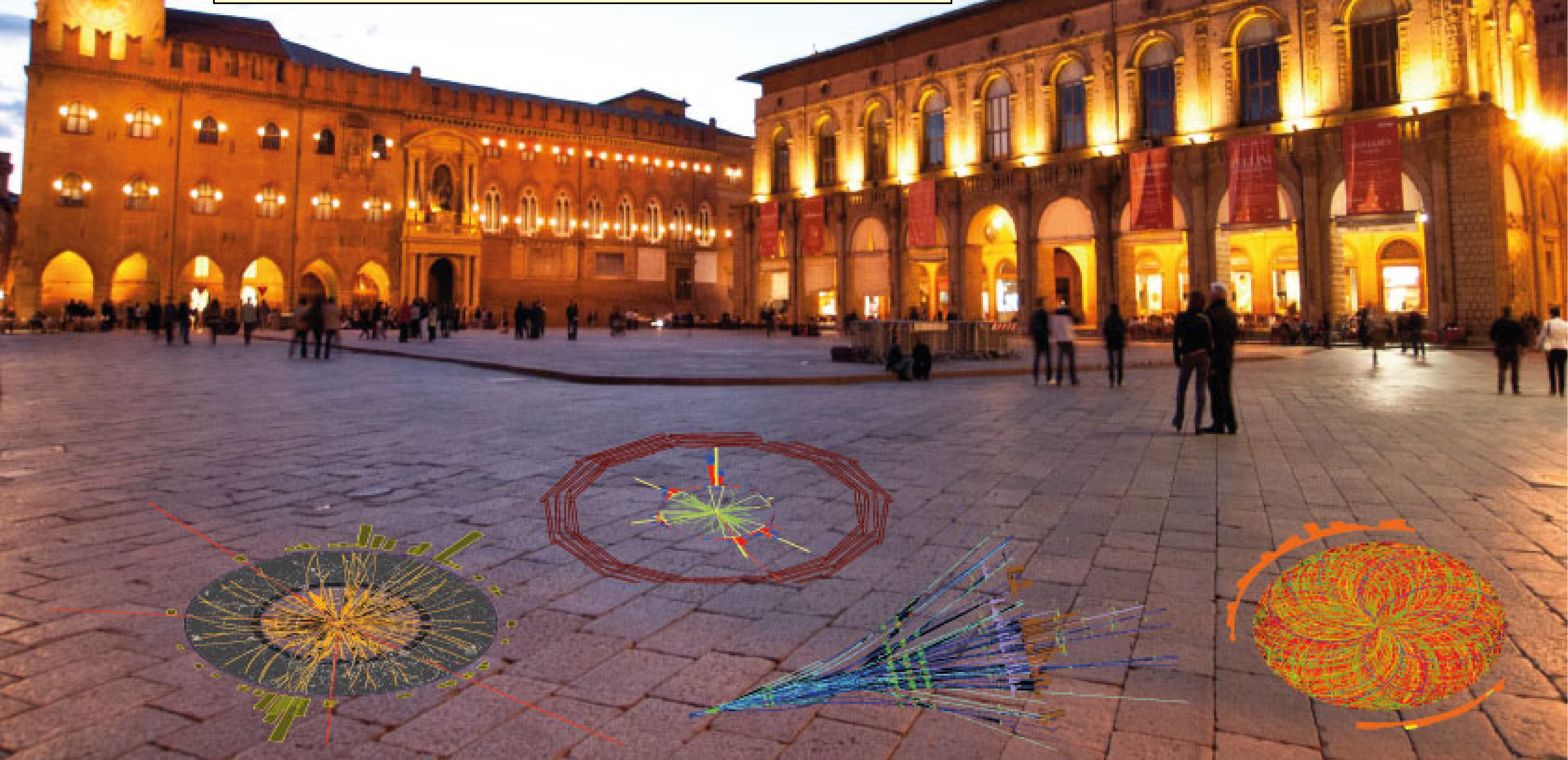
Experimental Review

A glance at a (very) few selected highlights from this week

Dave Charlton (U of Birmingham)

LHCP 2018, Bologna



Experimental Review

A glance at a (very) few selected highlights from this week

Dave Charlton (U of Birmingham)

LHCP 2018, Bologna

We have been spoilt by so many excellent presentations this week – talks and posters – as well as this exceptional environment for the meeting

With thanks to many people for discussions this week, including but not limited to:
Roberto Carlin, Gabriel Facini, Iwona Grabowska-Bold, Beate Heinemann, Phil Ilten, Roman Kogler, Alex Lenz, Andrea Mogini, Giovanni Passaleva, Shahram Rahatlou, Pierre Savard, Bjoern Schenke, Luca Silvestrini, Nick Styles, Dan Tovey, Vincenzo Vagnoni, Iacopo Vivarelli

Any mistakes – and provocations - are mine, not theirs!

Themes of the week

Approaching a decade after the start, the LHC is now a mature machine, and the detectors are stable, and very well understood

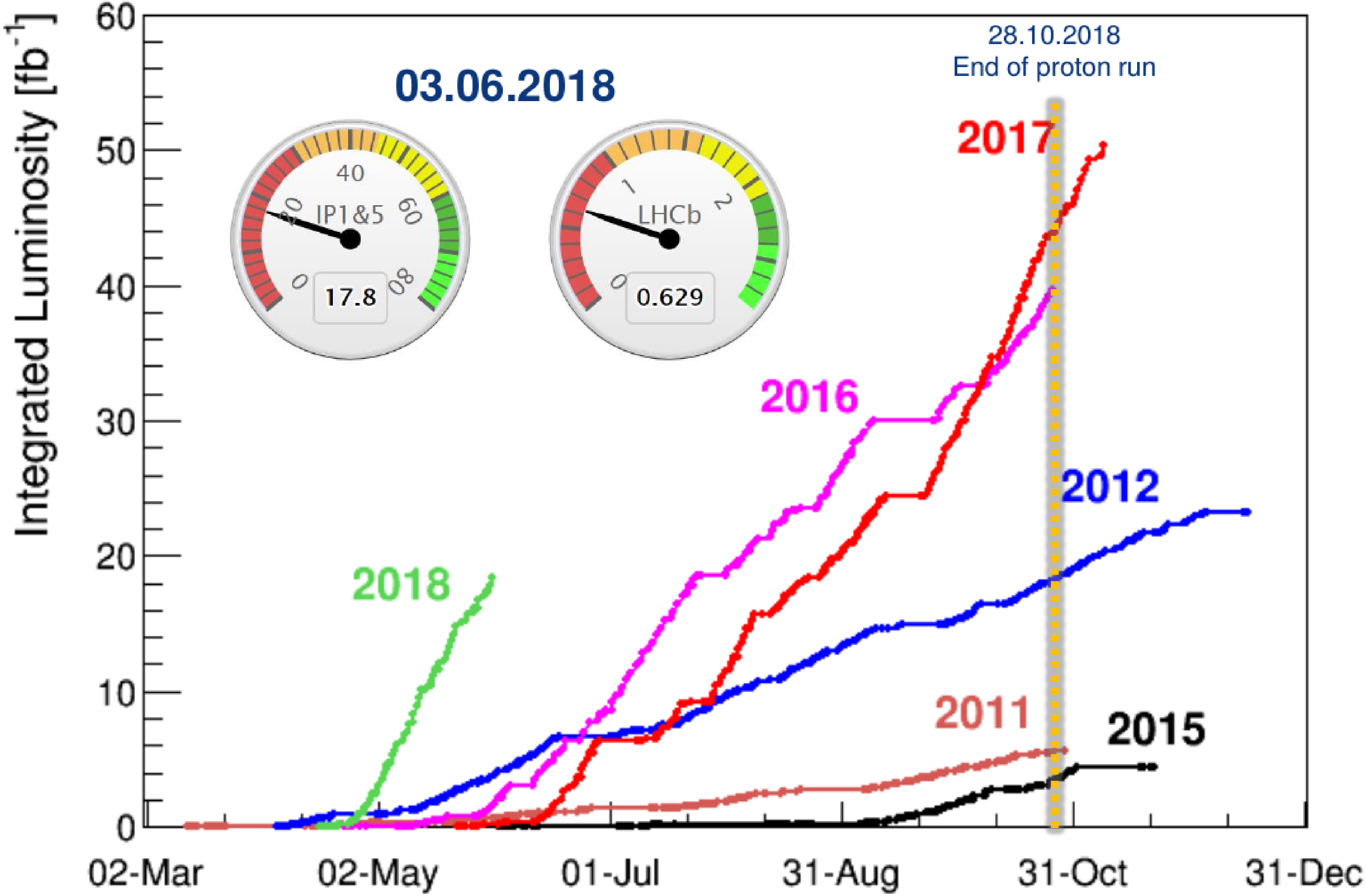
Very large 13 TeV & ion samples and exquisite detector performance enable:

- Major progress on “our scalar”
- A huge range of detailed measurements from all four experiments which further our understanding of many parts of the Standard Model and challenge state-of-the-art calculations
- Continuing searches:
  - For ATLAS and CMS this LHCP catches the tail of the (2015+)2016-data studies, and only the very first of the 2016+2017 searches
  - For LHCb, we have the Run-1 analyses but Run-2 results to come

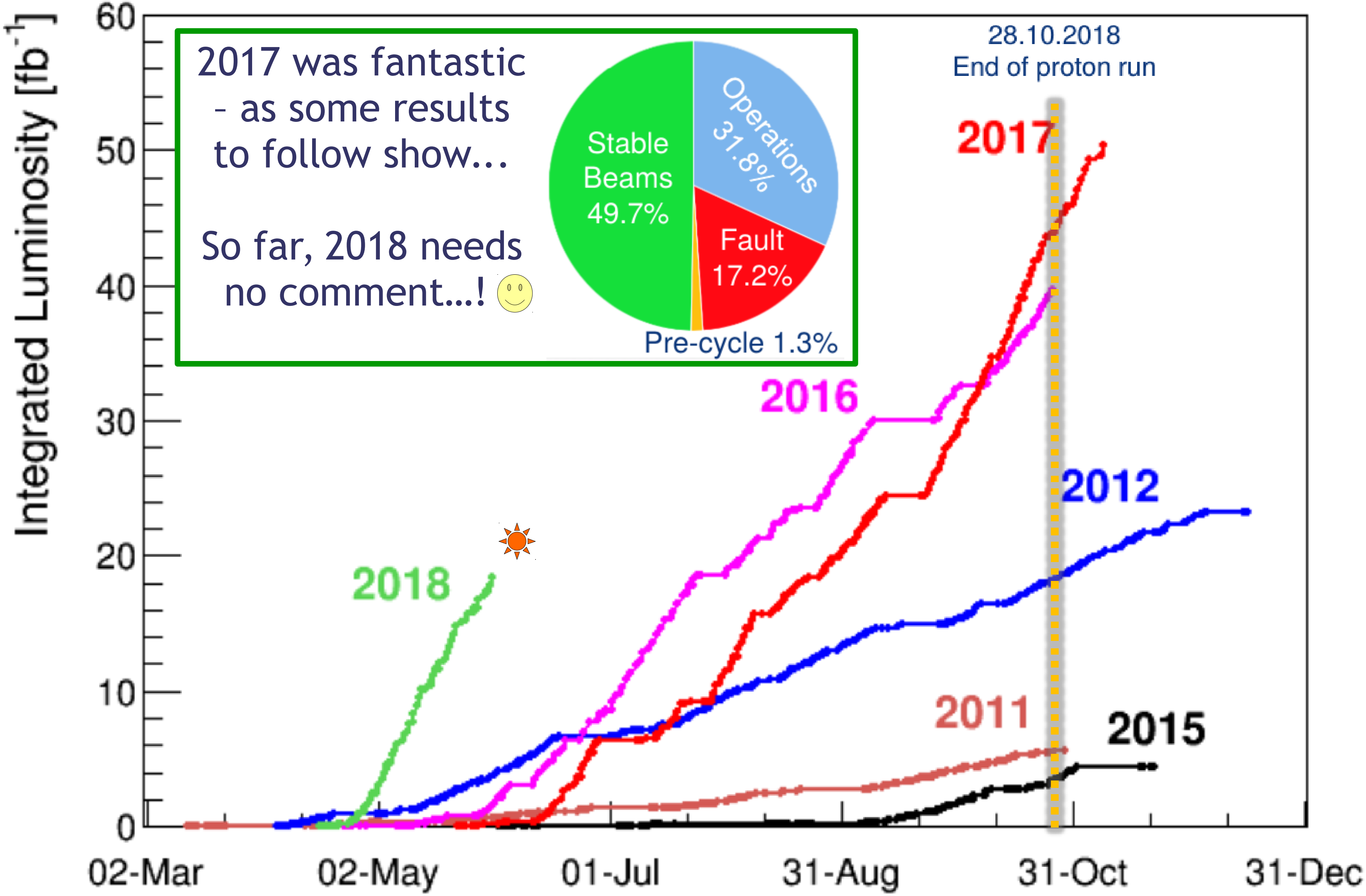
Large samples and exquisite detector performance

https://commons.wikimedia.org/wiki/File:Parmigiano_reggiano_factory.jpg

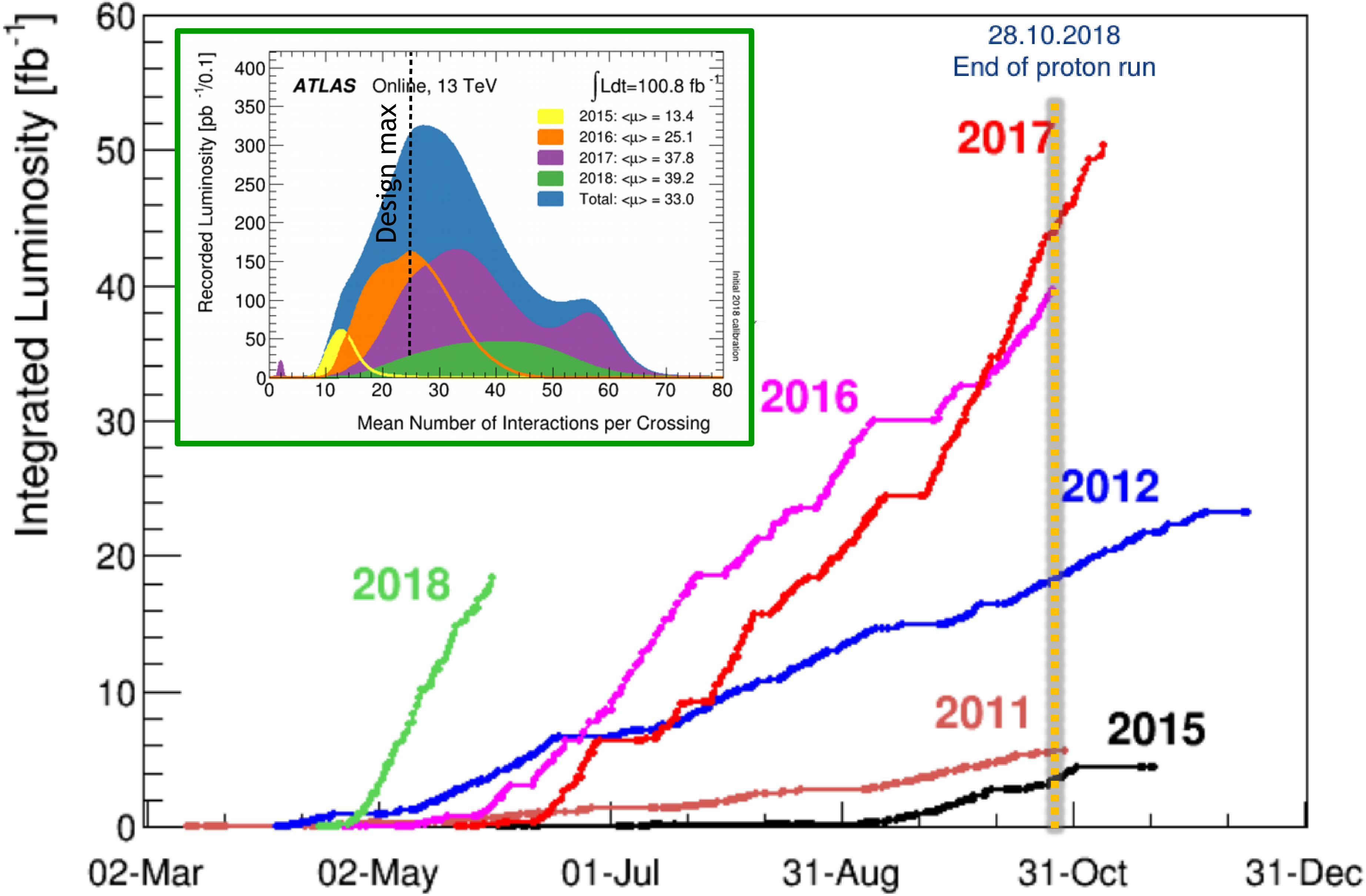
Wonderful LHC performance



Wonderful LHC performance



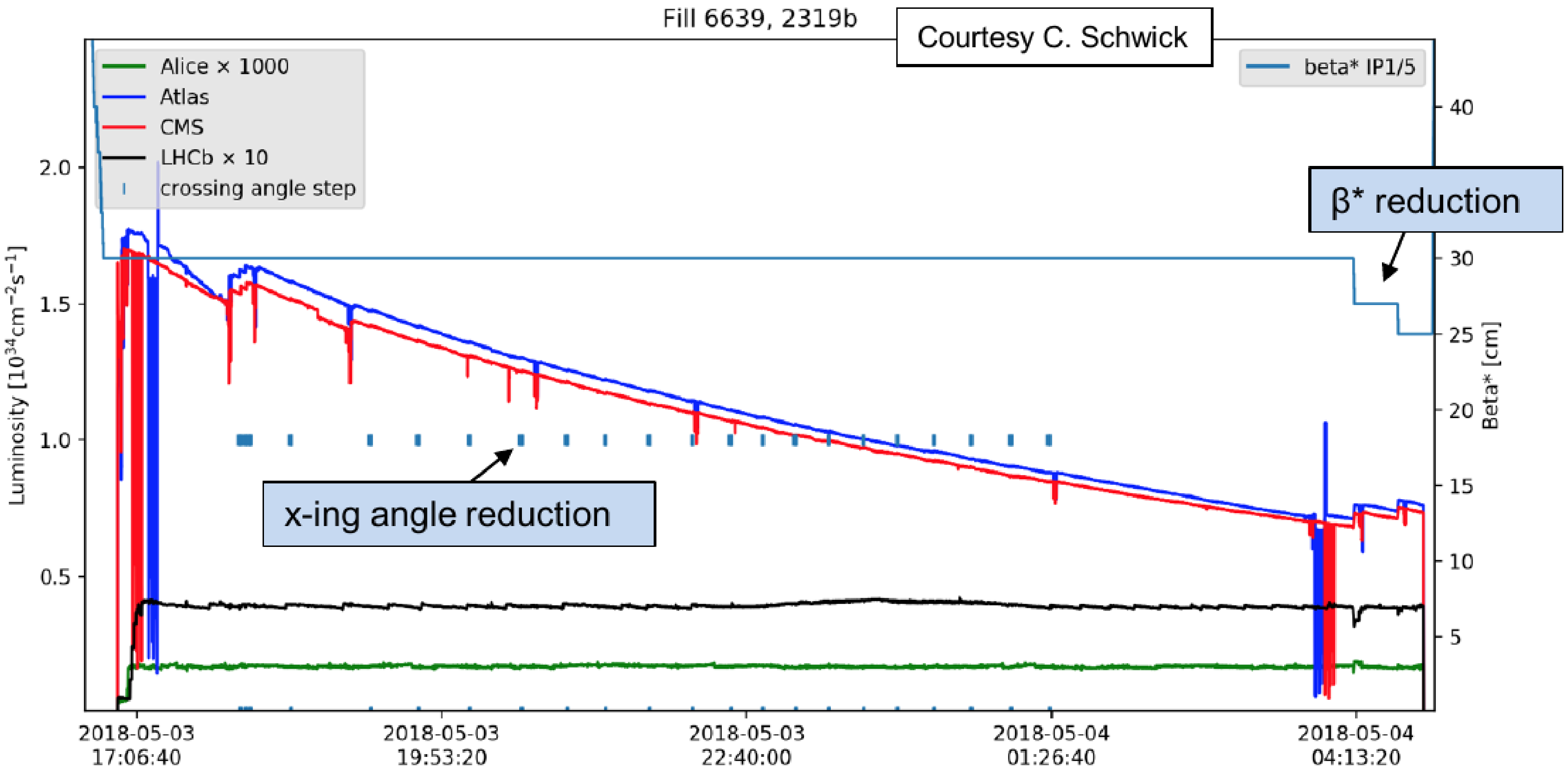
Wonderful LHC performance



Wonderful LHC performance

Ingenious use of levelling to optimise ATLAS+CMS luminosity delivery

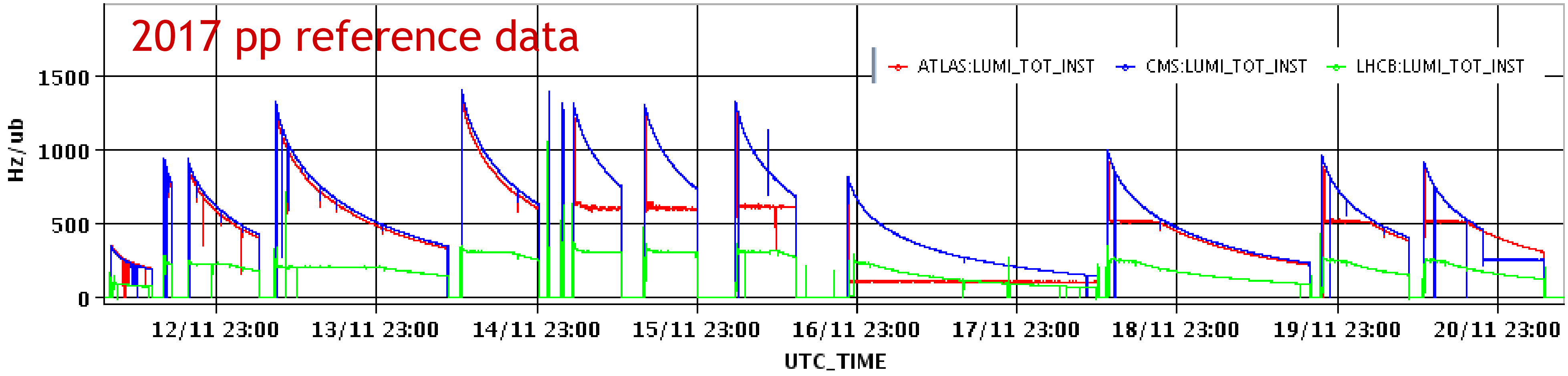
- “Continuous” beam crossing angle reduction to inch up lumi during fill
- Increase squeeze at end of fills (for now)
- All the time using continuous separation levelling for LHCb and ALICE



The flexible LHC: ions *et al*

Run-2 samples for the heavy-ion programme, so far

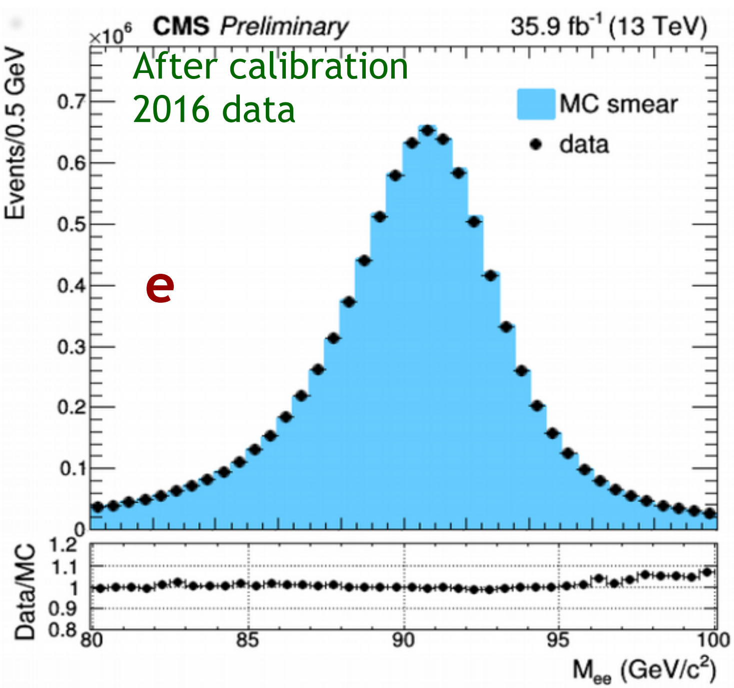
- $\surd s_{NN}$=5.02 TeV **Pb+Pb** 2015 *(2018 to come)*
- $\surd s_{NN}$=5.02, 8.16 TeV **p+Pb** 2016
- $\surd s_{NN}$=5.44 TeV **Xe+Xe** 2016 (6h)
- **$\surd s_{pp}$ =5.02 TeV** pp data 2015, 2016 and 2017

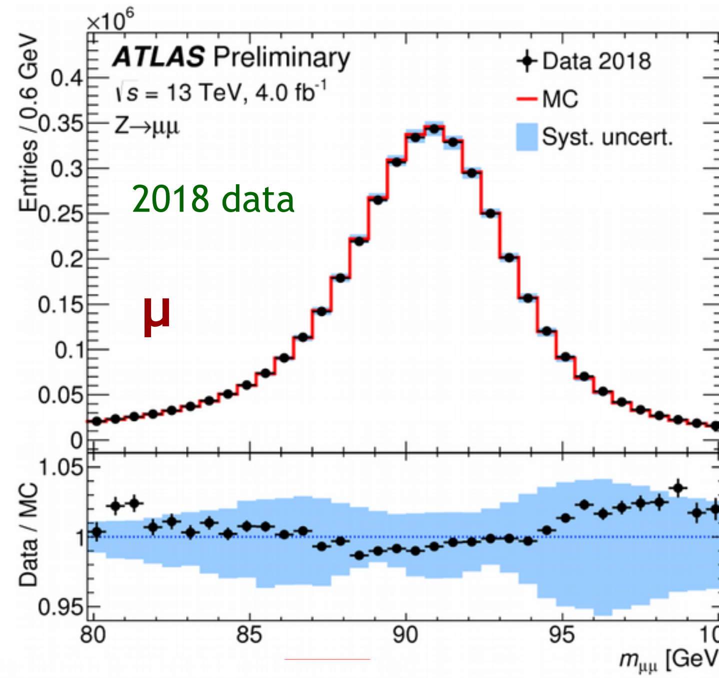


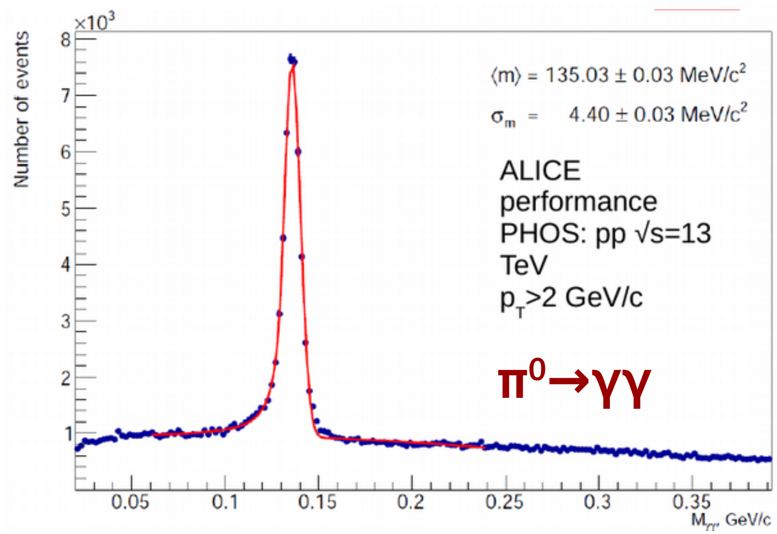
Plus other special runs (few days / year) mainly for forward physics (elastic scattering, diffraction)

Detector performance

The stunning performance of the LHC detectors continues to repay the thousands of staff-years and meticulous care put into building them – matched by the ingenuity of old and new analysis techniques

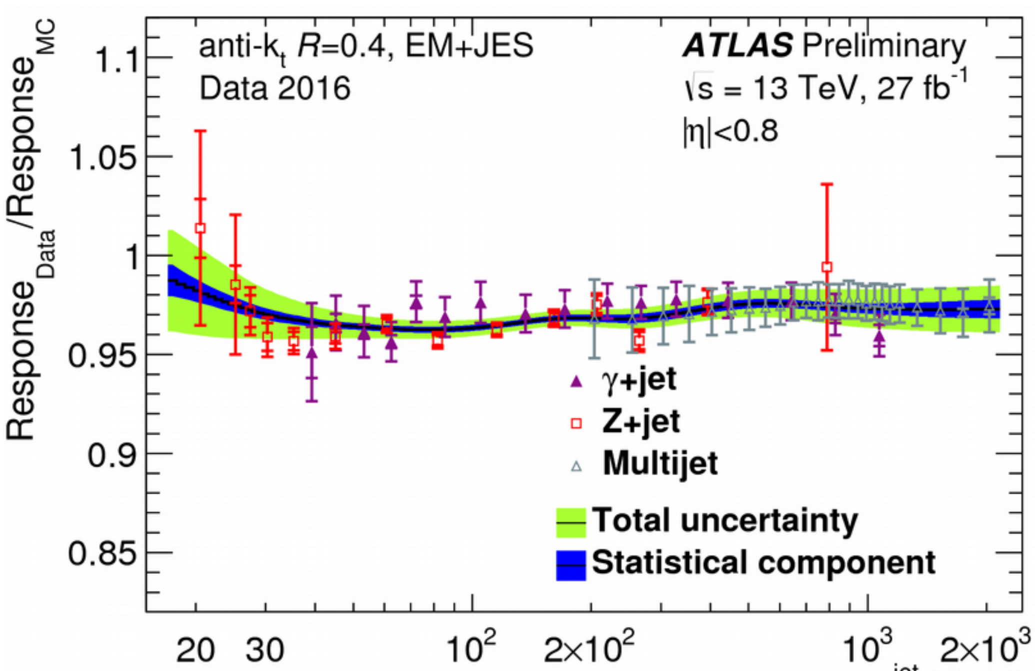




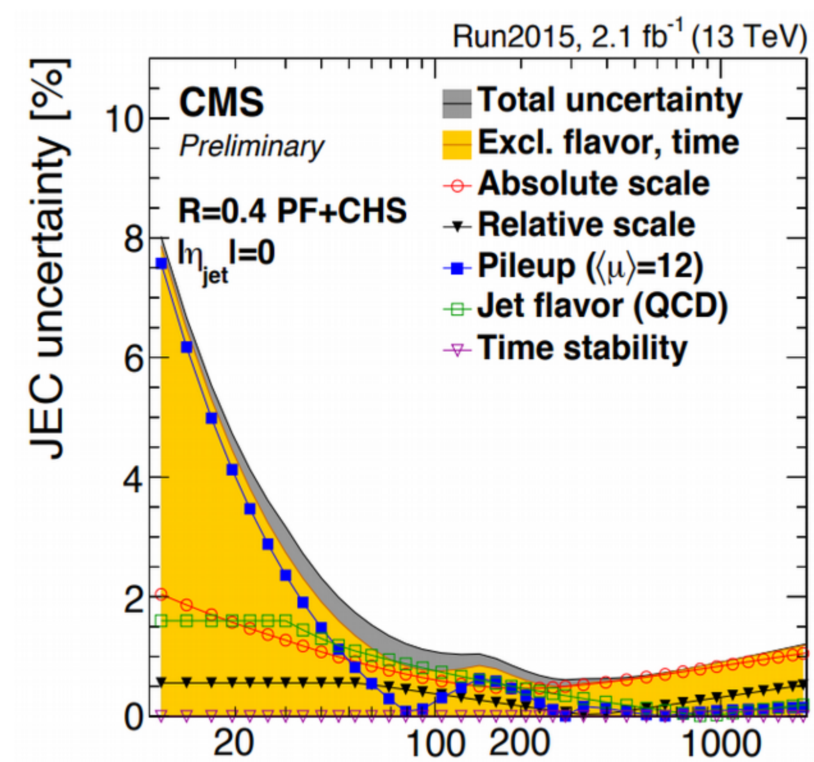


Detector performance

The stunning performance of the LHC detectors continues to repay the thousands of staff-years and meticulous care put into building them – matched by the ingenuity of old and new analysis techniques



Jet data/MC response

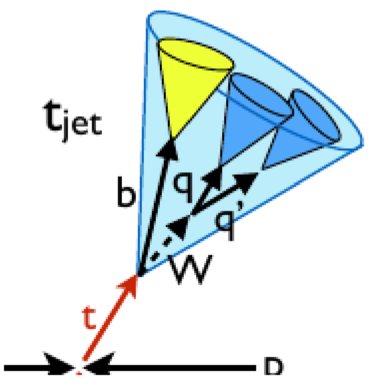


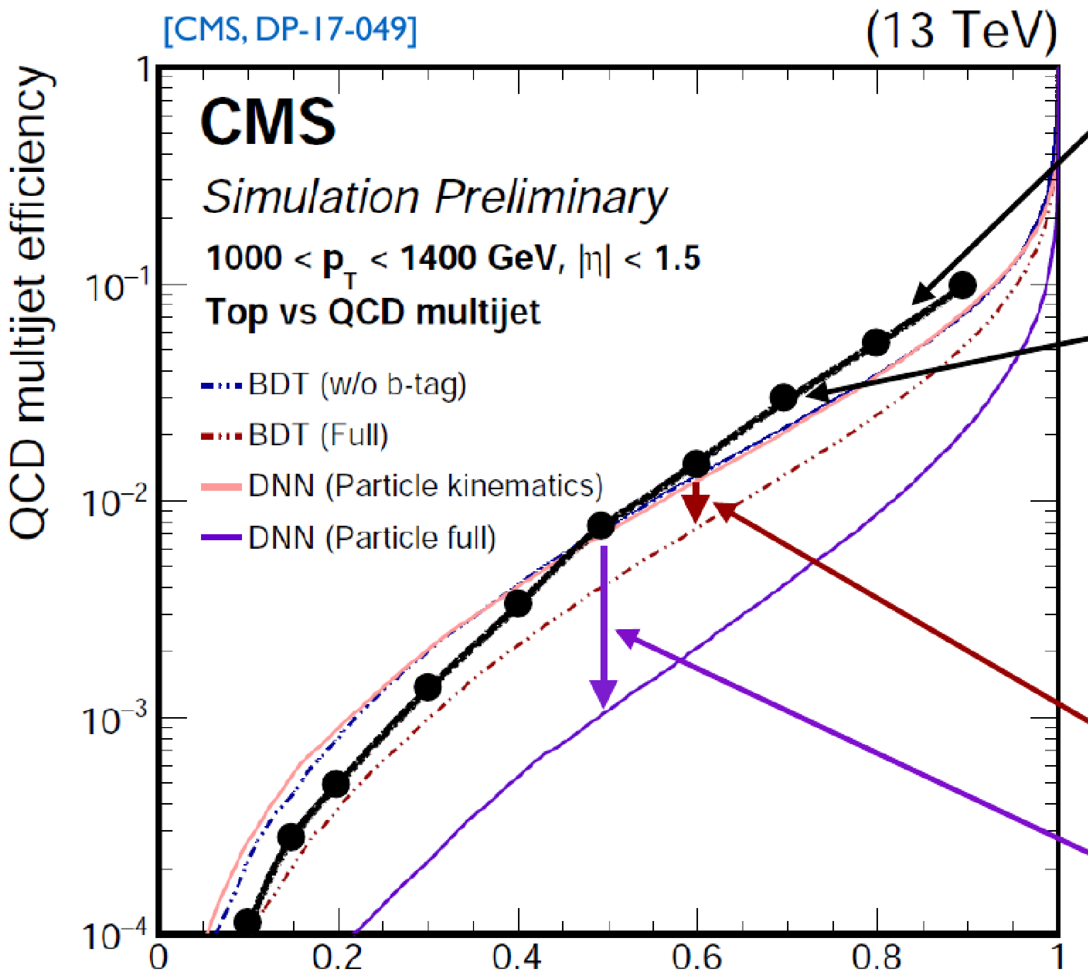
Jet energy correction uncertainty

Detector performance

The stunning performance of the LHC detectors continues to repay the thousands of staff-years and meticulous care put into building them – matched by the ingenuity of old and new analysis techniques

Boosted top tagger





soft drop mass, $\tau_{3/2}$, subjet b [CMS-PAS-JME-15-002]

today's standard

2-3% misidentification at 70% signal efficiency

A prime example for machine learning

gain from a BDT

gain from a deep neural network

Roman Kogler

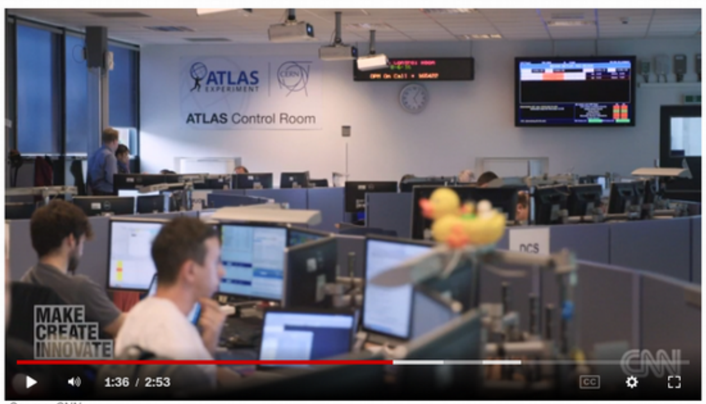
[see also ATL-PHYS-PUB-2017-004]

Progress with our scalar

We have been in the news…

To grasp the latest physics breakthrough, think of sumo wrestlers and barracudas

By Don Lincoln
Updated 2119 GMT (0519 HKT) June 4, 2018



Source: CNN

CERN: what they are looking for next 02:53

(CNN) — Scientific understanding proceeds by fits and starts, with an occasional detour down a wrong path. However, today the world's physicists have a real advance to celebrate. They have observed the most massive known fundamental subatomic particle directly interacting with an energy field that gives mass to the building blocks of the universe.

Don Lincoln

This has never been done before and it gives increased insight into a phenomenon that was only discovered just a few short years ago. This energy field is important because, without it, atoms couldn't exist.

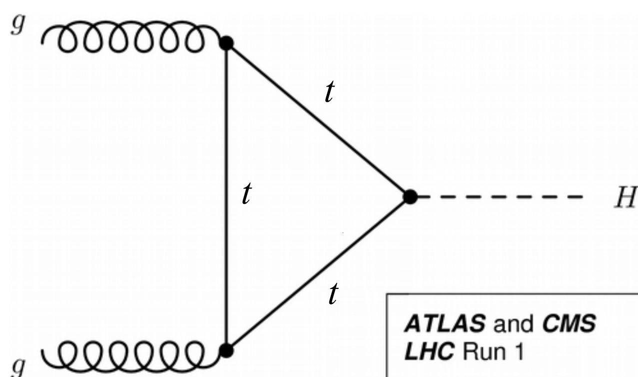
The discovery was announced at the Large Hadron Collider Physics (LHCP) 2018 conference in Bologna. Two independent experiments (ATLAS and CMS) searched for this phenomenon and both found clear evidence that it occurs. The two experiments have made their results available to the public and the scientific community, with the ATLAS paper being submitted and the CMS paper being published.

Our understanding of the origins of the mass of fundamental (e.g. containing no structure within them) subatomic particles is incomplete. In 1964, British physicist Peter Higgs and Belgian physicist Francois Englert independently developed ideas leading to what we now call the Higgs field, an energy field that permeates the universe and gives fundamental subatomic particles their mass. Mass is related to weight, and also to why it's hard to move heavy objects in outer space, where there is no weight. Without this field, these particles would have no mass at all.

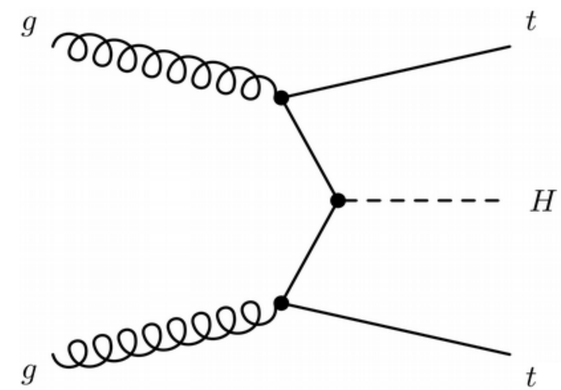
https://edition.cnn.com/2018/06/04/opinions/physics-discovery-lincoln/index.html

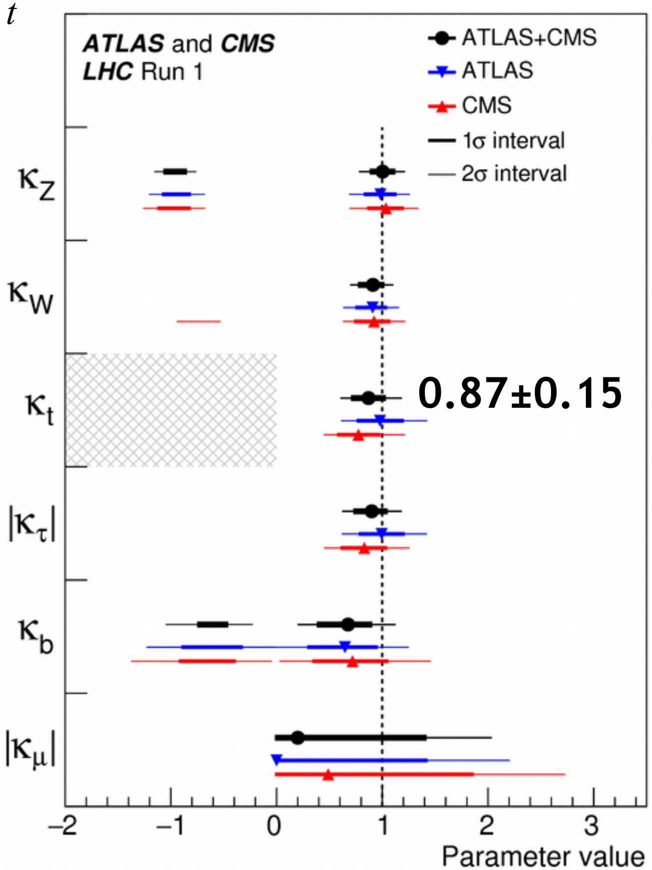
ttH coupling

While we were confident of the ttH vertex from the production cross-section, this is model-dependent, and the direct observation was missing



vs.





0.87±0.15

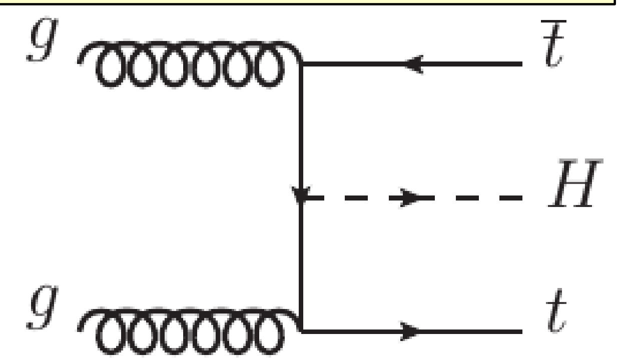
Plot assumes SM loop structures and no BSM decays

JHEP 08 (2016) 045

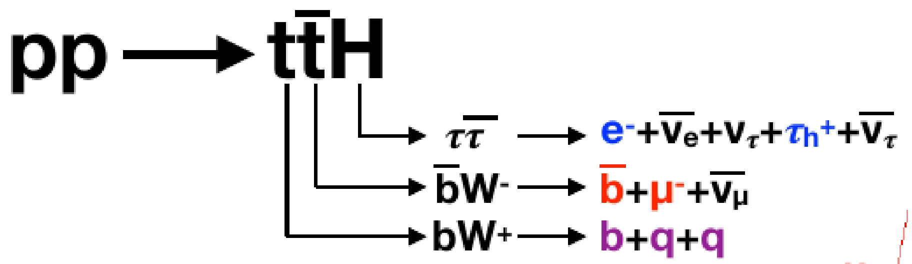
$t\bar{t}H$ observation

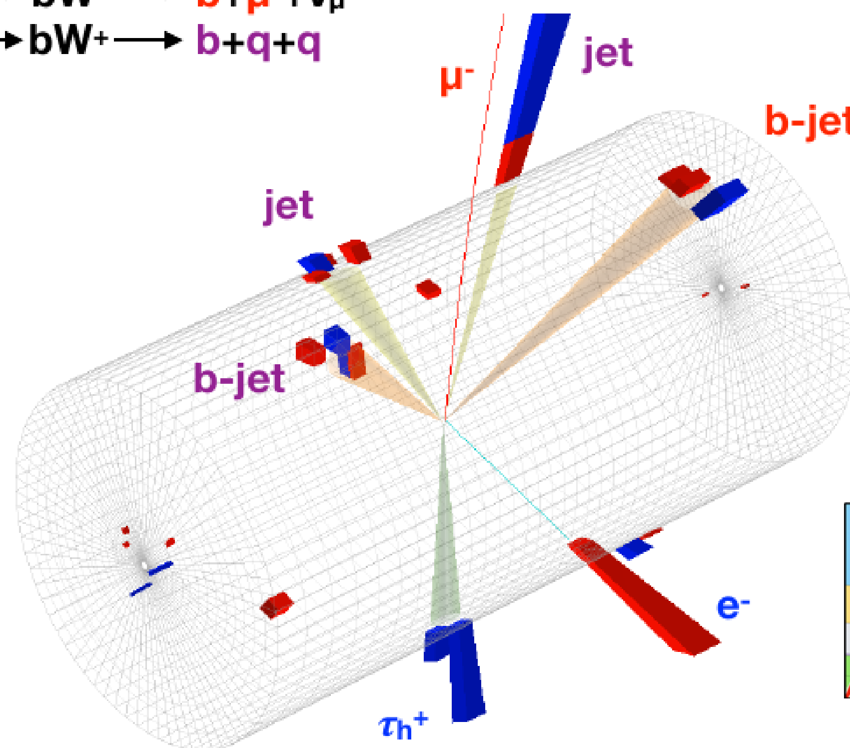
5σ observation of $t\bar{t}H$ from CMS and ATLAS

Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...



CMS $t\bar{t}H$ candidate event



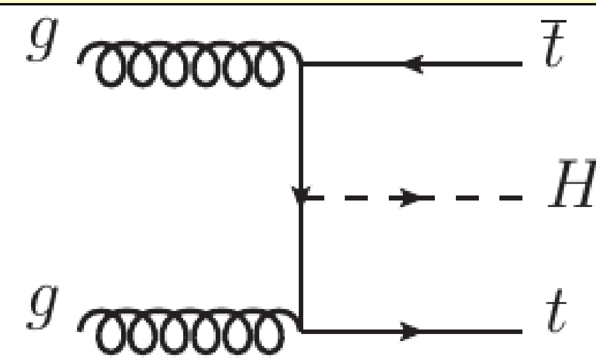


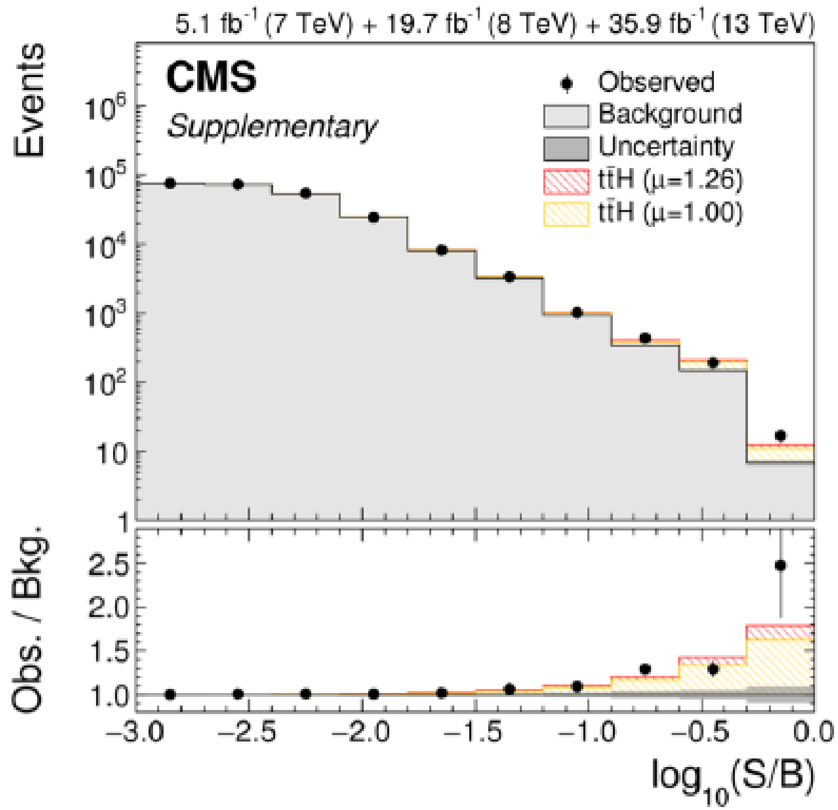
$t\bar{t}H$ observation

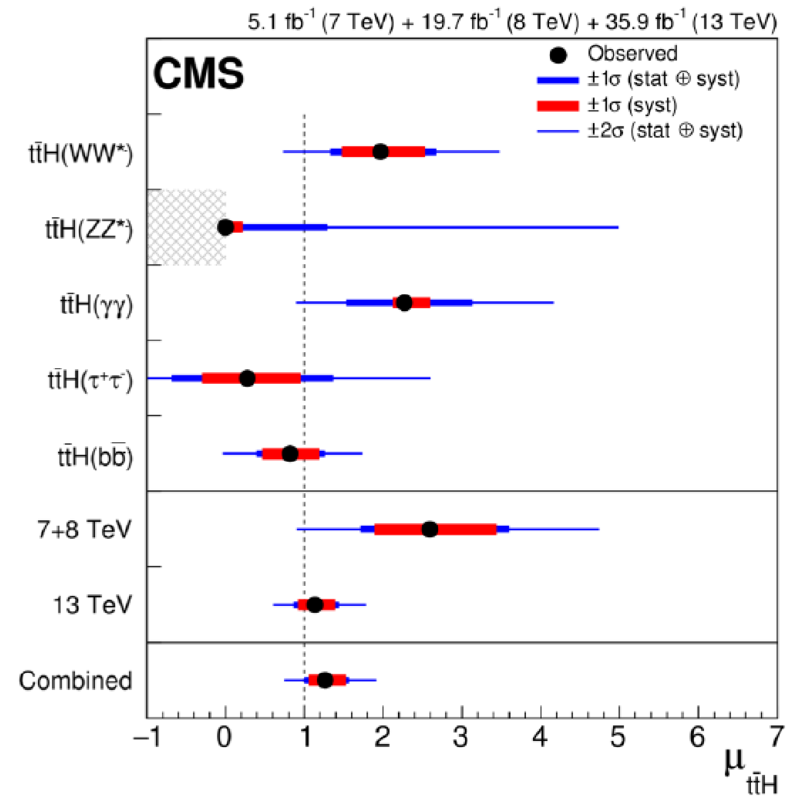
5σ observation of $t\bar{t}H$ from CMS and ATLAS

Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...

Phys. Rev. Lett. 120, 231801 (2018)







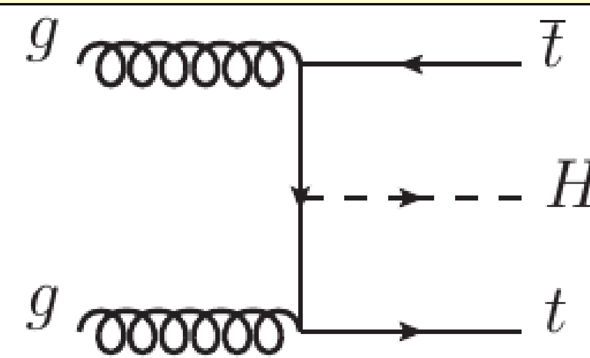
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat.})\,^{+0.17}_{-0.15}(\text{exp.})\,^{+0.14}_{-0.13}(\text{bkg. th.})\,^{+0.15}_{-0.07}(\text{sig. th.})$$

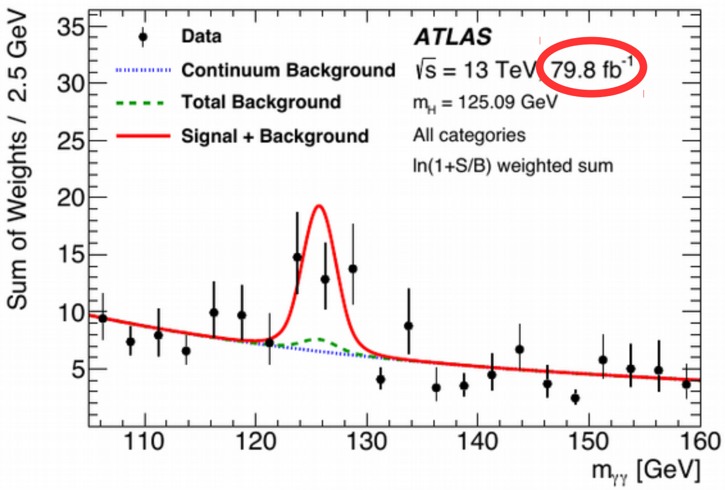
5.2σ (4.2σ exp)

tt̄H observation

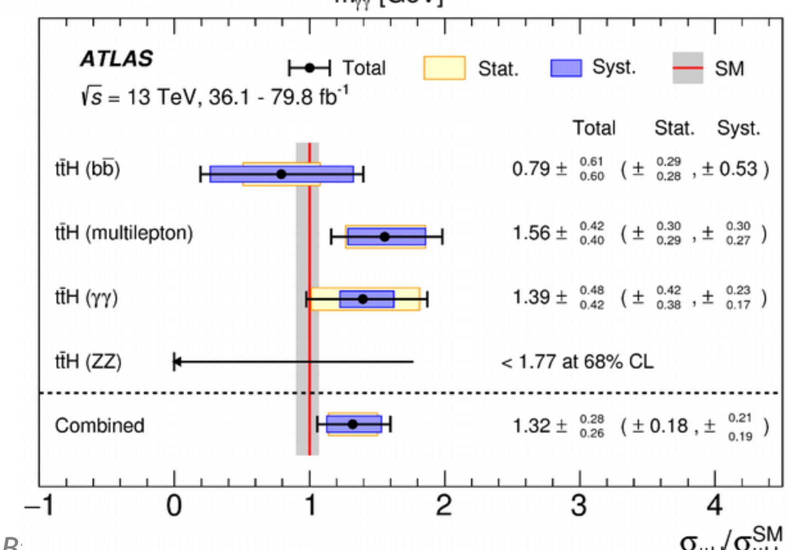
5σ observation of tt̄H from CMS and ATLAS

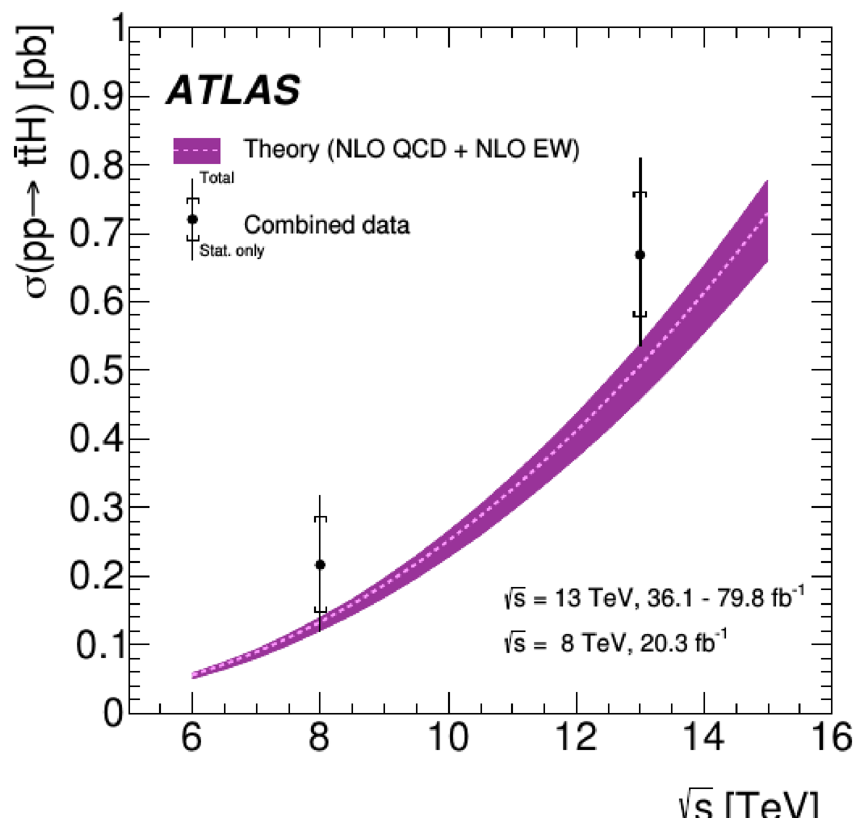
Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...





arXiv:1806.00425





Run1+Run2 6.3σ (5.1σ exp)

H decays to ττ

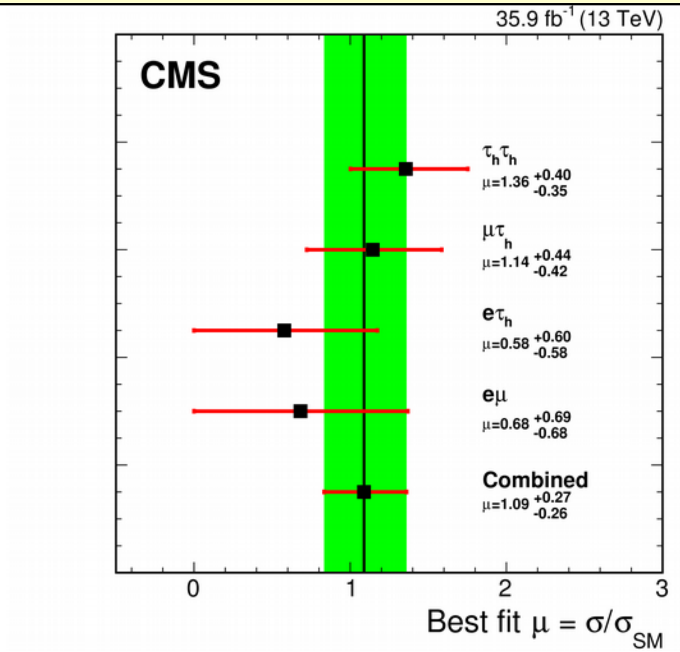
Again complex analyses, systematics have to be under excellent control

A striking success of the Run-1 ATLAS+CMS combination: Observation at 5.5σ (5.0 exp)

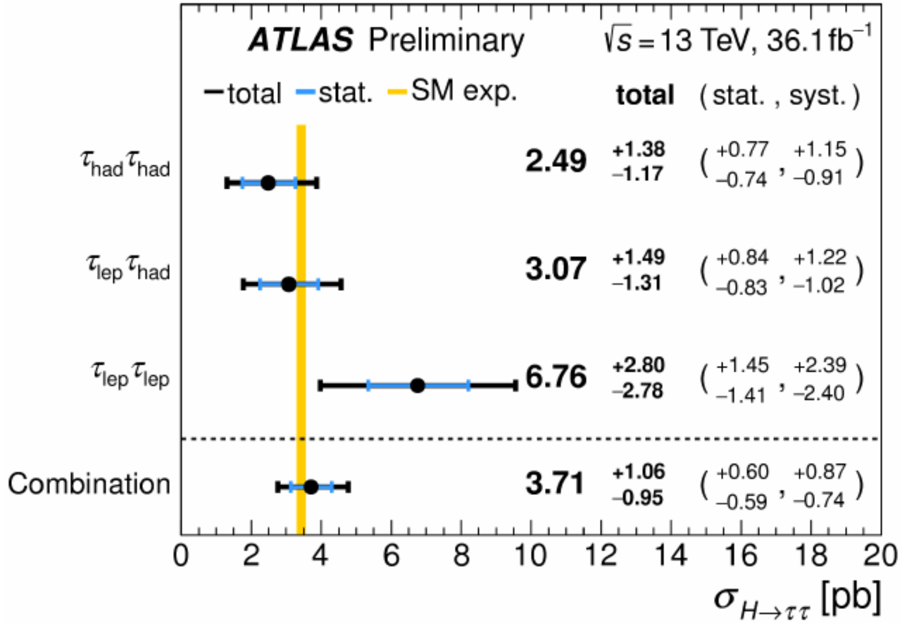
Now complemented by individual CMS and ATLAS 5σ's (Run-1+Run-2 / each 36 fb^{-1})

- CMS 5.9σ (5.9σ)
- ATLAS 6.4σ (5.4σ) new

Time to move on to measurements!



PLB 779 (2018) 283



ATLAS-CONF-2018-021

H decays to $b\bar{b}$

Results with 2016 data mainly released last year

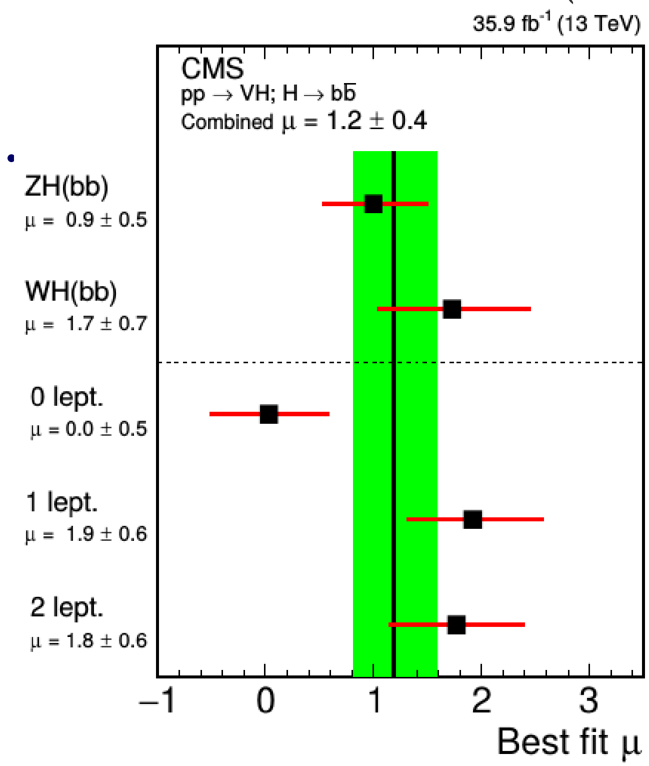
- Difficult analyses with many tough systematic errors, e.g. (W/Z)+HF backgrounds, b-tagging ..

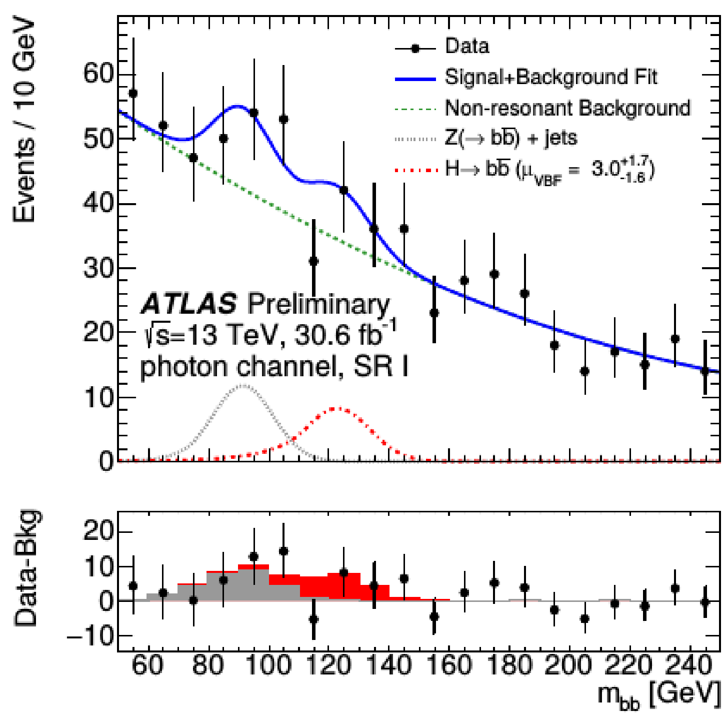
Run-1+Run-2 signal strengths:

$$\mu_{VH}^{CMS} = 1.06^{+0.31}_{-0.29} \qquad \mu_{VH}^{ATLAS} = 0.90^{+0.28}_{-0.26}$$

Both correspond to evidence at 3.6-3.8σ

PLB 780 (2018) 501



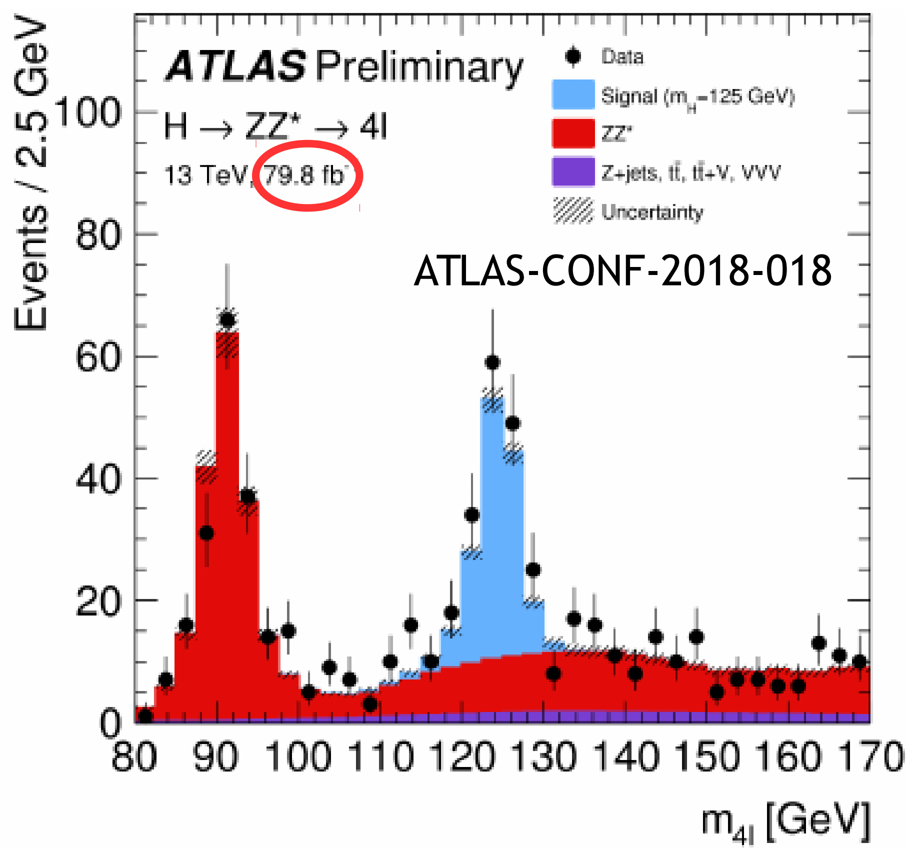


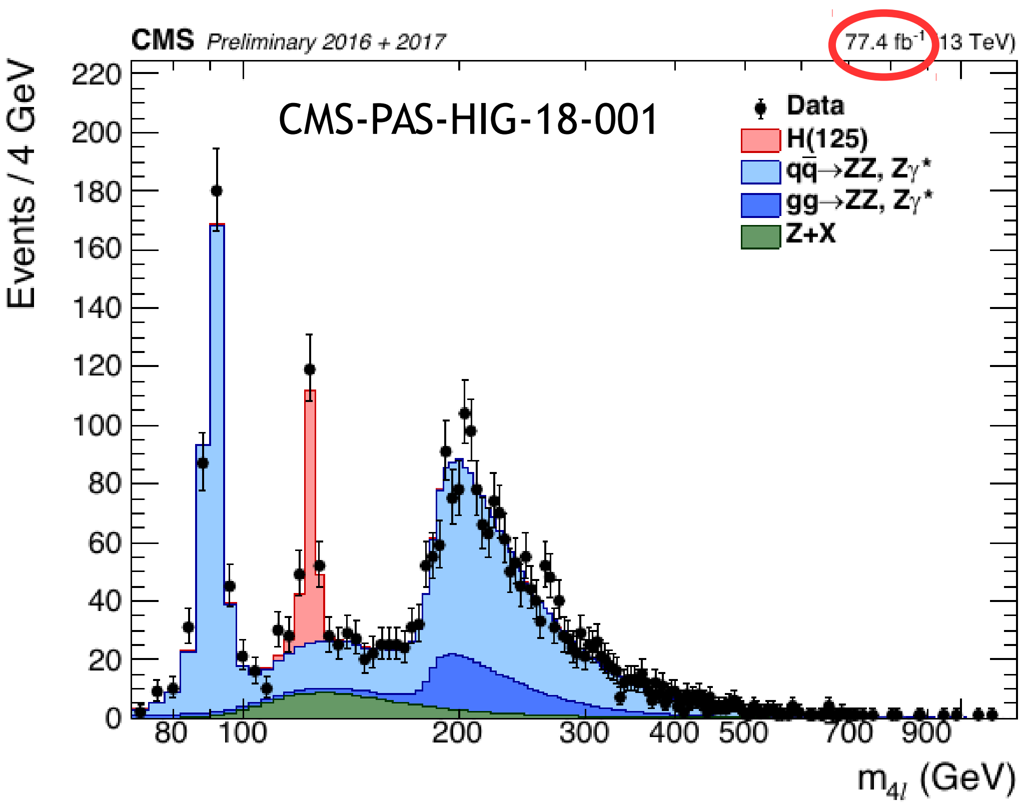
New this week: ATLAS update on H→bb from vector-boson fusion in 13 TeV data

CERN-EP-2018-140

Higgs to bosons – entering precision era

Run-2 analyses with 80 fb^{-1} for the first time – higher precision is coming!

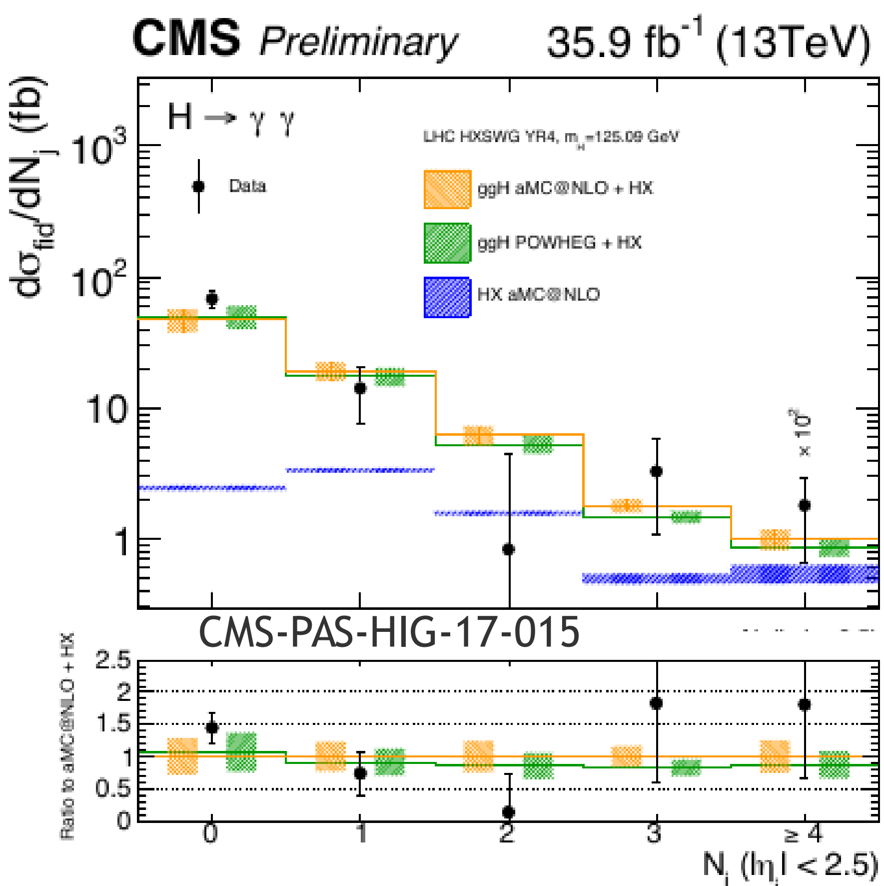




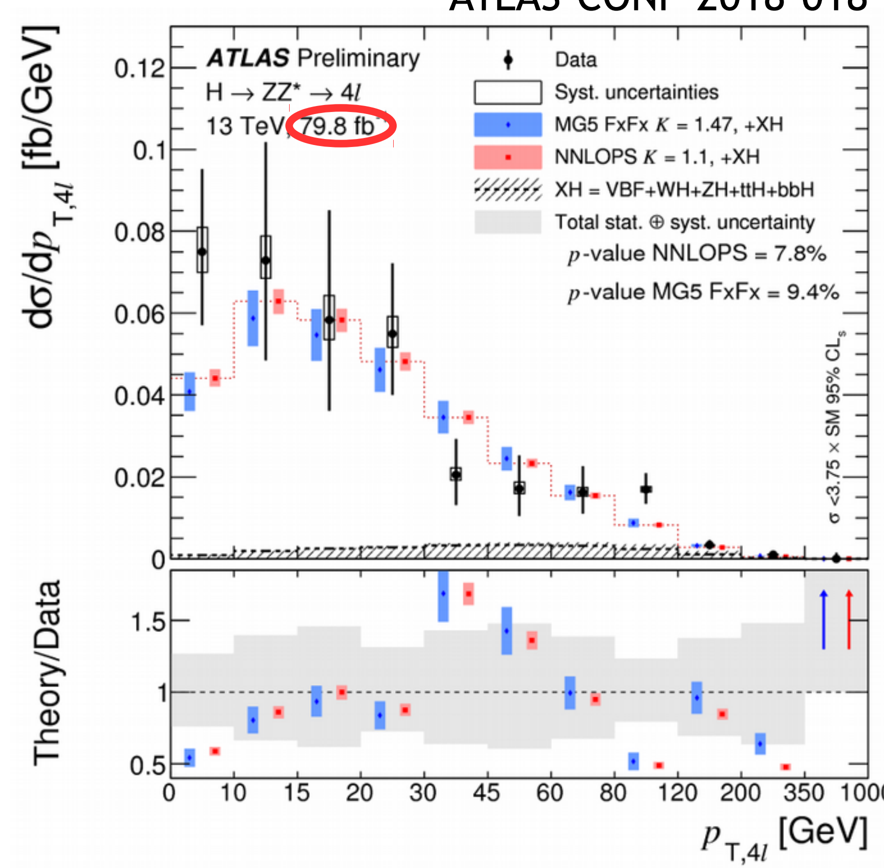
H differential cross-sections

Measurements of fiducial and differential cross-section distributions made already at Run-1 with low statistics

Much physics in $p_{T,H}$, for example



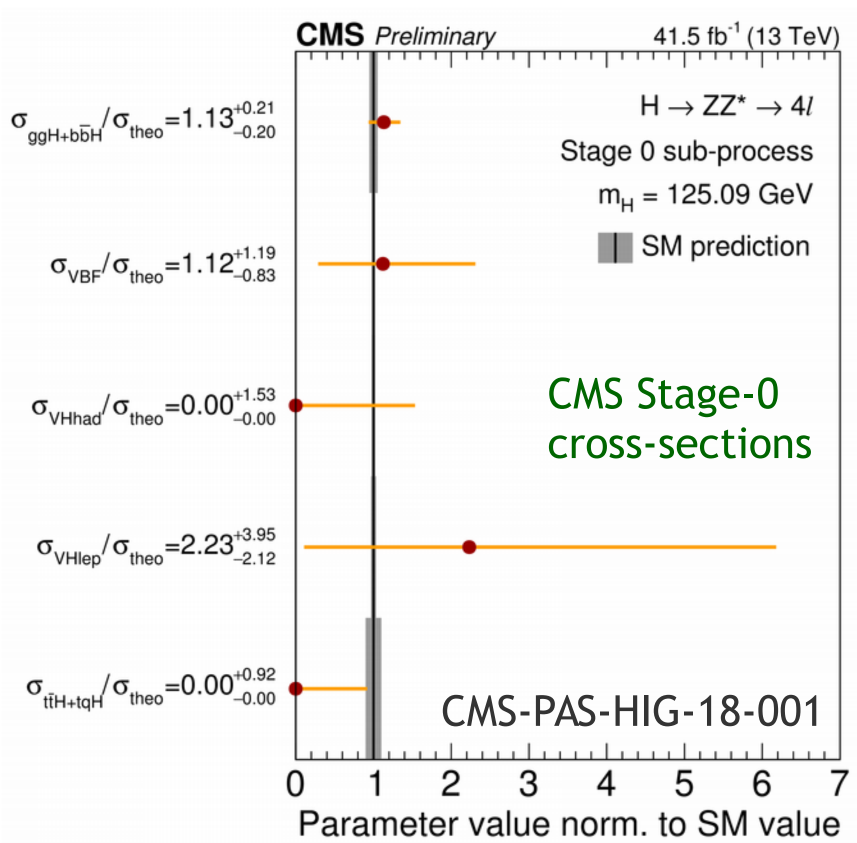
ATLAS-CONF-2018-018

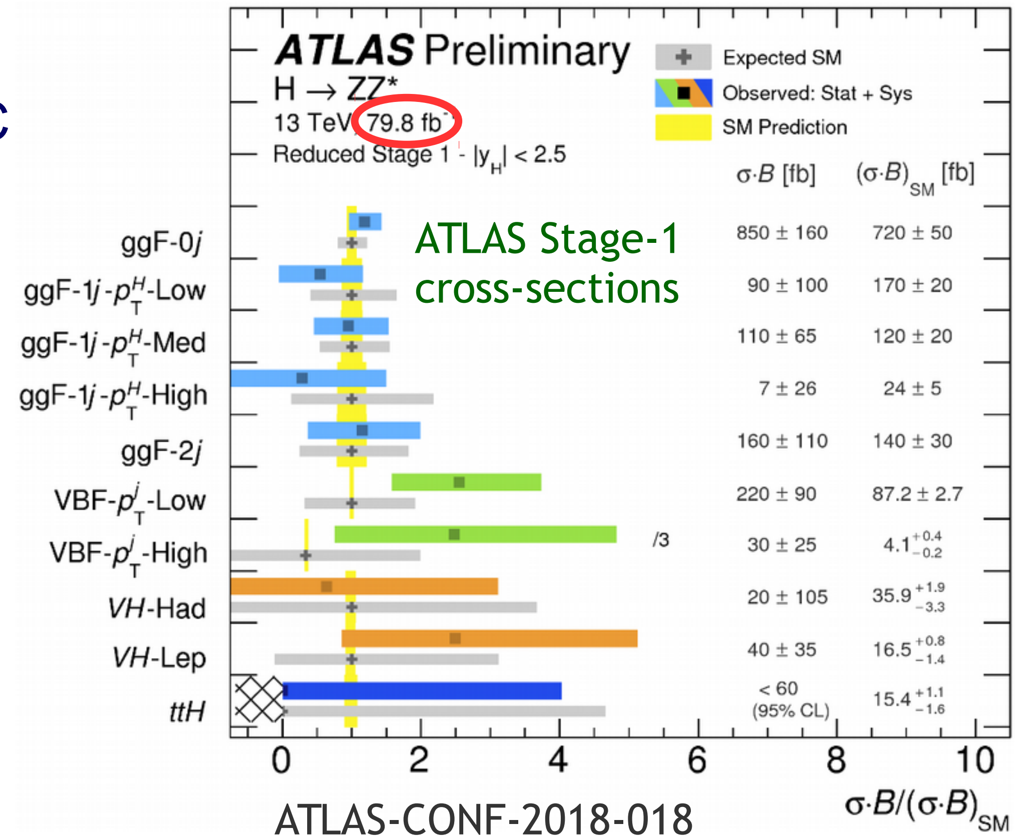


Standardised fiducial cross-sections

Simplified template cross-sections (STXS) defined by common effort in LHC Higgs cross-section group

Finer-grained cross-sections (“Stage-1”) becoming accessible now...

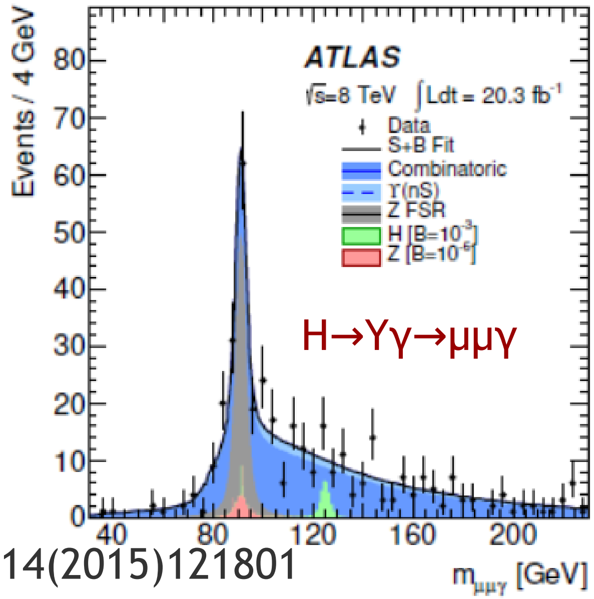




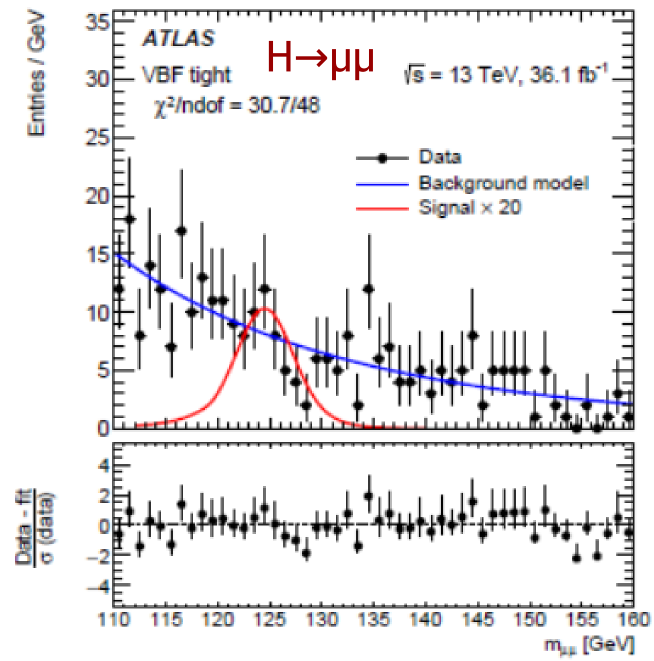
Using these, and/or individual experimental measurements, EFT fits will allow more detailed SM tests – and perhaps provide hints of BSM structure

H: rare decays, more scalars?

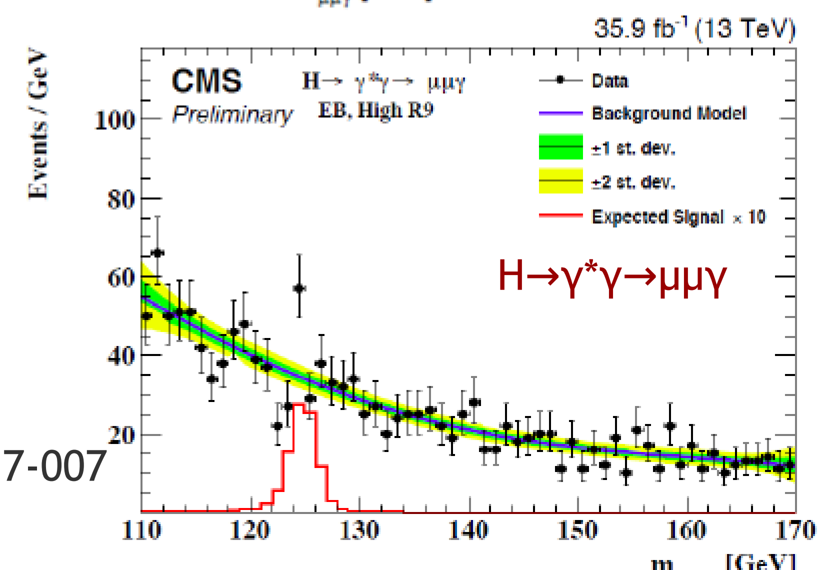
Many results, no surprises yet



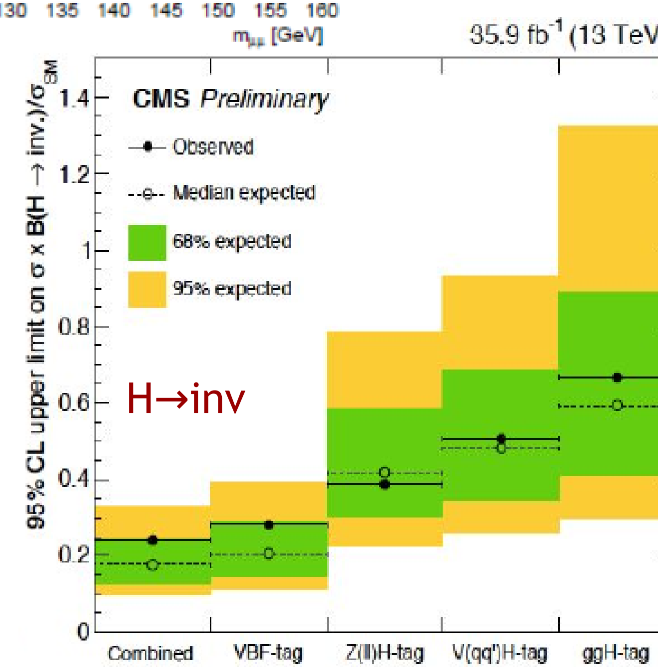
PRL114(2015)121801



PRL119(2017)051802



CMS-PAS-HIG-17-007

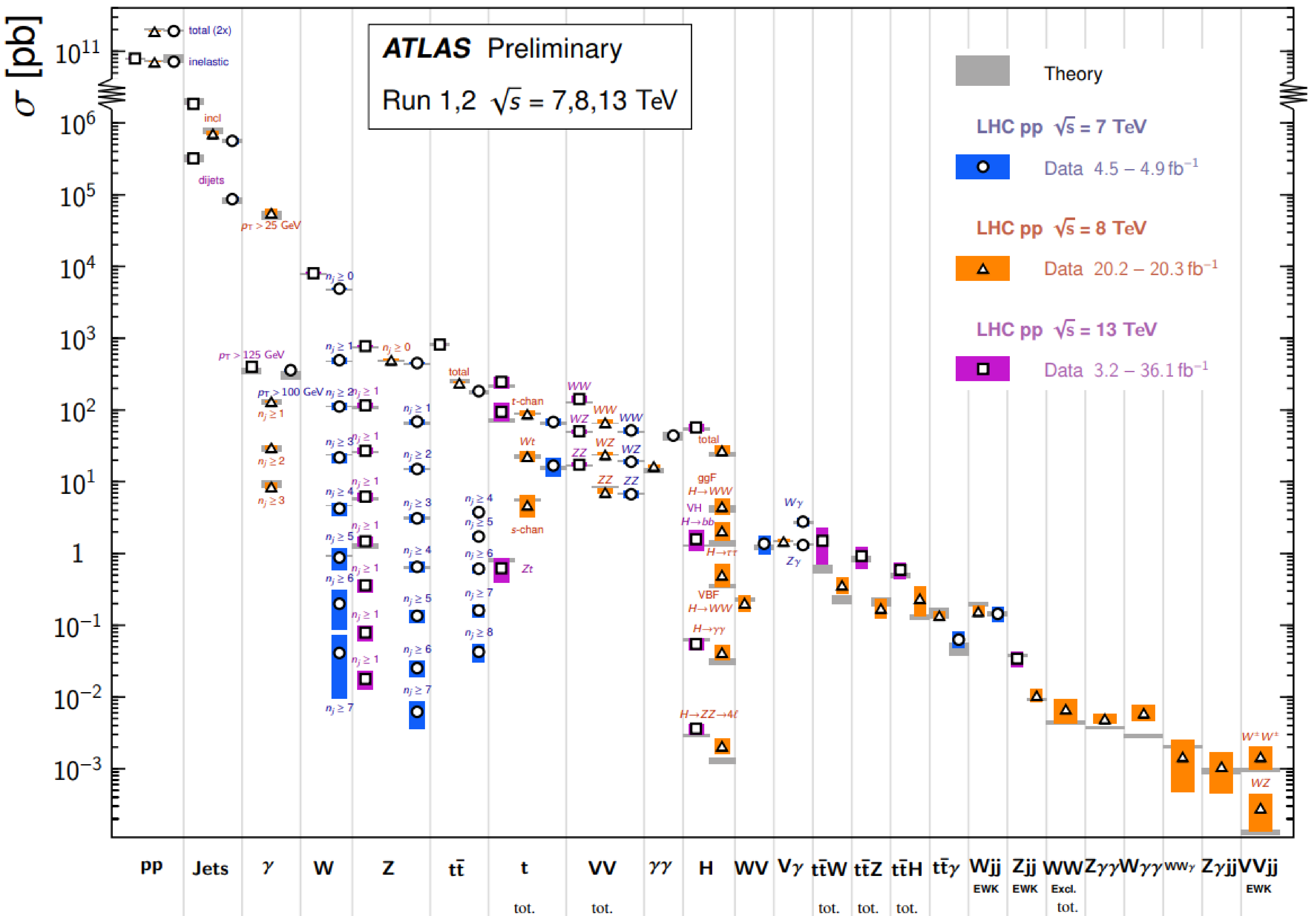


CMS-PAS-HIG-17-023

A superabundance of measurements

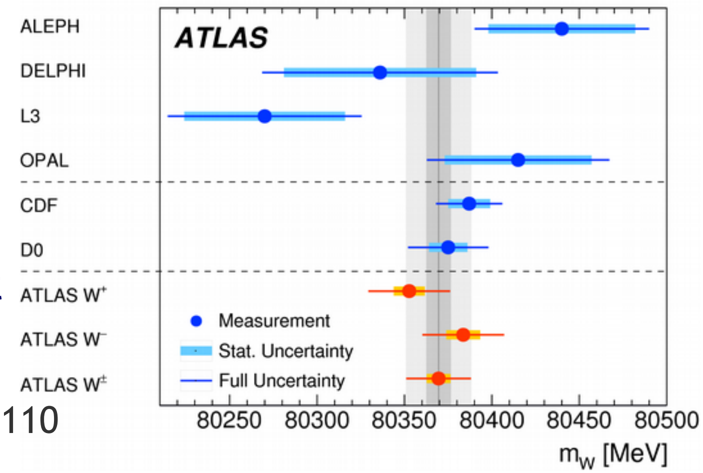
Standard Model Production Cross Section Measurements

Status: March 2018

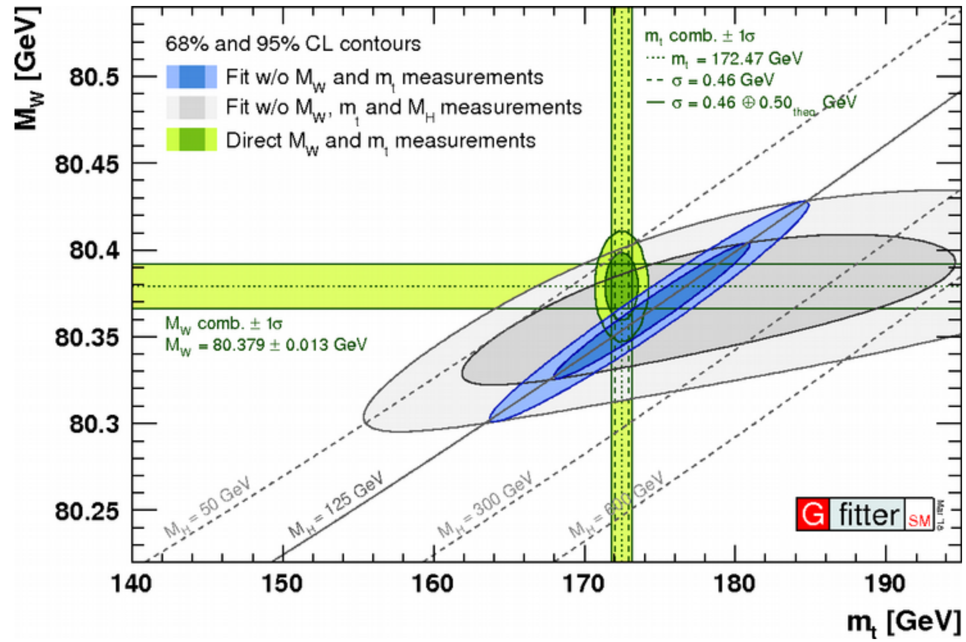


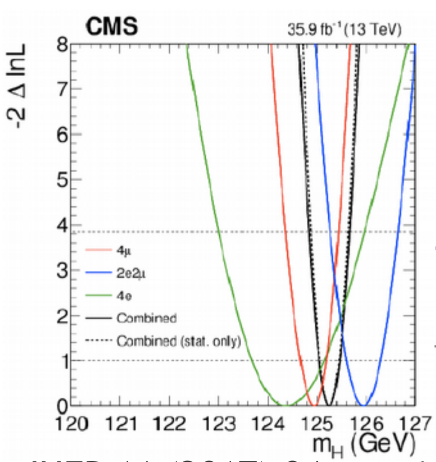
Precision EW mass measurements

±19 MeV m_W from ATLAS
Only LHC measurement to date



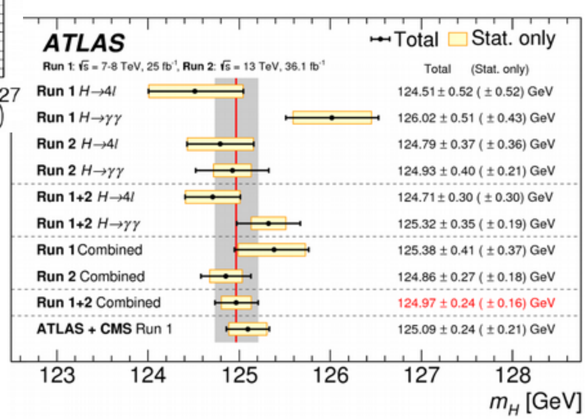
EPJC78 (2018) 110

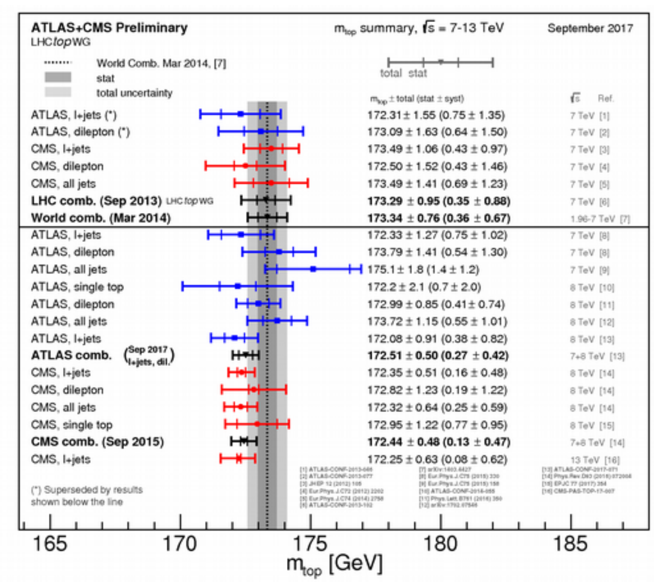




JHEP 11 (2017) 04

m_H / GeV
124.97±0.24 (ATLAS)
125.26±0.21 (CMS 4l@13 TeV)



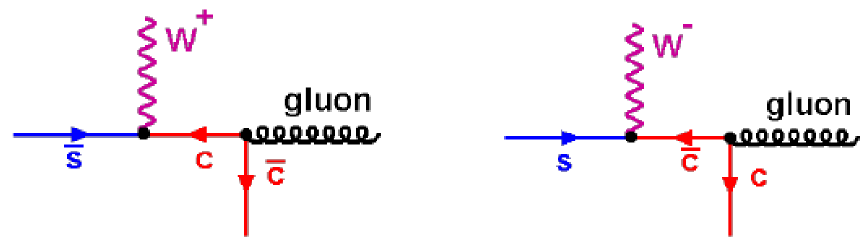


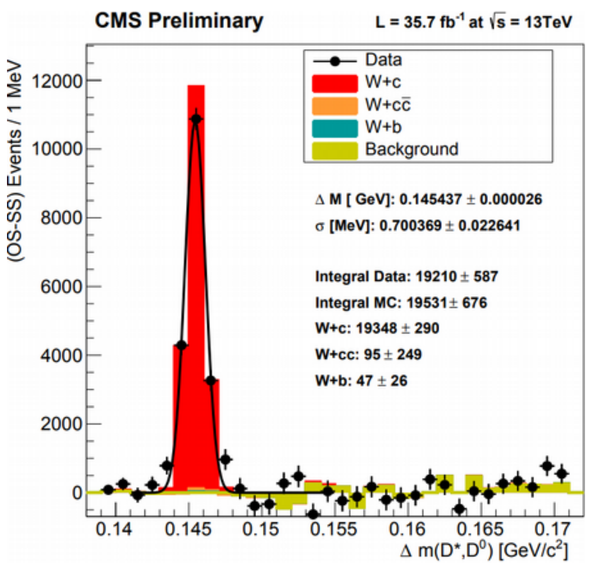
m_{top} error (ATLAS or CMS) from direct reco ~0.5 GeV

arXiv:1806.00242

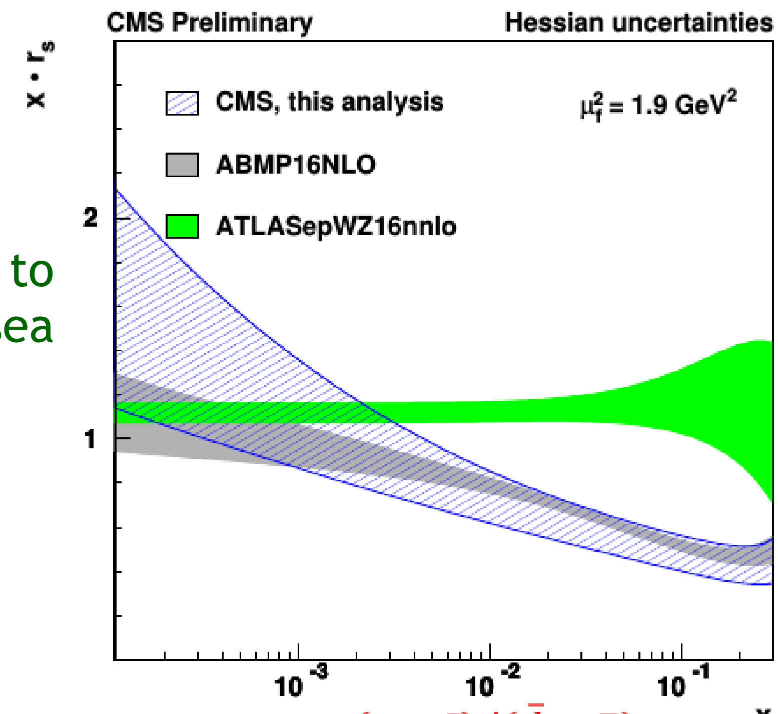
W + charm

New CMS result on W+c at 13 TeV → probes strange quark pdf – employs D* charm tag

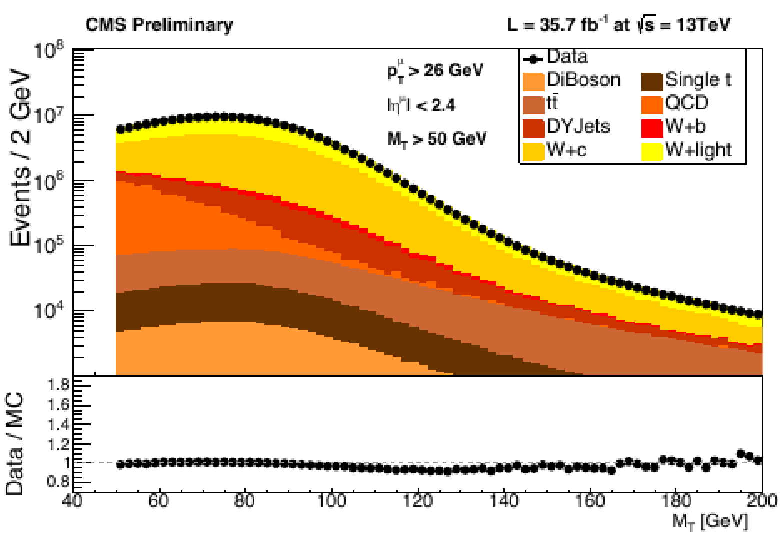




Sensitive to strange sea



$r_s = (s + \bar{s})/(\bar{d} + \bar{u})$

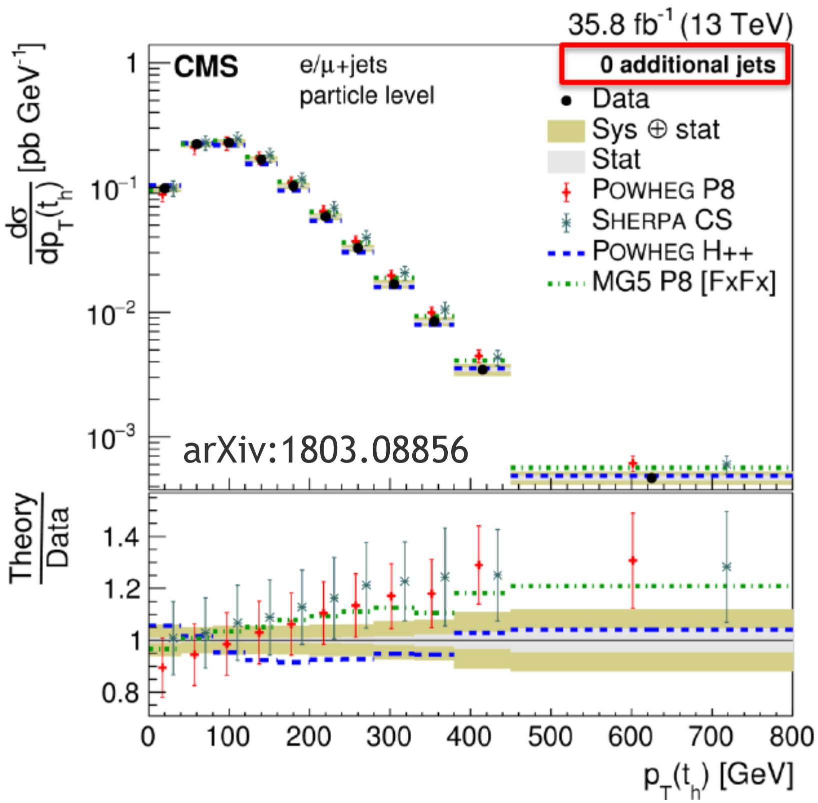


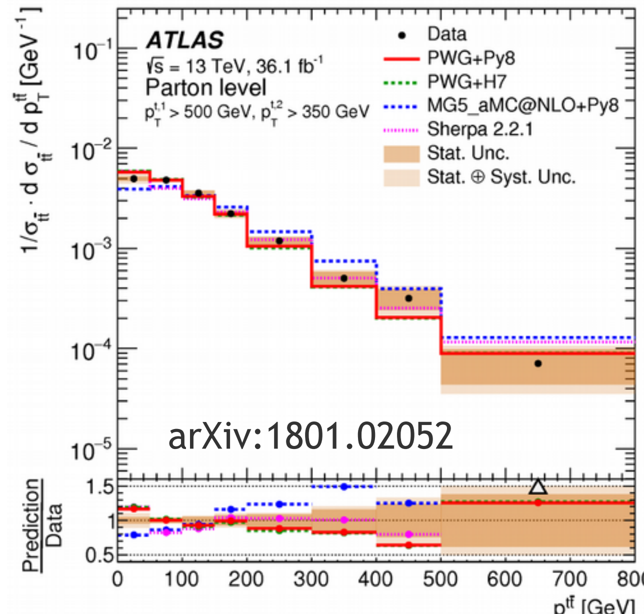
CMS-PAS-SMP-17-014

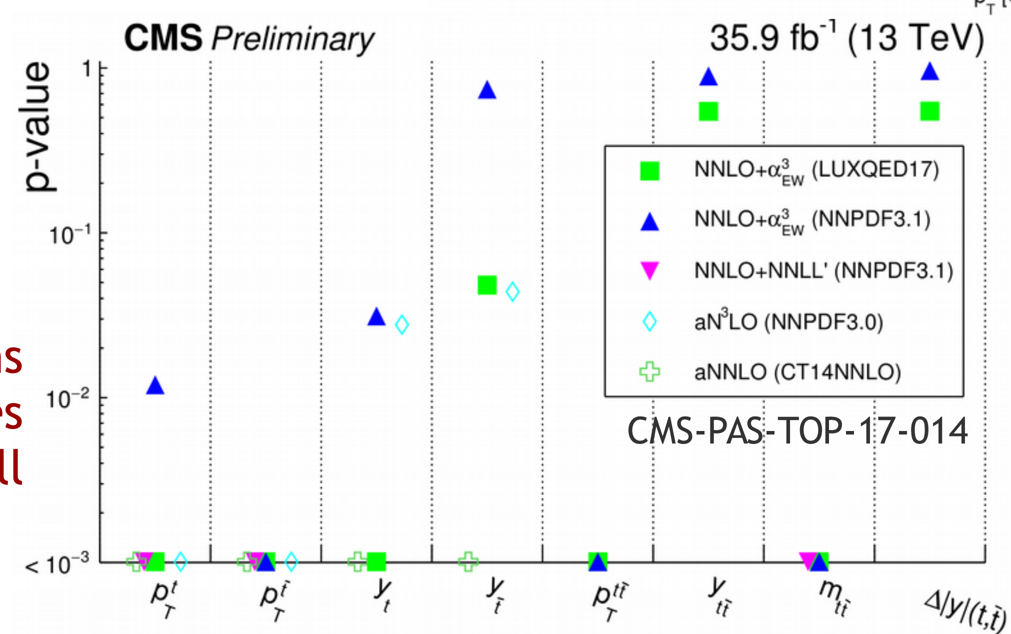
Tension with s-quark pdf from ATLAS - derived from inclusive W/Z production

Top pair production

Long-standing (Run-1) difficulties describing the observed p_T(top) spectrum, although NLO-based MC models much improved for Run-2

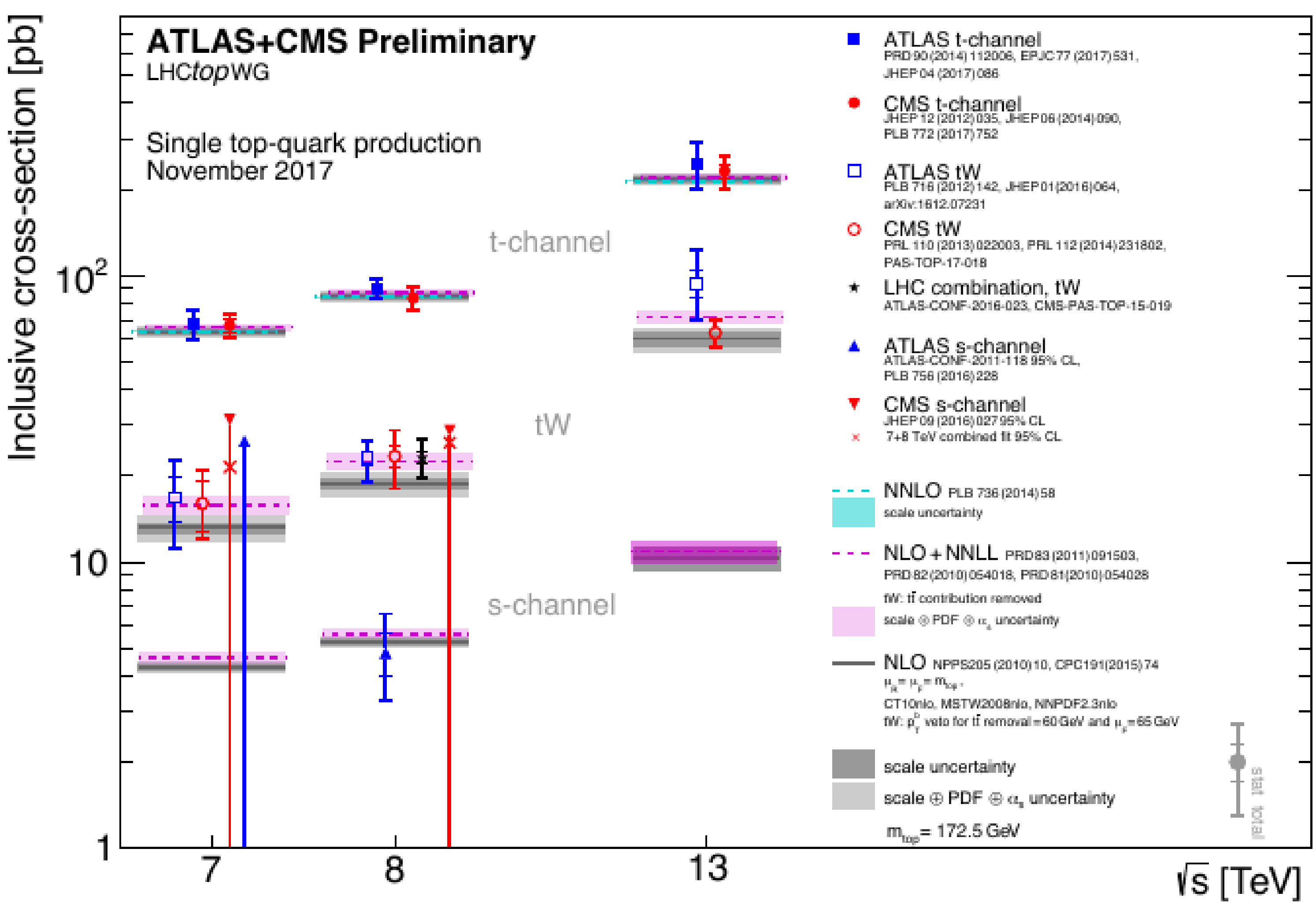


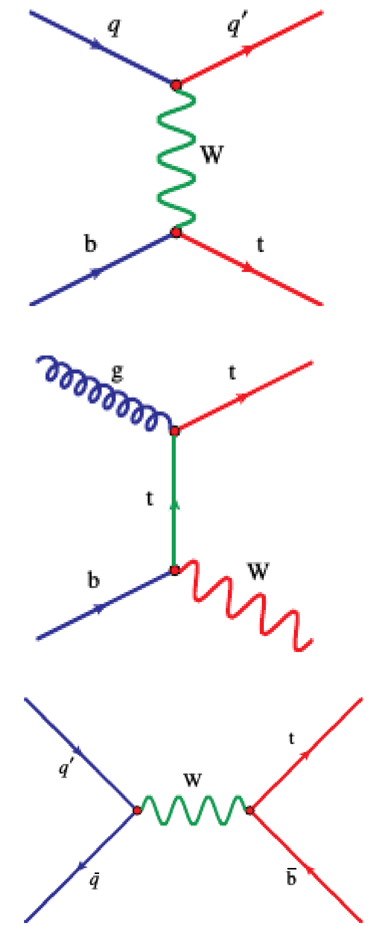




Still none of the predictions describe all of the observables well

Single top



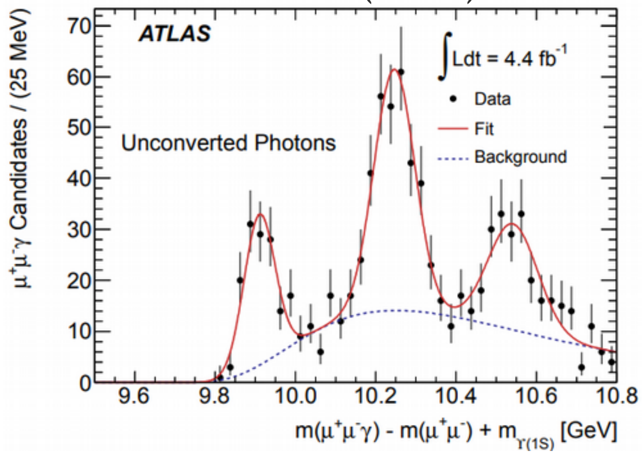


t-channel and Wt production measured differentially
s-channel still unobserved at LHC - observed at Tevatron
Other associated production channels tZq and tγq should be seen soon

Spectroscopy of $\chi_b(3P)$

PRL108 (2012) 152001

$\chi_b(3P)$ was the first new state found at the LHC



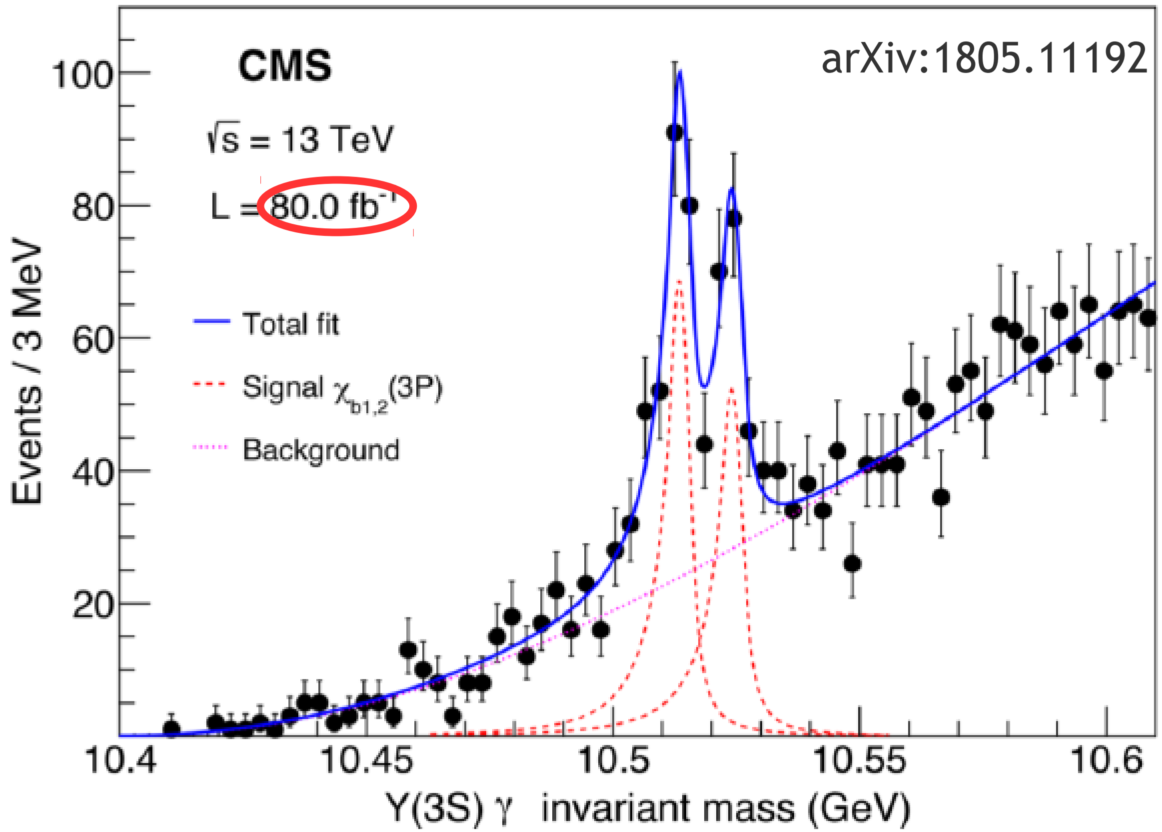
New analysis from CMS, obtains sufficient mass resolution to separate the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$, using

- Conversions
- Low-Δm decays to $\Upsilon(3S)\gamma$

$m(\chi_{b2}(3P)) - m(\chi_{b2}(3P))$ =
10.60 ± 0.64(stat) ± 0.17 (syst) MeV

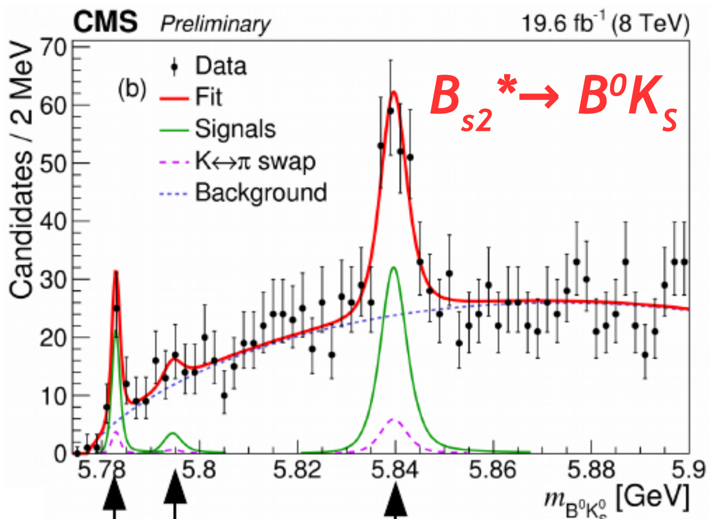
Precision spectroscopy!

arXiv:1805.11192



Heavy hadron spectroscopy

Multiple new states and decay modes being found (or not…) with the huge data samples

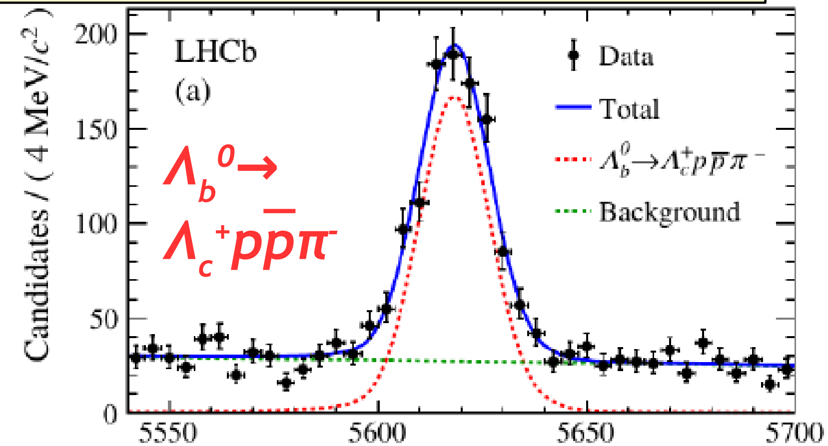


$B_{s2}^* \to B^{*0}K^0_S$

$B_{s1} \to B^{*0}K^0_S$ (3.6-3.9 σ)

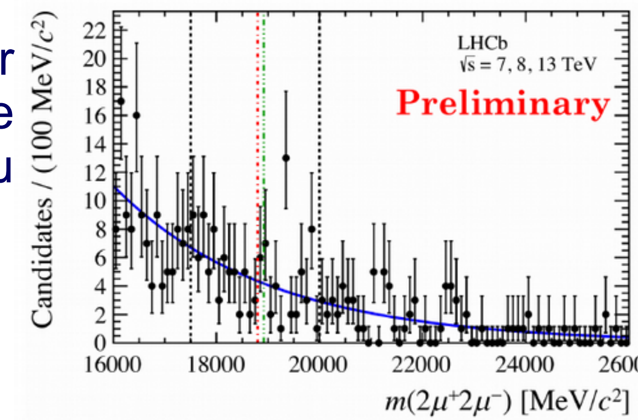
$B_{s2}^* \to B^0K^0_S$ (6.3-7 σ)

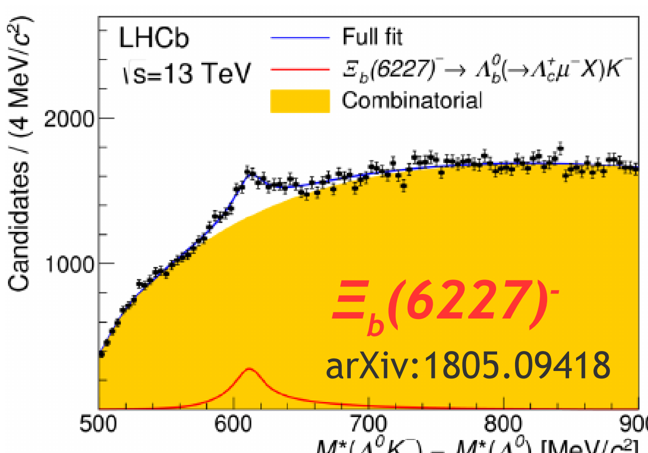
CMS-PAS-BPH-16-003



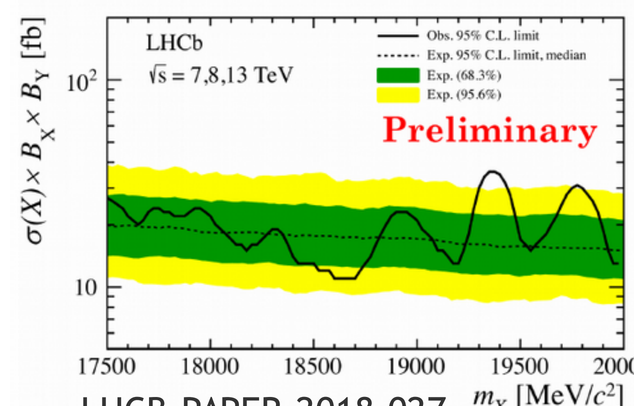
arXiv:1804.09617

No evidence for $b\bar{b}b\bar{b}$-state decaying to Υμμ





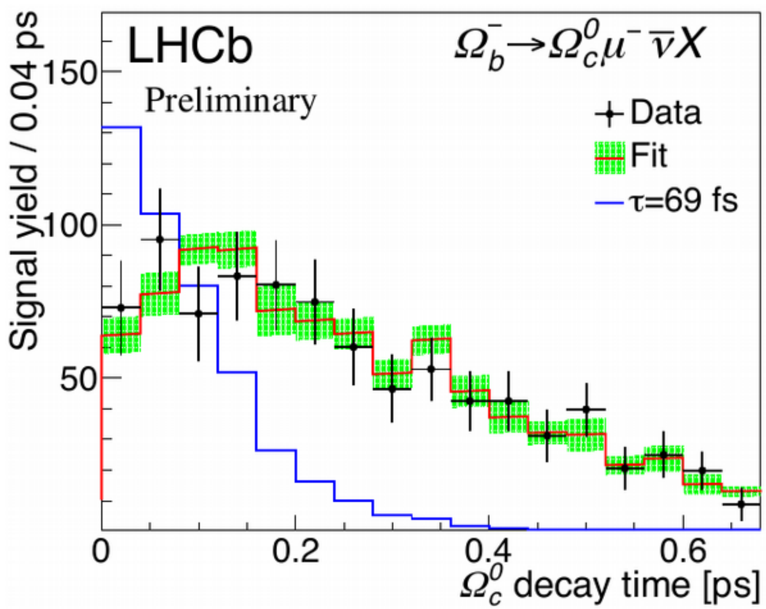
arXiv:1805.09418

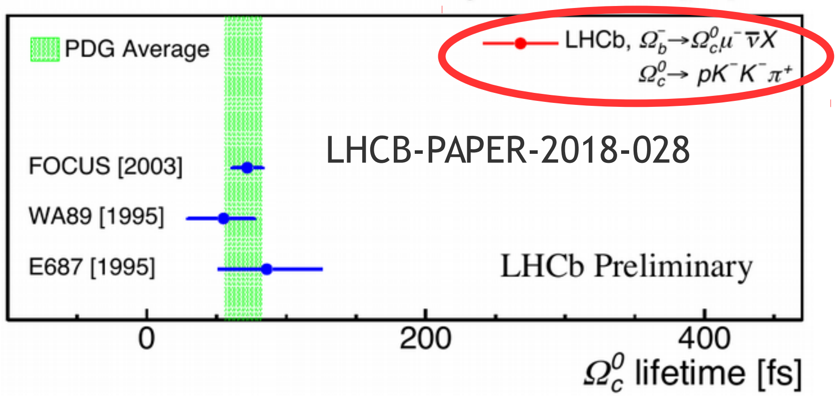


LHCB-PAPER-2018-027

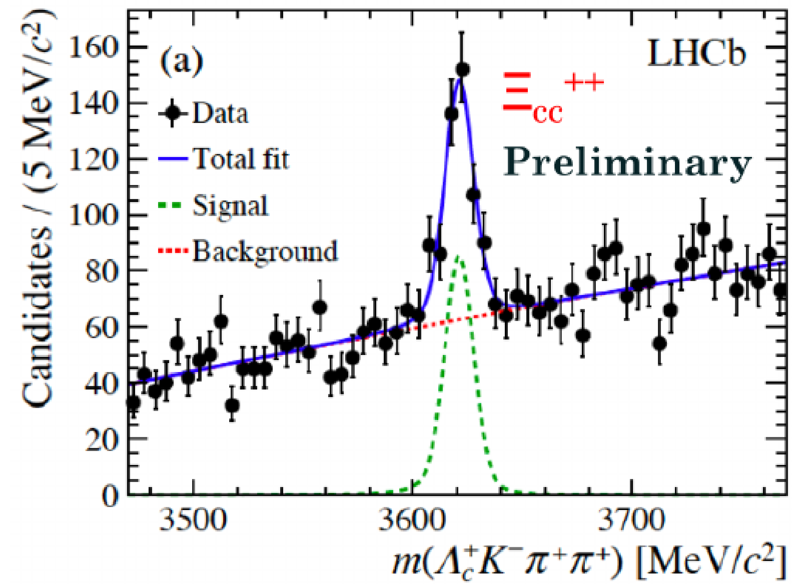
Heavy hadron lifetimes

New lifetime measurements, with puzzles





LHCb Ω_c lifetime measurement much higher than measured in previous experiments



First measurement of Ξ_{cc}^{++} lifetime

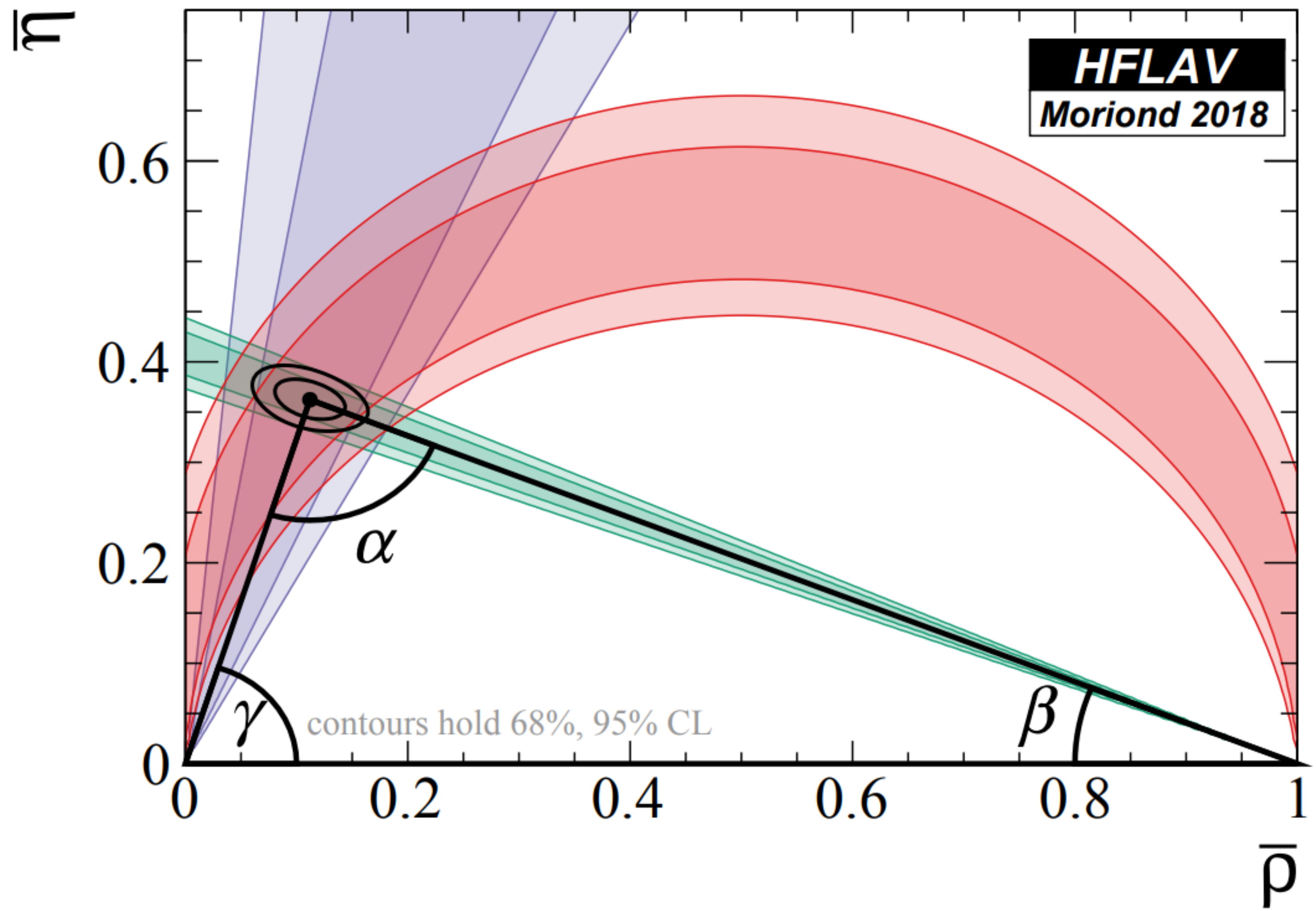
$$\tau(\Xi_{cc}^{++}) = 0.256 \pm^{0.024}_{0.022} \pm 0.014 \text{ ps}$$

arXiv:1806.02744

Measuring CKM γ with LHCb

Precision measurement of CKM angle γ a key LHCb goal, using B→DK decays, and requiring excellent understanding of D decay kinematics

Status of unitarity triangle angles as of Moriond-time



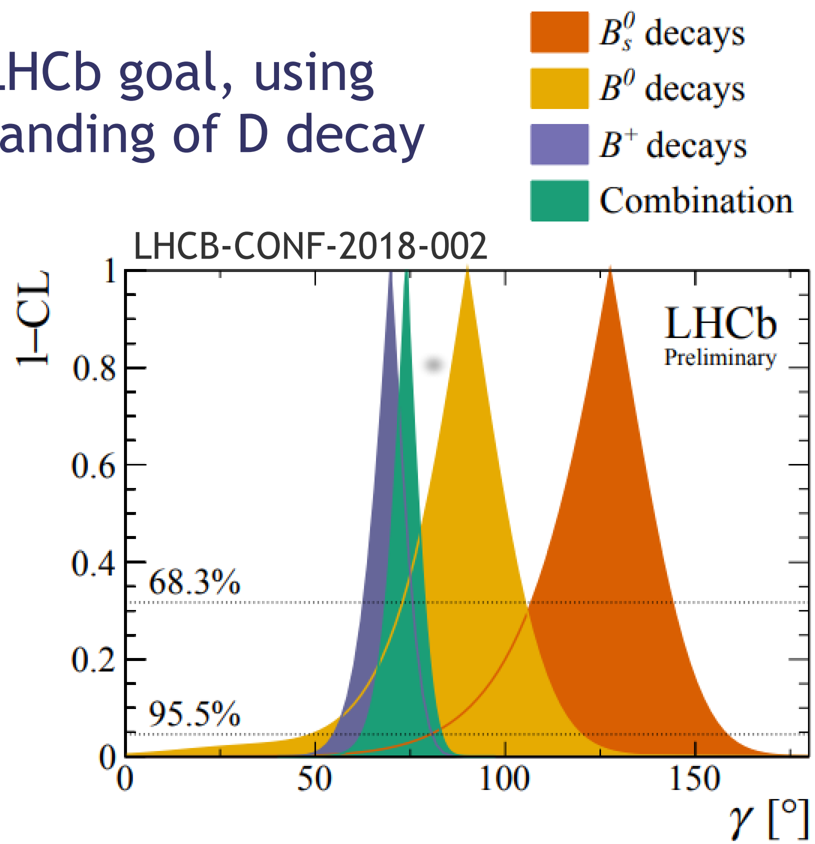
HFLAV average then:

$$\gamma = \left(73.5^{+4.2}_{-5.1}\right)^{\circ}$$

(including LHCb!)

Measuring CKM γ with LHCb

Precision measurement of CKM angle γ a key LHCb goal, using B→DK decays, and requiring excellent understanding of D decay kinematics



Many LHCb measurements, 3 new:

B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K_S^0K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV.

LHCb combination

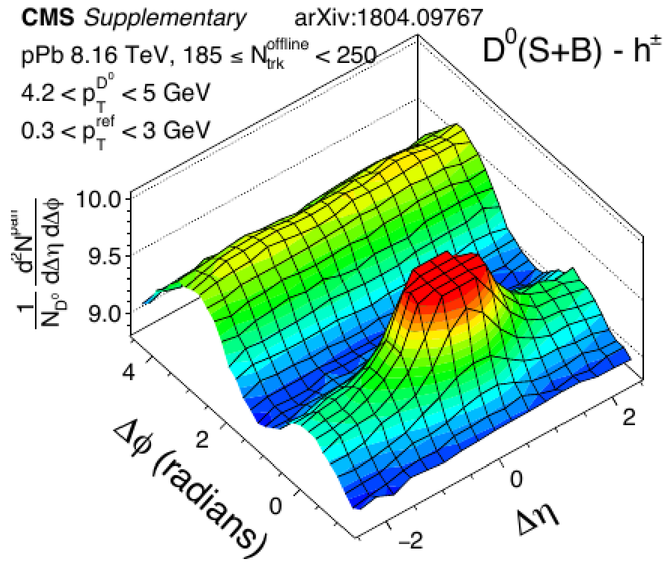
$$\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$$

Most precise single-experiment average
Precision now close to that on α

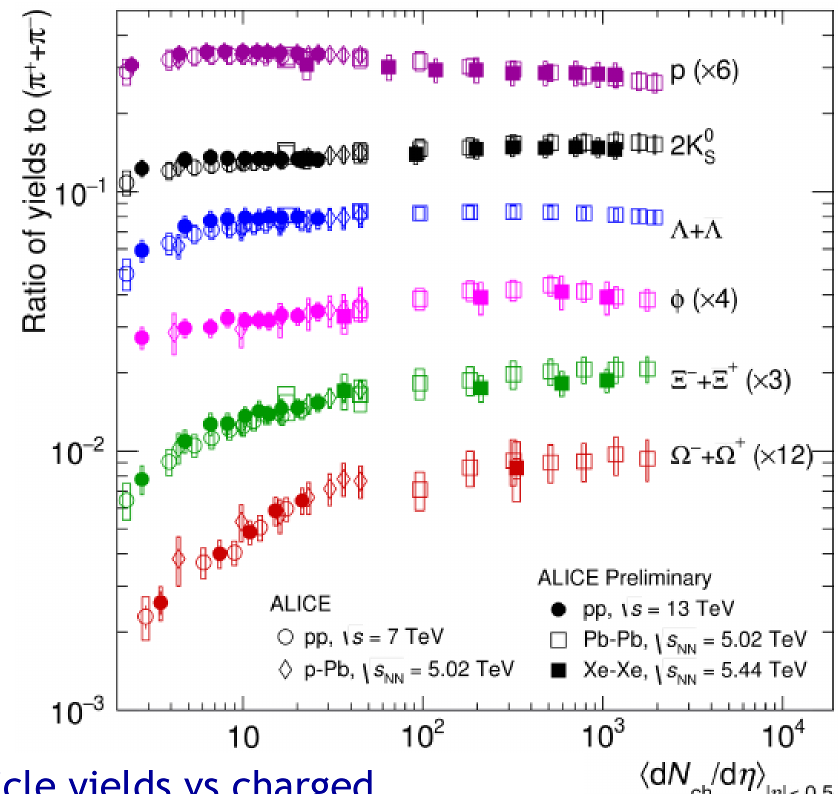
Heavy ions: collectivity and system size

Collective behaviour in large systems (e.g. central Pb+Pb) dominated by hydrodynamic flow, well established

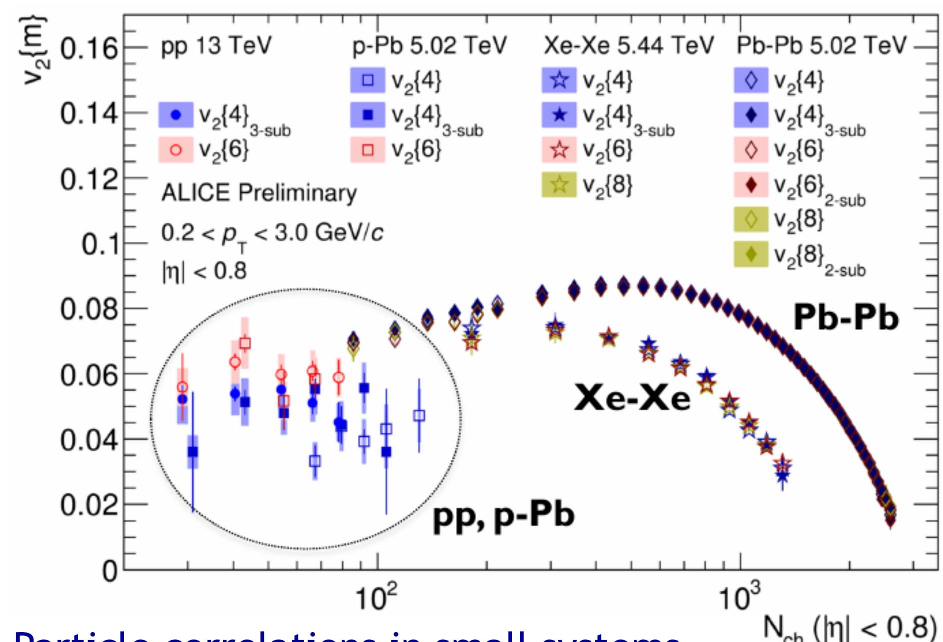
Many results available on correlations in different systems (pp, pPb, XeXe, PbPb), different probe particles → improve understanding of collective dynamics in smaller systems



Near-side ridge with D mesons in pPb



Particle yields vs charged multiplicity – system independent?

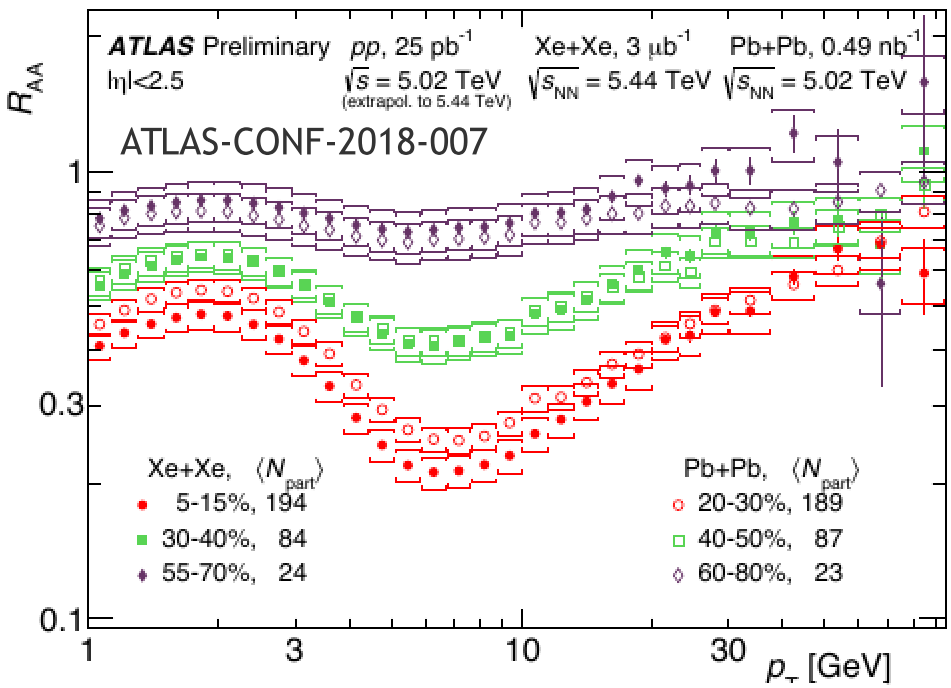


Particle correlations in small systems, apparently not purely from flow

Heavy ions: XeXe "microsample"

Six hours of data-taking in Oct 2017

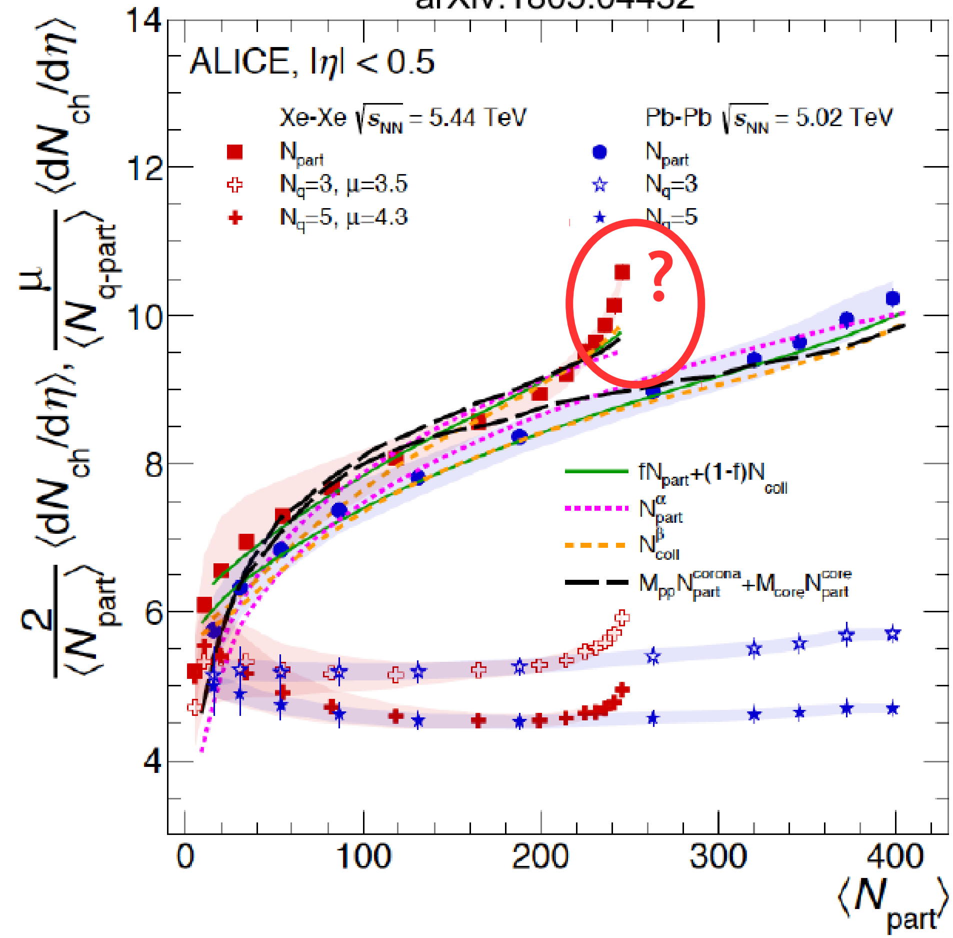
Even tiny amounts of data can provide new insights and pose new questions



R_{AA} = (yield in AA)/(yield in pp)

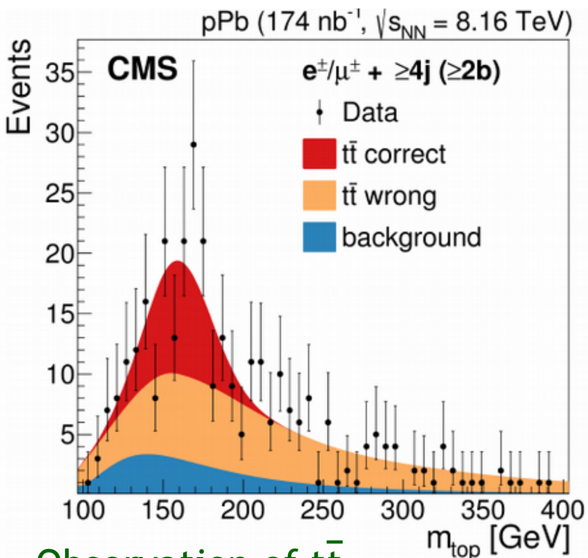
Similar p_T dependence in XeXe and PbPb collisions

arXiv:1805.04432



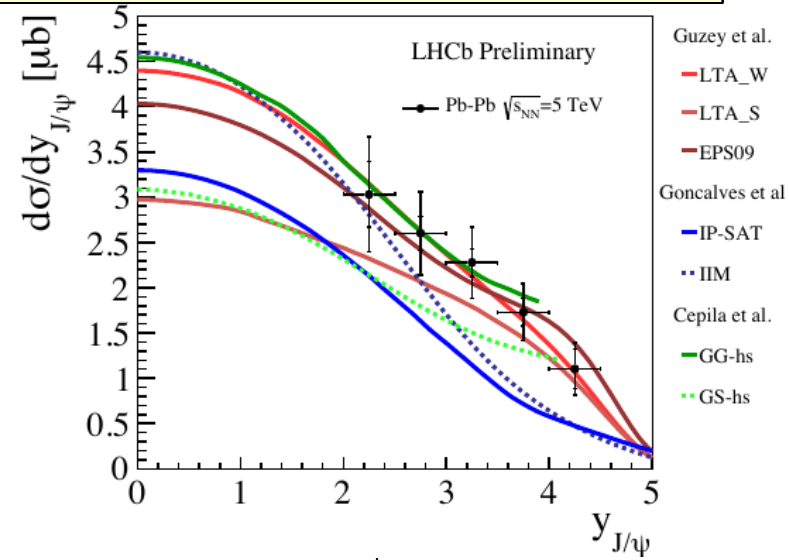
Sharp increase in multiplicity at high centrality in XeXe – not seen in PbPb

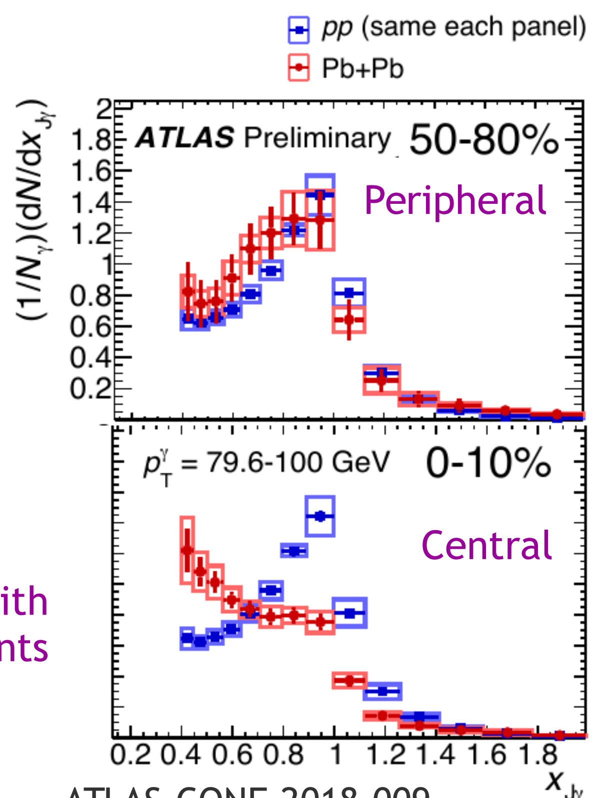
Heavy ions: hard probes



Observation of $t\bar{t}$ production in pPb collisions
PRL 119 (2017) 242001

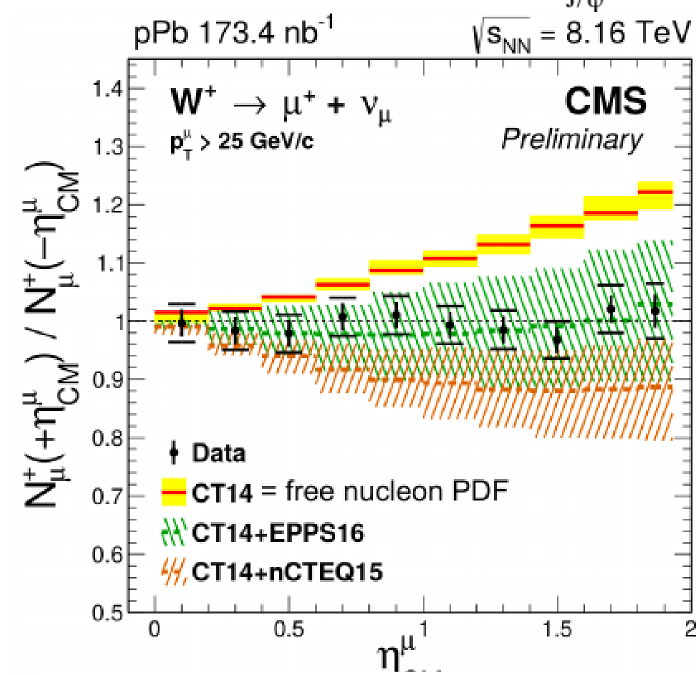
Fwd J/ψ production may be sensitive to nuclear gluon pdf at low-x





Jet quenching probed with photon+jet events

ATLAS-CONF-2018-009



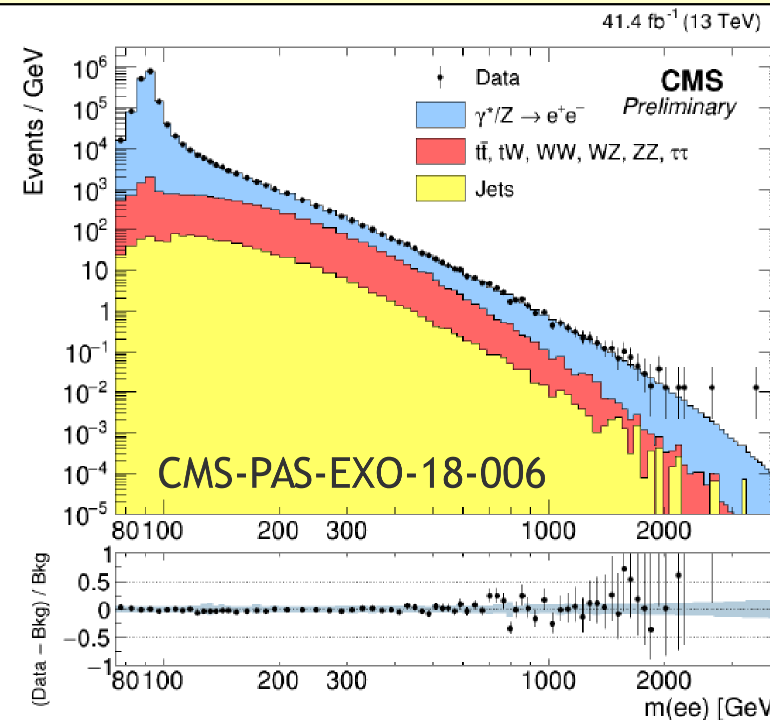
W production sensitive to nuclear effects on nucleon PDFs

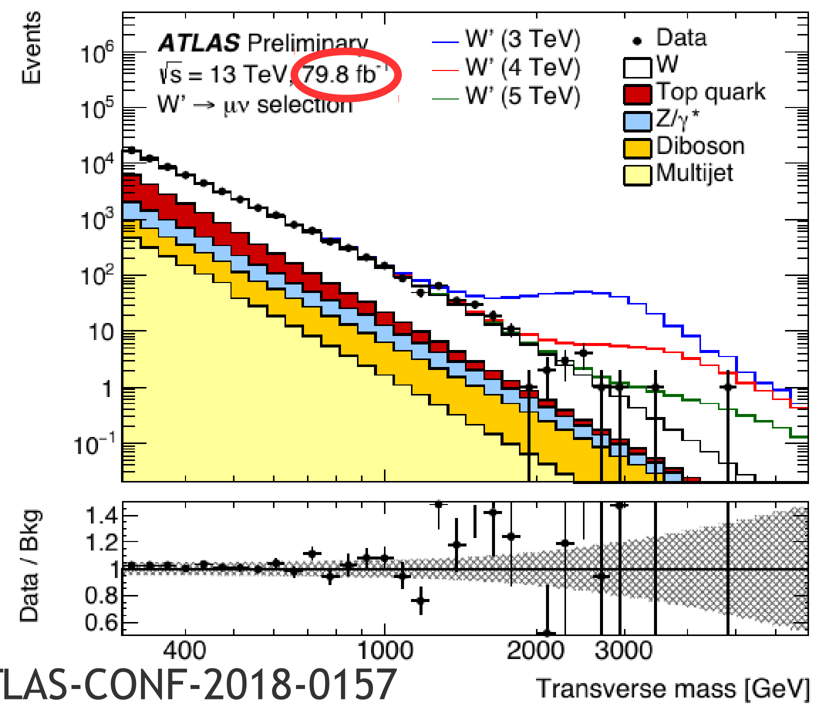
Searches continue

Searching fast…

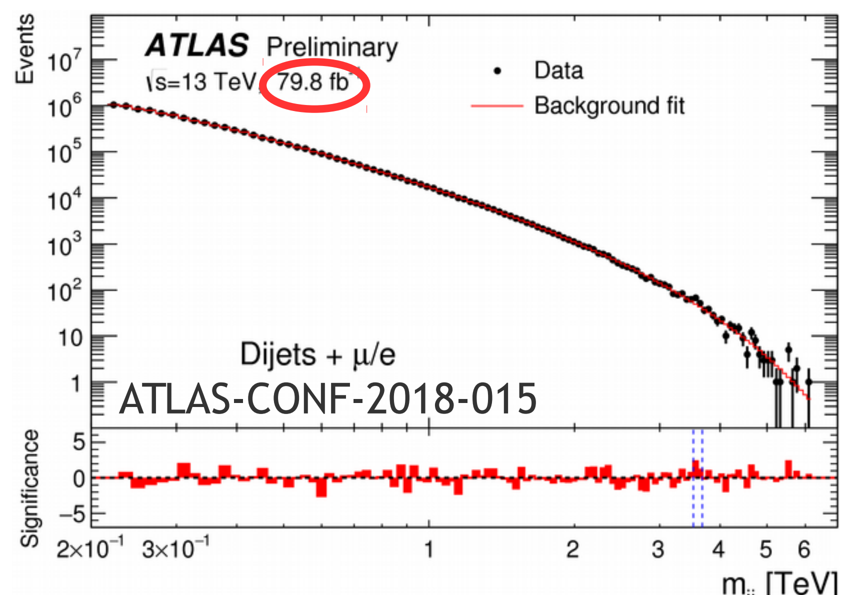
Several ATLAS, CMS searches already include 2017 data, in simpler topologies

- Z'→ee (CMS)
- W'→ℓν (ATLAS)
- VV→JJ resonances (ATLAS)
- Dijet resonances with a ℓ (ATLAS)
- Type-III seesaw heavy ℓ (ATLAS)
- L_μ-L_τ light boson in 4μ final state (CMS)





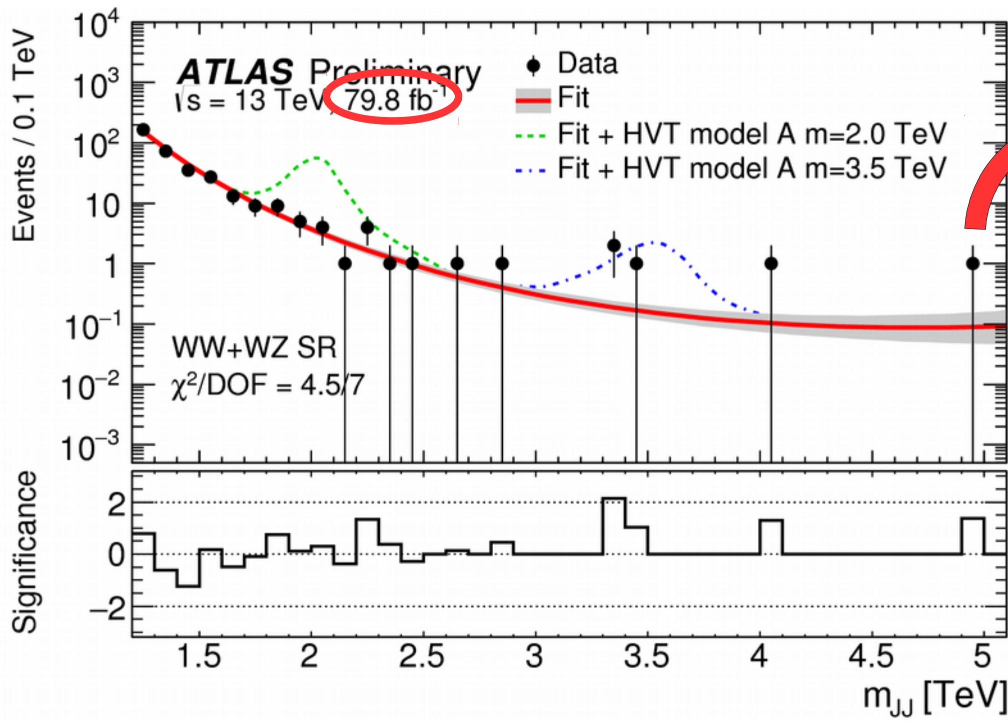
ATLAS-CONF-2018-0157

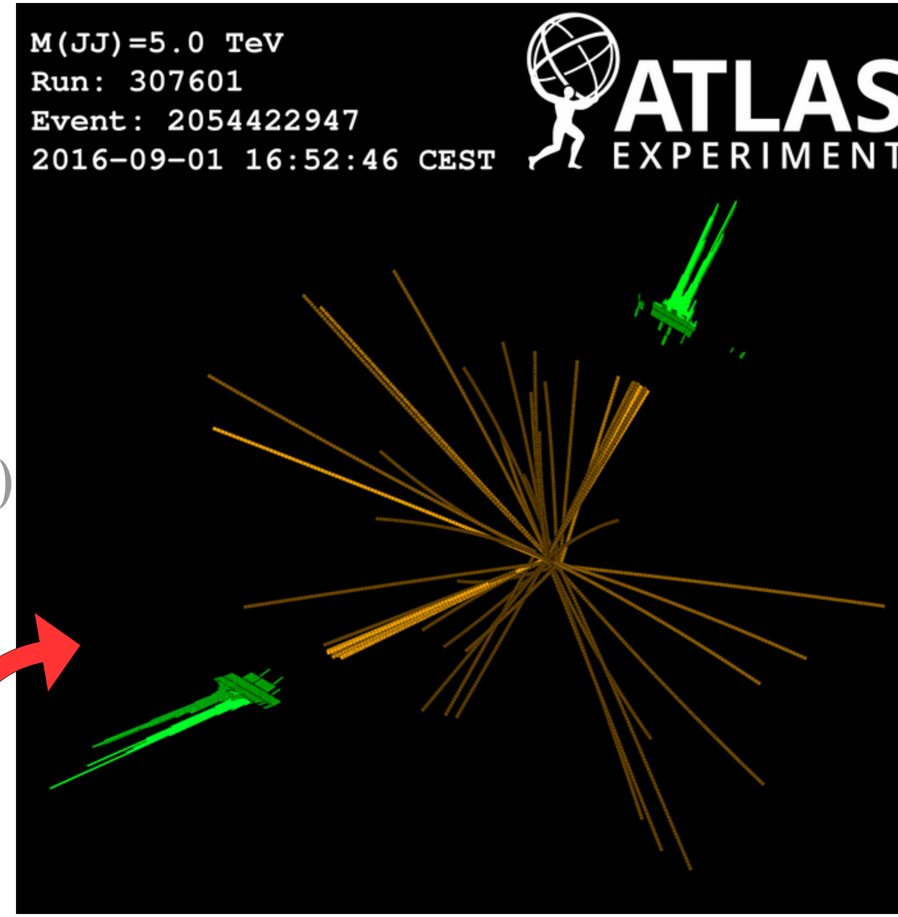


Searching fast...

Several ATLAS, CMS searches already include 2017 data, in simpler topologies

- Z'→ee (CMS)
- W'→ℓν (ATLAS)
- VV→JJ resonances (ATLAS)
- Dijet resonances with a ℓ (ATLAS)
- Type-III seesaw heavy ℓ (ATLAS)
- L_μ-L_τ light boson in 4μ final state (CMS)





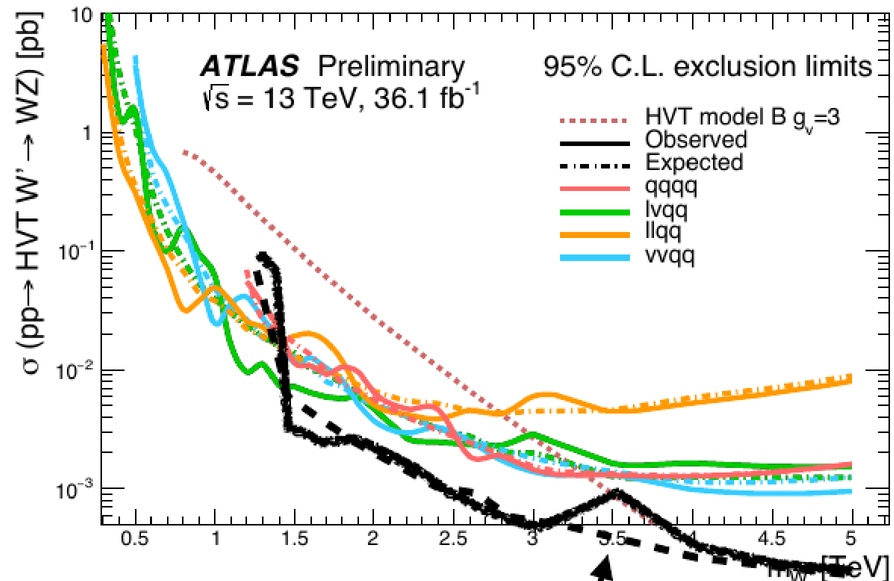
Striking visual impact of the power of the detectors

Searching fast...

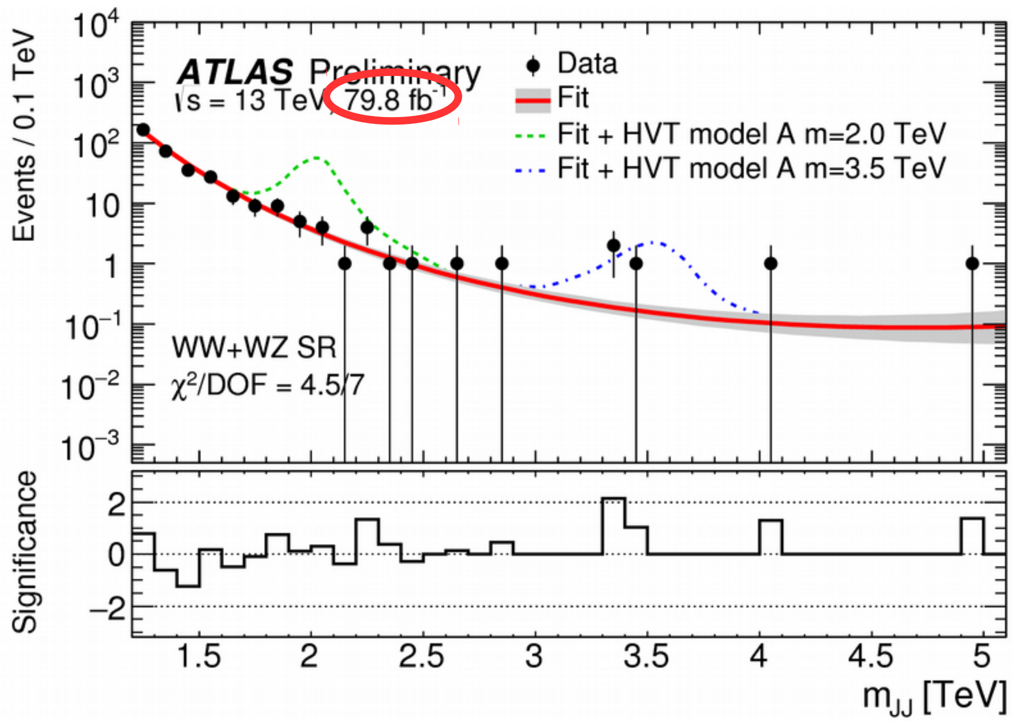
Several ATLAS, CMS searches already include 2017 data, in simpler topologies

- Z'→ee (CMS)
- W'→ℓν (ATLAS)
- **VV→JJ resonances (ATLAS)**
- Dijet resonances with a ℓ (ATLAS)
- Type-III seesaw heavy ℓ (ATLAS)
- L_μ-L_τ light boson in 4μ final state (CMS)

W'



new 80 fb⁻¹ result



Roman Kogler

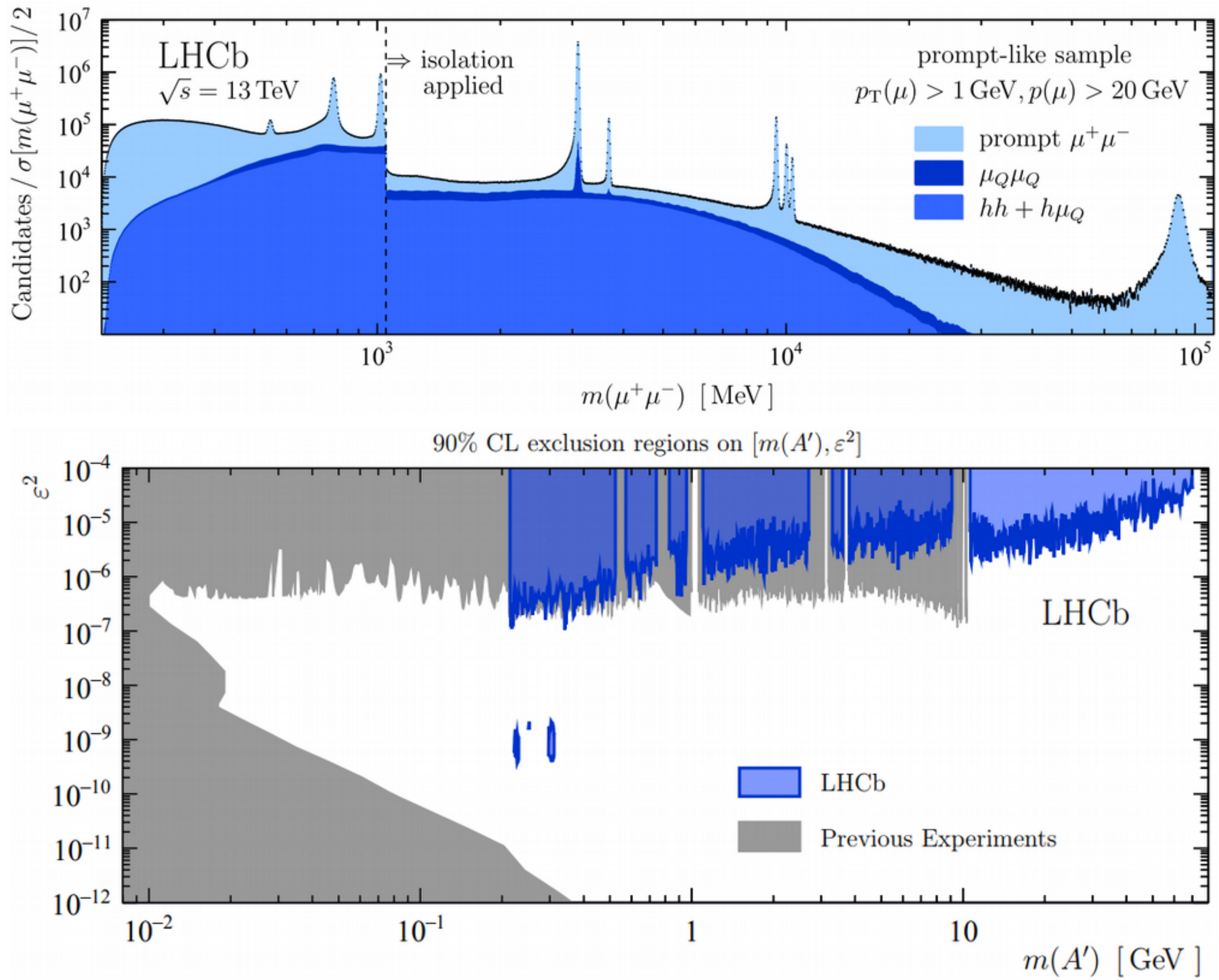
Probing new regions

LHCb search for dark photons decaying to dimuons – either prompt or displaced

Analysis enabled by the data reduction possible with offline-quality reconstruction at trigger

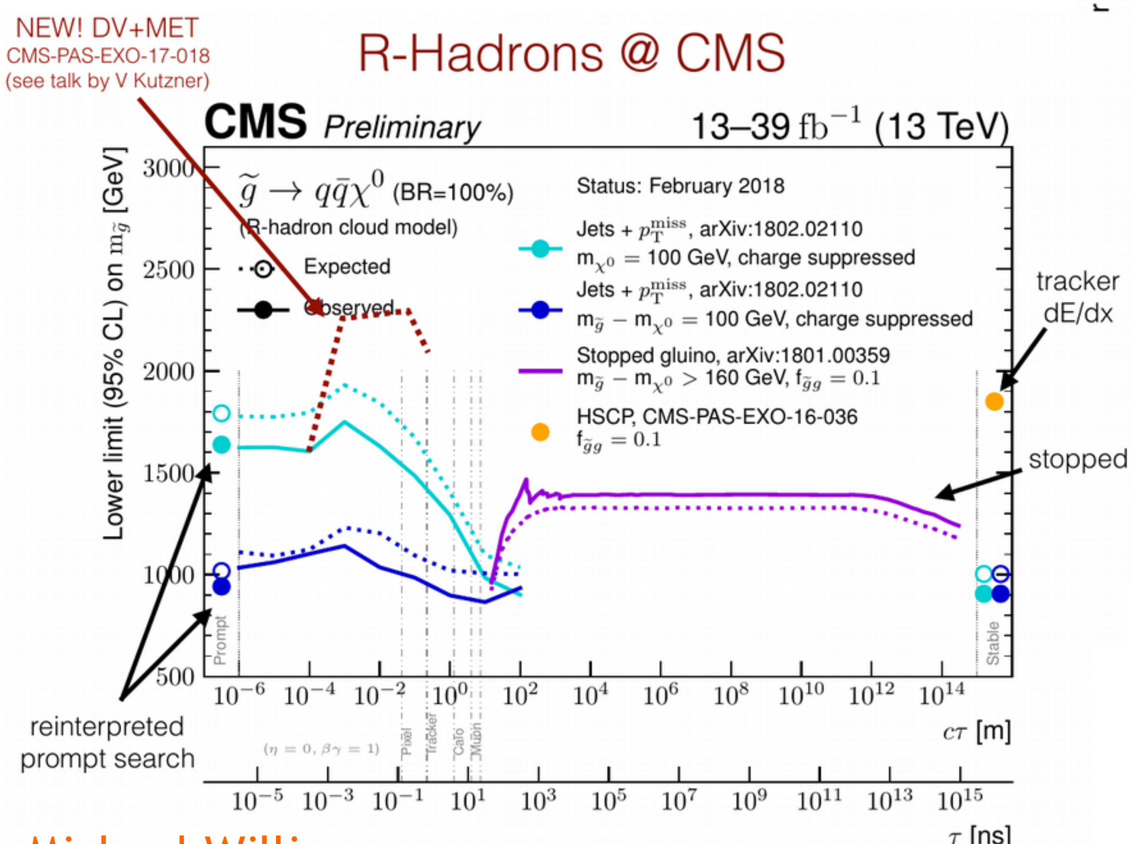
Results use 2016 data – big improvements expected with 2017

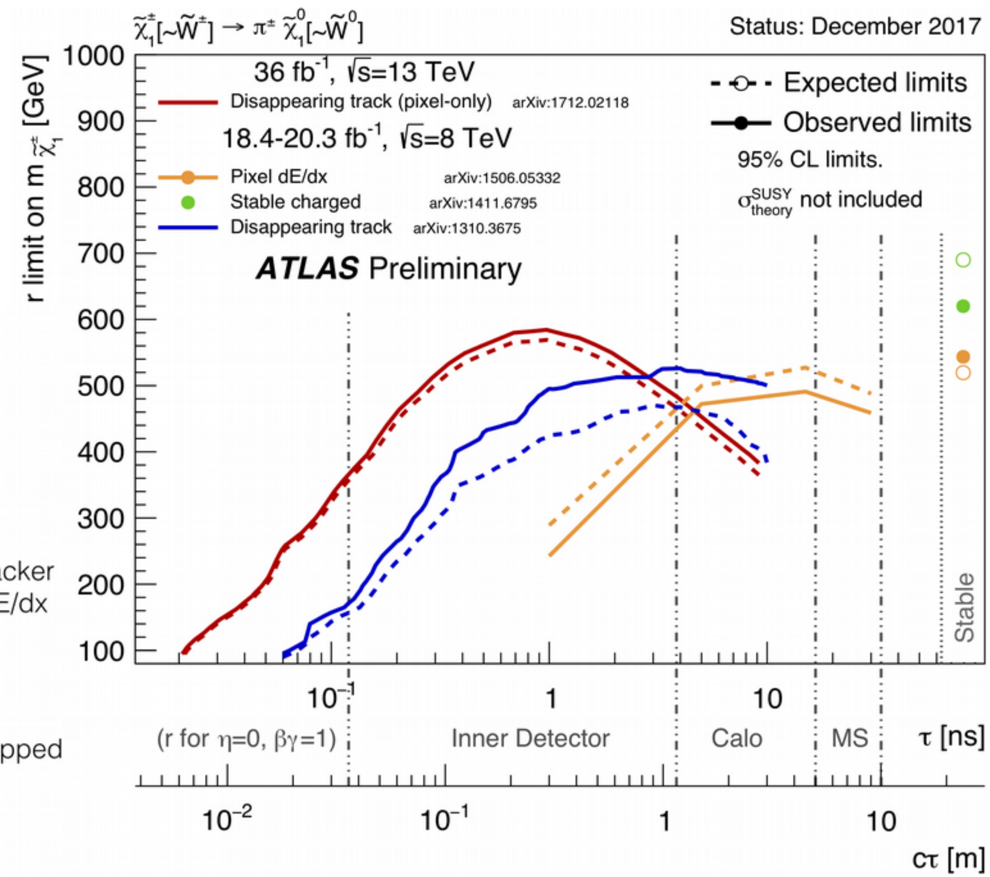
First constraints on dark photons using displaced vertex signature



Searching widely and deeply

In addition to "standard" SUSY and exotic topologies, also hunting for new long-lived particles, motivated e.g. in compressed models





Exploration of a zoo of topologies
No stone unturned...

Michael Williams

Tensions over flavour

Recent excitement about tensions in lepton-flavour universality (LFU) in B decays

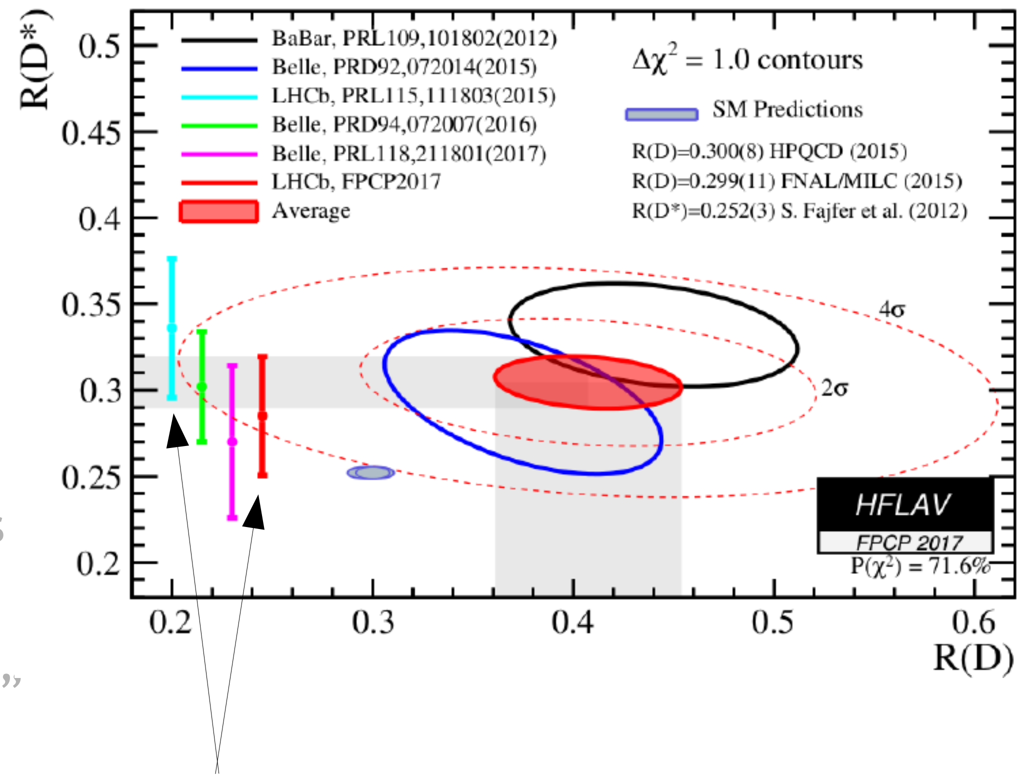
Two different cases

- Tau's in B decays (tree-level)
  - "Tensions" mainly from B factories
  - LHCb results so far consistent with both B factories and SM
  - Hadronic (3-prong) tau decay channel agrees with SM at 1σ

- μμ:ee flavour ratios in FCNC loop decays
  - Tensions at the 2.x σ level

Combined fits give striking "NP significances" – *caveat emptor* with a posteriori fits to complex analyses

Such combined analyses provide interesting areas to look while new LHCb/Bfactory results are gestating



LHCb (3-prong red)

As of yet, modest input here from LHC(b)
Sensitive to common assumptions?

Tensions over flavour

Recent excitement about tensions in lepton-flavour universality (LFU) in B decays

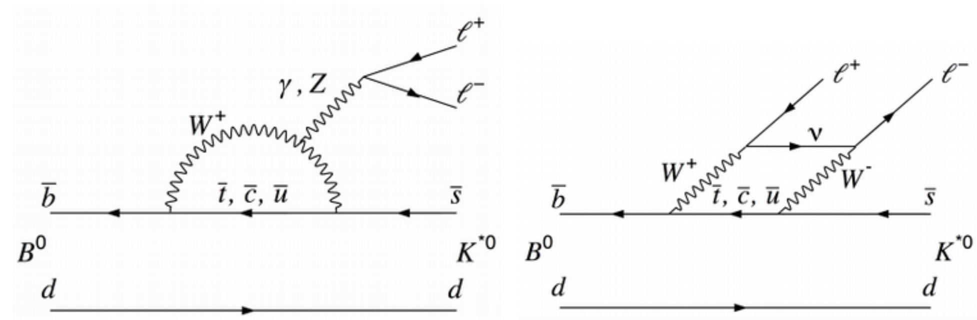
Two different cases

- Tau's in B decays (tree-level)
  - "Tensions" mainly from B factories
  - LHCb results so far consistent with both B factories and SM
  - Hadronic (3-prong) tau decay channel agrees with SM at 1σ

- μμ:ee flavour ratios in FCNC loop decays
  - Tensions at the 2.2-2.6 σ level

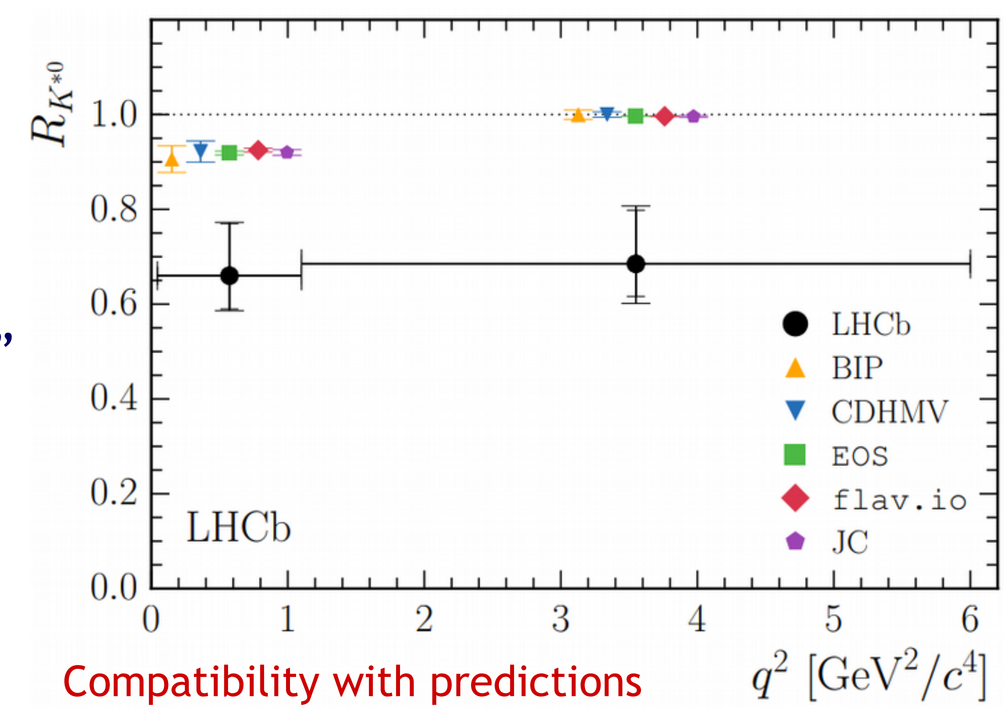
Combined fits give striking "NP significances" – *caveat emptor* with a posteriori TH fits to complex analyses

Such combined analyses provide interesting areas to look while new LHCb/Bfactory results are gestating (→Run-2 data!)



One example...

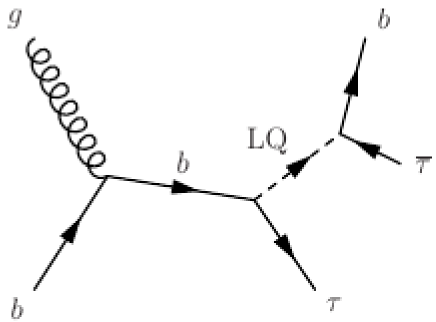
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

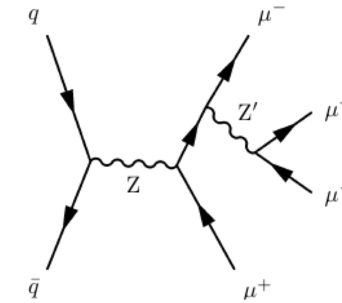


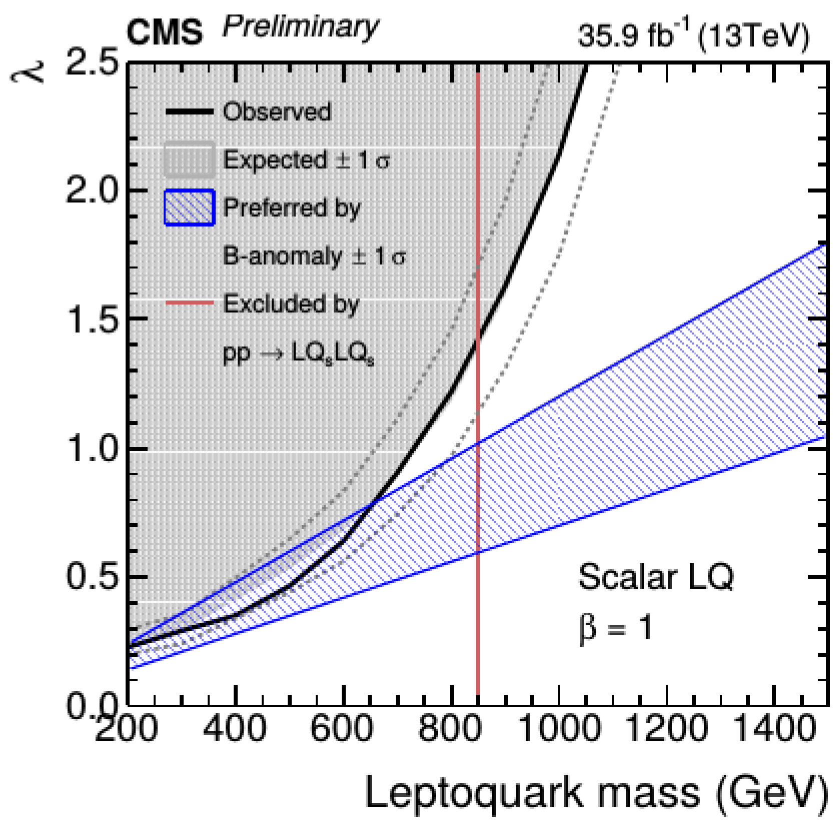
Compatibility with predictions
2.1-2.3σ ($0.045<q^2/\text{GeV}^2<1.1$)
2.4-2.5σ ($1.1<q^2/\text{GeV}^2<6$)

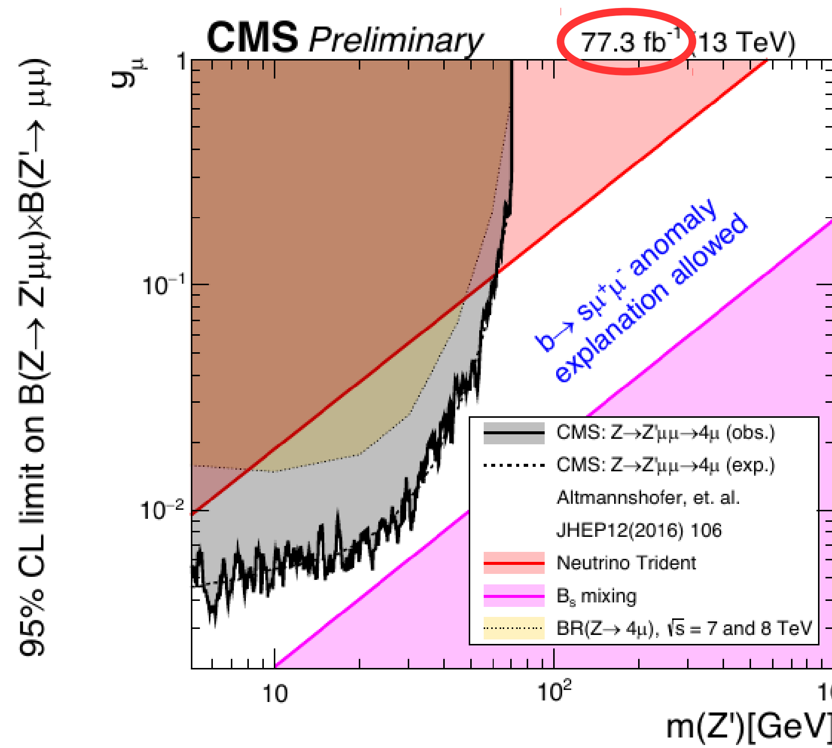
High-energy consequences?

CMS showed impressive new search results, also with 2017 data, motivated by the LFU tensions



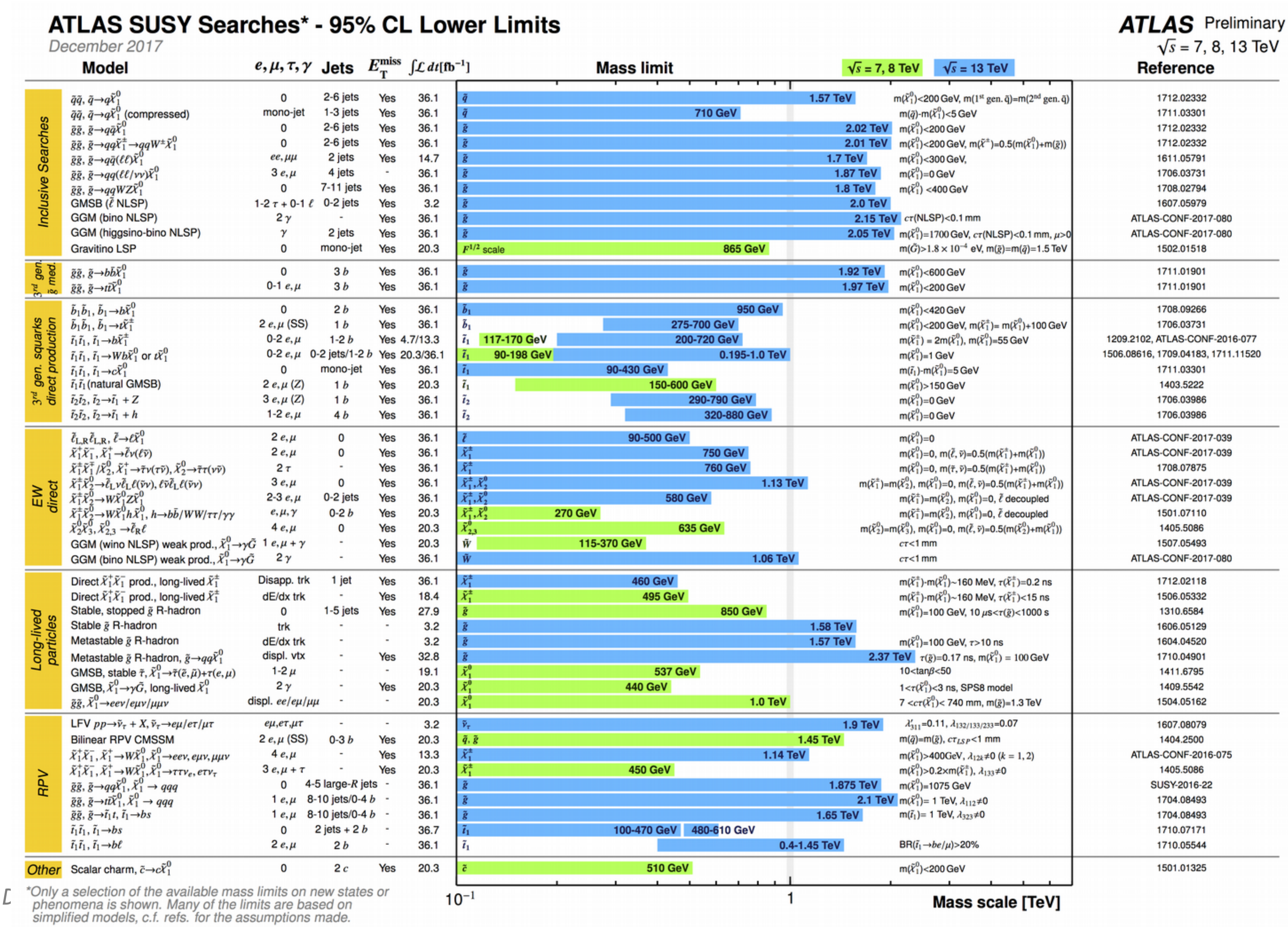






Keep looking!

Searching widely and deeply



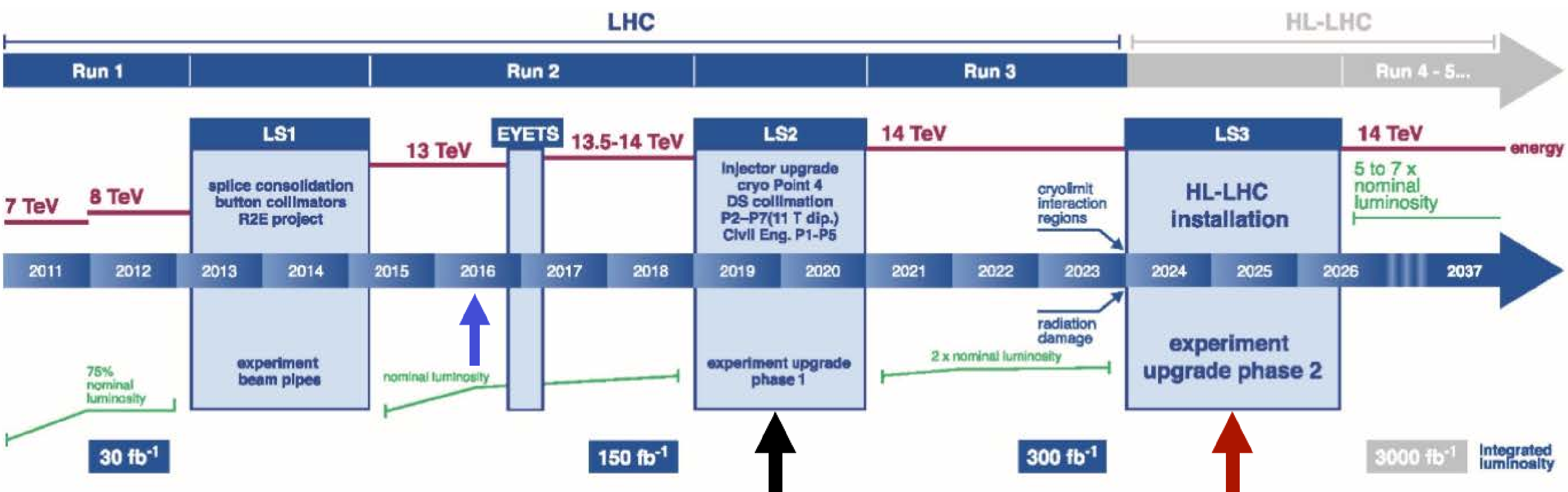
More to explore: A call to arms!

Gabriel Facini

- To start, 13 TeV searches had tremendous discovery potential
- After searching in 13 TeV, we need to ***keep going***
  - to **understand the detector** (this talk)
    and improve performance (next talk)
  - **cover the full parameter space**
  - **expand the signatures** studied in a given final state
  - **follow-up on interesting excesses** from other experimental results
  - **cover all possible final states** even without direct theory motivation.

The future is bright…

Much work now devoted to upgrades...

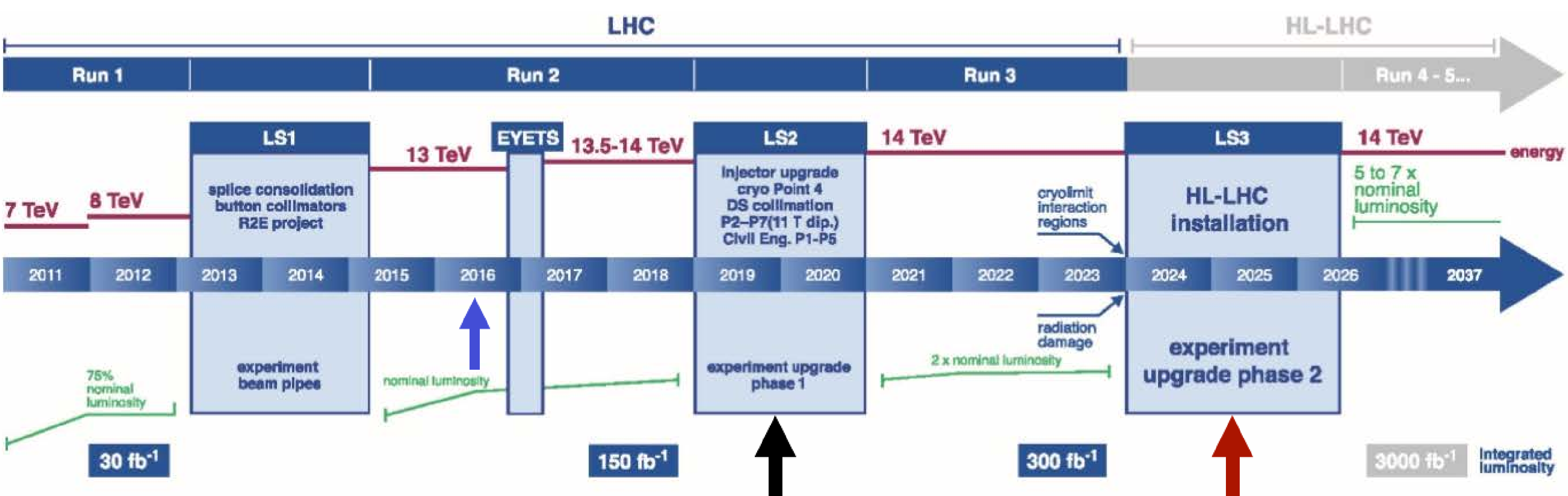


LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

Much work now devoted to upgrades...



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

Be gentle when asking when the latest updated results will come out, please...

HL-LHC approaches

This morning's talks provided excellent overviews of the experimental upgrade programmes … and Freddy discussed the magnet work on Monday

Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

11T dipole (Nb_3Sn): long prototype under assembly at CERN

By the time of LHCP 2019...

...we will all be going back to rebuild and refurbish our accelerators and detectors...

- LHC preparing for 14 TeV
- The injector upgrade/refitting (LIU) will be well underway
- The new shafts for HL-LHC will be going down...
- ALICE and LHCb will be taking out and replacing large parts of their detectors
- ATLAS and CMS will be taking out and replacing small(er) parts of their detectors

Will we start to see the first "full Run-2" results..?

In conclusion

Approaching a decade after the start, the LHC is now a mature machine, and the detectors are stable, and very well understood

- Major progress on “our” scalar: ttH is there at tree-level, and $y_t \approx 1$
- Measurement precision pushes calculations hard in many areas – and we see huge progress in higher-order calculations
- Few (if any) signs yet of the solutions to our bigger problems (DM, hierarchy, naturalness …), but there are many places to look, and flavour tensions to keep us excited
- Only one percent of the full LHC data sample analysed!

Completion of Run-2, upgrades and then much more data beyond: LHCPhysics will be the place to be for many years to come!


FINE