Heavy Flavours at LHC with ATLAS and CMS

Chiara Rovelli (INFN Roma)
On behalf of the ATLAS and CMS Collaborations

26ème Congres General de la SFP, 3-7 Jul 2023, Paris (France)

Flavour

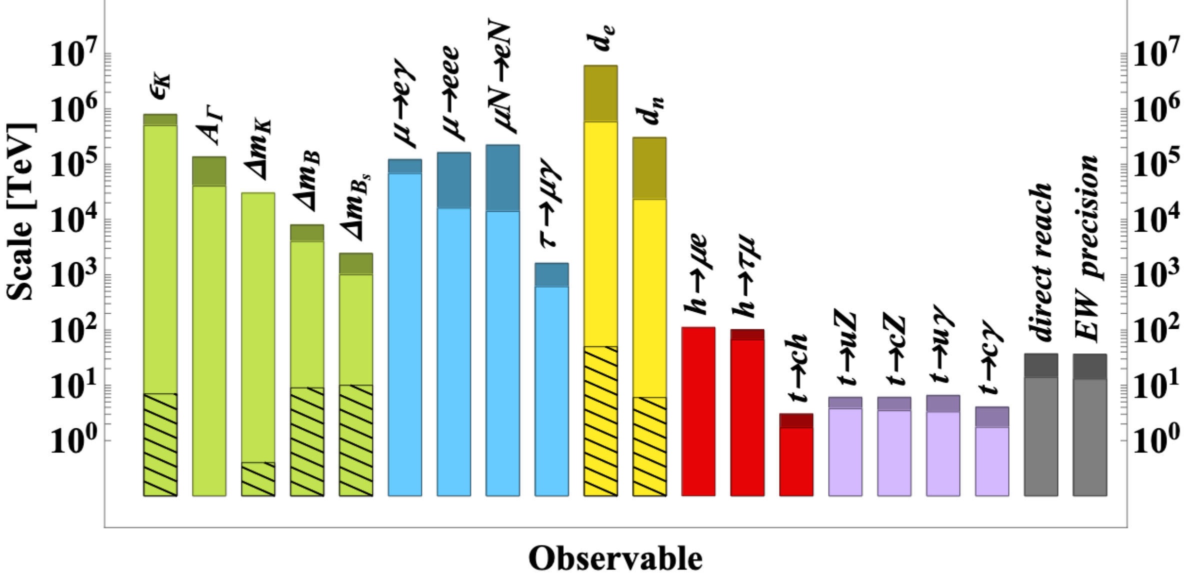
Flavour is one of the most puzzling aspects in the Standard Model

- Apparent hierarchy but hidden cause
- Quark-lepton symmetry?

Flavour physics provides a wide range of Standard Model tests, subjecting SM to deep scrutiny

Comparison of precise measurements with theory can probe the nature of new physics
in a complementary way to direct searches, not limited by collisions energy

ESPP 2020 Physics Book



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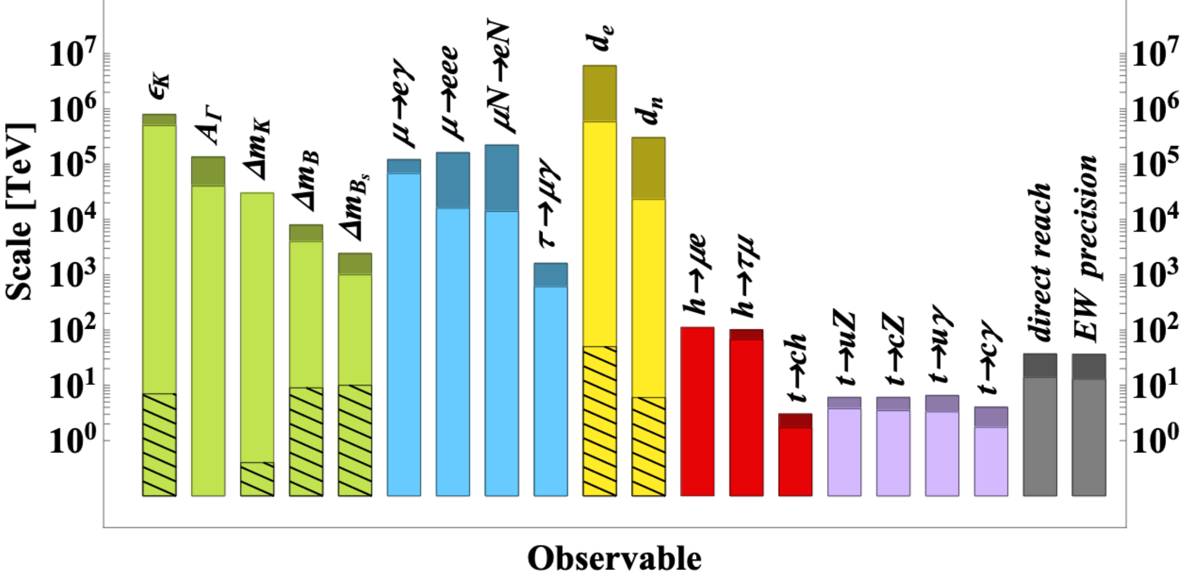
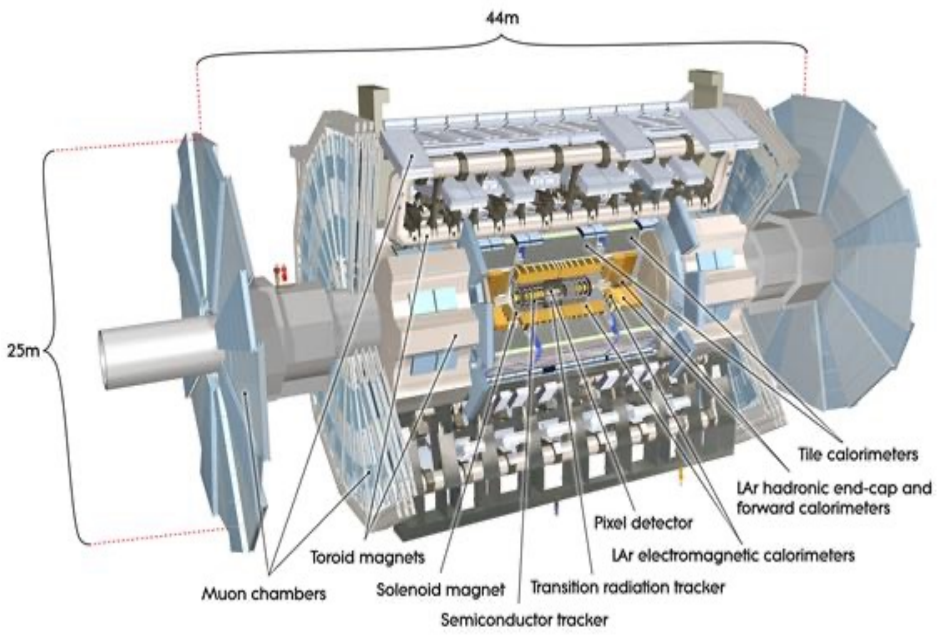


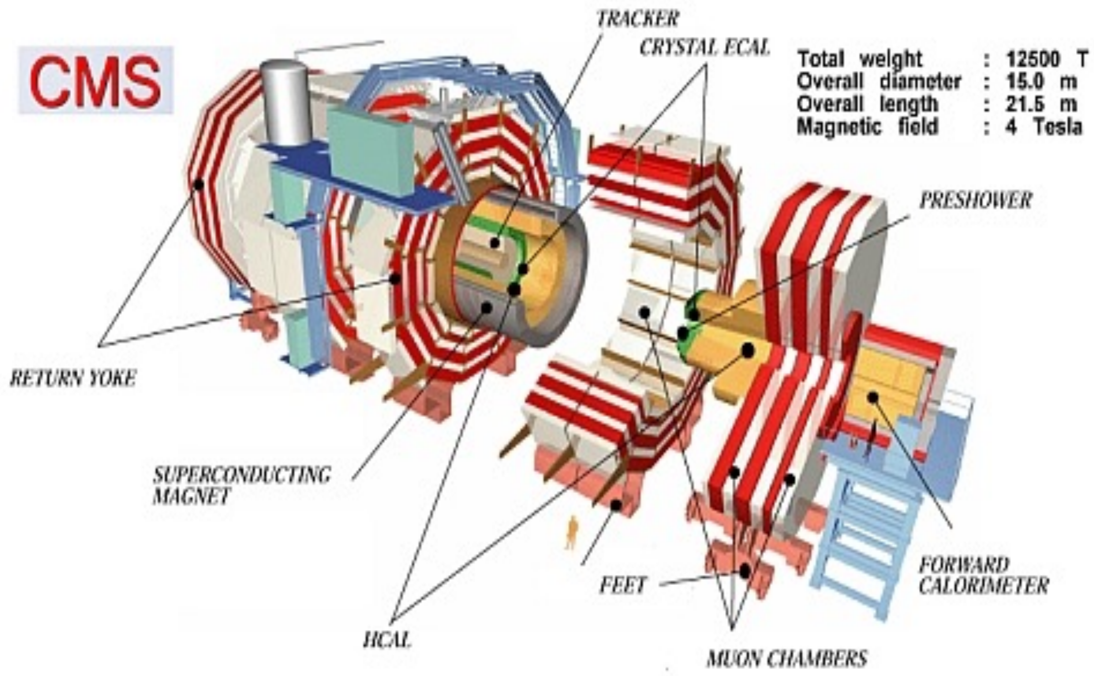
DISCLAIMER:

Very large topic, I selected only a few examples mainly from quark HF sector (neglecting Top)

Only a few examples from the lepton sector, namely tests of charged LFV

ATLAS and CMS





These are not B-Physics dedicated detectors

- No particle ID
- Different rapidity region e.g. wrt LHCb

Compensate with

- Excellent muon reconstruction efficiency and momentum resolution
- Optimal tracking and vertexing performance

B-physics: ~100 to 200 Hz out of the total trigger budget with standard running

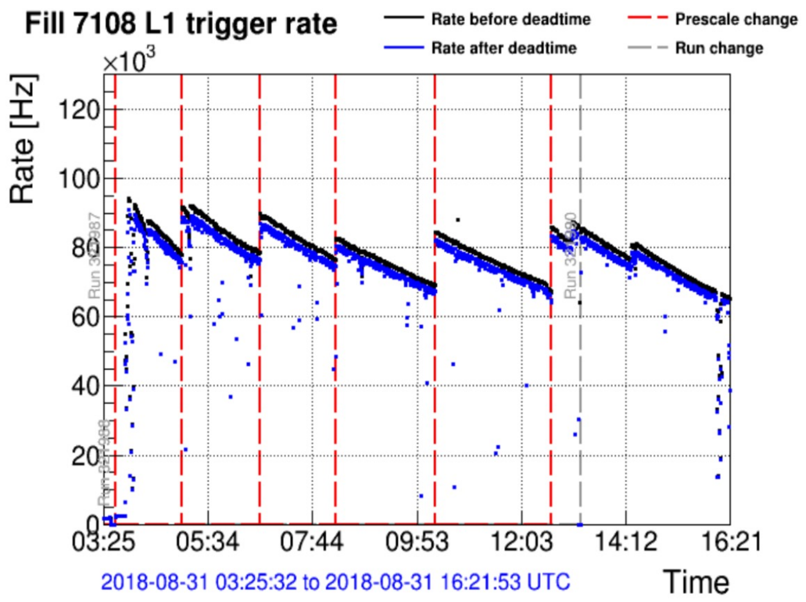
Triggering on B-Phys topologies

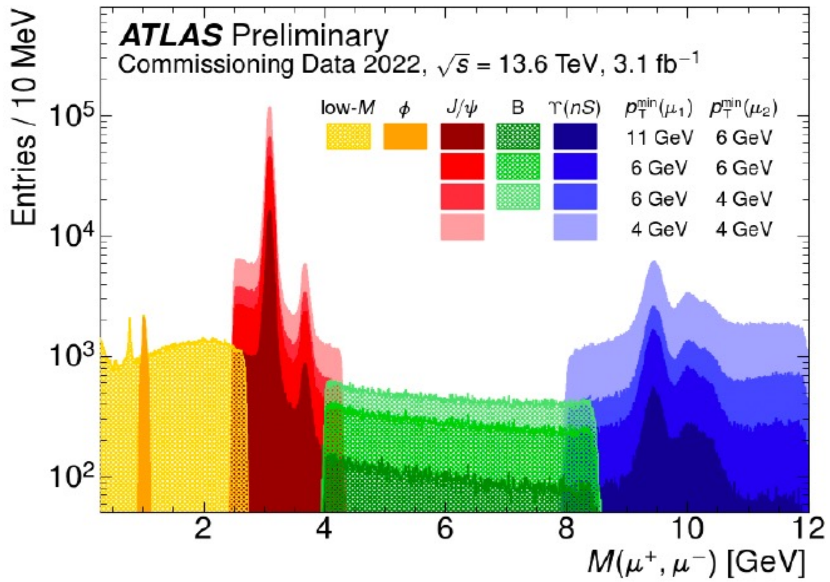
ATLAS and CMS operate at large instantaneous luminosity and lot of the trigger bandwidth is allocated to high-p_T physics

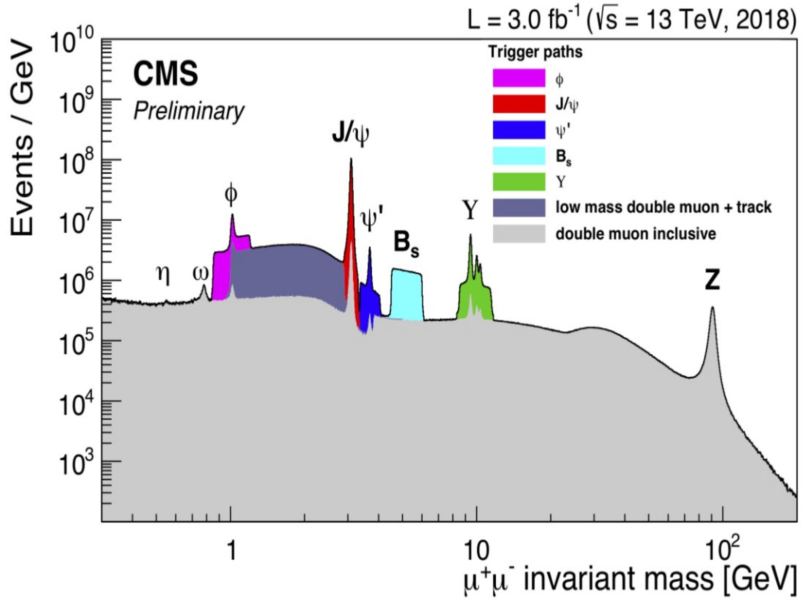
At high luminosity and high pileup, collecting low-p_T events within the allocated bandwitdh becomes challenging

Clever strategies needed:

- Topological triggers to complement inclusive ones
- CMS “Parking” startegy to profit from unused resources as lumi drops







CMS 2018 parking

CKM matrix and CP violation

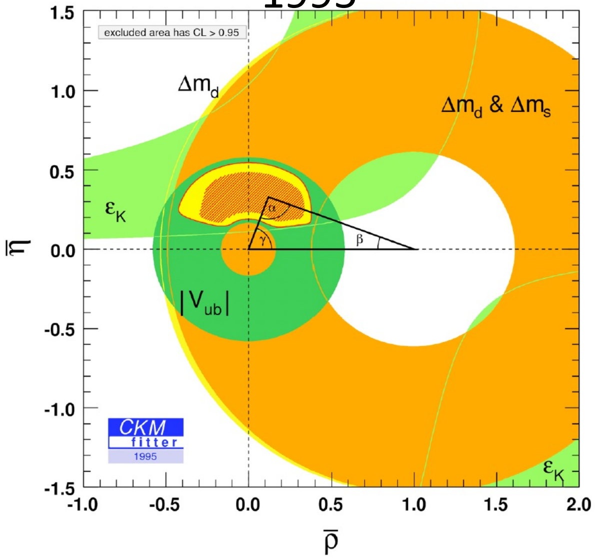
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{\mathrm{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \text{ where } V_{\mathrm{CKM}} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix}$$

The CKM matrix is a 3x3 unitary matrix whose elements represent the strength of flavor-changing weak interactions

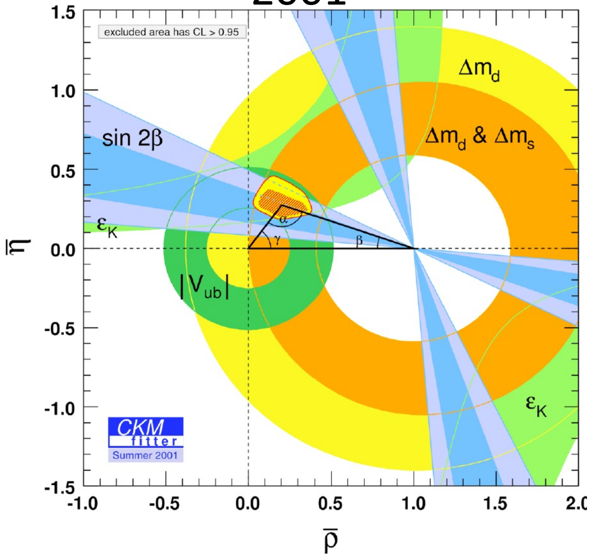
Only 4 parameters (3 mixing angles and 1 CP violating phase)

- Many measurements ⇒ Unitary Triangle is highly overconstrained
- Huge progresses in the last three decades

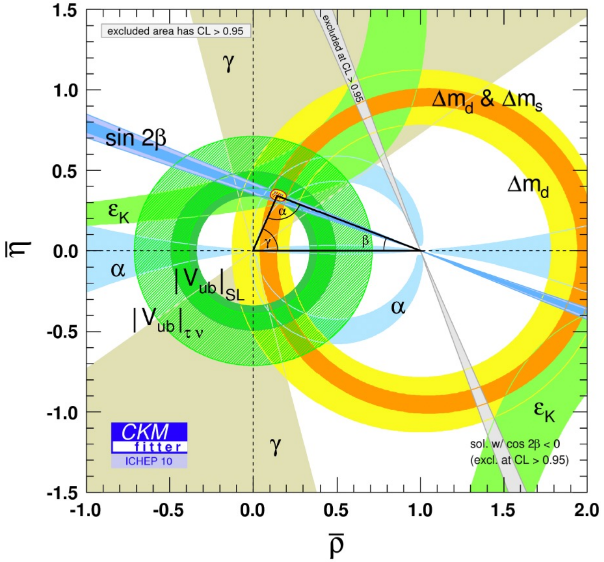
1995



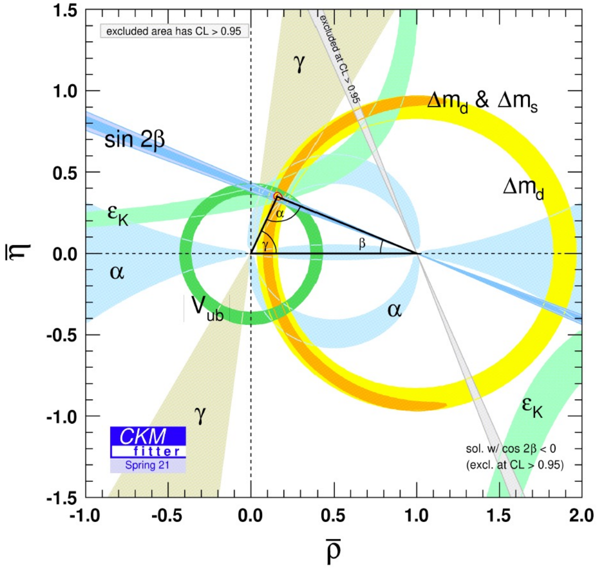
2001



2010



2021



One of the most powerfool tools to test the Standard Model

CKM matrix and CP violati...

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{\text{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \text{ where } V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{t\ldots} \end{bmatrix}$$

...3x3 unitary matrix whose elements ...of flavor-changing weak interactions

Only 4 parameters (3 mixing angles and 1...

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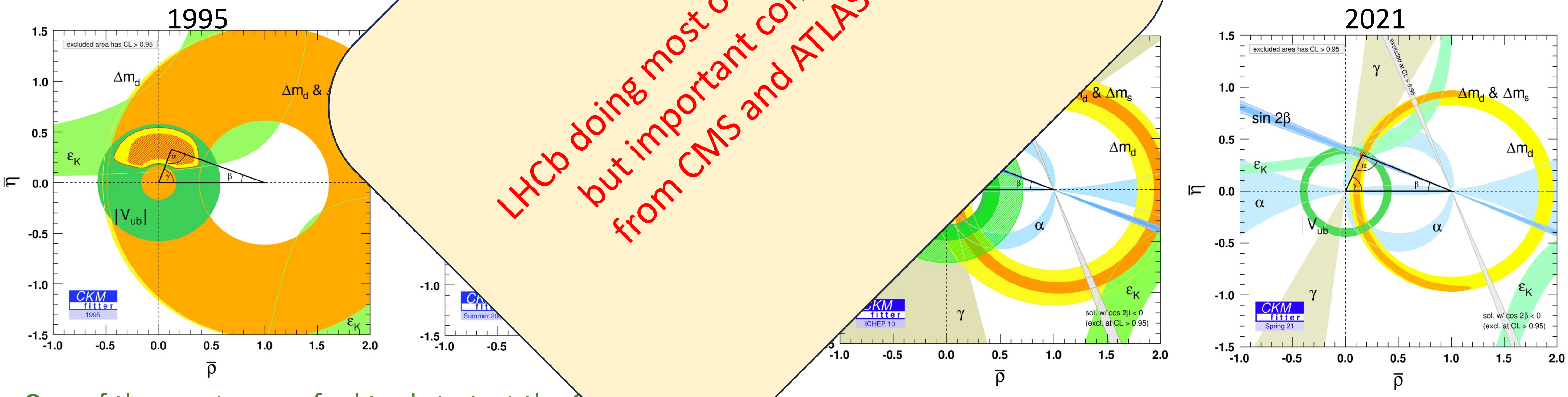
- Huge progresses in the last thre...

LHCb doing most of the work at LHC but important contributions from CMS and ATLAS as well



One of the most powerfool tools to test the St...

B^0_s mixing phase ($B_s \to J/\psi\ \phi$)

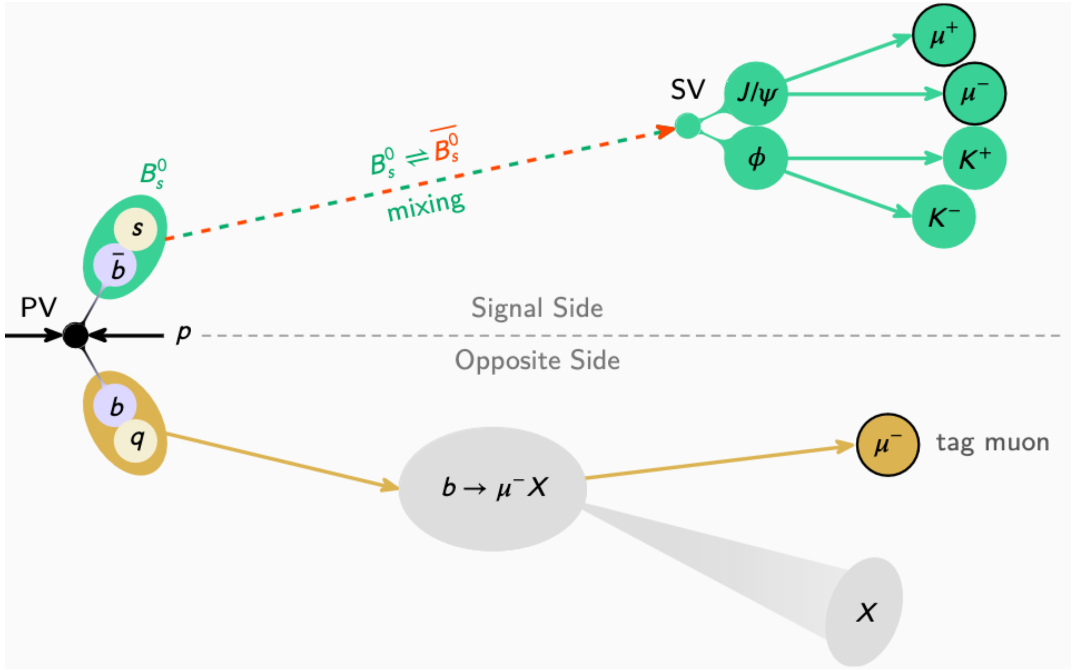
ϕ_s: weak phase difference between direct decay and decay through B^0_s mixing
$\Delta\Gamma_s$: decay width difference between light and heavy B^0_s mass eigenstates
⇒ Both sensitive to New Physics

Golden mode: $B^0_s \to J/\psi\ \phi\ \to \mu\mu KK$

Time dependent angular analysis

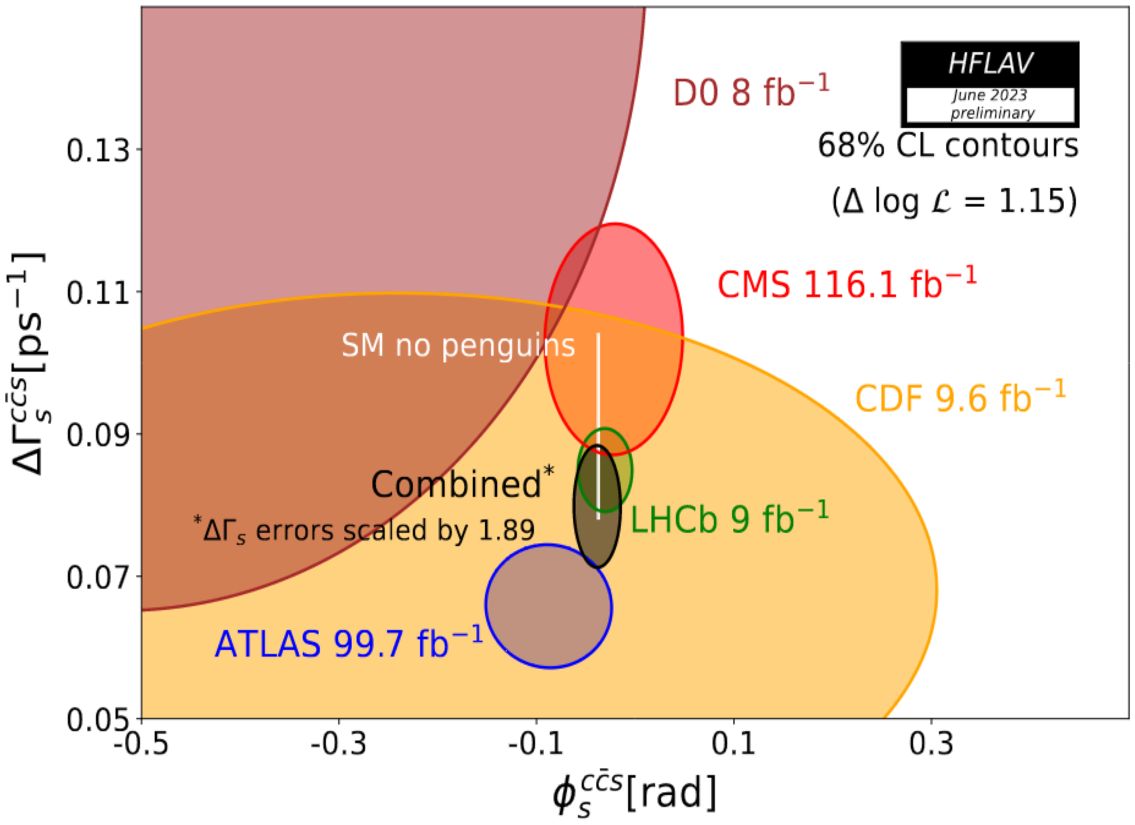
Crucial role of flavour tagging,
i.e. identification of the B flavour at production

⇒ Both ATLAS and CMS use opposite side taggers, with a tagging efficiency of 20-50%



ATLAS: Eur. Phys. J. C. 81 (2021) 342 (2015-17 + Run1)
CMS: Phys. Lett. B 816 (2021) 136188 (2017-18 + Run1)
LHCb: Eur. Phys. J. C. 79 (2019) 706, Recent CERN Seminar. (Run1+Run2)

B^0_s mixing phase ($B_s \to J/\psi\,\phi$)



	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]
ATLAS	$-0.087 \pm 0.036 \pm 0.021$	$0.0657 \pm 0.0043 \pm 0.0037$
CMS	$-0.021 \pm 0.044 \pm 0.010$	$0.1032 \pm 0.0095 \pm 0.0048$
LHCb (new)	$-0.039 \pm 0.022 \pm 0.006$	$0.0845 \pm 0.0044 \pm 0.0024$
CKMfitter	$-0.0368\ ^{+0.0006}_{-0.0009}$	
UTFit	-0.0368 ± 0.0010	
arXiv:1511.09466		0.085 ± 0.015

Good agreement of all LHC experiments with competitive results
Combined result consistent with predictions
Results still dominated by statistical uncertainty

$B^0, B^0_s \rightarrow \mu\mu$

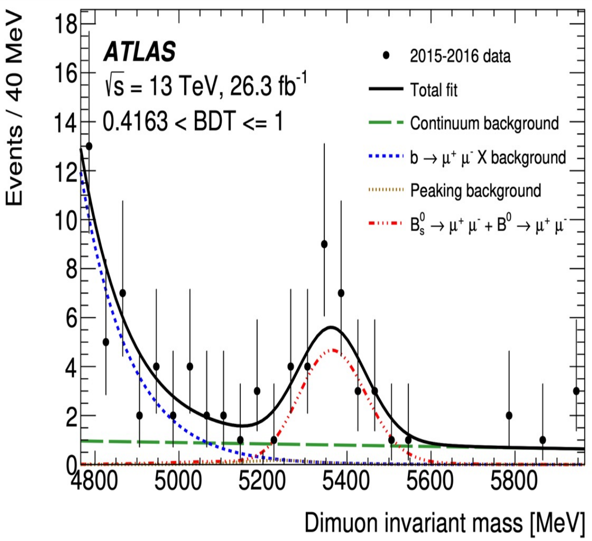
Rare decays are a perfect laboratory to search for new physics ⇒ complementary to direct searches

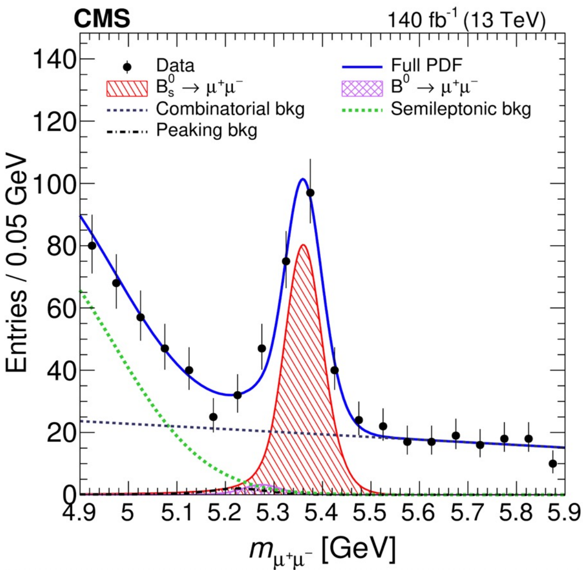
$B^0, B^0_s \rightarrow \mu\mu$ are the golden channels at LHC

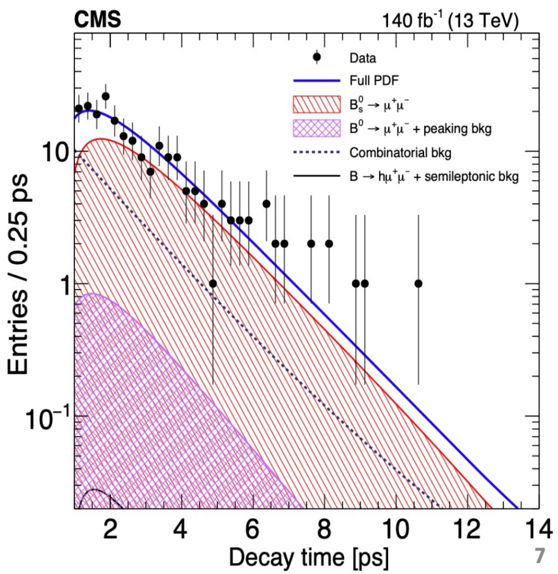
- Pure penguin decays (helicity suppressed)
- Very precise theoretical predictions
- Experimentally clean
- Highly suppressed in the SM, and enhanced elsewhere

In absence of CPV, only the heavier mass eigenstate (CP-odd) can decay to $\mu\mu$ (CP-odd as well)

Deviations from expected BR or expected lifetime of the heavier eigenstate would point to NP



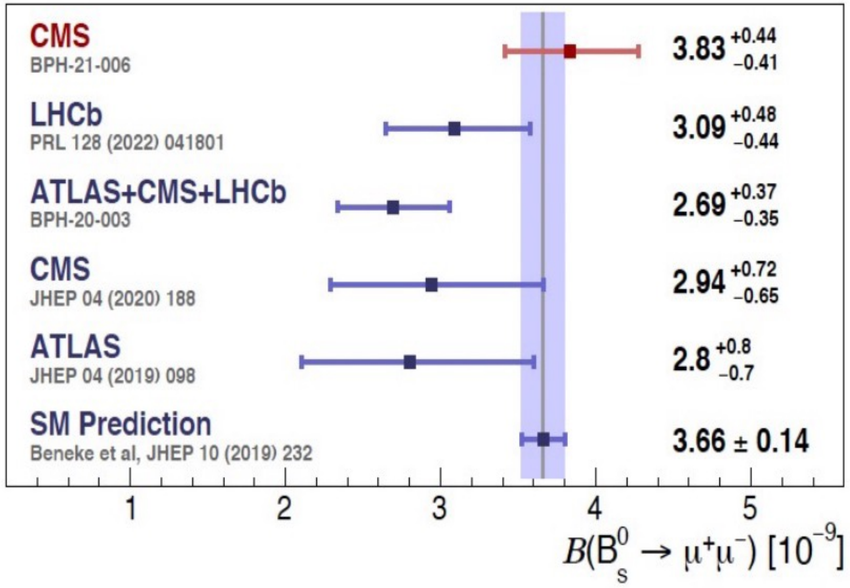




CMS (and LHCb) already published with Full Run2 statistics.
ATLAS update expected soon

ATLAS: JHEP04 (2019) 098 (2015-16)
CMS: Phys. Lett. B 842 (2023) 137955
LHCb: Phys. Rev. D105 (2022) 012010

B^0, $B^0_s \to \mu\mu$: branching ratio and lifetime



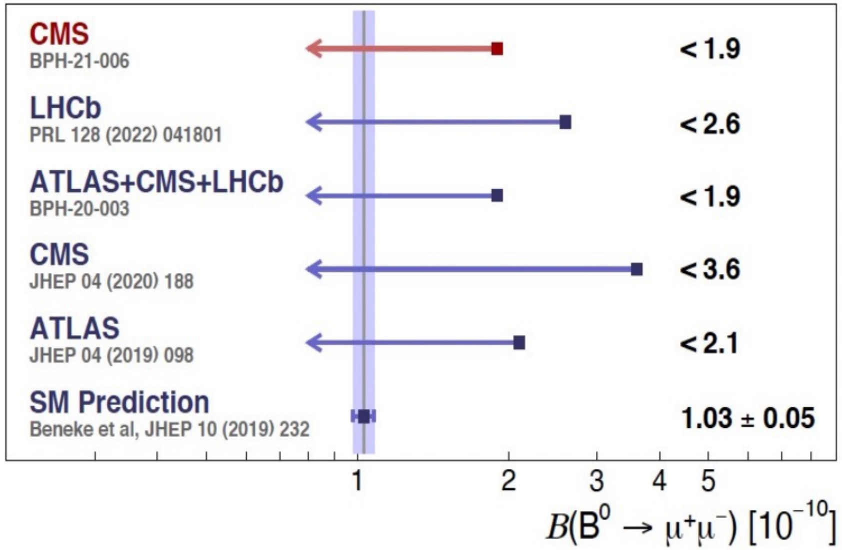
Relative B^0_s BR uncertainty with the new CMS result reduced from 23% to 11%

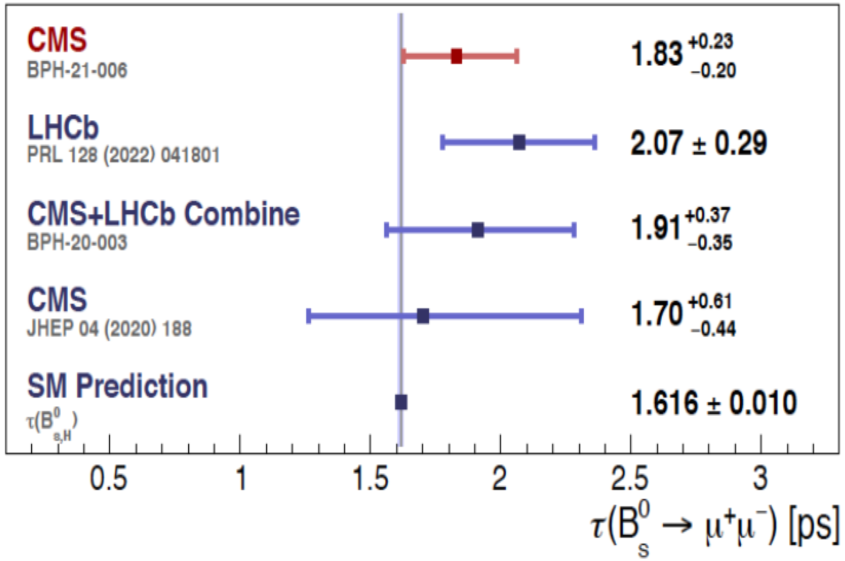
- Statistical uncertainties dominate in all measurements

Lot of work done

Long way to observe $B^0 \to \mu\mu(\gamma)$

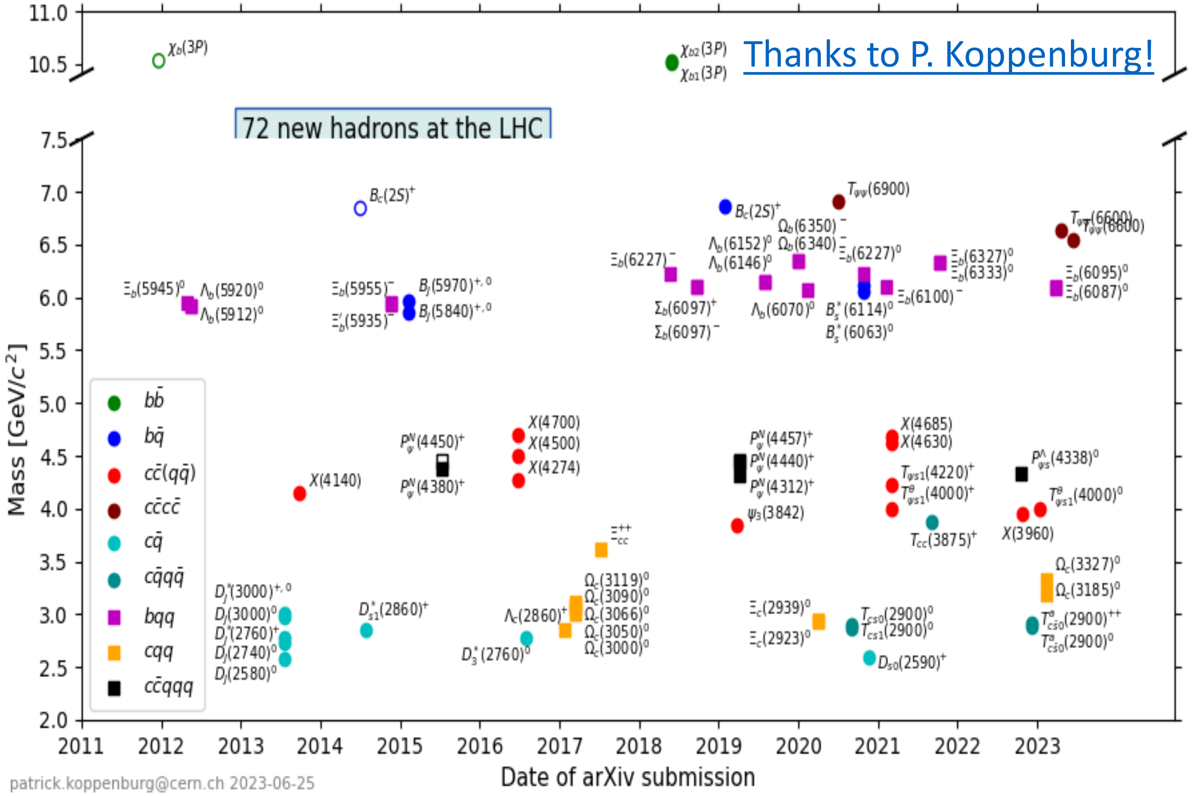
- No evidence yet
- Main challenge: combinatorial background





Spectroscopy

LHC: hadron factory, thanks to high luminosity and high b,c production cross-section



Thanks to P. Koppenburg!

Intensive spectroscopy program at LHC

Conventional Heavy Hadron:

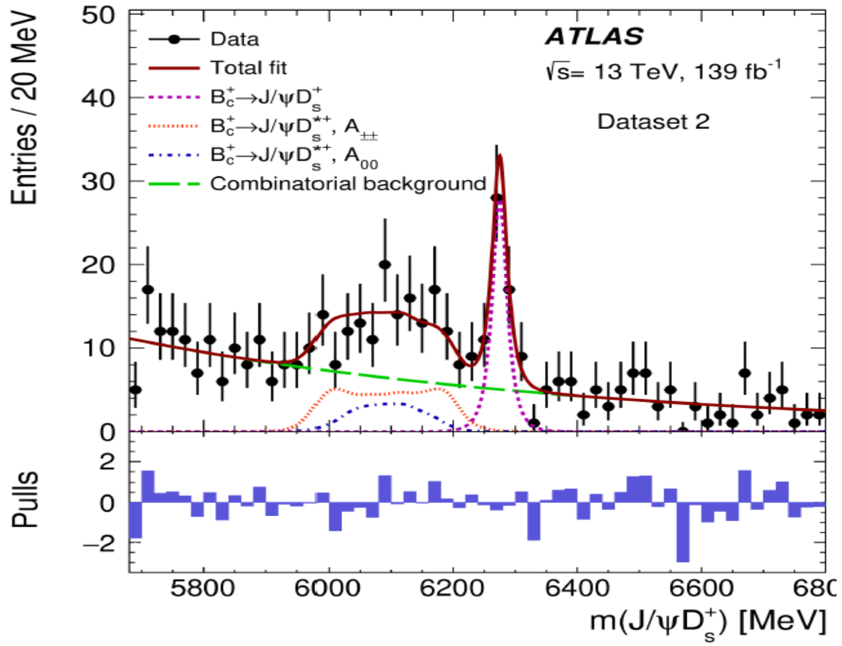
- Excited open flavour mesons
- Excited conventional charmonium
- Excited baryons
- ….
- Precise mass and BR measurements

Exotic spectroscocpy:

- $\chi_{c1}(3872)$ production and decay
- Other $c\bar{c}$ tetraquark candidates
- $c\bar{c}\, c\bar{c}$
- …..

LHCb main player here (64/72 new hadrons discovered at LHCb), but ATLAS and CMS also in the game

ATLAS and CMS Spectroscopy (highlights @LHCP)



ATLAS: JHEP 08 (2022) 087

High precision measurement of $B^+_c \rightarrow J/\psi\ D^+_s$ and $B^+_c \rightarrow J/\psi\ D^{*+}_s$ branching ratio with Full Run2 data. Current highest precision

CMS:

Eur.Phys.J.C 82 (2022) 499

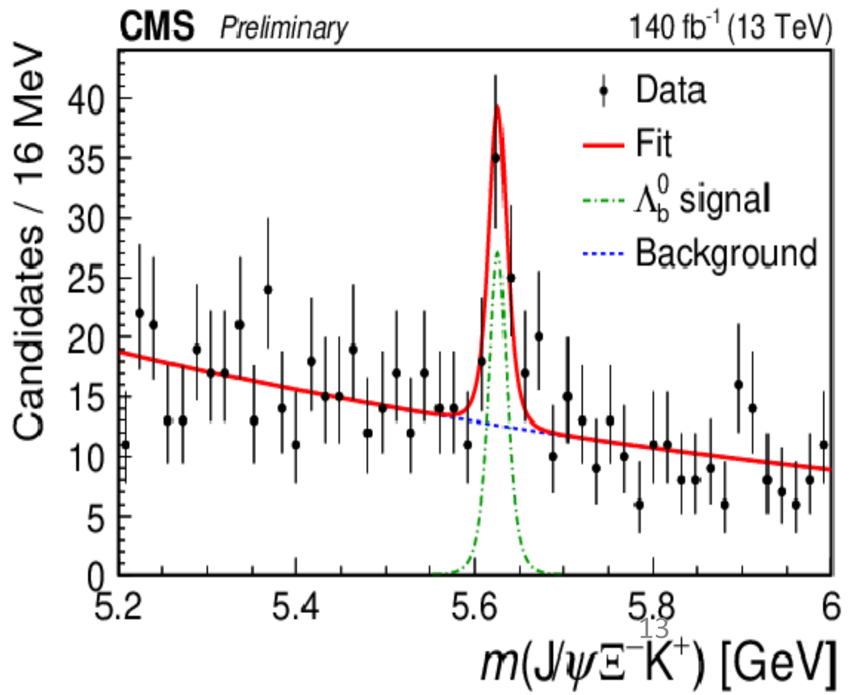
Observation of $B^0 \rightarrow \psi(2S)K^0_s\,\pi\pi$ and $B^0_s \rightarrow \psi(2S)K^0_s$ decays

Phys. Rev. Lett. 126 (2021) 25

Observation of a new excited beauty strange baryon decaying to $\Xi^-_b\pi\pi$

CMS-PAS-BPH-22-002 (new!)

Observation of the $\Lambda^0_b \rightarrow J/\psi\ \Xi^-\ K^+$ decay



Observation of new structures in di-charmonium mass spectra

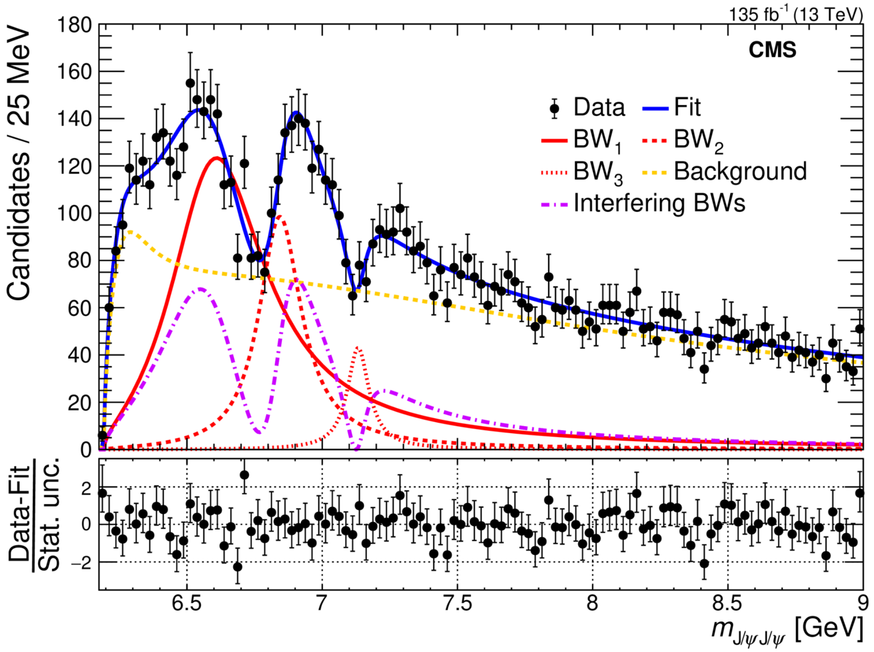
In 2020 LHCb reported the observation of a significant structure at 6900 MeV [Sci. Bull. 65 (2020) 23, 1983]
Both CMS and ATLAS investigated the J/ψ J/ψ mass spectrum; ATLAS also the J/ψ $\psi(2S)$ spectrum

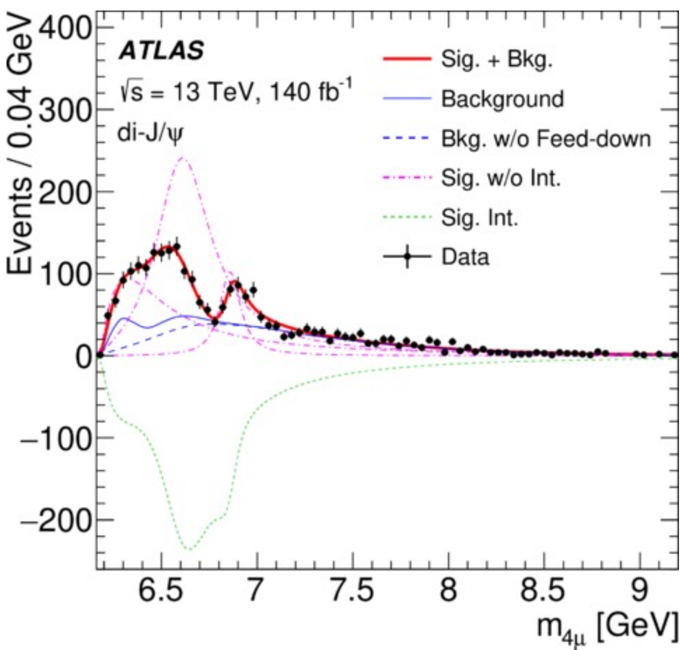
Observation of X(6900) confirmed by both experiments [ATLAS arXiv:2304.08962] [CMS arXiv:2306.07164]
- Parameters in agreement between the three experiments

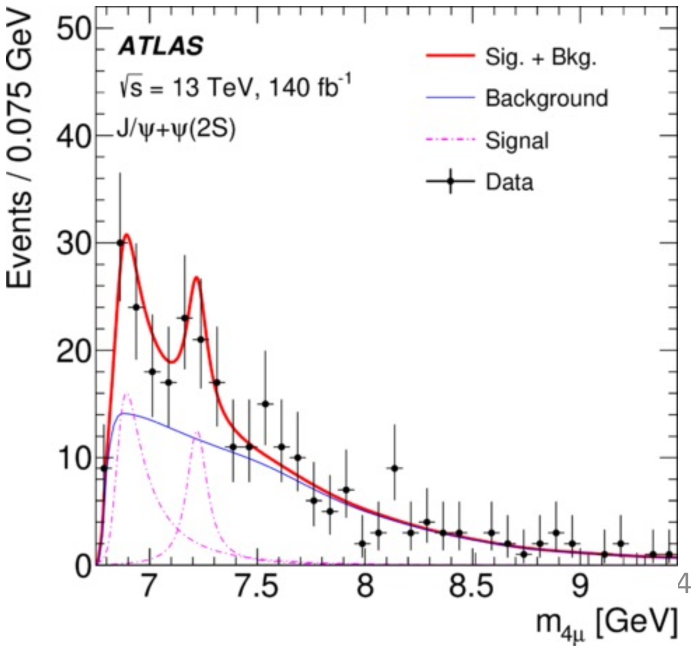
CMS also see structures at 6552 MeV (observation, 6.5σ) and 7287 MeV (evidence, 4.1σ)
- A model with three interfering signals significantly improves the fit quality (with mass and width shifted)

ATLAS also see a broad excess at low mass

Run3 data will allow more detailed studies of these structures

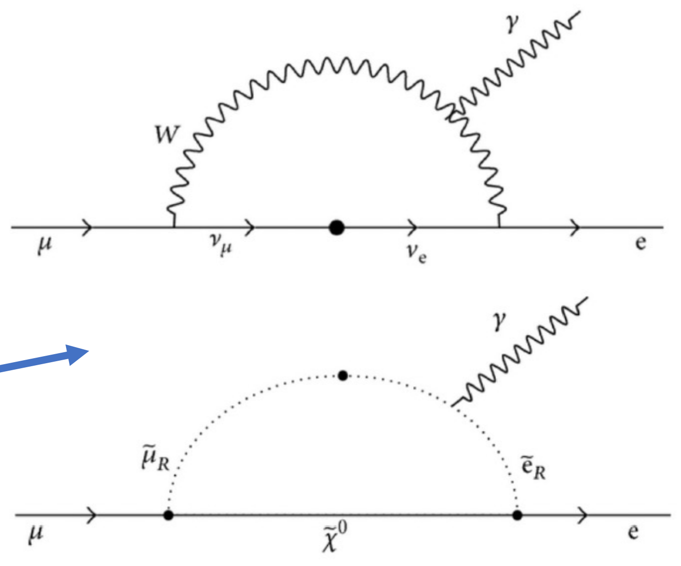






Lepton Flavour Universality and Violation

No observed transitions coupling charged leptons from different generations



Why??

- Weak force mixes quark of different generations
- Neutrino oscillations bring to LFV in neutral leptons in the Standard Model

LFV in SM rate far from current experimental sensitivity
but New Physics could enhance it in a significative way

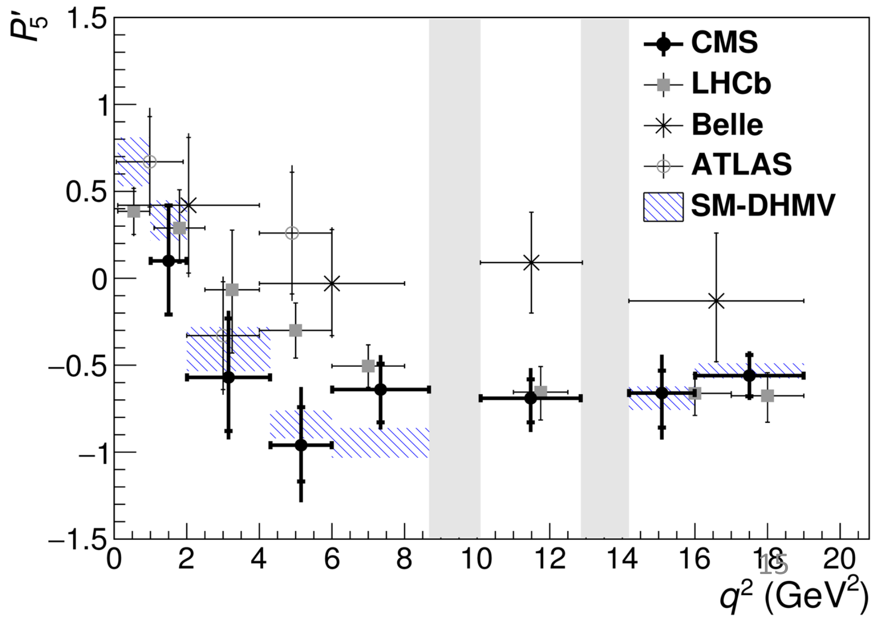
Many related searches at ATLAS and CMS:

- At high mass (Z', Leptoquarks…)
- In Z, Higgs and Top decays

Not covered here

- In tau decays → Next slide

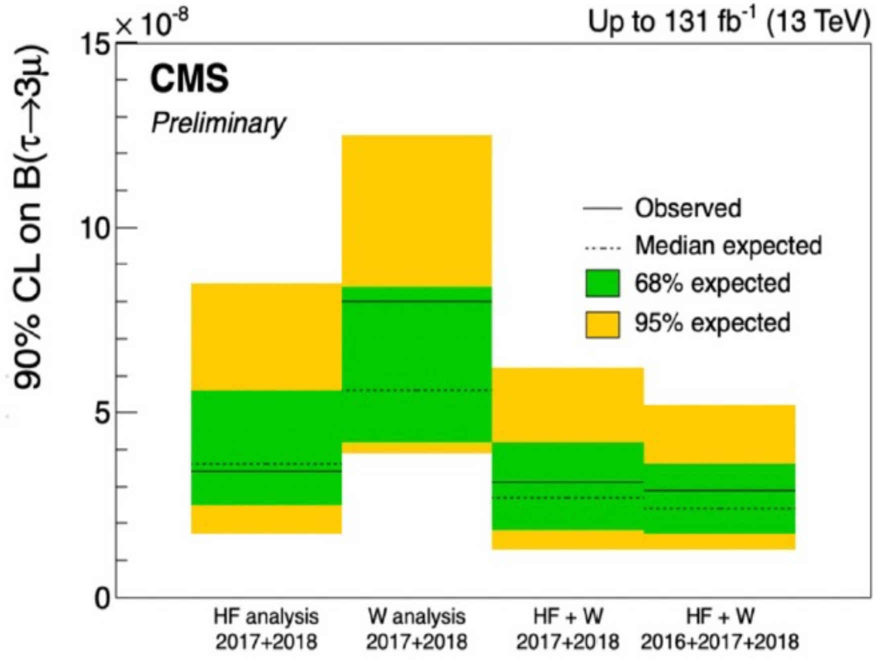
Interest in search for LFV and LFU also driven from flavour anomalies (*Not covered here*)



LFV in Tau decays ($\tau \rightarrow \mu\mu\mu$)

B-Factories exclusion limits @90%CL :
Belle, < 2.1 x 10^{-8} PLB 687 (2010) 139
Babar, < 3.3 x 10^{-8} PRD 81 (2010) 111101
Searches also performed at LHC by ATLAS, CMS and LHCb

New result released by CMS, adding 2017 and 2018 data (CMS PAS BPH-21-005)

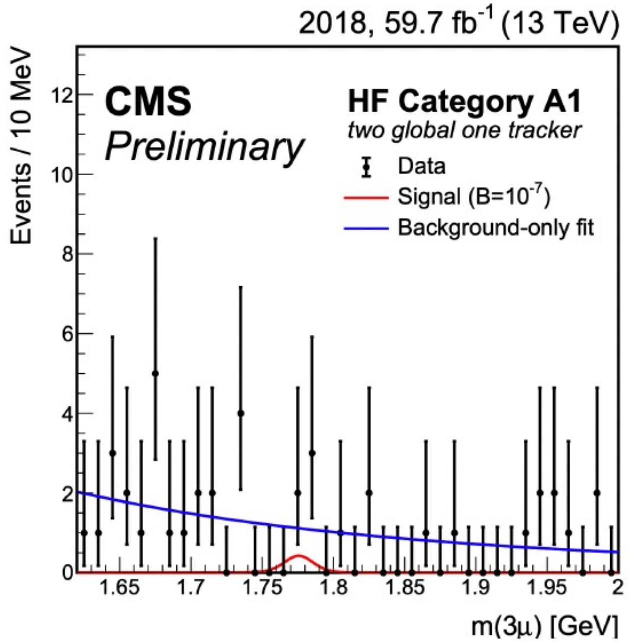


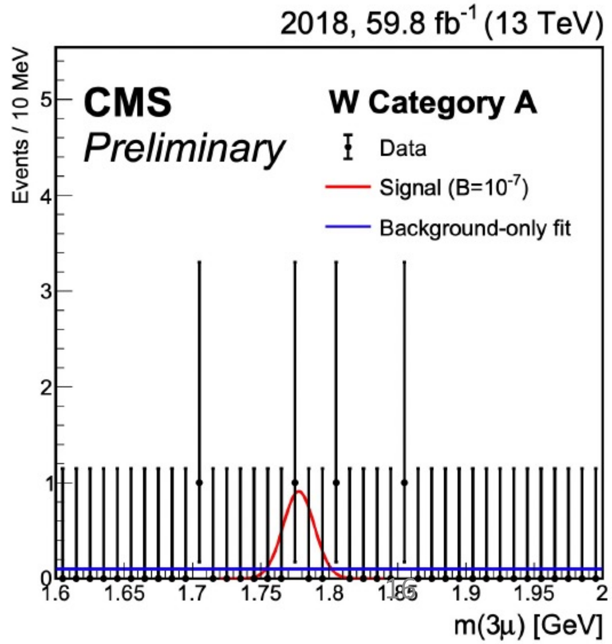
Include τ production from W decays and heavy flavor decays
=> complementarity

Signal and background separated exploiting BDT
Events categorized based on 3μ mass resolution

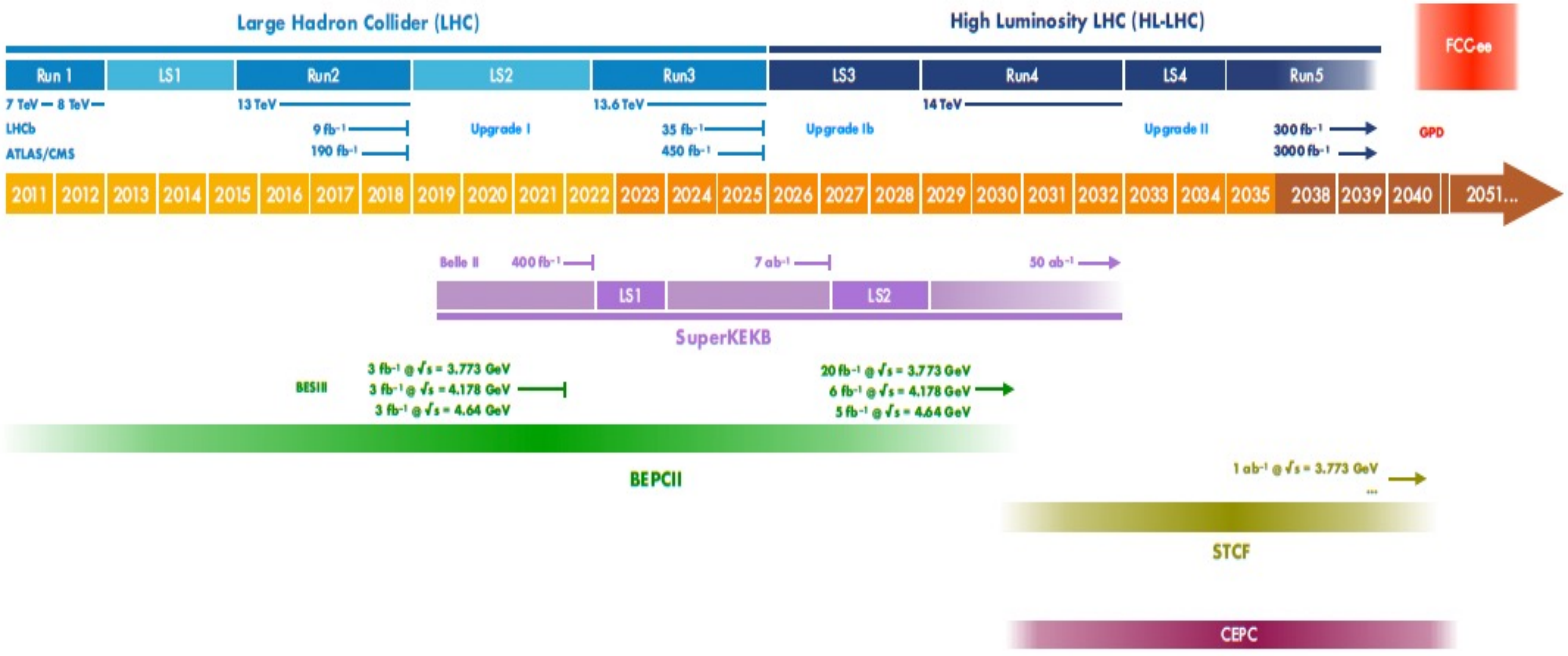
No signal observed, limit set:
B ($\tau \rightarrow \mu\mu\mu$) < 2.9 (2.4) x 10^{-8} obs (exp) @90% CL

Best LHC result
World's best still from Belle





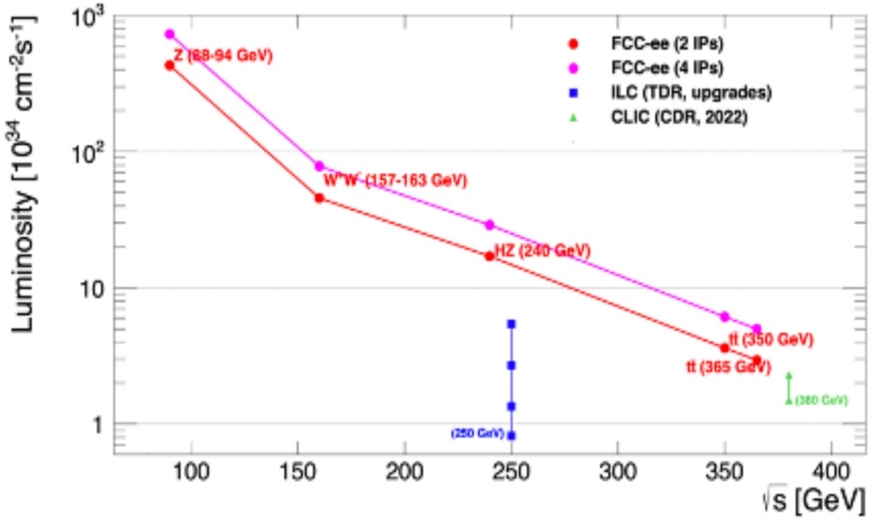
What's next?



F. Archilli, W. Altmannshofer
arXiv:2206.11331

FCC-ee

Slides largely inspired by Stephane Monteil's talk at FCC Week Jan.23
and Jernej F. Kamenik's talk at FCC Week Jun.23



FCC-ee will operate at Z, WW, HZ and tt energies
Flavour physics at all thresholds but the Z pole is the focus

FCC-ee expects to operate at Z-pole for 4 years:

- 10^5 Z/s and 50×10^{12} Z bosons in total
- clean environment: no pileup, controlled beam backgrounds

Boost at Z pole: $\langle E_{Xb} \rangle$ = 70% E_{beam}; $<\beta\gamma> \sim 6$

Z pole does not saturate all possibilities: e.g. WW operation will allow to collect several 10^8 W decays on shell and boosted
=> Direct access to |Vcb| and |Vcs|

High lumi is the crucial ingredient

@Z pole:
About 15 times the nominal Belle II anticipated
All species of b-hadrons produced
Expect ~4×10^9 Bc mesons

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

FCC-ee

Slides largely inspired by Stephane Monteil's talk at FCC Week Jan.23 and Jernej F. Kamenik's talk at FCC Week Jun.23

A complete flavour physics program:

Leptonic and semileptonic b decays

- Ultimate Vub precision possible with Bs $\rightarrow K l \nu$ and B$\rightarrow \pi l \nu$

Rare b-hadron decays

- E.g. to τs or neutrinos

CPV in b decays and mixing

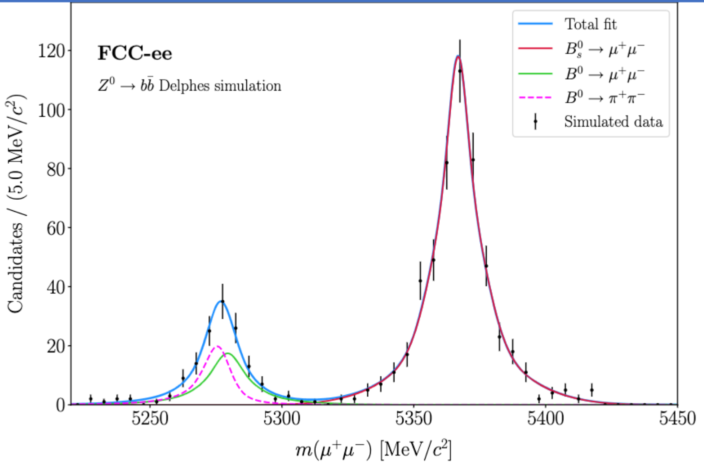
Tau physics

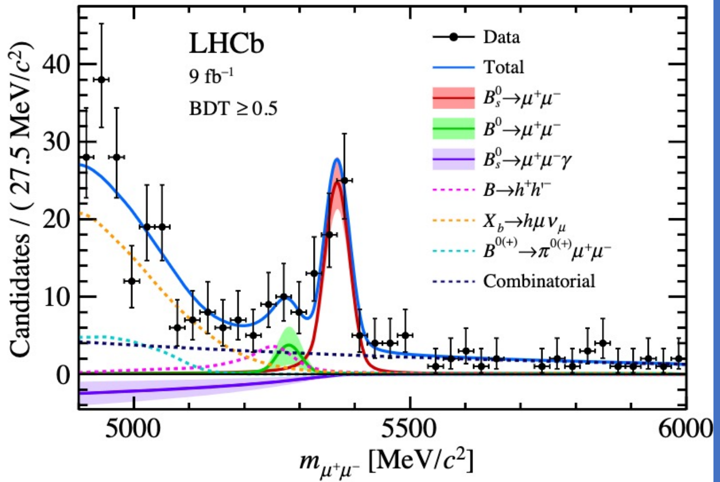
- Expect ultimate precision on LFU ratio $\Gamma(\tau \rightarrow e \nu \nu)/\Gamma(\tau \rightarrow \mu \nu \nu)$

Charm physics

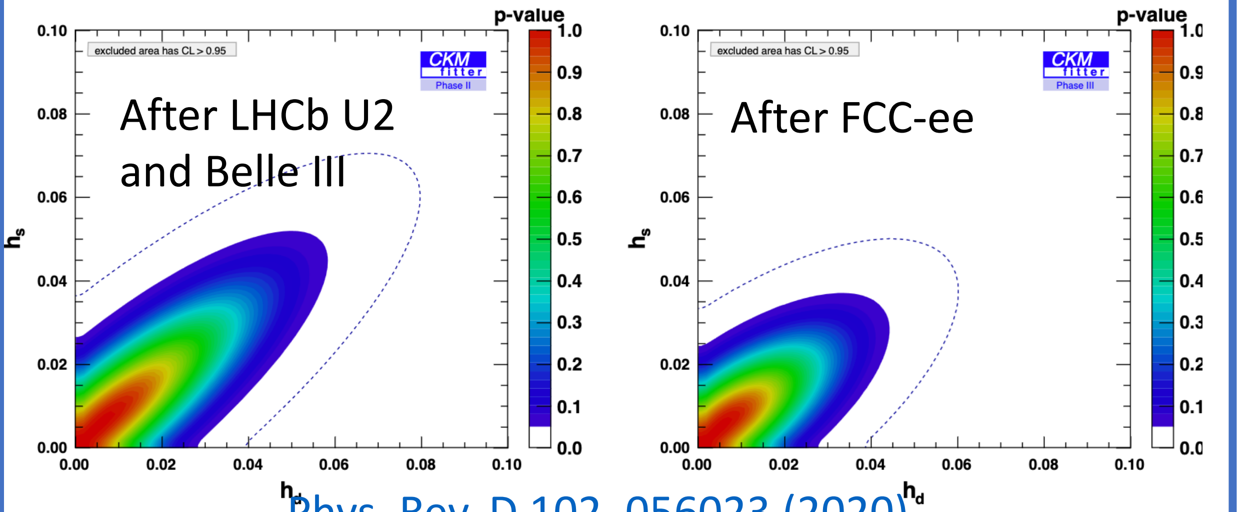
- CPV in radiative charm decays, rare D$\rightarrow [\pi, \rho]\nu\nu$ decays

Eur. Phys. J. Plus (2021) 136:837





Measurement of ultra-rare B$\rightarrow \mu\mu$ decay



Phys. Rev. D 102, 056023 (2020)

Program poses serious constraints on detector design and mainly vertexing, calorimetry and particle ID

Summary

The vast production of hadrons in the current era allows us to probe with extreme precision the extremely rare

Both ATLAS and CMS continues their Heavy Flavour programs:

- Analyses using Run2 data are being published
- New data are collected and analyzed in Run3

Despite not being dedicated experiments ATLAS and CMS also provide competitive results on many aspects

FCC-ee may give complementary contributions from the Z pole in the second part of this century

Thanks to its reach phenomenology, flavour physics allows precision measurements
which are a bridge to search for new physics. More to come!

For a complete view of ATLAS and CMS results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH/index.html

Backup

$B^0_s \to J/\psi\, \phi$ analysis strategy

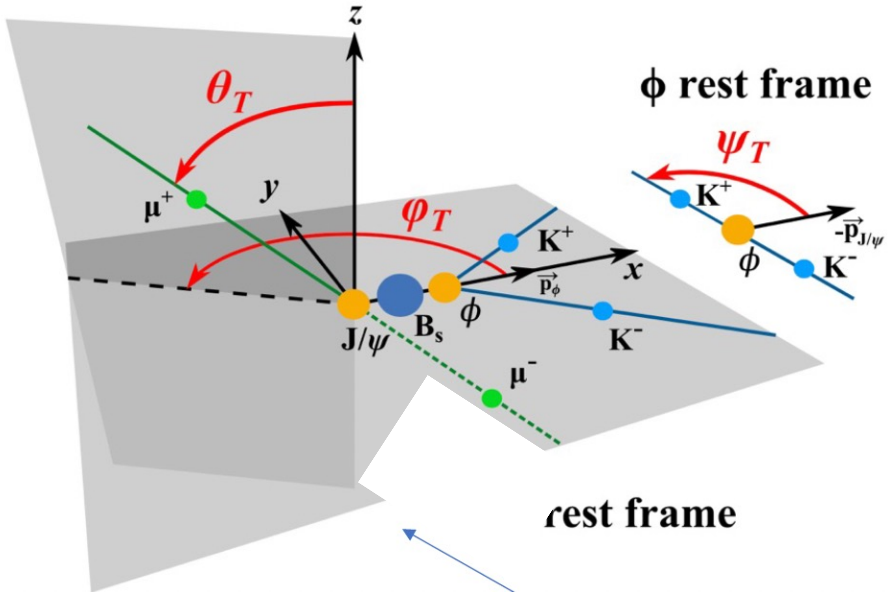
B^0_s decay into $J/\psi\, \phi$, which is a mixture of two CP eigenstates: odd/even

- Need to disentangle the two states using an angular analysis
- Time dependent analysis, proper decay time reconstructed

An unbinned maximum likelihood fit is performed extracting the parameters of interest.
Many observables measured simultaneously:

- Amplitude and strong phases: A_0, $A_\perp$, $A_\parallel$, A_S, δ_0, $\delta_\perp$, $\delta_\parallel$, δ_S, $(\delta_S - \delta_\perp)$
- CPV parameters: φ_S and $|\lambda|$
- Mixing parameters: $\Delta\Gamma_s$ and Δm_S
- B^0_s properties : $\Gamma_s = (\Gamma_H + \Gamma_L)/2$

CMS also measure Δm_S and $|\lambda|$, fixed to PDG and 1 for ATLAS



Observables used in the fit:

- m, proper decay time, angular observables
- per candidate quantities (resolution, flavour tagging probability)

$B^0_s \to J/\psi\ \phi$ tagger

Opposite-side taggers to identify the flavour of B^0_s and $\overline{B}{}^0_s$

CMS: muon tagger, using semi-leptonic decay $b \to \mu$ +X decays
ATLAS: muon, electron and b-jet taggers

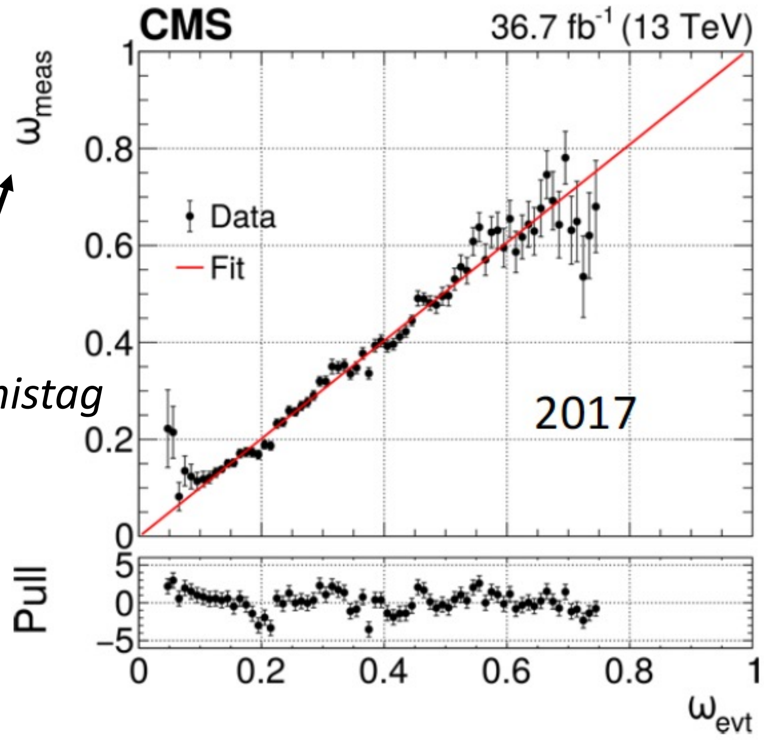
CMS: DNN, to reduce the mistag fraction
ATLAS: key variable Qx = charge of p_T-weighted tracks in a cone around the opposite side primary object (μ, e, b-jet)

Taggers Calibrated in data using $B^+ \to J/\psi\ K^+$

- Self-tagged events, charge of K determines flavour of B

Sources of dilution: cascade decays, pileup, gluon splitting, mixing

Per-event mistag probability



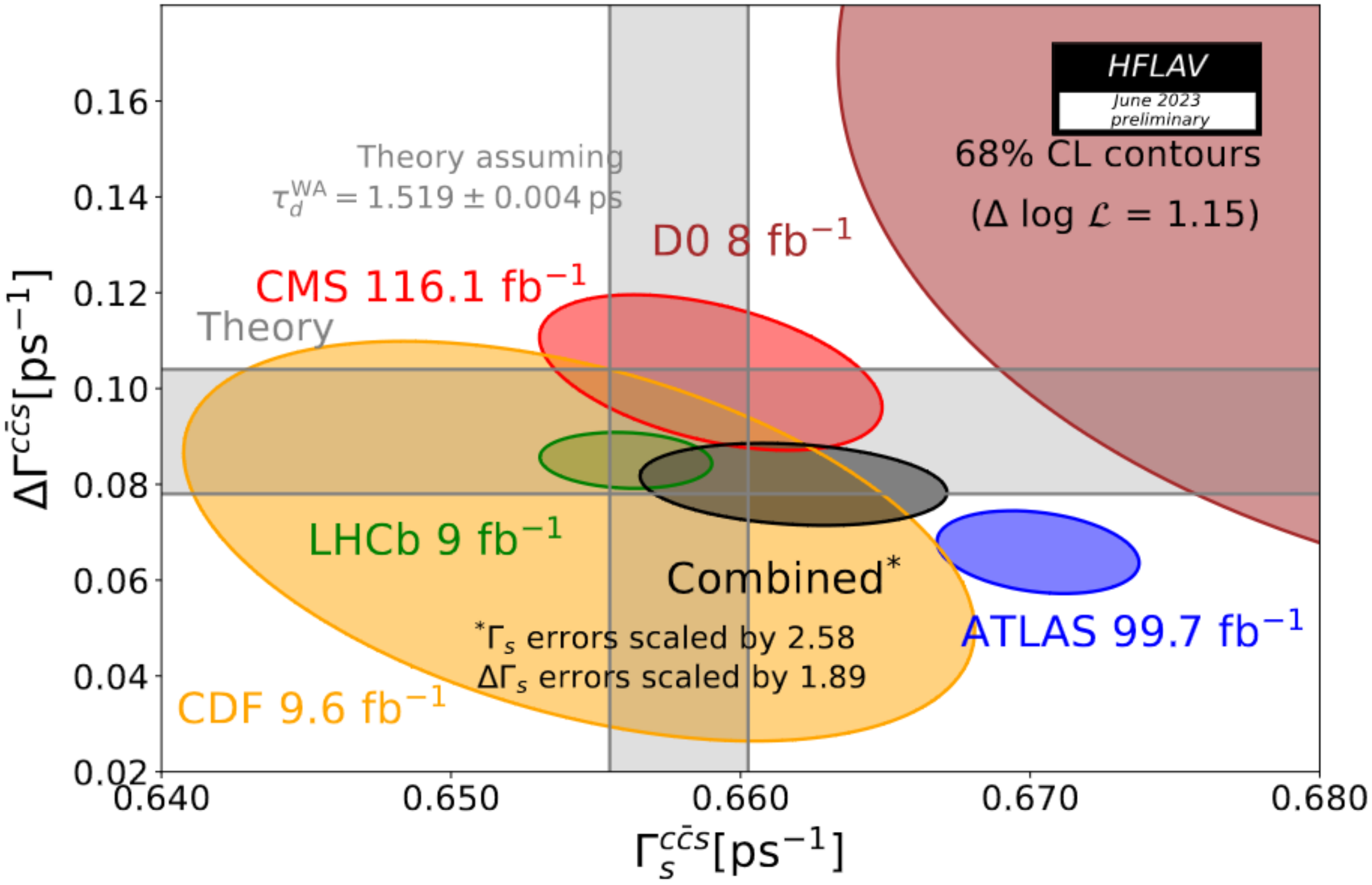
ATLAS

Tag method	ϵ_x (%)	D_x (%)	T_x (%)
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

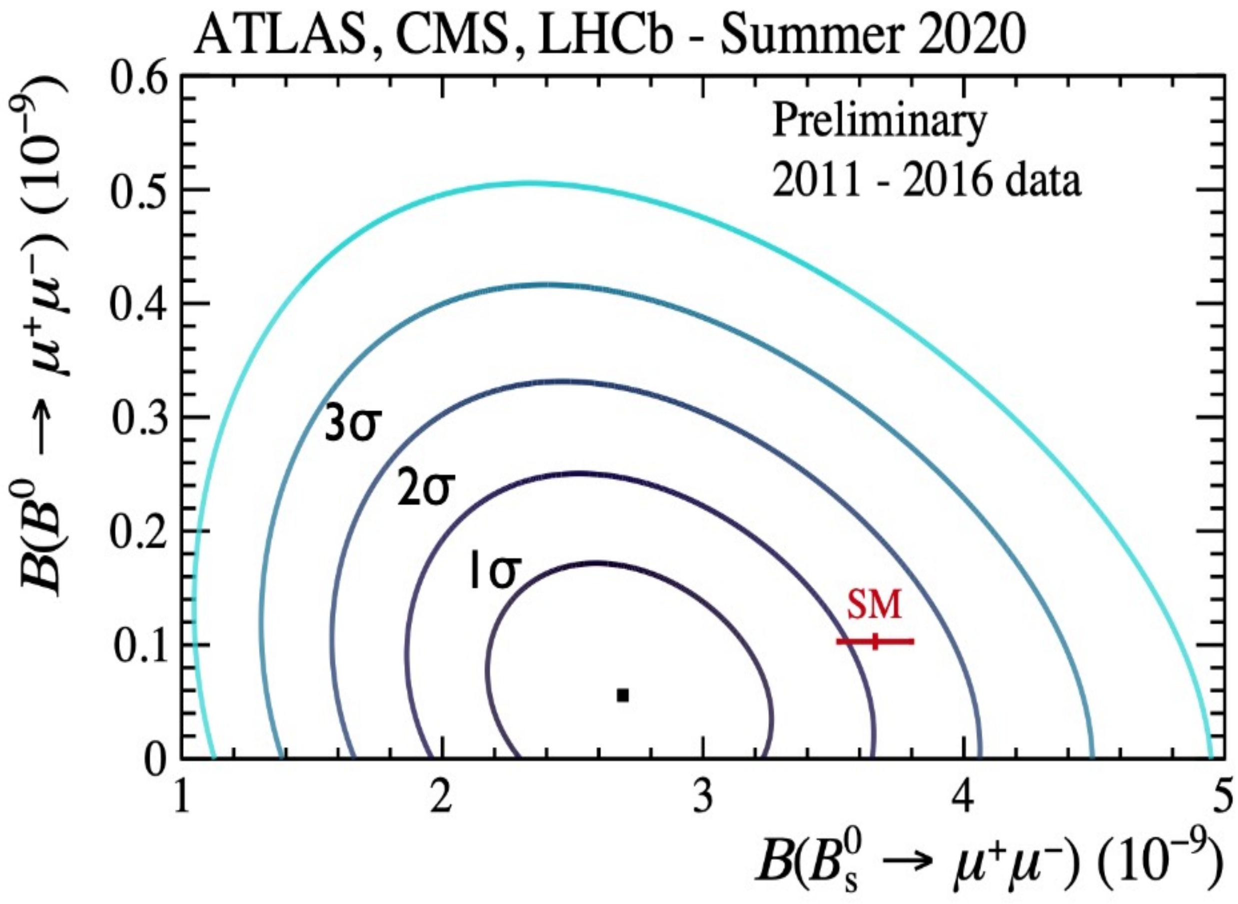
CMS

Data sample	ε_{tag} (%)	ω_{tag} (%)	P_{tag} (%)
2017	45.7 ± 0.1	27.1 ± 0.1	9.6 ± 0.1
2018	50.9 ± 0.1	27.3 ± 0.1	10.5 ± 0.1

B^0_s lifetime



Last ATLAS, CMS and LHCb $B^0_{(s)} \rightarrow \mu\mu$ combination



Data collected 2011-2016

Results compatible with SM wihin 2.1σ in the 2-dim plane

$B^0_{(s)} \rightarrow \mu\mu$ BR measurement

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \times \frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}} \times \frac{\epsilon_{B^+\to J/\psi K^+}}{\epsilon_{B_s^0\to\mu^+\mu^-}} \times \frac{f_u}{f_s}$$

$$or \left\{ = \mathcal{B}(B_s^0 \to J/\psi\phi) \times \frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B_s^0\to J/\psi\phi}} \times \frac{\epsilon_{B_s^0\to J/\psi\phi}}{\epsilon_{B_s^0\to\mu^+\mu^-}} \right\}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \times \frac{N_{B^0\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}} \times \frac{\epsilon_{B^+\to J/\psi K^+}}{\epsilon_{B^0\to\mu^+\mu^-}} \times \frac{f_u}{f_d}$$

Normalized to $B^+ \rightarrow J/\psi\ K^+$ and $B_s \rightarrow J/\psi\ \phi$ (cross-check)

Main backgrounds:

- 3-body and partial decays (muons from the same B)
- Combinatorial background (muons from different Bs)
- Fakes from B→ hh
  - Mainly from B→ Kπ and Bs → KK, with K and π decays-in-flight to muon and neutrino

$B^0_{(s)} \rightarrow \mu\mu$ BR measurement

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0_s\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}} \frac{\varepsilon_{B^+\to J/\psi K^+}}{\varepsilon_{B^0_s\to\mu^+\mu^-}} \frac{f_u}{f_s},$$

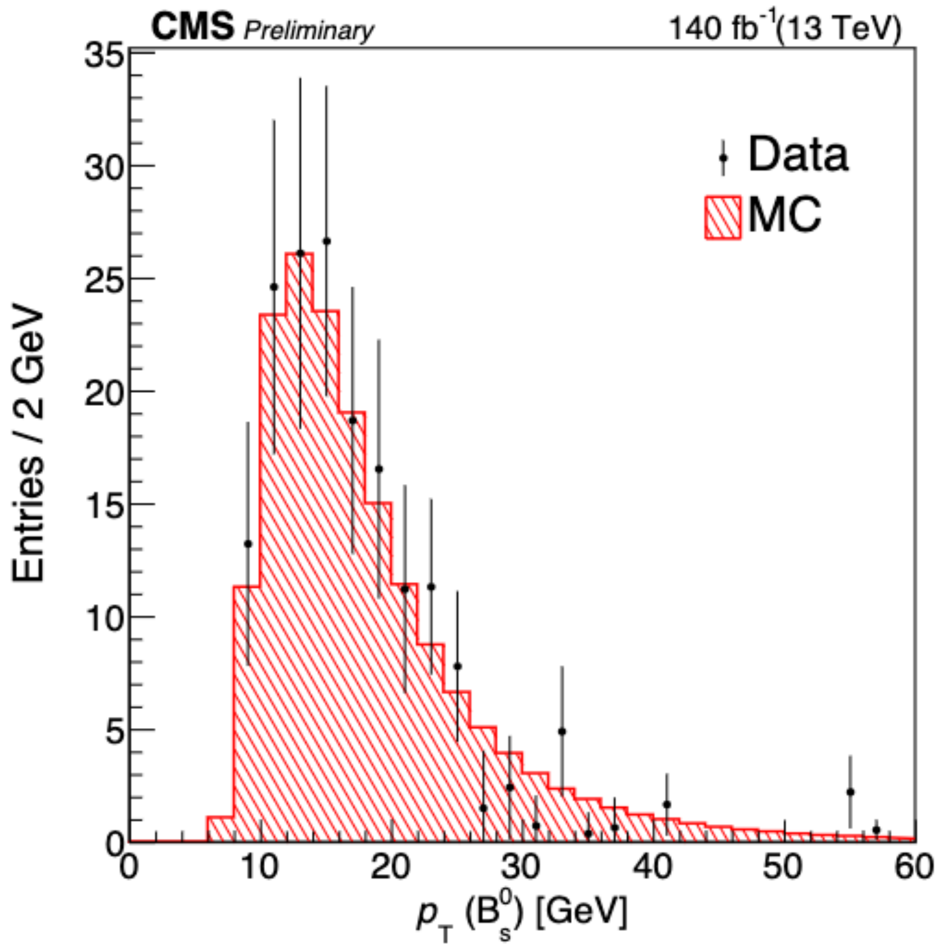
CMS measurement uses fs/fu = 0.231 $\pm$ 0.008

Based on LHCb p_T-dependent result
PRD 104 (2021) 032005

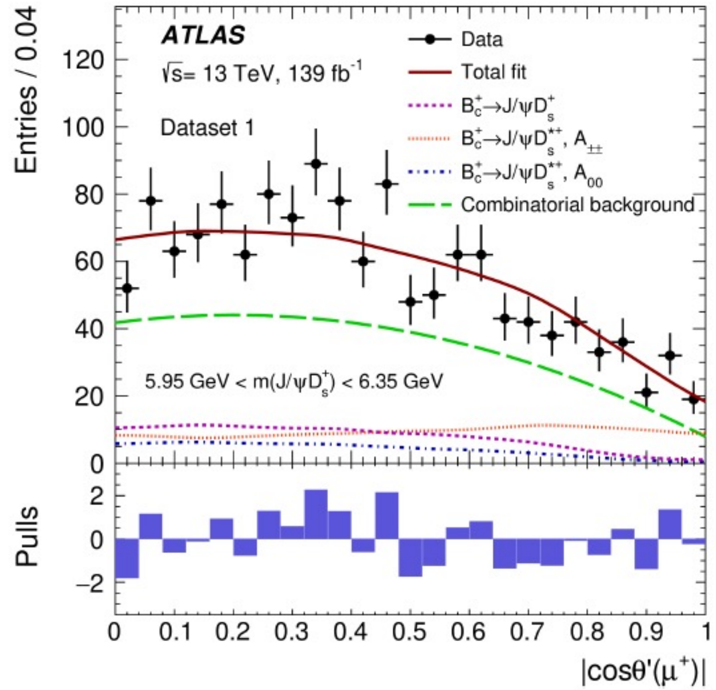
- Integrated with effective p_T distribution

Previous CMS result used fs/fu = 0.252 $\pm$ 0.032

Treated as an external uncertainty,
not constrained nuisance parameter



$B^+_c \to J/\psi\, D^+_s$ and $B^+_c \to J/\psi\, D^{*+}_s$



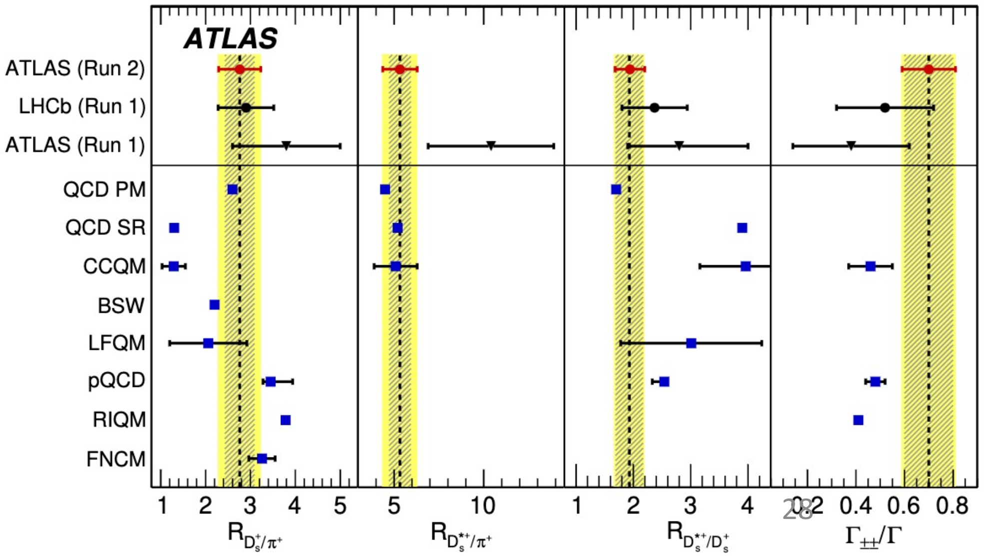
High precision BR and final state polarization measurement

Previous results: ATLAS and LHCb Run1

D^+_s and D^{+*}_s reconstructed from their decays
$D^+_s \to \varphi(KK)$ and $D^{*+}_s \to D^+_s\, \pi^0 /\gamma$ with partial reconstruction

$B^+_C \to J/\psi\, \pi^+$ as reference channel

2D fit to m(J/ψ D^+_s), $|\cos\vartheta'(\mu^+)|$ = helicity angle between D^+_s and μ^+ in the J/ψ rest frame



QCD PM (arXiv:hep-ph/9909423) agrees very well while others deviate in some cases or lack precision

$J/\psi\ J/\psi$ [CMS]

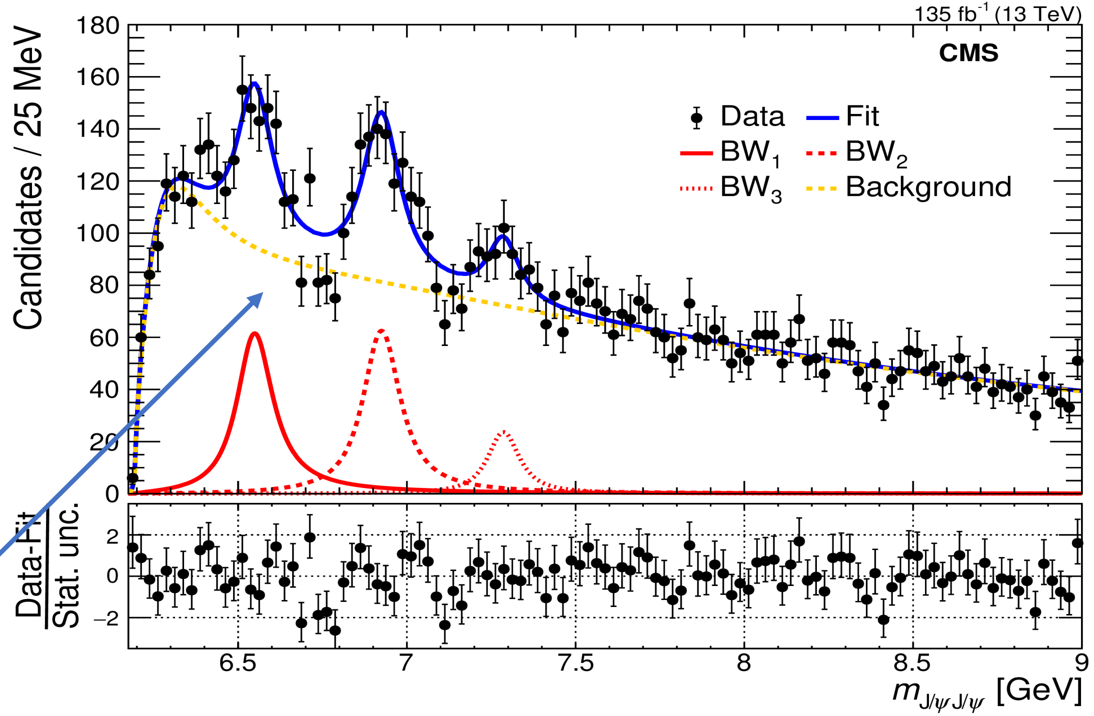
- NRSPS and NRDPS backgrounds components: MC-driven shapes $\chi^{\alpha}\exp\left(-\frac{\chi^{\beta}}{\gamma}\right) * Pol_2(\chi)$ where χ=$m_{J/\psi J/\psi}$
- Threshold enhancement: ad-hoc Breit Wigner
- Signals: Relativistic Breit-Wigner functions

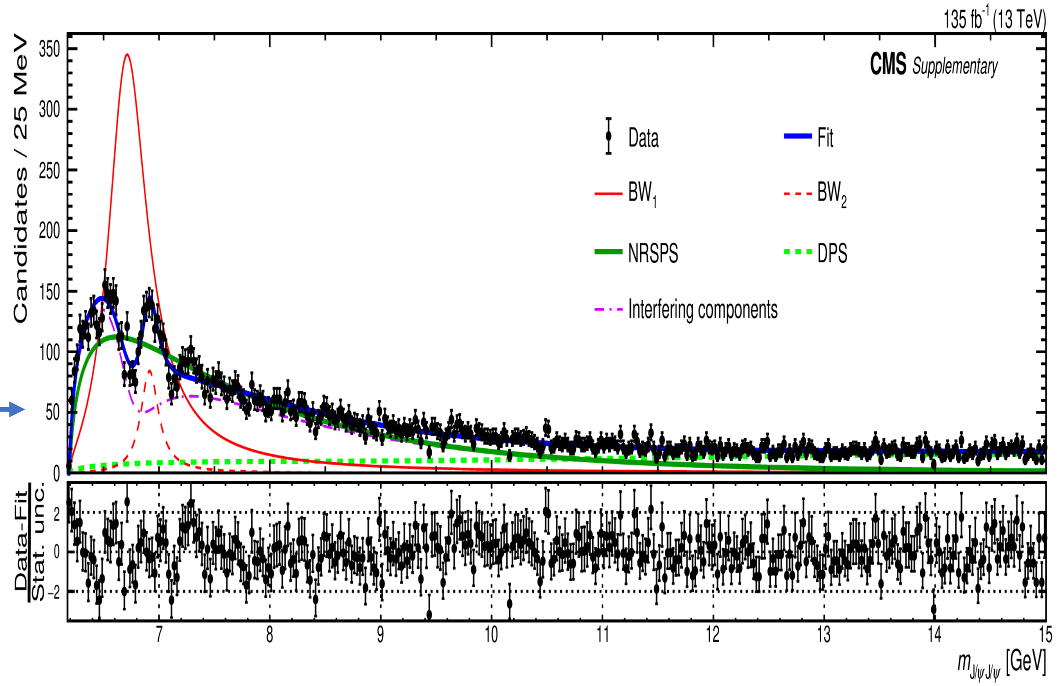
To better constrain SPS and DPS backgrounds the fit is up to 15 GeV

Main sistematic uncertainties:

- Signal and background shapes
- Including feed-downs X→ $[c\bar{c}]_1\ [c\bar{c}]_2 \rightarrow J/\psi J/\psi$

- Dips between peaks not well described
- LHCb interference model does not provide a good description of CMS data



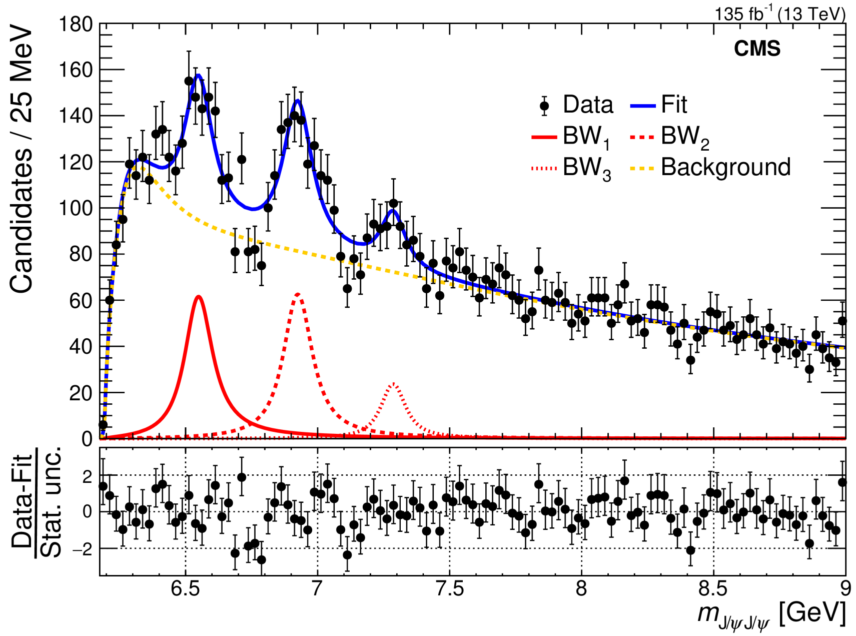


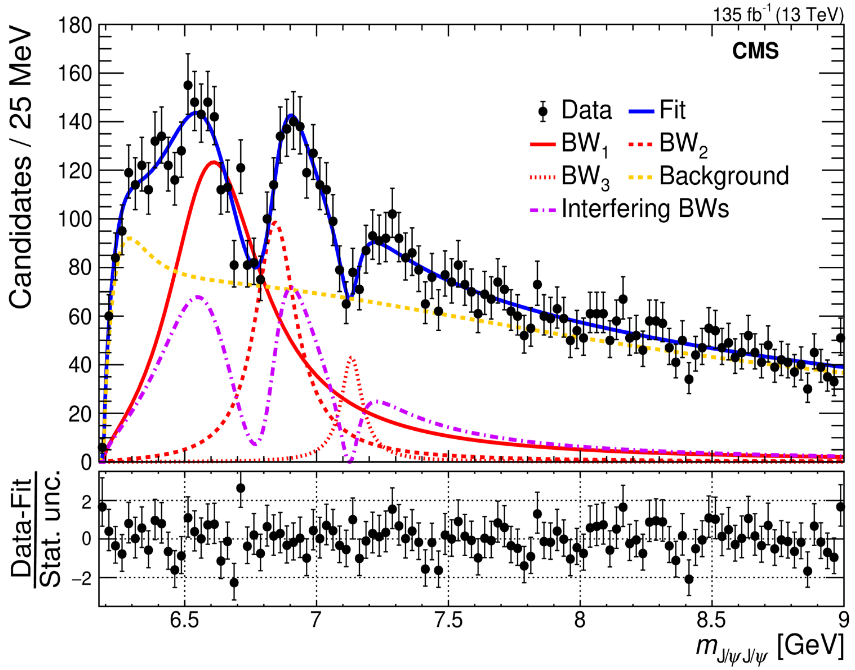
$J/\psi\ J/\psi$ [CMS]

Model with three interfering signals improves the quality of the fits

Masses and widths shifted wrt non-interference fit

		BW_1	BW_2	BW_3
No-interference	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}





$J/\psi\ J/\psi$ [ATLAS]

- Backgrounds estimated with a mixture of MC and corrections from data

- Two prompt charmonia:
  - Single parton scattering
  - Double parton scattering
- Two non prompt charmonia:
  - $b\bar{b} \rightarrow J/\psi\ J/\psi$
- ‘Others’:
  - prompt single charmonium production and non-resonant di-muon production
  - At least one charmonium candidate containing random combination of fake muons

Data control regions.
Reweighting between data and MC in $J/\psi\ J/\psi$ pT, $\Delta\varphi, \Delta\eta$, and others

J/ψ J/ψ [ATLAS]

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
J/ψ+$\psi(2S)$	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

- Significant excess of events (>5σ) in the J/ψ J/ψ channel
- A resonance around 6.9 GeV and a broad structure at lower mass are observed
- Models accounting for interference describe the data better and models without

- In the J/ψ $\psi(2S)$ channel a 4.7σ excess of events is observed when considering a model with two resonances, one of which near 6.9 GeV

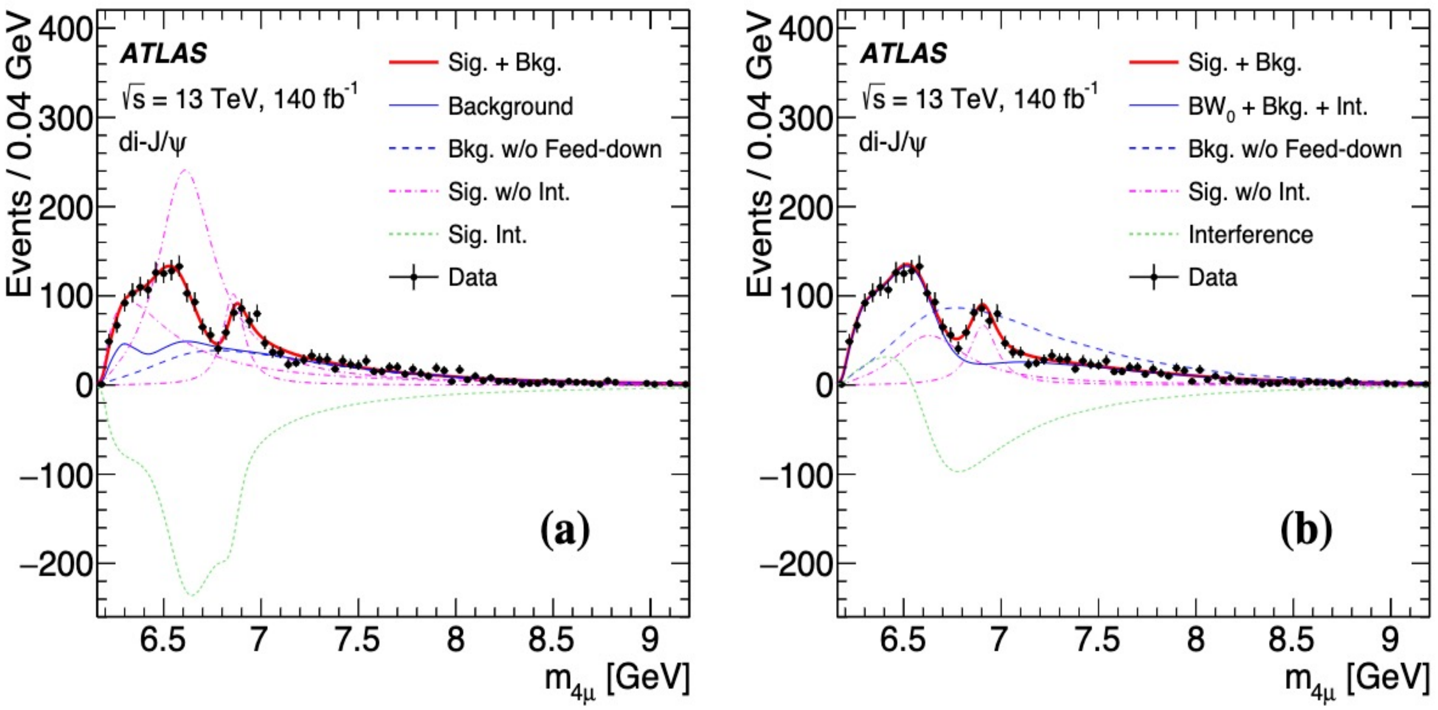
$J/\psi\ J/\psi$ [ATLAS]

Model a):
Three interfering S-wave Breit-Wigner resonances

Model b):
Two resonances, one interfering with
the SPS background and the second one standalone

Also tested:
- 2 resonances model with interference
- 3 resonances model without interference

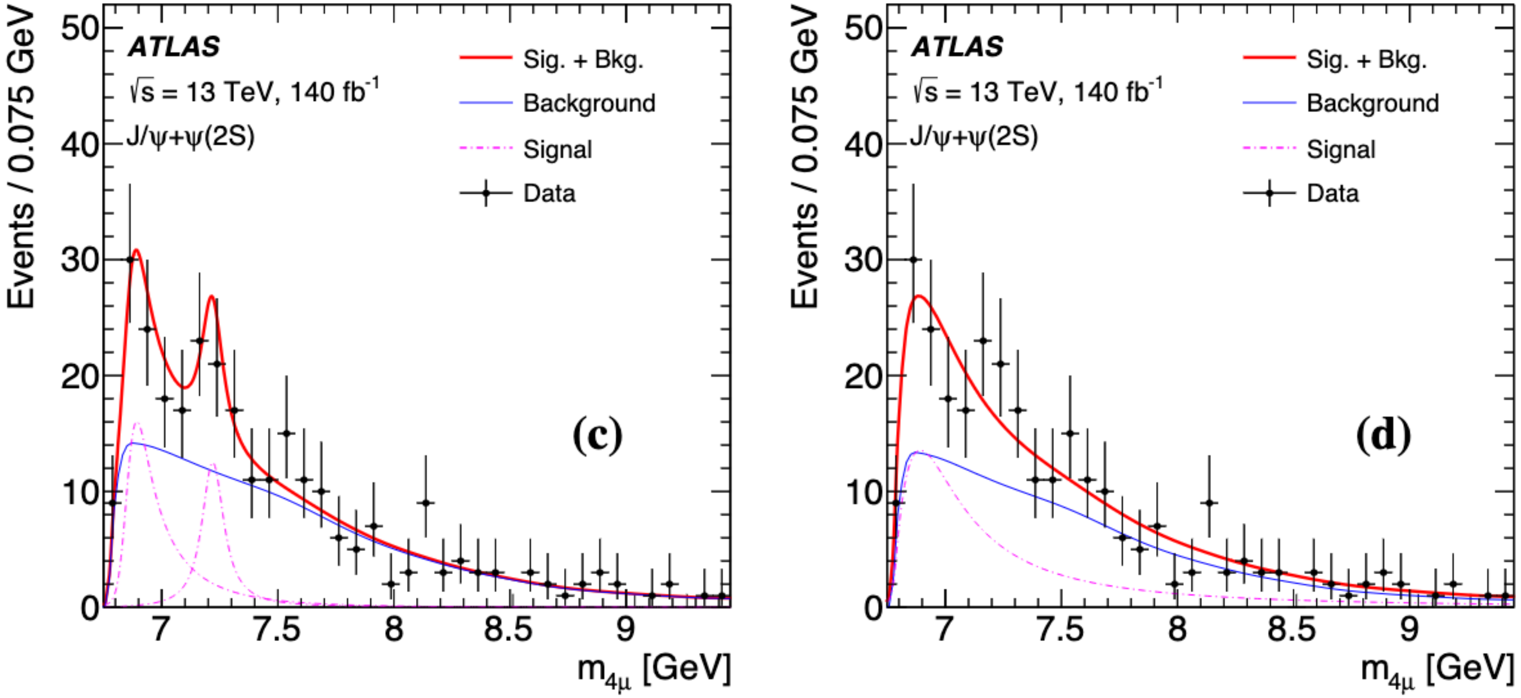
$\Rightarrow$ Excluded with >95%CL based on toy MC
when compared with Model a)



$J/\psi\ \psi(2S)$ [ATLAS]

Model c):
The same interfering resonances observed in $J/\psi\ J/\psi$ also decay into $J/\psi\ \psi(2s)$, in addition to a standalone 4th resonance in this channel

Model d):
A single resonance in this channel



$\tau \to \mu\mu\mu$ HF analysis

Large cross-section; low p_T and large background

Signal:

- Ds → τ + nu (including prompt Ds and B → Ds)
- B^+ or B^0 → τ + X

Normalization channel for Ds → τ events: Ds→φ(2μ)π
(event selections as close as possible to those for the signal channel)

Non-Ds contributions

- B→τ (~25% of the total): based on MC, but verified by comparing decay length of B → Ds in data and MC
- Very small contributions from Bs and D^+ based on MC and 100% uncertainty

Main backgrounds:

- Two real muons + 1 fake. Most common: B → D cascade decay
- 3 genuine muons, two of which from resonances

High level trigger:

- Three reconstructed tracks, two of which must be identified as muons with p_T > 3 GeV; the 3rd one p_T > 1.2 GeV
- Fitted to a displaced common vertex
- Invariant mass in 1.60-2.02 GeV

Collects events of τ→3μ signal and Ds→ϕ(2μ)π normalization channel at the same time with the same trigger

$\tau \to \mu\mu\mu$ W analysis

Relatively small cross-section; isolated and at higher p_T muons, large MET; low background

Signal: W-> l nu signature, where l = muon triplet

High level trigger:

- Three muons with p_T > 7, 1, 1 GeV respectively, and >15 GeV in total

Strategy:

- Loose pre-selection
- BDT to reduce background
- Event categorization and m(3μ) fit

$\tau \rightarrow \mu\mu\mu$ results

HF: B ($\tau \rightarrow \mu\mu\mu$) < 3.4 (3.6) x 10^{-8} obs (exp) @90% CL

W: B ($\tau \rightarrow \mu\mu\mu$) < 8.0 (5.6) x 10^{-8} obs (exp) @90% CL

HF and W analysis combined with the previously published 2016 CMS result
Result still dominated by statistical uncertainty

Comb: B ($\tau \rightarrow \mu\mu\mu$) < 2.9 (2.4) x 10^{-8} obs (exp) @90% CL