Recent results in heavy-flavour physics by ATLAS and CMS

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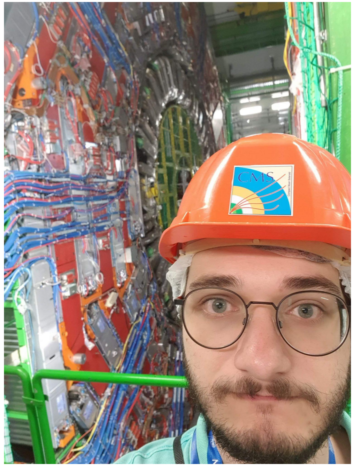

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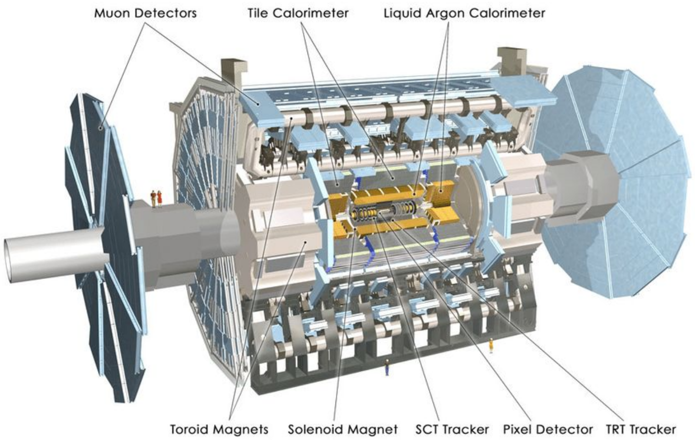
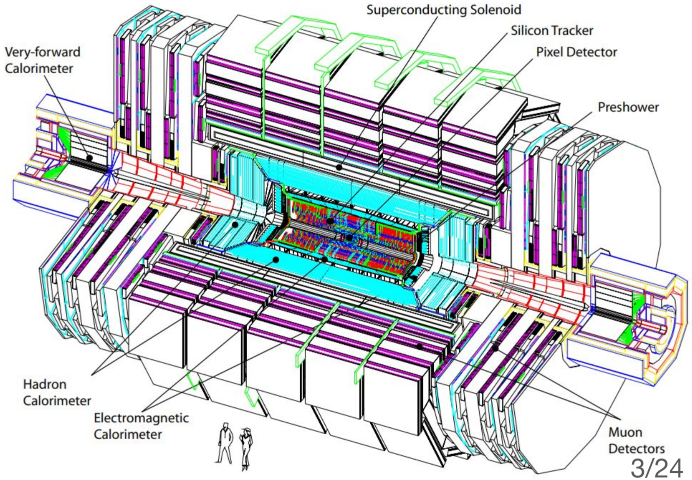
Introduction

- **In the last decade heavy-flavour physics has revealed itself as one of the most promising sectors in the search for physics beyond the Standard Model**
  - Several *anomalies* (slight discrepancies with SM predictions) have been observed in various types of measurements
  - **Cross-validation between experiments/results is essential**
- Flavour physics is studied both at dedicated experiments (e.g., LHCb at CERN and Belle II at KEK), but also at general-purpose ones
- **ATLAS and CMS have demonstrated time after time to be capable to produce high-quality results**
- At LHC, general-purpose detectors generally suffer from the lack of dedicated particle identification for light hadrons (kaons and pions)
- However they are not subjected to luminosity levelling
  - Greatly benefit from LHC upgrades
- Moreover their measurement is complementary to those obtained by LHCb, due to different kinematic acceptance
  - LHCb: $2 < \eta < 5$ *"forward region"*
  - ATLAS/CMS: $0 < \eta < 2.5$

ATLAS



CMS



Observation of triple J/ψ meson production

CMS-PAS-BPH-21-004

(preliminary)

Motivations

- **Triple J/ψ production as a probe of double- and triple-parton scatterings (DPS, TPS)**
  - Study unknown energy evolution of transverse (impact parameter *b*) proton shape
  - Probe generalized PDFs (x,Q^2,b) of the proton
  - Control backgrounds for rare SM resonance decays and BSM searches for multiple heavy particles
- **"Pocket formula":** $$\sigma_{\mathrm{DPS}}^{pp\to\psi_1\psi_2+X} = \left(\frac{k}{2}\right)\frac{\sigma_{\mathrm{SPS}}^{pp\to\psi_1+X}\,\sigma_{\mathrm{SPS}}^{pp\to\psi_2+X}}{\sigma_{\mathrm{eff,DPS}}}$$

  SPS cross sections

  combinatorial factor

  effective interaction area
  - σ_{eff} is derivable from p-p transverse overlap (assuming no parton correlation)
    - $\sigma_{\mathrm{eff}} \approx$ 20-30 mb from proton form-factor implemented in MC event generator
    - But experiments show:
      - $\sigma_{\mathrm{eff}} \approx$ 5 mb, from di-quarkonia f.s.
      - $\sigma_{\mathrm{eff}} \approx$ 15 mb, from jets, photons, EWK bosons
- **Idea:** study triple-parton scattering → $$\sigma_{\mathrm{TPS}}^{pp\to\psi_1\psi_2\psi_3+X} = \left(\frac{k}{3!}\right)\frac{\sigma_{\mathrm{SPS}}^{pp\to\psi_1+X}\,\sigma_{\mathrm{SPS}}^{pp\to\psi_2+X}\,\sigma_{\mathrm{SPS}}^{pp\to\psi_3+X}}{\sigma^2_{\mathrm{eff,TPS}}}$$
  - **Never observed so far**
  - Closely related to DPS: $\sigma_{\mathrm{eff,TPS}} = (0.82 \pm 0.11)\,\sigma_{\mathrm{eff,DPS}}$ [PRL118(2017)122001]
  - Triple prompt- J/ψ: DPS and TPS dominate [PRL122(2019)192002]

Triple J/ψ production diagrams

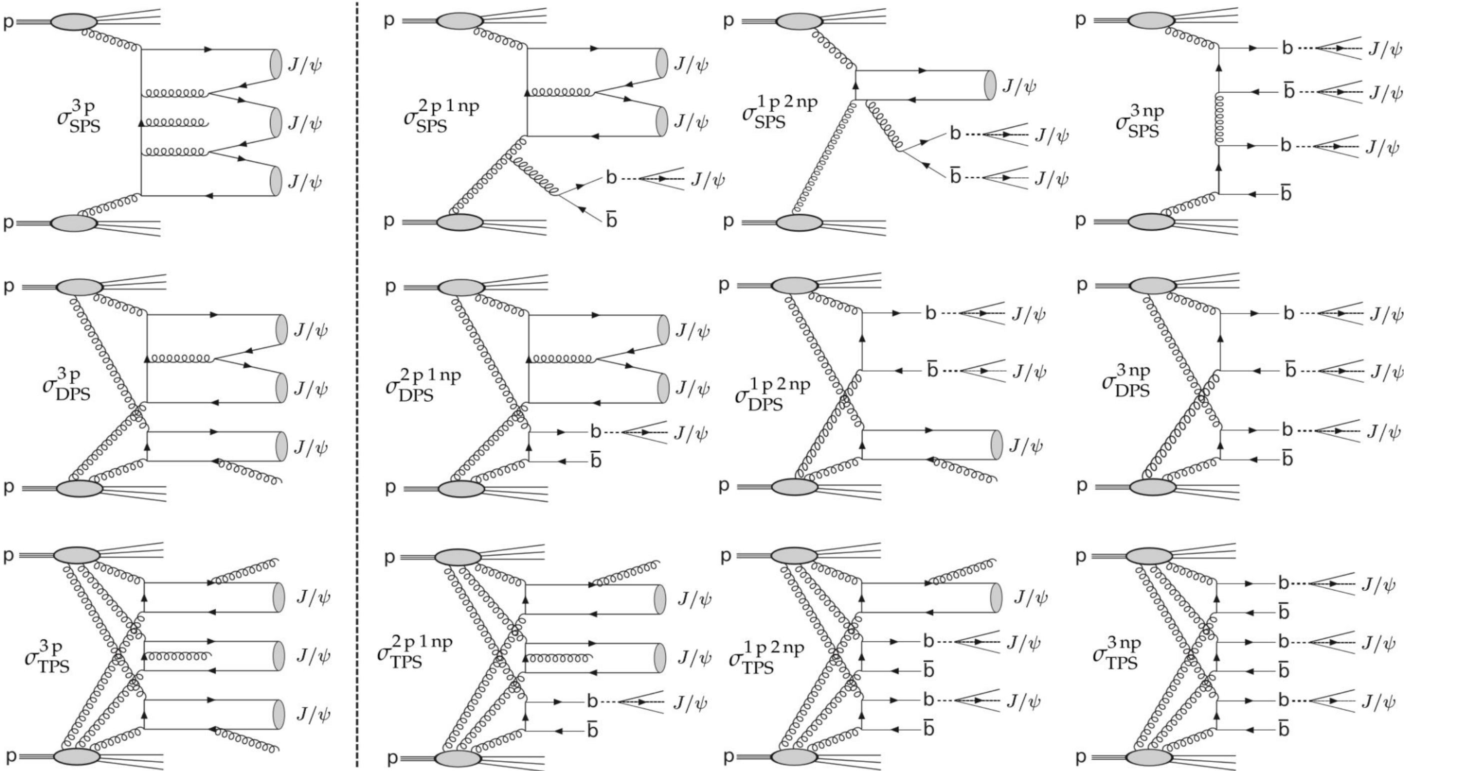
- σ(pp ➜ J/ψ J/ψ J/ψ X) = Mix of pp ➜ J/ψ (prompt) and pp ➜ b ➜ J/ψ (non-prompt) processes:

PROMPT **NON-PROMPT**

≈5% of total cross section SPS:

≈75% of total cross section DPS:

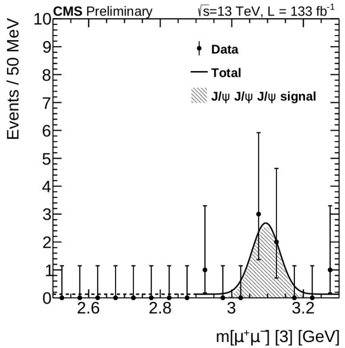
≈20% of total cross section TPS:



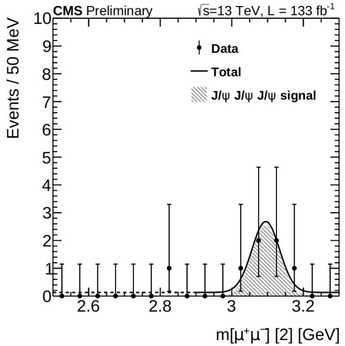
Analysis

- **Data taking period:** 2016+2017+2018
- **Center-of-mass energy**: 13 TeV
- **Integrated luminosity**: 133 fb^{-1}
- **Trigger**: $J/\psi \rightarrow \mu^+\mu^-$ candidate plus an additional muon
- **Selection:** 6 muons final state
  - $p_T > 3.5$ GeV for barrel and $p_T > 2.5$ GeV for endcap
  - Dimuon invariant mass between 2.9 and 3.3 GeV (± 6.5 times the J/ψ mass resolution)
  - **6 selected events** (4 in 2018 and 2 in 2017 data sets)
- Number of events extracted with a **3D unbinned extended ML fit** in the three $m_{J/\psi}$
  - *Signal*: Gaussian with resolution fixed from MC and mean fixed to PDG
  - *Background*: exponential
  - *Fit variables*: 8 yields accounting for all combinations each of the three J/ψ to either be signal or background
- **Signal yield: 5.0 ± 2.0 events** (6.7σ significance from likelihood ratio)
  - **First observation of triple parton scattering**
- **Checks**: toy pulls (no bias), fit in 2.5-3.3 GeV (N_{sig} = 5.0±2.2), with same-sign muon pairs (no events found)

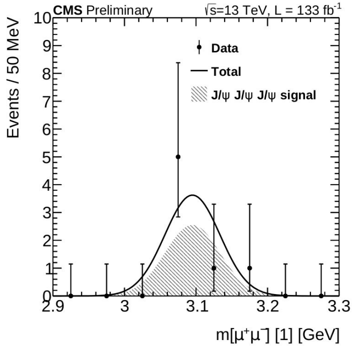
leading $p_T(\mu^+\mu^-)$



2nd-leading $p_T(\mu^+\mu^-)$



3rd-leading $p_T(\mu^+\mu^-)$



Results

- **Fiducial cross section measurement**

$$\sigma(pp \to J/\psi\, J/\psi\, J/\psi\, X) = \frac{N_{\text{sig}}}{\epsilon \cdot \mathcal{L}_{\text{int}} \cdot Br(J/\psi \to \mu\mu)^3}$$

Signal events
- N_{sig} = 5.0±2.0

Branching ratio
- $B^3_{J/\psi \to \mu\mu}$ = $(5.96\% \pm 0.03\%)^3$

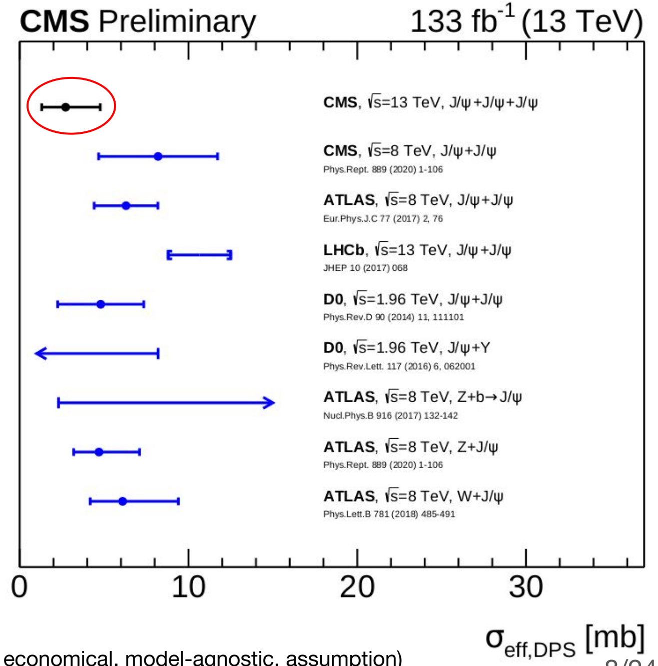
Efficiency
- trigger ≈ (84±3)%
- reconstruction ≈ (94.4±0.01)%
- muon ID ≈ (82.4±0.2)%

Luminosity
- L_{int} = 133 fb^{-1}

- **Result:** **σ(pp ➔ J/ψ J/ψ J/ψ X) = 272 ± 109(stat) ± 17(syst) fb**
- **From which can be derived*:**

$$\sigma_{\text{eff,DPS}} = 2.7 \pm 1.2(\text{exp}) \pm 1.5(\text{theo})\ \text{mb}$$

- **$\sigma_{eff,DPS}$ value is consistent with the world-data** obtained previously from diquarkonium production measurements



* Assuming that DPS/TPS cross sections can be expressed in terms of SPS single- and double-J/ψ cross sections (standard most economical, model-agnostic, assumption)

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

CMS-PAS-BPH-18-004

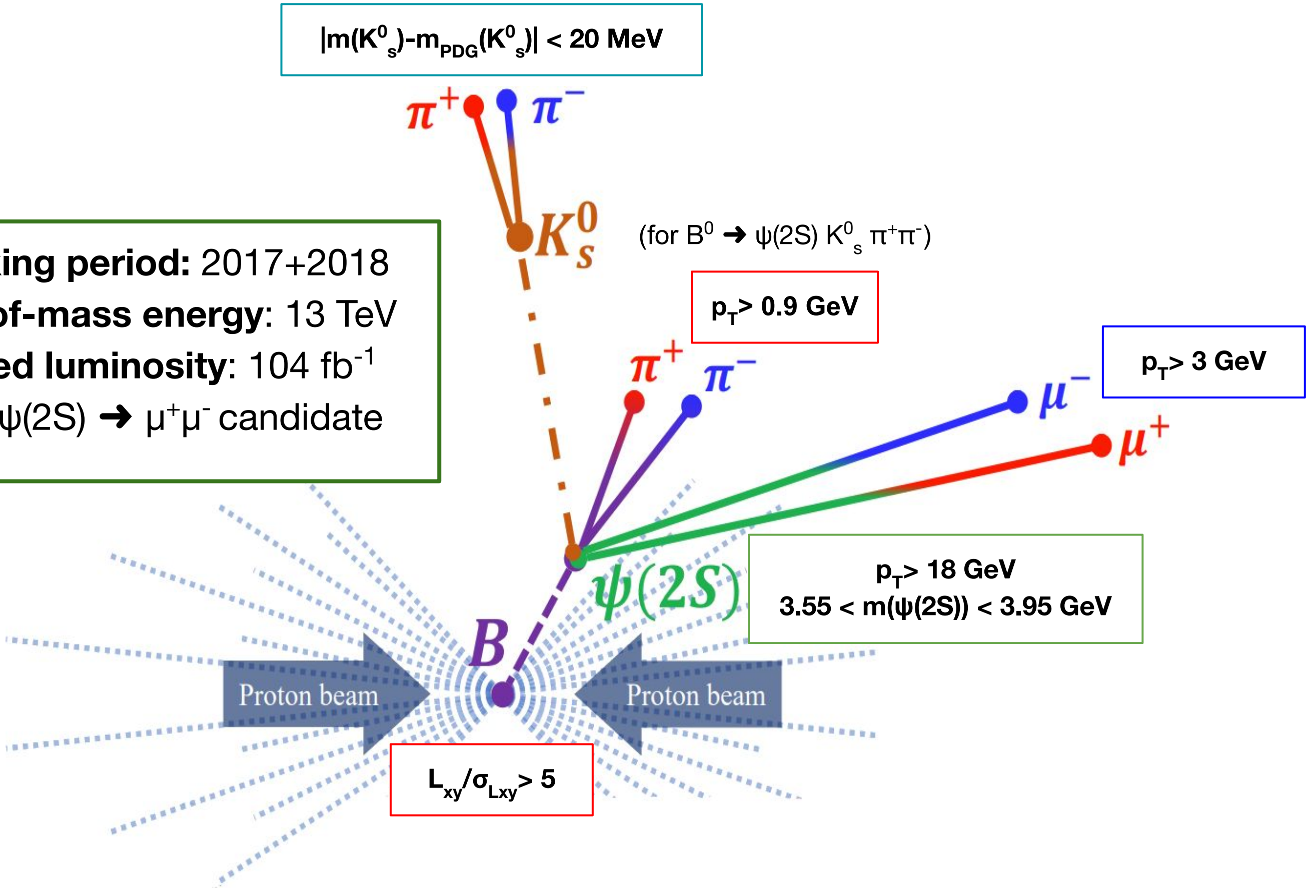
(preliminary)

Motivations

- **Decays with charmonium in final states are a good probe for time-dependent CP-violation measurement**
  - Tests of the flavour sector of the SM
  - Search for signs of New Physics
- **Many exotic states have been observed in the last 15 years, but the nature of most of them is still unclear**
  - $Z_c(3900)^{\pm} \rightarrow J/\psi\, \pi^{\pm}$ [Belle]
  - $Z_c(4200)^{\pm} \rightarrow J/\psi\, \pi^{\pm}$ [BaBar]
  - $Z_c(4430)^{\pm} \rightarrow \psi(2S)\, \pi^{\pm}$ [Belle]
  - $X(3915) \rightarrow J/\psi\, \omega$ [Belle]
  - $P_c(4457)^{+} \rightarrow J/\psi\, p$ [LHCb]
  - $Z_{cs}(4220)^{\pm} \rightarrow J/\psi\, K^{\pm}$ [LHCb]
- **This work present the search for the decays $B^0 \rightarrow \psi(2S)\, K^0_s\, \pi^+\pi^-$ and $B_s \rightarrow \psi(2S)\, K^0_s$**
  - Both can be used for CPV measurements
  - $B^0 \rightarrow \psi(2S)\, K^0_s\, \pi^+\pi^-$ can be used to search for intermediate exotic resonance

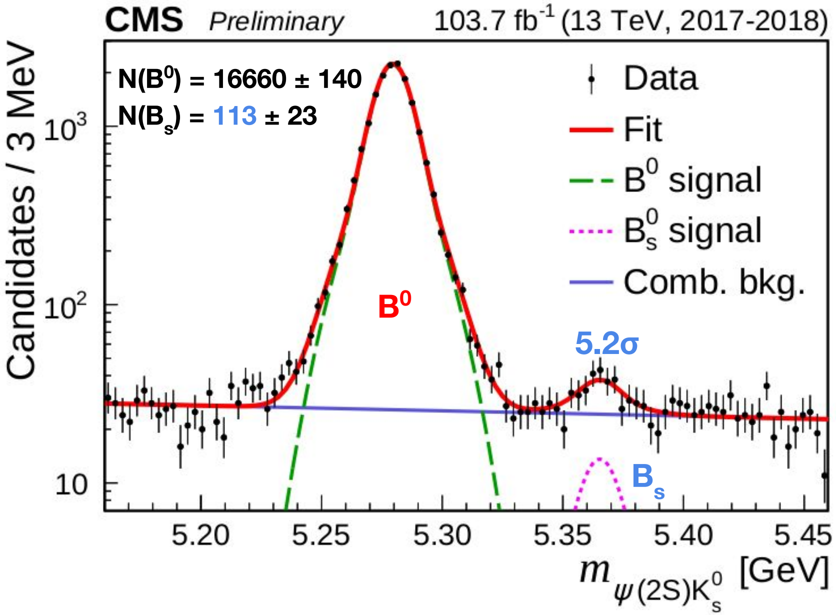
Candidate selection

- **Data taking period:** 2017+2018
- **Center-of-mass energy**: 13 TeV
- **Integrated luminosity**: 104 fb^{-1}
- **Trigger:** $\psi(2S) \rightarrow \mu^+\mu^-$ candidate

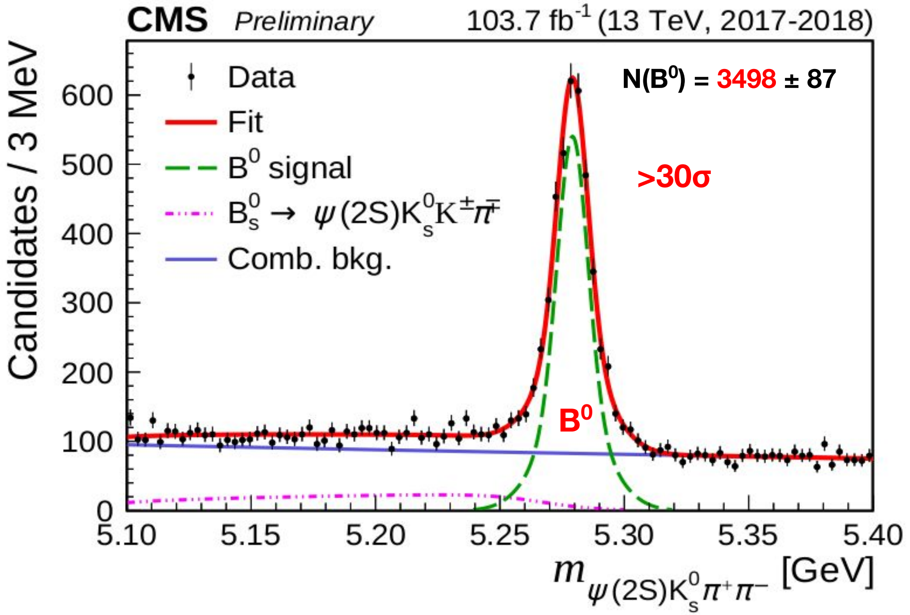


Results

$\psi(2S)K^0_s$



$\psi(2S)K^0_s\pi^+\pi^-$



- **First observation** of $B_s \to \psi(2S)K^0_s$ at 5.2σ
- **First observation** of $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ at >30σ

$$\frac{\mathcal{B}(B^0_s \to \psi(2S)K^0_S)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} \cdot \frac{f_s}{f_d} = (0.69 \pm 0.14\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst}))\%$$

$$\frac{\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} = (48.0 \pm 1.3\,(\mathrm{stat}) \pm 3.2\,(\mathrm{syst}))\%$$

Measurement of b-quark fragmentation properties in jets

arXiv:2108.11650 [hep-ex]

(submitted to JHEP)

Introductions

- **Heavy quark fragmentation is a crucial aspect of QCD**
- Reliable modelling of the fragmentation is of great importance for several measurements (e.g. H➜bb,tt, ...)
- Inputs to MC tuning still use LEP-era data

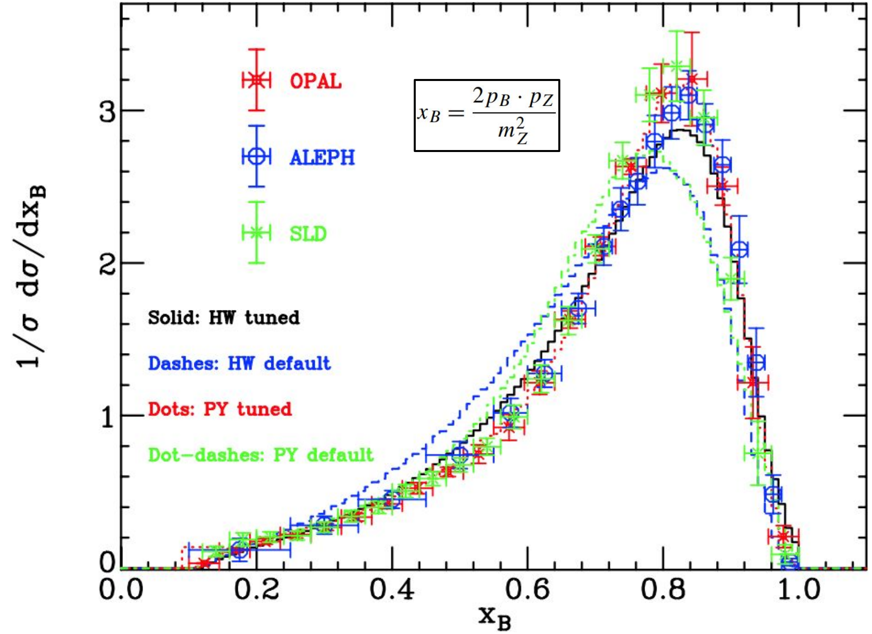


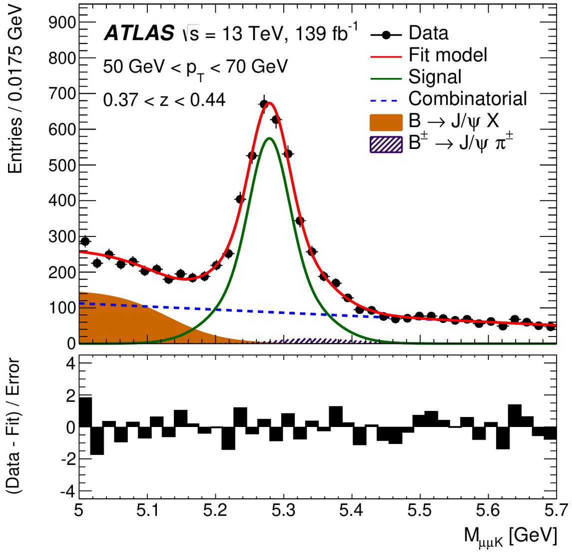
Figure: Data from LEP experiments on the B-hadron spectrum in e^+e^- annihilation, along with HERWIG and PYTHIA. From [EPJC65(2010)171].

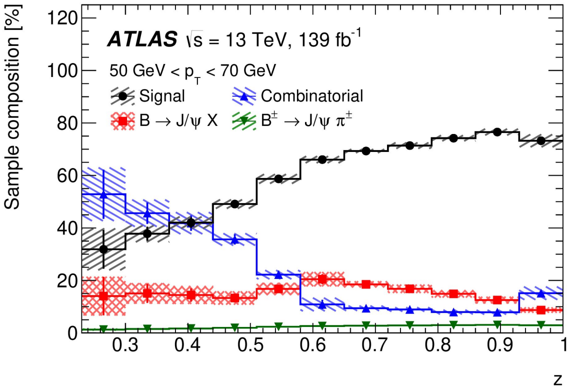
Analysis

- **The b-fragmentation is measured with the decay chain $B^{\pm} \rightarrow J/\psi\ K^{\pm} \rightarrow \mu^{+}\mu^{-}\ K^{\pm}$**
- Reconstructed B mesons are matched to jets and the longitudinal and transverse momentum profiles are defined as

$$\boxed{z = \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_j|^2}} \qquad \boxed{p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|\vec{p}_B \times \vec{p}_j|}{|\vec{p}_j|}}$$

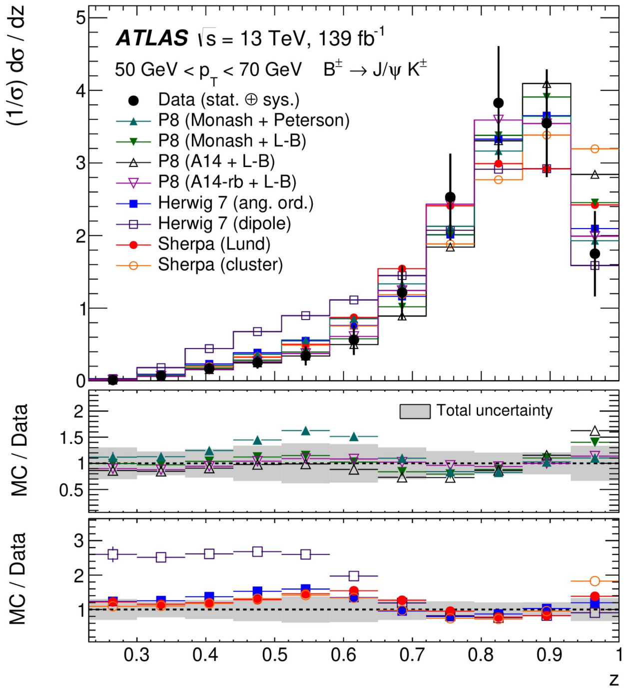
  - About 1.5M selected events
- Data are binned in three intervals of the jet p_T
  - [50, 70], [70, 100] and above 100 GeV
- A binned ML fit to the $B^{\pm}$ mass is performed in each of the (p_T, z) and (p_T, p_T^{rel}) bins to extract the number of signal events

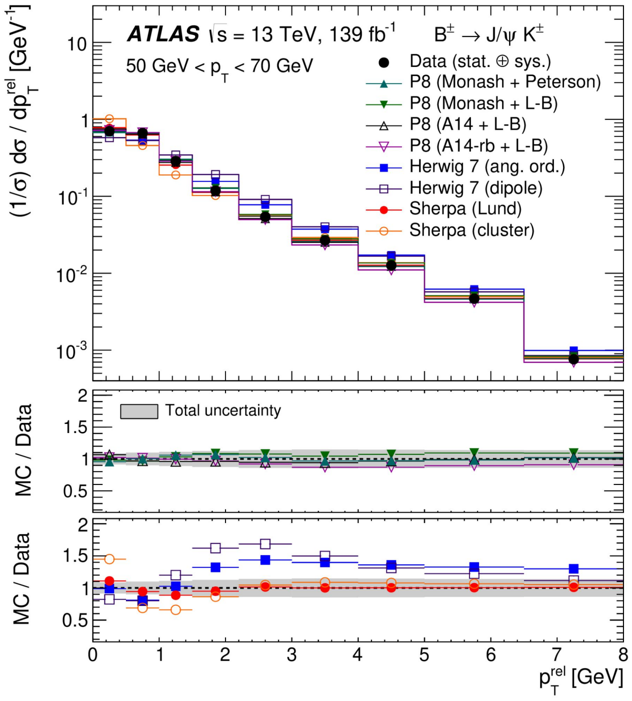


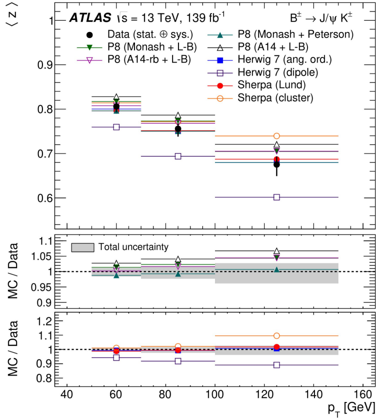


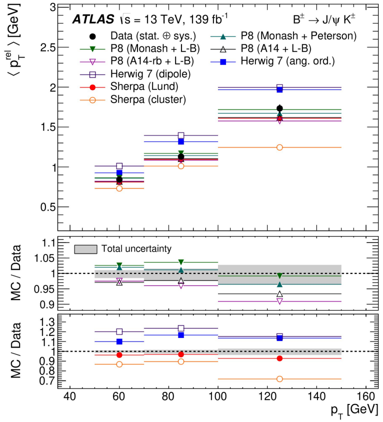
Results

Average values as a function of jet p_T









- All PYTHIA fragmentation models give a decent description
- SHERPA (cluster) and HERWIG7 (dipole) show clear disagreement in different regions

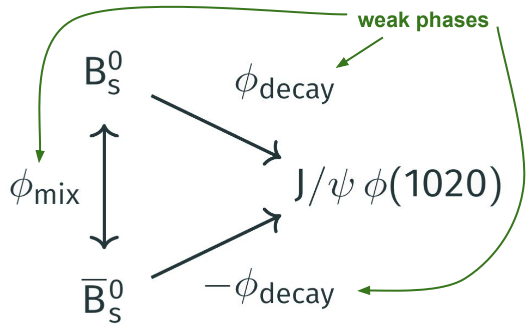
CP violation in B_s decays

Eur. Phys. J. C 81 (2021) 342 [ATLAS]

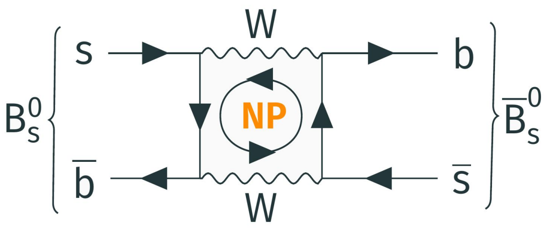
Phys. Lett. B 816 (2021) 136188 [CMS]

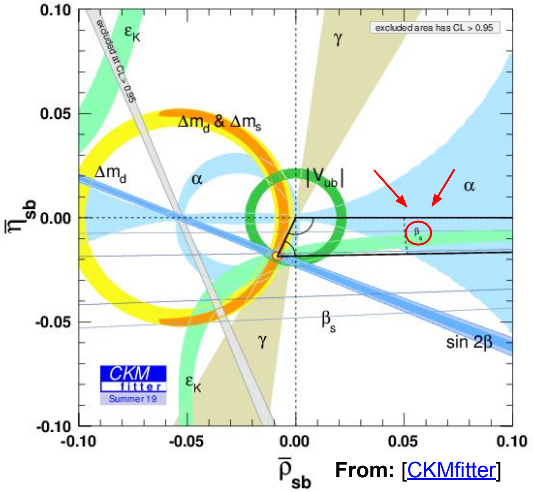
Motivations

- **Decays of B_s mesons allow to study the time-dependent CP violation generated by the interference between direct decays and flavour mixing**
  - CPV in the interference possible even if no CPV in decay and mixing
  - *Golden channel:* $B_s \to J/\psi\ \phi(1020) \to \mu^+\mu^-\ K^+K^-$
- **The weak phase ϕ_s is the main CPV observable**
  - Precisely predicted by the SM to be **$\phi_s \approx -2\beta_s \approx -37 \pm 1$ mrad**, where β_s is one of the angles of the B_s unitary triangle (determined very accurately by CKM global fits) [CKMfitter, UTfit]
- New physics can change the value of ϕ_s up to ~100% via new particles contributing to the flavour oscillations [RMP88(2016)045002]



$$\boxed{\phi_s = \phi_{\mathrm{mix}} - 2\phi_{\mathrm{decay}}}$$





From: [CKMfitter]

Measurement ingredients

- **Need to measure time-dependent flavour asymmetry**

final-state CP eigenvalue

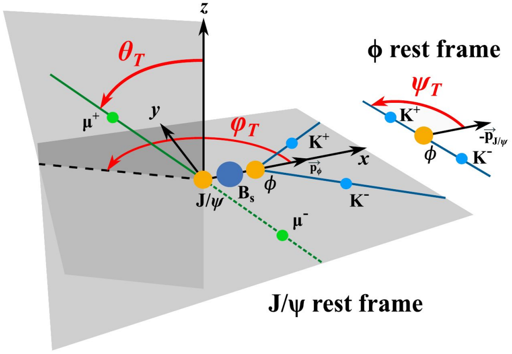
CP violation

flavour oscillations

$$a_{\mathrm{CP}}(t) = \frac{-\eta_{\mathrm{fs}}\,\sin(\phi_s)\,\sin(\Delta m_s t)}{\cosh(\frac{1}{2}\Delta\Gamma_s t) + \eta_{\mathrm{fs}}\,\cos(\phi_s)\,\sinh(\frac{1}{2}\Delta\Gamma_s t)}$$

- **Essential ingredients**
  a. Time-dependent **angular analysis** to separate the different CP eigenstate
  b. Excellent **time resolution** to see the fast B_s flavour oscillations (T ~ 350 fs)
  c. **Flavour tagging** to infer the initial B_s flavour

$$\text{sensitivity} \propto \sqrt{\frac{\epsilon_{\mathrm{tag}}\mathcal{D}^2_{\mathrm{tag}}N_{\mathrm{sig}}}{2}}\sqrt{\frac{N_{\mathrm{sig}}}{N_{\mathrm{sig}}+N_{\mathrm{bkg}}}}\,e^{-\frac{\sigma_t^2\Delta m_s^2}{2}}$$

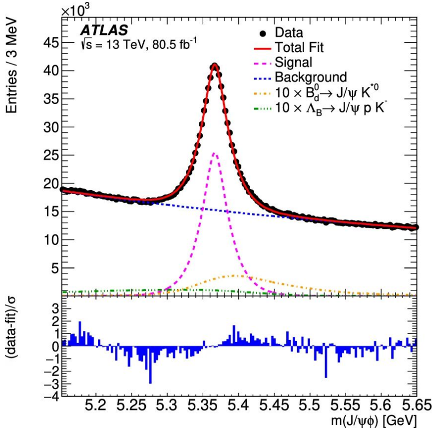


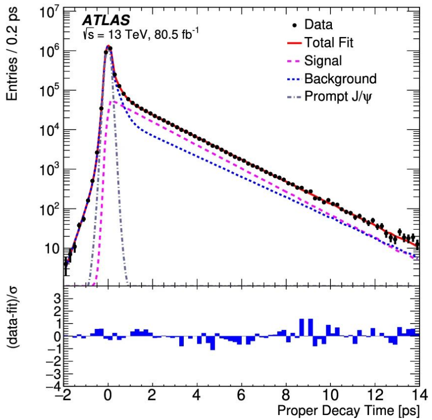
From: [PLB816(2021)136188]

Analysis

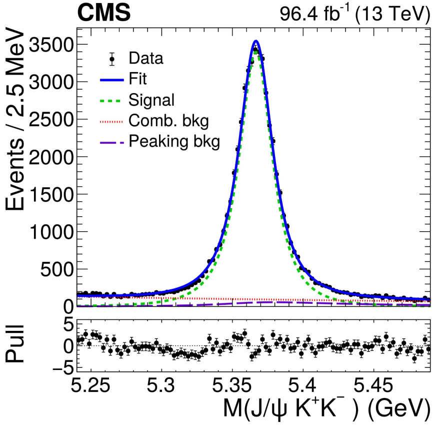
- **Dataset:** 2015-2017 (L_{int} = 80.5 fb^{-1})
- **Trigger:** J/ψ ➜ $\mu^+\mu^-$ candidate

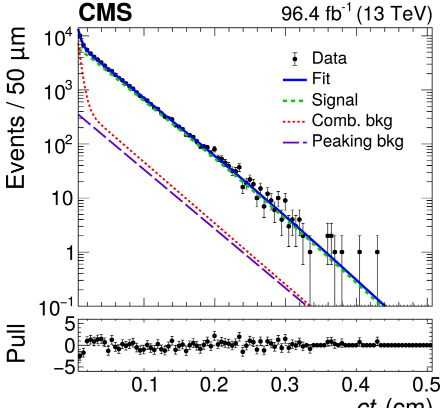
- **Decay lenght cut:** none
- **m(K$^+$K$^-$) interval:** [1008.5, 1030.5] MeV *(w.a. ± 11 MeV)*
- **Number of signignal candidates:** 453570 ± 740
- **Flavour tagging:** opposite-side muon, electron and jet
  - $\varepsilon_{tag} \approx 21\%$, $\omega_{tag} \approx 29\%$, $P_{tag} \approx 1.8\%$





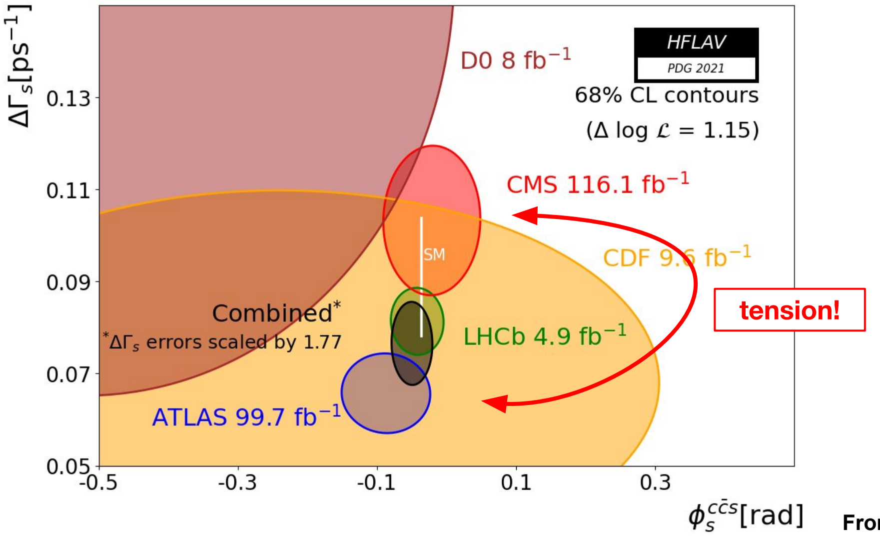
- **Dataset:** 2017-2018 (L_{int} = 96.4 fb^{-1})
- **Trigger:** J/ψ ➜ $\mu^+\mu^-$ candidate plus an additional muon (used for flavour tagging)
- **Decay lenght cut:** 70 μm (to reduce prompt bkg.)
- **m(K$^+$K$^-$) interval:** [1009.5, 1029.5] MeV *(w.a. ± 10 MeV)*
- **Number of signignal candidates:** 48500 ± 250
- **Flavour tagging:** opposite-side muon
  - $\varepsilon_{tag} \approx 50\%$, $\omega_{tag} \approx 27\%$, $P_{tag} \approx 10\%$



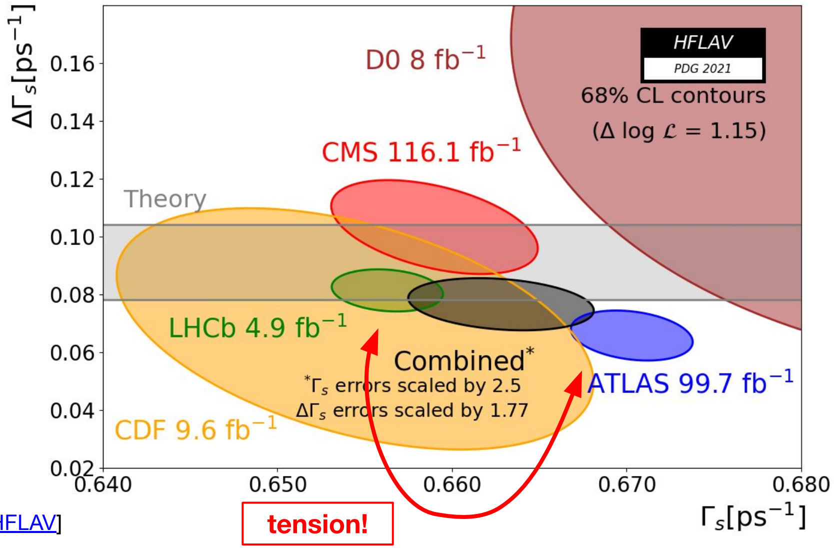


Results

- **An unbinned extended ML fit is used to extract several physics parameters describing the B_s system and the CPV in $B_s \to J/\psi\ \phi(1020)$**
- Both ATLAS and CMS measure ϕ_s, $\Delta\Gamma_s$, Γ_s, three decay amplitudes and respective strong phases
  - Additionally CMS measures Δm_s and the observable $|\lambda|$ related to the amount of direct CPV
- Both experiments combine the 13 TeV results with those obtained at 8 TeV
- **$\Delta\Gamma_s$ and Γ_s show tensions between experiments**
- Hopefully full Run-2 measurements will clarify the situation



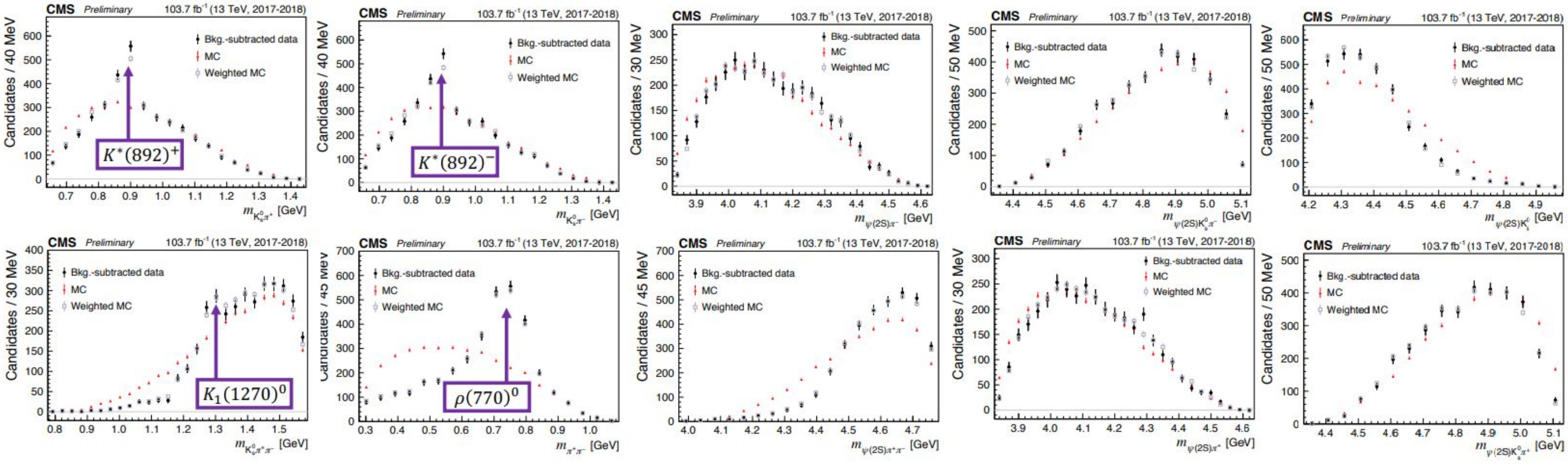
From: [HFLAV]



Conclusions

BACKUP

$B^0 \rightarrow \psi(2S)\, K^0_s \pi^+\pi^-$ intermediate invariant masses



- **The mass distributions of ψ(2S) and one or two light mesons do not present any significant narrow peaks that could indicate a contribution from an exotic charmonium state.**