ATLAS Highlights and Outlook

US LHC Users Association

Argonne National Laboratory
November 13, 2014

Chip Brock, for the ATLAS Collaboration
Michigan State University

ATLAS @work

efficient and productive

~90% usable data efficiency

2010: $\sqrt{s}$ = 7 TeV, 0.05/fb

2011: $\sqrt{s}$ = 7 TeV, 4.6/fb

2012: $\sqrt{s}$ = 8 TeV, 20.3/fb

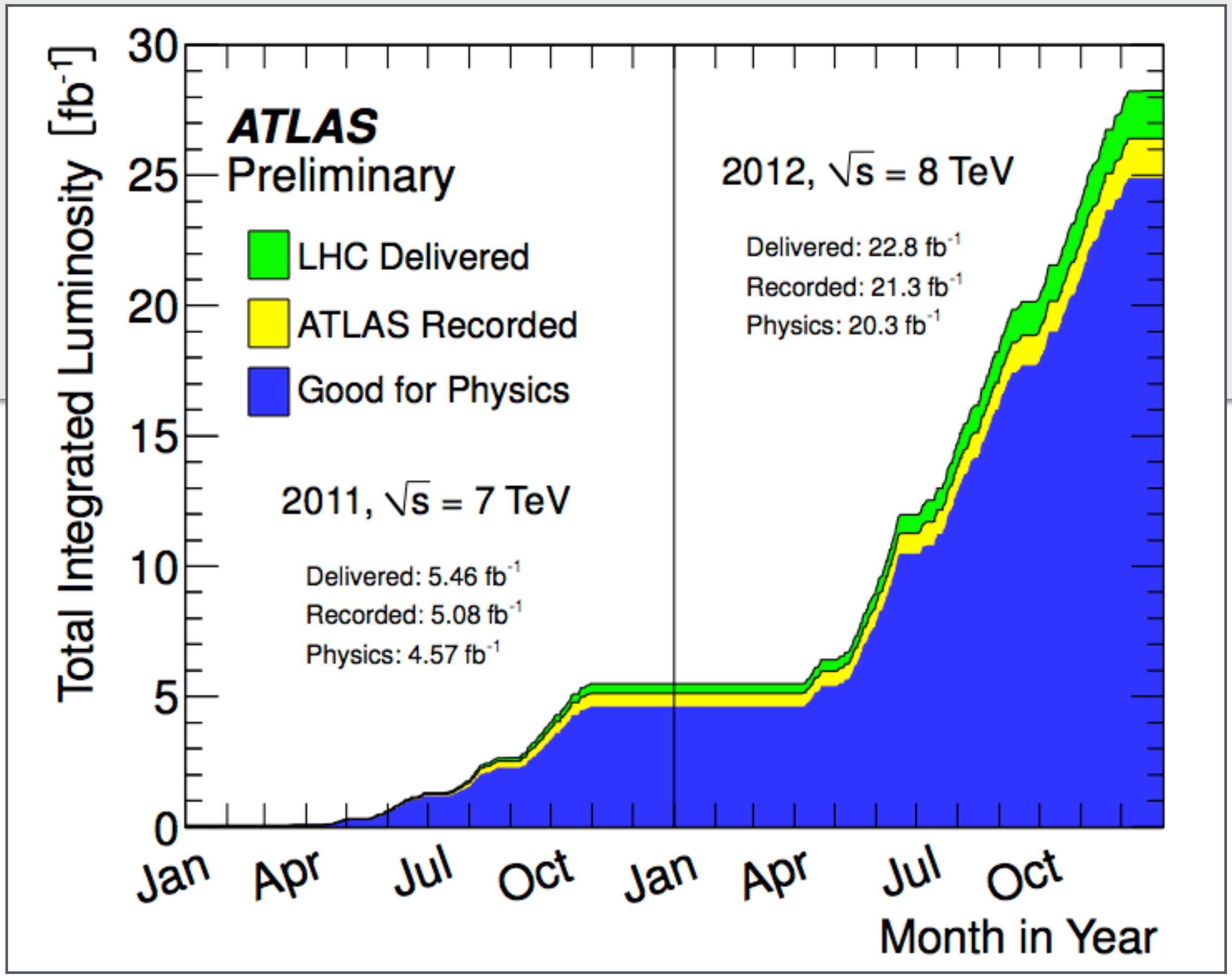
Run I results: a 2014 publication stream

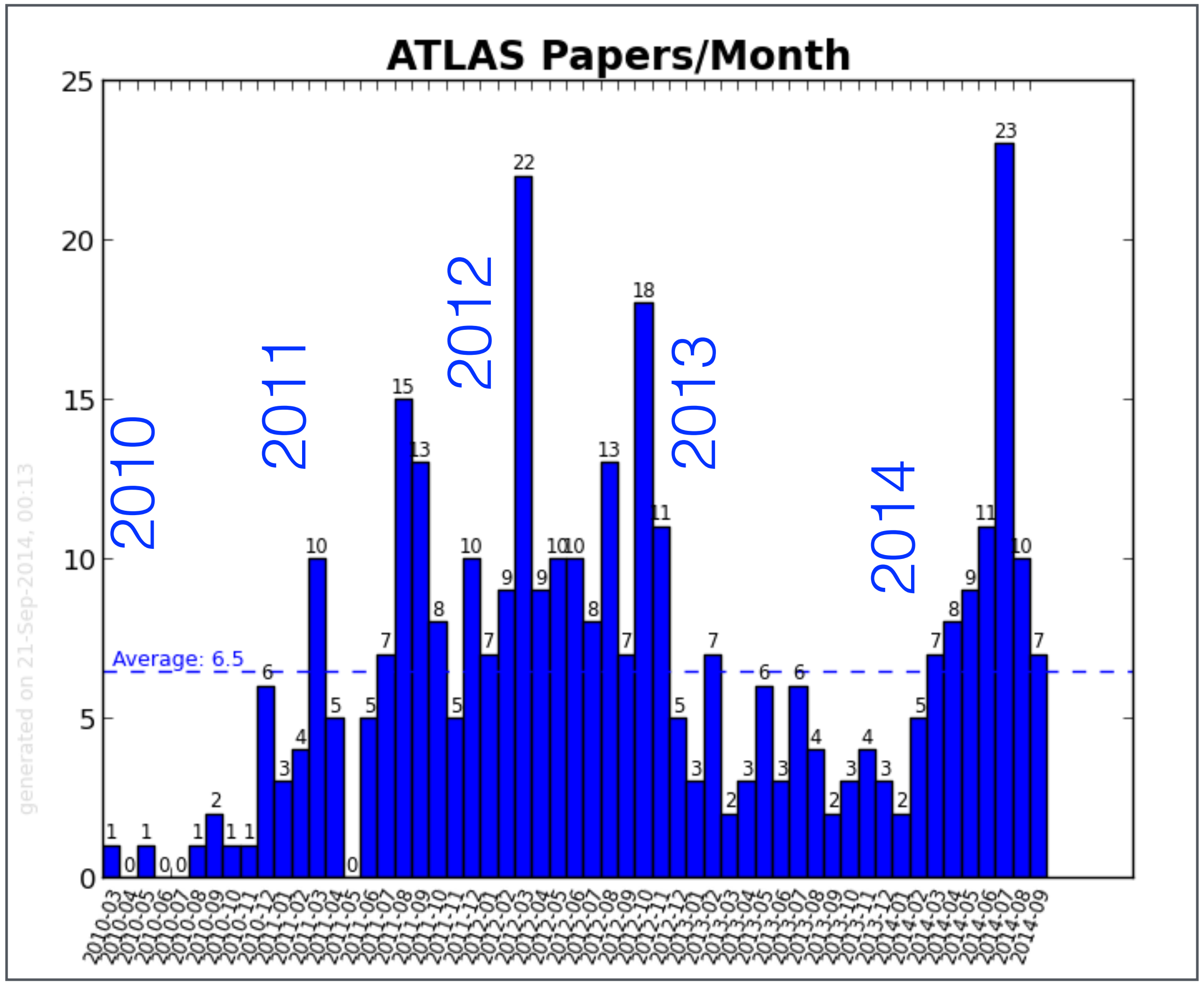
350 publications, ~150 performance

~100 to come

600 CONF notes

660 conference talks





Snowmass Energy Frontier

Research Program:

1. **Measure properties of the Higgs boson.**

   Including: mass, CP properties, and especially couplings

2. **Measure properties of the: t, W, and Z**

   Because they talk “loudly” to the Higgs

3. **Search for TeV-scale particles**

   A scale inspired by naturalness

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I'll add:

4. **Wrestle the Standard Model to the ground.**
5. **Search for kinematical anomalies wrt SM (see #4)**

Is excitement about Run 2…

sort of …underwhelming?

Rule of thumb: a x10 increase in $\mathscr{L}$ is like x2 in E_{cm}

and visa versa

Run 2 nearly gives us both leading to:

Unprecedented precision

W ’s, tops, Higgs!, flavor, inclusive σ ’s,

Significant discovery reach

surpass the 1 TeV SUSY scale, Z'/W', BSM Higgs

1%

buckle in

- The LHC running is just beginning

(Anadi Canepa, today)

"phase 0 upgrades"

"phase 1 upgrades"

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

Run I
8 TeV
0.75 10^{34} $cm^{-2}s^{-1}$

Run II
13-14 TeV
1.5 10^{34} $cm^{-2}s^{-1}$

Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

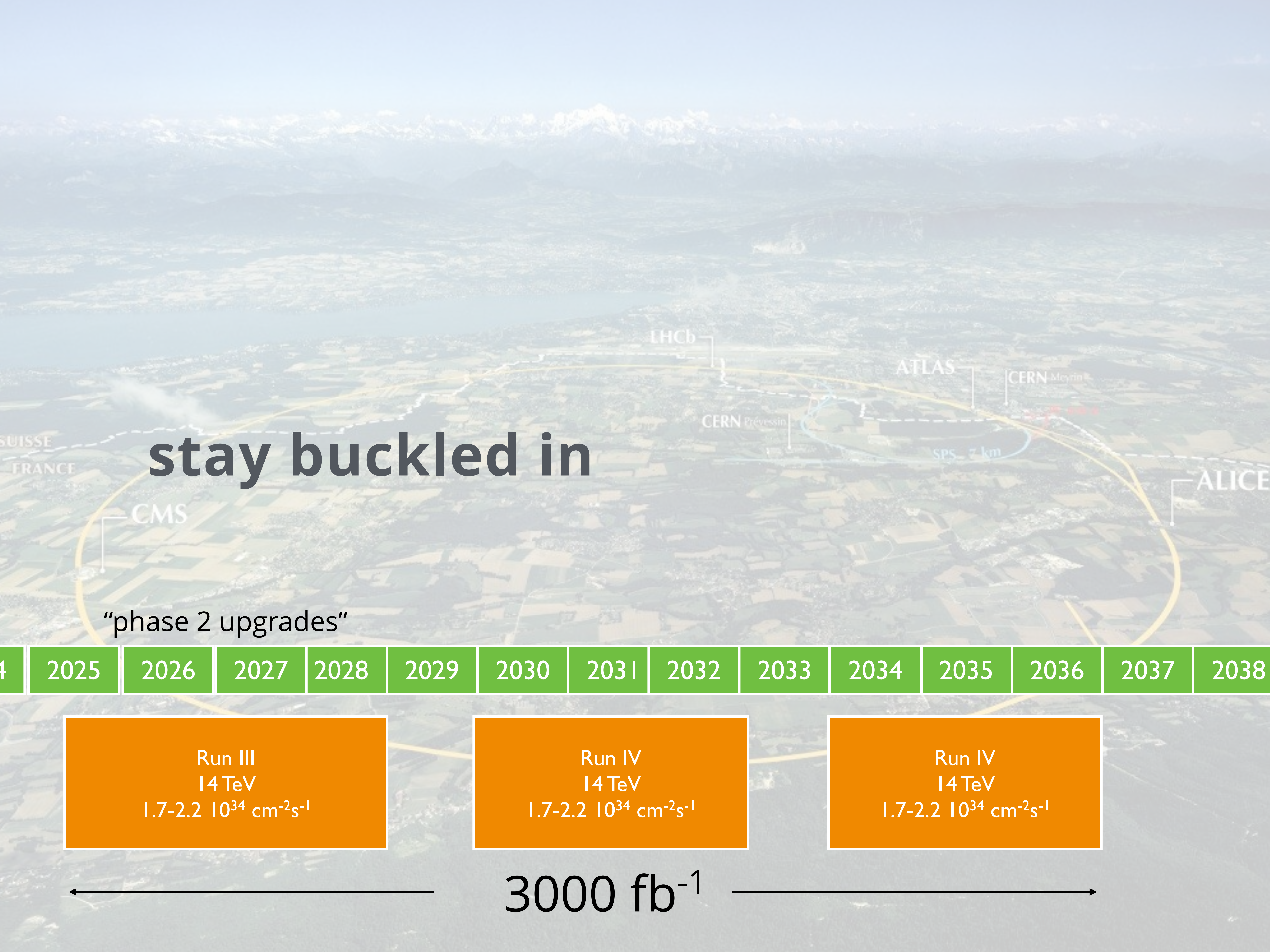
20 fb^{-1}

100 fb^{-1}

300 fb^{-1}

you are here

SUISSE
FRANCE
CMS
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
ALICE



stay buckled in

"phase 2 upgrades"

4	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038

Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

Run IV
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

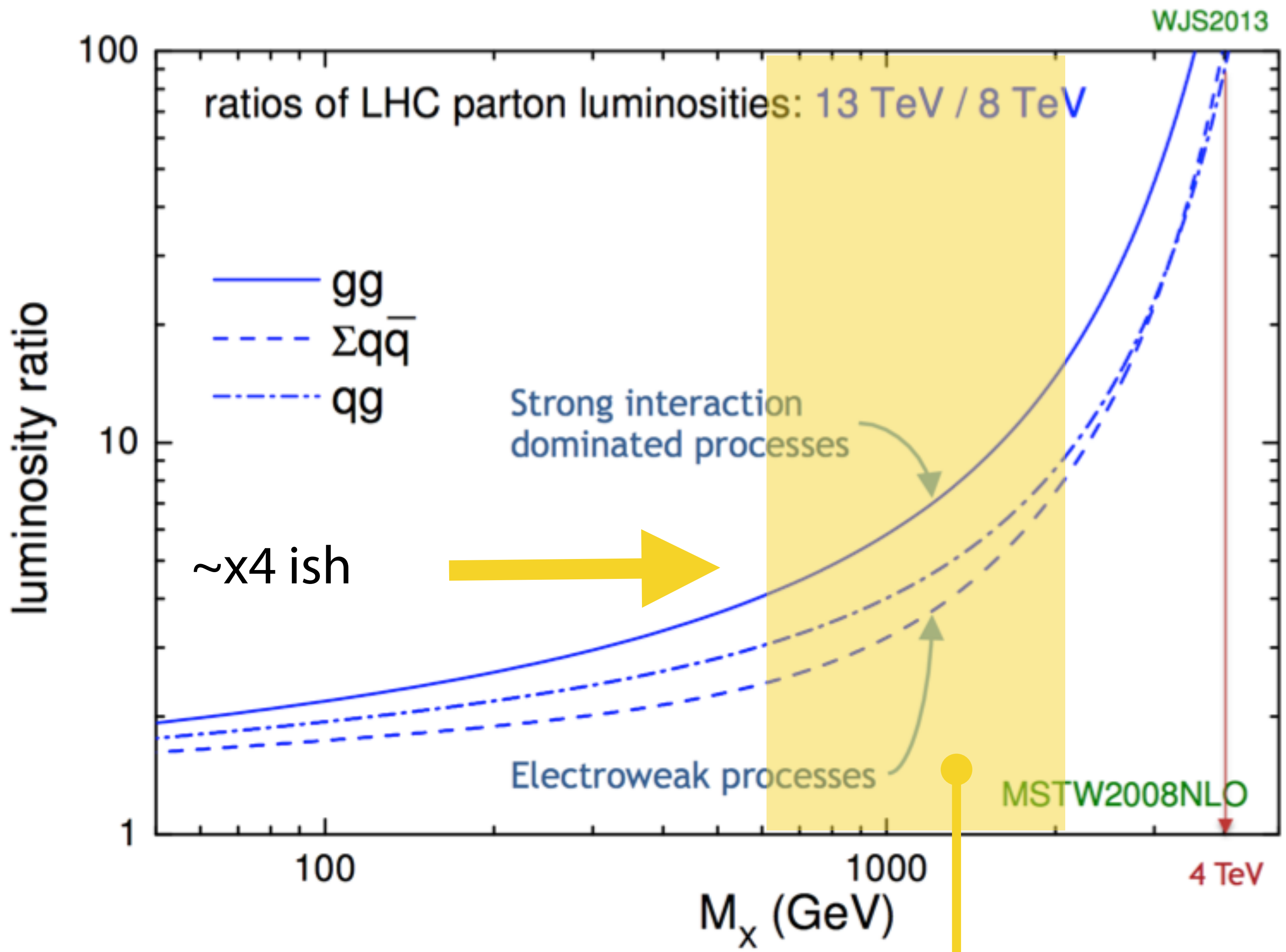
Run IV
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

3000 fb^{-1}

x2

Higher energy:

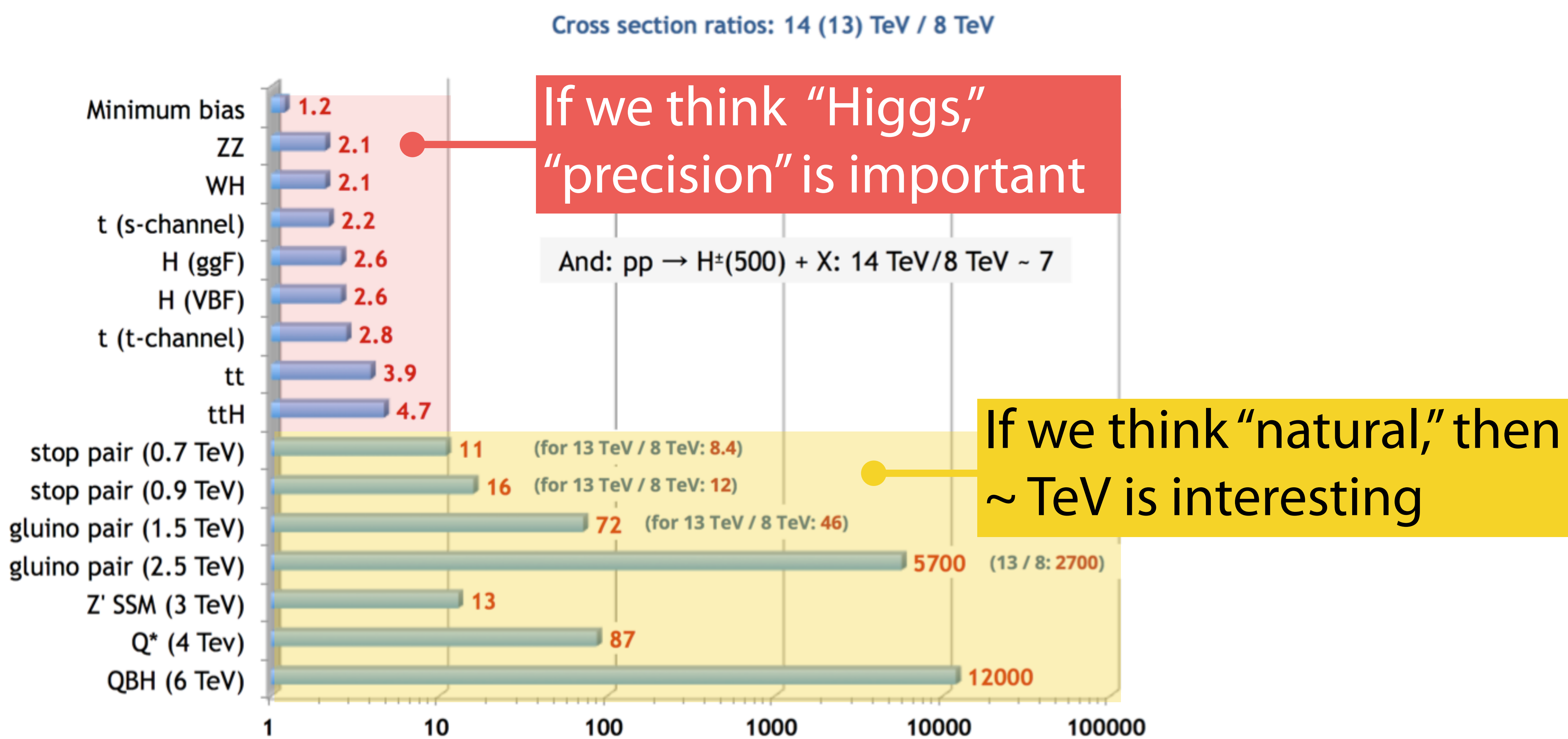
More parton luminosity



If we think "natural," then
~ TeV is interesting

Higher energy:

larger cross sections



Run 1 is essentially a wrap

Higgs Boson Physics

Notable results

from Run 1 we anticipated:

Discovery, first looks

from Run 1 we achieved:

Discovery, indeed. and more:

mass, couplings, important final states, differential distributions

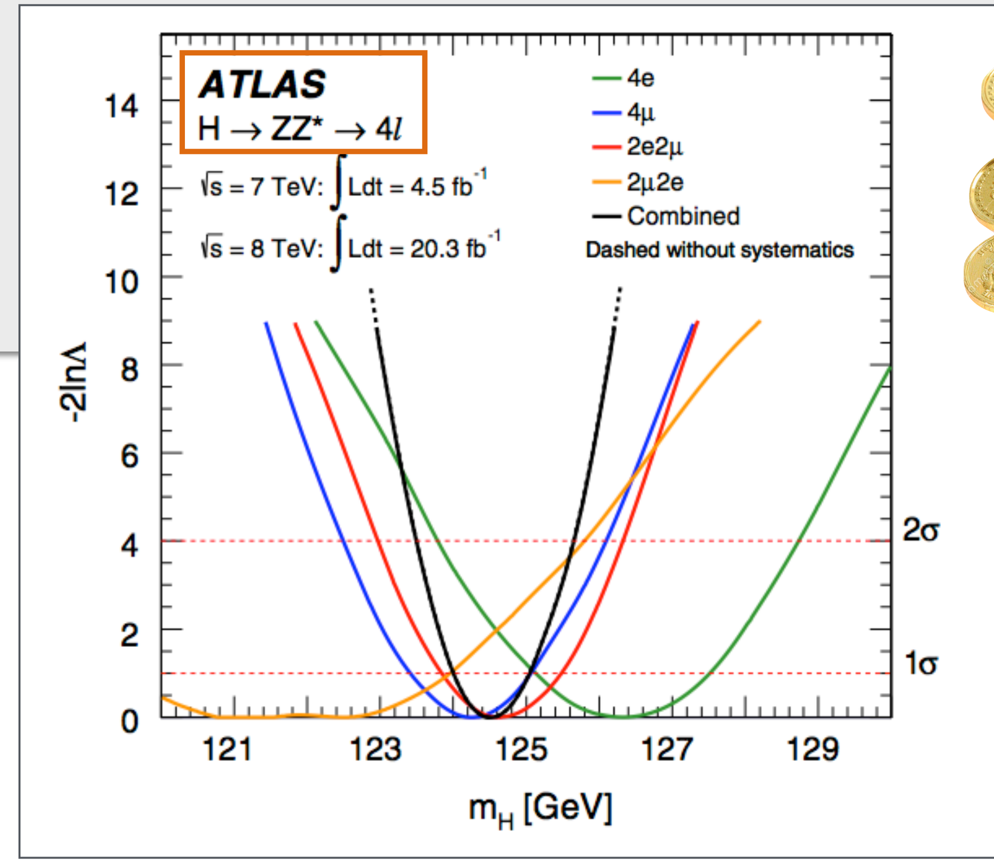
in Run 2, we expect:

Cross sections 13/14 TeV, ttH, high mass BSM searches, combination
precision couplings, differential distributions

~x10 more statistics

Higgs Boson mass

Agony and Ecstasy

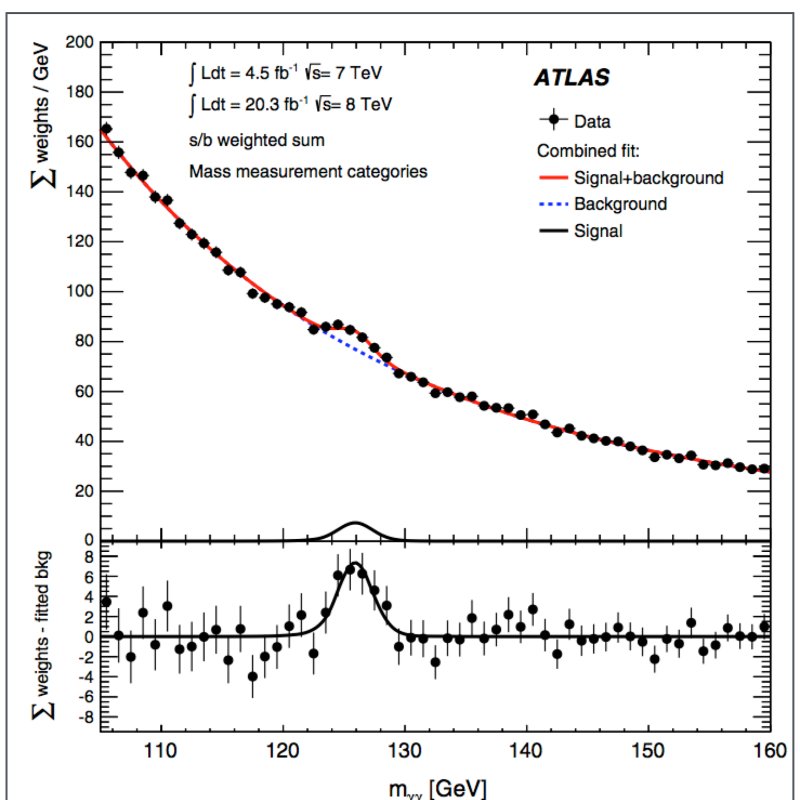


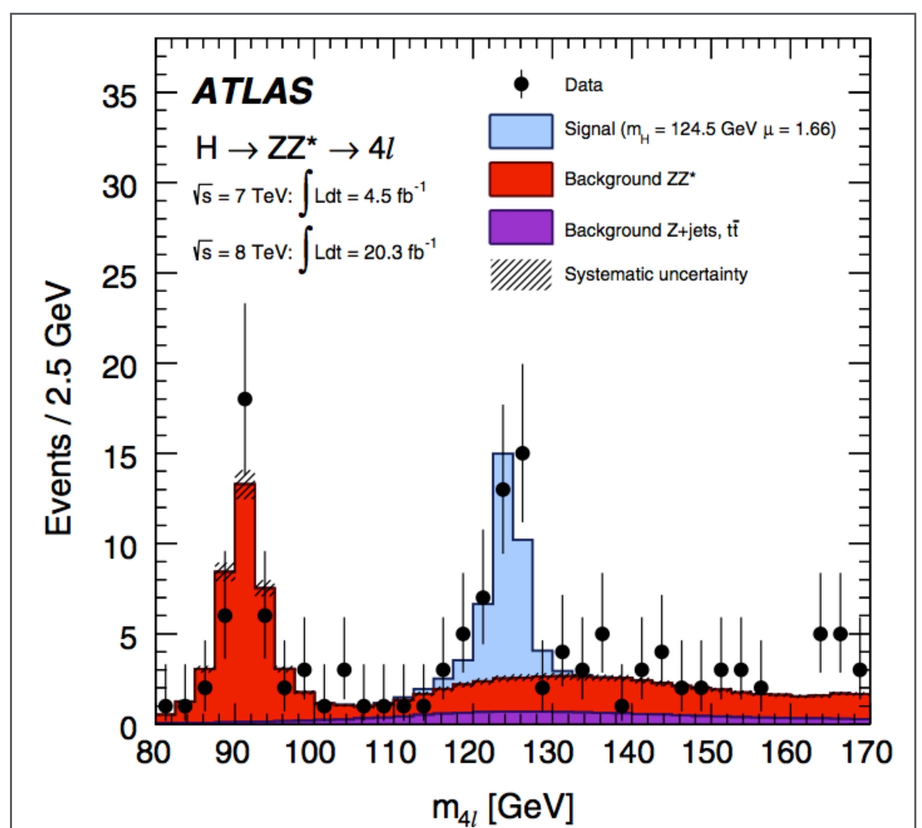
Agony:

m_H only ~ 125 GeV

Ecstasy:

m_H precisely = 125.36 ± 0.37 ± 0.18 GeV $\gamma\gamma$ and Z^*Z





(Laser Kaplan, Today)

~ 40 signal/channel

Run II: expect 400-500

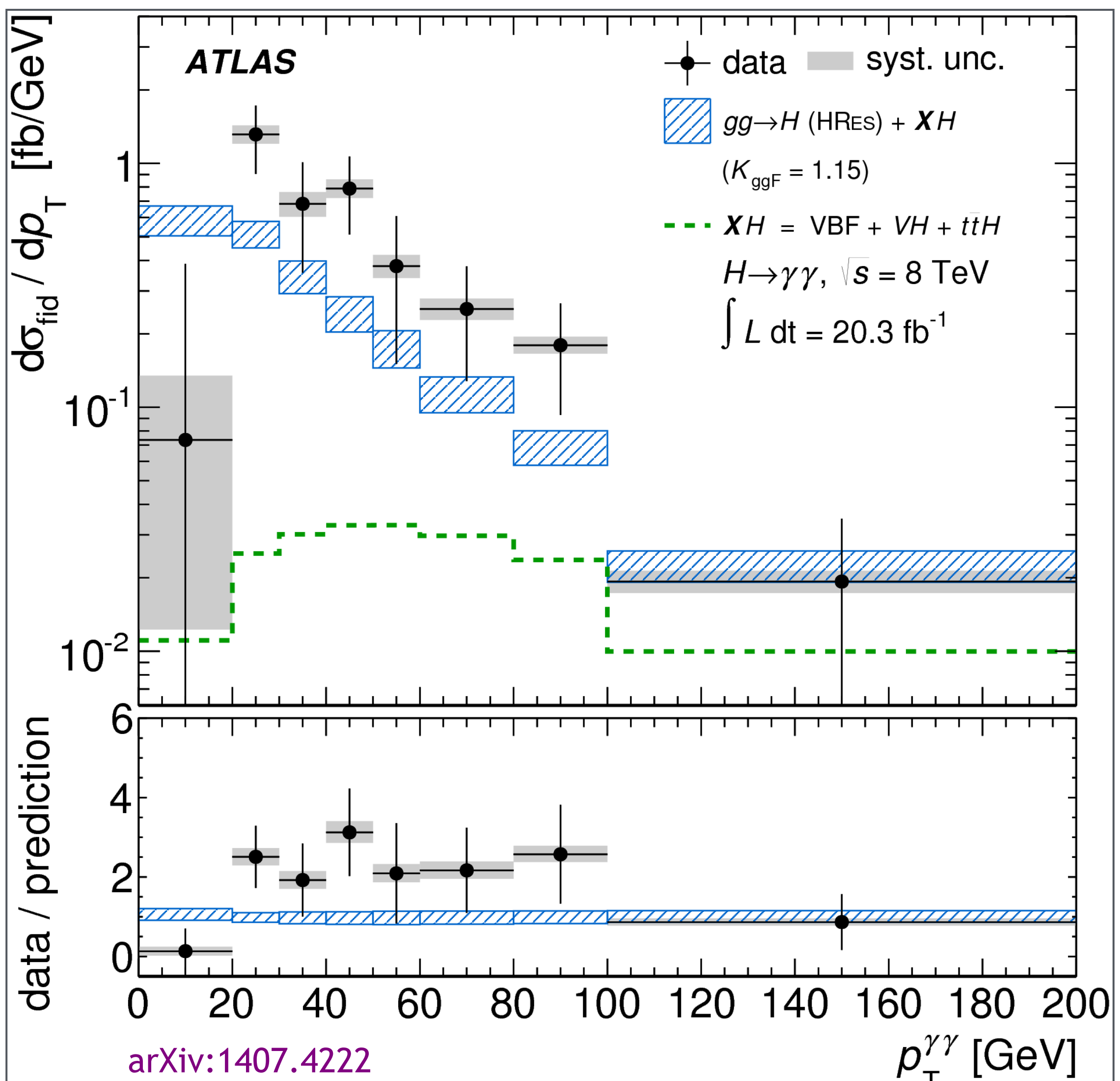
PHYSICAL REVIEW D 90, 052004 (2014)

Higgs in slices

differential distributions

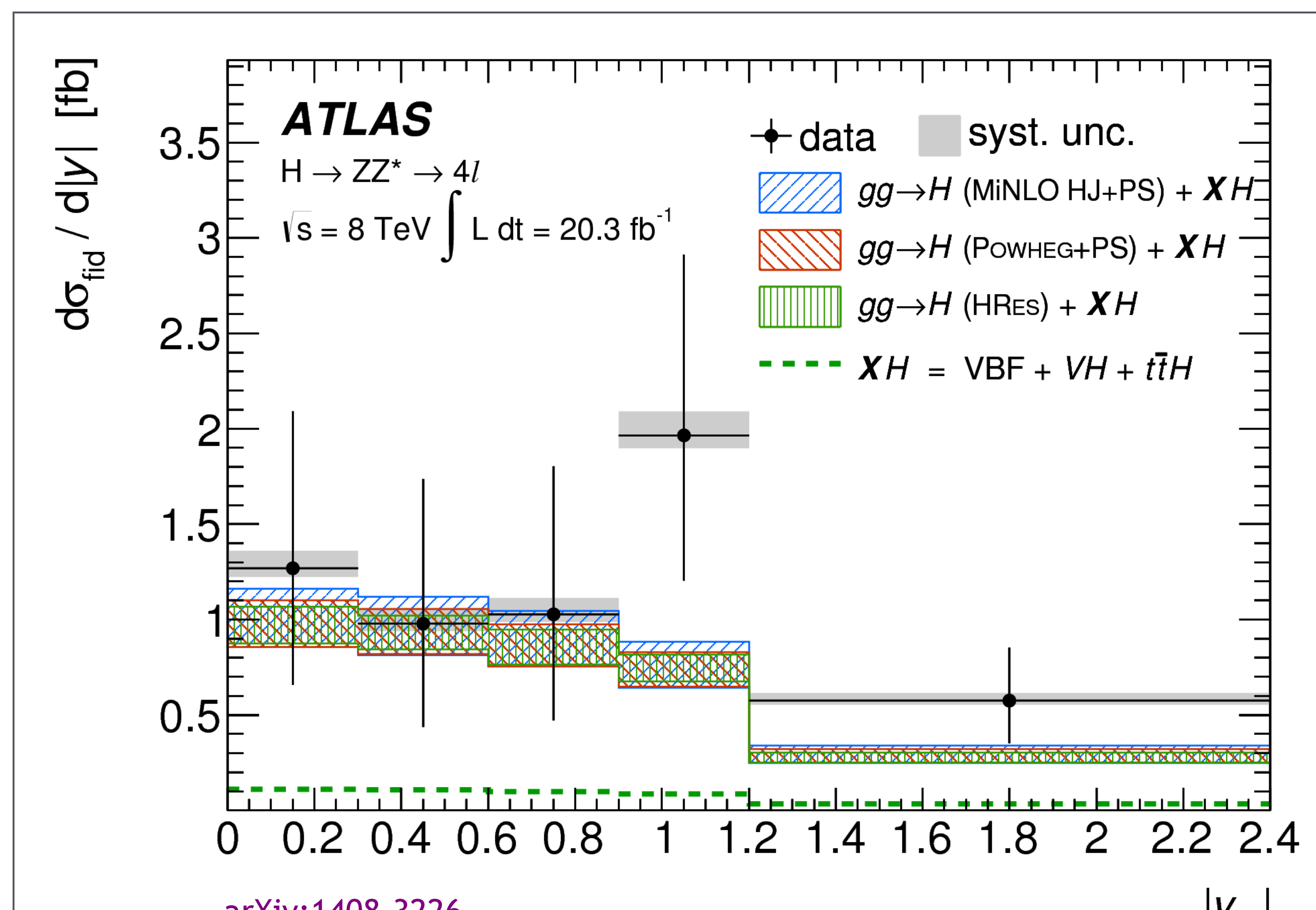
the details unfolded to the particle level

$H \to \gamma\gamma$ $gg \to H$ HRES



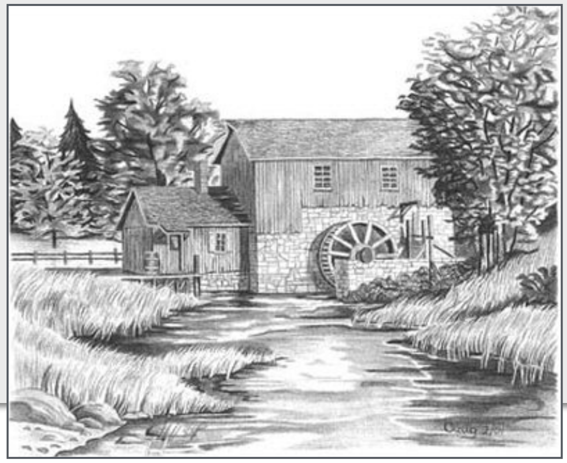
$H \to ZZ^* \to 4\ell$

$gg \to H$ MiNLO, POWHEG, HRES2



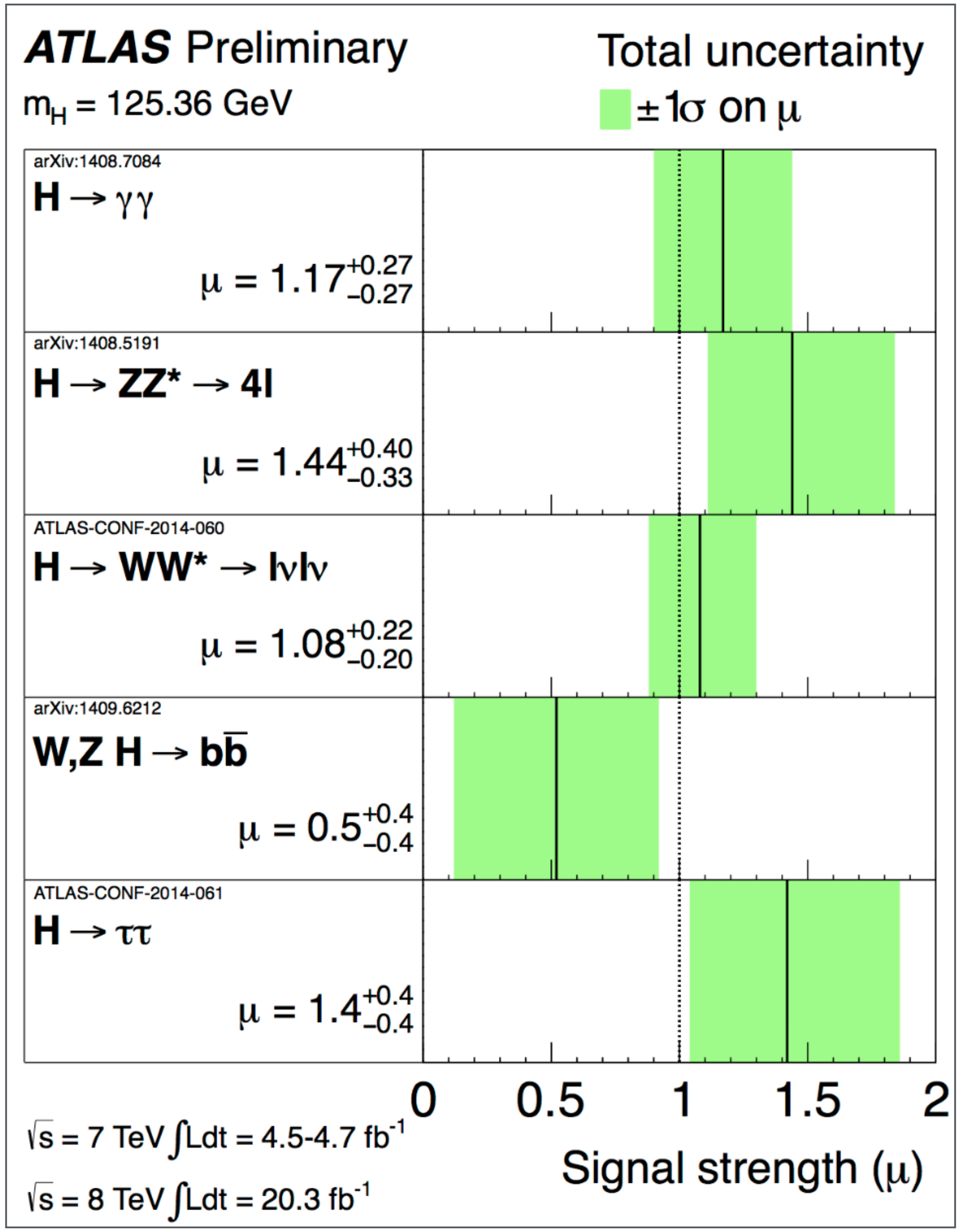
Higgs couplings, 1

signal strengths, small, vibrant industry



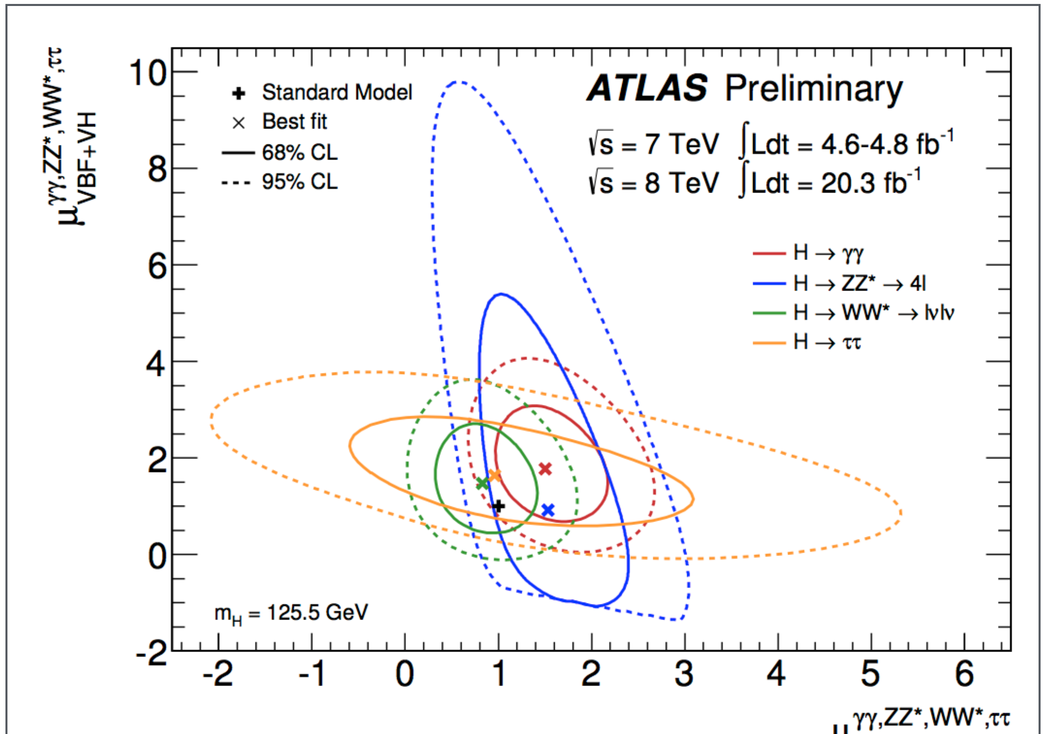
succession of assumptions

least constrained, signal strength:



other fits with constraints

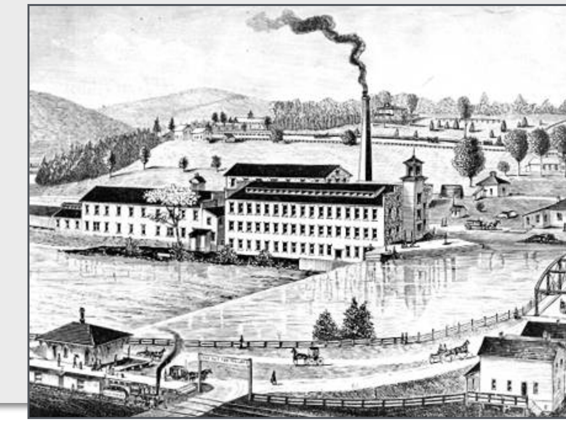
$$\mu_{VBF+VH} = \mu_{VBF} = \mu_{VH} \quad \mu_{ggf+t\bar{t}H} = \mu_{ggf} = \mu_{t\bar{t}}$$



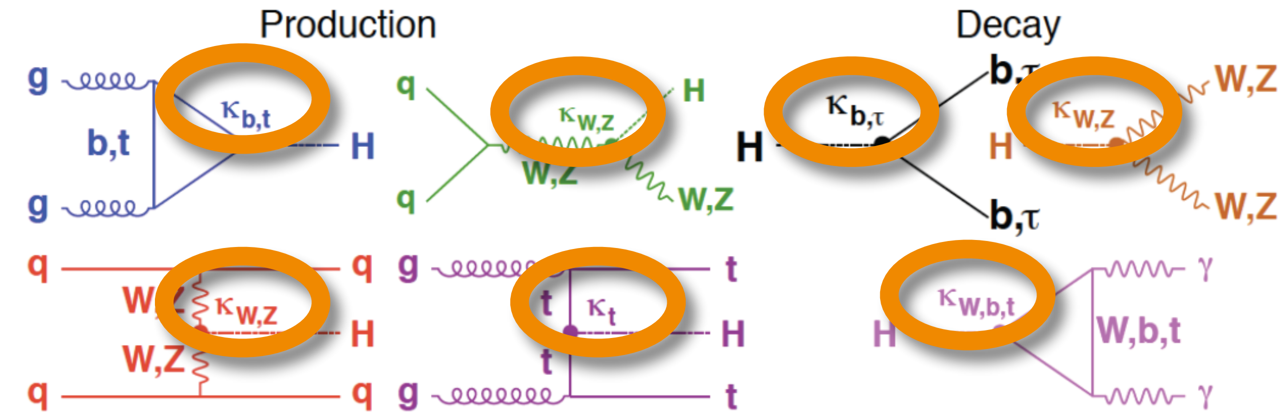
ATLAS-CONF-2014-009

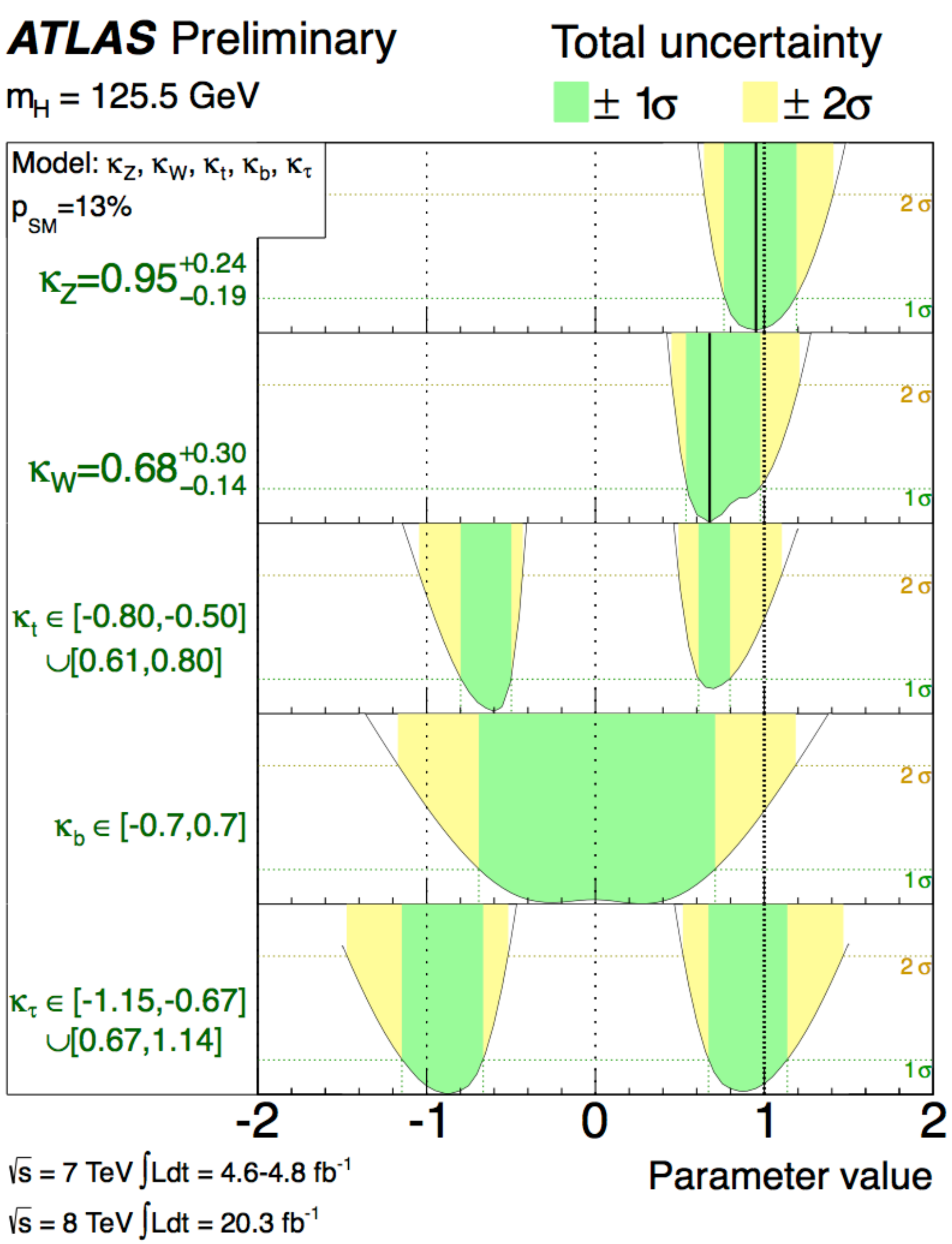
Higgs couplings, 2

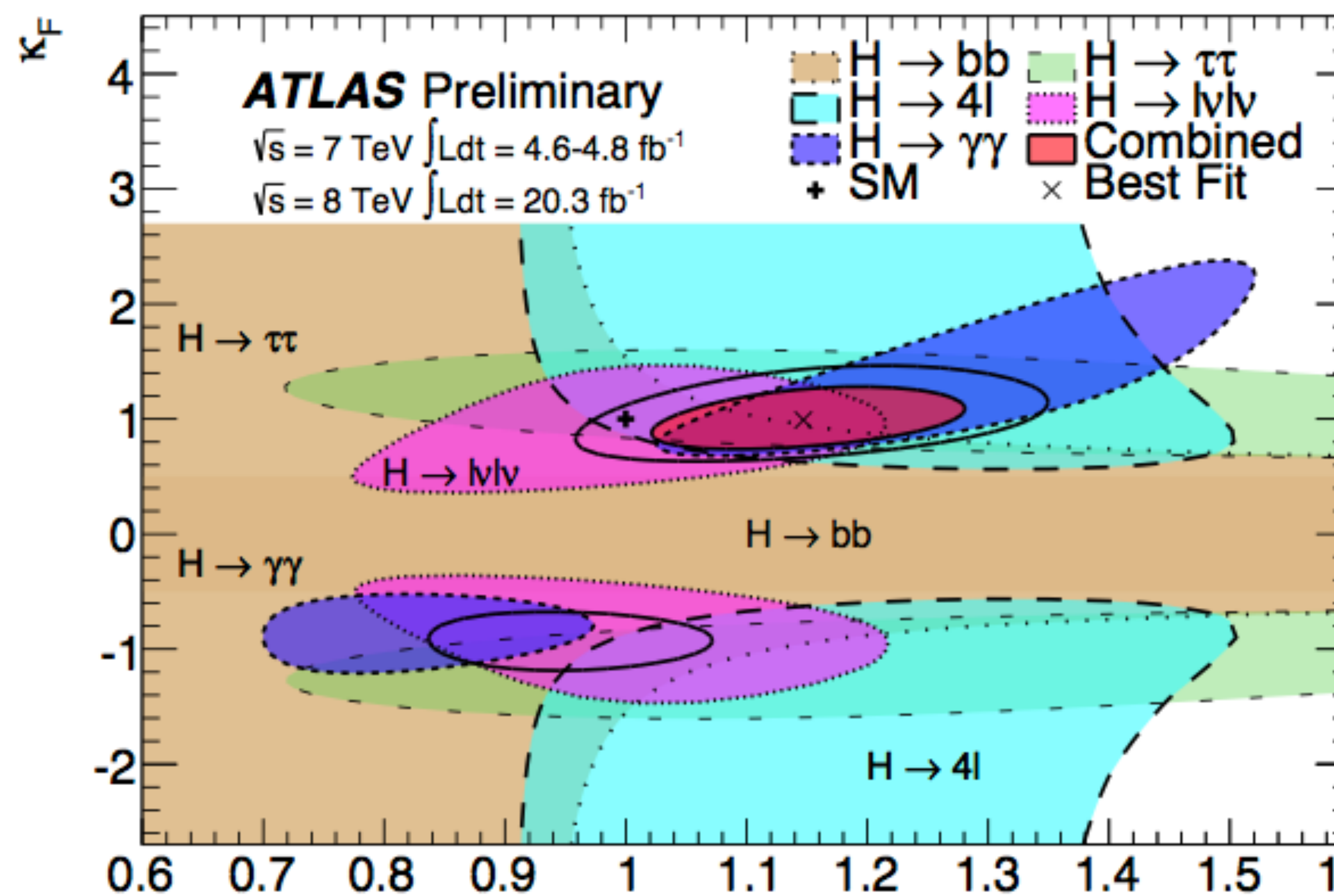
global fitting, big, growing industry



global fitting



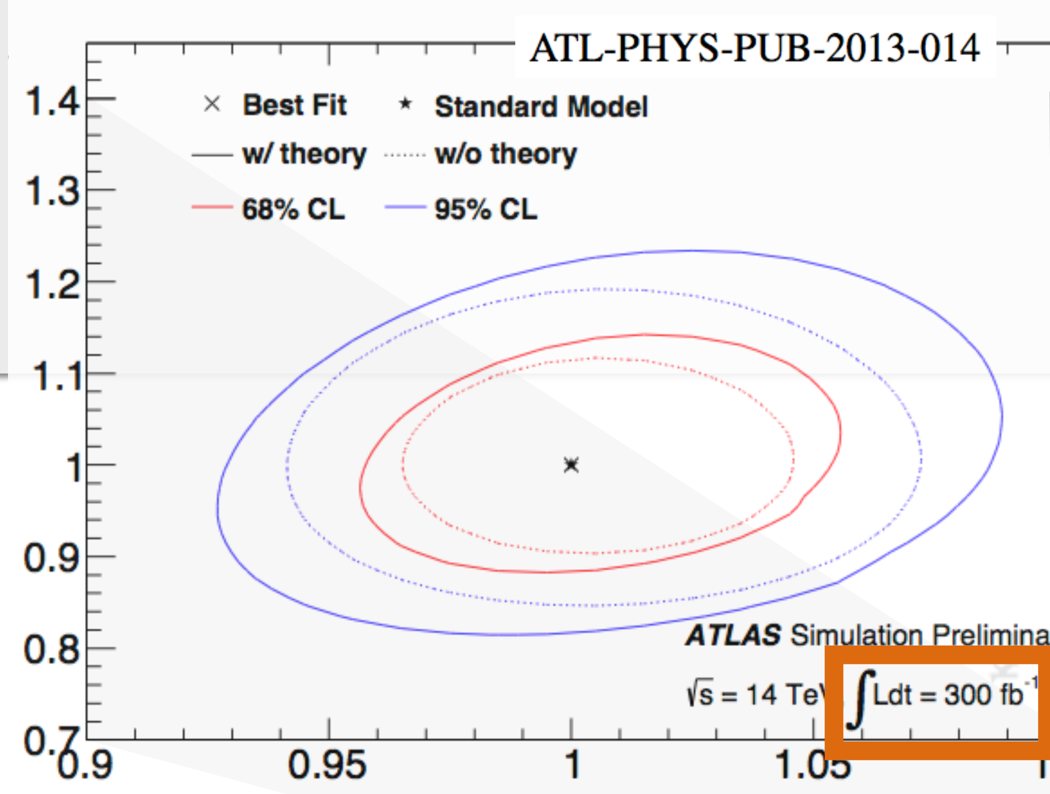


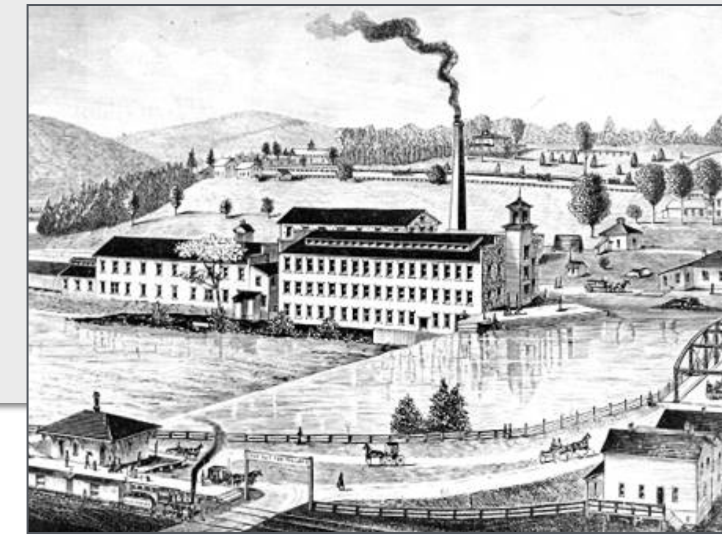


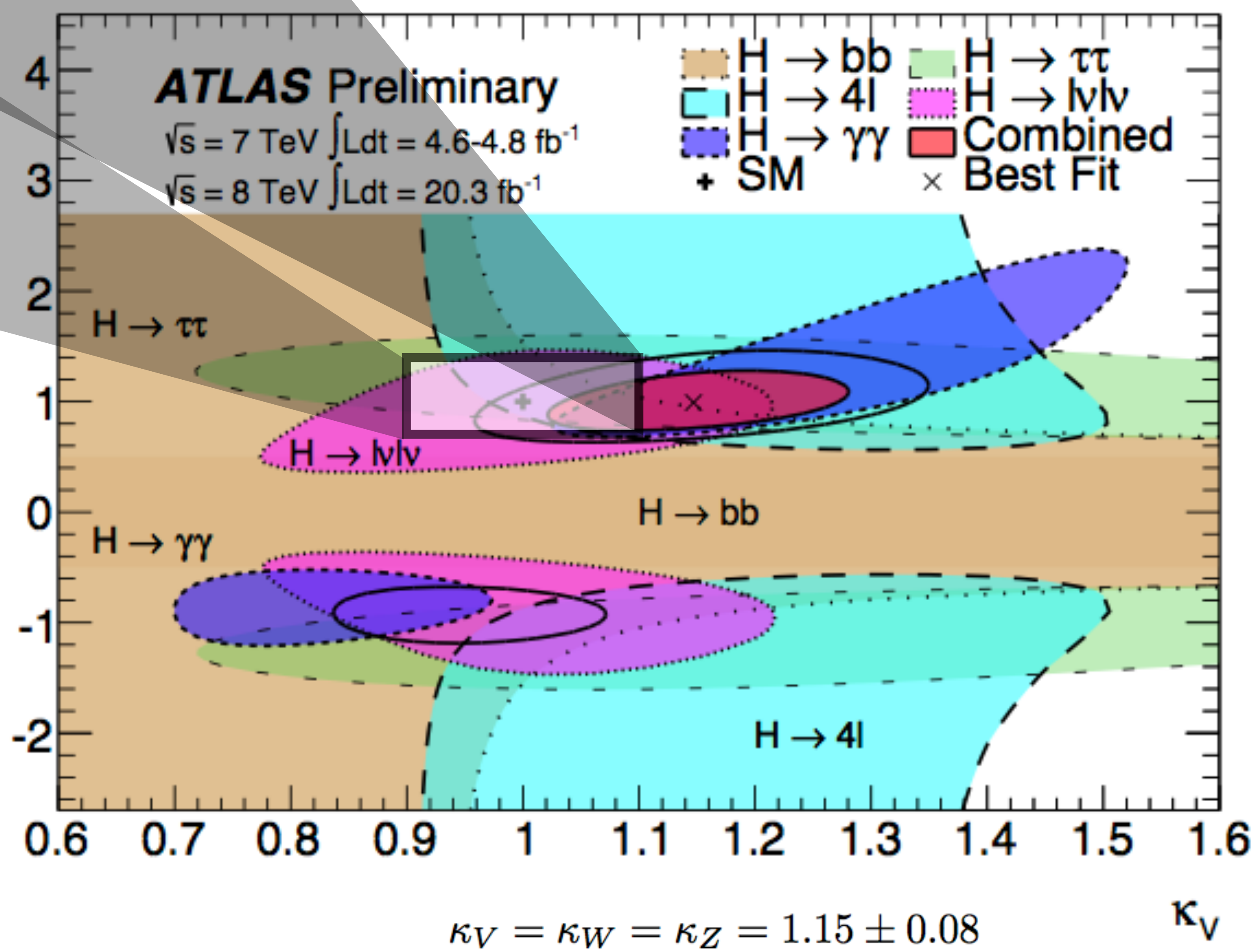
$$\kappa_V = \kappa_W = \kappa_Z = 1.15 \pm 0.08$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = 0.99 \pm 0.17$$

ATLAS-CONF-2014-009 κ_V







$$\kappa_V = \kappa_W = \kappa_Z = 1.15 \pm 0.08$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = 0.99 \pm 0.17$$

The precision Higgs Boson era has begun.

ATLAS-CONF-2014-009

But Wait... THERE'S MORE!

SM higgs final state configurations:

WW, $\tau\tau$, bb (Puja Saha, Friday)

fiducial and differential cross sections ZZ

tTH —> 2 gamma, constrain top Yukawa

on-off peak total width measurement

125 GeV Higgs Boson characteristics

differential distributions, CP, spin

BSM Higgs searches

Charged Higgs, LFV final states, Heavy Higgs, NMSSM, Invisible decays, Exotic Higgs, scalar diphoton

Standard Model Physics

Notable results

from Run 1 we anticipated:

"Rediscovery"...Precision total & inclusive cross sections, VV studies, differential cross sections. Did we expect MW?

from Run 1 we achieved:

Rediscovery, indeed.

in Run 2, we expect:

Re-rediscovery...Precision couplings, differential distributions, much pileup study.

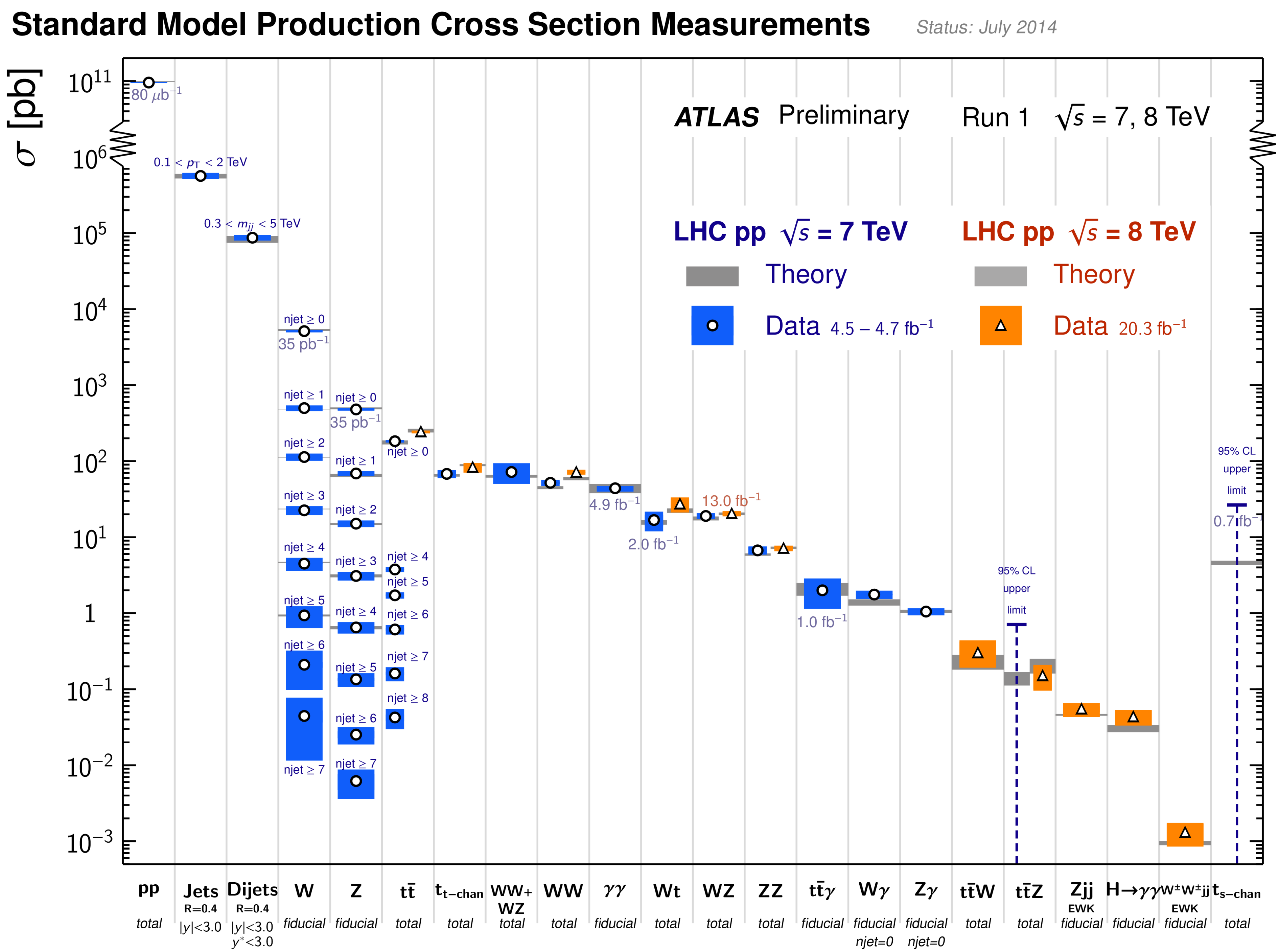
First M_W?

Attention to WW

5x - 10x more statistics

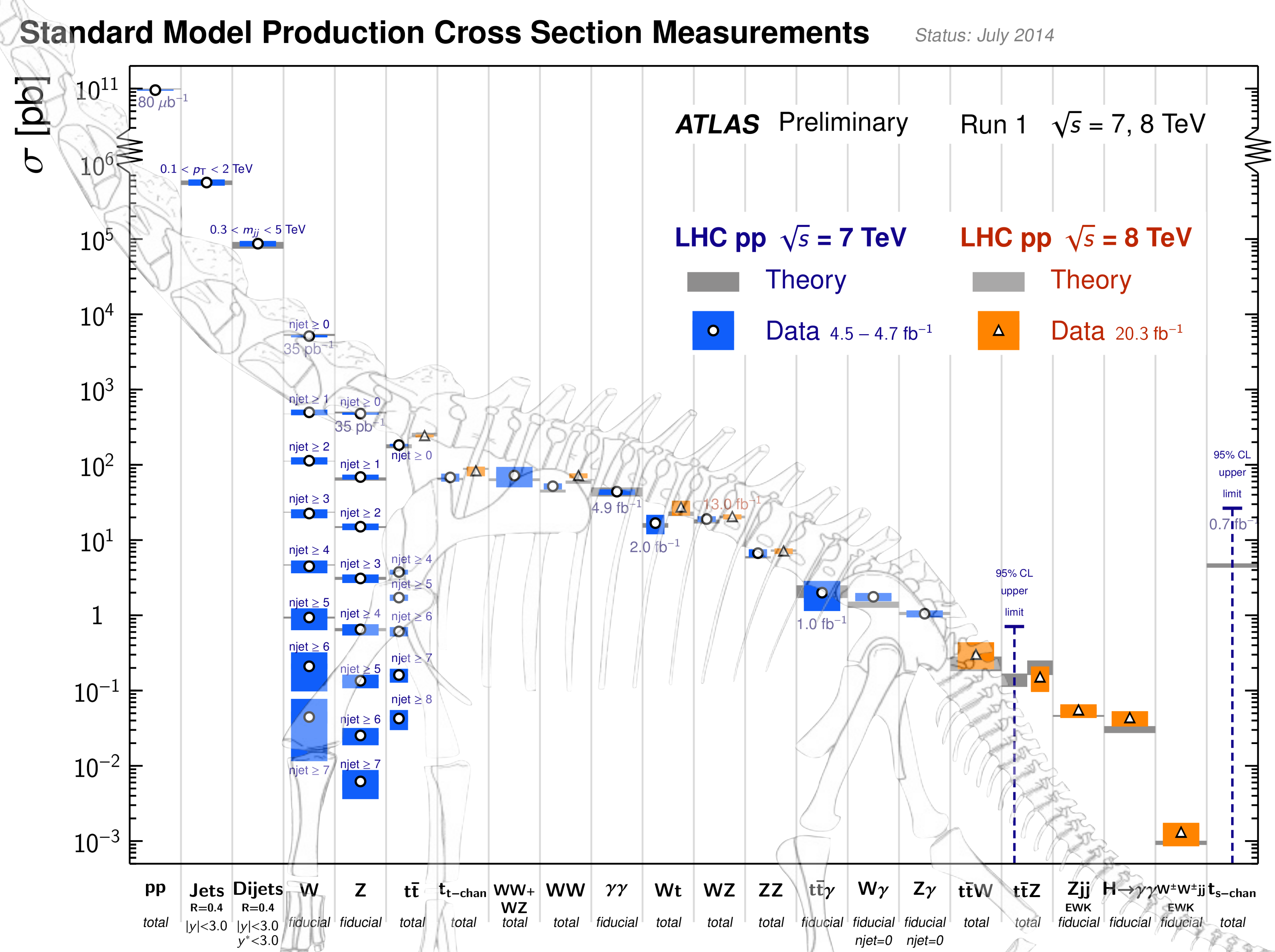
Standard Model Paleontology

pick your favorite dinosaur



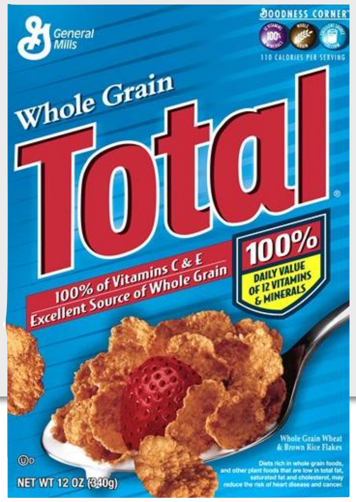
Standard Model Paleontology

pick your favorite dinosaur



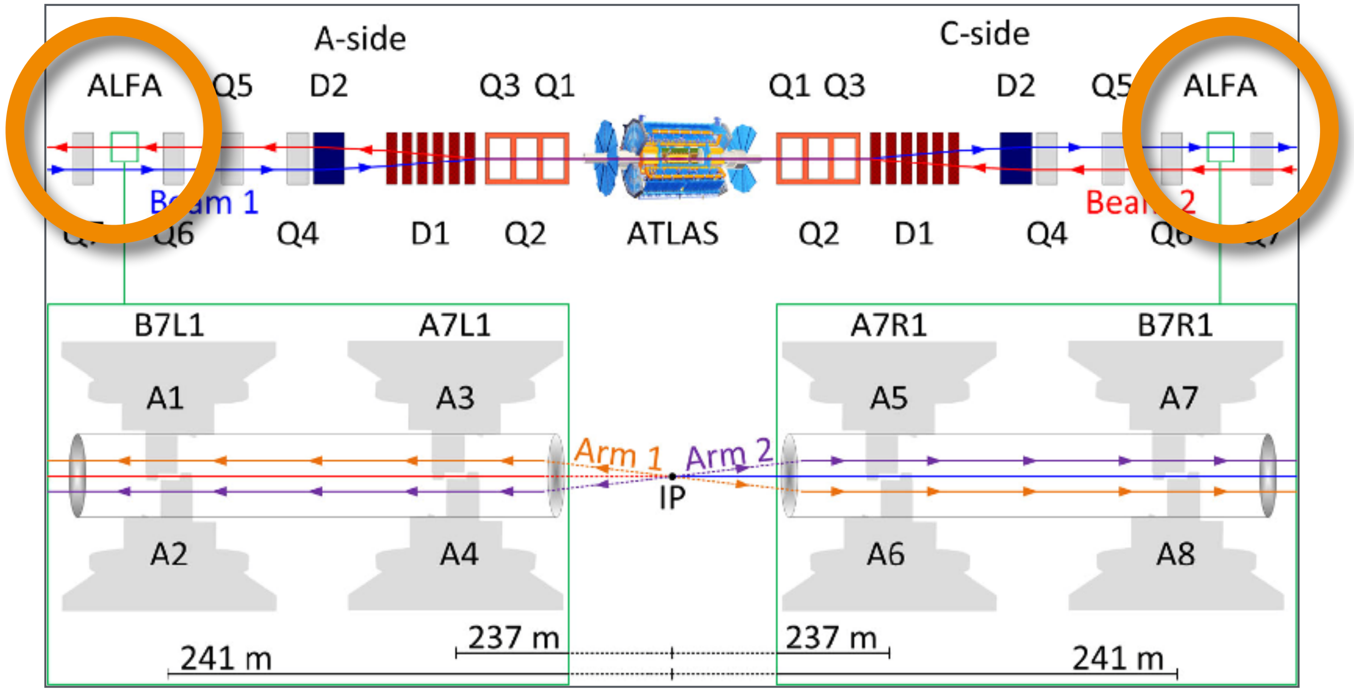
The basics

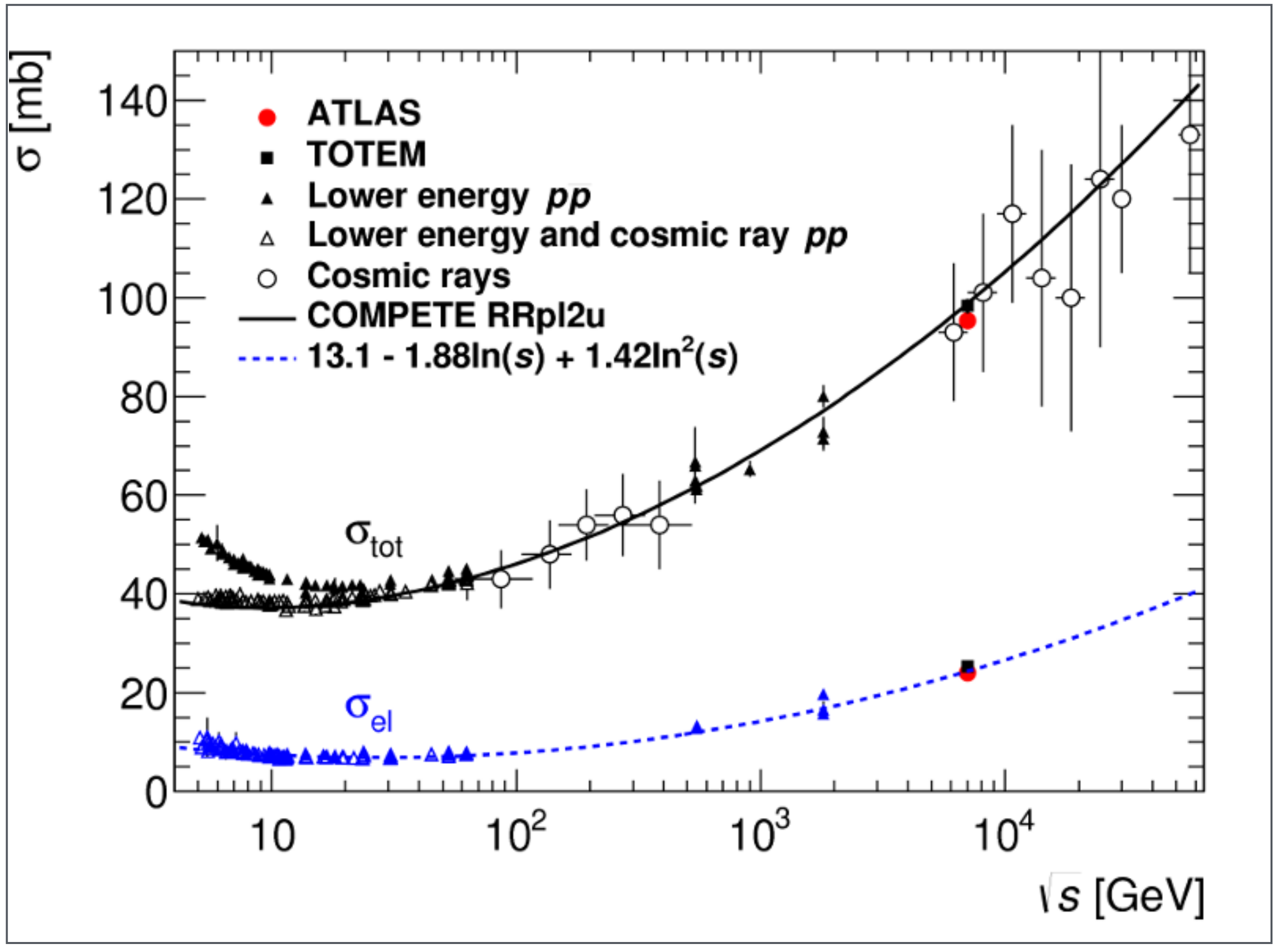
Elastic and total pp cross section



ALFA detectors at ±240m

special run of 80/ μb

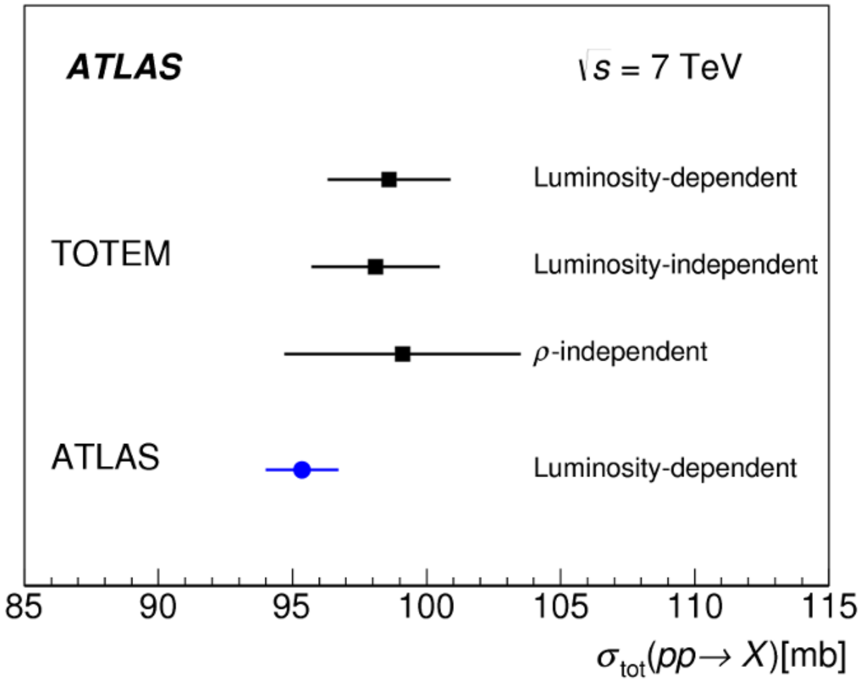




arXiv:1408.5778

Result: $\sigma_{\text{tot}}(pp \to X) = 95.35 \pm 0.38\,(\text{stat}) \pm 1.25\,(\text{exp}) \pm 0.37\,(\text{extr})$ **mb**

and elastic slope $B = 19.73 \pm 0.14\,(\text{stat}) \pm 0.26\,(\text{syst})\ \text{GeV}^{-2}$



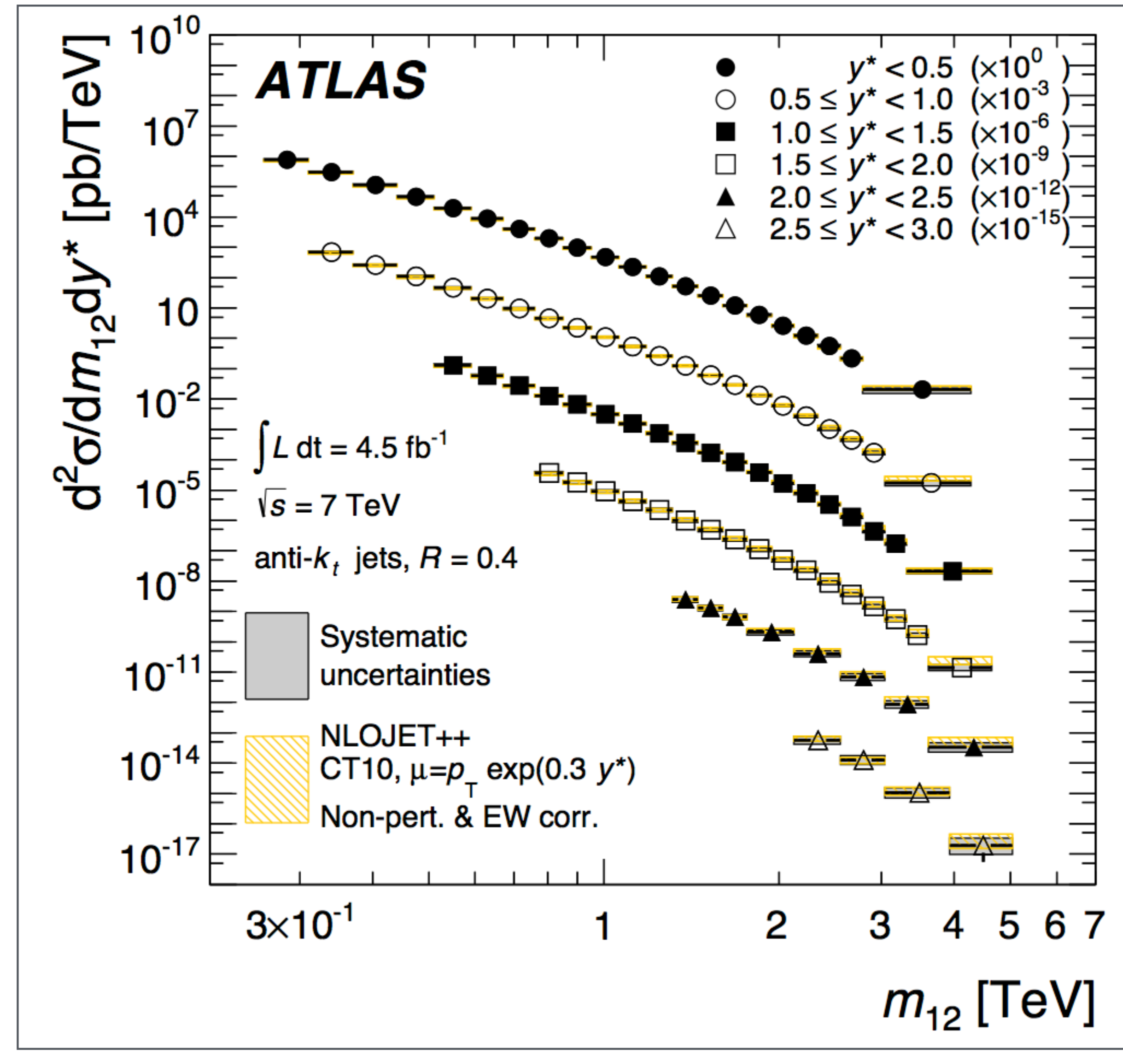
QCD jet physics

di- jet observables

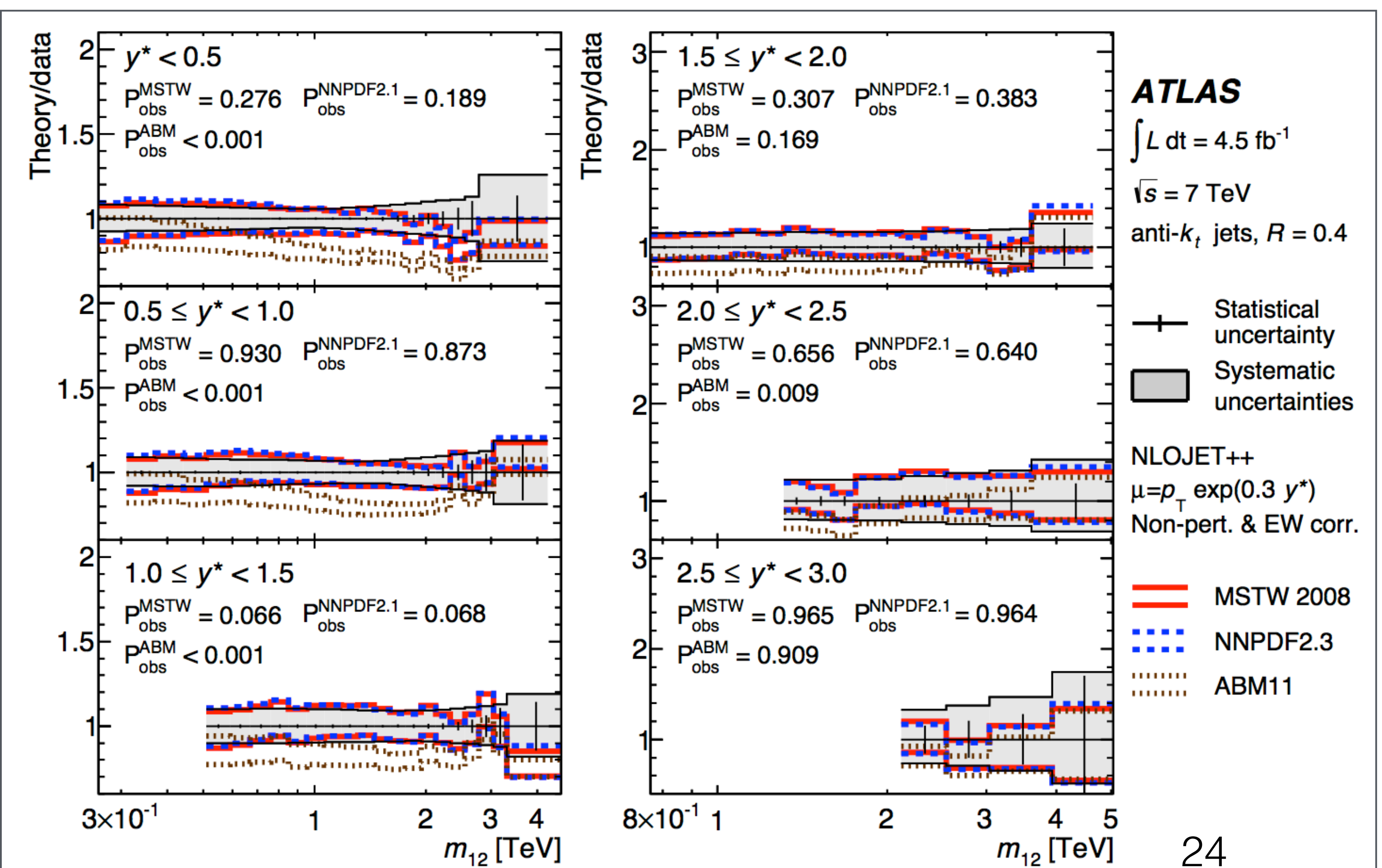
7 TeV running, double differential

Bins of m_{12} and rapidity

composite scale limit Λ < 6.9 - 7.7 TeV



arXiv:1312.3524



Agreement found:

NLOJet++ predictions using CT10, NNPDF2.1, and MSTW 2008

Disagreement found:

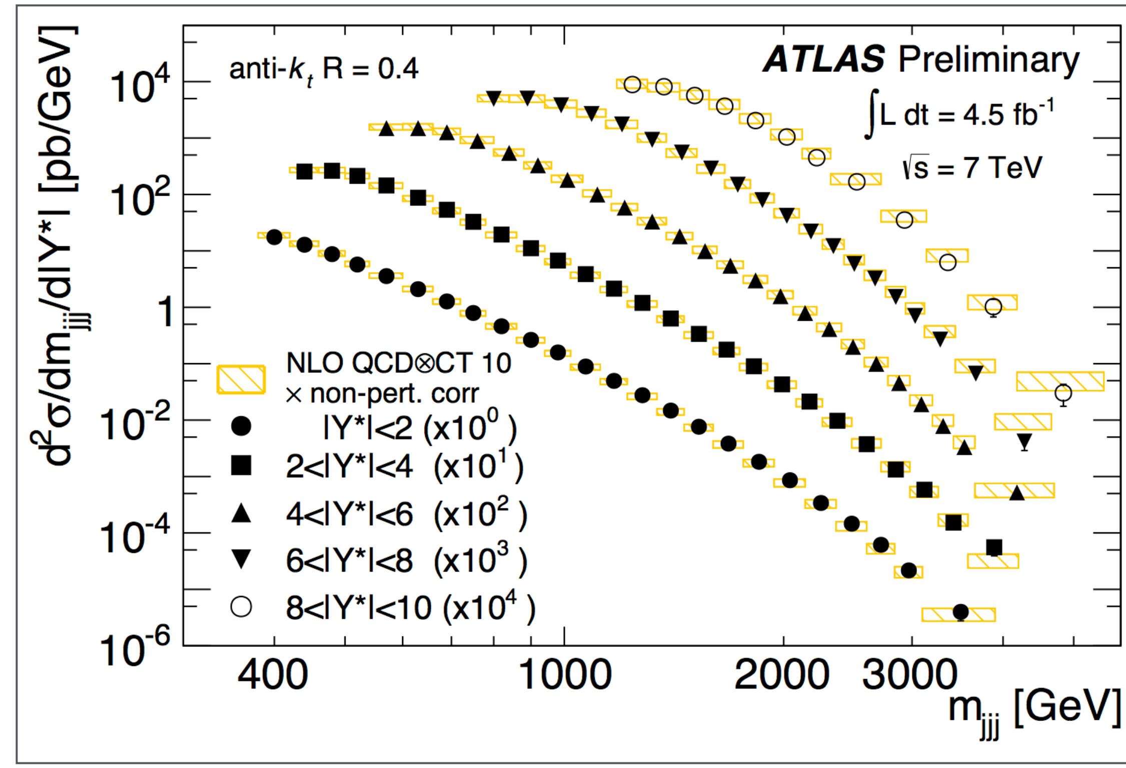
NLOJet++ predictions using ABM11 & HERAPDF1.5

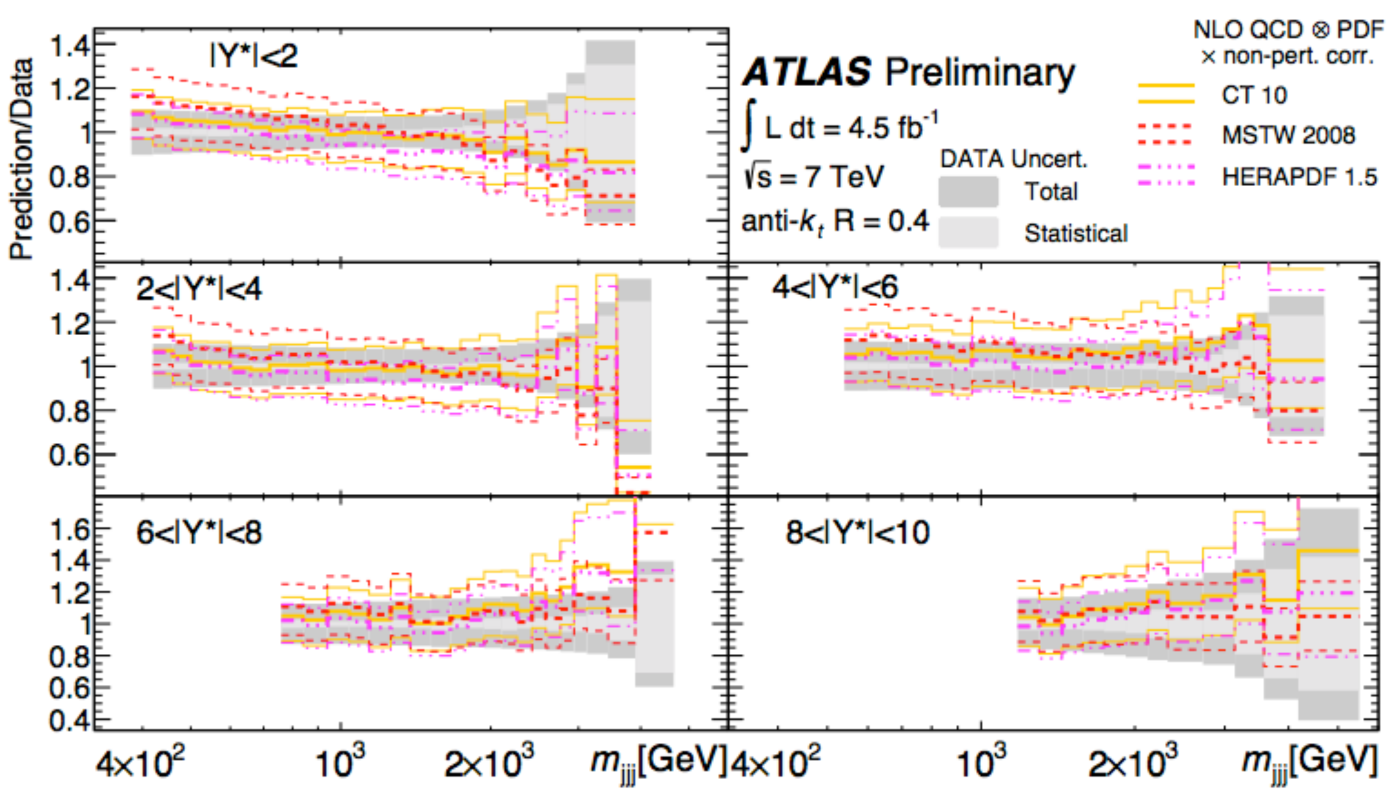
QCD jet physics

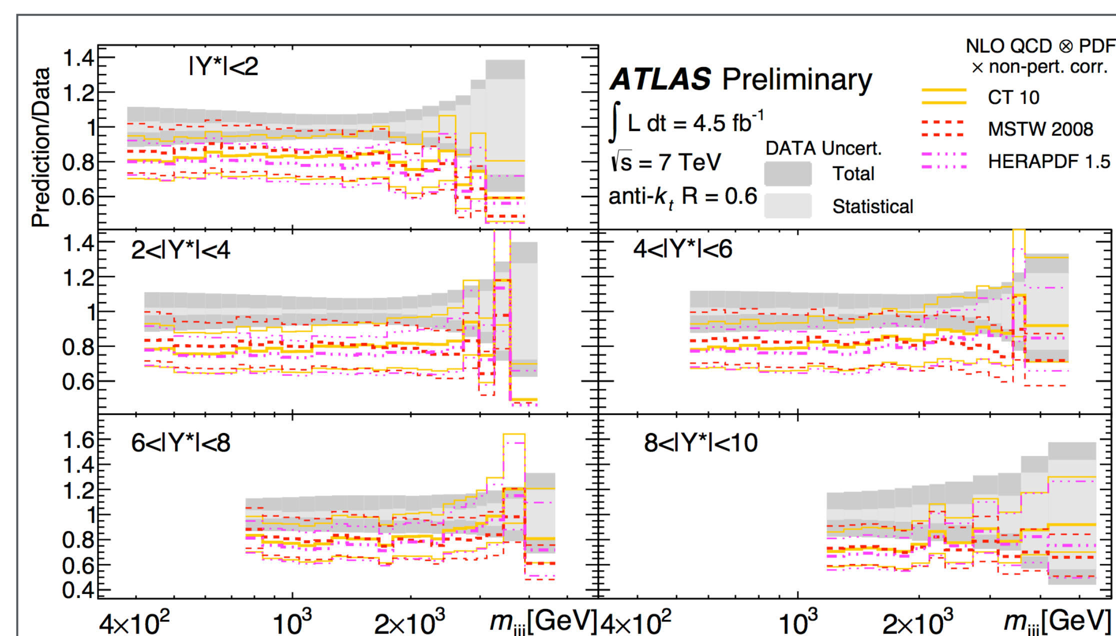
3 jet cross sections

7 TeV running, double differential, m_{jjj}

- good agreement with most NLO pdf for R =0.4, less for R = 0.6





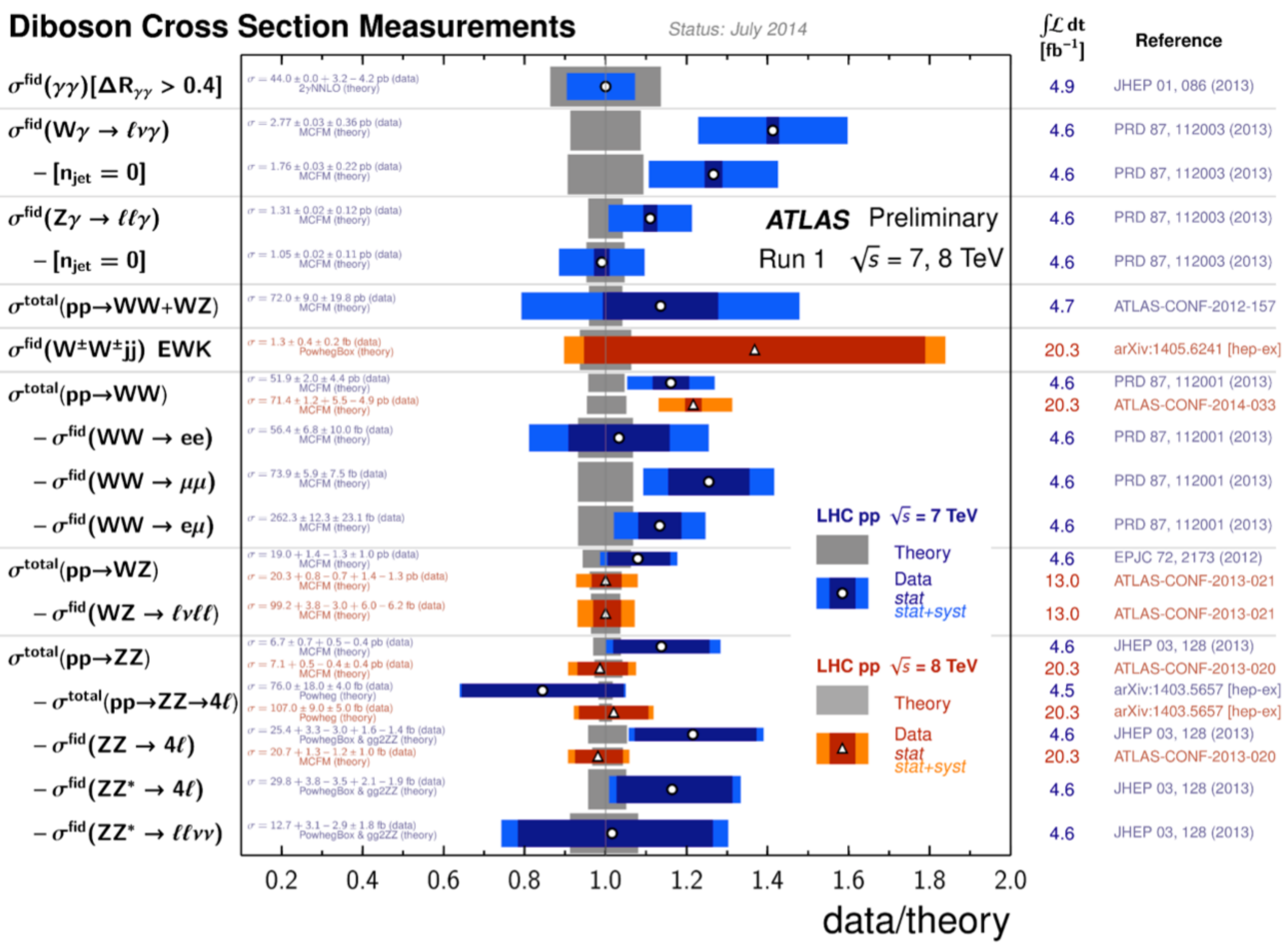


ATLAS-CONF-2014-045

Electroweak physics

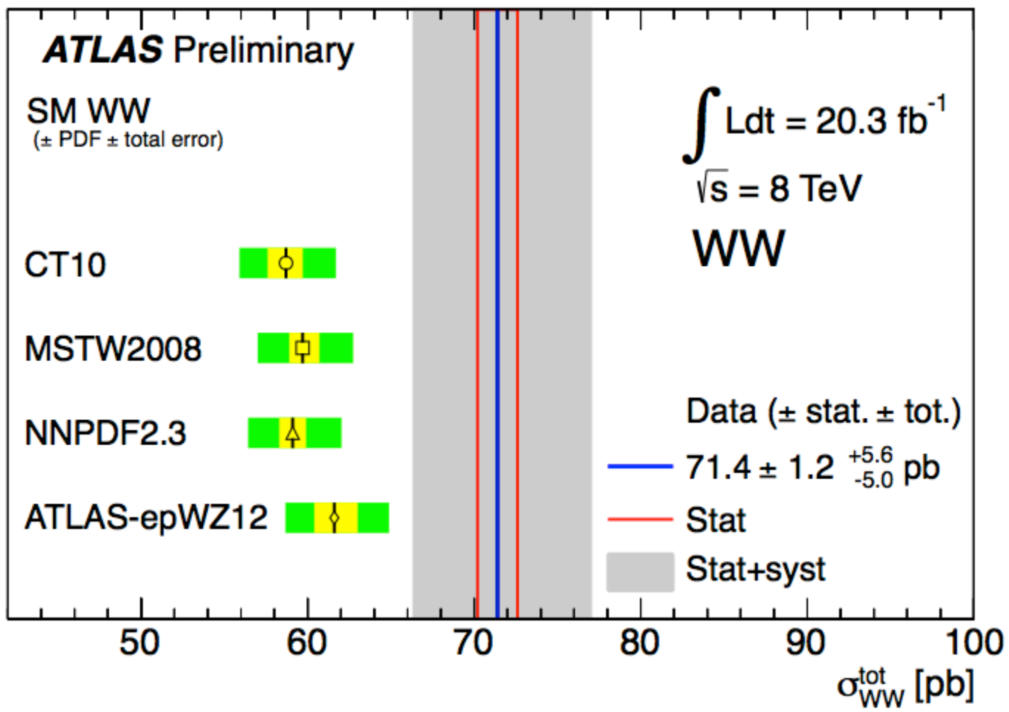
W^+W^- continues to be interesting

yesterday's background is today's confusion?



ATLAS-CONF-2014-033

Comparison with theory is difficult



tt and t backgrounds mandate a jet-veto requirement of p_T > 25 GeV

expect x10 or so more statistics

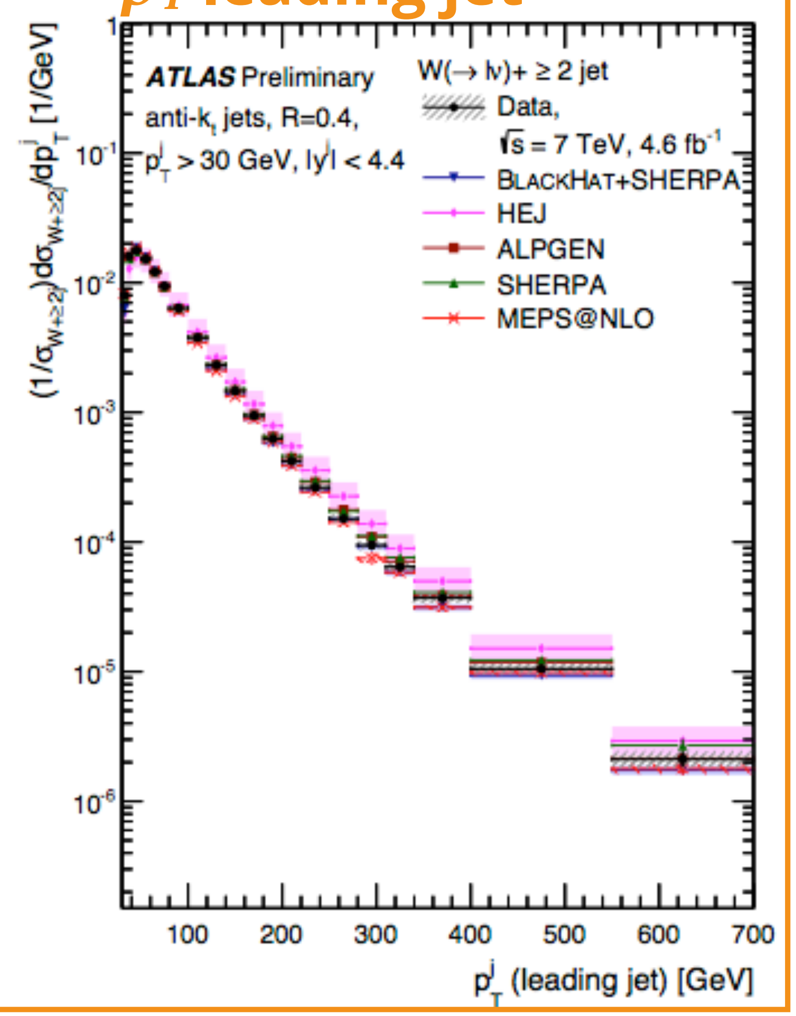
W+jets

up to 8!

7 TeV running, leptonic decay modes

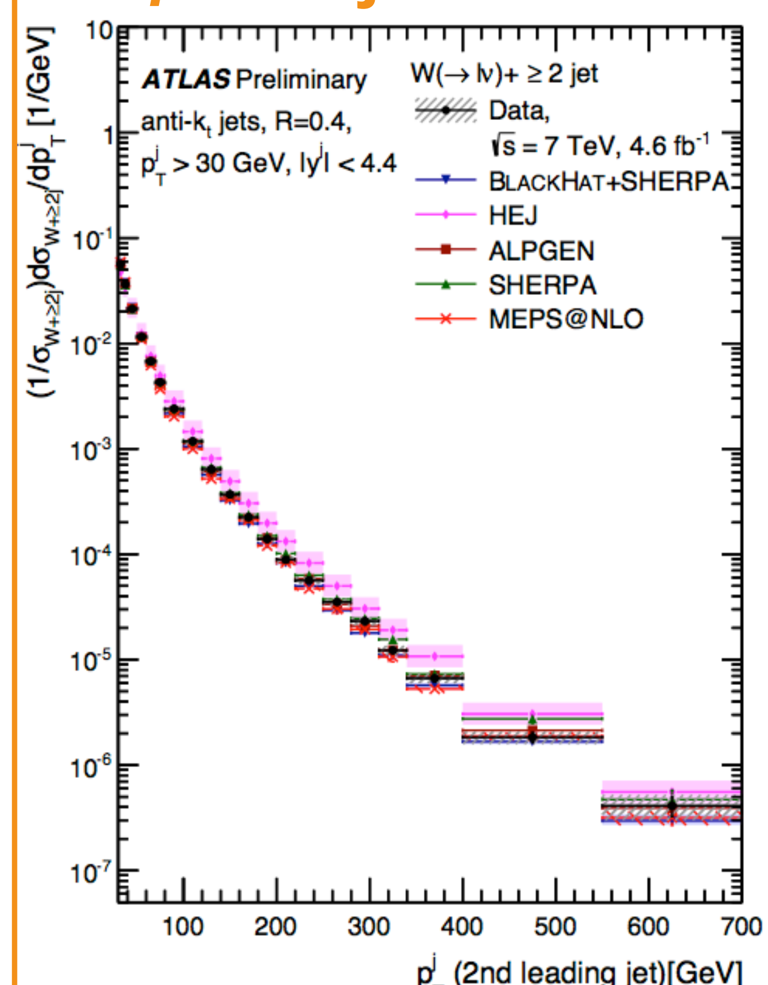
BLACKHAT+SHERPA, HEJ, ALPGEN, SHERPA AND MEPS@NLO

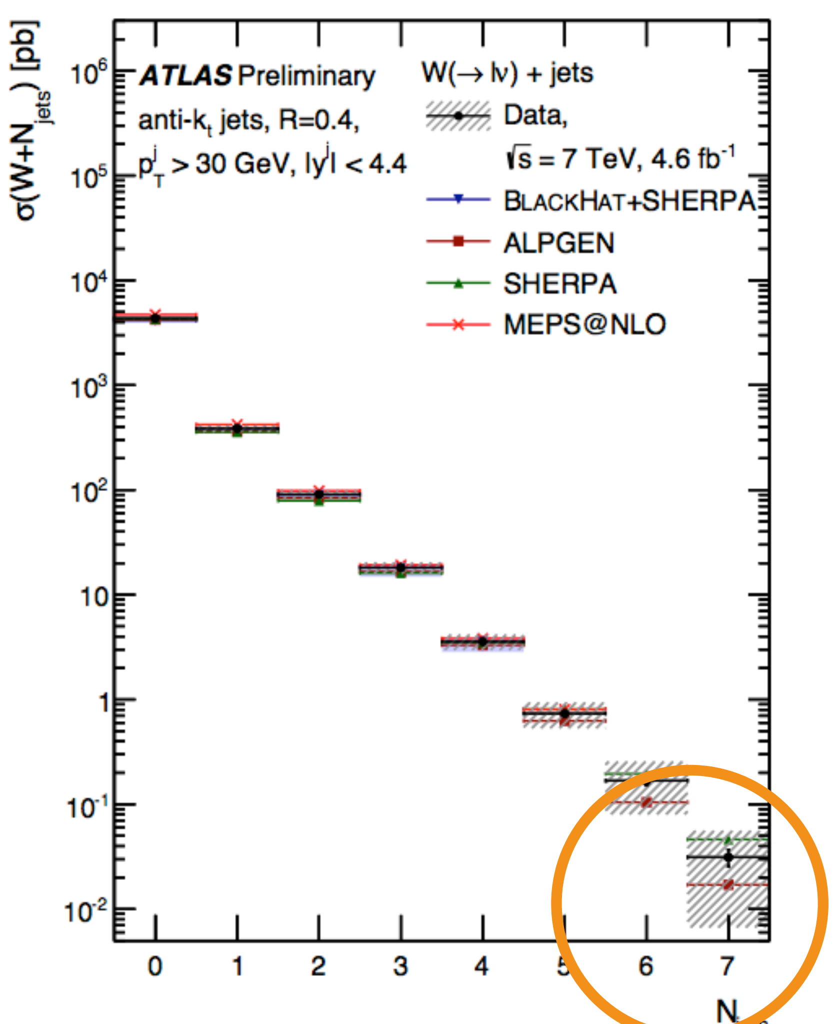
p_T **leading jet**

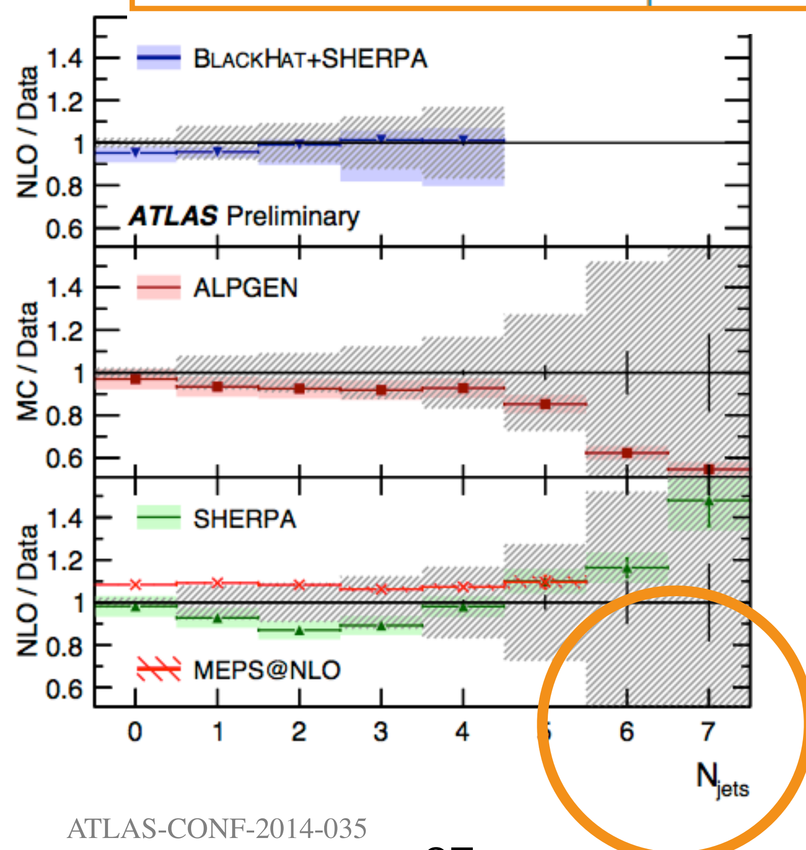


e.g. ≥ 2 j

p_T **2nd jet**







ATLAS-CONF-2014-035

generally, good agreement but no prediction fits all distributions

But Wait... THERE'S MORE!

Z/W production

heavy flavor: $W + c$ (arXiv:1402.6263) and $Z \to b\bar{b}$ (arXiv:1404.7042)

underlying event

$p_{\mathrm{T}}(Z)$

$W\gamma$, $Z\gamma$, ZZ, W^+W^-, $W^{\pm}Z$, fully leptonic and semileptonic

jet structure

inclusive jet m_{jj}, boosted W/Zs, jet gap studies

Multi-bosons

aQGCs, TCG for Z/γ - WW

QGC for $WWWW$

evidence for electroweak WW fusion (Jessica Metcalfe, Friday), Zjj production

evidence for WW —> WWjj scattering

Top quark Physics

Notable results

from Run 1 we anticipated:

precision cross sections, precision mass of 1-3.5 GeV, rediscovery of single top, single top Wt channel

from Run 1, we achieved:

precise cross sections, mass, distributions ttbar and single top

in Run 2, we expect:

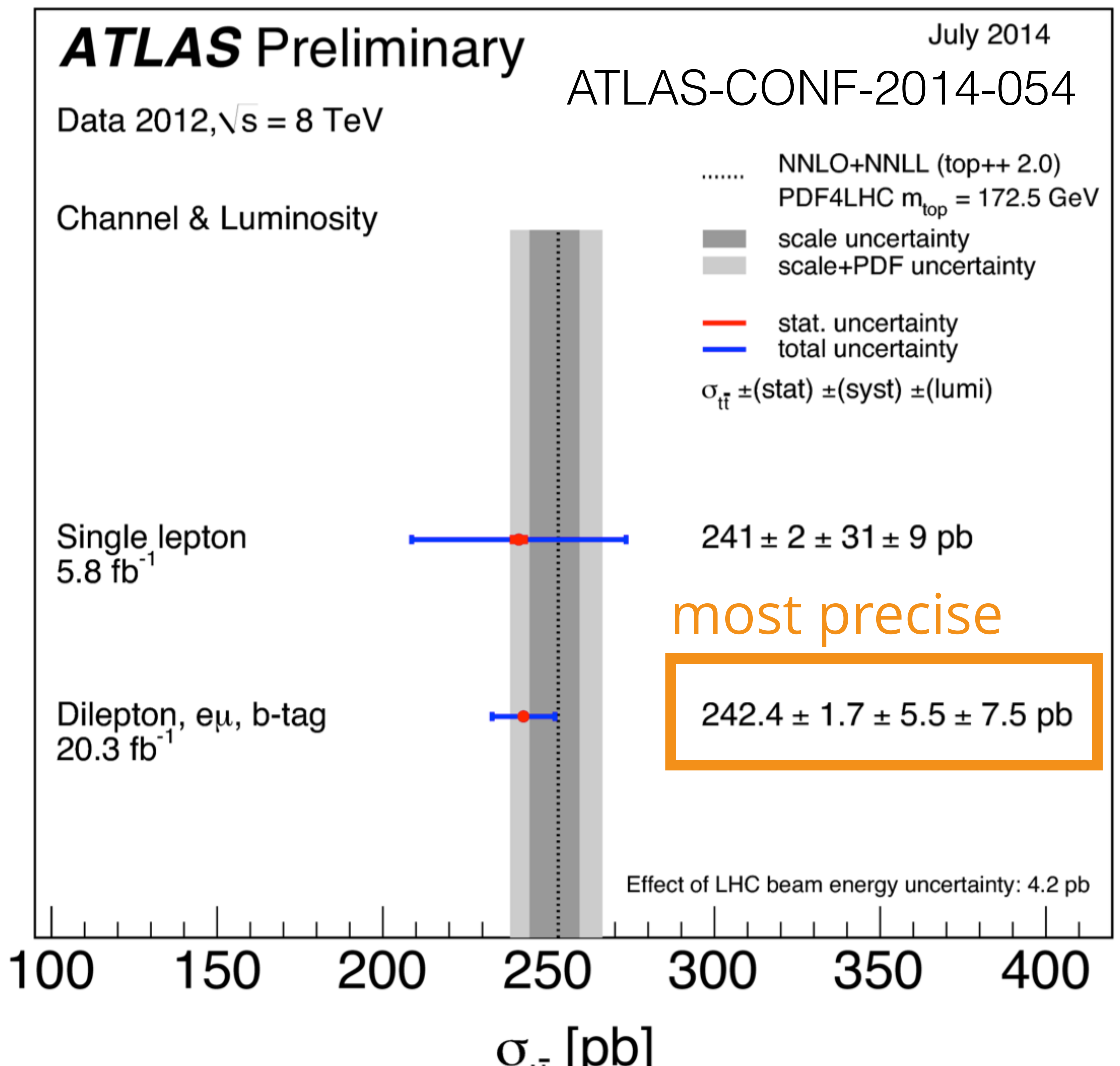
20x more statistics!

Top quark cross section

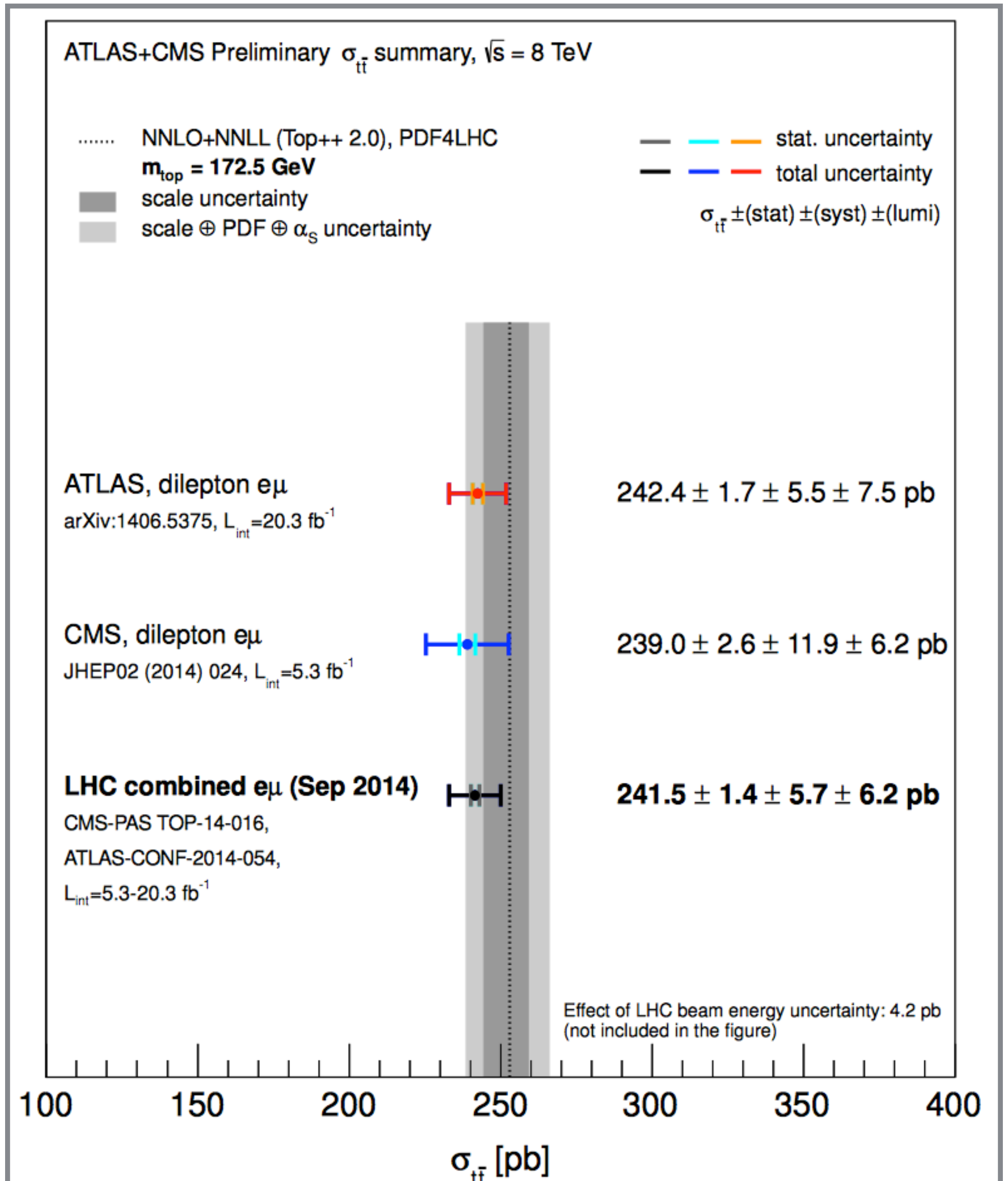
win-win

Most precise determinations from single and di-lepton channels

- NNLO+NNLL agreement
- largest sys: ttbar modeling & pdfs



Combined ATLAS+CMS $e\,\mu$



Single top, Wt

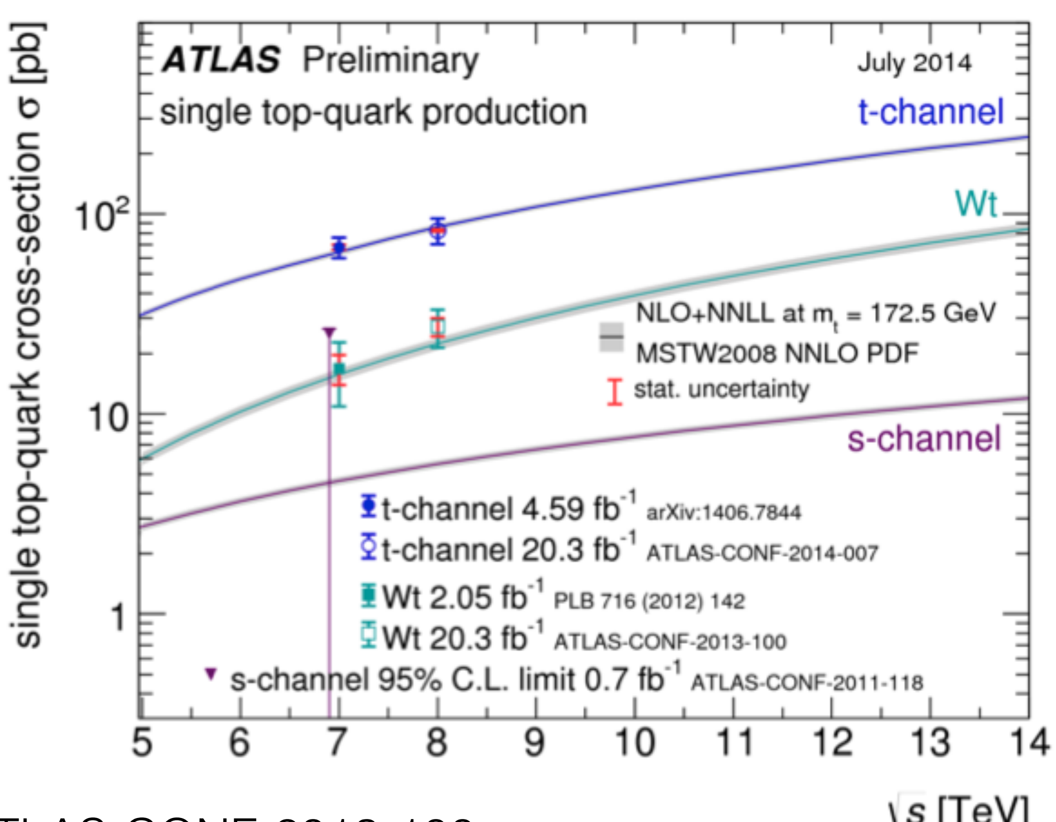
win-win

ATLAS evidence at 4.2σ

then ATLAS + CMS

agreement with NLO+NNLL

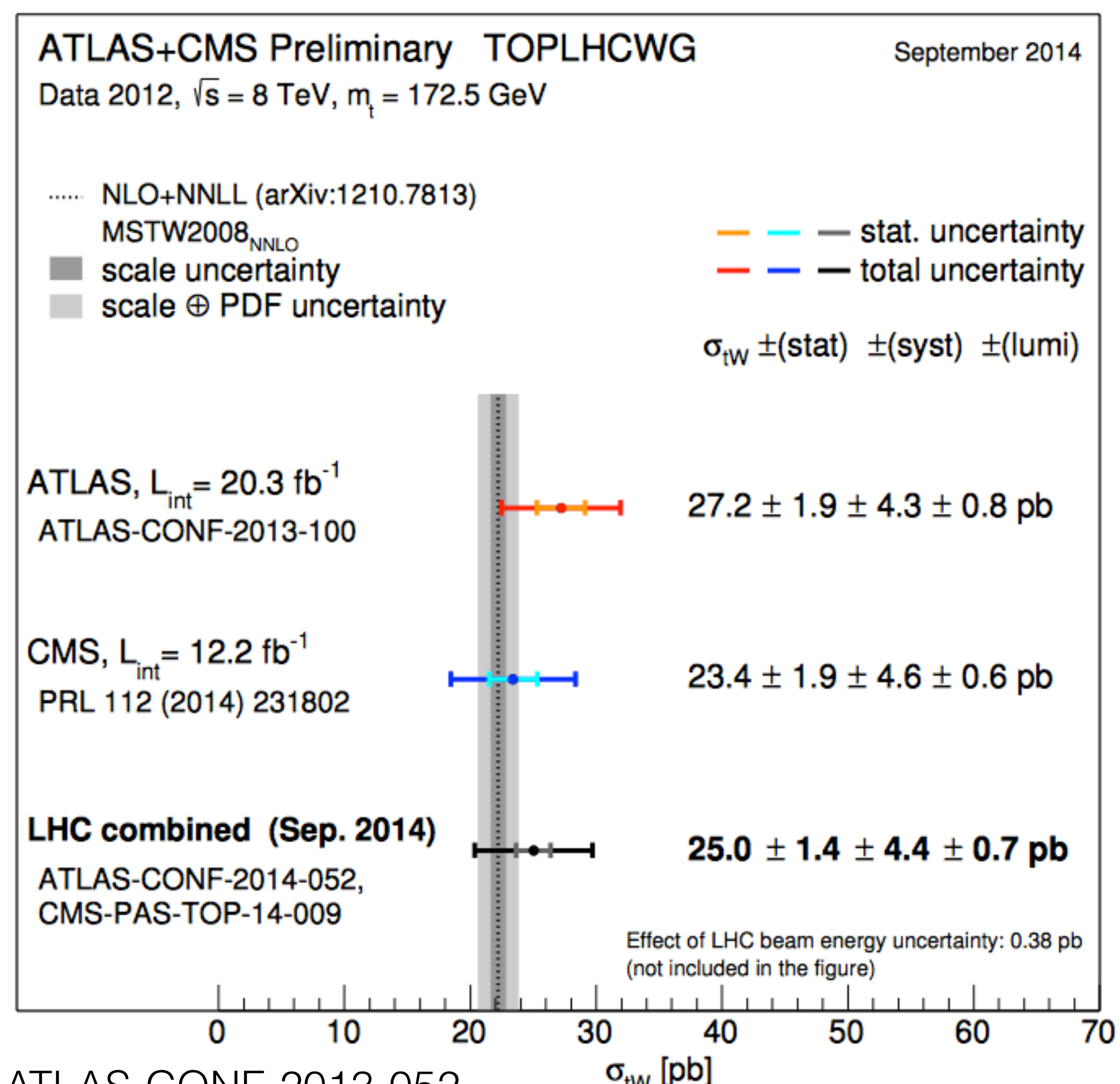
All 3 single top channels:



ATLAS-CONF-2013-100

ATLAS-CONF-2011-118 ATLAS-CONF-2014-007

Combined ATLAS+CMS Wt



ATLAS-CONF-2013-052

Top quark mass

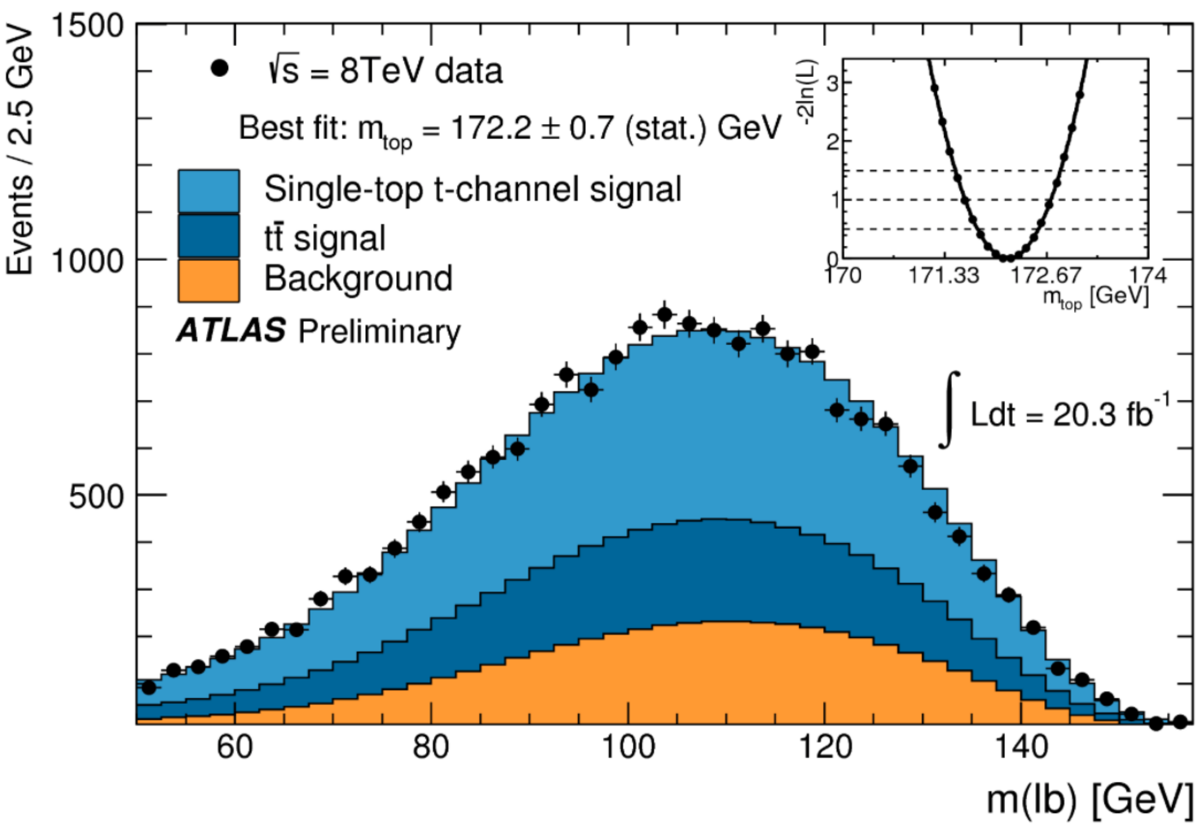
win-win-win

2008 estimates for 1/fb: ±1–3.5 GeV in three channels

Run 1 results? Better than predicted.

the world: < 0.5% uncertainties

Single top “enhanced”



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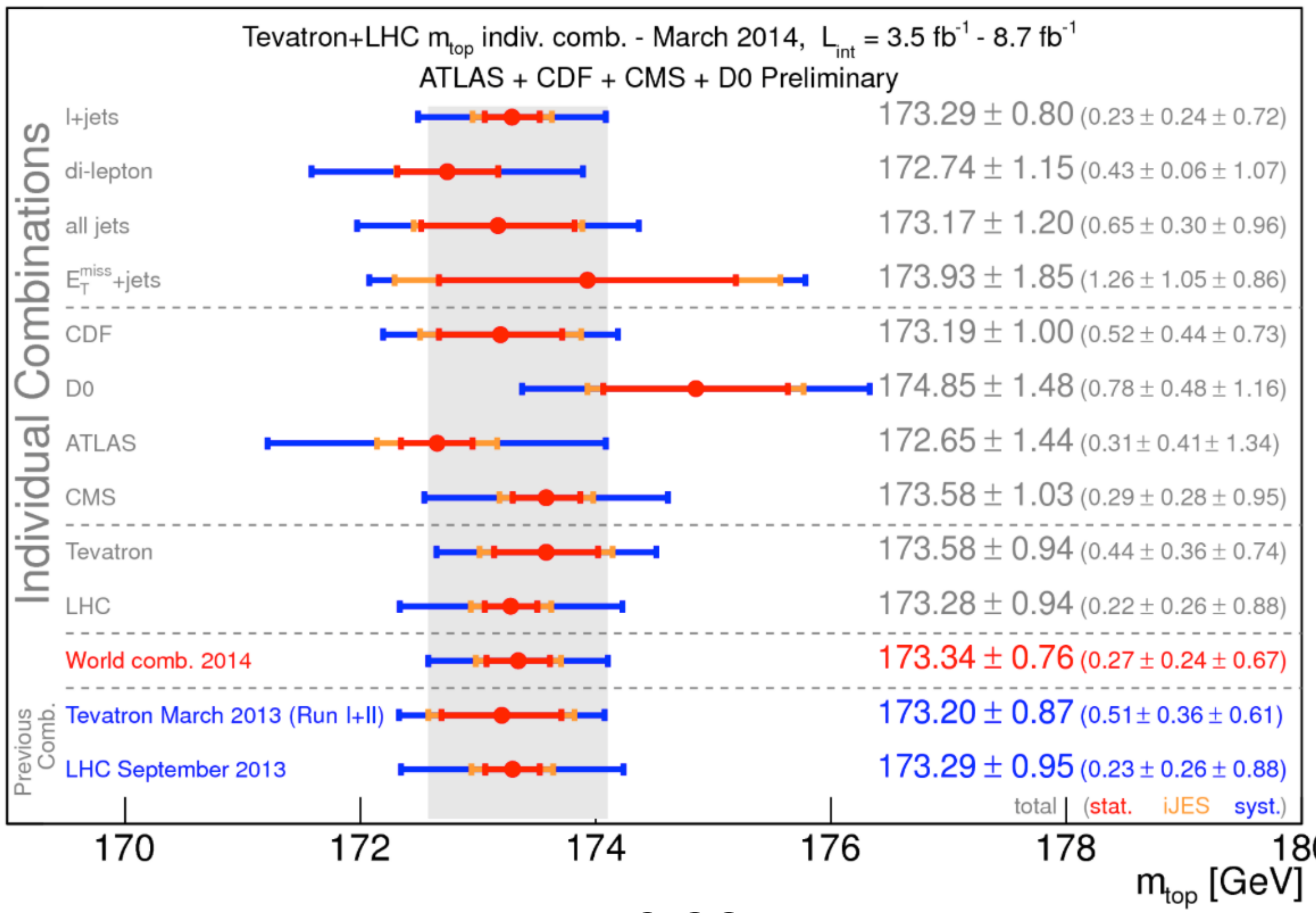
Combined ATLAS+CMS + CDF + D0



ATLAS-CONF-2014-008

But Wait... THERE'S MORE!

top cross sections

all hadronic final states, tau final states, ttbar/Z/WW

differential distributions: parton level, boosted ttbar, associated production with jets and heavy flavor, W/Z, high pt boosted

single top

CP violation

top mass

pole mass from cross section tail, t -T mass difference

top properties

charge, W polarization, FCNC searches, charge asymmetry, t polarization

Exotic Physics

Notable results

from Run 1 we anticipated:

supersymmetry discovery? no Higgs? Higgs? BSM Higgses (SP?), extension of Tevatron IVB' searches by x2 or more,

from Run 1 we achieved:

supersymmetry limits! one Higgs, BSM Higgs searches, IVB' searches

in Run 2, we expect:

early concentration on gluino searches, di- ℓ & di-jet bump searches

BSM Higgs hints

additional IVB' searches

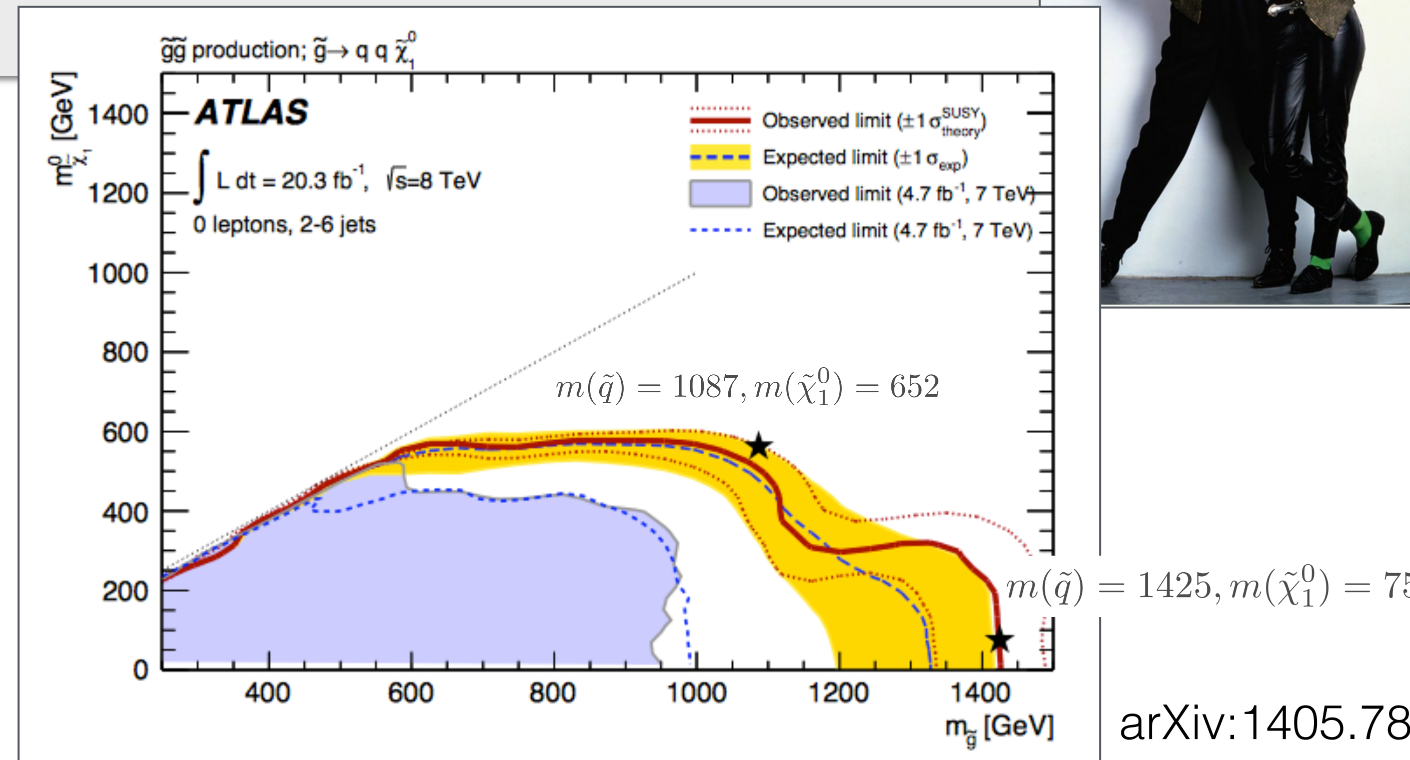
50x - 1000x more statistics!

Supersymmetric Physics

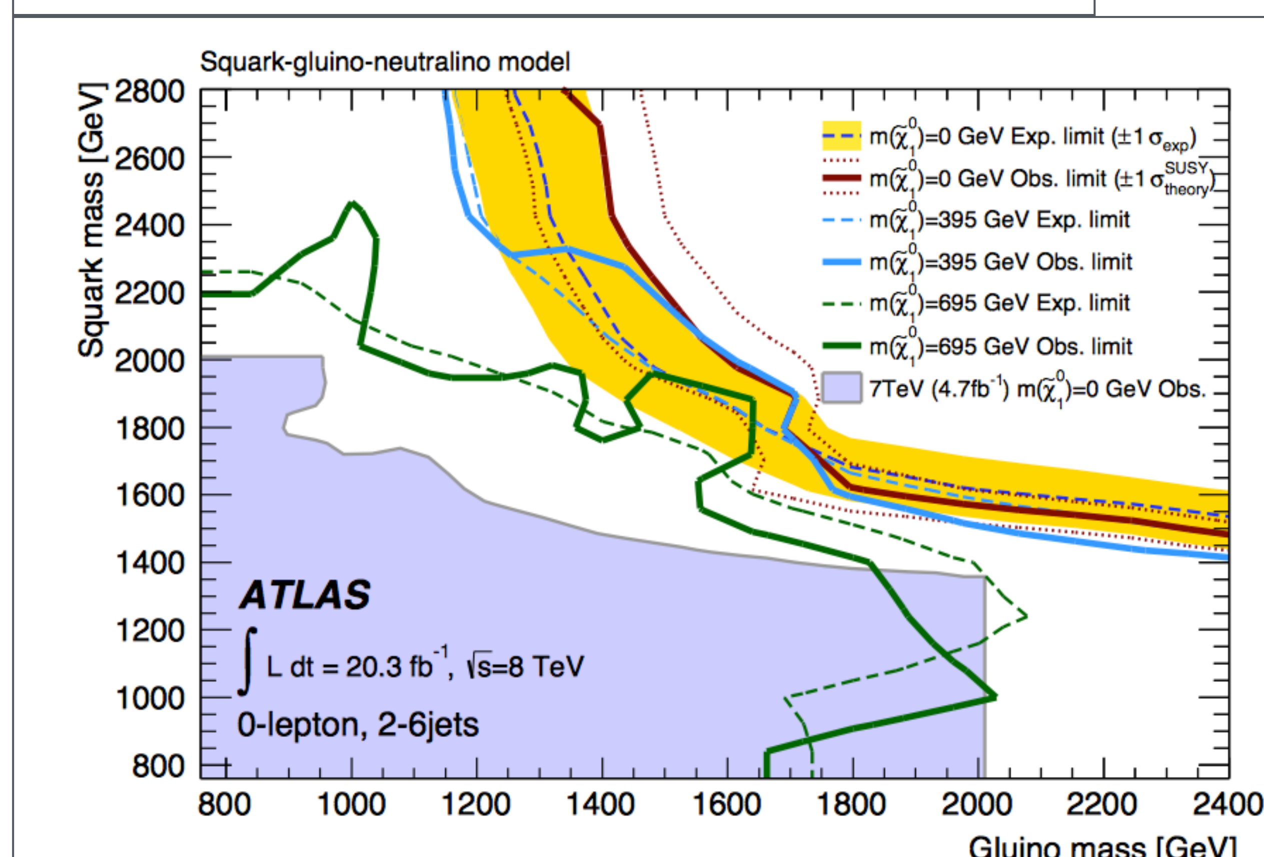
squarks and gluinos

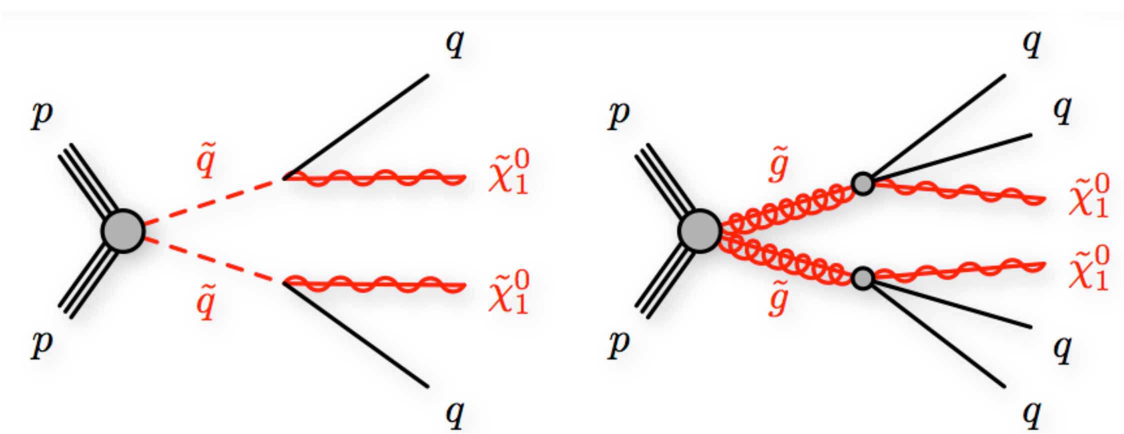
eg inclusive searches:

- 0 leptons + 2-6 jets + MET
- simplified models MSSM scenario
- strong production of gluinos + 1st- and 2nd-generation squarks
- direct decays to quarks and lightest neutralinos.



arXiv:1405.7875

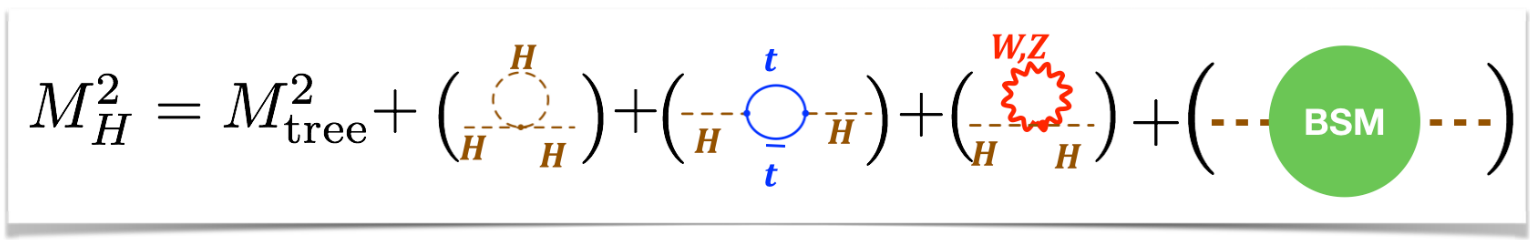


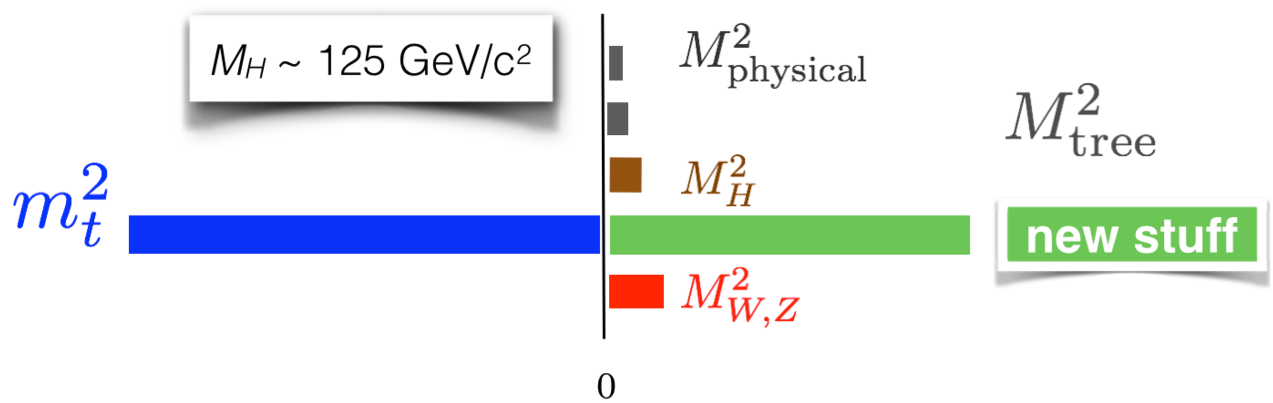


stop

“Natural” scenarios?

Tev-ish new particle solution?



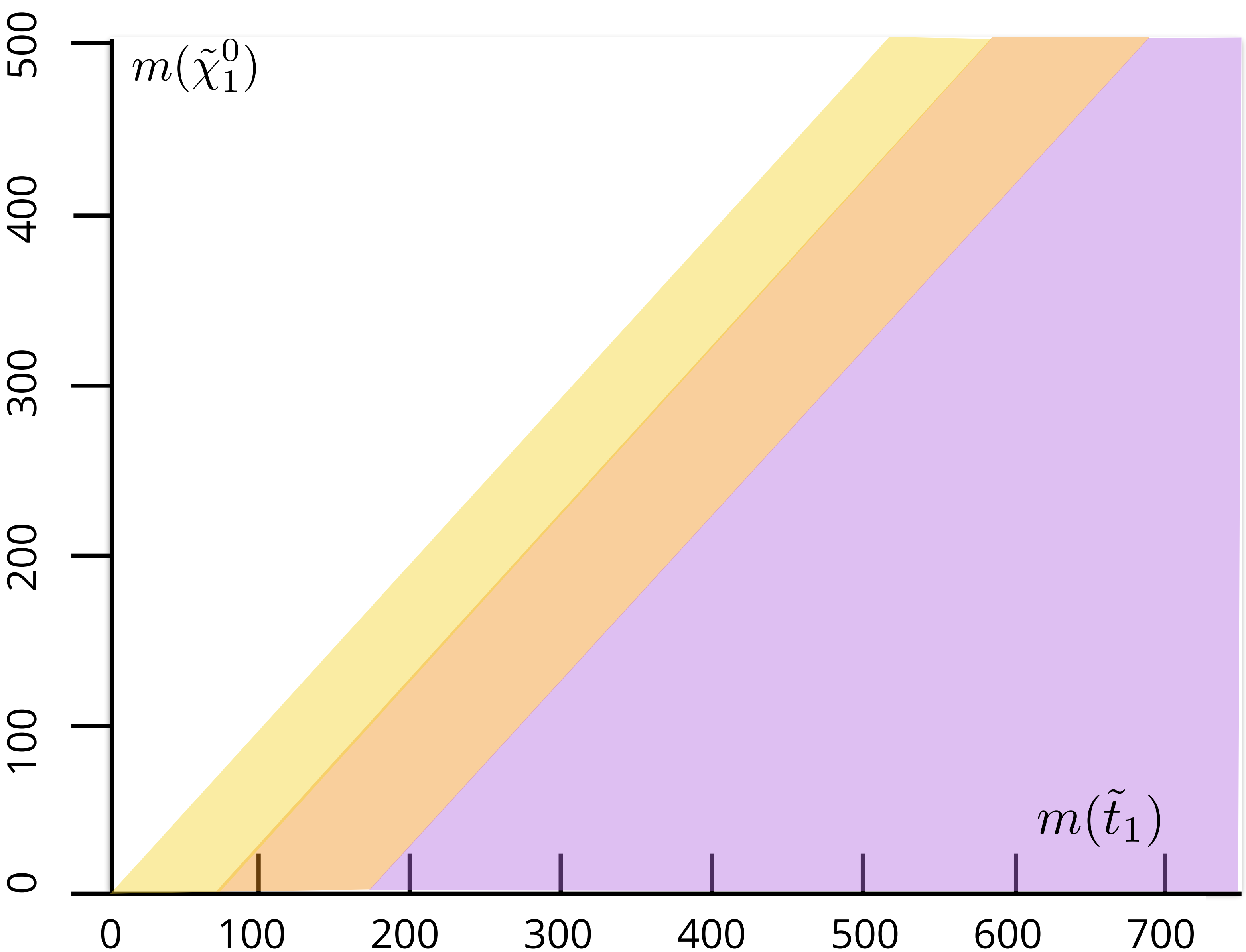


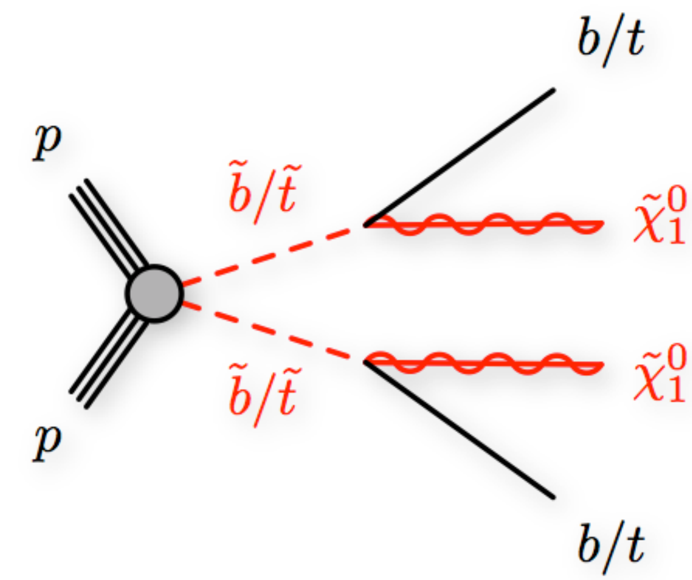
stop

naturally motivated

e.g. direct stop/sbottom production

look like conventional tT





Signature-based analyses:

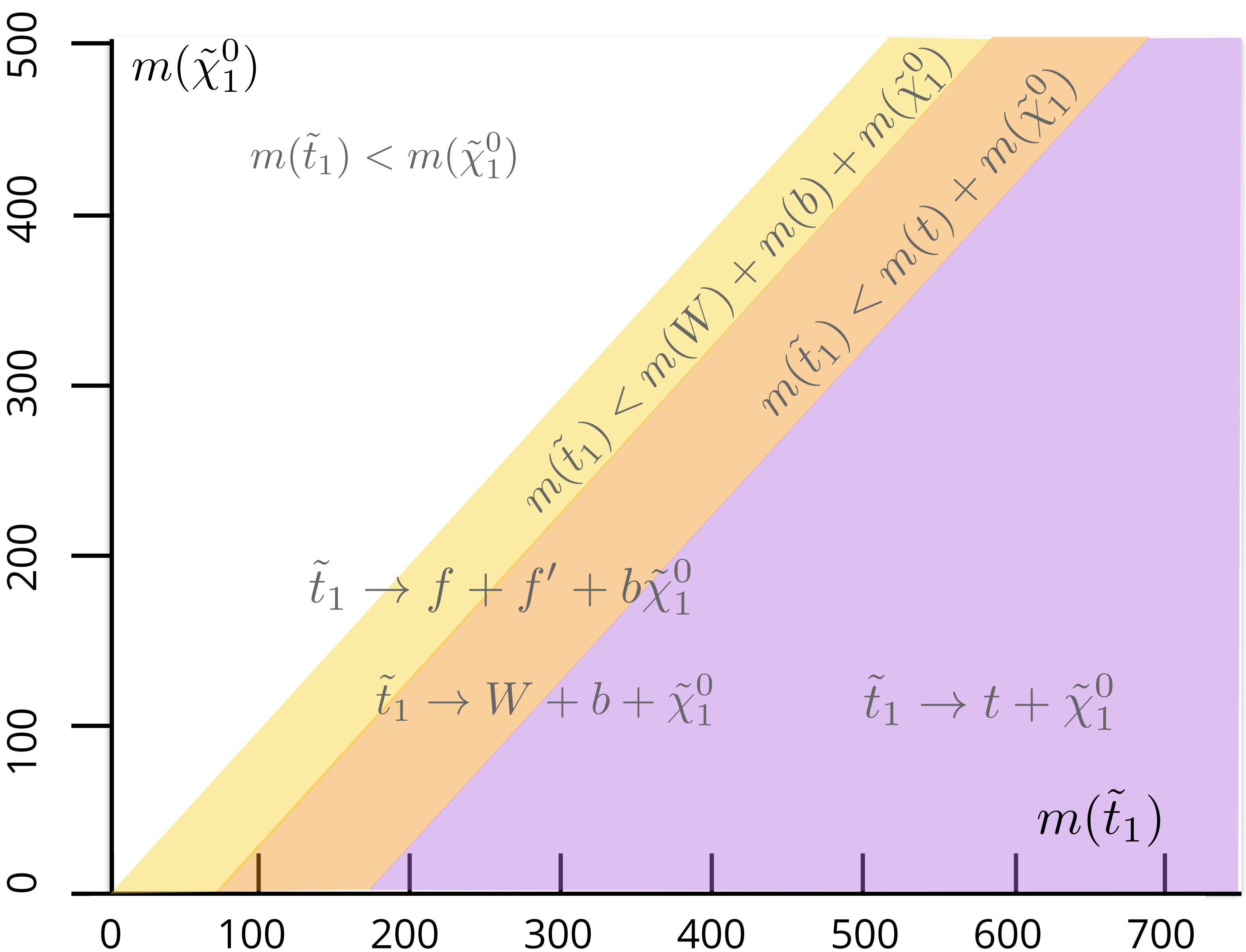
- 0L + 2 bjets + MET
- 0L + 6 (2b) jets + MET
- 1L + 4 (1b) jets + MET
- 2L + jets + MET

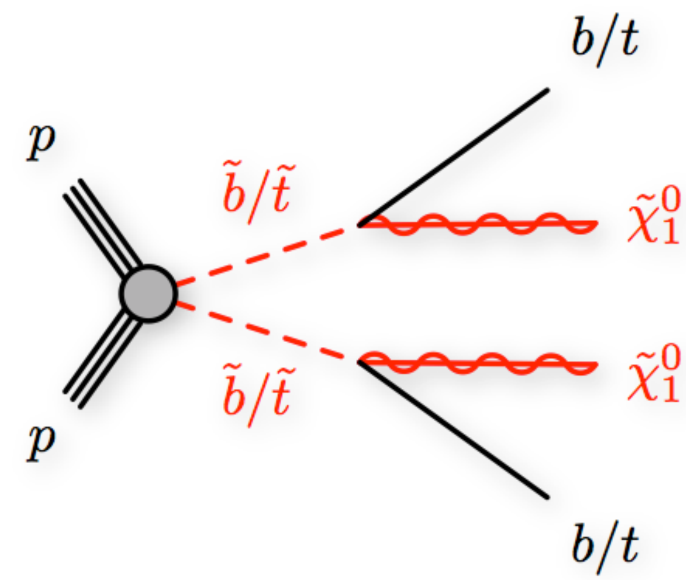
stop

naturally motivated

e.g. direct stop/sbottom production

look like conventional tT





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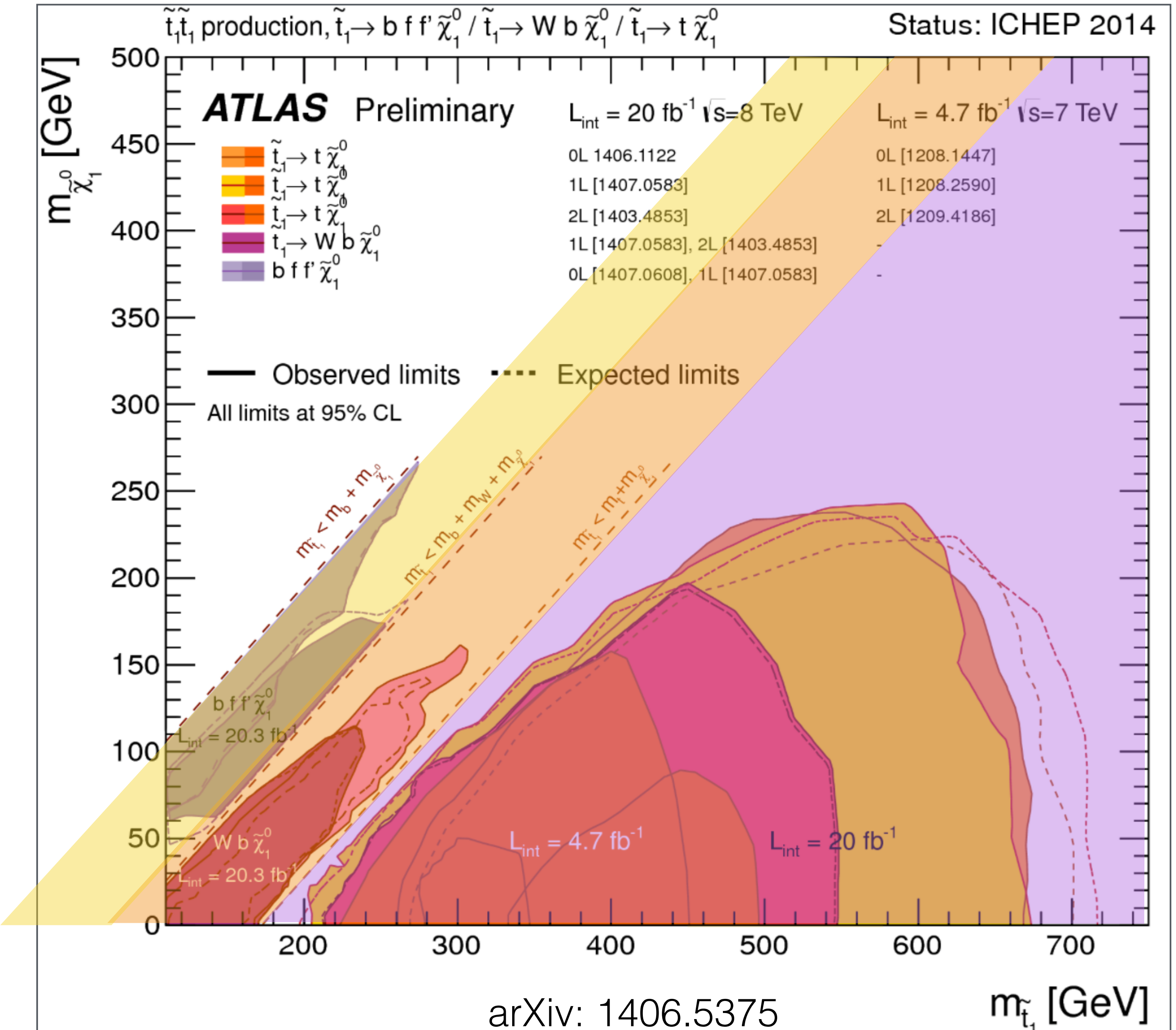

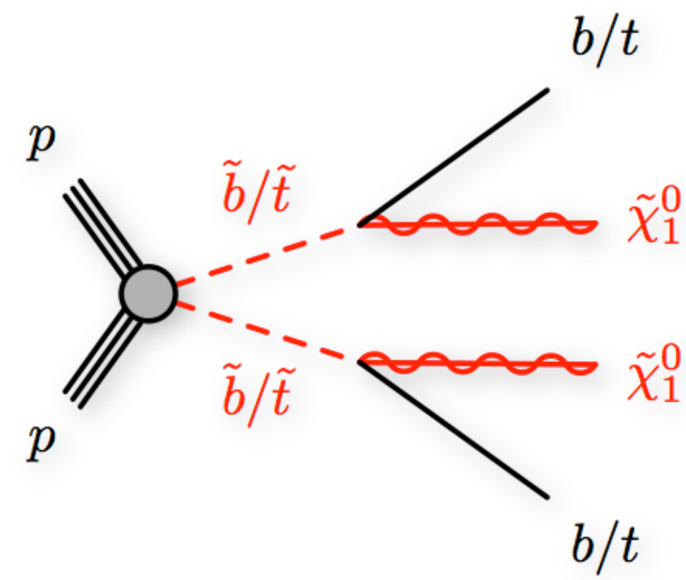

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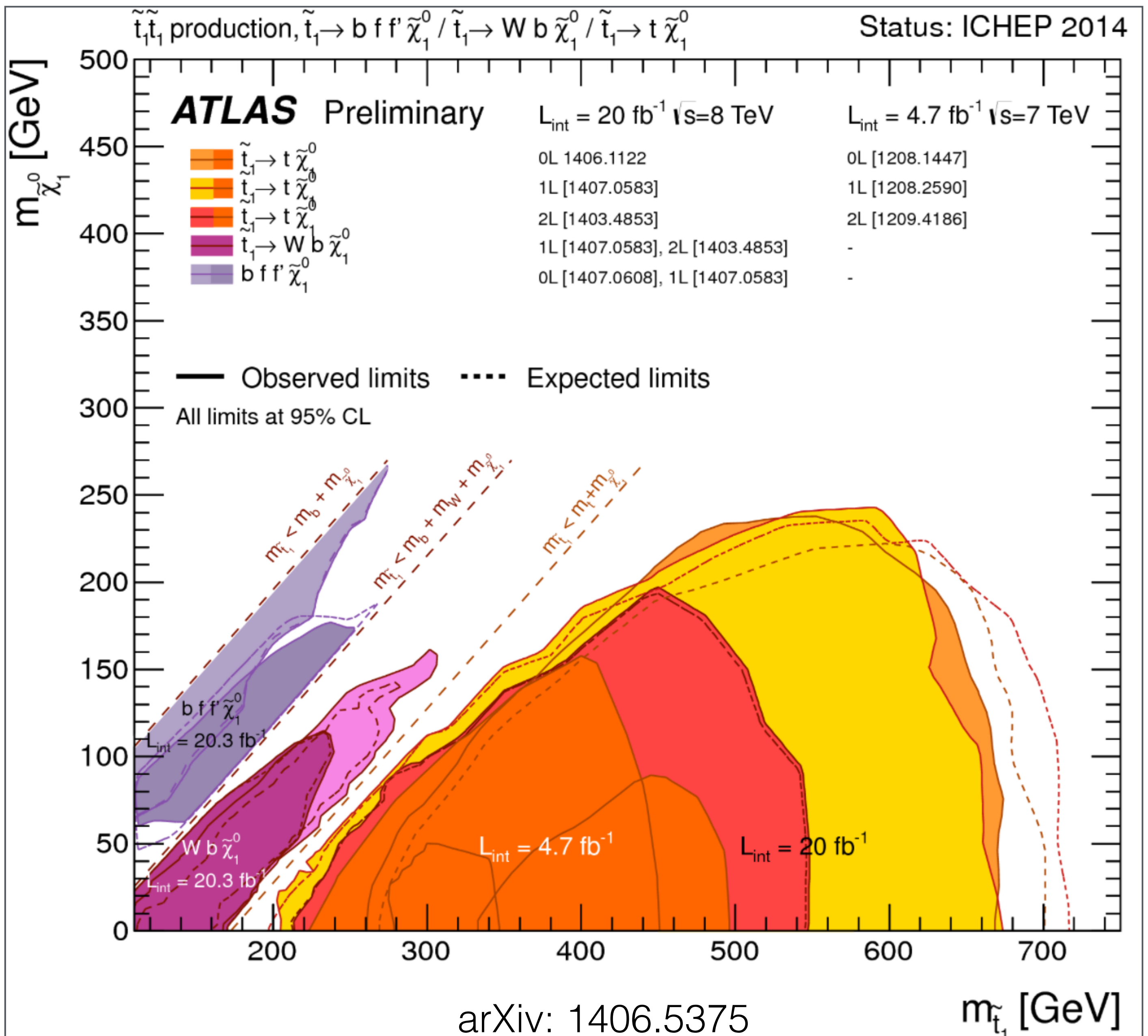
arxiv:1208.2590 (1 lepton 7 TeV)
arxiv:1209.4186 (2 leptons 7 TeV)
arxiv:1407.0583 (1 lepton 8 TeV, 20/fb)
arxiv:1406.1122 (0 lepton + 5/6 jets 8 TeV, 20/fb)
arxiv:1403.4853 (2 lepton + jets+ MET 8 TeV, 20/fb)
[7] arxiv:1407.0608 (0 lepton + jets (c-jets) + MET 8 TeV, 20/fb)

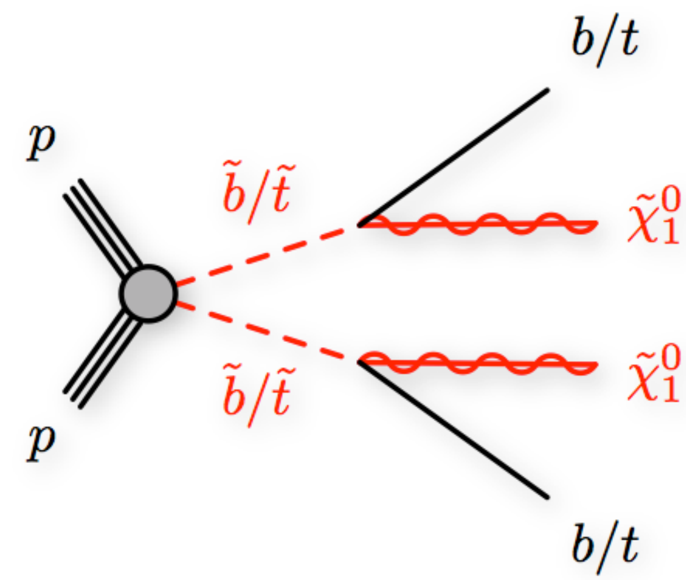
stop

naturally motivated

e.g. direct stop/sbottom production

look like conventional tT





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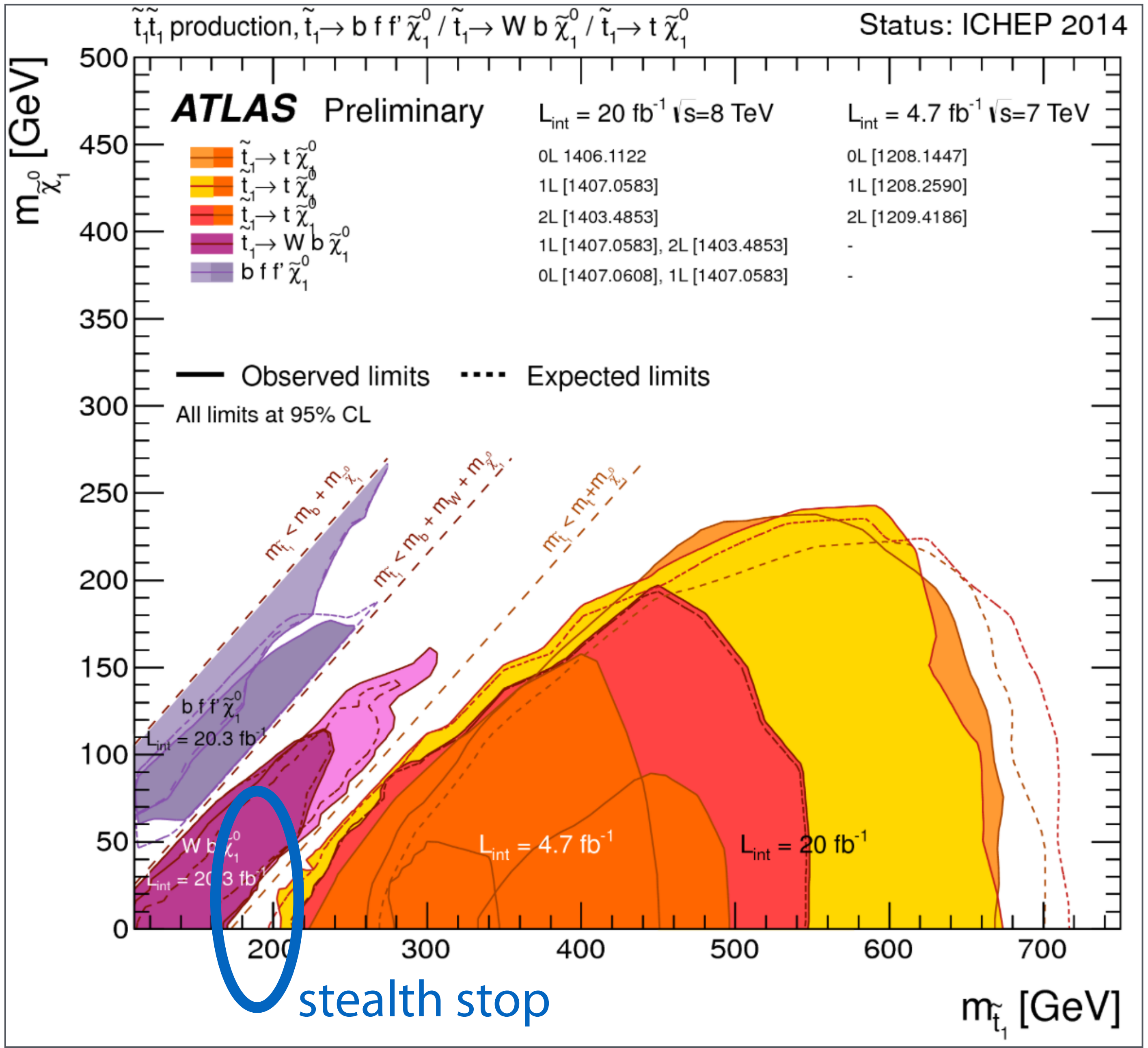
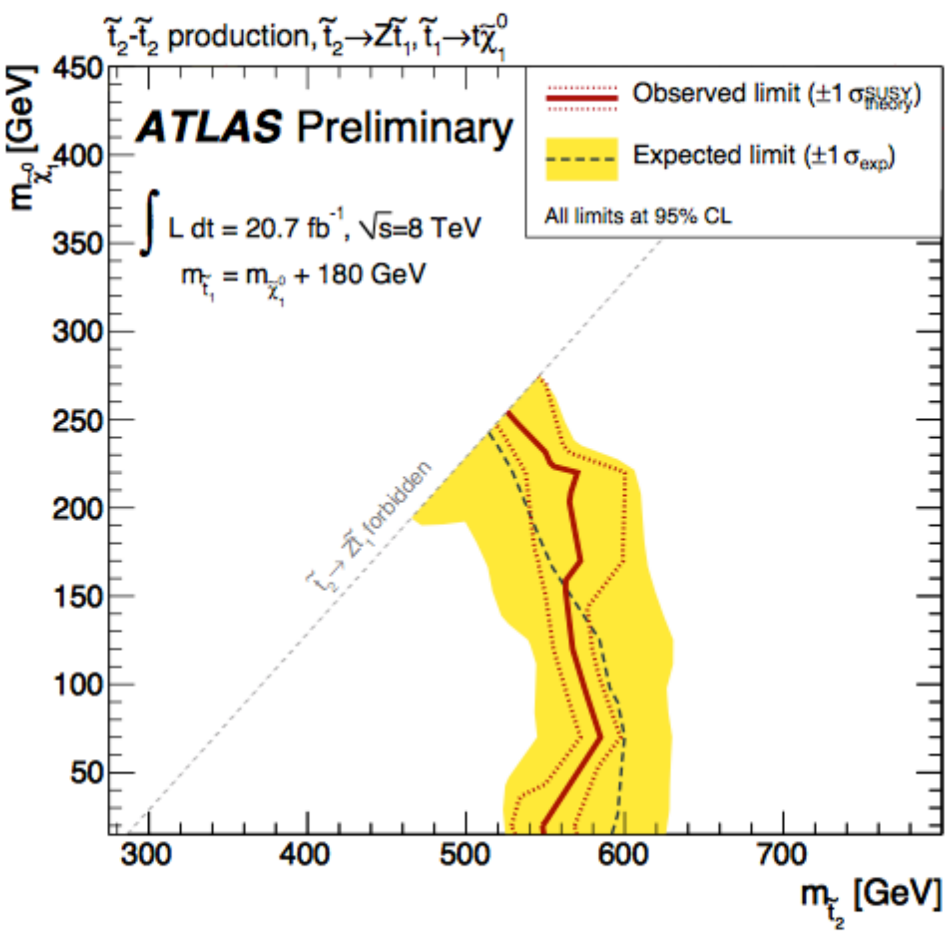
stealthy stop

kinematical no-man's land

second generation



$$\tilde{t}_2 \to Z + \tilde{t}_1 \to Z + t + \tilde{\chi}_1^0$$

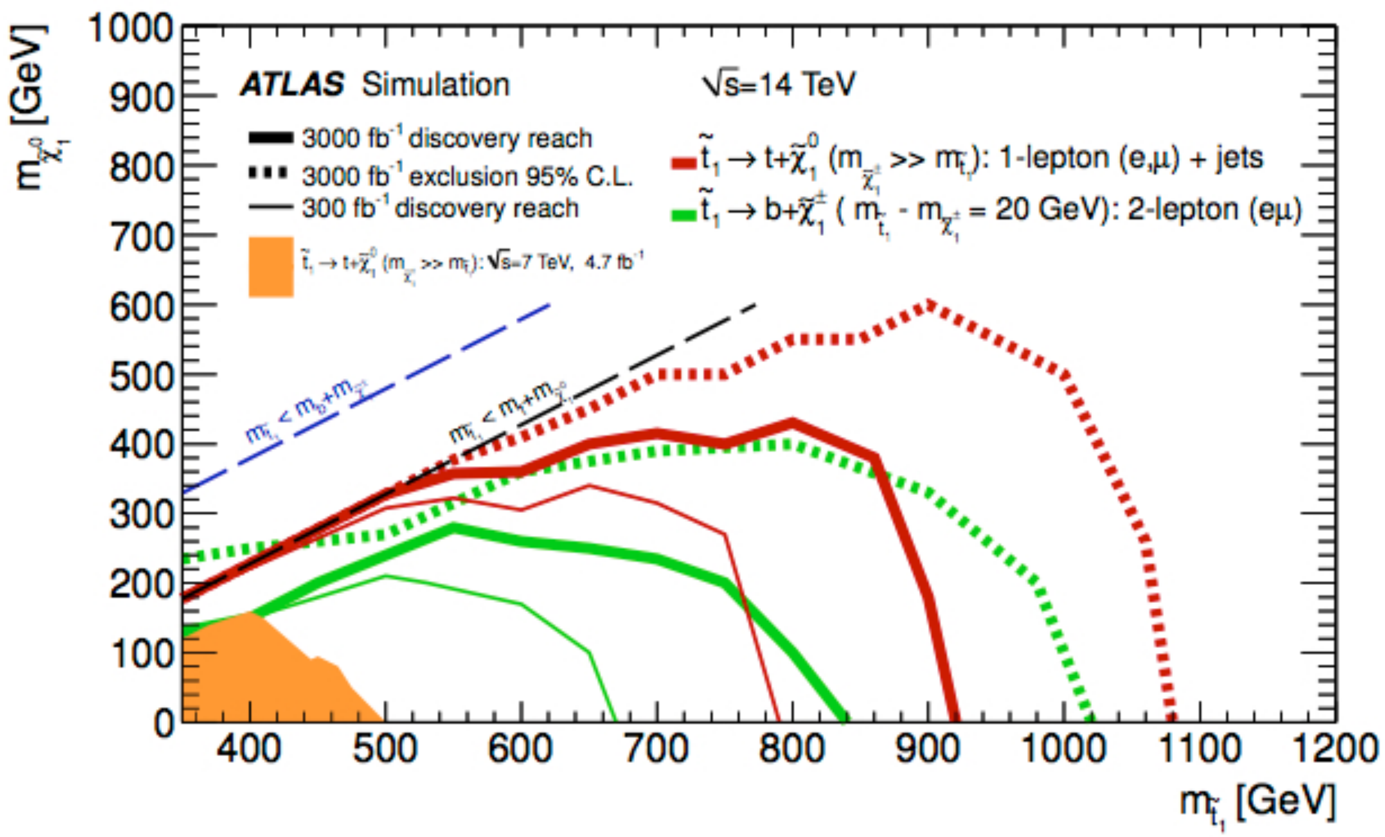


ATLAS-CONF-2013-025

Run 2

Center of mass energy directly extends searches

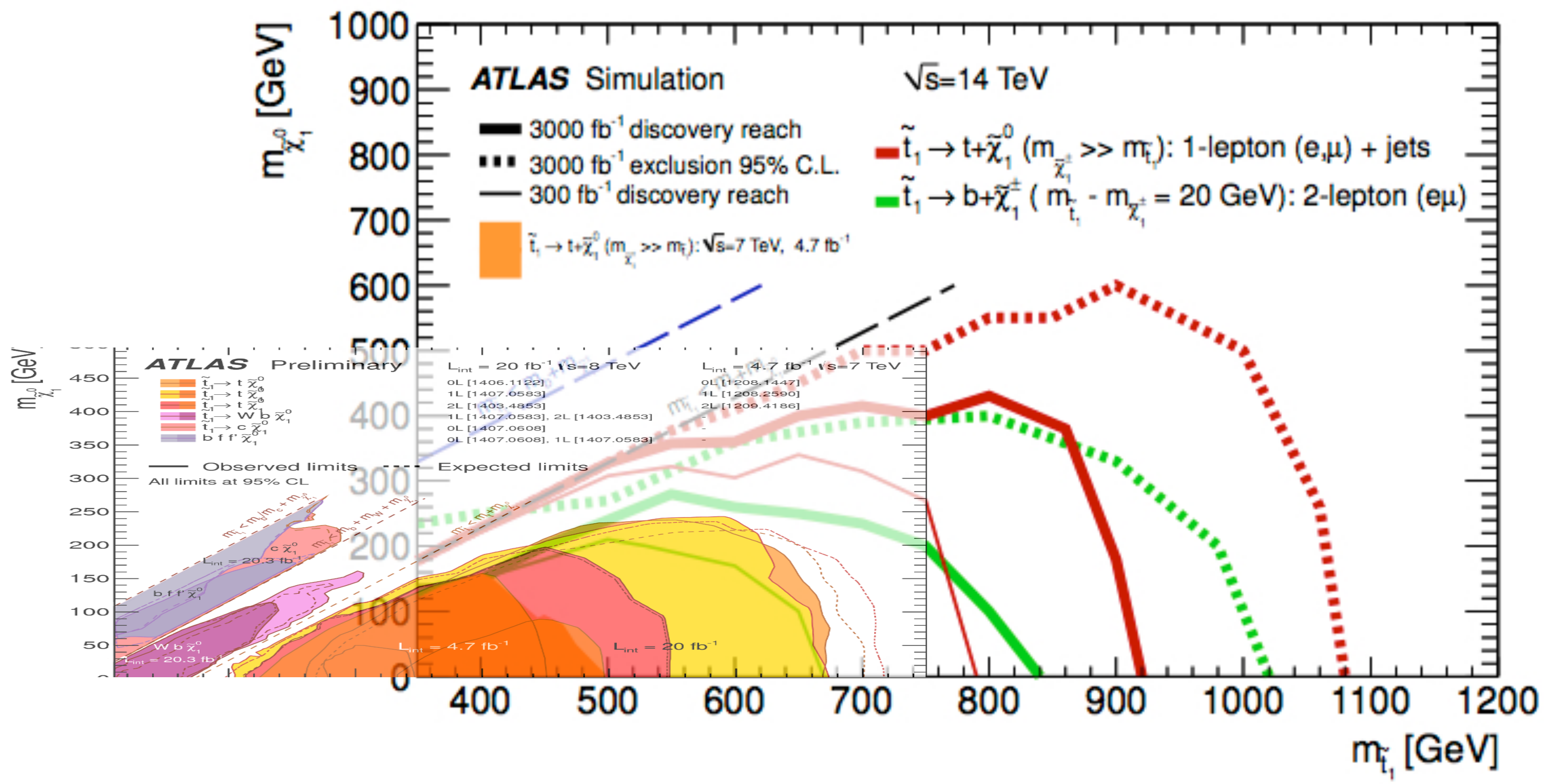
that rule of thumb…



ATL-PHYS-PUB-2012-001

Run 2

Center of mass energy directly extends searches



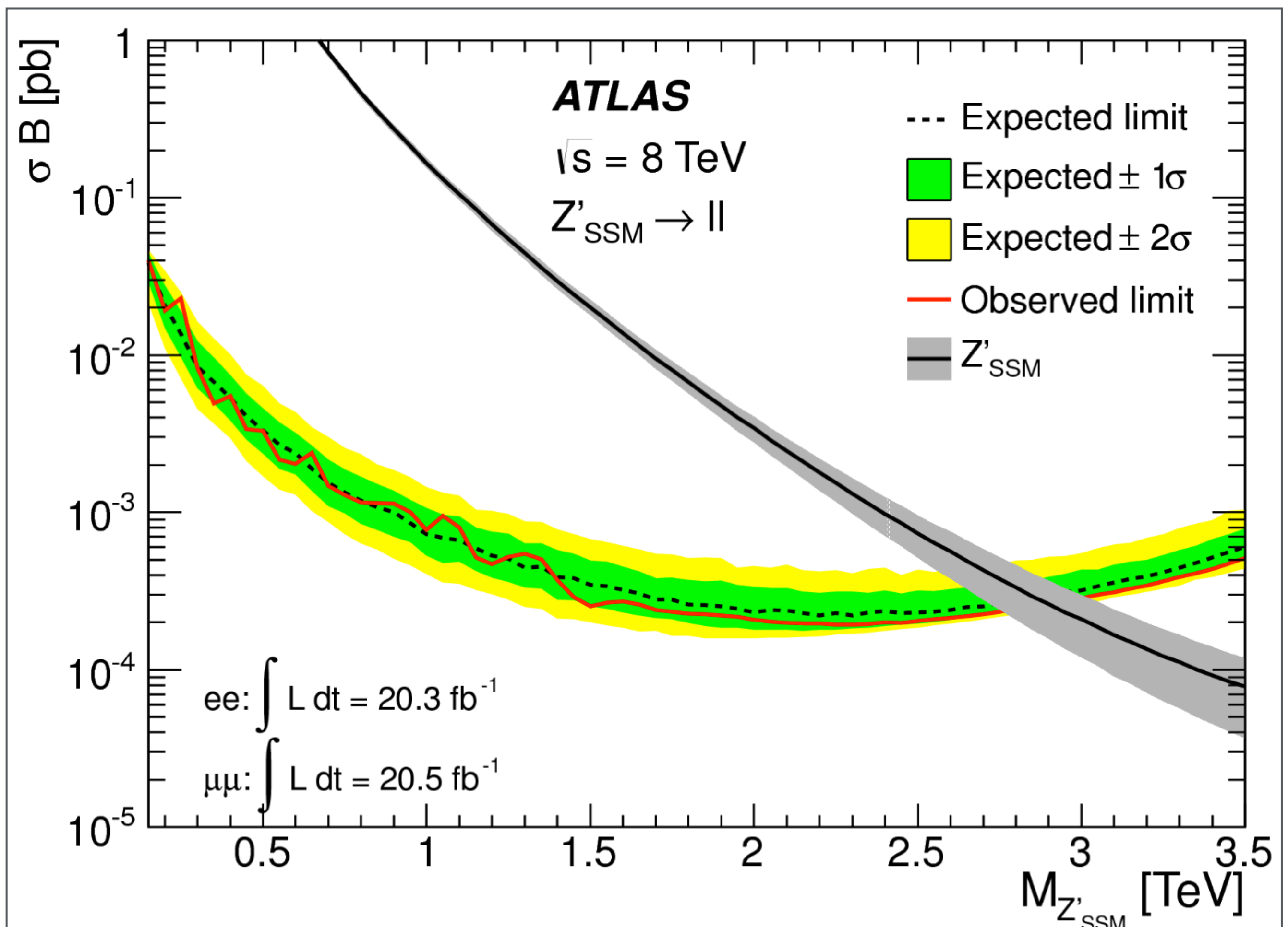
ATL-PHYS-PUB-2012-001

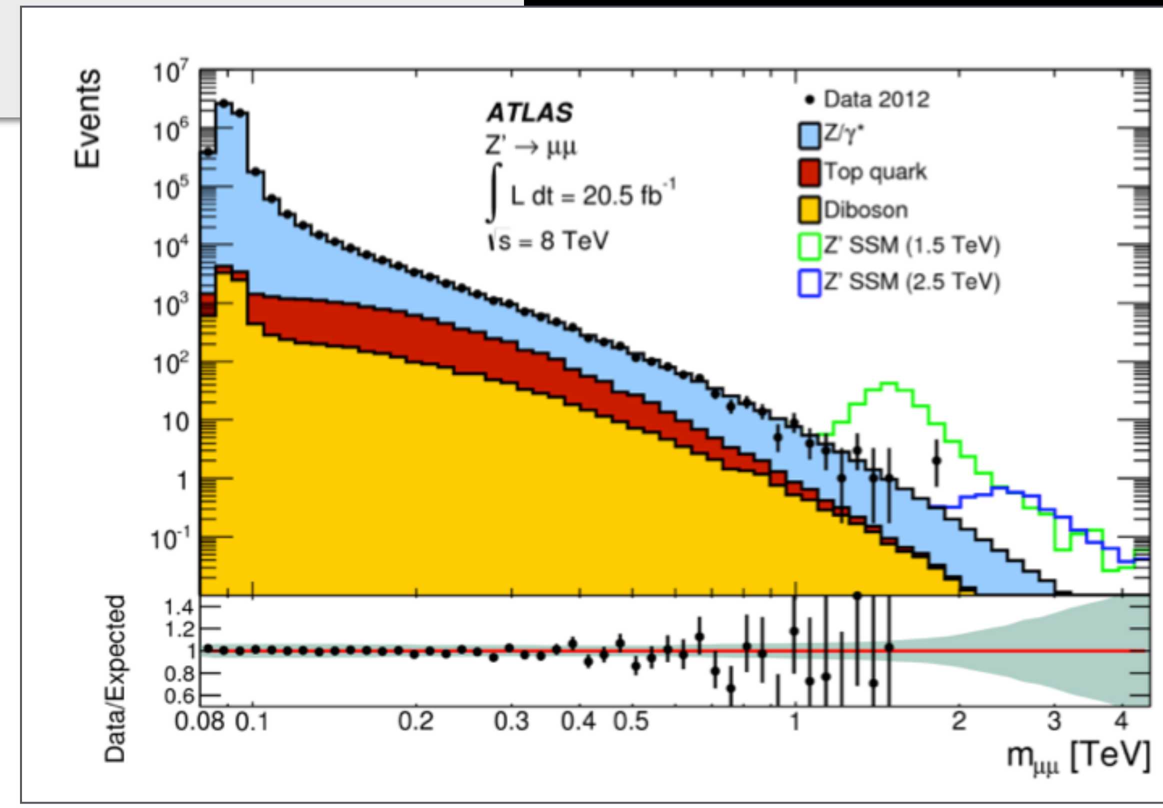
Z prime

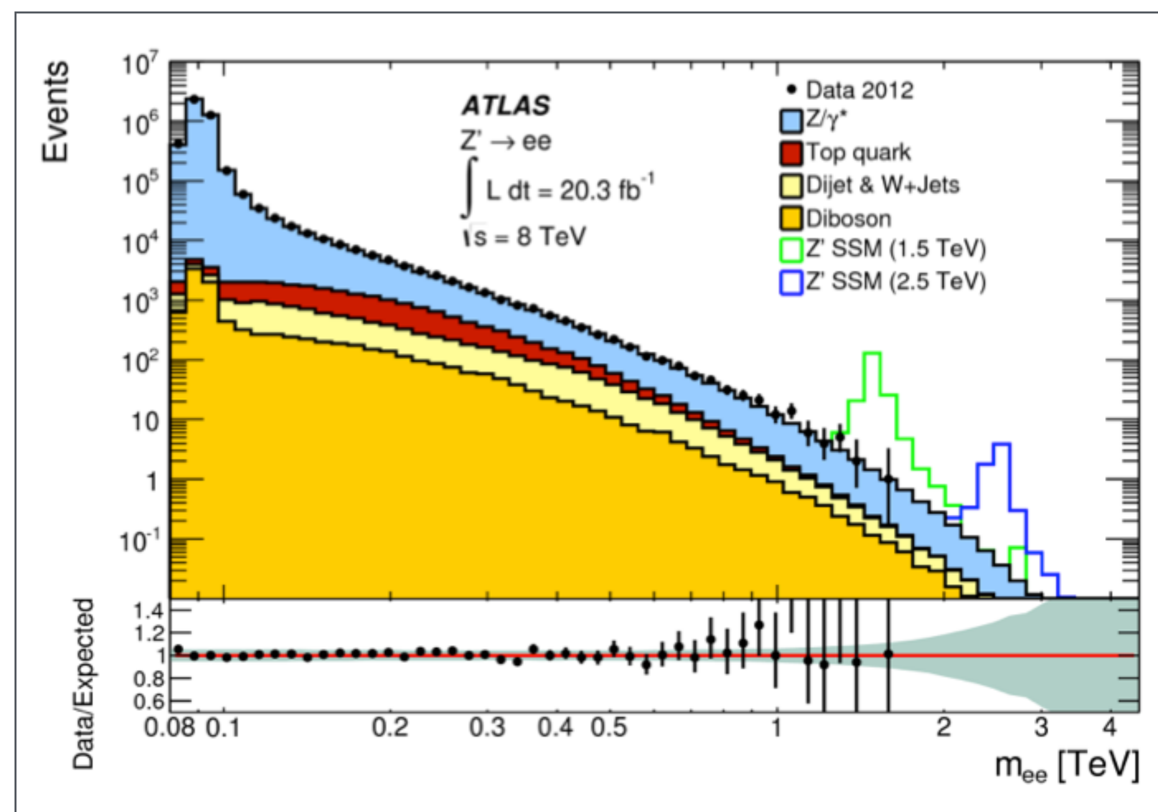
electrons and muons

a standard way to extend the SM

Snowmass suggests ~4TeV reachable







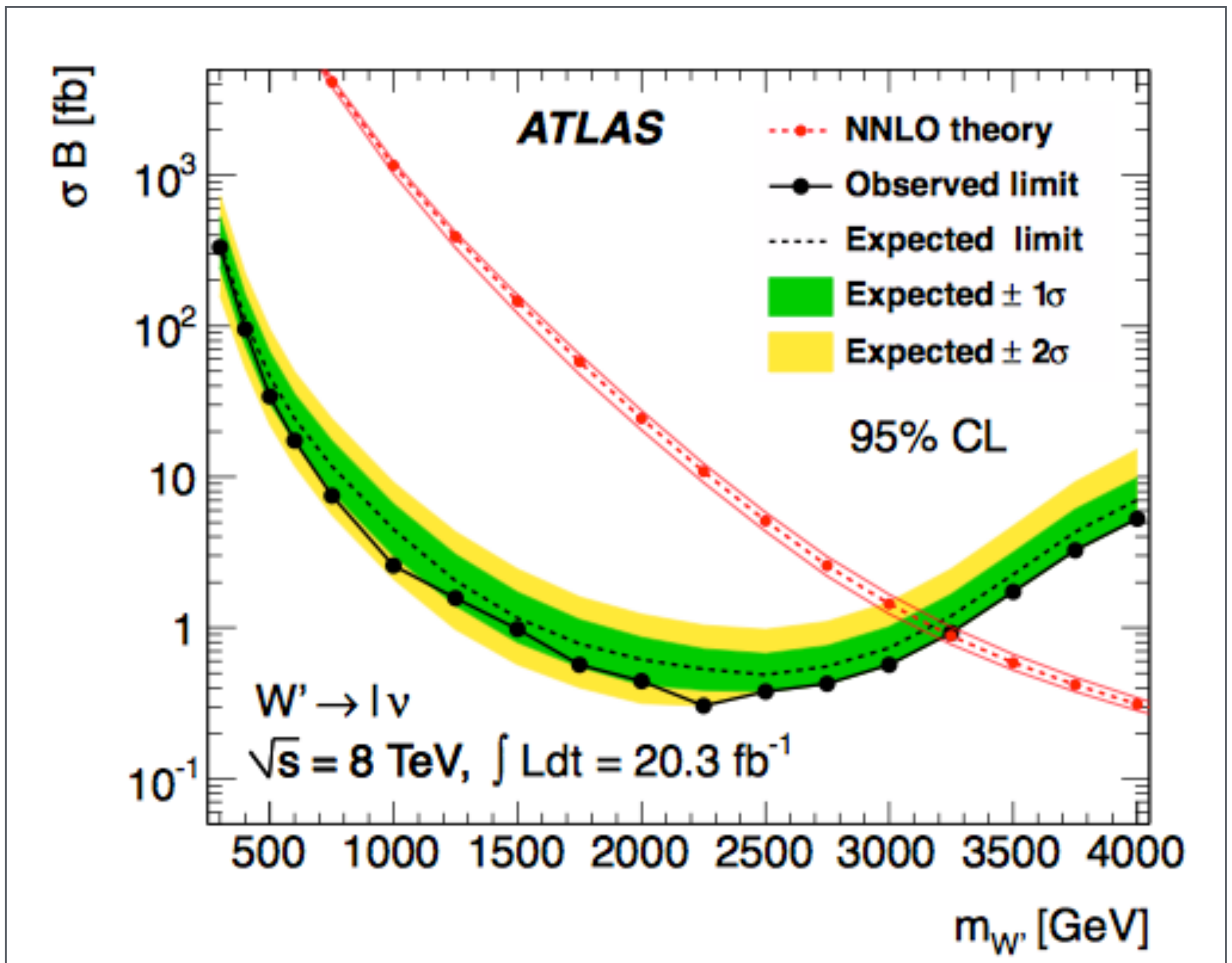
Phys. Rev. D 90, 052005 – Published 19 September 2014
G. Aad et al. (ATLAS Collaboration)

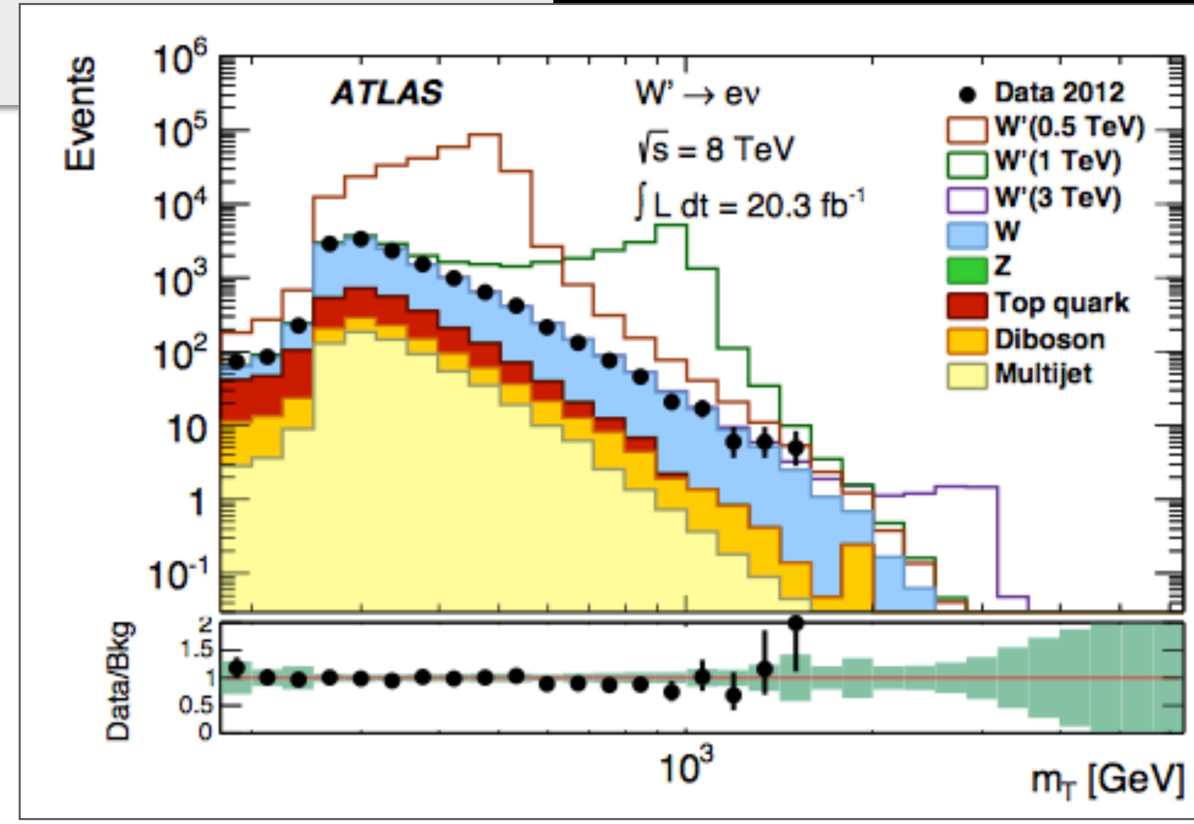
W prime

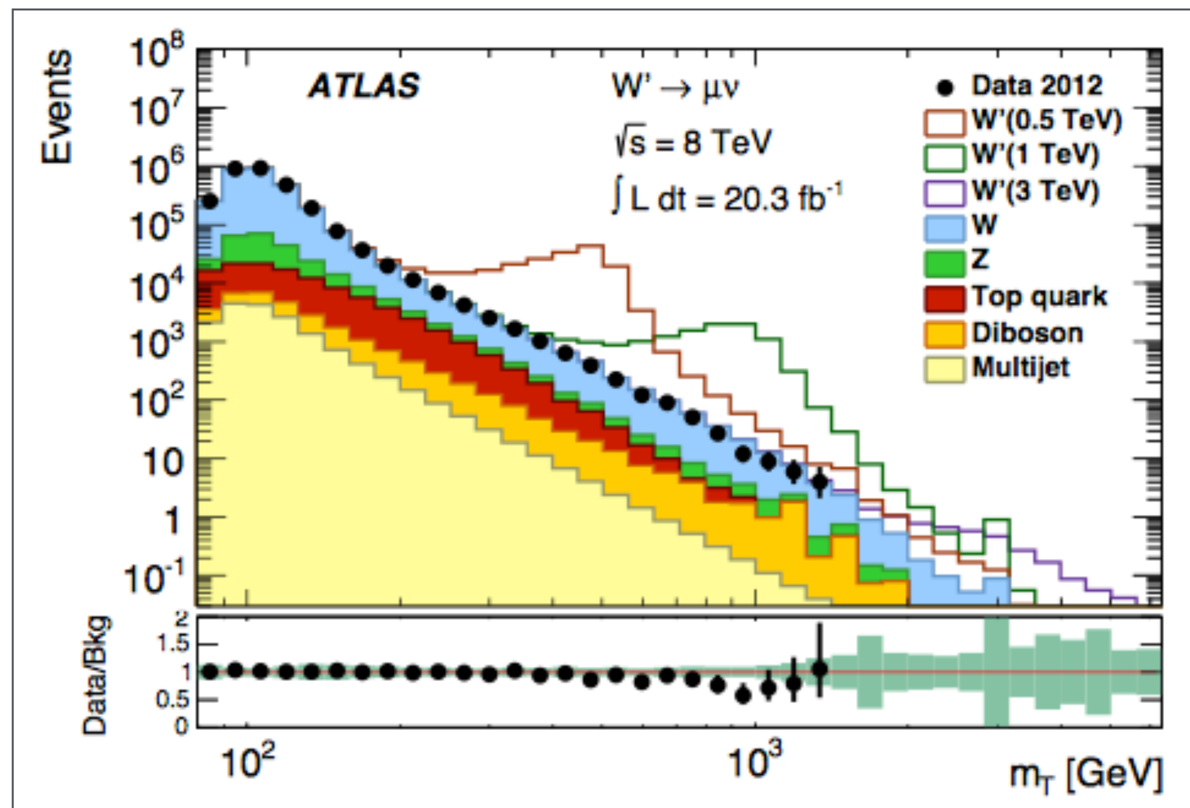
electrons and muons

a partner

arXiv:1407.7494v1

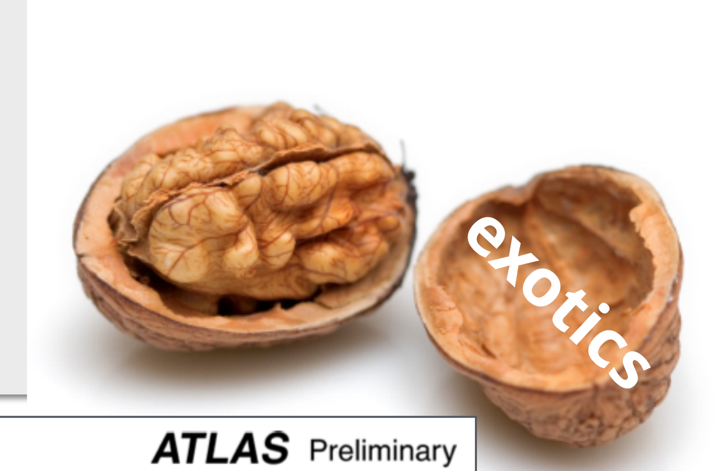


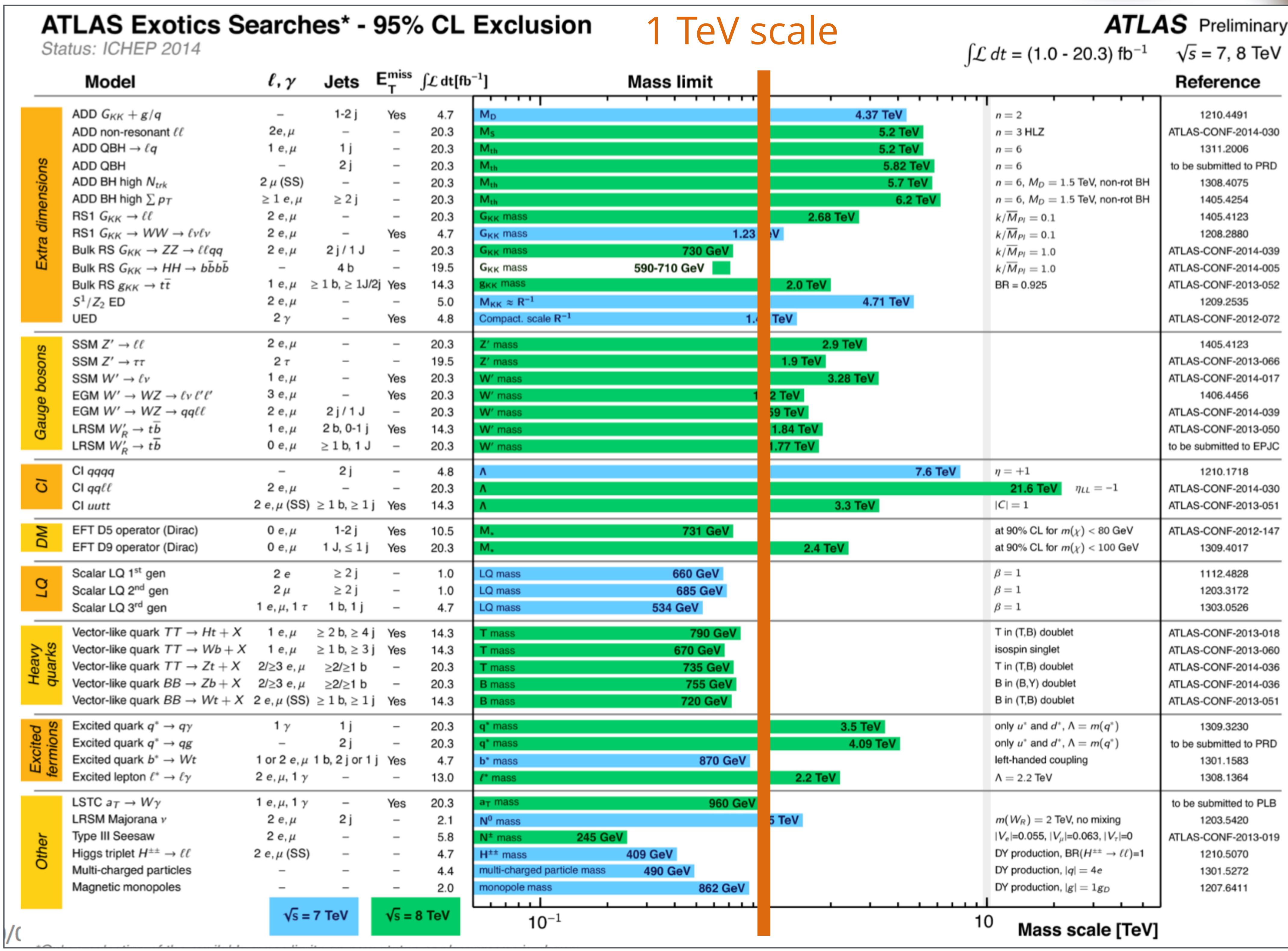




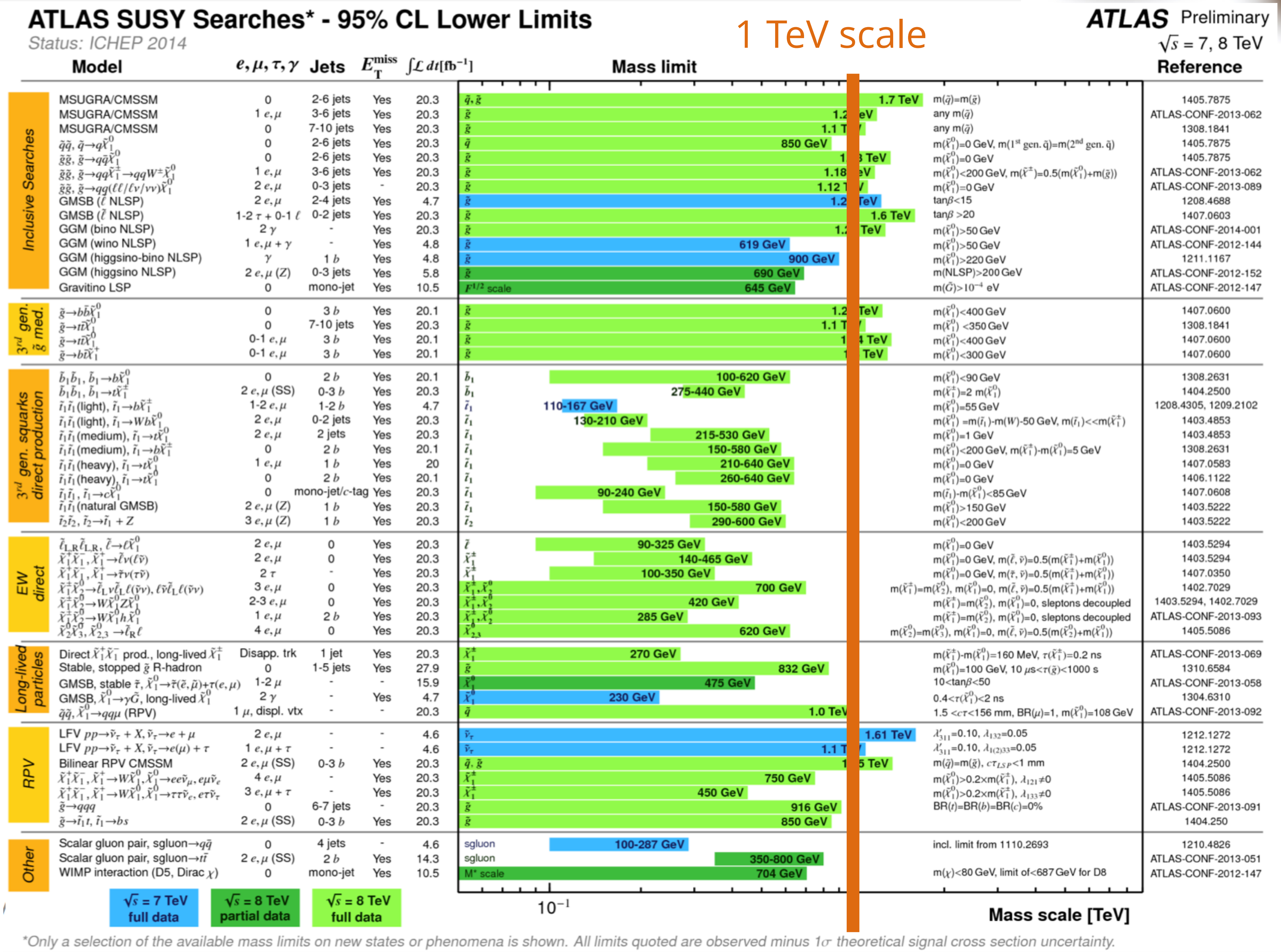
Exotics in a nutshell

a big nutshell





SUSY in a nutshell



But Wait... THERE'S MORE!

SUSY

- stop searches (Max Wanotayaroj, Friday)
- spin correlations
- Electroweak-ino production, many channels and assumptions
- GSMB models, delayed and non-pointing photons
- out of time events and disappearing tracks
- R-parity violating final states

Additional searches

- W' searches to hadronic final states (Ho Ling Li, Friday)
- dijet, ZZ, ZW, W\gamma, Z\gamma resonances
- Vector like quarks (Brad Schoenrock, Friday)
- Dark Matter inspired: Mono jets, tT, b, t
- LFV and long-lived neutral particles (Andrew Hard, Friday)
- prompt and non-prompt lepton jets (Hari Namasivayam, today)

Flavor Physics

Notable results

from Run 1 we anticipated:

measure: $bb \rightarrow J/\psi$, $pp \rightarrow J/\psi$, and $B^+ \rightarrow J/\psi + K^+$ cross section ratios

begin to contribute to world averages on B-hadron properties; start to set limits on rare decays

from Run 1 we achieved:

many production studies, χ, ψ studies, new physics searches, new b states

in Run 2, we expect:

increased statistics, improved performance/triggers, robust against $\mathscr{L}$

First excited B^*_c

open beauty discovery, *cb*

S. Godfrey PHYSICAL REVIEW D **70** 054017

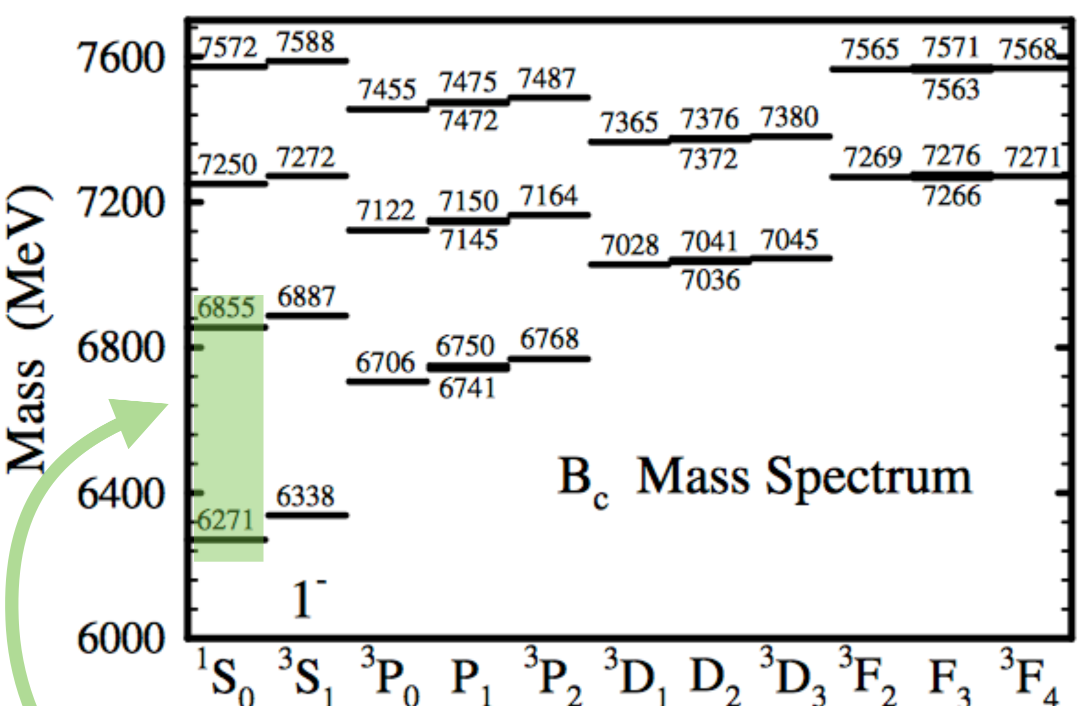
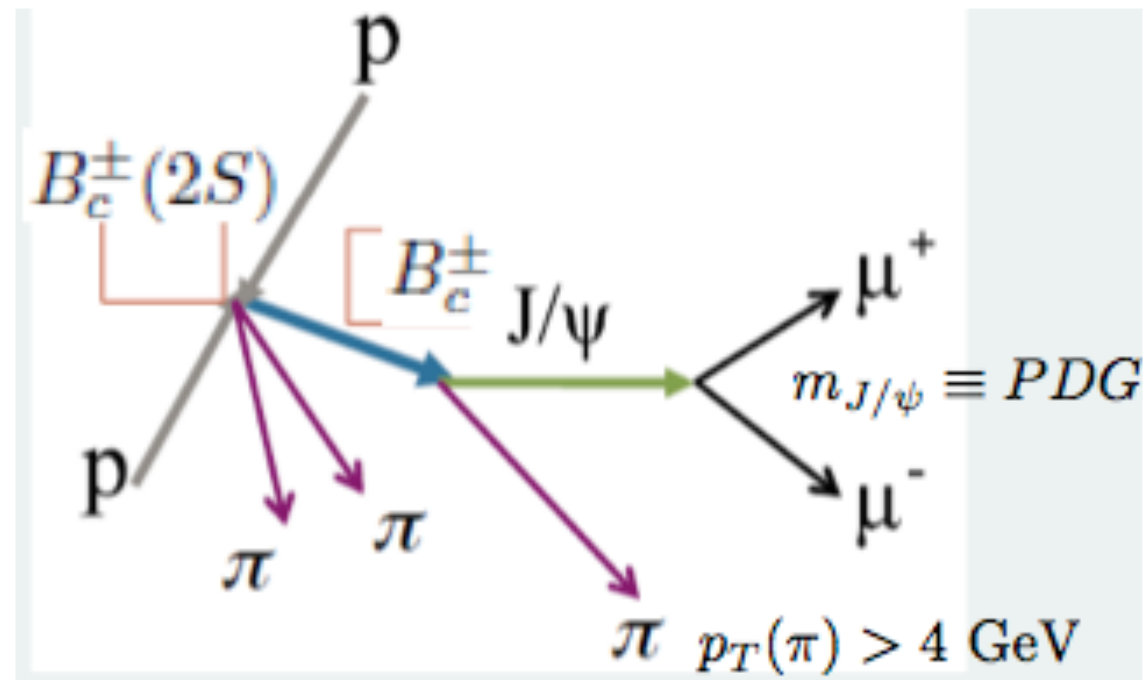


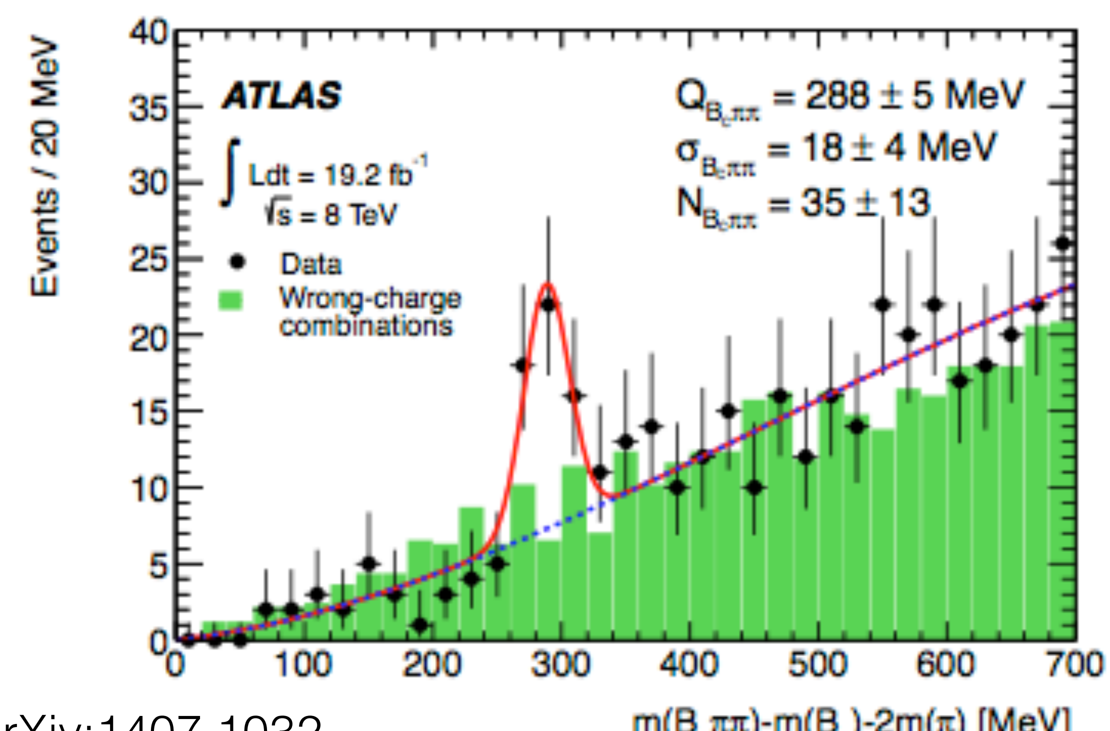
FIG. 1. The B_c mass spectrum.



$2^1S_0 \rightarrow 1^1S_0 + 2\pi$ E1 - E1 transition

Q values consistent with the production and decay of a new state, B*$_C$ with a mass of 6842 ± 4 ± 5 MeV

Significance is 5.2 σ with "look-back"



arXiv:1407.1032

But Wait...

THERE'S MORE!

Production and Decays, incl

$\psi(2s)$ in many distributions, prompt and non-prompt

W+ incl double parton scattering contribution

χ_c production, prompt?

$\Upsilon(1s,2s,3s)$ production

open charm/beauty, in jets, inclusive

Spectroscopy, incl

$\chi_b(3P)$ discovery, Λ_b mass, lifetime, PV in $\Lambda_b \rightarrow J/\psi\ \Lambda^0$, Rare Decays

Searches, incl

FCNC search for $B_{d/s} \rightarrow \mu^+ \mu^-$

Long Shutdown 1 Projects

Tracking system

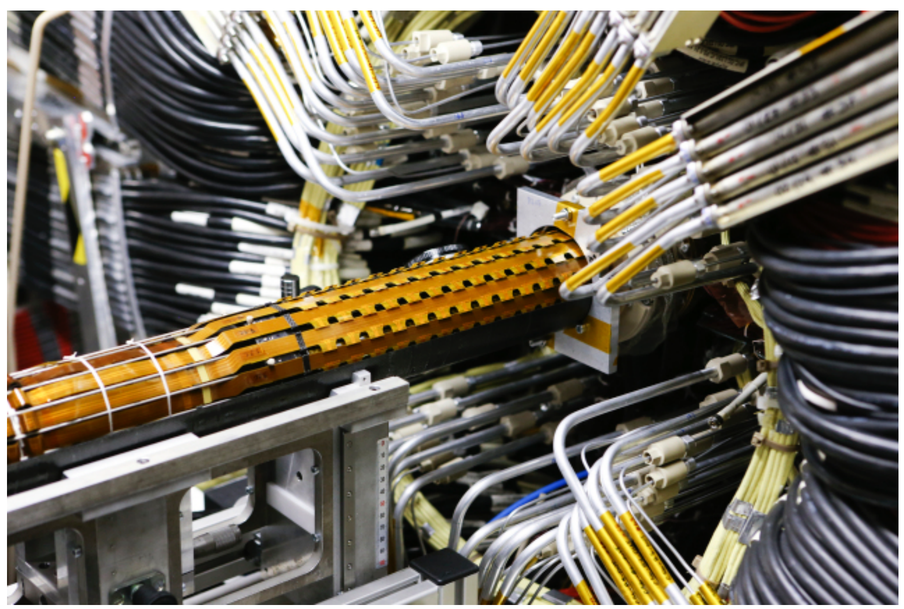
Insertable B Layer, aka IBL

5.1 to 3.3 cm to IP

pixels reduced: 50 x 250 μm

new sensors and readout chip

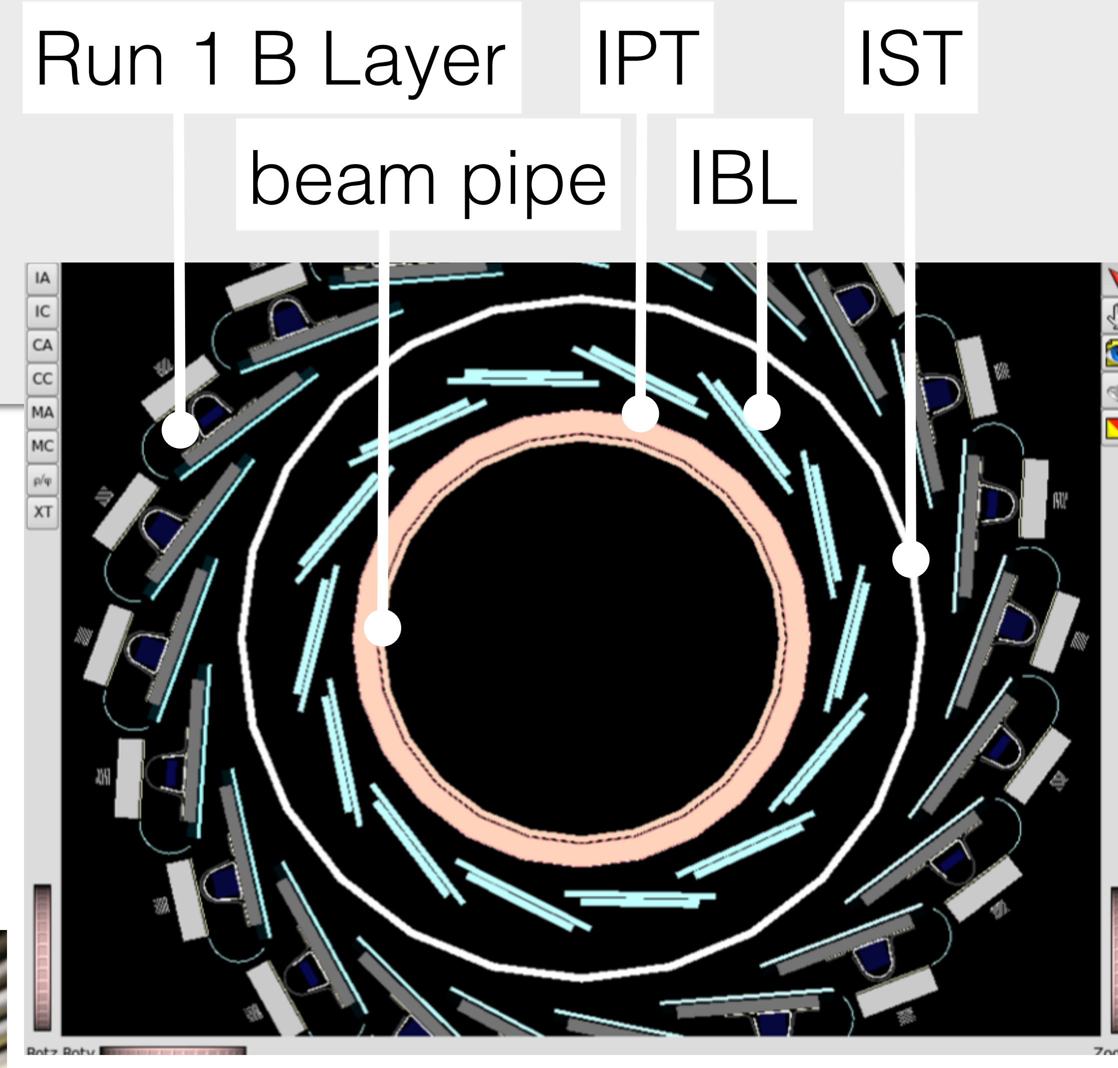
May 7:

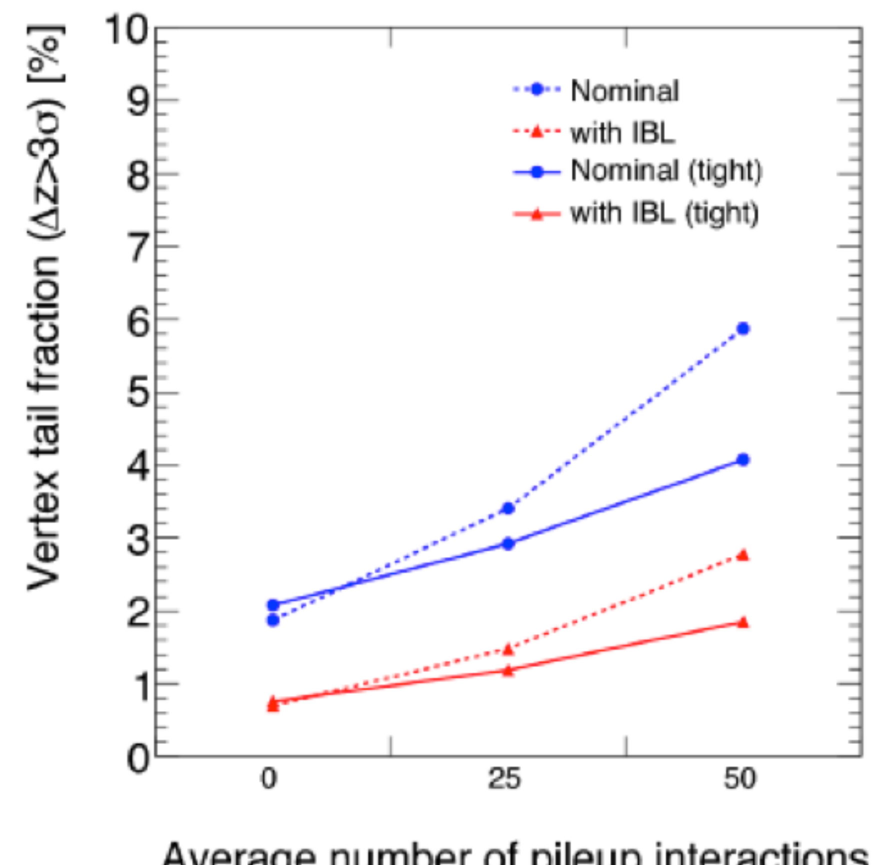


Gains:

- impact param
- light jet reject
- redundancy

Status: live >99.9%





Tracking and Calorimeter Systems

many projects

SCT and TRT readouts enhanced, operational

- new ROD in SCT
- 90 → 128 S links and compression leading to 100 kHz @ $\mu = 87$
- data compression, different gating in TRT leading to 104 kHz with 2% occupancy

Pixel Detector brought to surface, reinstalled

- Layer 0: 6.3% → 1.4%; Layer 2: 7% → 1.9%; now 98% functional of 1744
- new diamond/Si beam monitors installed
- prepared for IBL

LAr and Tilecal

- LVPS replaced (LAr) fixed (Tilecal): readouts tested to more than 100 kHz
- Phase 1 “demonstrator” installed
- Min-bias trigger scintillators

Muon system

staged from Run 1

New ROD for CSC system

limited ATLAS L1 trigger rate to 70 kHz…now 100 kHz

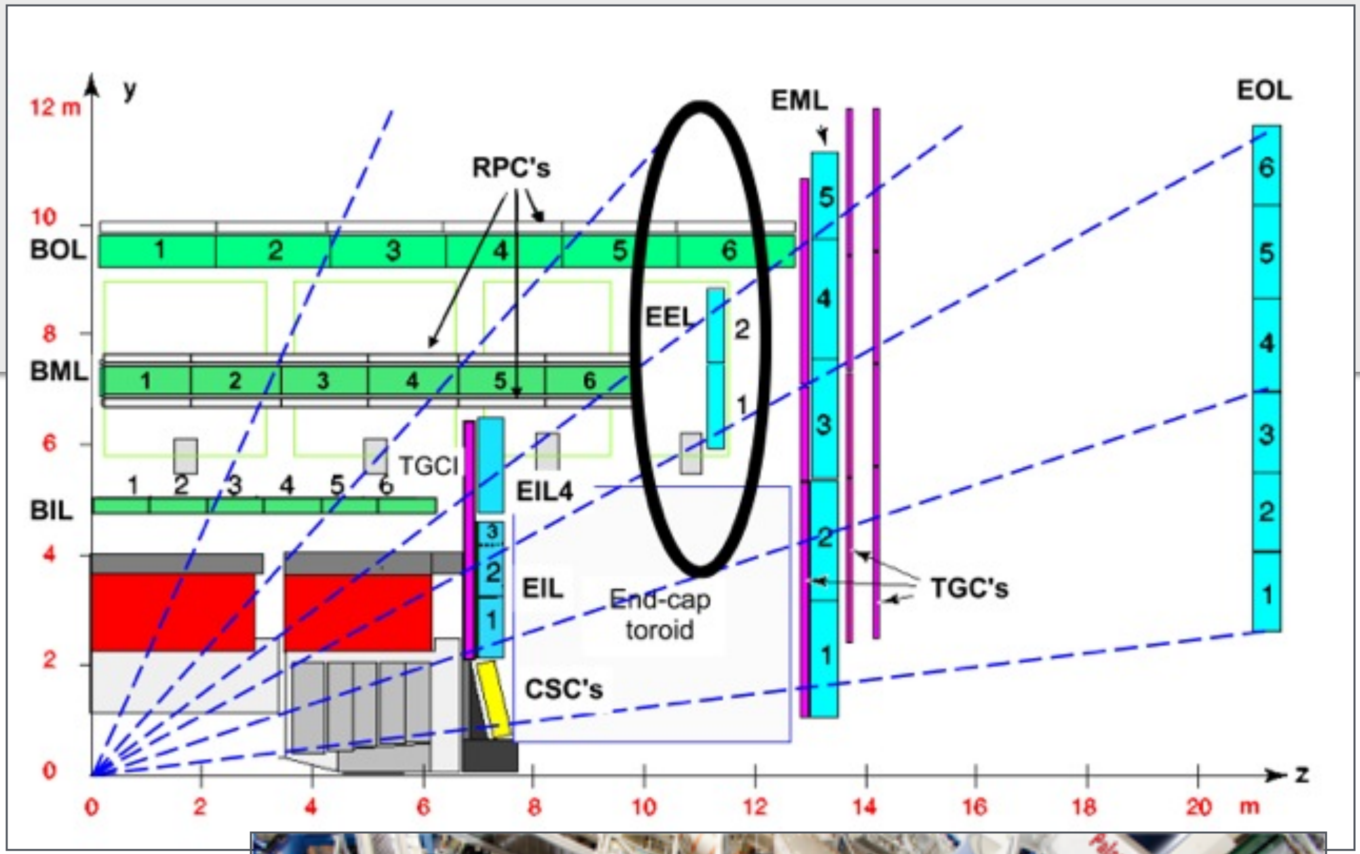
New EE endcap chambers

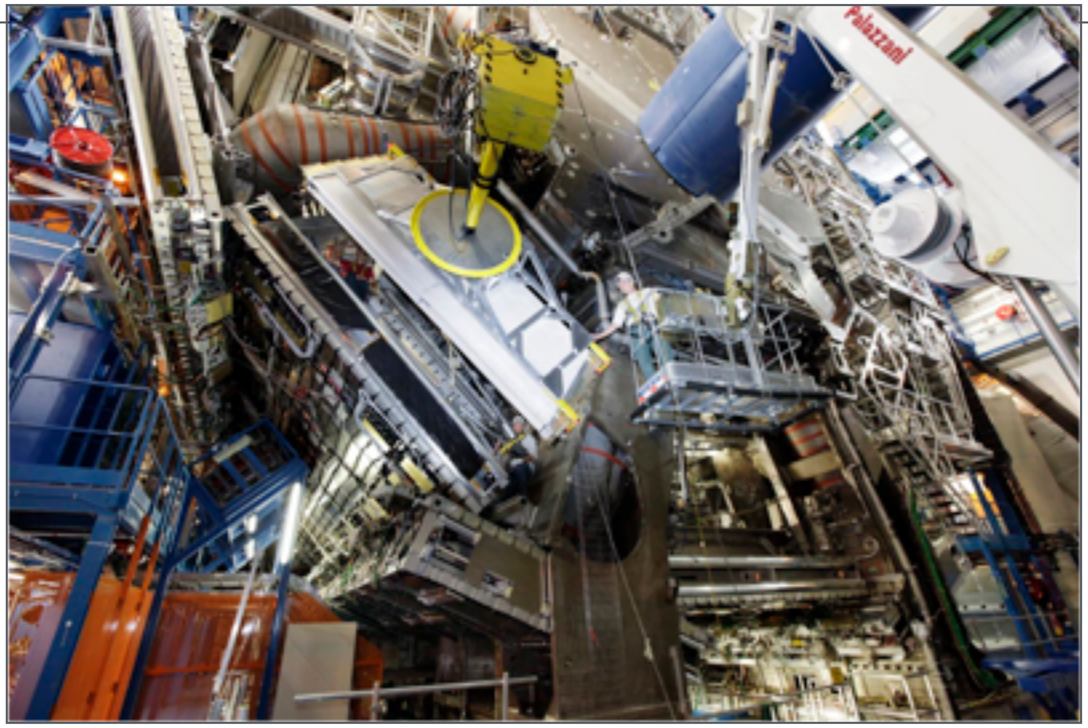
Repairs

Broken CSC chambers, repaired, reinstalled

RPC leak repairs

TGC chamber replacement requires detector to be closed





Trigger system

considerable enhancements

E_{CM} from 8 to 13 TeV (x2.5) +

$\mathscr{L}_{peak}$ 0.8 to 1.6 x $10^{34}/cm^2/s$

5x trigger rates from Run 1

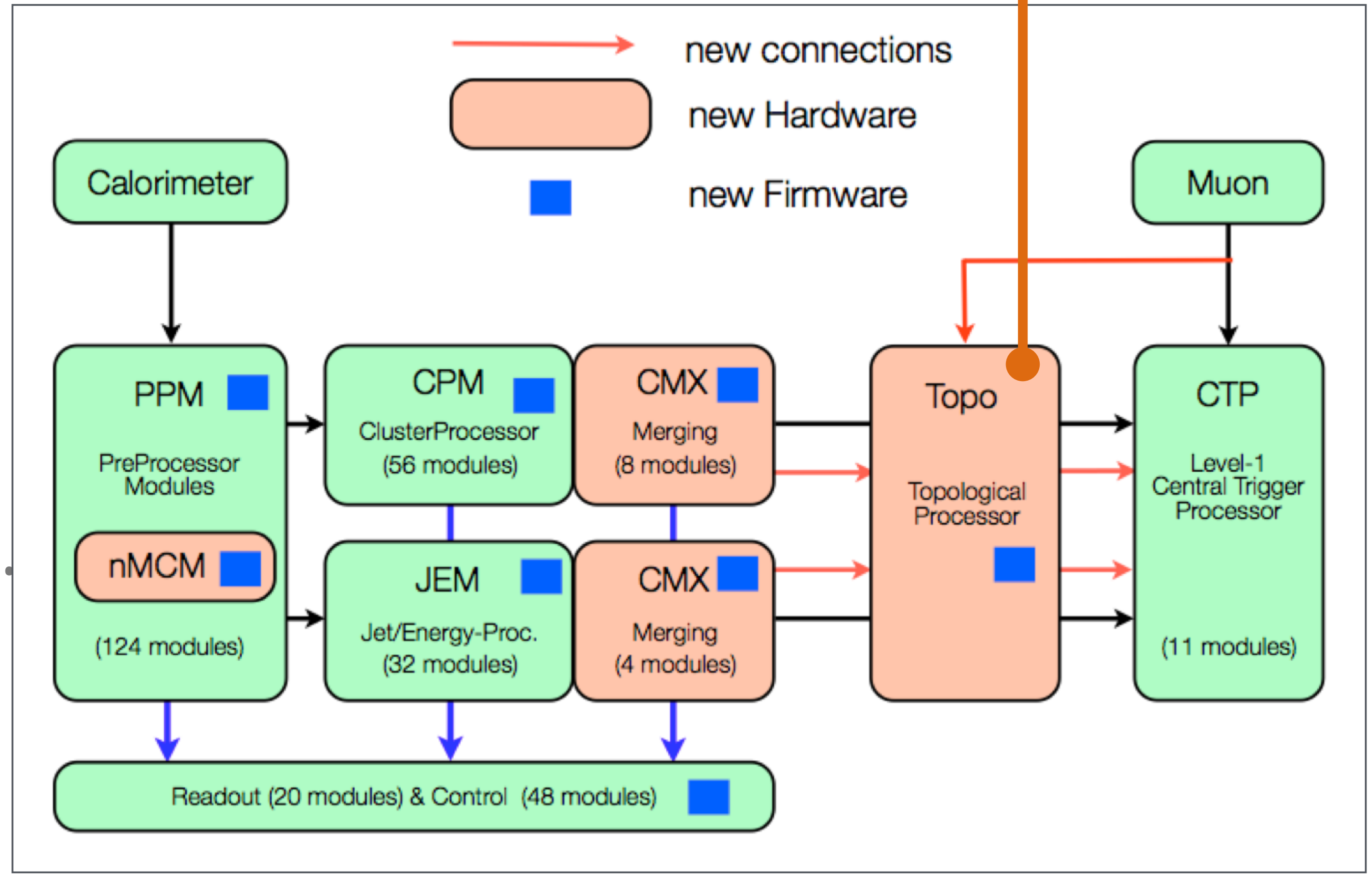
Upgrades to:

L1 rate, 70 kHz →100 kHz operation, factor 4/3 increase. **hardware**

HLT rate, 400 Hz → ~1 kHz operation, factor of ~2 increase. **algorithms**

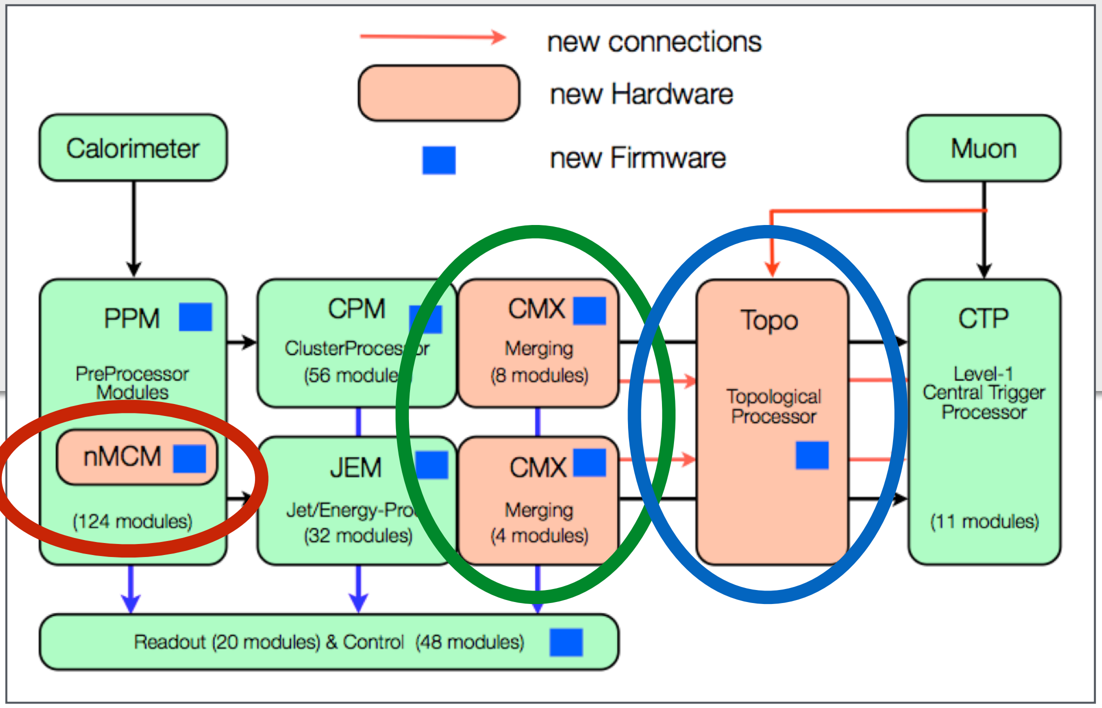
“L1Topo”: topological object correlations at L1

jet + Etmiss + angle sep & improved Etmiss



Trigger system

hardware



New preprocessors (nMCM)

80 MHz digitization, lower noise

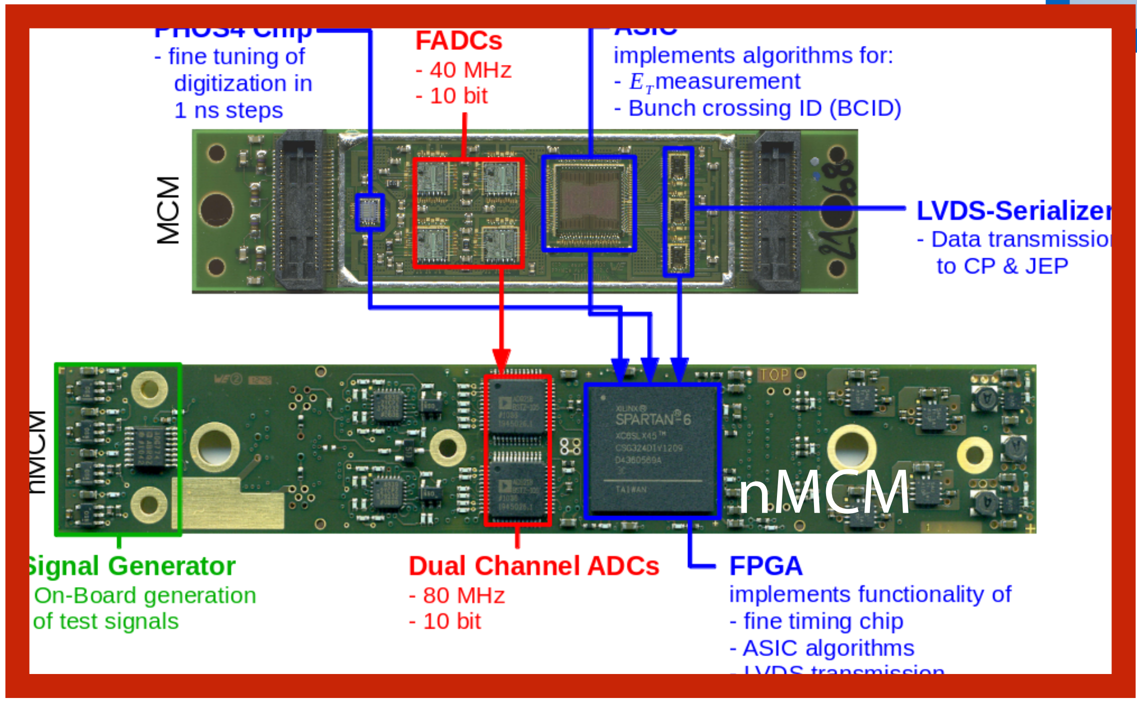
New merger modules (CMX)

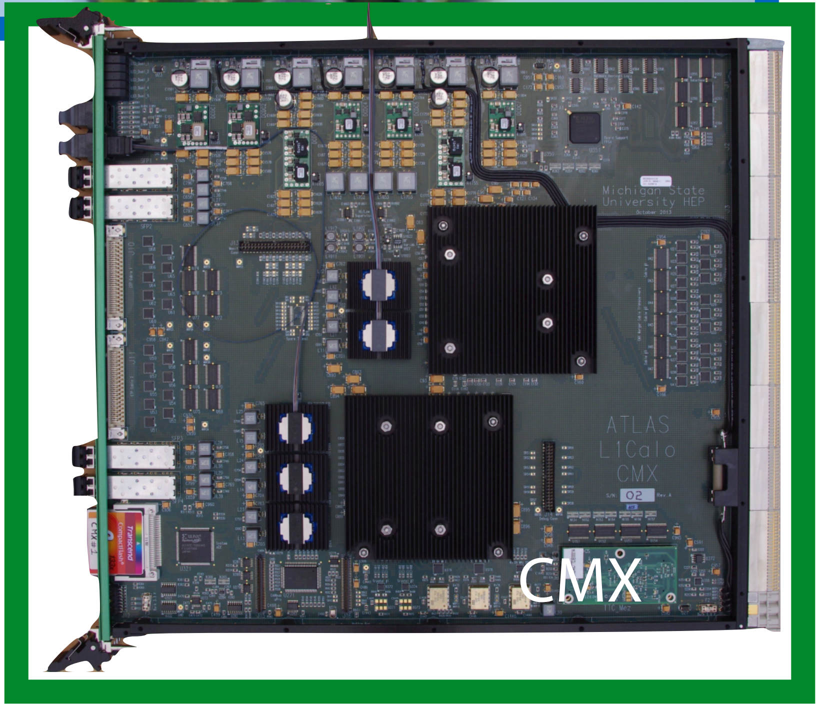
x4 speed enhancement over CMM

L1 Topo processor

trigger on object relations at L1 e.g. $\Delta\phi(E^{miss}{}_T, j)$

Commissioning underway in-situ

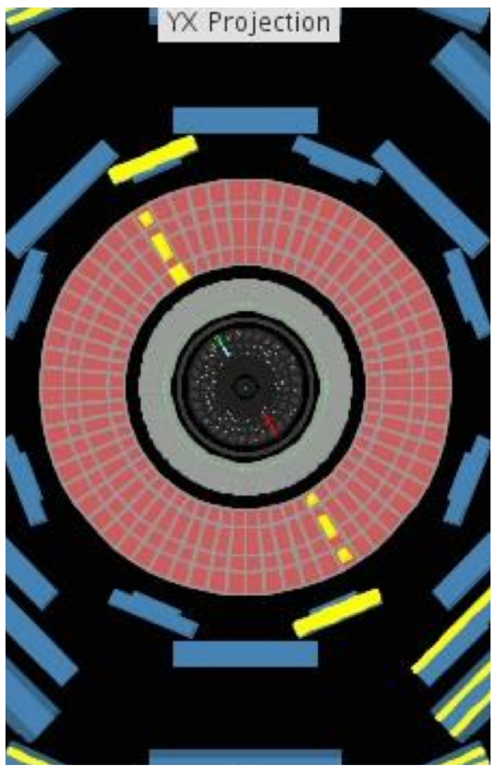




Commissioning

multiple “Milestone weeks”

24/5! M’s cosmic rays HLT & reco’d Tier 0



	M3	M4	M5	M6	M7
	May19-May 23	Jul 7-Jul 11	Sep 8-Sep 12	Oct 13-Oct 17	Nov 24-Dec 08
PIX		X[1], X[2]	X[2]		
IBL		X[1]	X[2]		
SCT		X	X[2]		
TRT					
LAR		X			
TIL		X			
MBTS		X			
L1Calo		X[2]	X[3]	X[4]	
CSC			X[2]	X[2]	
MDT					
RPC	X[1]				
TGC				X[2]	
BCM					
ALFA			X		
LUCID				X	
Lumi			X		

Commissioning

multiple “Milestone weeks”

24/5! M’s cosmic rays HLT & reco’d Tier 0

nCSC and IBL in for the first time

	M3	M4	M5	M6	M7
	May19-May 23	Jul 7-Jul 11	Sep 8-Sep 12	Oct 13-Oct 17	Nov 24-Dec 08
PIX		X[1], X[2]	X[2]		
IBL		X[1]	X[2]		
SCT		X	X[2]		
TRT					
LAR		X			
TIL		X			
MBTS		X			
L1Calo		X[2]	X[3]	X[4]	
CSC			X[2]	X[2]	
MDT					
RPC	X[1]				
TGC				X[2]	
BCM					
ALFA			X		
LUCID				X	
Lumi			X		

ATLAS reading out since “M5”

Computing & Software & Analysis

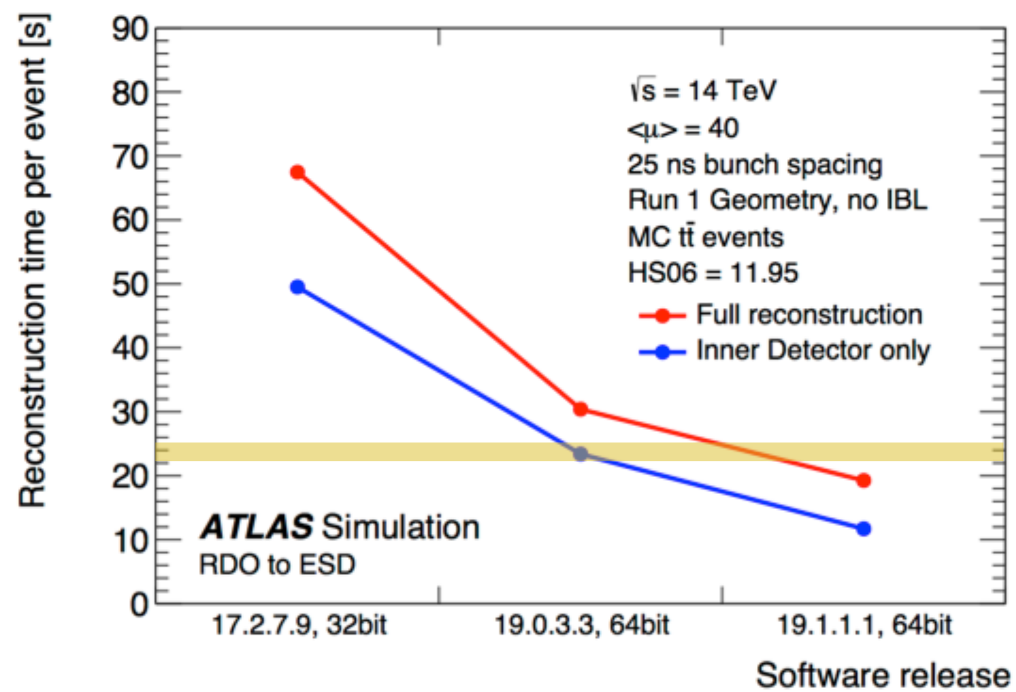
speed/efficiency and pileup

Many algorithmic, mathematical, fitting changes

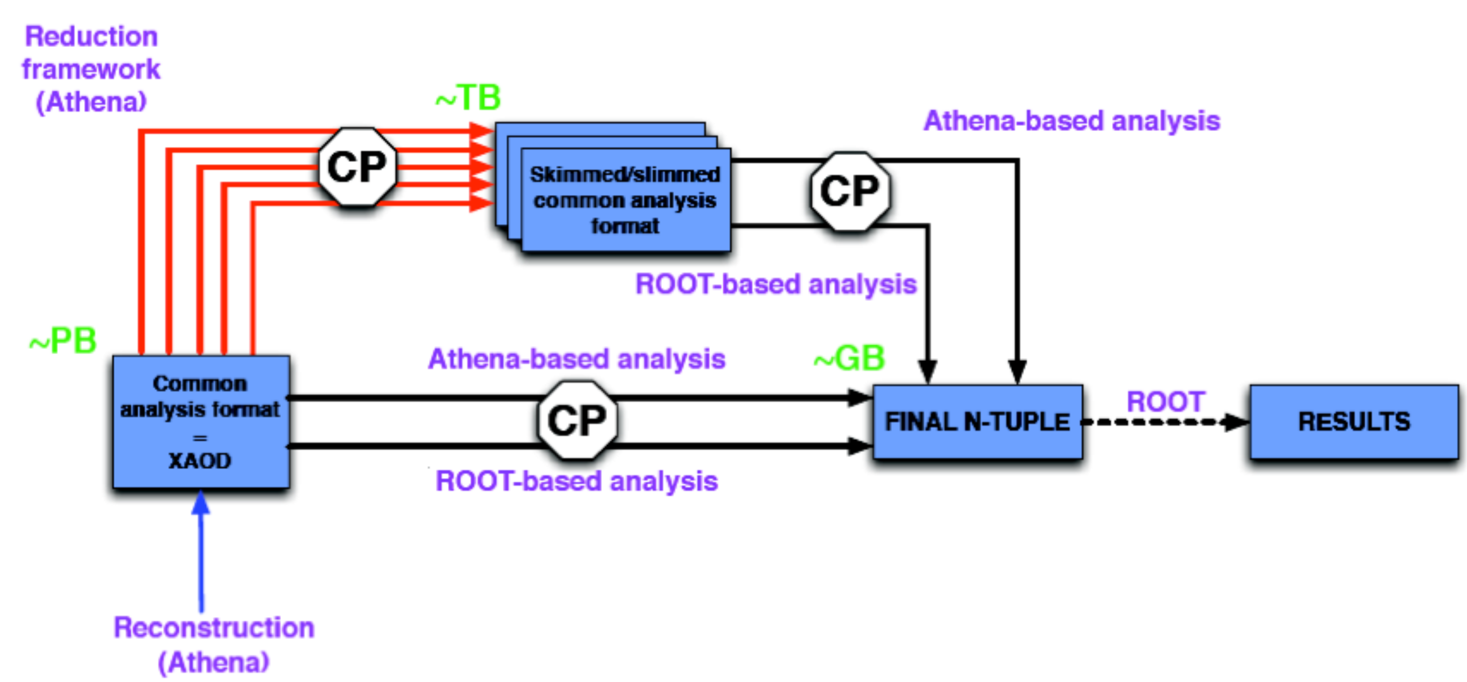
- factor >3 gains
- pileup robustness

Completely redesigned analysis model

- “xAOD” Athena reconstruction is ROOT-readable, tuning.
- disk usage tight…working on xAOD sizes
- memory usage gymnastics
- CP tools mostly migrated



budget @0.4 LHC eff



conclusion

Run 2 is an unusual event for all of us

we've seen CM energy increases:

tevatron 2 TeV to LHC 8 TeV

now we can anticipate:

14 TeV

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we've seen instantaneous $\mathscr{L}$ increases:

tevatron peak of 4 x 10^{32} /cm^2/s to LHC peak of 7 x 10^{33} /cm^2/s

now we can anticipate:

1.5 x 10^{34} /cm^2/s

conclusion

Run 2 is an unusual event for all of us

we've seen CM energy increases:

tevatron 2 TeV to LHC 8 TeV

now we can anticipate:

14 TeV

Orders of magnitude!

we've seen instantaneous $\mathscr{L}$ increases:

tevatron peak of 4×10^{32} /cm^2/s to LHC peak of 7×10^{33} /cm^2/s

now we can anticipate:

1.5×10^{34} /cm^2/s

Conclusions