B physics in ATLAS & CMS

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on behalf of the ATLAS and CMS Collaborations

2024 LHC Days Split

30th Sept - 4th October
Hvar, Croatia

B physics in ATLAS & CMS

two general purpose experiments probing heavy flavor physics

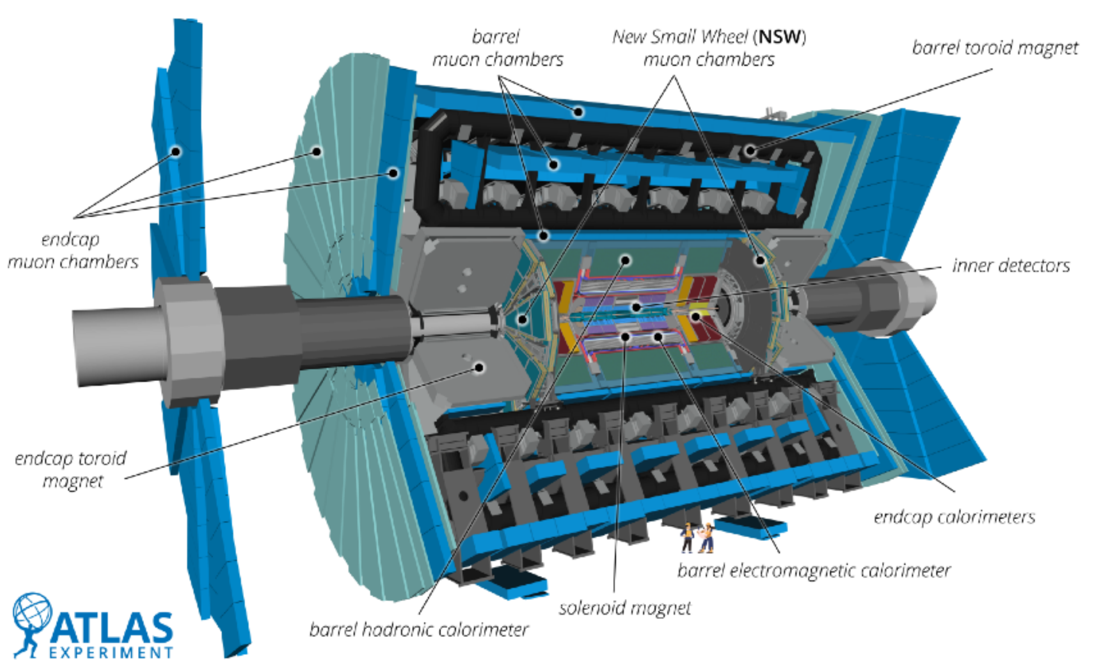
Both ATLAS and CMS have a rich and competitive heavy flavour program

- ★ Rare decays
- ★ CP and LFU violation
- ★ Quarkonium production and spectroscopy

Many results highly competitive with dedicated B-physics experiments

- excellent detector performance, large data samples
- *novel dedicated data-taking* approaches greatly expanded the original search/measurement program

Complementary rapidity region wrt LHCb



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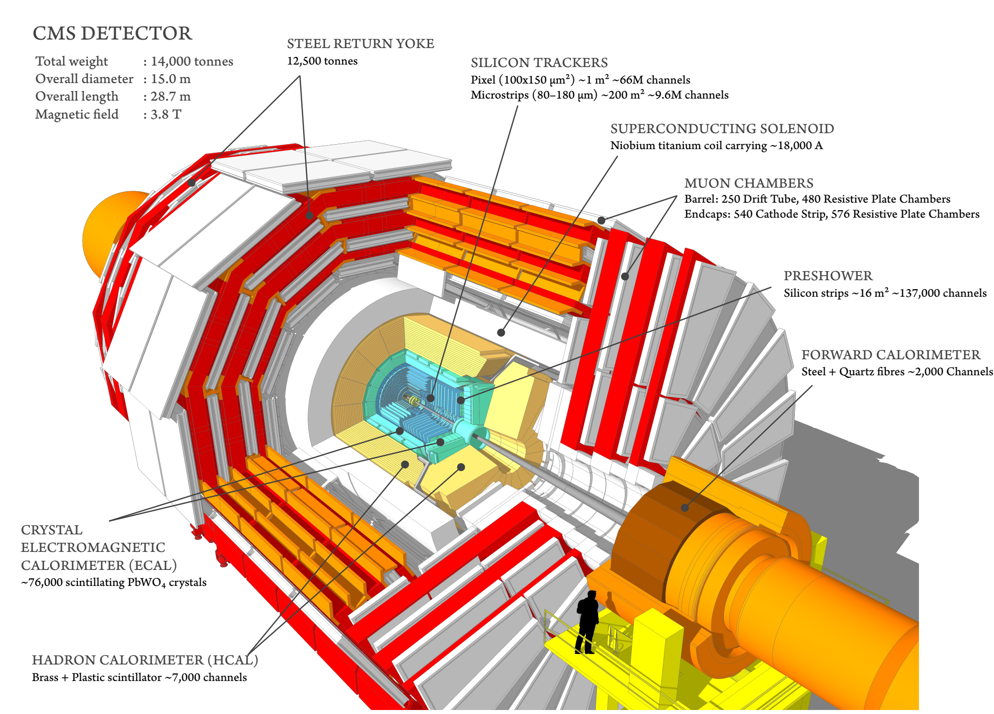


https://cds.cern.ch/record/2665537

outline

selected recent results from the two Collaborations

Charmonia production studies

- Measurement of double-differential and total charm-production cross sections — CMS-PAS-BPH-22-007
- Measurement of the production cross section of J/ψ and $\psi(2S)$ mesons — Eur. Phys. J. C 84(2024)169
- Measurement of the polarizations of prompt and non-prompt J/ψ and $\psi(2S)$ mesons — CMS BPH-22-009

Search for New Physics

- Measurements of the B_s effective lifetime — CMS BPH-22-001, JHEP 09 (2023) 199
- Test of LFU via $R(J/\psi)$ measurement — CMS BPH-22-012, CMS PAS BPH-23-001
- Full angular analysis of the $B^0 \rightarrow K^*\mu\mu$ decay — CMS PAS BPH-21-002
- Search for rare charm decays into two muons — CMS PAS BPH-23-008

Charm(onia) production studies

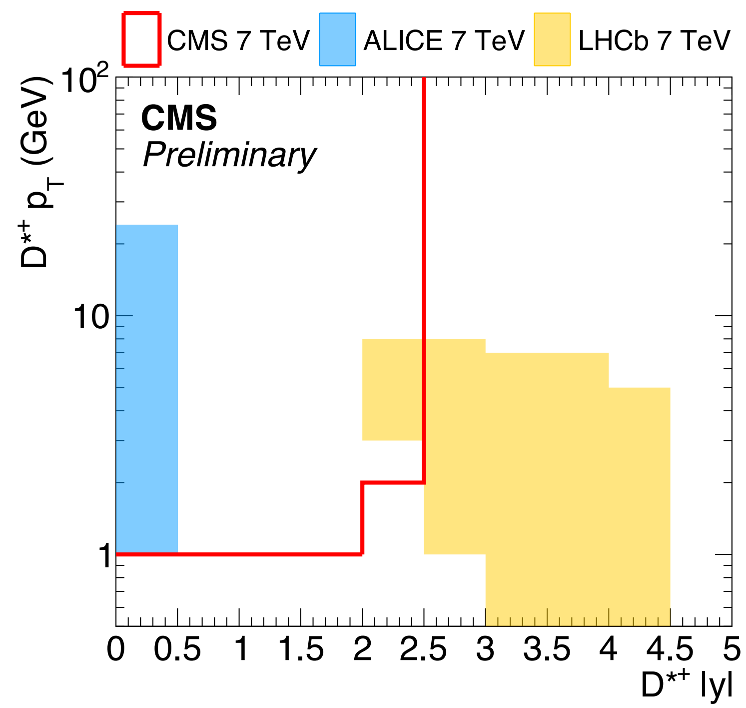
charm cross section | CMS

CMS-PAS-BPH-22-007

Measurement of double-differential and total charm-production cross sections at 7 TeV

Charm production measurements provide an important test of QCD models

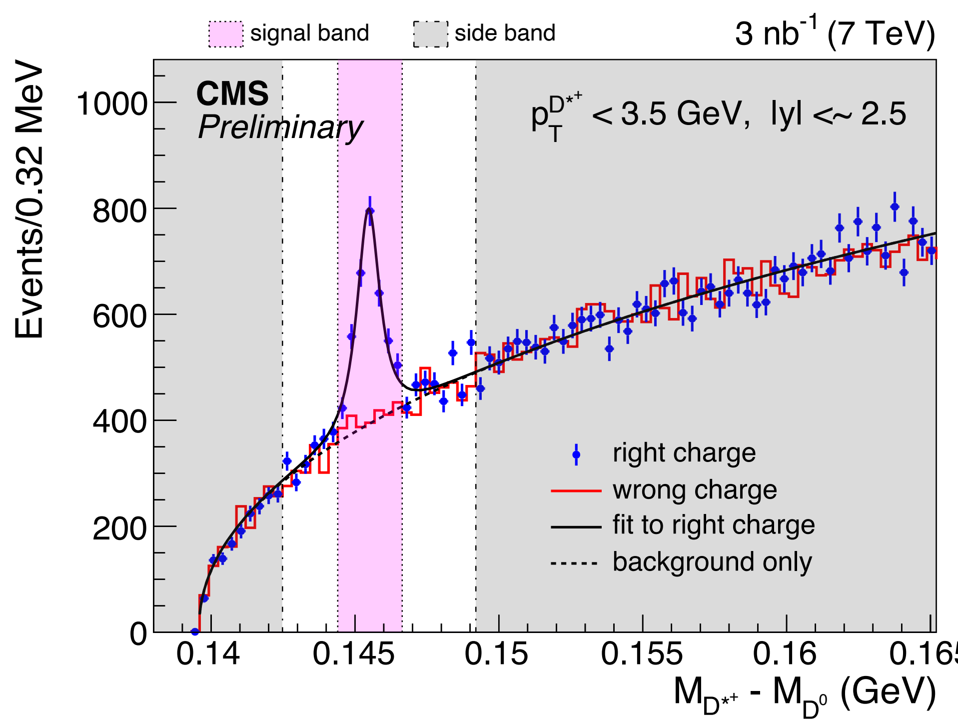
- charm mass scale close to Λ_{QCD} transition region of perturbative and non-perturbative regimes
- differential σ → NLO QCD predictions
- total σ → NNLO QCD predictions



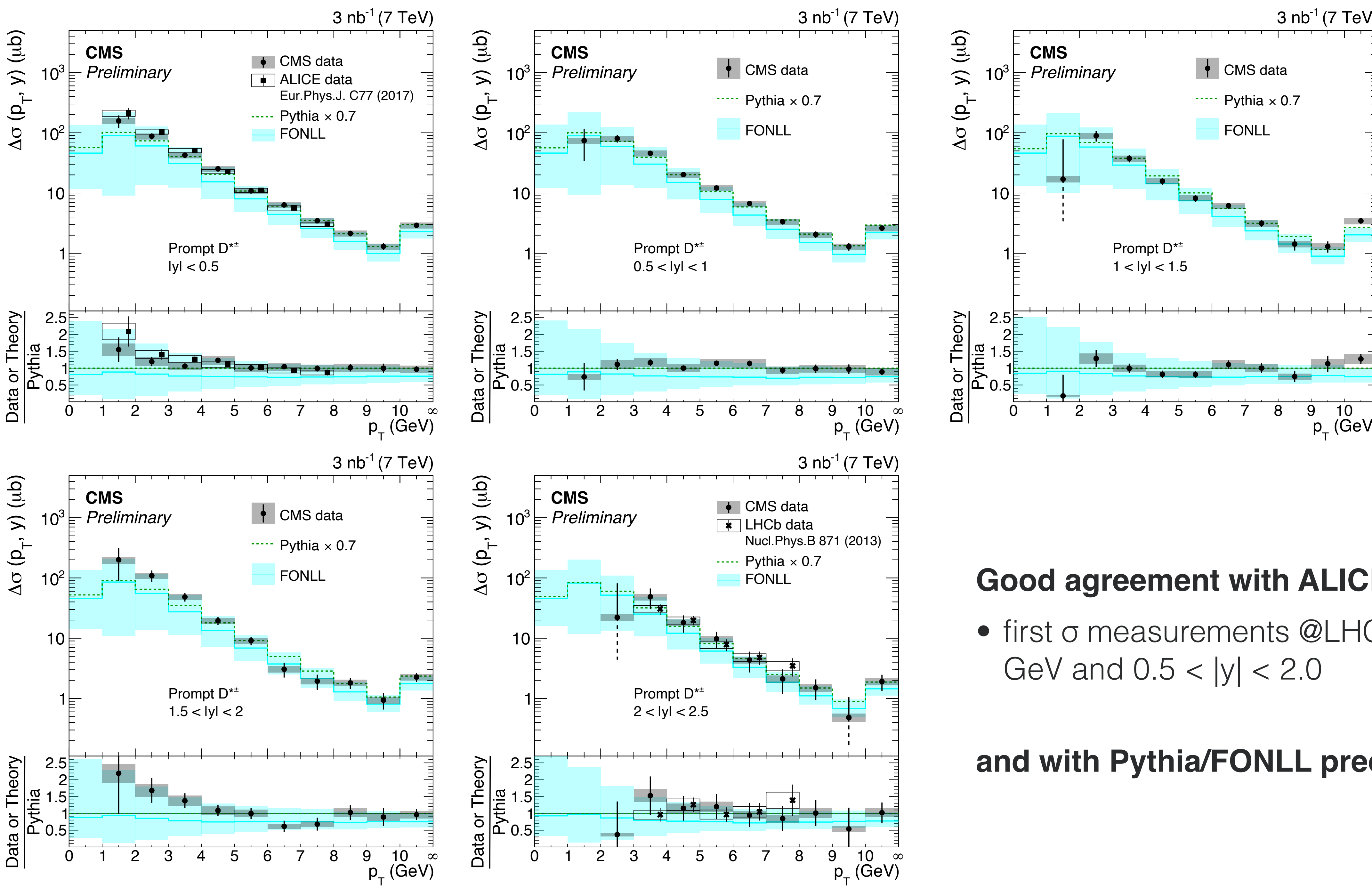
CMS dataset of pp collisions at 7 TeV (2010, 3.0 nb^{-1}) with special low-p_T tracking (down to < 100 MeV)

Measured through $D^{*+}(2010) \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$ decay chain reconstruction

- lower momentum (slow) of π_s^+ compared to K^- and π^+ allows to distinguish them
- collinearity of π_s^+ and D^{*+} provides optimal resolution on $m(D^{*+}) - m(D^0)$, strongly suppression of the combinatorial background



charm cross section | CMS

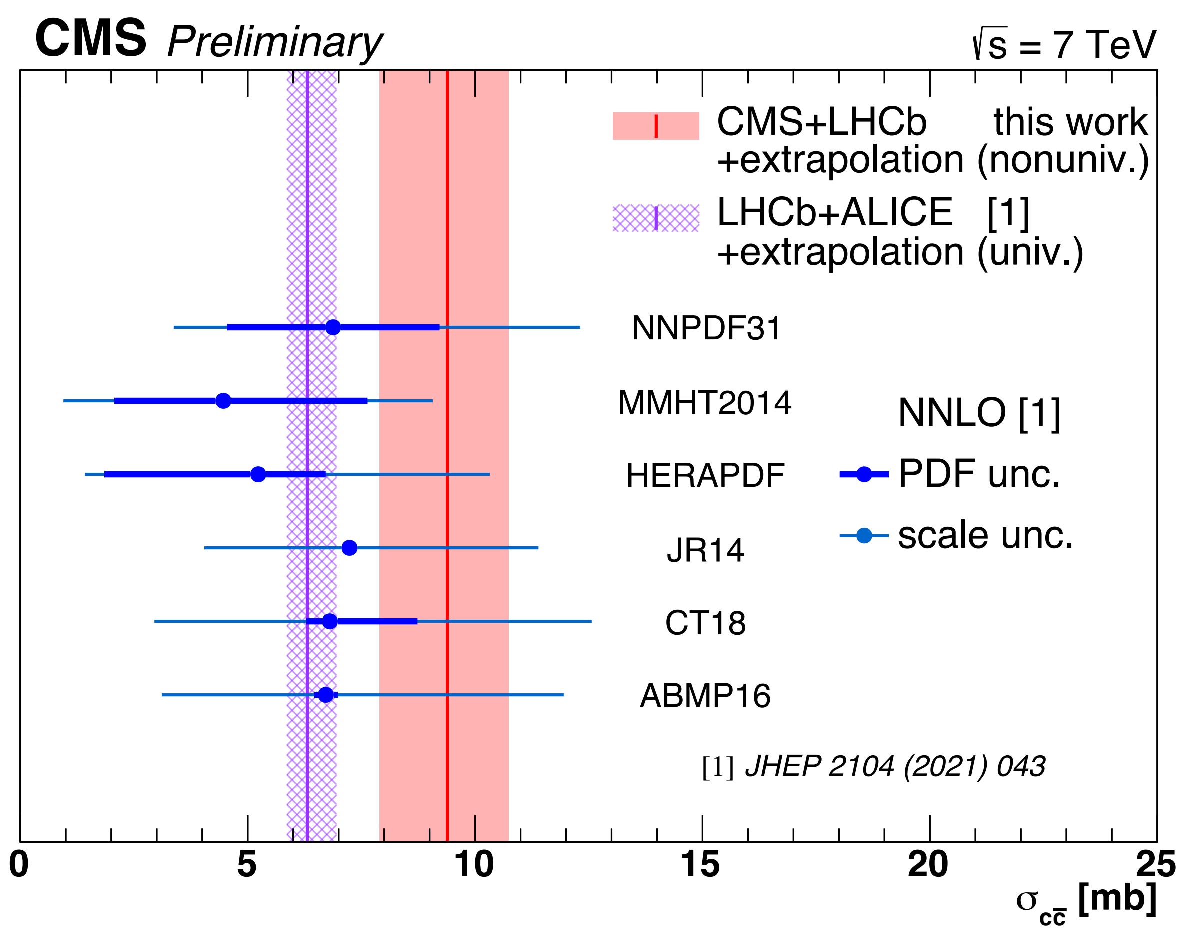


Good agreement with ALICE/LHCb data

- first σ measurements @LHC for p_T < 3.5 GeV and 0.5 < |y| < 2.0

and with Pythia/FONLL predictions

charm cross section | CMS



Considerably smaller uncertainties than NNLO theory

Consistent with the upper edge of the NNLO-theory band

Measurement of the fiducial cross section extrapolated to the full phase space

- using new phenomenological approach accounting for non-universality of charm fragmentation in the extrapolation
- as expected, increase in the measured cross section compared to previous results based on charm-fragmentation-universality assumption

Combined with measurement from LHCb @7TeV to cover the whole *y* phase space

- **largest phase space for charm production ever explored at LHC** → smallest extrapolation factor, minimal impact of theoretical uncertainties

$$\sigma_{c\bar{c},\mathrm{tot}} = 9.39^{+0.74}_{-0.74}(\mathrm{data})^{+0.77}_{-0.73}(\mathrm{ddFONLL})^{+0.83}_{-1.07}(f^{\mathrm{pp}})\ \mathrm{mb}$$

J/ψ & ψ(2S) xsec | ATLAS

Measurement of the production cross section of J/ψ and ψ(2S) mesons in pp collisions at 13 TeV with the ATLAS detector

Eur. Phys. J. C 84(2024)169

Significant extension of the kinematic range of quarkonium production measurements (up to 360 GeV for the J/ψ)

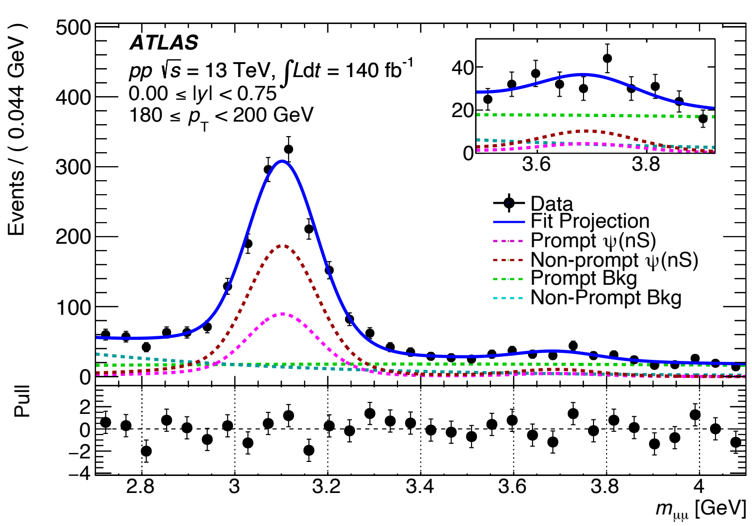
Two different triggers collecting data through 2015-2018

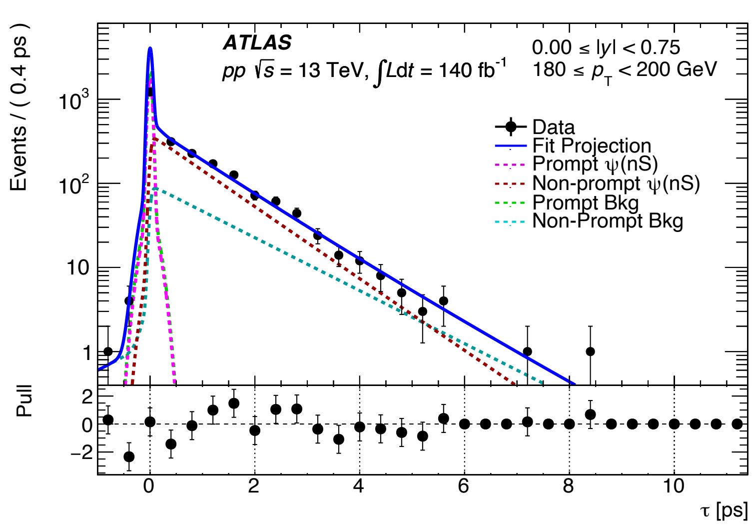
- dimuon trigger: low p_T (2.6 fb^{-1})
- single muon trigger: high p_T (140 fb^{-1})

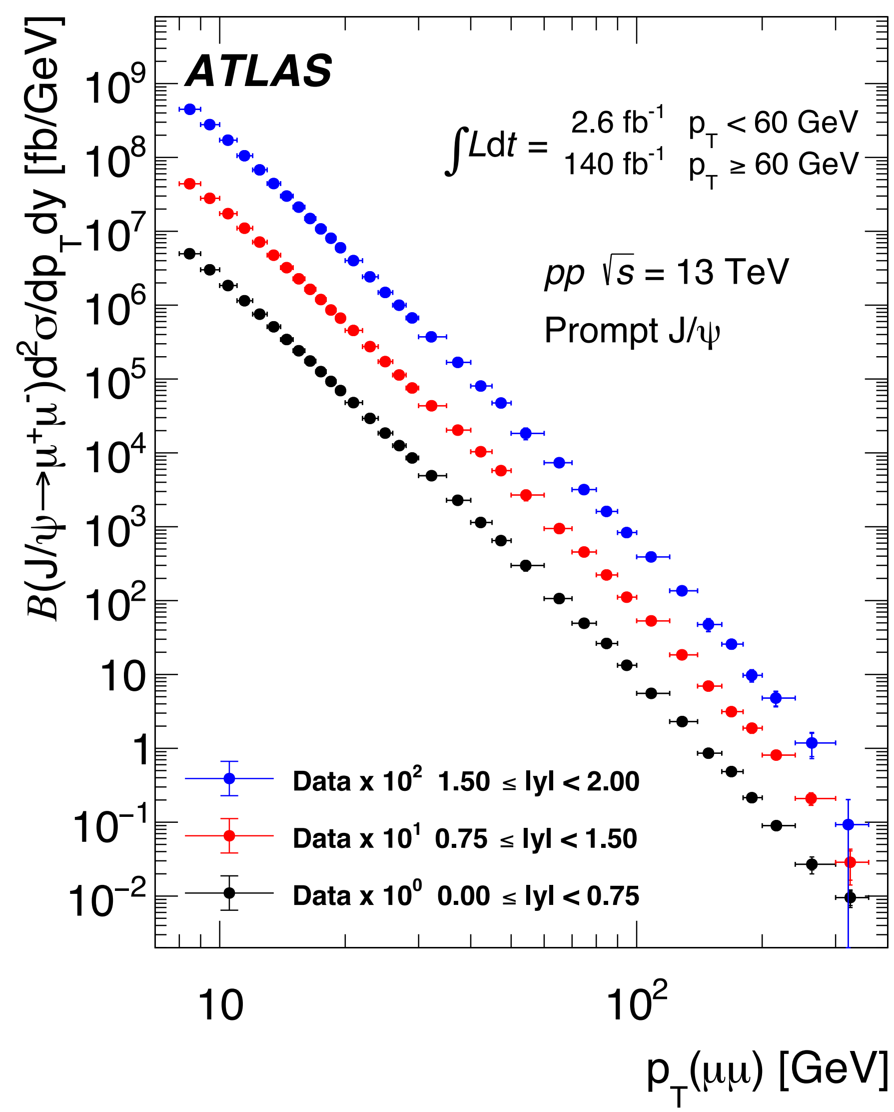
Prompt and non-prompt contributions measured

2D unbinned maximum-likelihood fit to dimuon invariant mass $m_{\mu\mu}$ and pseudo-proper decay time τ in 34 p_T x 3 *y* bins

- fine granularity at low p_T to reduce possible modelling biases





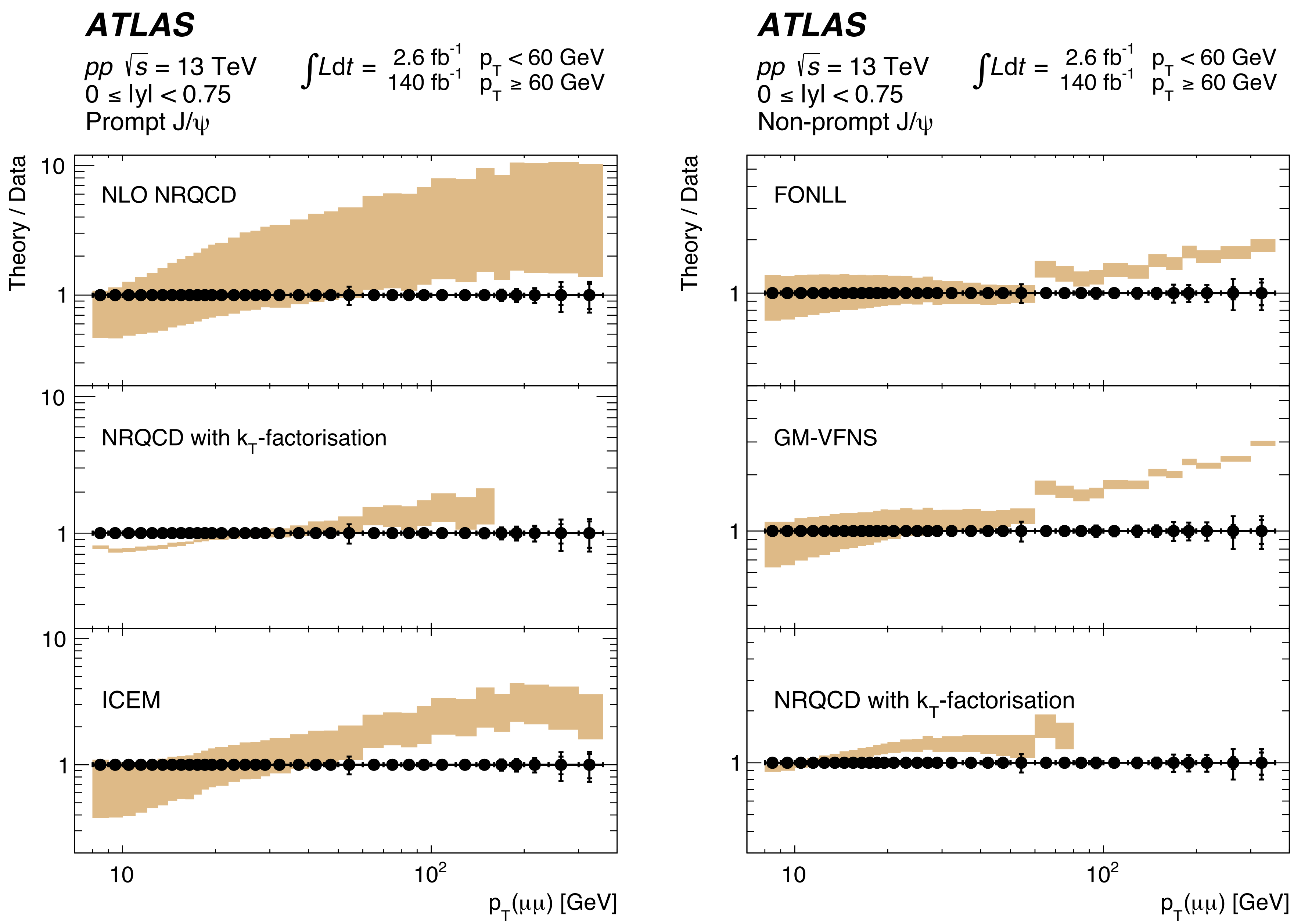


J/ψ & ψ(2S) xsec | ATLAS

Comparison to various theoretical predictions for prompt and non-prompt productions

no model able to describe the data over the whole p_T range, with general overestimation at high p_T

precious input to theorists for model tuning, especially at high p_T



J/ψ & ψ(2S) polarization | CMS

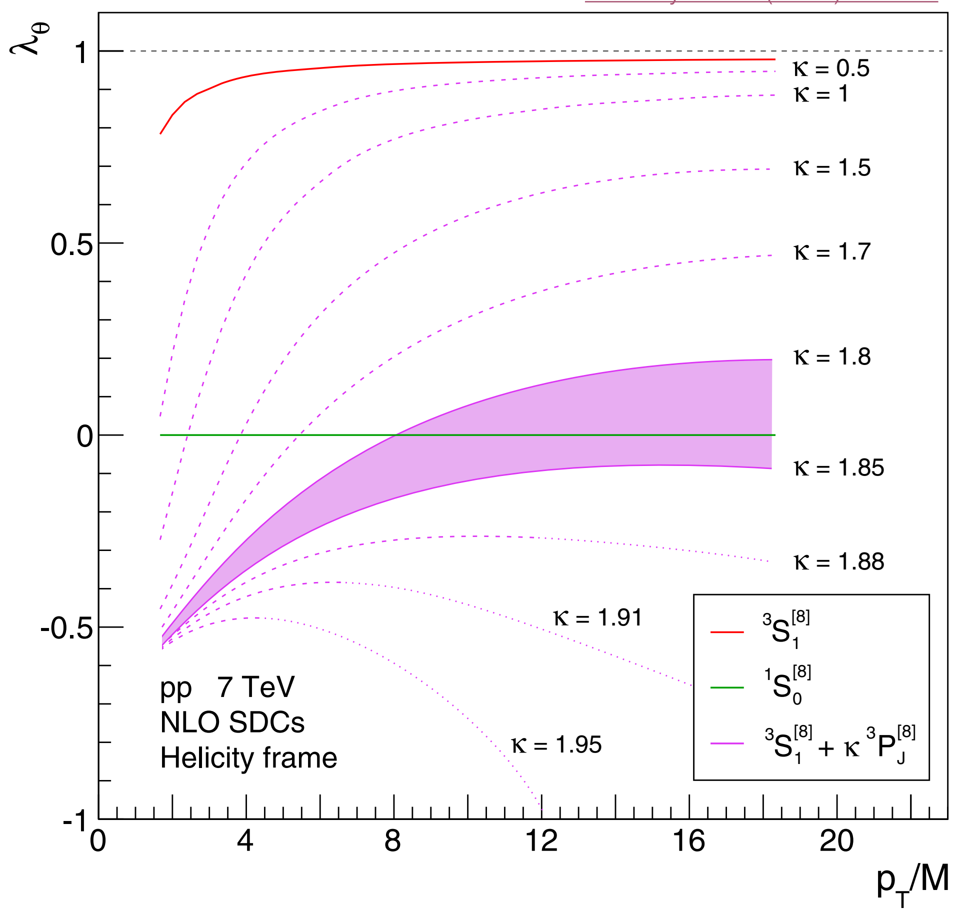
Measurement of the polarizations of prompt and non-prompt J/ψ and ψ(2S) mesons produced in pp collisions at 13 TeV

CMS BPH-22-009
subm. to PLB

Quarkonium polarization measurements provide information on details of the hadronization models

- directly reflects the mixture of S, L, J configurations and polarizations of the contributing pre-resonance states
- precise polarization measurement over p_T sensitive to relative contributions of the differently polarized colour octet terms

Eur. Phys. J. C (2019) 79: 457



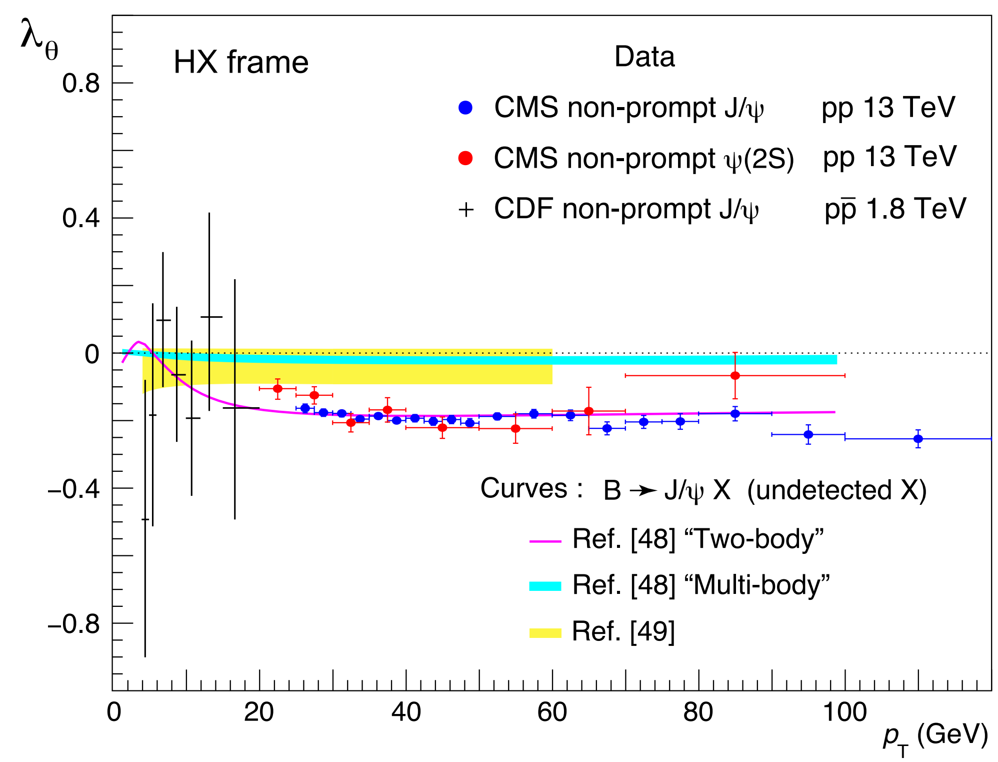
Polar anisotropy λ_θ measured vs p_T for J/ψ and ψ(2S) mesons

- based on the analysis of the dimuon decay angular distributions in the helicity frame
- data sample from 2017-2018 (103.3 fb^{-1})
- **prompt and non-prompt polarizations** measured separately

J/ψ & ψ(2S) polarization | CMS

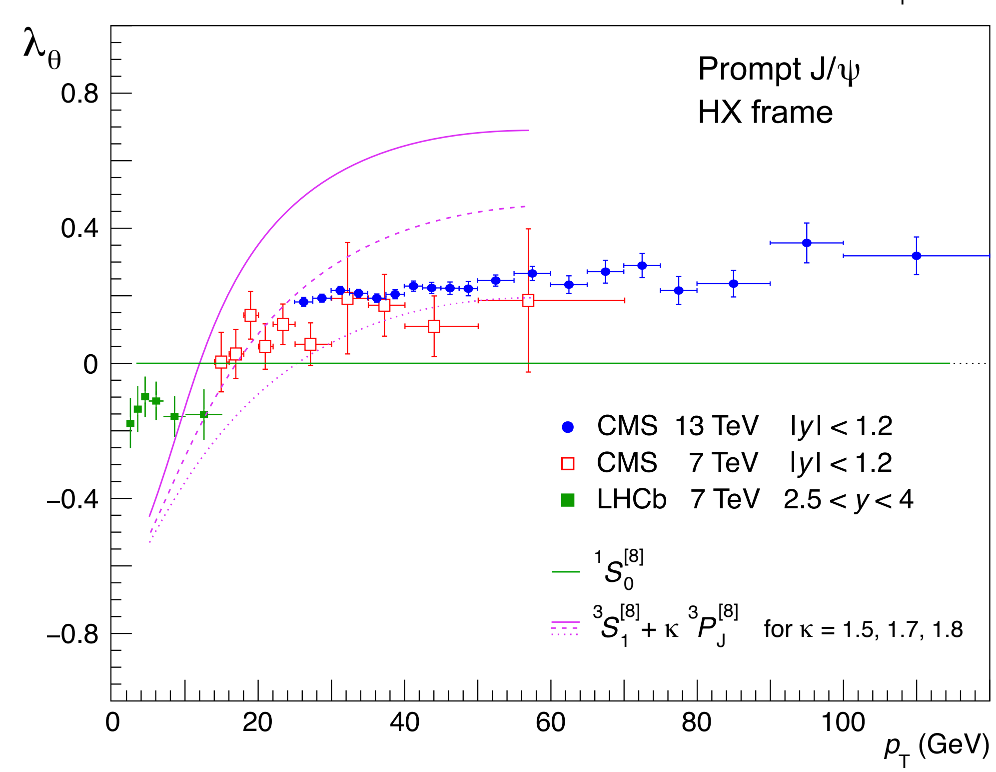
Non-prompt J/ψ and ψ(2S) measurements are compatible and both plateauing at $\lambda_\theta \approx -0.2$ for $p_T > 30$ GeV

- agree with predictions (JHEP10(2022)010) based on the hypothesis of **ψ predominantly produced by two-body B decays through colour-singlet processes**



Prompt polarization shows no evidence of strong transverse polarizations, even at large p_T values

- interpreted in NRQCD: no evidence of ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ dominance over unpolarized ${}^1S_0^{[8]}$ octet at large p_T
- prompt polarization varies significantly vs p_T



Significant constraints to phenomenological analyses, so far mostly focused on p_T-differential cross sections

Searches for NP in the flavour sector

B_s effective lifetime | intro

In the $B_s^0 - \bar{B}_s^0$ system, light and heavy mass eigenstates have sizable difference between their decay widths:

ΔΓ = 0.082 0.007 ps^{-1}

Effective lifetime τ^{eff} is defined as

$$\tau^{eff} = \frac{\tau_{B_s}}{1-y^2} \cdot \frac{1+2yA_{\Delta\Gamma}+y^2}{1+yA\Delta\Gamma} = \frac{\int t[\Gamma(B_s)+\Gamma(\bar{B}_s)]dt}{\int \Gamma(B_s)+\Gamma(\bar{B}_s)dt}$$

Sensitive to BSM physics, **e.g. new particles entering the mixing or changing the amount of CP violation**

- complementary to the branching fraction measurements

$B_s^0 \to \mu\mu$ is exactly CP-odd

$$\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)\ \mathrm{ps} \equiv \tau_{B^0_{s,H}}$$

$B_s^0 \to J/\psi K_S^0$ is quasi CP-odd

$$\tau_{J/\psi K_S^0}^{SM} = (1.62 \pm 0.02)\ \mathrm{ps} \simeq \tau_{B^0_{s,H}}$$

$B_s \to \mu\mu$ effective lifetime | ATLAS

Measurement of the $B_s^0 \to \mu\mu$ effective lifetime with the ATLAS detector

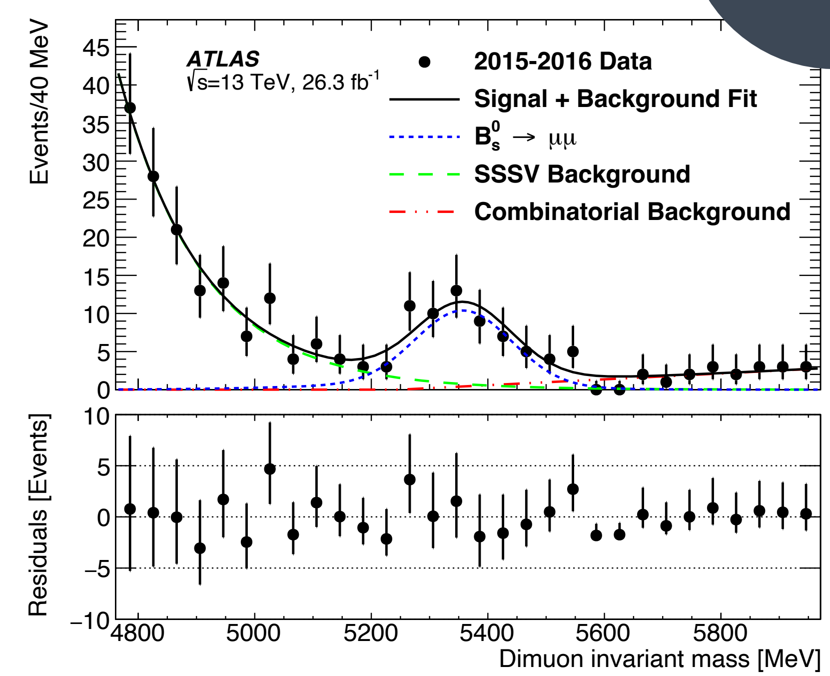
JHEP 09 (2023) 199

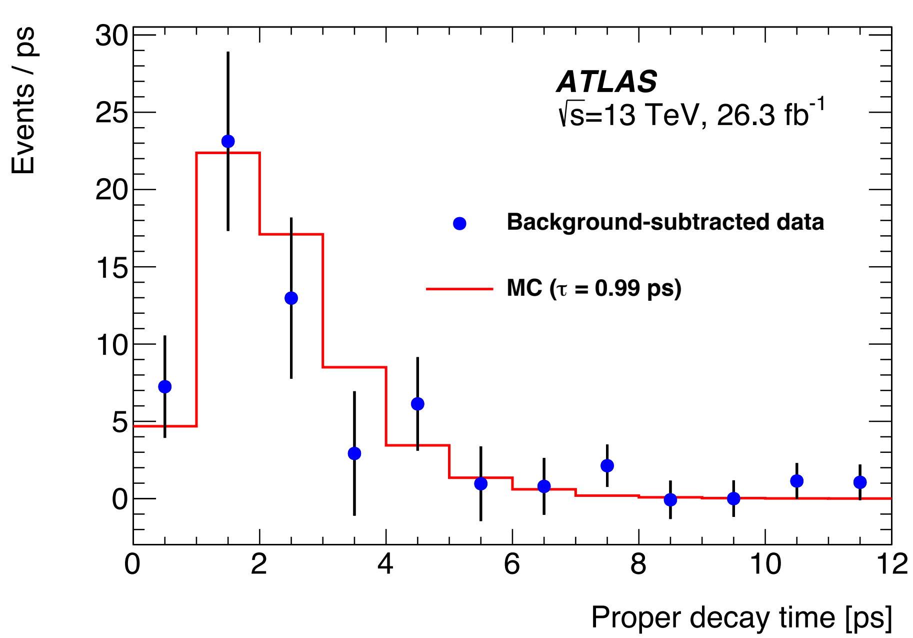
ATLAS measurement on Run2 data (2015-2016, 26.3 fb^{-1})

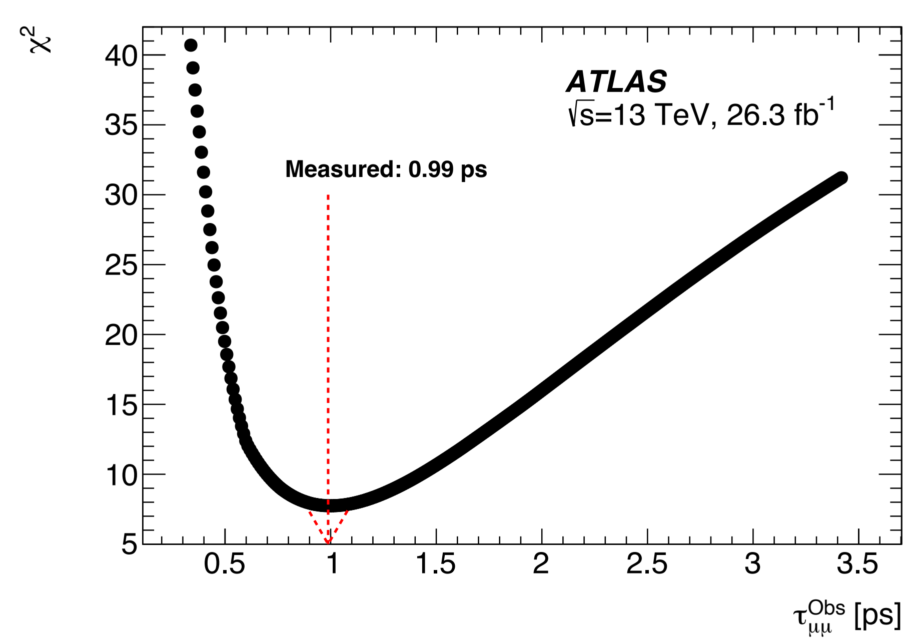
- Signal proper decay-time distribution from data obtained via *sPlot*
- Lifetime value extracted by a fit using simulated signal templates
  - χ^2 scan performed for several lifetime hypotheses

$$\tau_{\mu\mu}^{Obs} = 0.99^{+0.42}_{-0.07}(\text{stat}) \pm 0.17(\text{syst})\ \text{ps}$$

consistent with SM prediction







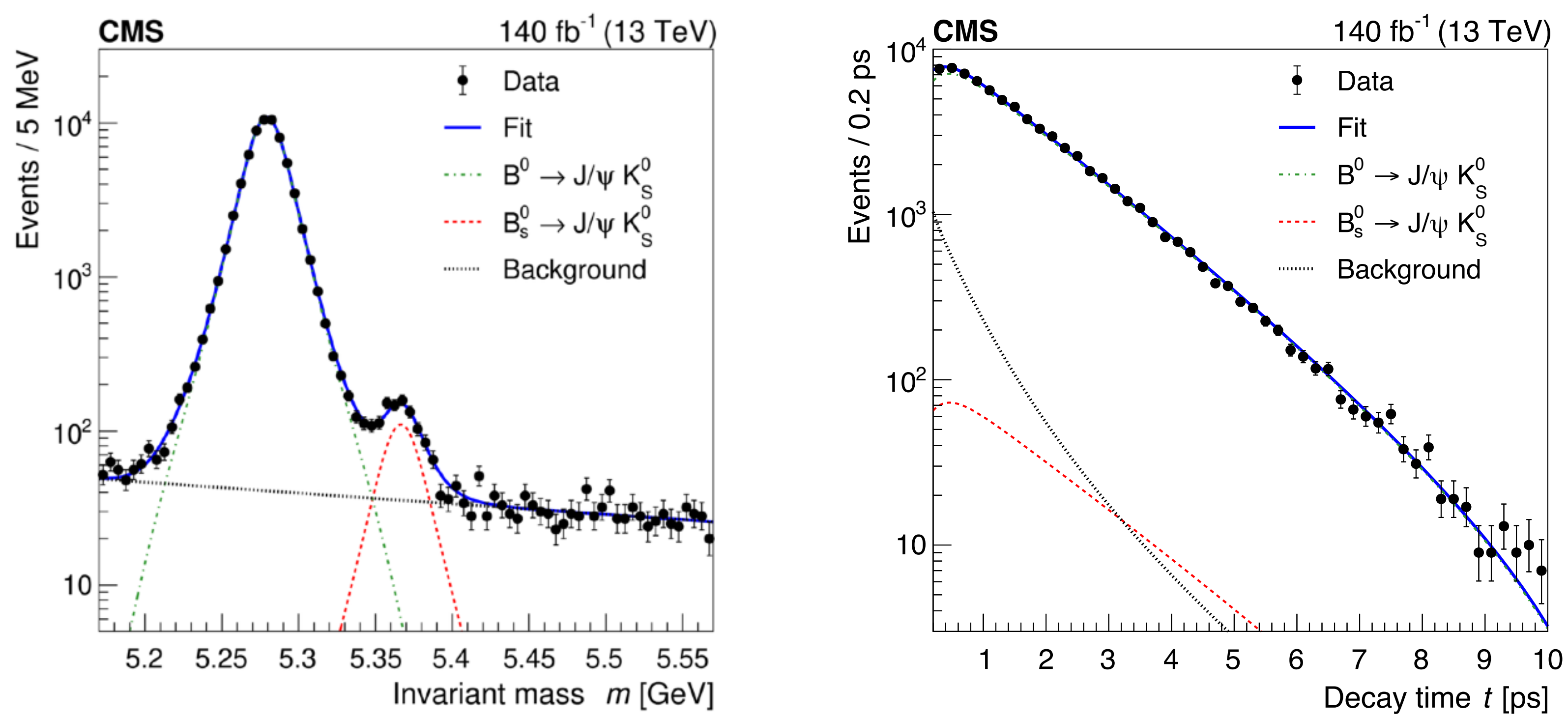
$B_s \rightarrow J/\psi K_S$ effective lifetime | CMS

Measurement of the $B^0 \rightarrow J/\psi K^0_S$ effective lifetime from pp collisions at 13 TeV

CMS BPH-22-001
subm. to JHEP

CMS analysis of 2016-2018 dataset (140 fb^{-1})

- using $K_S \rightarrow \pi\pi$ decays
- 2D unbinnned maximum likelihood fit to $m(J/\psi K_S)$ and proper decay time t
- Fit pdf comprises the efficiency parametrisation, obtained from studies on simulation



$$\tau(B^0_s \rightarrow J/\psi K^0_S) = 1.59 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\,\text{ps}$$

consistent with the SM prediction

most precise measurement to date

Measurement of R(J/ψ) | CMS

Test of lepton flavor universality in semileptonic B_c meson decays in pp collisions at 13 TeV

Lepton flavor universality in electroweak interactions is an accidental symmetry of the SM

LFU violation predicted by several BSM models:

- can be tested in Z and W decays, as well as in the b hadron sector

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$$

SM expectation = 0.2582 ± 0.0038

PRL 125, 222003

Tree level decay, complements other measurements of $R(H_c)$

Since B_c mesons cannot be produced at the existing B factories, **R(J/ψ) has not been extensively explored**

Only one available measurement, from LHCb R(J/ψ) = 0.71 ± 0.17(stat) ± 0.18(syst) (2σ from SM)

PRL 120, 121801

CMS searches, based on Run2 data, targeting both leptonic and 3-prong hadronic τ decays

- common denominator
- smaller dataset for leptonic channel due to trigger requirements (59.7 fb^{-1} vs 138 fb^{-1})

Measurement of R(J/ψ) | CMS

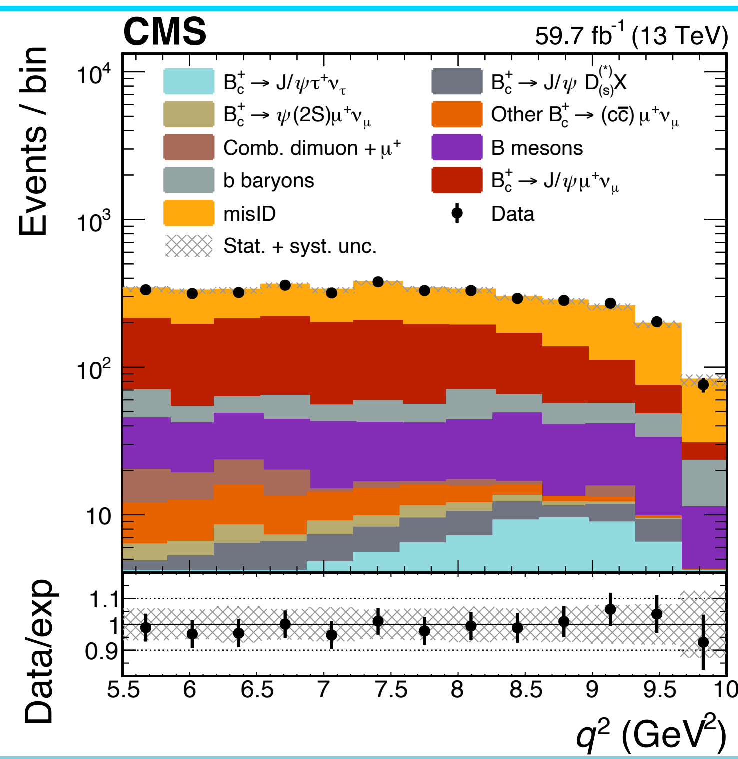
leptonic channel

final state signature: **3μ + neutrinos**

main bkg: muon fakes
combinatorial J/ψ + μ
other B_c decays

 # neutrinos & kinematic differences to disentangle numerator from denominator

CMS BPH-22-012



$$R(J/\psi) = 0.17^{+0.18}_{-0.17}(\text{stat})^{+0.21}_{-0.22}(\text{syst})^{+0.19}_{-0.18}(\text{theo})$$

Compatible with SM prediction (0.3σ) and with LHCb results (1.3σ)

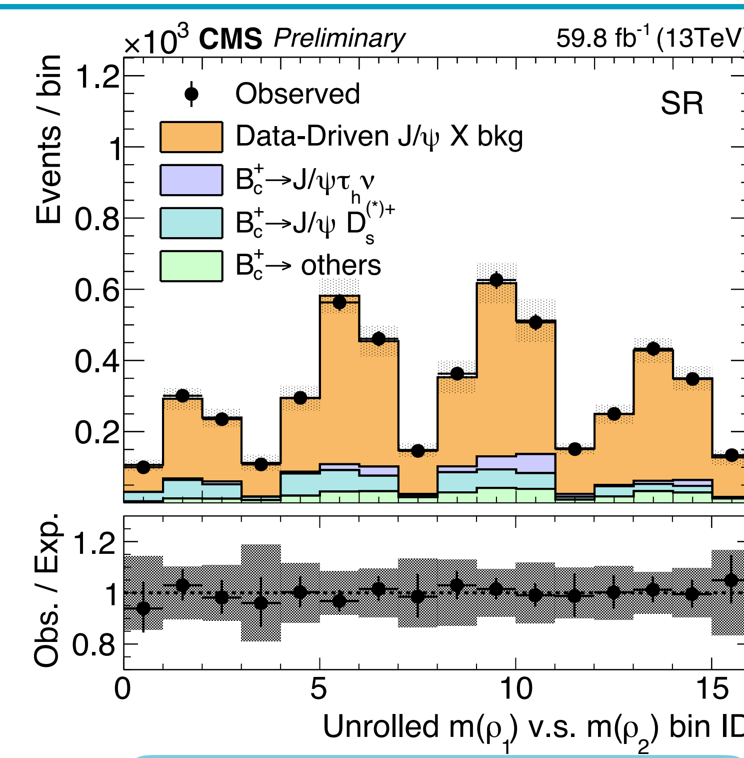
hadronic channel

final state signature: **2μ + 3 tracks + neutrinos**

main bkg: combinatorial J/ψ + X
B_c → J/ψ Ds(*)
other B_c decays

resonant structure of τ decay products to discriminate fakes

CMS PAS BPH-23-001

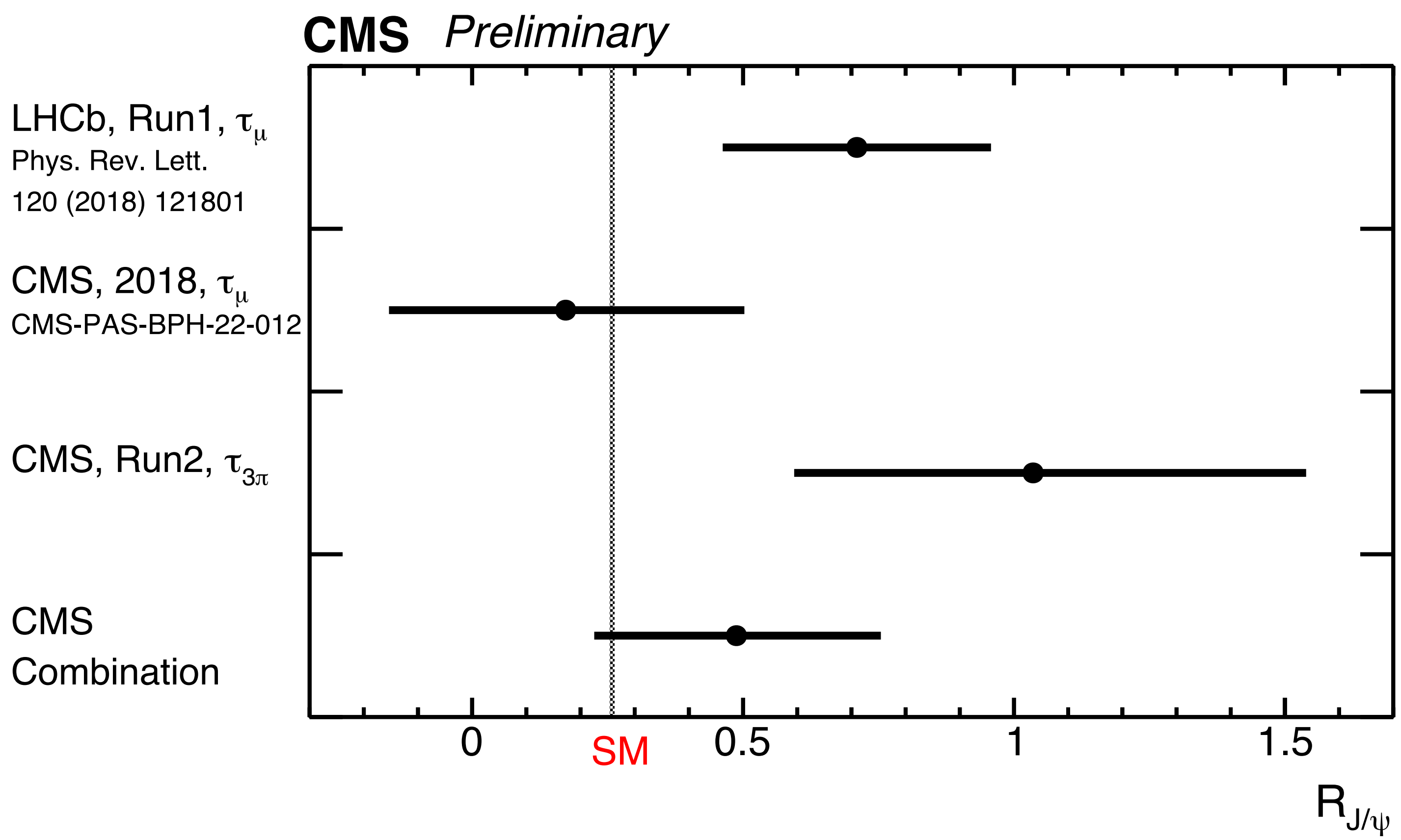


$$R(J/\psi) = 1.04^{+0.50}_{-0.44}$$

Compatible with SM prediction

Measurement of $R(J/\psi)$ | CMS

full combination of the two channels



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

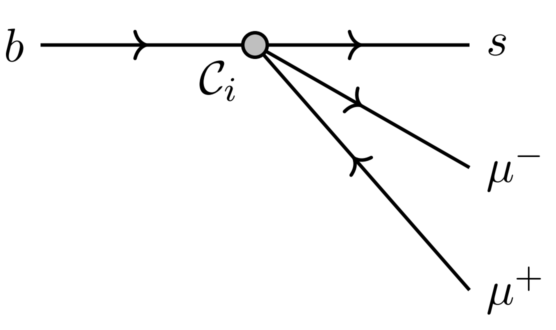
consistent with the SM prediction within 1σ standard deviation

$B^0 \to K^*\mu\mu$ angular analysis | CMS

Angular analysis of the $B^0 \to K^*(892)^0\mu^+\mu^-$ decay at 13 TeV

FCNC process proceeding at loop level in the SM (BR ~10^{-7})

- **sensitive to virtual NP particles** entering the loop and modifying BR and/or angular distribution



Effective approach used to describe the b→ sll decay

$$\mathcal{H}_{eff} \propto V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local operators

Wilson coefficients

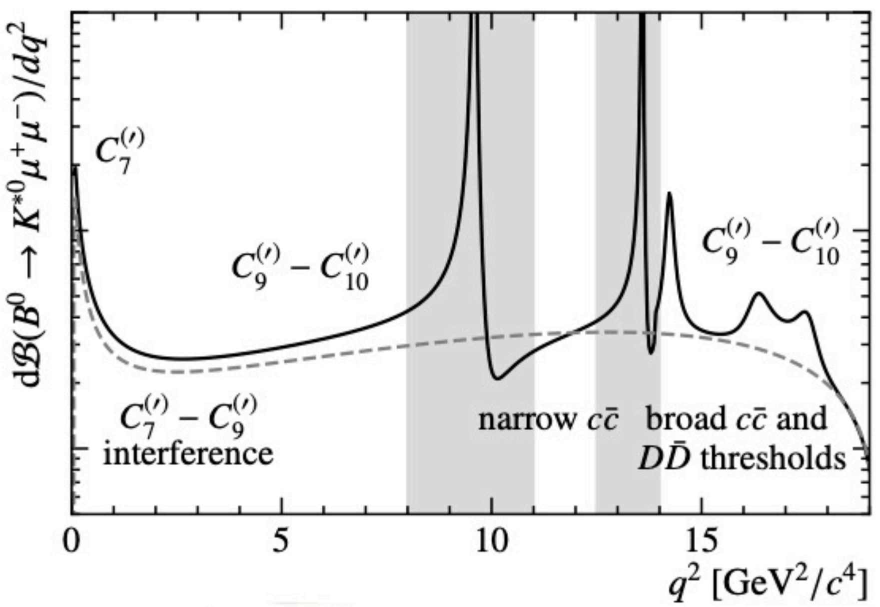
- NP could modify the Wilson Coefficients, or enable new operators

Different dimuon mass (q) ranges sensitive to different operators → measurements as a function of q^2

- NP contribution to C_9 expected to be constant vs q^2

Tensions with predictions based on the SM observed by LHCb

PRL 125, 011802

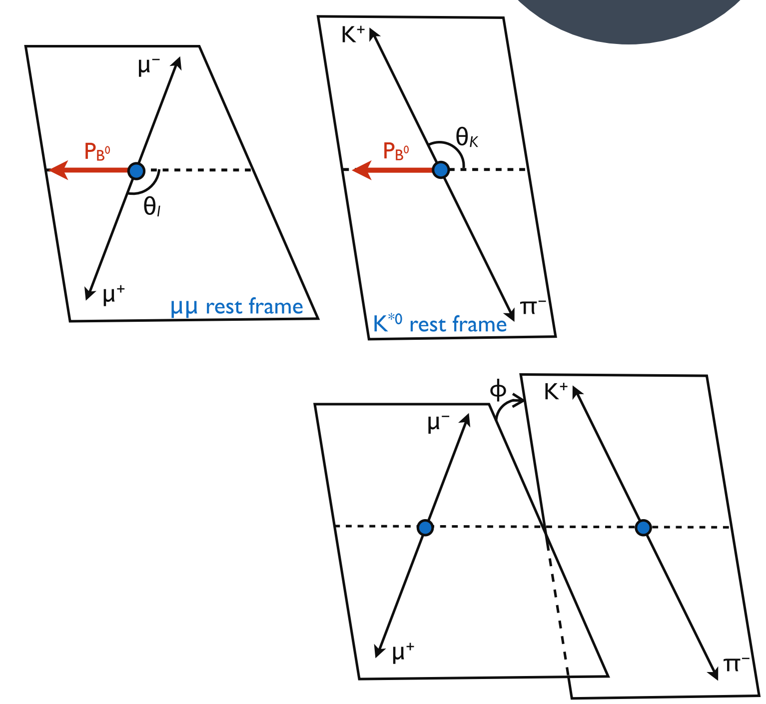


$B^0 \to K^*\mu\mu$ angular analysis | CMS

CMS-PAS BPH-21-002

First full angular analysis from CMS, based on Run2 dataset (140 fb^{-1})

- in bins of q^2 ranging from 1.1 to 16 GeV^2



Decay rate described as a function of $\Omega = (\cos\theta_K, \cos\theta_l, \phi)$, $q^2 = m^2(\mu\mu)$

$$\frac{d^4\Gamma}{dq^2 d^3\Omega} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\Omega)$$

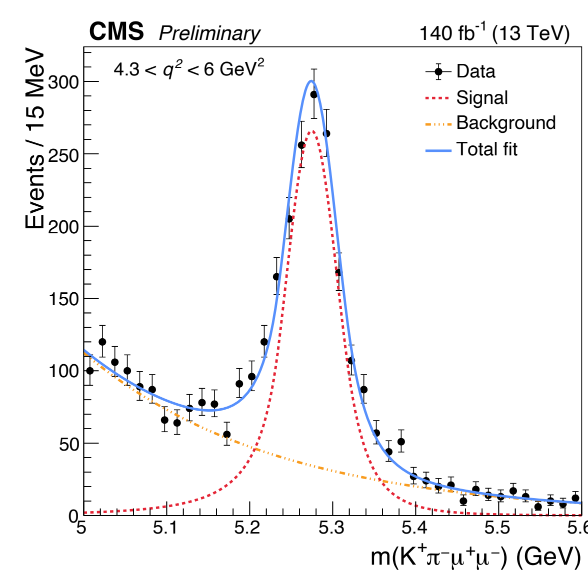
angular coefficients

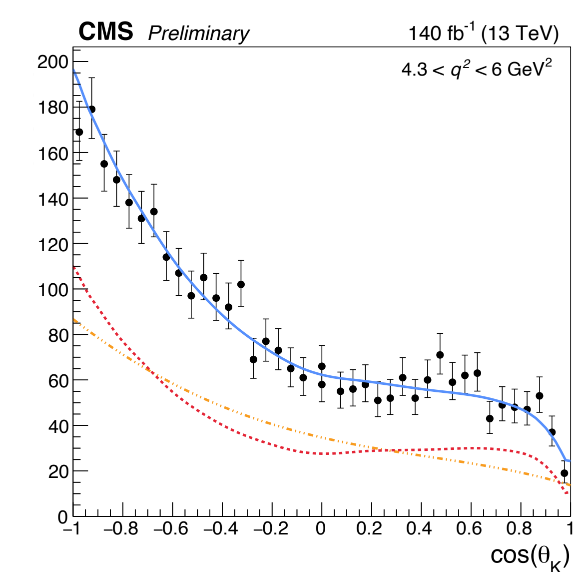
angular functions

The $J_i(q^2)$ are combinations of K^{*0} amplitudes which can be expressed using the set of angular observables $P_i^{(\prime)}$ JHEP 01 (2013) 048

- $P_i^{(\prime)}$ **have reduced form factor uncertainties**
- related to the Wilson Coefficients

Observables extracted from 4D unbinned fit to the mass and angular distributions in bins of q^2





$B^0 \to K^*\mu\mu$ angular analysis | CMS

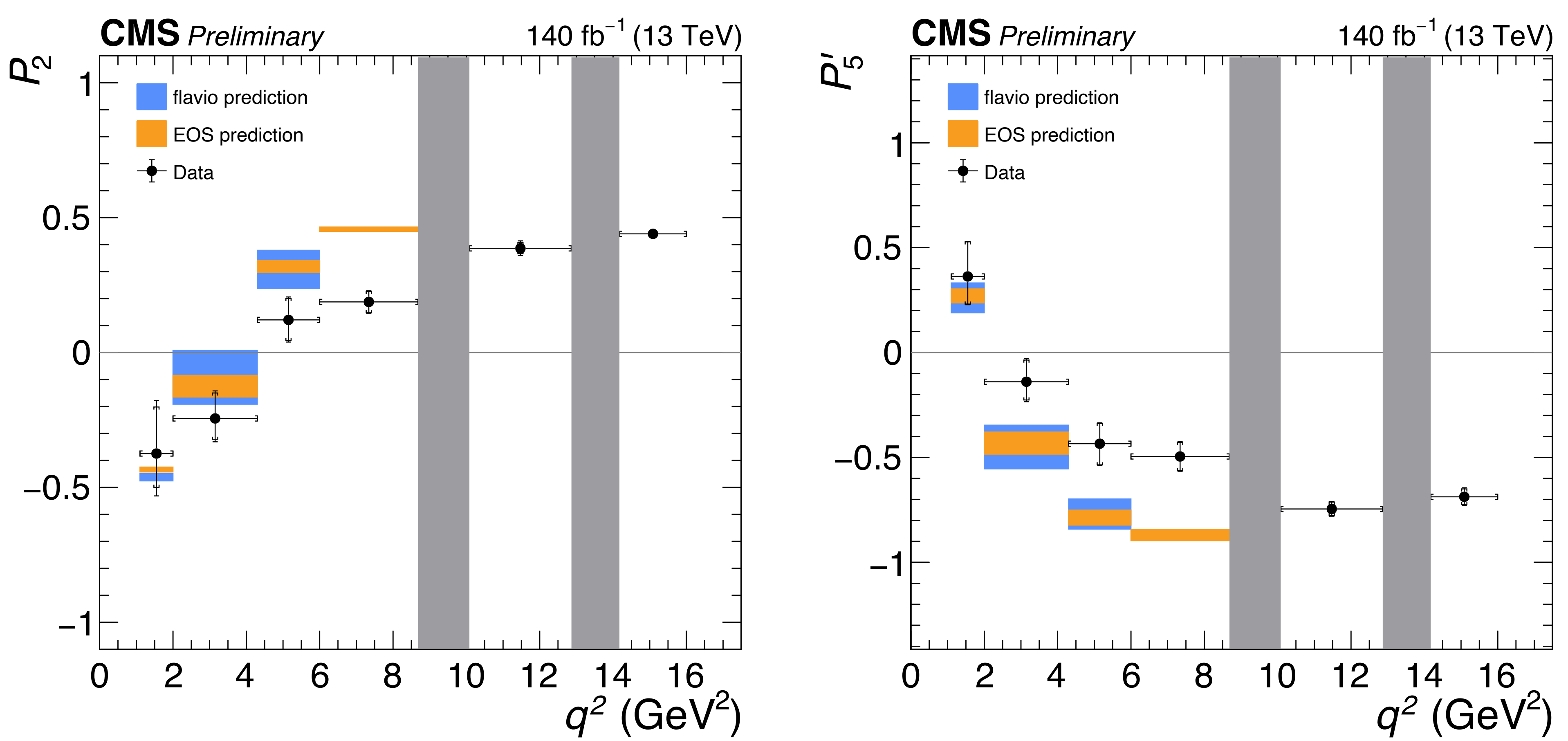
Results compared to two sets of predictions based on the SM

flavio: local form-factors (ff) from Lattice QCD and LCSR, QCDF for non-local ff

EOS: local ff from a combination of LQCD and LCSR, novel parametrization of non-local ff (JHEP 09 (2022) 133)

Good compatibility with SM predictions

some tensions in the q^2 region < J/ψ for the P_2 and P'_5 observables



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Good compatibility with SM predictions

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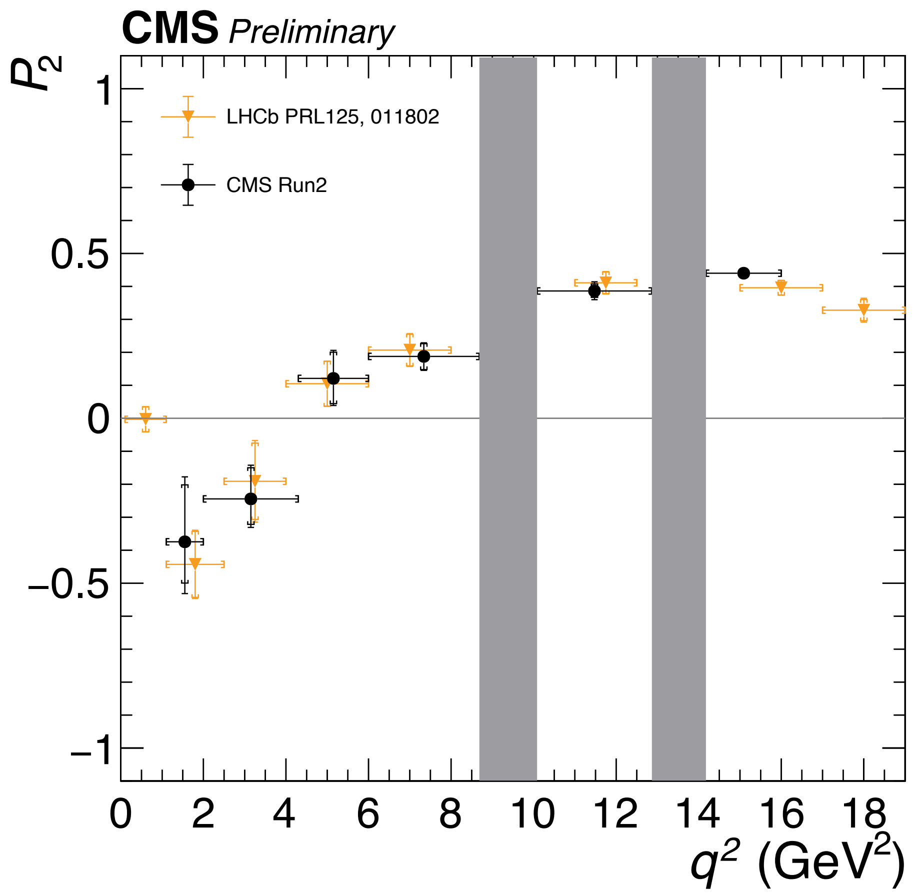
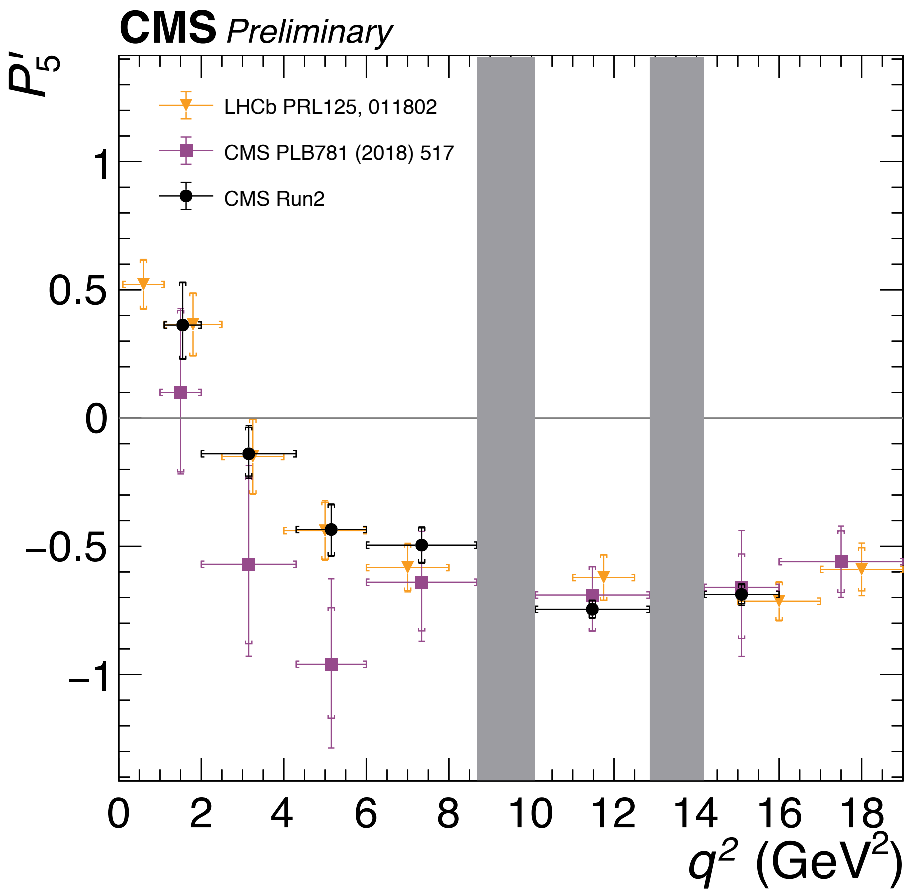
Among the most precise measurements, in agreement with LHCb





Search for D⁰→μμ | CMS

Search for rare charm decays into two muons

CMS PAS BPH-23-008

$D^0 \to \mu\mu$ is a **very rare FCNC process**, SM prediction for BR ~ 3 x 10^{-13}

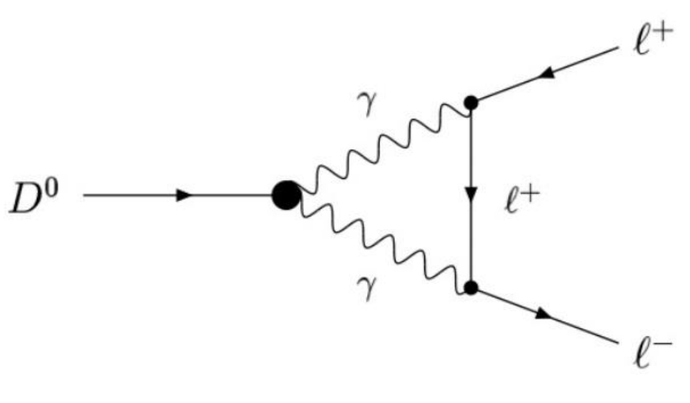
- loop contributions in charm decays are mediated by light quarks
- substantial long-distance contributions, challenging to predict analytically → large uncertainties on the SM prediction

However, any **(small) enhancement from NP should be easy seen**

- various NP models predict contributions at tree level

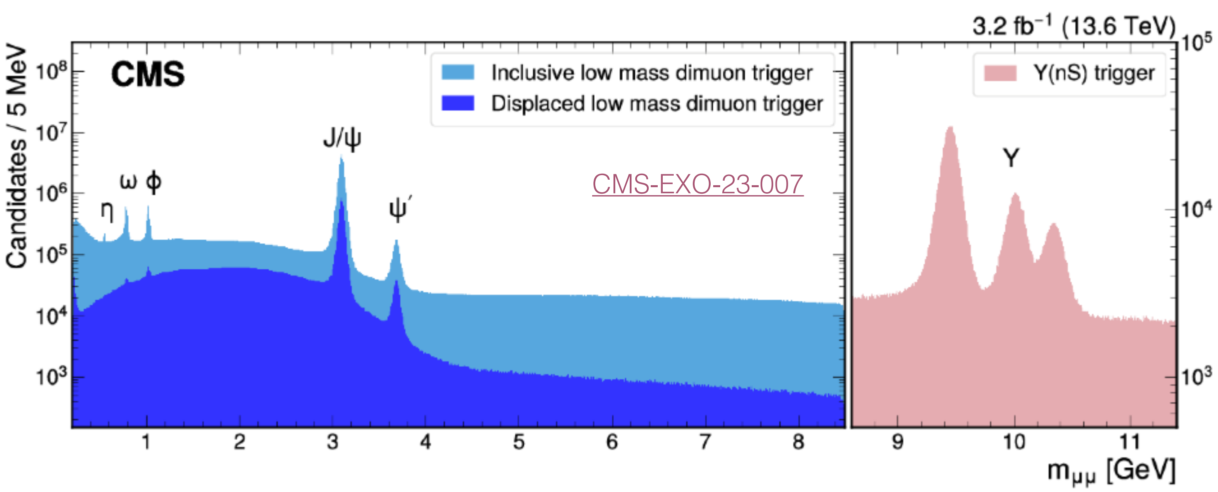
Current most sensitive measurement from LHCb

- upper limit for $B(D^0 \to \mu^+\mu^-)$ at 3.5×10^{-9} @95% CL



CMS search based on Run3 data (2022-2023, 64.5 fb^{-1})

- collected by **inclusive dimuon triggers**
- D^0 from $D^{*+}(2010) \to D^0\pi^+$ decays: small combinatorial bkgs and optimal resolution on $m(D^{*+}) - m(D^0)$
- $D^0 \to \pi^+\pi^-$ as normalisation channel

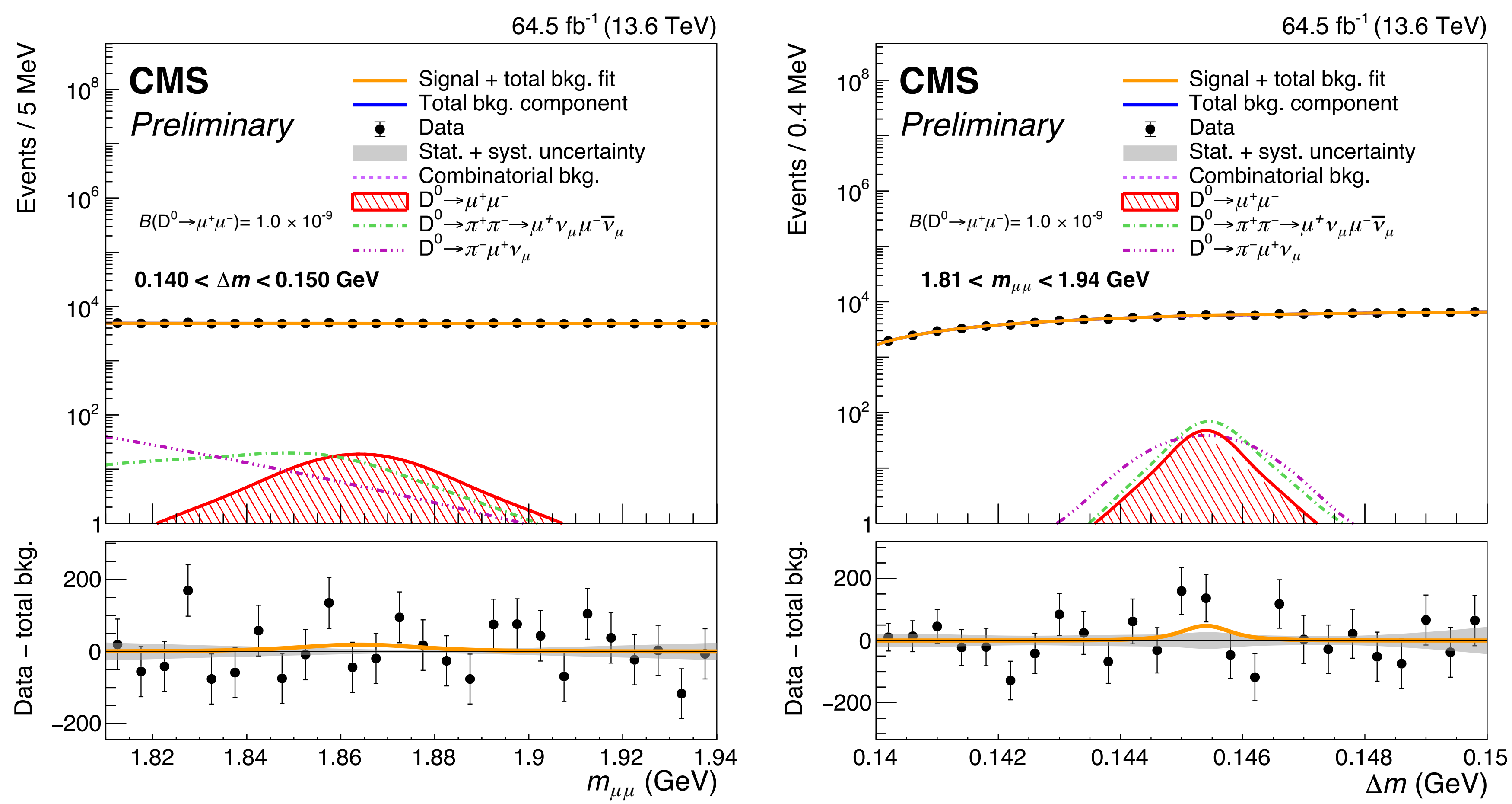


Search for $D^0 \rightarrow \mu\mu$ | CMS

Branching fraction extracted using a 2D UML fit on the invariant mass of D^0 candidates ($m_{\mu\mu}$) and $\Delta m = m(D^*\text{-}D^0)$

main uncertainties related to normalisation channel

no excess over the background is seen



$$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-9} \quad \text{@95\% CL}$$

Previous best limit improved by 35%

Summary

Many recent results from both ATLAS and CMS experiments, covering a wide range of flavour-physics topics

only a few selected publications were shown in this talk, many more available at
ATLAS physics results page
CMS physics results page

Competitive results
often improve current available best measurements

Additional datasets collected with innovative techniques are still to be explored and exploited

extra

charm sec extra

fragmentation non universality

arxiv 2311.07523

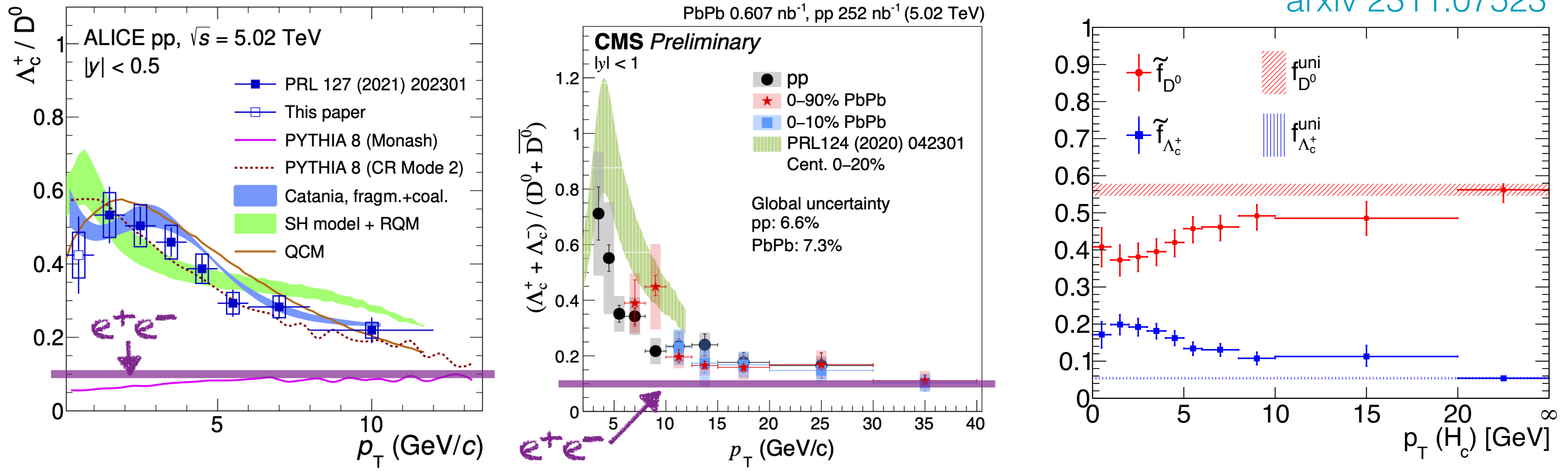


Figure 1: Λ_c^+/D^0 measurements from ALICE (left) and CMS (middle), with figures adapted from [5] and [6], respectively. As a reference, the fragmentation fraction of e^+e^- data [8] was added as the purple band. These measurements were used to derive p_T-dependent D^0 and Λ_c^+ production fractions for pp collisions (right).

Quarkonium polarization extra

Helicity frame definition

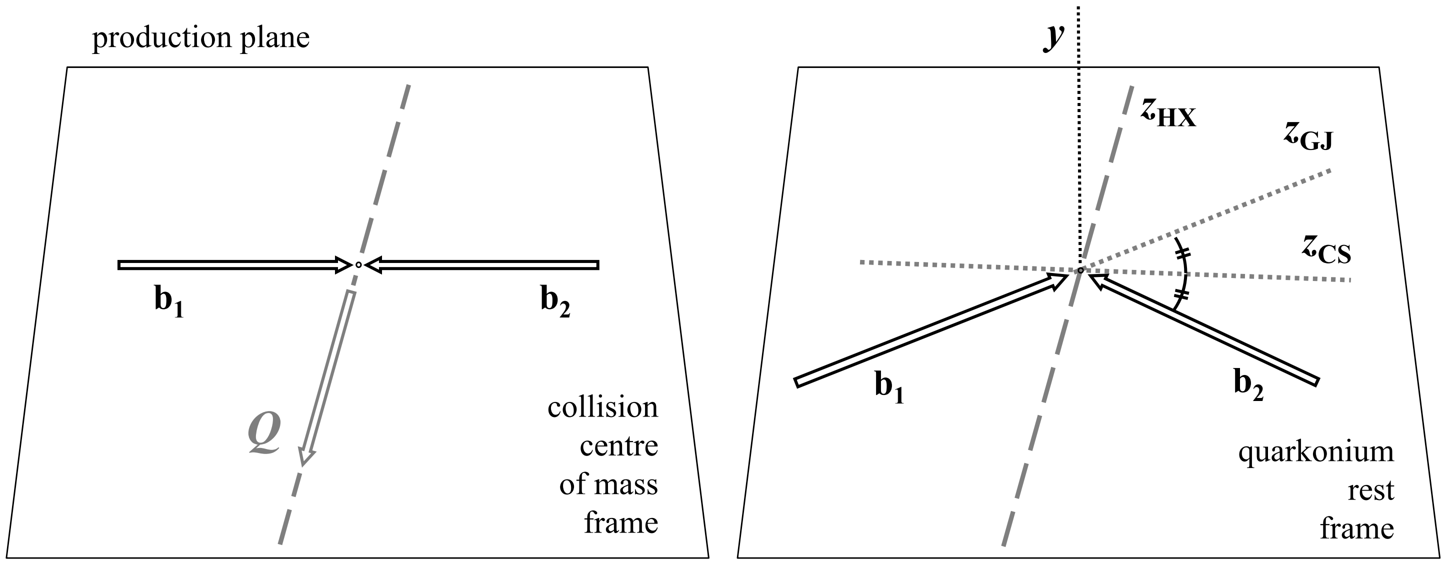
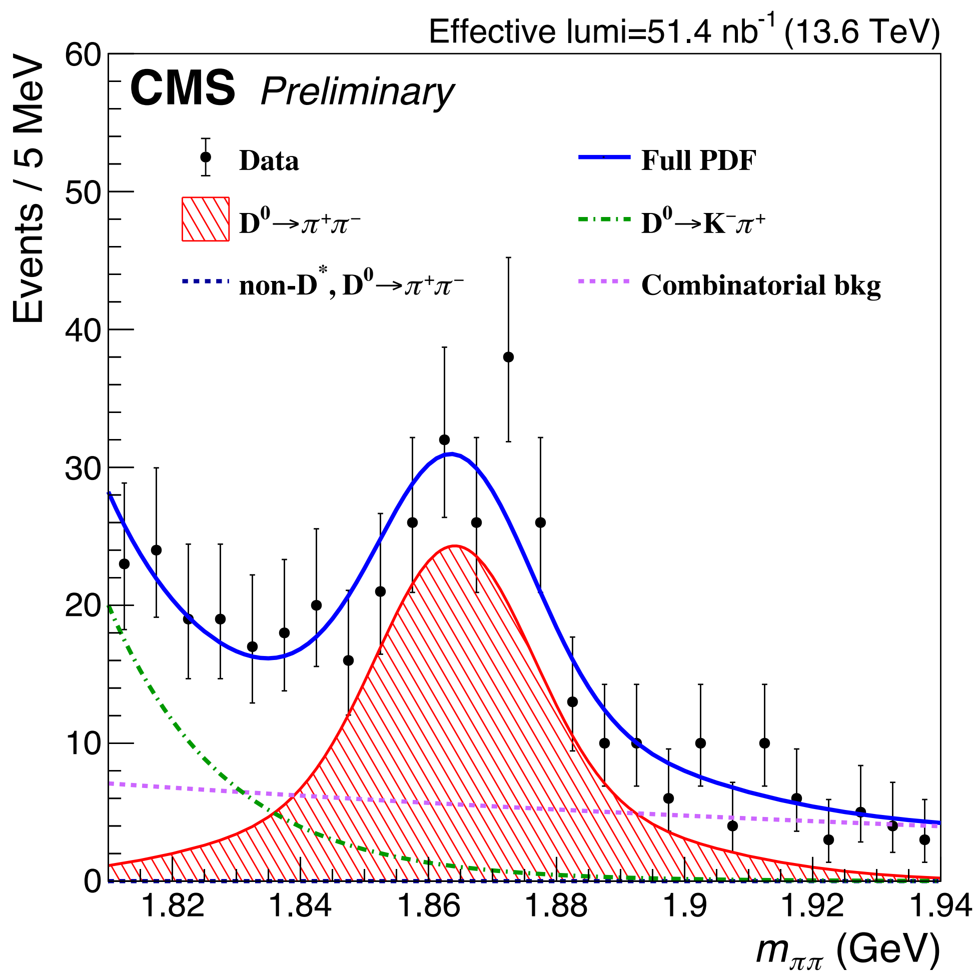


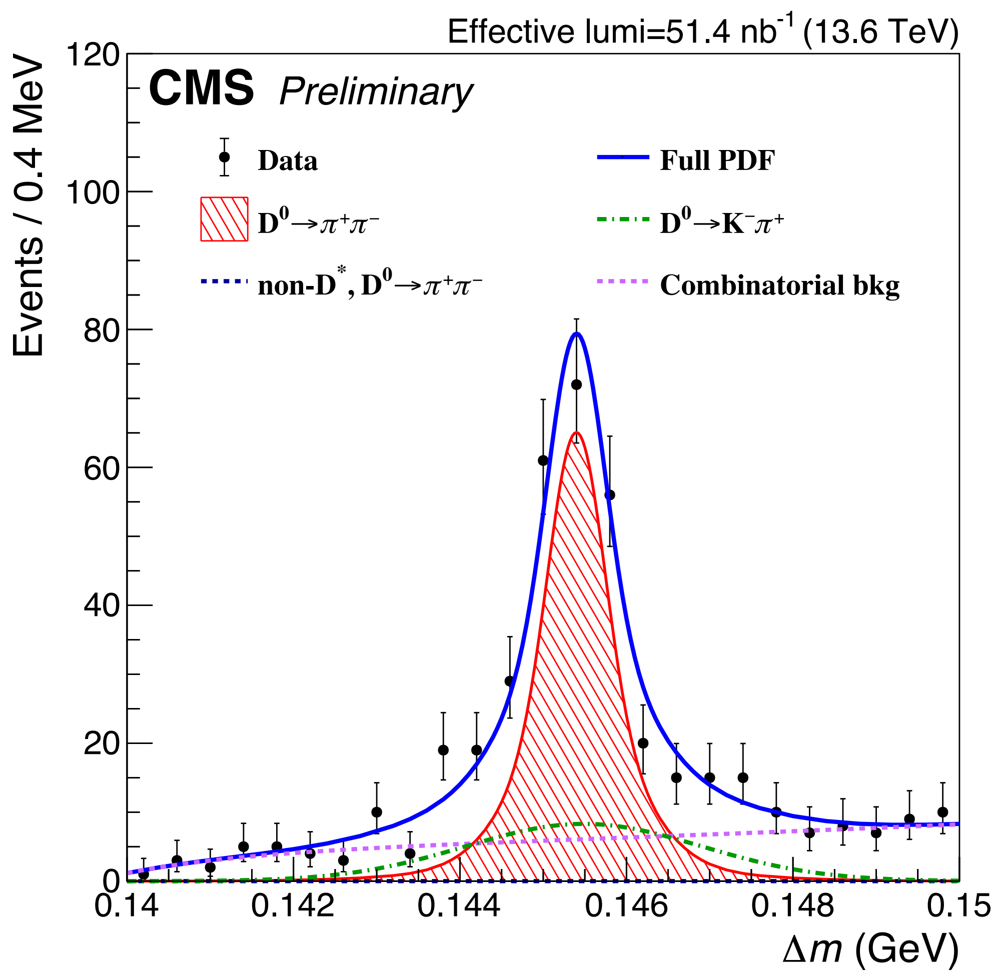
Figure 3: Illustration of three different definitions of the polarization axis z (CS: Collins-Soper, GJ: Gottfried-Jackson, HX: helicity) with respect to the directions of motion of the colliding beams (b_1, b_2) and of the quarkonium ($\mathcal{Q}$).

from Eur. Phys. J. C 69, 657–673 (2010)

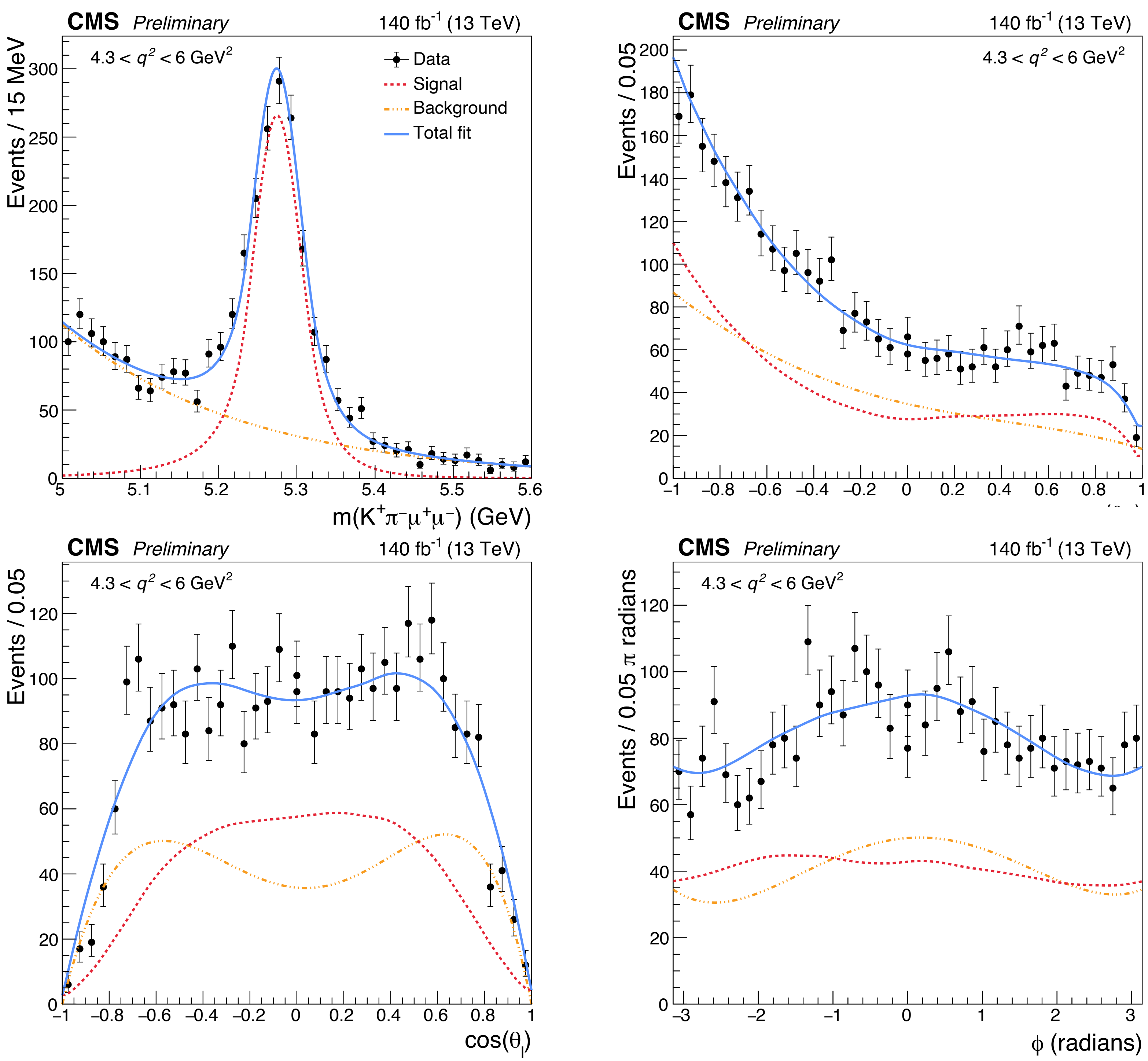
$D^0 \to \mu\mu$ search | extra

Normalisation channel



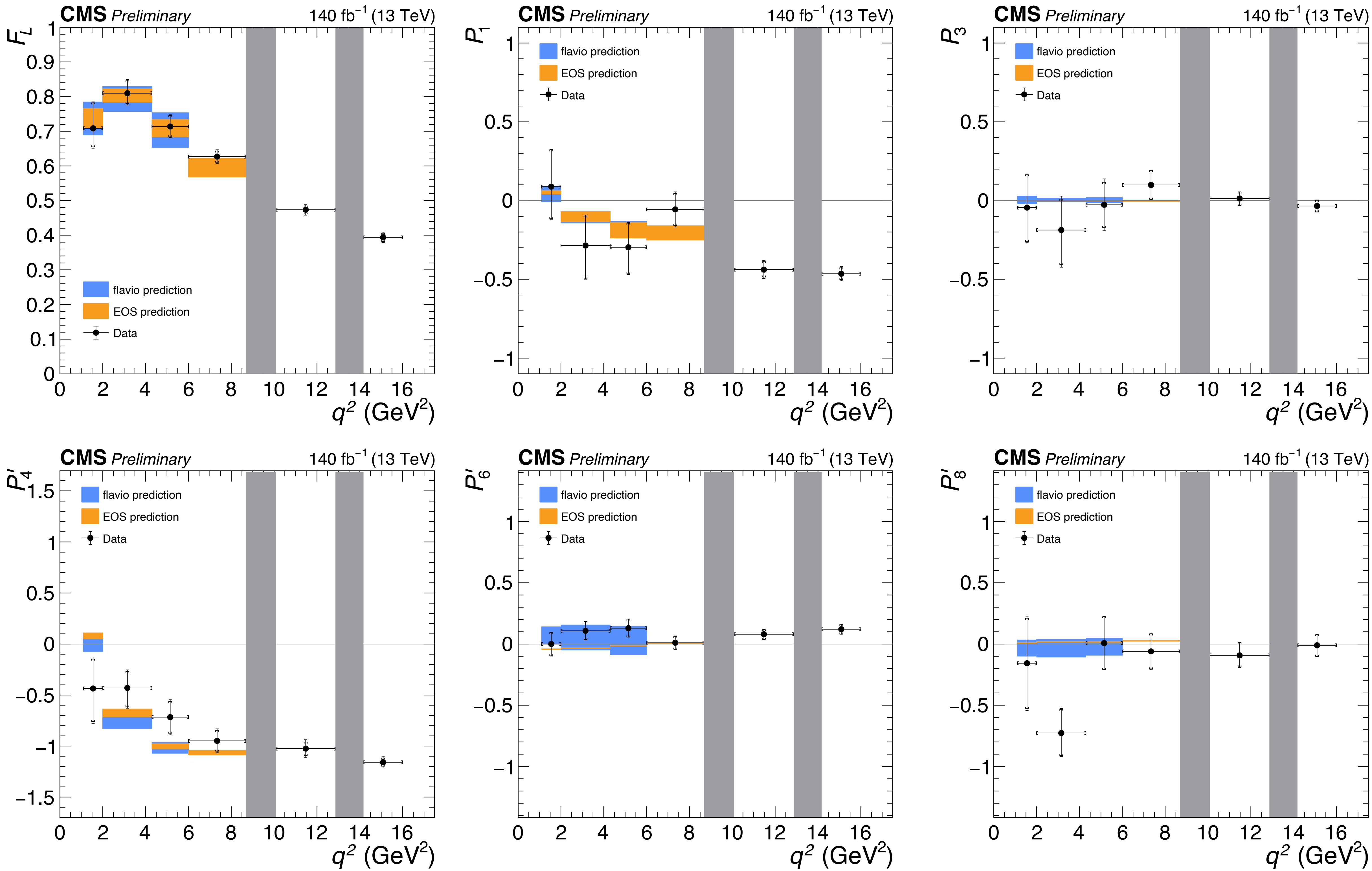


$B^0 \rightarrow K^*\mu\mu$ angular analysis | extra



projection of data and fit results on the mass and angular variable axes, for one q^2 bin

B⁰→K*μμ angular analysis | extra



CMS Parking for Run3 | extra