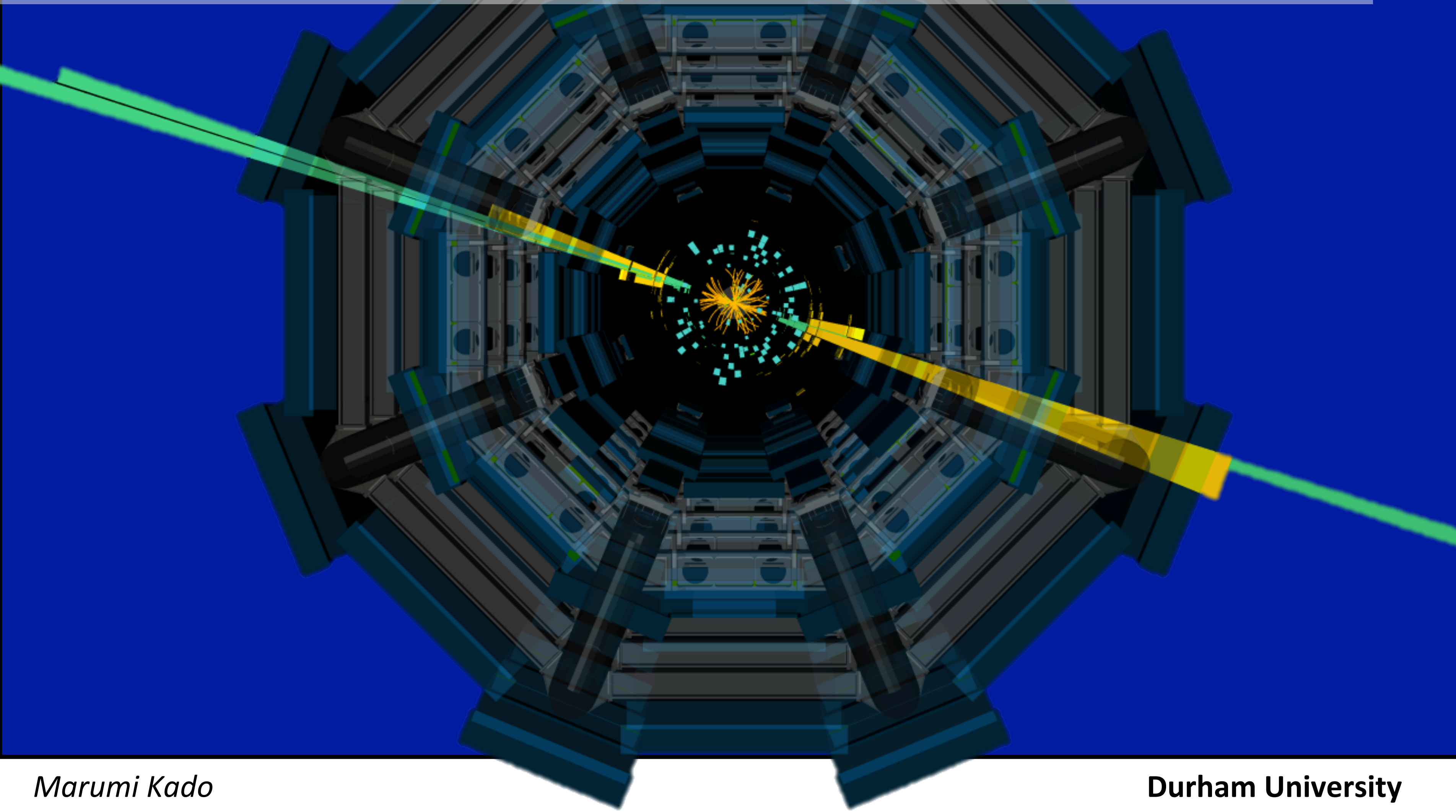
Recent Highlights from the LHC

Annual Theory Meeting IP^3 and STFC - Durham



Marumi Kado

LAL, Orsay and CERN

Durham University

December 19, 2016

Disclaimer

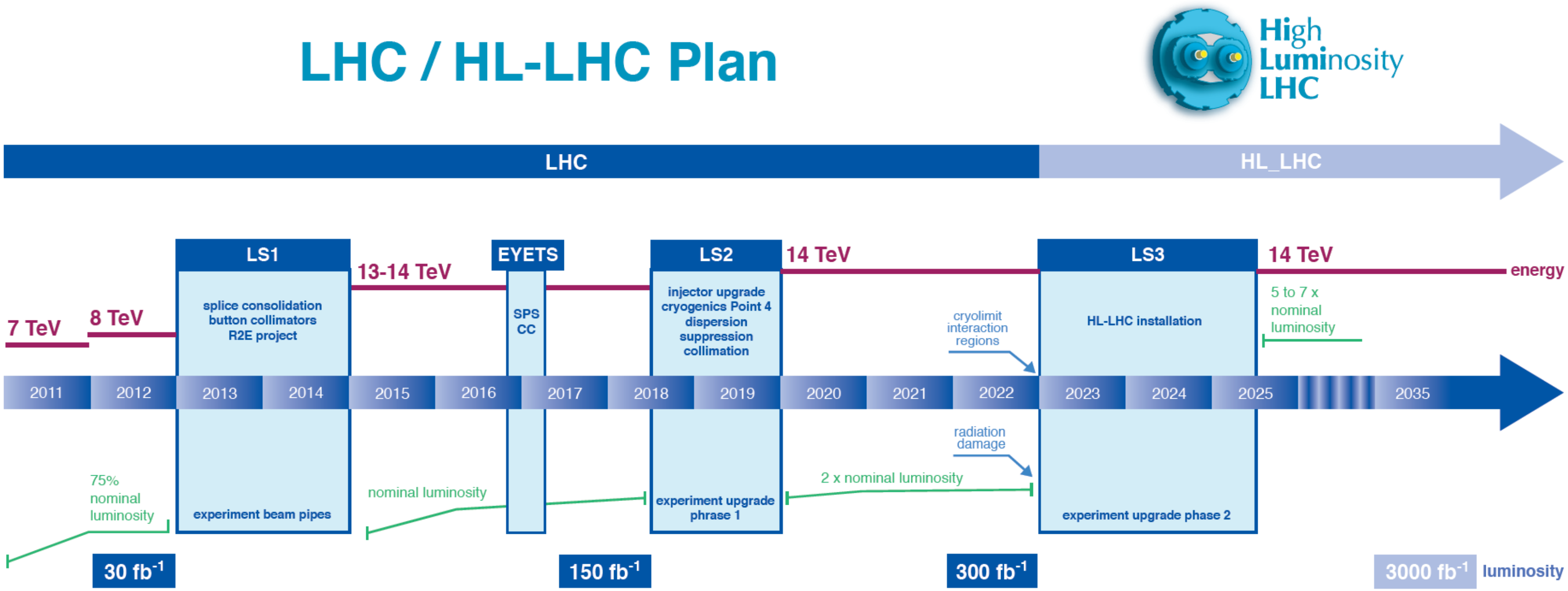
This talk will **mainly focus on results from the ATLAS and CMS collaborations published in 2016.**

It will not show the host of beautiful results from the other experiments (ALICE, LHCb, ALFA, TOTEM, LHCf, MoEDAL).

Complete list of publications from ATLAS and CMS

- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications

Machine Status (in a nutshell)



Where do we stand?

- 8^{th} year of the (25 year) program. Reaching almost nominal centre-of-mass energy and surpassed nominal luminosity estimates.
- At the start of an Extended YETS: in particular to replace CMS inner pixel detector.

2016 Outstanding performance of the LHC

- Peak luminosity from 1.5 10^{34} $cm^{-2}s^{-1}$
- Integrated delivered luminosity of 40 fb^{-1}.

Reappraised goal for Run-2

New target 150 fb^{-1} in 2018.

Machine Status (in a nutshell)

2016 was declared a production year… and the operation team delivered!

With immediate noticeable changes in 2016:

- A lower β^* of 40cm instead of 80cm in 2015.
- A smaller bunch spacing of 25ns

(Some of) **the reasons behind the outstanding luminosity reach in 2016**:

- High machine availability (less UFOs, many fixes and tunings)
- High luminosity lifetime (tunes, couplings and bunch length)
- High peak luminosity (low emittance with BCMS, low beta*, and crossing angle)

For more details see talk by B. Salvant at the LHCC

Such a complex project encountered various issues, very prompt solutions were found: **Congratulations to the Machine operations and coordination teams!**

Possible goals for next year

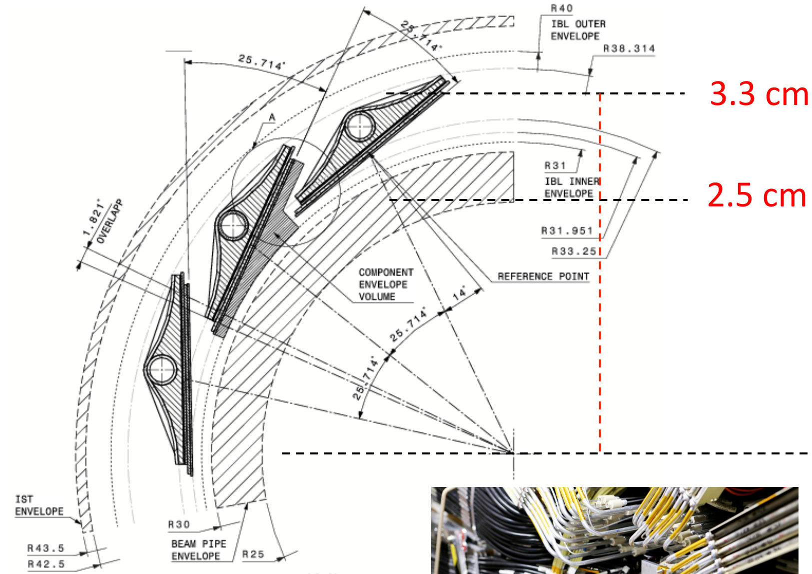
- Peak luminosity from 1.4 - 2 10^{34} $cm^{-2}s^{-1}$ (depending on BCMS scheme).
- Peak PU from 37 to 56.
- Integrated luminosity between 45 and 60 fb^{-1}.

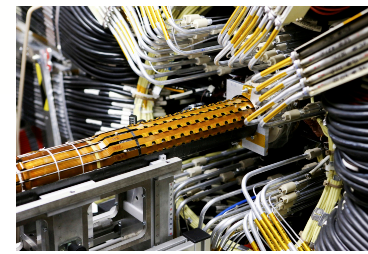
Main Detector Improvements

Important changes in all areas of the experiment

ATLAS – Phase 0

- 4th innermost layer of pixels (3.3 cm, 2nd layer at 5.05 cm)
- Consolidation: Complete muon coverage, Luminosity detectors, Repairs (LAr and Tile), Beam Condition. Monitors
- Infrastructure: New Beam Pipe, Magnets and Cryogenic system, Muon Chamber shielding, New pixel services
- Trigger/DAQ: Increase max L1 rate from 75kHz to 100kHz, new Central Trigger Processor, Merge L2 and HLT farms, Additional SFOs for higher output rate.
- Topological L1 triggers
- Fast Track Trigger



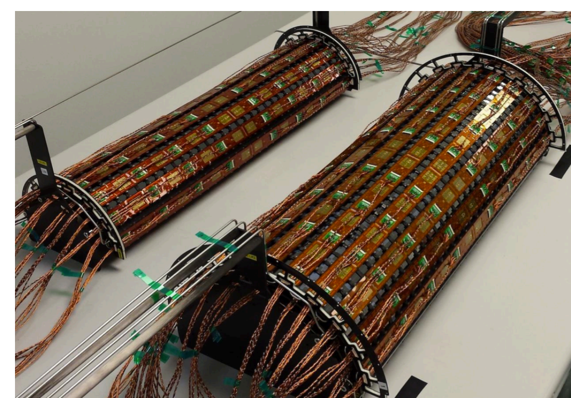


Inserted during LS1

CMS – Phase 0

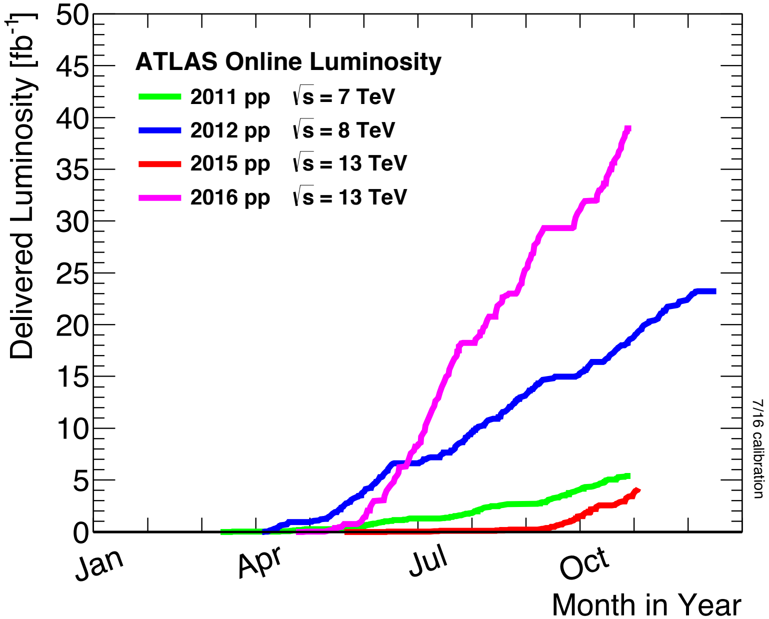
- Complete muon coverage
- Replace HCAL photodetectors
- During LS1 L1 Triger upgrade
- New Pixel detector: to be inserted during the EYETS
- L1 Trigger upgrade

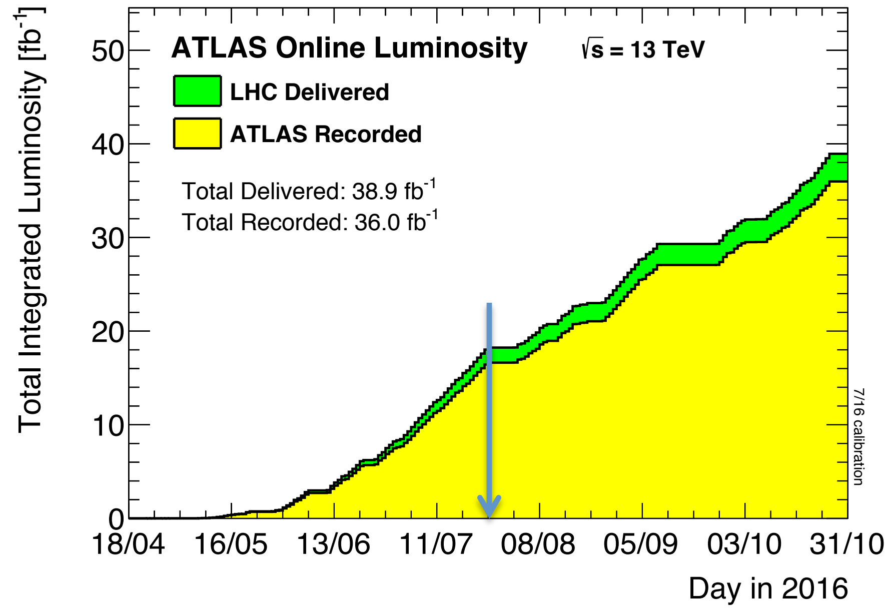
Both for ATLAS and CMS Reconstruction and analysis software are regularly updated.



To be inserted during EYETS

2016 Data





ATLAS and CMS Excellent data taking and data quality efficiencies:

- ATLAS has recorded 36.0 fb^{-1} and CMS 37.8 fb^{-1}.
- Pile-up conditions note that in 2015 – need to be careful to out-of time PU increase.

For the physics:

- Full 2015 O(30) x EPS 2015 / LP 2015 Luminosity
- ICHEP 2016 ~3 x Full 2015 Luminosity
- Full 2016 dataset ~ 3 x ICHEP 2016

Data set for results ICHEP

Typically 10 -12 fb^{-1} (ATLAS and CMS)

Hopefully soon results with 36.0 fb^{-1} then…

Doubling time of luminosity is now O(1 year)

Heavy Ion data

- PbPb collisions at centre-of-mass energies in excess of 1 PeV in 2015. Considerable stress on the performance of the reconstruction algorithms.
- pPb in 2016: Records luminosities obtained in pPb as well in 2016.

General Remarks

The outstanding performance of the LHC in 2016 has provided sufficient data to surpass the sensitivity (from the point of view of statistics) of early all Run 1 analyses.

Modeling systematic uncertainties play a crucial role in measurements and in a large number of searches, at Run 2 a qualitative improvement towards state-of-the-art Monte Carlo generators has been made.

The level of control of experimental systematic uncertainties (in-situ calibrations) require data (and time) is starting to reach the level of Run 1 (not in all areas).

Unlike in December 2015 (when a factor O(30) w.r.t. to summer of 2015 was available), this year the increase in luminosity O(3) does not justify a very prompt campaign of publication of results. No updates with the full 2016 statistics are available yet.

Where do we stand in the LHC Physic Program?

Initial Mission of the LHC:

- **The no-loose theorem**: Discover the Higgs boson or reveal strong dynamics in vector boson scattering

- **Probe the electroweak scale**: with direct searches for new phenomena beyond the Standard Model.

- **Probe the Standard model and higher scales indirectly**: Through CP-violation in Heavy Flavors, rare B decays, etc… Through precision measurements of Higgs couplings, standard EW parameters, anomalous couplings, etc…

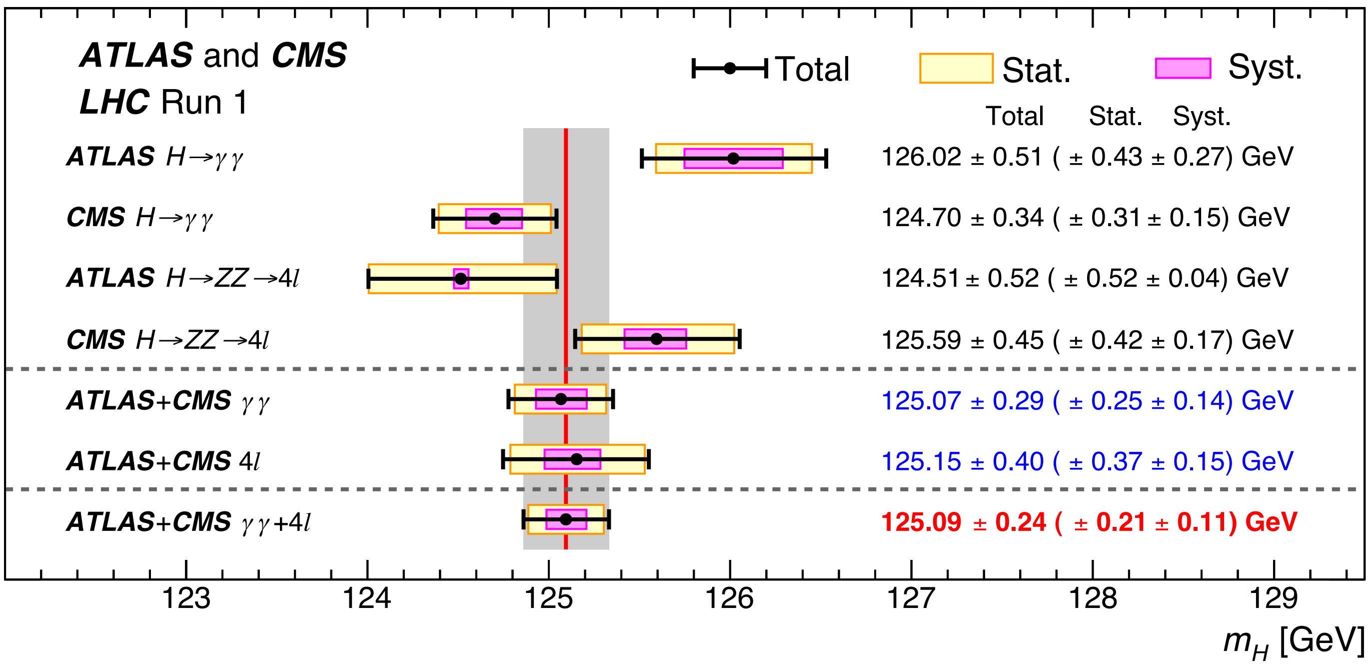
- **Study strongly interacting matter at extreme energy densities**.

In all these areas the LHC is already an immense success

A measurement of fundamental importance

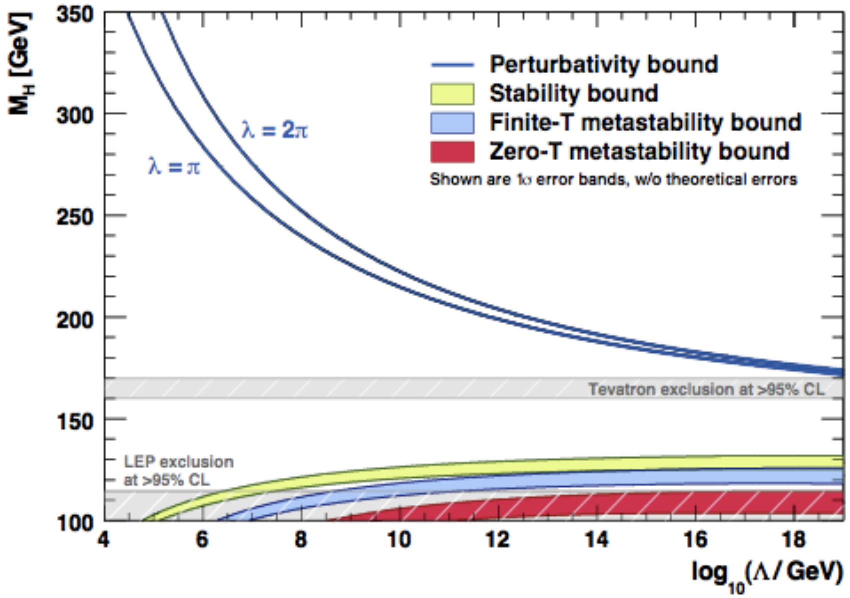
As far as we have been able to measure, the Higgs boson is Standard Model like. Within the SM, all its couplings are known.

The fundamental new parameter that we learned is its mass (and if the Higgs potential is SM-like also its self coupling).



2 per-mille precision Measurement, until last week the most precise measurement a the LHC (combined ATLAS and CMS).

Implications (I) – TH consistency



With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

- From the running of the self coupling (in the SM There is no need (or indication) that to preserve vacuum stability and avoid Landau pole (triviality) new physics is needed. With the measured value of the Higgs boson mass and **the top mass**, the self-coupling of the Higgs is vanishing at the Planck scale (is there an underlying principle to this?).

- Without a new scale there is no Hierarchy (problem).

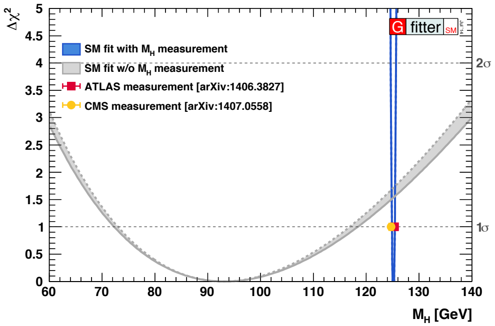
- With the Higgs discovery there is no No Loose theorem anymore.

Implications (II)

$$\rho = 1$$

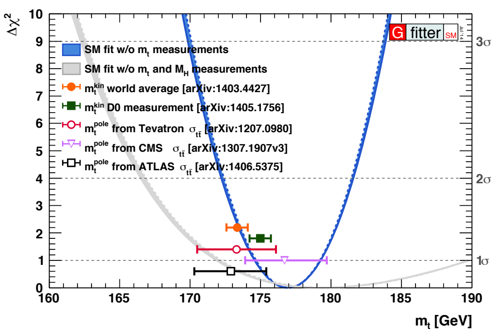
At tree level the EW gauge sector of the SM relies only on three free parameters (the fourth is determined, e.g. W mass from the precise knowledge of α, m_Z, G_F).

Higher order corrections introduce dependence on parameters from the Higgs and the fermion sectors, allowing precision electroweak data to yield indirect measurements (assuming SM)



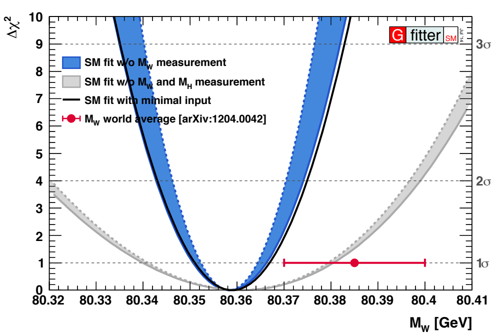
Higgs corrections are logarithmic in Higgs mass and yield indirect measurement in agreement with the direct one. Precise knowledge of the Higgs mass will not change this picture

$$\Delta\rho = -\frac{\alpha}{4\pi}\log\frac{m_H^2}{m_Z^2}$$



The larger corrections from the top and the knowledge of the Higgs mass yield a precise indirect constraint, however not competitive with the direct measurement.

$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2}$$



The knowledge of the Higgs mass has also improved the indirect W mass measurement at a precision (8 MeV) tice better than the WA (15 MeV) as of two weeks ago…

More precise measurement of the Higgs mass will not change this picture.

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

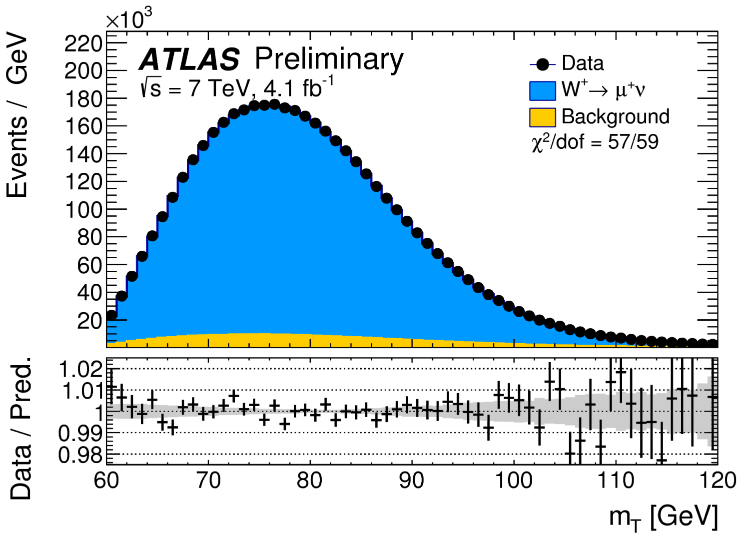
ATLAS-CONF-2016-113

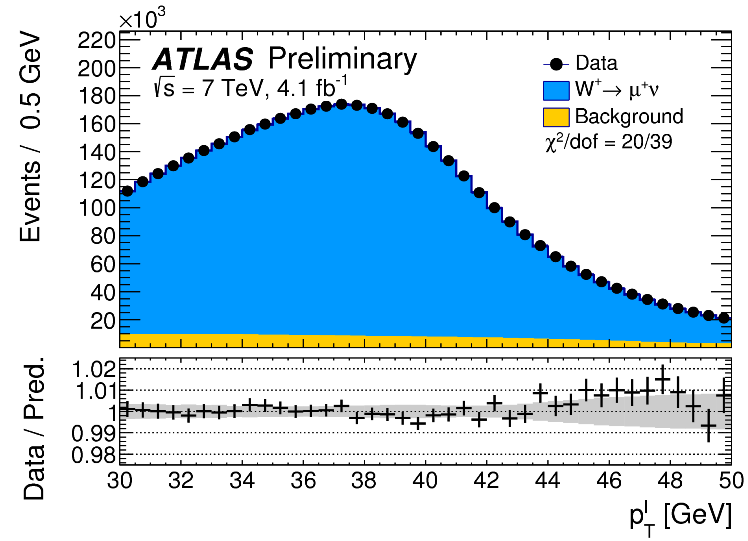
W Mass at the LHC

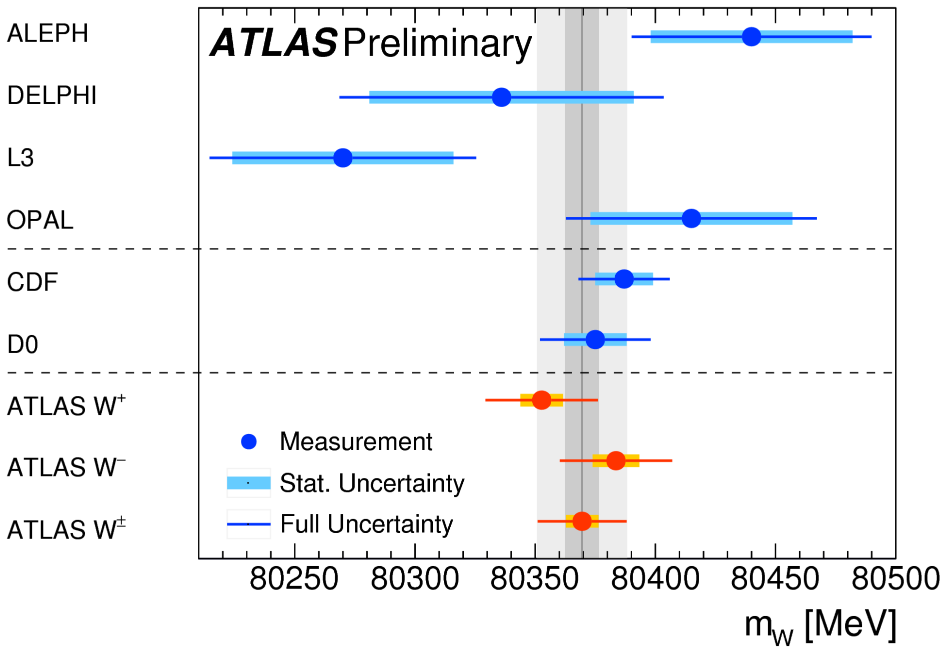
Milestone measurement presented last week!

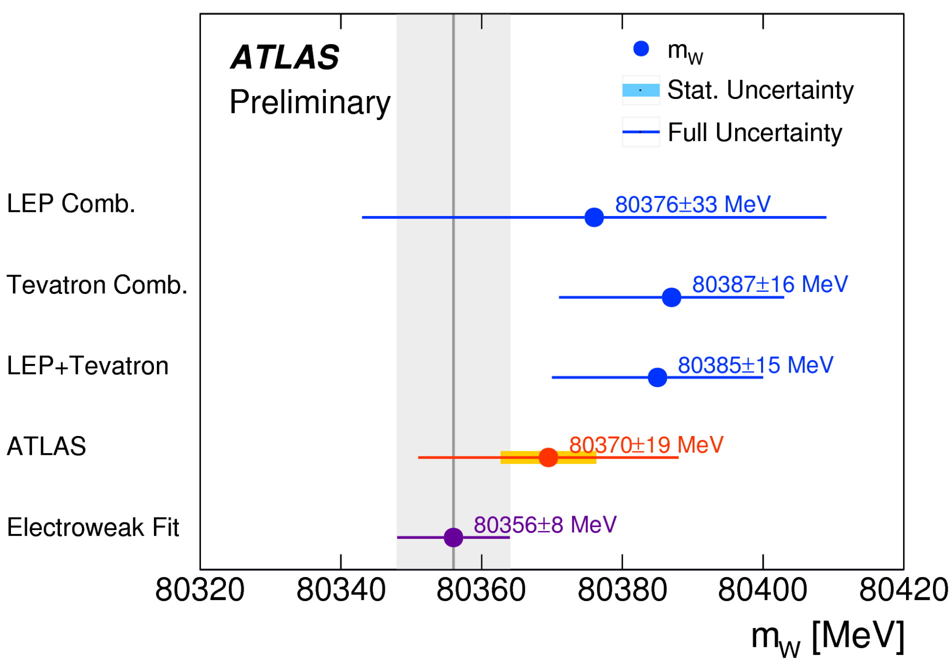
Analysis strategy based on two kinematic distributions fitted in several categories

Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_{T}^{ℓ}, m_{T}	p_{T}^{ℓ}, m_{T}
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$









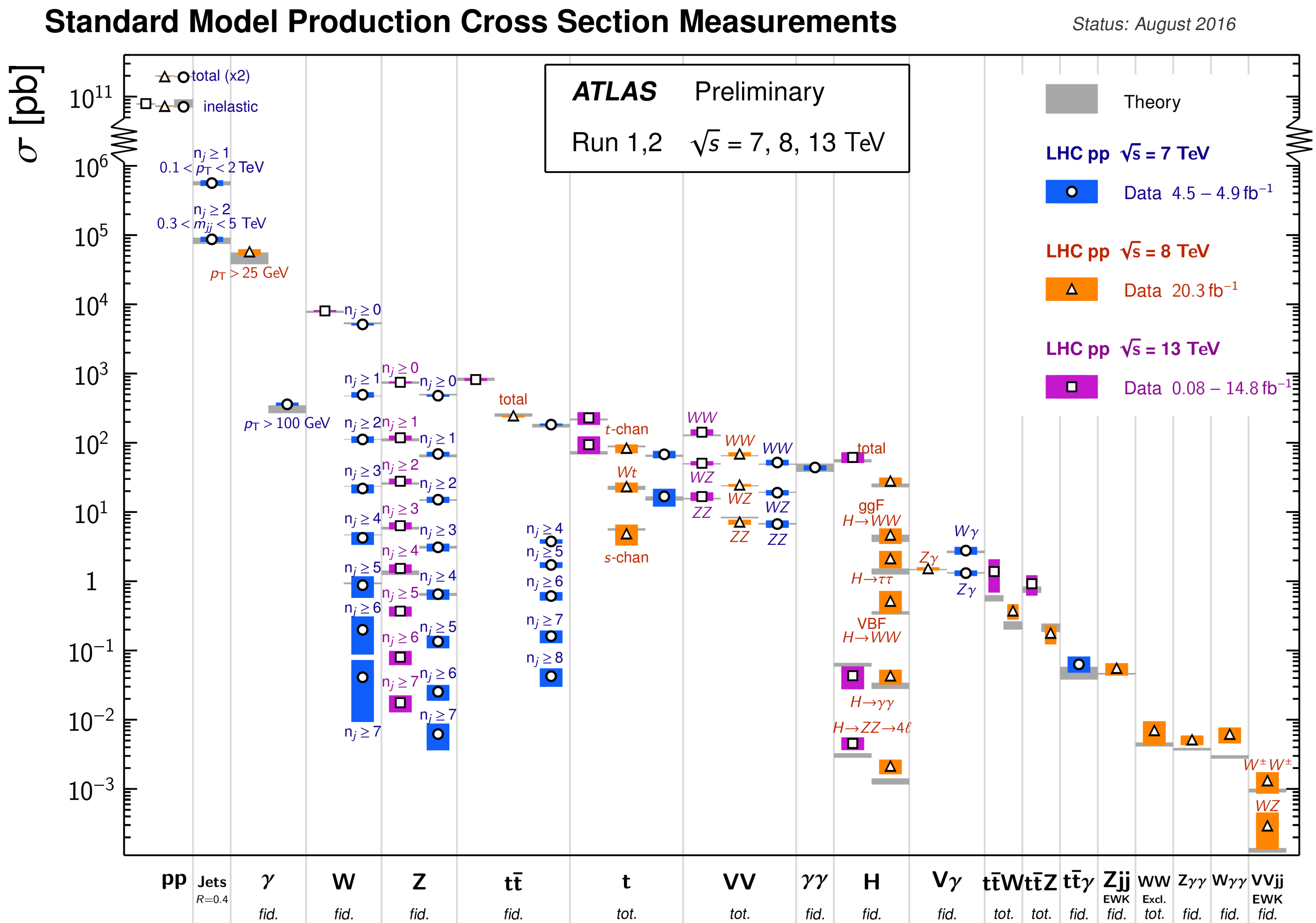
$$m_W = 80369.5 \pm 18.5\,MeV\ (\pm 6.8\,(Stat) \pm 10.6\,(Exp.\,Sys.) \pm 13.6\,(Mod.\,Sys.)\,MeV)$$

Best individual experiment ex-aequo with CDF measurement (CDF measurement has larger statistical component 12 MeV smaller systematics – still dominated by PDFs)

- Muon channel weighs 57% in the measurement
- The pT lepton measurement dominates weighing 86%
- Charges contribute similarly 52% vs 48%

- Systematics dominated
- Modeling systematic uncertainties are largest (PDF uncertainties are dominant among modeling systematics)
- Experimental calibration systematics not negligible.

Precision QCD Measurements at LHC



Excellent agreement of all cross section measurements with the SM prediction

Remarkable recent progress:

- in MC (in number of loops and legs)
- In Fixed order/resummed calculation
- Constant improvements in PDFs

Also extremely important past progress, e.g. fast jet alg. Allowing for IR and col. Safe jet algorithms at LHC

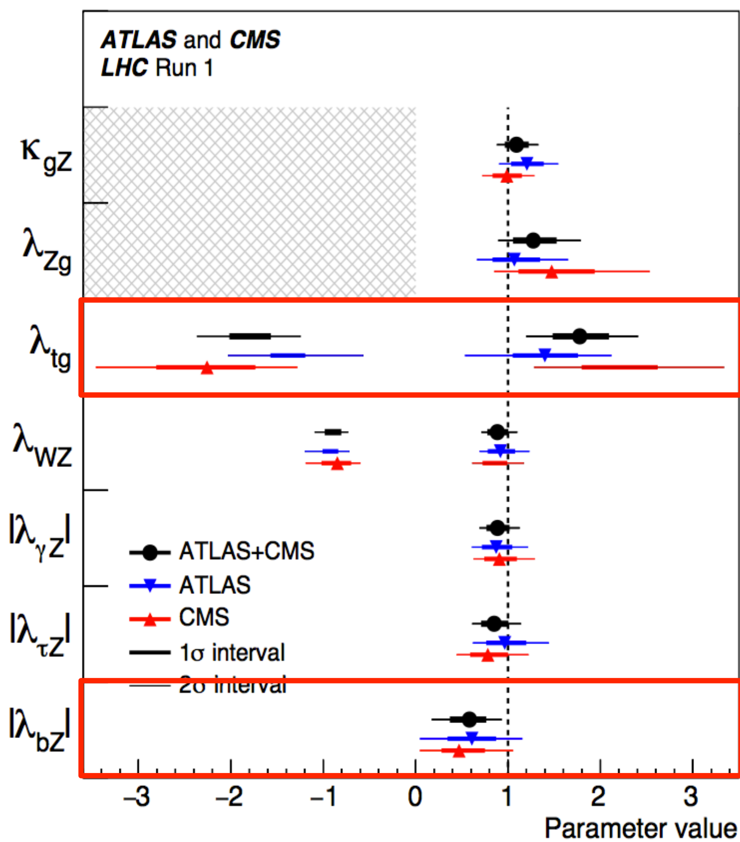
Run 2 Higgs Searches/Measurements

Selected Highlights

$$\mu = 1.09 \quad \pm 0.11$$
$$(\pm 0.07\,(Stat)$$
$$\pm 0.04\,(Exp)$$
$$\pm 0.03\,(Th.\,bkg)$$
$$\pm 0.07\,(Th.\,sig)\,)$$

Signal strength* illustrates the agreement of measurements with the SM and the importance of the TH input.

Very illustrative, but not transparent on the underlying assumptions and relies on the TH input at a given time.



Direct coupling to the Z

Direct coupling to the top*
(through ttH production channels)

Custodial Symmetry

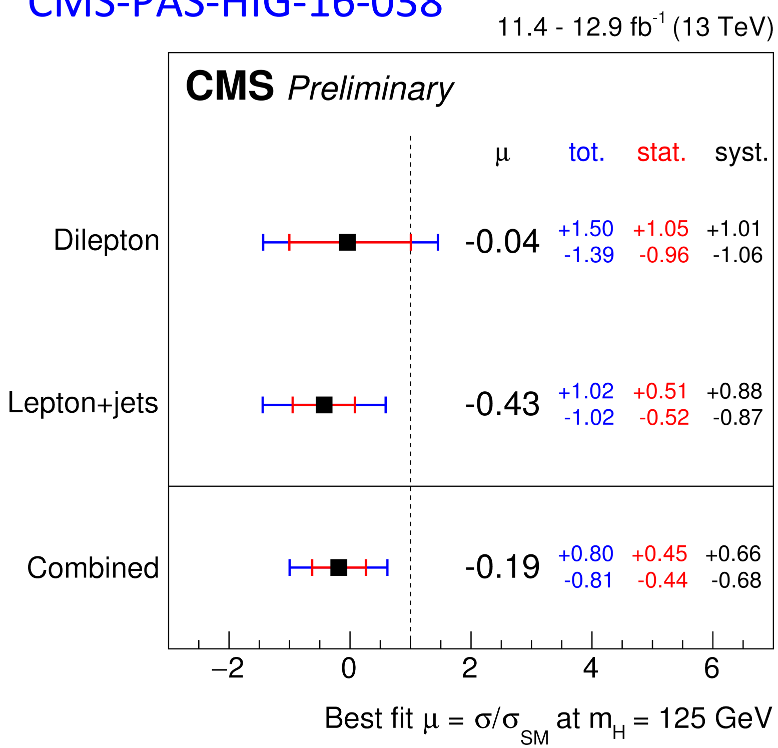
Direct copling to τ
(through VBF production)

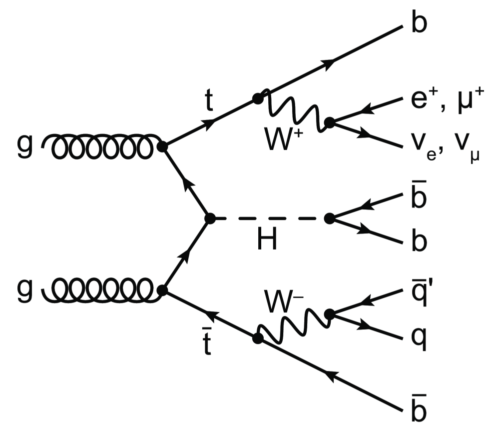
Direct coupling to b quarks*
(Through mainly VH channels)

JHEP 08 (2016) 045

Highly Anticipated Higgs Analyses at Run 2 (I)

CMS-PAS-HIG-16-038





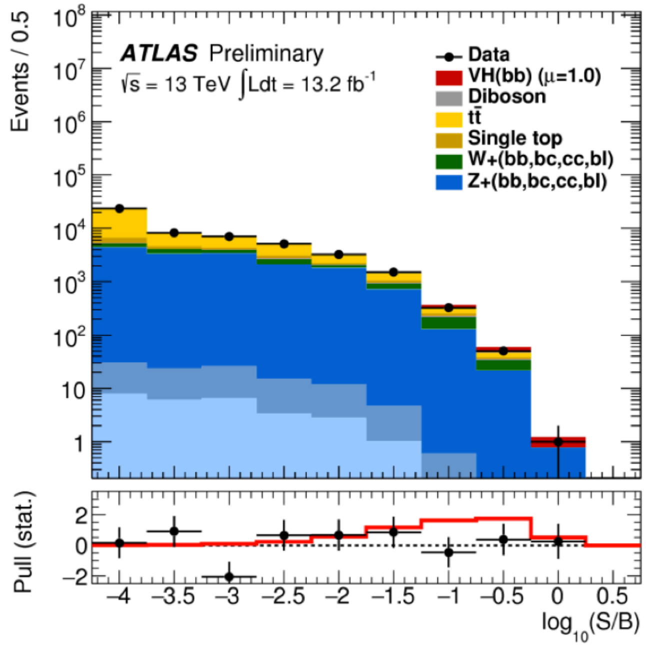
ttH Recent updateon the (bb) decay mode, completing the picture with the ICHEP dataset.

Analysis relying mostly on top modeling in very difficult regions e.g. 1L-6J-4b!

	γγ	bb	ML	Comb.
ATLAS Run 1	1.2 ± 2.6	1.4 ± 0.6 (stat) ± 0.8 (syst)	2.1 ± 1.1 (stat) ± 0.9 (syst)	1.7 ± 0.8
CMS Run 1	2.7 ± 2.6	0.7 ± 1.9	3.3 ± 1.4	2.8 ± 0.9
ATLAS Run 2	-0.3 ± 1.2	2.1 ± 0.5 (stat) ± 0.9 (syst)	2.5 ± 0.7 (stat) ± 1.1 (syst)	1.8 ± 0.7
CMS Run 2	$1.9^{+1.5}_{-1.2}$	-0.19 ± 0.8	$2.4^{+1.3}_{-1.2}$	0.8 ± 0.6

Highly Anticipated Higgs Analyses at Run 2 (II)

ATLAS-CONF-2016-091



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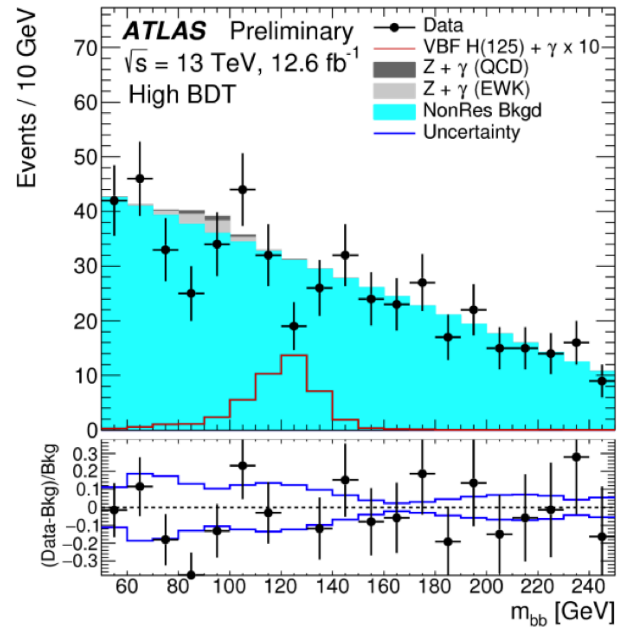
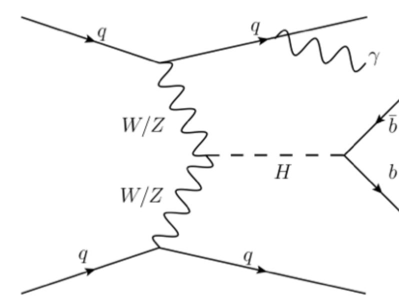


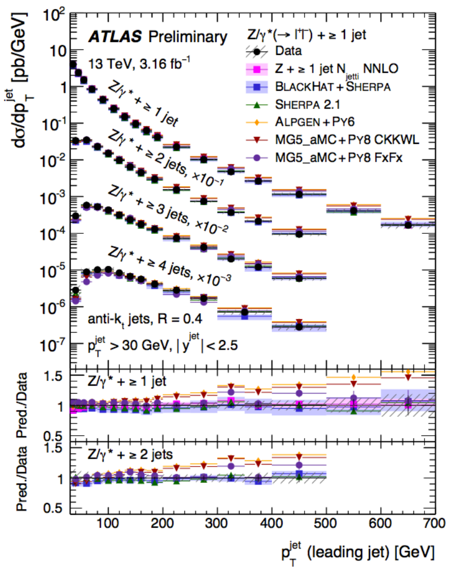


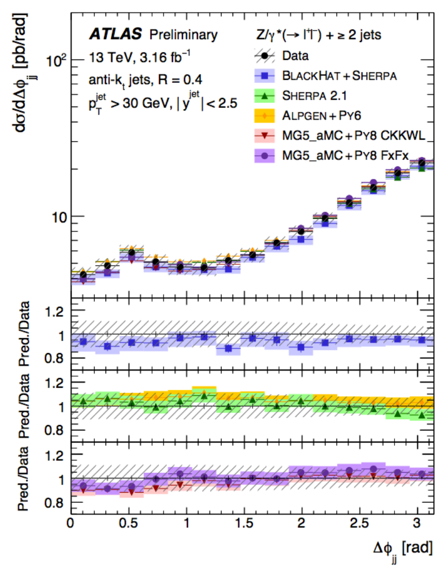
$$\mu_{VZ} = 0.91 \pm 0.17(\text{stat.})^{+0.32}_{-0.27}(\text{syst.})$$

	VH	ttH	VBF
ATLAS Run 1	0.52 ± 0.32 (stat) ± 0.24 (syst)	1.4 ± 0.6 (stat) ± 0.8 (syst)	-
CMS Run 1	1.0 ± 0.5	0.7 ± 1.9	2.8 ± 1.4
ATLAS Run 2	0.21 ± 0.36 (stat) ± 0.36 (syst)	2.1 ± 0.5 (stat) ± 0.9 (syst)	-3.9 ± 2.8
CMS Run 2	-	-0.19 ± 0.5 (stat) ± 0.7 (syst)	-3.7 ± 2.7

Modeling is Critical

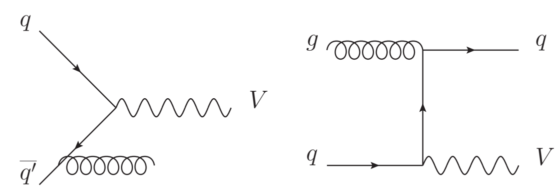
At Run 2: huge effort to use (and therefore validate) State-of-the-Art MC.



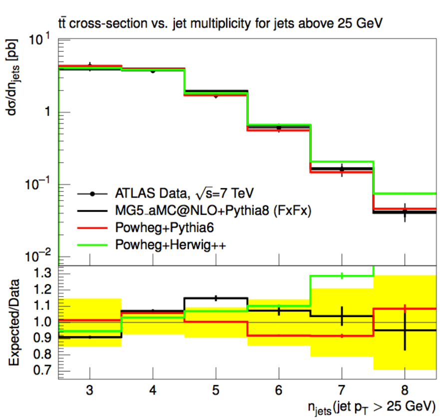


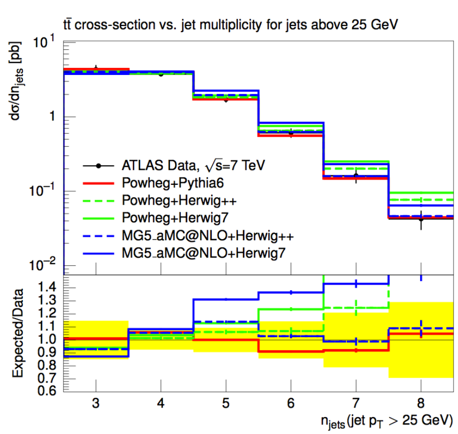
V+jets production

Crucial in the VH(bb) analysis and many more



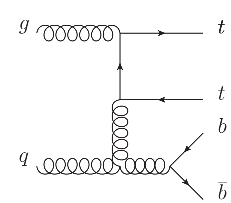
Already improvements w.r.t. to Run 1 and for the full dataset considering Sherpa 2.2.
This illustrates the very fast turn around to include latest MC developments.





Top(+jets) production

Crucial in the ttH(bb) analysis and many more



Crucial role played by HEPData
(and Rivet routines): **Huge thanks!**

Conclusion of Measurements

Vast number of beautiful measurements from the LHC (not covered in this talk) please see the following pages for complete works.

- ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- CMS http://cms-results.web.cern.ch/cms-results/public-results/publications
- LHCb http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html
- ALICE http://aliceinfo.cern.ch/ArtSubmission/submitted

Triumph of the Standard Model within current precision. Vast number of measurements still to come.

No no-loose theorem anymore and no indication from the Higgs mass

However there are still a vast number of important precision measurements to come.

- Gauge Hierarchy and Naturalness?
- Elementary?
- Grand Unification?
- Dark matter?
- Gravity?
- Strong CP problem?
- Neutrino masses and their nature?
- Matter-anti Matter asymmetry?
- Flavor hierarchy?

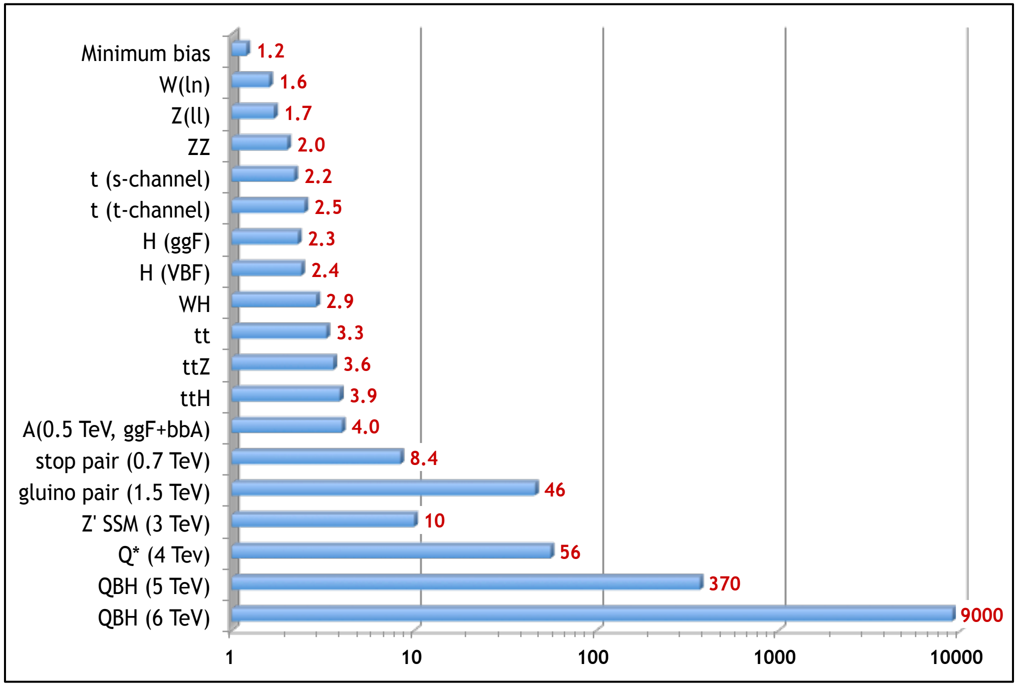
Direct Searches at the LHC

What are the guiding/organizing principles for searches at the LHC?

Direct Searches at LHC

The LHC is a discovery machine: Both at the Energy and the luminosity frontiers.

Ratio of parton luminosities



The **increase of centre-of-mass energy** at Run 2 has brought the potential for spectacular (prompt) discoveries 2015 and 2016 have been extremely exciting because

2015 -2016: **Discovery mode**, with a rapid doubling time of the luminosity.

Able to verify rapidly if any effect is a statistical fluctuation.

Strategy:

- Search exhaustively all possible relevant topologies where new physics scenarios can occur according. Leave no stone unturned.
- **Interaction with new TH/PH ideas is very important!**
- Keep track of possible excesses (Run 1 and 2015 data), and verify them with an independent sample.

Searches Overview

- **Searches high mass/transverse momentum resonant and non-resonant**
  - Topologies: $\gamma\gamma$, dilepton, dijet, diboson, photon-jet, lepton-jet, lepton-photon
  - Models: Z' (additional gauge groups, RS gravitons, VLQ)

- **DM Searches** (in simplified models)

  Topologies: Mono-jet, photon, vector-boson, Higgs, invisible Higgs decays.

- **RPC SUSY Searches** (in simplified models - and pMSSM scan)

  Topologies: 1-, 2-, 3-lepton(s), jets, photons and MET

- **Additional Higgs boson Searches**
  - States: CP-even and –odd neutral, charged Higgs, doubly charged Higgs
  - Topologies: $\tau\tau$, $\mu\mu$, tt, bb, VV, VH, HH (neutral), $\tau\nu$, cs, tb (charged), 4μ, 4τ, 2μ2τ, 4γ (aa NMSSM)
  - Models: MSSM, NMSSM, 2HDMs, Triplet models

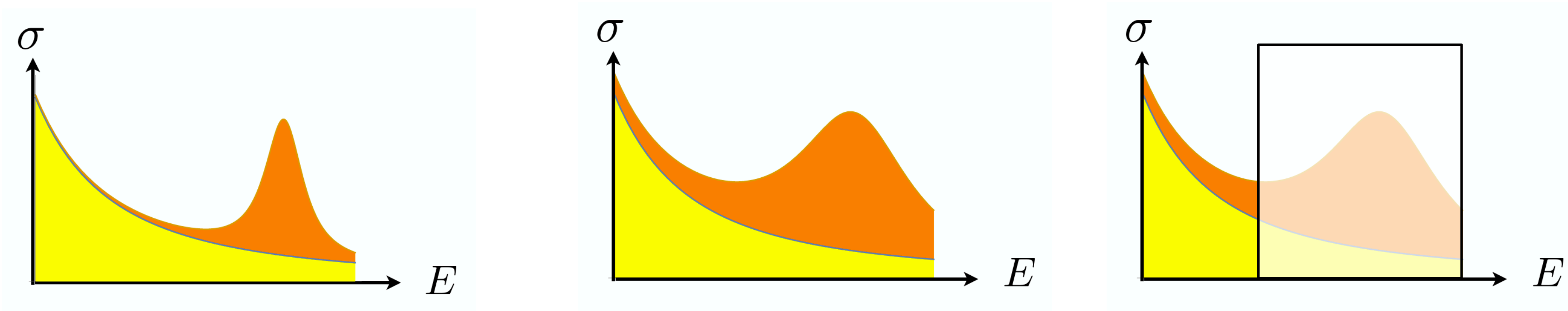
- **Complex signatures**
  - Models: RPV SUSY
  - Topologies: multi-lepton, multi-(b)-jets,

- **Unconventional signatures**
  - Heavy Stable Charged Particles (ionizing or stopping)
  - Models: SUSY scenarios or hidden sectors)

Unlike the searches carried out at the LHC, a non exhaustive set of results will be presented here.

High Mass and Transverse Momentum

Modes for discovery at LHC



R. Rattazzi HC2016

Search for narrow or less narrow peaks
(Depending on the underlying dynamics)

- W’ and Z’ (Extra dimensions)
- Additional Higgs bosons
- Excited quarks q^*
- Leptoquarks
- RS gravitons
- String resonances
- E6 diquarks
- Axi gluons

Non resonant searches

- ADD gravitons
- Quantum black holes
- Contact interactions

Topologies: Two photons, two jets, photon-jet, lepton-photon, lepton-jet, top pair, Z-photon, VV, VH, HH

Diphoton Search

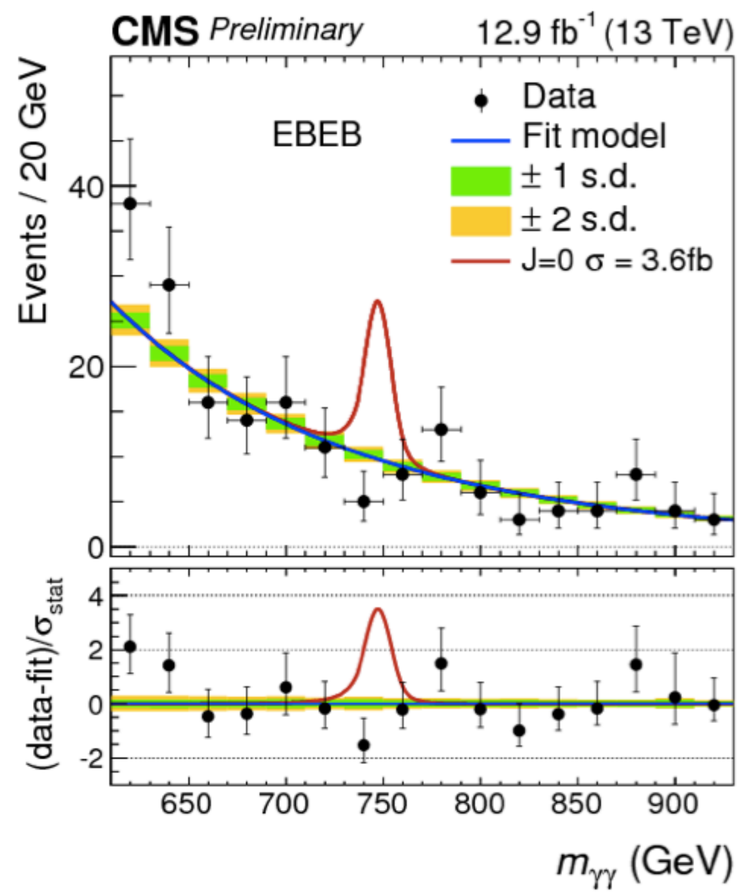
The 750 GeV Excess

* Definitely most interesting + likely LHC anomaly – Exciting!

[* Run 1 vs Run 2 tension, "other channels look elsewhere", width issue; also big co-incidence that $S/B \simeq$ few with $\mathcal{O}(10)$ events (but just where syst/background fluct. hurt!)]

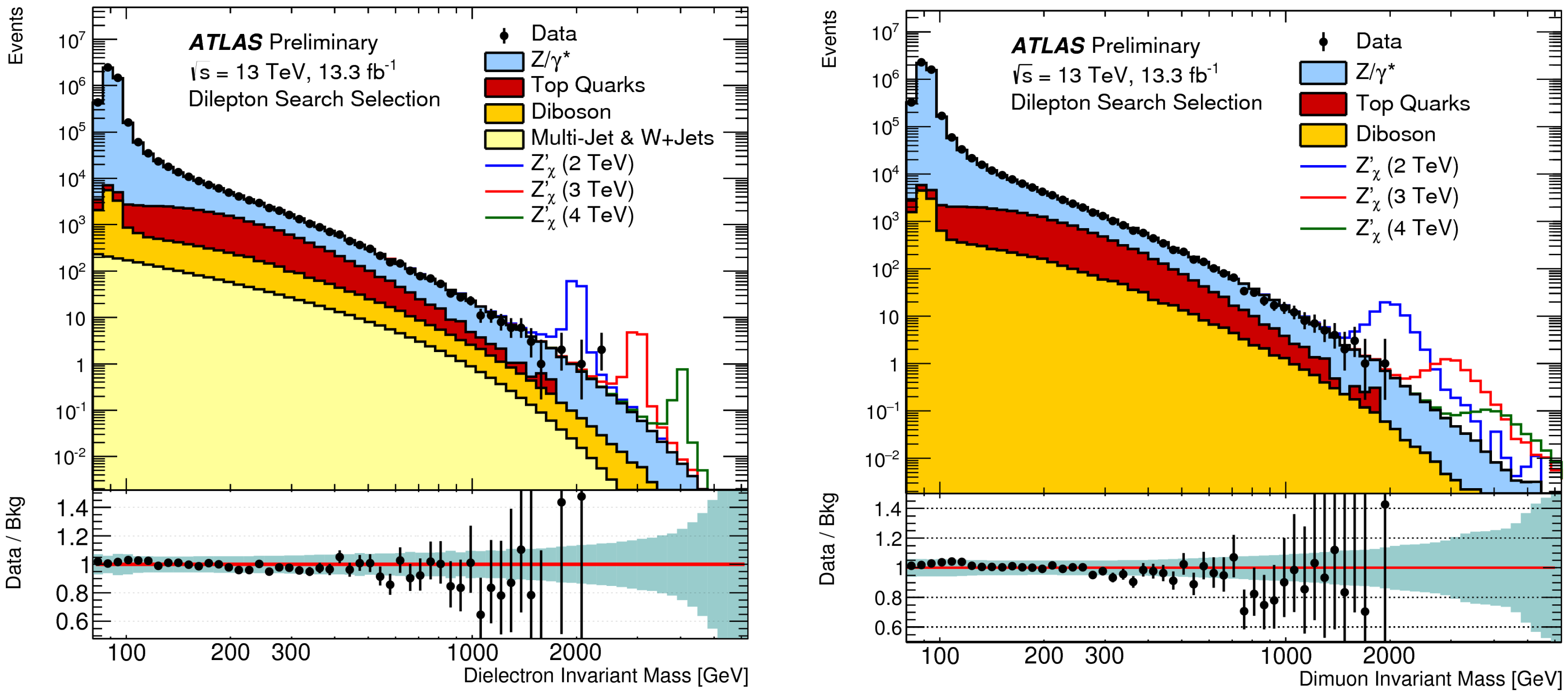
* I give it a ~ 10% chance of being real (= betting odds)

Nima Arkani Hamed (Aspen 2016)



Search for High Mass Z’

ATLAS-CONF-2016-045



- Understanding extrapolation of the calibration and the reconstruction efficiency at very high transverse momentum is critical.

- Limits ranging from 3.4 to 4 TeV