European Strategy for Particle Physics

ETH Institute for Particle Physics

Experimental Status: High Energy Frontier

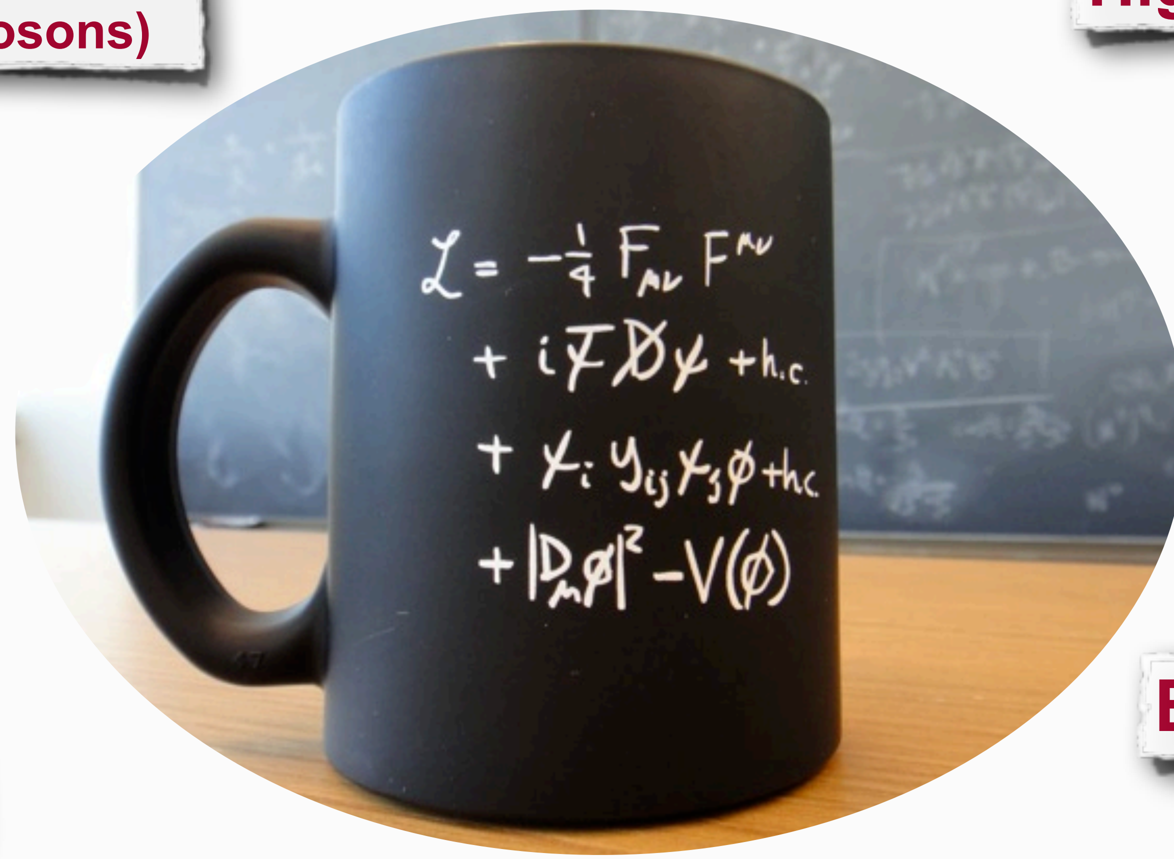
Günther Dissertori
ETH Zürich

Outline

QCD/EWK sector

(fermions and gauge bosons)

Higgs sector



Anomalies

BSM sector

Disclaimer: mistakes and omissions are purely my fault...

Great thanks to all those who gave input and feedback (via documents, or in direct conversations)

Executive Summary

- the **SM** (in terms of its QCD and EWK parts) **works perfectly well**, up to the % level, at the highest energies probed so far (7 and 8 TeV).

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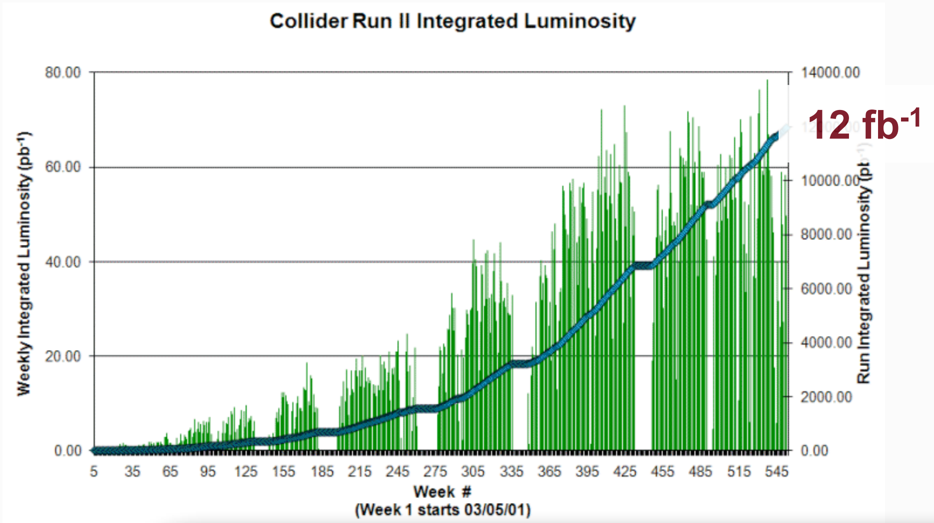
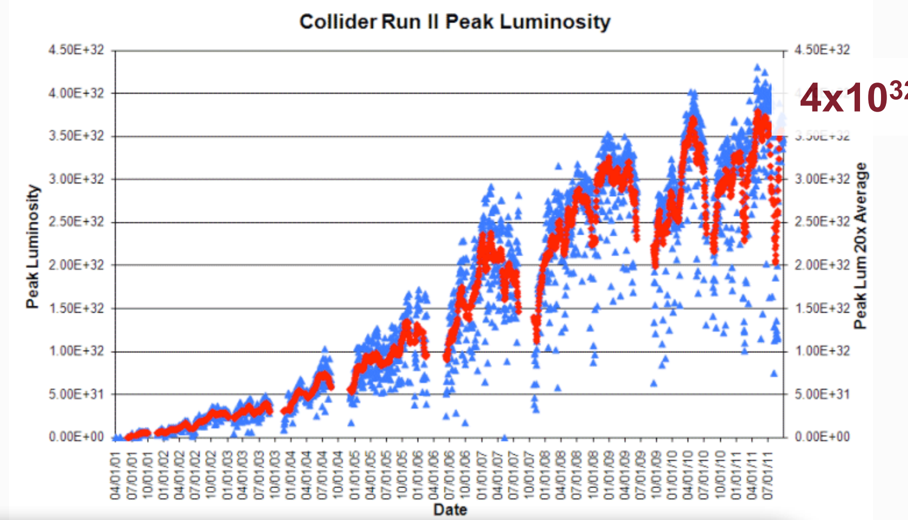
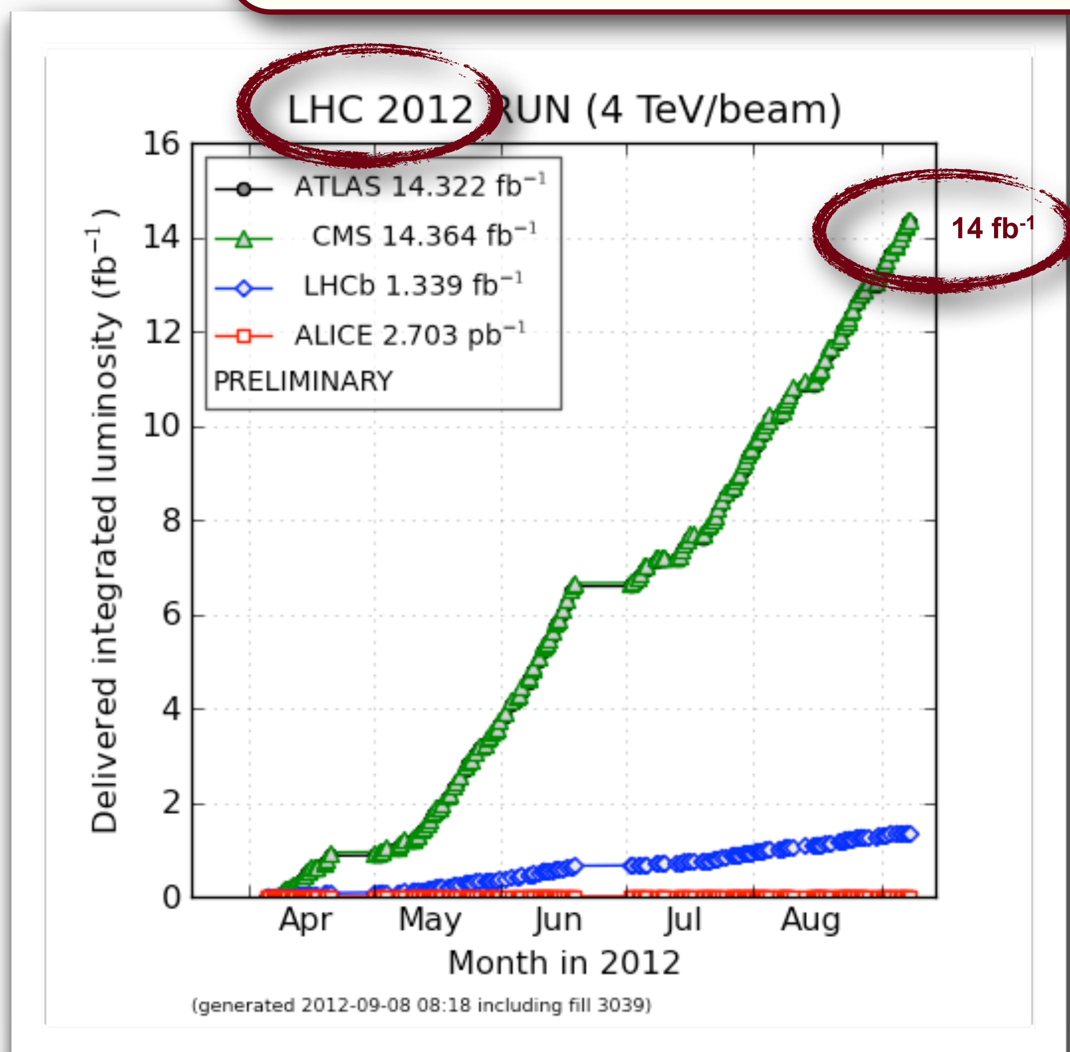
- **very few anomalies** in the world-wide HEF data, no strongly smoking gun
- most important: at the LHC, we are **JUST AT THE BEGINNING** of the HEF exploration!

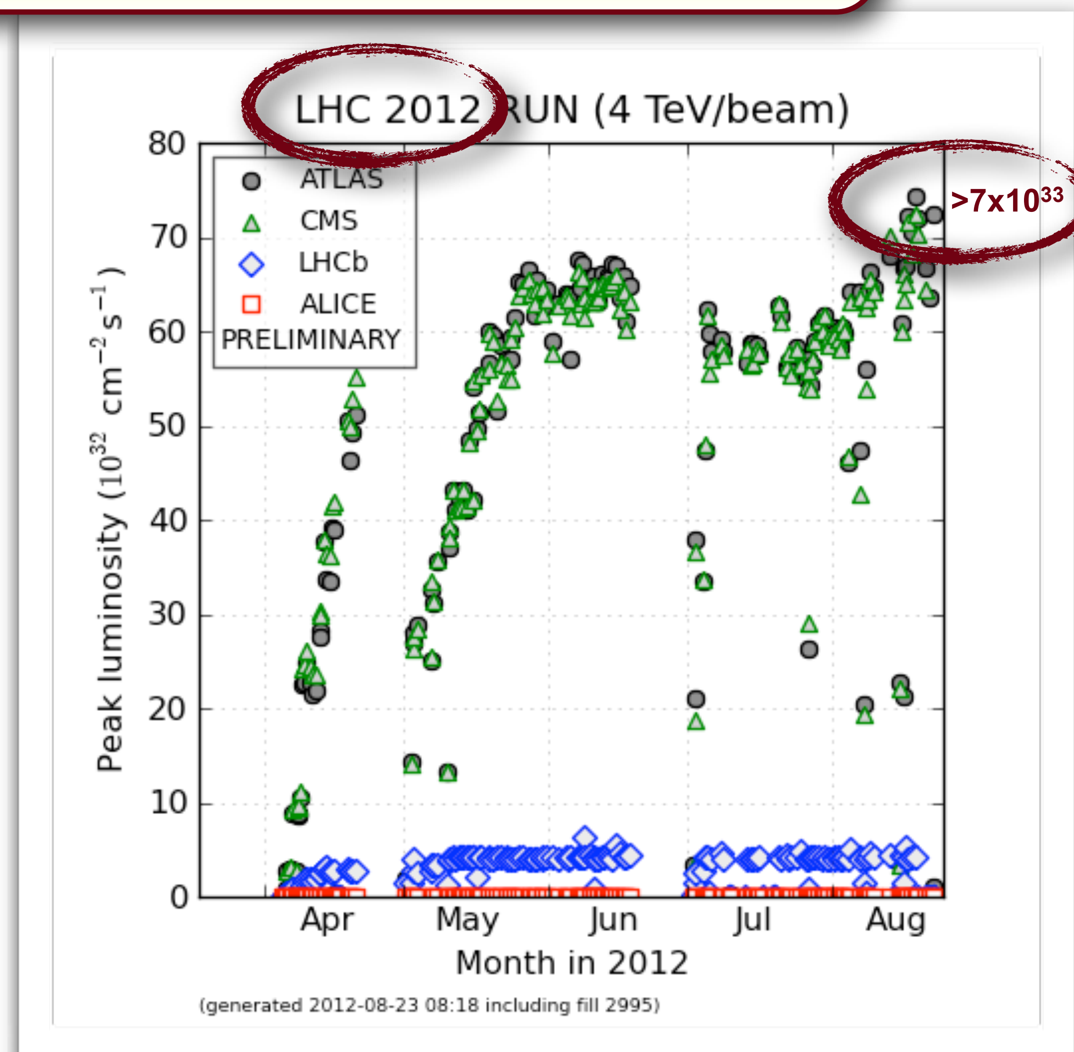
Excellent performance of our microscopes





Experiments: excellent data taking efficiencies, performances according to or often beyond expectations
High LHC luminosity came at the price of large pile-up: experiments coping well with it, so far





QCD/EWK sector:

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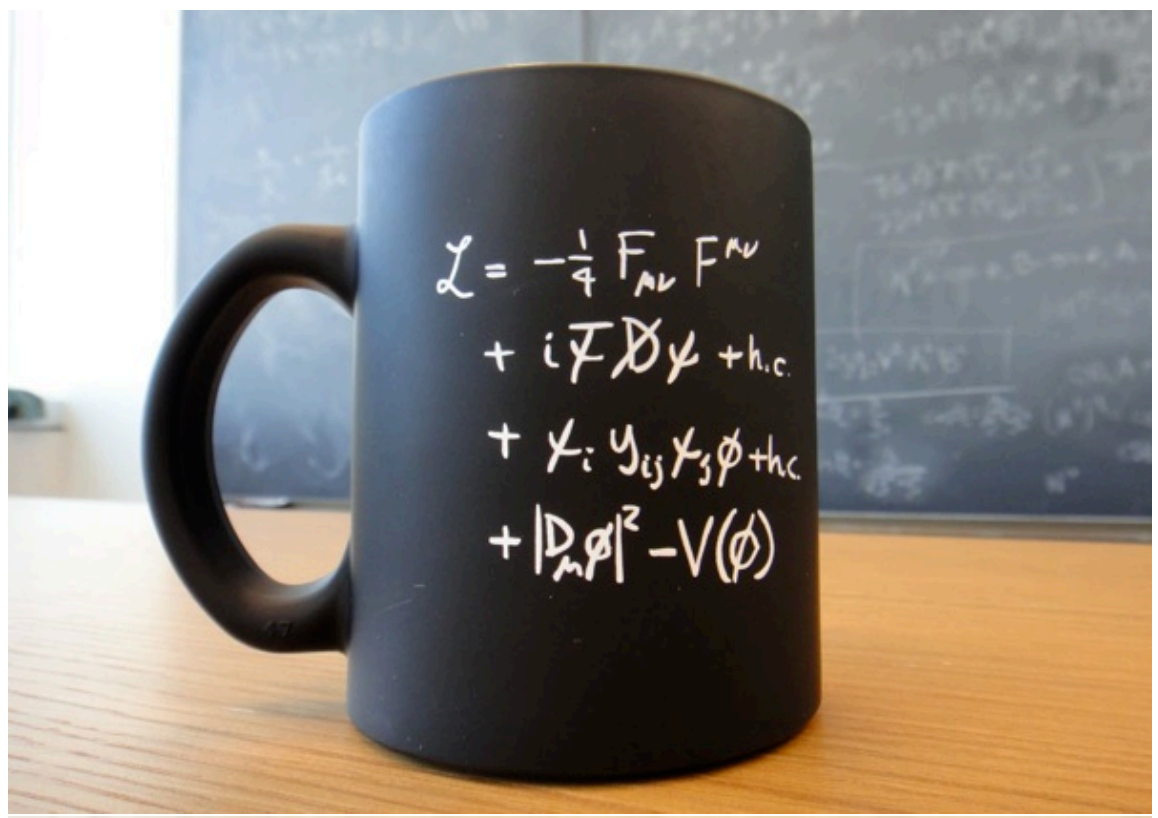
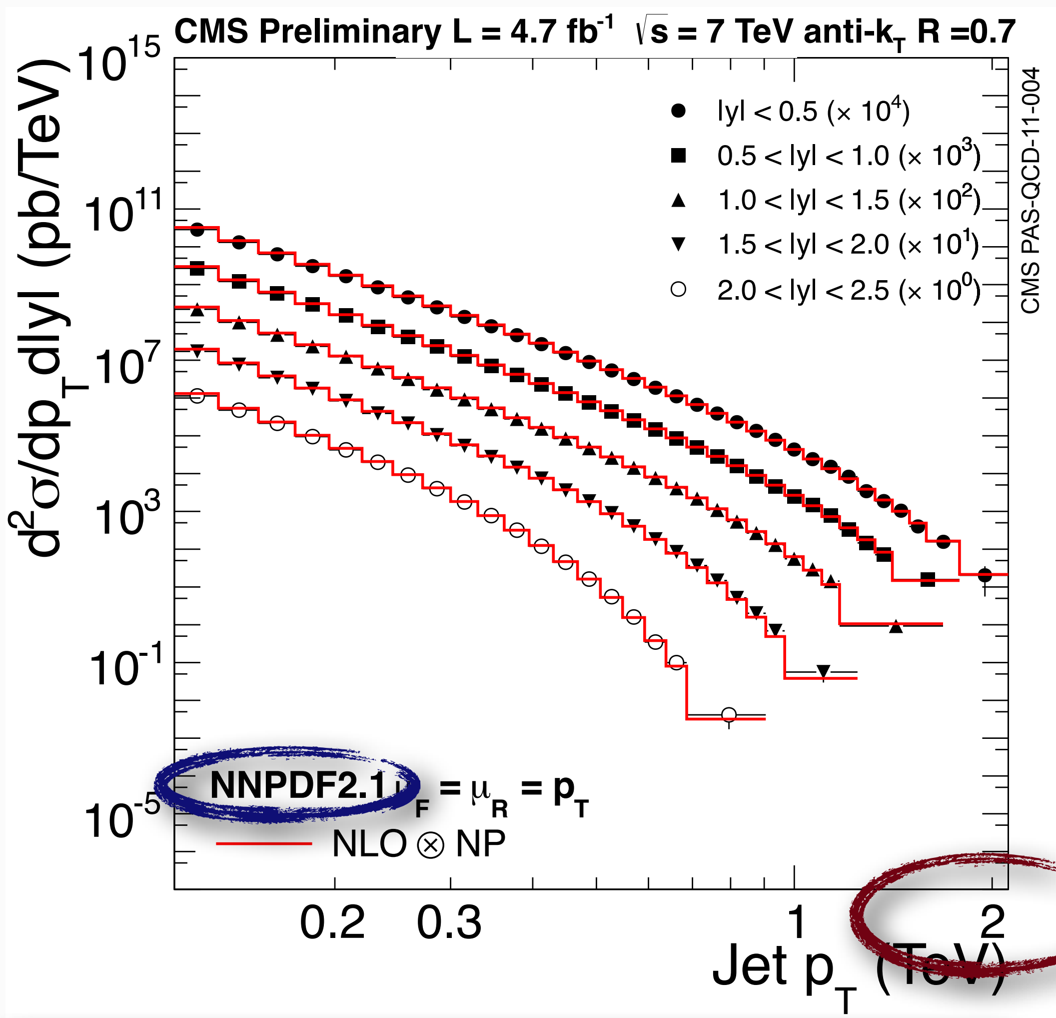
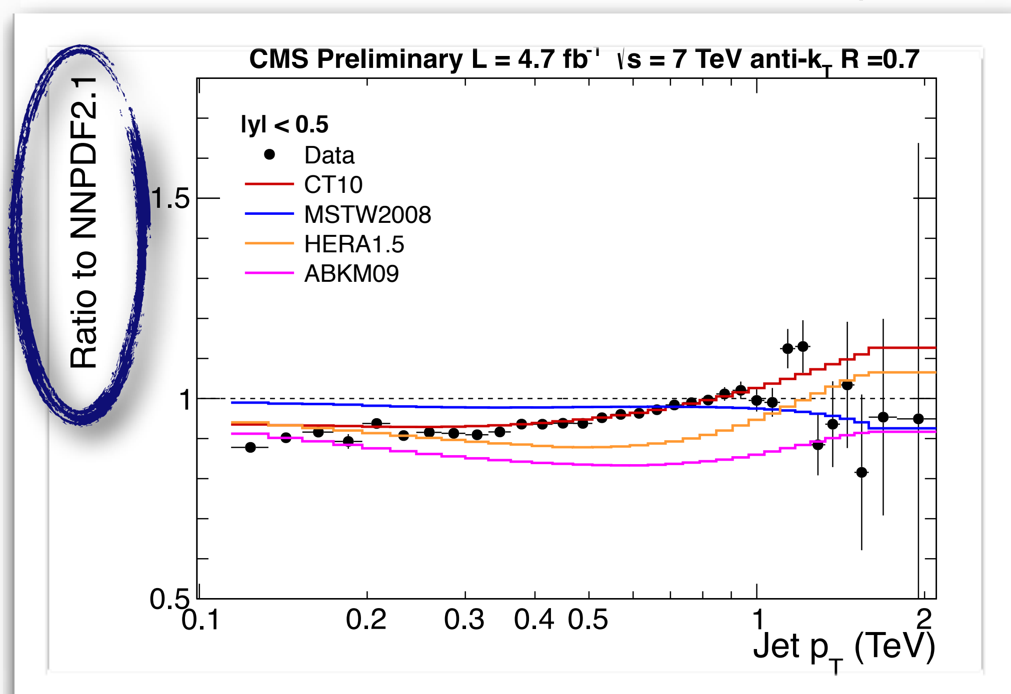


Jet Production





- NLO QCD describes data over ~9 orders of magnitude!
- excellent exp. progress: jet energy scale uncertainties at the 1-2% level
- for central rapidities: similar exp. and theo. uncertainties, 5 - 10%
- inclusive jet data : starts to be important tool for constraining PDFs, eg. also by using ratios at different c.o.m. energies

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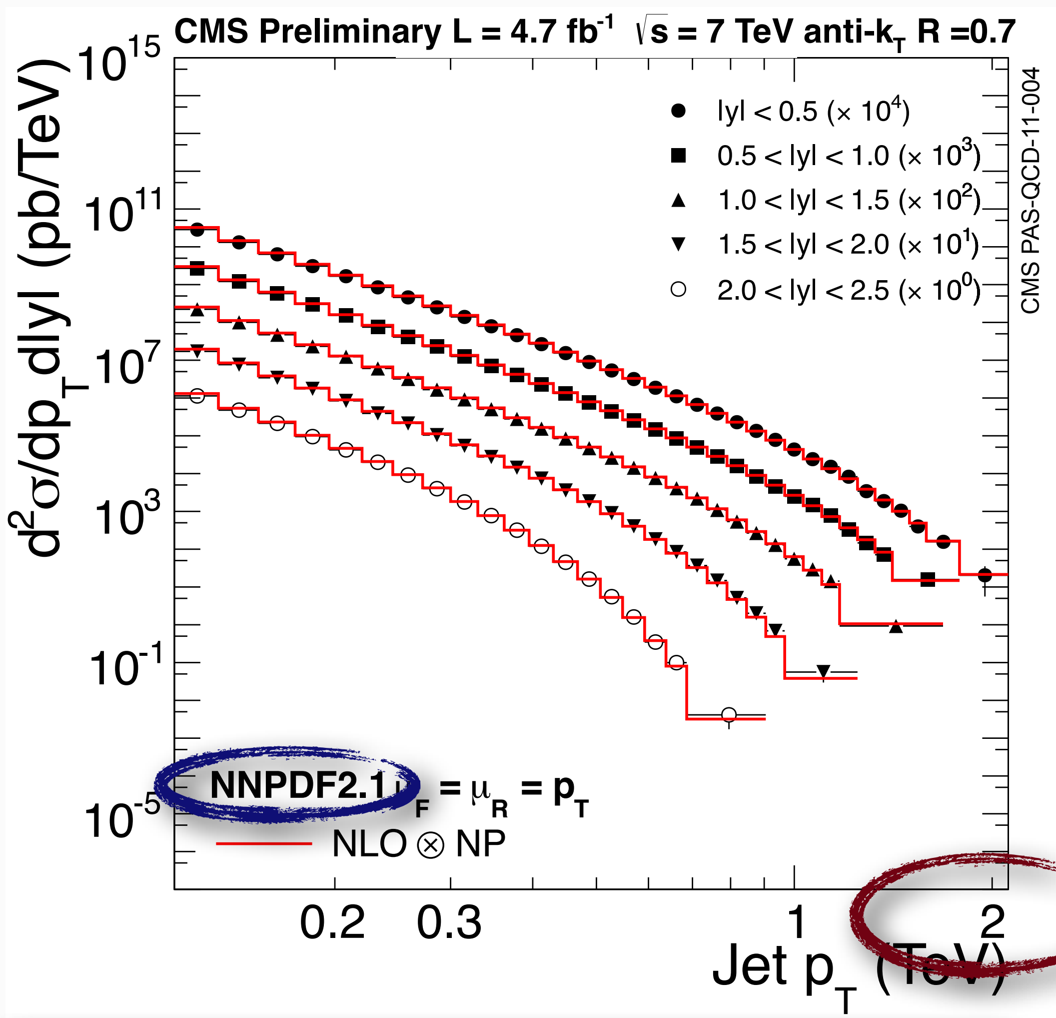

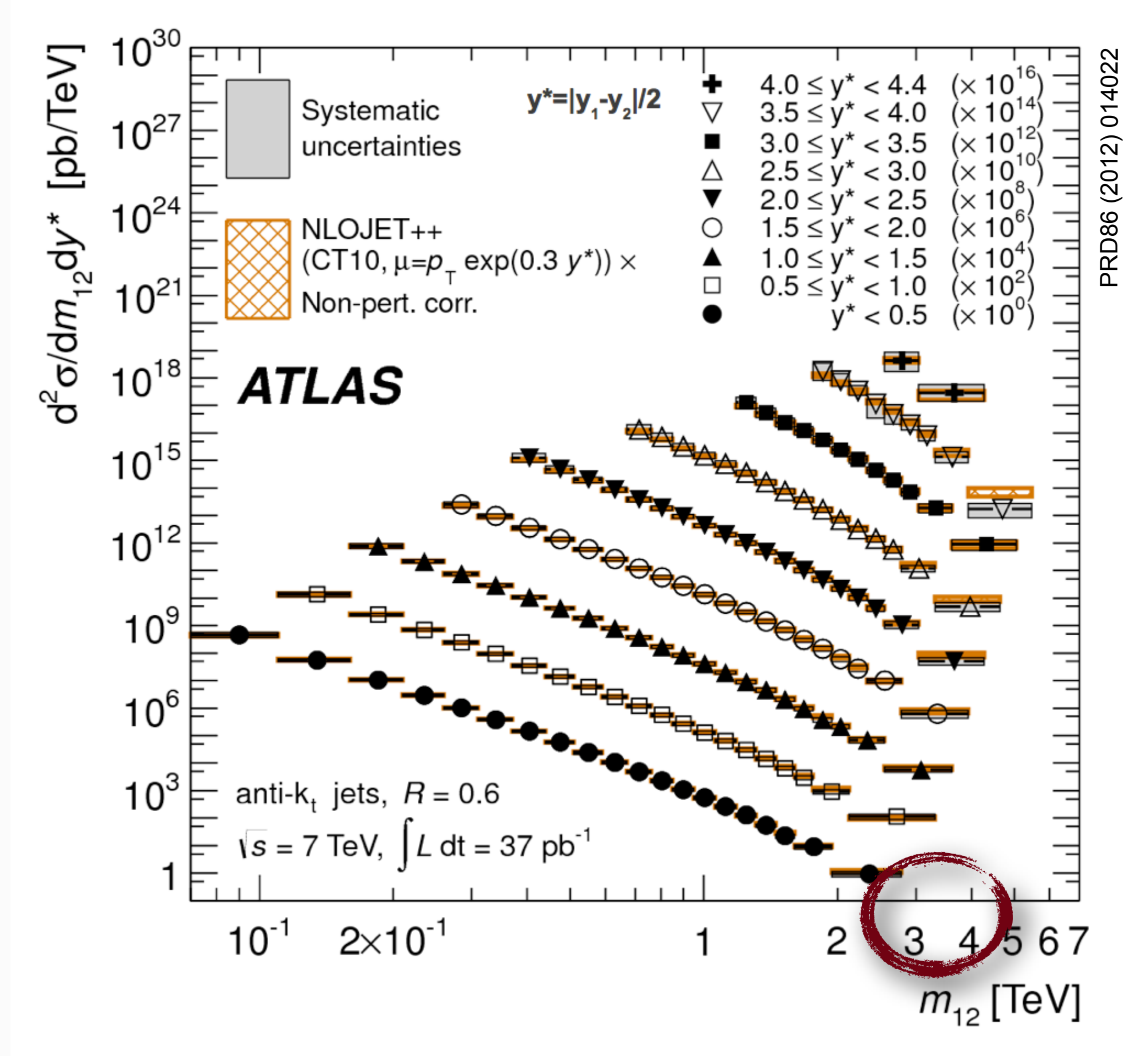

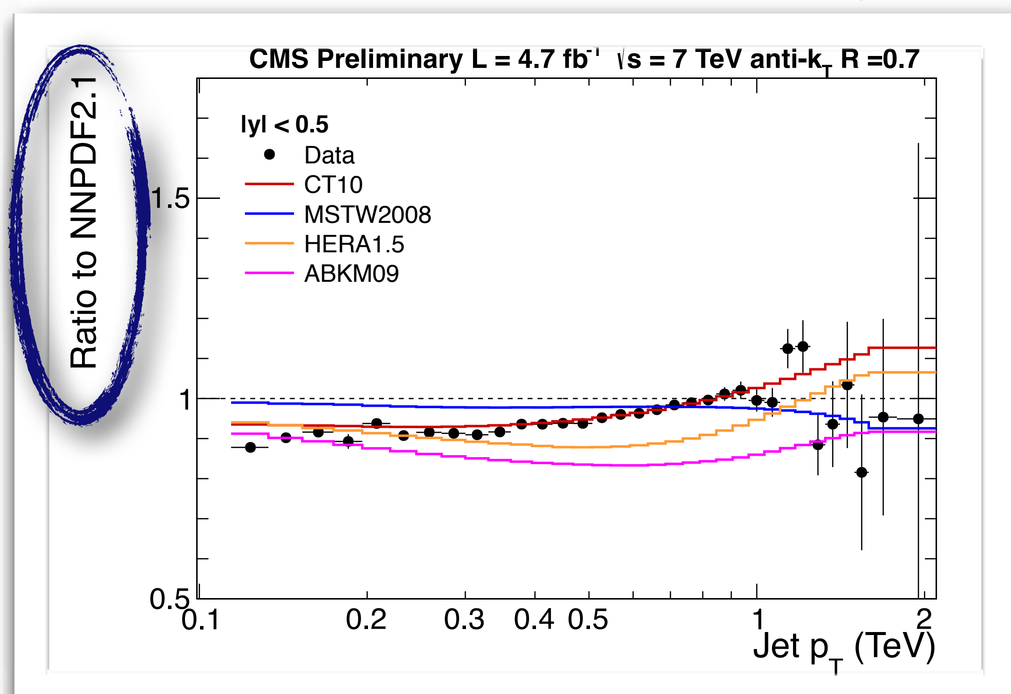

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W/Z (+Jet) Production

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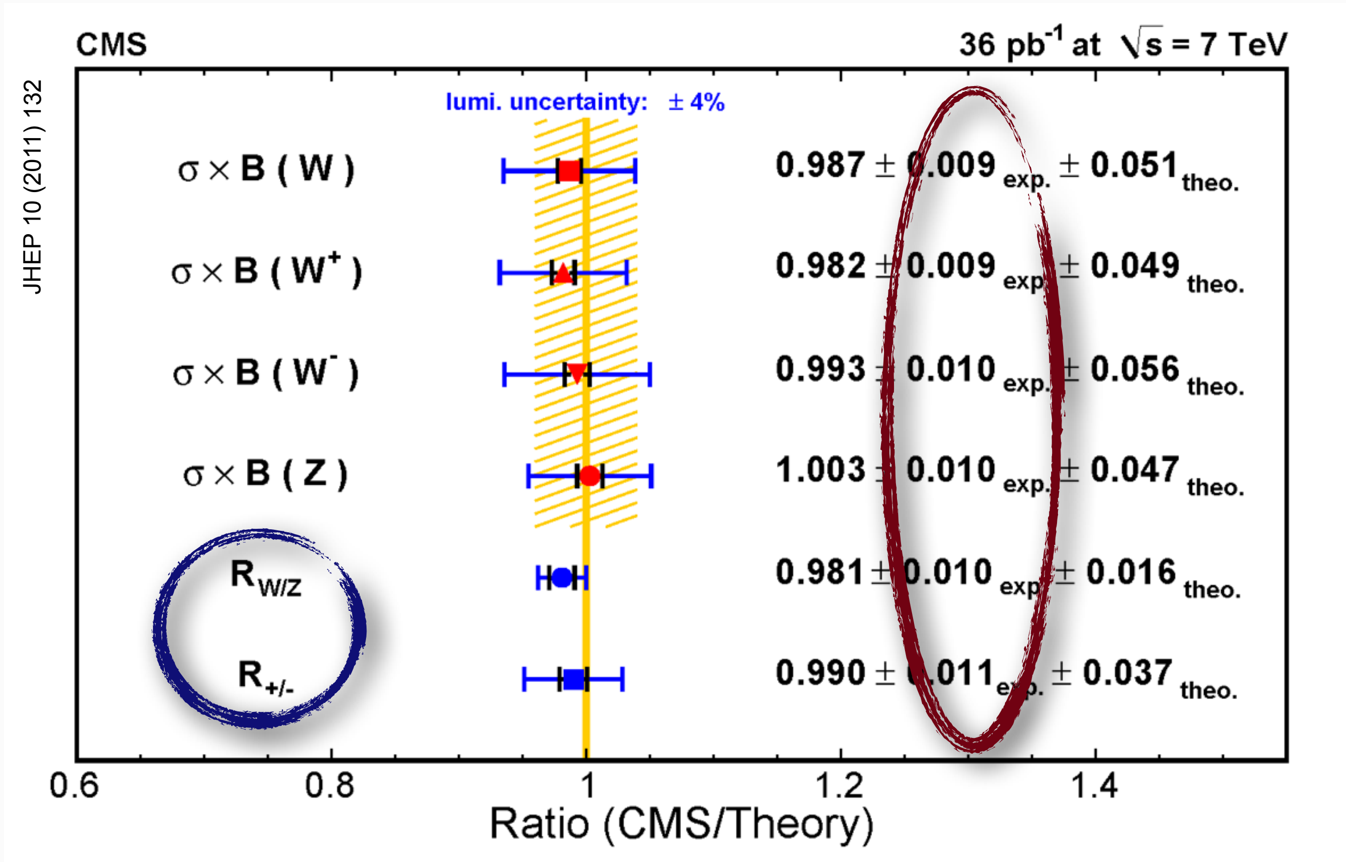

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- experimental precision at the 1% level, especially for ratio-observables
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- many diff. distributions measured
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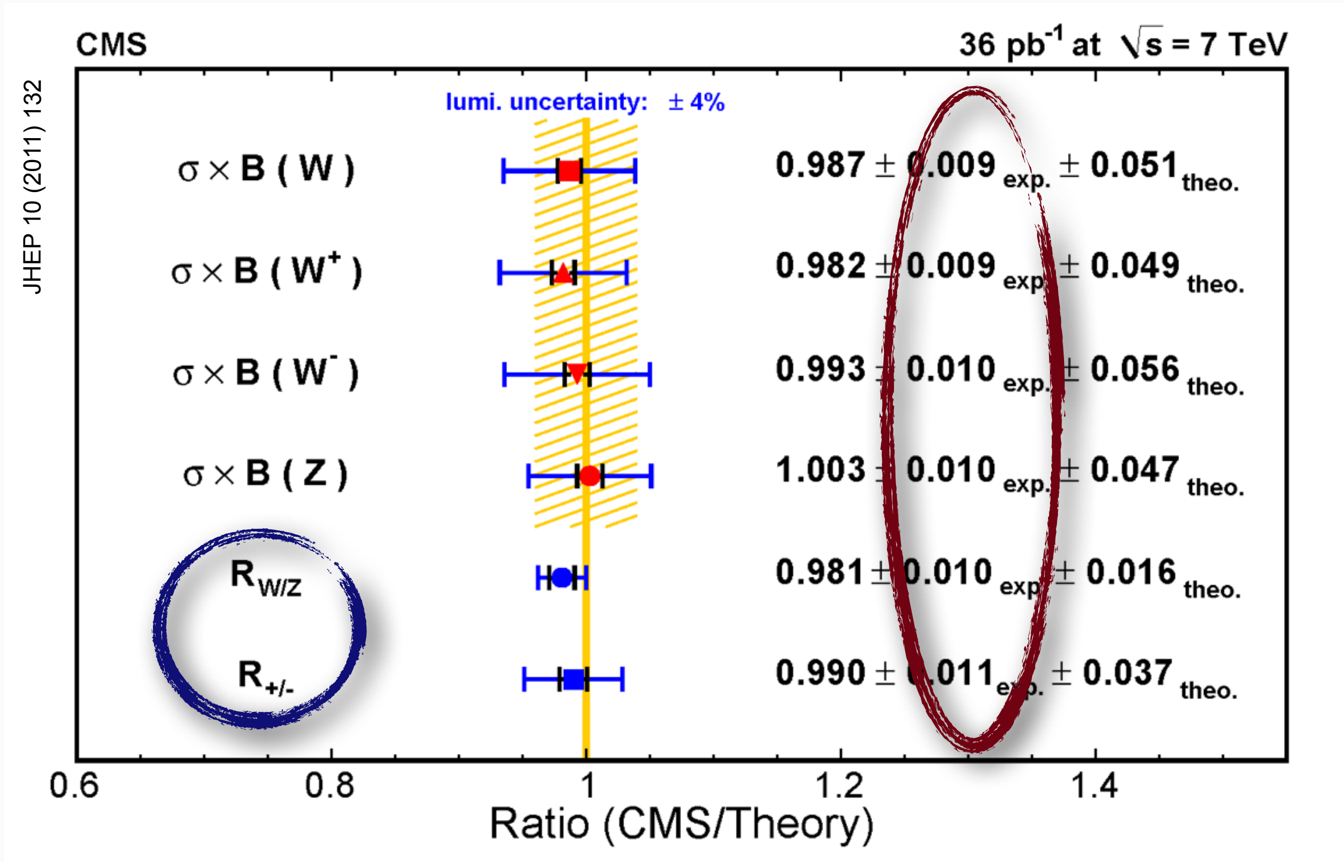
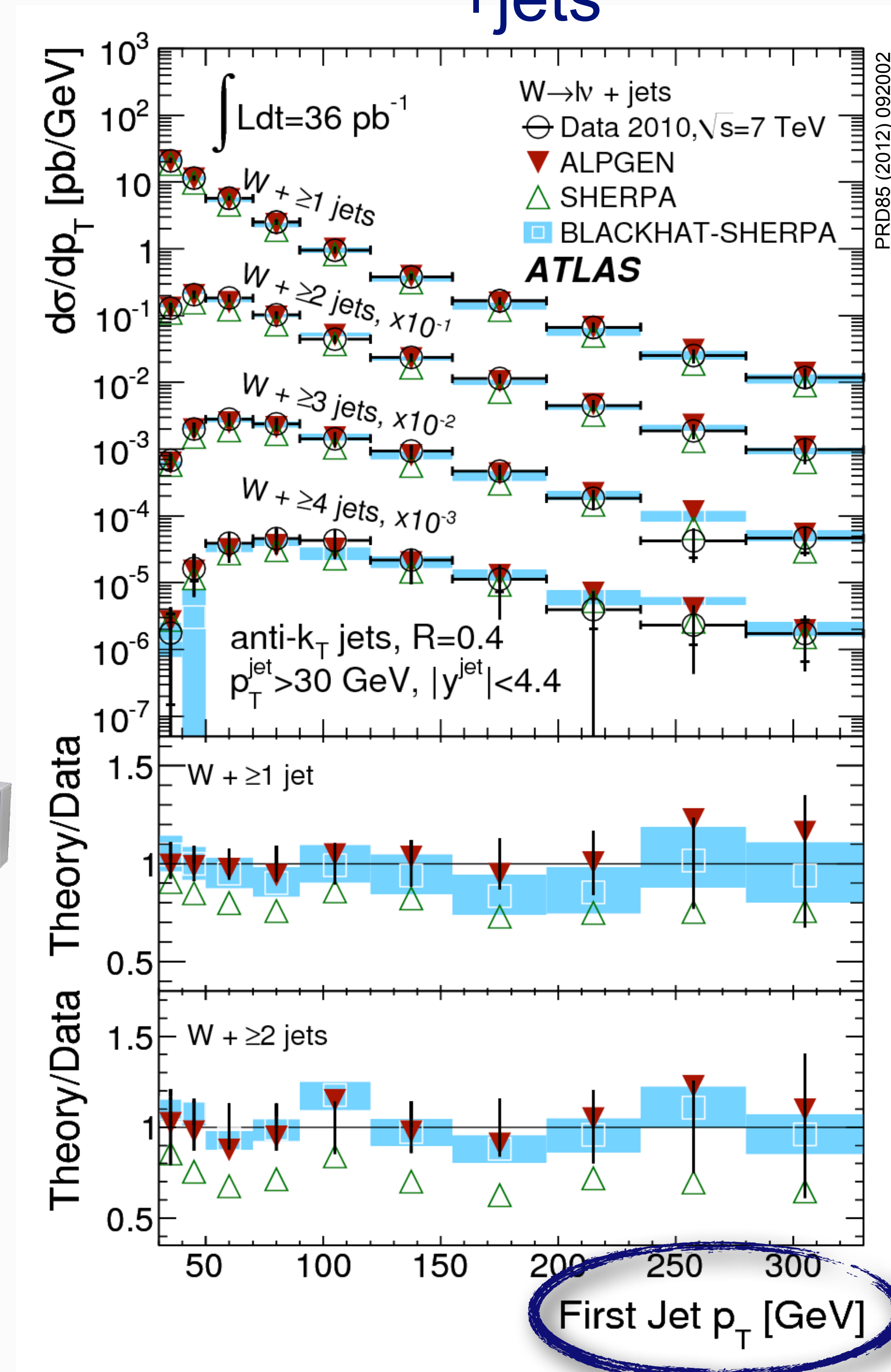


+jets



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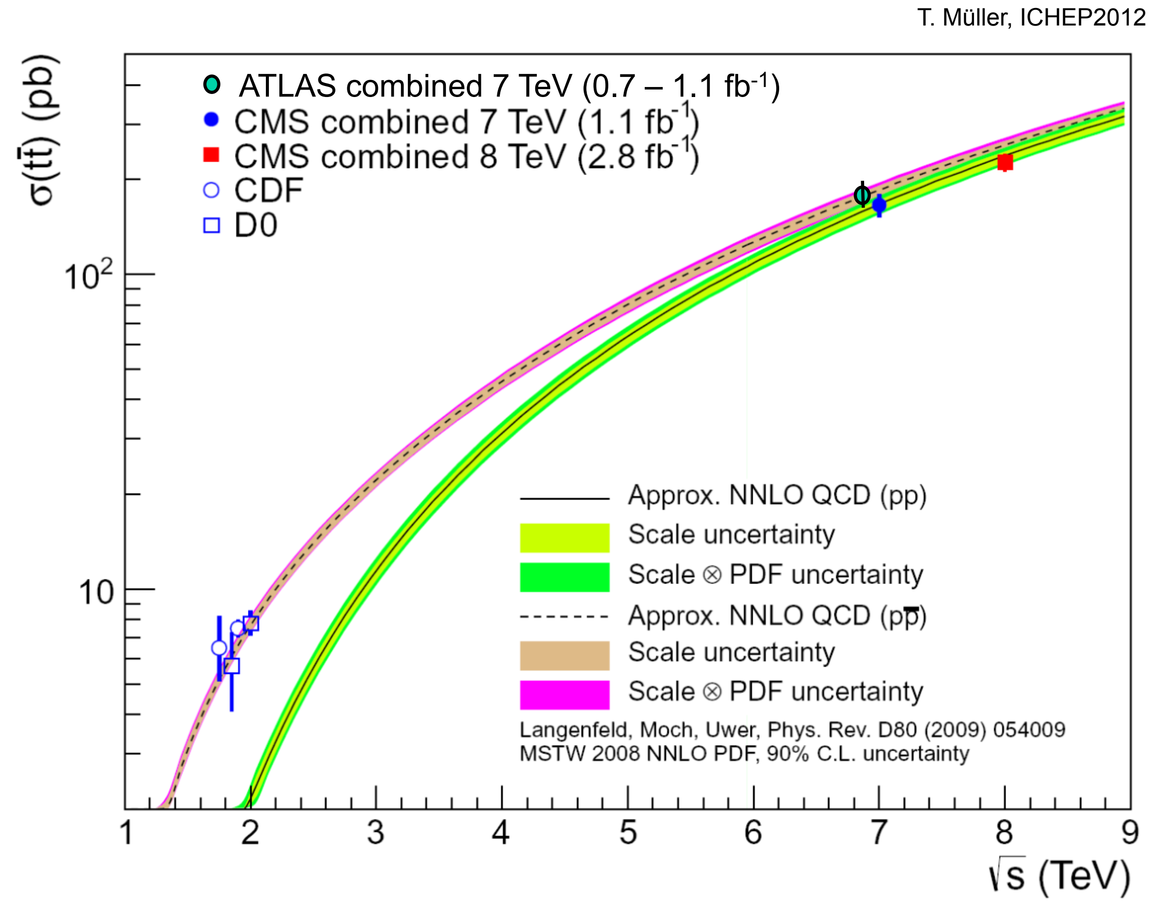
- **V+jets:**
- “triumph” for MCs with matched matrix elements and parton showers
- also multi-leg NLO calculations available by now
- confidence in background predictions for many searches

The TOP quark

Cross section



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- Total experimental uncertainty at the **6%** level! Recently even < 5%!
- similar to theoretical uncertainty (scales + PDF)
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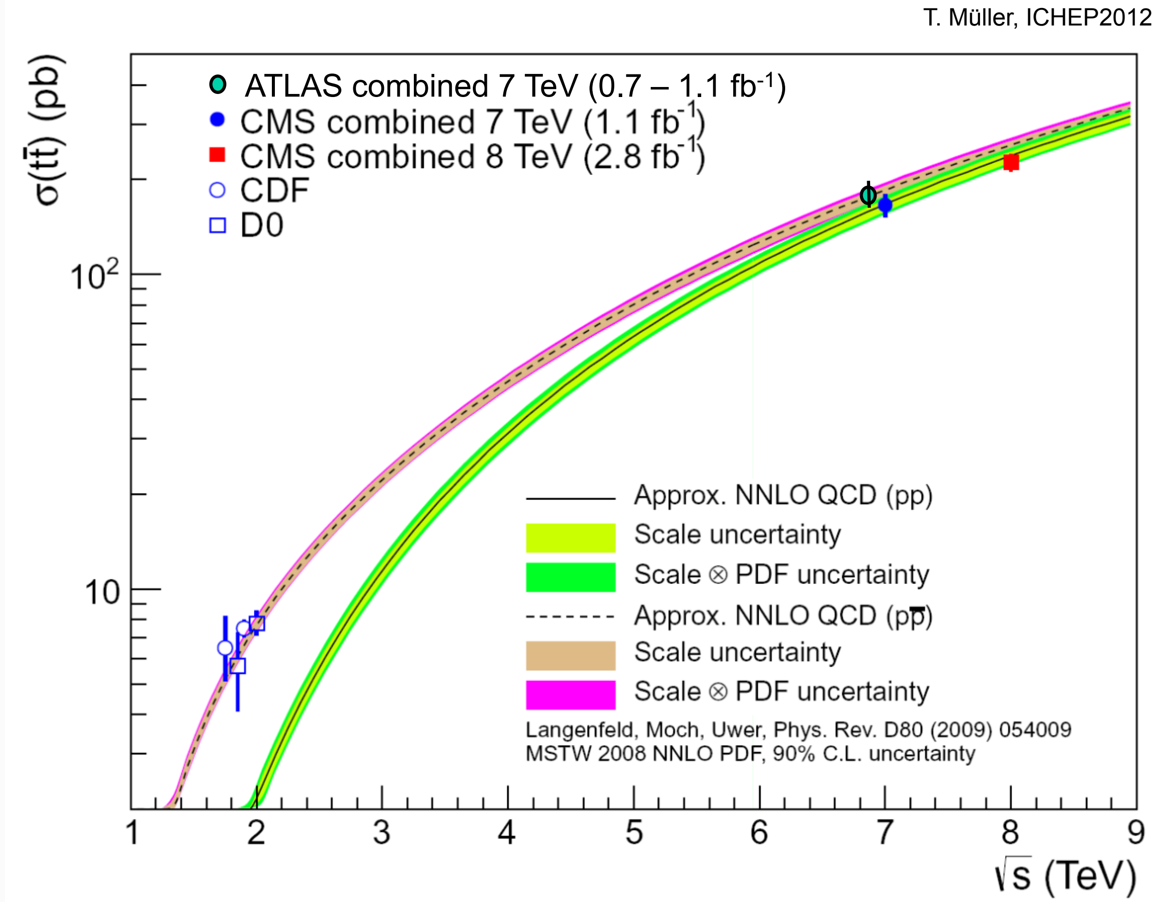
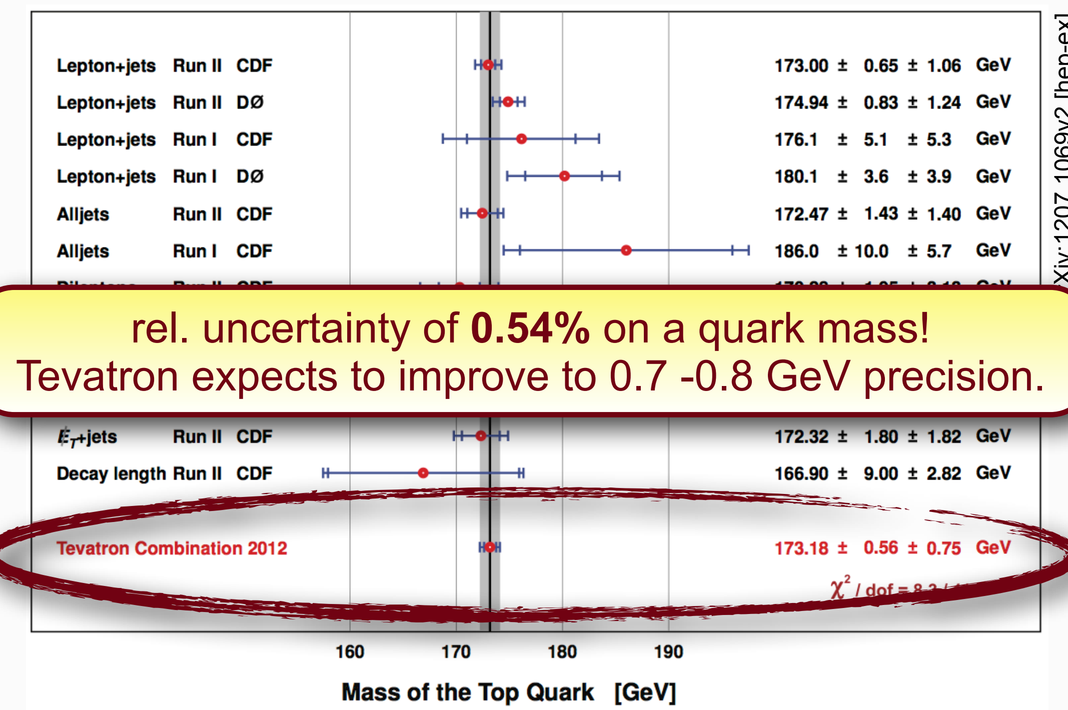
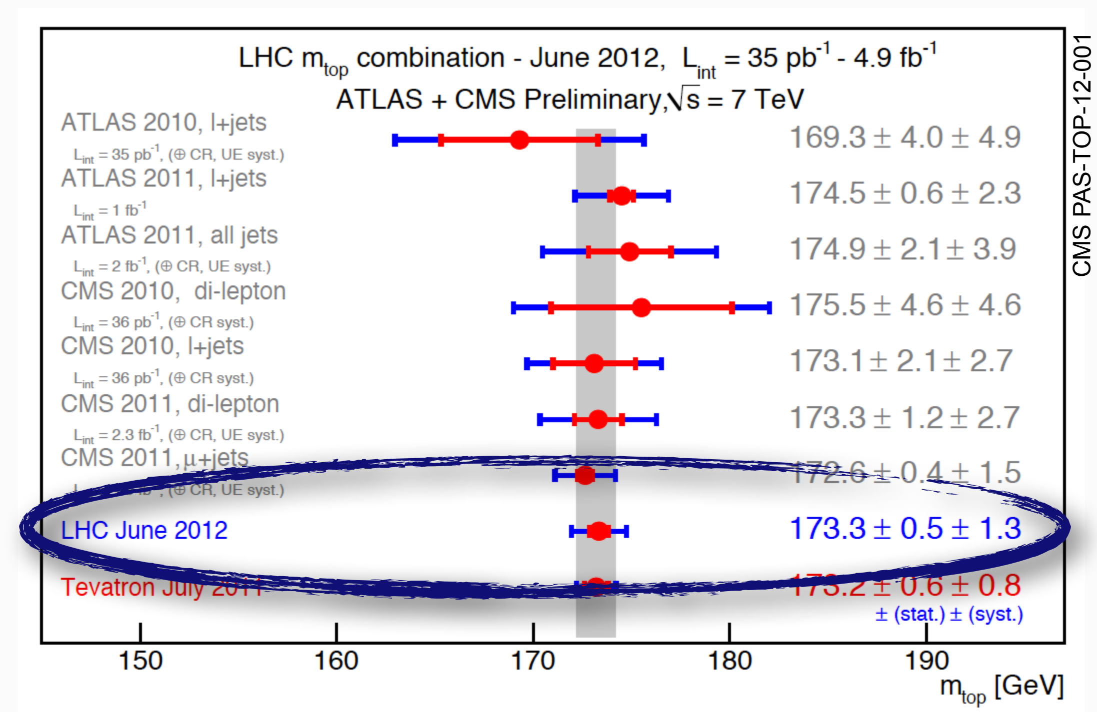


Mass (from kin. reconstruction)



rel. uncertainty of **0.54%** on a quark mass!
Tevatron expects to improve to 0.7 -0.8 GeV precision.



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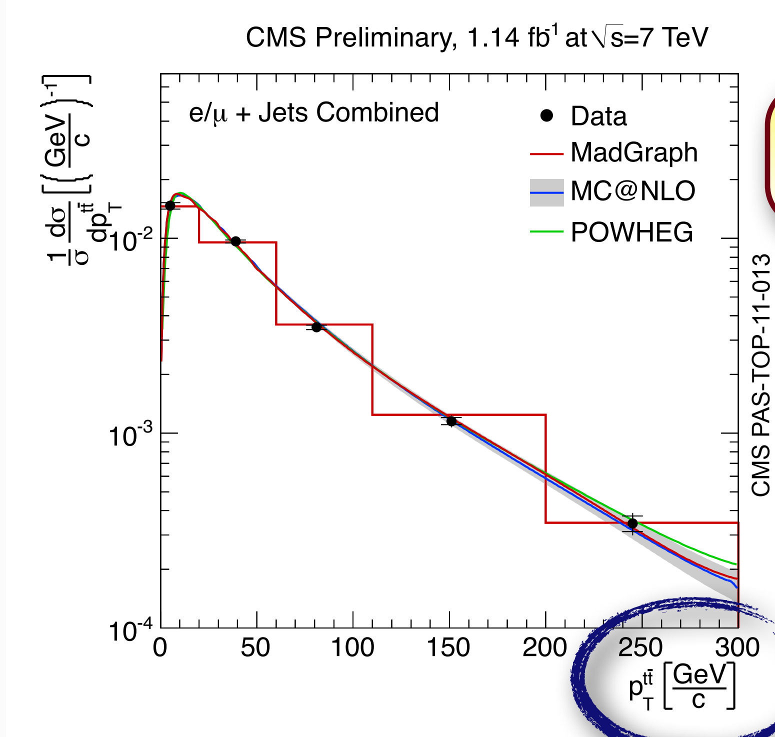
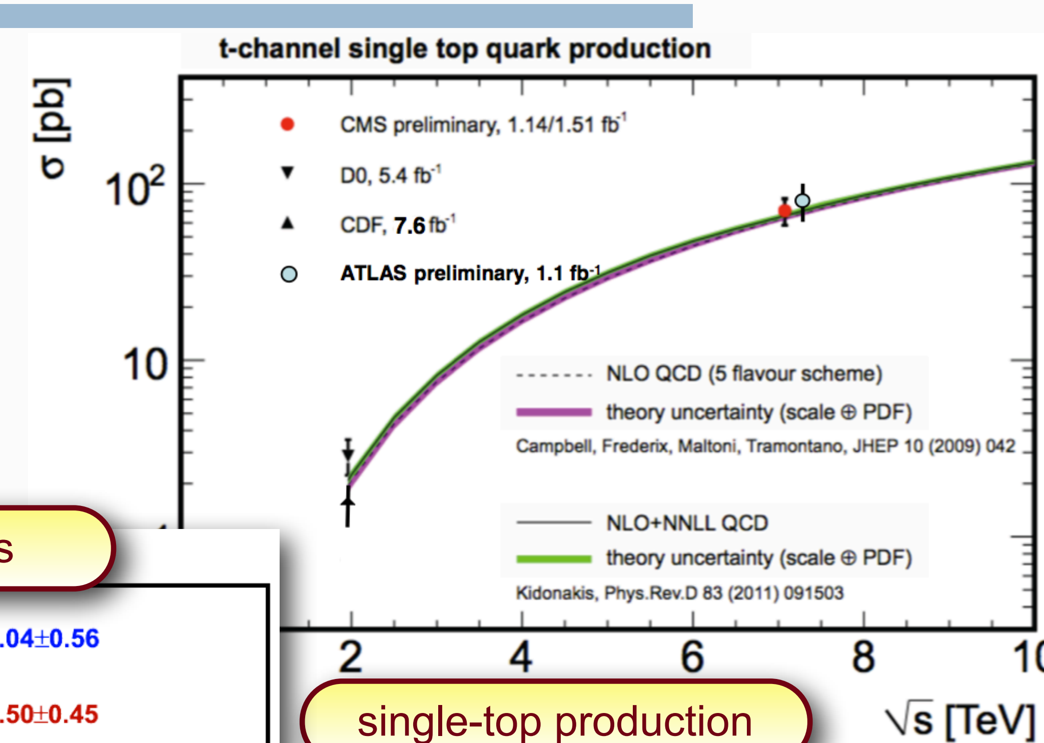
- **mass:**
- important caveat of direct reconstruction: which parameter is measured?
- theoretically cleaner method: from cross section; theory uncertainty (scales, alpha$_s$, PDF) puts limits (~6-7 GeV so far)
- proposed lepton colliders claim to attain O(100 MeV) precision

Probing the TOP

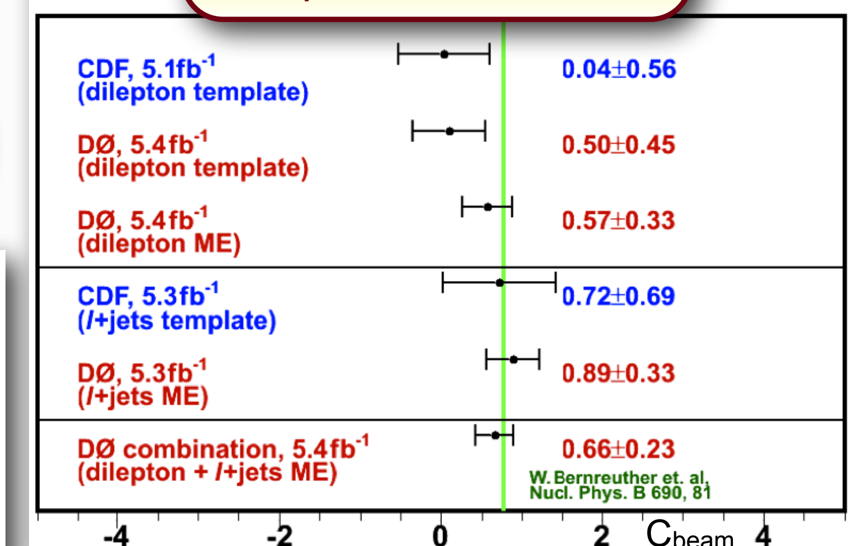


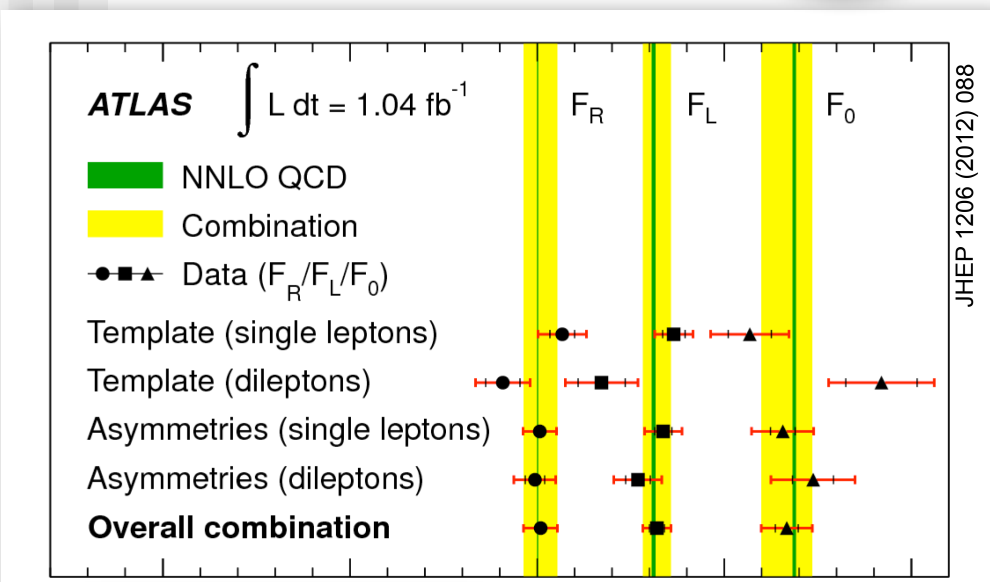
differential cross sections



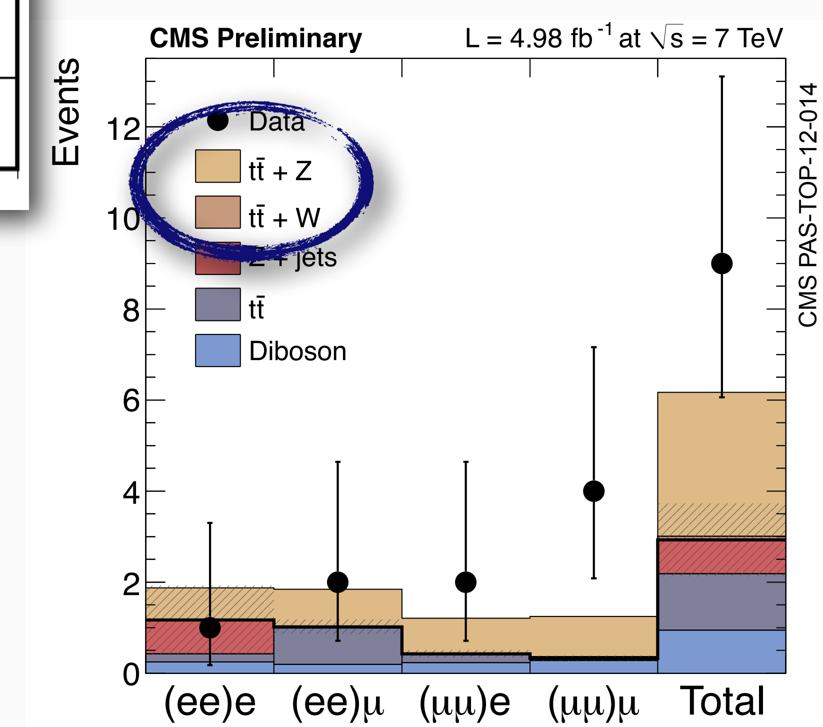
single-top production

spin correlations





W helicity fractions



very rare processes / couplings: ttV

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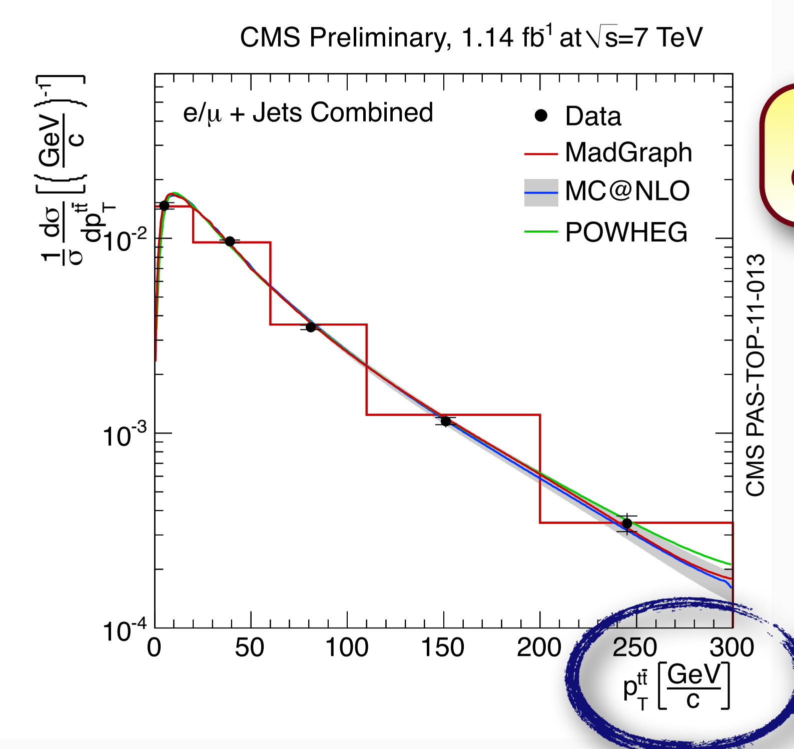

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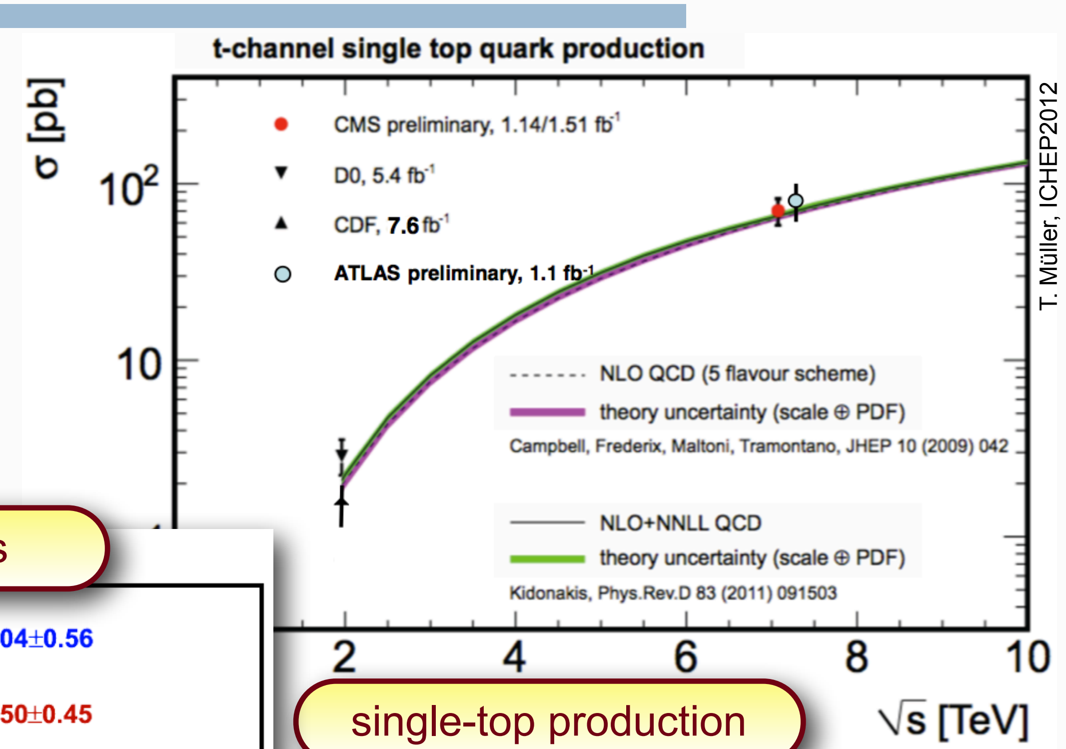

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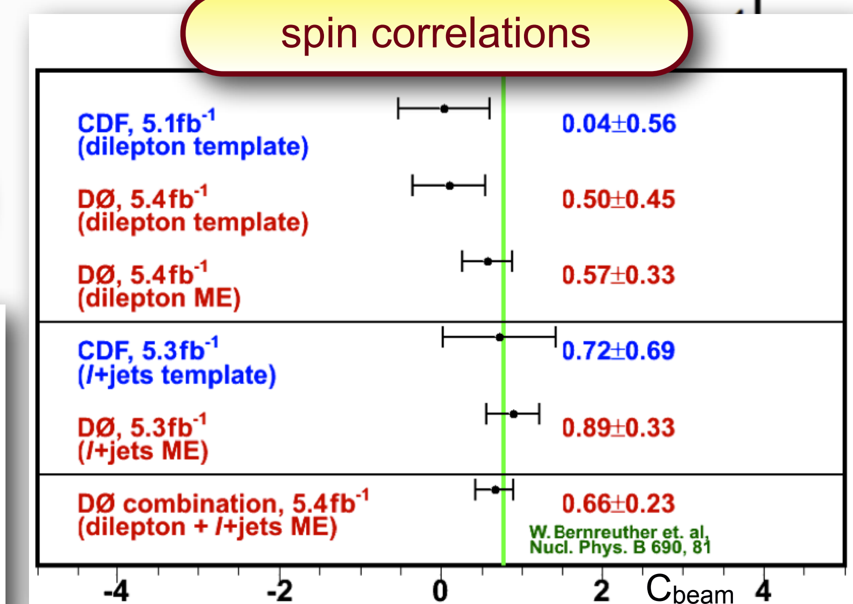

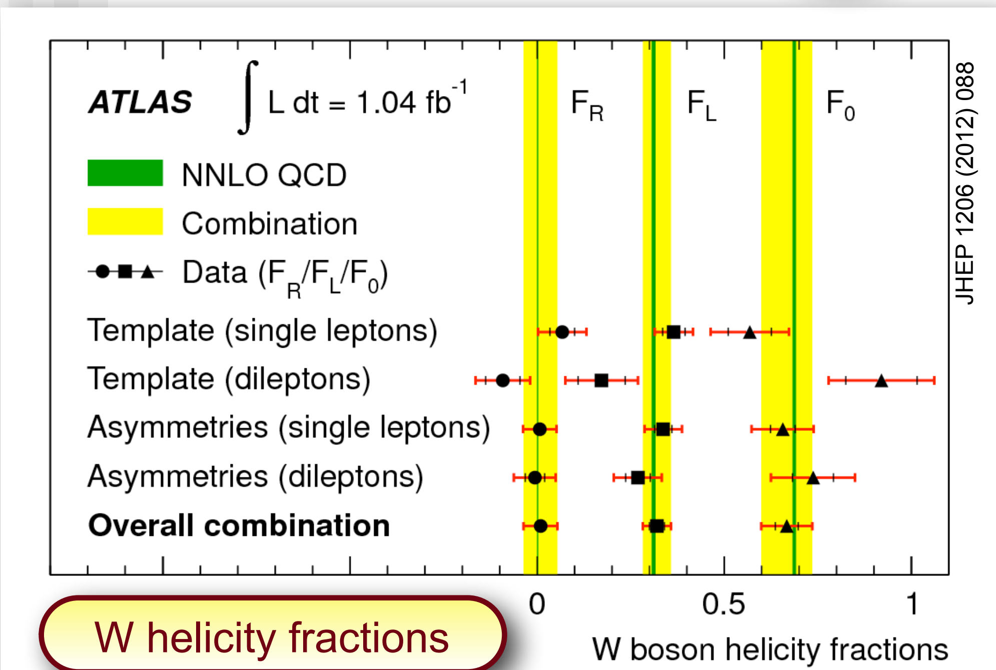

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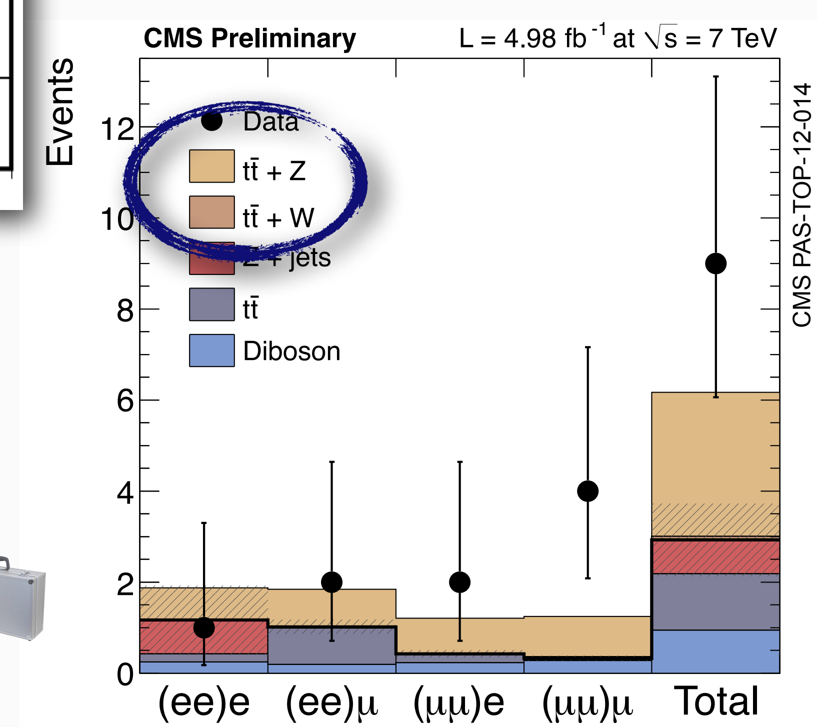
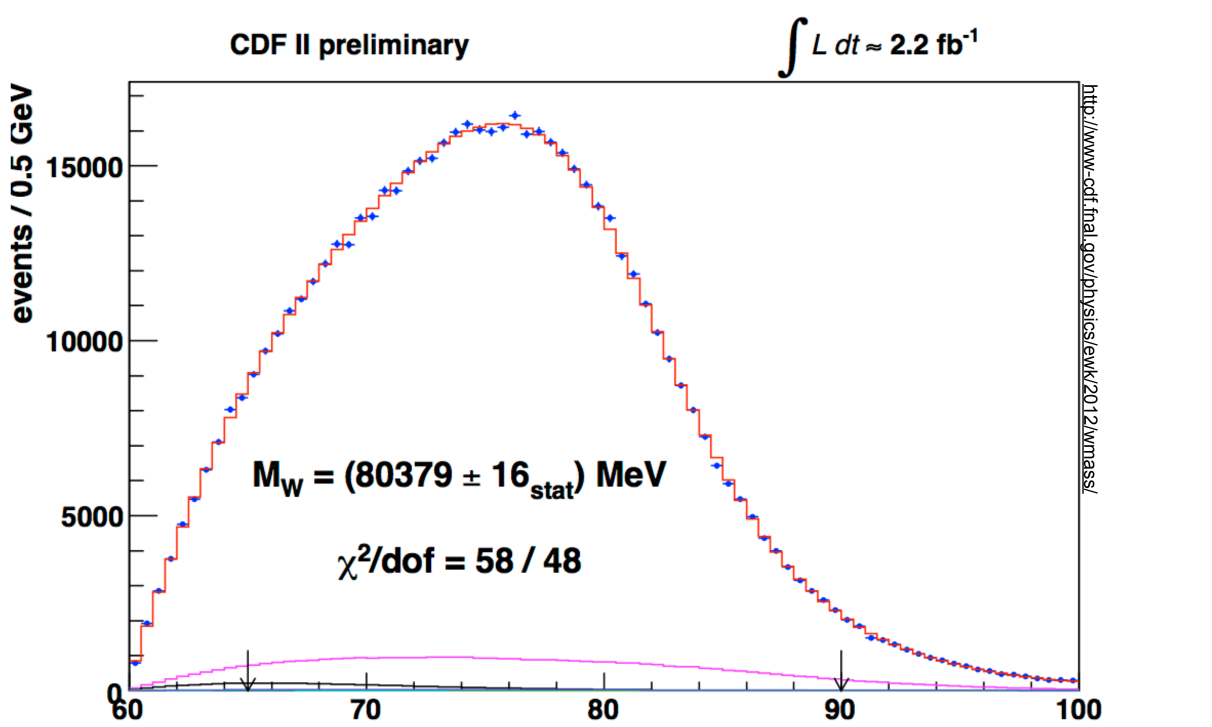


very rare processes / couplings: ttV

- **many properties tested:**
- see above, plus e.g. top charge, top width, top-antitop mass difference, charge asymmetry, top polarization, anomalous couplings (FCNC)
- agreement with SM predictions throughout, with an exception (see later)

The W mass

currently, best measurements from the TEVATRON



Also used: p_T and MET

arXiv:1203.0275 [hep-ex]

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Hadronic recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
Experimental subtotal	10
Parton distributions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson statistics	12
Total uncertainty	19

CDF: single most important uncertainty: PDF(similar for Dzero). Further improvements envisaged: PDF constraints from W charge asymmetry, extension of rapidity coverage.

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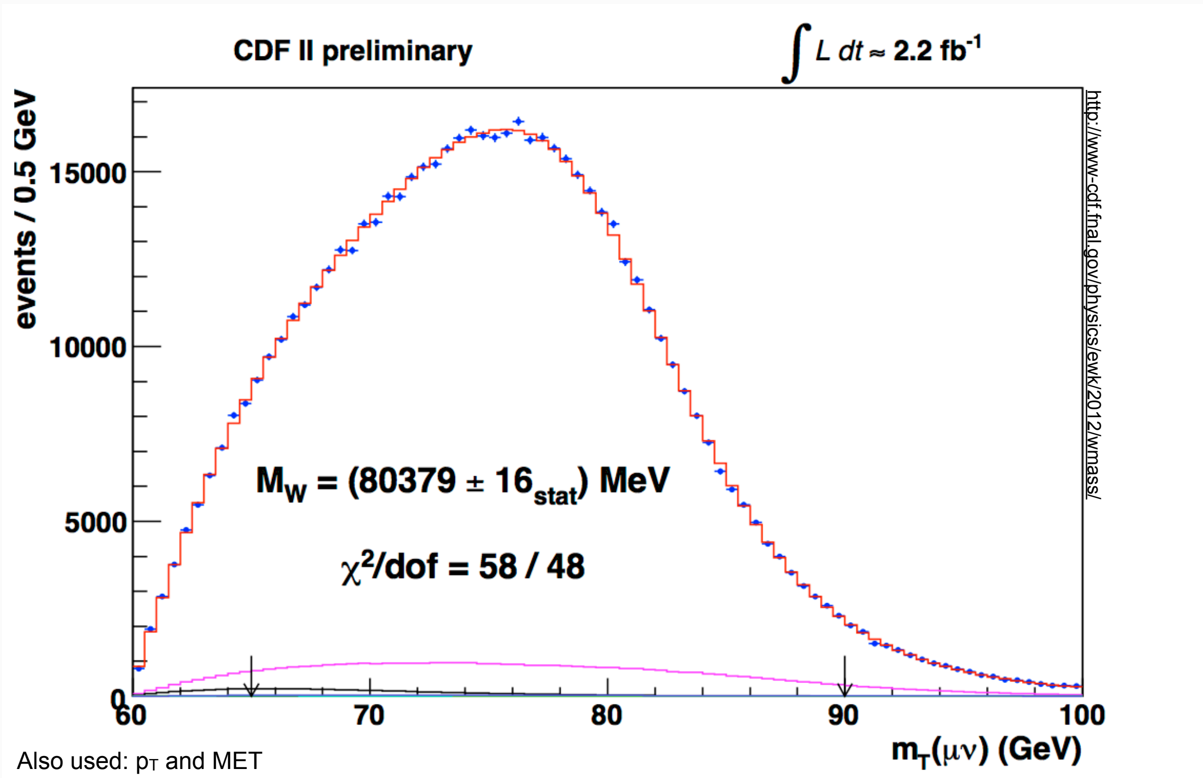

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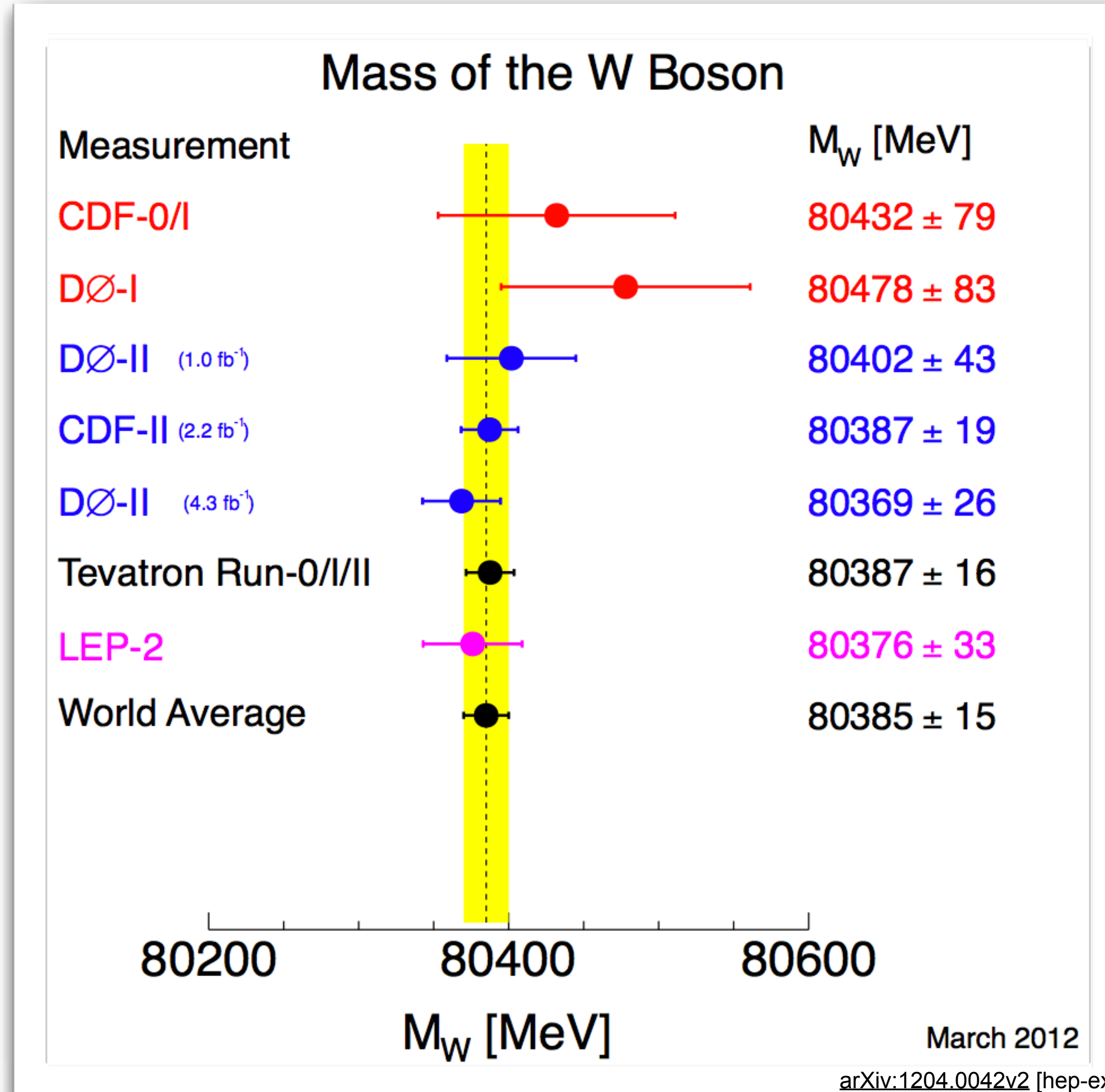
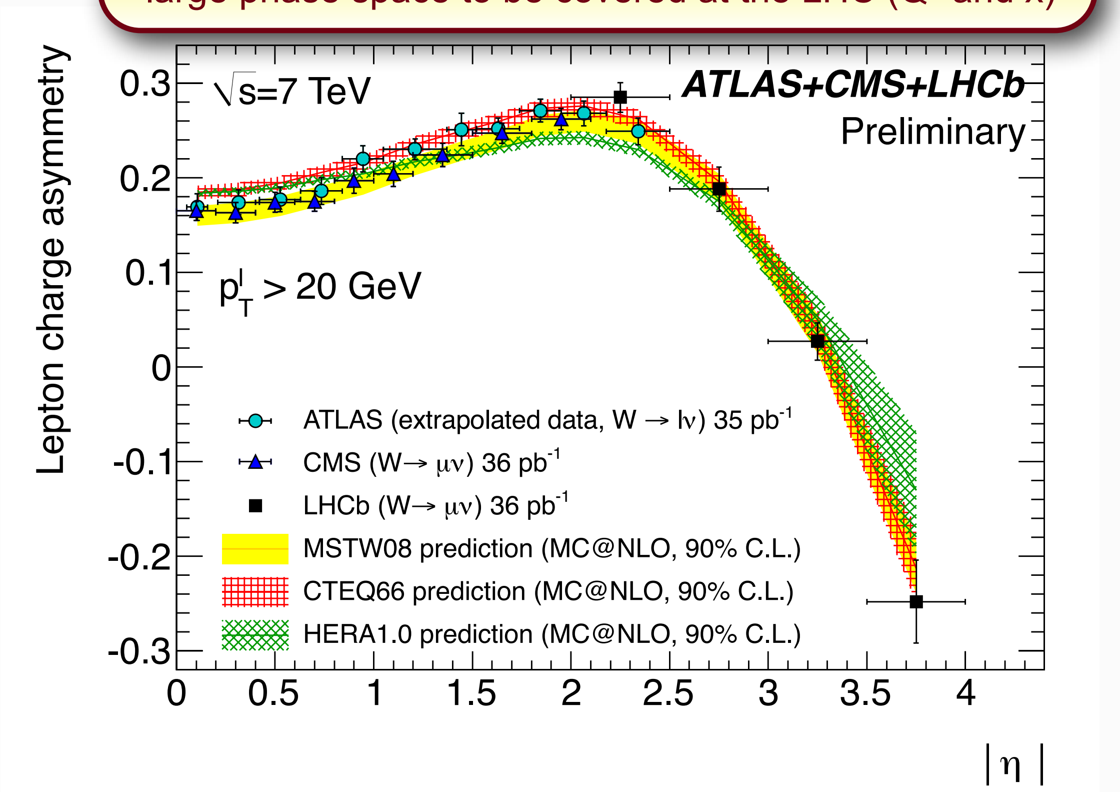


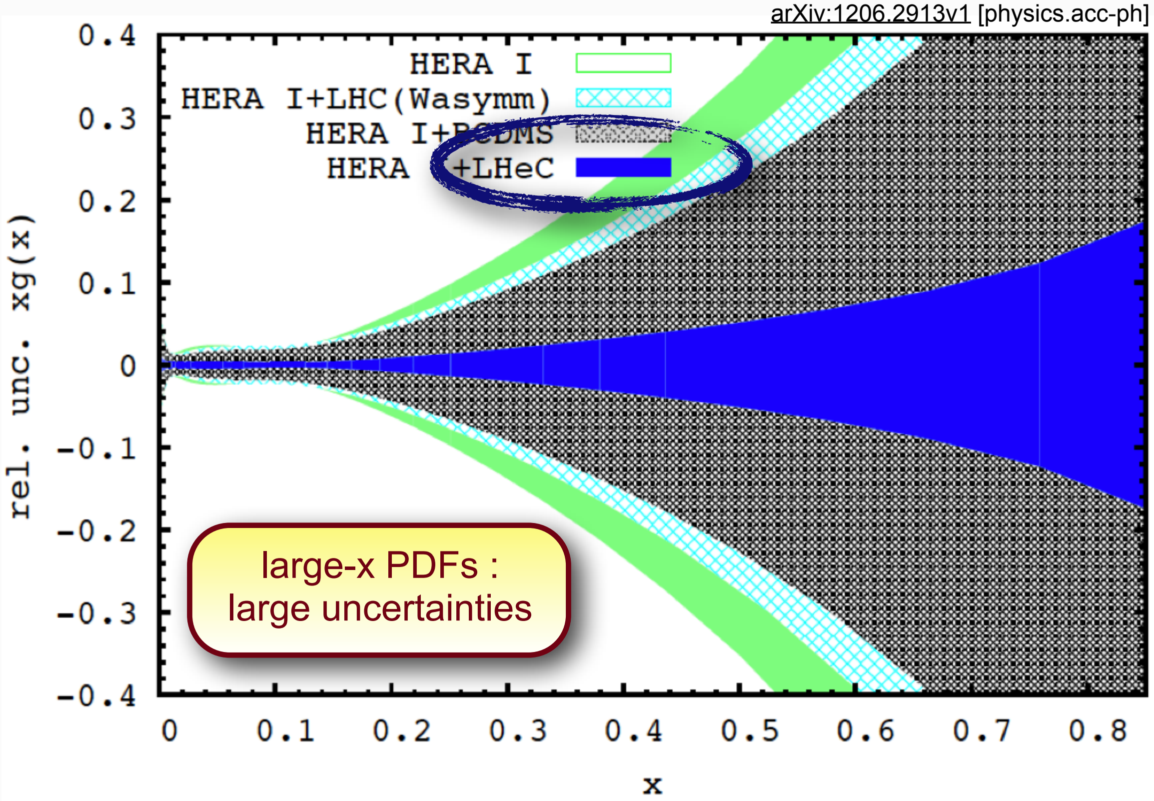
- where is the limit at hadron colliders?
- no LHC results so far, but claims are that pushing somewhat below 10 MeV might be possible
- proposed e^+e^- colliders claim to attain MeV-level precision

Improving the PDF knowledge

large phase space to be covered at the LHC (Q^2 and x)



arXiv:1206.2913v1 [physics.acc-ph]



large-x PDFs : large uncertainties

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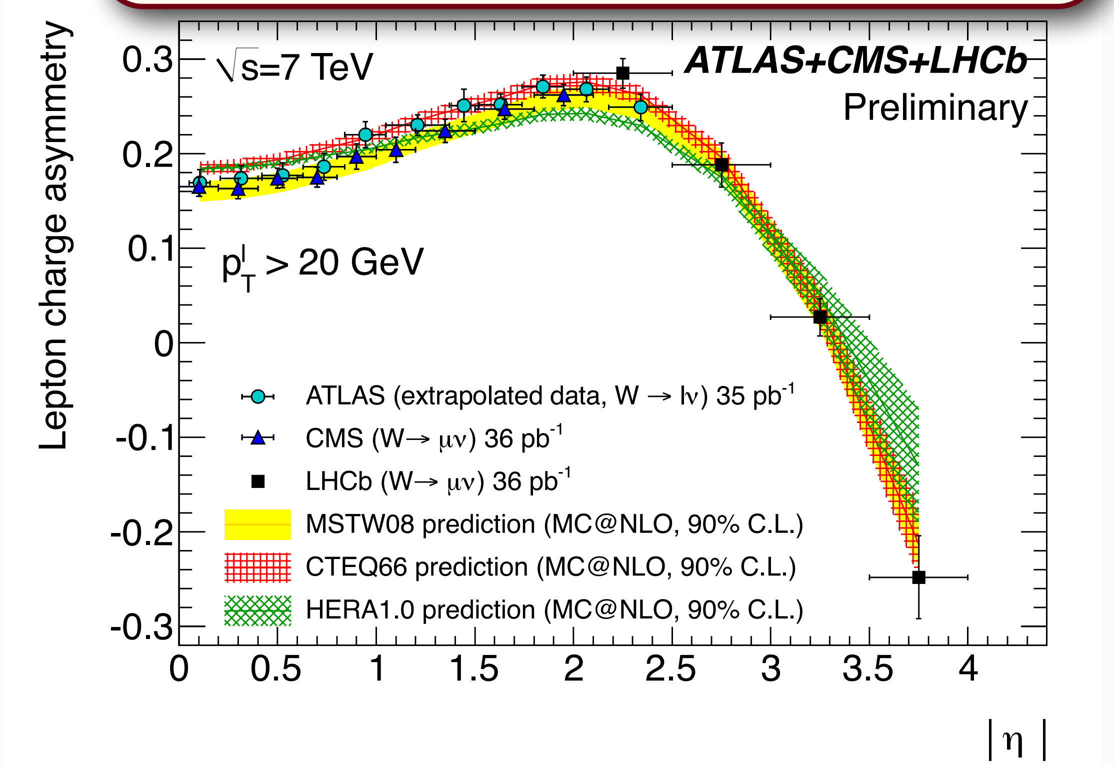

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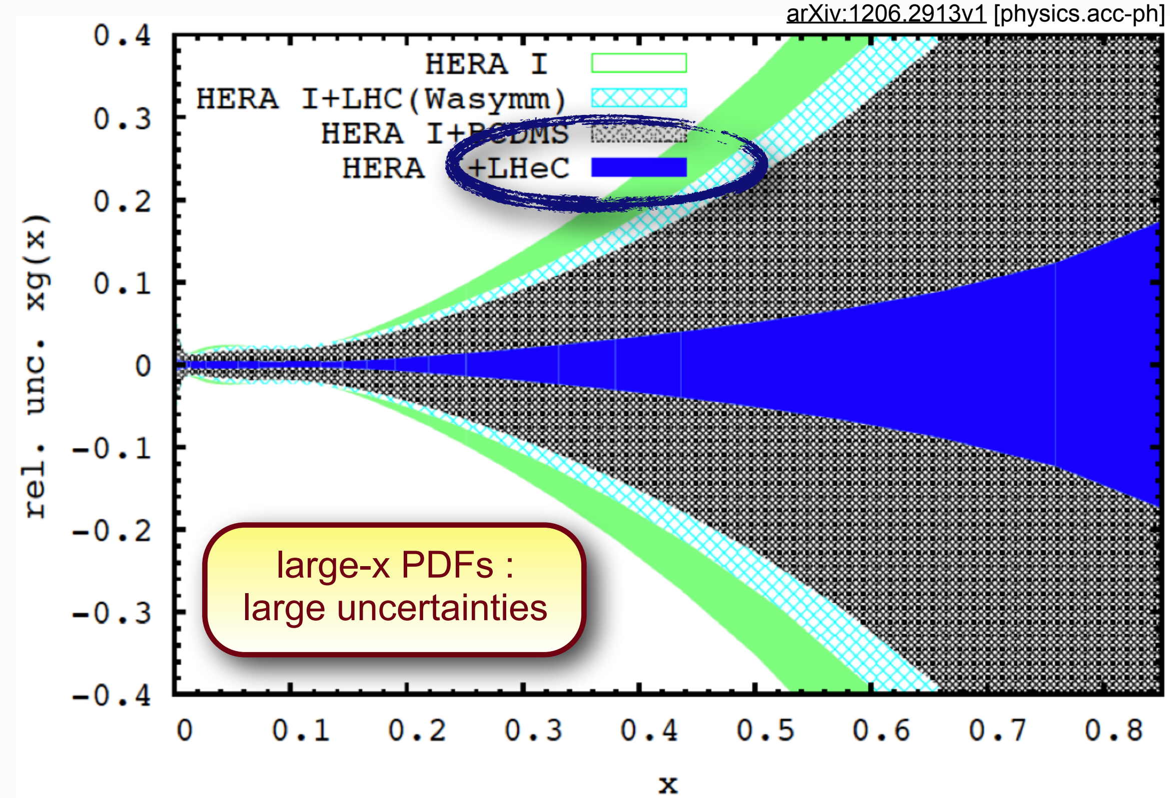

large-x PDFs :
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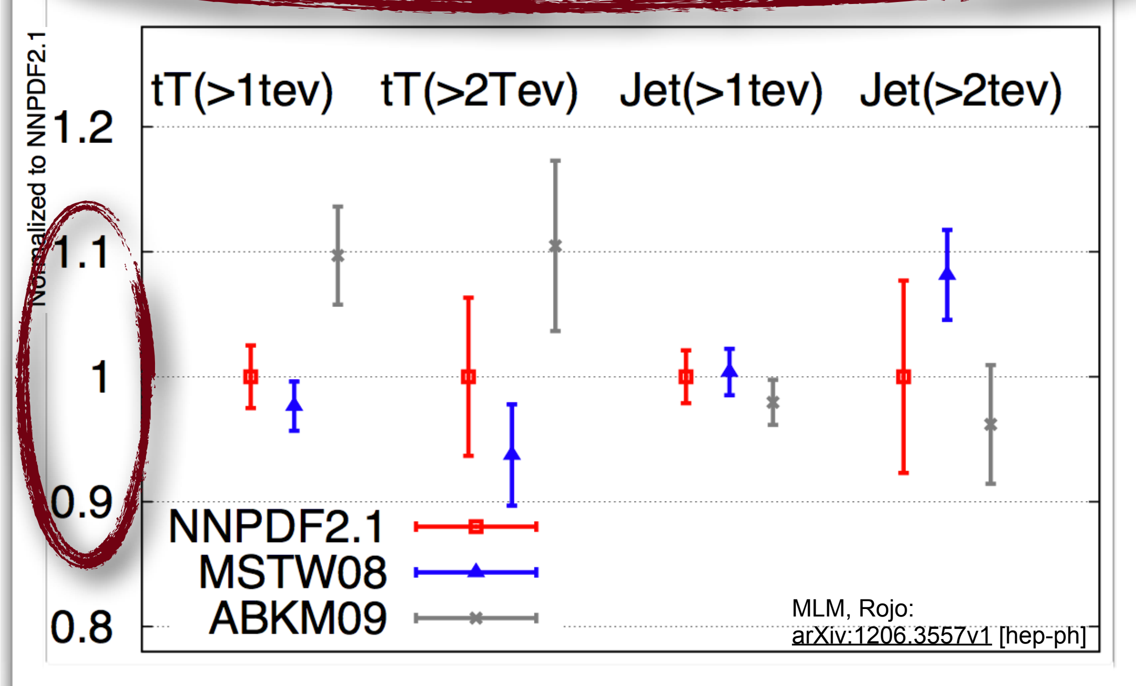
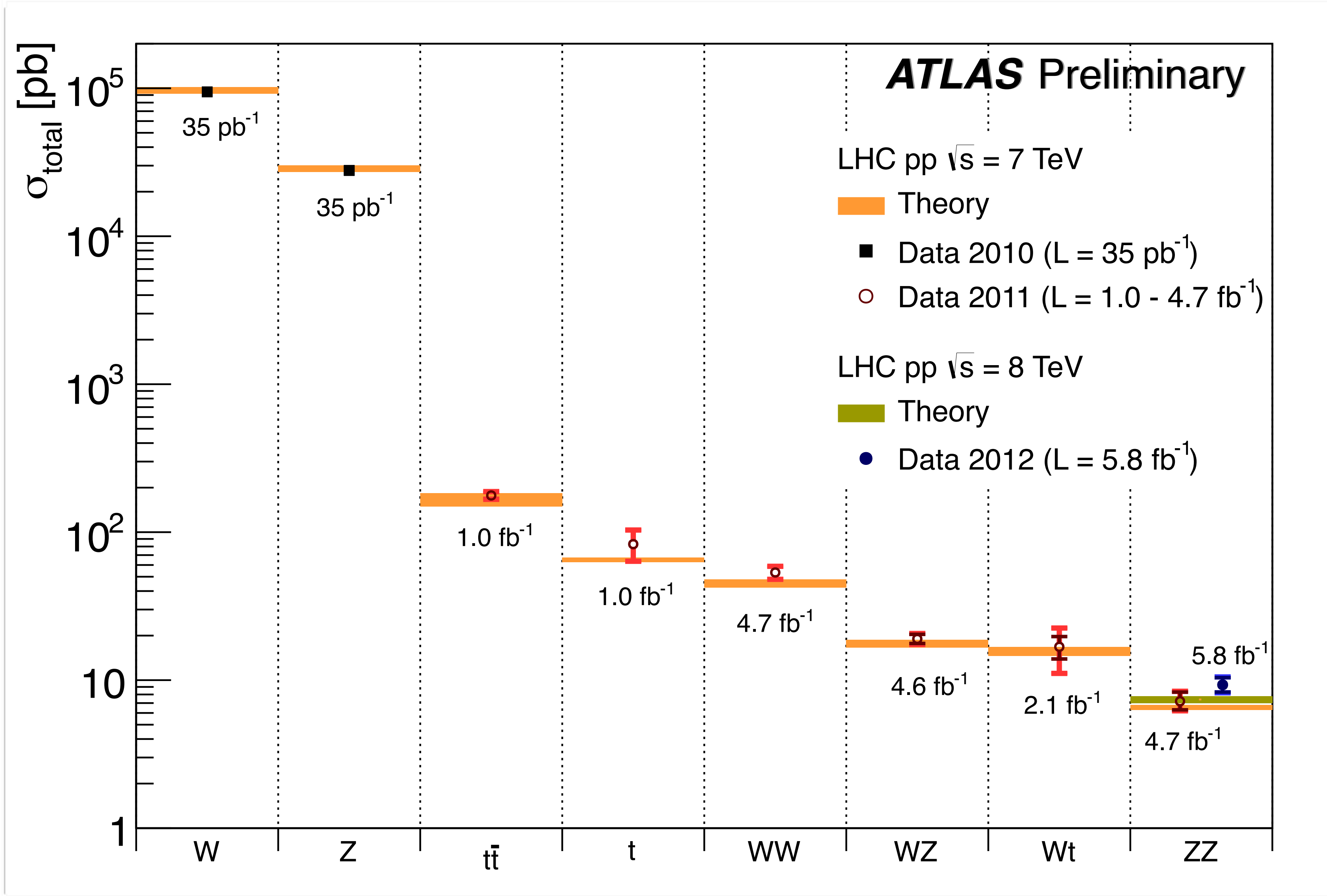
Cross section Ratios between 14 and 8 TeV



- in my mind, still a huge potential in LHC data for improving our PDF knowledge
- PDF fitter groups start to incorporate LHC data, much more hopefully to arrive in coming years
- large-x PDFs especially important for heavy-object searches
- **great potential in ratio observables**: either to obtain %-level (or better) theory predictions, or to constrain PDFs to the % level, over large x-range

The big picture

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots



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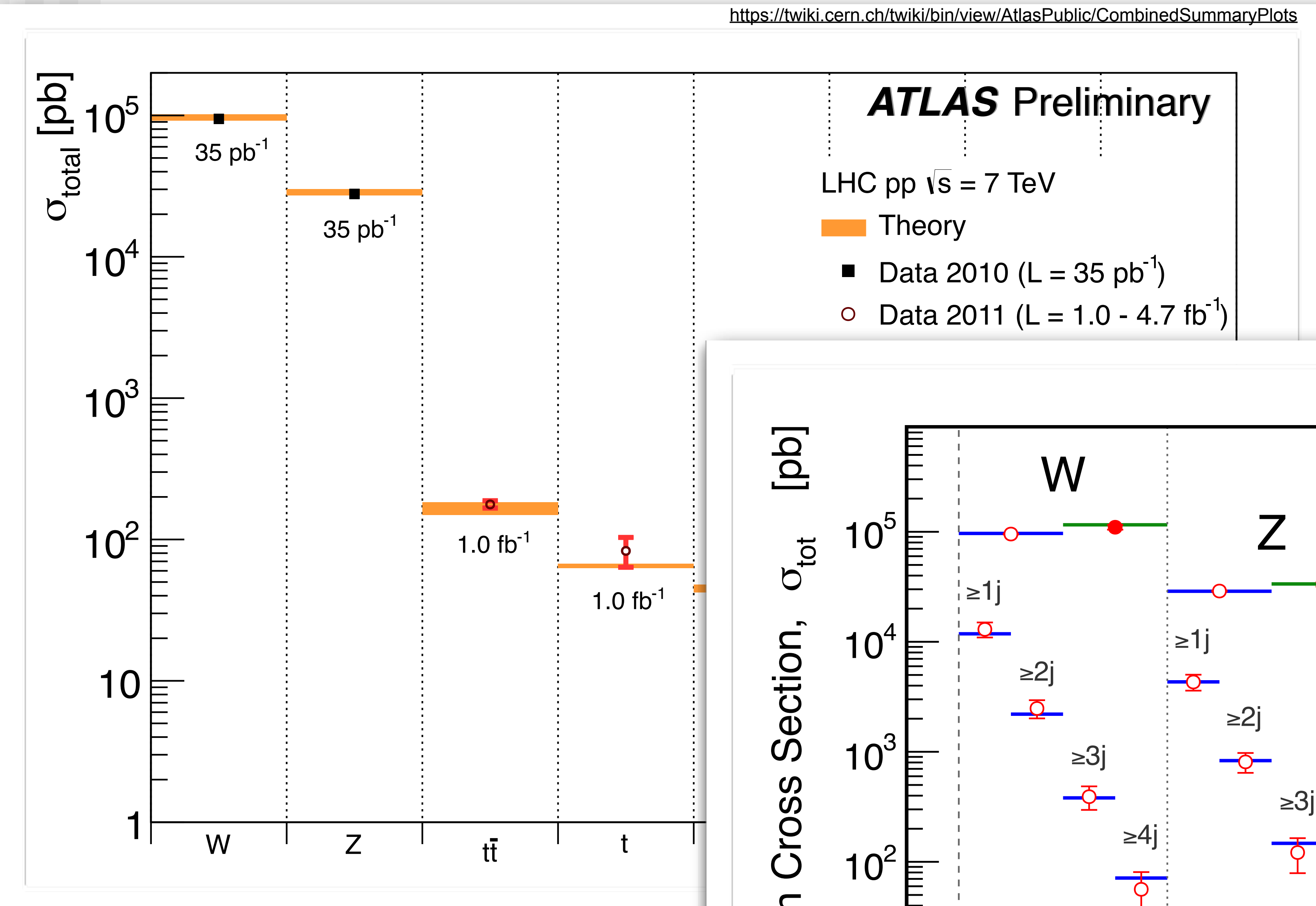

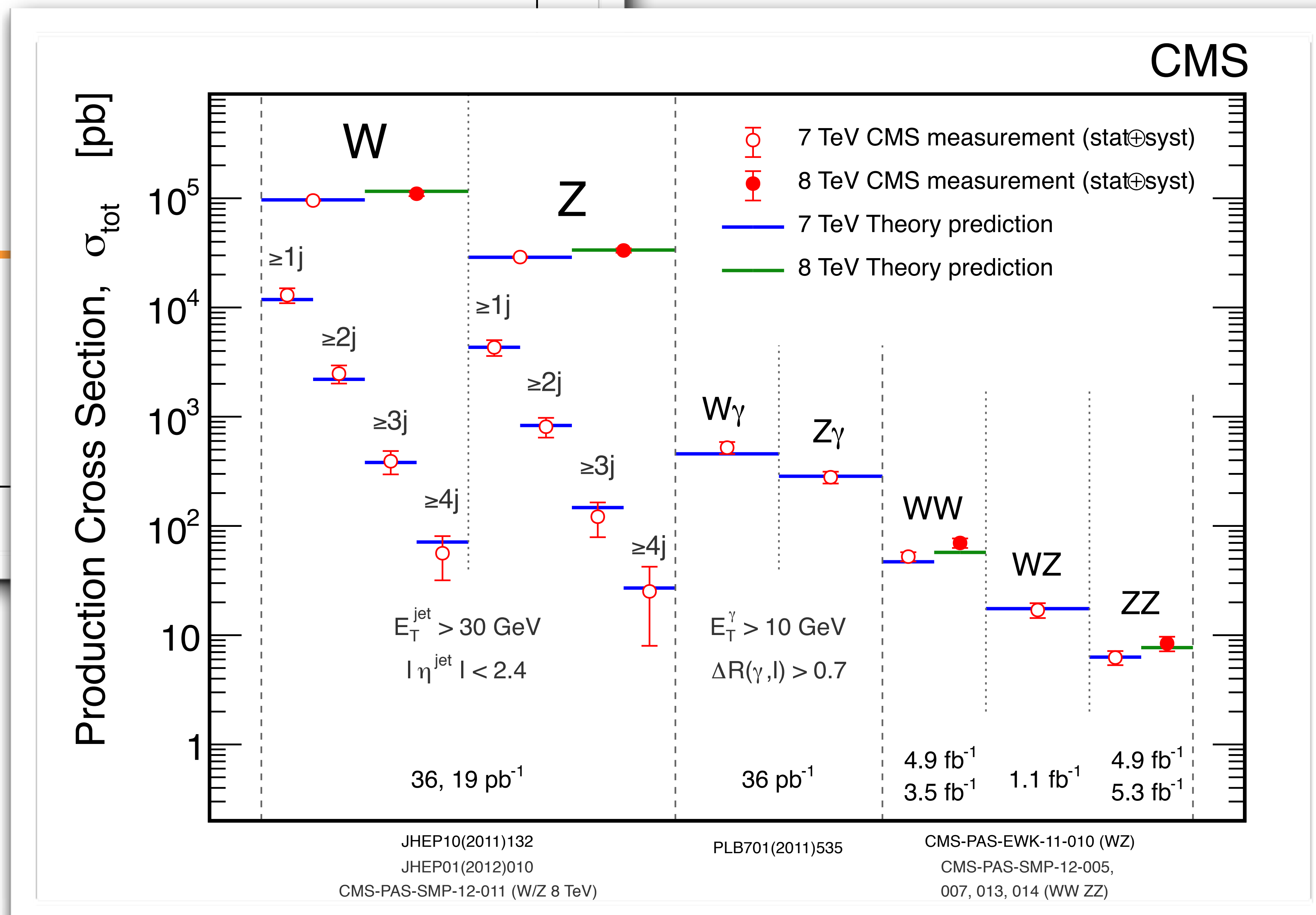

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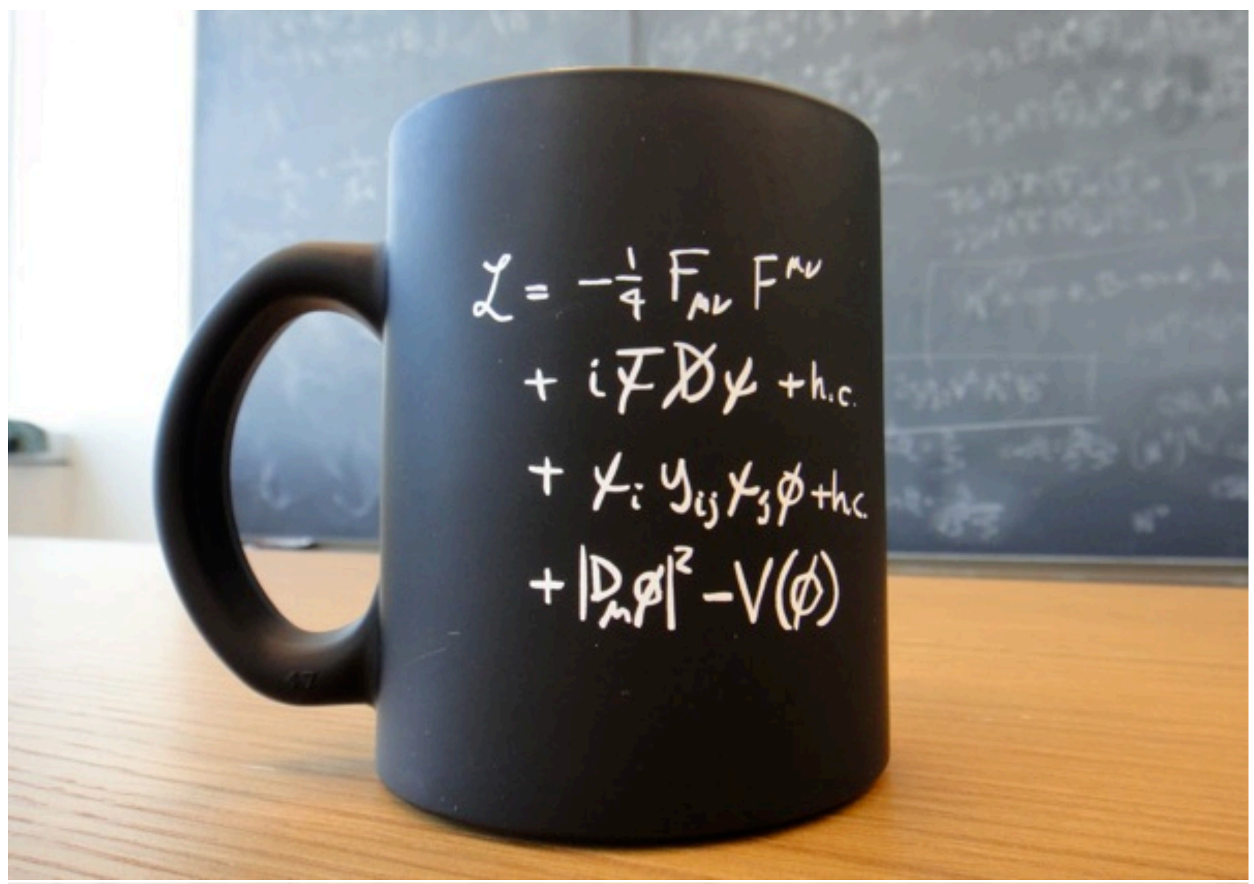
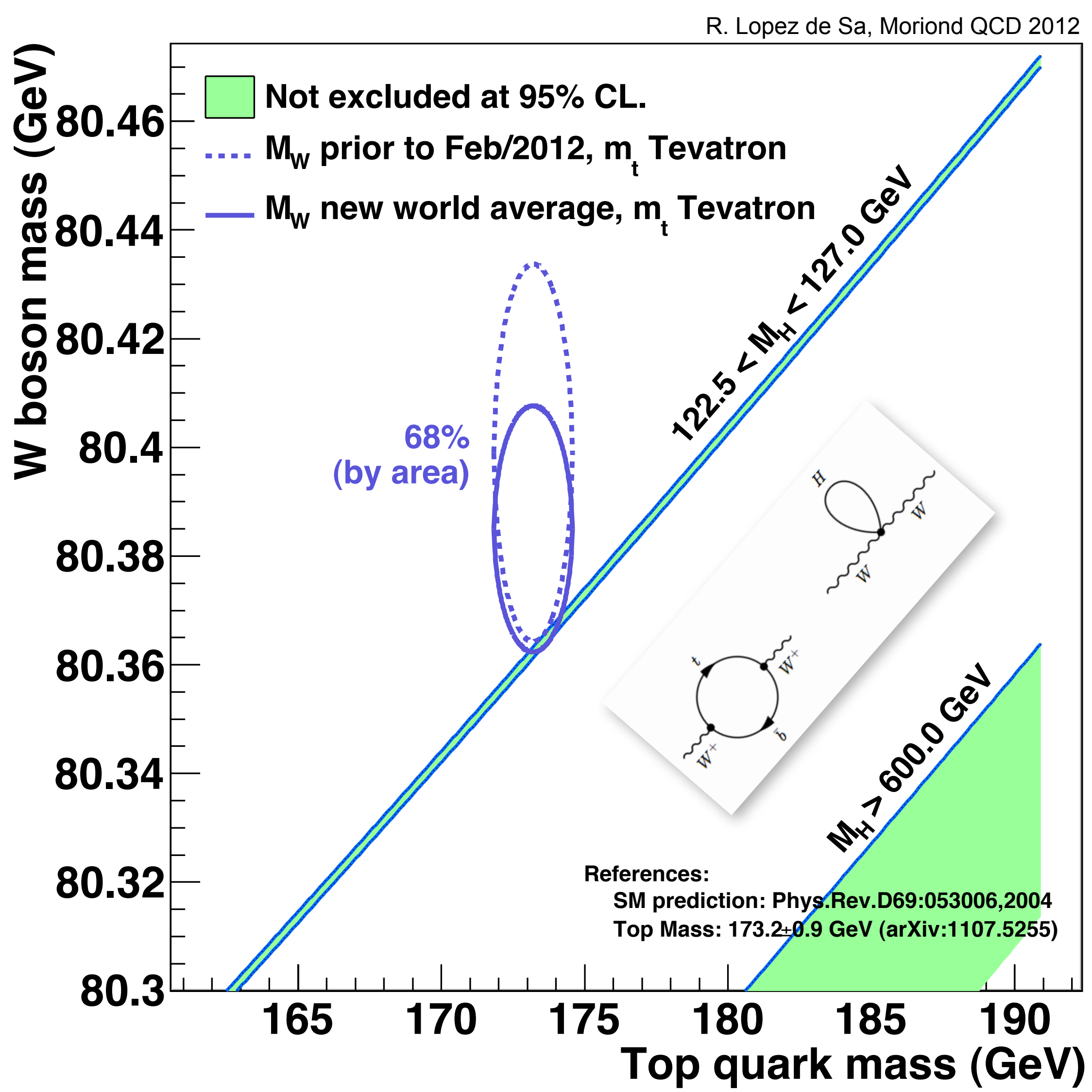
The Higgs sector



EWK fit: she did it again...



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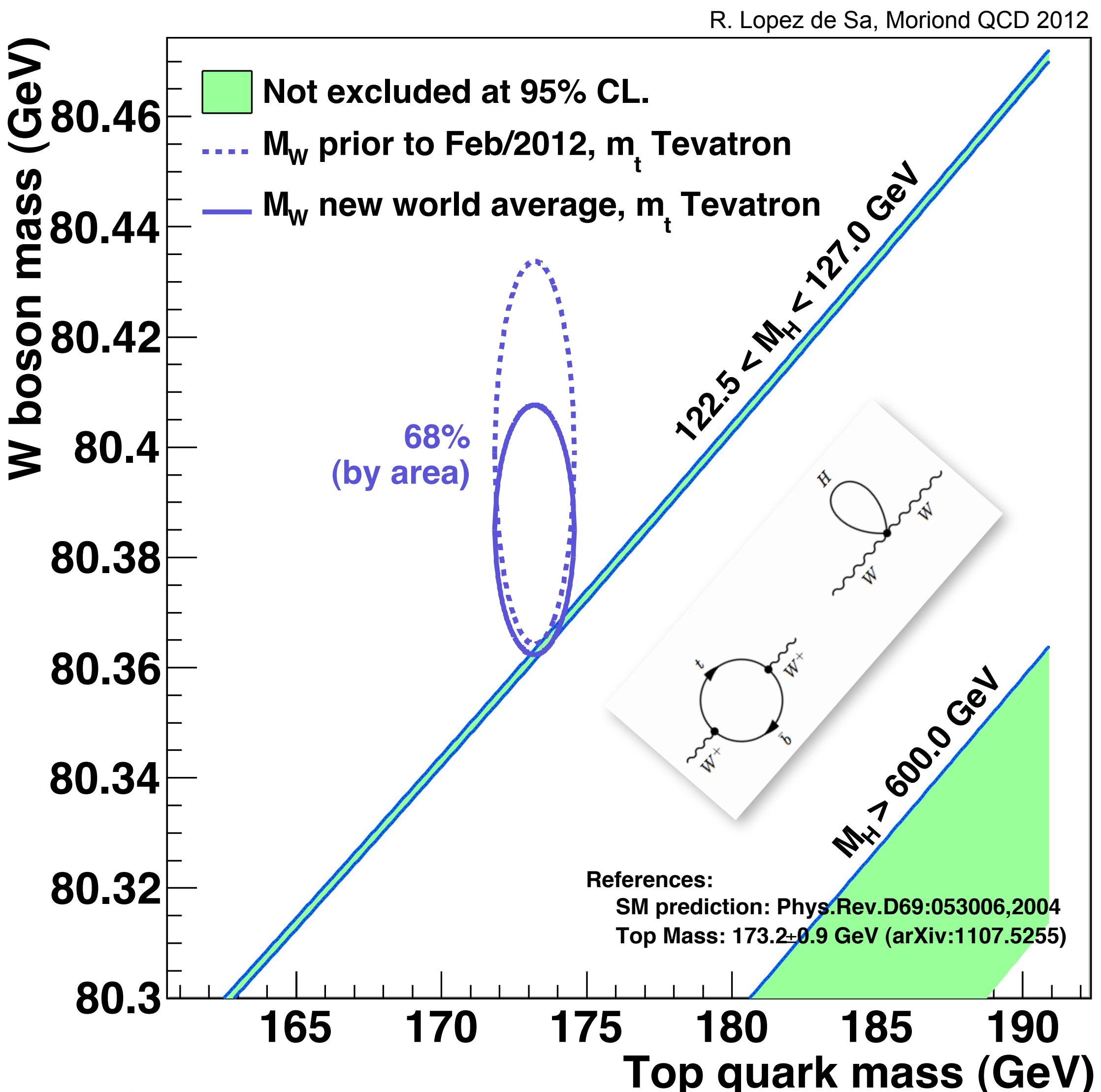

- private communication M. Grünewald:
- **adding m_H=125 ± 2 GeV to the EWK fit:**
  - gives χ^2 / Ndf = 17.95 / 14, Prob = 20.9%
  - was before: 16.85 / 13, Prob = 20.6%
  - changes in other parameters insignificant
  - most important changes in correlation matrix
- see also arXiv:1209.1101

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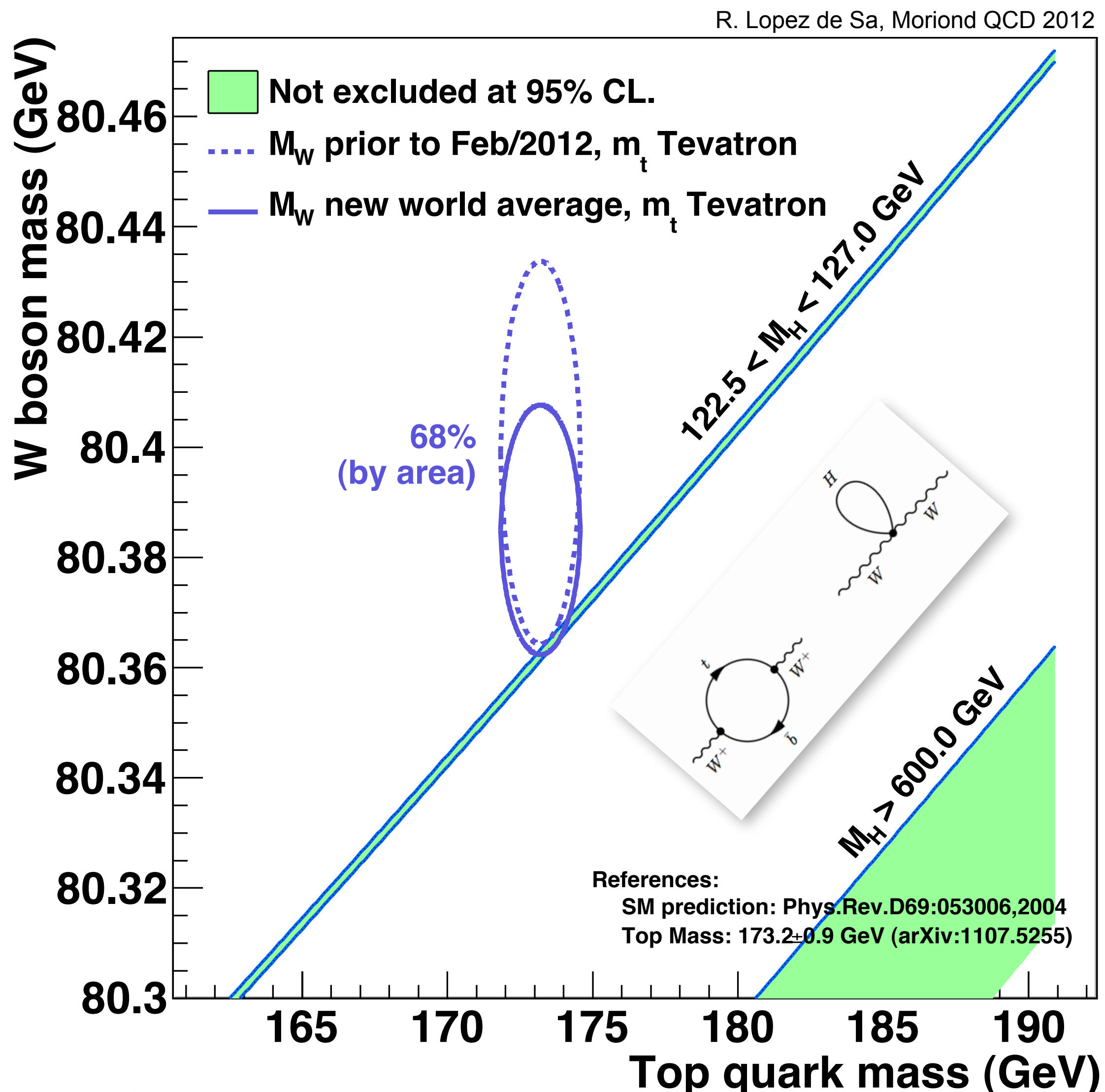
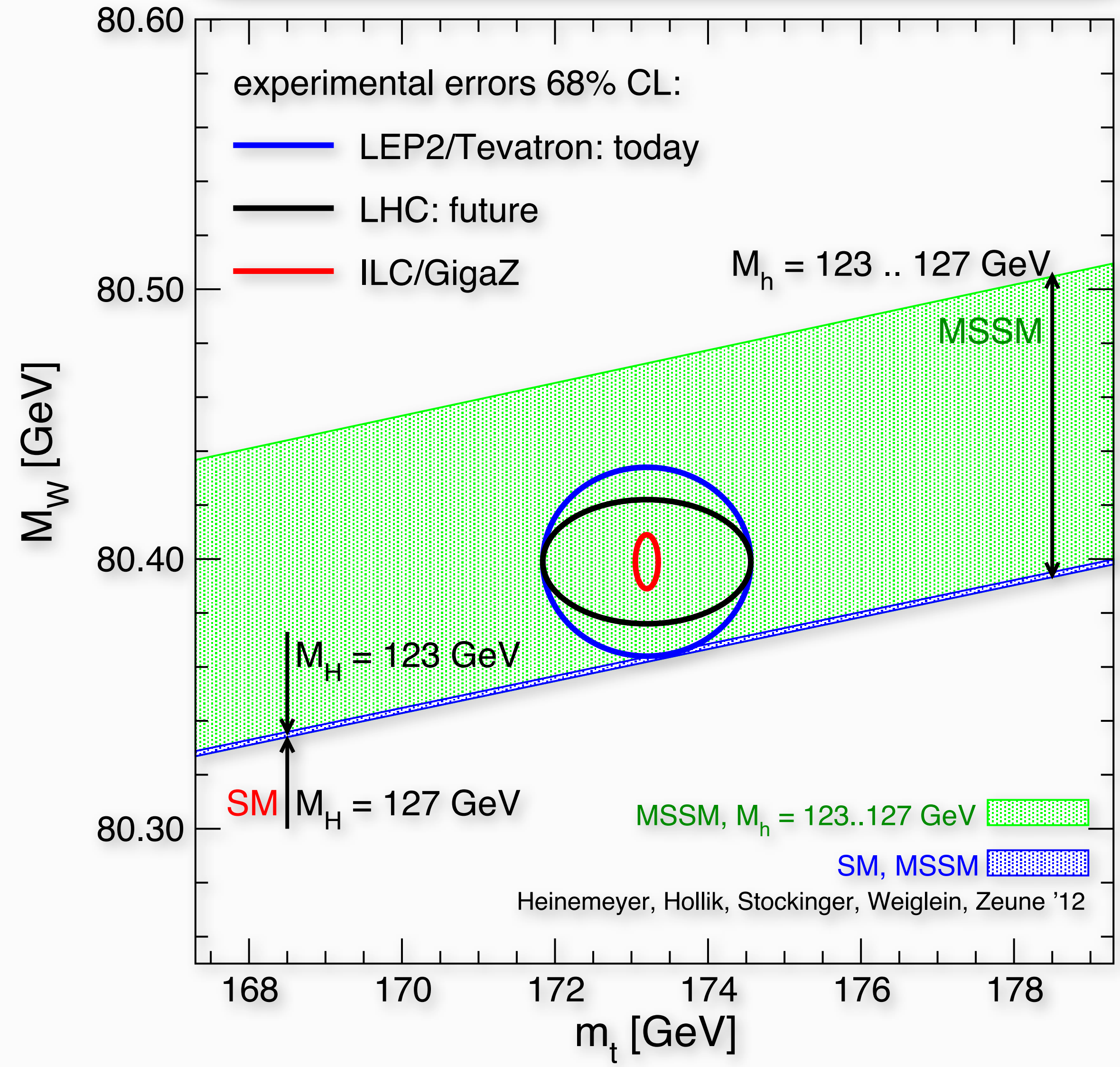


Extending the concept to a BSM framework, and projections:



see http://www.ifca.es/users/heinemey/uni/plots/

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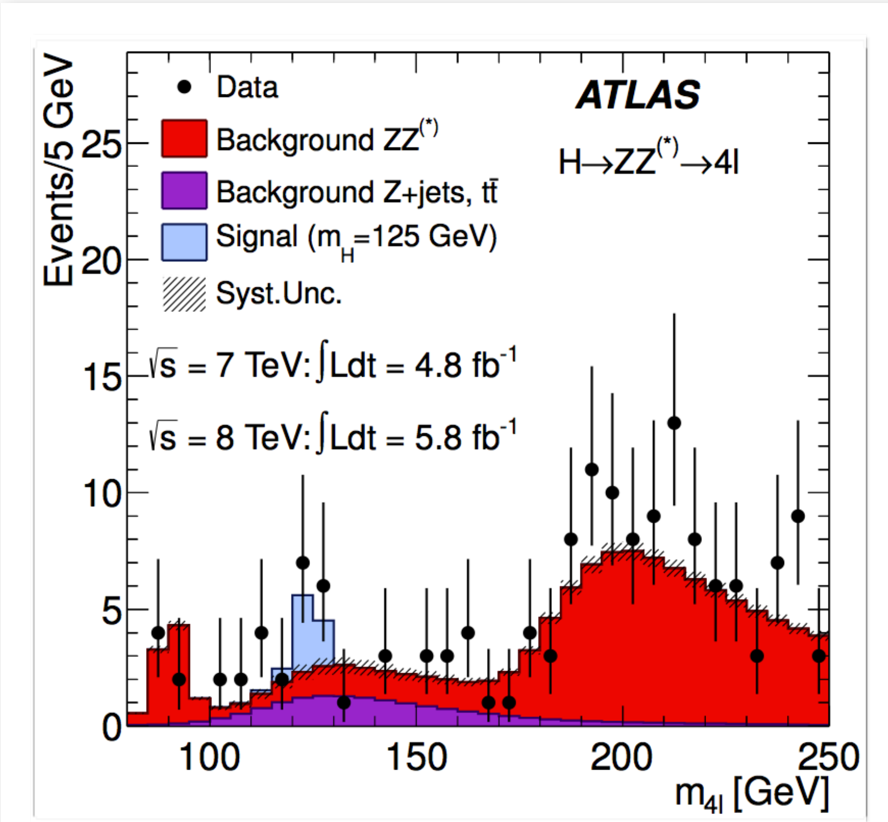
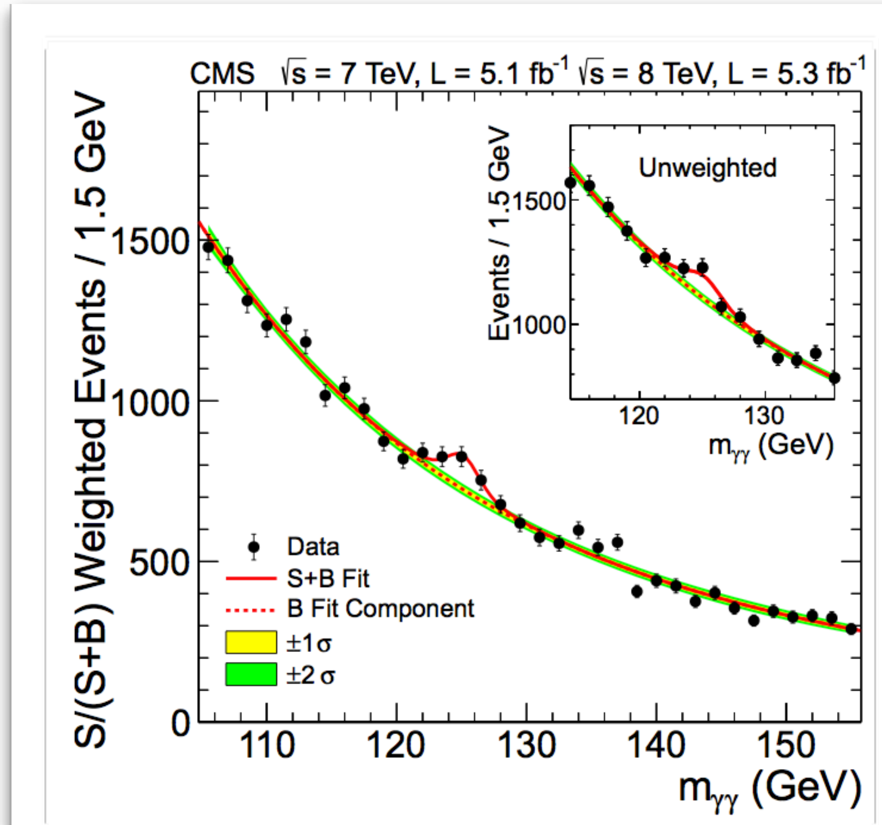
The LHC discovery



arXiv:1207.7214v1 [hep-ex]



arXiv:1207.7235v1 [hep-ex]

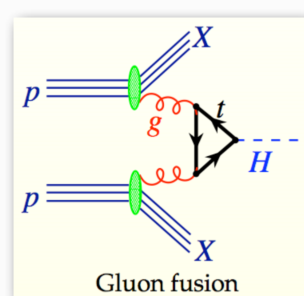
Channel	m_H range (GeV)	L_{2011} (fb^{-1})		L_{2012} (fb^{-1})		ggH		VBF		VH		ttH	
		A	C	A	C	A	C	A	C	A	C	A	C
$H \to \gamma\gamma$	110-150	4.8	5.1	5.9	5.3	√	√	√	√	-	-	-	-
$H \to \tau^+\tau^-$	110-140	4.7	5.1	-	5.0	√	√	√	√	√	√	√	-
$H \to b\bar{b}$	110-130	4.6	5.1	-	5.0	-	-	-	-	√	√	-	√
$H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$	110-600	4.8	5.1	5.8	5.3	√	√	-	-	-	-	-	-
$H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$	110-600	4.7	4.7	5.8	5.3	√	√	√	√	-	√	-	-
$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$	200-600	4.8	4.7	-	-	√	√	√	√	-	-	-	-
$H \to ZZ \to \ell^+\ell^-q\bar{q}$	130-600	4.8	4.7	-	-	√	√	√	√	-	-	-	-
$H \to WW \to \ell\nu q\bar{q}'$	300-600	4.8	4.7	-	-	√	√	√	√	√	-	-	-

from: Heinemeyer et al, *Implications of LHC results for TeV-scale physics: signals of electroweak symmetry breaking,* Submitted to the Open Symposium of the European Strategy Preparatory Group.

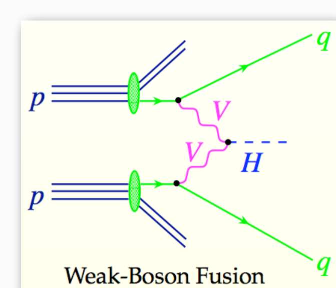
A=ATLAS
C=CMS
√ = channel analyzed

in terms of production,

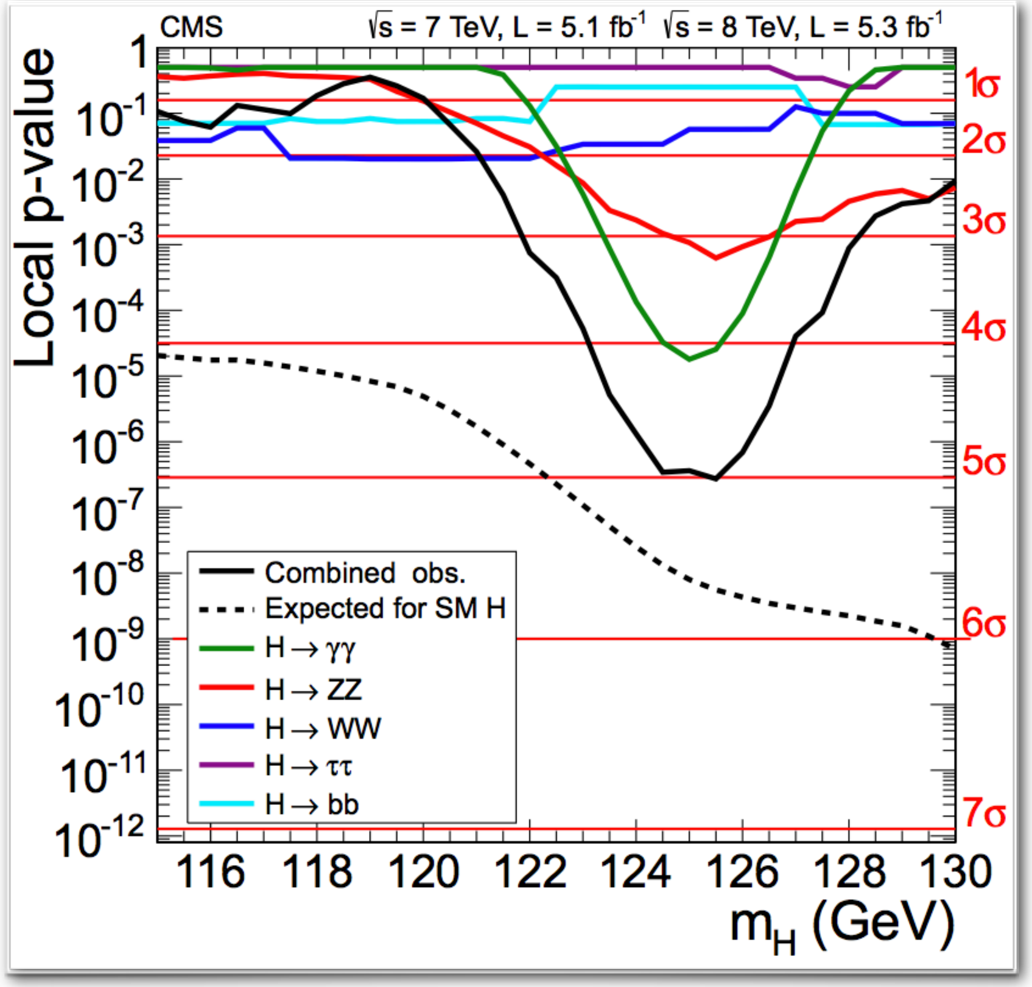
so far most of the LHC sensitivity comes from



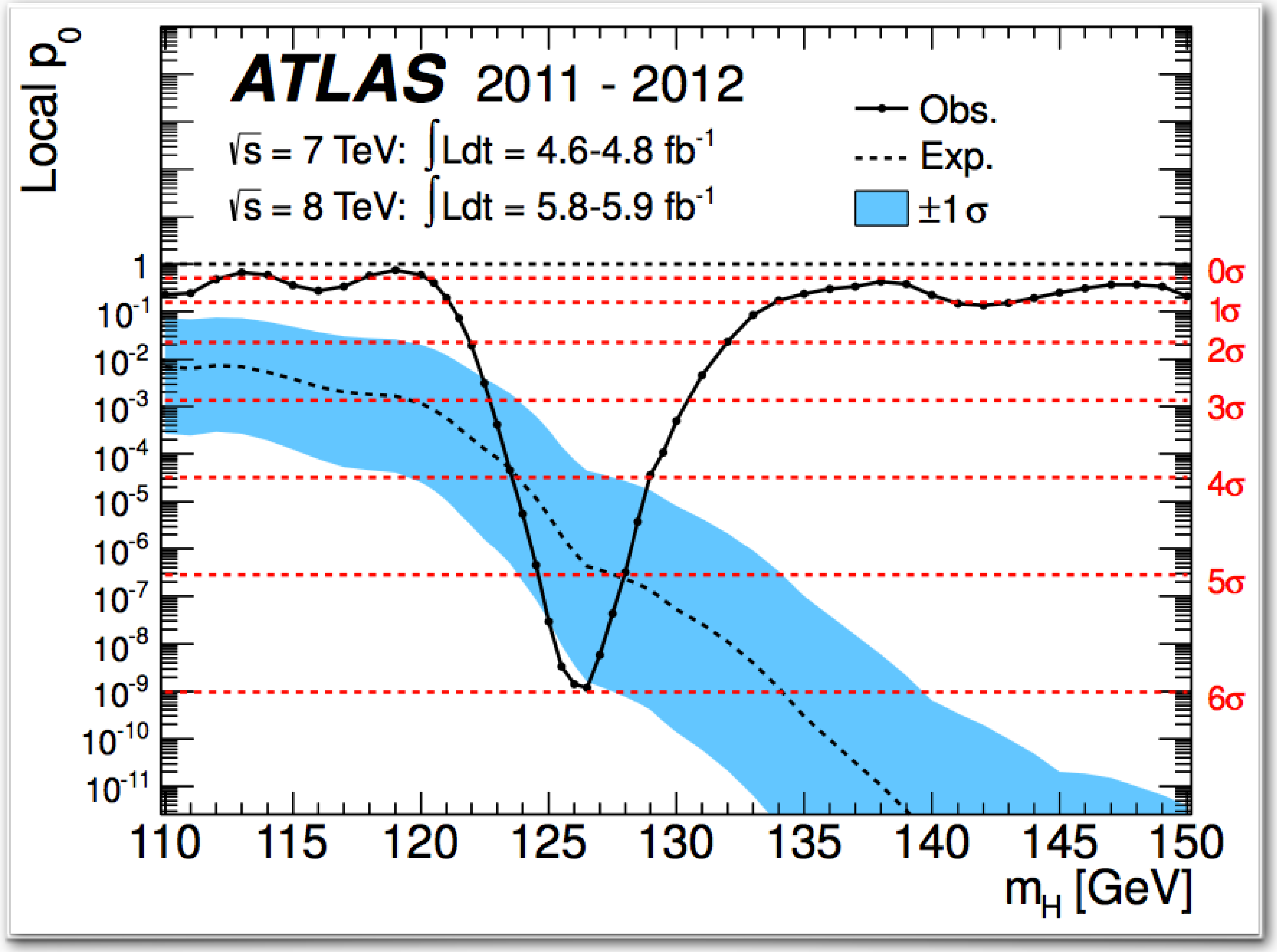
and



The LHC discovery



arXiv:1207.7235v1 [hep-ex]



arXiv:1207.7214v1 [hep-ex]

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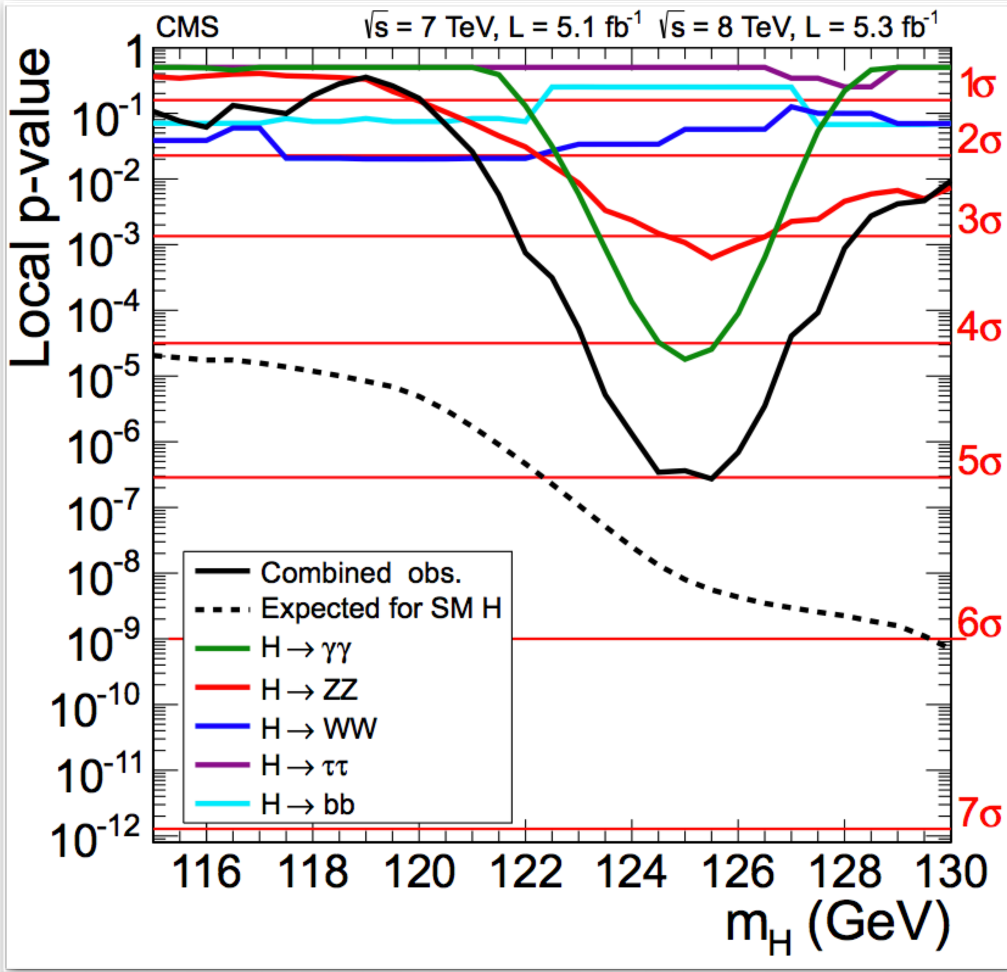
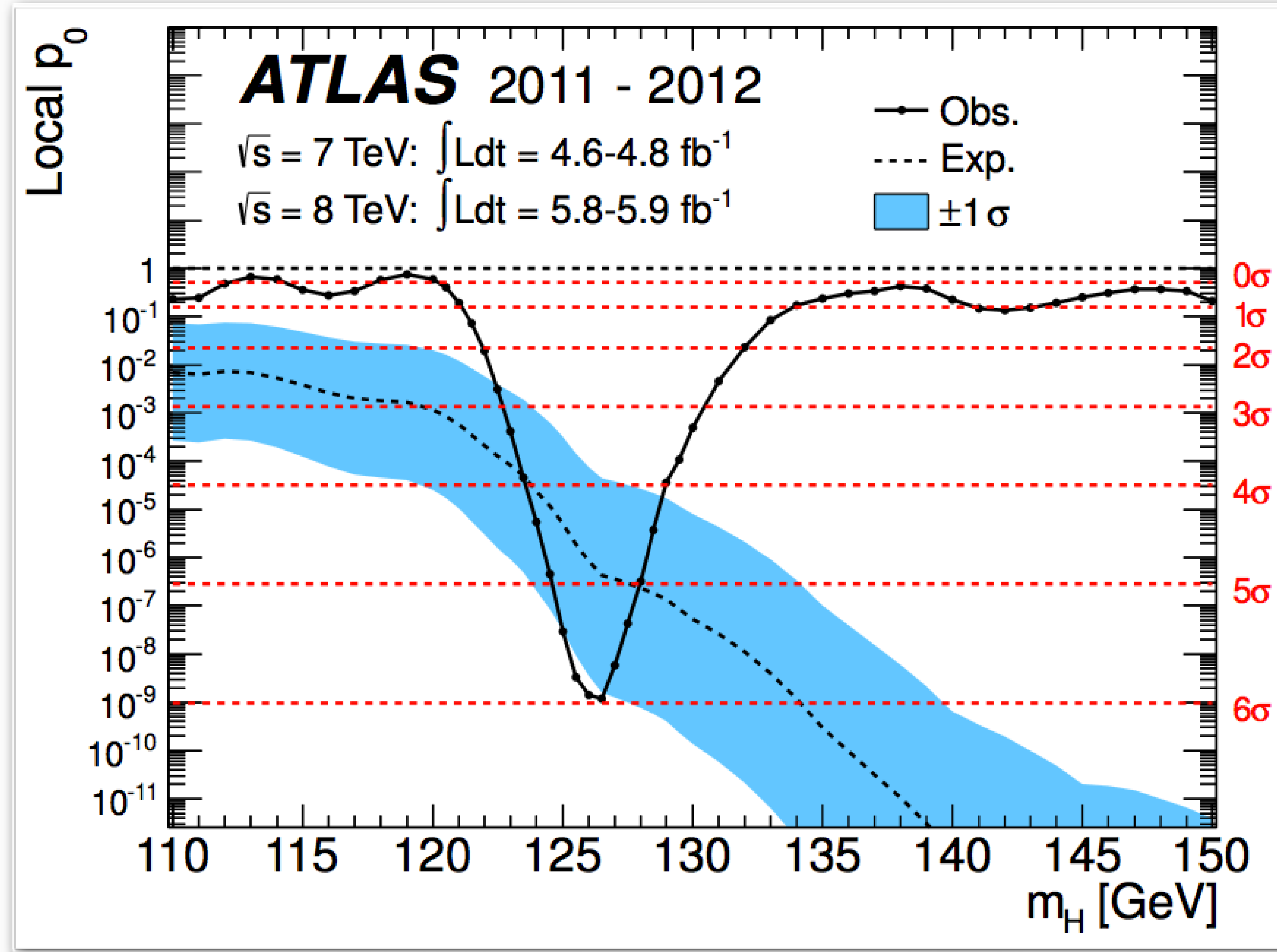


arXiv:1207.7235v1 [hep-ex]



arXiv:1207.7214v1 [hep-ex]

expected and observed p-values....

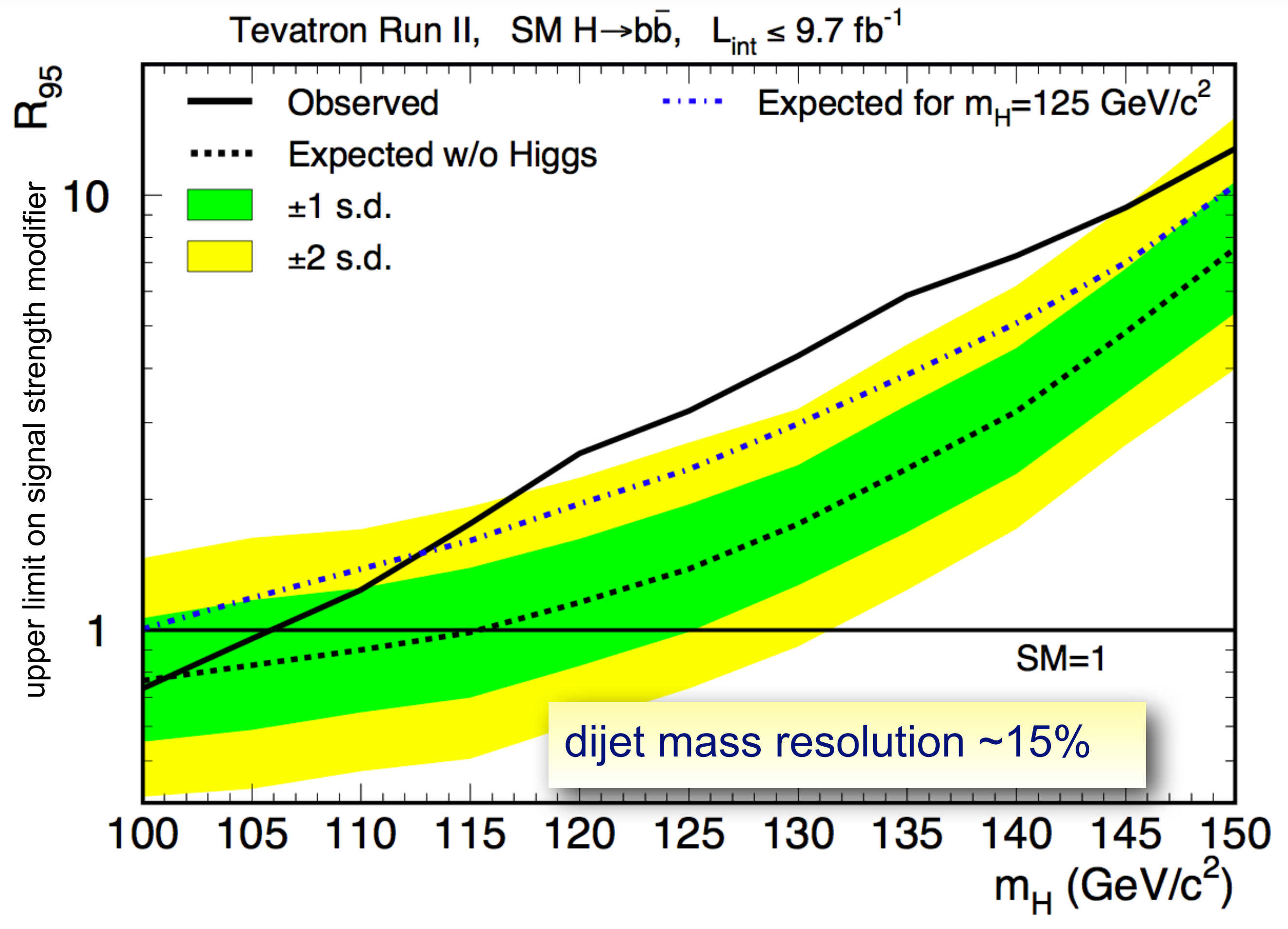
Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

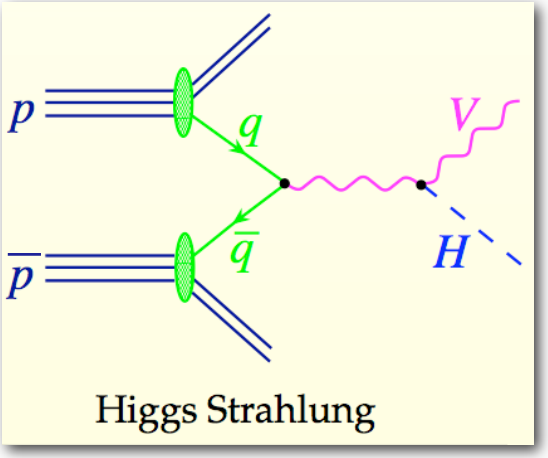
Search channel	Dataset	m_{max} [GeV]	Z_l [σ]	$E(Z_l)$ [σ]
$H \to ZZ^{(*)} \to 4\ell$	7 TeV	125.0	2.5	1.6
	8 TeV	125.5	2.6	2.1
	7 & 8 TeV	125.0	3.6	2.7
$H \to \gamma\gamma$	7 TeV	126.0	3.4	1.6
	8 TeV	127.0	3.2	1.9
	7 & 8 TeV	126.5	4.5	2.5
$H \to WW^{(*)} \to \ell\nu\ell\nu$	7 TeV	135.0	1.1	3.4
	8 TeV	120.0	3.3	1.0
	7 & 8 TeV	125.0	2.8	2.3
Combined	7 TeV	126.5	3.6	3.2
	8 TeV	126.5	4.9	3.8
	7 & 8 TeV	126.5	6.0	4.9

- ATLAS and CMS: significance driven by the γγ, ZZ and WW channels
- besides the excess at 125-126 GeV: 95% CL exclusion of a SM-like Higgs up to ~600 GeV

The TEVATRON evidence

arXiv:1207.6436v2 [hep-ex]





Z,W: lept. and inv. decays

H→bb

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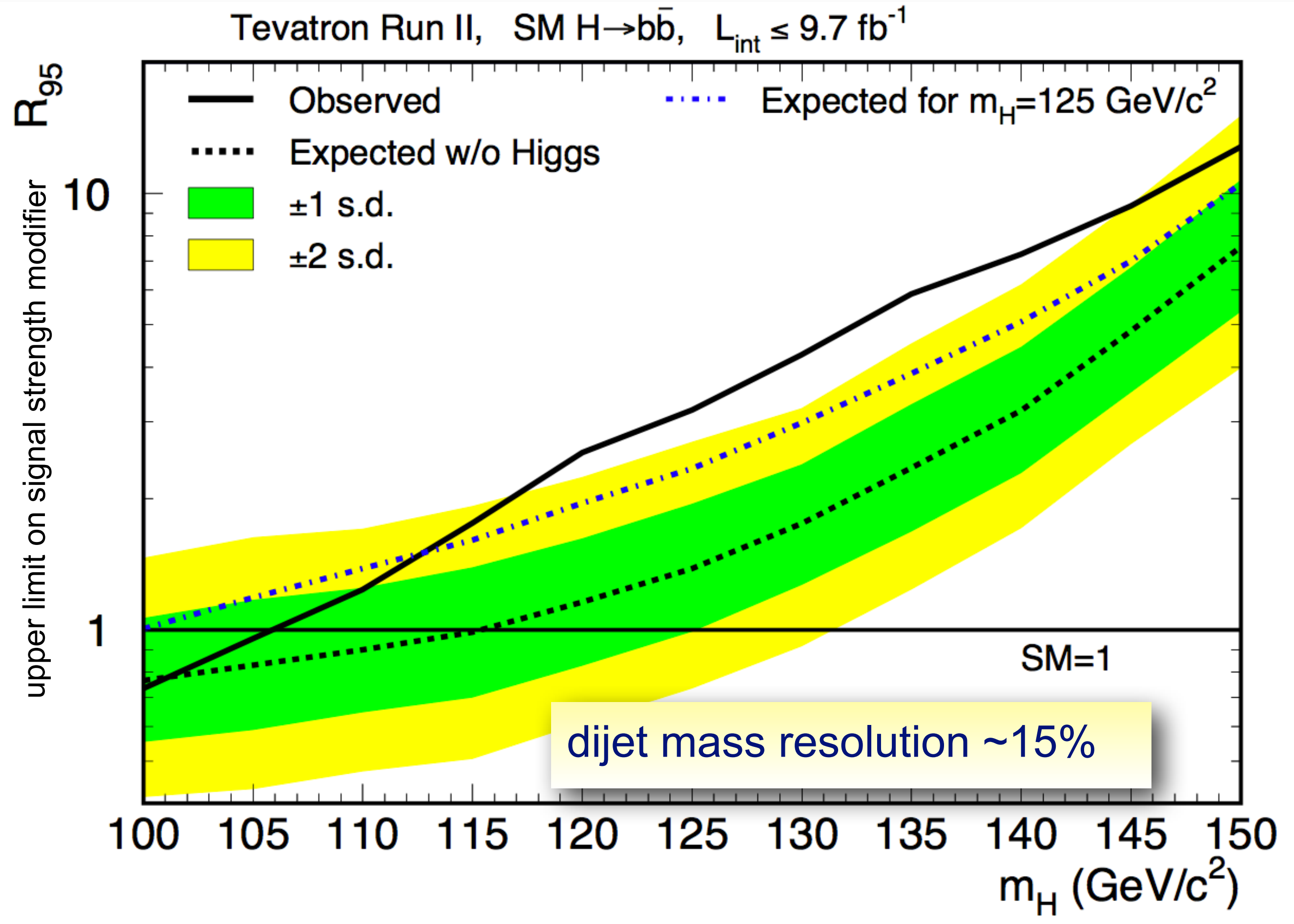
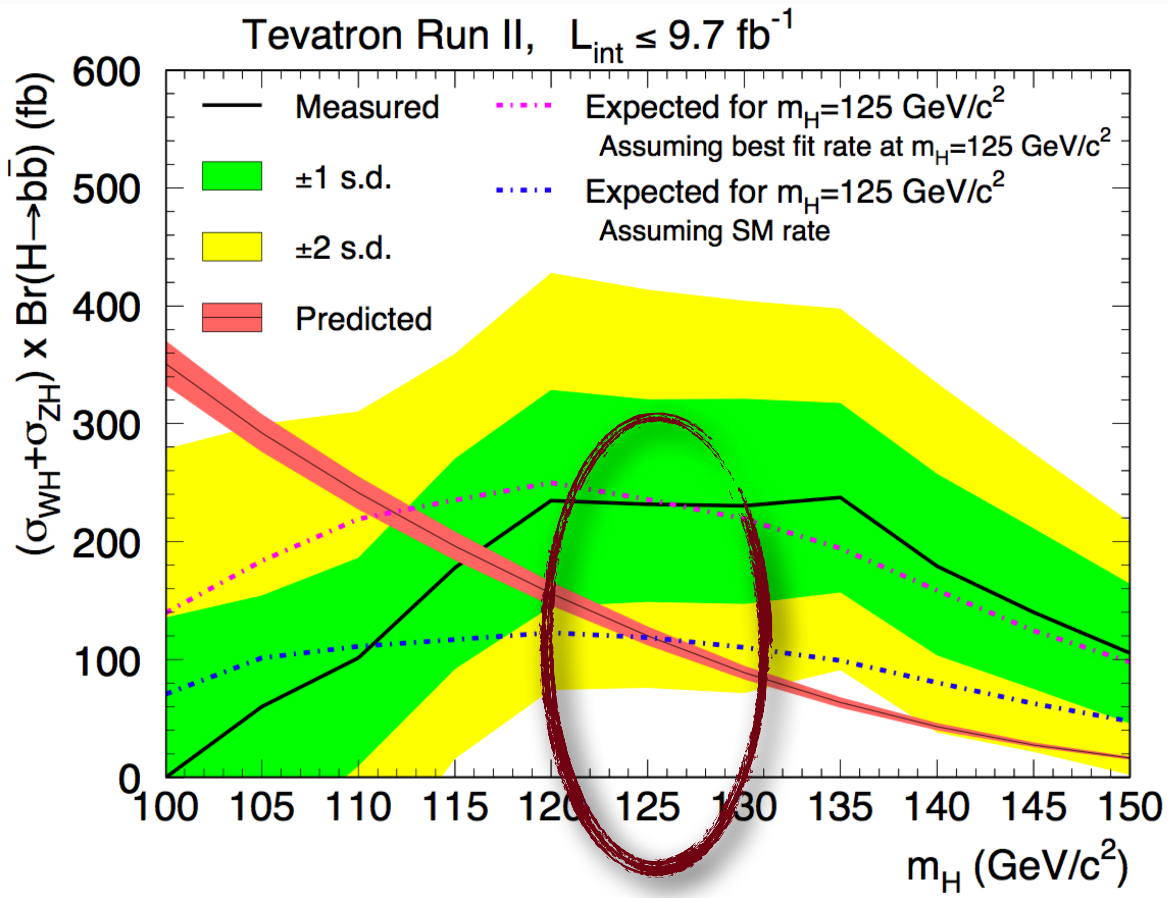
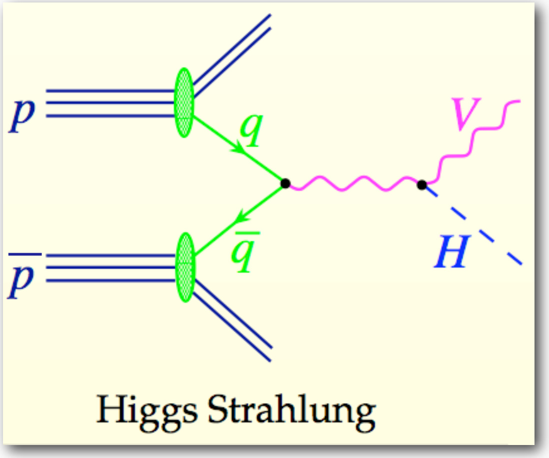
arXiv:1207.6436v2 [hep-ex]







Z,W: lept. and inv. decays

H→bb

- max. local significance: 3.3 σ at m_H=135 GeV
- **global significance (115-150 GeV) : 3.1 σ**
- local significance at m_H=125 GeV : 2.8 σ
- measured **σ x BR about 2x higher than expected** for a SM H at 125 GeV
- so far, most direct probe of Higgs coupling to bottom quarks
- Here shown: latest, most significant result, not include other channels

Properties of this boson

the shopping list

- mass
- spin and parity (J^P)
- CP (even, odd, or admixture?)
- couplings to vector bosons: is this boson related to EWSB, and how much does it contribute to restoring unitarity in $W_L W_L$ scattering
- couplings to fermions
  - is Yukawa interaction at work?
  - contribution to restoring unitarity?
- couplings proportional to mass ?
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- elementary or composite?
- self-interaction

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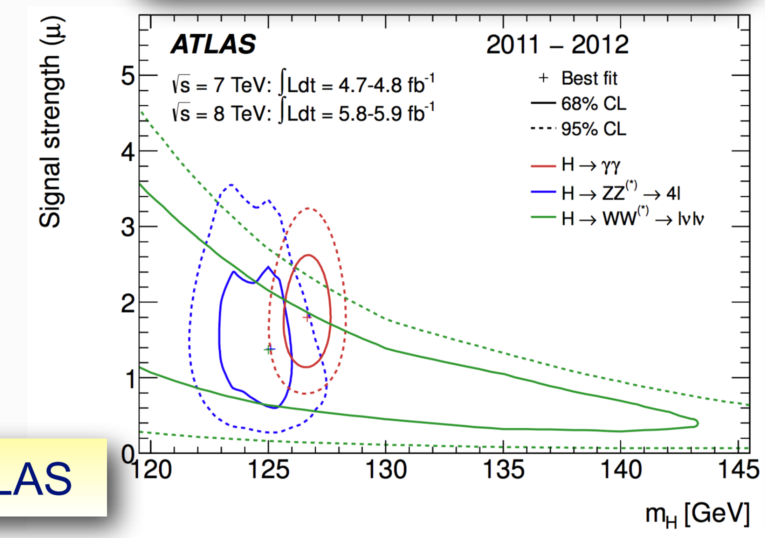
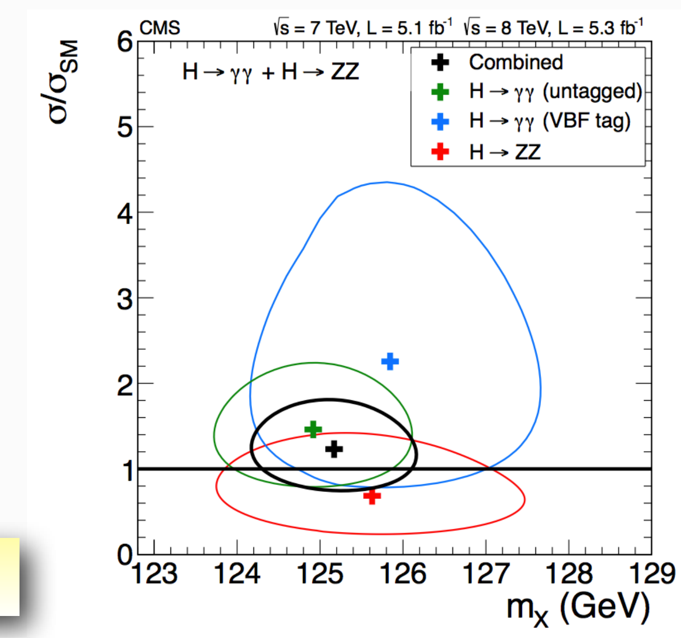
Mass vs signal strength:



ATLAS

$126.0 \ \pm 0.4 \text{ (stat)} \ \pm 0.4 \text{ (sys) GeV}$



CMS

$125.3 \pm 0.4 \,(\text{stat.}) \pm 0.5 \,(\text{syst.})\ \text{GeV}$

- expected precision at the LHC: ~100 MeV
- expected precision at a linear collider: ≲ 40-50 MeV

J^P and CP

Status and questions

- decay to two photons: cannot be spin 1 (Landau-Yang theorem)
- **J^P**: currently tested at the LHC, using angular correlations in ZZ*, WW* and γγ
- **J^P**: by end of 8 TeV run, assuming a total of 35/fb per exp: **~4 σ separation of 0^+ vs 0^- and 0^+ vs 2^+**
- **CP**: somewhat more tricky, basic question of possible mixture of CP-even and CP-odd
- If focus at LHC stays on WW*, ZZ* and VBF: limited sensitivity to distinguish pure CP-even state from admixture of CP-even and CP-odd components
- Linear collider: threshold behaviour of $e^+e^- \rightarrow ttH$ gives precision measurement of CP mixing.

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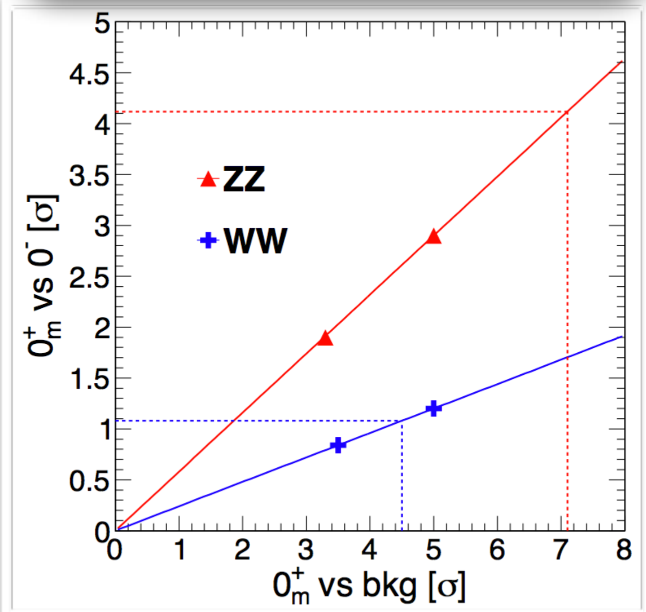
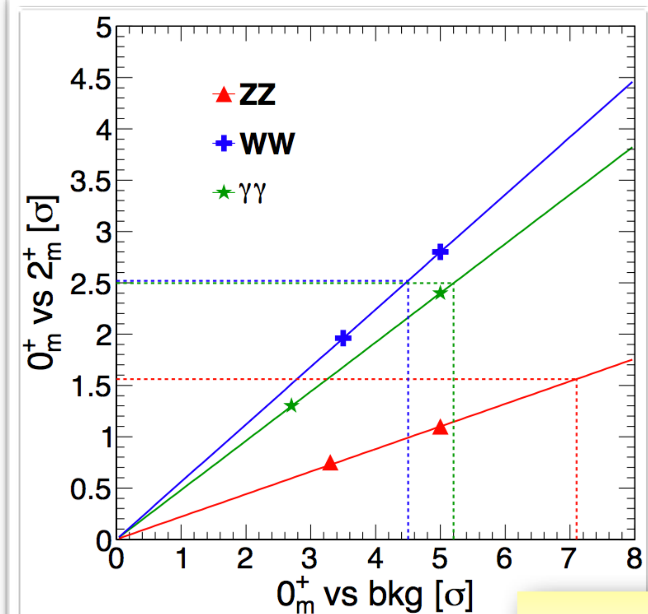
J^P: LHC 2012 prospects



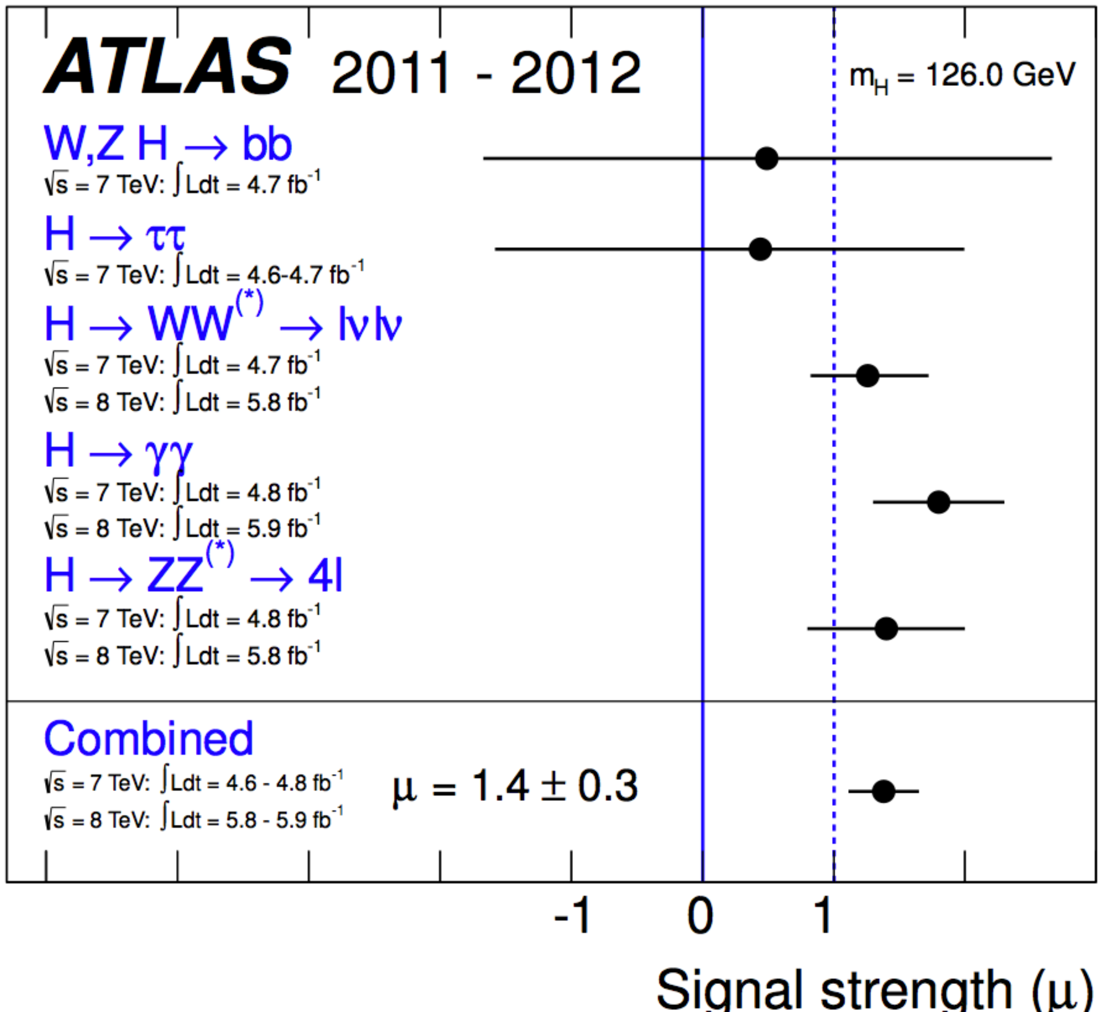
Expected hypotheses separation significance versus signal observation significance
arXiv:1208.4018v1 [hep-ph], Bolognesi et al.



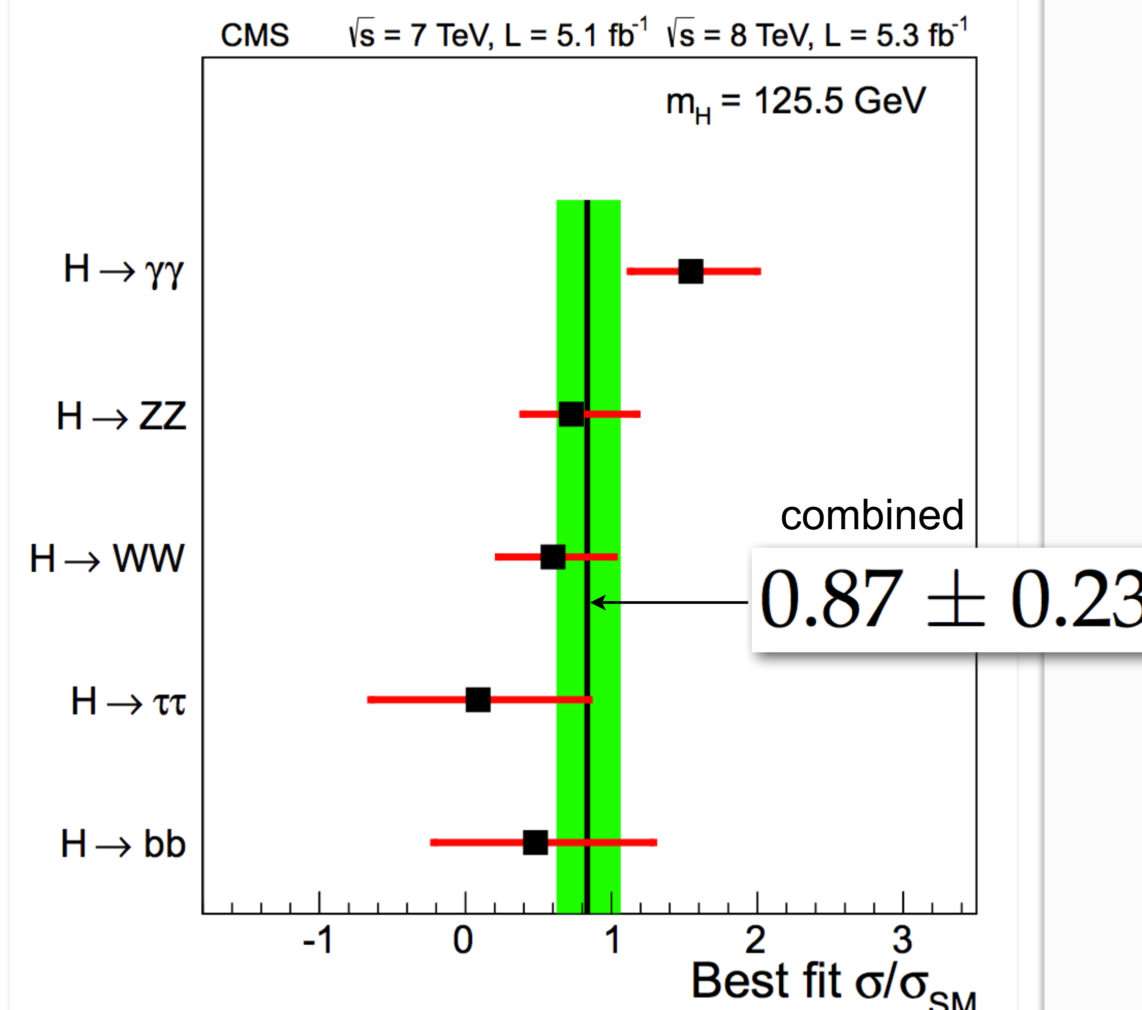
for 35/fb per exp.

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs background	7.1	4.5	5.2	9.9
0^+_m vs 0^-	4.1	1.1	0.0	4.2
0^+_m vs 2^+_m	1.6	2.5	2.5	3.9

Signal strength per channel



arXiv:1207.7214v1 [hep-ex]



arXiv:1207.7235v1 [hep-ex]

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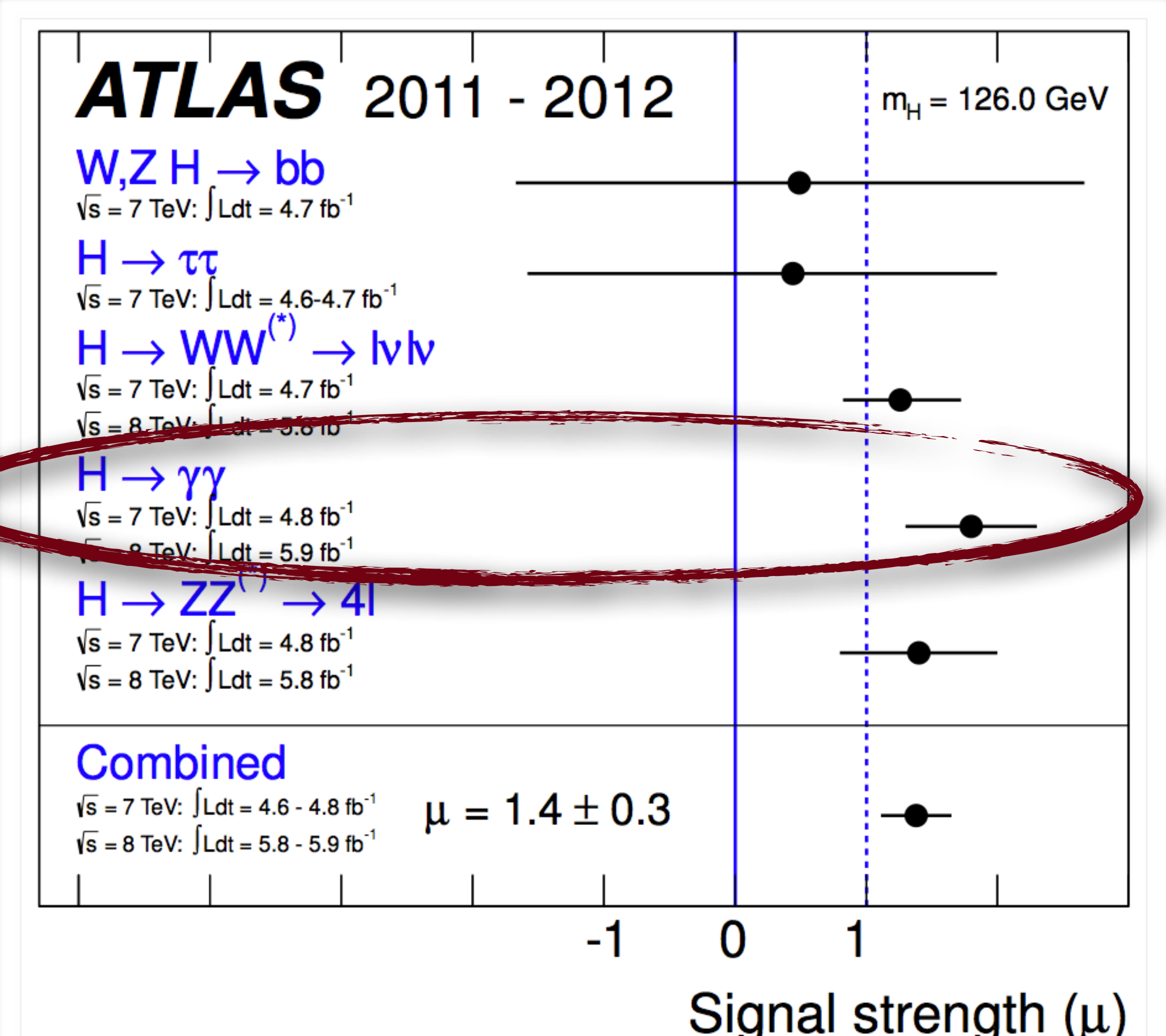

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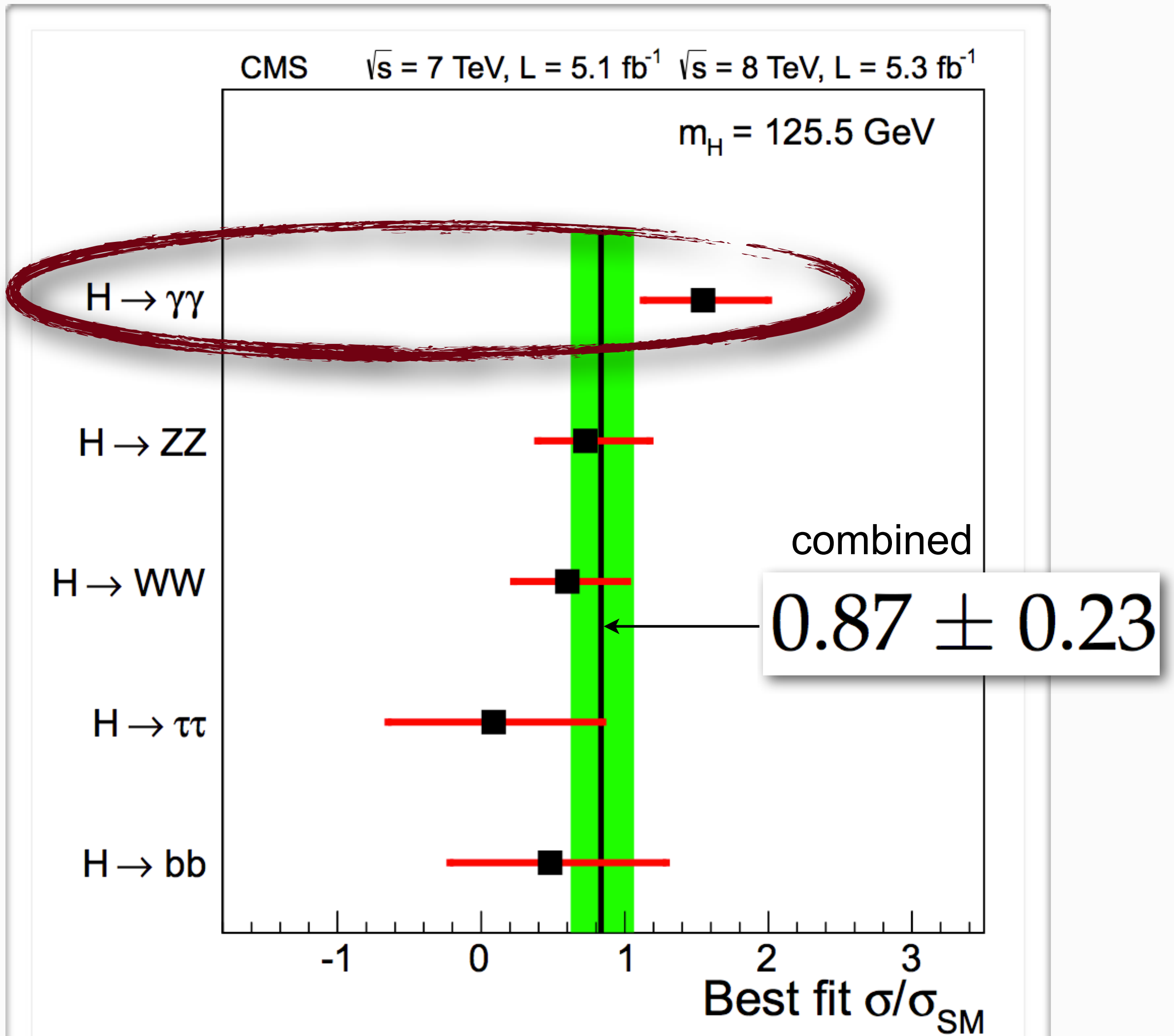
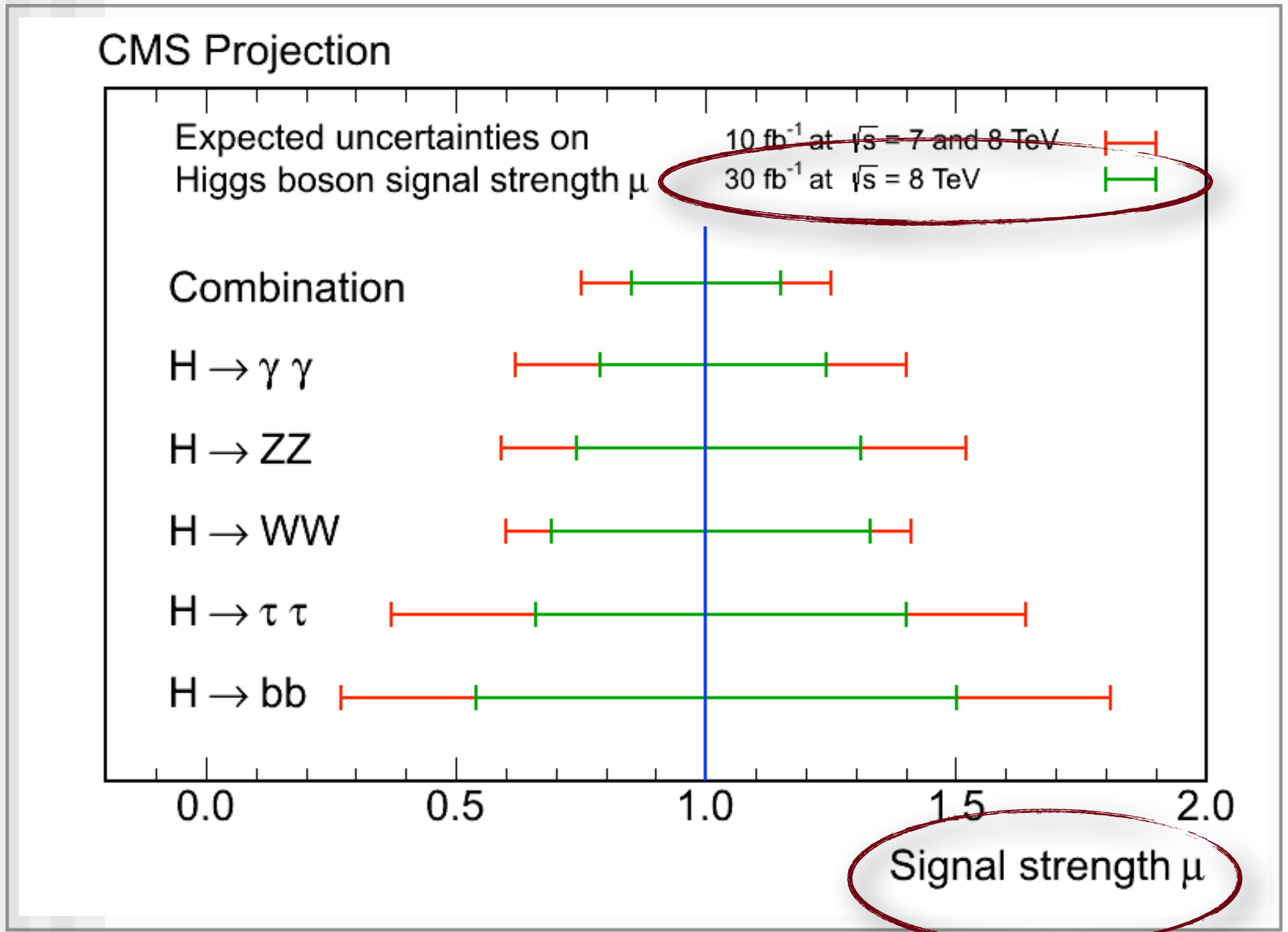


arXiv:1207.7235v1 [hep-ex]

- overall, consistency with SM
- however, most striking/interesting: **high γγ rate**, in both exps and both c.o.m. energies
  - ATLAS: 1.8 ± 0.5
  - CMS: 1.6 ± 0.4
- further data highly awaited, also to see development on the fermionic side
- interpretation in terms of couplings: see talk by Ch. Grojean

Projections : VERY PRELIMINARY

from the ATLAS/CMS input documents to the strategy process



- ~15 % precision on total signal strength achievable **with 30/fb at 8 TeV**
- **5σ each** in γγ and ZZ channels, **~3σ each** in WW, bb, tautau in reach

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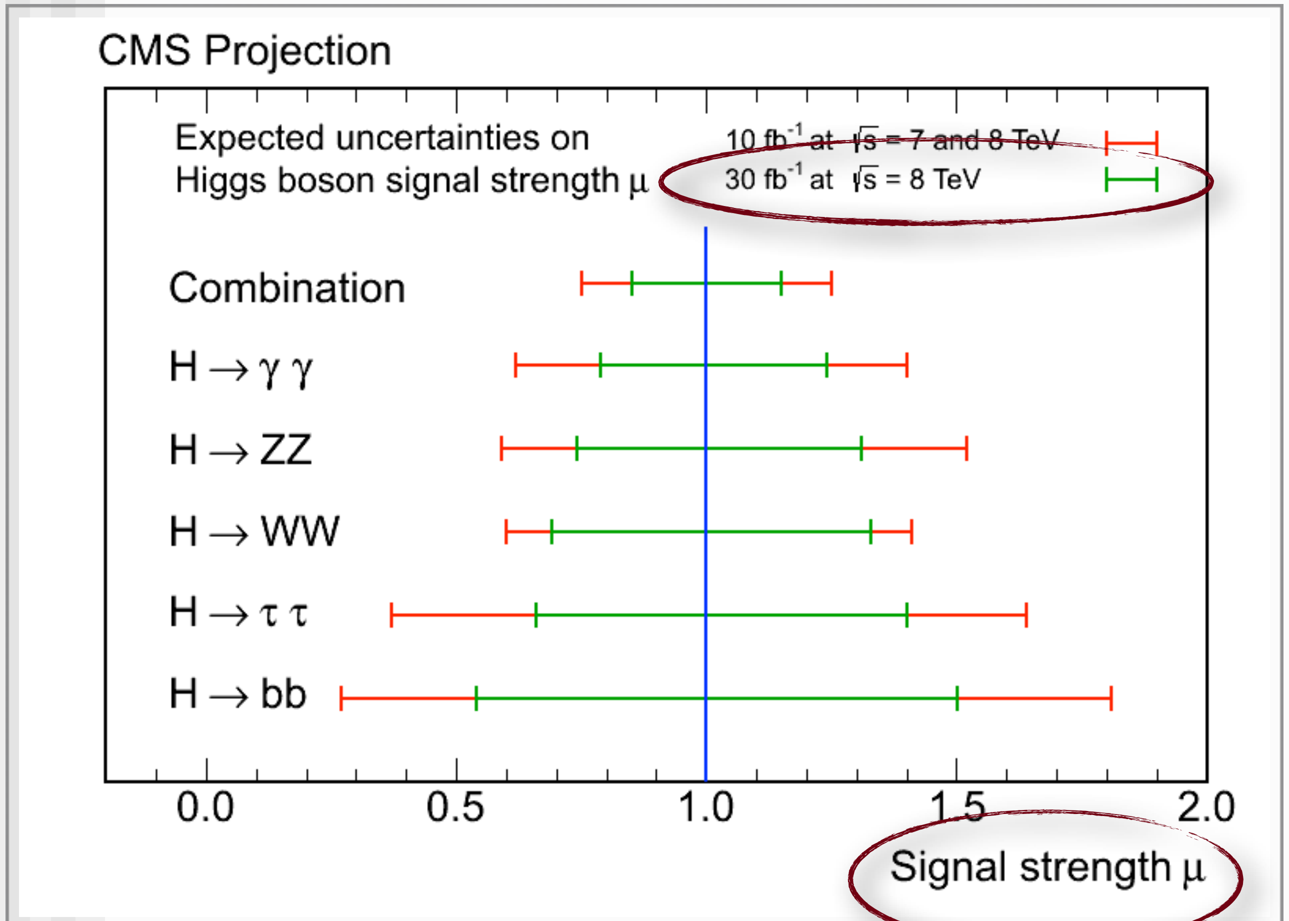

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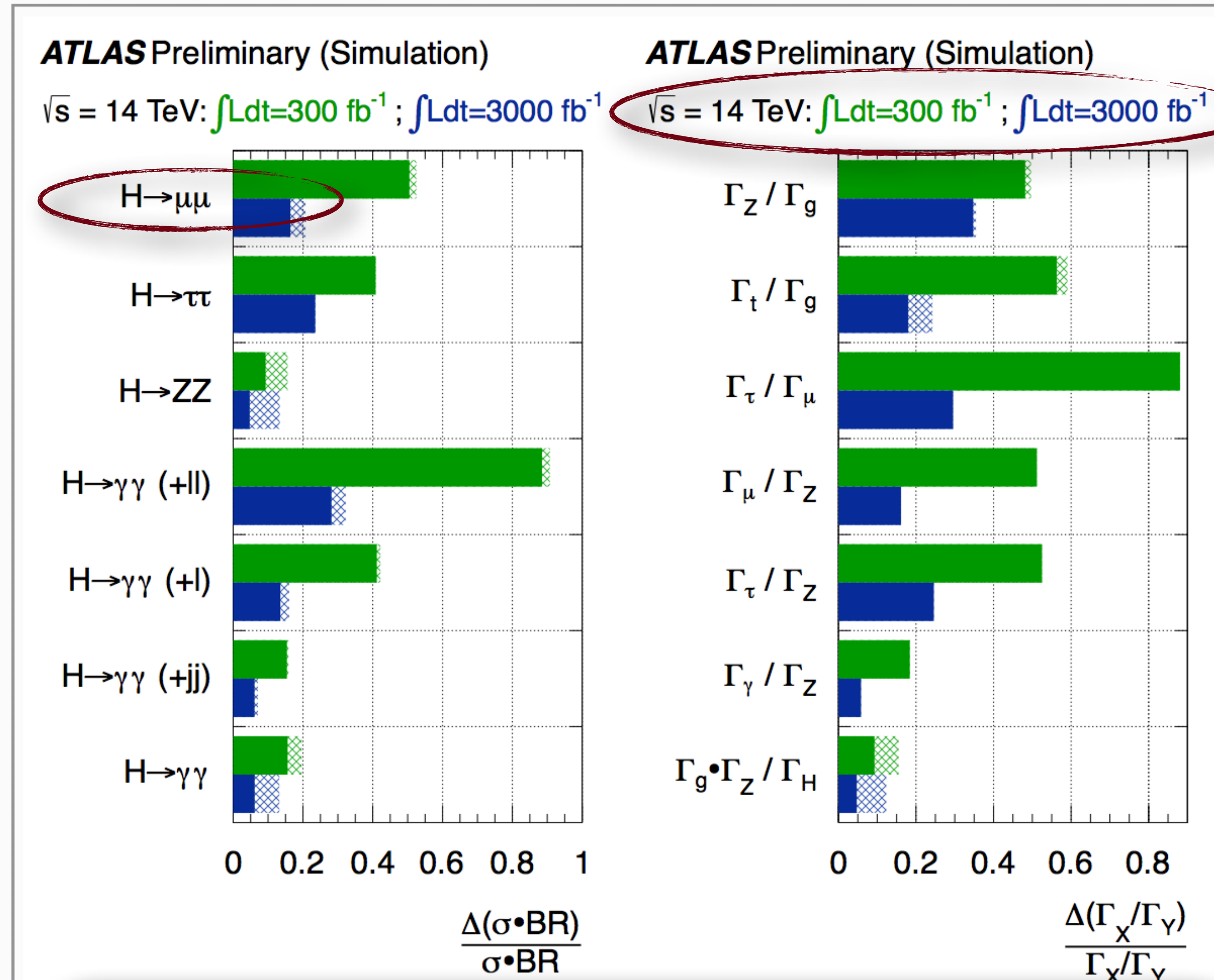

without further model assumptions on the total width: only ratios of partial widths accessible

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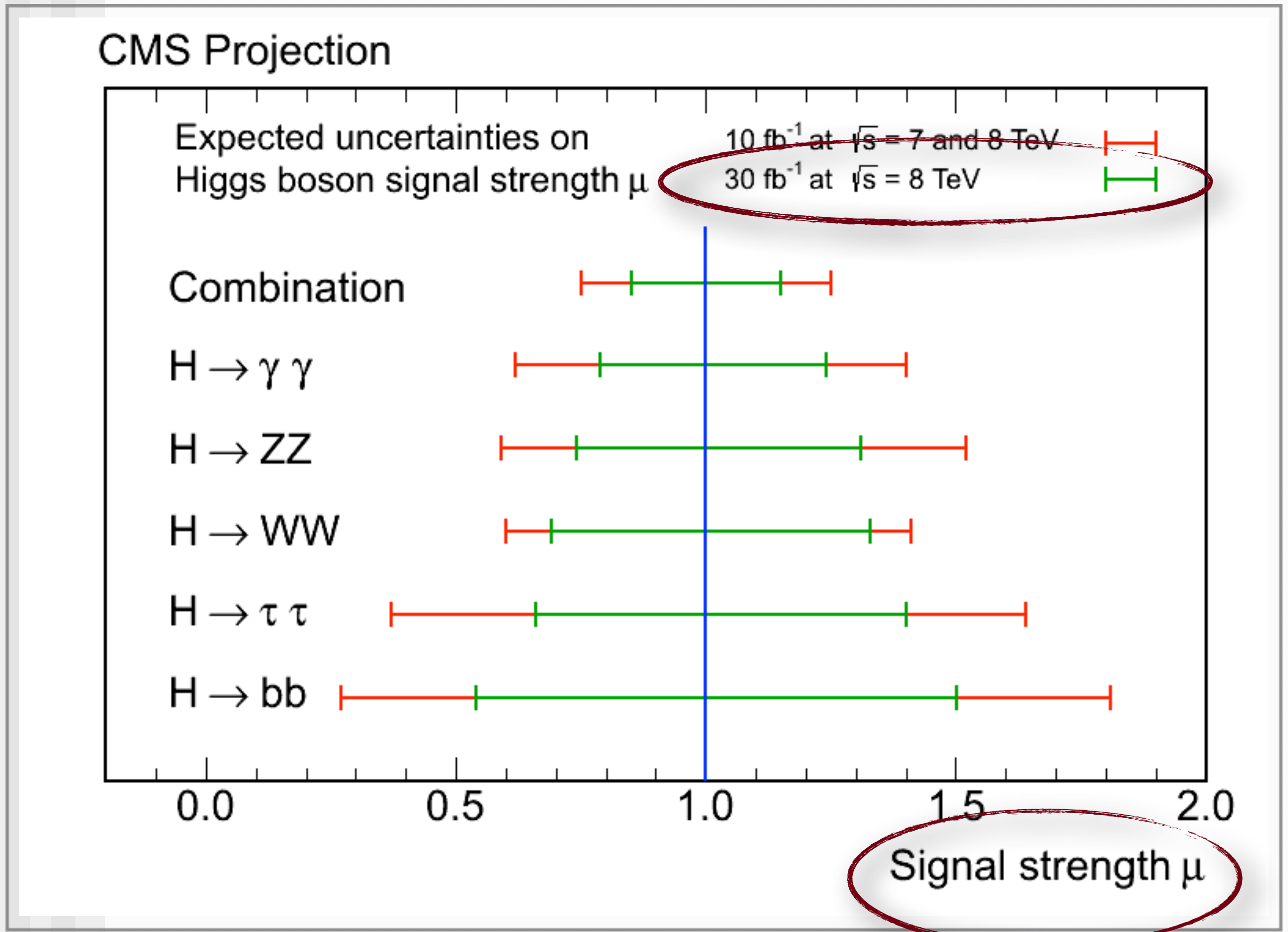

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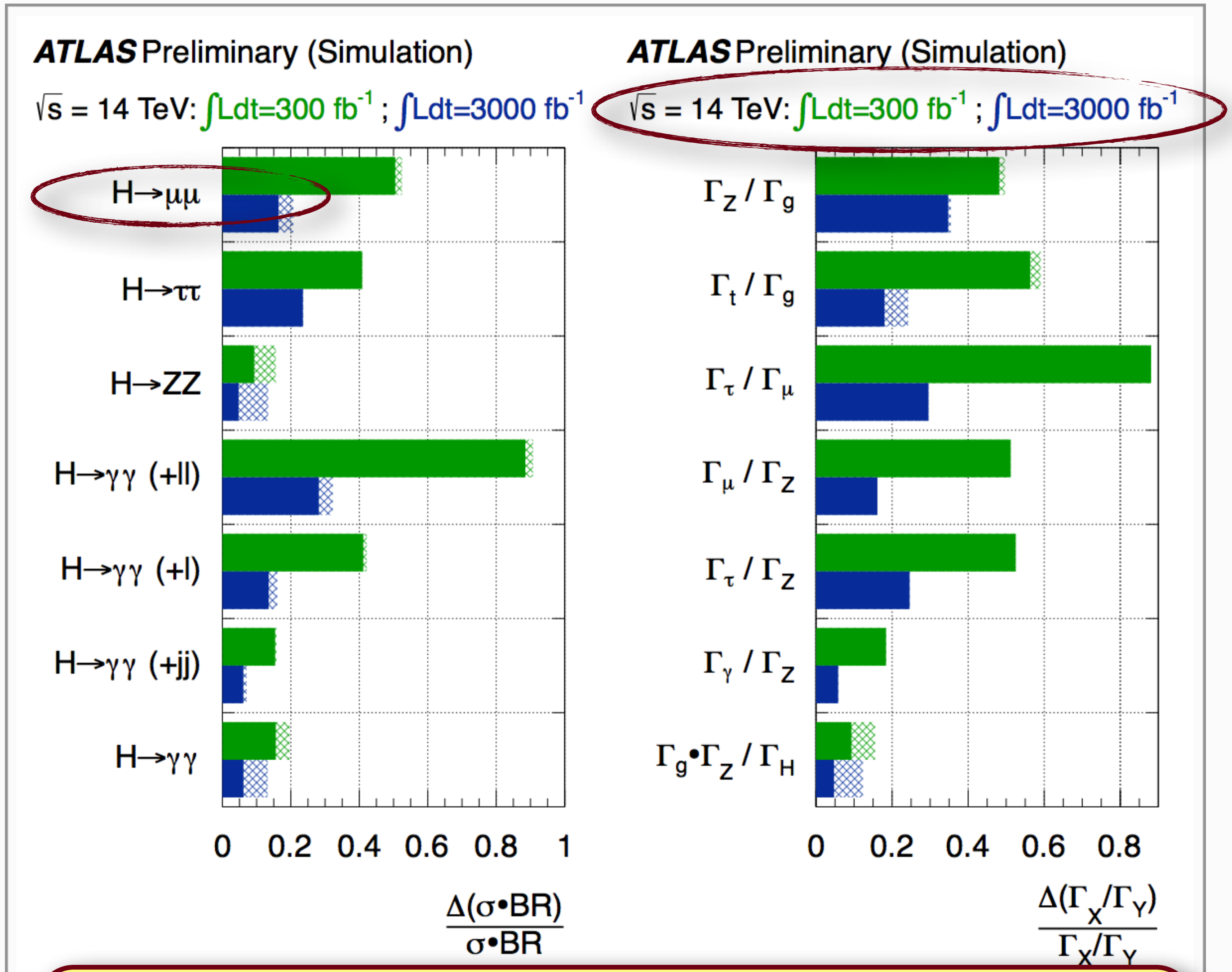


without further model assumptions on the total width: only ratios of partial widths accessible

- coupling scale factors: 5-10% precision achievable with 300/fb at 14 TeV
- ratios of partial widths: in the 5-30% range, for luminosities up to 3/ab
- very rare channels such as H→μμ accessible at the 20% level, with a HL-LHC
- Higgs self-coupling (double-Higgs production): most promising channels, such as bbγγ, currently under study. 3σ/exp possible at HL-LHC, and **30% prec. on λ_{HHH}** possible if more channels added and exps. combined
- **NOTE**: This is not the final word from the LHC experiments, in terms of projections
- lepton colliders: absolute coupling measurements at the % level, see more in talks by Ch. Grojean and T. Wyatt

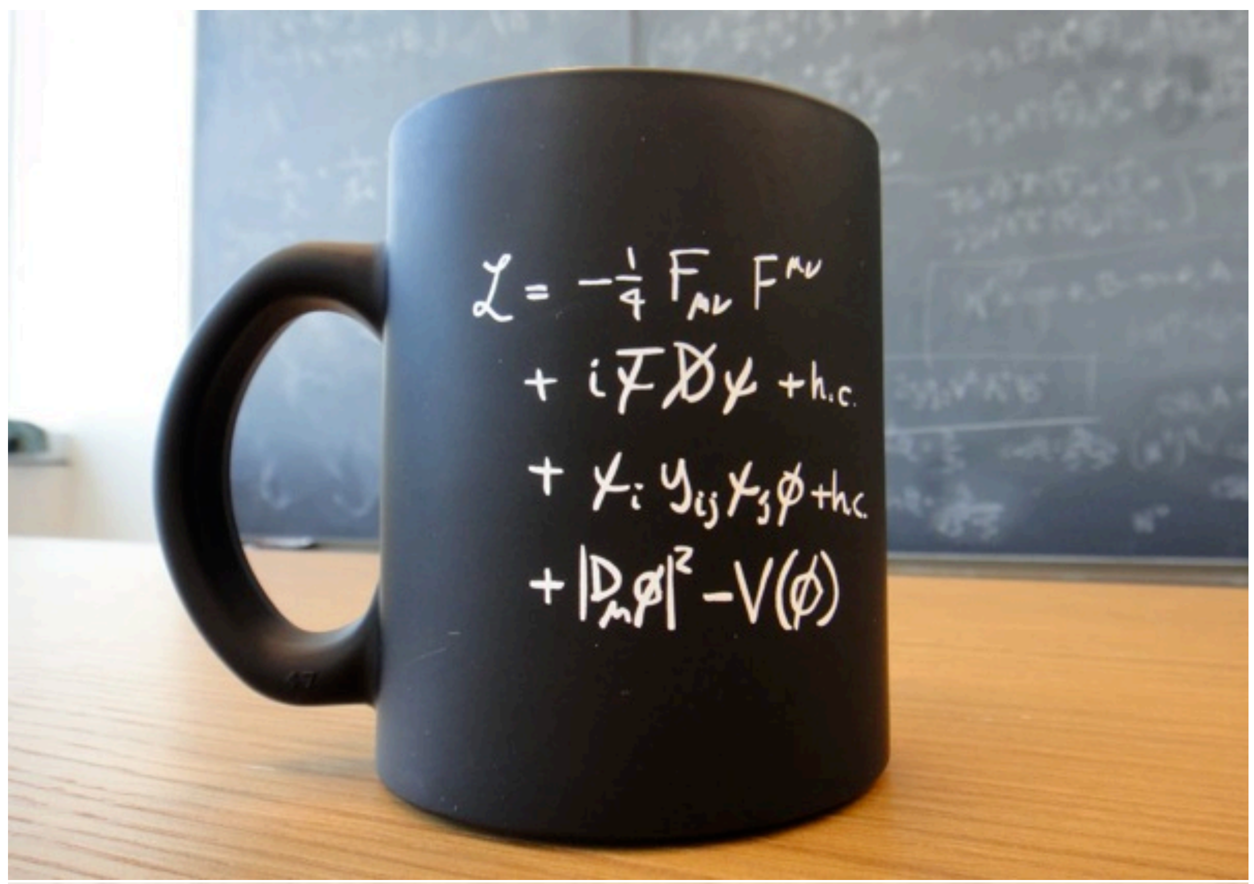
Most important of all...

seen in a talk by R. Erbacher at SUSY2012

our huge investments have paid off, since Danni has one less thing to worry about....

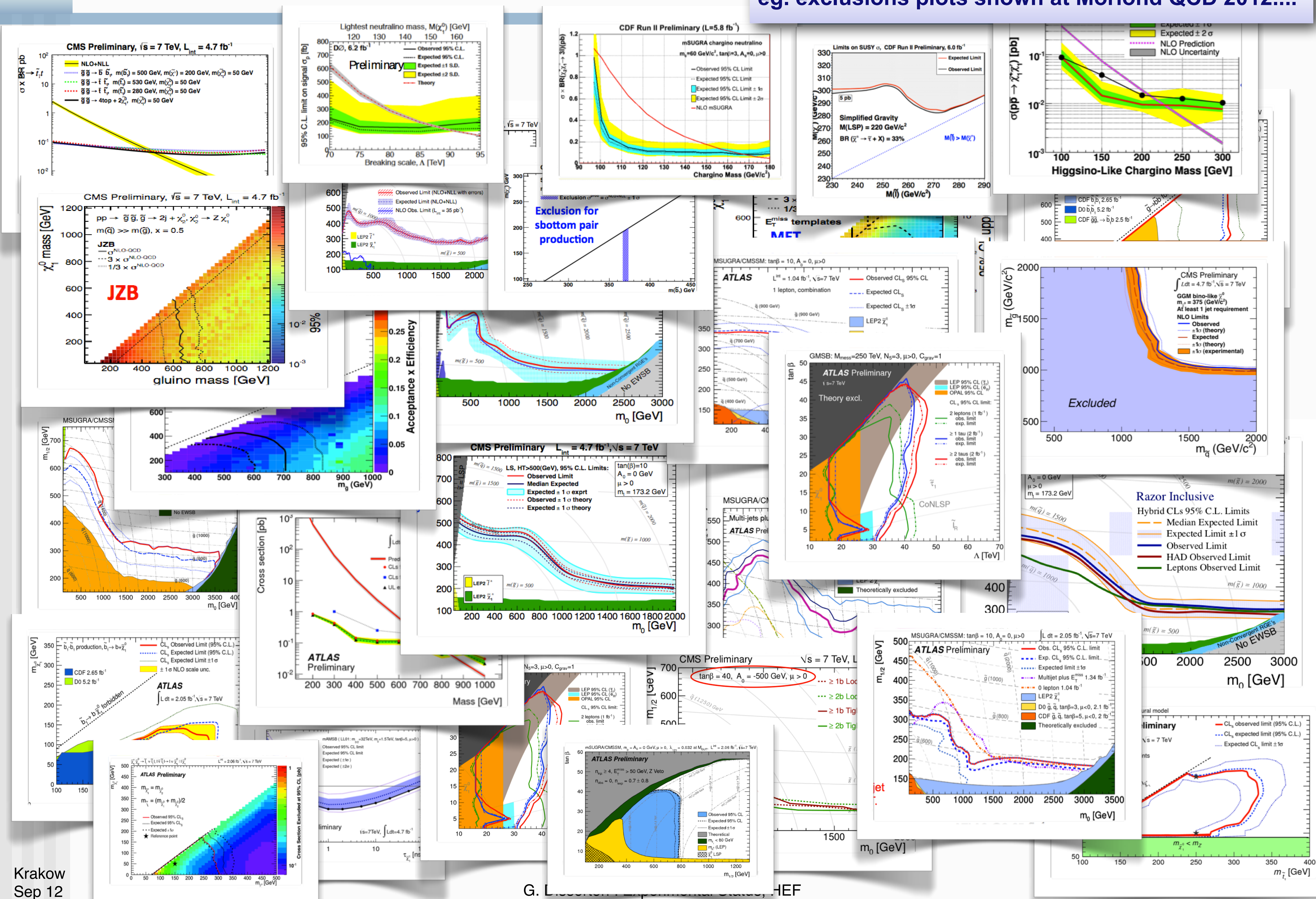
for the full picture you have to google....

BSM

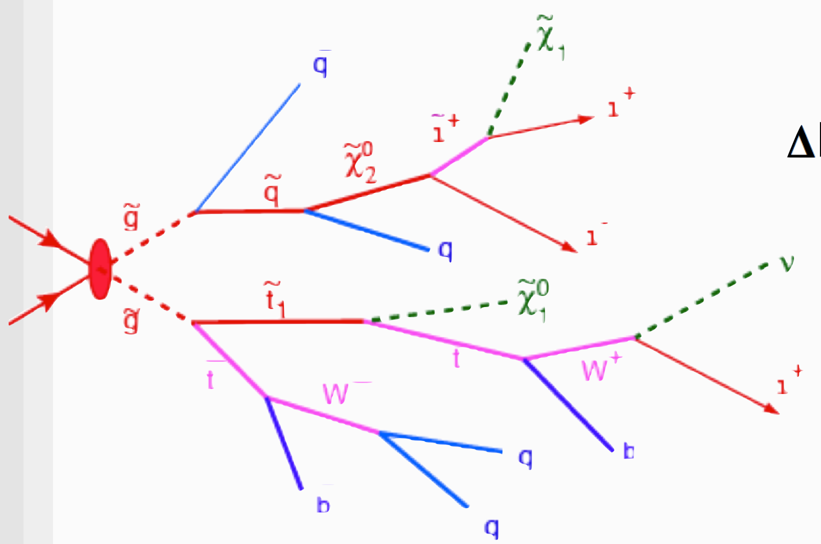

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

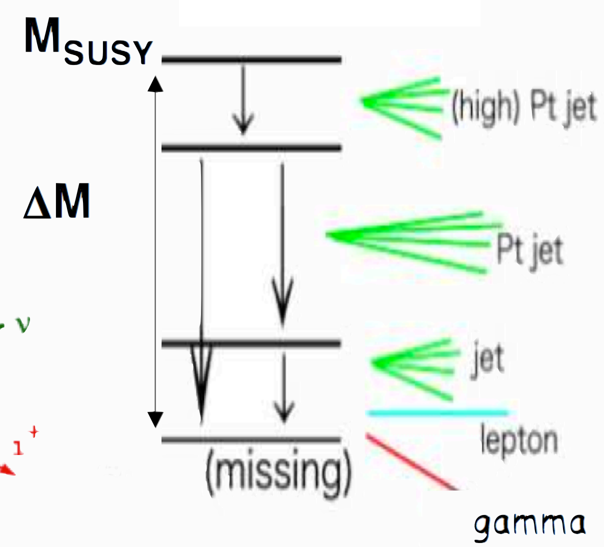
We have searched....

eg. exclusions plots shown at Moriond QCD 2012....



SUSY searches: The approach





$\text{MET} \sim \Delta M$

$H_T = \Sigma\, p_T(\text{jet})\ [+\ p_T(l,\gamma)]$

$M_{Eff} = \text{MET} + H_T = 2\, M_{SUSY}$

from Pallavorio, SUSY2012

- **generic approach**: search for strongly produced (heavy) sparticles, which decay via cascades
- assume a stable LSP → missing energy (MET)
- signatures: (many) jets, **large overall (transverse) energy in the event plus MET** (these are also basic trigger req.)
  - plus: lepton(s) and/or photon(s)
- design robust (inclusive searches), backgrounds derived/ controlled from data as much as possible
- Then: define signal regions, count events, including shape information, interpretations

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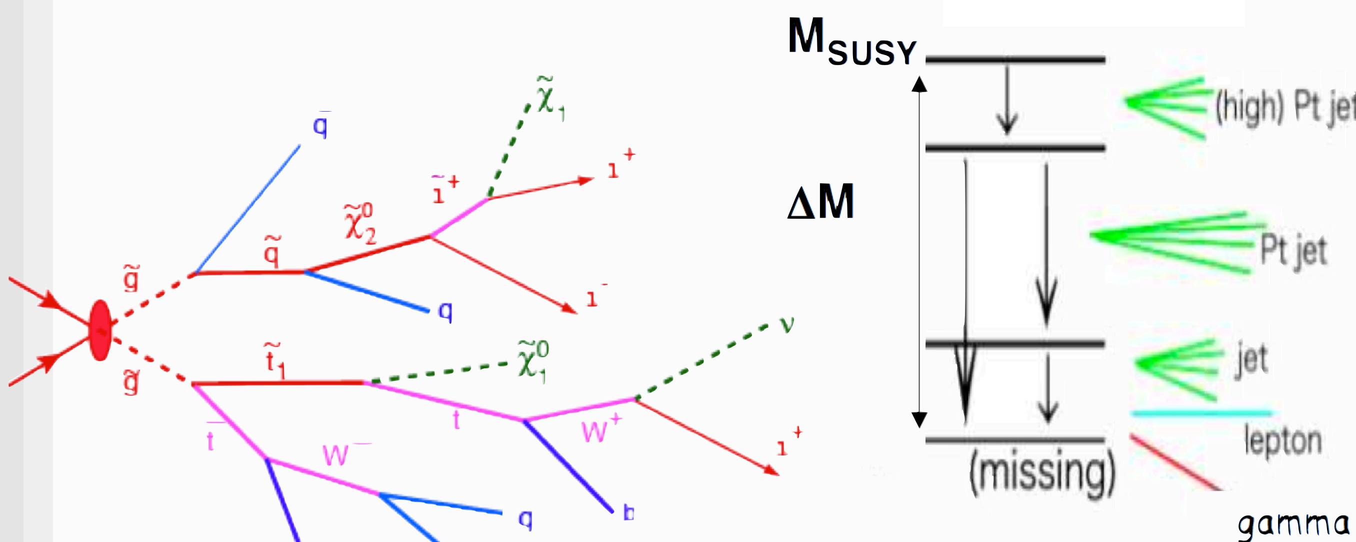
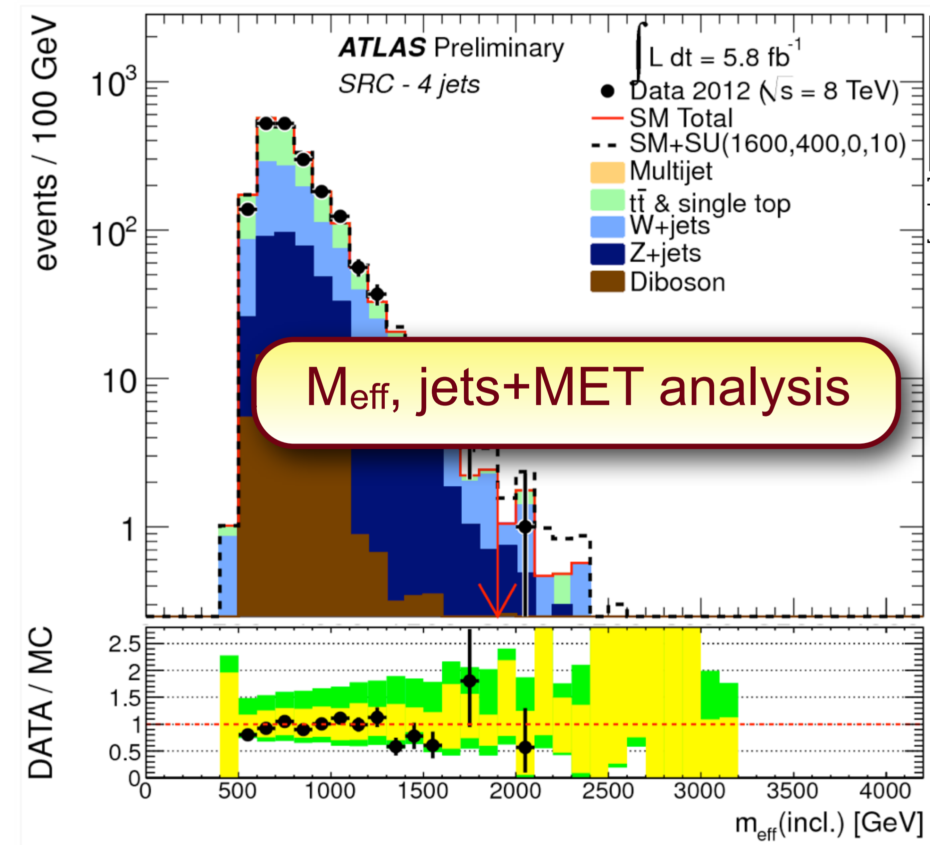
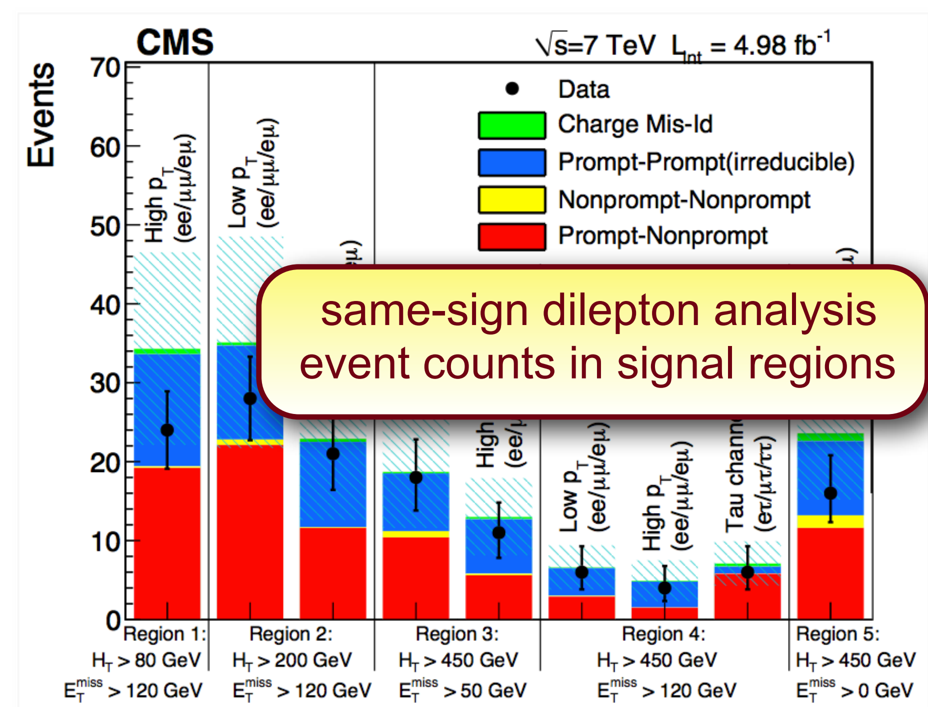


MET ~ ΔM
$H_T = \Sigma\, p_T(\text{jet})\ [+\ p_T(l,\gamma)]$
$M_{Eff} = MET + H_T = 2\, M_{SUSY}$

from Pallavorio, SUSY2012





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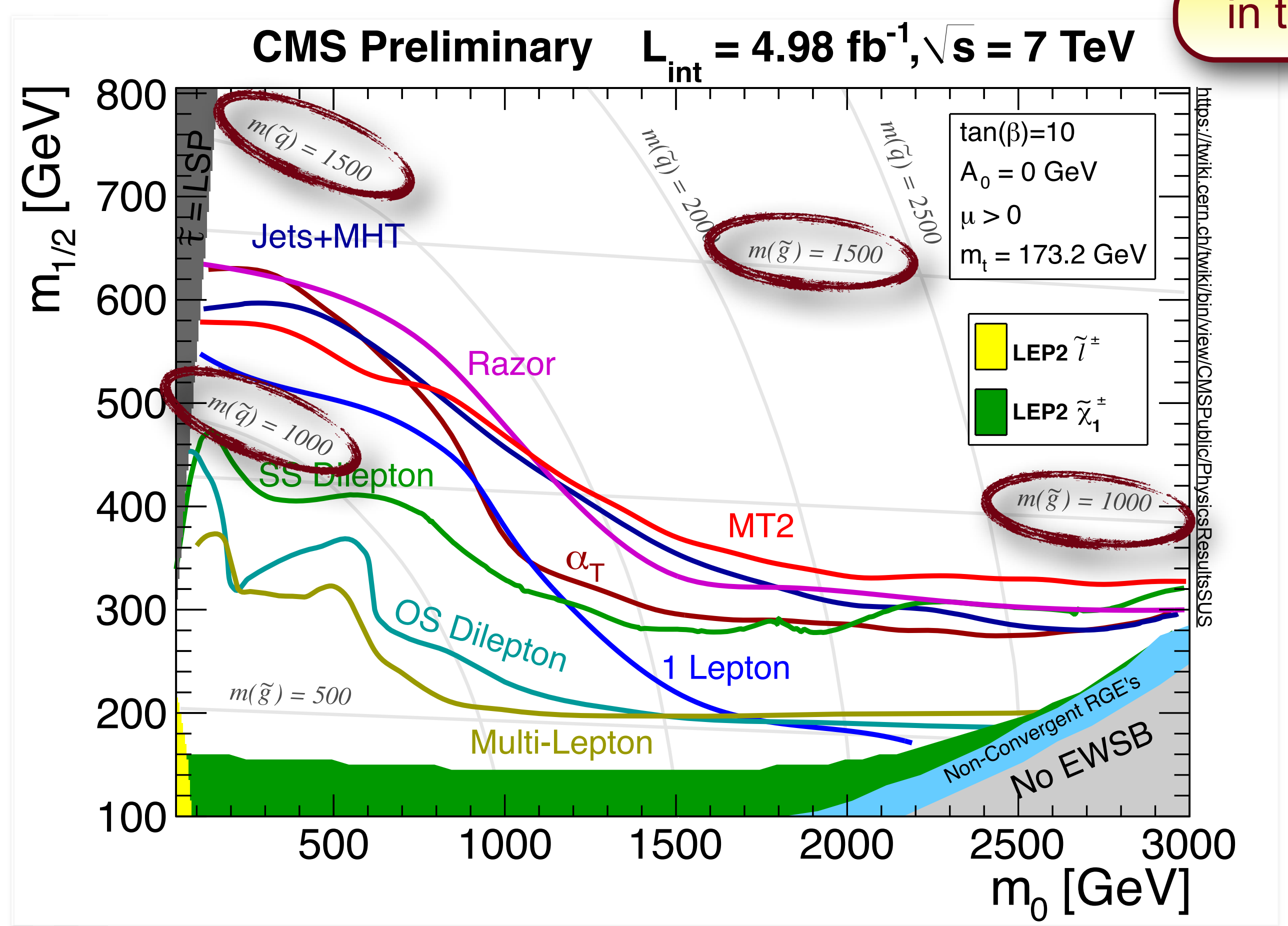
Interpretations of generic searches

in the context of a concrete model, here cMSSM



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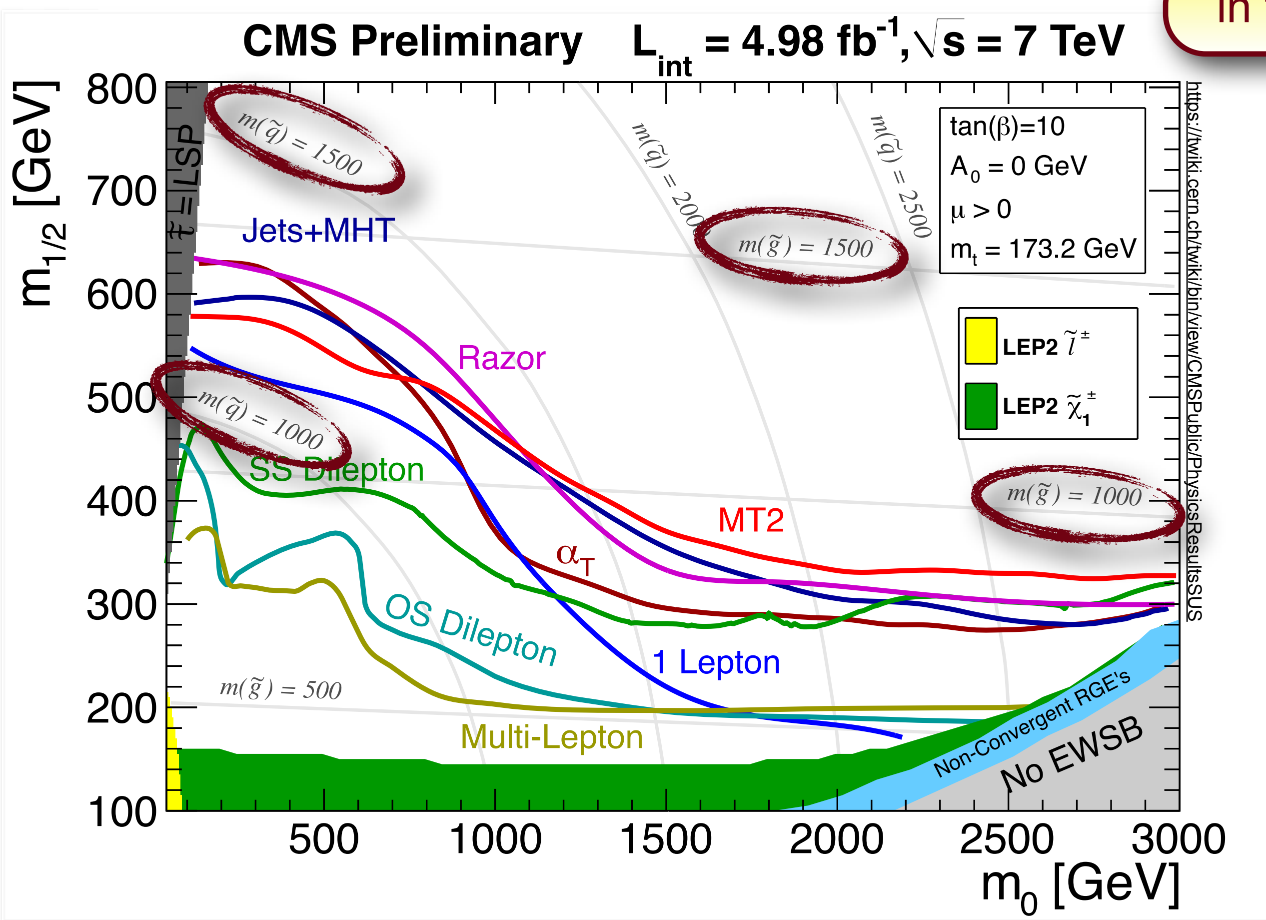
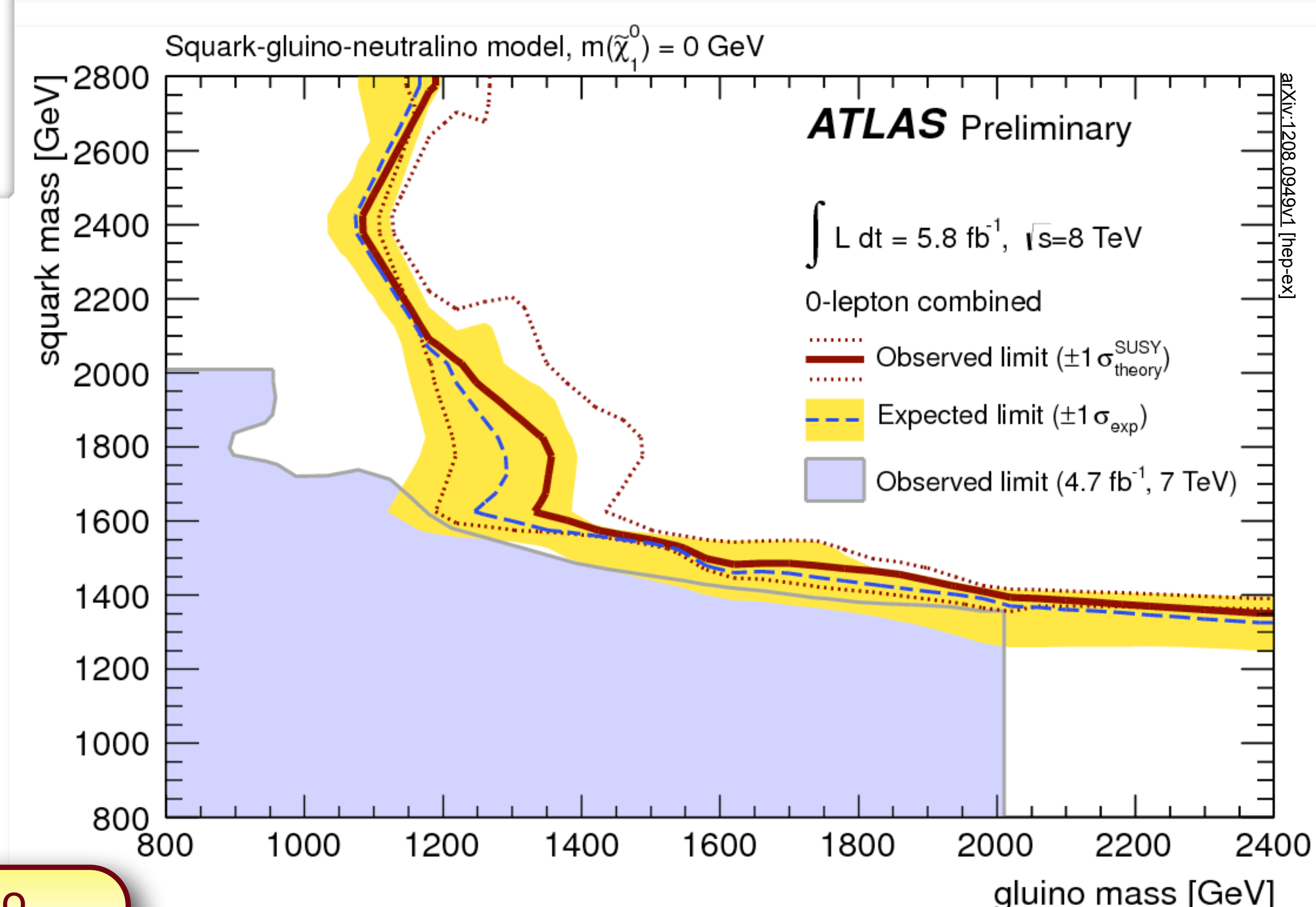
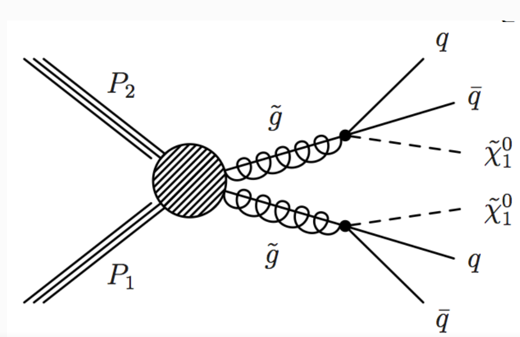


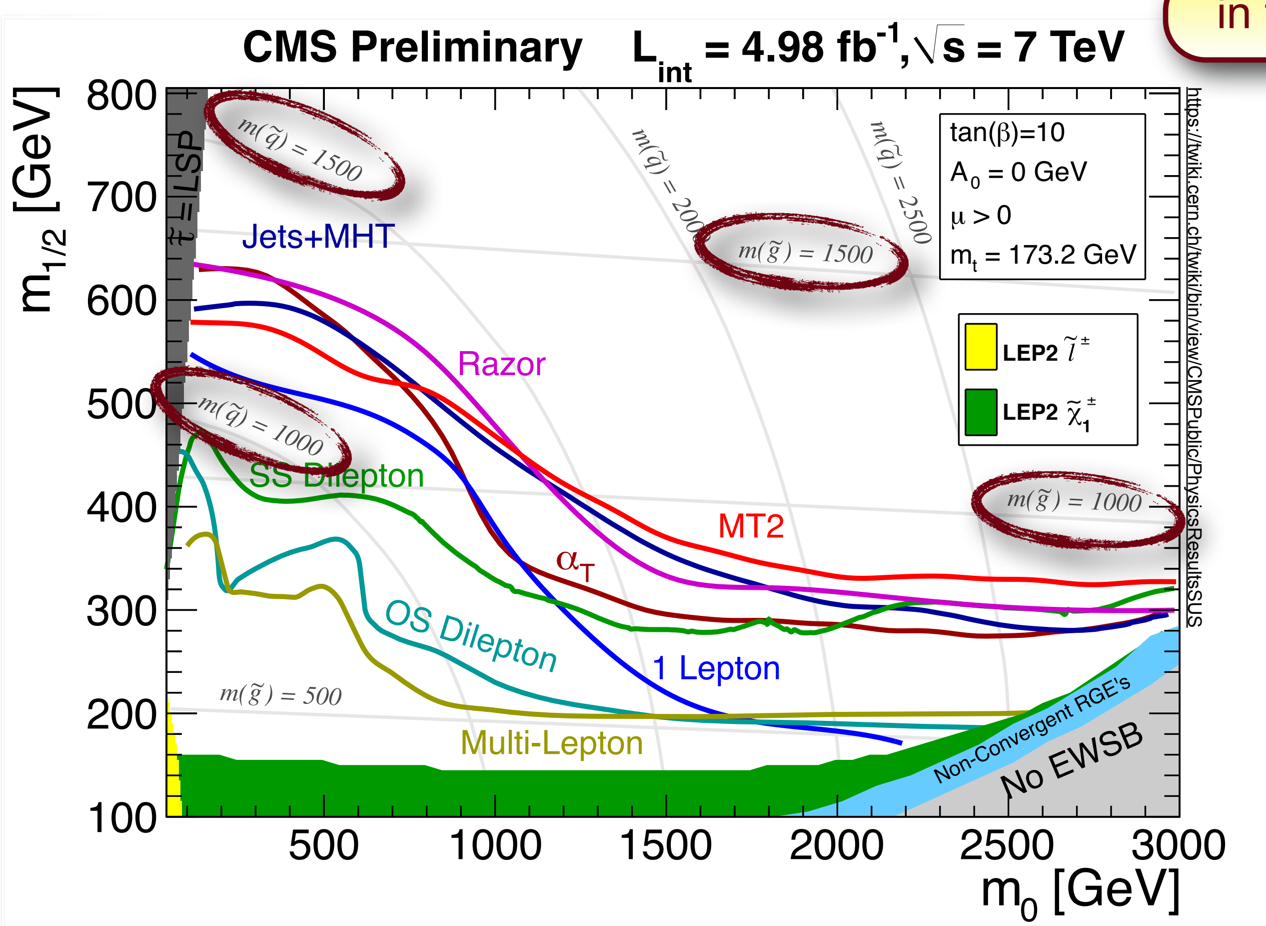


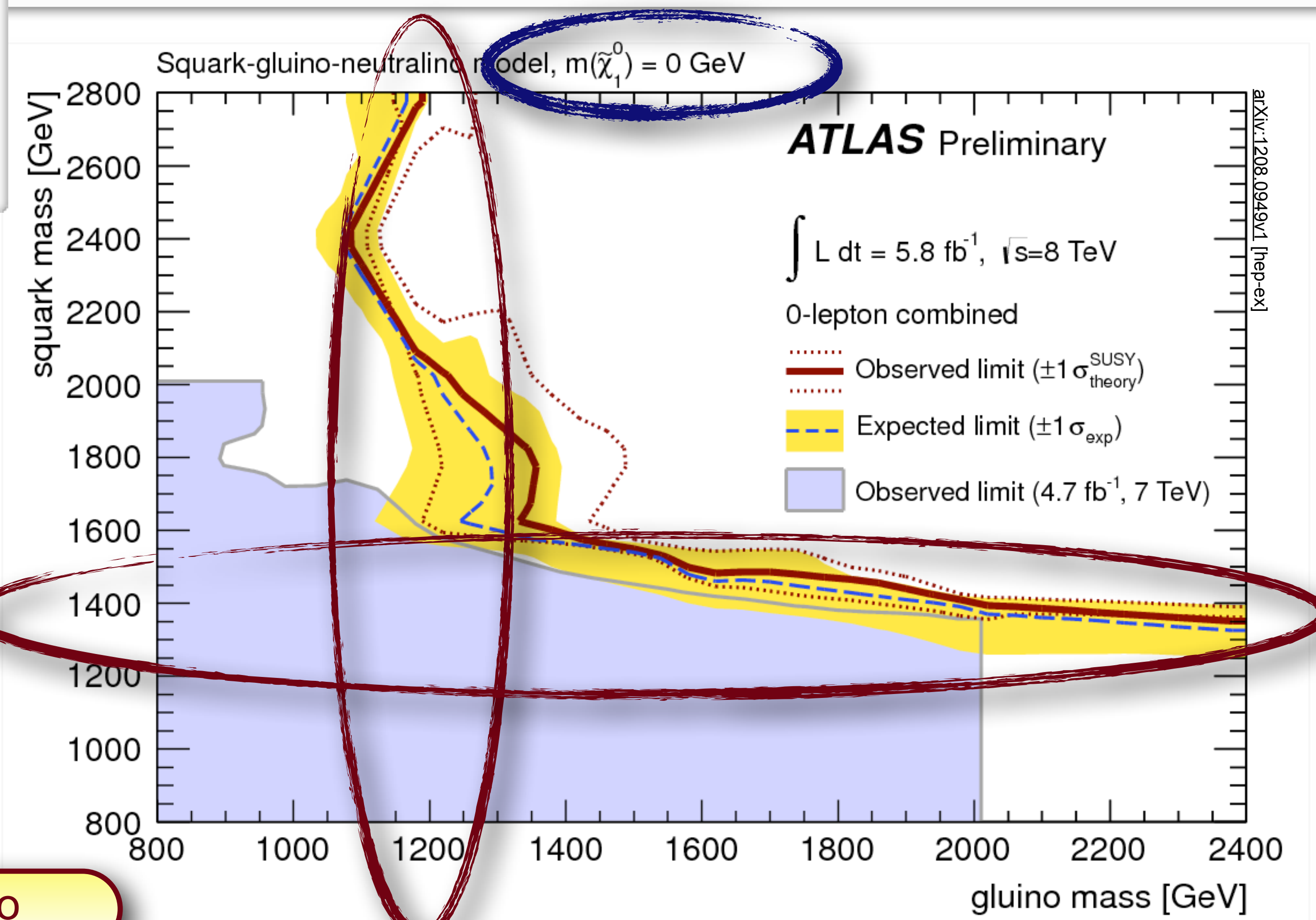


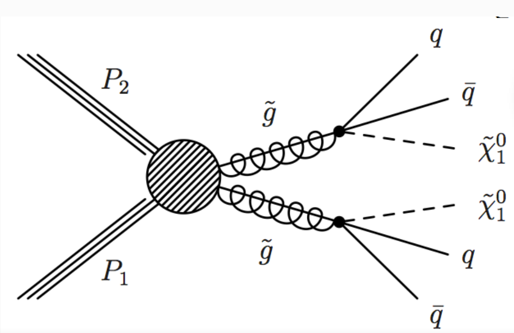
in the context of a simplified MSSM scenario

Interpretations of generic searches

in the context of a concrete model, here cMSSM







in the context of a simplified MSSM scenario

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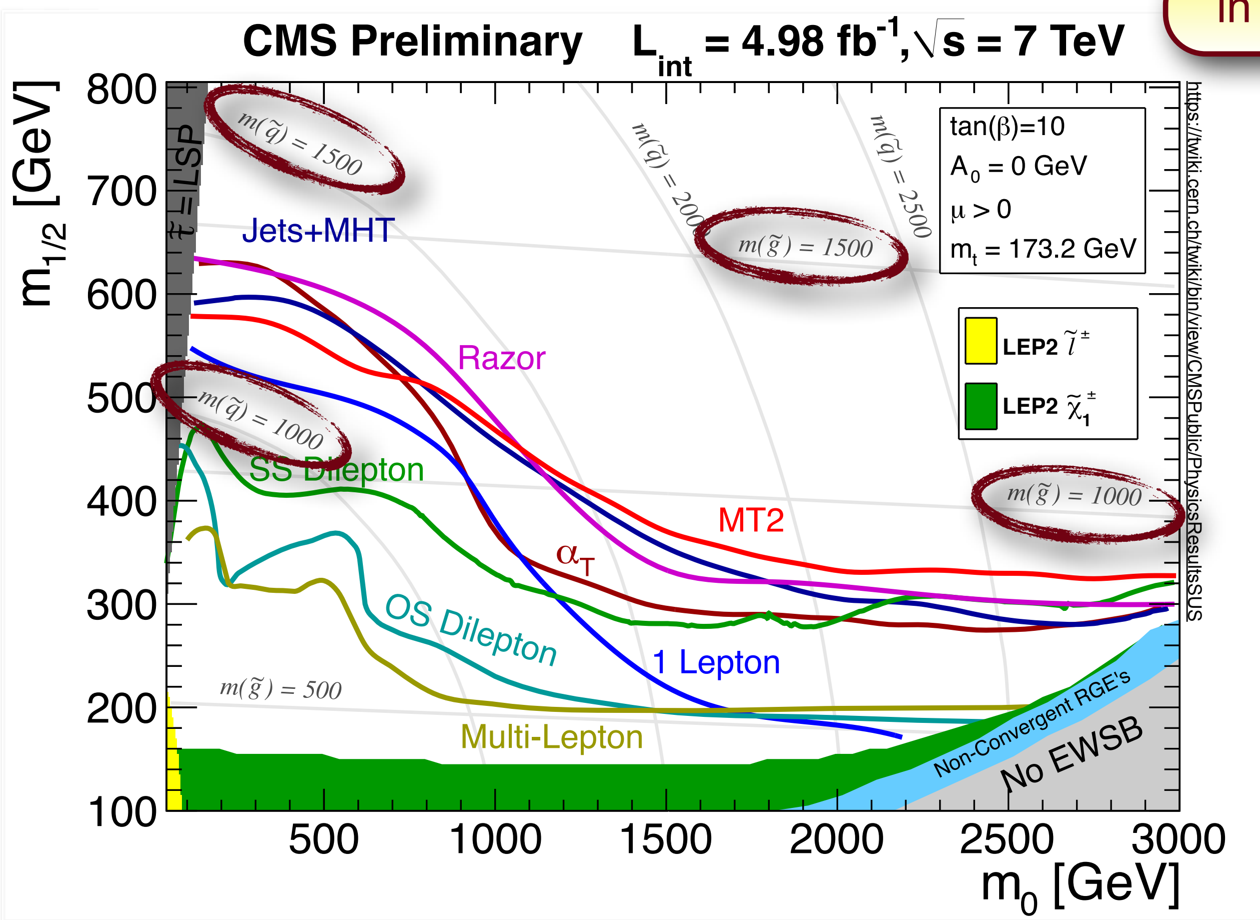
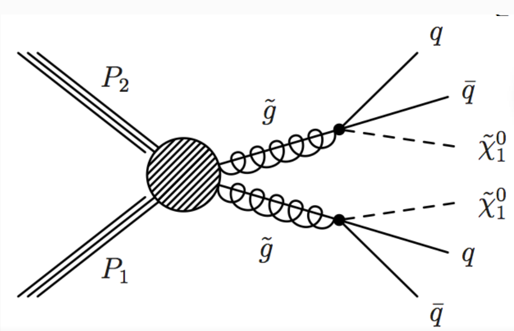
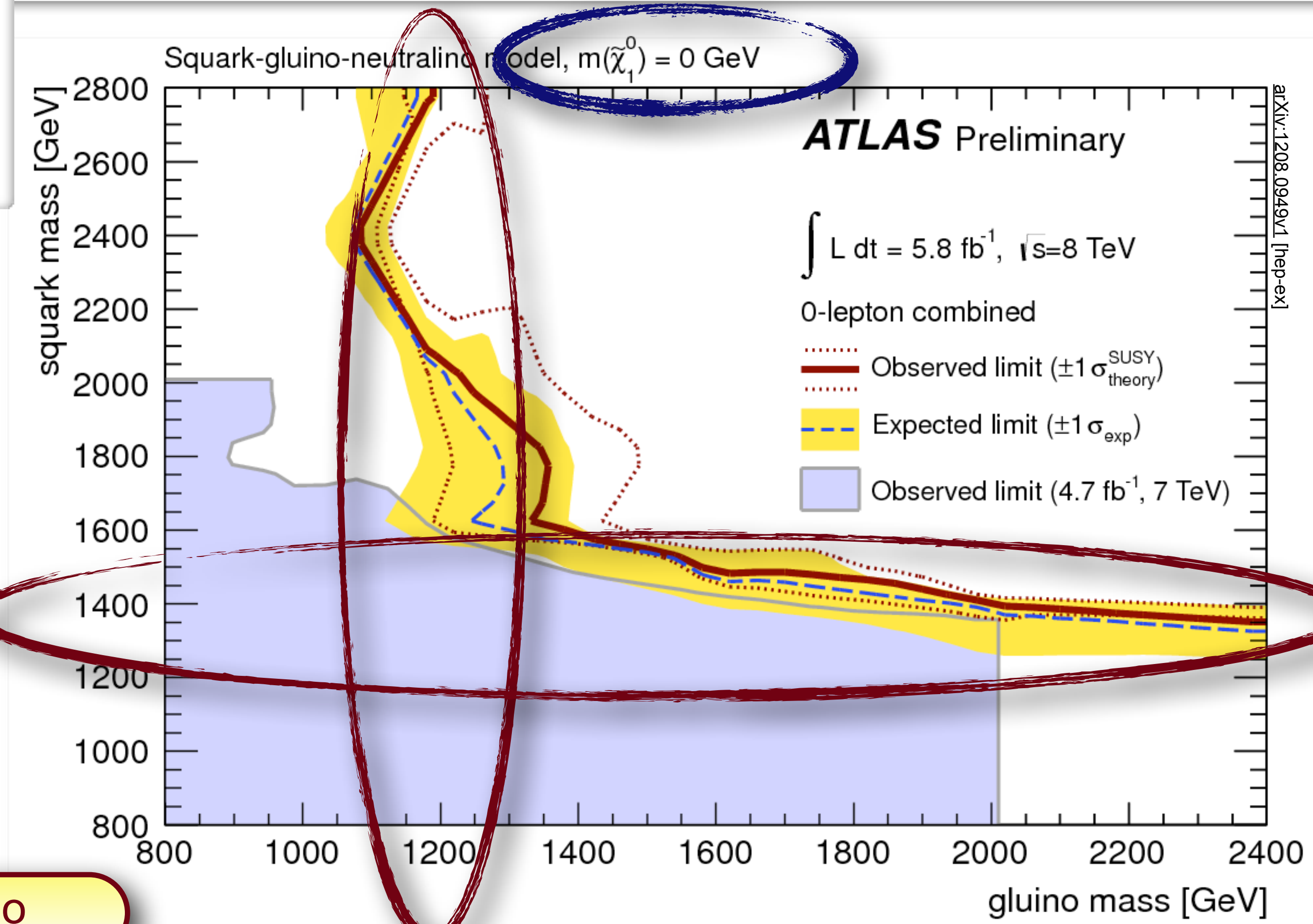


- squark/gluino masses excluded below ~ 1400/1200 GeV
- **for m(squark) = m(gluino), exclude below ~1500 GeV**
- these searches typically target large M_{eff} and large difference m(SUSY) - m(LSP)
- the very inclusive searches keep sensitivity even for m(LSP) up to a few hundreds of GeV (at some stage trigger-constrained)

- recently targeting more compressed spectra and higher jet multiplicities

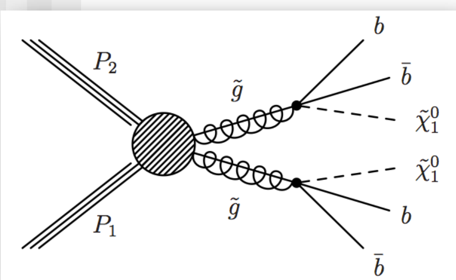


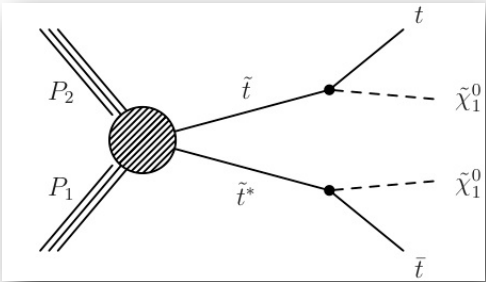


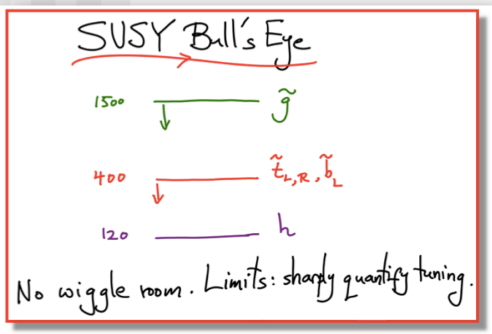
in the context of a simplified MSSM scenario

Focusing on the 3rd generation

- recently, addressing **"natural" SUSY scenarios, with "light" sbottom/stop**
  - and other squarks very heavy
- targeting direct or gluino-mediated sbottom/stop production
- eg. extending generic searches by adding b-tags, or "ttbar+MET" searches
- typical limits in these contexts (simplified models):
  - m(gluino) $\geqslant$ 800-1100 GeV, for m(LSP) $\leqslant$ 400 GeV
  - **m(sbottom), m(stop) $\notin$ ~[300-500] GeV, for m(LSP) $\leqslant$ 100-200 GeV**

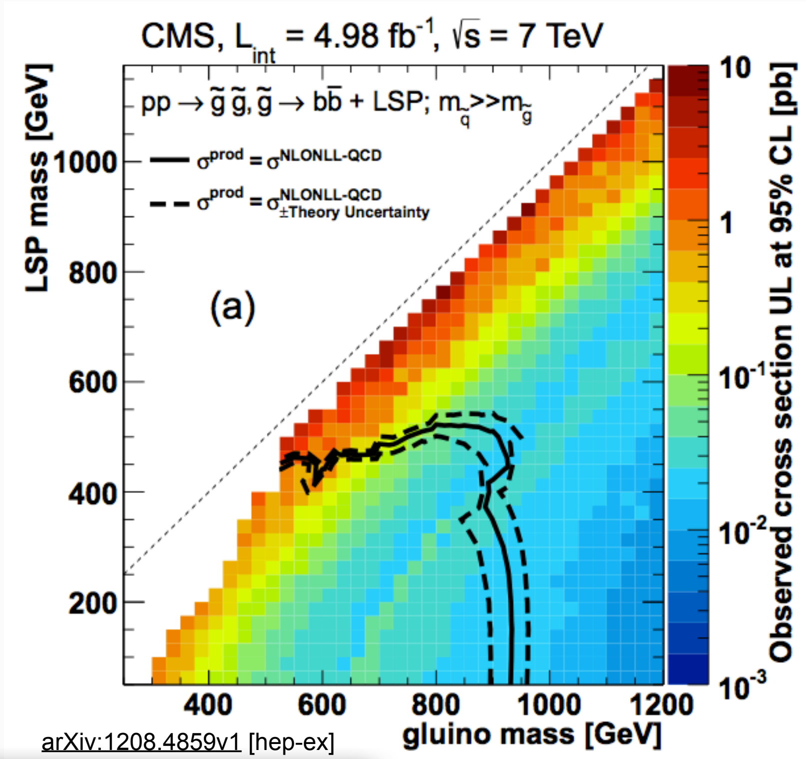






N. Arkani-Hamed, "Implications of LHC results for TeV-scale physics"

Focusing on the 3rd generation



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  - and other squarks very heavy
- targeting direct or gluino-mediated sbottom/stop production
- eg. extending generic searches by adding b-tags, or "ttbar+MET" searches
- typical limits in these contexts (simplified models):
  - m(gluino) ⪆ 800-1100 GeV, for m(LSP) ⪅ 400 GeV
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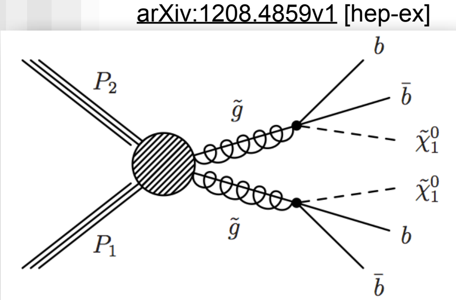

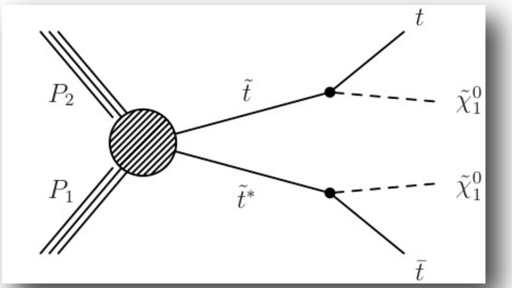

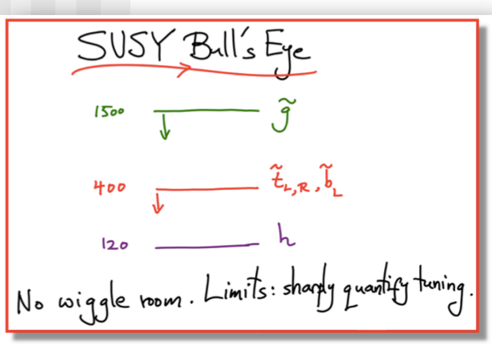

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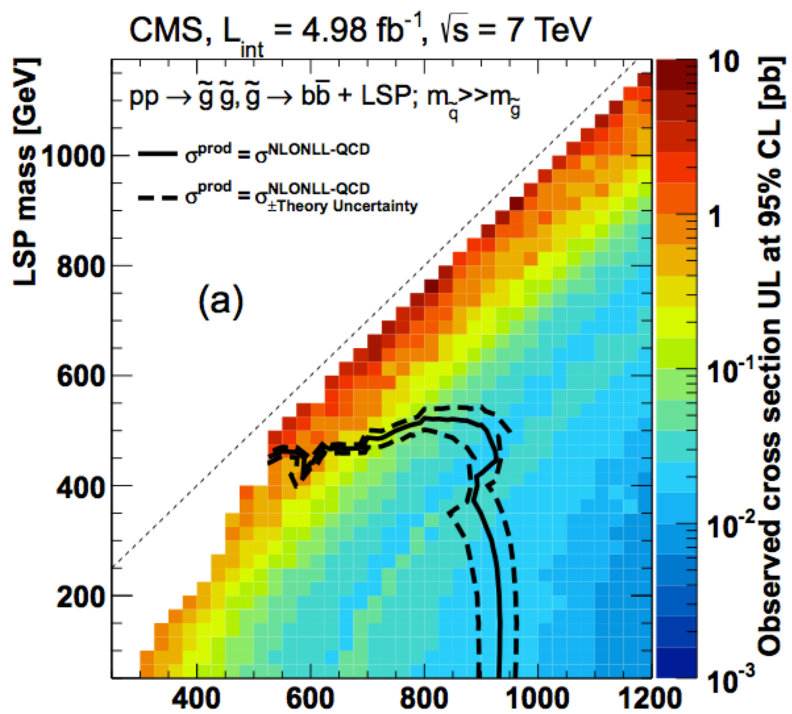
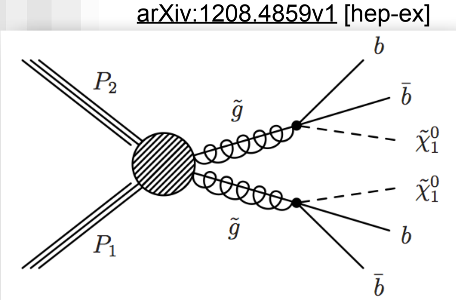
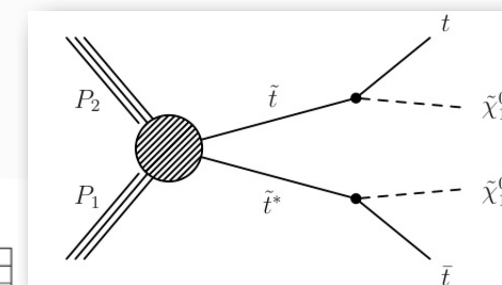
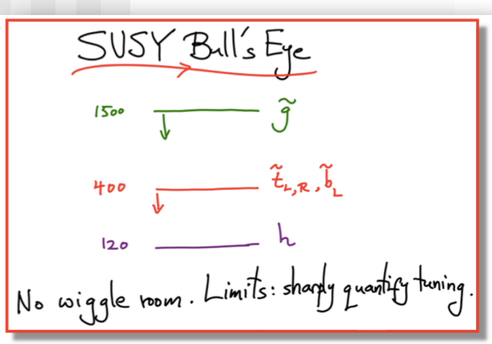


arXiv:1208.4859v1 [hep-ex]







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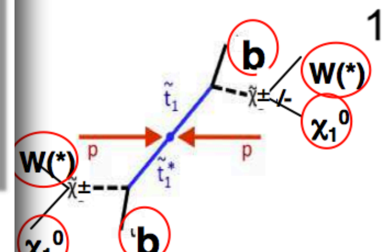
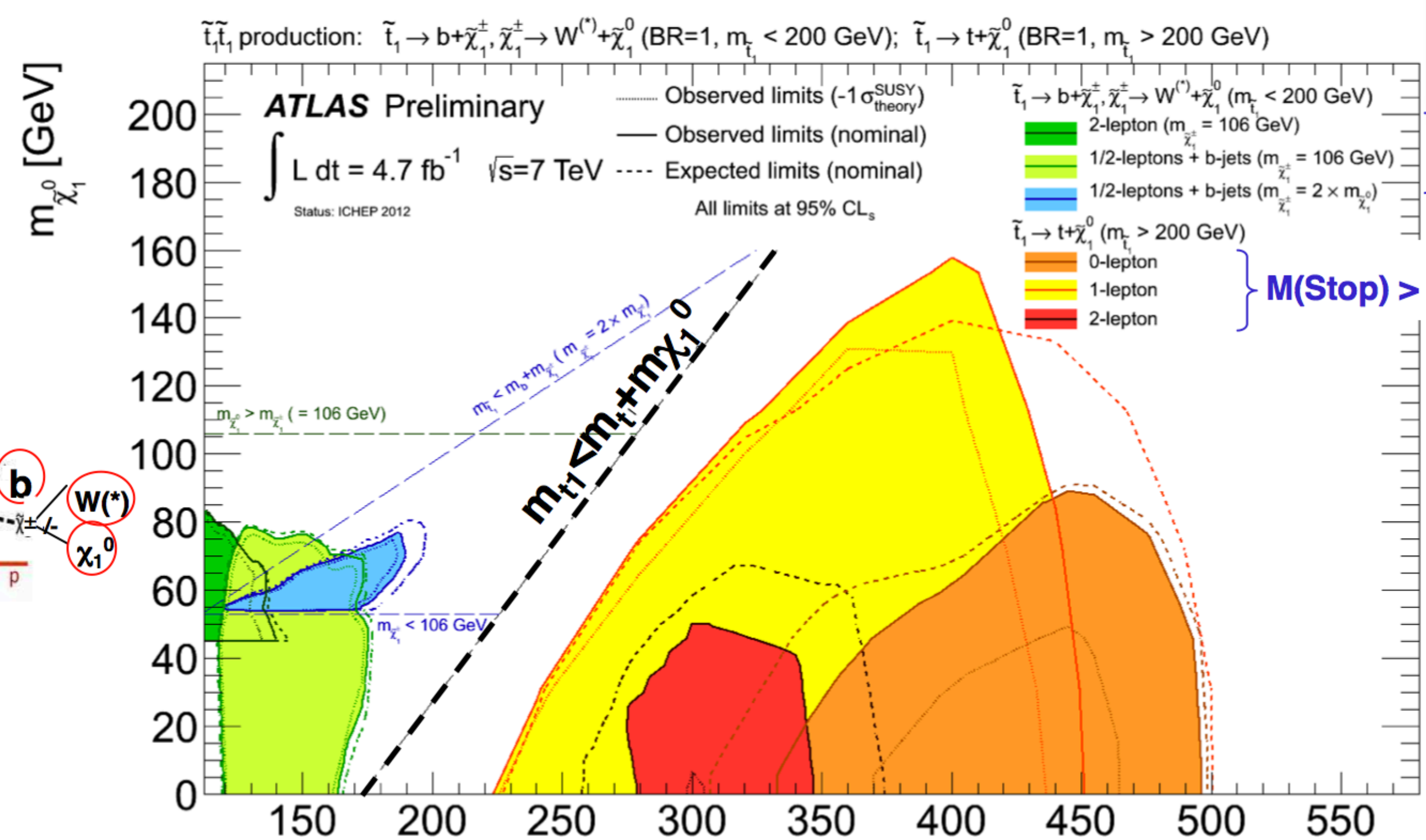
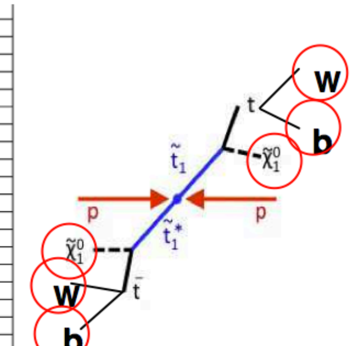




from Pallavorio, SUSY2012



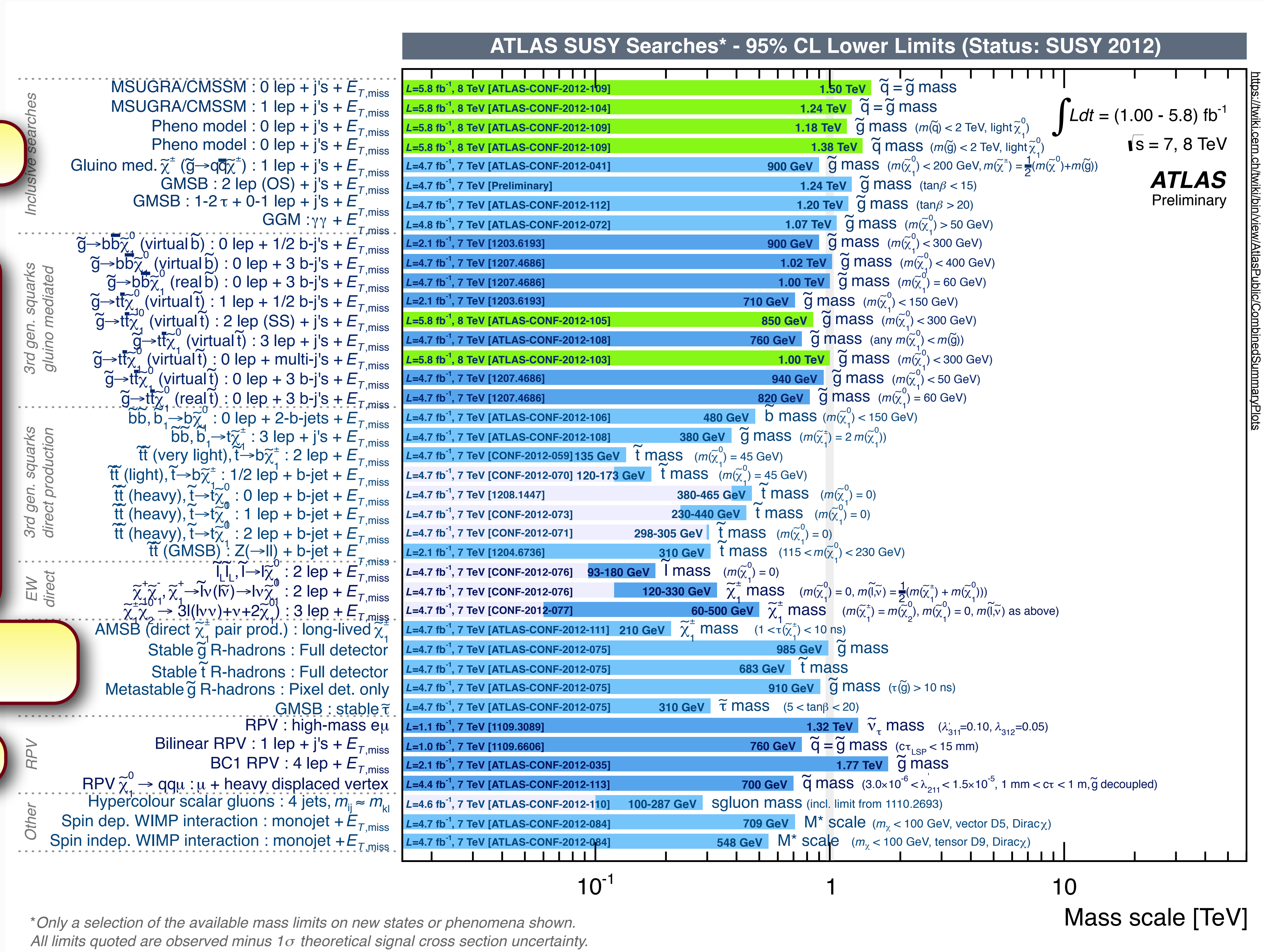
The big picture

inclusive searches

Natural SUSY

long-lived particles,
eg. split SUSY

RPV



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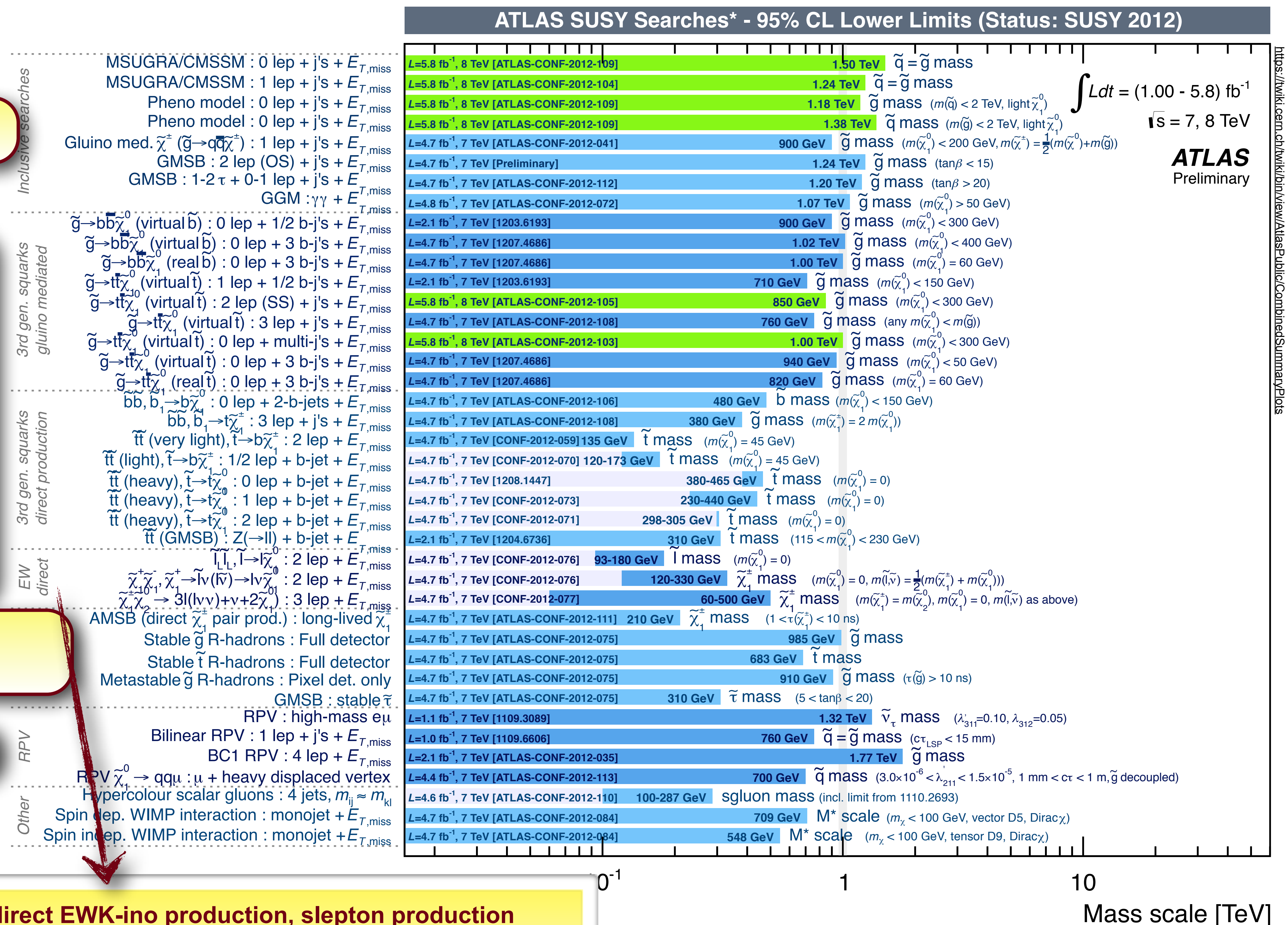

- **the new frontier: direct EWK-ino production, slepton production**
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- m(sleptons) excluded over a region [90-180] GeV, for m(LSP) = 0

The big picture

European Strategy for Particle Physics

ETH Institute for Particle Physics

inclusive searches

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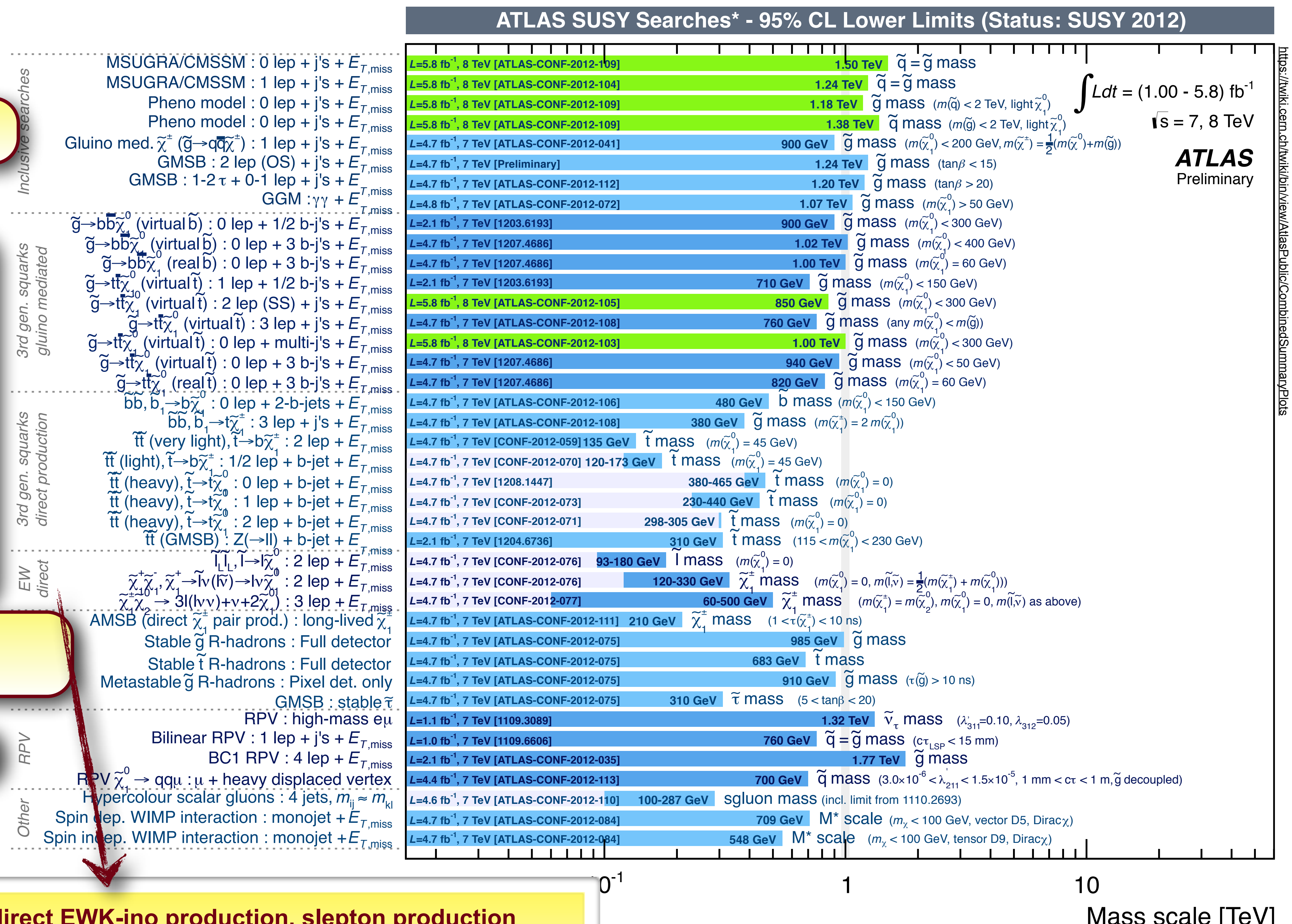

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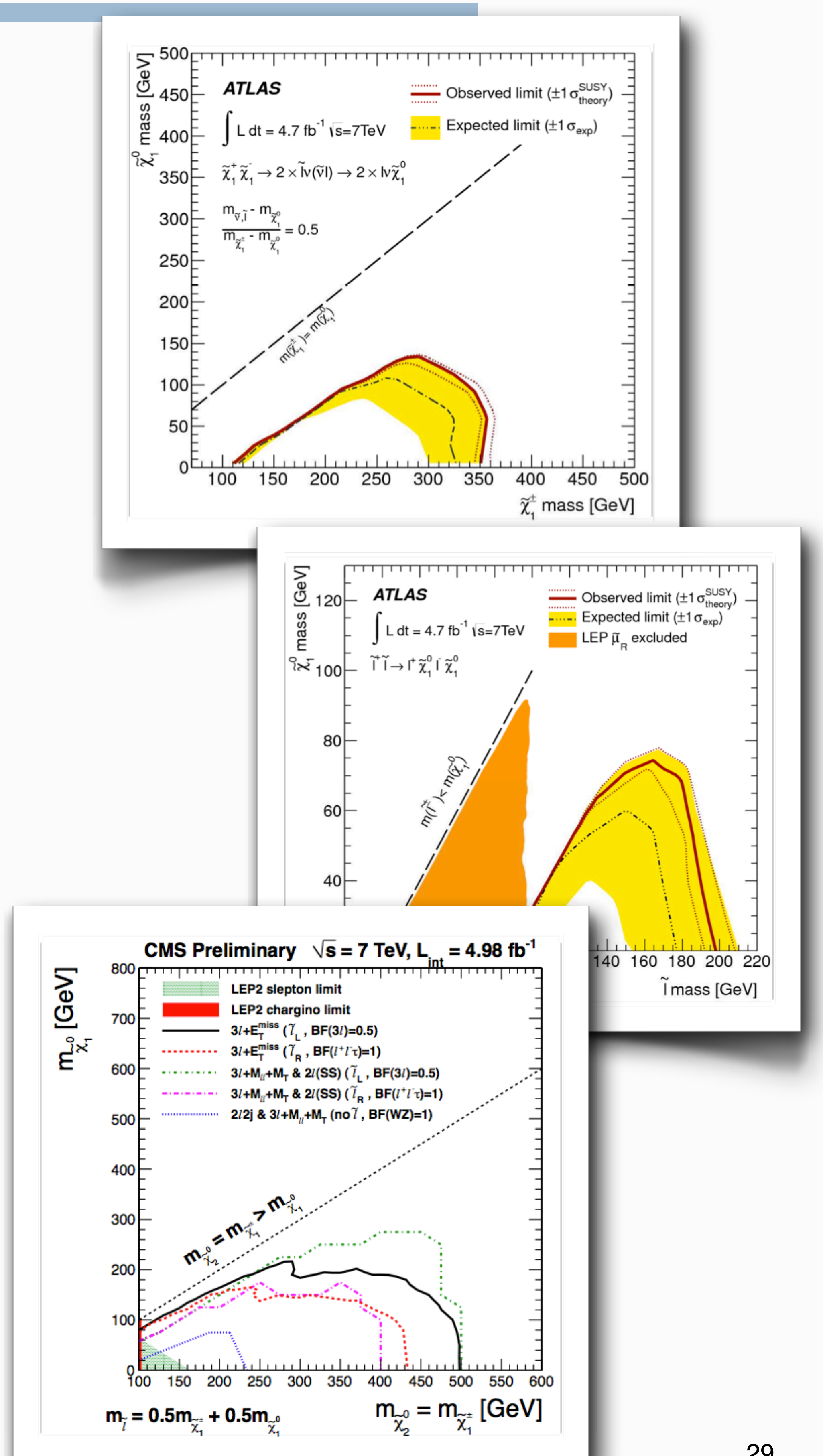
- impressive list, similar plethora of results from CMS
- but: **read the fine-print** !!

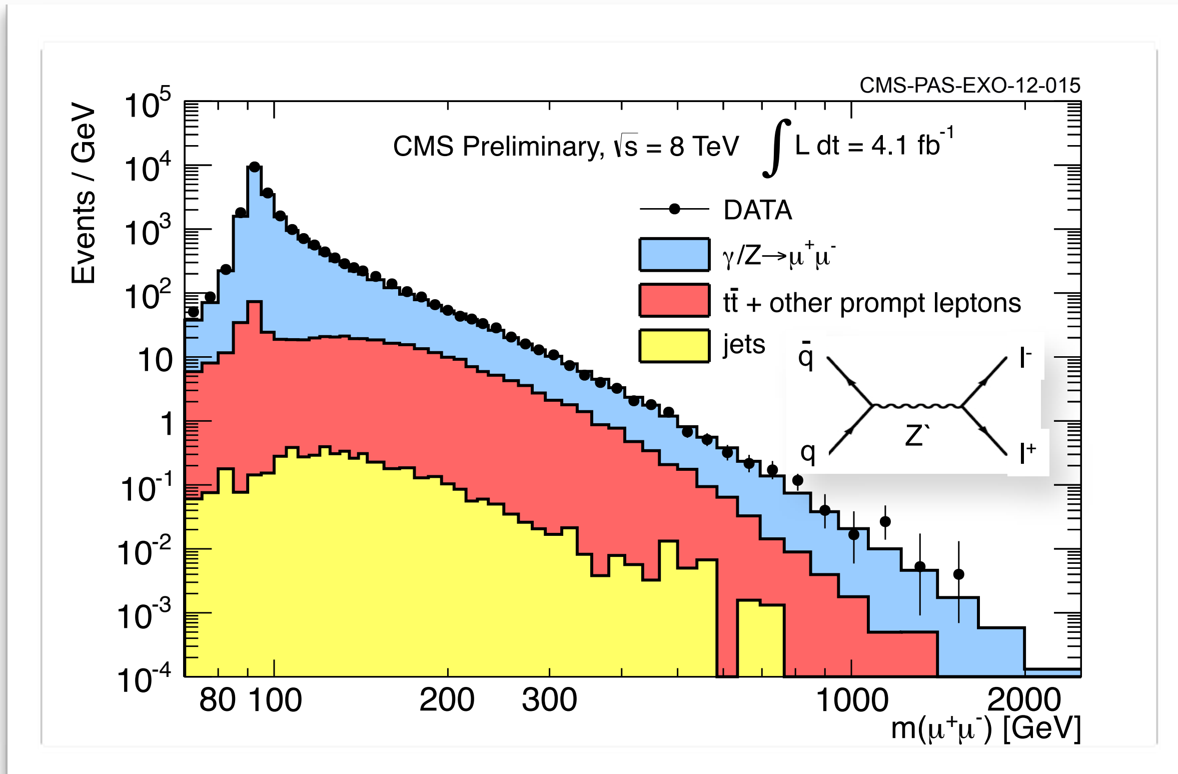
The “IF” files (ie. the fine-print)

- The experiments have already explored a very vast range of masses and parameters
- Though, too early to declare SUSY’s death, since there remain important parameter regions to be explored, and because
  - Difficult or impossible to give “absolute” limits, since basically always assumptions involved
  - limits quickly degrade or disappear when raising m(LSP) beyond several hundreds of GeV
  - inclusive searches often assume degenerate 1st and 2nd generation squarks. Limits decrease (by several hundreds of GeV) if this is given up
  - simplified models make strong assumptions on branching ratios, masses of intermediate states
  - theory uncertainties (cross sections/scales/pdfs, initial state radiation)



Exotica

- the philosophy: leave no stone unturned...
- examples:



- **Z' with SM-like couplings > 2.59 TeV**
- **W' with SM-like couplings > 2.85 TeV**

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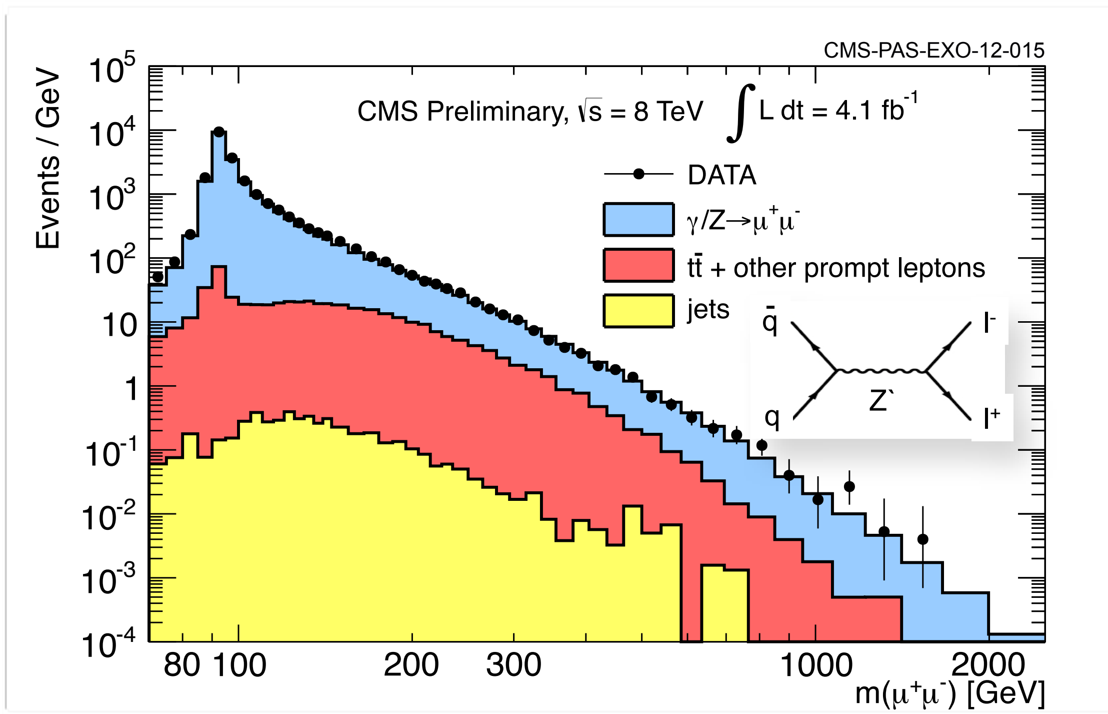

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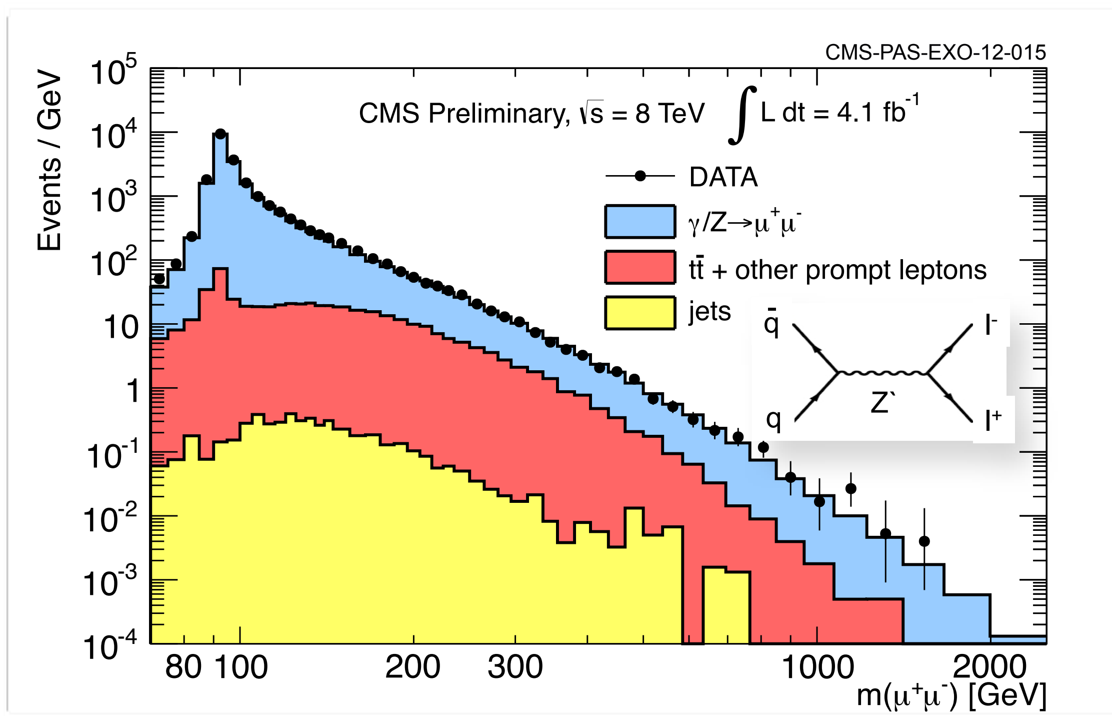

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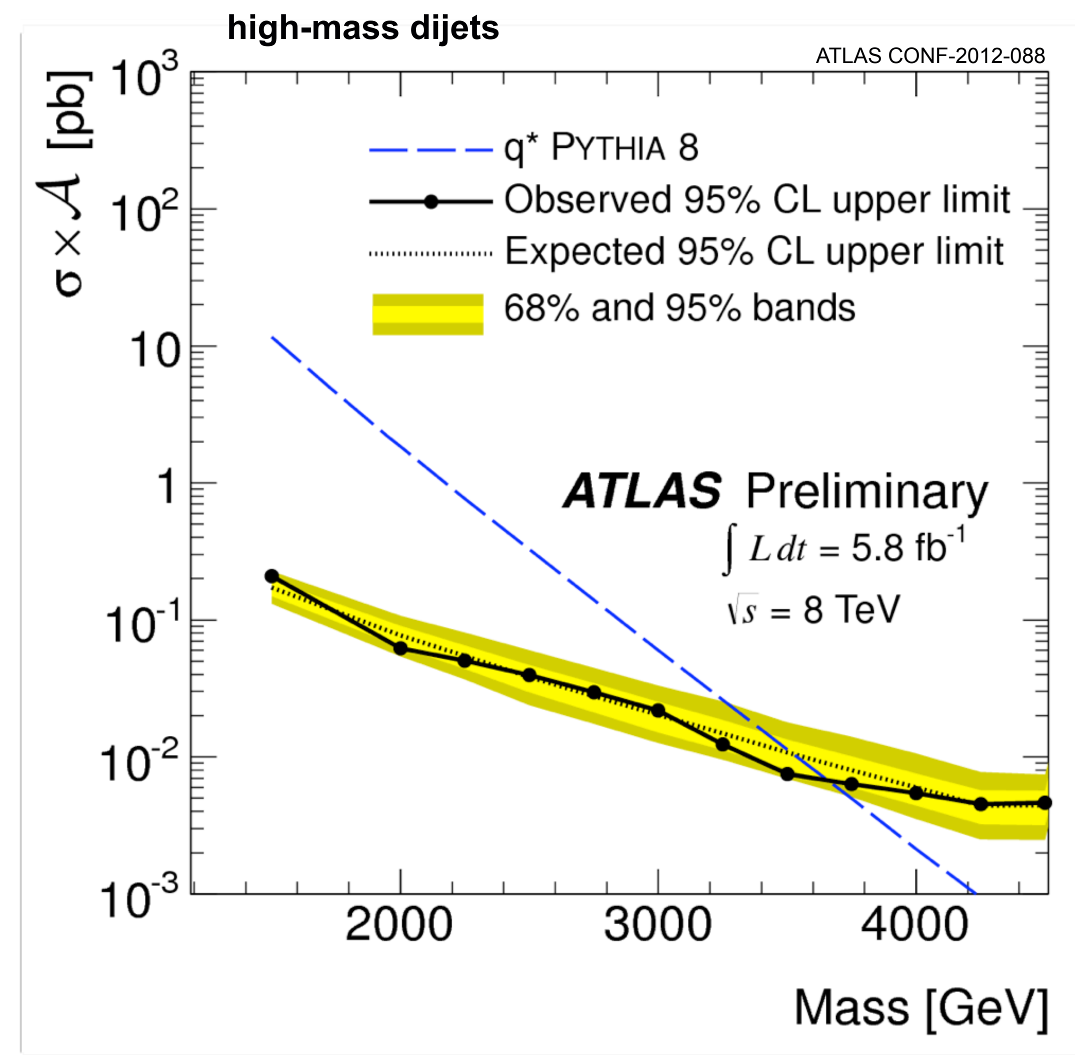
high-mass dijets

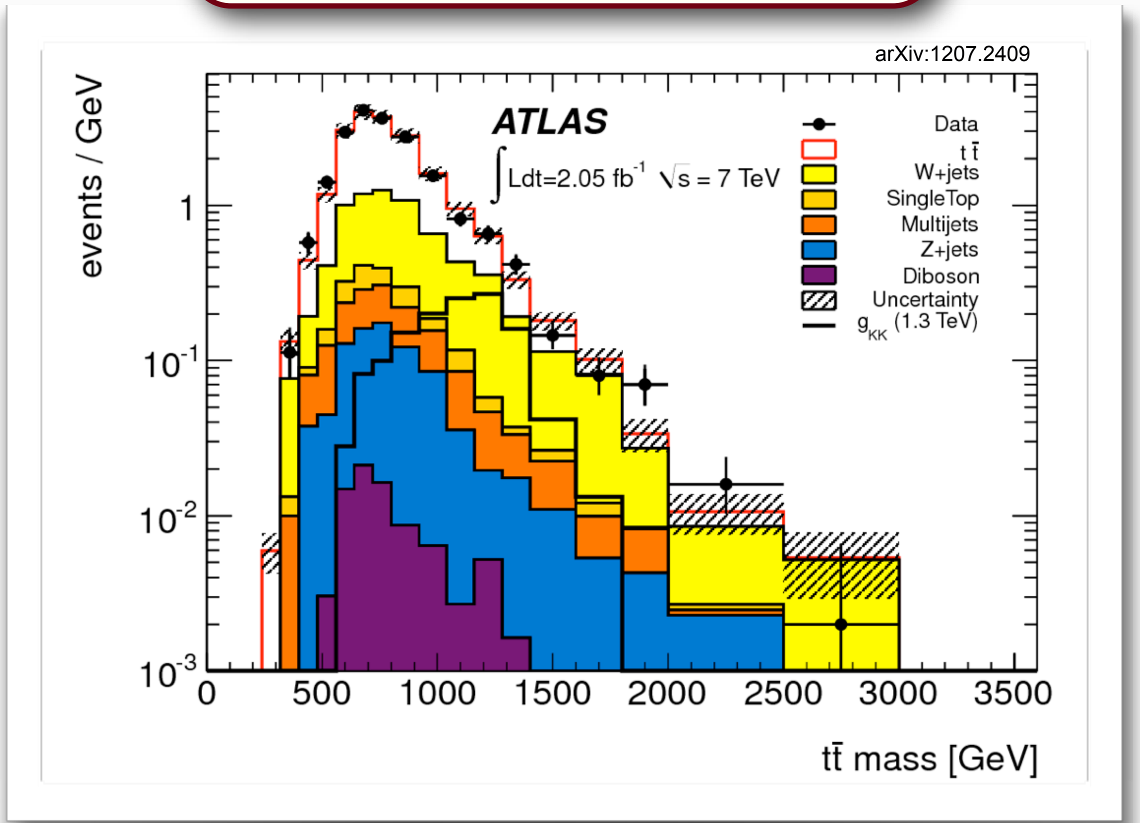


- **8 TeV data: excited quarks > 3.66 TeV**
- **7 TeV data: quark contact interactions, scale > 7.8 TeV**

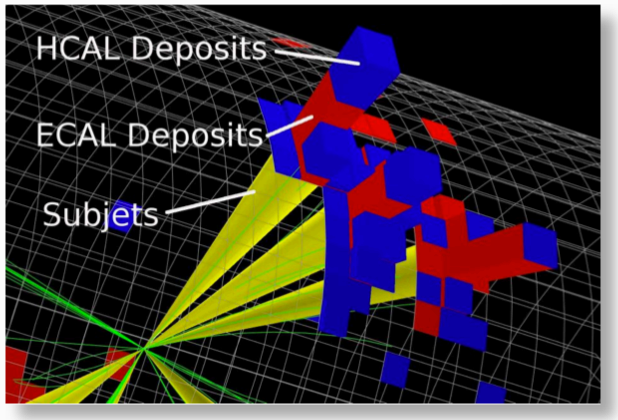
Exotica

- the philosophy: leave no stone unturned...
- **further** examples:

search for ttbar resonances



- **Kaluza-Klein gluon excluded for m<1.5 TeV**



Exotica

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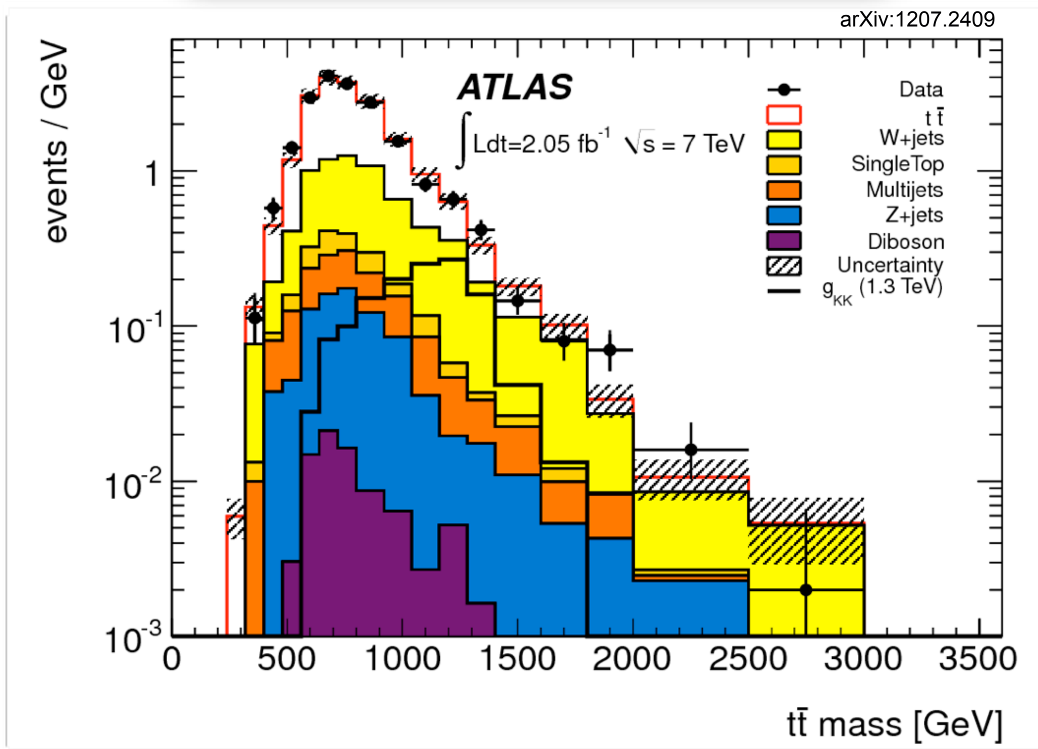
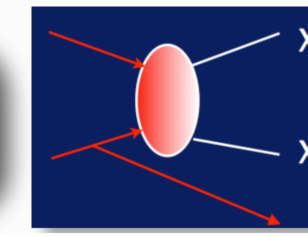
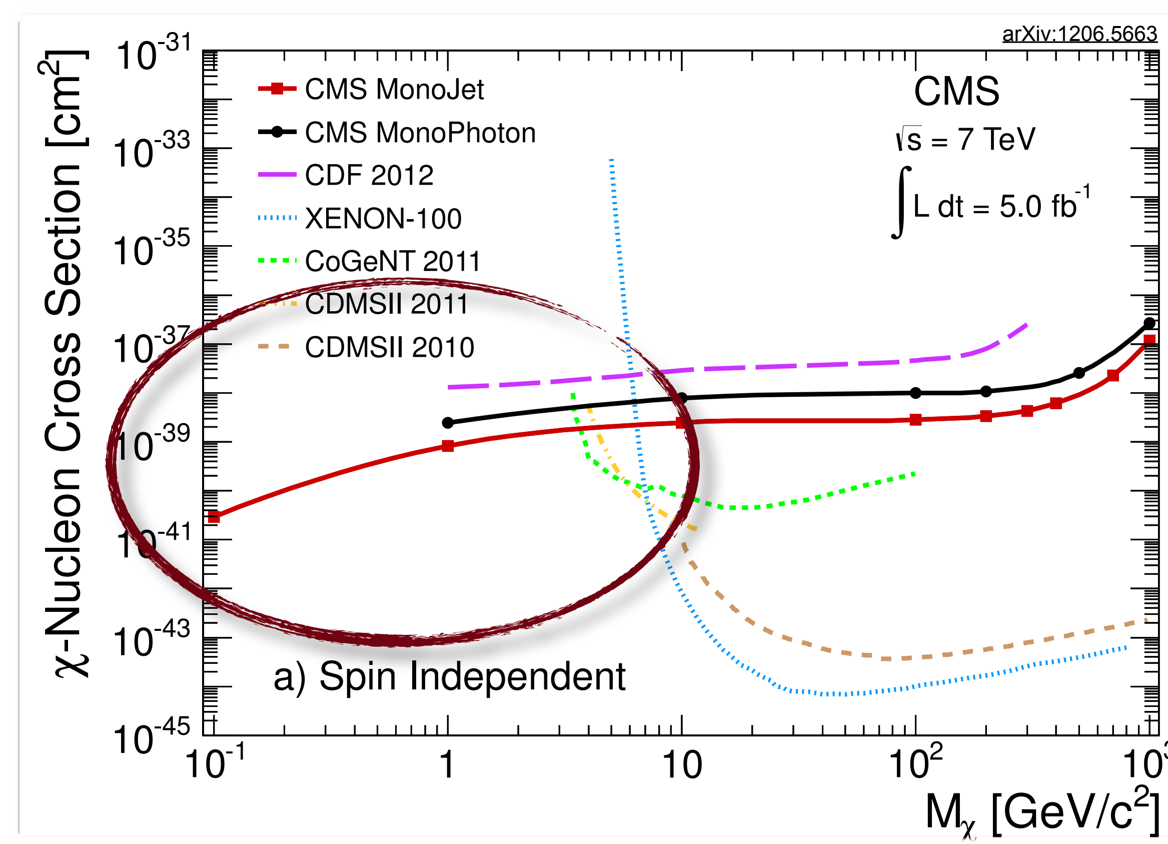
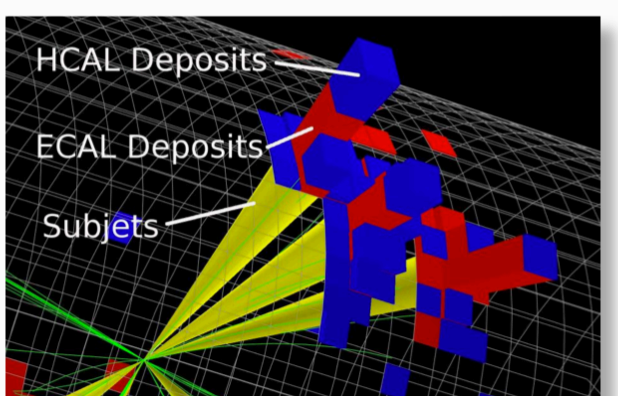


- **Kaluza-Klein gluon excluded for m<1.5 TeV**

mono-jet and mono-photon searches



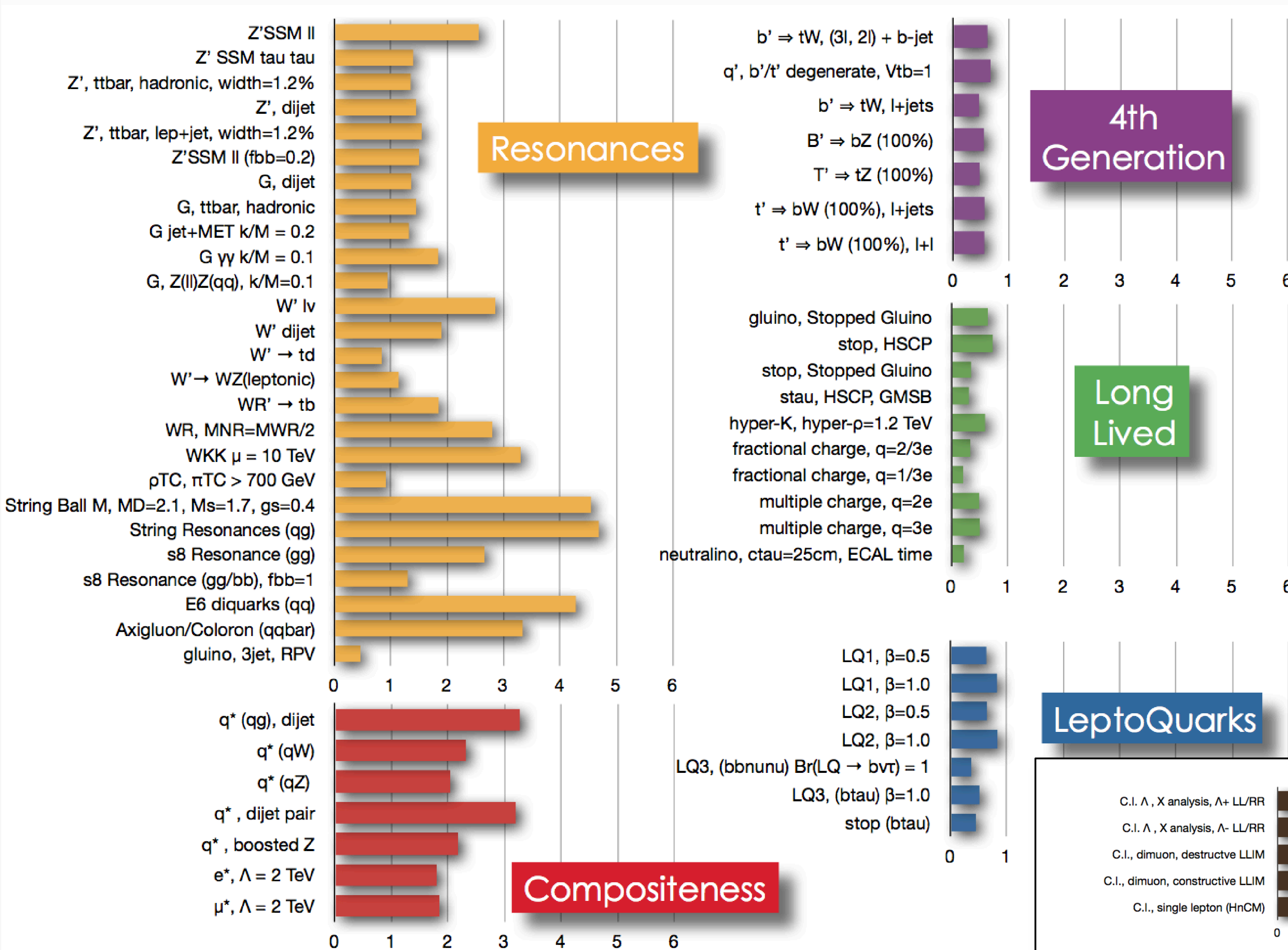


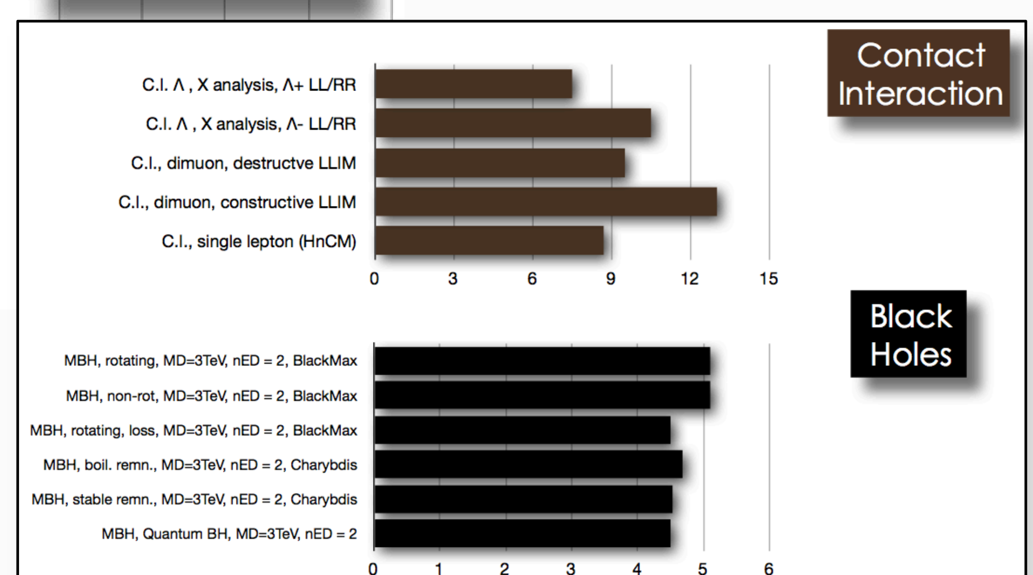


- **ttbar inv. mass spectrum** : no anomalies seen so far
- modern tools deployed (boosted top reconstruction)
- **mono-jet/photon searches**: nice complementarity with direct DM searches

Exotica: Executive summary

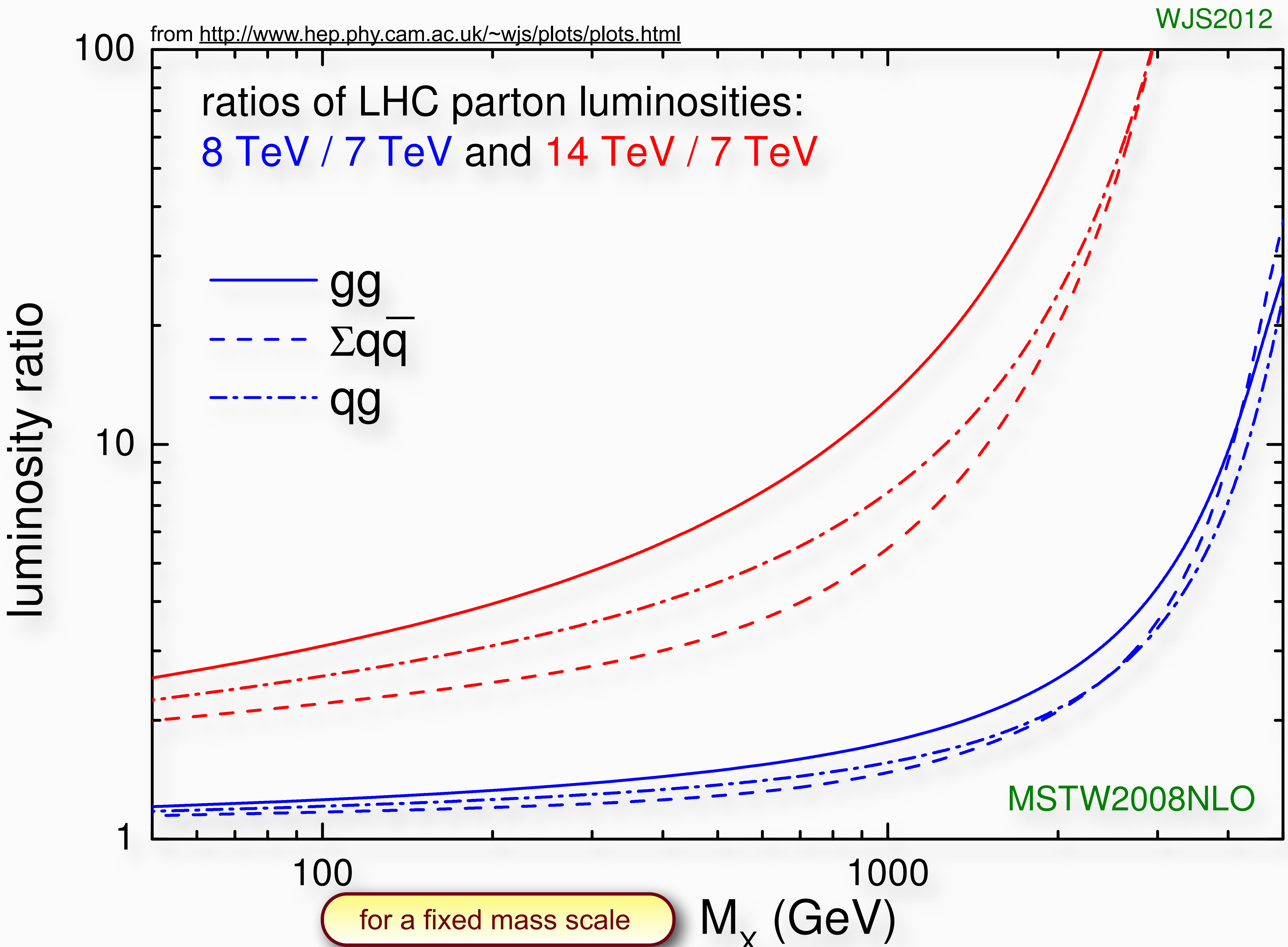
- CMS searches at ICHEP2012 (lower limits in TeV), similar picture for ATLAS





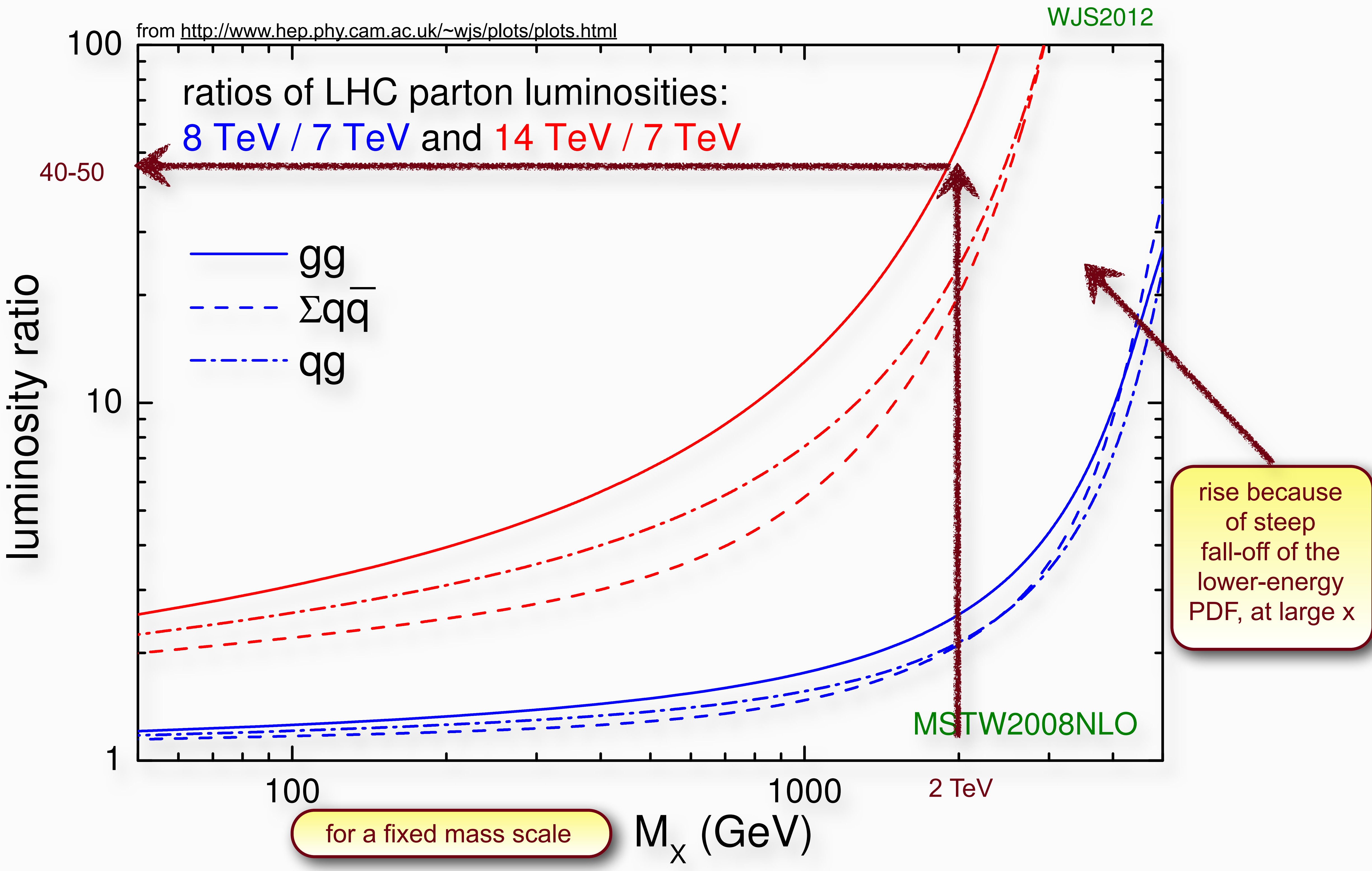
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/exo-limits-ichep2012.pdf

Parton luminosities



for a fixed mass scale

Parton luminosities



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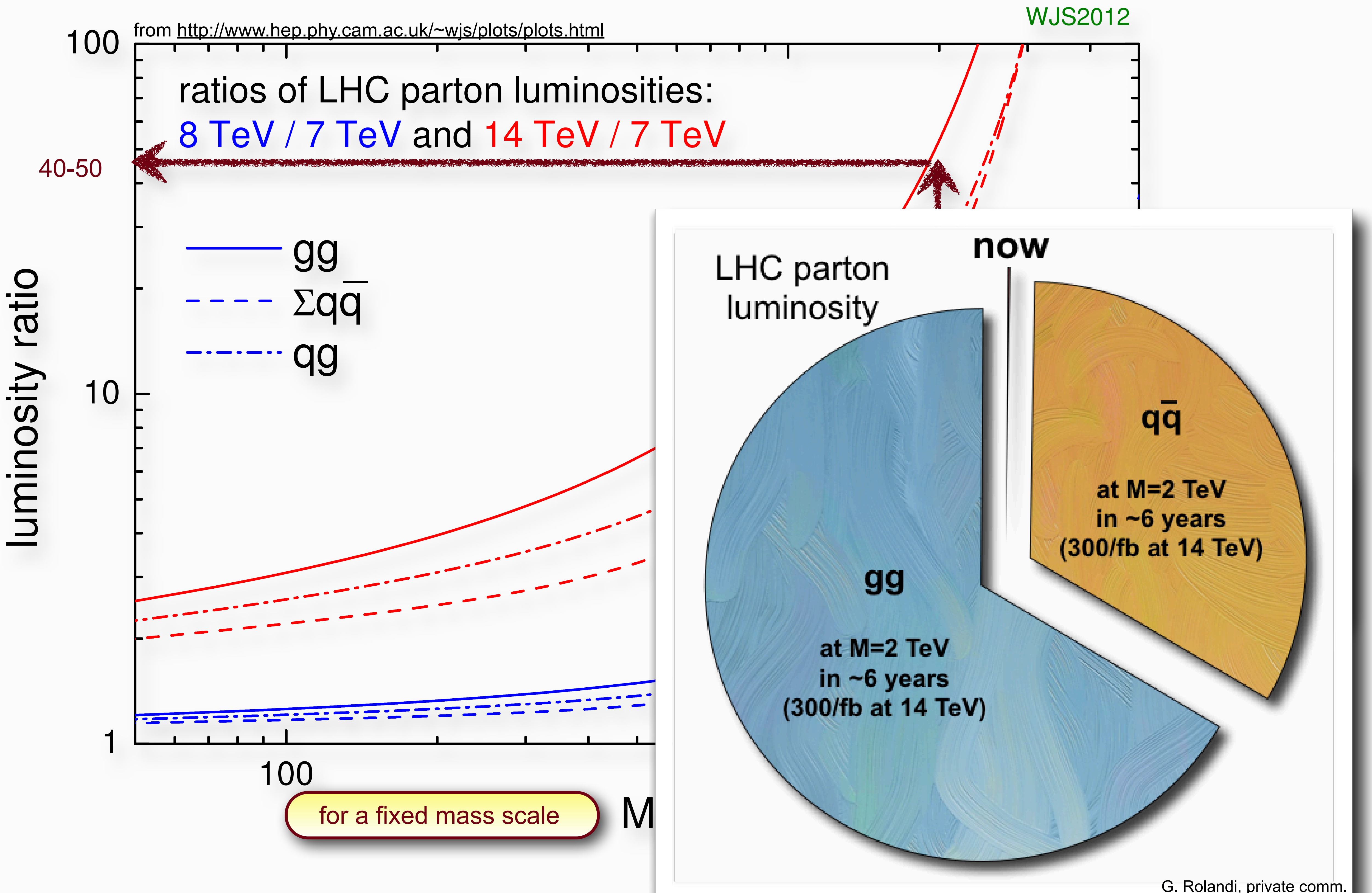
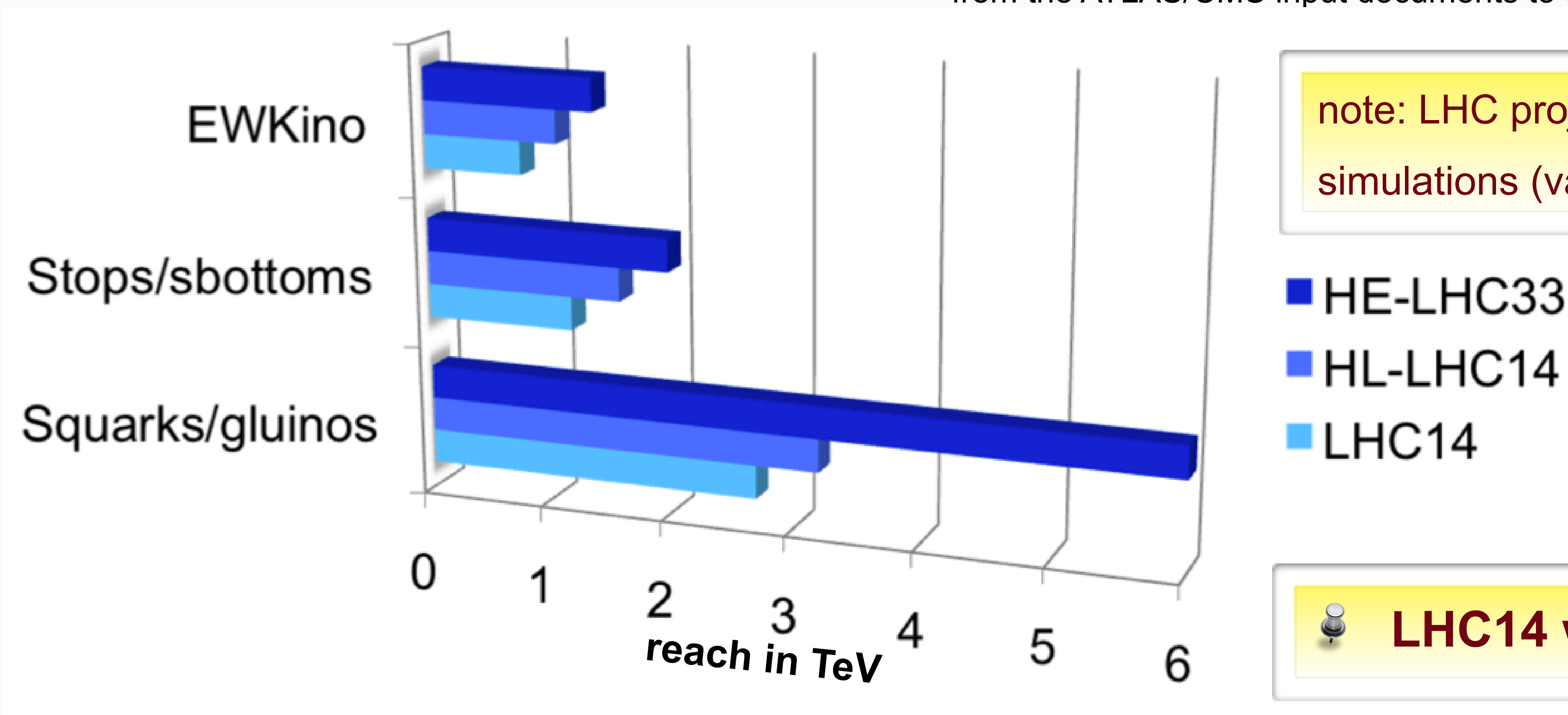


G. Rolandi, private comm.

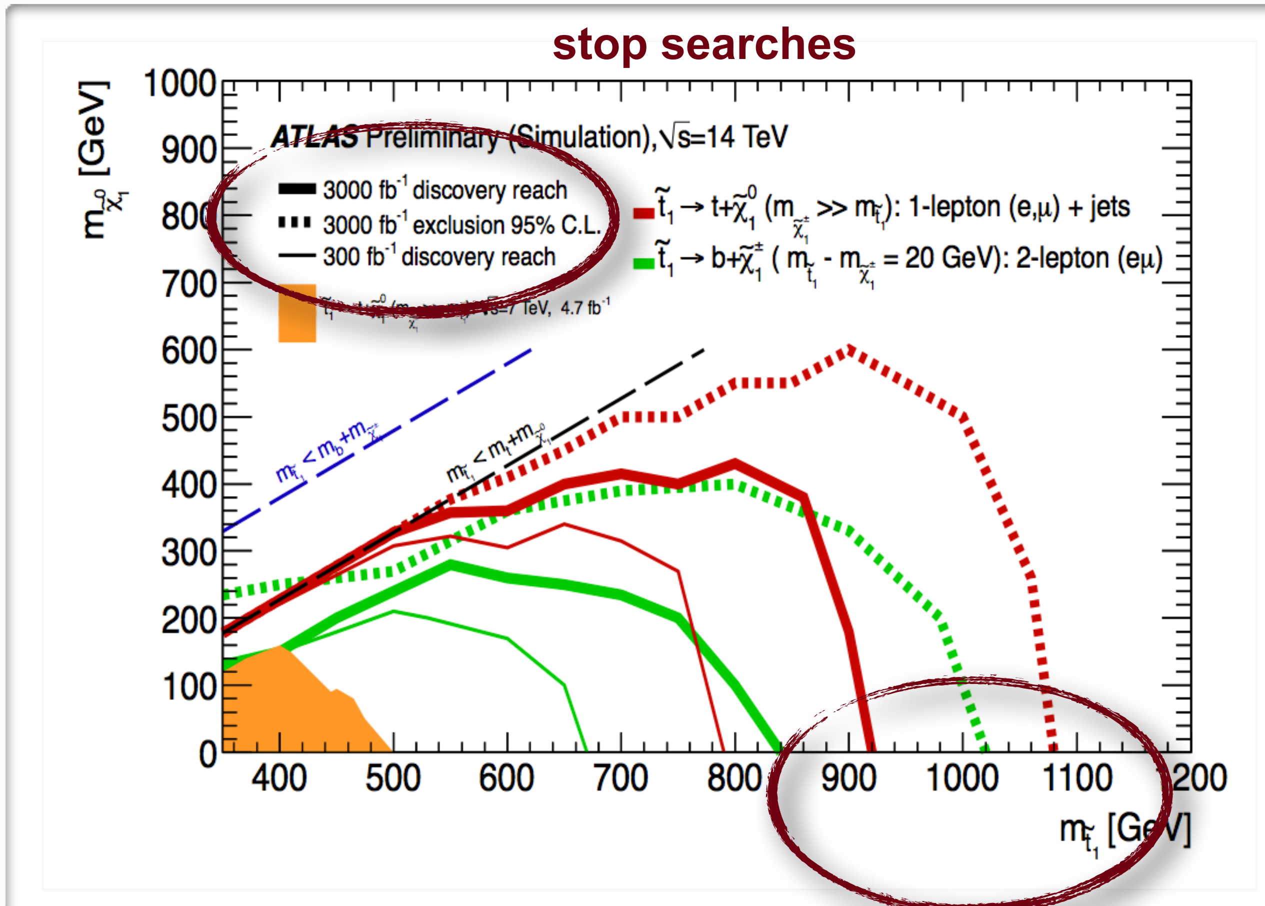
Prelim. Projections : direct searches

from the ATLAS/CMS input documents to the strategy process



note: LHC projections based on well-tested simulations (validated with current data)

LHC14 will be a new game!



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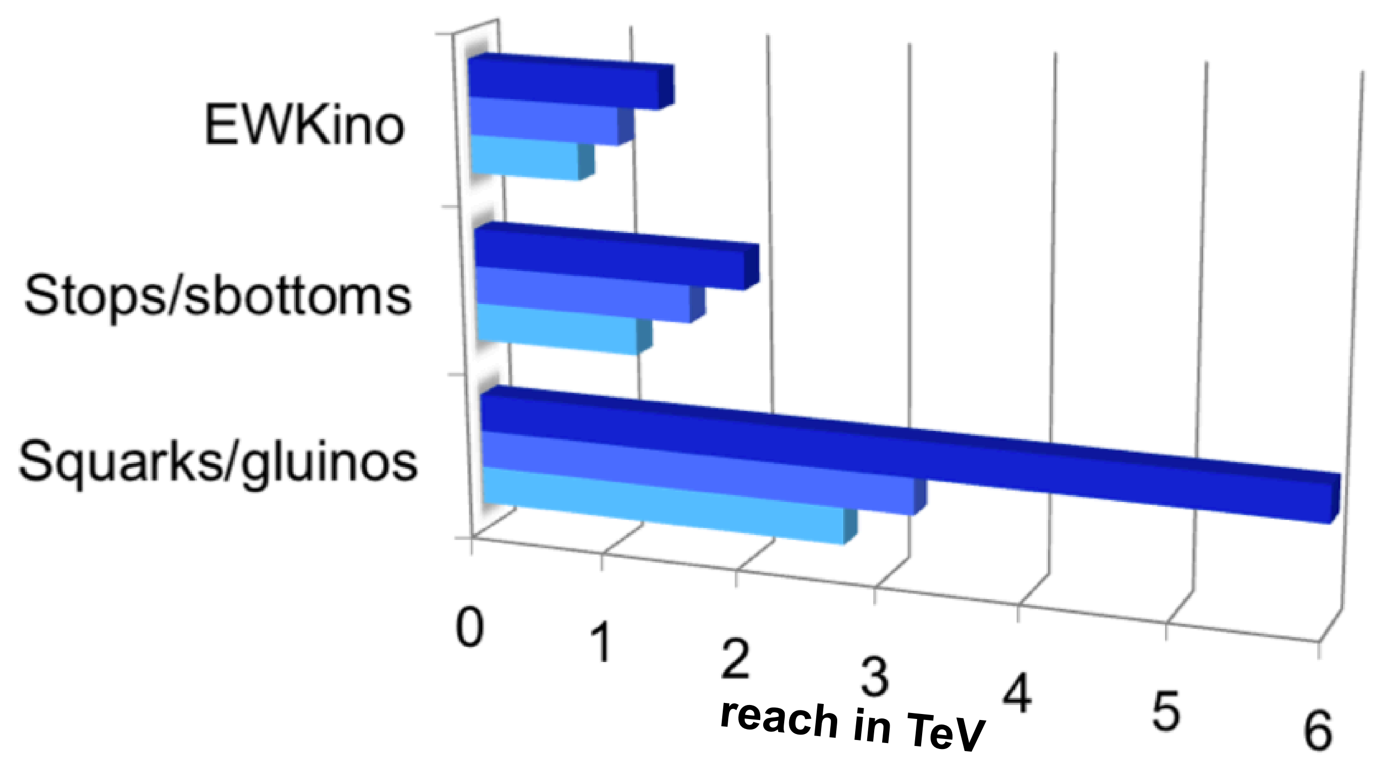

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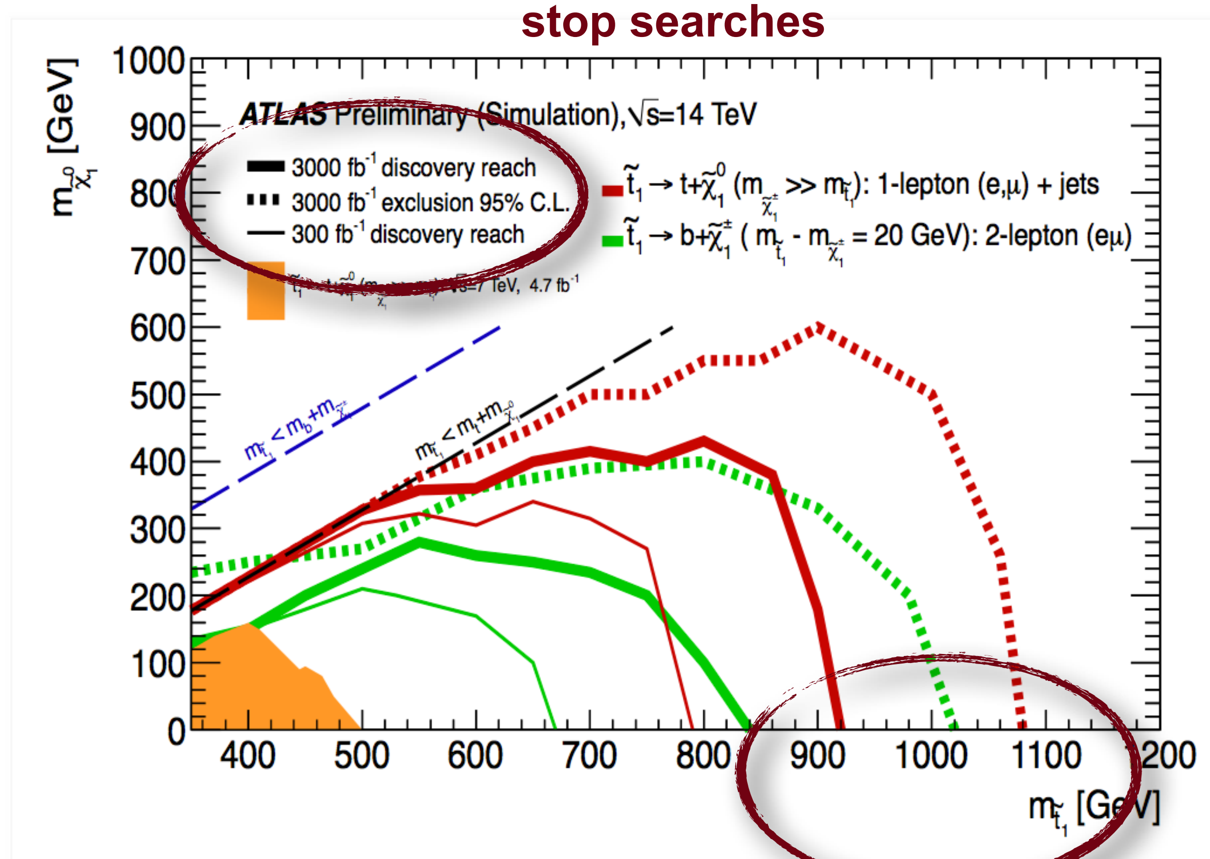
- **LHC14 will be a new game!**

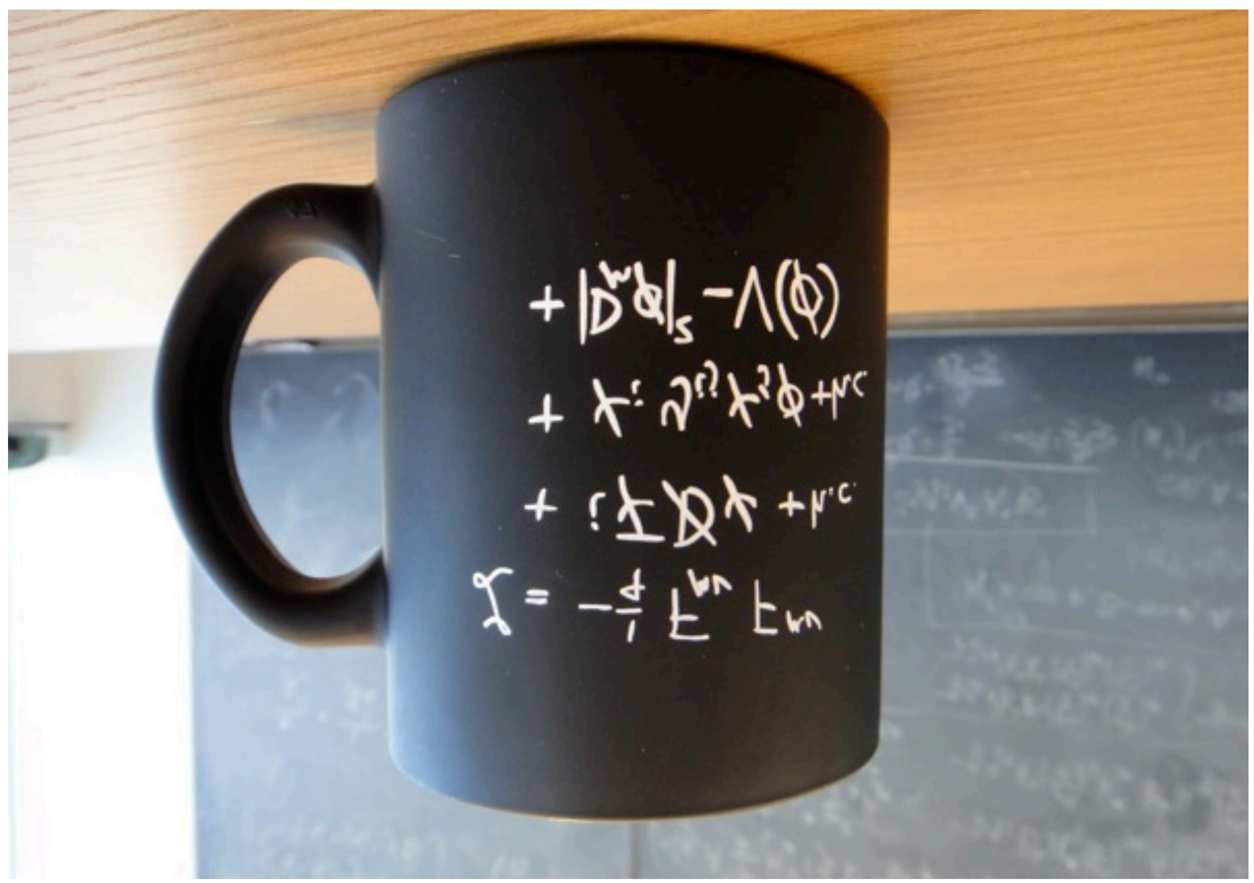
model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\text{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

- "large" masses, small couplings: HL-LHC
- "very large" masses: HE-LHC

stop searches

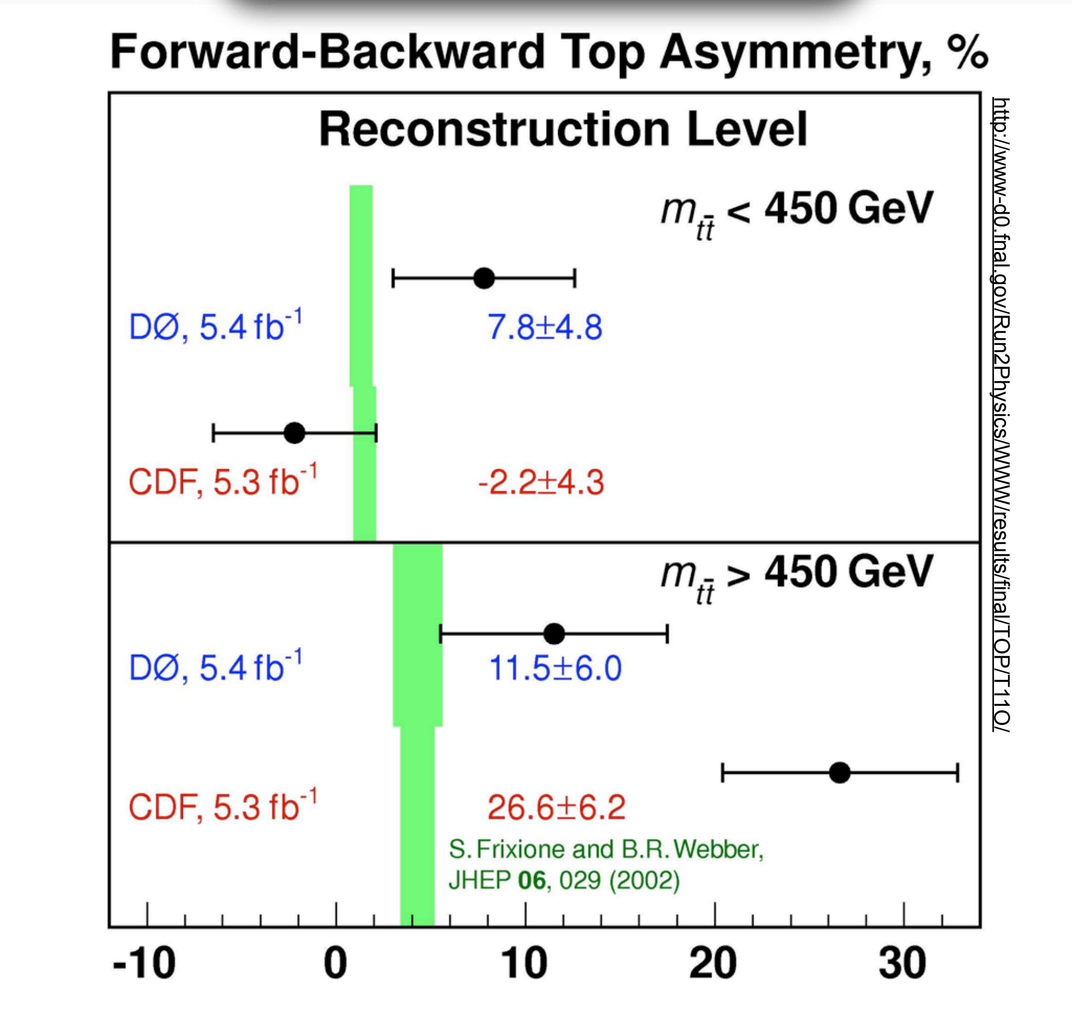


Anomalies



Anomalies (at large energy scales)

Top A_{FB} at the Tevatron



- Both experiments see asymmetry, in lepton+jets and dilepton channels, excesses at the 2-3 sigma level
- CDF sees strong dependence on M_{tt}, D0 is inconclusive
- Related (but not the same) observable at the LHC (charge asymmetry) : no anomalies seen so far
- no anomalies seen so far in top prod. cross section

Anomalies (at large energy scales)

ETH Institute for Particle Physics

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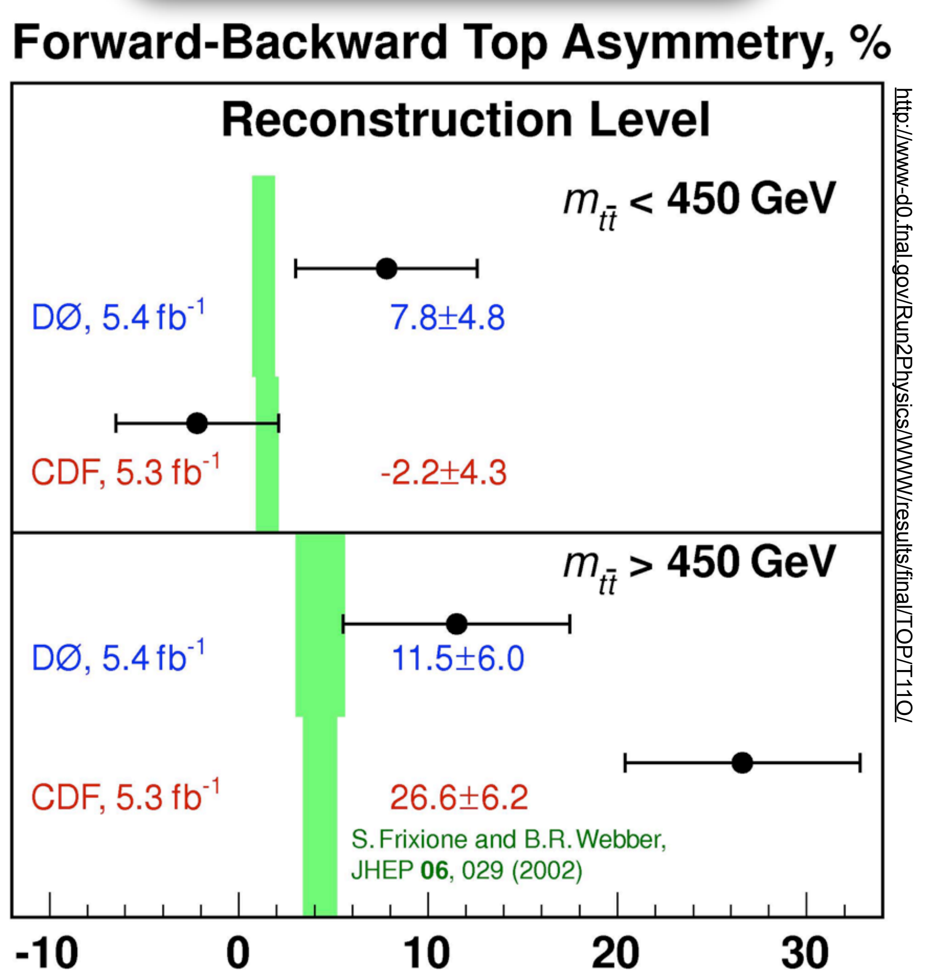

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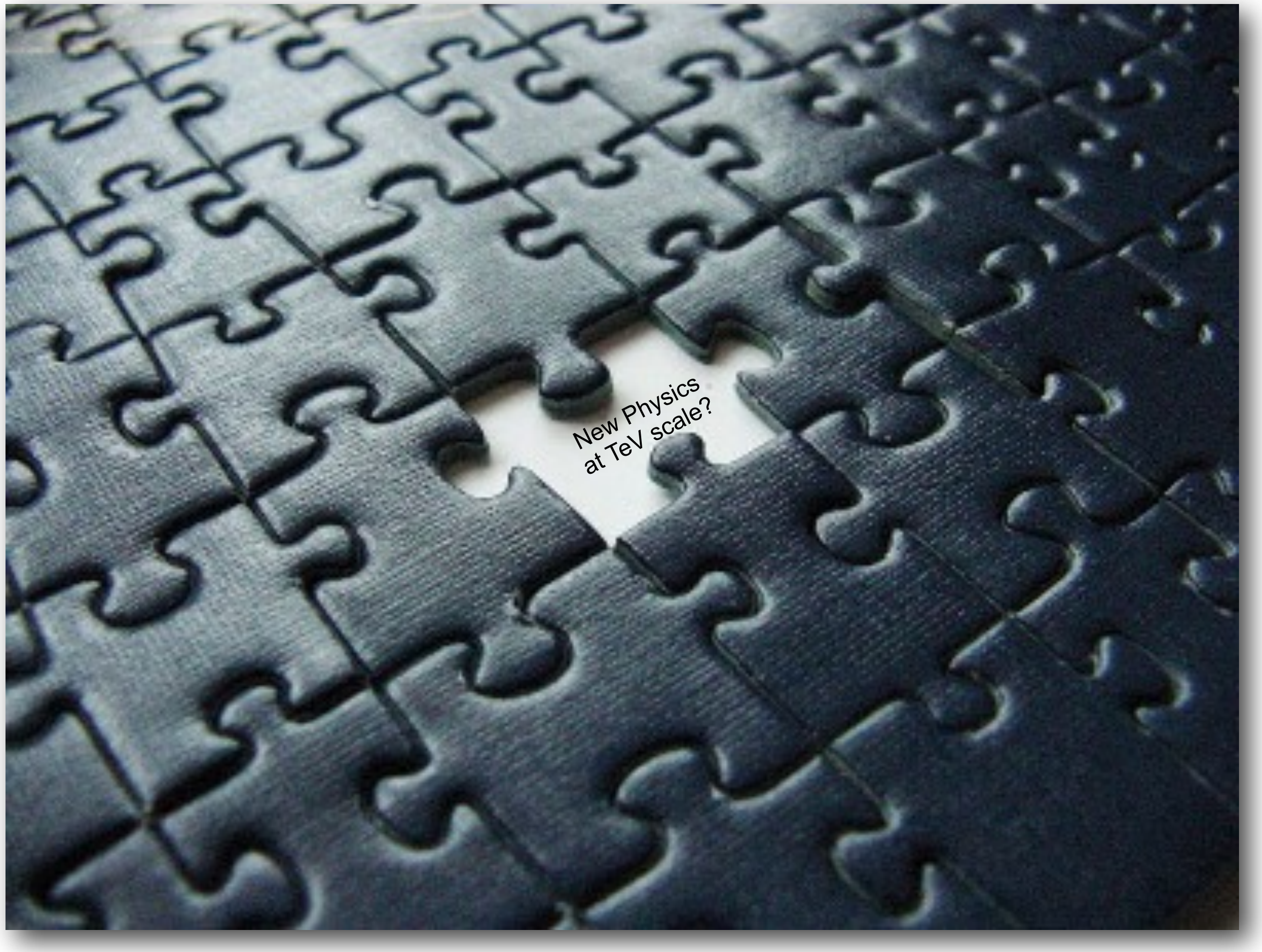
Others:

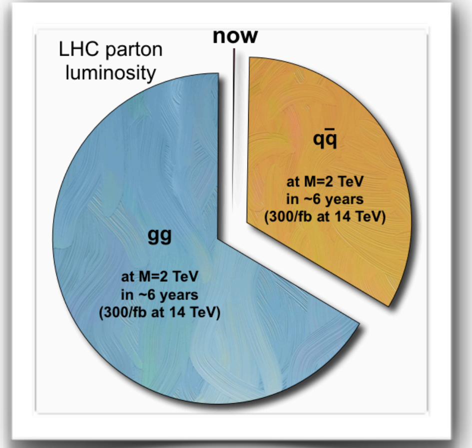
- CDF **bump in W+2jet** spectrum
  - not confirmed by other experiments
  - further investigations ongoing in CDF
- **W+b(b) cross sections**: higher than NLO predictions, both at Tevatron and LHC
  - just missing higher order terms?
- **EWK fit**: the tension between the lepton- and b- asymmetries
  - will stay with us for a long time (or maybe forever)
- **WW (and ZZ) cross sections** slightly high at the LHC, w.r.t. NLO predictions
  - WW: seen by both experiments, at 7 and 8 TeV
  - ZZ: ATLAS has slight excess at 8 TeV

Summary



Summary

- The experiments at the HEF are probing nature at the TeV scale
- The LHC experiments have given extensive proof of being able to deliver, at high quality and over short time scales
  - this promises well also for the coming years

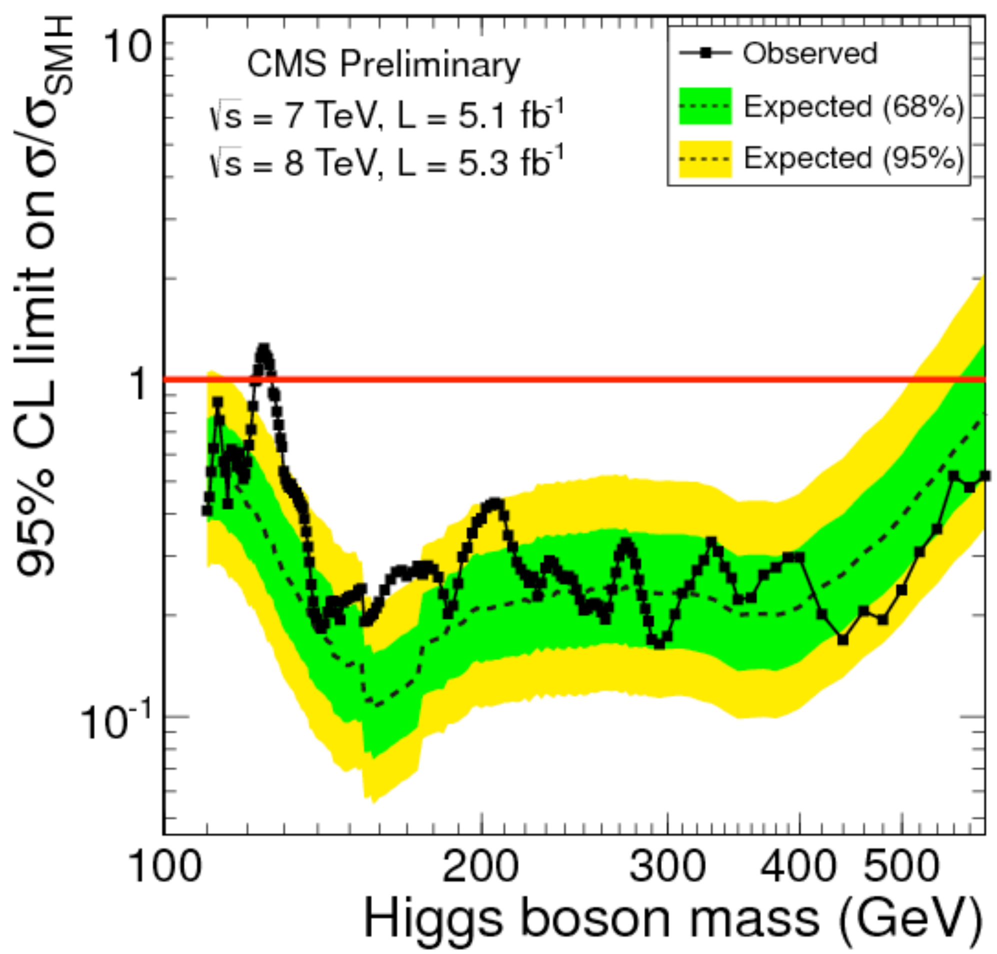


- The “14” TeV run will open a new door
- **The adventure in the TeV energy regime has just begun!**

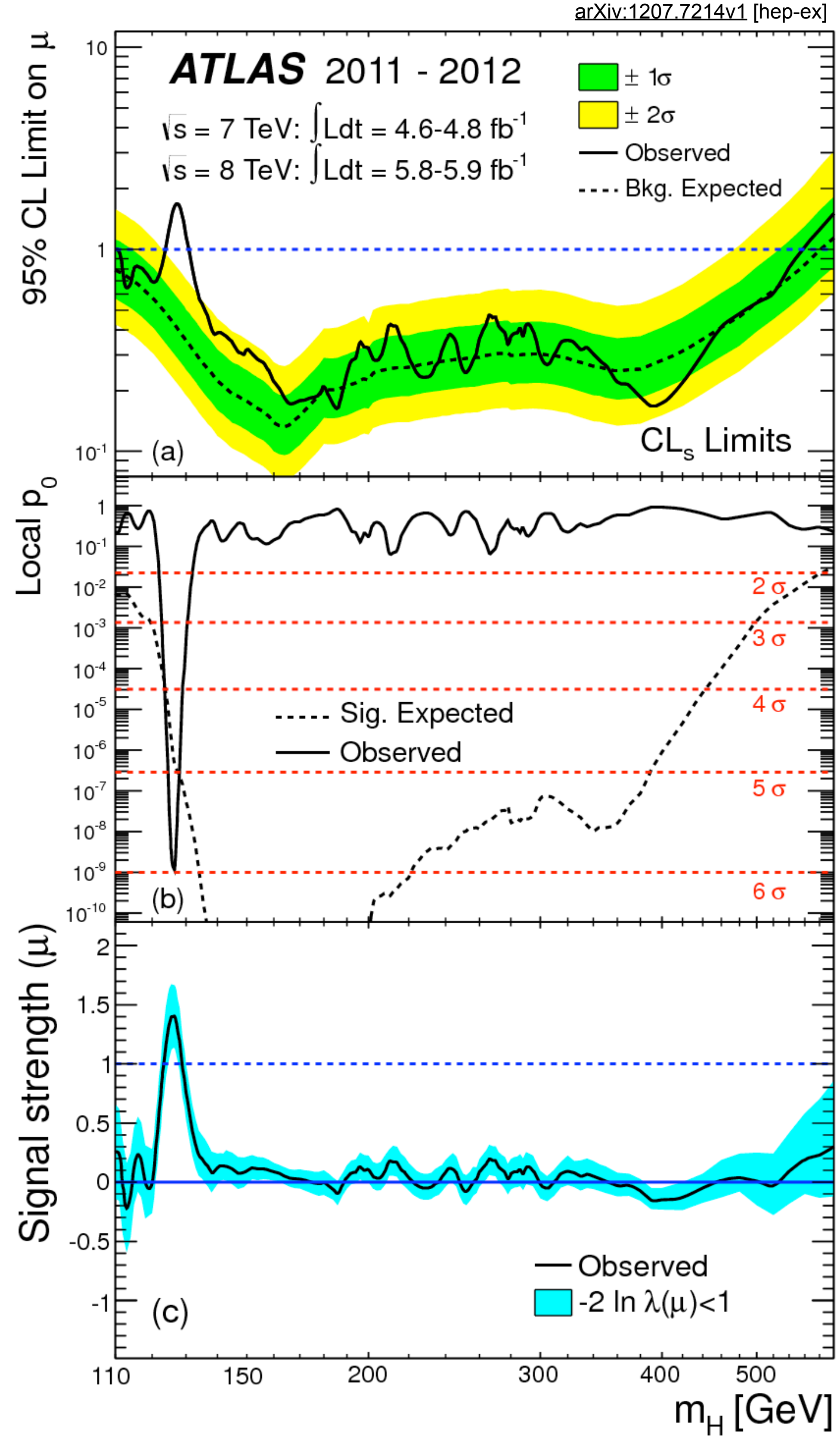
Backup

ETH Institute for Particle Physics

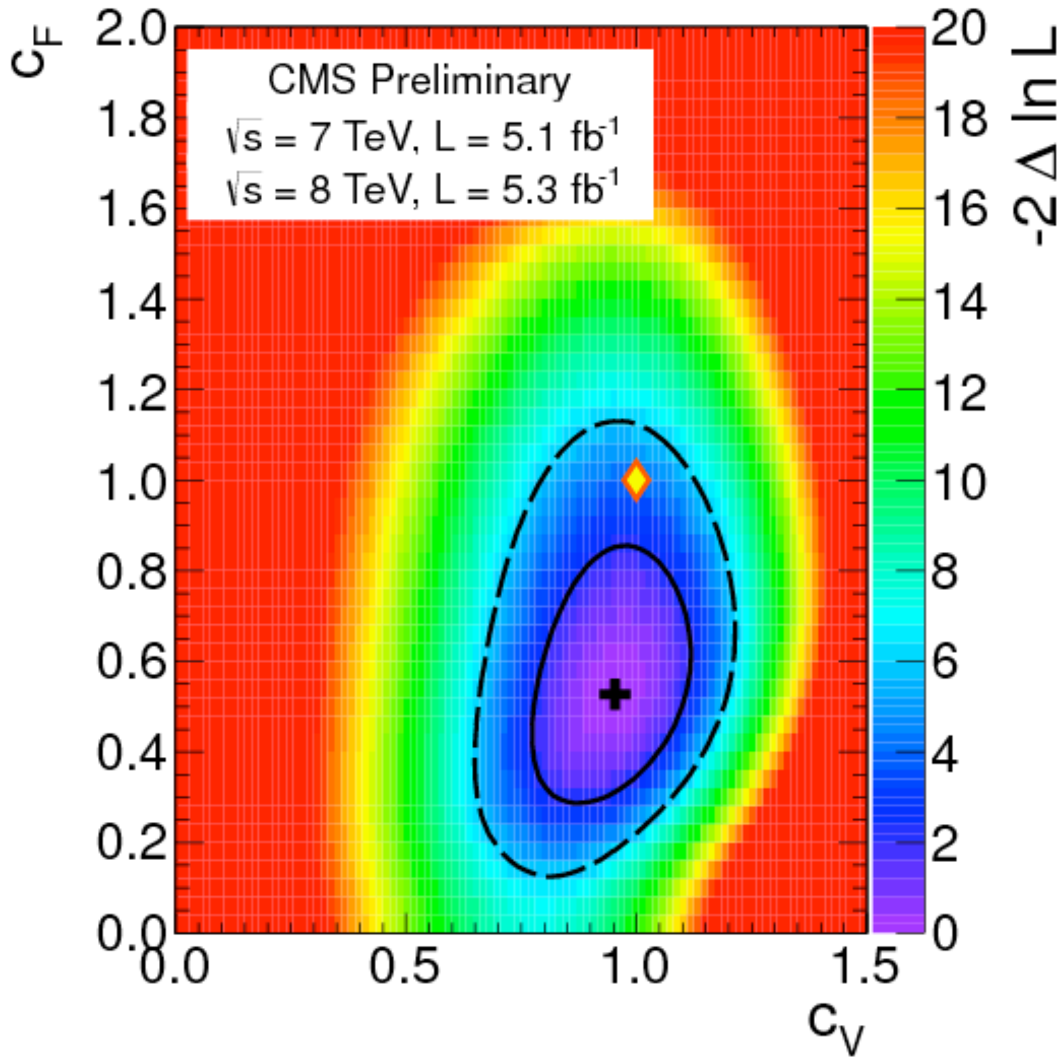
CMS-PAS-HIG-12-020



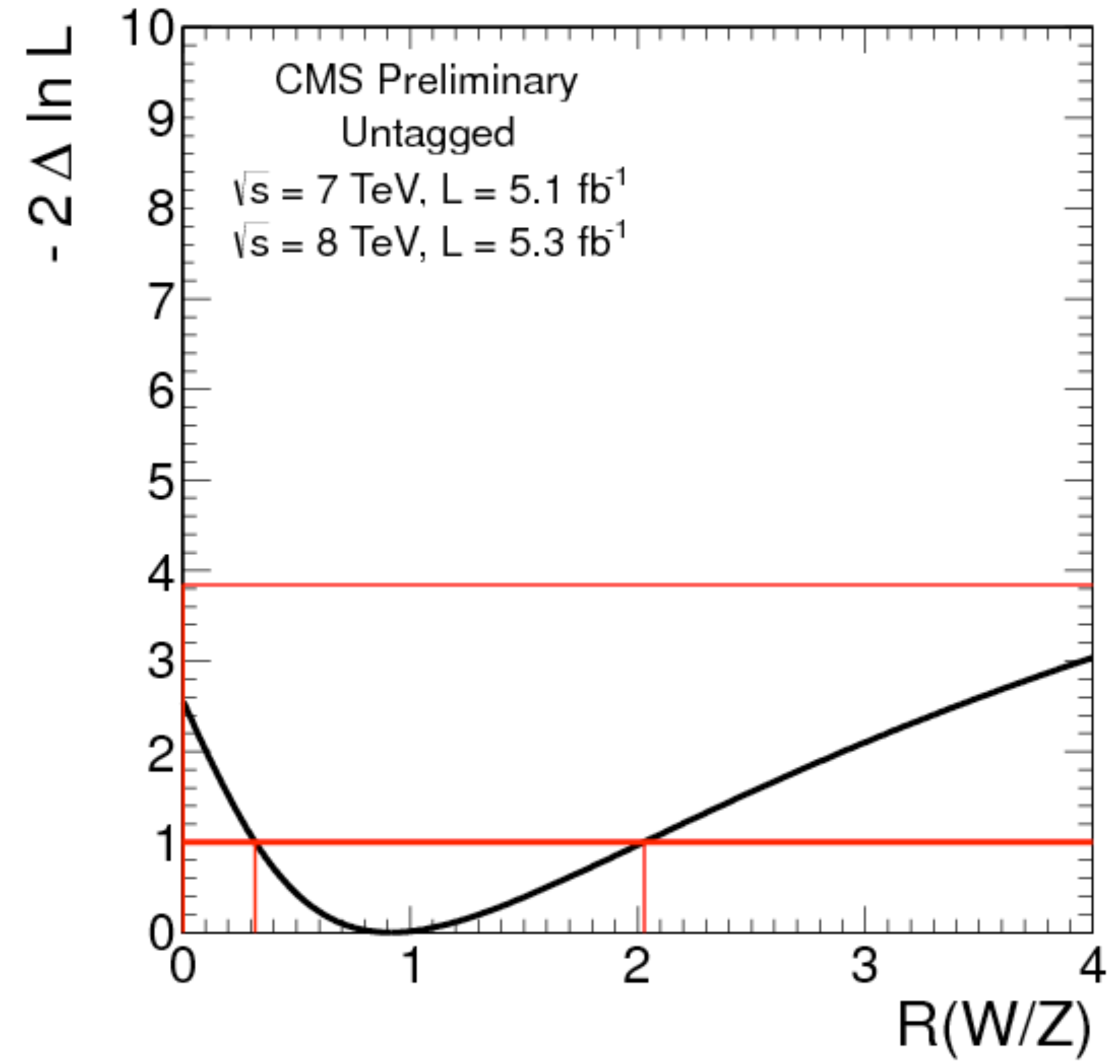
arXiv:1207.7214v1 [hep-ex]



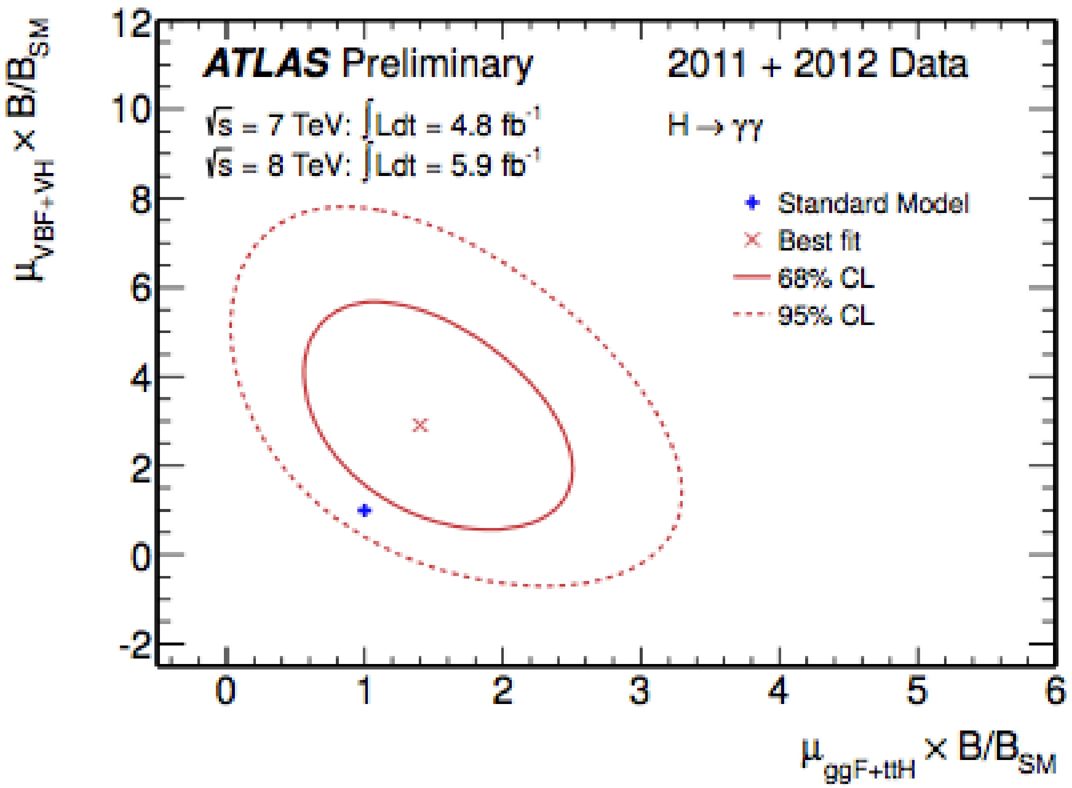
CMS-PAS-HIG-12-020

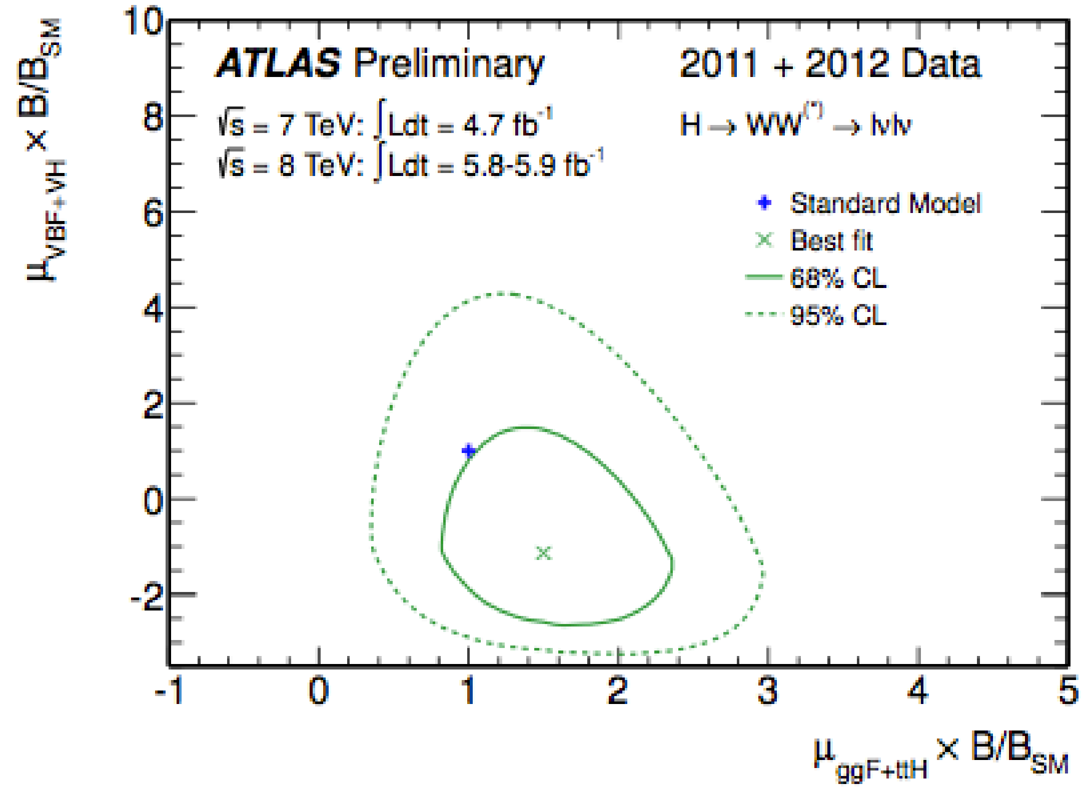


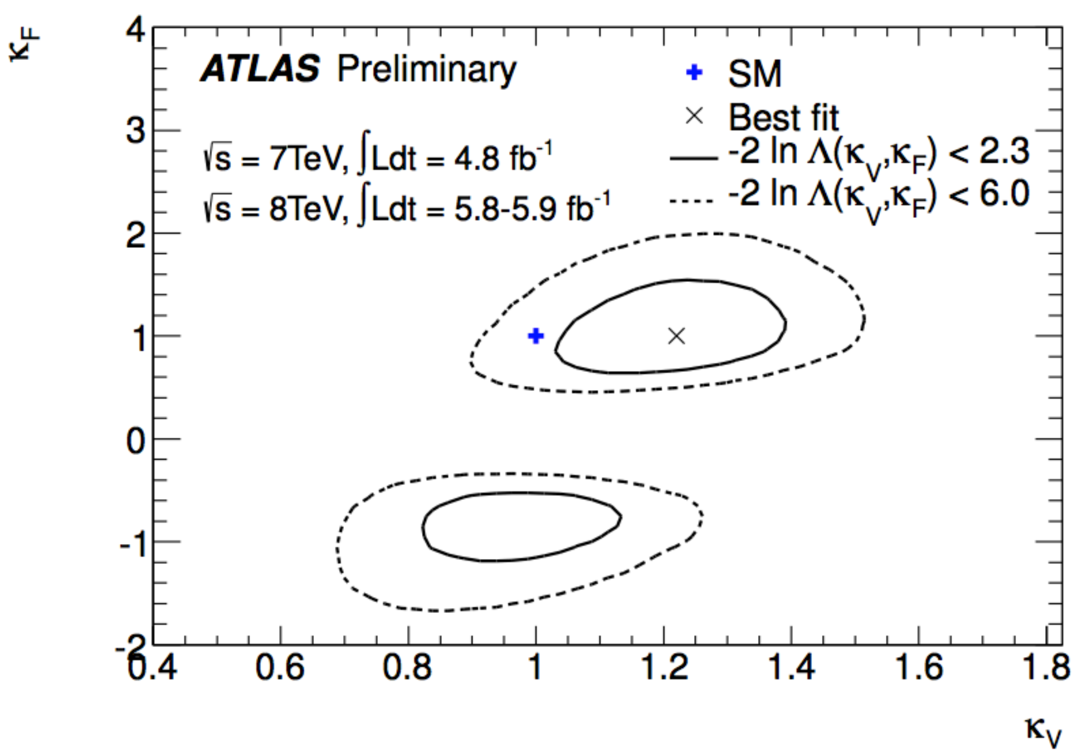
CMS-PAS-HIG-12-020

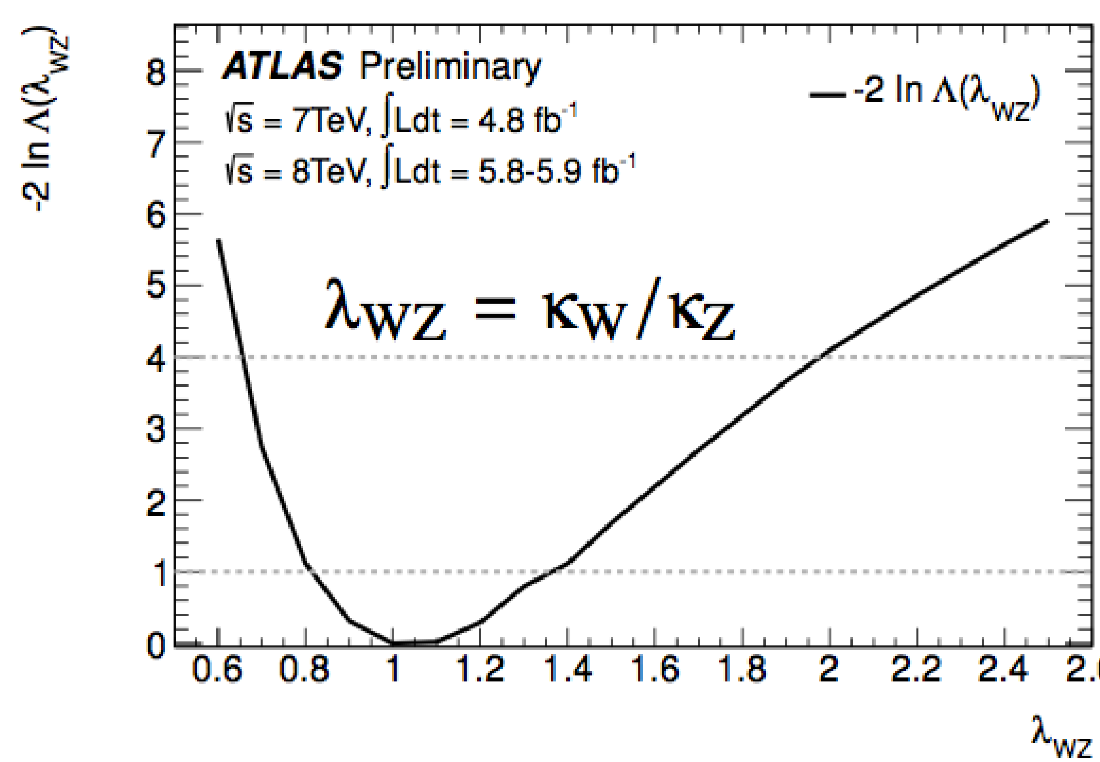


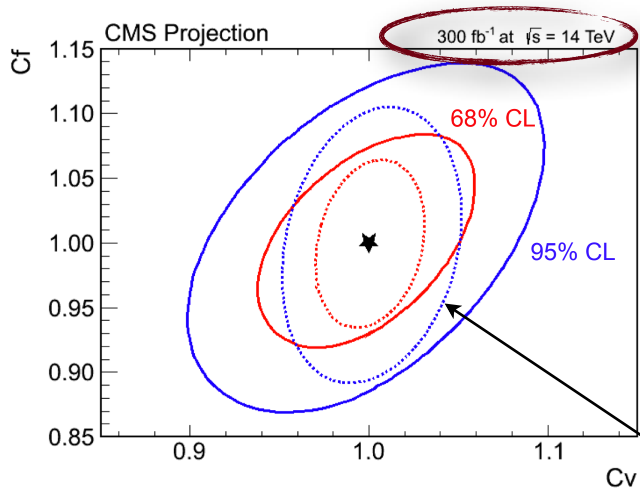
new results from ATLAS-CONF-2012-127





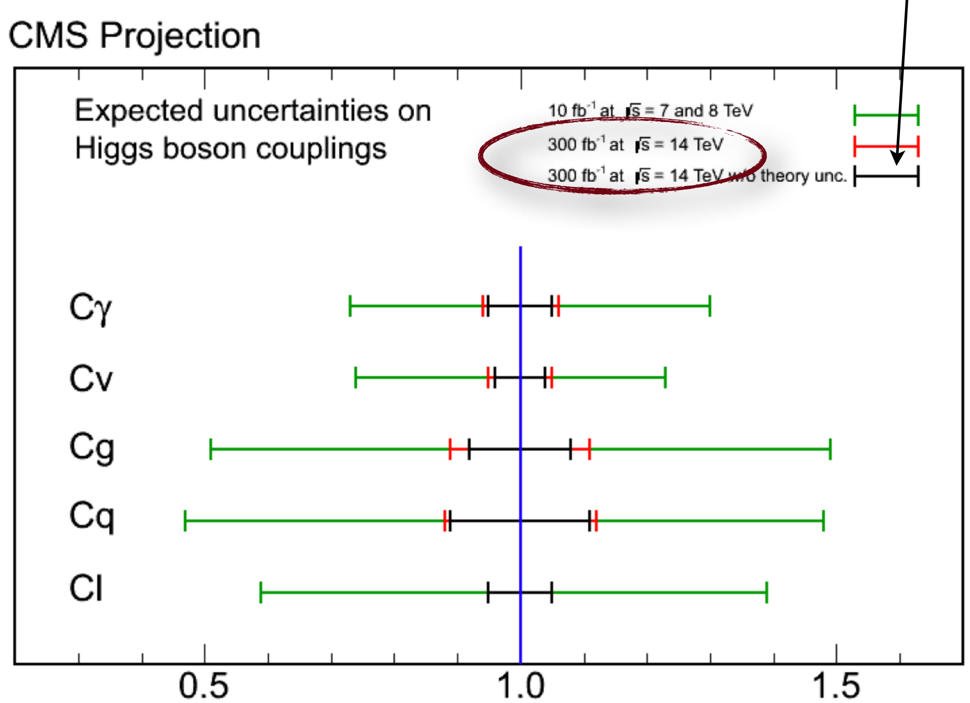


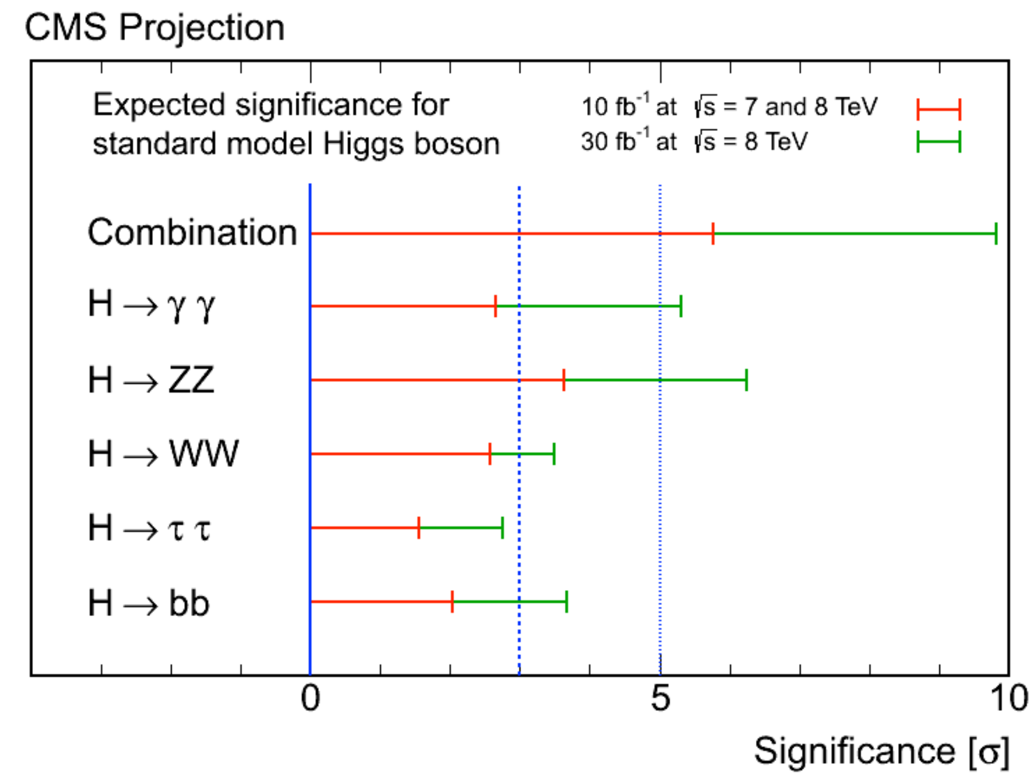


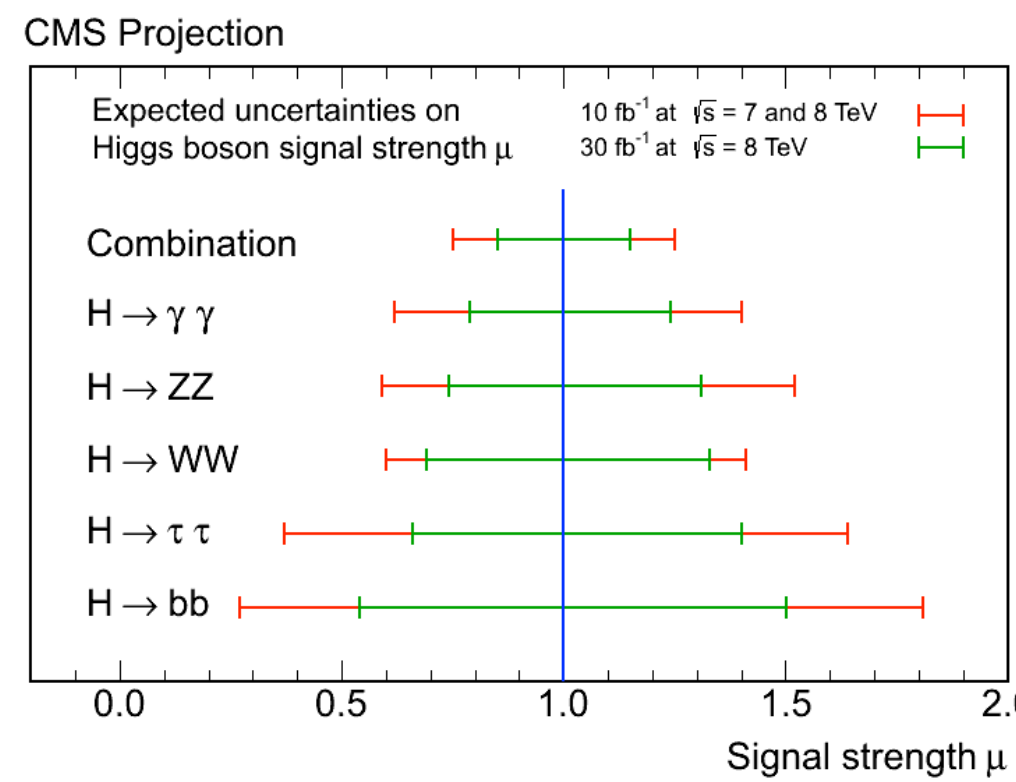


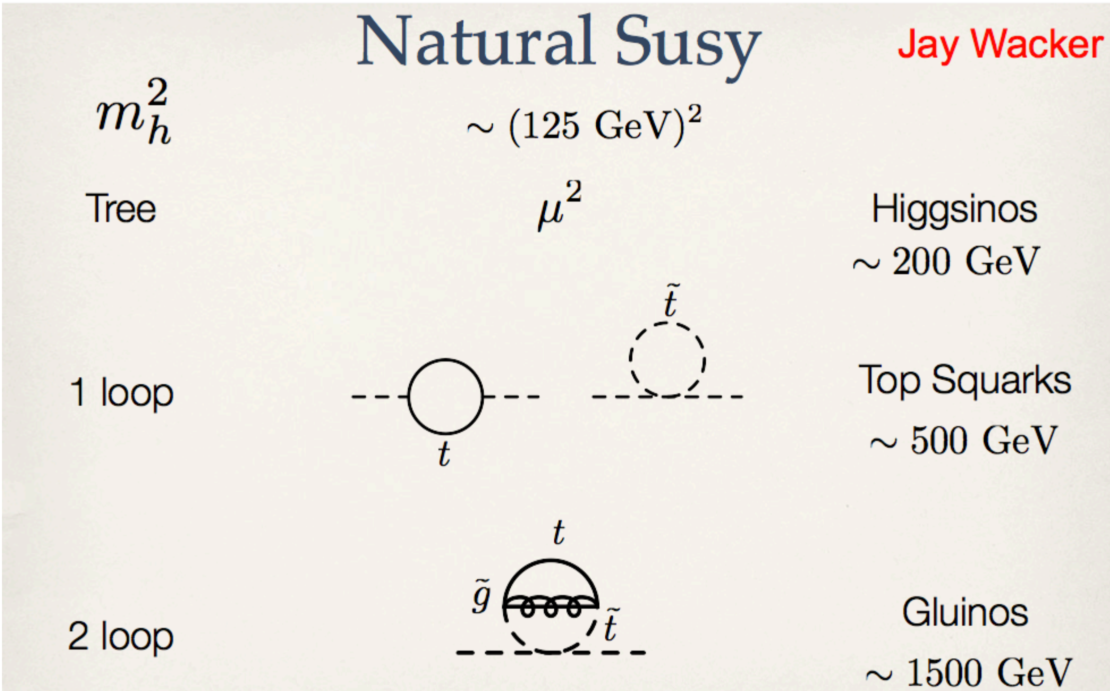
C_X: scale factors w.r.t. SM couplings

w/o theory uncertainty



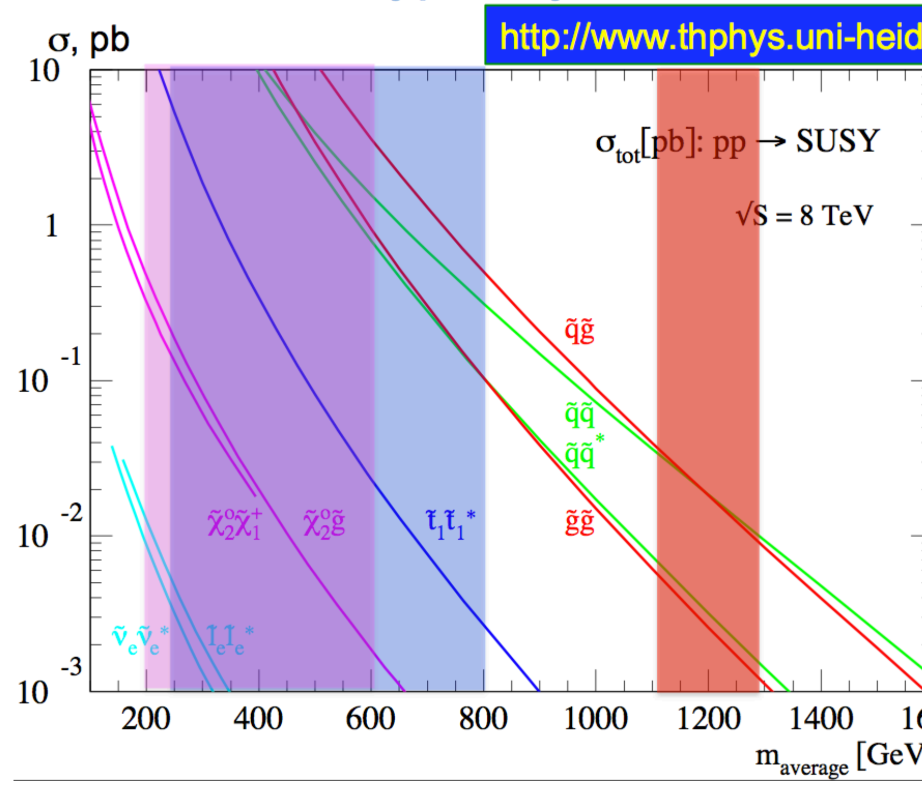






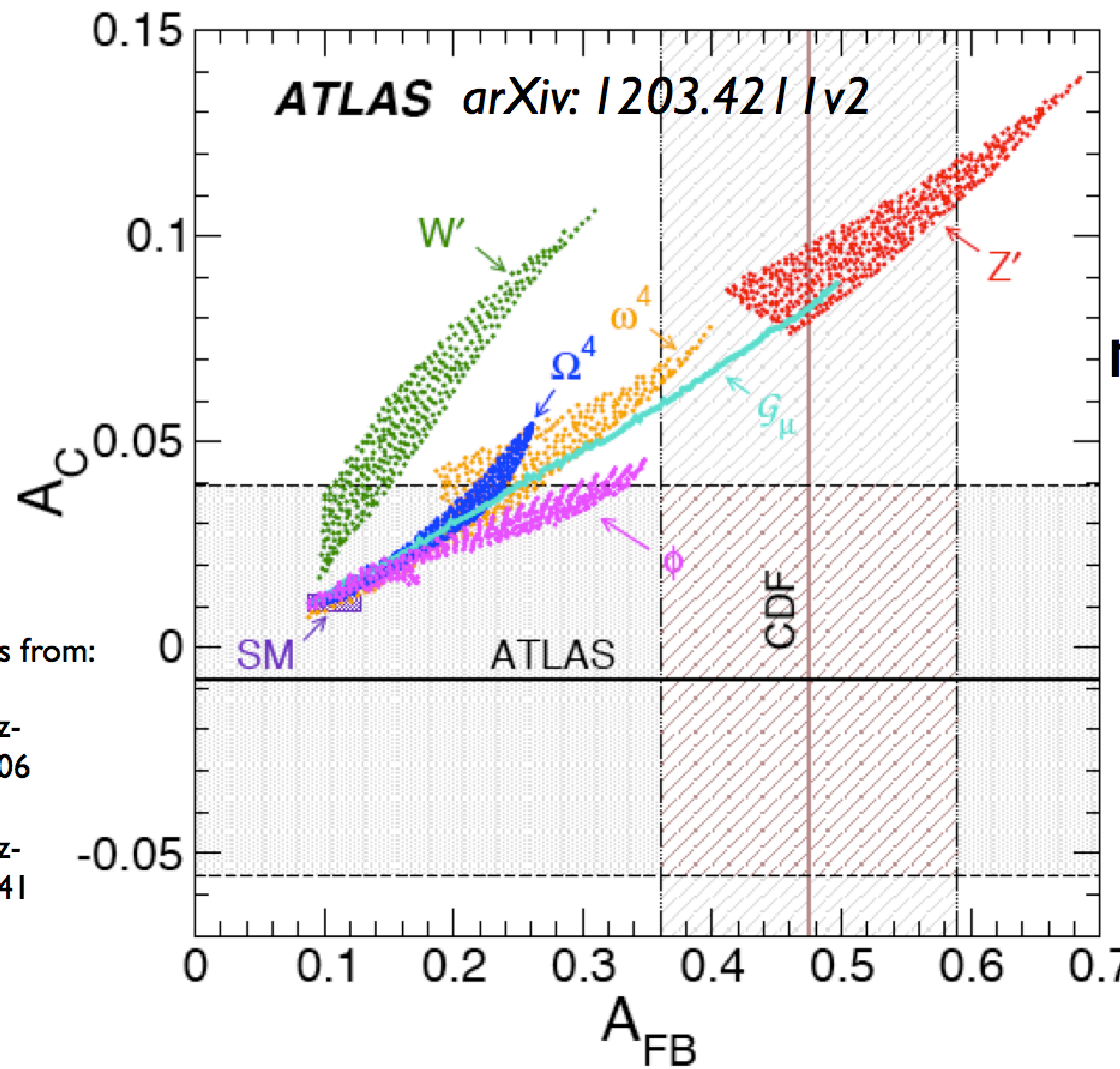
- With ~30/fb and 1 fb cross section produce 30 events; typically 1-10 events observed

http://www.thphys.uni-heidelberg.de/~plehn/



gg: M(g) < 1.3 TeV
tt: M(t) < 0.8 TeV
χχ: M(χ) < 0.6 TeV

Greg Landsberg



m_{tt}>450 GeV

New physics predictions from:

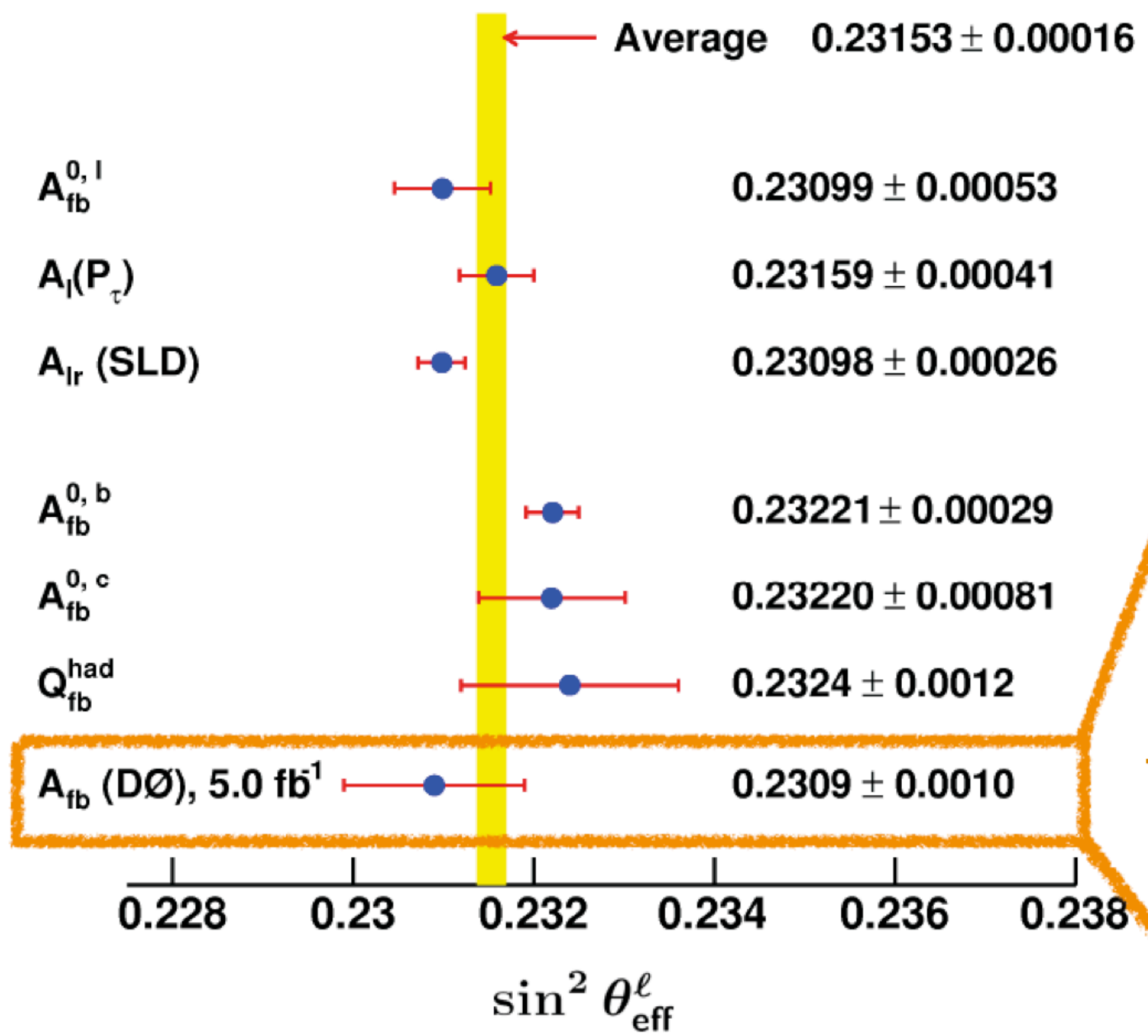
Aguilar-Saavedra, Perez-Victoria arXiv:1105:4606

Aguilar-Saavedra, Perez-Victoria arXiv:1107:0841

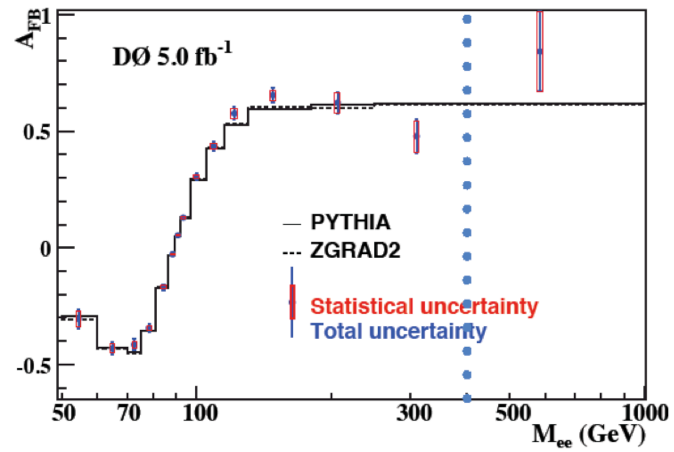
from R. Erbacher, SUSY2012

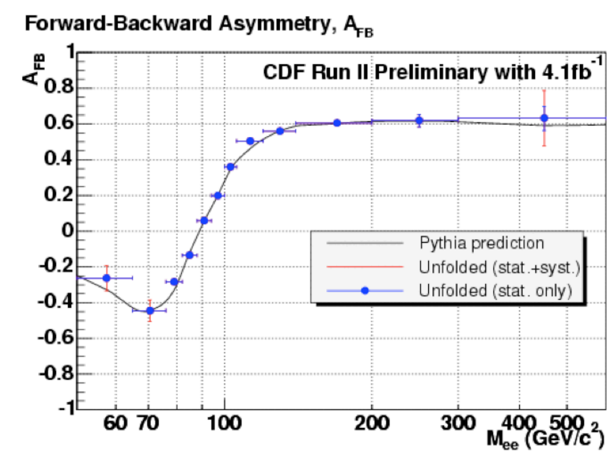
Z A_{fb}

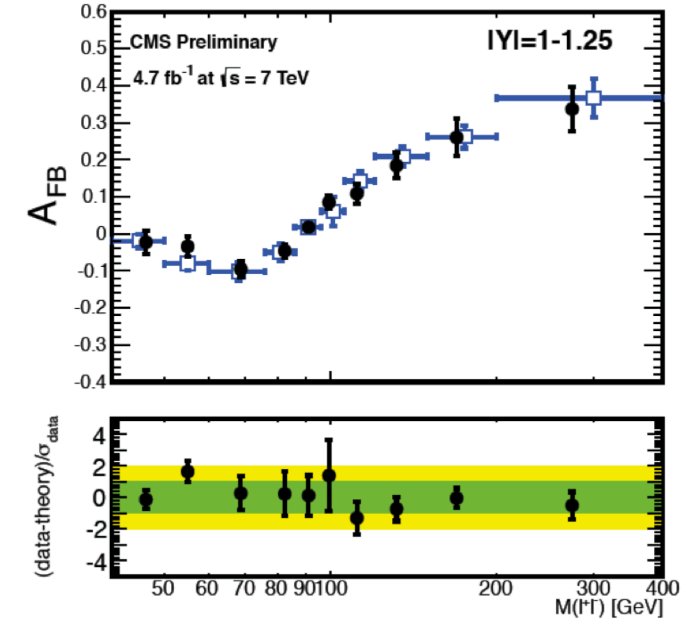
Extraction of $\sin^2\theta_{eff}$



Most precise from Z to light quark coupling





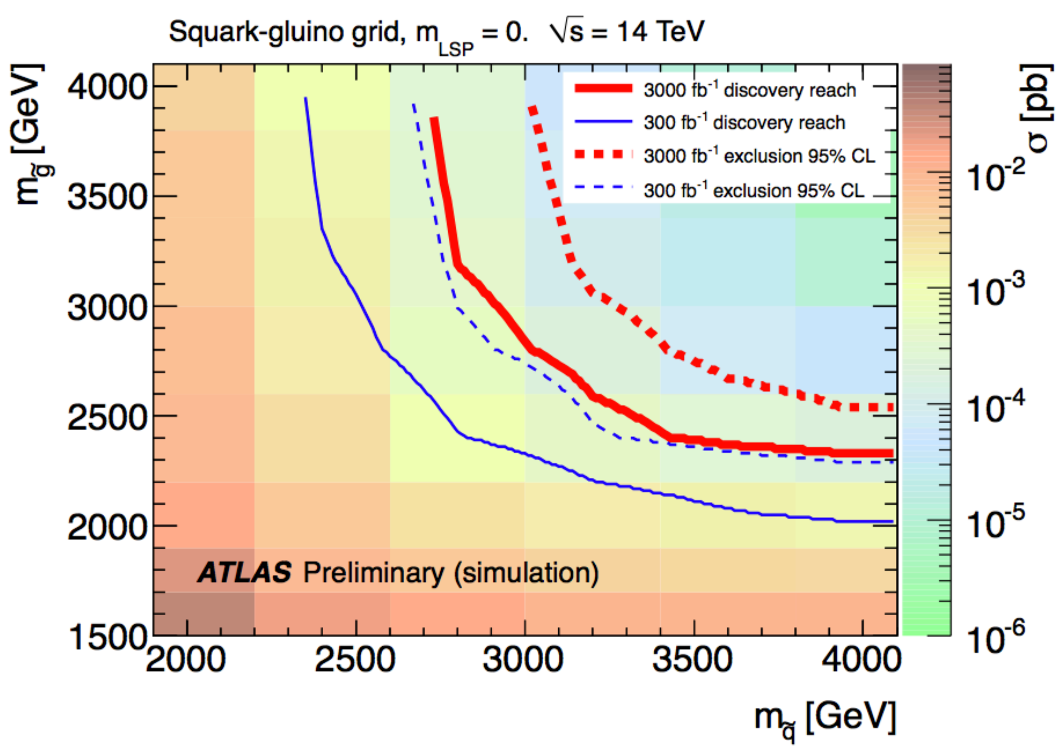


No evidence for new physics at high mass

from R. Erbacher, SUSY2012

Table 2: Predicted 95% confidence level constraints on anomalous triple-gauge couplings. Based on Ref. [1].

coupling	**LHC**	**HL-LHC**	**HE-LHC**
g_1^Z	0.0030	0.0019	0.0013
λ_γ	0.0009	0.0004	0.0004
λ_Z	0.0023	0.0014	0.0014
κ_γ	0.026	0.016	0.019
κ_Z	0.037	0.031	0.022



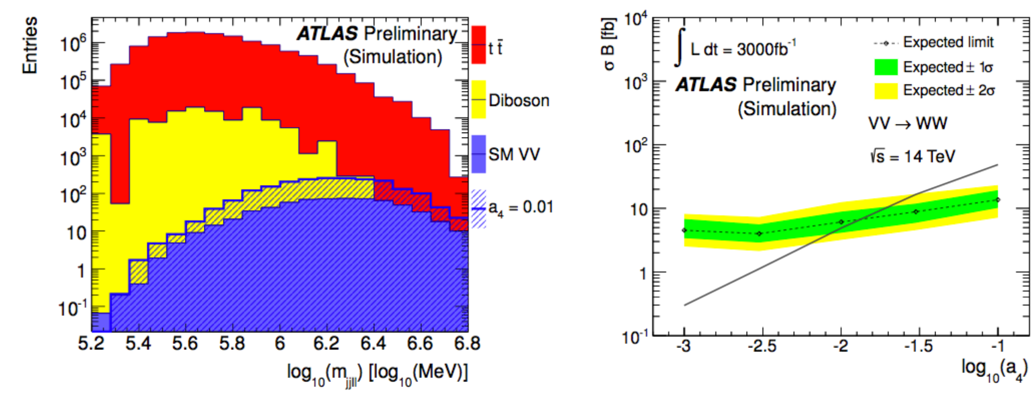


Figure 3: The reconstructed 4-body mass spectrum using the two leading leptons and jets for WW scattering in the $pp \rightarrow WW + 2j \rightarrow e\nu\mu\nu + 2j$ channel, showing backgrounds and signal for a value of $a_4 = 0.01$ (left), and the limit that can be set on the a_4 parameter (right) using the experimental σB limit (band) and the predicted cross section as a function of a_4 (solid line) for this channel.

Table 1: Summary of expected upper limits for a_4 at the 95% confidence level using the $pp \rightarrow WW + 2j \rightarrow e\nu\mu\nu + 2j$ search at $\sqrt{s} = 14$ TeV in the absence of a signal.

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
a_4	0.066	0.025	0.016