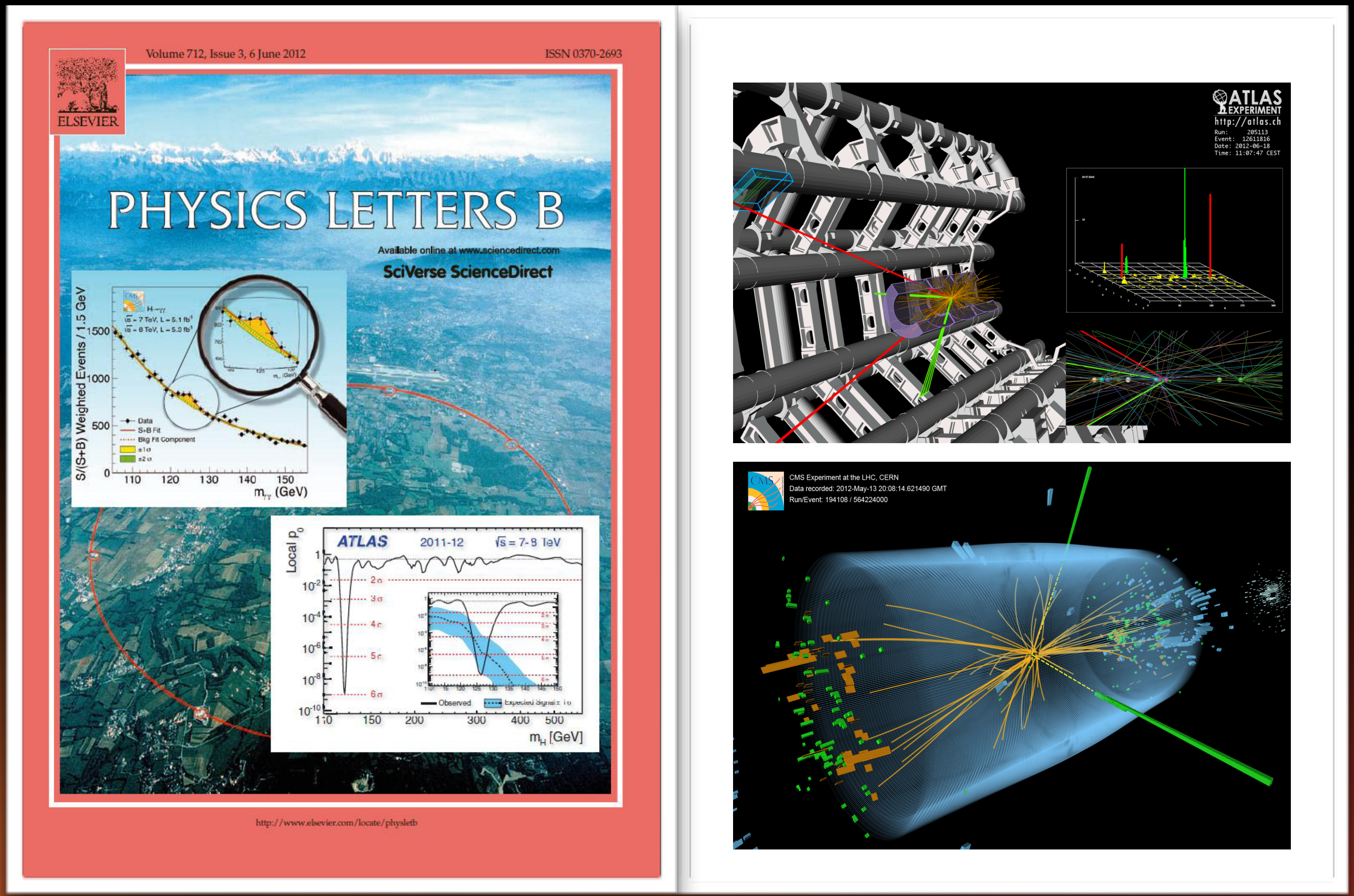
Recent Results from the Large Hadron Collider

Markus Elsing

COSMO 2012, September 10-14, Beijing

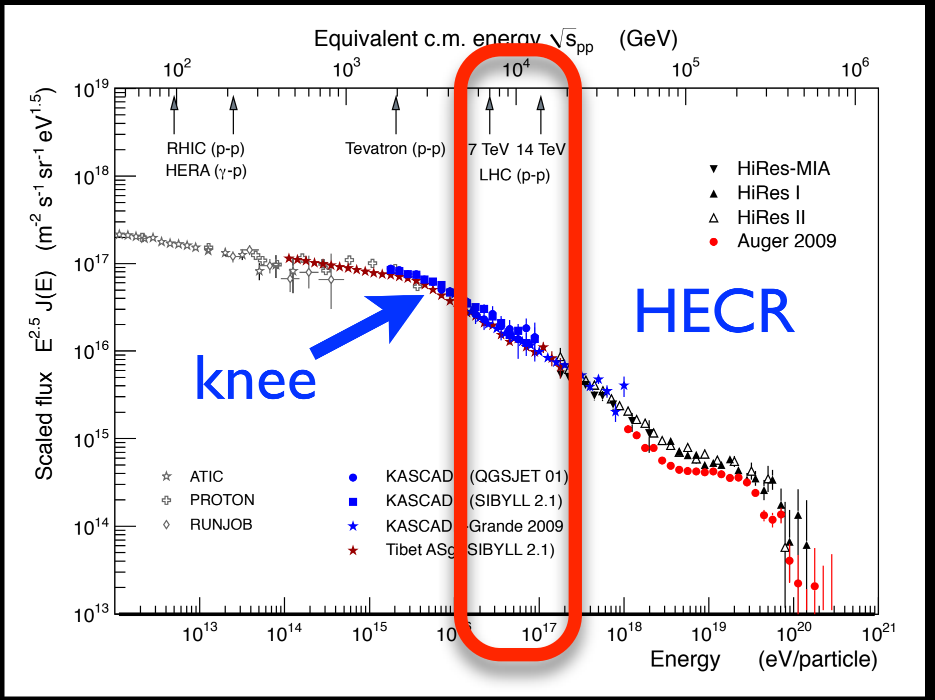


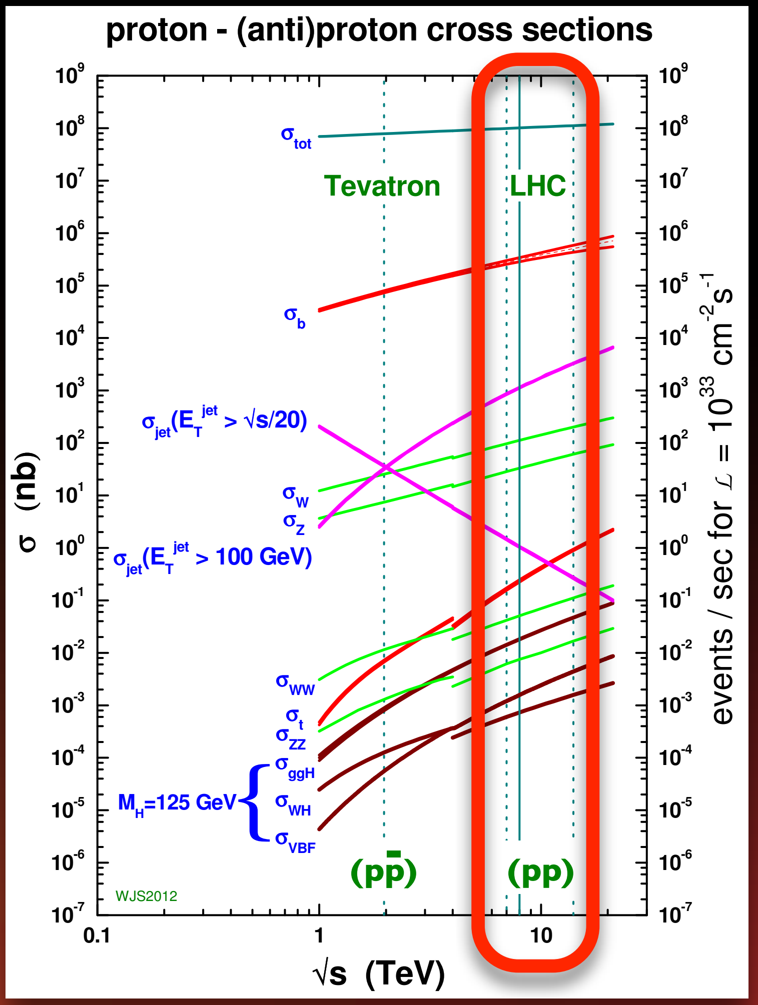
Introduction: LHC

- LHC is a high energy and high luminosity proton-proton collider
  - ➡ design centre-of-mass energy is *14 TeV* and design luminosity is $\mathscr{L} = 10^{34}\ cm^{-2}s^{-1}$
  - ➡ first collider to reach energy regime of HECR
  - ➡ expect ~23 interactions at a bunch crossing frequency of 40 MHz (!)

- LHC is a unique machine
  - ➡ first collider to explore the physics at the *TeV* scale
  - ➡ excellent sensitivity to rare (new physics) processes

- expected production cross-sections
  - ➡ large inclusive b, W/Z and top production rates
    - LHC is a combined b-, W/Z- and top-factory
  - ➡ cross-section for jet and W/Z production orders of magnitude larger than e.g. expected for Higgs
  - ➡ total cross-section dominated by soft interactions



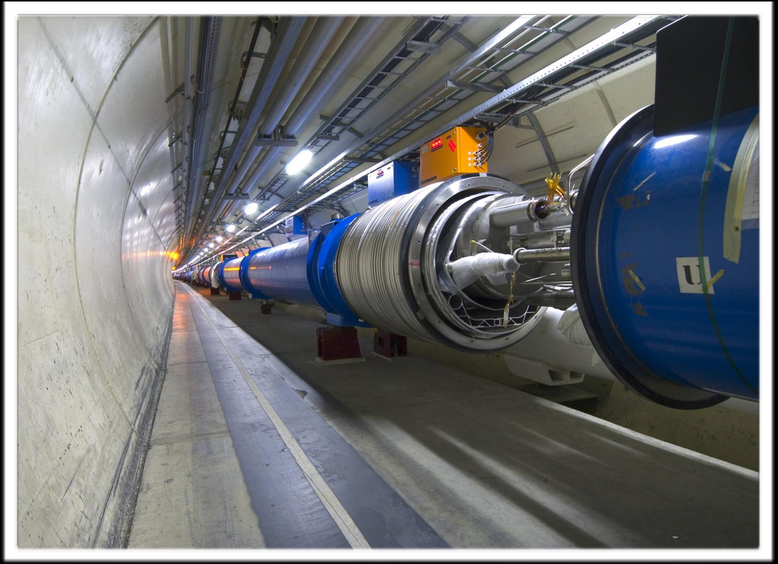


W.J. Stirling, private communication

Introduction: LHC Physics Programme

- proton-proton programme:
  I. mass and electroweak symmetry breaking
    - search for the Higgs Boson, measurement of its properties
  II. hierarchy in the TeV domain
    - search for new phenomena moderating the hierarchy problem
    - search for the unexpected at the high-energy frontier
  III. electroweak unification and strong interactions
    - precision measurements (m_{top}, M_W) and tests of the Standard Model
    - tests of perturbative QCD at the high-energy frontier
  IV. flavour
    - B-,D-mixing, rare decays and CP violation as tests of the Standard Model

- heavy ion programme: (not covered here)
  ➡ study quark-gluon plasma in Pb+Pb collisions at up to *5.5 TeV* per colliding nucleon



Peter Higgs visiting CERN in 2008

Introduction: LHC and Experiments

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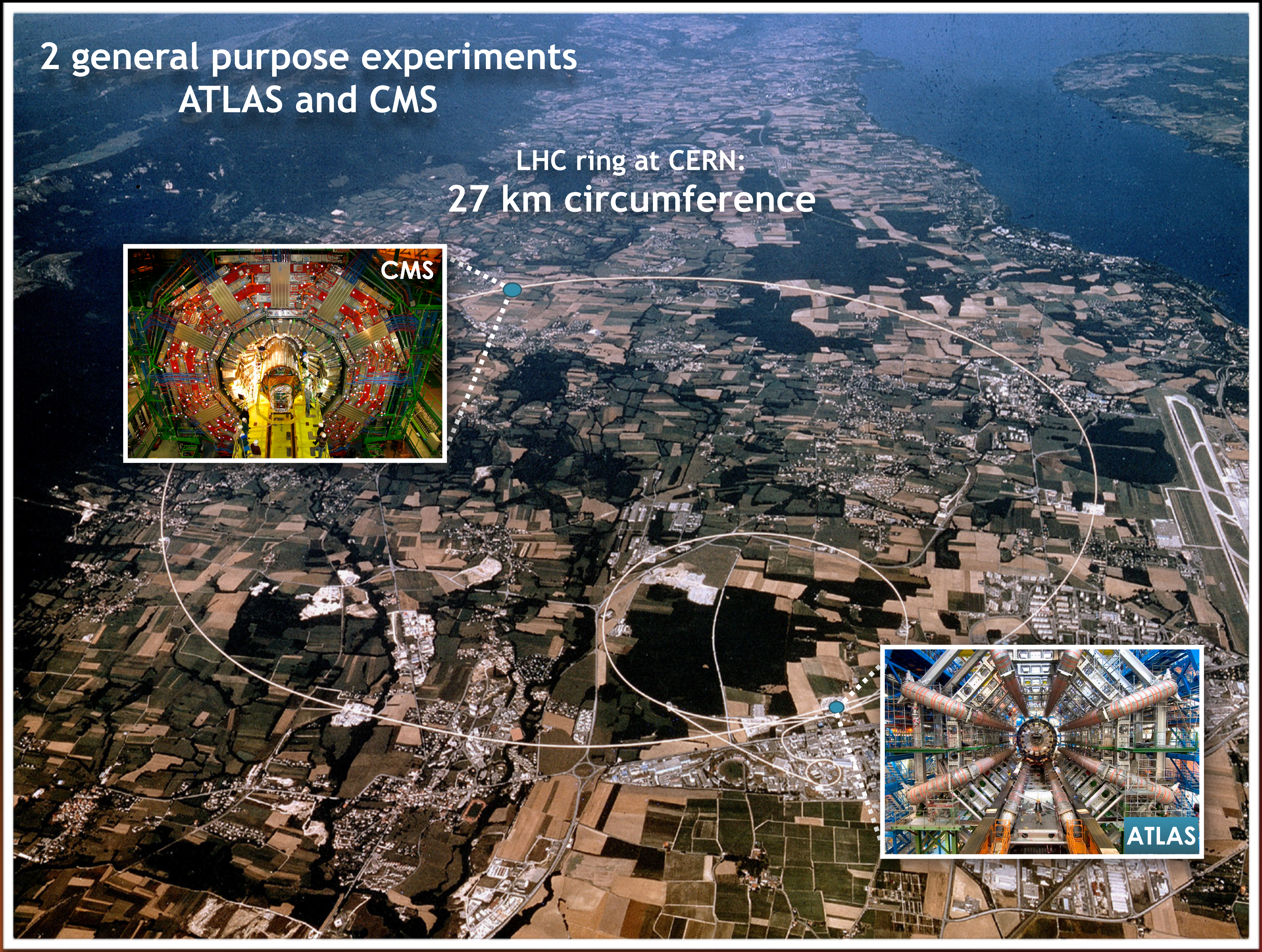
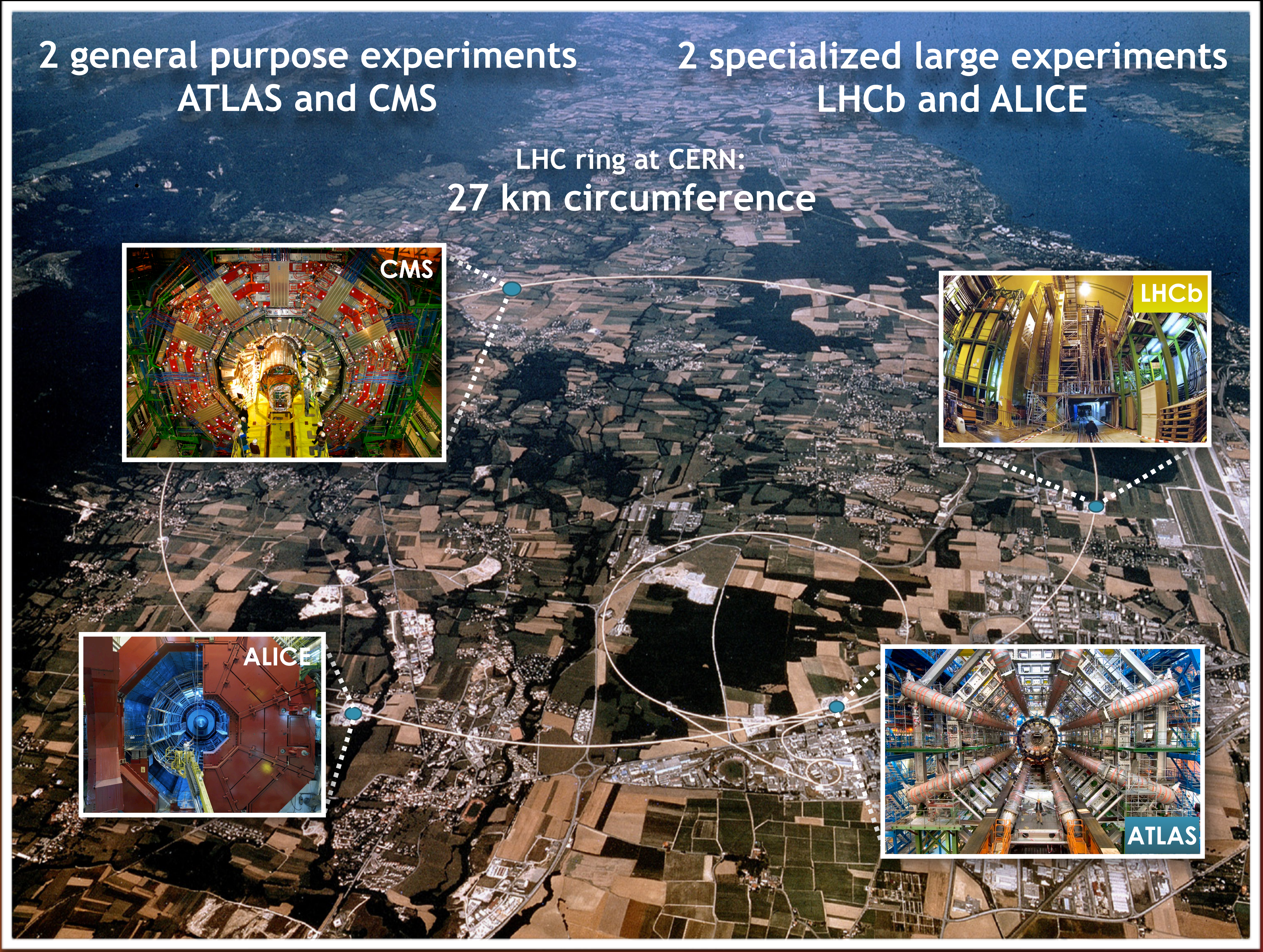
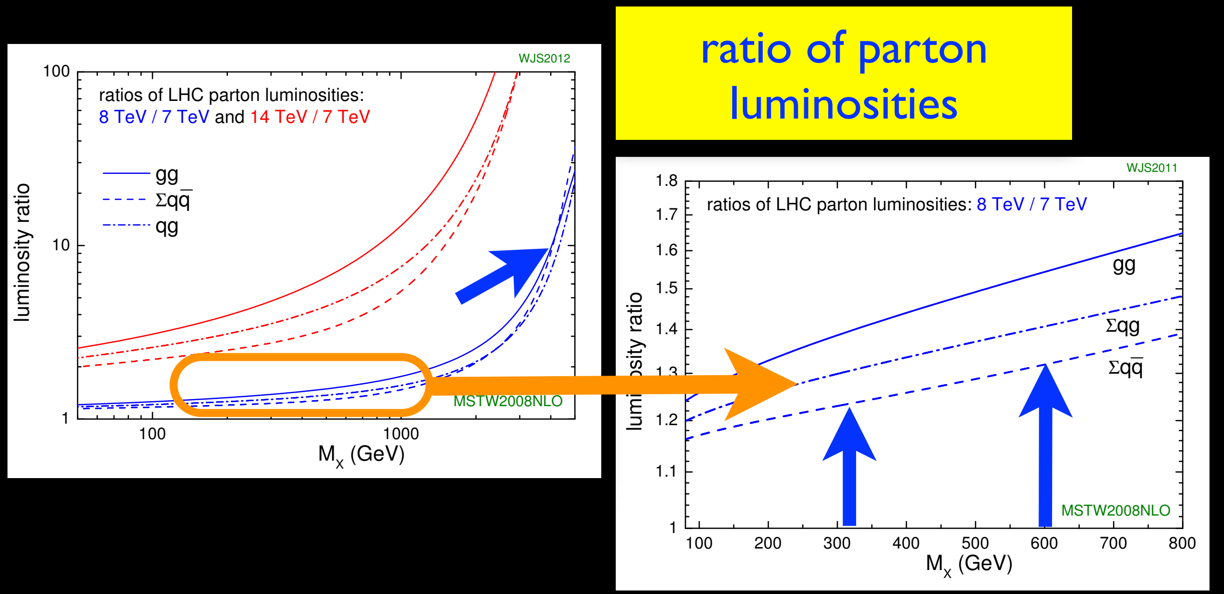


Introduction: LHC and Experiments



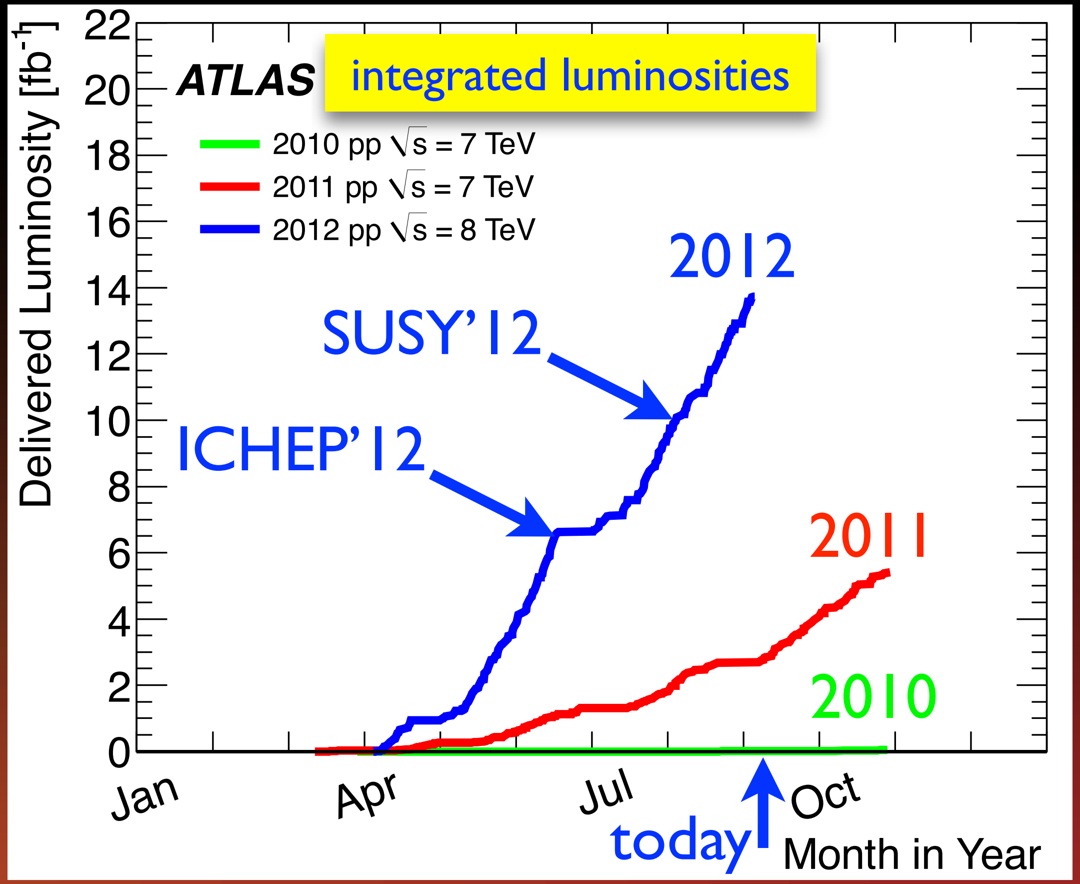
LHC Operation in 2010 to 2012

- first LHC running period
  - ➡ 2010+2011at *7 TeV* and *8 TeV* in 2012
  - ➡ increase in centre-of mass energy yields increase in parton luminosity, especially for large M_X processes
  - ➡ but jet, W/Z and top cross-sections scale fast, background for new physics searches



W.J. Stirling, private communication

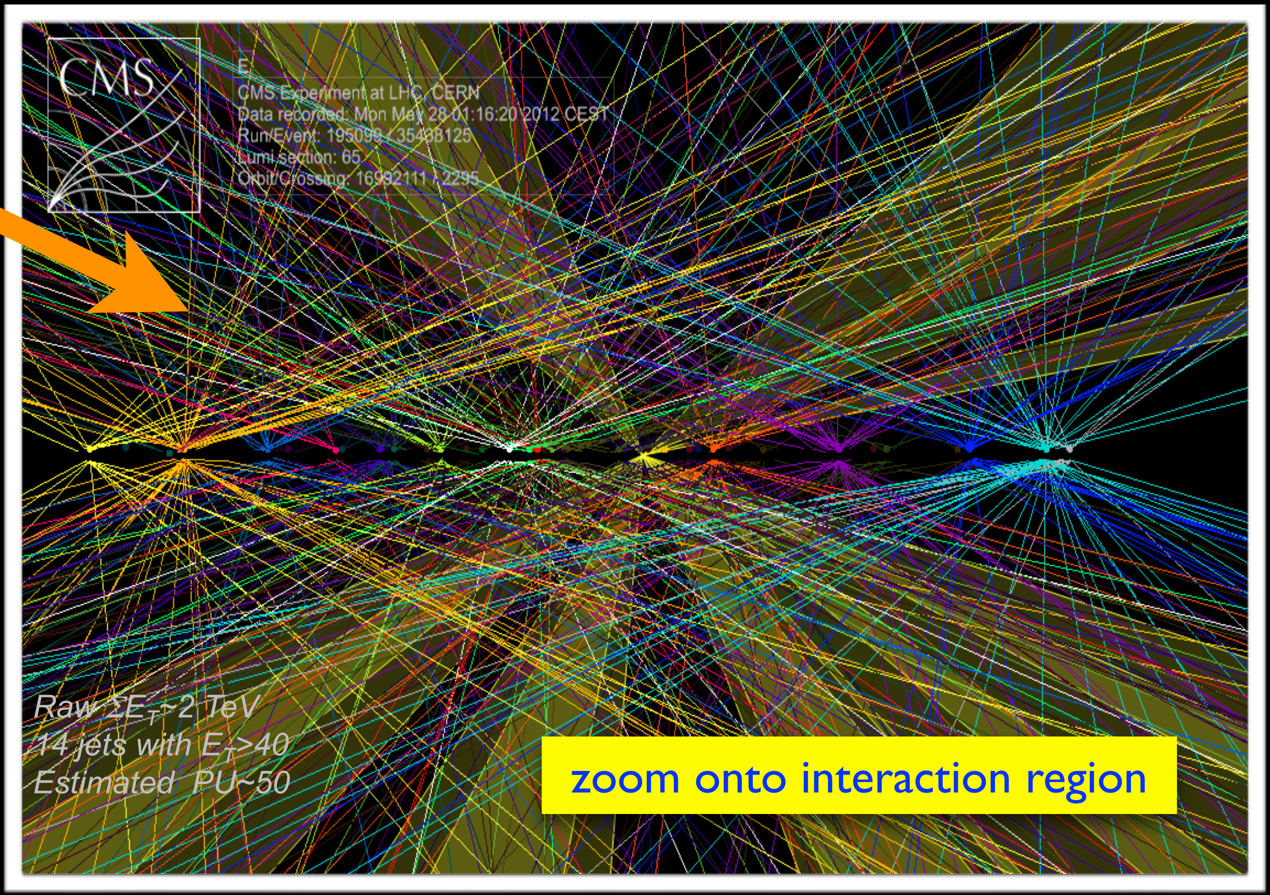
- outstanding LHC performance
  - ➡ peak luminosity of $7.7\times10^{33}\ cm^{-2}s^{-1}$ with half the number of bunches
  - ➡ expect to reach *20* fb^{-1} in 2012
    - p+p run this year extended by 2.5 months



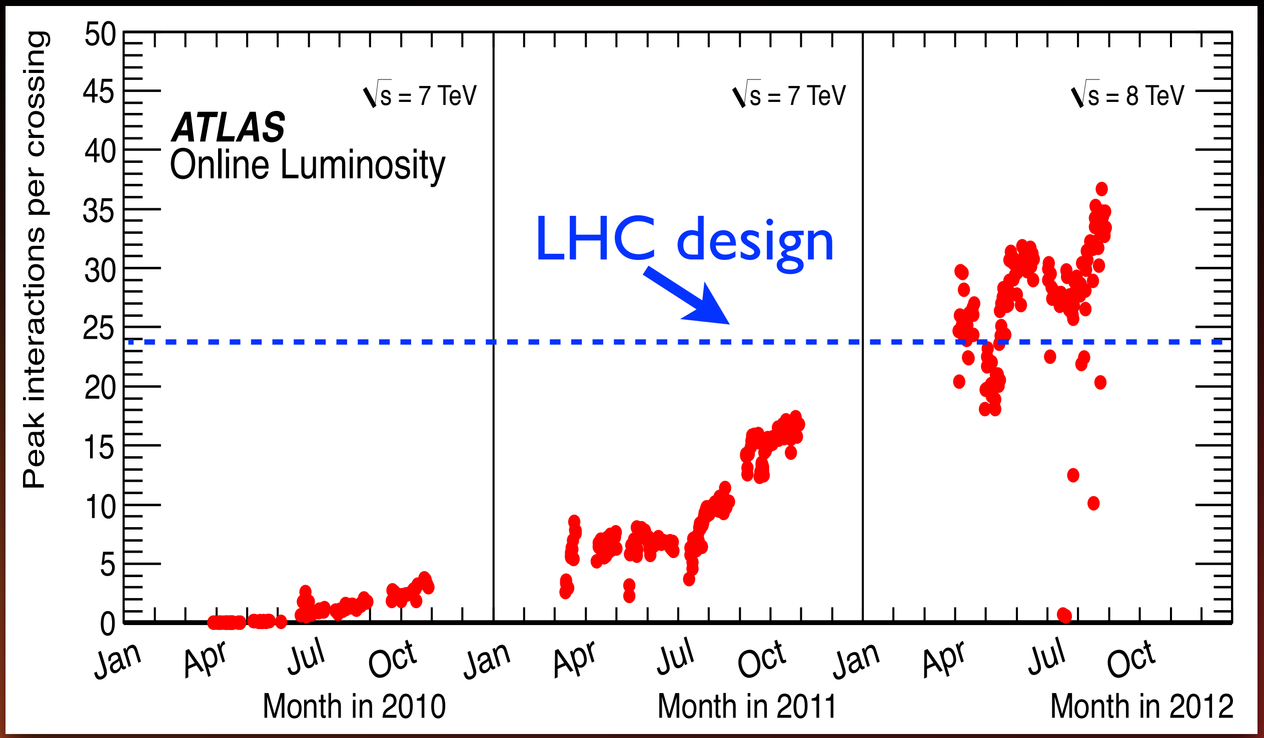
- presented in the following
  - ➡ *7 TeV* and latest *8 TeV* results
  - ➡ status of ICHEP'12, with SUSY'12 updates (most results based on *4.9* fb^{-1} at *7 TeV* and *5.9* fb^{-1} at *8 TeV*)

High Luminosity comes at a Price

- typical LHC event in 2012
  - ➡ large number of interactions in 1 event
    - so-called event "pileup"
  - ➡ exceeding detector design levels (!)

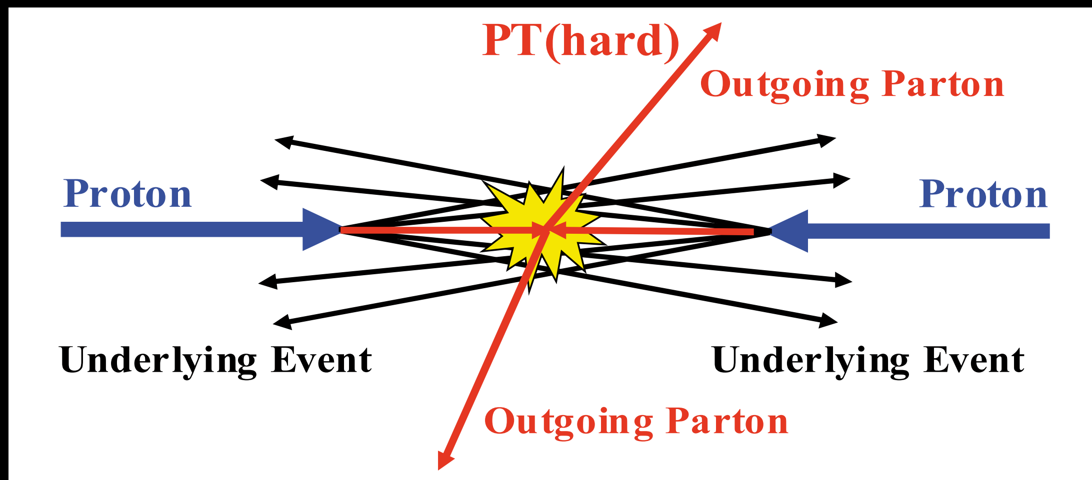


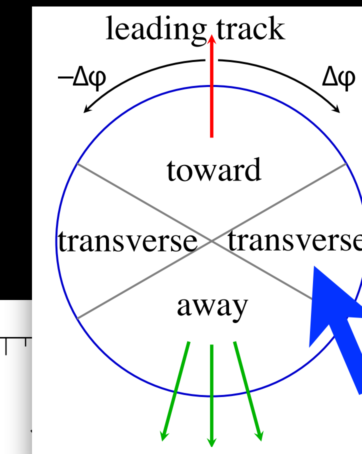
- challenge for the experiments
  - ➡ trigger: select interesting interactions, keeping acceptable total rate
  - ➡ data volume: from the detector recorded on tape and to be processed/analyzed on computing GRID worldwide
  - ➡ reconstruction and analysis: make sense out of these very complex events and extracting interesting physics information

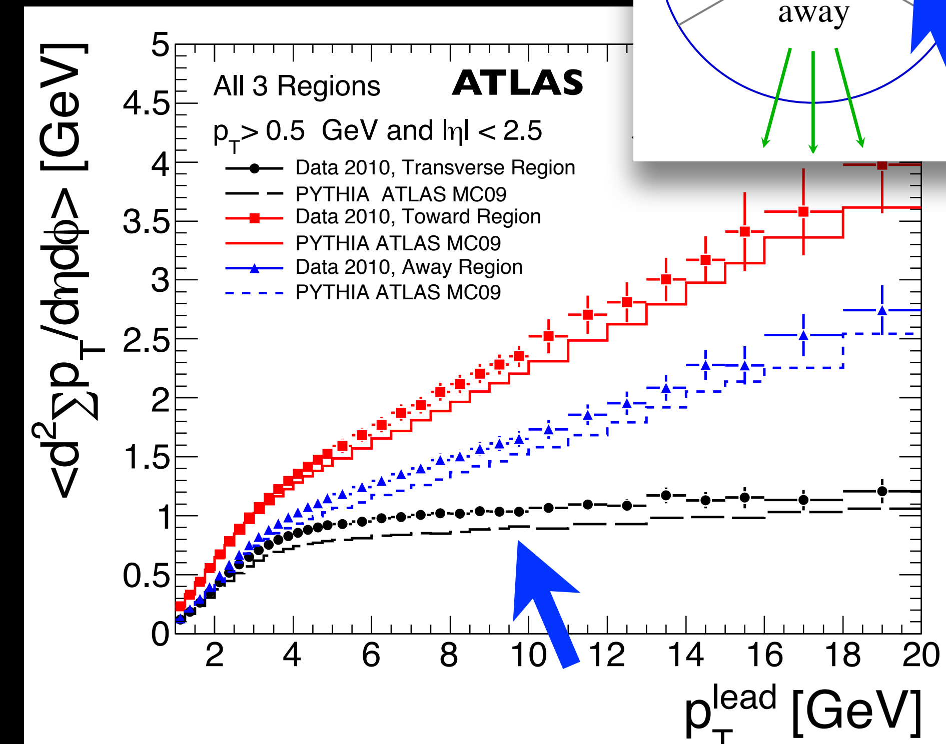


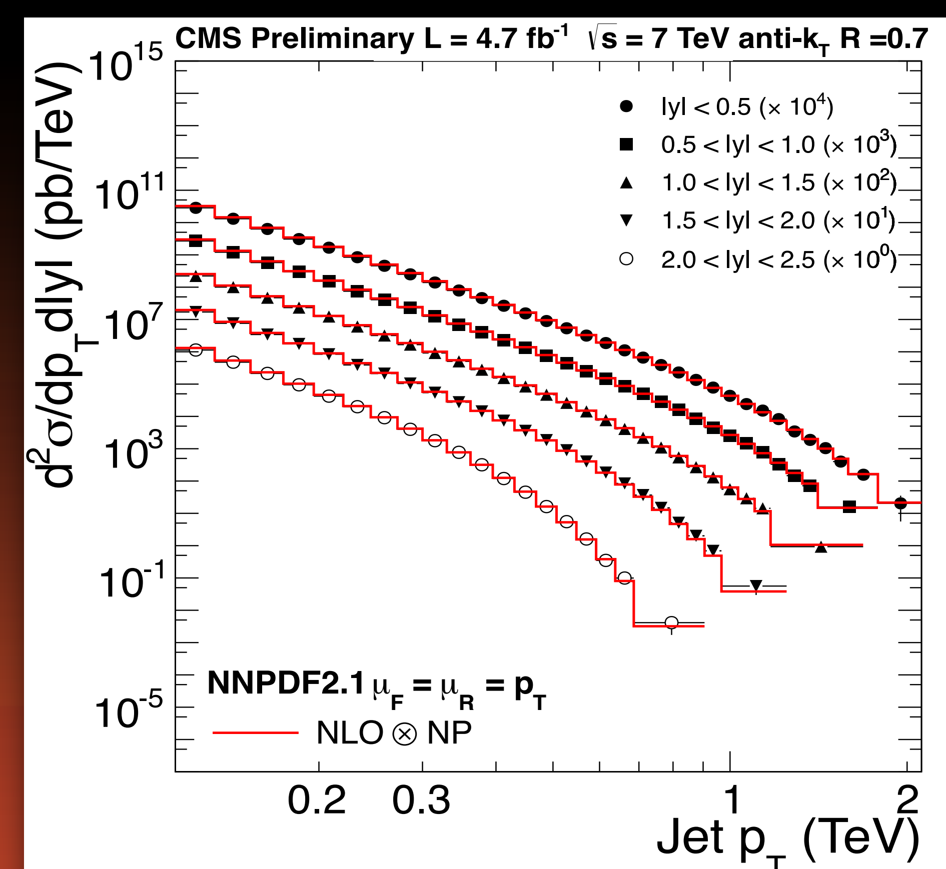
- huge development effort
  - ➡ during shutdown 2011/2012
  - ➡ experiments improved as well their sensitivity, especially for Higgs searches

Jets Production and Underlying Events





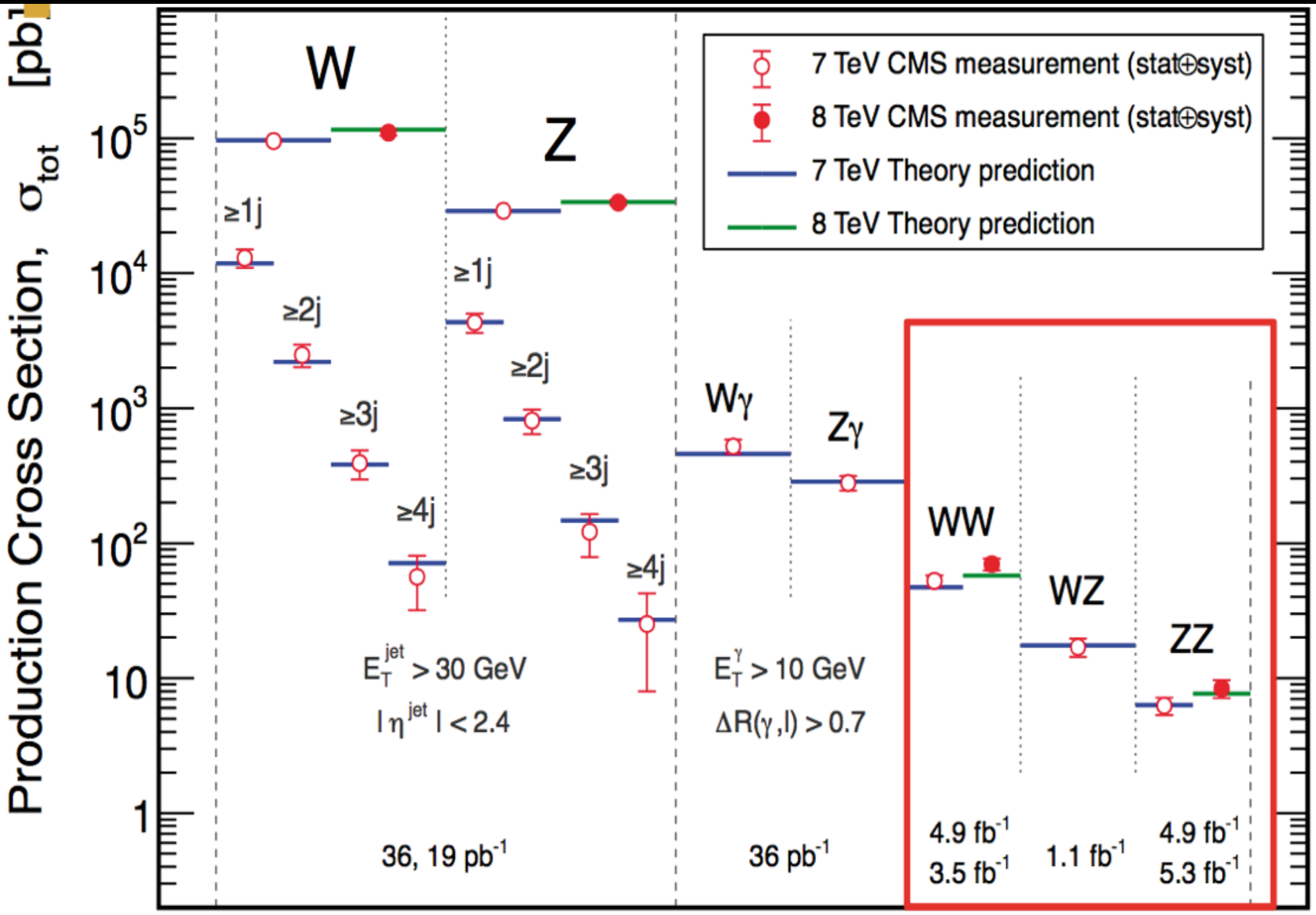


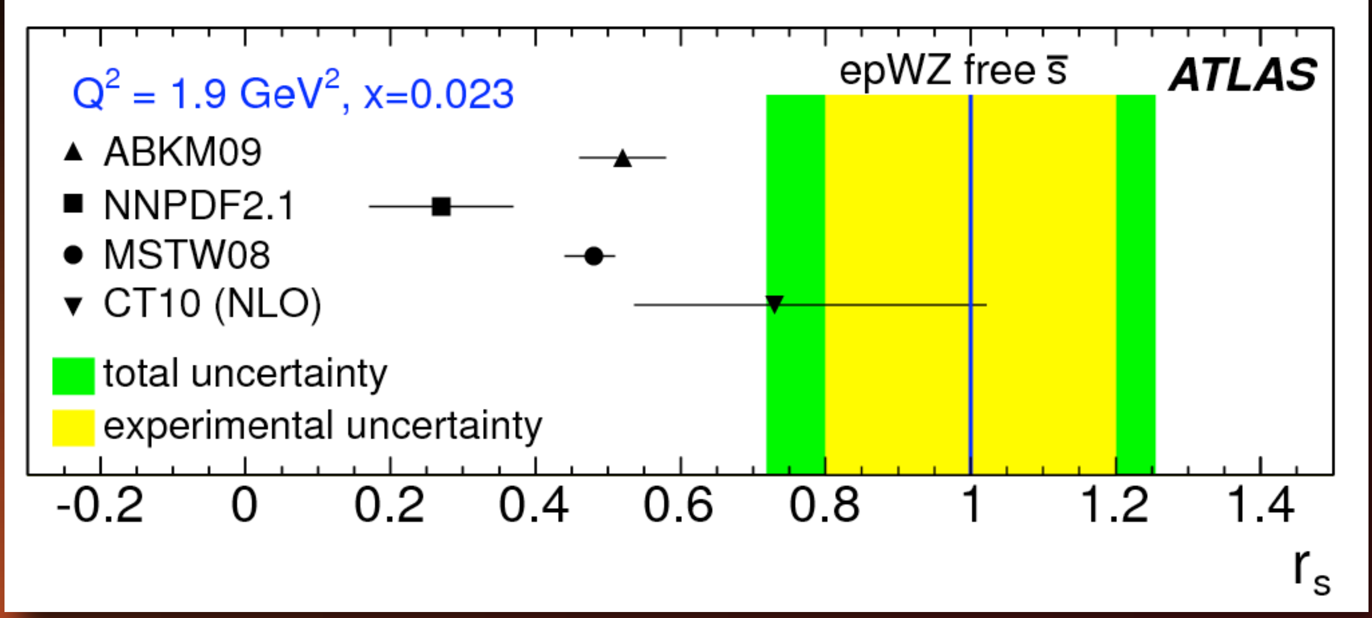


- underlying events
  - ➡ pre-LHC models predict e.g. too little transverse activity, region sensitive to multi-parton interactions
  - ➡ LHC results basis for improved MC tunes
    - good description achieved with modern codes like PYTHIA8 or HERWIG++
    - cosmic air shower models yield as well a good description (EPOS)
- jet production
  - ➡ excellent description by pQCD over many orders of magnitude (LHC covers huge range in p_T and $|y|$)
  - ➡ based on PDFs, constrained by HERA and TEVATRON

Standard Model Measurements

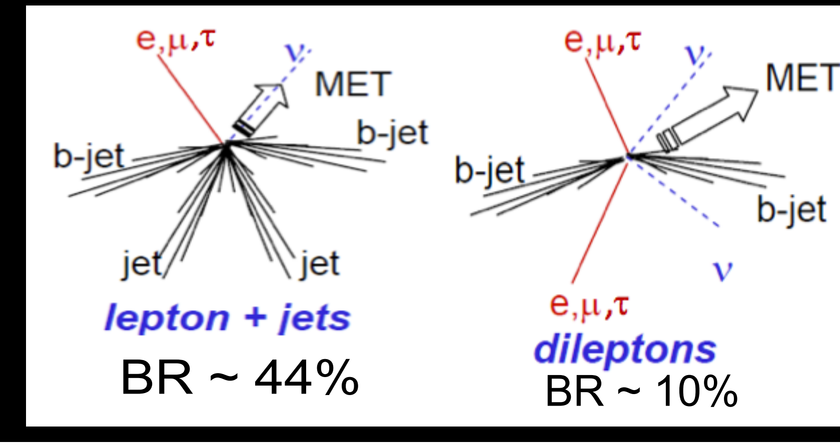
- $W^{\pm}/Z$, W/Z+jets and di-boson production
  - ➡ important tests of SM
  - ➡ background for searches (Higgs)
- W and Z studies
  - ➡ huge event rates
    - heavily used for calibration
  - ➡ W/Z rapidity distribution sensitive to strange quark sea contribution in proton PDFs
    - ATLAS compatible with no strange sea suppression
- di-boson production
  - ➡ can put limits on anomalous Triple Gauge Couplings
  - ➡ becoming competitive with LEP



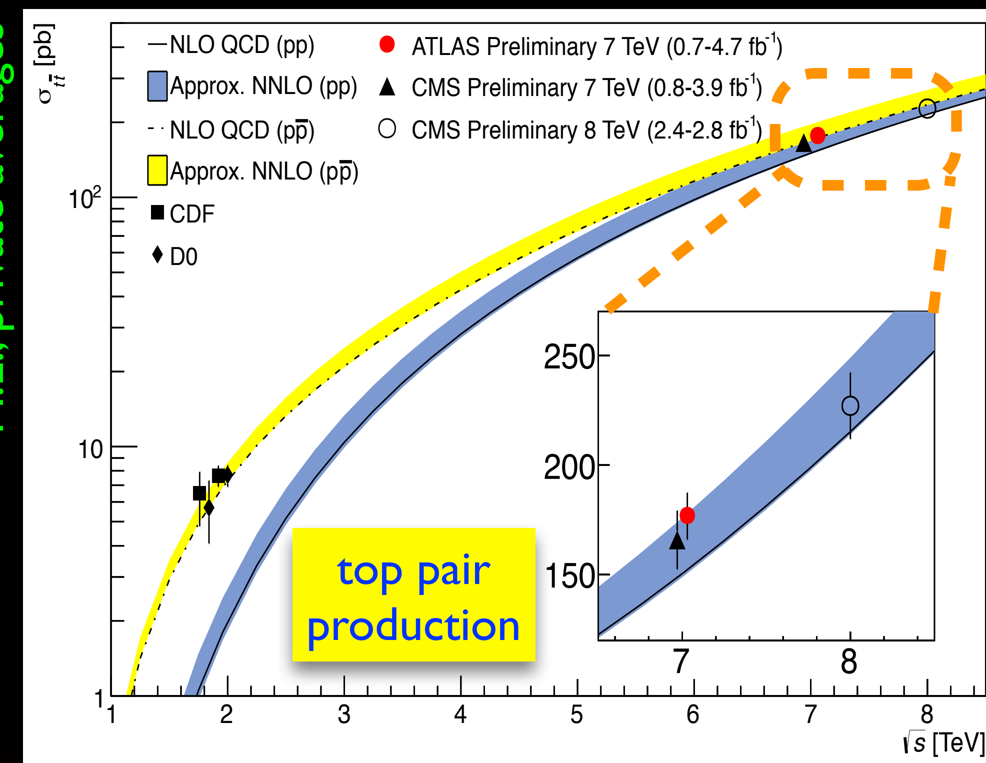


Top Cross-Sections and Mass

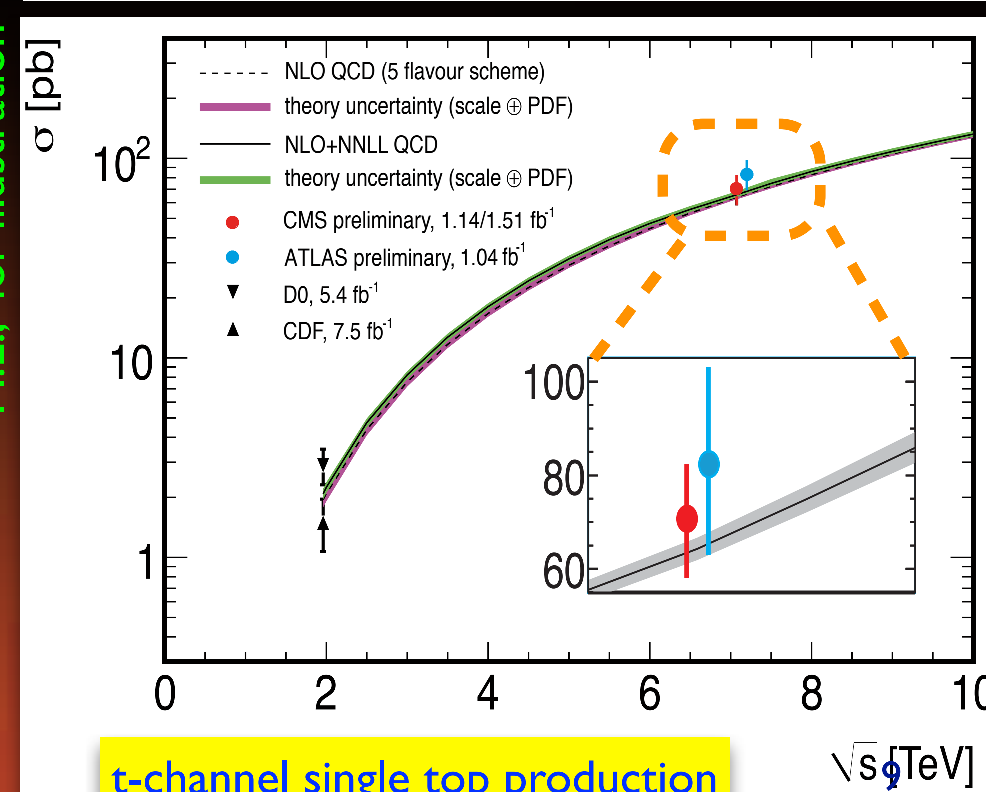
- LHC is a top factory
  - ➡ $t\bar{t}$ cross-section is large *~200 pb* (~4 million events so far)
  - ➡ rich top physics program
- top pair and single top production
  - ➡ several channels accessible, even all hadronic
  - ➡ *7* and first *8 TeV* results in agreement with SM
- precision top mass measurements
  - ➡ derive m_t from kinematic mass reconstruction
  - ➡ already systematically dominated (jet energy scale, ...)

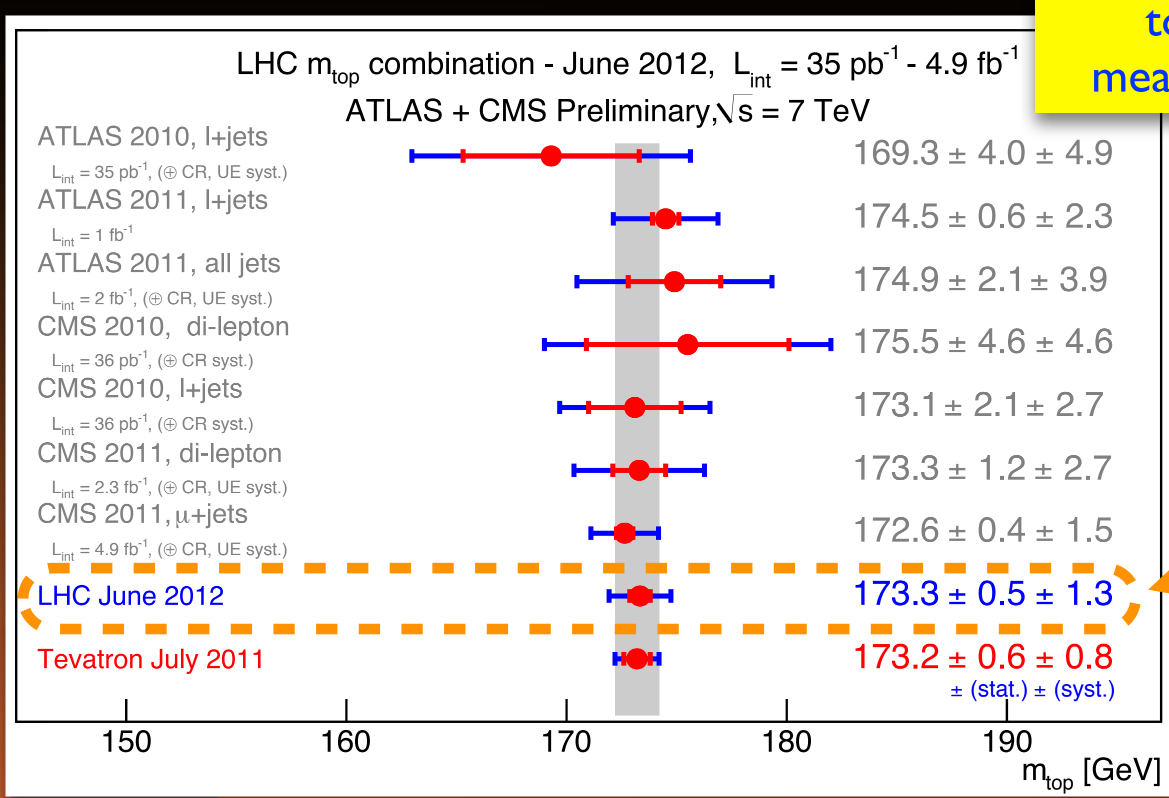


M.E., private averages



M.E., for illustration





top mass measurements

±0.8% starts being competitive

Markus Elsing

M_t and Electroweak Fit

- direct top and W mass measurements
  - ➡ mostly precise TEVATRON results
  - ➡ compatible with combined fit to electroweak precision data and a light Higgs
  - ➡ as well with MSSM

- precise measurements of top mass
  - ➡ experimental observable and pole mass ?

$$m_t^{exp} = m_{pole}(1 \pm \Delta)$$

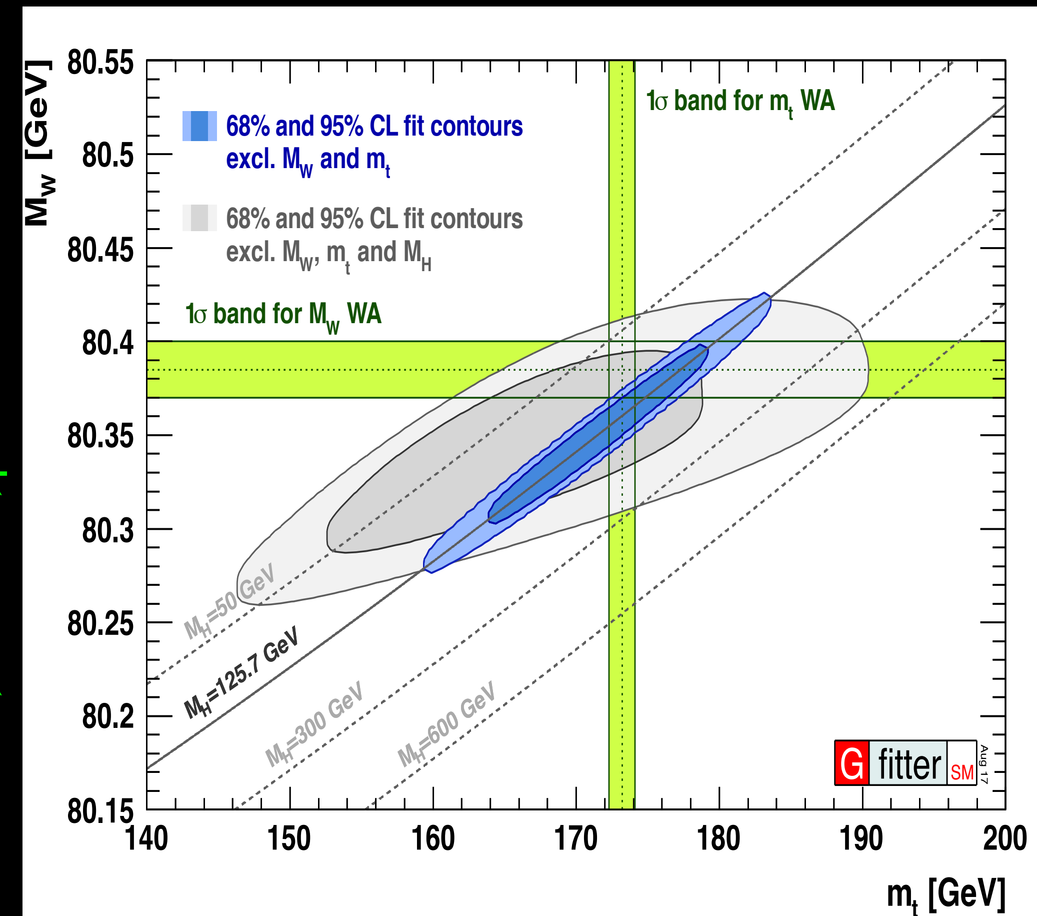
  - kinematic reconstruction from uncolored final state
  - sensitive to hadronisation effects (color reconnection...)
  - ➡ determine running mass ($\overline{\text{MS}}$-scheme) from CDF/DO top pair cross-section at NNLO, yields:

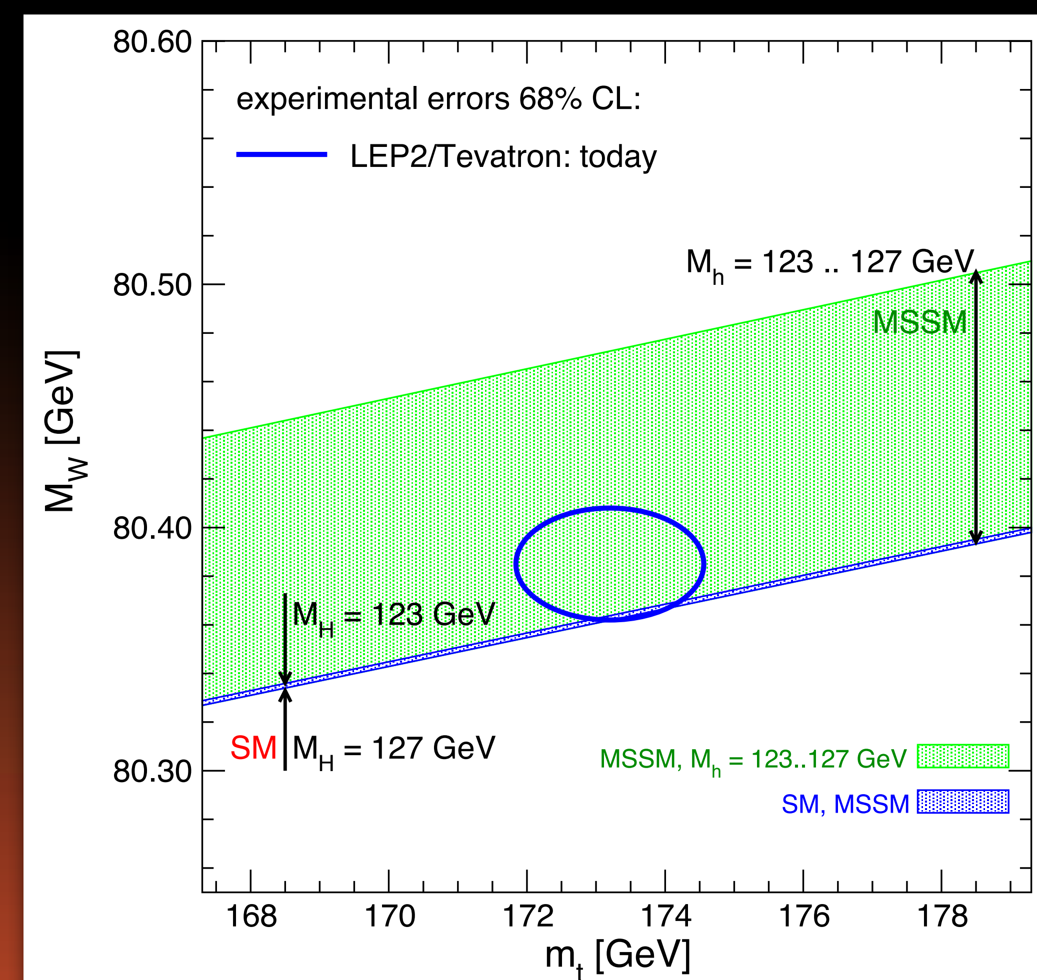
$$m_{pole} = 173.3 \pm 2.8\, GeV$$

  - close to world average, factor 4 larger uncertainty
  - PDF and α_s uncertainties currently limiting for LHC, may be reduced in the future ?

Alekhin, Djouadi, Moch, arXiv:1207.0980v2

Baak et al., GFITTER, private communication



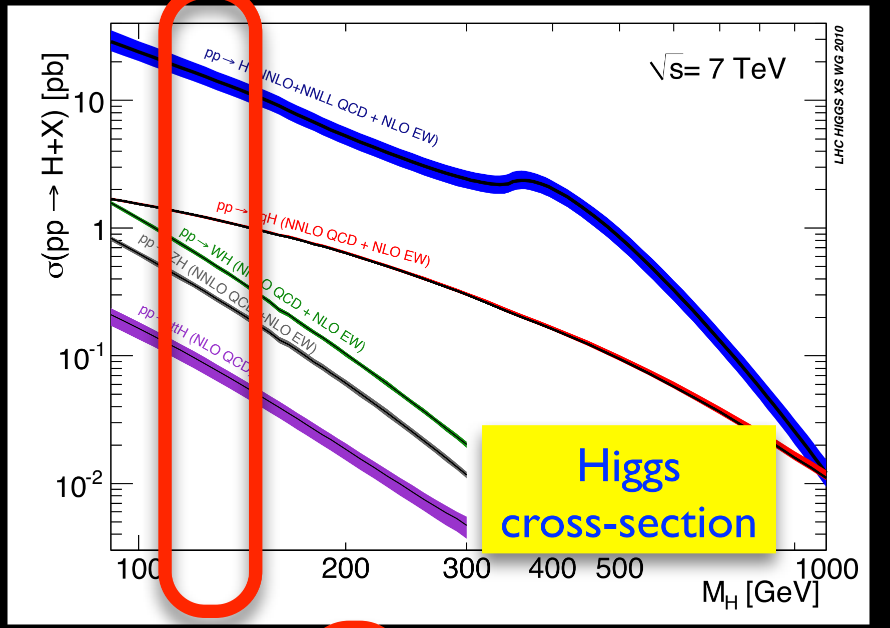


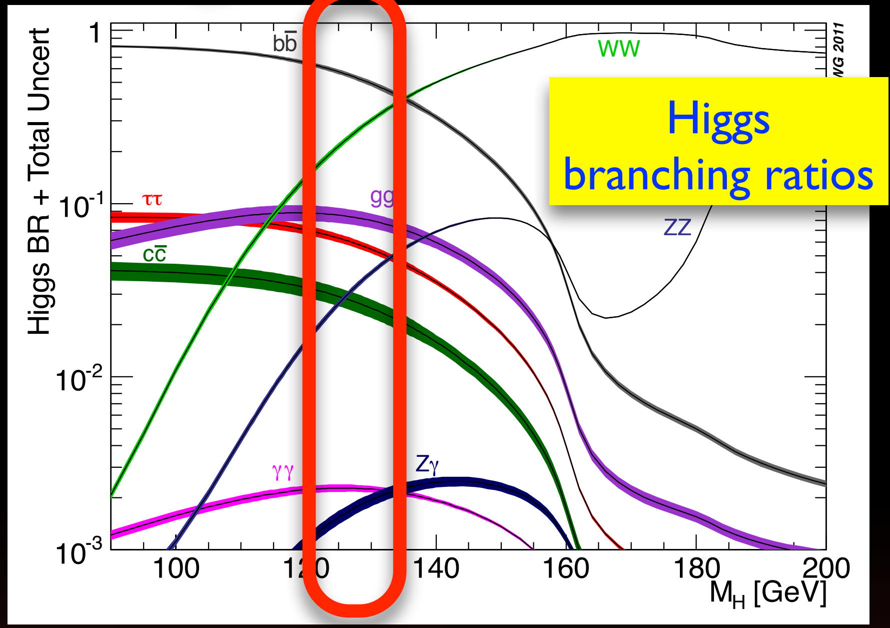
Heinemeyer, Hollik, Stockinger, Weiglein, Zeune

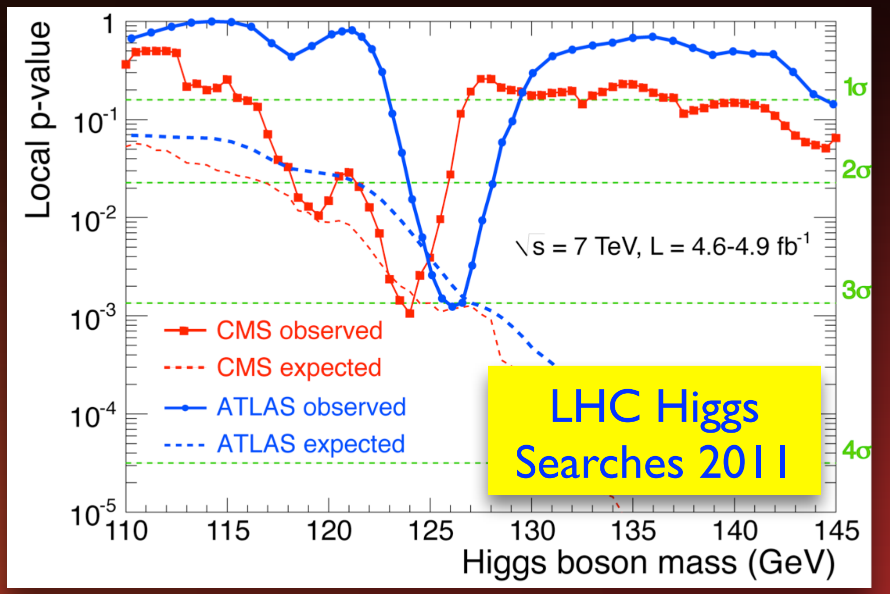
Searches for the SM Higgs

- SM Higgs phenomenology
  - ➡ precisely predicted, but Higgs mass
    - NLO and NNLO calculations (typical σ ~ 5-15%)
    - production dominated by gg fusion, then vector boson fusion (VBF), associated WH and ZH
  - ➡ cross-section and branching ratios are strong function of M_H
- Higgs searches in 2011 data
  - ➡ both experiments saw hints for a light Higgs
    - around ~*3σ* each, ignoring “look elsewhere effect”
    - indications as well in TEVATRON data
  - ➡ low mass region at LHC
    - many decay modes accessible (γγ,ZZ,WW,ττ,$b\bar{b}$)
    - γγ and ZZ yield excellent mass resolution (~1%)
  - ➡ challenging to control backgrounds, except for ZZ
- experiments “blinded“ their 2012 data
  - ➡ huge effort to optimize expected sensitivity (pileup)
  - ➡ and re-optimized analysis on published 2011 data
  - ➡ results updated using 2012 data (*8 TeV*) up to ICHEP

LHC Higgs XS Working Group







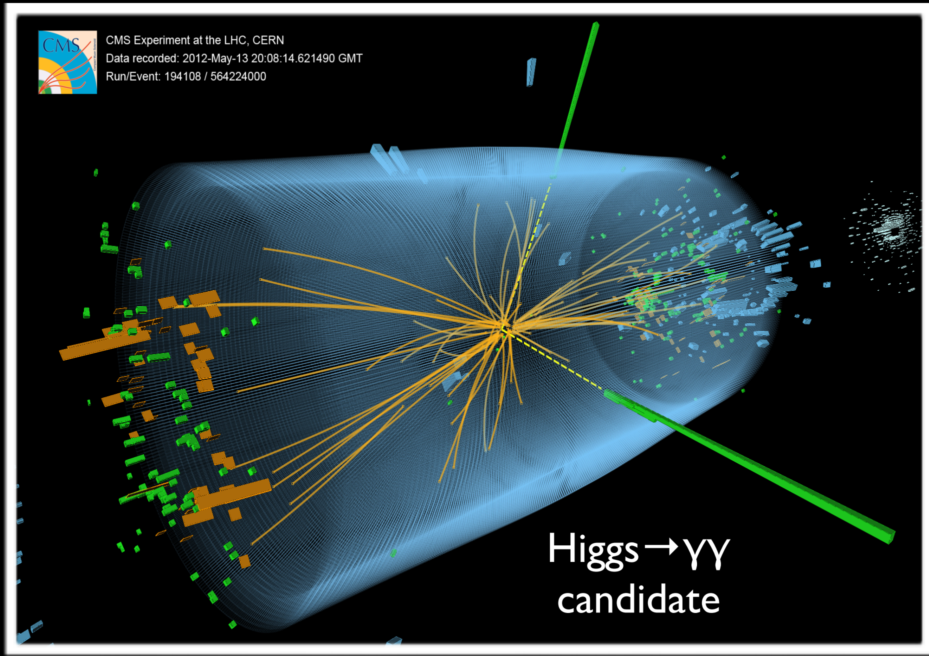
M.E., for illustration

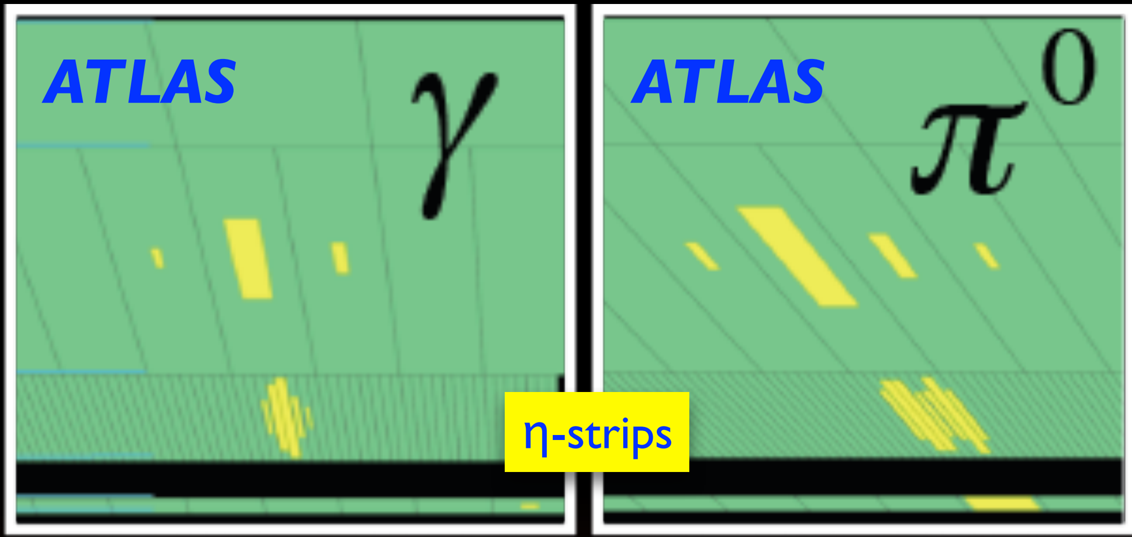
Overview: Higgs→γγ

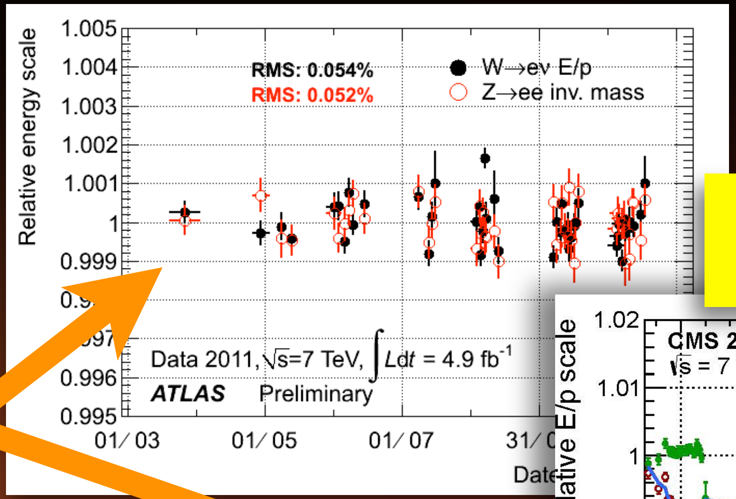
- experimental signature
  - ➡ 2 isolated photons $p_T > 40, 30$ *GeV with* $\varepsilon \sim 40\%$
  - ➡ expect ~*200* events at *S/B~3%*
- huge background
  - ➡ <u>irreducible:</u> continuum di-photons
  - ➡ <u>reducible:</u> mis-identified jets (π^0)
- sophisticated photon ID
  - ➡ shower shapes (especially ATLAS) and isolation yields: *bkg(γ+jet/γγ)~20%*
- excellent mass resolution

$$M_h^2 = 2E_1E_2\left(1-\cos\theta_{12}\right)$$

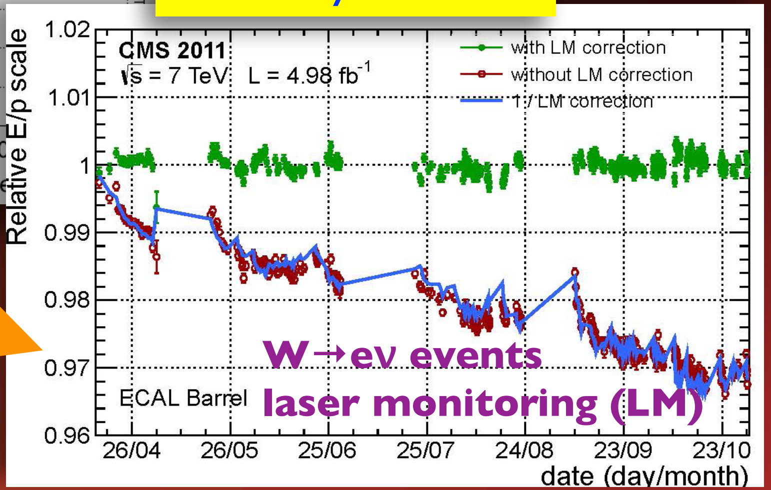
  - ➡ energies from precise shower calibration
  - ➡ angle from direction to primary vertex
    - CMS: sophisticated primary vertex tagging
    - ATLAS: ability to use photon pointing





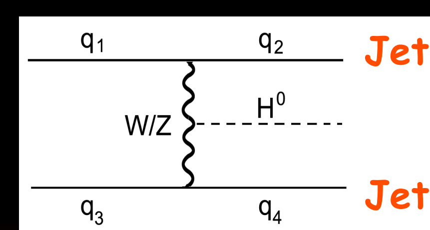


EM response stability vs time

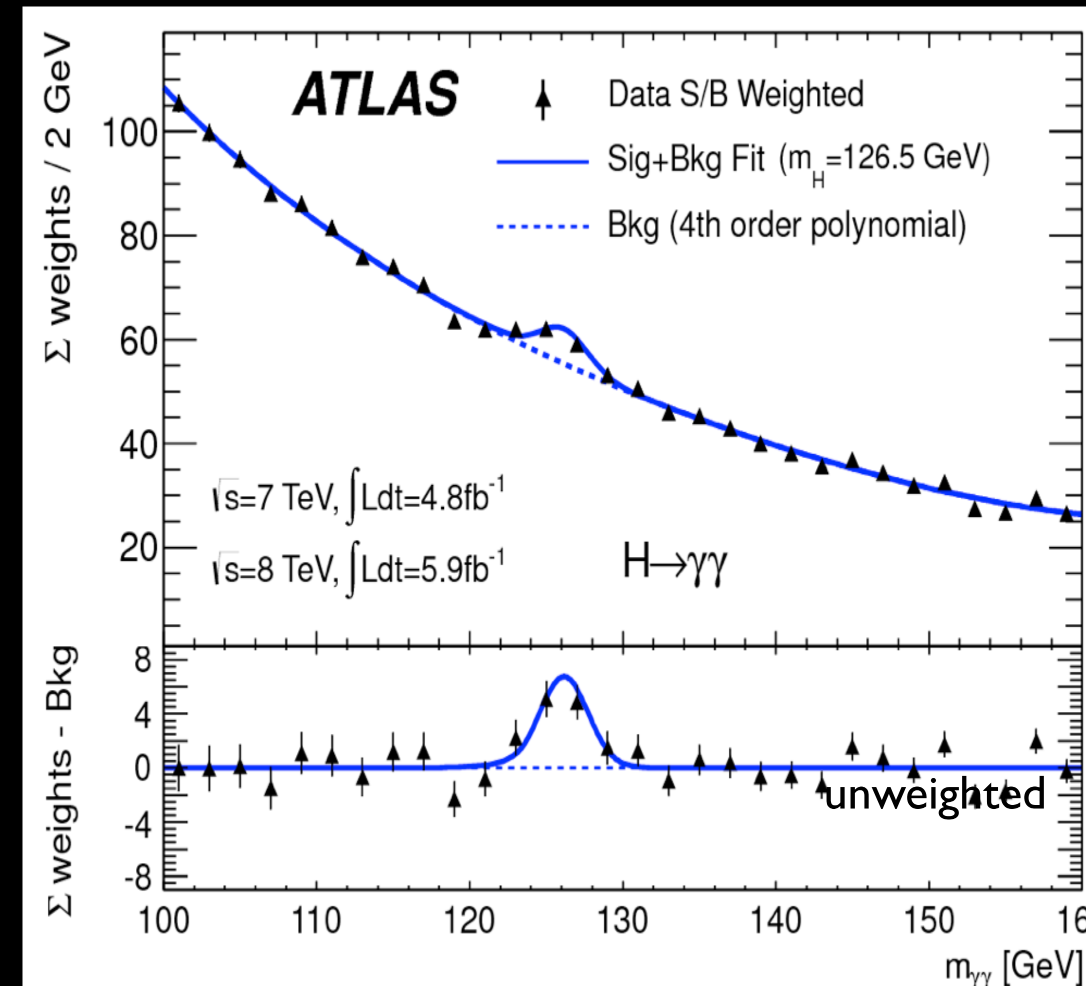


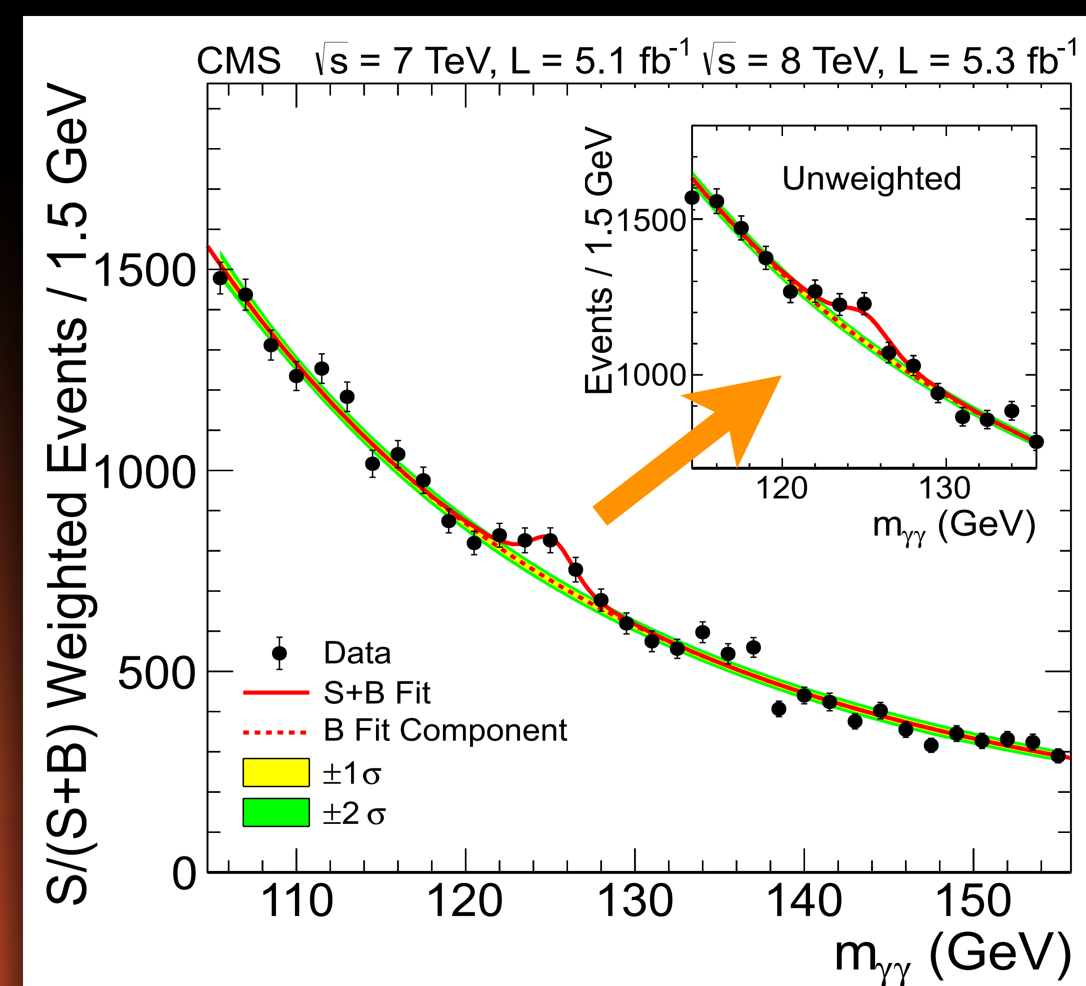
Signals: Higgs→γγ

- maximize expected sensitivity
  - ➡ separate events into categories with different *S/B* and mass resolution
    - ATLAS uses 9 classes according to *η*, conversions, p_{Tt}
    - CMS uses 4 classes from MVA combining all information
  - ➡ separate VBF channel
    - tagged using 2 forward jets



- for illustration only
  - ➡ combined signals from all classes, events weighted using expected *S/B*
- extract signal from a set of fits
  - ➡ background shapes in each class taken from data (!) using sidebands



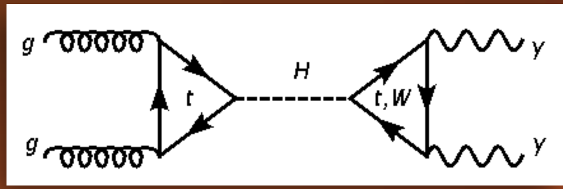


Results: Higgs→γγ

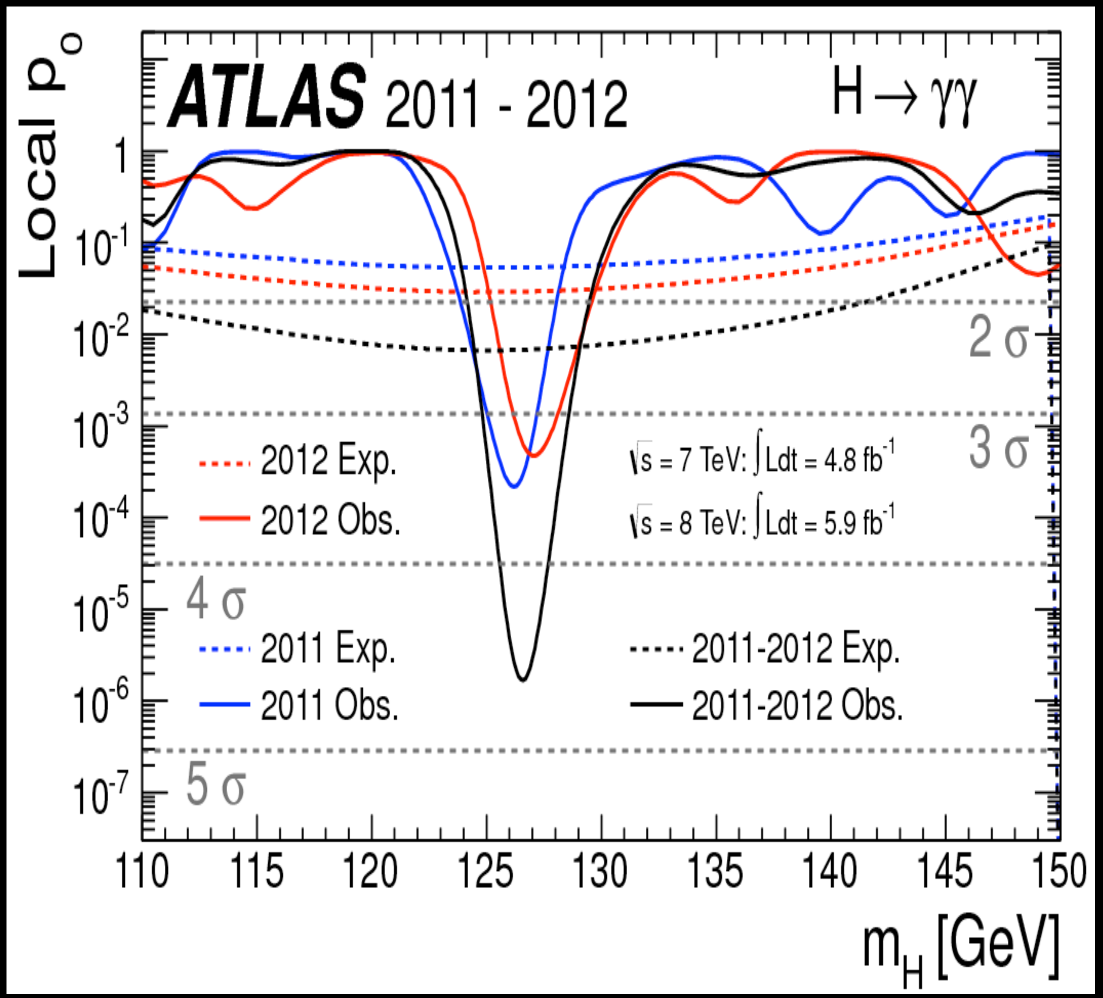
- combined *7 TeV* and *8 TeV* results:

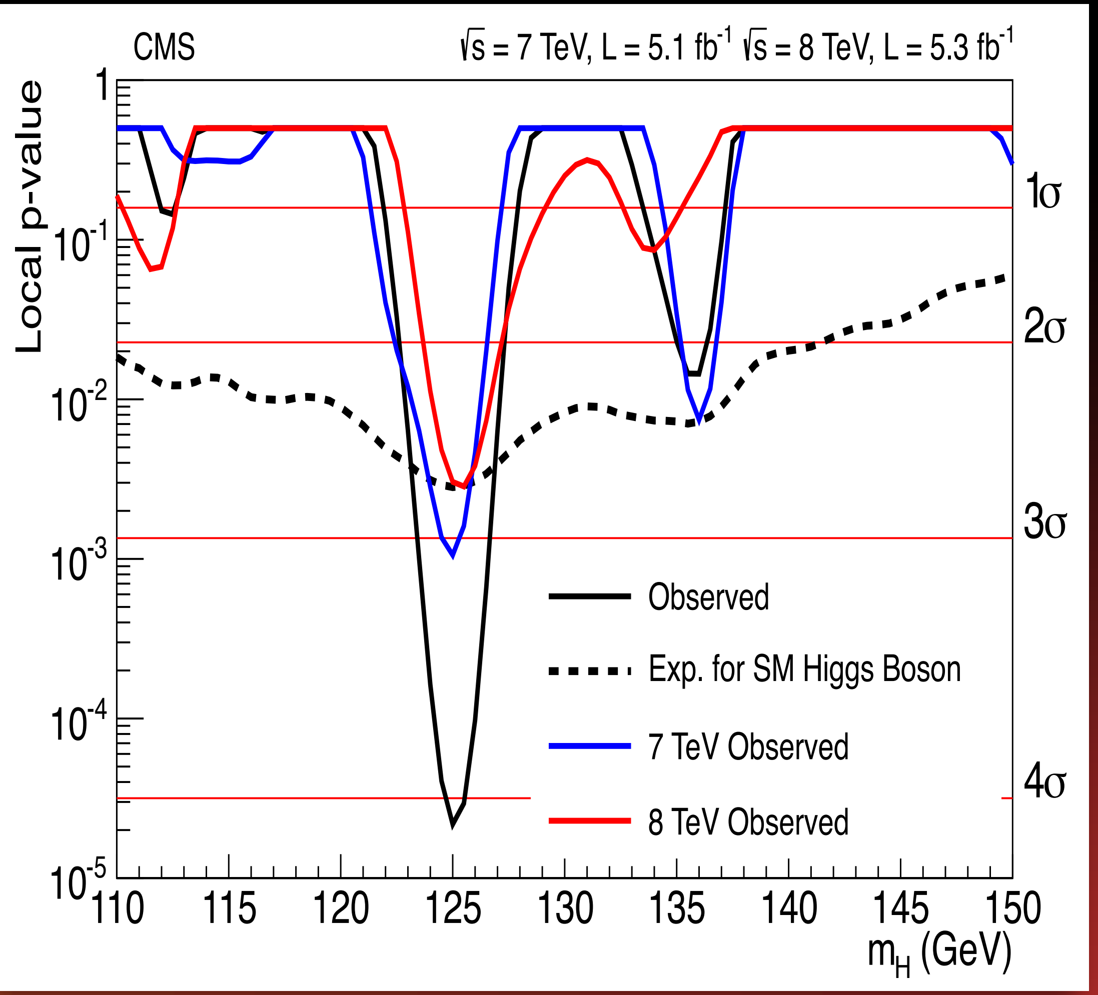
	ATLAS	CMS
M_h(min p_0)	126.5 GeV	125 GeV
local significance	**4.5 σ obs.**	**4.1 σ obs.**
signal strength $\mu=\sigma/\sigma_{SM}$	1.8±0.5	1.56±0.43

- new particle is a boson
  - ➡ it decays into γγ
  - ➡ probably not spin 1 (Landau Yang theorem)
- gg→Higgs→γγ
  - ➡ SM production and decay via loop processes

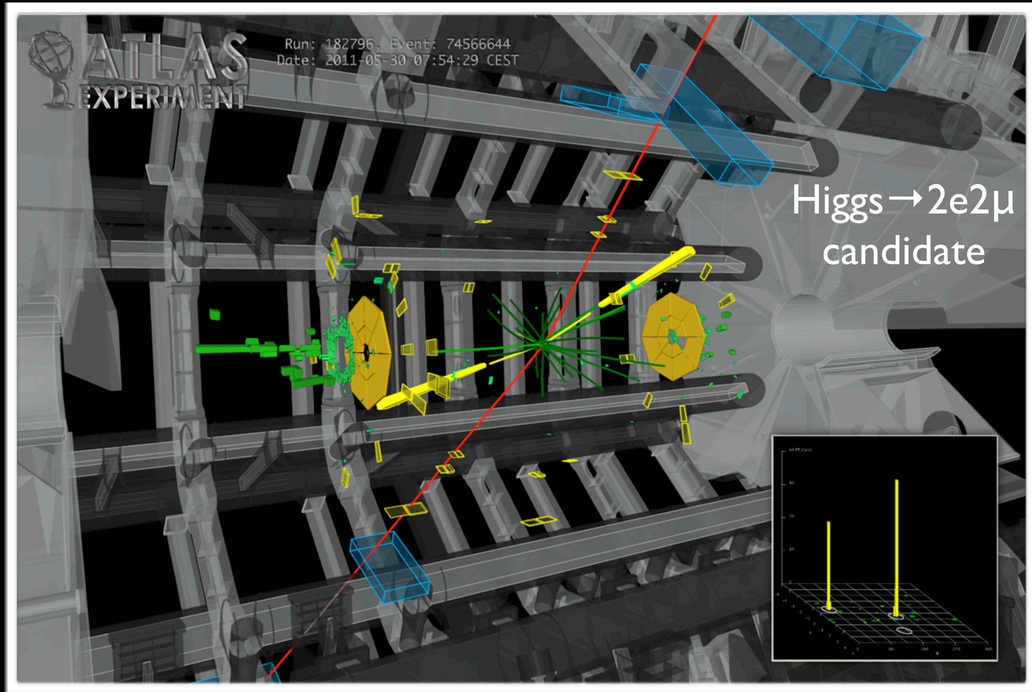


  - ➡ sensitive to t,W-couplings (and new physics)

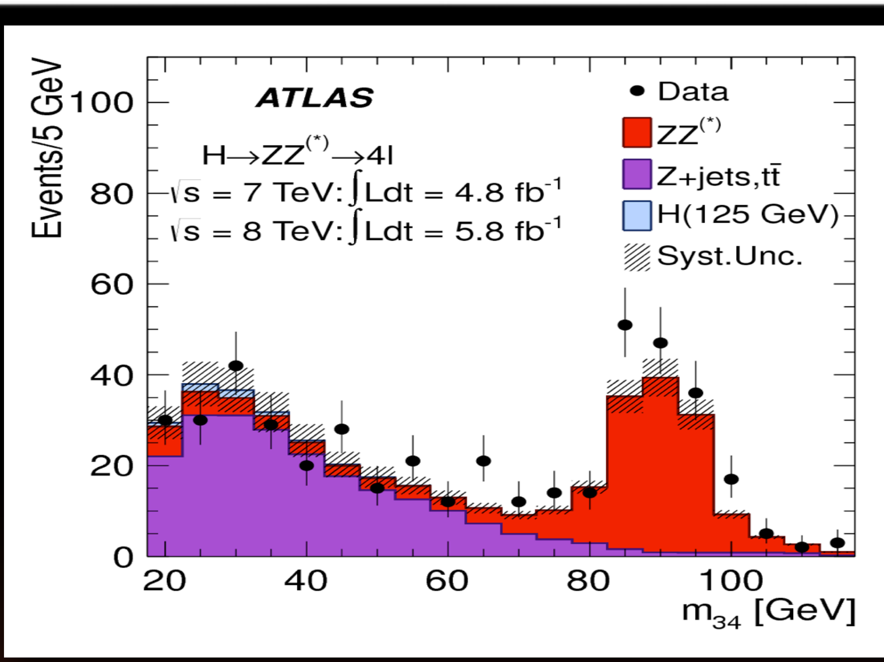




Overview: Higgs→ZZ*→4 l

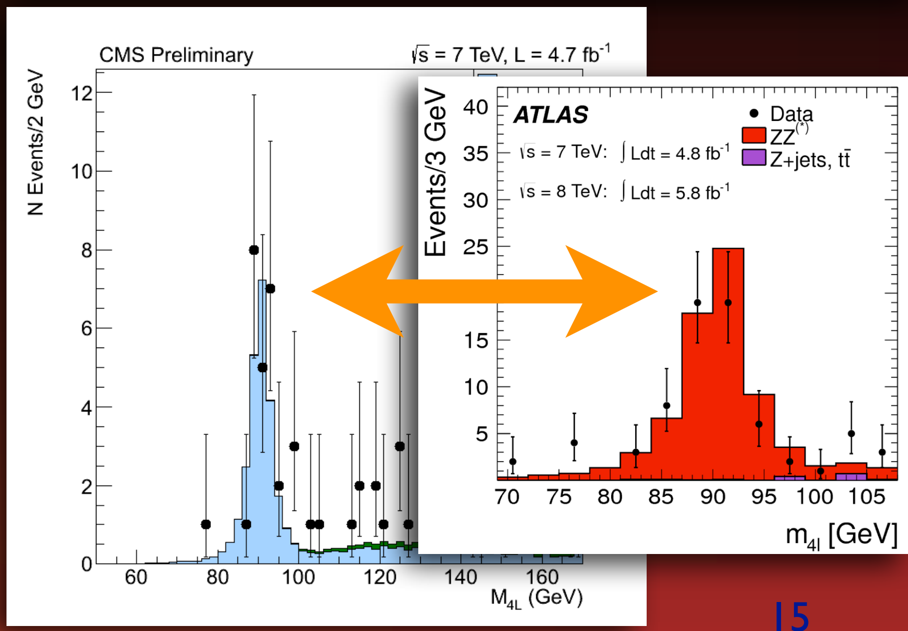


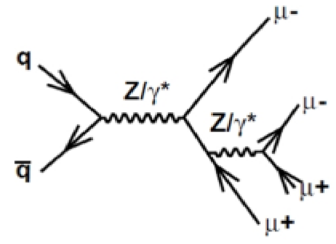
- experimental signature
  - ➡ isolated lepton pairs: 4e, 4μ, 2e2μ
  - ➡ golden channel:
    - few events, good *S/B*, good mass resolution
  - ➡ key: efficient lepton identification
    - performance improvements over shutdown
    - e.g. CMS: FSR γ recovery, ATLAS: μ *2.5<η<2.7*



- backgrounds
  - ➡ <u>irreducible:</u> continuum ZZ*/Zγ* production
    - shape from MC, measured ZZ cross section slightly above SM predictions (ATLAS, CMS)
  - ➡ <u>reducible:</u> Z+bb̄/jets, tt̄ (low mass)
    - estimate from data using control regions

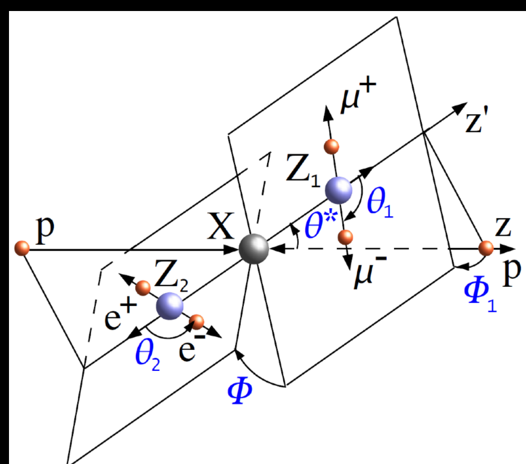
- check: ATLAS+CMS observe Z→4l

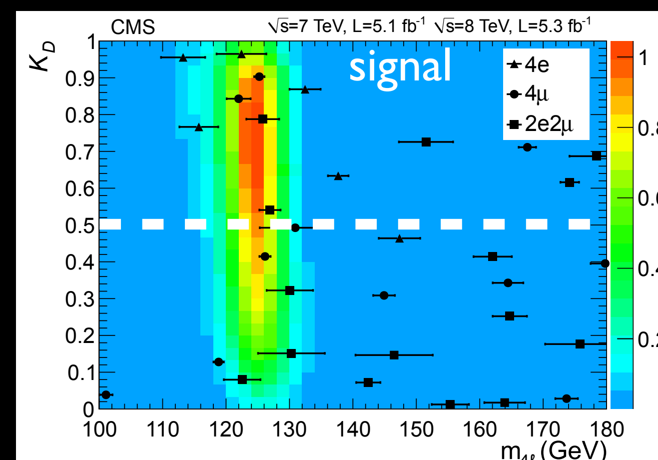




Signals: Higgs→ZZ*→4 l

- CMS: 2D fit for signal extraction
  - ➡ matrix element likelihood analysis (MELA) to separate signal and background

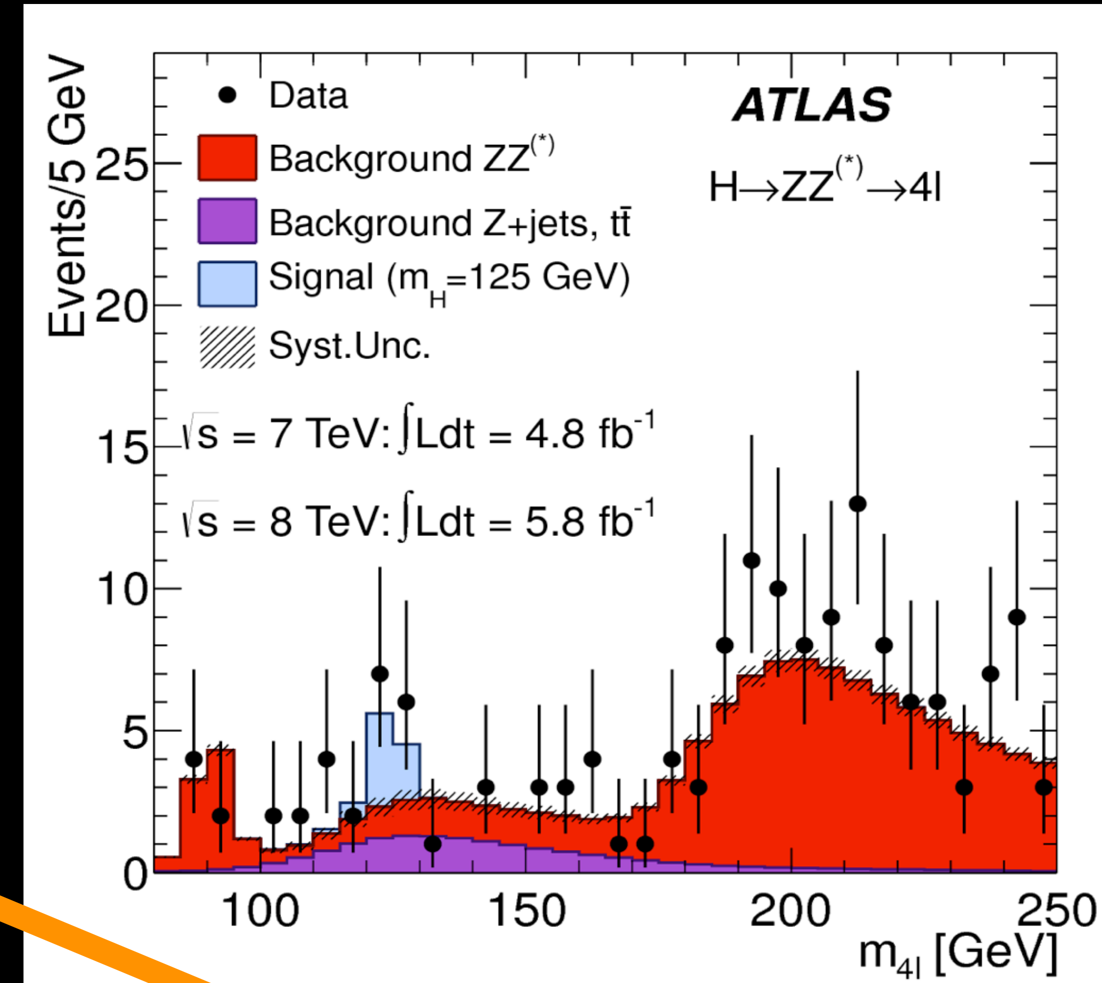


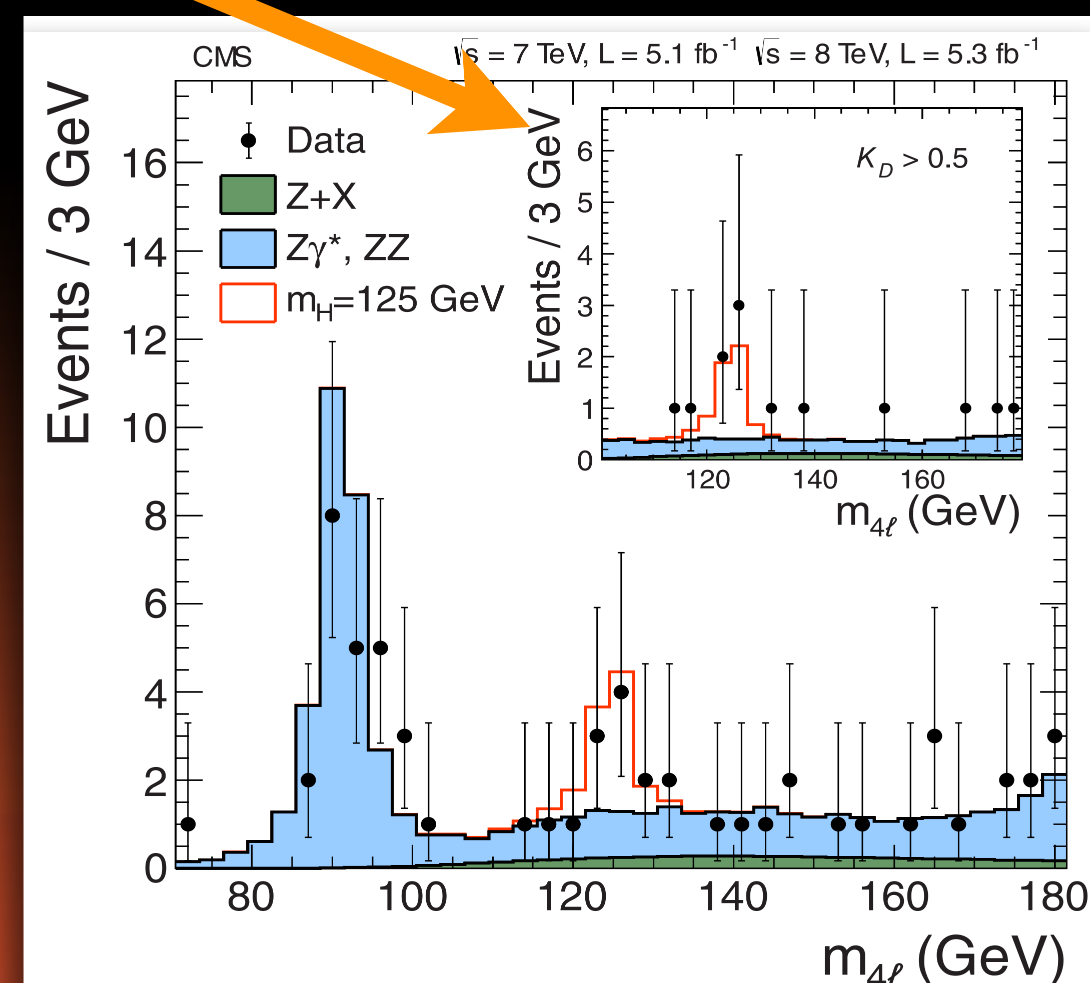


- events in signal region (~125 GeV)

CMS	4e	2e2μ	4μ	4l
exp. bkg	0.7±0.2	1.9±0.3	1.3±0.1	3.8±0.5
exp. sign	1.36±0.22	3.44±0.44	2.74±0.32	7.54±0.78
obs.	1	5	3	9

ATLAS	4e	2e2μ	4μ	4l
exp. bkg	1.53±0.21	2.07±0.20	1.25±0.07	4.85
exp. sign	0.90±0.14	2.29±0.33	2.09±0.30	5.28
obs.	2	5	6	13

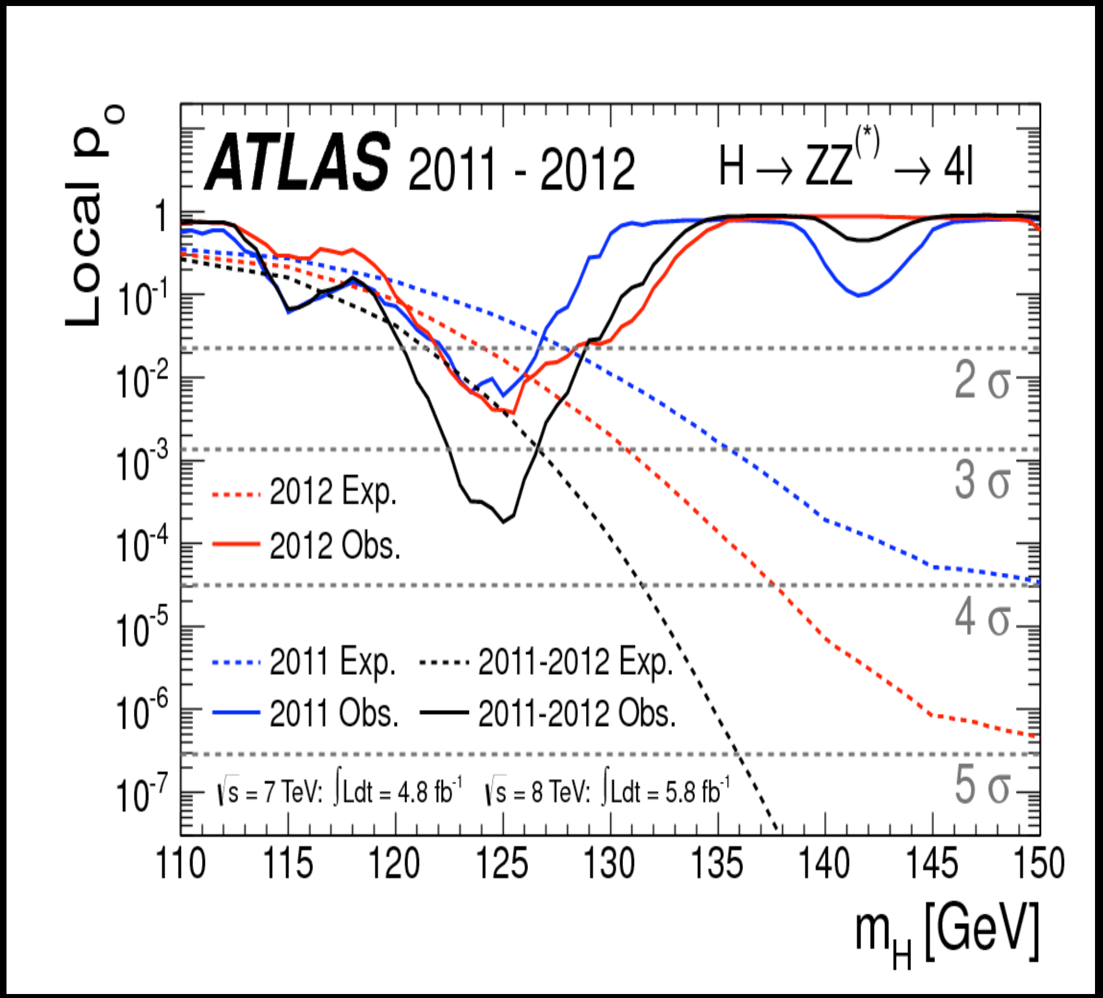


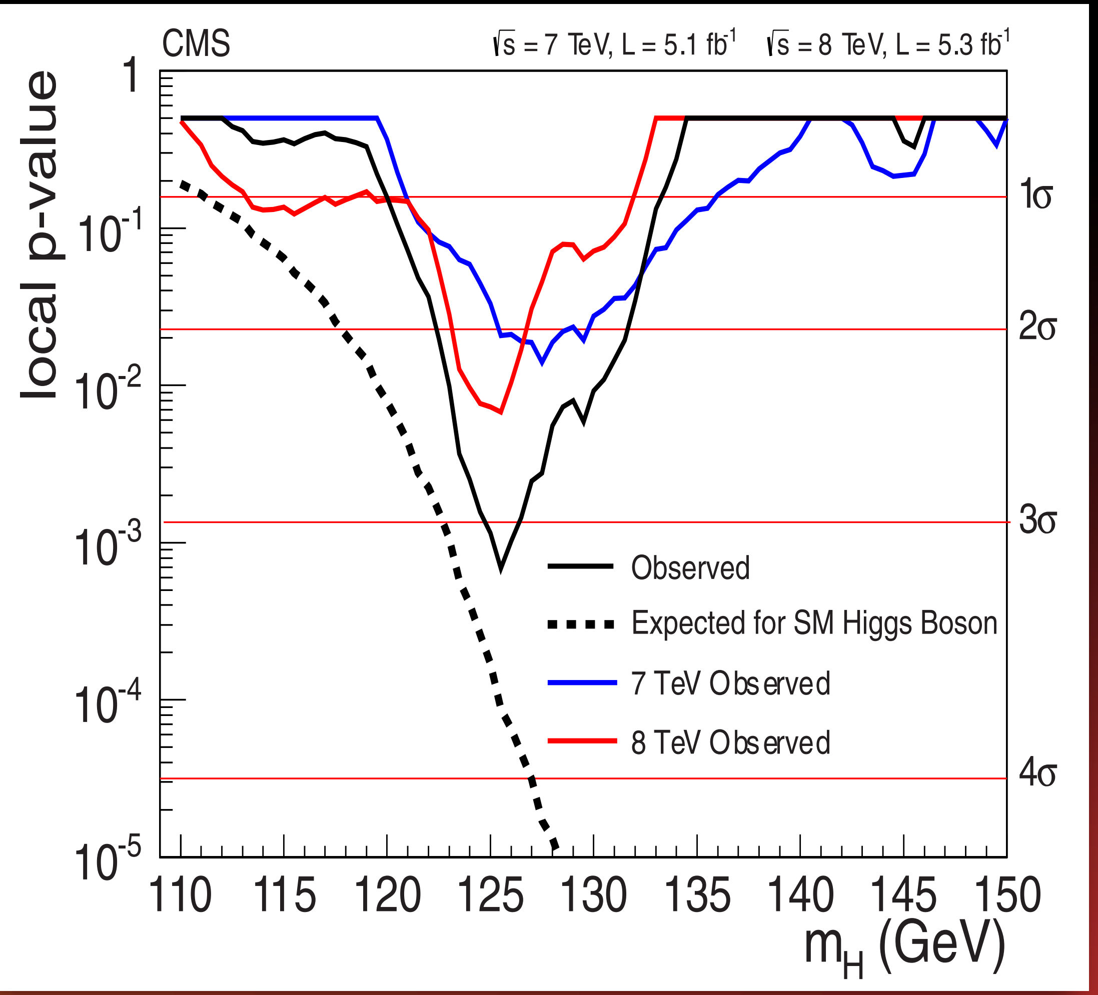


Results: Higgs→ZZ*→4 l

- combined *7 TeV* and *8 TeV* results:

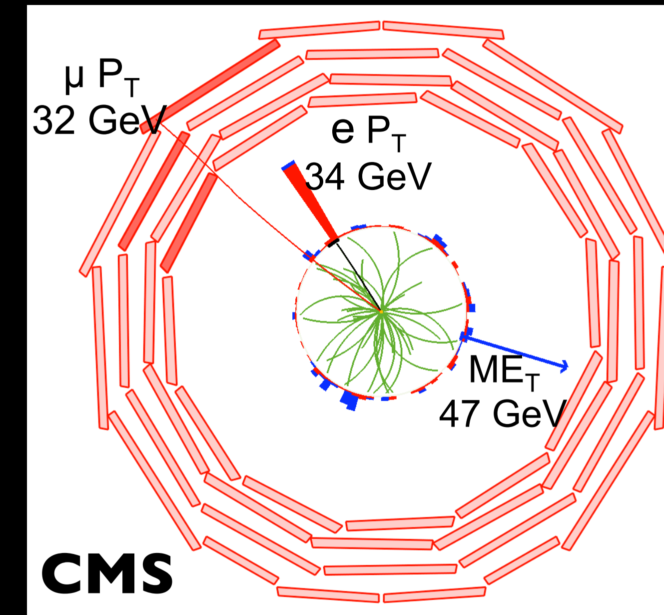
	ATLAS	CMS
M_h(min p_0)	125 GeV	125.6 GeV
local significance	**3.6 σ** obs.	**3.2 σ** obs.
	2.7 σ exp.	3.8 σ exp.
signal strength $\mu=\sigma/\sigma_{SM}$	1.4±0.6	$0.7^{+0.4}_{-0.3}$

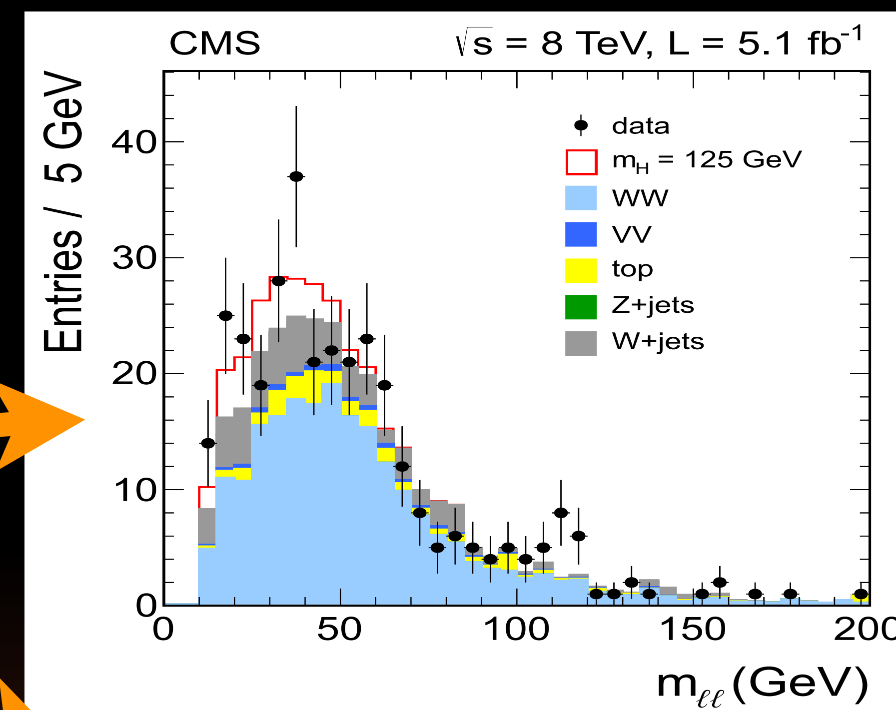


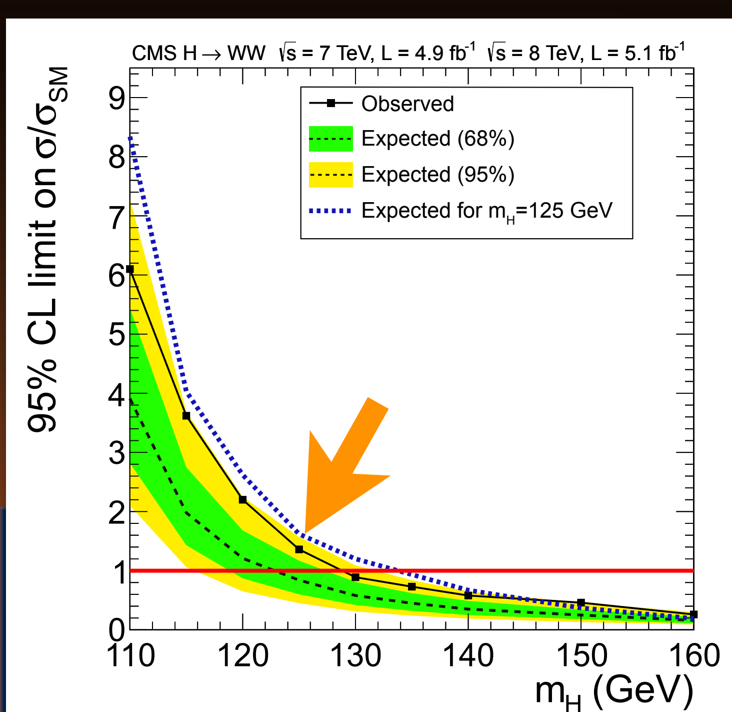


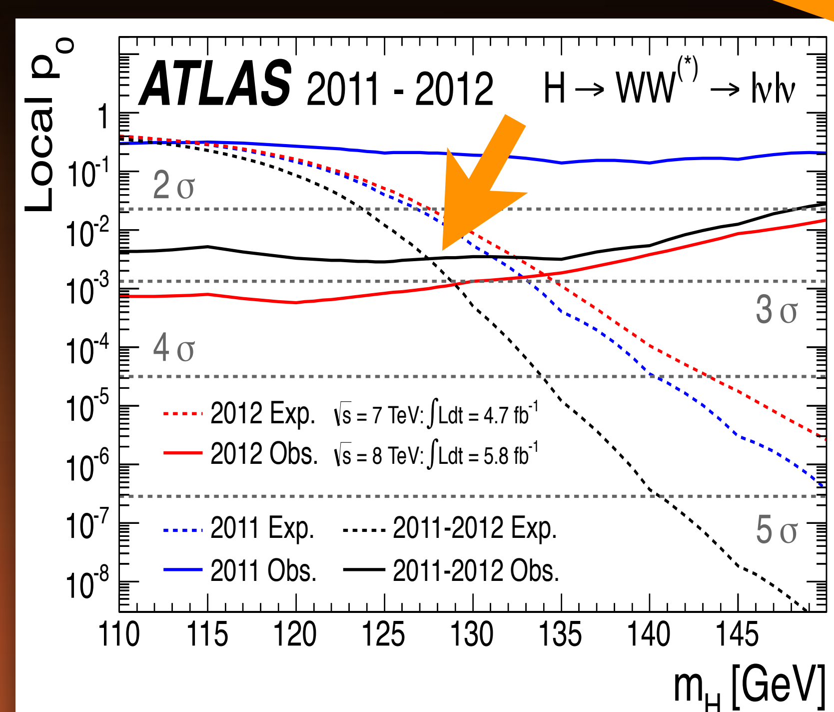
Higgs→WW→2l2ν

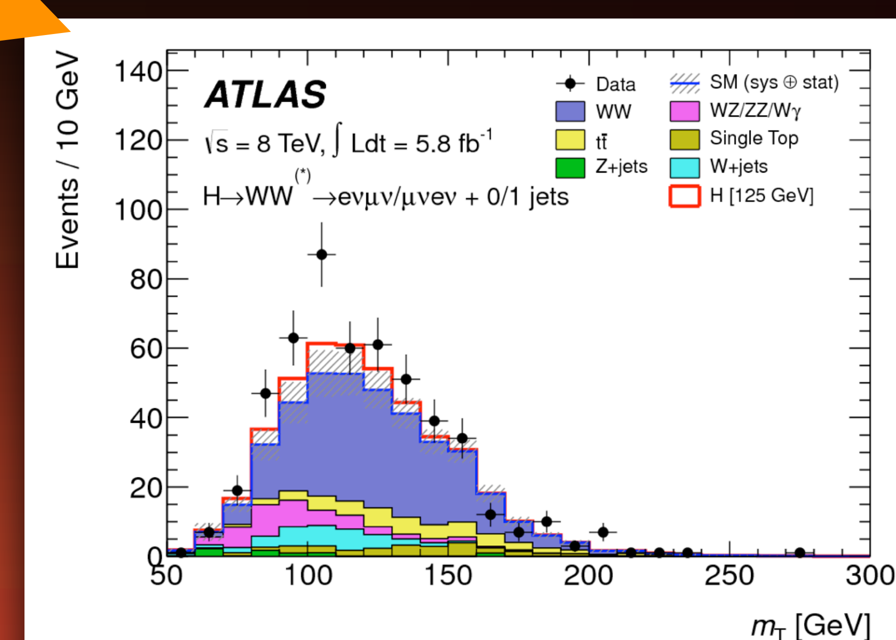
- experimental signature
  - ➡ 2 isolate leptons (e, μ), missing E_T, 0-2 jets (VBF)
  - ➡ large BR, but limited mass resolution (±*15 GeV*)
- backgrounds vary vs jet multiplicity
  - ➡ mostly $t\bar{t}$, irreducible WW, W/Z+jets
  - ➡ kinematic selection ($\Delta\phi_{ll}$, m_{ll}), b-tag veto (top)
- broad access compatible with SM
  - ➡ CMS updated ee, μμ and eμ with 2012 data
  - ➡ ATLAS updated only eμ
    - less sensitive to Drell-Yan at large pileup







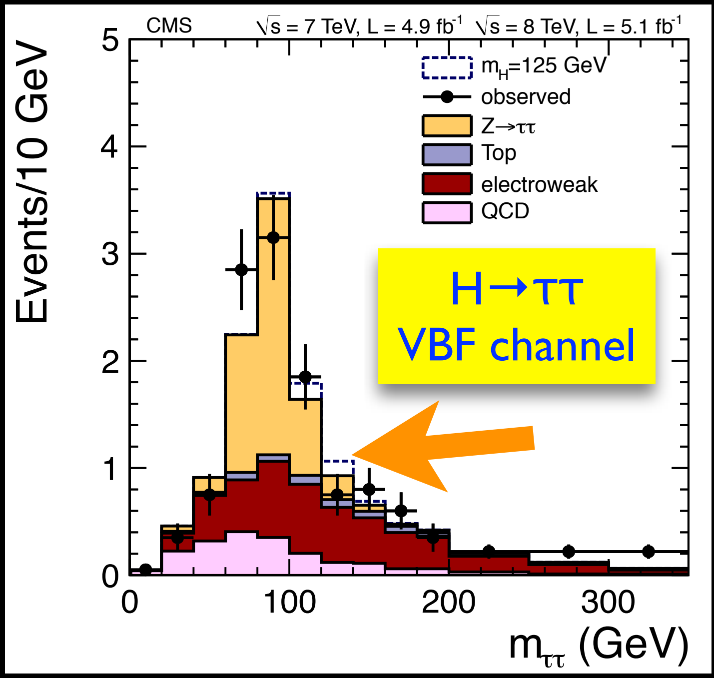


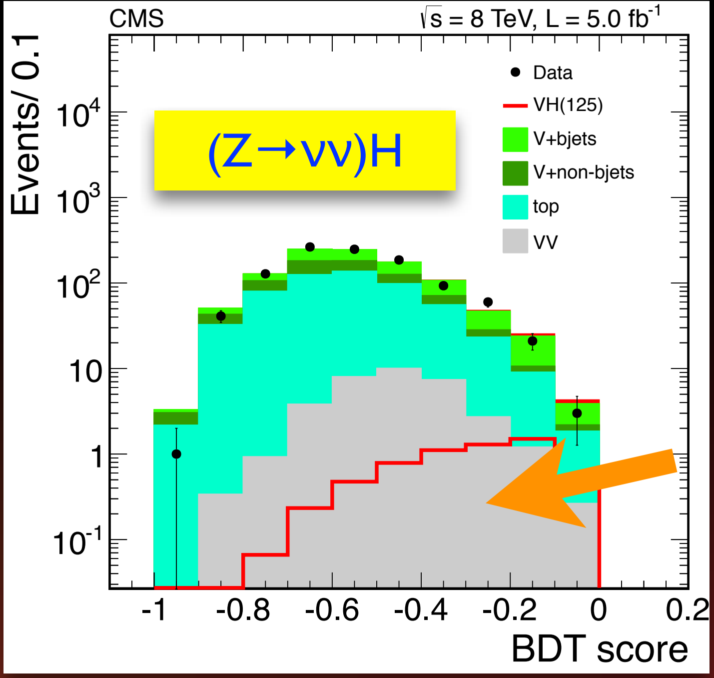


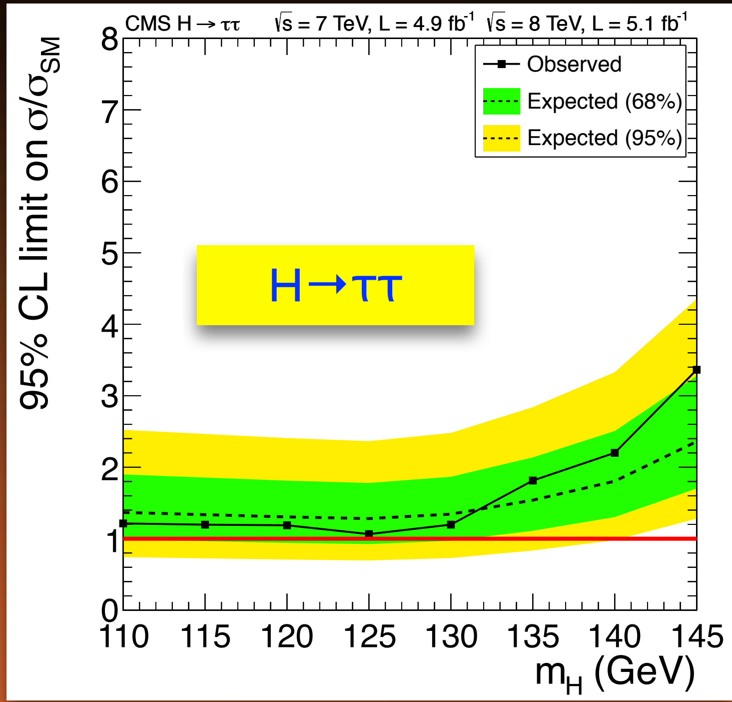
for completeness

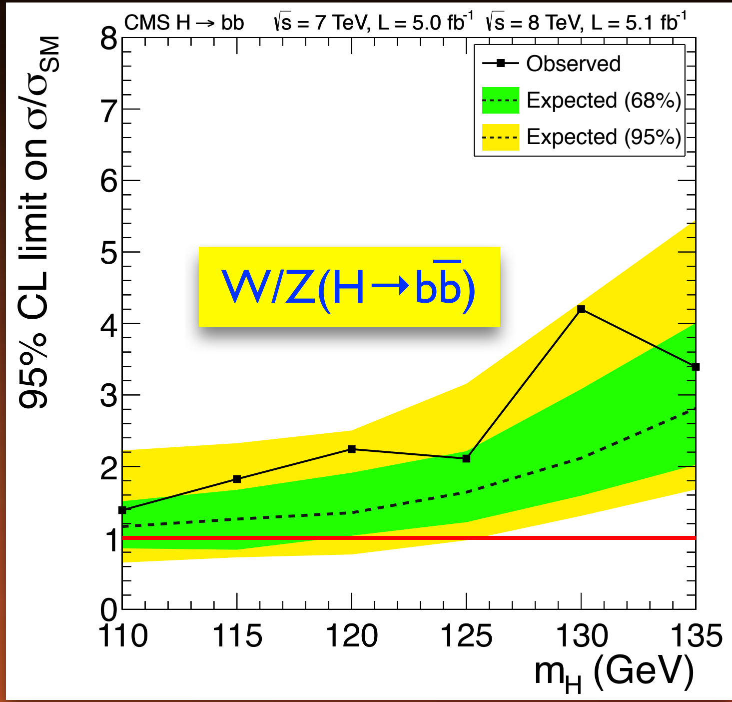
Higgs→ττ and W/Z(H→$b\bar{b}$)

- CMS updated both with 2012 data
  - ➡ Higgs→ττ in 4 final states $\mu\tau_h$, $e\tau_h$, eμ, uu
    - challenging large backgrounds (DY→ττ, W+jets, QCD)
    - VBF most sensitive, split others by 0/1 jet and low/high p_T
  - ➡ W/Z(H→$b\bar{b}$) in 3 final states (Z→ll)H, (W→lν)H, (Z→νν)H
    - largest SM BR at low mass, but huge QCD background
    - search in association with W or Z
    - sophisticated MVA to extract signal
  - ➡ total expected limits in both channels close to SM (μ=1)
    - CMS improved sensitivities by 50% (70%) w.r.t. 2011
    - observed limits are close, needs more data





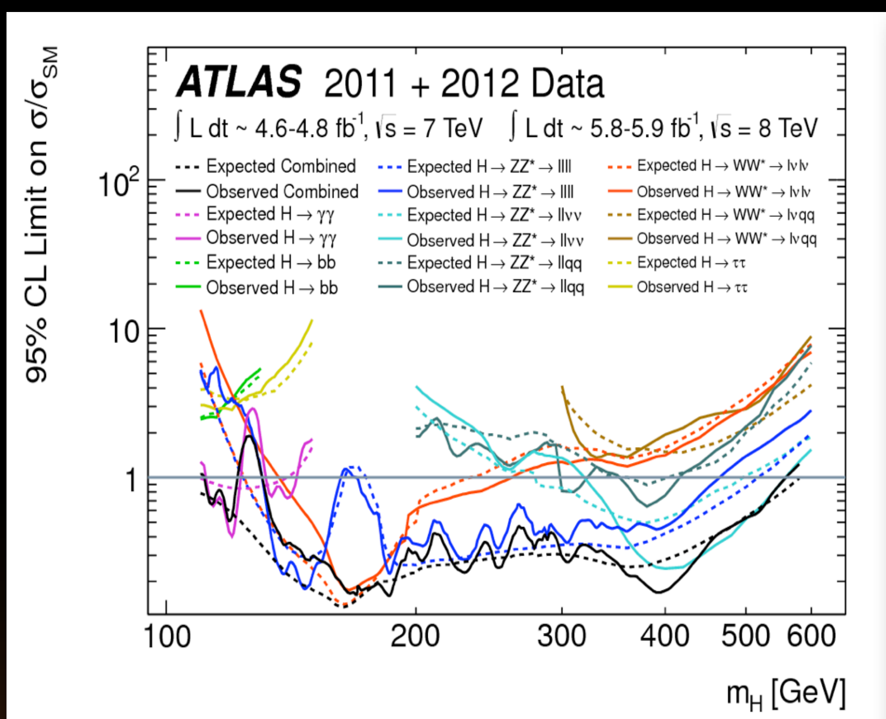


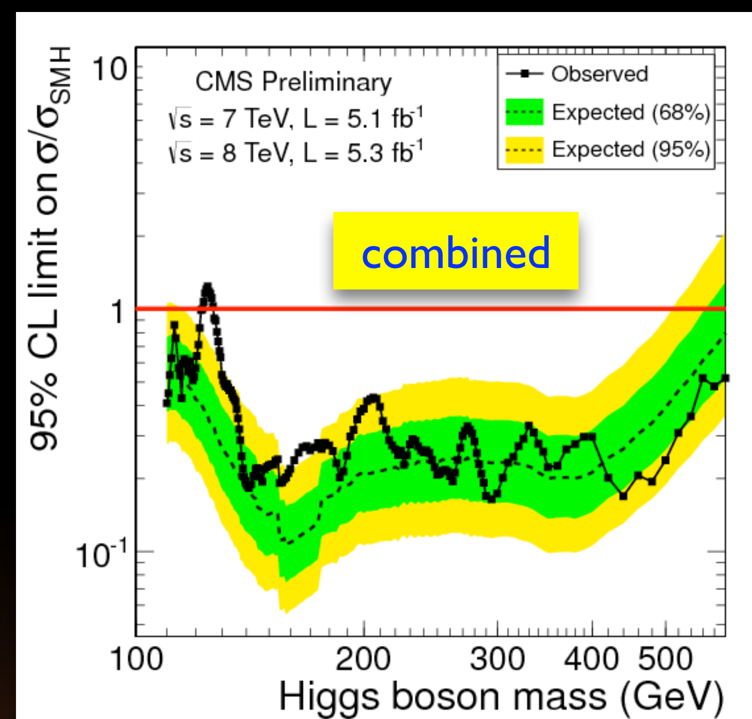


...ATLAS did not yet update their 2011 result with 2012 data, will be part of HCP updates in November

Putting All Together...

- full mass rage excluded, but window around *~125 GeV*
  - ➡ all channels, including those sensitive to high m_H





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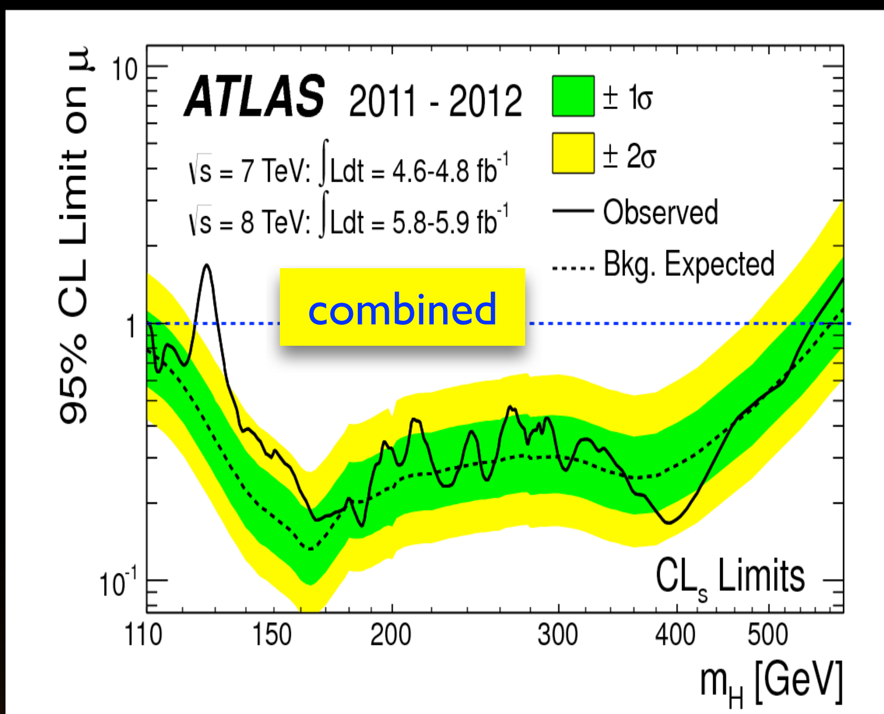
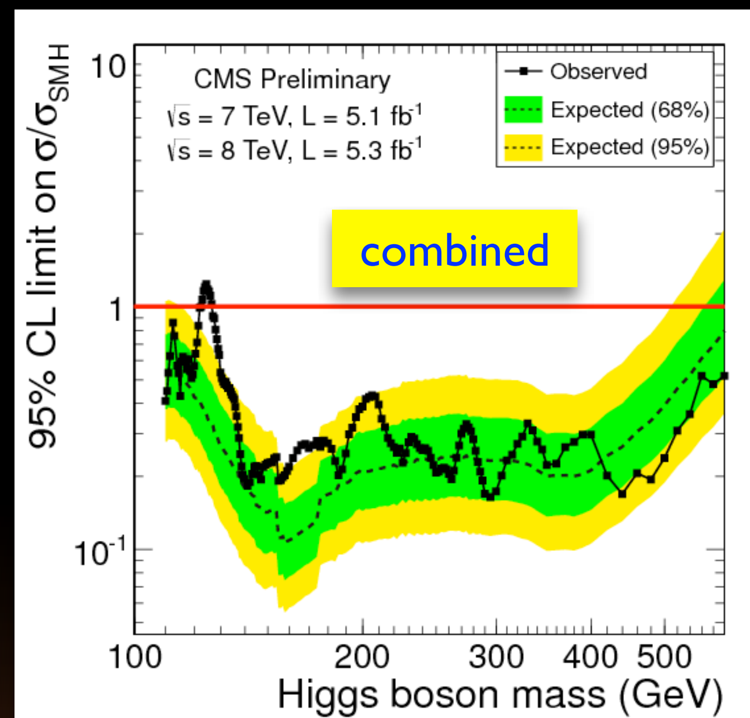
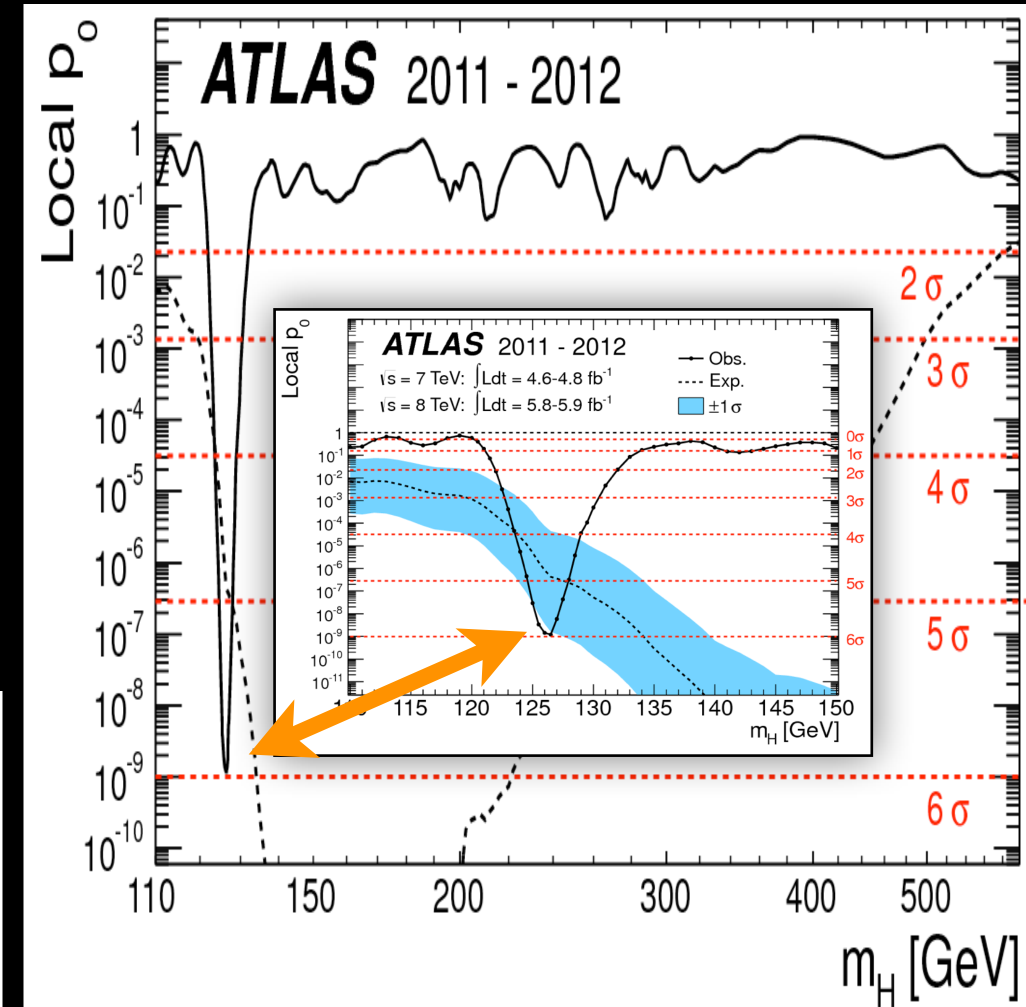
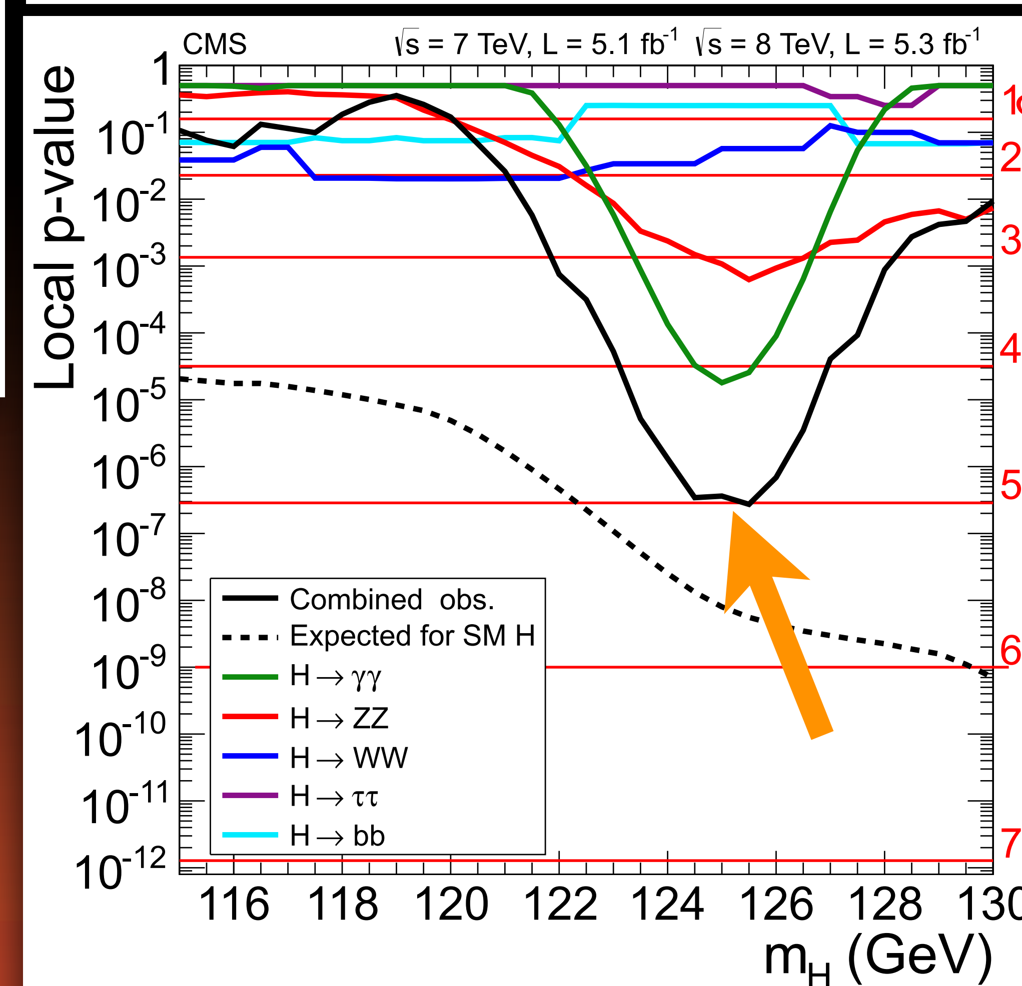








- local significance at min. p_0:

ATLAS	CMS
5.9 σ obs.	**5.0 σ obs.**
4.9 σ exp.	5.8 σ exp.

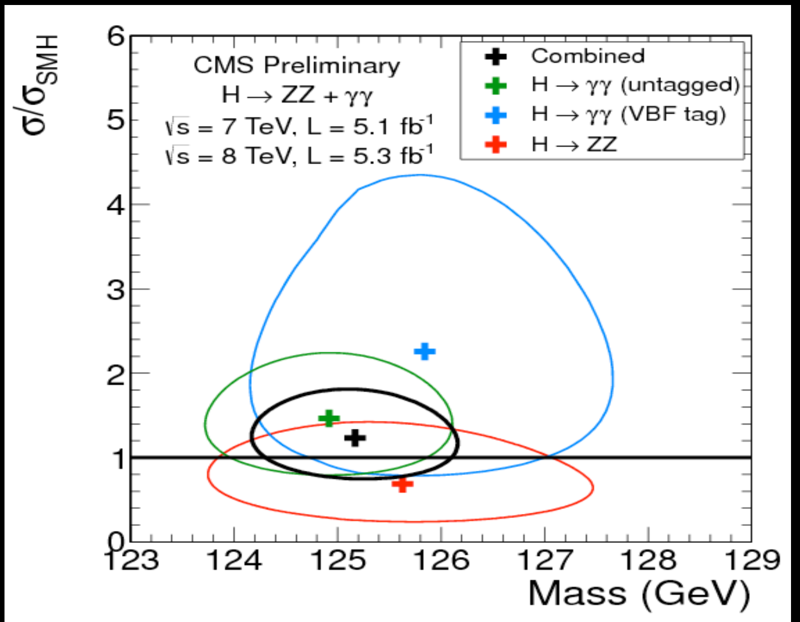
!

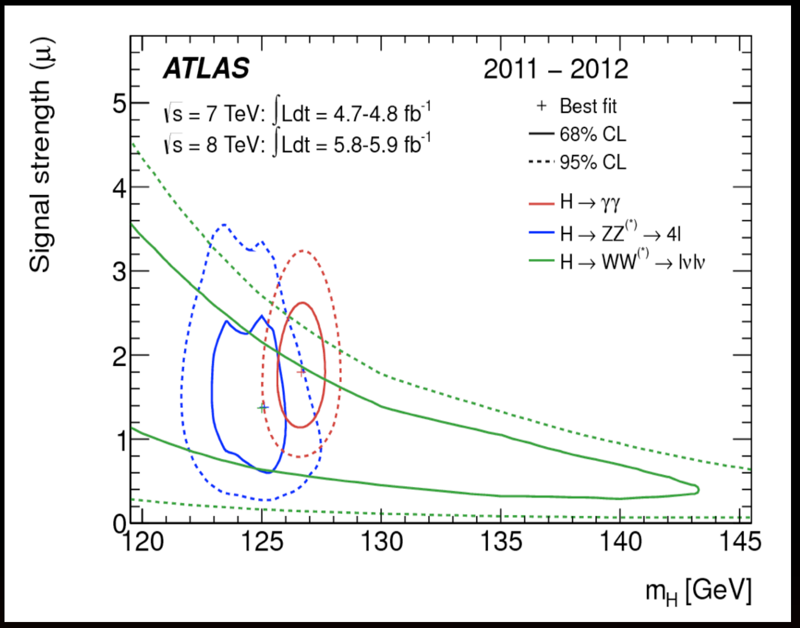
Properties of the New Particle

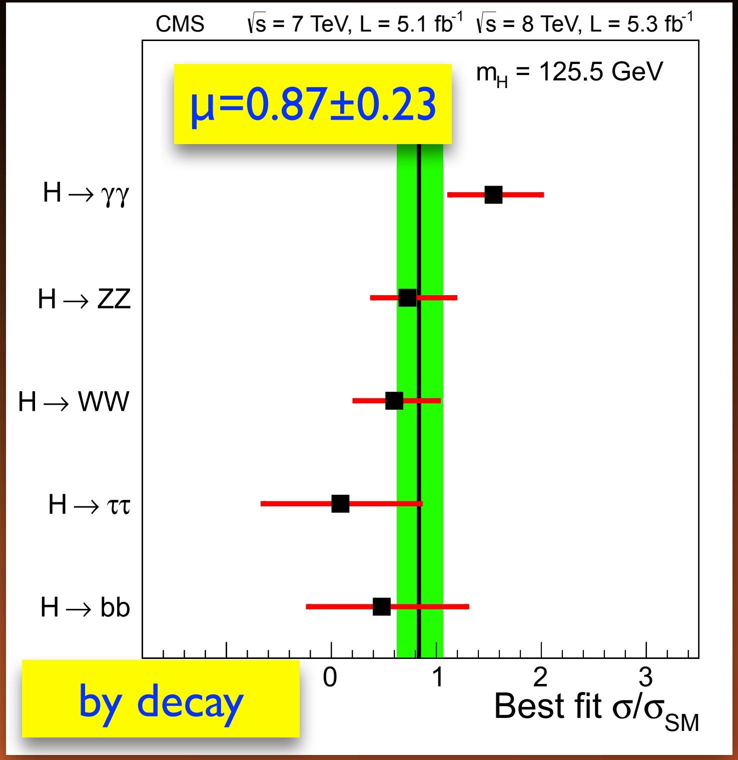
- establishing its nature: is it the SM Higgs ?
  - ➡ measure its mass, spin properties (J^{PC}), couplings, ...
  - ➡ it is a boson and probably not spin 1 ($H \rightarrow \gamma\gamma$)
- mass values:
  - ➡ naive average *125.7±0.4 GeV*

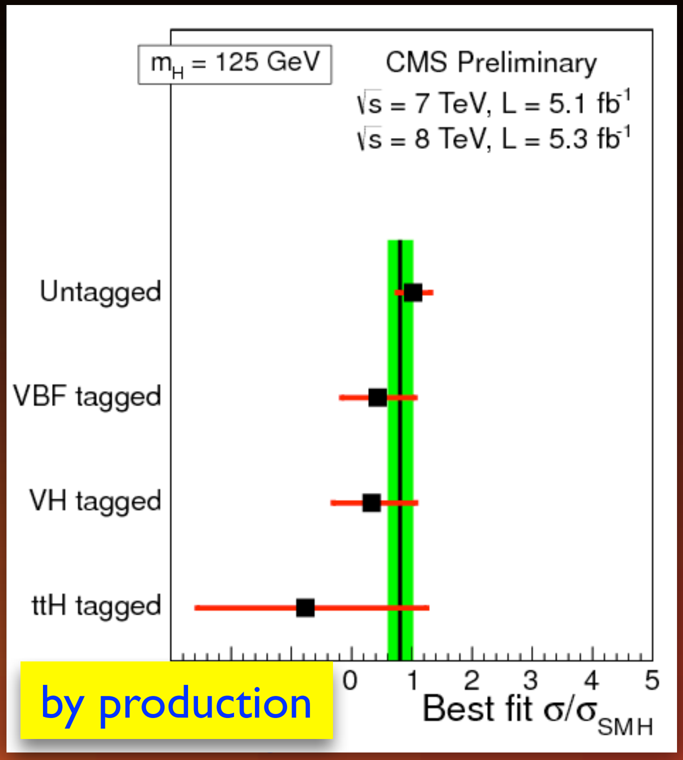
ATLAS	126.0±0.4±0.4 GeV
CMS	125.3±0.4±0.5 GeV

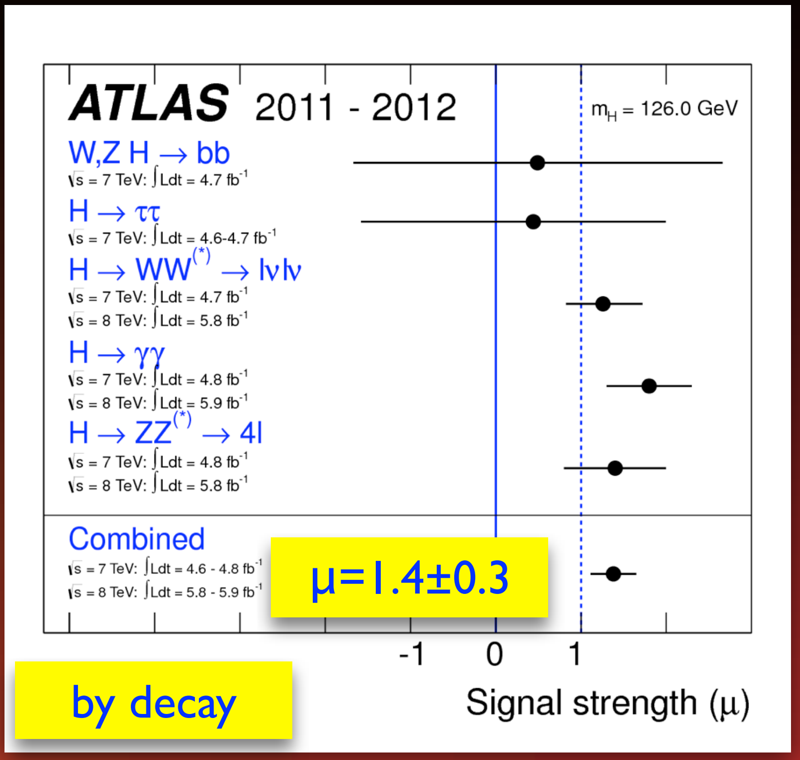
- experiments start to study couplings
  - ➡ disentangle decay and production properties







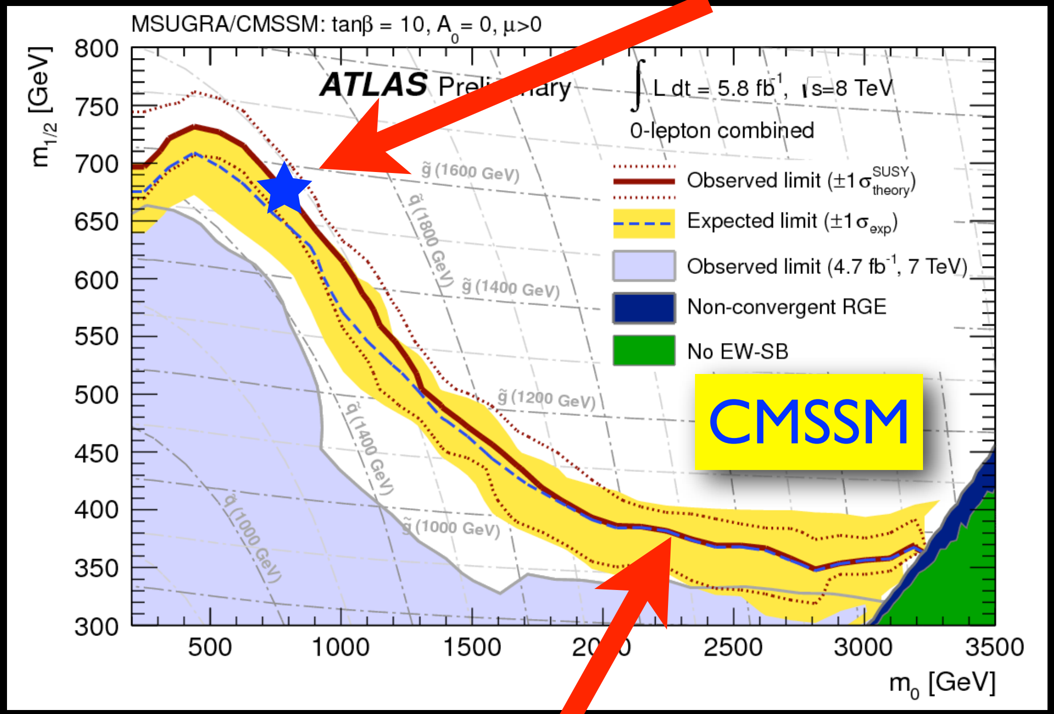




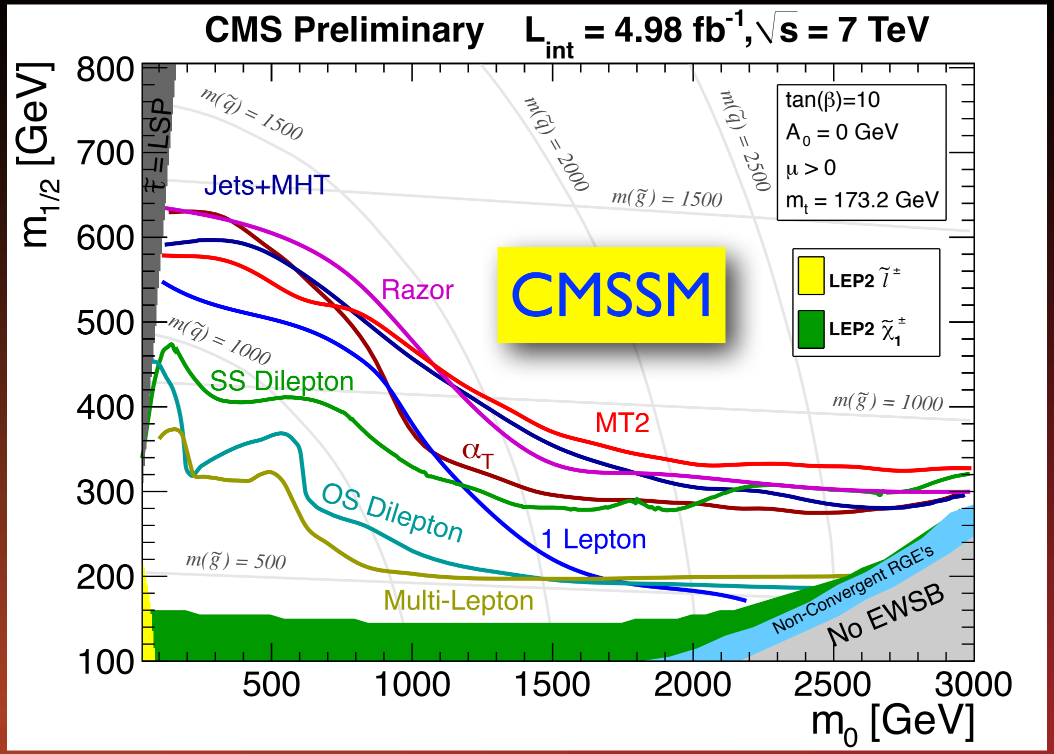
Searches for Supersymmetry

- motivations for (minimal) SUSY
  - ➡ provides solution for hierarchy problem
  - ➡ Higgs mechanism for EWSB is built in and predicts a light Higgs
  - ➡ unification of couplings
  - ➡ R-parity conservation: LSP is DM candidate
- SUSY is broken
  - ➡ plenty of SUSY breaking models (CMSSM, ...)
    - different sets of free SUSY parameters
    - each model has rich phenomenology
- recent results disfavor CMSSM
  - ➡ no light SUSY discovered (so far)
  - ➡ Higgs(?) at *125.7 GeV* still within SUSY reach
  - ➡ constraints from rare B decays ($B_s \to \mu\mu$ ...)
- instead, "bottom up" approaches
  - ➡ phenomenological SUSY model (pMSSM)
  - ➡ simplified models to express results for SUSY s-particle searches

excluded up to ~*1.5 TeV* for *m(q̃)=m(g̃)*

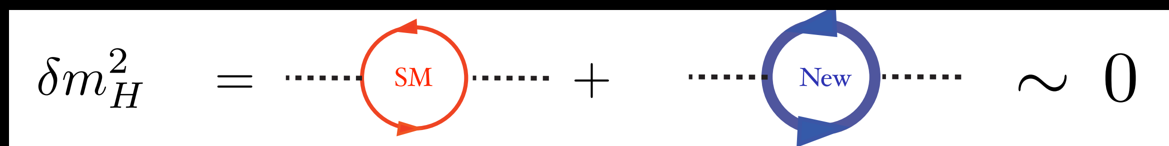


excluded *m(g̃)<1 TeV* for any *m(q̃)*



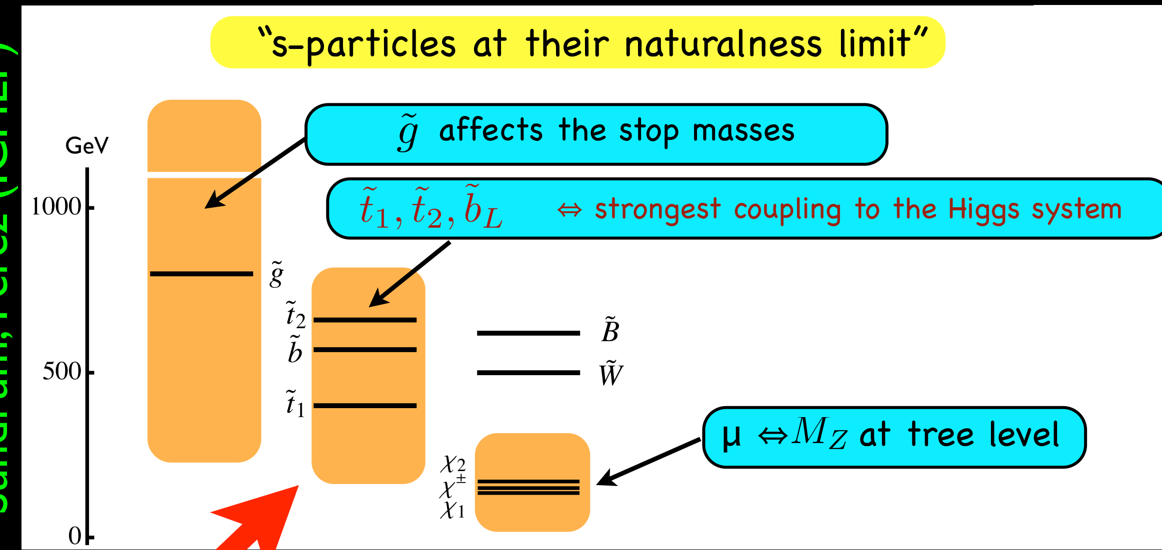
“Natural” SUSY ?

- not fine tuned Higgs requires:



➡ s-particles linked to Higgs loop need to be light

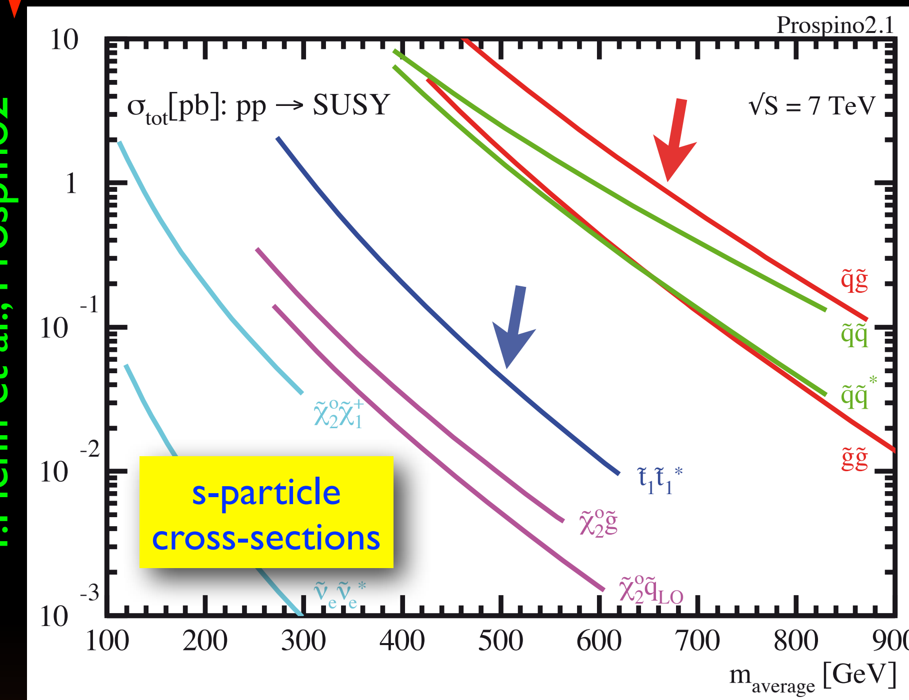
Sundrum, Perez (ICHEP)



- 3rd generation squarks

➡ cross-sections at LHC expected to be smaller than for 1st and 2nd generation

T.Plehn et al., Prospino2



- generic SUSY searches at LHC

➡ like: “0-lepton” (signature: jets + missing ET)

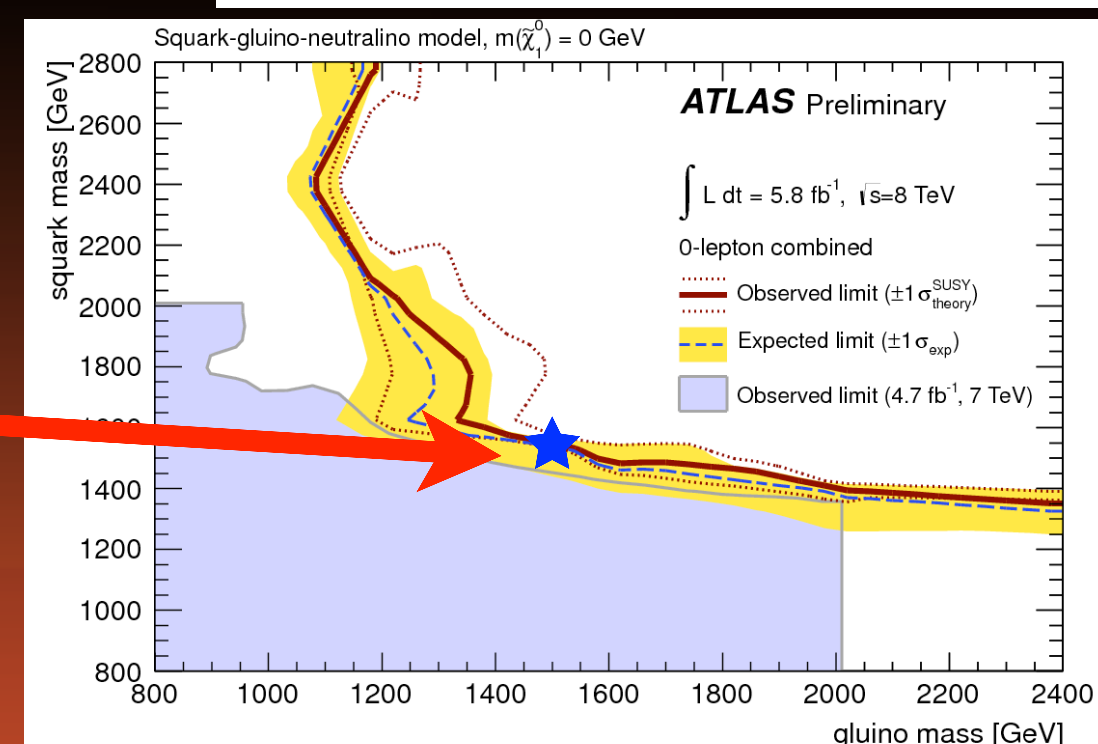
- interpretation in simplified model

➡ yield stringent limits on 1st and 2nd gen.

- excluded up to ~*1.5 TeV* for *m(q̃)=m(g̃)*

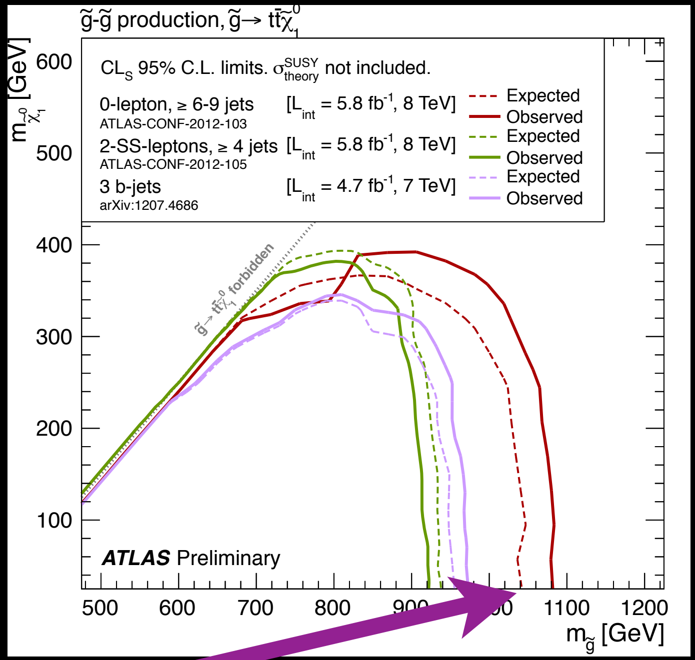
➡ not constraining 3rd generation squarks

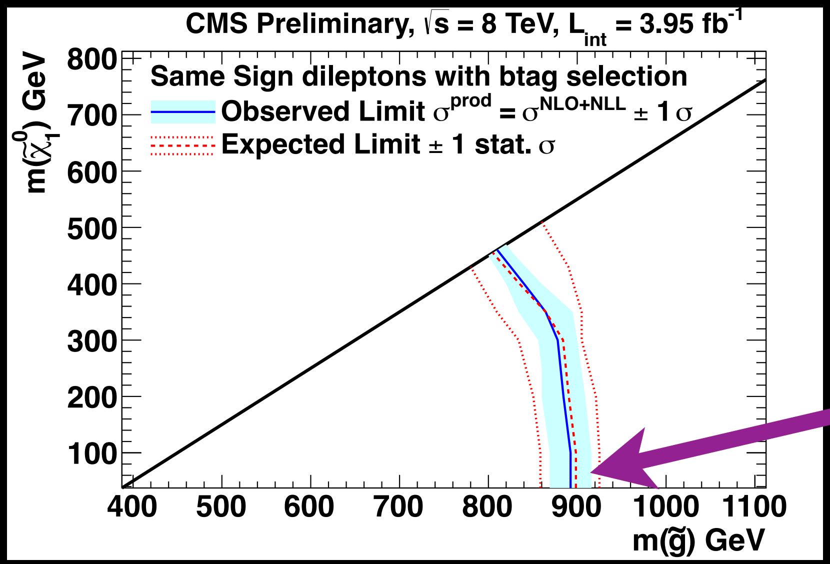
- needs specialized t̃ and b̃ searches

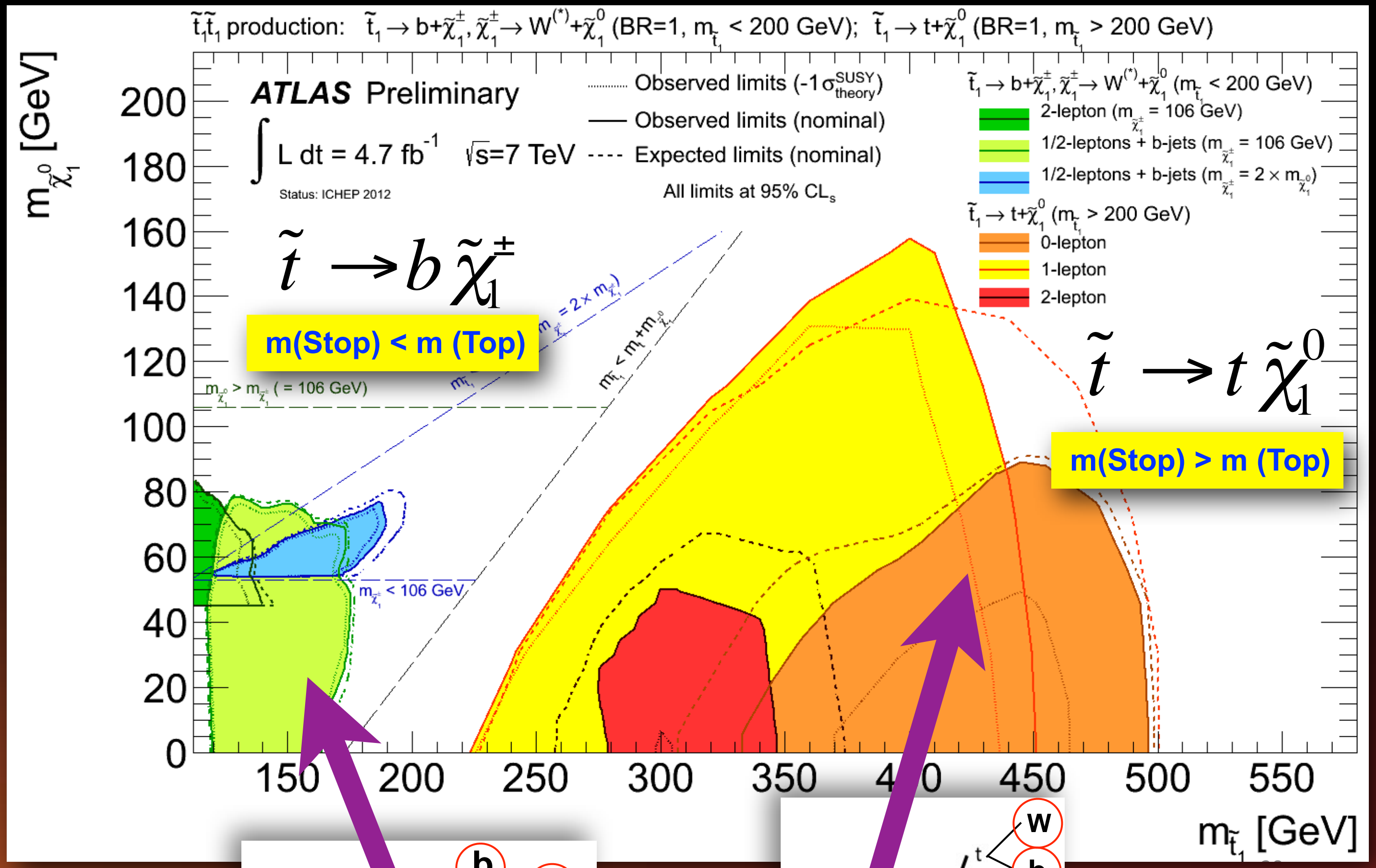


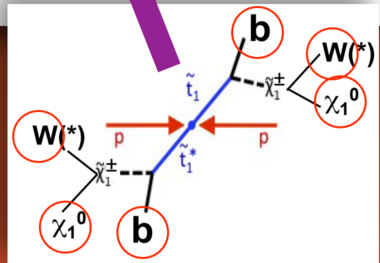
Dedicated Stop Searches

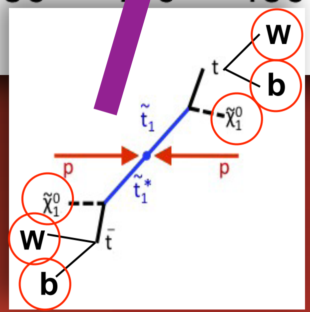
- simplified models
  - ➡ assumes 100% branching ratios
- gluino mediated Stop
  - ➡ 4 top squarks in final state
  - ➡ modes via virtual/on-shell stop
    - but limit on $m(\tilde{g})$ depends little on $m(\tilde{t})$ above/below $m(\tilde{g})$
  - ➡ sensitive to $m(\tilde{g})<1000$ GeV for $m(\tilde{\chi}_1^0)<380$ GeV
- direct Stop pair production
  - ➡ 2W+2b-jets+missing E_T
  - ➡ modes with $m(\tilde{t})$ above/below $m(t)$
    - combination of several signatures to maximize sensitivity
  - ➡ "If you cover the white then Weak scale SUSY is probably dead" R. Barbieri (ICHEP'12)



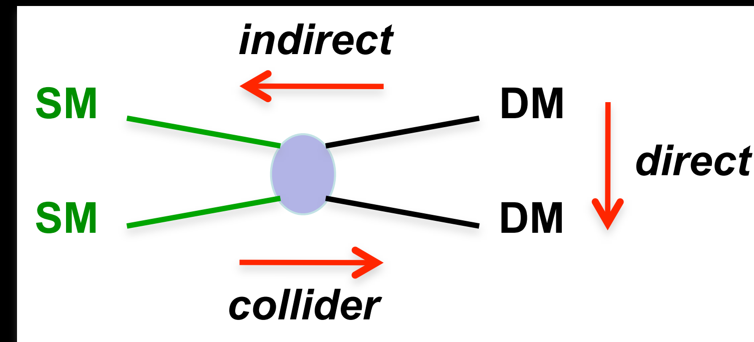


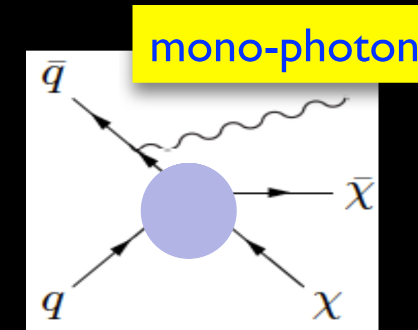


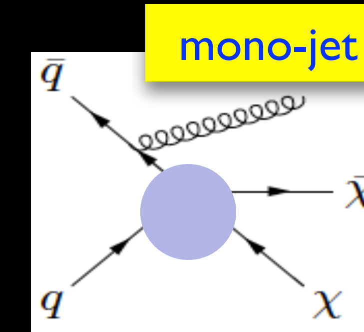




WIMP Searches







- complementary to (in)direct searches
  - ➡ experimental signature is γ/jet+missing E_T
- interpretation is model dependent
  - ➡ needs assumption about the "blue bubble"
  - ➡ effective theory approach for contact interaction
    - choice of operators (~Dn)
    - parameters mass m_χ and scale $\Lambda = M_*$

      J.Goodman et al., arXiv:1008.1783
  - ➡ *90% CL* limits on WIMP-nucleon cross-section for Dirac fermions X
    - operator for spin independent scattering

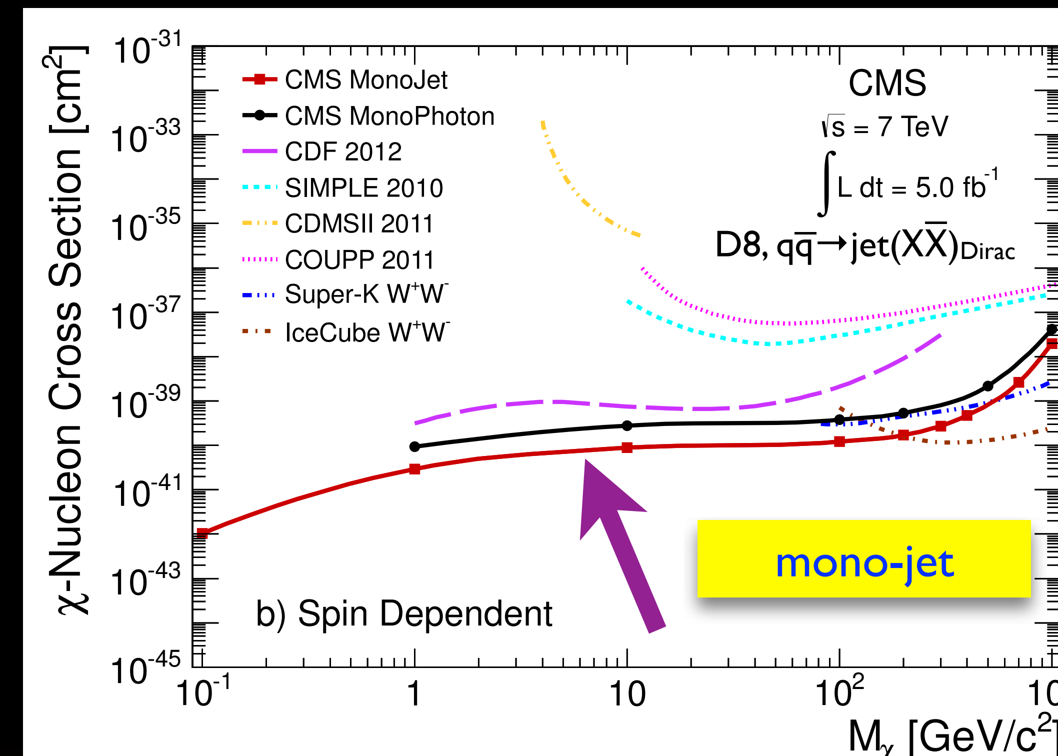
$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \quad \text{(D5)} \quad \text{(vector)}$$

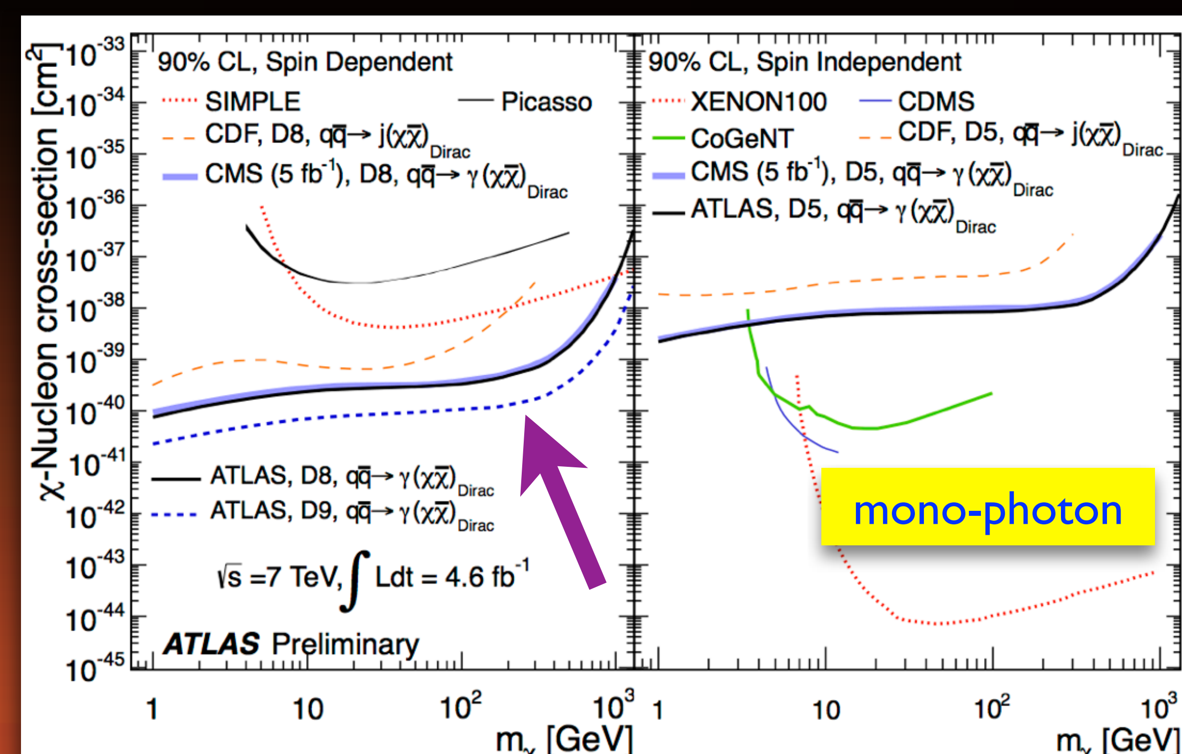
    - operator for spin dependent scattering

$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q \quad \text{(D8)} \quad \text{(axial)}$$

$$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q \quad \text{(D9)} \quad \text{(tensor)}$$

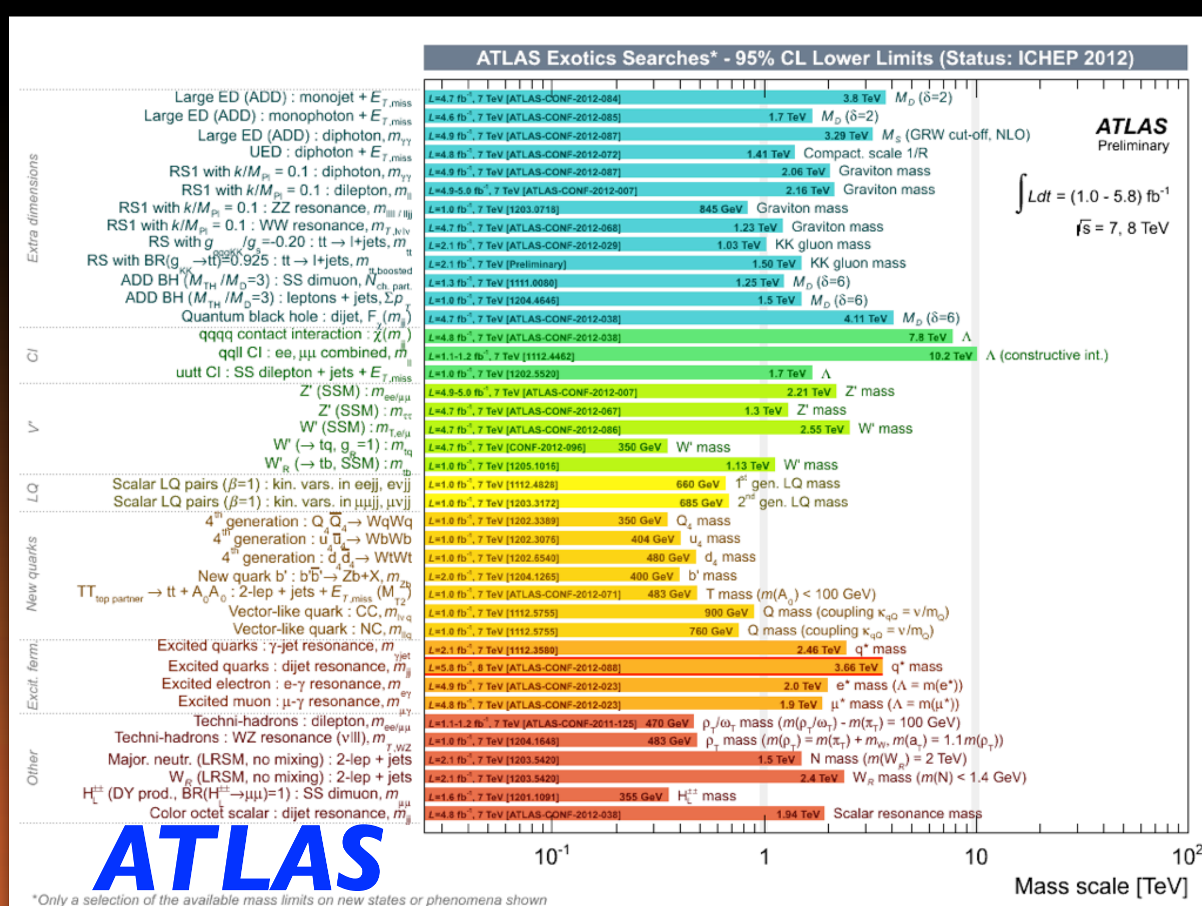
  - ➡ strong limits on spin dependent scattering

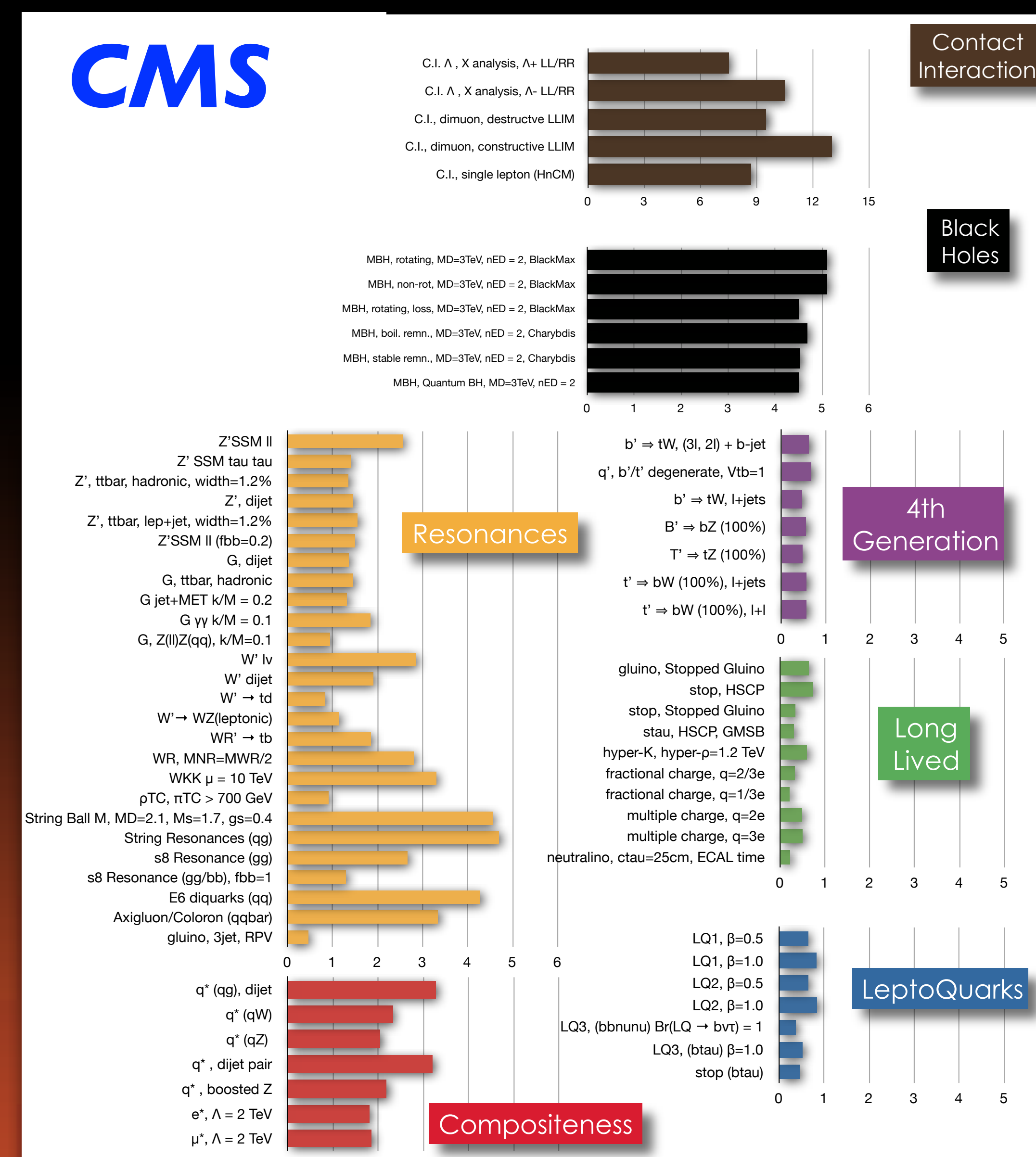




No TeV Scale New Physics (yet)

- huge list of experimental signatures and models covered
- typical limits achieved up to:
  - ➡ singly produced objects with QCD couplings ~ **3.5 TeV**
  - ➡ singly produced objects with EW couplings ~ **4 TeV**
  - ➡ pair produced objects with QCD couplings ~ **600 GeV**
  - ➡ unitarity limited rates ~ **4 TeV**
  - ➡ compositeness scale ~ **8 TeV**
- details in figures...





Indirect Constraints on New Physics

- LHCb took *1fb^{-1}* in 2011 (and in 2012)
  - ➡ excellent dataset to place indirect constraints on NP
  - ➡ precision measurements, compare to SM predictions
- rare *B* decays, especially: $B_s \to \mu\mu$
  - ➡ helicity suppressed in SM, large NP effects prediced
  - ➡ places stringent limit on models increasing BR

$BR(B_s \to \mu\mu) < 4.2 \times 10^{-9}$ (95%CL) SM:$(3.1 \pm 0.2) \times 10^{-9}$

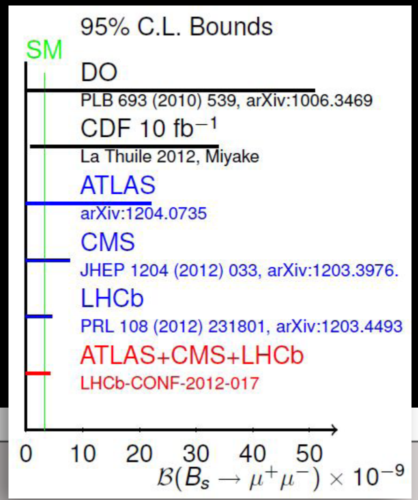
  - e.g. excludes large *tanβ* in 2HDM models (like SUSY)
- CP violation in *B* sector
  - ➡ new measurement of B_s mixing parameters
    - CP violating phase ϕ_s and width differences $\Delta\Gamma_s$
  - ➡ reduces phase space for NP:

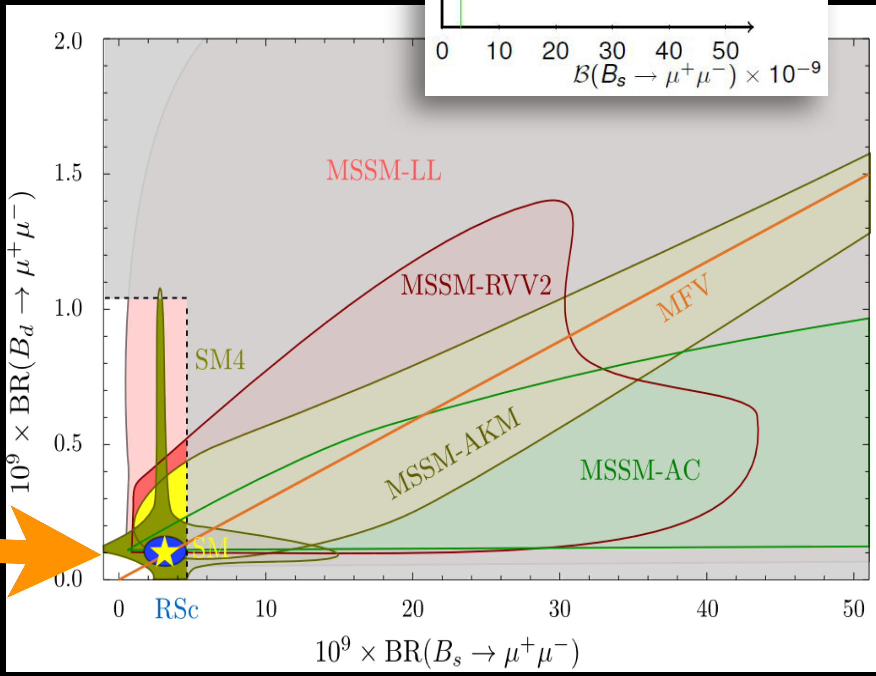
$\phi_s = -0.002 \pm 0.083 \pm 0.027\,rad$, $\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\,ps^{-1}$

- CP violation in charm sector ?

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$ (3.5σ)

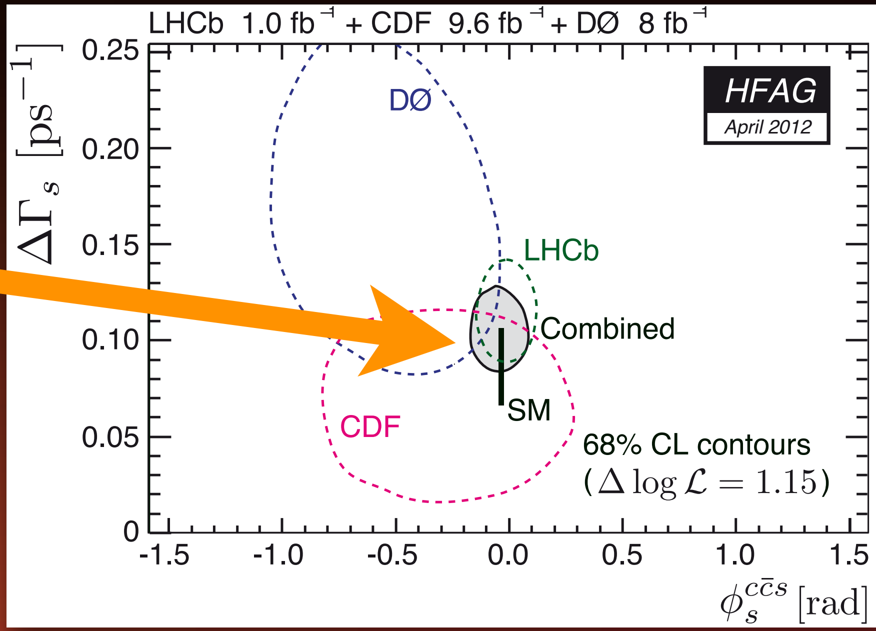
  - ➡ no 1% asymmetry in SM, but control on QCD effects ?





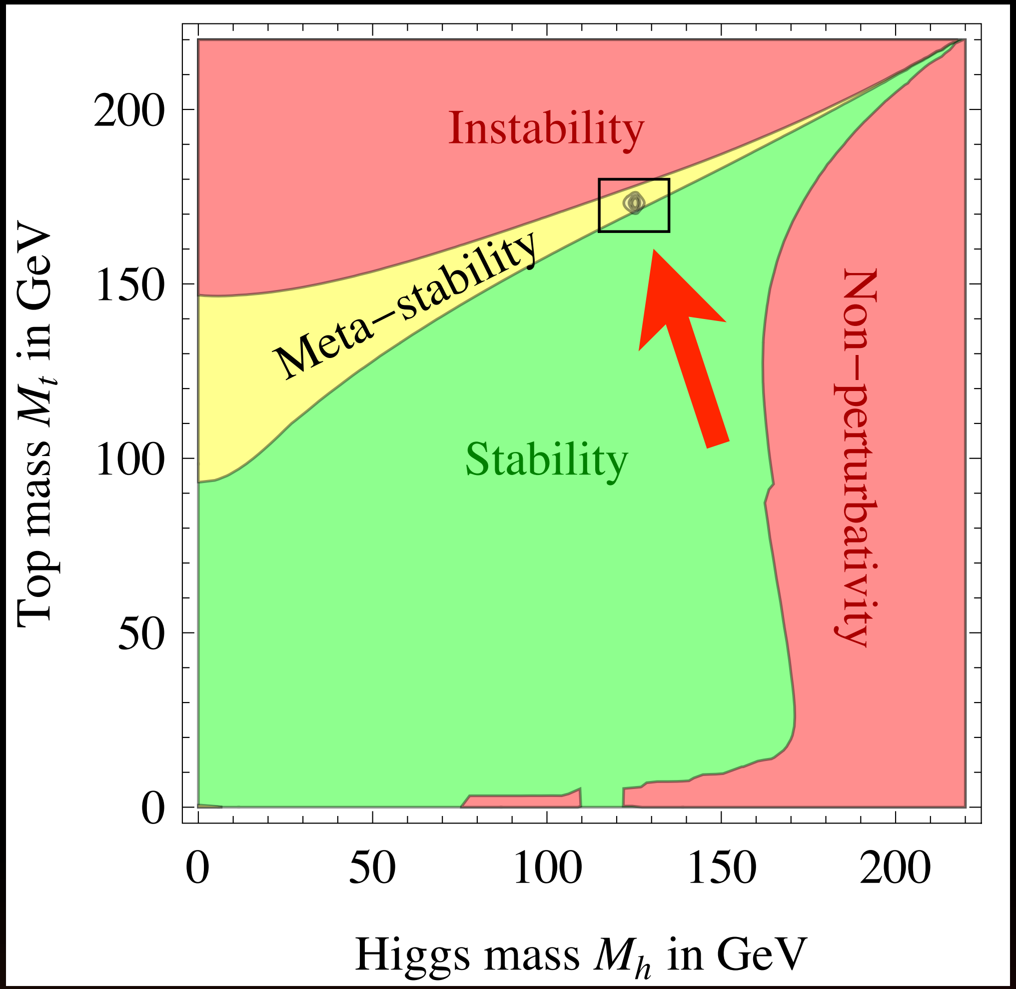
M.Straub, arXiv:1205.6094v1

Y.Amhis et al., HFAG, arXiv:1207.1158v1

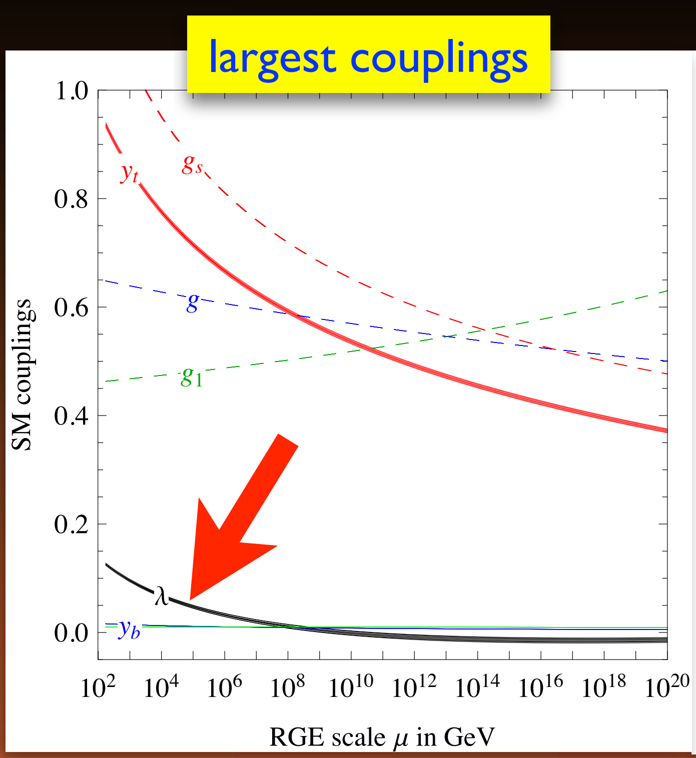


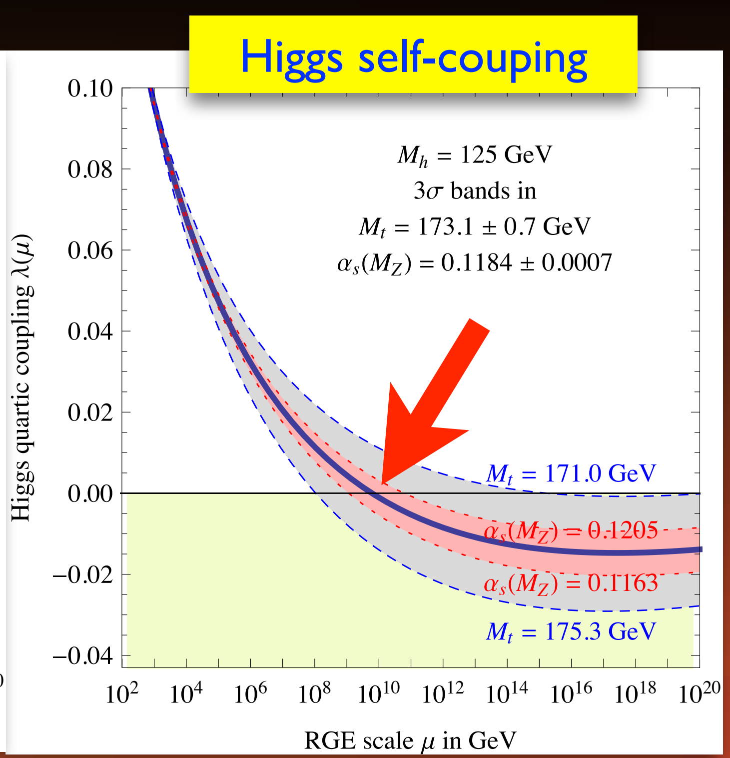
What if SM unchanged up to M_{Pl} ?

- no new physics up to very high scales ?
  - ➡ special meaning of **$\lambda \approx 0$** at **M_{Pl}** ?
- absolute vacuum stability with Higgs self coupling **$\lambda(M_{Pl}) \gtrsim 0$** ?
  - ➡ not quite achieved for current "best" values of M_t and M_H
  - ➡ see discussion of M_t, theoretical uncertainties...



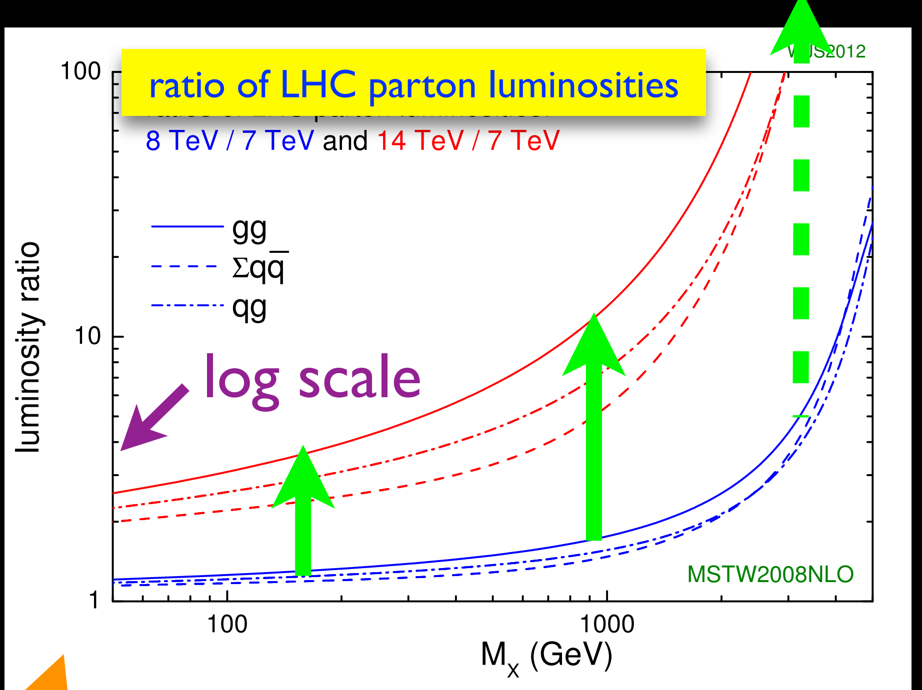
Degrassi et al., arXiv:1205.6497v1

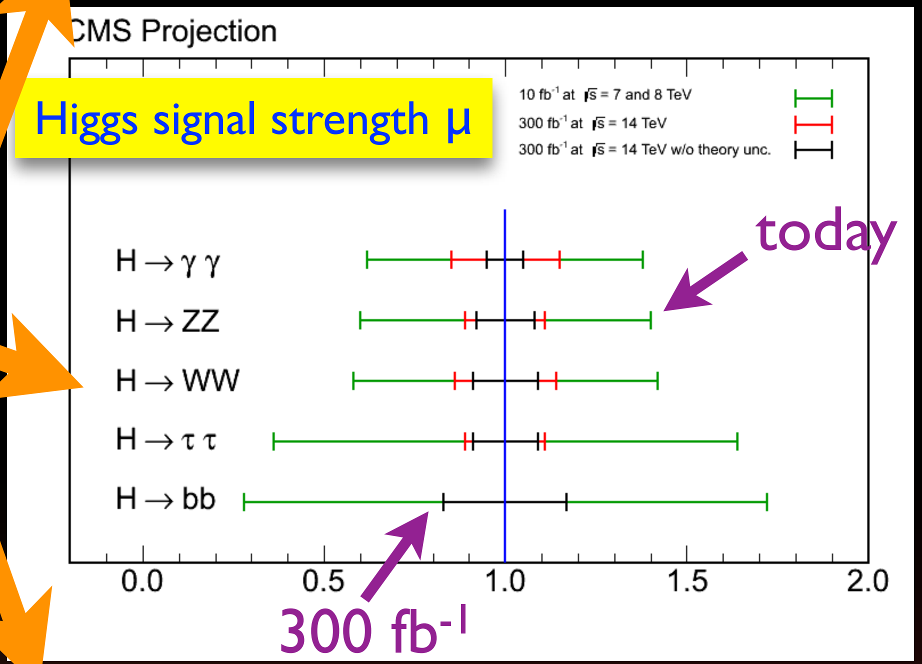


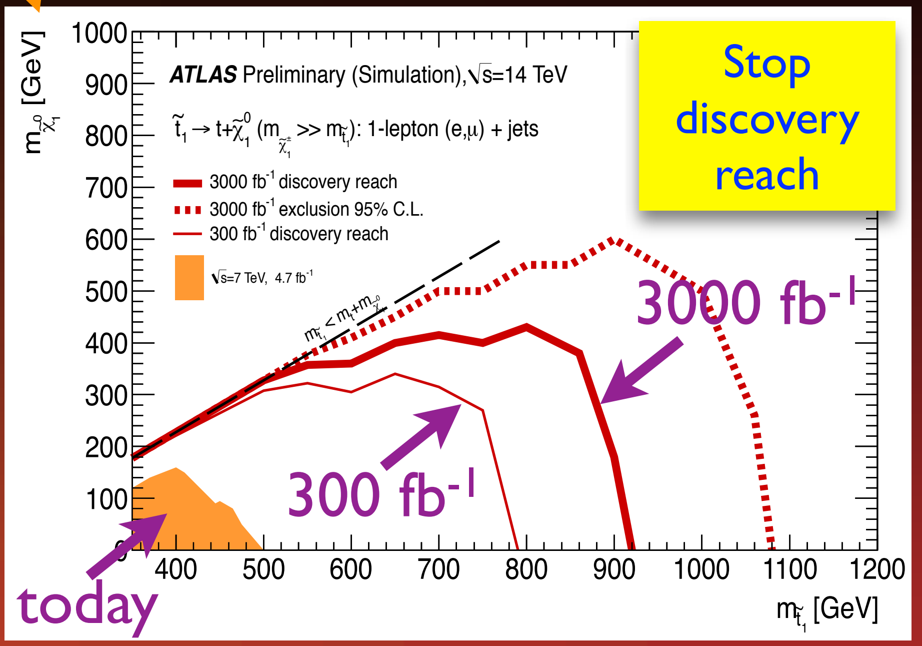


Future Prospects

- current pp run ends in 2012
  - ➡ hope to accumulate ~*20 fb*$^{-1}$ at 8 TeV before shutdown
  - ➡ prepare for *13-14 TeV* to accumulate another ~*100 fb*$^{-1}$ until 2018 and ~*350 fb*$^{-1}$ until 2021
  - ➡ High Luminosity LHC: ~*3000 fb*$^{-1}$ until 2030
- ATLAS/CMS physics reach driven by
  - increase in parton luminosity going from *8* to *14 TeV*
  - sensitivity to smaller cross sections
- LHCb plans for ~*50 fb*$^{-1}$ over 10 years
  - ➡ 10% on *BR*($B_s \to \mu\mu$), $\sigma(\phi_s)=\pm0.003$, ...
- very active detector upgrade programs
  - ➡ keep and improve on physics performance
  - ➡ sustain harder pileup and radiation environment
  - ➡ especially trigger is an issue:
    - keep p_T thresholds in ATLAS/CMS
    - no Level-1 trigger selection in LHCb (*40 MHz* readout)







Summary and Outlook

- LHC and experiments are doing fantastically well
  - ➡ very rich harvest of physics results, much broader than any talk could cover
  - ➡ apologies if I did not cover your favorite subject in the last 35 minutes
- a new Boson has been discovered !
  - ➡ its properties are compatible with Standard Model Higgs, but early to tell
  - ➡ exciting times for understanding the nature of EW symmetry breaking
- LHC is a discovery machine for new physics
  - ➡ experiments cover a huge spectrum of signatures and BSM models
  - ➡ no signs for TeV scale physics beyond the Standard Model yet
- this is just the start
  - ➡ machine upgrade from *8 TeV* to close to *14 TeV* in the 2013/2014 shutdown
  - ➡ expect to take ~*350* fb^{-1} at *14 TeV* until 2021 (before start of HL-LHC)

Acknowledgements

many thanks for help in preparing this talk, special plots and useful discussions to:

M.Baak, D.Berge, T.Eifert, M.Costa, M.Cristinziani, M.Duehrssen, D.Froidevaux, R.Hawkings, S.Heinemeyer, A.Hoecker, Z.Marshall, K.Moenig, K.Peters, R.Schwienhorst, ...

... and of course, all material presented here is the result of the fabulous work by many, many people...