

# 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

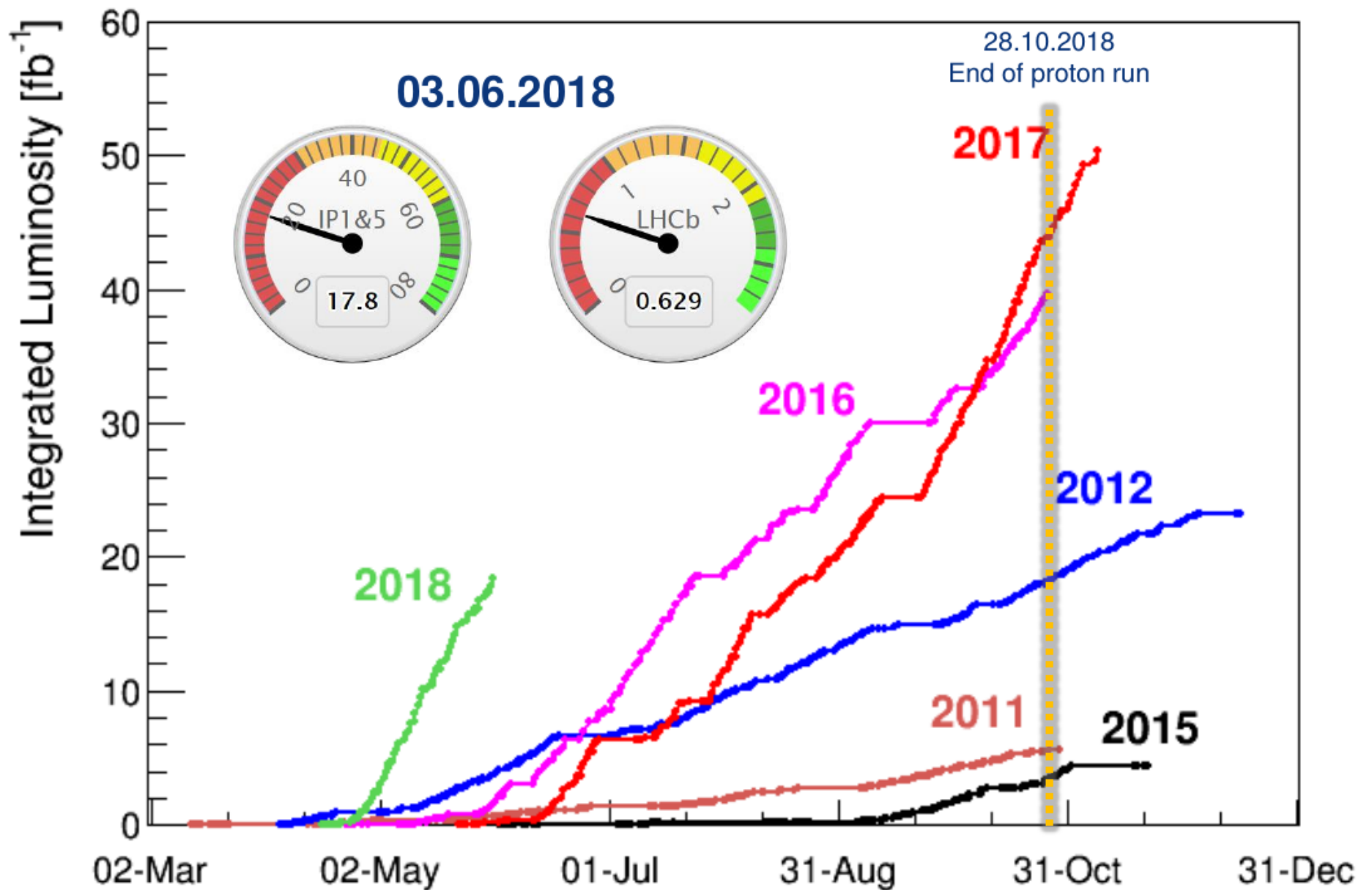




# Large samples and exquisite detector performance

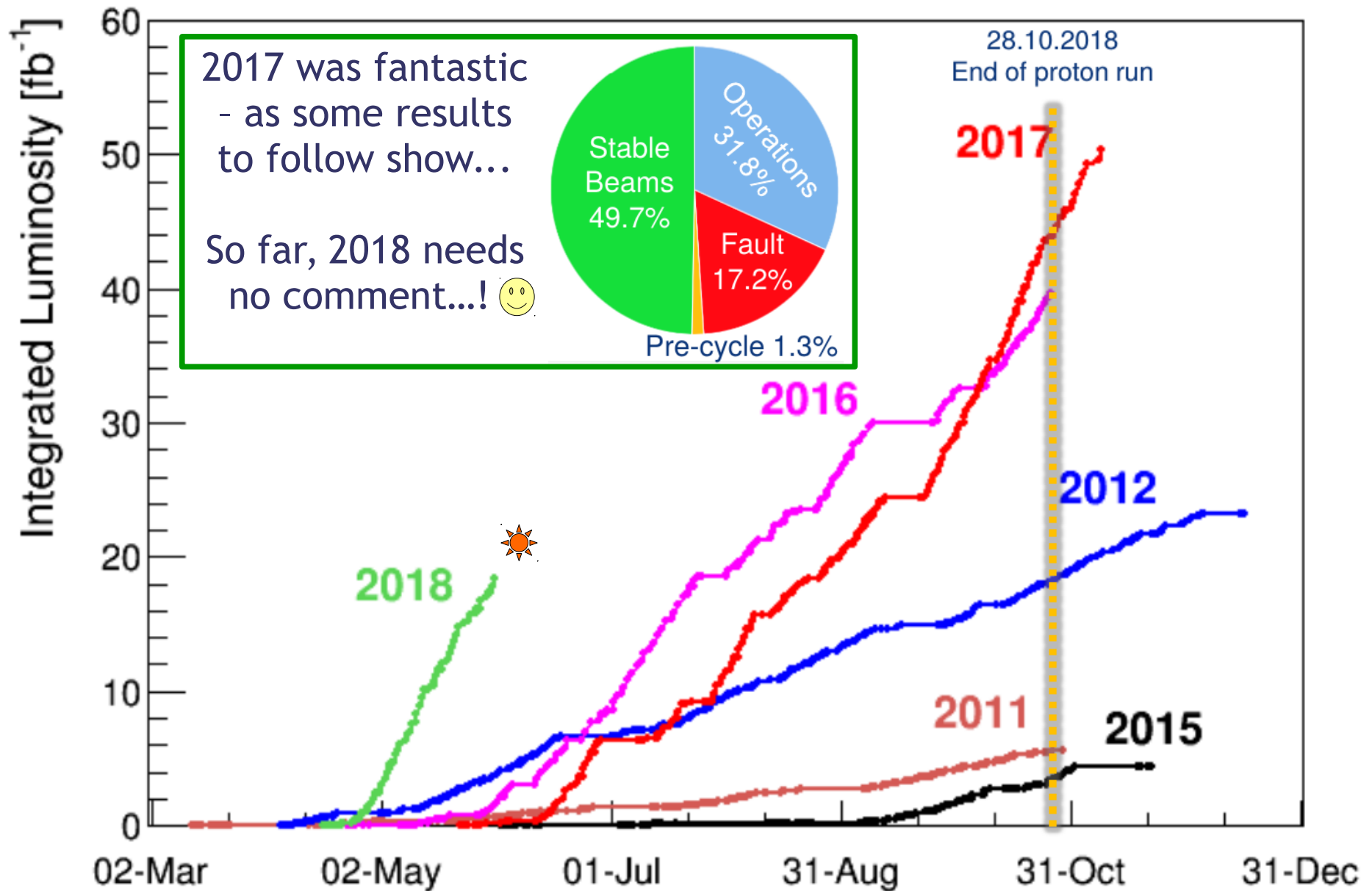


# Wonderful LHC performance

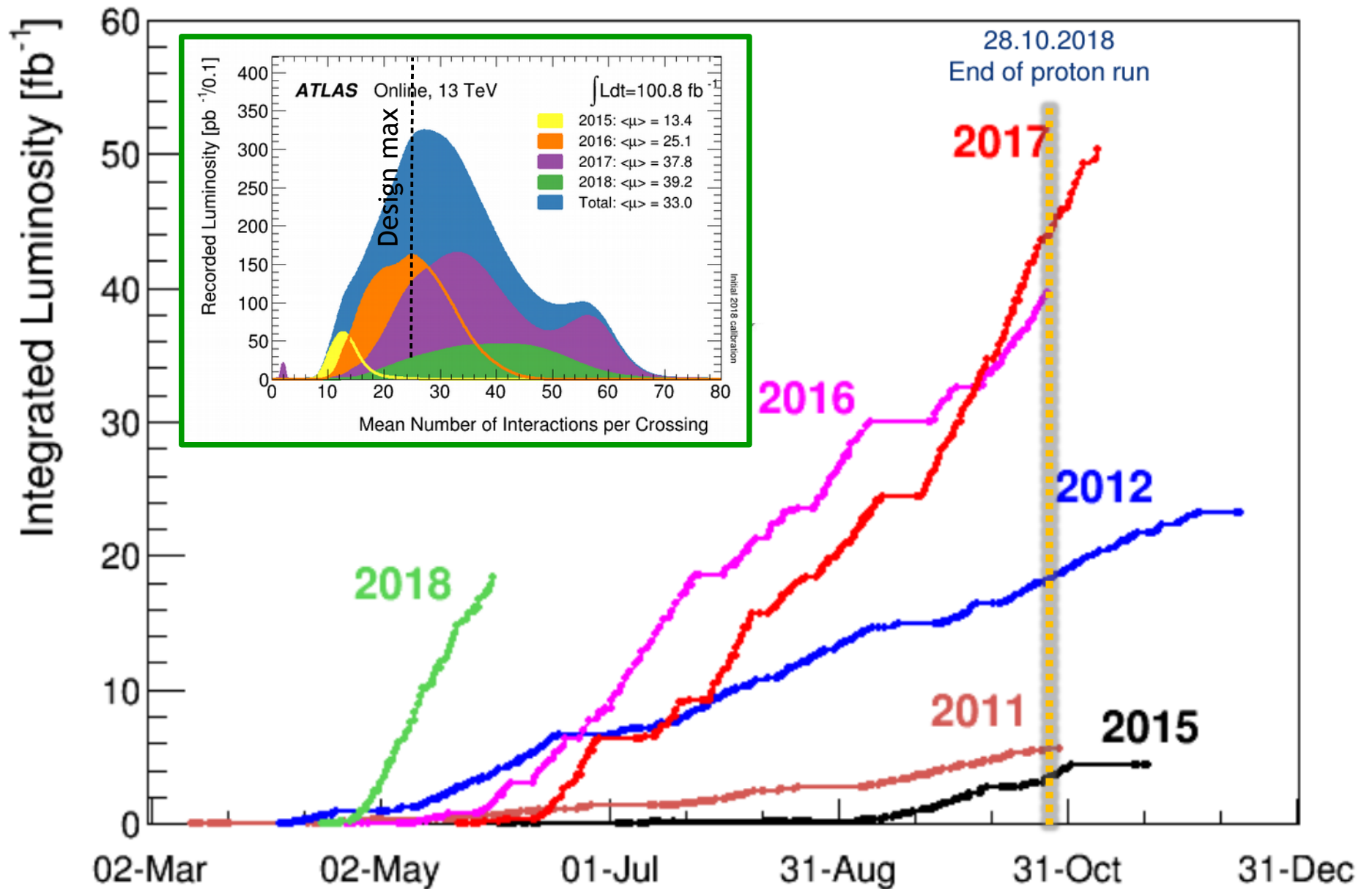




# Wonderful LHC performance



# Wonderful LHC performance

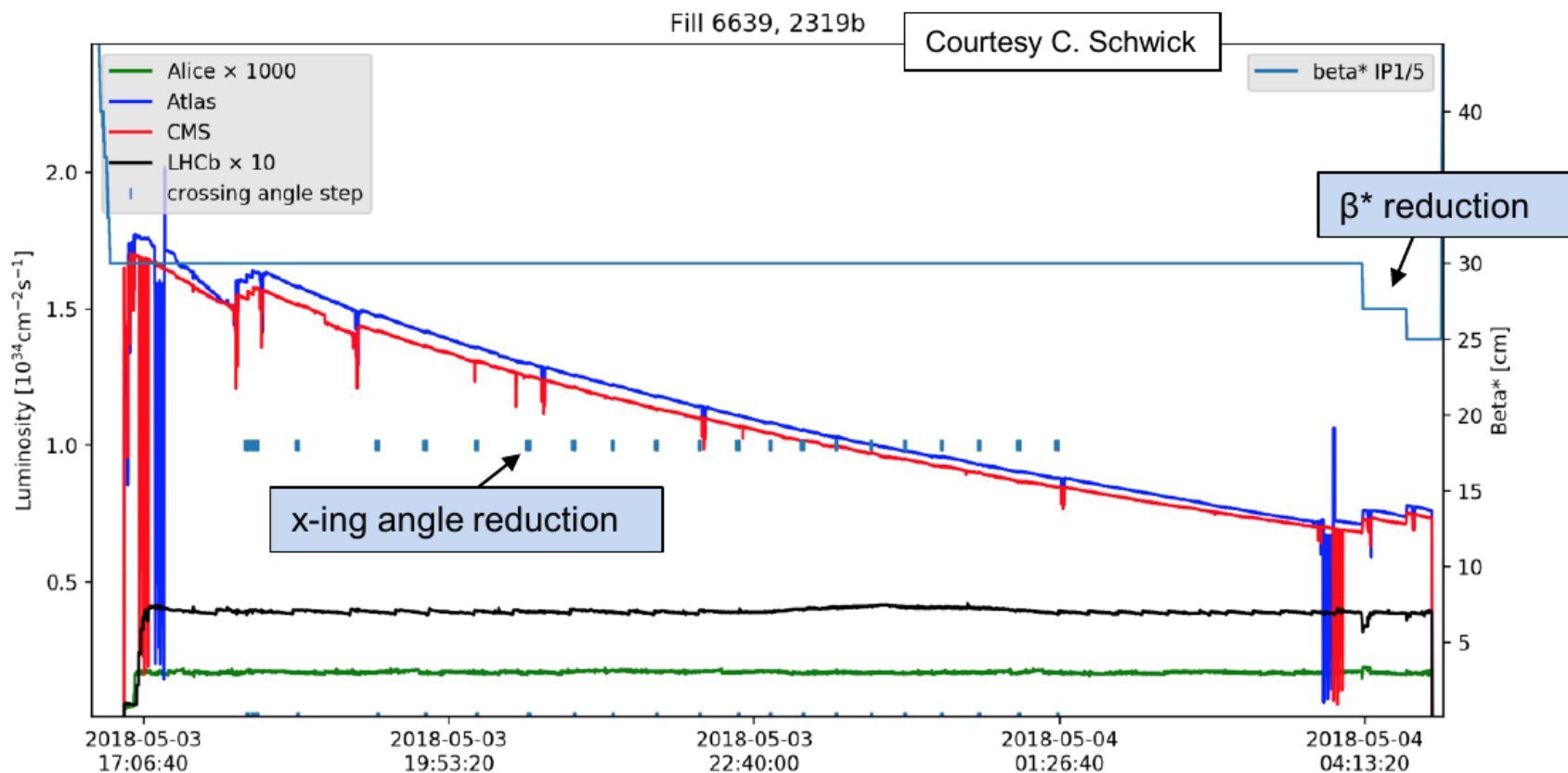




# Wonderful LHC performance

Ingenious use of levelling to optimise ATLAS+CMS luminosity delivery

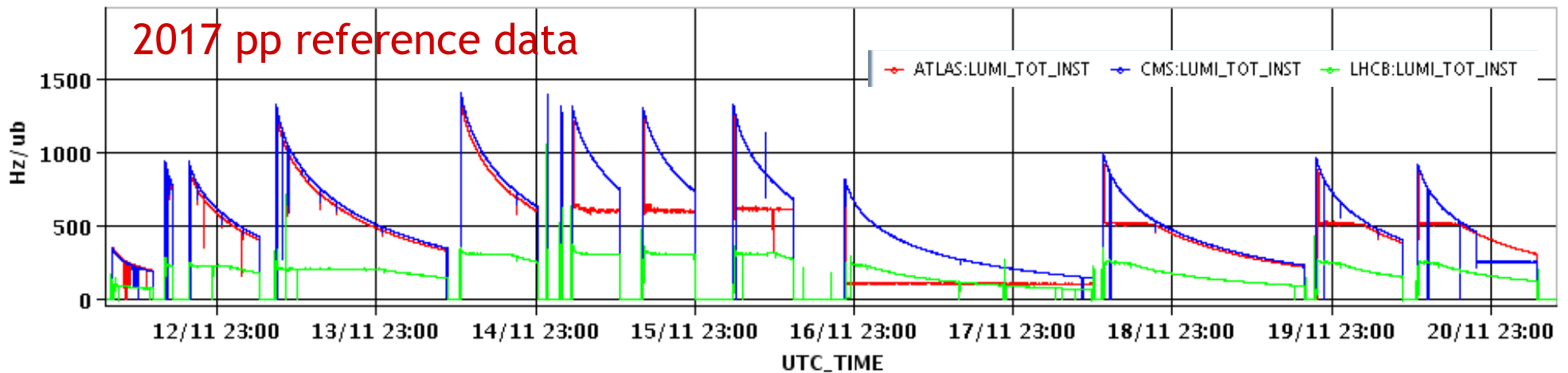
- “Continuous” beam crossing angle reduction to inch up lumi during fill
- Increase squeeze at end of fills (for now)
- All the time using continuous separation levelling for LHCb and ALICE



# The flexible LHC: ions *et al*

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

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

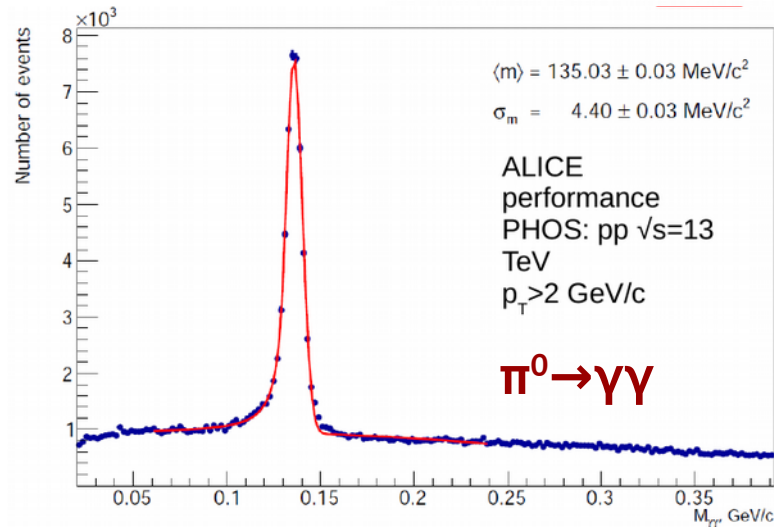
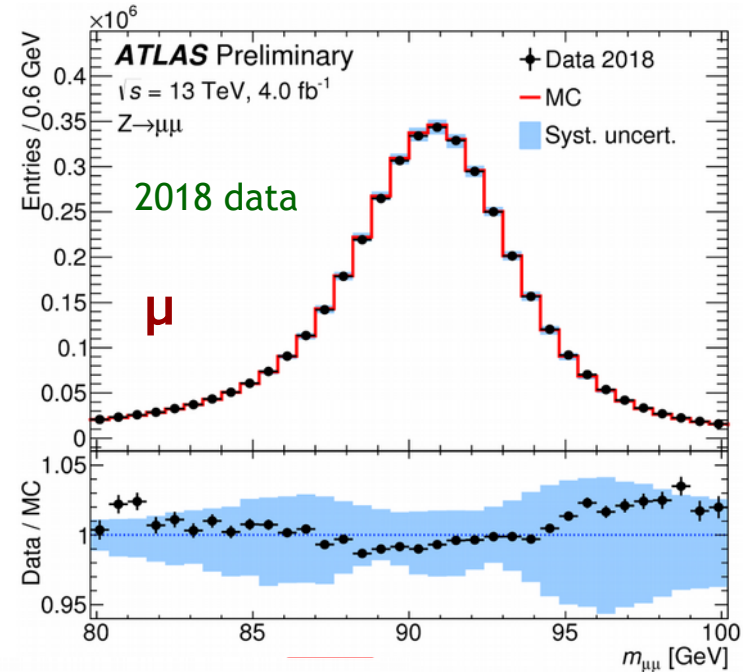
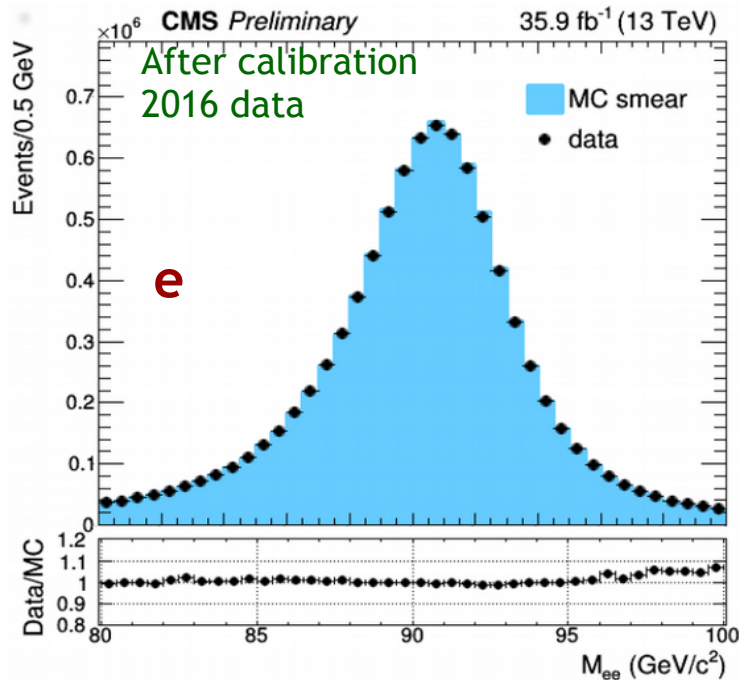


Plus other special runs (few days / year) mainly for forward physics (elastic scattering, diffraction)



# Detector performance

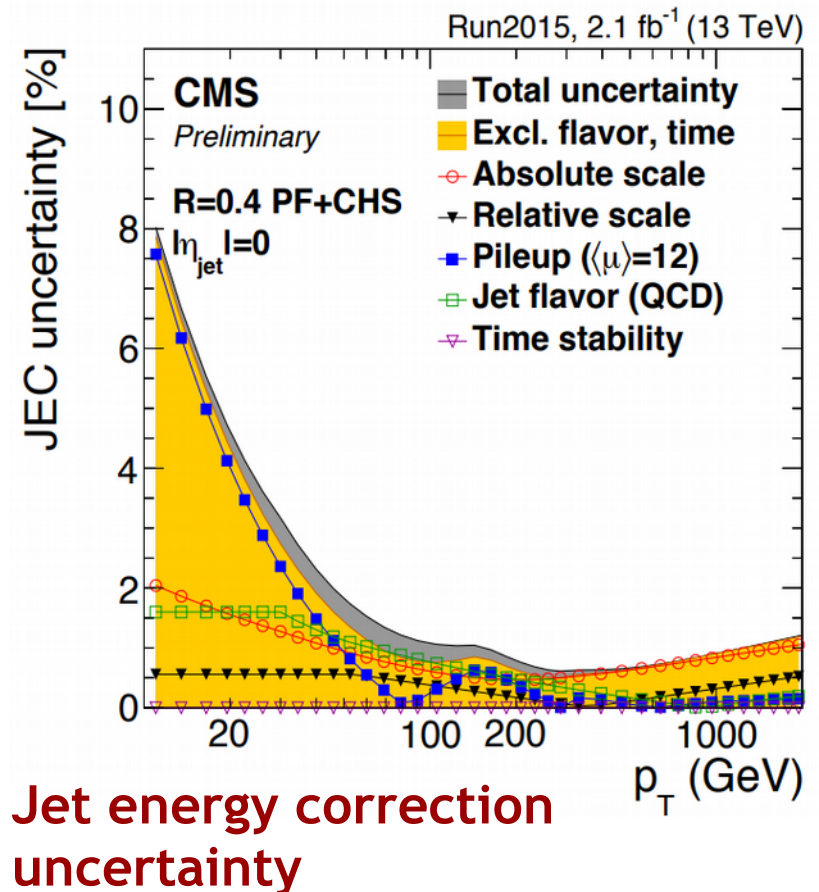
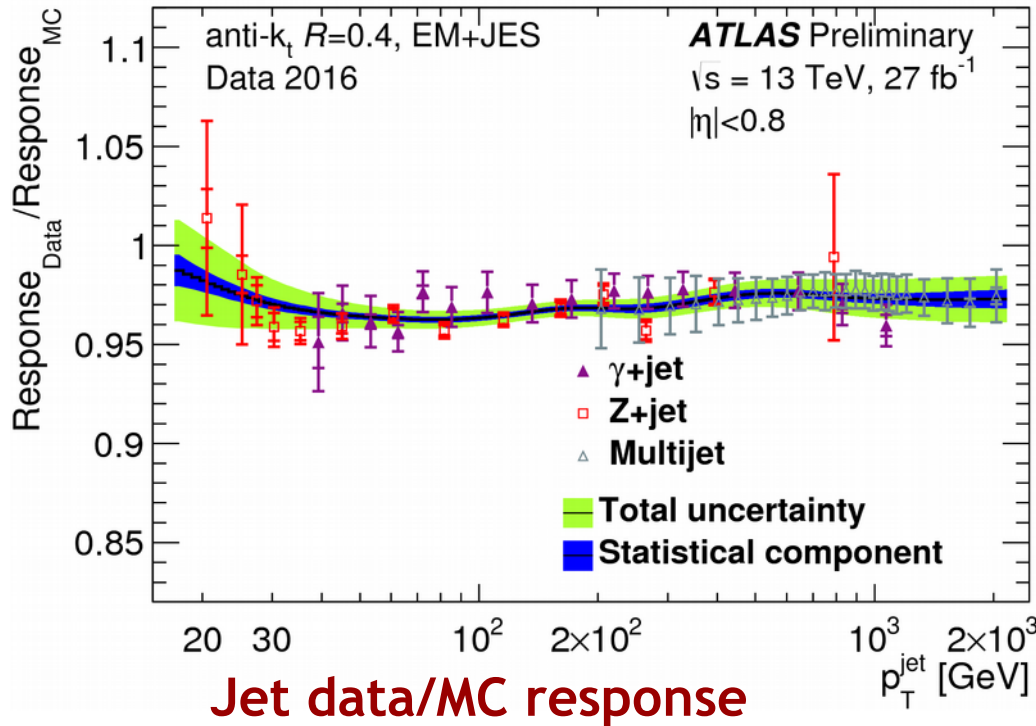
The stunning performance of the LHC detectors continues to repay the thousands of staff-years and meticulous care put into building them - matched by the ingenuity of old and new analysis techniques





# Detector performance

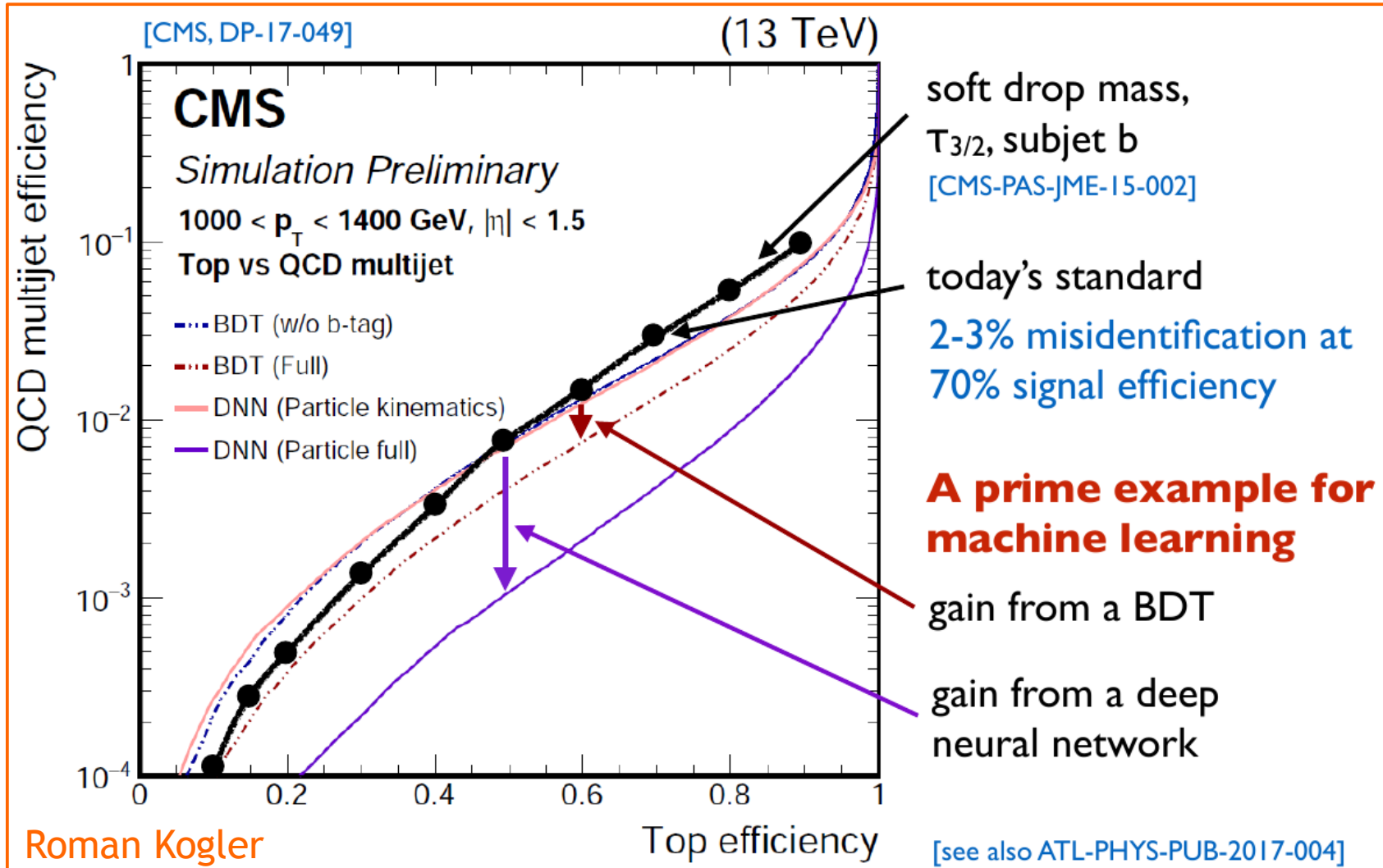
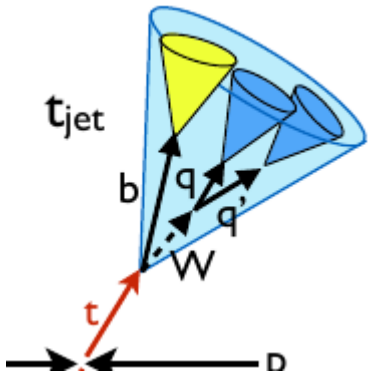
The stunning performance of the LHC detectors continues to repay the thousands of staff-years and meticulous care put into building them - matched by the ingenuity of old and new analysis techniques



# 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

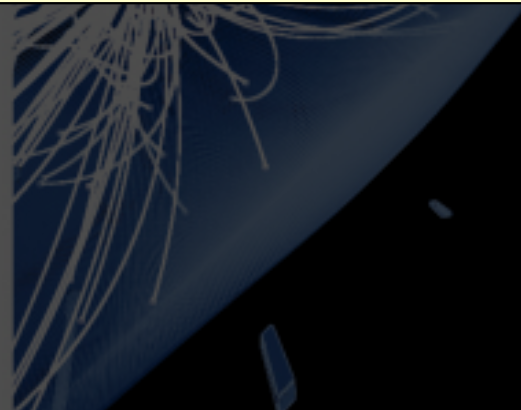
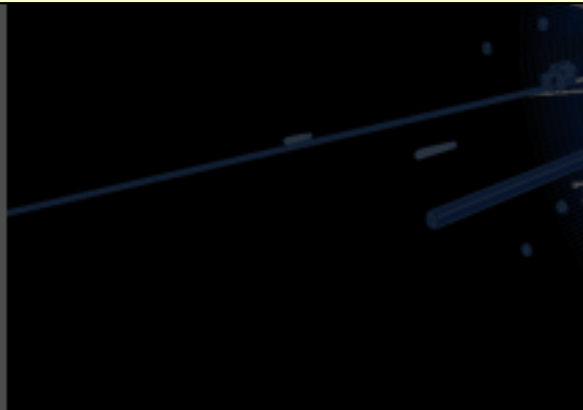


Roman Kogler

# e bosone di Higgs:

dai protagonisti, il racconto di due grandi scoperte

## Progress with our scalar



Conferenza spettacolo, organizzata  
in occasione della VI Conferenza  
Internazionale sulla fisica al Large Hadron  
Collider del CERN (LHCP2018), con:

**Fabiola Gianotti**

Direttore Generale del CERN

ore 21.00,  
**Aula Magna di Santa Lucia**  
**Via Castiglione 36, Bologna**

**INGRESSO LIBERO FINO**



# We have been in the news...



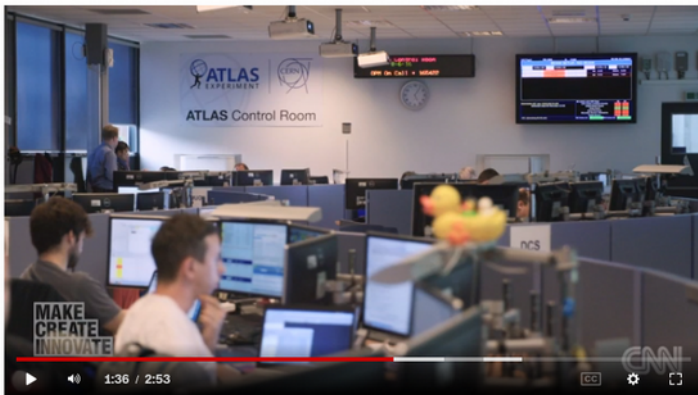
World » U.S. | Africa | Americas | Asia | China | Europe | Middle East | Opinion

International Edition +

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

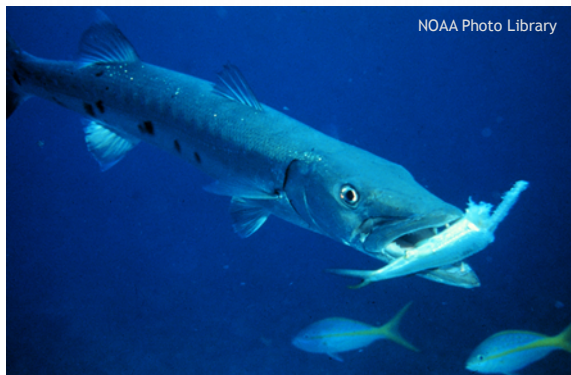
By Don Lincoln

🕒 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

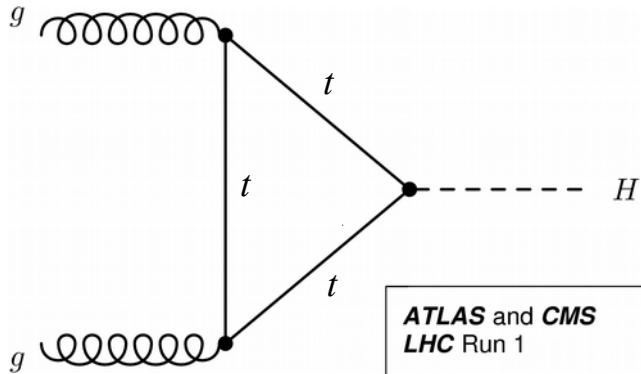
**submitted** and the CMS paper being **published**.

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.

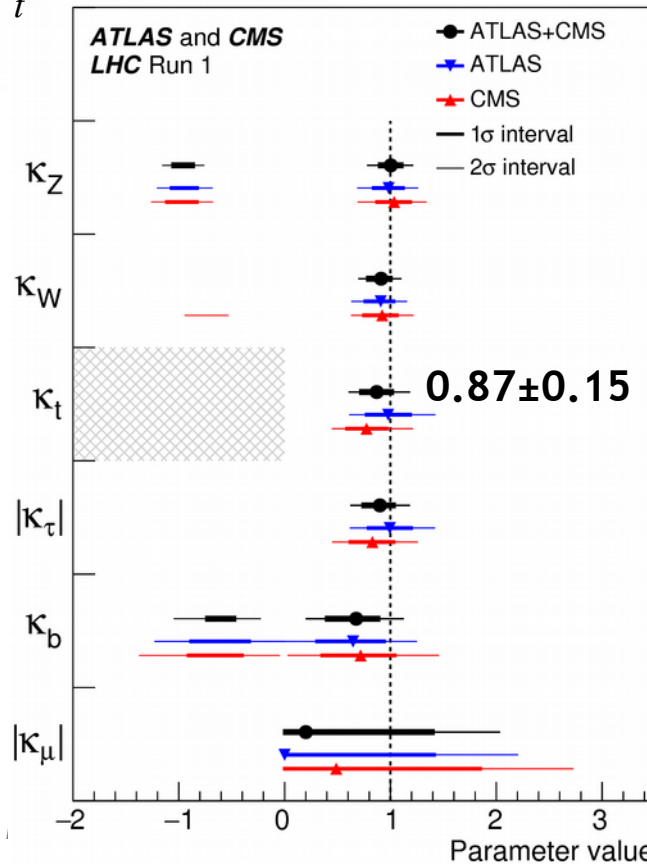
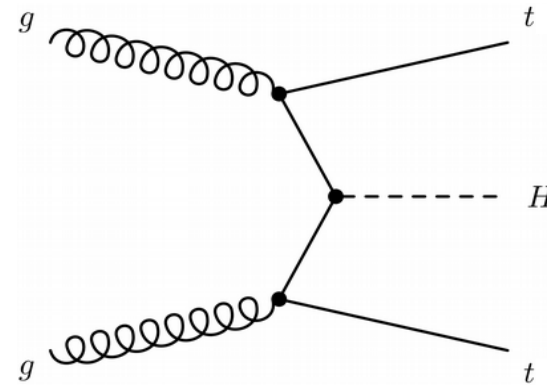
<https://edition.cnn.com/2018/06/04/opinions/physics-discovery-lincoln/index.html>

# 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.



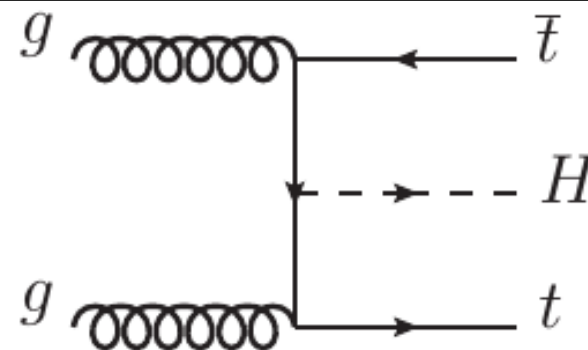
Plot assumes SM loop structures and no BSM decays

JHEP 08 (2016) 045

# $t\bar{t}H$ observation

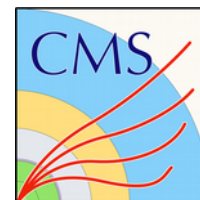
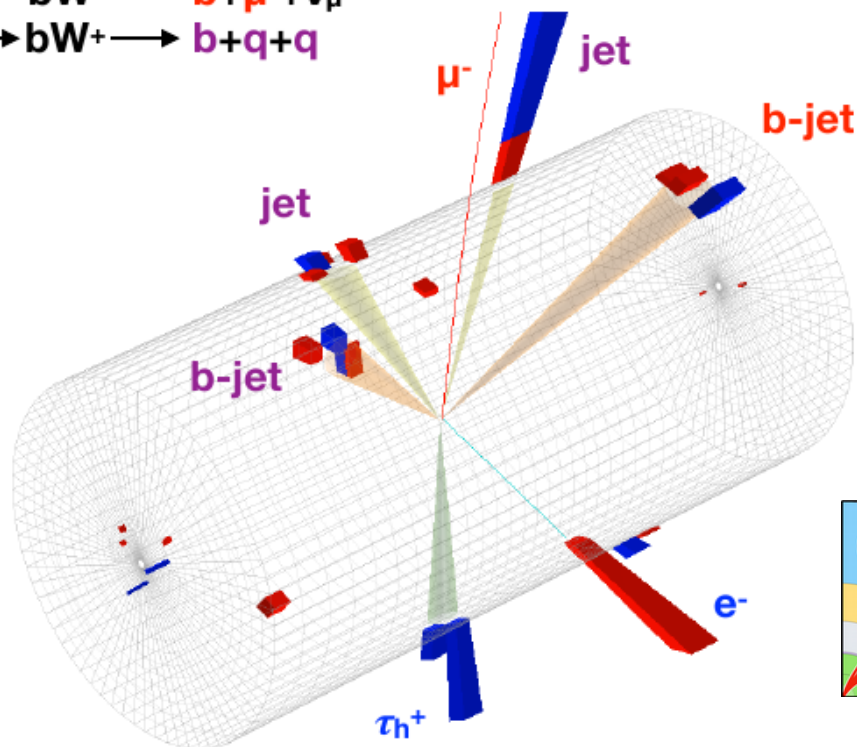
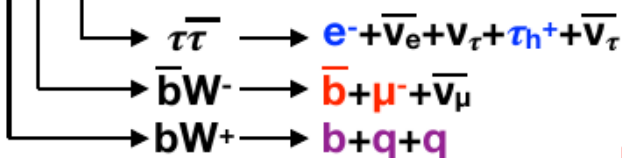
5 $\sigma$  observation of  $t\bar{t}H$  from CMS and ATLAS

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



$pp \rightarrow t\bar{t}H$

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



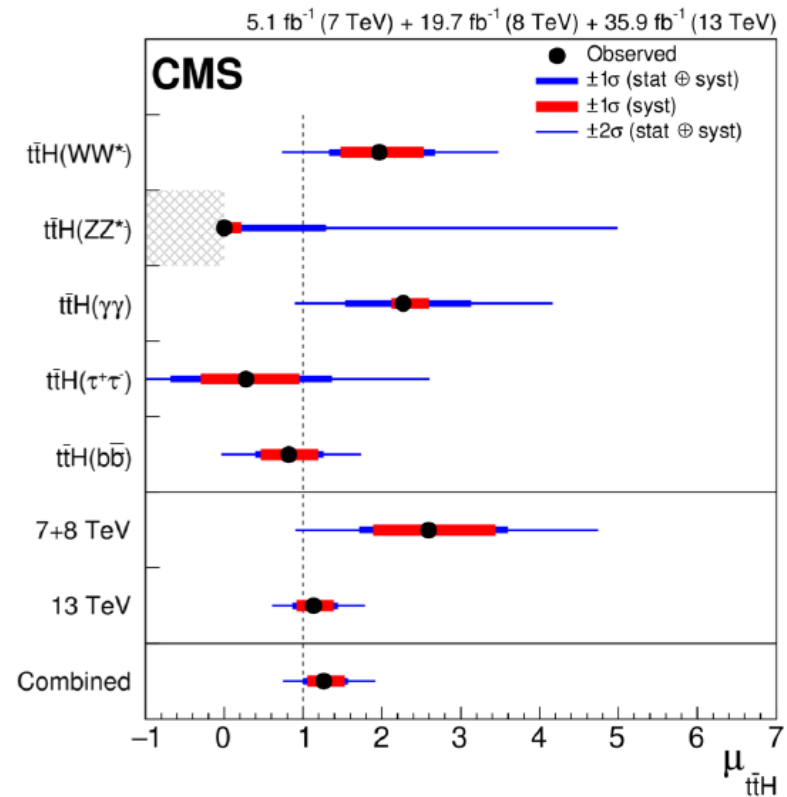
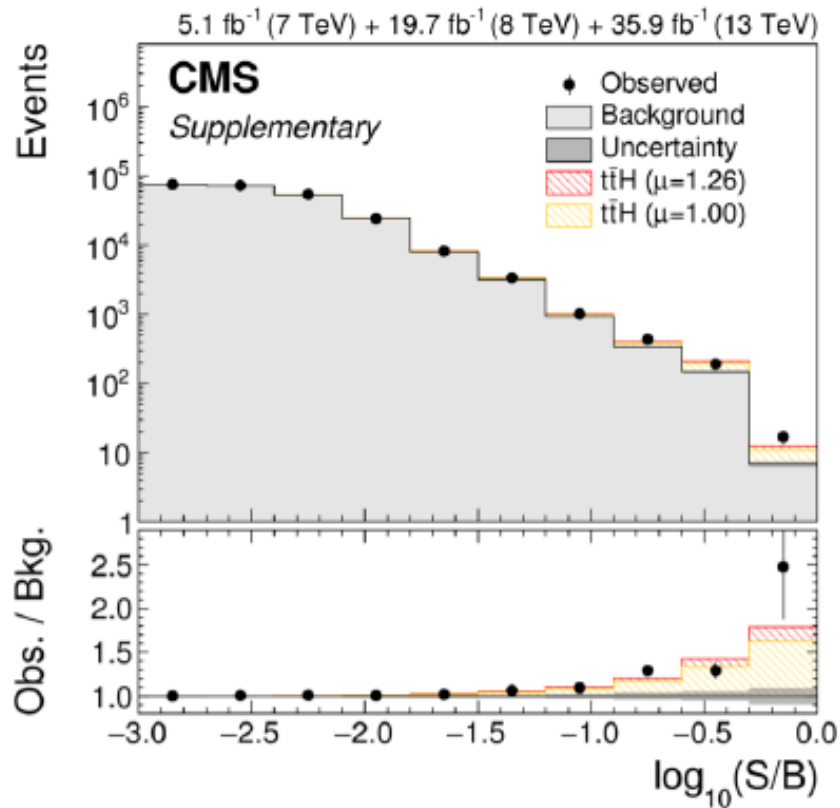
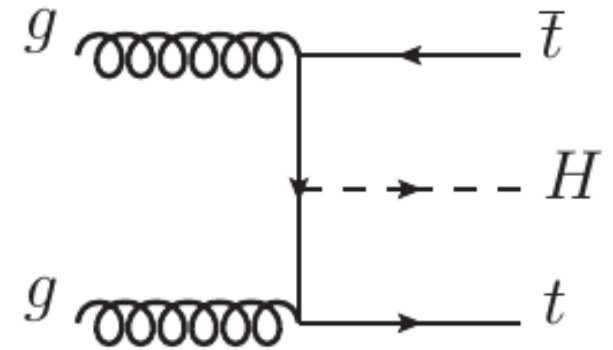


# $t\bar{t}H$ observation

5 $\sigma$  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)



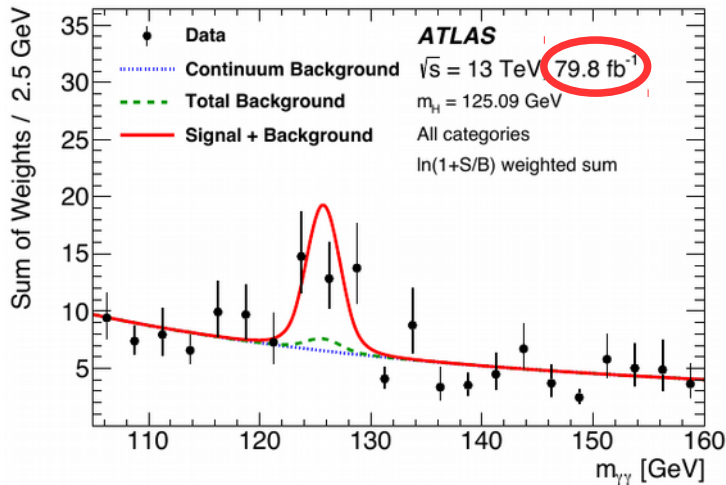
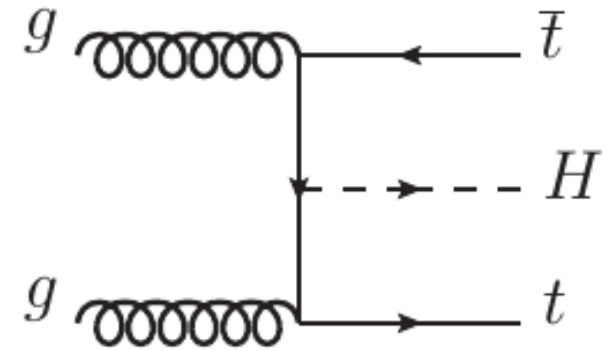
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{exp.})^{+0.14}_{-0.13}(\text{bkg. th.})^{+0.15}_{-0.07}(\text{sig. th.})$$

**5.2 $\sigma$  (4.2 $\sigma$  exp)**

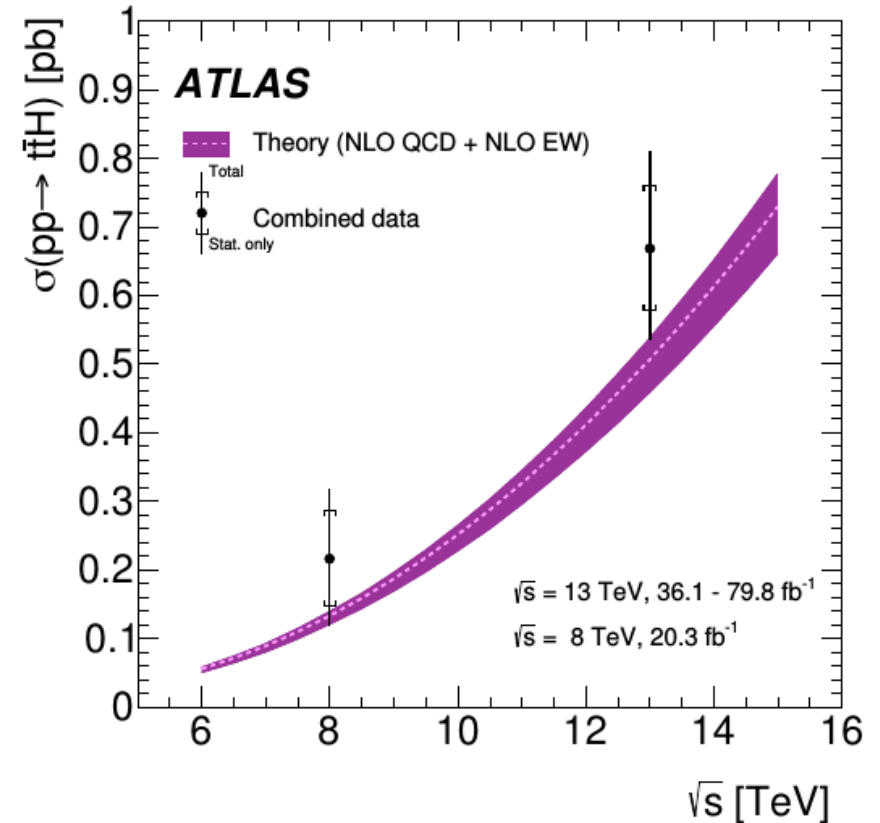
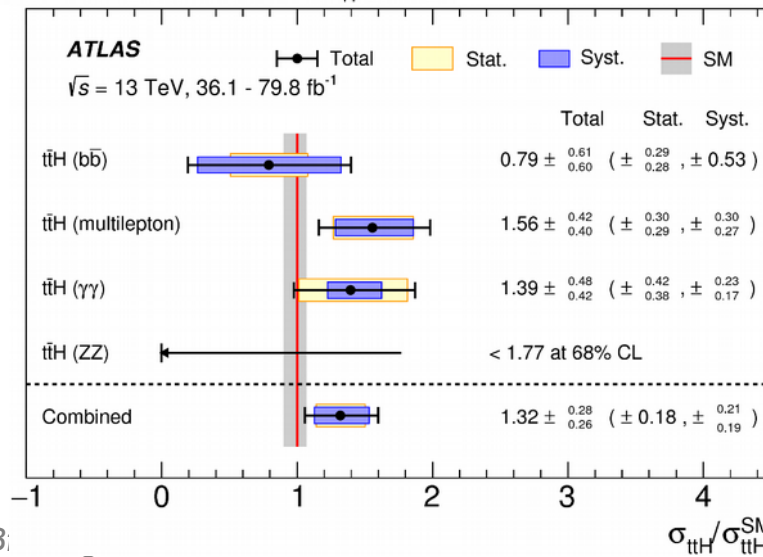
# $t\bar{t}H$ observation

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

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



arXiv:1806.00425



Run1+Run2 **6.3 $\sigma$**  (5.1 $\sigma$  exp)

# H decays to $\tau\tau$

Again complex analyses,  
systematics have to be under  
excellent control

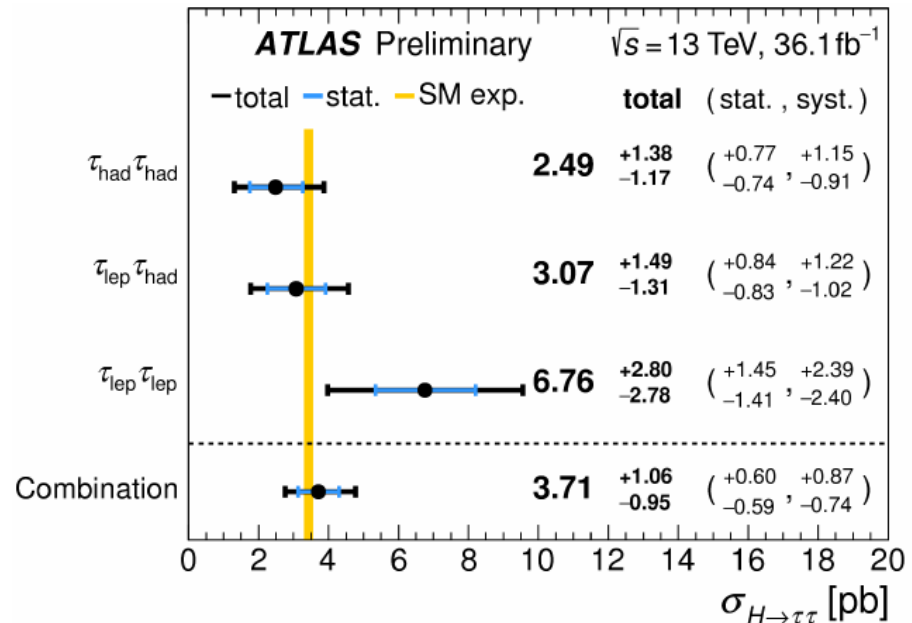
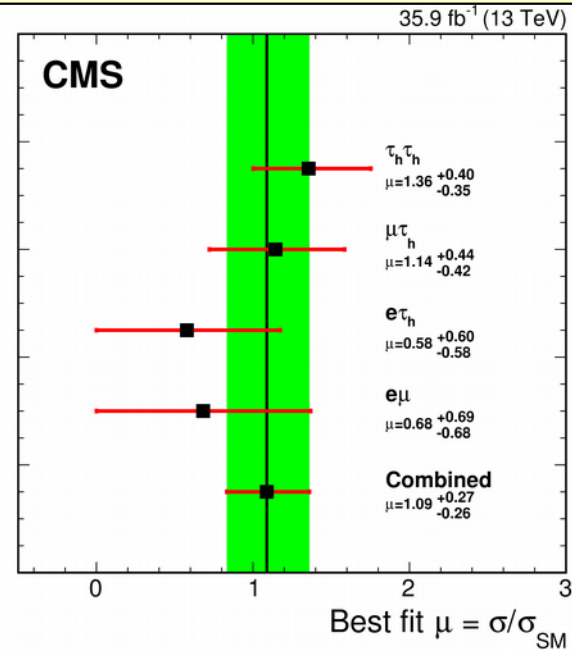
A striking success of the Run-1  
ATLAS+CMS combination:  
Observation at  $5.5\sigma$  (5.0 exp)

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

- CMS  $5.9\sigma$  ( $5.9\sigma$ )
- ATLAS  $6.4\sigma$  ( $5.4\sigma$ ) **new**

Time to move on to measurements!

PLB 779 (2018) 283





# H decays to $b\bar{b}$

PLB 780 (2018) 501

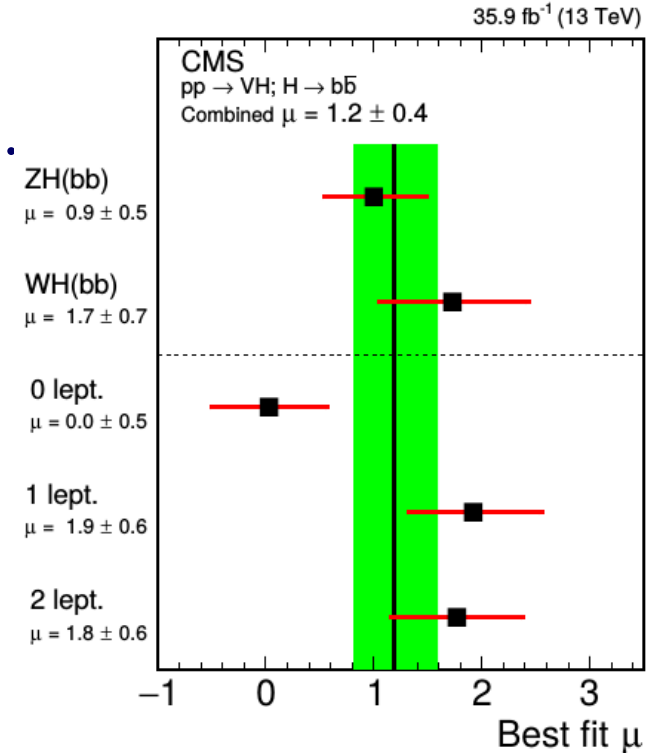
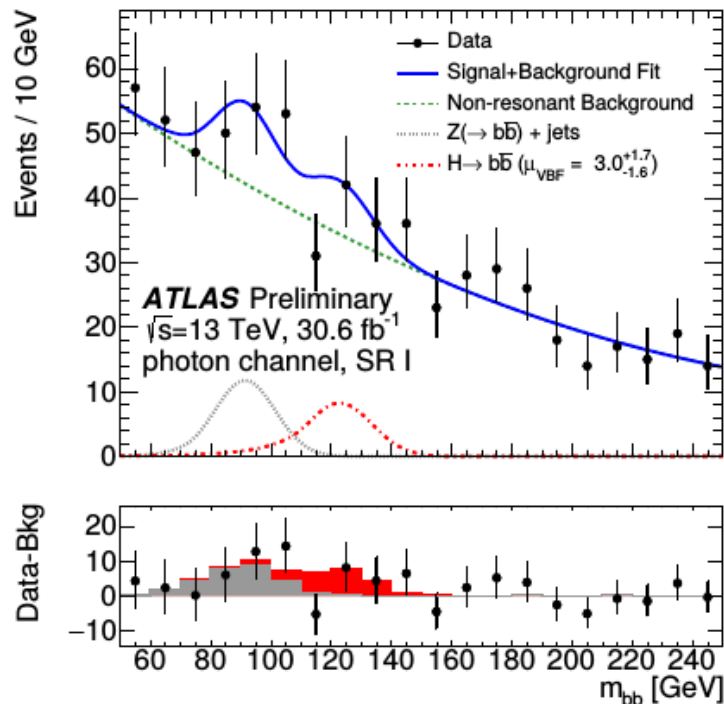
Results with 2016 data mainly released last year

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

Run-1+Run-2 signal strengths:

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

Both correspond to evidence at 3.6-3.8 $\sigma$

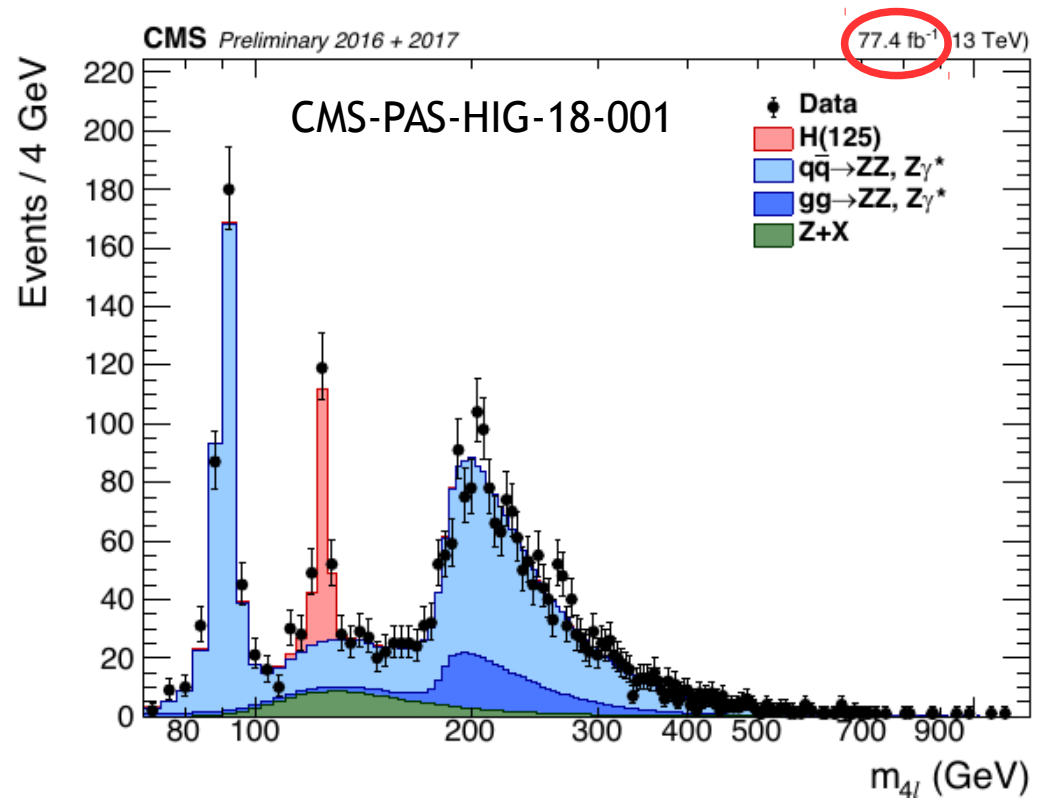
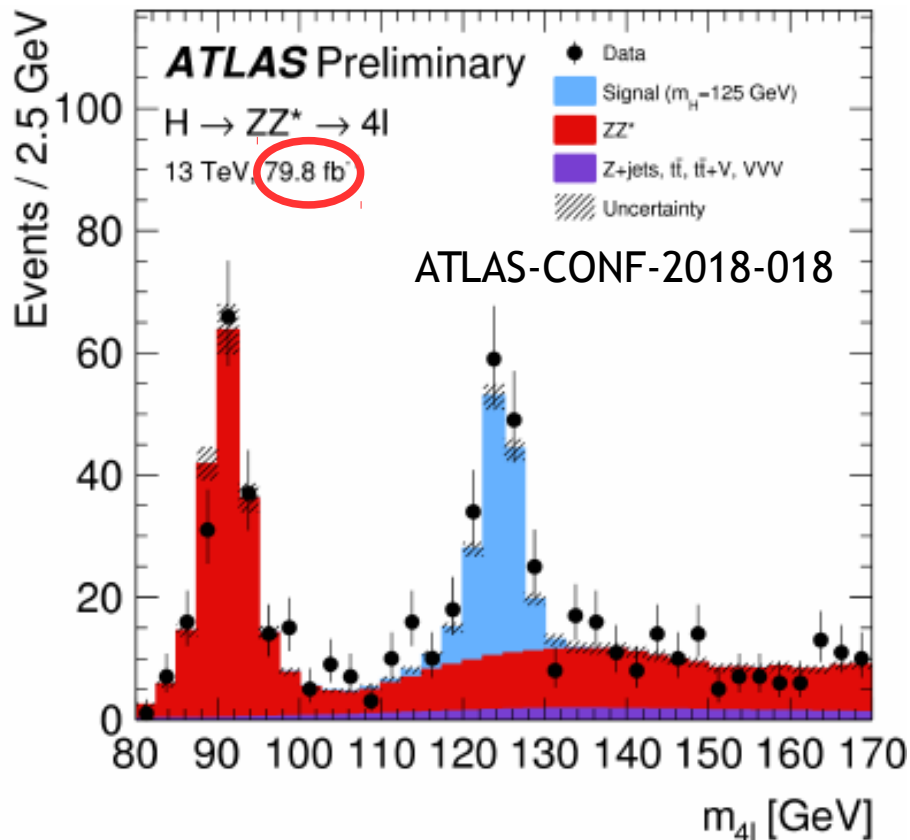


New this week: ATLAS update on  $H \rightarrow b\bar{b}$  from vector-boson fusion in 13 TeV data

CERN-EP-2018-140

# Higgs to bosons - entering precision era

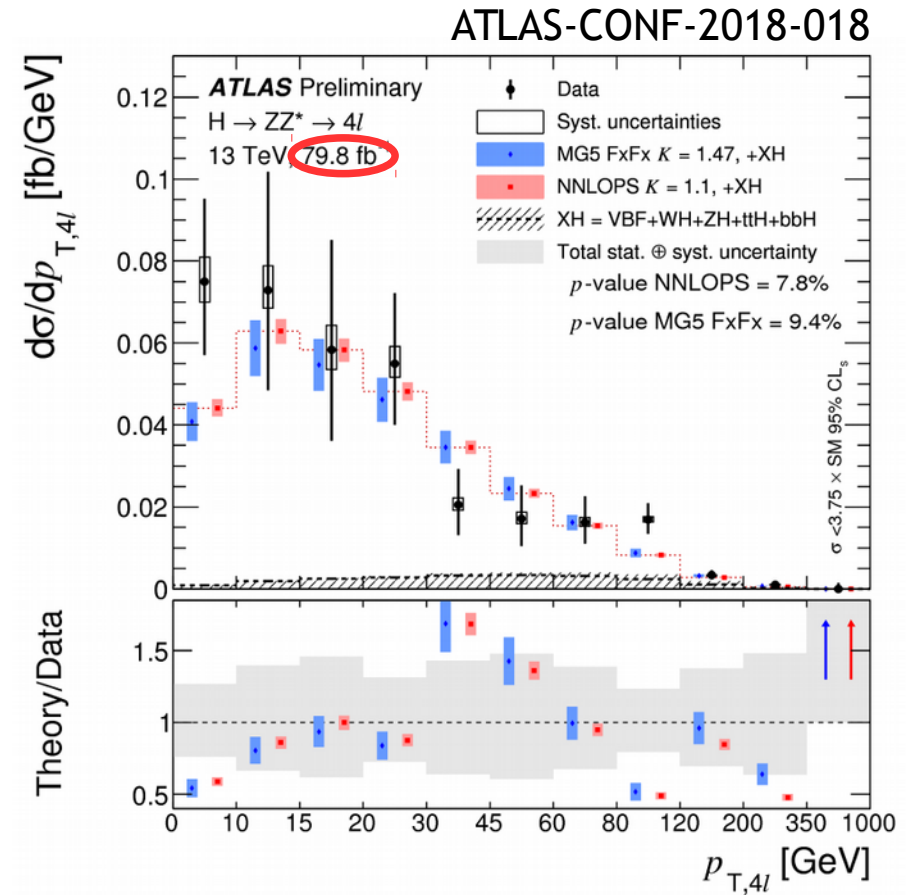
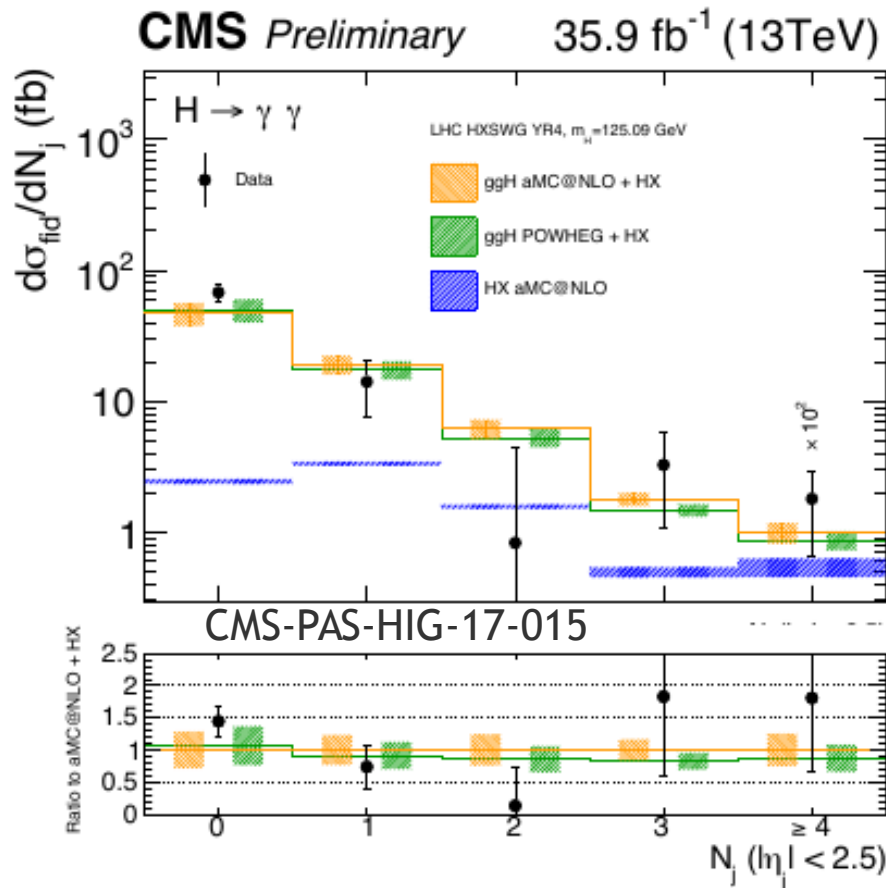
Run-2 analyses with  $80 \text{ fb}^{-1}$  for the first time – higher precision is coming!



# 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

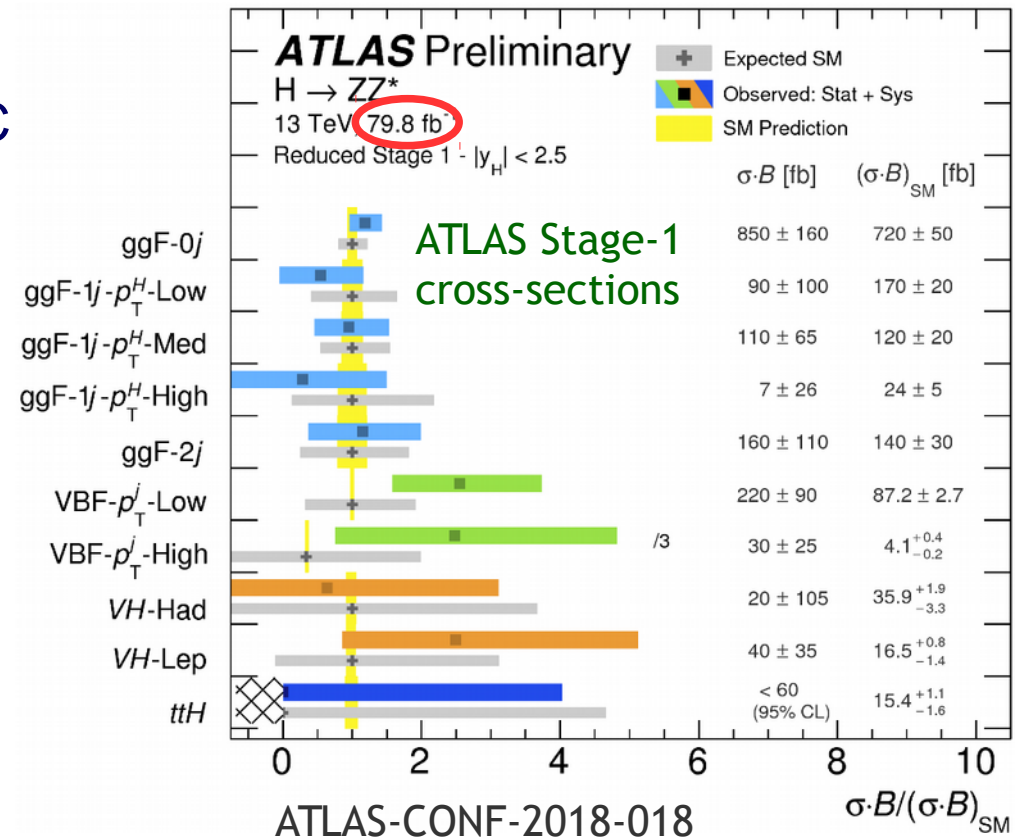
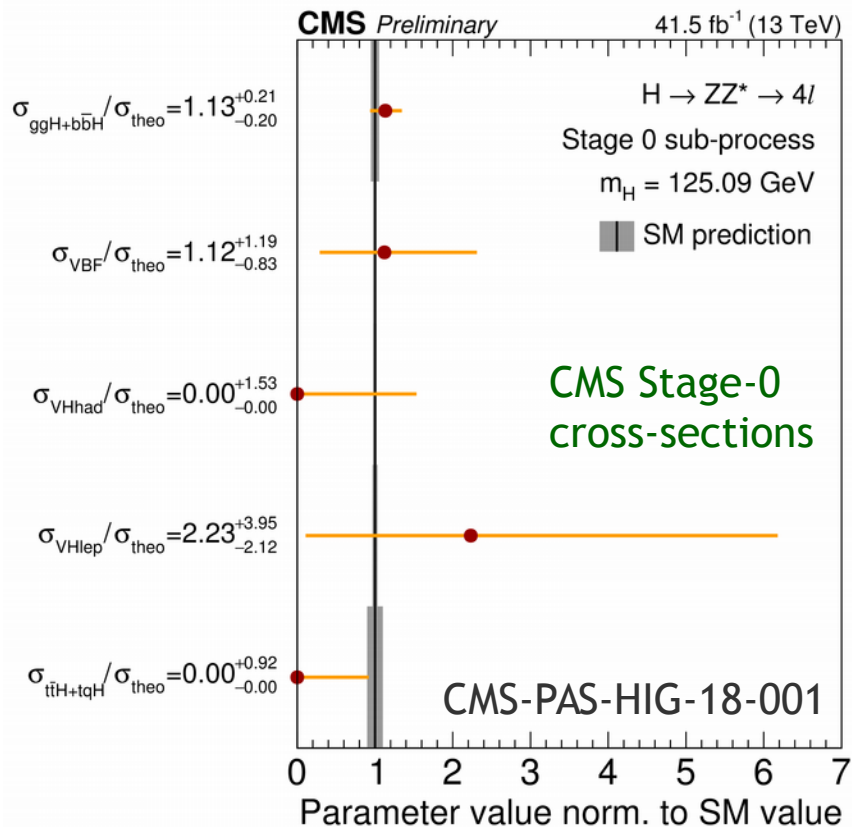




# Standardised fiducial cross-sections

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

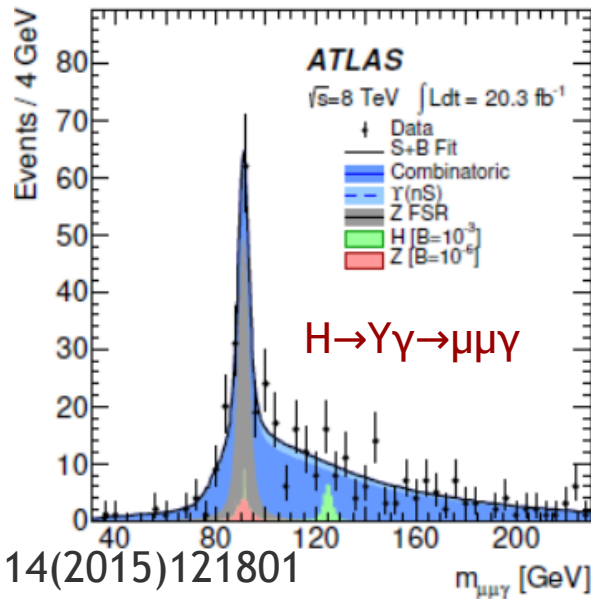
Finer-grained cross-sections (“Stage-1”) becoming accessible now...



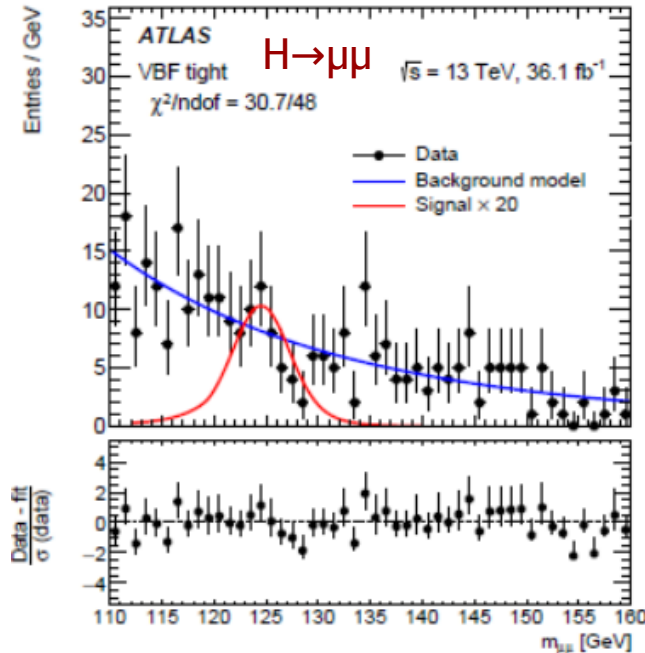
Using these, and/or individual experimental measurements, EFT fits will allow more detailed SM tests – and perhaps provide hints of BSM structure

# H: rare decays, more scalars?

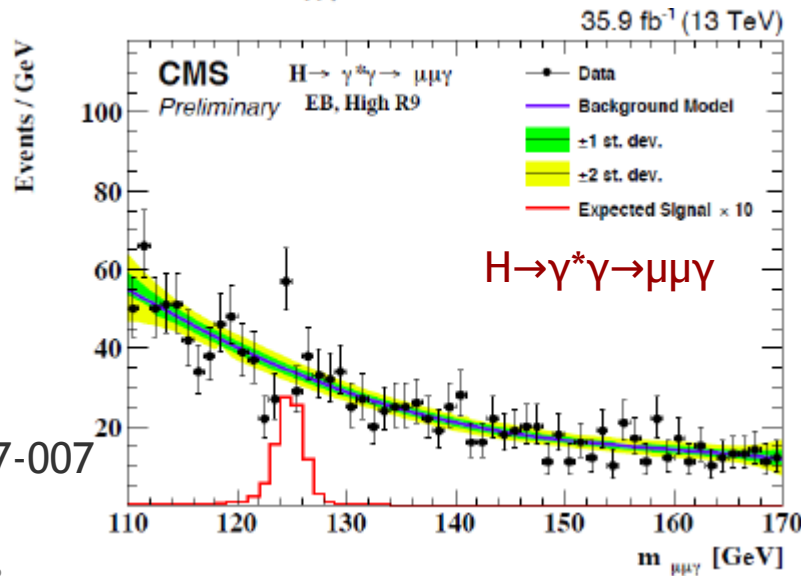
Many results, no surprises yet



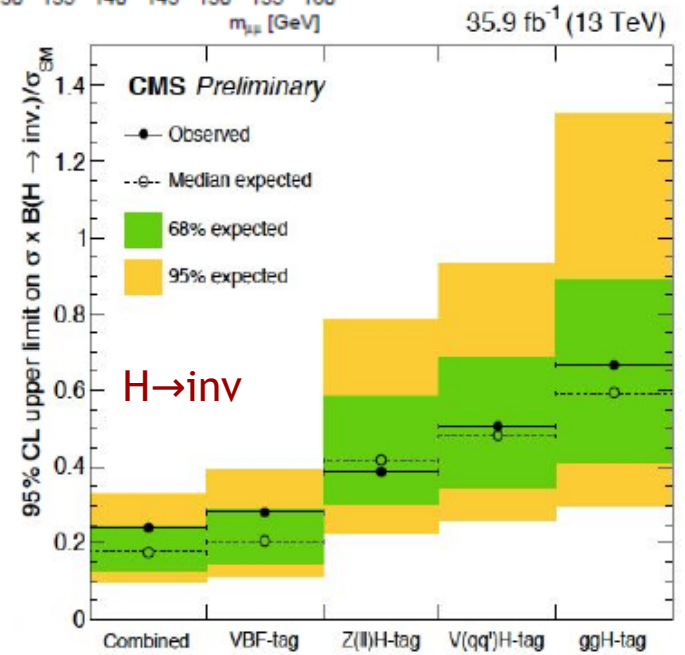
PRL114(2015)121801



PRL119(2017)051802




CMS-PAS-HIG-17-007



CMS-PAS-HIG-17-023

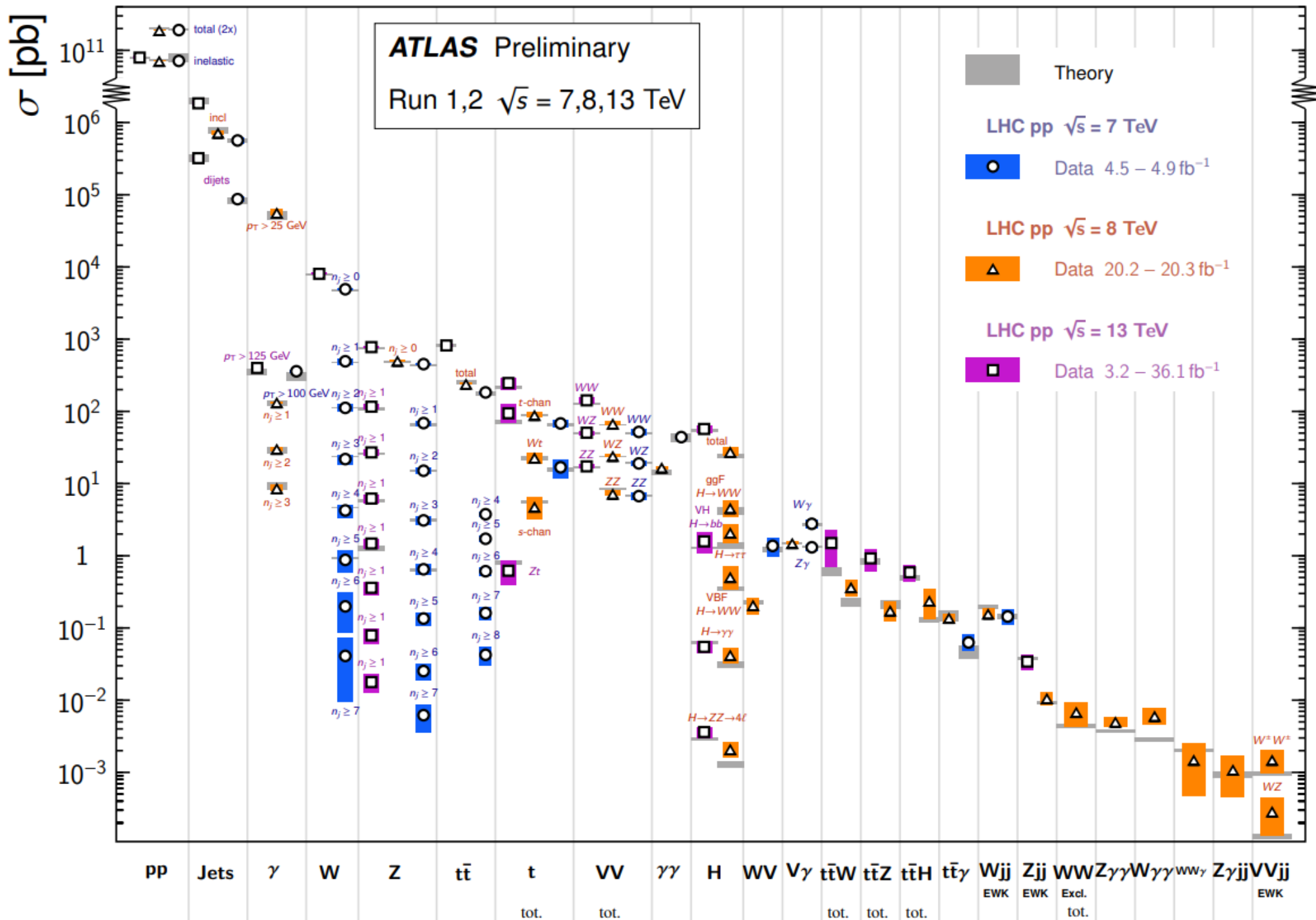


A large, rectangular white tray filled with fresh, yellow, ruffled pasta (farfalle). The pasta is piled high and covers most of the tray. In the center of the image, there is a yellow rectangular box with a black border containing the text "A superabundance of measurements" in bold, dark blue font. The background shows a kitchen counter and a small bowl of pasta in the top left corner.

# **A superabundance of measurements**

# Standard Model Production Cross Section Measurements

Status: March 2018

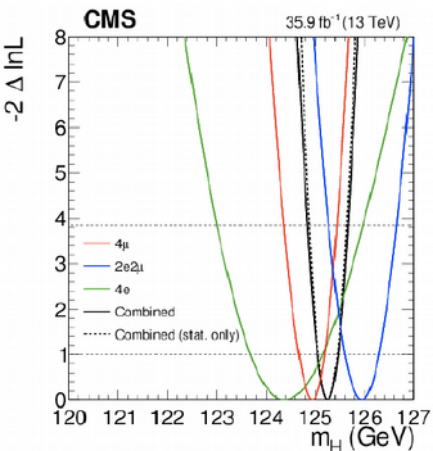
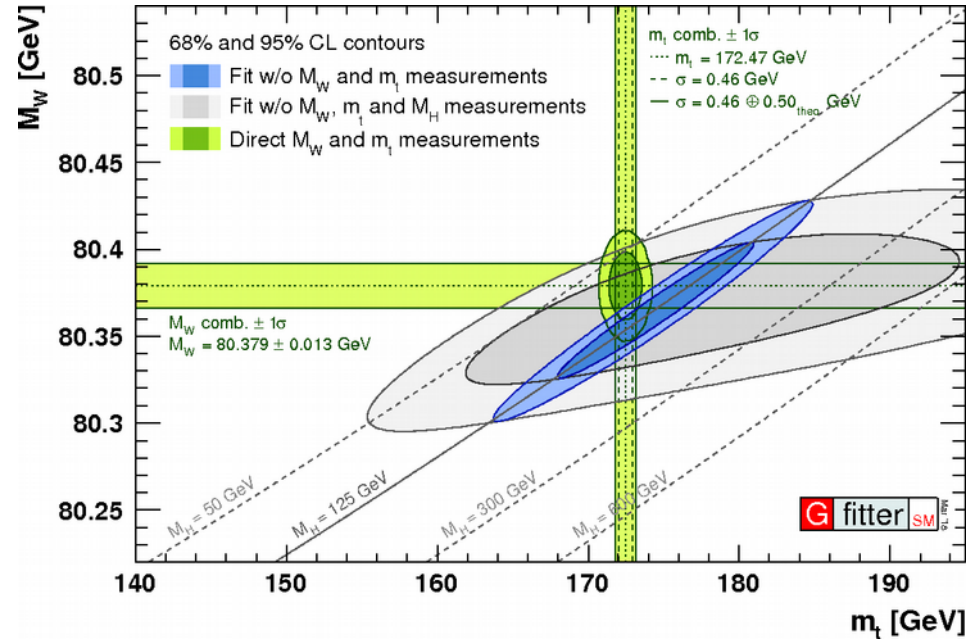
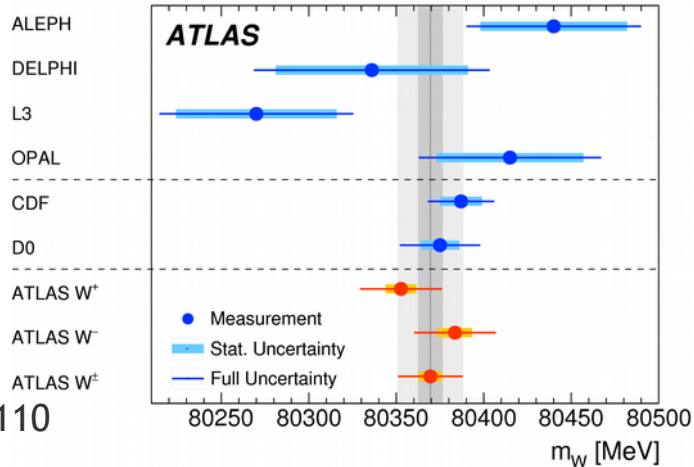




# Precision EW mass measurements

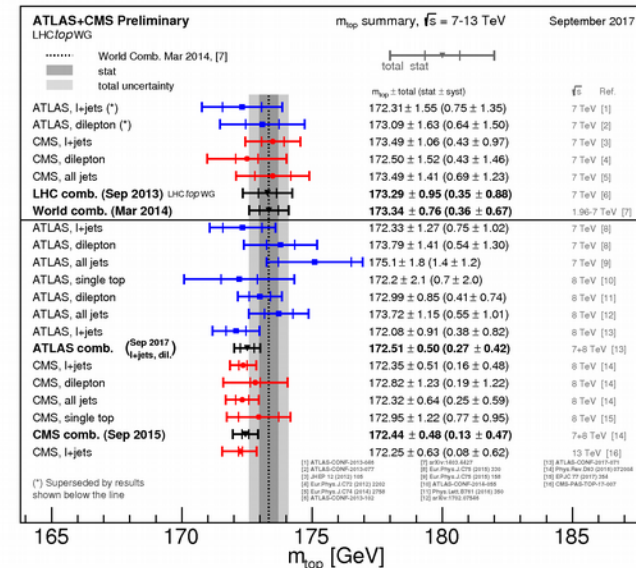
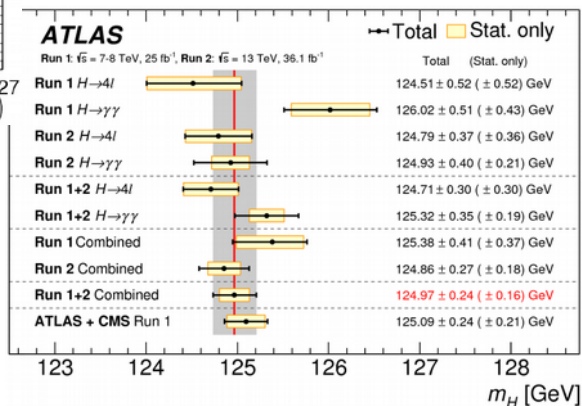
$\pm 19$  MeV  $m_W$   
from ATLAS  
Only LHC  
measurement  
to date

EPJC78 (2018) 110



JHEP 11 (2017) 04

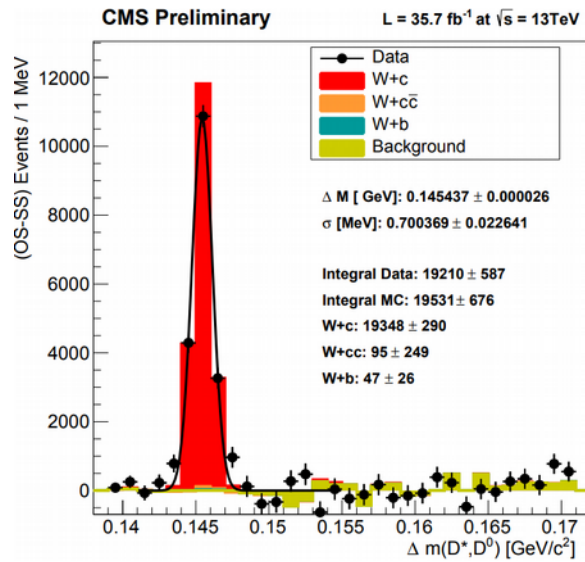
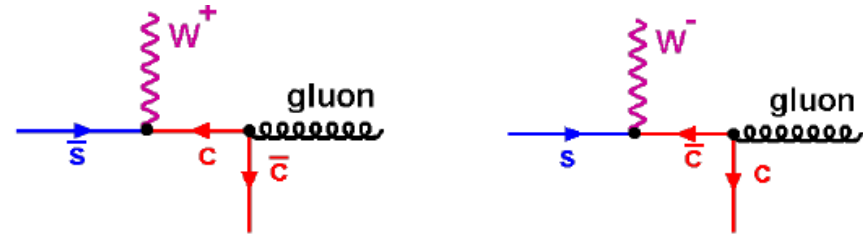
$m_H$  / GeV  
 $124.97 \pm 0.24$  (ATLAS)  
 $125.26 \pm 0.21$  (CMS 4l@13 TeV)



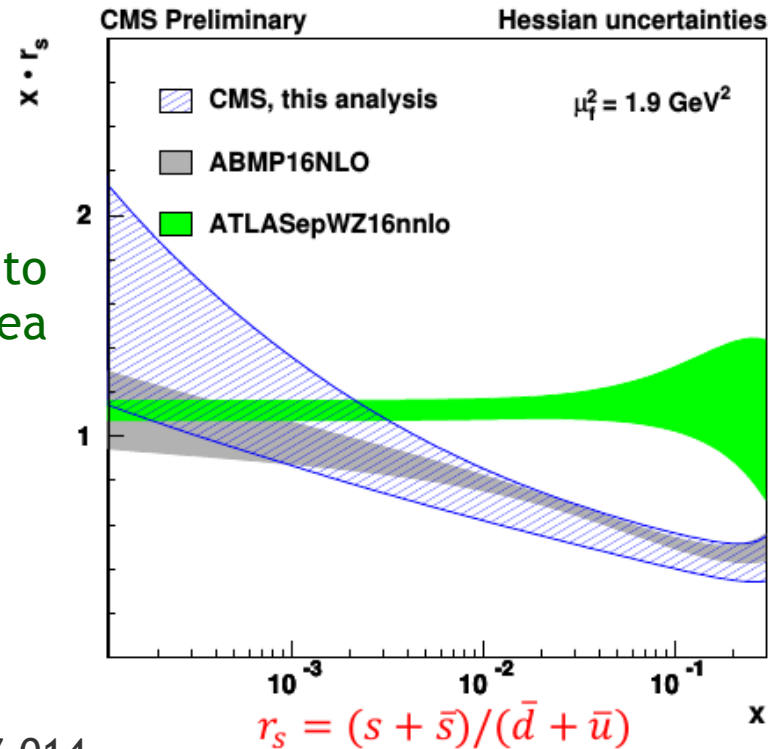
$m_{top}$  error  
(ATLAS or CMS)  
from direct  
reco  $\sim 0.5$  GeV

# W + charm

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

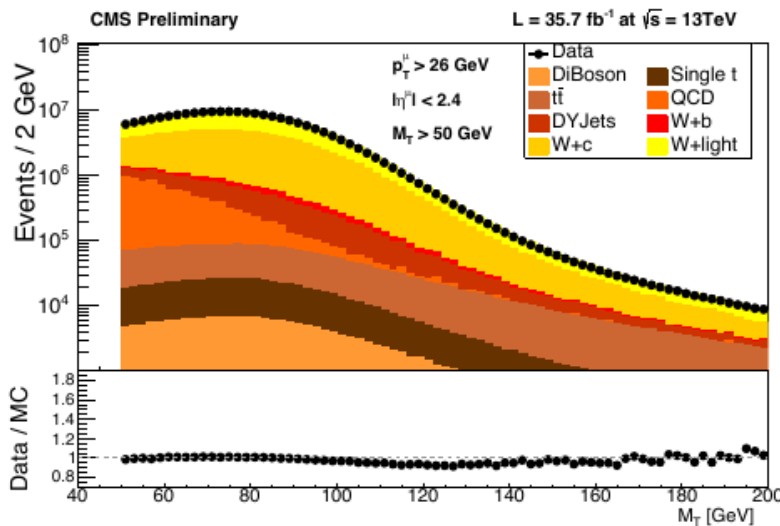


Sensitive to strange sea



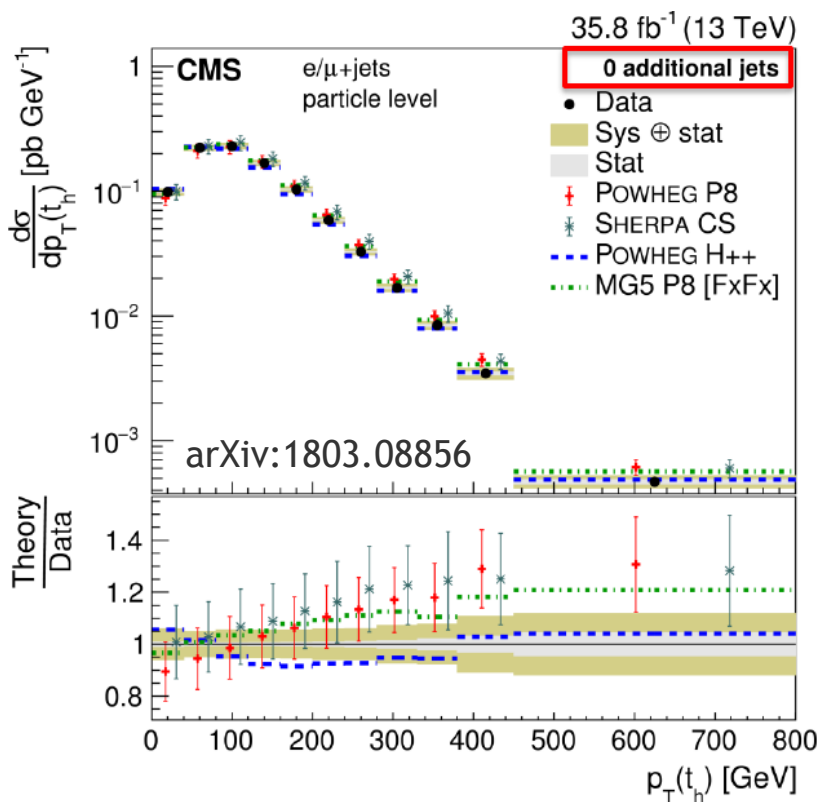
CMS-PAS-SMP-17-014

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

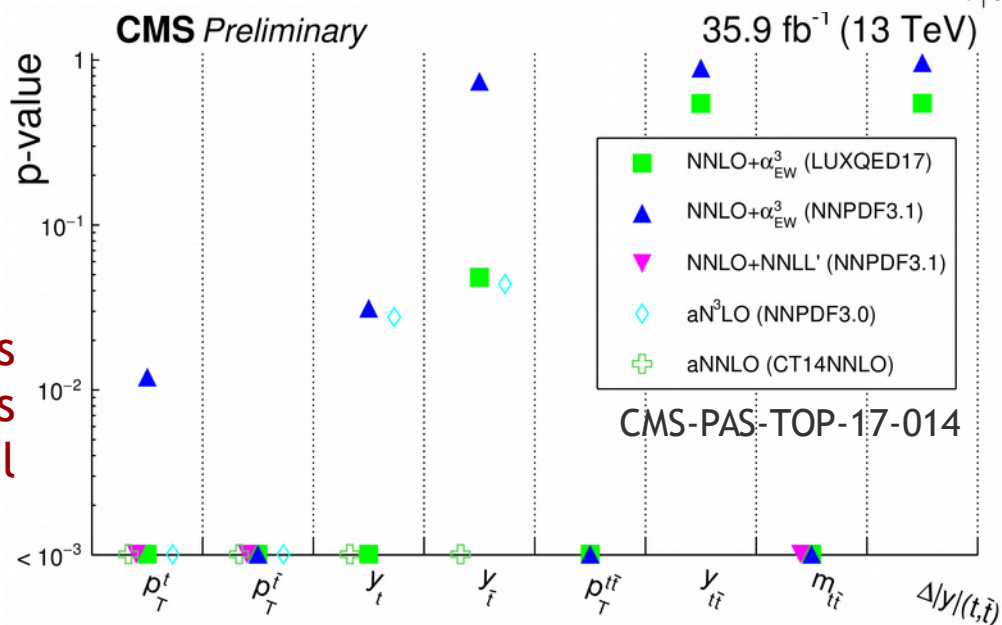
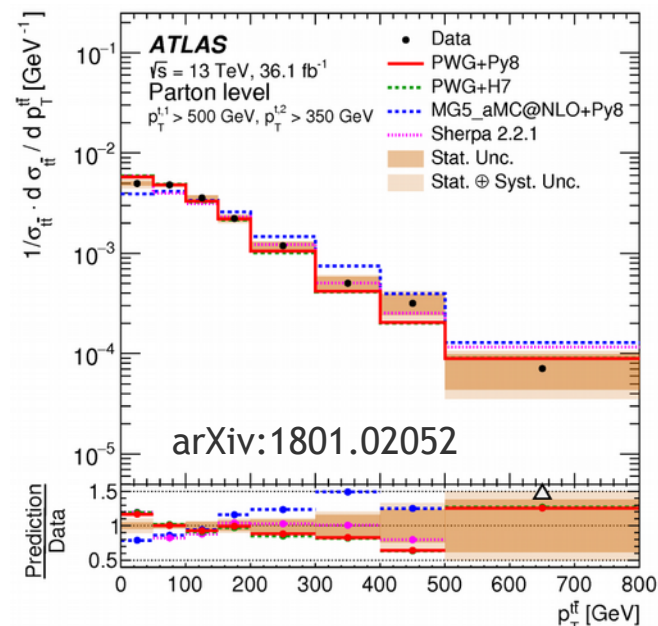


# Top pair production

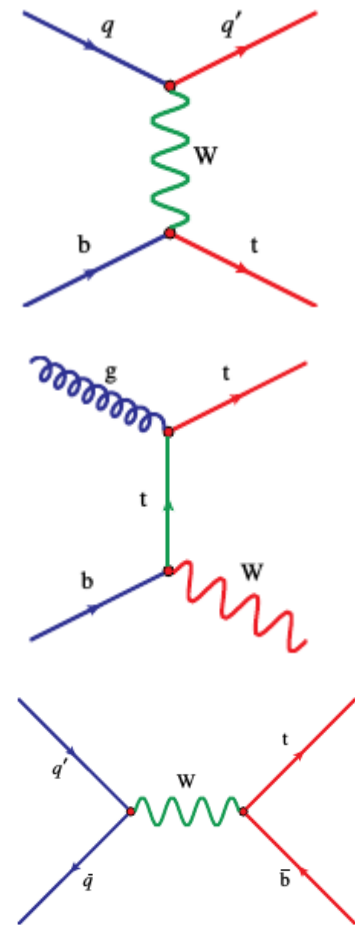
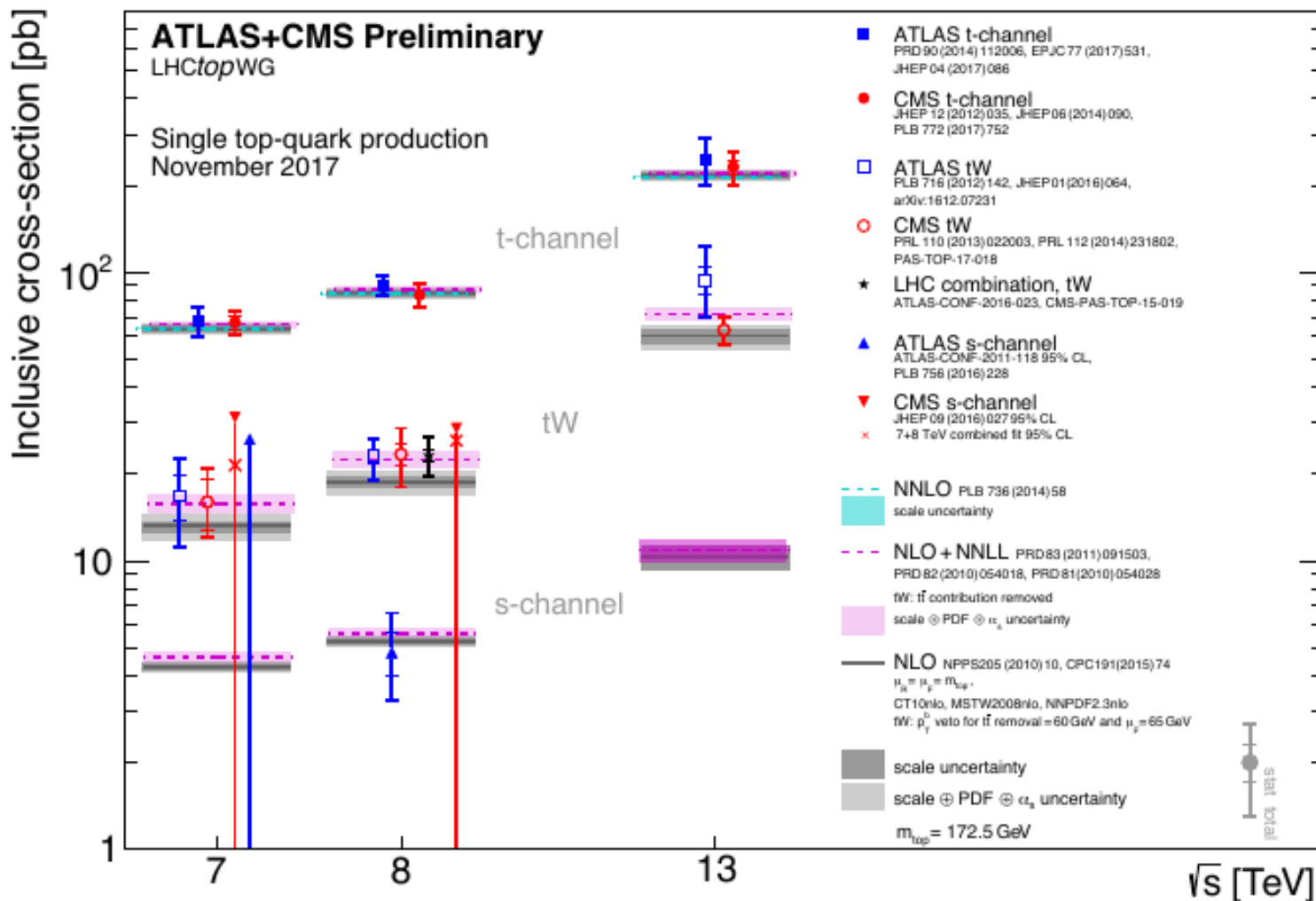
Long-standing (Run-1) difficulties describing the observed  $p_T(\text{top})$  spectrum, although NLO-based MC models much improved for Run-2



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 tq̄q should be seen soon



# Spectroscopy of $\chi_b(3P)$

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

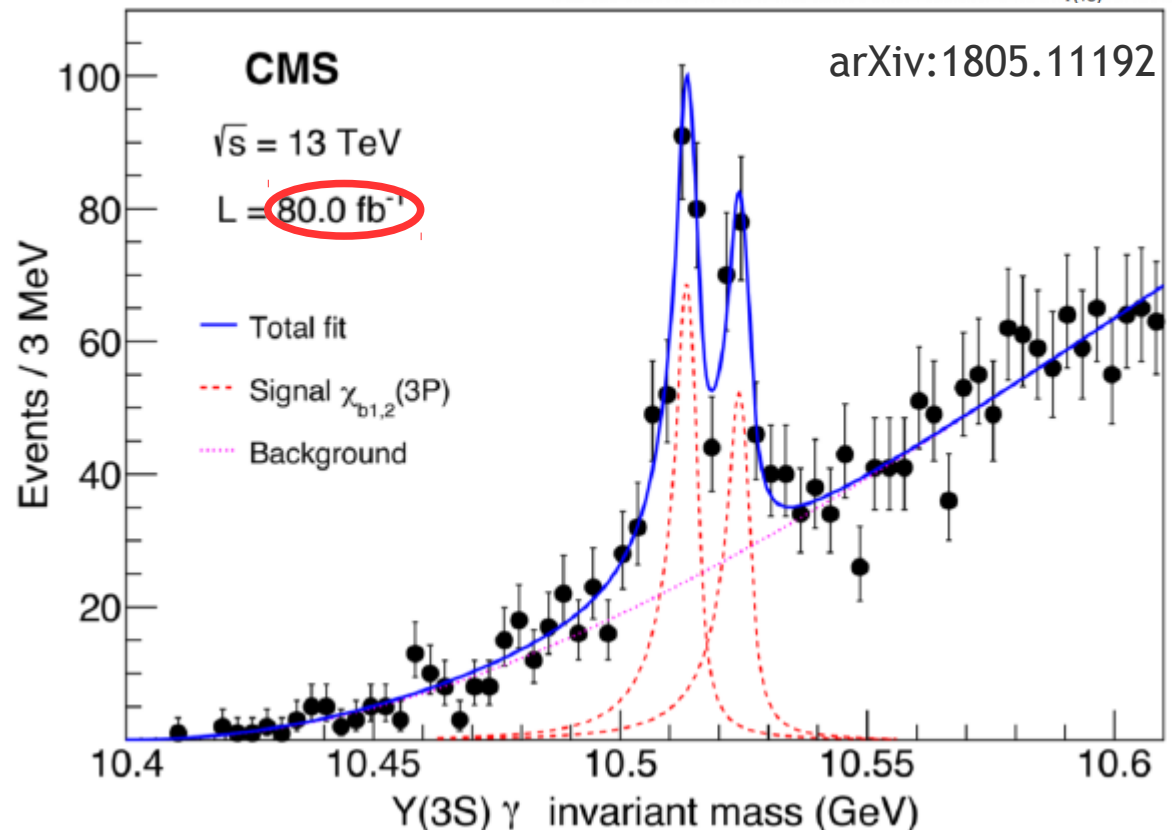
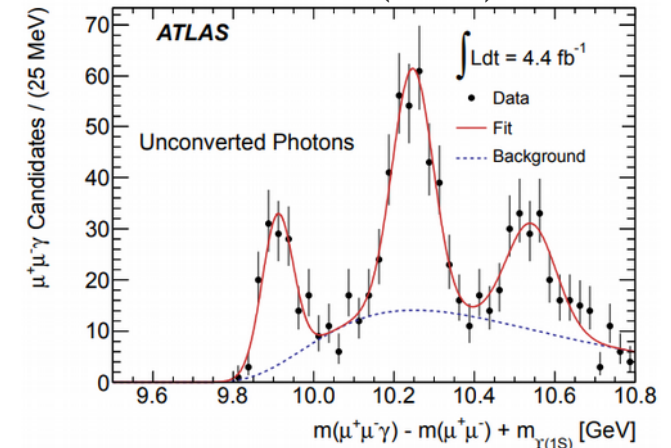
New analysis from CMS, obtains sufficient mass resolution to separate the  $\chi_{b1}(3P)$  and  $\chi_{b2}(3P)$ , using

- Conversions
- Low- $\Delta m$  decays to  $Y(3S)\gamma$

$$m(\chi_{b2}(3P)) - m(\chi_{b1}(3P)) = 10.60 \pm 0.64(\text{stat}) \pm 0.17(\text{syst}) \text{ MeV}$$

Precision spectroscopy!

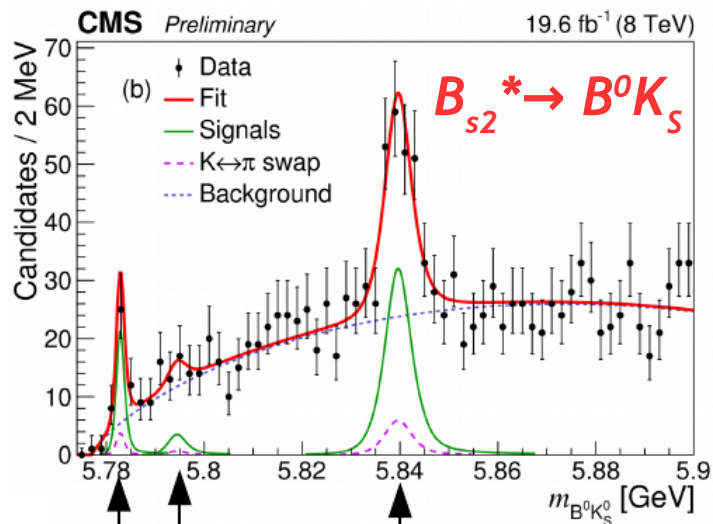
PRL108 (2012) 152001



arXiv:1805.11192

# Heavy hadron spectroscopy

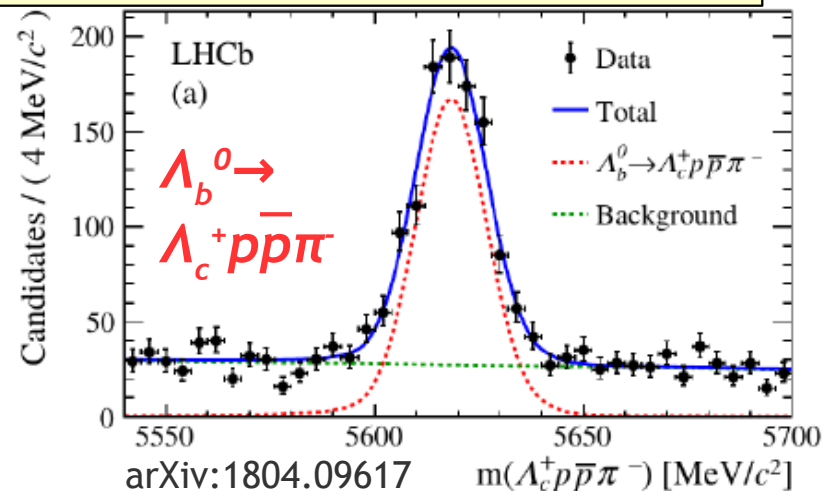
Multiple new states and decay modes being found (or not...) with the huge data samples



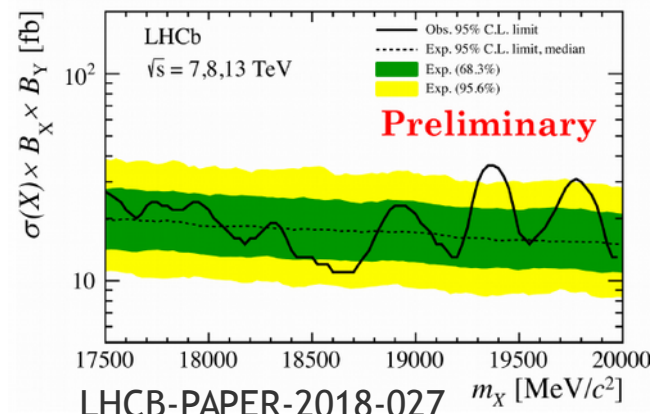
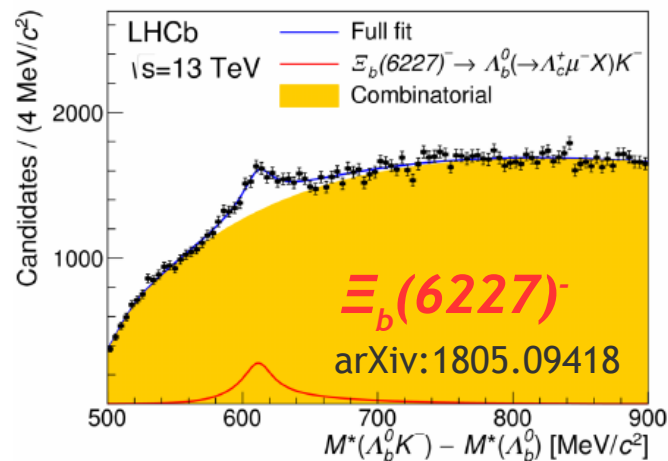
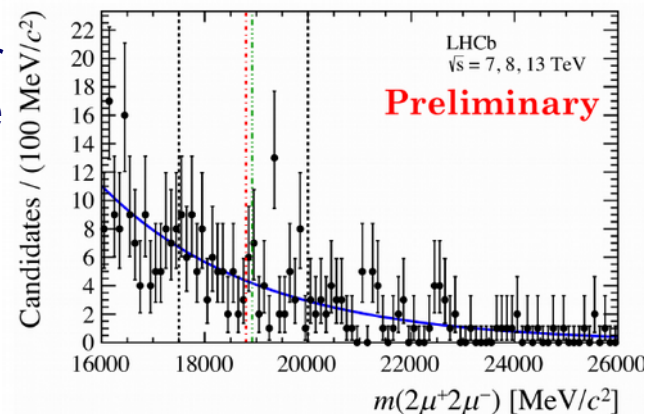
$B_{s1}^* \rightarrow B^{*0} K_s^0$   
(3.6-3.9  $\sigma$ )

$B_{s2}^* \rightarrow B^0 K_s^0$   
(6.3-7  $\sigma$ )

CMS-PAS-BPH-16-003

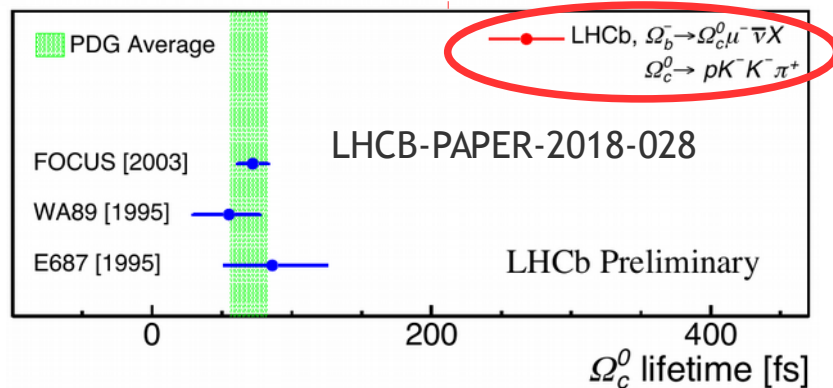
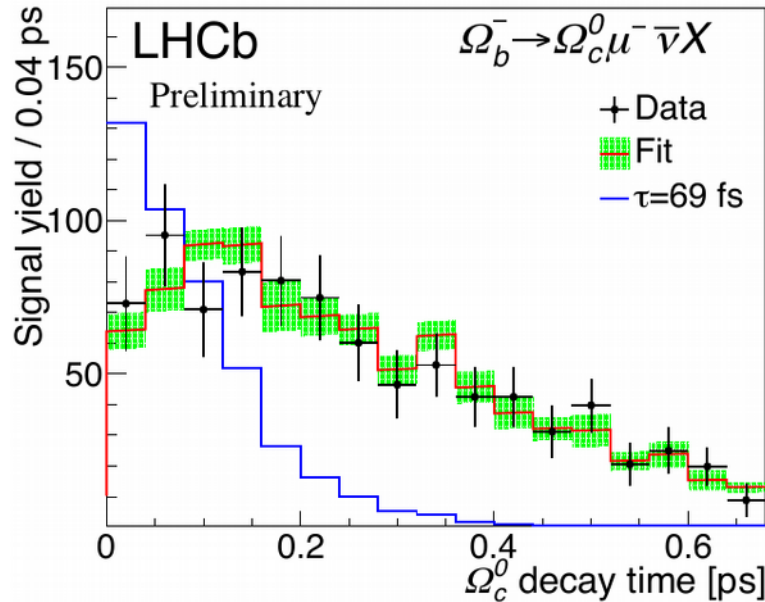


No evidence for  $b\bar{b}b\bar{b}$ -state decaying to  $\Upsilon\mu\mu$

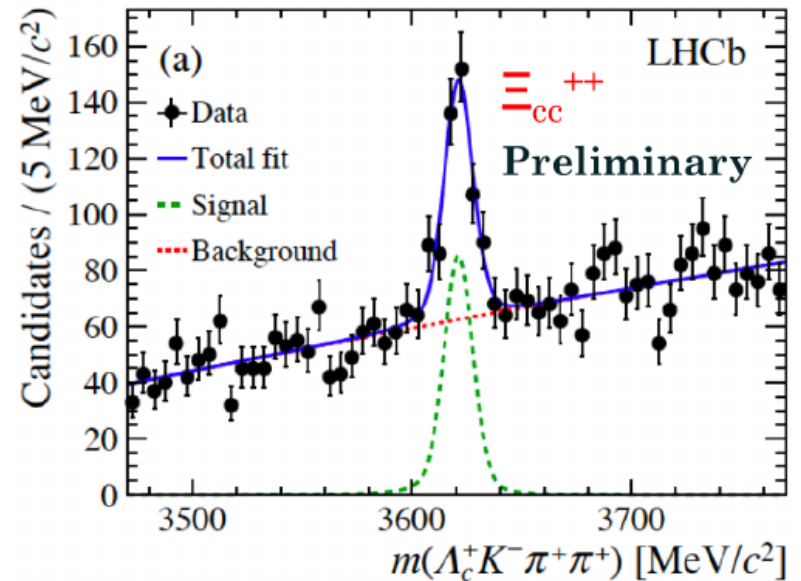


# Heavy hadron lifetimes

New lifetime measurements, with puzzles



LHCb  $\Omega_c$  lifetime measurement much higher than measured in previous experiments



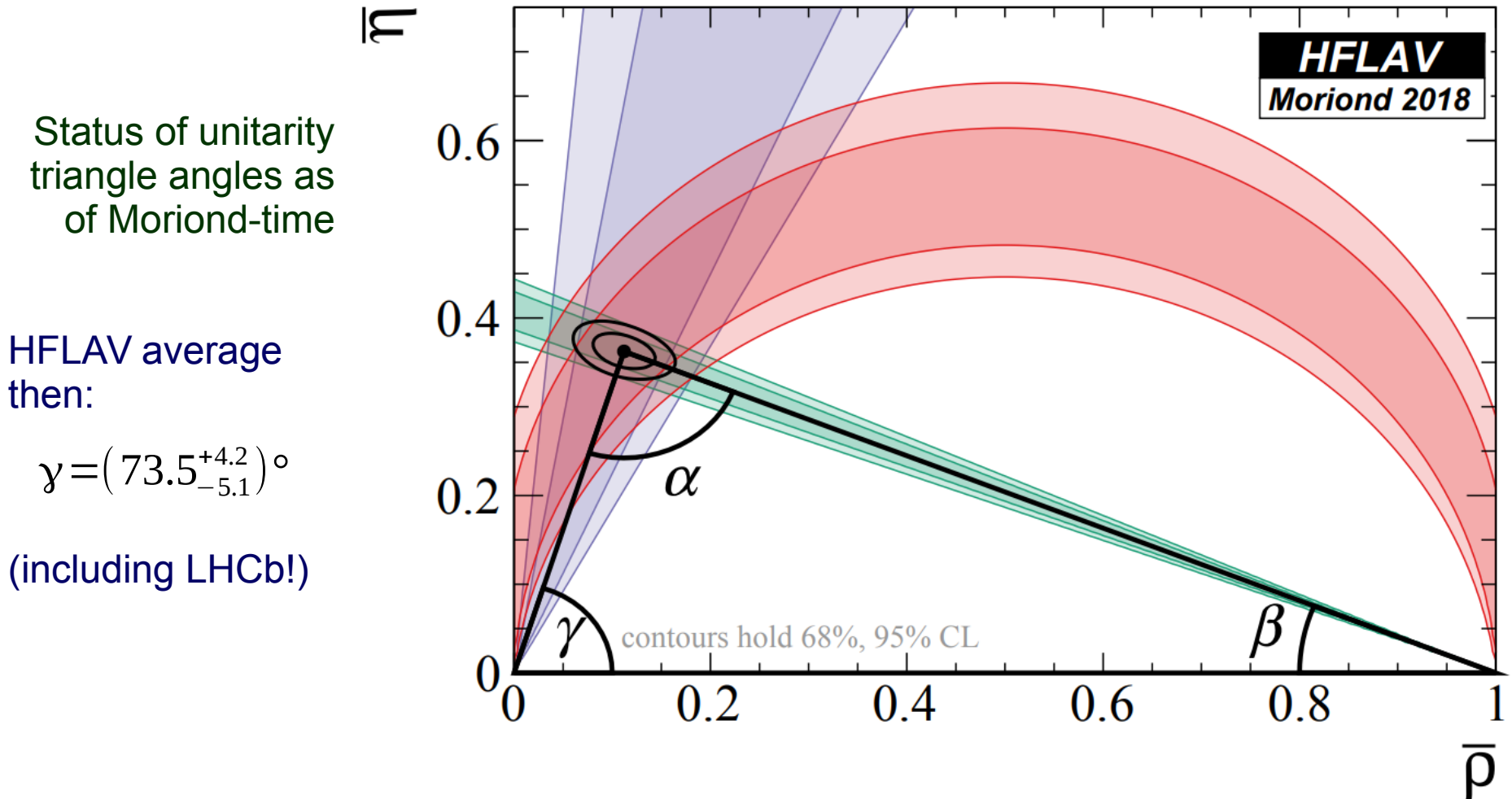
First measurement of  $\Xi_{cc}^{++}$  lifetime

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

arXiv:1806.02744

# Measuring CKM $\gamma$ with LHCb

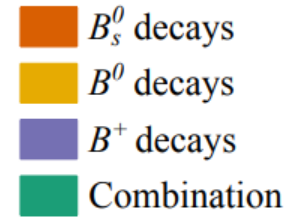
Precision measurement of CKM angle  $\gamma$  a key LHCb goal, using  $B \rightarrow DK$  decays, and requiring excellent understanding of D decay kinematics





# Measuring CKM $\gamma$ with LHCb

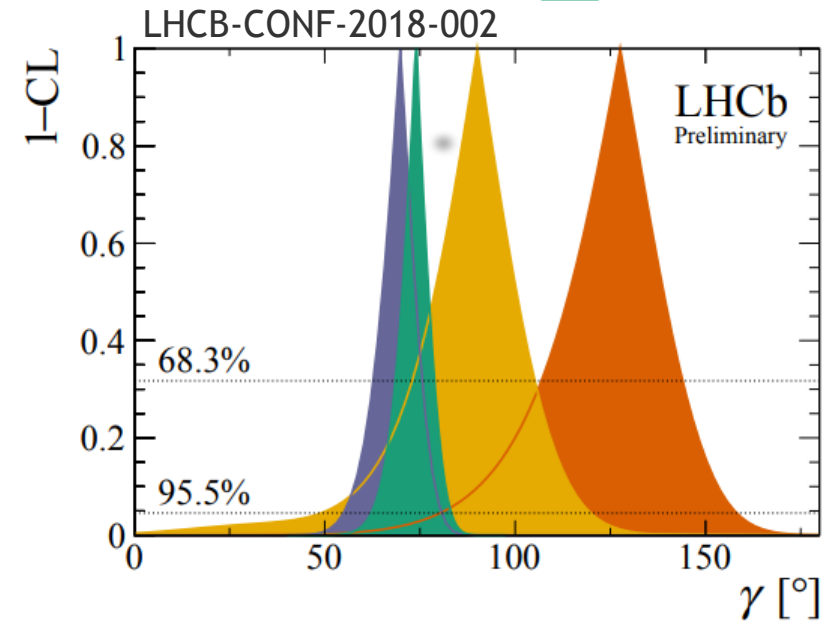
Precision measurement of CKM angle  $\gamma$  a key LHCb goal, using  $B \rightarrow DK$  decays, and requiring excellent understanding of D decay kinematics



Many LHCb measurements, 3 new:

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

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



LHCb combination

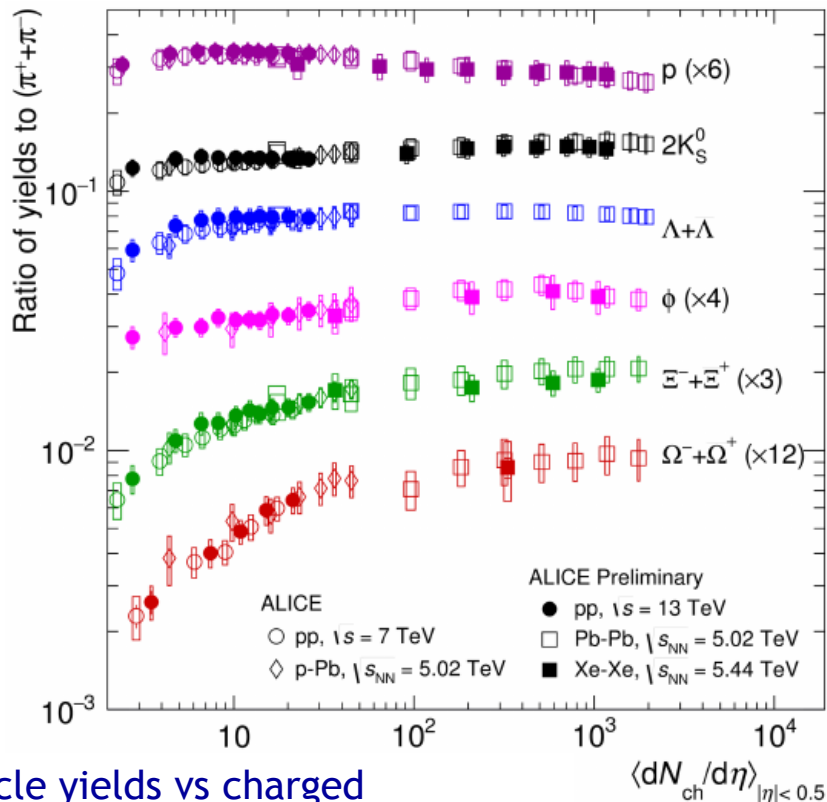
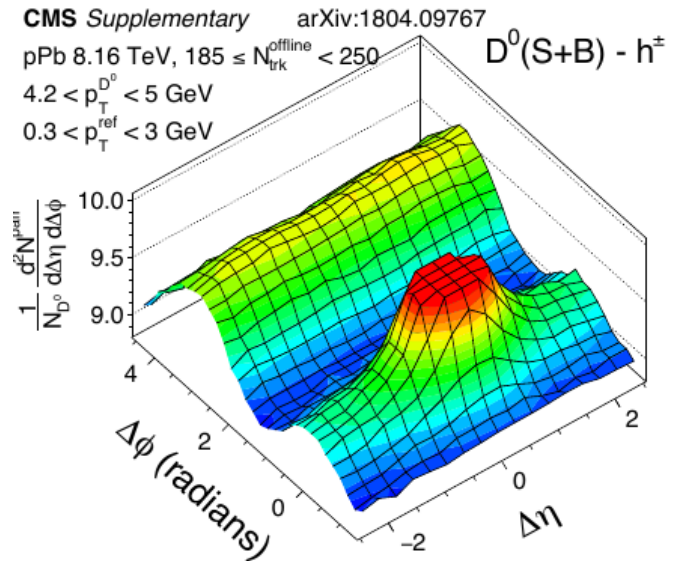
$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

Most precise single-experiment average  
Precision now close to that on  $\alpha$

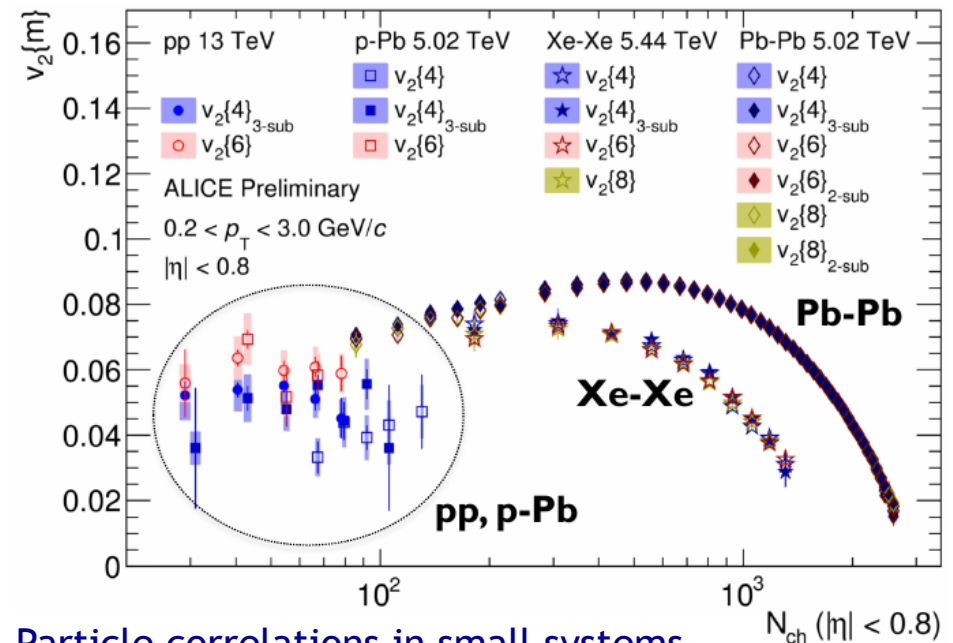
# Heavy ions: collectivity and system size

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



Particle yields vs charged multiplicity - system independent?

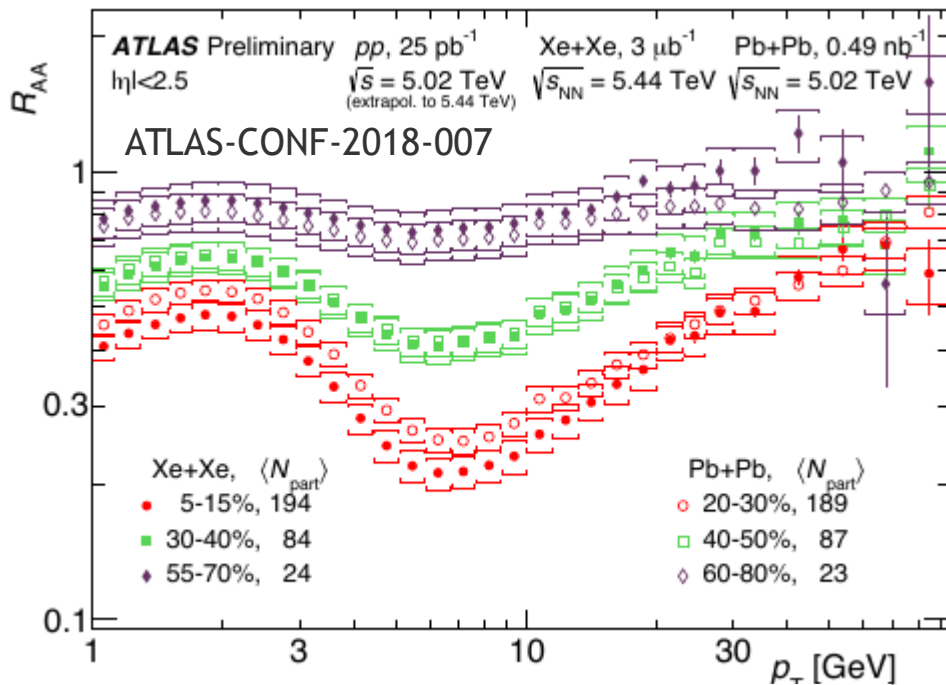


Particle correlations in small systems, apparently not purely from flow

# Heavy ions: XeXe "microsample"

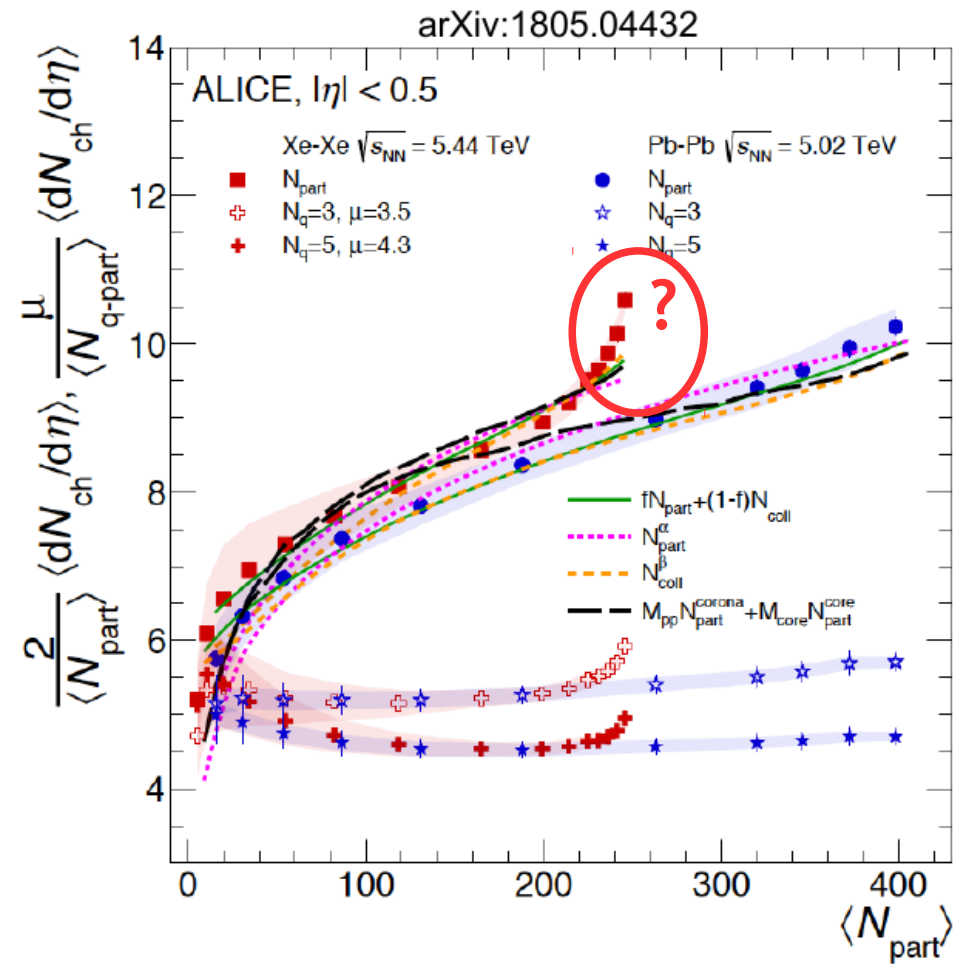
Six hours of data-taking in **Oct 2017**

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



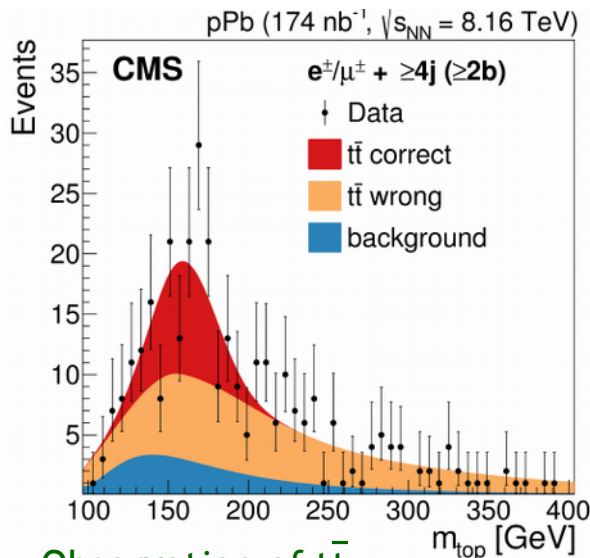
$$R_{AA} = (\text{yield in AA}) / (\text{yield in pp})$$

Similar  $p_T$  dependence in XeXe and PbPb collisions



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

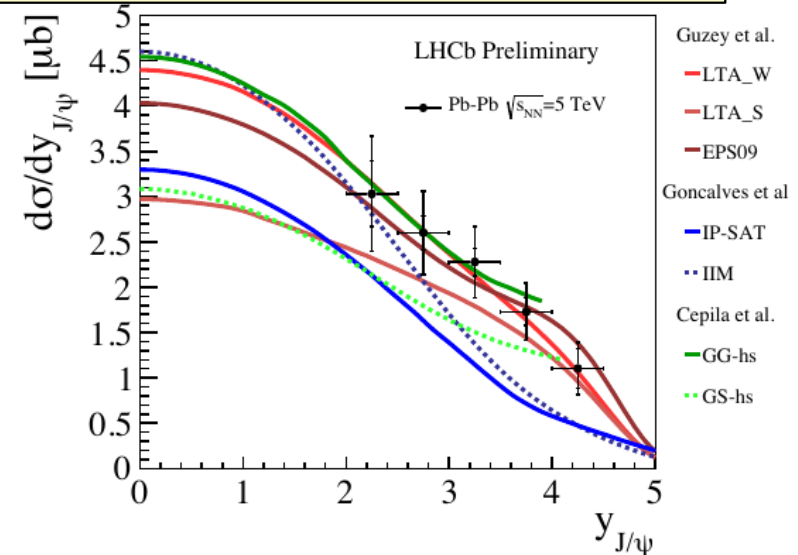
# Heavy ions: hard probes



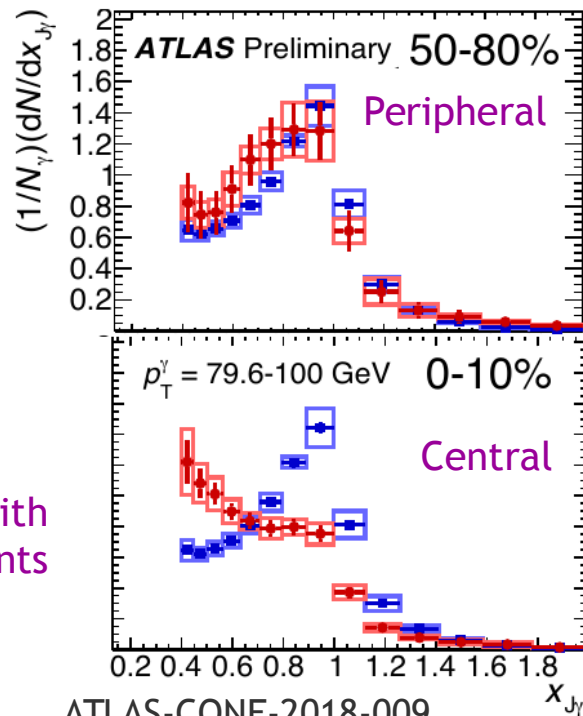
Observation of  $t\bar{t}$  production in pPb collisions  
PRL 119 (2017) 242001

Jet quenching probed with photon+jet events

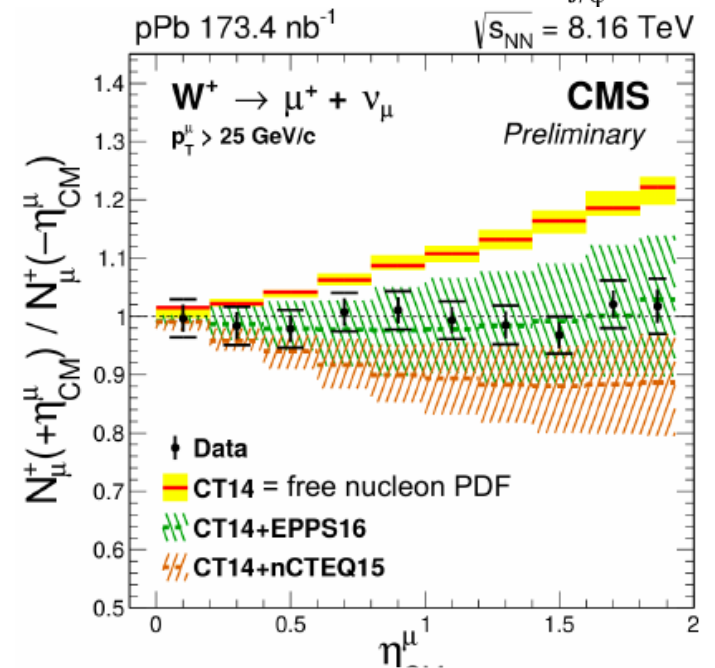
Fwd  $J/\psi$  production may be sensitive to nuclear gluon pdf at low-x



■  $pp$  (same each panel)  
■  $Pb+Pb$



ATLAS-CONF-2018-009



$W$  production sensitive to nuclear effects on nucleon PDFs



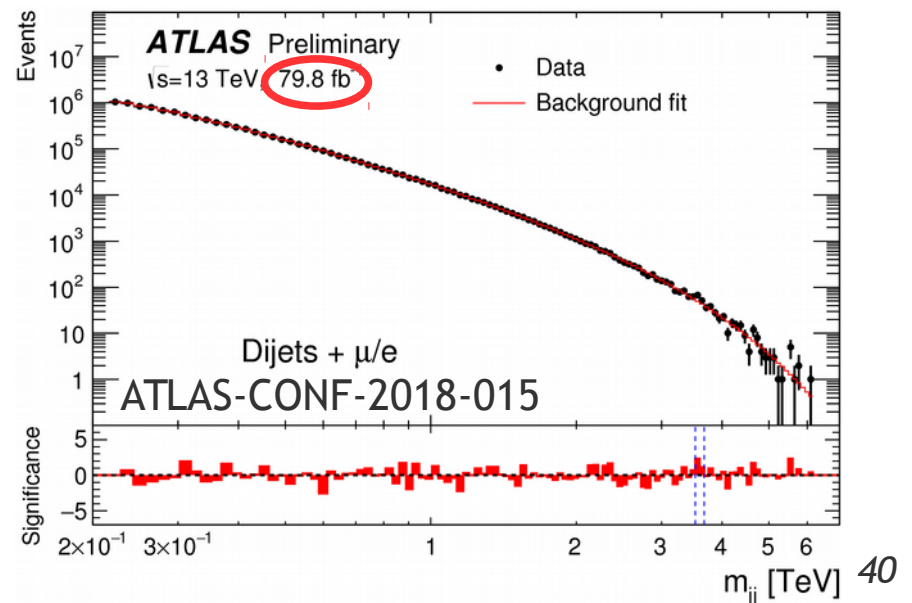
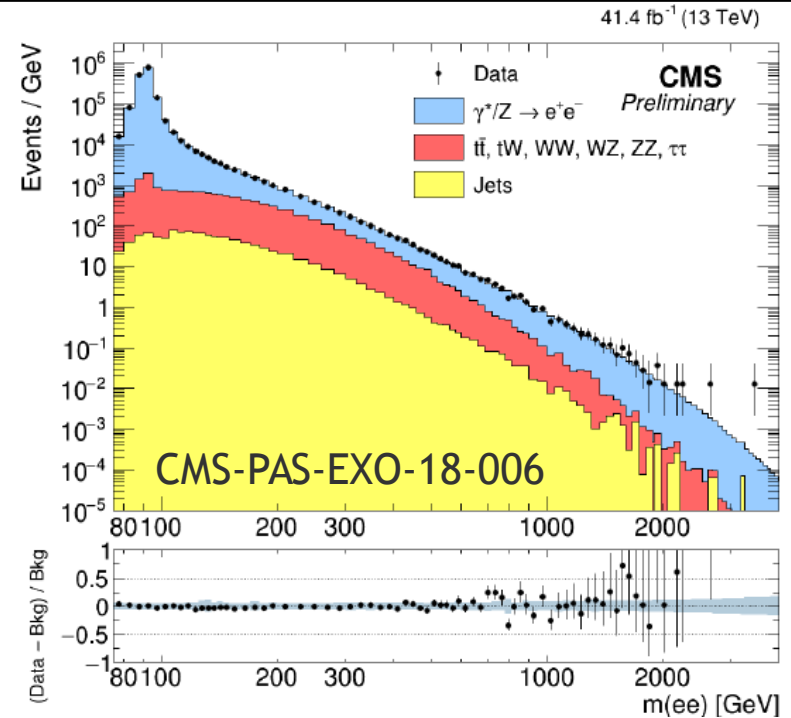
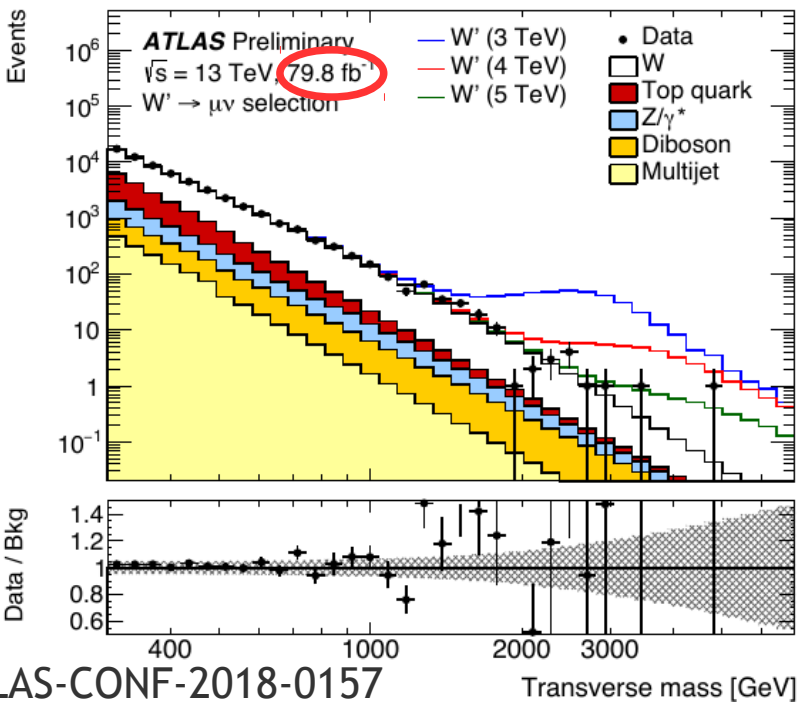
The image shows a grand, wood-paneled interior, likely a courtroom or a formal assembly hall. The walls are covered in dark wood paneling with intricate carvings and statues. A central text box is overlaid on the image. In the foreground, there is a wooden bench with a white, curved table on it. The room is lit by a chandelier in the upper right corner.

**Searches continue**

# Searching fast...

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

- $Z' \rightarrow ee$  (CMS)
- $W' \rightarrow \ell\nu$  (ATLAS)
- $VV \rightarrow JJ$  resonances (ATLAS)
- Dijet resonances with a  $\ell$  (ATLAS)
- Type-III seesaw heavy  $\ell$  (ATLAS)
- $L_\mu - L_\tau$  light boson in  $4\mu$  final state (CMS)

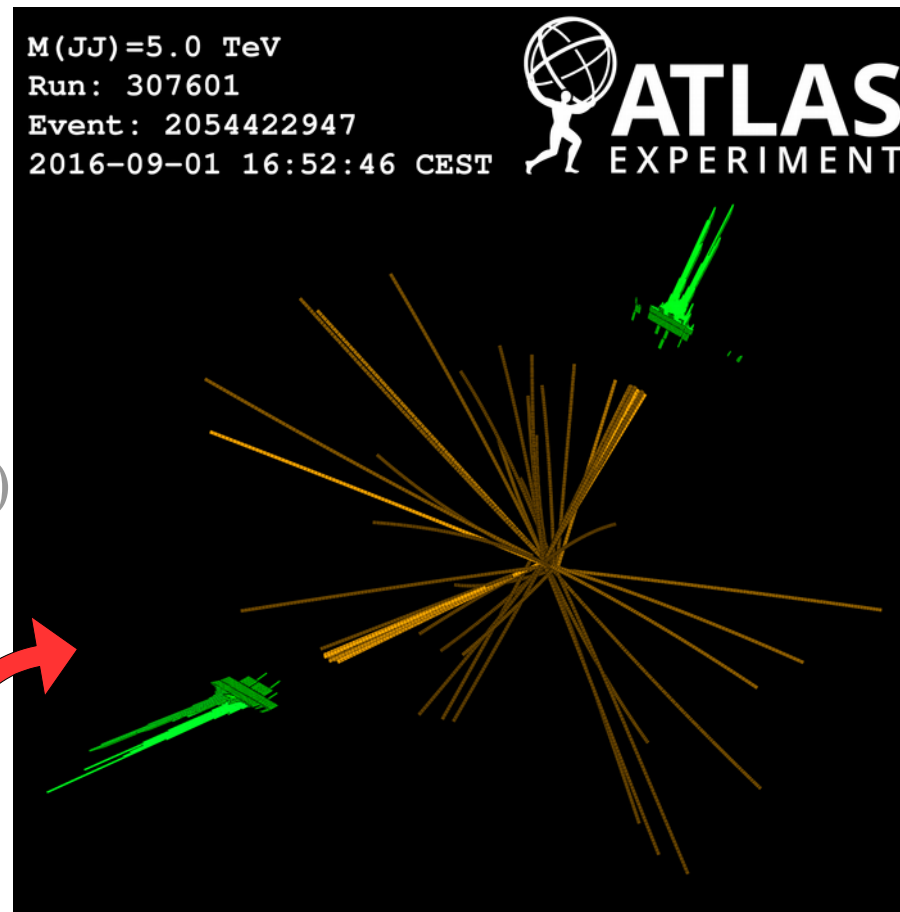
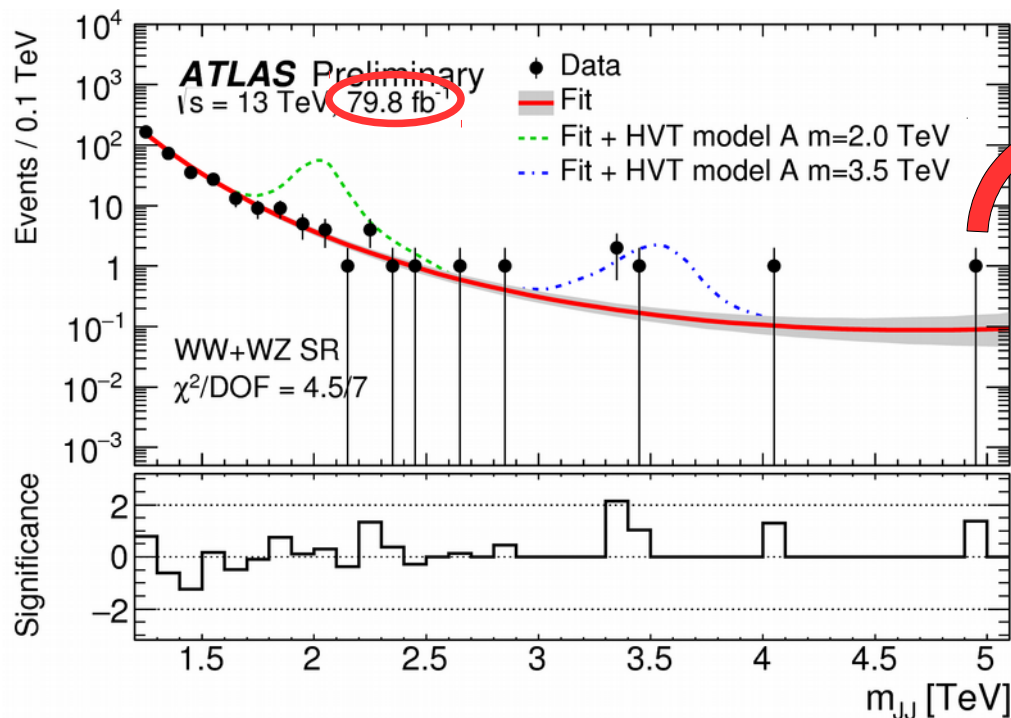




# Searching fast...

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

- $Z' \rightarrow ee$  (CMS)
- $W' \rightarrow \ell \nu$  (ATLAS)
- $VV \rightarrow JJ$  resonances (ATLAS)
- Dijet resonances with a  $\ell$  (ATLAS)
- Type-III seesaw heavy  $\ell$  (ATLAS)
- $L_\mu - L_\tau$  light boson in  $4\mu$  final state (CMS)

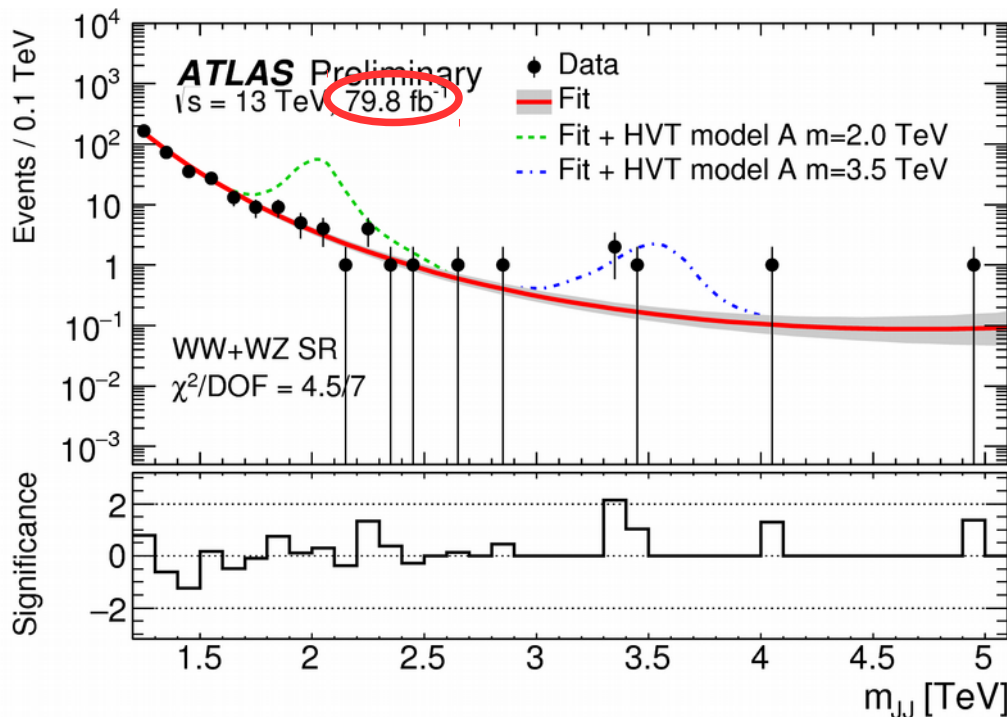


Striking visual impact of the power of the detectors

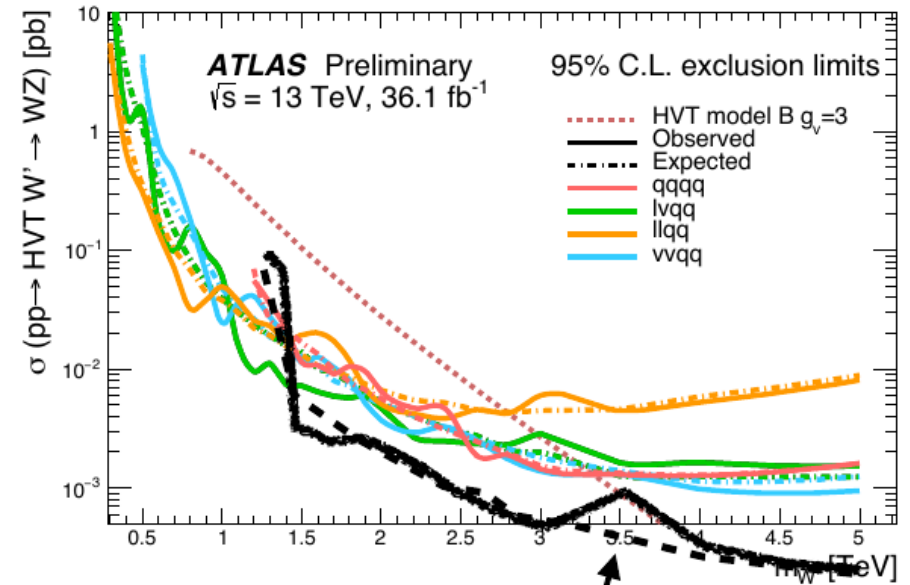
# Searching fast...

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

- $Z' \rightarrow ee$  (CMS)
- $W' \rightarrow \ell \nu$  (ATLAS)
- $VV \rightarrow JJ$  resonances (ATLAS)
- Dijet resonances with a  $\ell$  (ATLAS)
- Type-III seesaw heavy  $\ell$  (ATLAS)
- $L_\mu - L_\tau$  light boson in  $4\mu$  final state (CMS)



$W'$



new 80  $\text{fb}^{-1}$  result

Roman Kogler



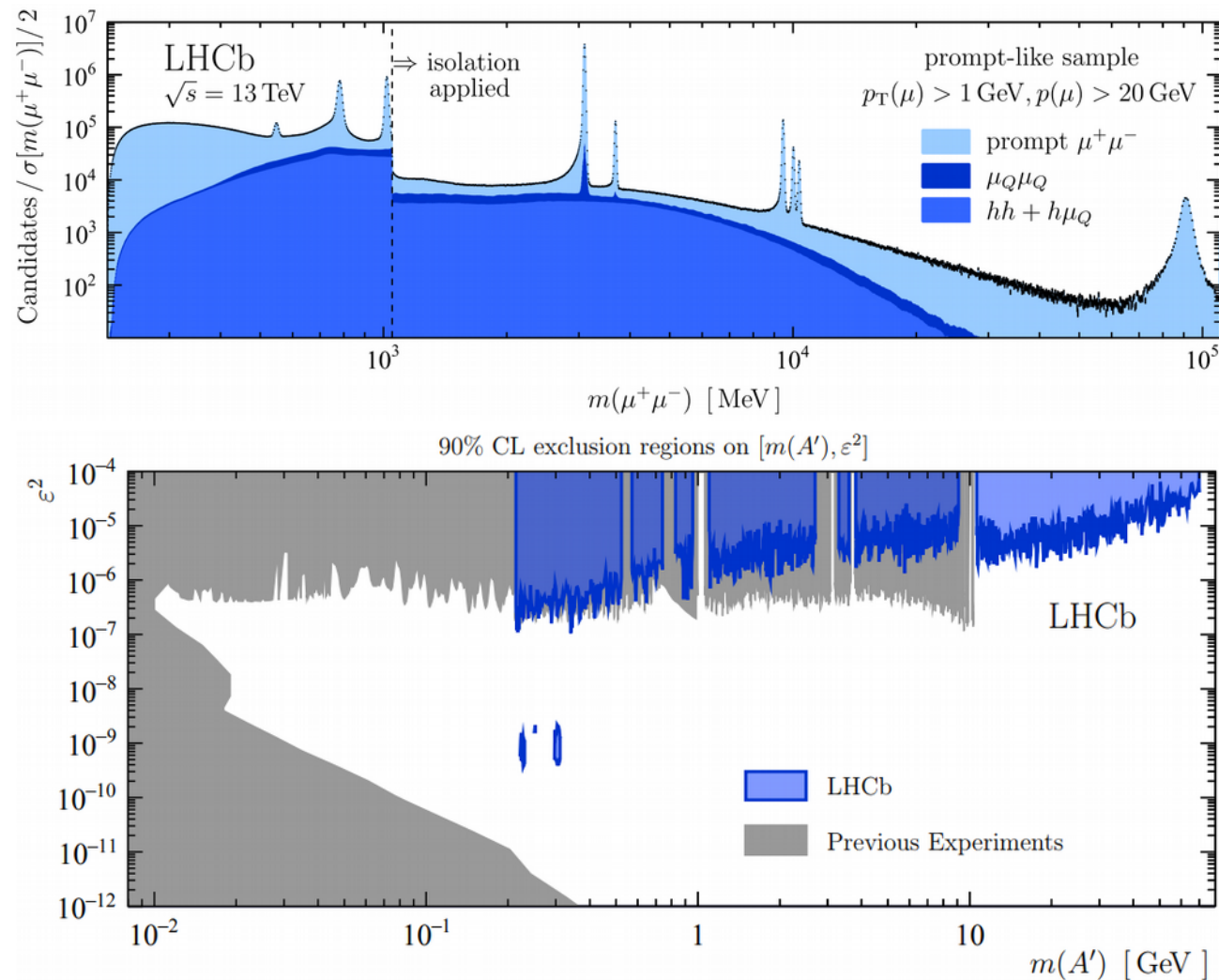
# Probing new regions

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

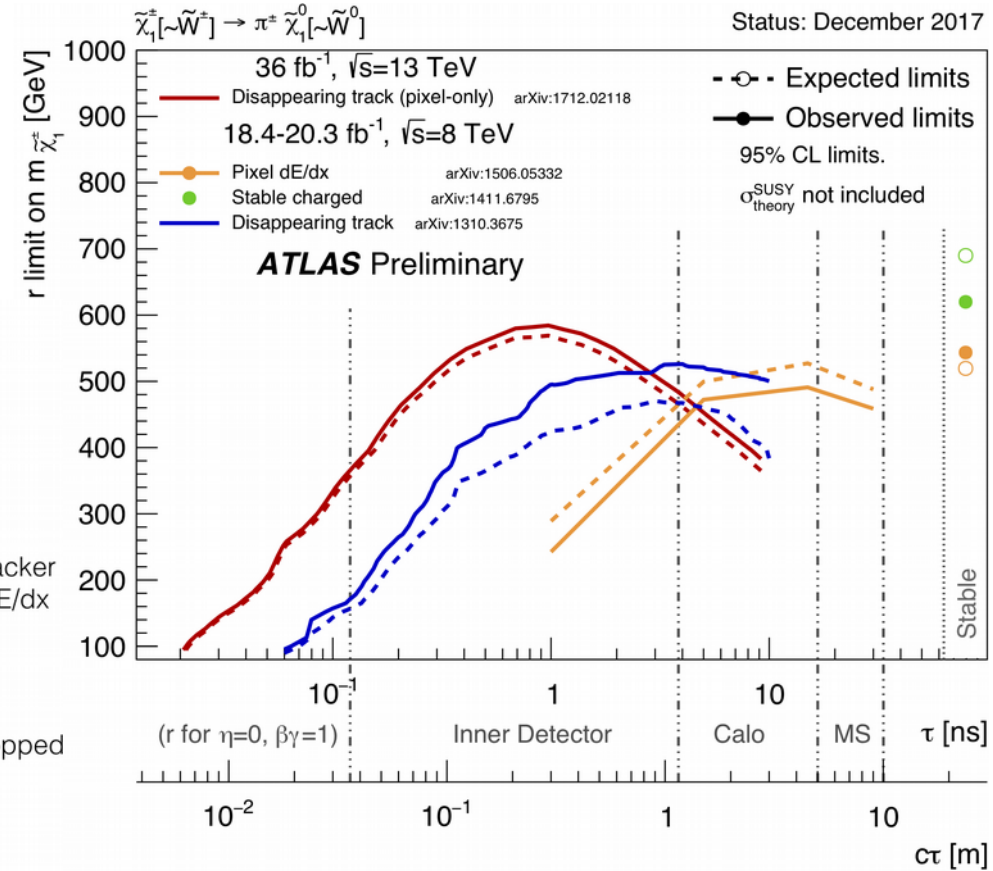
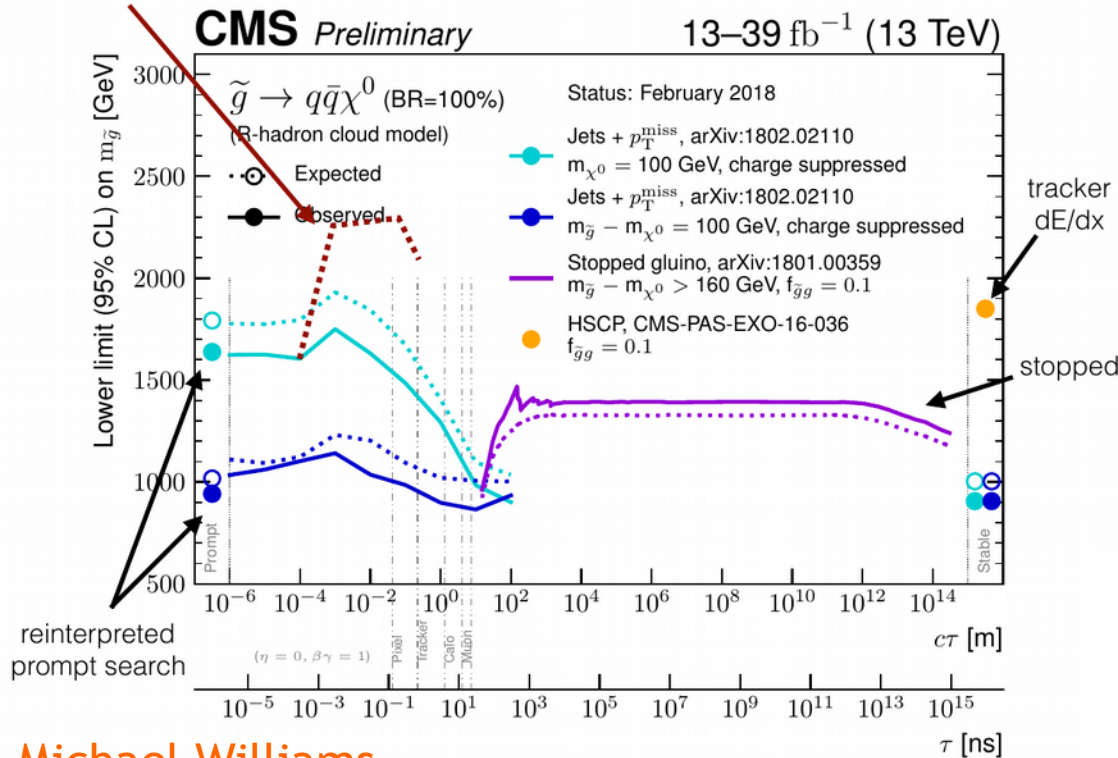


# Searching widely and deeply

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

NEW! DV+MET  
CMS-PAS-EXO-17-018  
(see talk by V Kutzner)

## R-Hadrons @ CMS



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

Michael Williams

# Tensions over flavour

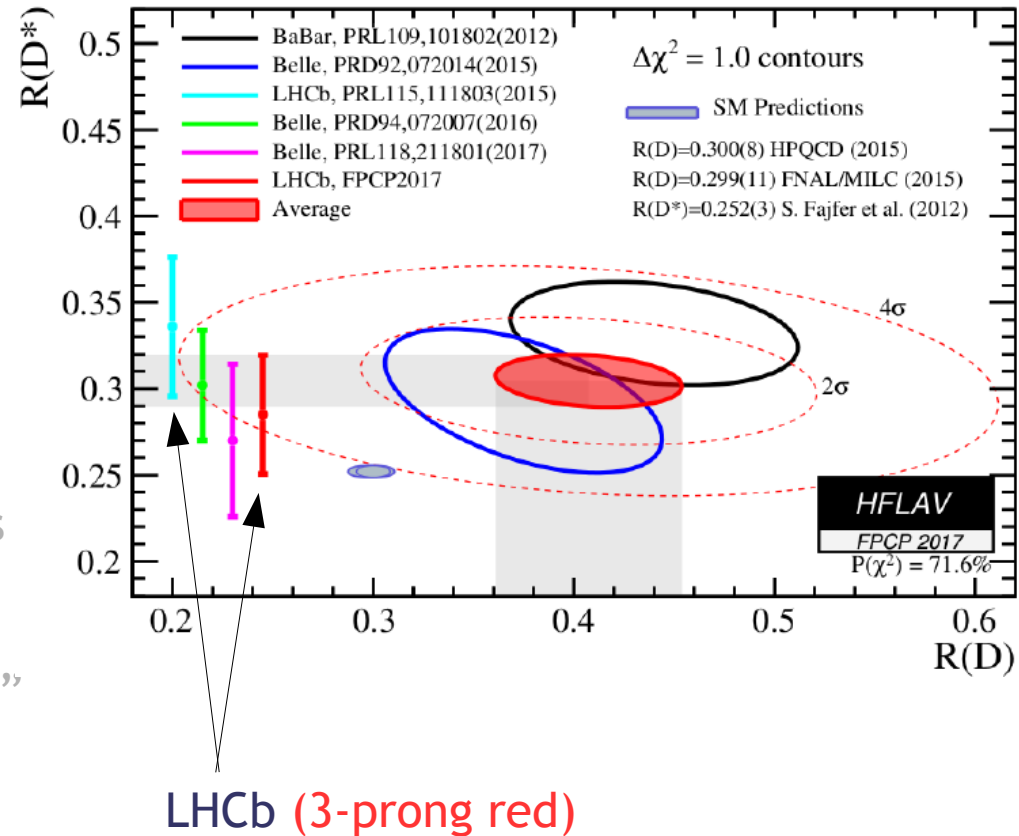
Recent excitement about tensions in lepton-flavour universality (LFU) in B decays

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  $1\sigma$
- $\mu\mu:ee$  flavour ratios in FCNC loop decays
  - Tensions at the  $2.x\sigma$  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



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

# Tensions over flavour

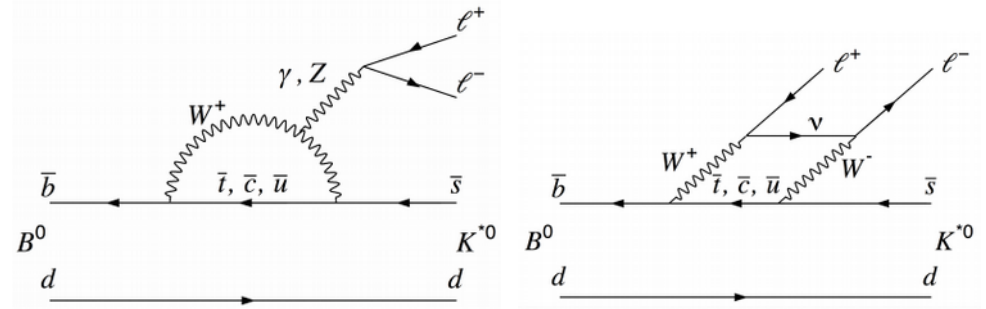
Recent excitement about tensions in lepton-flavour universality (LFU) in B decays

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  $1\sigma$
- $\mu\mu:ee$  flavour ratios in FCNC loop decays
  - Tensions at the  $2.2\text{-}2.6\sigma$  level

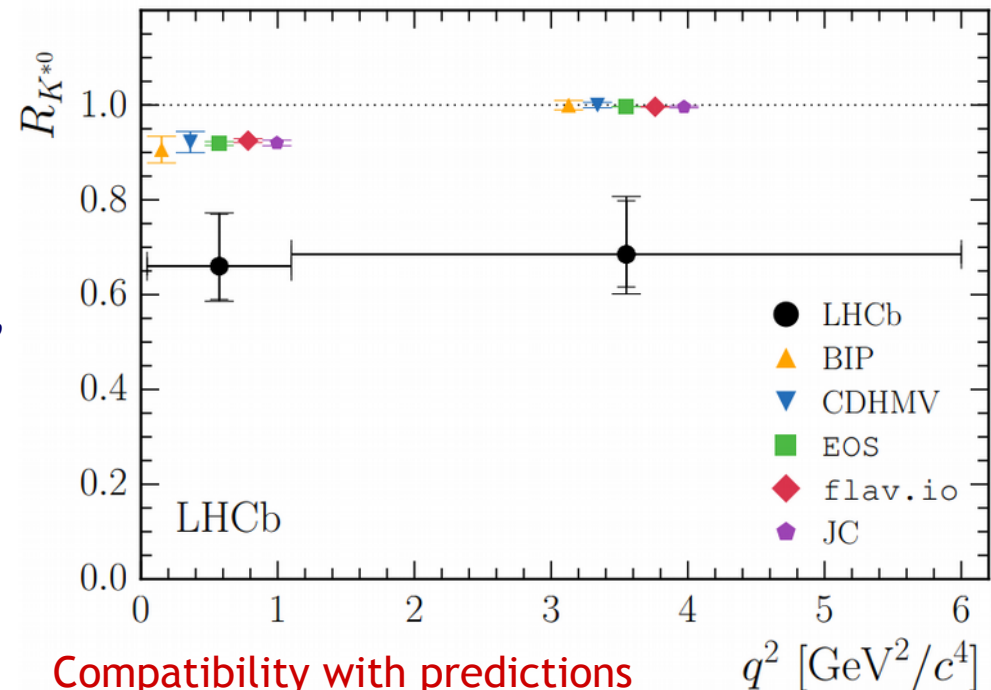
Combined fits give striking “NP significances” - *caveat emptor* with a posteriori TH fits to complex analyses

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



One example...

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

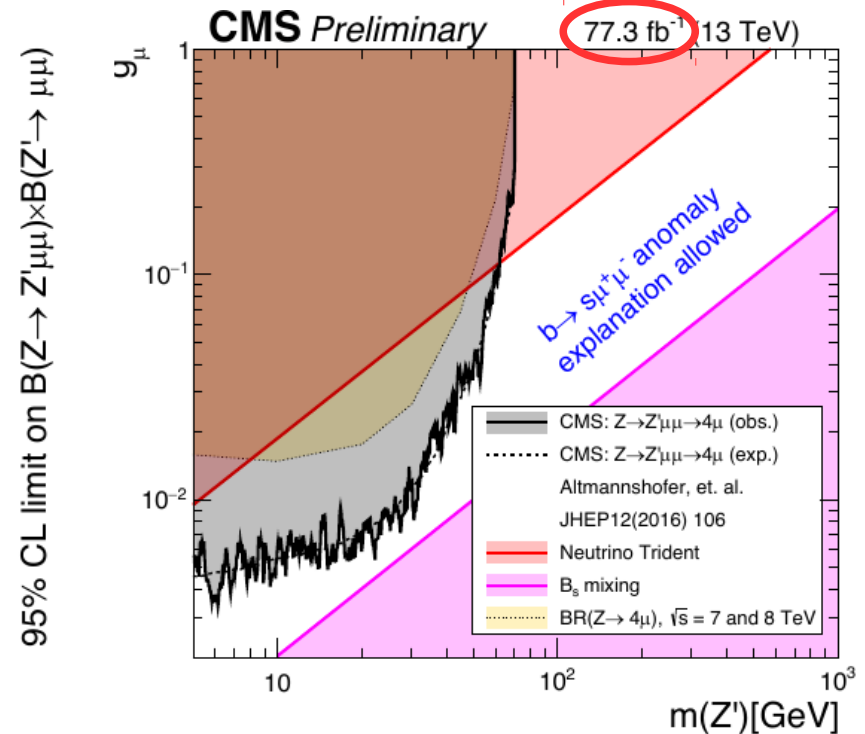
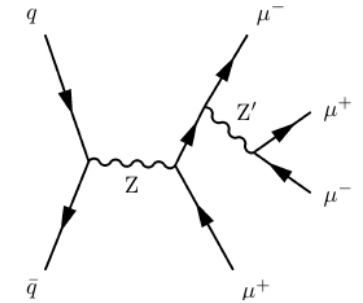
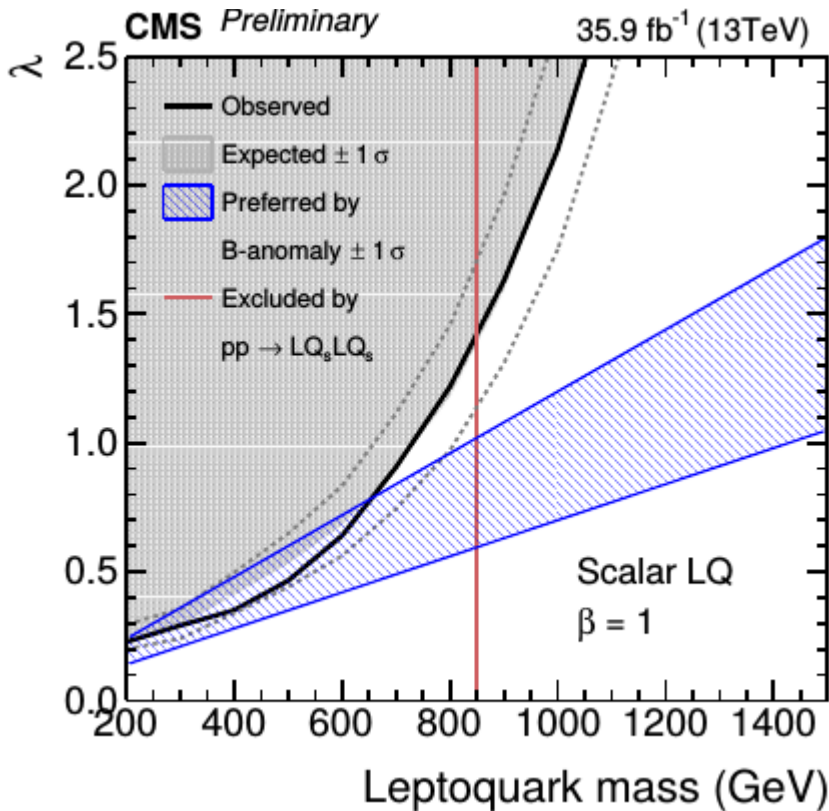
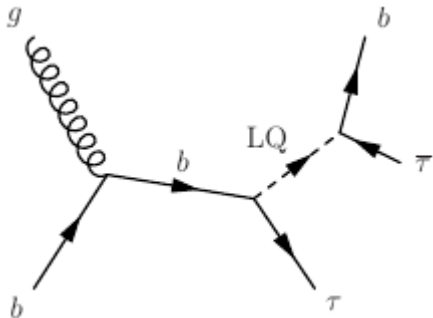


Compatibility with predictions  
 $2.1\text{-}2.3\sigma$  ( $0.045 < q^2/\text{GeV}^2 < 1.1$ )  
 $2.4\text{-}2.5\sigma$  ( $1.1 < q^2/\text{GeV}^2 < 6$ )



# High-energy consequences?

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



Keep looking!

# Searching widely and deeply

## ATLAS SUSY Searches\* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$  TeV

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	710 GeV	$m(\tilde{q}) - m(\tilde{\chi}_1^0) < 5$ GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^{\pm} \rightarrow q\tilde{q}W^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^{\pm}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{g}))$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	1.7 TeV	$m(\tilde{\chi}_1^0) < 300$ GeV,	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell\nu\nu)\tilde{\chi}_1^0$	$3e, \mu$	4 jets	-	36.1	$\tilde{g}$	1.87 TeV	$m(\tilde{\chi}_1^0) = 0$ GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	1708.02794
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV	$m(\tilde{\chi}_1^0) = 1700$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$	1607.05979
	GGM (bino NLSP)	$2\gamma$	-	Yes	36.1	$\tilde{g}$	2.15 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	36.1	$\tilde{g}$	2.05 TeV	$m(\tilde{\chi}_1^0) = 1700$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$	ATLAS-CONF-2017-080
Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}$	$\tilde{g}$	$m(\tilde{G}) > 1.8 \times 10^{-4}$ eV, $m(\tilde{g}) = m(\tilde{q}) = 1.5$ TeV	1502.01518	
3 <sup>rd</sup> gen. $\tilde{g}, \tilde{q}$ med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	1.92 TeV	$m(\tilde{\chi}_1^0) < 600$ GeV	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 b	Yes	36.1	$\tilde{g}$	1.97 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1711.01901
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	950 GeV	$m(\tilde{\chi}_1^0) < 420$ GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	275-700 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^0) + 100$ GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$	0-2 $e, \mu$	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	90-198 GeV	$m(\tilde{\chi}_1^0) = 1$ GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	90-430 GeV	$m(\tilde{\chi}_1^0) = 1$ GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	290-790 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 b	Yes	36.1	$\tilde{t}_2$	320-880 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	1706.03986
EW direct	$\tilde{\ell}_L, \tilde{\ell}_L, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	36.1	$\tilde{\ell}$	90-500 GeV	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\ell}\nu(\ell\nu)$	2 $e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$	750 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}\nu(\tau\nu), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau(\nu\nu)$	2 $\tau$	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$	760 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	1708.07875
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu_L\ell(\tilde{\nu}\nu), \tilde{\ell}\tilde{\nu}_L\ell(\tilde{\nu}\nu)$	3 $e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	1.13 TeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^{\pm}Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^{\pm}h, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_2^0$	635 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$c\tau < 1$ mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 $\gamma$	-	Yes	36.1	$\tilde{W}$	1.06 TeV	$c\tau < 1$ mm	ATLAS-CONF-2017-080
	Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$	460 GeV	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^{\pm}) = 0.2$ ns
Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	495 GeV	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^{\pm}) < 15$ ns	1506.05332
Stable, stopped $\tilde{g}$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	$m(\tilde{\chi}_1^0) = 100$ GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000$ s	1310.6584
Stable $\tilde{g}$ R-hadron		trk	-	-	3.2	$\tilde{g}$	1.58 TeV	-	1606.05129
Metastable $\tilde{g}$ R-hadron		dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	-	1604.04520
Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$		displ. vtx	-	Yes	32.8	$\tilde{g}$	2.37 TeV	$m(\tilde{\chi}_1^0) = 100$ GeV, $\tau > 10$ ns	1710.04901
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\ell}, \tilde{\mu}) + \tau(e, \mu)$		1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$\tau(\tilde{g}) = 0.17$ ns, $m(\tilde{\chi}_1^0) = 100$ GeV	1411.6795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$		2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$10 < \tan\beta < 50$	1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee\nu/\mu\nu/\mu\nu$		displ. $ee/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model	1504.05162
$7 < c\tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g}) = 1.3$ TeV		-	-	-	-	-	-	-	-
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{111}^0 = 0.11, \lambda_{132}/133/233 = 0.07$	1607.08079
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	$m(\tilde{q}) = m(\tilde{g}), c\tau_{LSP} < 1$ mm	1404.2500
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\nu, e\mu\nu, \mu\mu\nu$	4 $e, \mu$	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400$ GeV, $\lambda_{12k} \neq 0$ ( $k = 1, 2$ )	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^0), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$	1.875 TeV	$m(\tilde{\chi}_1^0) = 1075$ GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$	1 $e, \mu$	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	2.1 TeV	$m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{112} \neq 0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	1 $e, \mu$	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	1.65 TeV	$m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{323} \neq 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	100-470 GeV	$m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{323} \neq 0$	1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 $e, \mu$	2 b	-	36.1	$\tilde{t}_1$	480-610 GeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	1710.05544
	$\tilde{t}_1$	-	-	-	-	-	0.4-1.45 TeV	-	-
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	510 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1501.01325

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup>

1

Mass scale [TeV]

# 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.

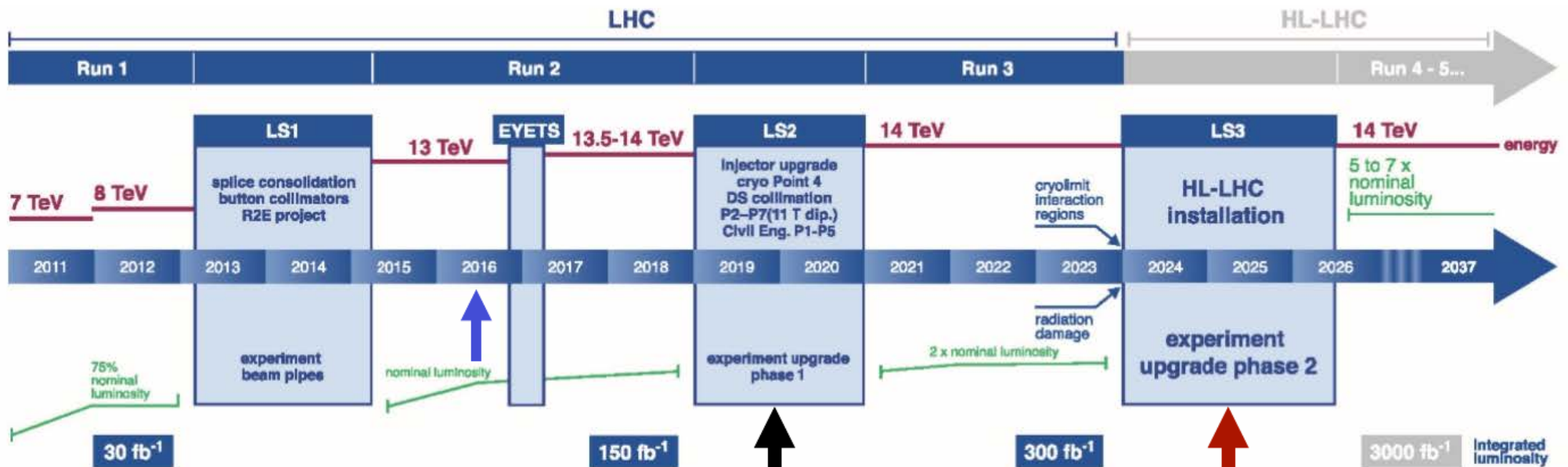


**The future is bright...**





# Much work now devoted to upgrades...



## LS2 (2019-2020):

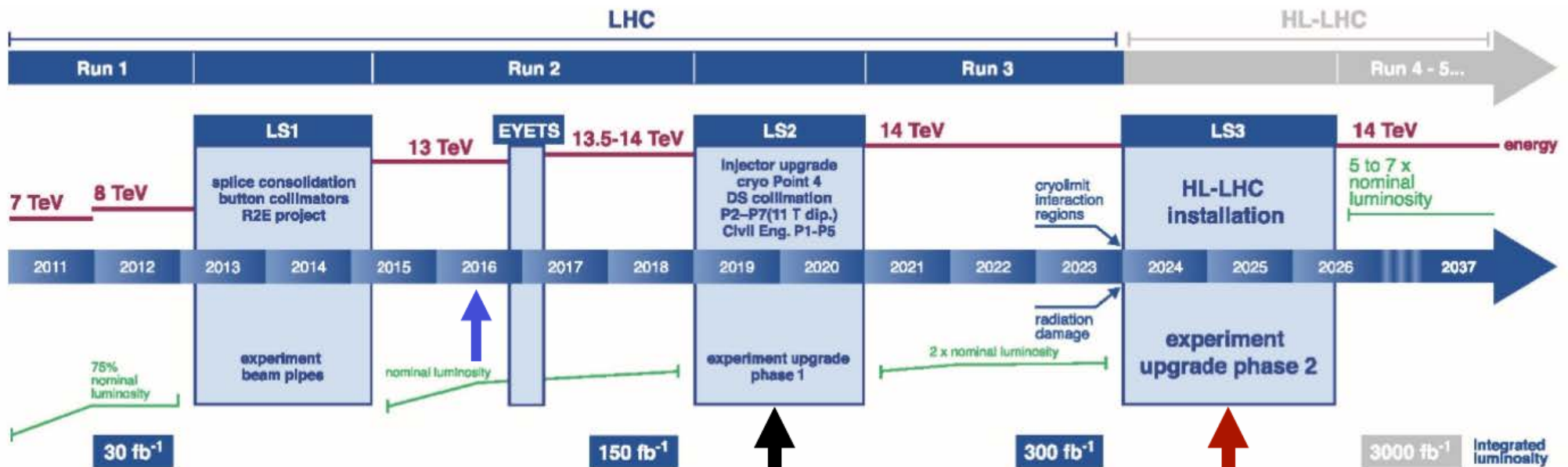
- LHC Injectors Upgrade (LIU)
- Civil engineering for HL-LHC equipment P1,P5
- First 11 T dipoles P7; cryogenics in P4
- Phase-1 upgrade of LHC experiments

## 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 ( $\text{Nb}_3\text{Sn}$ ): 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:  $t\bar{t}H$  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!





The image shows a grand, ornate lecture hall with a high ceiling and decorative elements. A large blue screen in the center displays the word "FINE" in a bold, black, serif font. The hall is filled with rows of brown chairs, and several people are seated at a long table in the foreground. The background features a large painting of a religious scene, flanked by two windows with decorative frames. The walls are adorned with intricate carvings and a large red banner. The overall atmosphere is formal and academic.

**FINE**