HP2024
NAGASAKI

Understanding initial and final state charm production in pPb collisions with CMS

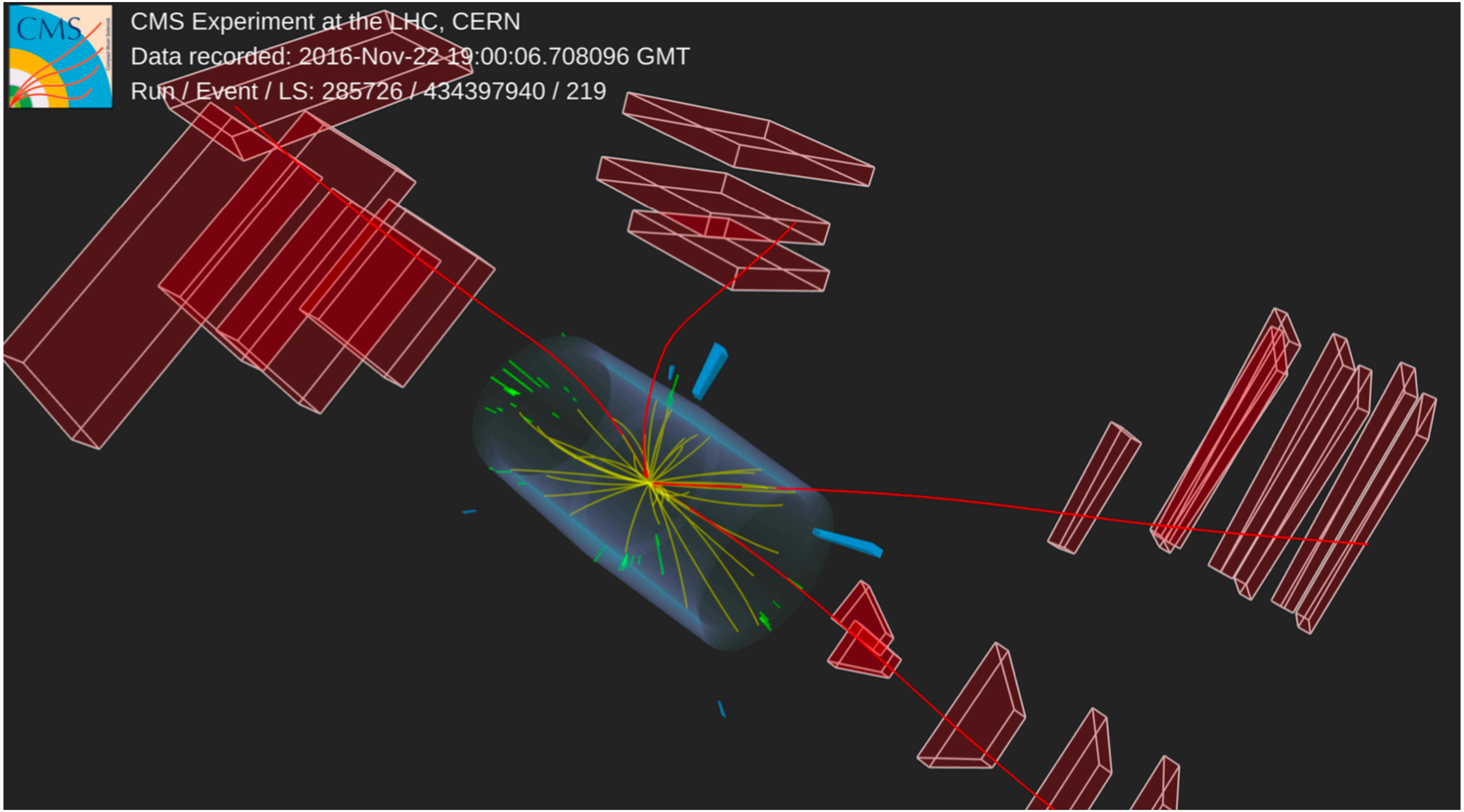
Soohwan Lee, on behalf of CMS
(Korea University)

Introduction

- Heavy flavor (HF) is great probe to study high-density QCD phenomena
  - Produced in initial hard scattering, $m_{HQ} \gg \Lambda_{\mathrm{QCD}}, m_{HQ} \gg T_{\mathrm{c}}, \ldots$
  - Testing our knowledge of HF production in small system crucial to extract hot QCD effect from heavy ion data
    - nPDF, multi parton interaction (MPI), hadronization, …
      - 2 recent final results from CMS to better understand charm in nuclear collisions

I) Measurement double J/ψ production in pPb

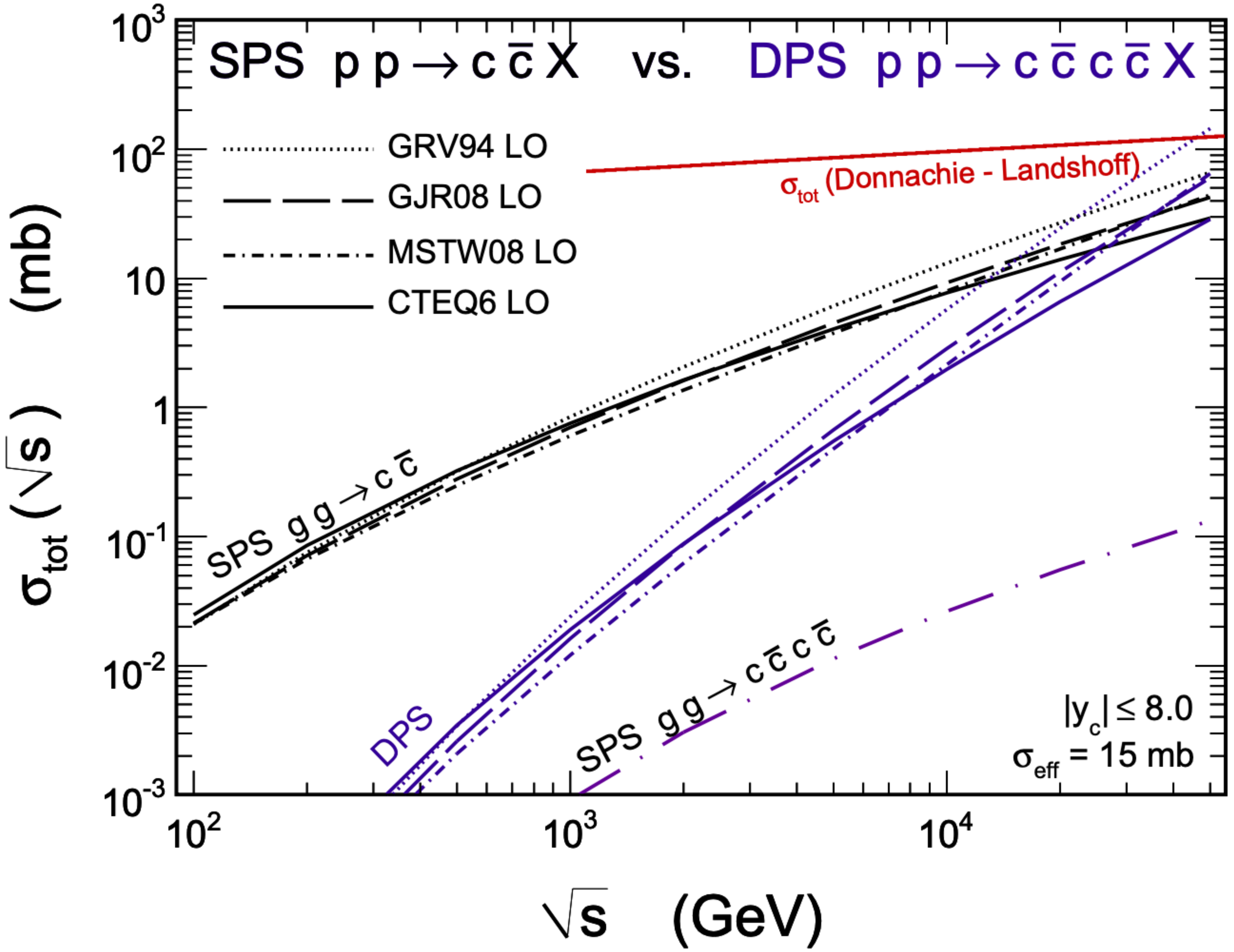
II) Baryon-to-meson ratio of Λ_{c}^{+} and D^{0} in pPb


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2016-Nov-22 19:00:06.708096 GMT
Run / Event / LS: 285726 / 434397940 / 219

Understanding initial multi charm production via double J/ψ

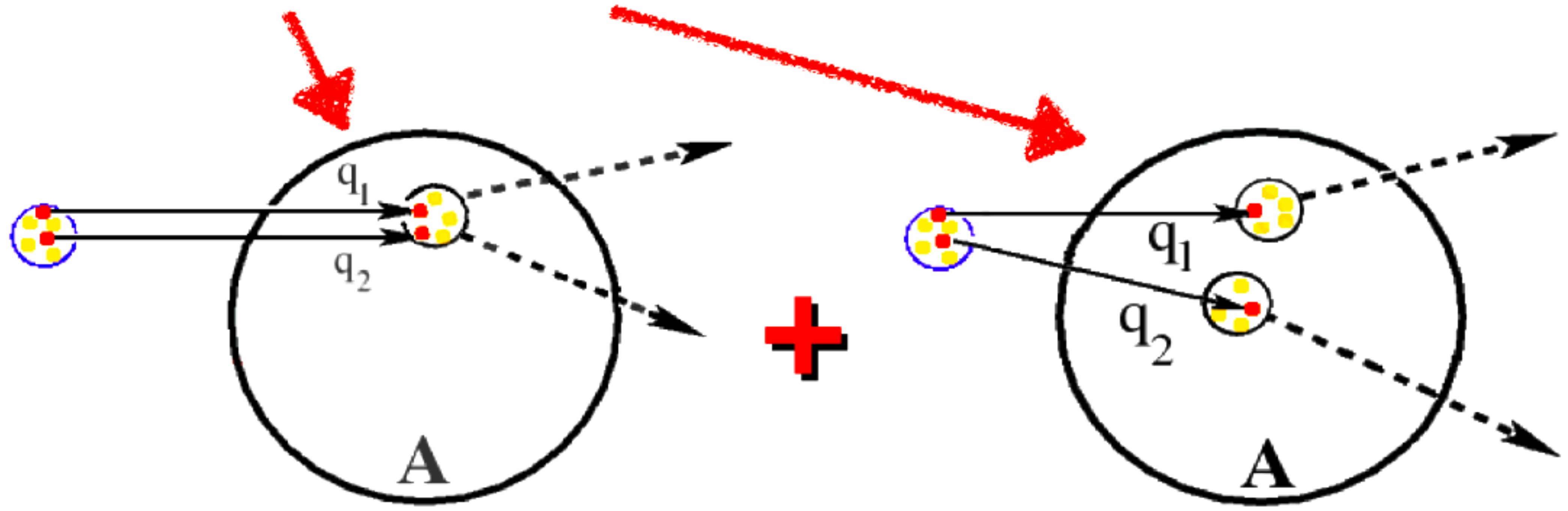
- Multi parton scattering is fundamental in hadron collisions
  - Cross section increase with $\sqrt{s_{NN}}$, and the nucleus A

arXiv.1212.5427



Understanding initial multi charm production via double J/ψ

- Multi parton scattering is fundamental in hadron collisions
  - Cross section increase with $\sqrt{s_{NN}}$, and the nucleus A
    - For double parton scattering (DPS), production in pPb enhanced by $A + A^{4/3}/\pi \sim 600$
- $\sigma^{DPS}_{pA\to ab} = \sigma^{DPS,1}_{pA\to ab} + \sigma^{DPS,2}_{pA\to ab}$



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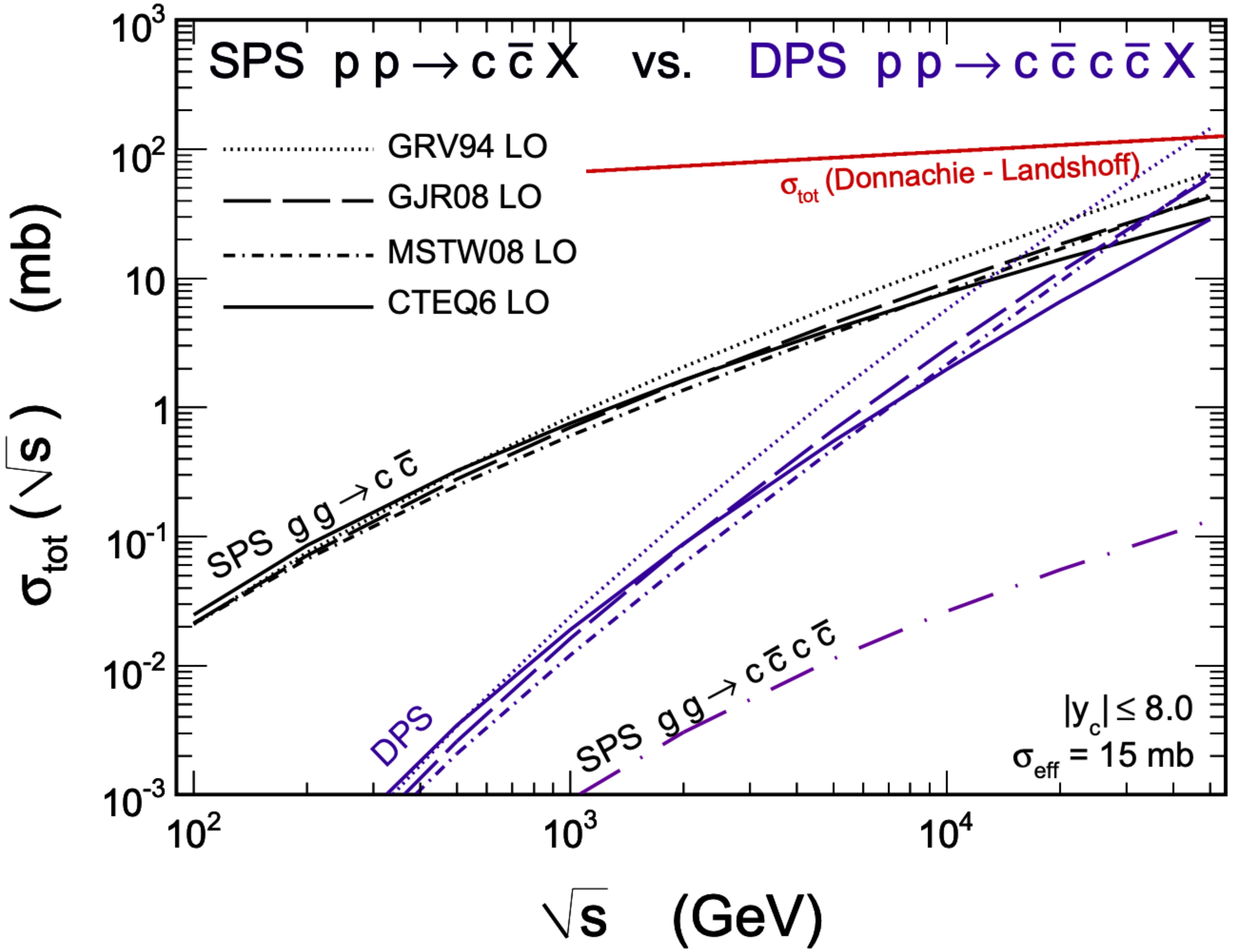

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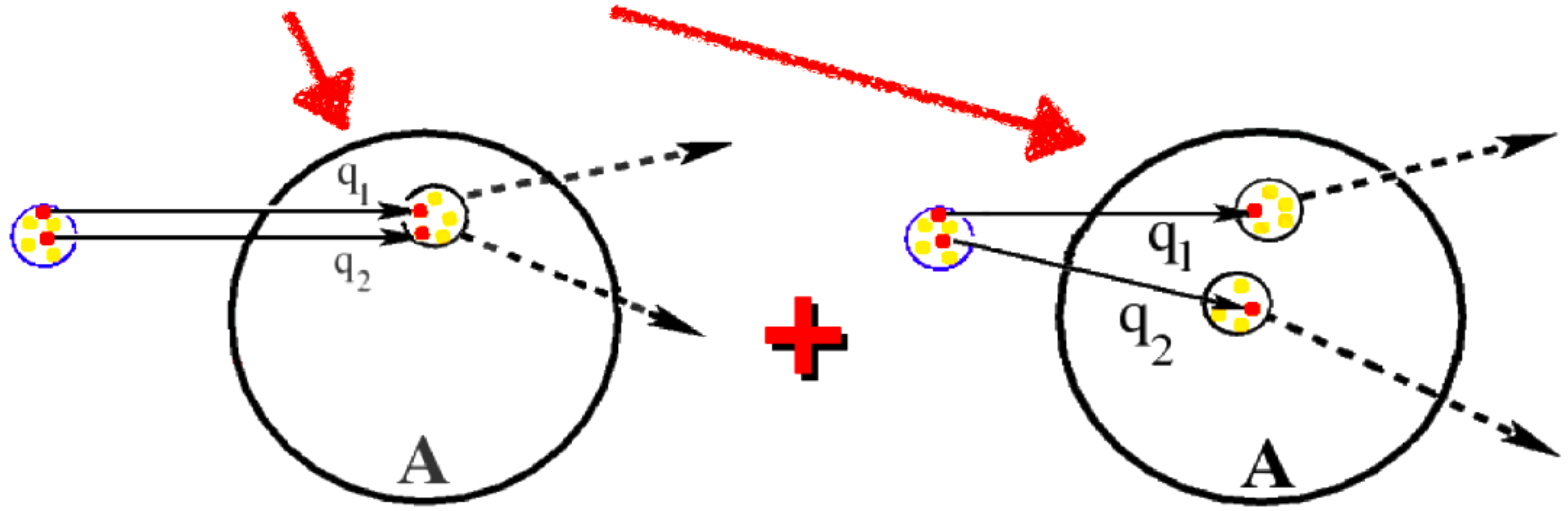

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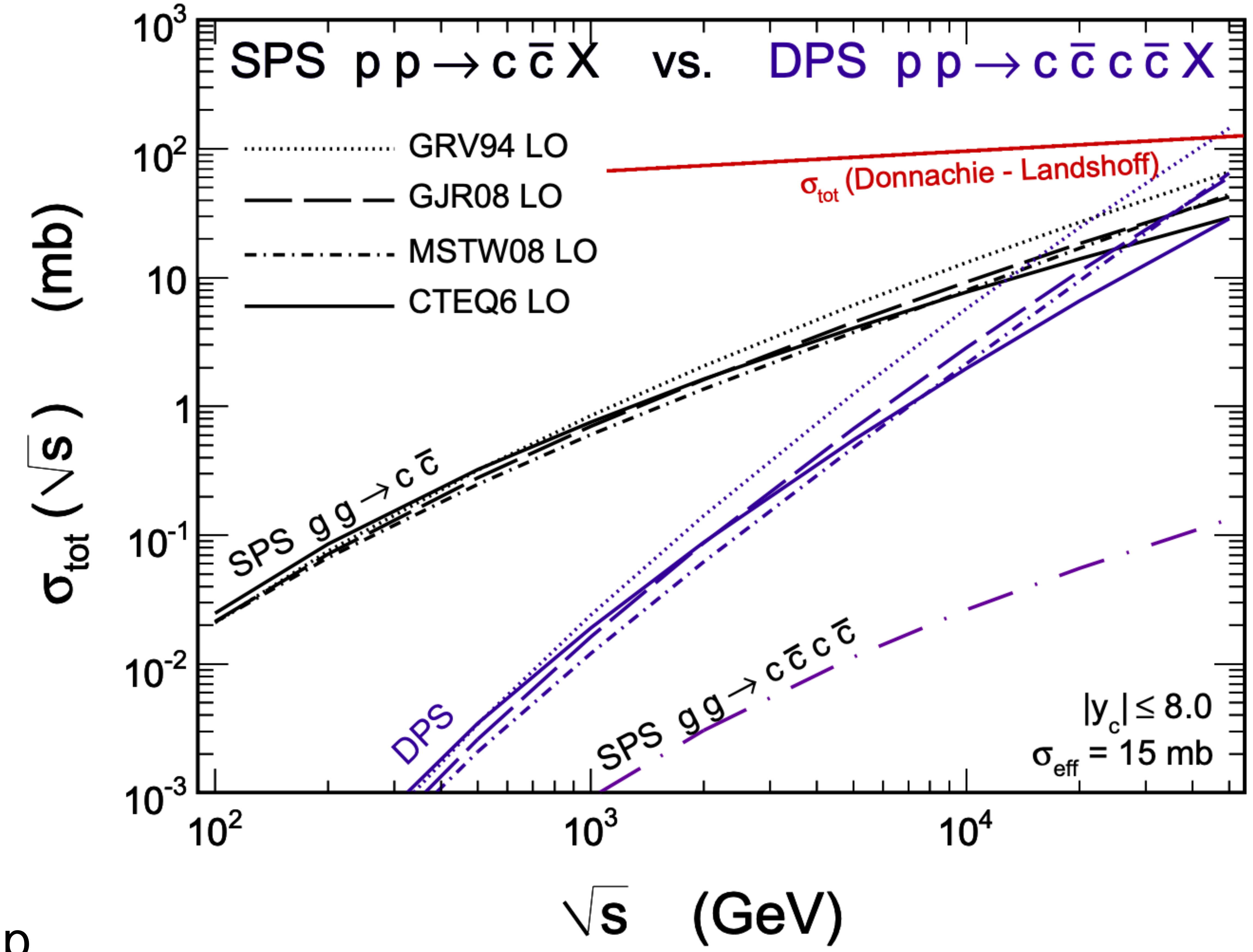

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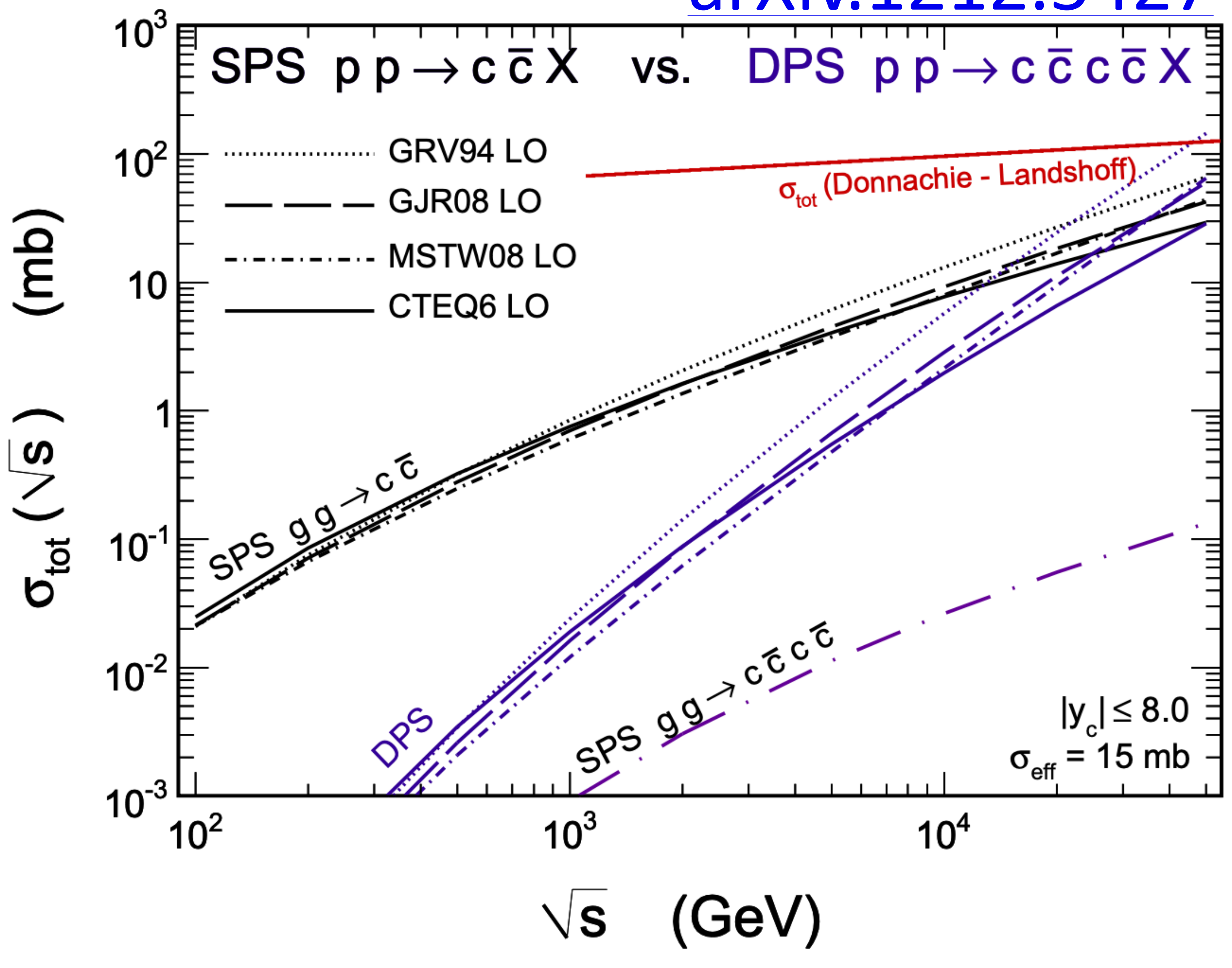
  - Understanding DPS process in nuclear collision can help understand parton structure in nucleus and it's geometry
  - Simple DPS cross section can be formulated in purely geometric approach

arXiv.1212.5427



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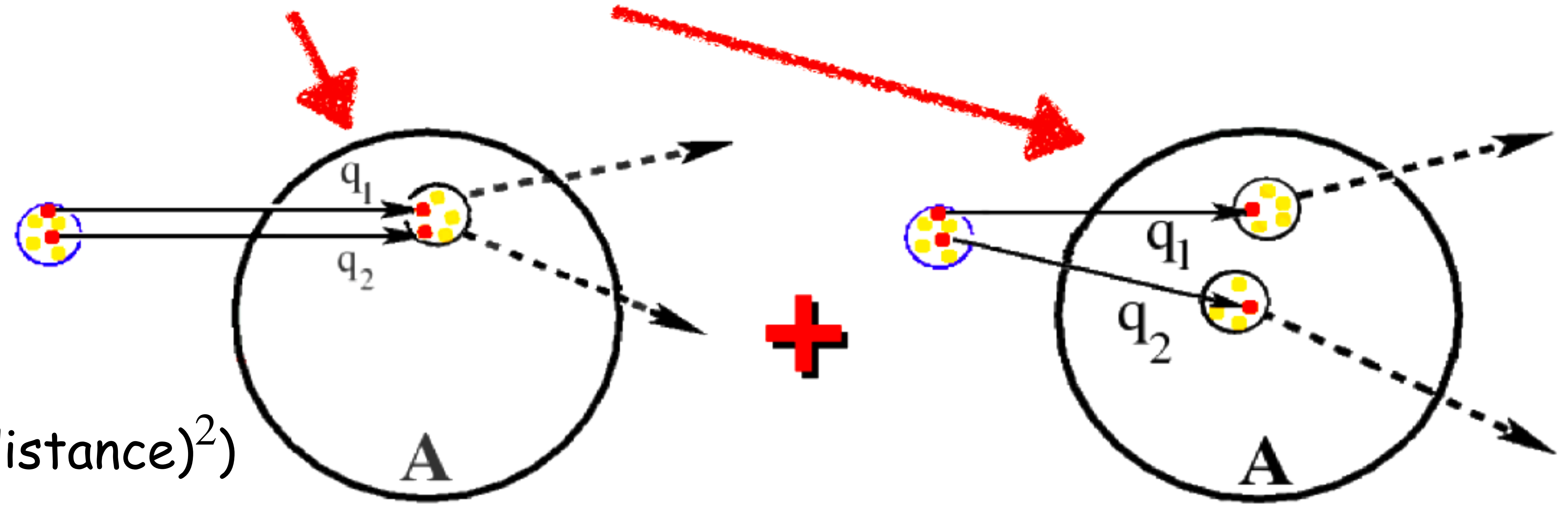


- $$\sigma_{\mathrm{DPS,pPb}} = \left(\frac{1}{2}\right) \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pPb}\to J/\psi + X}\sigma_{\mathrm{SPS}}^{\mathrm{pPb}\to J/\psi + X}}{\sigma_{\mathrm{eff,pPb}}}$$

(General expression in [1])

(Serves as (inter parton distance)^2)

This work: extracting $\sigma_{\mathrm{eff,pPb}}$ from di-J/ψ measurement

[1] DESY-THESIS 154 pp. (2019)

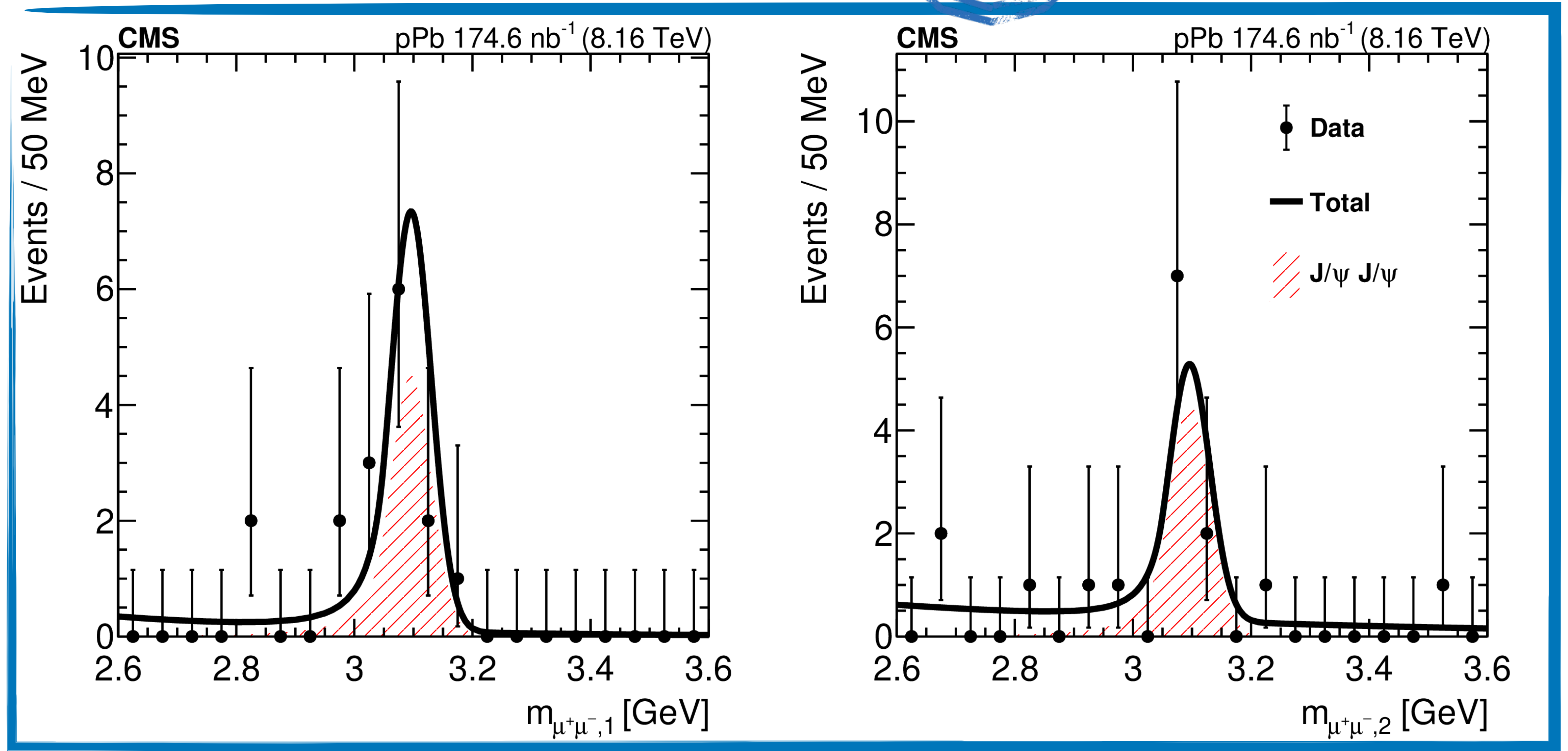
Double J/ψ production in pPb

CMS NEW Paper 24'Fall

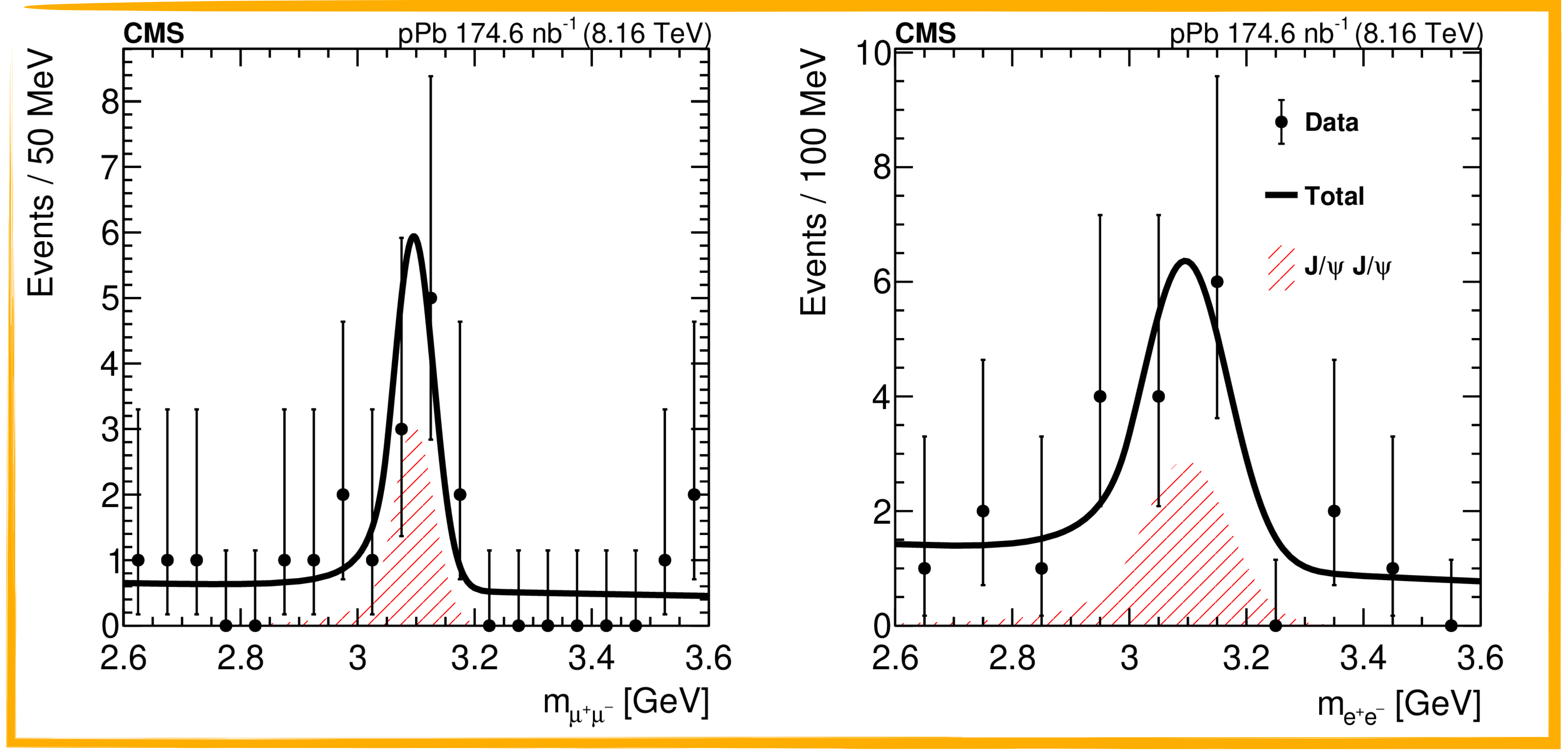
arXiv.2407.03223 (PRD accepted)

- pPb (Pbp) $\sqrt{s_{NN}}$ = 8.16 TeV data collected in 2016
  - Integrated luminosity: 174.56 nb^{-1}
- Leptonic decay channels of J/ψ considered
  - $J/\psi + J/\psi \rightarrow 4\mu$ (1)
  - $J/\psi + J/\psi \rightarrow \mu\mu + ee$ (2)
- 2D fit on mass distribution to extract signal
  - (1) : 8.5 ± 3.4 (stat.)
  - (2) : 5.7 ± 4.0 (stat.)
  - Combined with Fischer formalism, signal 5.3 σ !

(1)



(2)



- J/ψ mesons $p_T > 6.5\,\mathrm{GeV}$ and $|y| < 2.4$

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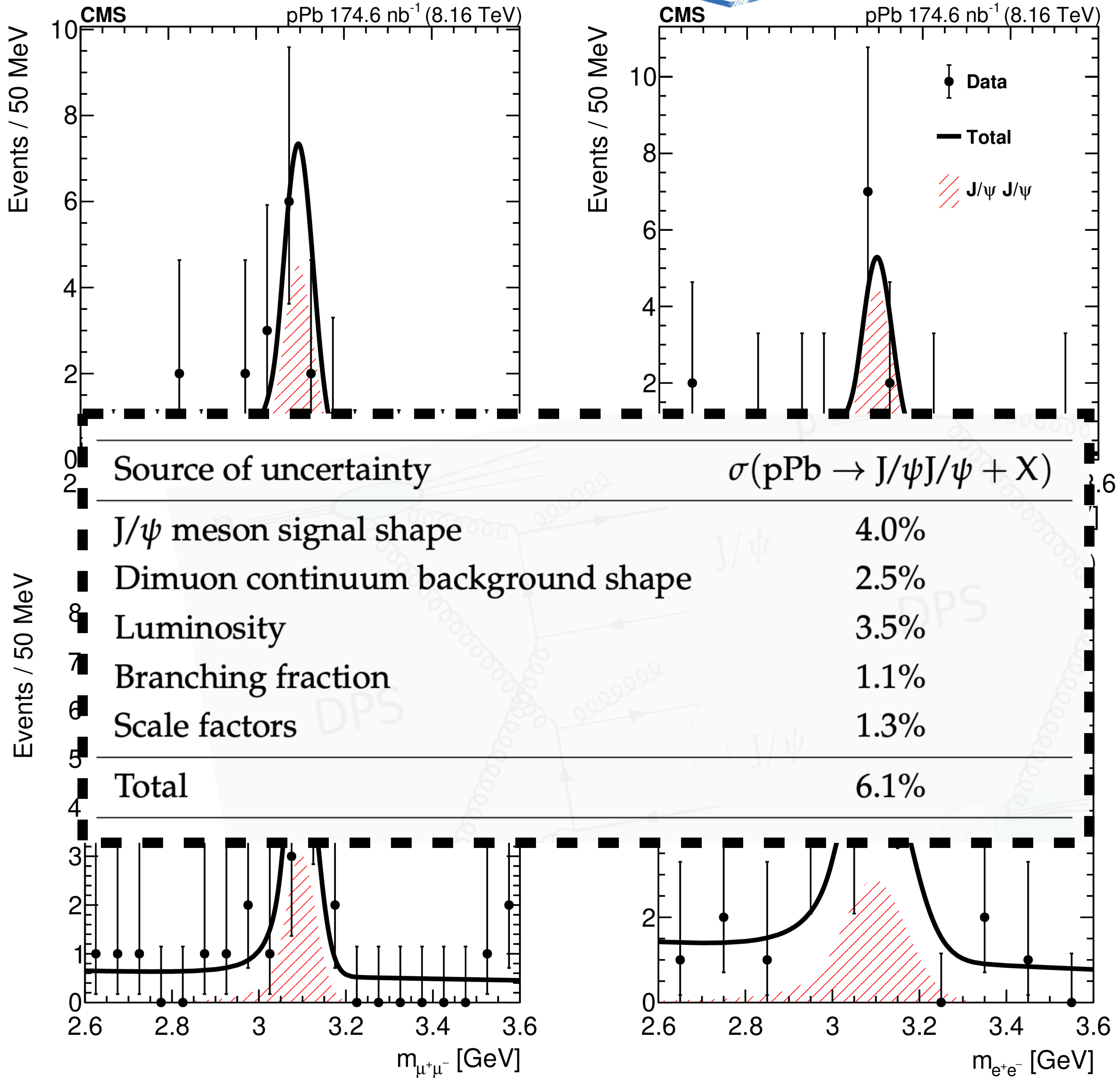
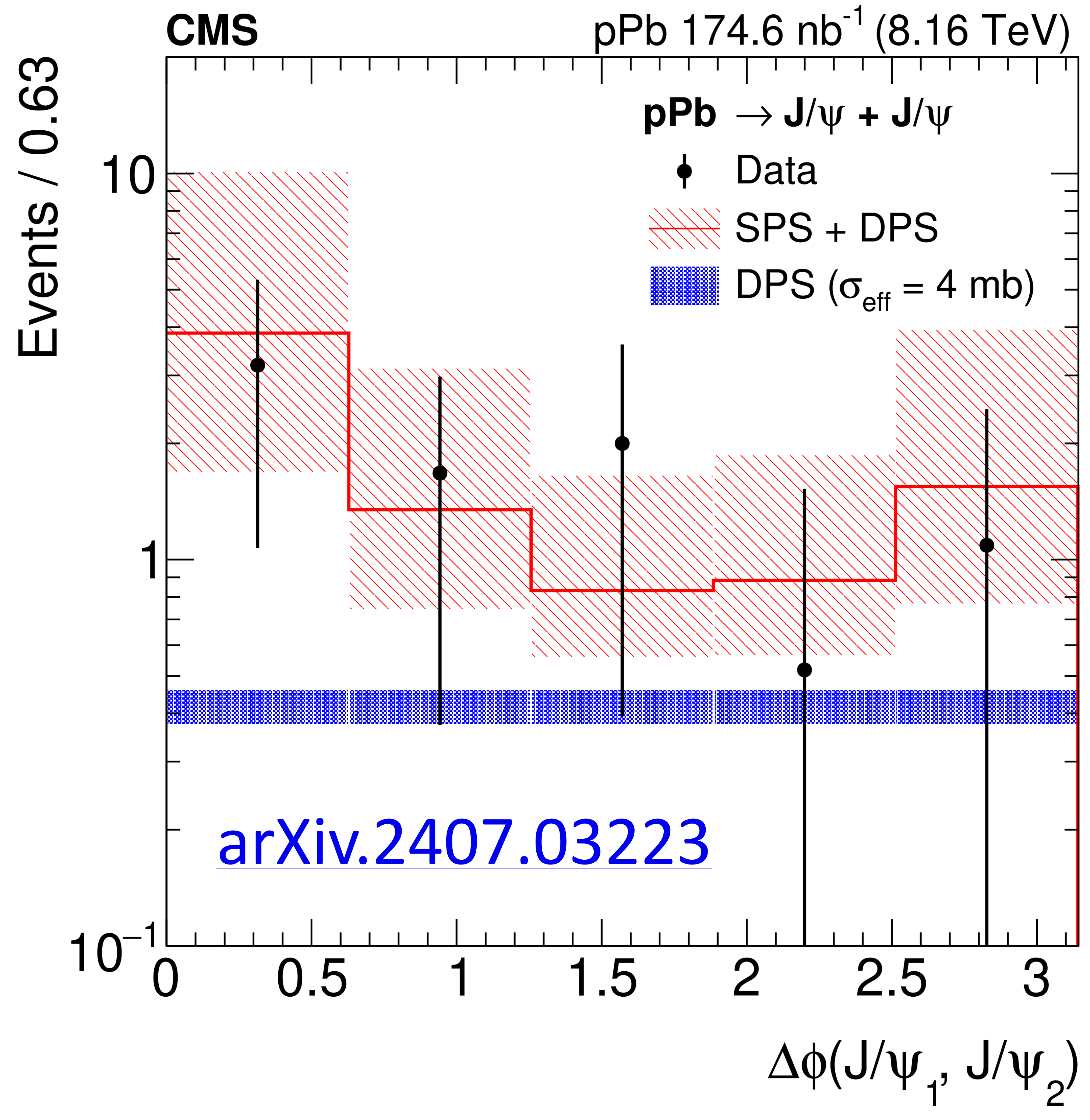
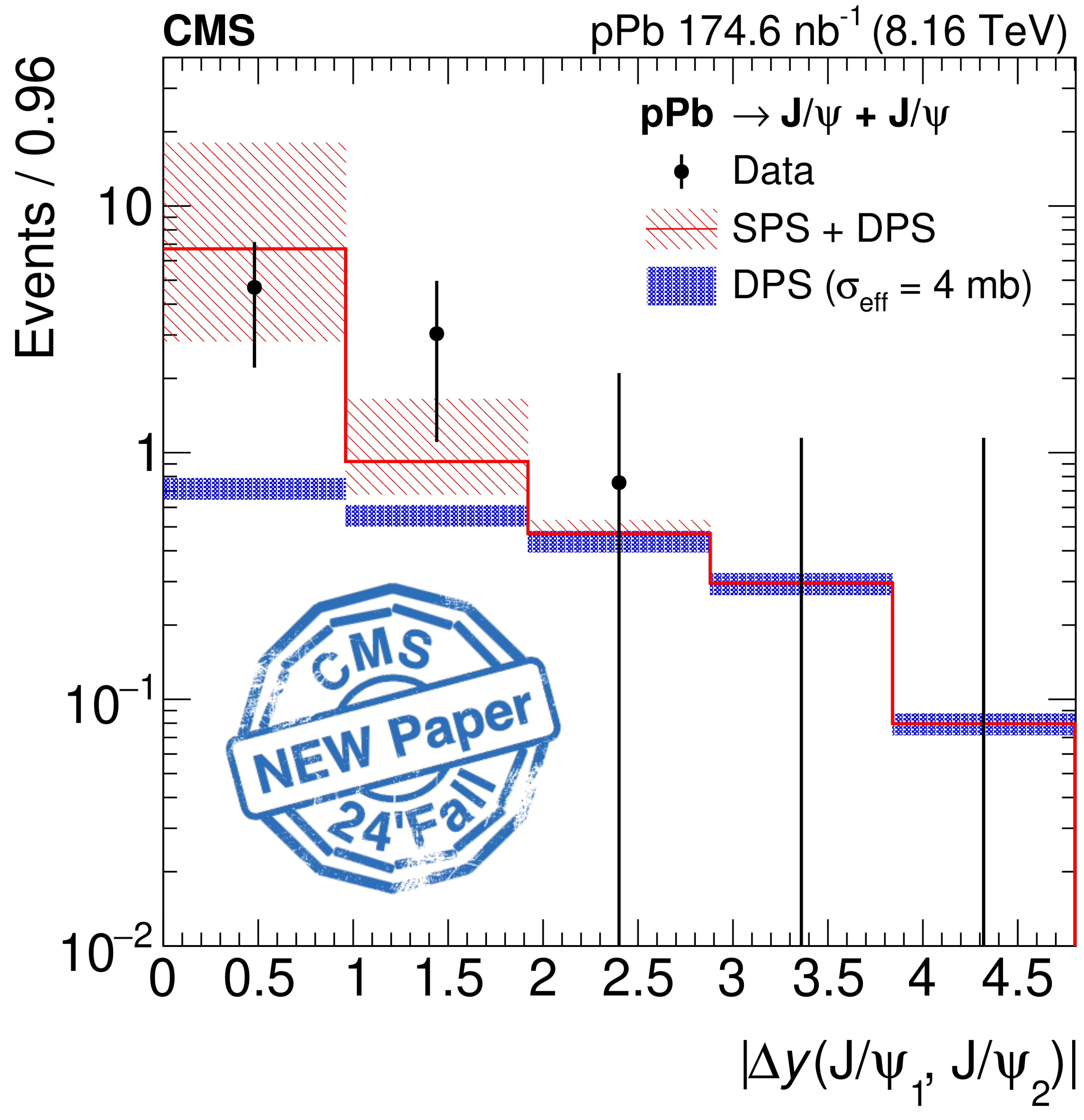
  - Total systematic 6.1 %



Source of uncertainty	$\sigma(\mathrm{pPb} \to \mathrm{J}/\psi\mathrm{J}/\psi + \mathrm{X})$
J/ψ meson signal shape	4.0%
Dimuon continuum background shape	2.5%
Luminosity	3.5%
Branching fraction	1.1%
Scale factors	1.3%
Total	6.1%

Extracting σ_{eff}





- SPS/DPS signal extracted from template fits
  - $N_{\text{SPS}} = 6.4 \pm 4.2$
  - $N_{\text{DPS}} = 2.1 \pm 2.4$
- Fiducial σ (nb) (see back up)
  - $\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi\,\text{J}\psi+\text{X}} = 16.5 \pm 10.8\,(\text{stat}) \pm 0.1\,(\text{syst})$
  - $\sigma_{\text{DPS}}^{\text{pPb}\to\text{J}/\psi\,\text{J}\psi+\text{X}} = 5.4 \pm 6.2\,(\text{stat}) \pm 0.4\,(\text{syst})$

Theoretical prediction of SPS σ from HELAC-ONIA + CT14nlo PDF, reweighted to EPPS16 nPDF

Process	Theoretical cross section
$\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi+\text{X}}\mathcal{B}(\text{J}/\psi\to\mu^+\mu^-)$	$4.51 \pm 0.42\,\mu\text{b}$
$\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi\text{J}/\psi+\text{X}}\mathcal{B}^2(\text{J}/\psi\to\mu^+\mu^-)$	$20.2^{+38.5}_{-13.1}\,\text{pb}$

$$\sigma_{\text{DPS,pPb}} = \left(\frac{1}{2}\right)\frac{\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi+\text{X}}\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi+\text{X}}}{\sigma_{\text{eff,pPb}}}$$

- Extracted DPS cross section correspond to $\sigma_{\text{eff,pPb}} = 0.53^{+\infty}_{-0.2}$ b
  - Data compatible with SPS only

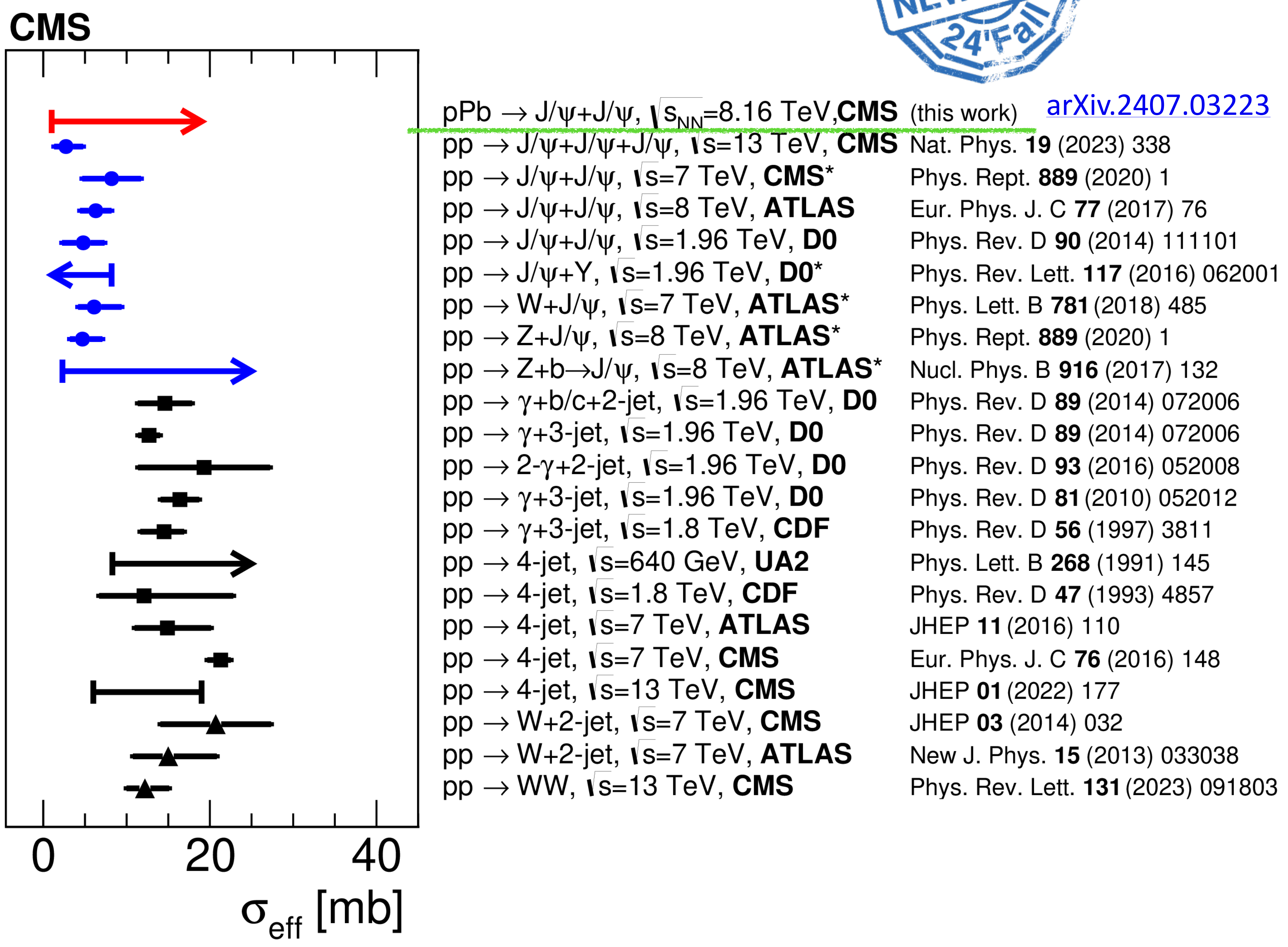
Result

- Equivalent pp $\sigma_{\rm eff}$ extracted assuming purely geometric effect (no parton correlation)

$$\sigma_{\rm eff} = \frac{\sigma_{\rm eff,pA}}{A - \sigma_{\rm eff,pA} F_{\rm pA}/A}$$

  - A = 208, $F_{\rm pA} = 29.5\ \mathrm{mb}^{-1}$ (from Glauber MC)

- $\sigma_{\rm eff} = 4.0^{+\infty}_{-1.5}$ mb → $\sigma_{\rm eff} > 1.0$ mb at 95 % C.L.



arXiv.2407.03223

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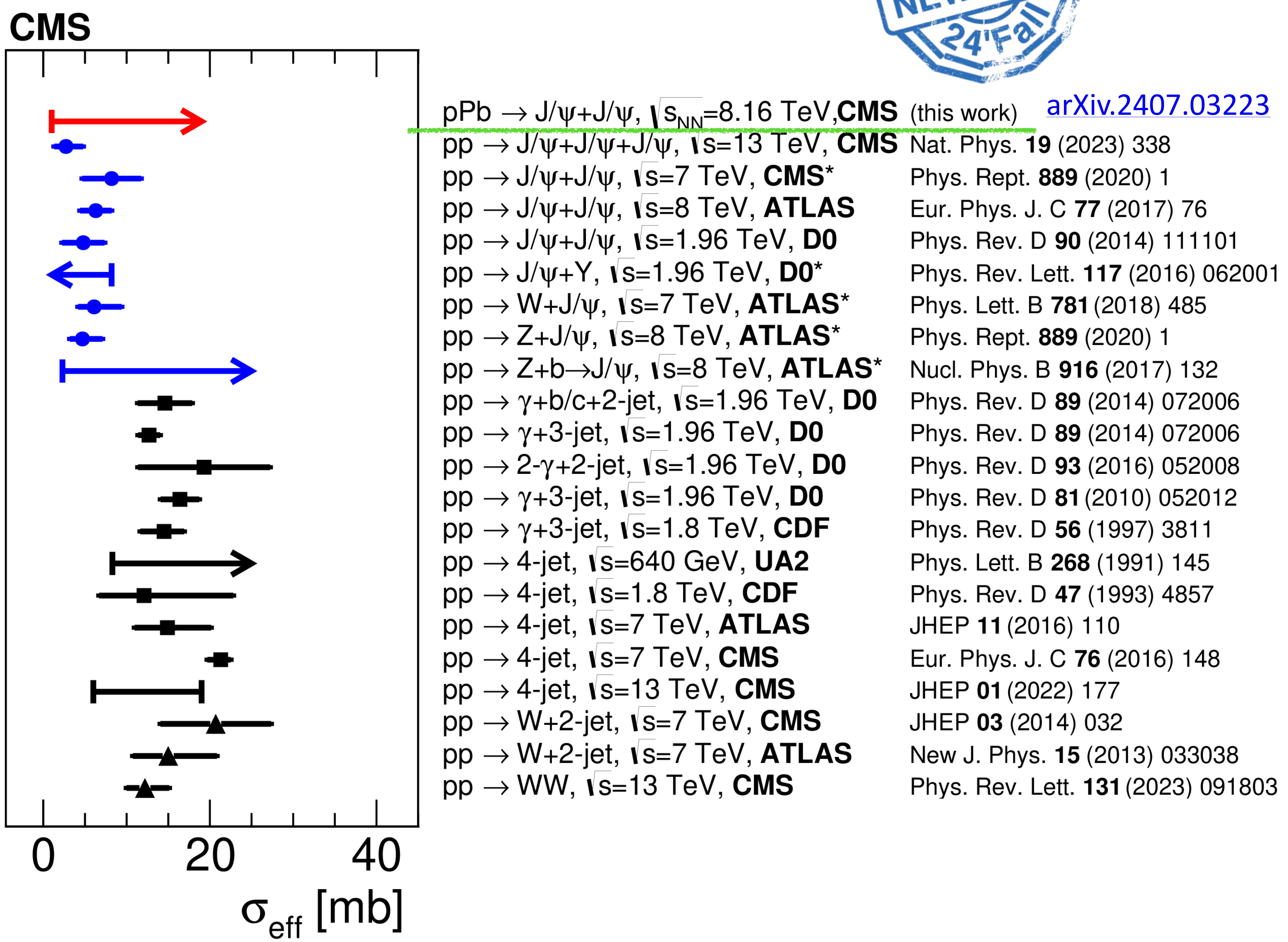
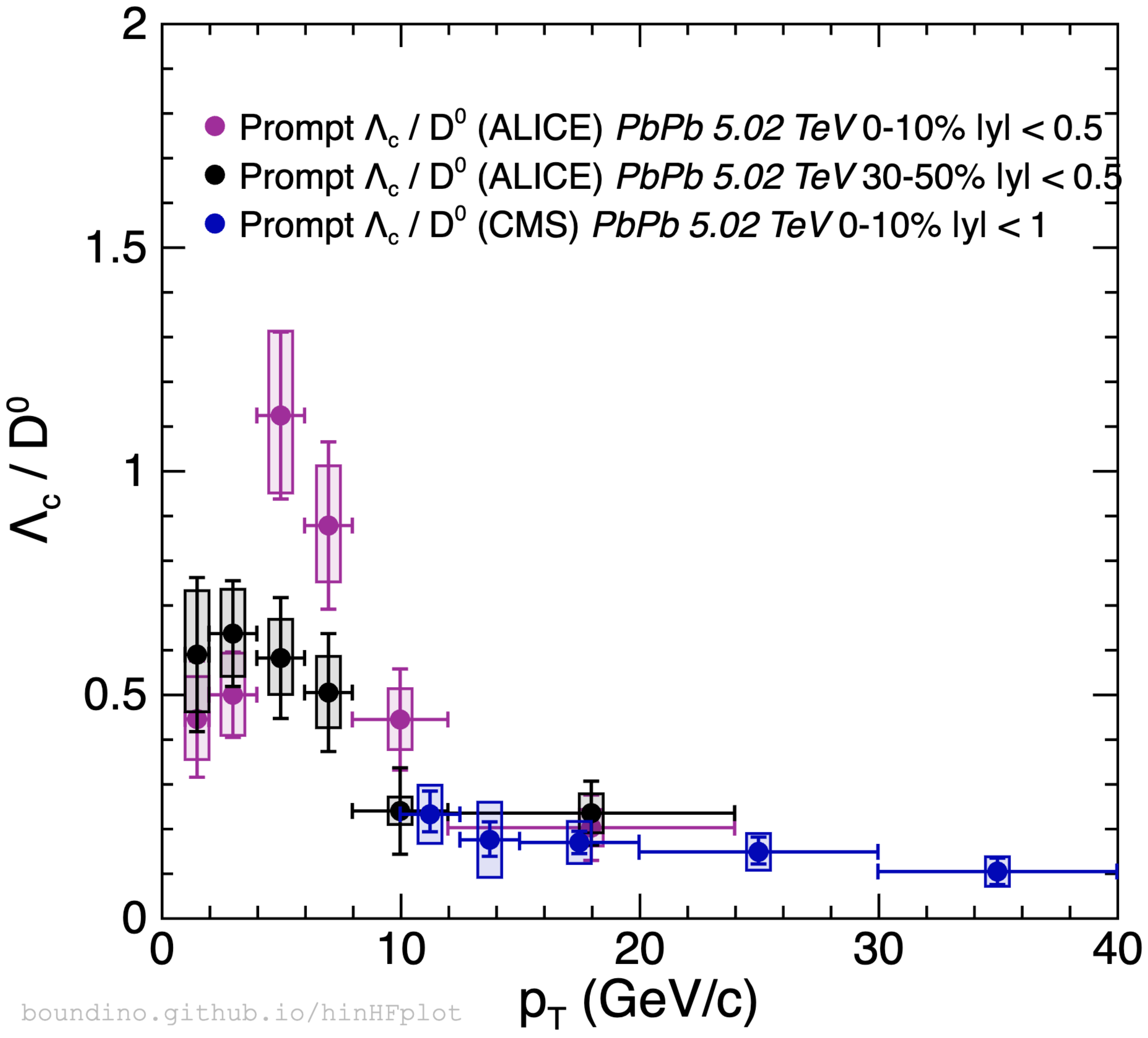
- $\sigma_{\text{eff}} = 4.0^{+\infty}_{-1.5}$ mb → $\sigma_{\text{eff}} > 1.0$ mb at 95 % C.L.
- Compatible with pp di-quarkonium results
  - Difference between measurement suggest DPS may depend on flavor/final state
  - Difference from nuclear gluon PDF?

arXiv.2407.03223



Probing final state charm production via baryon to meson ratio

- Λ_c^+ over D^0 ratio measured to study hadronization mechanism
  - Enhancement of baryon in central PbPb collision, coalescence in action
  - Study baryon to meson ratio in high multiplicity pPb collision for final state modification in small system!



PLB 839 (2023) 137796

JHEP 01 (2024) 128

Analysis method

- CMS 8.16 TeV pPb (Pbp) collision data from 2016
  - **Measured produced baryon to meson ratio $\Lambda_c^+ / \mathrm{D}^0$ in spectrum of p_T and reconstructed track multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$)**

Analyzed Λ_c^+ and D^0 (and their charge conjugate)

Reconstruction of Λ_c^+ from decay mode

$$\Lambda_c^+ \rightarrow \mathrm{K_S^0}(\rightarrow \pi^+\pi^-)\ \mathrm{p}$$

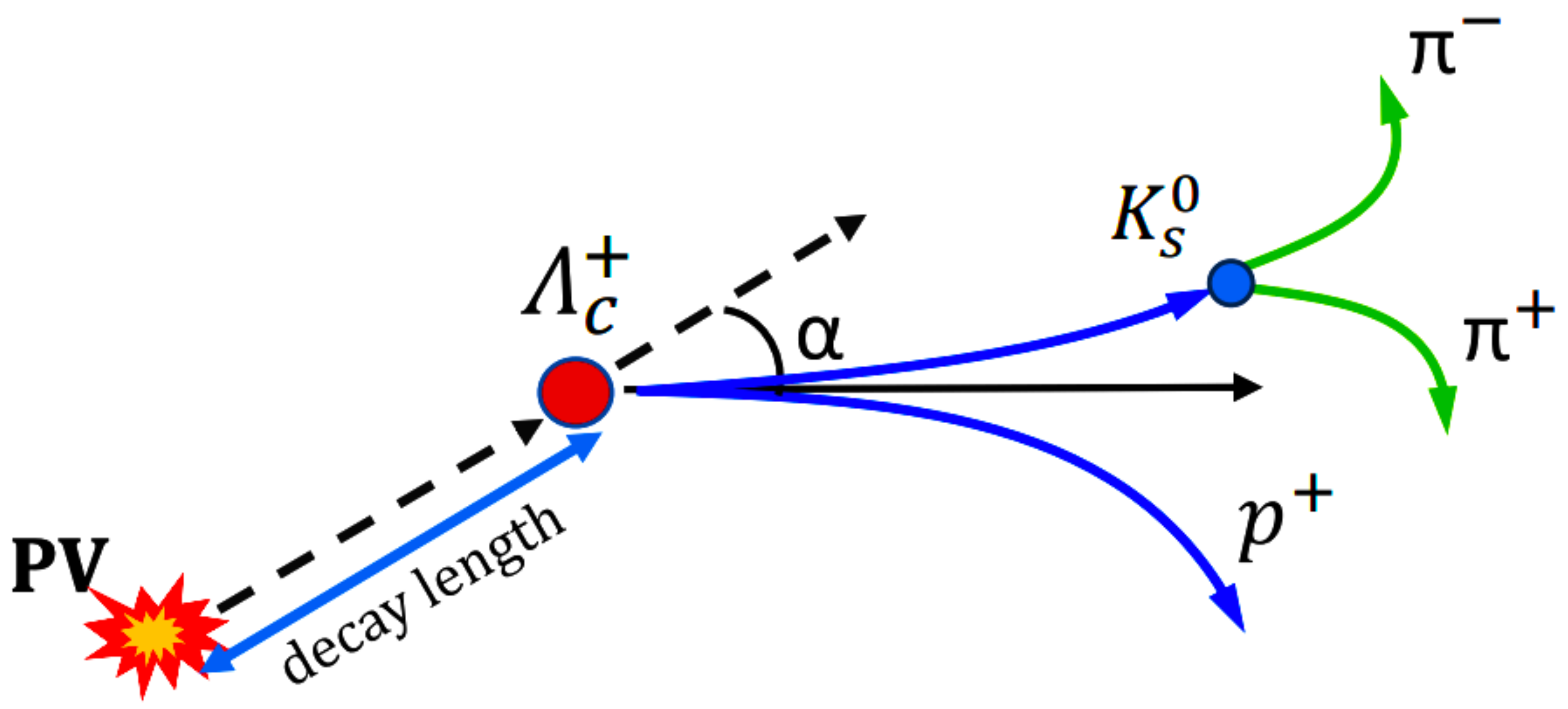
BR ~ 1.59 % ($\mathrm{K_S^0} \rightarrow \pi^+\pi^-$ BR ~ 69.2 %)

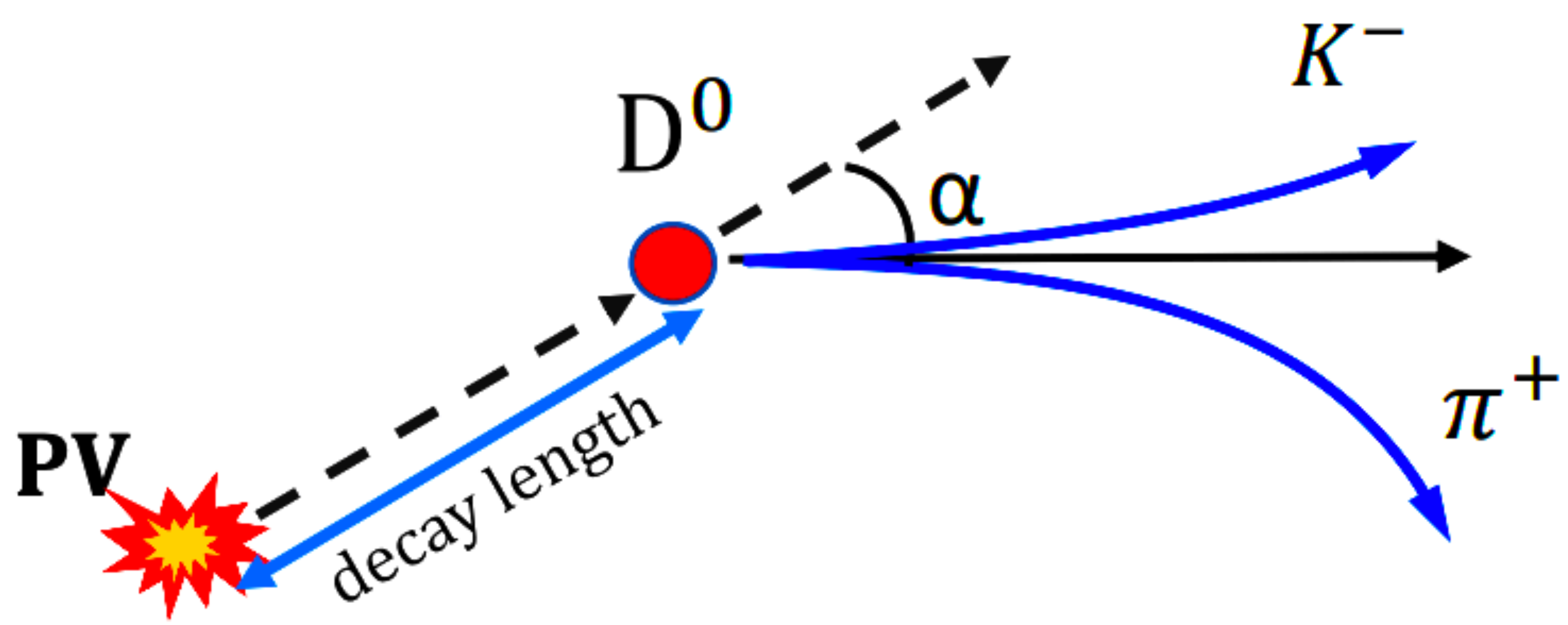
Signal enhanced via MLP leveraging candidate kinematics and proton dE/dx

Reconstruction of D^0 from decay mode

$$D^0 \rightarrow K^- + \pi^+$$ BR ~ 3.94 %

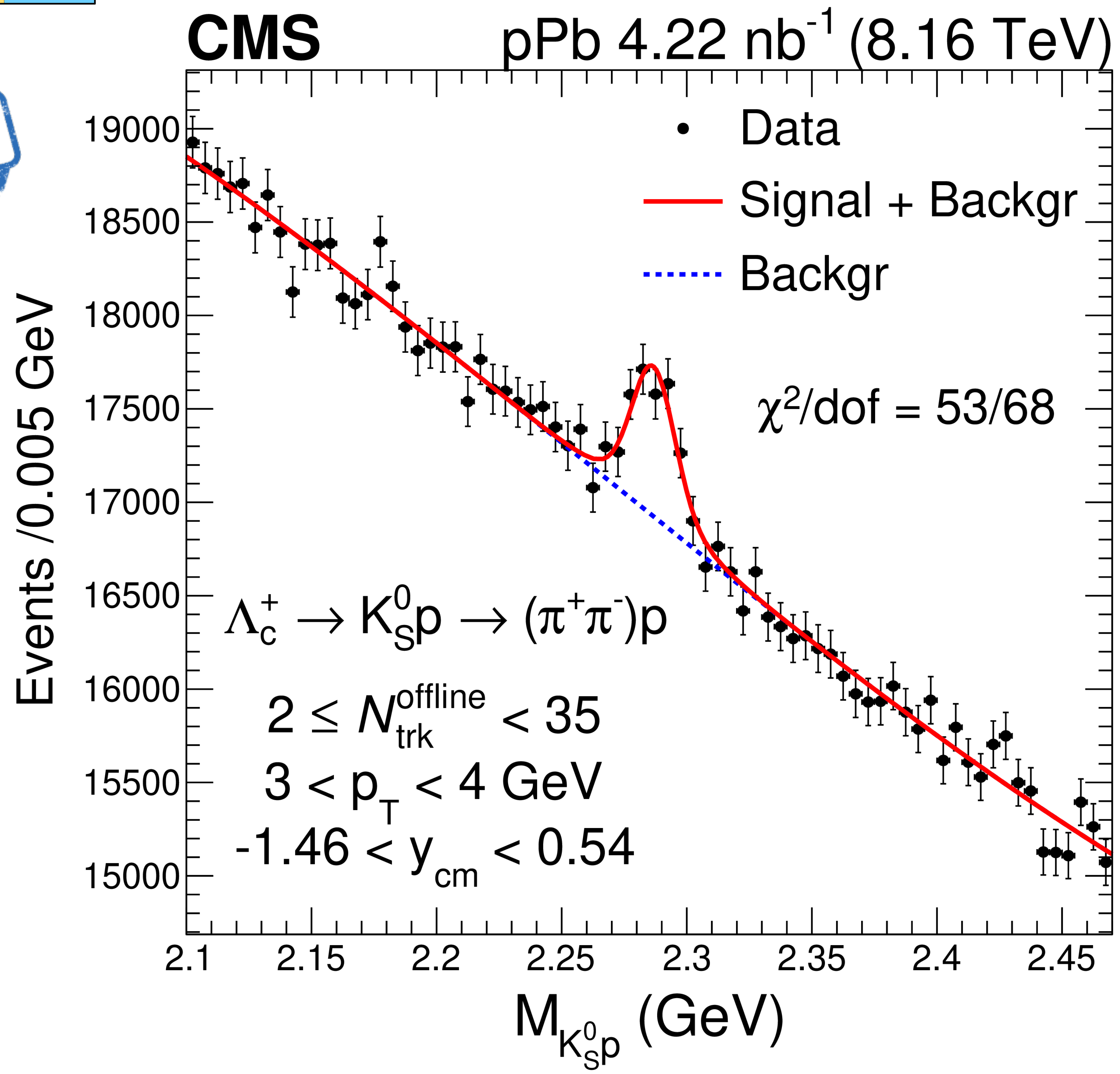
Signal enhanced via BDT

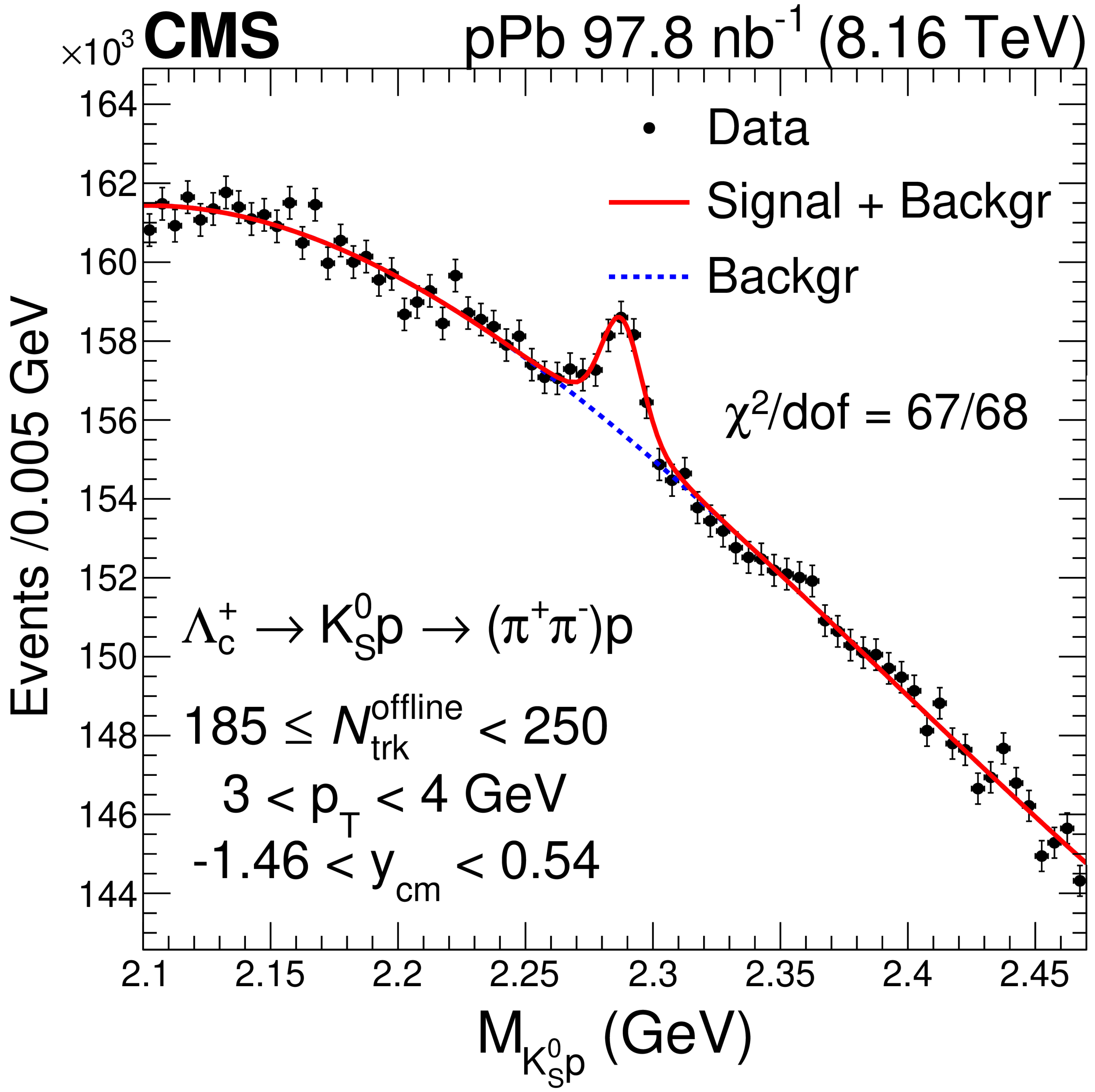




- Candidates built from all possible n-track combinations

Λ_c^+, D^0 Signal extraction





arXiv.2407.13615 (Submitted to PLB)

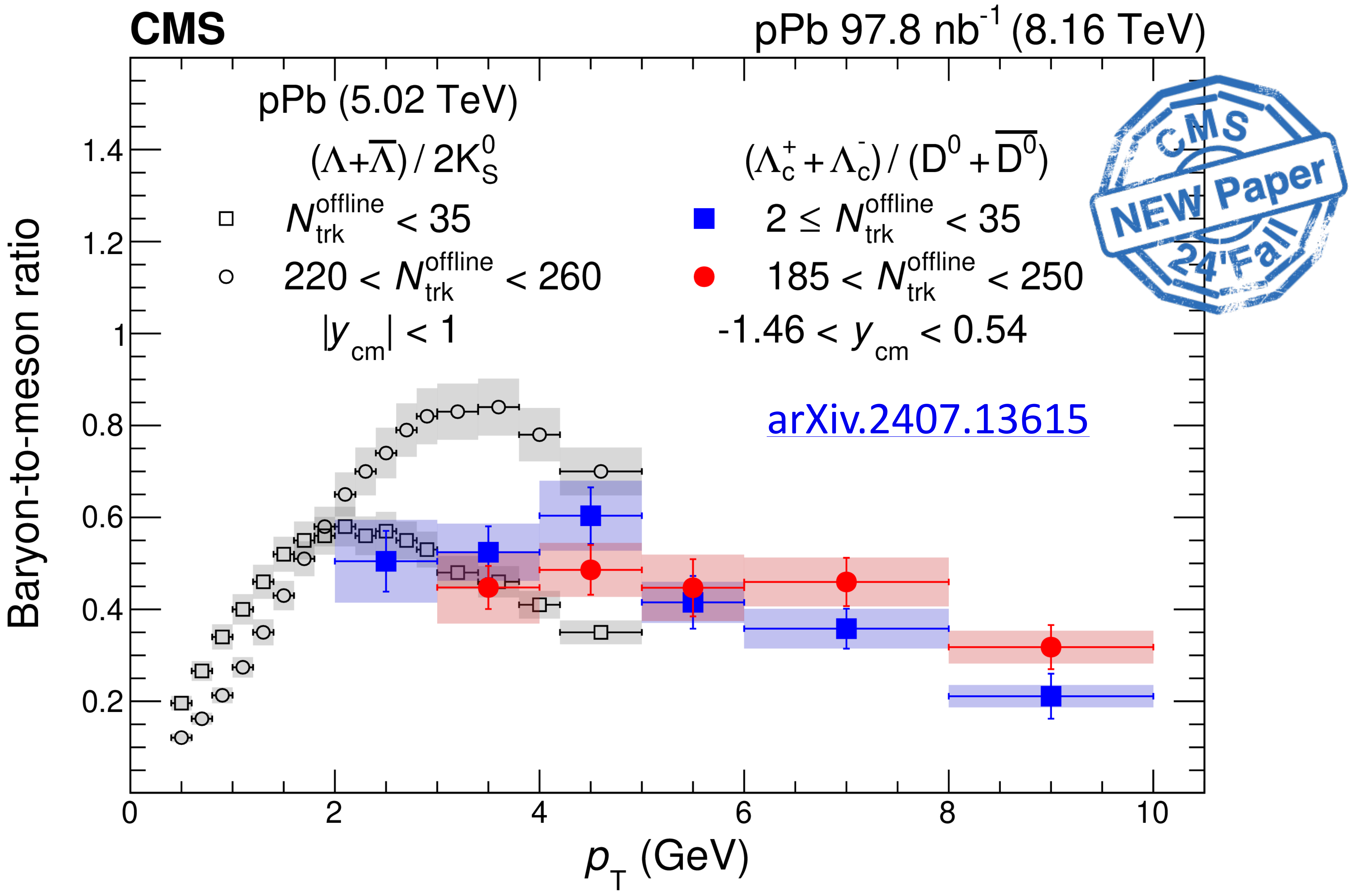
Systematic uncertainty

Source	Λ_c^+ (%)	D^0 (%)
Selections	2–6	1–5
Fit	6–28	<2
b feed-down	3–11	<15
Tracking efficiency	7	5
Pileup effects	3–6	<1
Branching fraction	5	1
Total	10–32	5–16

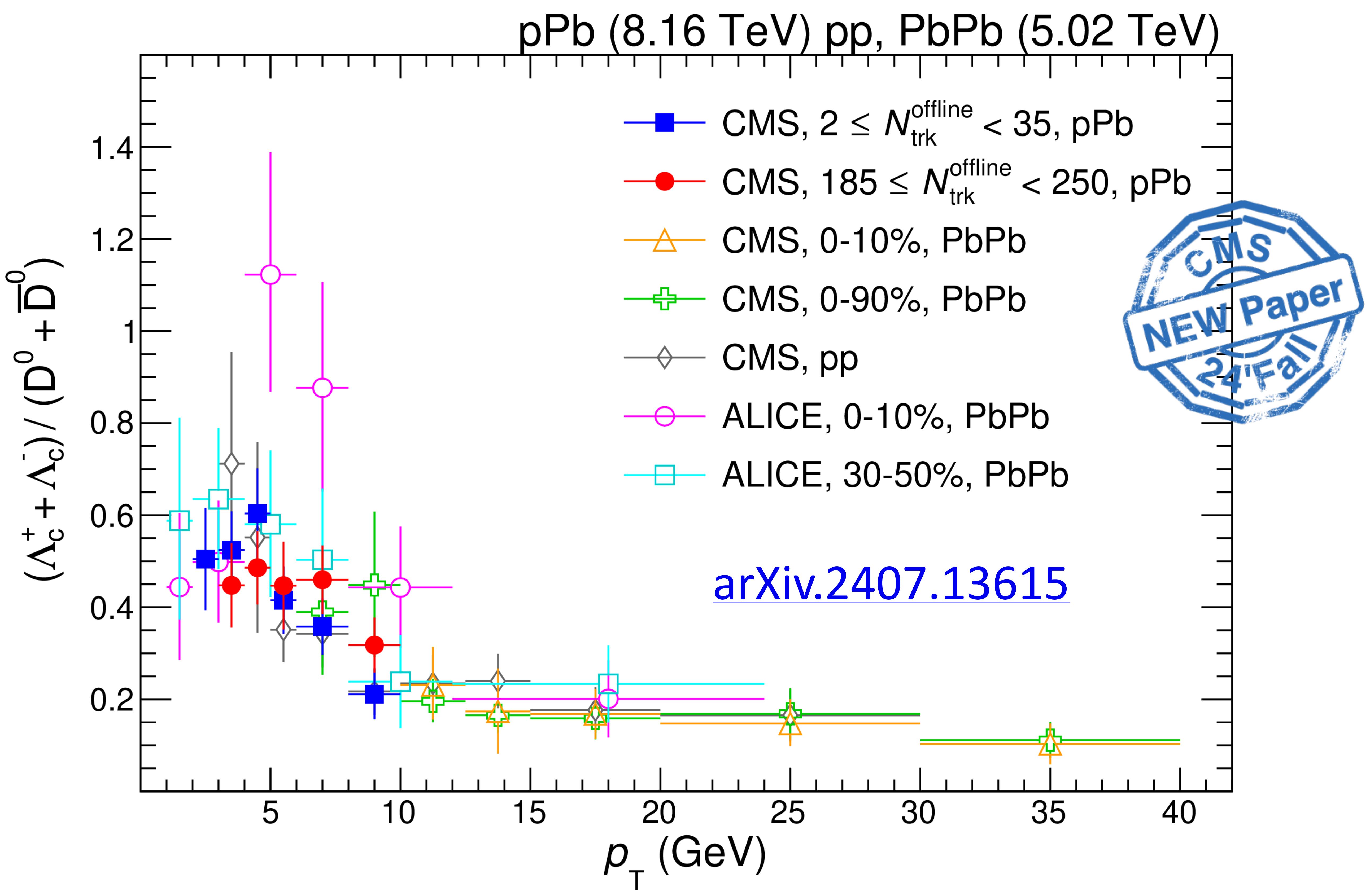
- Selected Λ_c^+ candidates with $|M_{\pi^+\pi^-} - M_{K_S^0}| < 0.02$ GeV, $|M_{K_S^0 p} - M_{\Lambda_c^+}| < 0.2$ GeV, $|M_{K^-\pi^+} - M_{D^0}| < 0.2$ GeV for D^0
- Raw yield extracted from extended maximum likelihood fit.
  - Λ_c^+ prompt fraction (f^{prompt}) estimated from FONLL + LHCb Λ_b^0 data (A scaled)
  - DCA based template fit to extract f^{prompt} for D^0 result

Results

Differential yield = $\frac{f^{\text{prompt}} N^{\text{sig}}}{2\alpha\varepsilon\Delta p_{\mathrm{T}}} \frac{1}{\mathscr{B}}$

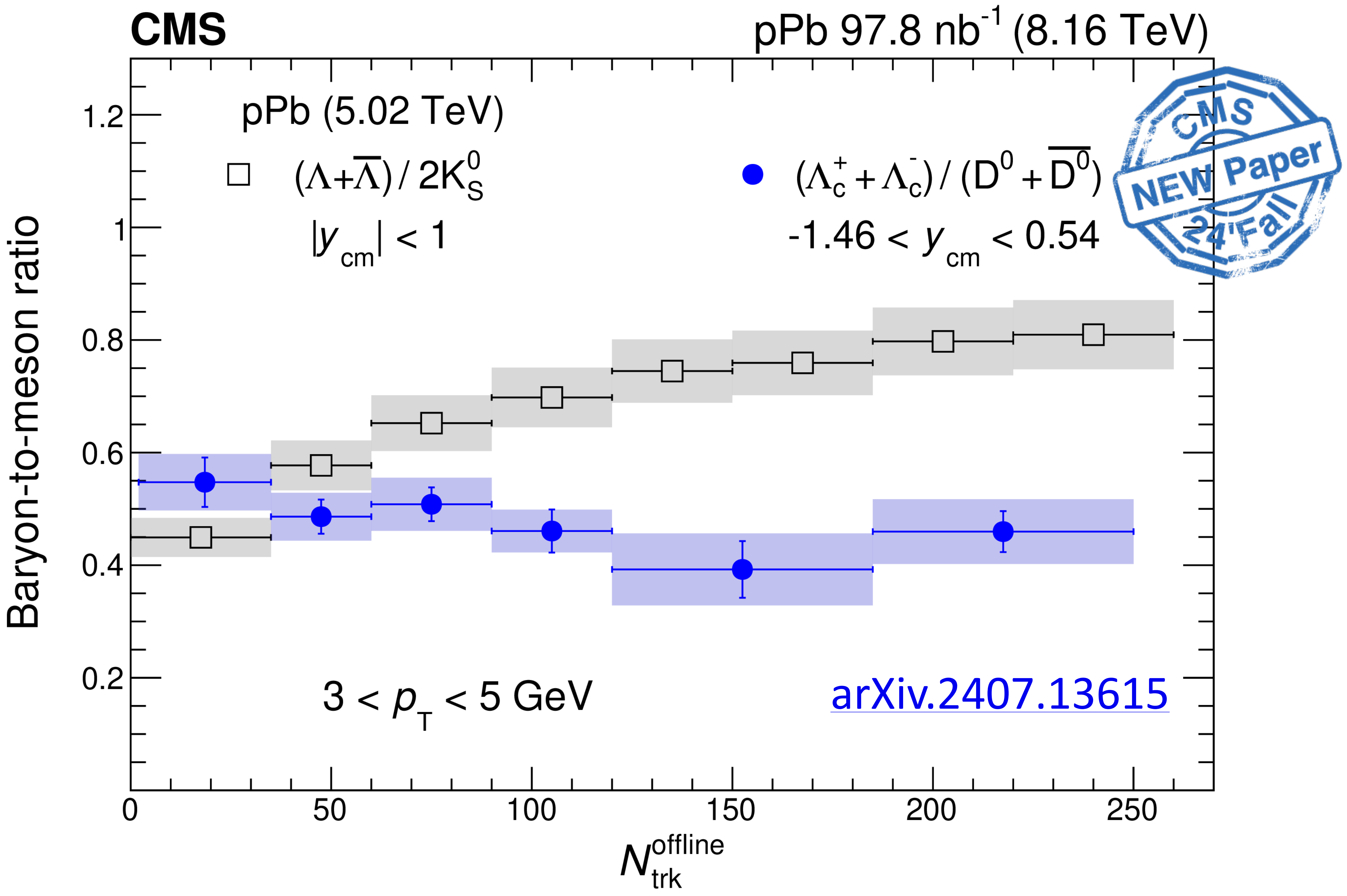


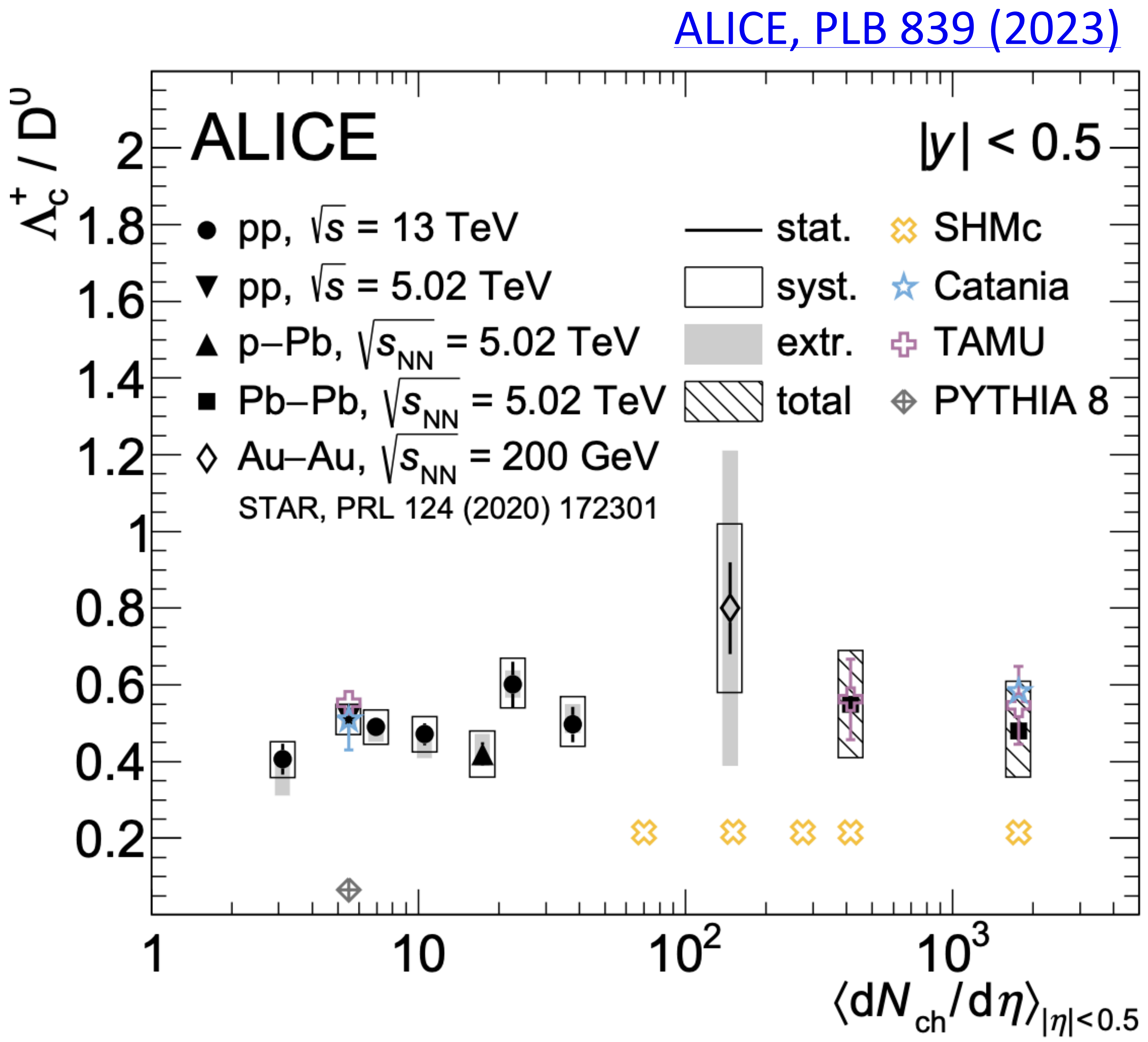
- Ratios of high and low multiplicity result compatible, decreasing with increasing p_{T}
  - Clear difference in trend for 3 GeV compared to strange sector →flavor dependent mechanism in roll



- High multiplicity pPb collision data comparable to semi-central PbPb
  - Also comparable to pp, large deviation seen only in central PbPb collision
- Ratio converges to same slope in higher $p_T \rightarrow$ less sensitivity to surrounding for fast escaping particles

Results

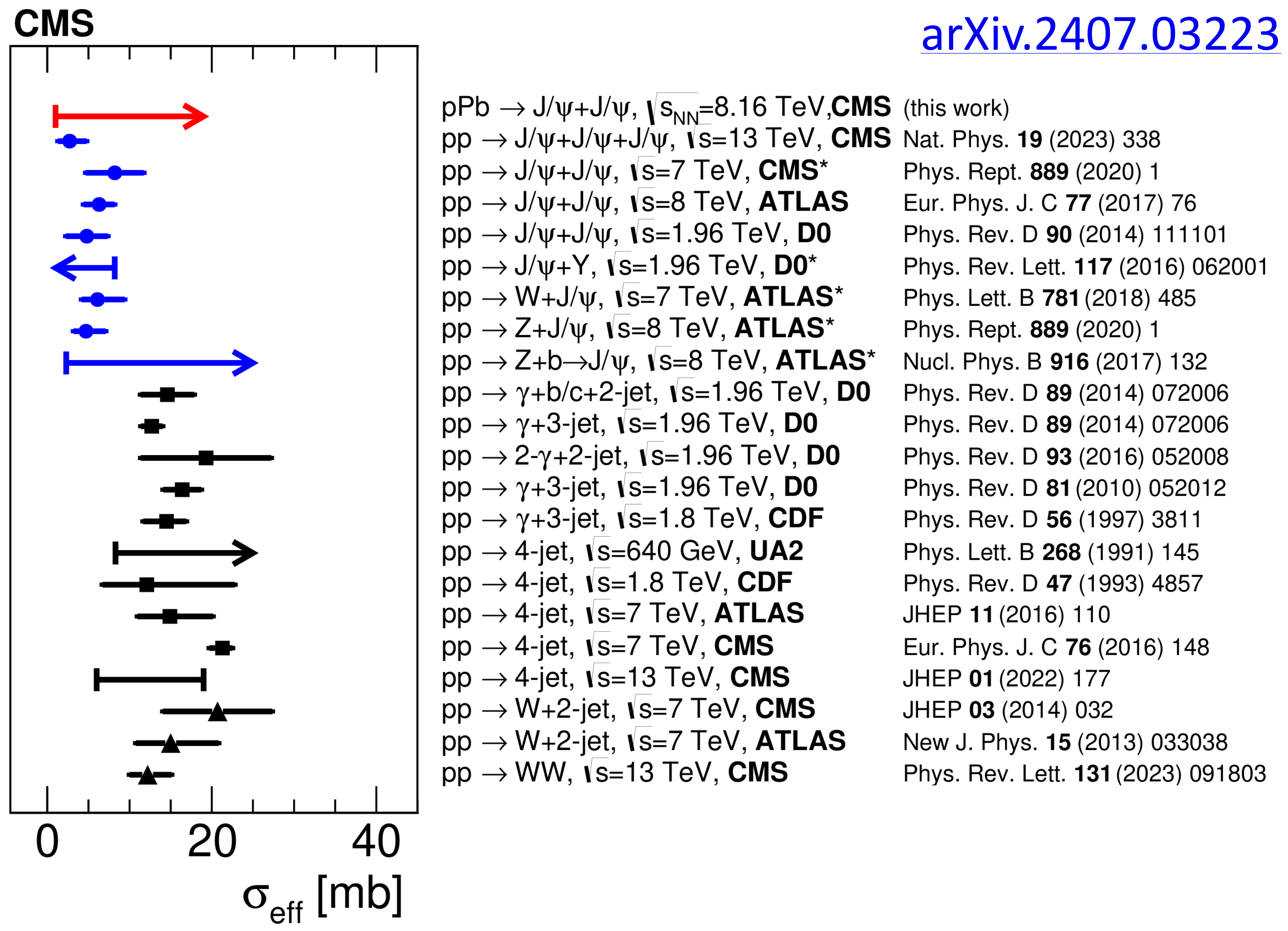


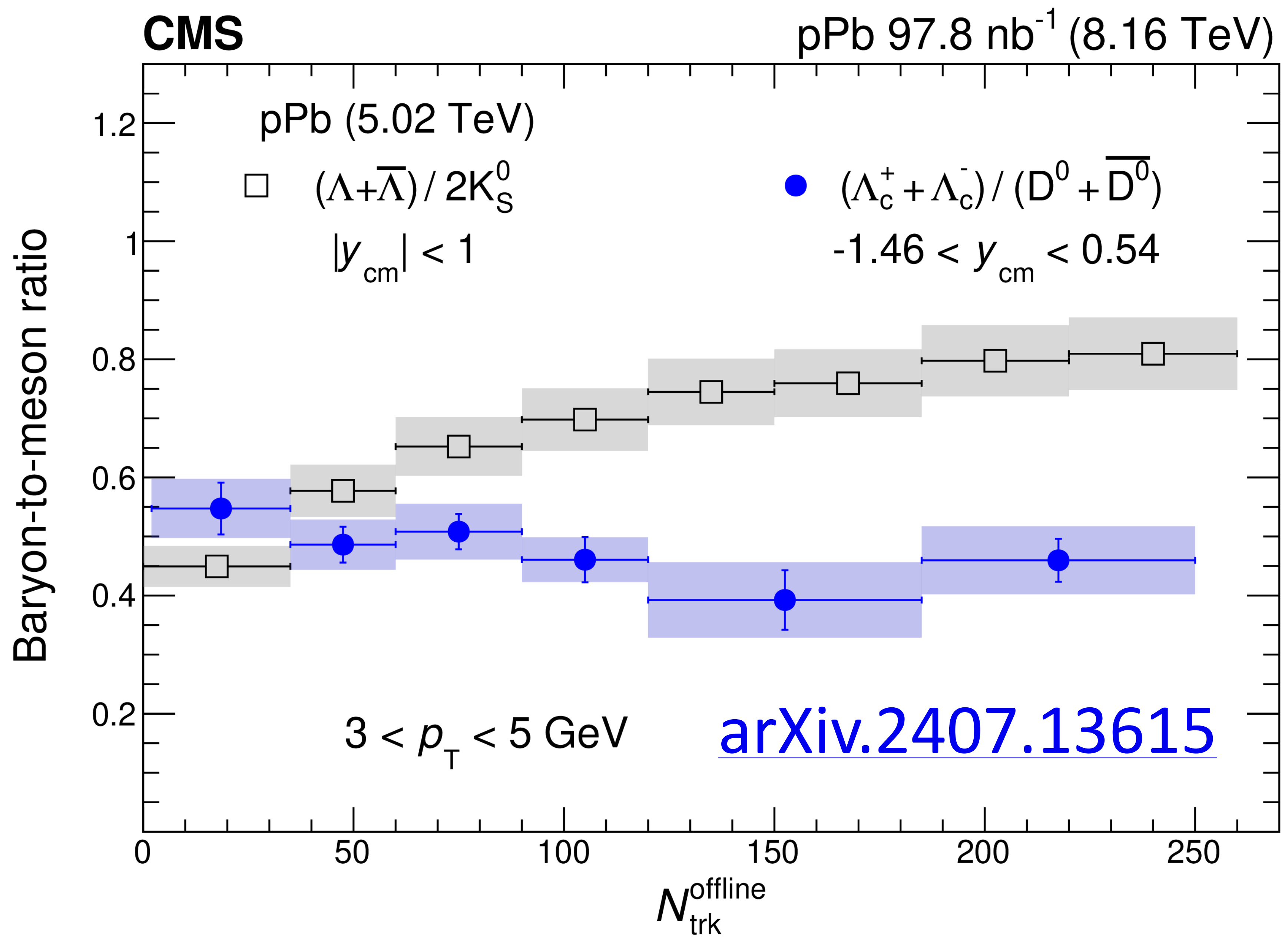


- Comparison of ratio from strange sector show flatter trend for charm consistent with ALICE result
  - Different hadronization timing (earlier for HF)?

Summary

- Associated production of charmonium via $J/\psi + J/\psi$
  - Independent extraction of σ_{eff}, compatible with pp result
    - Room for improvement with better statistical power
- Heavy quark hadronization in dense final state?
  - Coalescence maybe only in scene for c quark in central nuclear collision
  - Recent data suggest hadronization in action in earlier stage than light quarks

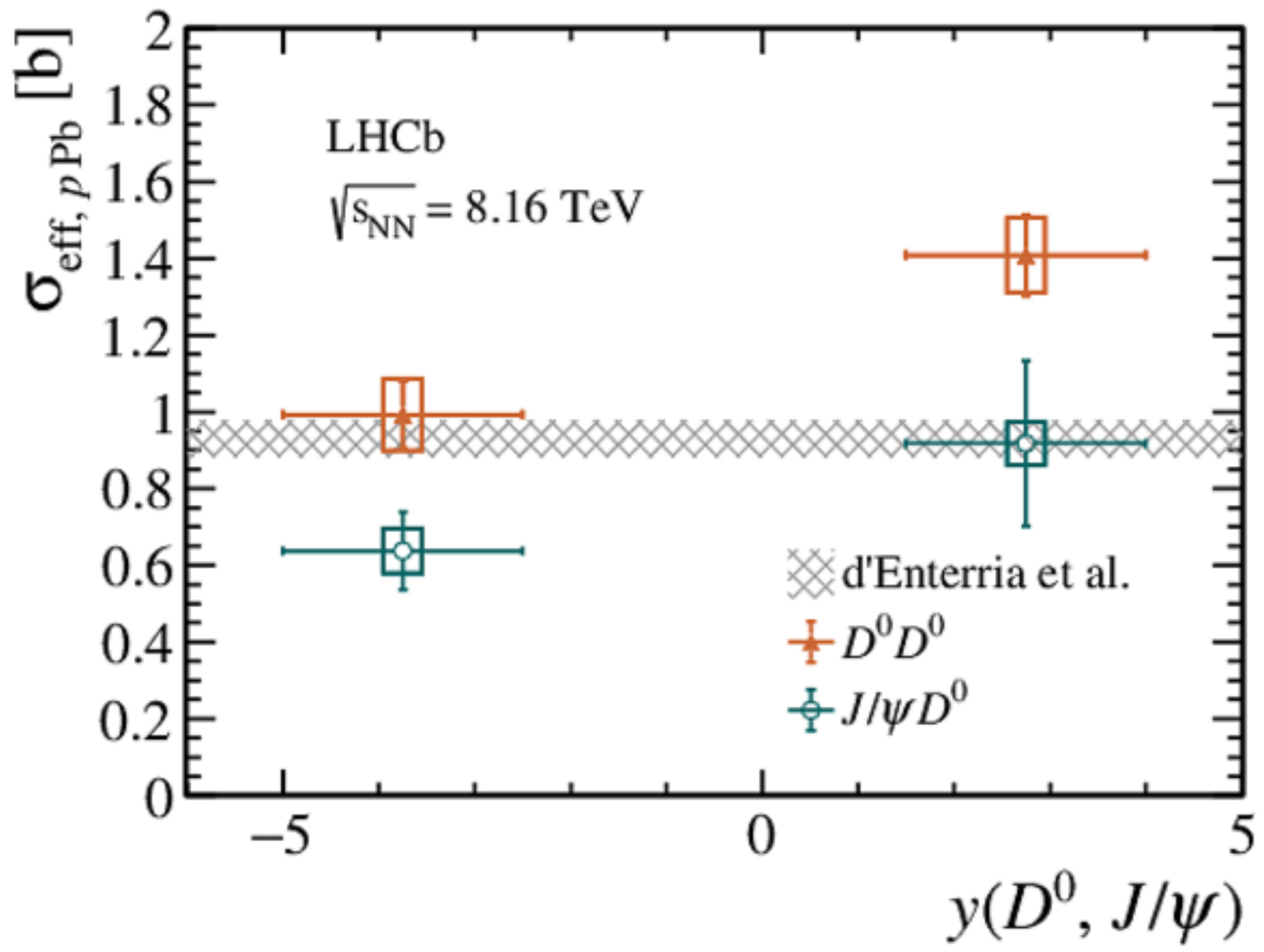




Thank you

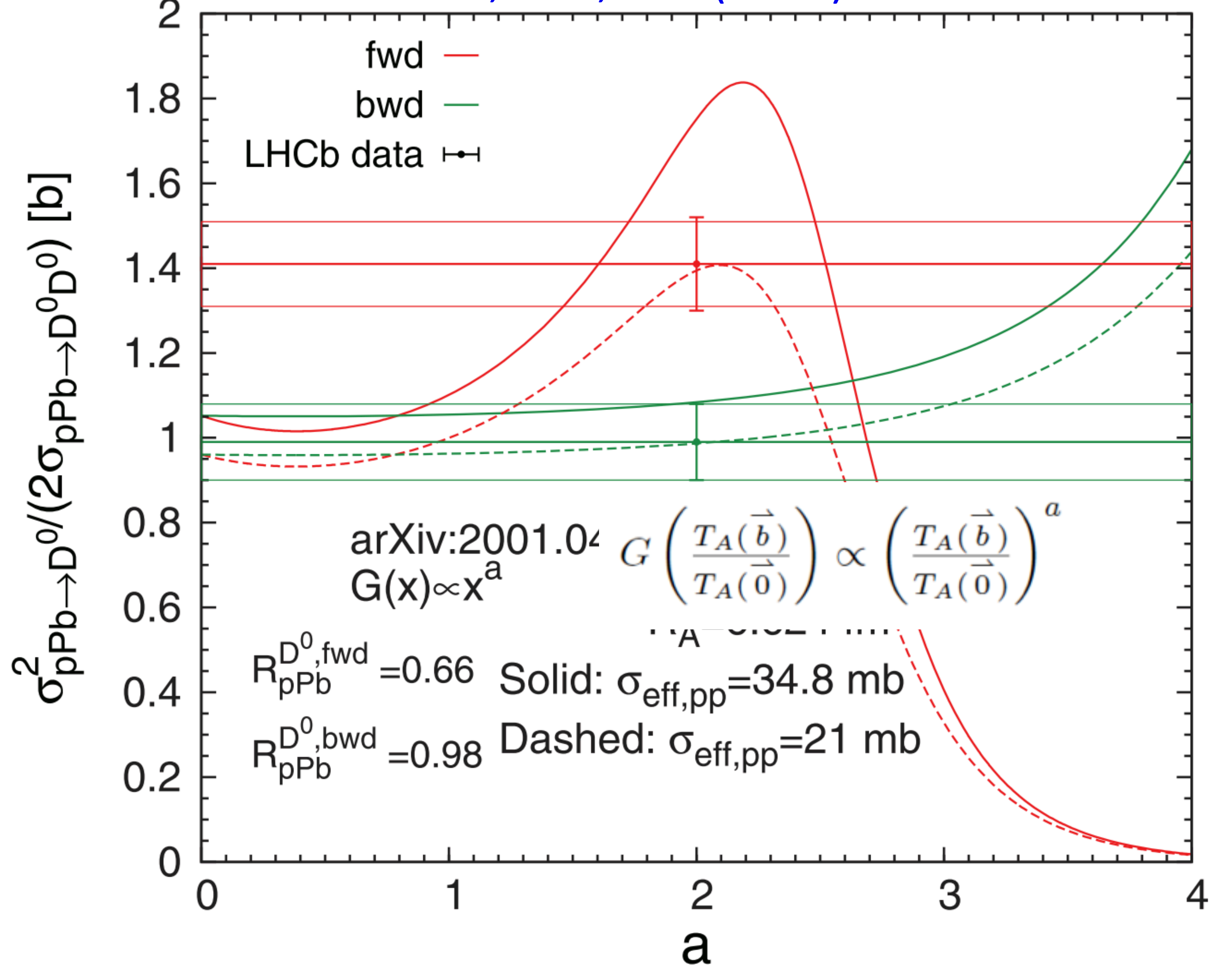
Future works

LHCB-PAPER-2020-010 (PRL 125 (2020) 212001)



- LHCb study on associated D^0 production in pPb measures $\sigma_{\mathrm{eff,pp}}$
  - Limit for pure geometric approach
    - J/ψ-D^0 vs. D^0D^0, forward/backward difference
  - Another way of probing transverse gluon PDF (shadowing)

Shao H.-S., PRD, 101 (2020) 054036



- Double heavy flavor production study in pPb collision continues ..

  Better statistical power with D^0?

  Stay tuned for future CMS results!

UNDER CONSTRUCTION

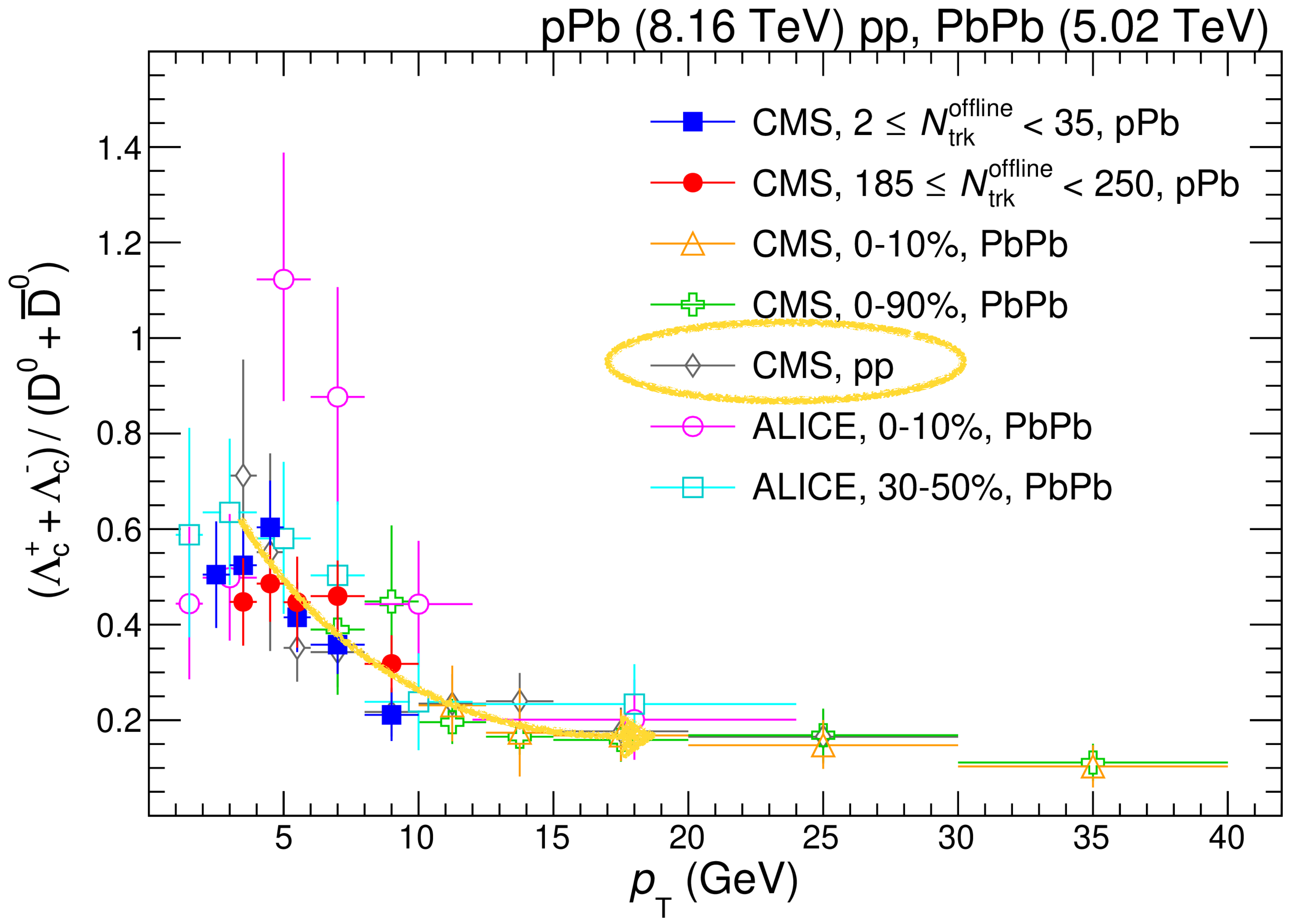
$G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a$

Analysis fiducial region

Particle	Fiducial requirement
Muons	$p_T > 3.4\,\text{GeV}$ for $\lvert\eta\rvert < 0.3$
	$p_T > 3.3\,\text{GeV}$ for $0.3 < \lvert\eta\rvert < 1.1$
	$p_T > 5.5\text{–}2.0\lvert\eta\rvert\,\text{GeV}$ for $1.1 < \lvert\eta\rvert < 2.1$
	$p_T > 1.3\,\text{GeV}$ for $2.1 < \lvert\eta\rvert < 2.4$
J/ψ mesons	$p_T > 6.5\,\text{GeV}$ and $\lvert y\rvert < 2.4$

- Fiducial σ (nb)
- $\sigma_{\text{SPS}}^{\text{pPb}\to J/\psi J\psi + X} = 16.5 \pm 10.8\,(\text{stat}) \pm 0.1\,(\text{syst})$
- $\sigma_{\text{DPS}}^{\text{pPb}\to J/\psi J\psi + X} = 5.4 \pm 6.2\,(\text{stat}) \pm 0.4\,(\text{syst})$

c vs. b



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