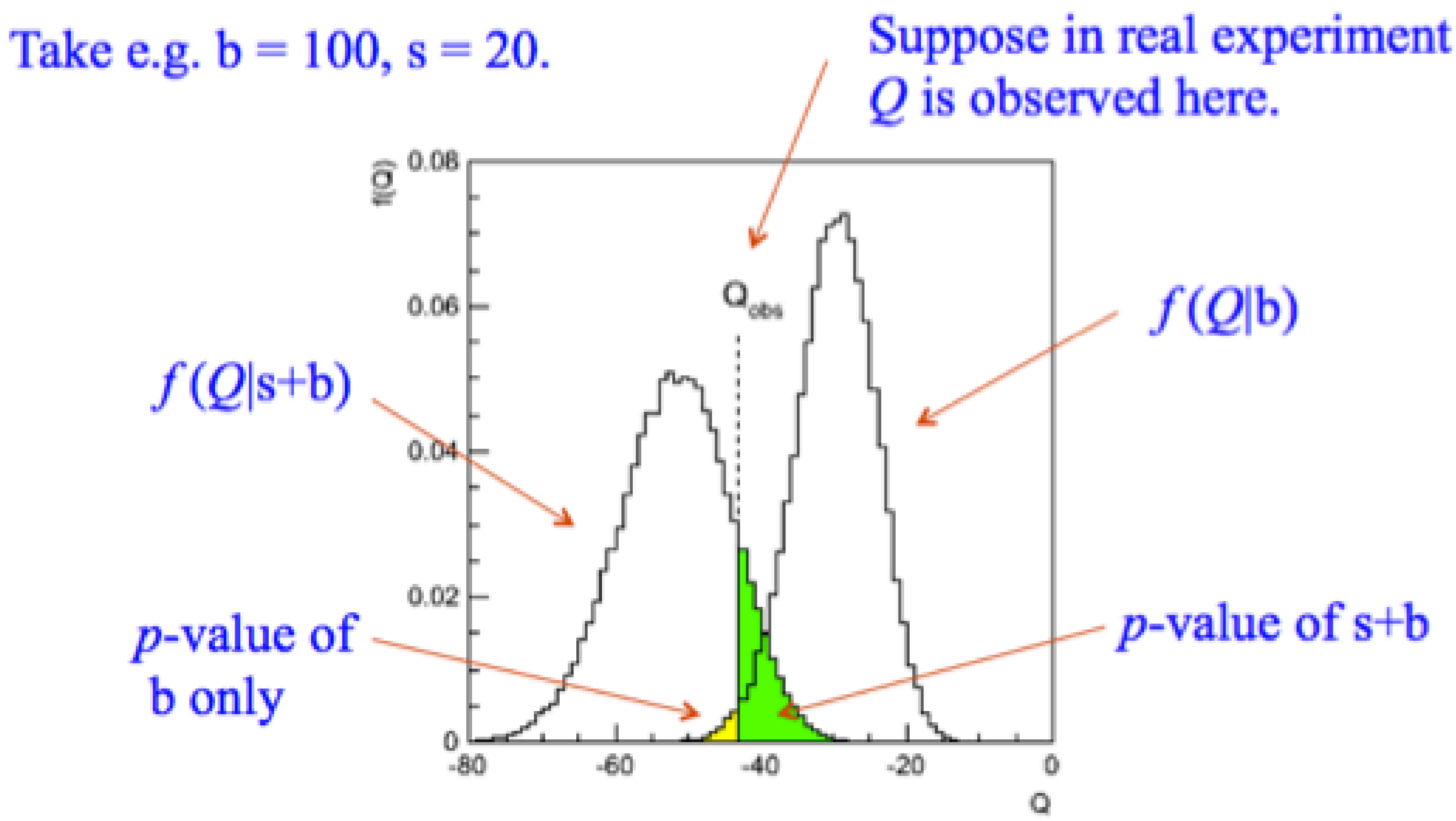
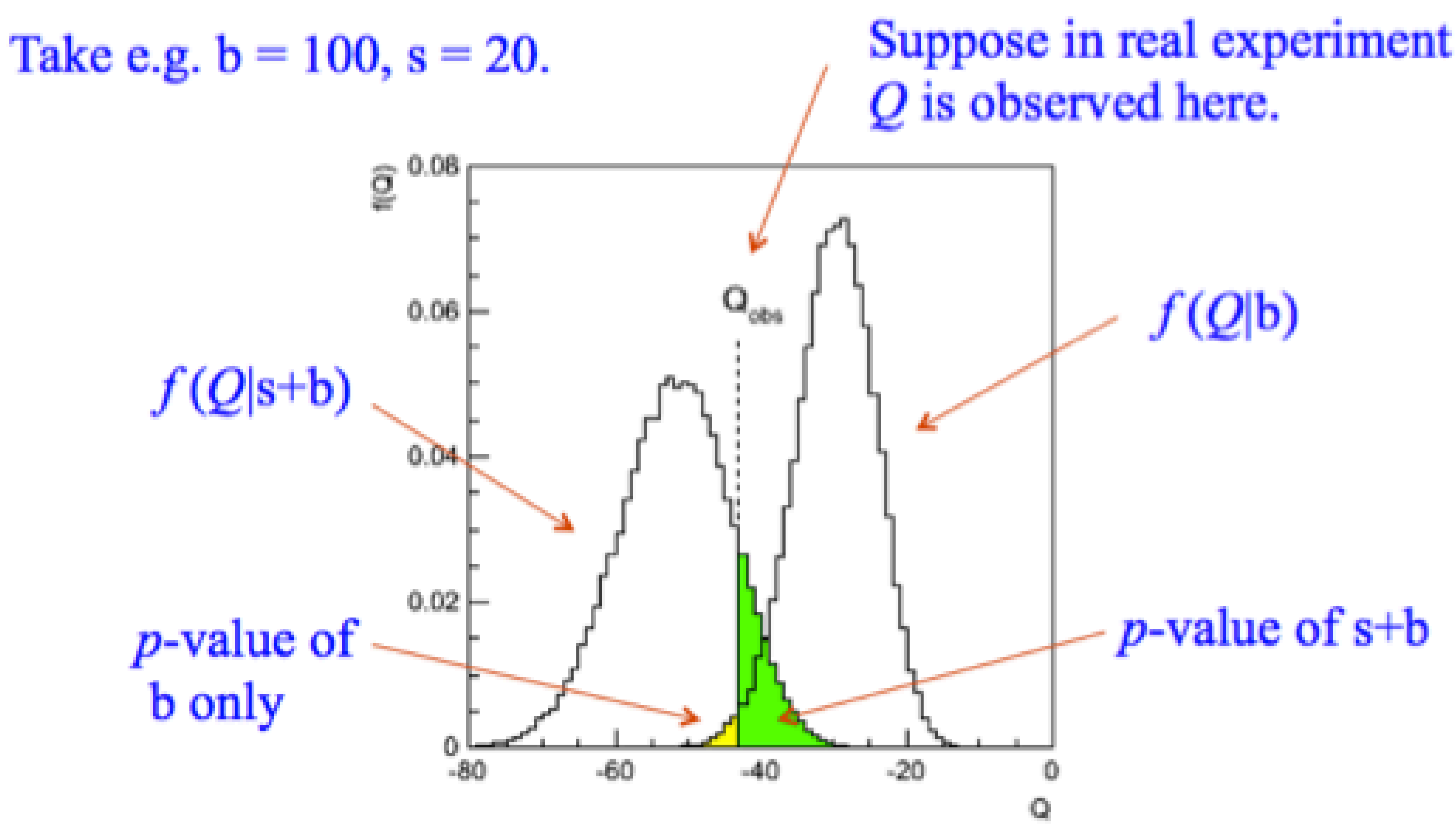



yellow = $p_b$ if $p_b$ <2.9 $10^{-7}$ reject the bkg only hp @ 5σ (discovery)

green = $p_{s+b}$ if $p_{s+b} < \alpha$ then reject that specific model at 1-α CL

# Some Stat.

slide adapted from M. Donega

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# Some Stat.

slide adapted from M. Donega

$$\mathcal{L}(\,\mathrm{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)=\mathcal{P}\,(\,\mathrm{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot p(\tilde{\theta}|\theta)$$

## The profile likelihood ratio

Likelihood ratio:
depends only on μ

float to maximize *L*

$$\lambda(\mu)=\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$$

float to maximize *L*

"θ double hat" means given the μ you are testing you maximize the likelihood wrt to all nuisance parameters.

It means $\hat{\hat{\theta}}$ are functions of μ !

The numerator is what we call the PROFILE LIKELIHOOD, "we profile away" the nuisance parameters

Profiling is a way of measuring the nuisance parameters from data at each toy => systematic become statistic uncertainty

At denominator you maximize the likelihood wrt to both $\hat{\mu}$ and $\hat{\theta}$

λ(μ) is the ratio of the profile likelihood and the maximum of the likelihood

Notes: λ(μ) ∊ [0,1] it reflects the level of agreement between the hp and the data

→1 if the tested μ is close to $\hat{\mu}$ (fit on data) and so also the nuisance parameters fit on data $\hat{\theta}$ are close the the ones that maximize the numerator $\hat{\hat{\theta}}$

→0 if the tested μ is way off the $\hat{\mu}$ (fit on data)

# Some Stat.



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Test statistics for discovery (i.e. test the $\mu = 0$ hp: $H_0$ is bkg only)

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

$\lambda(\mu) \in [0,1] \quad \Rightarrow \quad q_0 = -2 \ln \lambda(\mu) \in [\, 0,\infty)$

$\mu = 0$ (bkg only hp): $-2 \ln \lambda(0)$ → large values bad agreement
→ small values good agreement

We set $q_0 = 0$ for negative $\hat{\mu}$ because we only look at upward fluctuations as evidence of signal against the bkg only hp

Careful with $\mu$ and $\hat{\mu}$ !
$\mu$ is the physical quantity: the signal strength is $\mu \geq 0$
$\hat{\mu}$ is fit on data and can be positive or negative (it can fluctuate up or down)

In the large sample approximation the distribution of $\hat{\mu}$ becomes gaussian !
(and as usual this brings some simplifications)

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## Measured p-value

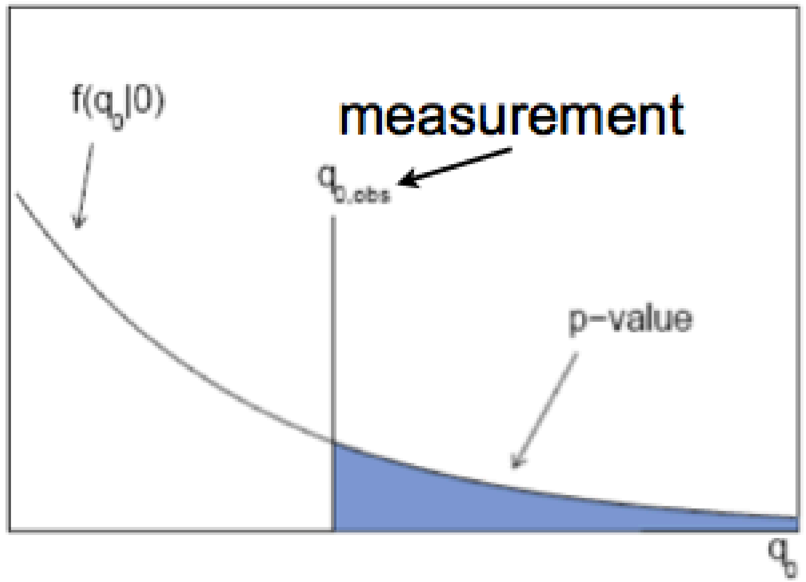
test statistics

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

large $q_0$ means bad compatibility

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$

pdf of $q_0$ under the hp of no signal




← good compatibility

bad compatibility →

(and as usual the p-value can be converted in σ)

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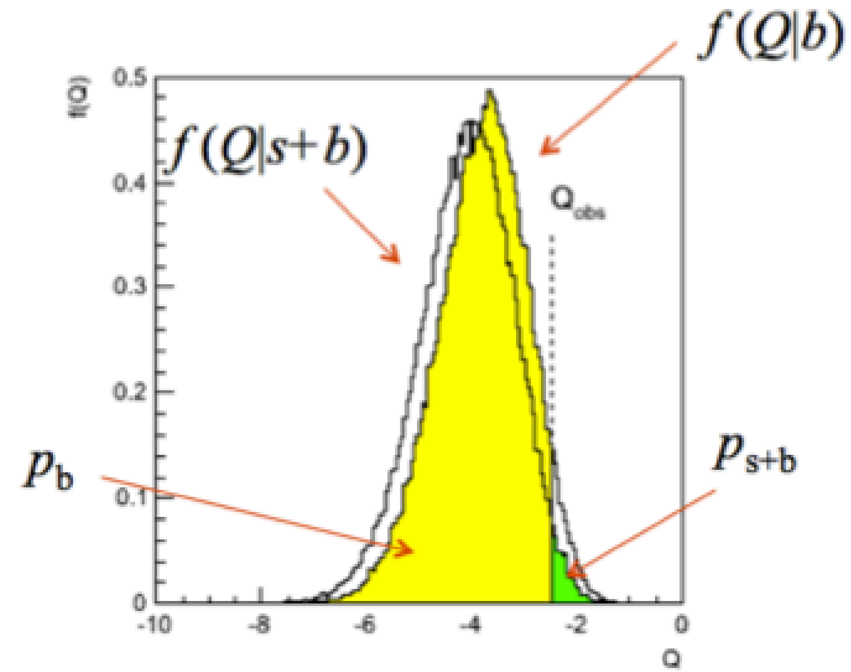
## CLs procedure

aka: "modified frequentist construction"

To cope with low sensitivity the CLs procedure corrects the p-value by a number that is smaller than 1.

$$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}}$$

$$= \frac{p_{s+b}}{1 - p_b}$$




A. Read definition

CLs+b: probability to get a result which is less compatible with a signal when the signal hypothesis is true
CLb: probability to get a result less compatible with the B only hypothesis than the observed one

If the two distributions are very well separated than $p_b$ will be very small ⇒ $1\text{-}p_b \sim 1$ and $CL_s \sim CL_{s+b}$ which is just the ordinary p-value of the s+b hypothesis

If the two distributions are very close than $p_b$ will be large ⇒ $1\text{-}p_b$ small ! So that the $CL_s$ is prevented to become very small !

The rejection now is decided on the corrected p-value and so $CL_s \leq \alpha$ and this prevents you to reject ho where you have little sensitivity !

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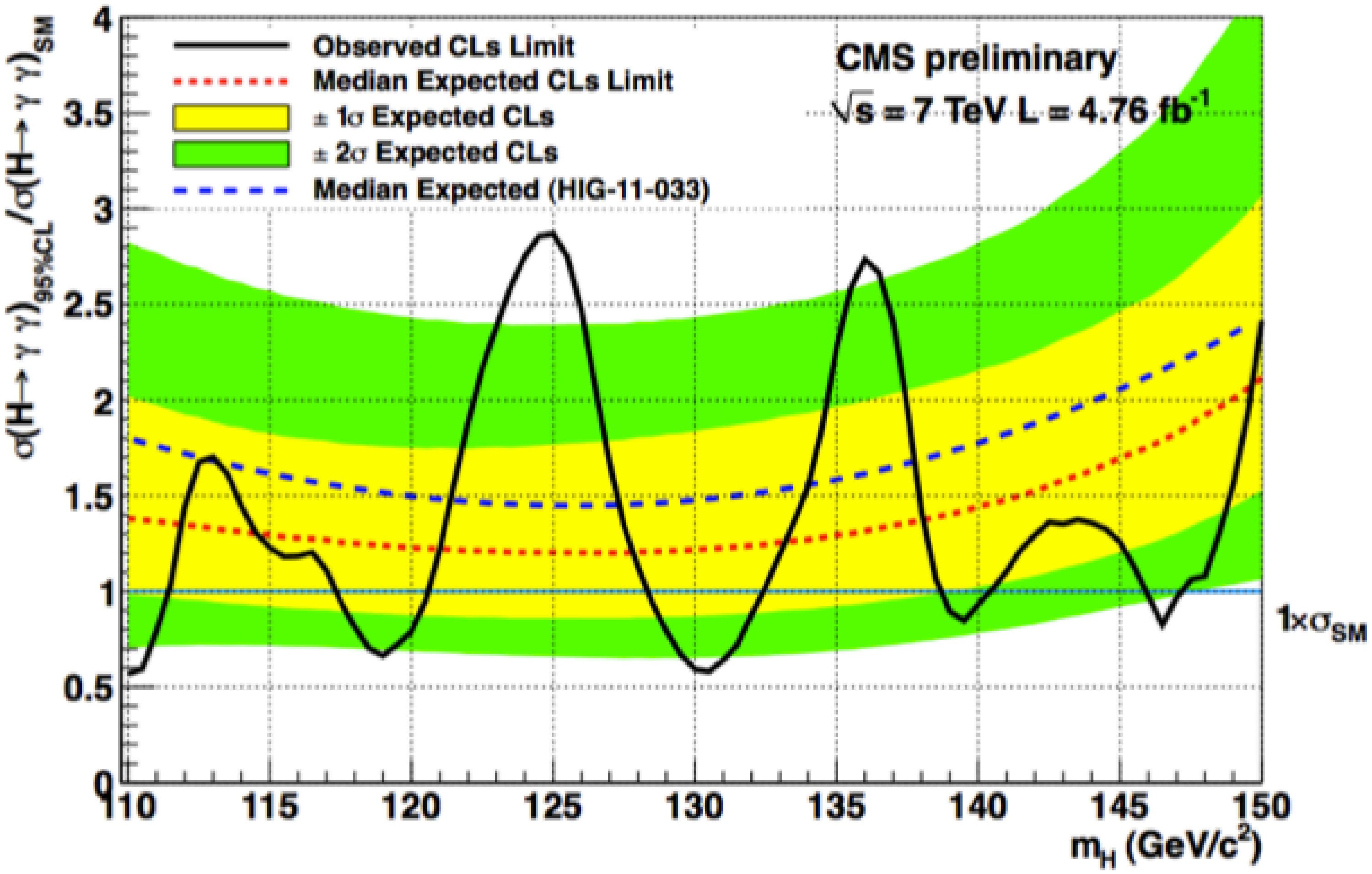
## Brazilian Flag plot

Expected: for each mass point you calculate the CLs upper limit on μ ($\mu_{up}$) in the background only hp (μ=0). The dashed line is the median of the $\mu_{up}$ distribution. (each toy has the equivalent integrated luminosity -number of events- as in data)

Observed: all data are used at each single mass hp point (x-axis). For each mass hp you calculate the CLs upper limit on μ ($\mu_{up}$).




If the observed limit is larger that the expected it means you have observed some excess of candidates in that region.

# Some Stat.



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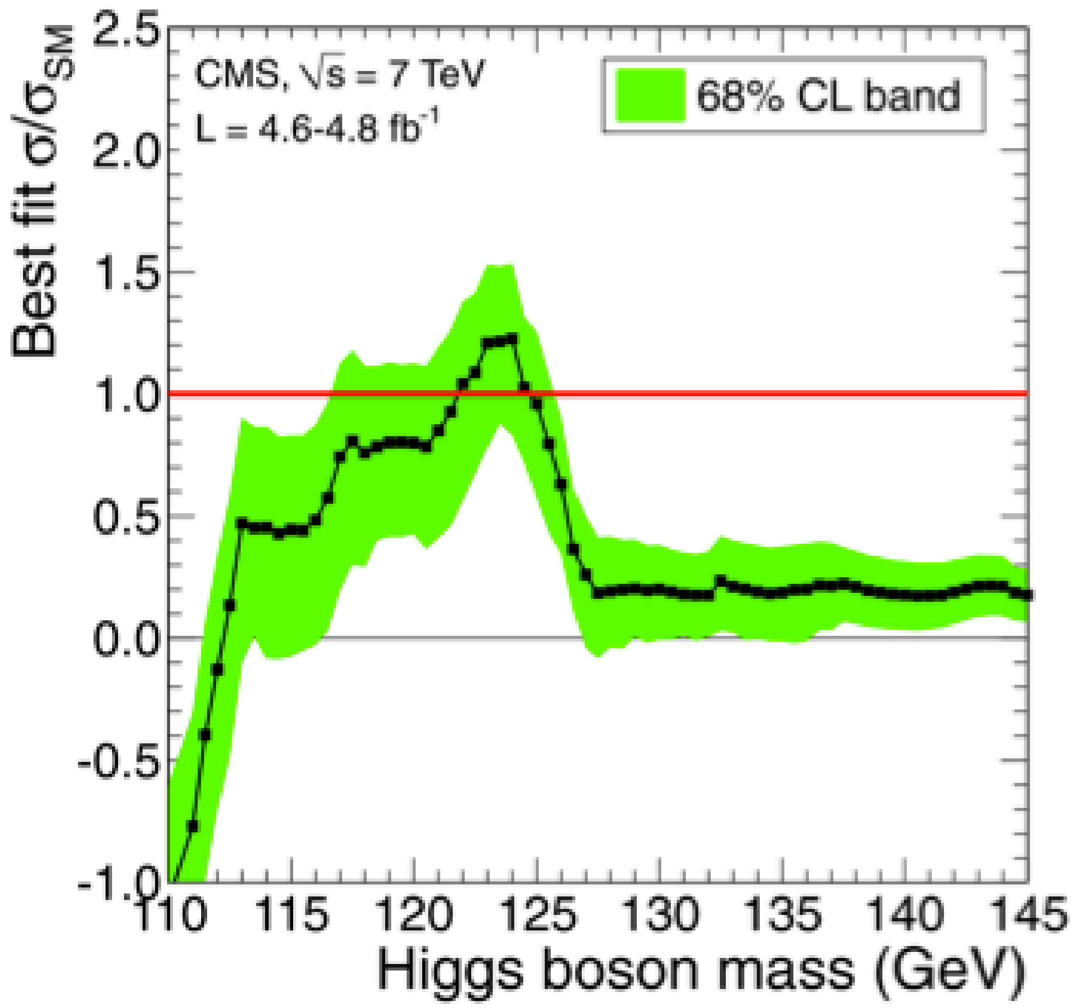
## Best fit plot

The best fit value of μ (i.e. $\hat{\mu}$) vs the hypothesis mass.
The green band (usually it's blue, but in CMS we have a lot of fantasy) is defined as:

$$-2\ln\lambda(\mu) = -2\ln(L(\mu)/L(\hat{\mu})) < 1 \text{ i.e., } \ln L(\mu) > \ln L(\hat{\mu}) - \frac{1}{2}$$




the 1σ in the gaussian (parabolic) case

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## p-value plot

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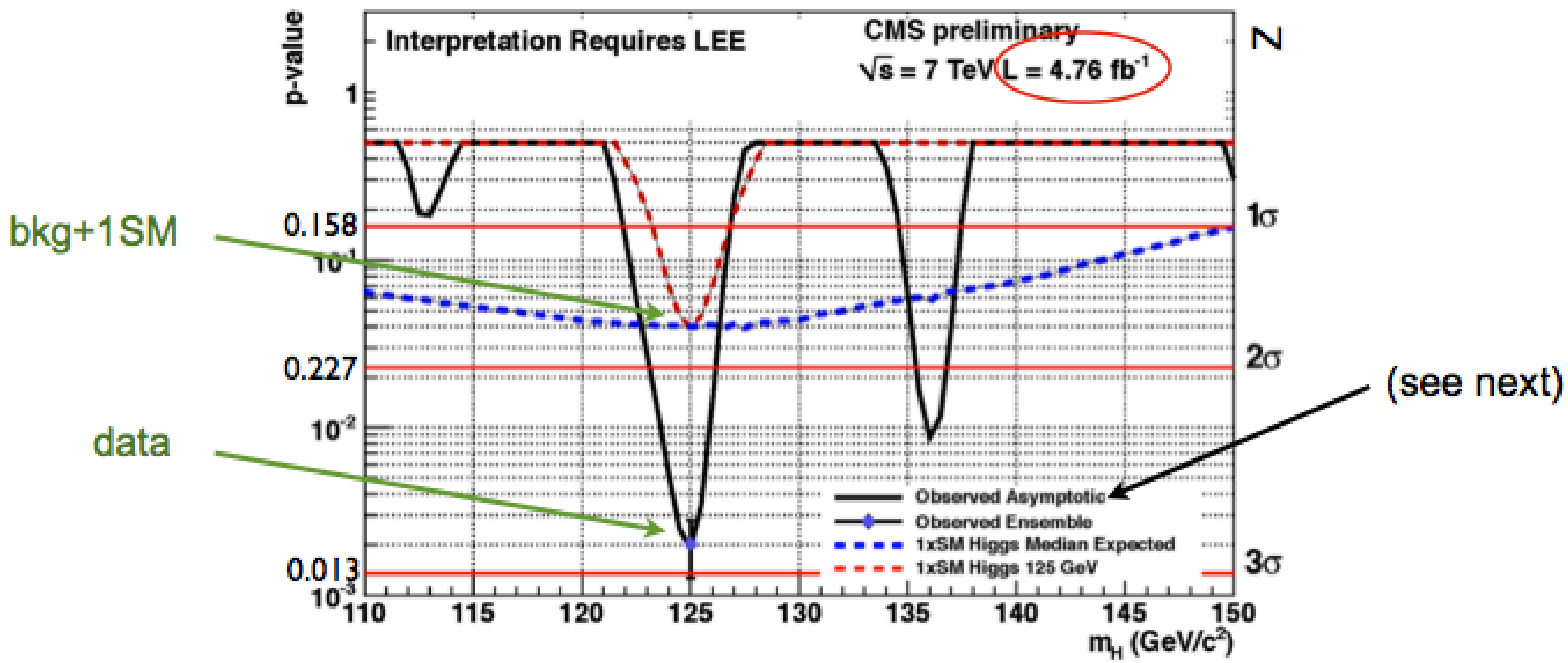
The local p-value is calculated at each mass hp in the background only hp. (the probability to have a fluctuation of the background as large or larger than the one observed)

Local $p_0$ means that it has not been corrected for any look-elsewhere-effect (see next)

The blue dashed line is the signal expected giving the median $p_0$ under the assumption of the Standard Model cross section $\mu=1$ at each mass point (red dashed line is when you inject a signal at 125 GeV).

Local p-value is related to (equivalent gaussian) significance Z as: p-value = erf(Z/sqrt(2))




A very small p-value means you're excluding the background only hp at a particular mass point, hence you might have signal