Measurements of strange and non strange beauty production in PbPb collisions at 5.02 TeV with the CMS detector

Ta-Wei Wang (MIT)
on behalf of the CMS collaboration

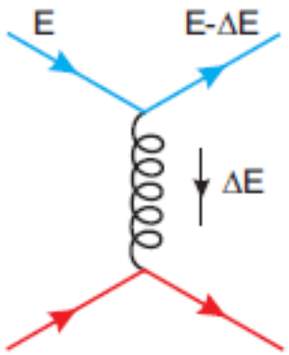
Quark Matter, Venezia, Italy
15, May, 2018

Flavor dependence parton energy loss

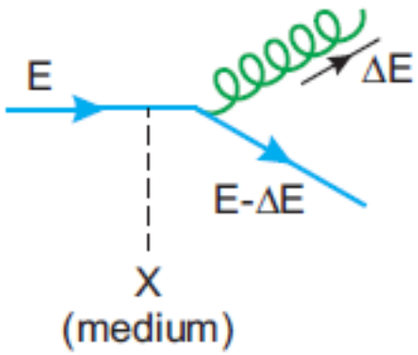
- Heavy flavor are predominantly produced in the early hard scattering, timescale < QGP formation
  ➜ full information of QGP evolution history
- Heavy ➜ negligible thermal production and annihilation rate
- Parton mass dependence of energy loss
- Medium induced energy loss (E_{loss}): 1. Collisional 2. Radiative
- Kinematics: "Dead cone effect" [1]: gluon radiation is suppressed at angles < quark mass/energy
  - E_{loss} in light quarks > E_{loss} in heavy quarks
- Suppression of induced radiation at low p_T and the disappearance of this effect at high p_T
- A measure to quantify this: nuclear modification factor (R_{AA})

$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} \Big/ \frac{d\sigma_{pp}}{dp_T}$$

Collisional



Radiative

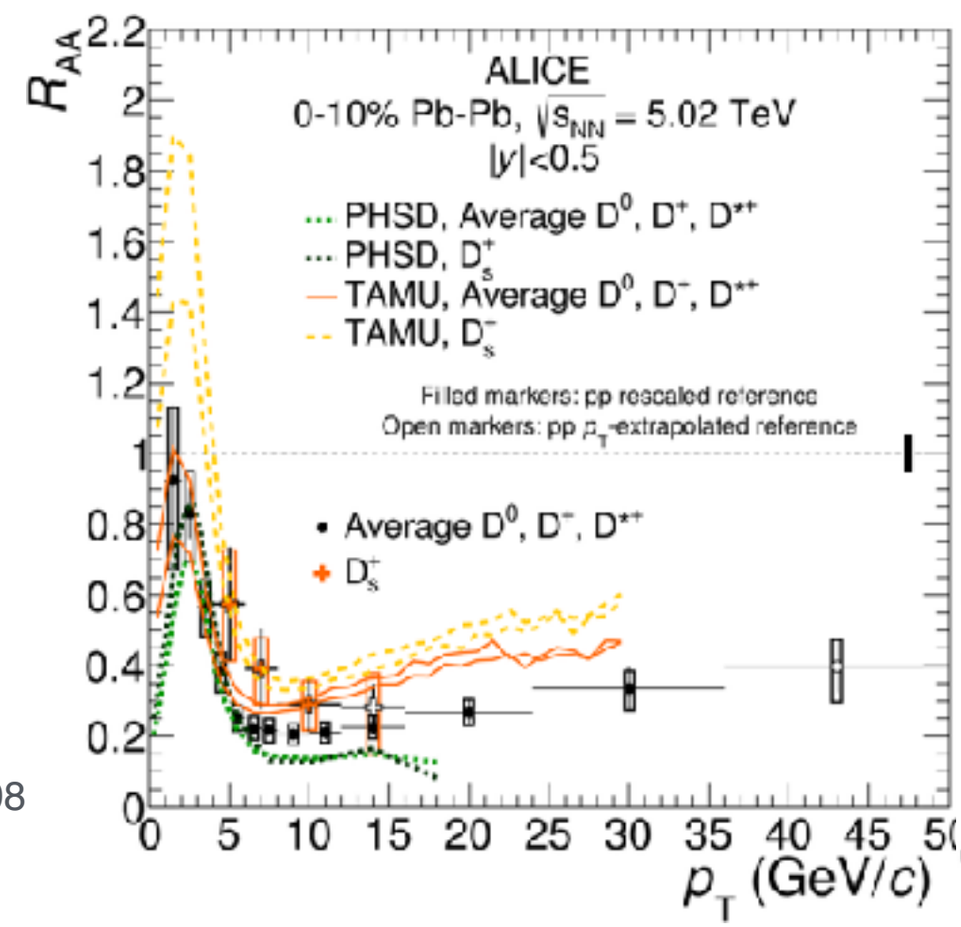


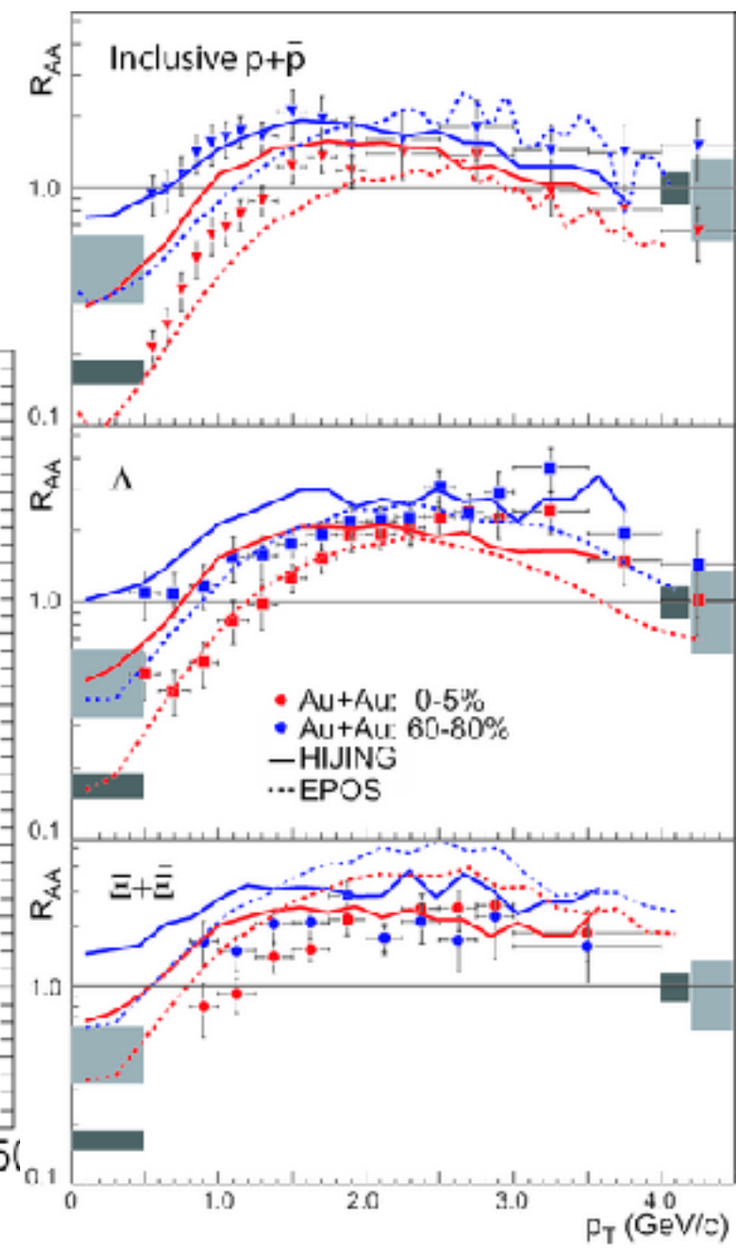
[1] Y.L. Dokshitzer, D. E. Kharzeev, Phys. Lett. B 519 (2001) 199.

Strangeness enhancement & recombination mechanism

- Proposed an enhancement of strangeness in the QGP state comparing to hadron gas [1]
- Verified by RHIC in strange baryon production measurements [2]
- Suggested that heavy quarks could hadronise via a recombination with other quarks in the medium in addition to fragmentation
- ALICE measurement of D_s production show indications of higher D_s meson R_{AA} w.r.t other D meson species [3]

- **Beauty quark: even cleaner probe**
- **First time probing combination of beauty and strange**





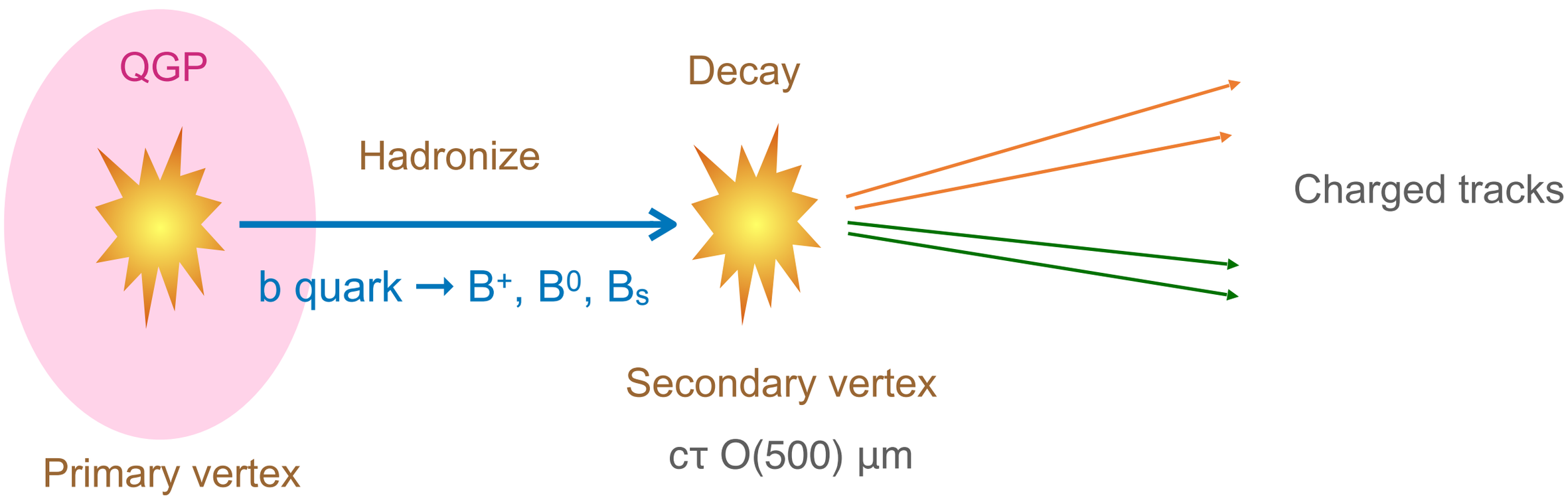
[1] J. Rafelski et. al, Phys. Rev. Lett. 48, 1066

[2] STAR Collaboration, Phys. Rev. C 77, 044908

[3] ALICE Collaboration, arXiv:1804.09083

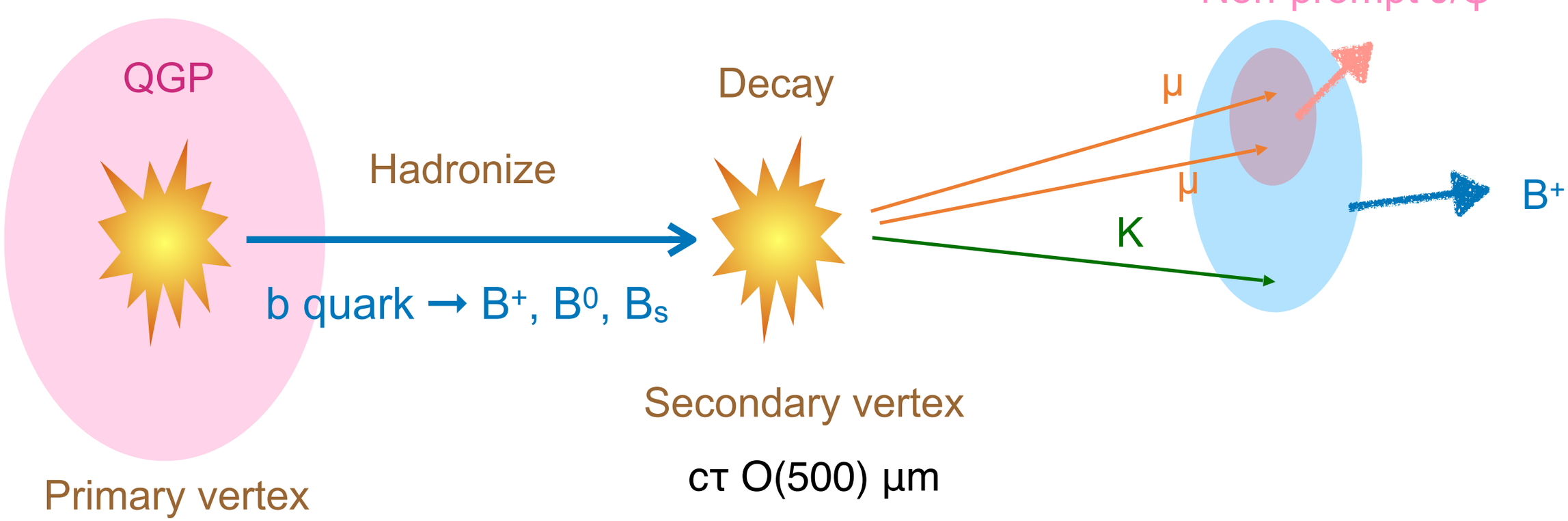
Measuring b hadron

- B quark decay kinematic:
- Comparable long decay length (exploit this)
    - Precise vertexing & tracking
    - High statistics dataset
    - No-hadronic PID utilized



Measuring b hadron

- Strategy 1, exclusive: full reconstruction of the B hadron decay chain
- Exclusive decay channels:
  - $B^+ \rightarrow J/\psi(\mu\mu) + K$ (branch ratio ~ 0.06%)
  - $B_s \rightarrow J/\psi(\mu\mu) + \phi(KK)$ (branch ratio ~ 0.03%)



Measuring b hadron

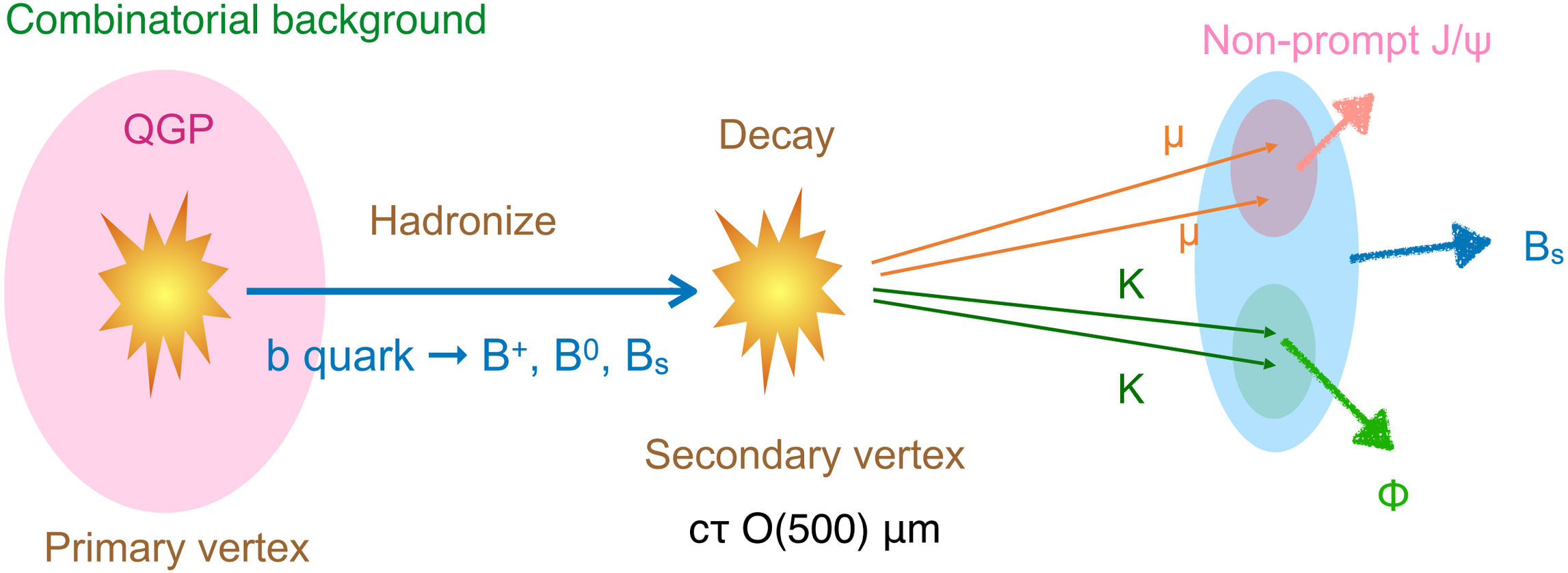
- Strategy 1, exclusive: full reconstruction of the B hadron decay chain
- Pros:

  Access to the original B hadron kinematics

  Distinguish B hadrons, e.g. B^+ v.s. B_s
- Cons:

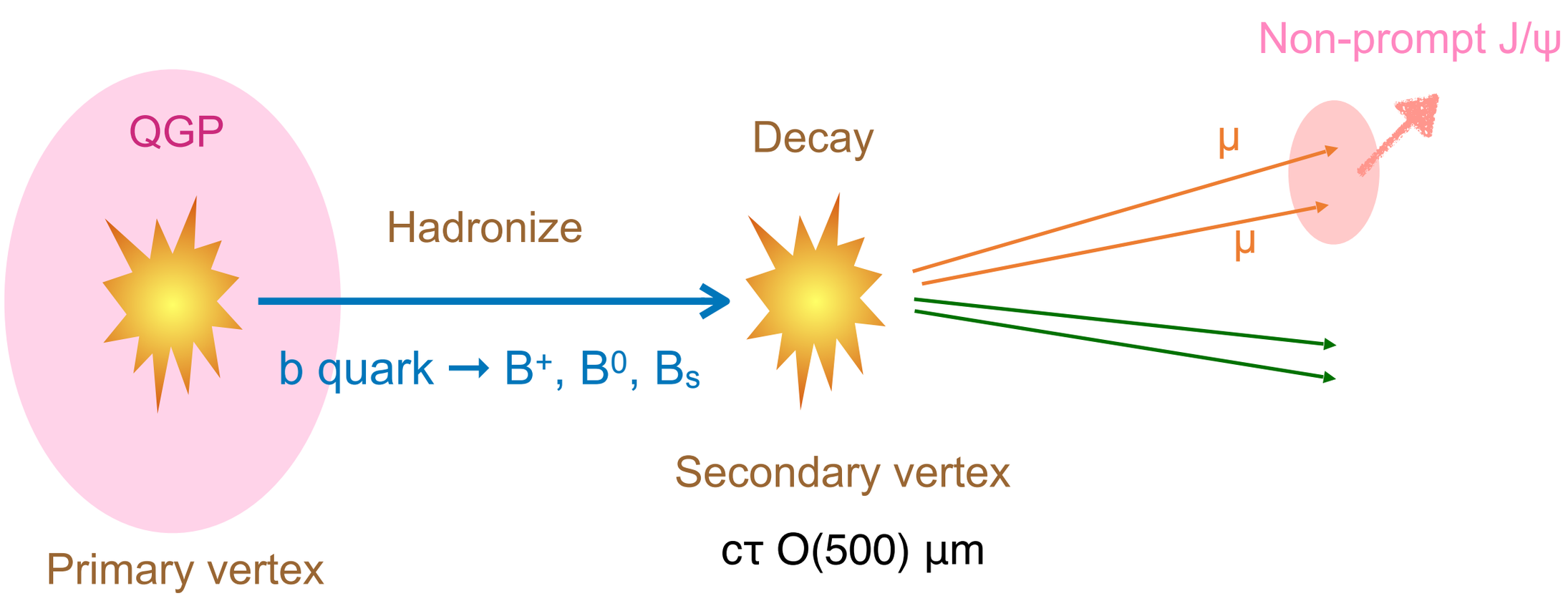
  Low Statistic

  Combinatorial background



Measuring b hadron

- Strategy 2, inclusive: reconstruction some of the daughter resonance of b hadrons
- Inclusive decay channels:
  - b hadrons → J/ψ(μμ)
  - b hadrons → D^0(πK)



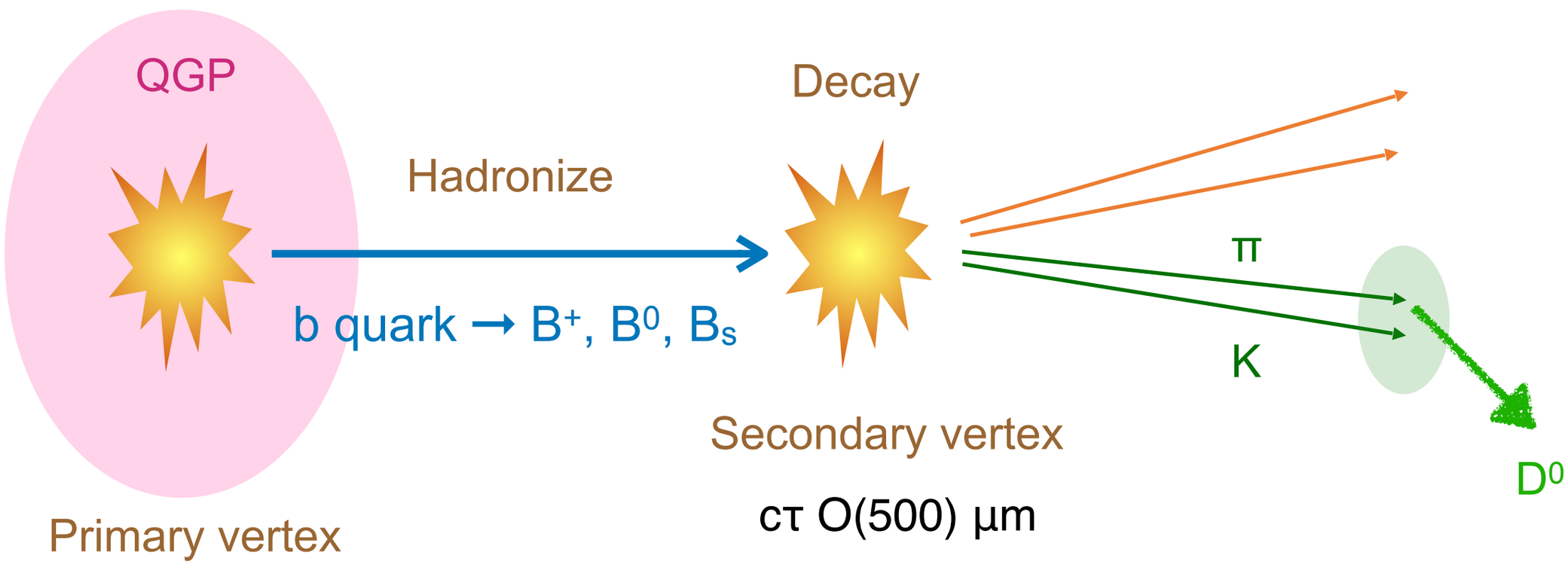
Measuring b hadron

- Strategy 2, inclusive: reconstruction some of the daughter resonance of b hadrons
- Pros:

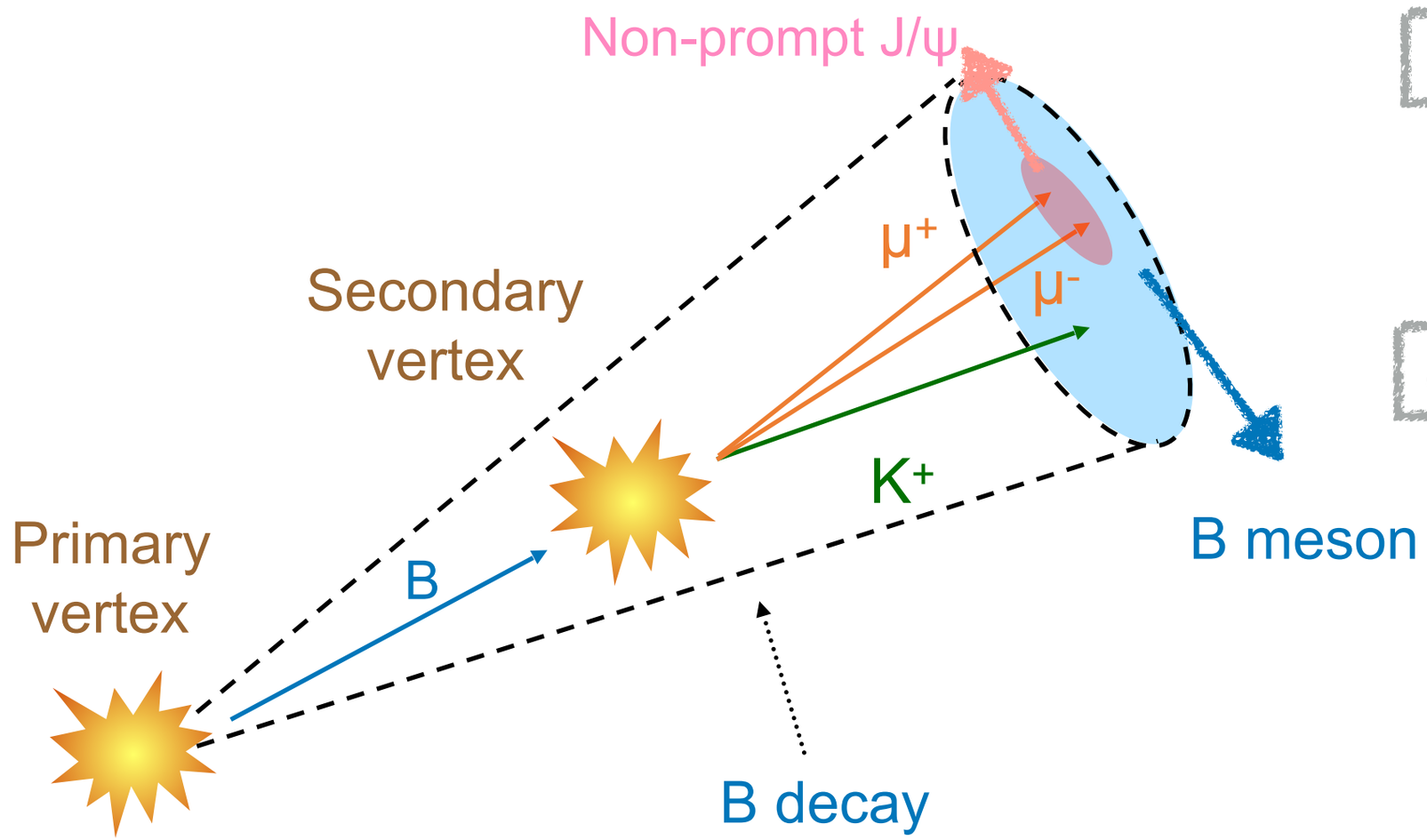
  High statistics

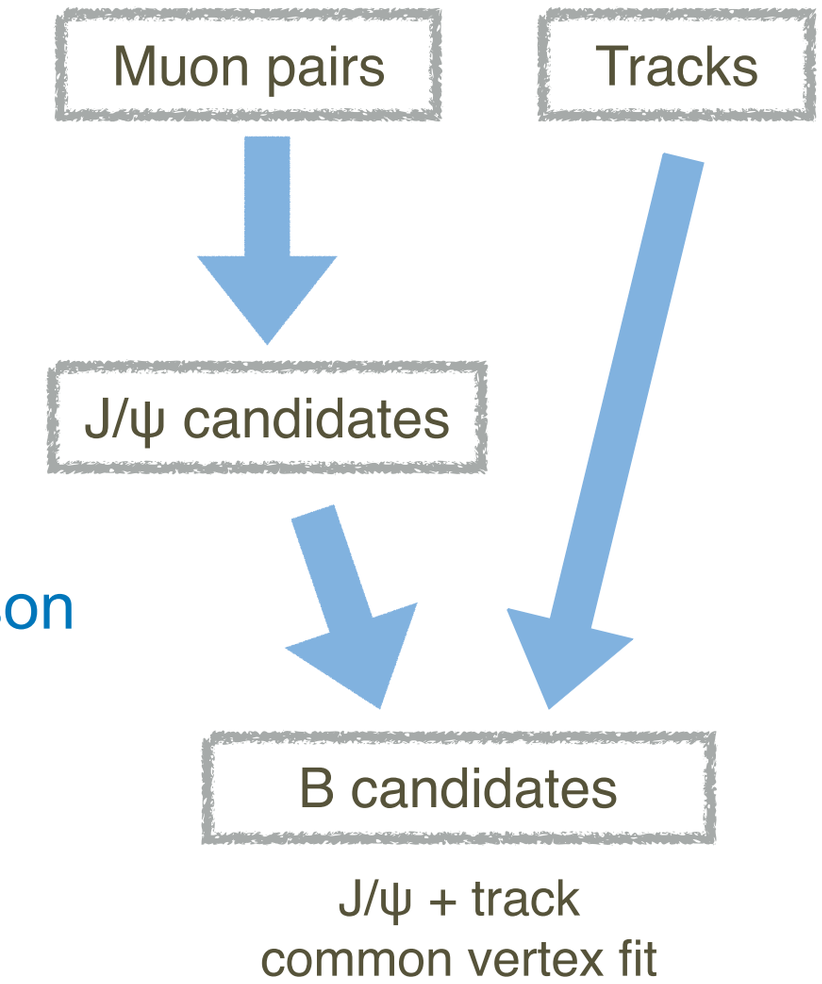
  High reconstruction efficiency
- Cons:

  Convolution of b mesons and b baryons decay



Full reconstruction: B^+





- **Signal channel: $B^+ \rightarrow J/\psi\ K^+$**
- Charged tracks are assigned a kaon mass
- Muon pair + track ➜ common vertex fitting

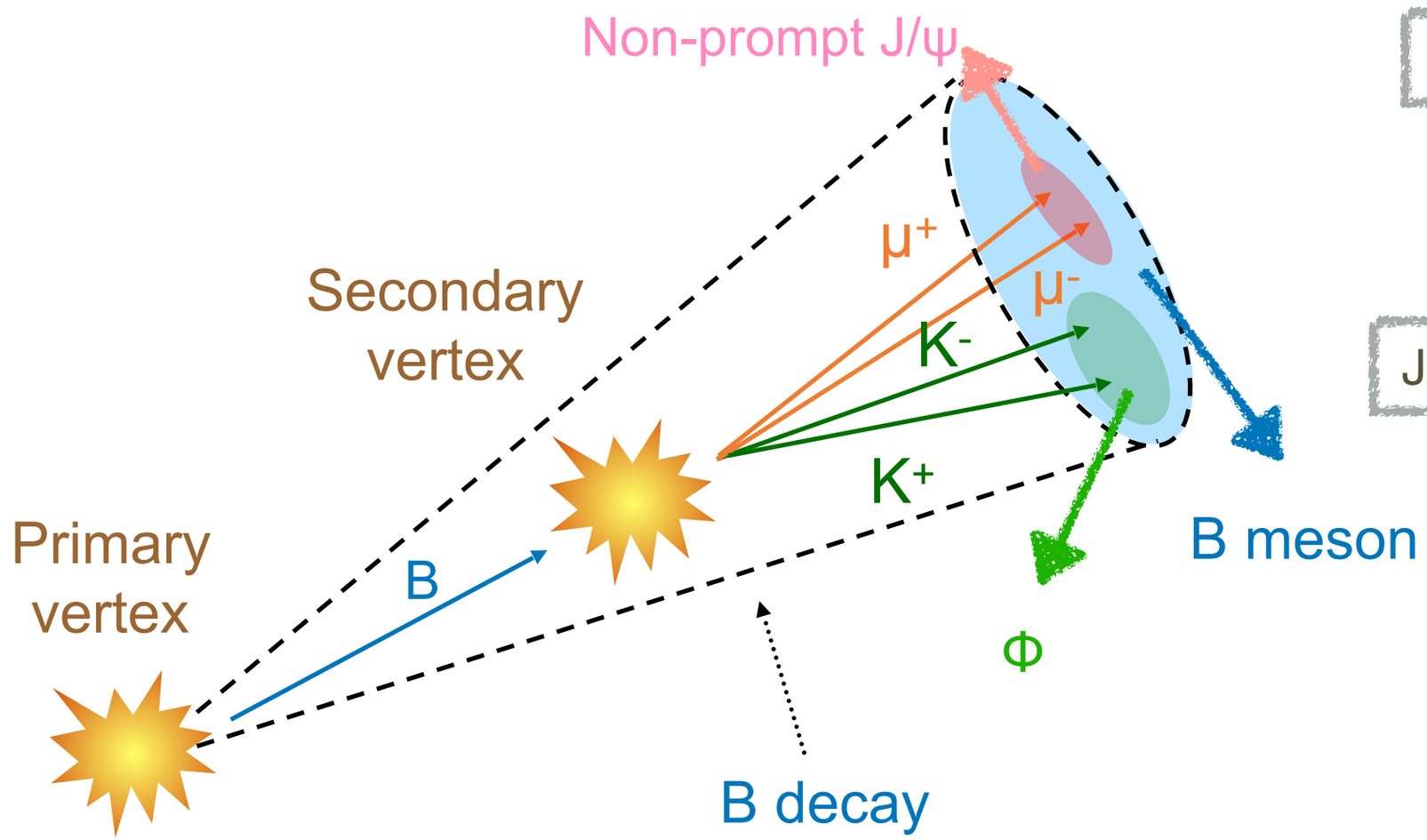
  ➜ fitting for yield extraction ➜ efficiency correction ➜ R_{AA}
- Cut optimization is crucial to beat down the massive combinatorial background

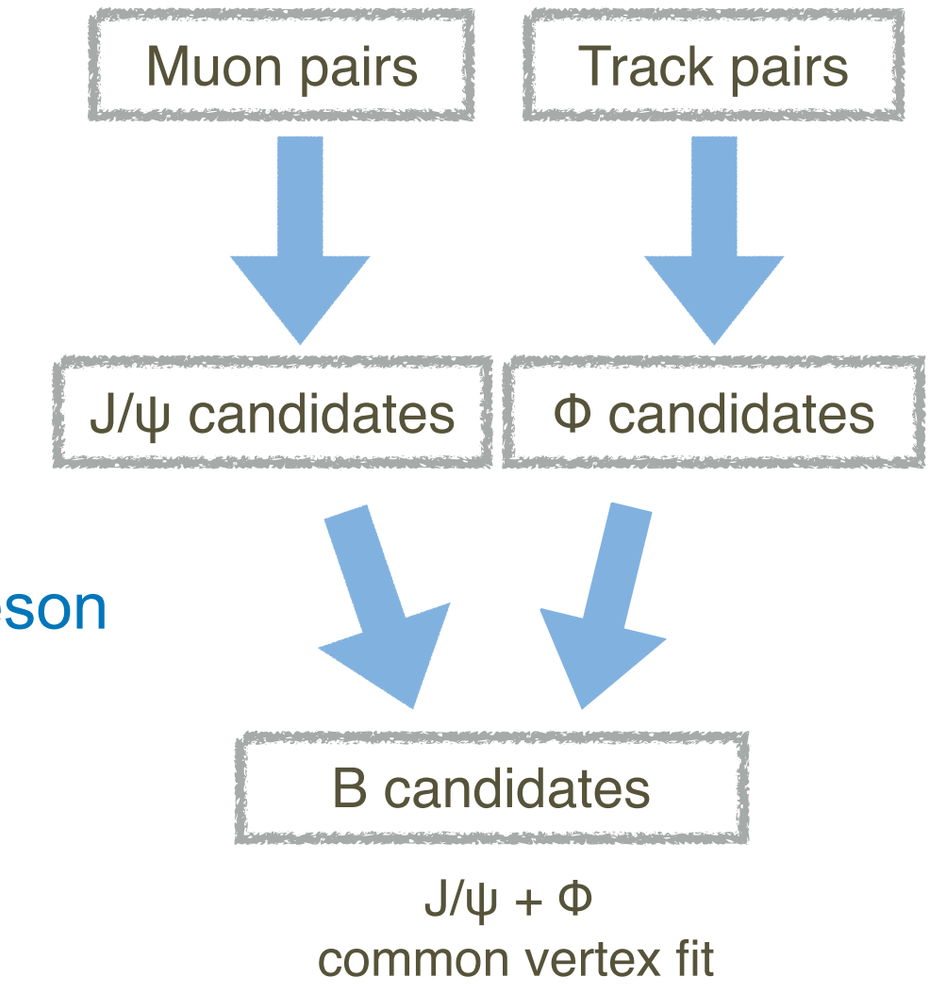
MVA cut optimization

Boosted Decision Tree (BDT):

- Track kinematics (p_T, rapidity…)
- Vertex fitting probability
- Opening angle
- Decay length

Full reconstruction: B_s





- **Signal channel: $B_s \rightarrow J/\psi\ \Phi$**
- Charged tracks are assigned a kaon mass
- Muon pair + track pairs ➜ common vertex fitting

  ➜ fitting for yield extraction ➜ efficiency correction ➜ R_{AA}
- Cut optimization is crucial to beat down the massive combinatorial background

MVA cut optimization

Boosted Decision Tree (BDT):

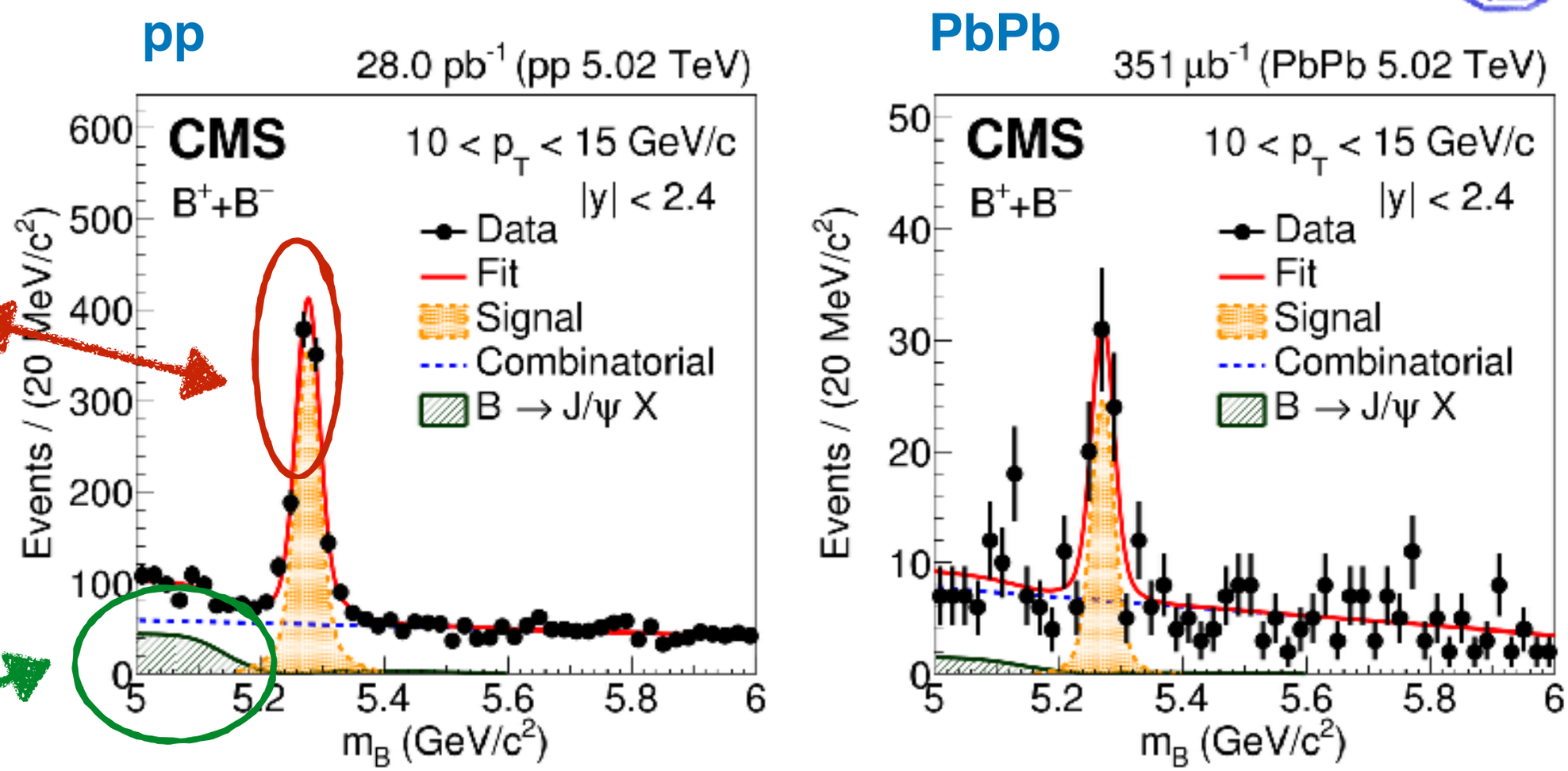
- Track kinematics (p_T, rapidity…)
- Vertex fitting probability
- Opening angle
- Decay length

Signal extraction: B^+

- Signals extracted: fit on invariant mass spectra (maximum likelihood)
- Peaking background: B hadrons other than the signal decay channel
  - Examples: $B^+ \rightarrow J/\psi + K^{*+}$ or $B^0 \rightarrow J/\psi + K^{*0}, K^0$…etc

Signal:
Double Gaussian with same mean

Peaking BG:
error function + two sided Gaussian

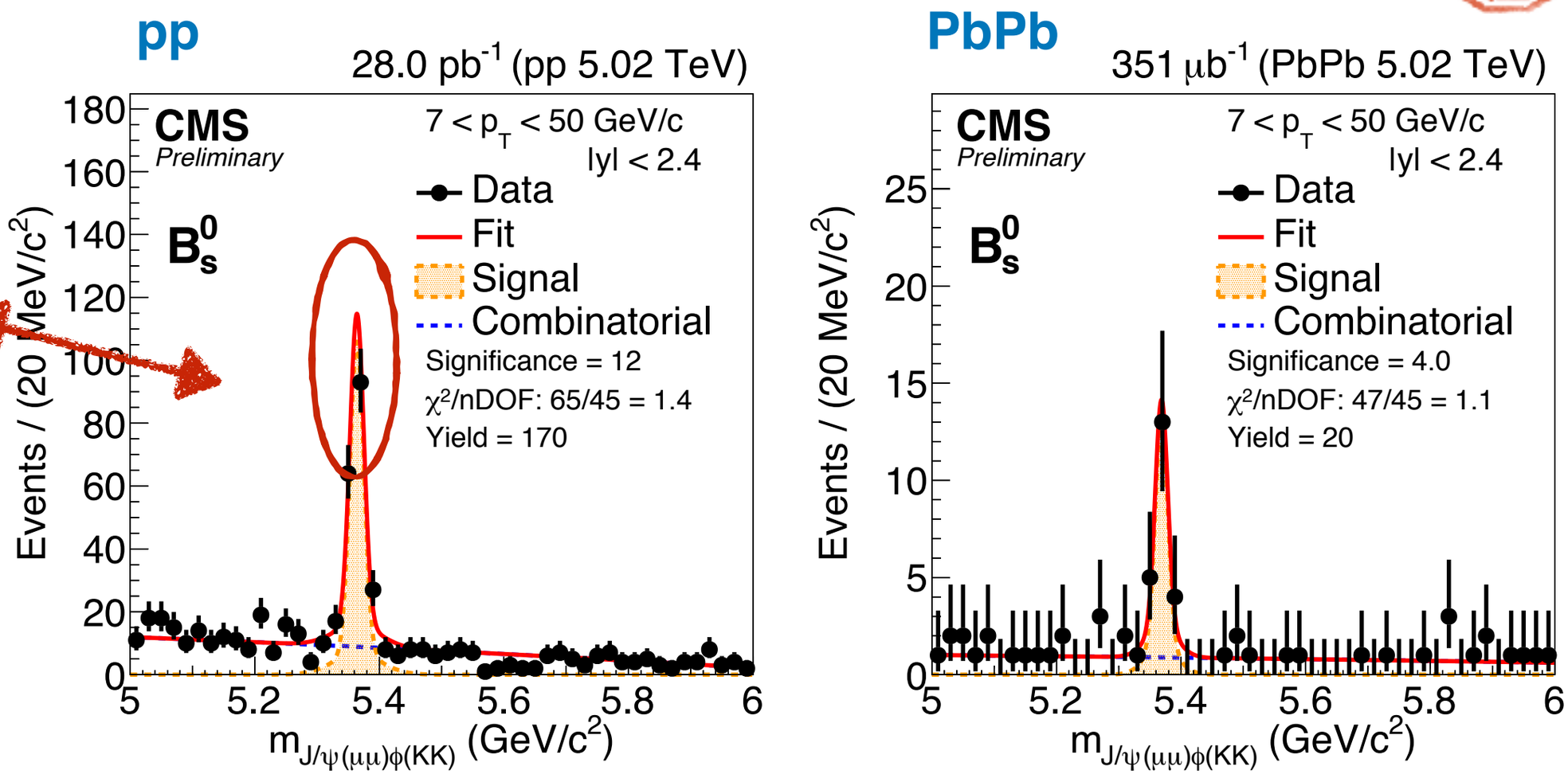


Phys. Rev. Lett. 119, 152301

Signal extraction: B_s

- Narrow natural width of Φ meson ➜ no peaking background components
- First fully reconstructed B_s meson measurement in heavy-ion collision by CMS

Signal:
Double Gaussian
with same mean



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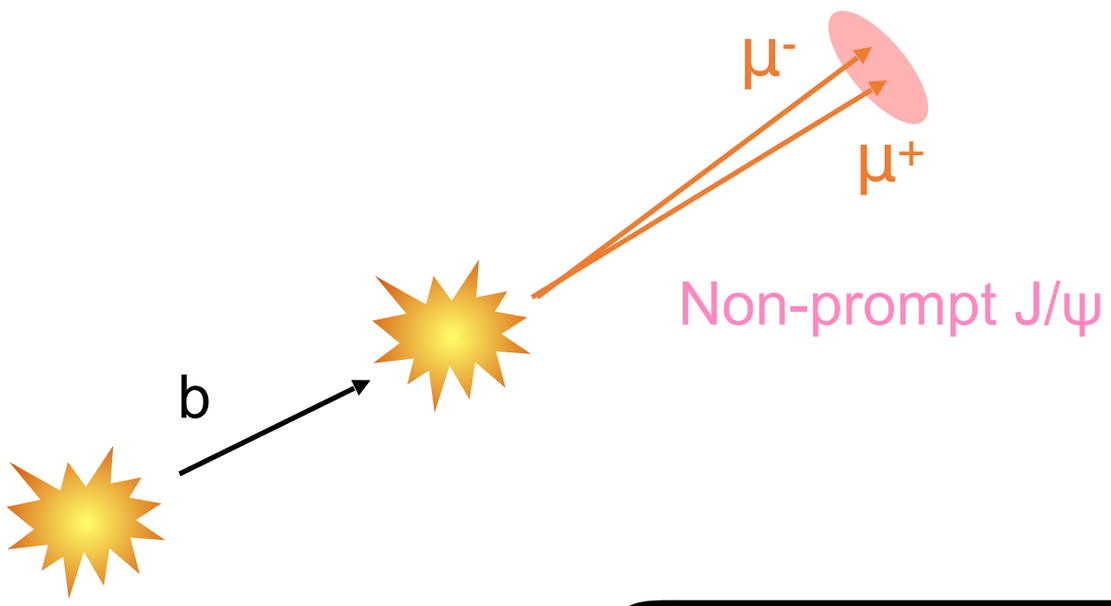
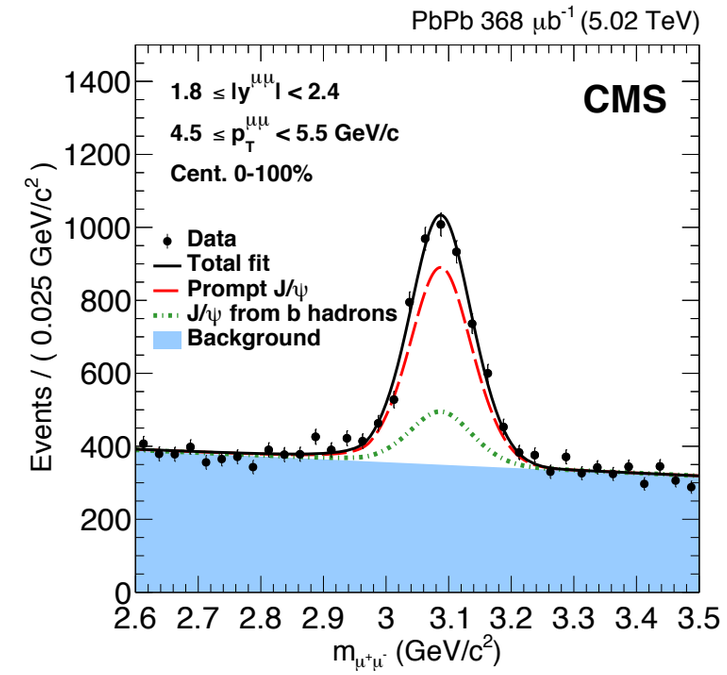
Partial reconstruction: non-prompt J/ψ

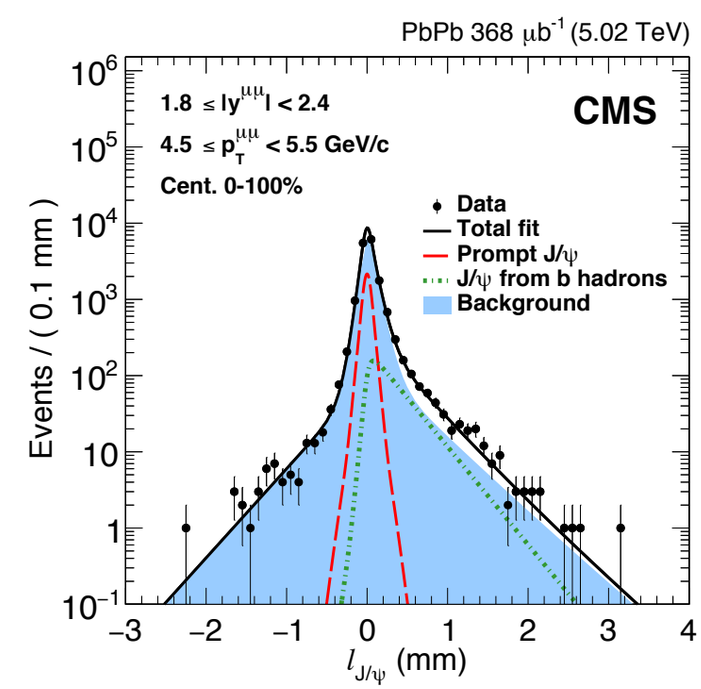
- Distinguish non-prompt component from prompt component
- Utilize the fact that b hadrons has a long decay length





All J/ψ

prompt J/ψ: direct production + feed down (ex ψ')	non-prompt J/ψ: from B decays (ex B → J/ψ X)

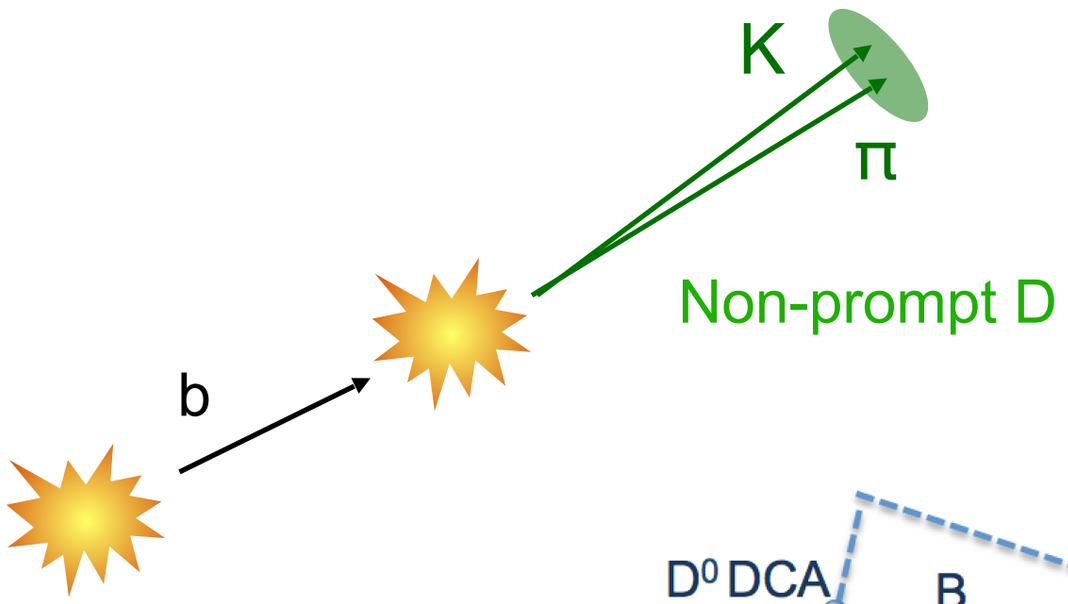


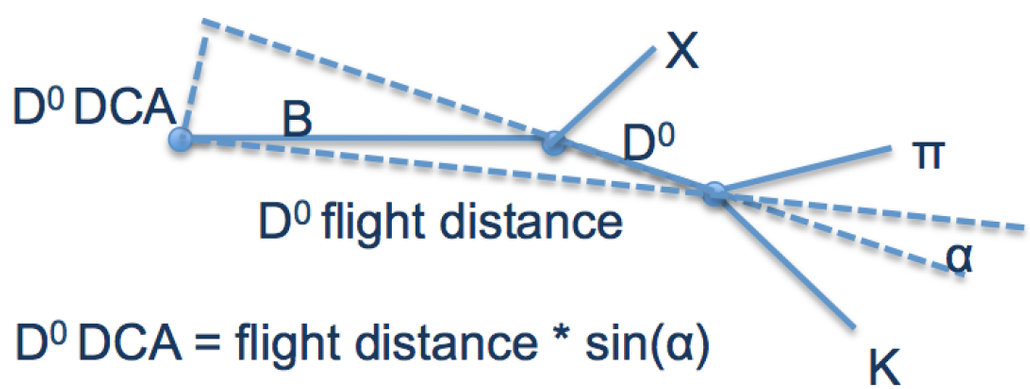
1. Muon pair fit to a common vertex → J/ψ candidates
2. 2D Fit on invariant mass and decay length spectra
3. Extracted yields corrected using a data-driven approach (tag & probe)

arXiv:1712.08959
Submitted to Eur. Phys. J. C

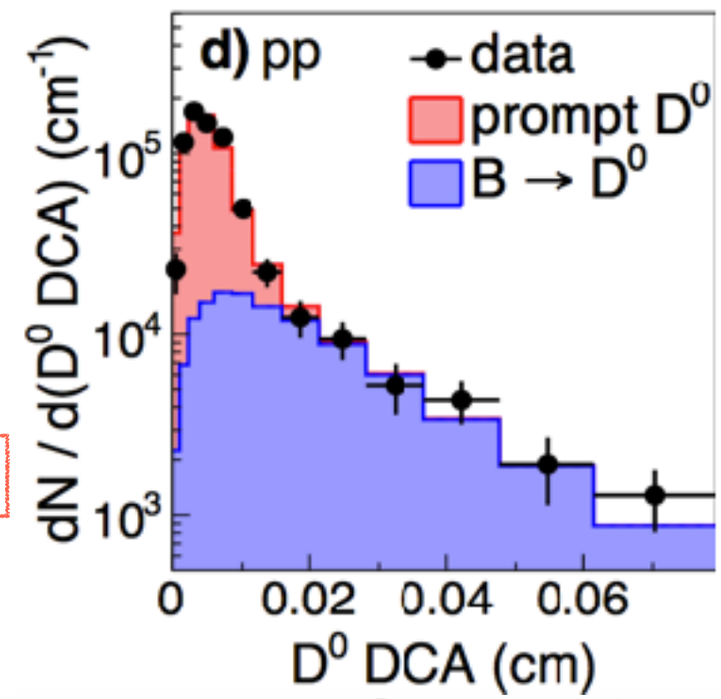
Partial reconstruction: non-prompt D

- Distinguish non-prompt component from prompt component
- Distance of closest approach (DCA)

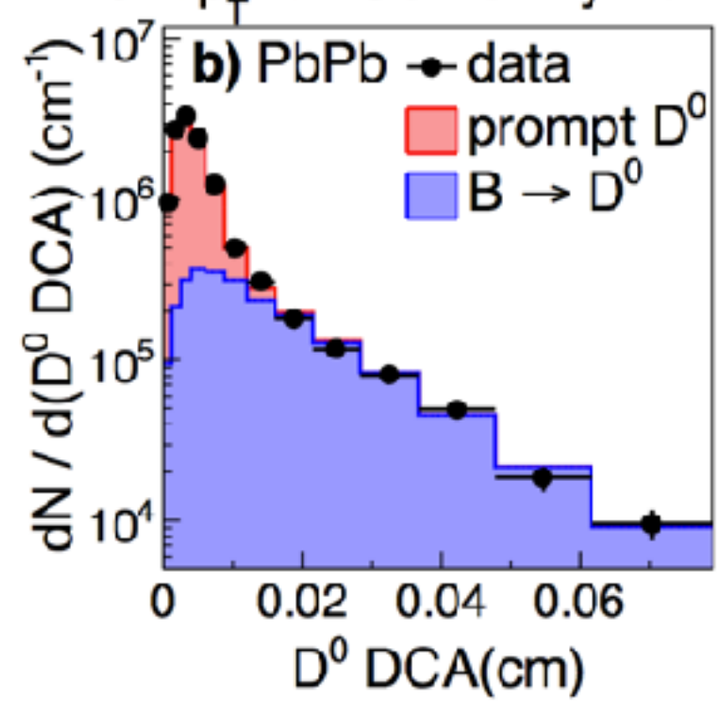




W. Xie's poster



$6 < p_T < 7$ GeV/c $|y| < 1$



1. Track pair fit to a common vertex → D candidates
2. Signal extraction in DCA interval → DCA distribution
3. Template fit (from simulation) on DCA distribution to extract non-prompt D

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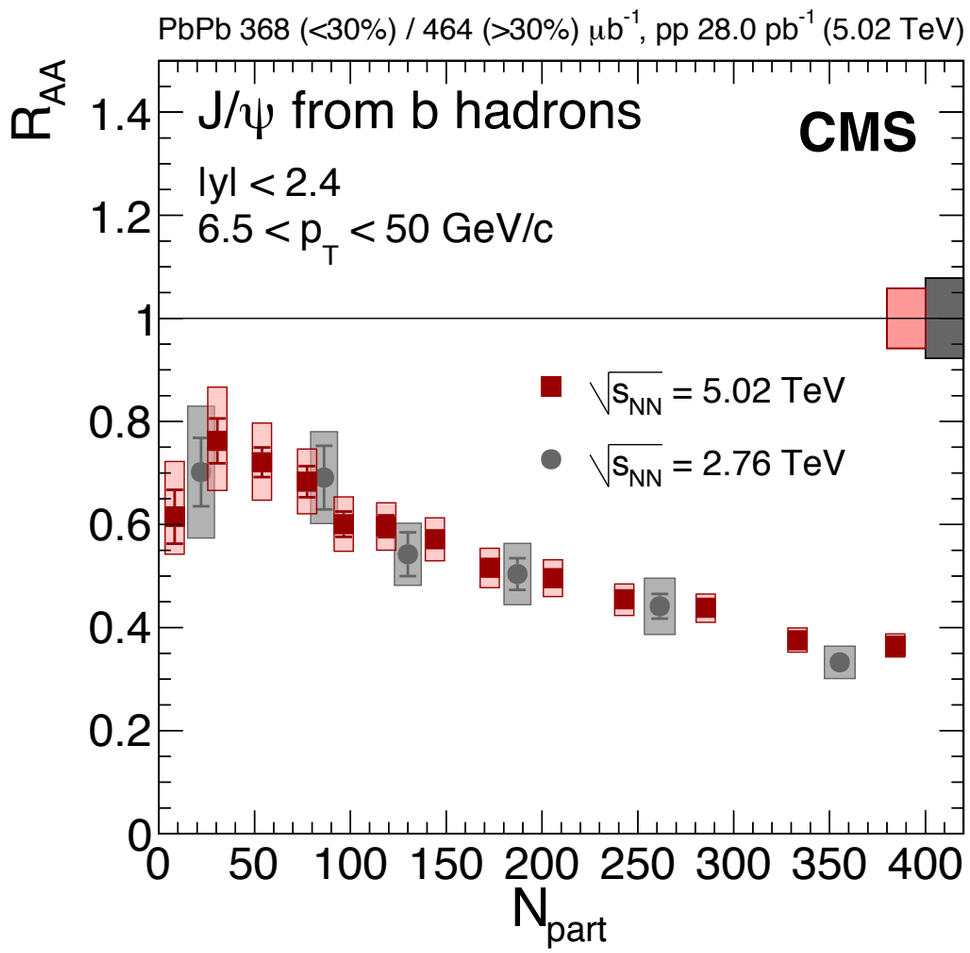
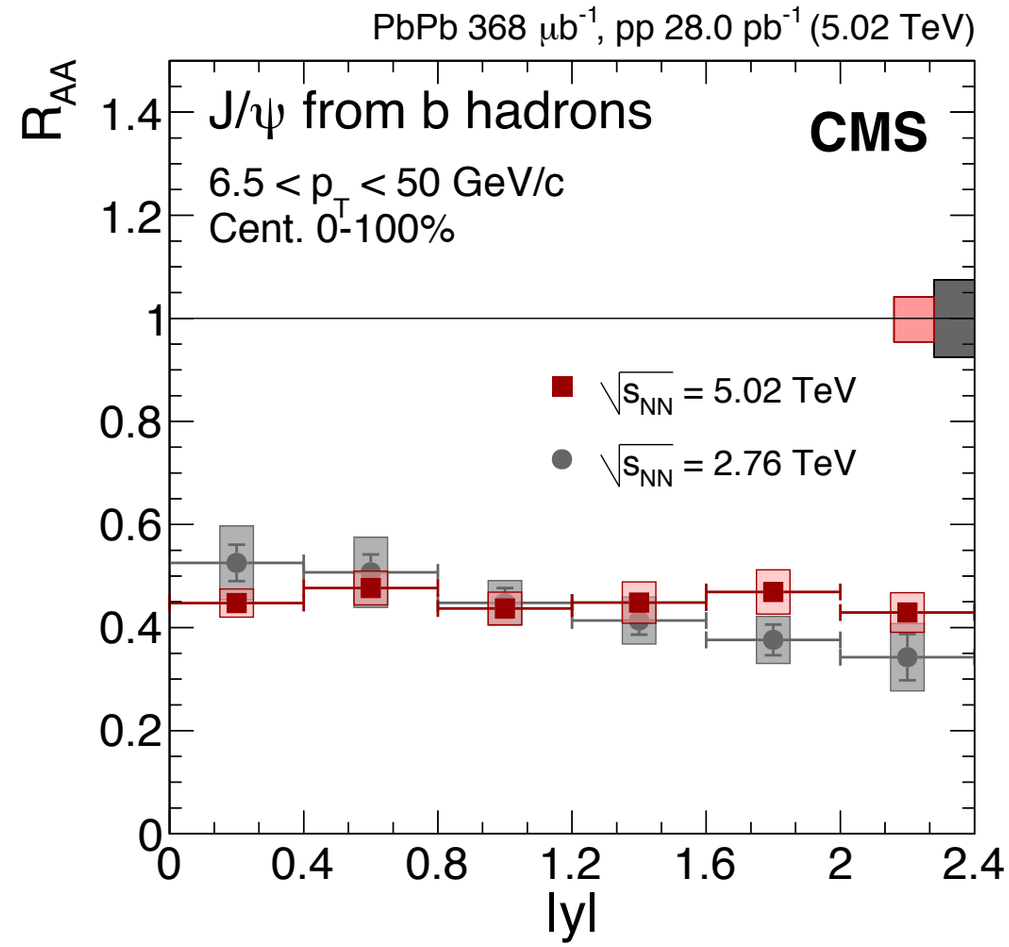
Non-prompt J/ψ & D @ 5.02 TeV

Non-prompt J/ψ R_{AA} v.s. N_{part} and rapidity

- Strong suppression of non-prompt J/ψ production
- Increased suppression with event activity in both collision energy
- No significant difference in R_{AA} between the two collision energies
- Interplay between: 1). initial momentum spectrum. 2). increase energy loss ??

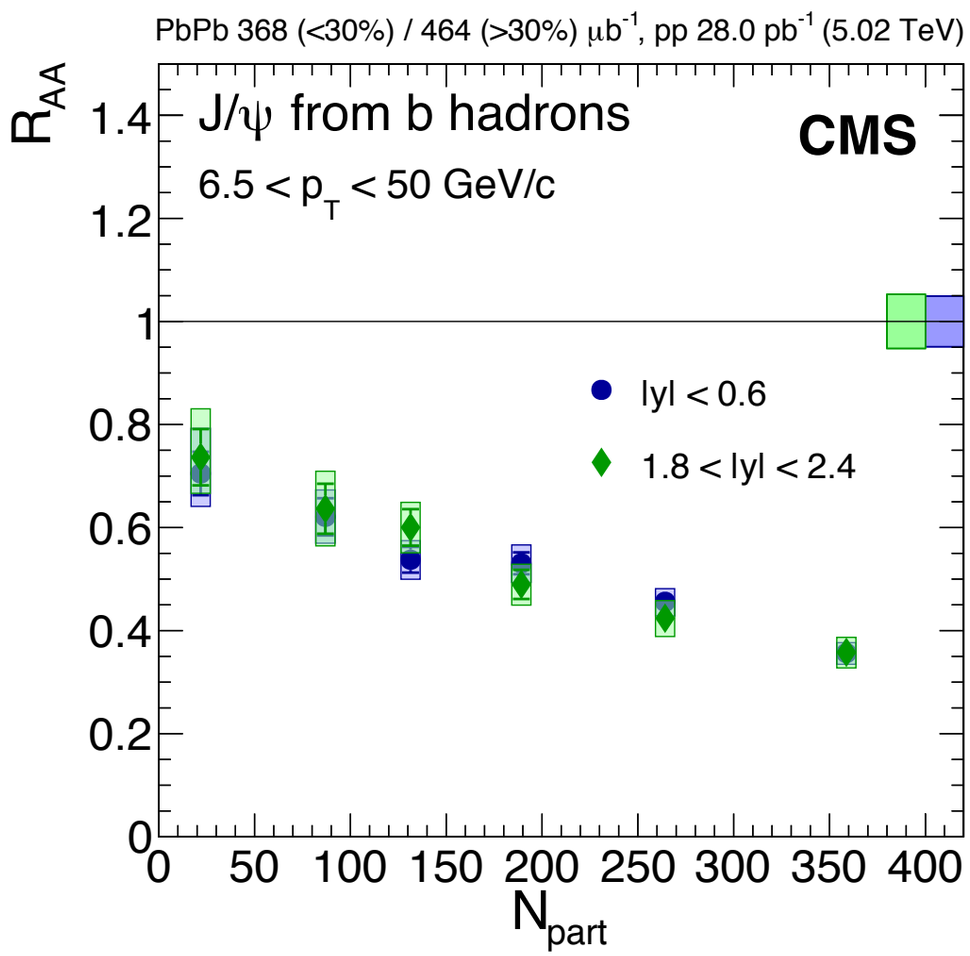


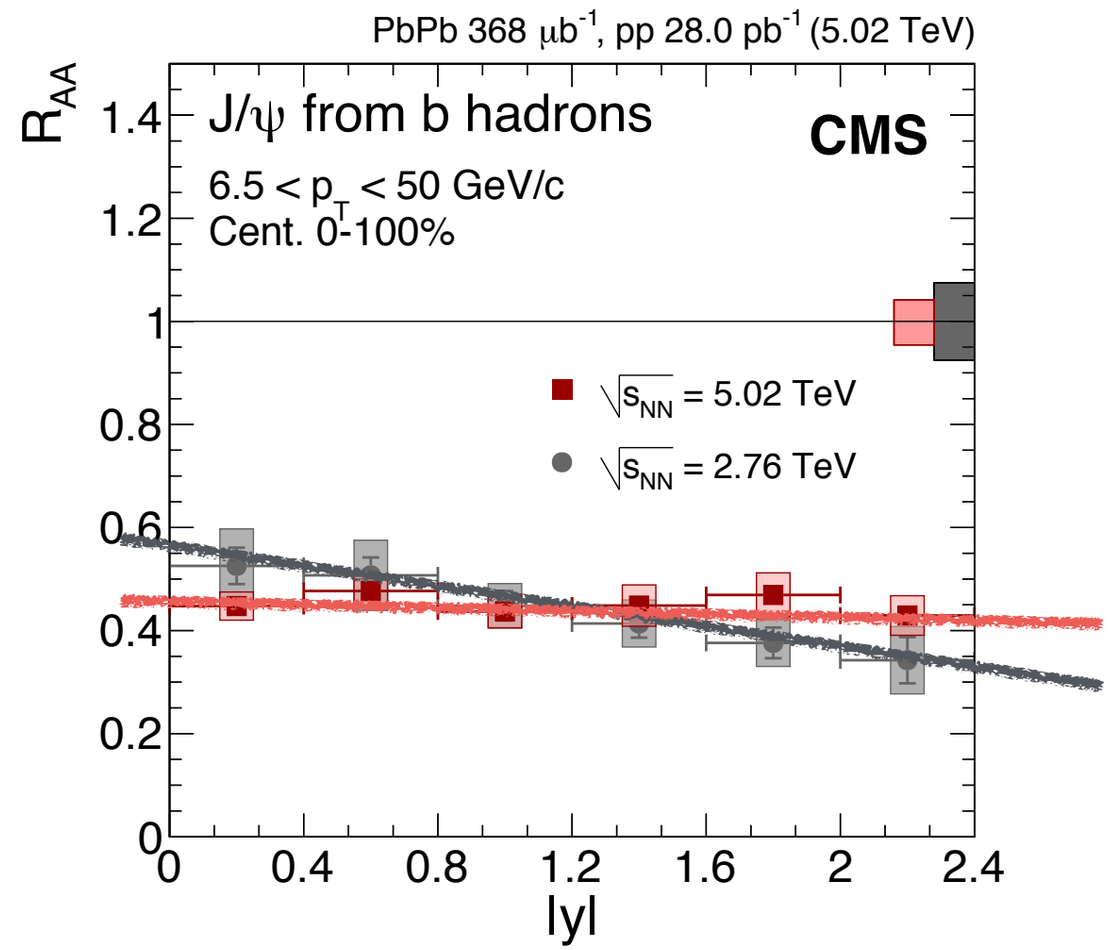


arXiv:1712.08959 (5.02 TeV), EPJC 77 (2017) 252 (2.76 TeV)

Non-prompt J/ψ R_{AA} v.s. N_{part} and rapidity

- At 2.76 TeV, some mild indication of rapidity dependance was seem
- No y-dependence at 5 TeV, and the results are compatible with the 2.76 TeV results

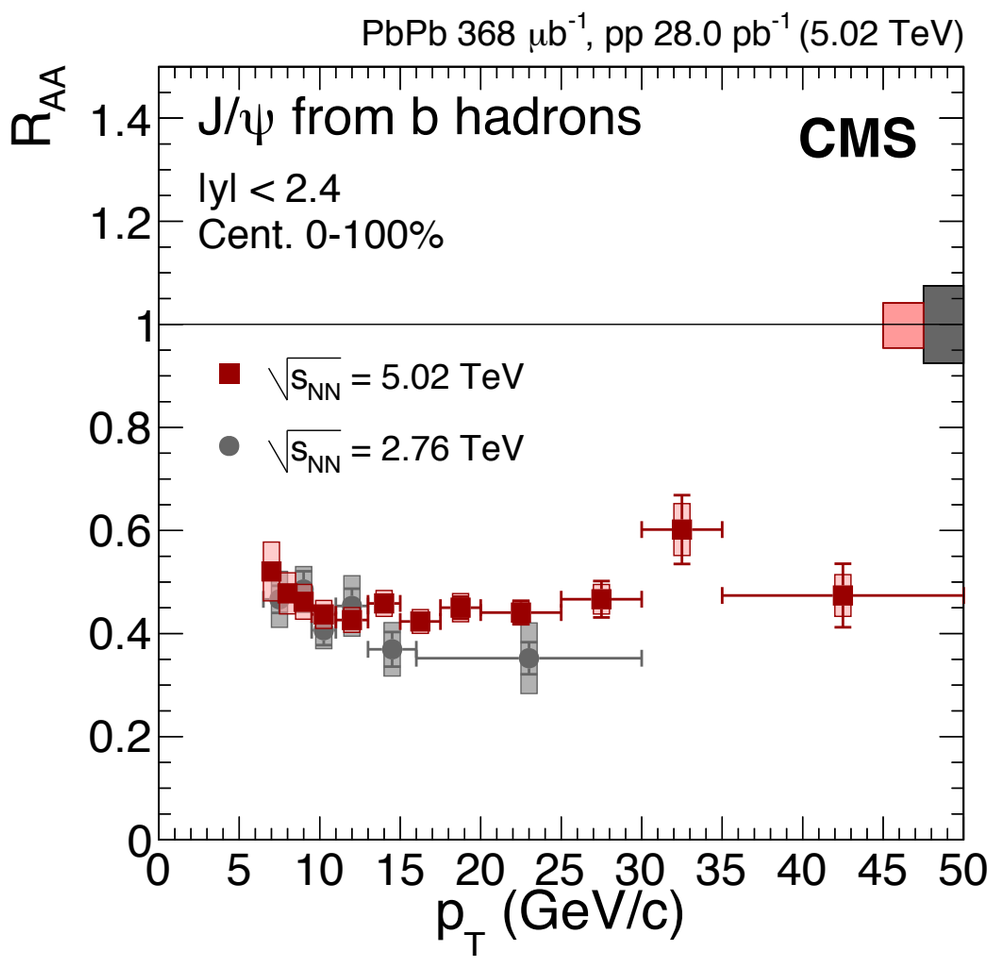


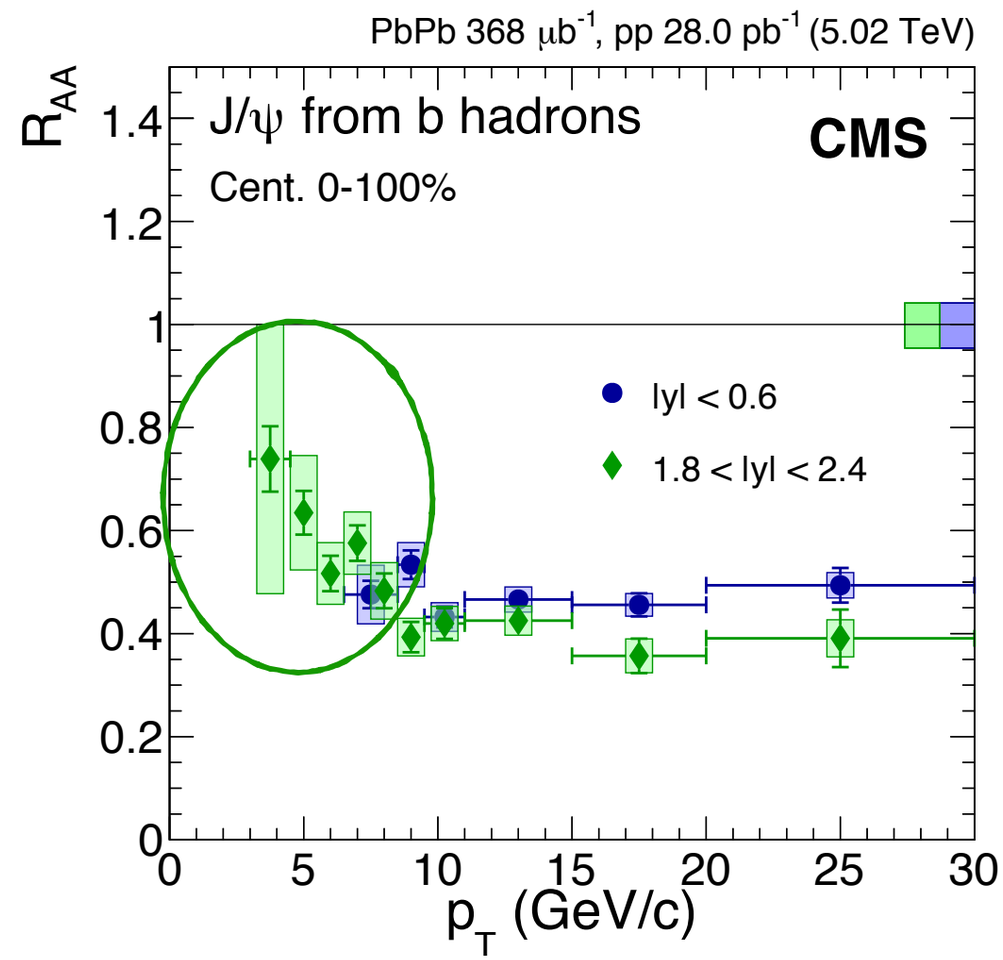


arXiv:1712.08959 (5.02 TeV), EPJC 77 (2017) 252 (2.76 TeV)

Non-prompt J/ψ R_{AA} v.s. p_T

- Measurement down to p_T 3 GeV at forward rapidity
- R_{AA} dependence for low p_T J/ψ





arXiv:1712.08959 (5.02 TeV), EPJC 77 (2017) 252 (2.76 TeV)

Non-prompt D^0 R_{AA} v.s. p_T

- Suppression of non-prompt D production in PbPb collisions

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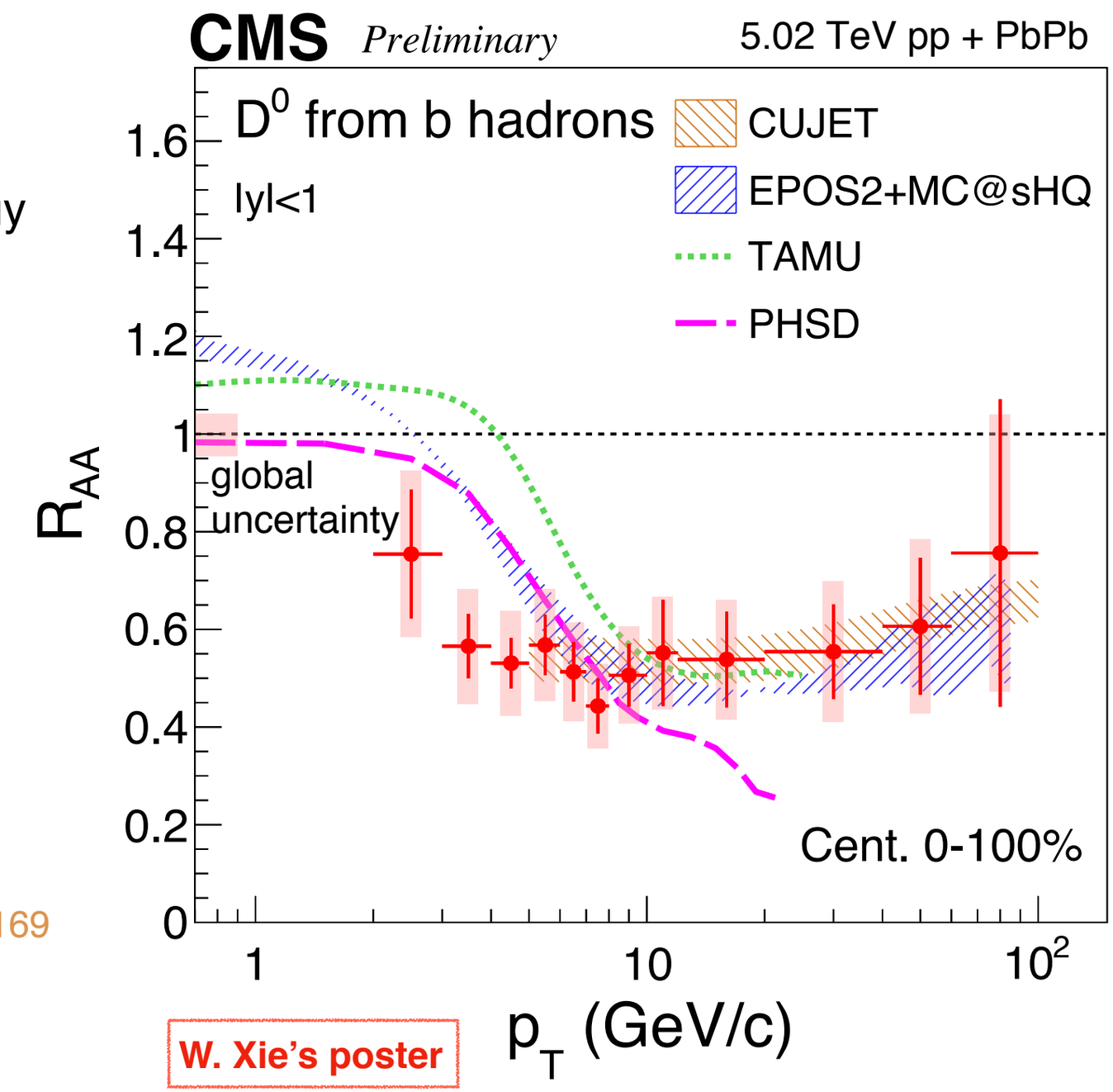
- Compatible with theory prediction that includes both collisional and radiative energy loss (e.g., CUJET)
- The model including only collisional energy loss (PHSD), seems to predict a different behavior compared with other models and data at high-p_T



X. Jiechen et al., Journal of High Energy Physics **2** (2016) 169
P. B. Gossiaux et al, Nucl. Phys., A931 (2014) 581
M. He et al., Physics Letters B **735** (2014) 445 – 450
T. Song et al., hys. Rev. C **92** (2015)

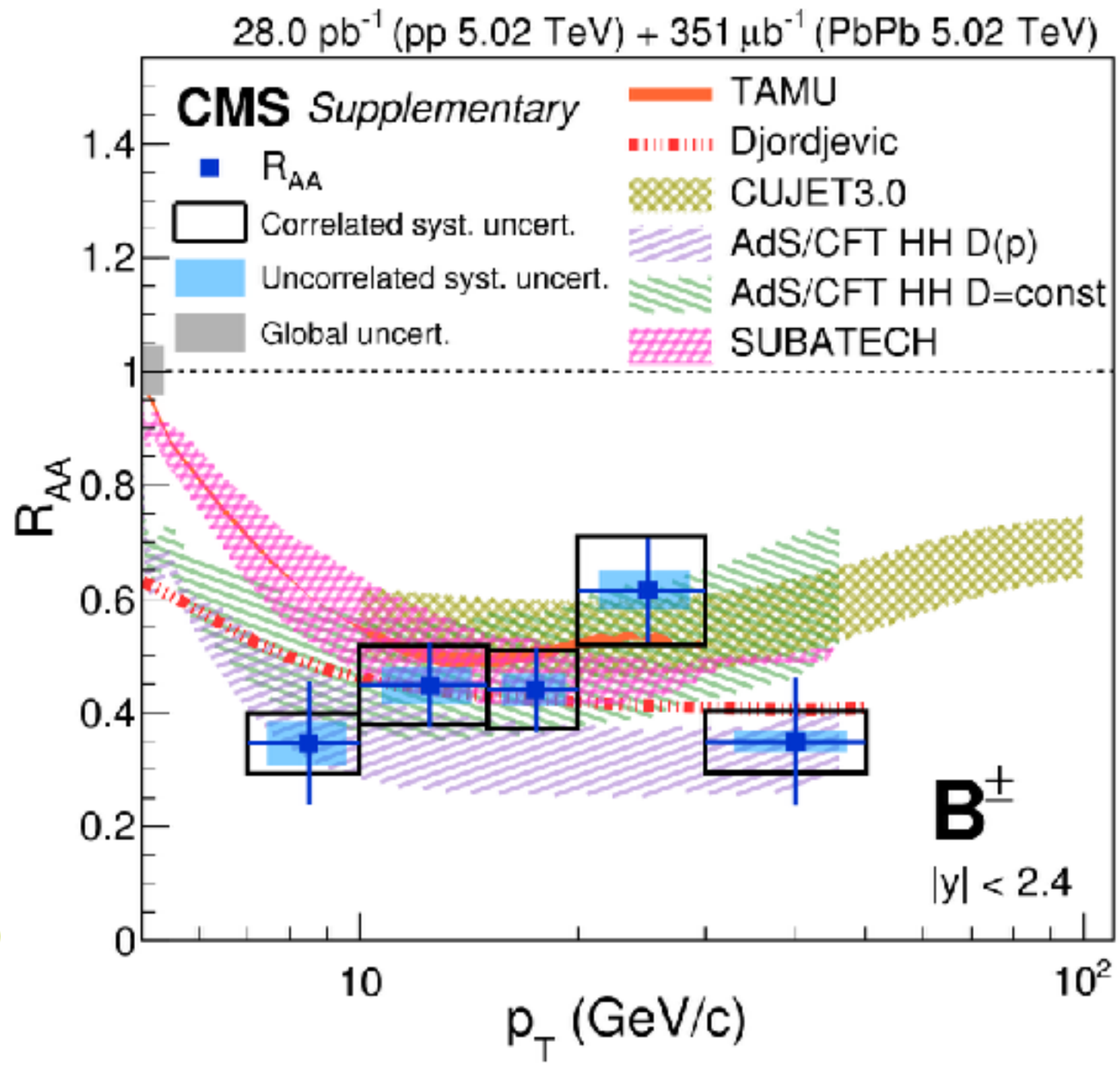
B^+ & B_s

@ 5.02 TeV

B^+ nuclear modification factor

- Suppression of B^+ meson production in PbPb collisions
- B^+ meson $R_{AA} \sim 0.3$ to 0.6 with no obvious trend within uncertainty
- Compatible with theory prediction within uncertainty for p_T 10-50 GeV/c
- Necessity for high p_T measurement : distinguishing pQCD vs AdS/CFT base models

Phys. Rev. Lett. 119, 152301



M. He et al., Physics Letters B **735** (2014) 445 – 450
M. Djordjevic, *Phys. Rev. C* **94** (Oct, 2016) 044908
X. Jiechen et al., Journal of High Energy Physics **2** (2016)
W. A. Horowitz, Phys. Rev. D 91 (2015) 085019
P. B. Gossiaux et al, Nucl. Phys., A931 (2014) 581

R_{AA} zoo: B v.s. D v.s. light

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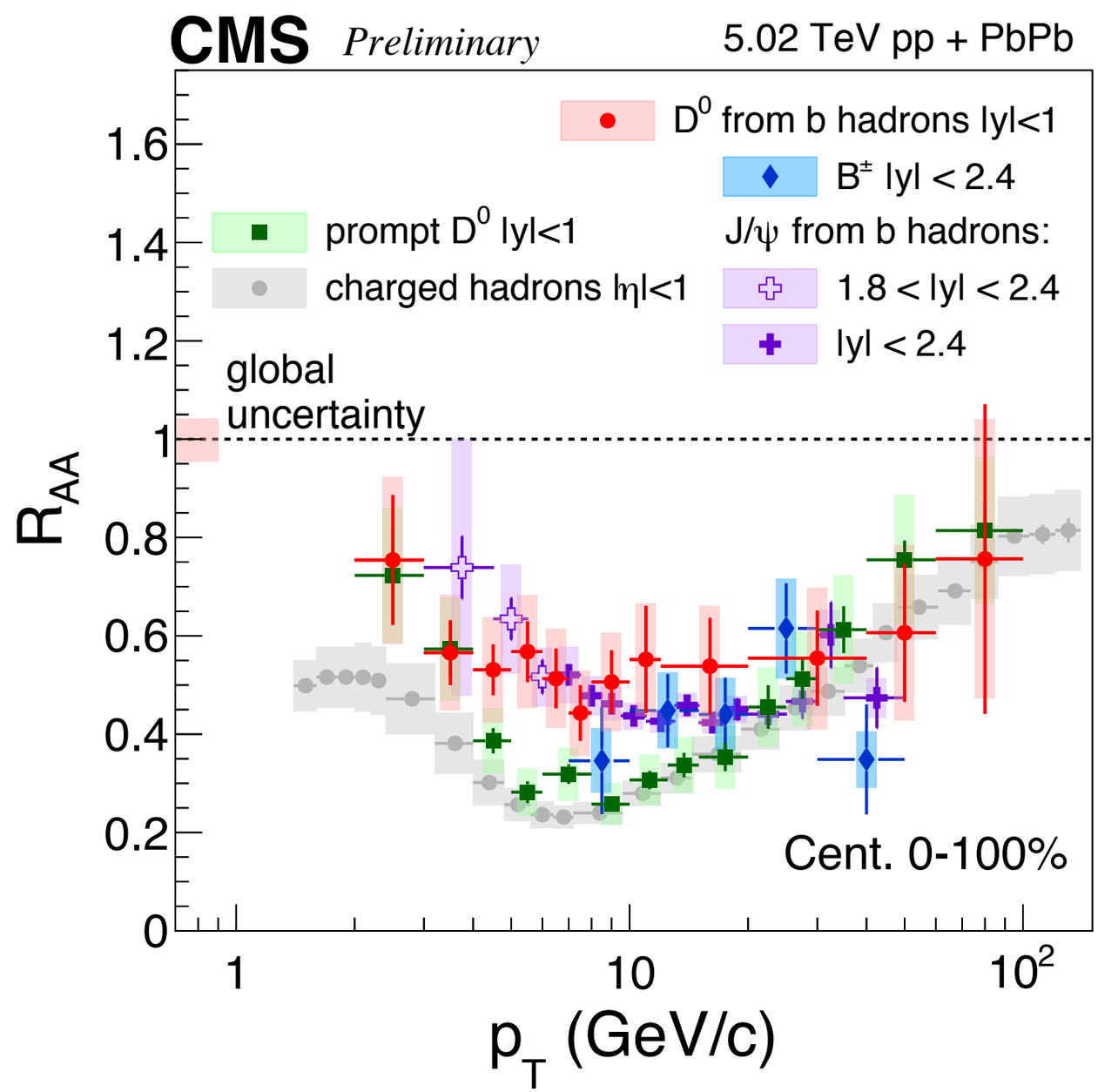
Phys. Rev. Lett. 119, 152301

arXiv:1708.04962

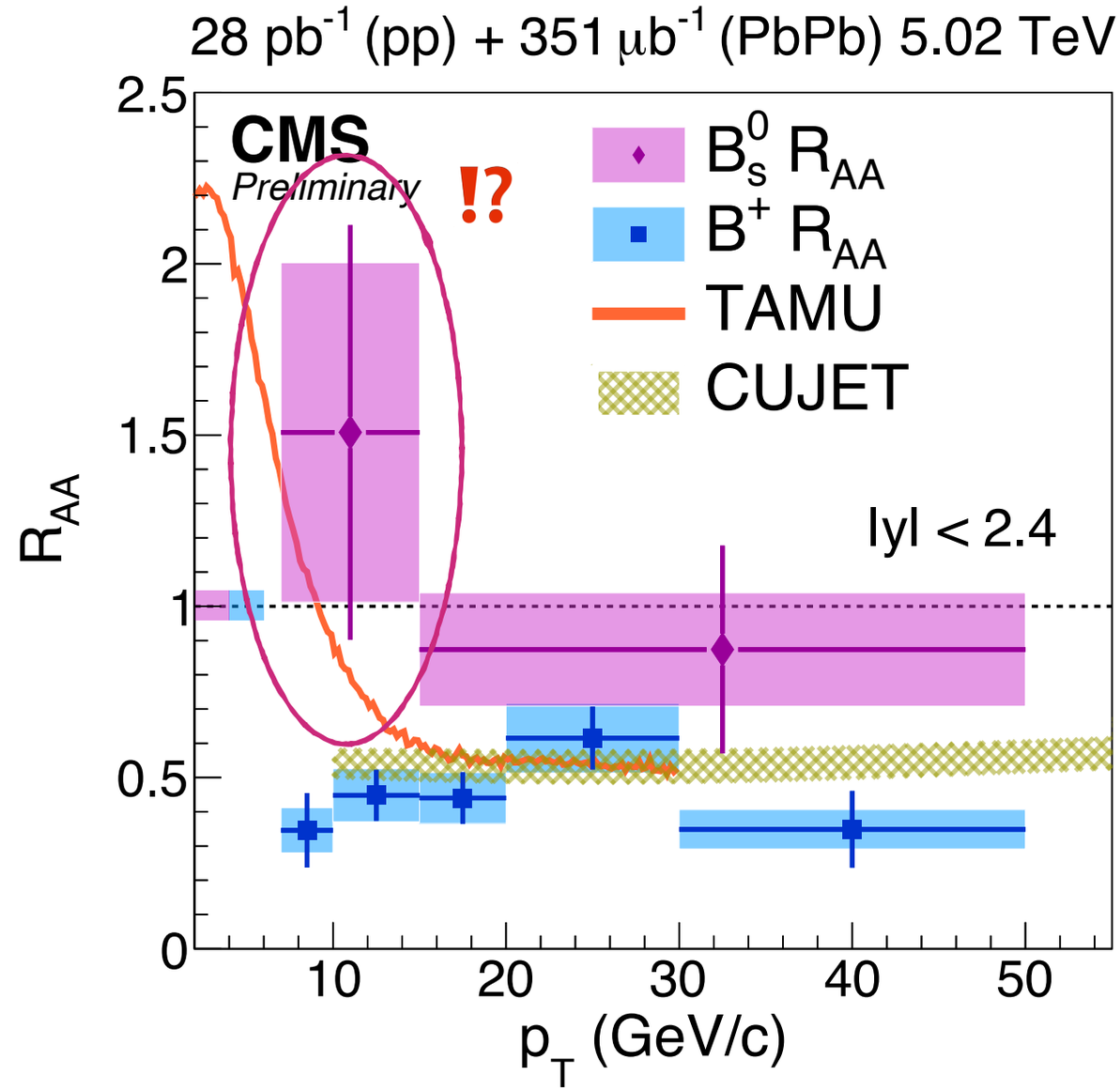
JHEP 04 (2017) 039

- Compatible results from three beauty R_{AA} measurements (non-prompt D, B^+, and non-prompt J/ψ)
- Beauty seems to separate from charm and light flavor at ~ 20 GeV
- R_{AA} between prompt D, charged particle, B^+, non-prompt J/ψ and non-prompt D merging above ~ 20 GeV
- Note:
  - Rapidity range
  - Inclusive vs exclusive
  - B to J/ψ or D kinematic



B_s nuclear modification factor

- Results derived in two B_s p_T bins (7~15 and 15~50 GeV)
- Indication of less suppression of B_s comparing to B^+
- **<u>Substantial statistical and systematic uncertainty</u>**



M. He et al., Physics Letters B **735** (2014) 445 – 450

X. Jiechen et al., Journal of High Energy Physics **2** (2016) 169

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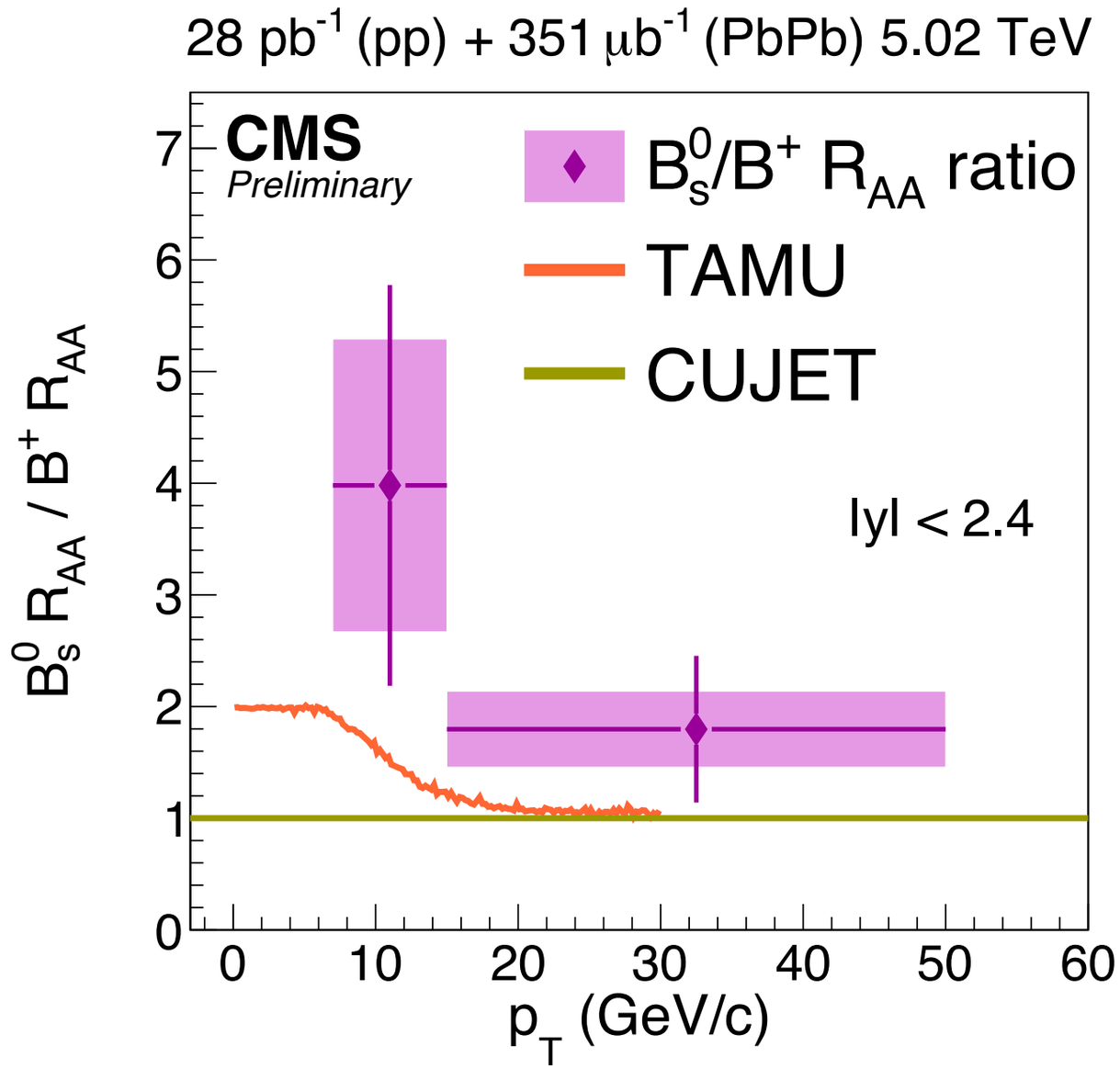
B_s nuclear modification factor

- B_s / B^+ R_{AA} ratio
- Correlated systematic uncertainties sources (e.g., muon acceptance) are cancelled
- **<u>CMS's capability to perform fully reconstructed B_s measurement</u>**
- Incoming LHC run ➜ more precise measurement



M. He et al., Physics Letters B **735** (2014) 445 – 450

X. Jiechen et al., Journal of High Energy Physics **2** (2016) 169

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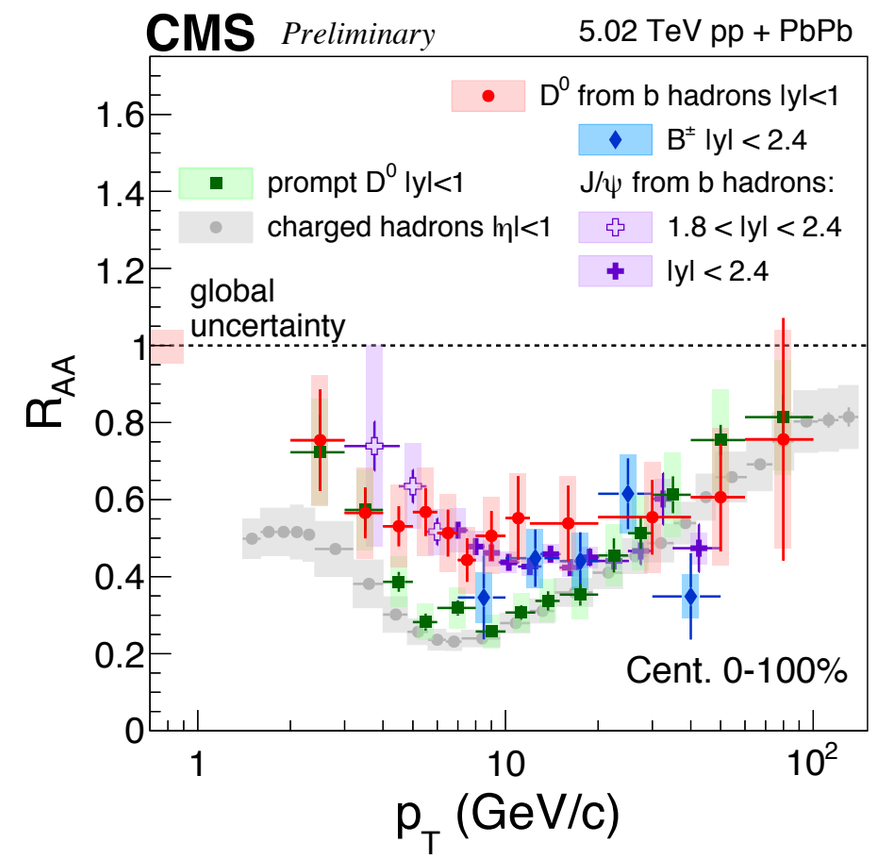
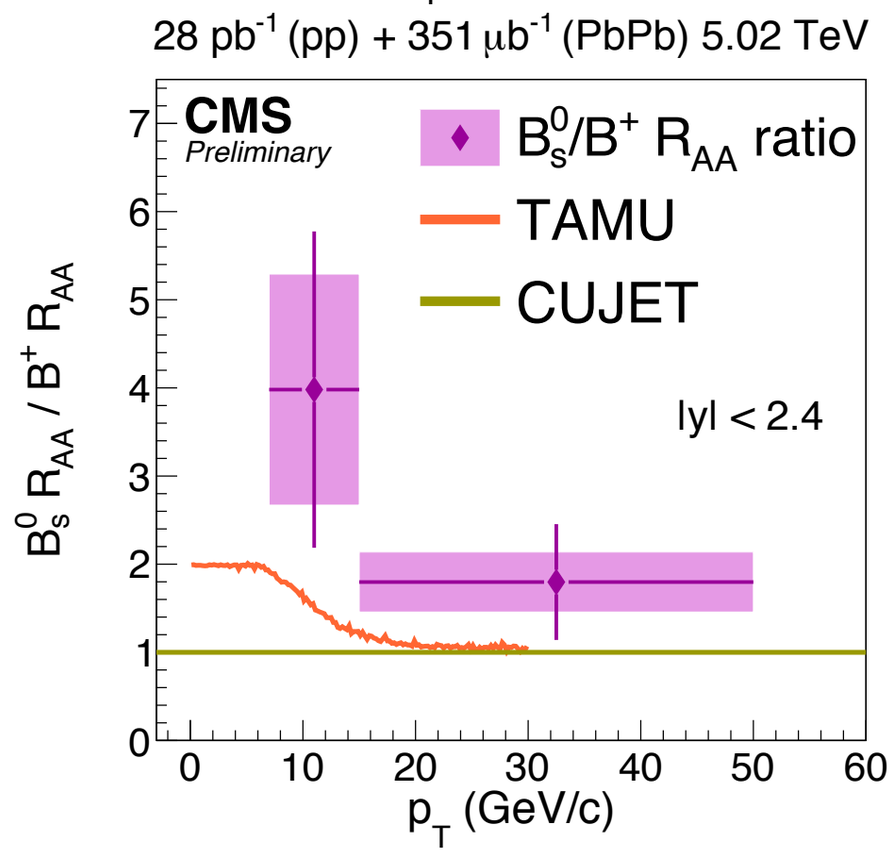
Summary & outlook

- CMS beauty quark measurements (exclusive and inclusive), results are consistent
- Suppression for B^+, non-prompt J/ψ, and non-prompt D
- Beauty seems to separate from charm and light flavor at ~ 20 GeV
- First B_s measurement in heavy ion collision (albeit with a substantial uncertainty)
- Comparison between B^+ and B_s at low p_T unveils information on flavor recombination.
- Future HL-LHC data with more precise measurements

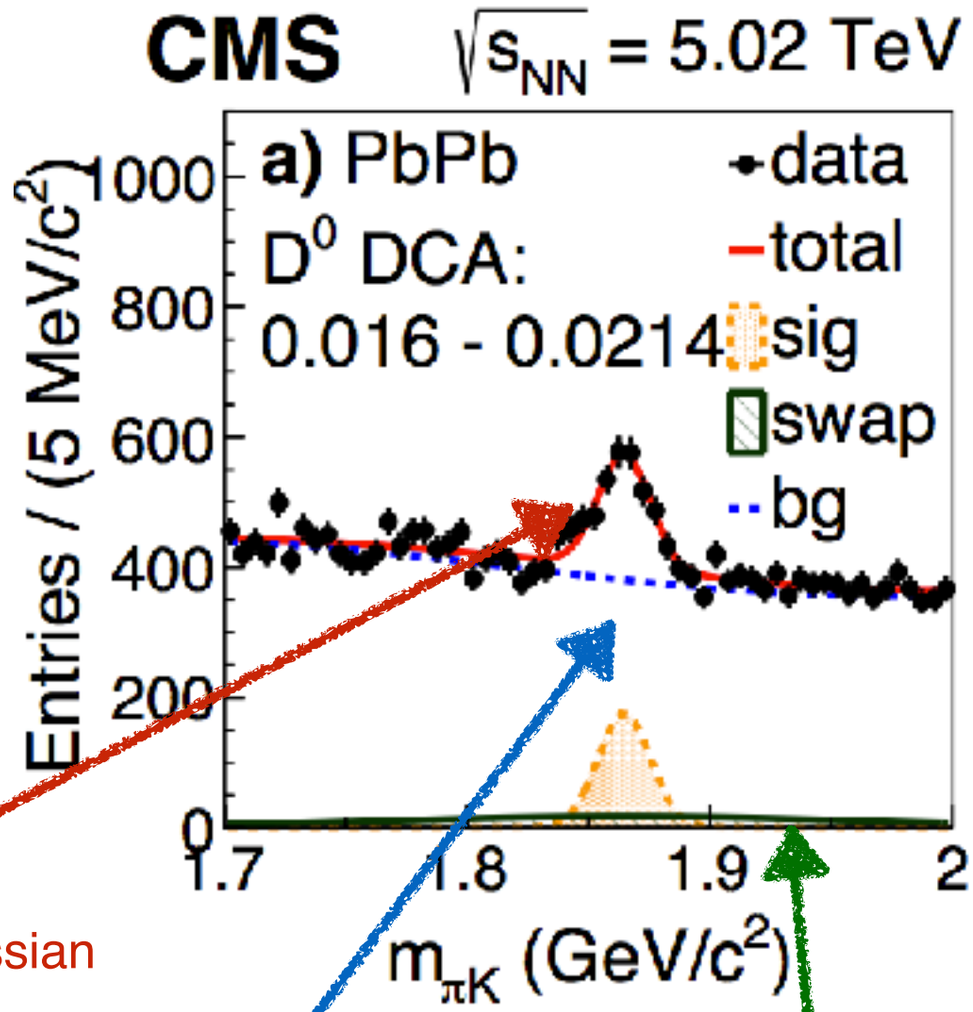


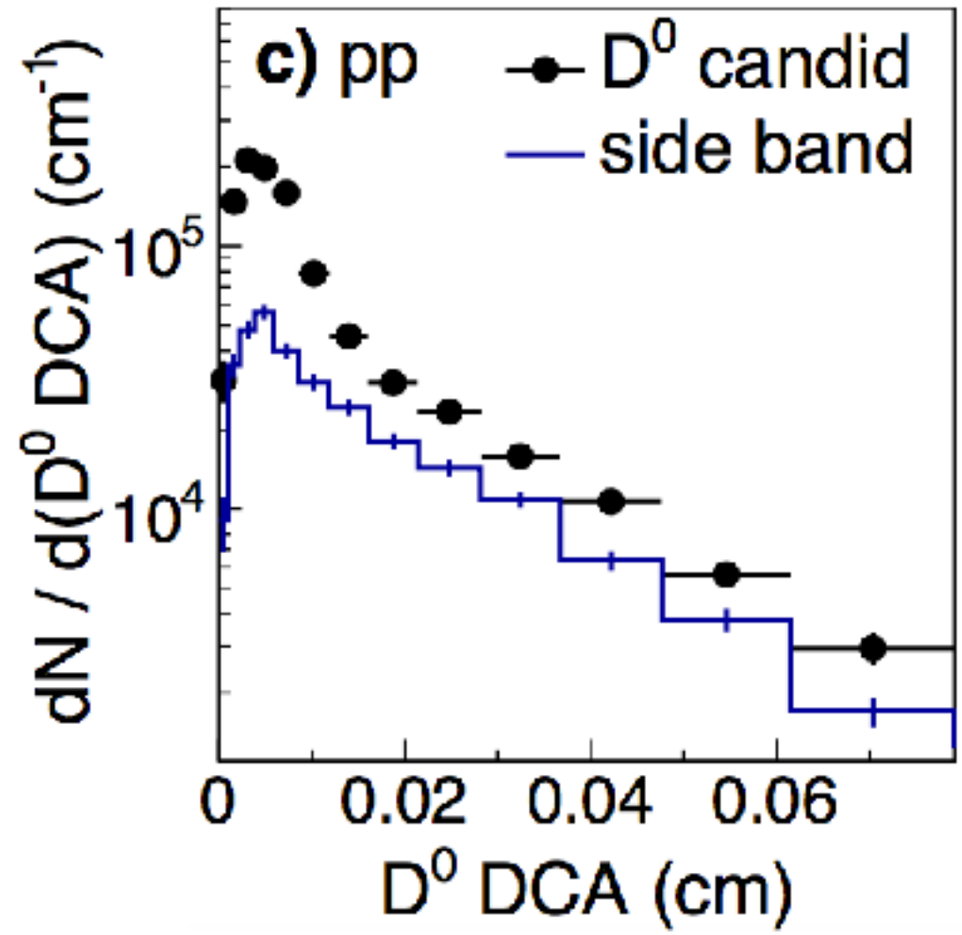


– The MIT group's work was supported by US DOE–NP

Backups

Signal extraction: non-prompt D





Signal:

Double Gaussian

with same mean

Combinatorial BG:

3rd order polynomial

Swapped BG:

Wrong track mass

assumption

- **Signal region DCA**
- **Sideband region DCA (X 0.5)**

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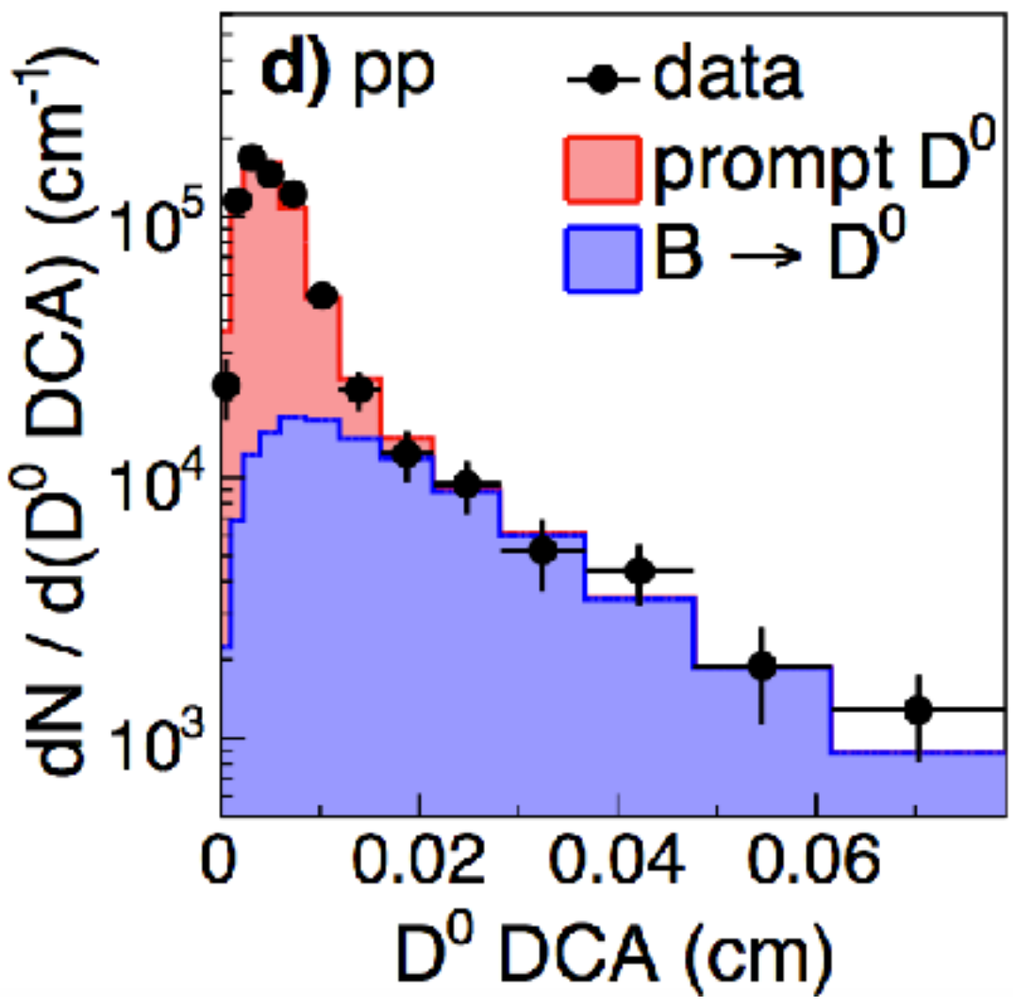
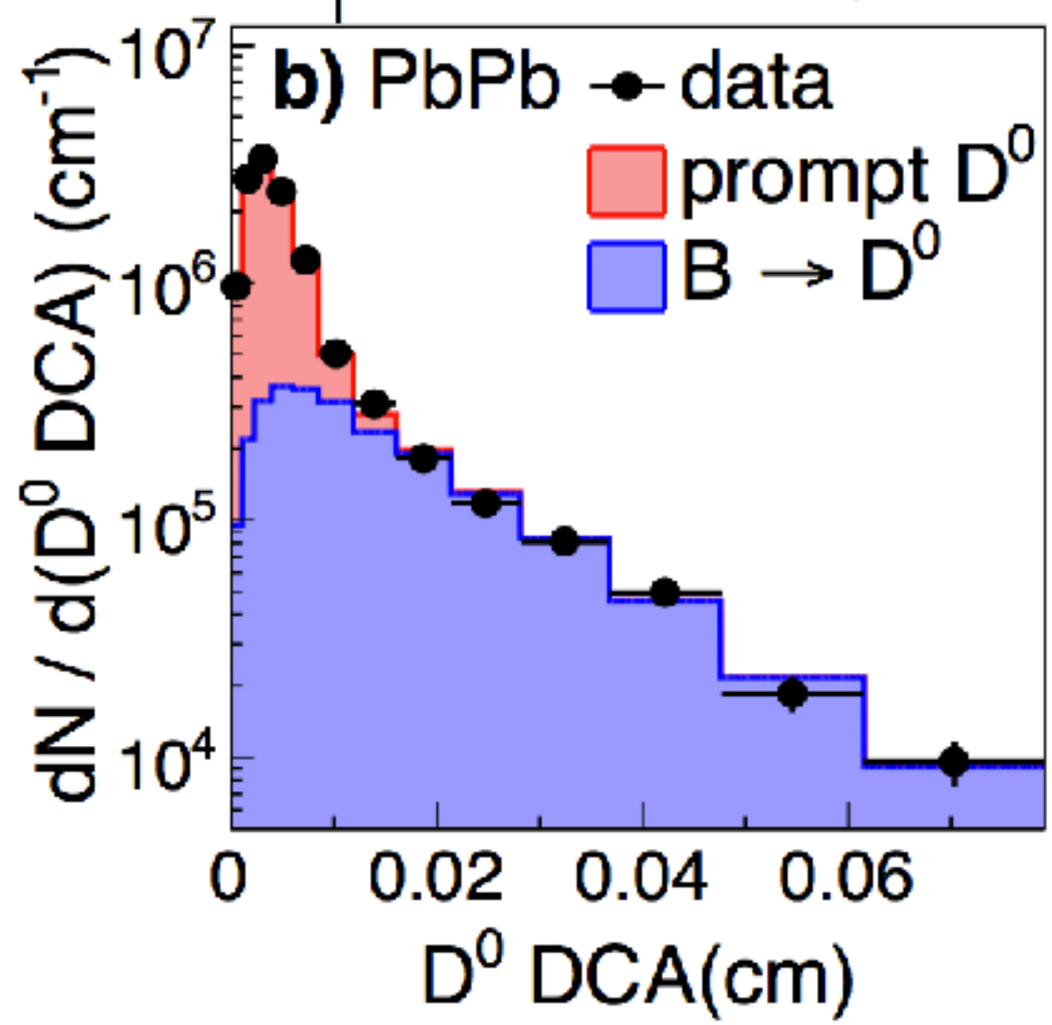
Signal extraction: non-prompt D

- Two components template fit (from simulation) on data DCA distribution
- Corrected for potential difference in resolution between data and simulation

pp



PbPb $6 < p_T < 7$ GeV/c $|y| < 1$



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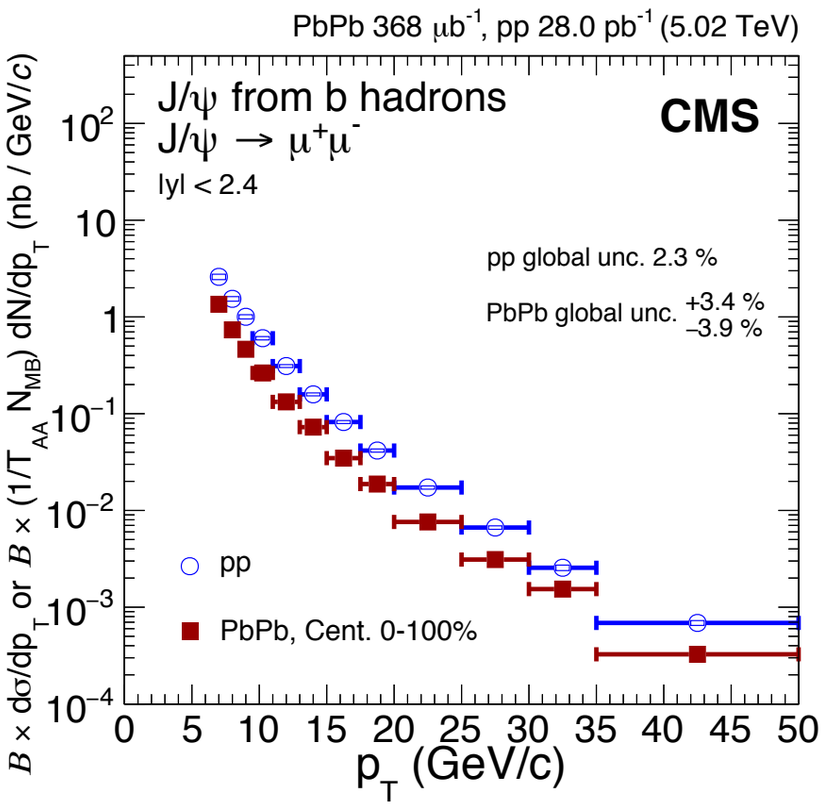
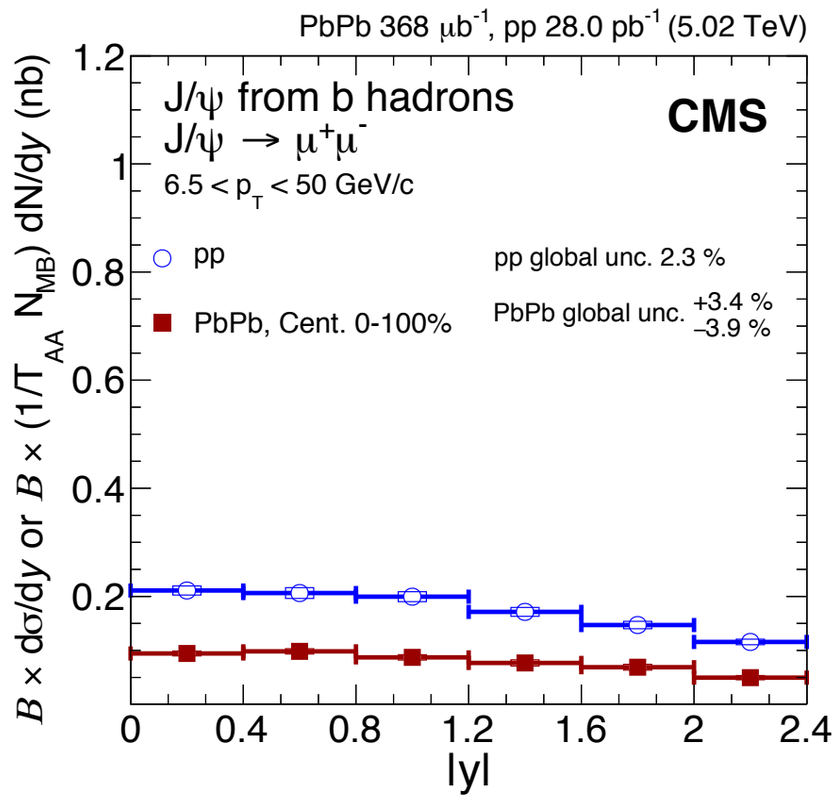
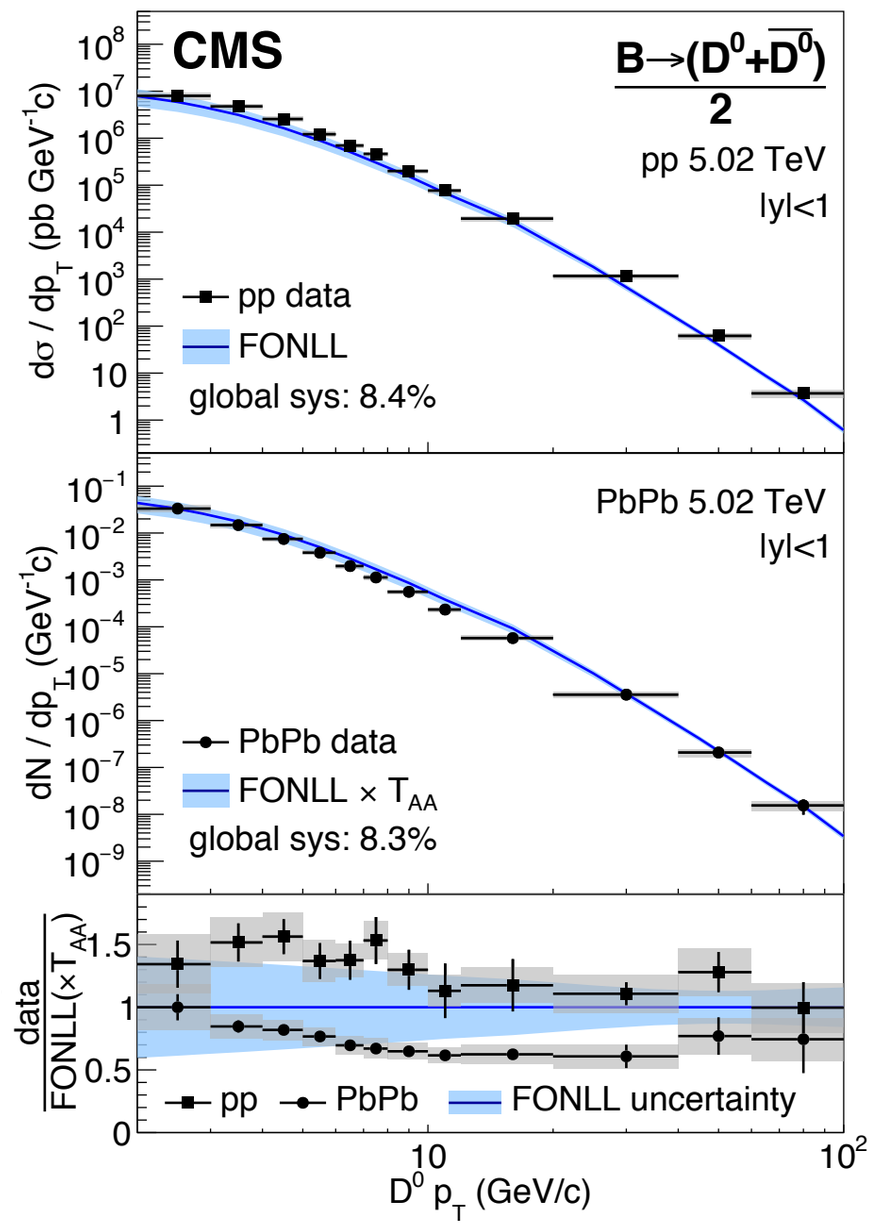
Non-prompt cross sections

- Cross section measured between p_T 6.5~50 GeV, |y|<2.4 (J/ψ) and 2~100 GeV, |y|<1.0(D^0)





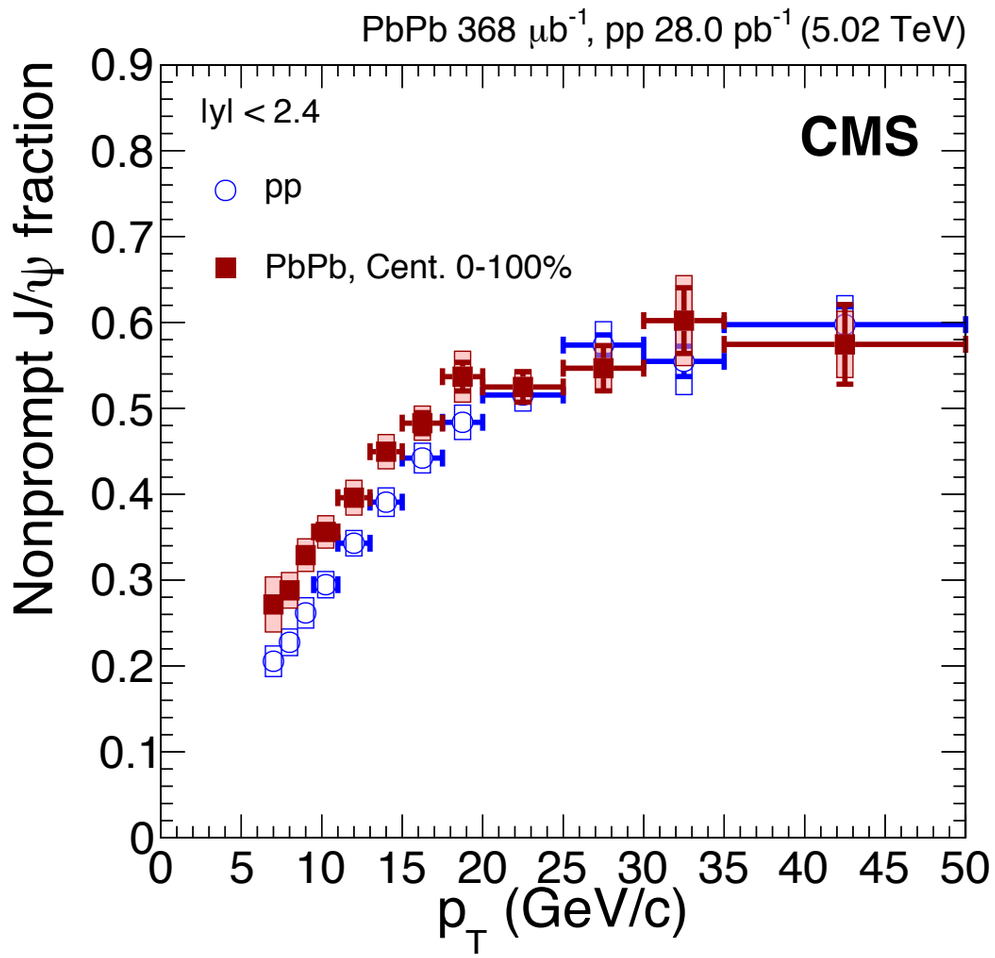


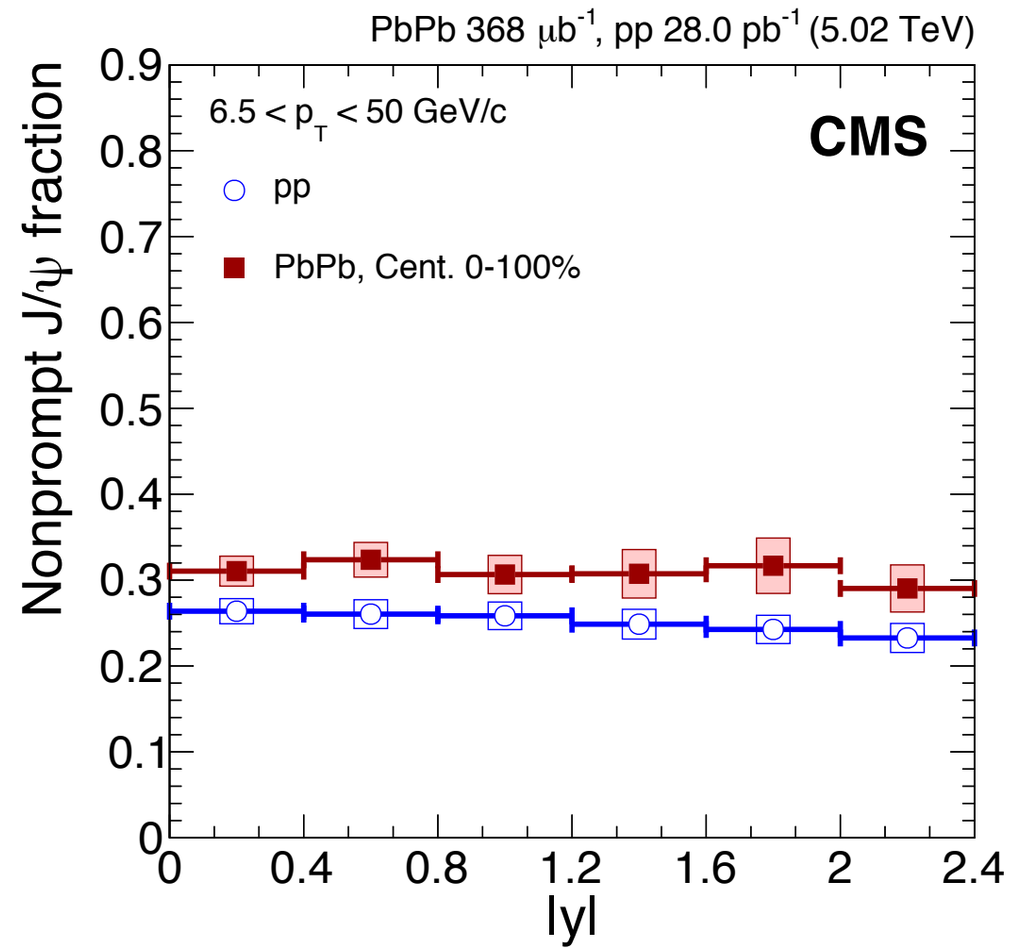
arXiv:1712.08959

HIN-16-016

Non-prompt J/ψ fraction

- Proportion of measured J/ψ mesons coming from b-hadron decays
  - A. PbPb > pp ➜ indication of R_{AA} non-prompt > prompt ??
  - B. Strong p_T dependence, non-prompt fraction increases with p_T (20% to 60%)
  - C. No significant dependence on rapidity is observed

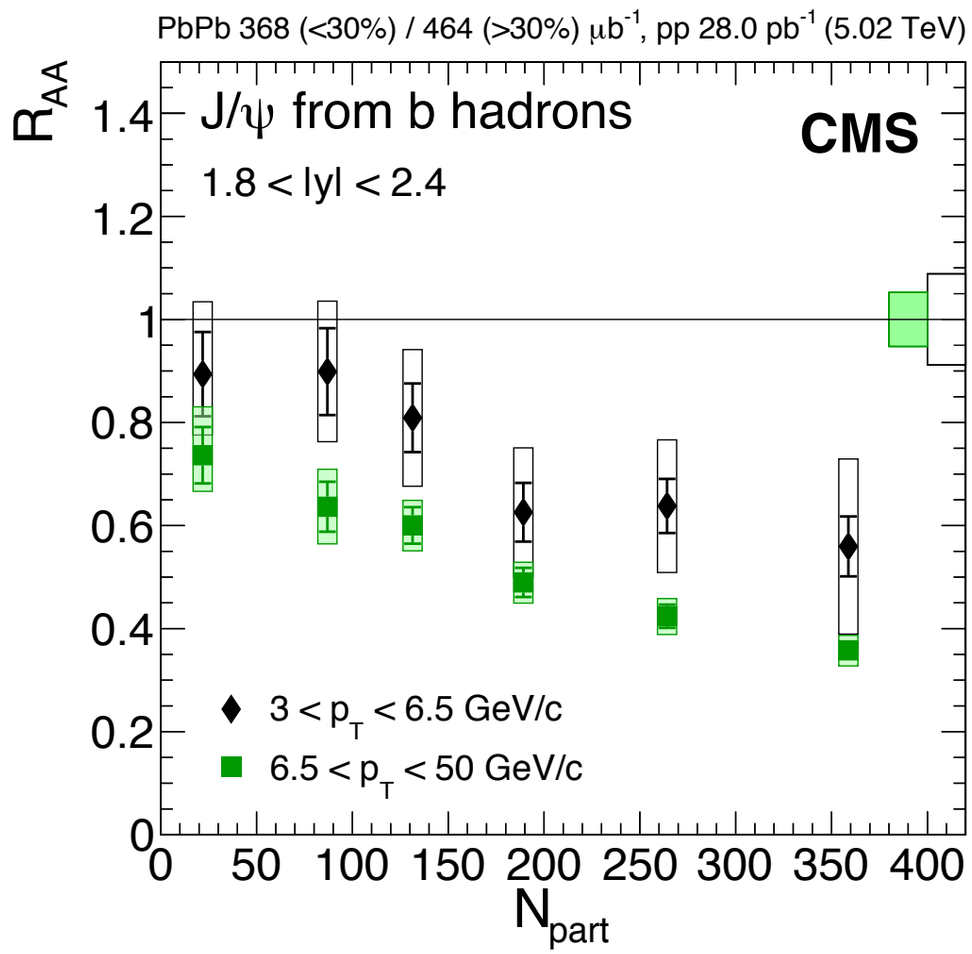


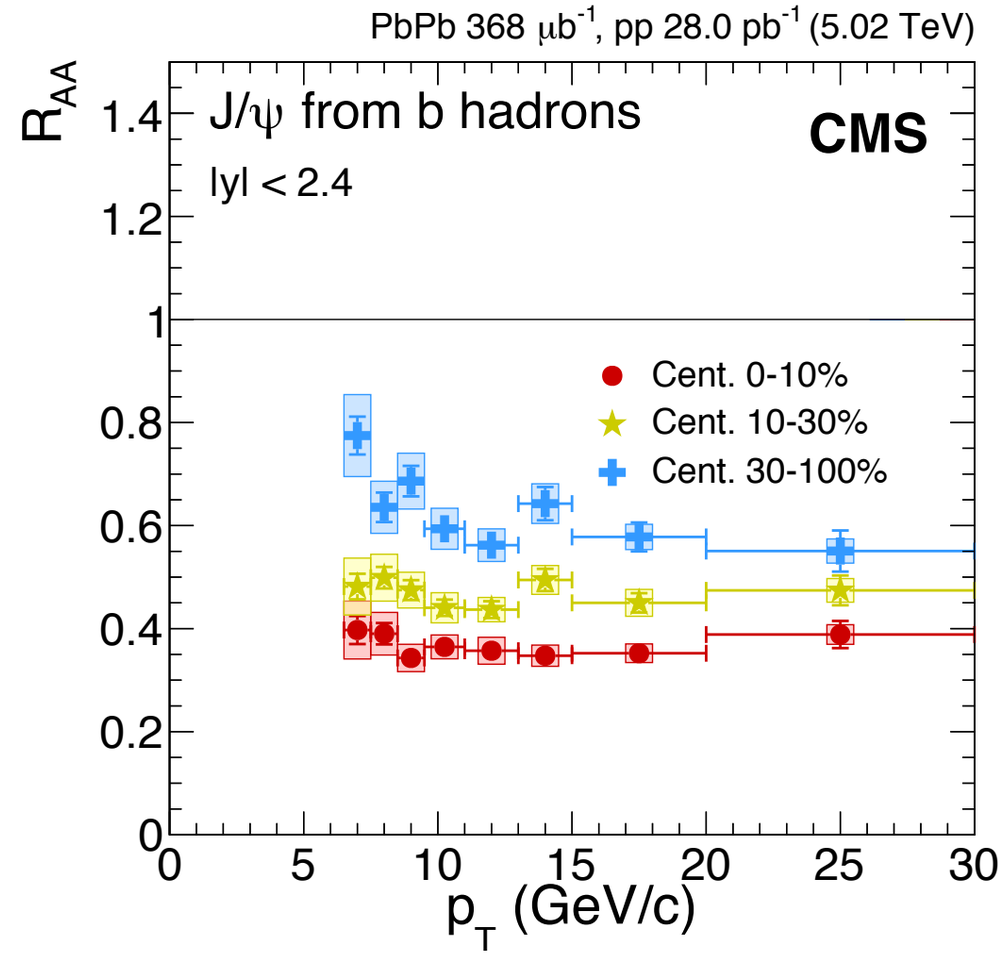


arXiv:1712.08959. Submitted to Eur. Phys. J. C

Differential R_{AA} v.s. N_{part} and p_T

- Similar information, more suppressed for higher p_T and in central collision





arXiv:1712.08959

MVA optimization

To reach high signal to background significance (low production rate of b)

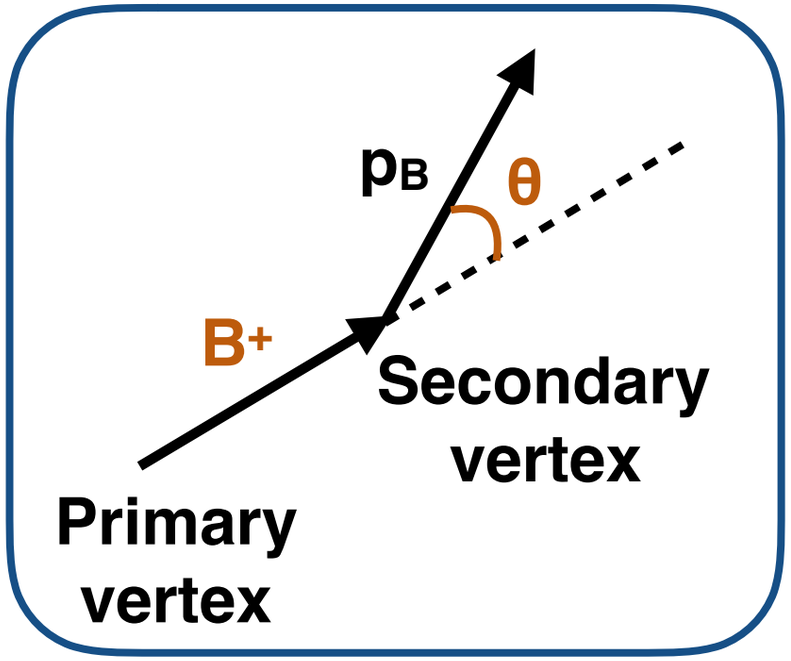
→ Multivariate analysis (MVA) for cut value optimization

Variables employed in MVA

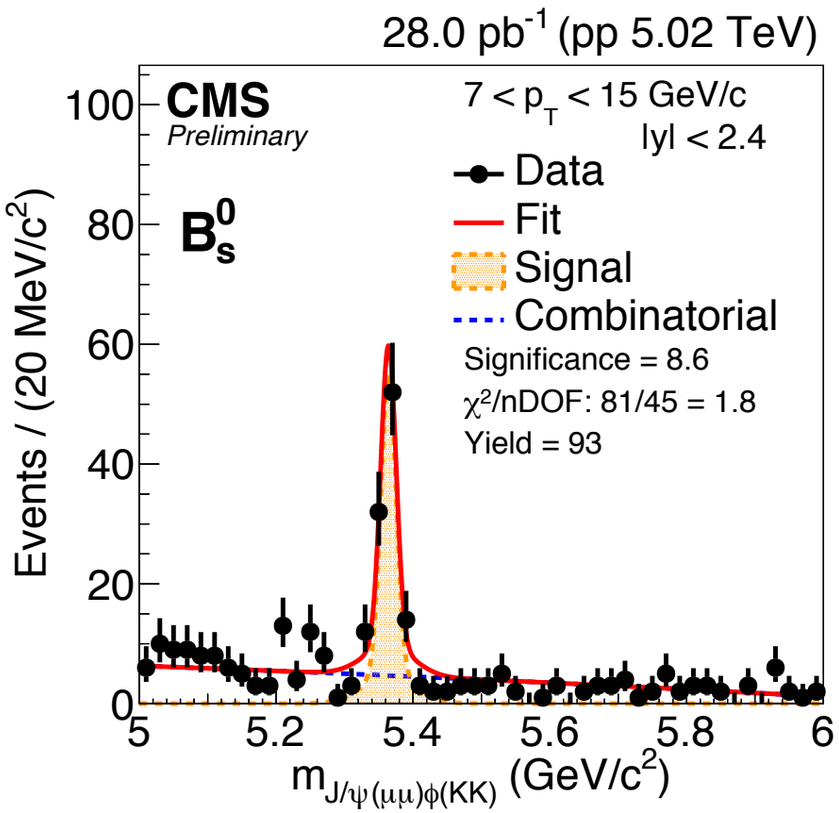
- **track kinematic:** track p_T and pseudorapidity
- **Probability of the vertex fit (χ^2):** B secondary vertex fitting probability
- **Normalized d_0:** normalized distance between primary vertex and B secondary vertex
- **Opening angle(θ):** angle between B meson displacement vector and B meson momentum

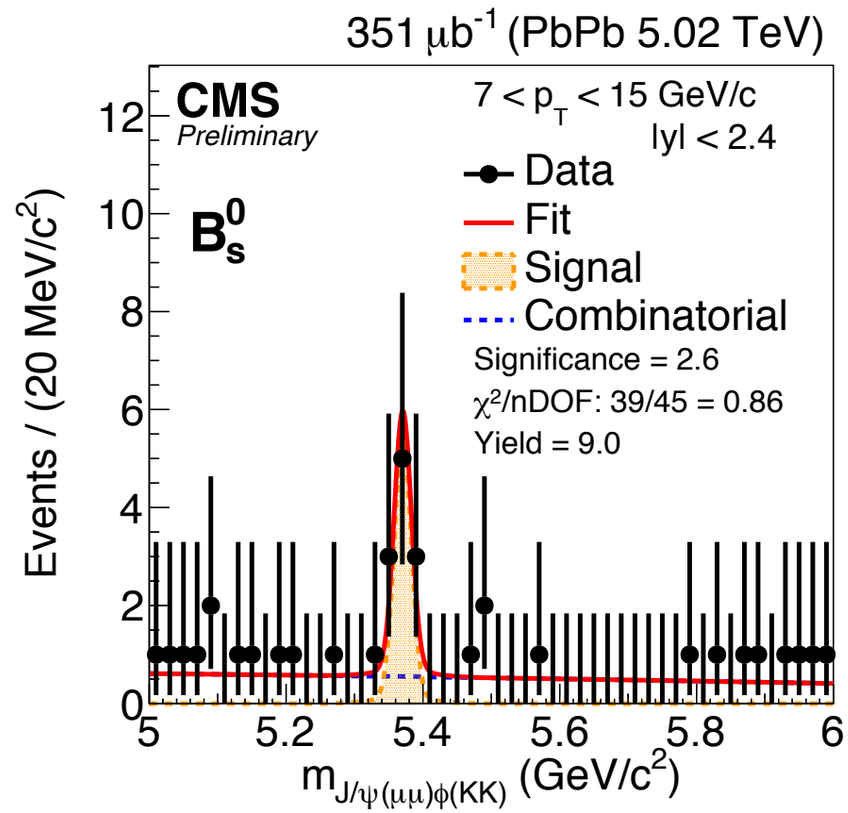
Maximize Figure of merit: $S/\sqrt{(S+B)}$

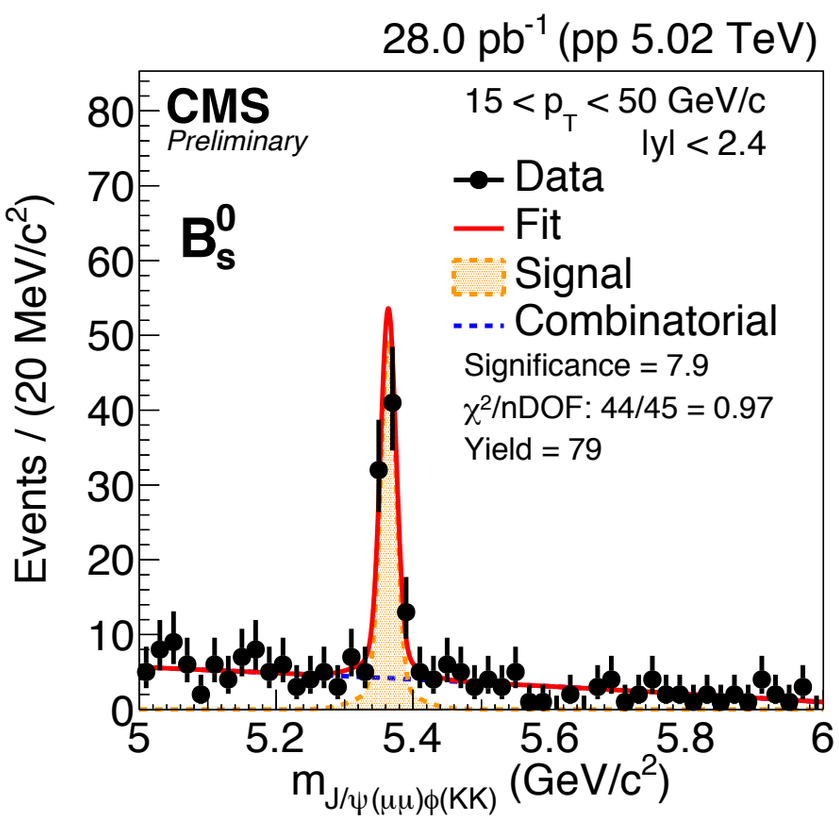
- **S:** signals from simulation (normalized to FONLL prediction)
- **B:** background from real data (sidebands of the B mass spectrum)
- Optimization conducted independently for pp and PbPb

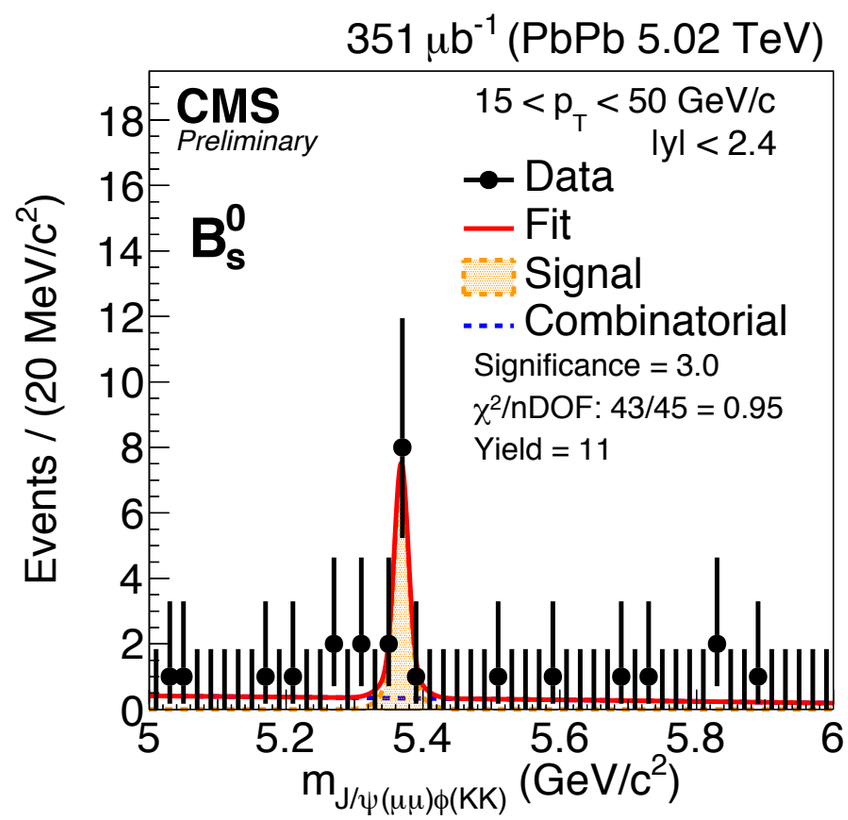


Signal extraction: B_s





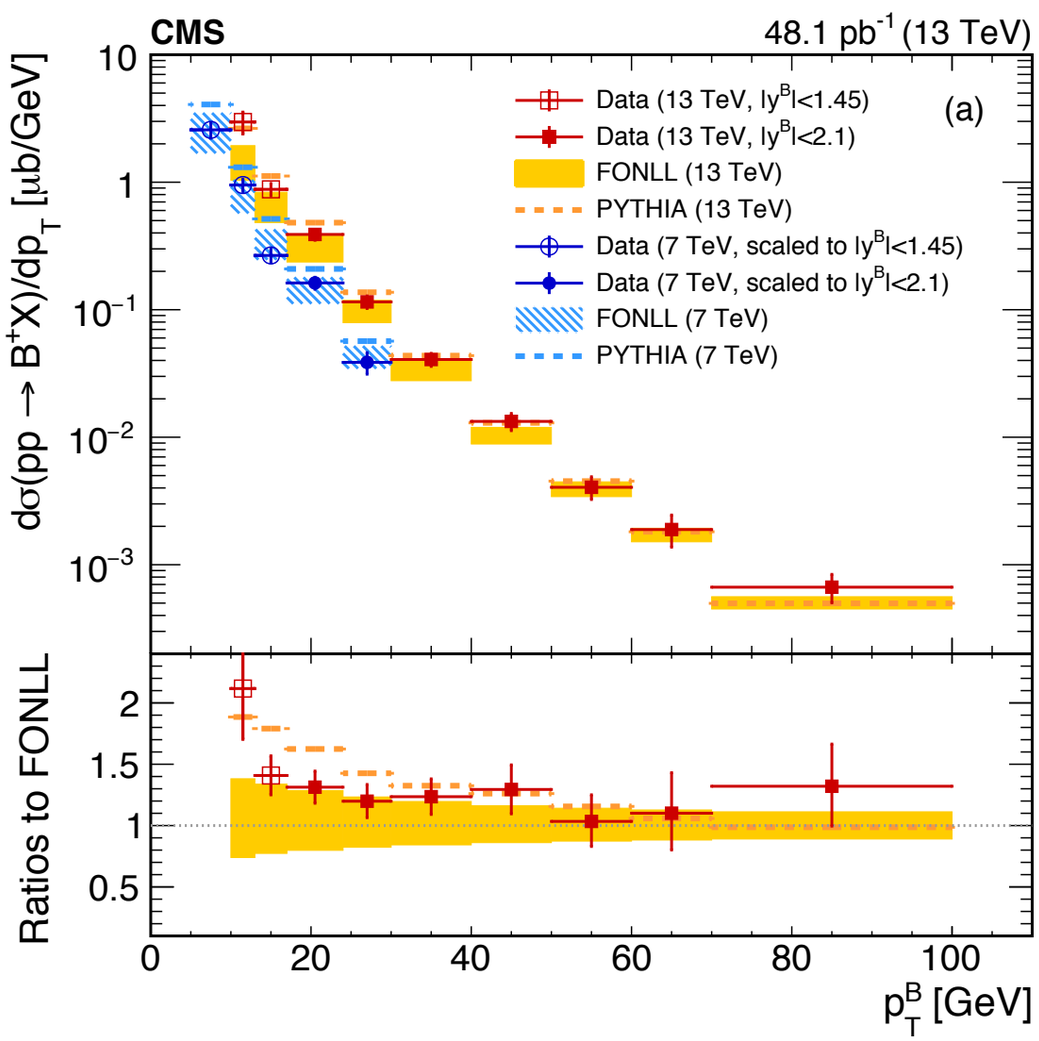




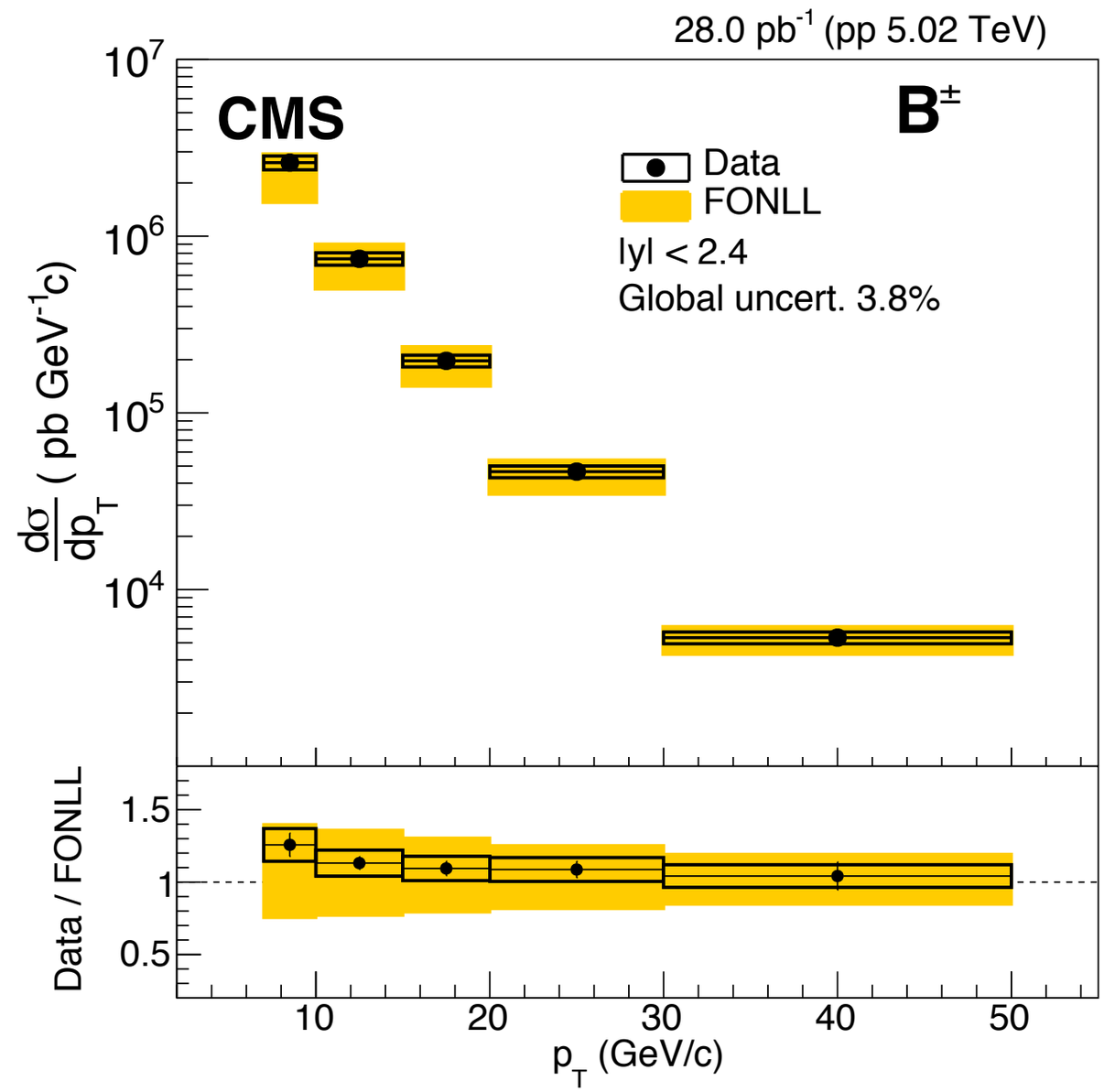
HIN-17-008

Cross section in pp

Compatible with pp 13 and 7 TeV results: upper edge of FONLL @ low p_T



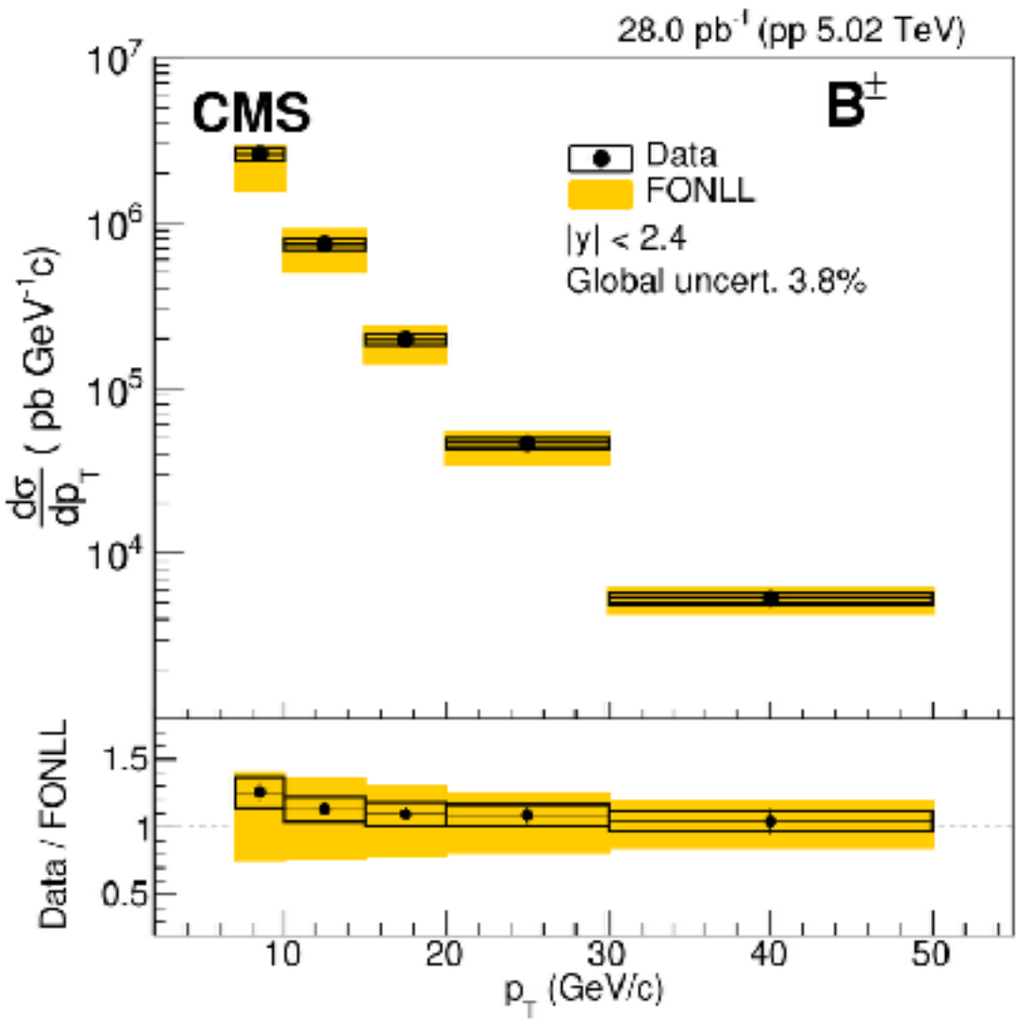
Phys. Lett. B 771 (2017) 435



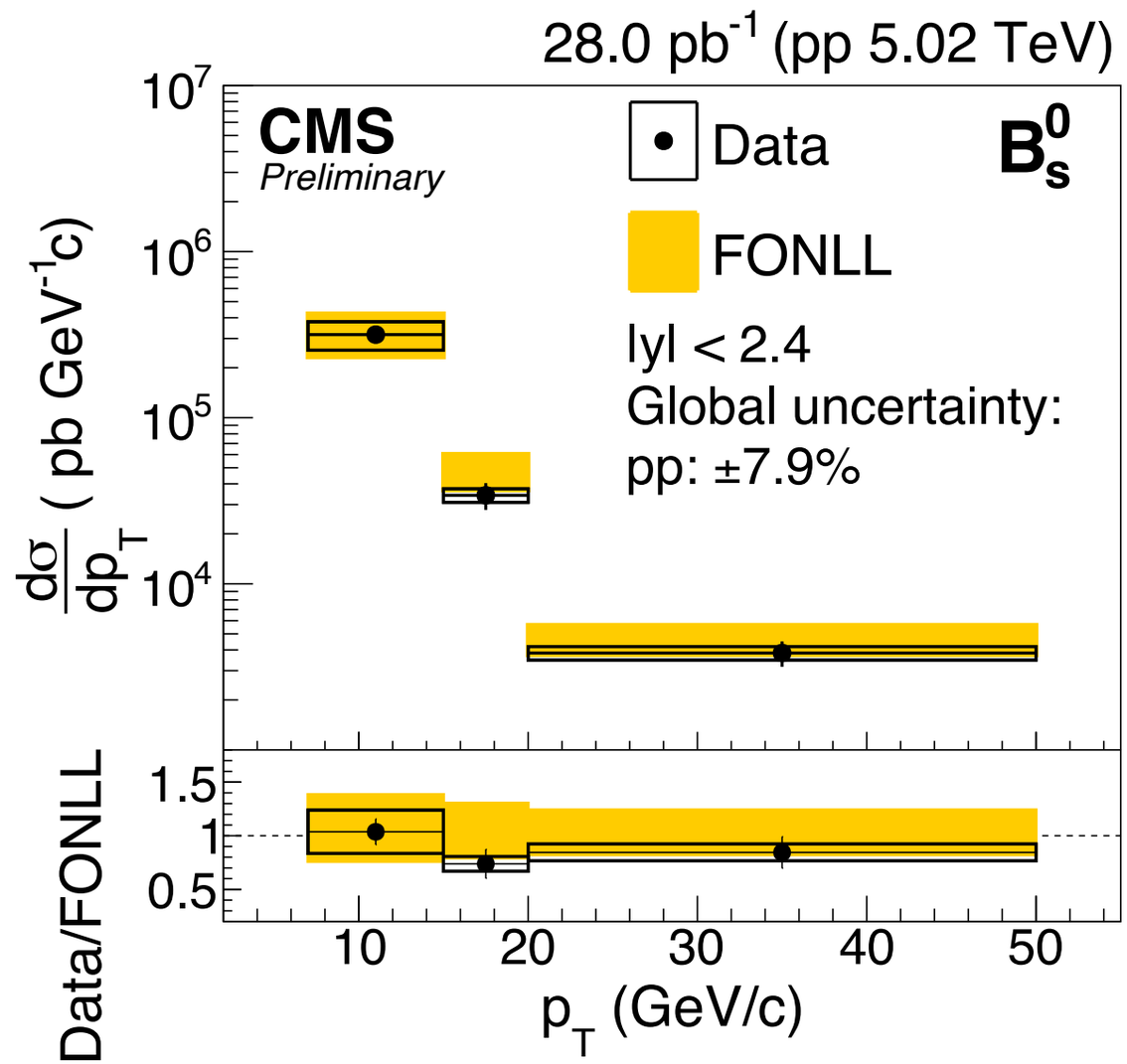
Phys. Rev. Lett. 119, 152301

Cross section in pp

- Result derived in 5(3) $B^+(B_s)$ p_T bins, from 7 to 50 GeV in $|y| < 2.4$
- Consistent with FONLL predictions [1]



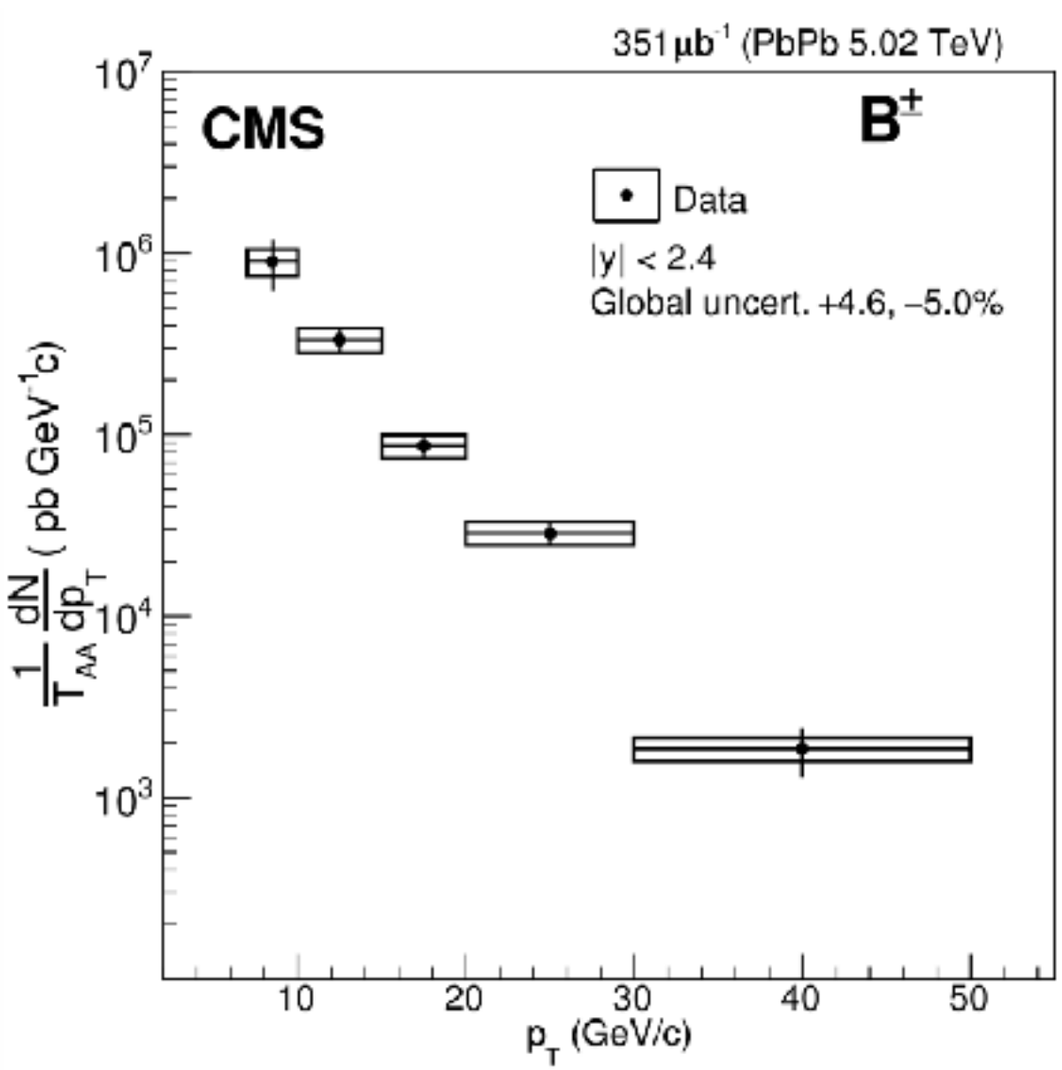
Phys. Rev. Lett. 119, 152301



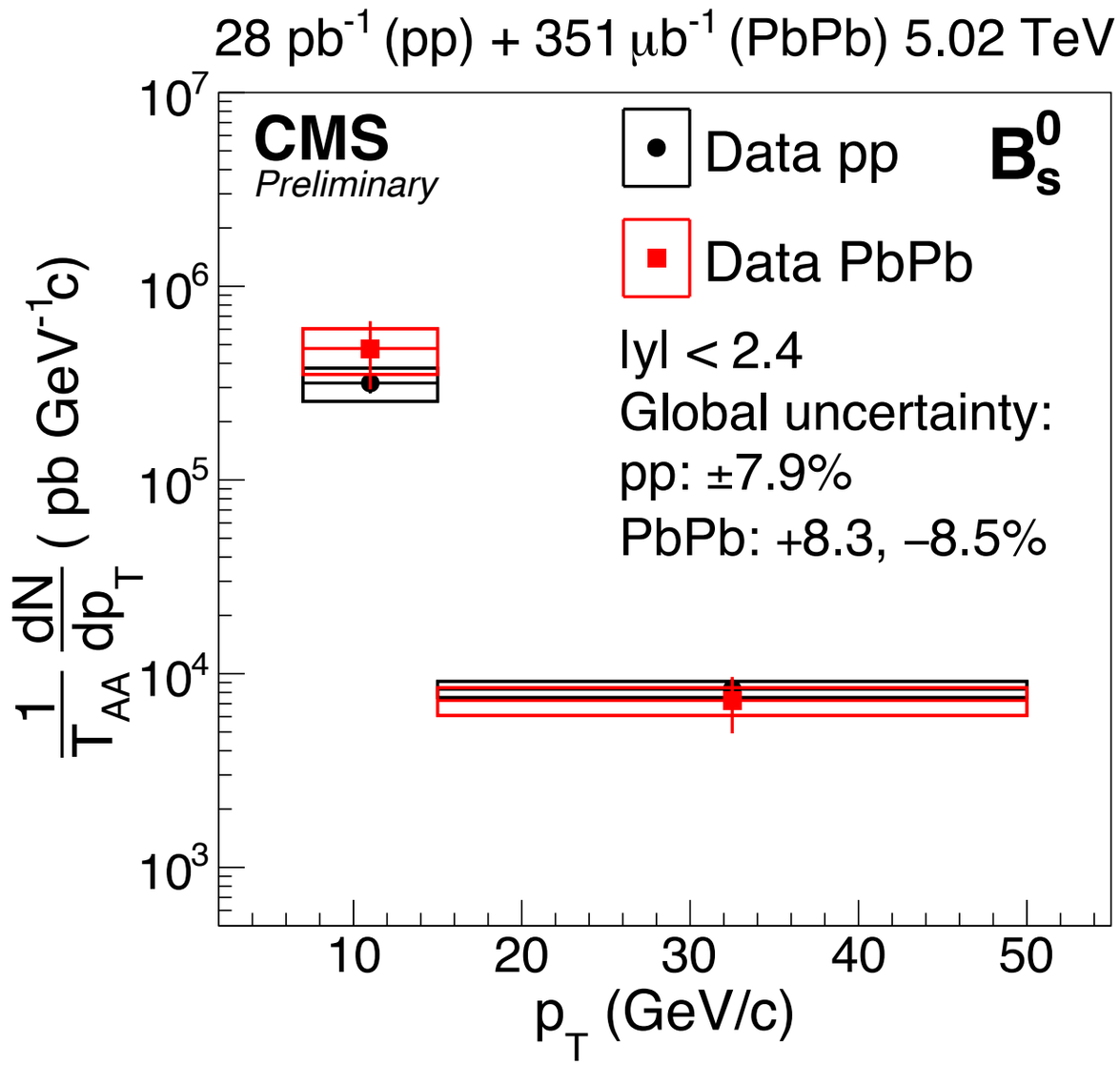
HIN-17-008

[1] M. Cacciari, M. Greco, P. Nason, “The pT Spectrum in Heavy-Flavour Hadroproduction”, JHEP 007, 9805 (1998)

Cross section in PbPb



Phys. Rev. Lett. 119, 152301

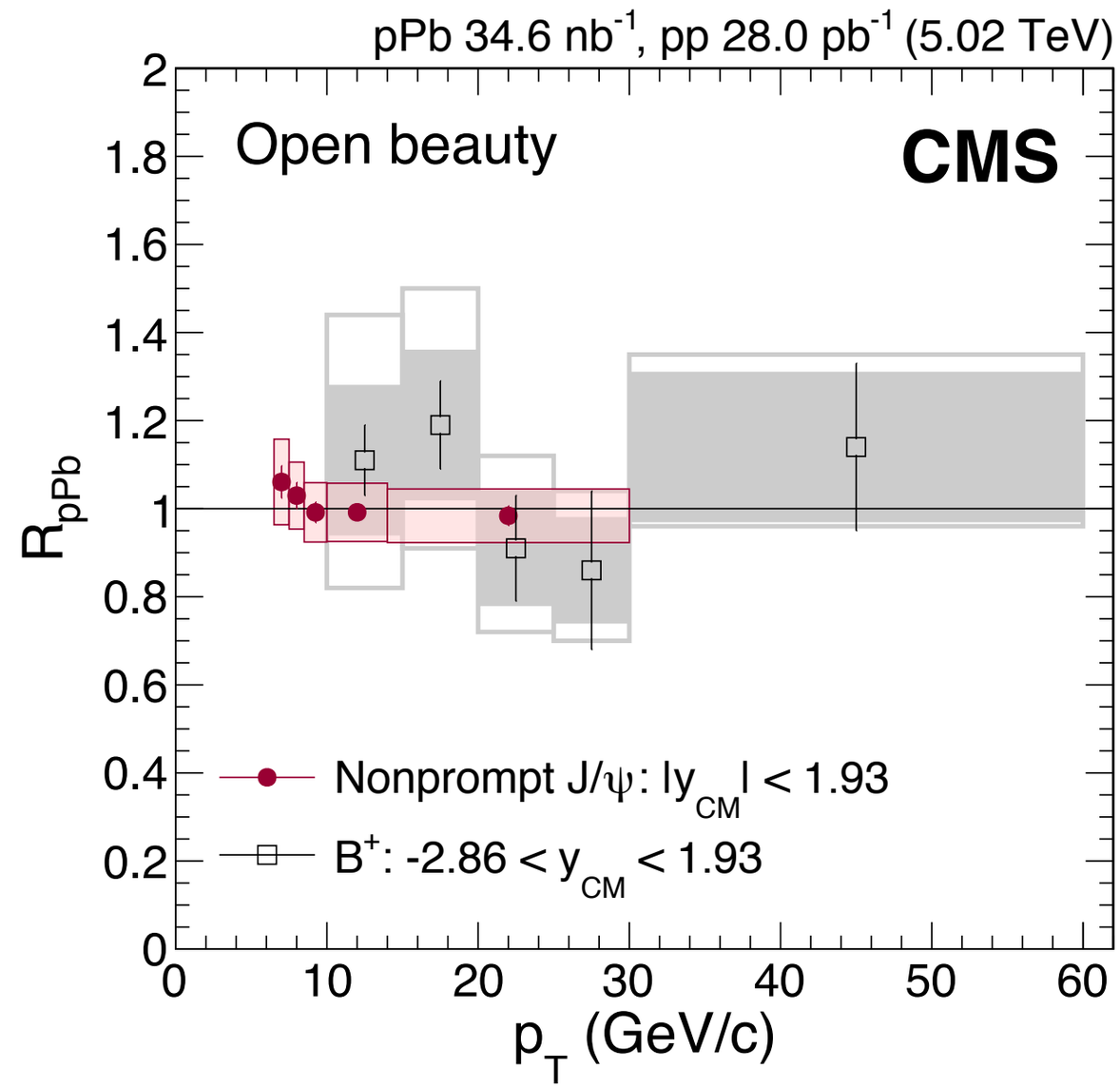


HIN-17-008

Cold nuclear matter effect?

- Suppression observed in both non-prompt J/ψ and B meson in PbPb collisions
  - Consequence of CNM effect? e.g. Modification of nPDF and potential nuclear absorption

- CMS measurements of both non-prompt J/ψ[1] and B meson[2] in pPb collisions
  - No evidence of suppression observed in pPb collisions
  - The suppression seen in PbPb is likely a final state effect.



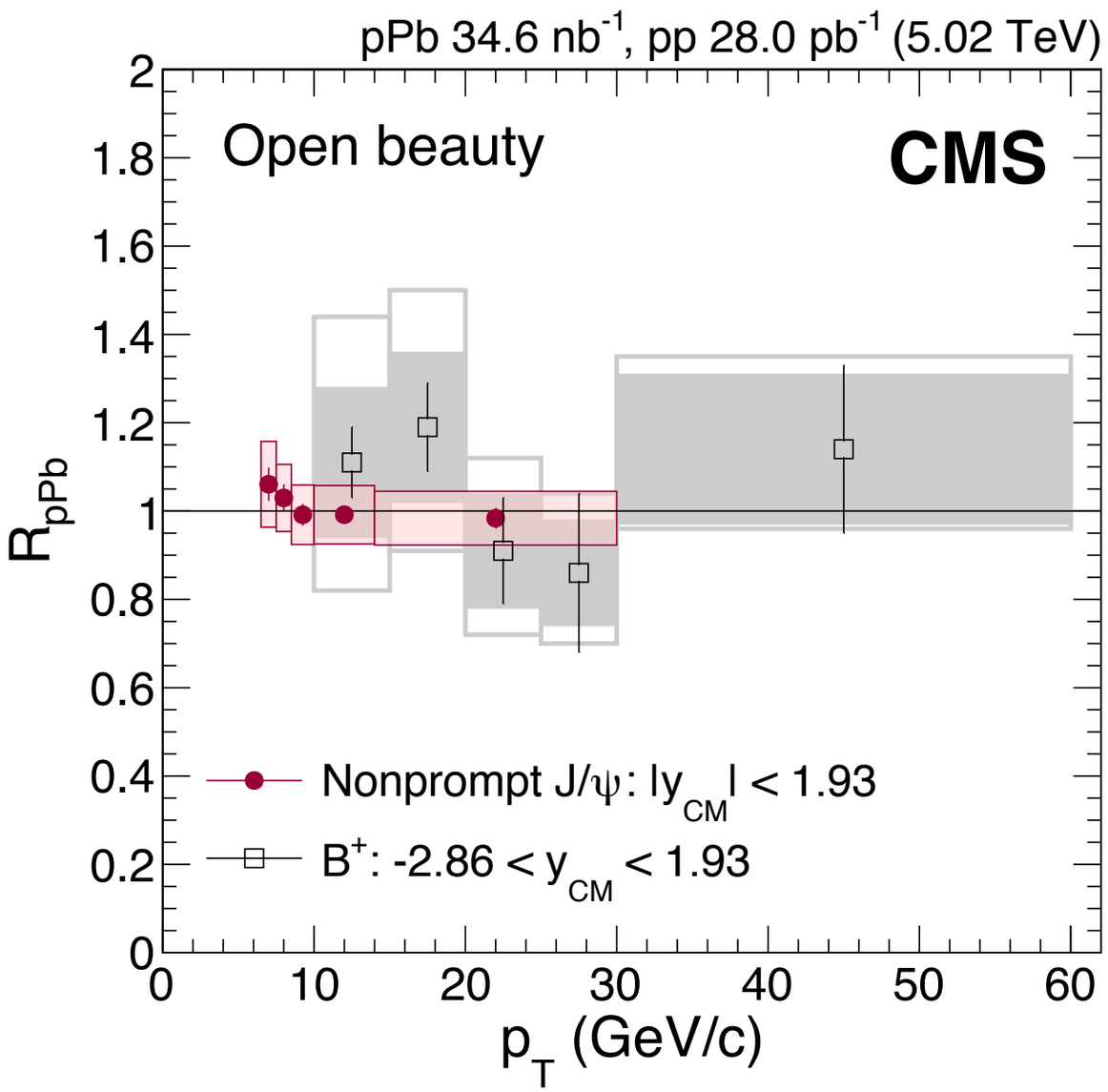
[1] EPJC 77 (2017) 269

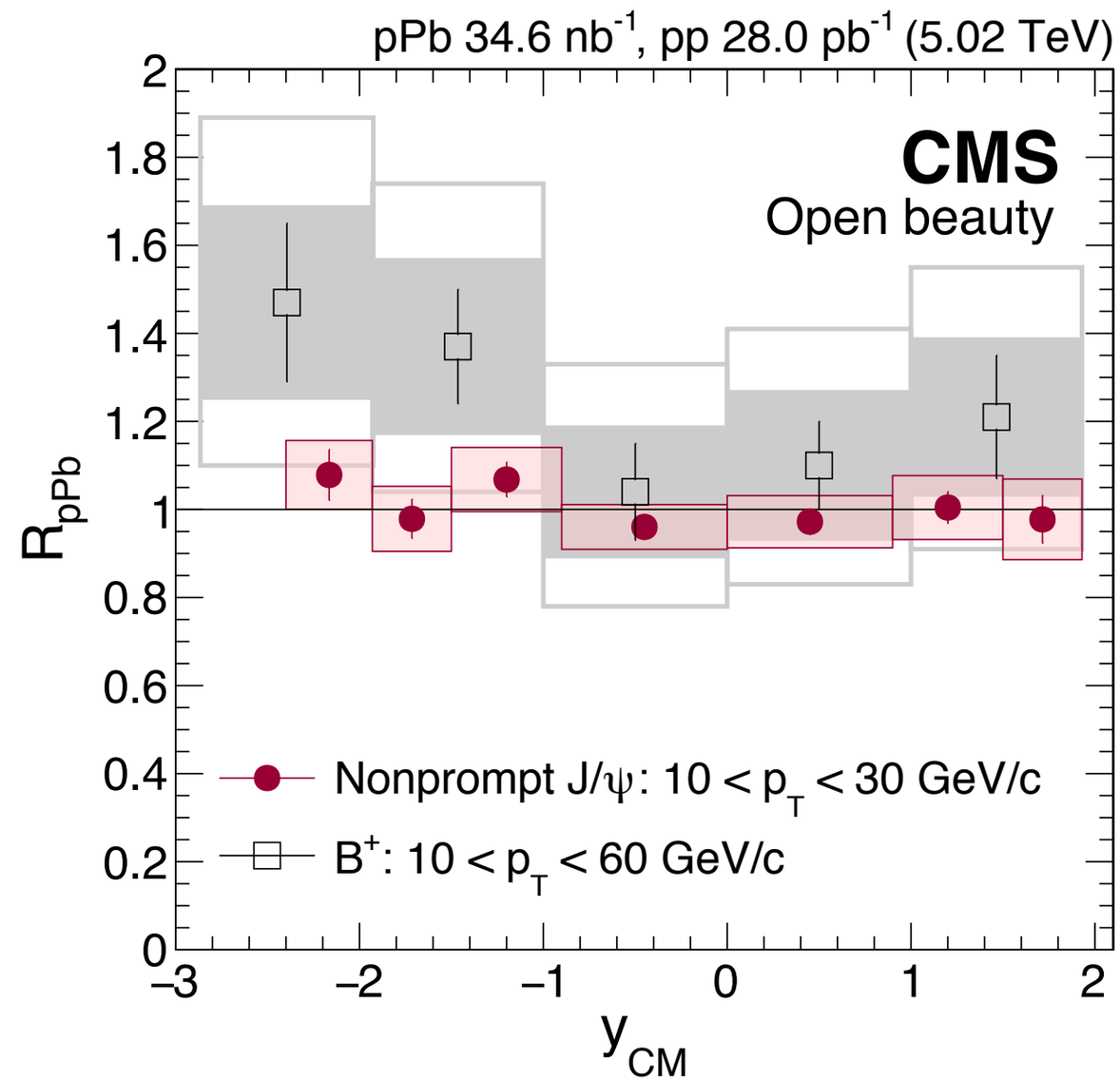
[2] Phys. Rev. Lett. 116, 032301

Cold nuclear matter effect?

[1] EPJC 77 (2017) 269

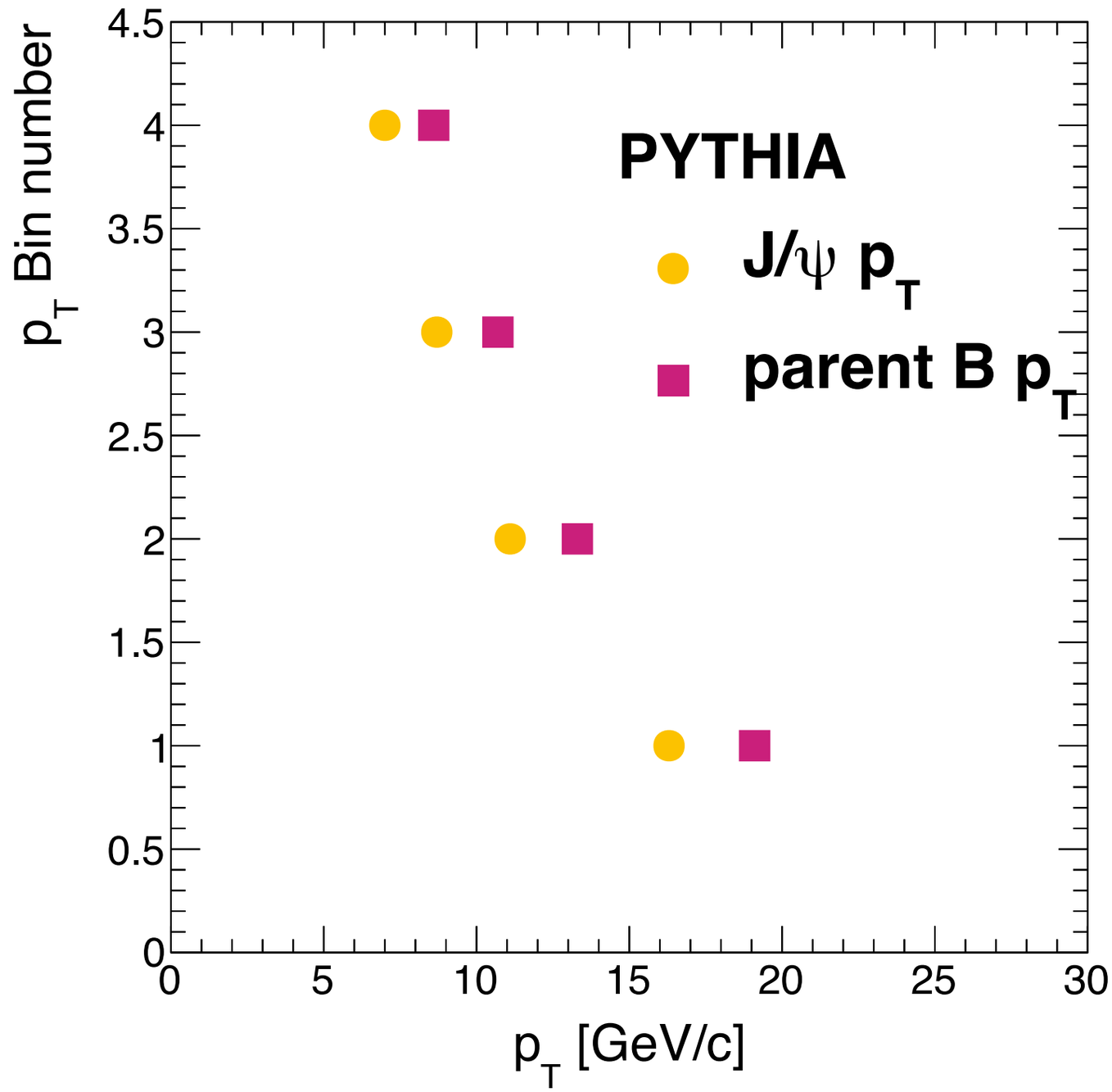
[2] Phys. Rev. Lett. 116, 032301





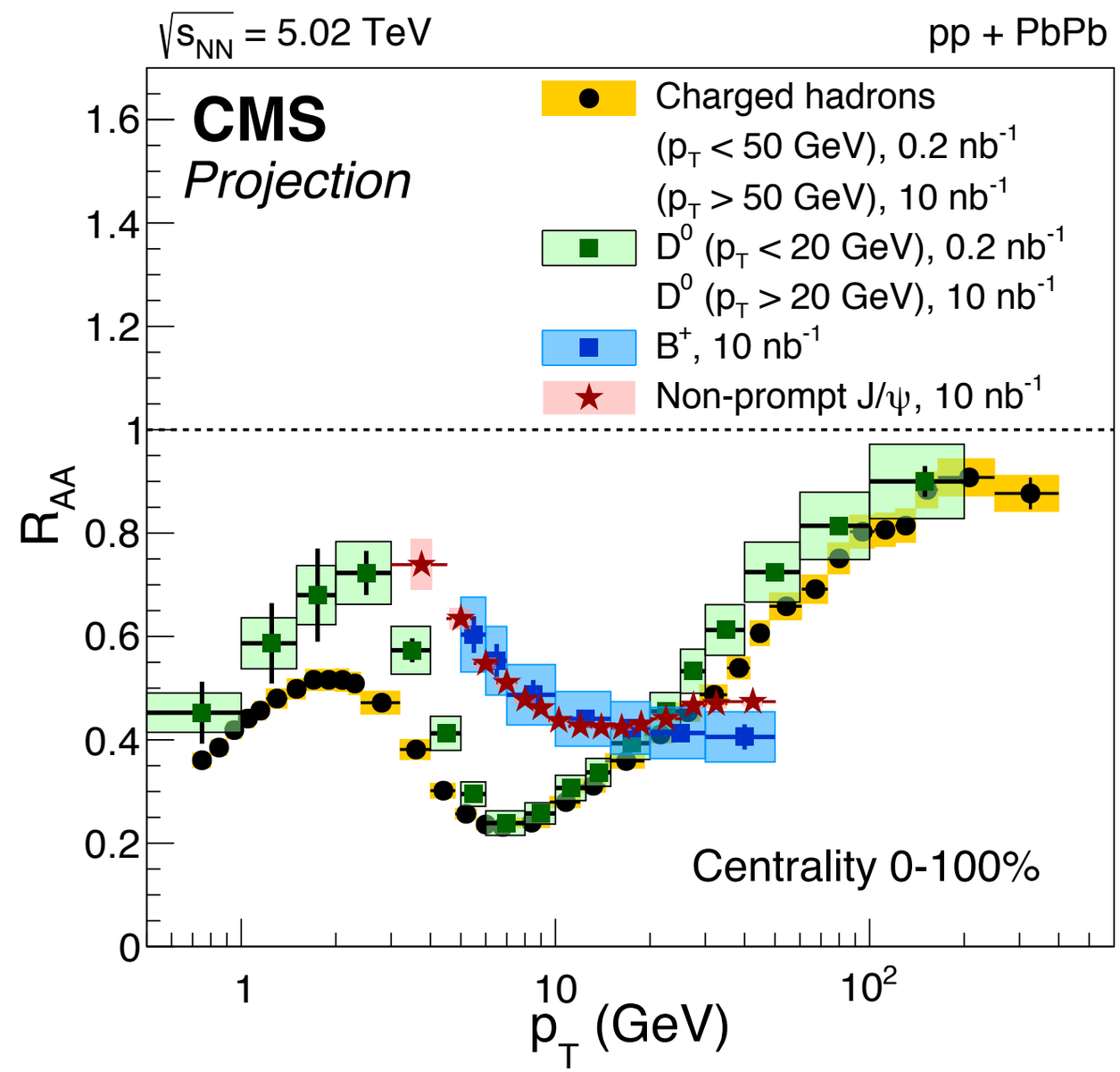
B to J/ψ kinematics difference

- The difference in p_T between parent B meson and J/ψ



Future

- **Future prospect: HL-LHC**
  - 25 times more statistic expected (factor of 5 reduction in uncertainty)
  - Comparison @ low p_T ➜ more definite conclusion on flavor dependence energy loss



B meson projection central value based on Djordjevic (PRC 94 (2016) 044908)