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Production and rare decays of heavy flavor at CMS

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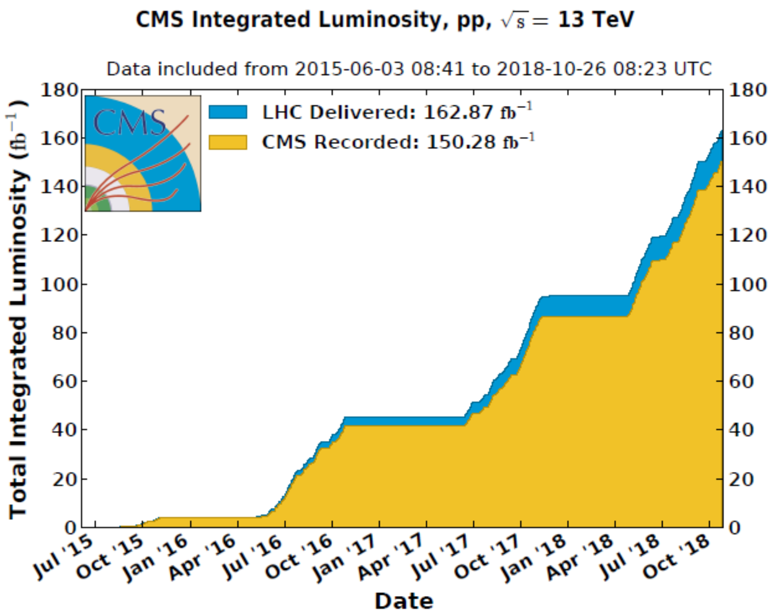
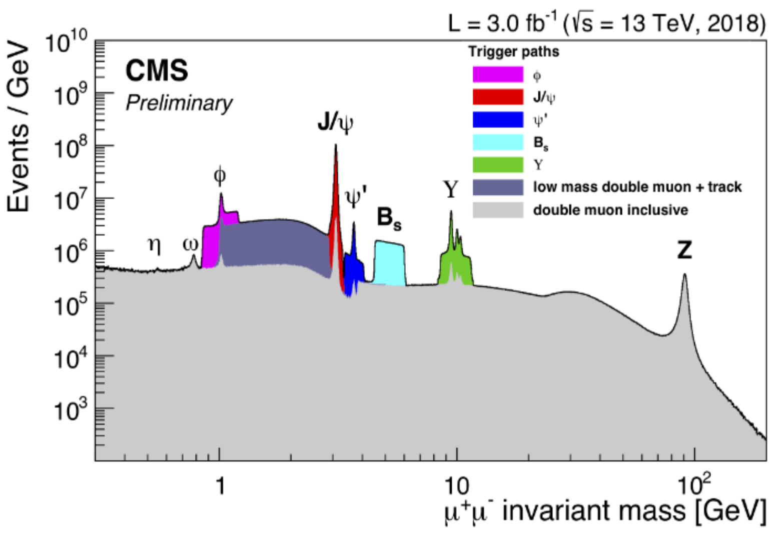
Outline:

1. Introduction
2. f_s/f_d measurements with CMS.
3. Rare process: associative production of Z boson with Y(1S)
4. Search for VERY rare decay D0 $\rightarrow$ μ+ μ-
   --- towards the depth gained by LHCb.
5. Summary

Introduction: the discussed results were obtained with the RUN II and RUN III data





- 160 fb^{-1} has been delivered by the LHC in Run 2 (2015-2018) at $\sqrt{s}$=13 TeV.

- Very efficient data collection by CMS with improved track momentum resolution → recorded over 140 fb^{-1} of physics-quality data.

- Ingenious di-muon inclusive trigger algorithms were developed for efficient online event selection.

⇓

CMS is contributing intensively into the heavy flavor and particularly in the searches of the BSM Physics in ***b-hadron decays***

In this talk selected ***new results*** from 13 and 13.6 TeV data sample will be discussed arXiv:2506.06152

Submitted to Phys. Rev. Lett.

Search for VERY rare decay D0 → μ+ μ-

Studies of rare decays of hadrons have long been considered one of the most promising avenues for discovering physics beyond the standard model (SM). Contributions from new physics effects are more easily detected in rare decays, as the smaller SM contributions make deviations more apparent. Decays mediated by flavor changing neutral currents, which are forbidden at tree level in the SM, have been studied in various experiments.

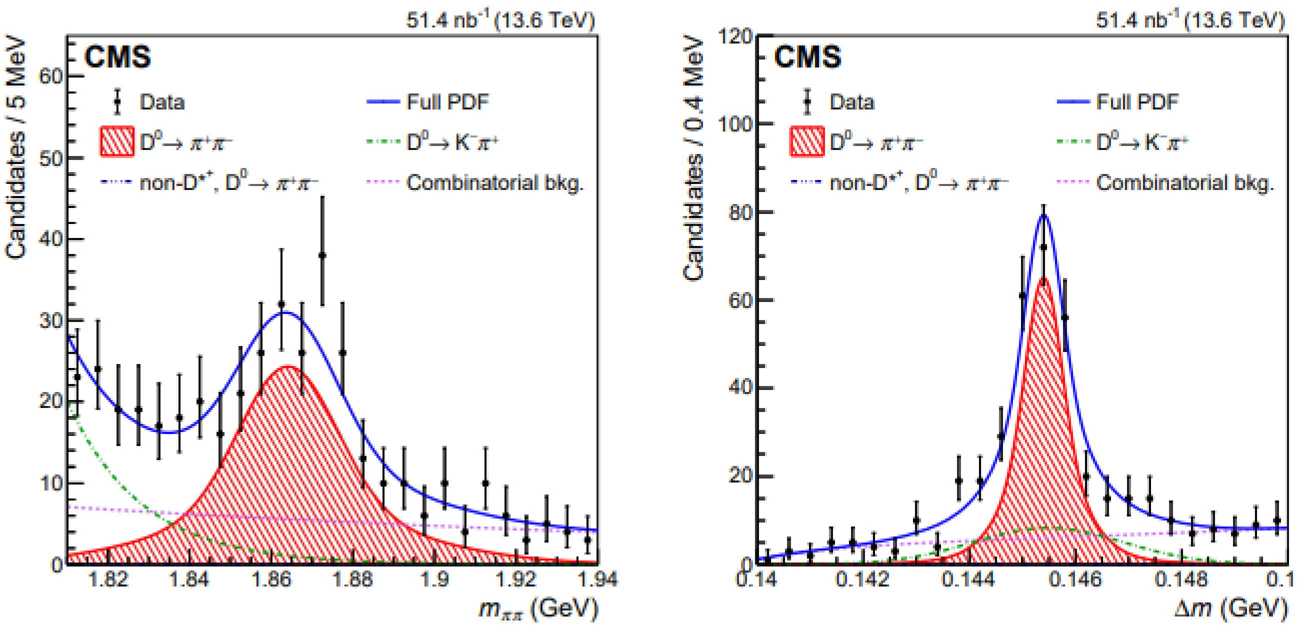
An important distinction between rare decays of charm hadrons and those of bottom or strange hadrons is that the loop contributions in charm decays are mediated by lighter quarks. This leads to substantial long-distance SM contributions, which are challenging to calculate, motivating searches where the beyond SM predictions substantially exceed those of the SM. The rare decay of the D0 meson into two muons is one such case. The SM prediction for the branching fraction Br(D0 → μ +μ −) is around **3×10^{-13}**

the LHCb Collaboration, set an upper limit on B(D0 → μ +μ −) at 3.1 (3.5) × 10^{-9} at 90 (95)% confidence level

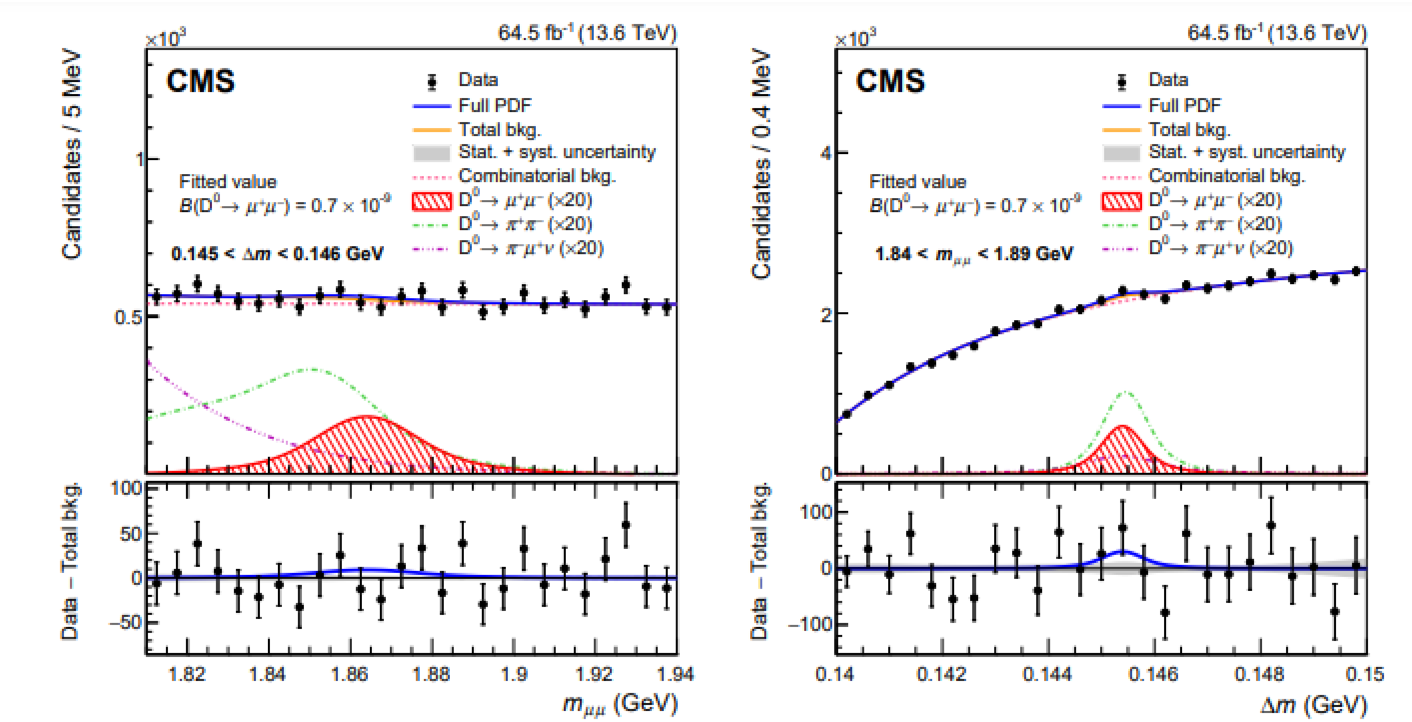
We report a search for D0 → μ +μ − decays by the CMS experiment based on pp collision data collected in 2022–2023 at a center-of-mass energy of 13.6 TeV, corresponding to an integrated luminosity of 64.5 fb^{-1} .
This search is enabled by **a new inclusive dimuon trigger**, which significantly broadens the scope of the CMS flavor physics program and is used here for the first time.

Search for VERY rare decay D0 → μ+ μ-

Use D*+→ D0 pi+ decay to suppress the background.
Use normalization channel D0 → pi+ pi- with as possible the same selection criteria



Search for VERY rare decay D0 → μ+ μ-



No obvious excess of events is observed and UL is set

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) < 2.1\,(2.4) \times 10^{-9} \text{ at } 90\,(95)\%\text{ CL.}$$

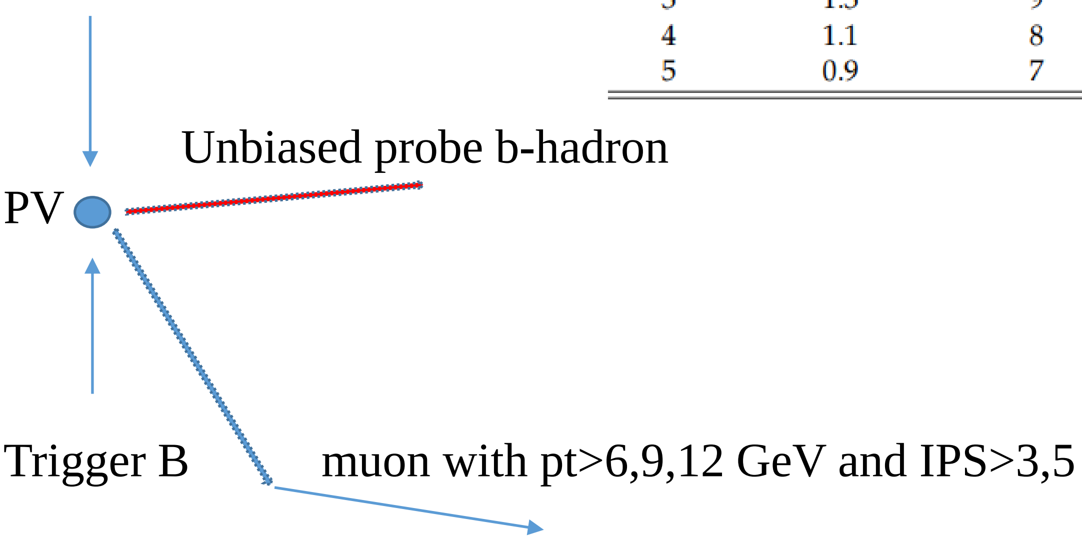
This is the most stringent limit of FCNC in the charm sector.
It can be used to set constraints on scenarios that modify Br(D0→ mu+mu-)

Method and data sample we used

BParking trigger which collected and storage 10 billion unbiased b-hadron decays.

in 2018 a dedicated trigger was proposed, developed and successfully implemented: BParking

Setting	Peak $\mathcal{L}$ $[10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	L1 p_T^{μ} thr. [GeV]	HLT p_T^{μ} thr. [GeV]	HLT μ IP_{sig} thr.	Purity [%]	Peak HLT rate [kHz]
1	1.7	12	12	6	92	1.5
2	1.5	10	9	6	87	2.8
3	1.3	9	9	5	86	3.0
4	1.1	8	8	5	83	3.7
5	0.9	7	7	4	59	5.4



Stored on tape;
Long delay in reconstruction

Measurement of B meson production fractions at $\sqrt{s}$=13 TeV

Why interesting:

CMS PAS BPH-21-007

- These fractions are closely related to the b quark fragmentation fractions
- Directly enter the precision measurements of branching fractions of B^0_s mesons
- The knowledge of **fs/fu** is the dominant systematic uncertainty in measurement of $B^0_s \to \mu^+\mu^-$

As independent Branching fraction measurements of B0s meson decay modes
with a precision better than ~20% are not available,

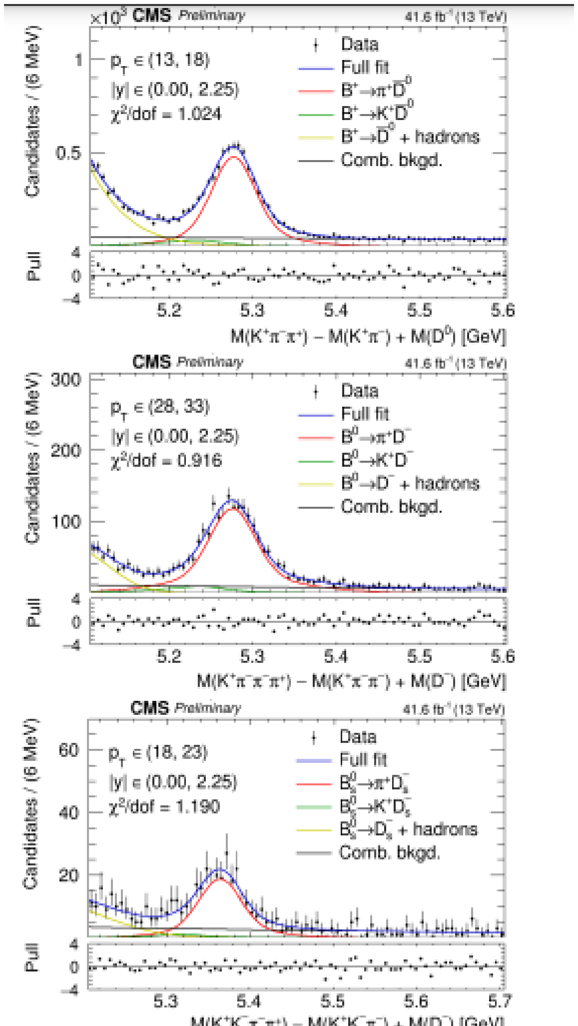
the only way to extract fs/fu is by using **theoretical expectations** –
available for the open charm decays (like B0s $\to$ Ds- π+),

but no reliable calculations exist for charmonium modes (like $B \to J/\psi\ K$).

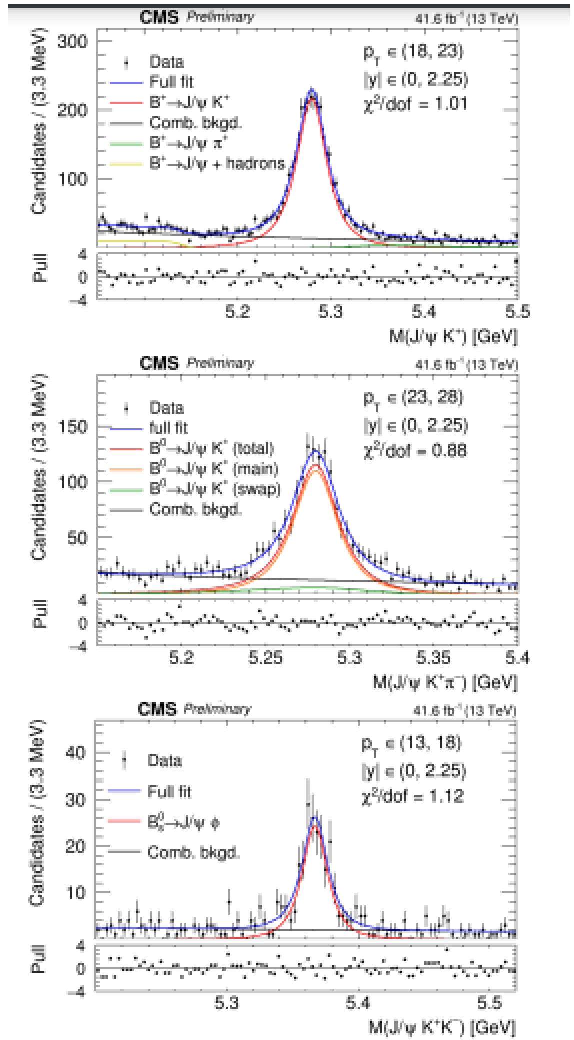
Therefore we rely on the measured fs/fu in hadronic open charm channels.

Measurement of B meson production fractions at √s=13 TeV

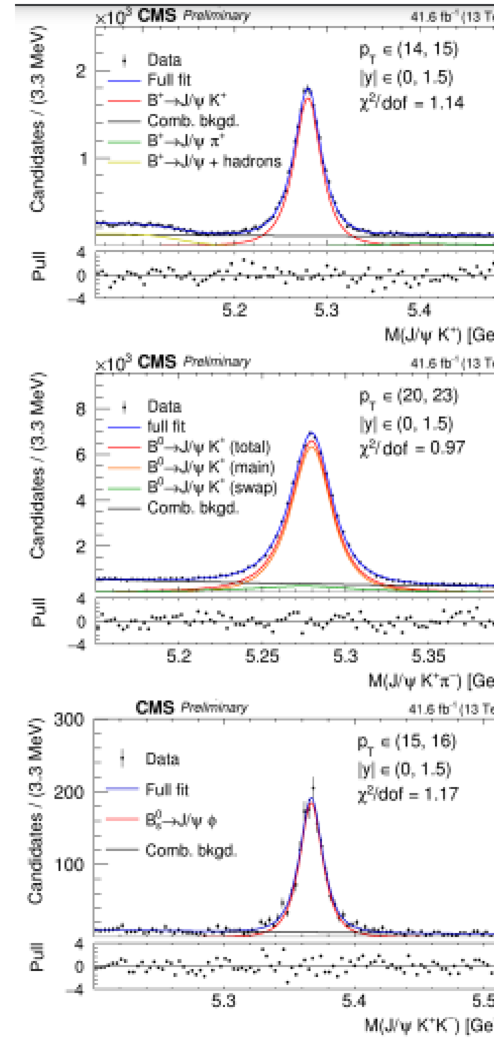
Hadronic decays



Charmonium decays in the probe side analysis

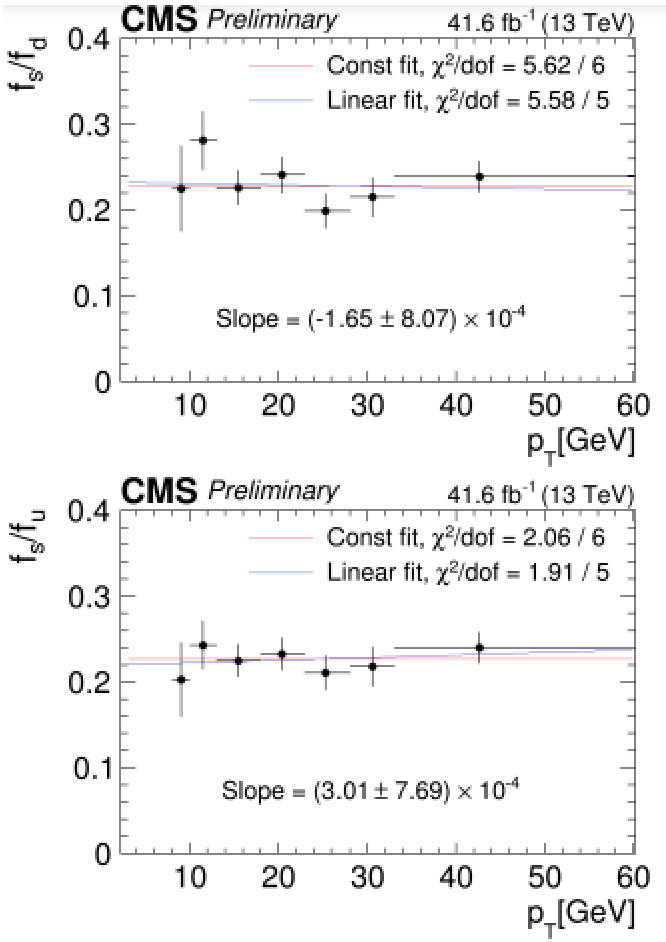


Charmonium decays in the tag side analysis



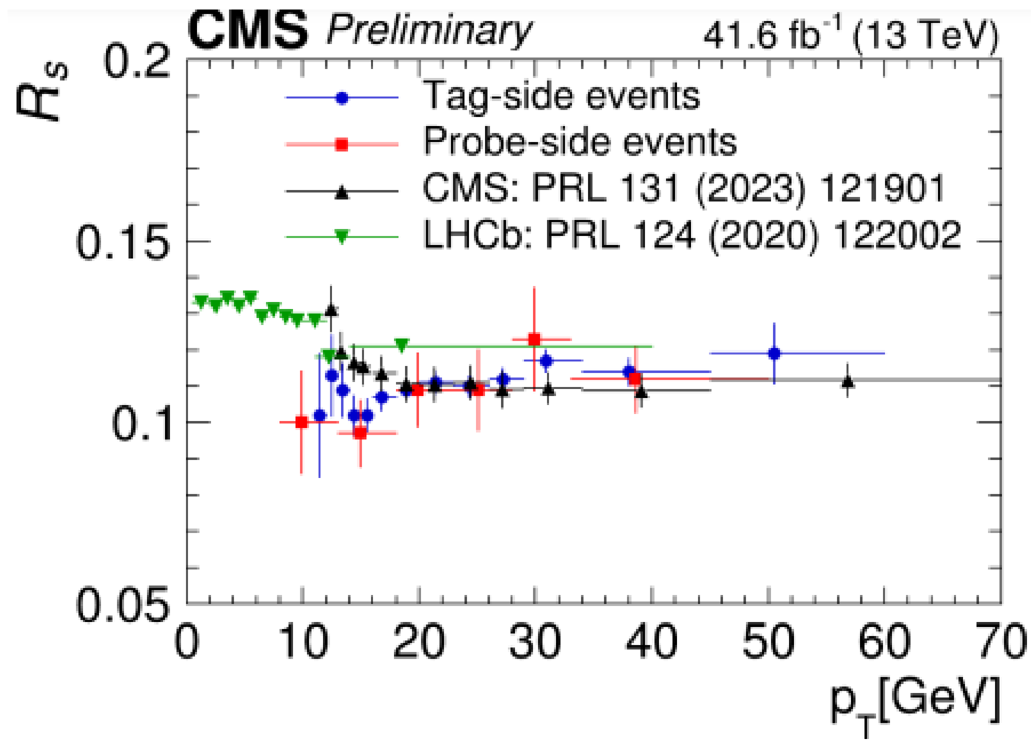
Measurement of B meson production fractions at √s=13 TeV (results)

Using open-charm hadronic decays



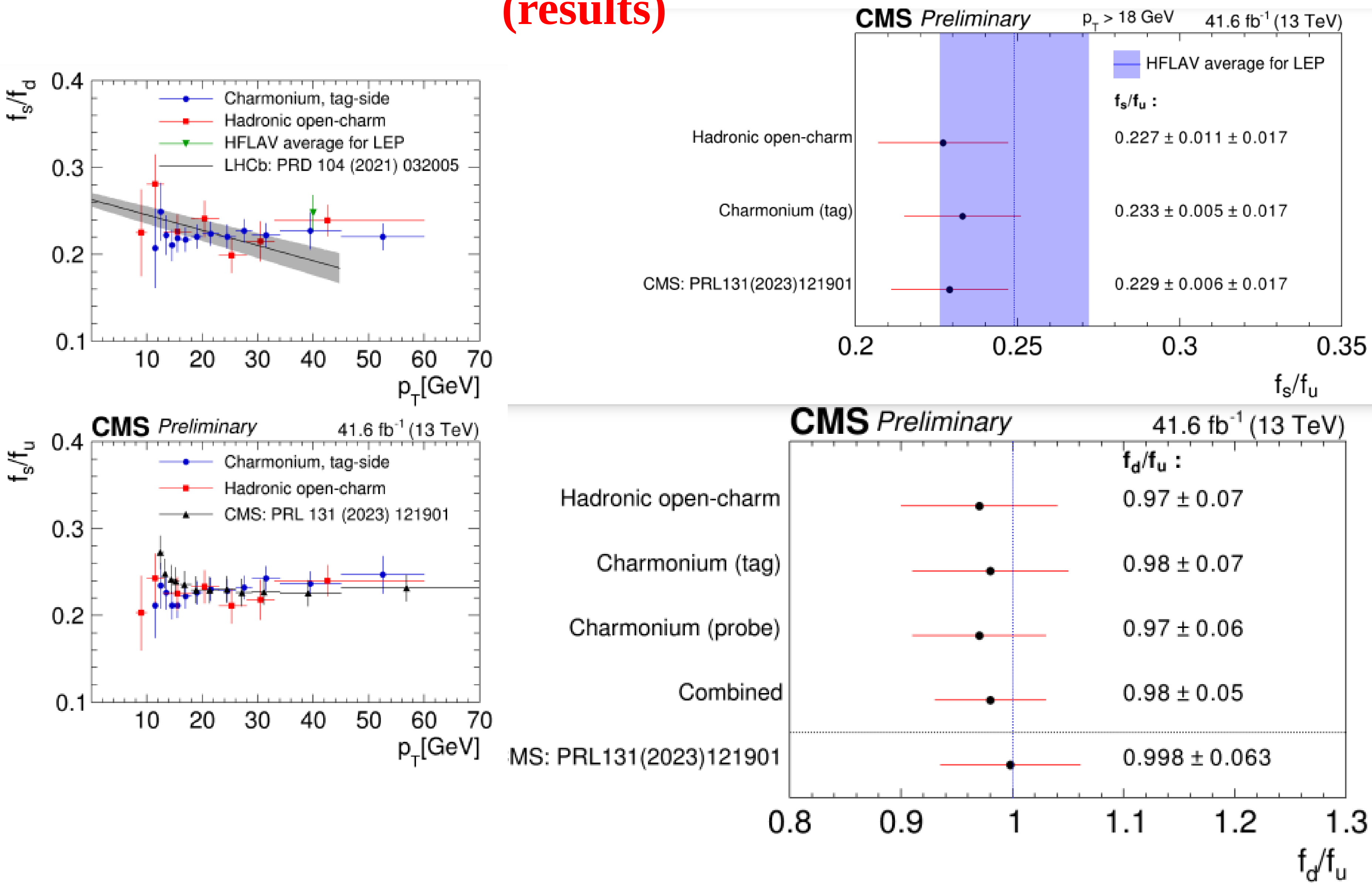
fs/fu = 0.227 ± 0.011 ± 0.017

Using charmonium decays



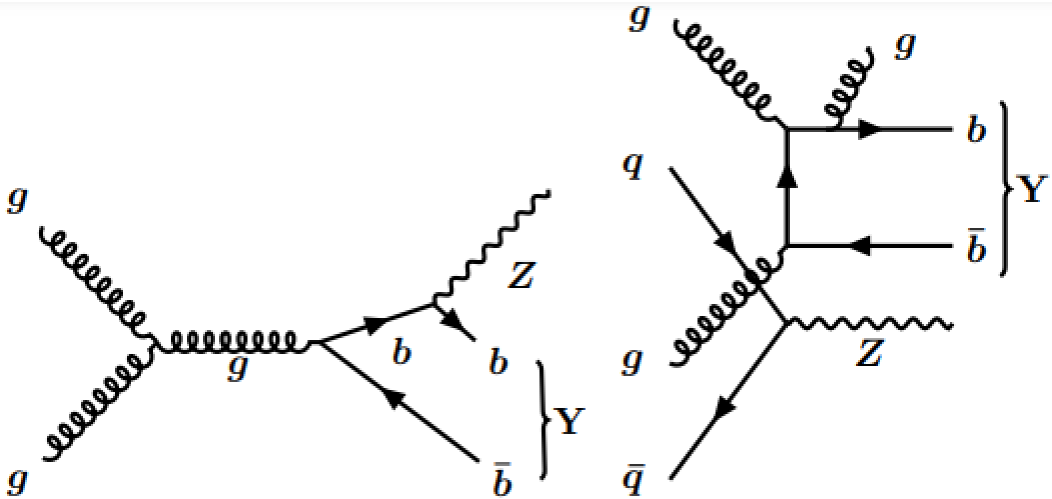
$$\mathcal{R}_s = \frac{N_{corr}(B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-))}{N_{corr}(B^+ \to J/\psi(\mu^+\mu^-)K^+)} = \frac{f_s}{f_u} \frac{\mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi K^+)}$$

Measurement of B meson production fractions at $\sqrt{s}$=13 TeV (results)



Measurements of the Υ(1S) production in association with a Z boson at √s=13 TeV

CMS PAS BPH-23-007



DPS is closely related to the spread of the partons within the nucleon

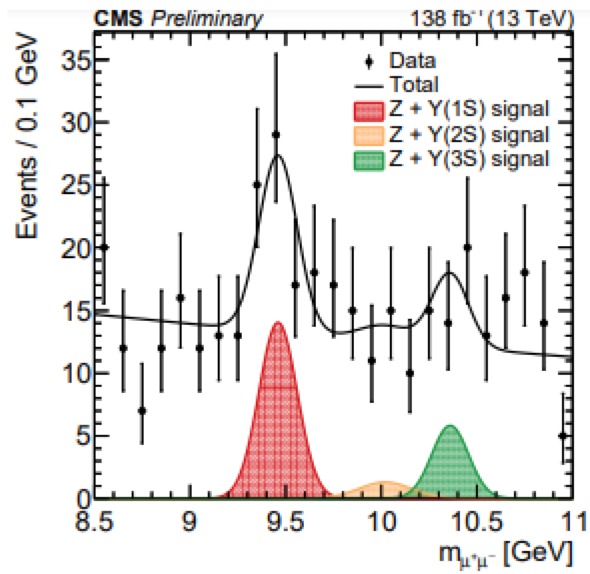
Despite extensive studies, the exact production mechanism of heavy quarkonia in hadronic collisions has yet to be completely understood.

Binding into a physical quarkonium state
is inherently nonperturbative and therefore constitutes a much greater challenge, mainly because of the difficulties in the calculations of the long-distance matrix elements that express the hadronization probability of a heavy-quark pair to evolve into a quarkonium state.

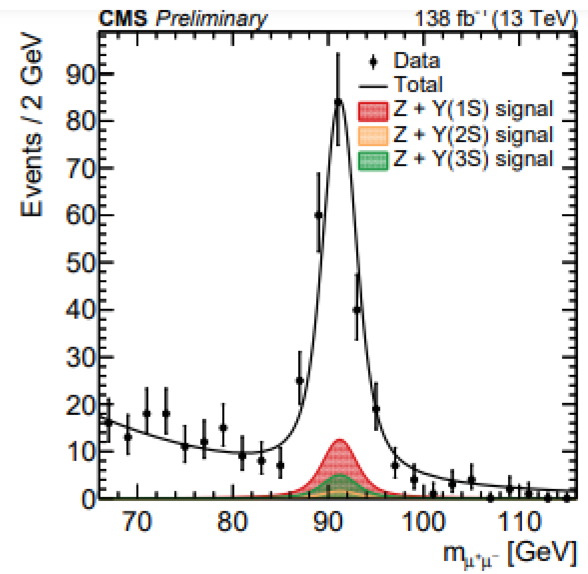
The picture even more complex for quarkonium produced in association with electroweak bosons, and the tension with theory is more pronounced. A major complicating factor is that two different production mechanisms contribute to these processes. Quarkonium along with the Z can be produced through the interaction of a single pair of partons, a process known as single-parton scattering (SPS), or through the interactions of two pairs of partons, double-parton scattering (DPS)

Measurements of the Υ(1S) production in association with a Z boson at √s=13 TeV

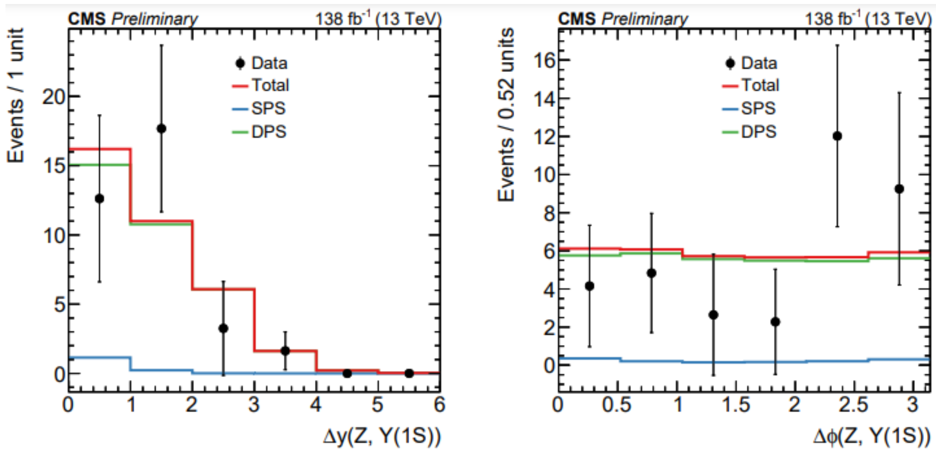
Υ(nS) candidates



Z candidates

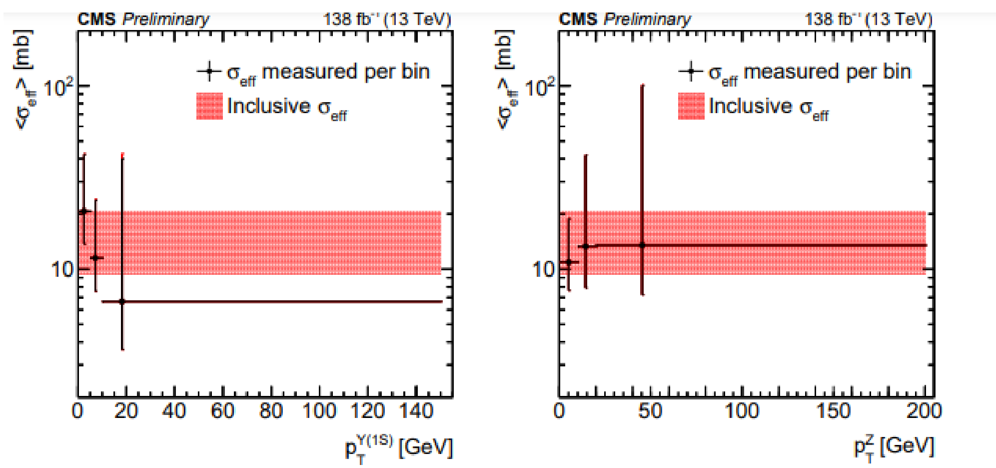


Measurements of the Υ(1S) production in association with a Z boson at √s=13 TeV



We measure the ratio of the fiducial cross sections

$$\frac{\sigma(pp \to Z + \Upsilon(1S))\mathcal{B}(Z \to \mu^+\mu^-)\,\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)}{\sigma(pp \to Z)\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)}$$



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

Also derived DPS cross section ratio
$R^{DPS}{}_{Z+\Upsilon(1S)}$= [20.2±7.5±0.6]x10^{-3}

Although designed for high-pt physics,
CMS is good experiment for heavy flavor physics

Summary

- New result on a search for FCNC decay in charm sector:
  1) - the first measurement from parked inclusive di-muon data set (2022-2023)→
  2) - most stringent limit of FCNC in the charm sector

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.1\,(2.4) \times 10^{-9} \text{ at } 90\,(95)\% \text{ CL.}$$

- New measurement (Run 2, √s=13 TeV) of B meson production fractions fd/fu = 0.98 ± 0.05 for pt>10 GeV and fs/fu = 0.227 ± 0.011 ± 0.017 (hadronic) and 0.233 ± 0.05 ± 0.017 (charmonium-tag) for pt>18 GeV.

Important for B0s Br.fr. normalization.

- The first study of the associate production of an Υ(1S) meson and a Z boson at √s=13 TeV (2016-2018): we measured the ratio of the fiducial cross section

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

Also derived DPS cross section ratio $R^{DPS}_{Z+Y(1S)}$= [20.2±7.5±0.6]x10^{-3}
Unique to constrain DP distribution functions including lattice and effective models

CMS will continue to test the SM prediction in **Heavy Flavor** sector using Run 2 and Run 3 data.

Backup slides