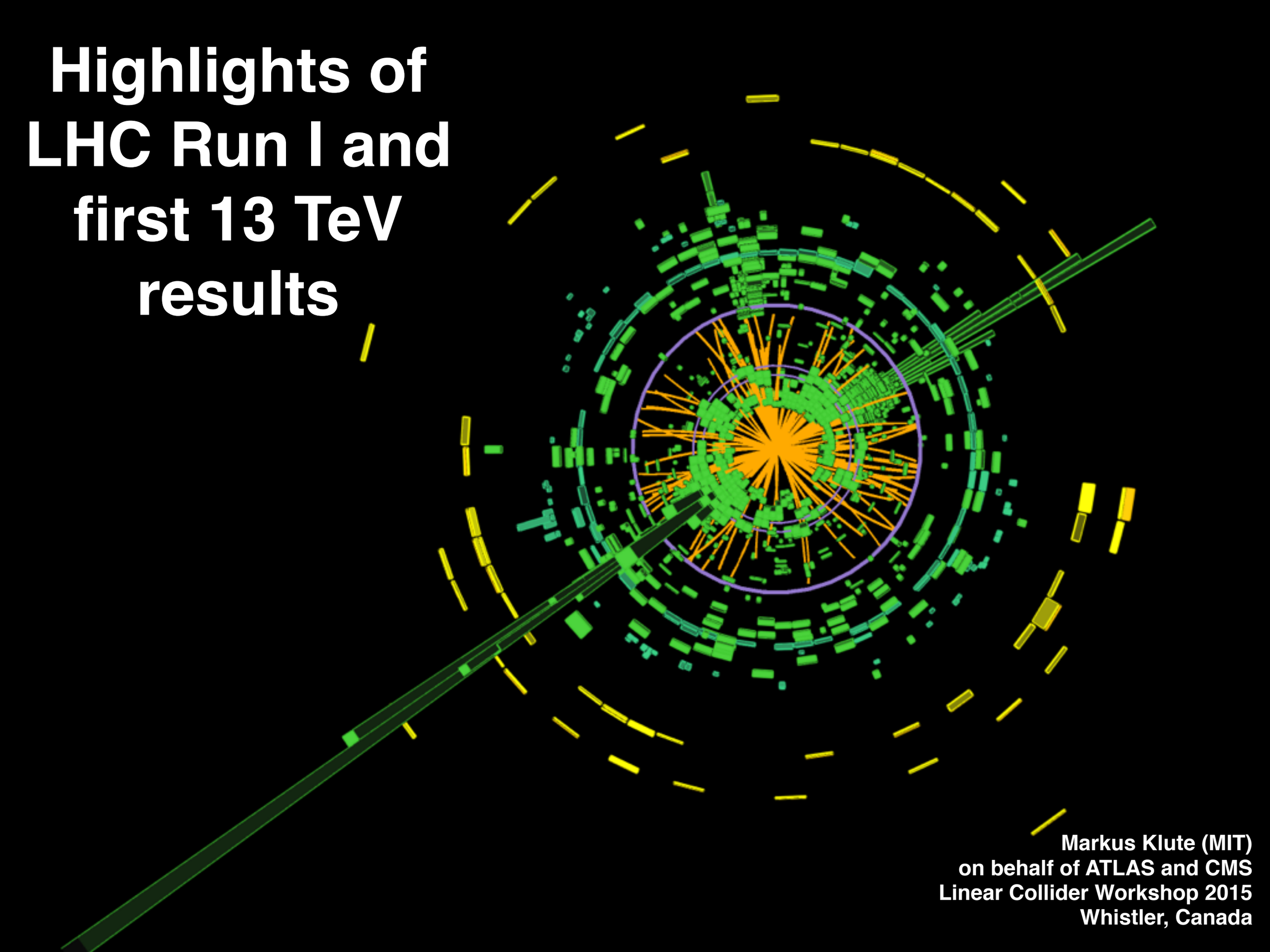
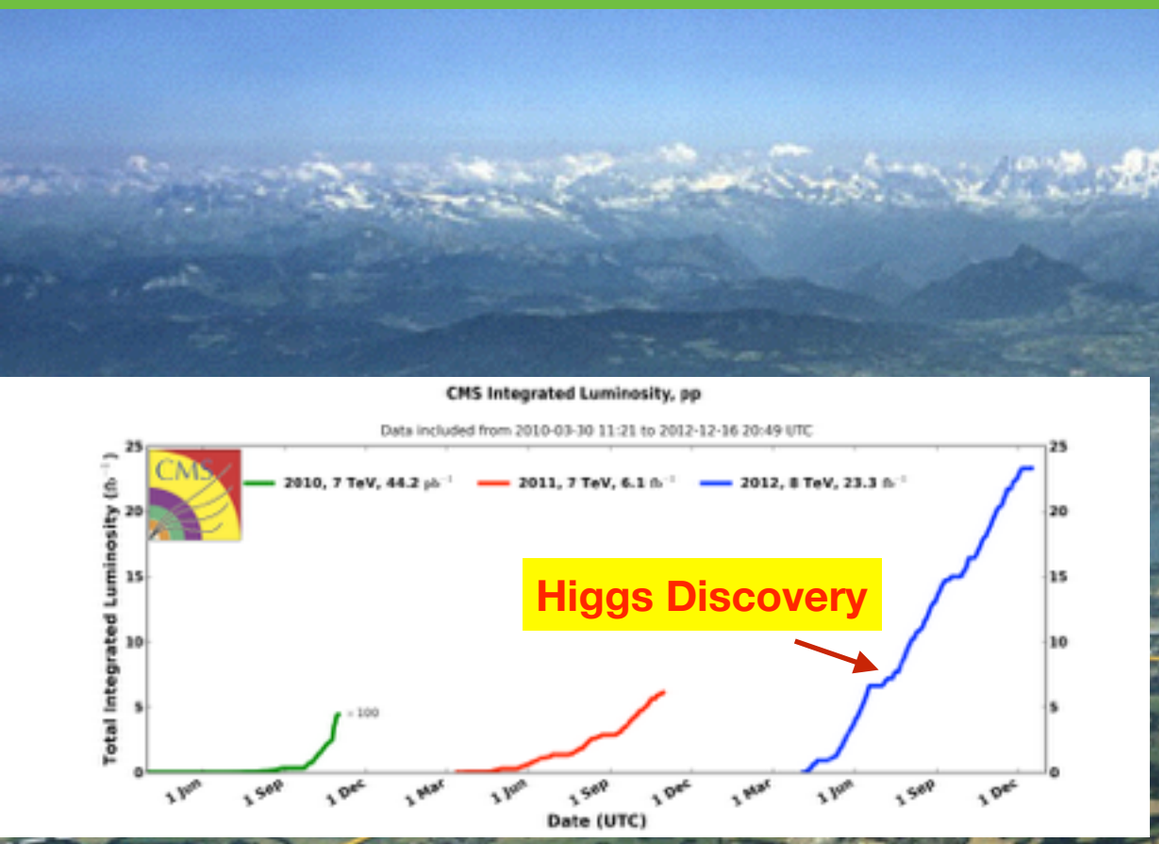
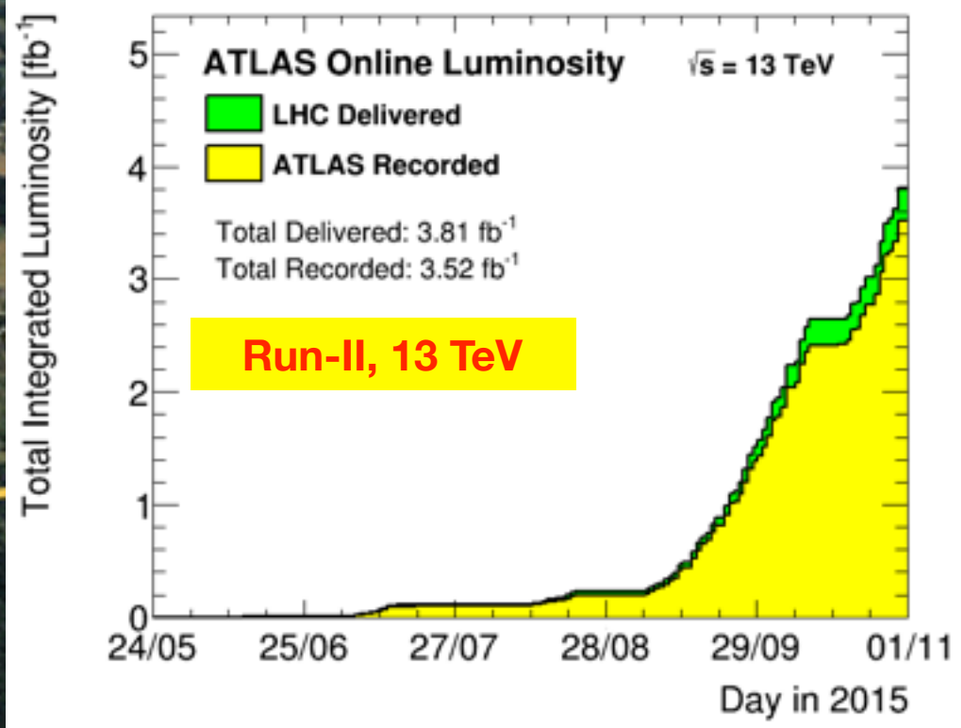
Highlights of LHC Run I and first 13 TeV results



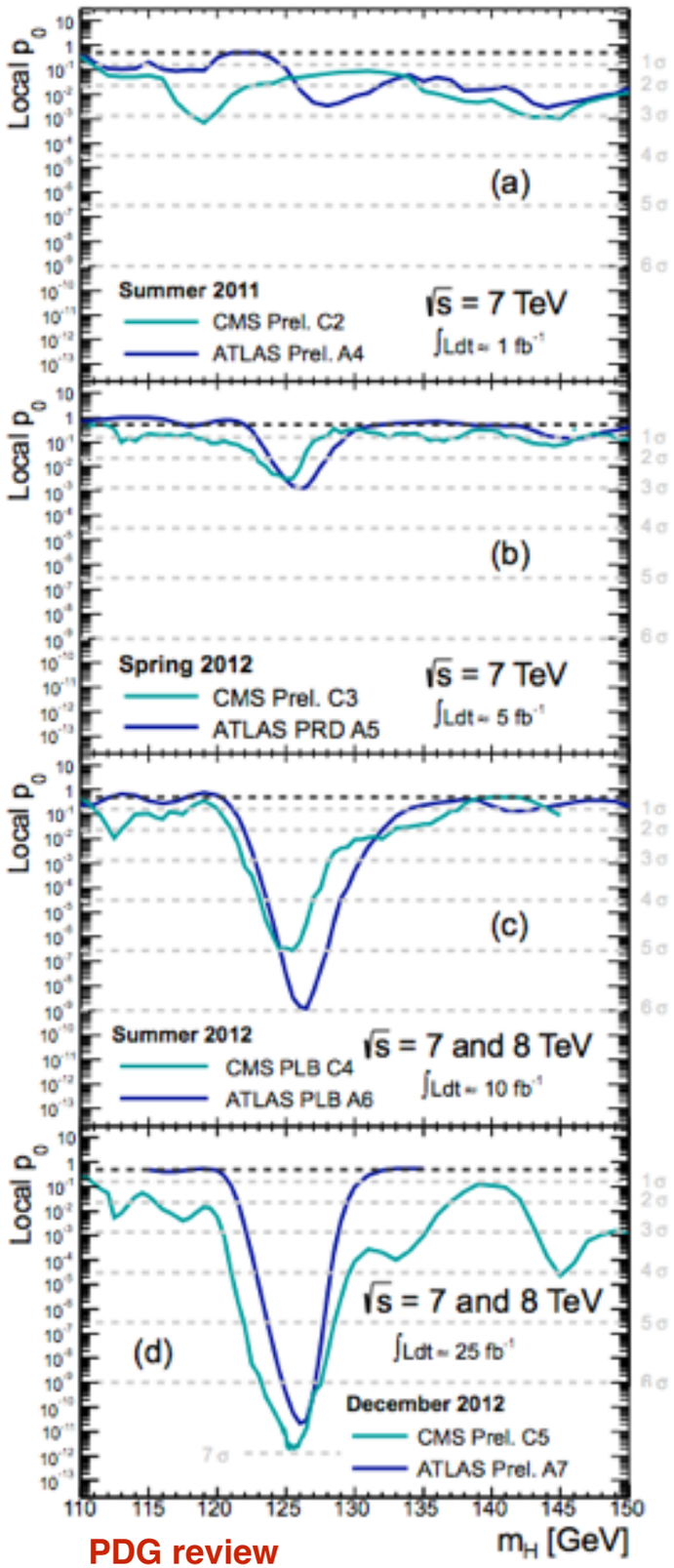
Markus Klute (MIT)
on behalf of ATLAS and CMS
Linear Collider Workshop 2015
Whistler, Canada

Large Hadron Collider - Run I and II





Higgs Boson Discovery



PDG review

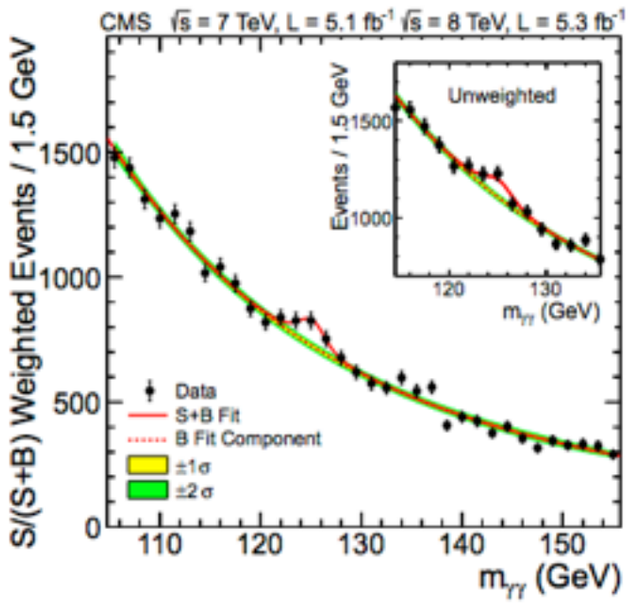
Summer 2011

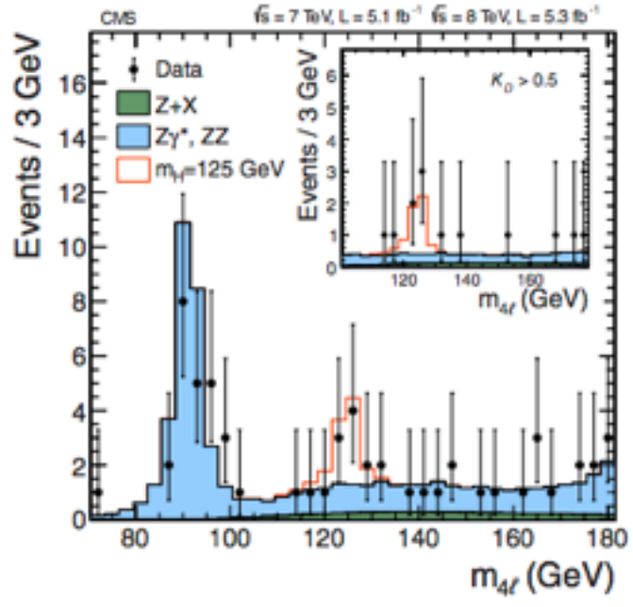
End of 2011

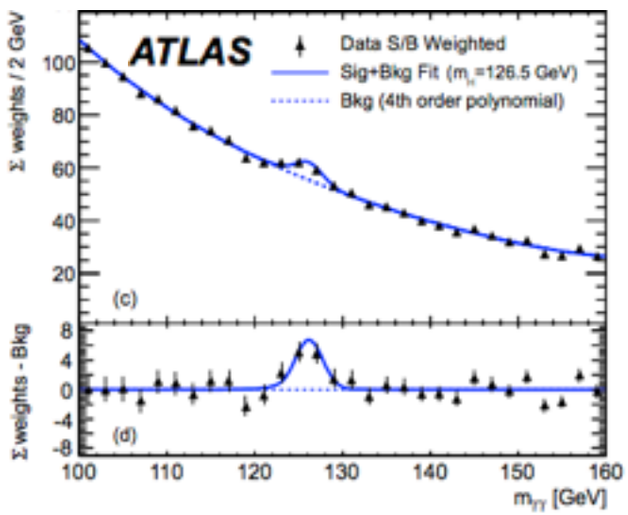
Summer 2012

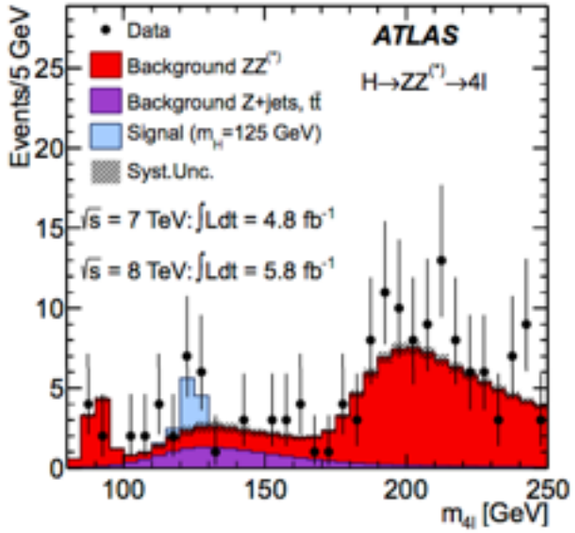
End of 2012

- **Observation by ATLAS and CMS**
- **Independent confirmation by two experiments and two final states**
- **ATLAS and CMS paper with more than 5000 citations each (> 4/day)**





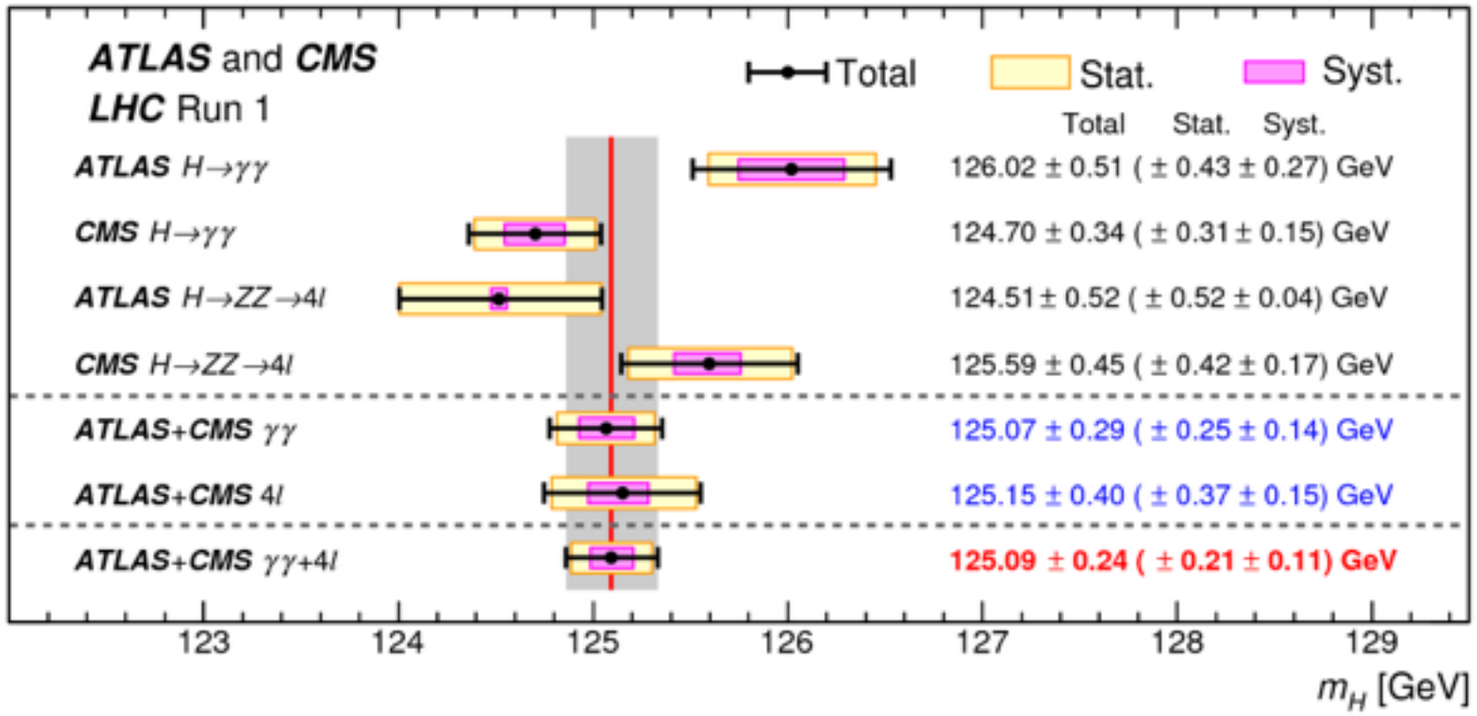




Overview of Higgs Results

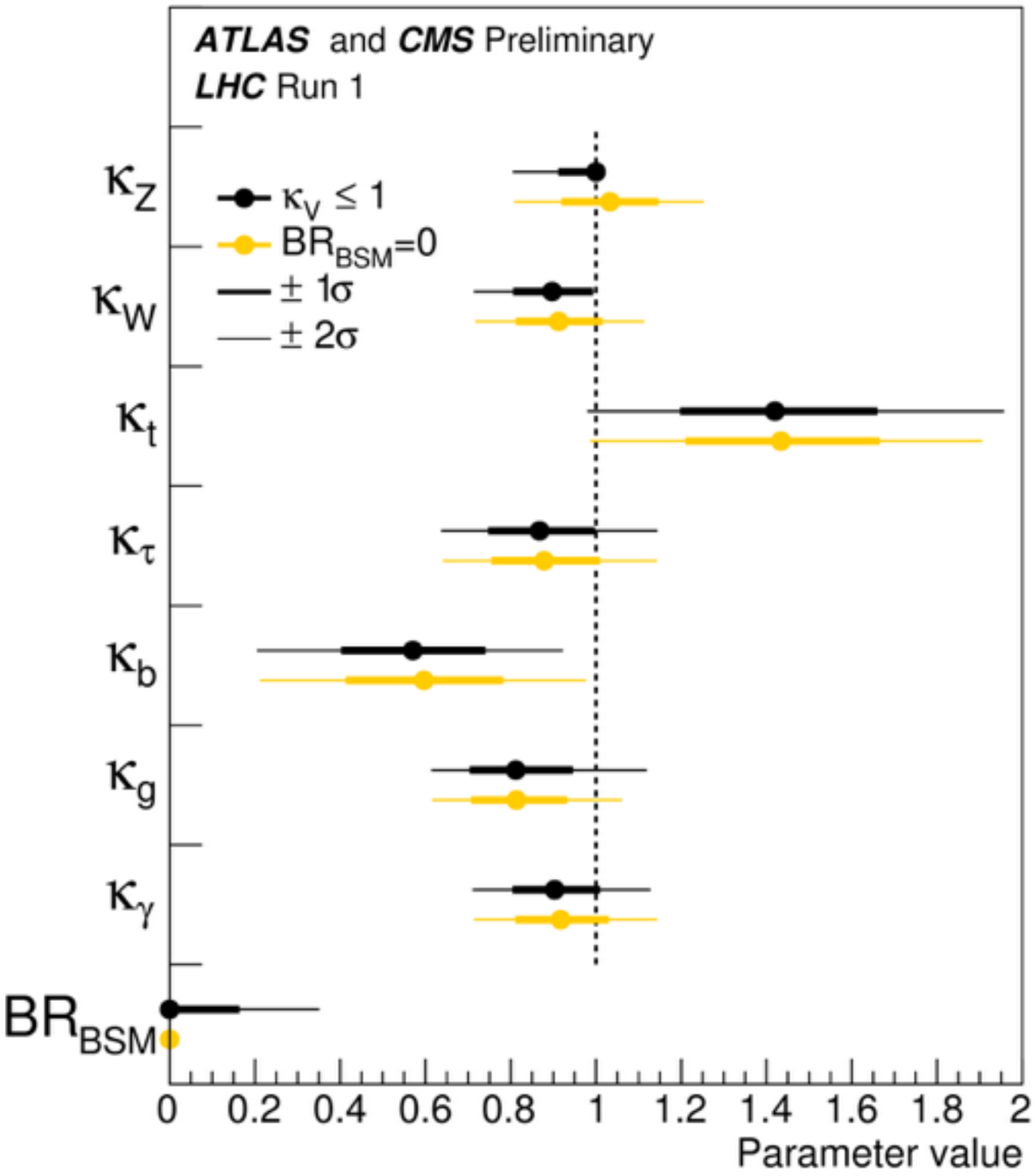
- **Combined ATLAS and CMS measurements using LHC Run-1 dataset**
- **Precision (0.2%) limited by statistical uncertainty**

  $m_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst) GeV
- **Established that particle masses and couplings to the Higgs boson relate**
- **Discovered particle looks in all aspects like the SM Higgs boson**
- **No additional Higgs bosons or BSM decays observed**



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Higgs Coupling Measurements



Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $BR_{BSM} = 0$				
κ_Z	$1.03^{+0.11}_{-0.11}$	$^{+0.10}_{-0.11}$	$1.00^{+0.14}_{-0.14}$	$1.07^{+0.17}_{-0.18}$
κ_W	$0.91^{+0.10}_{-0.10}$	$^{+0.10}_{-0.11}$	$0.92^{+0.13}_{-0.13}$	$0.90^{+0.15}_{-0.15}$
κ_t	$1.43^{+0.23}_{-0.22}$	$^{+0.26}_{-0.32}$	$1.31^{+0.30}_{-0.32}$	$1.56^{+0.34}_{-0.32}$
κ_τ	$0.88^{+0.13}_{-0.12}$	$^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.17}$	$0.82^{+0.19}_{-0.17}$
κ_b	$0.60^{+0.18}_{-0.18}$	$^{+0.25}_{-0.24}$	$0.61^{+0.26}_{-0.26}$	$0.61^{+0.27}_{-0.26}$
κ_g	$0.81^{+0.11}_{-0.10}$	$^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.15}$	$0.70^{+0.15}_{-0.13}$
κ_γ	$0.92^{+0.11}_{-0.10}$	$^{+0.12}_{-0.12}$	$0.88^{+0.15}_{-0.14}$	$0.96^{+0.17}_{-0.15}$

ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

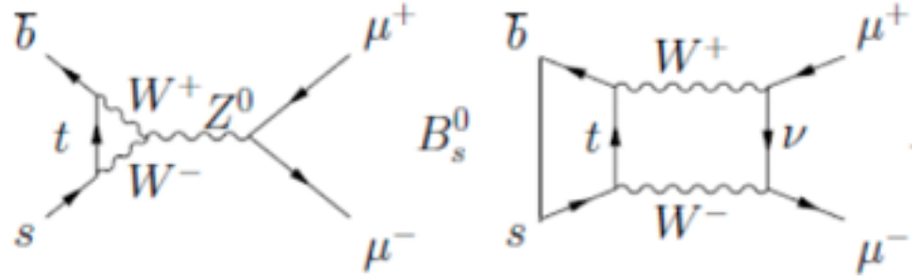
- **Coupling modifier measured with varying assumptions on total width**
- **Precision already ~10% for Z, W, and photon couplings**

First Observation

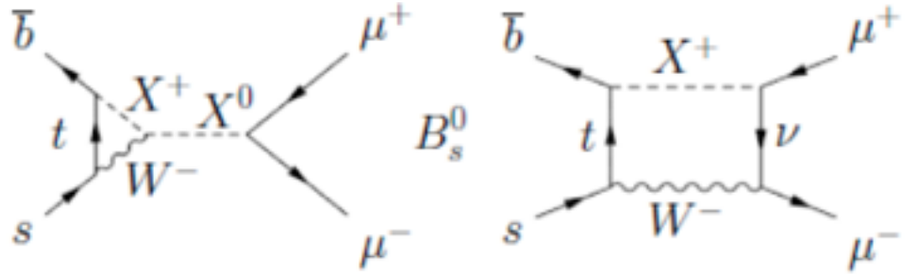
- ➡ First $B_s \to \mu\mu$ observation
- ➡ Combined CMS and LHCb analysis
- ➡ Concluded a three decade long search

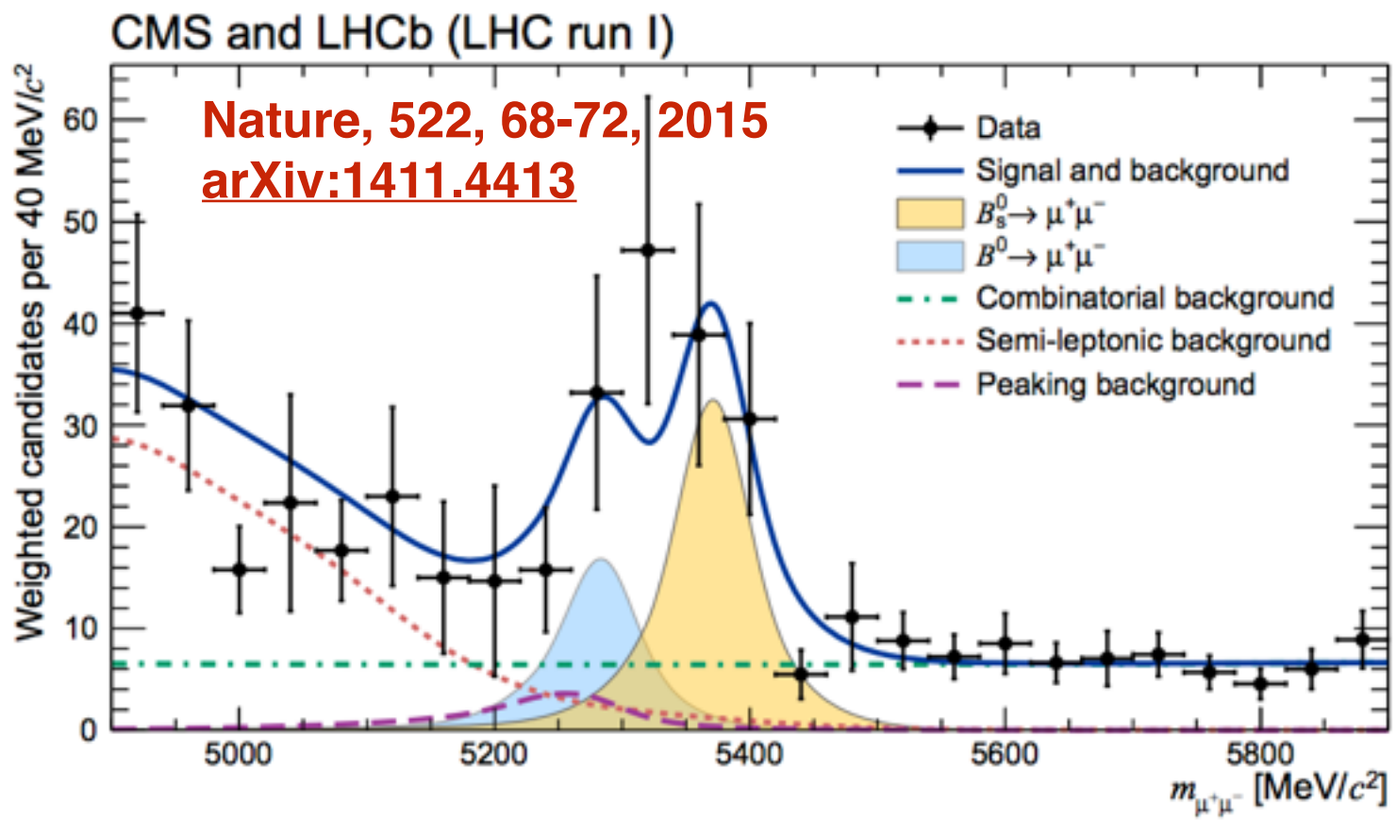
$$\mathcal{B}(B_s \to \mu\mu) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \quad S = 6.2\sigma \text{ (Exp: } 7.4\sigma)$$
$$\mathcal{B}(B_d \to \mu\mu) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \quad S = 3.0\sigma \text{ (Exp: } 0.8\sigma)$$

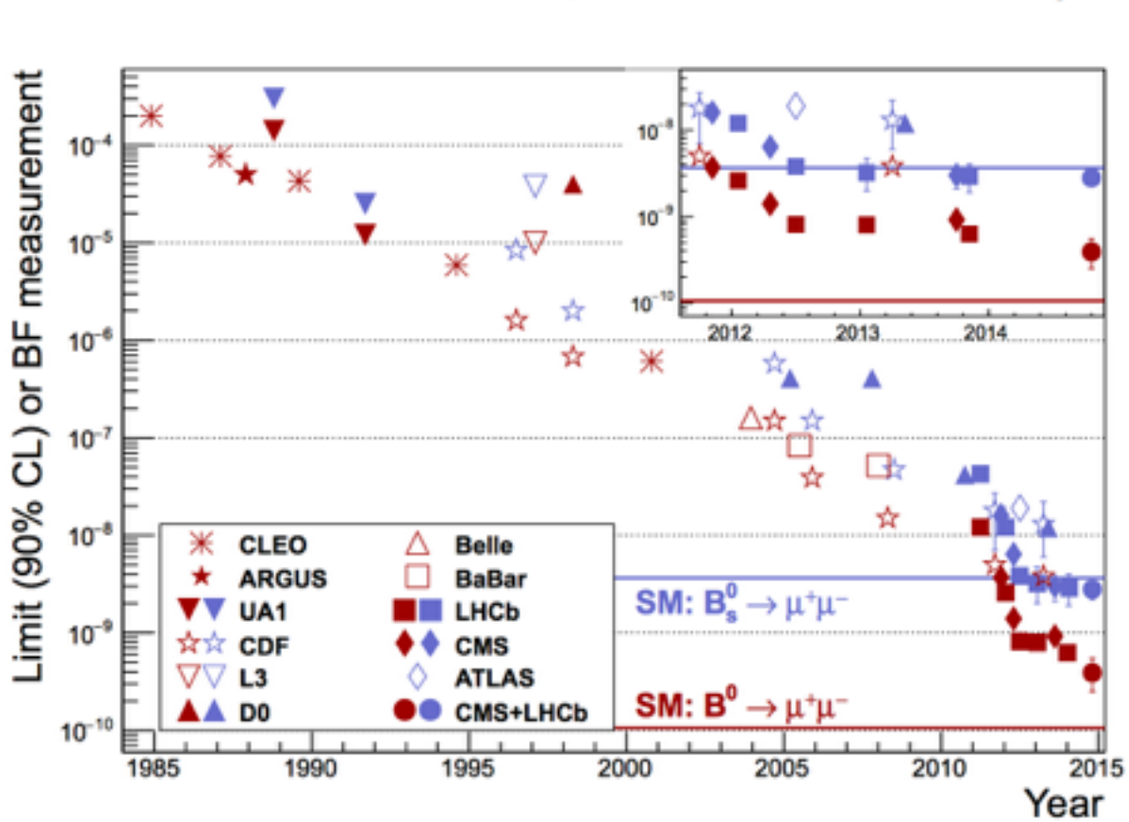
SM:



BSM:







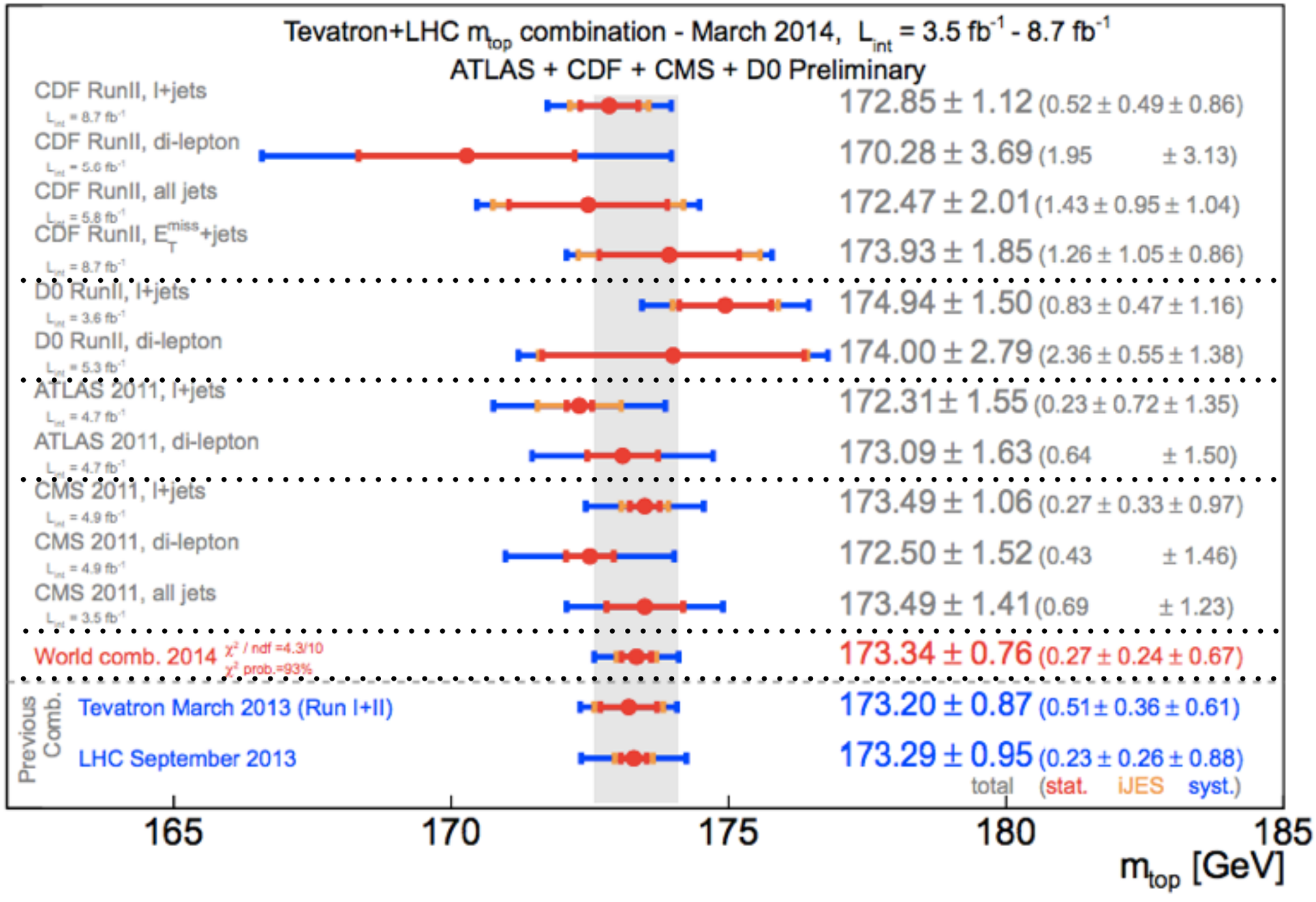
Precision Top Mass Measurements

CDF

D0

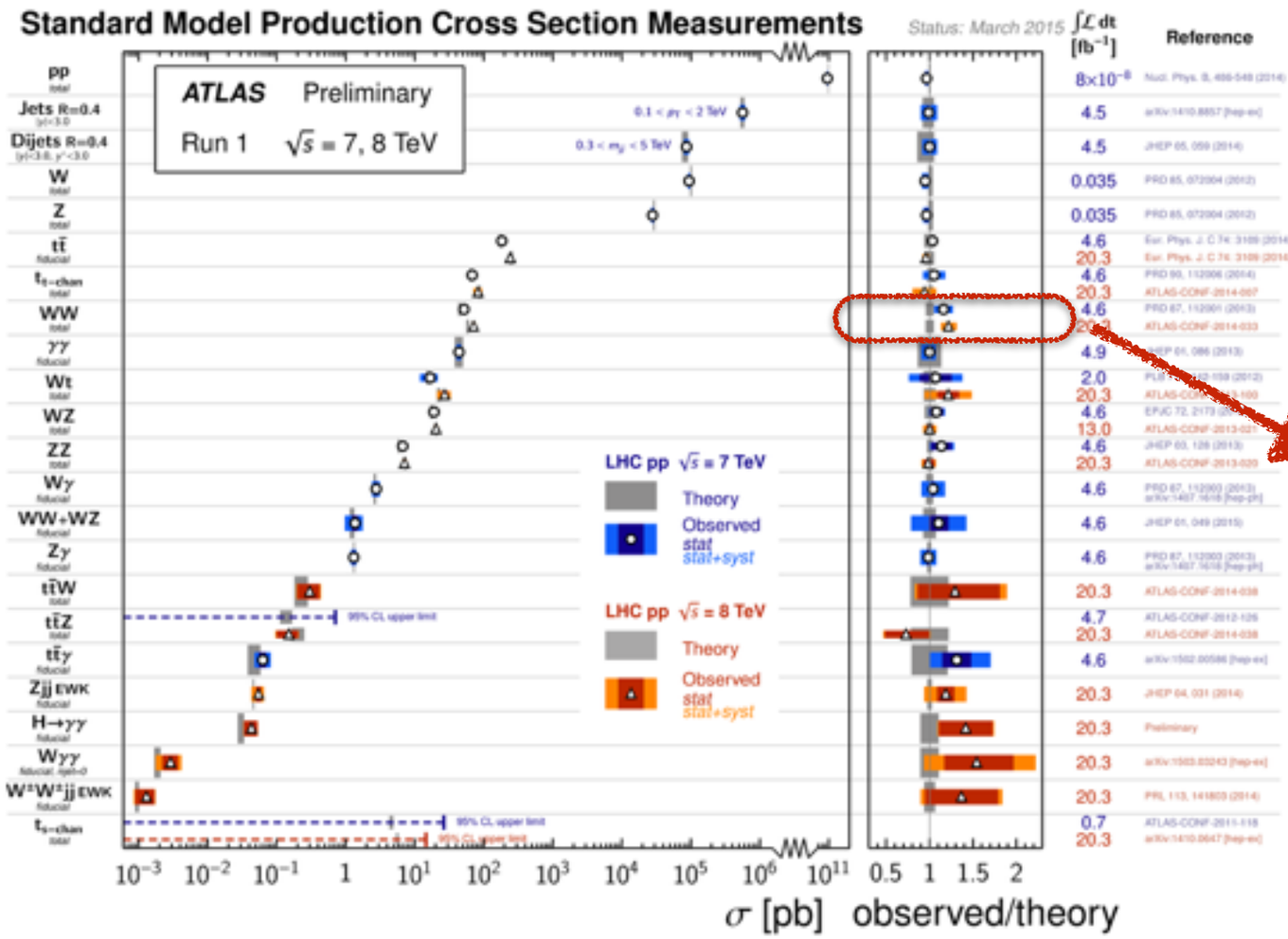
ATLAS

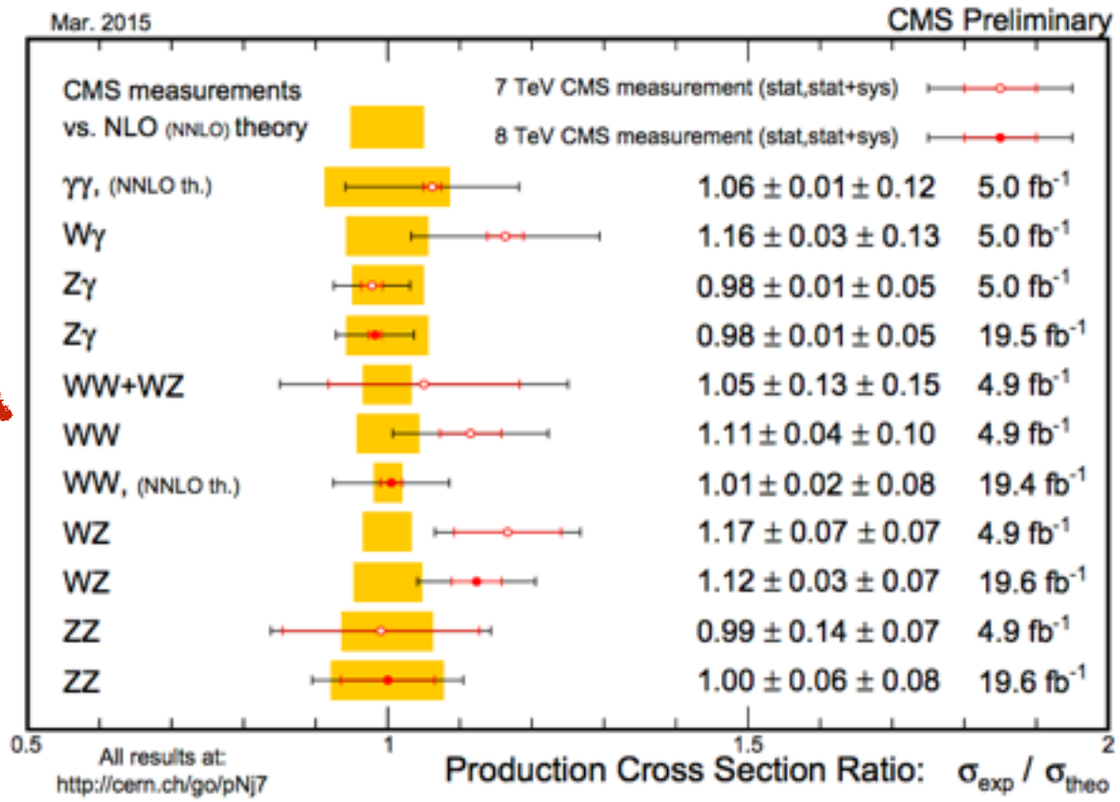
CMS



➡ **Updated CMS combination yields: 172.44 ± 0.13 ± 0.47 GeV**

Precision Cross Sections

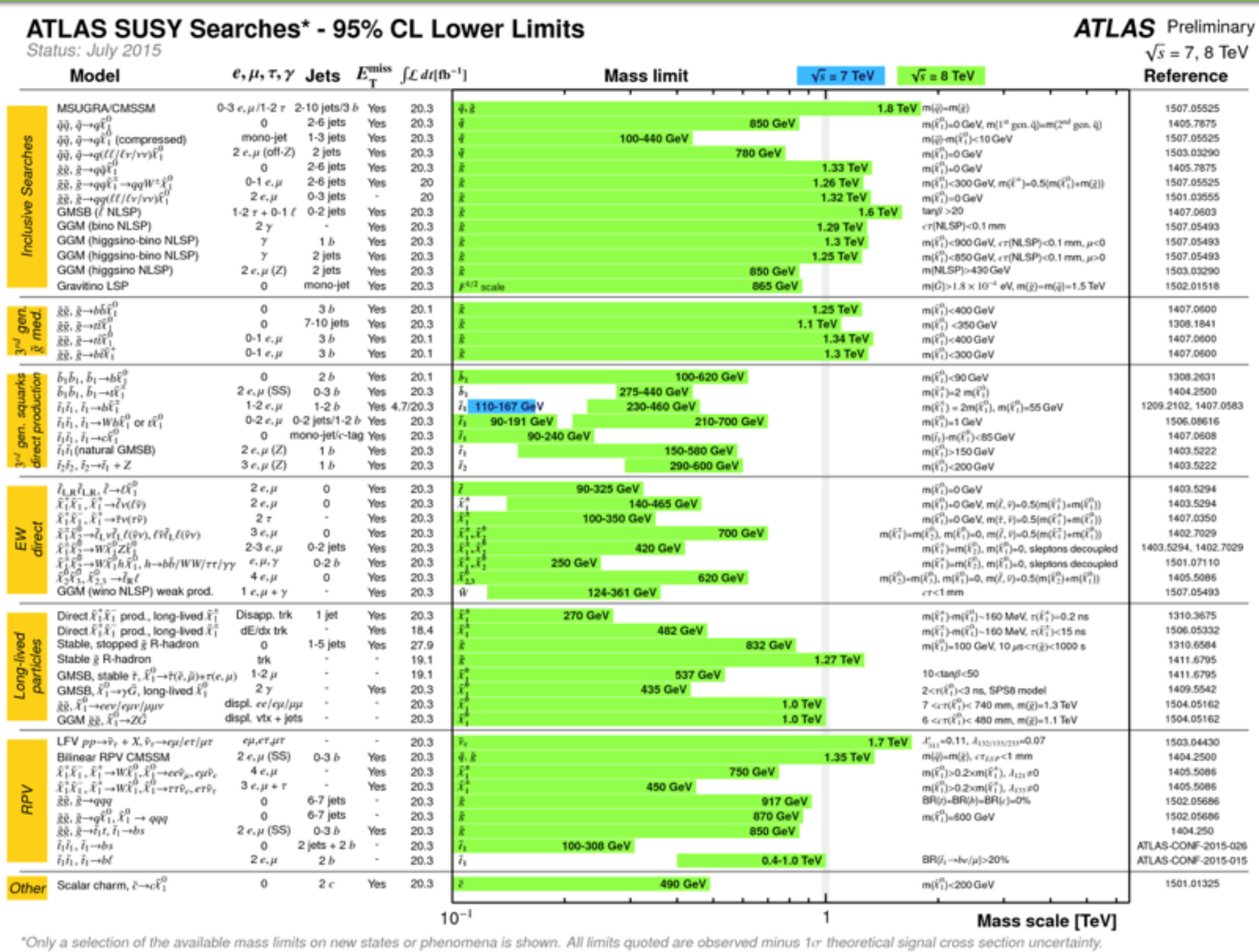




More than 800 paper between ATLAS and CMS,
not even counting LHCb and ALICE results

Selected highlights are minor fraction of the total LHC physics program

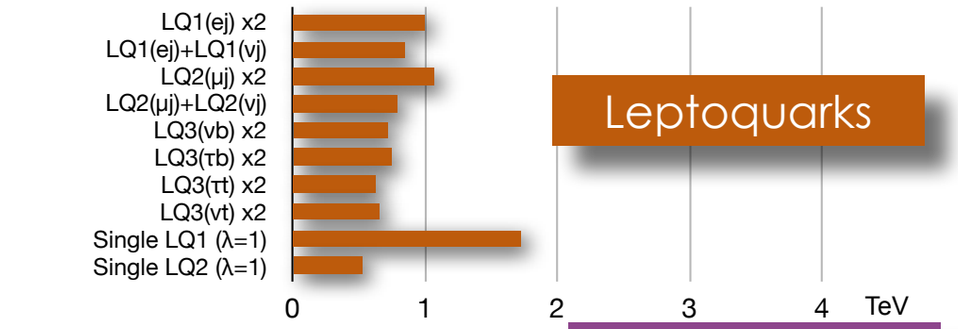
LHC SUSY Searches



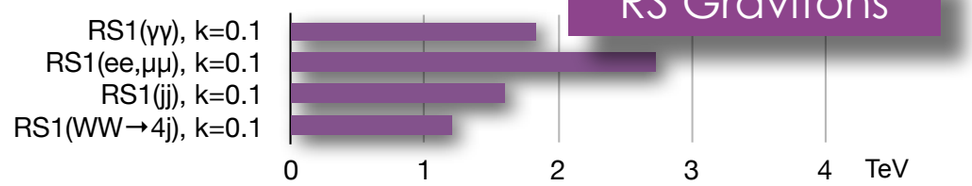
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

➡ **Similar picture from CMS**

LHC Non-SUSY Searches

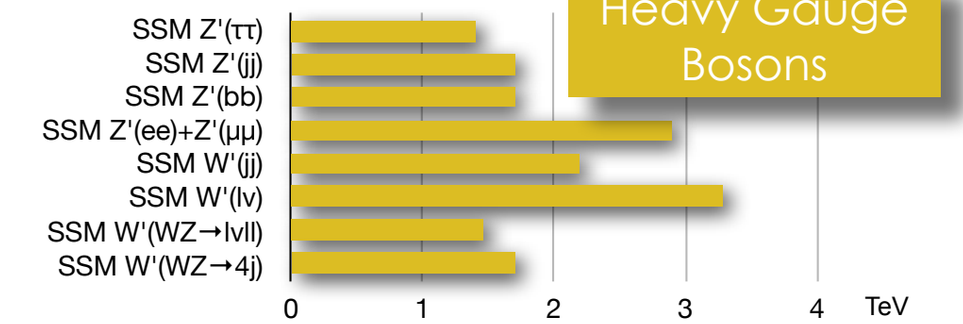


Leptoquarks

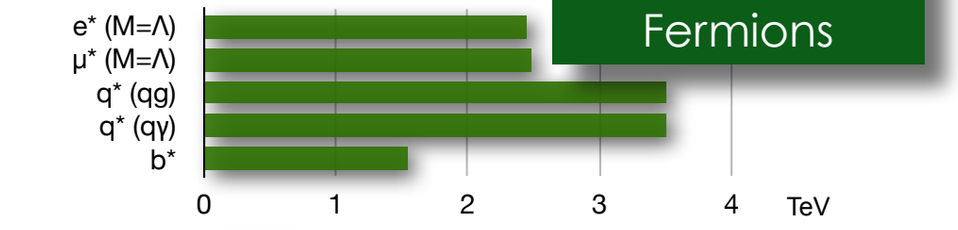


RS Gravitons

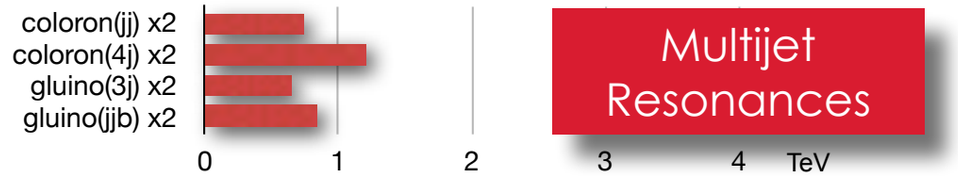
CMS Preliminary



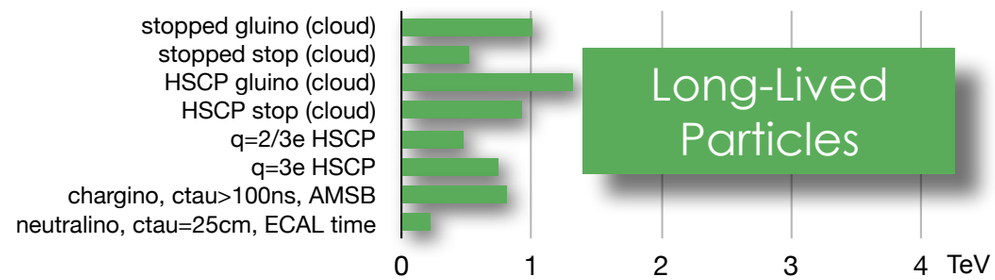
Heavy Gauge Bosons



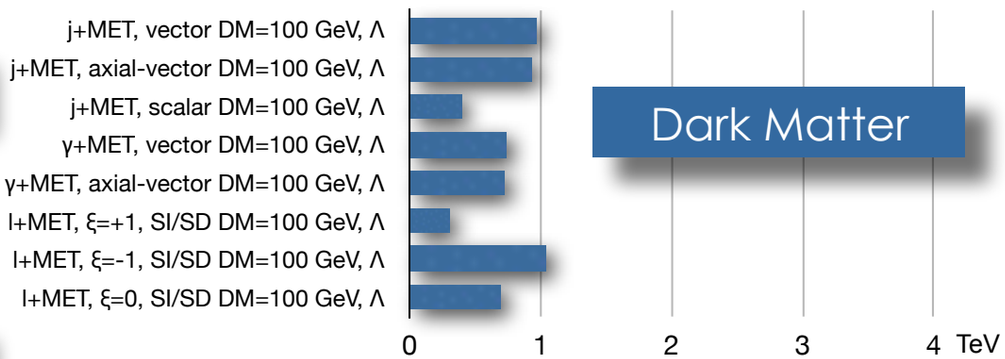
Excited Fermions



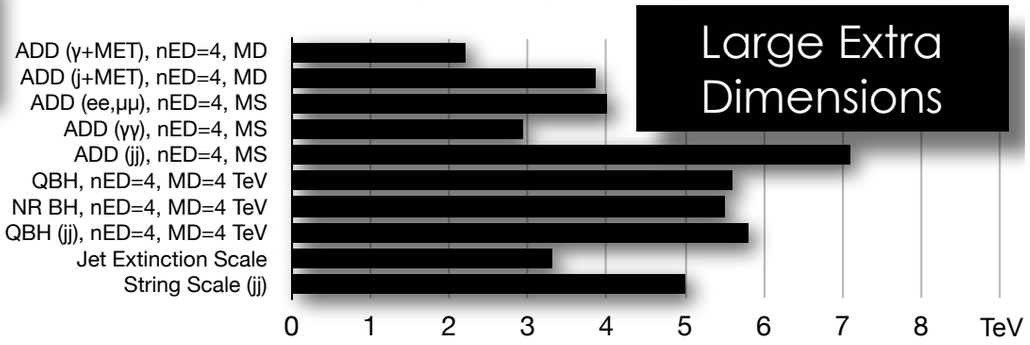
Multijet Resonances



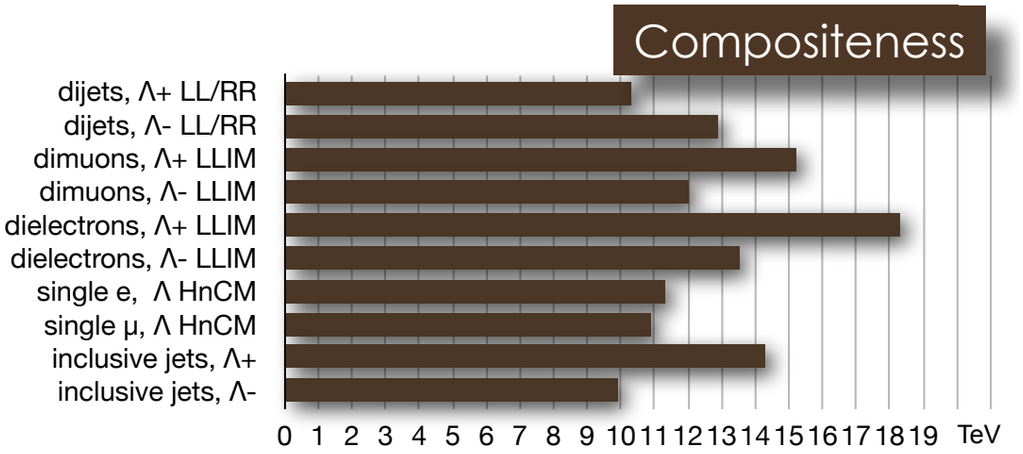
Long-Lived Particles



Dark Matter



Large Extra Dimensions



Compositeness

CMS Exotica Physics Group Summary – Moriond, 2015

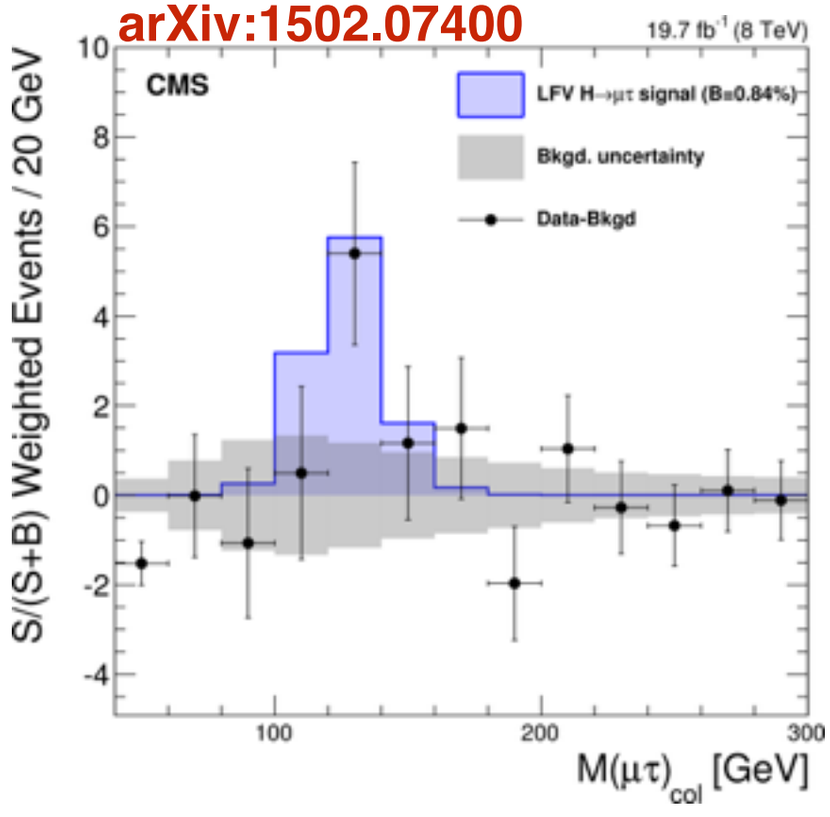
➡ **Similar picture from ATLAS**

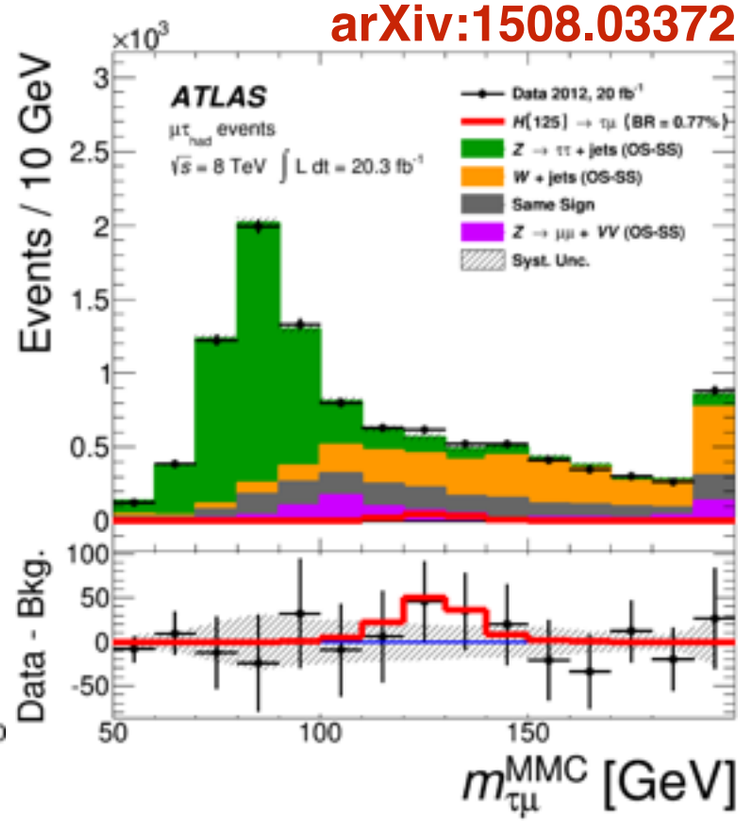
To watch out for …

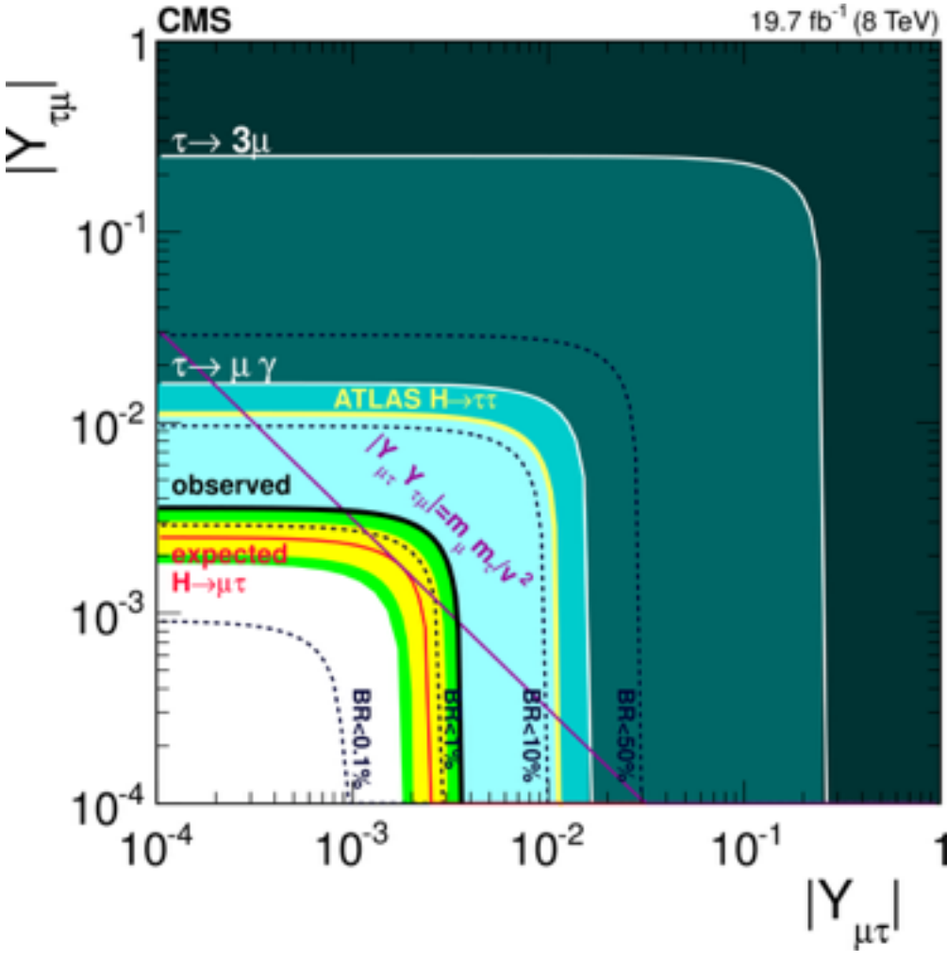
- ➡ We have a number of > 2σ deviations which might be first indication of new physics
- ➡ All have been vetted by the community and some generated considerable excitement
- ➡ Eyeballing the probability to have a few 3σ deviations is NOT small. No detailed statistical evaluation has been performed
- ➡ These excesses are interesting highlights of Run I. Run II will clear the clouds and confusion

To watch out for in Higgs …

- ➡ **Lepton-Flavor-Violating Higgs searches**
- ➡ **CMS reports an excess of 2.5σ**
- ➡ **ATLAS has less sensitivity and also a few more events than expected**







➡ **CMS**

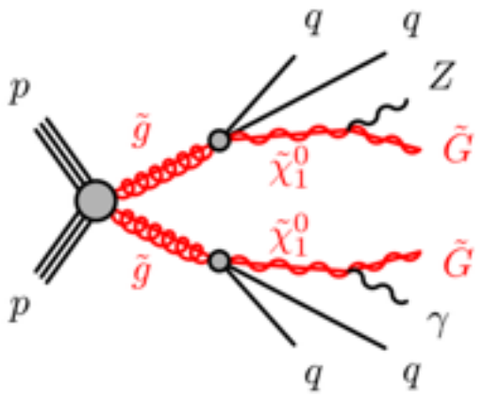
$$\mathrm{BR}(h \to \mu\tau) < 1.51\%,\ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

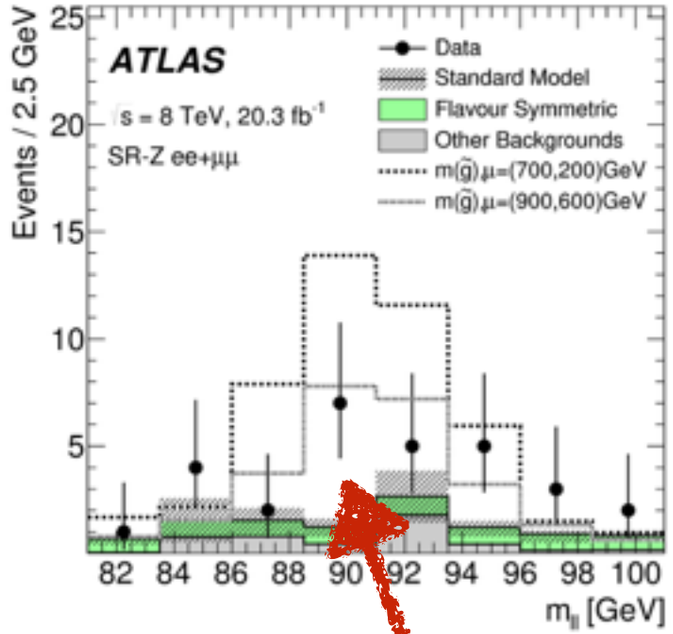
➡ **ATLAS**

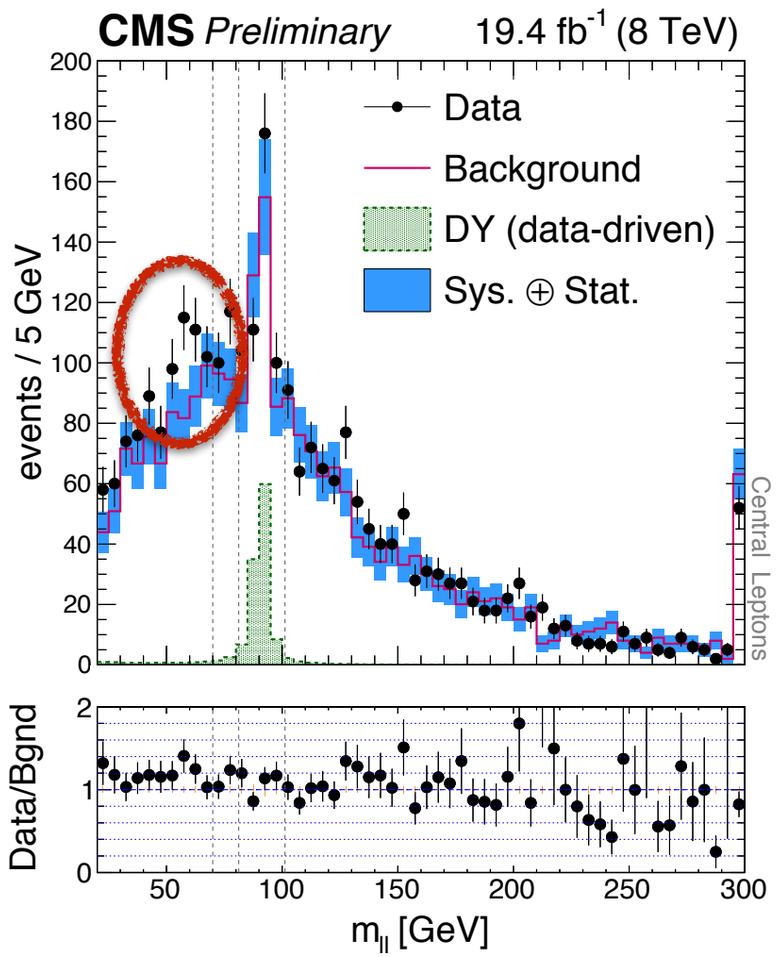
$$\mathrm{BR}(h \to \mu\tau) < 1.85\%,\ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) = (0.77 \pm 0.62)\%$$

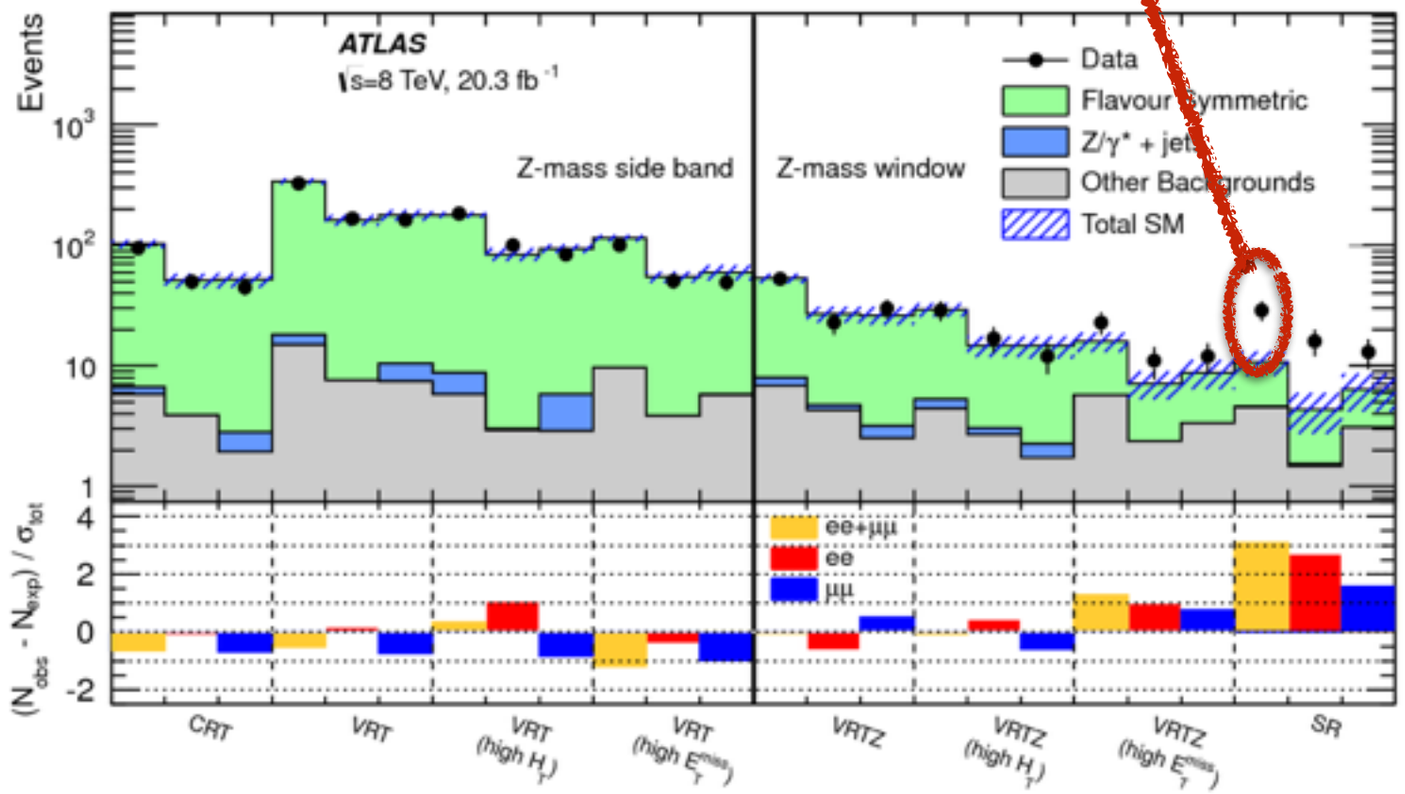
To watch out for in SUSY …

- ➡ **Search for SUSY in events with jets, missing ET, and two leptons**
- ➡ **CMS saw a ~2.5σ excess for a lower mass non-resonant decay**
- ➡ **ATLAS saw a ~3σ excess when leptons came from a Z boson**
- ➡ **Neither confirmed by the other experiment**





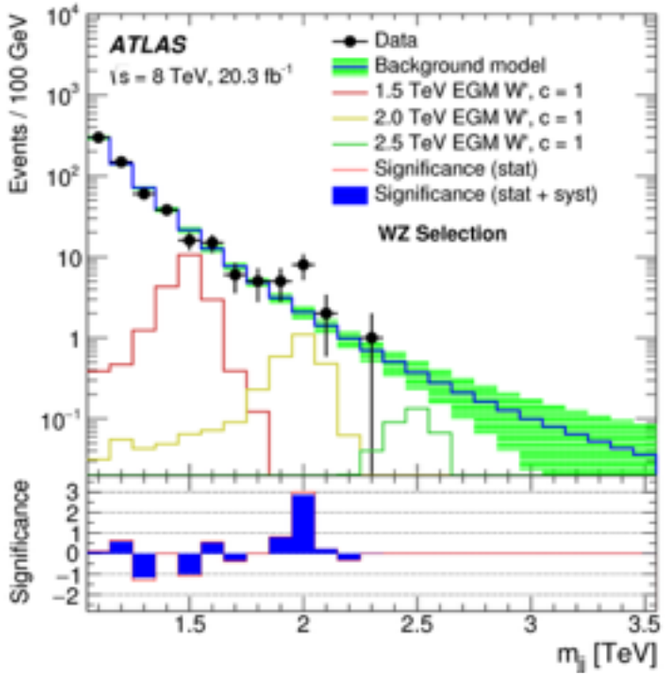


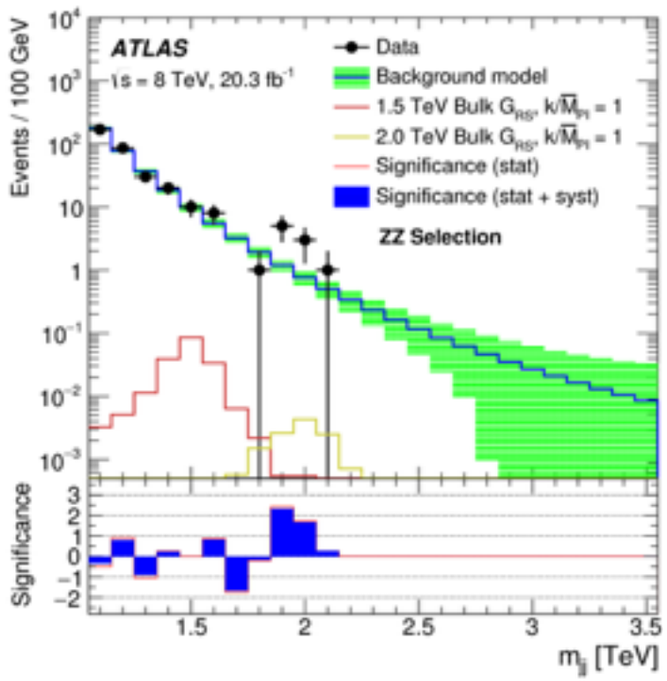


To watch out for in Exotics …

- ➡ **Another ATLAS and CMS excess; ATLAS at 2.5σ**
- ➡ **Constistent(ish) with 2 TeV W'-like particle**
- ➡ **Using boosted jets and hadronic W and Z boson tagging**

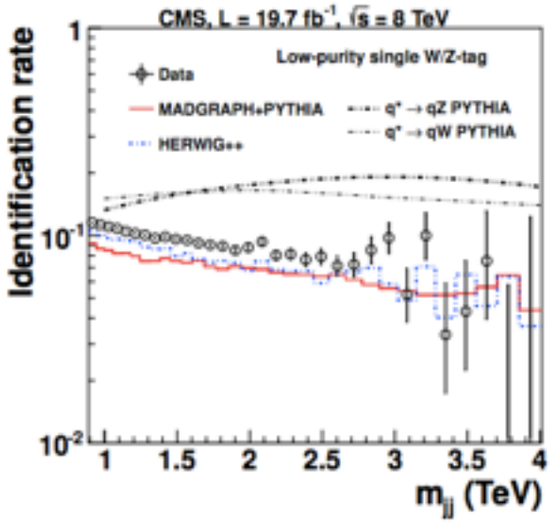
arXiv:1506.00962 (84 citation since June)

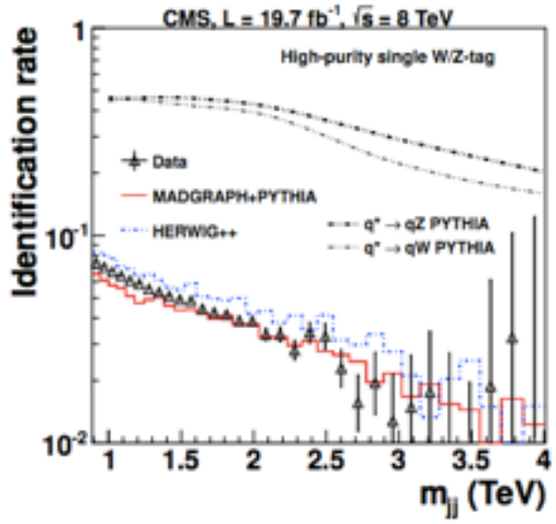


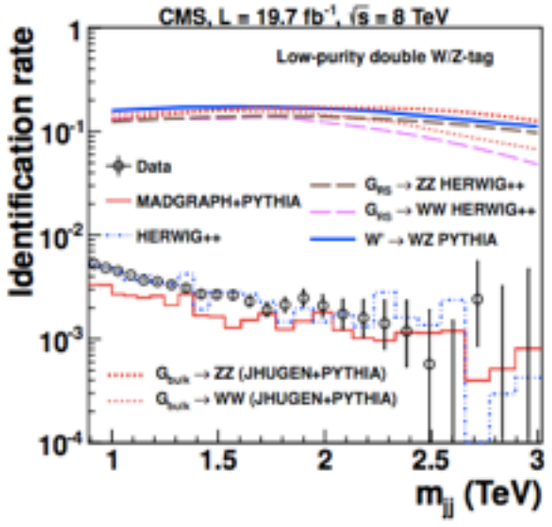


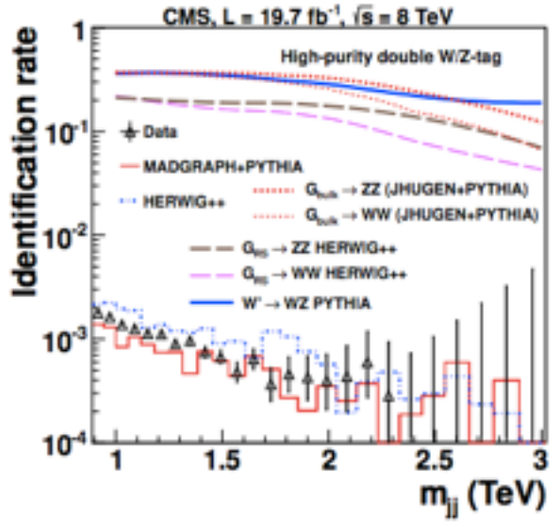
similar events in those two distributions

arXiv:1405.1994

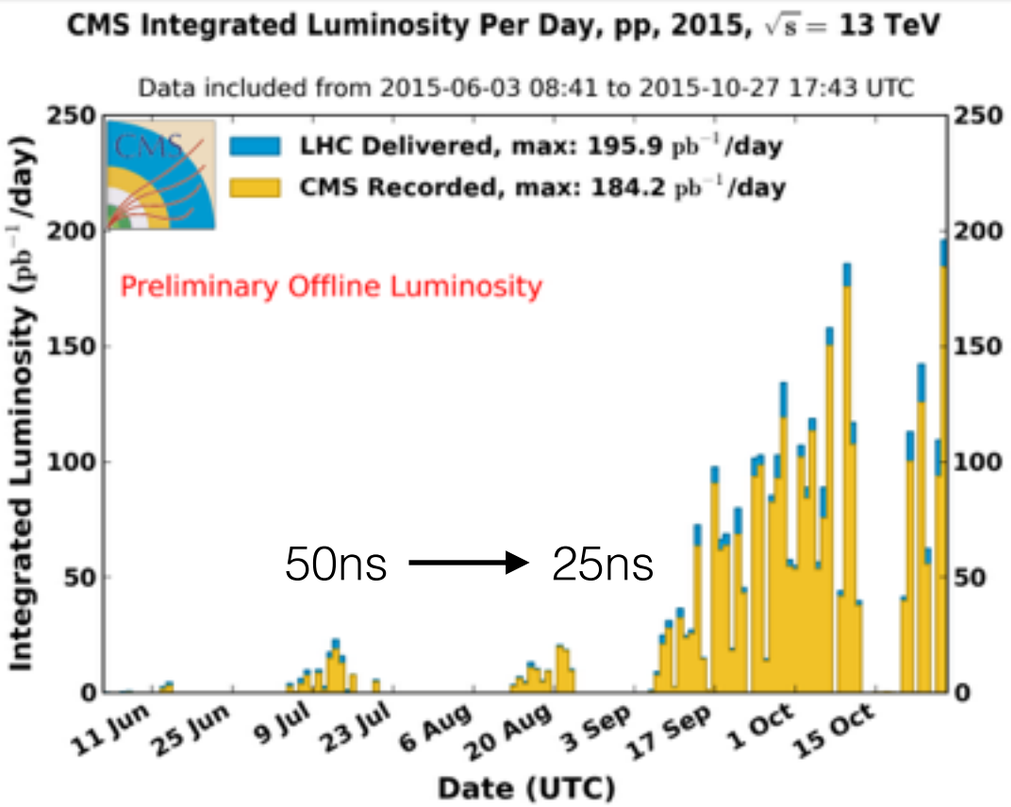


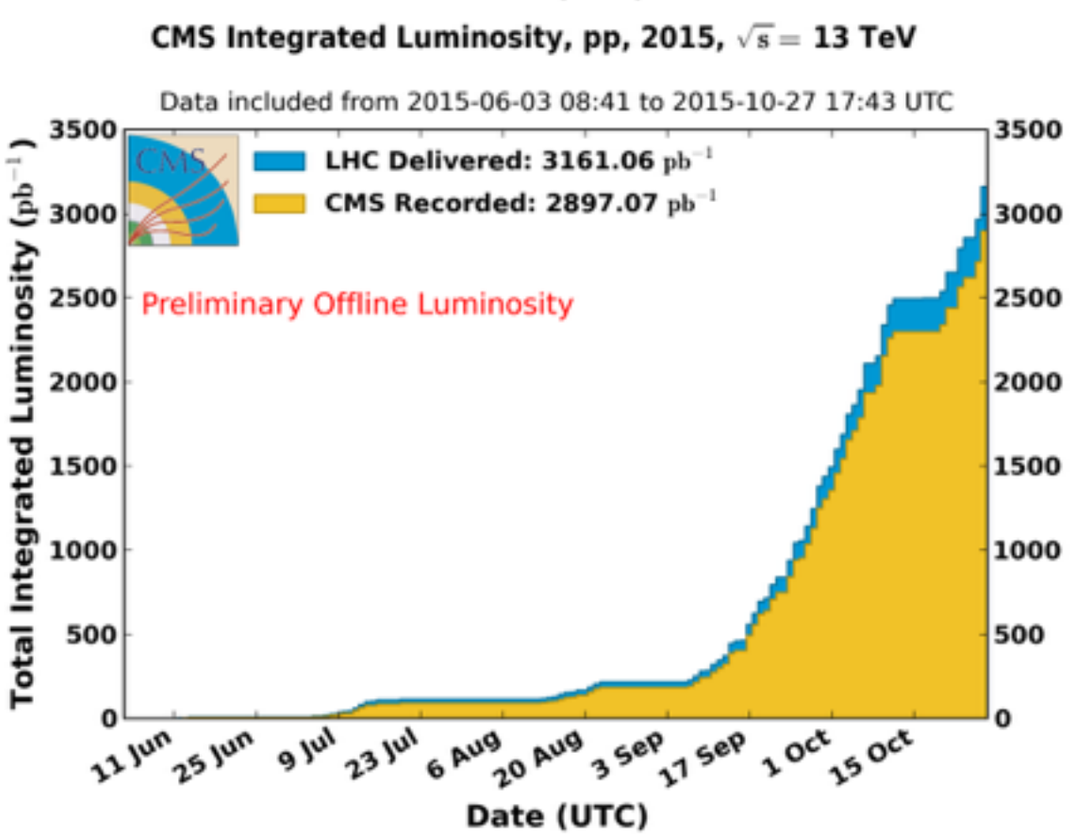




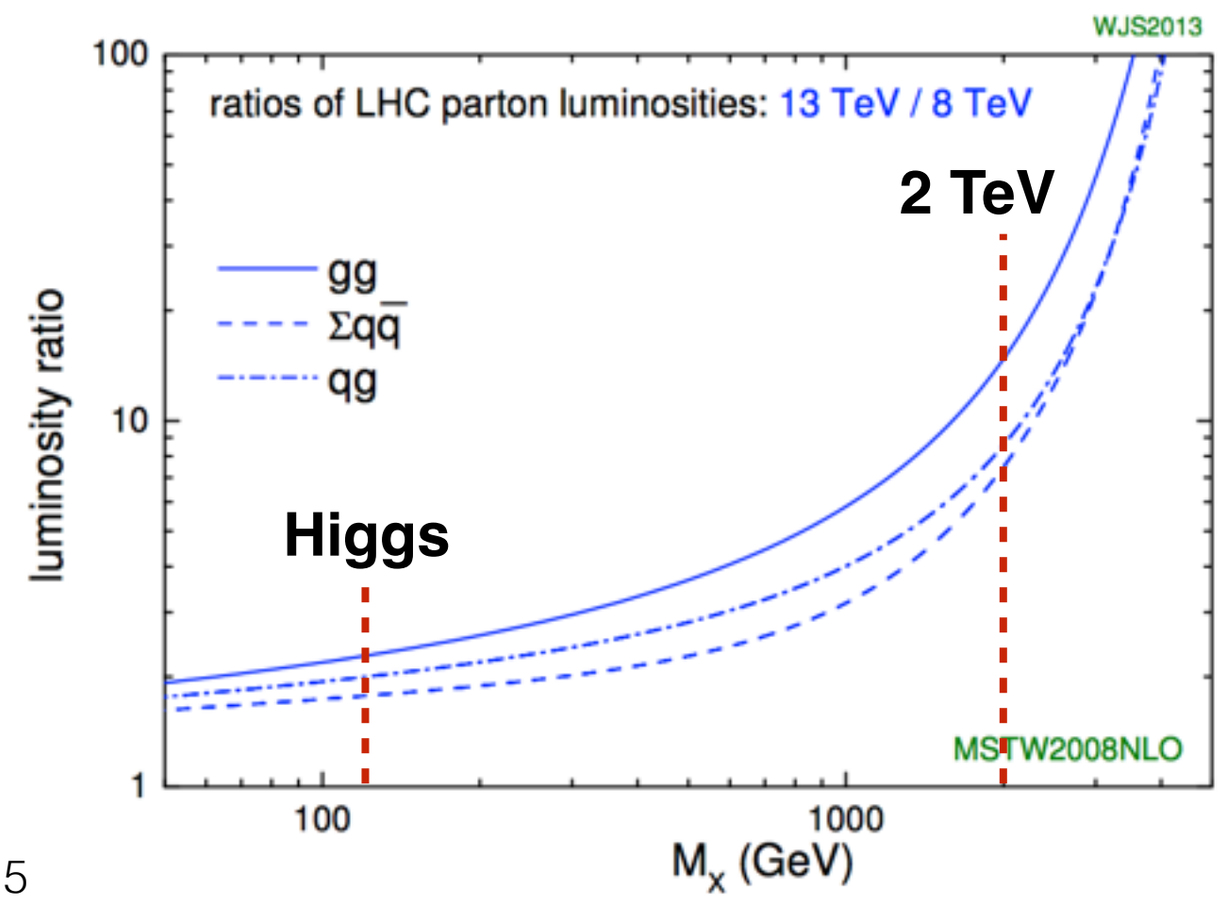


Commissioning Year 2015



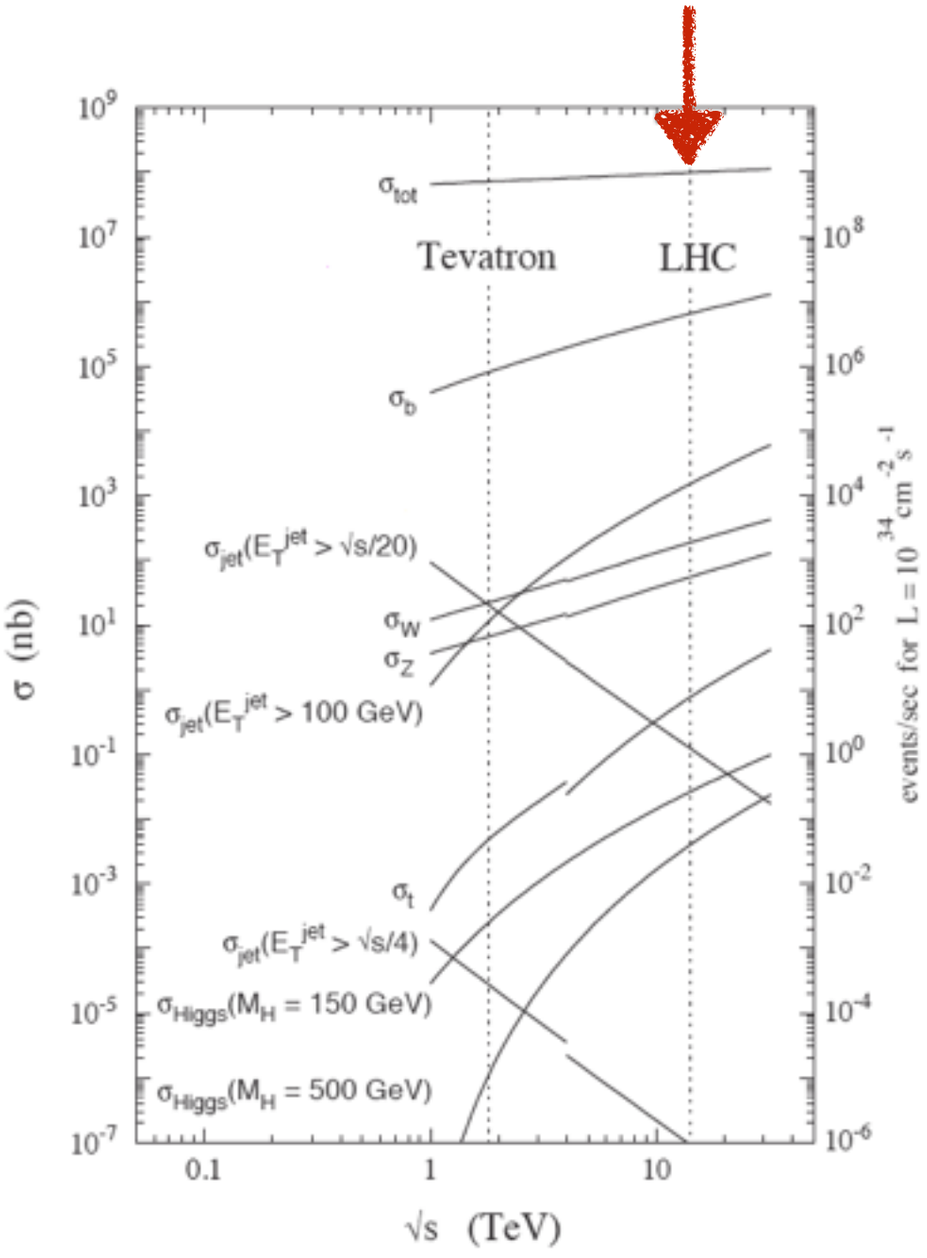


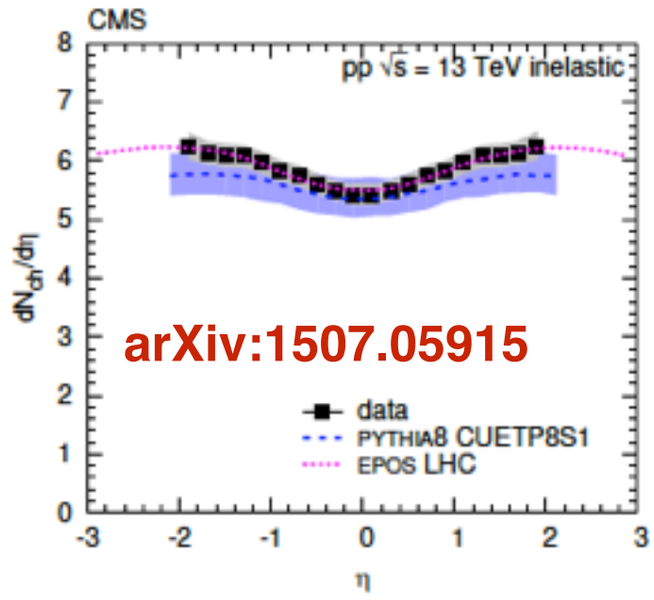
	peak lumi E34 $cm^{-2}s^{-1}$	day of proton physics	approx. int lumi [fb^{-1}]
2015	~0.5	65	3
2016	1.2	160	30
2017	1.5	160	36
2018	1.5	160	36

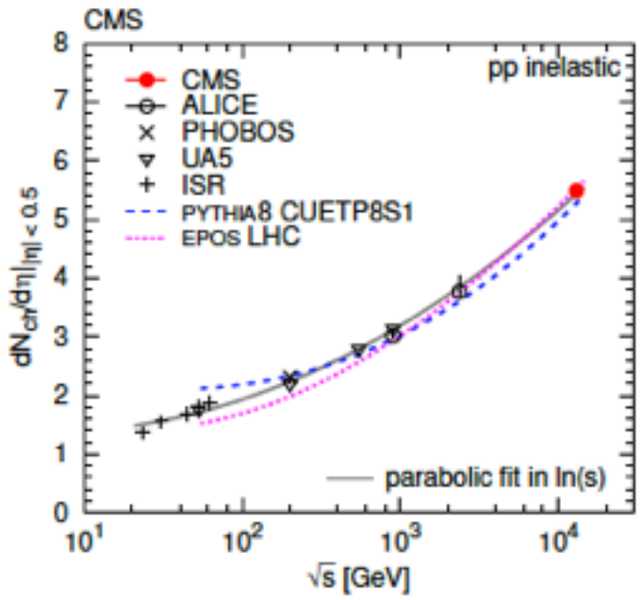


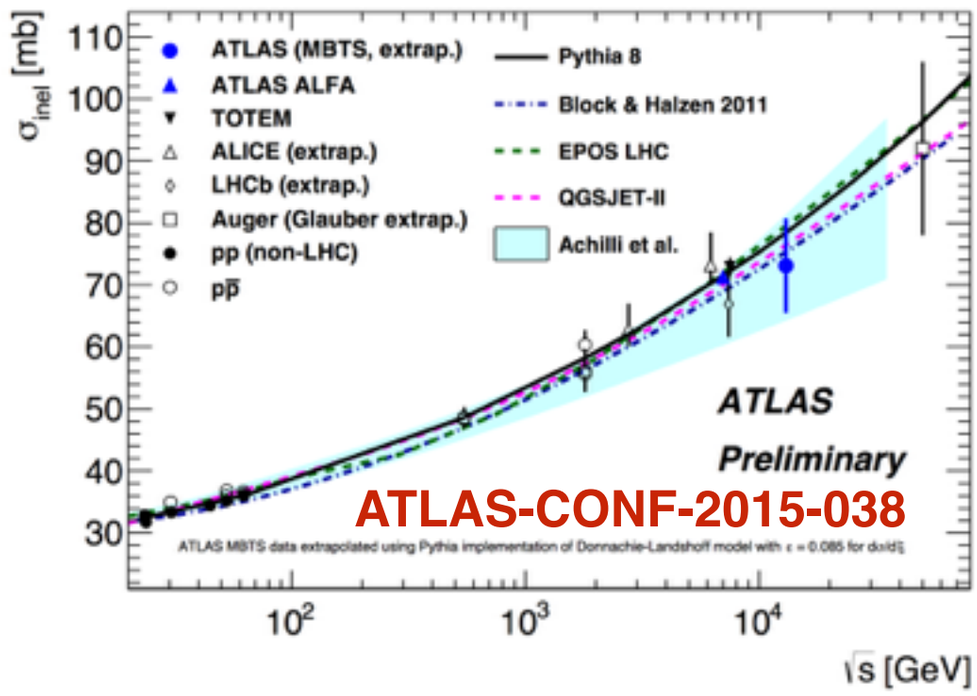
First 13 TeV Results

- ➡ Measurements of event properties and production rates
- ➡ The first of the first …
  - ◉ pseudorapidity distribution of charge hadrons
  - ◉ inelastic cross sections



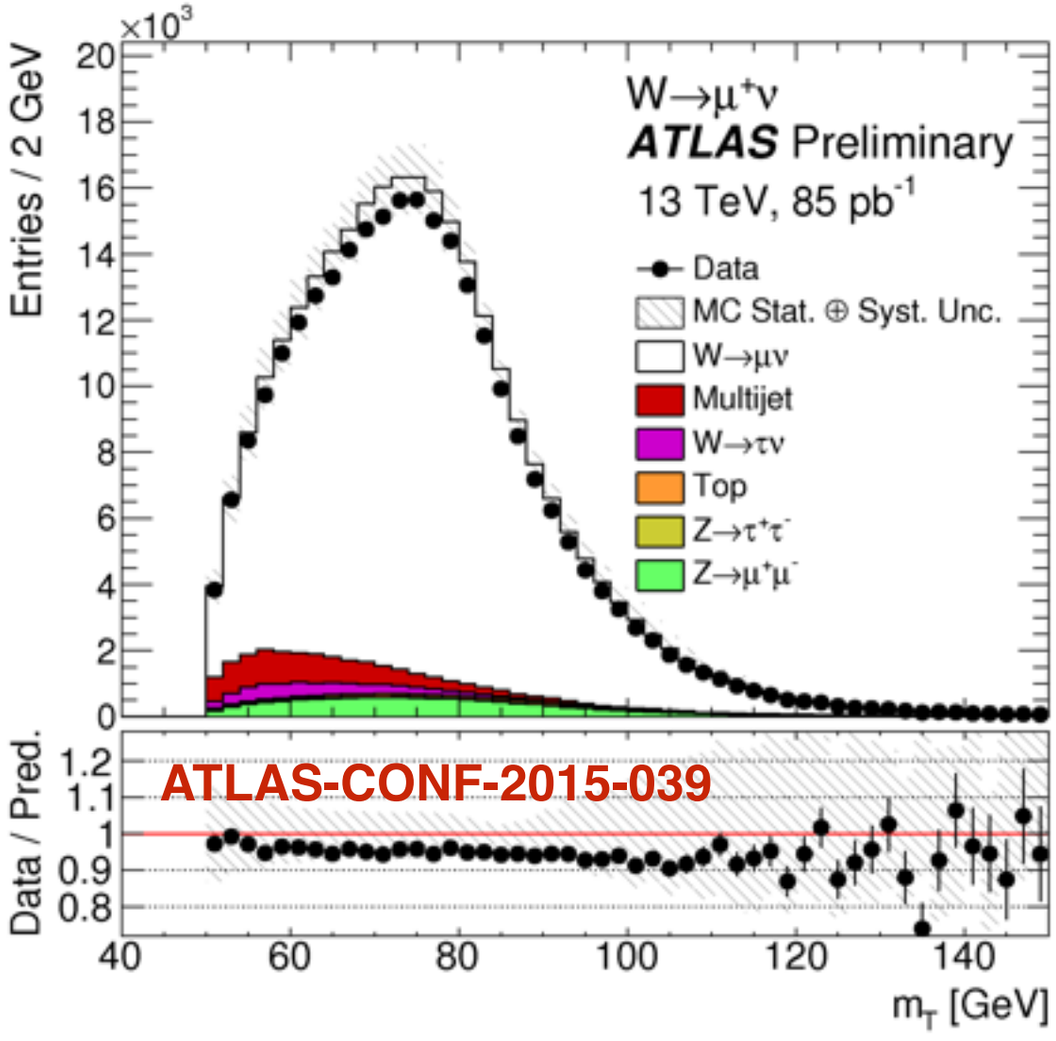


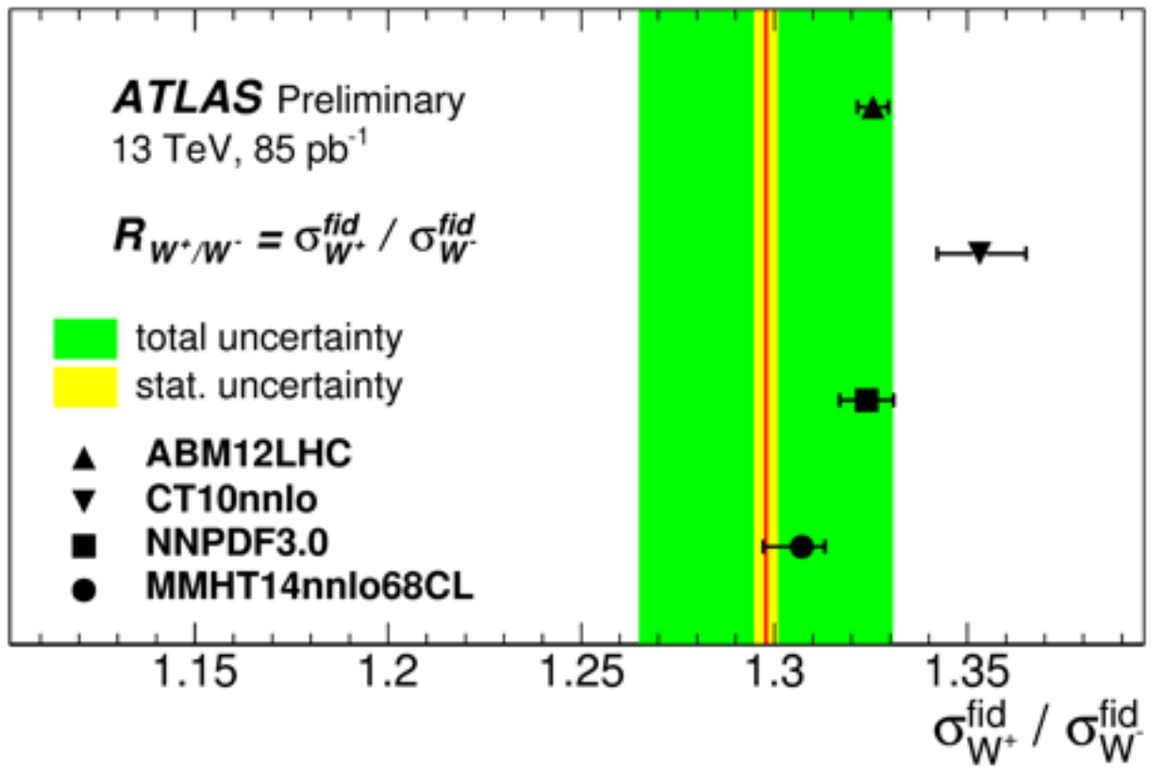


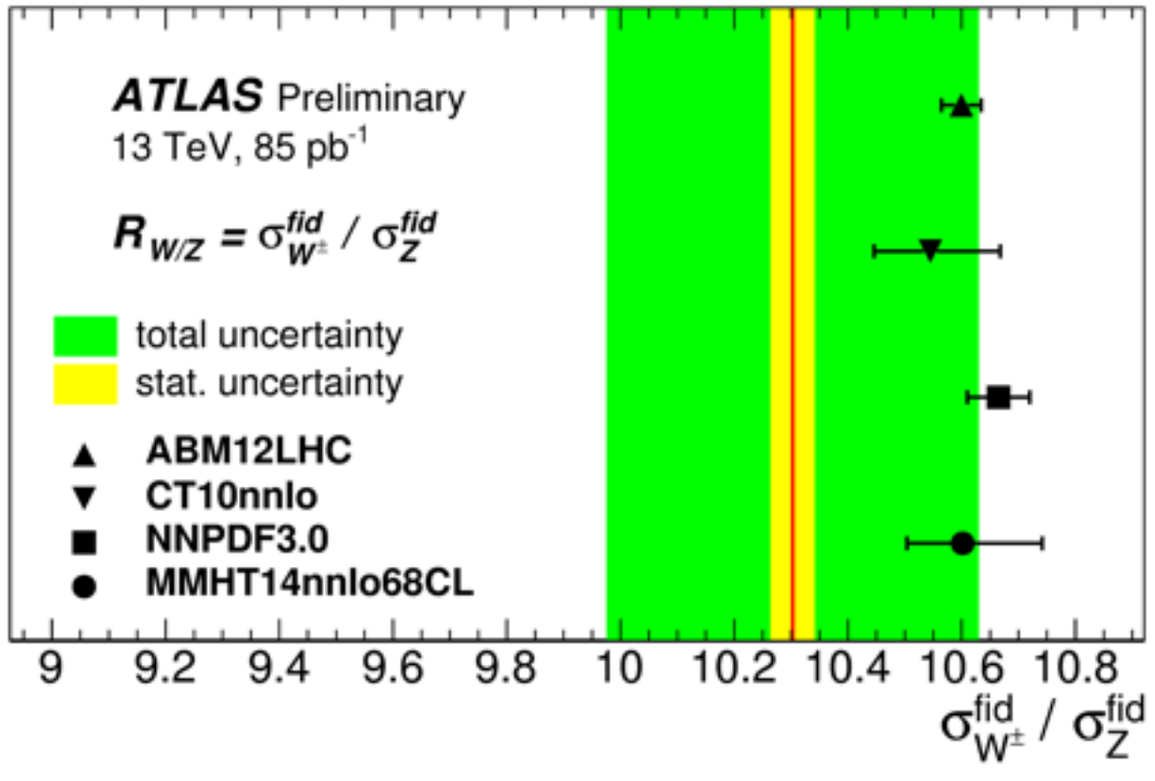


First 13 TeV Results: W and Z bosons

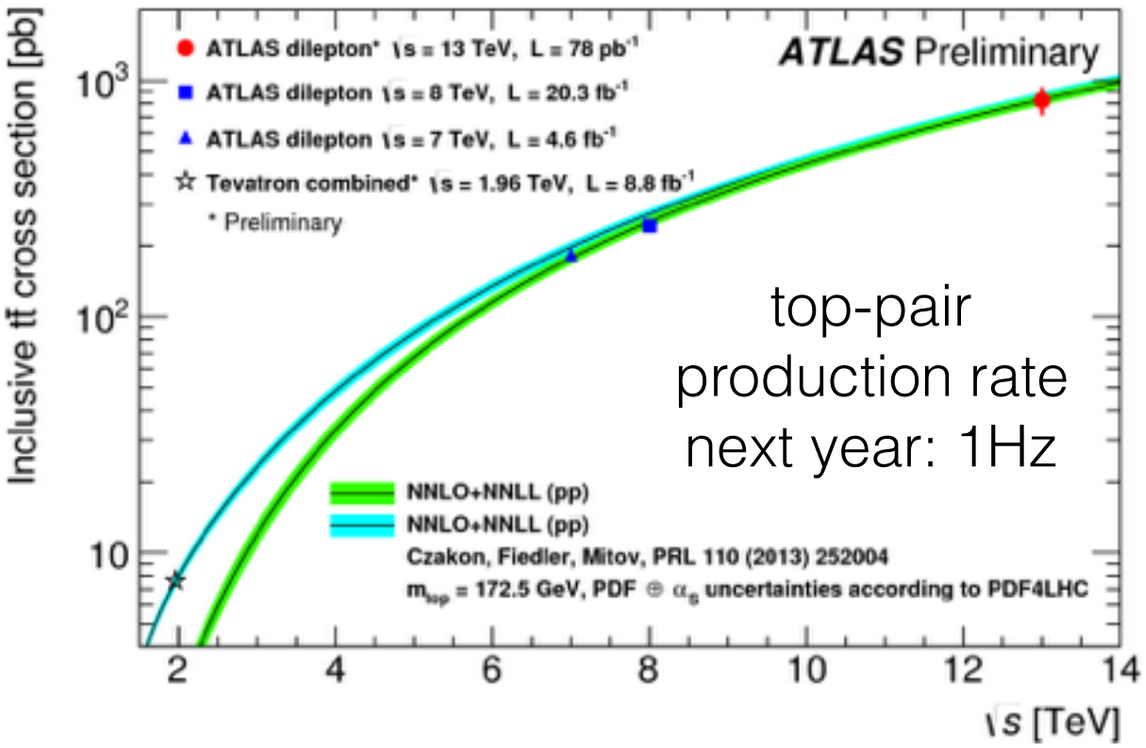
- ➡ **Precision tests of QCD**
- ➡ **Constraints on proton structure**
- ➡ **Commissioning electrons, muons, and missing transverse energy**
- ➡ **Luminosity calibration not final**



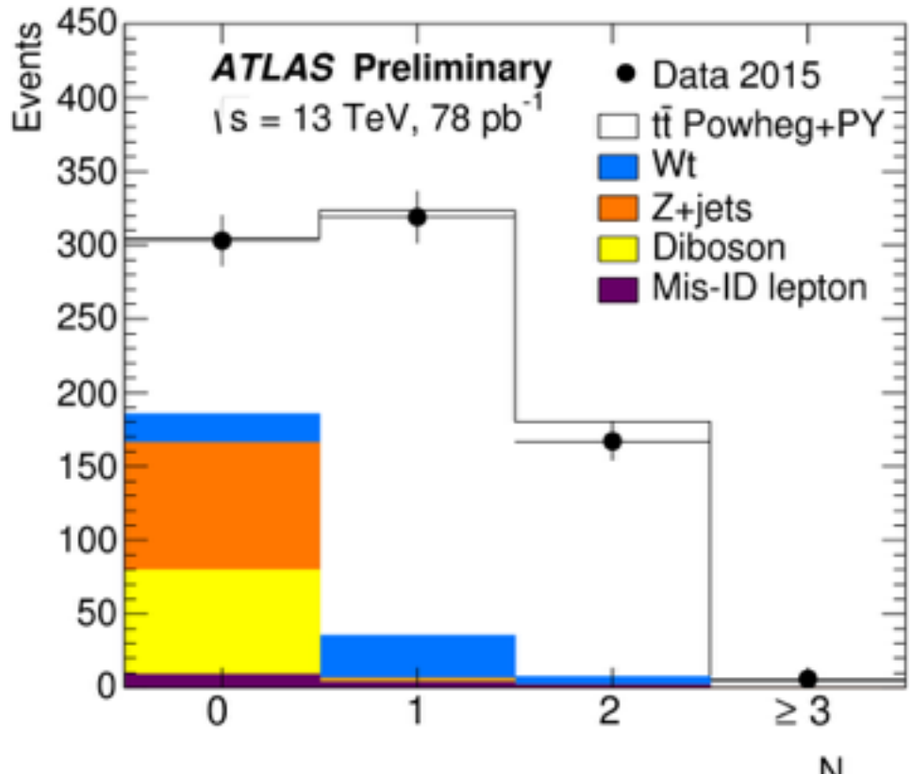


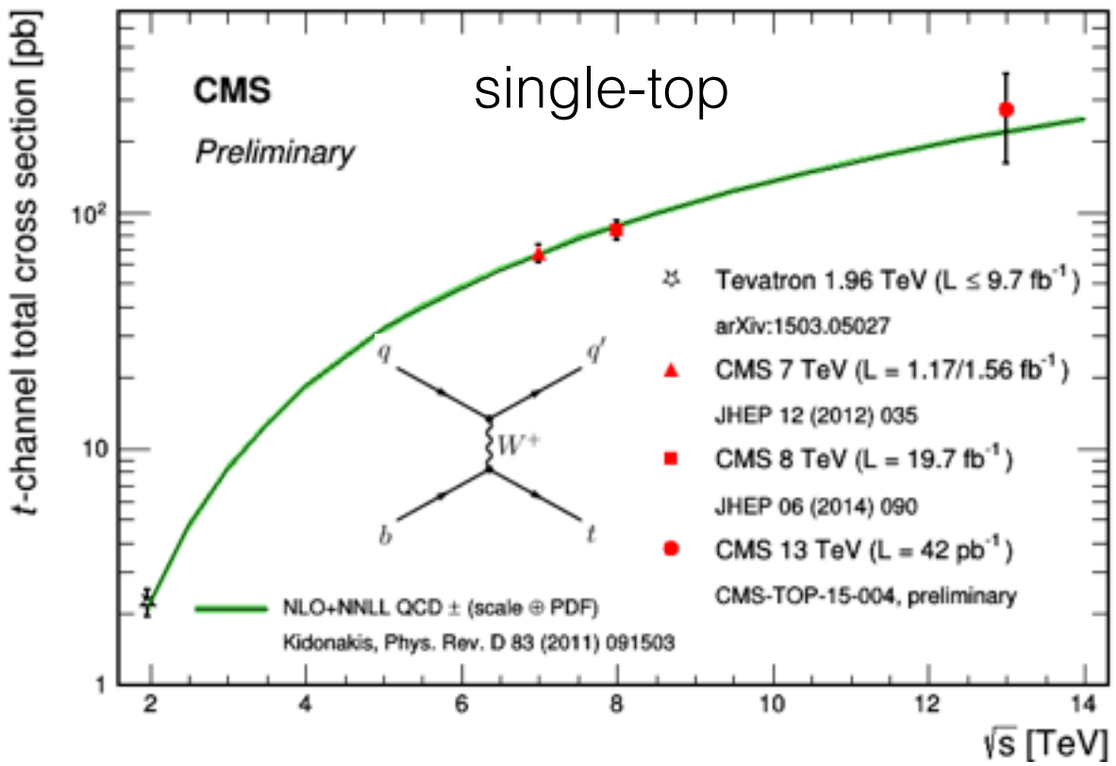


First 13 TeV Results: Top

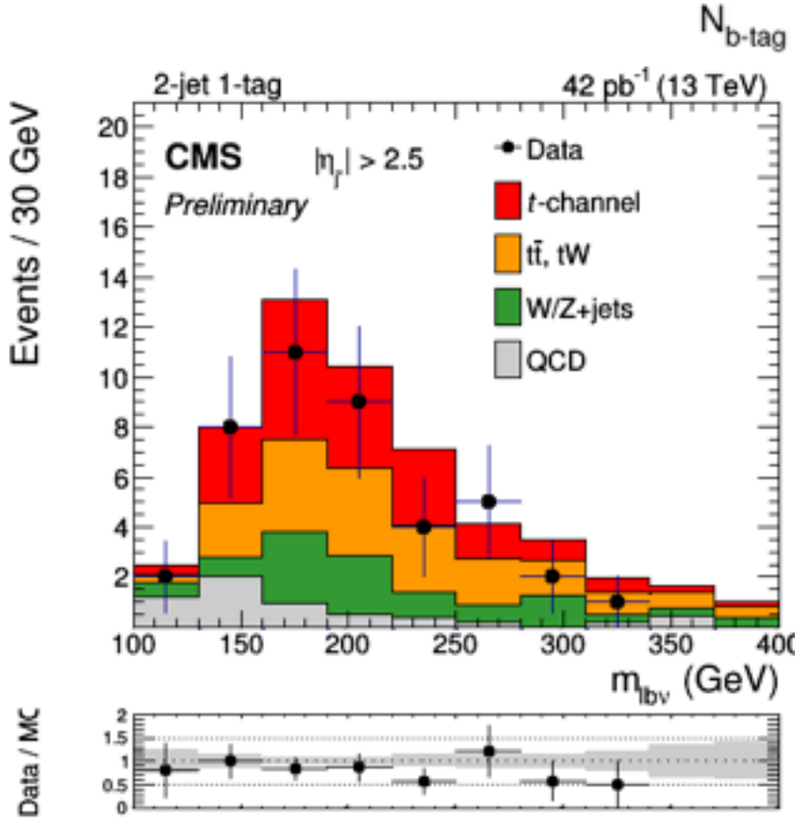


top-pair production rate next year: 1Hz



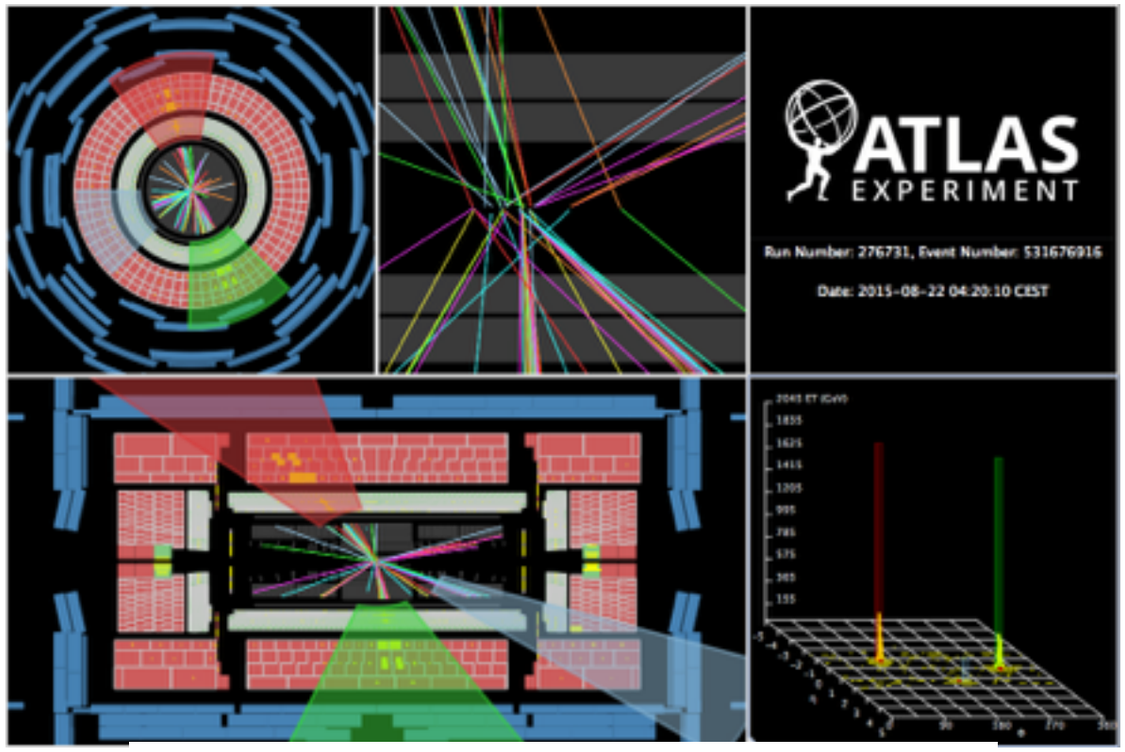


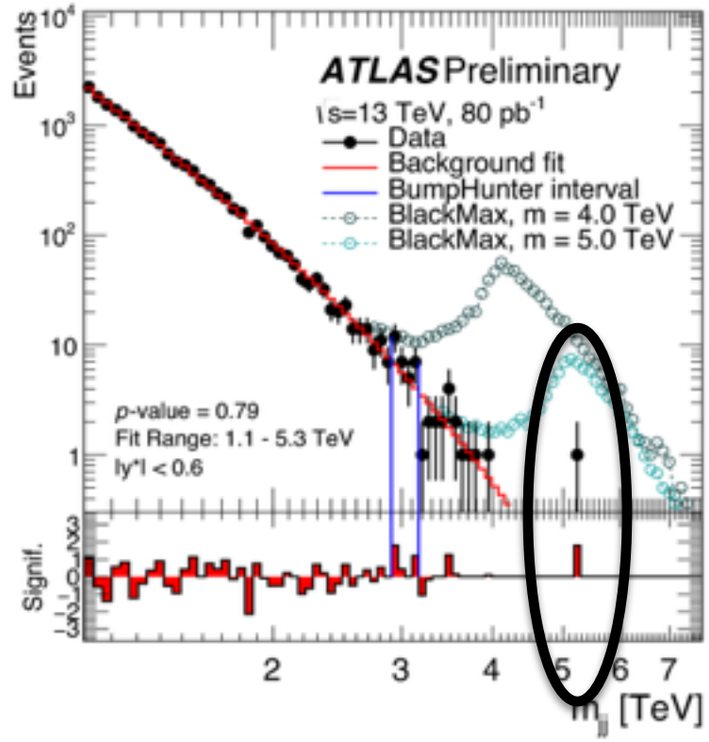
single-top



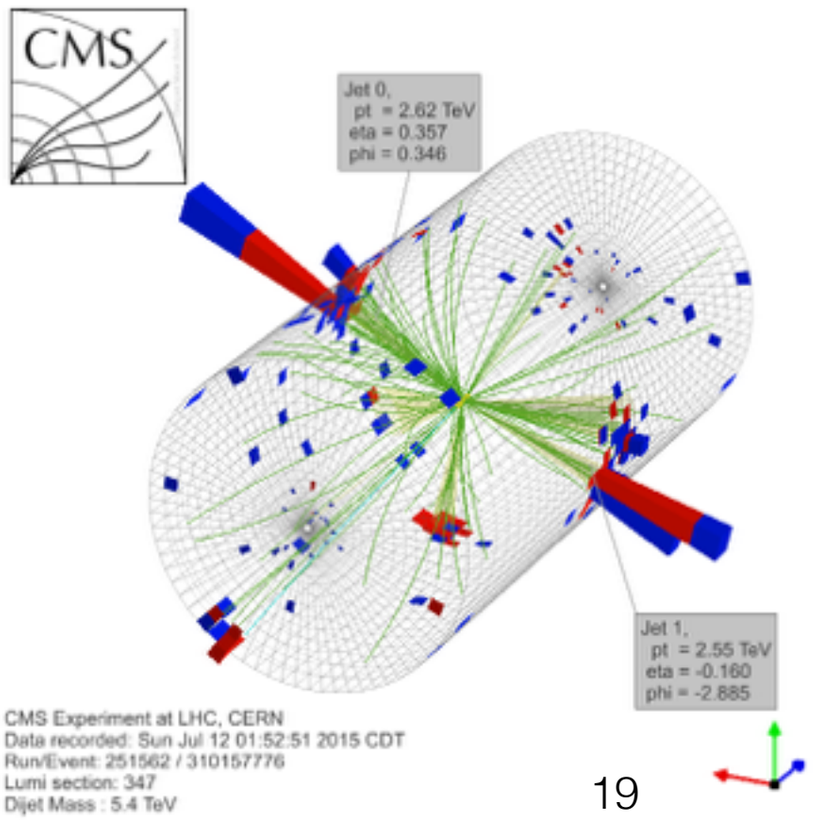
First 13 TeV Results: Jet Resonances

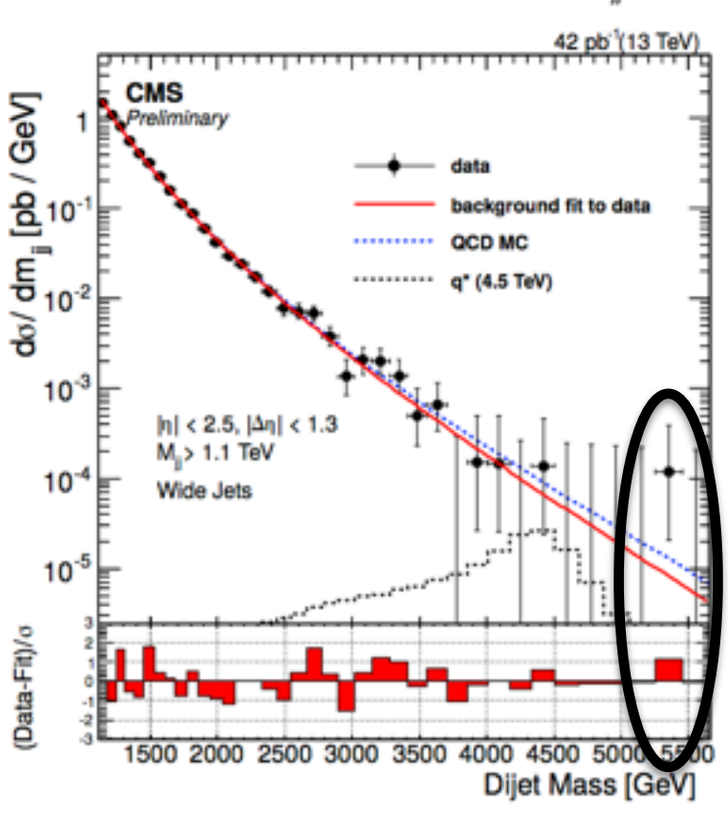
M=5.2 TeV



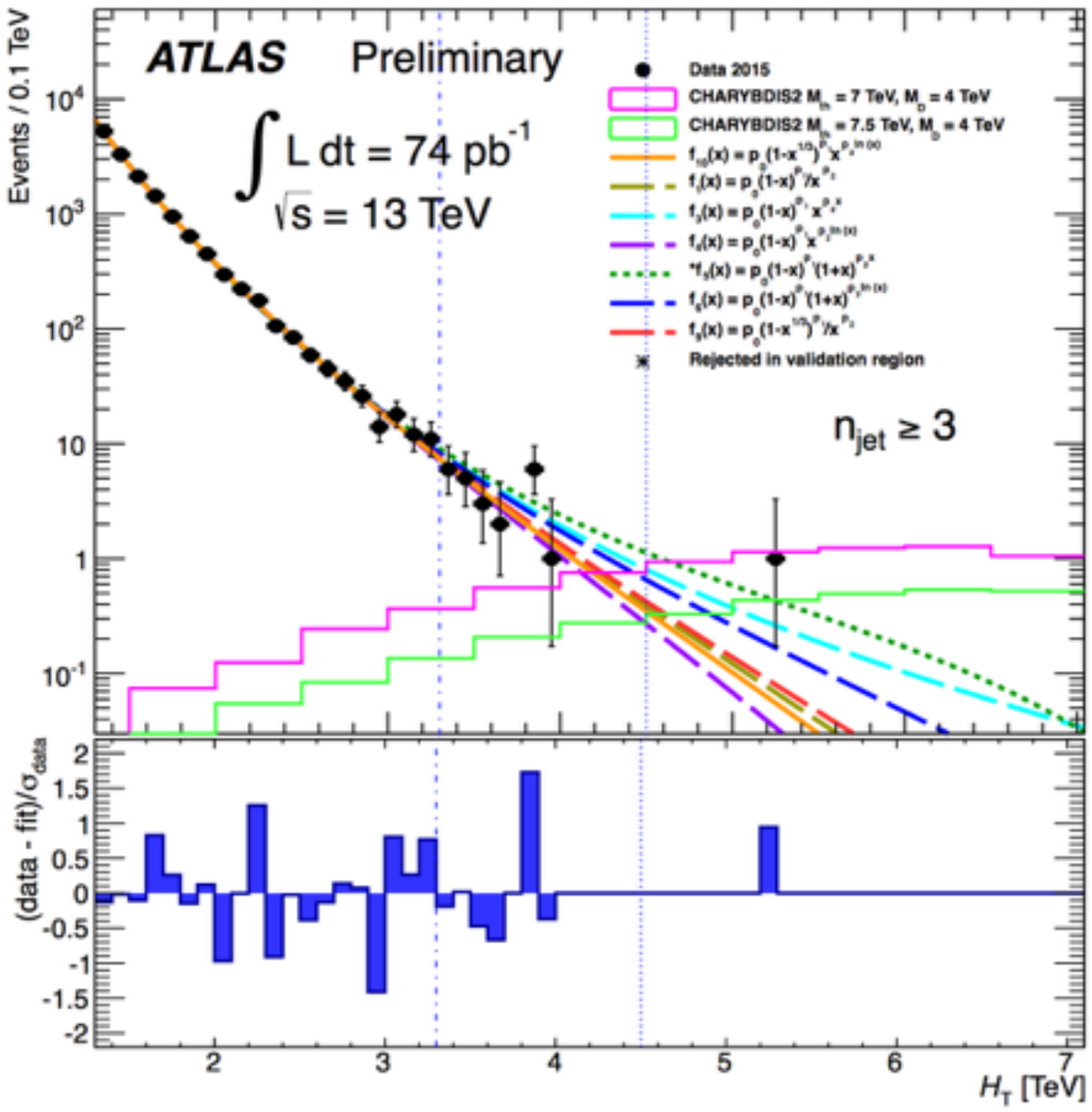


M=5.4 TeV

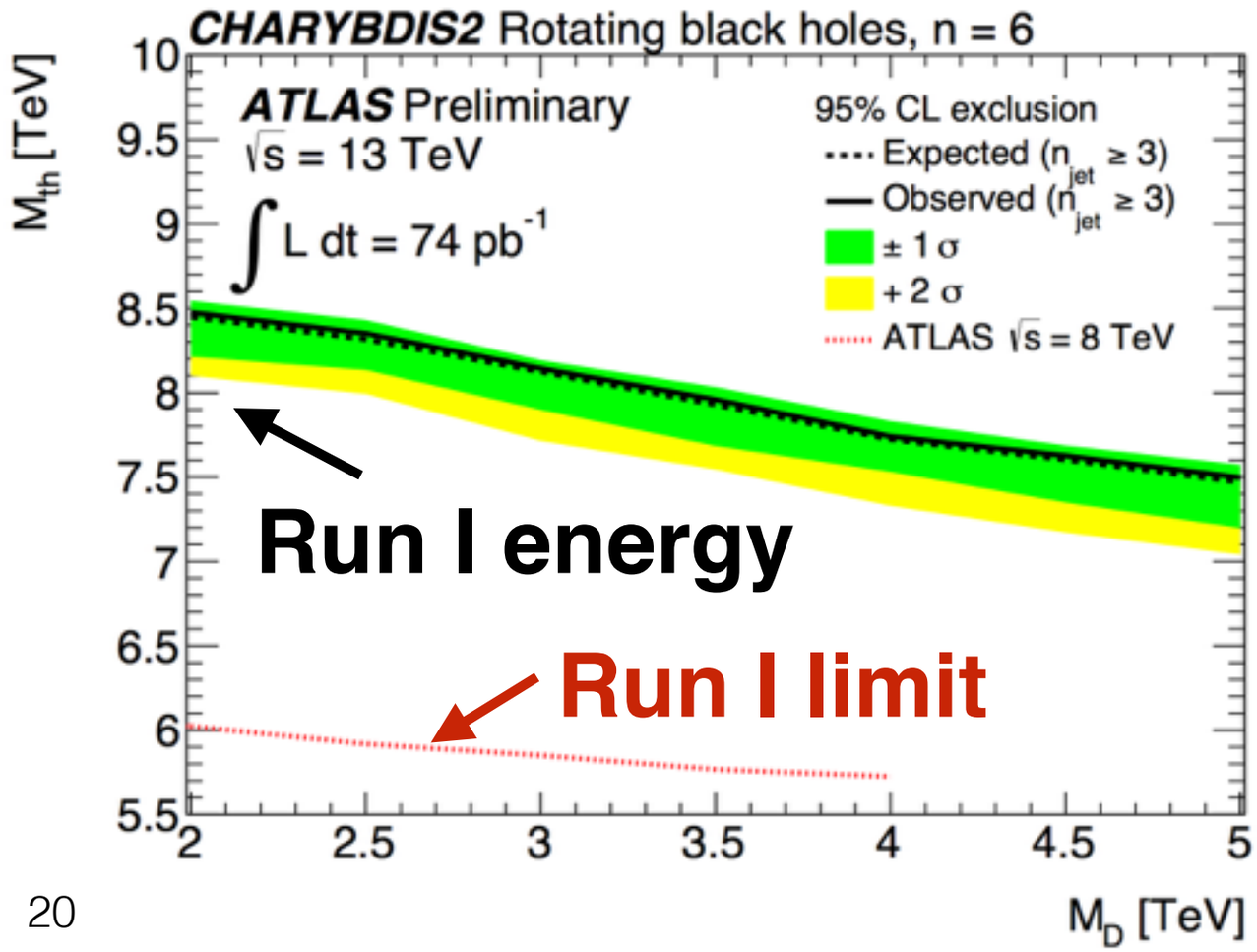




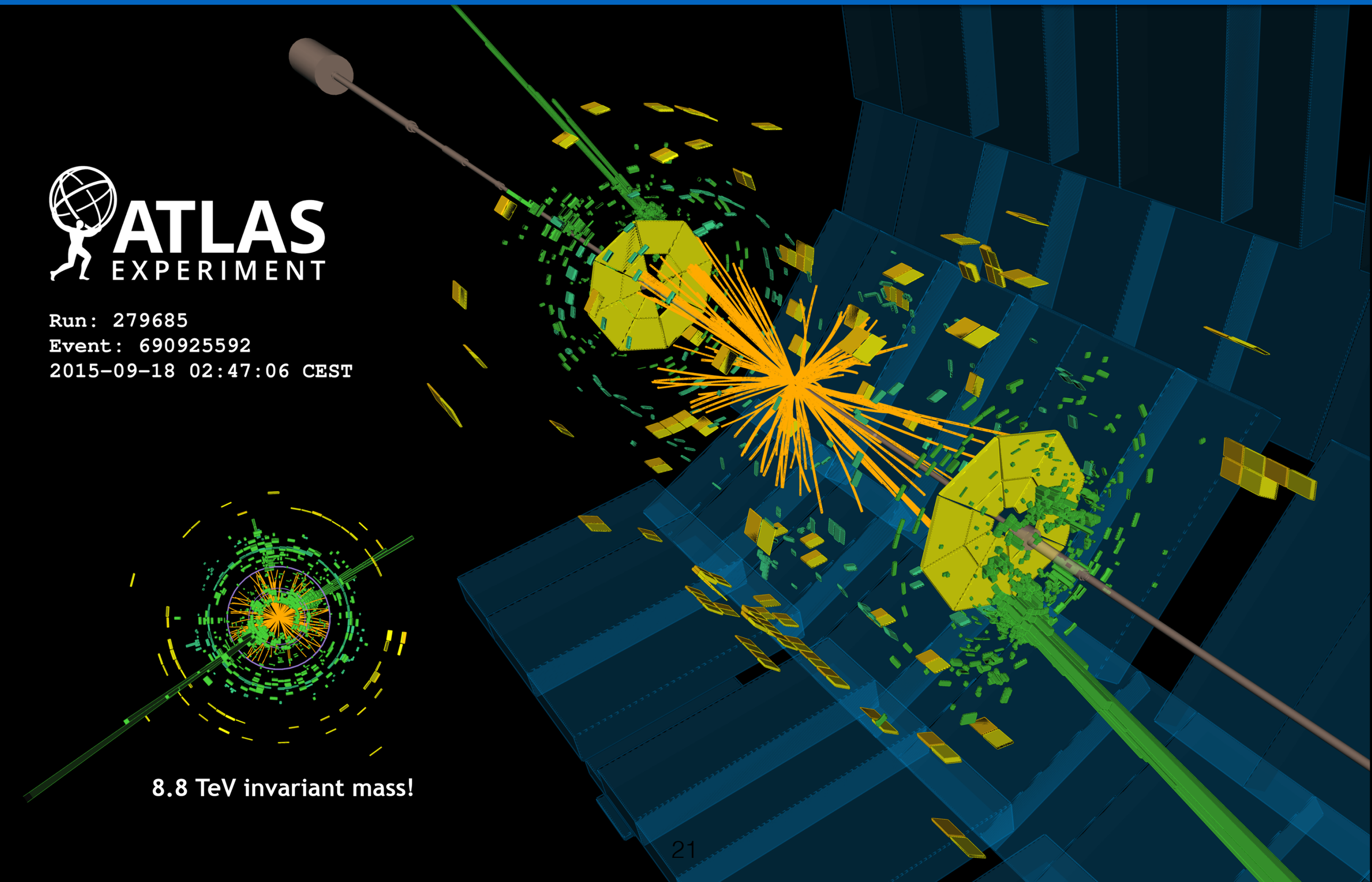
First 13 TeV Results: Jet Resonances



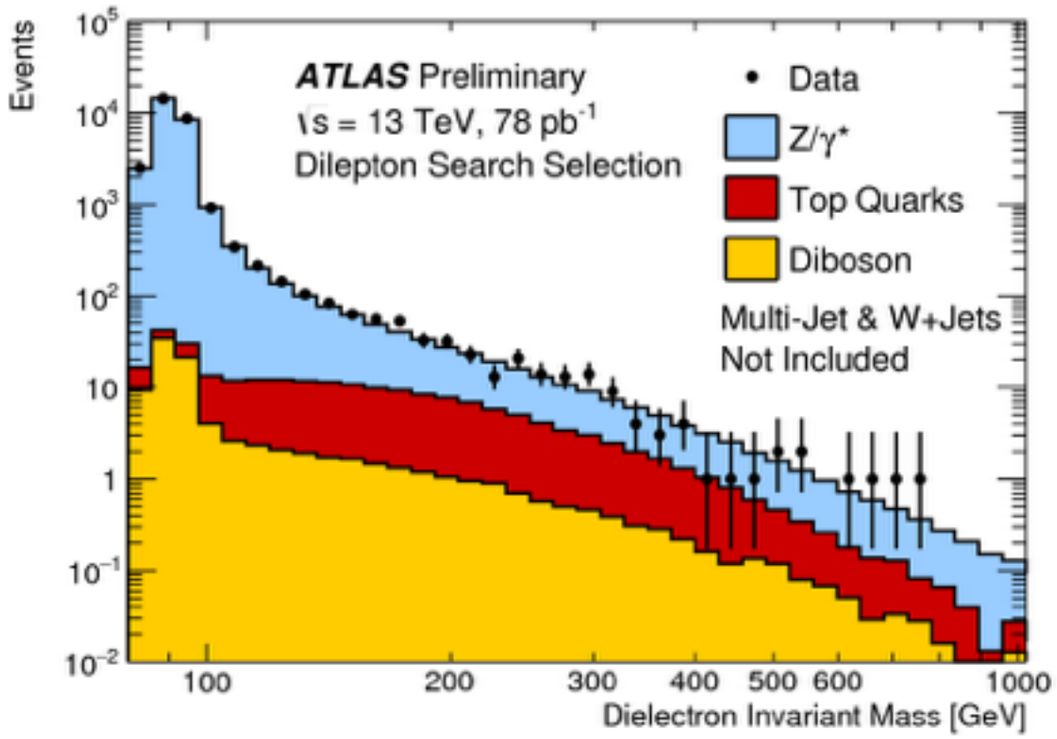
- ➡ Searches for black holes
- ➡ HT is sum of transverse momenta of all jets
- ➡ Superseded Run I results early in Run II

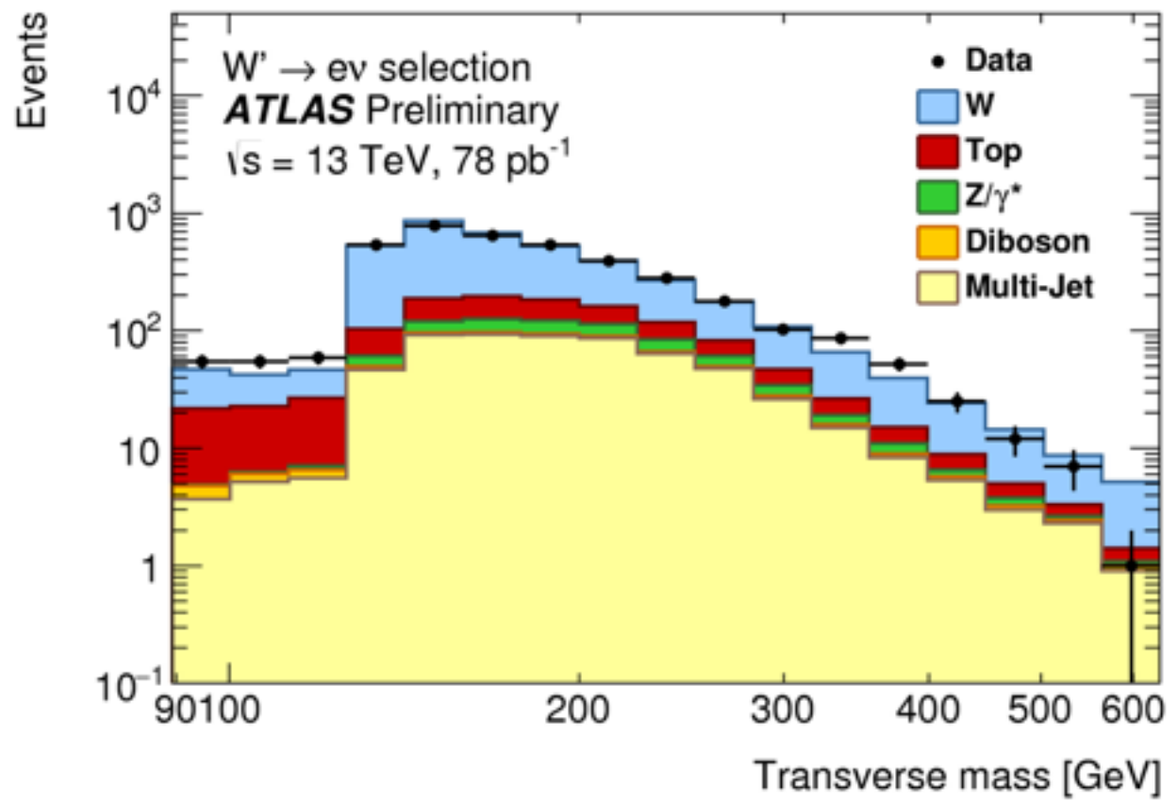


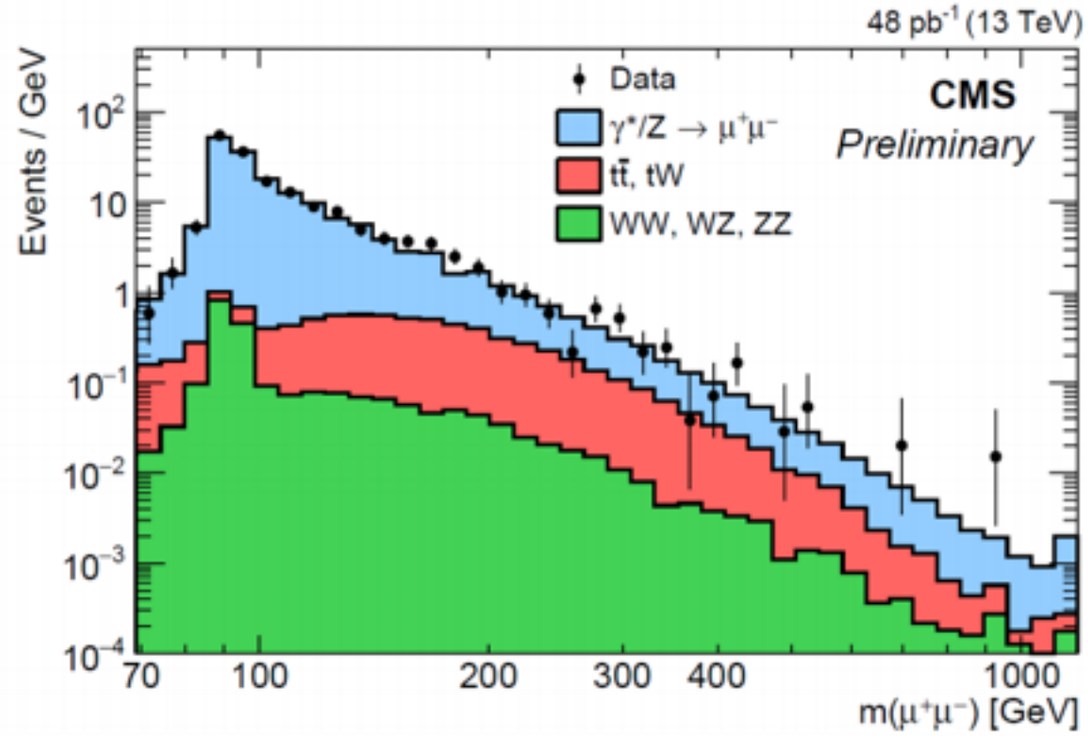
First 13 TeV Results: Jet Resonances



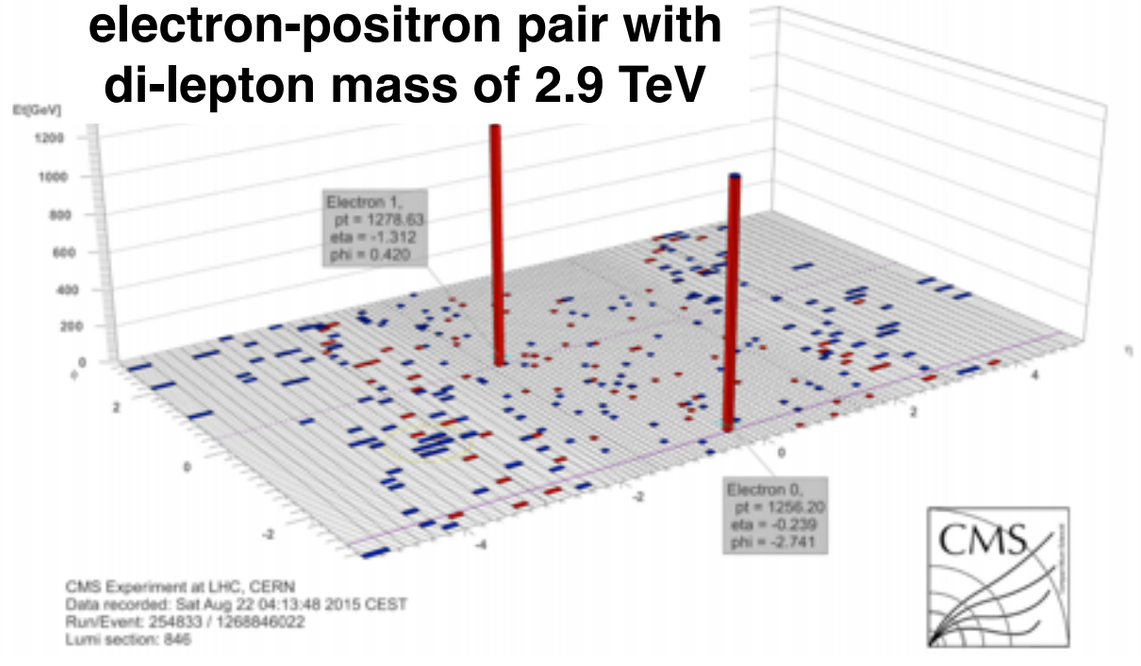
First 13 TeV Results: W' and Z' searches



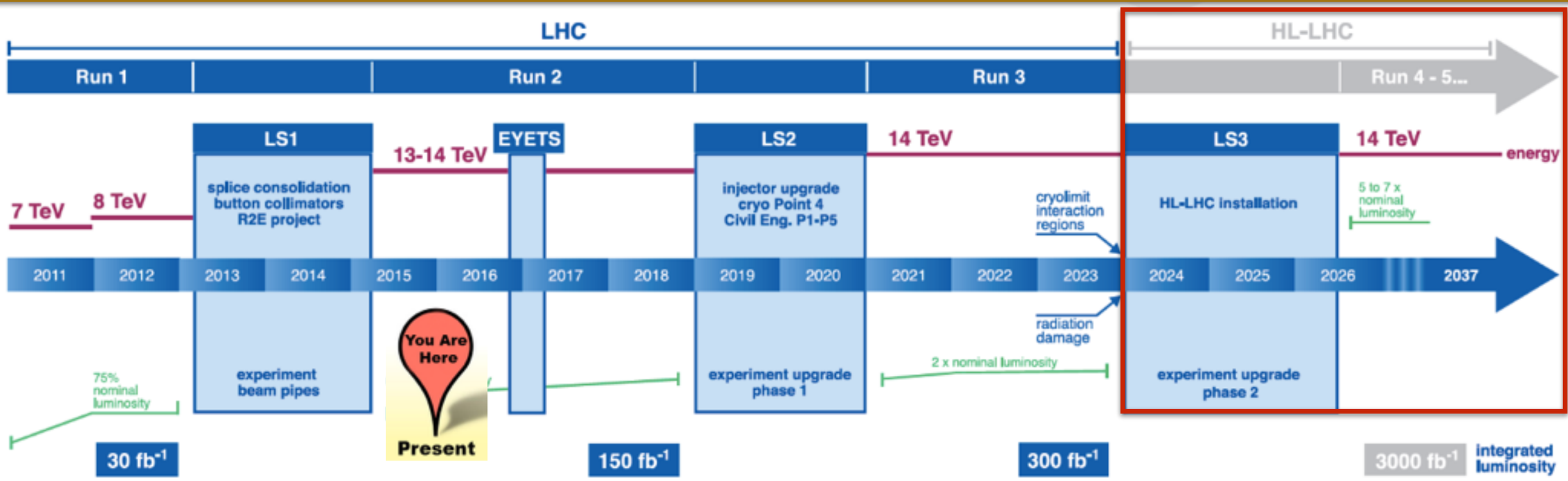




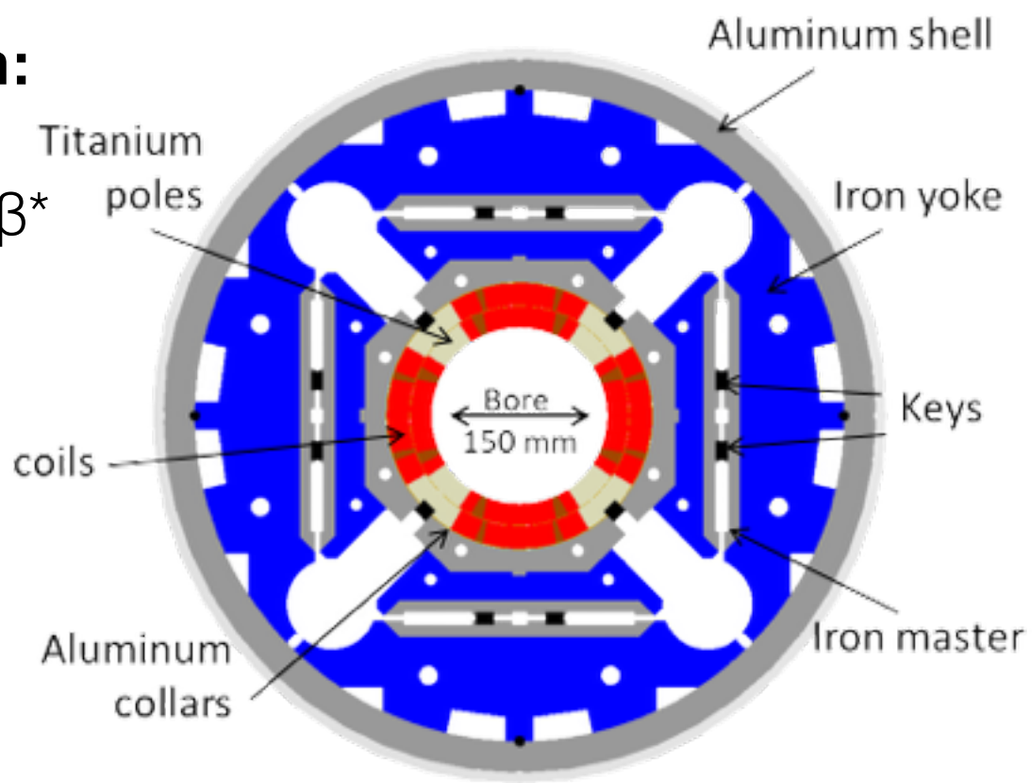
electron-positron pair with di-lepton mass of 2.9 TeV



Exploiting the LHC Physics with the HL-LHC



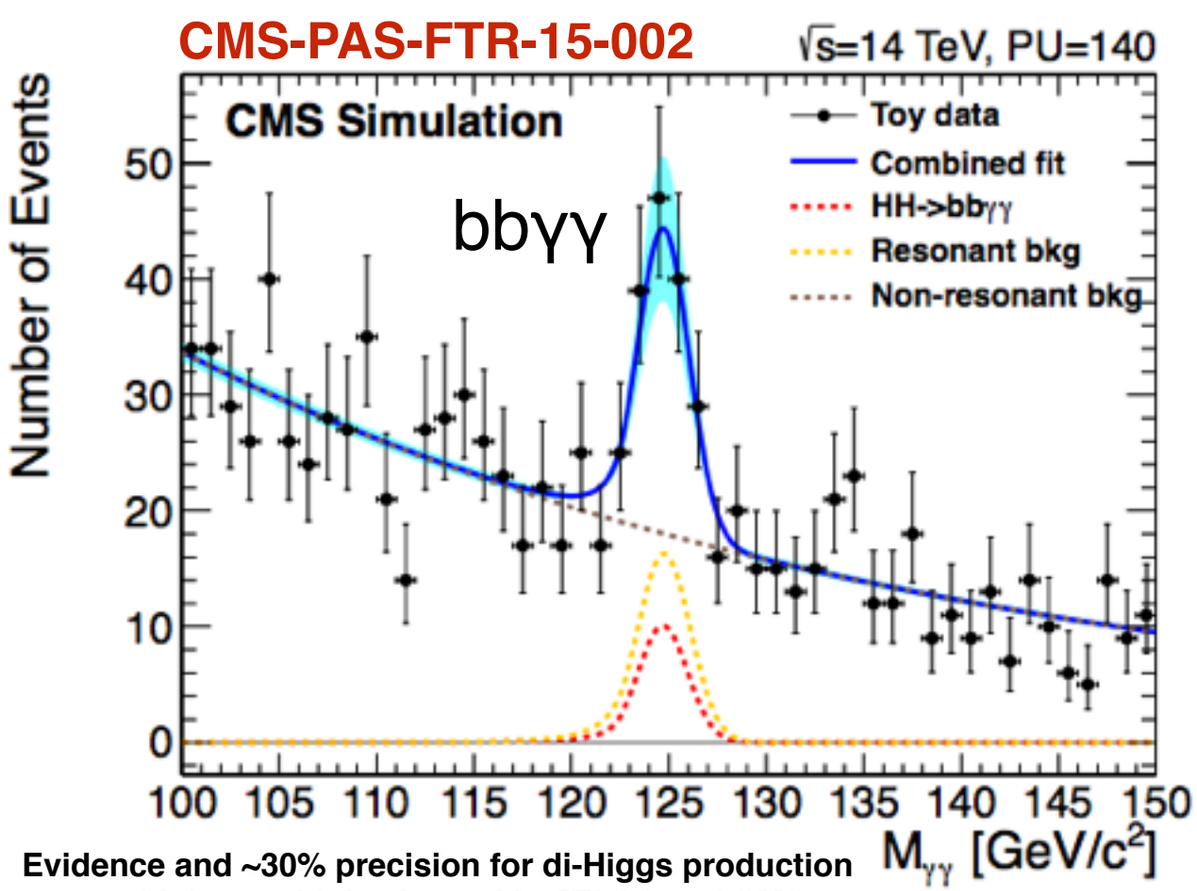
- ➡ **HL-LHC needs new technology in iteration region: Nb_3SN**
  - 12T quadrupoles with 150mm aperture to shrink β*
- ➡ **HL-LHC enables 20+ year program with large discovery potential**
- ➡ **Baseline detector upgrades endorsed. Experiments moving towards the developing of Phase-II TDRs**



Exploiting the LHC Physics with the HL-LHC

	$\Delta\kappa_\gamma$	$\Delta\kappa_W$	$\Delta\kappa_Z$	$\Delta\kappa_g$	$\Delta\kappa_b$	$\Delta\kappa_t$	$\Delta\kappa_\tau$	$\Delta\kappa_\mu$
Run I Combination	12	10	10	15	25	29	15	
CMS projection 300fb^{-1}, 14 TeV	5	4	4	6	10	14 **(9)**	6	23
CMS projection 3000fb^{-1}, 14 TeV	2	2	2	3	4	7 **(4)**	2	8 **(5)**

- **Precision measurements of SM parameters, including the Higgs boson, and potentially of BSM parameter**
- **Sensitivity to rare SM & BSM processes**
- **Extension of discovery reach in high-mass region**



Evidence and ~30% precision for di-Higgs production combining multiple channel in ATLAS and CMS

Conclusion

- **Fantastic results - in quality and quantity - from LHC Run I**
- **Exploration of Higgs Physics at the LHC on its way**
  - New information on Higgs physics expected in 2016
  - HL-LHC will set a high bar for Higgs physics
- **Non-Higgs Run I searches yield null results**
  - Stringent limits on new physics
  - And a handful of intriguing channels to look out for
- **First 13 TeV (Run II) results on limited dataset available**
  - Understanding often already comparable to Run I
  - First measurements completed, many searches under way
  - Sensitivity of Run I and II comparable for m_X = ~2 TeV
- **HL-LHC enables a 20+ year research project with large discovery potential**