

# Heavy Flavour physics at ATLAS and CMS

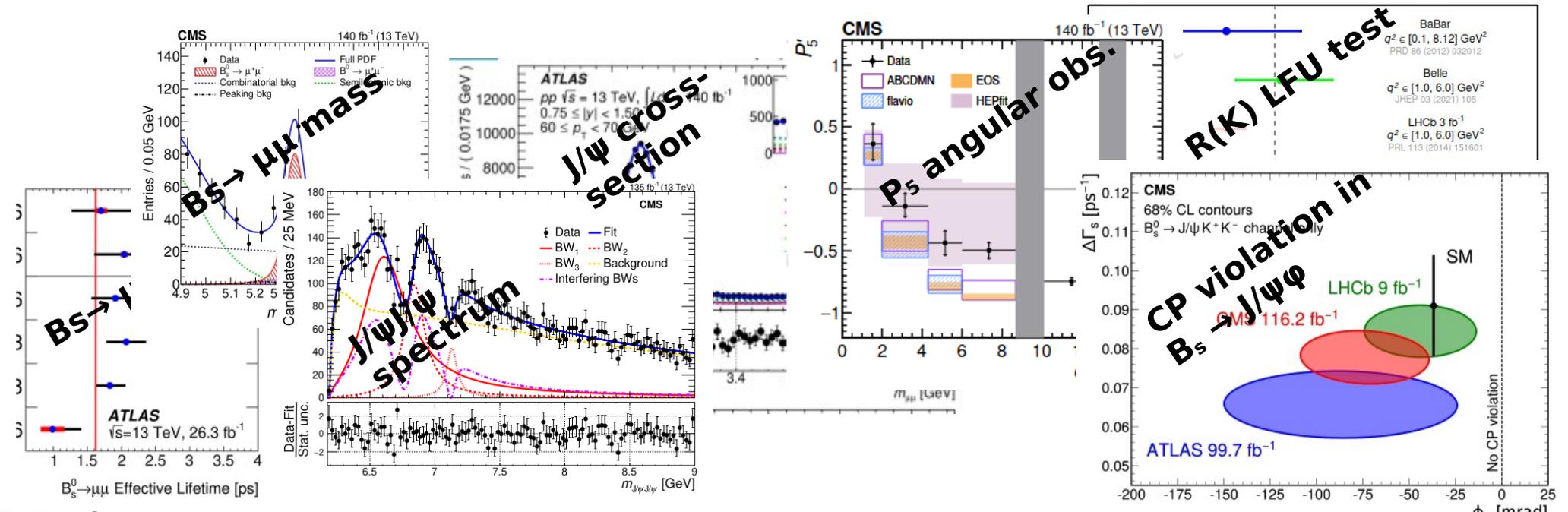
**G. Karathanasis (CERN) on behalf of the ATLAS and CMS collaborations**

**25/04/2025**

# Overview



- Absence of New Physics (NP) in direct searches → indirect searches more appealing → **Significant contribution by ATLAS and CMS in heavy flavour (HF) measurements**
- HF observables sensitive to NP even beyond to what LHC can directly produce
- Thus far: ATLAS and CMS plethora of vibrant results in a complementary program to dedicated experiments



- Absence of New Physics (NP) in direct searches → indirect searches more appealing → **Significant contribution by ATLAS and CMS in heavy flavour (HF) measurements**
- HF observables sensitive to NP even beyond to what LHC can directly produce
  
- Focus today: **Summary of the most recent HF analyses**

## Production measurements

[Differential cross-section measurements of D/Ds using  \$\phi\(\mu\mu\)\pi\$  decay \[ATLAS, Run 2\]](#)

[Cross-section of associated production Y\(1S\) meson Z boson \[CMS, Run2, New for winter conferences\]](#)

[B meson production fractions using open-charm and charmonium decays \[CMS, Run2, \*\*New for Moriond\*\*\]](#)

## Properties & Branching fractions

[B meson lifetime measurement using  \$B^0 \rightarrow J/\psi K^{\*0}\$  decays \[ATLAS, 2015+Run2\]](#)

[Search for  \$D \rightarrow \mu\mu\$  decays \[CMS, Run3\]](#)

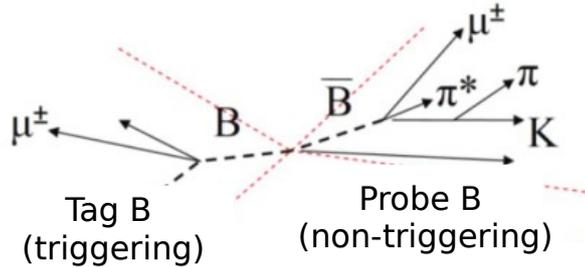
[Measurement of  \$BF\(B\_c \rightarrow J/\psi \tau \nu\) / BF\(B\_c \rightarrow J/\psi \mu \nu\)\$  ratio in three-prong  \$\tau\$  decays \[CMS, Run2\]](#)

# Production measurements

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# B meson production fractions [New]

- Goal: Production fractions ratios (PFR)  $f_u/f_s$ ,  $f_d/f_s$  and  $f_u/f_d$  in open-charm and charmonium decays
- Motivation: PFR source of systematic uncertainty (e.g  $B_s \rightarrow \mu\mu$ )  $\rightarrow$  need to be measured in precision
- Final states: Open-charm (like  $B_s^0 \rightarrow \pi^+ D_s^-$ ), Charmonium (like  $B_s^0 \rightarrow J/\psi\phi$ )



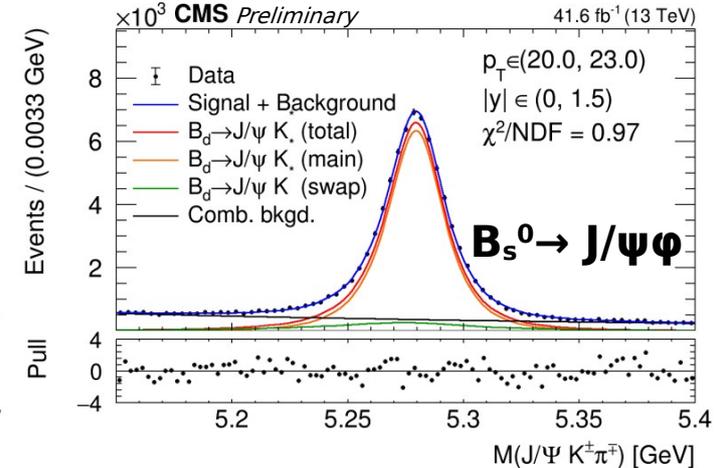
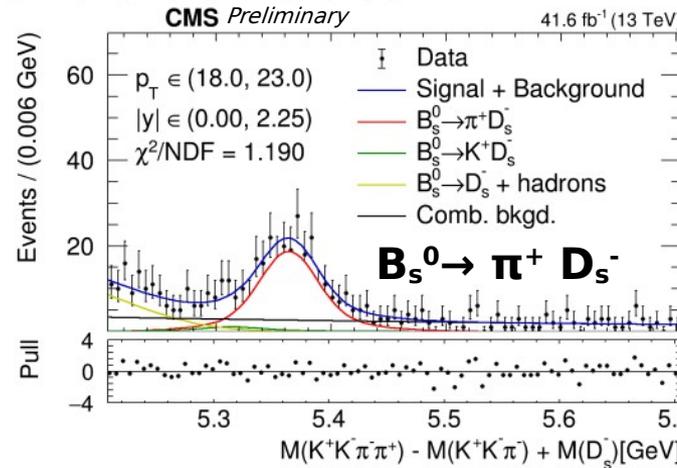
Dataset: High intensity single-muon, (2018)

Strategy:

- **PFR in open-charm in probe B**
- **Relative PFR,  $\mathcal{R}_s^{(d)}$  in charmonium both tag/probe**
- **Normalize  $\mathcal{R}_s^{(d)}$  to open-charm PFR**

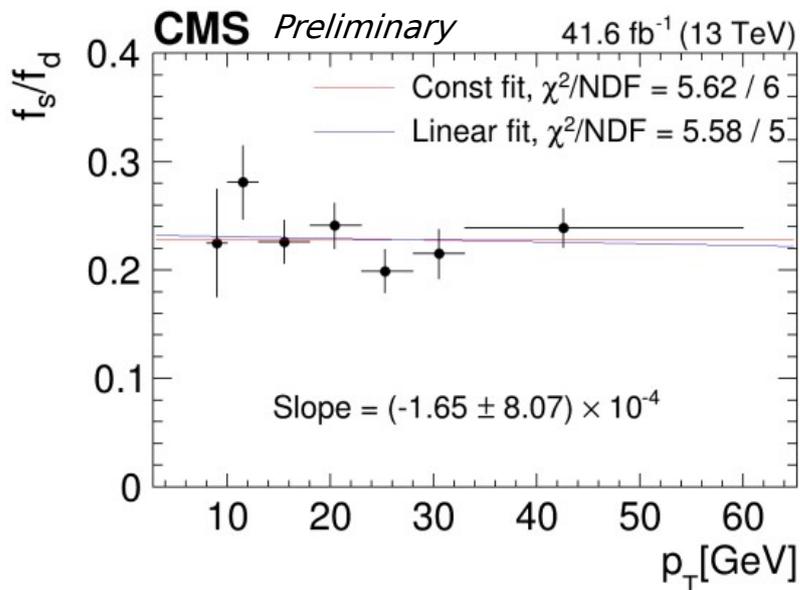
For open-charm (charmonium)

- Build D ( $J/\psi$ ) from tracks (muons)  $\rightarrow$  build B
- BDT (orthogonal cuts) selection
- Divided in 7 (13) bins in  $p_T$  and 5 (6) bins in  $y$



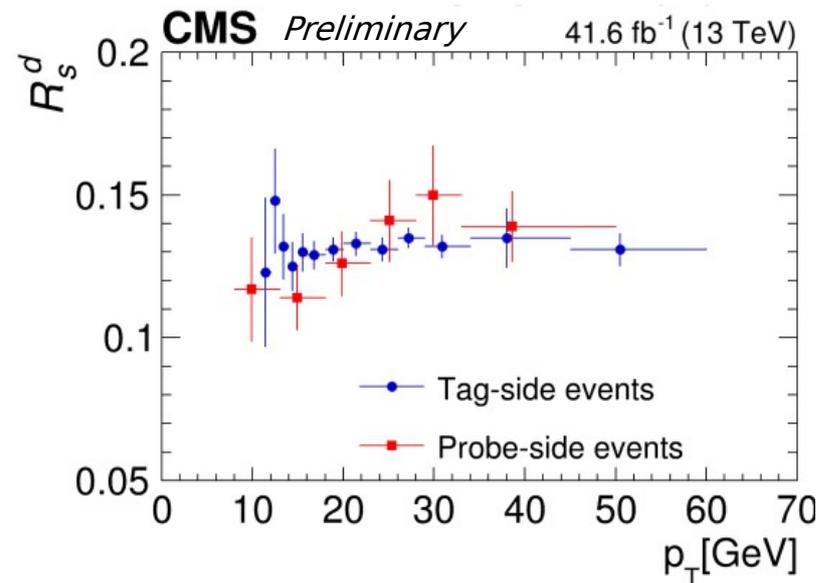
## $f_s/f_d$ and $f_s/f_u$

- First measurement of PFR in CMS using fully-hadronic states
- Utilizing theoretical inputs



## $\mathcal{R}_s$ and $\mathcal{R}_s^d$

- Both in probe and tag B
- Measure  $p_T$  dependence with high stats

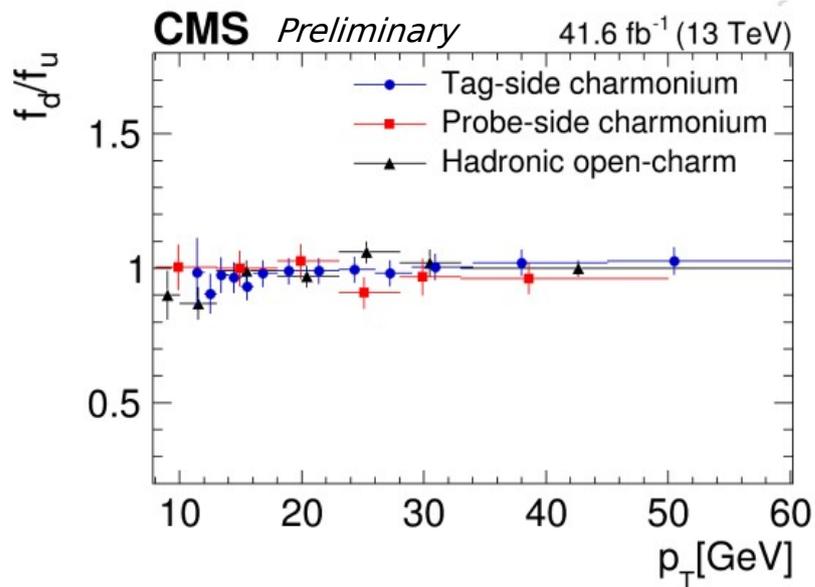


**Clearly, results do not show  $p_T$  dependence in high  $p_T$  region**

# B meson production fractions [New]

## Measurement of $f_d/f_u$

- Correct BF for isospin invariance
- Perform fit on both open-charm and charmonium

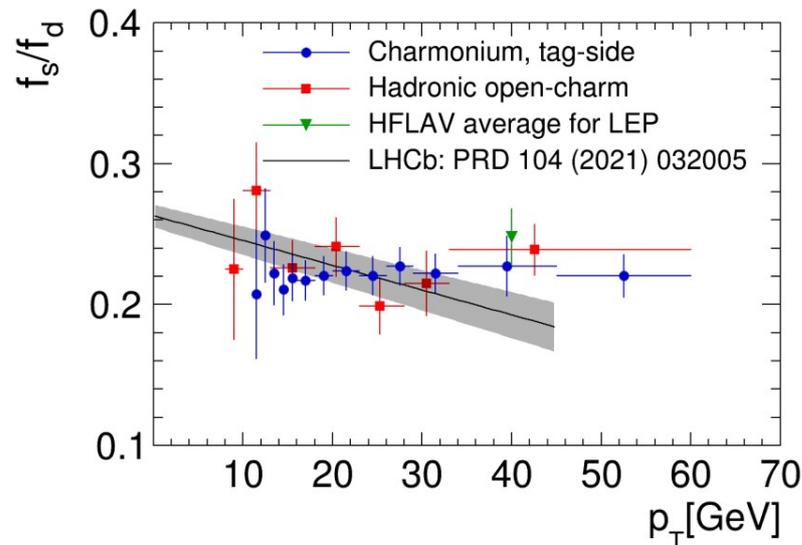


Combined result:  $f_d/f_u = 0.98 \pm 0.05$

## Measurement of PFR from $\mathcal{R}_s \mathcal{R}_s^d$

- Derived in probe side
- Absolute normalizations calculated with:

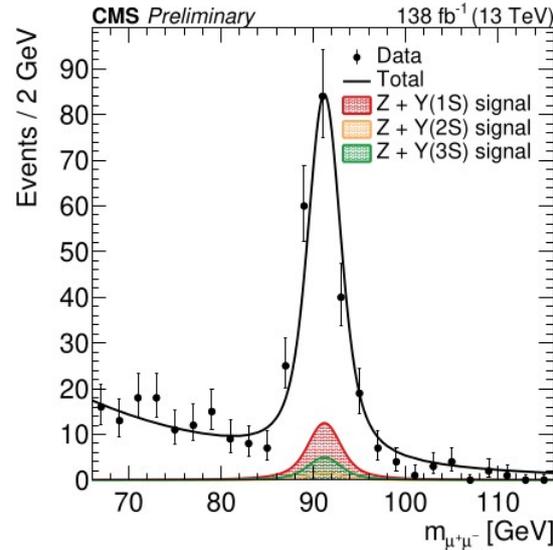
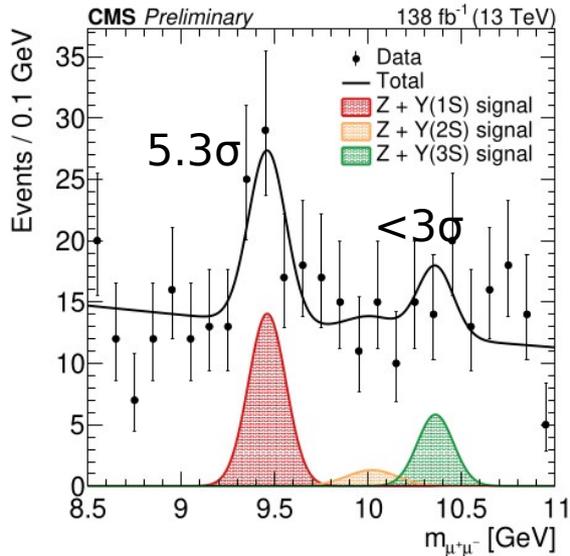
$$-- C_{sd(su)} = f_s/f_{d(u)}(\text{open-charm}) / \mathcal{R}_s^{(d)}$$



- Compatible with low  $p_T$  dependence
- In tension with the assumed linear trend
- $f_s/f_d = 0.223 \pm 0.015$
- $f_s/f_u = 0.233 \pm 0.018$

# Z+Y(1S) associated production [New]

- Motivation: Z+Y dominated by DPS → Tool to understand the structure of proton
- Final state: 4 muons divided in signal (Z+Y → 4μ) and normalization (Z → 4μ)



Dataset: 2 or 3 muon trigger, Run2

Strategy:

- 1) 4 isolated and prompt muons; Z+Y → 4μ or Z → 4μ channels
- 2) 2D fit on mass of Y and Z measure fiducial cross-section ratio
- 3) 2D fit on sPlot weighted  $\Delta y$  and  $\Delta\phi$  to extract DPS fraction

Fiducial cross section ratio

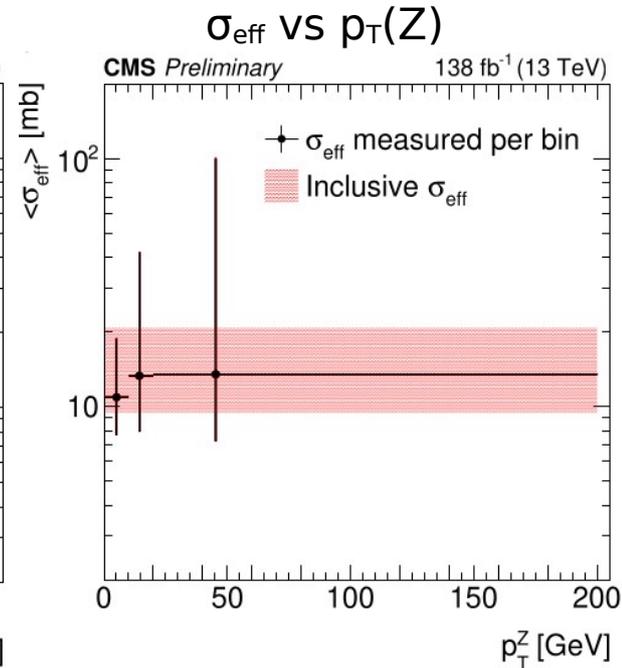
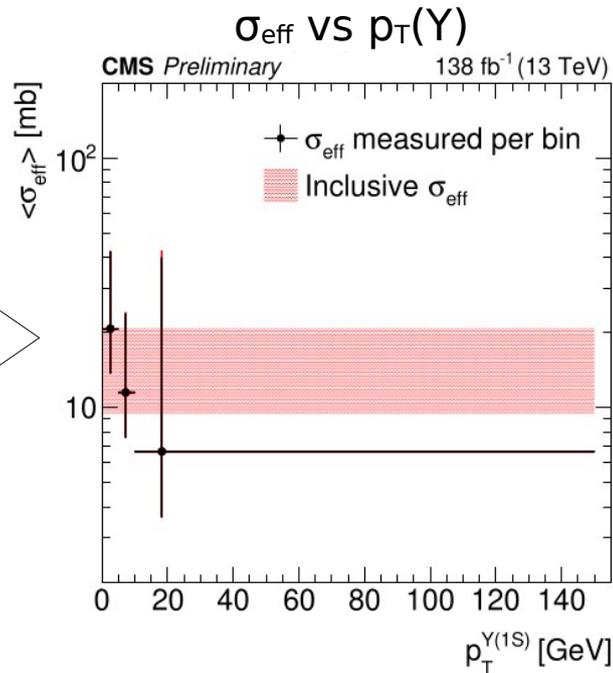
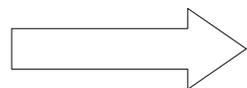
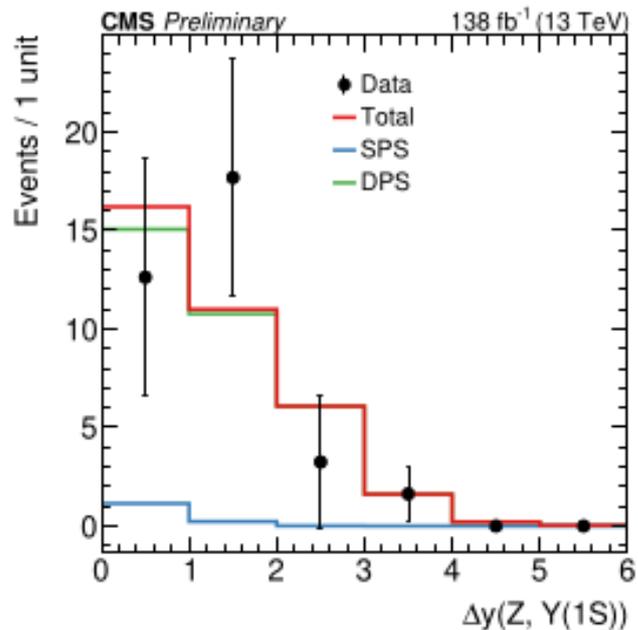
$$R_{Z+Y(1S)} = [\sigma(Z + Y(1S)) \cdot \text{BF}(Z \rightarrow 2\mu) \cdot \text{BF}(Y \rightarrow 2)] / [\sigma(Z) \cdot \text{BF}(Z \rightarrow 4\mu)] \Rightarrow$$
$$\mathbf{R_{Z+Y(1S)} = 21.1 \pm 5.5(\text{stat}) \pm 0.6(\text{syst}) 10^{-3}}$$

# Z+Y(1S) associated production [New]

Simultaneous fit of  $\Delta y(Z+Y(1S))$  and  $\Delta\phi(Z+Y(1S))$  using SPS/DPS templates

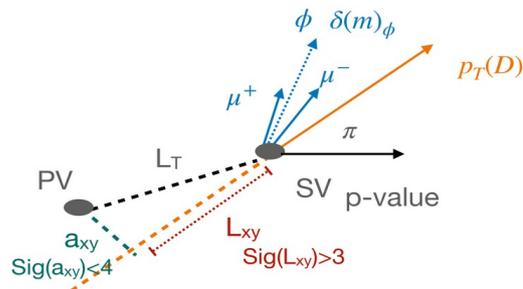
DPS effective cross section:

- $R_{Z+Y(1S)}^{\text{DPS}} = 20.2 \pm 7.5 \text{ (stat)} \pm 0.6 \text{ (syst)} 10^{-3}$
- Effective DPS cross section,  $\sigma_{\text{eff}} = 13.0^{+7.8}_{-3.5} \text{ mb}$
- Additionally  $\sigma_{\text{eff}}$  measured in bins of  $p_T(Y,Z)$



# Differential cross-section of $D/D_s$

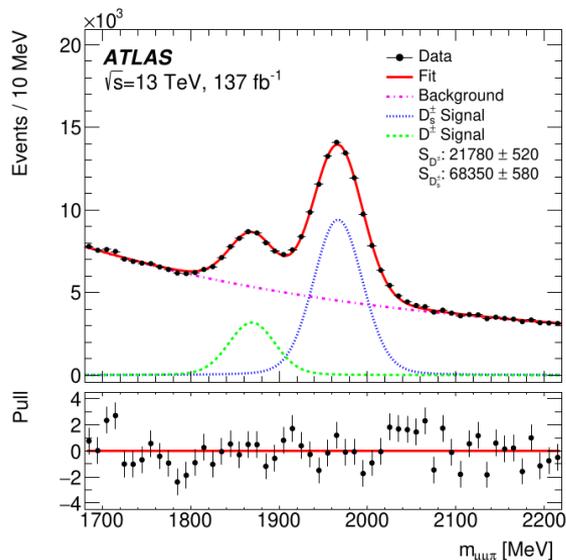
- Motivation: Test of perturbative QCD estimation; input to theoretical calculations
- Final state:  $D/D_s$  in  $D \rightarrow \phi(\mu\mu)\pi$  decays



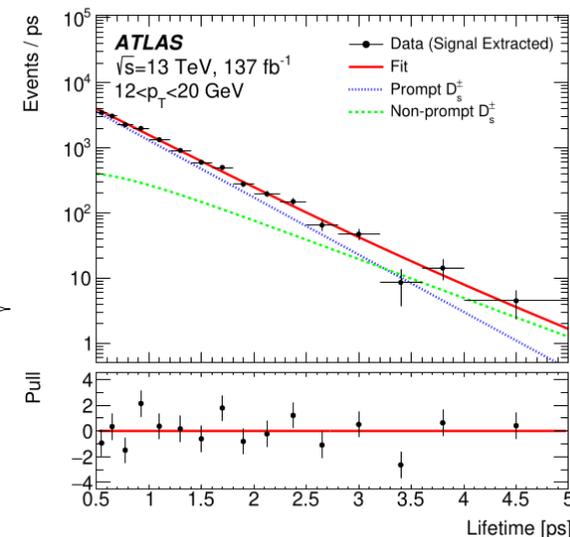
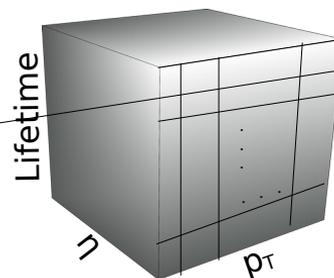
Dataset: Dimuon, (Run2)

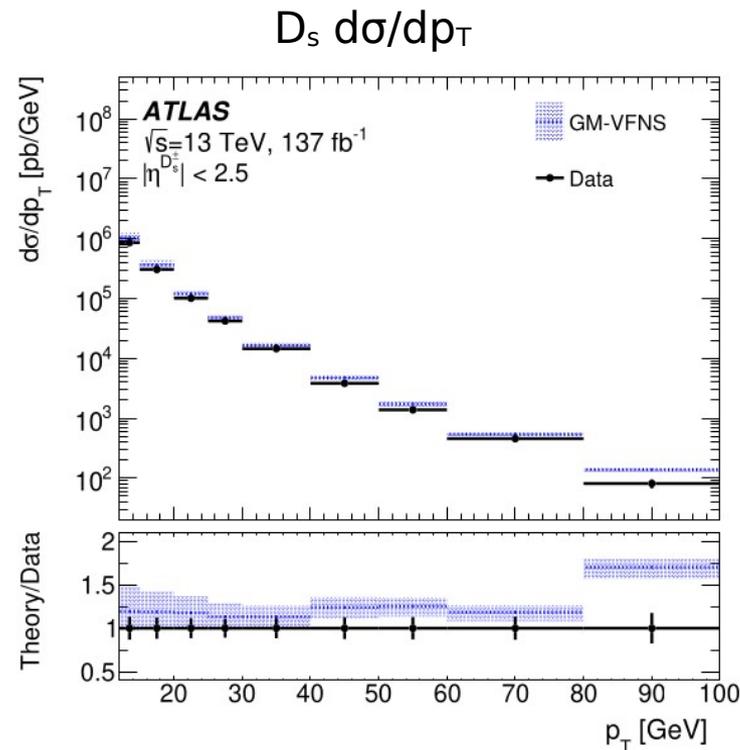
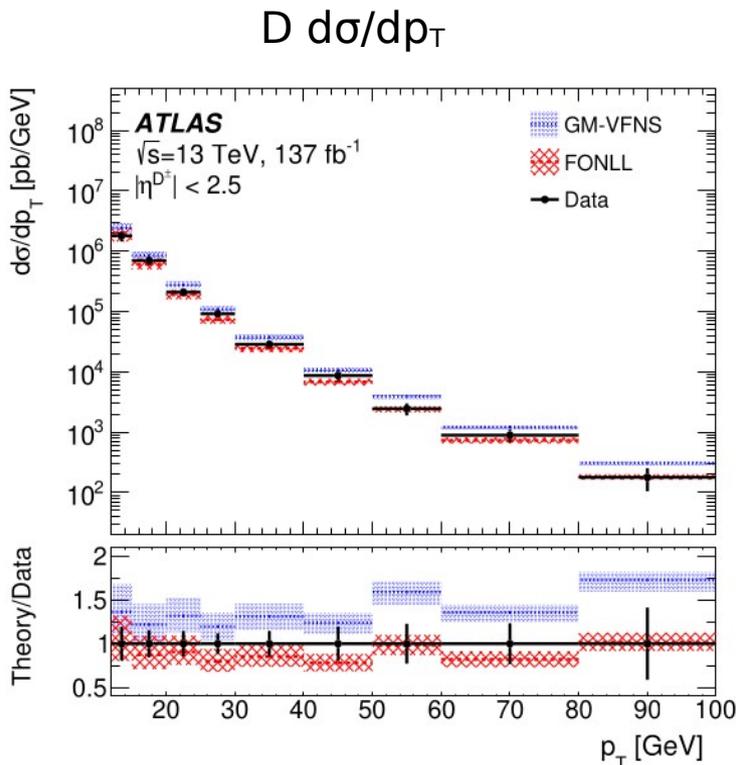
Strategy:

- 1) Select  $\mu \rightarrow$  Create  $\phi \rightarrow$  combine  $\phi$  with tracks  $\rightarrow$  build D
- 2) Divide in bins of  $p_T$ ,  $\eta$  and pseudo-proper lifetime  $\rightarrow$  fit  $m(D)$
- 3) **Fraction of non-prompt D  $f_{NP}$  fit from lifetime slices**
- 4) Reweight MC with  $f_{NP} \rightarrow$  Measure  $\sigma$  in bins of  $p_T / \eta$



## Extracting fraction of non-prompt D





**Mostly consistent within the uncertainties, with a slight deviation in the high  $p_T$ .**

# Properties & Branching fractions

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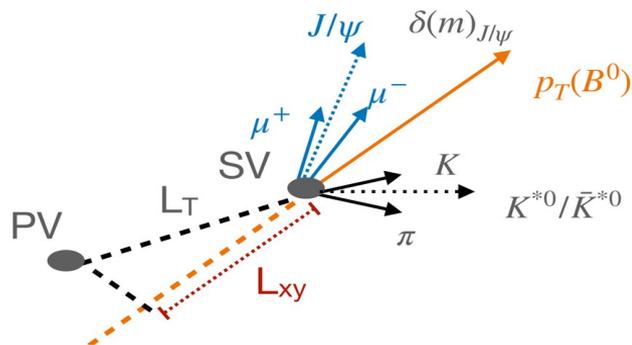
# $B^0 \rightarrow J/\psi K^{*0}$ lifetime measurement

- Motivation: Improve understanding of weak sector
- Final state:  $B \rightarrow J/\psi(\rightarrow \mu\mu) K^*(\rightarrow K\pi)$ ; select  $K^* / \bar{K}^{*0}$  based on the closeness to  $M(K^*)$

Dataset: Dimuon, (2015+Run2)  $140 \text{ fb}^{-1}$

Strategy:

- 1) Apply cuts on  $\mu \rightarrow$  build  $J/\psi \rightarrow$  build  $K^* \rightarrow$  build  $B^0$
- 2) PV to minimize 3D impact parameter
- 3) Calculate proper decay time,  $t$ : [ $t = L_{xy} m(B) / p_T(B)$ ]
- 4) 2D fit on mass and  $t$  & decay width  $\Gamma$

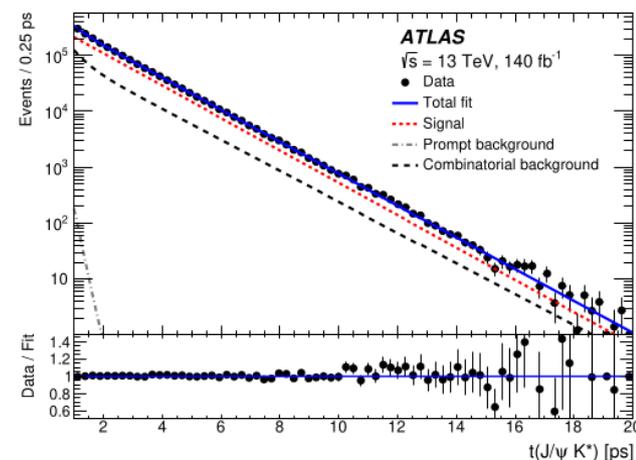
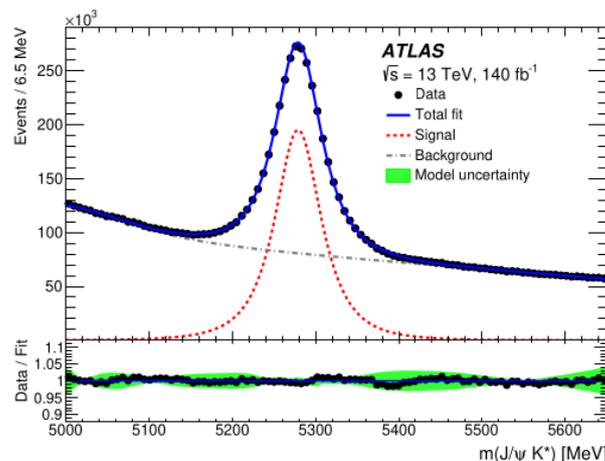


Signal:

- $m(B)$ : Johnson SU
- $t(B)$ : Exponential\*3 Gaussian

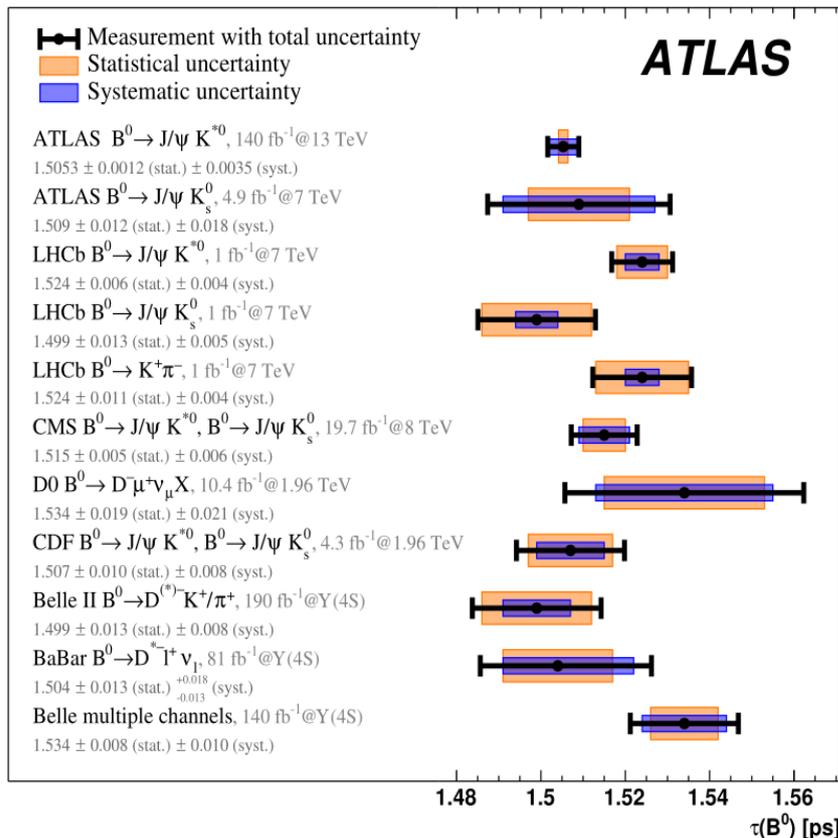
Background:

- $m(B)$ : Polynomial+sigmoind
- $t(B)$ : Exponential\*3Gaussian+3Gaussian



$$\tau_{B^0} = 1.5053 \pm 0.0012(\text{stat.}) \pm 0.0035(\text{syst.}) \text{ ps};$$

# $B^0 \rightarrow J/\psi K^{*0}$ lifetime measurement



Decay width ( $\Gamma$ ) is calculated from  $\tau_{B^0}$  using:

$$\tau_{B^0} = \frac{1}{\Gamma_d} \frac{1}{1 - Y^2} \left( \frac{1 + 2Ay + Y^2}{1 + Ay} \right),$$

With:

$\Gamma_d$  = average width of light and heavy mass eigenstates of  $B^0$

$Y$  = difference of light and heavy width normalized to  $2 \Gamma_d$

$A$  = production rate asymmetry

$$\Gamma_d = 0.6639 \pm 0.0005 \pm 0.0016 \pm 0.0038 \text{ ps}^{-1}$$

Stat.      Syst.      Ext.

$$\Gamma_d / \Gamma_s = 0.9905 \pm 0.0022 \pm 0.0036 \pm 0.0057$$

Stat.      Syst.      Ext.

Theory  $\Gamma_d/\Gamma_s$

Model	$\Gamma_d/\Gamma_s$
HQE [16]	$1.003 \pm 0.006$
Lattice QCD [17]	$1.00 \pm 0.02$

**Most precise single measurement to date**

# Search for $D^0 \rightarrow \mu\mu$

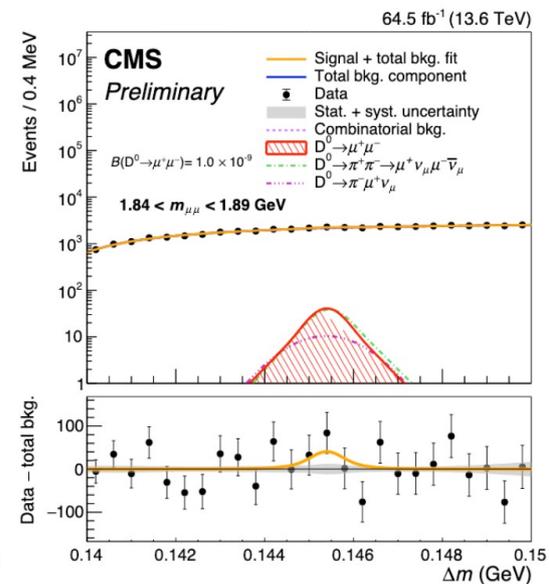
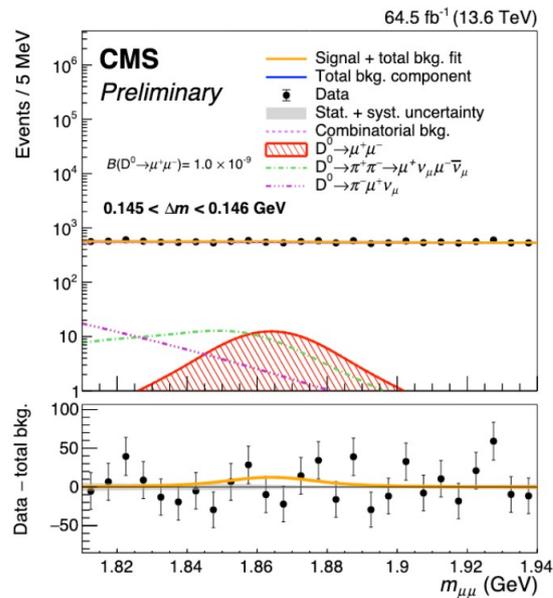
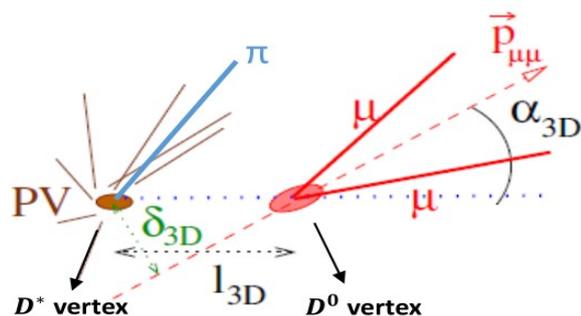
- Motivation: As rare decay (FCNC) highly suppressed in SM ( $O \sim 10^{-13}$ )  $\rightarrow$  sensitive to NP effects
- Final state:  $D^* \rightarrow D^0 (\mu\mu) \pi$  as signal;  $D^* \rightarrow D(\pi\pi)\pi$  as normalization channel
- Key point: **Use  $D^* \rightarrow D^0 \pi$  decay chain to reduce background**

## Strategy:

- Apply cuts  $\mu \rightarrow$  build  $D \rightarrow$  soft  $\pi \rightarrow$  build  $D^*$
- 2D fit in  $\Delta m = m(D^*) - m(D)$  and  $m(D)$
- $D^{*+} \rightarrow D(\pi\pi)\pi$  normalization;

## Dataset:

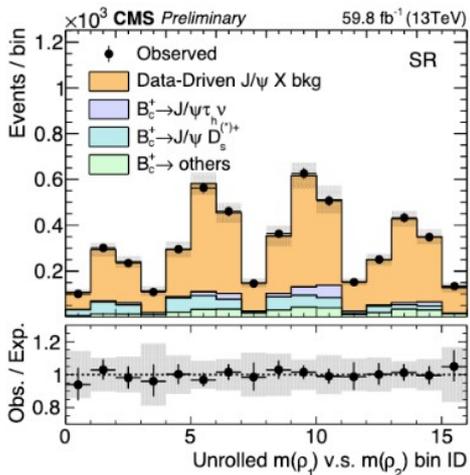
- High rate dimuon, Run3 (2022+2023)
- Zero bias for , Run3 (2022+2023)



**BF ( $D^0 \rightarrow \mu\mu$ )  $< 2.6 \cdot 10^{-9}$  @ 95% CL**  
 Most stringent limit to date

# Ratio of $\text{BF}(B_c \rightarrow J/\psi \tau \nu) / \text{BF}(B_c \rightarrow J/\psi \mu \nu)$

- $R(J/\psi) = \text{BF}(B_c \rightarrow J/\psi \tau \nu) / \text{BF}(B_c \rightarrow J/\psi \mu \nu)$
- Motivation: New physics contributions may introduce Lepton Flavour Universality (LFU) violation
- Final state:  $B_c \rightarrow J/\psi \tau \nu$ , with  $J/\psi \rightarrow \mu\mu$  &  $\tau \rightarrow 3\pi$



Dataset:  $J/\psi(\mu\mu)$ +track trigger, Run2

Strategy:

- Apply cuts on  $\mu \rightarrow$  build  $J/\psi \rightarrow$  find  $\tau$  using 3 tracks  $\rightarrow$  build B
- Exploit the decay chain of  $\tau \rightarrow \alpha \nu \rightarrow \rho(770)\pi \nu \rightarrow 3\pi \nu$
- Unroll both  $\rho$  candidate masses and fit the in 1D distribution
- Result combined with the previous CMS measurement of  $R(J/\psi)$  with  $\tau \rightarrow \mu \nu$  decay ([CMS-BPH-22-012](#))

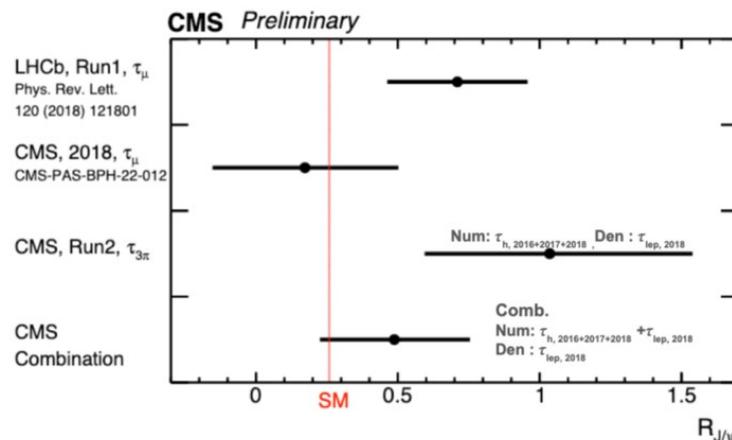
Result:

- Fitting hadronic channel alone:

$$R(J/\psi)_{\text{hadr}} = 1.04^{+0.5}_{-0.44}$$

- Combining leptonic & hadronic channels:

$$R(J/\psi)_{\text{comb}} = 0.49 \pm 0.25 \text{ (syst)} \pm 0.09 \text{ (stat)}$$

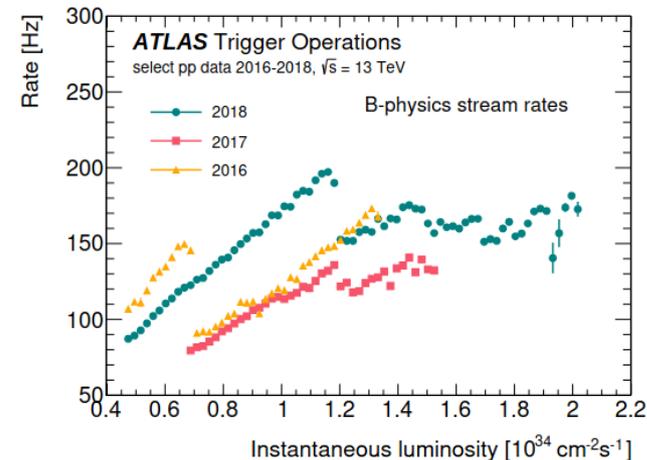


# A glance into the Run 3 improvements



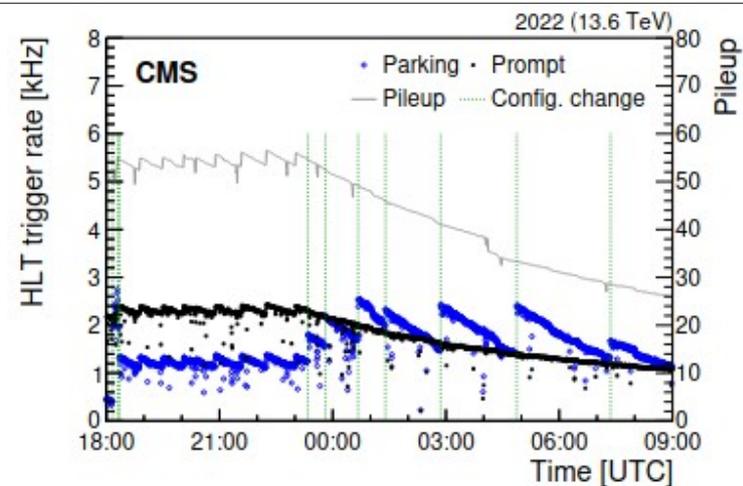
## ATLAS

- High-rate parking already in place from Run1 and Run 2
- In Run 3: The rate increased up to 600Hz
- Complemented by soft di-electron trigger is used
- For more: [arXiv document](#)



## CMS

- High-rate parking with dimuons through whole Run3
- High-rate parking with dielectrons for precise LFU tests
- High-rate scouting strategy for 2025-26
- Details in: [arXiv document](#)
- State-of-the-art same-sign flavour tagger ([BPH-23-004](#)) key for CMS CPV studies

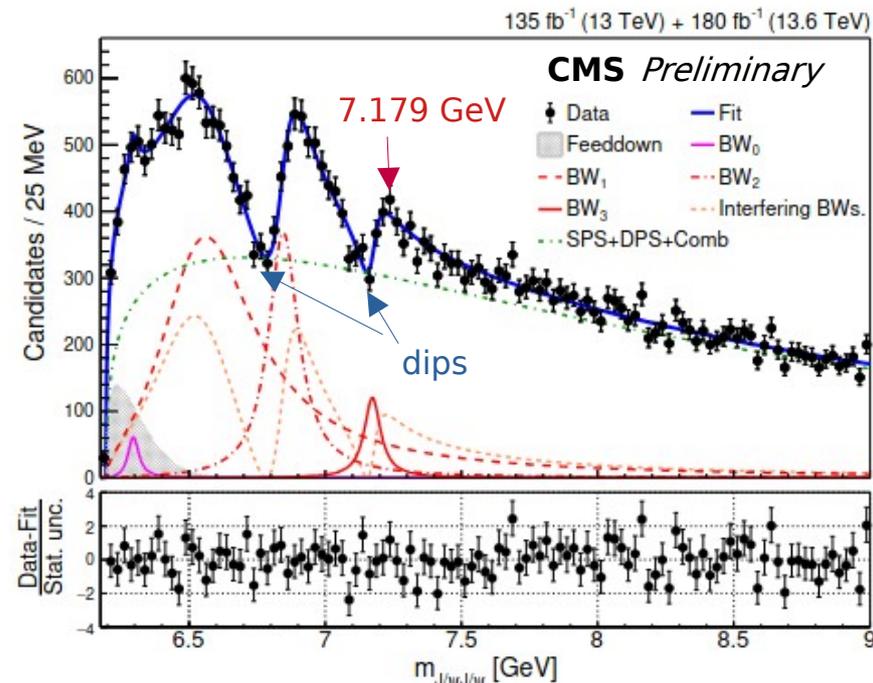


- Update of the CMS analysis  
“[New Structures in the  \$J/\psi J/\psi\$  mass Spectrum](#)”  
using high intensity Run3 dimuon parking
- 4 muons  $\rightarrow$  2  $J/\psi$  candidates  $\rightarrow$  common vertex
- **$\sim 4$  times more  $J/\psi J/\psi$  candidates in Run3 wrt Run2 with only 1.3 times more luminosity**  
 $\rightarrow$  BPH-Parking is the game changer for the CMS HF program

## Results:

- More than  $5\sigma$  for the **7.179 GeV** peak
- More than  $5\sigma$  for the **interference model** (“dips”)
- Details will soon be in [preliminary BPH results](#)

## CMS-BPH-24-003

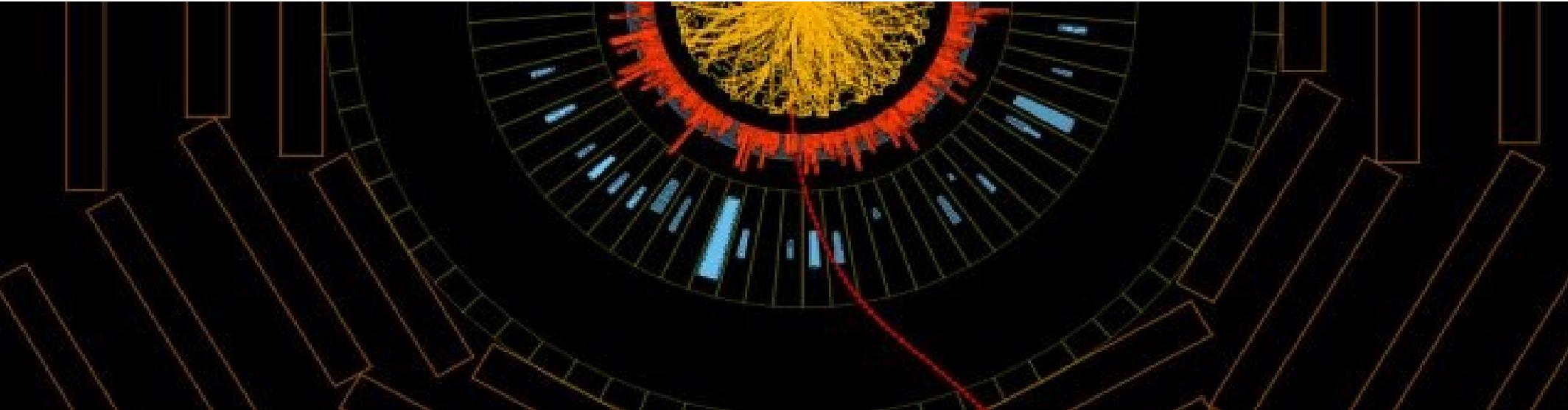


# Summary



- Many exciting new results by ATLAS and CMS
- So far no significant deviation is observed from SM expectation
- Run 3 will be very interesting with new high statistics data coming

**Stay tuned for more exciting results !!!**

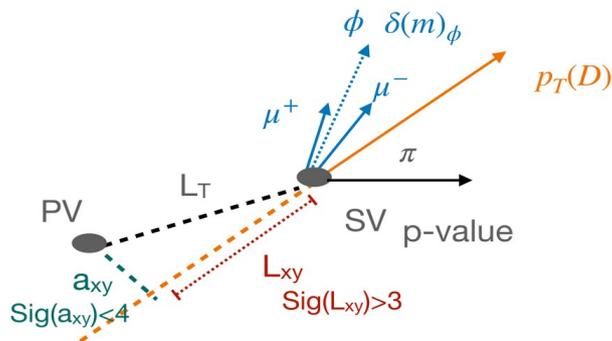






## Motivation

- Fundamental test of perturbative QCD estimation → Valuable input to improve theoretical calculations
- Heavy flavour production crucial to many analysis (signal or background)
- Production of  $D/D_s$  in  $\phi(\mu\mu)\pi$

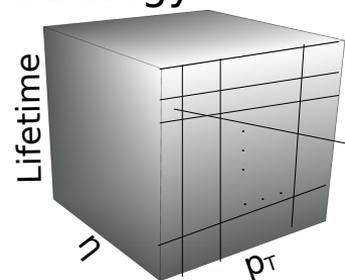


Dataset: Dimuon, (Run2) 137 fb<sup>-1</sup>

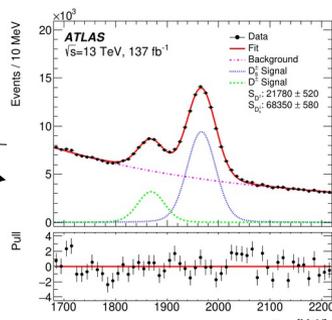
## Selection:

- 1) Apply  $p_T(\mu) > 6$  or  $11$  GeV .& .  $|\eta| < 2.5$  .& . ID
- 2) Create  $\phi$  candidate (window depends on  $\eta$ )
- 3) Combine  $\phi$  with tracks to built SV
- 4) Apply cut on displacement significance of SV
- 5) SV probability  $> 15.8\%$

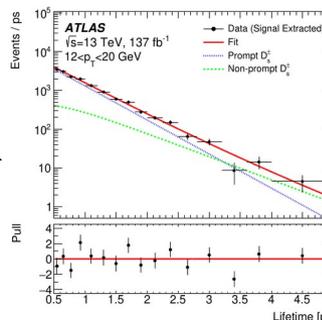
## Strategy



Divide in bins of  $\eta$ ,  $p_T$  and pseudo-proper lifetime



Fit  $m(\mu\mu\pi)$  in each bin

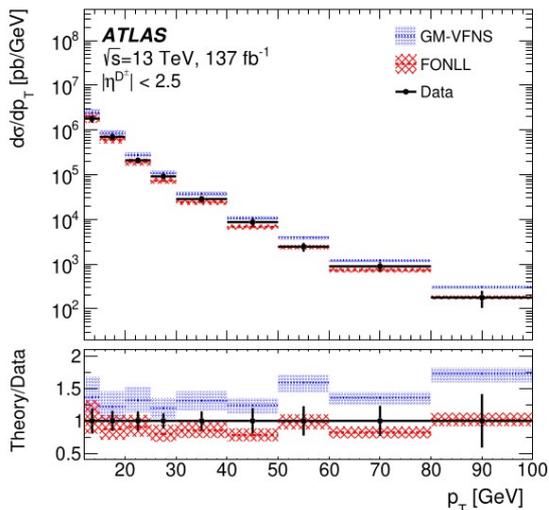


Measure the non-prompt  $D(D_s)$  fraction,  $f_{NP}$

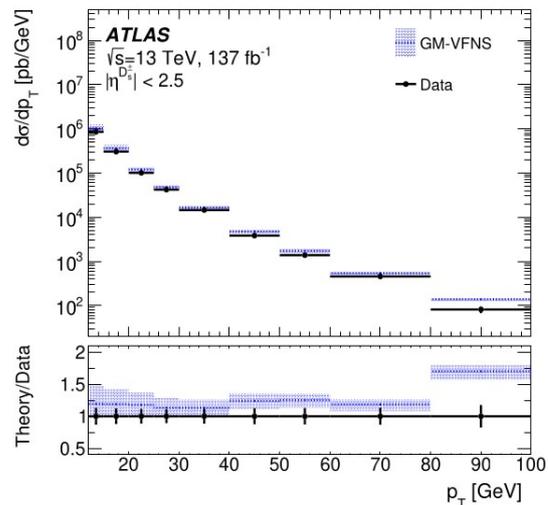
$$\frac{d\sigma}{dp_T} \Big|_i = \frac{S_{D^\pm/D_s^\pm}^i}{\int \mathcal{L} dt \times C^i \times \mathcal{B}(D^\pm/D_s^\pm \rightarrow \phi(\mu\mu)\pi^\pm) \times \Delta^i p_T},$$

$$\frac{d\sigma}{d|\eta|} \Big|_j = \frac{S_{D^\pm/D_s^\pm}^j}{\int \mathcal{L} dt \times C^j \times \mathcal{B}(D^\pm/D_s^\pm \rightarrow \phi(\mu\mu)\pi^\pm) \times \Delta^j |\eta|}$$

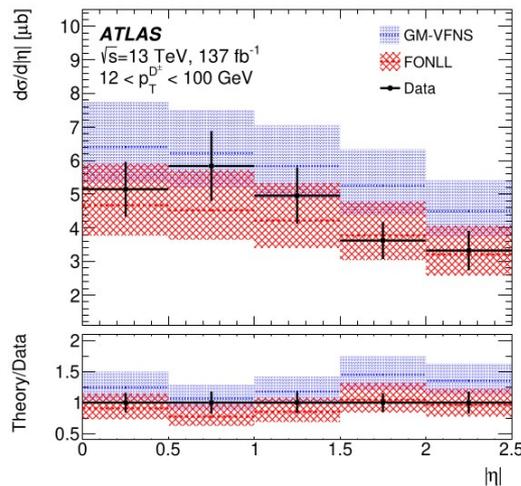
- Use  $f_{NP}$  to reweight MC → get acceptance \* efficiency (C)
- Measure signal using mass fits in bins of  $p_T$  (i) and  $\eta$  (j)
- Independent fits for  $D / D_s$



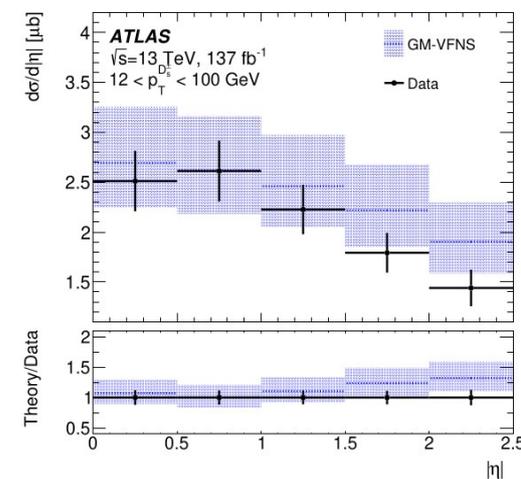
Differential cross-section of D in:  
 ← bins of  $p_T$   
 bins of  $\eta$  →



Differential cross-section of  $D_s$  in:  
 ← bins of  $p_T$   
 bins of  $\eta$  →



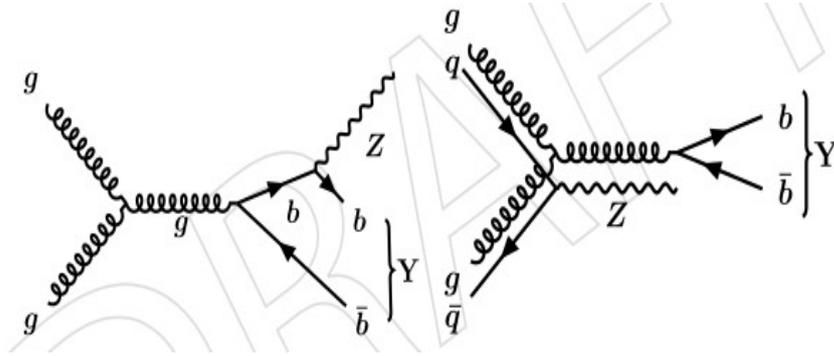
- Dominant systematic for  $\sigma(D)$  is the background model
- Dominant systematic for  $\sigma(D_s)$  is the branching fraction



**Results**  
 Mostly consistent within the uncertainties, with a slight deviation in the high  $p_T$ .

## Motivation

- Investigate the quarkonia formation in hadronic collisions using Z+Y events
- Process dominated by double scattering (DPS) → Tool to understand the structure of proton
- Higher than predicted rate can be evidence of new particle decay to  $b\bar{b}$ +Z



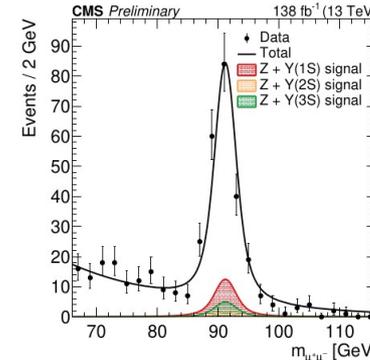
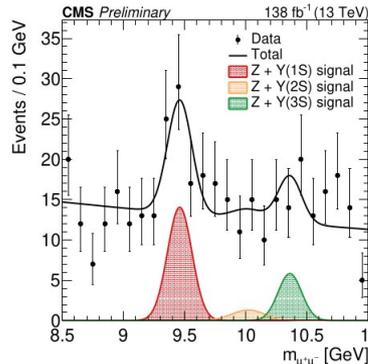
Dataset: Events triggered with 2 or 3 muons, (Run2) 138 fb<sup>-1</sup>

## Strategy:

- Select event with 4 isolated and prompt muons
- Divided in signal (Z+Y → 4μ) and normalization (Z → 4μ) channels
- 2D fit on mass of Y and Z measure fiducial cross section in  $p_T(\mu_1-Z) > 30$ ,  $p_T(\mu_2-Z) > 15$ ,  $p_T(\mu-Y) > 3$  GeV .& .  $|\eta| < 2.4$
- 2D fit on sPlot weighted  $\Delta y$  and  $\Delta \phi$  to extract DPS fraction

## Yield extraction

- Mass Z PDF: Breit-Wigner \* Gaussian
- Mass Y PDF: Gaussians
- Background: Exponential



- Yields:
  - ZY(1S):  $34.6 \pm 9.0$
  - ZY(2S):  $2.9 \pm 6.7$
  - ZY(3S):  $13.9 \pm 7.2$

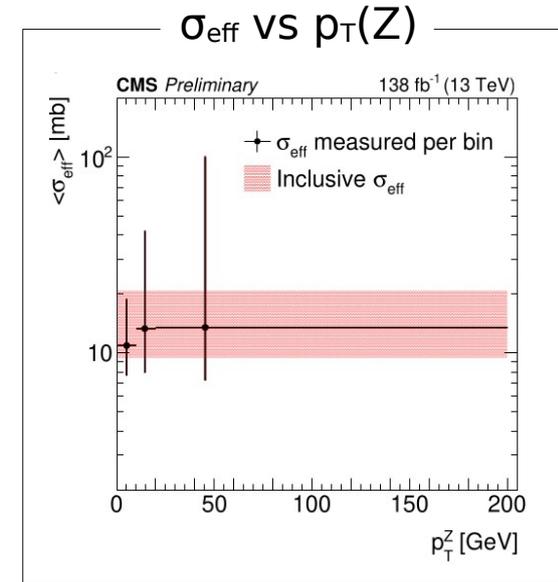
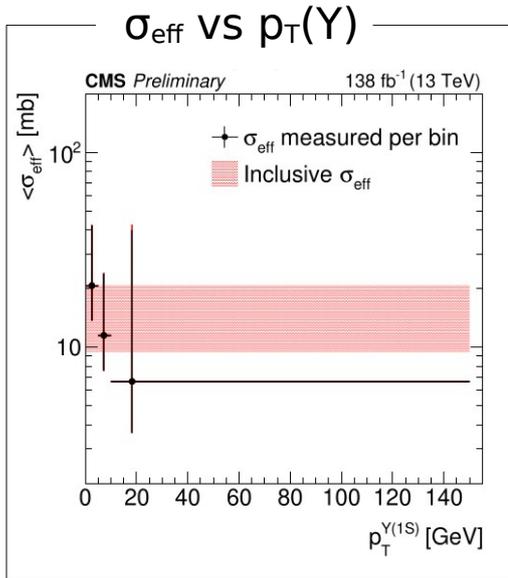
Fiducial cross section ratio

The measurement of  $[\sigma(Z + Y(1S)) \cdot \text{BF}(Z \rightarrow 2\mu) \cdot \text{BF}(Y \rightarrow 2)] / [\sigma(Z) \cdot \text{BF}(Z \rightarrow 4\mu)]$ ,  $R_{Z+Y(1S)}$  is:

$$R_{Z+Y(1S)} = 21.1 \pm 5.5(\text{stat}) \pm 0.6(\text{syst}) 10^{-3}$$

DPS effective cross section:

- Fitting simultaneously  $\Delta y(Z+Y(1S))$  and  $\Delta\phi(Z+Y(1S))$  sPlot weighted distributions, with SPS/DPS templates  
 → Measure  $R_{Z+Y(1S)}^{\text{DPS}} = 20.2 \pm 7.5(\text{stat}) \pm 0.6(\text{syst}) 10^{-3}$
- Effective DPS cross section,  $\sigma_{\text{eff}} = 13.0^{+7.8}_{-3.5} \text{ mb}$
- Additionally  $\sigma_{\text{eff}}$  measured in bins of  $p_T(Y, Z)$



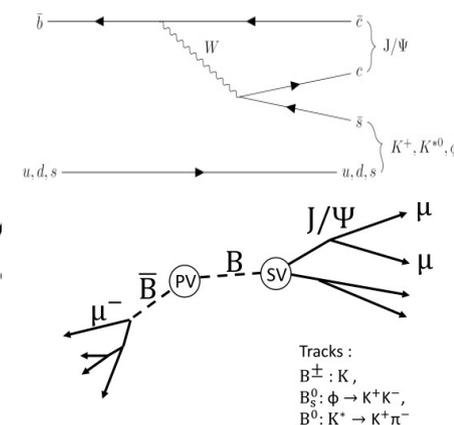
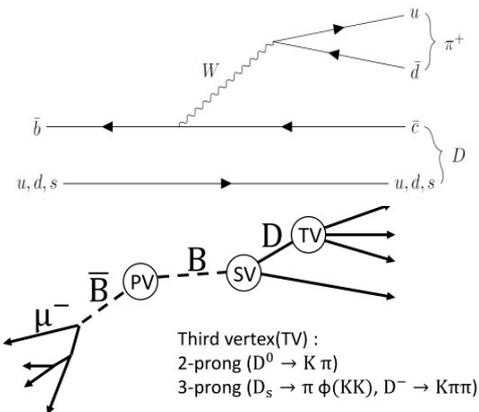
## Motivation

- Production fractions ratios, PFR, important ingredient for many measurements
- Source of systematic uncertainty → need to be measured in precision
- Previous PFR measurements showed dependence with  $p_T(B)$

Dataset: High intensity single-muon, (2018)  $41.6 \text{ fb}^{-1}$

## Strategy:

- Measure PFR in full hadronic open charm decays using theoretical calculations
- Measure the relative PFR,  $\mathcal{R}_s^{(d)}$ , using charmonium decay
- Use open charm PFR to normalize the charmonium  $\mathcal{R}_s^{(d)}$ , extract the absolute normalization



## Hadronic

- Decays:  $B^0 \rightarrow \pi^+ D^- (K^+ \pi^- \pi^-)$ ,  $B_s^0 \rightarrow \pi^+ D_s^- (\pi^- \phi(KK))$ ,  $B^- \rightarrow \pi^- D^0 (K \pi)$
- Using the “probe-side” (i.e. non triggering B)
- Create D vertex → combine with  $\pi$  to build B
- BDT discriminator for selection

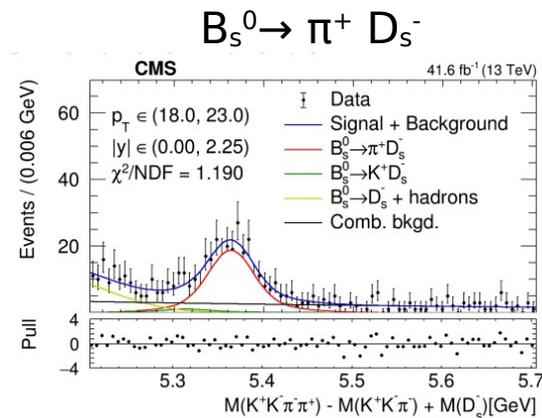
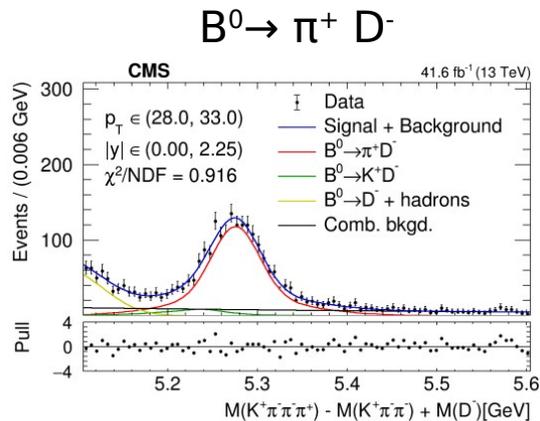
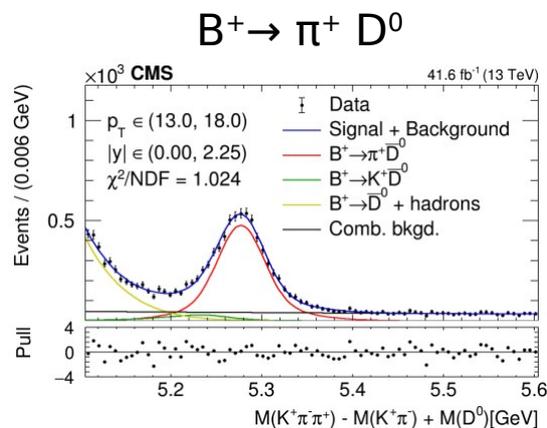
## Leptonic

- Decays:  $B^0 \rightarrow J/\psi K^{*0} (K \pi)$ ,  $B_s^0 \rightarrow J/\psi \phi (KK)$ ,  $B^- \rightarrow J/\psi K$
- Using the “tag-side” and “probe-side” (i.e. triggering and non triggering B)
- Select leptons and built  $J/\psi$
- Combine with tracks to built B apply cuts

# Production fractions in hadronic & charmonium decays

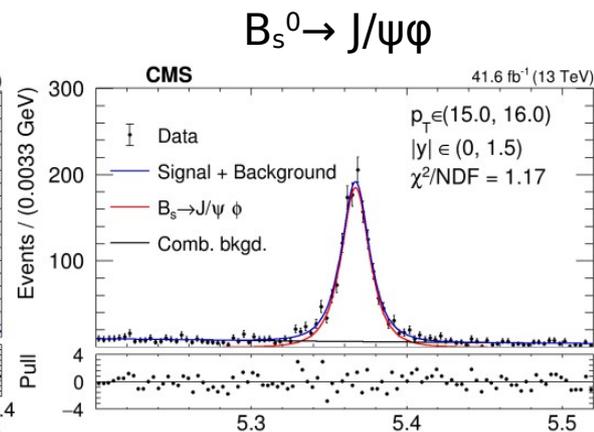
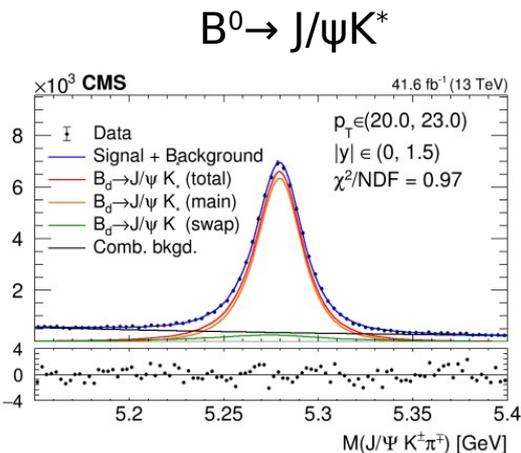
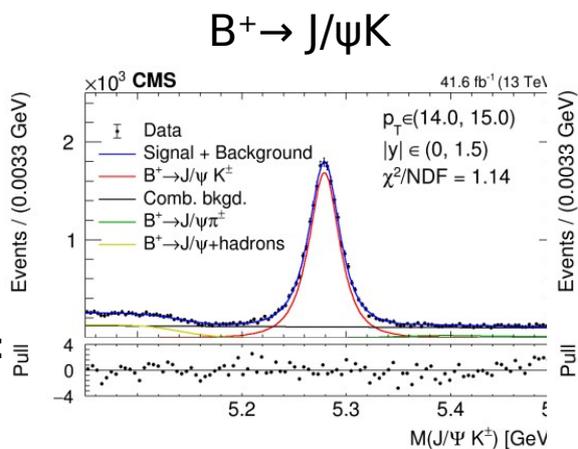
## Hadronic

- Fit in 7 bins in  $p_T$  and 5 in  $y$
- Signal PDF: double Gaussian
- Comb. BKG PDF: Exponential
- $B \rightarrow DX$  BKG PDF: Error function



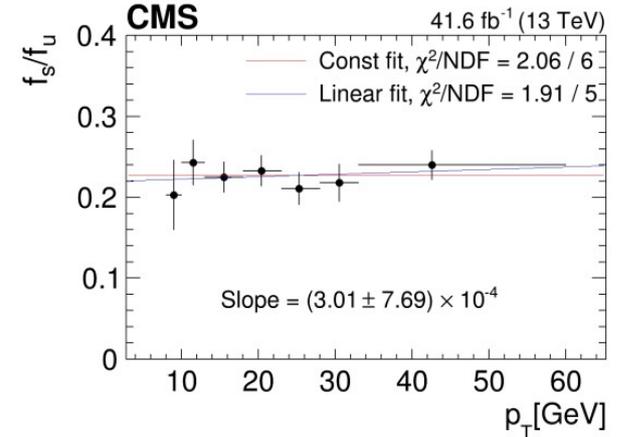
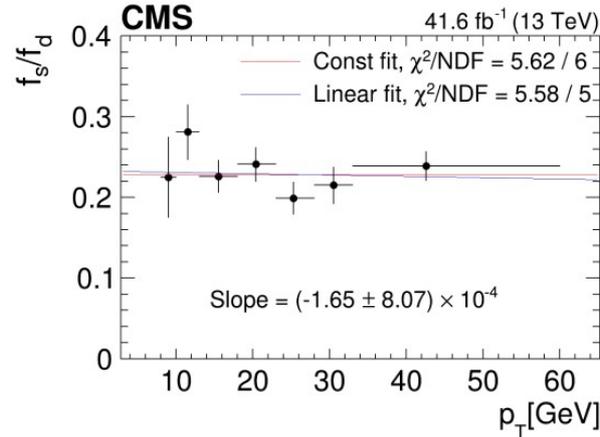
## Leptonic

- Fit in 13 bins in  $p_T$  and 6 in  $y$
- Signal PDF: Johnson
- Comb. BKG PDF: Exponential
- $B \rightarrow J/\psi X$  BKG PDF: Error function



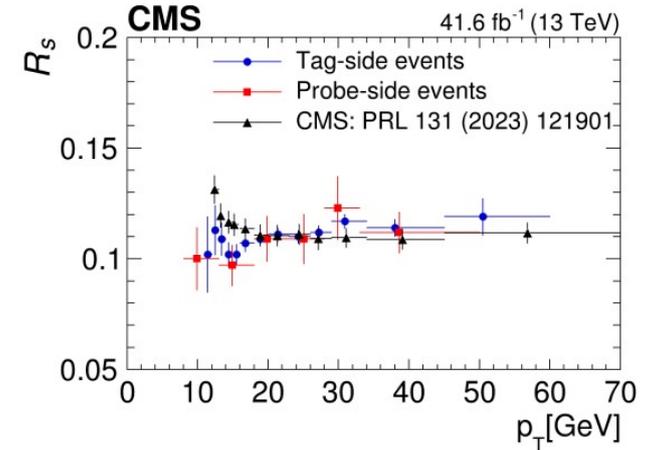
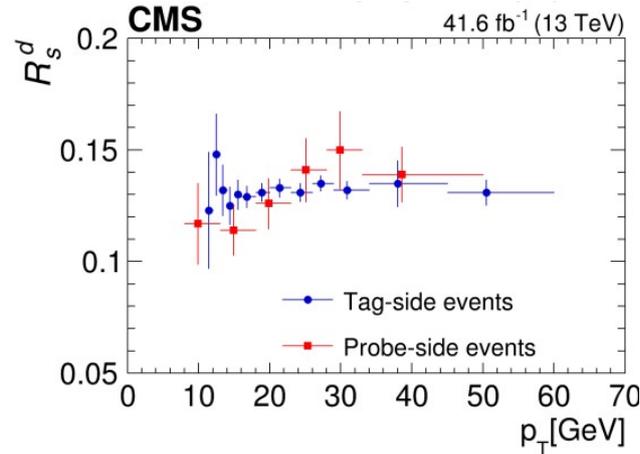
## PFR from open-charm decays

- Full hadronic open charm decays
- First measurement of this in CMS
- Results compared with both hypothesis
- Low  $p_T$  trend not observed might be from limited statistics



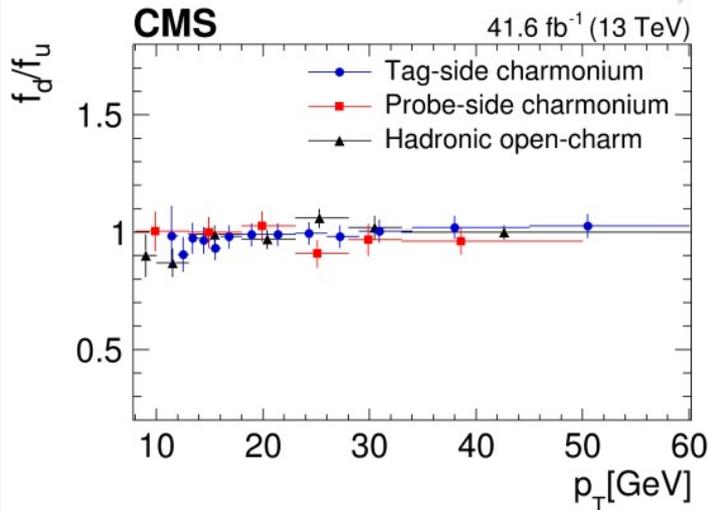
## $\mathcal{R}_s \mathcal{R}_d$ from charmonium

- Measurement for both tag and probe sides
- Not observed any statistically significant trend with  $p_T$
- Consistent though with  $p_T$  dependence at low  $p_T$



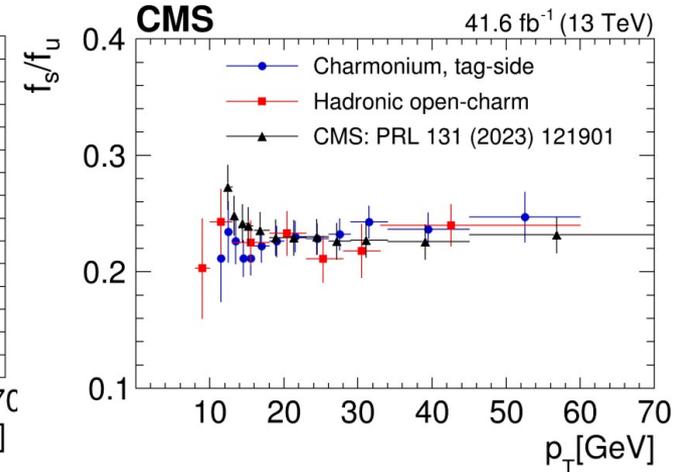
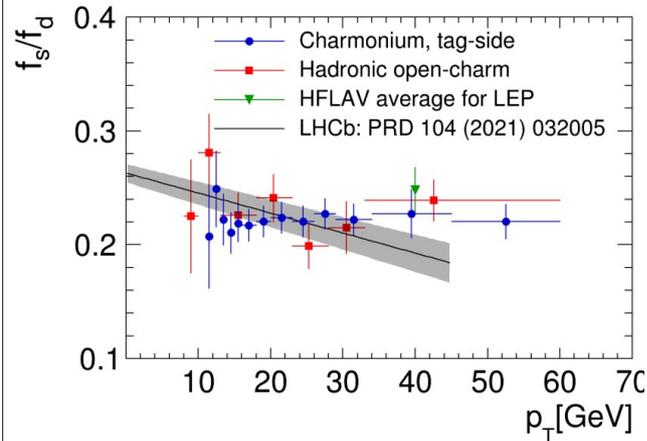
## Measurement of $f_d/f_u$

- Correct Branching fractions w/o assuming isospin invariance
- Perform fit on both hadronic open charm and tag side charmonium
- Result:  $f_d/f_u = \mathbf{0.98 \pm 0.05}$



## Measurement of PFR from $\mathcal{R}_s \mathcal{R}_s^d$

- Only probe side charmonium events used
- Absolute normalizations calculated with:
  - $C_{sd} = f_s/f_d(\text{open-charm}) / \mathcal{R}_s^d$
  - $C_{su} = f_s/f_u(\text{open-charm}) / \mathcal{R}_s$
- Results compatible with low  $p_T$  dependence but in tension with the linear trend
- In the region w/o no  $p_T$  dependence:
  - $f_s/f_d = \mathbf{0.223 \pm 0.015}$
  - $f_s/f_u = \mathbf{0.233 \pm 0.018}$



# Properties & Branching fractions

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# $B^0 \rightarrow J/\psi K^{*0}$ lifetime measurement

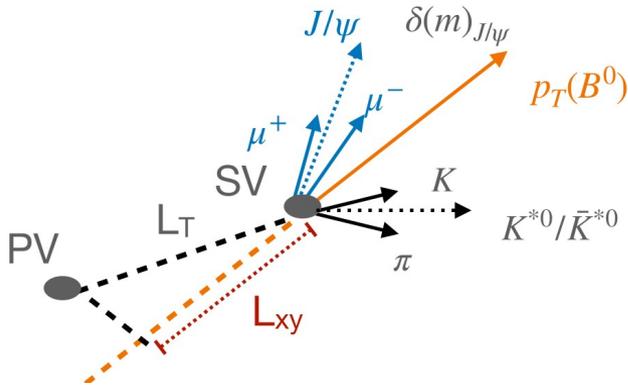
## Motivation

- Measure the lifetime of  $B^0 \rightarrow$  improve understanding of weak sector
- In SM b-hadrons lifetimes differ due to corrections of Pauli interference and weak annihilation
- Potential deviation could be evidence of new physics

Dataset: Dimuon, (2015+Run2)  $140 \text{ fb}^{-1}$

## Selection:

- 1) Apply  $p_T(\mu) > 4, 6$  and  $11 \text{ GeV}$  .&  $|\eta| < 2.5$  .& ID
- 2) Built  $J/\psi \rightarrow \mu\mu$  using kinematic fit
- 3)  $K^* \rightarrow K\pi$  built from non- $\mu$  tracks;  $p_T(K, \pi) > 1, 0.5 \text{ GeV}$  and mass cuts
- 4)  $K^*$  and  $K^{*-}$  hypothesis tested  $\rightarrow$  keep the closest to  $M(K^*)$
- 5)  $B^0$  created from kinematic fit of  $J/\psi$  and  $K^*$  tracks to a common vertex
- 6) Find the production primary vertex selected to minimize 3D impact parameter



Proper decay time is determined by:

$$t = \frac{L_{xy} m_B}{p_{TB}}$$

$L_{xy}$  = transverse decay length  
 $m_B$  = B candidate mass  
 $p_{TB}$  = B candidate momentum

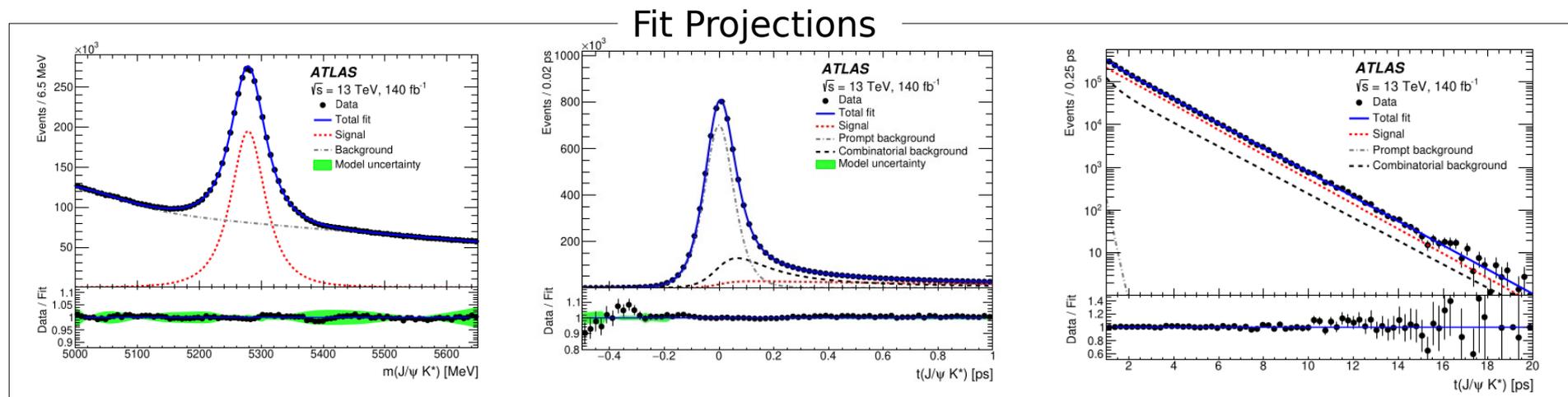
# $B^0 \rightarrow J/\psi K^{*0}$ lifetime measurement

Simultaneously fit mass and  $\tau$  of  $B^0$ :

$$\ln L = \sum_{i=1}^N w(t_i) \ln [f_{\text{sig}} \mathcal{M}_{\text{sig}}(m_i) \mathcal{T}_{\text{sig}}(t_i, \sigma_{t_i}, p_{T_i}) + (1 - f_{\text{sig}}) \mathcal{M}_{\text{bkg}}(m_i) \mathcal{T}_{\text{bkg}}(t_i, \sigma_{t_i}, p_{T_i})]$$

$\mathcal{M}_{\text{sig}}$ : Mass PDF for signal (Johnson SU)  
 $\mathcal{T}_{\text{sig}}$ : Proper decay time PDF for signal  
 (Exponential\*Resolution)

$\mathcal{M}_{\text{sig}}$ : Mass PDF for BKG (polynomial + sigmoid)  
 $\mathcal{T}_{\text{sig}}$ : Proper decay time PDF for BKG  
 (Exponential\*Resolution [displaced] +  
 Resolution [prompt])



**$B^0$  lifetime ( $\tau_{B^0}$ ) =  $1.5053 \pm 0.0012(\text{stat.}) \pm 0.0035(\text{syst.})$  ps**

# $B^0 \rightarrow J/\psi K^{*0}$ lifetime measurement

Decay width ( $\Gamma$ ) is calculated from  $\tau_{B^0}$  using:

$$\tau_{B^0} = \frac{1}{\Gamma_d} \frac{1}{1 - y^2} \left( \frac{1 + 2Ay + y^2}{1 + Ay} \right),$$

With:

$\Gamma_d$  = average width of light and heavy mass eigenstates of  $B^0$

$Y$  = difference of light and heavy width normalized to  $2 \Gamma_d$

$A$  = production rate asymmetry

$$\Gamma_d = 0.6639 \pm 0.0005 \pm 0.0016 \pm 0.0038 \text{ ps}^{-1}$$

Stat.      Syst.      Ext.

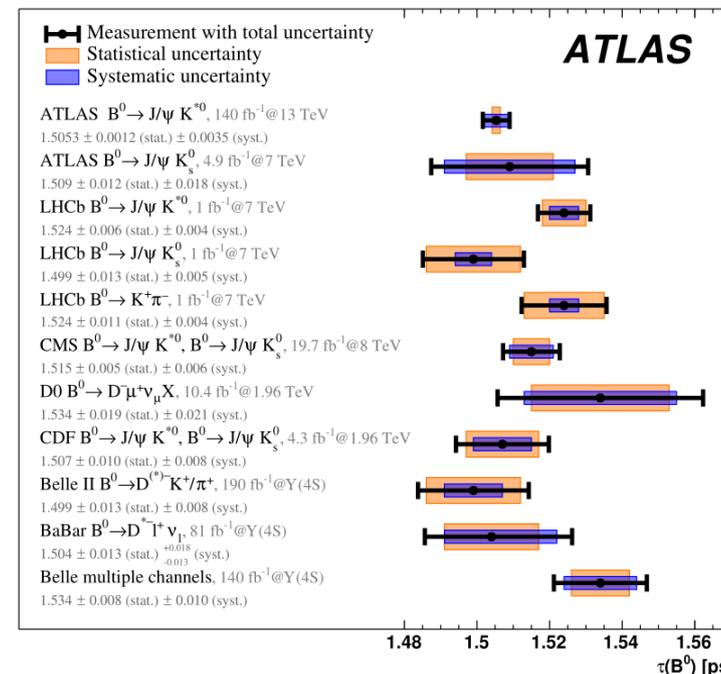
$$\Gamma_d / \Gamma_s = 0.9905 \pm 0.0022 \pm 0.0036 \pm 0.0057$$

Stat.      Syst.      Ext.

Theory  $\Gamma_d/\Gamma_s$

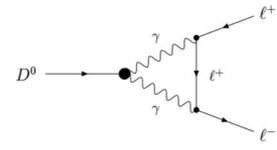
Model	$\Gamma_d/\Gamma_s$
HQE [16]	$1.003 \pm 0.006$
Lattice QCD [17]	$1.00 \pm 0.02$

Most precise single measurement to date



## Motivation

- Rare decay (FCNC) highly suppressed in SM ( $O \sim 10^{-13}$ )
- Enhancement in BF predicted by several NP models
- Less explored with respect to B rare decays



## Strategy:

- To reduce the background search for  $D^{*+} \rightarrow D^0(\mu\mu)\pi^+$
- Extra  $\Delta m = m(D^{*+}) - m(D)$  observable to enter the fit
- Use the  $D^{*+} \rightarrow D(\pi\pi)\pi$  as normalization channel to cancel any dependence on the  $\sigma(D^{*+})$

## Dataset:

- High rate dimuon stream, Run3 (2022+2023)  $64.5 \text{ fb}^{-1}$
- Zero bias for the normalization channel, Run3 (2022+2023)  $51.4 \text{ nb}^{-1}$

## Selection

- 1) Apply  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.4$  to all  $\mu$
- 2) Create  $D^0$  candidates with fit to a common vertex
- 3) Find the PV as the vertex with closest impact parameter
- 4) Select tracks from the PV as  $\pi$  candidates to build the  $D^*$  candidates
- 5) Cuts on vertex probability, distance from PV, pointing angle
- 6) Final selection using a BDT discriminator

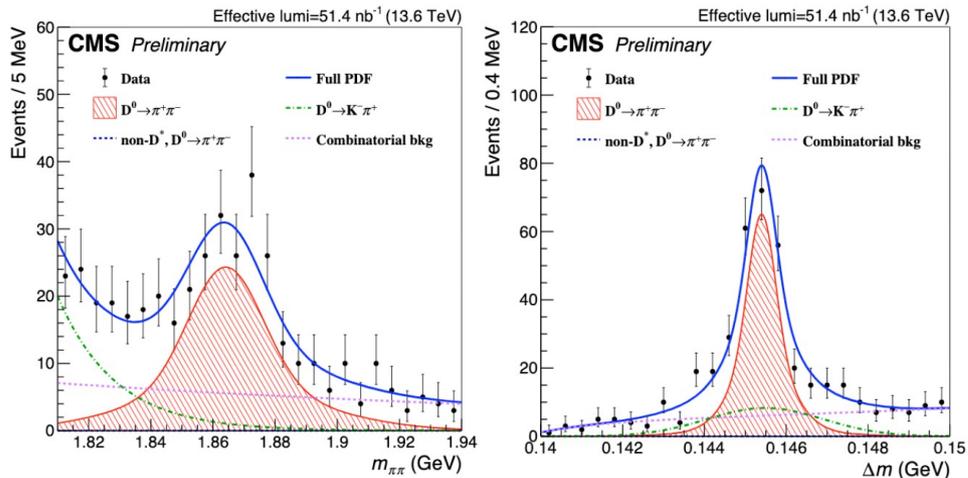
Applied both to signal and normalization channel

# Search for $D^0 \rightarrow \mu\mu$

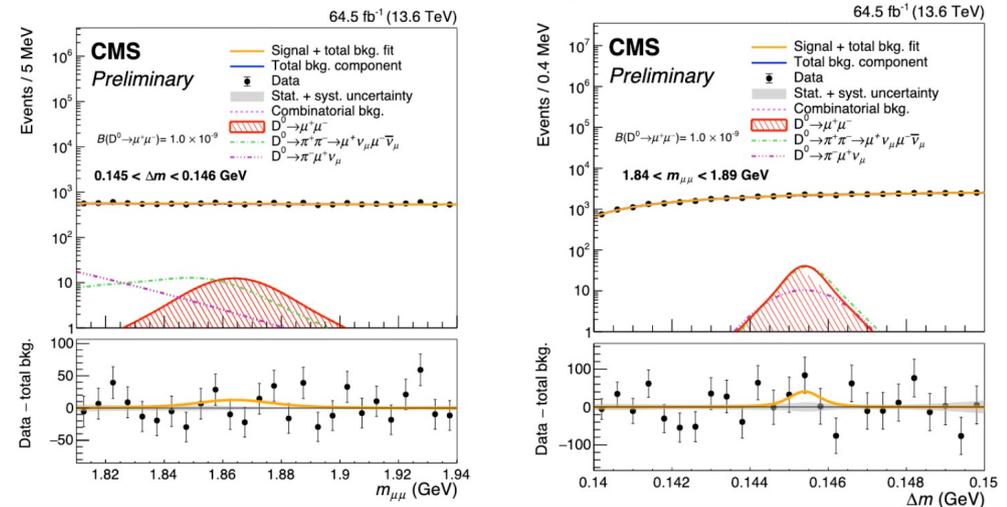
## Fitting procedure:

- Same 2D ( $m_{\mu\mu}$  &  $\Delta m$ ) fit for signal and normalization channel
- $D^0 \rightarrow \mu\mu$  signal PDF: 2 Gaussians in  $m_{\mu\mu}$  and 3 Gaussians in  $\Delta m$
- Combinatorial background: describe profiling method
- Fake  $\mu$  background: same as signal PDF with different parameters

### $D^{*0} \rightarrow (\pi\pi)\pi$



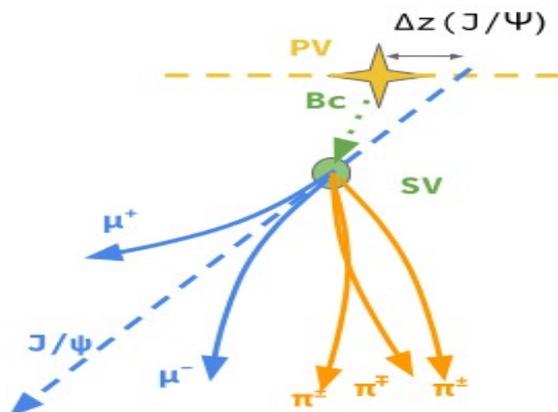
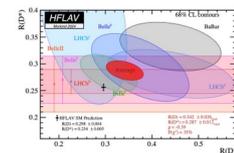
### $D^{*0} \rightarrow (\mu\mu)\pi$



**BF ( $D^0 \rightarrow \mu\mu$ )  $< 2.6 \cdot 10^{-9}$  @ 95% confidence level**  
 Most stringent limit to date

## Motivation

- Lepton Flavour Universality (LFU): Couplings of Z,W to leptons independent of flavour
- New physics contributions may introduce LFU violation
- LHCb measured  $2\sigma$  deviation from SM expectation ([PRL 125, 222003 \(2018\)](#))



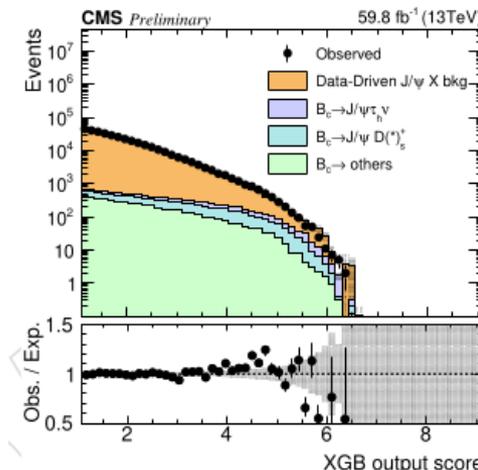
Dataset:  $J/\psi(\mu\mu)$  .&. track trigger, (Run2)  $138 \text{ fb}^{-1}$

## Strategy:

- Measure  $R(J/\psi) = B_c \rightarrow J/\psi \tau \nu / B_c \rightarrow J/\psi \mu \nu$ , with  $\tau \rightarrow 3\pi(+\pi^0)+\nu$
- Event triggered by the  $J/\psi \rightarrow \mu\mu$
- Hadronic  $\tau$  reconstructed using tracks close to  $J/\psi$
- Result combined with the previous CMS measurement of  $R(J/\psi)$  with  $\tau \rightarrow \mu\nu$  decay ([CMS-BPH-22-012](#))

## Selection

- 1) Apply  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.4$  to all  $\mu$  and built the  $J/\psi$  vertex
- 2) Require displacement of  $J/\psi > 3\sigma$  wrt beam axis
- 3) Find hadronic  $\tau$  using 3 tracks close to the PV in  $\Delta z$  and close to  $J/\psi$
- 4) Tracks of  $\tau$  fitted to a common a vertex with probability  $> 10\%$
- 5) Additional cuts on mass and displacement applied
- 6) Final selection using a BDT discriminator trained on MC



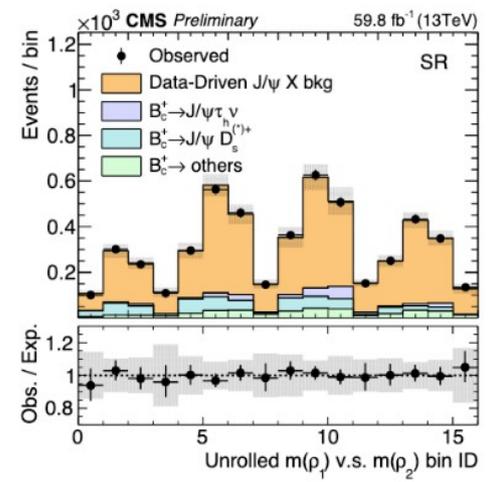
# Ratio of the $B_c \rightarrow J/\psi \tau \nu$ and $B_c \rightarrow J/\psi \mu \nu$ branching fractions



CMS-BPH-23-001

## Signal extraction:

- Exploit the decay chain of  $\tau \rightarrow \alpha \nu \rightarrow \rho(770) \pi \nu \rightarrow 3 \pi \nu$
- Pair pions in triplet and compute their mass
- Signal is expected to have  $\rho$  mass in one of the combinations
- Unroll both  $\rho$  candidate masses in 1D distribution
- Fit unrolled  $\rho$  to get the signal yield



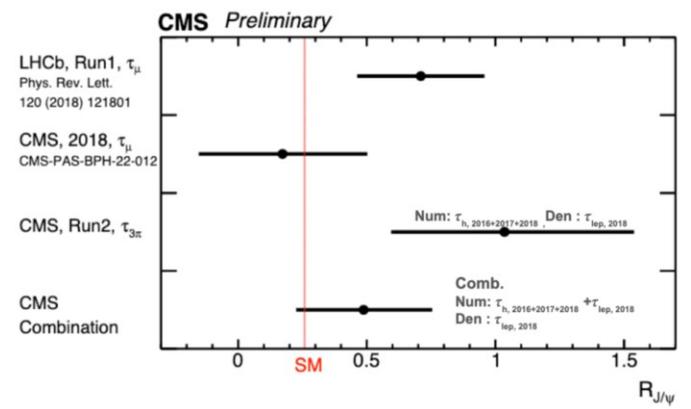
## Results:

- Fitting hadronic channel alone:

$$R(J/\psi)_{\text{hadr}} = 1.04^{+0.5}_{-0.44}$$

- Combining leptonic & hadronic channels:

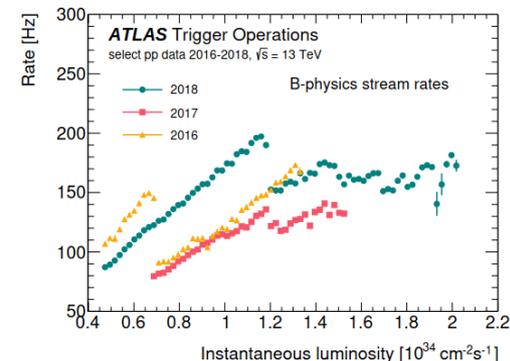
$$R(J/\psi)_{\text{comb}} = 0.49 \pm 0.25 \text{ (syst)} \pm 0.09 \text{ (stat)}$$



# A glance into the Run 3 improvements

## ATLAS

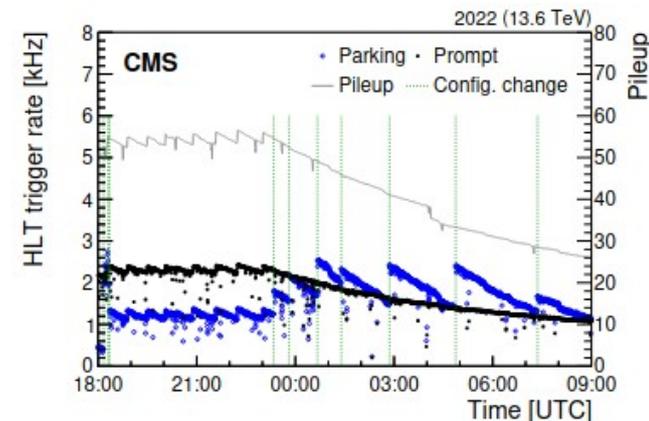
- Data high-rate parking already in place from Run1 and Run 2
- In Run 3: The rate increased up to 600Hz
- Complementary a soft di-electron trigger is used
- For more: [arXiv document](#)



## CMS

- High-rate parking strategy with dimuons through whole Run3
- High-rate parking strategy with dielectrons for precise LFU tests
- Described in detail in [arXiv document](#)
- State-of-the-art same-sign flavour tagger ([BPH-23-004](#))

Category	$\epsilon_{\text{tag}}$ [%]	$D_{\text{tag,eff}}^2$	$P_{\text{tag}}$ [%]
Only OS muon	$6.07 \pm 0.05$	0.212	$1.29 \pm 0.07$
Only OS electron	$2.72 \pm 0.02$	0.079	$0.214 \pm 0.004$
Only OS jet	$5.16 \pm 0.03$	0.045	$0.235 \pm 0.003$
Only SS	$33.12 \pm 0.07$	0.080	$2.64 \pm 0.01$
SS + OS muon	$0.62 \pm 0.01$	0.202	$0.125 \pm 0.003$
SS + OS electron	$2.77 \pm 0.02$	0.150	$0.416 \pm 0.005$
SS + OS jet	$5.40 \pm 0.03$	0.124	$0.671 \pm 0.006$
Combined	$55.9 \pm 0.1$	0.100	$5.59 \pm 0.02$



- Update of the CMS analysis “[New Structures in the  \$J/\psi J/\psi\$  mass Spectrum](#)” using high intensity Run 3 dimuon parking
- 4 muons in  $|\eta| < 2.4$
- OS pairs create 2  $J/\psi$  candidates
- All muons fit to a common vertex
  
- 4 times more  $J/\psi J/\psi$  candidates with only 2.5 times more data thanks to high-intensity dimuon triggers
- More than  $5\sigma$  for the 7.179 GeV peak
- More than  $5\sigma$  for the interference model (creates the “dips”)
  
- More details will become soon available in [preliminary BPH results](#)

## CMS-BPH-24-003

