LHC Run2 and Future Prospects

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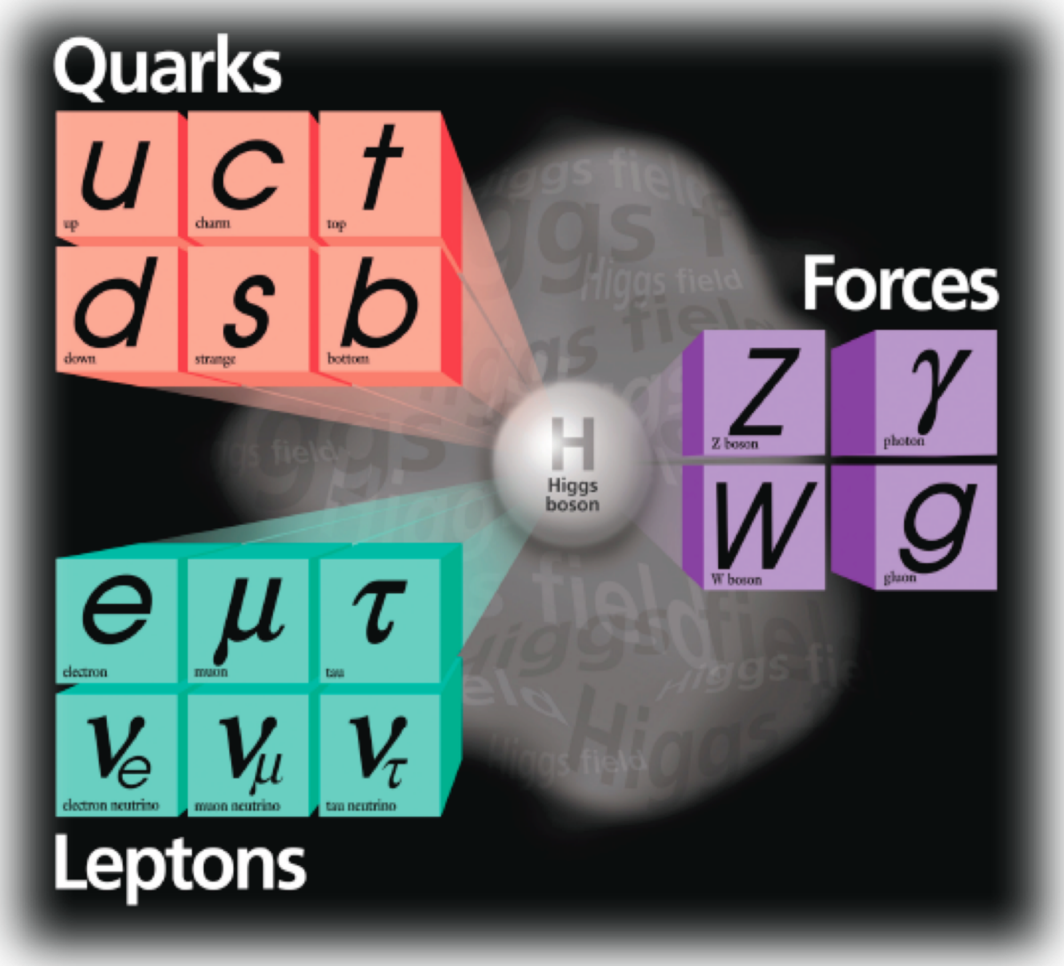
Maratea - June 29, 2018

Standard Model of Particle Physics

The SM works well up to an energy scale of a few hundred GeV

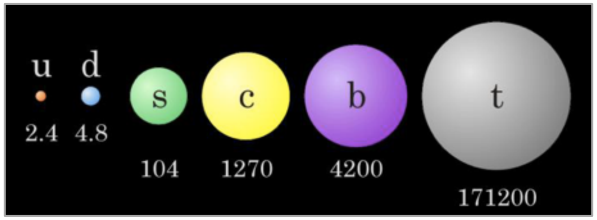


BUT it is incomplete, i.e.:

- Missing dark matter candidate

AND fundamental answers are still missing:

- Why 3 families of quarks and leptons?
- Why the masses of fundamental particles span several orders of magnitude?



Mass of quarks in MeV/c^2
Drawing not in linear scale !!

Cross sections

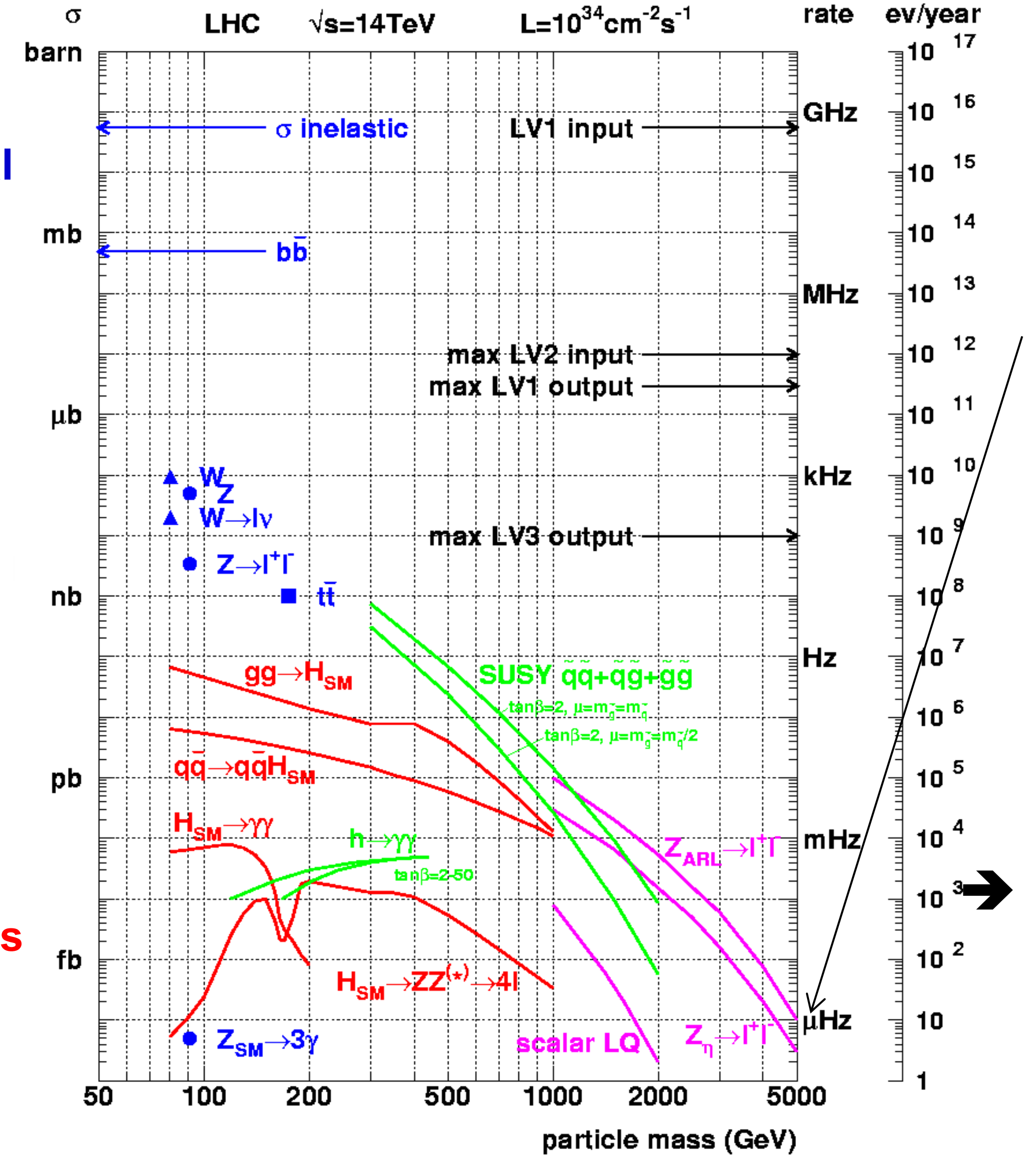
12 order of magnitude

Total

HF

SM

Higgs



RARE PROCESSES

$$R = \mathcal{L}\sigma$$

$$\mathcal{L} = f\frac{n_1 n_2}{A}$$

Number of p per beam

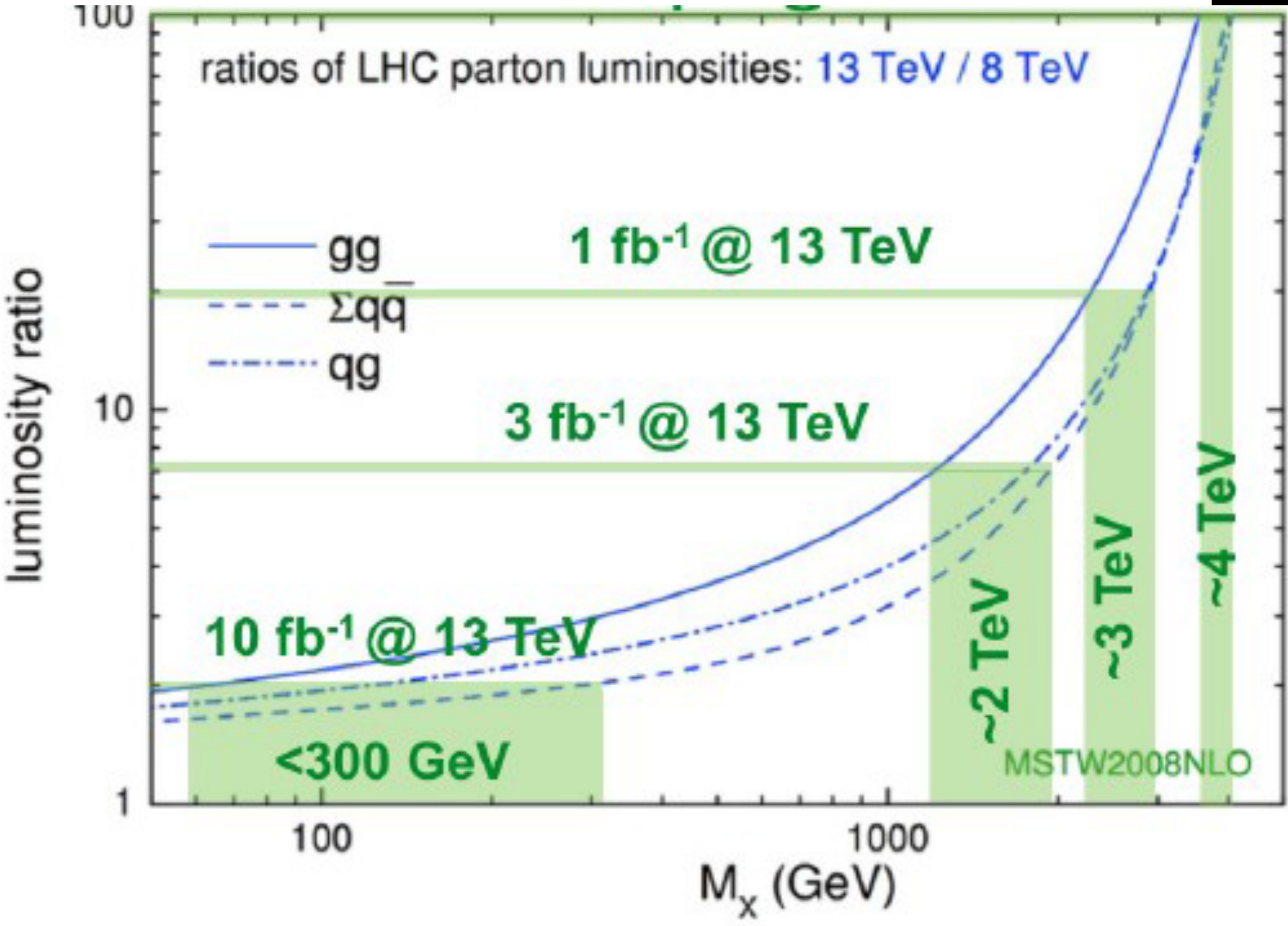
Collision frequency

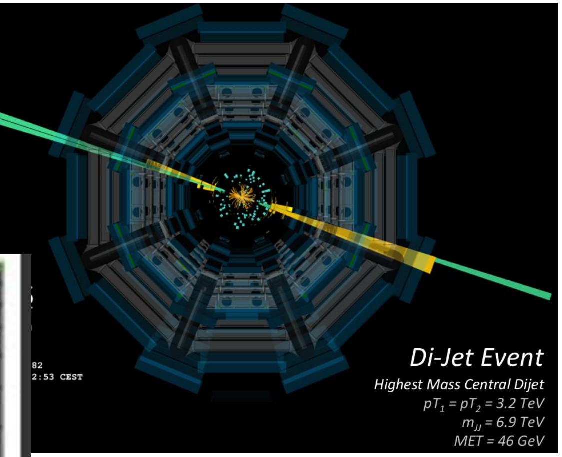
Area of collision

➔ **The maximum achievable luminosity (L) is needed**

1H/10^{12} events

New energy frontier





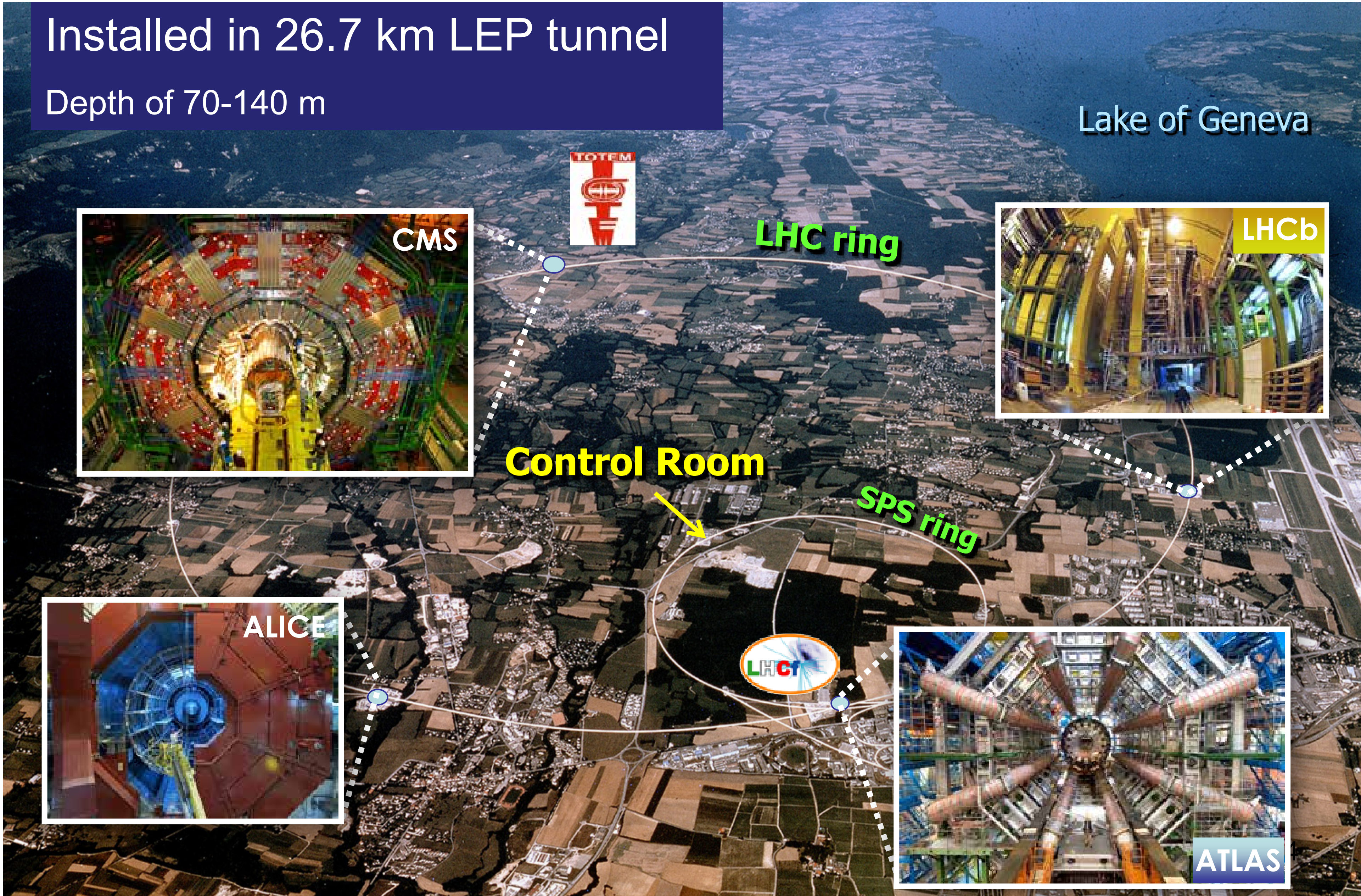
Outline

- The need of the Large Hadron Collider
- The experiments and the enabling technologies
- The physics: before LHC and Run1 – a short recap
- The ongoing Run2 – what’s new
  - Standard Model (SM)
  - BSM
  - Flavour physics
  - Heavy ions
- Prospects for near and far future

Large Hadron Collider (LHC)

Installed in 26.7 km LEP tunnel

Depth of 70-140 m



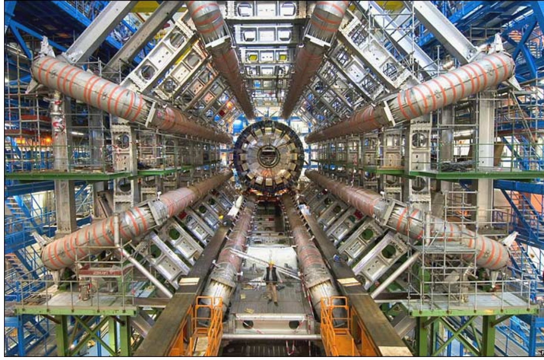
Multi-purpose, high resolution and hermetic detector

Magnets: Central Solenoid + 3 Toroids

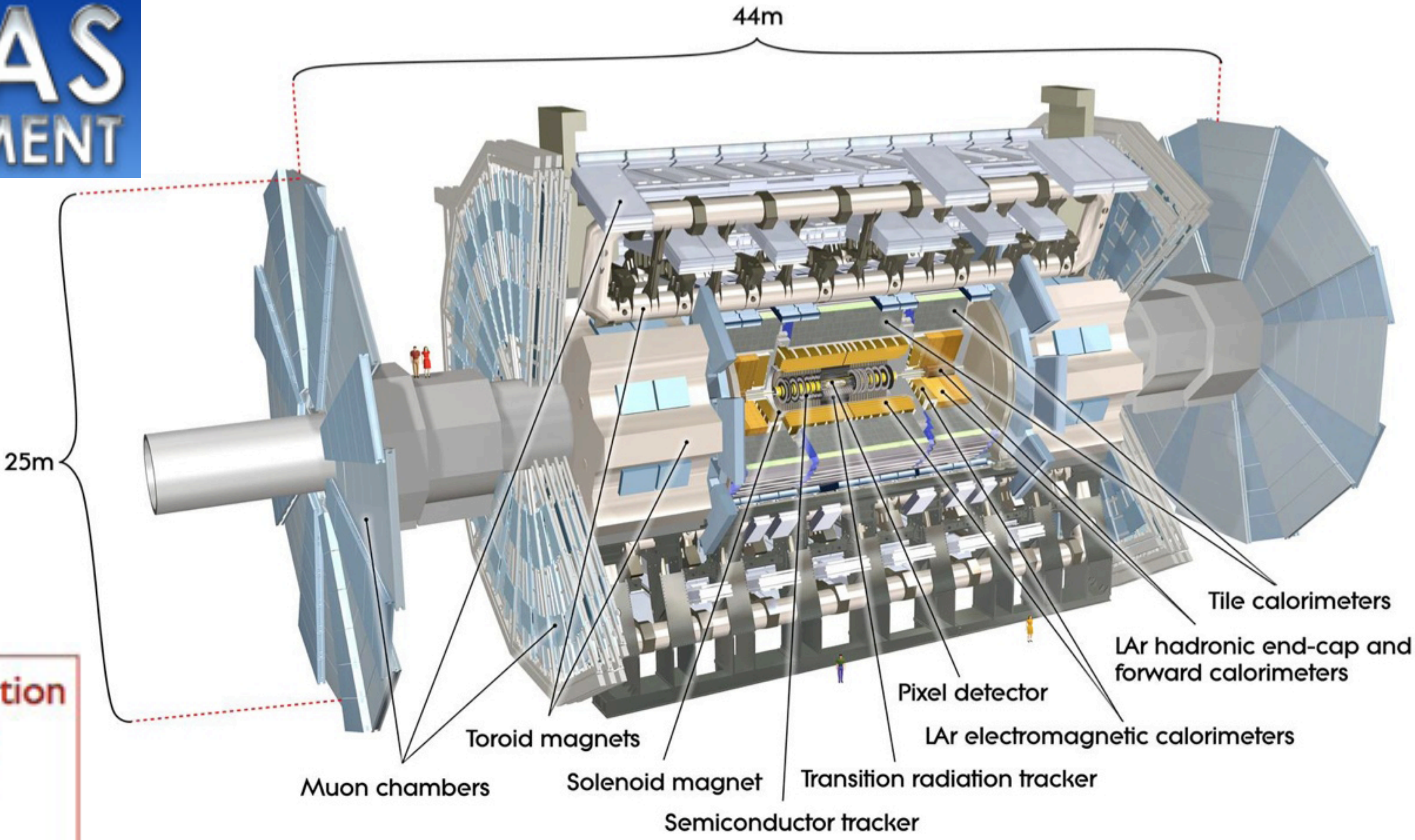
Tracking: Silicon, Transition Radiation Tracker

Calorimeter: EM (LAr), Had Cal

Muon: Trigger + Precision chambers



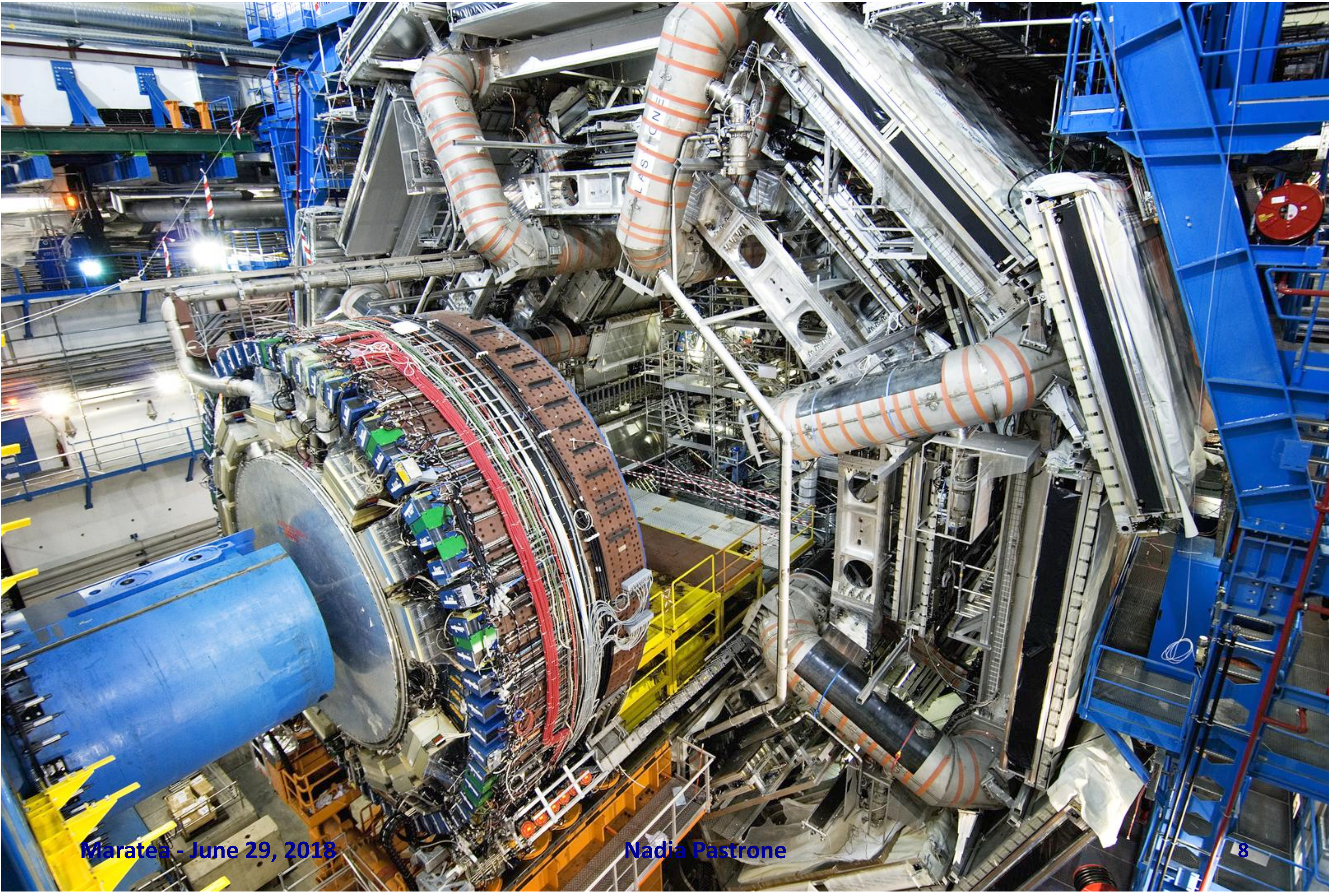
ATLAS EXPERIMENT



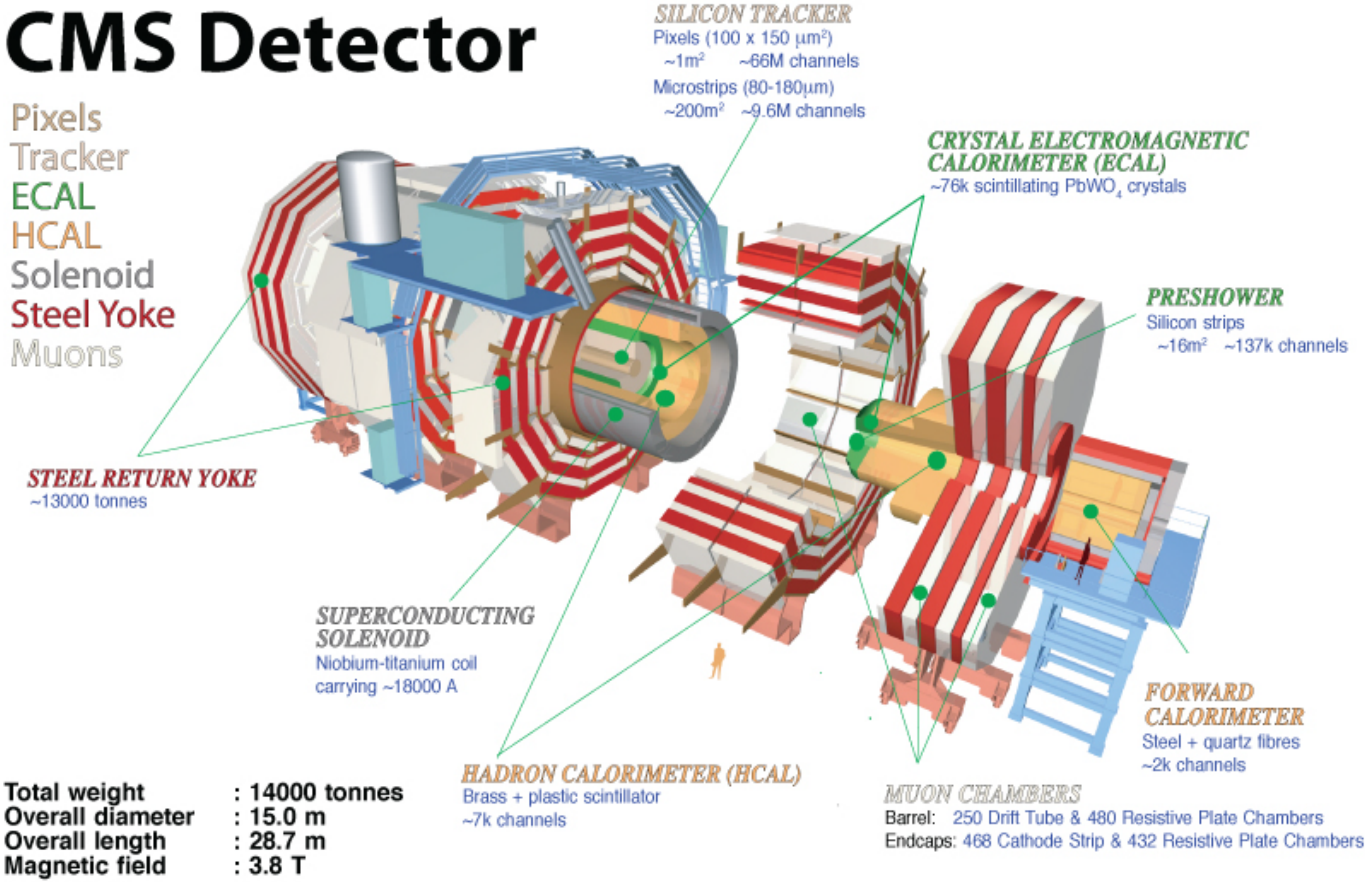
Object Reconstruction

- leptons (e, μ, τ)
- photons
- jets
- b-jets
- Etmiss

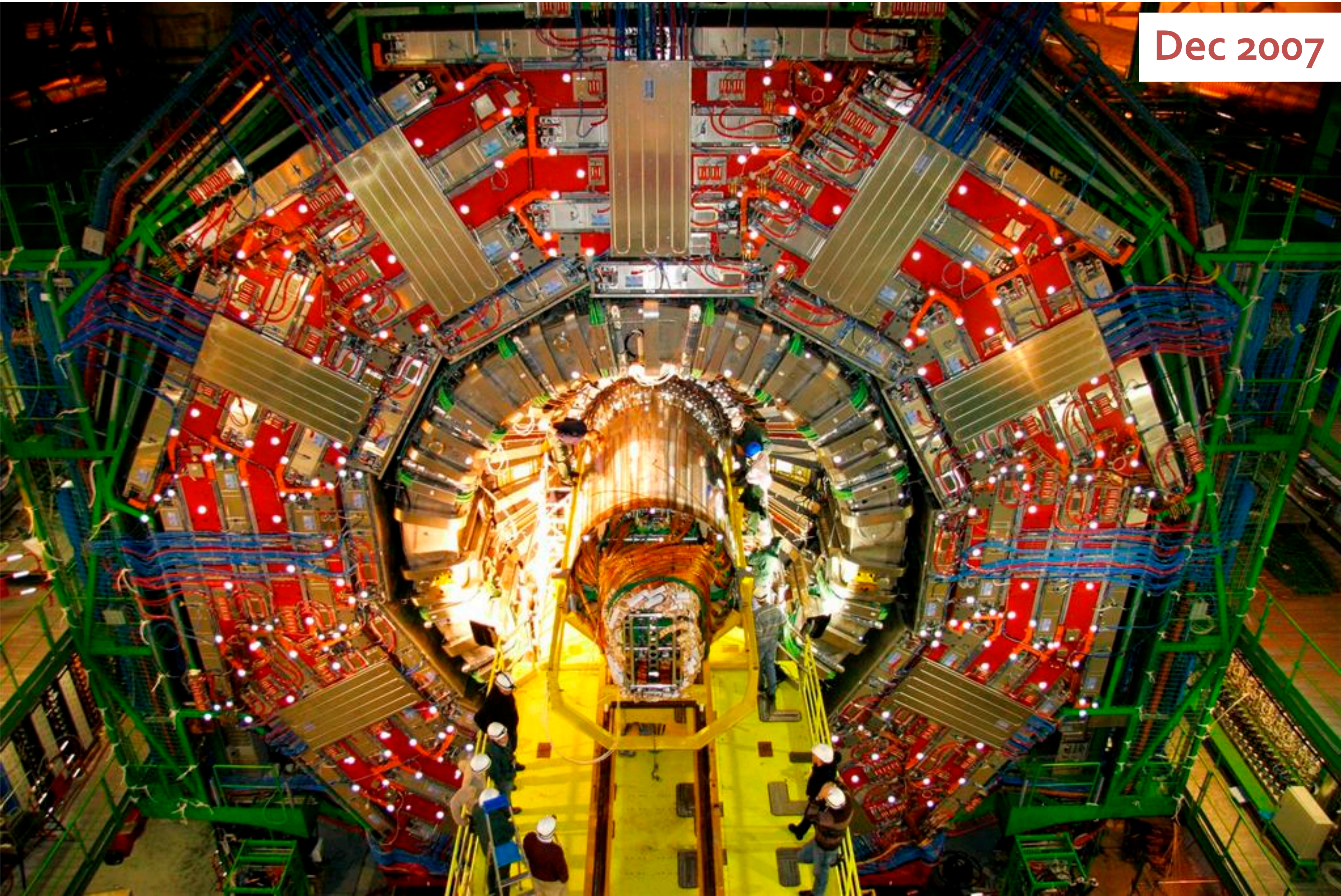
ATLAS: during construction



CMS

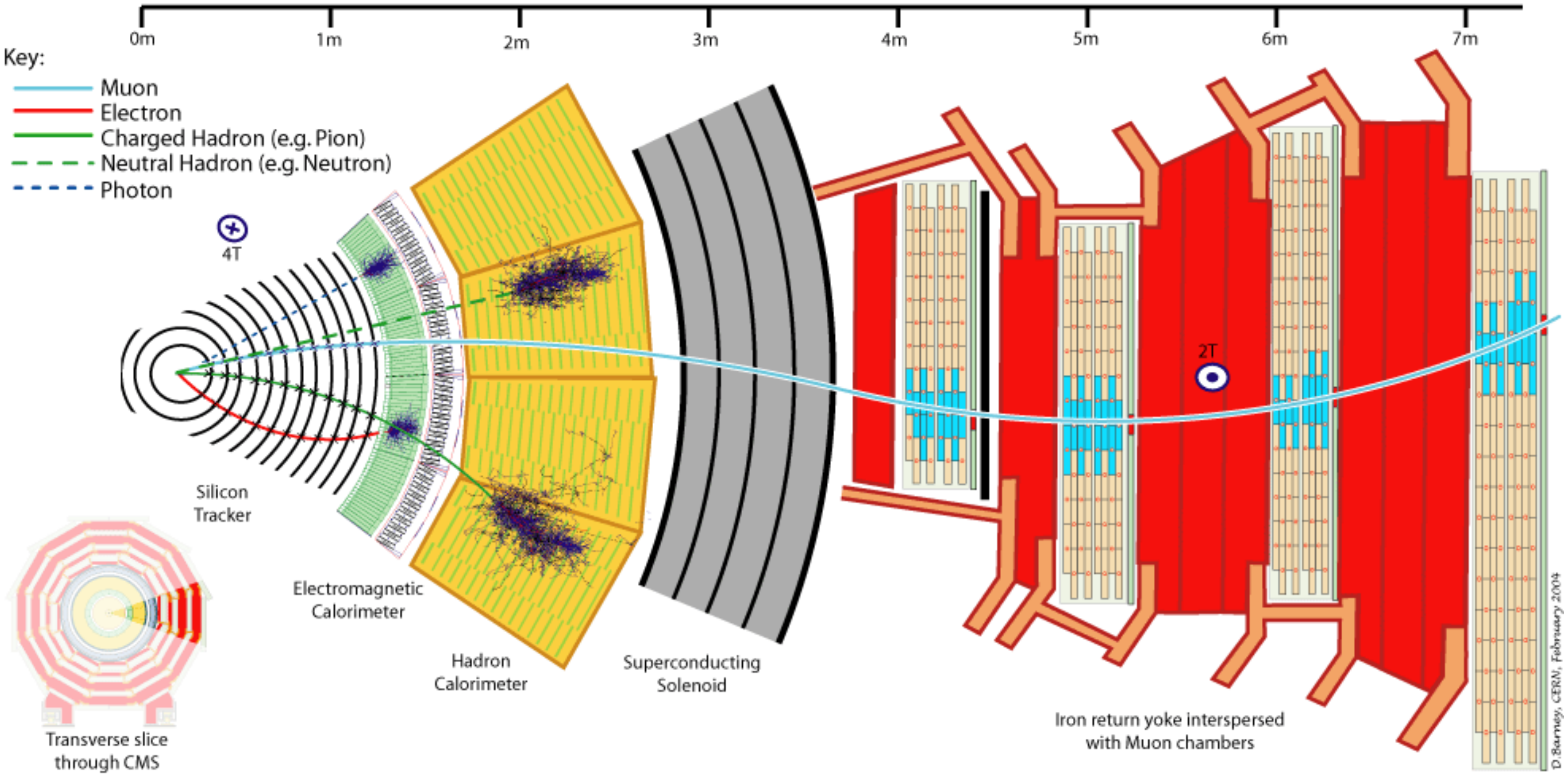

CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

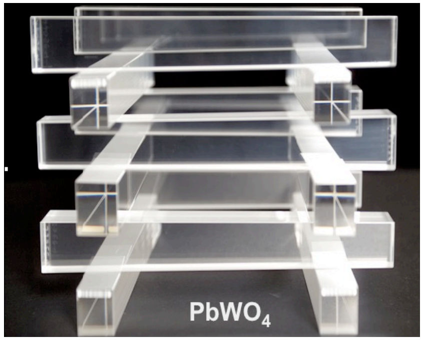
CMS tracker installation

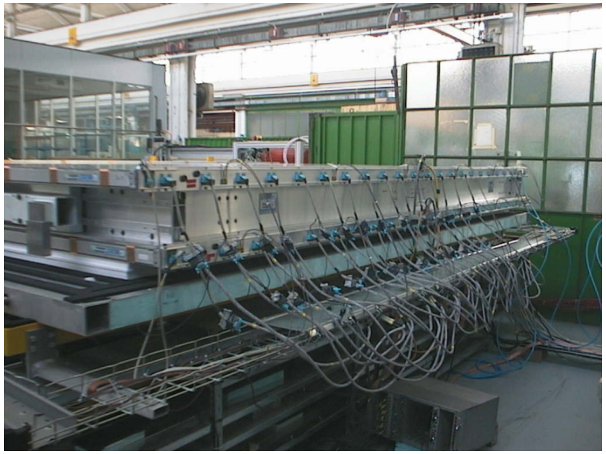


Dec 2007

Compact Muon Solenoid slice

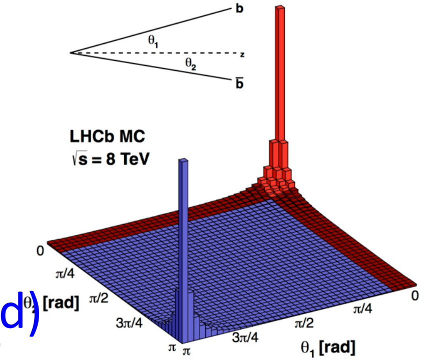


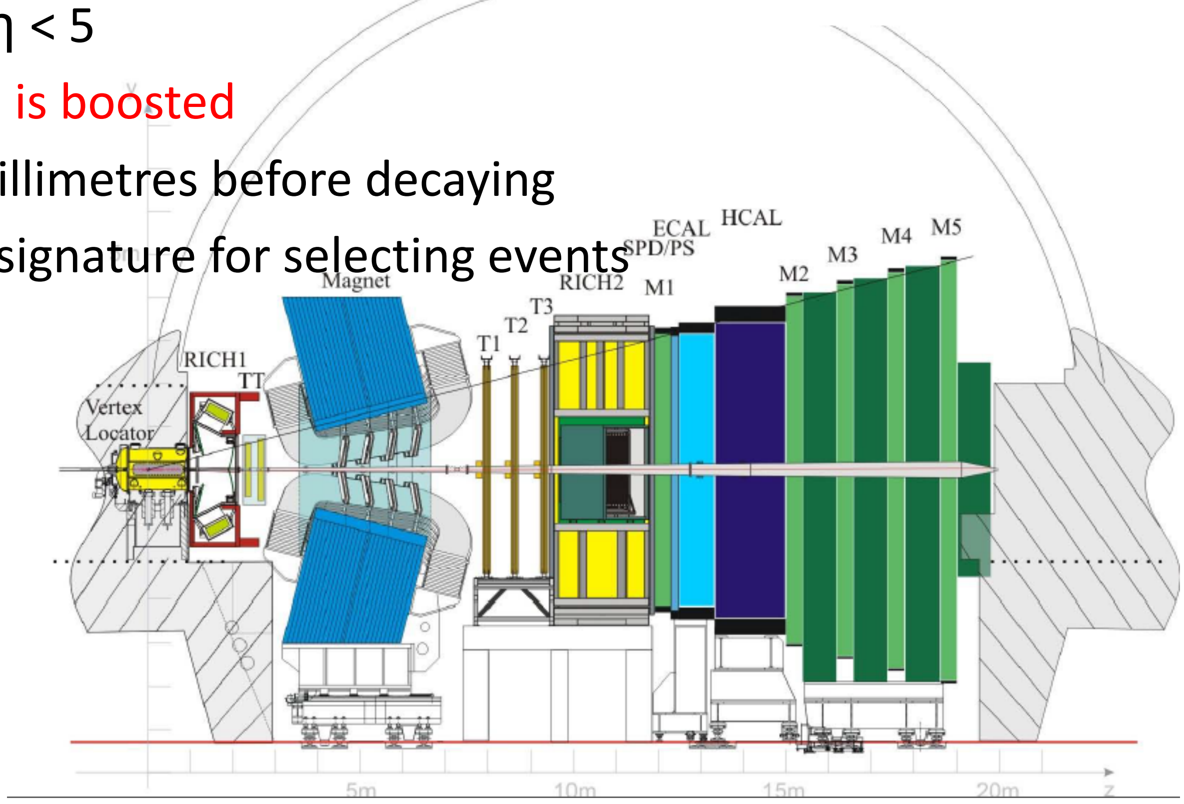




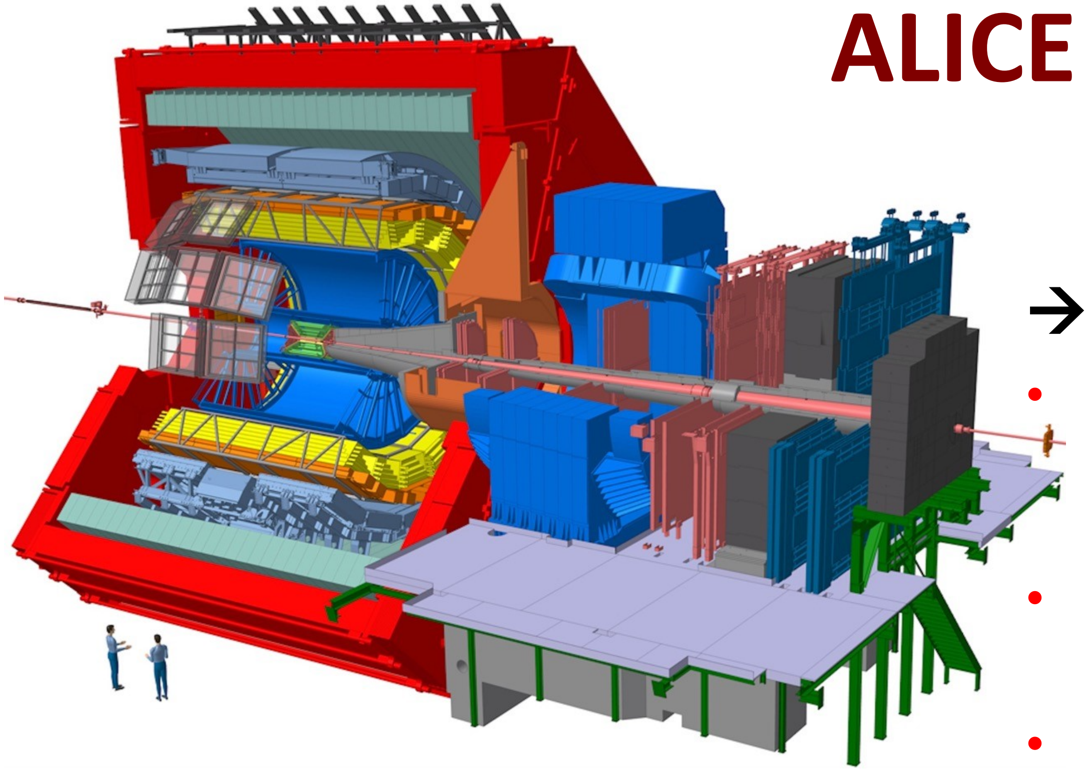
Large Hadron Collider beauty experiment

- LHCb is mainly (but not only) studying beauty (and charm) physics
  - At the LHC, the production of heavy quark pairs is peaked forward/backward
  - The detector is a single arm spectrometer
    - Both *b*-hadrons go together forward (or backward)
    - Acceptance 2 < η < 5
  - A *b*-meson / baryon is boosted
    - It flies several millimetres before decaying
    - This is the main signature for selecting events





ALICE

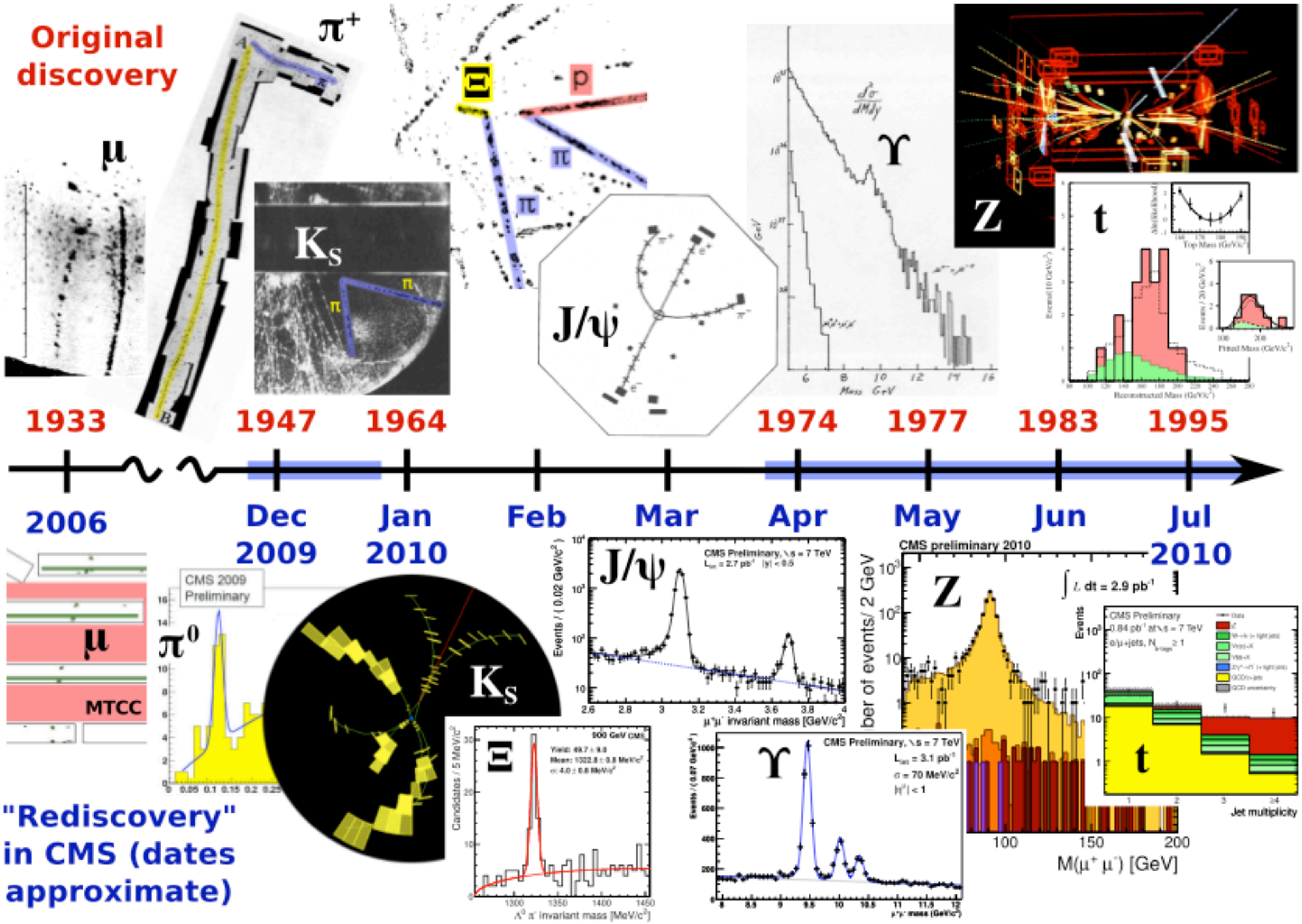


→ to be installed in LS2

- **New Inner Tracking System (ITS)**
  - MAPS: improved resolution, less material, faster readout
- **New Forward Muon Tracker (MFT)**
  - vertex tracker at forward rapidity
- **New TPC Readout Chambers**
  - 4-GEM detectors
- **New trigger detectors (FIT, AD)**
  - + centrality, event plane
- **Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal, PHOS, integrated Online-Offline system**

record minimum-bias Pb-Pb data currently <1 kHz
→ at 50 kHz after LS2 upgrade

Standard Model re-discovery @ LHC



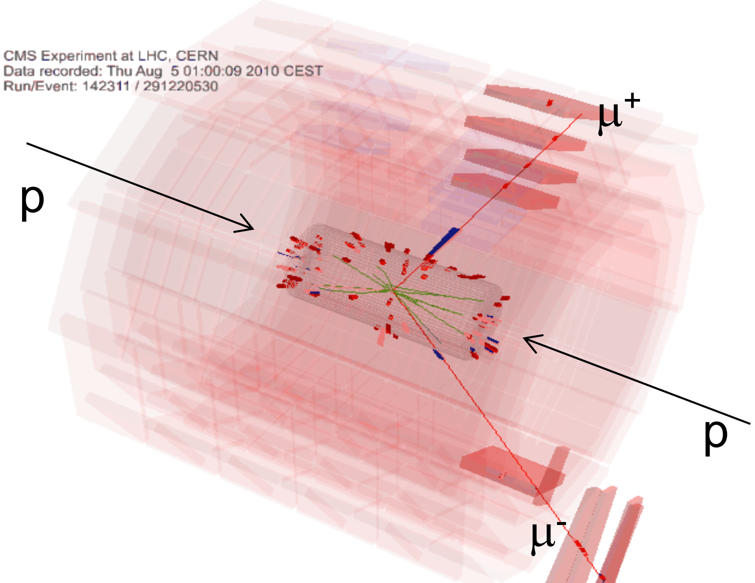
Original discovery

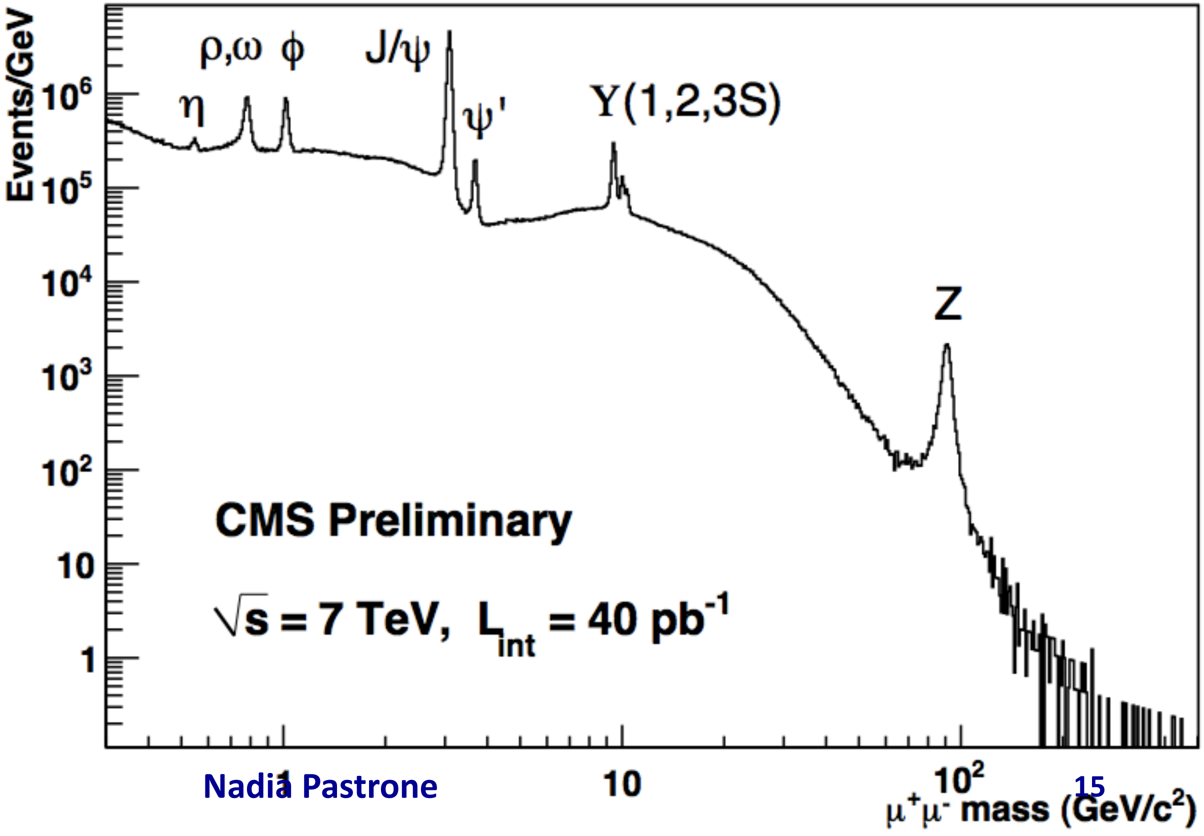
1933 1947 1964 1974 1977 1983 1995

2006 Dec 2009 Jan 2010 Feb Mar Apr May Jun Jul 2010

"Rediscovery" in CMS (dates approximate)

First data


CMS Experiment at LHC, CERN
Data recorded: Thu Aug 5 01:00:09 2010 CEST
Run/Event: 142311 / 291220530
p
μ^+
p
μ^-


Events/GeV
10^6
10^5
10^4
10^3
10^2
10
1
η
ρ,ω
φ
J/ψ
ψ'
Υ(1,2,3S)
Z
CMS Preliminary
$\sqrt{s} = 7$ TeV, $L_{int} = 40$ pb^{-1}
1
10
10^2
$\mu^+\mu^-$ mass (GeV/c^2)

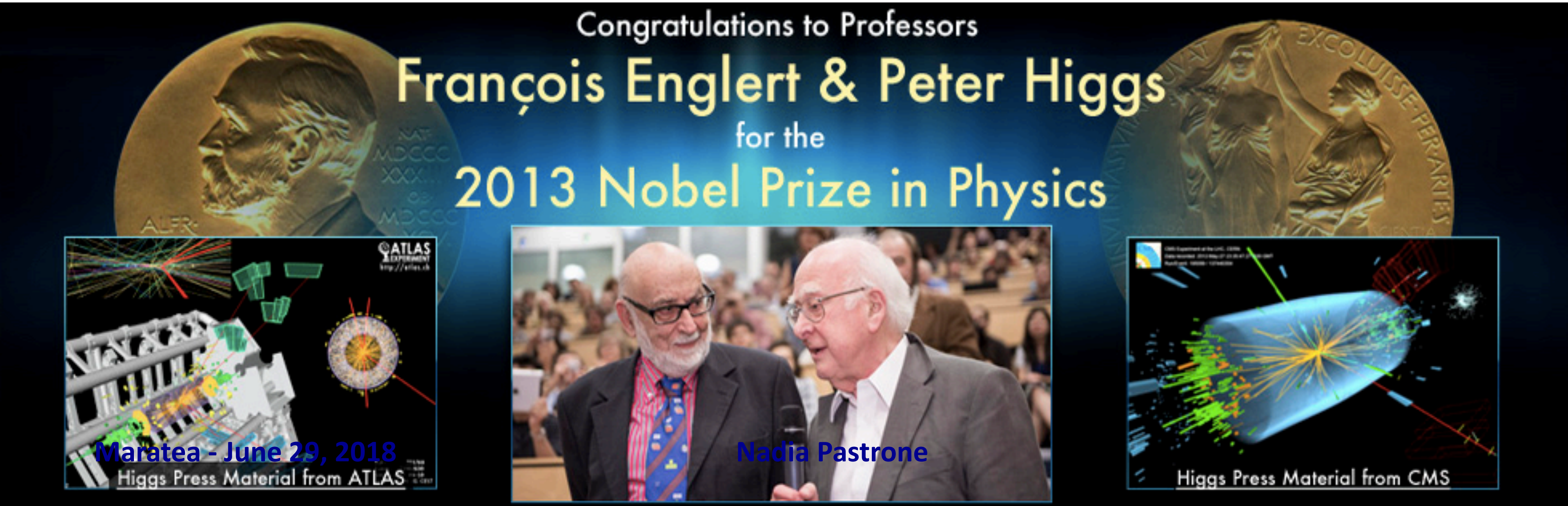
2013 Nobel Prize in Physics

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

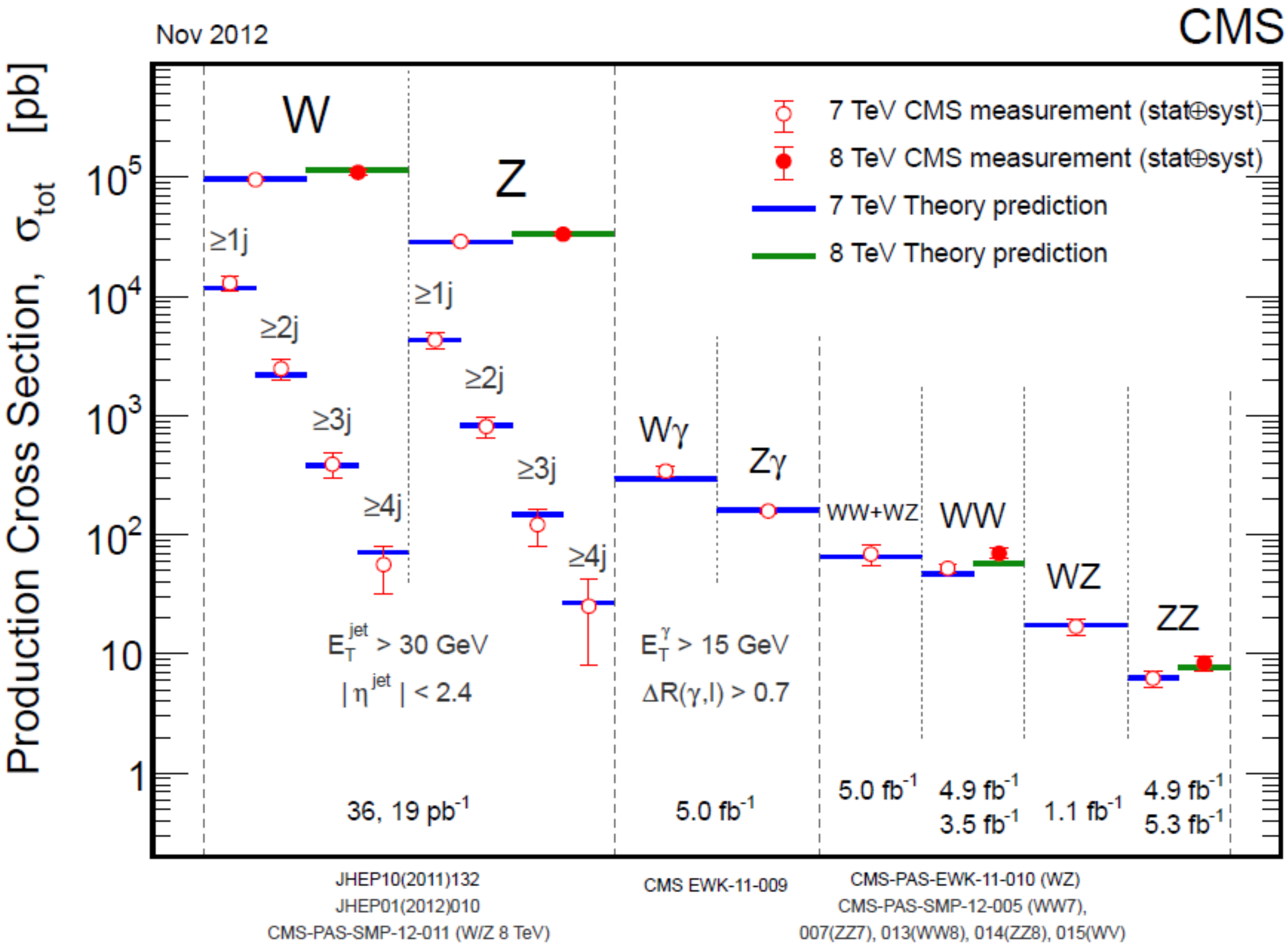
François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

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



A comparison to theory predictions



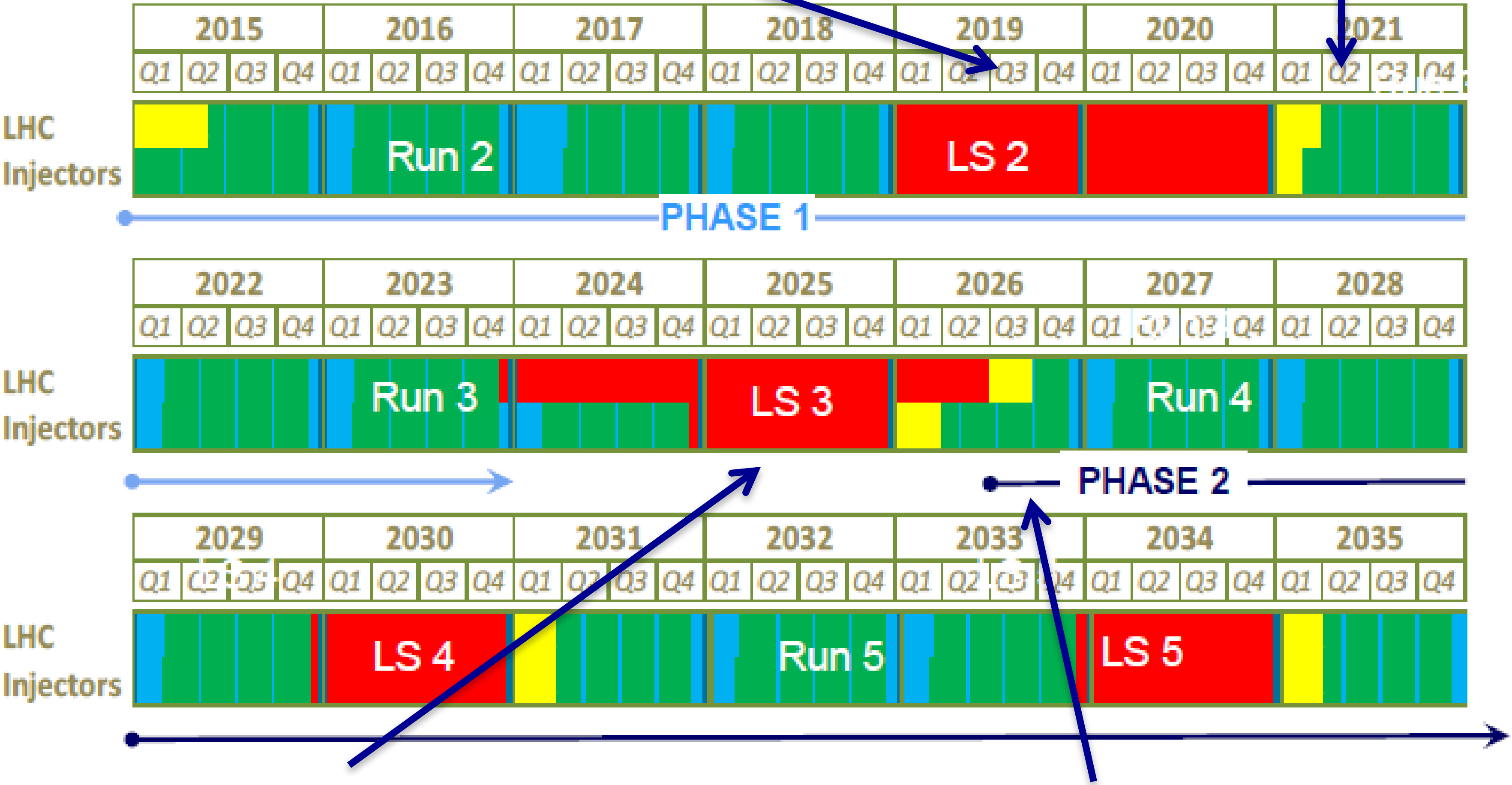
LHC: present schedule

Phase 1 Upgrade

ALICE, LHCb major upgrade

ATLAS, CMS minor upgrade

Heavy Ion Luminosity from 10^{27} to 7 x10^{27}

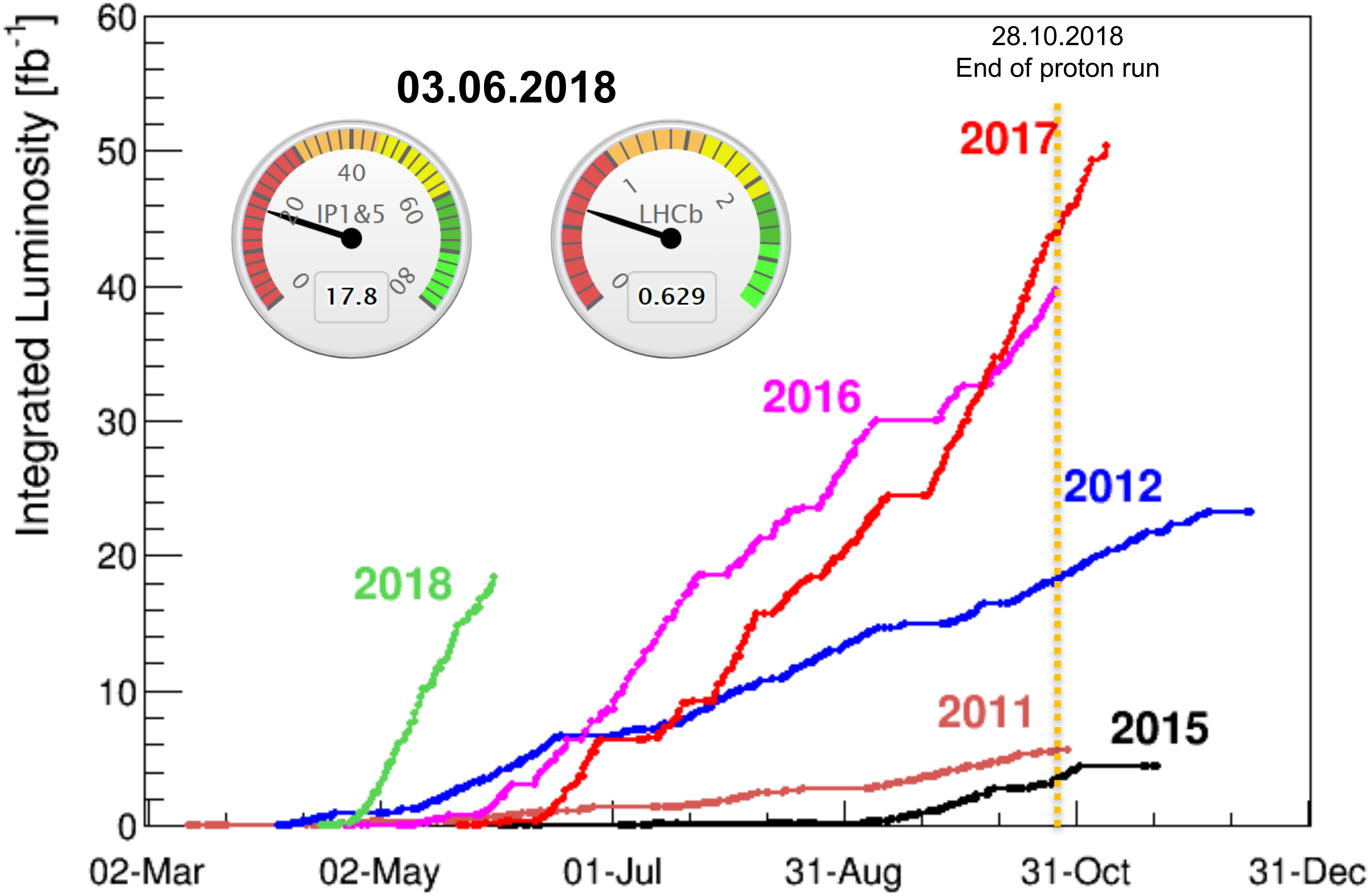


PHASE 2 Upgrade

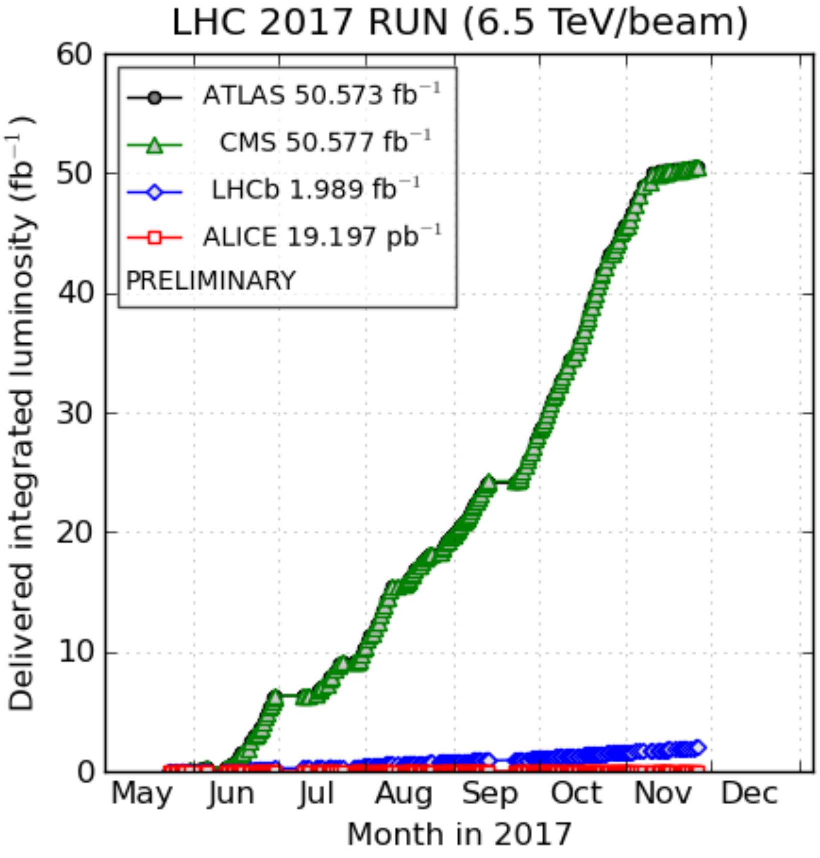
ATLAS, CMS major upgrade

HL-LHC, pp luminosity from 10^{34} (peak) to 5 x10^{34} (levelled)

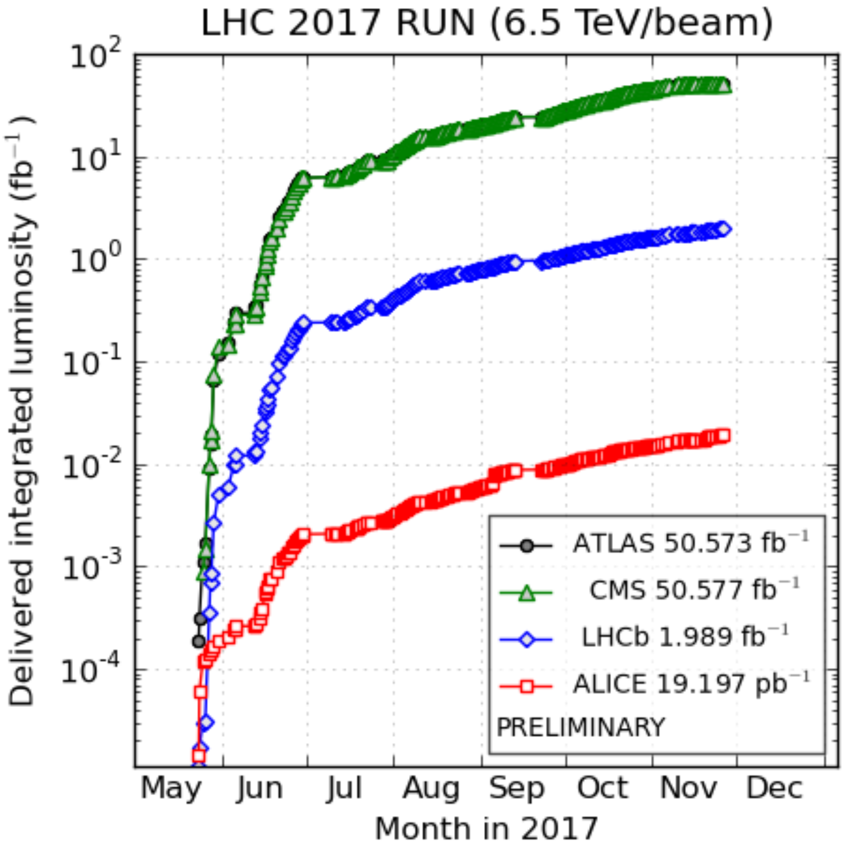
Multi-annual integrated performance



2017 pp collisions - luminosity

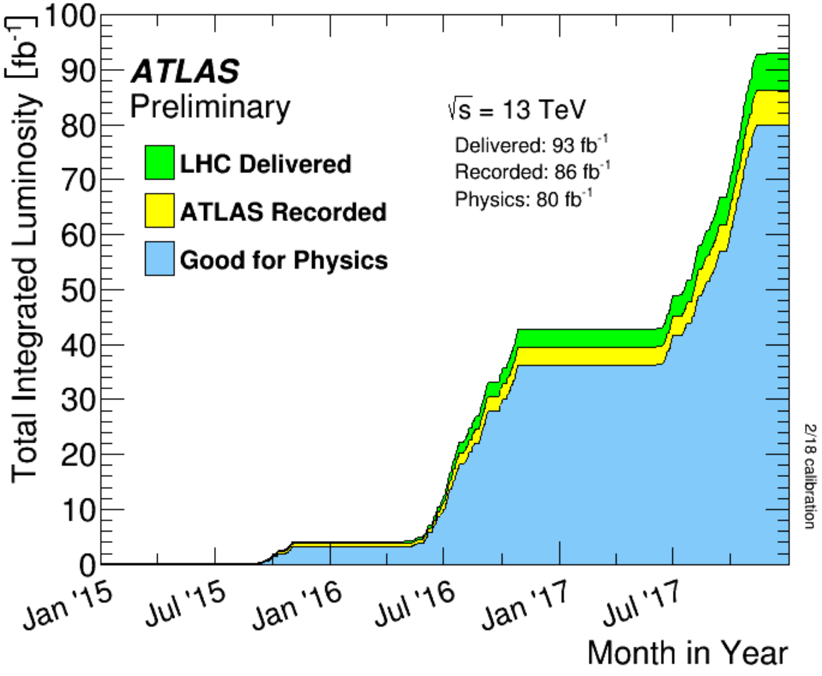


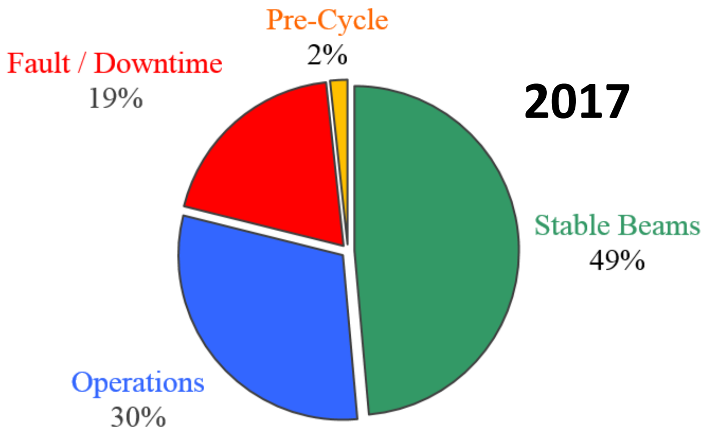
(2018-05-28 20:32 including fill 6417; scripts by C. Barschel)

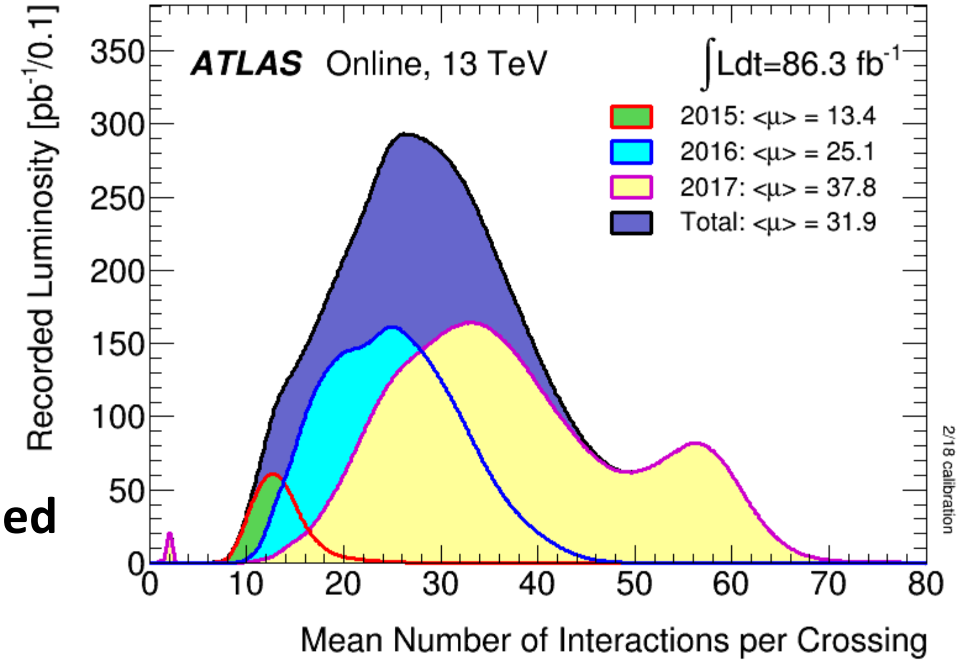


(2018-05-28 20:32 including fill 6417; scripts by C. Barschel)

Run2 pp data recorded ATLAS/CMS







Excellent performance of the LHC

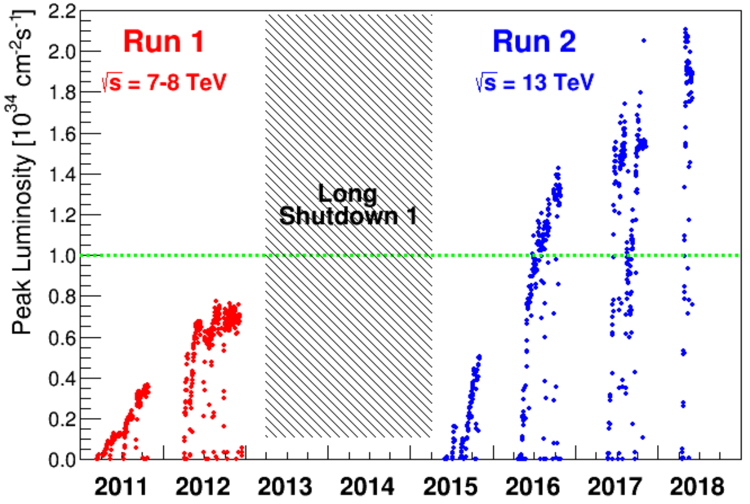
~25 fb^{-1} delivered in RUN 1

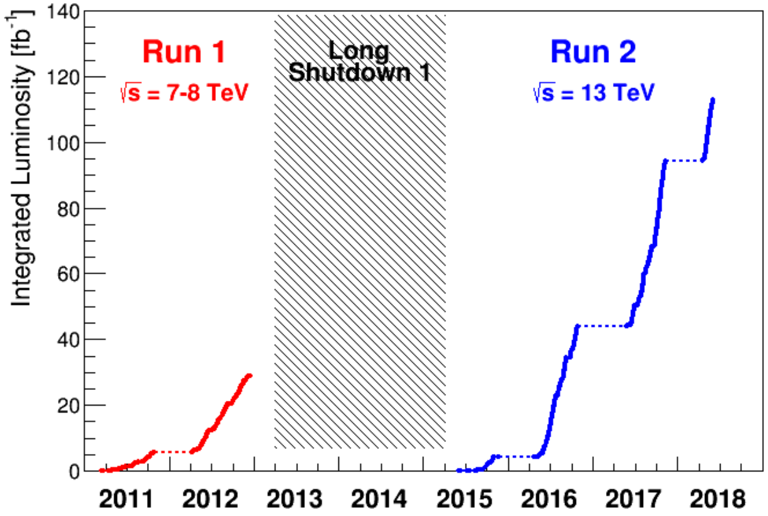
~100 fb^{-1} in Run 2

instantaneous luminosity in RUN 2 reached

$2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ (twice the design value)

Run1-Run2 luminosity production





Peak Luminosity

- 2018 shows steepest increase in peak luminosity of all years

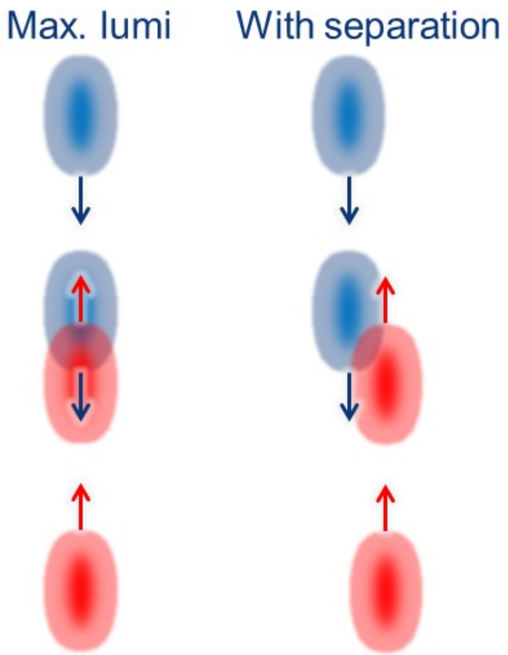
Period	Int. Luminosity [fb^{-1}]
Run 1	**29.2**
Run 2: 2015	**4.2**
Run 2: 2016	**39.7**
Run 2: 2017	**50.2**
Run 2: 2018	**17.8**
Total Run 1+ 2	**141.1**

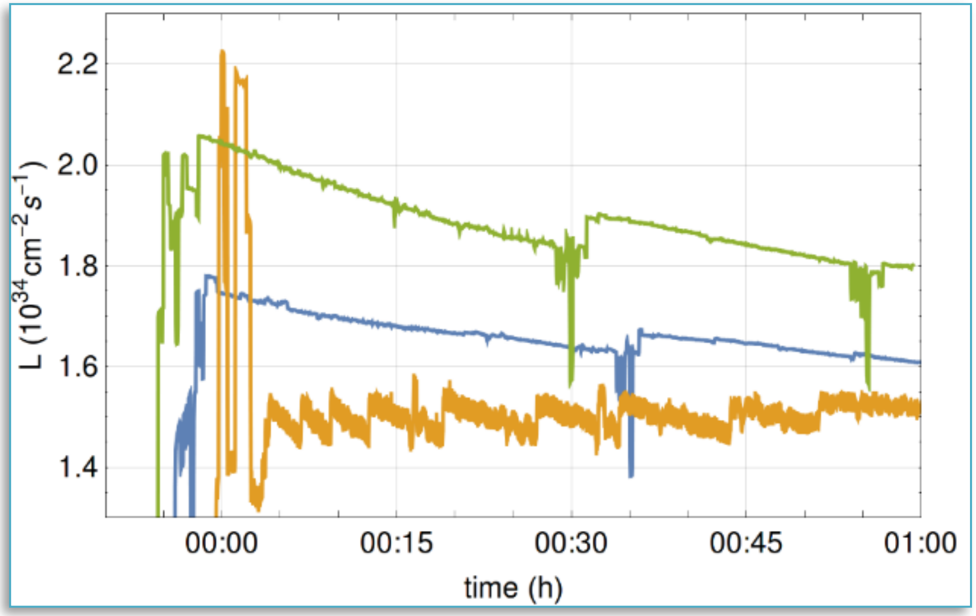
LHC 2017: separation levelling

- Introduced separation levelling for all experiments

➔ Separation levelling is used since many years for ALICE and LHCb

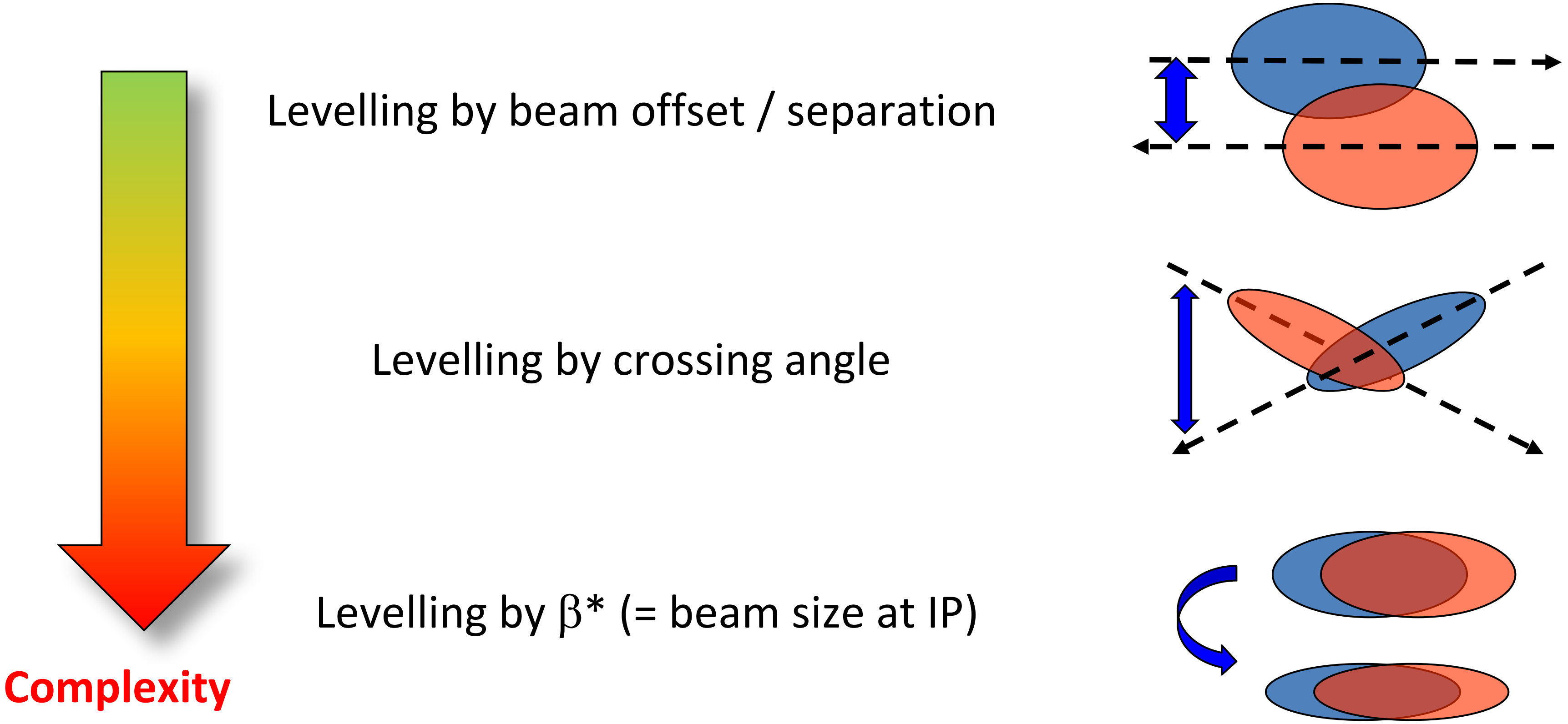
- Initial spike before leveling reaching 2.2 × 10^{34} $cm^{-2}s^{-1}$





Luminosity levelling

- In certain conditions and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – **levelling**
- Each levelling technique has its advantages and drawbacks



Levelling by beam offset / separation

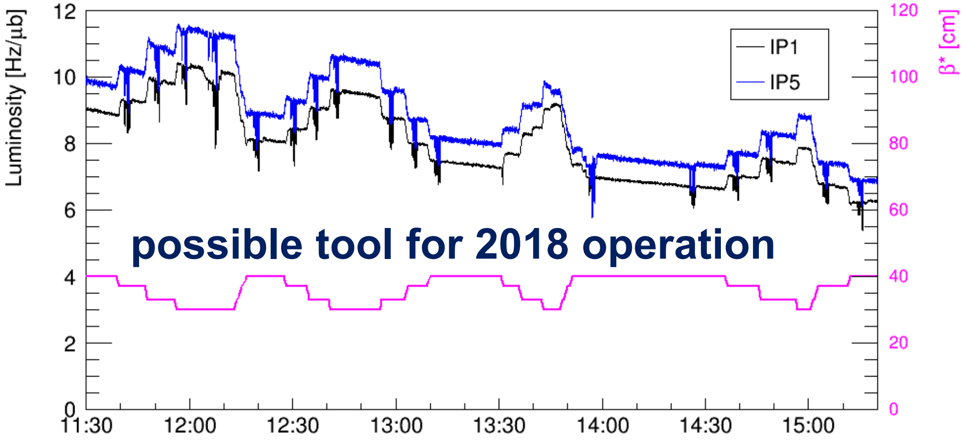
Levelling by crossing angle

Levelling by β* (= beam size at IP)

Complexity

LHC

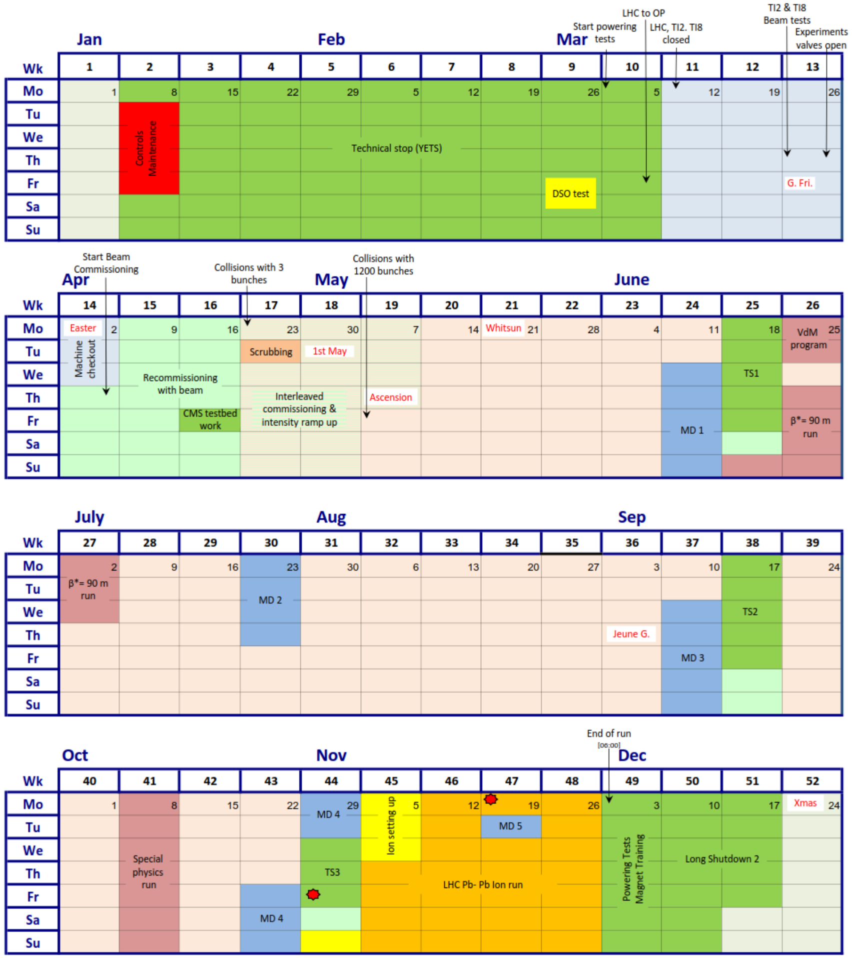
Main levelling technique for HL-LHC



possible tool for 2018 operation

Luminosity evolution during β^* levelling: back and forth between 30 cm and 40 cm. The beams remained head-on ***within ~ 2 μm*** *!*

2018: a production year to complete Run 2 (13 TeV)



Goal: 60 fb^{-1} ATLAS/CMS
2 fb^{-1} for LHCb
with 131 days of p-p physics
55 fb^{-1} and 1.8 fb^{-1} if 119 days
(LHC high availability and >50% stable beams)
Pb-Pb run : 24 days + 4 days setting-up
Goal: > 600 μb^{-1} ALICE (Run 2 > 1nb^{-1})

2018 Machine beam parameters

Parameter	Design	2018
Bunch population N_b [10^{11} p]	1.15	**~1.2 (→ 1.4)**
No. bunches per train	288	**144**
No. bunches	2780	**2556**
Emittance ε [mm mrad]	3.5	**~2.2**
Full crossing angle [μrad]	**285**	**300 → 260**
β^* [cm]	55	**30 → 27.5 → 25**
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	**~2**
Integrated luminosity [fb^{-1}]		**~60**

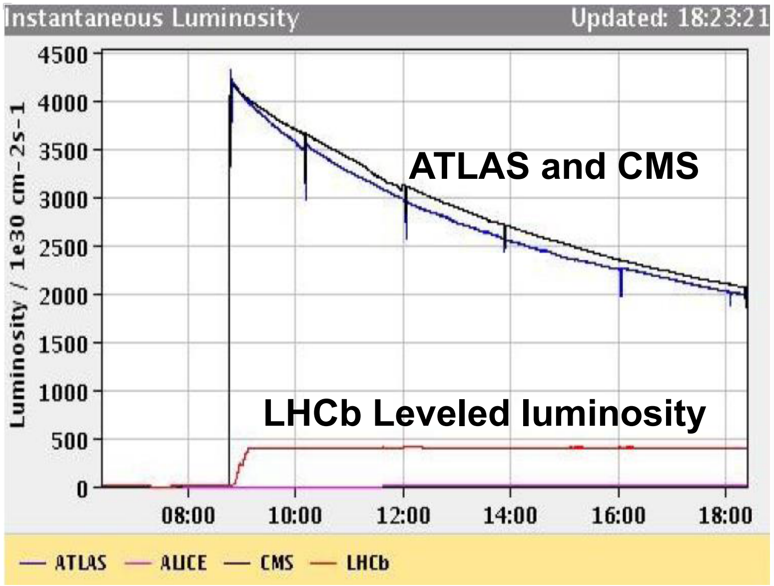
The "CMS bump" to compensate ground movement was increased from **-1.5 mm** to **-1.8 mm**

LHCB: Data Taking

- **RUN1**:3 fb^{-1} of data collected

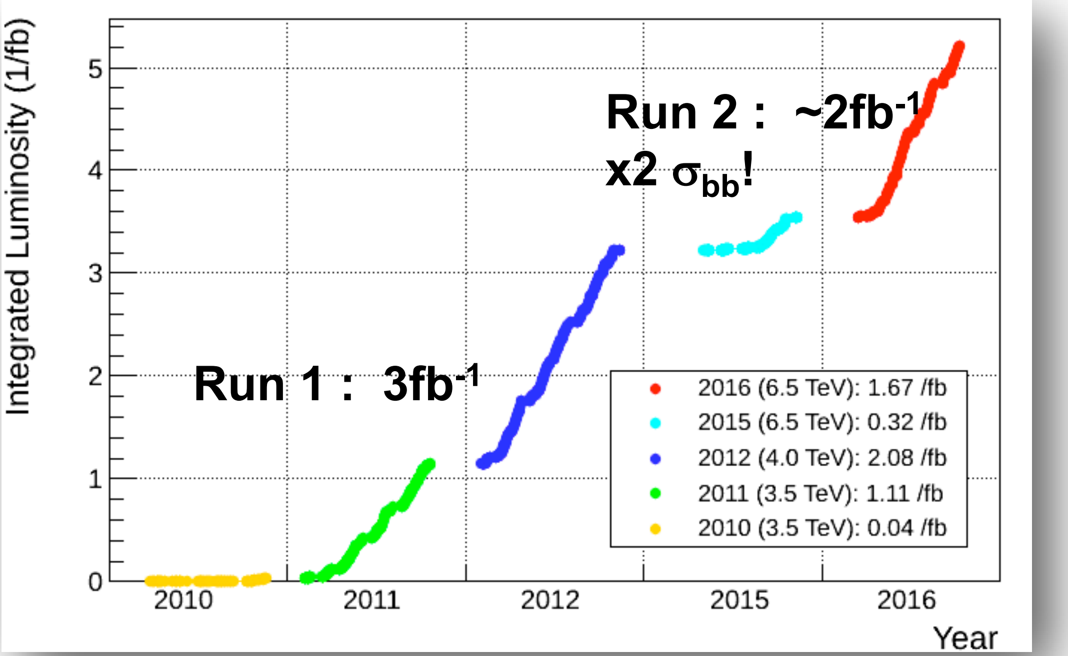
  ➔ ~3 x 10^{11} b-anti-b pairs produced within LHCb @ √s = 7-8 TeV
- **RUN2:** operating at 13 TeV higher energy and at 25 ns bunch-crossing (+ detector improvements)

  ➔ larger b-sample for same luminosity!
- Run 2 will go to end of 2018 – expect to increase the beauty sample by x3 or more.



ATLAS and CMS

LHCb Leveled luminosity



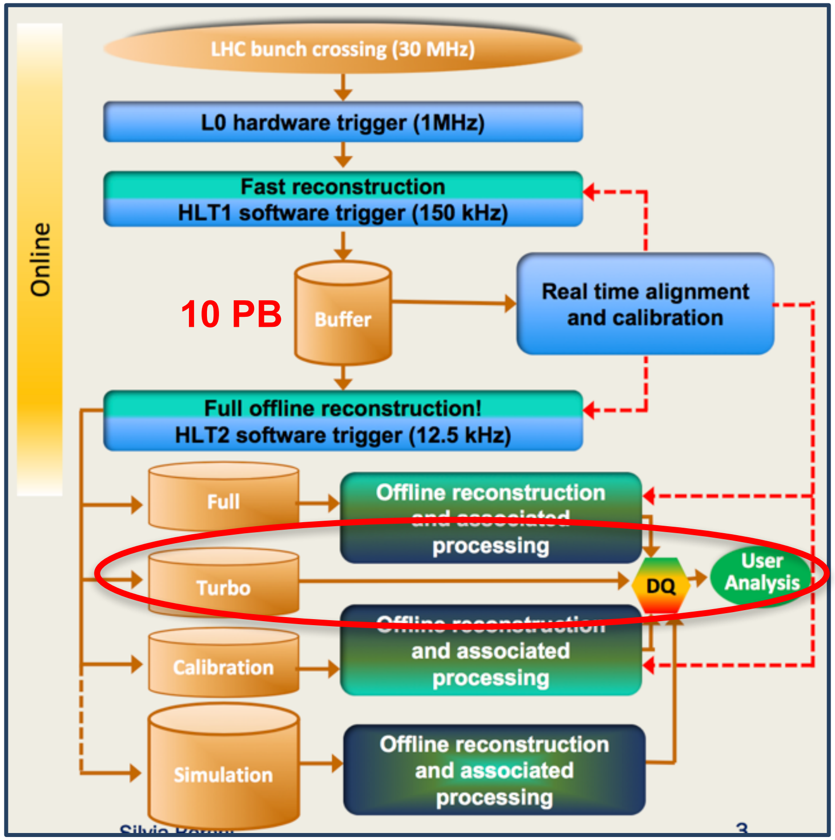
Run 1 : 3fb^{-1}

Run 2 : ~2fb^{-1} x2 σ_{bb}!

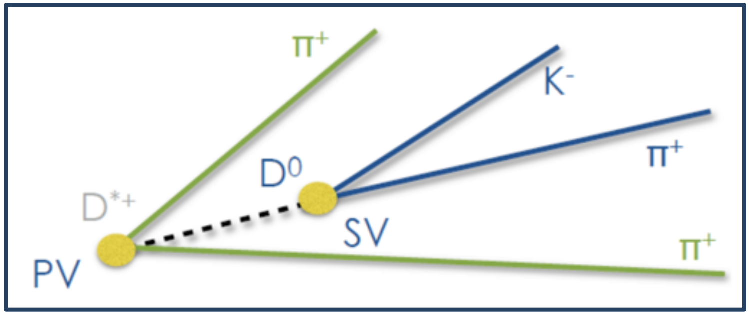
LHCb running strategy for 2018

- Same strategy as 2017. Aim at maximum stability for maximum luminosity
- Last year for the current LHCb!

- TURBO was optimized in 2017
  - Selected data saved in a format ready for the analysis
    no offline reconstruction
  - **An anticipation of the upgrade trigger**

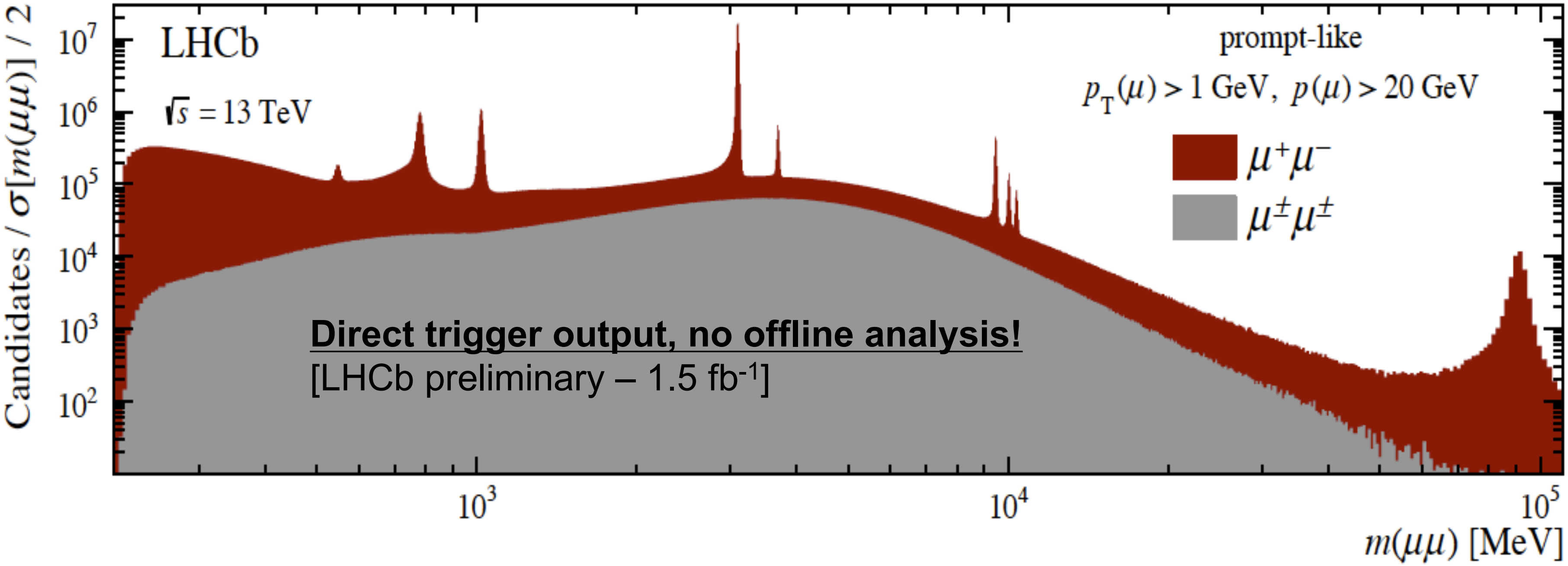


TURBO SP (2017 - 2018)
selective persistence: Save useful information “a la carte”



An application of Turbo: search for dark photons $A' \to \mu^+\mu^-$

A promising channel to detect dark photons is $A' \to \mu^+\mu^-$

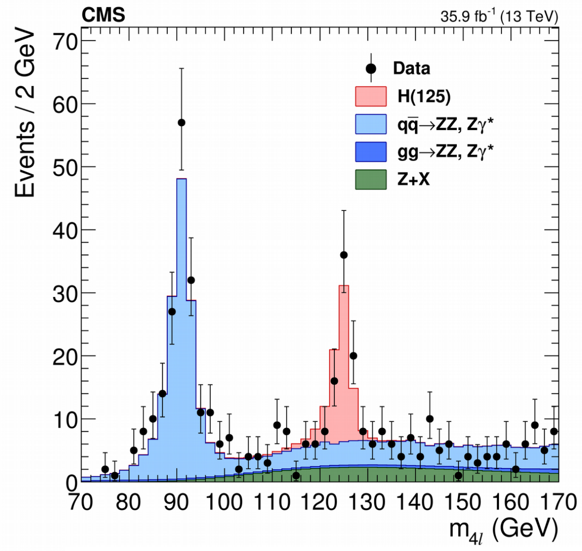


Direct trigger output, no offline analysis!
[LHCb preliminary – 1.5 fb^{-1}]

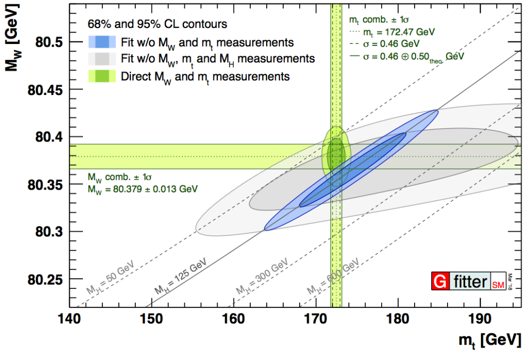
[Phys. Rev. Lett. 120, 061801 (2018) Run 2, 1.6 fb^{-1}]

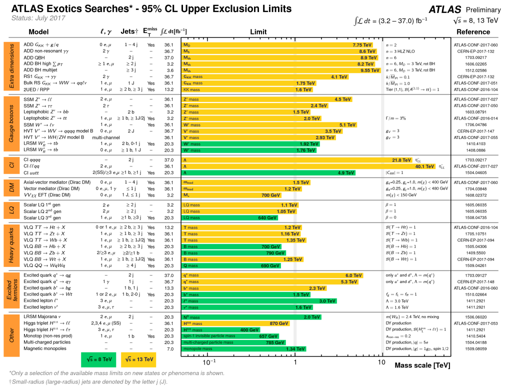
Run2 physics results

- **Higgs Sector**
  - Mass
  - Coupling to Bosons and Fermions
- **Standard Model Precision measurements**
  - W and Top Mass
  - Standard Model Fits
- **Searches**
  - Exotics
  - SUSY
- **Flavour physics**
  - CKM matrix and unitarity triangle tests
  - Spectroscopy and exotic hadronic states
  - Rare decays, FCNCs and R(K$^{(*)}$)
- **Heavy ions results**



[Gfitter, 1803.01853]




ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 37.0)$ fb^{-1}

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

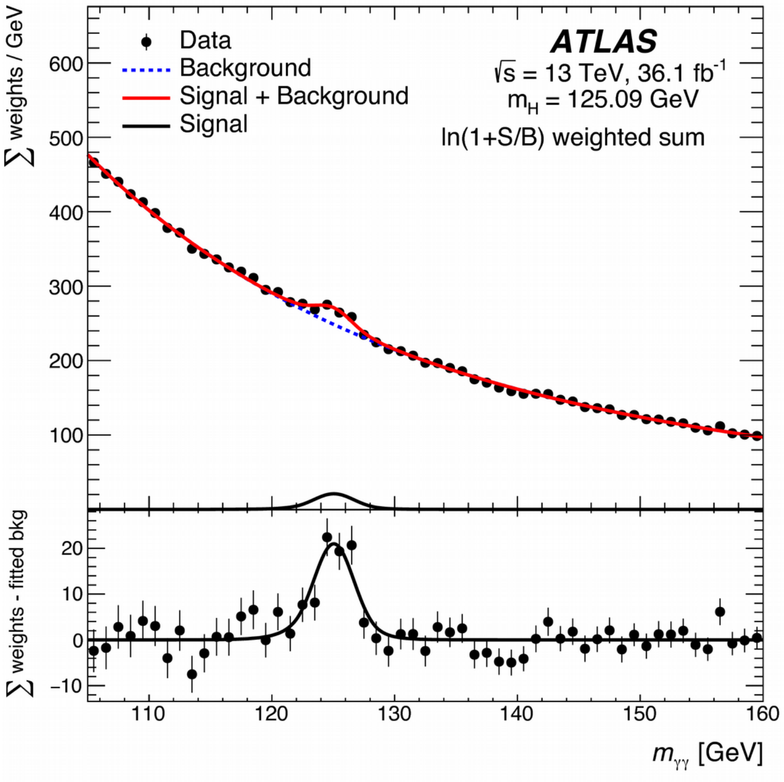
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt$[fb^{-1}]	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D	7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass	1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass	1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass	4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass	1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass	2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass	5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass	3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass	1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass	1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ	40.1 TeV η_{LL}^-		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ	4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med}	1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass	1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass	1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass	1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass	700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass	790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass	1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q* mass	6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b* mass	2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b* mass	1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

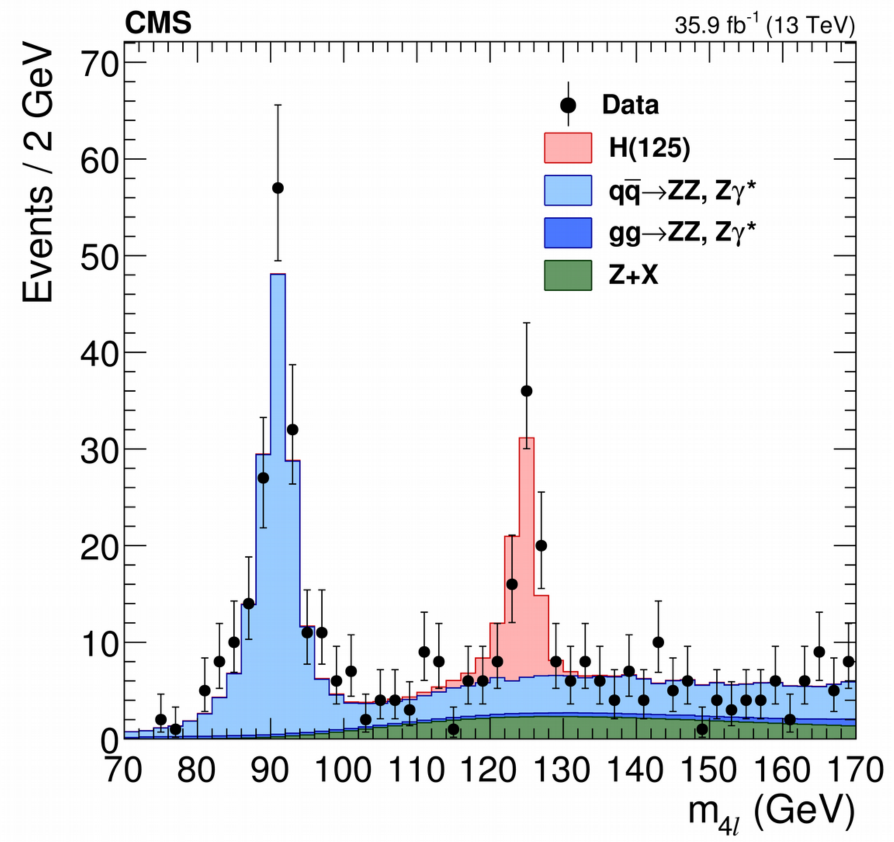
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Higgs sector

Higgs golden channels

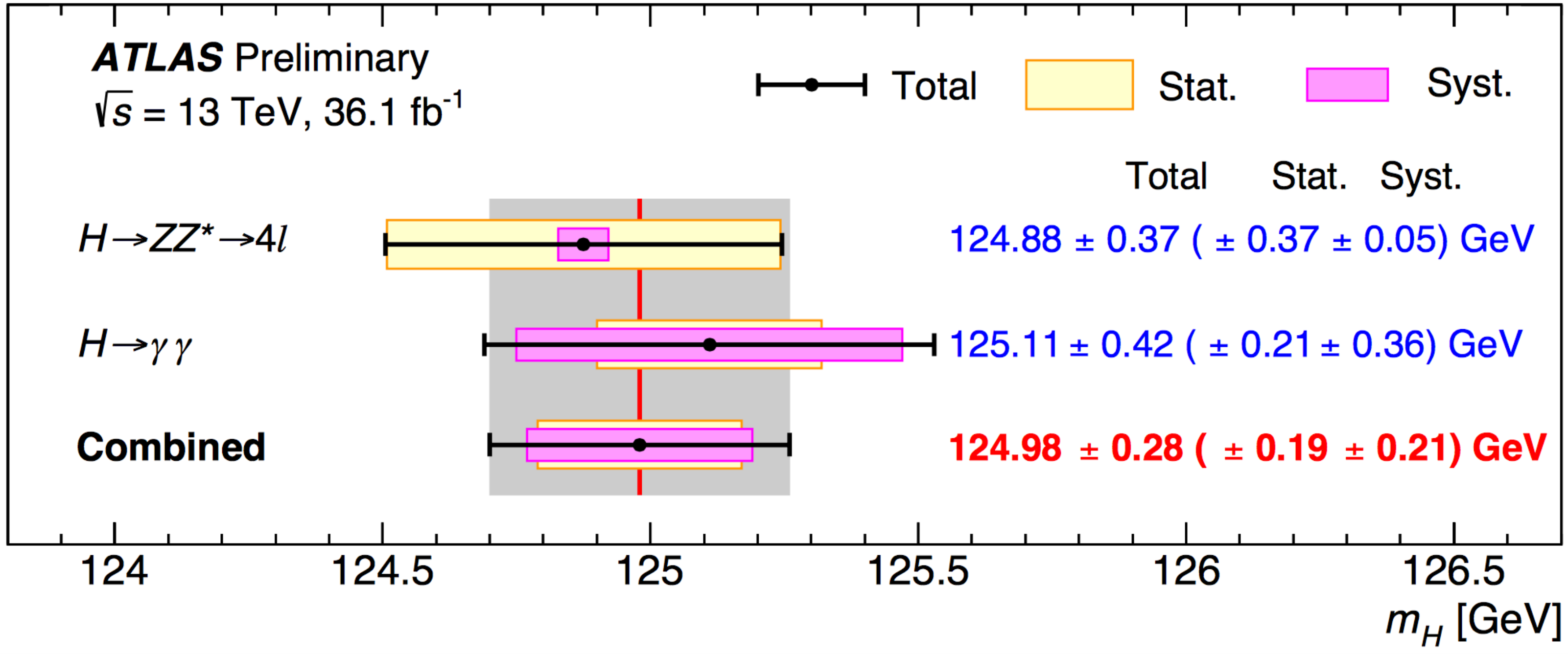




Higgs Boson Mass measured with high precision by ATLAS and CMS using the fully reconstructed final states: H-> γγ and H->ZZ->4l (e,μ)

All measurements in good agreement

Higgs Mass

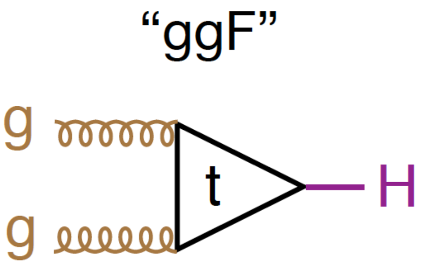


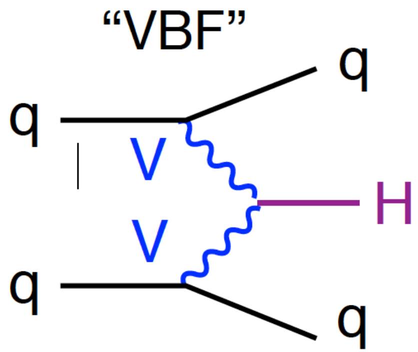
CMS Mass Measurement using only H->4l
12% more precise than Run 1 ATLAS+ CMS comb.

$$\boxed{m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \mathrm{stat.} \pm 0.08\ \mathrm{sys.})\ \mathrm{GeV}}$$

Higgs Production and Branching fraction

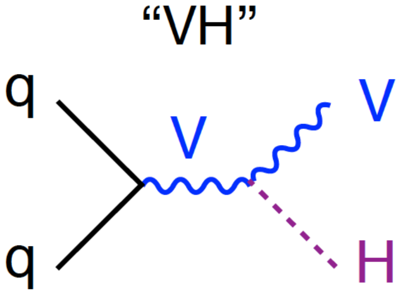
- Different production mechanisms and decays to measure
- Use of different experimental signatures
- Some very clean decays with low BR (γγ, 4l), other very difficult with higher rates (bb, WW, tt,)

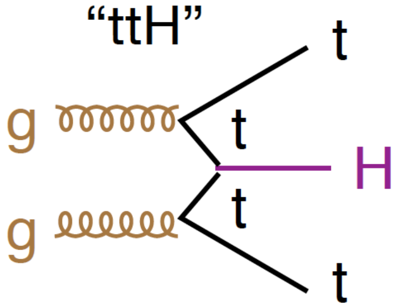


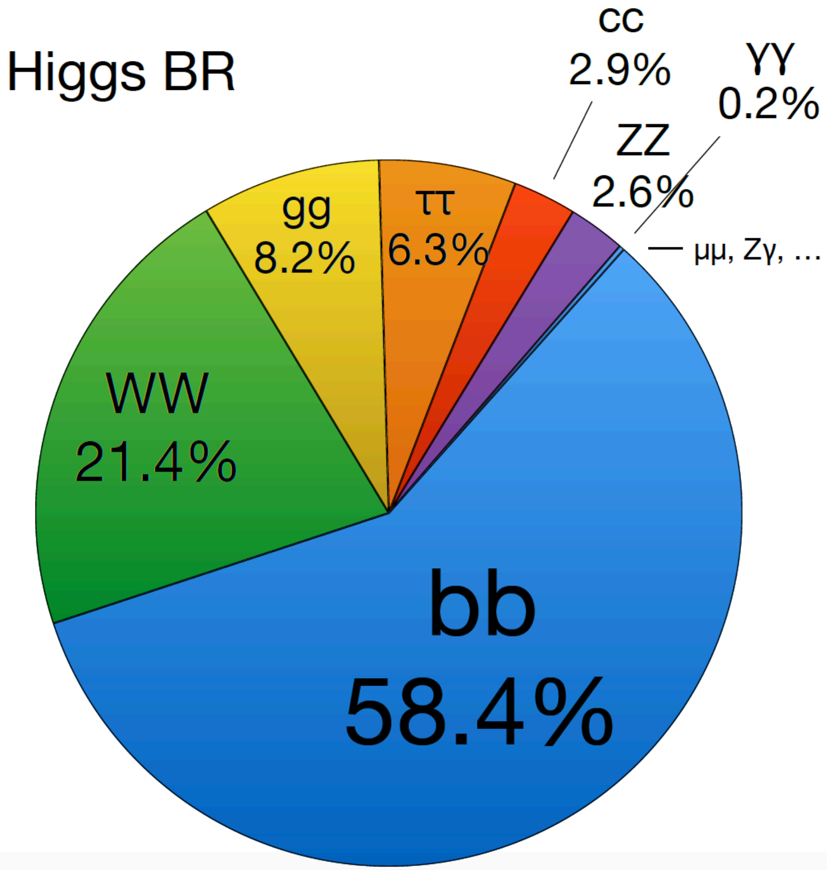


49 pb	3.8 pb
2.2 pb	0.51 pb

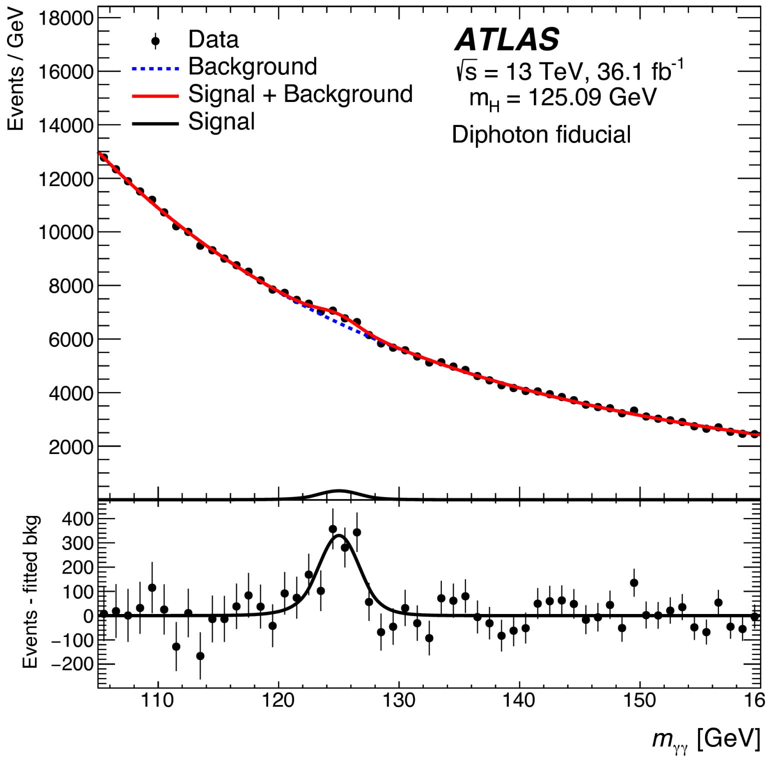
@ 13 TeV

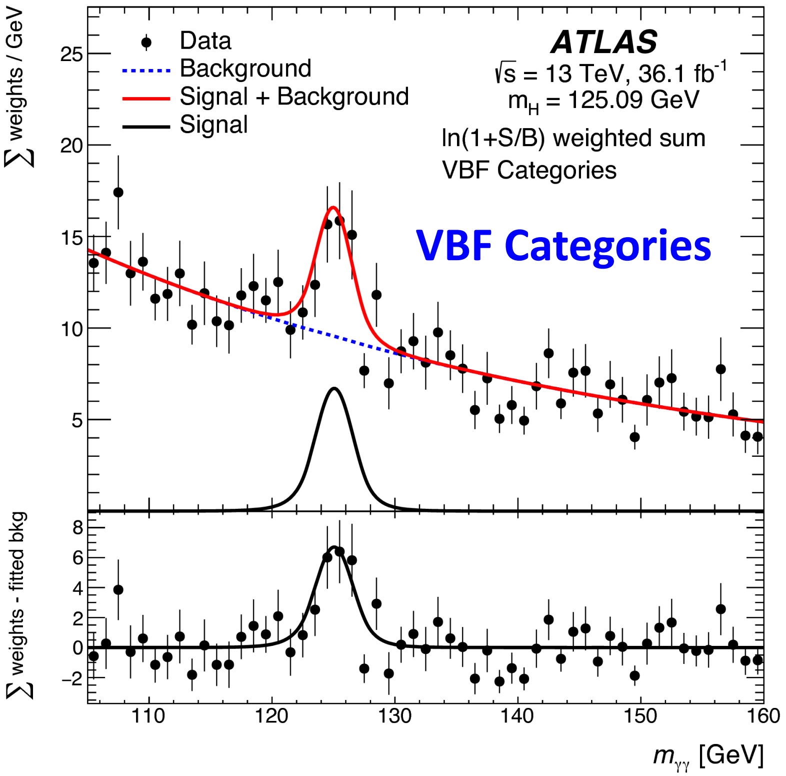






Coupling to Bosons H -> $\gamma\gamma$

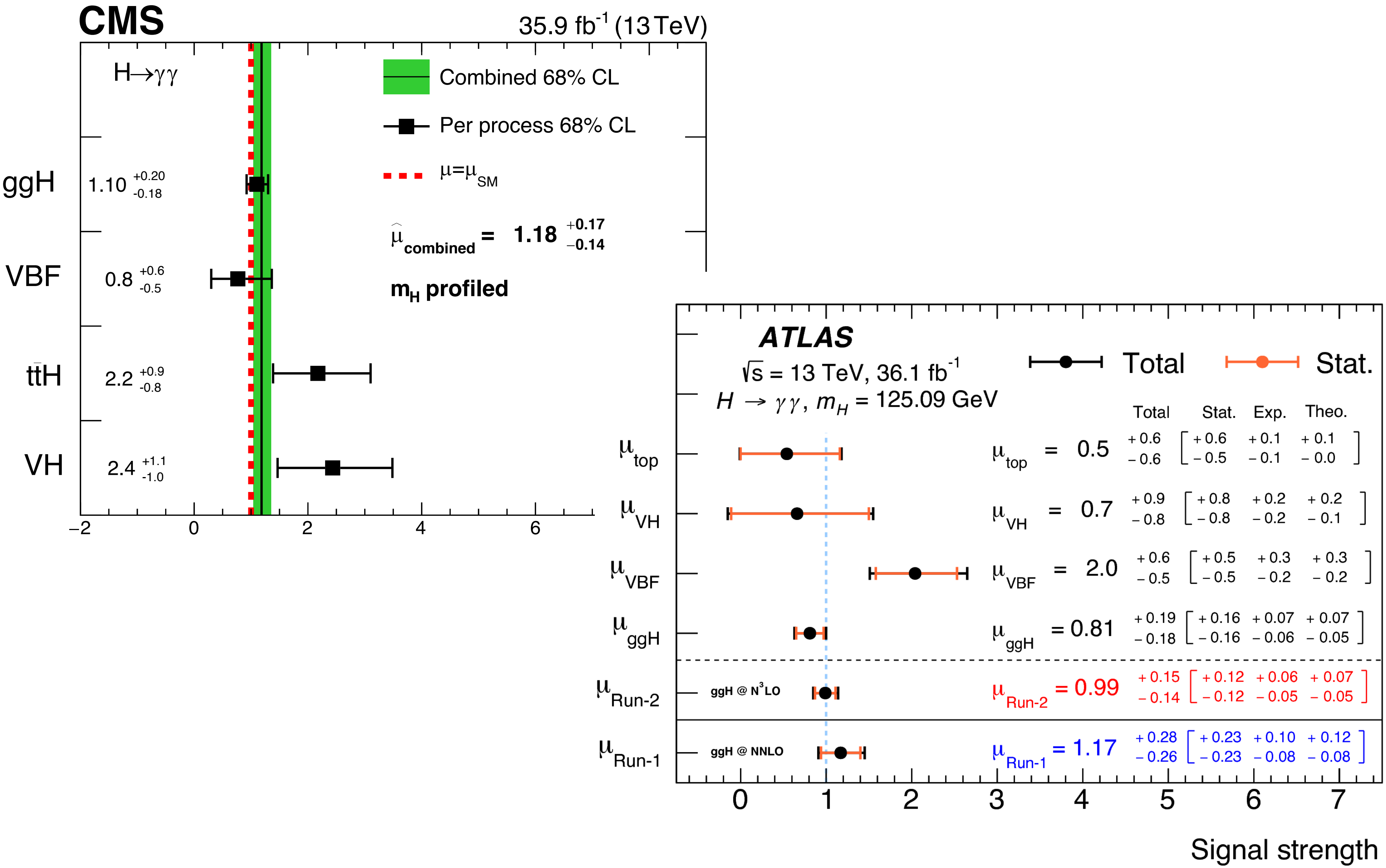




VBF Categories

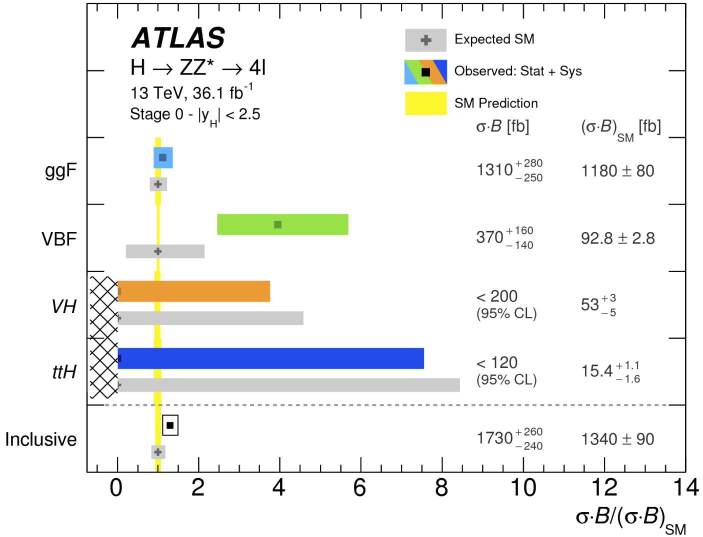
- The Higgs decay in $\gamma\gamma$ has a clean signature over a smooth background
- It is used to disentangle the different production mechanisms allowing a measurement of their signal strenght : μ

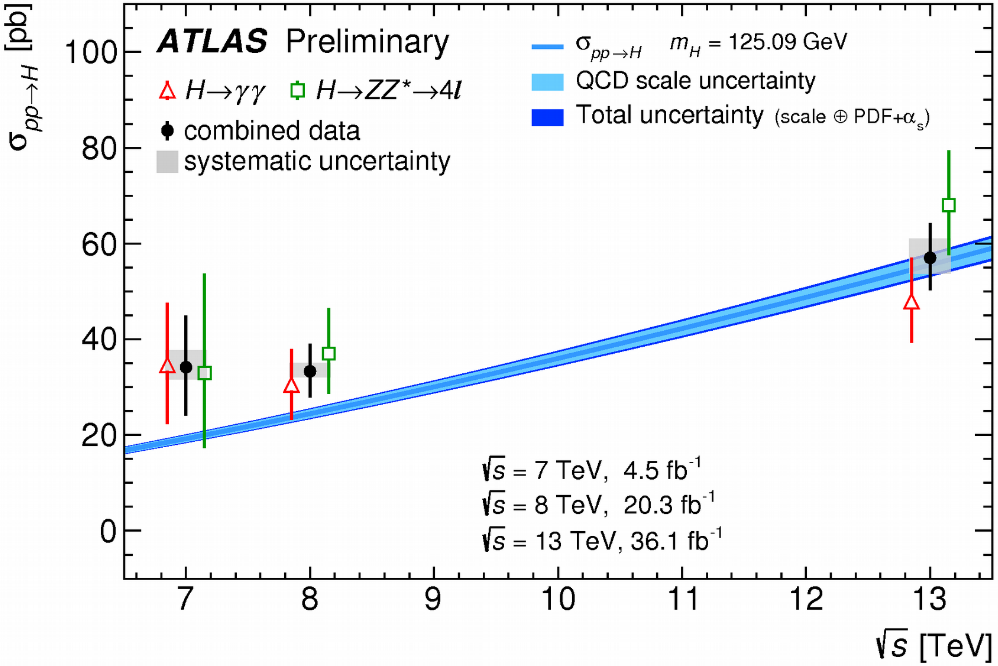
Bosons H->γγ: signal strenght μ

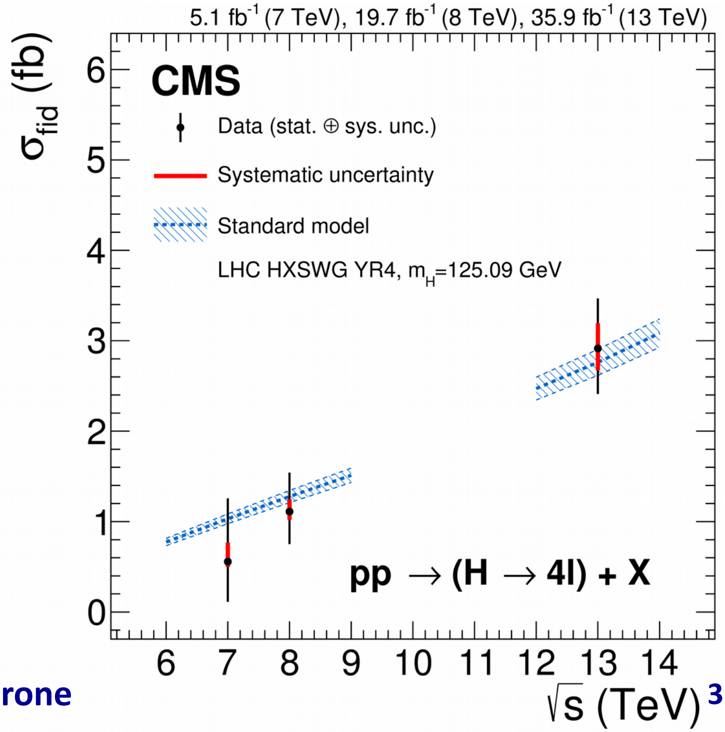


Coupling to Bosons H-> ZZ

- Very clean signature but very low rate
- Measurement of ggH and VBF production
- Measurement of total fiducial cross section

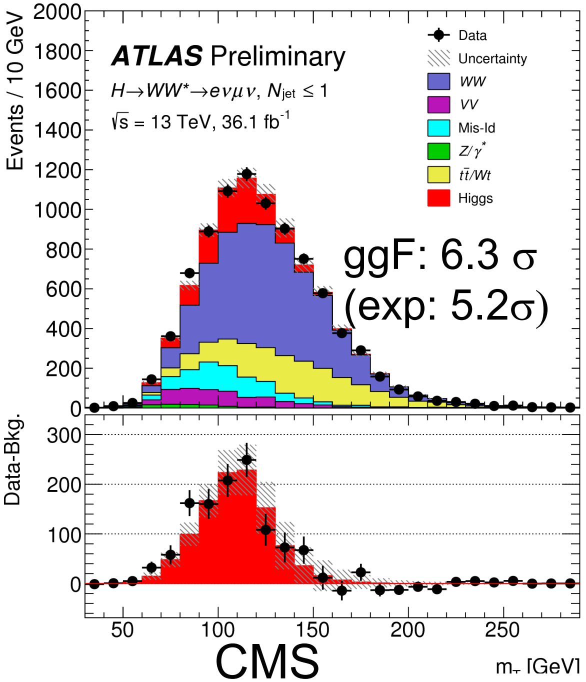




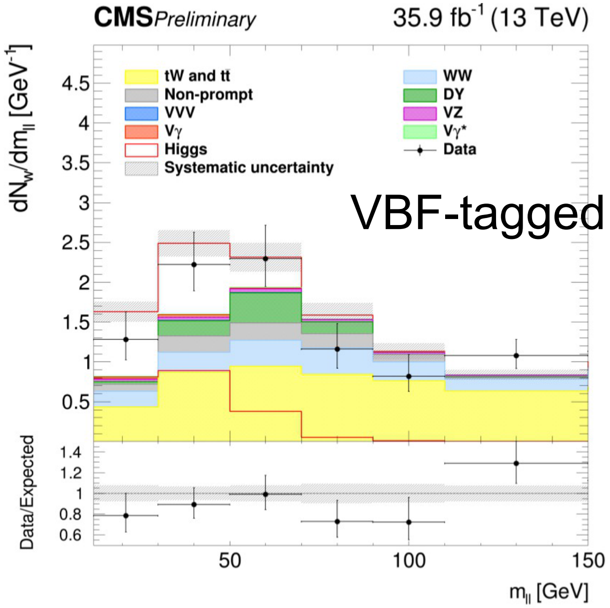


Coupling to Bosons H-> WW

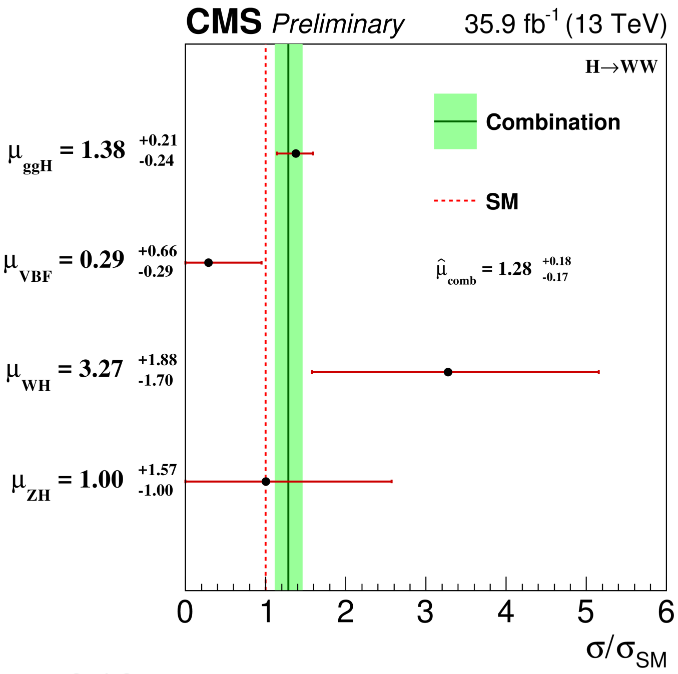
- Larger usable branching fraction (2l2ν) but much larger background
- No Higgs mass reconstruction, rely on lepton kinematics (Mt, Mll, θ_{ll})



ggF: 6.3 σ (exp: 5.2σ)



VBF-tagged



CMS

$$\hat{\mu} = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10(\text{stat})^{+0.11}_{-0.11}(\text{syst})^{+0.10}_{-0.07}(\text{theo.})$$

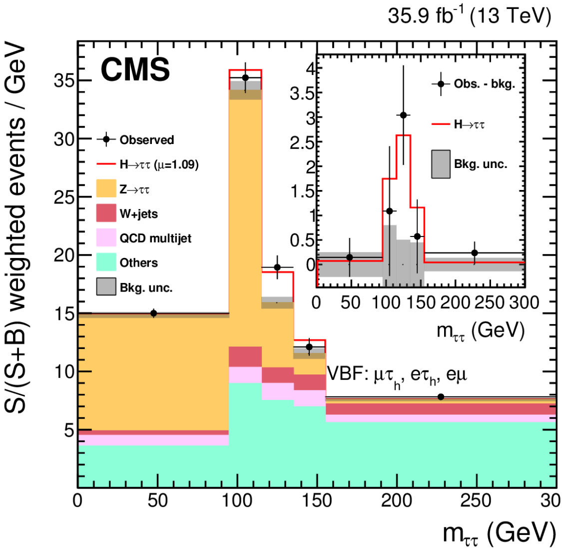
ATLAS

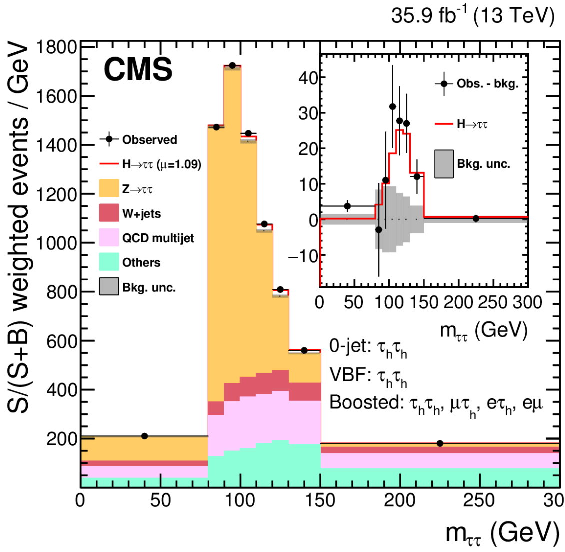
$$\mu_{\text{ggF}} = 1.21^{+0.12}_{-0.11}(\text{stat.})^{+0.18}_{-0.17}(\text{sys.}) = 1.21^{+0.22}_{-0.21}$$

$$\mu_{\text{VBF}} = 0.62^{+0.30}_{-0.28}(\text{stat.}) \pm 0.22(\text{sys.}) = 0.62^{+0.37}_{-0.36}$$

Coupling to Fermions H-> $\tau\tau$

- Search for H->$\tau\tau$ with τ decaying in $e\mu$, $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$
- Largest background from Z->$\tau\tau$ and hadronic multijet events
- Search in categories aiming at ggH and VBF production

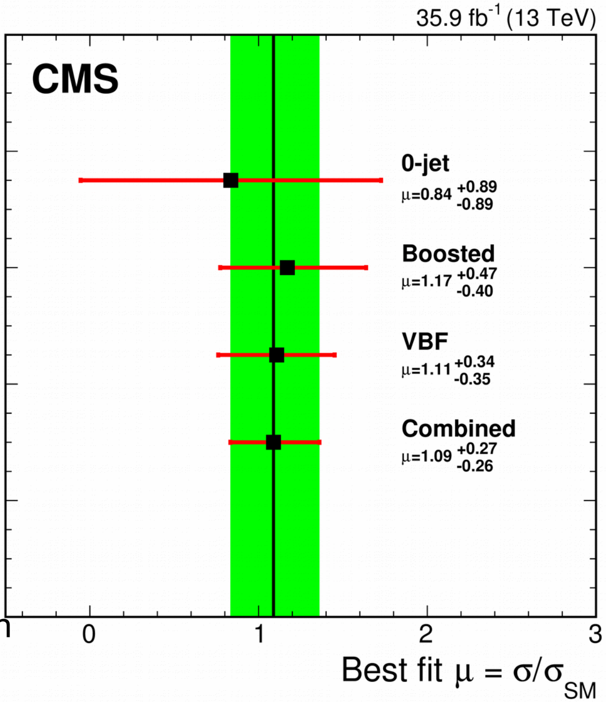


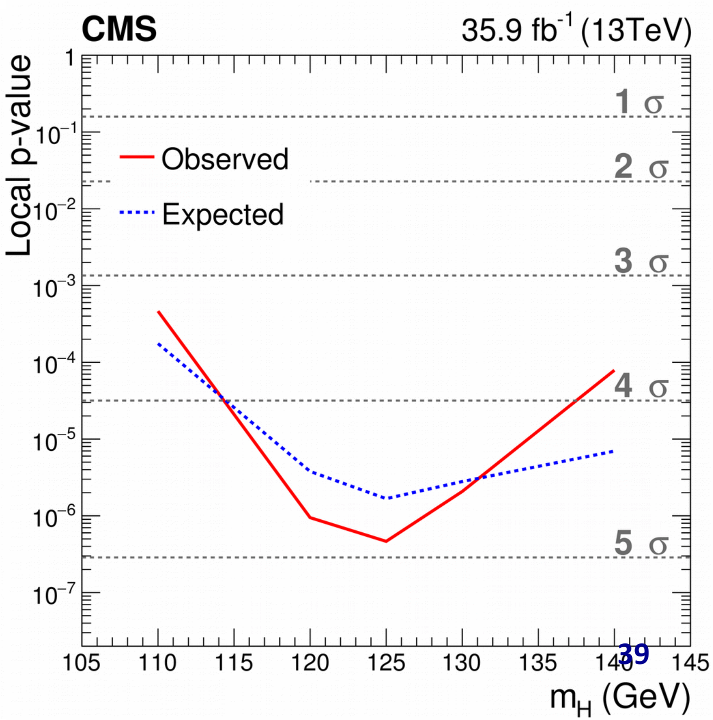


Observation of H-> $\tau\tau$

μ= 1.09 ± 0.26

Significance: 4.9 σ (5.9 σ for comb. of 13 & 7-8 TeV)

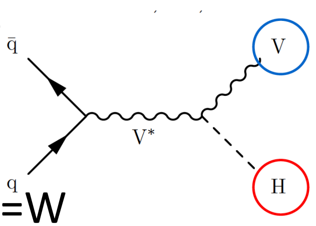


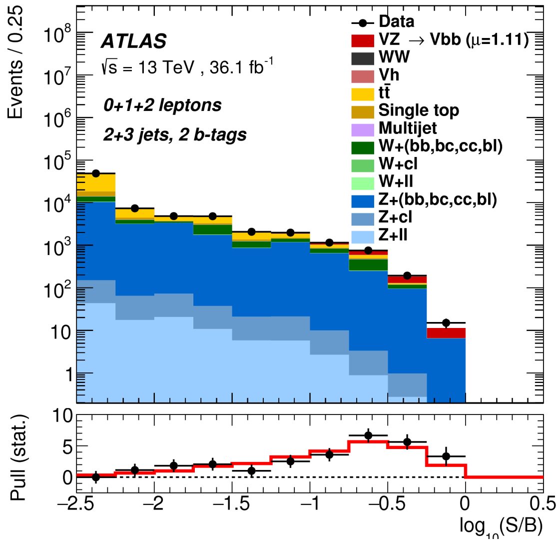


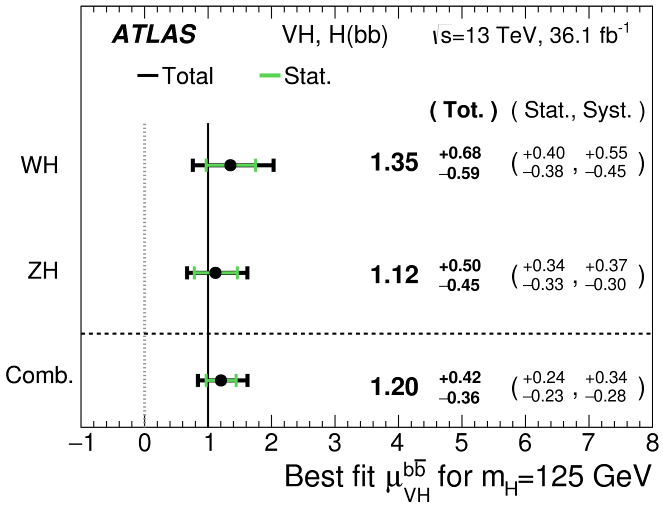
First observed in run 1 by ATLAS and CMS Combination

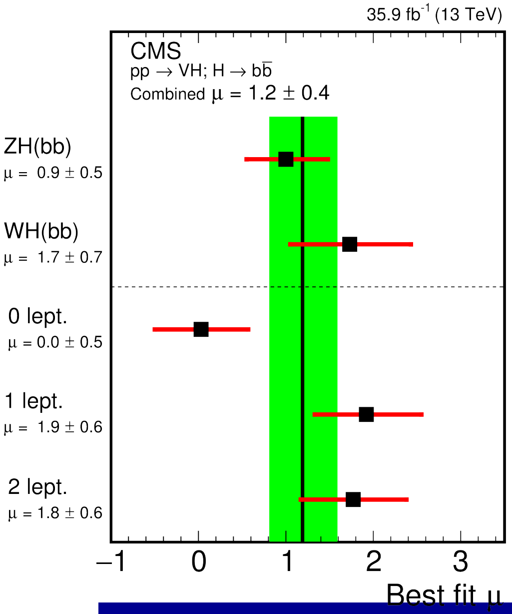
Coupling to Fermions H-> bb

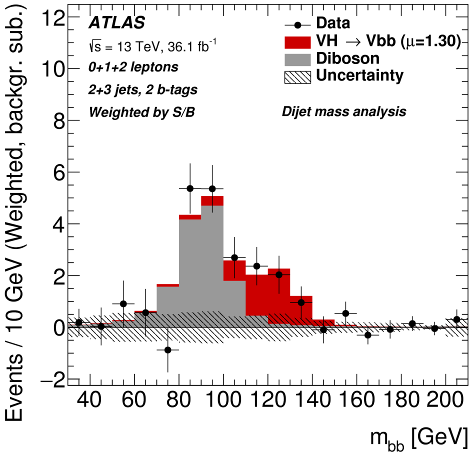
- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Need to use exclusive (rare) production mechanism to gain sensitivity: VH H->bb (V=W or Z)
- Final states with 2 tagged b Jets and 0,1 or 2 leptons











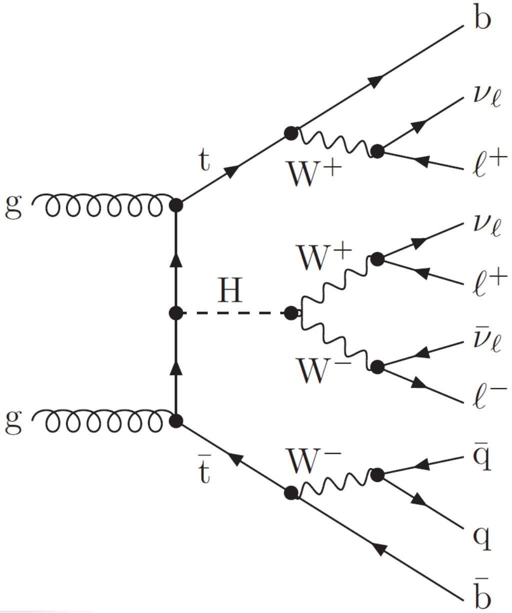
Evidence of VH(bb) production

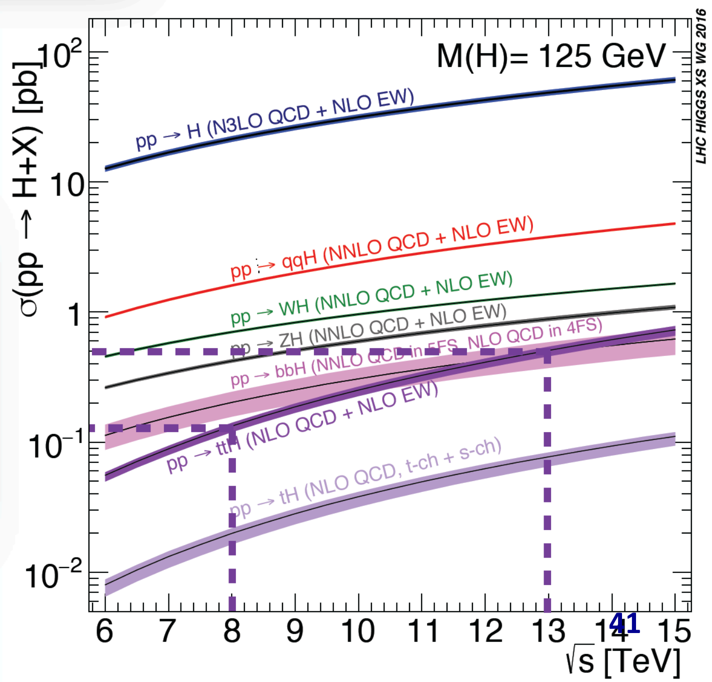
Observed (expected) significance

	Run II	Run I+II
ATLAS	3.5 (3.0)	3.6 (4.0)
CMS	3.3 (2.8)	3.8 (3.8)

Coupling to Fermions: ttH

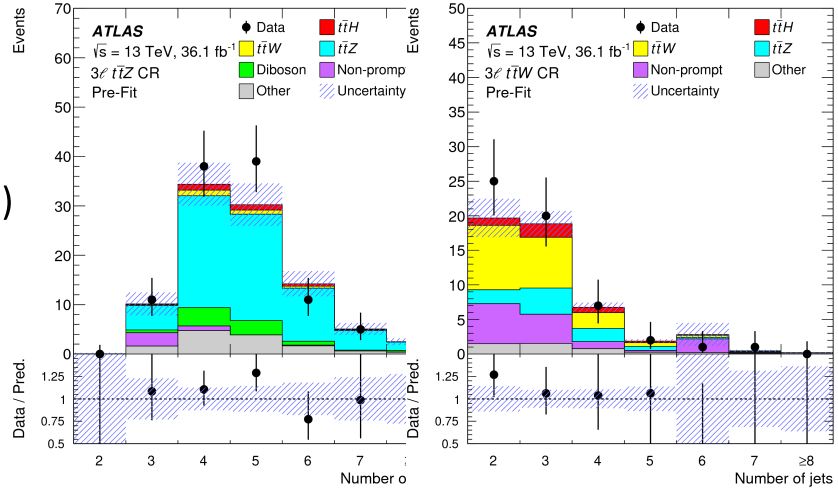
- Very interesting:
  - give direct acces to the Yukawa coupling between the top quark and the Higgs
- Very challenging:
  - Very small production cross section (O(0.5)pb @ 13 TeV
  - Many complex final states and large irreducible backgrounds
- Complex analyses:
  - Use of BDTs, MVA, Deep Machine Learning techniques
- Results from ttH-> Multilepton final states and ttH, (H-bb)



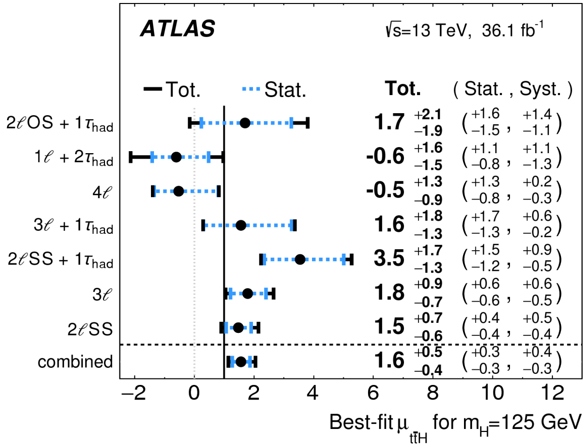


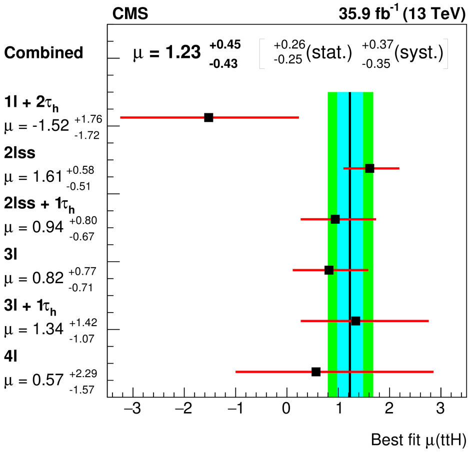
ttH-> Multileptons

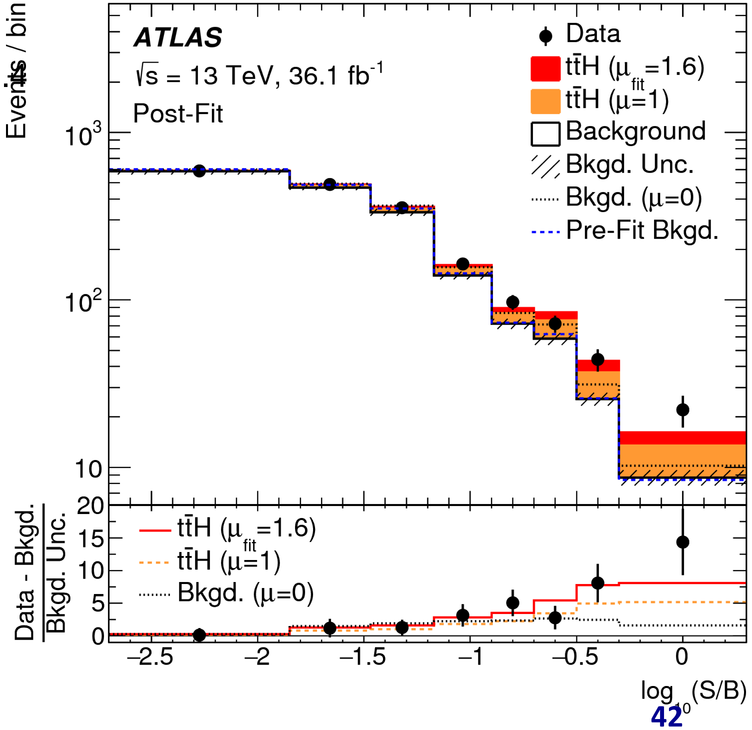
- Target Higgs decays to WW, ττ and ZZ
  - Two same sign or >=3 charged leptons+ additional requirements on b-jet multiplicities (and/or τ_h for CMS)
    - CMS uses also 1 lepton and $2\tau_h$
- Irreducible background: ttW, ttZ, with prompt leptons
- Reducible background: mostly tt+γ with mis-reconstructed leptons



ATLAS comb. $\mu=1.6^{+0.5}$-, CMS comb. $\mu=1.23^{+0.5}$-0.4







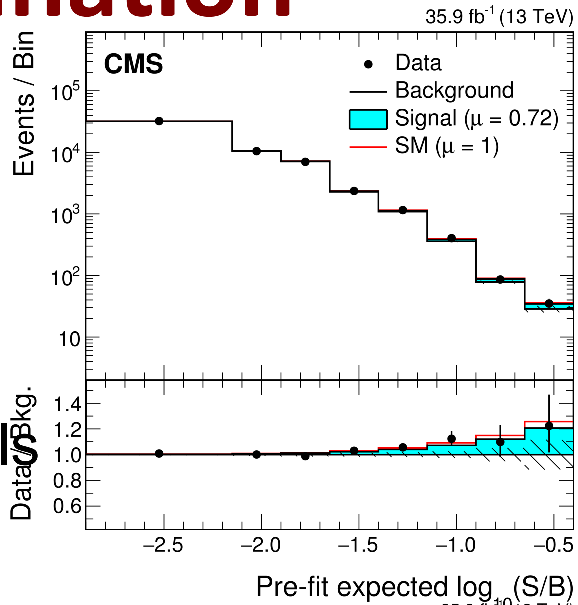
Evidence for ttH production in leptonic final states

CMS : 3.2 σ (2.8 σ exp.)

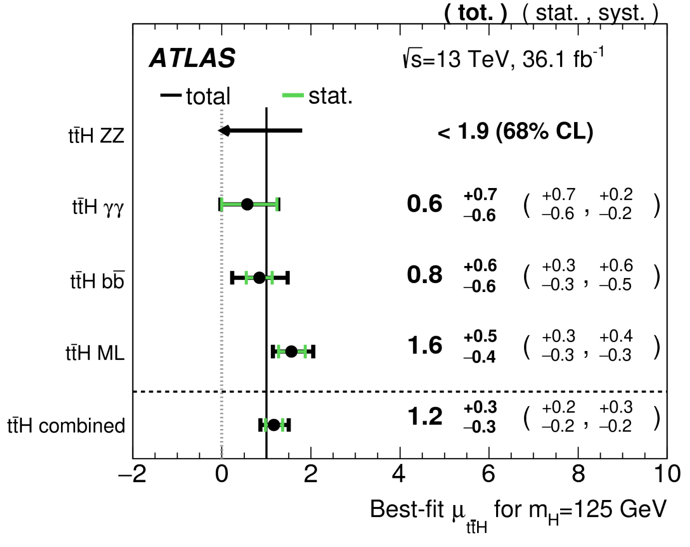
ATLAS: 4.1 σ (2.8 σ exp.)

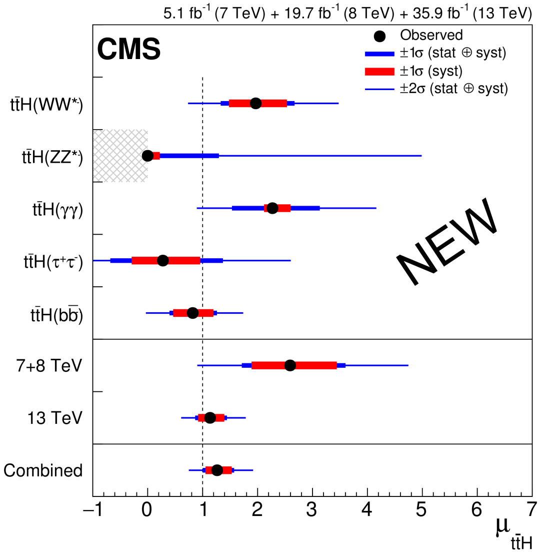
ttH (H->bb) and Combination

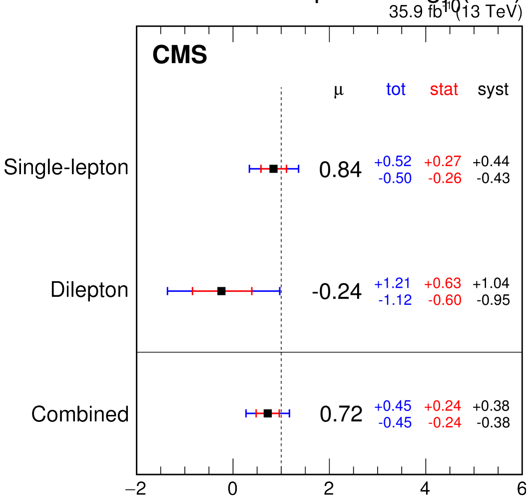
- ATLAS and CMS use channels with 1 or 2 leptons and N_{jet}>= 4, >=3b, to exploit leptonic t decays to reduce huge backgrounds
- CMS also uses the all hadronic final state: higher rates but even larger background



Combined signal strength of all ttH channels in agreement with SM predictions







ATLAS Combination Run2 m=1.2+-0.3   Evidence ttH Prod. 4.2s (3.8σ exp.)

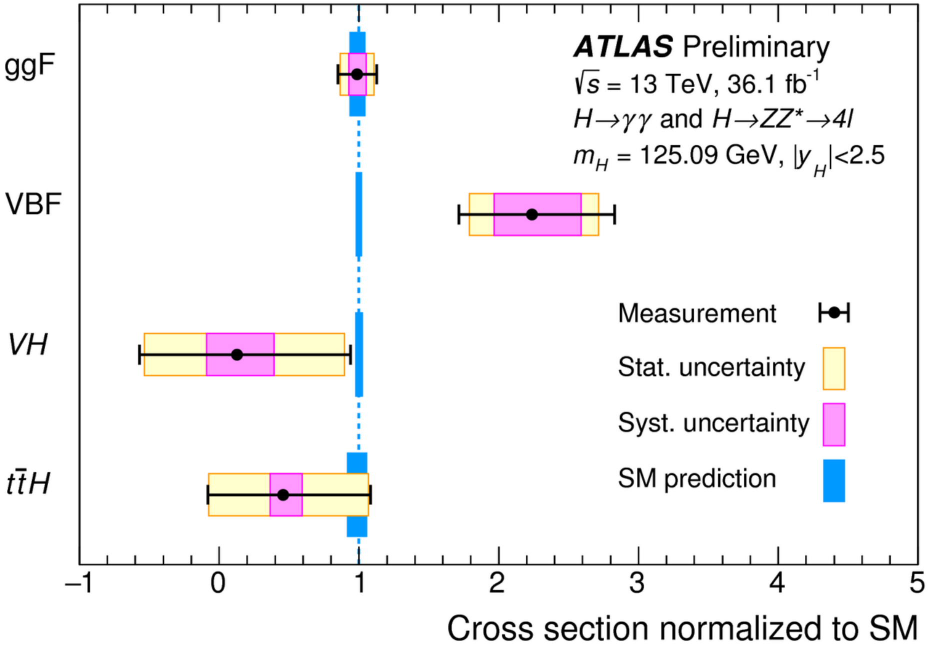
CMS Combination   Run2 m=1.18+0.31-0.27 Evidence tth Prod 4.2 σ

CMS Combination Run1+Run2 m=1.26+0.31-0.26 Obs. of ttH with 5.2s (4.2σ exp)

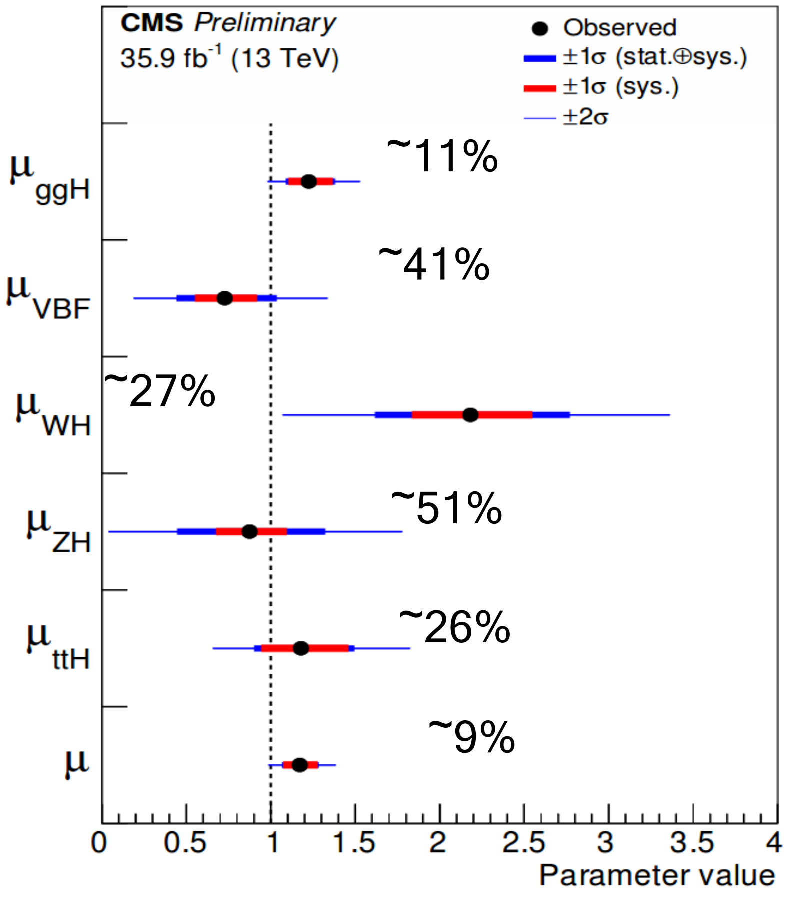
The Higgs Sector summary

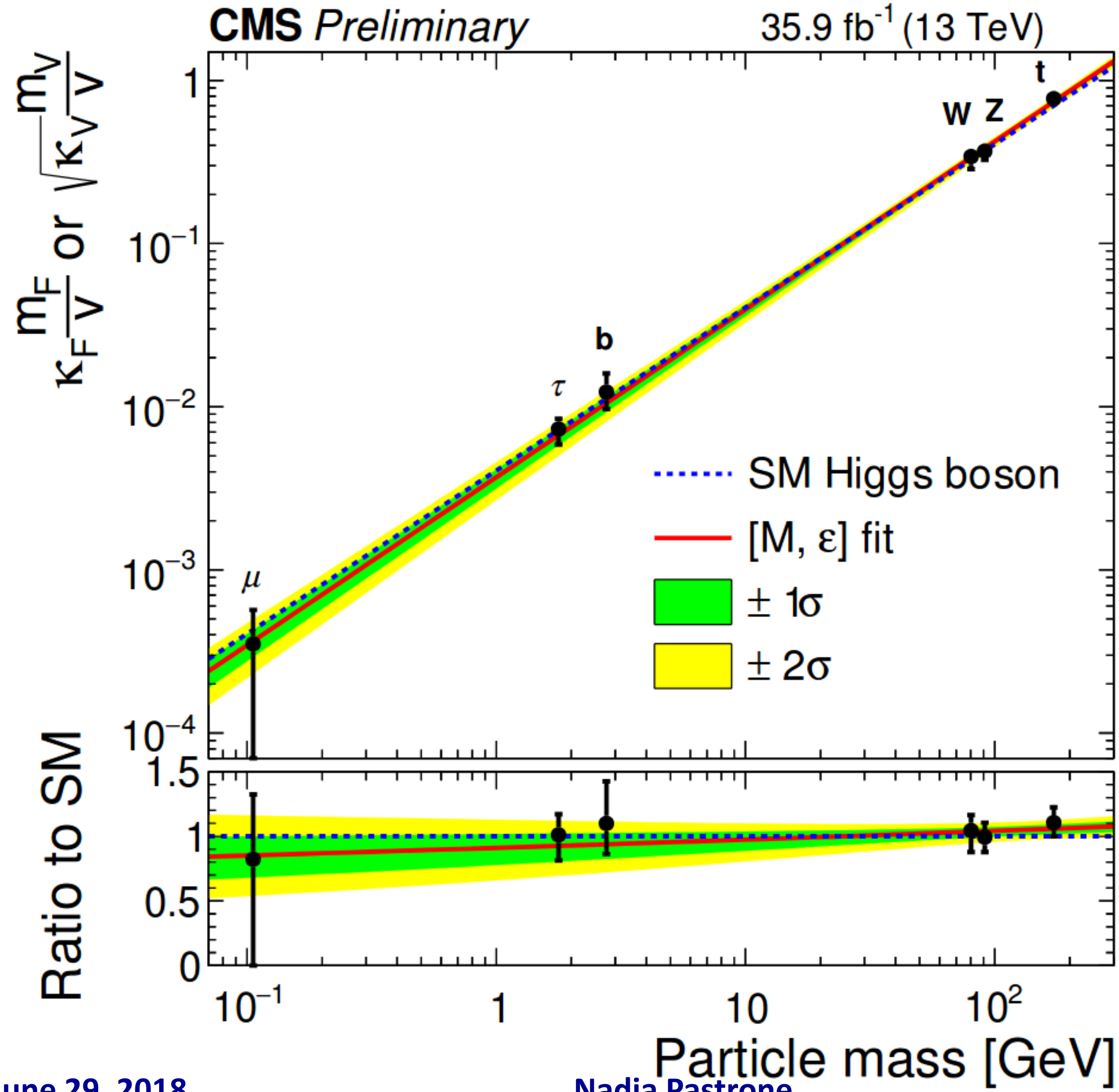
- CMS μ combination: $\mu = 1.17^{+0.10}_{-0.10}$
- Cross sections measurements in agreement with SM
- Differential Cross Sections also in good agreement with SM

Cross sections normalised to SM from ZZ and γγ combination



Higgs production

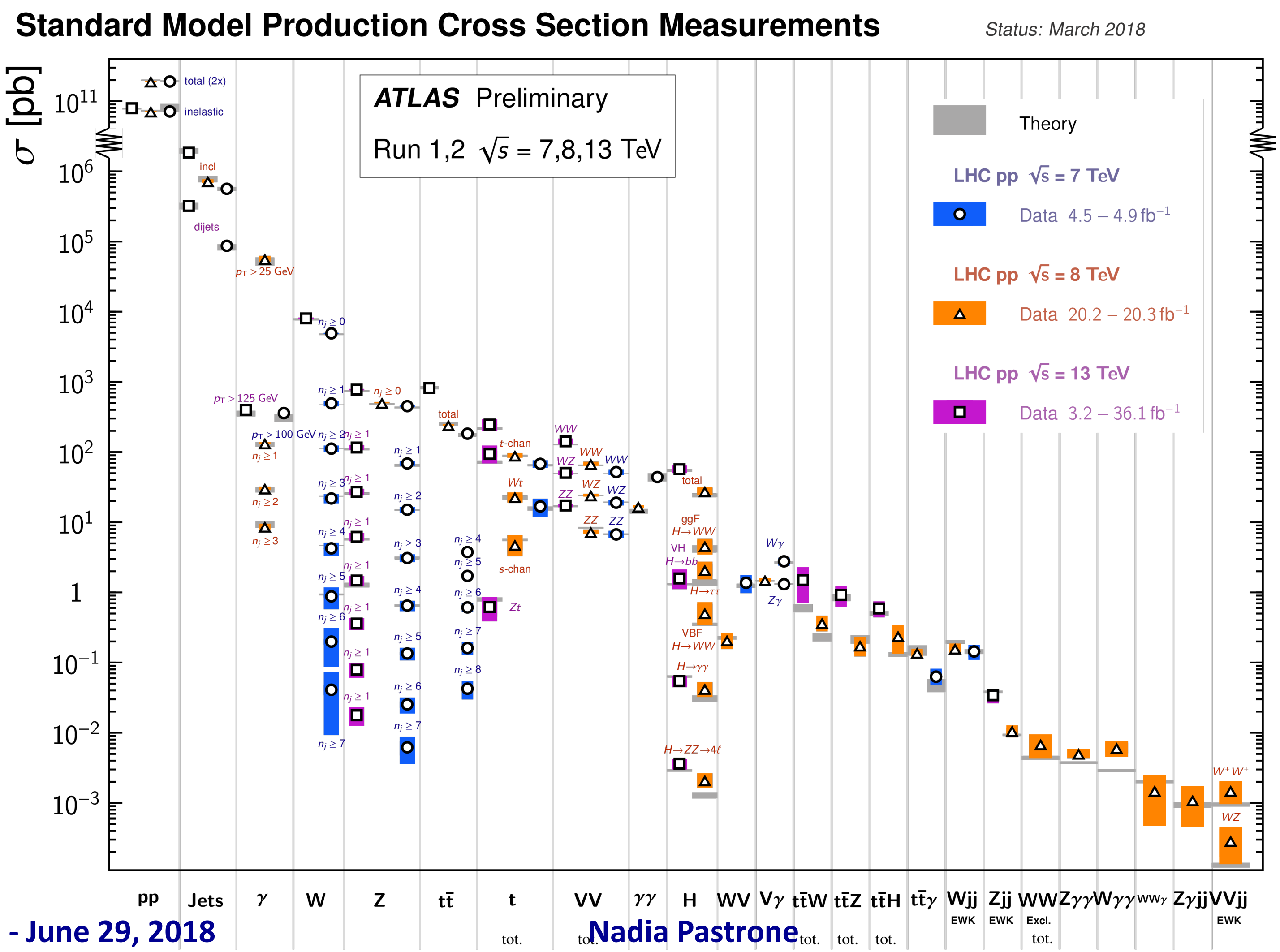



CMS Preliminary
35.9 fb^{-1} (13 TeV)
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
t
W
Z
b
τ
μ
SM Higgs boson
[M, ε] fit
± 1σ
± 2σ
Ratio to SM
1.5
1
0.5
0
10^{-1}
1
10
10^2
Particle mass [GeV]

SM precision measurements

SM and QCD

Impressive number of measured cross sections in very good agreement with expectations



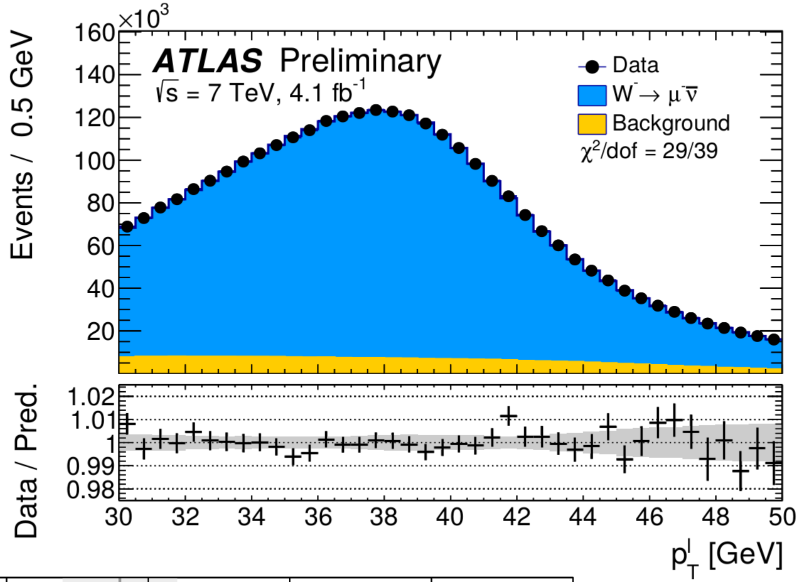
W boson mass

Early 2011 data with low Pile-Up
4.6 fb^{-1} @ √s = 7 TeV

m_W = 80.370 ± 0.019 GeV

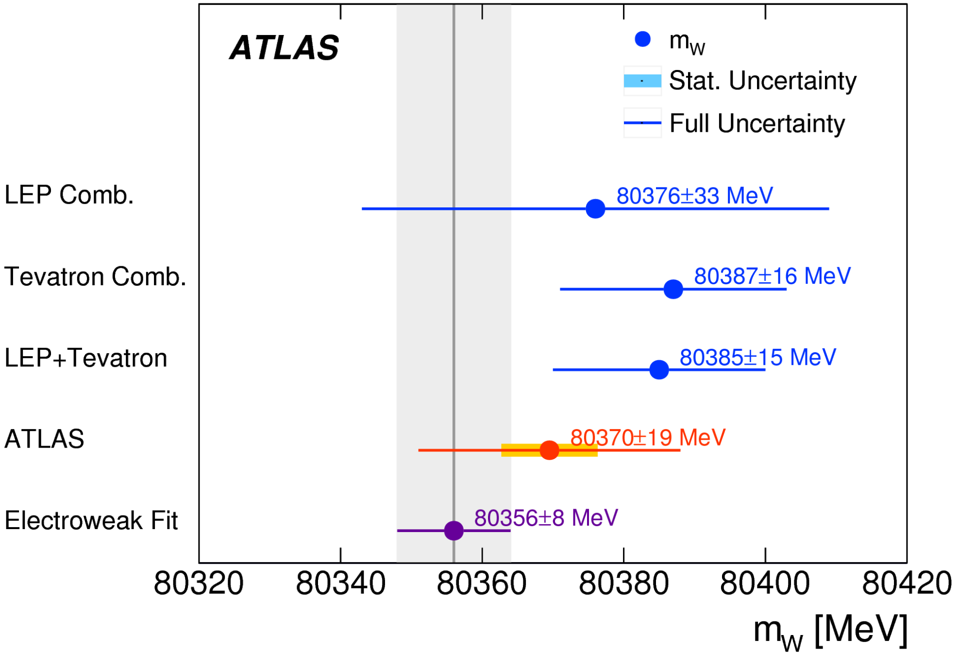
± 7 MeV statistical
± 11 MeV systematic
± 14 MeV modeling

Muon Pt



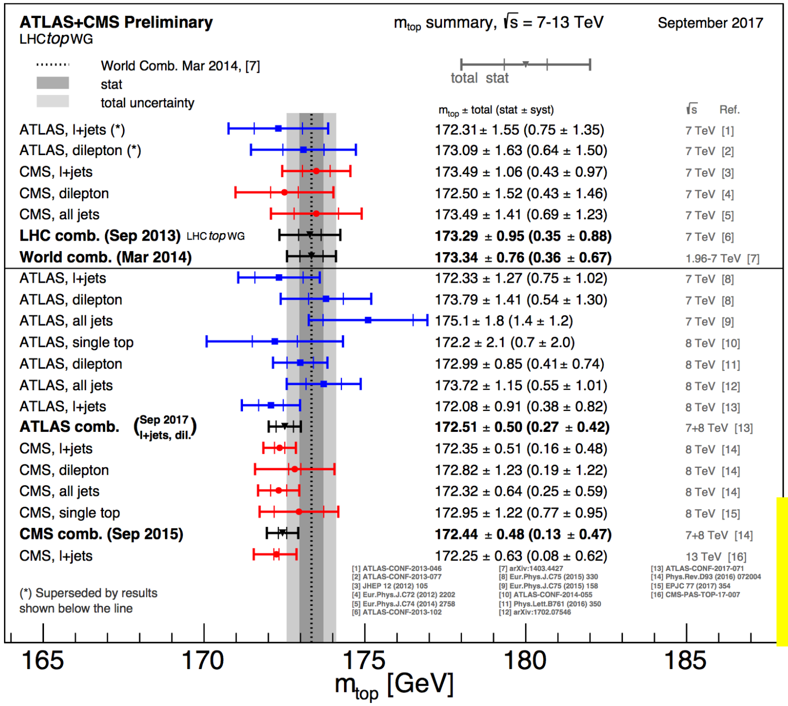
Huge amount of work to understand detector response and the modelling of kinematic quantities (Mt, P_t^l)
(relies on large Z → ℓℓ sample)

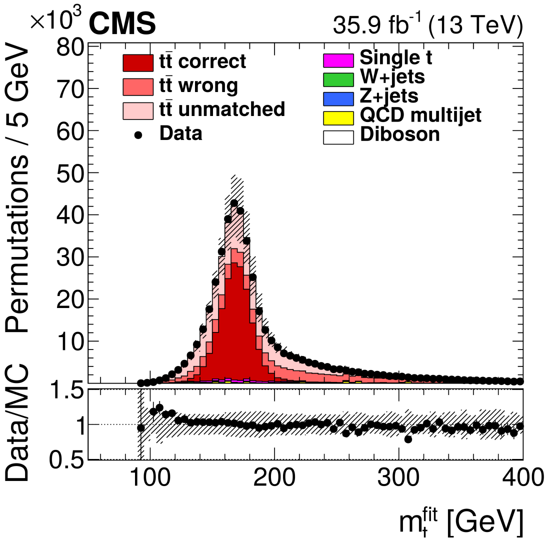
Similar precision reached as for current best CDF measurement

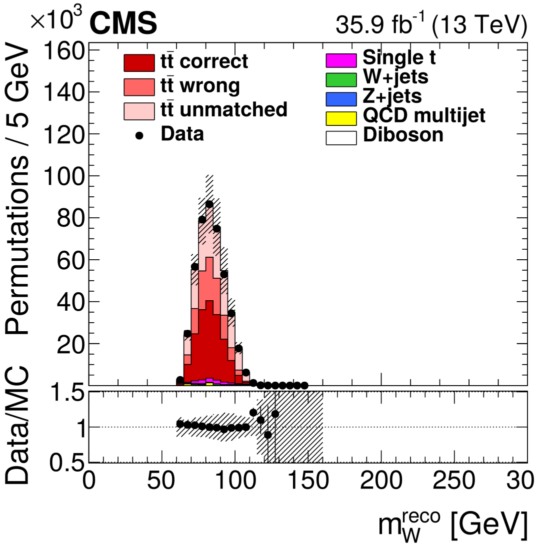


Measurement of the Top Mass

- Large Top production cross section
  - Many precision measurements on Top Properties
- Many differenet methods and final states used to extract Top Mass
  - Direct methods, (Templates, Ideograms)
  - Indirect method (based on measured Xsect.)





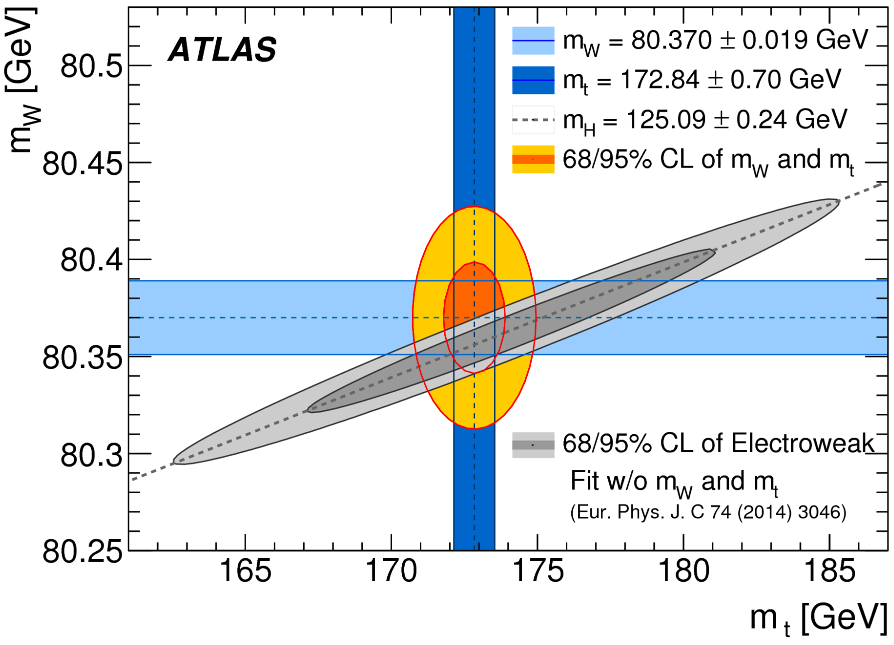


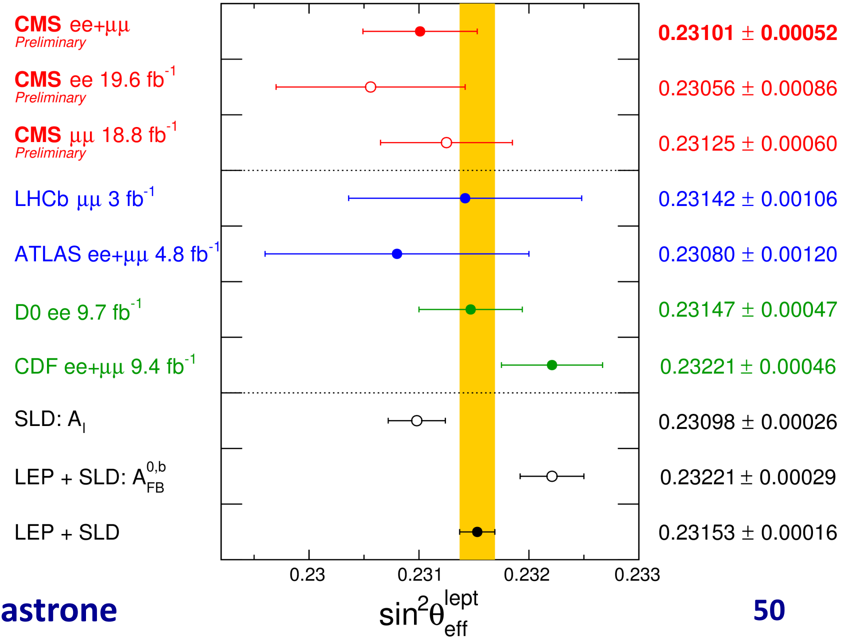
ATLAS Combination m_{top}=172.51+-0.5

CMS Combination m_{top}=172.44+-0.48

Standard Model

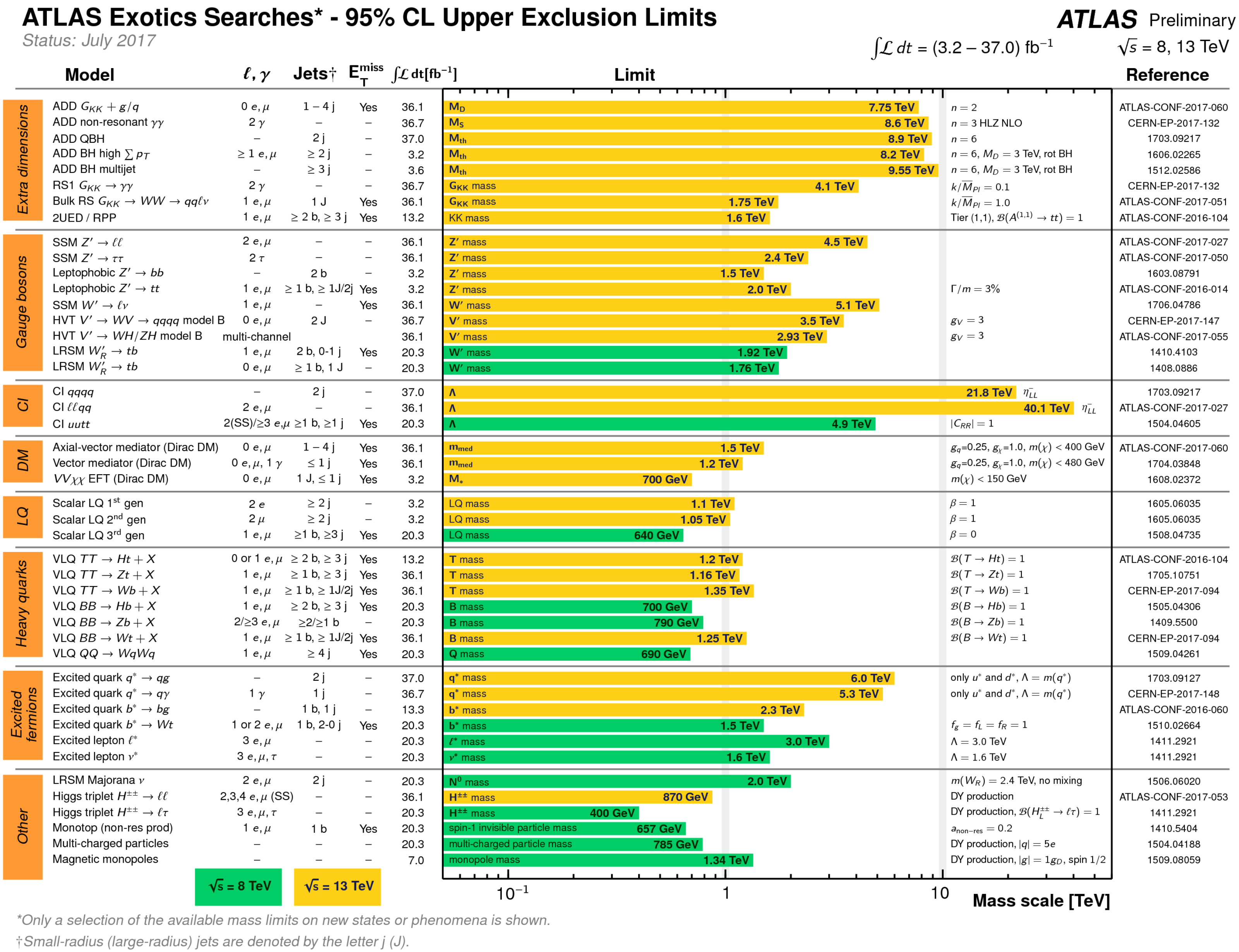
- A precision measurement of m_{top} m_W and m_H allows a stringent test of the SM
  - Aim at improving further the precision on Mw with dedicated runs
- Precision measurement of $\sin^2\theta_w$ by A_{fb} consistent with previous measurements and with SM





BSM Searches

Exotics



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 37.0)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	🟨 V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η_{LL}^{-}	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	🟨 Λ 40.1 TeV	η_{LL}^{-}	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	🟨 m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

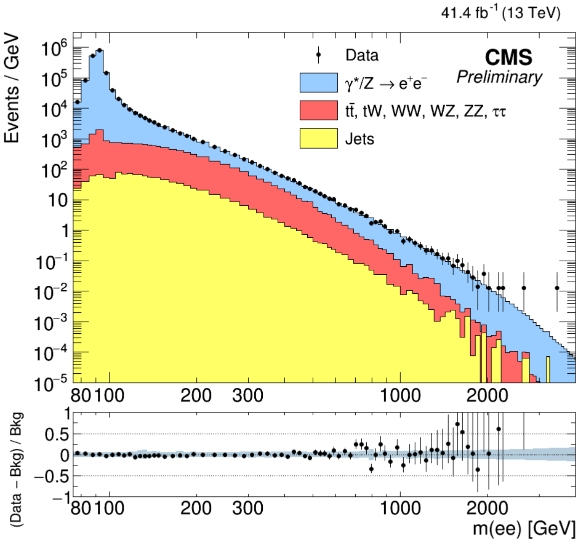
🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

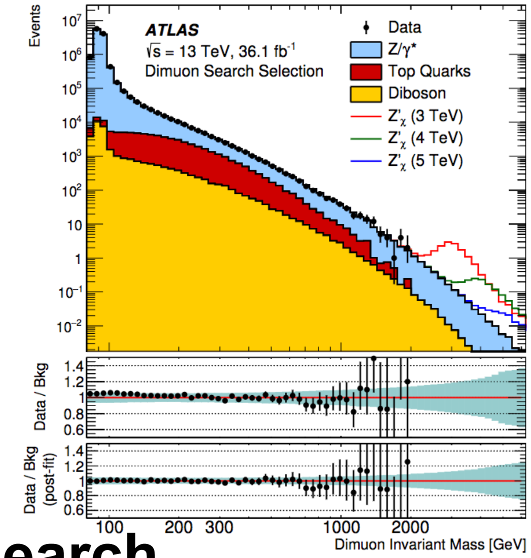
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

New Bosons

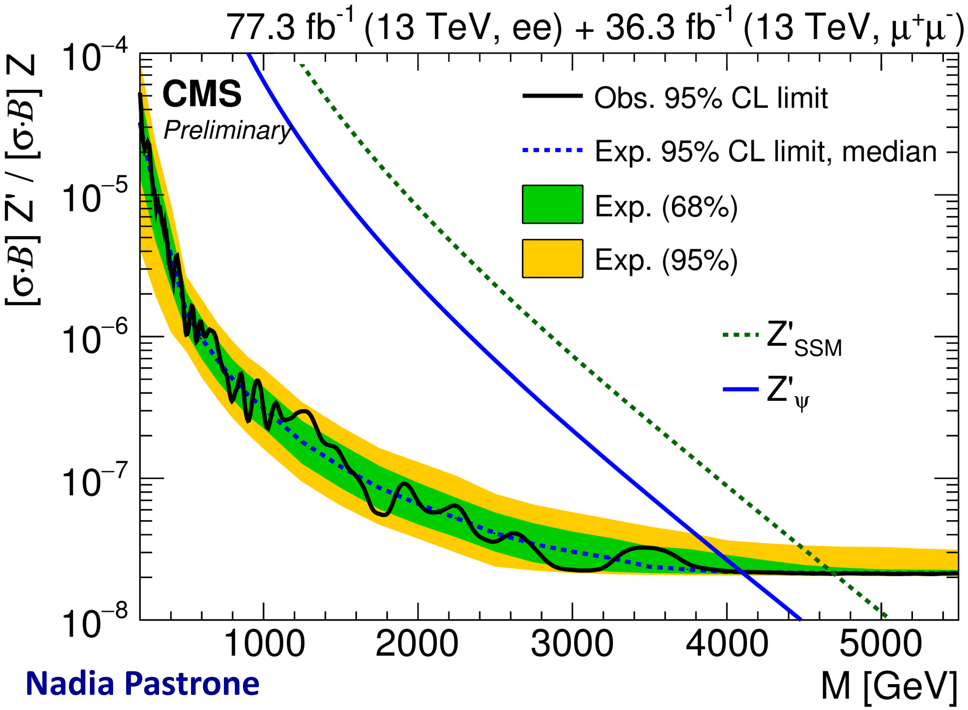
- Di-lepton (ee, μμ), (eν,μν) final states offer a very clean signature to searches of new Heavy Bosons eg Z', W'





Z' search

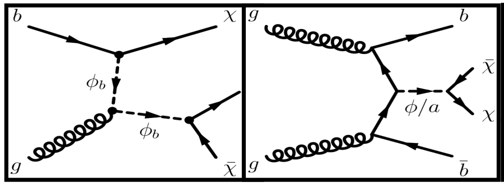
- No significant excess observed



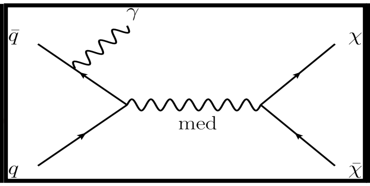
- Results interpreted in many models e.g.:
  - M (Z' $_{SSM}$) > 4.7 TeV
  - M (Z'$_\psi$) > 4 TeV

- Searches in the Mono-X final states
  - One well reconstructed object with large Missing Energy due to WIMP
  - Many models constrained up to 1-2 TeV
- Searches also in the Di-Jet final states exclude up to 2.7 TeV for almost whole DM range

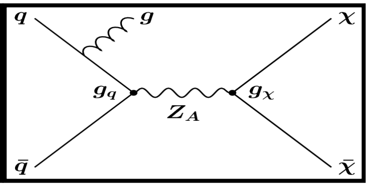
Mono b



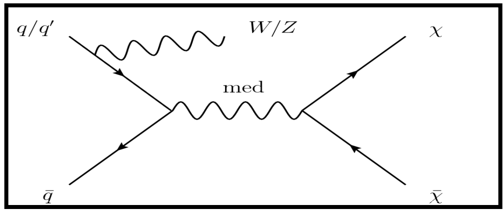
Mono γ



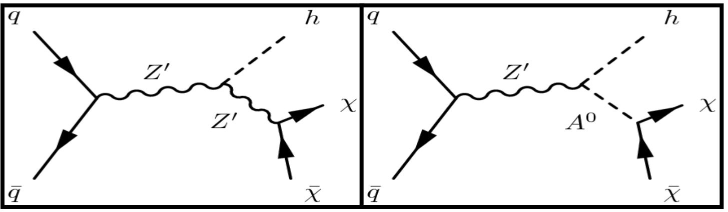
Mono Jet



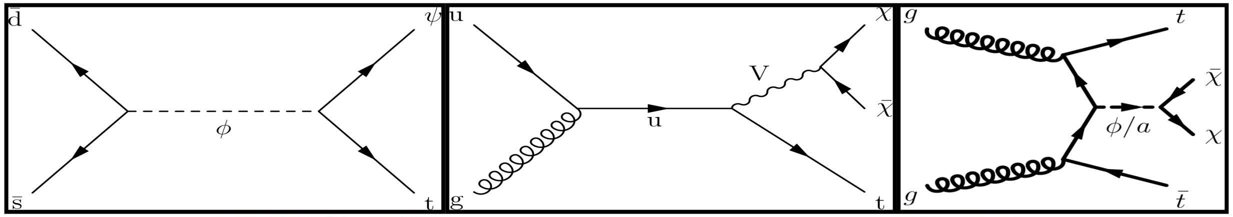
Mono V

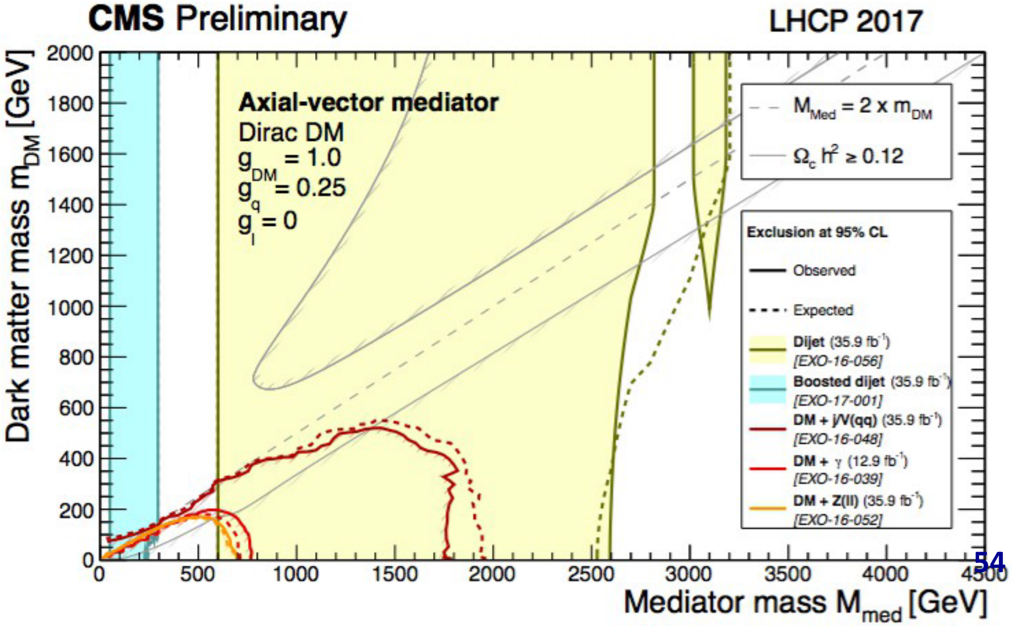


Mono H



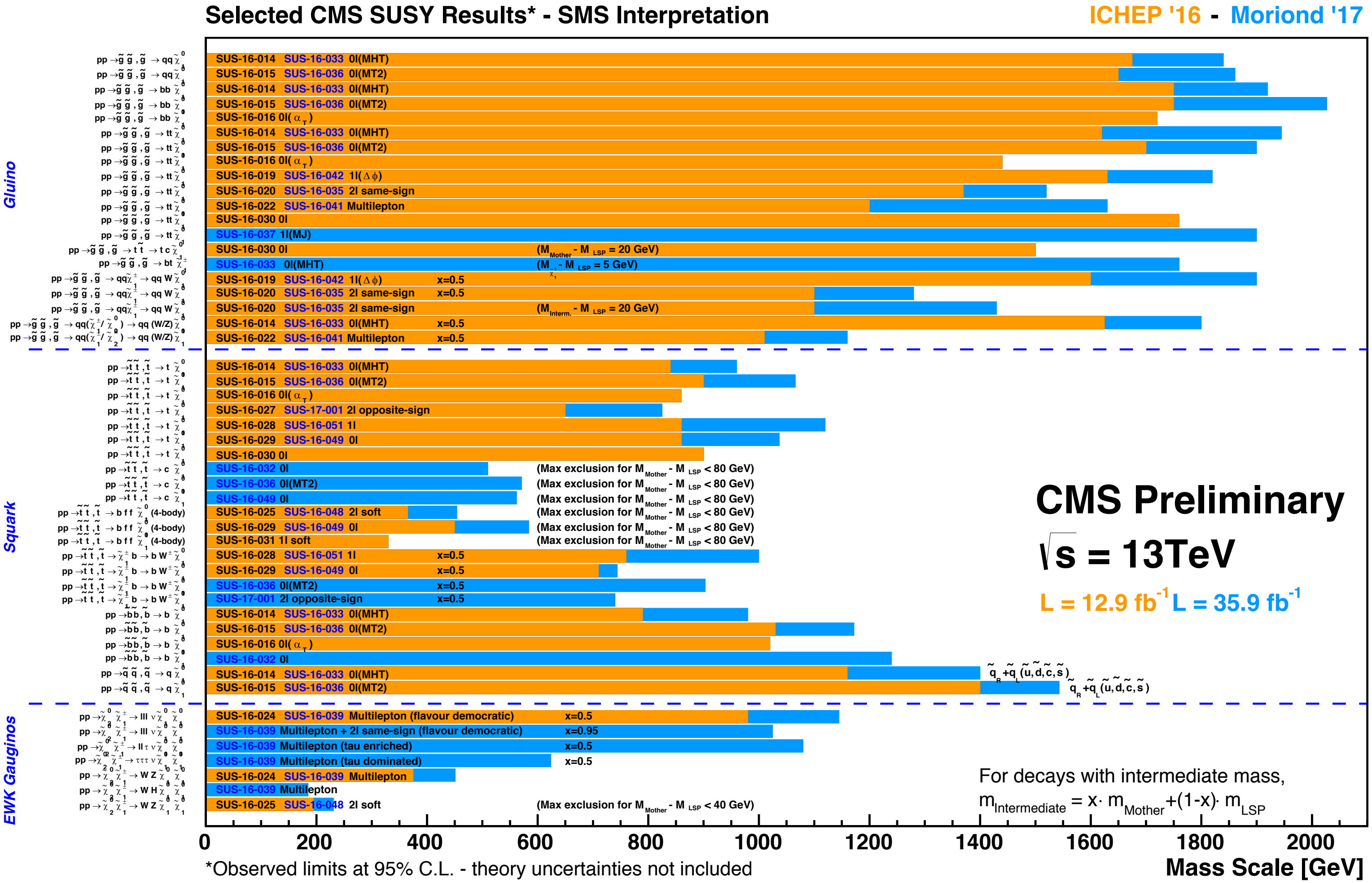
Mono Top





Maratea - June 29, 2018

SUSY Searches



*Observed limits at 95% C.L. - theory uncertainties not included

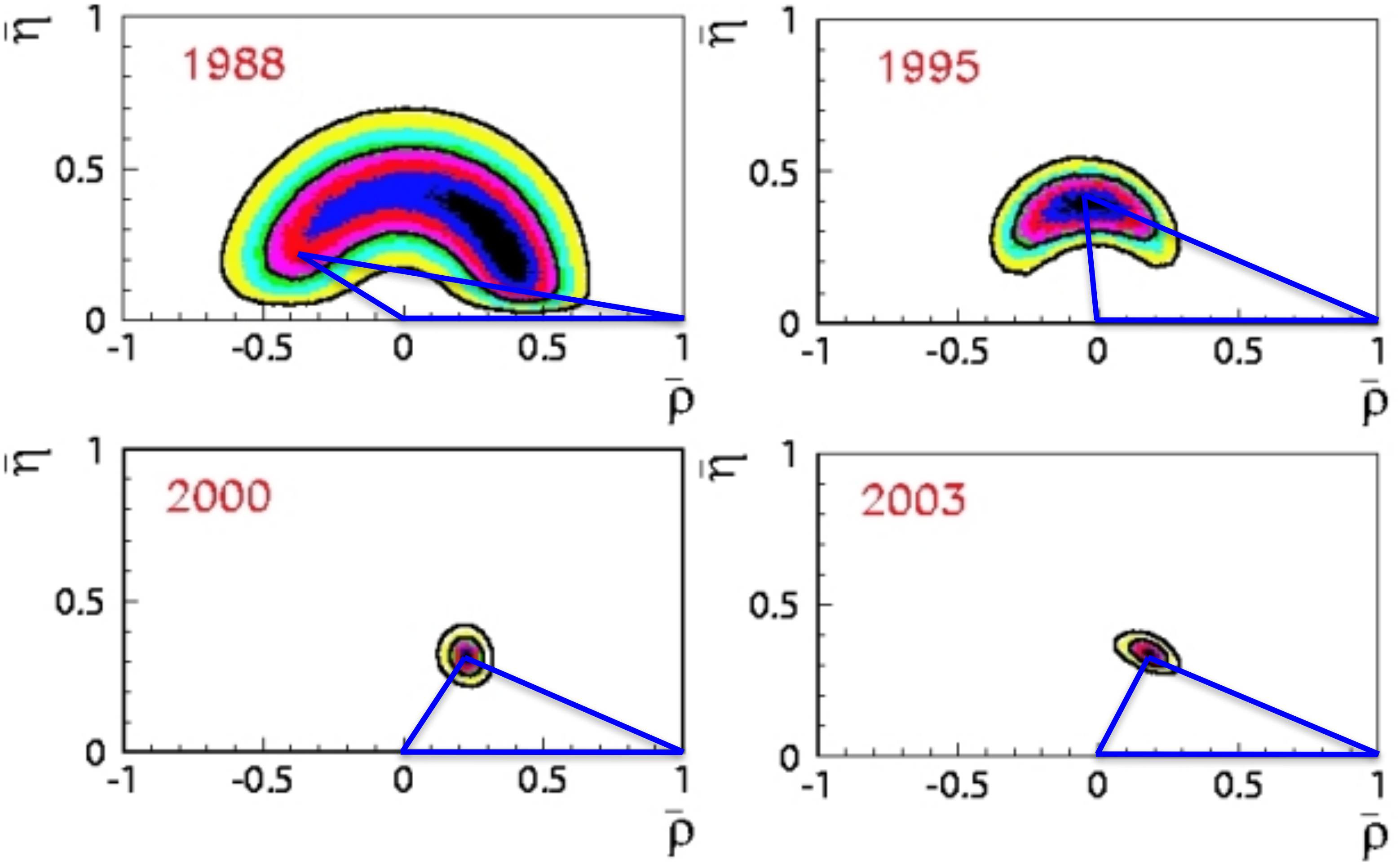
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

Strong Production (Gluino and Squark) well tested: Limits in TeV range

Moving to electroweak production and non-conventional signatures

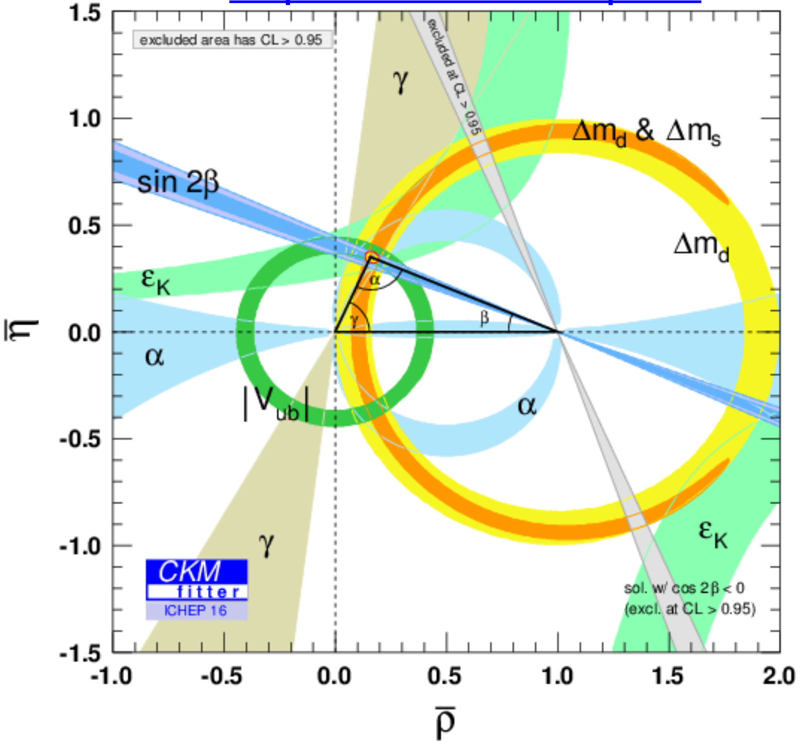
Flavour physics

History of the Unitarity Triangle

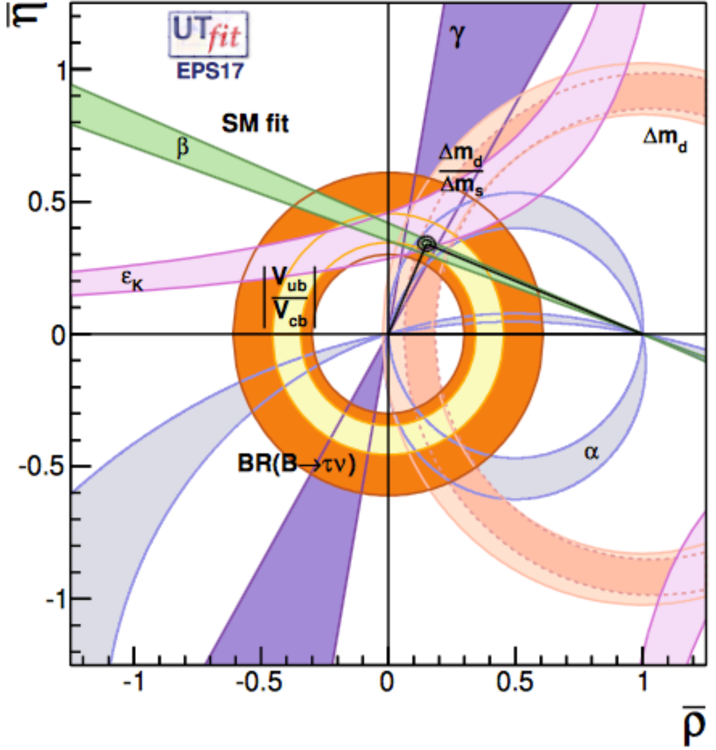


Where we are with global UT fits

http://ckmfitter.in2p3.fr



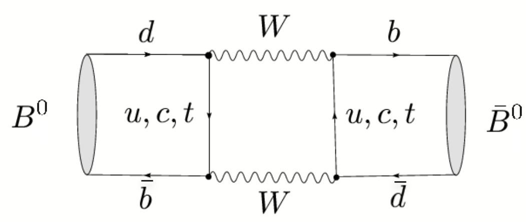
http://www.utfit.org

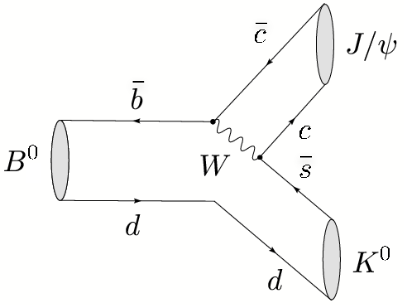


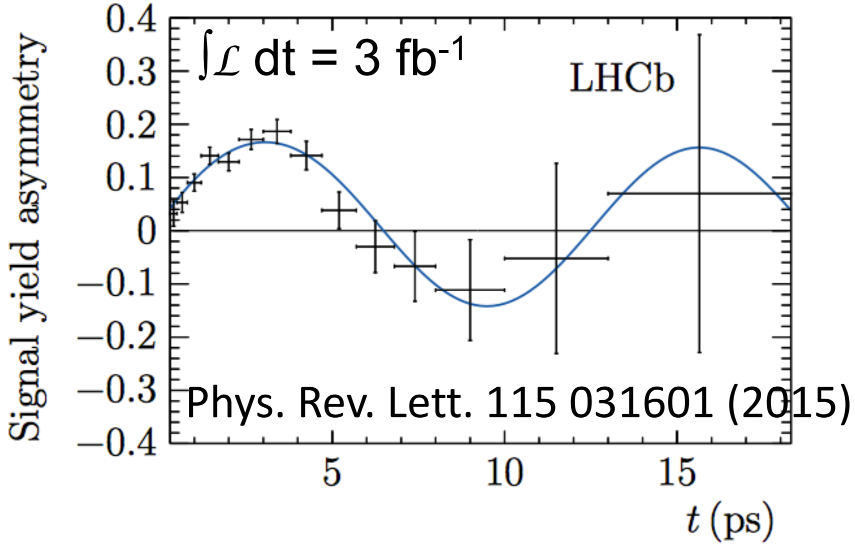
- In the presence of relevant new physics effects, the various contours would not cross each other in a single point
- Certainly that's a great success of the Standard Model CKM picture, but there is still room for new physics at the 10% level

Measurement of sin2β

- *CP* violation due to interference between B^0-B^0 mixing and b→ccs transitions

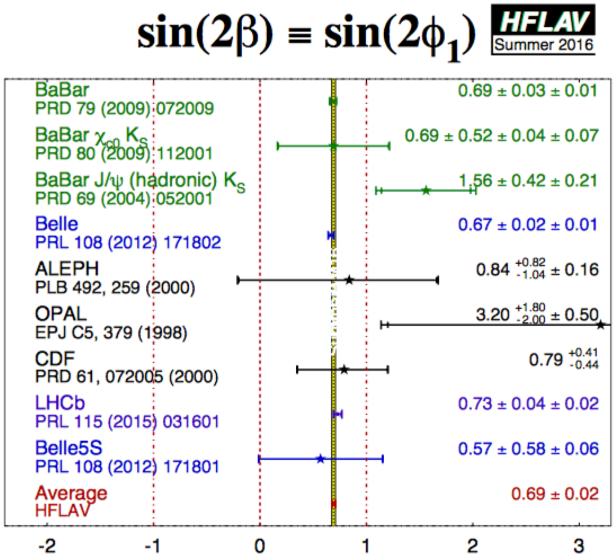


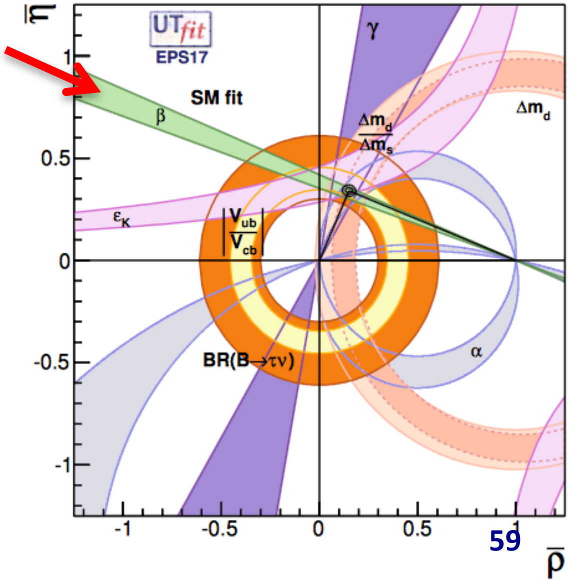




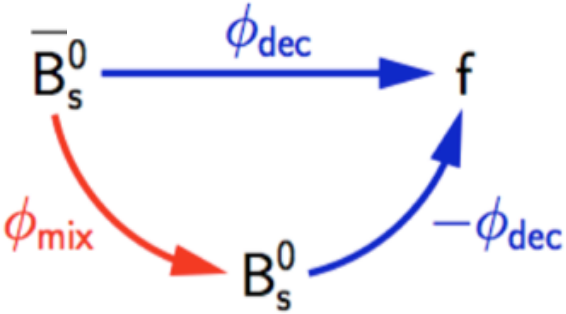
Phys. Rev. Lett. 115 031601 (2015)

- LHCb has reached the precision of the *B* factories and will soon surpass that with Run-2 data

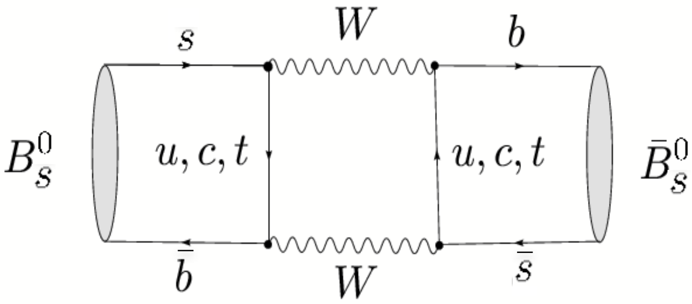


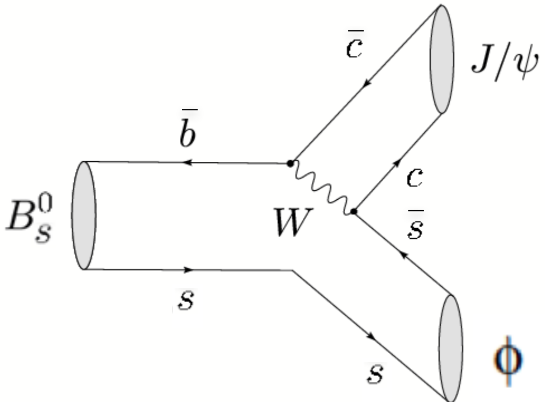


ϕ_s from $b\to c\bar{c}s$ transitions



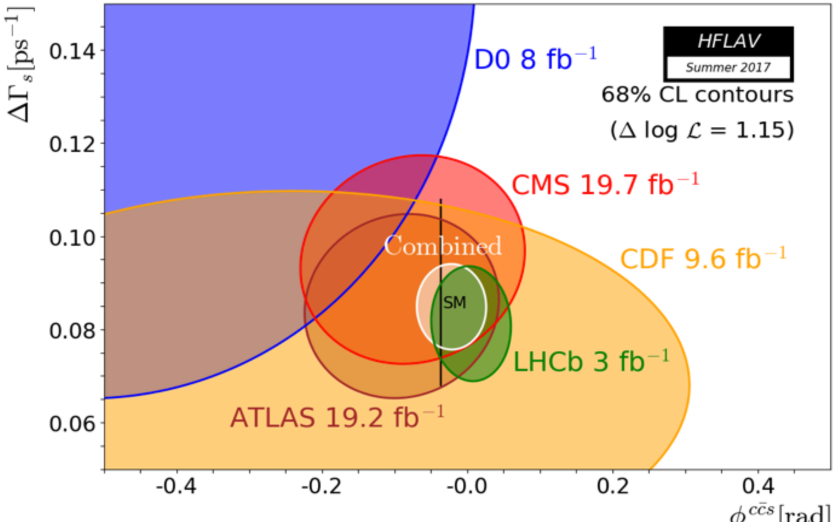
- Golden mode $B_s \to J/\psi\phi$ proceeds (mostly) via a $b\to ccs$ tree diagram
- Interference between B_s mixing and decay graphs



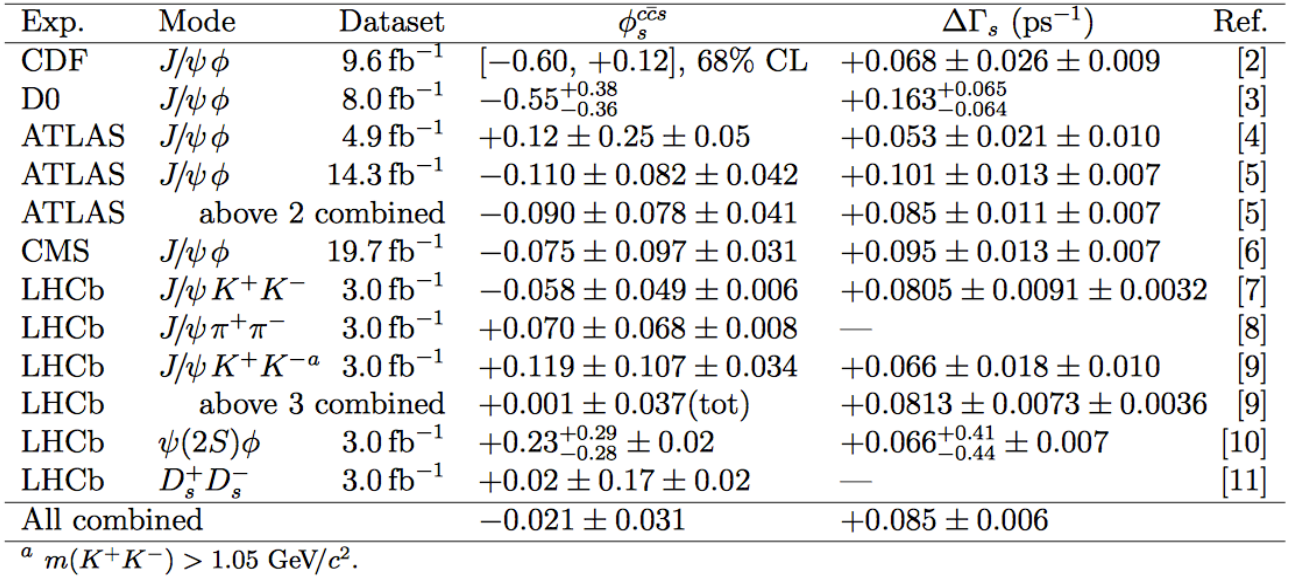


- Measures the phase-difference ϕ_s between the two diagrams, precisely predicted from global CKM fits in the Standard Model to be
$\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad → can be altered by new physics

Measurement of ϕ_s



- ϕ_s precision mostly driven by LHCb
- Latest HFLAV world average
  - $\phi_s = -21 \pm 31$ mrad
- Still compatible with the SM at the present level of precision



Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	$9.6\,\text{fb}^{-1}$	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\phi$	$8.0\,\text{fb}^{-1}$	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\phi$	$4.9\,\text{fb}^{-1}$	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\phi$	$14.3\,\text{fb}^{-1}$	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$	[5]
ATLAS	above 2 combined		$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	[5]
CMS	$J/\psi\phi$	$19.7\,\text{fb}^{-1}$	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi K^+K^-$	$3.0\,\text{fb}^{-1}$	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$	[7]
LHCb	$J/\psi\pi^+\pi^-$	$3.0\,\text{fb}^{-1}$	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	$J/\psi K^+K^{-a}$	$3.0\,\text{fb}^{-1}$	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$	[9]
LHCb	above 3 combined		$+0.001 \pm 0.037$(tot)	$+0.0813 \pm 0.0073 \pm 0.0036$	[9]
LHCb	$\psi(2S)\phi$	$3.0\,\text{fb}^{-1}$	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	[10]
LHCb	$D_s^+D_s^-$	$3.0\,\text{fb}^{-1}$	$+0.02 \pm 0.17 \pm 0.02$	—	[11]
All combined			-0.021 ± 0.031	$+0.085 \pm 0.006$	

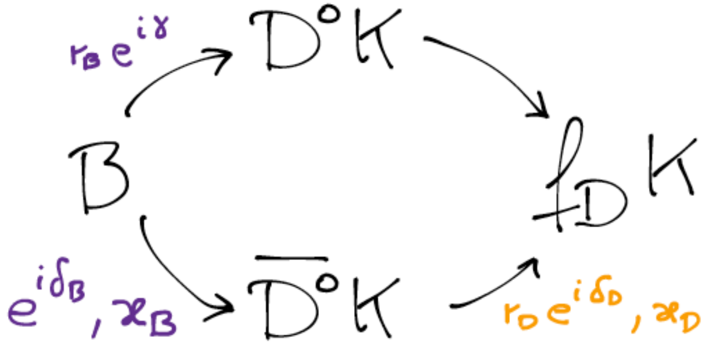
^{a} $m(K^+K^-) > 1.05\ \text{GeV}/c^2$.

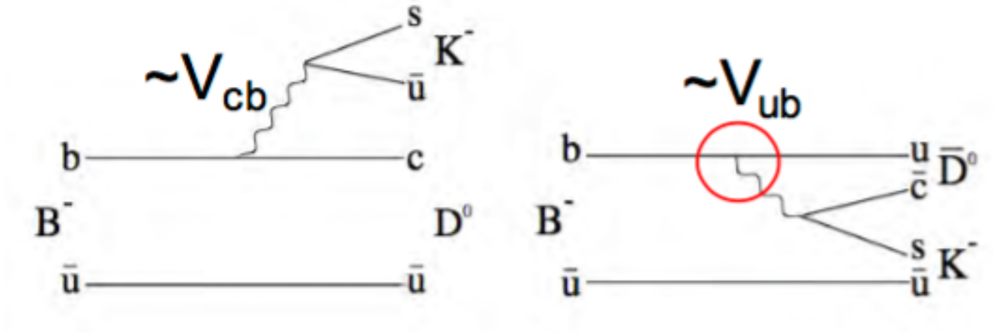
See HFLAV page for the list of references

http://www.slac.stanford.edu/xorg/hflav/

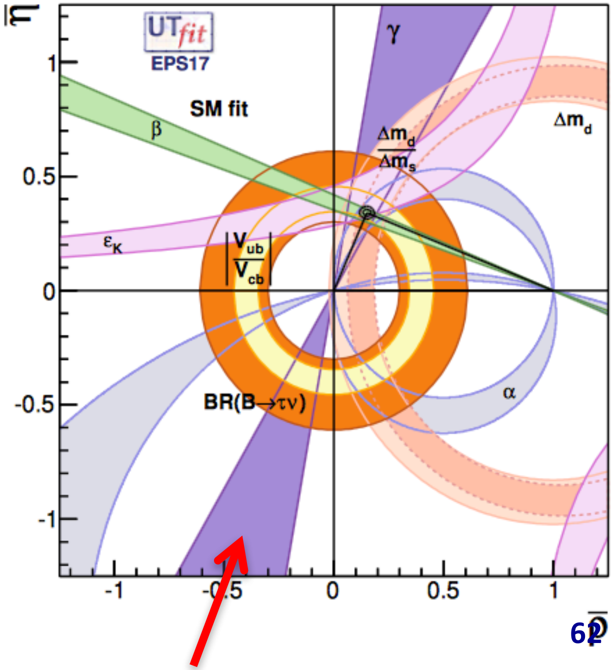
Measurement of γ

- **γ is the least known angle of the UT,** although not for too long yet, measured via the interference between $b \rightarrow u$ and $b \rightarrow c$ tree-level transitions



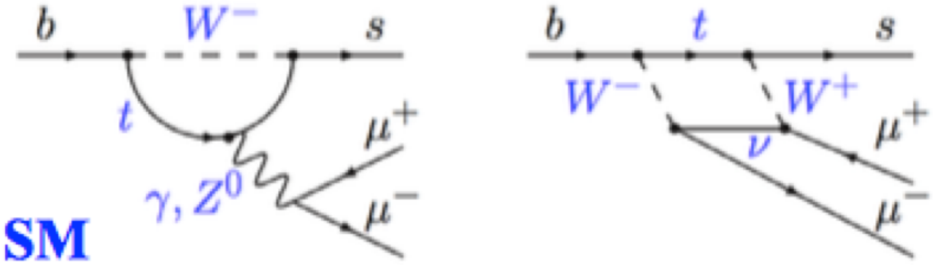


- Simple and clean theoretical interpretation, **but statistically very challenging**

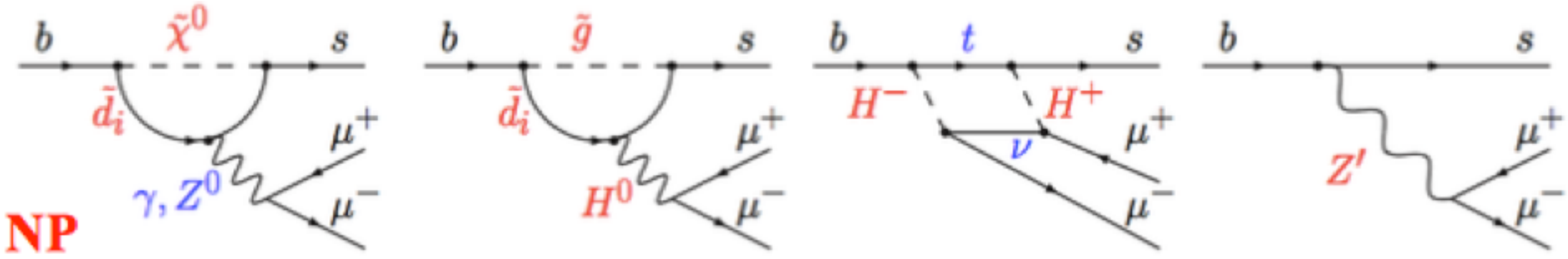


Searches for new physics in $b \rightarrow s\ell^+\ell^-$ transitions

- Quark-level transitions entering some of the most relevant decay amplitudes to search for new physics effects



- The presence of new particles may lead to observable effects



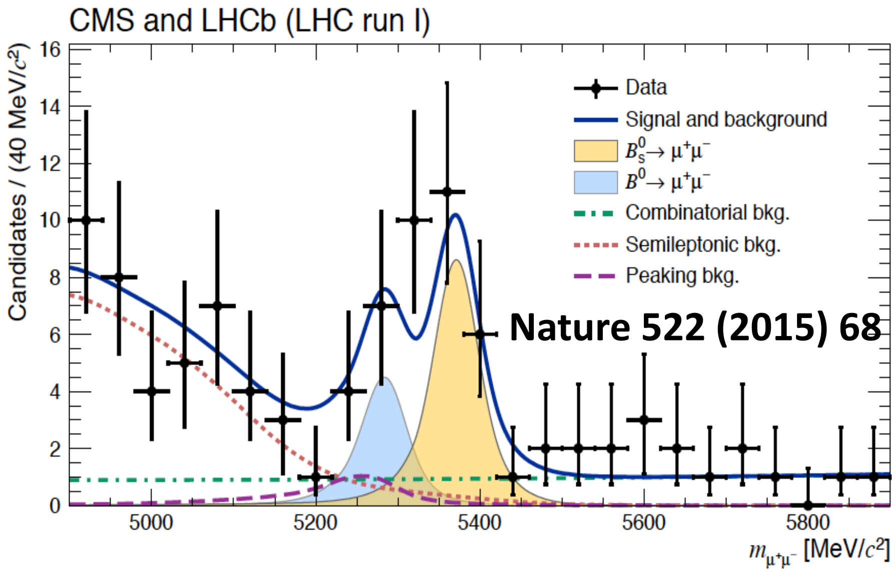
$B^0 \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$

- CMS and LHCb performed a combined fit to their full Run-1 data sets

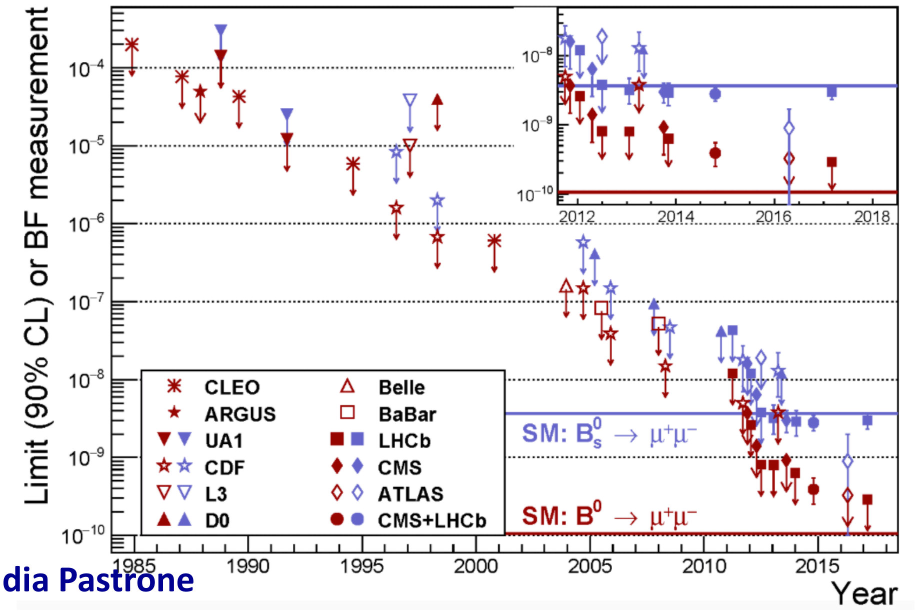
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

- $B_s \to \mu\mu$ 6.2σ significance was first observation
  - Well compatible with the Standard Model
- More recently, also ATLAS published a measurement with Run-1 data



Nature 522 (2015) 68



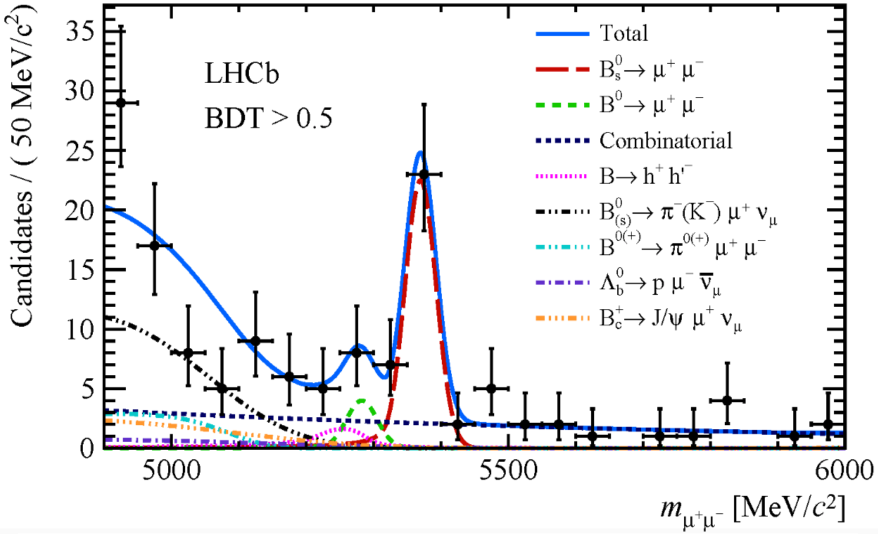
EPJC 76 (2016) 513

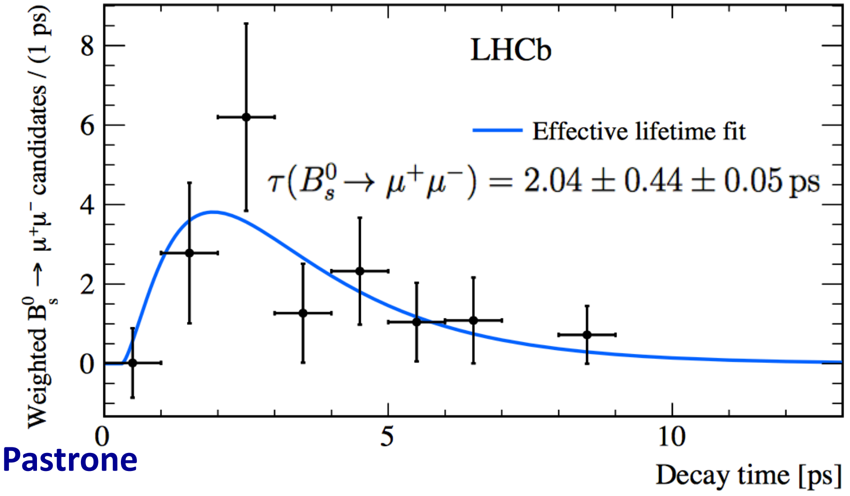
B→*μμ* at LHCb with Run-2 data

- New measurement from LHCb using Run-2 data has led in 2017 to the first observation of the $B_s \rightarrow \mu\mu$ decay from a single experiment

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

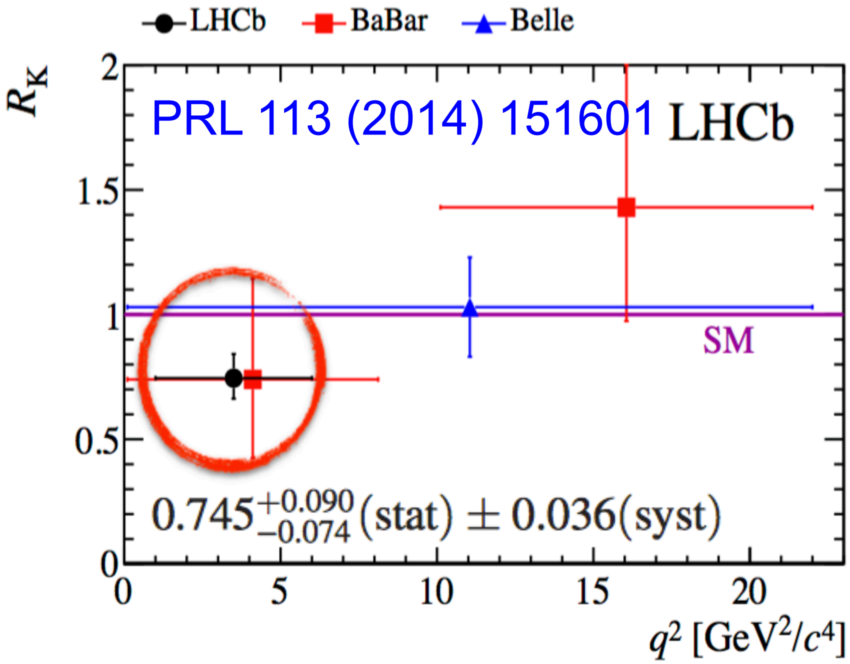
- Moreover, it starts to be possible to measure other properties, such as the "effective" lifetime, that will be useful for discriminating between new physics models



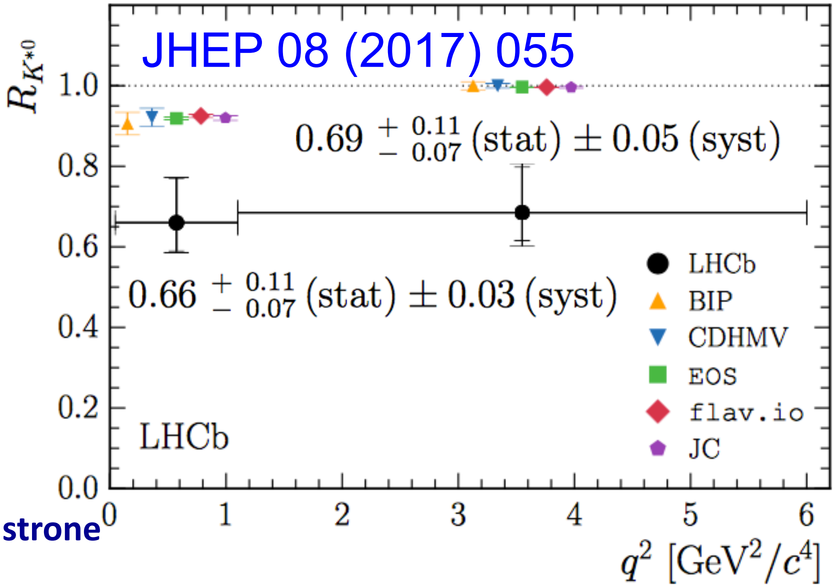


Lepton-flavour universality tests in $b \rightarrow s\ell^+\ell^-$

- Measure ratios
  $R_K = \mathrm{BF}(B^+ \rightarrow K^+\mu^+\mu^-) / \mathrm{BF}(B^+ \rightarrow K^+e^+e^-)$
  $R_{K^*} = \mathrm{BF}(B^0 \rightarrow K^{*0}\mu^+\mu^-) / \mathrm{BF}(B^0 \rightarrow K^{*0}e^+e^-)$
- Theoretically very clean
  - Observation of non-LFU would be a clear sign of new physics
- For the moment at the 3σ-ish level from the SM
- Updates with Run-2 data as well as other new measurements with different decay modes expected during the course of the year



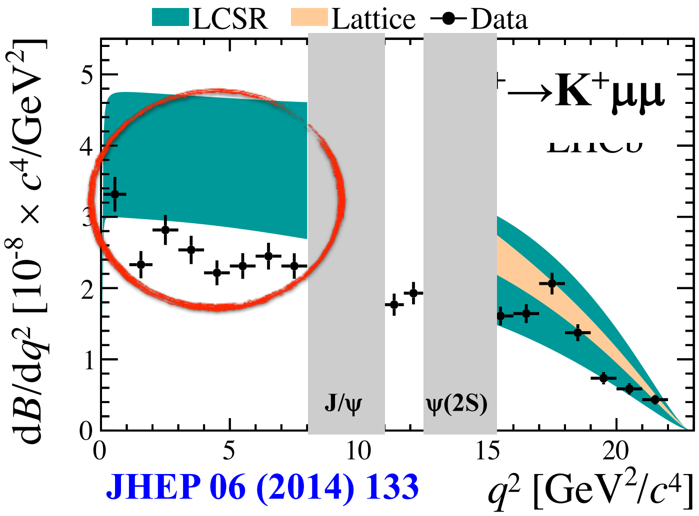
PRL 113 (2014) 151601



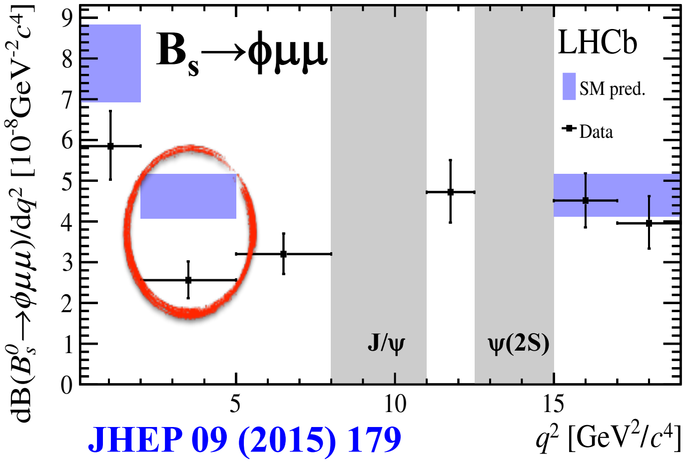
JHEP 08 (2017) 055

Other anomalies in the $b \rightarrow s\ell^+\ell^-$ sector

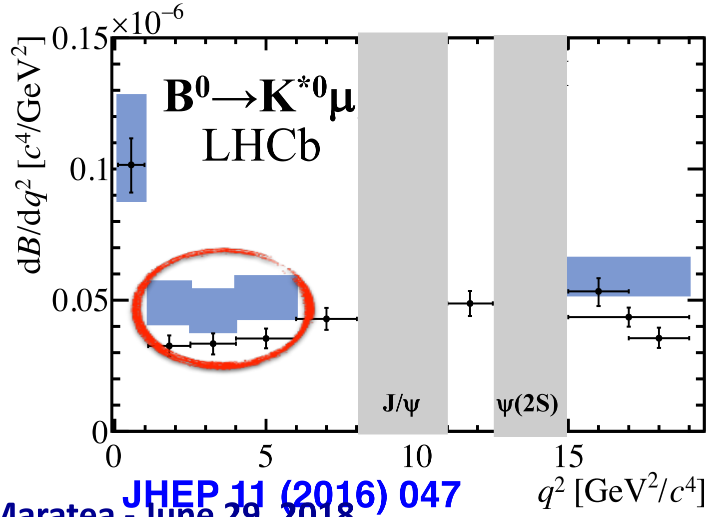
- E.g., differential BFs consistently lower than SM expectations, although control of hadronic uncertainties in the predictions is matter of lively debates



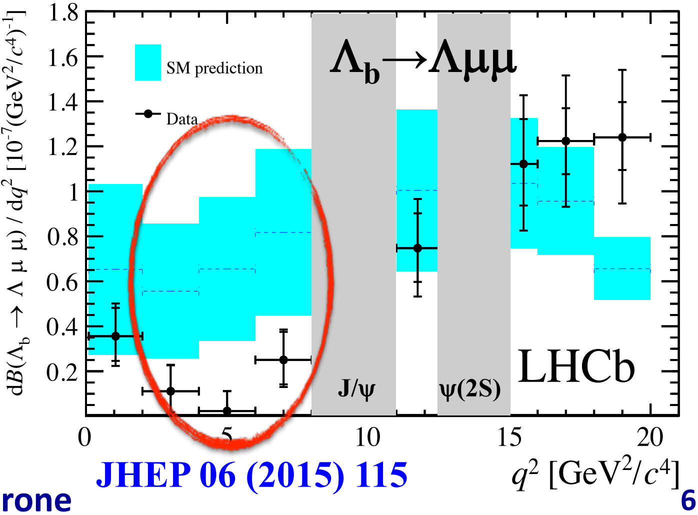
JHEP 06 (2014) 133



JHEP 09 (2015) 179



JHEP 11 (2016) 047
JHEP 04 (2017) 142



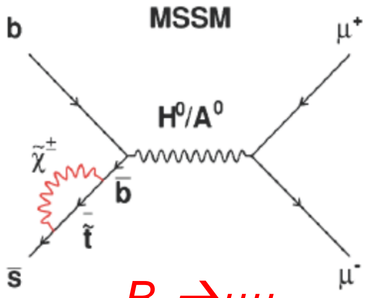
JHEP 06 (2015) 115

New physics searches in flavour in a nutshell

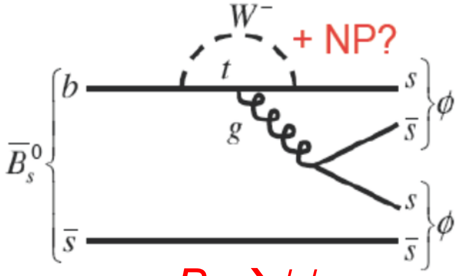
- Classic broad-range measurements
  - CKM physics, search for very rare decays
- Measurements in specific sectors where anomalies are emerging in recent years
  - Lepton-flavour universality in $b \rightarrow s\ell^+\ell^-$ quark-level transitions, and related $b \rightarrow s\ell^+\ell^-$ picture of decay rates
  - Lepton-flavour universality in semileptonic *b*-hadron decays

New physics searches in the flavour sector

- Instead of searching for new particles produced directly, look for their indirect effects to low energy processes (e.g. *b*-hadron decays)

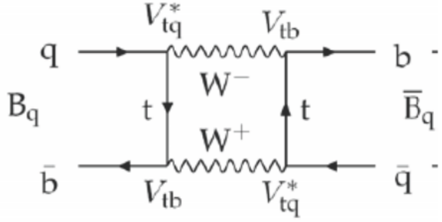


$B_s \rightarrow \mu\mu$



$B_s \rightarrow \phi\phi$

B-$\bar{B}$ mixing



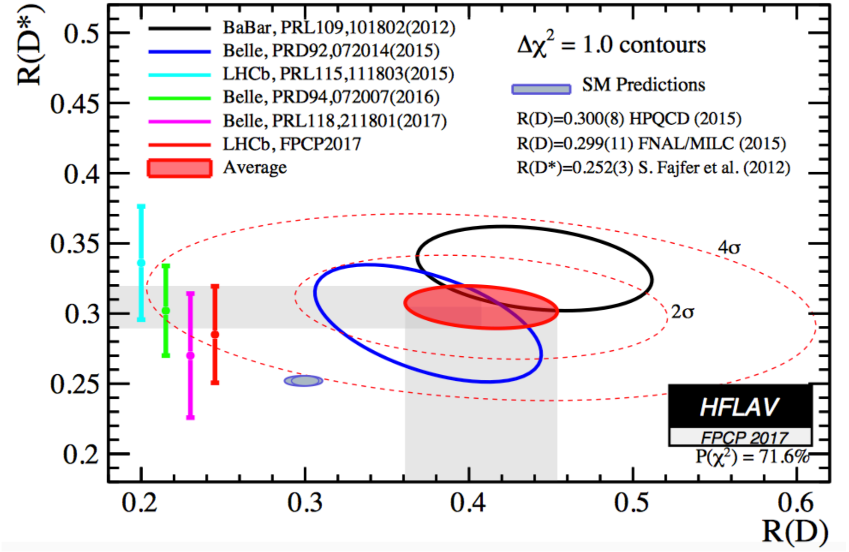
+ NP?

- General amplitude decomposition in terms of couplings and scales

$$A = A_0 \left[c_{SM} \frac{1}{M_W{}^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- By studying *CP*-violating and flavour-changing processes, two fundamental tasks can be accomplished
  - Identify new symmetries (and their breaking) beyond the Standard Model
  - Probe mass scales not accessible directly at a collider like the LHC

LFU tests in semileptonic *b*-hadron decays



- Measure ratio

  $R_D^{(*)} = BF(B \rightarrow D^{(*)}\tau\nu)/BF(B \rightarrow D^{(*)}\mu\nu)$

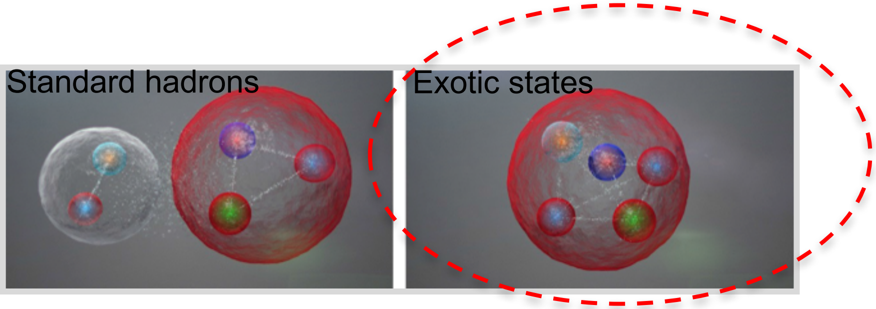
- Measurements of R(D) and R(D*) by BaBar, Belle and LHCb
  - Overall average shows a 4σ discrepancy from the SM
  - LHCb has recently demonstrated to be able to make the measurement also with 3-prong τ decays [arXiv:1708.08856]
- LHCb can also perform measurements with other *b* hadrons
  - Recent determination of $R(J/\psi) = BF(B_c \rightarrow J/\psi\tau\nu) / BF(B_c \rightarrow J/\psi\mu\nu)$ at about 2σ from the SM [arXiv:1711.05623]
  - Other modes with B_s and Λ_b decays will also come

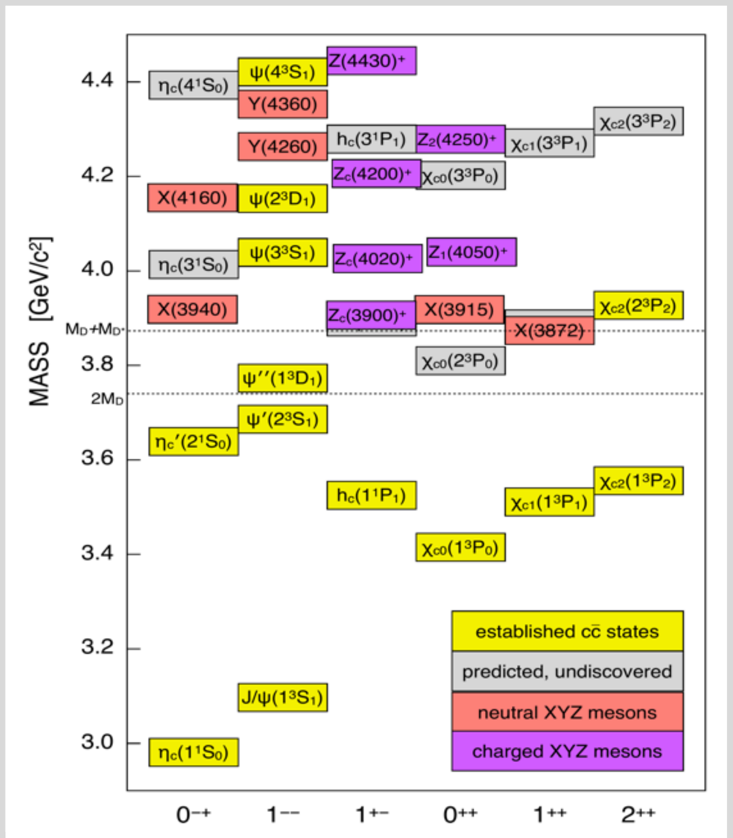
Spectroscopy at LHCb

- LHCb particularly suitable for hadron spectroscopy:
  - Large production cross section
  - Excellent mass resolution
  - Excellent vertexing and PID (→ low background)

- Many new states have been observed in heavy flavor spectroscopy: see for example the charmonium spectrum

- Many of them can be interpreted as “standard” hadronic states while others require an “exotic” interpretation

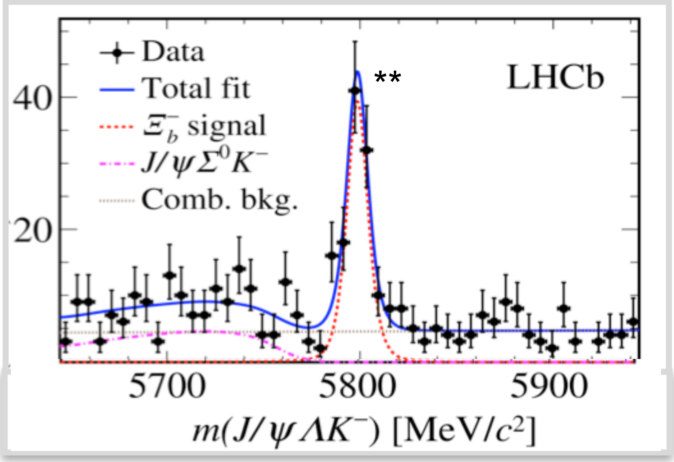




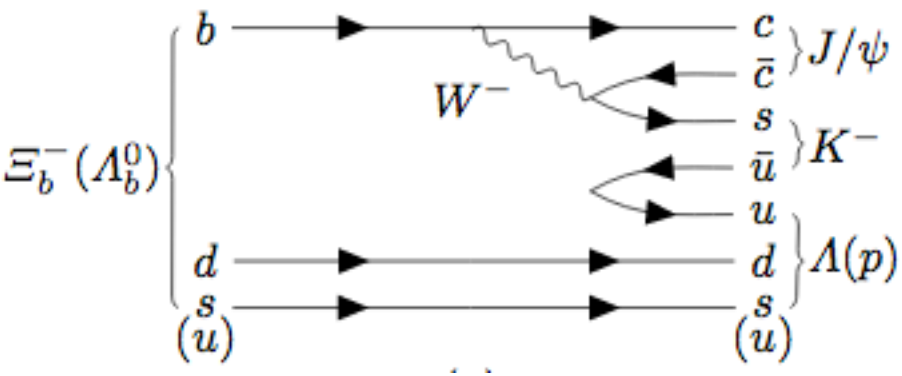
[PoS Bormio 050(2015) arXiv:1511.01589]

The decay $\Xi^-_b \to J/\psi\Lambda K^-$

- Paper on observation of his decay just released on arXiv:1701.05274, subm. to PLB
- It may proceed through P_c states with open strangeness:
- It is the analogous of $\Lambda_b \to J/\psi pK$ with an s spectator quark

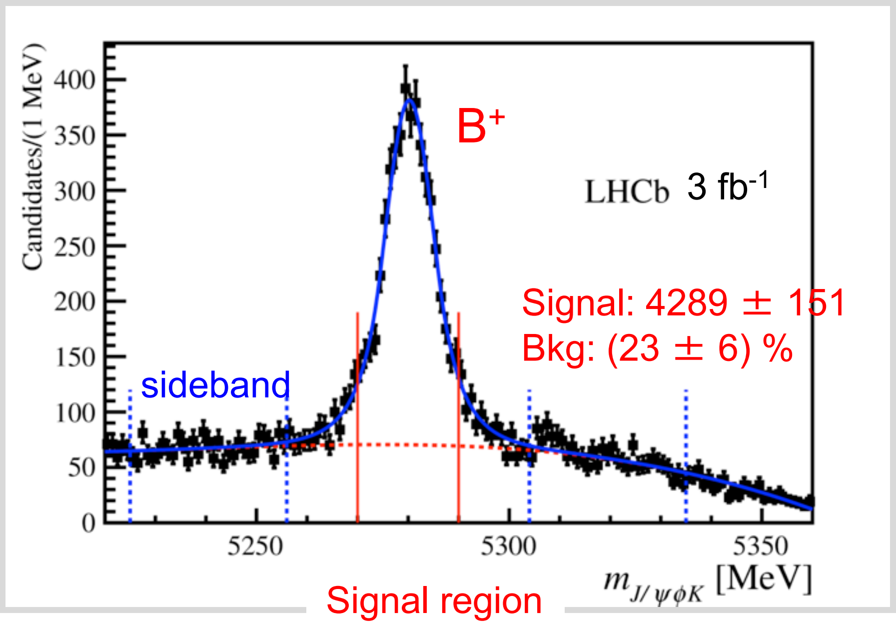


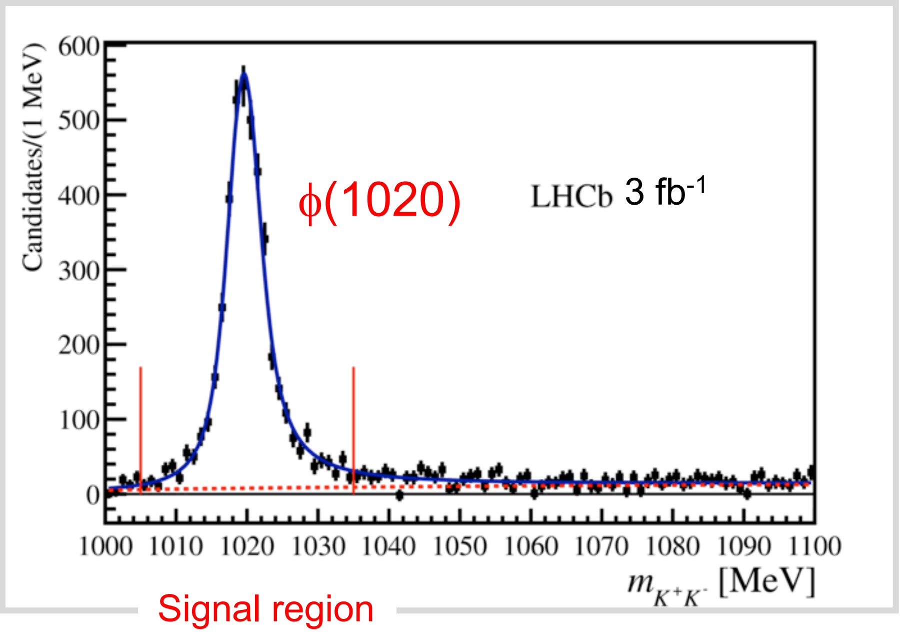
**only L candidates made with 2 long tracks



Exotic states in $B^+ \rightarrow J/\psi\phi K^+$

- LHCb exploits the largest sample of $B^+ \rightarrow J/\psi\phi K^+$ decays so far, trying to shed light on these states.

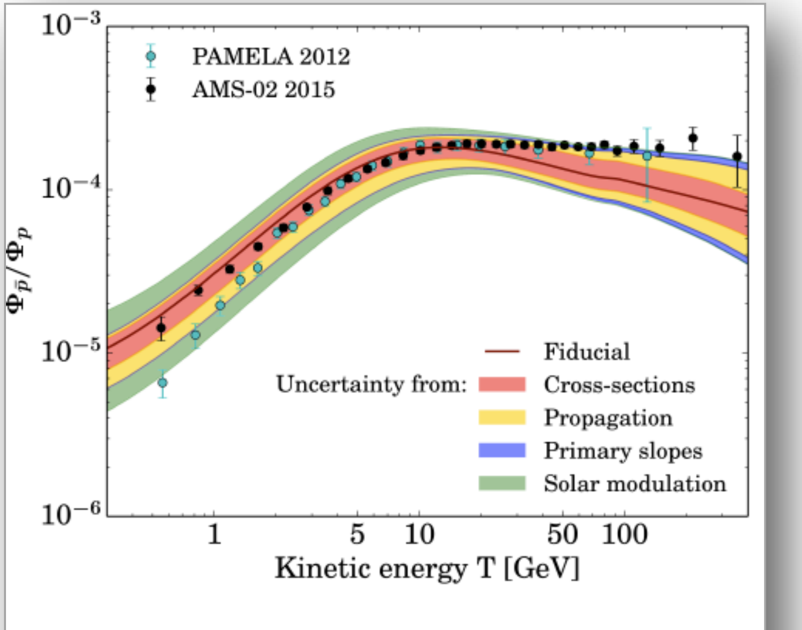




Fixed target

Cosmic ray physics at LHCb: p+He→anti-p+X

- The recent AMS02 results provide unprecedented accuracy for measurement of anti-p/p ratio in cosmic rays at high energies [PRL 117, 091103 (2016)]
- Hint for a possible excess, and milder energy dependence than expected
- Prediction for anti-p/p ratio from spallation of primary cosmic rays on intrestellar medium (H and He) is presently limited by uncertainties on anti-p production cross-sections, particularly for p-He
- No previous measurement of anti-p production in p-He, predictions from soft QCD models vary within a factor 2



Giesen et al., JCAP 1509, 023 (2015)

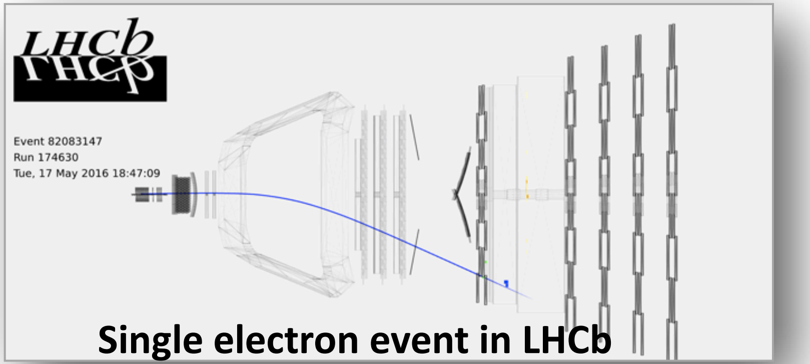
- The LHC energy scale and LHCb+SMOG are very well suited to perform this measurement

Cosmic ray physics at LHCb: p+He→anti-p+X

- LHCb took p-He collision data in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{NN}} = 110$ GeV
- Anti-protons are identified using the RICH detectors
- The luminosity is measured using elastic scattering of protons on atomic electrons
  - Fully elastic regime in the LHCb acceptance
  - Very well known theoretically

- A luminosity measurement at the 10% level can be obtained (main uncertainty: gas contamination !)

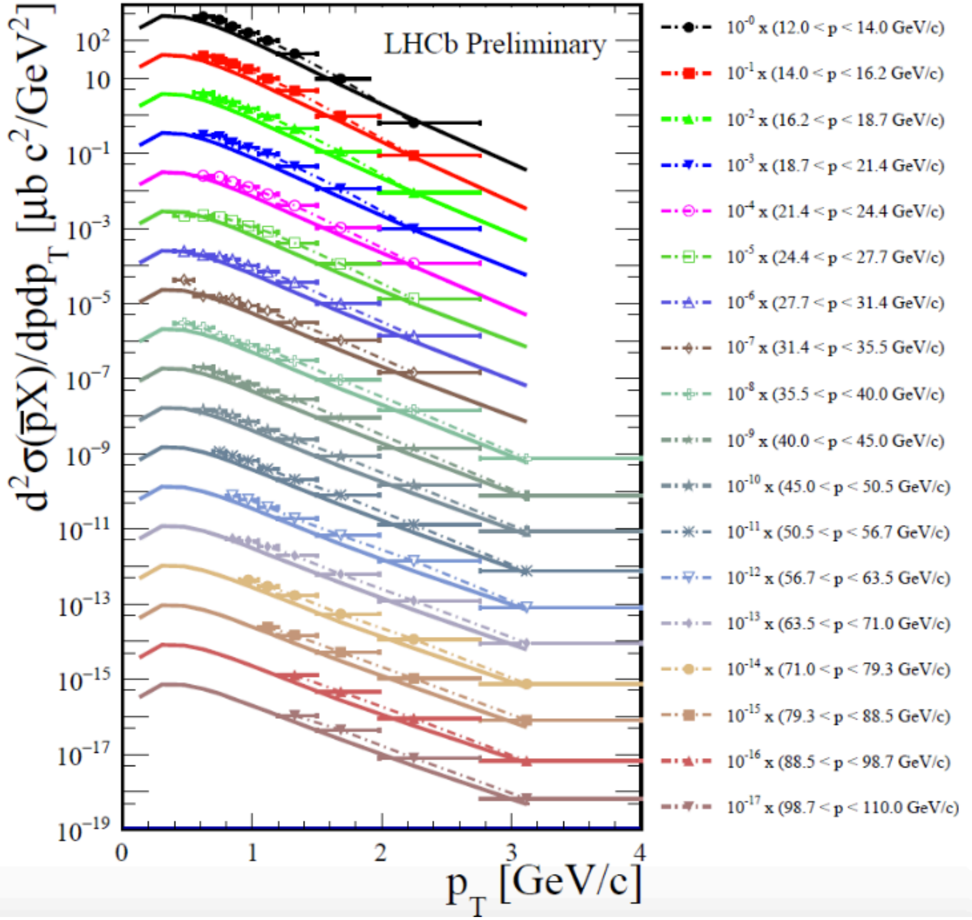
- $L = 0.443 \pm 0.011 \pm 0.027 \text{ nb}^{-1}$



Single electron event in LHCb

Antiproton production in fixed-target *p*He collisions

- Antiproton cross section measured with 10% precision
- Theoretical interpretation on its way
- Additional production measurements are also important
    - E.g., antiprotons from Λ decays
- Further results expected in the near future



LHCb-CONF-2017-002
(paper in preparation)

Heavy ions collisions

QGP properties

hadron chemistry

nucleosynthesis in QGP

increased precision on QGP parameters

new insights on jet quenching

collective effects in small systems

important progress in system-size dependence

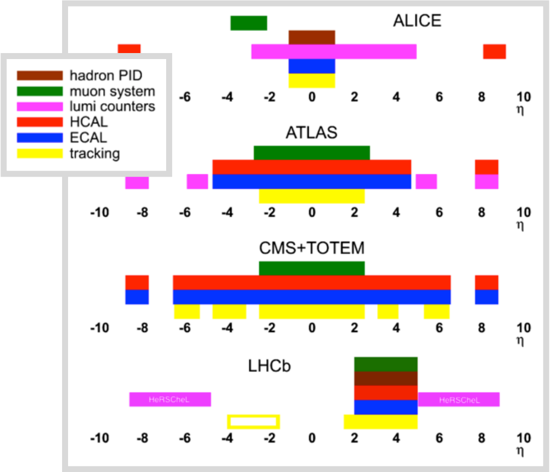
properties, buildup of collective effects

closing in on medium effects in small systems?

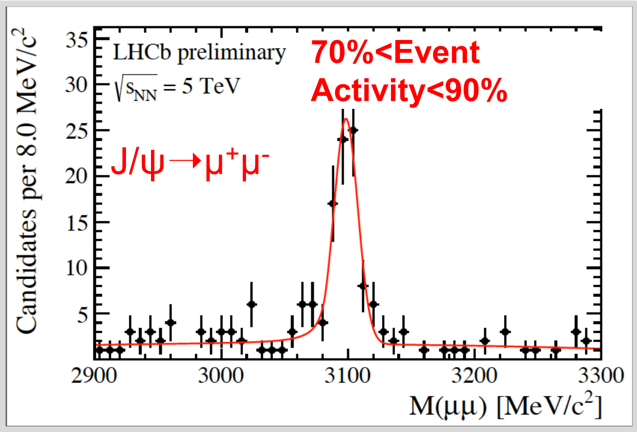
rich input for pp modeling

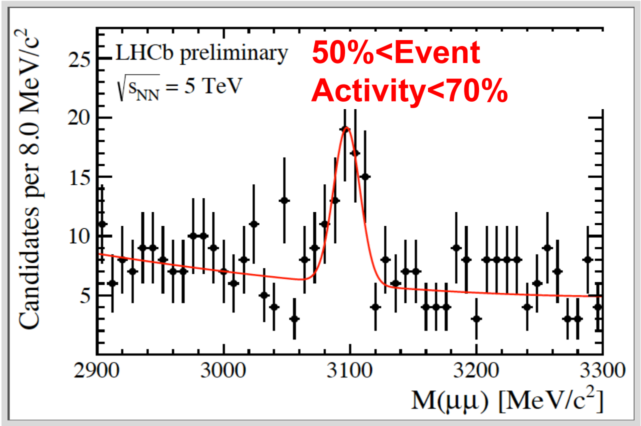
LHCb Heavy Ions: J/ψ and D^0 signals in PbPb collisions

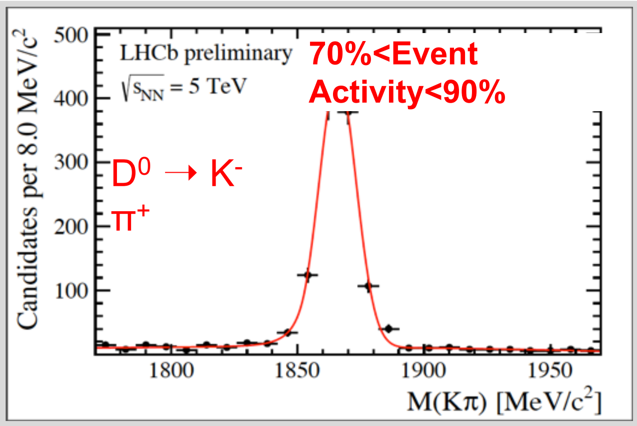
- LHCb has an interesting HI physics program exploiting the complementary geometry and its PID capability

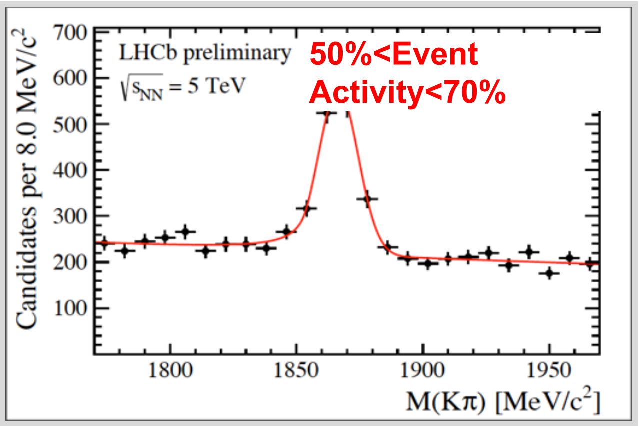


- Only pPb in Run 1
- In Run 2 we took data also in PbPb
- Challenging! But results coming out



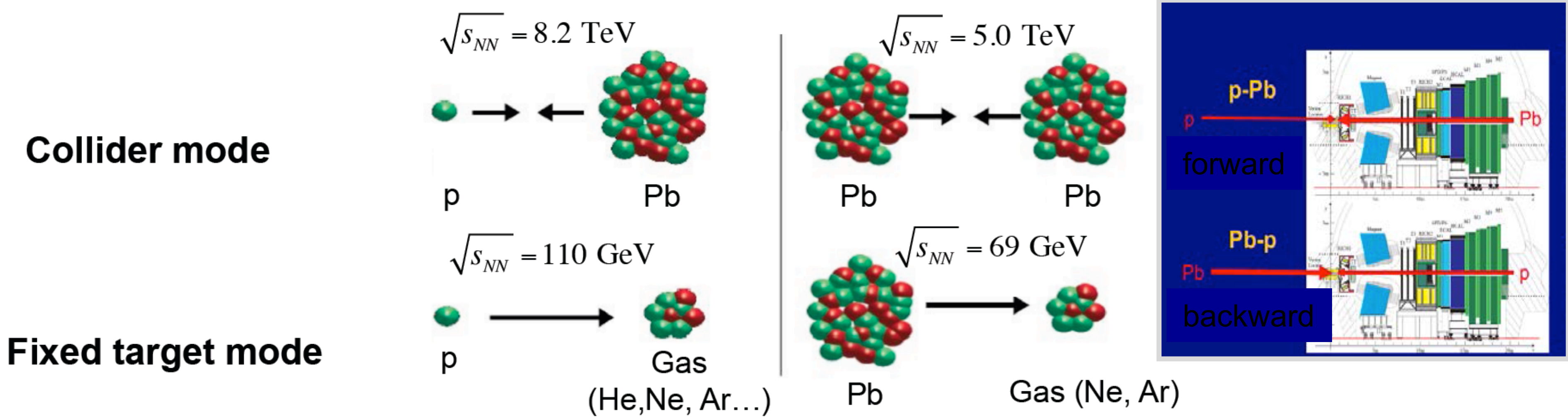






Heavy ion and fixed target physics at LHCb

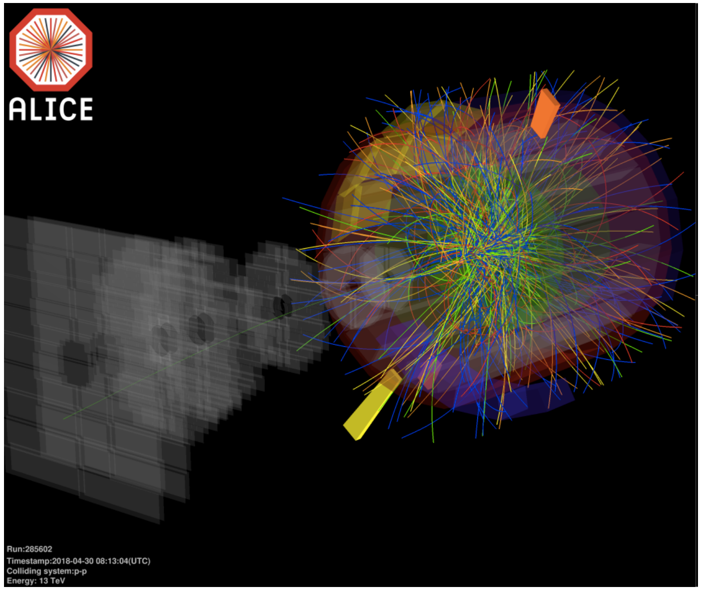
- LHCb can operate in collider mode, fixed target mode or both in parallel!



- Collider mode: forward/backward coverage
- Fixed target mode: central and backward coverage

@ $\sqrt{s_{NN}}$ between SPS and RHIC

Ultrarelativistic Nuclear Collisions



basic idea: compress large amount of energy in small volume

→produce a “fireball” of hot matter:

temperature O(10^{12} K)

~ 10^5 x T at centre of Sun

~ T of universe @ ~ 10 μs after Big Bang

extreme conditions: how does matter behave?

→phase transition

deconfined QCD medium (Quark-Gluon Plasma, QGP)

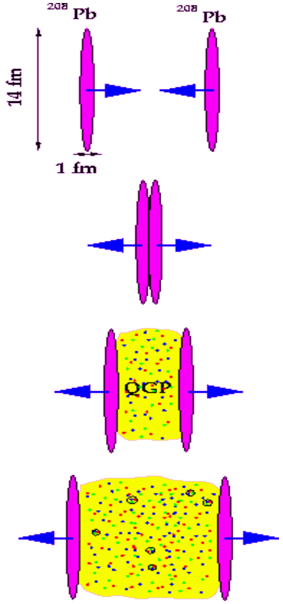
predicted by QCD

evidence for QGP already at lower energy (CERN-SPS, BNL-RHIC)

LHC: high statistics and controlled probes

→ quantitative study of properties of QCD medium

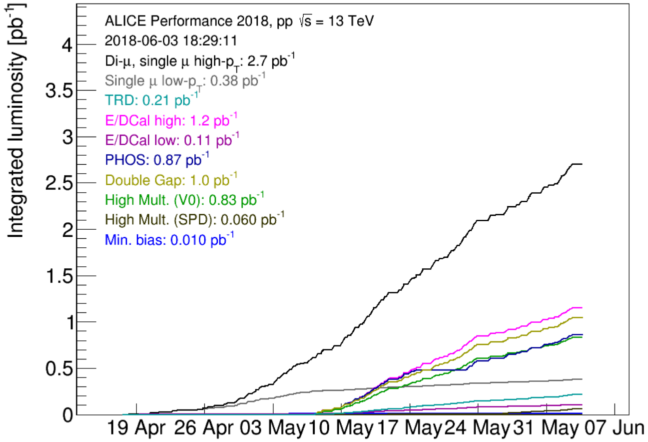
viscosity, opacity, transport, diffusion, …



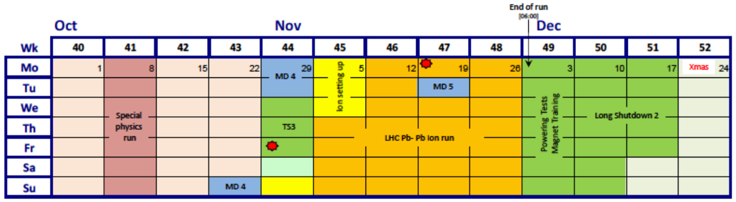
Status of data taking

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	by end of 2018	*5.02*	*~1 nb^{-1}*
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}

- 2018 campaign in full swing!

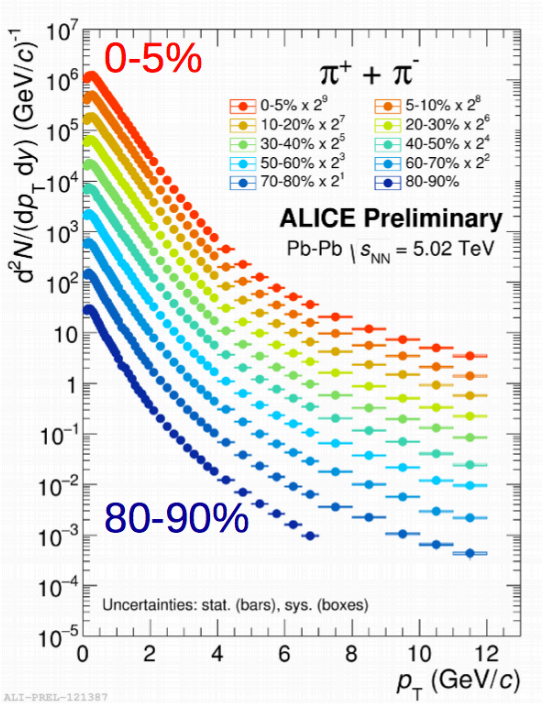


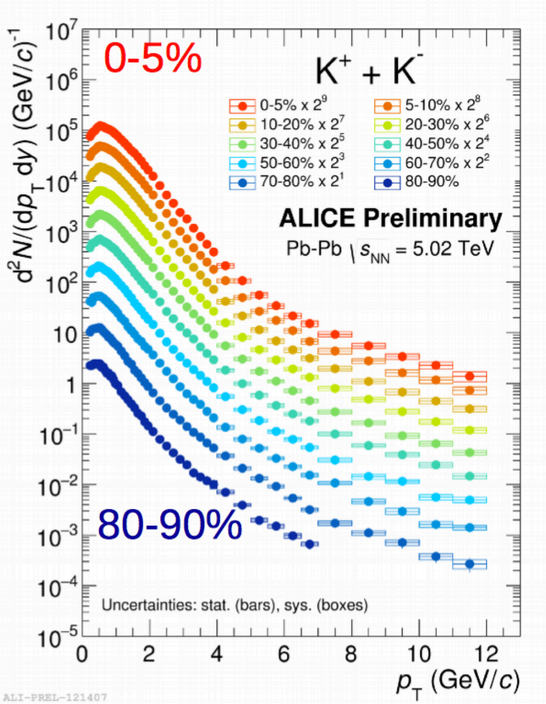
- high statistics Pb-Pb run in November!

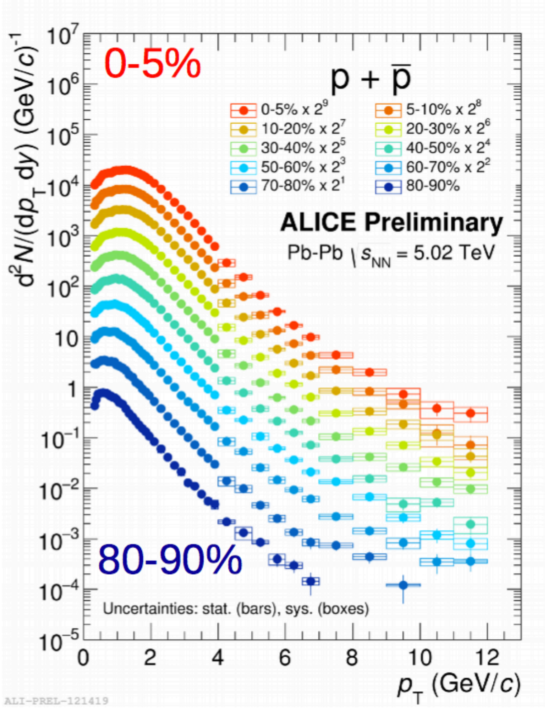


Identified particles

Textbook-quality Run 2 data!

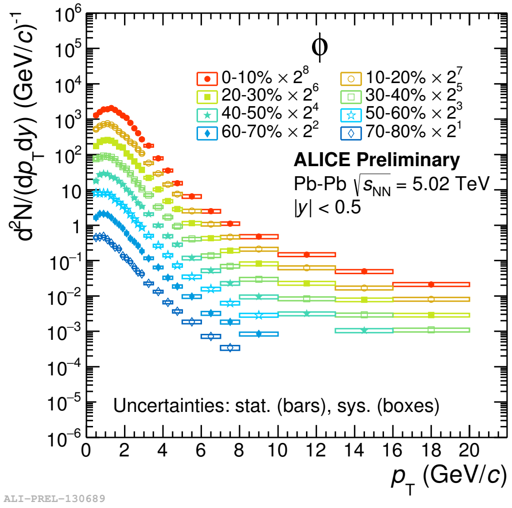




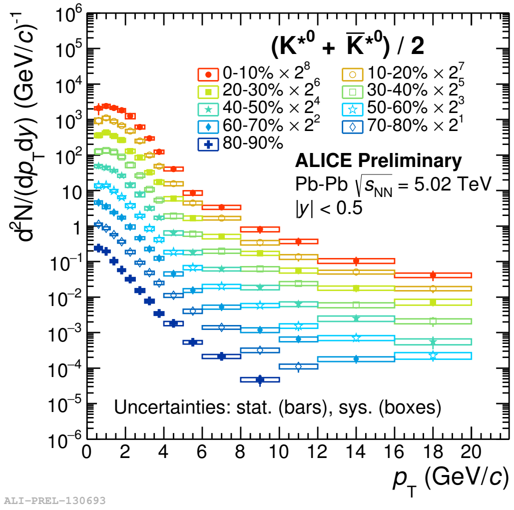


More and more species

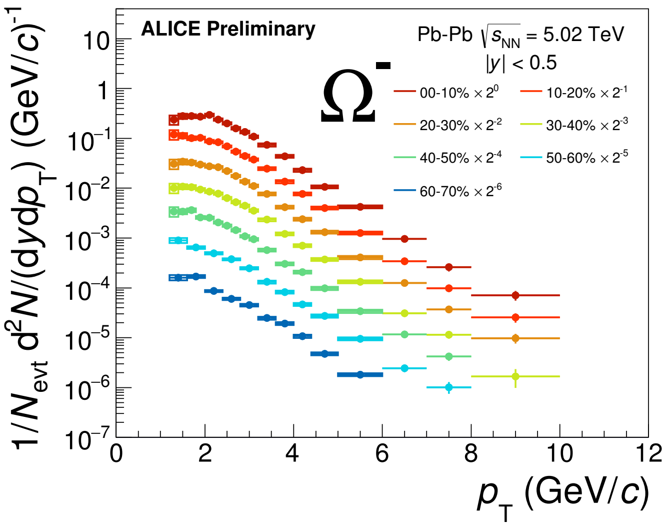
Resonances, hyperons,…



ALI-PREL-130689



ALI-PREL-130693

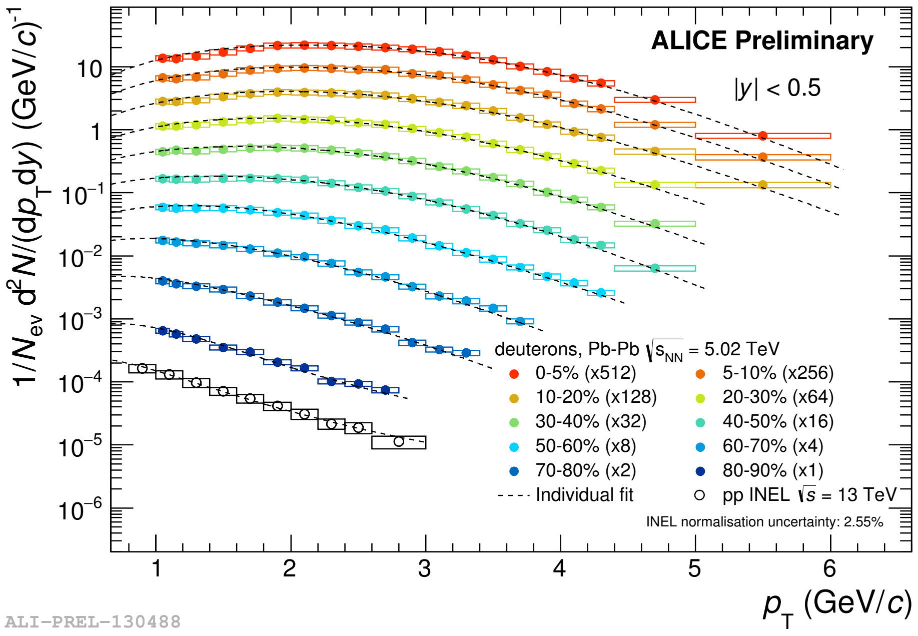


ALI-PREL-131316

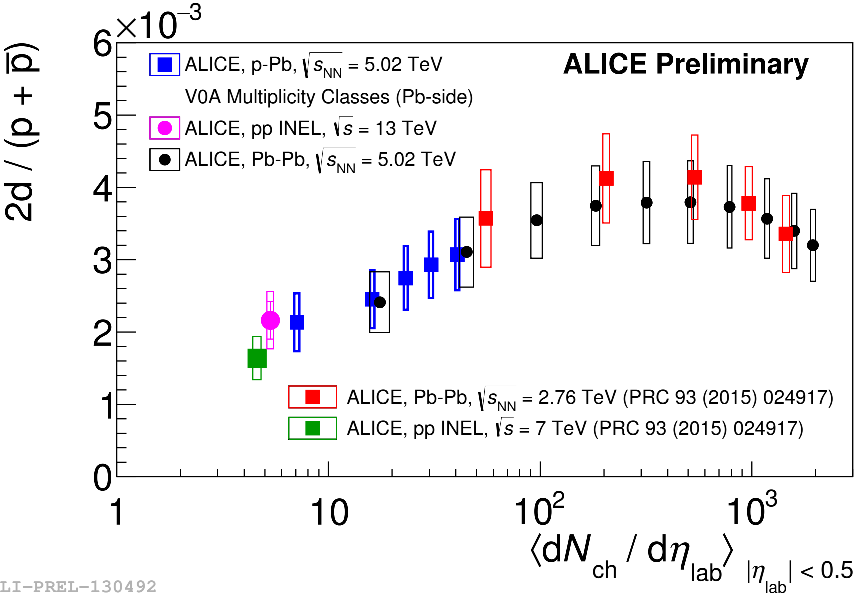
→ QGP hadronisation, radial expansion, freeze-out, …

Deuterons

ALICE-PUBLIC-2017-006



ALI-PREL-130488



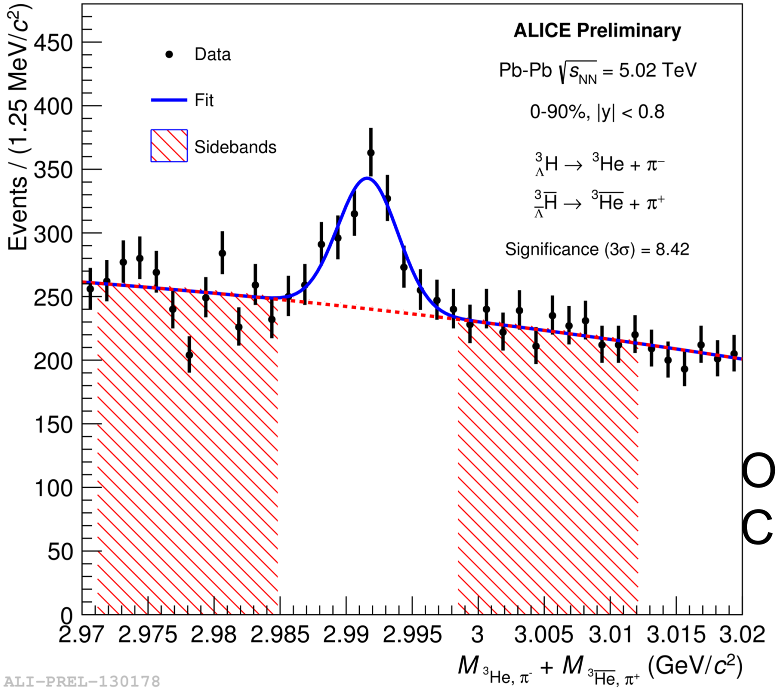
ALI-PREL-130492

Coalescence probability decreases as system size grows

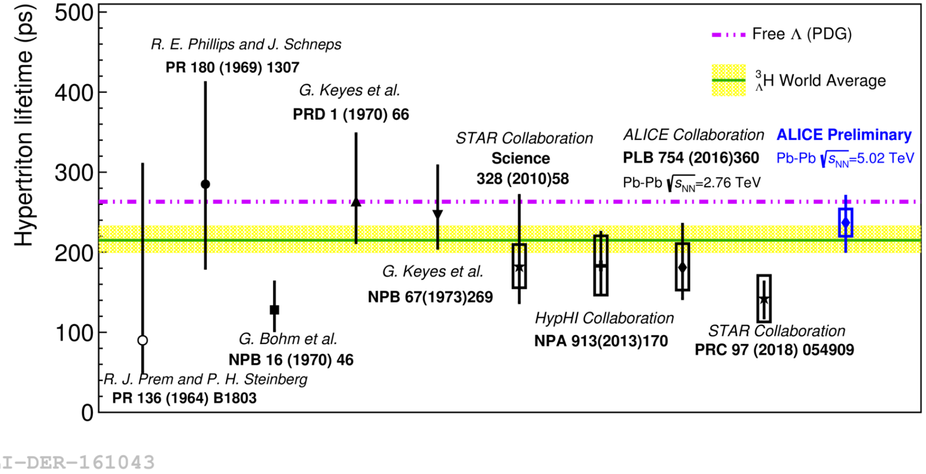
Hypertriton: lifetime

$^3{}_\Lambda$H: pnΛ bound state

$^3{}_\Lambda H \rightarrow {}^3He + \pi^-$



ALI-PREL-130178

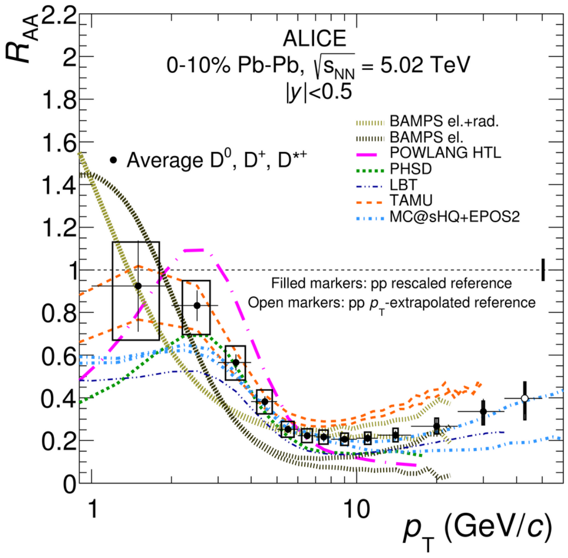


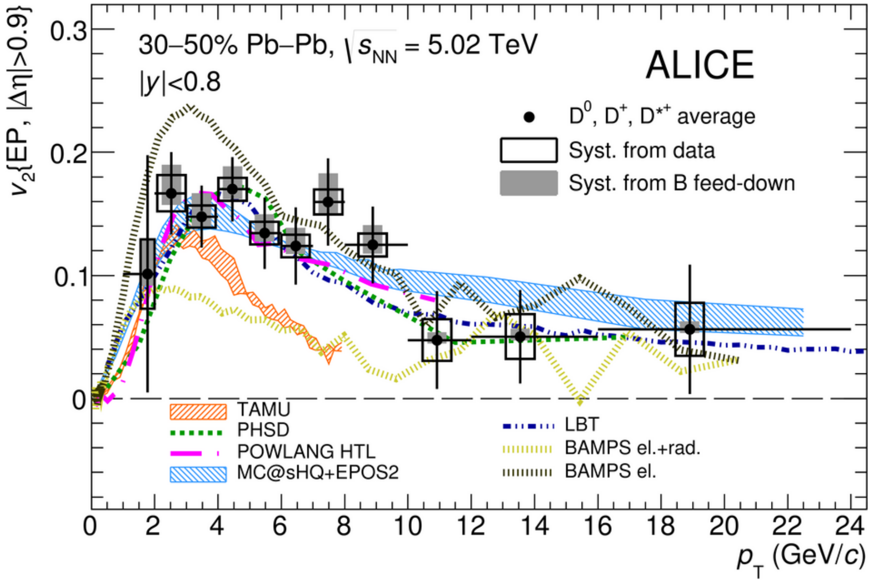
ALI-DER-161043

One of the most precise determinations of the lifetime
Consistent with world data and with free Λ lifetime

Charm: constraining the QGP transport properties

[arXiv:1804.09083]

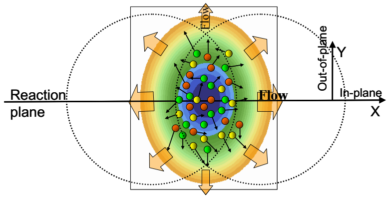




$$R_{AA} = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{pp}}$$

$$\frac{dN(p_T,\varphi)}{d\varphi} \propto 1 + 2v_1\cos(\varphi-\psi_1) + 2v_2\cos(2[\varphi-\psi_2]) + \ldots$$

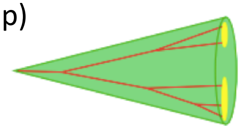
- powerful constraint from combination of R_{AA} and v_2



Jet shape studies

e.g.: declustering: “peel apart” the shower

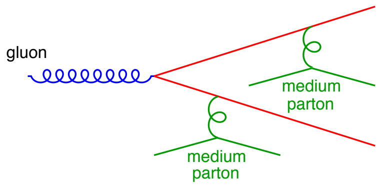
(Soft Drop)



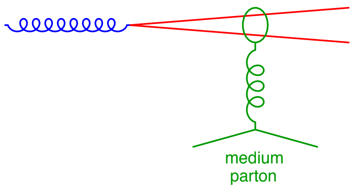
$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$

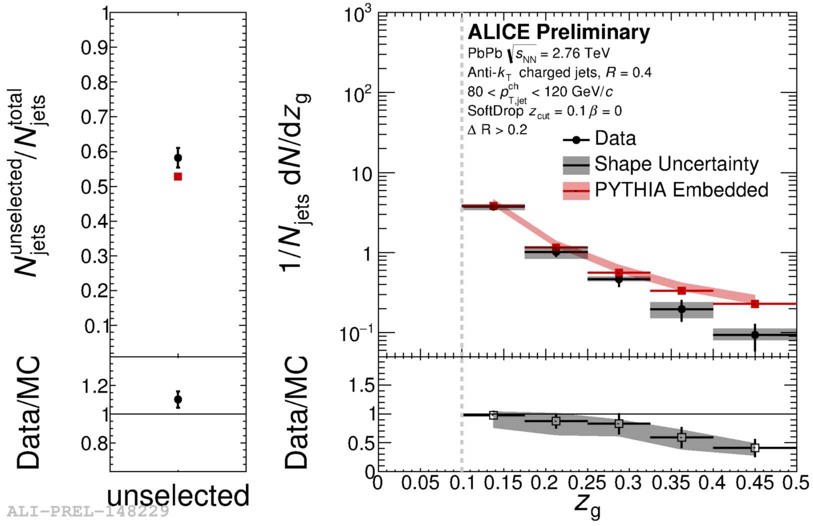
sensitive to coherence of energy loss

incoherent



coherent

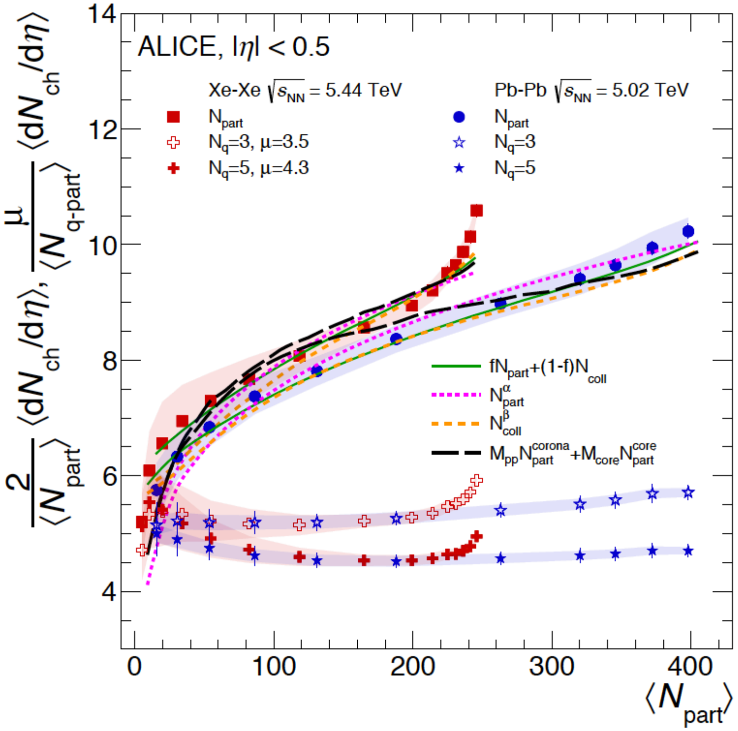




→ suppression of symmetric splittings at large ΔR

Xe-Xe: multiplicity

6-hour run in 2017



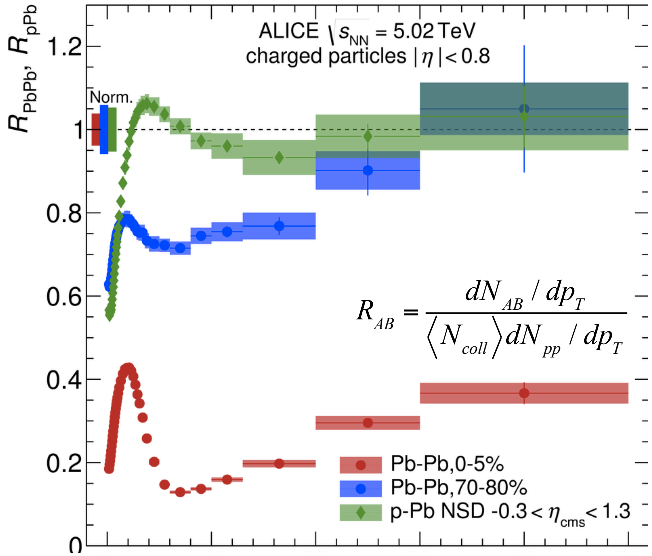
- N_{part} scaling violated → N_{quark} ~ works
  - already known from Pb-Pb
- strong increase of N_{ch}/N_{part} for central Xe-Xe
  - Xe-Xe: more N_{ch} than Pb-Pb at same N_{part}
  - Xe deformation?
  - not fully understood yet…

[arXiv:1805.04432]

Energy loss in p-Pb?

charged particles

Pb-Pb central, Pb-Pb peripheral, p-Pb

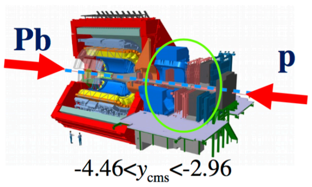


ALICE, arXiv:1802.09145

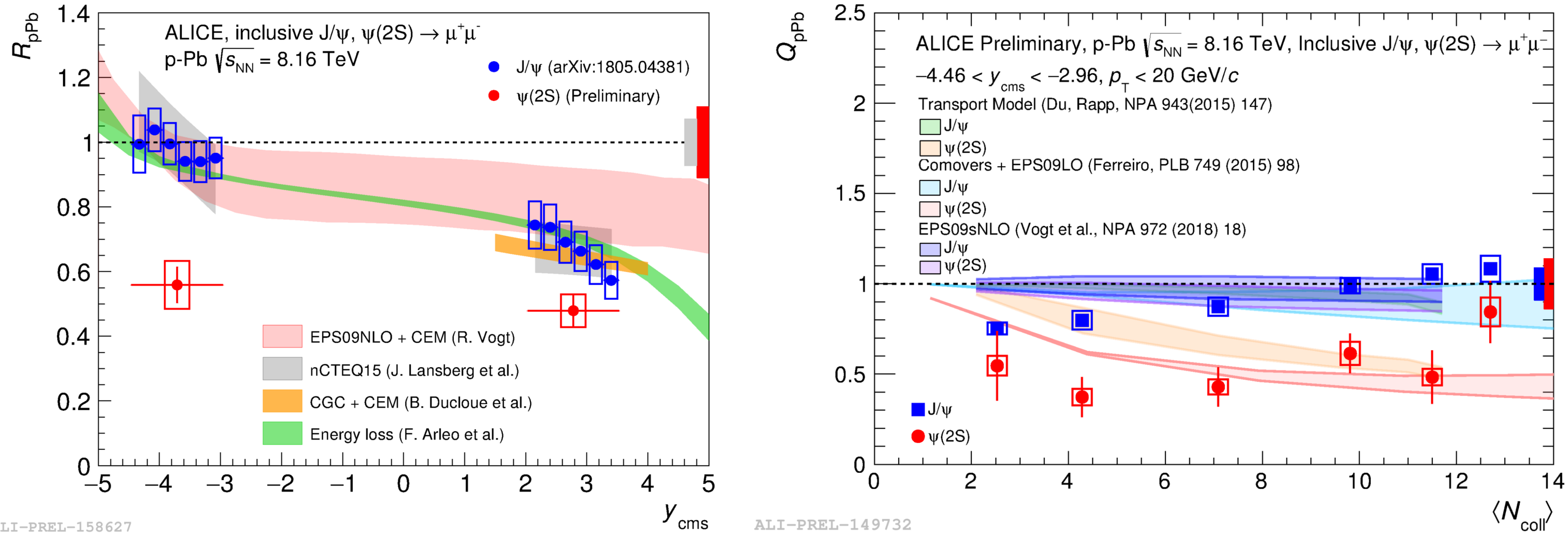
- collective effects in p-Pb
  - long-range correlations (v_2)
  - mass-dependence similar to Pb-Pb
  - stangeness enhancement pattern

- but still no evidence of jet quenching
  - system size, hence effect, smaller
  - but some predictions of sizeable effect, e.g.:
    Zakharov, J Phys G 41 (2014) 075008, arXiv:1311.1159
    Z B Kang et al, Phys Rev C92 (2015) 054911, arXiv:1507.05987
  - dependence on event activity is important!

Charmonia in p-Pb collisions



- moderate J/ψ suppression (consistent with shadowing)
- but ψ(2S) more suppressed (especially in Pb hemisphere)

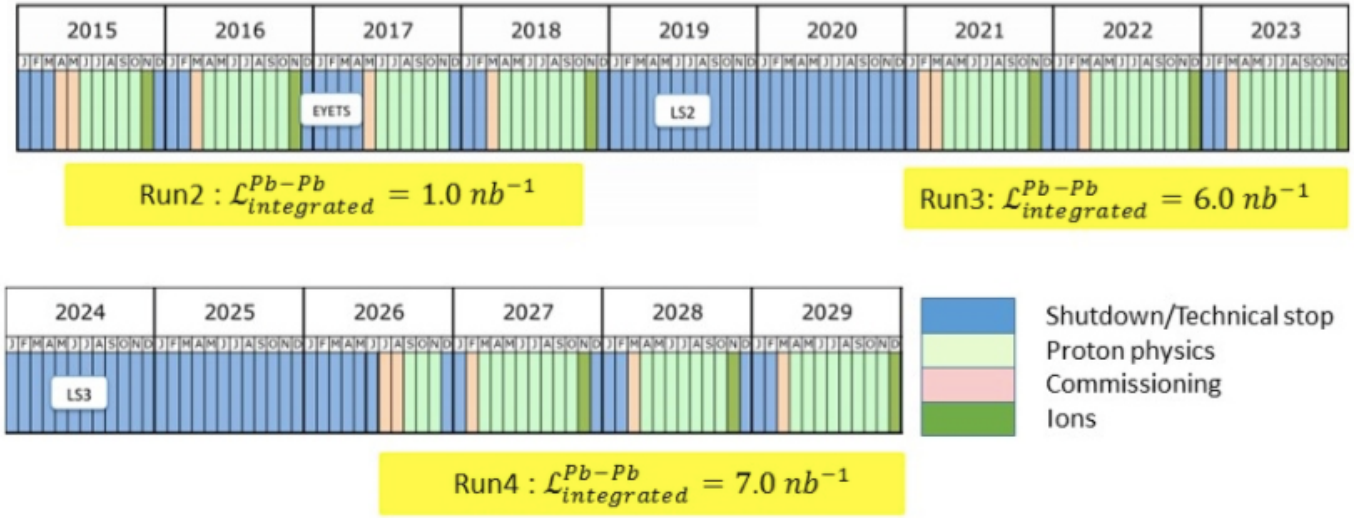


→ final-state effects?

Future prospects

Run3 and HL-LHC

LHC - heavy ions run



Run2 : $\mathcal{L}_{integrated}^{Pb-Pb} = 1.0\ nb^{-1}$

Run3: $\mathcal{L}_{integrated}^{Pb-Pb} = 6.0\ nb^{-1}$

Run4 : $\mathcal{L}_{integrated}^{Pb-Pb} = 7.0\ nb^{-1}$

- LS2:
  - LHC injector upgrades, Pb-Pb rate → 50 kHz (now ~10 kHz)
  - ALICE upgrades
- Run 3 + Run 4:
  - experiments request > 10/nb (ALICE: 10/nb + 3/nb at 0.2 T)
  - in line with latest projections from machine group

ALICE upgrade @ Run3 and Run4

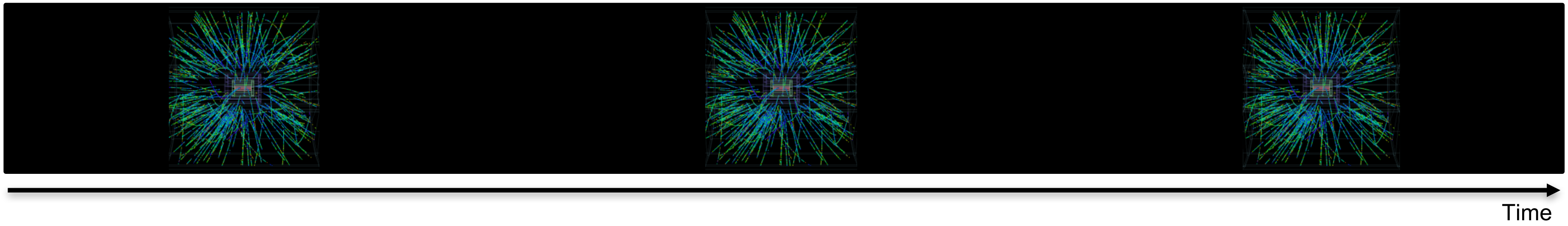
PHYSICS GOAL: x 100 statistics increase for Run 3 and Run 4!

- study heavy quark interaction in QCD medium
  → heavy flavour dynamics and hadronisation at low p_T
- study charmonium regeneration in QGP
  → charmonium down to zero p_T
- chiral symmetry restoration and QGP radiation
  → vector mesons and virtual thermal photons (di-leptons)
- production of nuclei in QGP
  → high-precision measurement of light nuclei and hypernuclei

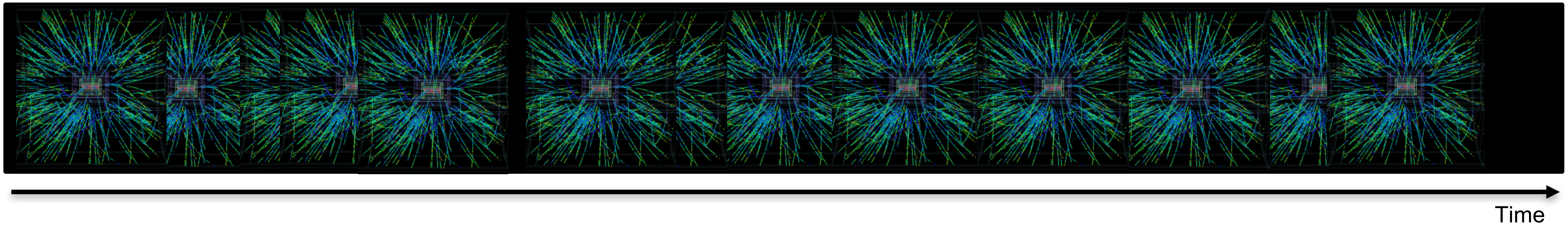
TPC at high rate

- Goal: replace existing MWPC-based Readout Chambers and Front-End Electronics in LS2 to allow **continuous readout** of Pb-Pb collisions at 50 kHz in RUN3 and 4
- Technical solution: **4-layer GEM** detectors

- currently: average time between collisions ~125 μs ~ TPC drift time
  - 1 event in TPC at any given time → triggerable



- after upgrade: average time between collision ~ 20 μs << TPC drift time
  - 5 events in TPC at any given time → continuous readout



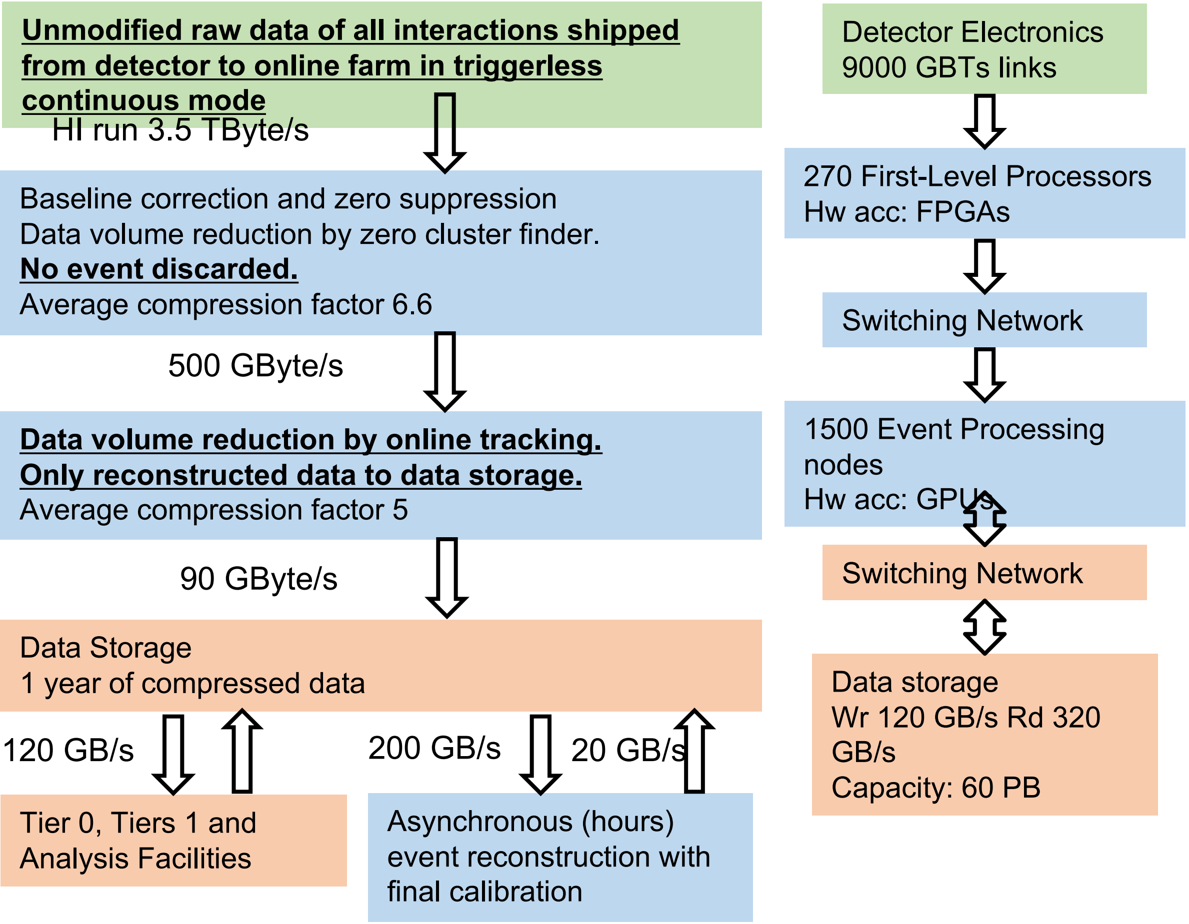
O² System

Requirements

1. LHC min bias Pb-Pb at 50 kHz
2. very small signal over background
   → triggering not possible
3. support for continuous read-out

New computing system

- ➔ read-out the data of all interactions
- ➔ compress data intelligently
  → online reconstruction
- ➔ common online-offline computing system → O²



Unmodified raw data of all interactions shipped from detector to online farm in triggerless continuous mode

HI run 3.5 TByte/s

Baseline correction and zero suppression
Data volume reduction by zero cluster finder.
No event discarded.
Average compression factor 6.6

500 GByte/s

Data volume reduction by online tracking.
Only reconstructed data to data storage.
Average compression factor 5

90 GByte/s

Data Storage
1 year of compressed data

120 GB/s

200 GB/s

20 GB/s

Tier 0, Tiers 1 and Analysis Facilities

Asynchronous (hours) event reconstruction with final calibration

Detector Electronics
9000 GBTs links

270 First-Level Processors
Hw acc: FPGAs

Switching Network

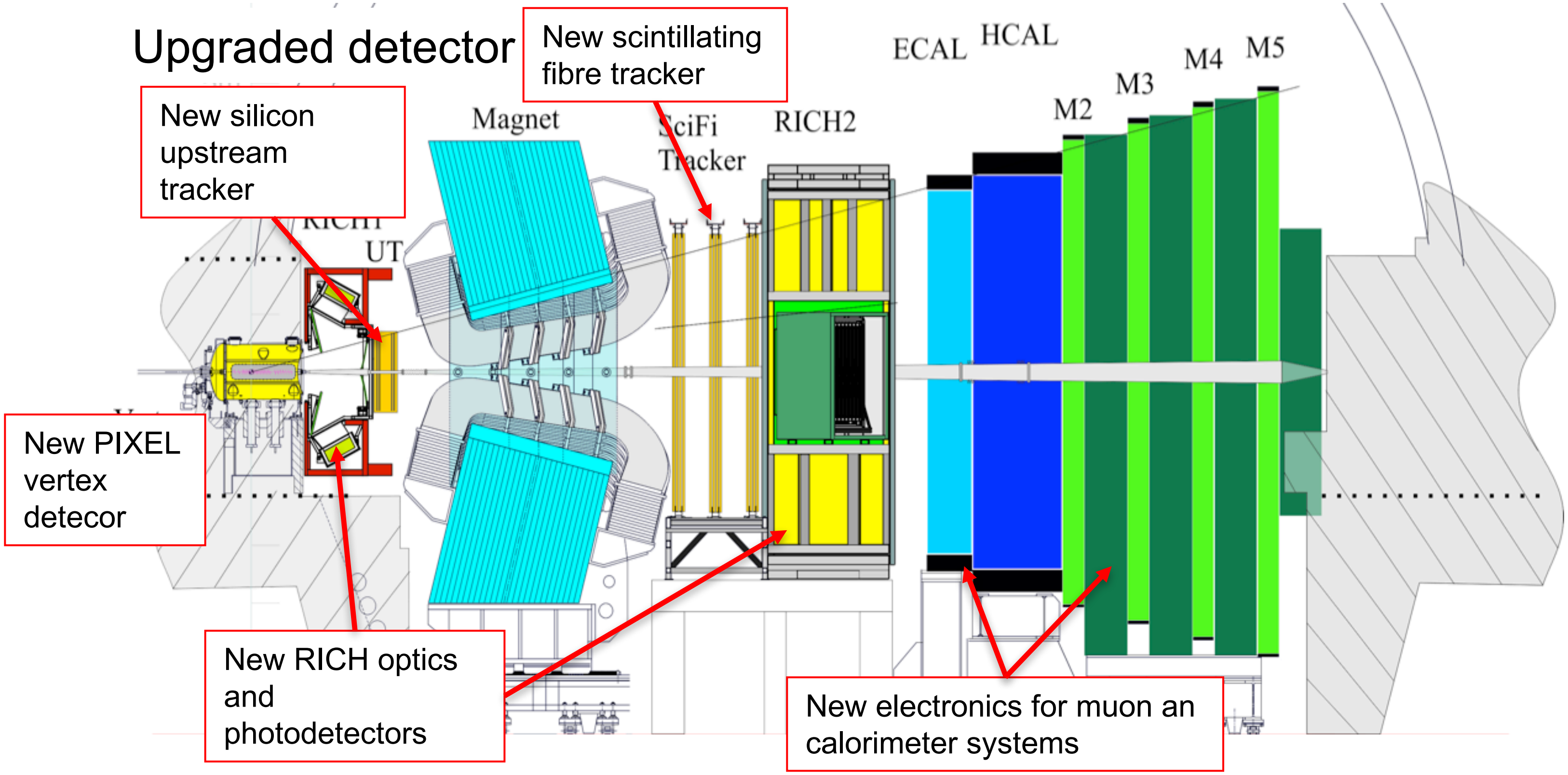
1500 Event Processing nodes
Hw acc: GPUs

Switching Network

Data storage
Wr 120 GB/s Rd 320 GB/s
Capacity: 60 PB

The LHCb upgrade in a snapshot

All sub-detectors read out at 40 MHz for a **fully software trigger**



Upgraded detector

New scintillating fibre tracker

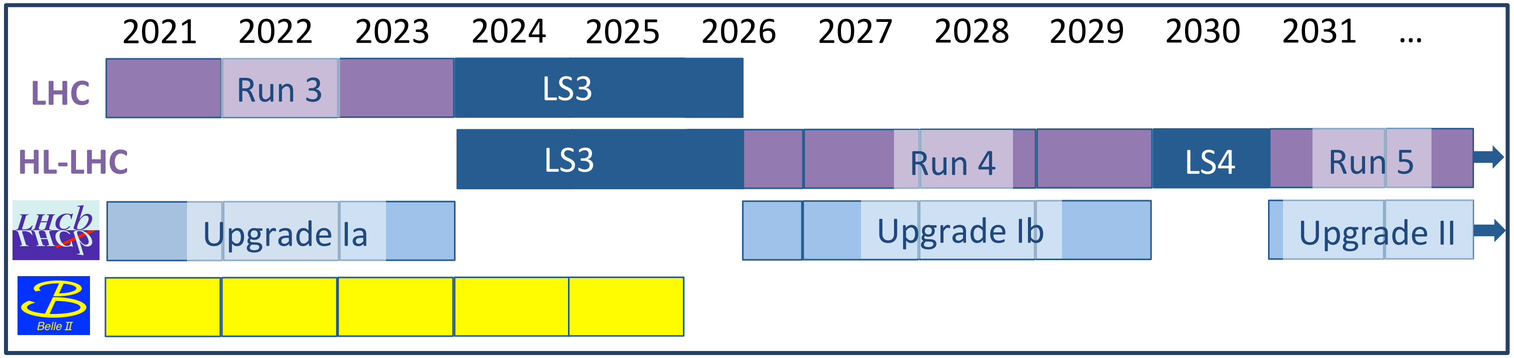
New silicon upstream tracker

New PIXEL vertex detecor

New RICH optics and photodetectors

New electronics for muon an calorimeter systems

LHCb Upgrade II – not approved yet



LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	***300 fb^{-1}**

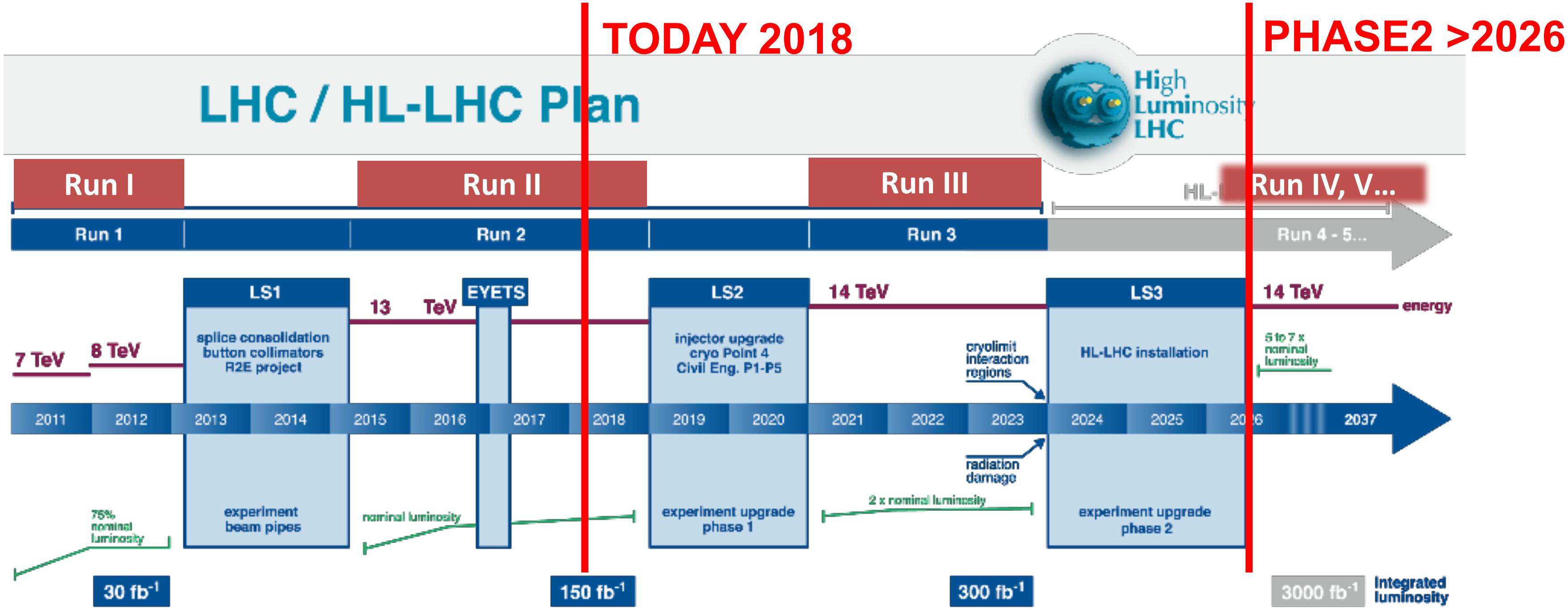
- **assumes a future upgrade to raise instantaneous luminosity to $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$**

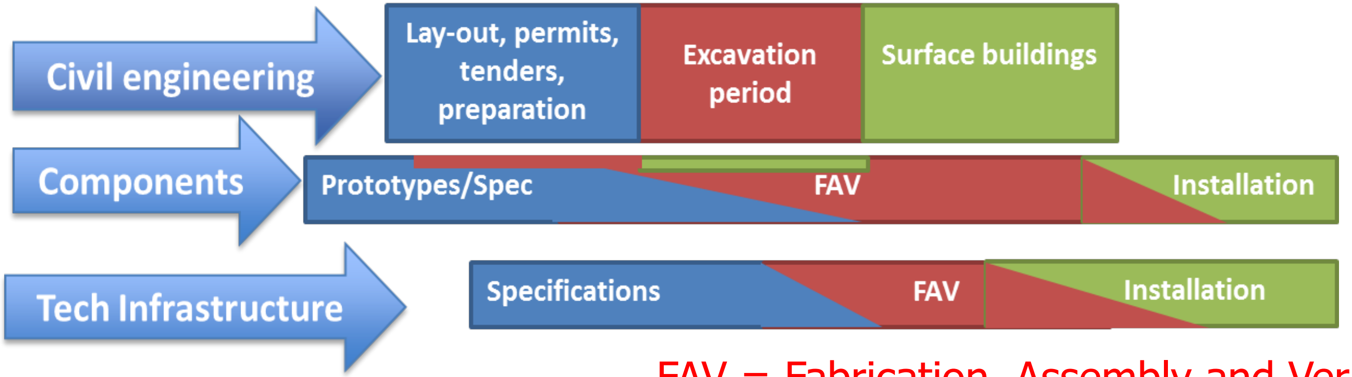
[CERN-LHCC-2017-003]

- **First upgrade in LS2 ➔** instantaneous luminosity up to $2\text{x}10^{33}$ $\text{cm}^{-2}\text{s}^{-1}$
- **Expression of Interest for a further upgrade during LS4** to reach $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ (~50 fb^{-1}/year), called Upgrade II ➔ pileup ~50 - very challenging !!!

High Luminosity LHC

- a “landmark project” in the ESFRI roadmap
- formally approved by the CERN Council





Civil engineering: Lay-out, permits, tenders, preparation | Excavation period | Surface buildings

Components: Prototypes/Spec | FAV | Installation

Tech Infrastructure: Specifications | FAV | Installation

FAV = Fabrication, Assembly and Verification

Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

enabling a total integrated luminosity of **3000 fb^{-1}**

implying an integrated luminosity of **250-300 fb^{-1} per year**,

design for **μ ~ 140 (~ 200)** (➔ peak luminosity of **5 (7.5) 10^{34} cm^{-2} s^{-1}**)

design equipment for ‘ultimate’ performance of **7.5 10^{34} cm^{-2} s^{-1}**
and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation

LHC Upgrade Goals: Performance optimization

Luminosity recipe :

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

→1) maximize bunch intensities → Injector complex

→2) minimize the beam emittance LIU ⇔ IBS

→3) minimize beam size (constant beam power); → triplet aperture

→4) maximize number of bunches (beam power); → 25ns

→5) compensate for 'F'; → Crab Cavities

→6) Improve machine 'Efficiency' → minimize number of unscheduled beam aborts

11 Tesla dipole (Nb_3Sn) long prototype

Conclusions and outlook

- 2018 run restarted very well: LHC continues to provide a wealth of excellent physics results
- Already ~ 100 fb^{-1} delivered by LHC to ATLAS and CMS is only 3% of the full LHC program ➔ precision measurements in the Higgs sector start to be feasable
- Flavor sector can complement with indirect measurements the direct searches while exploring SM and rare decays
- In the current state with fundamental physics, it is necessary to have a programme as diversified as possible: maintaining the broadest possible physics programme in the long term will be crucial
- LS2 shutdown for machine and experiments upgrade is close
- Looking into the far future seeking for new opportunities !!