

Production of charm and beauty at CMS

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- 1 Measurement of B meson production fractions in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ using hadronic open-charm and charmonium decays
- 2 Observation of the $\Upsilon(1S)$ meson production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$
- 3 Measurement of double-differential and total charm-production cross sections at 7 TeV
- 4 Conclusion

I. Measurement of B meson production fractions
using open charm and charmonium decays
in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

<https://cds.cern.ch/record/2928055/files/BPH-21-007-pas.pdf>

- The production fractions of B^+ , B^0 , and B_s^0 mesons in pp collisions are crucial inputs to:
 - Branching fraction measurements of rare decays
 - Precision studies of flavor physics
 - Tests of isospin symmetry
- Previous measurements (LEP, Tevatron, LHC) were either limited in precision or kinematic reach.

- Measure the production fraction ratios:

$$\frac{f_d}{f_u}, \quad \frac{f_s}{f_u}$$

using both open-charm and charmonium decay channels of B mesons.

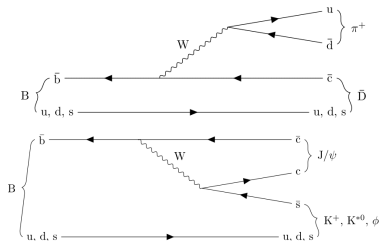
- Provide **absolute normalization** of charmonium-based production fractions using open-charm channels.
- Test **isospin symmetry** in b -hadron production at $\sqrt{s} = 13\text{TeV}$.
- CMS data from 2018 using a special data parking strategy.
- Kinematic coverage:
 - $8 < p_T < 60\text{ GeV}$
 - $|y| < 2.25$

Open-charm decays:

- $B^+ \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^\pm$
- $B^0 \rightarrow \pi^+ D^-$, $D^- \rightarrow K^+ \pi^\pm \pi^\pm$
- $B_s^0 \rightarrow \pi^+ D_s^+$,
 $D_s^+ \rightarrow \pi^\pm \phi \rightarrow \pi^\pm K^+ K^-$

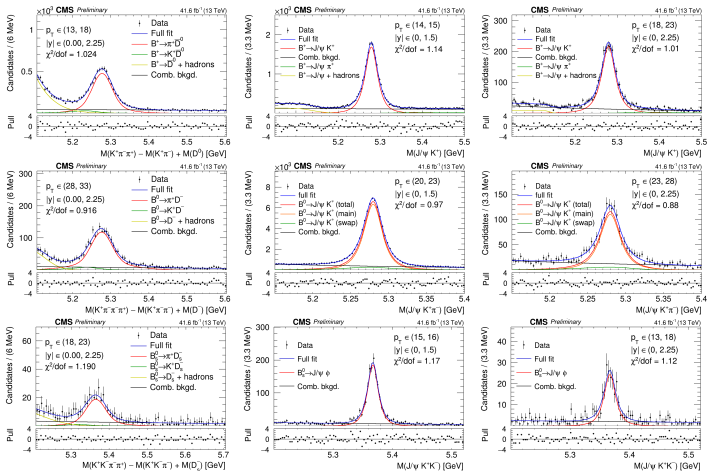
Charmonium decays:

- $B^+ \rightarrow J/\psi K^+$
- $B^0 \rightarrow J/\psi K^{*0}$, $K^{*0} \rightarrow K^+ \pi^\pm$
- $B_s^0 \rightarrow J/\psi \phi$, $\phi \rightarrow K^+ K^-$

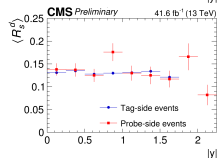
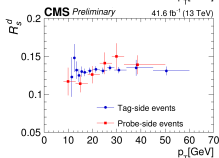
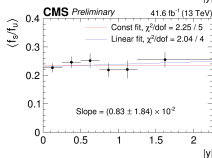
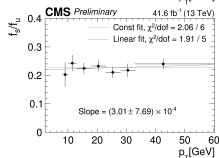
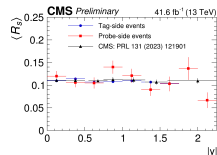
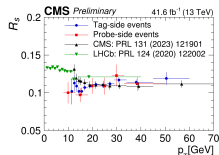
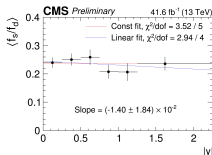
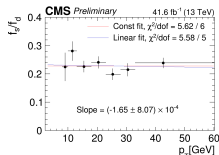


Signal extraction

- Signal extraction via invariant mass fits for each decay mode.
- Efficiency corrections applied using MC simulation and data-driven methods.



- Charmonium yields are **normalized to open-charm yields** for absolute measurement.
- Results are shown as functions of p_T and $|y|$.



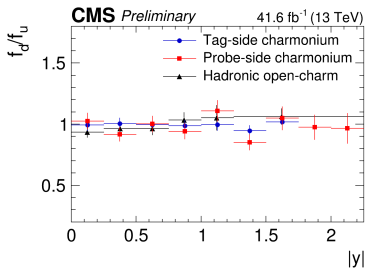
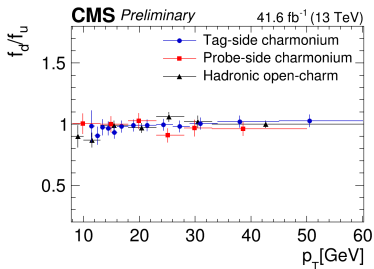
Key Results

- Measured production fraction ratios:

$$f_s/f_d = 0.223 \pm 0.015$$

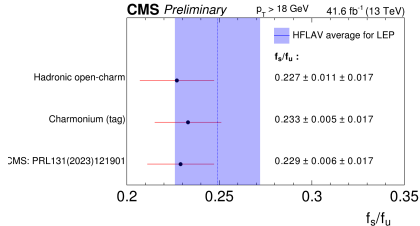
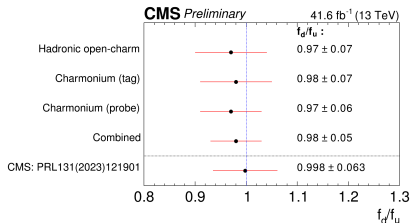
$$f_s/f_u = 0.233 \pm 0.018$$

- No significant deviation from isospin symmetry observed (f_d/f_u is consistent with 1).
- World-average values for several branching ratios improved.



Conclusions

- First CMS measurement of B meson production fractions using open-charm decays.
- Provides absolute normalization for charmonium decay modes.
- Results are important for precision flavor physics and global averages.
- Supports isospin symmetry in pp collisions at 13 TeV.

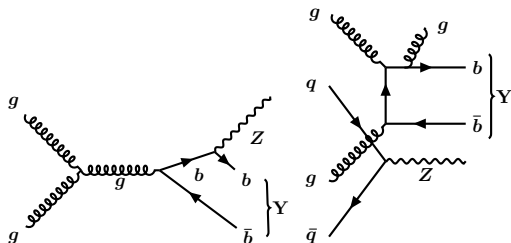


II. Observation of the $\Upsilon(1S)$ meson production
in association with a Z boson
in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

<https://cds.cern.ch/record/2921885/files/BPH-23-007-pas.pdf>

Motivation

- Study of quarkonium $\Upsilon(1S)$ production in association with electroweak bosons probes QCD and parton correlations. In such processes, two production mechanisms contribute:
 - Single-parton scattering (SPS)
 - Double-parton scattering (DPS)
- The DPS contribution is characterized by an effective cross section σ_{eff} .



- First observation of $Z + \Upsilon(1S)$ production at $\sqrt{s} = 13 \text{ TeV}$.
- Dataset: full Run 2 CMS data (2016–2018), 138 fb^{-1} .
- Both Z and $\Upsilon(1S)$ are reconstructed via dimuon decays:

$$Z \rightarrow \mu^+ \mu^-, \quad \Upsilon(1S) \rightarrow \mu^+ \mu^-$$

- Normalized using the $Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ channel.
- Measure the fiducial cross-section ratio:

$$\mathcal{R}_{Z+\Upsilon(1S)} = \frac{\sigma(\text{pp} \rightarrow Z + \Upsilon(1S)) \mathcal{B}(Z \rightarrow \mu\mu) \mathcal{B}(\Upsilon(1S) \rightarrow \mu\mu)}{\sigma(\text{pp} \rightarrow Z) \mathcal{B}(Z \rightarrow \mu\mu\mu\mu)}$$

- Extract effective DPS cross section:

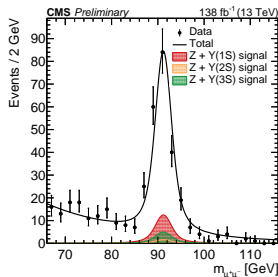
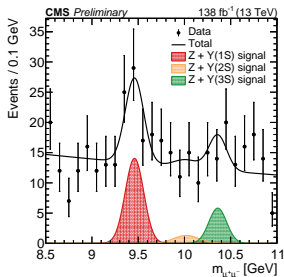
$$\sigma_{\text{eff}} = \frac{\sigma(\Upsilon(1S))}{\mathcal{R}_{Z+\Upsilon(1S)}^{\text{DPS}}} \frac{\mathcal{B}(Z \rightarrow \mu\mu) \mathcal{B}(\Upsilon(1S) \rightarrow \mu\mu)}{\mathcal{B}(Z \rightarrow \mu\mu\mu\mu)} \frac{A_{Z+\Upsilon(1S)}}{A_Z}$$

- Both inclusive and differential σ_{eff} are measured depending on Z and $\Upsilon(1S)$ p_{TS} .

Signal Extraction

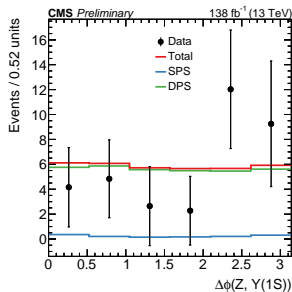
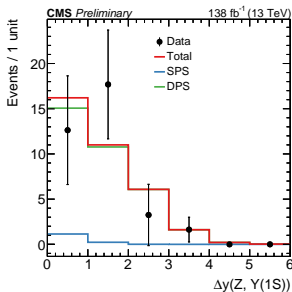
- Barrel $\mu^+\mu^-\mu^+\mu^-$ from a common vertex, passing special quality criteria
- All muons are required to be isolated from the hadronic activity in the event
- 2D fit with 3 $\Upsilon(1S)$ (nS) to be signal or background in association with Z to be signal or background as well.
- Statistical significance of $Z + \Upsilon(1S)$ is 5.2σ

$Z \rightarrow \mu^+\mu^- + Y(1S) \rightarrow \mu^+\mu^-$		$Z \rightarrow \mu^+\mu^- \mu^+\mu^-$
All muons	$ \eta \leq 2.4$	
p_T [GeV]	$30, > 15 > 3,3$	$> 20, > 10, > 5,5$



Signal yield decomposition to SPS and DPS

- Signal events weights extracted with the sPlot technique
- These weights are applied to the rapidity (Δy) and azimuthal ($\Delta\phi$) separations between the Z and the $\Upsilon(1S)$ candidates.
- SPS and DPS yields are extracted from (Δy) and ($\Delta\phi$) template fit with shapes derived from simulation.



Differential σ_{eff} Measurement

- Beyond the inclusive measurement, σ_{eff} is measured in bins of:
 - $p_T(\Upsilon(1S))$
 - $p_T(Z)$
- Event-by-event sPlot weights from the fit are used to extract p_T distributions.
- The number of DPS events per bin is computed by:
 - 1 Subtracting the SPS expectation (from simulation) from the total yield.
 - 2 Correcting for bin-by-bin efficiency using simulation.
- $\Upsilon(1S)$ production cross sections are taken from theory.

$p_T^{\Upsilon(1S)}$ [GeV]	$\mathcal{R}_{Z+Y(1S)} (\times 10^{-3})$	$\mathcal{R}_{Z+Y(1S)}^{\text{DPS}} (\times 10^{-3})$	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]	$\mathcal{R}_{Z+Y(1S)} (\times 10^{-3})$	$\mathcal{R}_{Z+Y(1S)}^{\text{DPS}} (\times 10^{-3})$	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)

Results And Conclusion

- Measured fiducial ratio:

$$\mathcal{R}_{Z+\Upsilon(1S)} = (21.1 \pm 5.5 \text{ (stat)} \pm 0.6 \text{ (syst)}) \times 10^{-3}$$

- Effective DPS cross section:

$$\sigma_{\text{eff}} = 13.0^{+7.8}_{-3.5} \text{ mb}$$

- First differential measurements of σ_{eff} versus: $p_T(\Upsilon(1S))$, $p_T(Z)$.
- First observation and measurement of $Z + \Upsilon(1S)$ associated production at the LHC.
- Results favor DPS-dominated production mechanism.

$$\mathcal{R}_{Z+\Upsilon(1S)}^{DPS} = (20.2 \pm 7.5 \text{ (stat)} \pm 0.6 \text{ (syst)}) \times 10^3$$

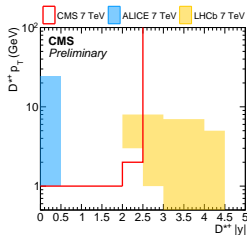
- Opens a new channel for probing parton correlations and proton structure in transverse plane.
- Provides input for modeling multiple parton interactions (MPI) in event generators.

III. Measurement of double-differential and total
charm-production cross sections
in proton-proton collisions at $\sqrt{s} = 7$ TeV

<https://cds.cern.ch/record/2905307/files/BPH-22-007-pas.pdf>

Introduction and selection

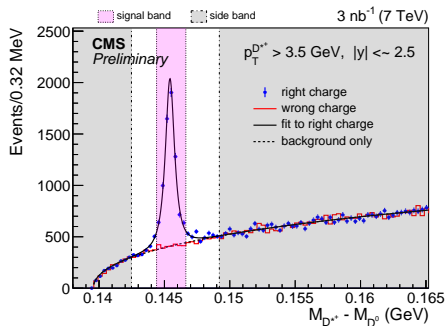
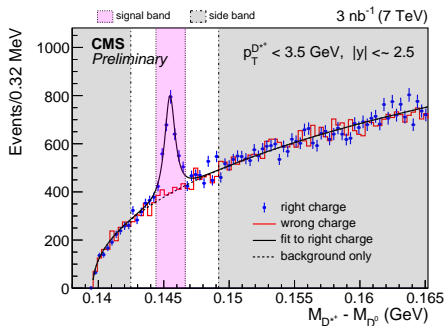
- Open-charm production in pp collisions is a key probe of QCD, especially in the transition region between hard and soft scales.
- Charm-pair production contributes $\sim 10\%$ to the total pp cross section at LHC energies.
- This CMS study at $\sqrt{s} = 7$ TeV:
 - Measures double-differential charm production cross section.
 - Minimizes extrapolation uncertainty using wide kinematic coverage.
 - Includes treatment of charm fragmentation nonuniversality for the first time.
 - $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$, bkg from $[K^\pm \pi^\mp] \pi^+$



Variable	selection criterion
Transverse momentum of K, p_T^K	> 0.3 GeV
Transverse momentum of π , p_T^π	> 0.5 GeV
d_{xy} of K and π from PV	< 0.15 cm
d_{xy} of π_s^+ from PV	< 0.3 cm
d_z of K and π from PV	$< 0.1 / \sin \theta$ cm
d_z of π_s^+ from PV	$< 0.2 / \sin \theta$ cm
dE/dx of K for $p^K < 1.5$ GeV	$\in [0.6 / p^K + 2, 1.0 / p^K + 3.5]$
Transverse momentum of D^0 , $p_T^{D^0}$	> 0.9 GeV
d_z distance between D^0 vertex and PV (dZ_{vtx})	< 2 cm
mass of the K- π system, m_{D^0}	$\in [1.5, 2.3]$ GeV
d_{xy} and d_z ($d_{z\pi_s}$) distances between π_s^+ and D^0 vertex	< 2 cm
mass difference between D^* and D^0 , after refit, ΔM	< 0.165 GeV

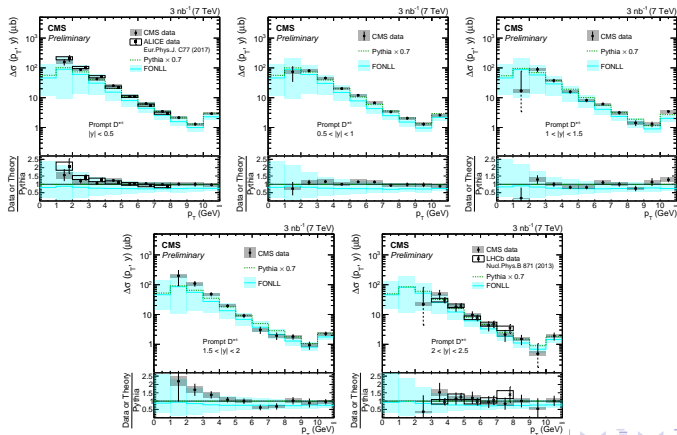
Signal extraction

- 50% minimum bias trigger, 50% events triggered by the other pp interaction
- contribution of beauty decays 5 – 10%
- Signal extracted from $M - M_{D^0}$ distribution
- Fit model: threshold background + Johnson signal function (cross-checked with MC)



Results: $D^{*+} + D^{*-}$ Cross Sections

- Bin-integrated double-differential cross sections $\Delta\sigma(p_T, |y|)$ for prompt $D^{*+} + D^{*-}$ mesons
- Comparisons with ALICE ($|y| < 0.5$) and LHCb ($2 < |y| < 2.5$) show agreement
- CMS provides first results in $|y| = [0.5, 2.0]$ at low p_T

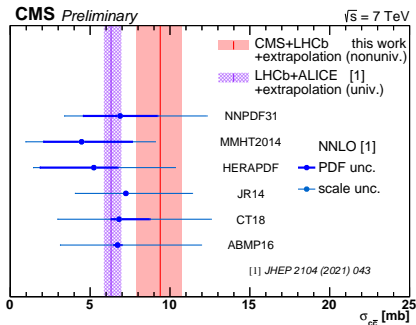


Total Charm Production Cross Section at 7 TeV

- Combining with LHCb (forward region), total charm pair production cross section is measured with the smallest extrapolation factor to date (~ 1.4), and with no universality assumption

$$\sigma_{c\bar{c}}^{\text{tot}} = 9.39_{-0.74}^{+0.74}(\text{data})_{-0.32}^{+0.31}(\tilde{f})_{-0.51}^{+0.64}(\text{PDF})_{-0.41}^{+0.30}(\mu_f, \mu_r, m_c, \alpha_K)_{-1.07}^{+0.83}(f_{D^{*+}}) \text{mb},$$

- Consistent with upper edge of NNLO QCD.



- The CMS Collaboration has performed several precision measurements of heavy-flavor production:
 - Measured production fractions of B^+ , B^0 , and B_s^0 using open-charm and charmonium decays.
 - Provided double-differential and total cross sections for prompt $D^{*\pm}$ meson production down to low p_T .
 - First measurement of $\Upsilon(1S)$ production in association with a Z boson and extraction of σ_{eff} for DPS.
- The **CMS experiment continues to collect data** with enhanced detectors and higher luminosity in Run 3.
- With more statistics and improved techniques, future analyses will further deepen our understanding of QCD, flavor physics, and proton structure.

Thank you for your attention!