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# Recent results on Heavy Flavour production with the CMS experiment

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# Outline

1. **Measurement of prompt open-charm production cross sections in p-p collisions at $\sqrt{s}$ = 13 TeV [CMS-PAS-BPH-18-003]**

2. **Relative cross sections of $B_c(2S)^+$ and $B_c^*(2S)^+$ states with respect to the $B_c^+$ state in proton-proton collisions at $\sqrt{s}$ = 13 TeV [arXiv:2008.08629, submitted to PRD]**

3. **Measurement of the Υ(1S) pair production cross section and search for resonances decaying to Υ(1S)$\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV [Phys. Lett. B 808 (2020) 135578]**

# Prompt open-charm production

**Measurement of the differential cross-section of prompt open-charm production** on 29 $nb^{-1}$ of pp collisions at $\sqrt{s}$ = 13 TeV in 2016

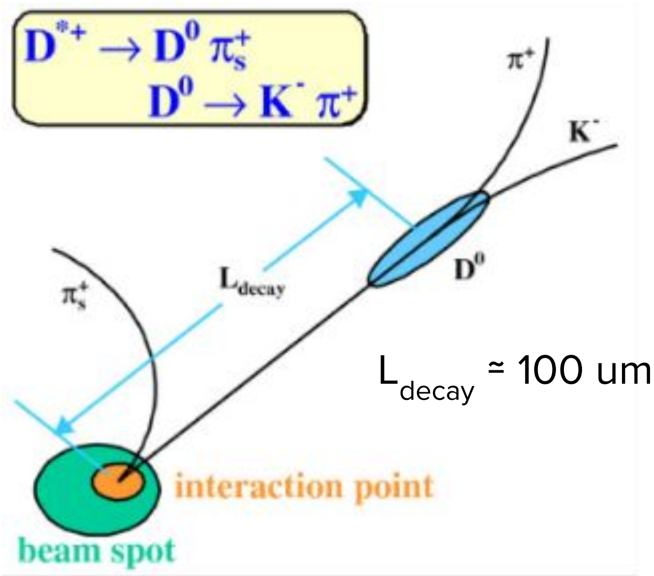
**Charm physics @ LHC:** production cross section $10^6$ times greater than $e^+e^-$ machines 👍
complex initial state (PU) and high background 👎
c produced with boost in LHCb (asymmetric collisions)
CMS unfavoured being a “central” detector

**First result on charm production from CMS in pp collisions**

**Kinematic range:** 4 GeV < $p_T(D)$ < 100 GeV && $|\eta(D)| < 2.1$
**ZeroBias trigger** (the most inclusive one)

Interest in **prompt** production of D mesons (from PV or charm excited states)

- $D^{*+} \rightarrow D^0 \pi^+_{slow} \rightarrow K^- \pi^+ \pi^+_{slow}$
- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$



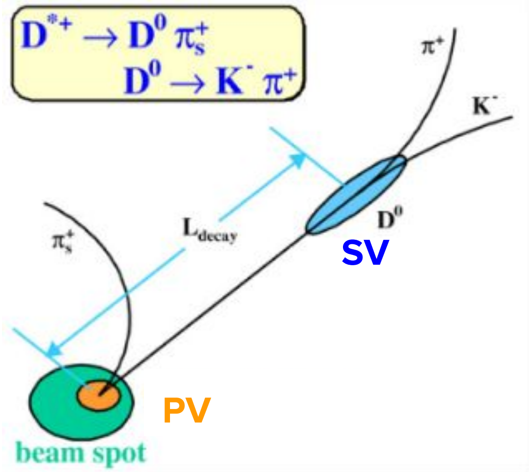

$L_{decay}$ ≃ 100 um

Possible contamination: c from b decays

# D mesons: reconstruction

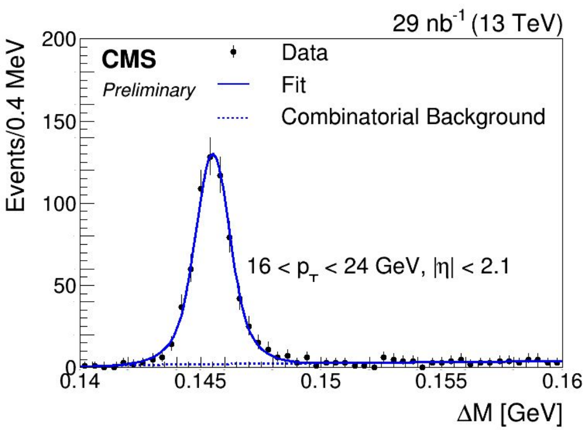
## Requirements:

- “high quality” tracks (no hadronic PID in CMS)
- *tracks*: $p_T > 0.5$ GeV (0.3 GeV for $\pi_s$)
- 2 (3) charged tracks combined to form $D^0$ ($D^+$) candidate
- parallel direction of the meson wrt PV-SV distance vector
- Cut on decay length significance (specific to each meson)

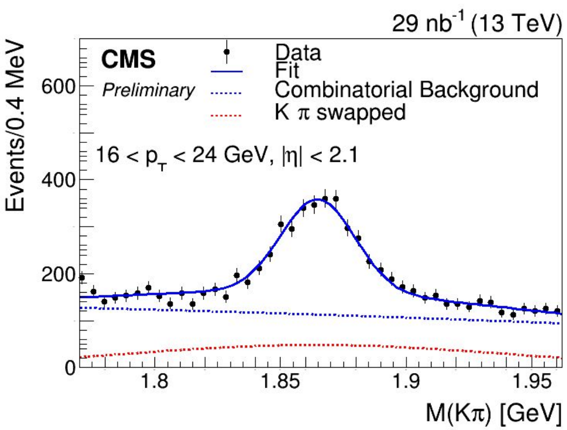



## Reconstructed mass distributions:

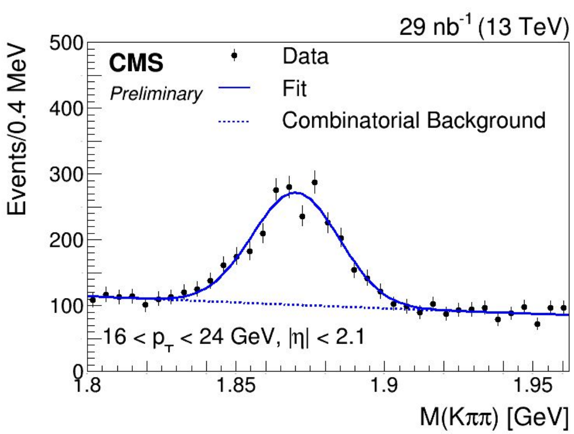
D*




$D^0$




$D^+$




$\Delta M = m(K\pi\pi_s) - m(K\pi)$

# D mesons: signal yield determination

**Signal**: sum of two gaussians with common mean

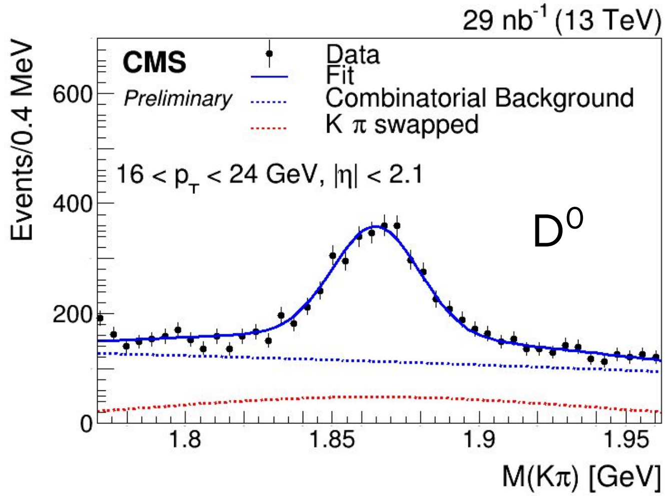
**Combinatorial background**:

$(D^0/D^+)$ 3rd degree polynomial

$(D^{*+})$ phenomenological threshold function

**K-π swapped background** ($D^0$ only):

Gaussian shape from simulation

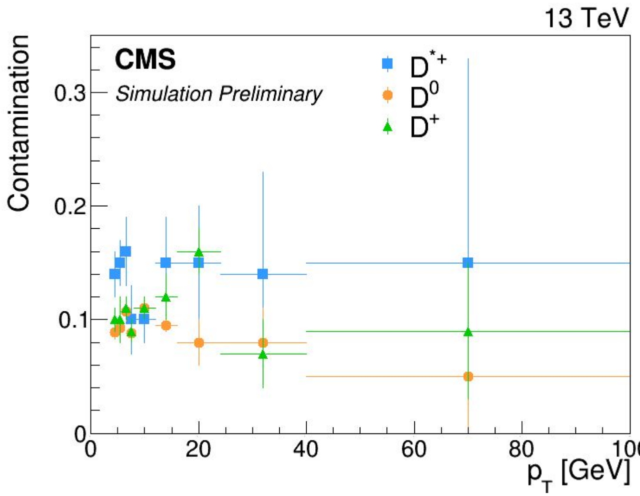


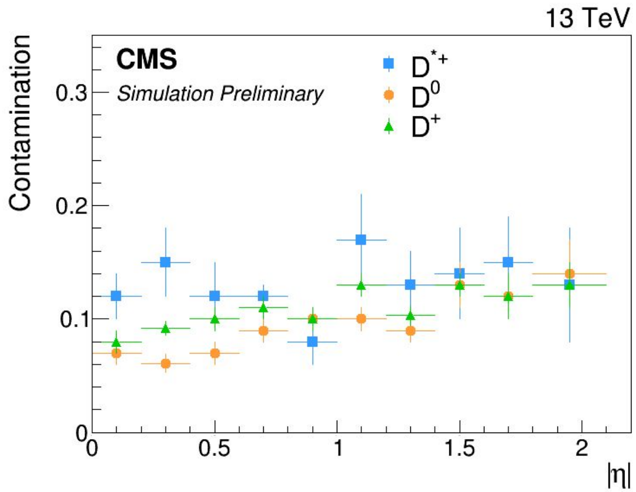

**Non prompt-contamination** from charmed mesons coming from B mesons

Bin-by-bin subtraction from the “visible” yield

*From simulation*:

non-prompt relative contamination ≃ 10-15%




Systematic uncertainties in backup

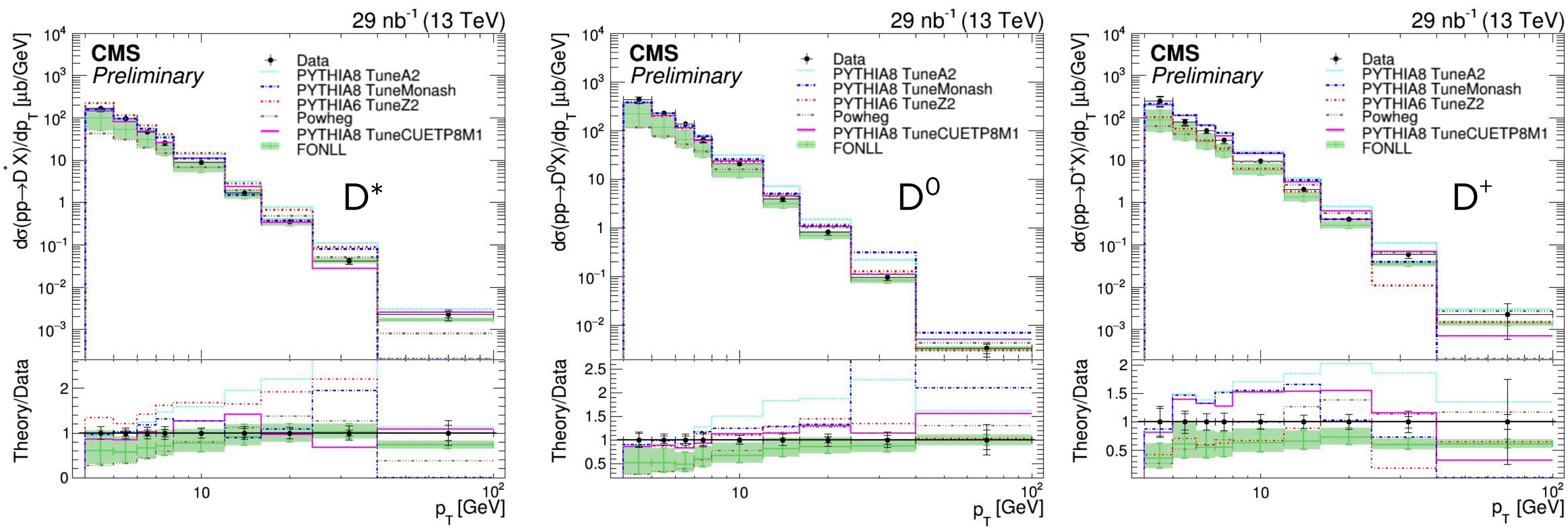
# D mesons: differential cross sections

**Differential cross sections**
in $p_T$ and pseudorapidity

$$\frac{d\sigma(pp \to DX)}{dp_T} = \frac{N_i(D \to f)}{\Delta p_T \mathcal{B}(D \to f)\mathcal{L}\varepsilon_{i,tot}(D \to f)},$$

$$\frac{d\sigma(pp \to DX)}{d|\eta|} = \frac{N_i(D \to f)}{\Delta \eta \mathcal{B}(D \to f)\mathcal{L}\varepsilon_{i,tot}(D \to f)},$$

**Agreement with predictions** from PYTHIA and FONLL (fixed-order next-to-leading logarithm)




Differential cross section in rapidity bins in backup

# State of the art of open-charm production

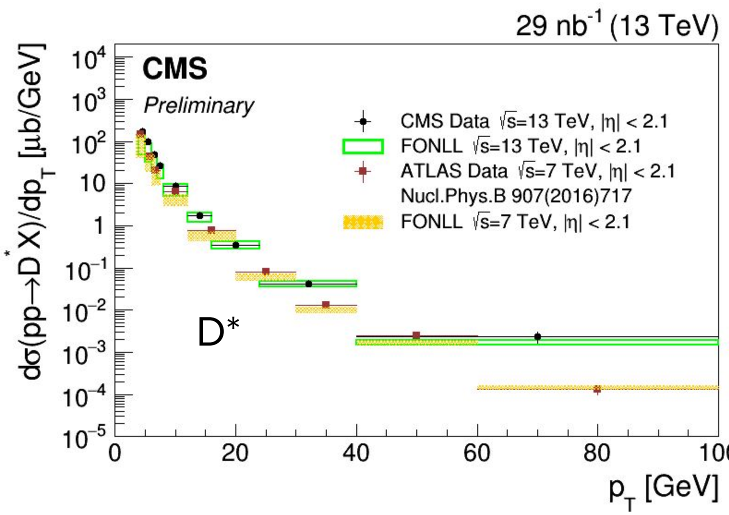
- In the next slides a comparison with other results on open-charm production cross section from the **LHC experiments** is shown

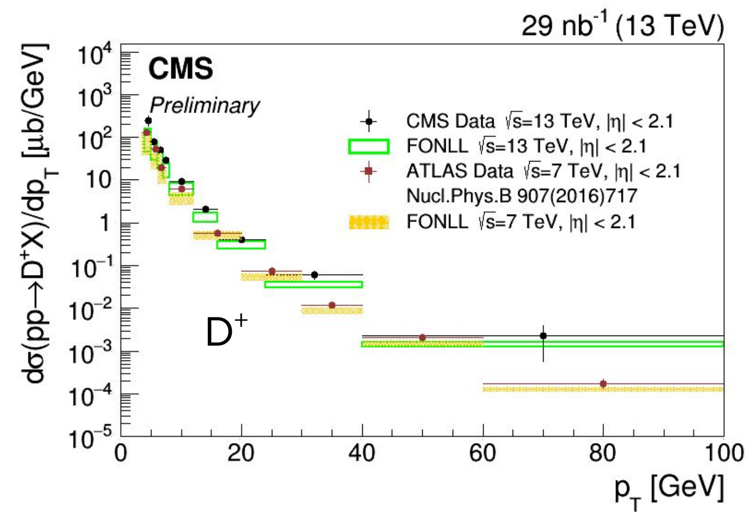
- **FONLL predictions** are used to compare CMS measurements with previous results already published within LHC

- **CMS measurements show a good agreement with previous results,** considering the evolution in the center of mass energy scale and the kinematic dependences as described by the theory predictions

# Comparison with measurements at 7 TeV

**CMS vs ATLAS:** same kinematic range, different √s: scaling with c.m. energy

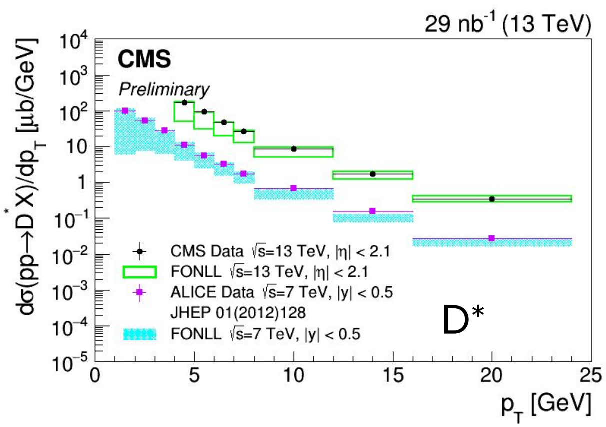


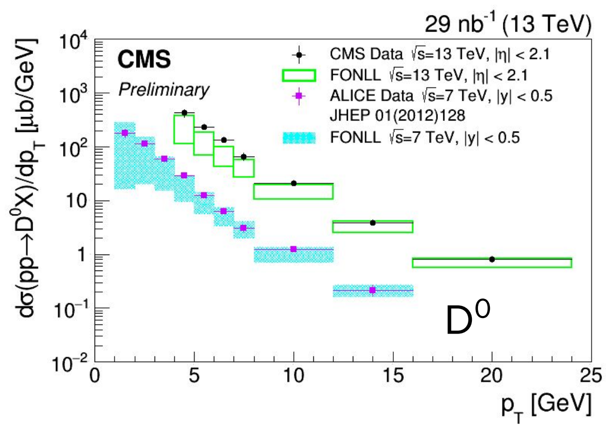



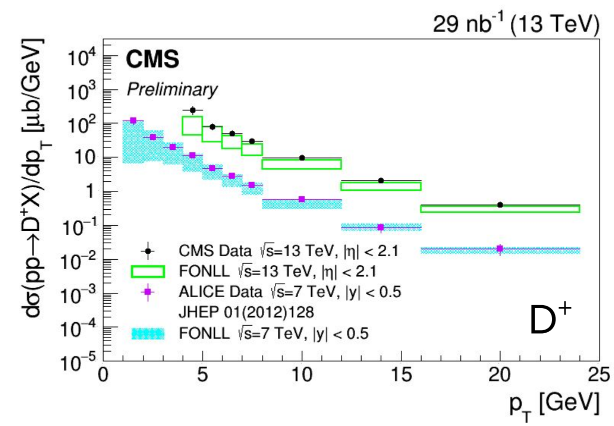

**CMS vs ALICE:** different kinematic range

factor 2 from c.c. states not included by ALICE

CMS data shown for $p_T$ < 24 GeV



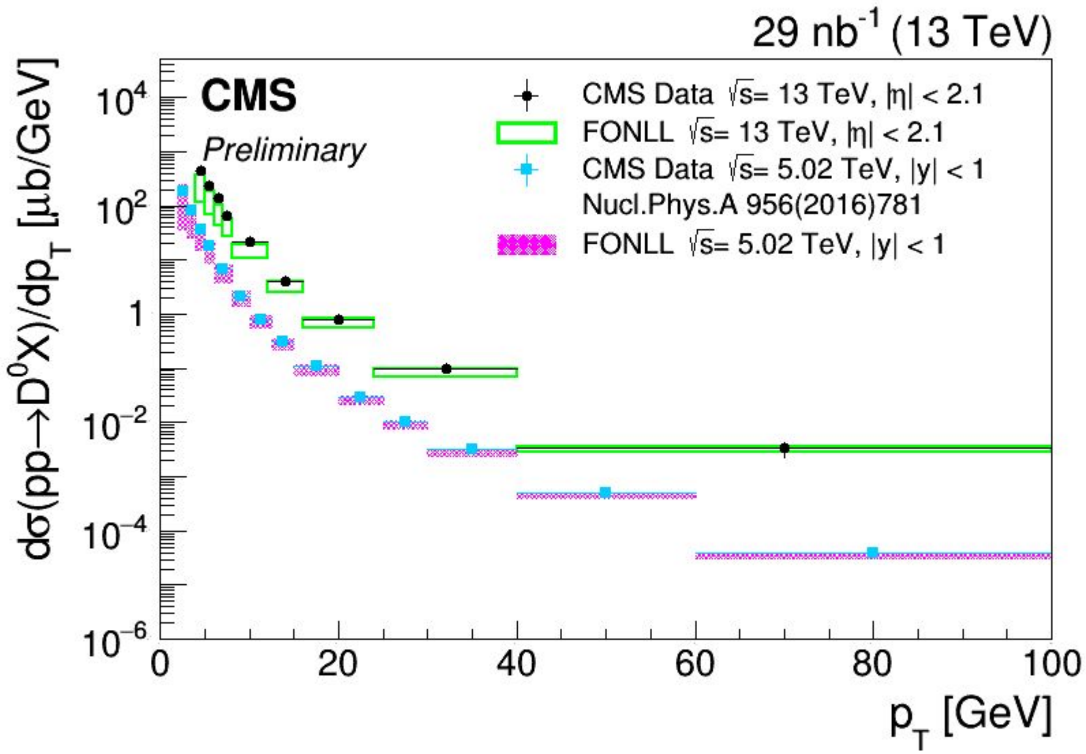



# Comparison with measurements at 5.02 TeV

## p-p vs Pb-Pb @ CMS:

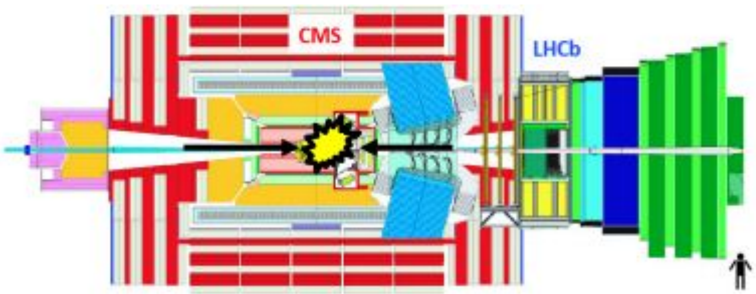
- different kinematic range and binning
- good agreement between theory and data

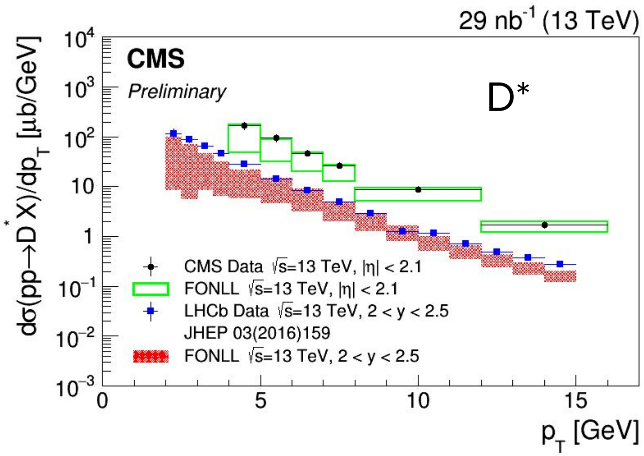


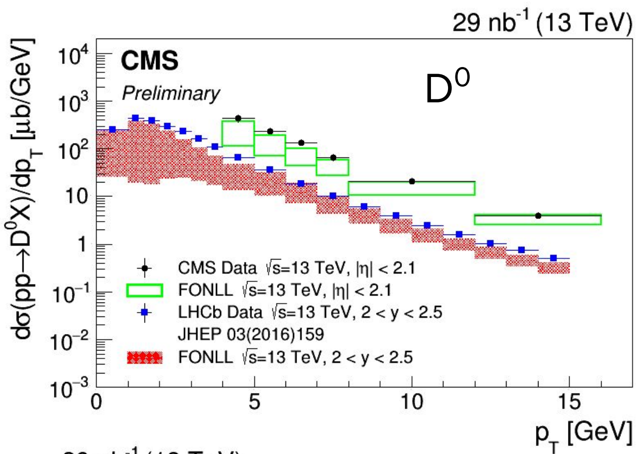
# Comparison with measurements at 13 TeV

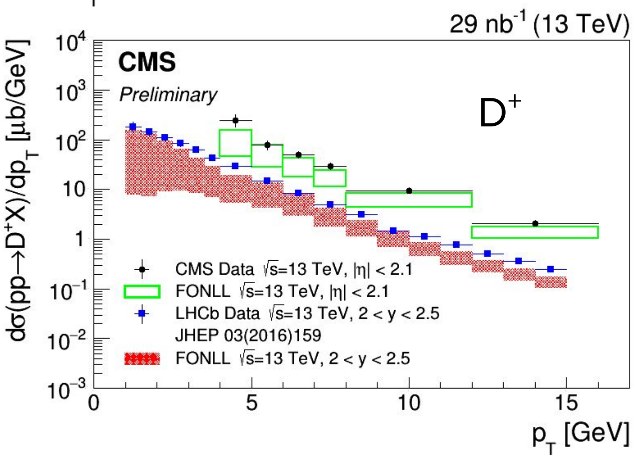
## CMS vs LHCb:

- complementary acceptance
- only the first rapidity bin is shown for LHCb
- CMS data are reported only for $p_T < 16$ GeV



# $B_c(2S)$ mesons production

★ Observation of $B_c(2S)^+$ and $B_c^*(2S)^+$ states with pp collisions at $\sqrt{s}$ = 13 TeV with 143 fb$^{-1}$ (full Run 2) [1]

[1] Phys. Rev. Lett. 122 (2019) 132001

**NEW Measurement of relative cross sections:**

**Differential cross sections in $p_T$ and rapidity bins**

**Kinematical range**: $p_T(B_c^+) > 15$ GeV and $|y| < 2.4$

**$R^{*+}$:** relative cross section of $B_c^*(2S)^+$ to $B_c^+$
**$R^+$:** relative cross section of $B_c(2S)^+$ to $B_c^+$
**$R^{*+}/R^+$:** relative cross section of $B_c^*(2S)^+$ to $B_c(2S)^+$

$$R^+ \equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-) = \frac{N(B_c(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)},$$

$$R^{*+} \equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-) = \frac{N(B_c^*(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)},$$

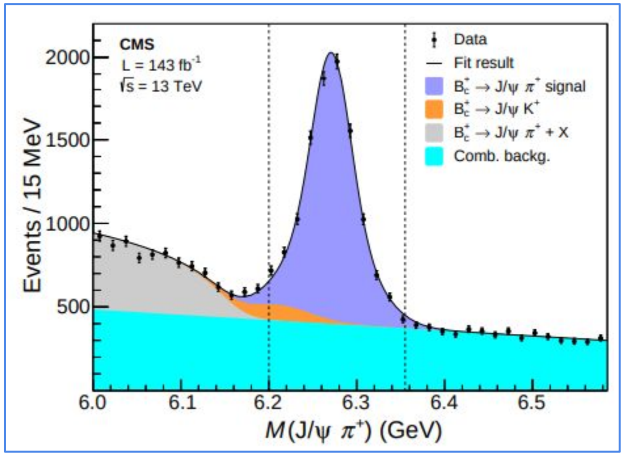
$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)} \frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)} \frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

$B_c^*(2S) \to B_c^*\pi\pi$ followed by $B_c^* \to B_c + \gamma_{lost}$ ( ≃ 55MeV: missing energy not detected)
The $B_c^*$ meson is assumed to decay to the $B_c$ ground state and a soft photon with a BF of 100%

# $B_c$(2S) and $B_c$*(2S) signal yields

## $B_c^+ \rightarrow J/\psi\pi^+$ candidates fit

$N(B_c)$ = 7629 +/- 225 events




## $B_c$(2S) candidates:

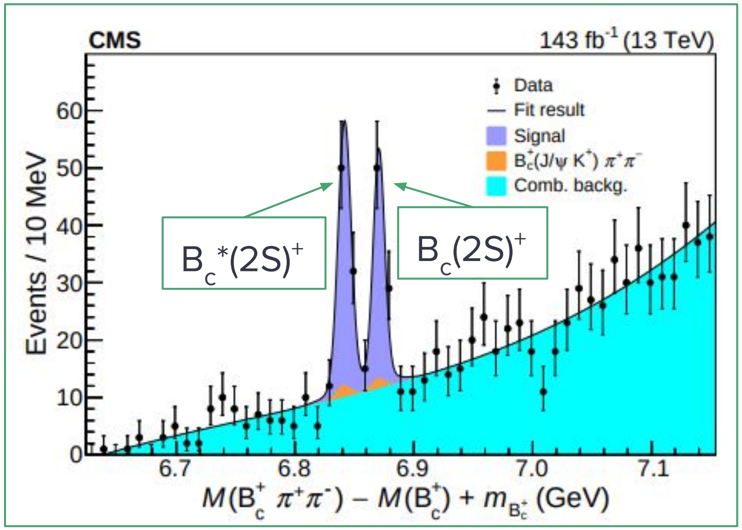
- $B_c^+$ + two OS tracks
- m($J/\psi\pi$) in [6.2, 6.355] GeV

**Signal**: two gaussians

**Background**:

Combinatorial: Chebychev-3 polynomial

Gaussian for each $B_c \rightarrow J/\psi K$ contribution




$N(B_c^*(2S)^+)$ = 67 +/- 10 evts

$N(B_c(2S)^+)$ = 52 +/- 9 evts

$\Delta M$ = 28.9 +/- 1.5 MeV

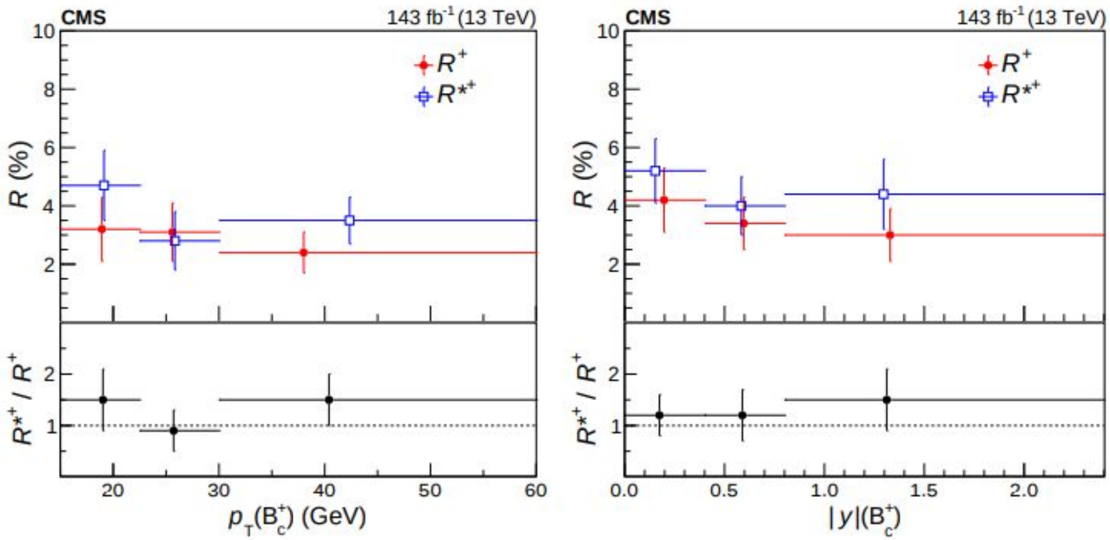
Yields enter the ratios once corrected by relative efficiencies

$$R^{+} = (3.47 \pm 0.63\,(\mathrm{stat}) \pm 0.33\,(\mathrm{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\mathrm{stat}) \pm 0.56\,(\mathrm{syst}))\%,$$
$$R^{*+}/R^{+} = 1.35 \pm 0.32\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}).$$

Details on event reconstruction and systematic uncertainties in backup

# Differential cross section and ππ mass distribution

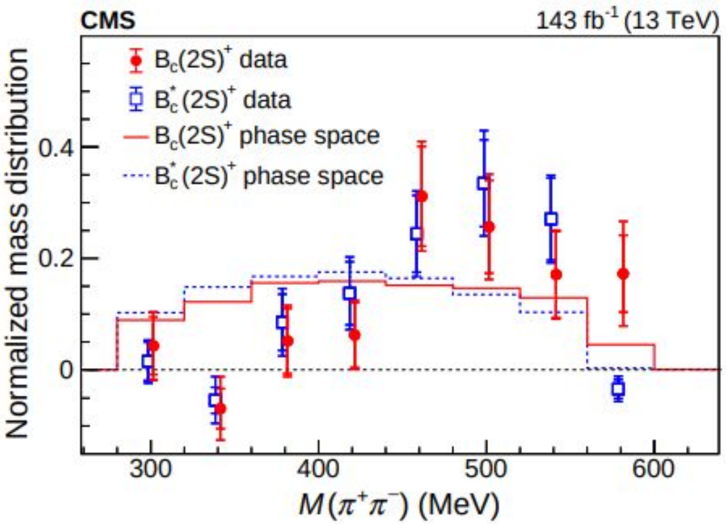
## No significative dependence of the cross section on $p_T(B_c)$ or $\eta(B_c)$ observed




## Invariant mass of di-pion system

Different models [2] [3] bring to different predictions on the production ratios and di-pion system

No significant difference from phase space observed at this level of statistics and uncertainties




[2] [Berezhnoy, A. V. et al. Mod. Phys. Lett. A34 (2019) 1950331]
[3] [E. Eichten, C. Quigg, PRD 99 (2019) 054025]

# Measurement of Υ(1S) pair production

**Measurement of fiducial cross-section for Υ(1S) pair production and search for resonances decaying to Υ(1S)μμ in pp collisions at √s = 13 TeV with 35.9 fb$^{-1}$** (2016 data)

**Fiducial region**: |y(Υ(1S))| < 2.0
**Final state**: four muons

- **Quarkonium pair production** is an important probe for perturbative and non-perturbative processes in QCD
- Insight into particle production at LHC:
  **single-parton scattering** (SPS): dominant → strongly correlated → small |Δy|
  **double-parton scattering** (DPS): difficult to calculate → less correlated → large |Δy|
- Potential ground for discovery of tetraquark bound state or generic resonance with mass close to twice the Υ(1S) mass

See Di Florio's talk tomorrow Spectroscopy #1

**Fiducial cross section**: $\sigma_{\rm fid} = \frac{N^{\rm corr}}{\mathcal{L}\mathcal{B}^2},$ $\mathcal{B}(Y(1S) \to \mu\mu) = (2.48 \pm 0.05)\%$

$N^{\rm corr}$ = # of Υ(1S)Υ(1S) events corrected by efficiency

# Υ(1S)Υ(1S): event selection and yield

**Requirements:**

- *HLT level*: OS μμ pair in Υ mass window + third muon
- 4 muons in final state paired in Υ states
- $p_T$ thresholds for barrel/endcap after pairs are formed
- veto on J/ψ ➜ μμ

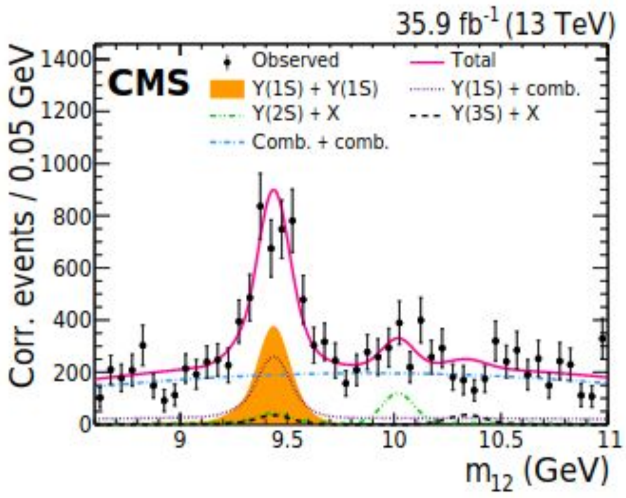
**Events corrected by efficiency and acceptance**

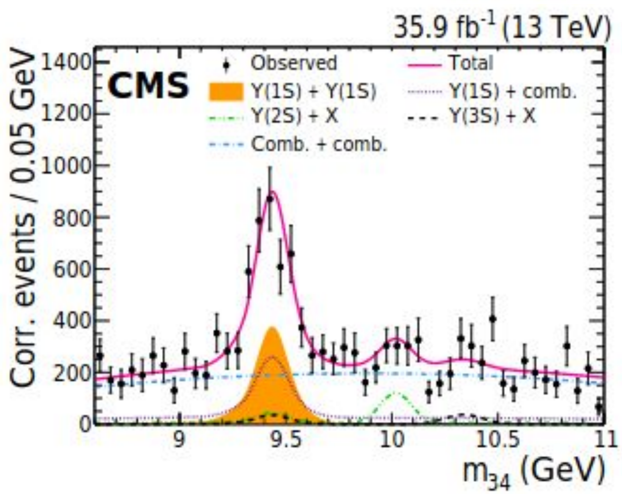
**2D UML simultaneous fit on two μμ invariant masses:**

Signal: sum of two CB with same mean
(shape from simulation *in backup*)

Background: Υ(2S), Υ(3S): gaussian
combinatorial: $2^{nd}$ order Chebychev

$$\sigma_{\mathrm{fid}} = 79 \pm 11\,(\mathrm{stat}) \pm 6\,(\mathrm{syst}) \pm 3\,(\mathcal{B})\ \ \mathrm{pb},$$




Result assuming Υ(1S) unpolarised

Consistent with CMS measurement at 8 TeV [JHEP 05 (2017) 013]



Details on event weighting and systematic uncertainties in backup

# Measurement of DPS-to-inclusive fraction

Bottomonia from DPS are less correlated than SPS:

**in DPS larger |Δy(Υ(1S), Υ(1S))|**

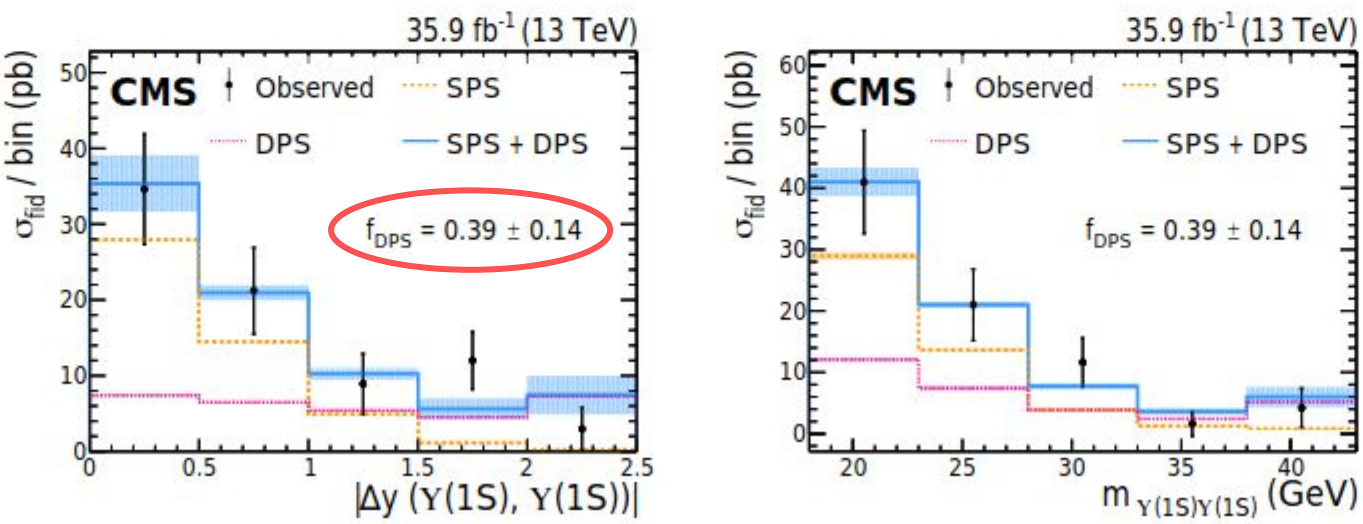
Shapes from SPS and DPS separately extracted from MC

DPS: PYTHIA
SPS: HELAC-Onia + NLO*CSM predictions

$$f_{\mathrm{DPS}} = \frac{\sigma_{\mathrm{fid}}^{\mathrm{DPS}}}{\sigma_{\mathrm{fid}}^{\mathrm{SPS}} + \sigma_{\mathrm{fid}}^{\mathrm{DPS}}},$$

**$f_{DPS}$ estimated from fit on fiducial cross section in |Δy(Υ(1S), Υ(1S))| and m(Υ(1S)Υ(1S)) bins**

$$f_{DPS} = \begin{cases} (39 \pm 14)\% & using\ |\Delta y(\Upsilon(1S), \Upsilon(1S))| \\ (27 \pm 22)\% & using\ m_{\Upsilon(1S)\Upsilon(1S)} \end{cases}$$



# Conclusions

- **LHC provides high luminosity: heavy flavour production cross section several order of magnitudes greater than e-e colliders**

- **CMS exploits its 4π coverage and high resolution to perform challenging measurements in Heavy Flavour physics**

- **The presented recent CMS measurements concern from charmed mesons to double bottomonia production and they are generally in good agreement with previous LHC results (when available)**

- **Recent results from the CMS proved that the experiment is suitable for challenging measurements in Heavy Flavour physics, so further investigation on Quantum Chromo-dynamics will be possible**

# THANKS FOR YOUR ATTENTION

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# BACKUP

# D mesons: event selection

| Variables | $D^{*+}$ | $D^0$ | $D^+$ |
|---|---|---|---|
| PV selection: | largest $\sum p_T^2$ | largest $\sum p_T^2$ | largest $\sum p_T^2$ |
| Tracks: $p_T{}^{min}$ [ GeV ] | 0.5 (0.3 for the $\pi_s$) | 0.8 | 0.7 |
| Tracks: reduced $\chi^2$ | $< 2.5$ (3 for the $\pi_s$) | $< 2.5$ | $< 2.5$ |
| Tracks: N Tracker Hits | $\geq 5$ ($> 2$ for the $\pi_s$) | $\geq 5$ | $\geq 5$ |
| Tracks: N Pixel Hits | $\geq 2$ (none for the $\pi_s$) | $\geq 2$ | $\geq 2$ |
| Tracks: $IP_{xy}$ [ cm ] | $< 0.1$ (sig. $< 3$ for $\pi_s$) | $< 0.1$ | $< 0.1$ |
| Tracks: $IP_z$ [ cm ] | $< 1$ (sig. $< 3$ for $\pi_s$) | $< 1$ | $< 1$ |
| $\lvert M_{cand} - M^{PDG}\rvert$ [ GeV ] | $< 0.023$ | $< 0.10$ | $< 0.10$ |
| SV fit CL | $> 1\%$ | $> 1\%$ | $> 1\%$ |
| Pointing, $cos\Phi$ | $> 0.99$ | $> 0.99$ | $> 0.99$ |
| L significance: | $> 3$ | $> 5$ | $> 10$ |
| Arbitration | min $\Delta M$ | min $\lvert$M(K$\pi$) - M$^{PDG}$(D$^0$)$\rvert$ | min $\lvert$M(K$\pi\pi$) - M$^{PDG}$(D$^+$)$\rvert$ |

# D mesons: D* threshold function and systematic uncertainties

## Phenomenological threshold function for D* background:

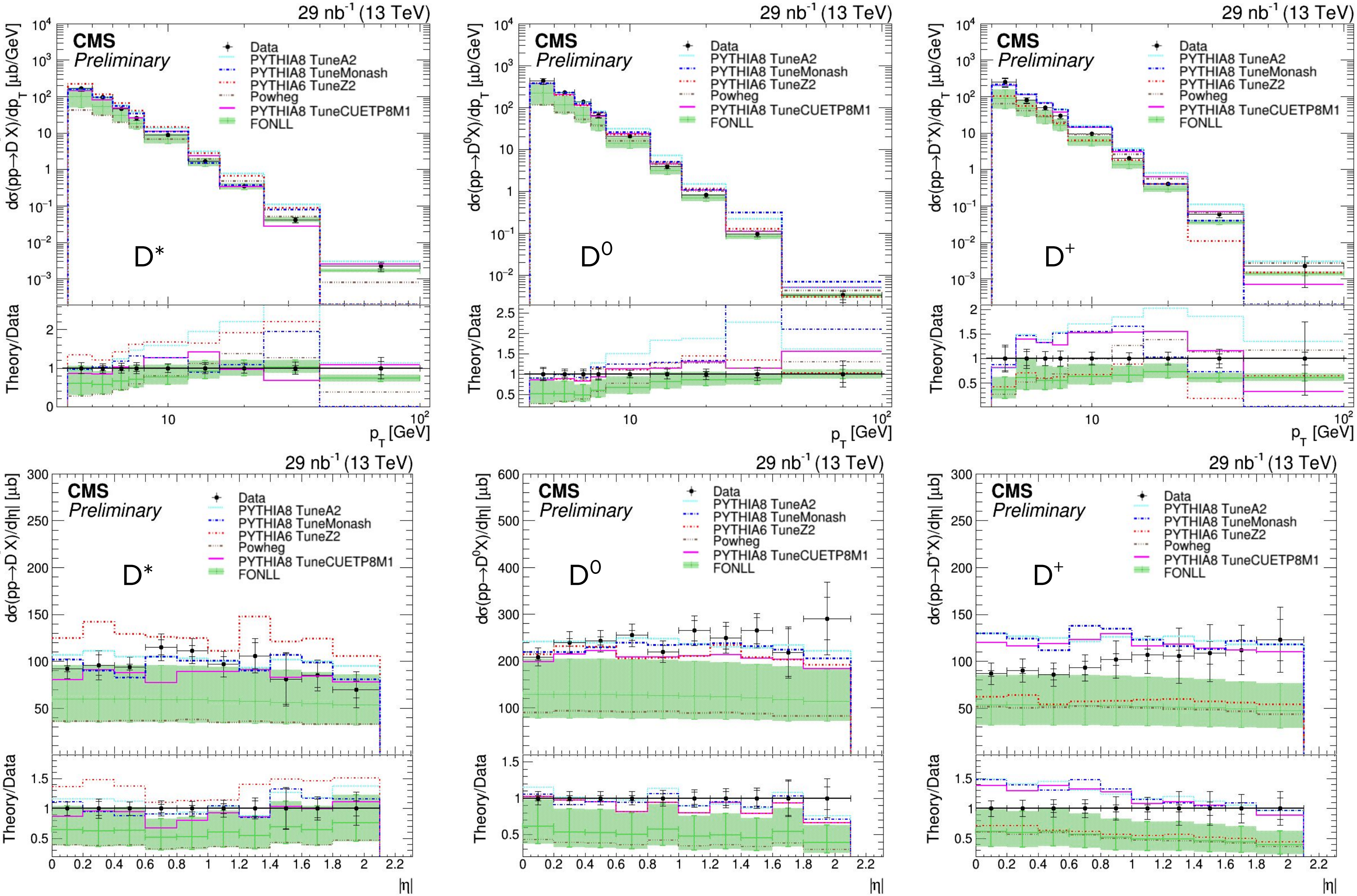
- $M_0$: endpoint = pion mass
- $p_0$, $p_1$, $p_2$:parameters

$$f = \left(1 - e^{-\frac{\Delta M - M_0}{p_0}}\right)\left(\frac{\Delta M}{M_0}\right)^{p_1} + p_2\left(\frac{\Delta M}{M_0} - 1\right)$$

## Systematic uncertainties

| | Relative uncertainties (%) | | |
|---|---|---|---|
| | $D^{*+}$ | $D^0$ | $D^+$ |
| Signal efficiency calculation | 0.3 | 0.3 | 3.5 |
| Secondary decay contamination | 2.9 | 0.8 | 1.4 |
| PU reweighting | 1.0 | 1.0 | 2.0 |
| Branching fraction | 1.1 | 0.8 | 1.7 |
| Tracking efficiency | 9.4 | 4.2 | 6.1 |
| Signal modeling | 3.6 | 5.0 | 4.2 |
| Background modeling | 1.2 | 4.8 | 8.0 |
| Luminosity | 2.5 | 2.5 | 2.5 |
| Time-dependent inefficiencies | 1.4 | 1.4 | 1.4 |
| Total | 11.0 | 8.7 | 12.2 |

# D mesons: differential cross section



# $B_c$(2S): hyperfine structure

$B_c^*(2S) \to B_c^* \pi^+ \pi^-$ followed by $B_c^* \to B_c \gamma_{lost}$

Soft photon (55 MeV in the rest frame) not detected, we end up seeing

**$B_c^*(2S) \to B_c \pi^+ \pi^-$ plus "missing energy"**

**Same final state as $B_c(2S) \to B_c \pi^+ \pi^-$**

A two-peak structure in the Bc $\pi^+ \pi^-$ mass distribution is expected,

with the $B_c(2S)^*$ peak at a mass shifted by

**$\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c^*(2S)) - M(B_c(2S))]$**

which is predicted to be around 20 MeV.

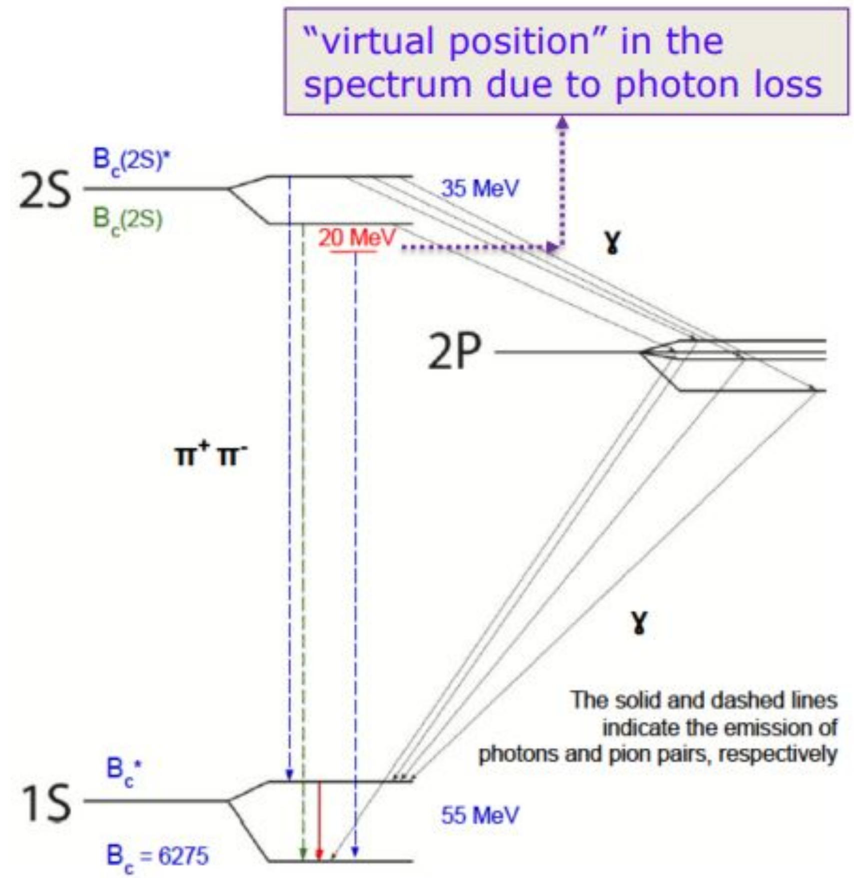
The two-peak can be appreciated only if $\Delta M$ value is larger than experimental resolution!

Predictions indicate:

**$[M(B_c^*(1S)) - M(B_c(1S))] > [M(B_c^*(2S)) - M(B_c(2S))]$**

that would imply that the

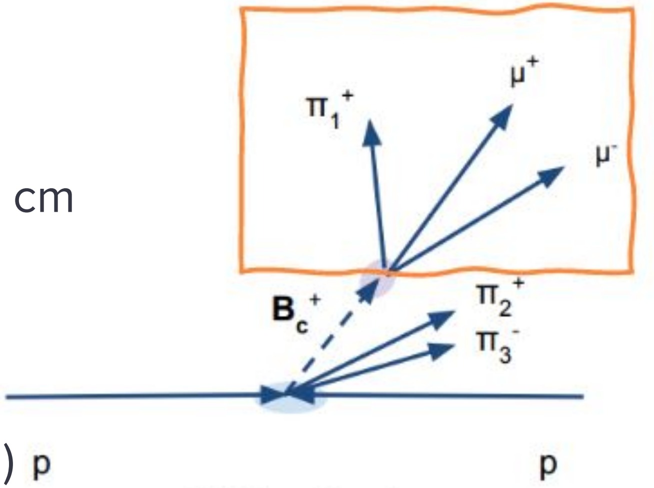
**$B_c^*(2S)$ peak is the lower peak!**



# $B_c(2S)$: event selection

**HLT Requirements (DoubleMu4_JpsiTrk_displaced):**

- OS muon pair in [2.9, 3.3] GeV
- dimuon vertex $\chi^2$ probability > 10%
- distance of closest approach between muons < 0.5 cm
- significance(flight distance) > 3
- $p_T(\mu) > 4$ GeV && $|\eta(\mu)| < 2.5$
- cos(dimuon_transverse_pointing_angle) > 0.9 (*)
- third track (from μμ-vtx, $p_T > 1.2$ GeV, $\eta < 2.5$, sip > 2)




$B_c(2S) \rightarrow B_c \pi^+ \pi^-$

**Offline requirements:**

- Muons matching trigger muons
- High quality muons
- $|\eta(\mu)| < 2.4$ and cos(dimuon_transverse_pointing_angle) > 0.98 (*)
- muons close in angular space: $(\Delta\eta)^2 + (\Delta\phi)^2 < 1.2^2$

**Integrated Luminosity per year**: 2.8, 36.1, 42.1, 61.6 1/fb

(*) cosine of the angle formed by the flight direction and the momentum in the transverse plane

# $B_c$ reconstruction

## $B_c$ candidates fit

**Signal**: weighted sum of two gaussians with same mean

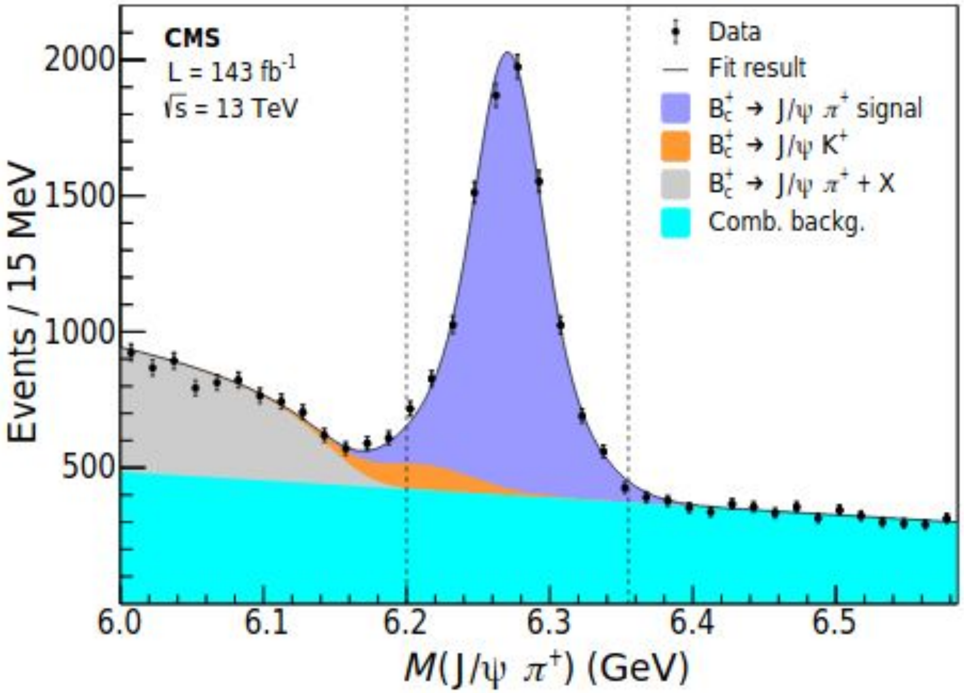
$$wG(\mu,\sigma_1) + (1-w)G(\mu,\sigma_2),$$

w = 0.47 $\sigma_1$ = 21 MeV $\sigma_2$ = 42 MeV

**Background**:

- Combinatorial: Chebychev polynomial
- $J/\psi K$: shape from simulation
- $J/\psi\pi + X$: ARGUS function

$N(B_c)$ = 7629 +/- 225 events



# $B_c(2S)$ cross section ratios

**Reconstruction efficiencies** (MC studies):

- statistical: finite size of simulated events
- dispersion: average over four years
- pions: π reconstruction efficiency

| | Central | Stat. | Spread | Pions |
|---|---|---|---|---|
| $\epsilon(B_c(2S)^+)/\epsilon(B_c^+)$ | 0.196 | 1.1% | 1.8% | 4.2% |
| $\epsilon(B_c^*(2S)^+)/\epsilon(B_c^+)$ | 0.187 | 1.0% | 1.6% | 4.2% |
| $\epsilon(B_c^*(2S)^+)/\epsilon(B_c(2S)^+)$ | 0.955 | 1.4% | 0.9% | — |

**Systematic uncertainties:**

- from signal yield
  (evaluated with different fit models)
- from efficiency
- from correlations in di-pion kinematics

| | $R^+$ | $R^{*+}$ | $R^{*+}/R^+$ |
|---|---|---|---|
| $J/\psi\,\pi^+$ fit model | 5.5 | 5.5 | — |
| $B_c^+\pi^+\pi^-$ fit model | 5.9 | 2.9 | 2.9 |
| Efficiencies: statistical uncertainty | 1.1 | 1.0 | 1.4 |
| Efficiencies: spread among years | 1.8 | 1.6 | 0.9 |
| Efficiencies: pion tracking | 4.2 | 4.2 | — |
| Decay kinematics | 1.5 | 6.9 | 4.2 |
| Helicity angle | 1.0 | 6.0 | 3.5 |
| Total | 9.5 | 12.0 | 6.4 |

**Results**:

$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$
$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$

# Υ(1S)Υ(1S) production: event selection

**HLT requirements:**

- three muons
- two muons with mass in [8.5, 11.4] GeV
- dimuon vertex $\chi^2$ probability > 0.5%

**Offline requirements:**

- $p_T(\mu) > 2$ GeV and $|\eta(\mu)| < 2.4$
- Best vertex-$\chi^2$ for arbitration of best muon combination (98% eff on MC)
- Three (of four) muons must be associated with trigger muons
- $\mu\mu$ mass closest to Υ(1S) world-average for arbitration
- New $p_T$ threshold for muons: $p_T(\mu) > 2.5$ GeV
- prob($\chi^2$, 4$\mu$) > 5% and prob($\chi^2$, Υ(1S)) > 0.5%
- muons separated with $\Delta R > 0.02$
- on OS mixed-pairs: veto on J/$\psi$ mass

  (window of 2$\sigma$, resolution depends on kinematics in [0.03, 0.12] GeV)

**Extra requirements (Υ(1S) pair only):**

- $|y(\mu\mu)| < 2.0$
- $p_T(\mu) > 3.5$ GeV for central muons, $|\eta(\mu)| < 0.9$

**Extra requirements (resonance search only):**

- mass of Υ(1S) candidate within 2$\sigma$, resolution depends on kinematics in [0.06, 0.15] GeV

# $\Upsilon(1S)\Upsilon(1S)$: shape of $\Upsilon(1S)$ signal

| Process | Uncorrected yield |
|---|---|
| $\Upsilon(1S) + \Upsilon(1S)$ | $111 \pm 16$ |
| $\Upsilon(2S) + \Upsilon(2S)$ | $3.6\,^{+4.4}_{-3.6}$ |
| $\Upsilon(3S) + \Upsilon(3S)$ | $1.1\,^{+1.4}_{-1.1}$ |
| $\Upsilon(1S)$ + combinatorial | $166 \pm 33$ |
| $\Upsilon(2S)$ + combinatorial | $25 \pm 18$ |
| $\Upsilon(3S)$ + combinatorial | $1.1\,^{+11}_{-1.1}$ |
| $\Upsilon(2S) + \Upsilon(1S)$ | $19 \pm 10$ |
| $\Upsilon(3S) + \Upsilon(1S)$ | $17 \pm 11$ |
| Combinatorial + combinatorial | $561 \pm 41$ |

# Y(1S)Y(1S): yields

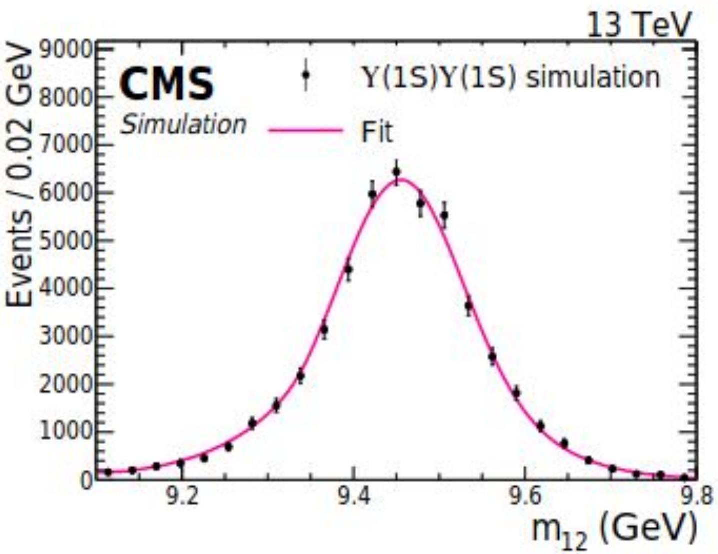
## Event-by-event weight:

$$\omega = \left[A_1 A_2 \epsilon_1^{\text{reco}} \epsilon_2^{\text{reco}} \left(1 - (1 - \epsilon_1^{\text{vtx}})(1 - \epsilon_2^{\text{vtx}})\right) \epsilon^{\text{evt}}\right]^{-1},$$

- A: acceptance for Y(1S) to μμ in fiducial region
- $\varepsilon^{reco}$: probability that a Y(1S) to μμ with |y(Y(1S))| < 2.0 and |η(μ)| < 2.4 is selected
- $\varepsilon^{vtx}$: probability that a selected Y(1S) has prob($\chi^2$, Y(1S)) > 0.5%
- $\varepsilon^{evt}$: probability that a selected event has prob($\chi^2$, 4μ) > 5% and cross-paired muons have invariant mass out of [m(J/ψ) - 2σ, m(J/ψ) + 2σ]

## Shape of Y(1S) signal from simulation:

- Sum of two Crystal Ball with same mean
- Different resolutions for barrel/end-cap muons



# Υ(1S)Υ(1S): effect of the polarization

**Υ(1S) pair polarization assumed to be negligible in acceptance and efficiency corrections**

**Previous measurements from CMS [A] and LHCb [B] show no polarization in single Υ(1S) production**

Polarization affects the angular distribution of the Υ(1S) → μμ decay products:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\cos\theta\,\mathrm{d}\phi} \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi),$$

- (θ, φ) direction of $\mu^+$
- $\lambda_\theta$, $\lambda_\varphi$, $\lambda_{\theta\varphi}$: angular distribution parameters

Effect of polarization on fiducial cross section:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\lambda_\theta$ | $-1.0$ | $-0.5$ | $-0.3$ | $-0.1$ | $+0.1$ | $+0.3$ | $+0.5$ | $+1.0$ |
| $\Delta\sigma_{\mathrm{fid}}$ | $-60\%$ | $-22\%$ | $-12\%$ | $-3.7\%$ | $+3.4\%$ | $+9.4\%$ | $+14\%$ | $+25\%$ |

[A] [CMS Collaboration, arXiv:1209.2922]
[B] [LHCb Collaboration, arXiv:1709.01301]

# Υ(1S)Υ(1S): systematic uncertainties

| Uncertainty source | Uncertainty (%) | Impact on $\sigma_{\text{fid}}$ (pb) |
|---|---|---|
| Integrated luminosity | 2.5 | 2.0 |
| Muon identification | 2.0 | 1.6 |
| Trigger | 6.0 | 4.7 |
| Vertex probability | 1.0 | 0.8 |
| $\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ | 4.0 | 3.2 |
| Signal and background models | 1.2 | 1.0 |
| Method closure | 1.5 | 1.2 |
| Total | 8.1 | 6.4 |

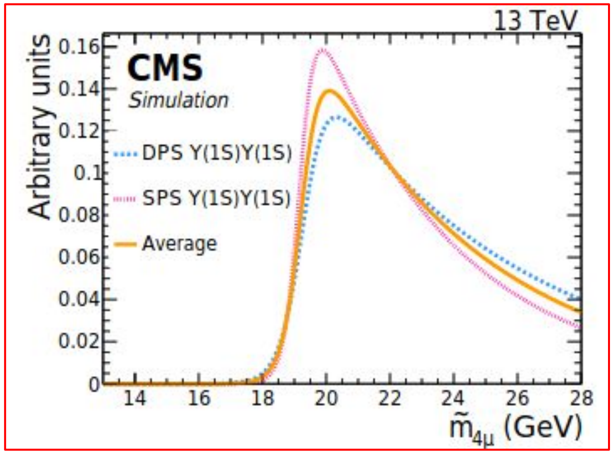
# Search for resonance in Υ(1S)μμ

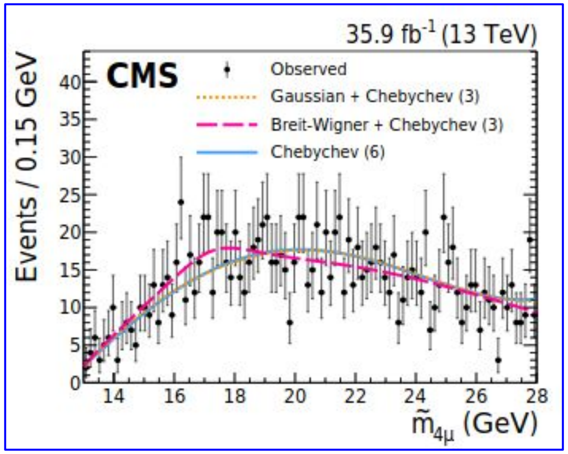
**New variable** to improve resolution by 50% for signal events

$$\tilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)},$$

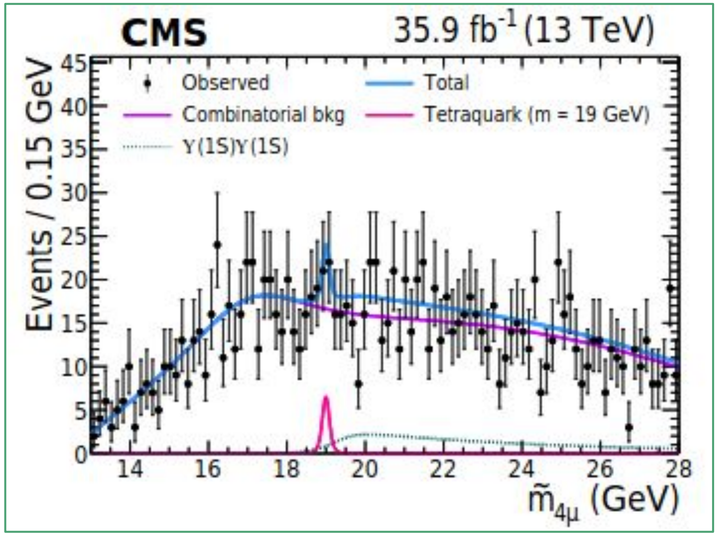
Background sources:

- non resonant ΥΥ (from MC):
  sigmoid * exponential
- combinatorial:
  from control region:
  4μ-vtx $\chi^2$ in $[10^{-10}, 10^{-3}]$




Example signal for a tetraquark (modeled as $\chi_{b1}$(1P)) of m = 19 GeV and significance 1σ



# Upper limits @ 95% CL for resonance production

Largest excess at
m = 25.1 GeV
scalar hypothesis
2.4σ of local significance

No excess of events compatible with a signal is observed