LHC results and prospects from a theorist's viewpoint

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Strings 2011
Uppsala, 27 June 2011

Preamble

The Standard Model of strong and electroweak interactions (effectively coupled to gravity)

quantitatively describes most observations

Neutrino oscillations call for minor modifications

More serious exceptions with gravity and cosmology:

dark matter, dark energy, inflation, baryogenesis, …

Big open question is on EW symmetry breaking:

Minimal SM realization (elementary scalar doublet)

or

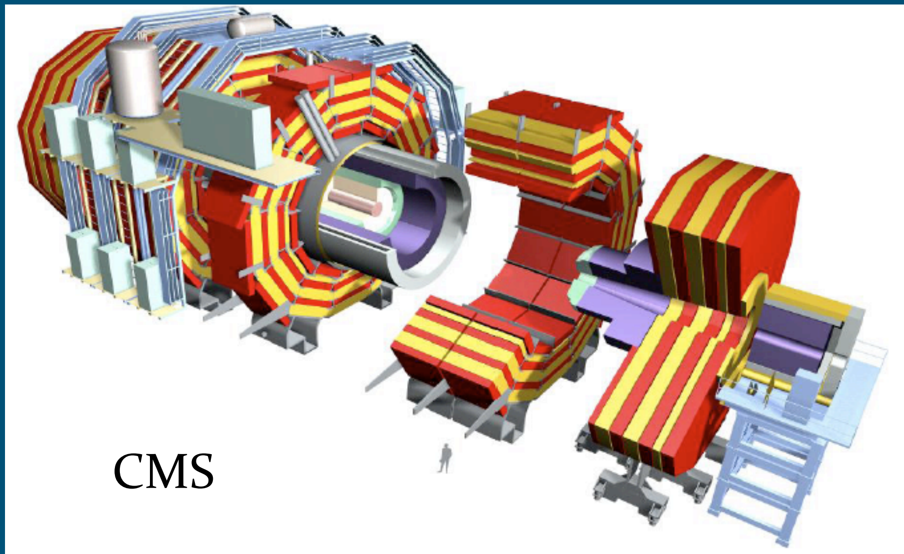
some (weakly/strongly coupled) alternative?

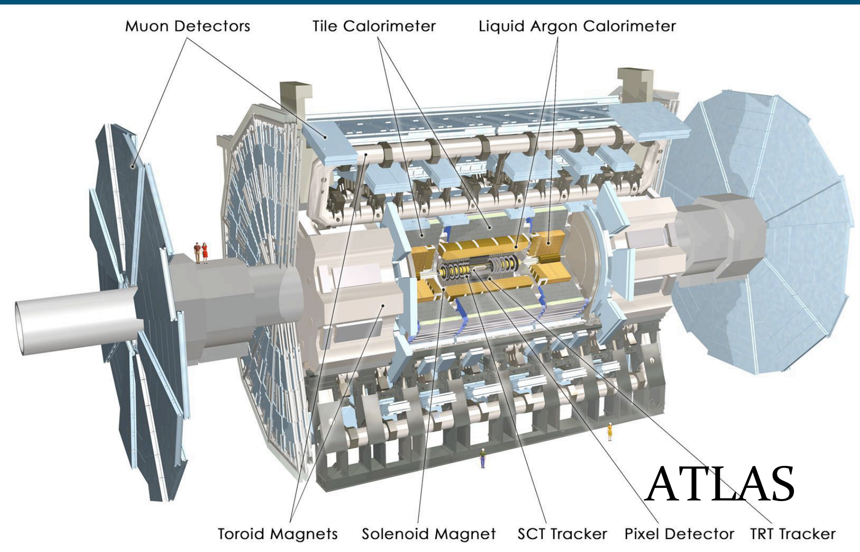
Bound to find an answer within the TeV scale

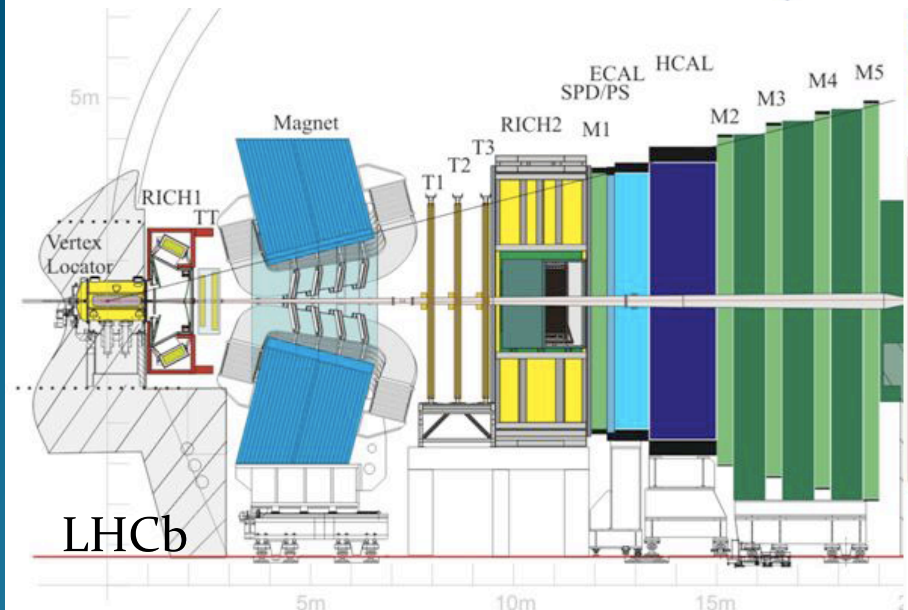
LHC built to answer this question with
two general-purpose detectors:
ATLAS (A Toroidal Lhc ApparatuS)
CMS (Compact Muon Solenoid)
after the inputs from
LEP (e^+e^- collider, $\sqrt{s} \leq 209$ GeV, stopped in 2000)
Tevatron ($p\bar{p}$ collider, $\sqrt{S} \cong 2$ TeV, ending in 2011)

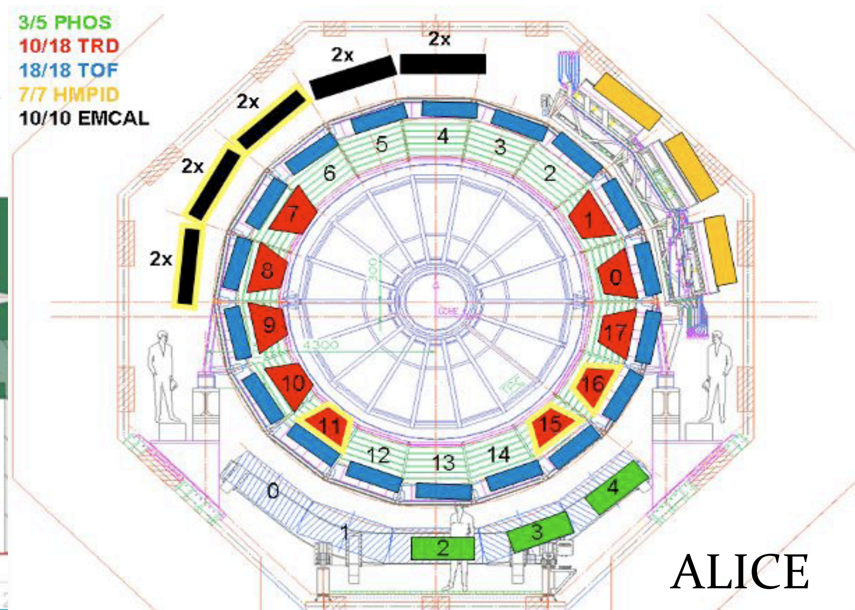
In addition, two major (broadly) dedicated detectors:
LHCb (designed for forward direction, e.g. B physics)
ALICE (designed for studying heavy-ion collisions)

The 4 main LHC Detectors









Related questions at the LHC

If indeed a light SM-like Higgs boson is found:

- to what accuracy does it have SM-like couplings?
- is it accompanied by other TeV-scale physics that solves the hierarchy problem (SUSY, xdim, …)?

If instead a light SM-like Higgs boson is ruled out:

- what replaces it to restore unitarity beyond TeV?
- how is this reconciled with the SM precision tests?

Another plausible argument for exploring the TeV scale: WIMP candidates to solve the Dark Matter problem

An indirect window to higher scales through more precision tests in flavour physics (FCNC & CP violation in B physics)

And also QCD at high T/density in UR heavy-ion collisions

Large Hadron Collider (pp collisions)

Design parameters:

$$\sqrt{S} = 14\,\text{TeV} \qquad L_{peak} = 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$$

2010 ($\sqrt{S}$ = 7 TeV):

$$L_{peak} \sim 2 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1} \qquad \int L\,dt \sim 50\,\text{pb}^{-1}$$

2011 ($\sqrt{S}$ = 7 TeV):

$$L_{peak} \sim 1.3 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1} \qquad \int L\,dt \sim 1.1\,\text{fb}^{-1}$$

already achieved: 3 fb^{-1} by end-of-year?

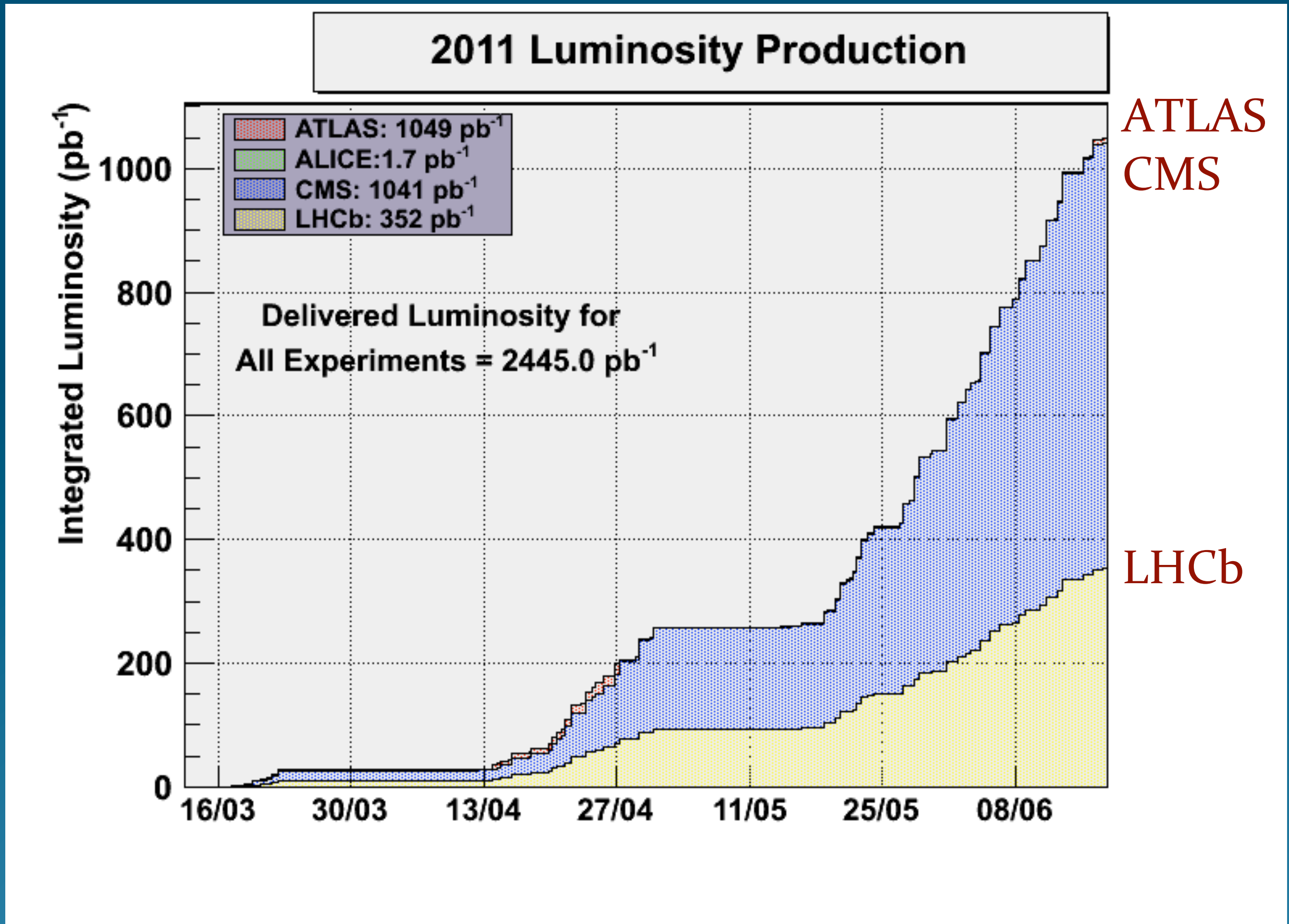
2012 ($\sqrt{S}$ > 7 TeV ?):

8-10 fb^{-1} before 20-month shutdown in 2013-4?

Tevatron ($p\bar{p}$ collisions)

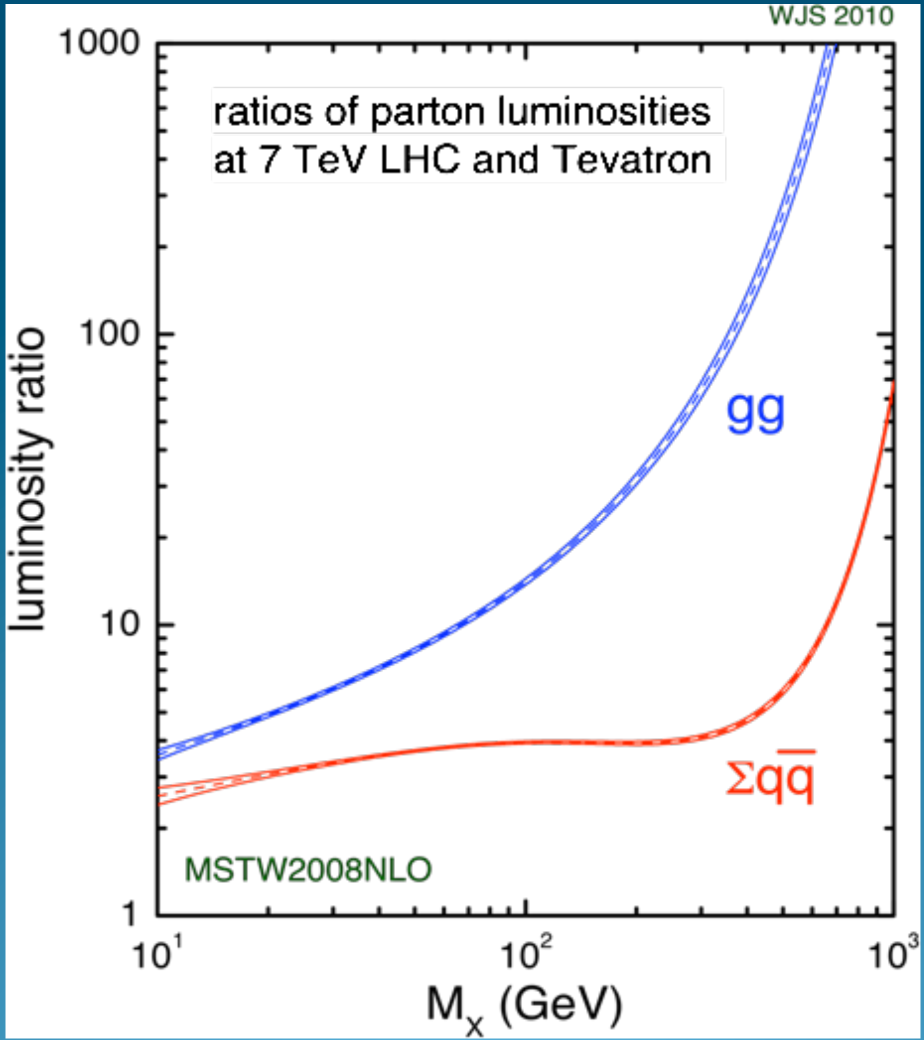
$$\sqrt{S} \simeq 2\,\text{TeV} \qquad \int L\,dt \sim 10\,\text{fb}^{-1}\ \text{by end 2011}$$

The 2011 LHC luminosity production



Presented by Steve Myers on June 21 and already dated ($200\ pb^{-1}$/week or more are now possible in “good” weeks and there are still 15 weeks of physics left in 2011)

Tevatron vs. LHC luminosity ratio

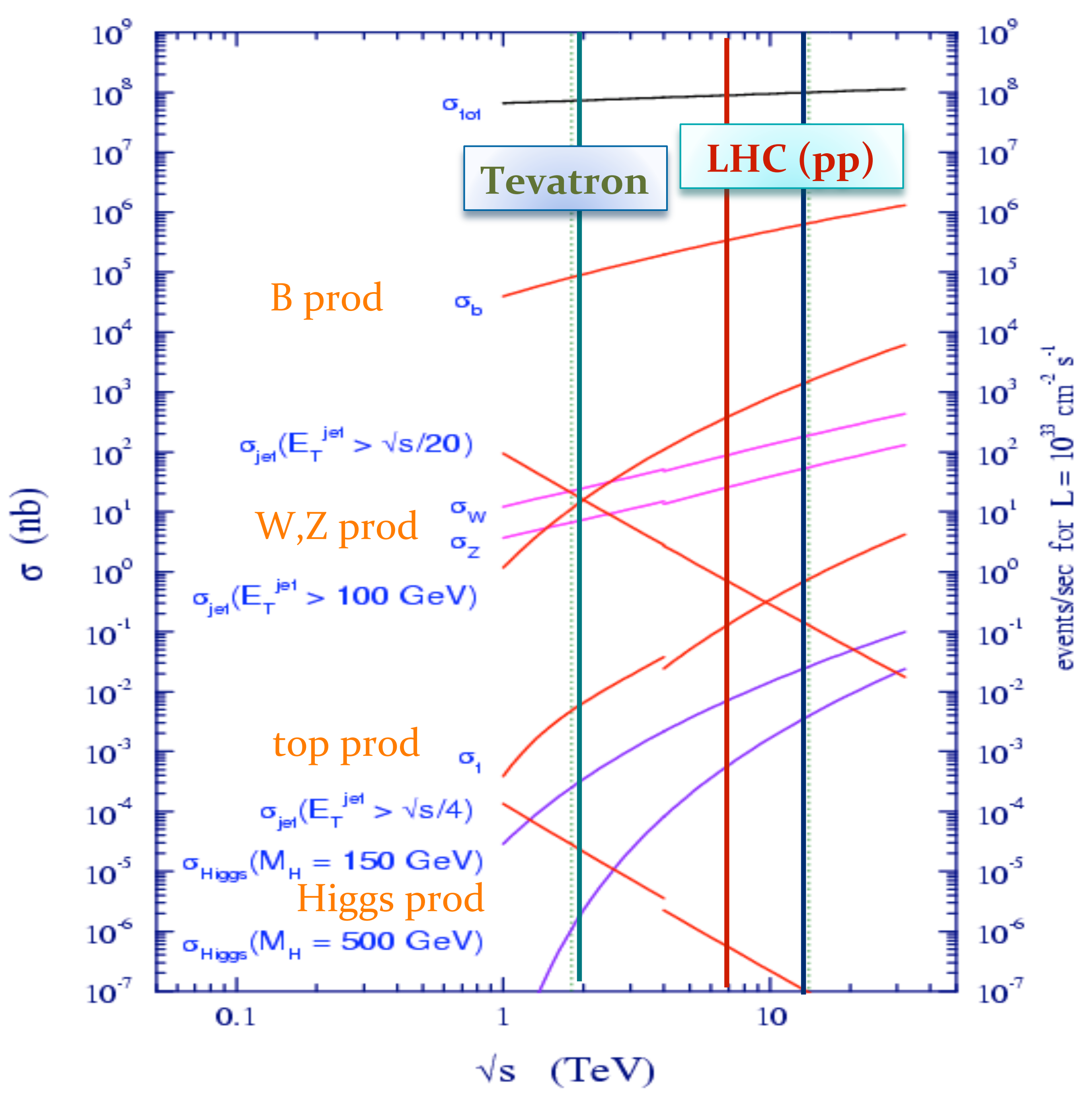


Collision energy

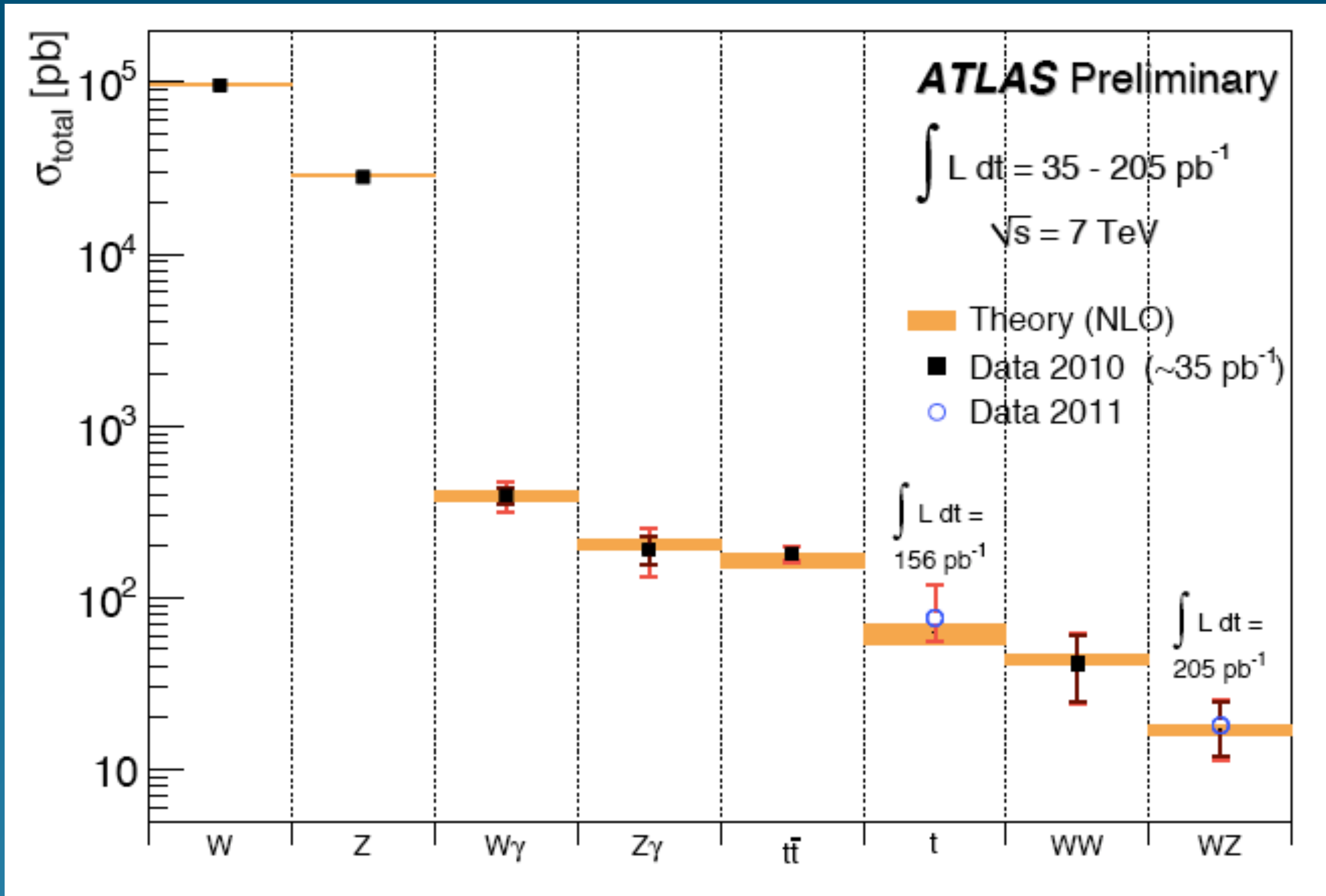
Tevatron:
1.96 TeV

LHC in 2011
7 TeV
Later up to
14 TeV

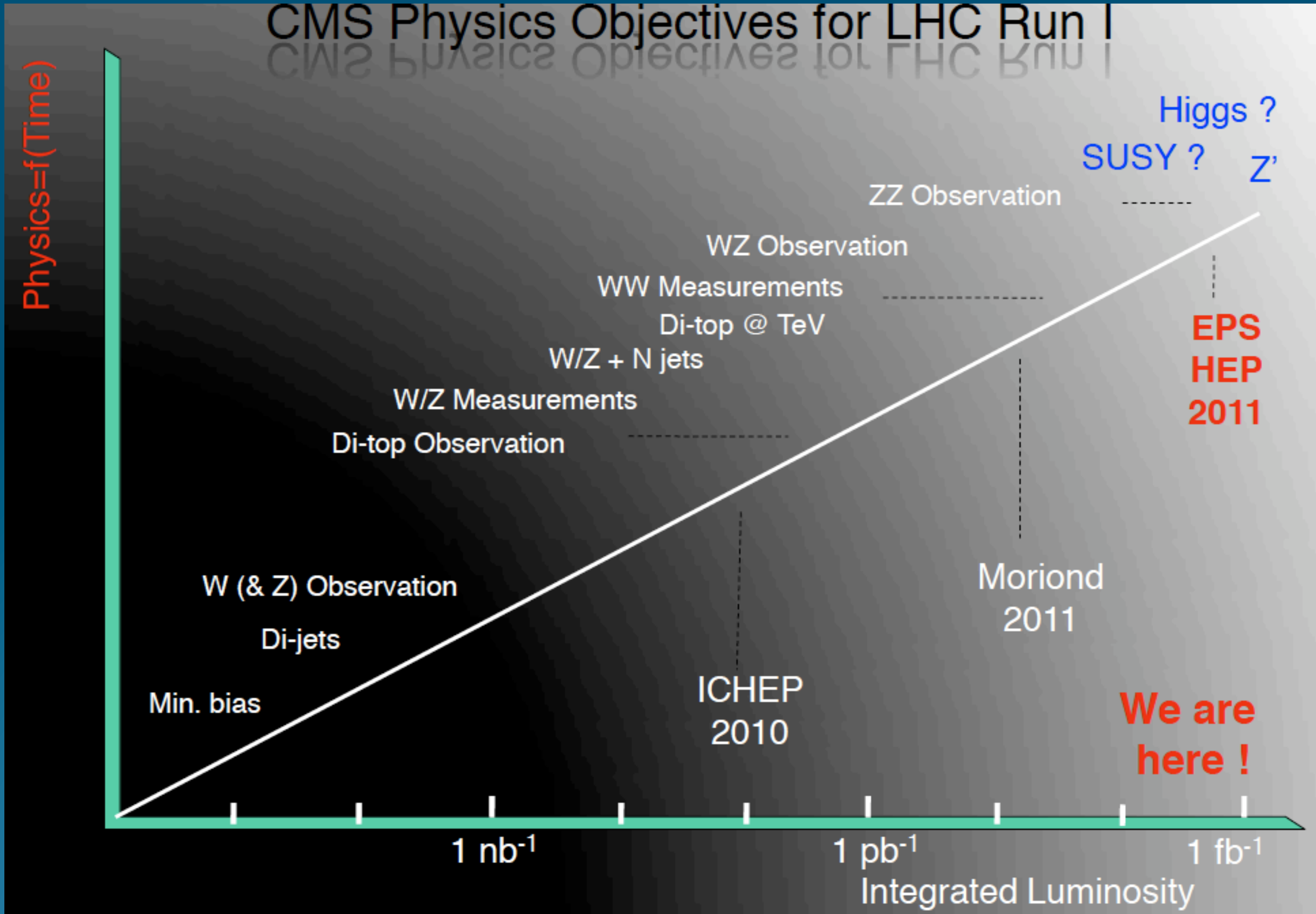
$N_{events} = \sigma\ L\ T$



The ATLAS path towards discoveries



The CMS path towards discoveries



My personal selection for today:

1. SM Higgs boson: to be or not to be?
2. Desperately seeking SUSY
3. Early new physics? A case study
4. Indirect signals of new physics

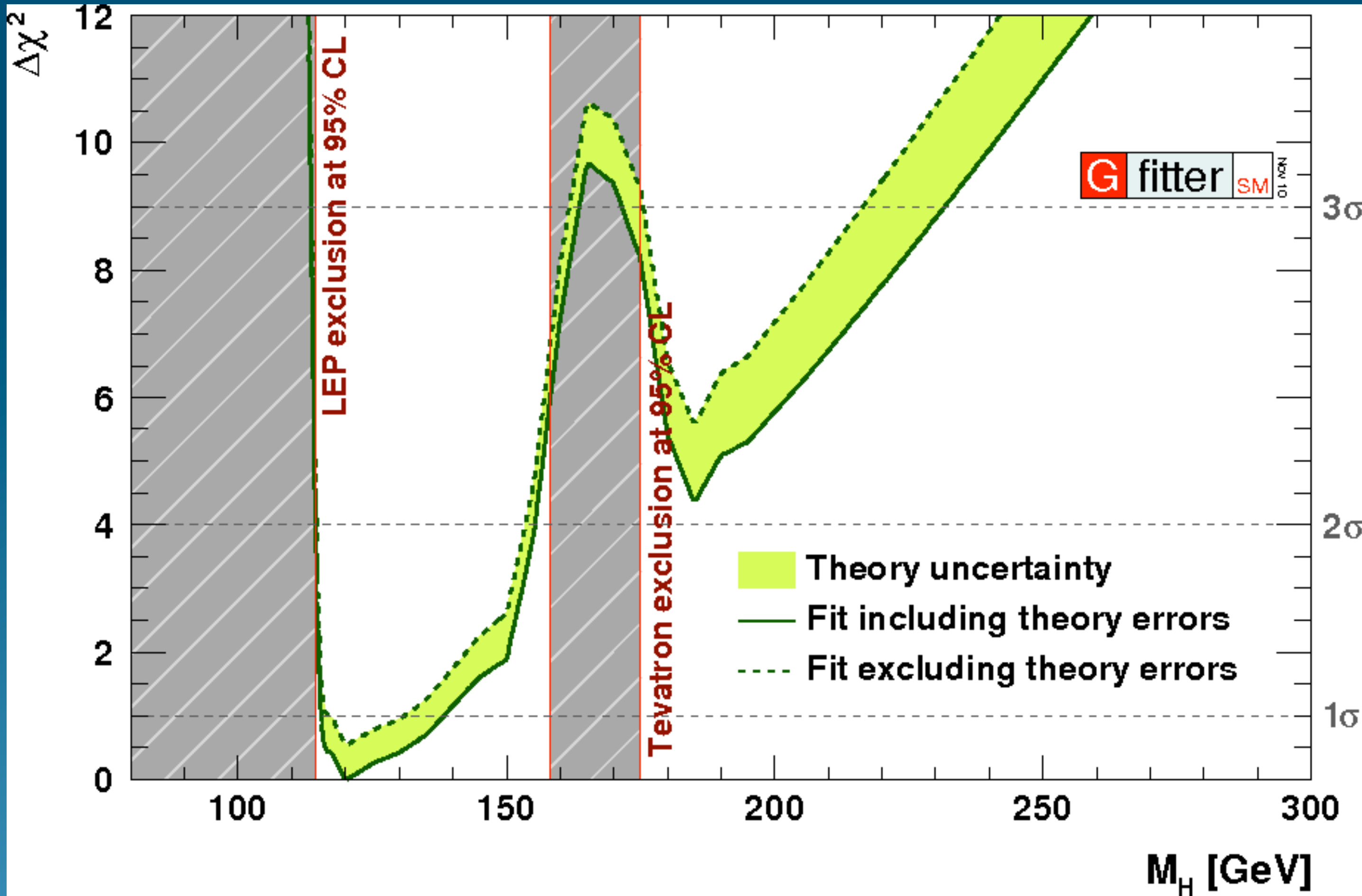
1. SM Higgs boson: to be or not to be?

Direct + indirect info on the SM Higgs boson

LEP [4 expts]:
$m_H > 114.4$ GeV
at 95% CL

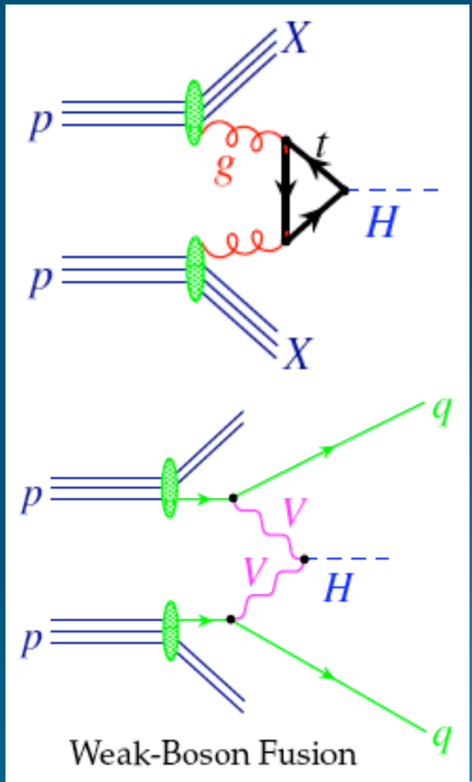
EW fit dominated by M_W and leptonic + b asymmetries

Tevatron [CDF+D0]:
$158 < m_H < 173$ GeV Excl. 95% CL

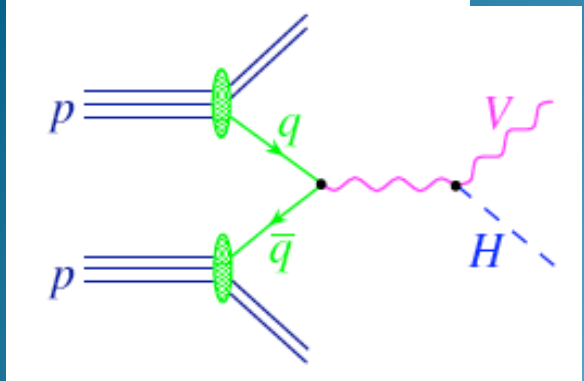


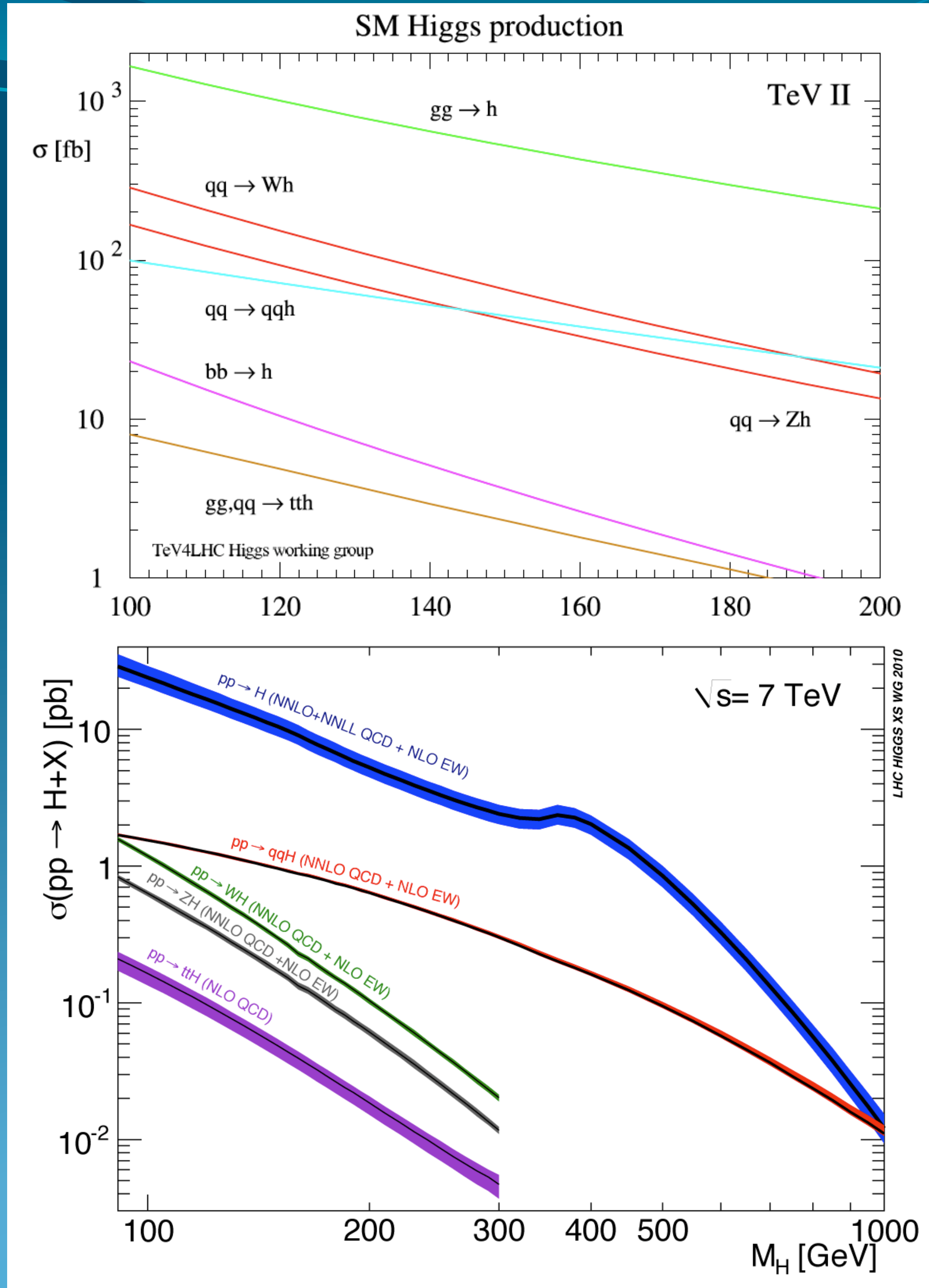
In the SM, the only unknown parameter is m_H

SM Higgs production

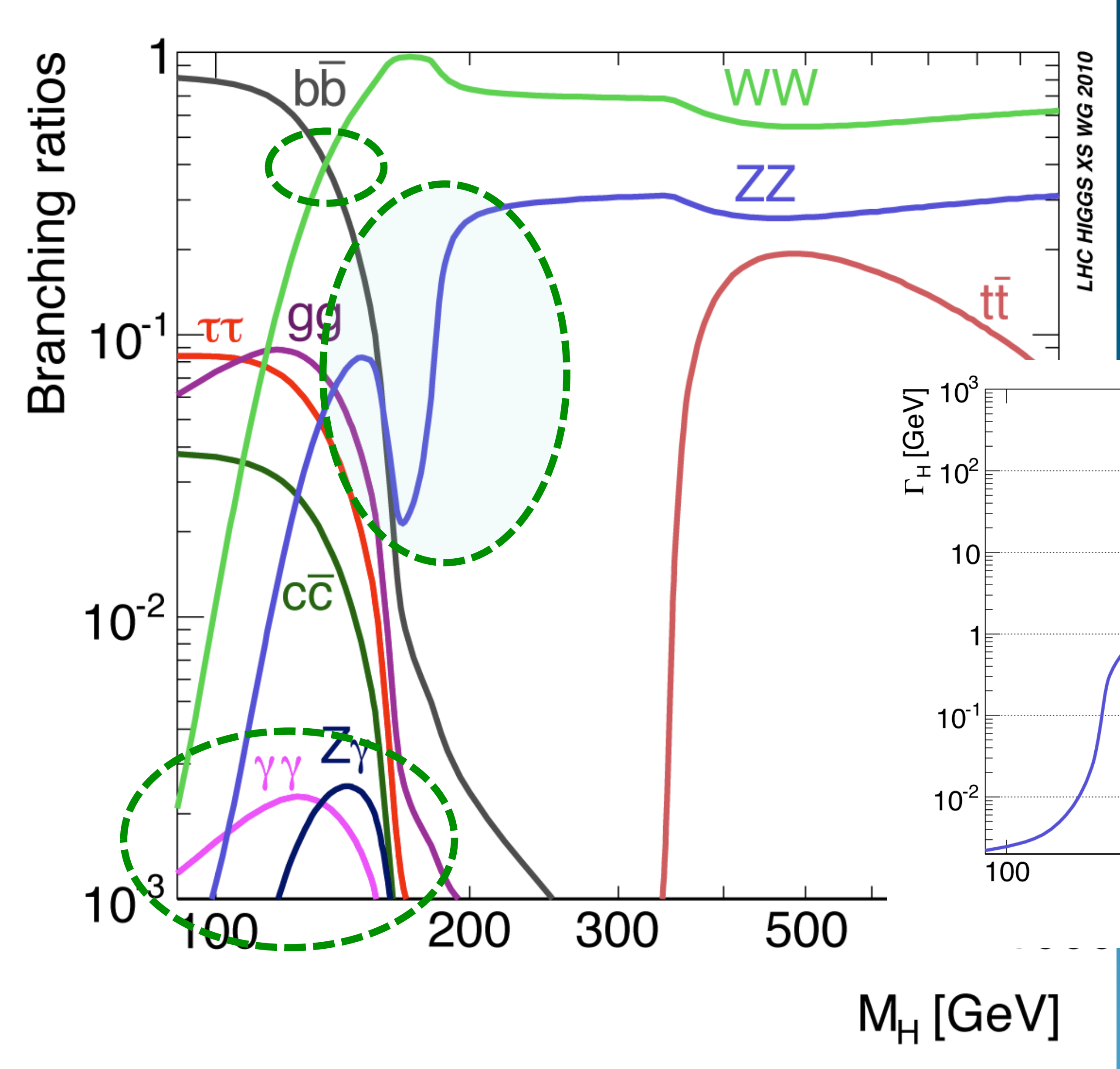


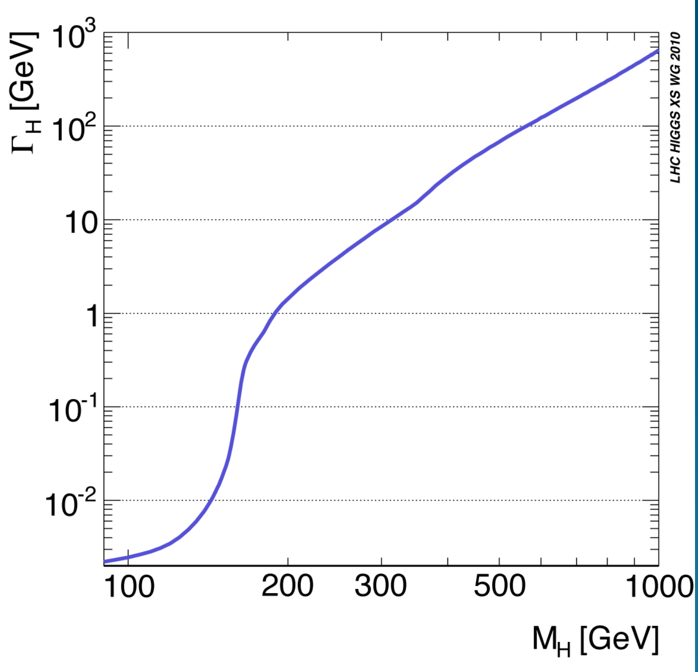
(V=W,Z)





SM Higgs branching ratios and width





The Tevatron and LHC search strategies

Low mass region ($m_H < 130$ GeV)

V + H→bb (mostly Tevatron)

H→γγ (mostly LHC)

•H→WW→2l2ν

•qqH→ττ, qqH→bb

•V + H→WW→lνjj

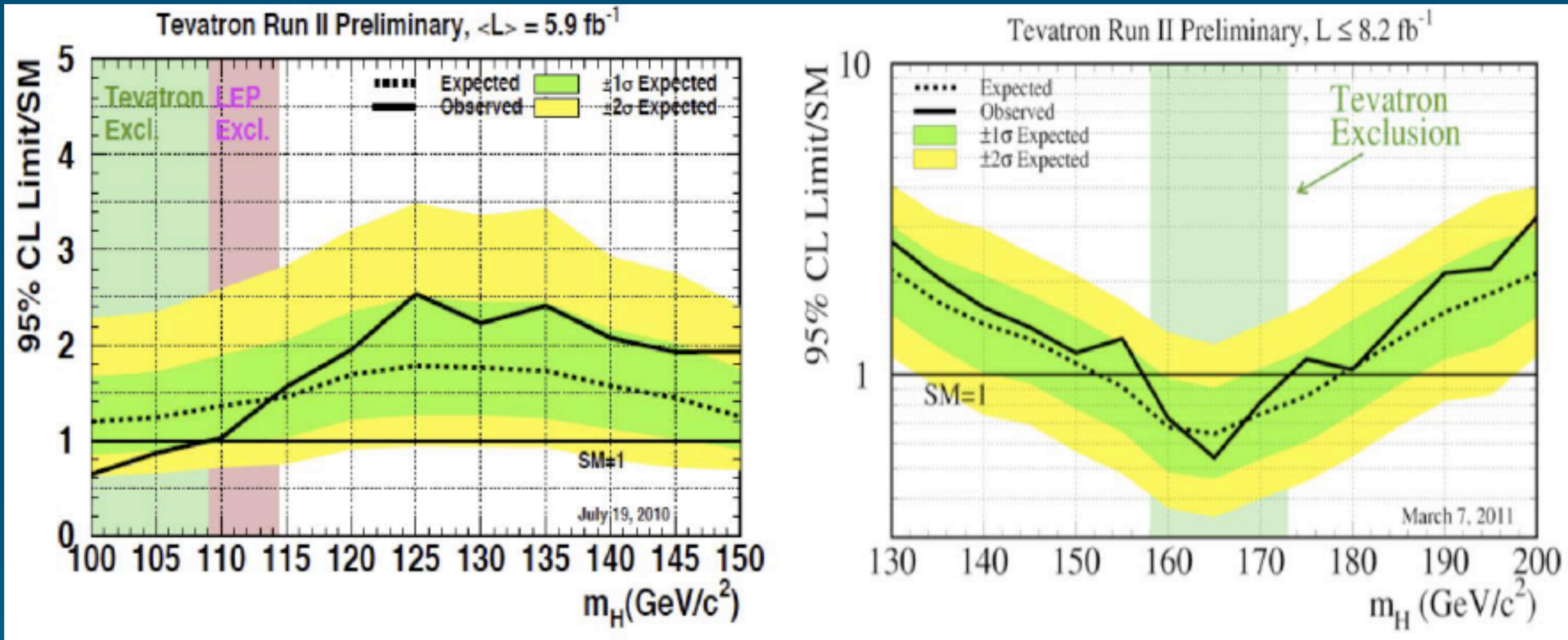
LHC: small S, worse S/N ratio than Tevatron

Higher mass region ($m_H > 130$ GeV)

H→WW, ZZ

LHC: larger S, better S/N ratio than Tevatron

Present combined Tevatron limits



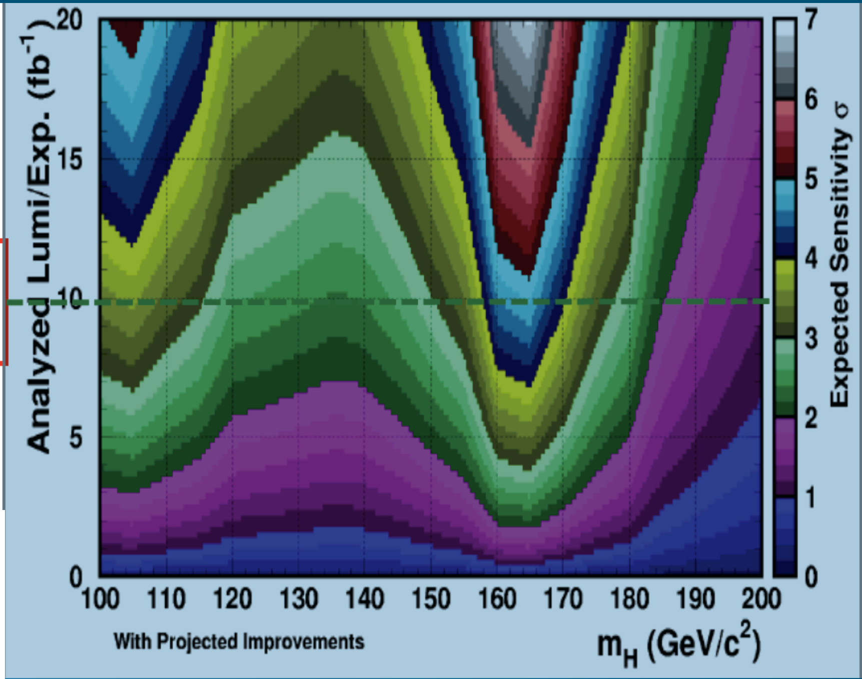
(still from Summer 2010)

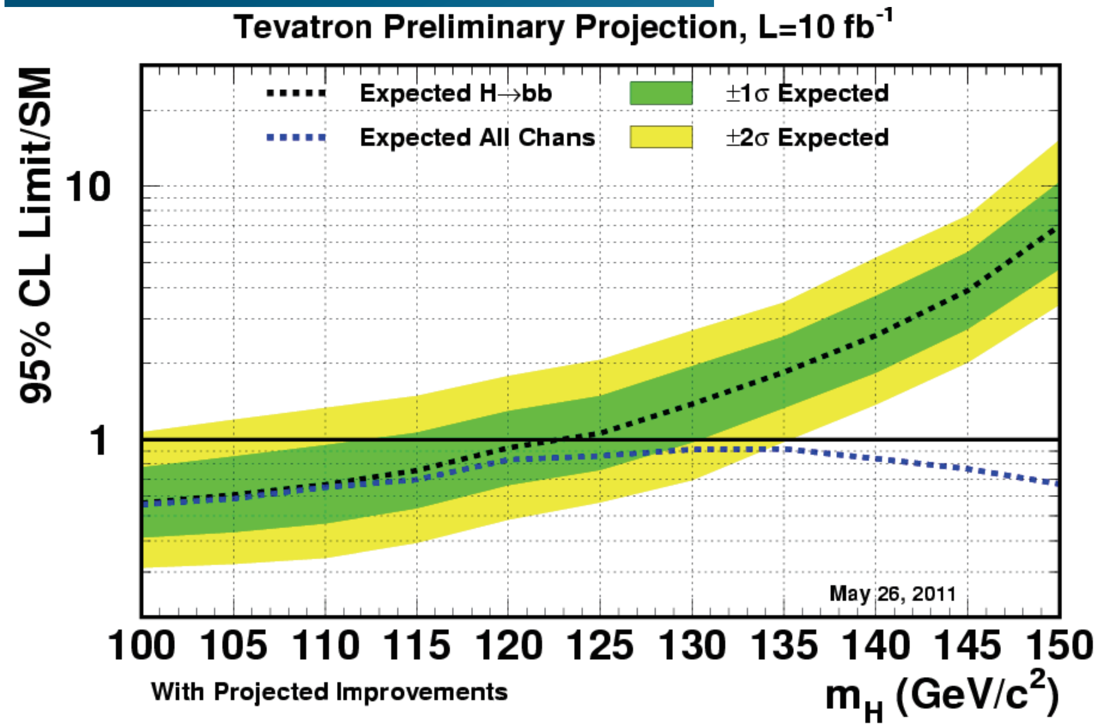
95% CL excluded:
158<m_H< 173 GeV
(Winter 2011)

Residual Tevatron sensitivity

Tevatron @ end 2011:
~10 fb^{-1} of useful data
95% CL: 114-185 GeV
3σ: ~115, 150-178 GeV

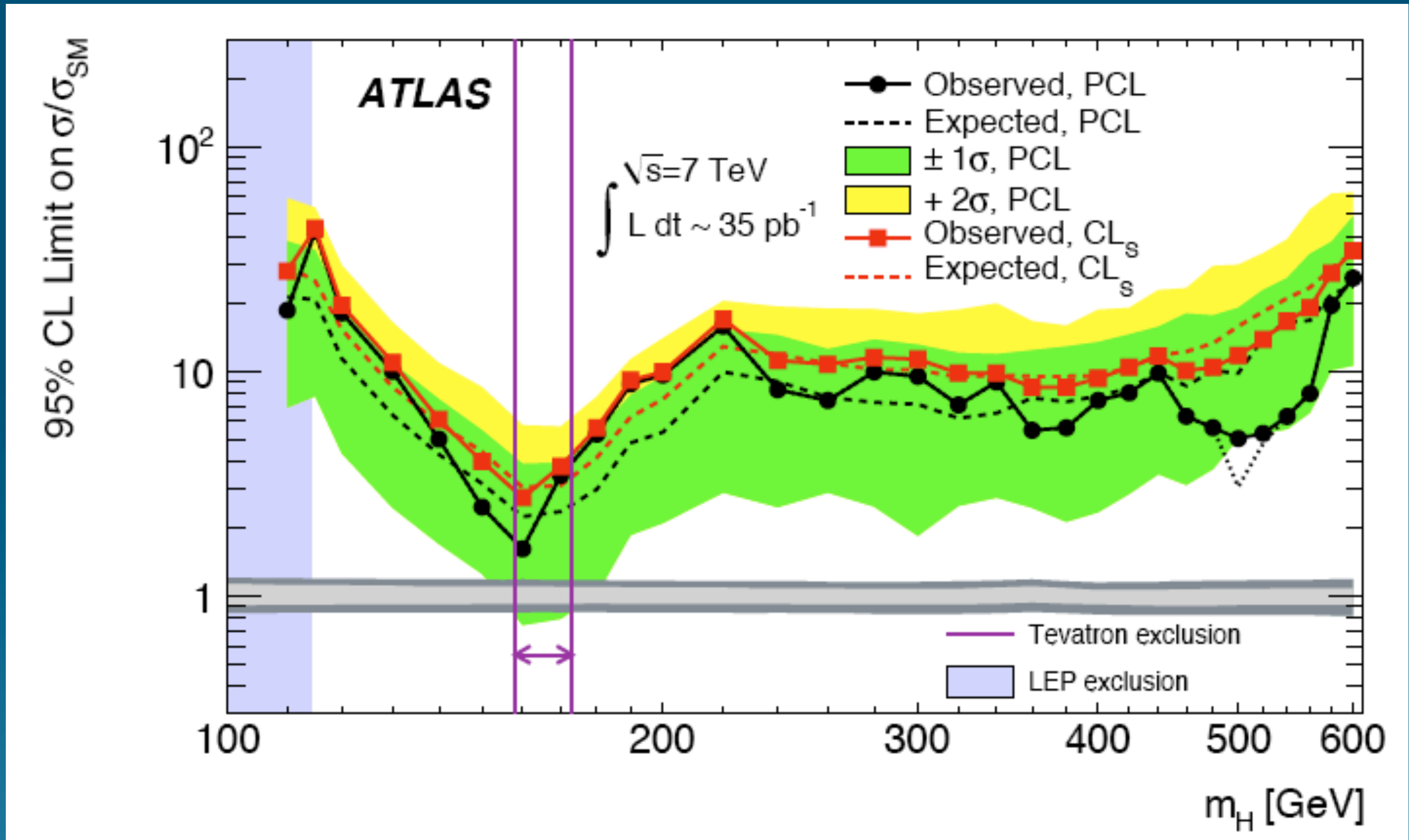
>2.4σ for m_H<185 GeV
3σ for m_H~115 GeV





Below SM line in whole range, low masses better (VH, H→bb) complementary to LHC

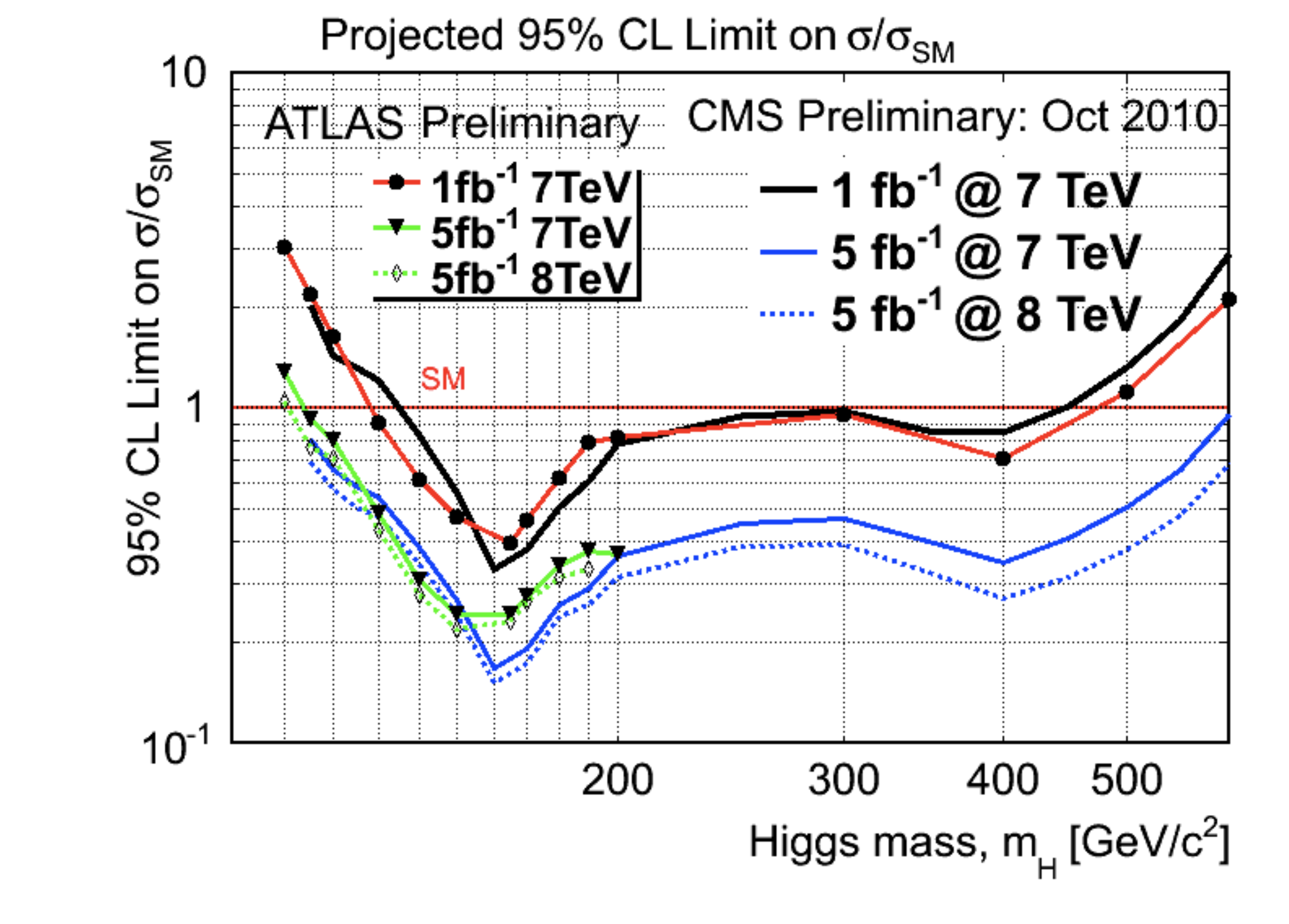
First LHC studies with 2010 data



Uses H->γγ, H->ZZ->4l/2l2ν/2l2q, H->WW->2l2ν/lνqq

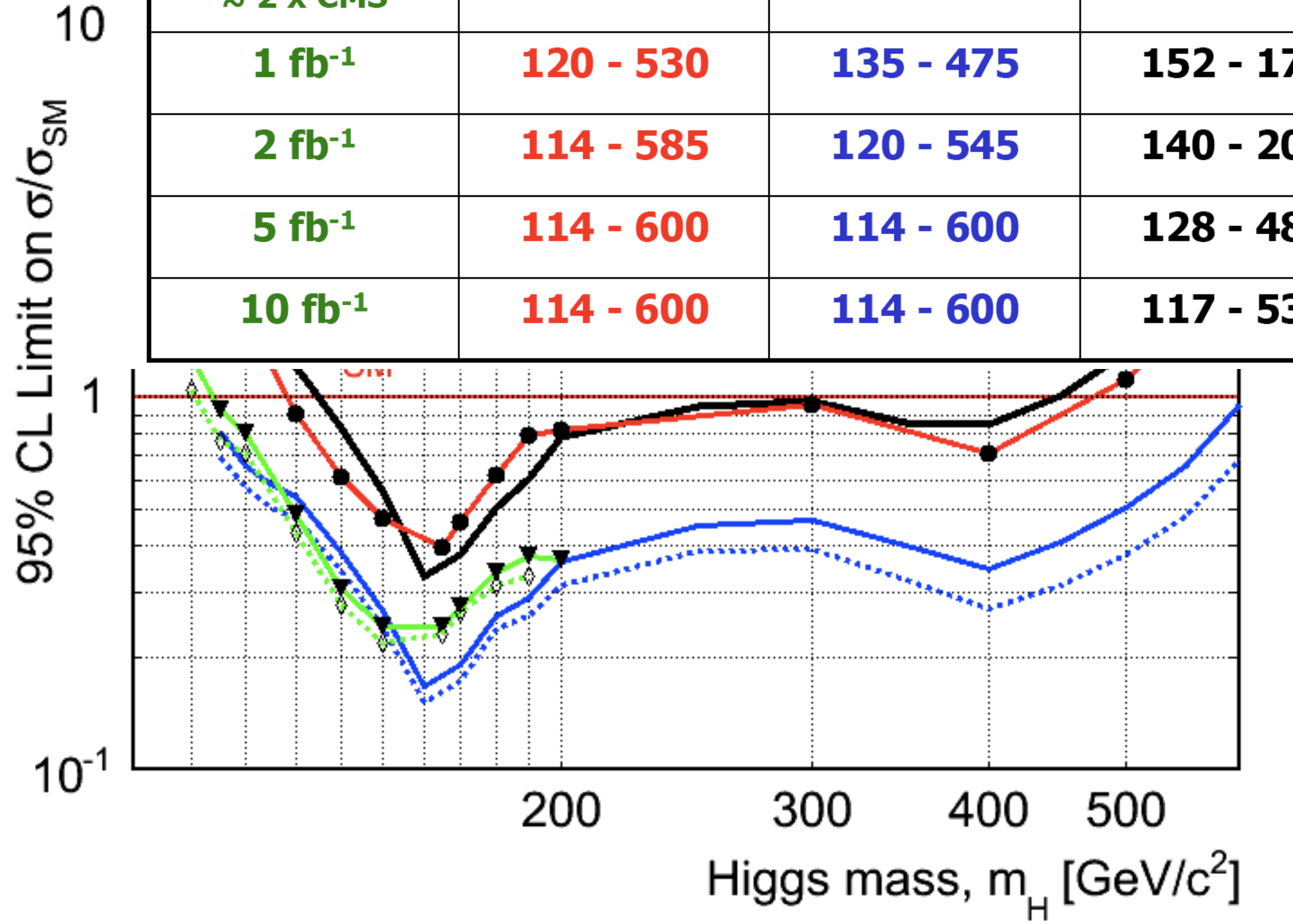
First Higgs search papers also produced by CMS (WW, ττ)

Short-term (2011-2) prospects at the LHC



Short-term (2011-2) prospects at the LHC

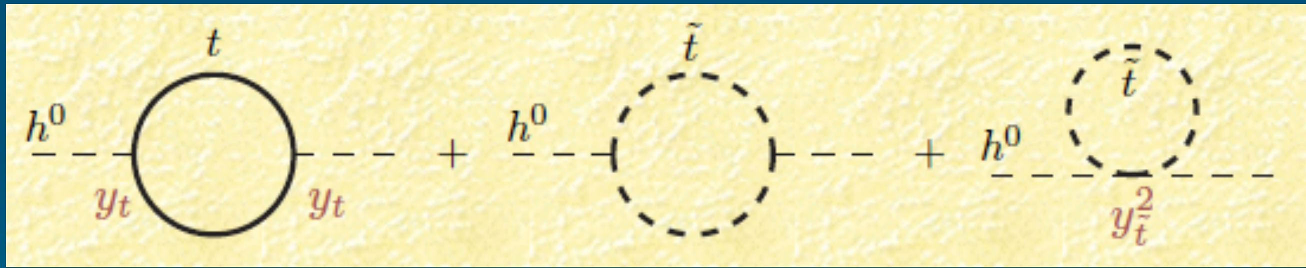
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535



2. Desperately seeking SUSY

Why SUSY at the weak scale?

SUSY can solve the hierarchy problem
thanks to its special renormalization properties



$$\delta m_H^2 \sim -\frac{3h_t^2}{8\pi^2}\Lambda^2 \quad \rightarrow \quad \delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

Power-dependence on SUSY-breaking masses
only mild logarithmic dependence on cutoff

Naturalness preserved up to very high scales
if superparticle masses are at the weak scale

SUSY phenomenology, simplified

No detailed model of SUSY breaking is fully convincing

Broad scenarios for SUSY phenomenology at colliders:

(R-Parity assumed)

- o Heavy gravitino (weak scale mass)
  - MSSM + soft terms
  - MSSM LSP stable (WIMP dark matter)
- o Light gravitino (mass < keV)
  - MSSM + goldstino multiplet
  - MSSM LSP → particle + (goldstino)

What else is needed to discuss searches?
Would like many parameters in terms of a few:
explicit "models" of susy-breaking "mediation"
Concrete risk of "wandering in parameter space"
when discussing experimental searches at colliders

The classic SUSY signature at the LHC

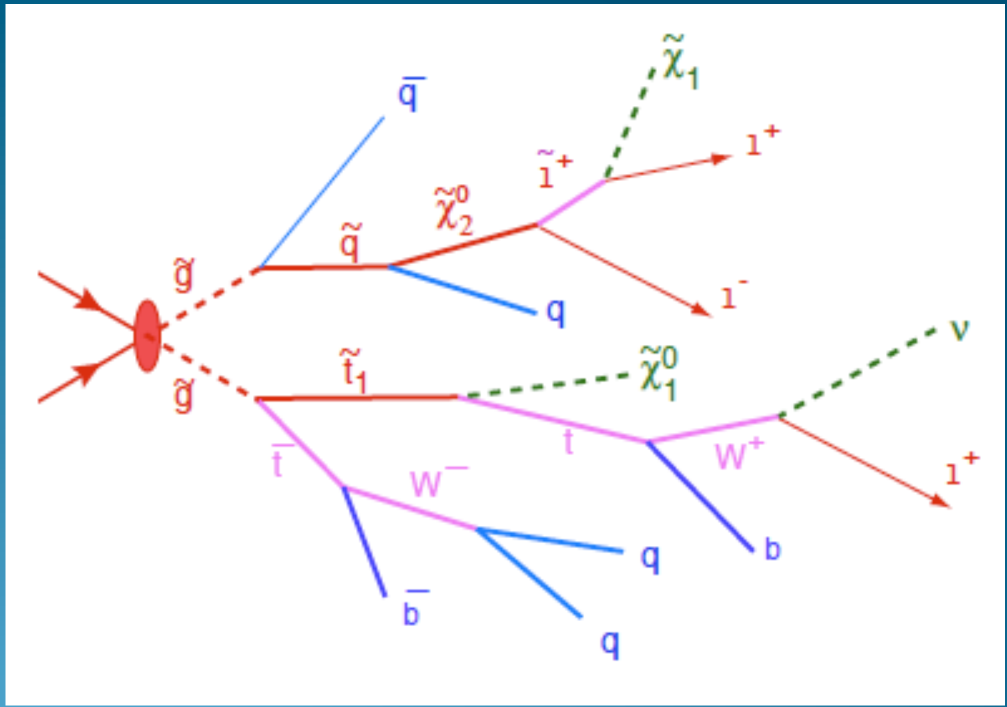
- Gluino/squark pair production (strong) and decay:

  Multi-jets + missing E_T

  (+ possible isolated leptons and/or gauge bosons)

After seeing deviations from SM expectations need efforts to reconstruct SUSY spectrum from data, e.g.:

- Edges in invariant mass distributions
- Methods analogous to W "transverse mass"

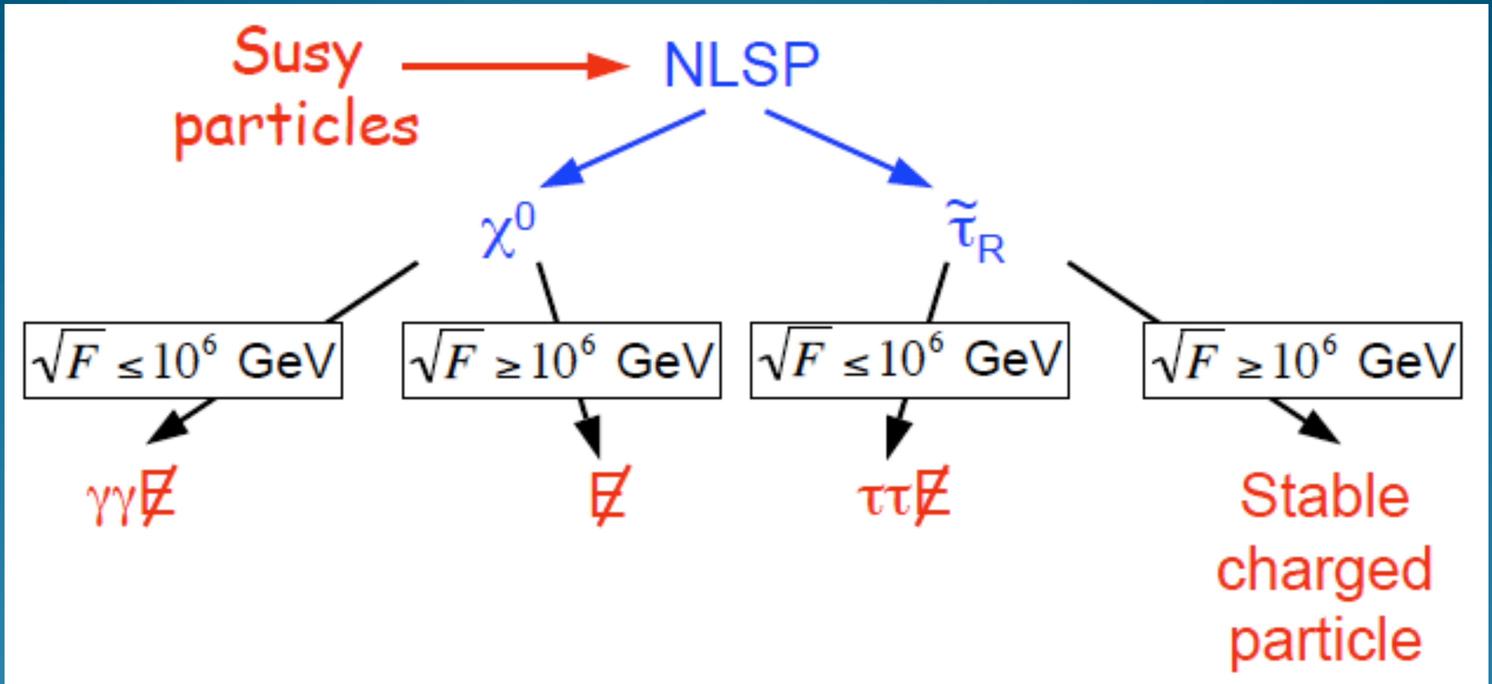


Many other possible signals being considered

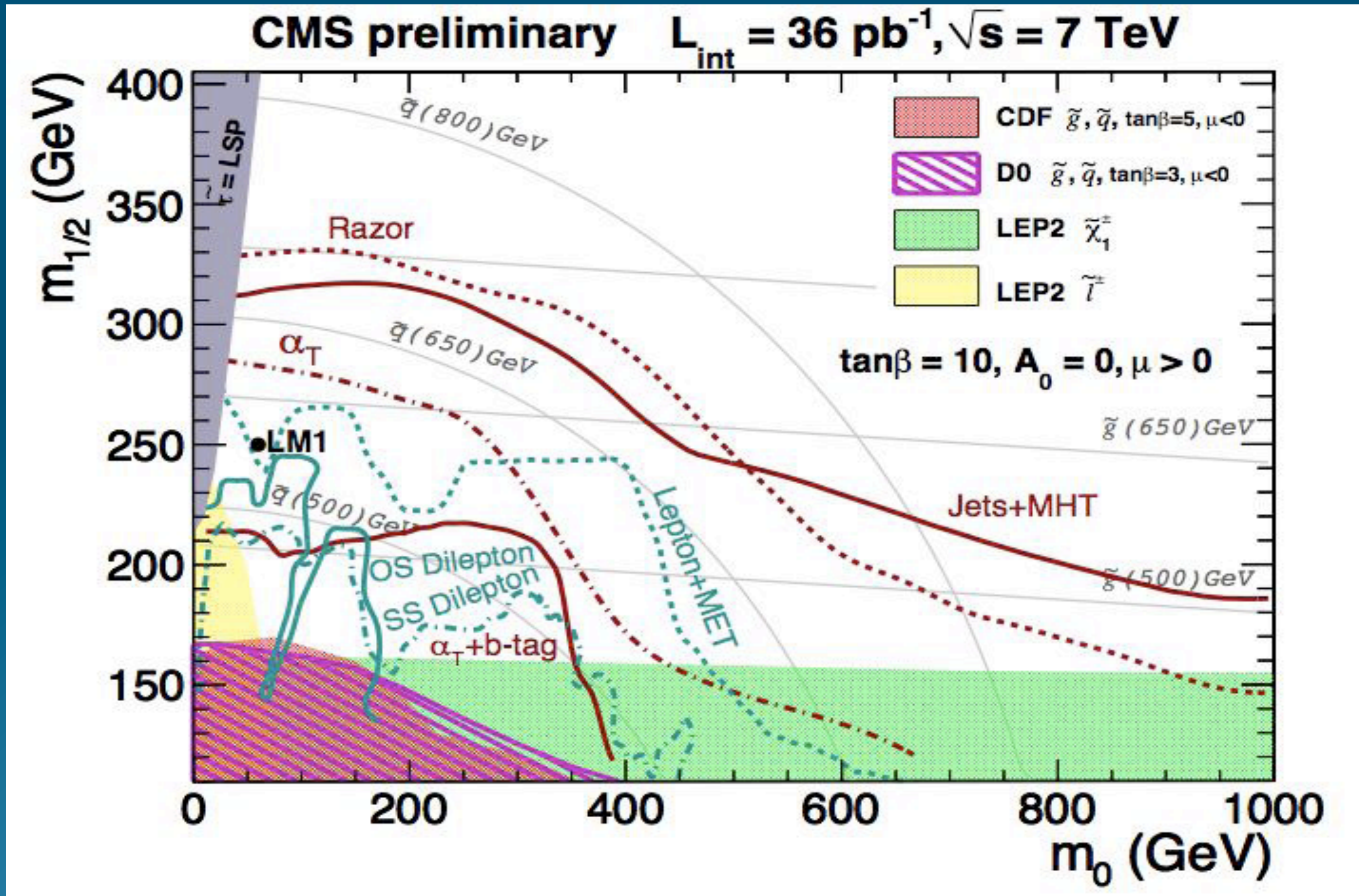
More SUSY signatures at the LHC

- Chargino/neutralino pair-production (weak) and decay: Tri-leptons + missing E_T
- Top pairs + missing E_T from stop pair production

Signatures of light gravitino scenario (e.g. gauge mediation)

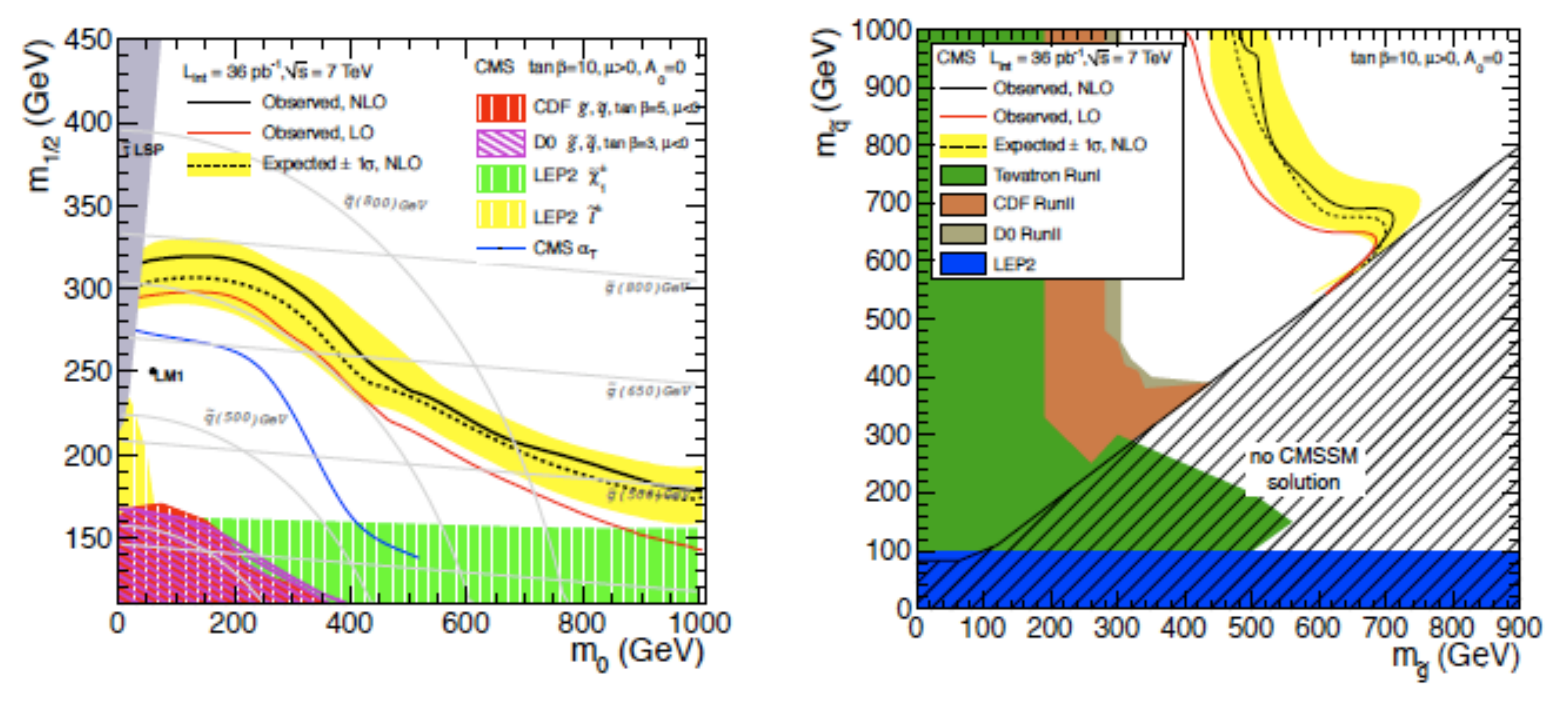


Supersymmetry searches in CMS



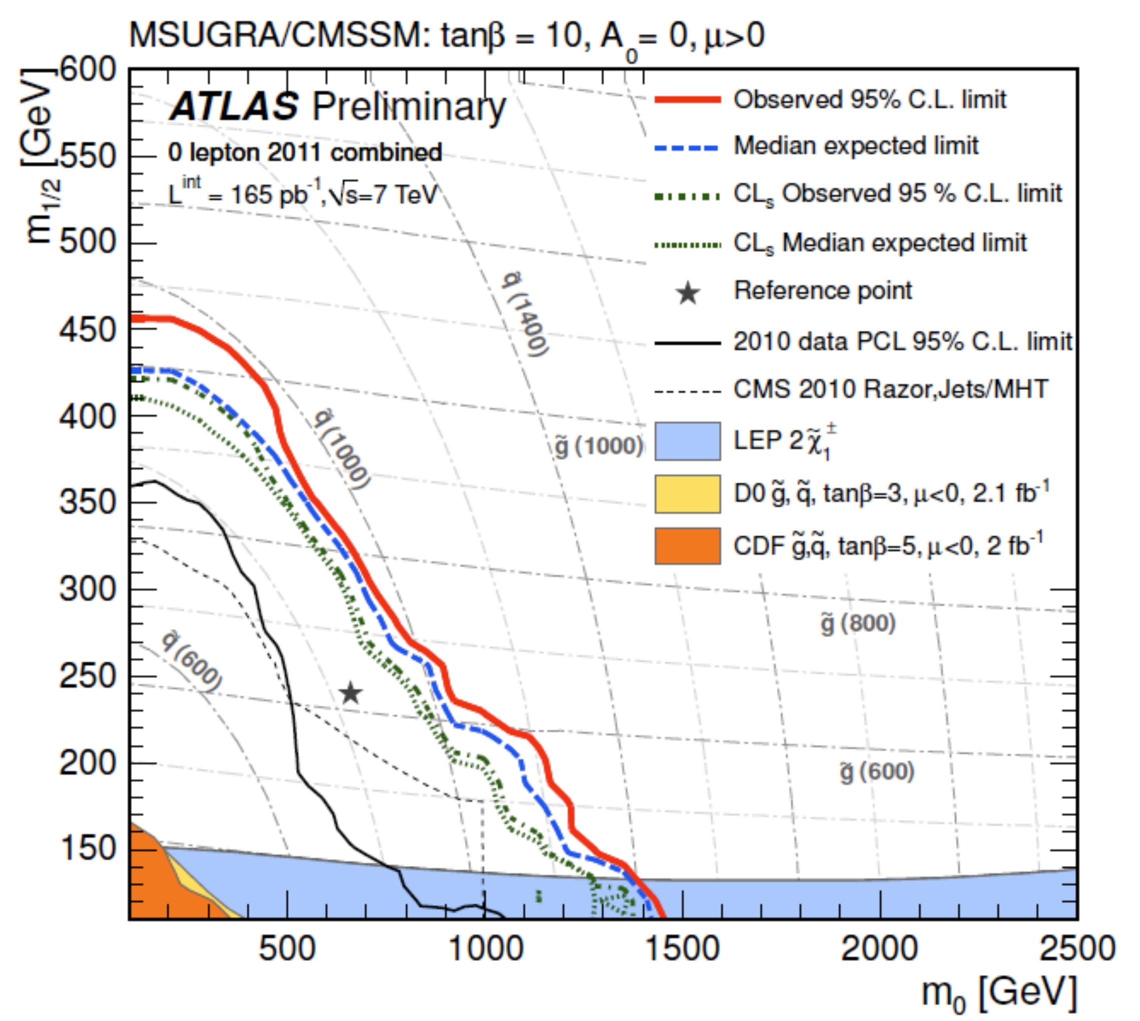
Results of several CMS analyses of 2010 data: jets + MHT, ad hoc kinem. variables, lepton + MET, SS/OS dileptons,…

More on supersymmetry searches in CMS



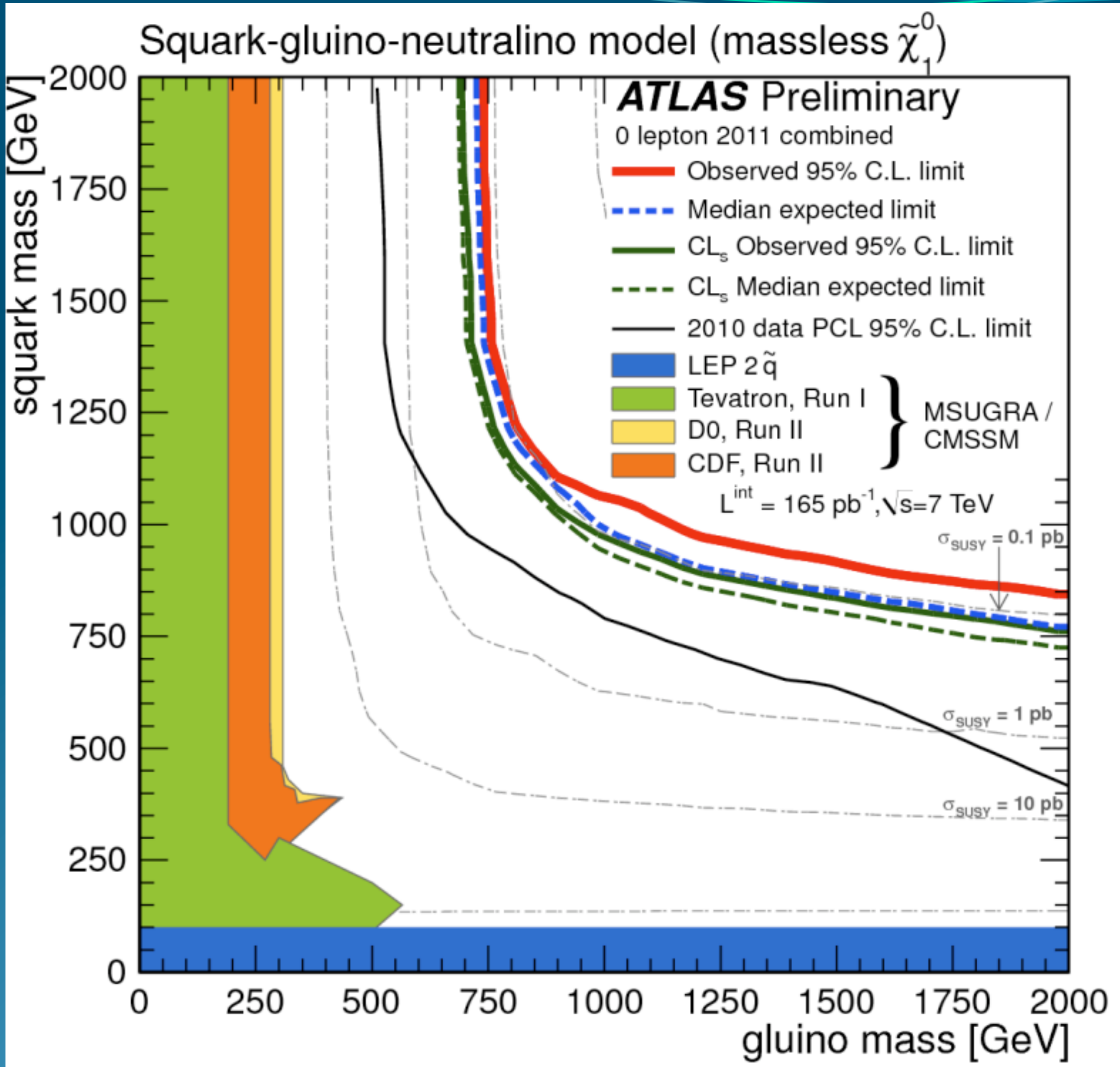
Multi-jet + MET analysis included in previous plot, but now also with intepretation in (m_{gluino} , m_{squark}) plane

Supersymmetry searches with ATLAS 2011 data



Multi-jet + MET + 0 lepton analysis with 165 pb^{-1} of 2011 data (analysis with 1 lepton gives slightly less stringent bounds)

Supersymmetry searches with ATLAS 2011 data



Attempt at discussing multi-jet + MET searches in a simplified model with 2 gen. squarks + gluino + single (massless) neutralino to avoid getting lost in par. space

The MSSM fine-tuning problem

concrete MSSM realization poses a tuning problem, especially when extrapolating the MSSM to high scales

$$m_Z^2 \sim -2m_H^2 = -2\mu^2 + \frac{3\lambda_t^2}{2\pi^2} m_{\tilde{t}}^2 \log\frac{M_P}{m_{\tilde{t}}} + \ldots \sim -2\mu^2 + O(1) m_{\tilde{t}}^2 + \ldots$$

naturalness suggests light SUSY: $m_{\tilde{t}} \sim \mu \sim m_Z$

Things are made worse by the upper bound on the Higgs mass

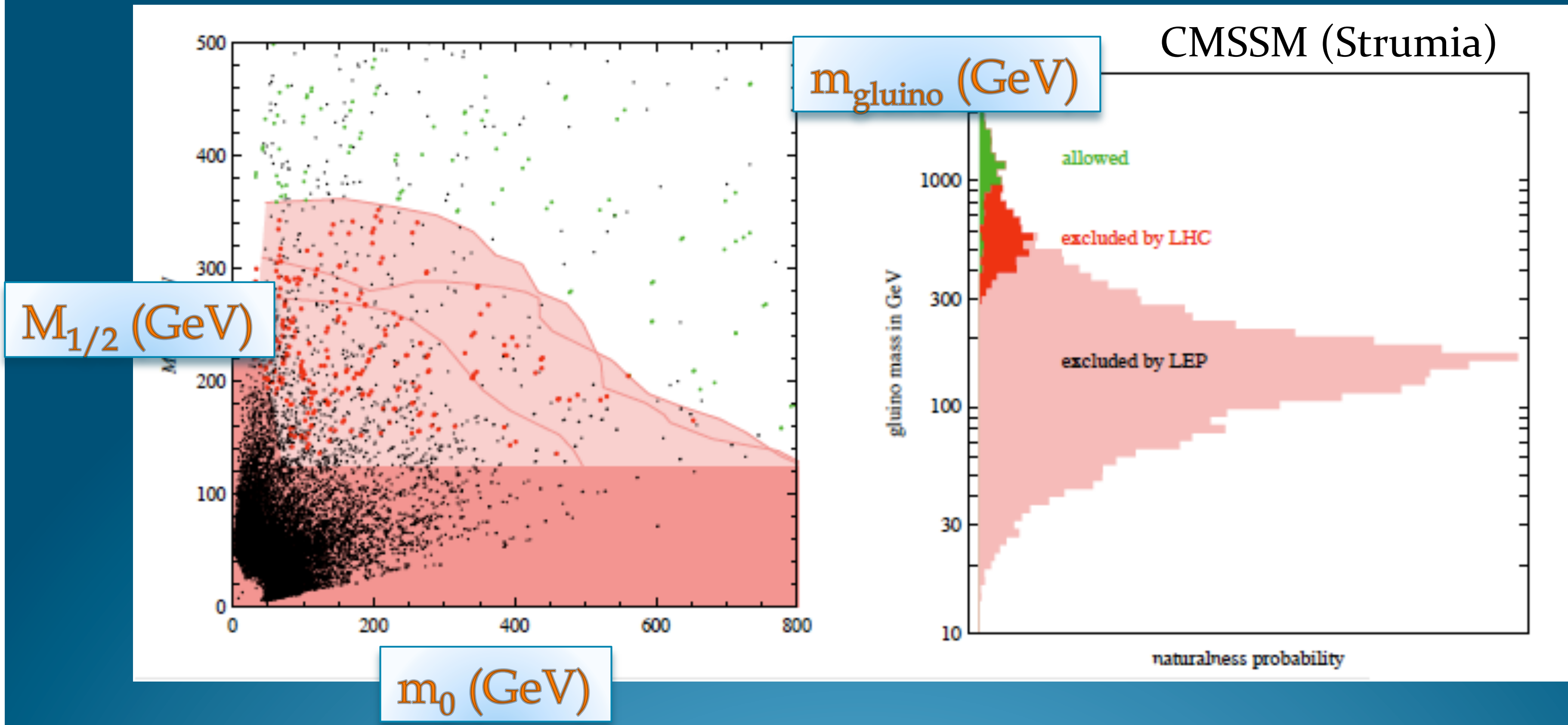
$$m_h^2 < m_Z^2 + m_t^2 \frac{3\lambda_t^2}{2\pi^2} \log\frac{m_{\tilde{t}}}{m_t} \;\; \& \;\; m_h > 114.4\, GeV \quad \Rightarrow \quad m_{\tilde{t}} > 500\text{-}1000\, GeV$$

O (%) fine-tuning required without further theoretical input

There are ways to do better, e.g. adding a singlet (NMSSM), (complicating the analysis of Higgs and neutralino sectors) and/or lowering the MSSM cutoff (but gauge unification?)

The new bounds from the LHC make the problem more acute

MSSM fine-tuning and the early LHC

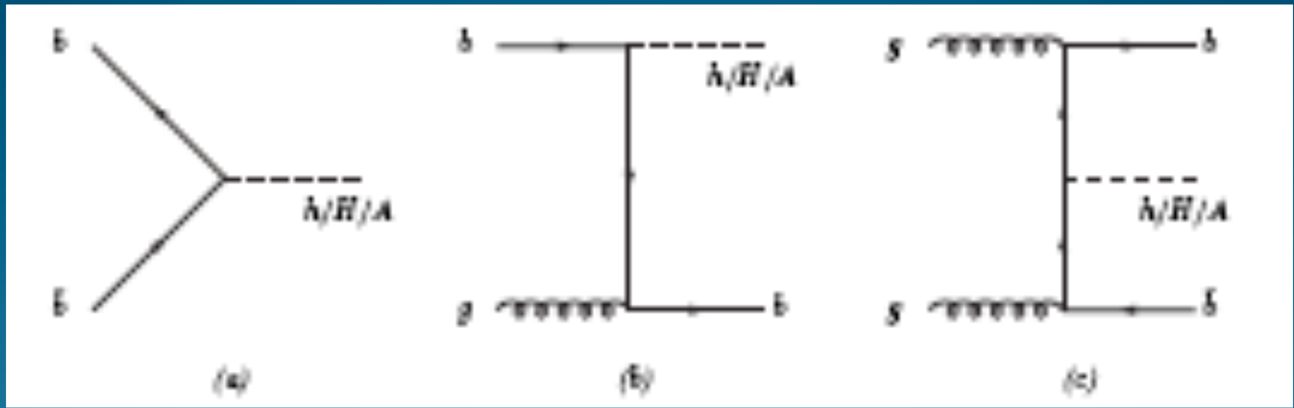


“Naturalness scan” of the “CMSSM” (not fully updated):

- darker pink region: excluded by LEP
- lighter pink region: excluded by early LHC

MSSM neutral Higgses at large tanβ

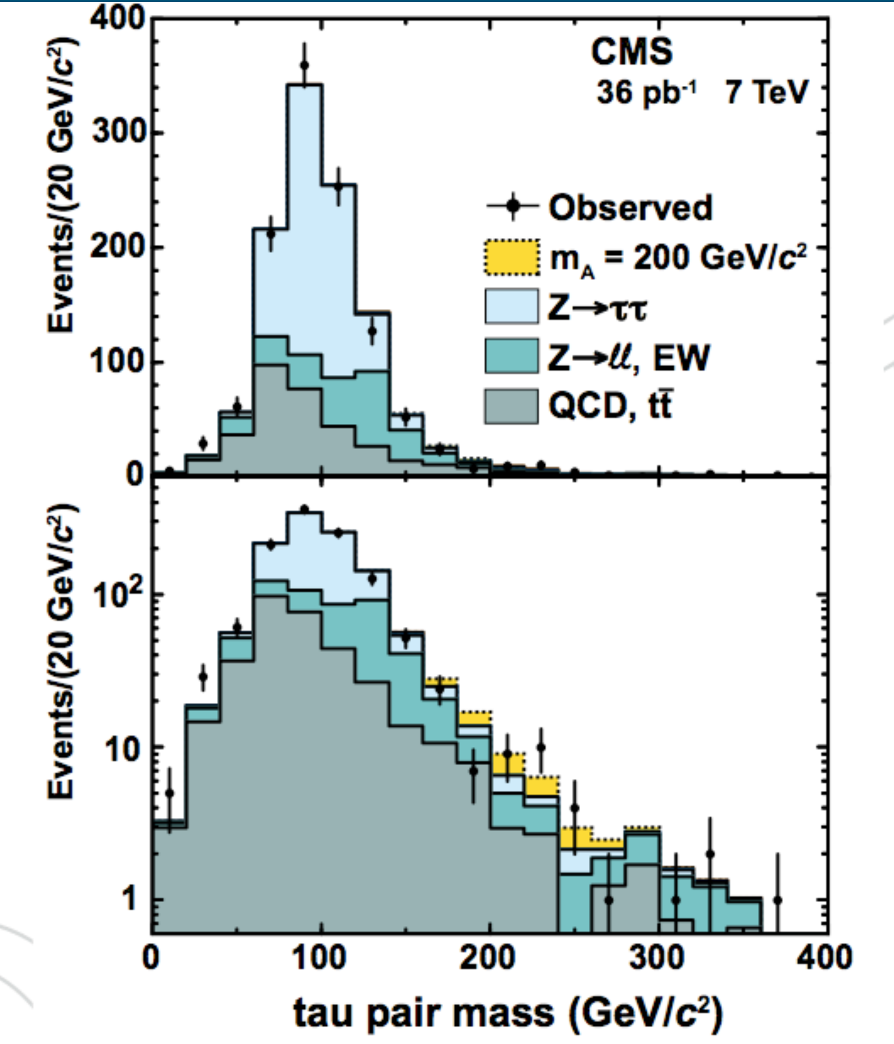
For the MSSM neutral Higgs bosons, possible strong enhancements [for large $\tan\beta = v_2/v_1$] of gluon-gluon fusion (via b loop) and of associated production with b

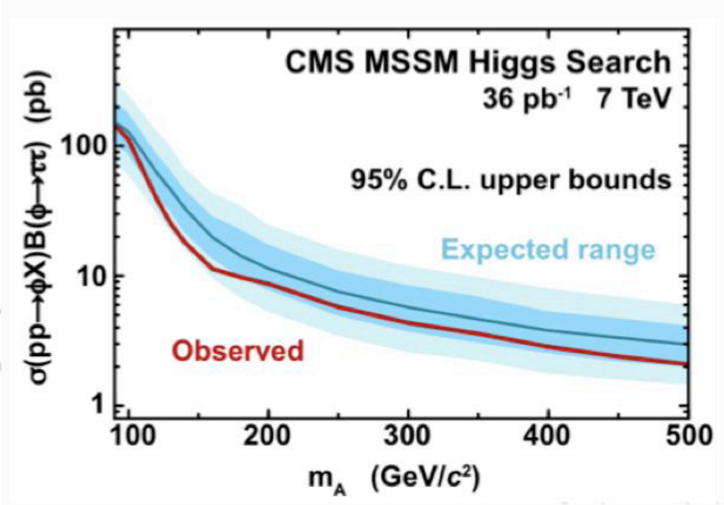


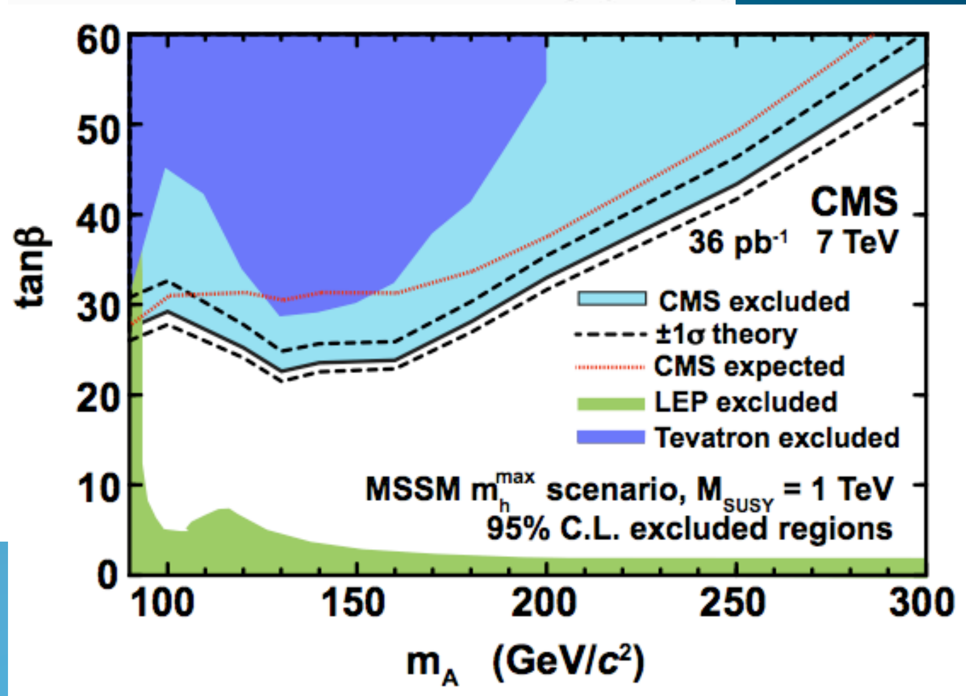
Bounds difficult to interpret: strong model-dependence due to large 1-loop threshold corrections to bottom mass

Possible signal (ϕ=h,H,A): Inclusive $\phi \rightarrow \tau\,\tau$

MSSM φ → τ τ : exploring new territory



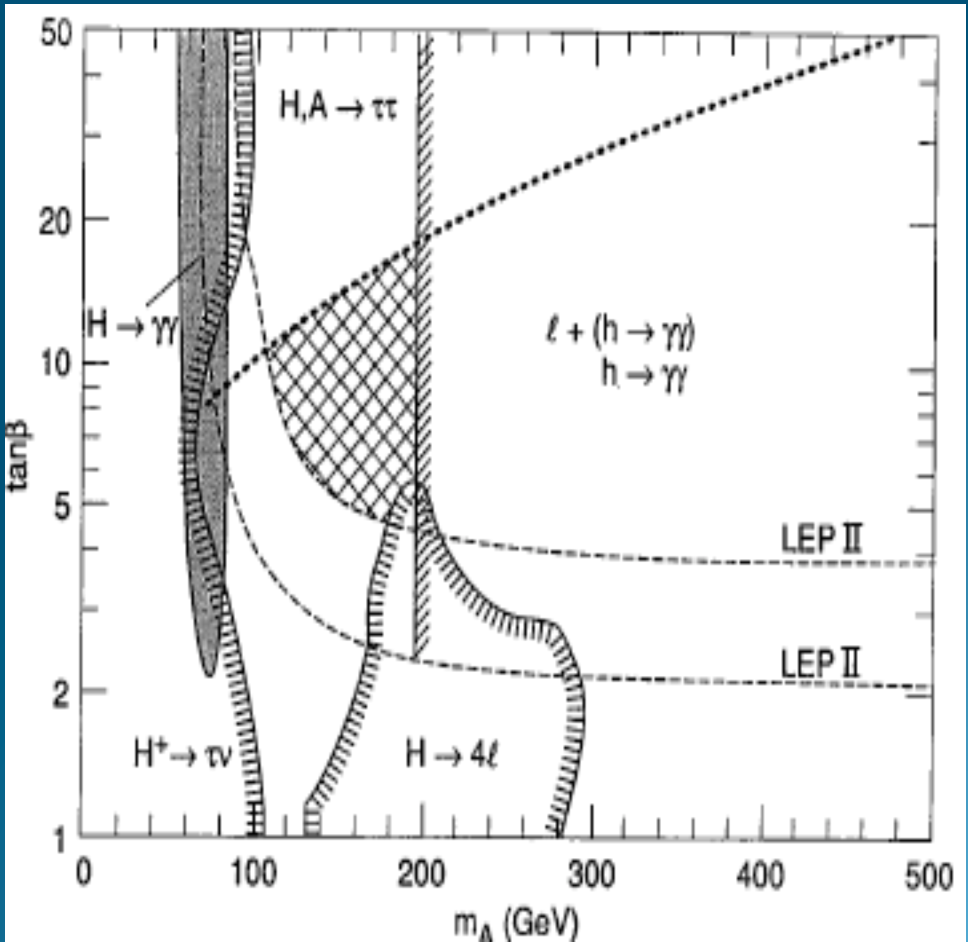




Comparable results also from ATLAS

MSSM Higgs bosons at the LHC

An ultra-simplified initial study
(and a personal memory)



[Z.Kunszt & FZ, LHC workshop, Aachen 1990]

Huge amount of work by now, it would take very long to describe it

A very complicated problem:
- Many parameters
- Many new particles around

(even in "constrained" MSSM)

SUSY-Higgs searches intertwined with SUSY-particle searches

"Benchmark scenarios" used so far to optimize detectors and analyses

But data now drive the analyses as long as they come and are progressively understood

3. Early new physics? A case study

A case study: Z' models

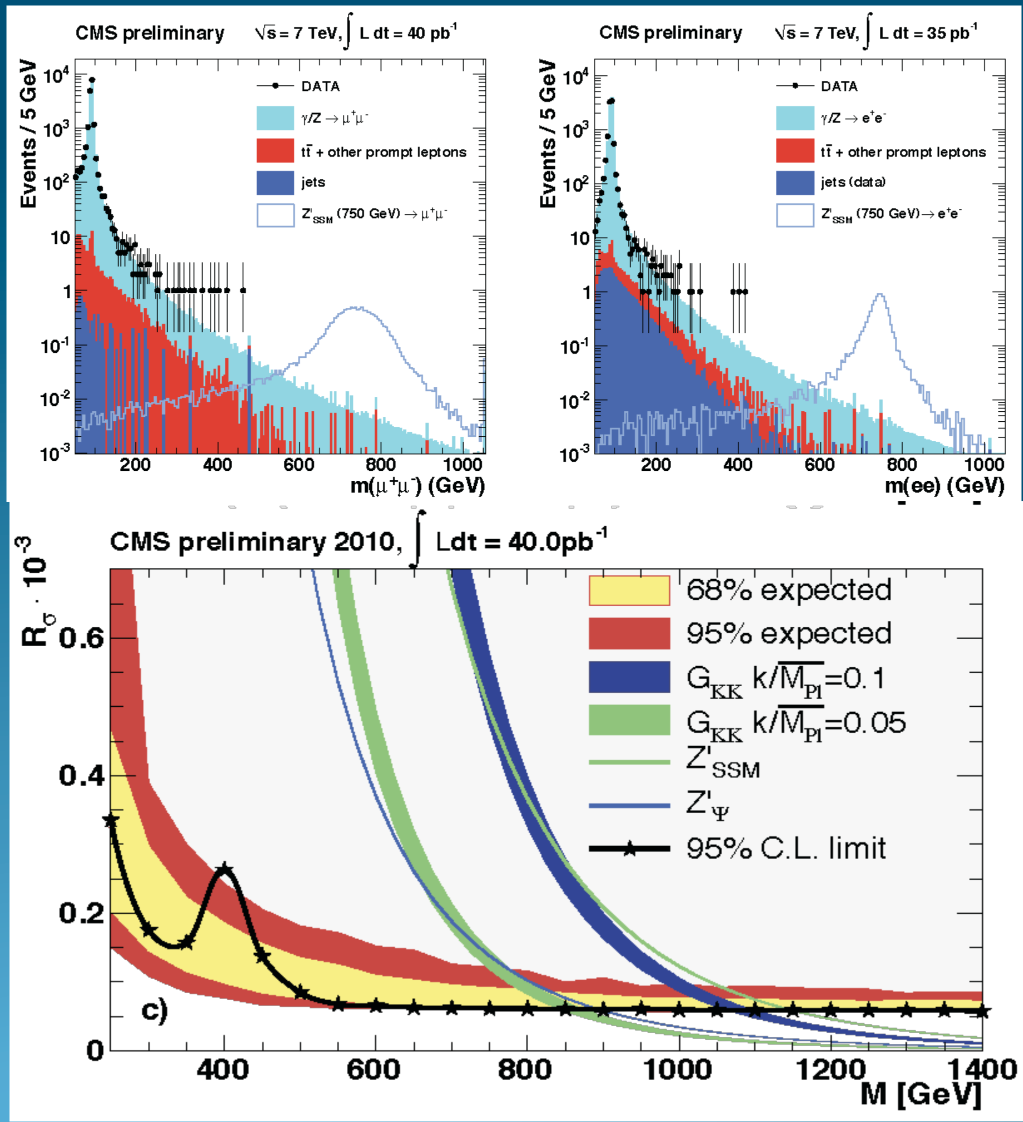
Clean/Easy signal at hadron colliders (typical early search) High-p_T lepton pairs as from

$Z' \rightarrow e^+ e^-, \mu^+ \mu^-$

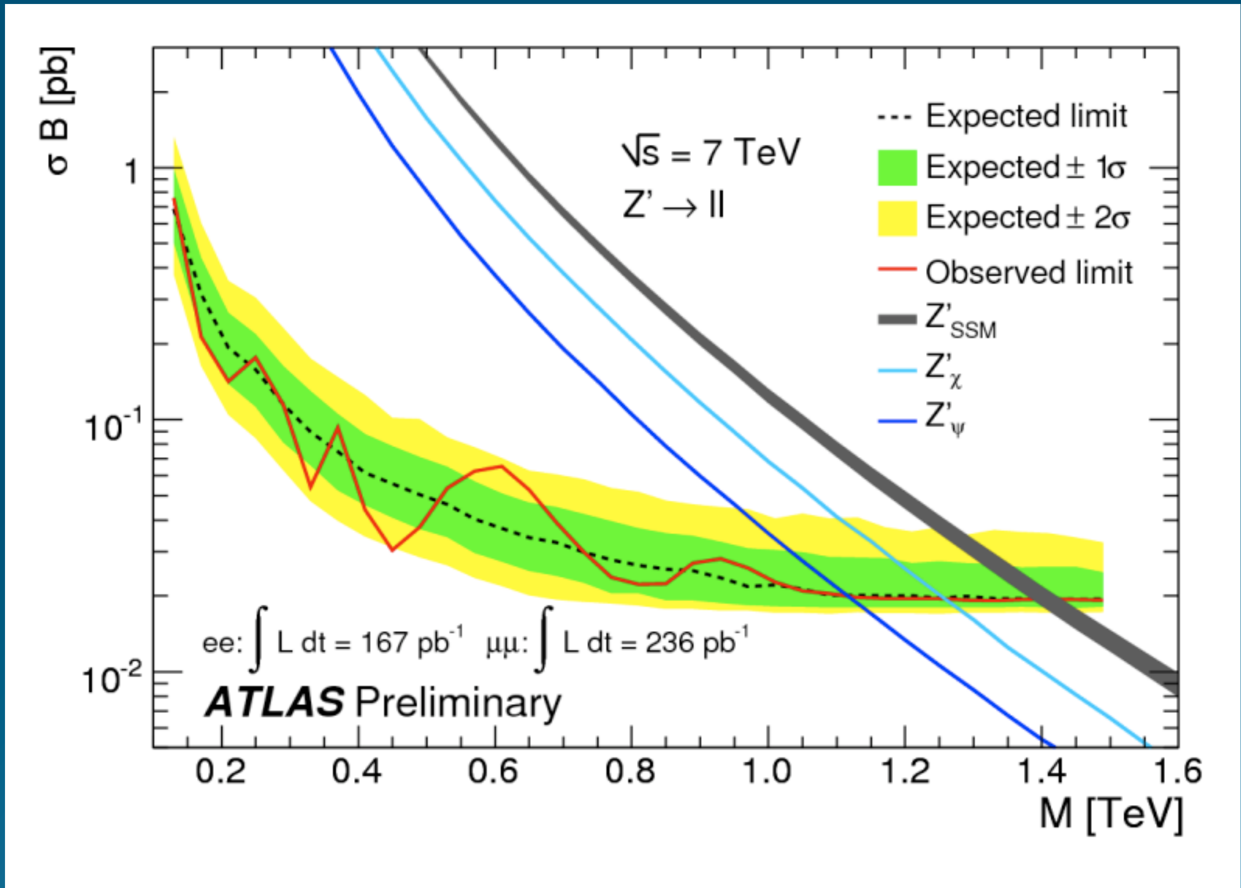
Motivated by GUTs, brane models, extra dimensions, composite Higgs, etc

Only relevant background tails of Drell-Yan production via Z/γ

Question: when do we enter into uncharted territory? Competition not only from Tevatron, also EWPTs count



Preliminary ATLAS results with some 2011 data



Legenda:

Z'_{SSM} : couplings to SM fermions as for Z, none to bosons

Z'_{χ} : SO(10)/SU(5)

Z'_{ψ} : E_6/SO(10)

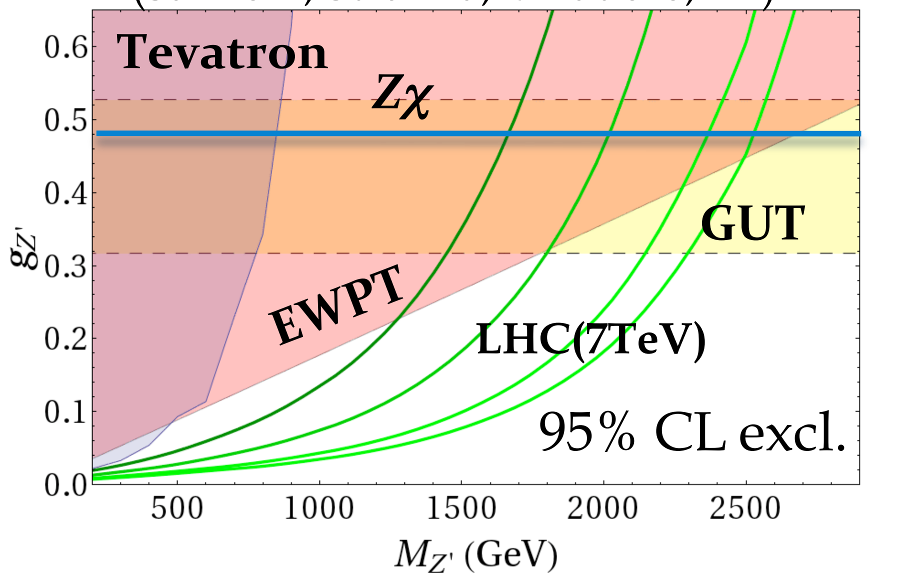
in both cases with SUSY-GUT inspired coupling constants

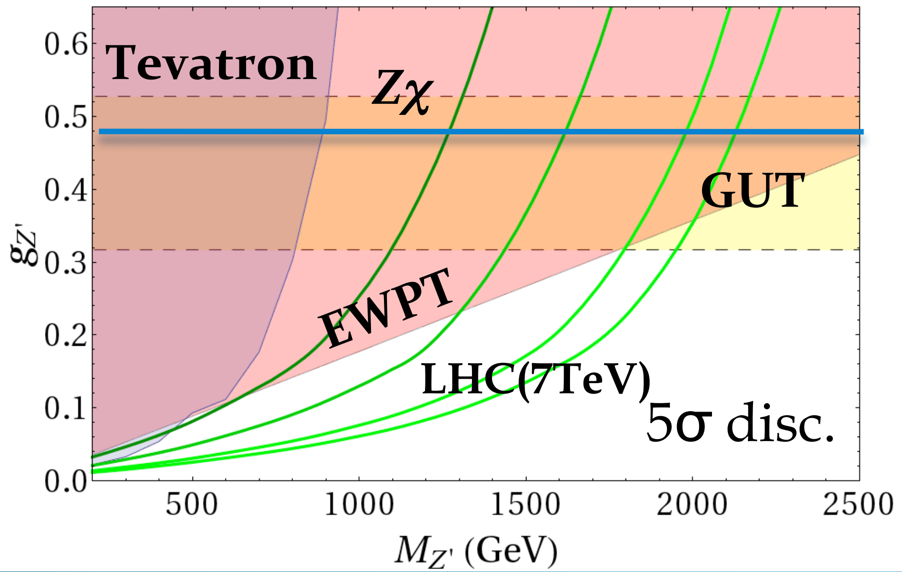
New ATLAS 95% CL limits (in GeV):

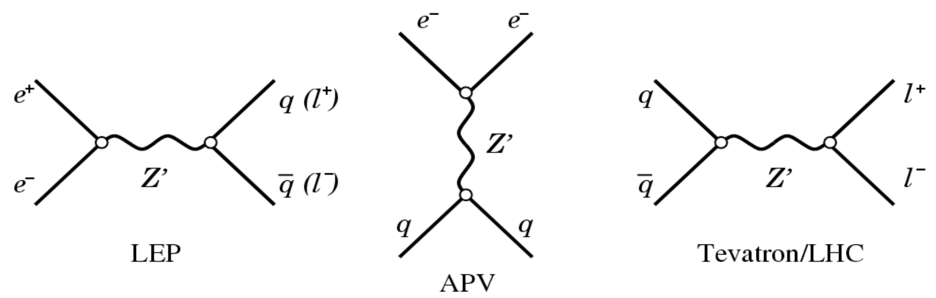
$Z'_{SSM} > 1407$, $Z'_{\chi} > 1259$, $Z'_{\psi} > 1116$

LHC discovery reach (χ model)

(Salvioni, Strumia, Villadoro, FZ)







Z'_{SSM} (coupling fixed):
EWPT 95% CL limit ~ 2 TeV,
still above LHC (~1.4 TeV)

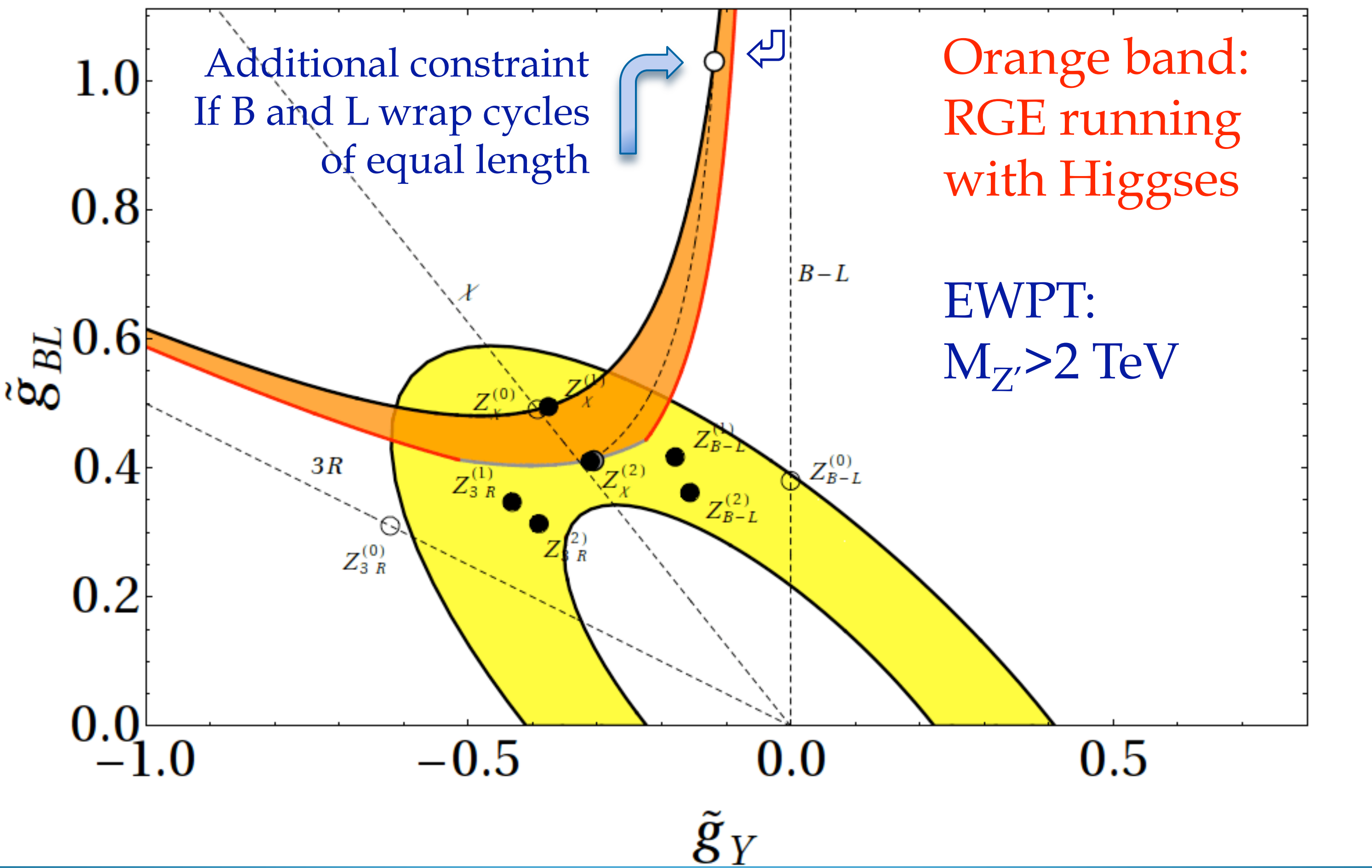
Z'_{χ} (variable coupling):
green lines: 0.2,1,5,10 fb^{-1}
Tevatron: small masses/couplings
EWPT: dominate over Tevatron for GUT-preferred values of couplings and large enough masses (PDFs)
LHC starts becoming competitive now, not yet for GUT-preferred couplings in minimal contexts

Minimal Z′ models from D-branes

[see, e.g., Ghilencea-Ibanez-Irges-Quevedo, hep-ph/0205083]

$$g_{BL} = -\frac{1}{2g_Y}(g_Y^2 + g'^2)$$

Minimal set of parameters: $M_{Z'}$, g_Y, g_{BL}

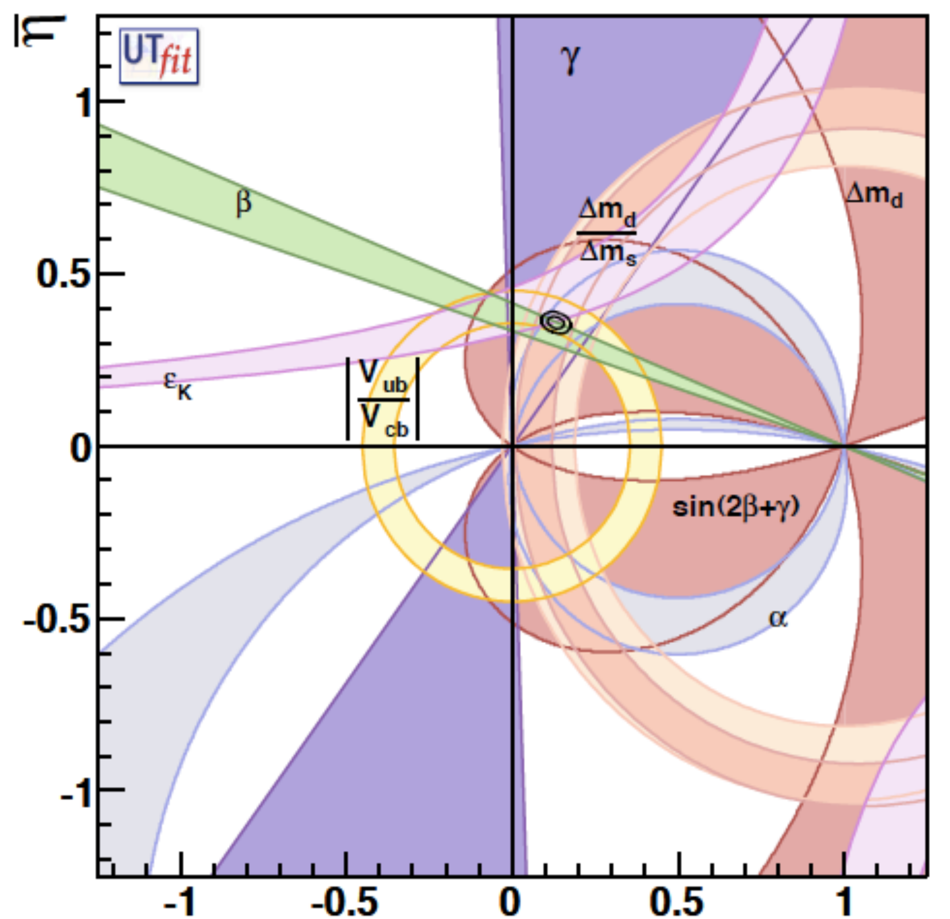


4. Indirect signals of new physics?

Flavour precision tests: a window on high scales

Much progress in the last years (B-factories, Tevatron):
no confirmed deviation from SM (GIM, CKM) found

The unitarity triangle



$\bar{\rho}+i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$

Some examples:

Δm_s $\quad B \to \tau\nu$

$B \to X_s \gamma$ $\quad B \to X_s l^+ l^-$

$B_s \to \mu^+\mu^-$ CDF bound

$\mu \to e\gamma$ MEGA bound
MEG coming

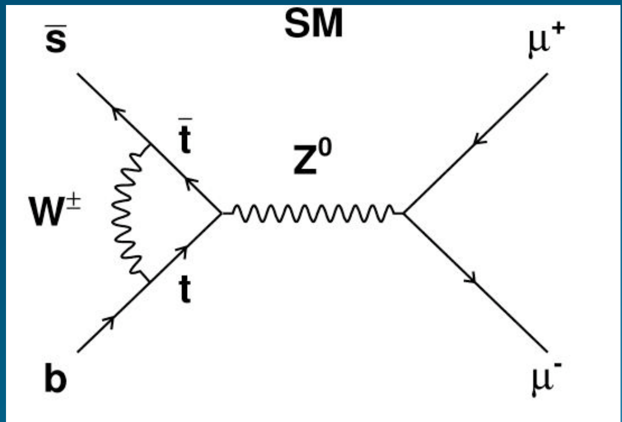
More K and B decays
CP-violation in B system
Tree-level vs. 1-loop UT

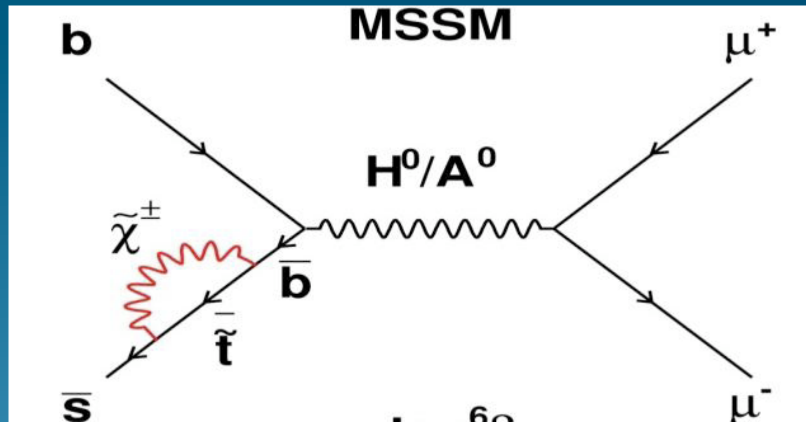
Progress comes now
rapidly from LHCb

A case study: $B_s \rightarrow \mu\,\mu$ (Z-penguin dominated)

Precisely predicted in the SM:

$$BR(B_s \to \mu^+\mu^-)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$$



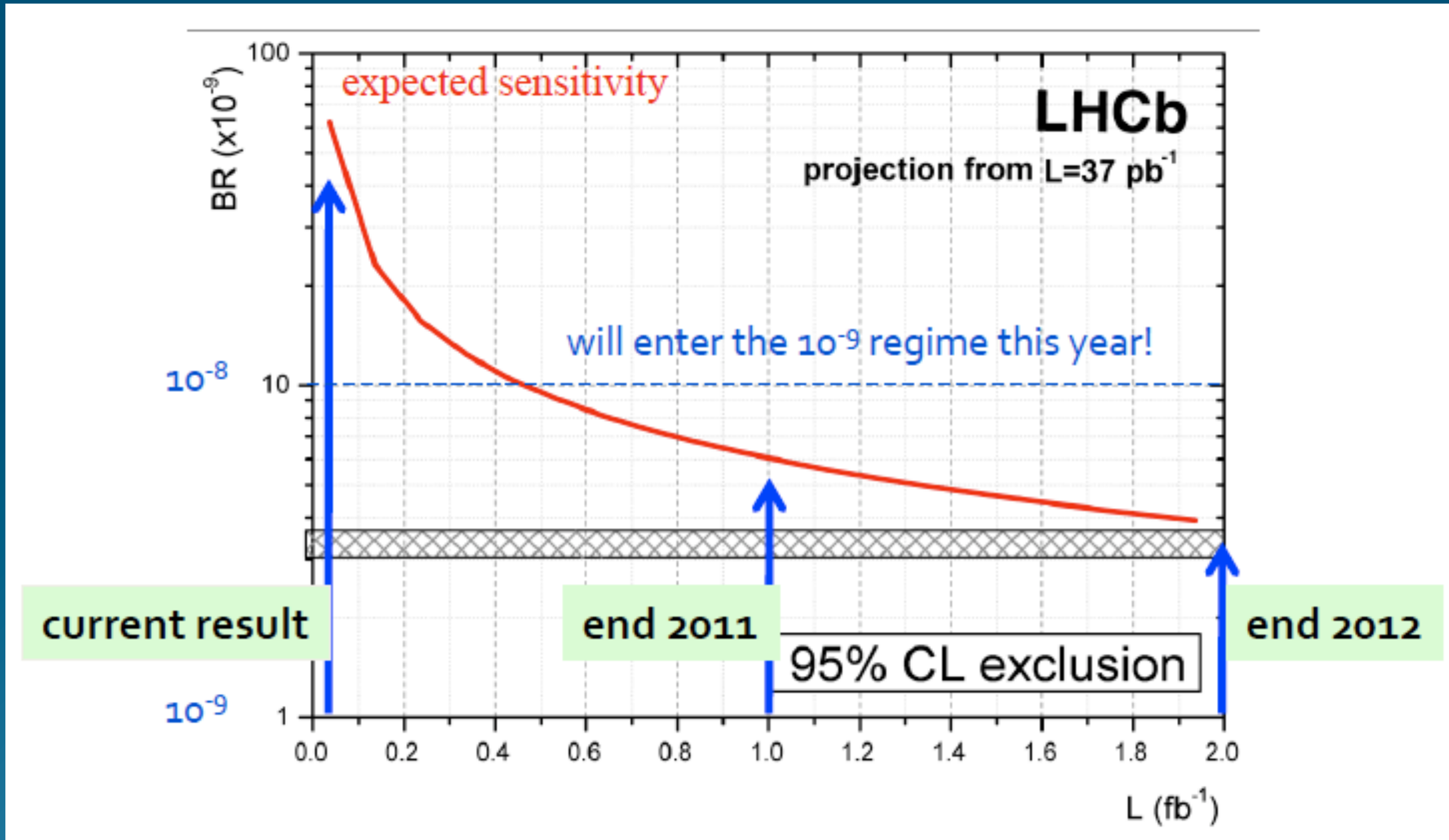


Can receive NP contribution, e.g. MSSM @ large tan β

Current best limit [CDF, 3.7 fb^{-1}]: < 43 x 10^{-9} @ 95% CL

LHCb competitive with 37 pb^{-1}: < 56 x 10^{-9} @ 95% CL

Outlook for $B_s \rightarrow \mu\,\mu$ at LHCb in 2011-2

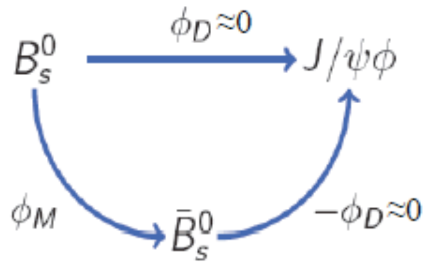


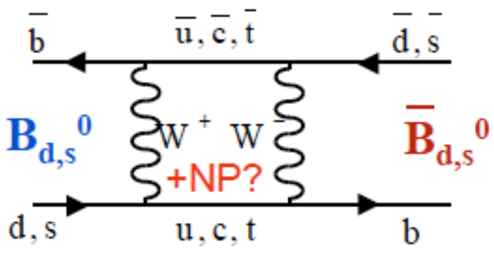
In this channel, also ATLAS and CMS become competitive with increasing luminosity

CP violation in $B_s \rightarrow J/\psi\ \phi$ decays at LHCb in 2011-2

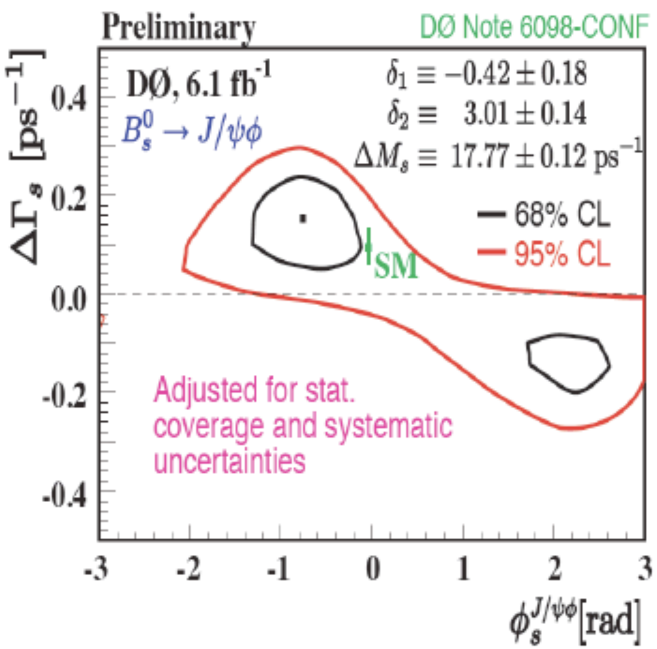
Mixing induced CP violation in $B_s \rightarrow J/\Psi\ \Phi$

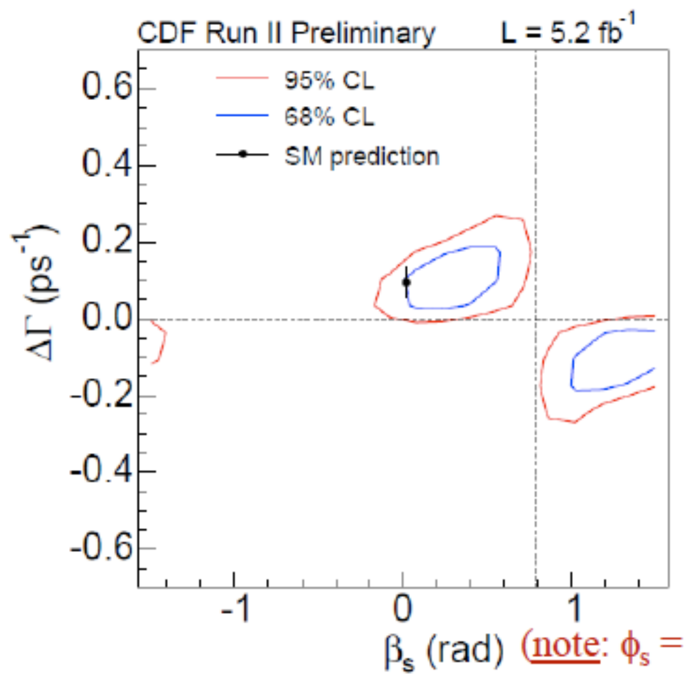
- ✓ mixing phase very precisely known in Standard Model: $\phi_s = -2\beta_s = -0.0363 \pm 0.0017$
- ✓ sensitive to New Physics effects
- ➢ $\phi_s = \phi_s(SM) + \phi_s(NP)$





Intriguing results by Tevatron





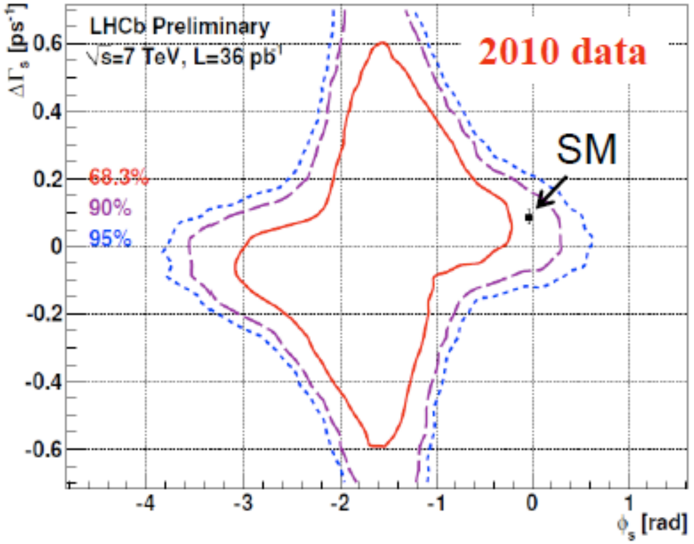
(note: $\phi_s = -2\beta_s$)

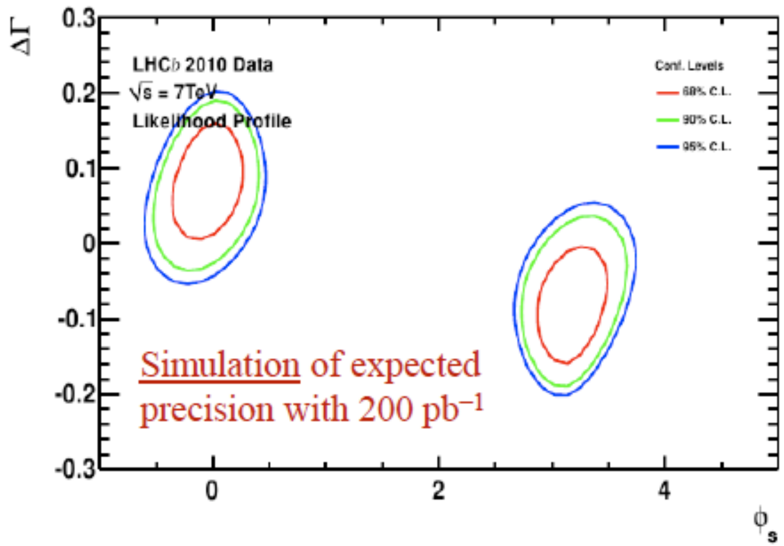
CP violation in $B_s \rightarrow J/\psi\ \phi$ decays at LHCb in 2011-2

Mixing induced CP violation in $B_s \rightarrow J/\Psi\ \Phi$

[LHCb-CONF-2011-006]

$\phi_s \in$ [-2.7, -0.5] rad at 68% CL
$\phi_s \in$ [-3.5, 0.2] rad at 95% CL





➤ expect $\sigma(\Phi_s) \sim 0.2\text{-}0.3$ rad with 200 pb^{-1}

Further improvements expected with full 2011 data set:

✓ ~30 times larger sample than 2010
✓ improved 'opposite side tagging' (present $\varepsilon D^2 = 2.2 \pm 0.5\%$)
✓ including 'same-sign' kaon tagger

Tentative conclusions (expiration date 1 month?)

- By 2011 or at most 2012 we will know whether a SM-like Higgs boson is there or not, after > 20 years of efforts!

- No sign of supersymmetry yet, but improved limits beyond Tevatron bounds: fine-tuning problem for supersymmetry? Are we missing something important with naturalness?

- More data-driven searches entering uncharted territory in 2011: surprises may come at any moment now!

- Keep an eye on flavor physics: first signals of new physics may well come from rare decays or CP-violating processes

We are lucky to live in times where so important questions can be posed and actually answered!

First answers will open more questions, whose answer may also be found, with some patience, when LHC energy, luminosity and detectors further improved

Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.

Galileo

I value more finding some truth, although on a light subject, than having long discussions about the greatest questions without achieving any truth.

Thank you for your attention!

Spare slides

Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints

An example: $\mathcal{A}(W_L^+ W_L^- \to Z_L Z_L)$ $(s \gg m_W^2)$

$$i\frac{s}{v^2}$$

$$-i\frac{s^2}{v^2(s-m_h^2)}$$

➔ $$-i\frac{m_h^2}{v^2}\frac{s}{s-m_h^2}$$

$A(W_L W_L)$ saturate unitarity at $E \sim 4\pi m_W/g \sim 1.2$ TeV

No SM Higgs ➔ new states must appear to restore unitarity

Precision tests of EW breaking

Electroweak theory tested at the level of quantum corrections
by precision measurements at SLC, LEP, Tevatron and more:
large number of observables, many with per-mille accuracy

SM radiative corrections vs. m_t and m_h

For fixed values of the remaining SM input parameters:

$$\Delta m_W \simeq -(57\,MeV)\ \log X_h - (9\,MeV)\ (\log X_h)^2 + (0.54\,GeV)\ (X_t^2 - 1)$$

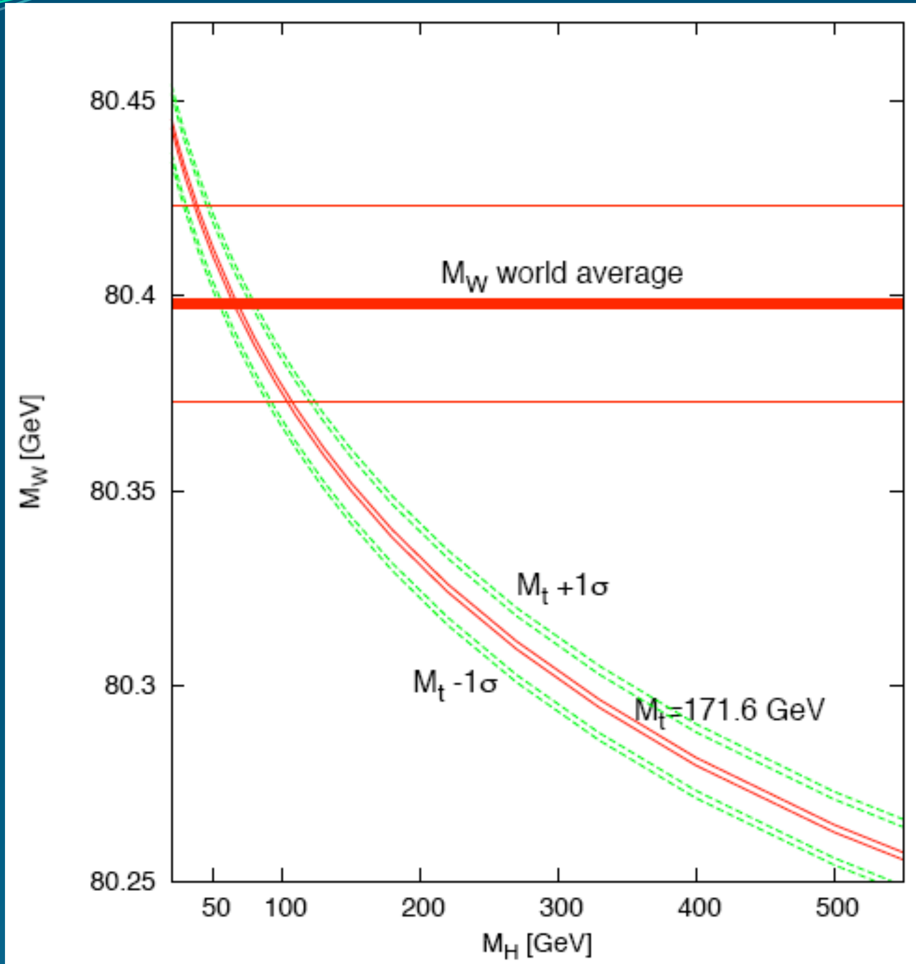
$$\Delta \sin^2_{eff} \simeq 4.9 \times 10^{-4}\ \log X_h + 3.4 \times 10^{-5}\ (\log X_h)^2 - 2.8 \times 10^{-3}\ (X_t^2 - 1)$$

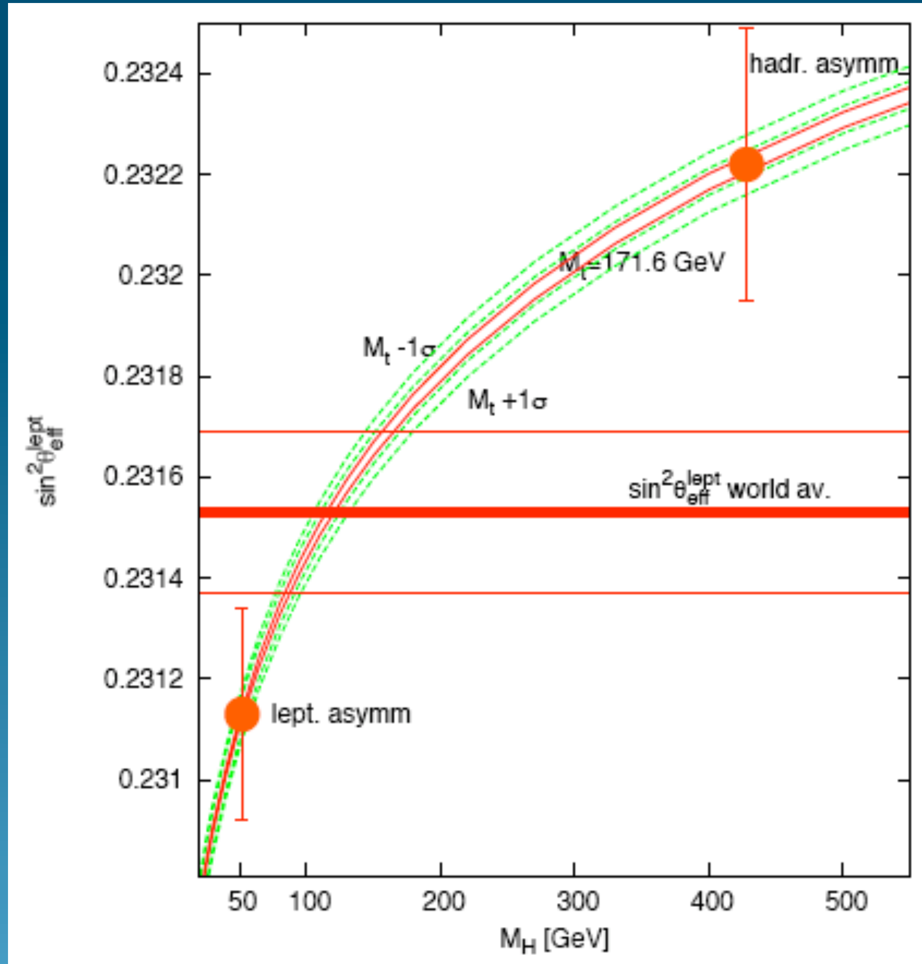
$$X_h = \frac{m_h}{100\,GeV} \qquad X_t = \frac{m_t}{174.3\,GeV}$$

Now that m_t is precisely known, indirect constraints on m_h
Correlations: $m_t\downarrow \Rightarrow m_h\downarrow$ $\quad m_W\downarrow \Rightarrow m_h\uparrow$ $\quad s2w_l\downarrow \Rightarrow m_h\downarrow$

What prefers a light Higgs?

[Gambino]





Correlations: $M_{top}\downarrow \rightarrow m_H\downarrow$ $M_W\downarrow \rightarrow m_H\uparrow$ $s2w_l\downarrow \rightarrow m_H\downarrow$

- M_W points to a light Higgs, with good accuracy
- Some tension in leptonic vs. hadronic asymmetries

Can we exclude a heavy SM-like Higgs?

(is working on those LHC analyses a poor investment?)

Within the SM model, the evidence for a light Higgs is not as bullet-proof as it may seem

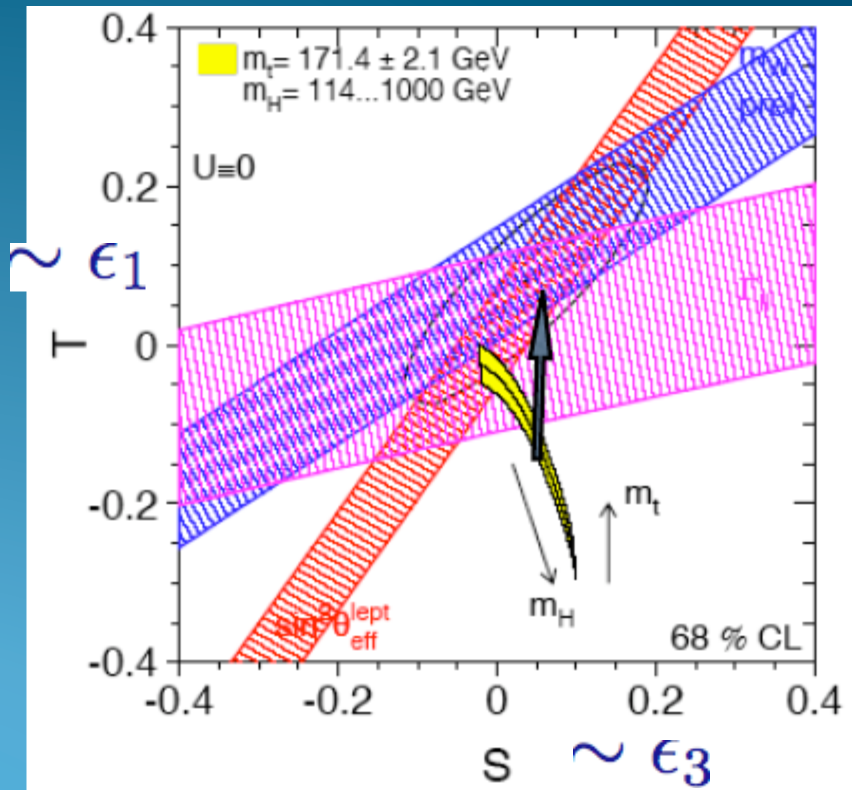
Beyond the SM, simple (but ad hoc) modifications can reconcile precision tests with a heavier Higgs

Pushing m_H up requires

$$\Delta T = 0.2 - 0.3 \quad \Delta S = small$$

Various possibilities explored:
[Peskin-Wells, Barbieri et al, …]

- A second "inert" doublet H_2
- SUSY with large NH_1H_2 coupling
- A (tuned) fourth generation
- New EW fermions



Wolfenstein parametrization of CKM matrix

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\bar{\rho} = \rho(1 - \lambda^2/2 + \ldots)$$

Z penguin diagram for b➔s:

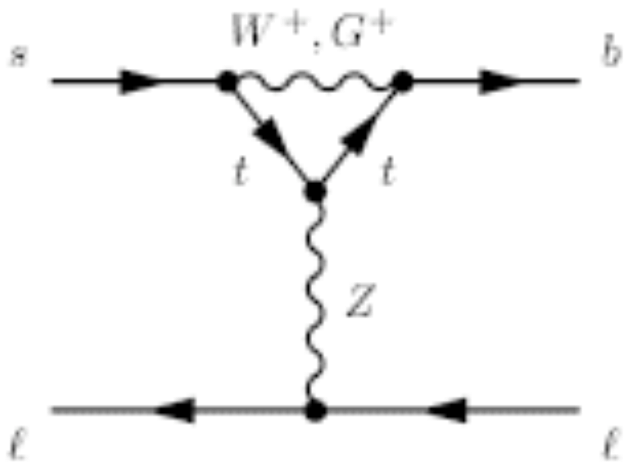


Fig. 19: Left: Z-penguin contribution to $B_s \to \ell^+\ell^-$.

BSM variations on SM Higgs searches

How could SM Higgs production/decay be altered?

Main mechanisms:

- New Higgs couplings to light enough exotic particles (if not excluded by direct searches or indirect constraints): not only new final states, also new virtual states in loops

- Modified tree-level couplings to SM particles, e.g. due to the mixing of the SM-like Higgs with other scalar states

Innumerable examples in extensions of the SM, both supersymmetric and non-supersymmetric, large number of possibilities to be kept in mind detection can be easier or more difficult

Hiding the Higgs at the LHC?

One can imagine "nasty" new physics, compatible with existing constraints even if not strongly motivated, that could make life much more difficult at the LHC

Simplest example:
[Wise et al, Wilczek et al, Grossman et al, …]
one real singlet scalar (or more) coupled to the SM only via a quartic mixing term in the Higgs potential
dilution of the SM Higgs signals via mixing and/or decays into invisible channels (a hidden sector)

"Subtle is the Lord, but not malicious…"