



Heavy Quark production and energy loss: Experiments

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Why we like heavy quarks?

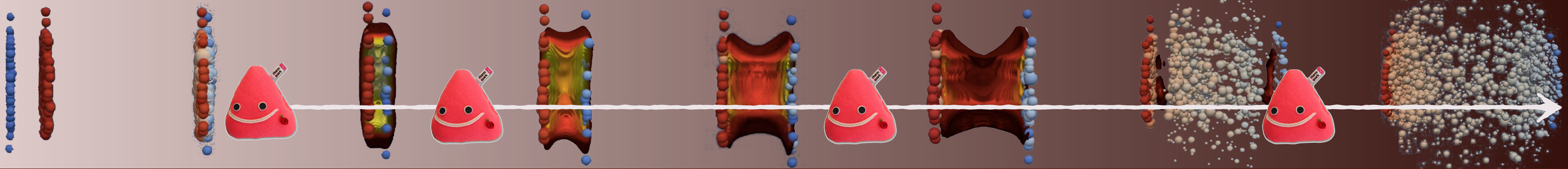
BESTSELLERS

- Higgs boson \$11.99
- Photon \$11.99
- Electron-neutrino \$11.99
- Proton \$11.99
- Charm quark \$11.99**
- Big Proton with Mini Quarks and Gluon \$41.99

Charm quark/粲夸克

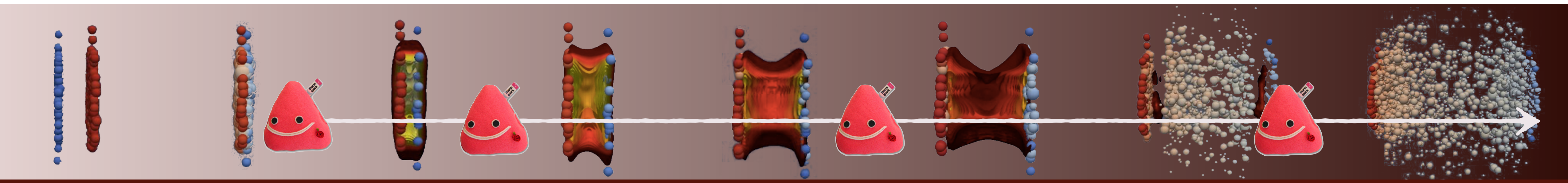
**Particle zoo
Best-selling quark!**

Why we like heavy quarks?



- Produced in **initial hard scatterings** (< 0.1 fm)
 - $(m_c, m_b \gg T_{\text{QGP}})$
 - Bring info of early stage
- Production **cross section calculable with pQCD**
 - $(m_c, m_b \gg \Lambda_{\text{QCD}})$
 - Slow “hard probes”
- Possible to probe the **strong and short lived EM-field**
 - Different response for opposite charges
- **Energy loss**
 - pQCD: collisional + radiative
 - AdS/CFT: drag force
 - **Mass hierarchy**: dead cone effect
- **Diffusion: Brownian motion**
 - Spatial **diffusion coefficient** D_s
- **Hadronization**
 - **Keep identity**
 - Charm number conservation

Why we like heavy quarks?



- Produced in **initial hard scatterings** (< 0.1 fm)
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- Energy loss**
 - \rightarrow pQCD: collisional + radiative
 - \rightarrow AdS/CFT: drag force
 - \rightarrow Mass hierarchy: dead cone effect
- Diffusion: Brownian motion**
 - \rightarrow Spatial diffusion coefficient D_s

- Hadronization**
 - \rightarrow Keep identity
 - \rightarrow Charm number conservation

Modification in pA

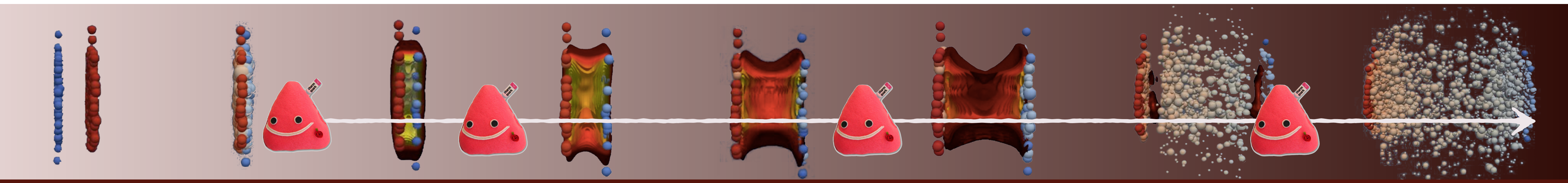
Azimuthal anisotropy v_n

Correlations

R_{AA}

Baryon/meson

Why we like heavy quarks?



↑ nPDF

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 - $\rightarrow (m_c, m_b \gg T_{\text{QGP}})$
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- Production cross section calculable with pQCD**
 - $\rightarrow (m_c, m_b \gg \Lambda_{\text{QCD}})$
 - \rightarrow Slow “hard probes”

↑ Initial fluctuations

- Possible to probe the **strong and short lived EM-field**
 - \rightarrow Different response for opposite charges

↑ Energy loss

- \rightarrow pQCD: collisional + radiative
- \rightarrow AdS/CFT: drag force
- \rightarrow Mass hierarchy: dead cone effect

Diffusion: Brownian motion

- \rightarrow **Spatial diffusion coefficient D_s**

• Hadronization

- \rightarrow Keep identity
- \rightarrow Charm number conservation

Modification in pA

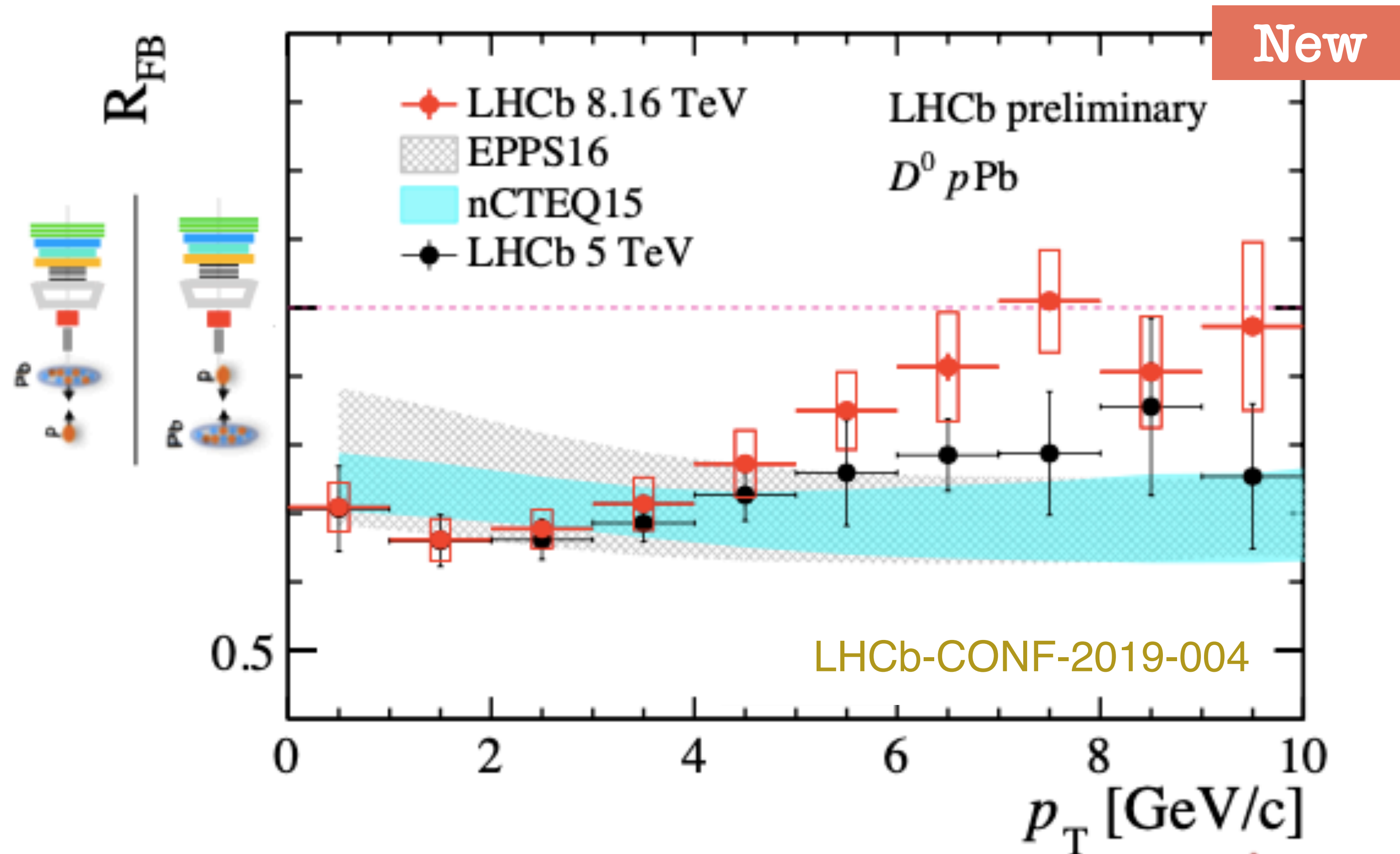
Azimuthal anisotropy v_n

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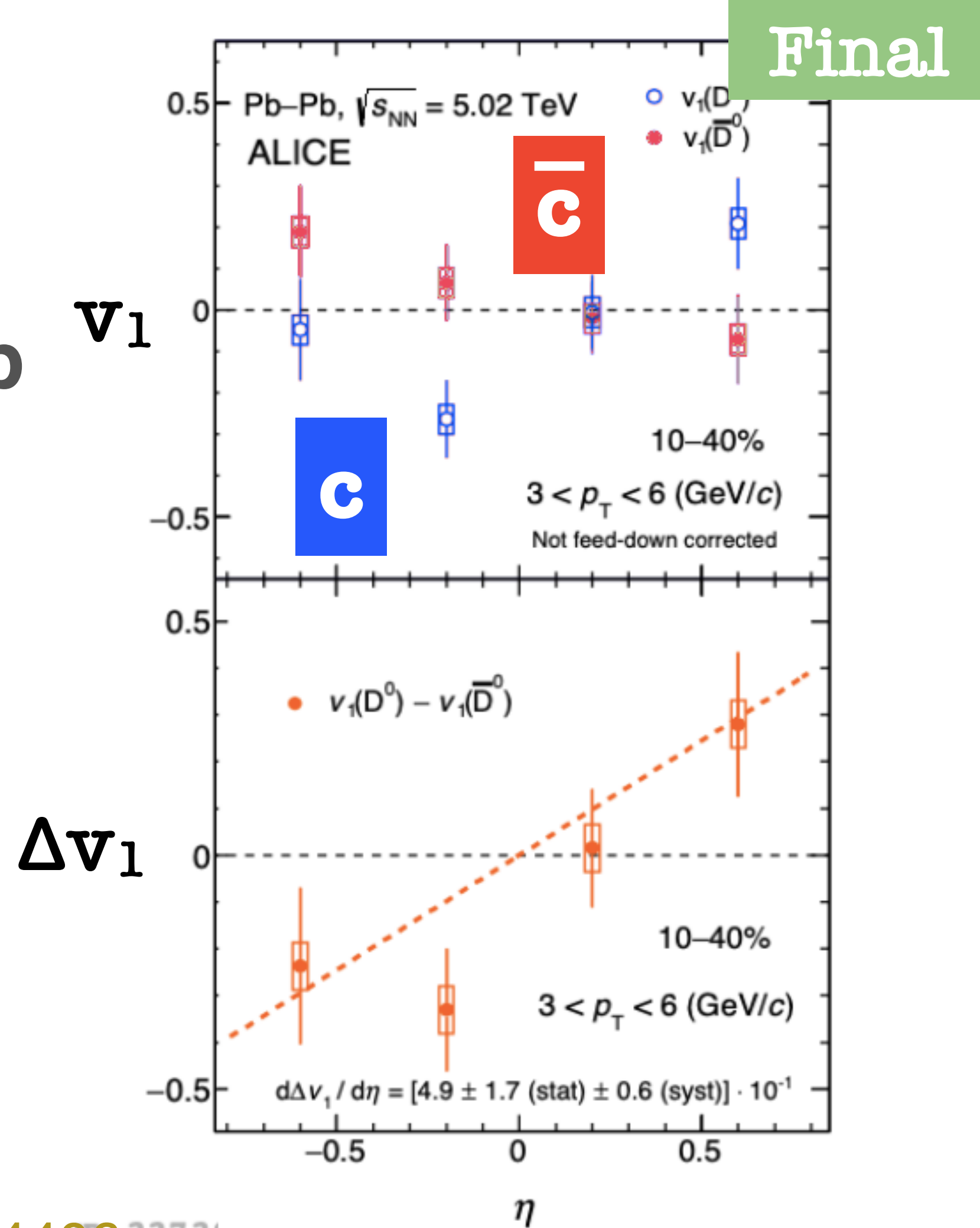
Constrain nPDF



- D meson in pPb contributes to constraining gluon nPDF down to $x \sim 10^{-5}$
- Tension between data and nPDF model predictions?

Probing the strong initial EM-field

ALICE
 $D^0 v_1$
 in PbPb



arXiv:1910.14406

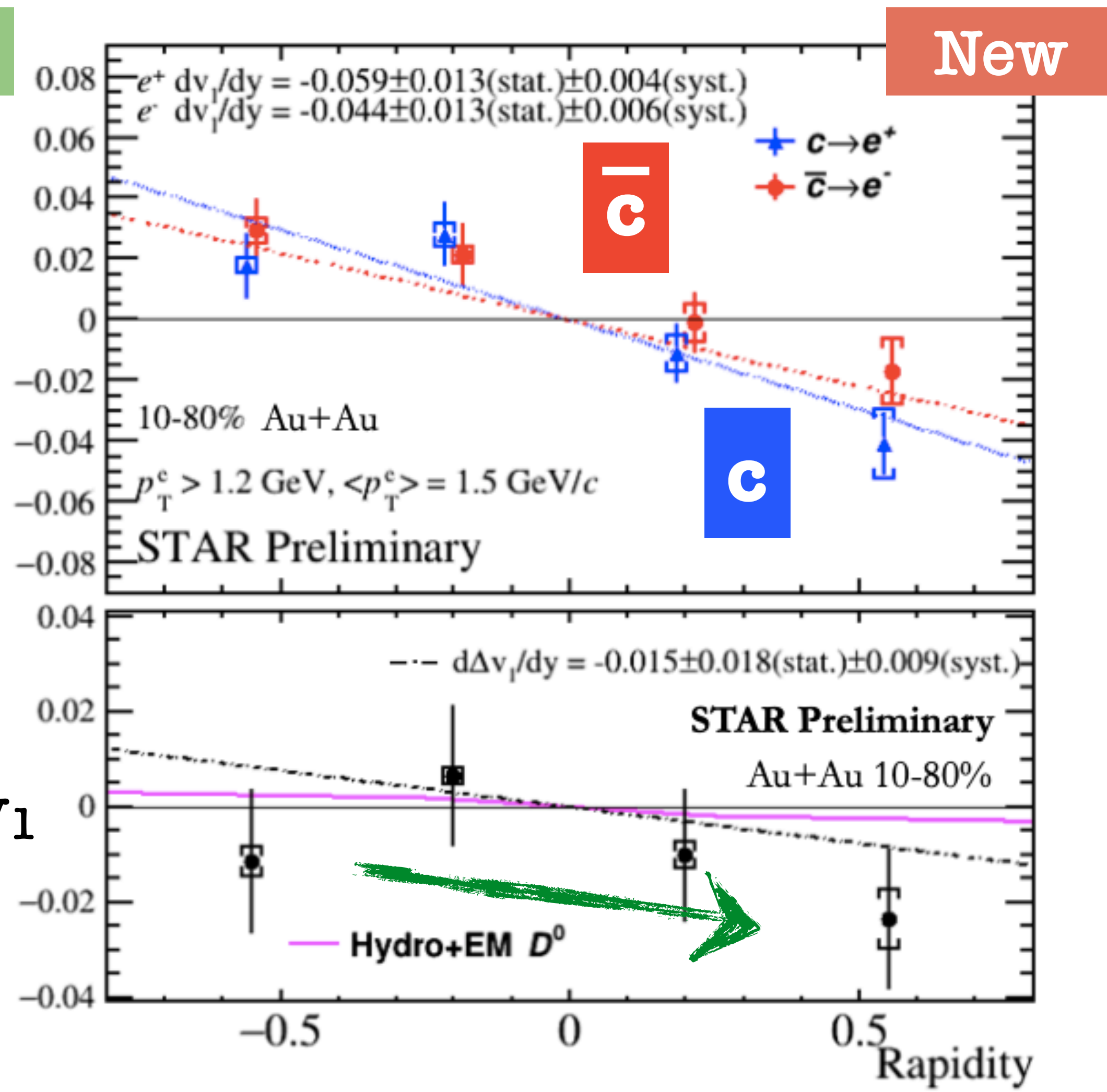
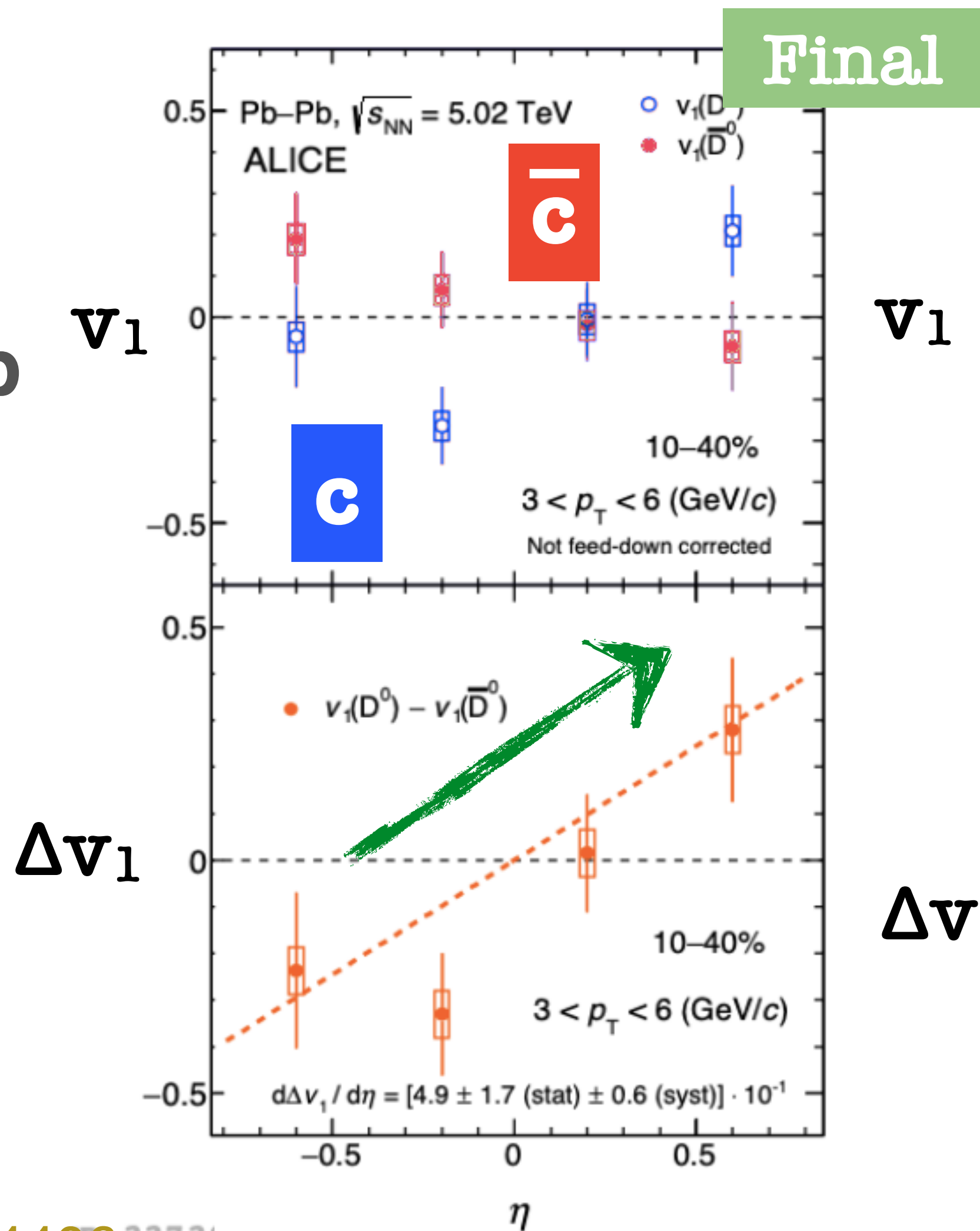
S. Tang 5 Nov, 16:40

M. Kelsey, 5 Nov, 17:40

- Δv_1 slope ($d\Delta v_1/d\eta$): slope(D^0) $\sim 10^{-1} \gg$ slope (h^\pm) $\sim 10^{-4}$

Probing the strong initial EM-field

ALICE
 $D^0 v_1$
 in PbPb



STAR
 $c \rightarrow e v_1$
 in AuAu

arXiv:1910.14406

S. Tang 5 Nov, 16:40

M. Kelsey, 5 Nov, 17:40

- $d\Delta v_1/d\eta$ slope: negative (RHIC) vs. positive(LHC)?

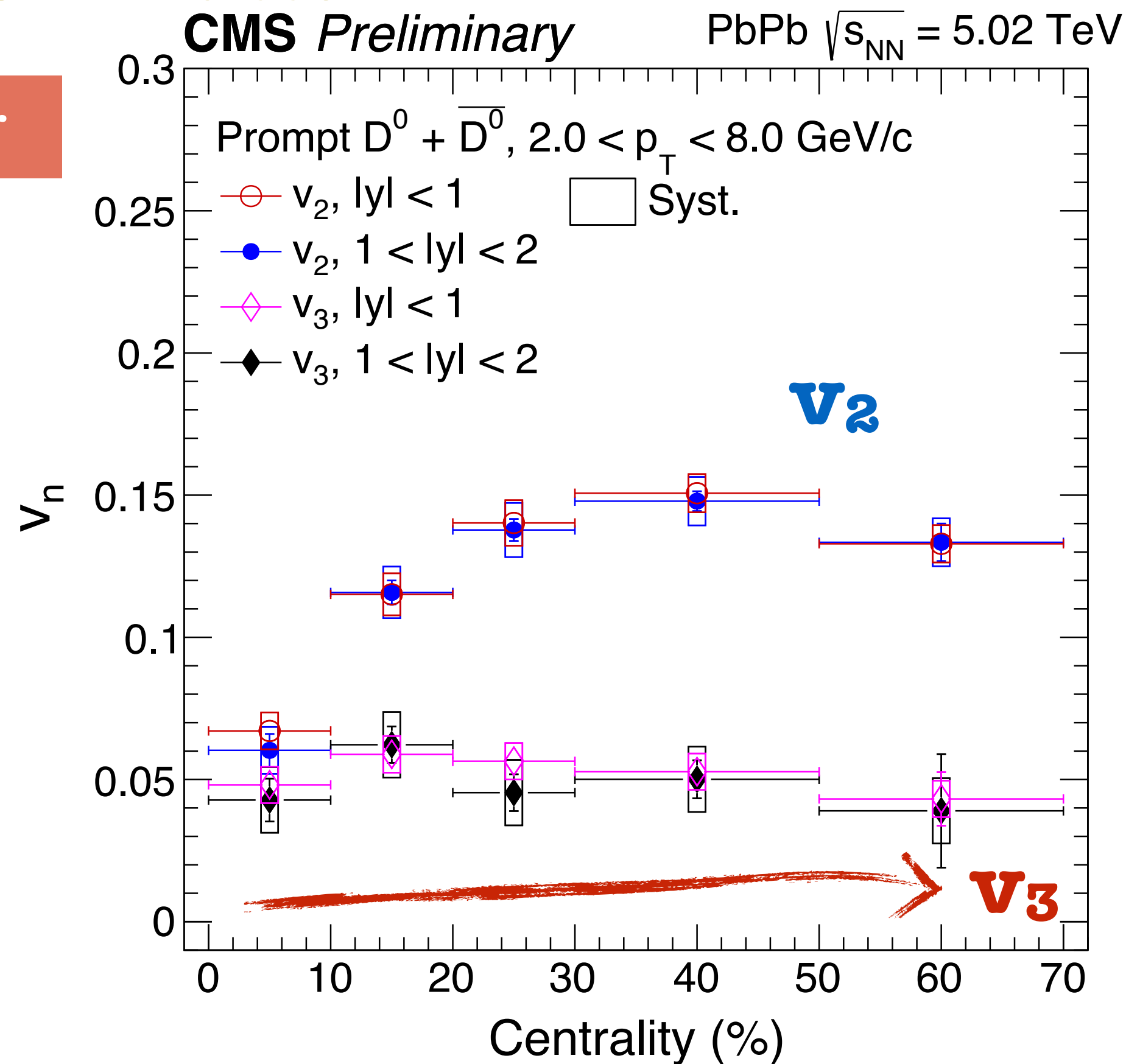
Probing initial fluctuations: heavy flavor v_3

CMS-PAS-HIN-19-008

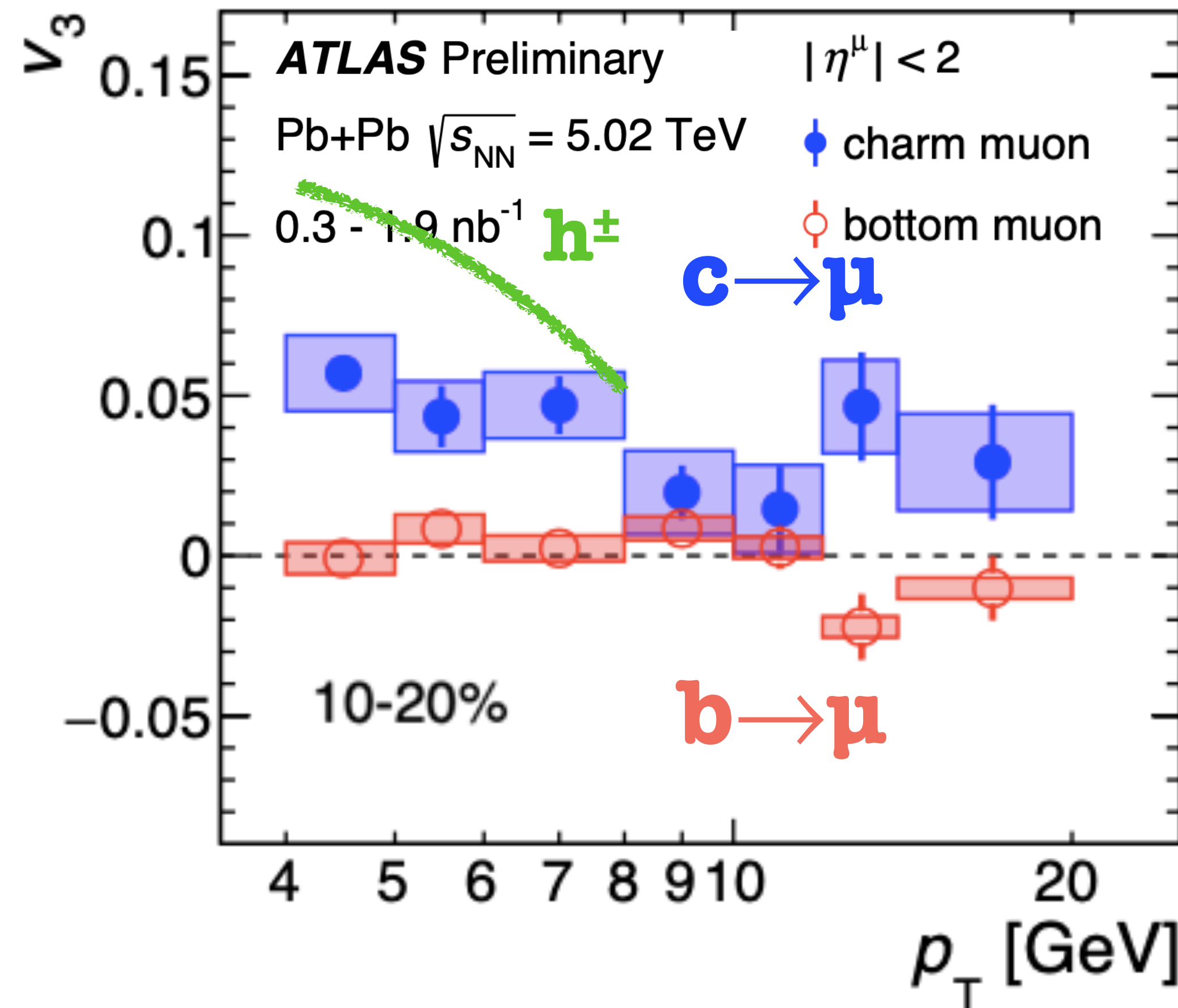
v_3 in PbPb

ATLAS-CONF-2019-053

New



- No centrality dependence



New

- $v_3(h^\pm) > v_3(\text{charm}) > v_3(\text{beauty}) \approx 0$



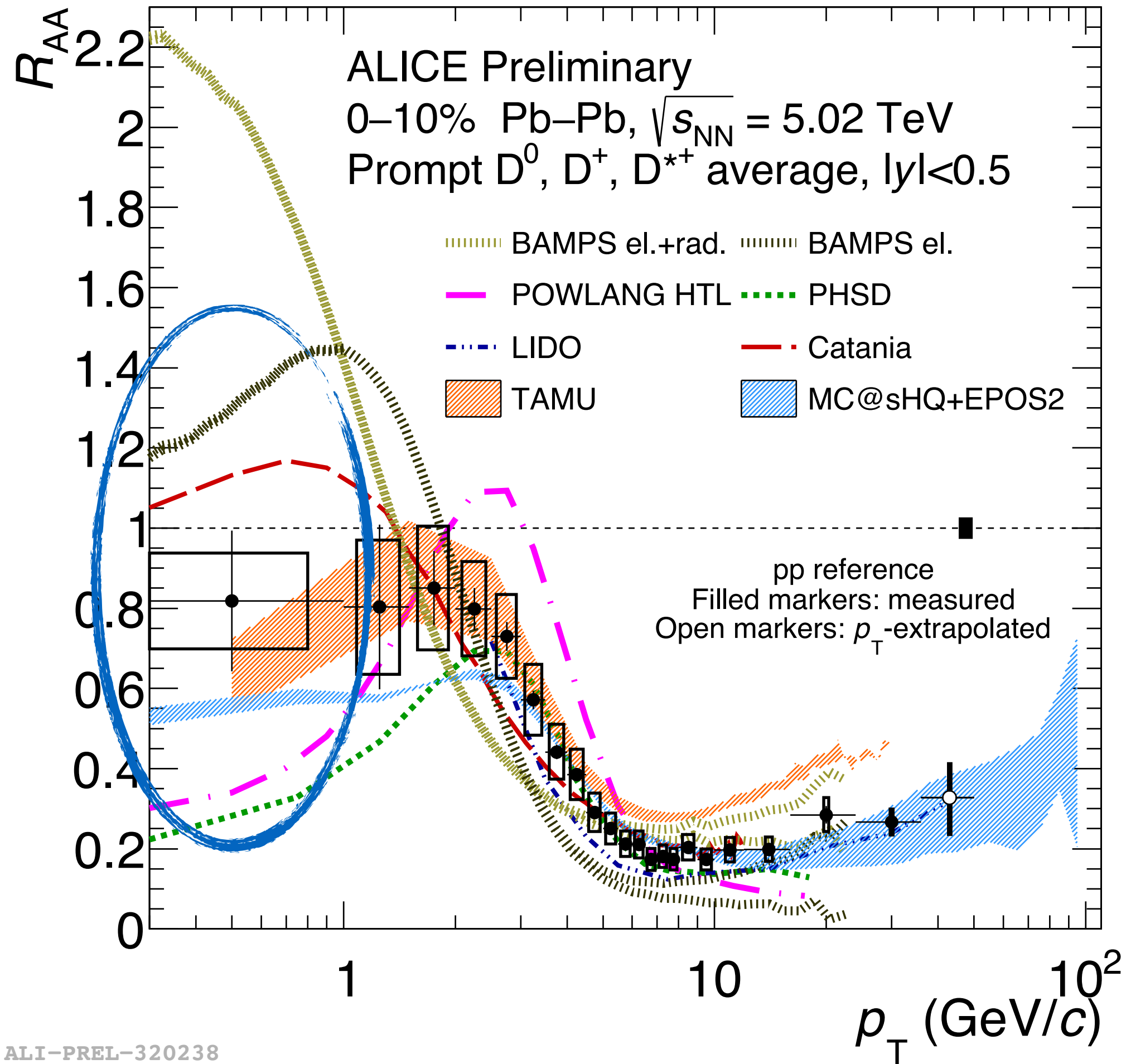
Take-home note (I): Initial stages

New knowledge

- ✓ D meson **constrains nPDF** down to $x \sim 10^{-5}$
- ✓ **Tension** between D^0 R_{FB} and nPDF model predictions
- ✓ $d\Delta v_1/d\eta$ to detect strong initial **EM-field**:
 - ➔ **slope(D^0)** \gg **slope(h^\pm)** observed in ALICE
 - ➔ **Different slope signs** between RHIC & LHC with large uncertainties
- ✓ Precise HF v_3 to probe initial fluctuations
 - ➔ **$v_3(h^\pm) > v_3(\text{charm}) > v_3(\text{beauty}) \approx 0$**

Energy loss in medium: Open *charm* R_{AA}

New

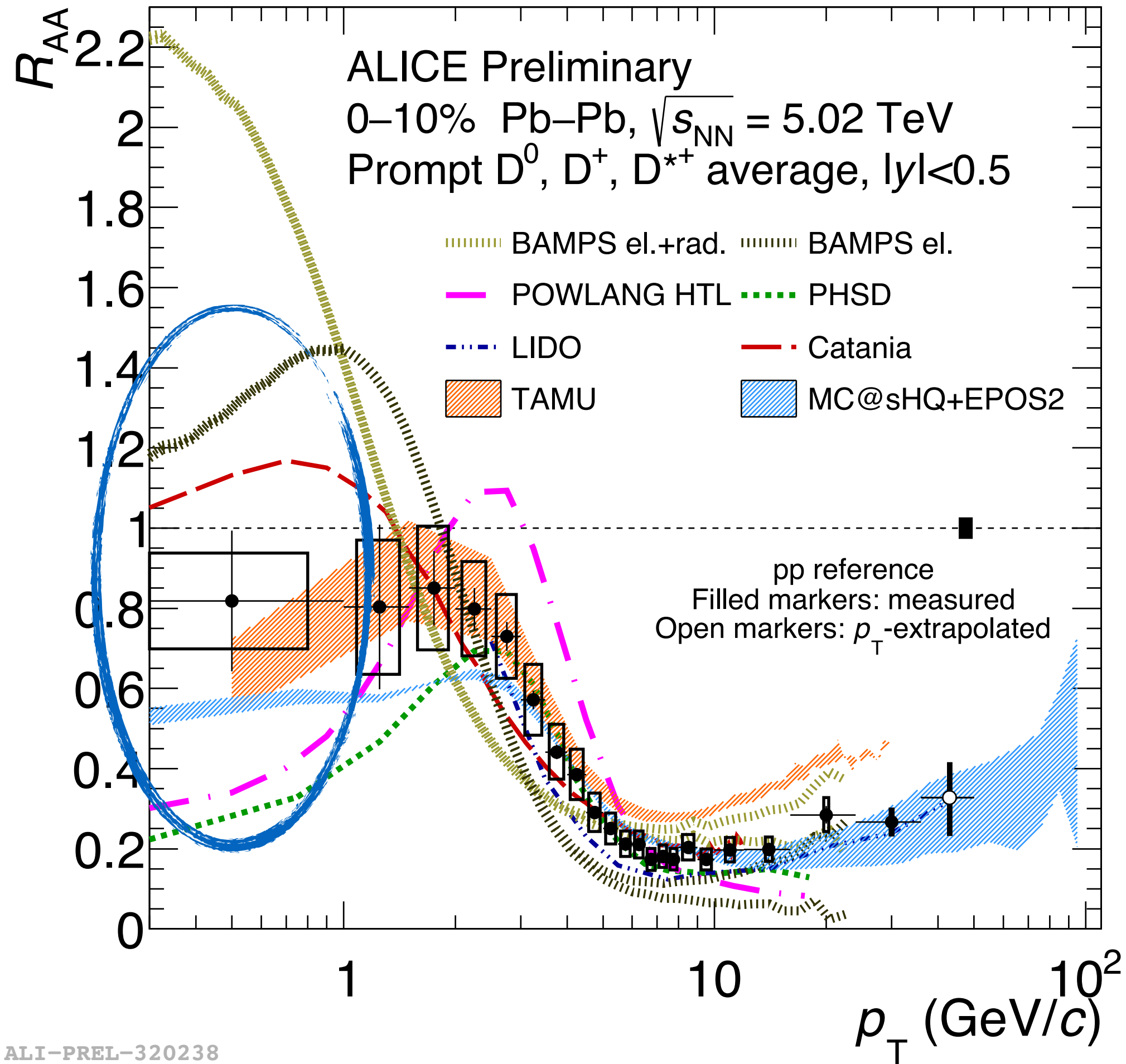


- Down to $p_T=0$ at LHC!
- Strong constraints to theories
 ➔ Interplay of radial flow, recombination, shadowing etc.

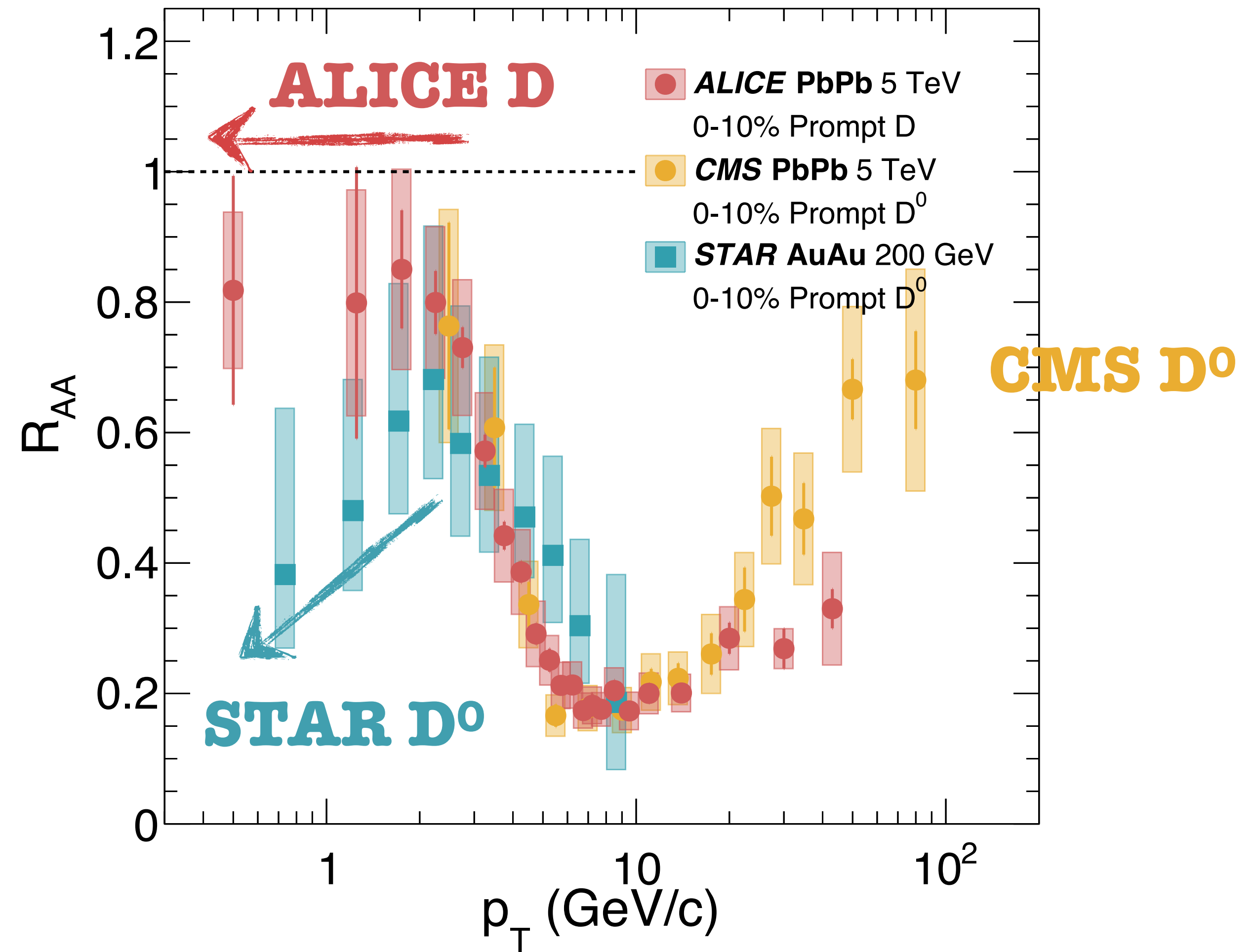


Energy loss in medium: Open *charm* R_{AA}

New



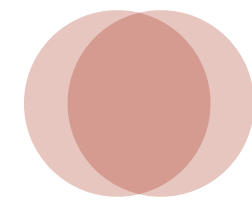
World open charm R_{AA} (0-10%)



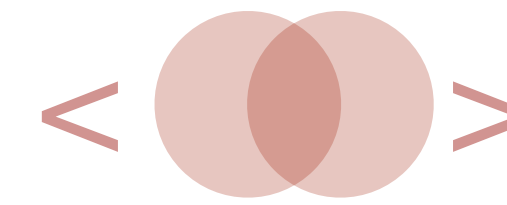
- Difference trend between LHC and RHIC?



Energy loss in medium: Open *beauty* R_{AA}



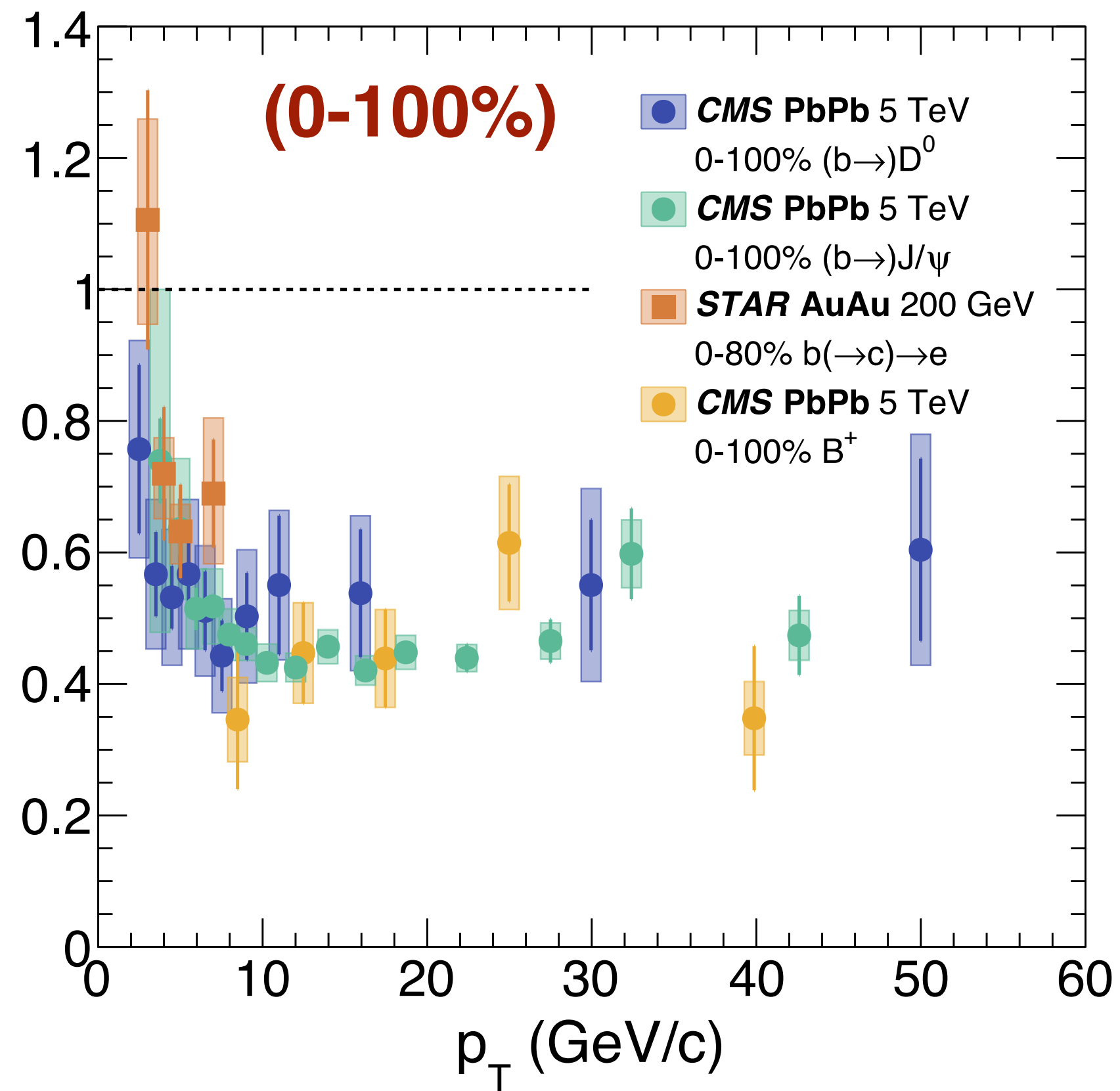
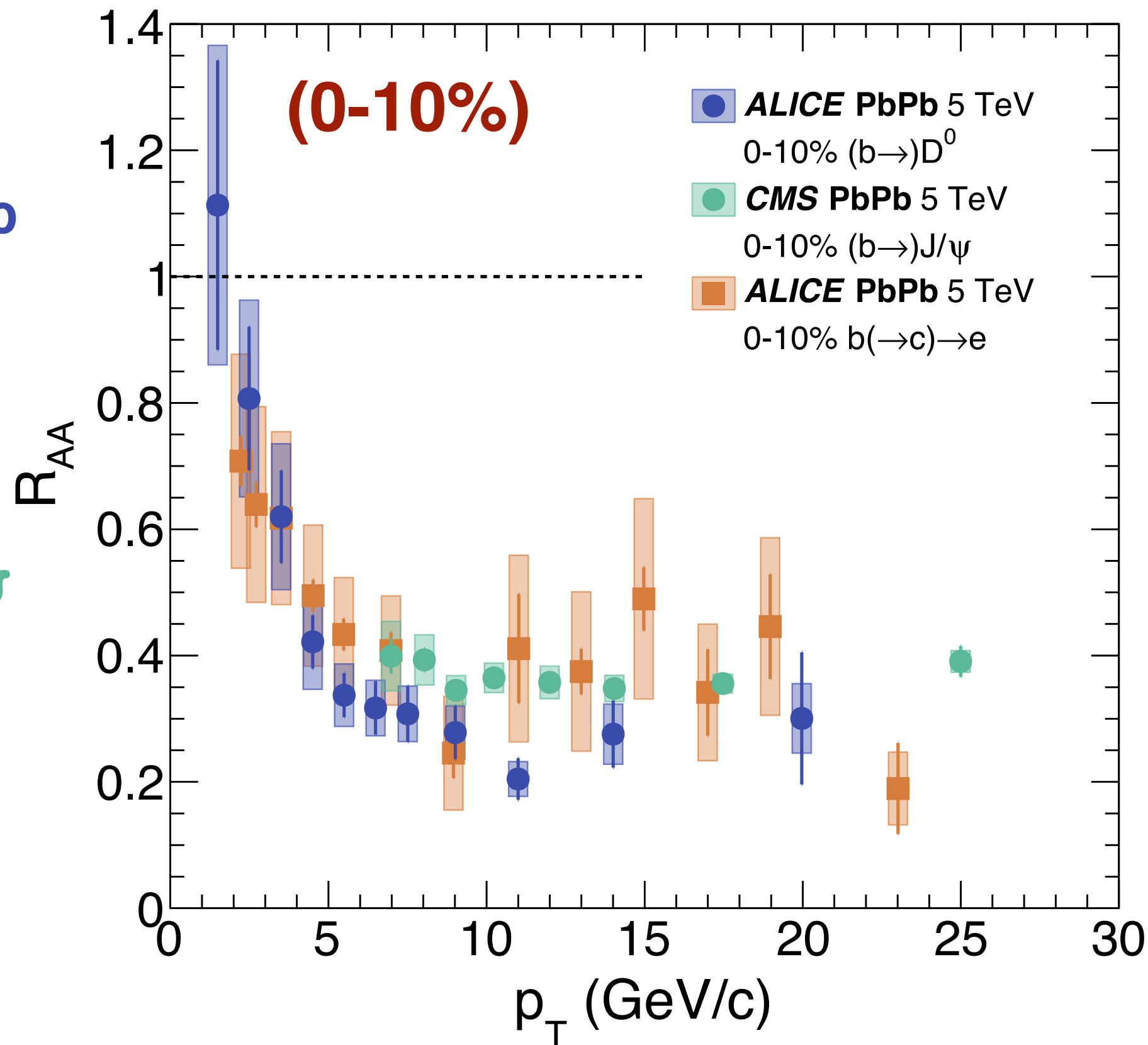
World open beauty R_{AA}



New!
ALICE $b \rightarrow D^0$

New!
ALICE $b \rightarrow e$

CMS $b \rightarrow J/\psi$



CMS $b \rightarrow D^0$

New!
STAR $b \rightarrow e$

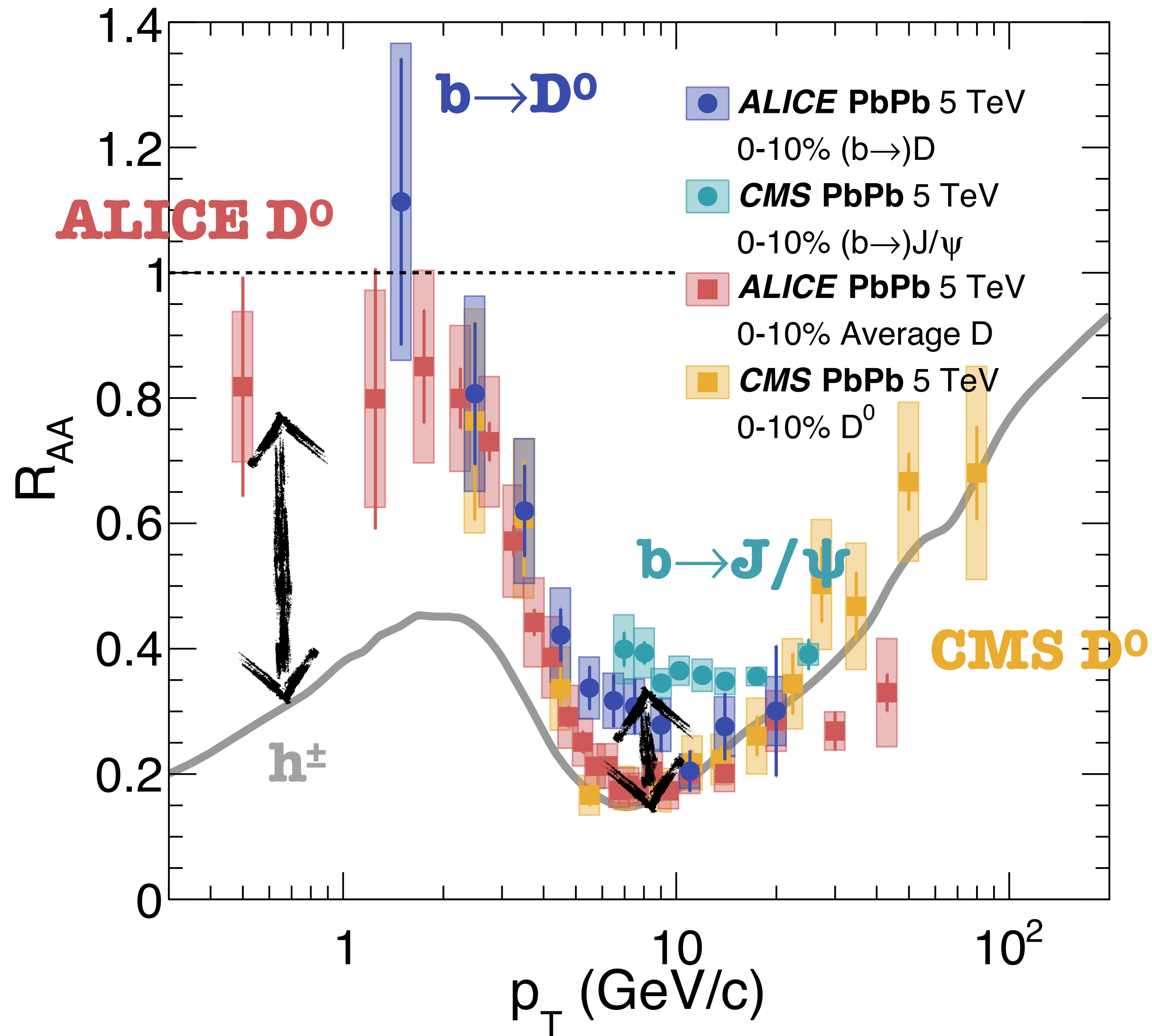
CMS $b \rightarrow J/\psi$

CMS B^+

• New players in the game!

M. Kelsey, 5 Nov, 17:40
 D. Thomas, 5 Nov, 12:00

Energy loss in medium: Flavor hierarchy



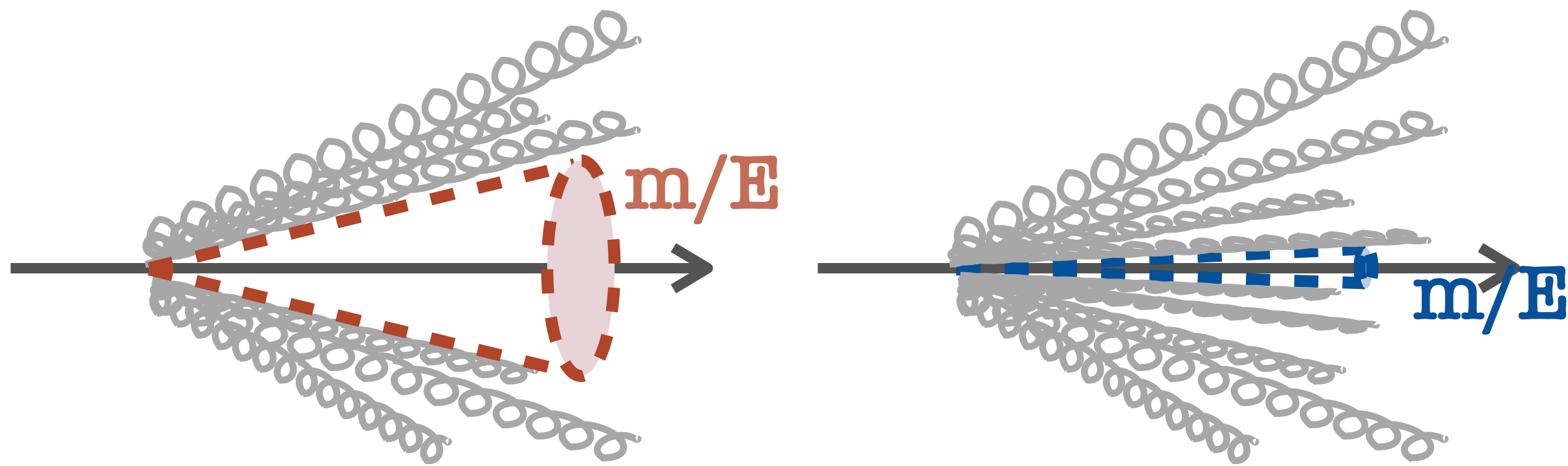
- Low- p_T :
 - ➔ $R_{AA}(\text{beauty}) ? R_{AA}(\text{charm}) > R_{AA}(\text{light})$
 - ➔ Radial flow? shadowing? etc
- Intermediate p_T :
 - ➔ $R_{AA}(\text{beauty}) > R_{AA}(\text{charm}) \approx R_{AA}(\text{light})$
 - ➔ Dead cone effect?

One source of flavor hierarchy: Dead cone effect

- **Dead cone effect**
 - ➔ Radiation (for both vacuum and medium induced) is suppressed inside $\theta < m/E$

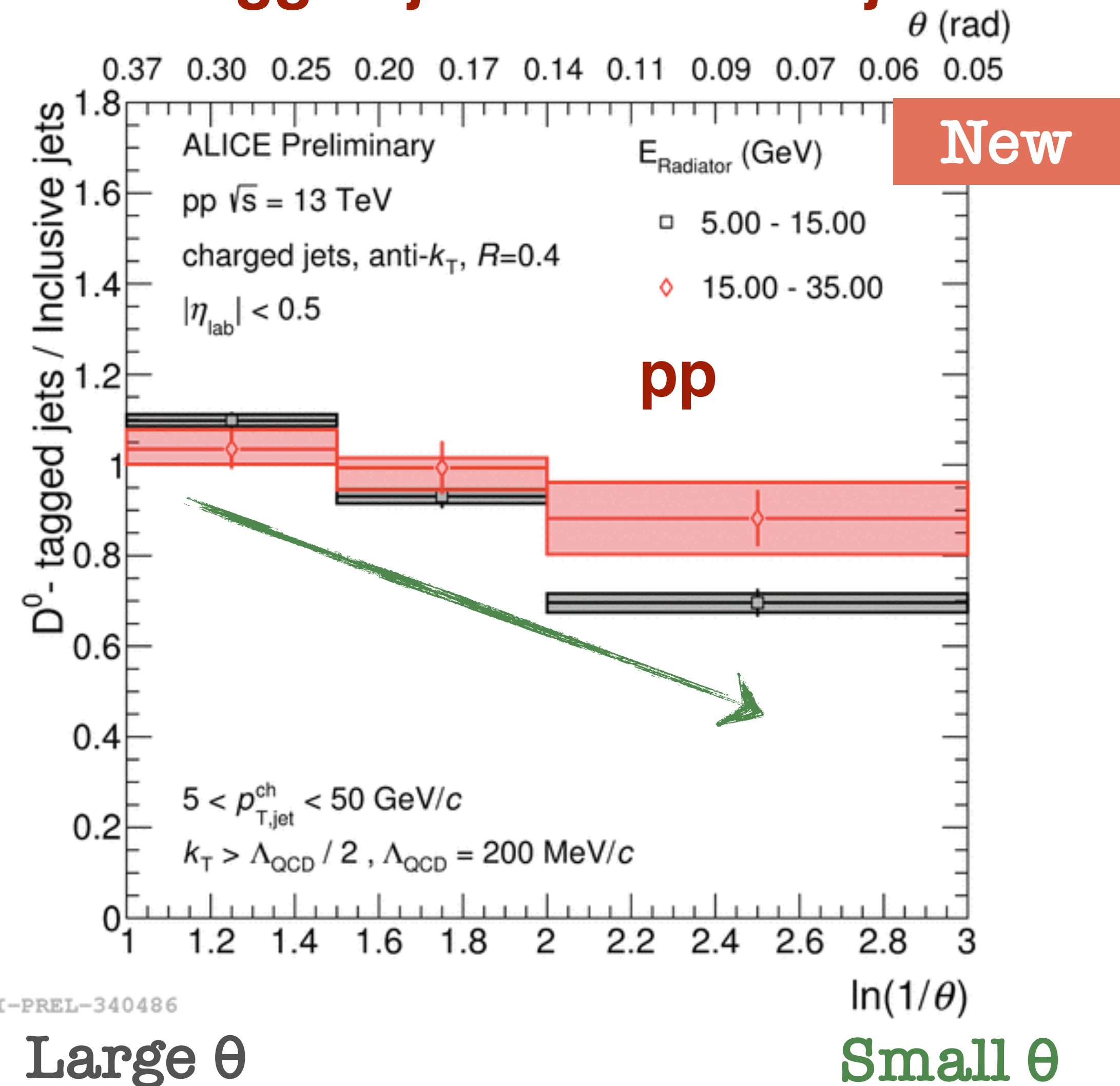
Large parton mass

Small parton mass



- **D-tagged jets have lower splitting at small angle**
- First direct observation of dead cone effect!
- Lower-energy radiator has stronger effect

D⁰-tagged jets / Inclusive jets





Take-home note (II): Energy loss

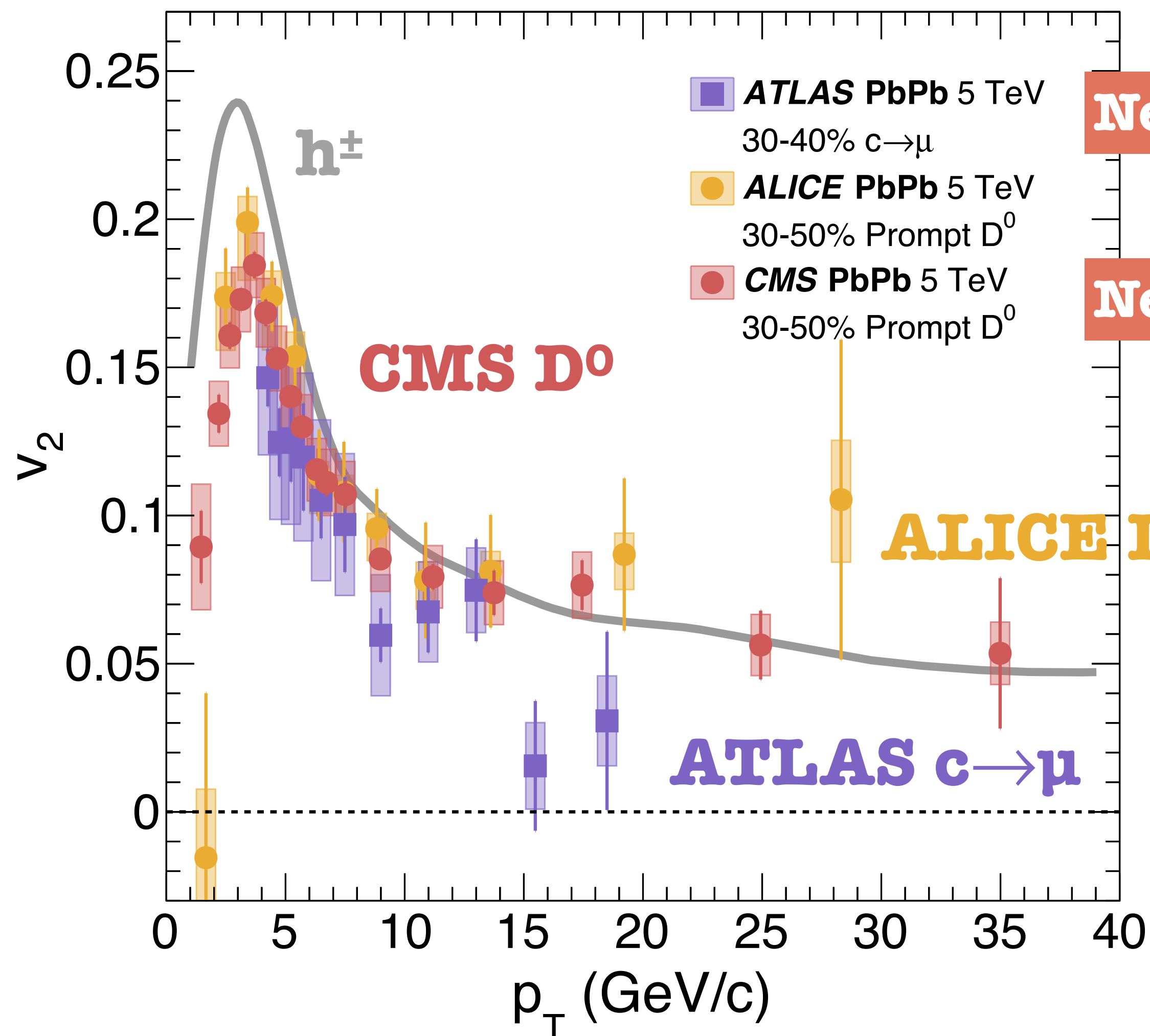
New knowledge

- ✓ D meson R_{AA} measured down to $p_T=0$ at LHC
 - ➔ Hint of different trend RHIC & LHC
- ✓ Intermediate p_T :
 - ➔ $R_{AA}(\text{beauty}) > R_{AA}(\text{charm}) \approx R_{AA}(\text{light})$
- ✓ Low p_T :
 - ➔ $R_{AA}(\text{charm}) > R_{AA}(\text{light})$
- ✓ Dead cone effect directly observed using D-tagged jets in pp

Open *charm* collective flow in AA

ATLAS-CONF-2019-053
CMS-PAS-HIN-19-008

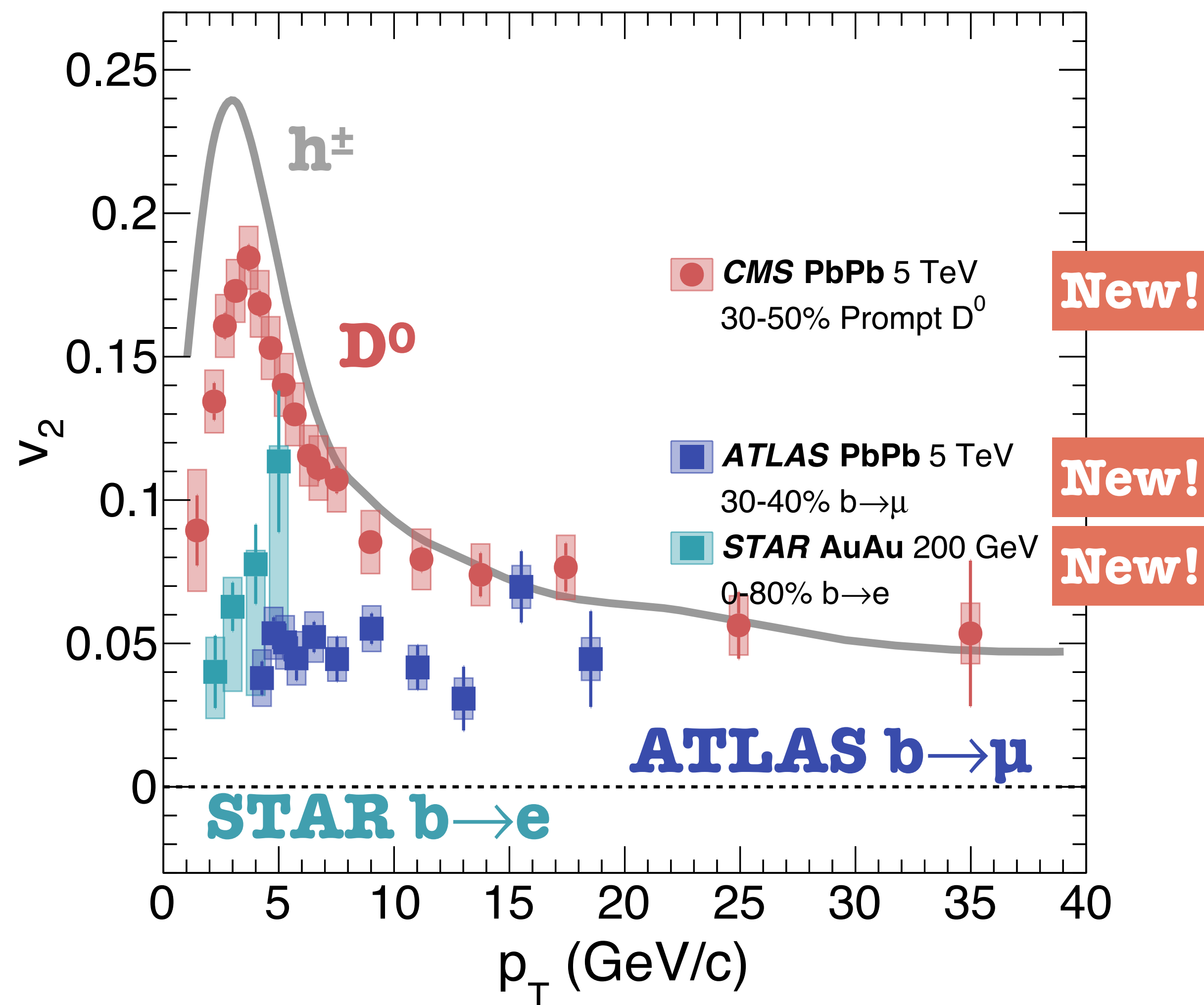
Open charm v_2 compilation



- High-precision
- Prominent flow structure
- Good agreement among measurements
- ➔ $c \rightarrow \mu$ shift a bit to low- p_T : daughter μ
- $v_2(h^\pm) > v_2(\text{open charm})$

S. Lim, 5 Nov, 9:00
C. Bernardes, 5 Nov, 15:20

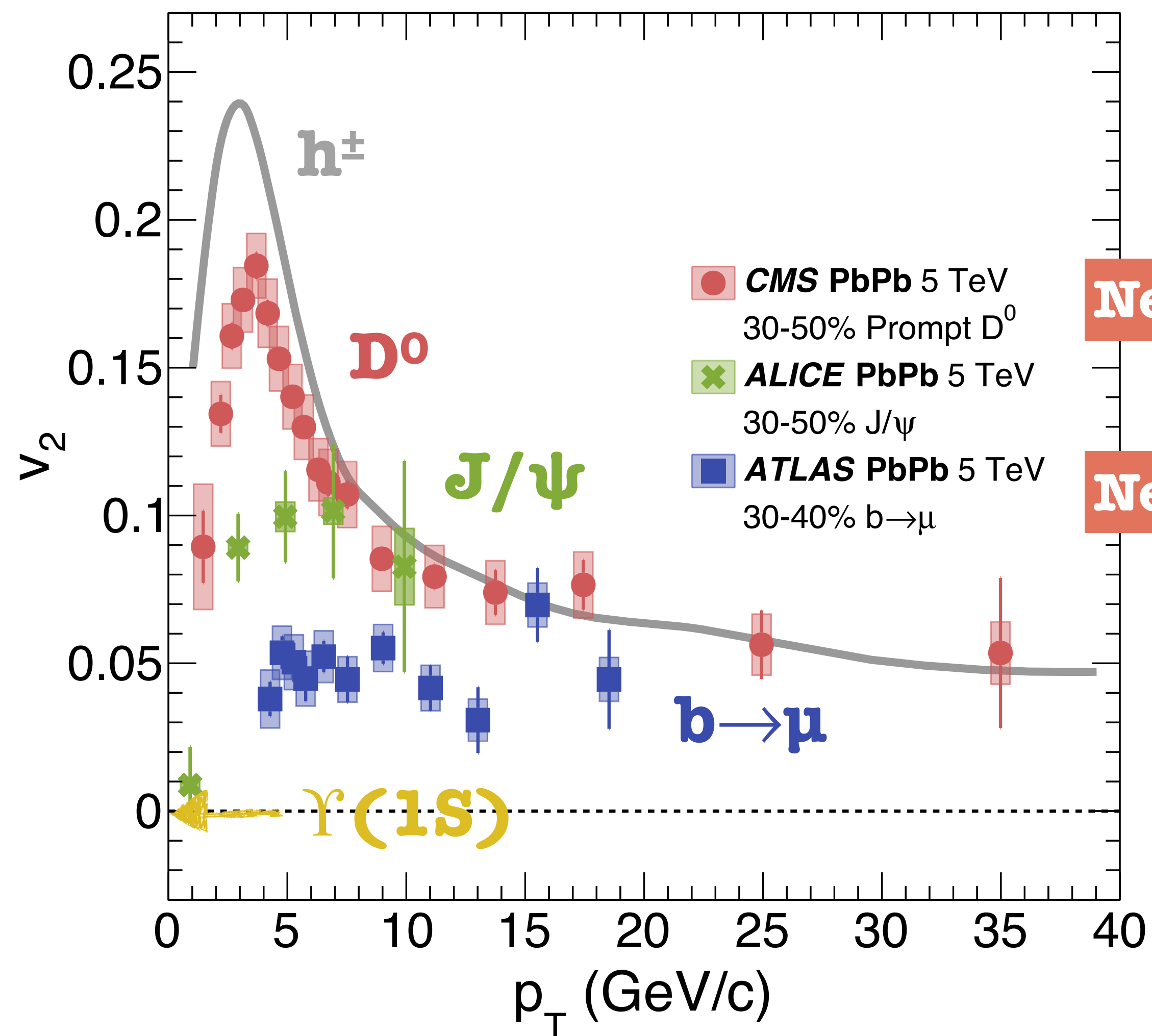
Open charm v_2 compilation



- **Non-zero** open **beauty** v_2 in AA collisions at **RHIC** ($\sim 3.4\sigma$) and **LHC**!

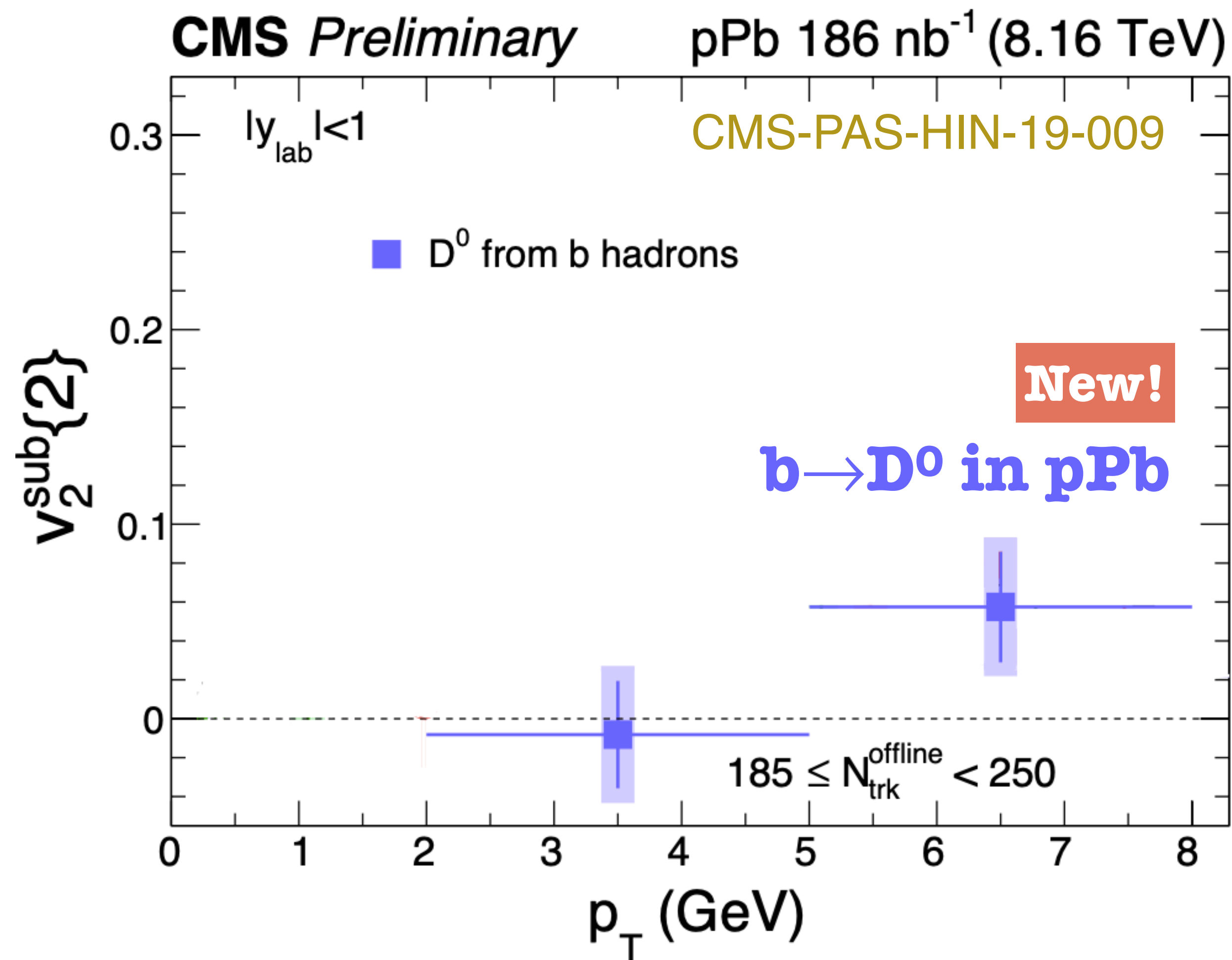
S. Lim, 5 Nov, 9:00
M. Kelsey, 5 Nov, 17:40
C. Bernardes, 5 Nov, 15:20

Open charm v_2 compilation



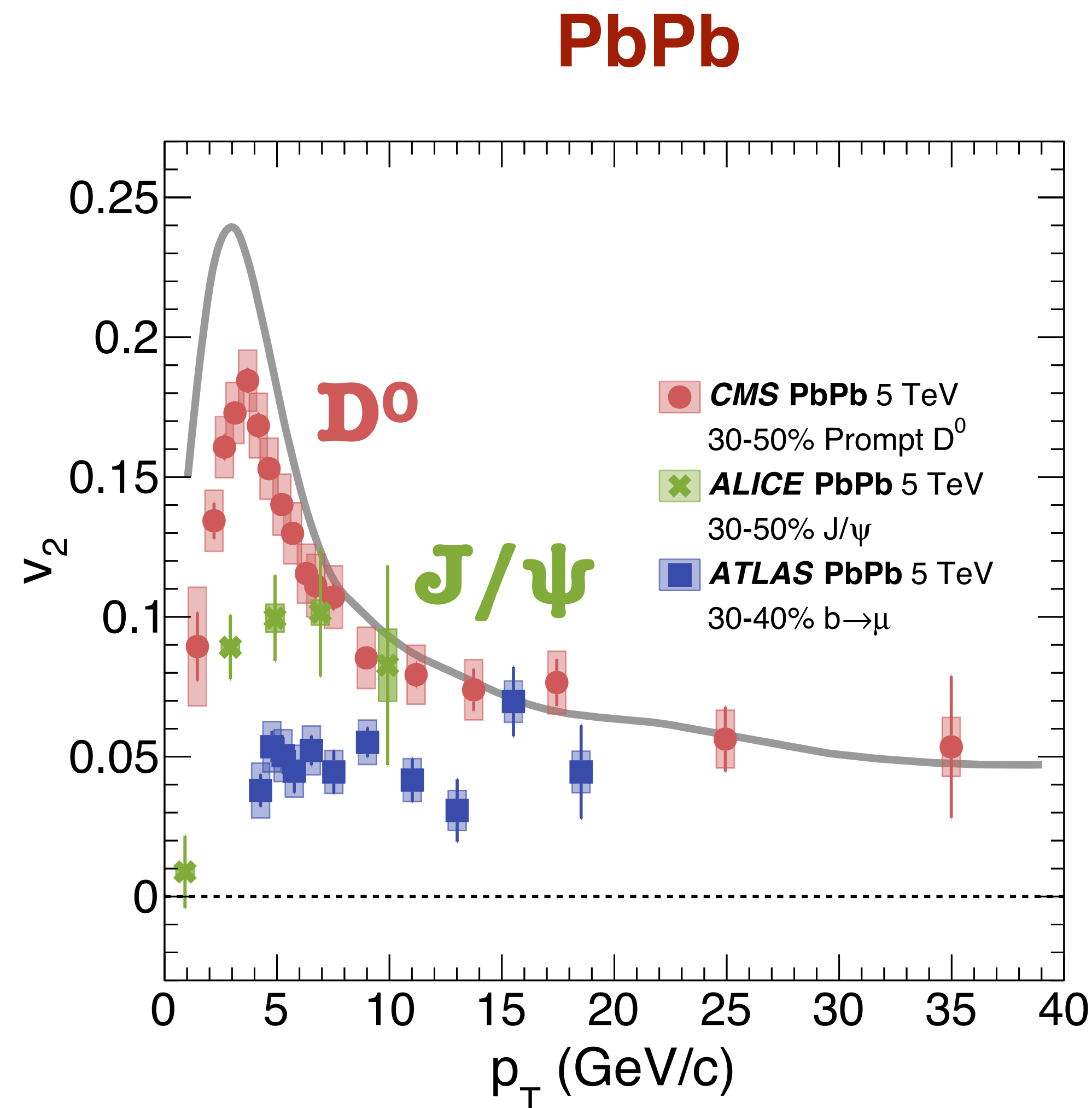
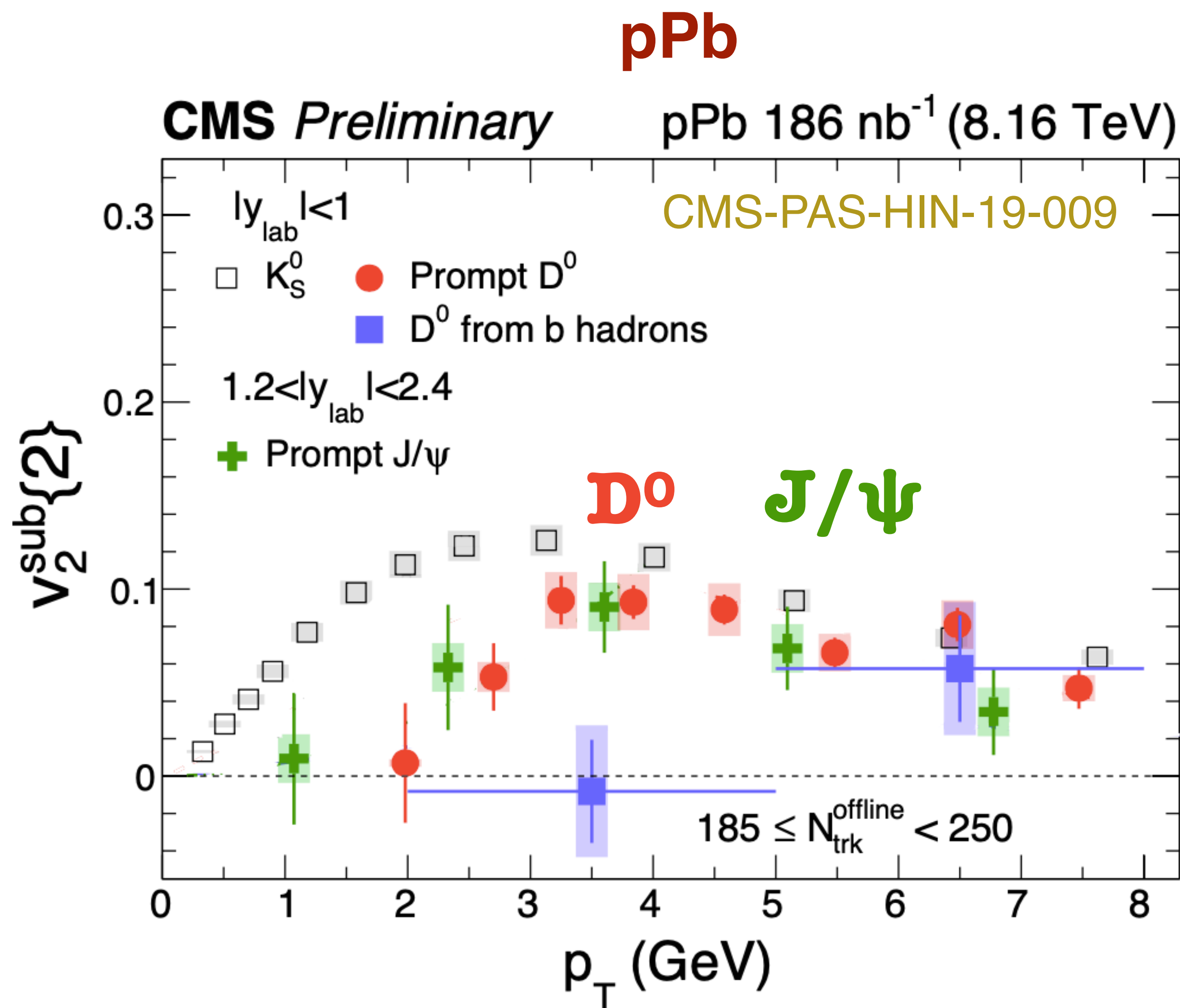
- \bullet $v_2(h^\pm)$
- \bullet v
- \bullet $v_2(\text{open charm})$
- \bullet v
- \bullet $v_2(\text{hidden charm})$
- \bullet v
- \bullet $v_2(\text{open beauty})$
- \bullet v
- \bullet $v_2(\text{hidden beauty})$
- \bullet \approx
- \bullet 0

Collective phenomena in small system (pA)



- v_2 (open beauty) ≈ 0 in pA?

Collective phenomena in small system (pA)



- $v_2(D^0) \approx v_2(J/\psi)$ in pPb: final state interactions cannot explain

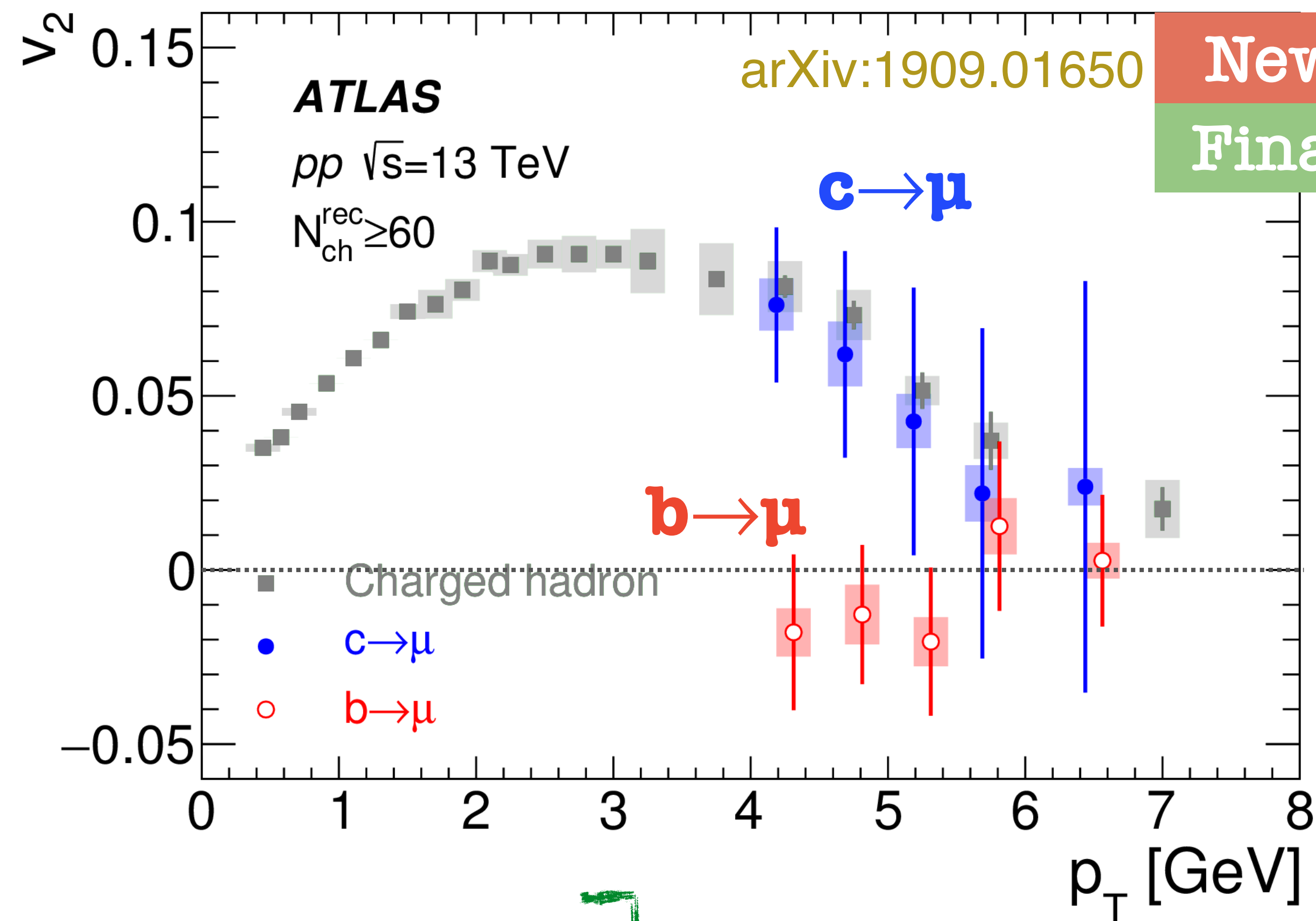
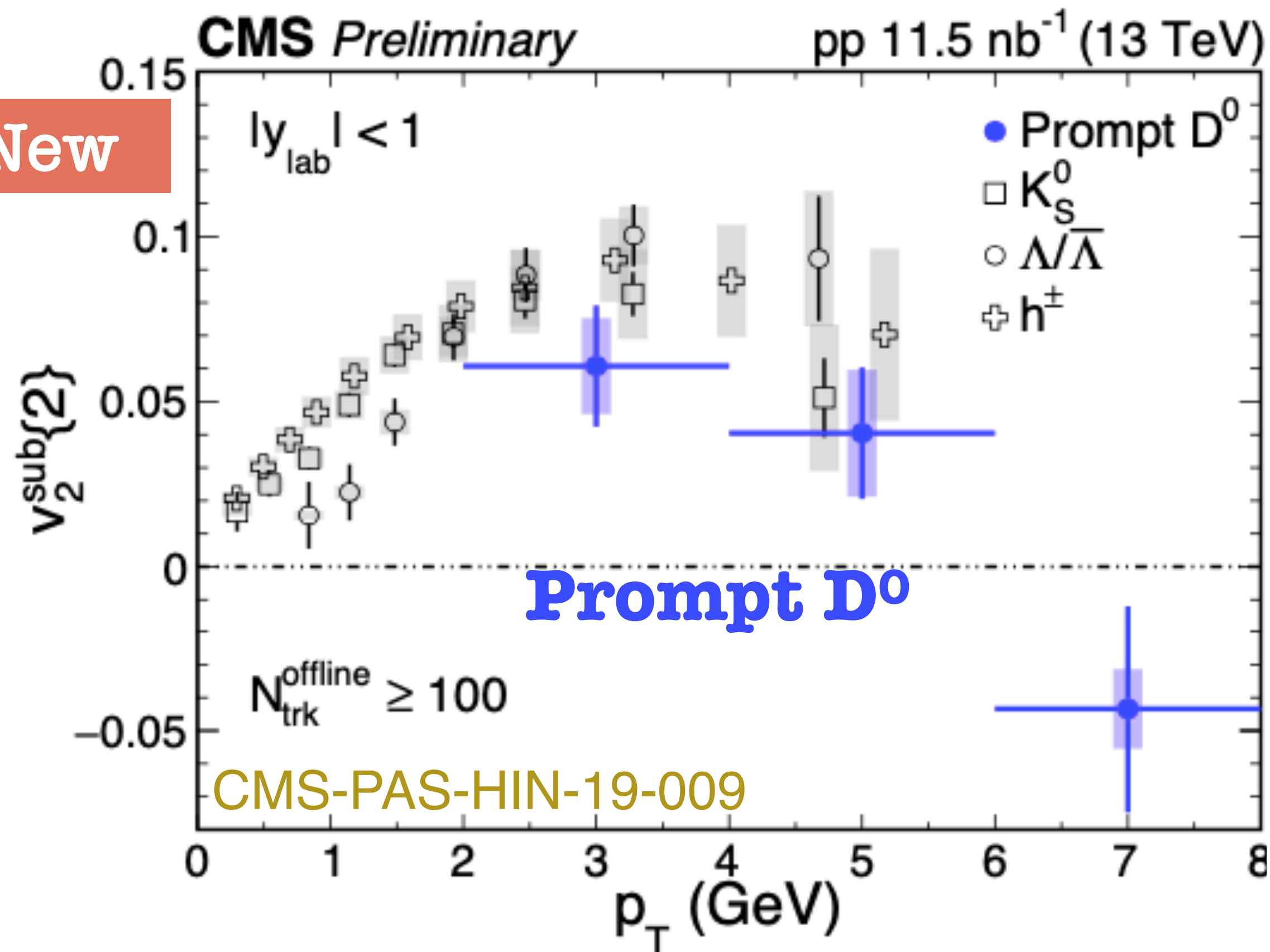
A.A. Baty, 5 Nov, 08:40

Collective phenomena in small system (pp)

A.A. Baty, 5 Nov, 08:40

S. Lim, 5 Nov, 09:00

v_2 in high-multiplicity pp



- v_2 (open charm) $\ll v_2$ (light) at intermediate p_T
- v_2 (open beauty) ≈ 0

similar w/ pPb



Take-home note (III): Collectivity

New knowledge

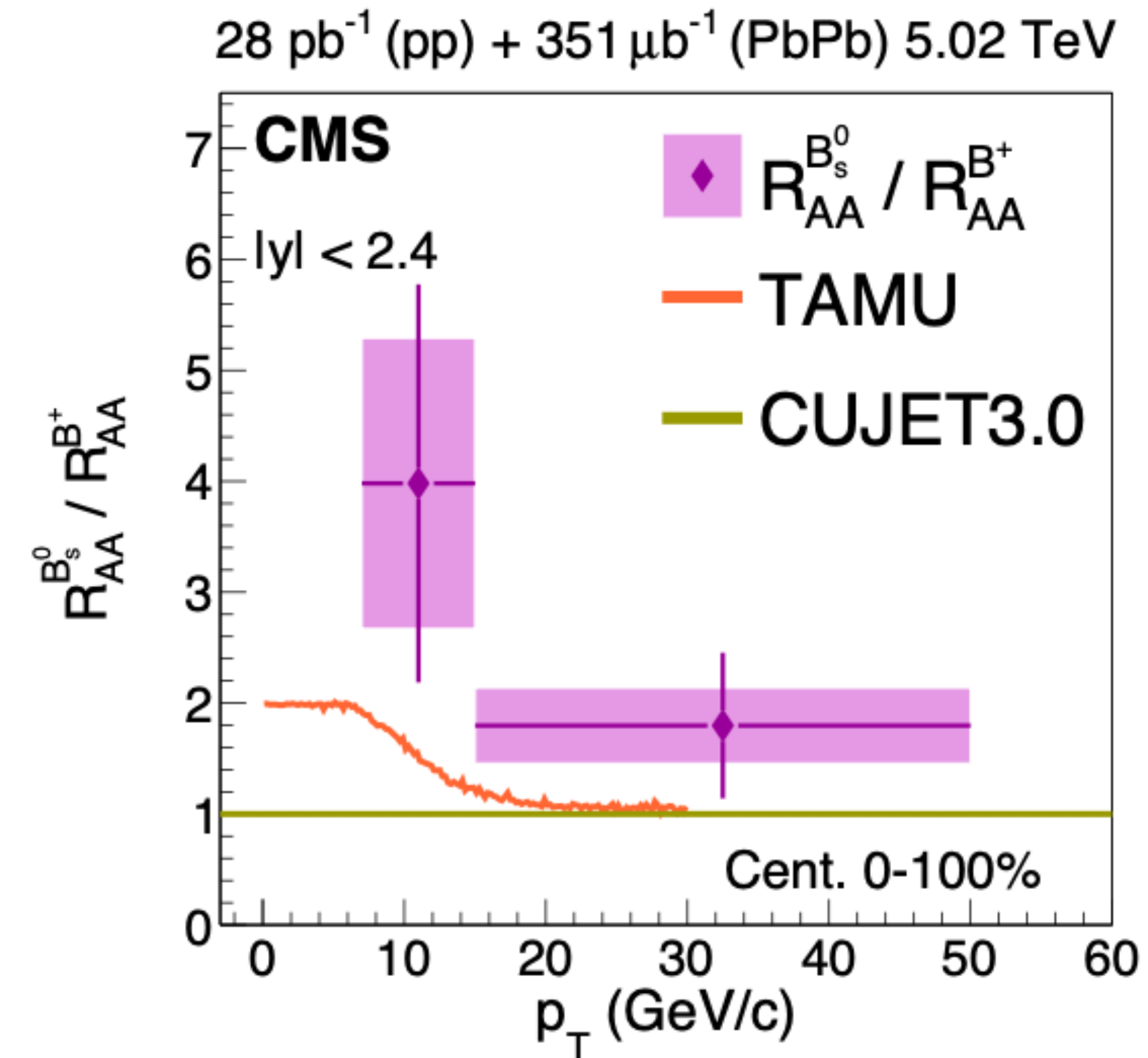
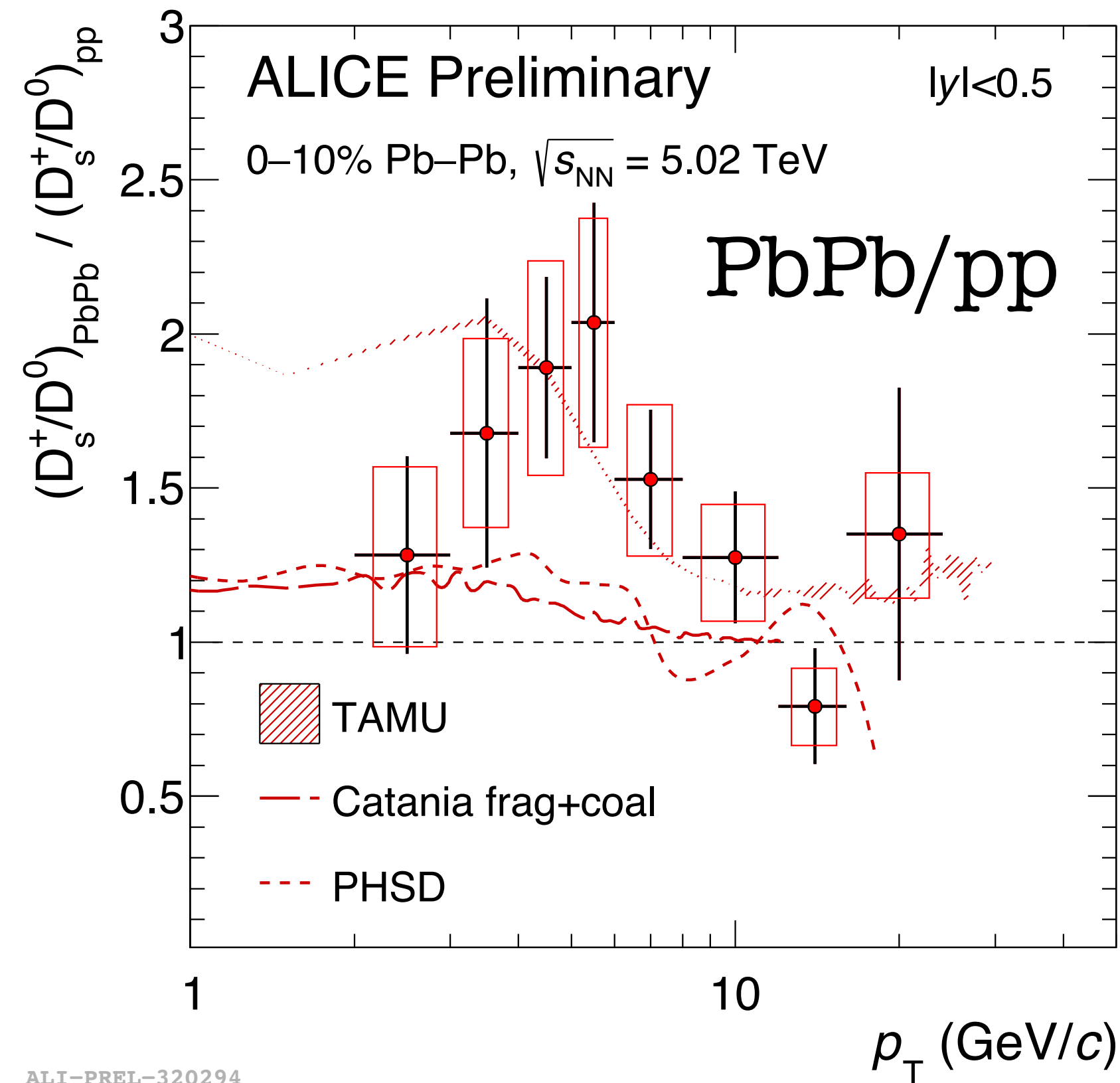
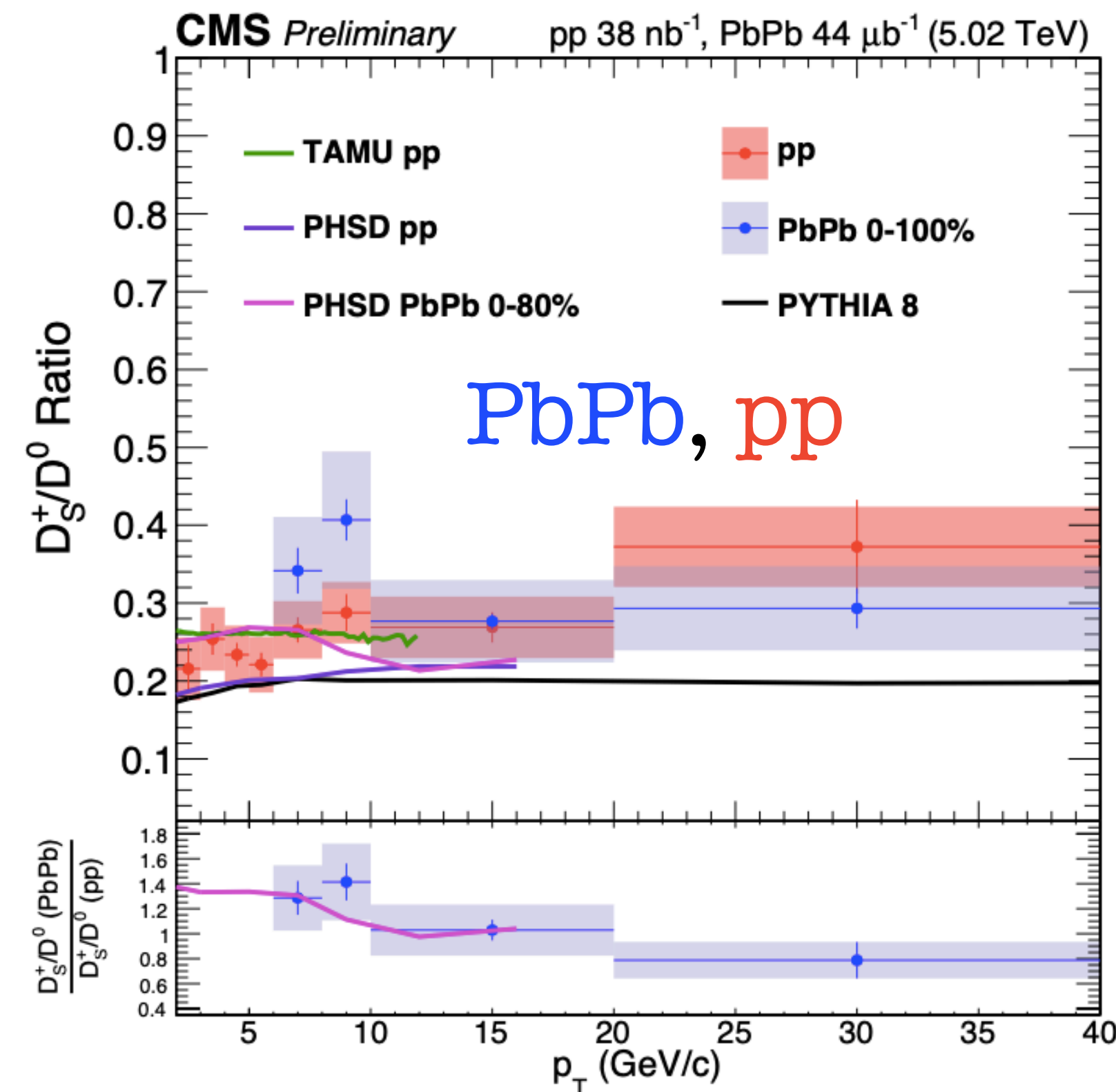
- ✓ Non-zero open beauty v_2 in heavy-ion collisions at both RHIC and LHC
- ✓ Flavor hierarchy in heavy-ion collisions:
 - ➔ $v_2(\text{light}) > v_2(\text{charm}) > v_2(\text{beauty})$
- ✓ pPb: $v_2(J/\psi) \approx v_2(D^0)$
- ✓ High-multiplicity pp:
 - ➔ Non-zero v_2 (open charm)
 - ➔ $v_2(\text{open beauty}) \approx 0$
 - ➔ Similar behavior with pPb

Hadronization in bulk: strangeness

New CMS D_s/D^0

New ALICE D_s/D^0

B_s/B^+



CMS-PAS-HIN-18-017

ALI-PREL-320294

- Hint of strange heavy flavor hadron enhanced in heavy-ion collisions

G.M. Innocenti, 5 Nov, 11:00

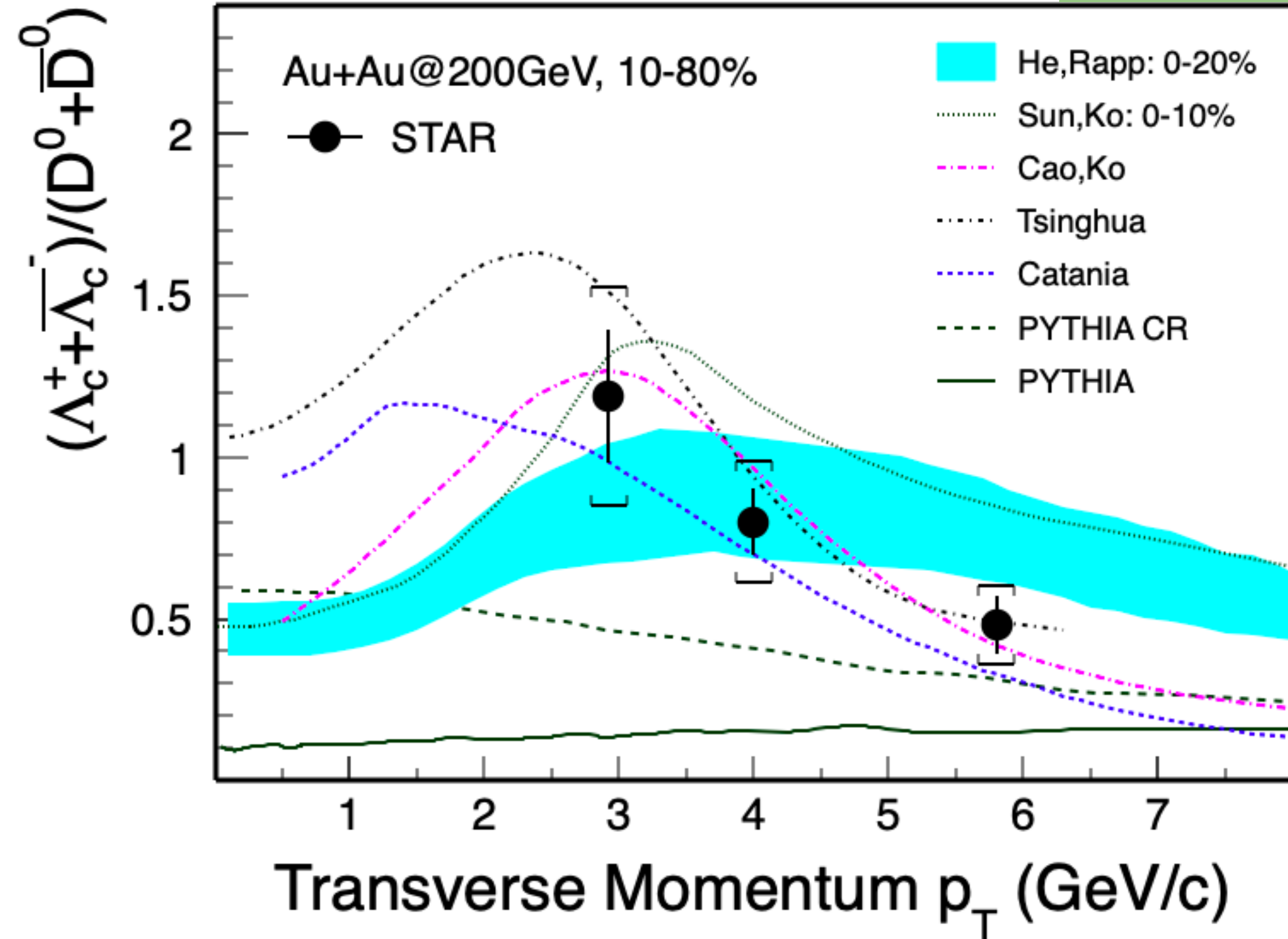
Z. Shi, 6 Nov, 16:20

Hadronization in bulk: Λ_c/D^0 ratio in AA

RHIC

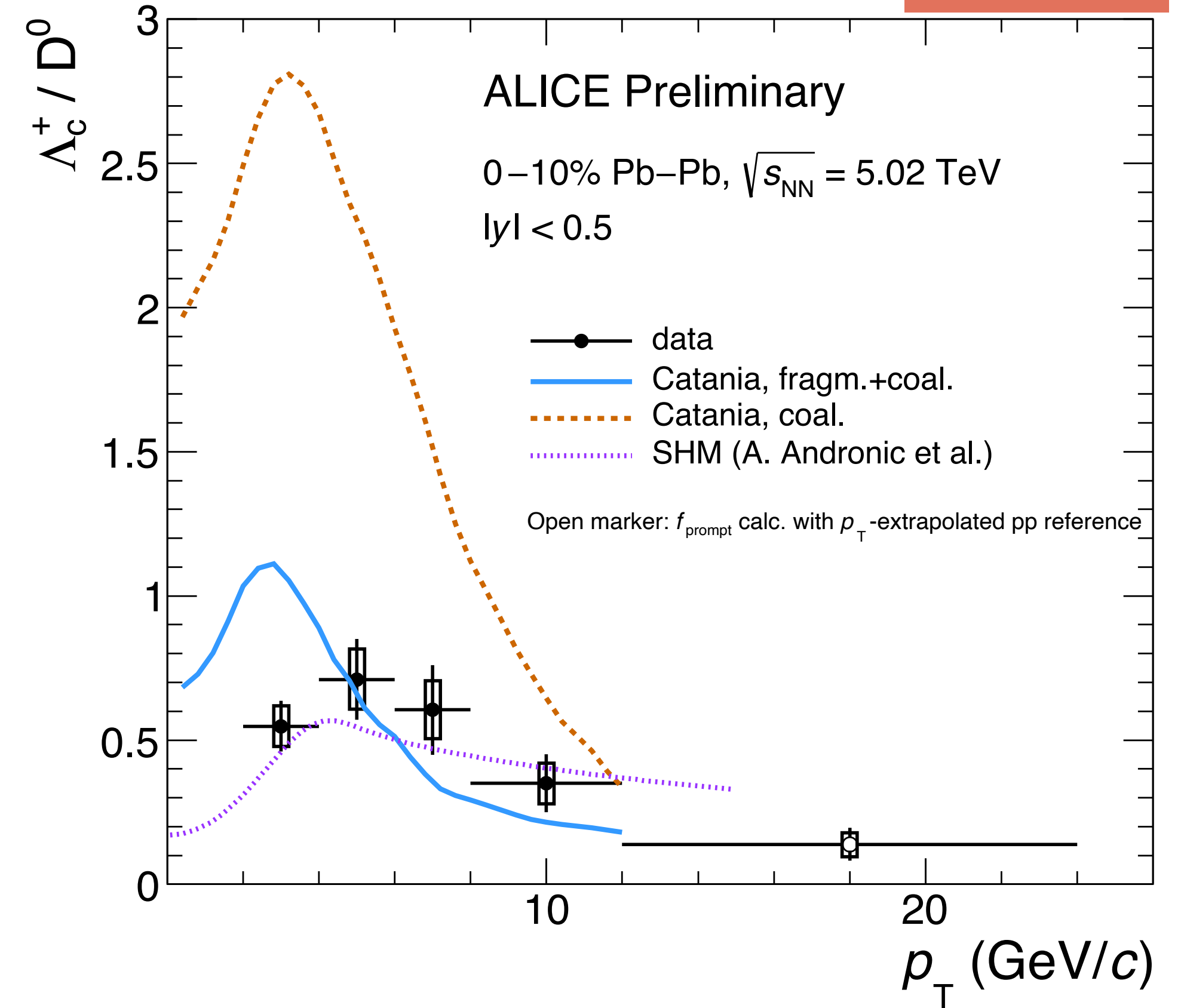
Final

arXiv:1910.1462



LHC

New



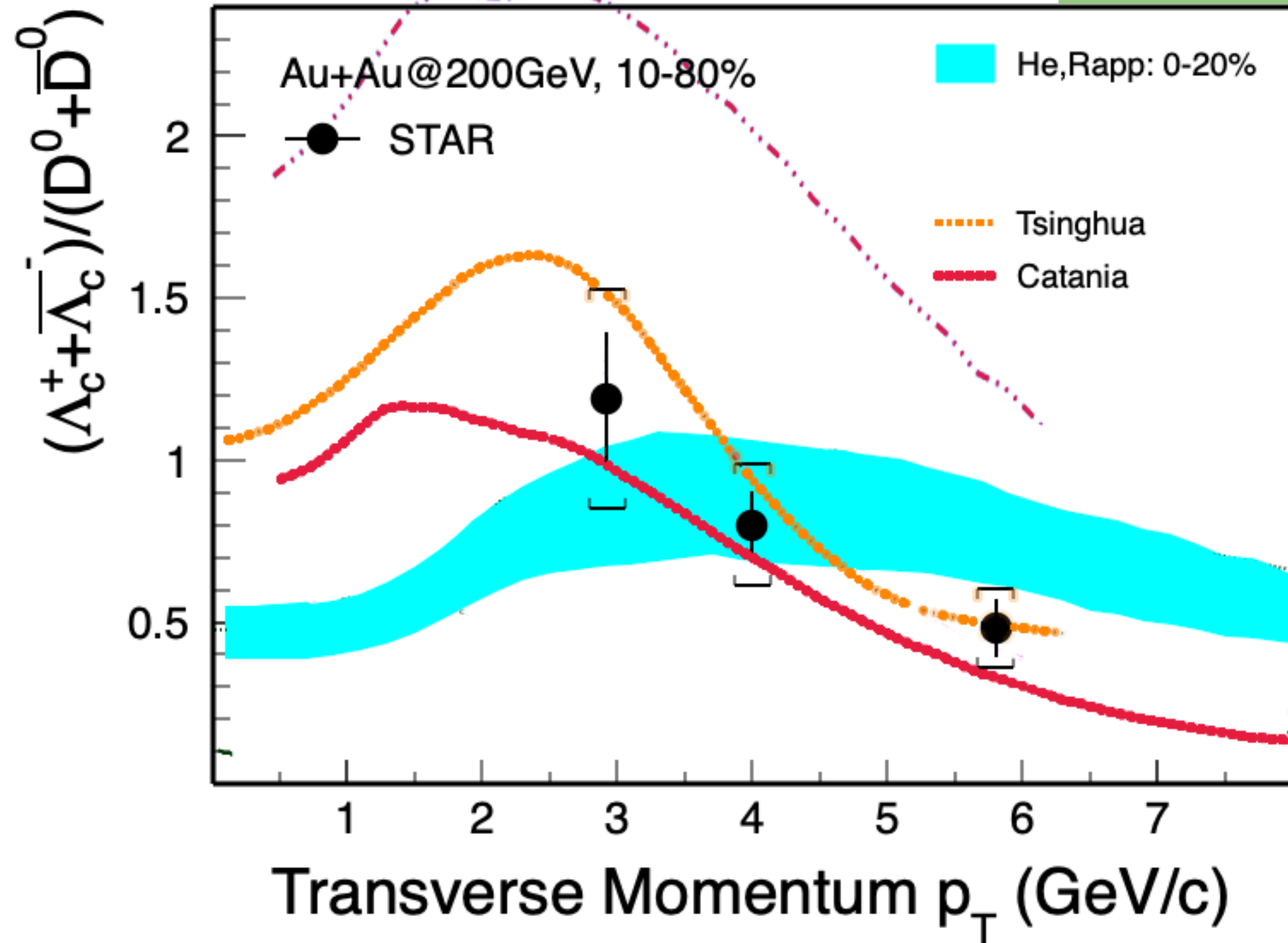
ALI-PREL-321682

Hadronization in bulk: Λ_c/D^0 ratio in AA

arXiv:1910.1462

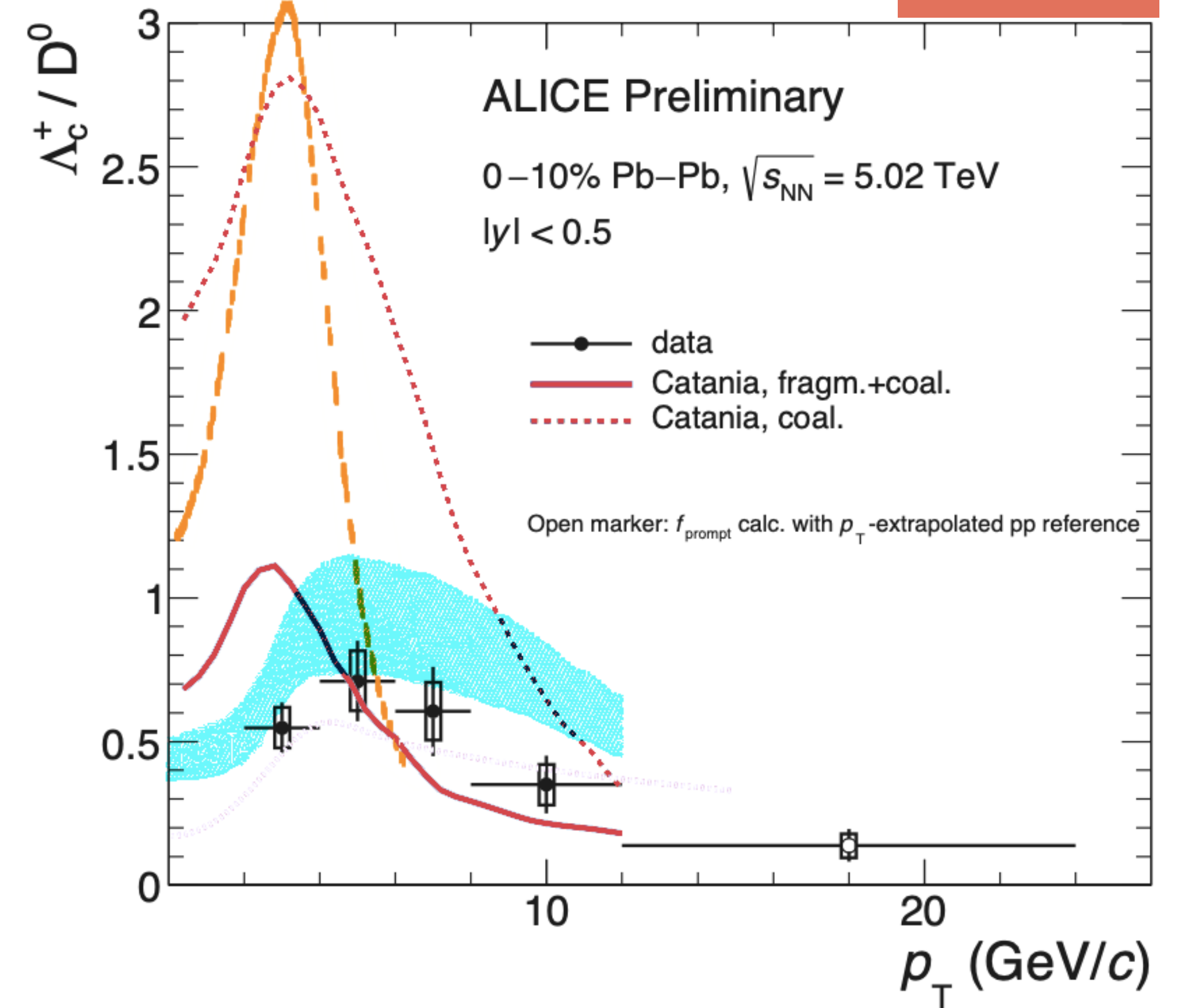
RHIC

Final



LHC

New



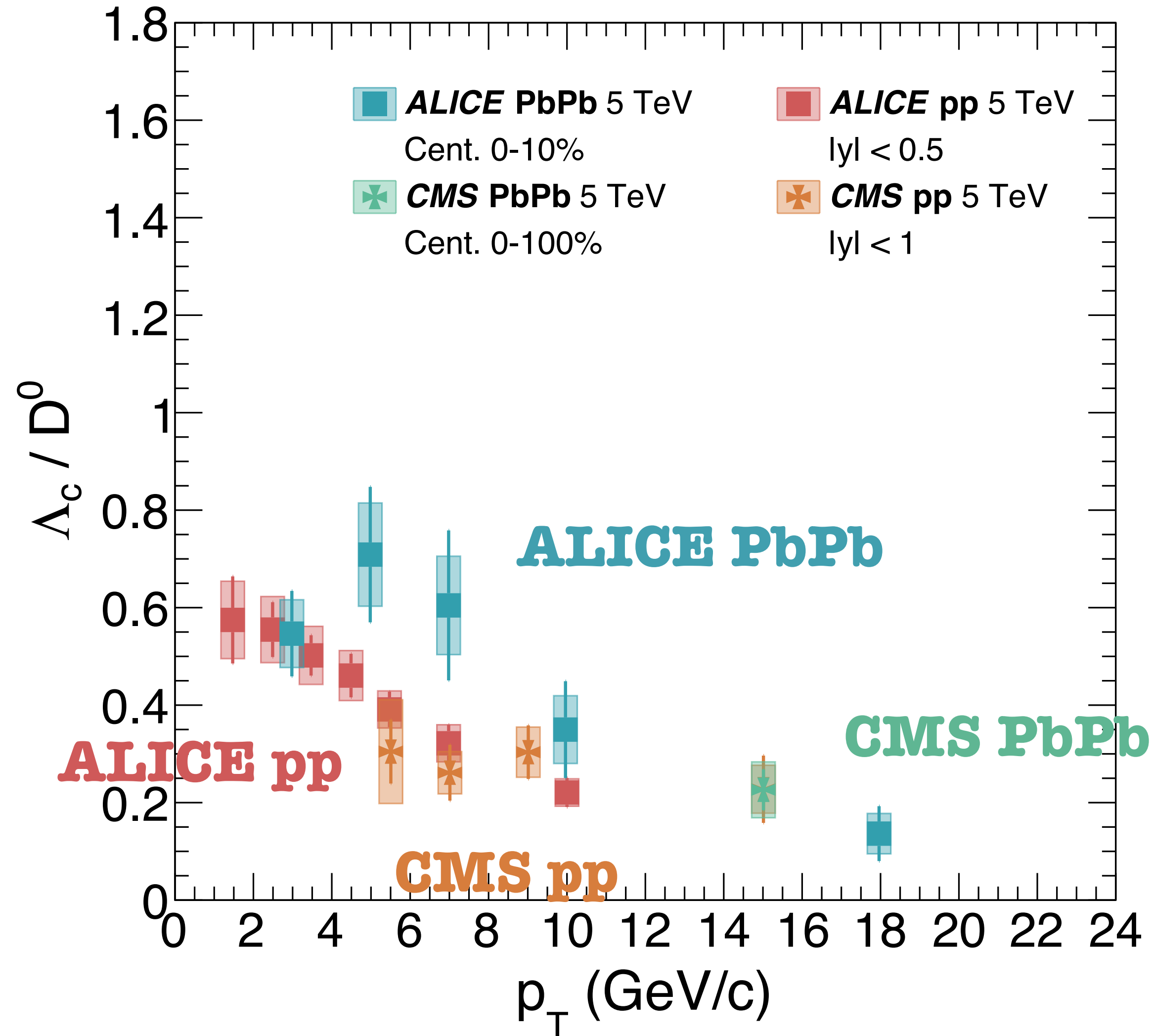
ALI-PREL-321682

- Good constraints to require describing RHIC and LHC simultaneously

Hadronization in bulk: Λ_c/D^0 ratio in AA

LHC vs. RHIC

G.M. Innocenti, 5 Nov, 11:00



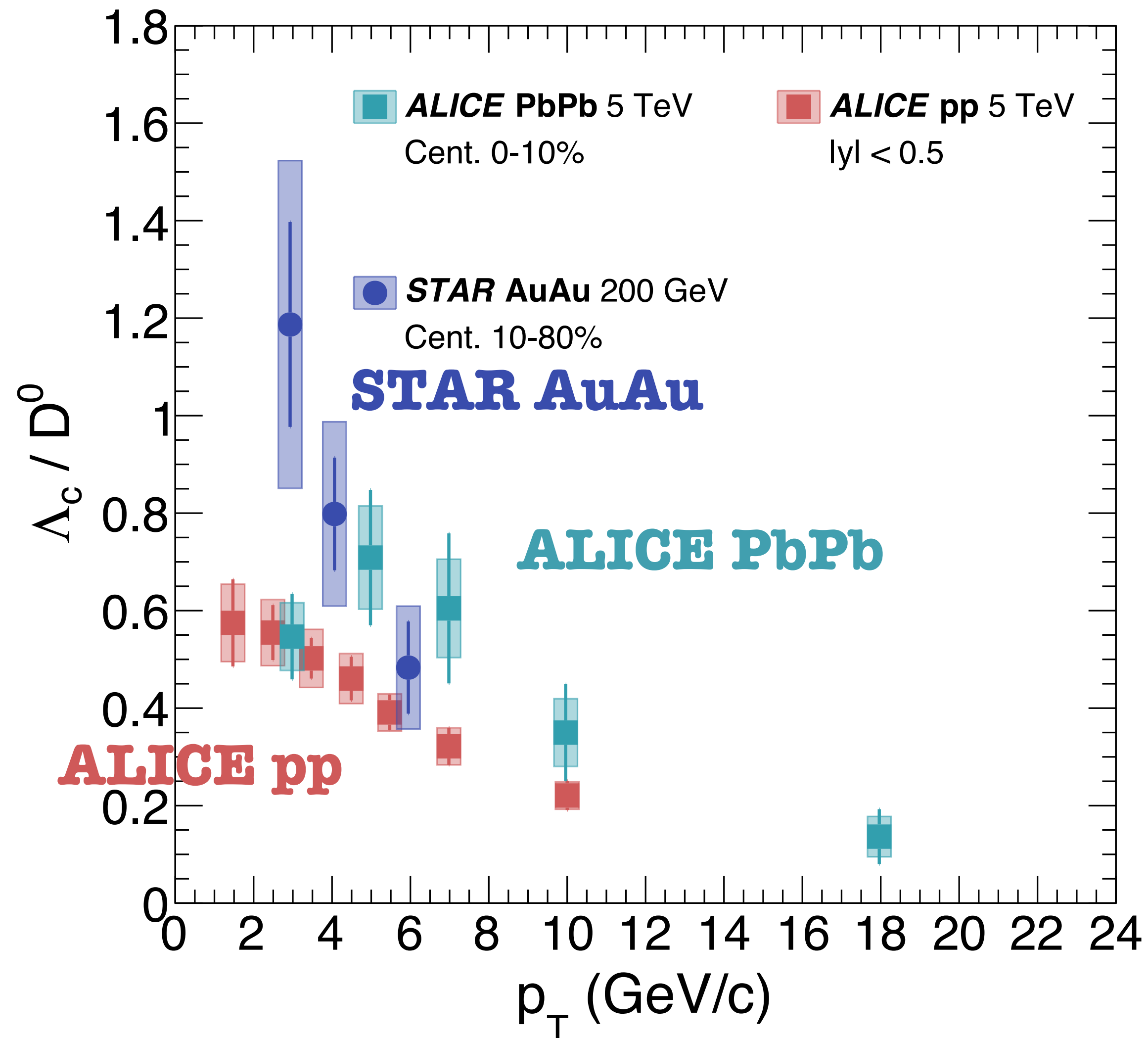
- ALICE and CMS agree in pp and PbPb
- LHC: mildly enhanced in PbPb w.r.t. pp and peak at $\sim 4-6$ GeV/c

arXiv:1906.03322
arXiv:1910.1462

Hadronization in bulk: Λ_c/D^0 ratio in AA

LHC vs. RHIC

G.M. Innocenti, 5 Nov, 11:00



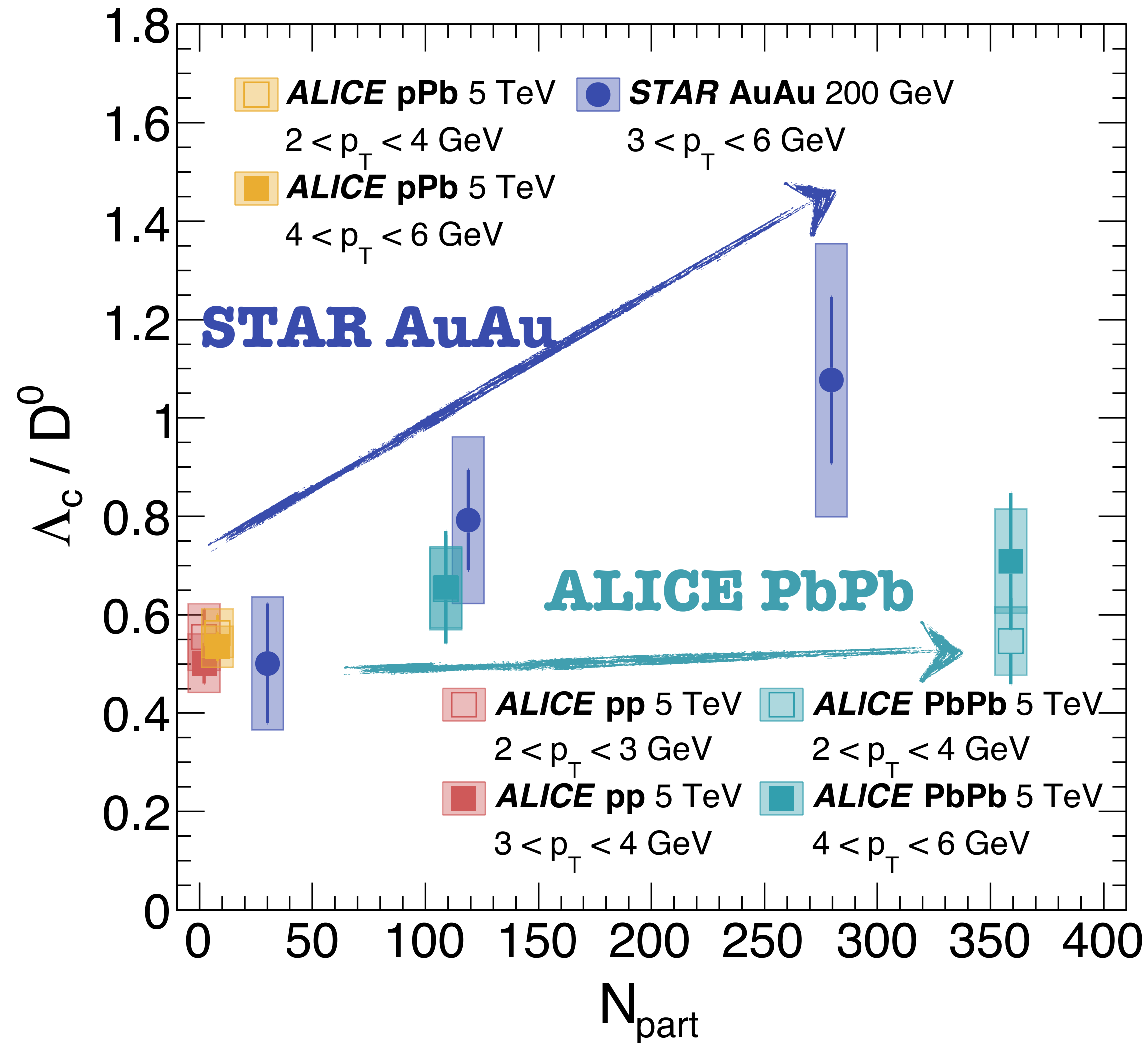
- ALICE and CMS agree in pp and PbPb
- LHC: mildly enhanced in PbPb w.r.t. pp and peak at $\sim 4-6$ GeV/c
- RHIC: stronger enhanced?

arXiv:1906.03322
arXiv:1910.1462

Hadronization in bulk: Λ_c/D^0 ratio in AA

LHC vs. RHIC

G.M. Innocenti, 5 Nov, 11:00

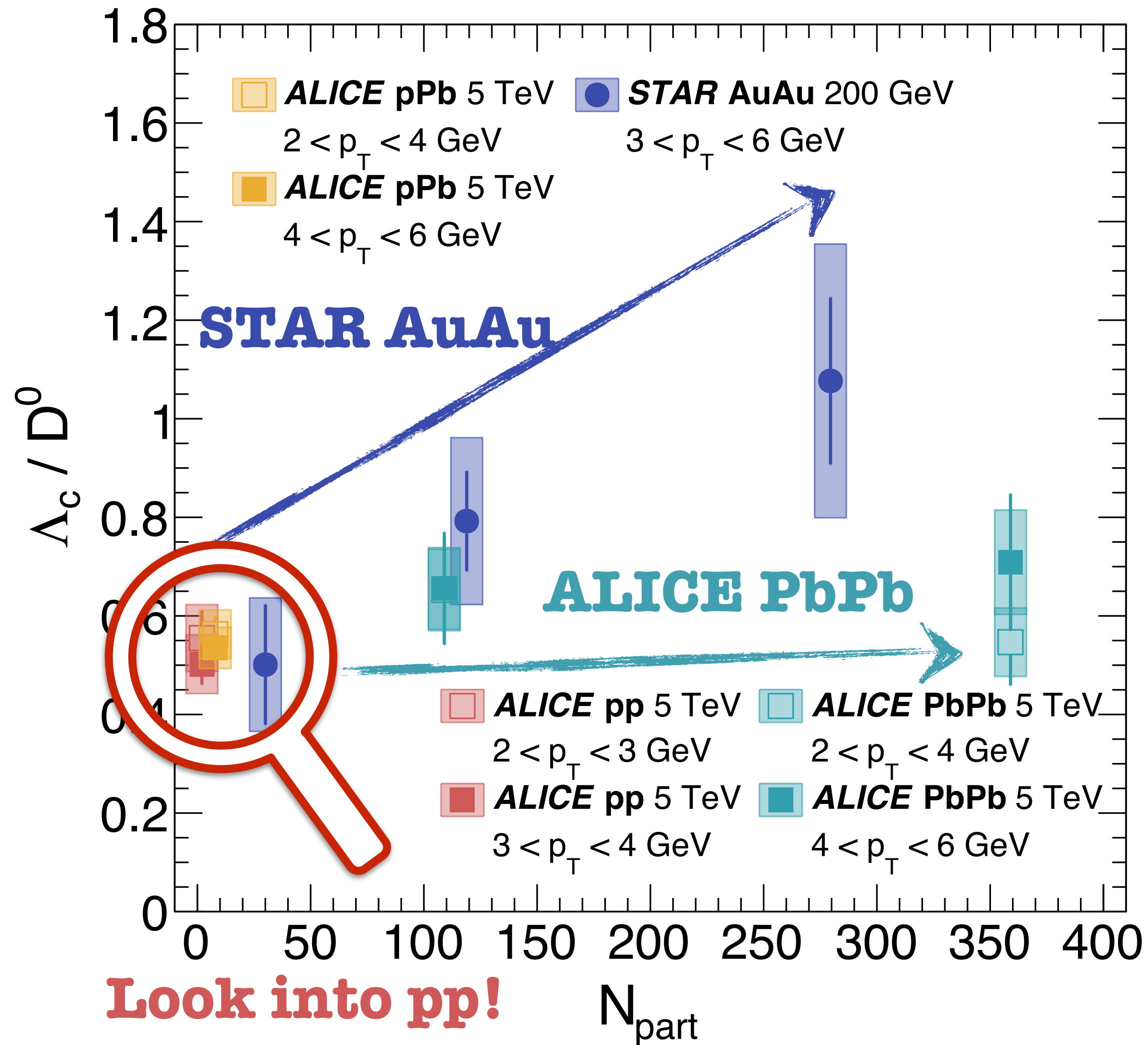


- RHIC has stronger dependence on N_{part} than LHC?

arXiv:1906.03322
arXiv:1910.1462

Hadronization in bulk: Λ_c/D^0 ratio in AA

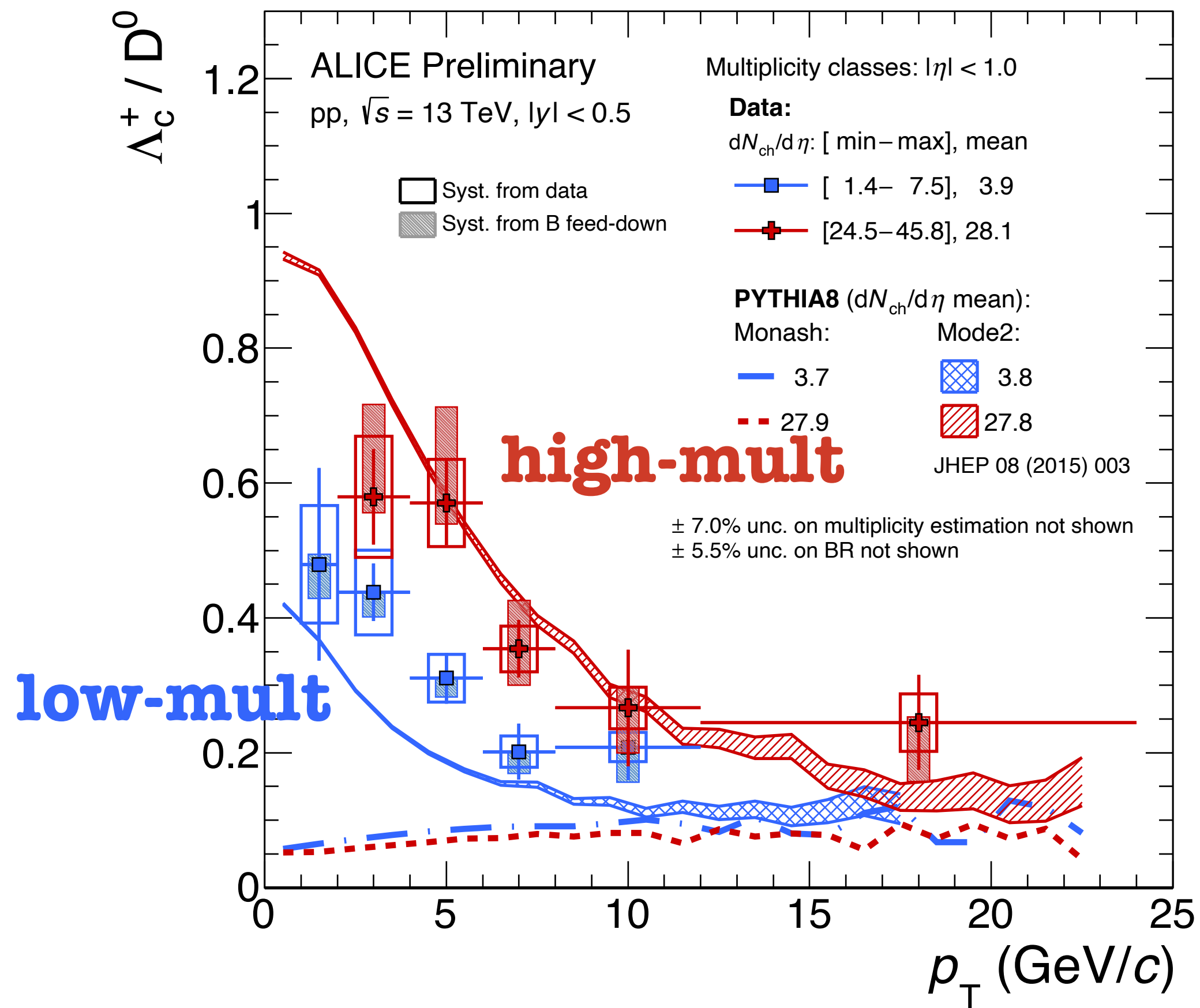
LHC vs. RHIC



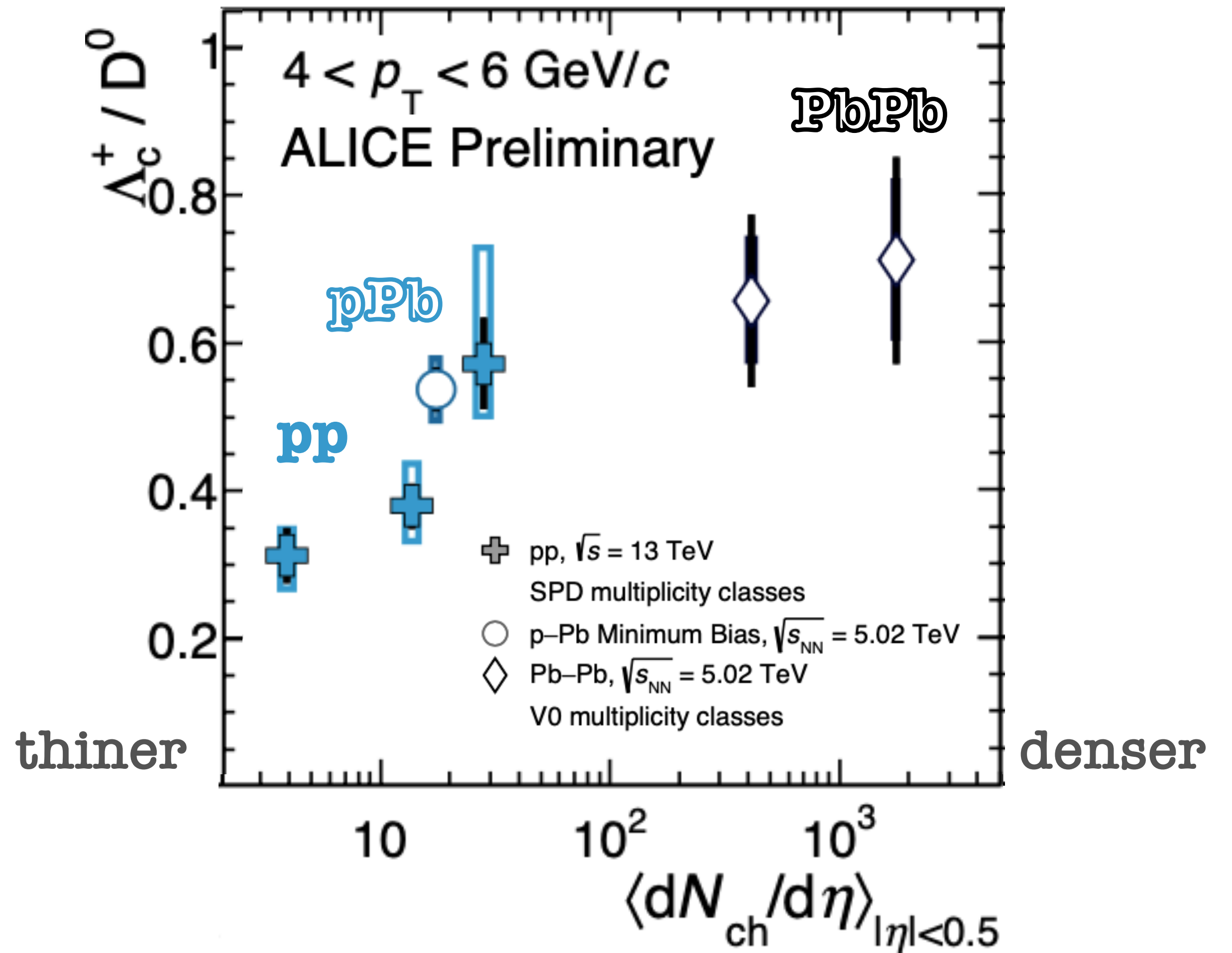
- RHIC has stronger dependence on N_{part} than LHC?

Hadronization in jet (“recombine”): Λ_c/D^0 ratio in pp

G.M. Innocenti, 5 Nov, 11:00



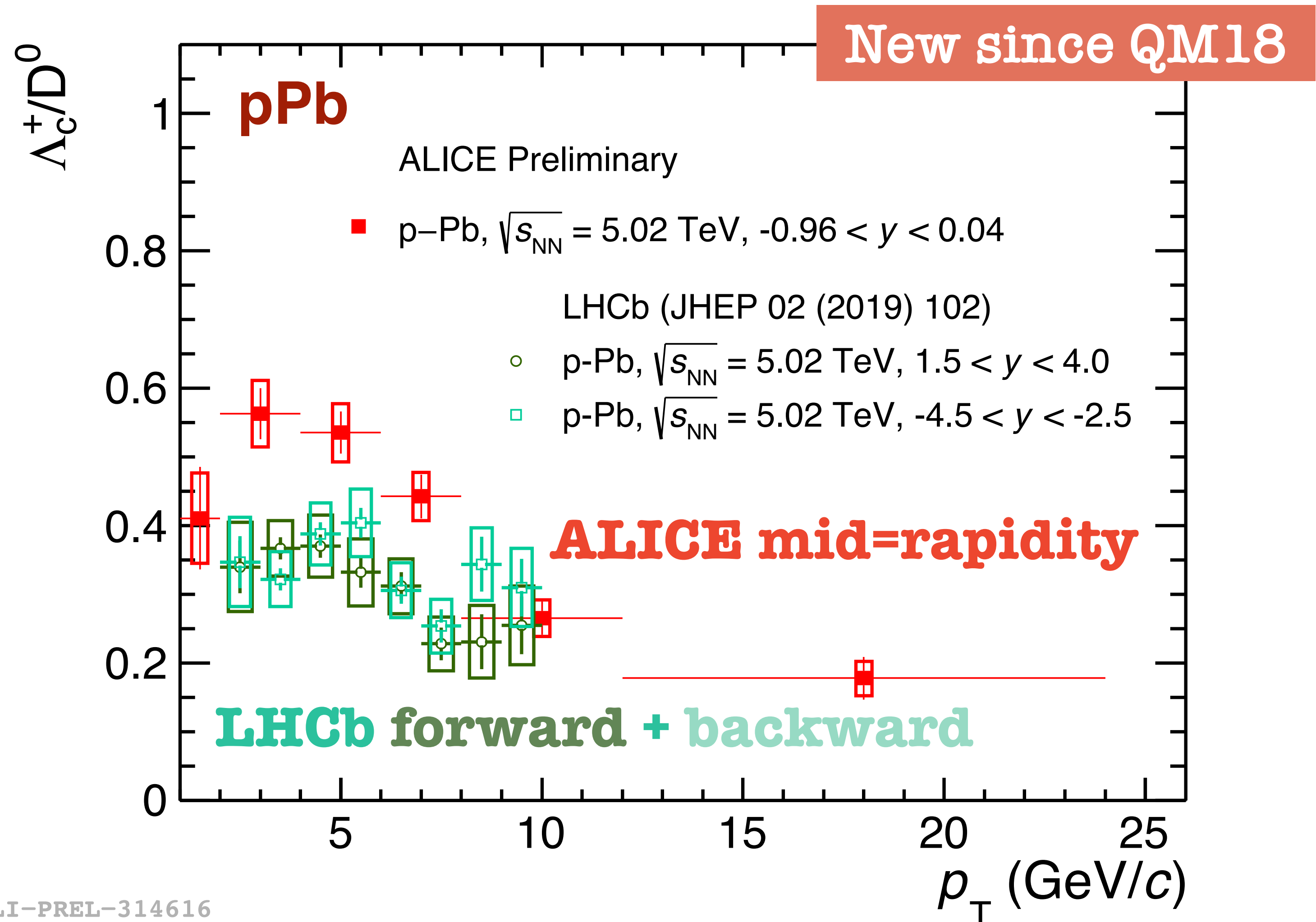
ALI-PREL-336442



• high-mult > low-mult at ~ 4 -6 GeV/c

• Is there/where is a saturation?

More info of hadronization: Λ_c/D^0 ratio in pPb



ALI-PREL-314616

- Λ_c/D^0 ratio: nPDF effect almost cancelled
- Λ_c/D^0 (mid-rapidity) $>$ Λ_c/D^0 (FB) \Rightarrow Tension or feature?



Take-home note (IV): Hadronization

New knowledge

- ✓ Hint of **strange** HF hadron enhanced in HI
- ✓ Λ_c/D^0 **enhanced** in HI
- ✓ Λ_c/D^0 increases vs. **multiplicity** in pp
- ✓ Λ_c/D^0 **tension** between mid-rapidity and forward/backward in pPb



Summary: Note of take-home notes

Repeat..

- ✓ **Tension** between D^0 R_{FB} and nPDF model predictions
- ✓ **Zero v_3 (open beauty)** in heavy-ion collisions
- ✓ D^0 R_{AA} **down to $p_T=0$**
- ✓ Direct observation of **dead cone effect**
- ✓ **Non-zero v_2 (open beauty)** in heavy-ion collisions
- ✓ **Non-zero v_2 (open charm)** in pp
- ✓ Λ_c/D^0 increases vs. **multiplicity** in pp



Back-up

Thanks for your attention!