Production of Heavy Flavours at CMS

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Overview

This Talk

Recent CMS results on production of heavy flavour hadrons and quarkonia in pp collisions

- Measurement of double-differential and total charm cross section at 7 TeV
- Measurement of B meson production fractions in pp collisions at 13 TeV using
- Measurements of $\Upsilon(1S)$ production in association with a Z boson at 13 TeV

References:
[BPH-22-007]
[BPH-21-007]
[BPH-23-007]

Other CMS B-physics Talks

- "Recent Heavy Flavour Physics results by the CMS experiment" by A. Beletti
- "Lepton flavour (universality) violation studies with heavy flavor at CMS" by C. Basile
- "Observation of a family of all-charm tetraquarks with spin-2 and positive parity at CMS" by X. Wang

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

[BPH-22-007]

Motivation and Context

Charm mass scale close to Λ_{QCD}

- transition region of perturbative and non-perturbative regimes
- **challenging perturbative calculation**

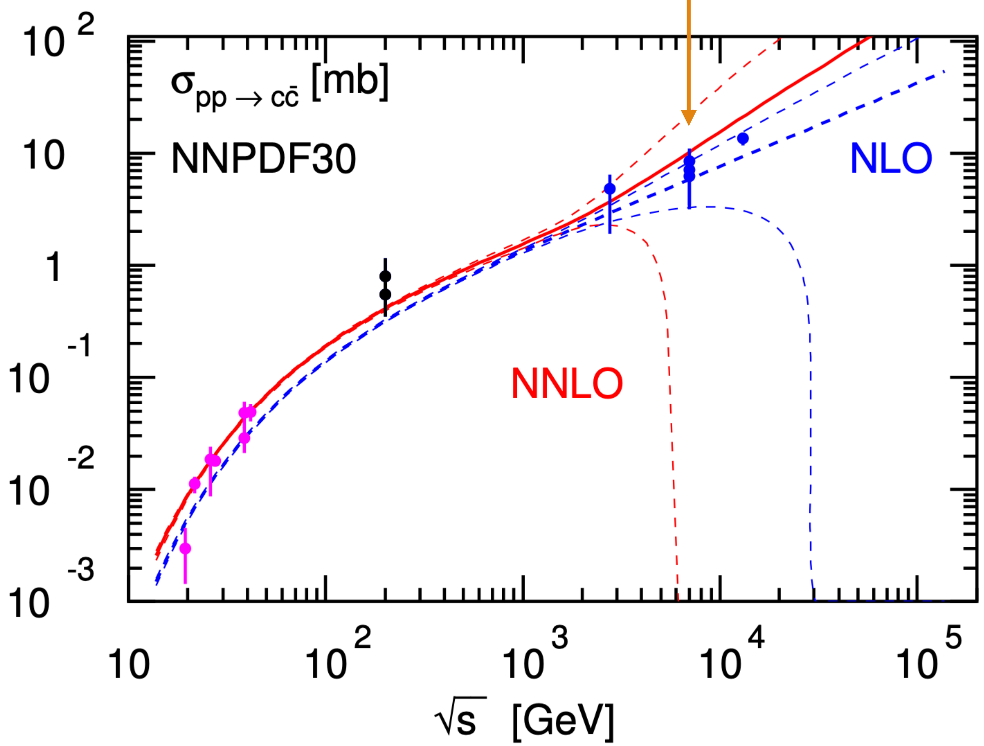
Best theoretical predictions

  - NLO+NLL (FONLL) for differential cross section
  - NNLO for total cross section (σ)

$\sigma_{c\bar{c}}$ measurements to compare with NNLO

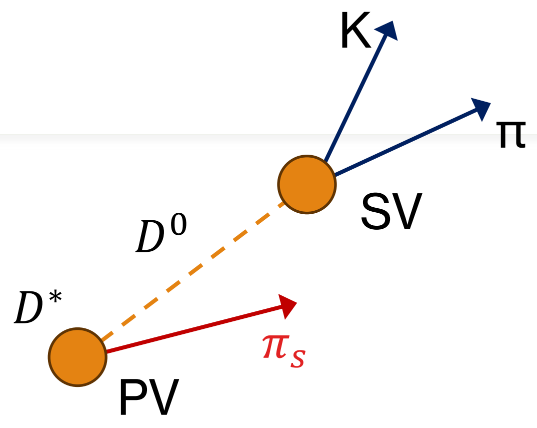
- fiducial cross section extrapolated
  - State of the art results based on fragmentation universality assumption
  - Recent ALICE result: charm fragmentation non-universal [JHEP 12 (2023) 086]

This analysis



[Eur. Phys. J. C 76, 471 (2016)]

D* reconstruction strategy



- Focus on prompt D* in the decay:
  - $D^{*+} \rightarrow D^0\pi_s^+ \rightarrow K^-\pi^+\pi_s^+$

Slow pion (π^+_s) low p_T (due to small $m(D^{*+}) - m(D^0)$)

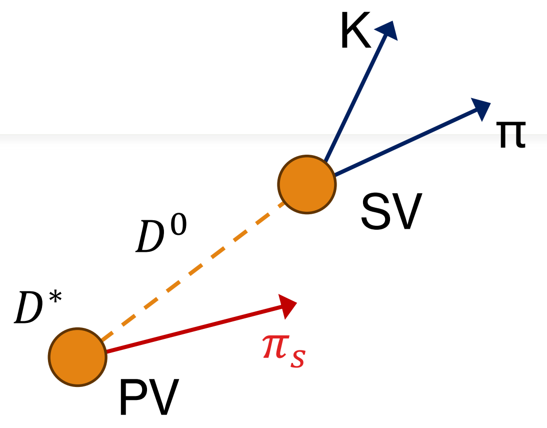
K-π charge univocally defined based on π_s charge

Provides excellent $\Delta m = m(D^{*+}) - m(D^0)$ resolution, reducing combinatorial background

- 7 TeV 2010 pp data ($\sim 3.0\ \text{nb}^{-1}$) [All open Data]
  - Special low p_T tracking down to ~70 MeV
  - zero-bias and minimum-bias triggers + di-e/μ triggers (removing triggered pp vertex)
    - Multiple candidates per-event are allowed (coming from different PVs)
- Selections strategy*
  - D^0 built from K and π tracks with opposite charge, vertex fit with p-value > 1%
  - π_s^+ must be from same PV as D^0, with p_T > 70 MeV

* Detailed list of selections in backup

D* reconstruction strategy



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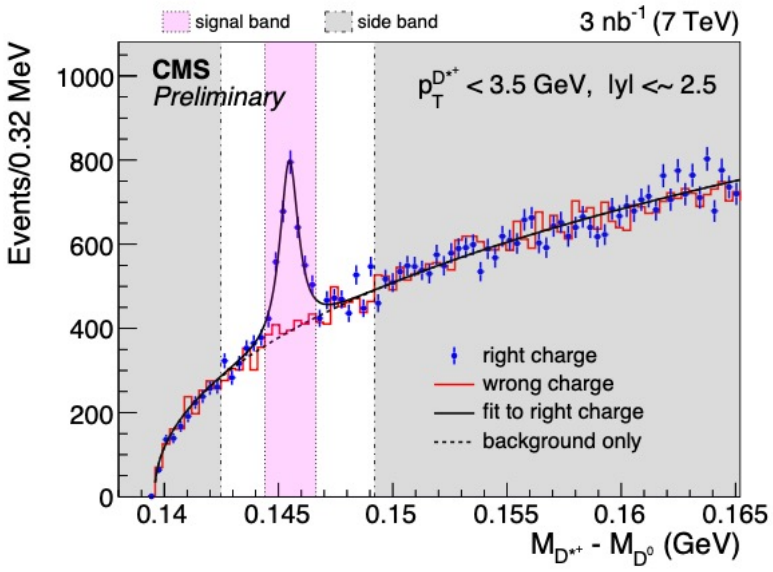
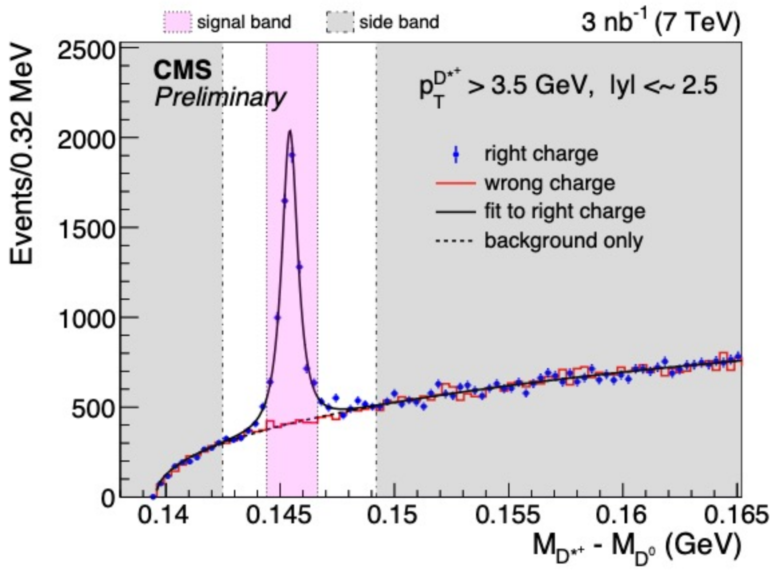
Right-charge $K^{\mp}\pi^{\pm}\pi^{\pm}$: signal + combinatorial background.

Wrong-charge $K^{\mp}\pi^{\mp}\pi^{\pm}$: combinatorial background

Background Subtraction:

- Wrong-charge normalized via sidebands
- Signal yield from integration over the background-subtracted signal region



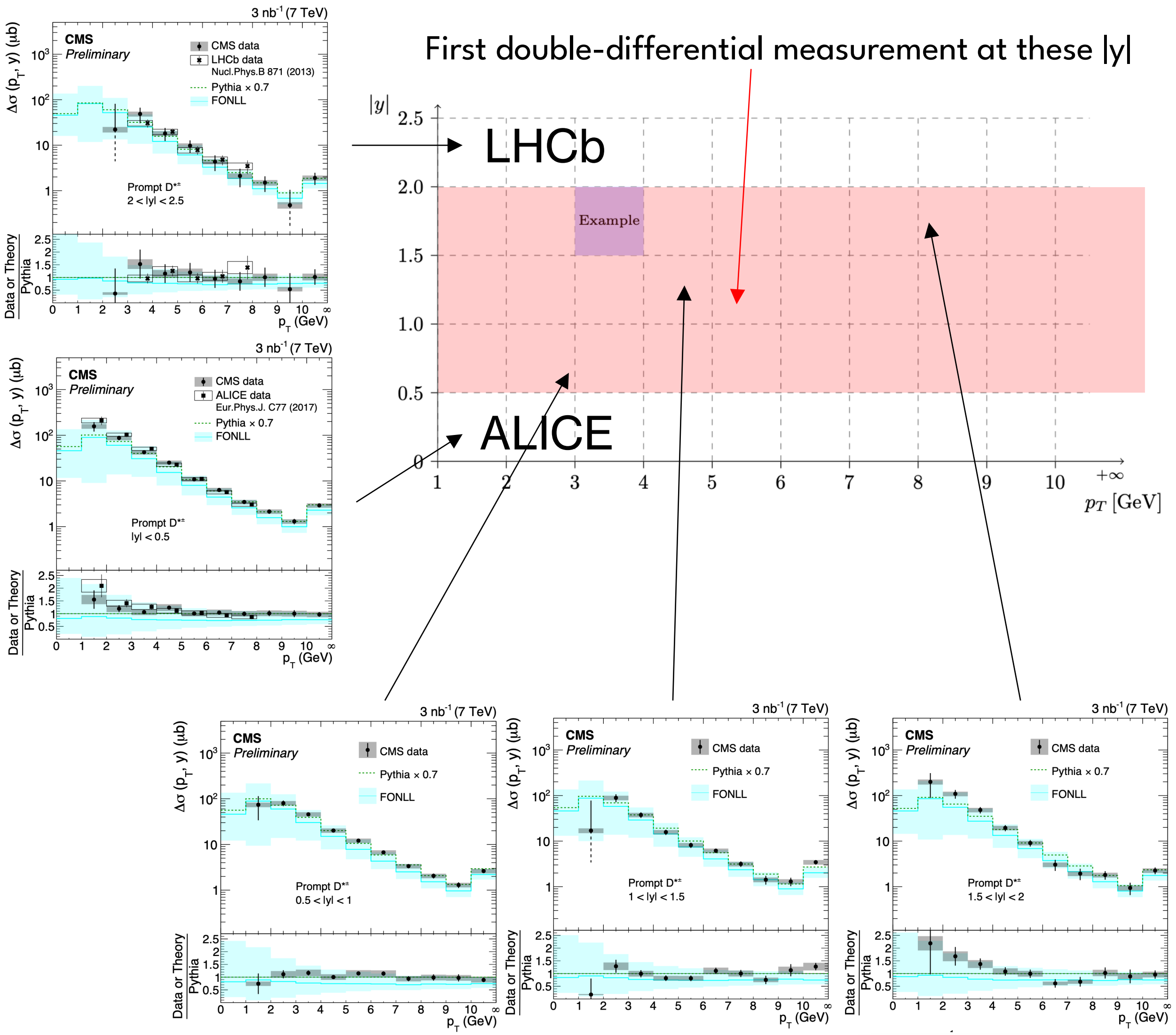


Differential D^* cross section extraction

- Data are consistent with PYTHIA predictions (globally scaled to data) and FONLL predictions
  - FONLL based on **fragmentation universality assumption**
  - No strong deviations from **fragmentation universality** are observed for D^* mesons
- The **total fiducial cross section** measured by CMS for is:

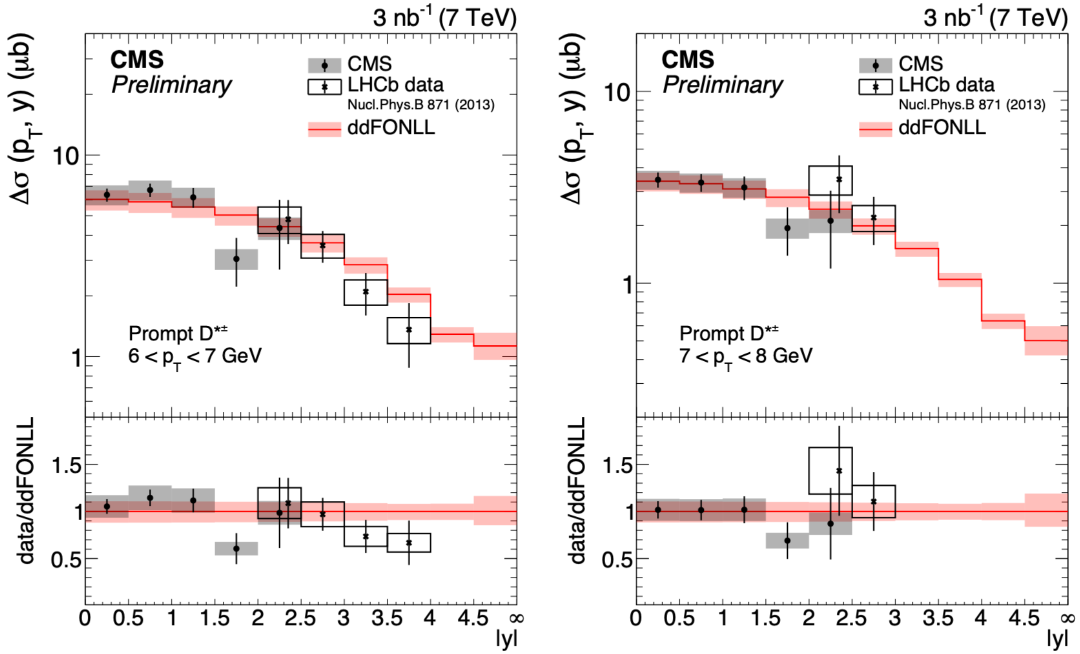
$$\sigma_{\text{fiducial}}^{\text{CMS}} = 1.28^{+0.22}_{-0.22}\ \text{mb}$$

Good agreement with ALICE and LHCb



Total charm cross section

- Combination of **CMS and LHCb** results
  - Complementing each other over different y ranges
  - Uncovered |y| regions determined via ddFONLL*
- The $c \rightarrow D^*$ fragmentation fraction $f^{pp}_{D^{*+}}$
  - Extrapolated from e^+e^- results



smallest extrapolation ever for charm at LHC

$2.22^{+0.25}_{-0.25}$ [mb]

$0.94^{+0.10}_{-0.11}\,(\tilde{f})^{+0.21}_{-0.17}(\mathrm{PDF})^{+0.10}_{-0.14}(\mu_f, \mu_r, m_c, \alpha_K)$ [mb]

$$\sigma_{c\bar{c}} = \frac{\Delta^{data}_{D^{*+}}(measured\ PS) + \Delta^{ddFONLL}_{D^{*+}}(unmeasured\ PS)}{2 * f^{pp}_{D^{*+}}}$$

$0.168^{+0.015}_{-0.019}$

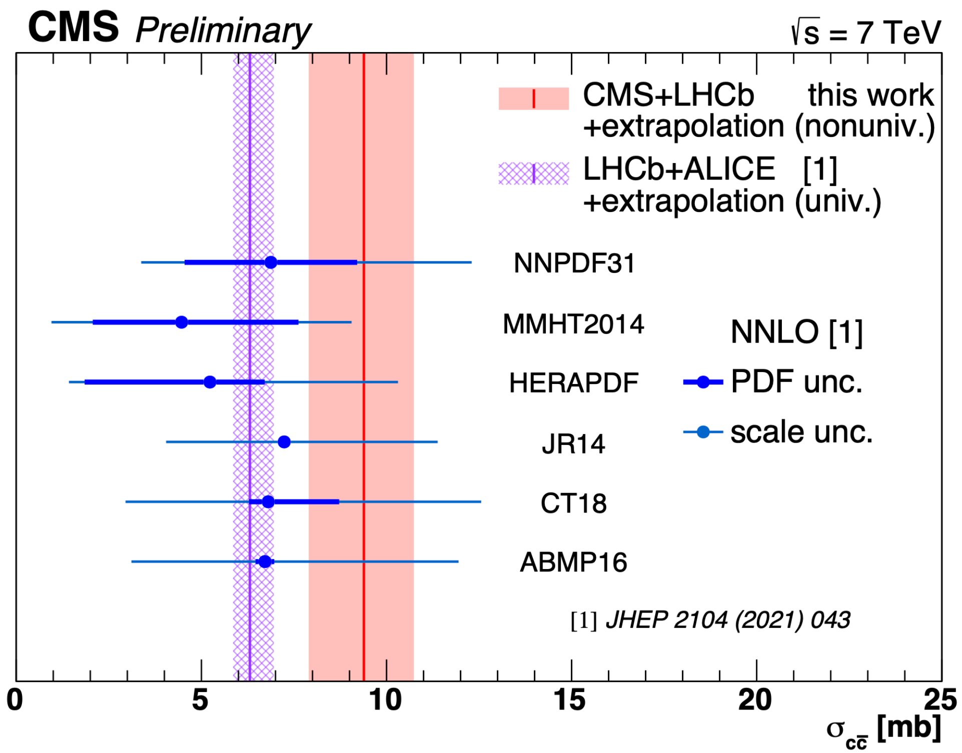
*** ddFONLL = Data-Driven FONLL**
The “universal” fragmentation fraction is replaced by a p_T-dependent hadron-production fraction directly obtained from measurements at LHC

arXiv:2406.03581v1

Theory comparison

- Compared with the highest order QCD theory (NNLO) and data based on fragmentation universality assumption
  - consistent with upper edge of uncertainty band of NNLO theory
  - total charm cross section was previously underestimated with the universality assumption

$$\sigma_{c\bar{c},tot} = 9.39^{+1.35}_{-1.49}\ mb$$



Measurement of B meson production fractions in pp collisions at 13 TeV

[BPH-21-007]

Overview

The Production fractions (f_u, f_s, f_d)

- Probabilities for a b quark to hadronize into a B^+, B_s, B^0mesons

Production fraction ratio (PFR)

- Input for B_s^0 branching fraction measurements (e.g. f_s/f_d main uncertainty in $B_s^0 \to \mu\mu$ analysis)
- Strong interest in exploring the p_T dependence of f_s/f_d

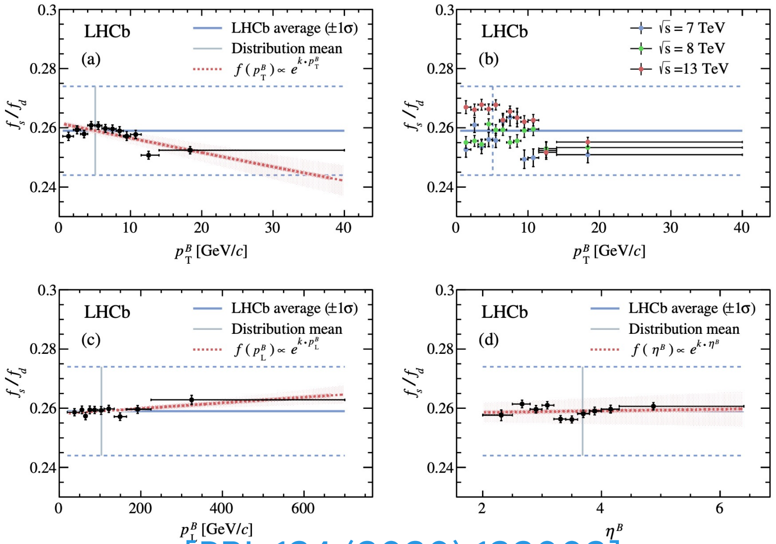
The CMS analysis:

Hadronic open-charm

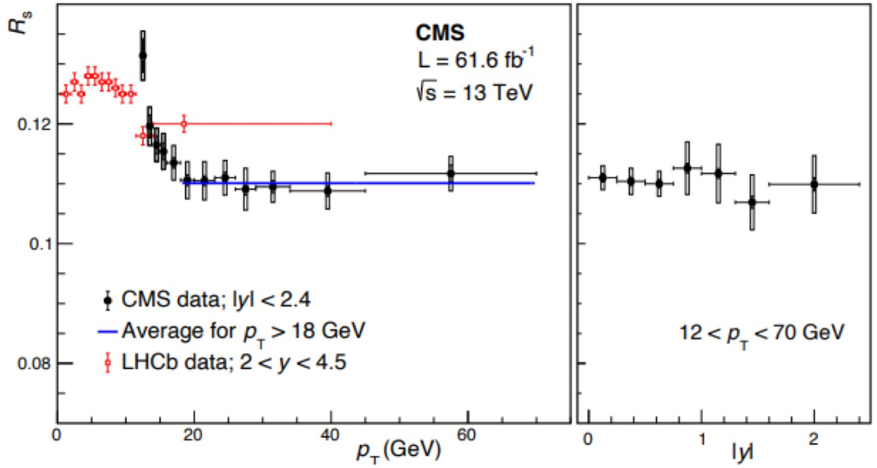
- to measure PFR values

Charmonium

- relative PFRs
- dependency of PFRs on p_T



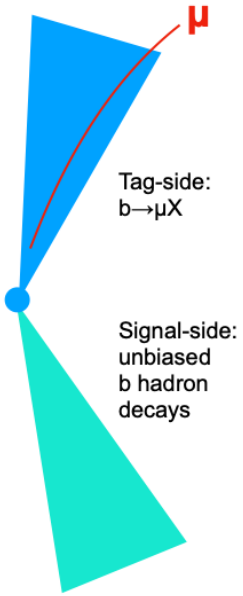
[PRL 124 (2020) 122002]



[PRL 131 (2023) 121901]

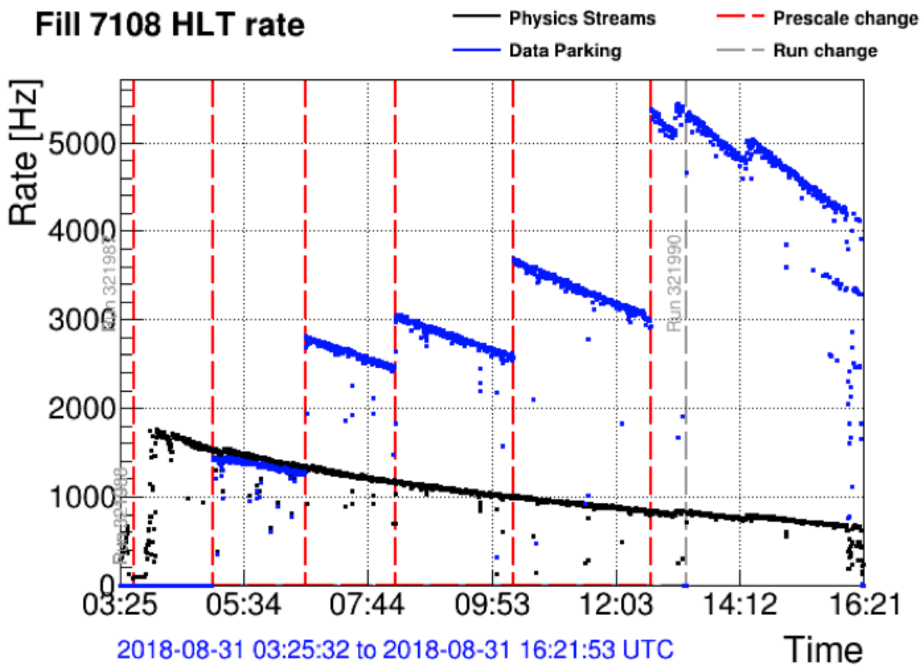
B Parking

- Both analysis relies on CMS 2018 B-Parking Dataset



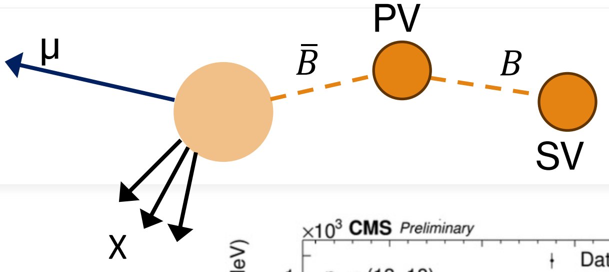
2018 B-Parking:

- Collected from single muon triggers
- Rate that increases in steps as the rate of the Physics Stream decreases
- Integrated luminosity of 41.5 ±1.0 fb^{-1}
  - ~10 billion unbiased decays of hadrons containing b quarks



[CMS DP -2019/043]

Hadronic open-charm



N. Events corrected with eff

Main equation:

$$\frac{f_s}{f_d} = \frac{\mathcal{B}(B^0 \to \pi^+ D^-)}{\mathcal{B}(B_s^0 \to \pi^+ D_s^-)} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to \pi^- \varphi(K^+K^-))} \frac{N_{corr}(B_s^0)}{N_{corr}(B^0)}$$

Only for f_s/f_x

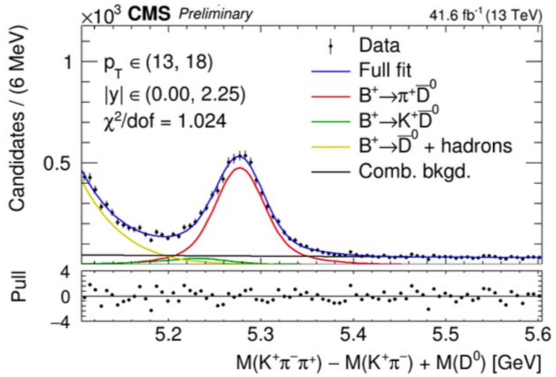
$$= \frac{\mathcal{B}(B^0 \to K^+ D^-)}{\mathcal{B}(B_s^0 \to \pi^+ D_s^-)} \frac{\mathcal{B}(B^0 \to \pi^+ D^-)}{\mathcal{B}(B^0 \to K^+ D^-)} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to \pi^- \varphi(K^+K^-))} \frac{N_{corr}(B_s^0)}{N_{corr}(B^0)}$$

- Measurement of $\mathcal{B}(B_s^0 \to \pi^+ D_s^-)$ relies on f_s/f_d
- $\frac{\mathcal{B}(B^0 \to K^+ D^-)}{\mathcal{B}(B_s^0 \to \pi^+ D_s^-)}$ from theory

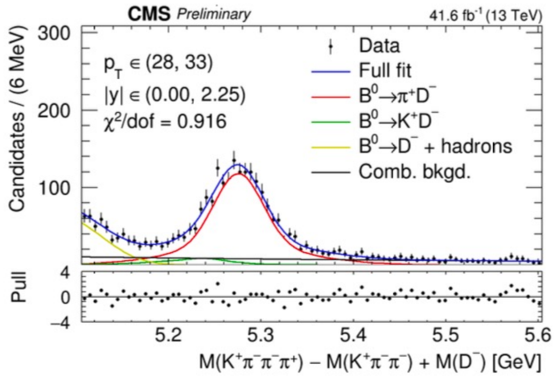
Selections*

- Standard kin-selections (p_T, η, mass, vtx_prob ...)
- BDT to suppress combinatorial bkg with thresholds optimized maximizing $S/\sqrt{S+B}$

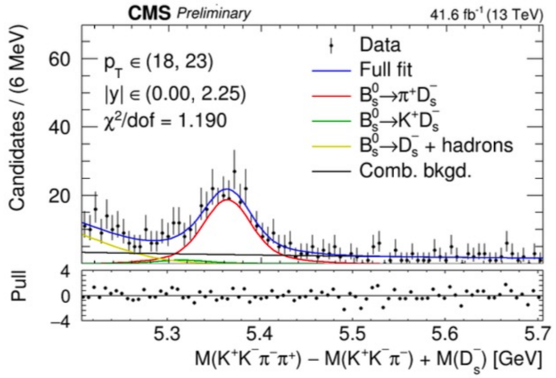
$B^+ \to \pi^+ \overline{D^0}(K^+\pi^-)$



$B^0 \to \pi^+ D^-(K^+\pi^-\pi^-)$

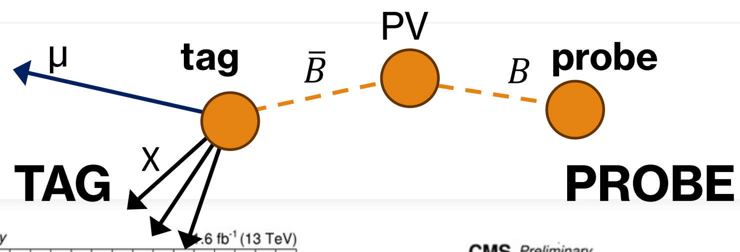


$B_s^0 \to \pi^+ D_s^-(\pi^- \varphi(K^+K^-))$



* Detailed list of selections in backup

Charmonium



Main equation:

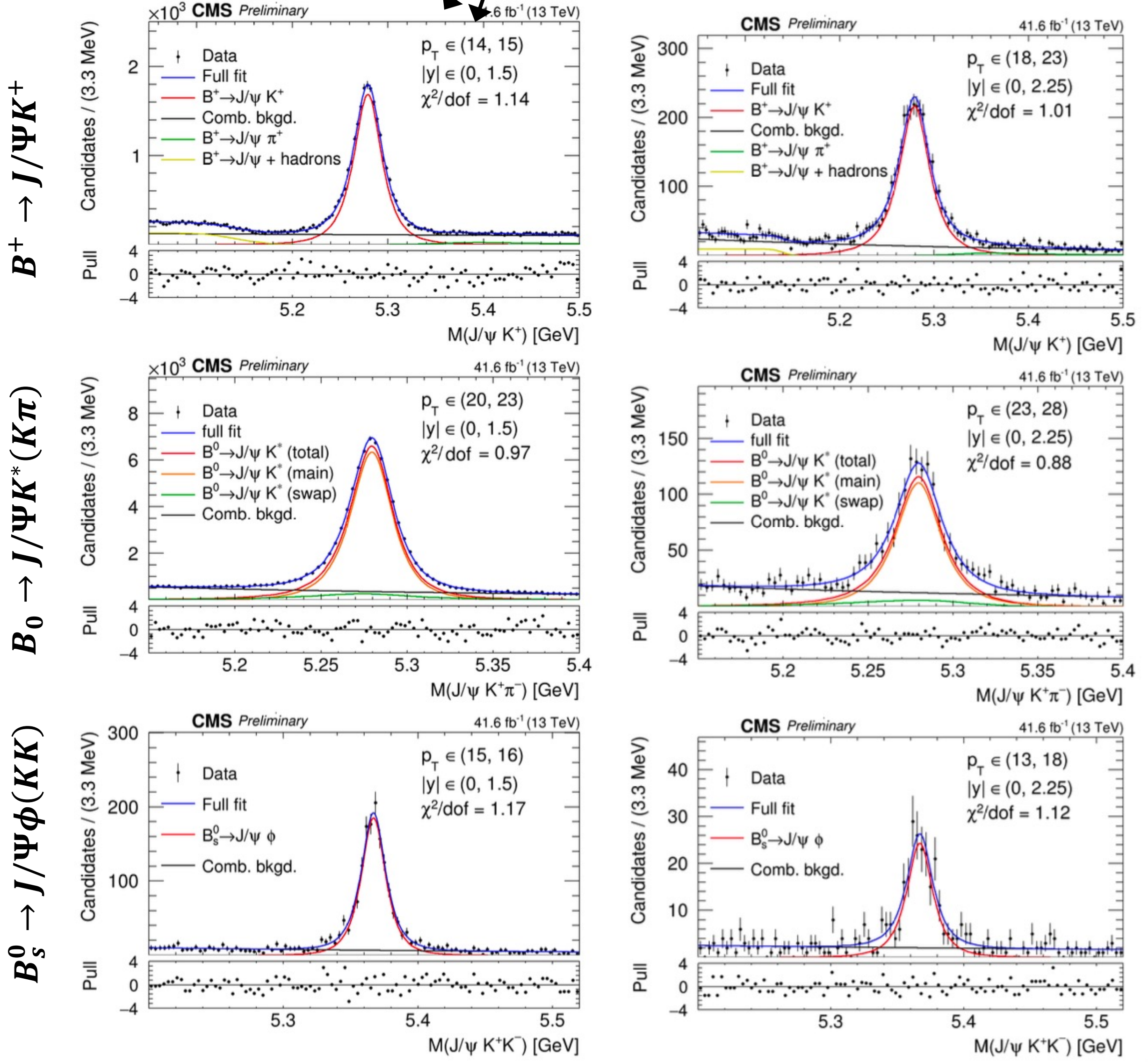
$$R_s^{(d)} = \frac{N_{corr}^{B_s^0}}{N_{corr}^{B^+(B^0)}}$$

$$\frac{f_d}{f_u} = \frac{\mathcal{B}(B^+ \to J/\Psi K^+)}{\mathcal{B}(J/\Psi K^*(K\pi))} \frac{N_{corr}^{B^0}}{N_{corr}^{B^+}}$$

- $R_s^{(d)}$ cannot be directly connected to PFR
  - Can only determine a trend in p_T or rapidity
  - Conversion achieved using hadronic open-charm channel

Selections*

- Standard selections (p_T, η, mass, vtx_prob …)
- Both tag and probe side of the trigger are used



* Detailed list of selections in backup

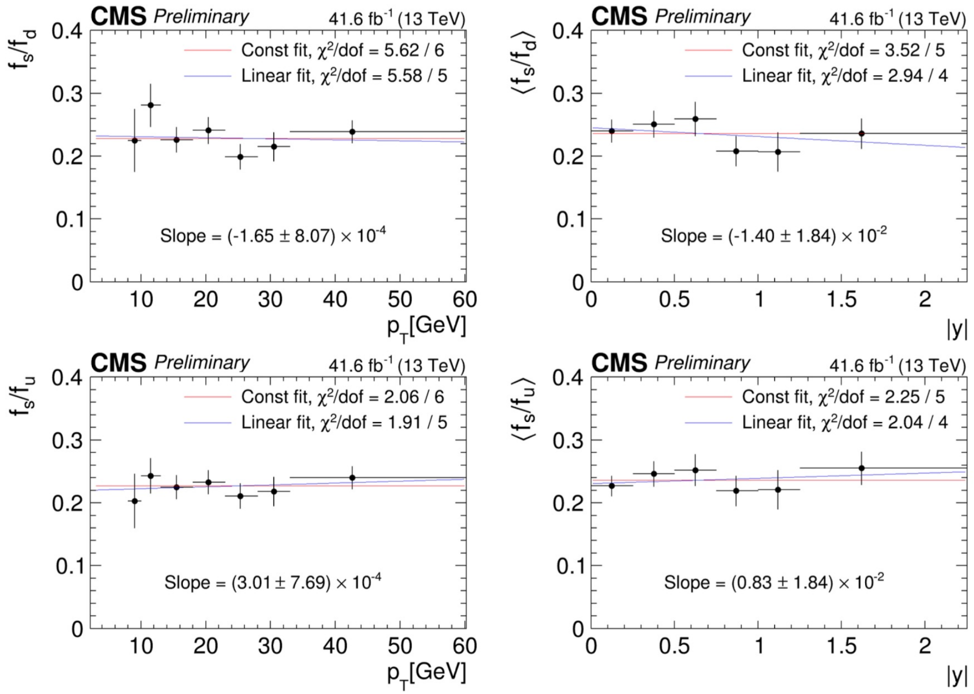
Results

Hadronic open-charm: f_s/f_d and f_s/f_u

- f_s/f_u = 0.227 ±0.011 (stat) ±0.017 (syst)
- f_s/f_d = 0.224 ±0.011 (stat) ±0.014 (syst)

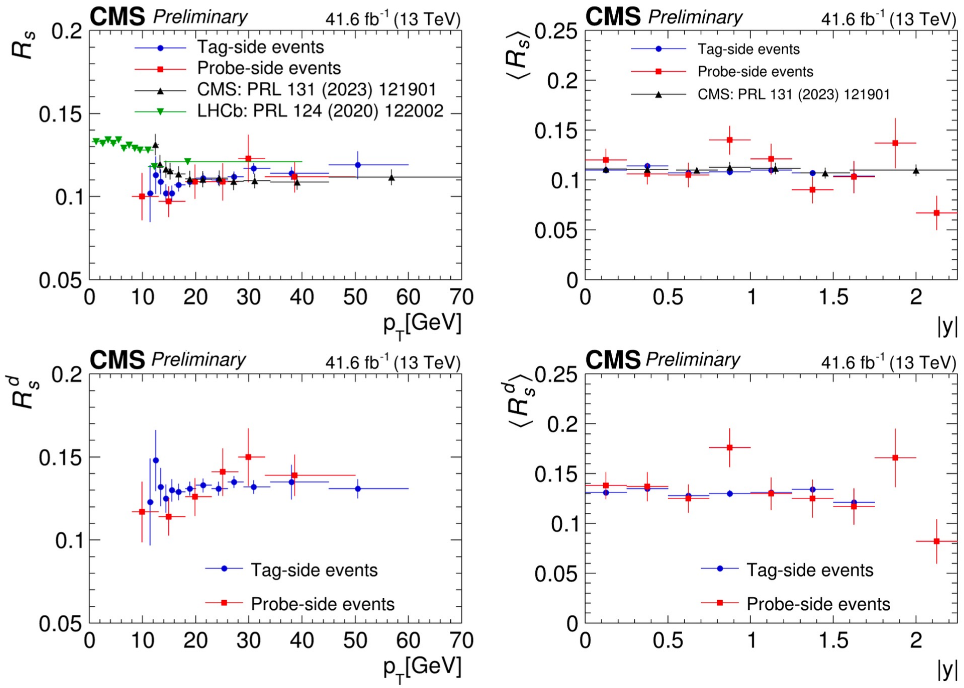
Average of measurements at p_T>18 GeV

Compatible with the LEP result: f_s/f_d = 0.249 ±0.023



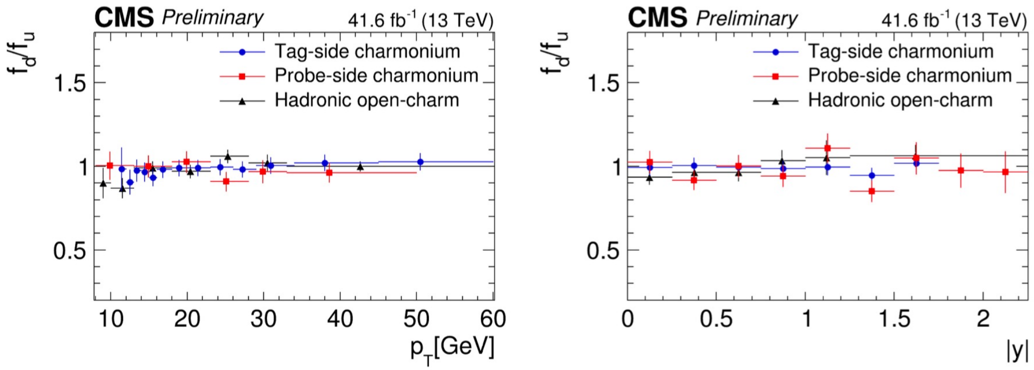
Charmonium: Relative PFRs

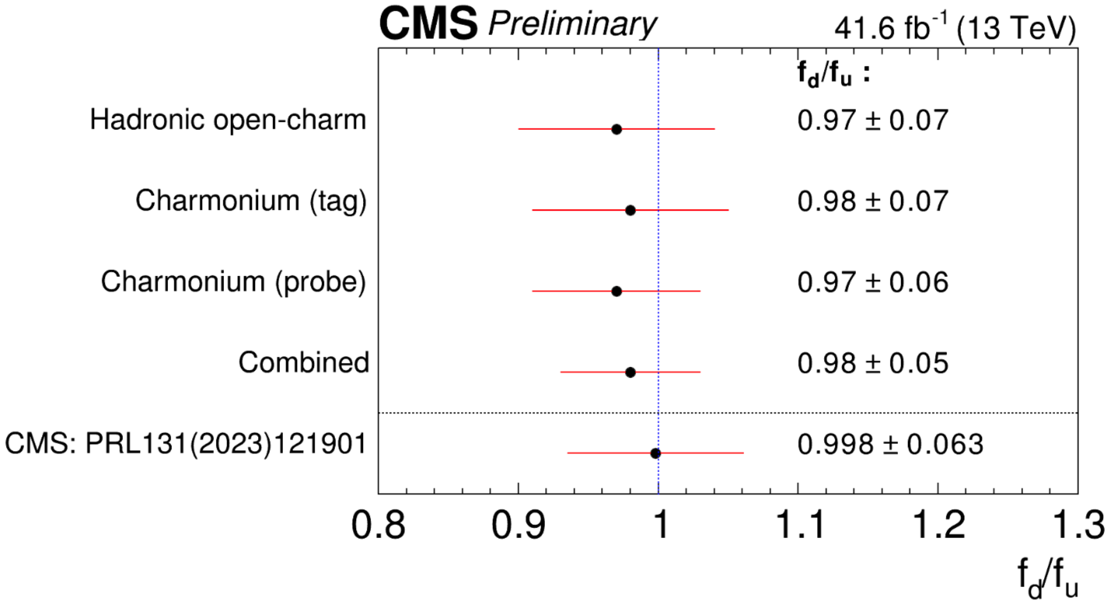
- Do not exhibit any statistically significant dependence on p_T or |y|
- Consistent with previous CMS result [PRL 131 (2023) 121901]



Results

Hadronic open-charm & Charmonium: f_d/f_u





Hadronic open-charm & Charmonium: Relative PFRs to PFRs

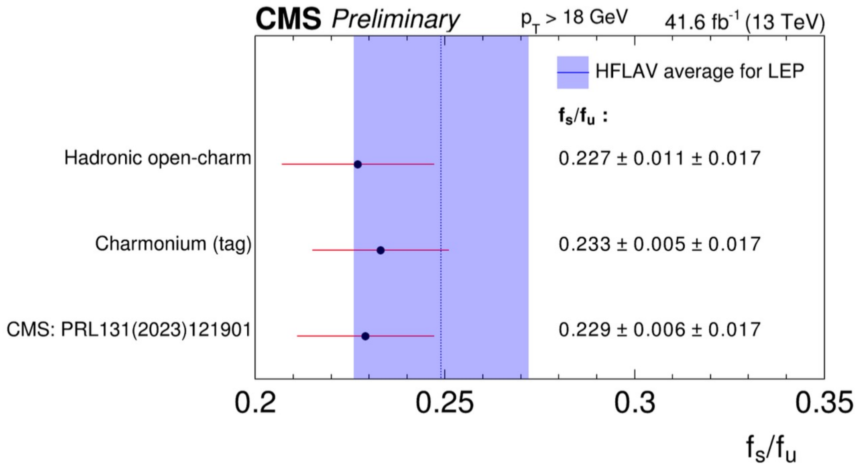
$$R_s^{(d)} \rightarrow f_s/f_{u(d)}$$

$$c_{su} = f_s/f_u(\text{open-charm})/\mathcal{R}_s(\text{charmonium})$$

$$= \Phi_{PS} \left|\frac{V_{us}}{V_{ud}}\right|^2 \left(\frac{f_K}{f_\pi}\right)^2 \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{1}{N_a N_F} \frac{\mathcal{B}(B^\pm \to \pi^+ D^0)}{\mathcal{B}(B^0 \to K^+ D^-)}$$

$$\times \frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D_s^- \to \pi^-\phi)} \frac{N_{corr}(B^+ \to \pi^+\overline{D}^0)}{N_{corr}(B_s^0 \to J/\psi\phi)} \frac{N_{corr}(B^+ \to J/\psi K^+)}{N_{corr}(B^+ \to \pi^+\overline{D}^0)}$$

= 2.075 ± 0.191



Measurements of $\Upsilon(1S)$ production in association with a Z boson at 13 TeV

[BPH-23-007]

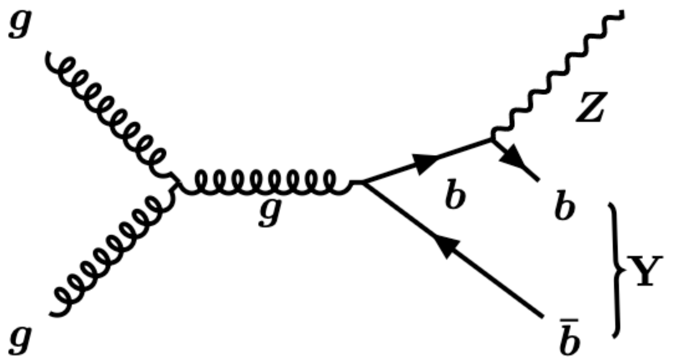
Z + Υ(nS) Associated Production: SPS vs DPS

Measure fiducial cross section for Z + Υ(1S)

- Compute effective DPS cross section (σ_{eff})

Heavy quarkonium production in hadronic collisions is **not fully understood**

- Multiple and competing models describe quarkonium formation
- Tensions are more pronounced when produced with electroweak (EW) bosons

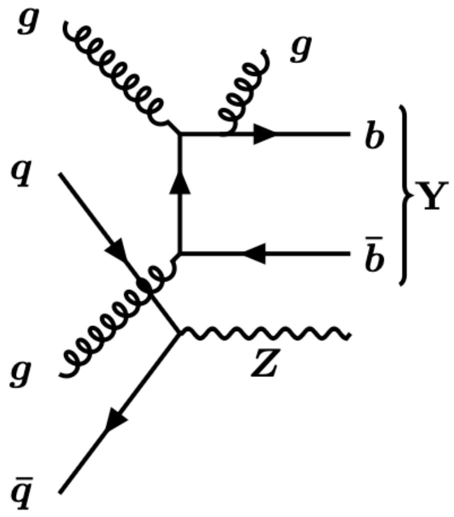


Single-Parton Scattering (**SPS**)

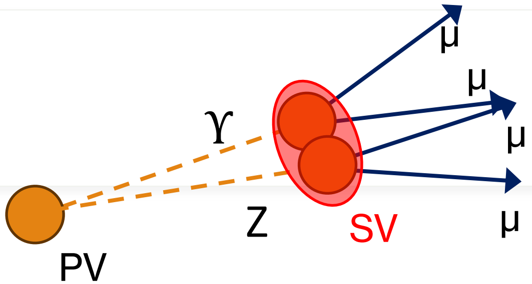
- Z + Y(nS) from a single parton pair

Double-Parton Scattering (**DPS**)

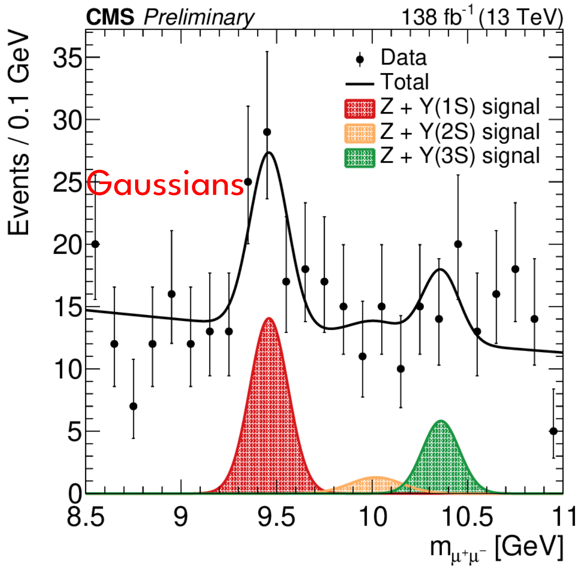
- Z and Y(nS) from two independent parton pairs

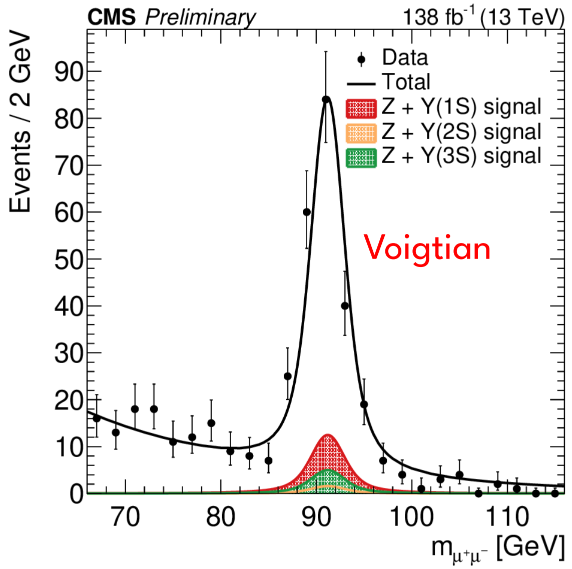


Signal Extraction



- Run2 (2016-2018) pp collisions (~138 fb^{-1})
- **Signal Channel*:**
  - Z + Υ(nS) → (Z → $\mu\mu$) + (Υ(nS) → $\mu\mu$)
  - **MC: DPS** via PYTHIA8 **SPS** via HELAC-ONIA
- **Normalization channel**
  - $Z \rightarrow 4\mu$
- 2D extended unbinned maximum likelihood fit of Z and Υ(nS) masses



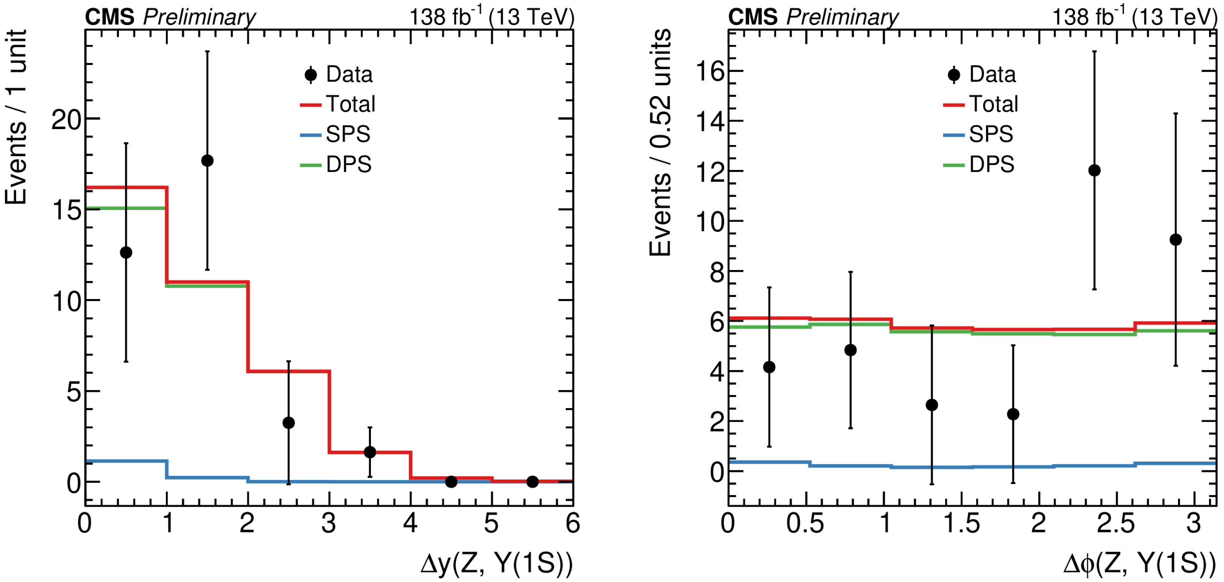


- The fit yielded these **signal rates:**
  - **Z + Υ(1S)**: 34.6 ± 9.0 > 5.3 σ !
  - **Z + Υ(2S)**: 2.9 ± 6.7
  - **Z + Υ(3S)**: 13.9 ± 7.2

* Detailed list of selections in backup

SPS/DPS Separation

- Simultaneous fit of the **rapidity (Δy)** and **azimuthal ($\Delta\phi$) separations** between the Z and ϒ(1S) candidates
- Resulting yields:
  - $N^{SPS}_{Z+\Upsilon(1S)} = 1.7 \pm 8.7$
  - $N^{DPS}_{Z+\Upsilon(1S)} = 32.9 \pm 8.7$



Data: obtained via sPlot technique
SPS and DPS templates: derived from simulation

Fiducial Cross Section Ratio and σ_{eff} Calculation

Fiducial Cross Section Ratio

$$\mathcal{R}_{Z+\Upsilon(1S)} = \left(\frac{N^{SPS}_{Z+\Upsilon(1S)}}{\epsilon^{SPS}_{Z+\Upsilon(1S)}} + \frac{N^{DPS}_{Z+\Upsilon(1S)}}{\epsilon^{DPS}_{Z+\Upsilon(1S)}} \right) \frac{\epsilon_{Z\to\mu^+\mu^-\mu^+\mu^-}}{N_{Z\to\mu^+\mu^-\mu^+\mu^-}}$$

(48.51±0.09)%

(50.13±0.04)%

(42.42± 0.05)%

1860±60

Efficiencies computed from MC simulations

Number of events in the norm. channel

[21.1 ± 5.5 (stat) ± 0.6 (syst)] $\times 10^{-3}$

Effective double-parton scattering cross section (σ_{eff})

Υ(1S) cross section is taken from data-constrained theory [1] [2] [3]

274 ±5 nb

(37.6 ±1.0)%

$$\sigma_{\text{eff}} = \frac{\sigma(\Upsilon(1S))}{\mathcal{R}^{DPS}_{Z+\Upsilon(1S)}} \frac{\mathcal{B}(Z \to \mu^+\mu^-)\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)}{\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)} \frac{A_{Z+\Upsilon(1S)}}{A_Z}$$

Efficiencies of fiducial cuts computed from MC

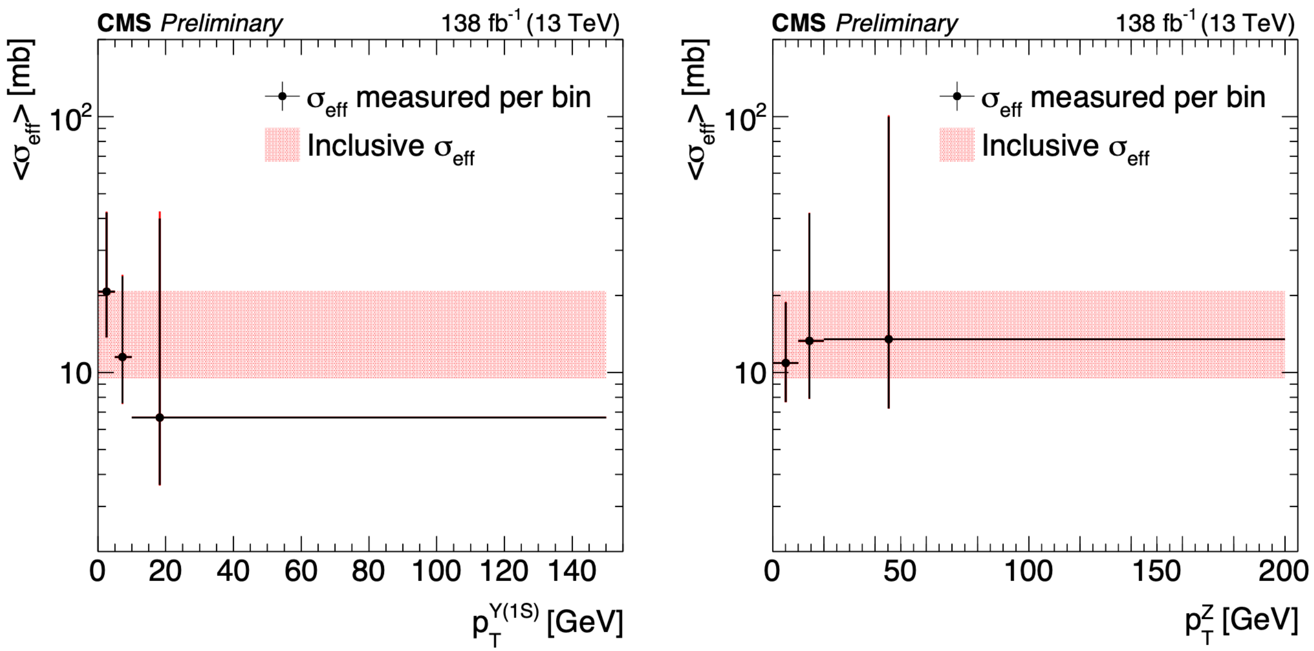
[20.2 ± 7.5 (stat) ± 0.6 (syst)] $\times 10^{-3}$

(26.3 ±0.8)%

$$\sigma_{\text{eff}} = 13.0^{+7.9}_{-3.5}\ \text{mb}$$

Differential σ_{eff} Measurements

- Same strategy allows to compute $\boldsymbol{\sigma_{eff}}$ in bin of Υ(1s) and Z p_T
- Consistent with result in double-quarkonium measurements
- This result could be an input for constraining double-parton distribution functions in multiparton interactions



Summary

Total charm cross section at 7 TeV (BPH-22-007):

- Innovative inclusion of **fragmentation non-universality** effects;
- Excellent agreement with QCD predictions.

B meson production fractions at 13 TeV(BPH-21-007):

- Two different sub- analysis using B parking data;
- All the PFRs agreed with theory and previous measurements.

Associated Z + Υ(1S) production at 13 TeV (BPH-23-007):

- First **evidence (>5σ)** of Z + Υ(1S) production at CMS.
- First measurement of Z + Υ(1S) effective DPS cross section

Thanks for your attention!

Backup

D^* reconstruction strategy - Selections

[BPH-22-007]

Table 1: Summary of selection criteria for tracks and D^* candidates

Object	**Variable**	**Selection**
Kaon (K)	p_T	> 0.3 GeV
	d_{xy} from PV	< 0.15 cm
	d_z from PV	$< 0.1/\sin\theta$ cm
	dE/dx (for $p < 1.5$ GeV)	$\in [0.6/\lvert p\rvert + 2,\ 1.0/\lvert p\rvert + 3.5]$
Pion (π)	p_T	> 0.5 GeV
	d_{xy}, d_z from PV	Same as K
Slow pion (π_s^+)	p_T	> 70 MeV
	d_{xy} from PV	< 0.3 cm
	d_z from PV	$< 0.2/\sin\theta$ cm
	d_{xy}, d_z from D^0 vertex	< 2 cm
D^0	p_T	> 0.9 GeV
	Vertex fit p-value	> 0.01
	d_z(PV–SV)	< 2 cm
	$m(K\pi)$	$\in [1.5,\ 2.3]$ GeV
	p_T^{frac}	> 0.1
D^*	ΔM	< 0.165 GeV
	$\cos\phi$	> 0.8
	d_{lsig}	see table below

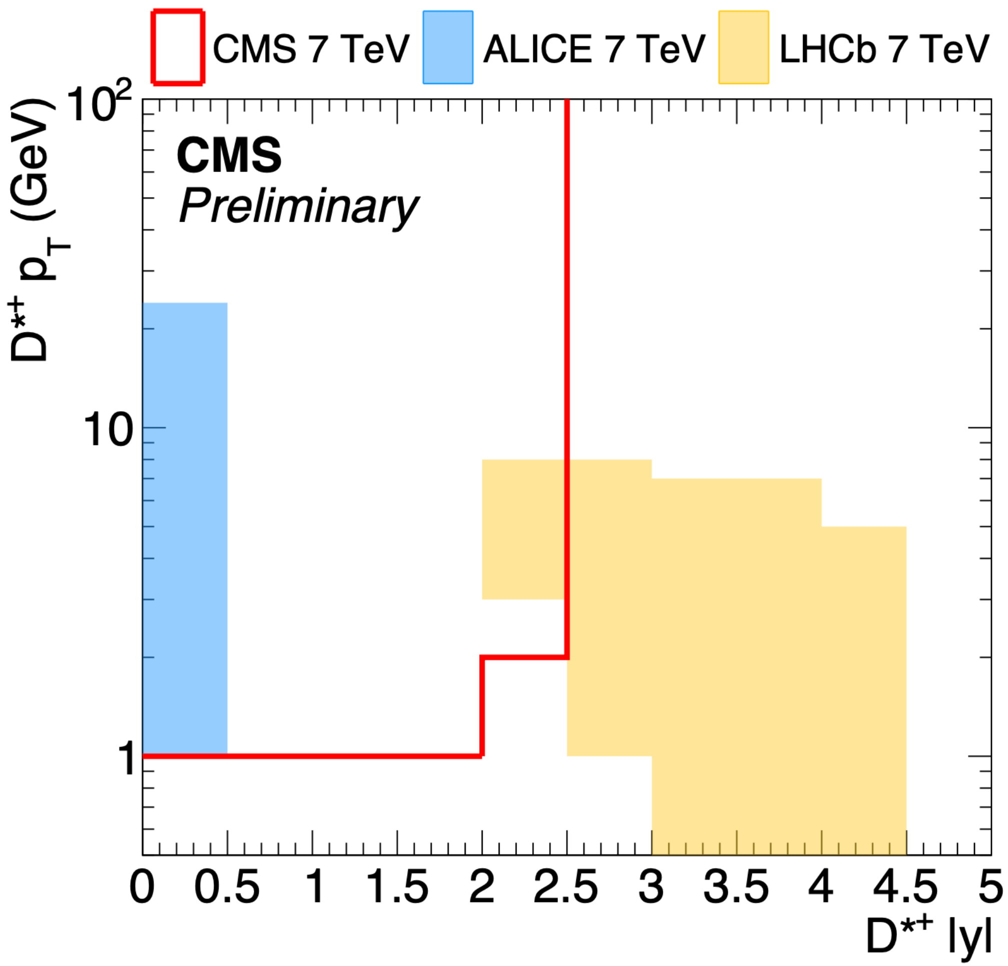
Table 2: Additional selection depending on D^* p_T category

$p_T(\mathbf{D}^*)$	$m(K\pi)$ **[GeV]**	**Additional cuts**
$[1.0,\ 3.5]$ GeV	$[1.84,\ 1.89]$	$d_{lsig} > 1.5$ & $p_T^{\text{frac}} > 0.15$ or $d_{lsig} > 3$ or ($d_{lsig} > 2$ & $\cos\phi > 0.995$)
> 3.5 GeV	$[1.85,\ 1.88]$	$d_{lsig} > 0$ & $p_T^{\text{frac}} > 0.15$ or $d_{lsig} > 2$

D^* phase space

[BPH-22-007]

- Actual phase space in transverse momentum and rapidity for prompt-D^* production cross sections covered by ALICE, LHCb, and CMS



Systematic uncertainties

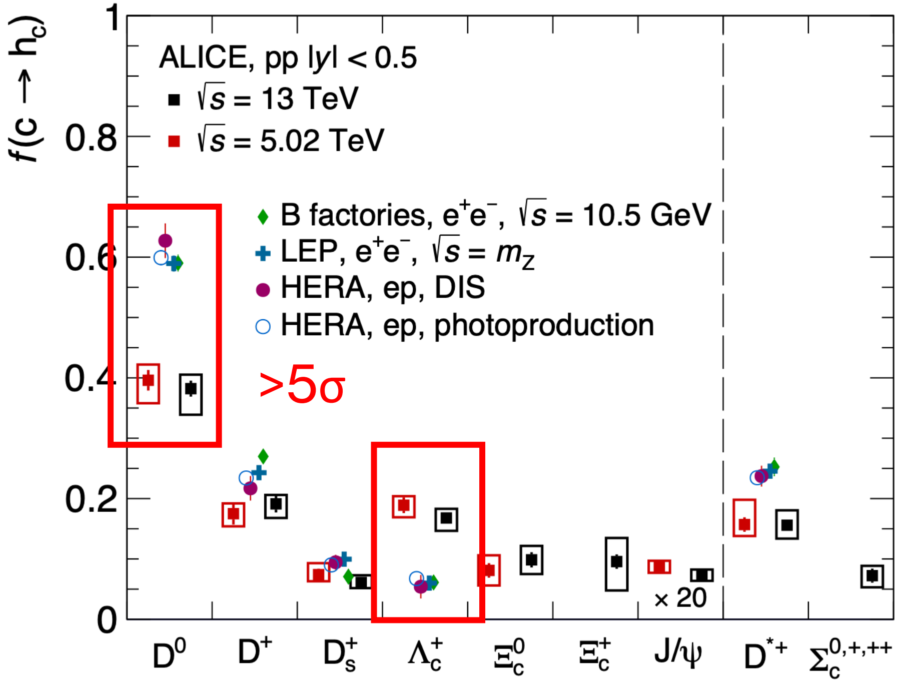
[BPH-22-007]

Source	uncertainty
Statistical	7–15%
Effective luminosity	4%
Branching fraction	1%
Tracking efficiency	8%
Pileup dependence	5%
Era and NMB dependence	3%
Wrong sign normalization	1%
Signal tail systematics	3%
Total all-bin systematics	11%
MC statistics	1–5%
Beauty fraction subtraction	1–3%
Total systematics	11–13%

Fragmentation non-universality

[BPH-22-007]

Charm breaks fragmentation universality!



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Data-driven FONLL

"Charm total cross sections with nonuniversal fragmentation treatment"
A. Geiser, Y. Yang, S. Moch, O. Zenaiev

arXiv:2406.03581v1

FONLL (NLO+NLL QCD theory)

UNIVERSALITY ASSUPTION!

fragmentation fraction from $e^+e^-/e\,p$ collisions

$$d\sigma_{H_c}^{\mathrm{FONLL}} = f_{H_c}^{\mathrm{uni}} \cdot \left(d\sigma_{pp\to c}^{\mathrm{FONLL}} \otimes D_{c\to H_c}^{\mathrm{NP}}\right)$$

Perturbative $c\bar{c}$ differential cross section up to NLO+NLL

nonperturbative fragmentation function

Fixed QCD parameters!

factorization and renormalization scales μ_f, μ_r

Charm pole mass m_c

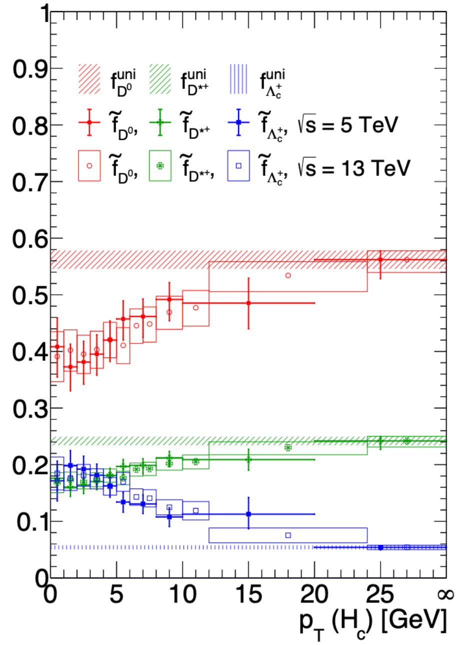
Data-driven FONLL (ddFONLL)

μ_f, μ_r, m_c are free parameters

NP fragmentation function with Kartvelishvili parametrization (introduce α_s parameter)

$$d\sigma_{H_c}^{\mathrm{ddFONLL}} = \tilde{f}_{H_c}(p_T) \cdot \left(d\sigma_{pp\to c}^{\mathrm{FONLL}} \otimes D_{c\to H_c}^{\mathrm{NP}}\right)$$

p_T dependent - hadron-production fraction directly obtained from measurements at LHC



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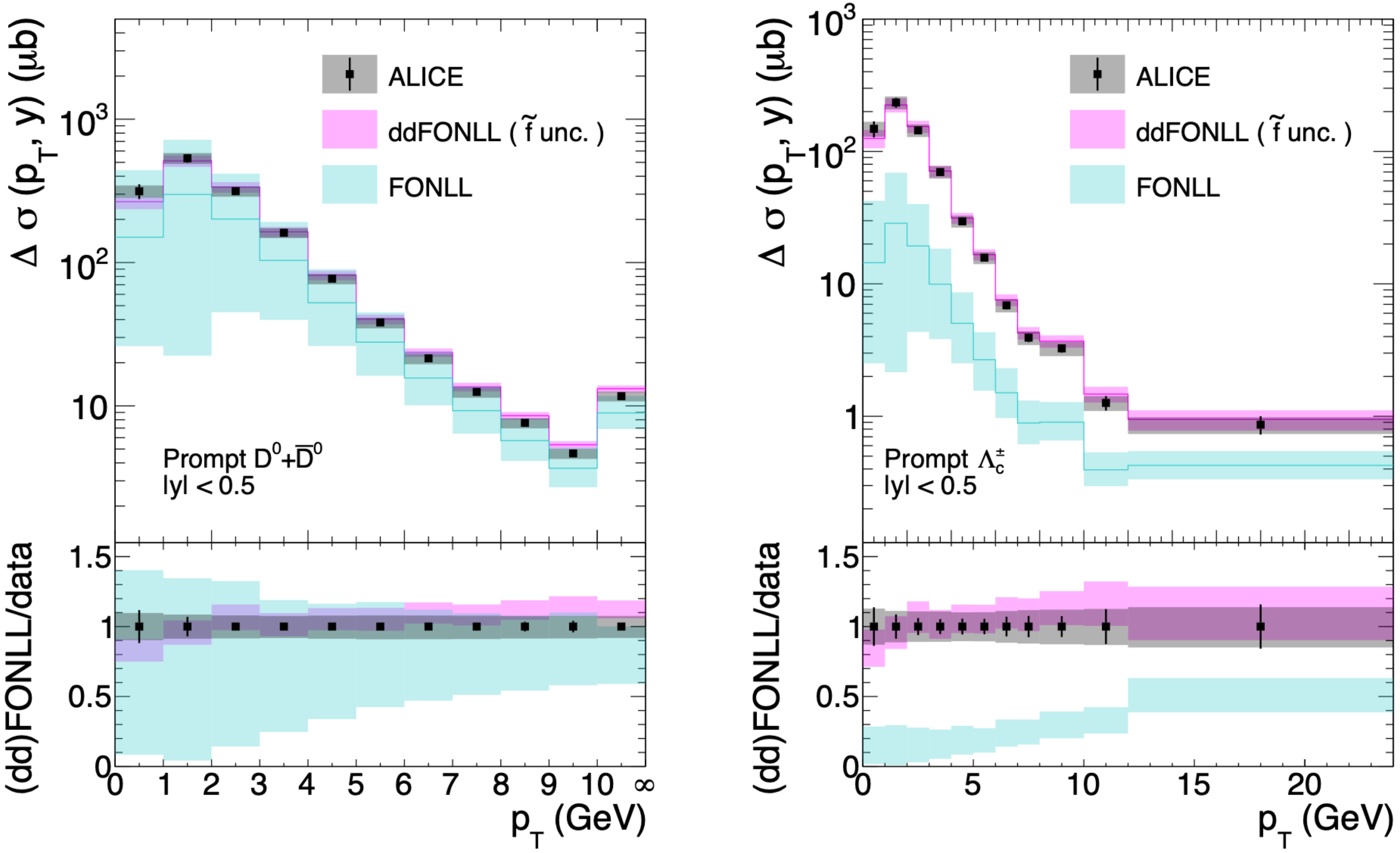

Selections

[BPH-21-007]

Hadronic open-charm

Variable	Selection B^+	B^0	B^0_s
General track selection			
Track p_T		$> 1\,\text{GeV}$	
Track $\lvert\eta\rvert$		< 2.4	
$\Delta z(\text{track}, \mu_{\text{trig}})$		$< 0.5\,\text{cm}$	
Track IP_{sig}		> 1	
D candidate selection			
D candidate leading-track p_T		$> 1.5\,\text{GeV}$	
TV fit probability		> 0.01	
$S_{xy,\text{TV}}$		> 5	
D candidate mass window	$\pm 20\,\text{MeV}$	$\pm 20\,\text{MeV}$	$\pm 15\,\text{MeV}$
$\lvert M(K^+K^-) - m(\phi)\rvert$	–	–	$< 10\,\text{MeV}$
B candidate selection			
p_T of the remaining B candidate track		$> 1.5\,\text{GeV}$	
$S_{xy,\text{SV}}$		> 7	
$\cos\alpha_B$		> 0.999	

Charmonium

Variable	Selection B^+	B^0	B^0_s
General track selection			
Leading (subleading) track p_T	$> 0.85\,\text{GeV}$	$> 0.85\ (0.60)\,\text{GeV}$	$> 0.85\ (0.60)\,\text{GeV}$
Track $\lvert\eta\rvert$		< 2.4	
$\Delta z(\text{track}, \text{PV})$		$< 1\,\text{cm}$	
Muon candidate selection			
Muon p_T	$p_T > \begin{cases} 3.5\,\text{GeV} : \lvert\eta\rvert < 1.1 \\ 3.5 + \frac{1.5-3.5}{1.5-1.1}(\lvert\eta\rvert - 1.1)\,\text{GeV} : 1.1 < \lvert\eta\rvert < 1.5 \\ 1.5\,\text{GeV} : \lvert\eta\rvert > 1.5 \end{cases}$		
Muon identification		Soft ID [18]	
$\lvert M(\mu\mu) - m(J/\psi)\rvert$		$< 150\,\text{MeV}$	
B candidate selection			
SV fit probability		> 0.07	
$S_{xy,\text{SV}}$		> 4	
$\cos\alpha_B$		> 0.997	
Intermediate resonance masses			
$\lvert M(K^+K^-) - m(\phi)\rvert$	–	$> 10\,\text{MeV}$	$< 10\,\text{MeV}$
$\lvert M(K^+\pi^-) - m(K^{*0})\rvert$	–	$< 50\,\text{MeV}$, closest permutation	$> 50\,\text{MeV}$, both permutations

Systematic uncertainties

[BPH-21-007]

Hadronic open-charm

Source	f_s/f_u (%)	f_s/f_d (%)	f_d/f_u (%)
N_a, N_F	4.22	4.22	—
Lifetime ratio	0.40	0.40	—
Branching fractions	5.36	4.03	5.46
Tracking efficiency	2.1	—	2.1
BDT performance	1.18	2.23	2.24
B_s^0 nonresonant component subt.	0.9	0.9	—
Total global systematic uncertainty	7.4	6.3	6.3
Statistical uncertainty in simulation	1.7–3.1	2.2–3.7	2.1–3.6
Signal and background shapes	0.8–2.4	0.8–2.8	0.7–2.1
Reweighting in p_T and $\|y\|$	0.0–1.4	0.0–1.6	0.1–1.1
Total systematic uncertainty	< 8.7	< 7.8	< 7.8

Charmonium

Source	Tag			Probe		
	$\mathcal{R}_s$ (%)	$\mathcal{R}_s^d$ (%)	f_d/f_u (%)	$\mathcal{R}_s$ (%)	$\mathcal{R}_s^d$ (%)	f_d/f_u (%)
Stat. uncert. in simulation	0.7–6.7	0.8–9.3	0.7–7.2	1.9–4.9	1.7–4.8	1.6–4.2
Signal and bkg. shapes	0.8–4.7	0.6–5.2	0.5–4.2	1.3–7.9	1.1–6.4	0.9–6.4
Trigger SF	1.9–2.6	1.9–2.7	1.9–2.7	—	—	—
Reweighting in p_T and $\|y\|$	0.0–5.3	0.0–4.3	0.0–6.5	0.0–3.7	0.0–3.8	0.0–4.9
Total syst. uncertainty	<8.5	<9.8	< 8.8	<10.0	<8.1	<7.7

Data and Event Selection

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Data

Run2 (2016-2018) p-p collisions (~138 fb^{-1})

Double | Triple –muon triggers

MC Simulations

- **DPS** simulated using PYTHIA8
- **SPS** simulated with HELAC-ONIA 2.5.5
- Normalization channel simulations of $Z \to 4\mu$

Signal Z + ϒ(nS)

4 isolated muons → build OS pairs for Z and ϒ(nS).

- **ϒ(nS) muons:**
  - Soft ID, p_T > 3 GeV, |η| < 2.4
  - Invariant mass in [8.5, 11] GeV, |y| < 2.4, fit prob.> 5%
- **Z muons:**
  - Tight ID, p_T > 30 and 15 GeV, |η| < 2.4
  - Invariant mass in [66, 116] GeV, fit prob.> 5%

All four muons must come from a common vertex (fit prob. > 1%)

Norm. Z→4μ

4 muons, with total charge = 0

- Tight ID, p_T > 20, 10, 5, 5 GeV
- All OS pairs must have m(μμ) > 1 GeV

Choose **2 OS pairs** maximizing mass difference between dimuon pairs

- OS pairs common vertex with fit prob. > 5%

Systematic uncertainty

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Source of systematic uncertainty	Value
Υ(nS) signal model	1.75%
Υ(nS) background model	0.27%
Z signal model (Z + Υ(nS))	1.05%
Z signal model (Z $\to 4\mu$)	1.62%
Z background model (Z + Υ(nS))	0.66%
Z background model (Z $\to 4\mu$)	0.22%
Finite MC sample size	0.23%
$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$	1.61%
$\mathcal{B}(Z \to \mu^+\mu^-)$	0.20%
$\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)$	4.00%
$\sigma_{\Upsilon(1S)}$ from theory	1.93%
Total	5.46%

Systematic uncertainties affecting σ_{eff}

Systematic uncertainties affecting $R_{\Upsilon(1S)}$ → Total: 2.73%

Differential σ_{eff} Measurements

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$p_T^{Y(1S)}$ [GeV]	$\mathcal{R}_{Z+Y(1S)}$ ($\times10^{-3}$)	$\mathcal{R}^{DPS}_{Z+Y(1S)}$ ($\times10^{-3}$)	σ_{eff} [mb]
0–5	7.1 ± 3.5 (stat + syst)	7.0 ± 3.6 (stat + syst)	$20.7^{+21.8}_{-7.0}$ (stat + syst)
5–10	6.6 ± 3.1 (stat + syst)	6.4 ± 3.3 (stat + syst)	$11.5^{+12.6}_{-4.0}$ (stat + syst)
10–150	7.2 ± 3.0 (stat + syst)	6.5 ± 5.5 (stat + syst)	$6.7^{+36.2}_{-3.1}$ (stat + syst)
p_T^{Z} [GeV]	$\mathcal{R}_{Z+Y(1S)}$ ($\times10^{-3}$)	$\mathcal{R}^{DPS}_{Z+Y(1S)}$ ($\times10^{-3}$)	σ_{eff} [mb]
0–10	24.3 ± 8.8 (stat + syst)	24.0 ± 10.1 (stat + syst)	$10.9^{+8.0}_{-3.3}$ (stat + syst)
10–20	20.5 ± 9.8 (stat + syst)	19.7 ± 13.4 (stat + syst)	$13.3^{+28.8}_{-5.4}$ (stat + syst)
20–200	21.4 ± 11.1 (stat + syst)	19.4 ± 16.8 (stat + syst)	$13.5^{+87.6}_{-6.3}$ (stat + syst)