LHC Run-2 and Future Prospects

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(Sept. 2019)

Outline

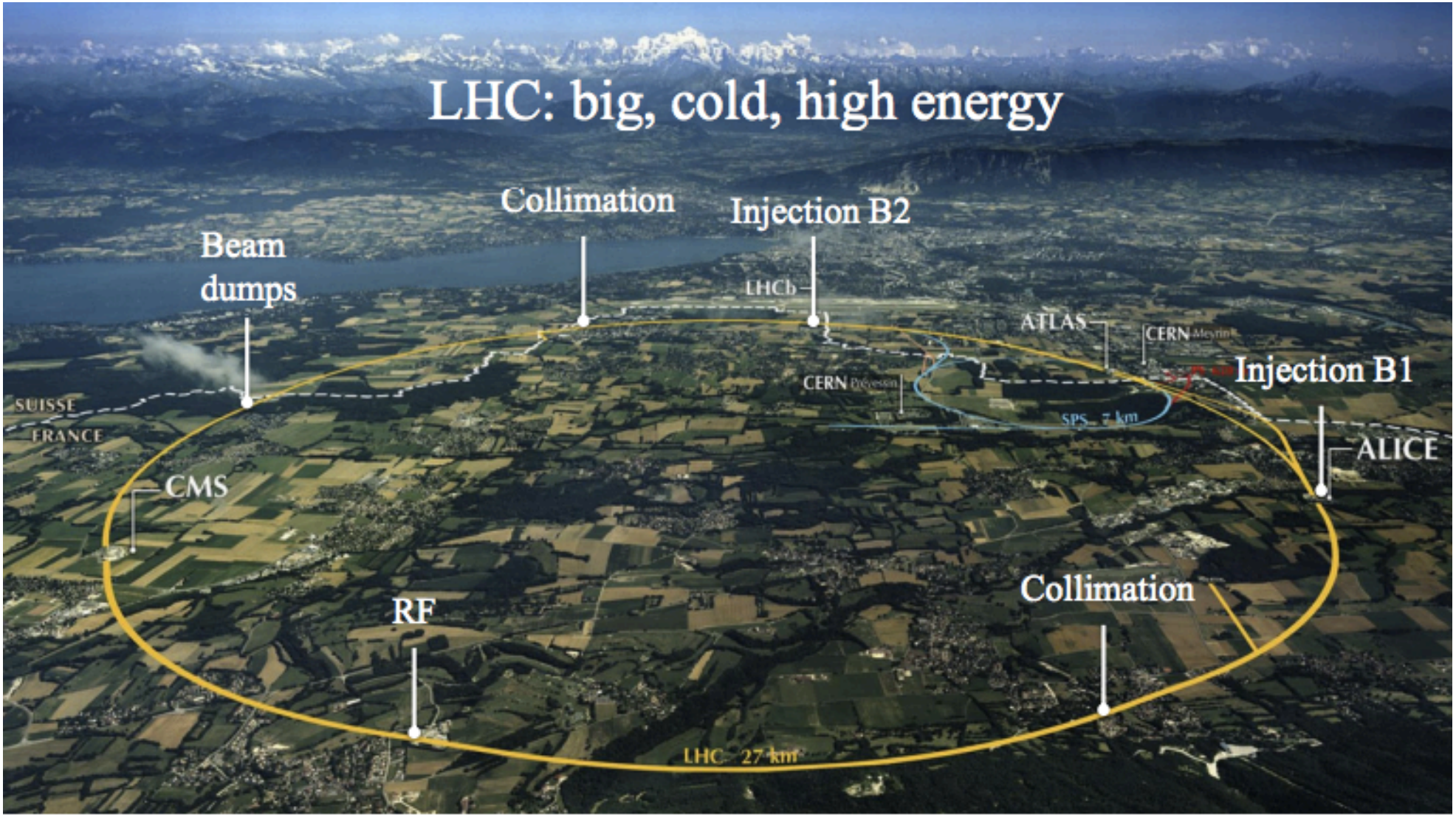
- Brief discussion on LHC
- Highlights from LHC results in Run-2, and future prospects
  - Mostly ATLAS/CMS but also LHCb
  - Will not show heavy ion results, so ALICE not covered
    - See dedicated heavy ion lectures
  - Try to show the diversity of LHC physics and the versatility of the LHC and detectors
  - Try to mention various experimental innovations where relevant

Usual Caveats...

- Impossible to cover all the highlights in a fair way in 1 lecture
  - I have had to make tough choices on what to show
- Since I work on ATLAS a slight bias towards ATLAS in results shown
  - In nearly all cases ATLAS/CMS results are comparable

The LHC machine in Run-2

LHC: big, cold, high energy



1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

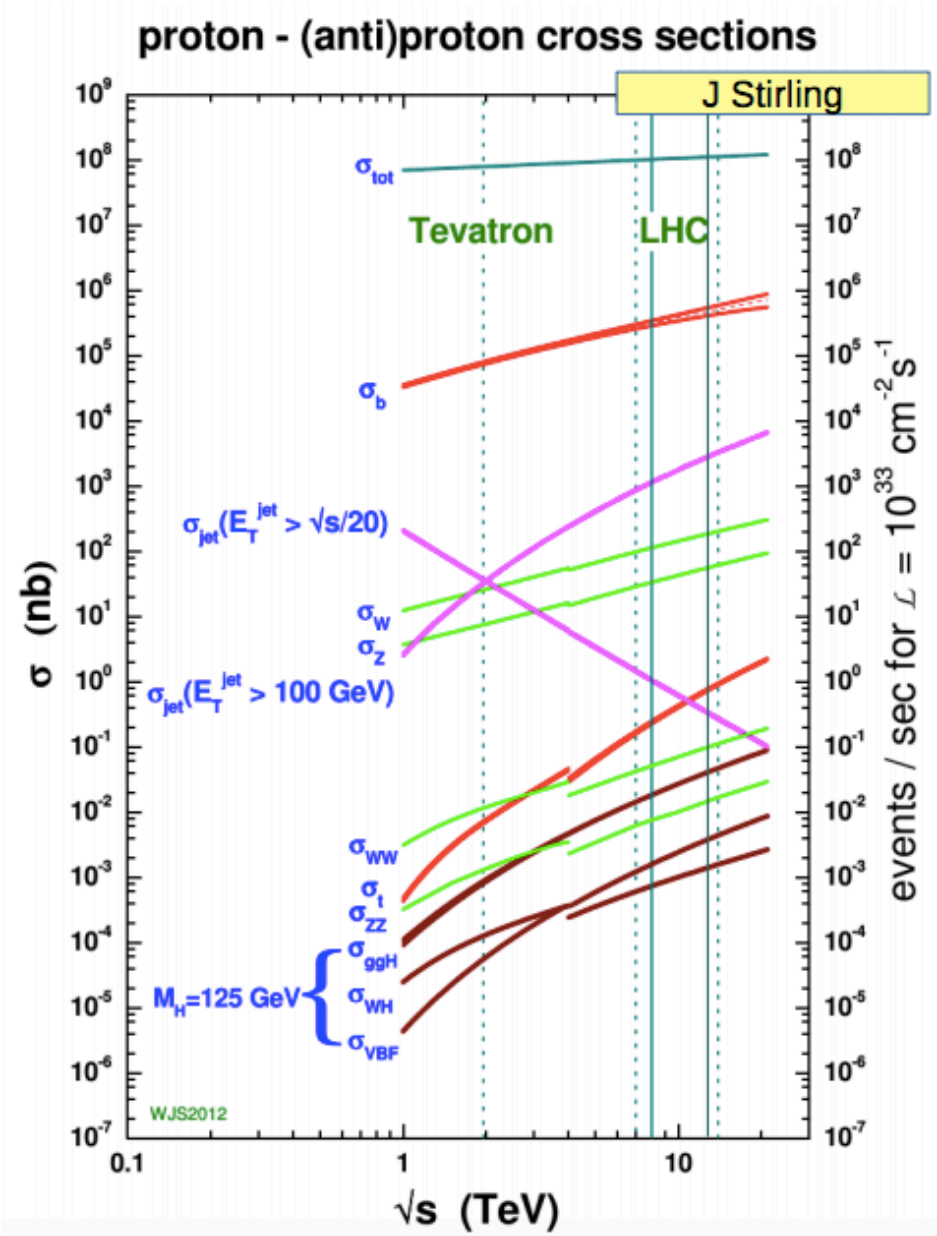
150 tonnes helium, ~90 tonnes at 1.9 K
350 MJ stored beam energy in 2016
1.2 GJ magnetic energy per sector at 6.5 TeV

Key parameters

Key parameters at a collider
- Collision energy
  - Set by dipole bending magnets
- Luminosity
  - How many collisions occur

Number of events for a given process:
N = cross-section x luminosity

where cross-section depends on the collisions energy



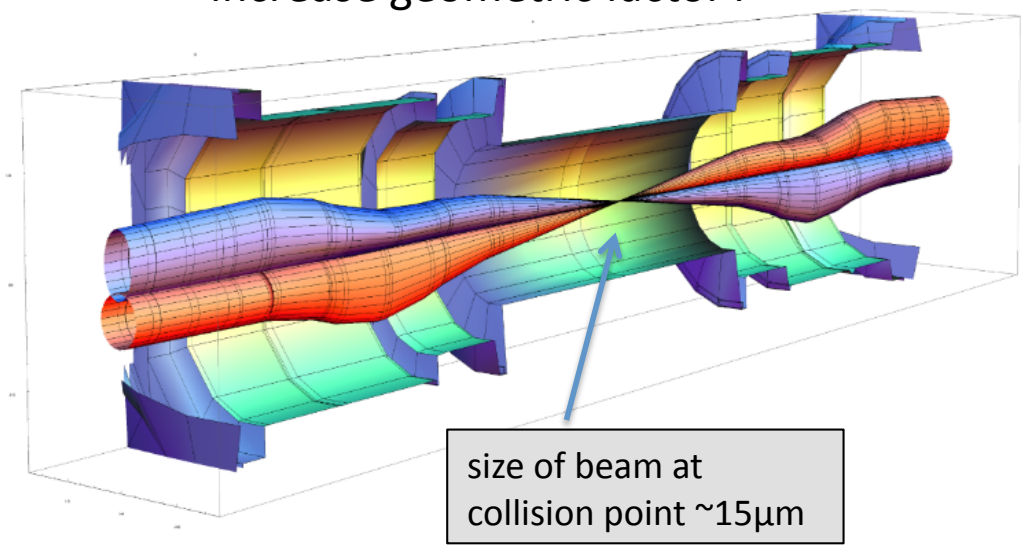
Luminosity

Luminosity given by:

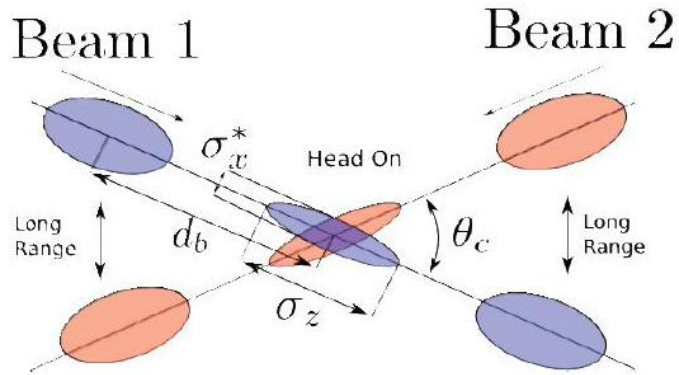
$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

pileup related to lumi/bunch

Maximize by:
-increase number of bunches (n_b)
-increase number of protons per bunch ($N_{1/2}$)
-decrease beam size at collision point (emittance: ε_n, squeeze: β^*)
-increase geometric factor *F*



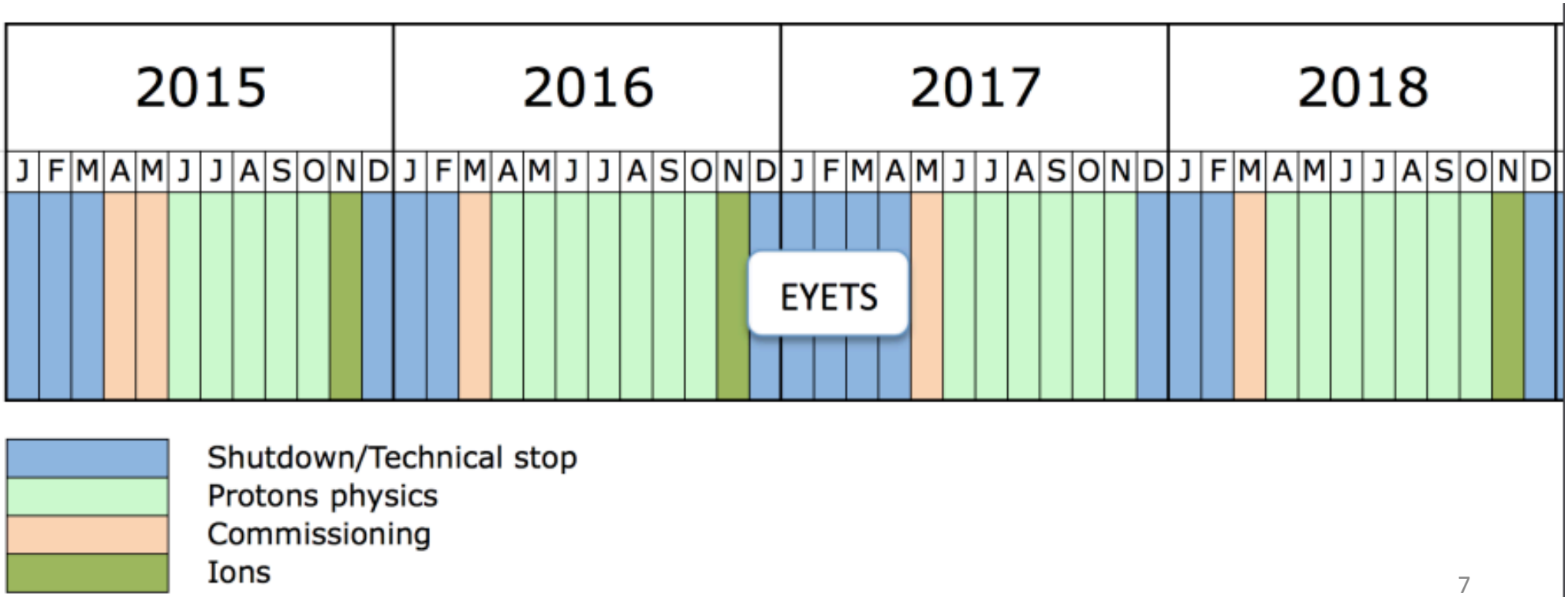
size of beam at collision point ~15µm



crossing angle needed to avoid parasitic collisions and long range beam-beam effects – reduces luminosity.

Brief summary of LHC Run-2

- In 2015 the LHC re-started operations after a 2 year shutdown
  - Nearly doubled collision energy 8 TeV -> 13 TeV
  - Reduced the bunch spacing from 50 ns -> 25 ns
- Run-2 of the LHC: 2015-2018



Brief summary of LHC Run-2

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Year	peak luminosity ($x10^{34}cm^{-2}s^{-1}$)	integrated luminosity (/fb)	Stable beams fraction (%)	main challenges
2015	0.5	~4	~30%	cryogenics – electron cloud, radiation to electronics
2016	1.5	40	~50%	leak in SPS beam dump
2017	1.5 (levelled)	50	~50%	losses in cell 16L2 due to accidental air intake. mitigated by running with fewer bunches.
2018	2.0	60	~50%	-

- 2015:
  - Challenging year for the LHC operations, with many systems dealing with challenges associates with running at higher energy (radiation), and 25ns bunch spacing (e-cloud)
- 2016-2018:
  - Systems performed very well
    - Extremely impressive availability (~50% of allocated physics time)
  - Pushing performance to increase luminosity, despite technical challenges
  - Design luminosity achieved and surpassed (2x achieved!)

Comparison of key LHC parameters

	Design	Run-1	2015	2016	2017	2018
Energy (TeV)	14	7/8	13			
Bunch Spacing (ns)	25	50	25			
Bunch Intensity ($\times 10^{11}$ ppb)	1.15	1.6	1.2	1.1	1.25	1.15
# bunches	2800	1400	2200	2200	1900	2500
Emittance (µm)	3.5	2.2	3.5	2.5	2.0	2.2
β* (cm)	55	80	80	40	30	30->25
Crossing angle (µrad)	285		290	280	300->240	300->260
Peak Lumi ($cm^{-2}s^{-1}$)	1.0×10^{34}	0.8×10^{34}	0.5×10^{34}	1.5×10^{34}	1.5×10^{34} (levelled)	2.0×10^{34}
Peak pileup	25	45	25	45	65	60

Performance steadily increasing, main parameters better than design except energy and number of bunches.

The near future….

LHC Run-3

	Design	Run-1	Run-2	Run-3
Energy (TeV)	14	7/8	13	14
Bunch Spacing (ns)	25	50	25	25
Bunch Intensity ($\times 10^{11}$ ppb)	1.15	1.6	1.2	up to 1.8
# bunches	2800	1400	2500	2800
Emittance (µm)	3.5	2.2	2.2	2.5
β* (cm)	55	80	30->25	30->25
Crossing angle (µrad)	285		300->260	300->260
Peak Lumi ($cm^{-2}s^{-1}$)	1.0×10^{34}	0.8×10^{34}	2.0×10^{34}	2.0×10^{34}
Peak pileup	25	45	60	55

Run-3: 2021-23

higher bunch intensity, following complete upgrade of injector chain

luminosity levelled to give acceptable pileup level and due to LHC cryogenics. May be able to run for >10hrs at 2×10^{34}

Run-3 expected to deliver similar luminosity to Run-2
Around 200/fb in full Run-3. (Some components have integrated lumi lifetime)

The far future….

High Luminosity (HL)-LHC

	Design	Run-1	Run-2	HL-LHC
Energy (TeV)	14	7/8	13	14
Bunch Spacing (ns)	25	50	25	25
Bunch Intensity ($\times 10^{11}$ ppb)	1.15	1.6	1.2	2.2
# bunches	2800	1400	2500	2800
Emittance (µm)	3.5	2.2	2.2	2.5
β* (cm)	55	80	30->25	->15
Crossing angle (µrad)	285		300->260	300->?
Peak Lumi ($cm^{-2}s^{-1}$)	1.0×10^{34}	0.8×10^{34}	2.0×10^{34}	5.0×10^{34} (7.0×10^{34})
Peak pileup	25	45	60	150 (200)

nearly double bunch intensity, following complete upgrade of injector chain

significantly more squeezed beam, due to replacement of final focusing magnets

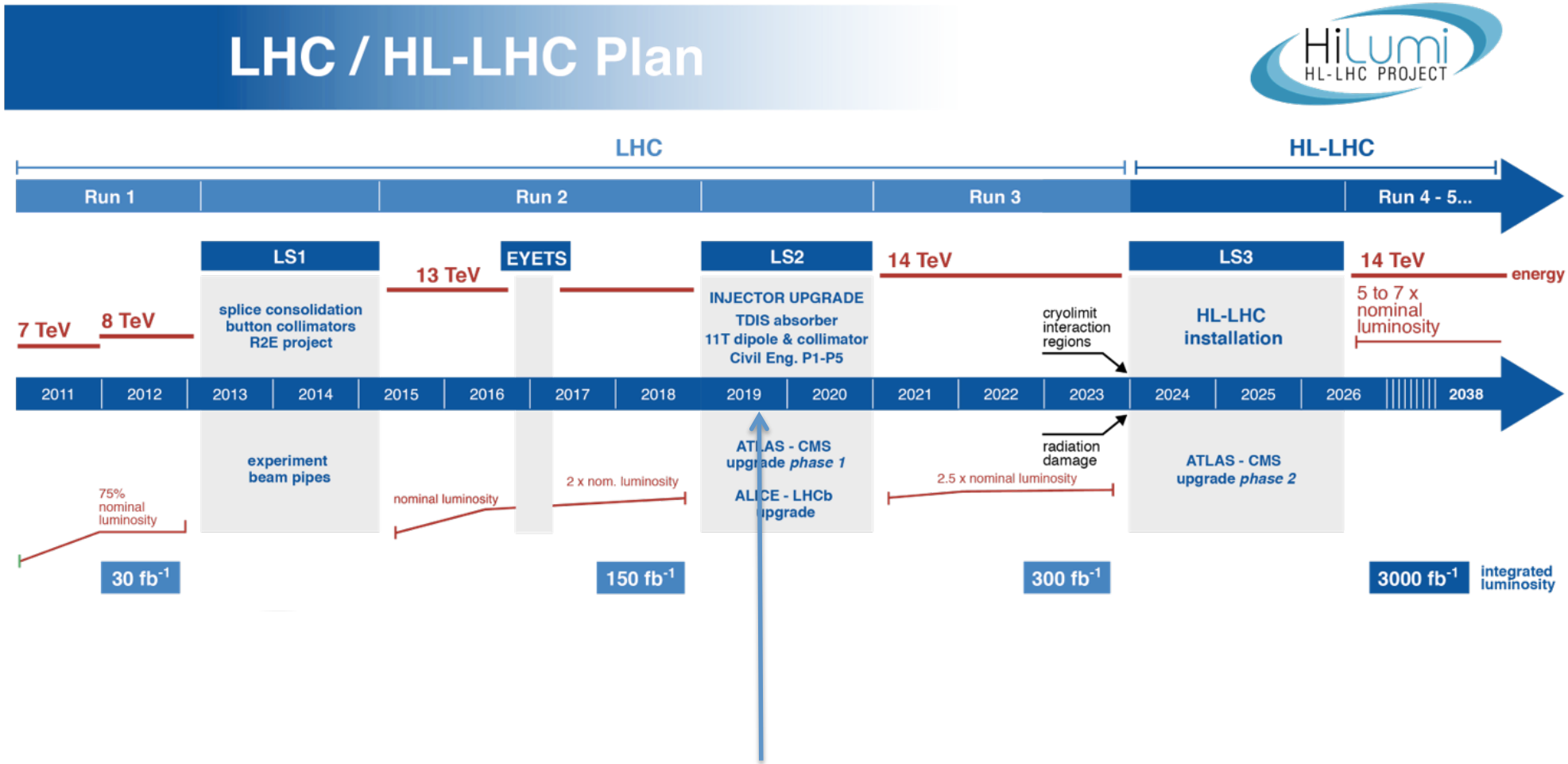
luminosity levelled to give acceptable pileup level.

HL-LHC project designed to give 3000/fb in ~10 years

Very large pileup requires major upgrade of ATLAS/CMS detectors in LS3 (2024-26)

The far future….

High Luminosity (HL)-LHC



We are here!

Incredible flexibility of the LHC

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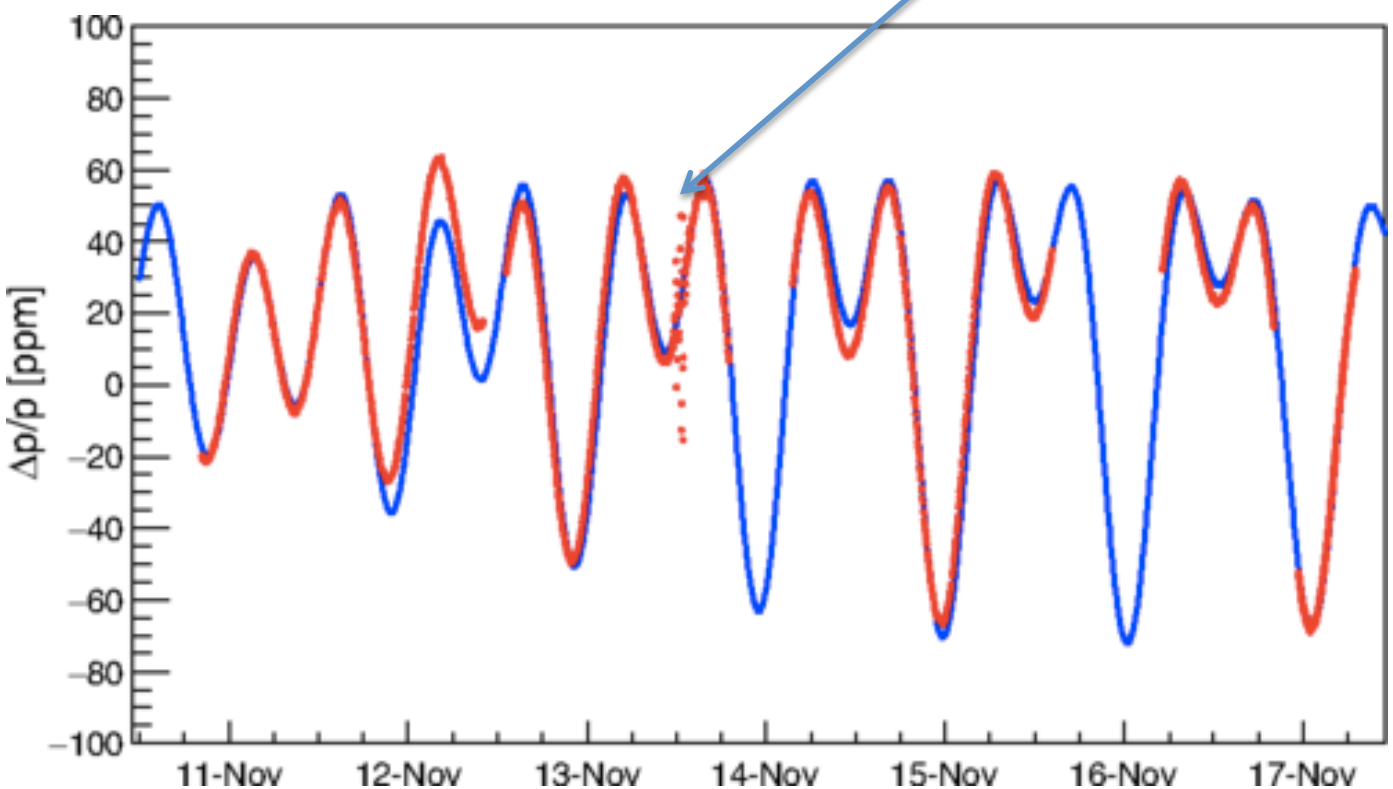
- In Run-2 the LHC has carried out a number of special runs on top of the usual high luminosity, high energy p-p
- Heavy ion collisions:
  - p-Pb (2 energies)
  - Pb-Pb
  - A short pilot physics run colliding Xe ions
- Forward physics runs with special large-β* optics
  - ~parallel beam at IP, no focusing
  - For elastic scattering measurements (at two energies 13 TeV and 0.9 TeV)
- Lower energy pp run
  - 5 TeV as reference data for Pb-Pb collisions
    - same energy as nucleon collision energy in Pb run
- Low pileup pp running for ATLAS/CMS
  - Important for precision W-boson physics, such a W-mass measurement

An example of the precision of the LHC

In November 2016 during the p-Pb run, we had very long fills (>24hrs).
This allowed the effect of the tidal forces on the LHC ring to be observed (red) and compared to the old model from LEP (blue)

magnitude 7.8 earthquake in New Zealand!



The beam energy is known to ±0.1% from the magnetic model, and validated to 0.7% using the orbit in p-Pb collisions.

Phys. Rev. Accel. Beams 20, 081003 (2017)

An example of the precision of the LHC

Phys. Lett. B761 (2016) 136

Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b-tagged jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

This paper describes a measurement of the inclusive top quark pair production cross-section ($\sigma_{t\bar{t}}$) with a data sample of 3.2 fb^{-1} of proton–proton collisions at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV, collected in 2015 by the ATLAS detector at the LHC. This measurement uses events with an opposite-charge electron–muon pair in the final state. Jets containing b-quarks are tagged using an algorithm based on track impact parameters and reconstructed secondary vertices. The numbers of events with exactly one and exactly two b-tagged jets are counted and used to determine simultaneously $\sigma_{t\bar{t}}$ and the efficiency to reconstruct and b-tag a jet from a top quark decay, thereby minimising the associated systematic uncertainties. The cross-section is measured to be:

$$\sigma_{t\bar{t}} = 818 \pm 8\,(\text{stat}) \pm 27\,(\text{syst}) \pm 19\,(\text{lumi}) \pm 12\,(\text{beam})\ \text{pb},$$

where the four uncertainties arise from data statistics, experimental and theoretical systematic effects, the integrated luminosity and the LHC beam energy, giving a total relative uncertainty of 4.4%. The result is consistent with theoretical QCD calculations at next-to-next-to-leading order. A fiducial measurement corresponding to the experimental acceptance of the leptons is also presented.

The beam energy is known to ±0.1% from the magnetic model, and validated to 0.7% using the orbit in p-Pb collisions.

Phys. Rev. Accel. Beams 20, 081003 (2017)

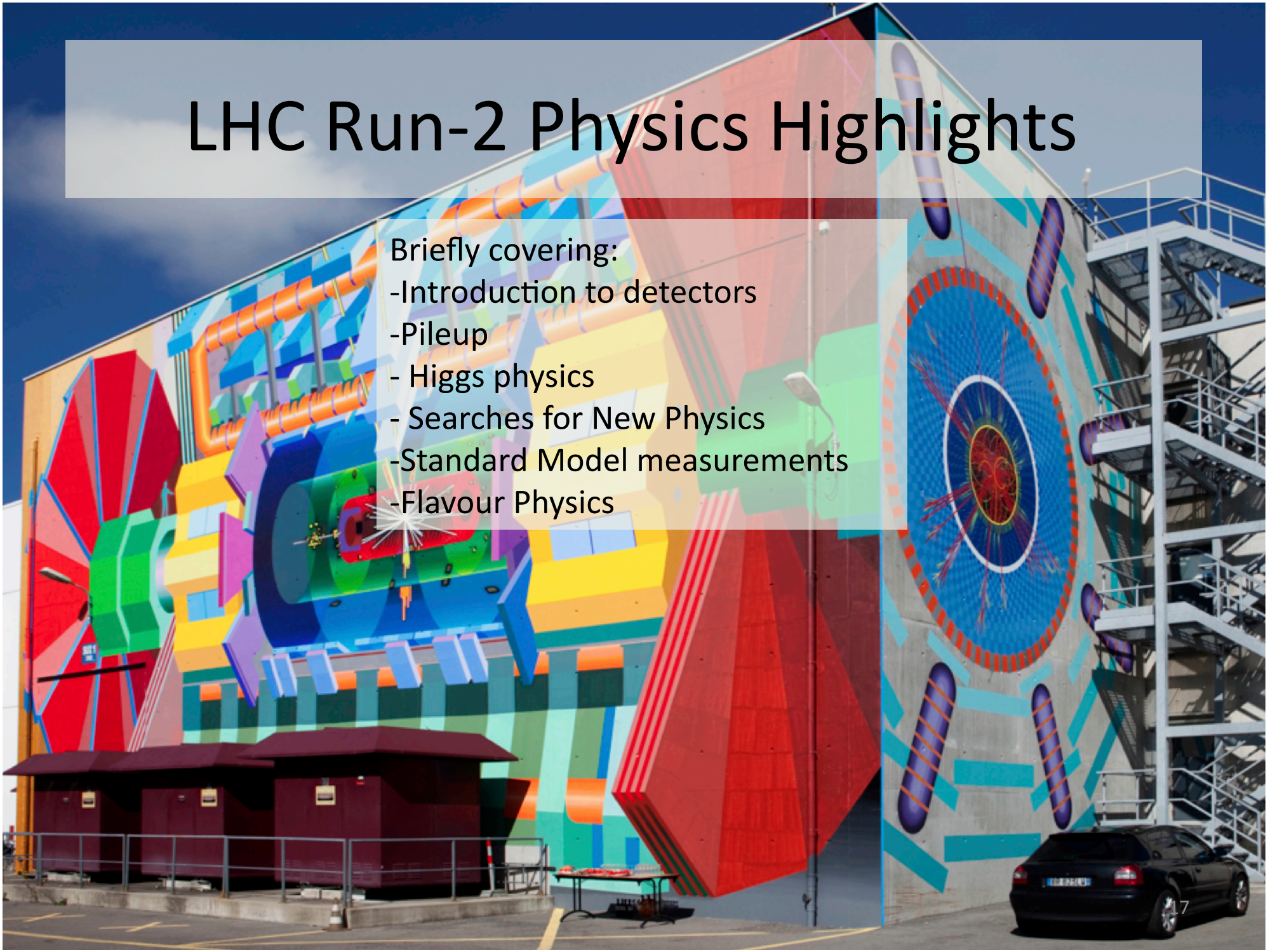
Although precise measurement of beam energy is much less important at the LHC than at LEP – this can still be a relevant systematic uncertainty for precise measurements.

(my) Key messages on LHC

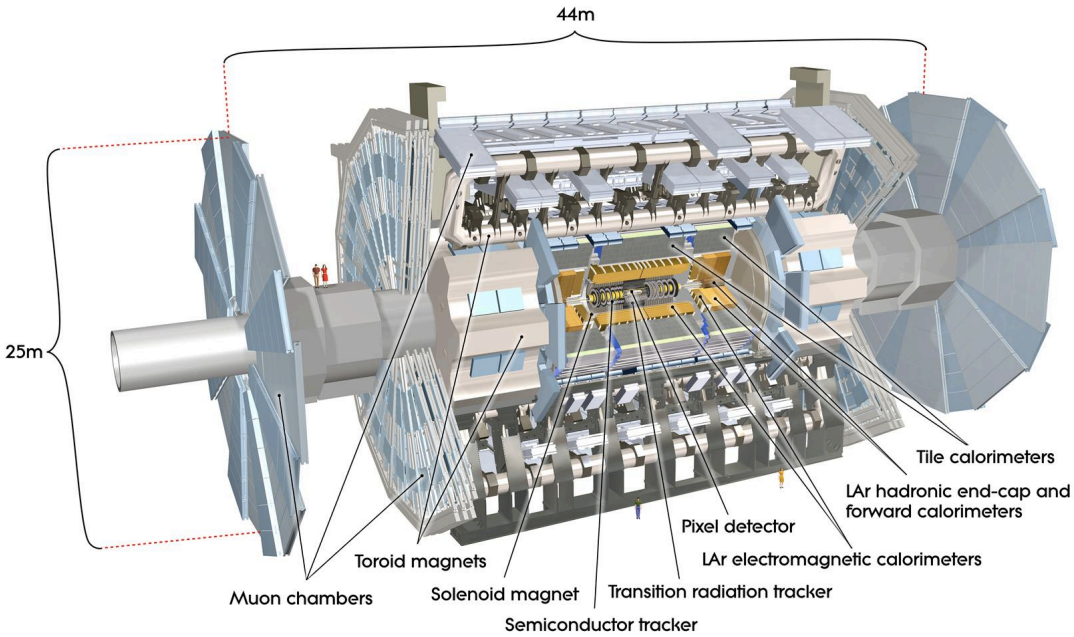
- LHC has run extremely well in Run-1 and Run-2:
  - Exceptional availability, and pushing luminosity performance
- Every year, unexpected challenges. But (so far) mitigated by clever ideas/tricks
- Design and construction of the LHC and injector complex very high quality, allows a lot of flexibility to go beyond the design in many ways!
  - Testament to the many brilliant people who worked on this
- We are lucky to have such an amazing tool
  - Bodes well for the future of our science

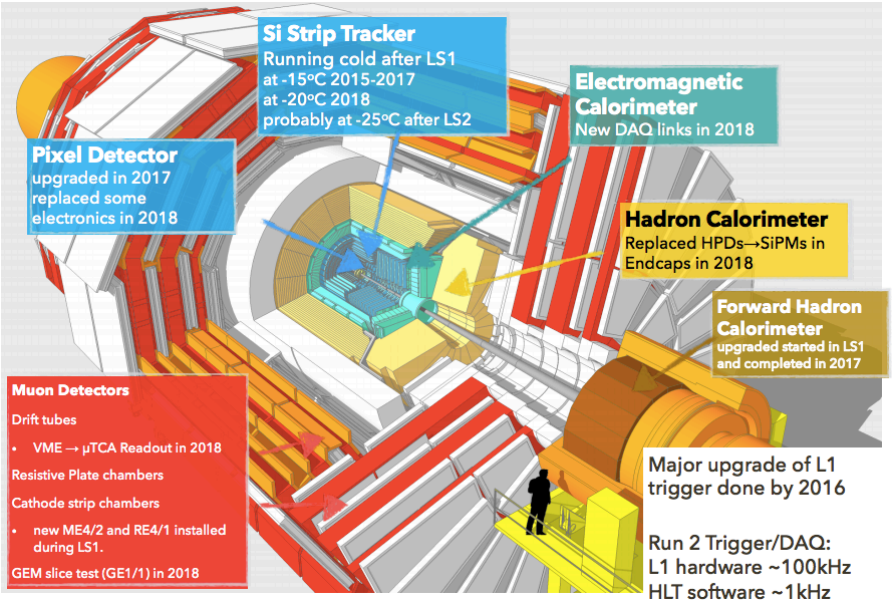
LHC Run-2 Physics Highlights

Briefly covering:
-Introduction to detectors
-Pileup
- Higgs physics
- Searches for New Physics
-Standard Model measurements
-Flavour Physics



ATLAS/CMS Detectors





ATLAS and CMS designed to do the same physics

Different detector design choices in particular:

-Magnet

- ATLAS: Solenoid (2T) + 3 Toroids (muon system)
- CMS: Large Solenoid (3.8T)

-Calorimeters

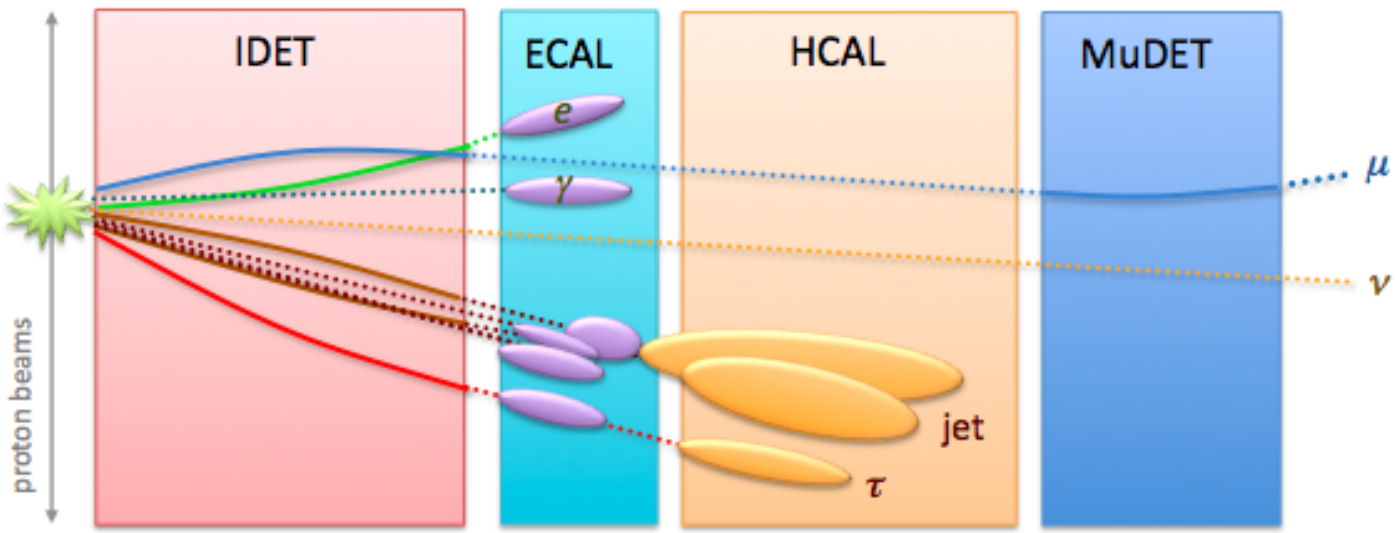
- ATLAS: LAr ECAL (longitudinal granularity), outside solenoid
- CMS: Crystal ECAL, inside solenoid

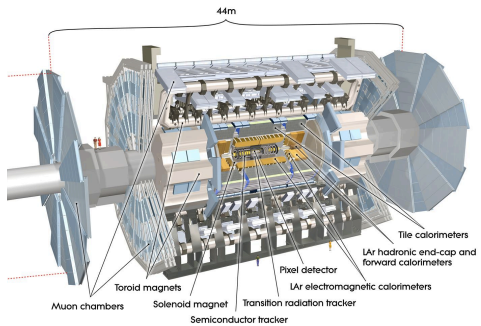
Despite these differing design choices both have very similar physics performance!

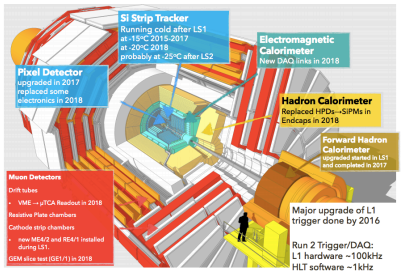
ATLAS/CMS Detectors

Different sub-detectors in ATLAS/CMS allow to efficiently reconstruct and identify:
- electrons, muons, photons,
- hadronic jets (initiated from quarks or gluons) (tagging those from b-quarks),
- hadronic tau decays
-missing transverse energy (MET), can come from SM neutrino, weakly interacting new physics particles or detector effects

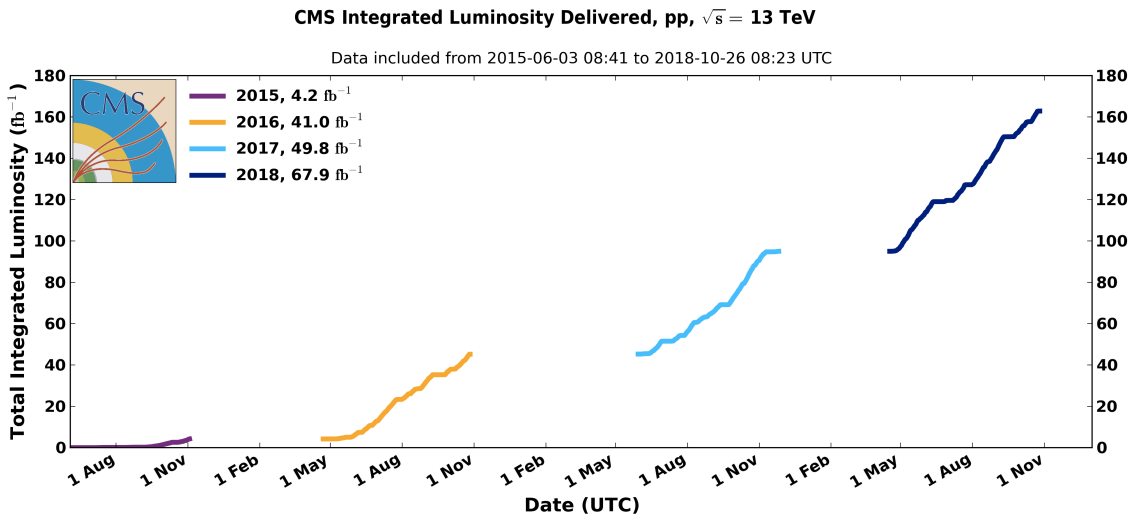
Online selection of interesting events (trigger) very big challenge. Bunch crossing rate 40Mhz and write ~1kHz of events to tape for offline analysis. Sophisticated hardware and software trigger needed to select events of interest.







Run-2 Dataset



Vast Run-2 dataset (~140/fb good data), provides huge physics potential

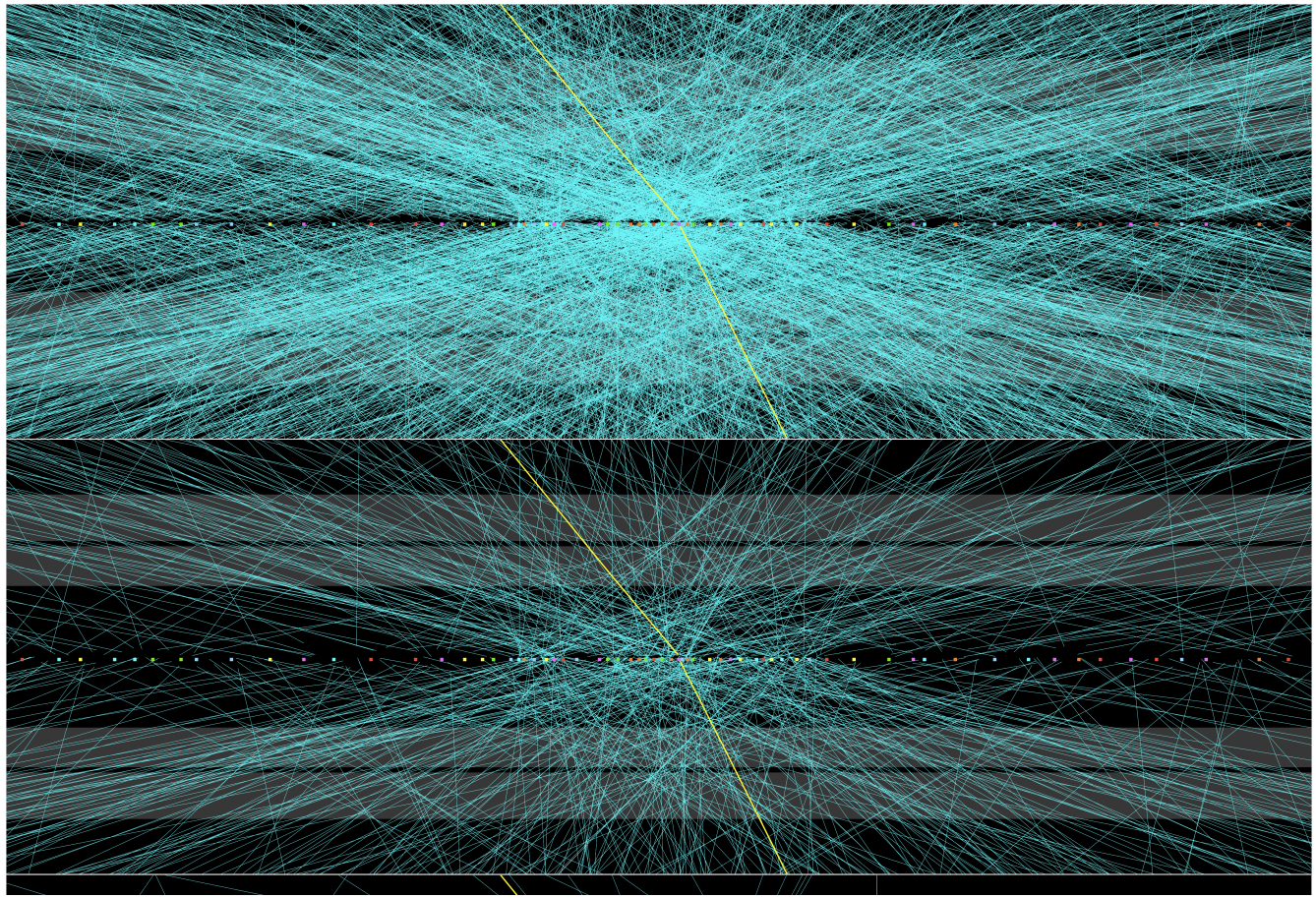
Particle Type	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV
Higgs Boson	~7.7 million
Top Quark	~275 million
Z Boson	~2.8 billion (→ll, 290 million)
W Boson	~12 billion (→lν,3.7 billion)
Bottom Quark	~40 trillion (≪ because of acceptance)

A. Hoecker (CERN)

But at the cost of high pileup….

Run-2 pileup in ATLAS/CMS

Pileup is one of the leading challenges for the LHC experiments. Additional soft interactions on top of the interaction of interest complicate the event reconstruction and analysis, especially for neutral objects that don't have charged tracks that can be associated to the different reconstructed pp vertices.

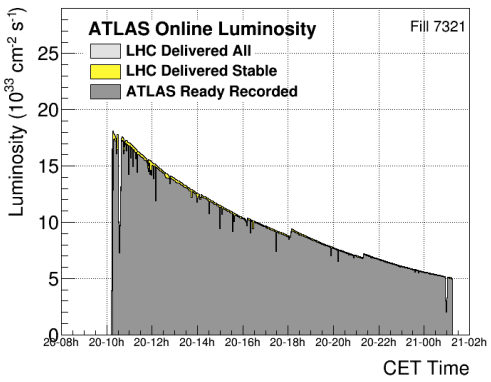


A reconstructed Z->μμ event with 65 reconstructed pp interaction vertices.
Muon tracks shown in yellow.
The tracks are shown for
(top) p_T>0.1GeV
(bottom) p_T>1 GeV

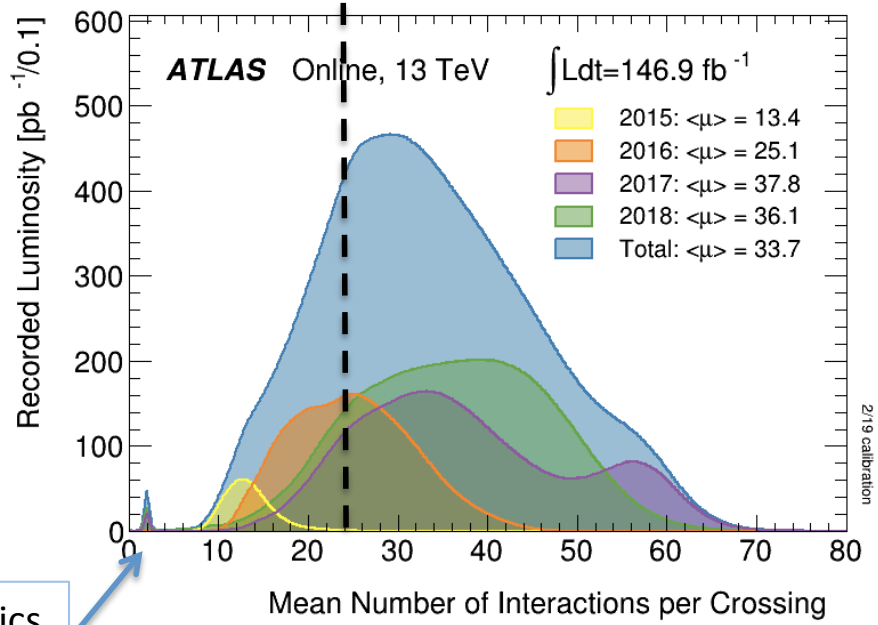
Run-2 pileup in ATLAS/CMS

Pileup is one of the leading challenges for the LHC experiments. Additional soft interactions on top of the interaction of interest complicate the event reconstruction and analysis, especially for neutral objects that don't have charged tracks that can be associated to the different reconstructed pp vertices.

The average pileup in the Run-2 dataset was ~34. But with a peak above 60, mostly coming from 2017 running with fewer, high intensity bunches. In 2018 running with more bunches allows higher luminosity, but with less pileup (much better for physics!)



LHC design peak pileup



Small dataset with low-pileup for W physics

Physics performance at high pileup

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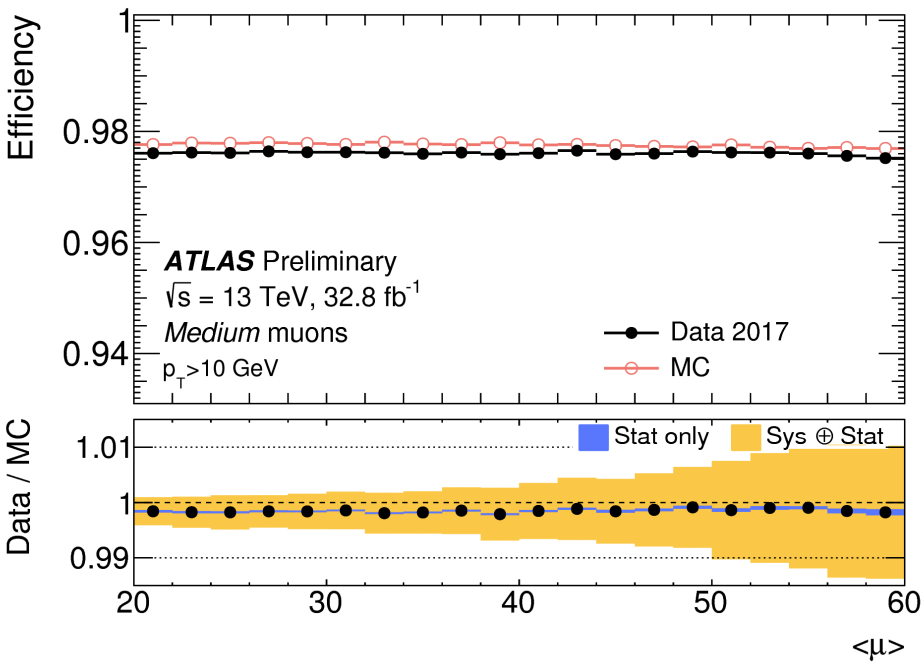
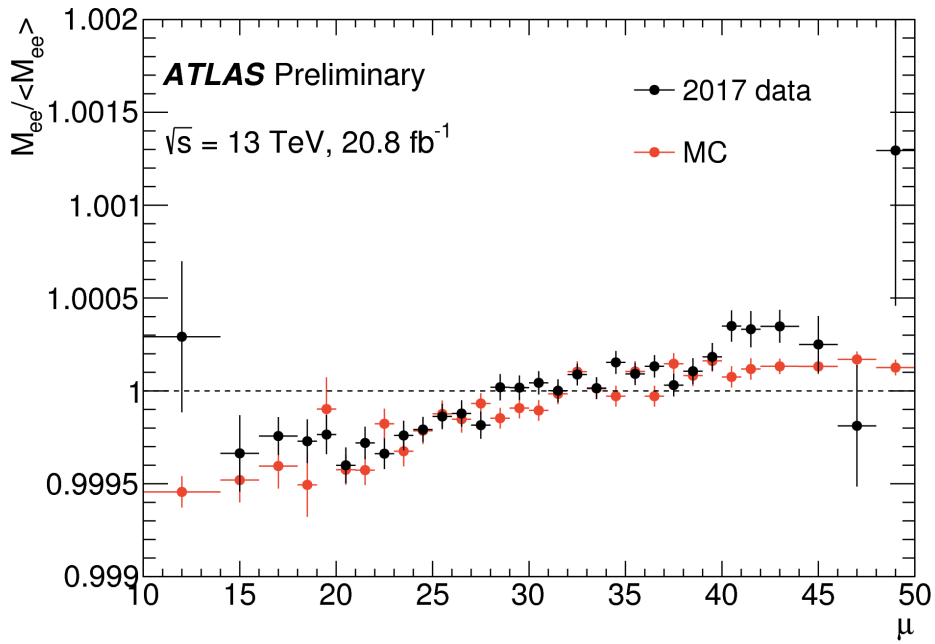
A huge effort has gone into making the reconstruction of particles robust against pileup.
Keeping high efficiency, and good resolution even at a pileup of 60 is very challenging.
Two examples:



Muon efficiency very high, and stable with pileup, and well reproduced by simulations.



Electron energy scale stable with pileup and well reproduced by simulation.

ATL-PHYS-PUB-2018-007

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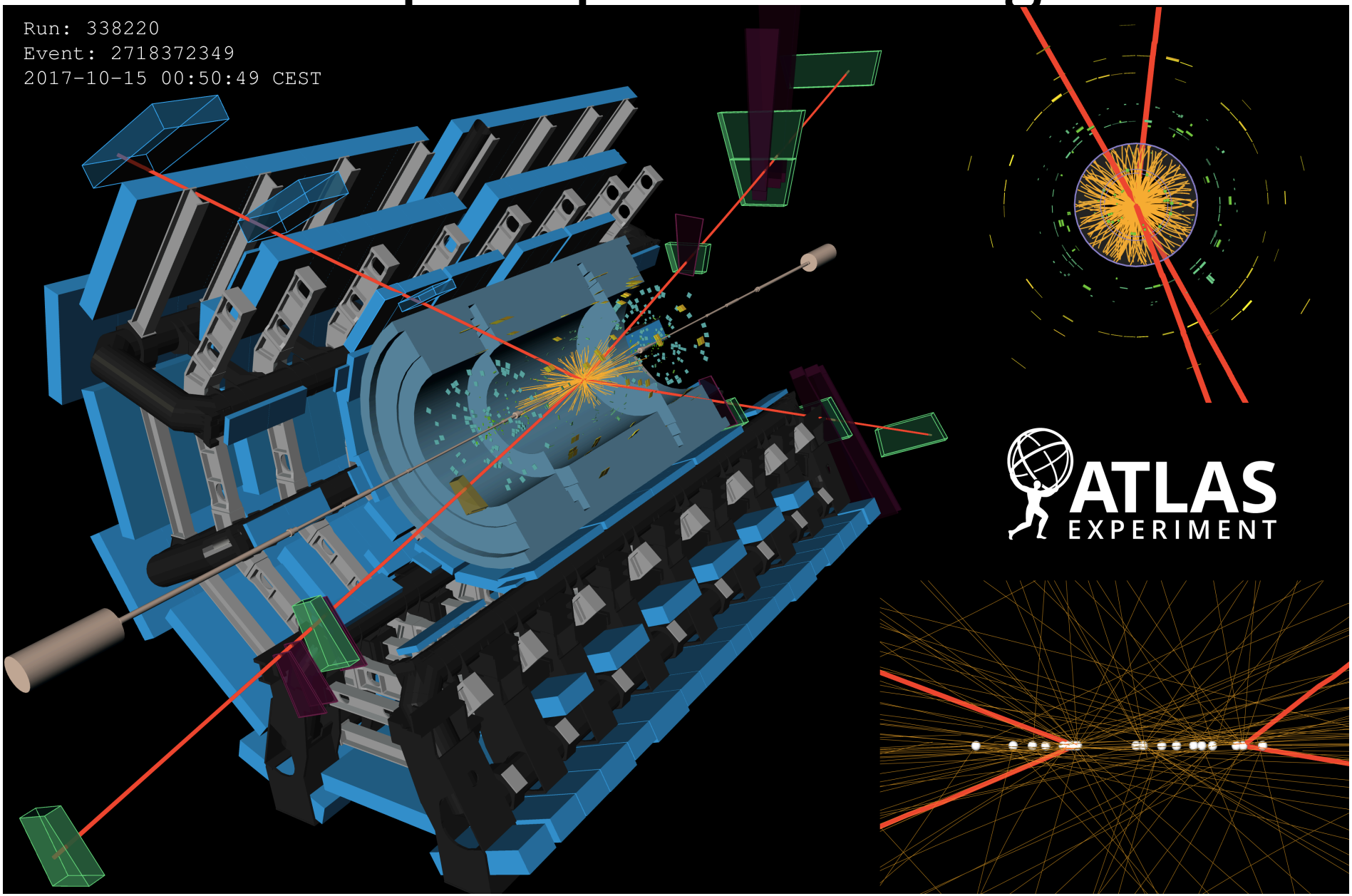
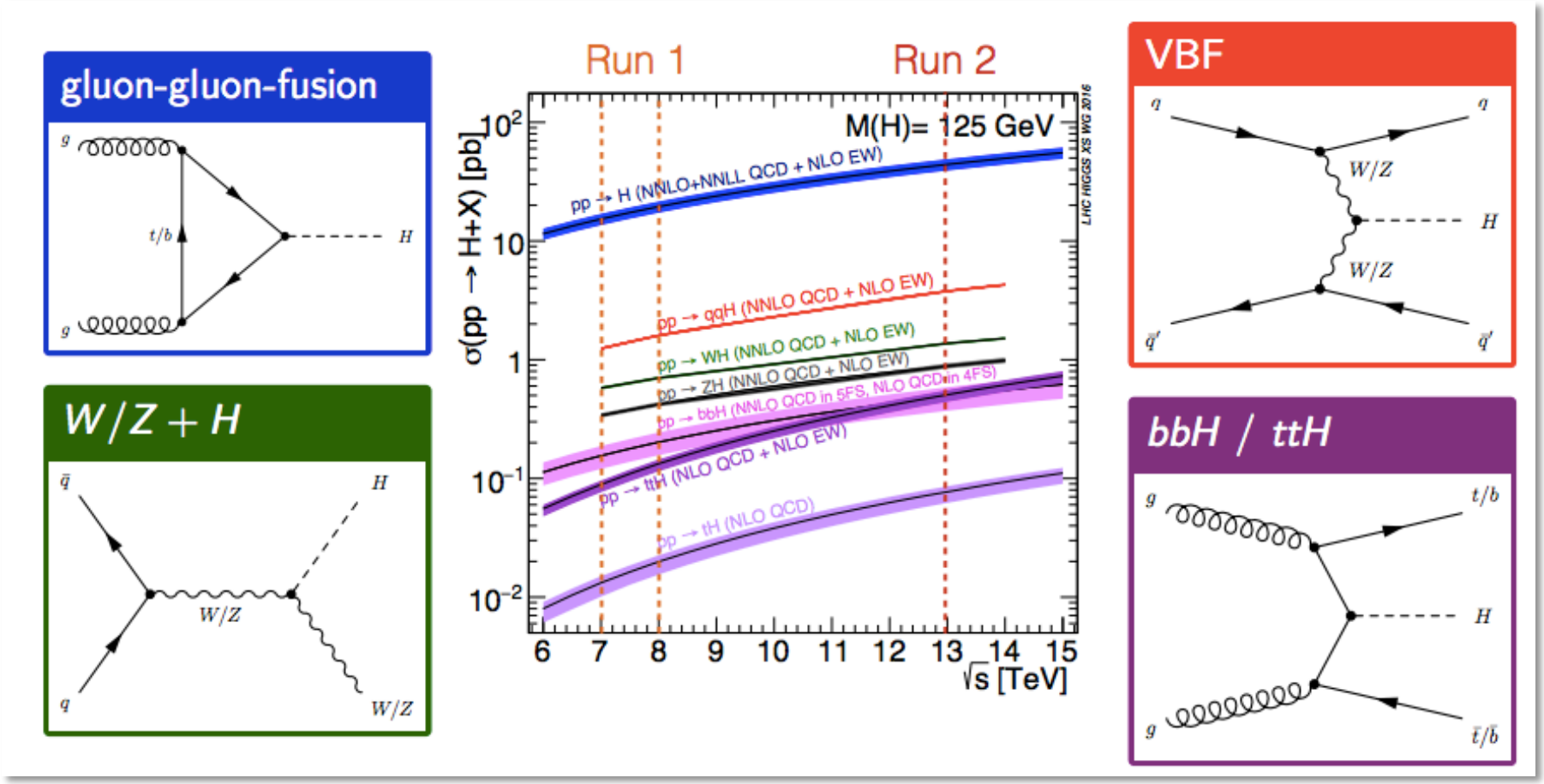
Run-2 pileup – a new regime



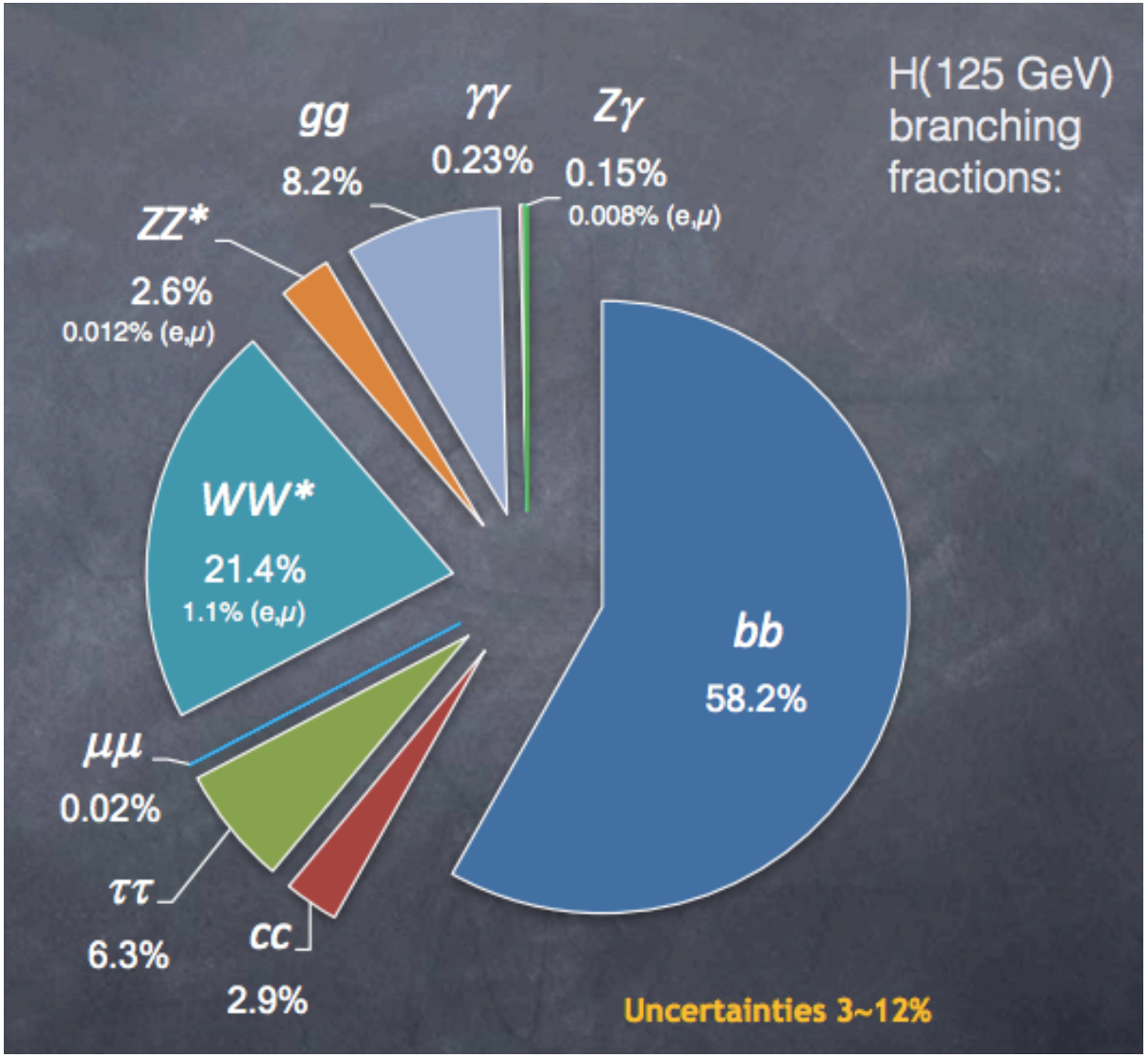
Brief reminder of LHC Higgs physics

Production:



Brief reminder of LHC Higgs physics

Decay:



A. Hoecker (CERN)

Mass resolution very good (1-2%) for:
H->ZZ*->4l
H->γγ
Much worse(10-20%) for:
H->bb
H->ττ
H->WW*

Higgs Discovery at LHC

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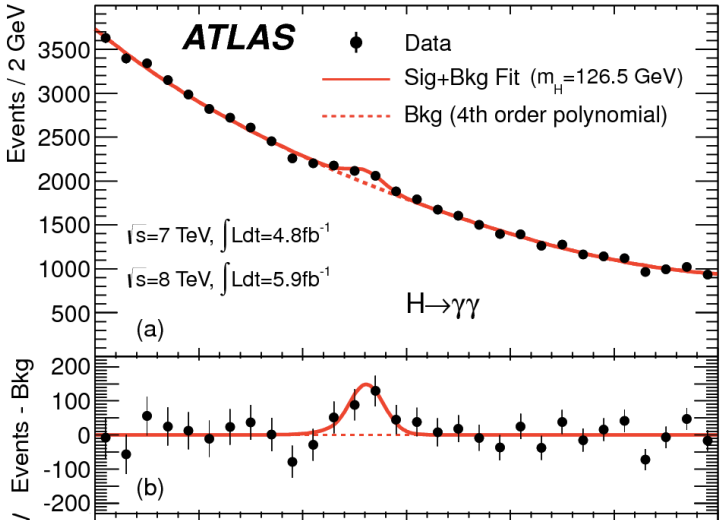

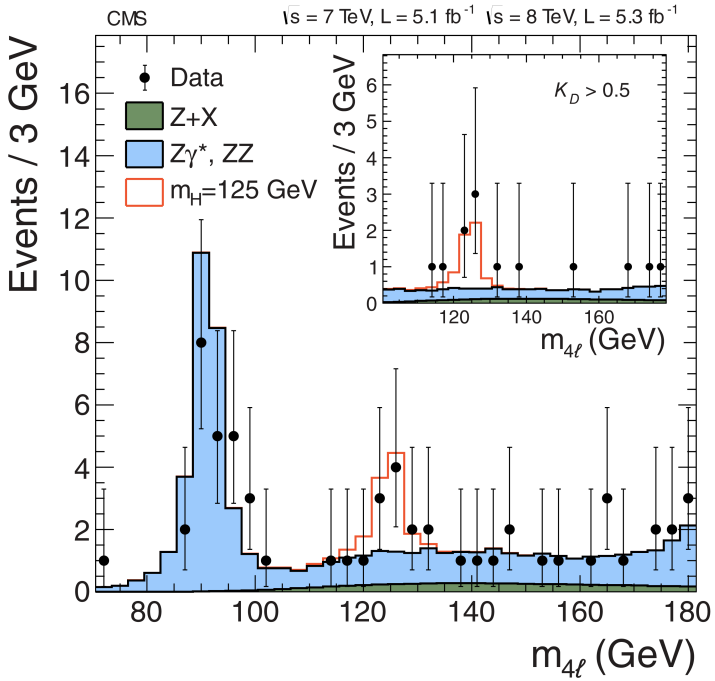

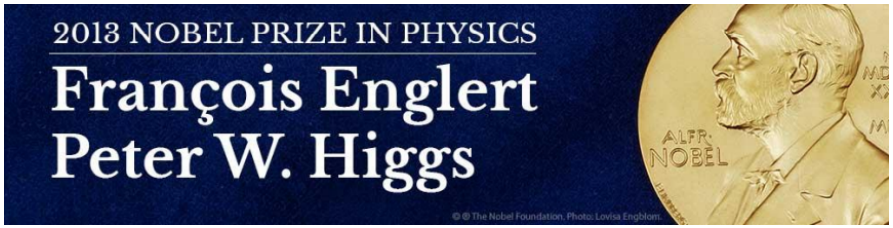

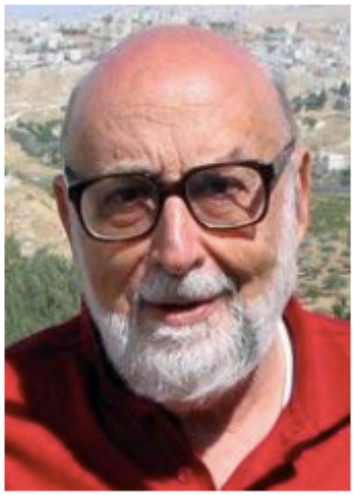

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Higgs Discovery at LHC – and now

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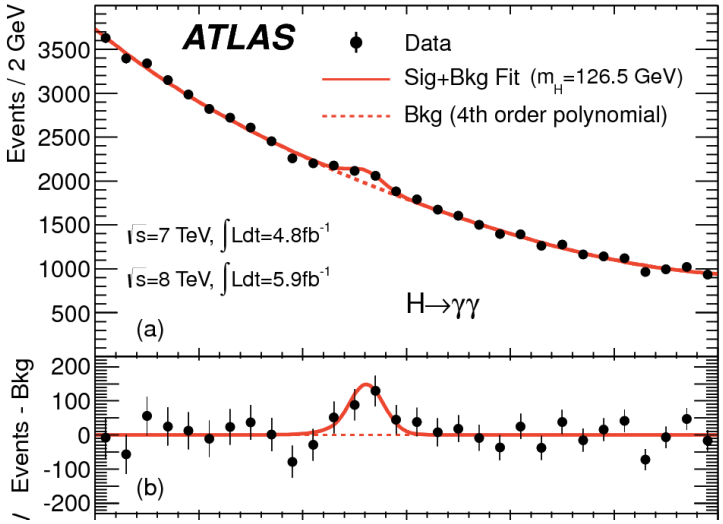

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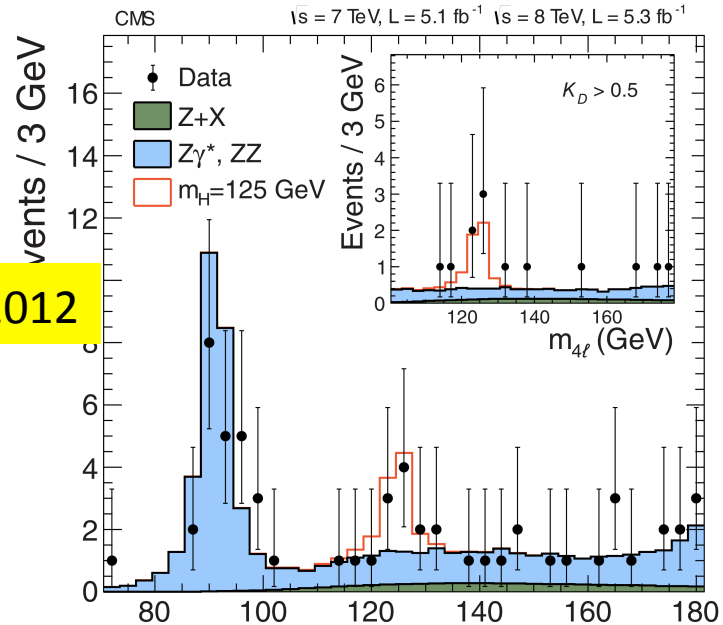
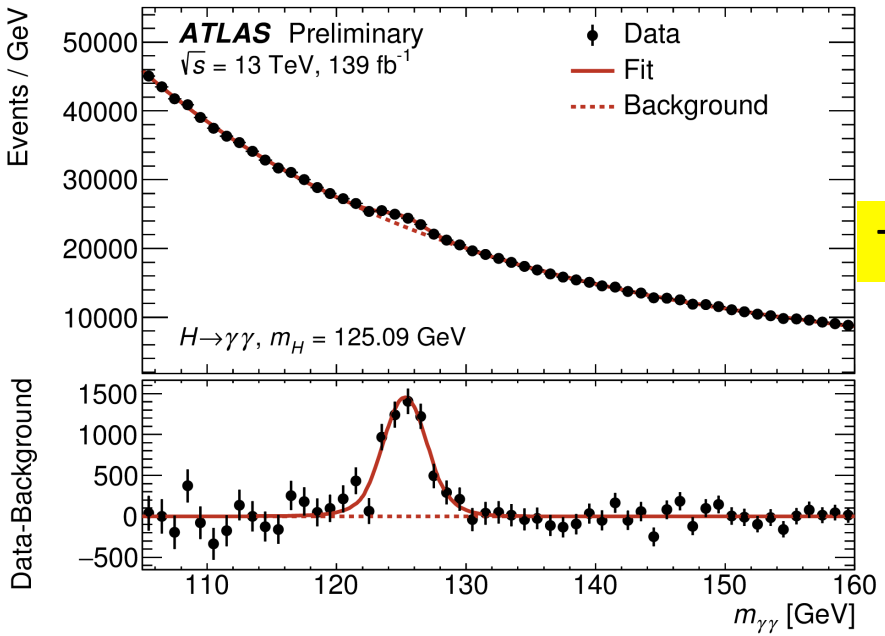
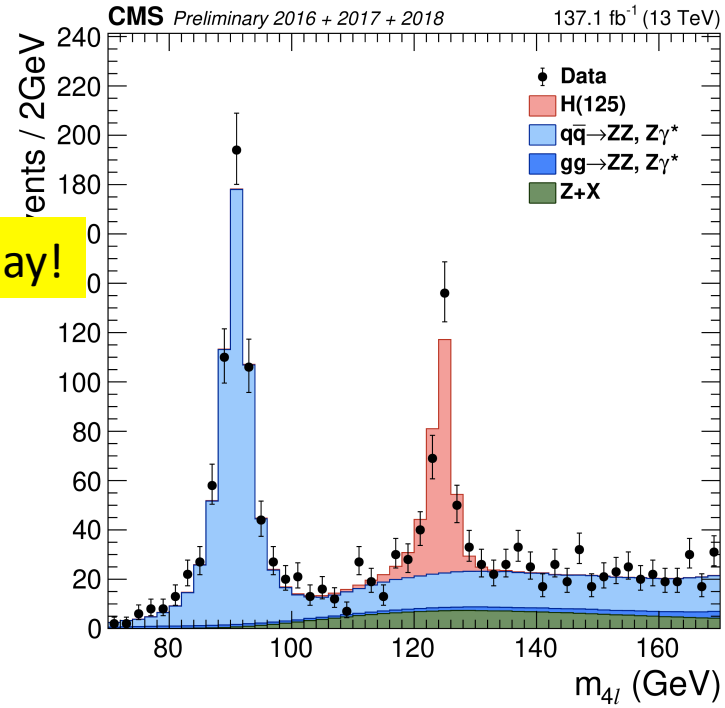




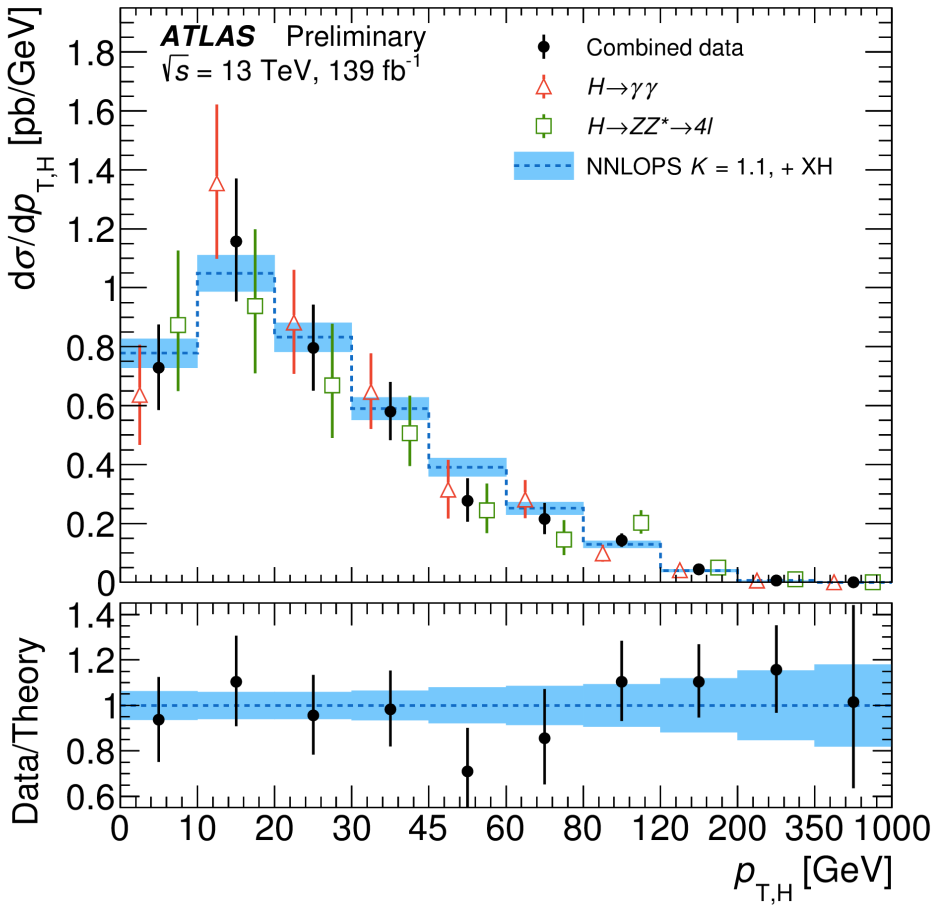
Today!



Differential measurements

Much larger samples of reconstructed Higgs bosons allow to measure the differential cross section as function of H pT, y, Njets and jet pT using the two high purity channels H->γγ, H->ZZ*->4l. Combining these channels to give the best precision. Results compared to various theoretical predictions. Generally data well described by predictions at current level of precision. Differences between measurement and prediction could be an indication of new physics!

ATLAS-CONF-2019-032



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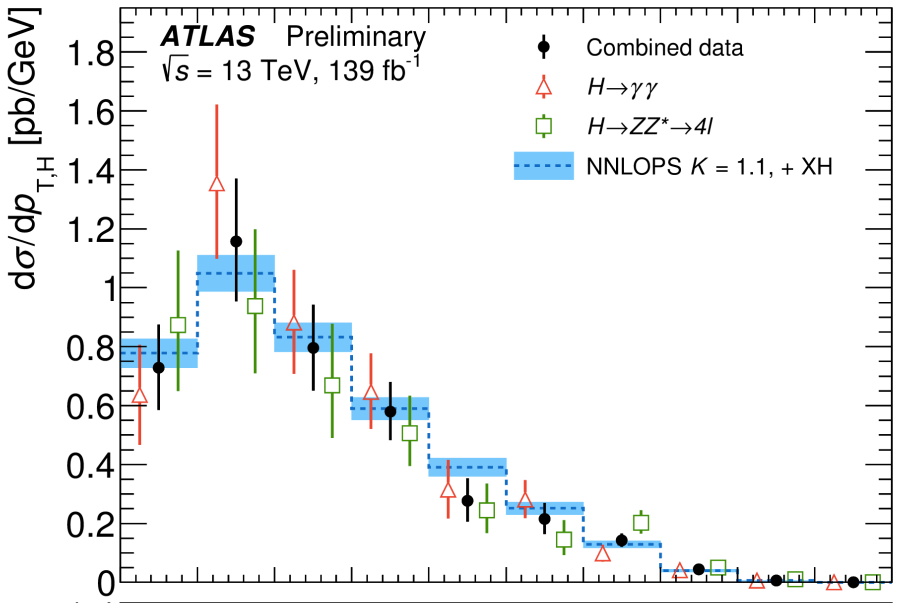
Much larger samples of reconstructed Higgs bosons allow to measure the differential cross section as function of H pT, y, Njets and jet pT using the two high purity channels H->γγ, H->ZZ*->4l. Combining these channels to give the best precision. Results compared to various theoretical predictions. Generally data well described by predictions at current level of precision. Differences between measurement and prediction could be an indication of new physics!

ATLAS-CONF-2019-032



Total Higgs production cross-section:

$$\sigma(pp \to H) = 56.7\,^{+6.4}_{-6.2}(\gamma\gamma),\ 54.4\,^{+5.6}_{-5.4}(4\ell),\ 55.4\,^{+4.3}_{-4.2}(\text{comb})\ \text{pb}$$

(Precision of 7.7%)

SM: 55.6 ± 2.5 pb (NLO–3NLO QCD, NLO EW)

Higgs couplings

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Measuring the rate of the different Higgs production and decay modes allows to constrain the Higgs couplings. With more data have been able to constrain all of the major production and decay modes that are accessible at the LHC.

1. Couplings to vector bosons (W,Z) well established – measured to ~10% level
2. Coupling to 3rd generation fermions established;
   - Direct coupling measured in decays to tau leptons and b-quarks, and production with top
   - Indirect coupling inferred from gluon fusion production (dominated by top loop in SM)

Coupling fit to all channels used to derive measured couplings with respect to SM.

	γγ	ZZ*	WW*	bb	cc	ττ	μμ	Combined
ggF	**Observed**	**Observed**	**Observed**	-	-	UL	UL	**Observed**
VBF	UL	UL	UL	UL	-	**Evidence**	UL	**Observed**
VH	UL	UL	UL	**Observed**	UL	-	-	**Observed**
ttH	**Evidence**	UL	**Evidence**	UL	-	**Evidence**	-	**Observed**
Combined	**Observed**	**Observed**	**Observed**	**Observed**	-	**Observed**	UL	

Inspired by G. Salam's talk at LHCP 2018

What the Higgs tells us

ESHEP 2019
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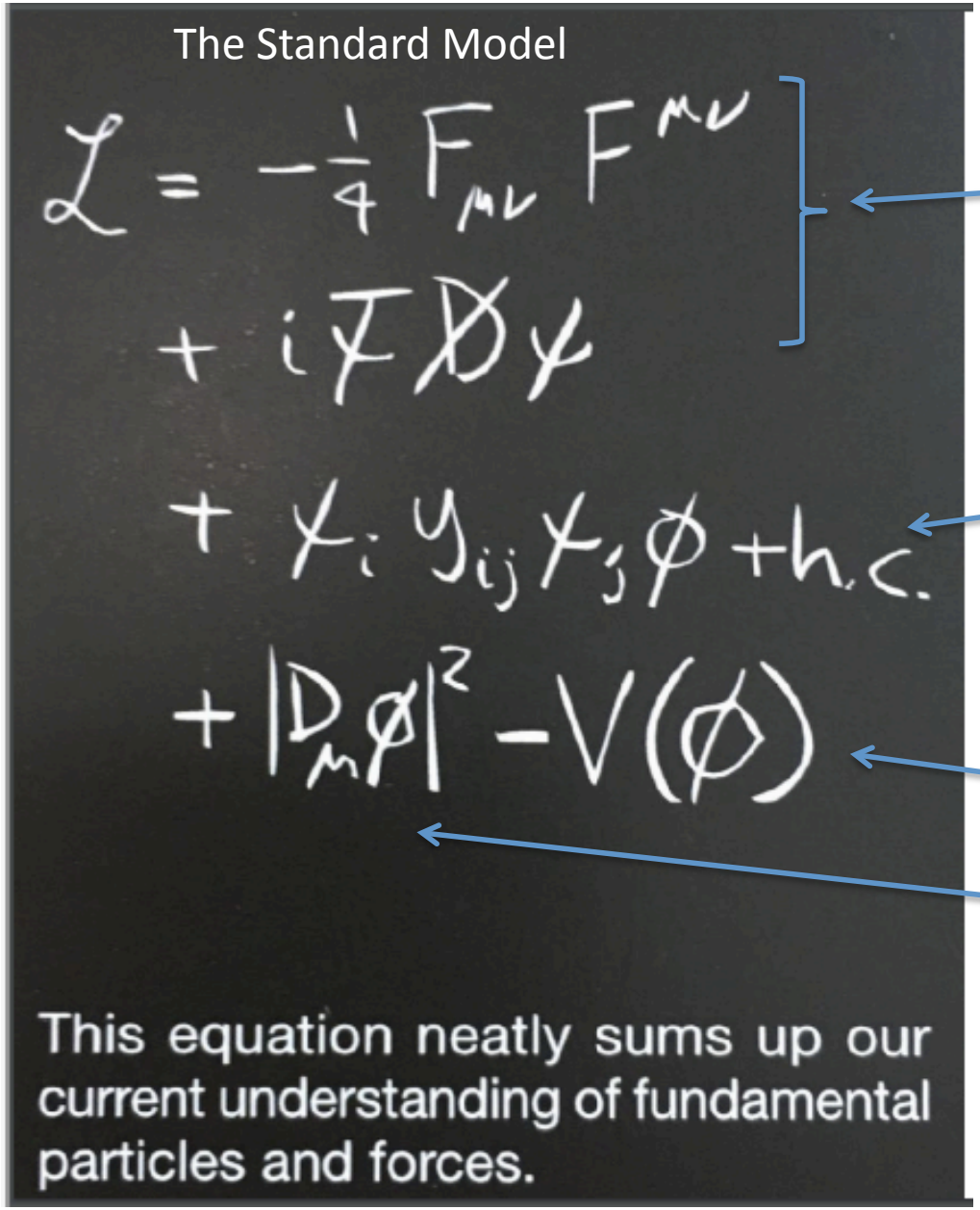


Gauge interactions, well studied in last 50 years

Yukawa coupling (Higgs to fermions) not a gauge interaction. Never studied before. Higgs coupling to fermions is the first time we can really study this!

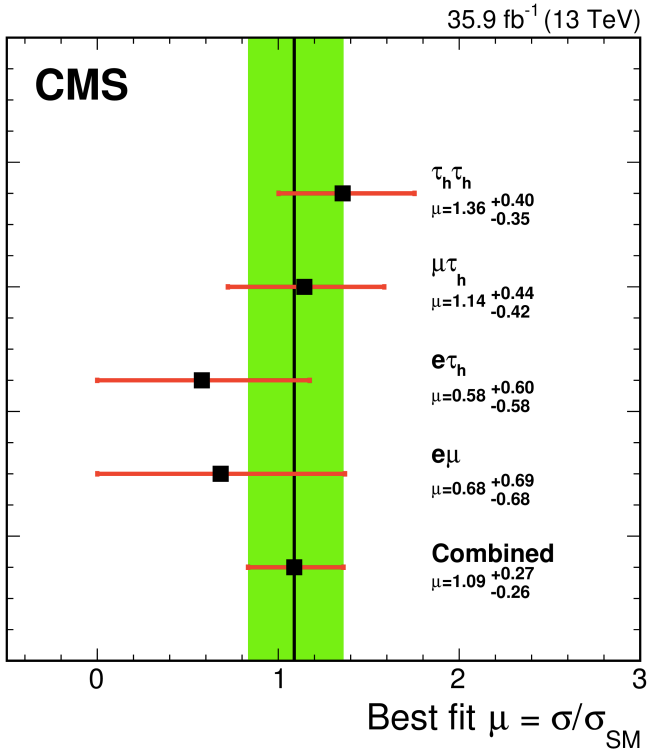
Higgs potential. Need HH production to study this!

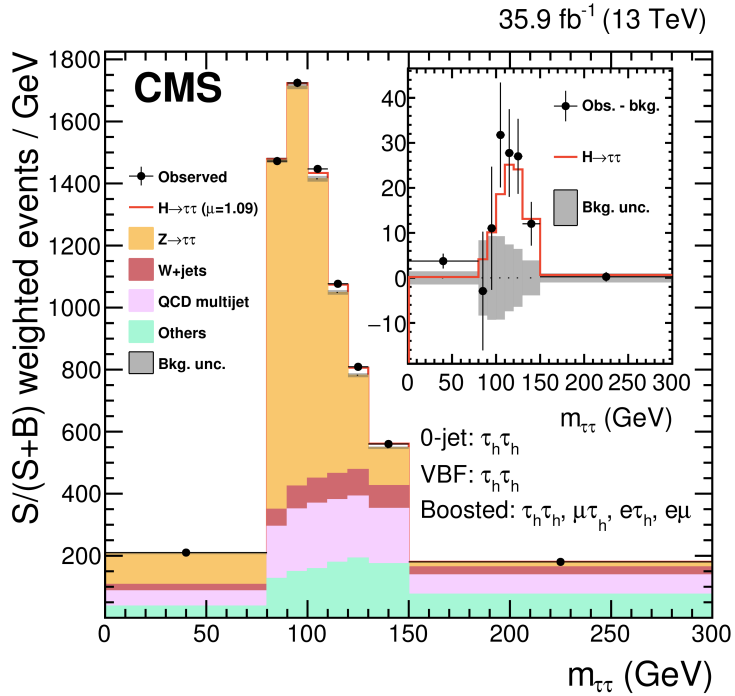
Higgs coupling to vector bosons. Gauge interaction with scalars. Similar to what we have seen before.

PLB 779 (2018) 283 (CMS) / PRD 99 (2019) 072001 (ATLAS)

H->ττ observation

H->ττ crucial for demonstrating Higgs coupling to leptons, and third generation fermions.
Complex analysis using both leptonic and hadronic τ-decays (had-had, lep-had, lep-lep channels).
To control backgrounds have selections targetting VBF production and high-pT Higgs production.
Main background is Z->ττ, Higgs signal is ~x1000 smaller and is close in di-tau mass.





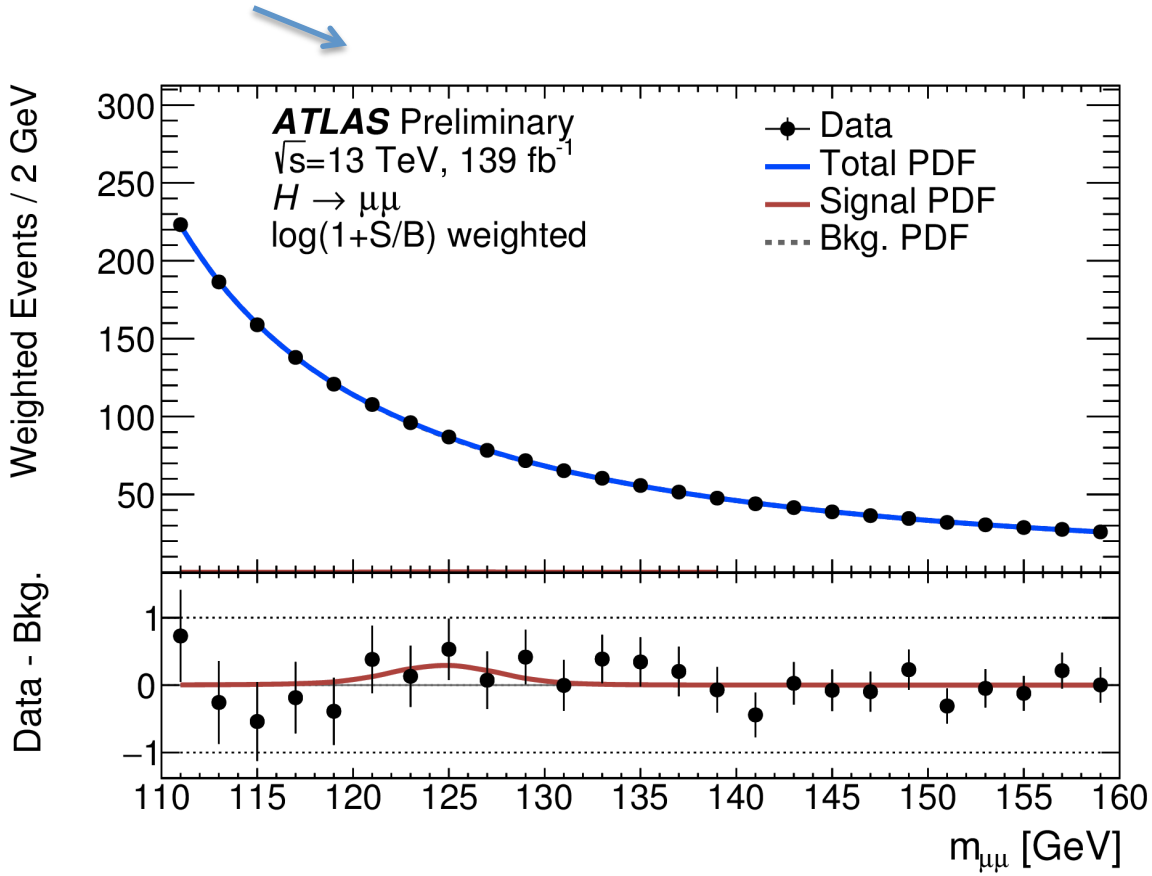
Combined with Run-1 this gives a significance of 5.9σ(5.9σ exp.).
Measured cross section compatible with SM.

PRL 122 (2019) 021801 (CMS) / ATLAS-CONF-2019-028

H->ττ & H->μμ

H->ττ observation along with the fact that we do not see evidence for H->μμ, implies that the Higgs does not couple equally to leptons. Very different coupling from what has been seen so far…

Search for H->μμ: No sign of an excess of events at the Higgs mass



H->μμ challenging due to the tiny signal, and large irreducible background. CMS stronger magnetic field (=>better di-muon mass resolution) is an advantage.
Current sensitivity at the ~1σ level.
H->ee not possible at the LHC (ATLAS-CONF-2019-037)

PLB 786 (2018) 59 (ATLAS) / PRL 121 (2018) 121801 (CMS)

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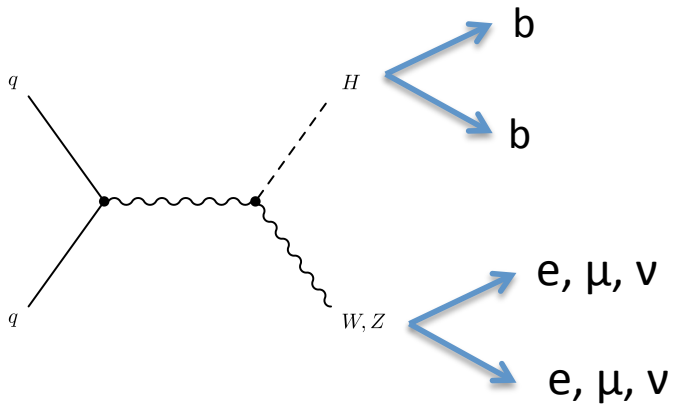
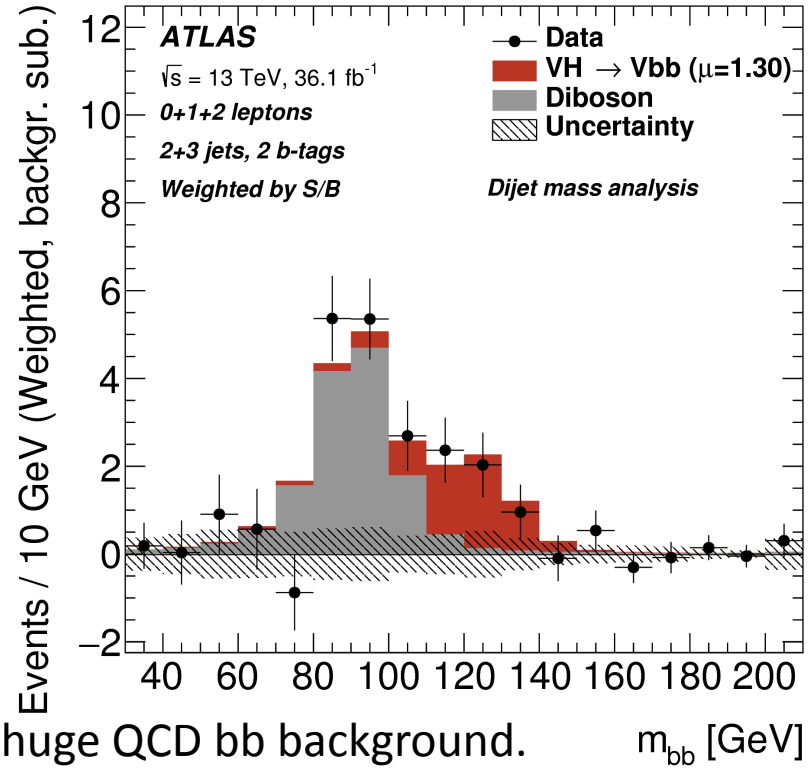
Observation of H->bb



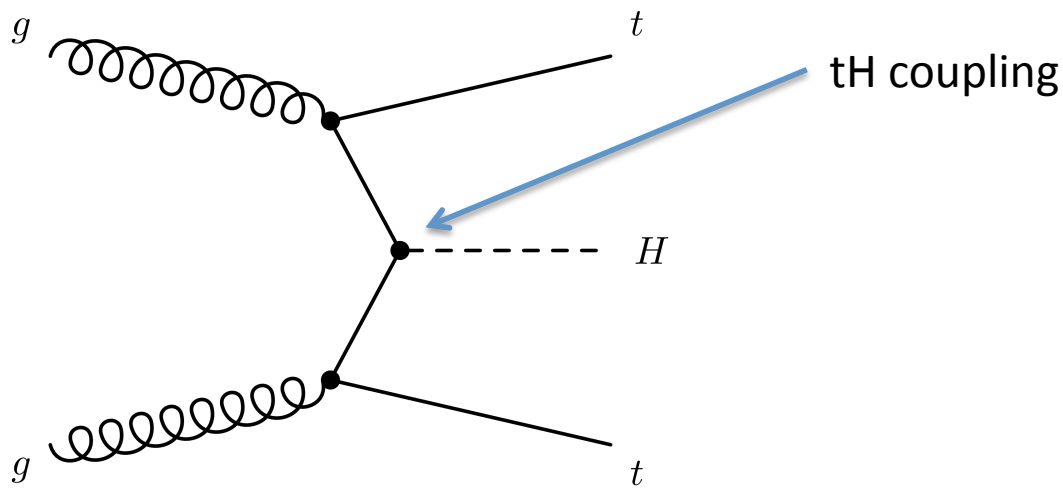


Decay to bottom quarks observed.
Inclusive search for H->bb impossible due to huge QCD bb background.
VH production channel used to allow to trigger events, and to control the background.
V means Z->ll, νν, W-> lν (triggers on 1 lepton, or large missing E_T).
Observe clear peak in di-bjet mass peak over background expectation and separated from Z->bb peak in VZ production (which acts as an important validation of the analysis).

Combined with Run-1 this gives a significance of 5.4σ(5.5σ exp.).
Measured cross section compatible with SM:
μ(H->bb) = 1.2±0.3, μ(Z->bb) = 1.2±0.2

PLB 784 (2018) 173 (ATLAS) / PRL 120 (2018) 231801 (CMS)

Observation of ttH production

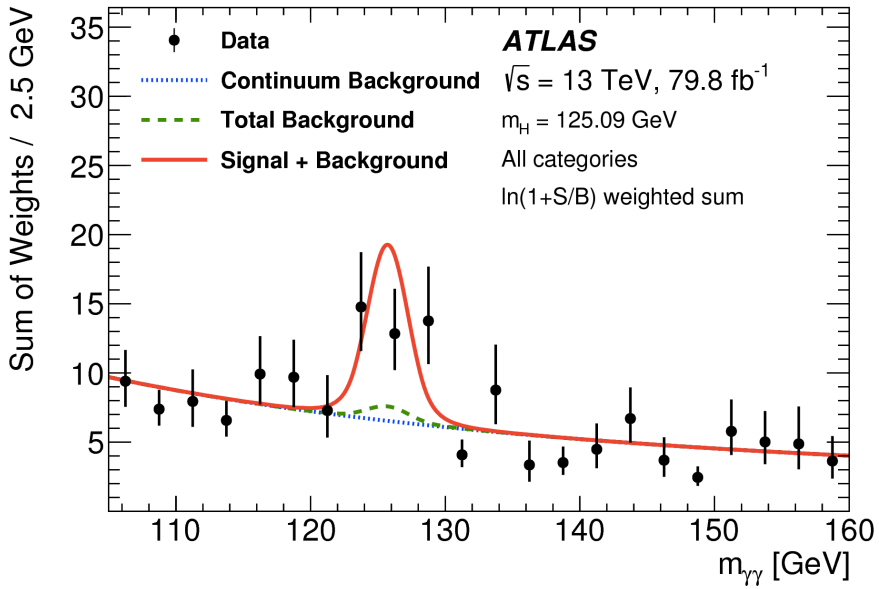


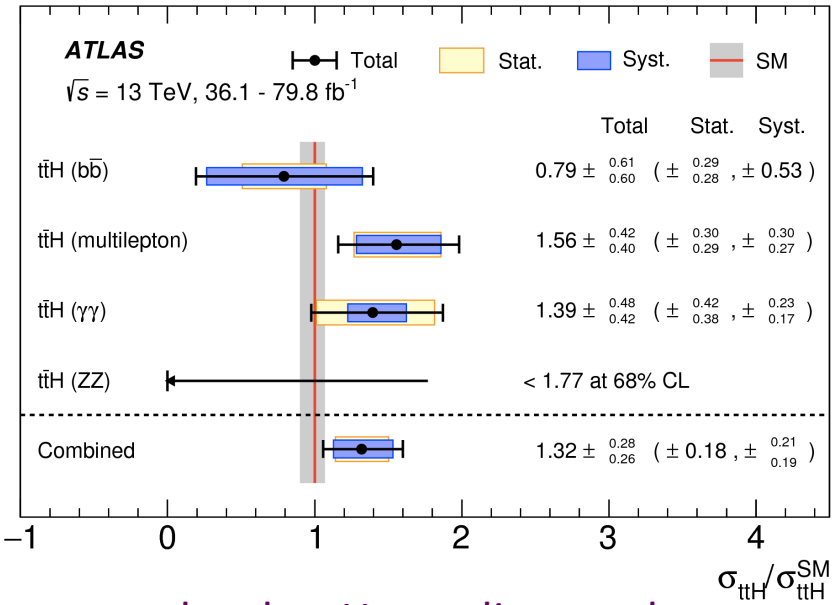
Since the Higgs is too light to decay to 2 top quarks, the tH coupling can be measured via ttH production. The final state is very heavy, so the cross section is low (~1% of inclusive Higgs production), and it is a complex final state.

To search for this a large number of channels are combined with semi-leptonic and di-leptonic decays of the tops, and considering Higgs decays to: bb, ZZ*, WW*, ττ, γγ

PLB 784 (2018) 173 (ATLAS) / PRL 120 (2018) 231801 (CMS)

Observation of ttH production





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To search for this a large number of channels are combined with semi-leptonic and di-leptonic decays of the tops, and considering Higgs decays to: bb, ZZ*, WW*, ττ, γγ

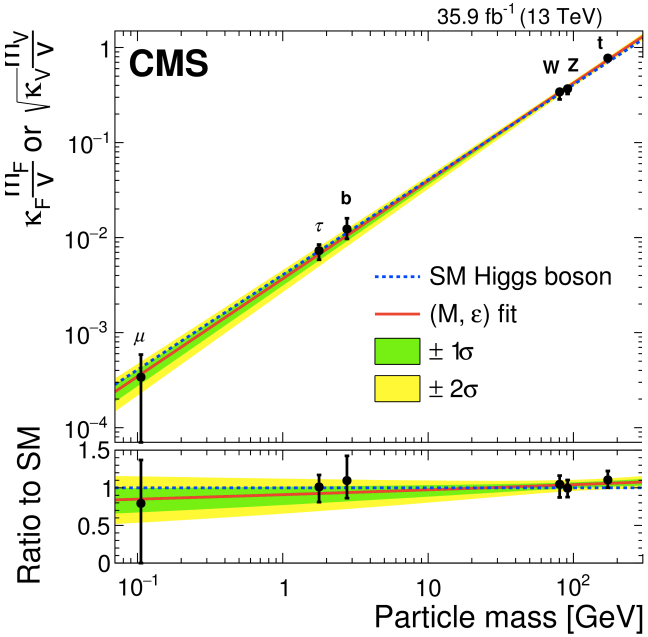
Analysis uses sophisticated techniques (BDTs) to improve sensitivity for the different challenging final states, with very small signals.

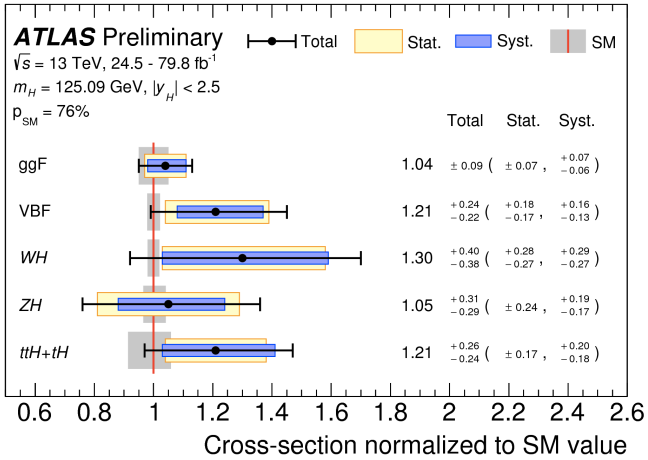
Using 36/fb of data for H->WW*,ττ,bb and 80/fb for H->γγ,ZZ*, combining these gives 5.9σ (Obs.), 4.9σ (Exp) significance. Combining with Run-1 gives 6.3σ/5.1σ.

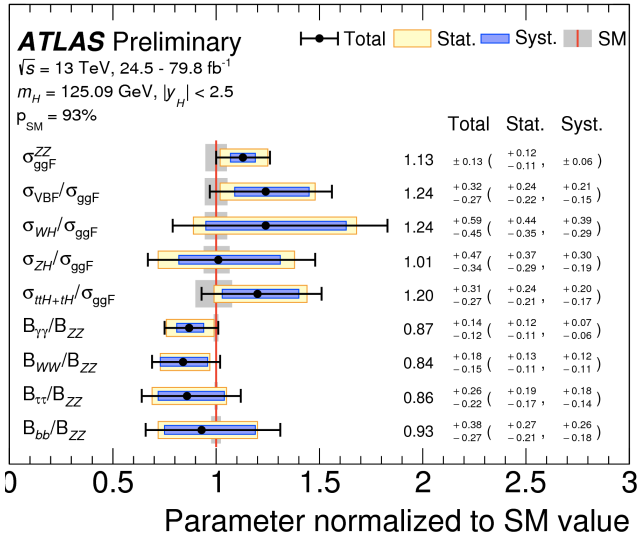
Measured μ-value = 1.3±0.3 – consistent with SM.

ATLAS-CONF-2019-005/ EPJC 79 (2019) 421 (CMS)

Higgs couplings





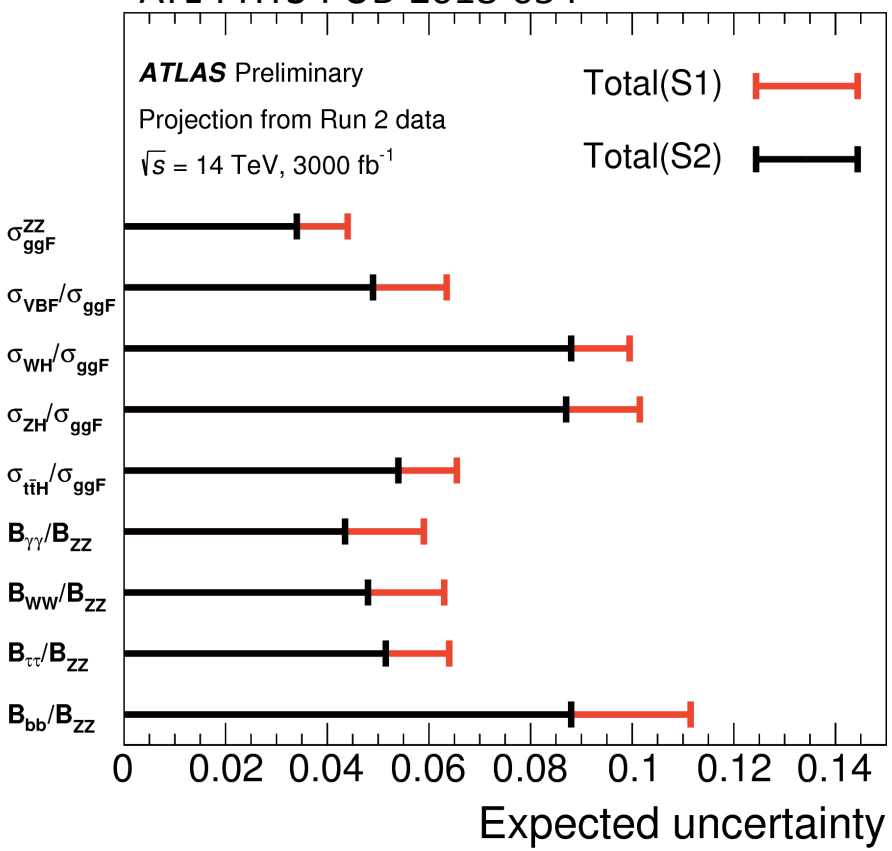


	γγ	ZZ*	WW*	bb	cc	ττ	μμ	Combined
ggF	Observed	Observed	Observed	-	-	UL	UL	Observed
VBF	UL	UL	UL	UL	-	Evidence	UL	Observed
VH	UL	UL	UL	Observed	UL	-	-	Observed
ttH	Evidence	UL	Evidence	UL	-	Evidence	-	Observed
Combined	Observed	Observed	Observed	Observed	-	Observed	UL	

Higgs prospects

Improve precision on Higgs couplings to few-% level (where deviations from BSM can show up)
Observe coupling to 2nd generation fermions:
    H->μμ, H->cc
Observe rare SM decays e.g. H -> Z gamma
Improve limits on non-SM Higgs decays (H->invisible, LFV decays H->mu tau etc..)
More precise differential measurements going to higher pT

ATL-PHYS-PUB-2018-054



Run-2 systematics

Improved systematics

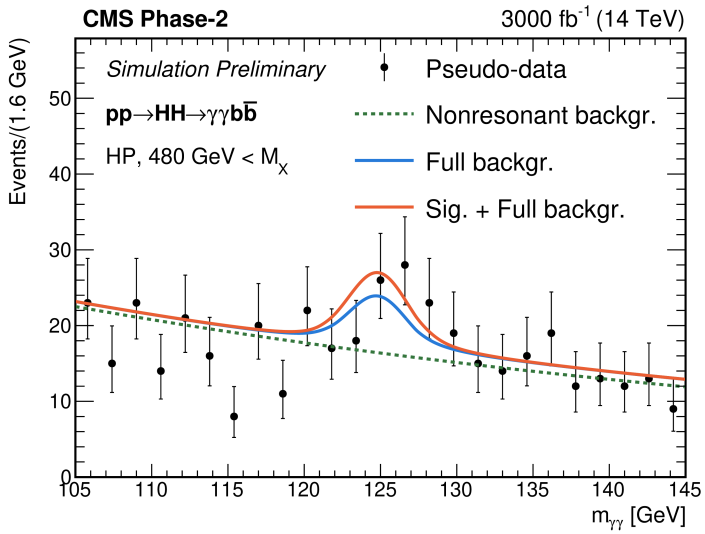
Higgs prospects

Improve precision on Higgs couplings to few-% level (where deviations from BSM can show up)
Observe coupling to 2nd generation fermions
    H->μμ, H->cc
Observe rare SM decays e.g. H -> Z gamma
Improve limits on non-SM Higgs decays (H->invisible, LFV decays H->mu tau etc..)
More precise differential measurements going to higher pT

Far future: Evidence for HH production – very important but extremely challenging (v.low BF)

CMS Example (CMS-PAS-FTR-18-019):

Channel	Significance Stat. + syst.	Stat. only
bbbb	0.95	1.2
bb$\tau\tau$	1.4	1.6
bbWW($\ell\nu\ell\nu$)	0.56	0.59
bb$\gamma\gamma$	1.8	1.8
bbZZ($\ell\ell\ell\ell$)	0.37	0.37
Combination	2.6	2.8



New physics searches

ATLAS/CMS have a huge programme of searches for new physics. Covering:
- Supersymmetry
- New gauge bosons
- Dark matter particles
- Extra Higgs bosons
- Unconventional signatures (long lived particles etc..)
- etc…

Can only show a few examples here.

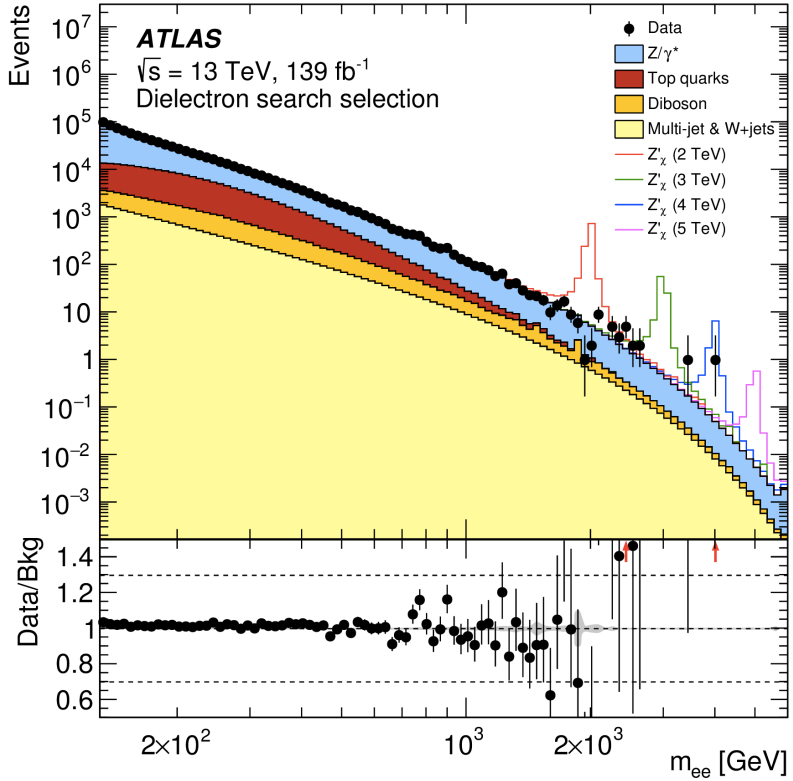
Bottom line, despite a very thorough search programme, no significant excess observed.
From these searches, strong limits have been placed on new physics models.
For some models with strongly interacting new particles we reach a point where more luminosity will not give a large improvement in limits (or discovery potential), higher energy needed.
However for many cases (especially for weakly interacting new particles) much more data is needed to get to the ultimate reach.
In addition new techniques and clever ideas are needed to increase sensitivity in many places.

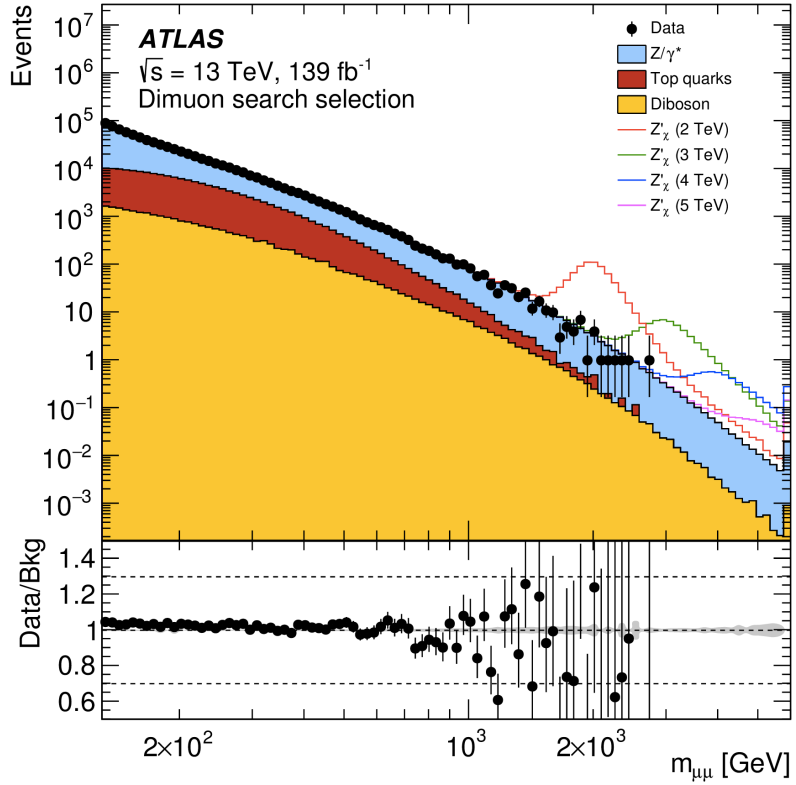
Phys. Lett. B 796 (2019) 68 / CMS-PAS-EXO-19-019

ESHEP 2019
CERN-JINR

Searches for heavy gauge bosons (Z')

Search for a heavy Z-like boson (Z') decaying to an e^+e^- or $\mu^+\mu^-$.
Key is efficient reconstruction of very high pT leptons with good momentum resolution.
Analysis looks for excess of events at high di-lepton mass. Highest lepton pT up to ~2 TeV!





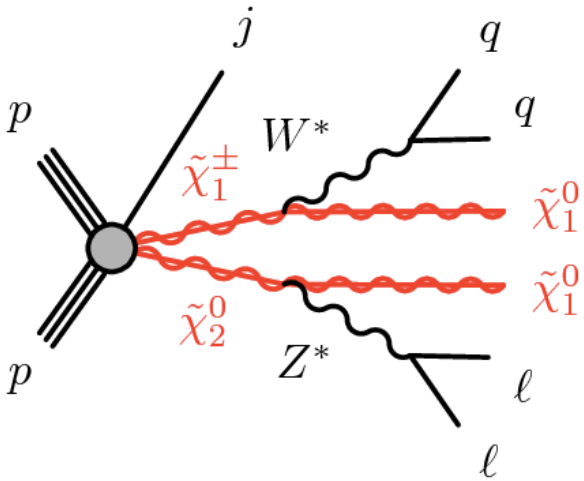
Distribution of di-lepton mass for electron and muon channels, showing also example signals.
Considerably worse mass resolution for muon channel – limited by muon detector alignment.
Very high pT tracks too straight to measure curvature well. Whereas electron resolution improves with energy.

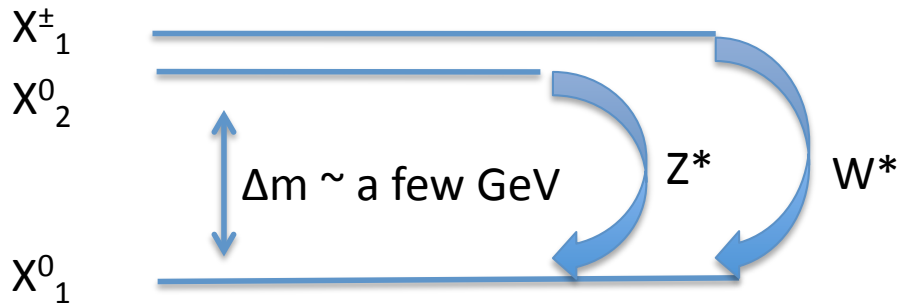
Exclude SSM Z' with masses up to 5.1 TeV.

ATLAS-CONF-2019-014

Search for Higgsino production

Higgsino, SUSY partner of Higgs, expected to be light in natural SUSY models.
Triplet of states with very small mass splitting: Decay via virtual Z or W can give leptons and MET, but very low pT. Look for events with high pT ISR jet to boost signal system – increase lepton pT and MET in detector. Lepton pT still very low – push detector to limits to utilize lowest possible pT electrons and muons.





For pure Higgsino mass splitting from radiative corrections a few hundred MeV.
Even small mixing with wino/bino gives bigger splitting up to ~10 GeV even for higgsino dominated states.

ATLAS-CONF-2019-014

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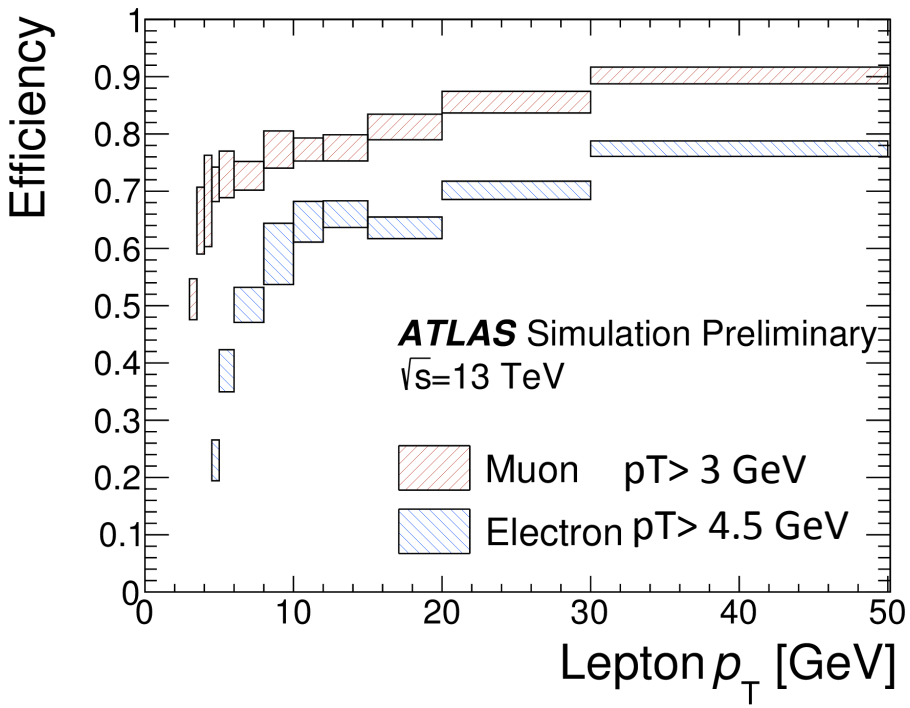
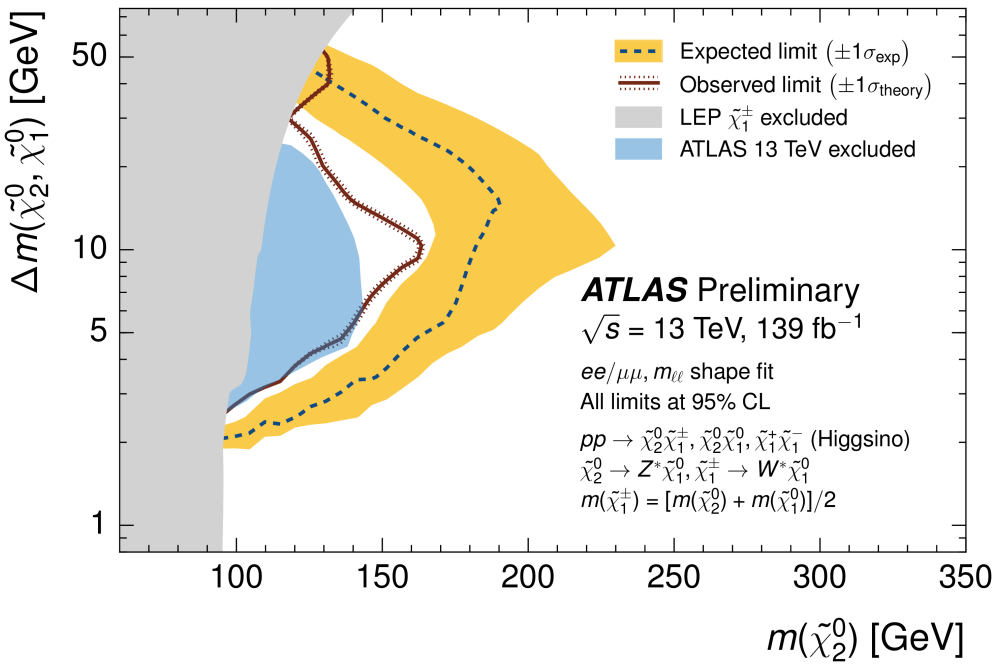


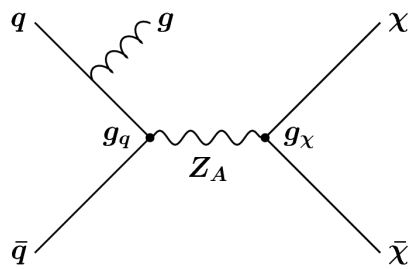


Exclude higgsino with mass up to ~160 GeV, going beyond LEP limit of ~100 GeV for the first time.
Sensitive for mass splittings down to 2 GeV.

JHEP 01 (2018) 126 / PRD 97 (2018) 092005

Dark Matter searches

Dark matter particles could be pair produced in LHC collisions – but would not be detected.
Use initial-state-radiation to tag such events – e.g.



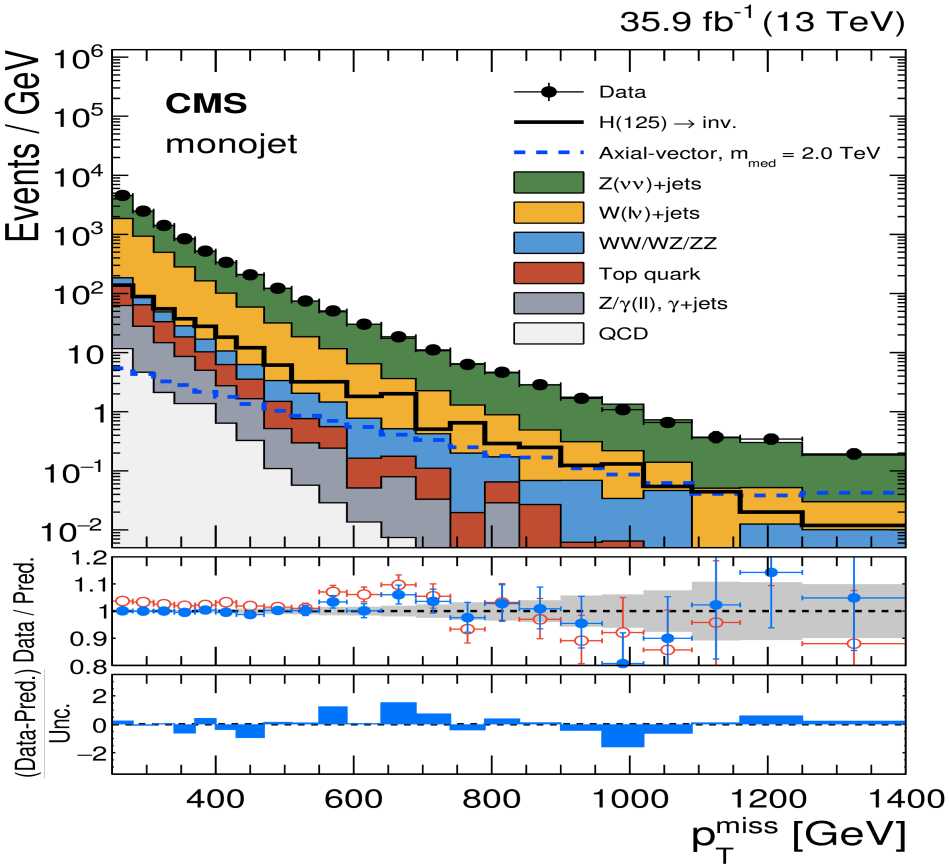
Could also radiate a photon, W/Z or Higgs boson

Signature:
high pT jet + MET

-Veto leptons, and b-jets to reduce backgrounds from W+jets and top
-Non-collision background/noise rejected

Main backgrounds from:
Z(->νν)+jet(s) (60%)
W(->lν)+jet(s) lepton missed (30%)

- Signal has slightly harder MET spectrum than background.



JHEP 01 (2018) 126 / PRD 97 (2018) 092005

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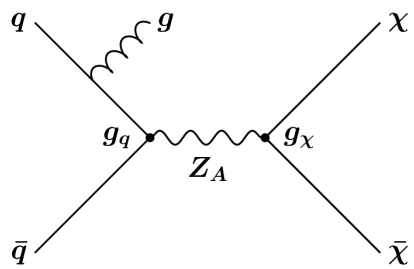
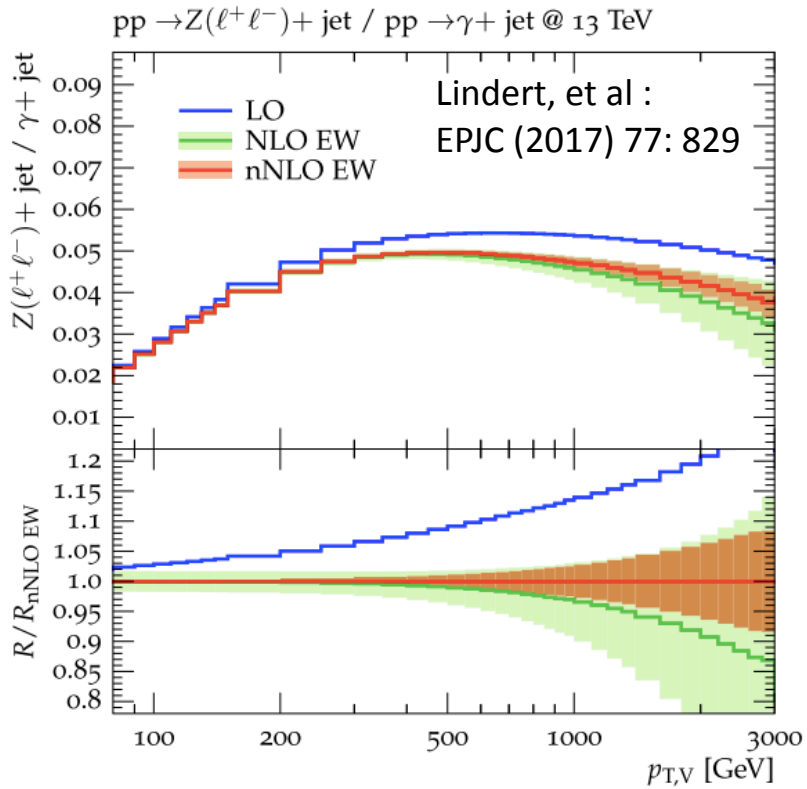


Could also radiate a photon, W/Z or Higgs boson

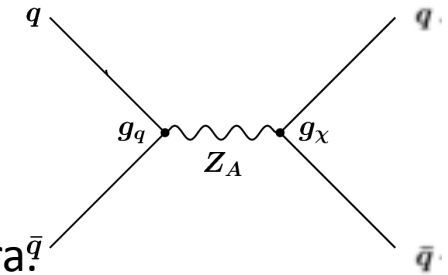
- Need to control the background at few-% level - very challenging.
-Use Z(ll)+jets, W(lv)+jets and γ+jets control regions to estimate background
- Need very precise theoretical estimate of the ratios:
W(lv)+jets/Z(->vv)+jet(s)
γ+jets/Z(->vv)+jet(s)
in bins of MET. Requires higher order EWK corrections.



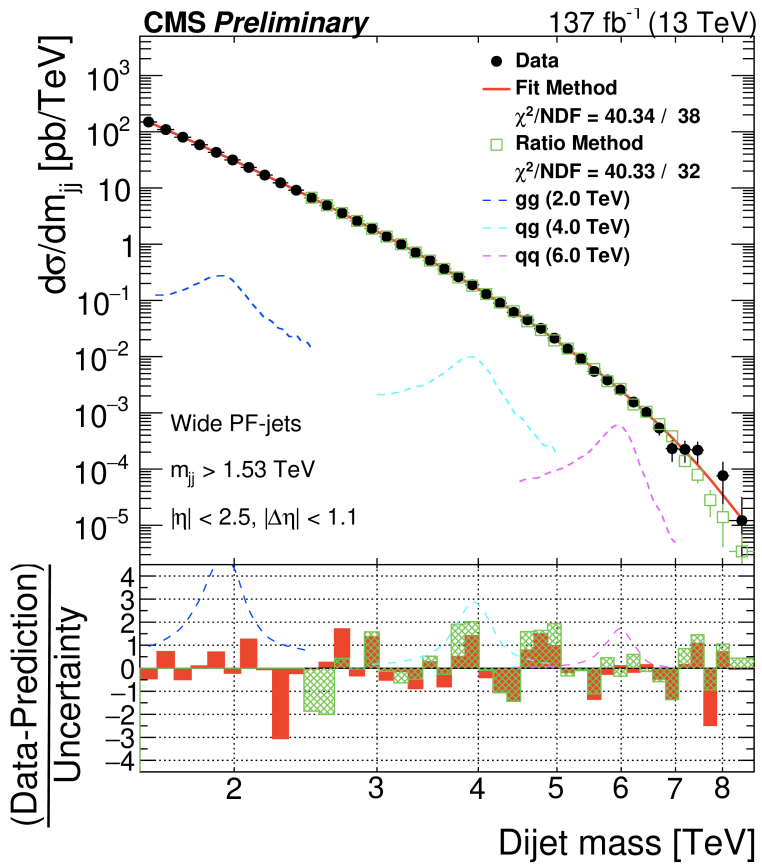
CMS-PAS-EXO-19-012 / ATLAS-CONF-2019-007

Dark Matter Mediator searches

The mediator could also decay to SM particles (e.g. quarks) and could be directly observed in LHC collisions.



This could show up as a bump in the di-jet mass spectra?
No bumps observed – but mass spectra starts at ~1 TeV due to trigger thresholds on jets (needed to keep trigger bandwidth under control).
What if the mediator is light, but with weak coupling?



JHEP 08 (2018) 130 (CMS) / PRL 121 (2018) 081801 (ATLAS)

Dark Matter Mediator searches

ESHEP 2019
CERN-JINR

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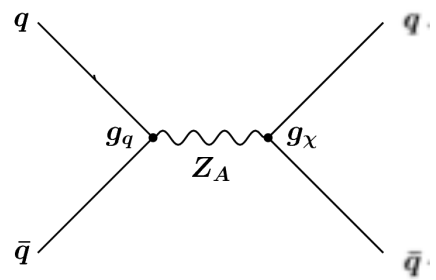
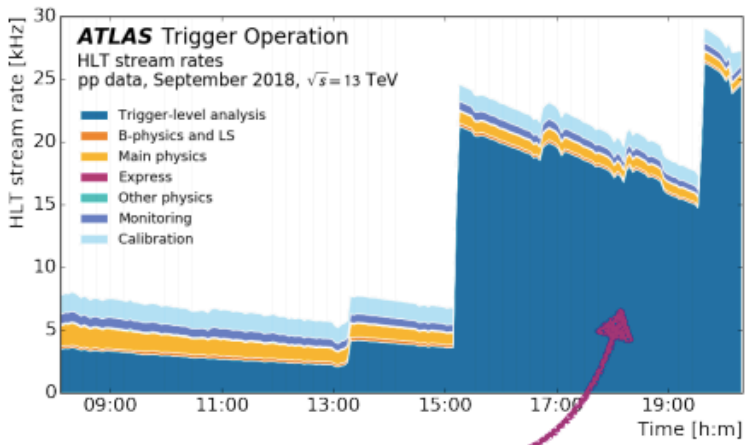
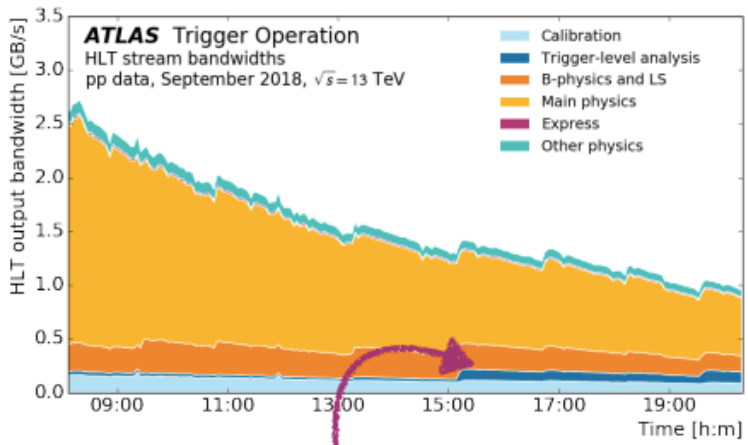


New idea 'Data Scouting' / 'Trigger level analysis':
For high rate low pT jet triggers write out *trigger level* jet information only.
High rate, but small event size (<5% of usual event) – does not have a big effect on total bandwidth (which is the limitation).



Huge increase in trigger rate



Minimal increase in output to disk!

JHEP 08 (2018) 130 (CMS) / PRL 121 (2018) 081801 (ATLAS)

Dark Matter Mediator searches

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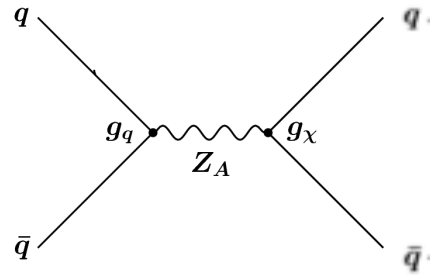

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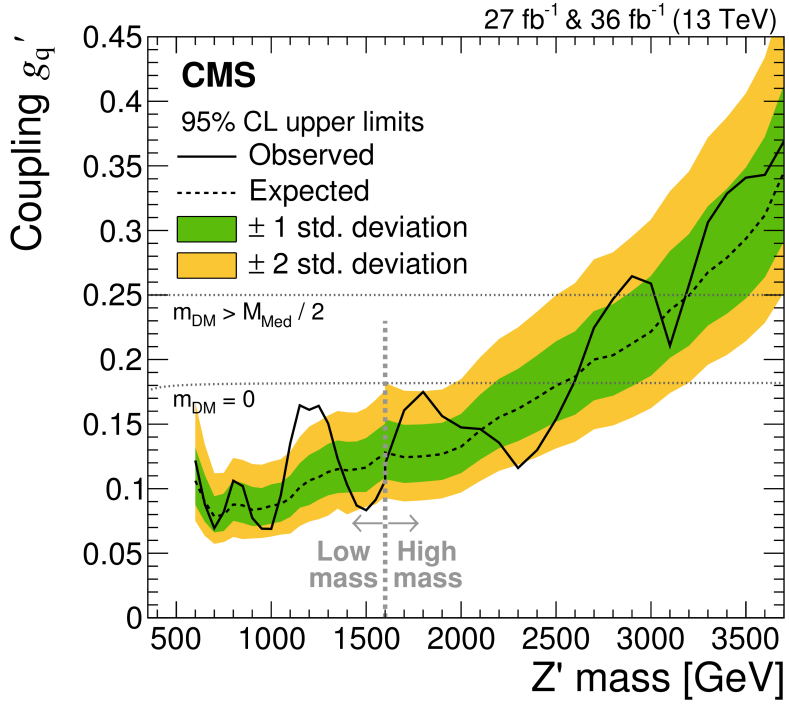
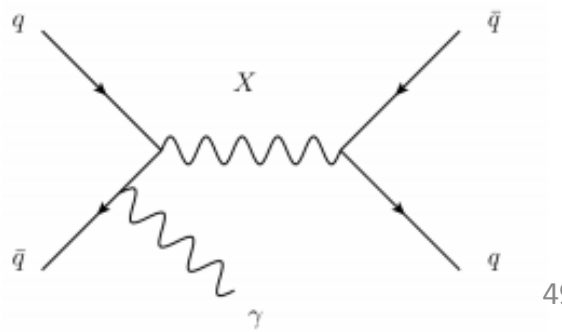


Requires careful validation of trigger level jet reconstruction/calibration – allows to constrain resonances down to a few-100 GeV mass.

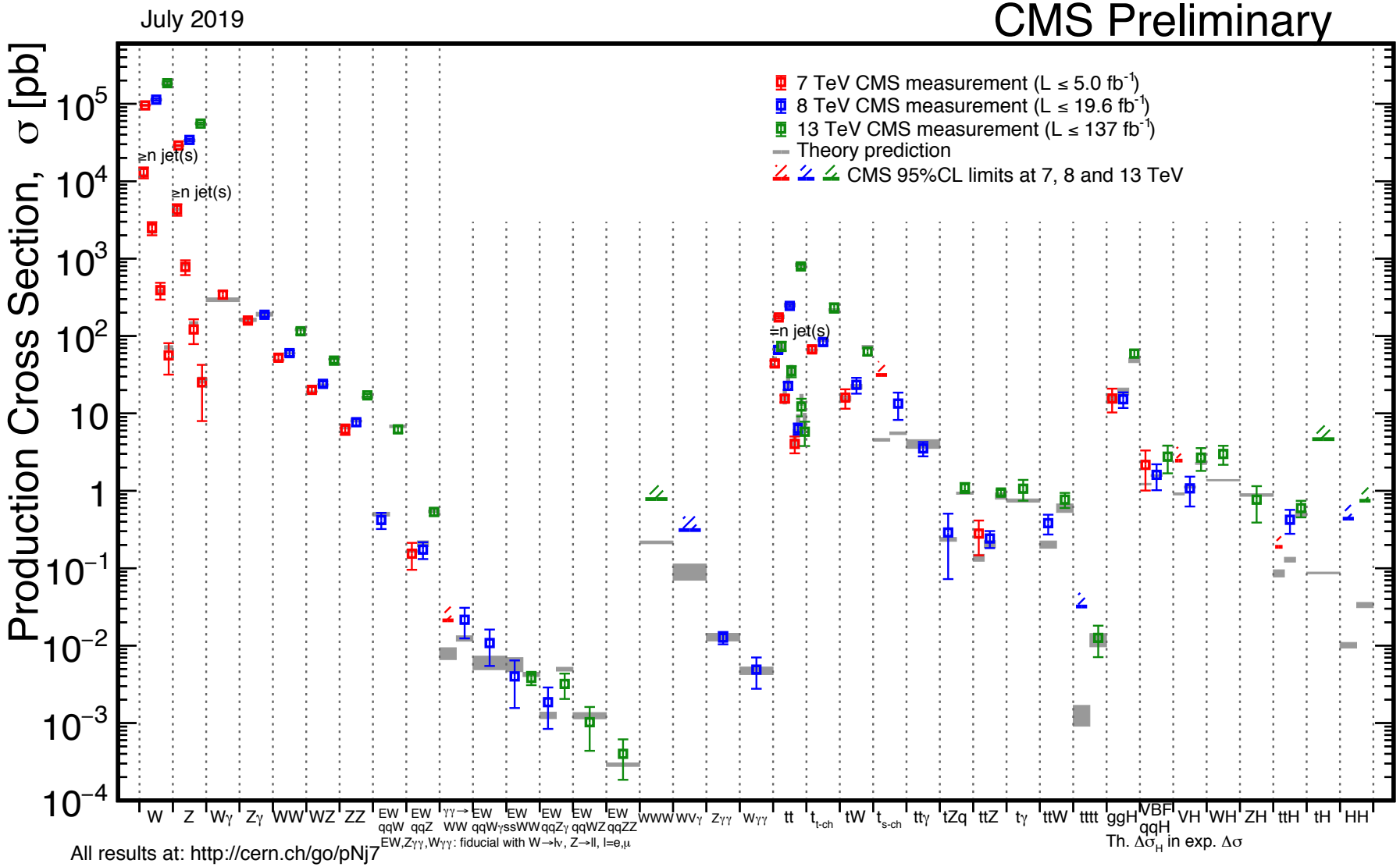
Other tricks – use Initial-State-Radiation photon (or gluon) to trigger event:



Standard Model Measurements

ESHEP 2019
CERN-JINR

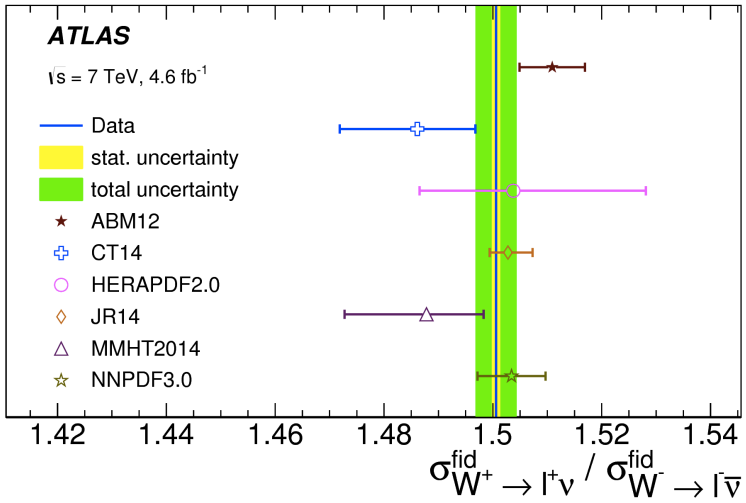
ATLAS/CMS have a large programme of SM cross section measurements, including very precise W,Z and top cross-sections, di-boson, jet cross sections etc…
Luminosity precision ~2.5% from detailed van der Meer scan analysis, much better than originally thought possible.

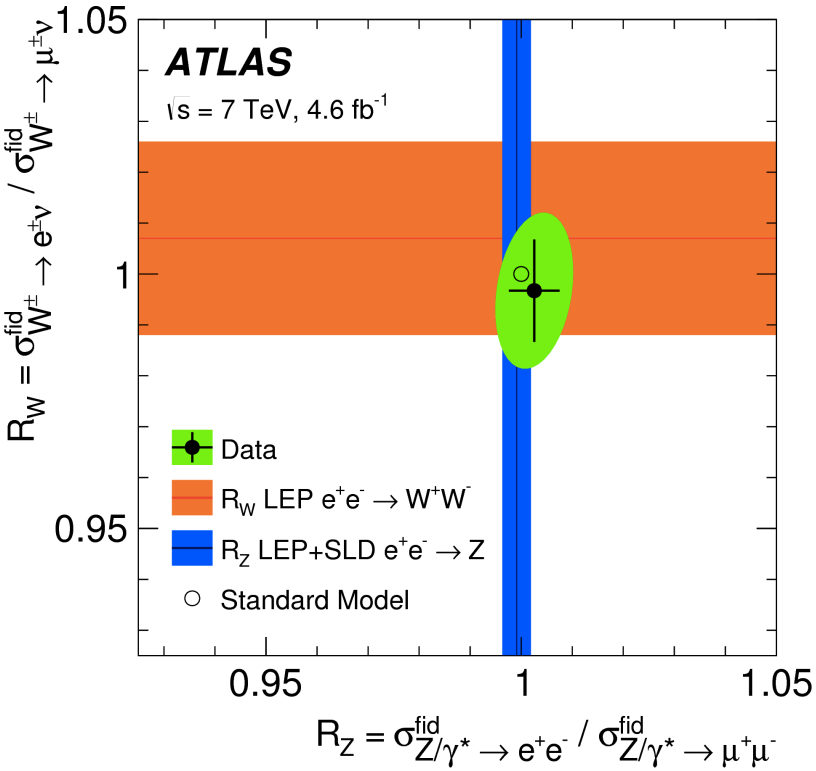


All results at: http://cern.ch/go/pNj7

Eur. Phys. J. C 77 (2017) 367

Precise W/Z cross sections (7 TeV)





Impressive sub-% level experimental uncertainty with 1.8% luminosity uncertainty. Ratios (where luminosity cancels) are powerful tests, can constrain PDFs, and test lepton universality.

Source	W x-sec	Z x-sec
Lepton	0.30%	0.34%
MET	0.25%	-
Background	0.38%	0.08%
Theory Modeling	0.18%	0.22%
Data statistics	0.04%	0.08%
Total experimental	**0.60%**	**0.43%**
Luminosity	1.8%	

Eur. Phys. J. C 78 (2018) 110

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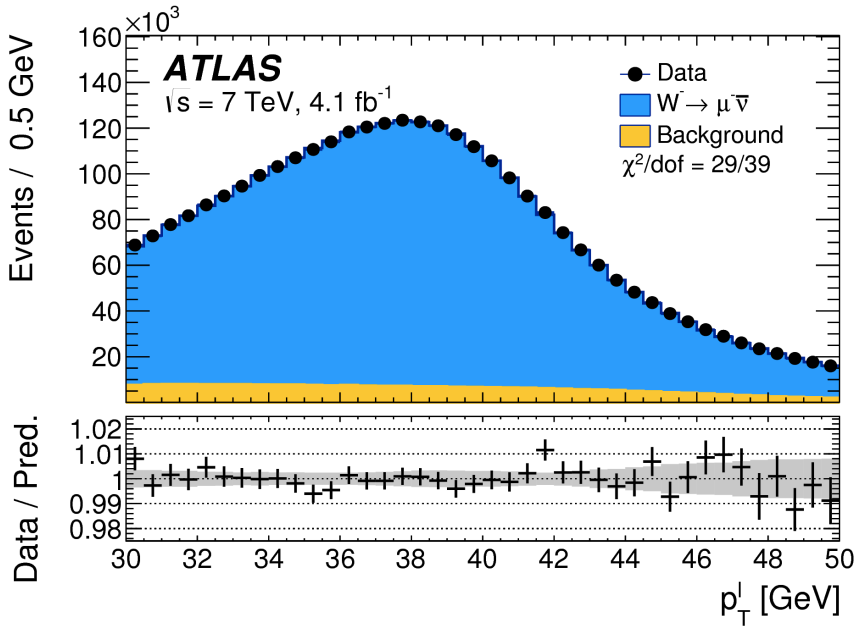
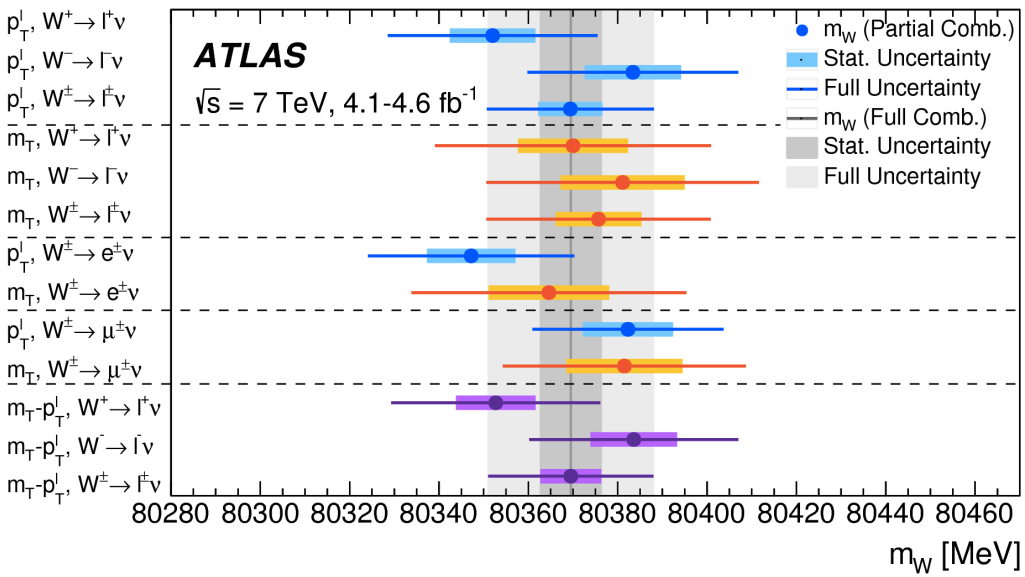
Precision W-boson mass measurement

W-boson mass fundamental SM parameter, with important sensitivity in EWK fit.
Measure the W mass using the pT spectra of the lepton (e,μ), or the mT spectra, by fitting templates with different mass hypotheses to the corrected-data.
Need very precise understanding of experimental systematic uncertainties, lepton efficiency, scale and resolution, but also resolution on the hadronic recoil (which gives MET). Pileup has a big effect on this.
Important theory systematics from PDFs (extrapolating W pT from measured Z pT)



Example distribution (pT of –ve muons) used to extract W-mass.



Comparison of the fitted W mass in different channels (+/-/e/μ) /methods (mT/pT)

Eur. Phys. J. C 78 (2018) 110

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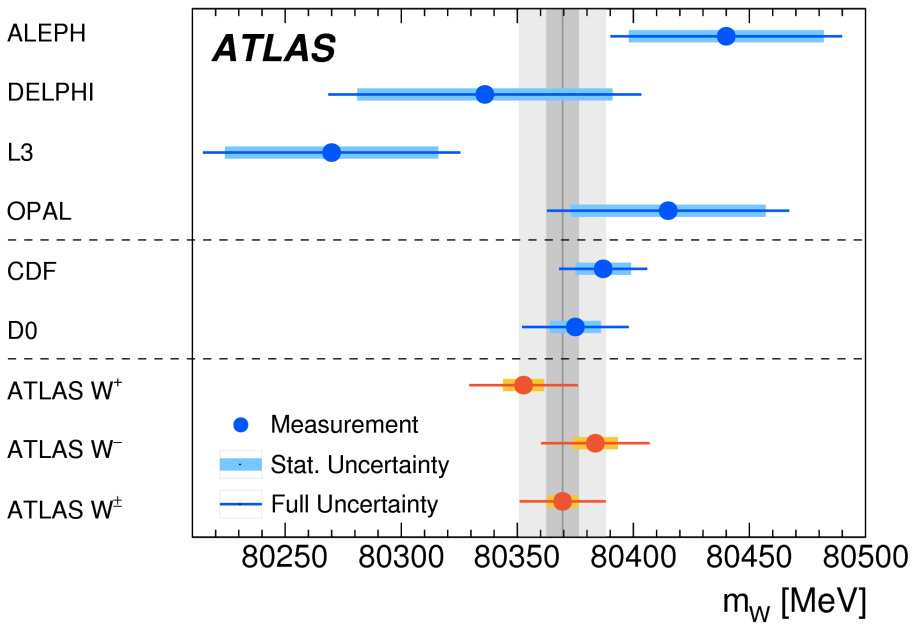

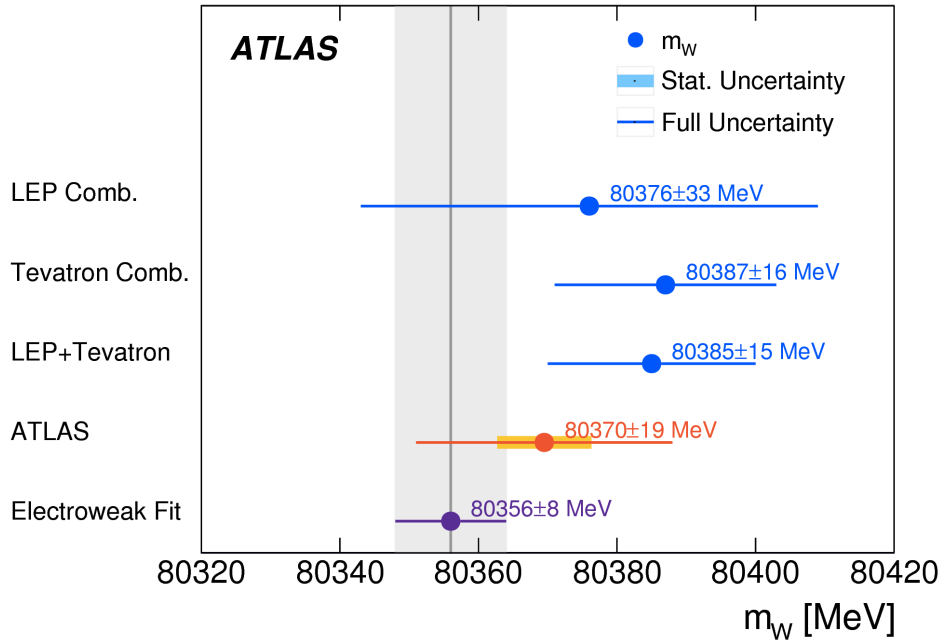

Result with precision at same level as best single experiment (CDF) (19MeV), compatible with world average, but slightly lower, improves compatibility with expectation from EWK fit.

Eur. Phys. J. C 78 (2018) 110

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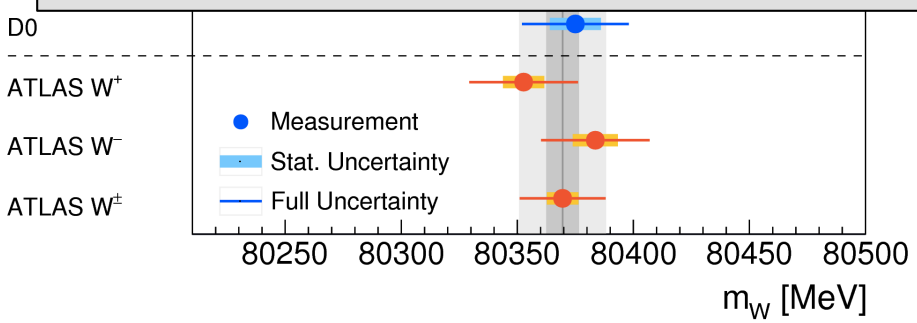
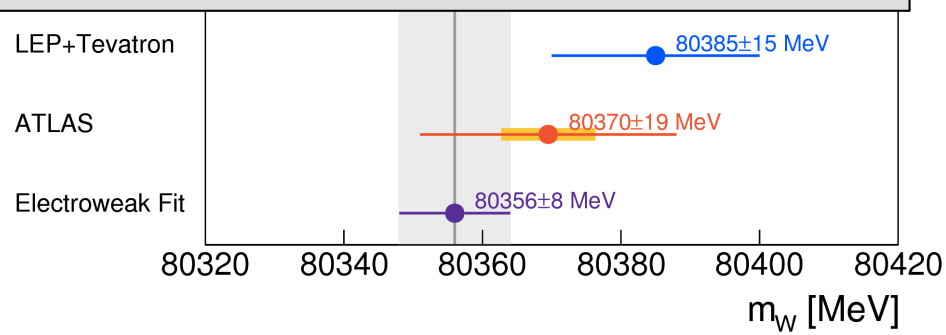
Short term prospects:
Hope to use low-pileup data taken in 2017/8 to improve precision to ~10-15 MeV level!
Longer term prospects:
Upgraded detectors with larger tracking acceptance can reduce PDF uncertainties even further…





Result with precision at same level as best single experiment (CDF) (19MeV), compatible with world average, but slightly lower, improves compatibility with expectation from EWK fit.

Eur. Phys. J. C 78 (2018) 891

Precision top mass measurement

ESHEP 2019
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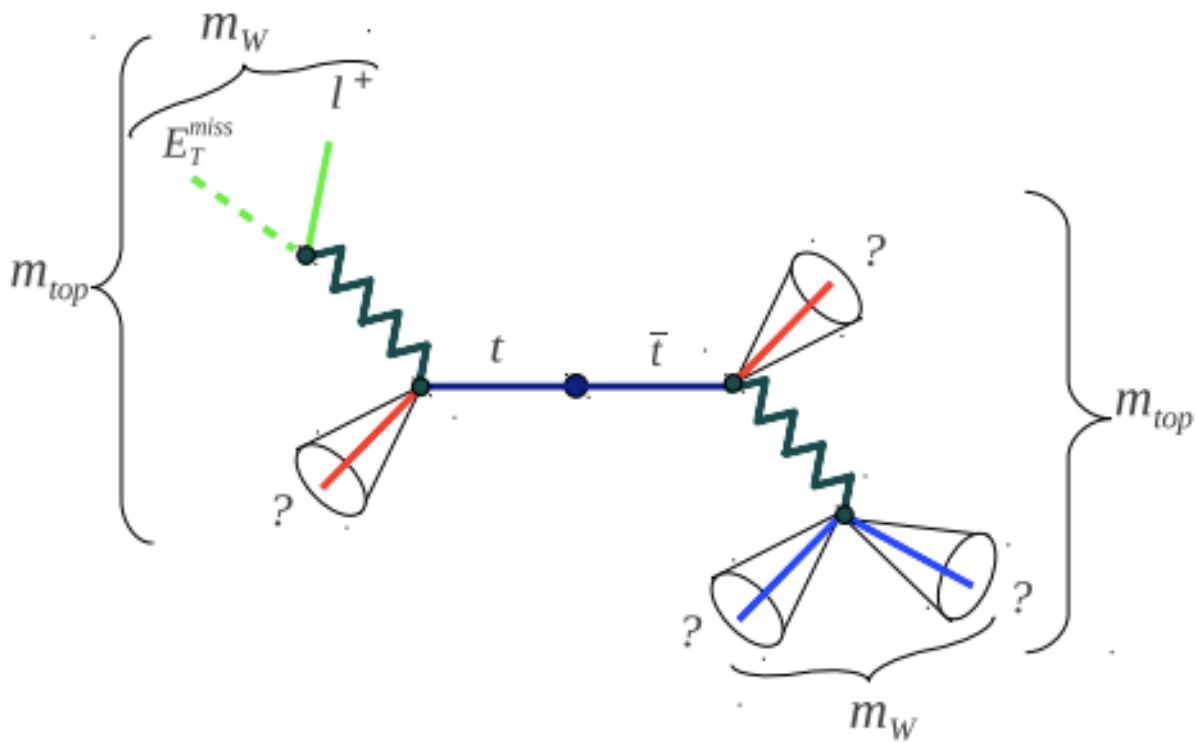
top-quark mass a fundamental parameter of the SM, crucial input for precision EWK fit.
Due to large coupling to Higgs also plays an important role in the stability of the universe!
Can be measured in different ways:
-direct: reconstruct top decays (using 0,1,2 lepton decays)
-indirect: measure property that depends on top mass (e.g cross-section)

Recent precise direct measurement from CMS in 1-lepton + jets final state.
-Select events with e/μ + 4 jets including 2 b-tagged jet
-Multiple permutations for reconstructed top candidates per event



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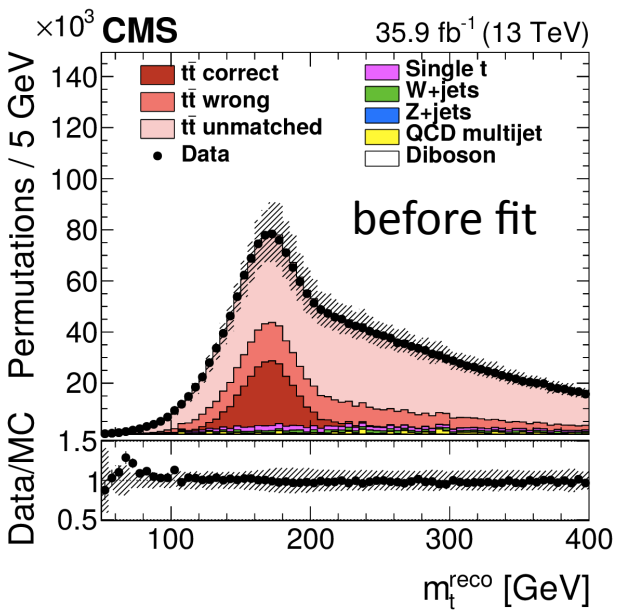
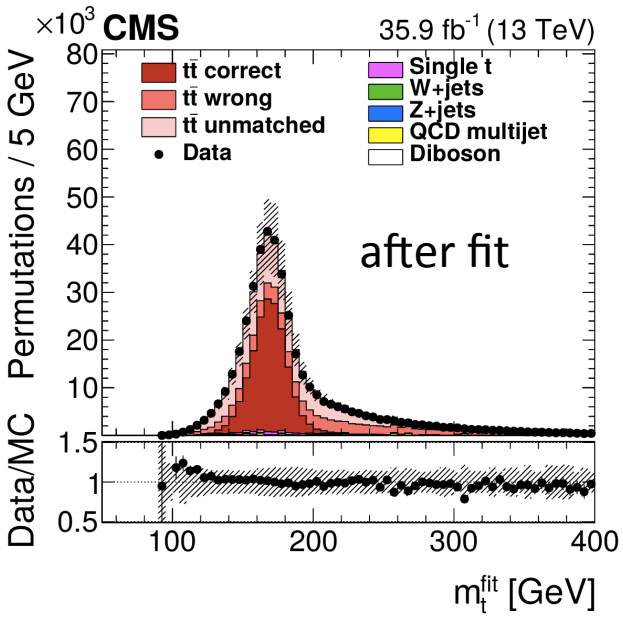
-Multiple permutations for reconstructed top candidates per event
-Kinematic fit (with W-mass constraint):
- improves mass resolution
- cut on goodness-of-fit increased fraction of correct permutations (15% -> 50%)





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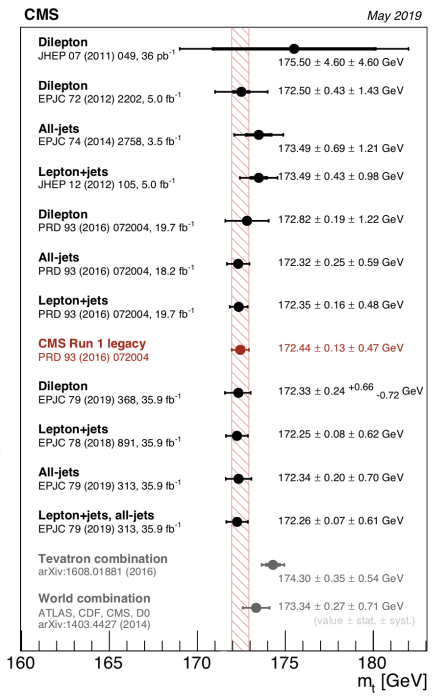
- cut on goodness-of-fit increased fraction of correct permutations

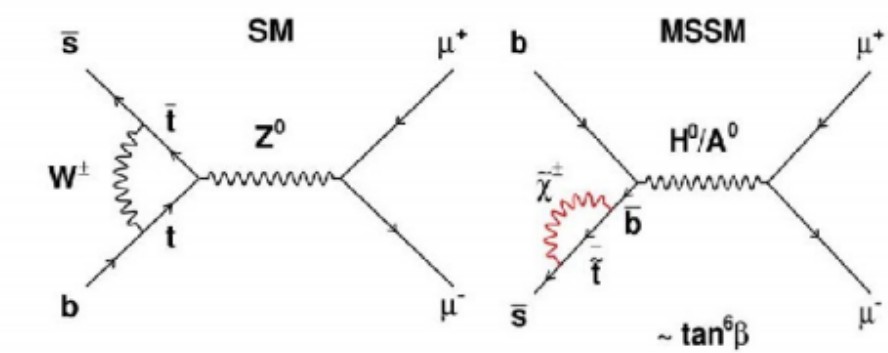
Extract top mass from template fit to MC samples made with different values of m_t
Dominant systematic uncertainty: Jet Energy Scale – constrained from the data in a 2D fit.

Result: m_t = 172.25 ± 0.08(stat) ± 0.62(syst)



Rare decays: $B_s \to \mu^+\mu^-$

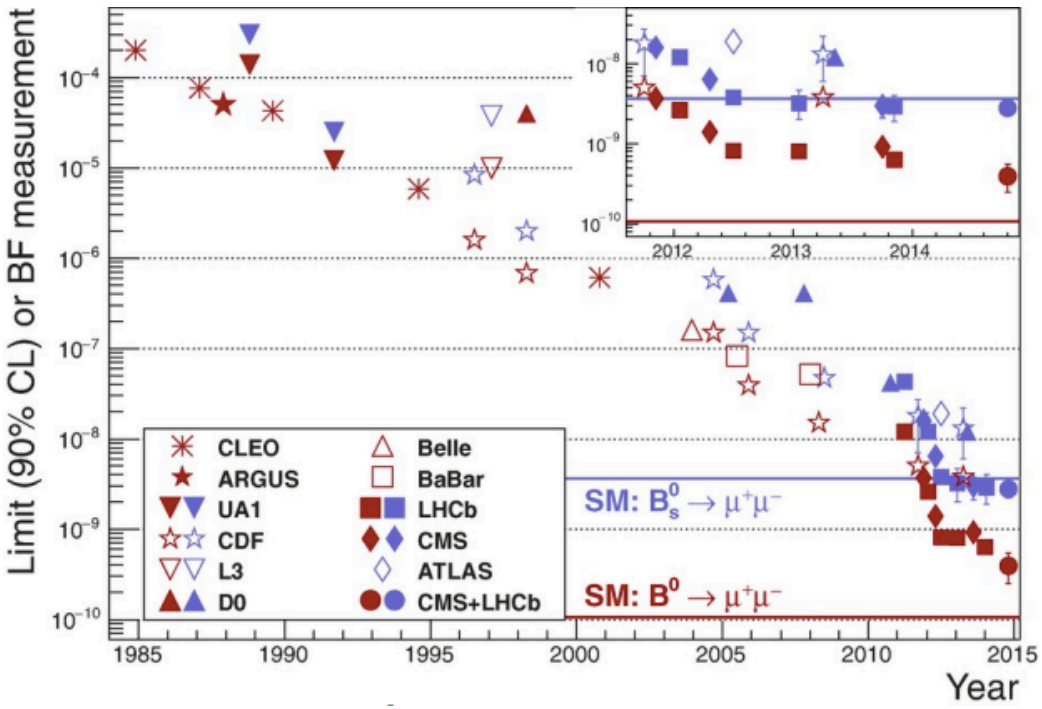
Very rare decay in SM, with possible large enhancement with New Physics (e.g. MSSM):



Theoretically clean.
Flavour changing neutral current.
Loop and helicity suppressed in SM.

$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

Long history of searches for this decay, finally SM sensitivity reached with LHC:



Rare decays: $B_s \to \mu^+\mu^-$

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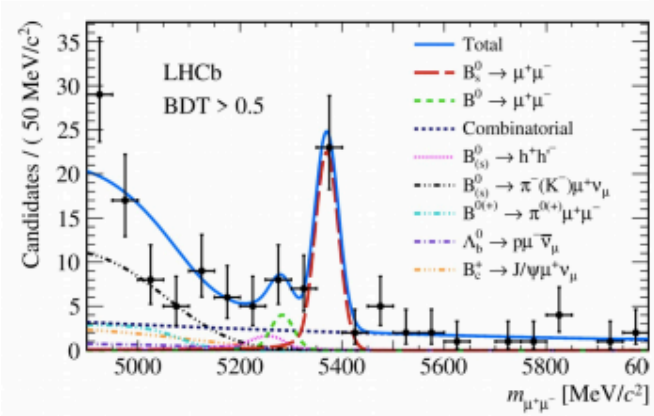
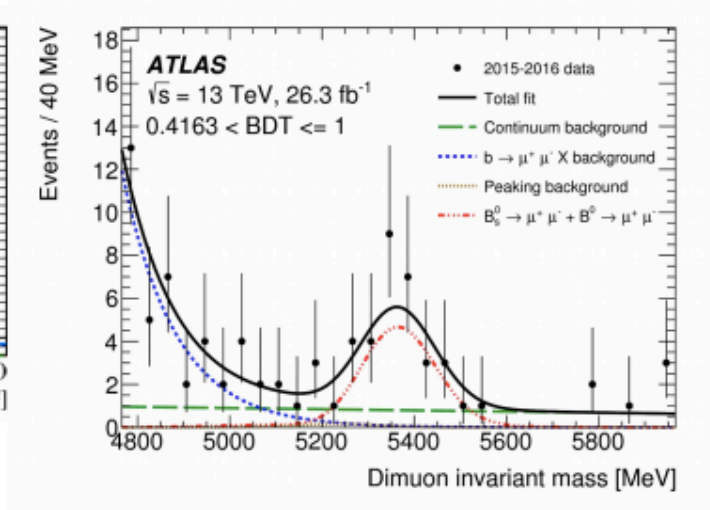
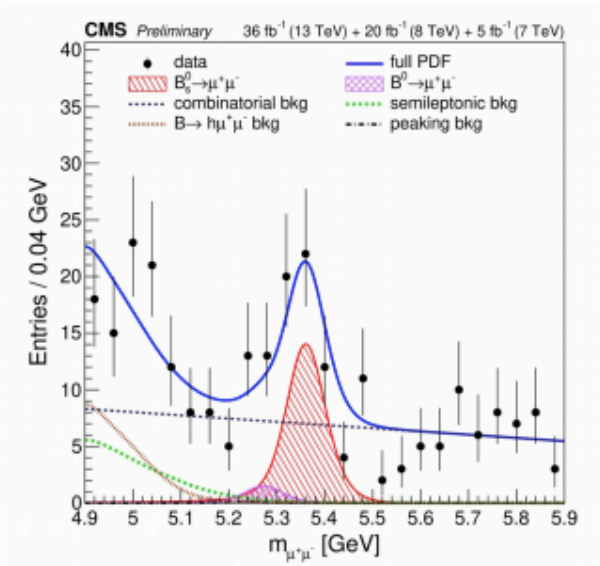
LHCb PRL 118 (2017) 191801



ATLAS JHEP 04 (2019) 098



CMS-PAS-BPH-16-004



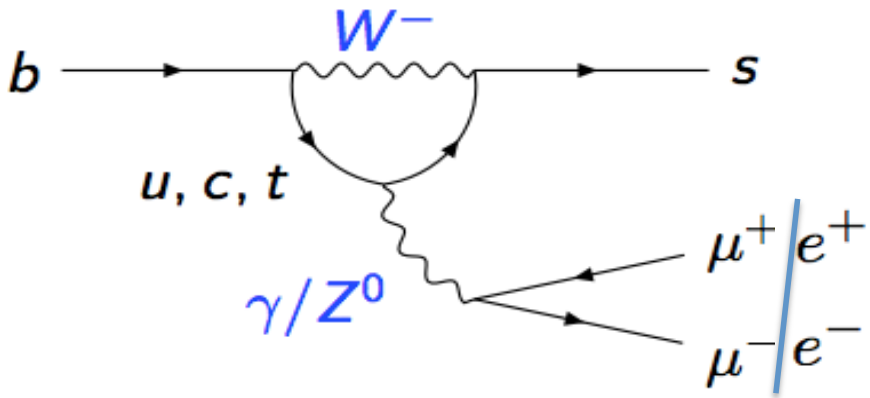
Di-muon resolution very important to obtain good sensitivity: LHCb > CMS > ATLAS.
ATLAS/CMS have much larger dataset than LHCb (which is levelled at a pileup of ~1.1).
But LHCb has much better trigger efficiency for such events.

Experiment	Result ($\times 10^{-9}$)	Luminosity
ATLAS	2.8 ± 0.8 (4.6σ)	25/fb (7/8 TeV) + 25/fb (13 TeV)
CMS	2.9 ± 0.7 (5.6σ)	25/fb (7/8 TeV) + 36/fb (13 TeV)
LHCb	3.0 ± 0.6 (7.8σ)	3/fb (7/8 TeV) + 1.4/fb (13 TeV)

All results consistent with SM, although all slightly lower than expectation.

Lepton Flavour Universality tests in B decays

In SM lepton universality is a key principle. Exchanging e, μ, τ should give same coupling up to effects related to phase-space / Higgs (small effects in many cases)



$= 1 + O(10^{-3})$

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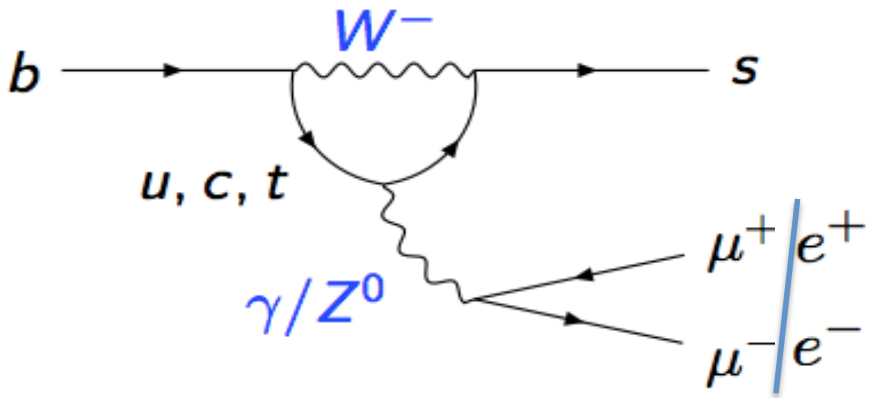

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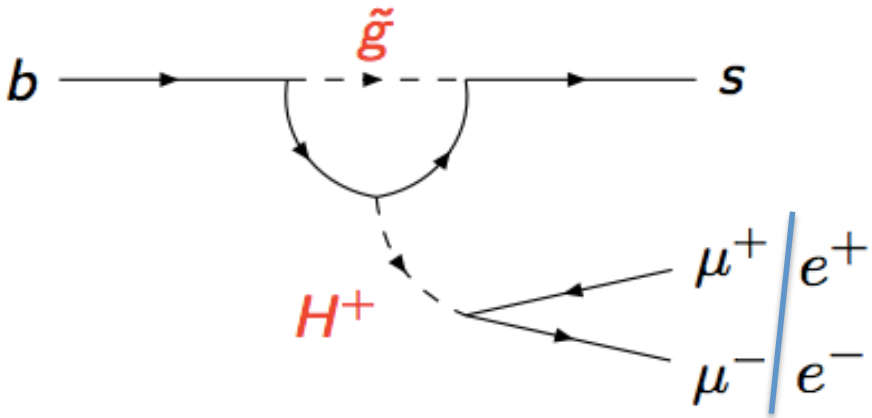
BSM can have large effects:



$\neq 1 + O(10^{-3})$

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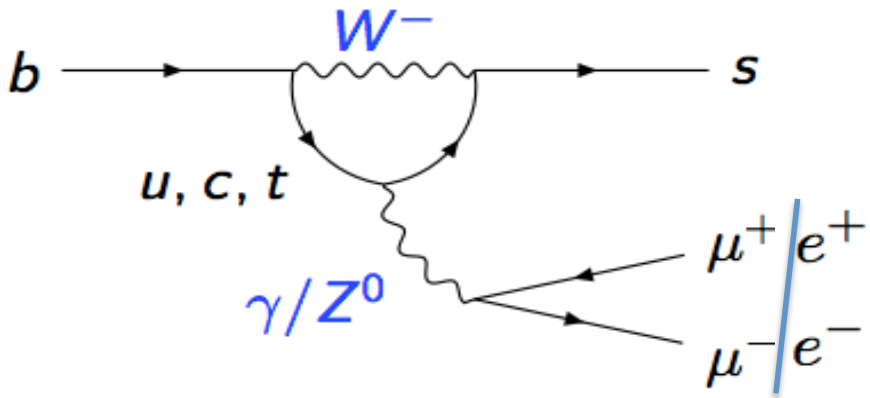
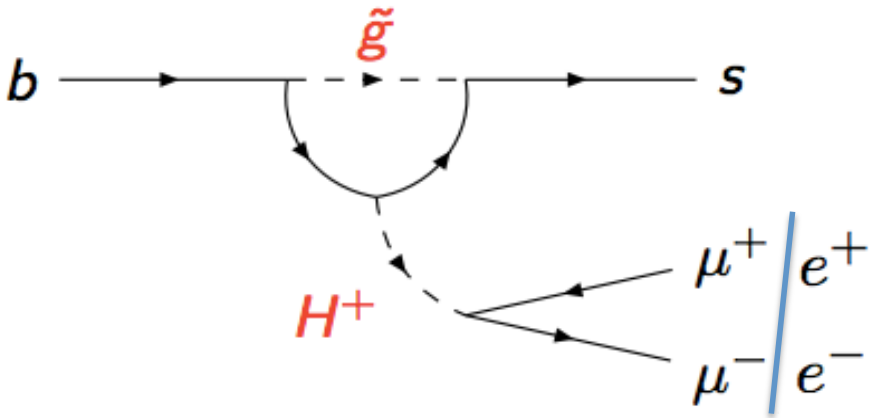


$= 1 + O(10^{-3})$

Study by measuring:
R_K = BF(B -> K μμ) / BF(B -> K ee)
R_{K*} = BF(B -> K* μμ) / BF(B -> K* ee)
in bins of di-lepton mass (q^2)

BSM can have large effects:



$\neq 1 + O(10^{-3})$

JHEP 08 (2017) 055 / PRL 122, 191801

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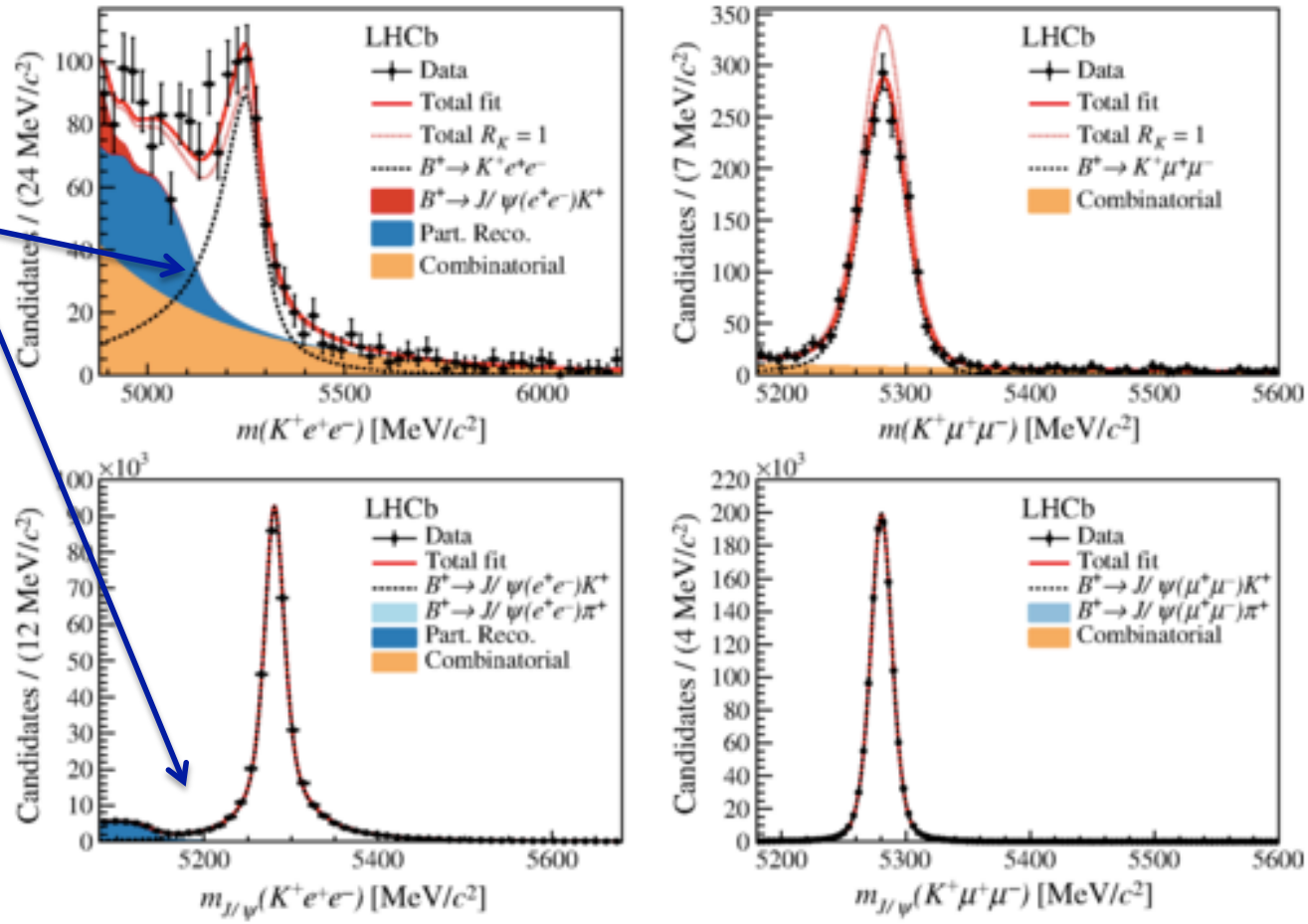
Lepton Flavour Universality tests in B decays

Experimental complication – electron bremsstrahlung makes mass resolution much worse in electron channel – normalize by BF(B->J/ψ(μμ)K) / BF(B->J/ψ(ee)K) to take into account differences in efficiency between electrons and muons.

Signal peak has large low-mass tail in ee mode due to bremsstrahlung.
Note different mass range shown for ee/μμ.



JHEP 08 (2017) 055 / PRL 122, 191801

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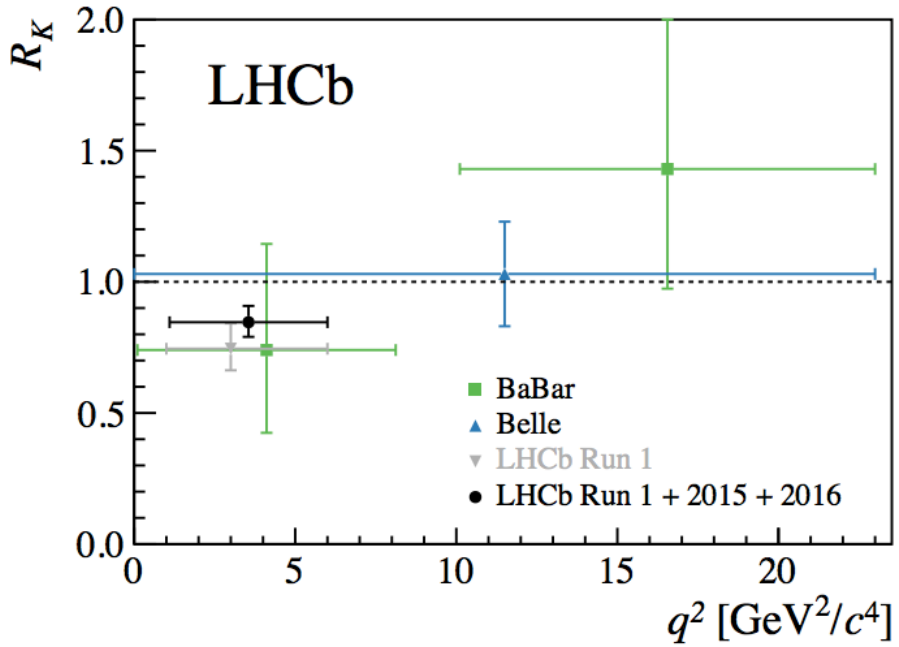
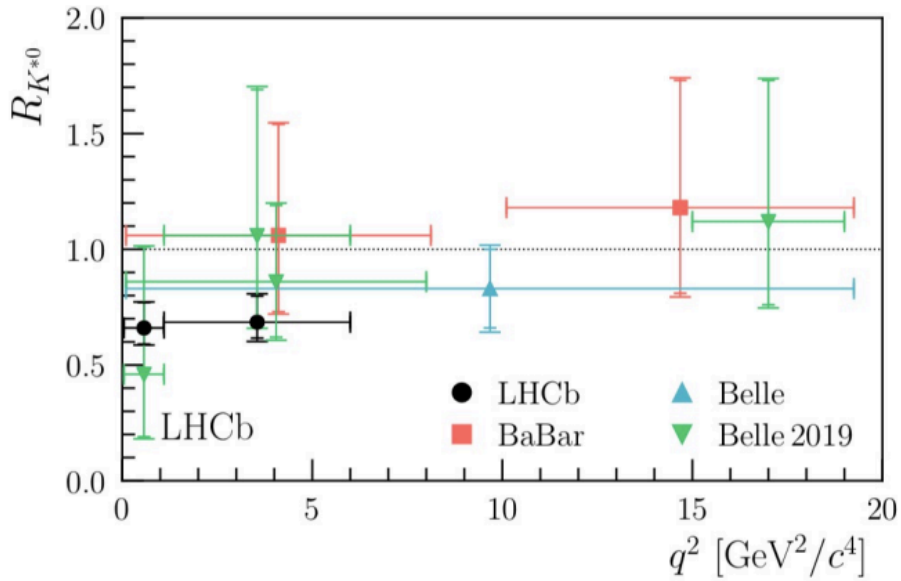




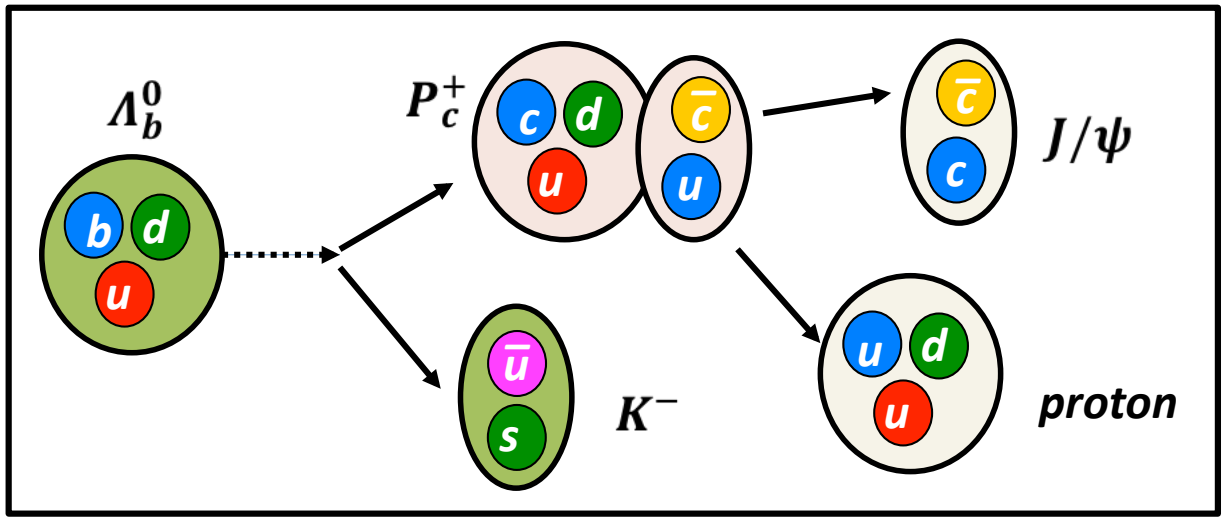
Measurement	Dataset	Value (stat) (syst)	Compatibility with SM
R_K	Run1+Run2	$0.85^{+0.06}_{-0.05} \pm 0.015$	~2.5σ
R_{K^*} low-q^2	Run1	$0.66^{+0.11}_{-0.07} \pm 0.03$	~2.2σ
R_{K^*} high-q^2	Run1	$0.69^{+0.11}_{-0.07} \pm 0.05$	~2.4σ

Intriguing results!
Most exciting anomalies observed at the LHC at the moment.
Awaiting updated results – and also input from Belle-2.

PRL 115, 072001 (2015)

Pentaquarks

- As well as well-known baryon (qqq) and meson (qq) bound states, QCD predicts exotic tetraquark and pentaquark colourless states
- Many searches for pentaquarks in the past with some unconfirmed signals from experiments
- First unambiguous observation by LHCb in 2015 - studying the decay



Select events with J/Ψ(ll), p, K with combined mass of Λ_b.
Look at mass of pairs of decay products (Kp) / (J/Ψp) – Dalitz analysis.

PRL 115, 072001 (2015)

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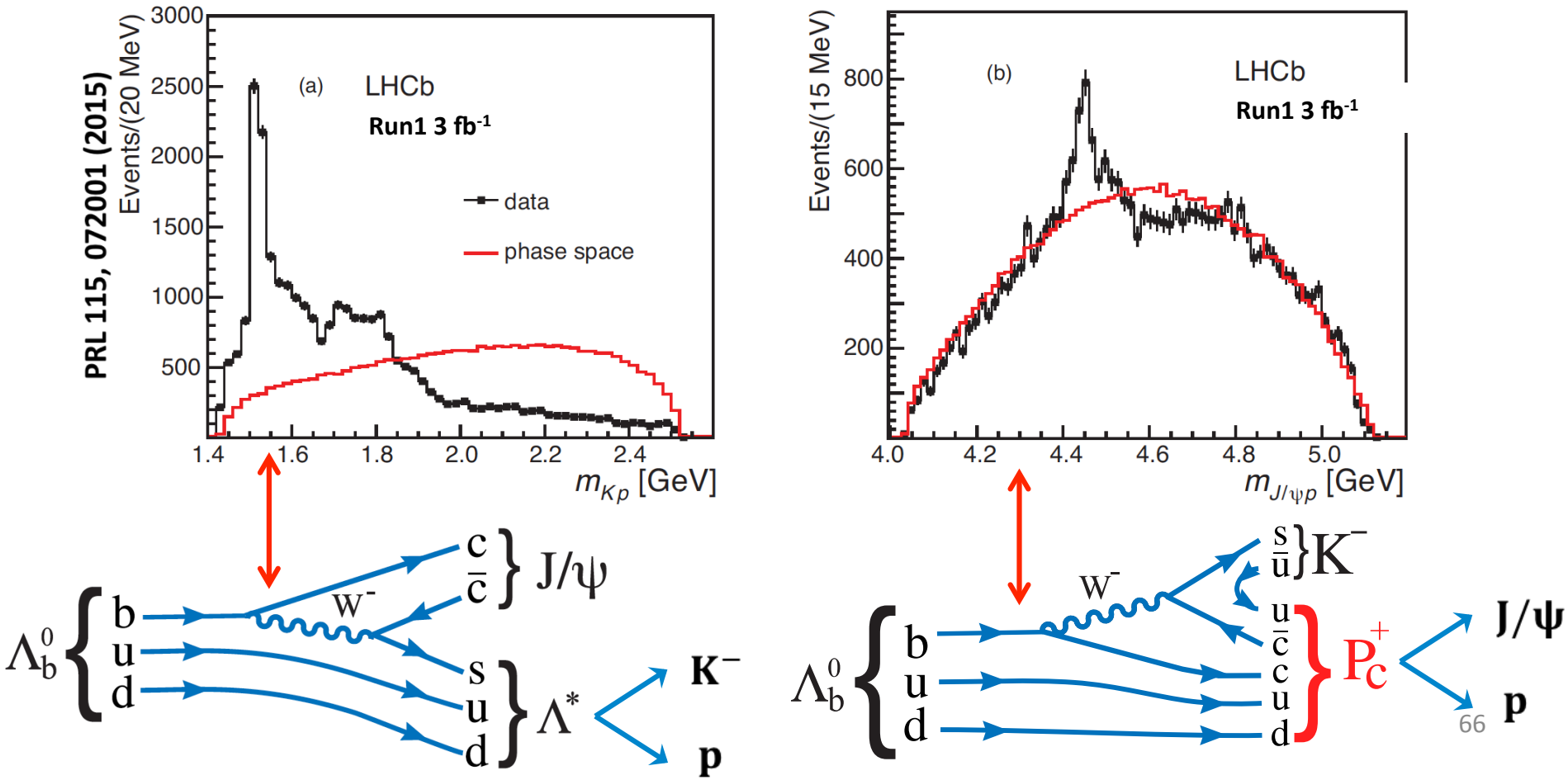
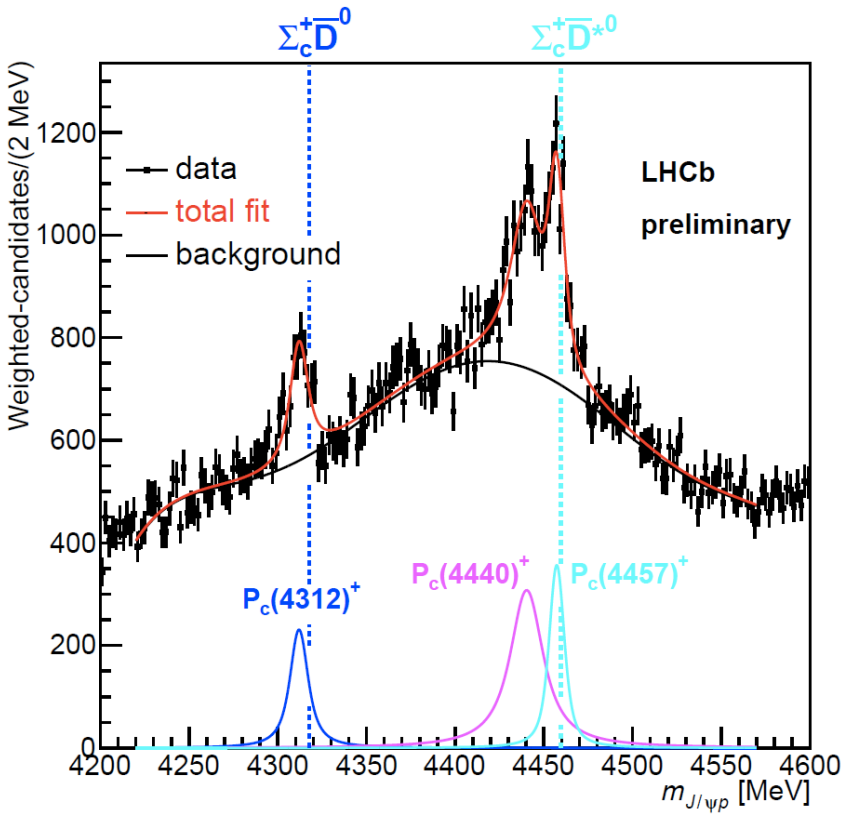


PRL 115, 072001 (2015), PRL 122, 222001 (2019)

Pentaquarks

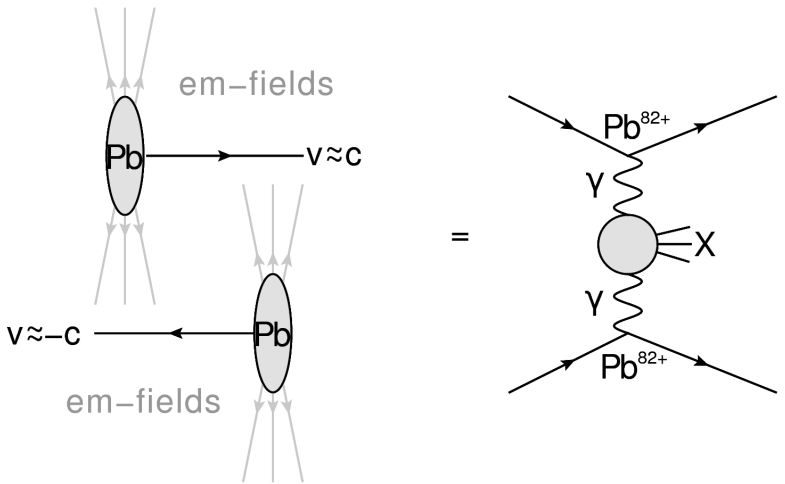
- As well as well-known baryon (qqq) and meson (qq) bound states, QCD predicts exotic tetraquark and pentaquark colourless states
- Many searches for pentaquarks in the past with some unconfirmed signals from experiments
- Further analysis with more data shows this is actually 2 closely spaced narrow pentaquark states, and another lower mass narrow pentaquark state is observed

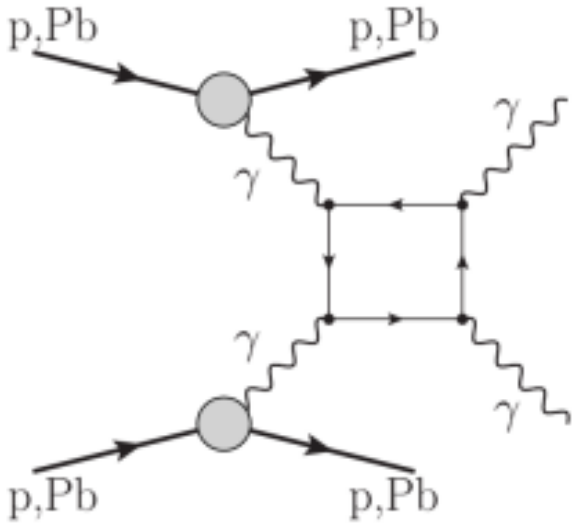


3/fb Run-1 + 6/fb Run-2

PRL 123 (2019) 052001 (ATLAS) / 1810.04602 (CMS)

Light-by-Light Scattering

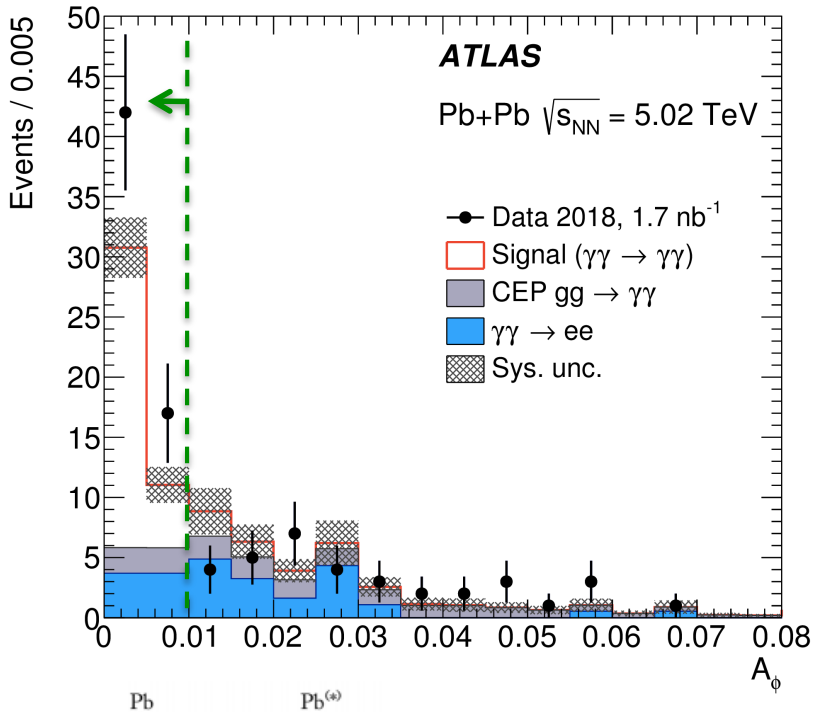


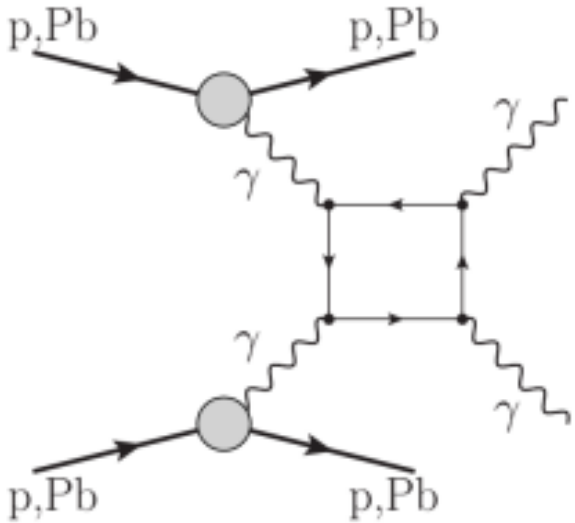


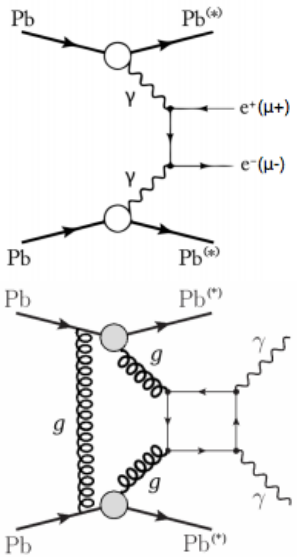
Light-by-Light (LbL) scattering predicted in QED but not in classical EM theory
Rare process $O(\alpha_{EM}^4) \sim 10^{-9}$
Take advantage of large EM fields in ultra-peripheral Pb ion collisions
(when ions do not directly collide but pass very closely)
Photon interaction probability proportional to Z^4
⇒Pb collisions enhanced by $82^4 = 4.5 \times 10^7$ compared to *pp* collisions

PRL 123 (2019) 052001 (ATLAS) / 1810.04602 (CMS)

Light-by-Light Scattering







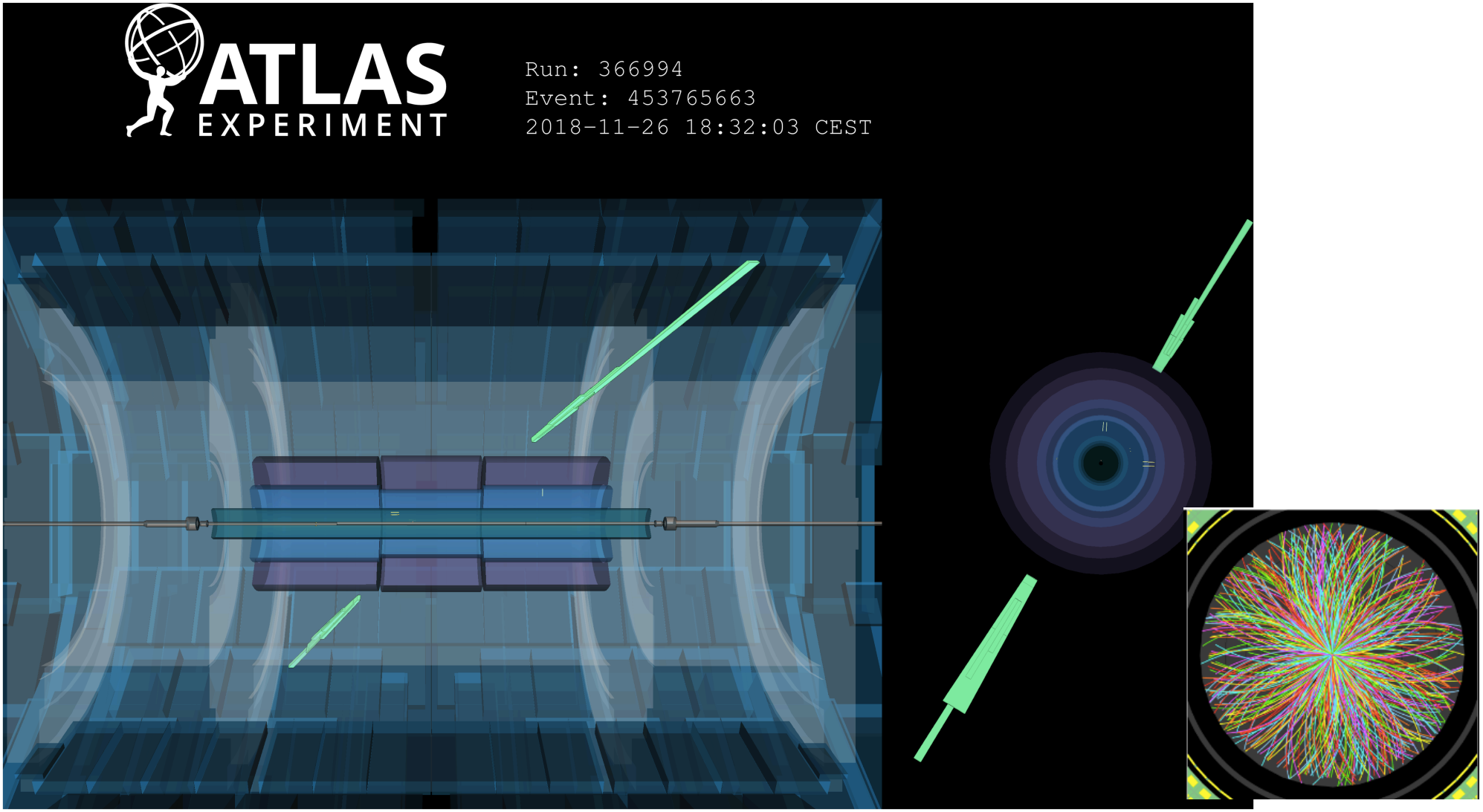
Select events with little activity
Only 2, back-to-back, very low energy photons (E_T>3GeV)
Dedicated low energy photon reconstruction and dedicated trigger developed for this analysis.

59 LbyL events observed
12 ± 3 expected background (significance 8.2σ)
Background mostly central exclusive production of e^+e^-
Measured cross section: 78 ±13 (stat) ±8 (sys) nb
SM expectation: 49 ±5 nb

PRL 123 (2019) 052001 (ATLAS) / 1810.04602 (CMS)

Light-by-Light Scattering

Two back-to-back photons (E_T= 11 GeV, 10 GeV) A_ϕ= 0.002 no additional activity in the detector



Incredibly empty event – especially for heavy ion collision which usually has very high track multiplicity and total calorimeter energy.

LbL measurements also sensitive to BSM effects (e.g. Axion-like-particle searches)

Summary

- LHC experiments ran very well in LHC Run-2, producing high quality physics with the high pileup Run-2 data
- Large luminosity, high quality datasets allows:
  - More and more precise probing of the Higgs boson
    - All major production/decay channels accessible at the LHC have been established
  - Searches for new physics
    - No surprises seen yet!
    - Searches cover a large range of signatures ranging from ultra low pT to ultra high pT
    - Intriguing results from Lepton Flavour Violation in B-decays from LHCb
  - Very precise Standard Model measurements and observation of rare SM processes
- Increased dataset, improved detector and clever new ideas will allow us to push the Standard Model further in the coming years!

Acknowledgements

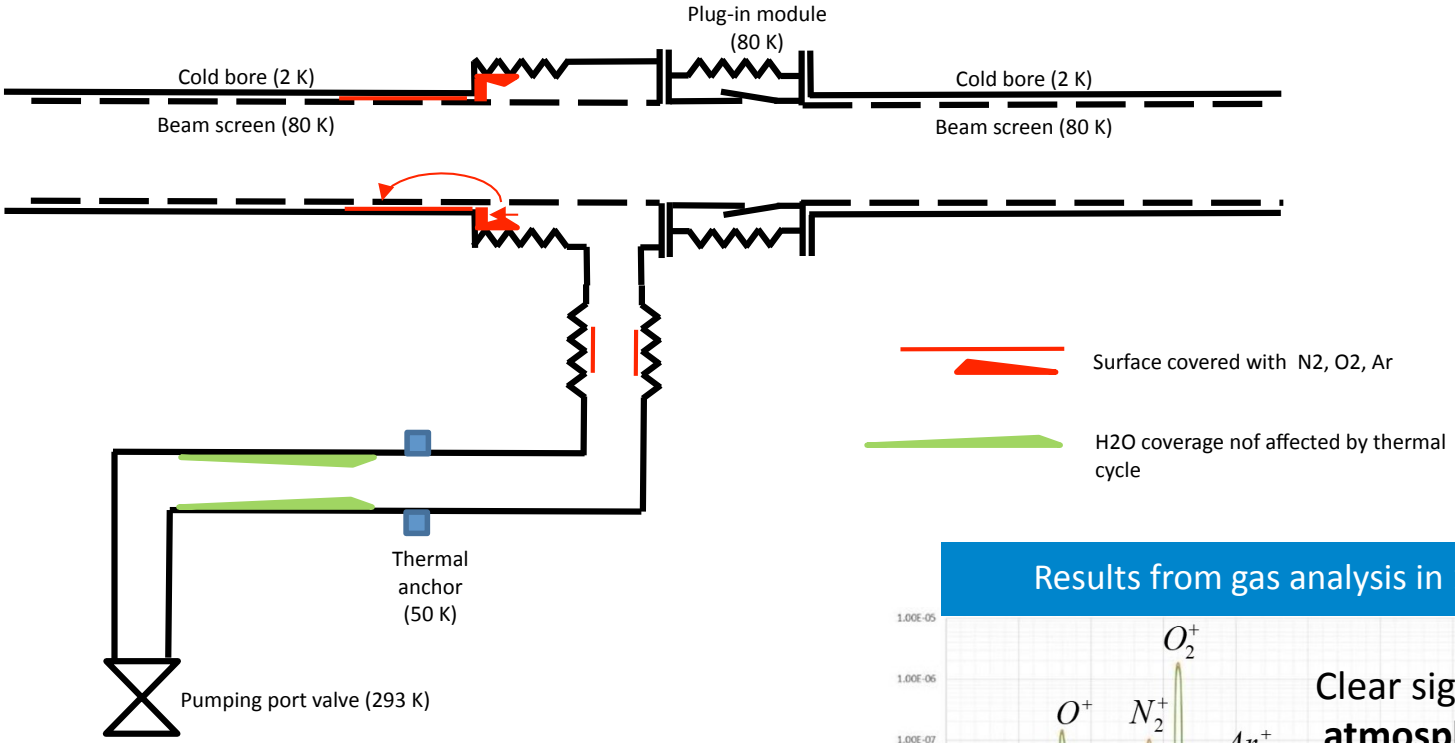
- I have 'borrowed' material and ideas from the following people – many thanks!
  - A. Hoecker (CERN)
  - G. Salam (Oxford)
  - R. Silva Coutinho (Zurich)
  - T. Gershon (Warwick)
  - L. Zhang (Tsinghua)
  - P. McBride (Fermilab)

Backup slides…

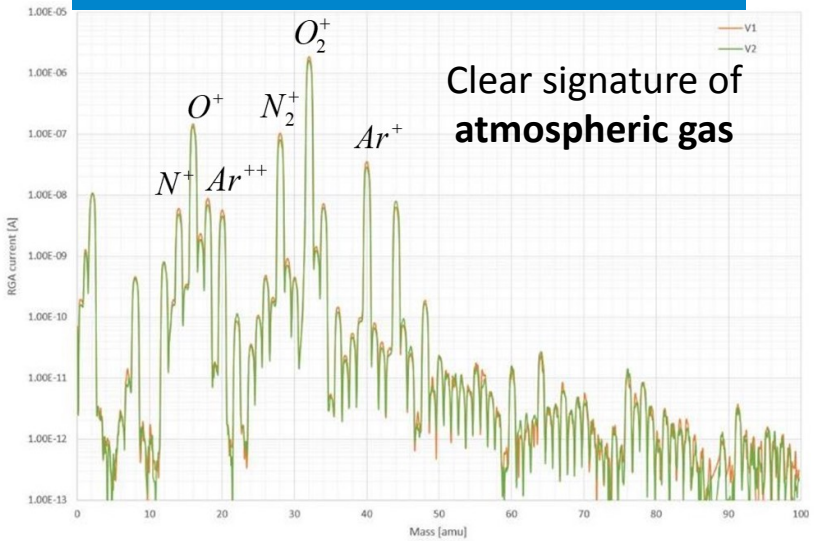
LHC “16L2”: Air inlet as “most probable” cause

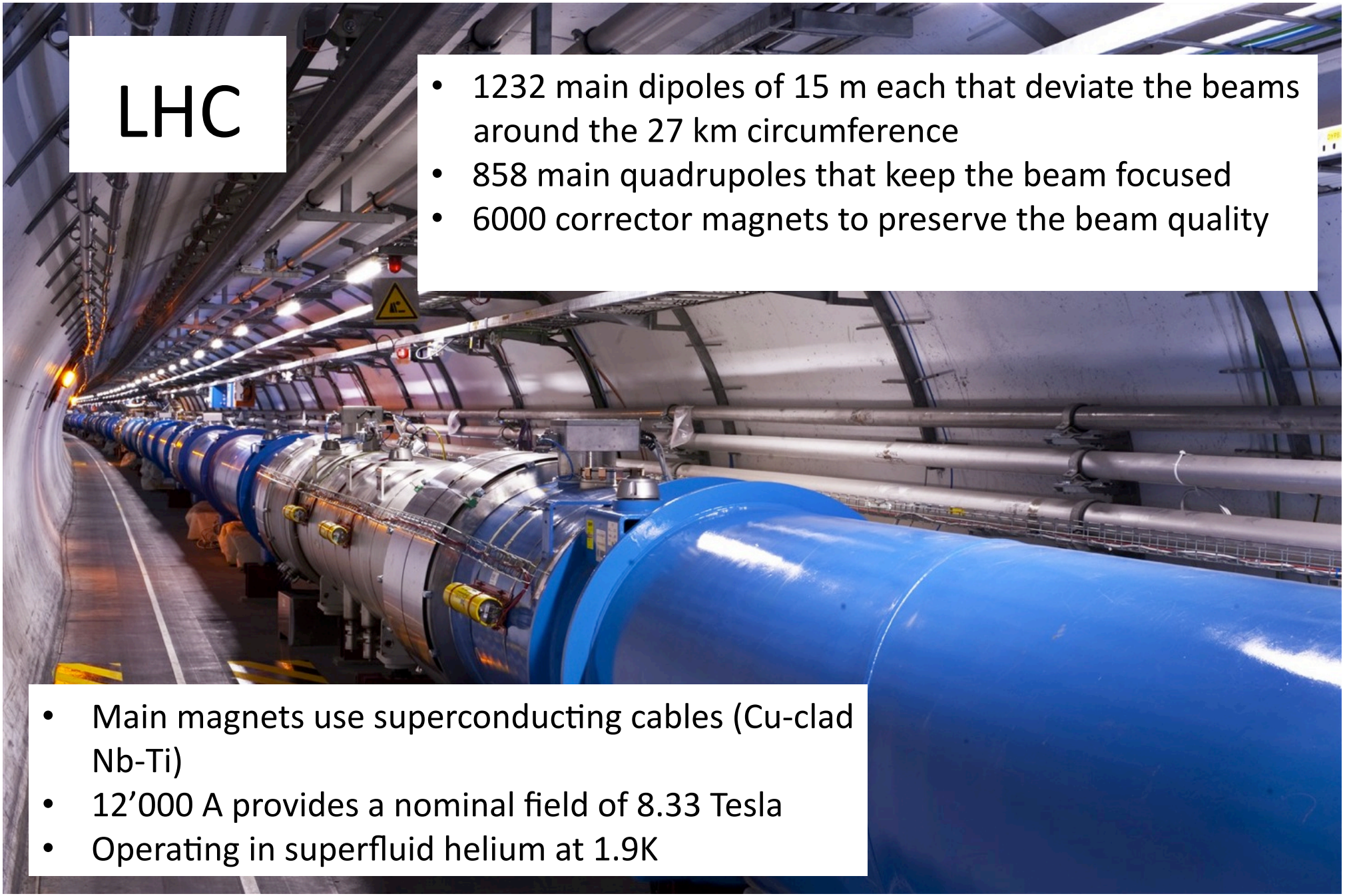
Situation at the end of first BS thermal cycle to 80 K

(No pumping though pumping port)



Results from gas analysis in 16L2





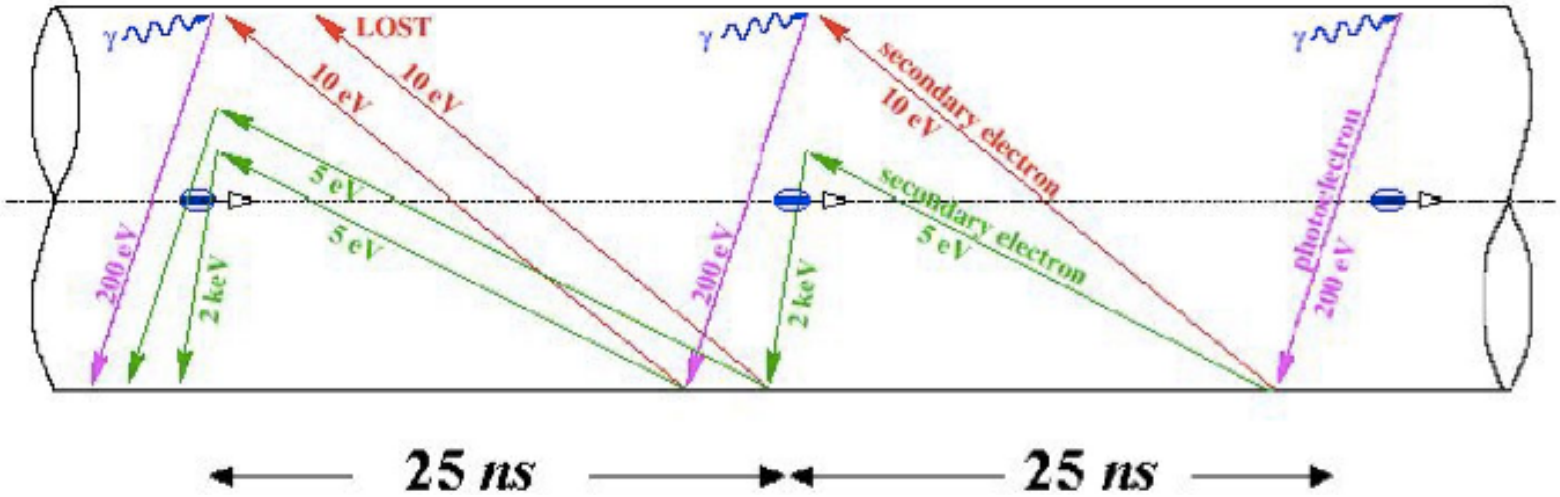
LHC

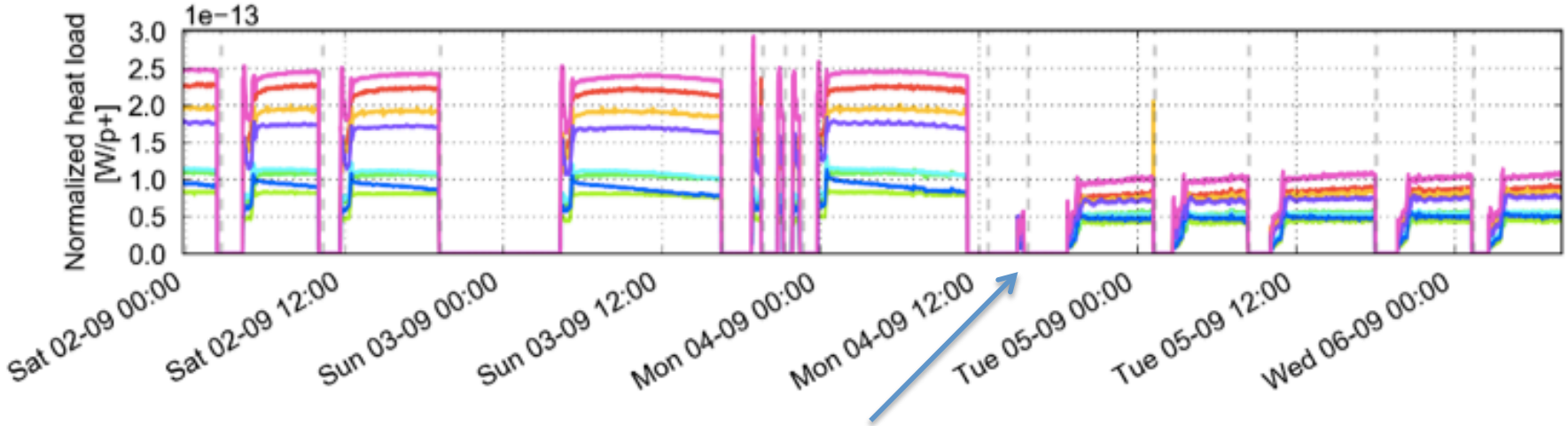
- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality

- Main magnets use superconducting cables (Cu-clad Nb-Ti)
- 12’000 A provides a nominal field of 8.33 Tesla
- Operating in superfluid helium at 1.9K

Electron cloud in the LHC

Avalanche effect with 25ns beam.
Causes beam induced heating, and hence can limit bunch intensity.

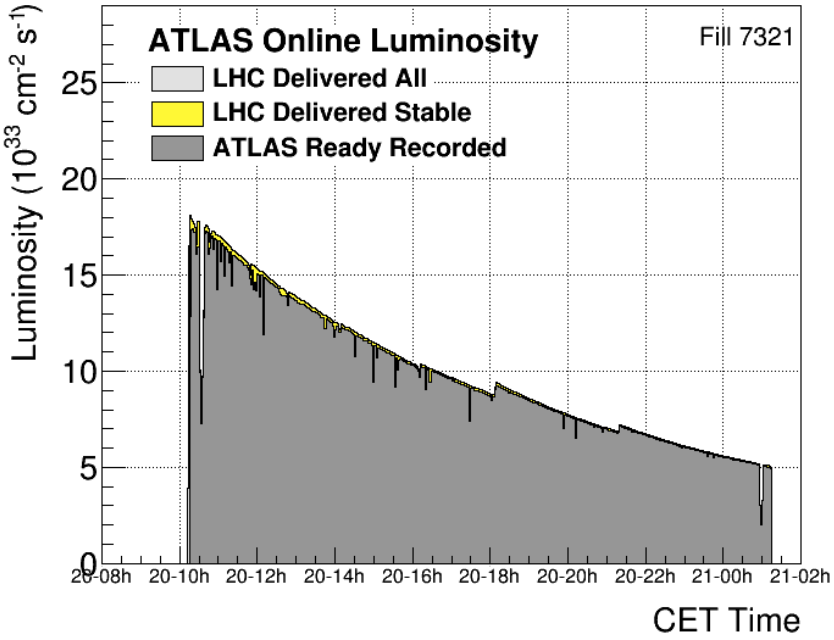




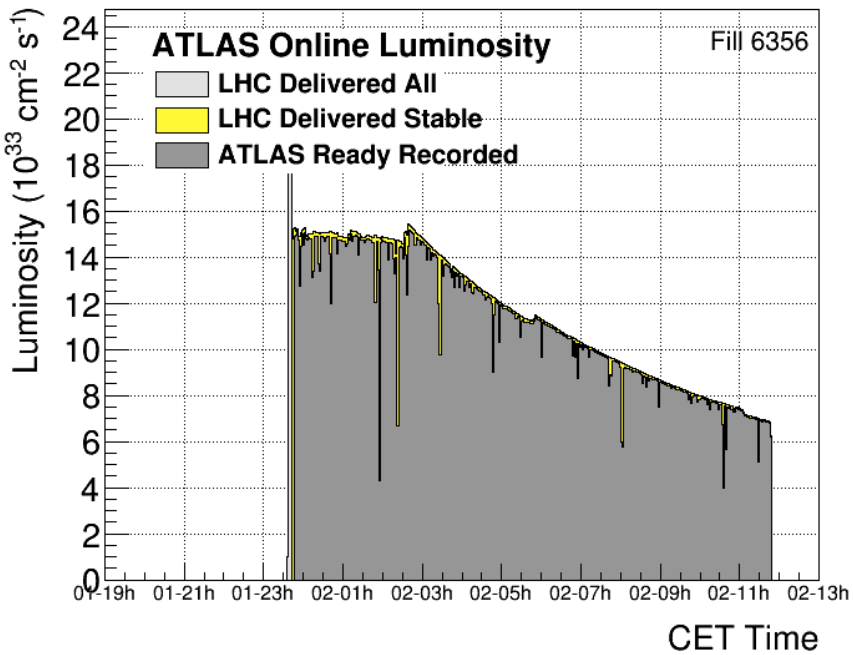
Running with 8b4e (gaps in 25ns trains) dramatically reduces the heat load from e-cloud

LHC fills

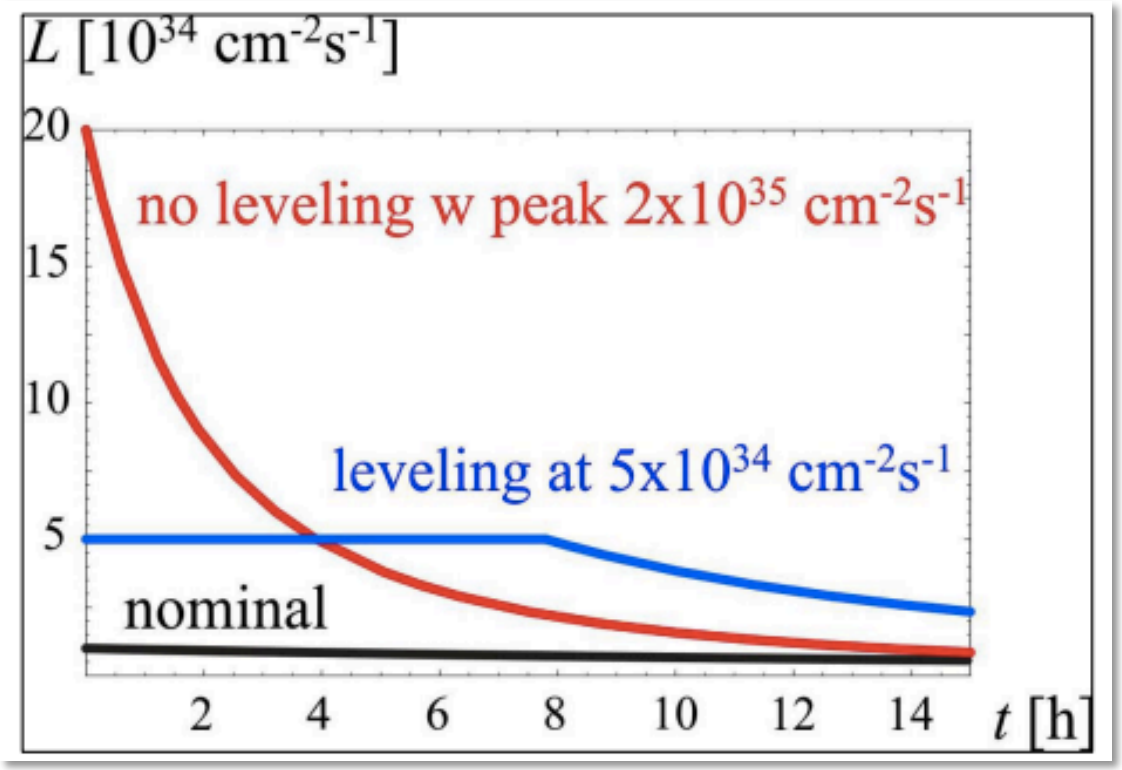
Typical fill. Luminosity falls off during ~12hr fill due to protons being 'burnt-off' by the collisions



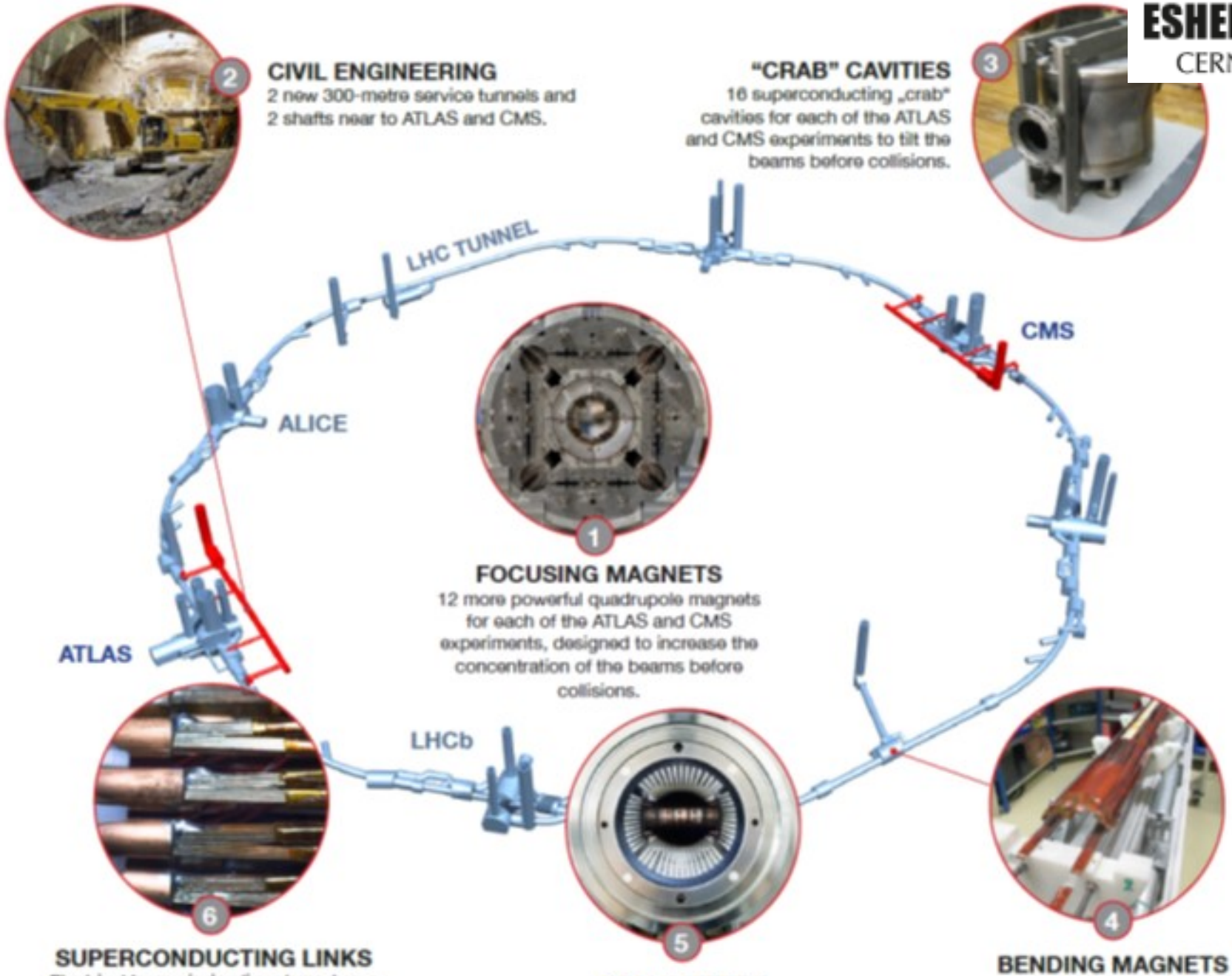
Levelled fill. Luminosity deliberately reduced at start of fill (by offsetting colliding beams) means fill can run for longer as less protons burnt-off at start.



HL-LHC luminosity profile

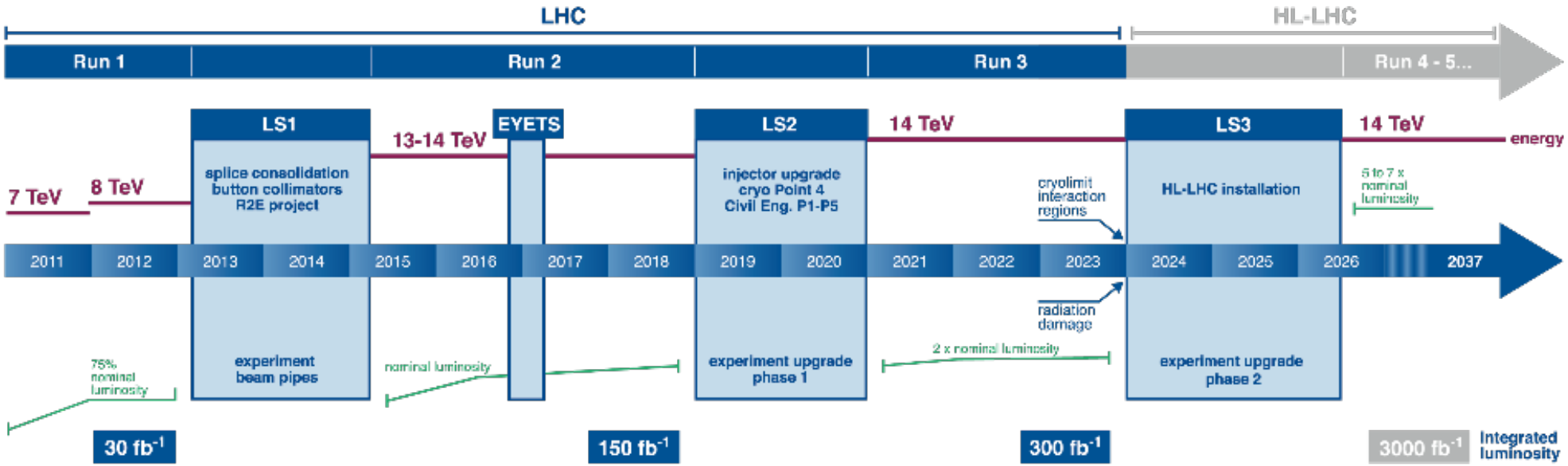


Luminosity leveled at 5e34 to limit pileup to manageable level for experiments.


2
CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.
"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.
3
LHC TUNNEL
CMS
ALICE
1
FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.
ATLAS
LHCb
6
5
4
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.
COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.
BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

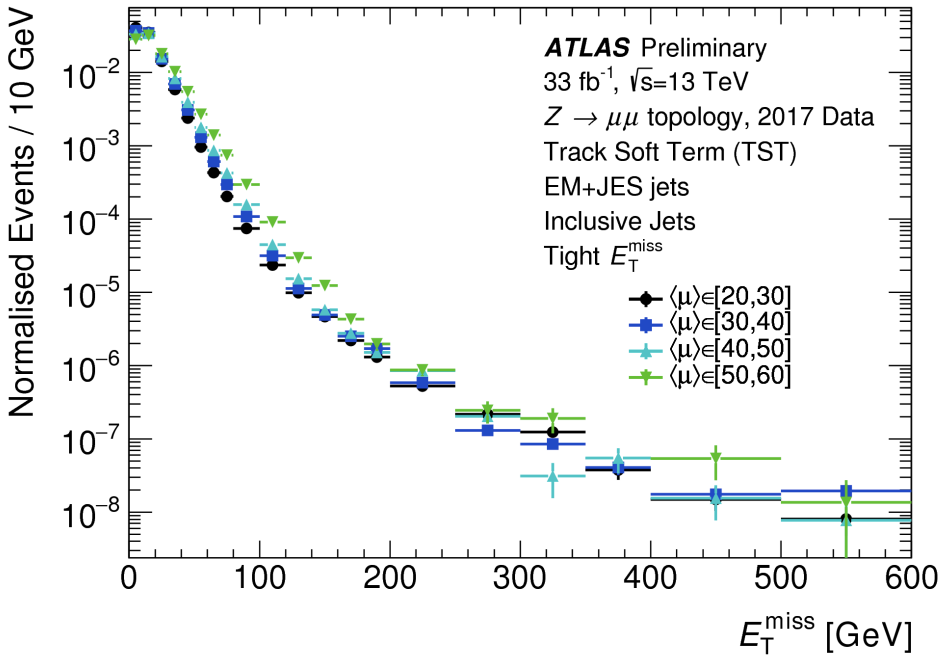
Detector upgrades

In order to be able to cope with the pileup and radiation that HL-LHC will provide, large parts of the detector will need to be upgraded in LS3. Aim is to keep the same performance (or improve) compared to the original detector operating at low pileup.
Large scale ~250M CHF project / experiment, dominated by replacing the full tracker.

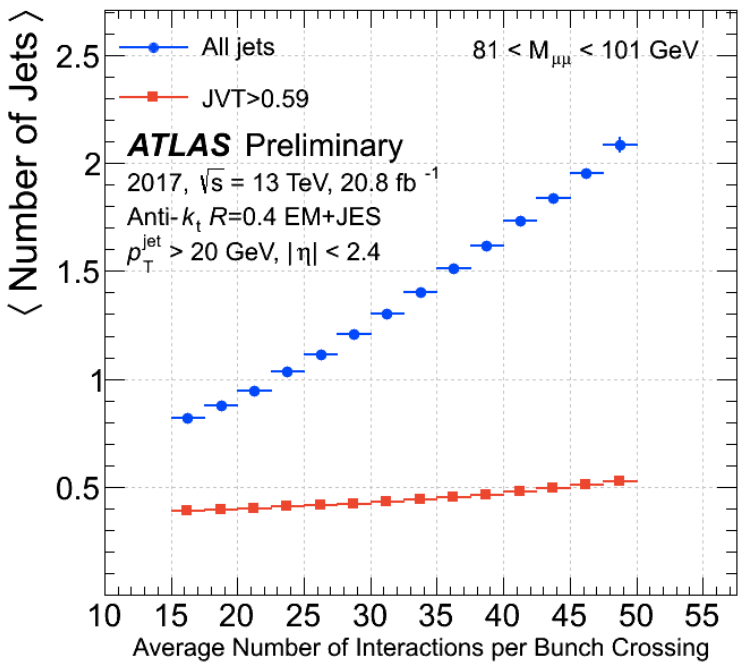


Physics performance at high pileup

A huge effort has gone into making the reconstruction of particles robust against pileup. Keeping high efficiency, and good resolution even at a pileup of 60 is very challenging.
Missing energy and jet reconstruction particularly effected by the contribution from soft pileup interactions.



Missing transverse energy a key variable in SUSY and Dark Matter searches. Resolution starts to degrade at highest pileup (>50).



Jet multiplicity grows with pileup. But requiring most of the jet energy comes from the same vertex, makes the multiplicity much more stable with pileup.

ATL-PHYS-PUB-2018-007

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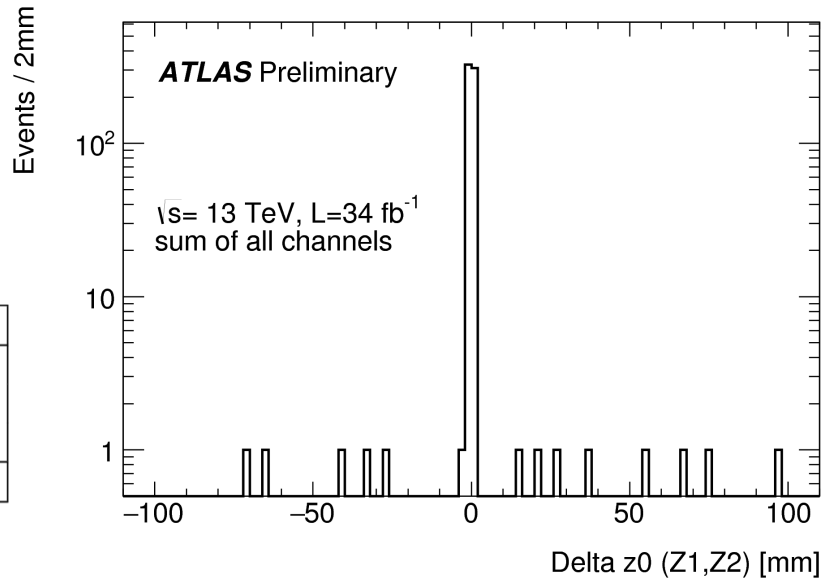
Run-2 pileup in ATLAS

With the 2017 data we reached a regime where the probability of multiple hard scatter processes, from separate pp interactions, in the same event becomes relevant.

Look for events with 2 leptonically decaying Z bosons, and plot difference in production point (z0). See 13 events where the 2 Z candidates originate from points separated by at least 5mm. Broadly consistent with expectations.

Final state	Number of observed events	Number of expected events
$e^+e^-e^+e^-$	2	2.1
$\mu^+\mu^-e^+e^-$	6	6.6
$\mu^+\mu^-\mu^+\mu^-$	5	5.4
Sum over all channels	13	14.1



Such events can present a background for certain physics analyses, and need to be taken into account.
Using tracking information to require the hard-scatter processes come from the same vertex reduces such backgrounds by a factor of ~100. But for processes involving photons this can not be done.

ATLAS-CONF-2018-018

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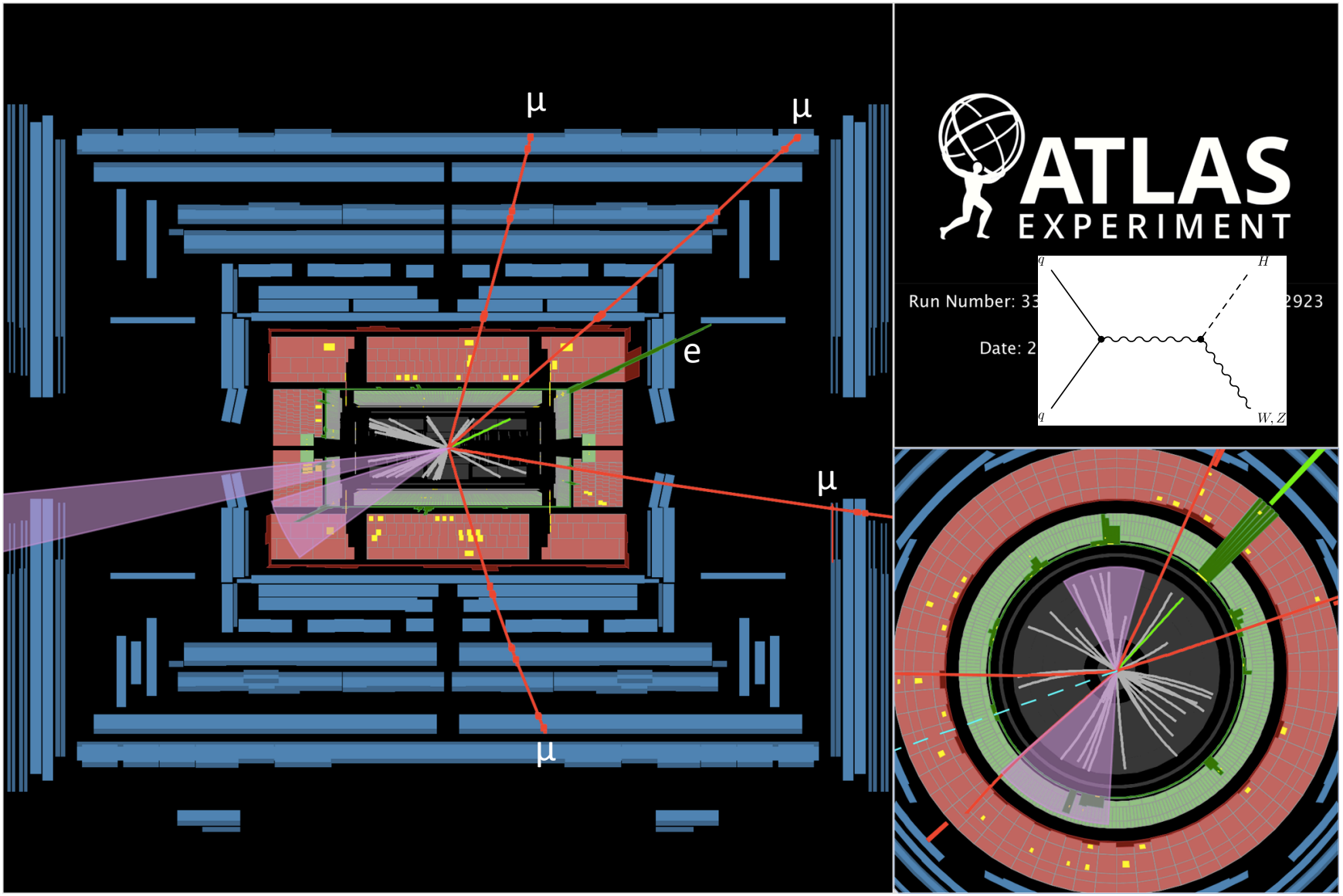
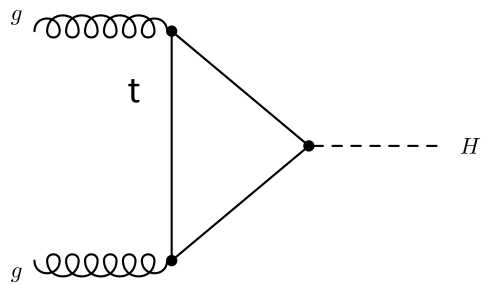
Candidate W(->eν) H(->4μ) event. The 4 muons (red lines) have a mass of 124.6 GeV, with the electron (green) and MET consistent with a W decay.
S/B~7 for such an event!

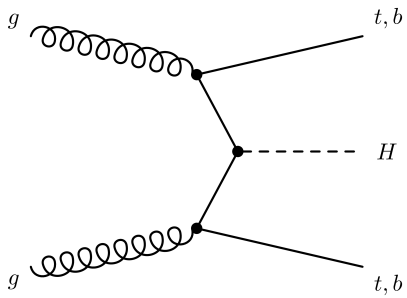


ttH production – why this is interesting

Yukawa coupling (like H->ττ), demonstrates coupling to quarks, but also…

In SM gluon fusion production of Higgs boson goes through a loop diagram with the top quark the main contribution in the loop:





Therefore, in the SM, the top Yukawa coupling can be indirectly inferred from a combined fit to Higgs measurements in modes dominated by gluon fusion. However, in BSM heavy new particles in the loop can also play a role.

Directly measuring the top coupling and comparing with the indirect measurement is therefore a powerful test of the SM.

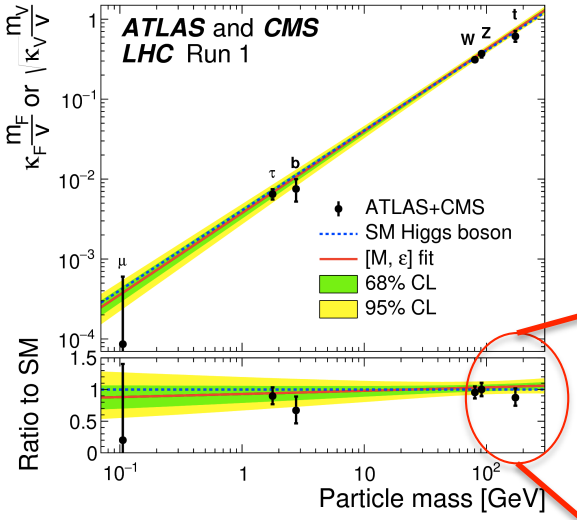
Since the Higgs is too light to decay to top, this is measured in ttH production.

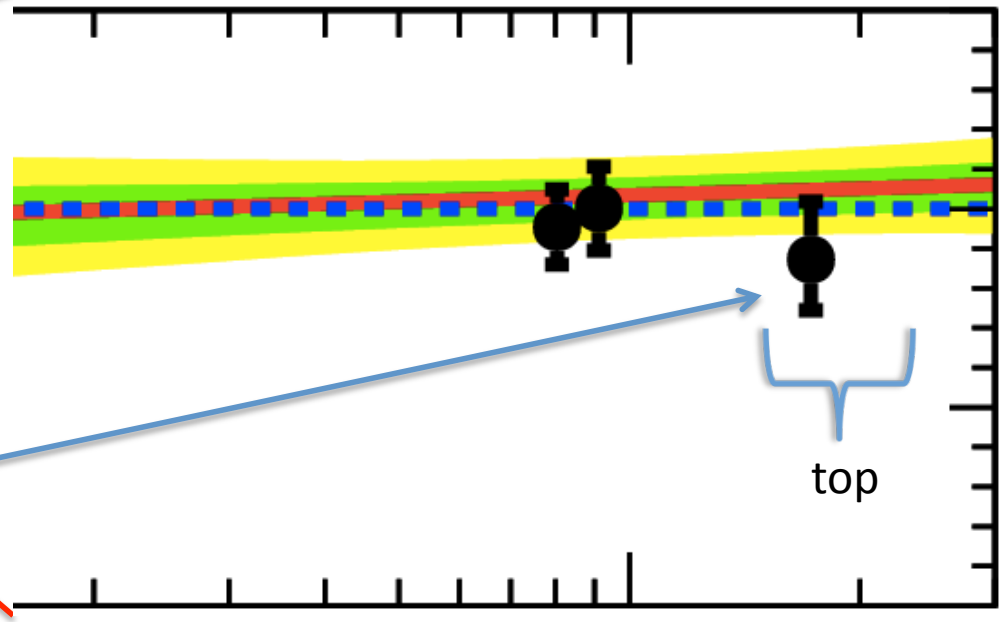
The ttH final state is very heavy, so the cross section is low (~1% of inclusive Higgs production), and it is a complex final state.

To search for this a large number of channels are combined with semi-leptonic and di-leptonic decays of the tops, and considering Higgs decays to: bb, ZZ*, WW*, ττ, γγ

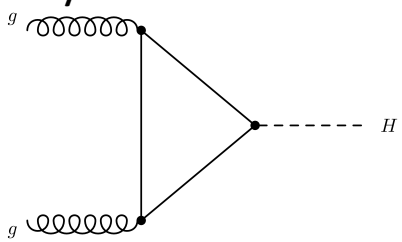
PLB 784 (2018) 173 (ATLAS) / PRL 120 (2018) 231801 (CMS)

Observation of ttH production





(mostly) Indirect measurement of top-Higgs coupling from contributions in loop (mostly from gluon fusion production)



PLB 784 (2018) 173 (ATLAS) / PRL 120 (2018) 231801 (CMS)

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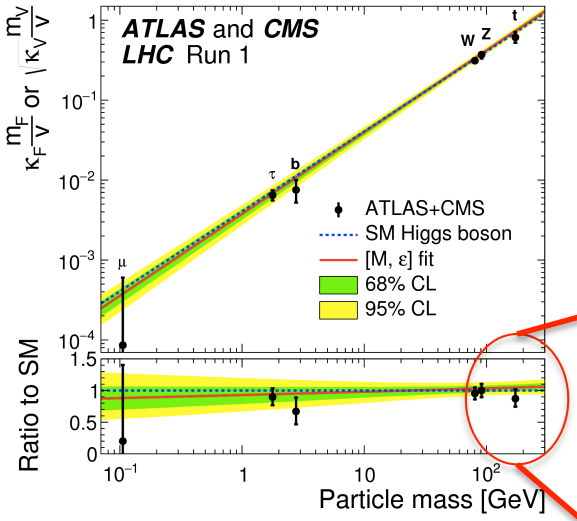
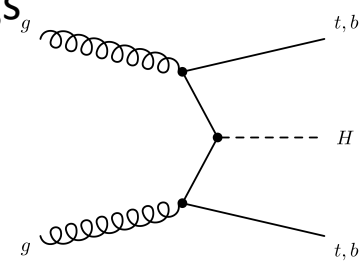
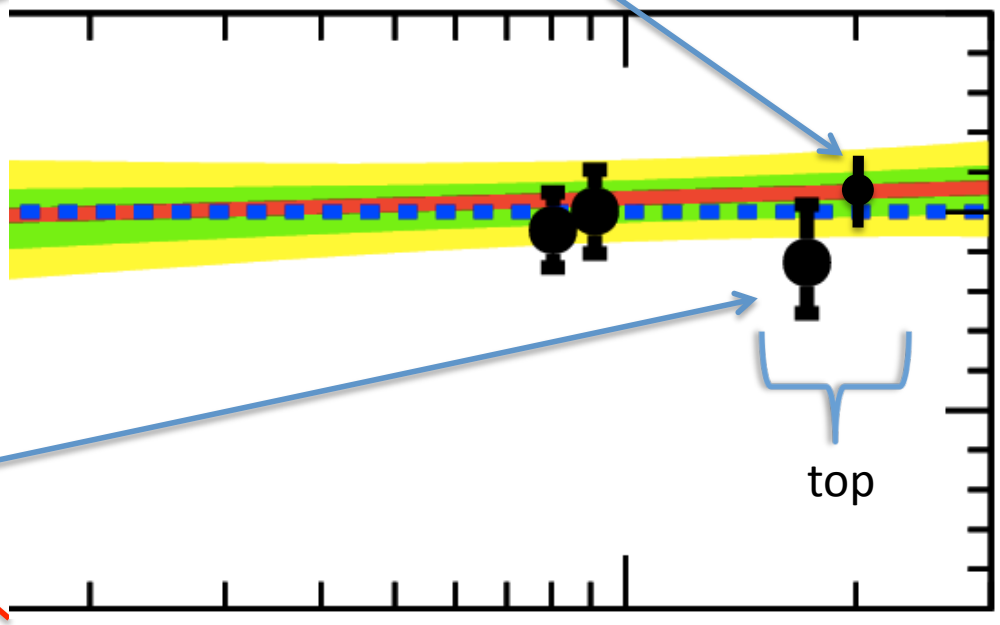
Observation of ttH production

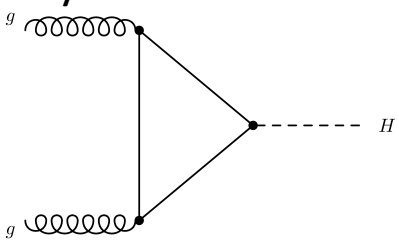


Direct measurement of top-Higgs coupling from ttH production measurement (μ=1.3±0.3 =>κ_t/κ_t^{SM}=1.15±0.15) (added by me for illustration)





(mostly) Indirect measurement of top-Higgs coupling from contributions in loop (mostly from gluon fusion production)



With current precision fully consistent, constraining possible new physics contributions to the loop in gluon fusion Higgs production.

Eur. Phys. J. C 78 (2018) 891

Precision top mass measurement

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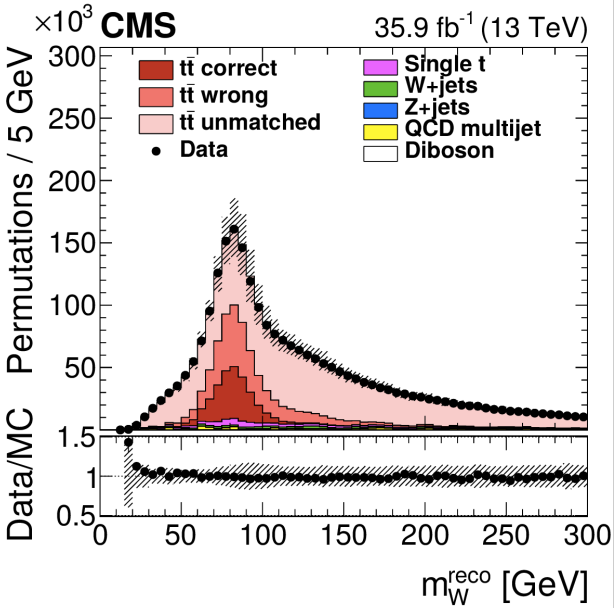

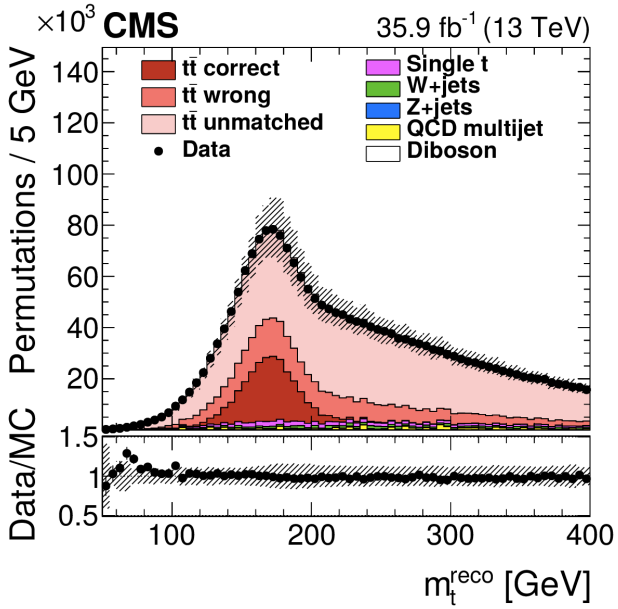

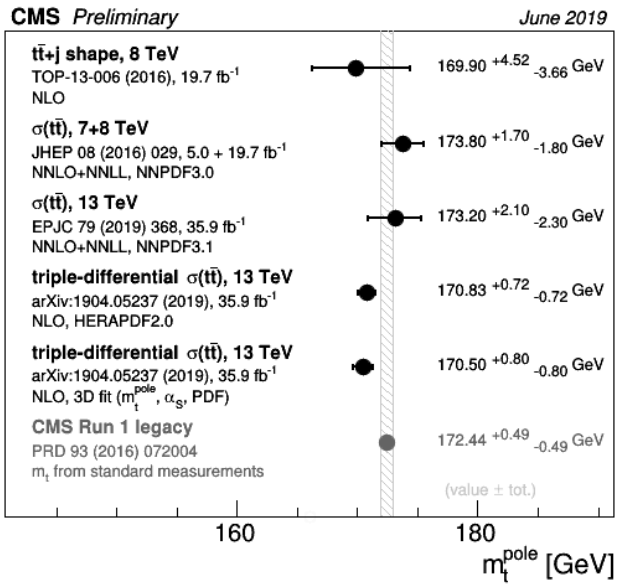

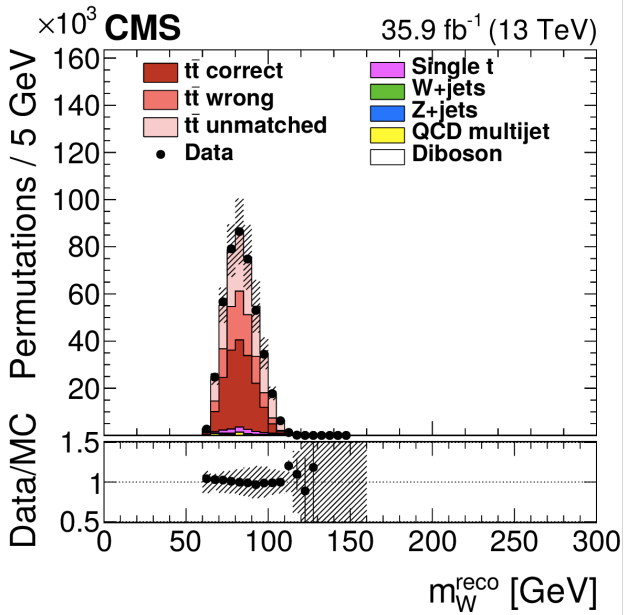

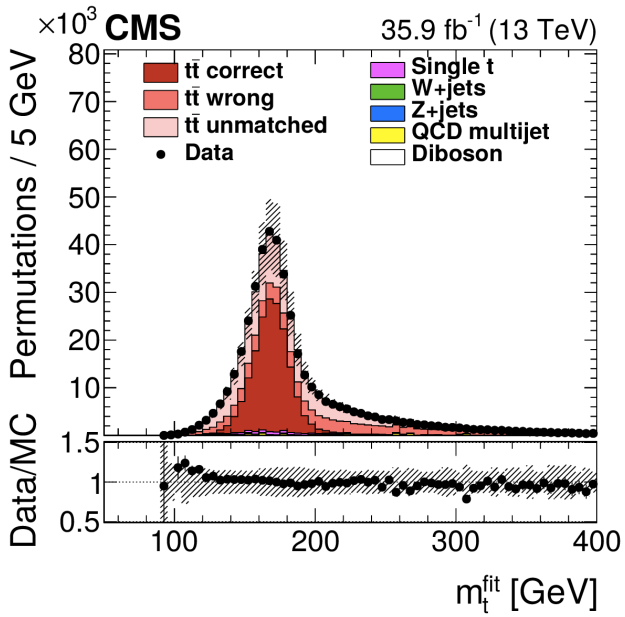

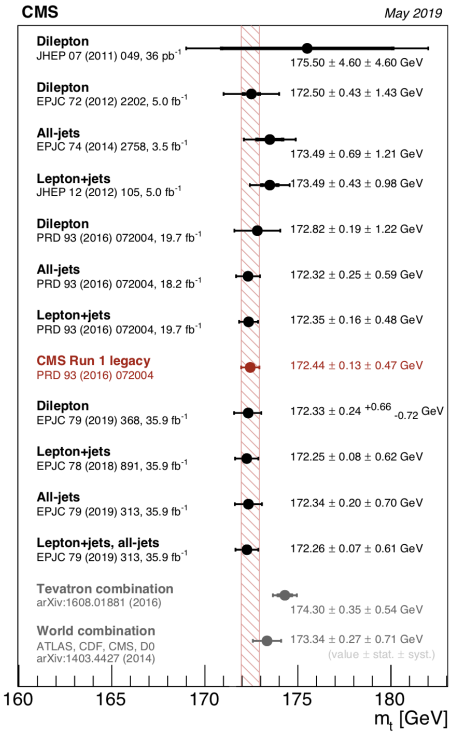

Precision top mass measurement

ESHEP 2019
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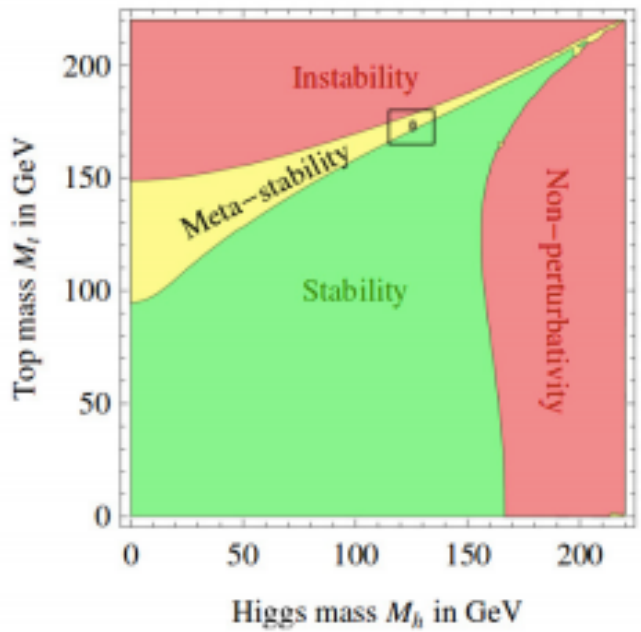
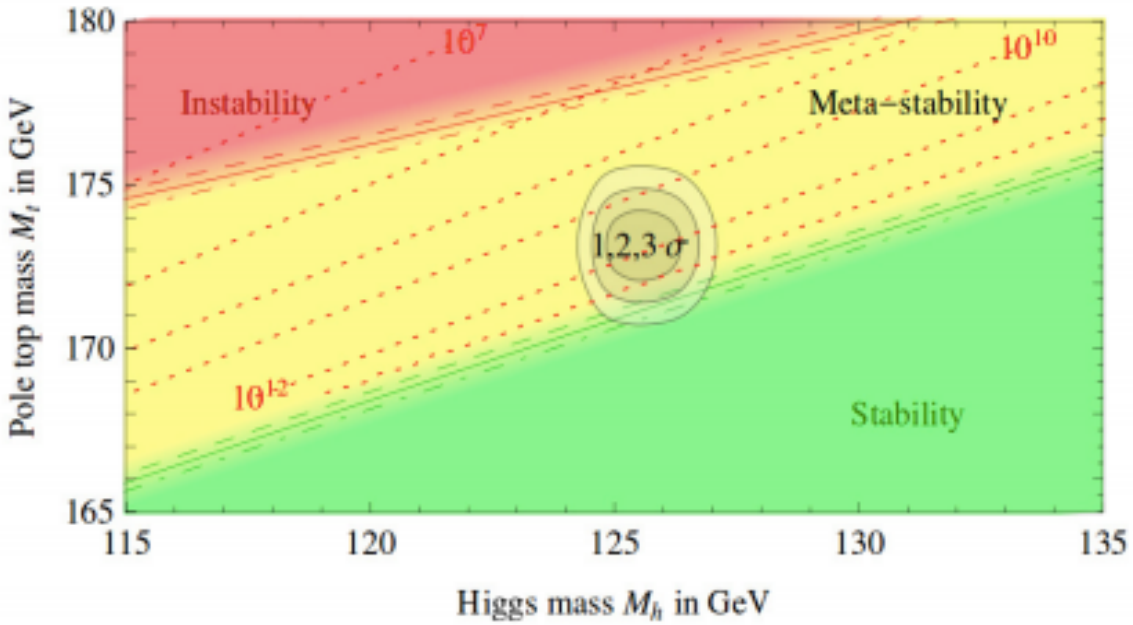
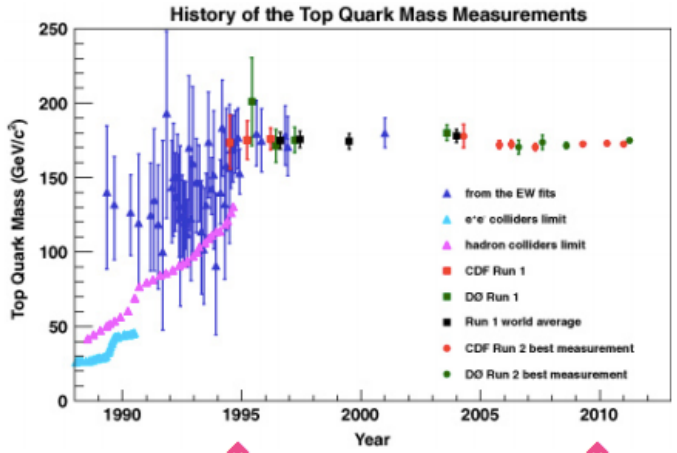
JHEP08 (2012) 098

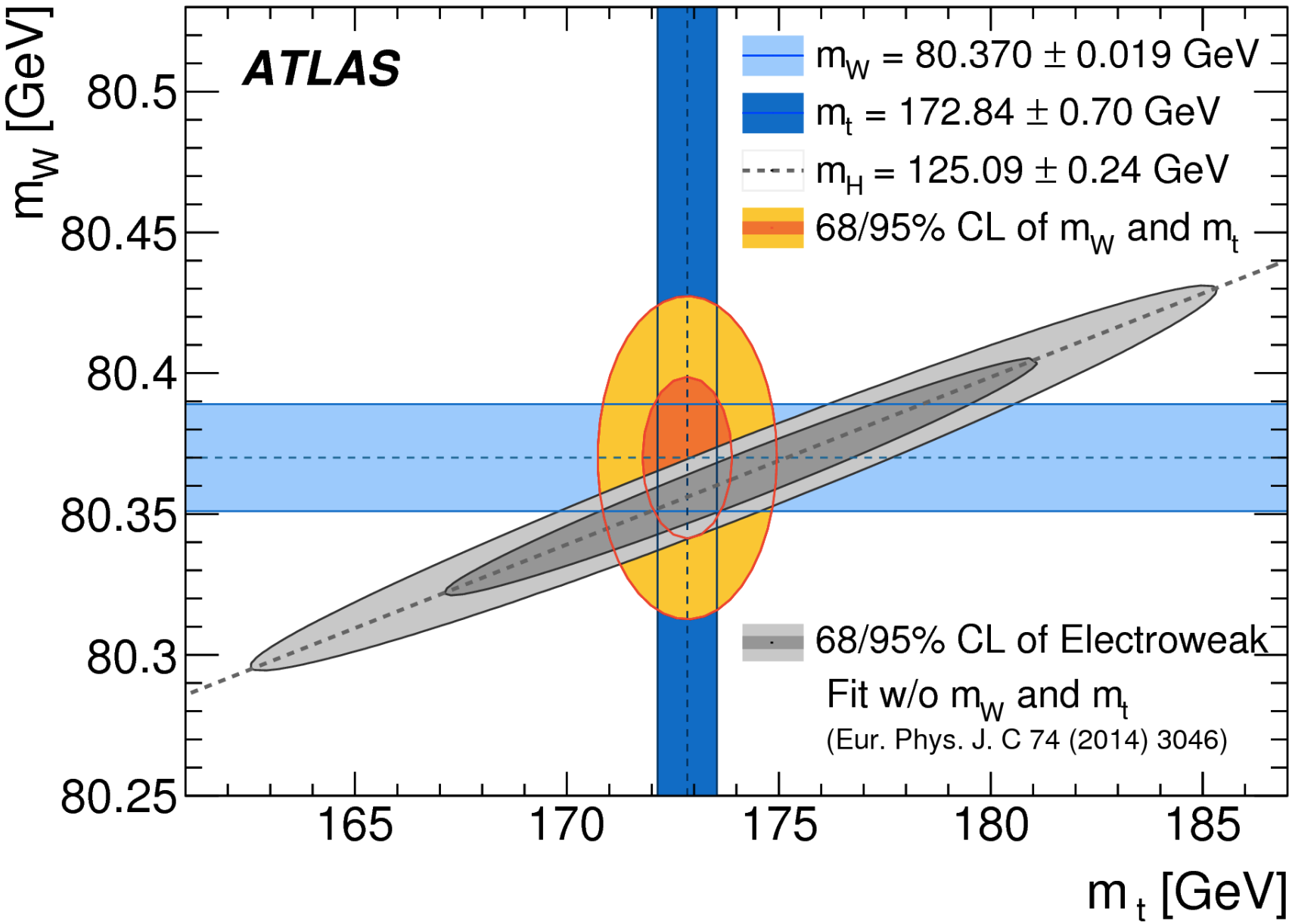






First discovery
with ≈ 20 events

"Re-discovery"
with 46 events


ATLAS
m_W = 80.370 ± 0.019 GeV
m_t = 172.84 ± 0.70 GeV
m_H = 125.09 ± 0.24 GeV
68/95% CL of m_W and m_t
68/95% CL of Electroweak Fit w/o m_W and m_t
(Eur. Phys. J. C 74 (2014) 3046)
m_W [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
165
170
175
180
185
m_t [GeV]

PRL 115, 072001 (2015)

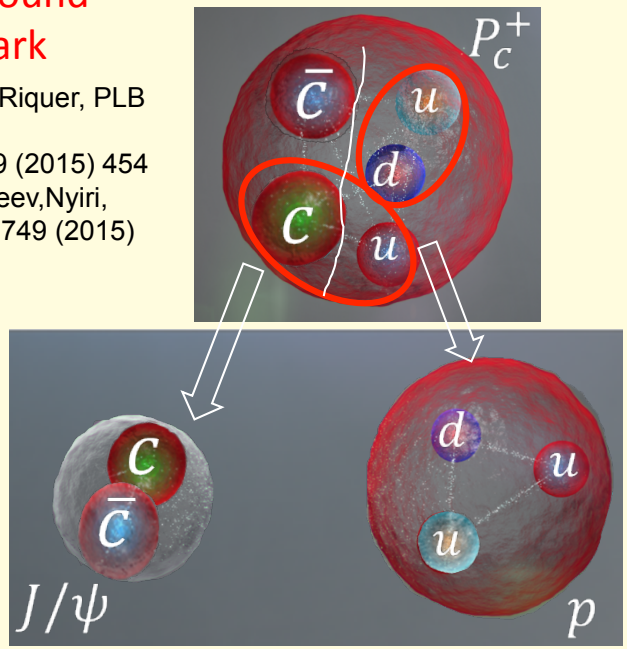
Pentaquarks

ESHEP 2019
CERN-JINR

Tightly-bound pentaquark

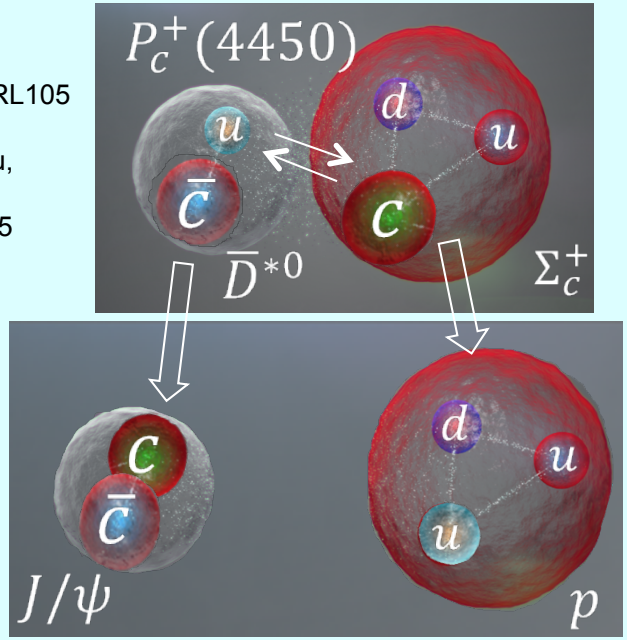
Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$



Loosely-bound pentaquark

Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others



$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$