Trigger Talk
What have we learned from experiments?

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9th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions

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Guangzhou (China)

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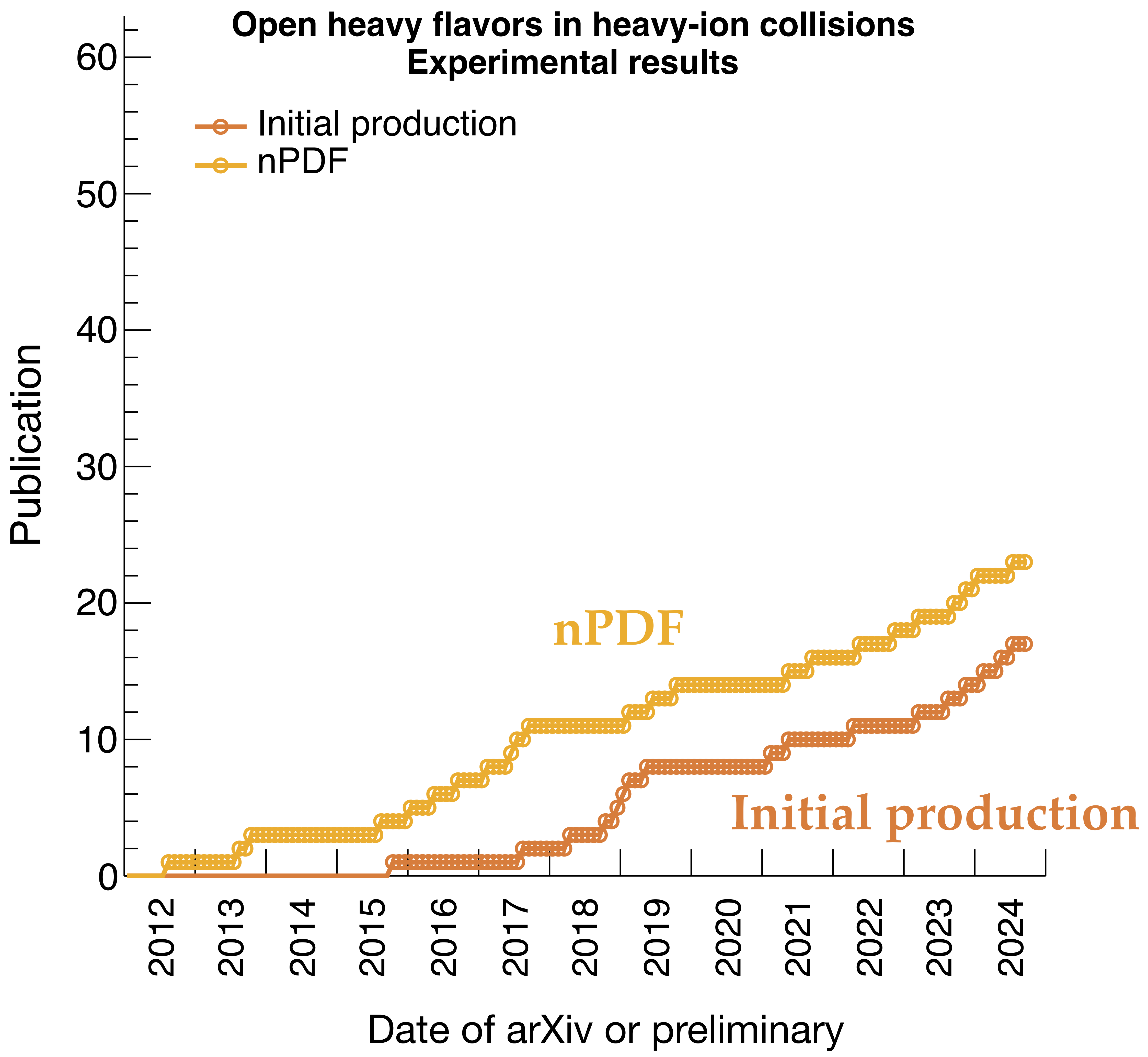
Heavy Flavors Textbook Knowledge

Heavy quarks (charm, beauty) → large mass $\mathbf{m_Q}$

Expect…

- Produced early $\tau \sim 1/m_Q$
  - Unique access to high temperature stage
  - Keep identity in HI collisions $m_Q \gg T_{QGP}$
- **Hard scattering quark production** can be calculated with perturbative QCD even at zero p_T $m_Q \gg \Lambda_{QCD}$
  - Different length scale structure by varying p_T
  - Good probe to constrain gluon **nuclear PDF** with easy control of production and wide $(x, 1/Q^2)$



Lesson #0

No significant deviation from pQCD calculations found in data for initial parton production

HF meson productions and total charm/beauty cross-sections in pp

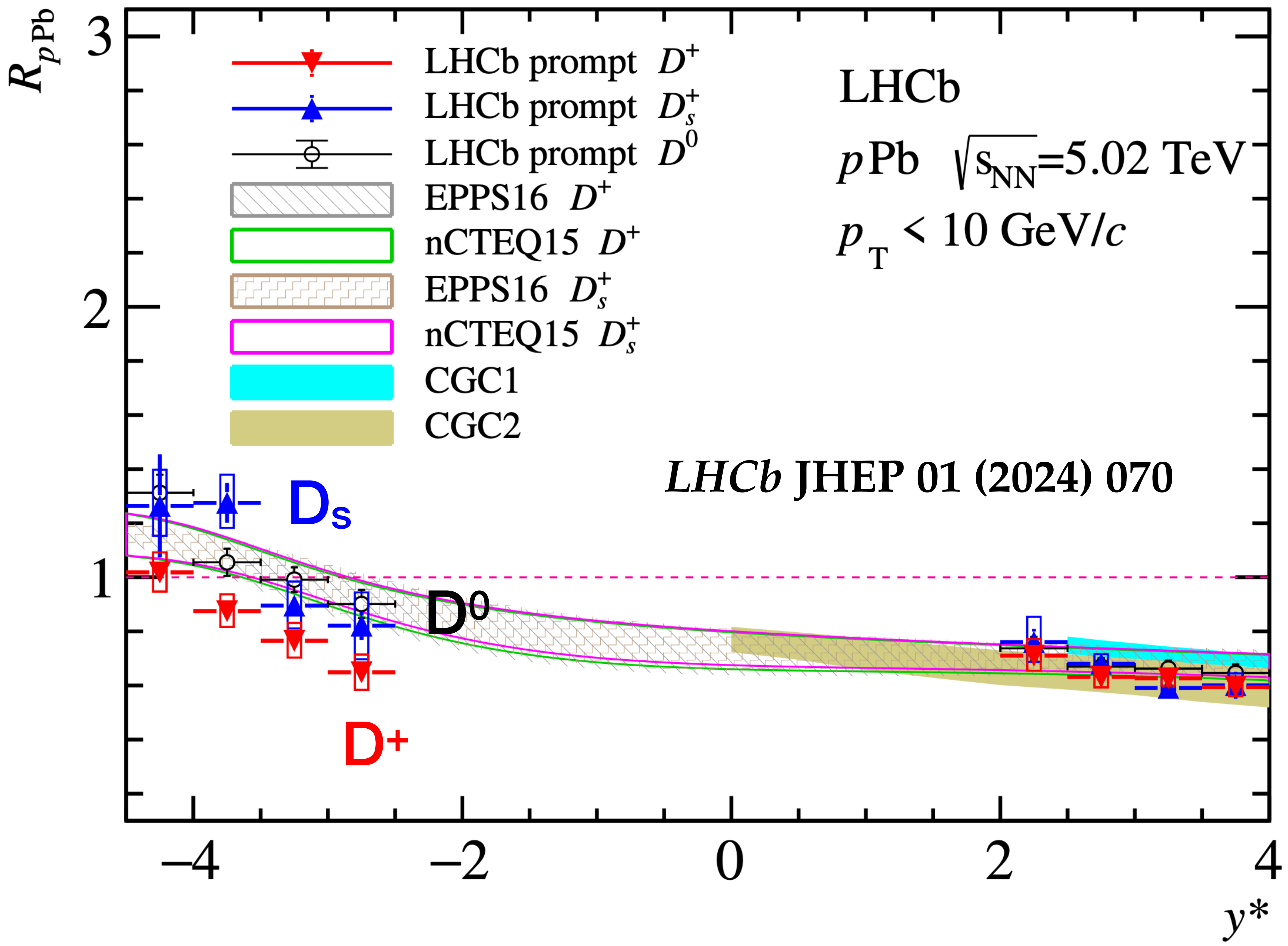
Charm conservation kept in AA collisions within nPDF uncertainties

Theoretical uncertainty » experimental uncertainty now

More differential tests ⇔ Constrain parameters + PDF + hadronization

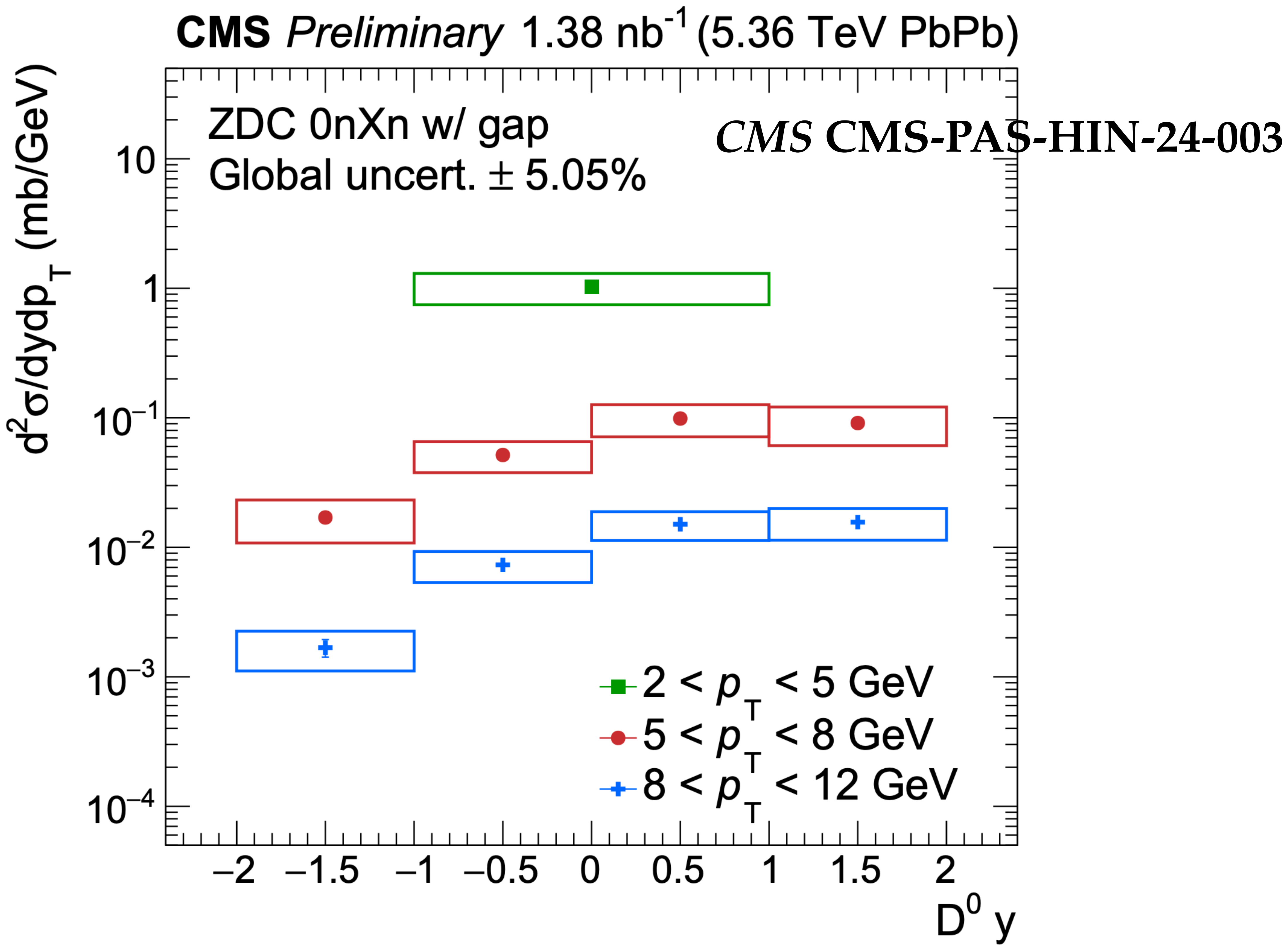
Gluon Structure in Nuclei nPDF Constraints

State-of-Art Precision pA collisions



- One of the strongest constraints on gluon nPDF
- Divergence of different hadron species
  → convoluted with final state effects

New Frontier photo-nuclear UPC



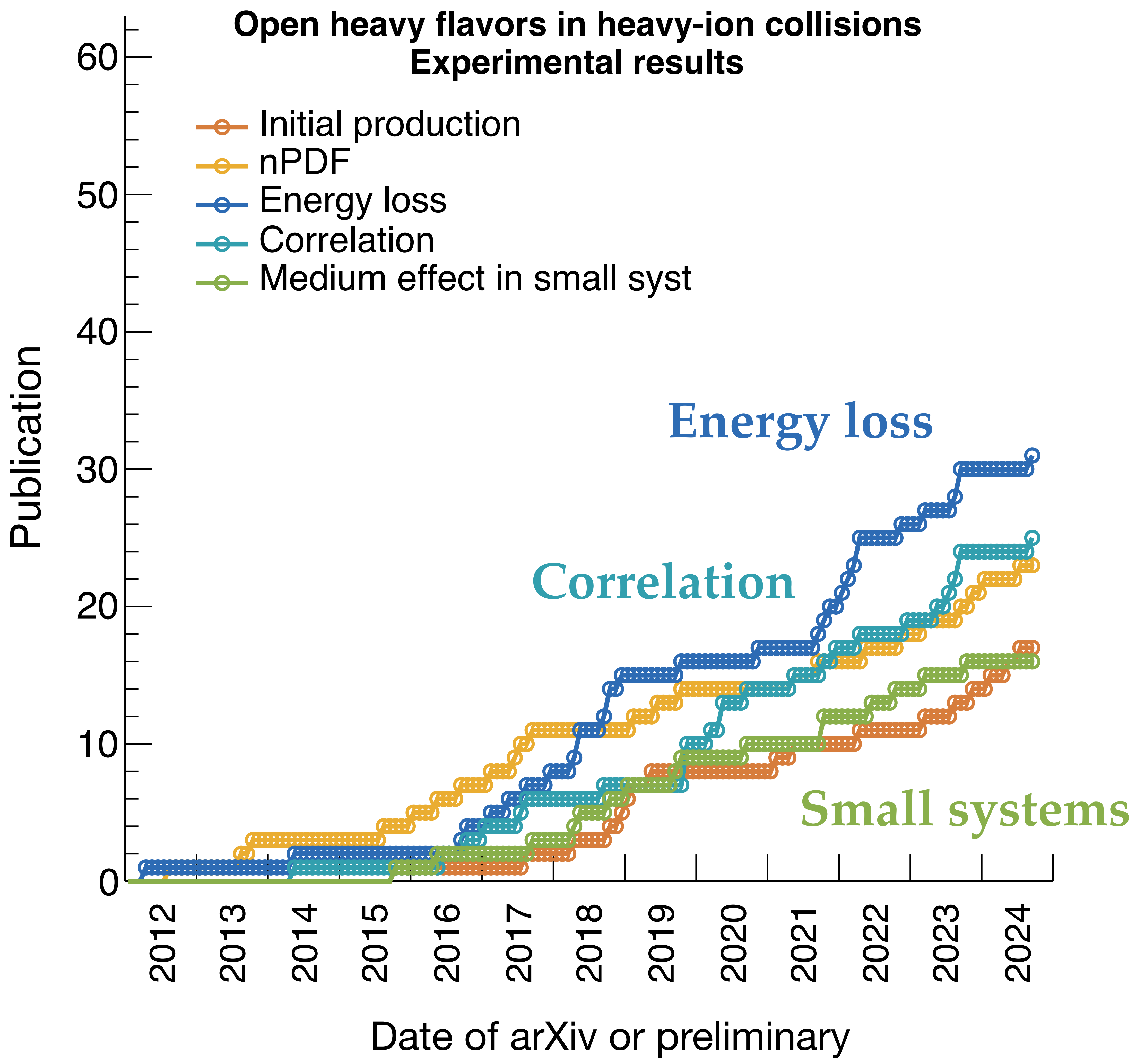
- Very clean final states and potential for large y
  → Open up a new collision system at LHC

Heavy Flavors Textbook Knowledge

Heavy quarks (charm, beauty) → large mass $\mathbf{m_Q}$

- Small momentum transfer with medium $m_Q \gg T_{QGP}$
  - Brownian motion diffusion → Can trace dynamics of individual quarks with Langevin* framework
  - If momentum exchange sufficiently → **collectivity**

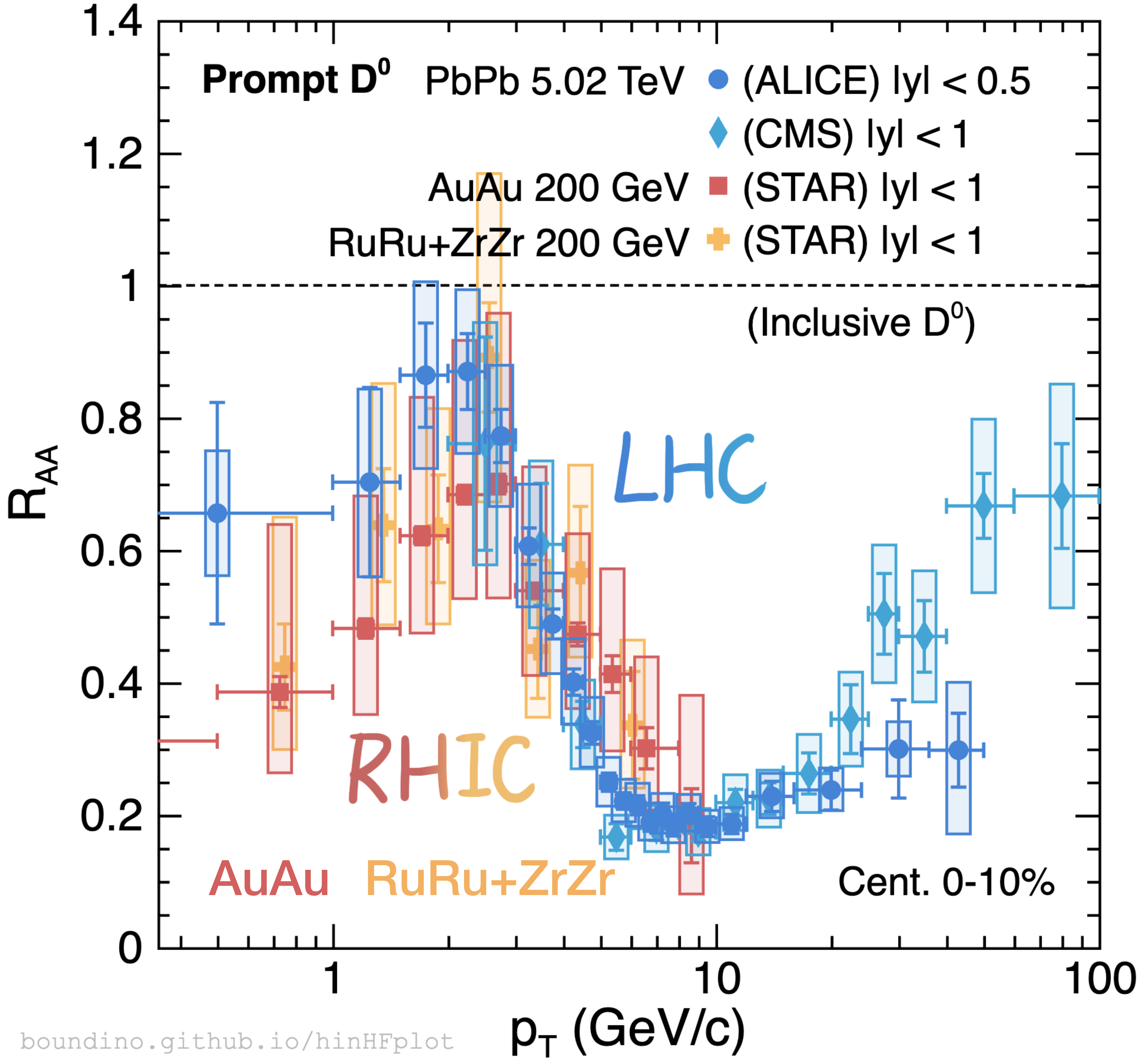
- Different **energy loss** behaviors $m_Q \gg m_q$



*or Boltzmann framework

Nuclear Modification R_{AA} D^0 Mesons

D^0 R_{AA} in central AA collisions

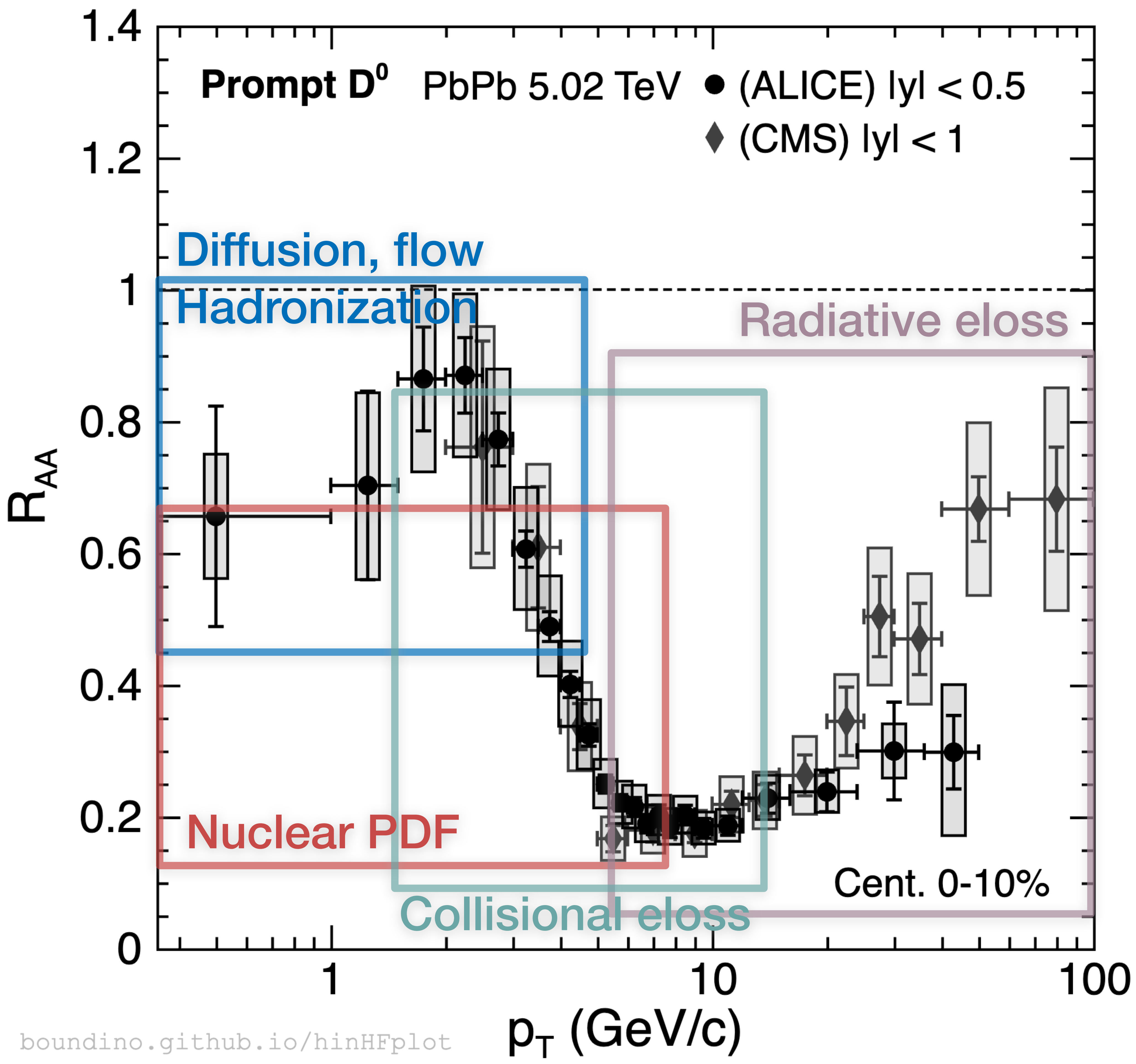


- Strong prompt D^0 suppression in wide kinematics
  pQCD picture:
  - **high p_T** Quenching in charm sector: medium induced radiative energy loss
  - **low p_T** Collisional energy loss plays a more important role for heavy quarks
- Similar R_{AA} between LHC and RHIC
  - Interplay of spectra shape **RHIC steeper** + energy loss **LHC stronger**
  - But sensitive to centrality when $p_T > 4$ GeV
  - Hope for better precision in LHC Run 3 and RHIC especially at low p_T

ALICE **JHEP 01 (2022) 174** *CMS* **PLB 782 (2018) 474** *STAR* **PRC 99 (2019) 034908** *STAR* **Preliminary**

D^0 R_{AA} Understanding the Shape

D^0 R_{AA} in central AA collisions



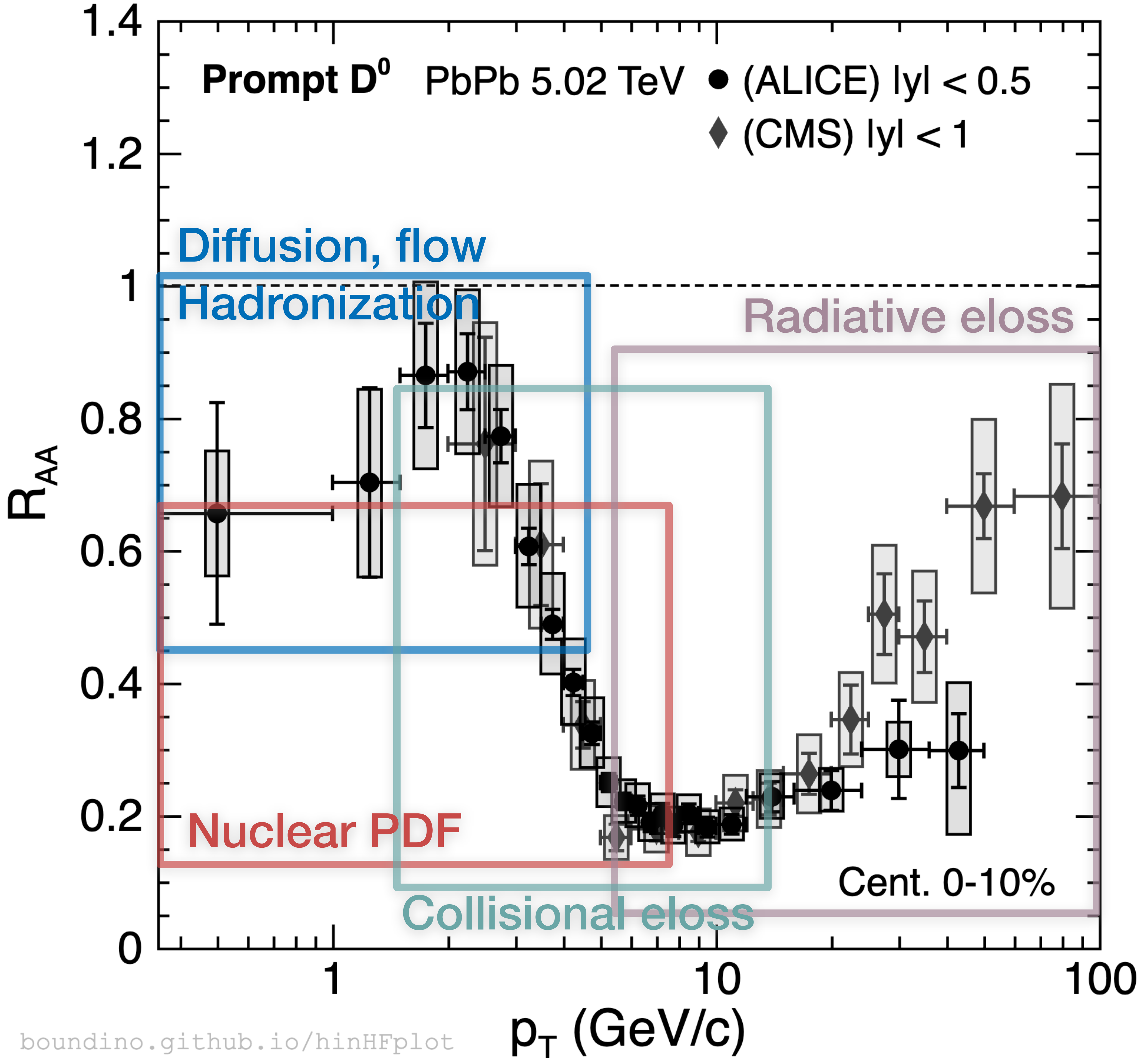
Our current understanding…

- Energy loss suppress intermediate to high p_T
  - dE/E decreases at high p_T
- Radial flow push very low energy charm quarks to higher p_T and hadronization picks light flavor kinematics
- Shadowing suppress the total yield

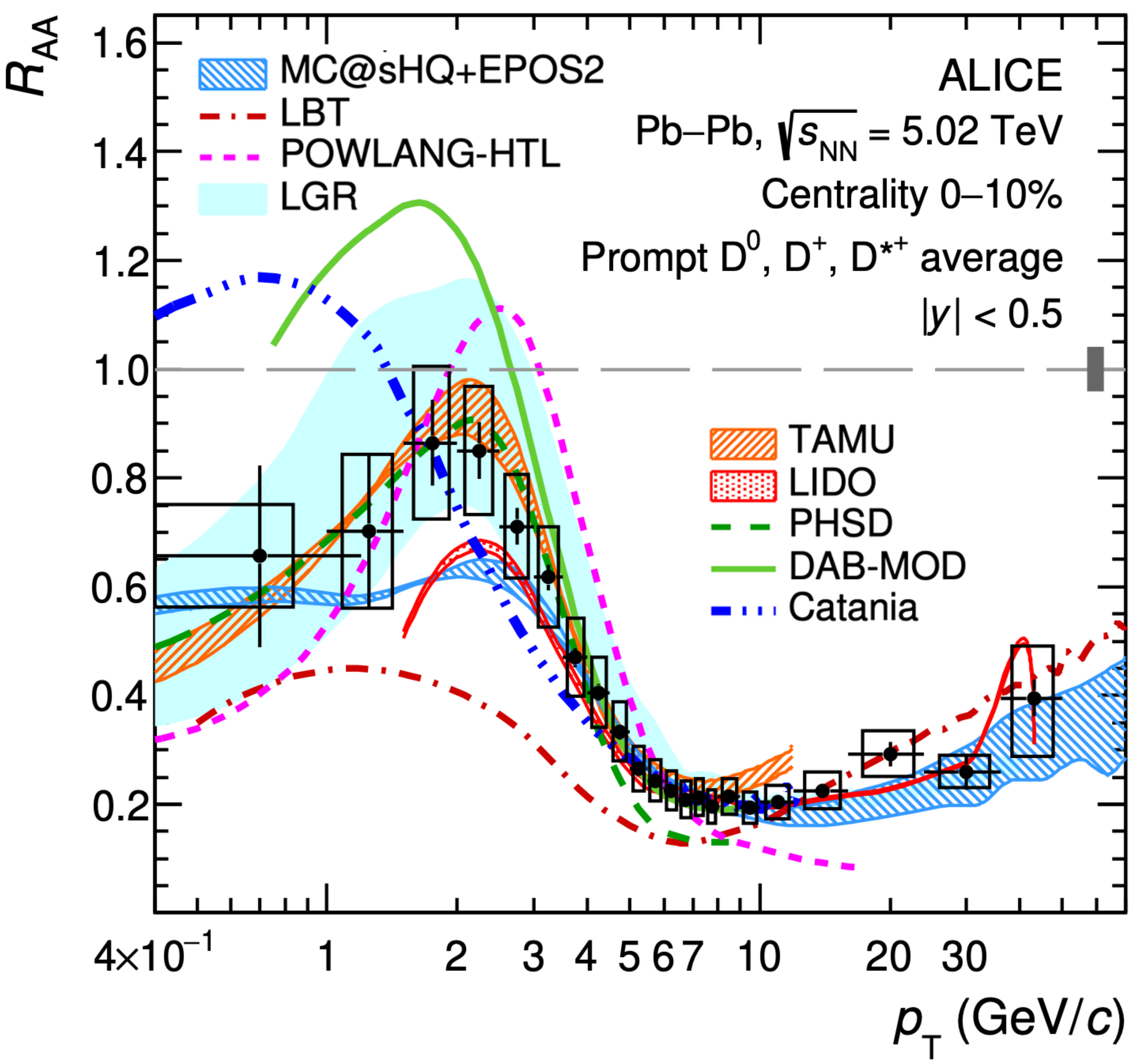
ALICE **JHEP 01 (2022) 174** *CMS* **PLB 782 (2018) 474**

D^0 R_{AA} Understanding the Shape

D^0 R_{AA} in central AA collisions



ALICE JHEP 01 (2022) 174

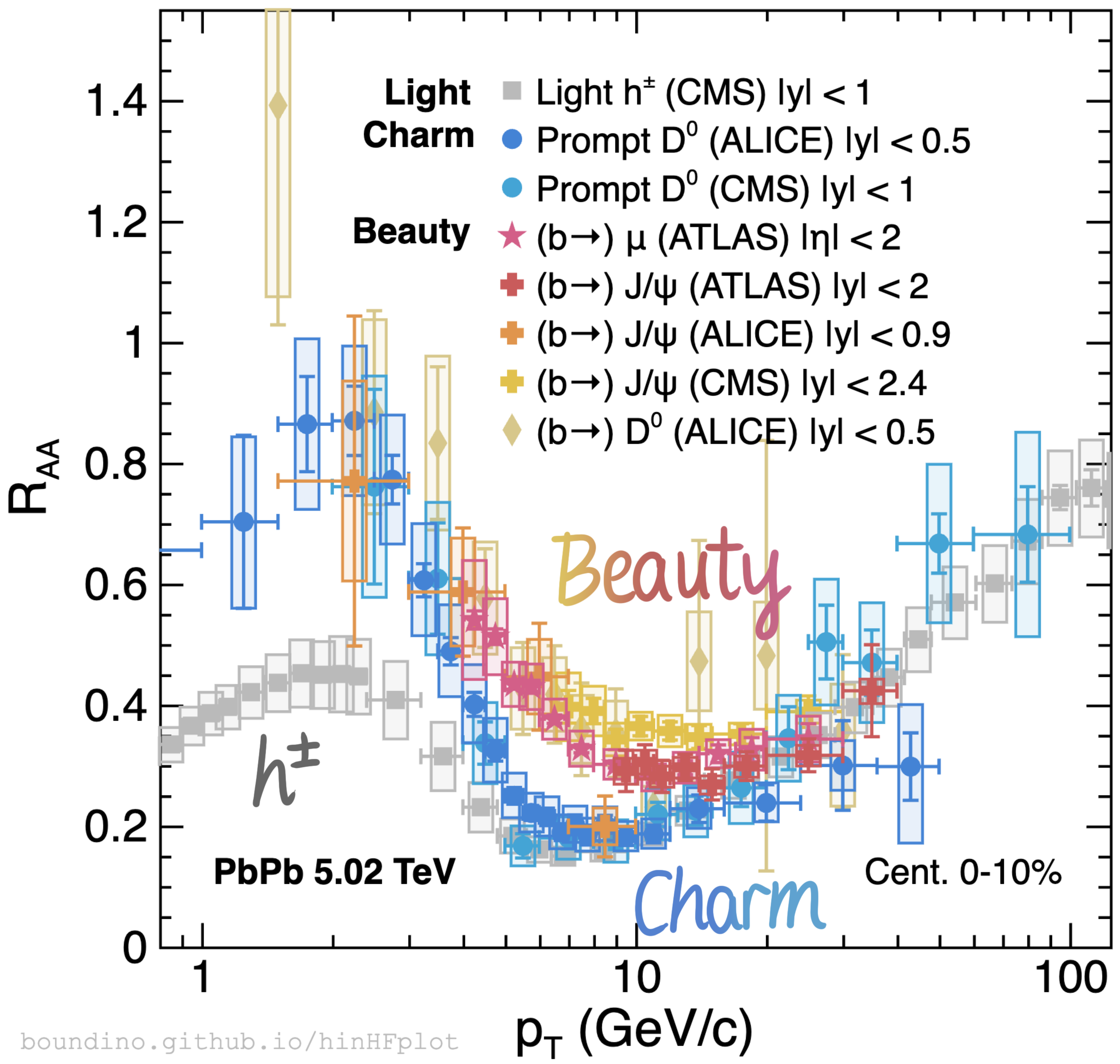


- Transport models are fairly successful but can't describe full p_T

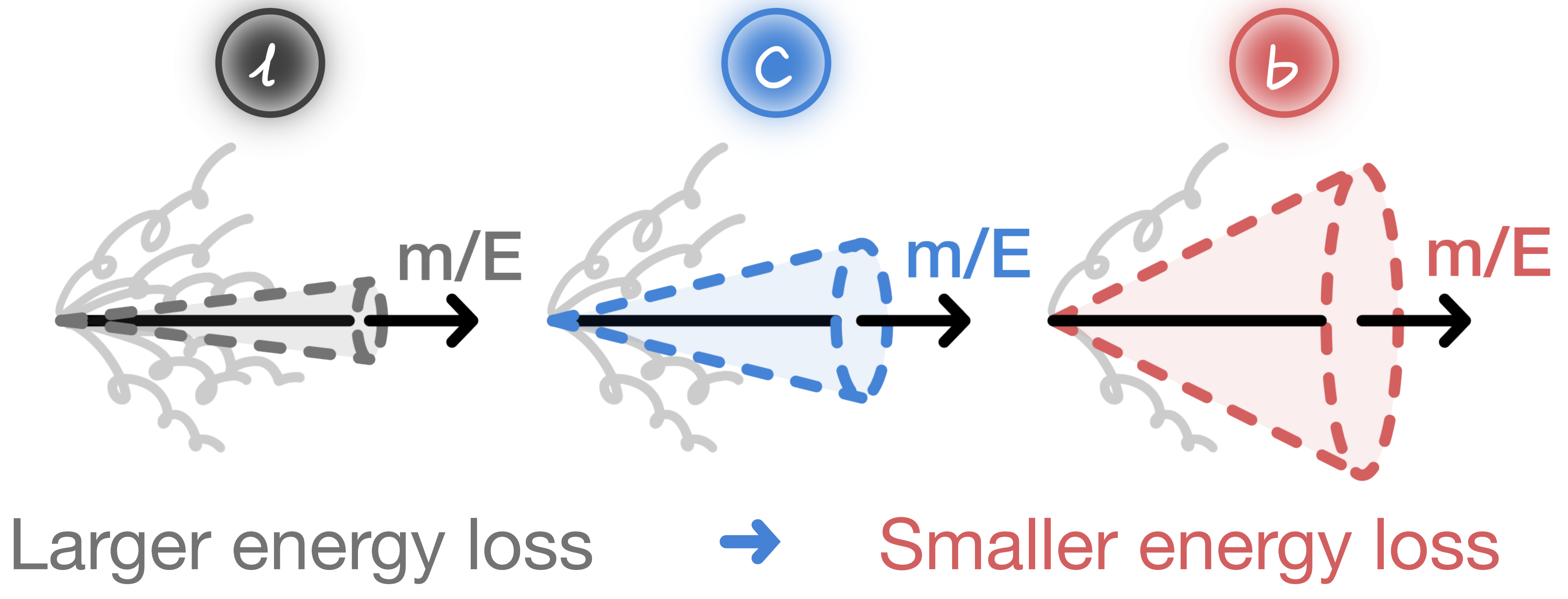
R_{AA} Mass Dependence of Energy Loss

R_{AA} for different flavors

Yu.L. Dokshitzer, D.E. Kharzeev **PLB 519 (2001) 199**



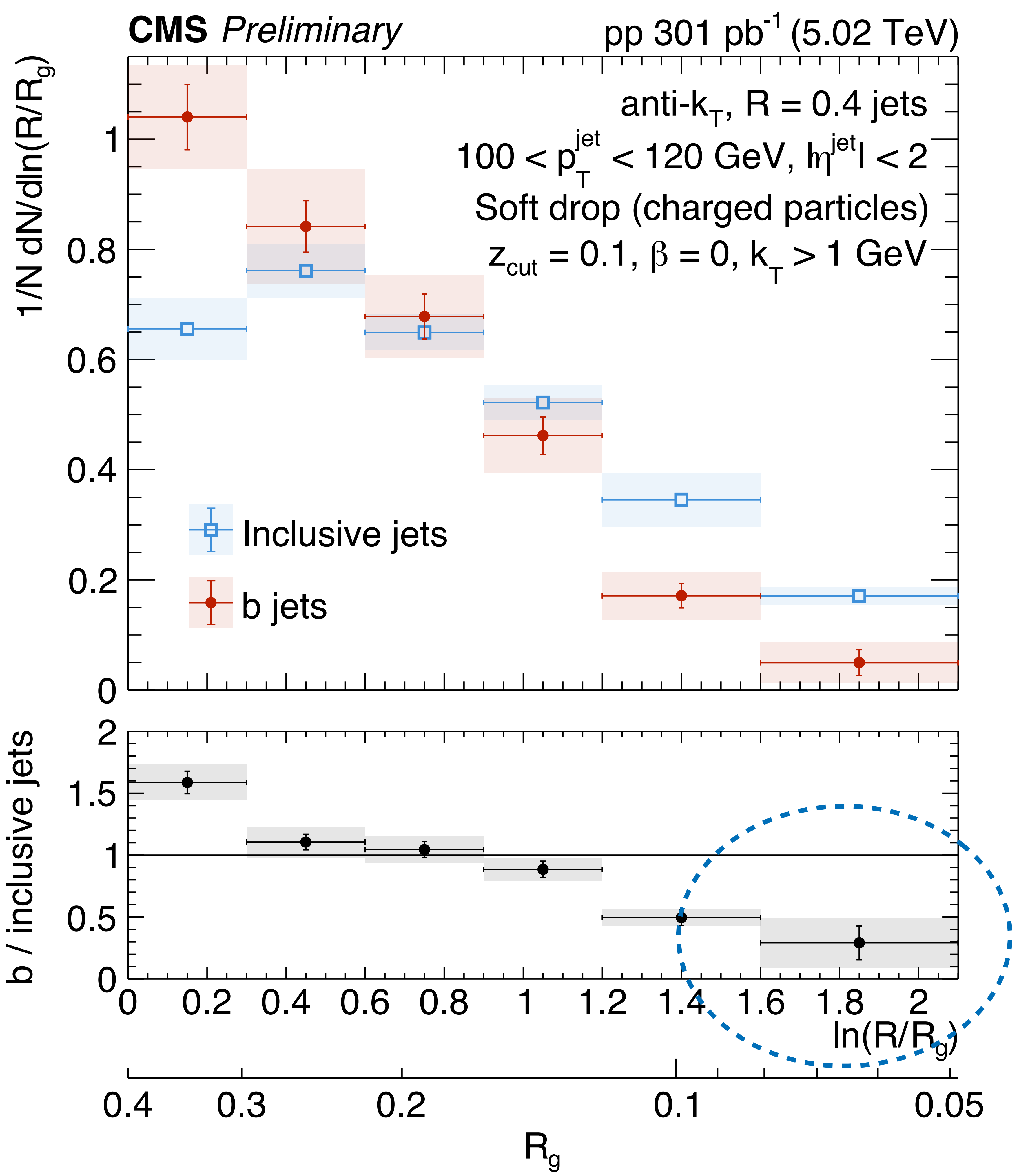
- Mass dependent energy loss Dead cone effect
  - Radiation is suppressed inside $\theta < m/E$
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$



Can we see the dead cone?

ATLAS PLB 829 (2022) 137077 *ATLAS* EPJC 78 (2018) 762 *ALICE* HEP 02 (2024) 066 *CMS* EPJC 78 (2018) 509 *ALICE* JHEP 12 (2022) 126

Dead Cone & More HF Jet Substructure



Suppression of small angle emissions

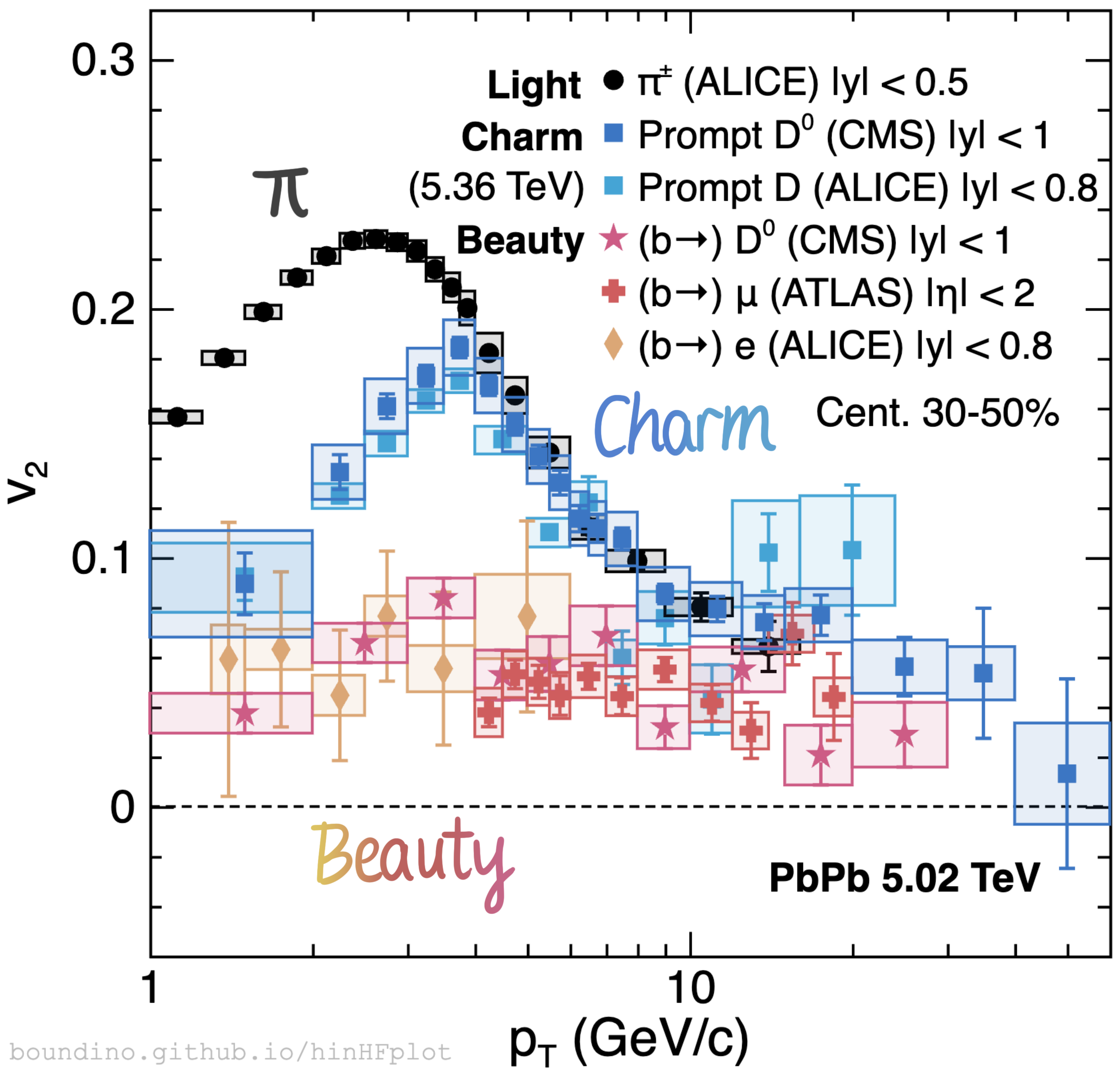
- Direct observation of dead cones in pp
  - Advanced tools of 2 languages: Lund plane, EEC
  - Progress in **experiments** for both languages
- Unveil medium dynamics in heavy-ion collisions
  - Medium induced radiation may fill dead cones
    - Isolate medium effects!
    - Progress in **theories** for both languages
  - Hope to learn more prospects in the following days!

N. Armesto et al PRD 69 (2004) 114003
L. Cunqueiro et al PRD 107 (2023) 094008
C. Andres et al PRD 110 (2024) L031503

ALICE Nature 605 (2022) 440 *CMS* CMS-PAS-HIN-24-007
ALICE Preliminary (D-tagged jet EEC) *CMS* CMS-PAS-HIN-24-005

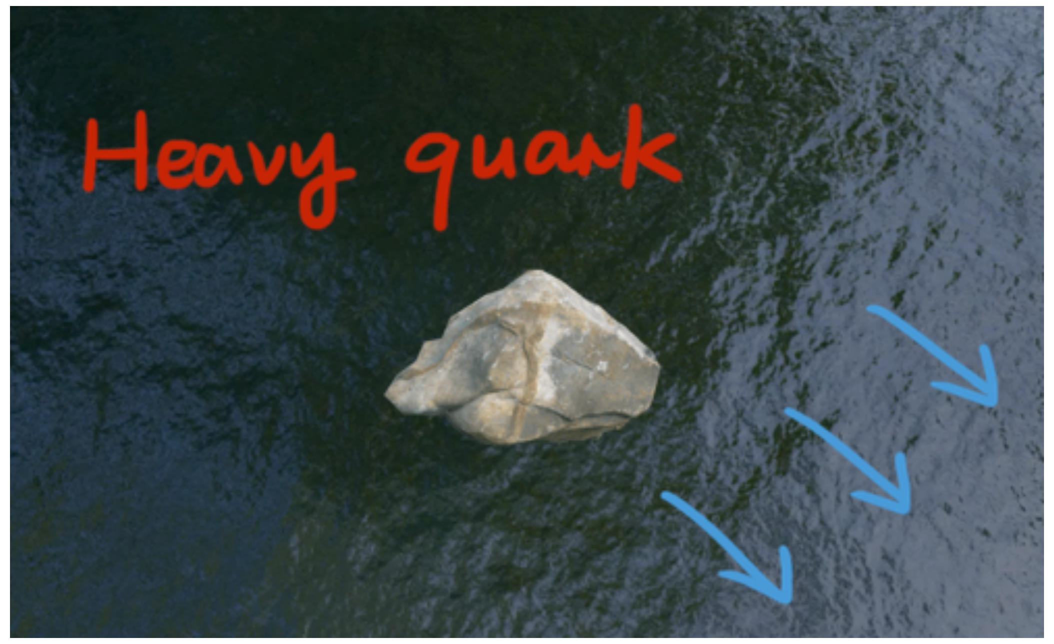
Collective Flow Flavor Dependence

v2 for different flavors

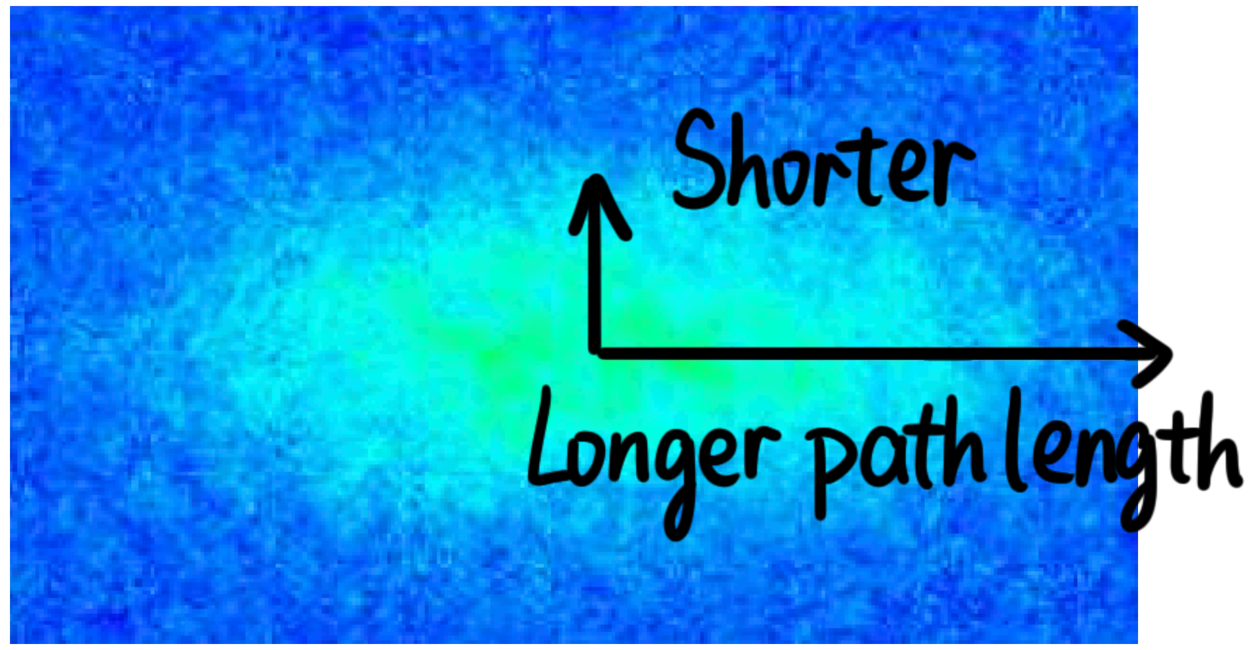


- Charm quarks explicitly take part in **collective motion**
  - Strong coupling
- Non-zero beauty flow signal is significant
- **Thermalization** degree varies vs flavors

Low p_T: elliptic flow



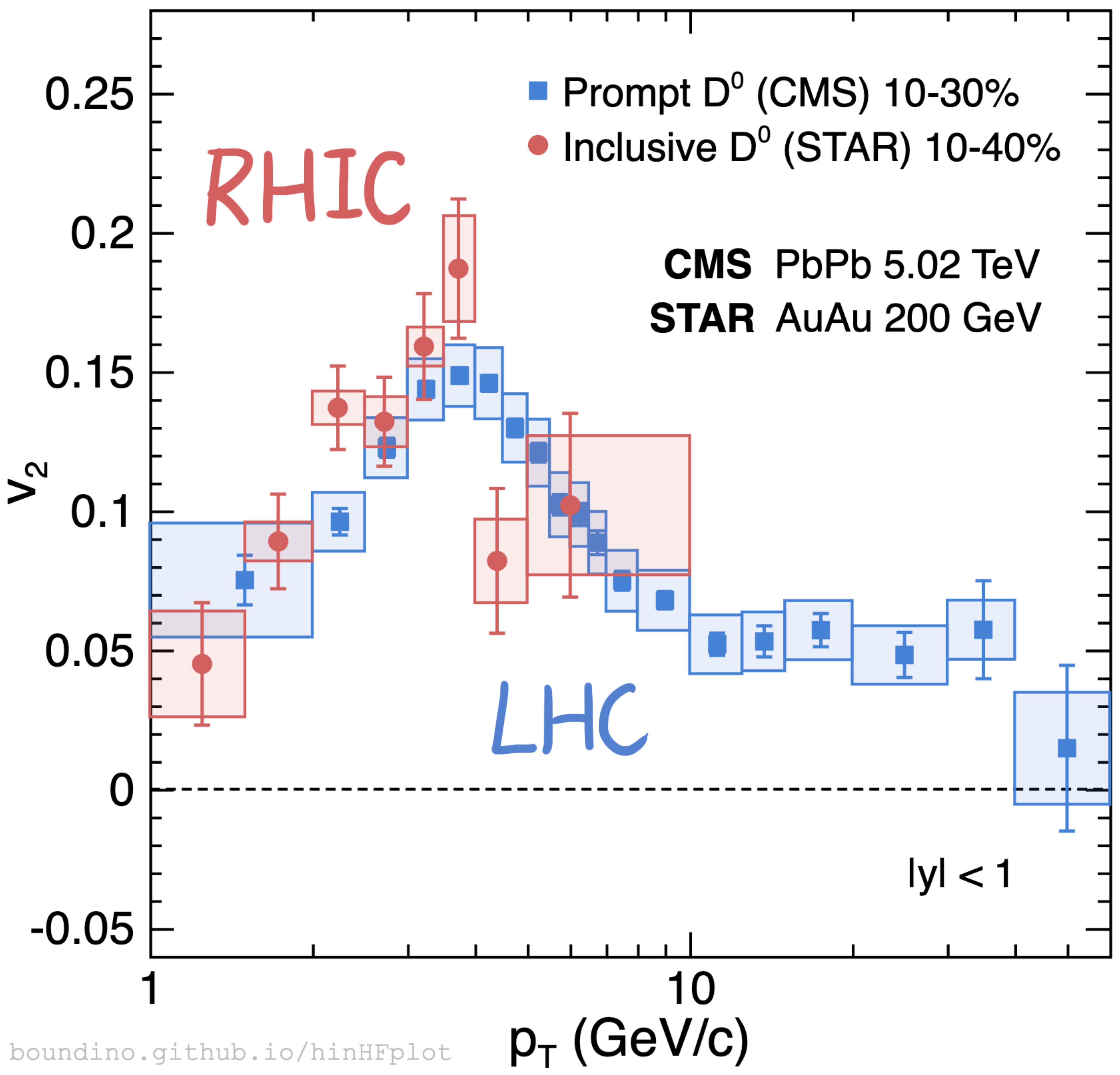
High p_T: path-length dependence of energy loss



CMS PLB 816 (2021) 136253 *ALICE* Preliminary *CMS* PLB 850 (2024) 138389 *ATLAS* PLB 807 (2020) 135595 *ALICE* PRL 126 (2021) 162001

Collective Flow LHC vs RHIC

Open charm v_2 for RHIC vs LHC



- **Similar** D v_2 between LHC and RHIC
  - Indicate similar flow strength despite different temperature & size?
- Miss precise **beauty** v_2 measurements at RHIC

CMS PLB 816 (2021) 136253 *STAR* PRL 118 (2017) 212301

Lesson #1

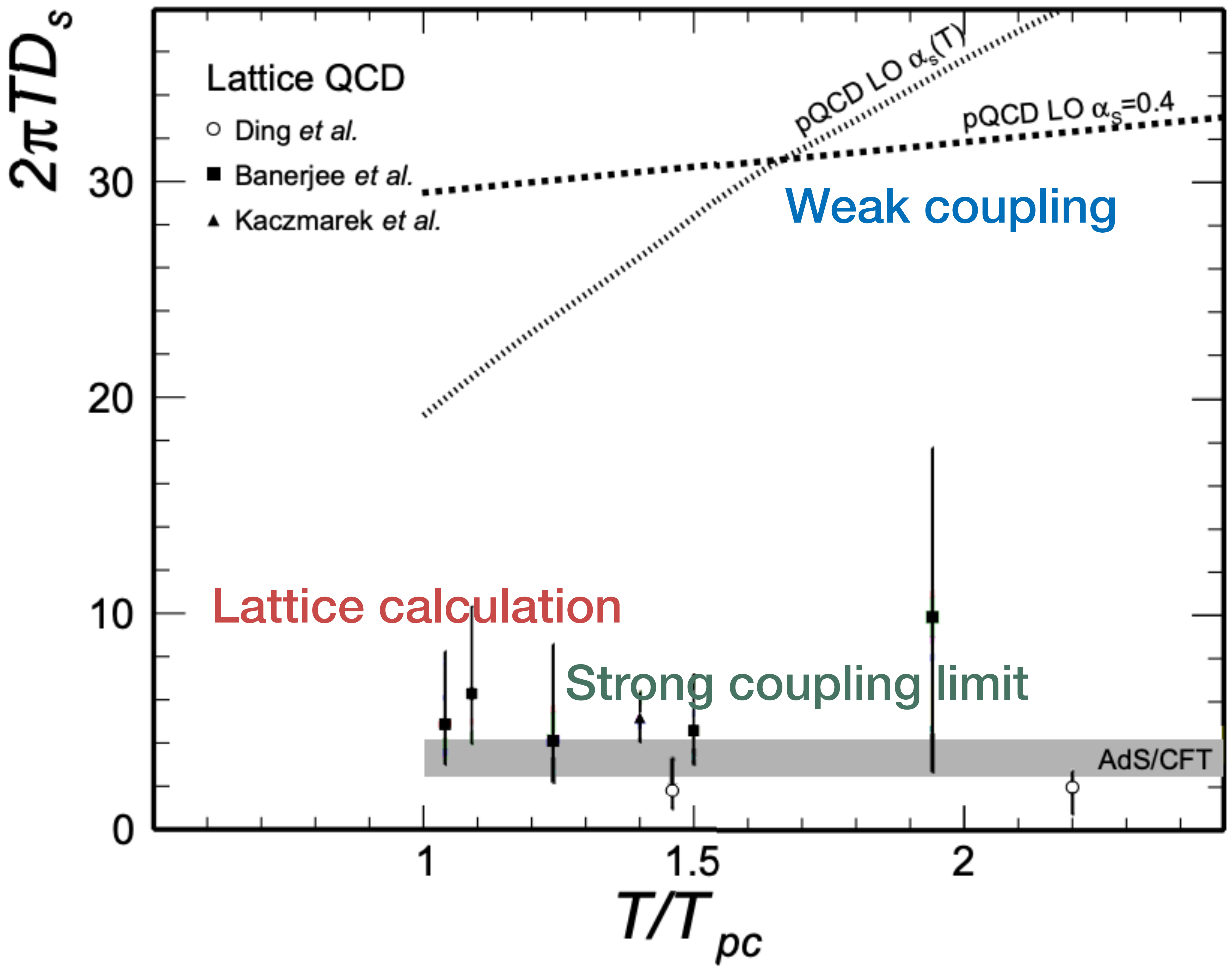
Very strong coupling between heavy quarks and medium

strong (flavor dependent) energy loss and collectivity are well established

seeing the thermalization process of HQ, different from soft and jets

Diffusion Spatial Diffusion Coefficient D_S

Spatial diffusion coefficient D_S(T, p=0)



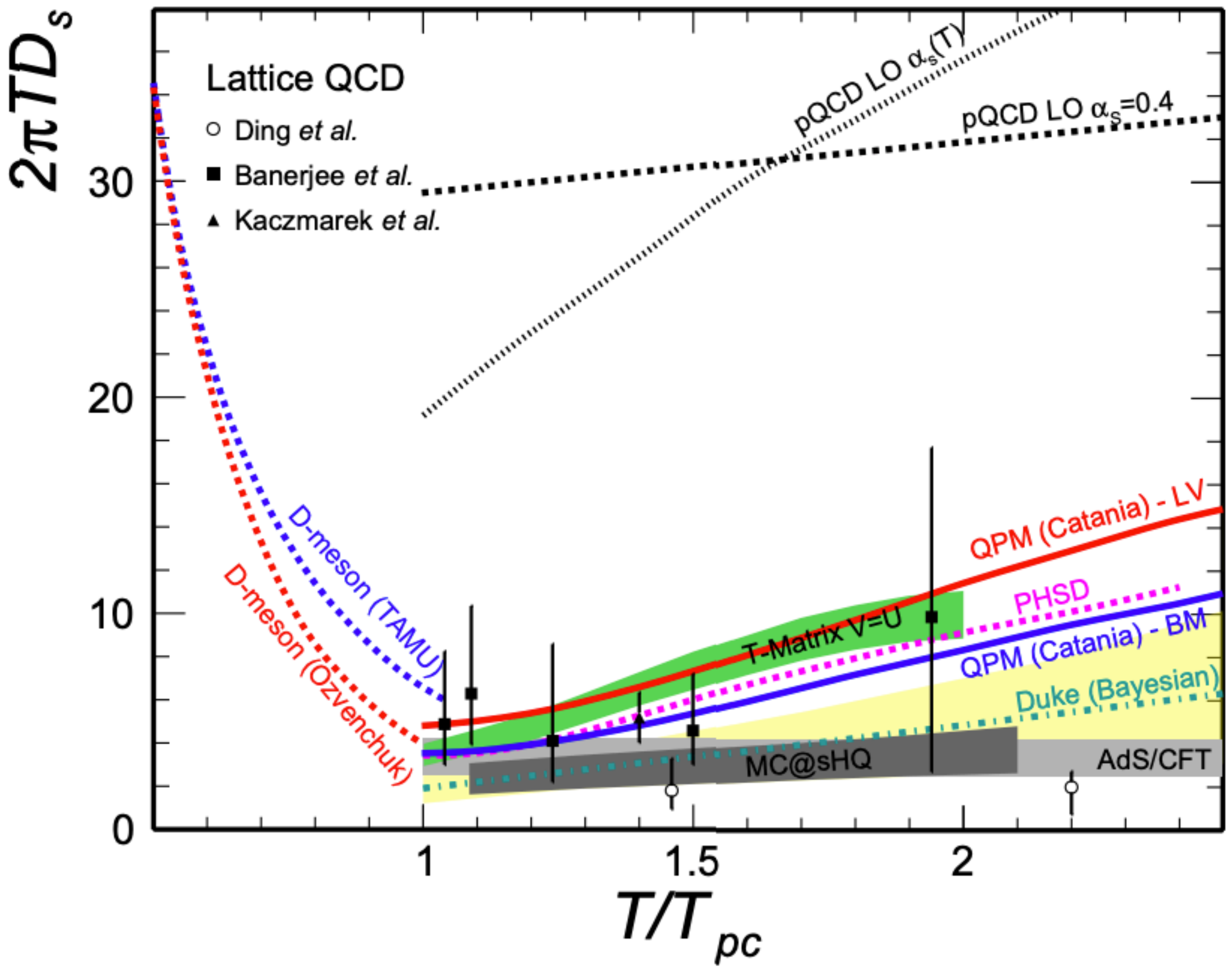
- First principle calculation
  - **LO pQCD** Weak coupling limit
  - **AdS/CFT** Strong coupling limit
  - **Lattice QCD** Not accessible at finite momentum

    Need **phenomenological models**

X. Dong, Y.-J. Lee, R. Rapp **Annual Rev**

Diffusion Spatial Diffusion Coefficient D_S

Spatial diffusion coefficient D_S(T, p=0)



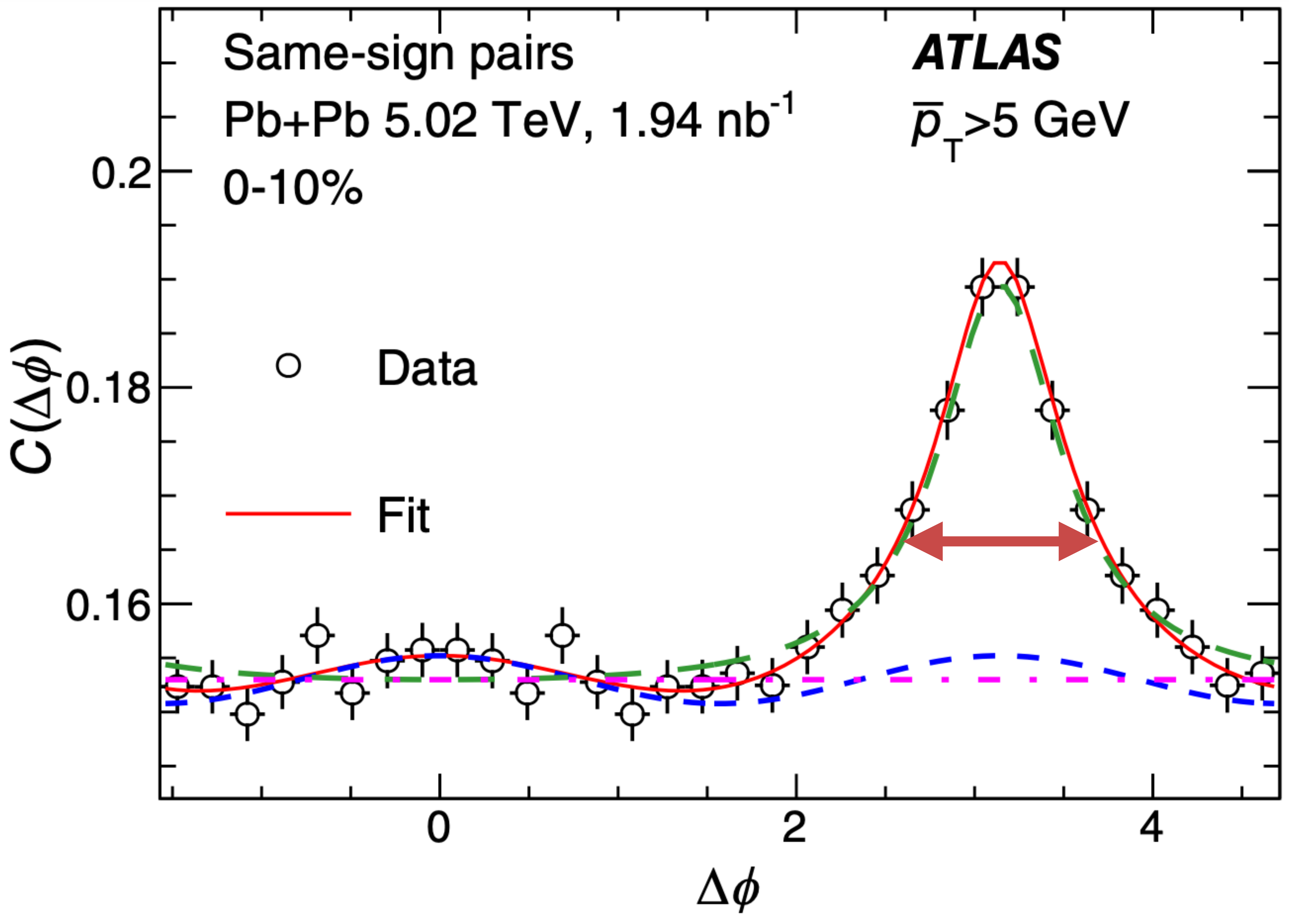
- First principle calculation
  - **LO pQCD** Weak coupling limit
  - **AdS/CFT** Strong coupling limit
  - **Lattice QCD** Not accessible at finite momentum
    Need **phenomenological models**
- **Models** that can describe data R_{AA} & v_2 have
  - D_S close to AdS/CFT strong interaction limit
  - different momentum dependence of coefficients
  - poor control of hadronization process

X. Dong, Y.-J. Lee, R. Rapp **Annual Rev**

S. Cao et al **PRC 99 (2019) 054907**

Diffusion Beyond R_{AA} and v_2

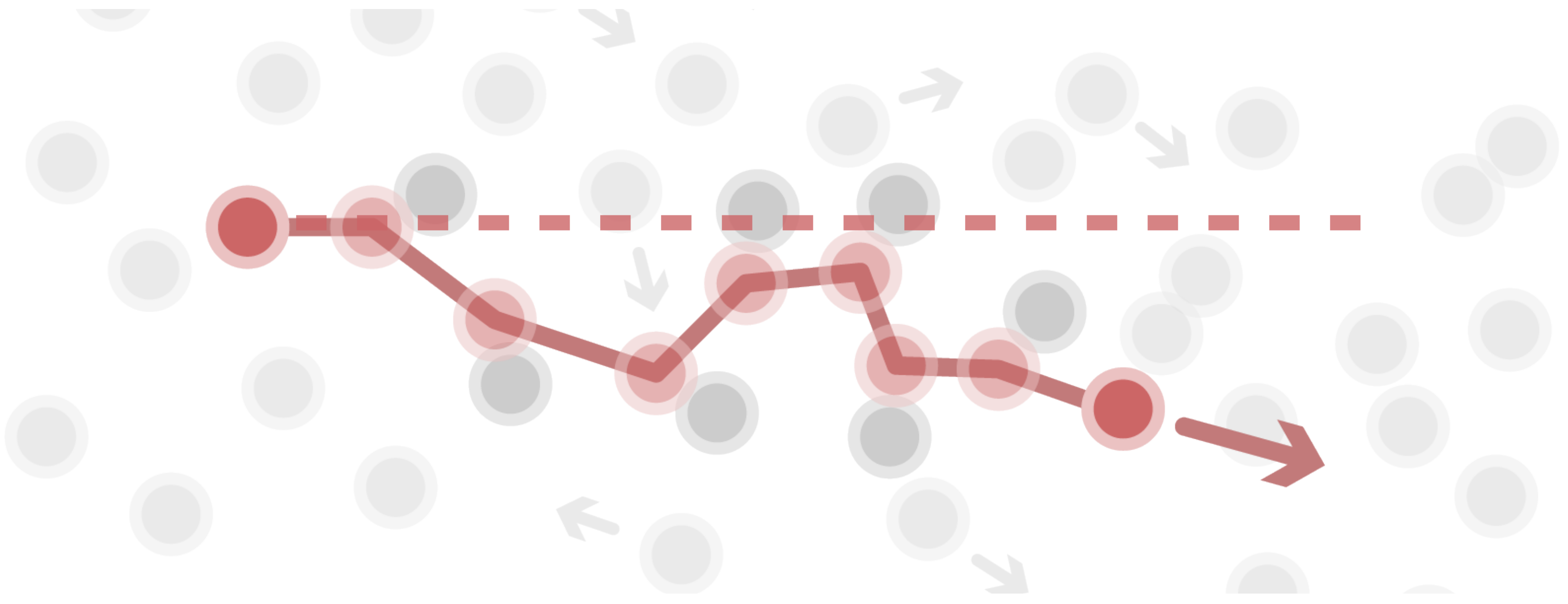
(HF→)μ - (HF→)μ correlation



ATLAS PRL 132 (2024) 202301

Want to know how much the heavy quarks are deviated from original direction after diffusion

- D-D̄ correlation down to 0 p_T **dream measurement**



- Back-to-back (HF→)μ pair angle correlation
  - Away side **width** in PbPb has no broadening from pp
  - Possibly because the parent heavy quark p_T is not sufficiently low

Lesson #2

Diffusion (probably) happens

Hope of probing individual diffusion/drag coefficients

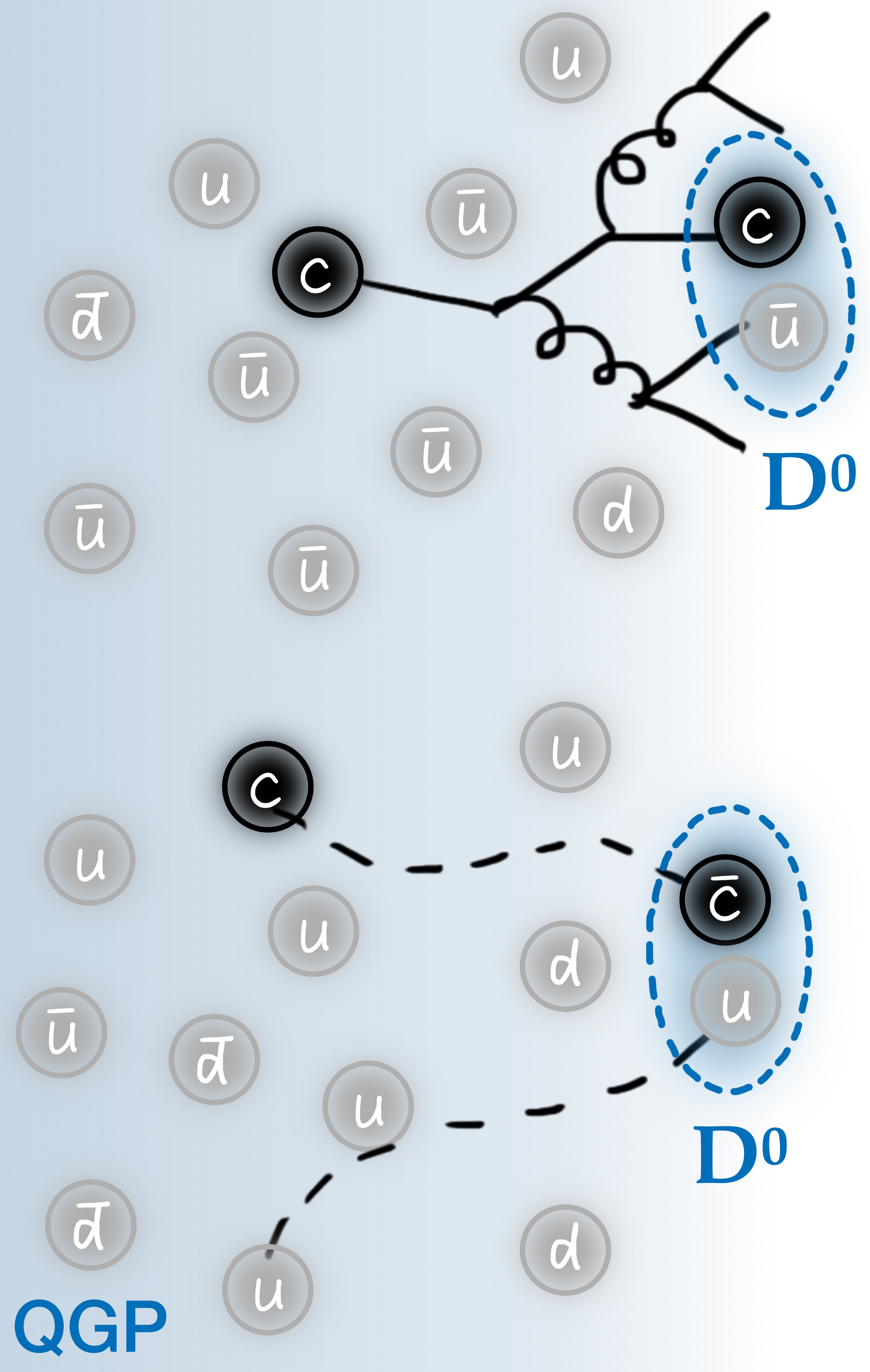
observables beyond R_{AA} and v_2

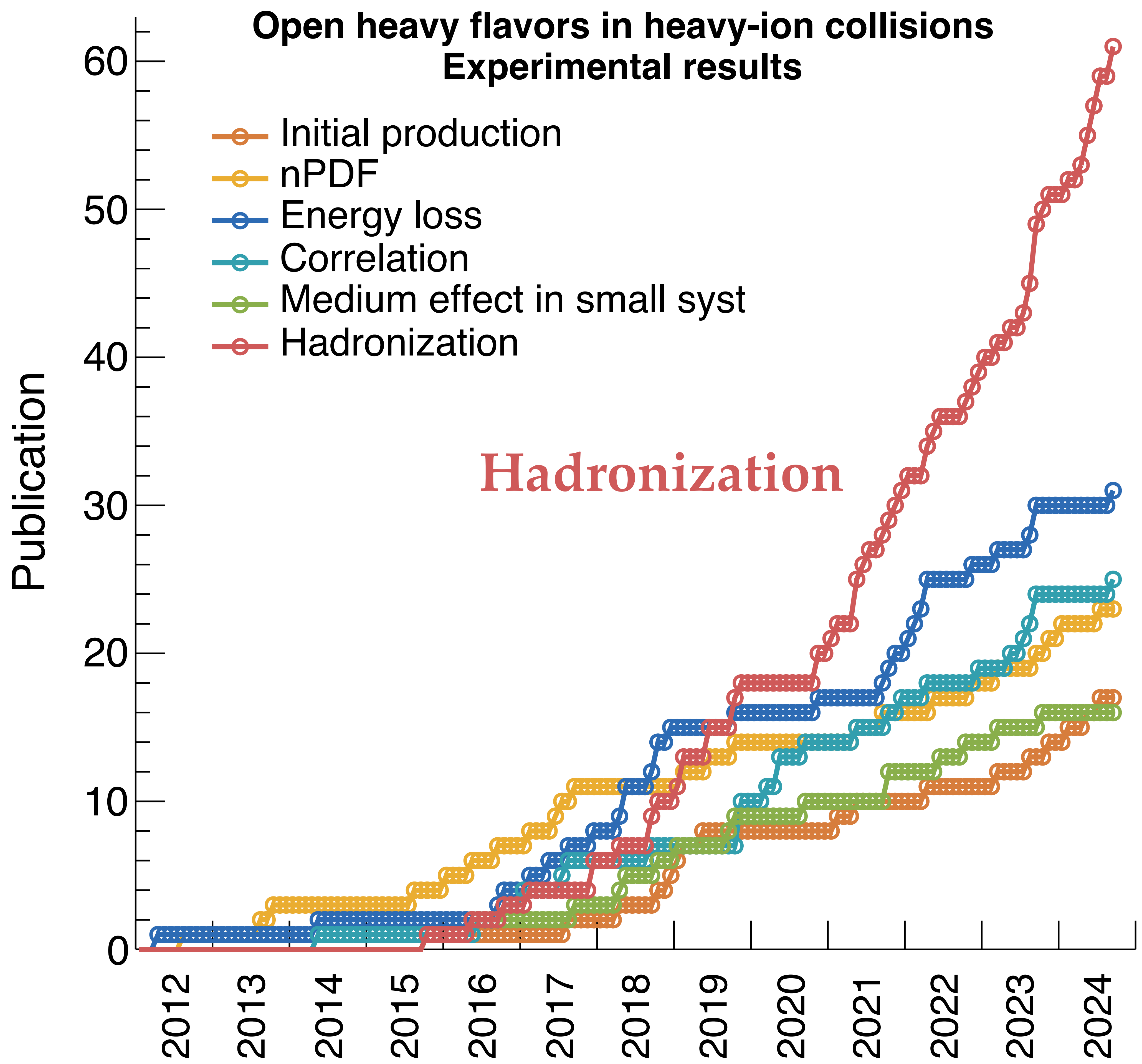
beauty can resolve some diversity in models

“Poor” knowledge of non-medium effects keeps from extracting better transport coefficients

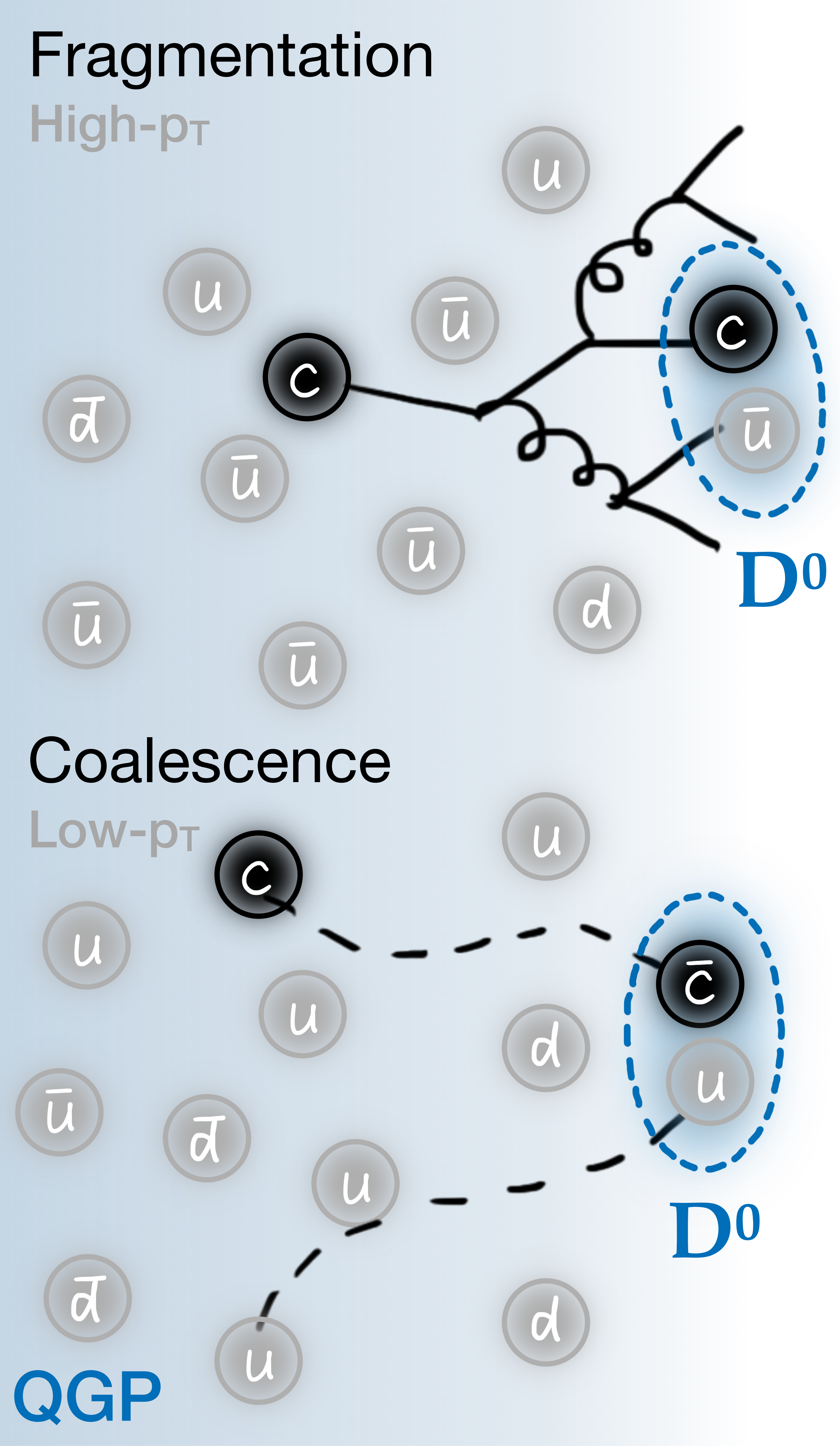
hadronization!, nPDF, initial state, …

Hadronization How Quarks Form Hadrons





Hadronization Modification In Medium



- Fragmentation universality assumed across collision systems
  - Successful in HF meson production in pp
  - **Lesson from LF** additional coalescence (recombined with light quarks in medium) to describe in-medium modification in AA collisions

- Hadrons with **different quark content** as experimental proxy

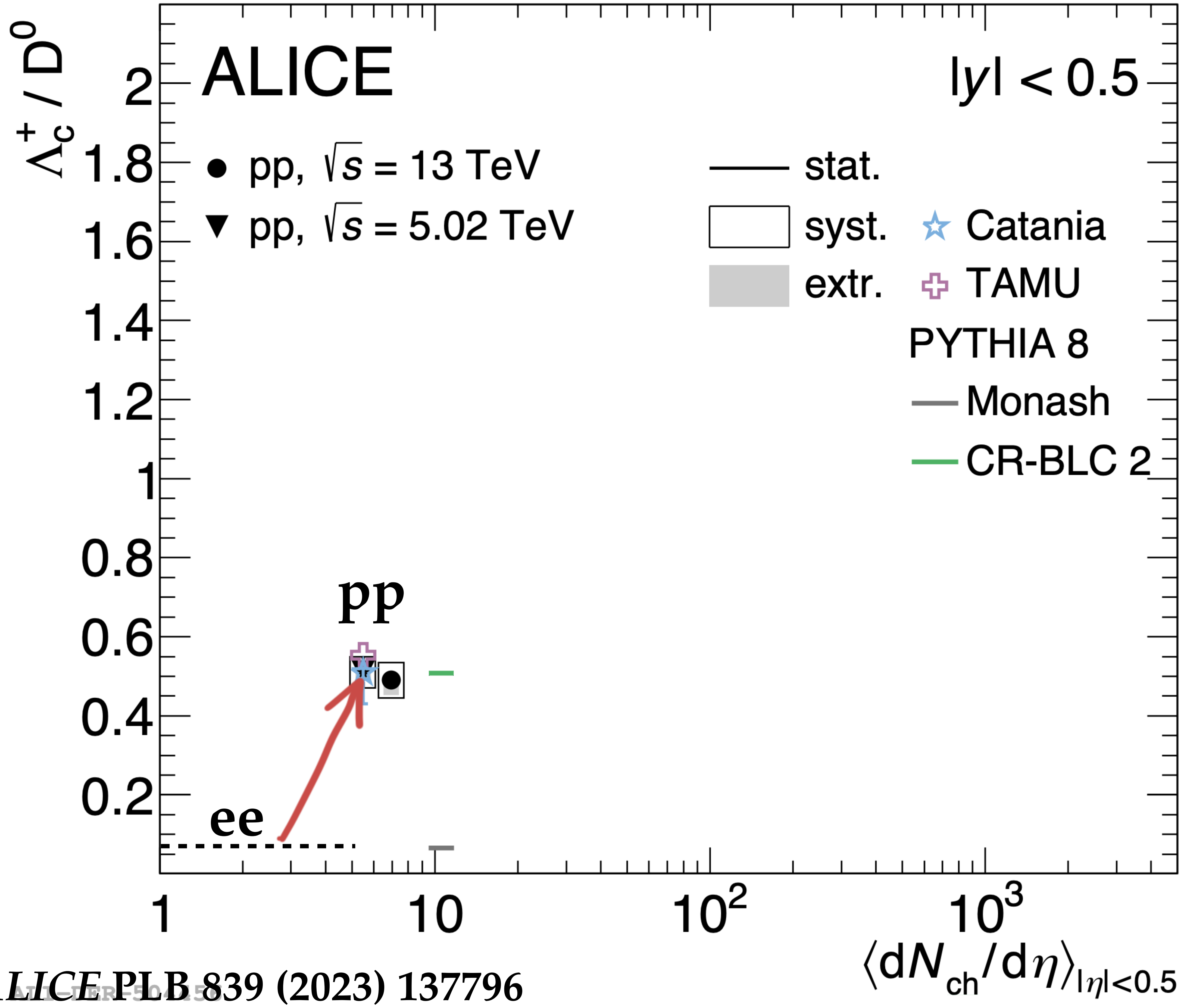
If there is coalescence

Higher $\mathbf{D_s / D^0}$ expected
strangeness enhancement

Higher $\mathbf{\Lambda_c / D^0}$ expected
more valence quarks

Integrated Λ_c / D^0 In pp Collisions

Λ_c / D^0 vs Multiplicity



ALICE PLB 839 (2023) 137796

Old news: p_T-Integrated yield ratio Λ_c / D^0

- **Enhanced:** e^+e^- to pp (<0.1 → ~0.5)

Most microscopic → Most static

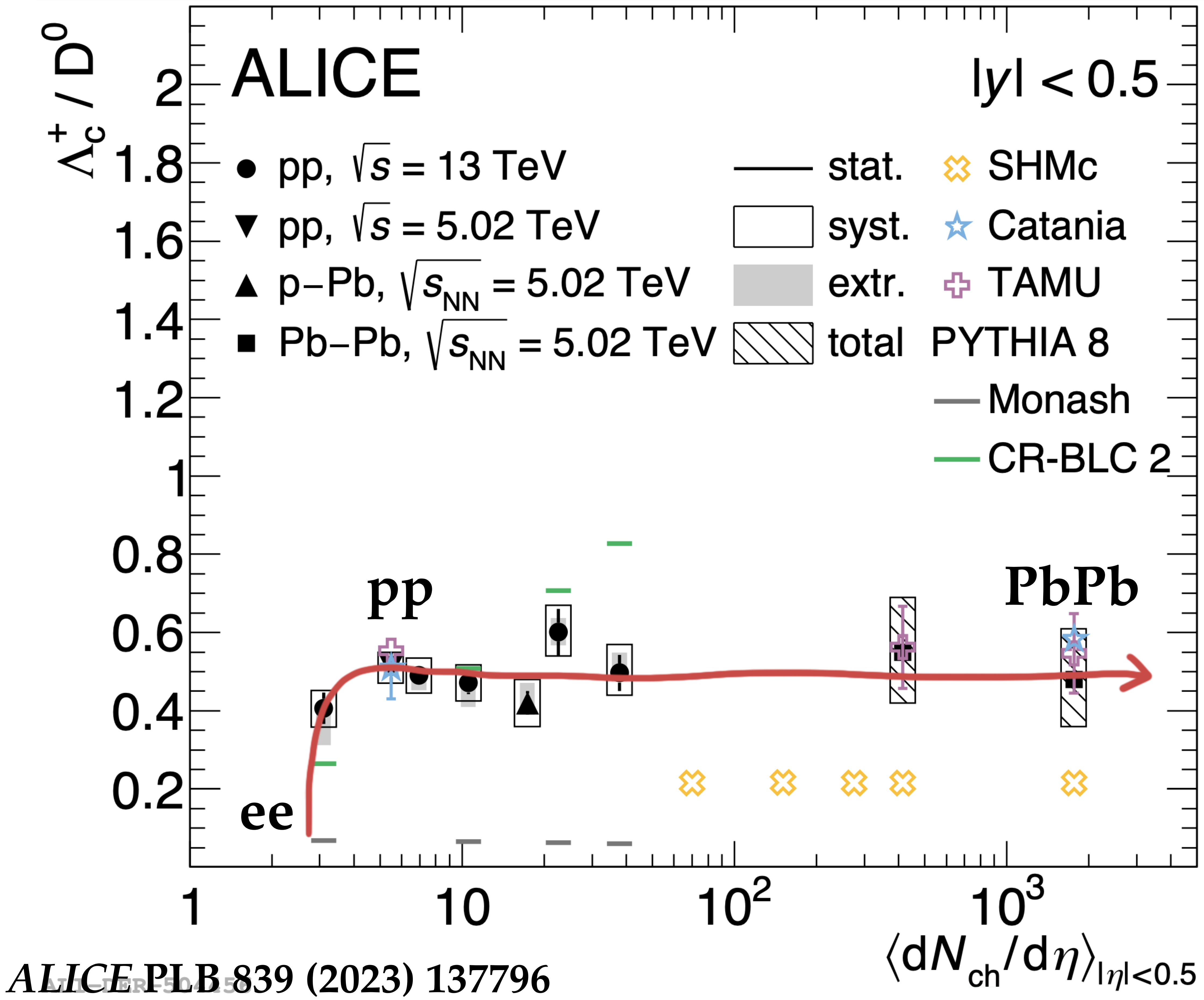
String model	Coalescence model	Statistical hadronization model
Extension of fragmentation Junction topology color reconnection (CR) beyond leading color	Assume coalescence happens in pp as well	Get feed down from additional excited states from RQM

J. Altmann et al. arXiv:2405.19137

J. Zhao et al. PRD 109 (2024) 054011

Integrated Λ_c / D^0 In pp Collisions

Λ_c / D^0 vs Multiplicity



ALICE PLB 839 (2023) 137796

Old news: p_T-Integrated yield ratio Λ_c / D^0

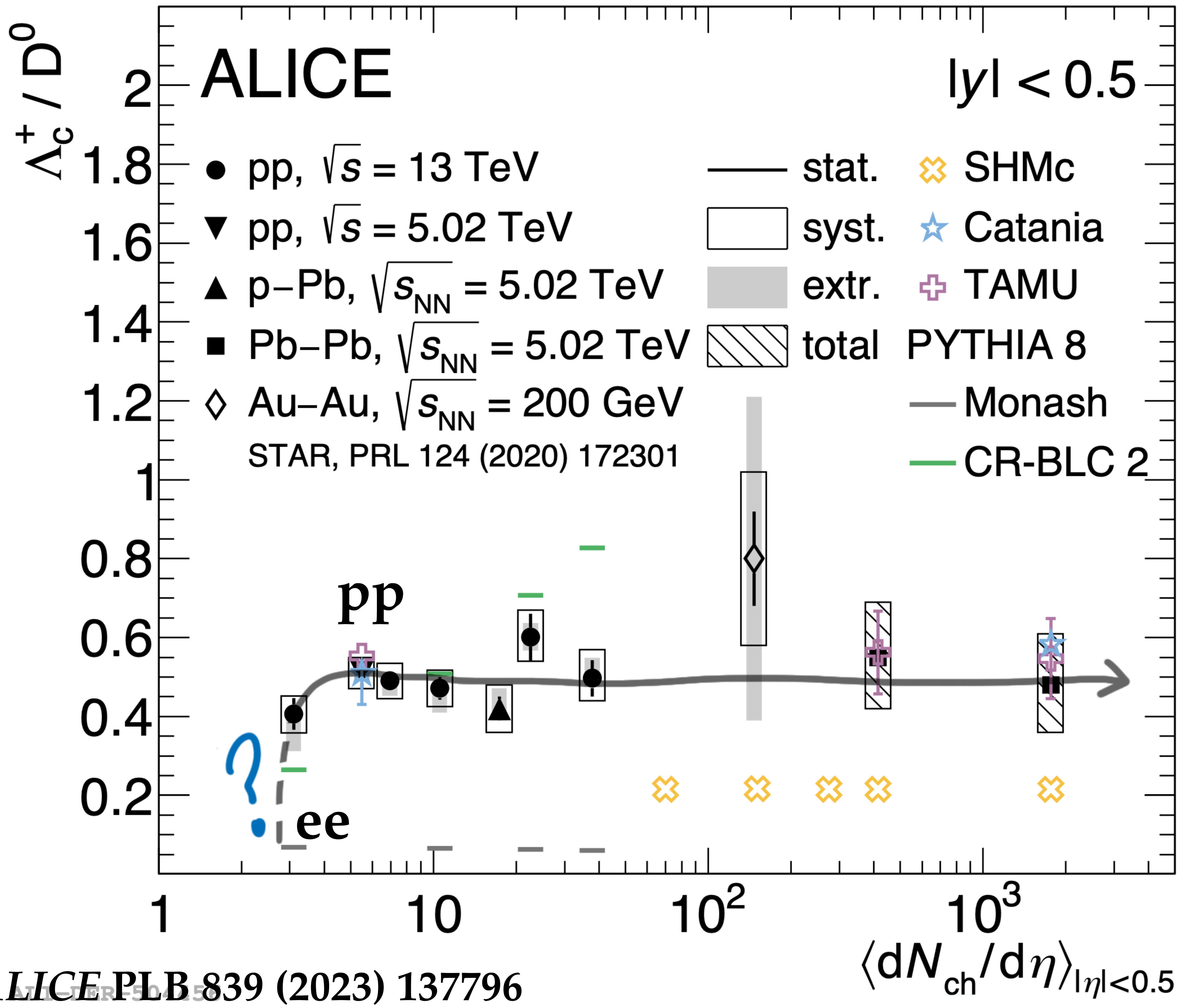
- **Saturated:** pp to central PbPb (~0.5)

Most microscopic ····················► Most static		
String model Extension of fragmentation No saturation mechanisms	**Coalescence model** Chemical equilibrium / similar T_{QGP}	**Statistical hadronization model** Chemical equilibrium

J. Altmann *et al.* arXiv:2405.19137
J. Zhao *et al.* PRD 109 (2024) 054011

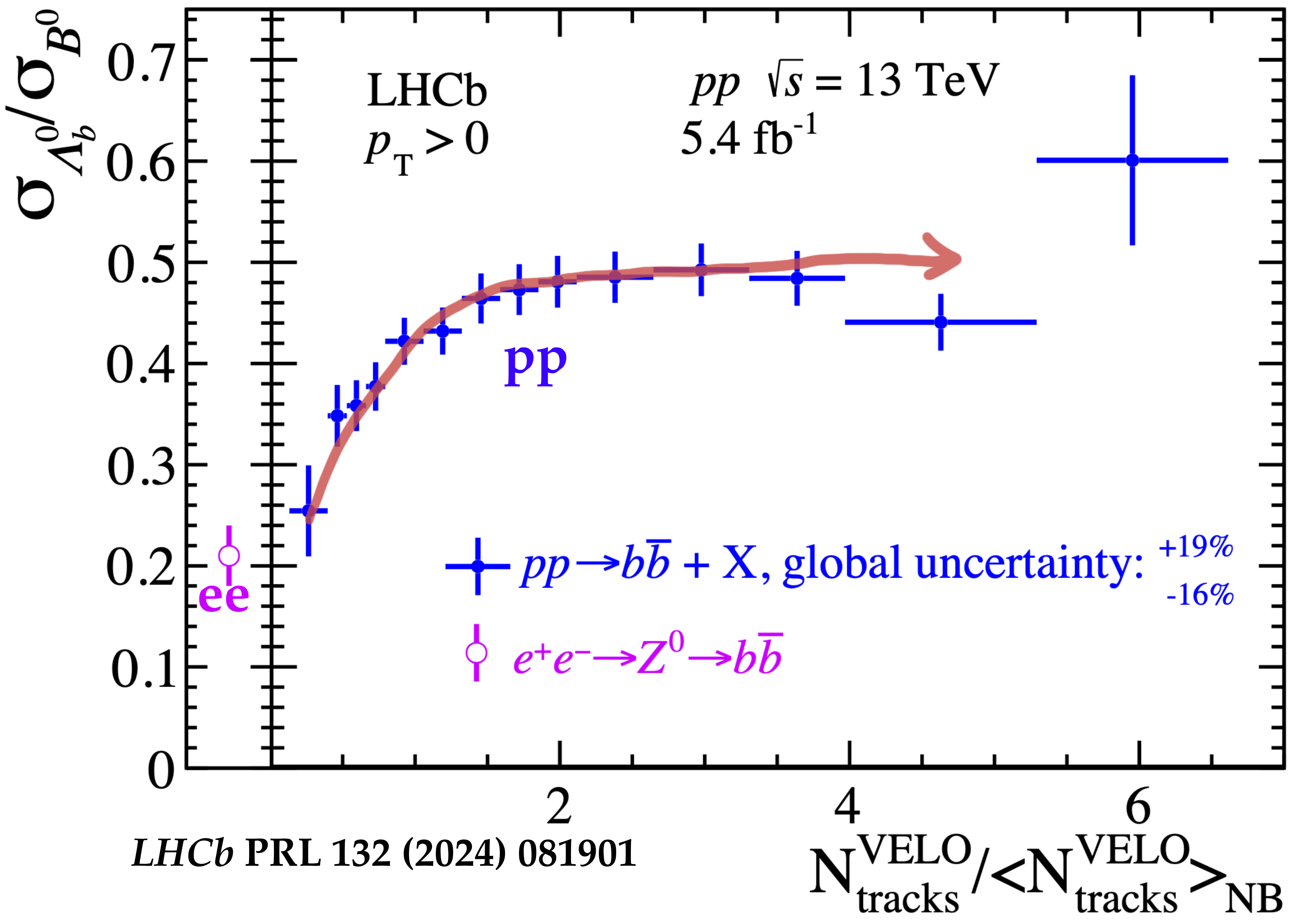
Baryon Abundance Charm vs Beauty

Integrated p_T Λ_c / D^0



ALICE PLB 839 (2023) 137796

Integrated p_T Λ_b / B^0



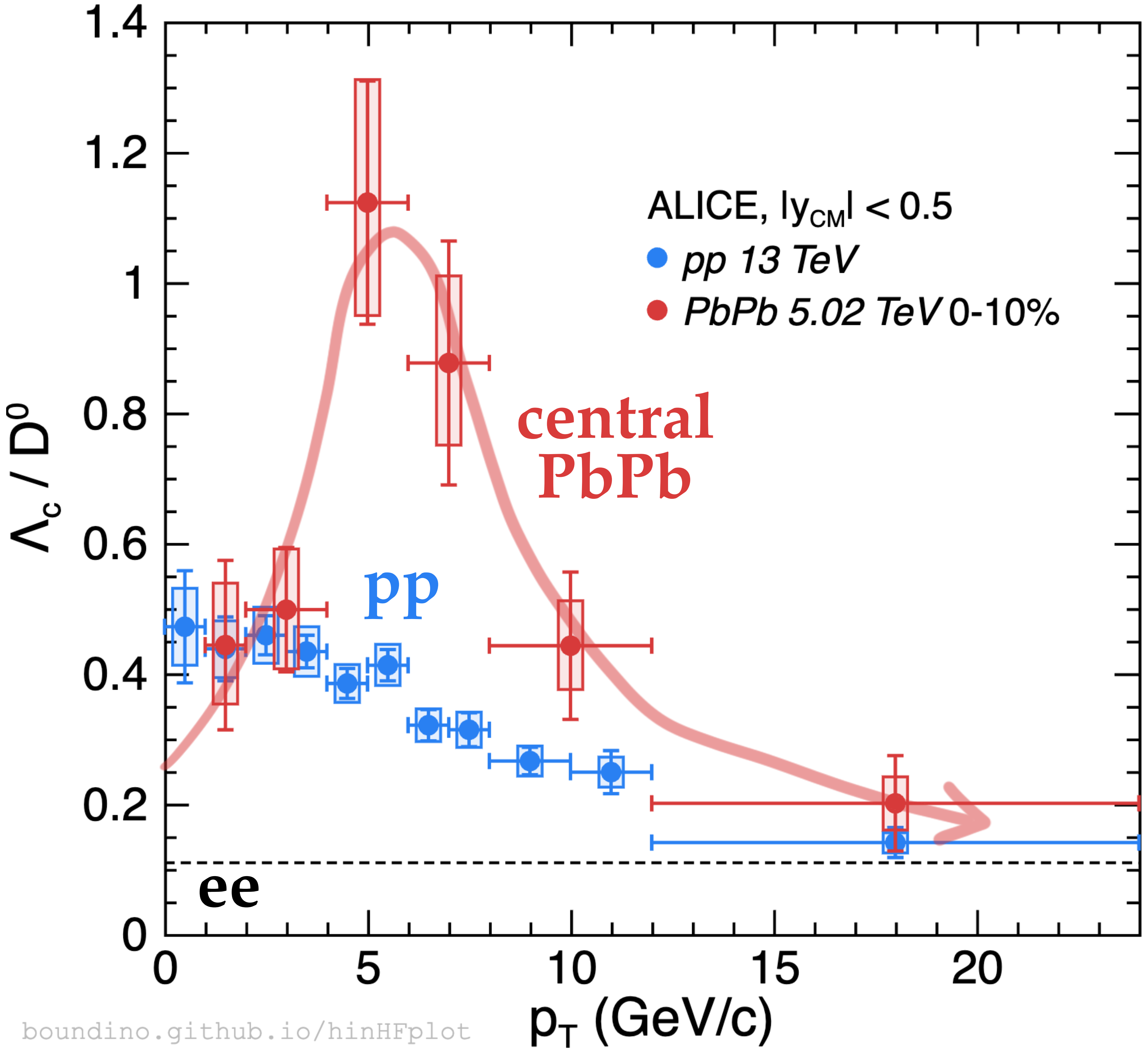
LHCb PRL 132 (2024) 081901

- **Beauty** sector similar behavior from e^+e^- to high-multiplicity pp
  - Manage to smoothly connect to LEP → Is it same for charm?

Λ_c p_T Redistribution Radial Flow

- Although the integrated yield ratio is saturated, p_T dependence is modified

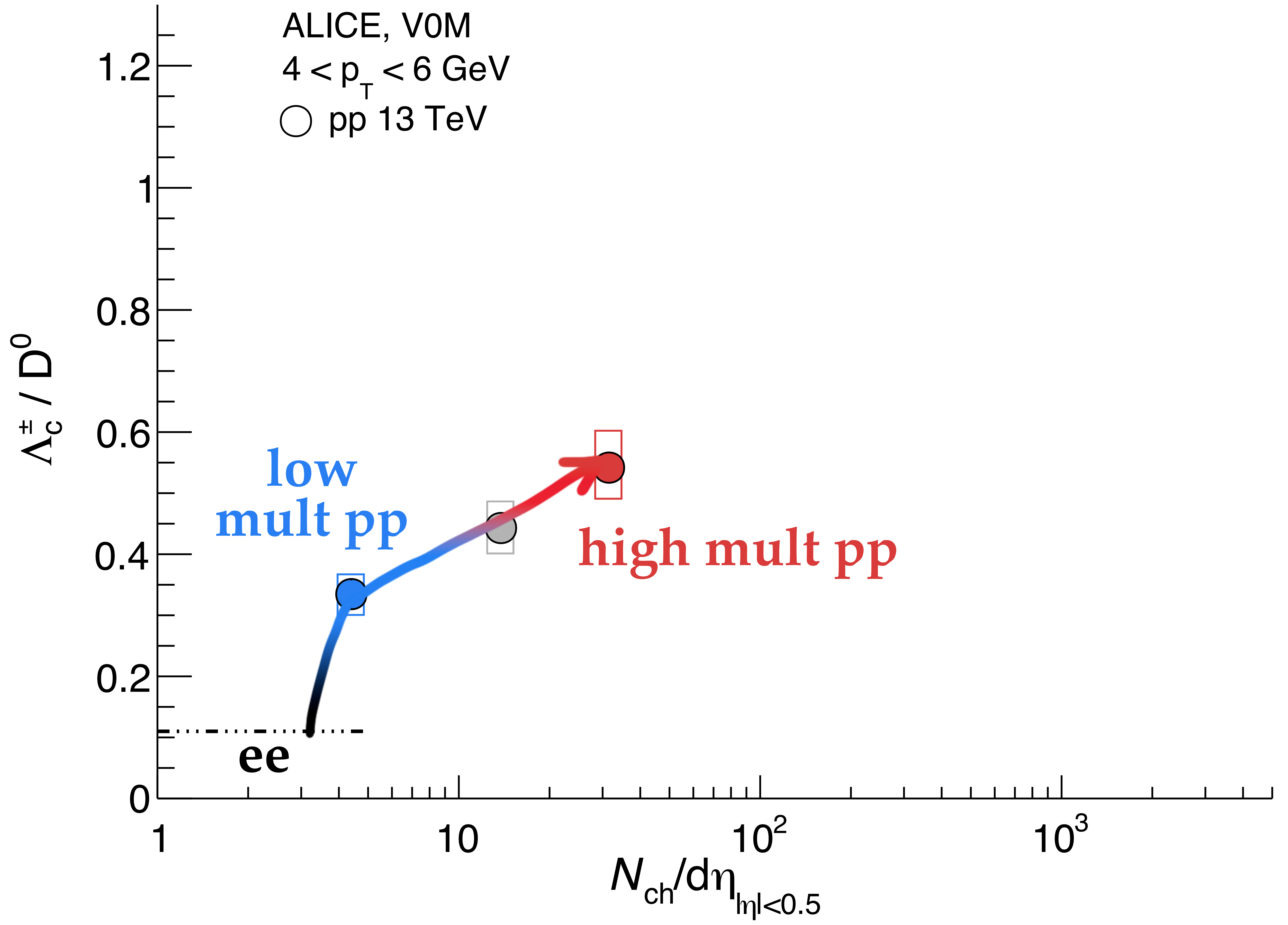
- The "bump" (PbPb lower than pp at most low p_T) can be interpreted as consequence of radial flow
  - Not a new idea for light flavors in hydro models
    - Used to explain Λ/K^0
  - The charm and light quarks being recombined are pushed to higher p_T

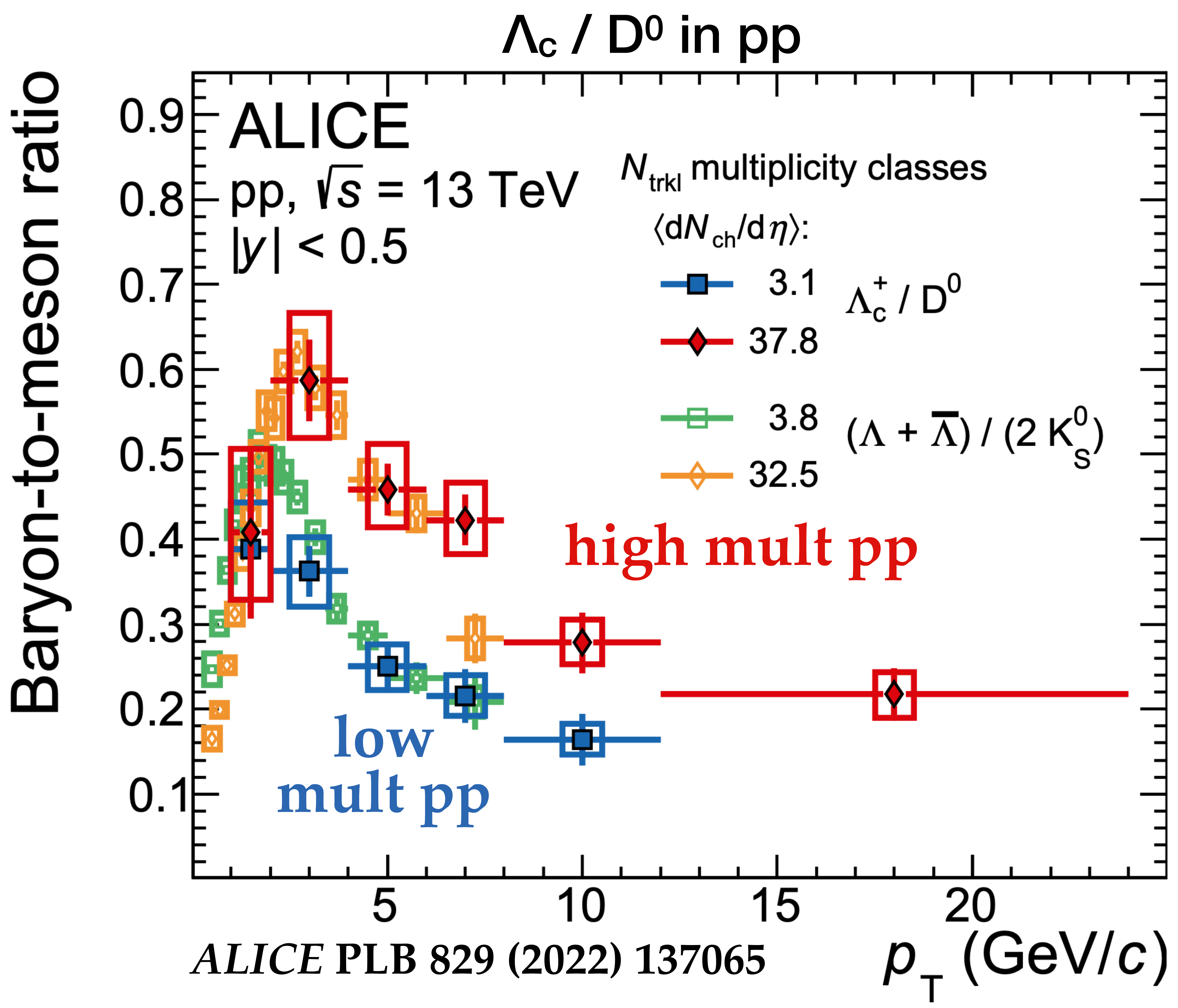


ALICE PLB 839 (2023) 137796

ALICE JHEP 12 (2023) 086

Λ_c p_T Redistribution Across Collision Systems

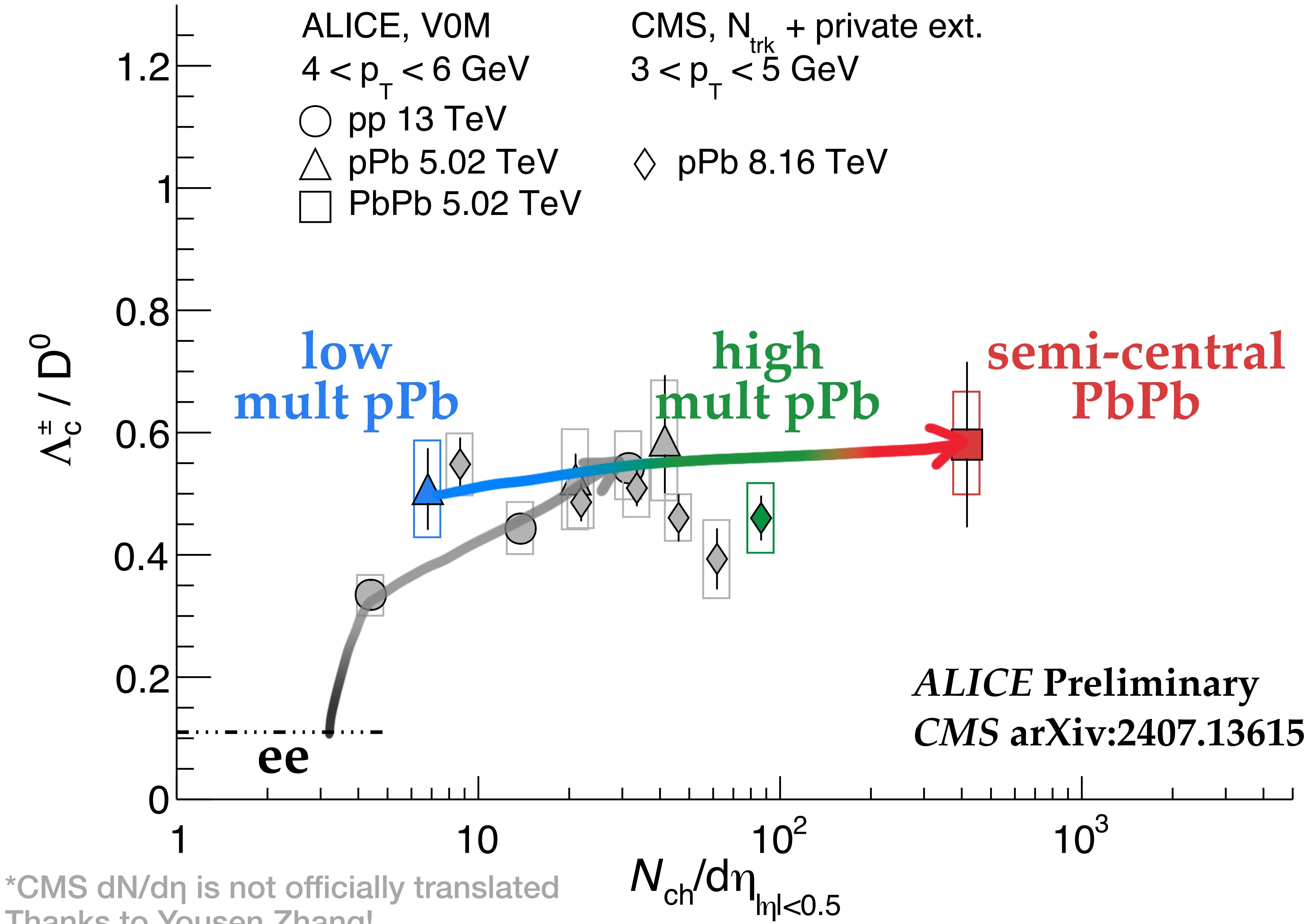




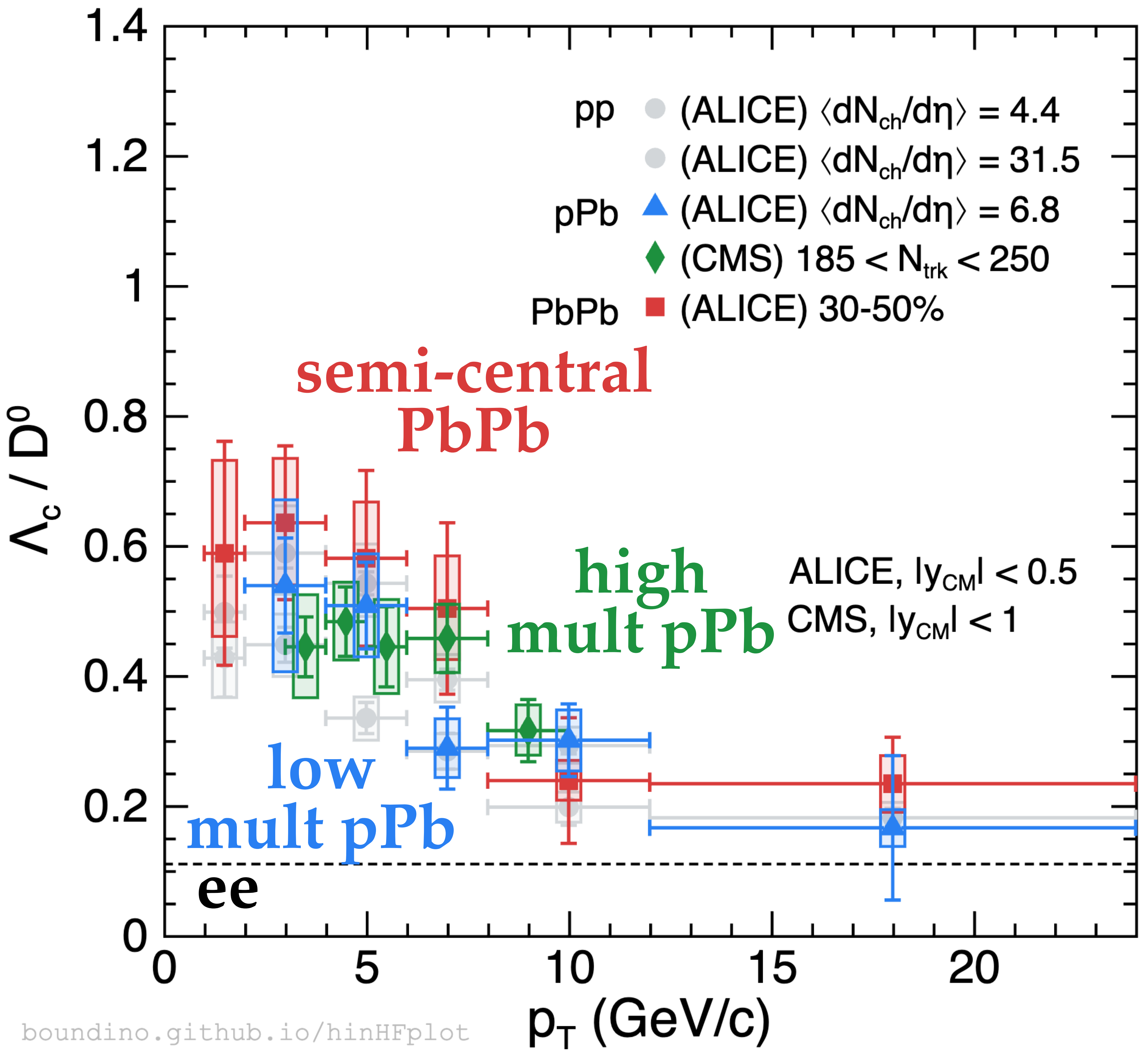
- Momentum redistribution already happens in high-multiplicity pp

- Similarity between strange and charm
  - Coincidence or feature?

Λ_c p_T Redistribution Across Collision Systems



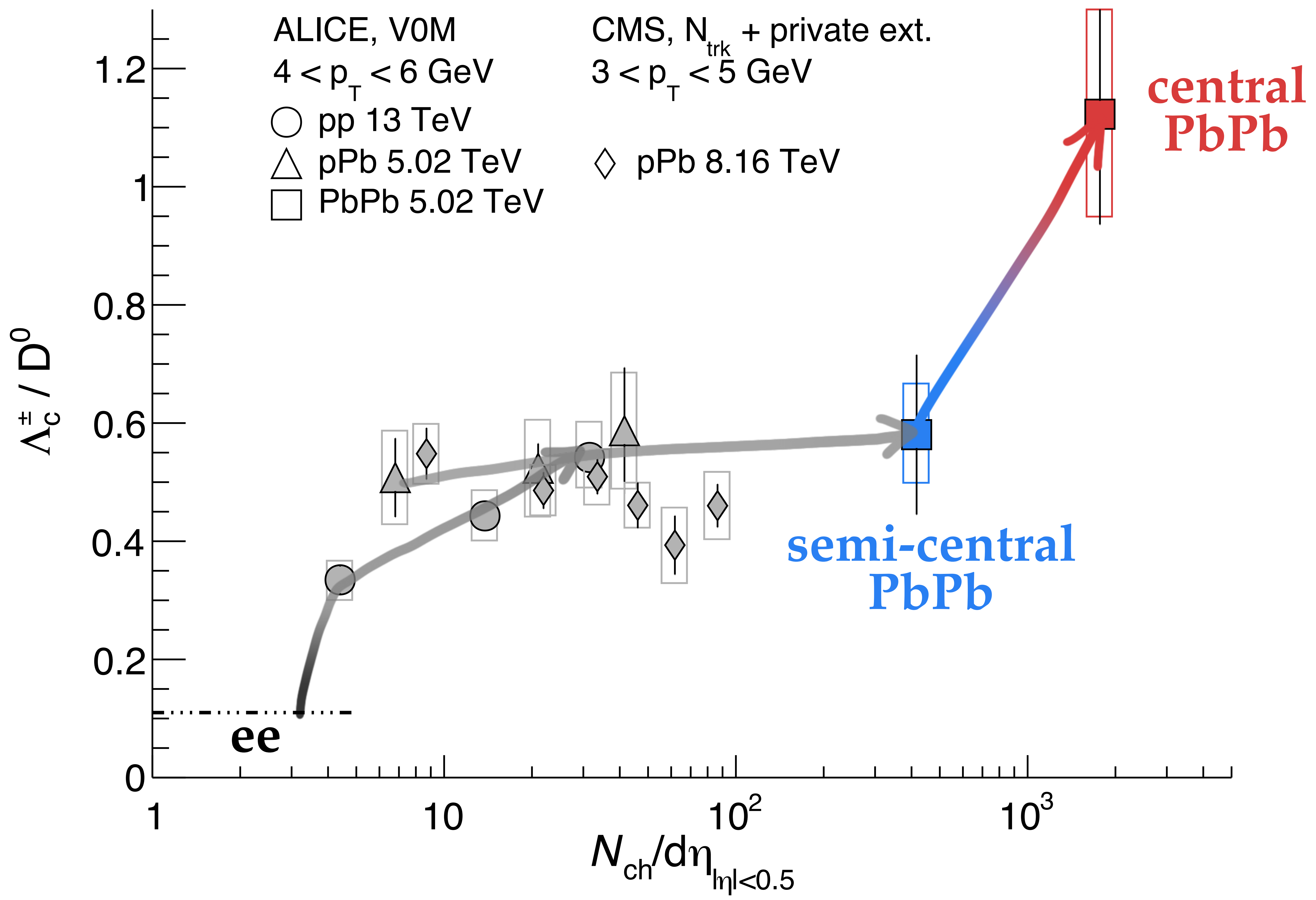
*CMS dN/dη is not officially translated
Thanks to Yousen Zhang!

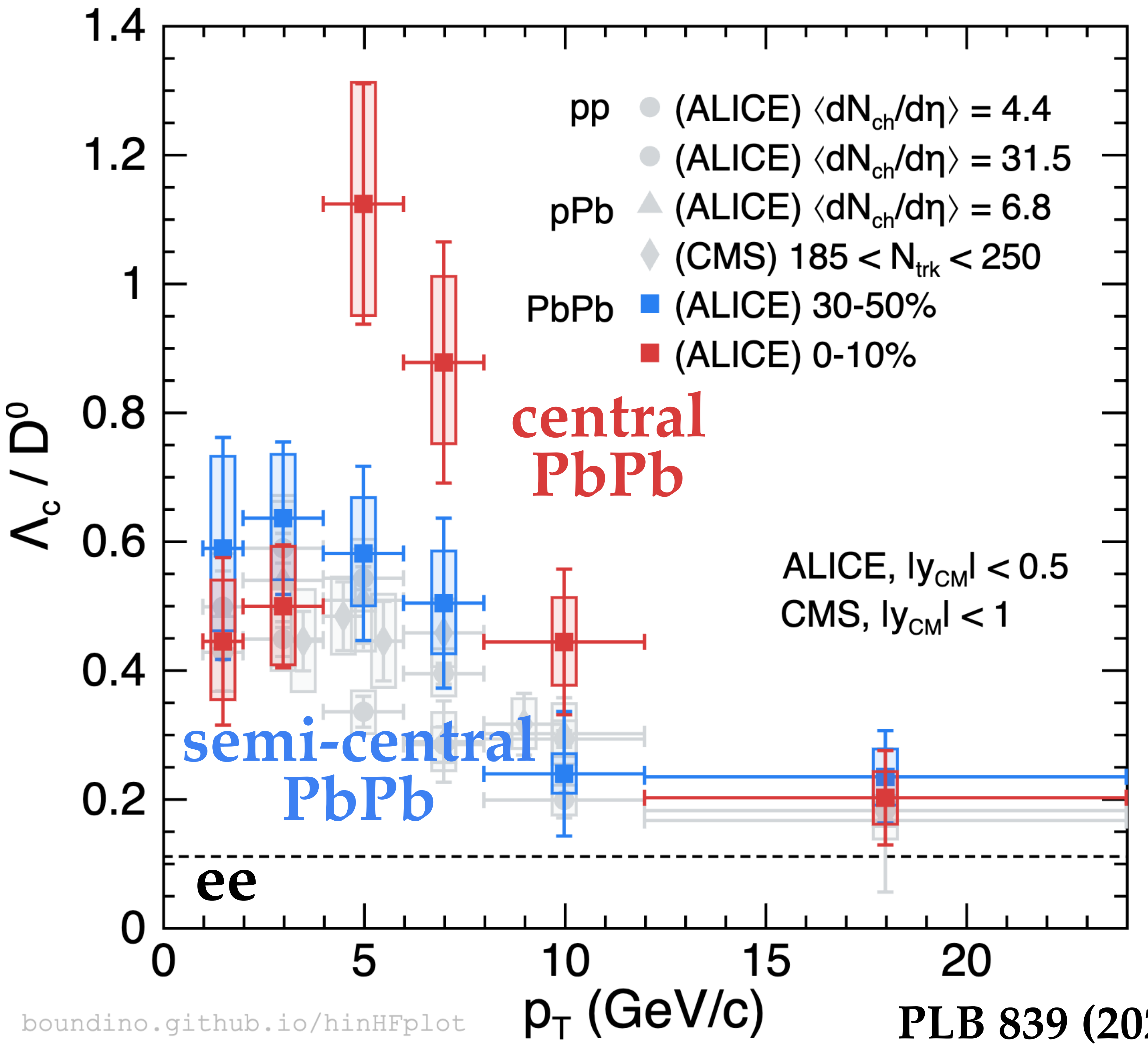


- Across a wide multiplicity range, not only the integrated yield ratio, but also the p_T distributions change quite mildly

- **Puzzling** to me: not likely to have *same* flow strengths of small and large systems?
- As contrary to Λ/K^0 which continually has stronger modification in larger systems

Λ_c p_T Redistribution Across Collision Systems

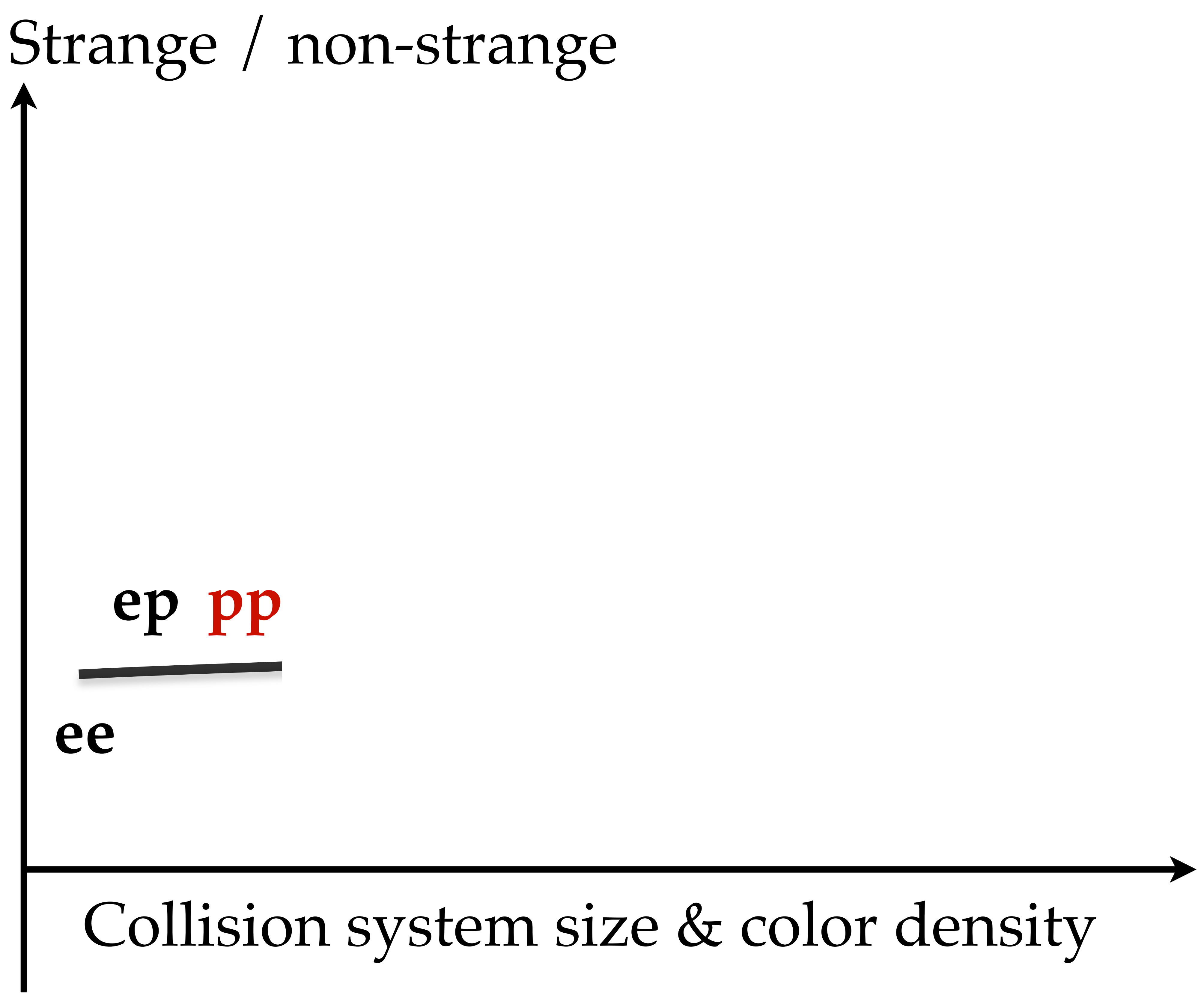


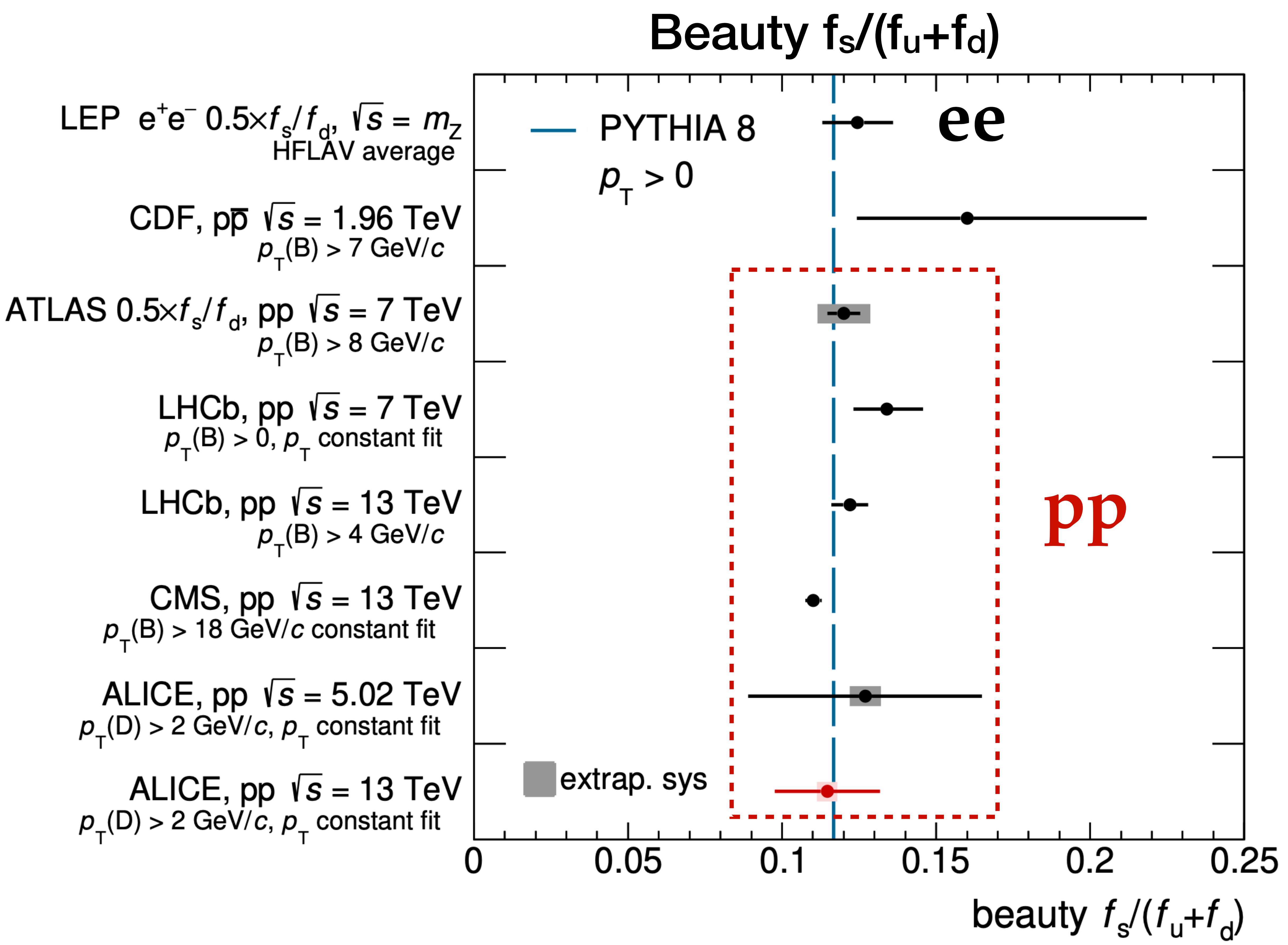


PLB 839 (2023) 137796

- The shape changes dramatically in central PbPb → Strongest radial flow
- Hope for better precision with Run 3 data

Strangeness Across Collision Systems



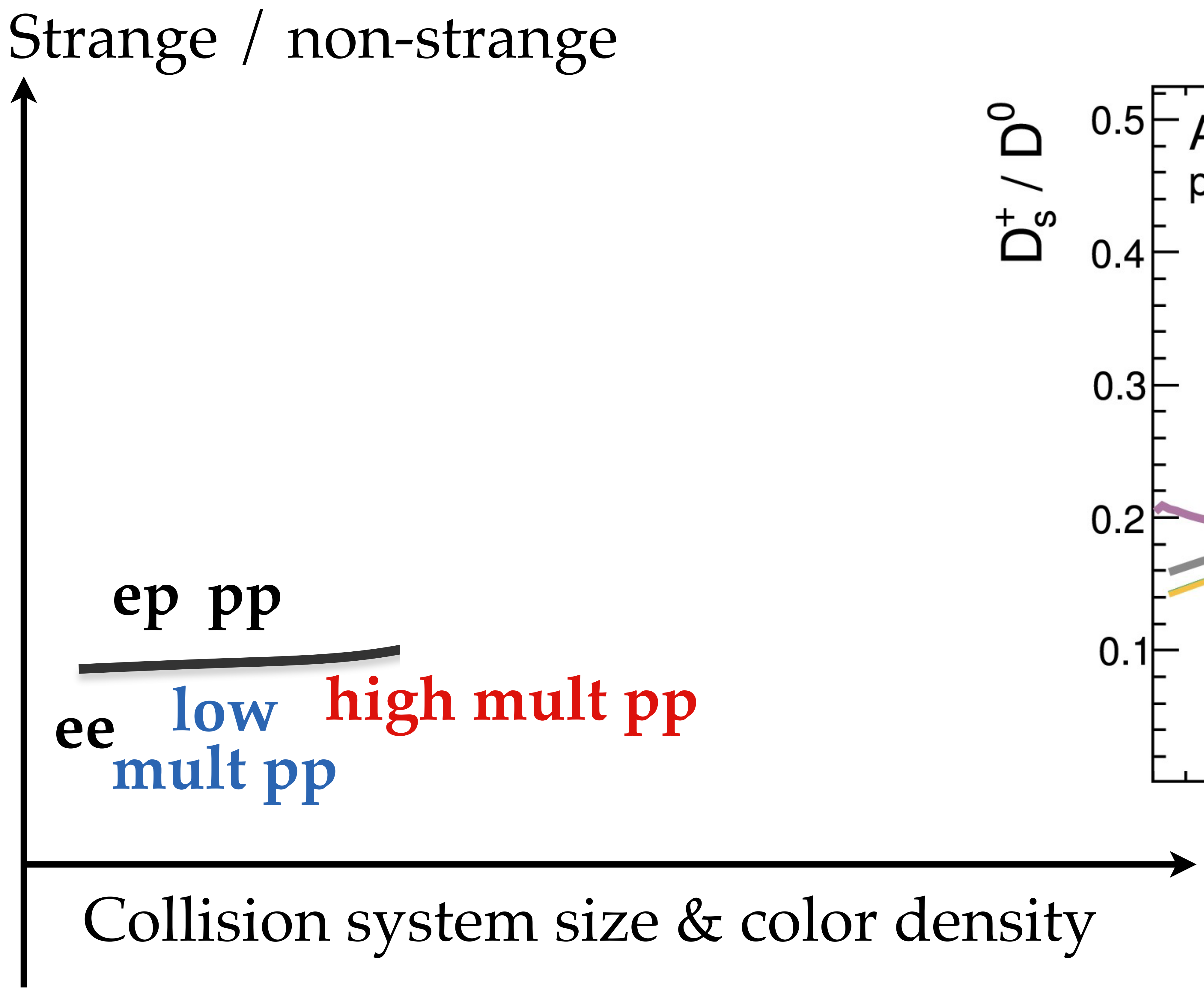


- Keep fragmentation universality

- $f_s/(f_u+f_d)$ consistent between e^+e^-, ep and pp for both **charm** and **beauty**

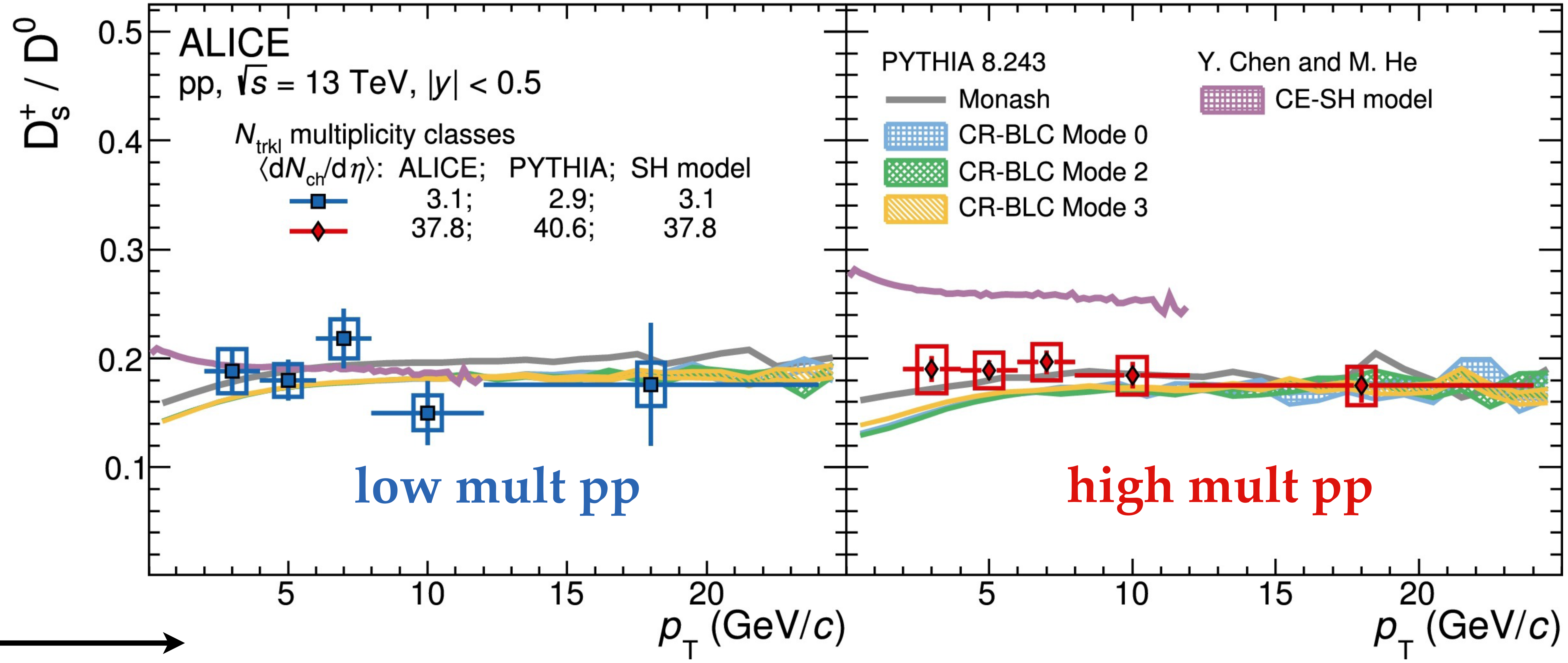
ALICE **arXiv:2402.16417**

Strangeness Across Collision Systems



D_s / D^0 in pp

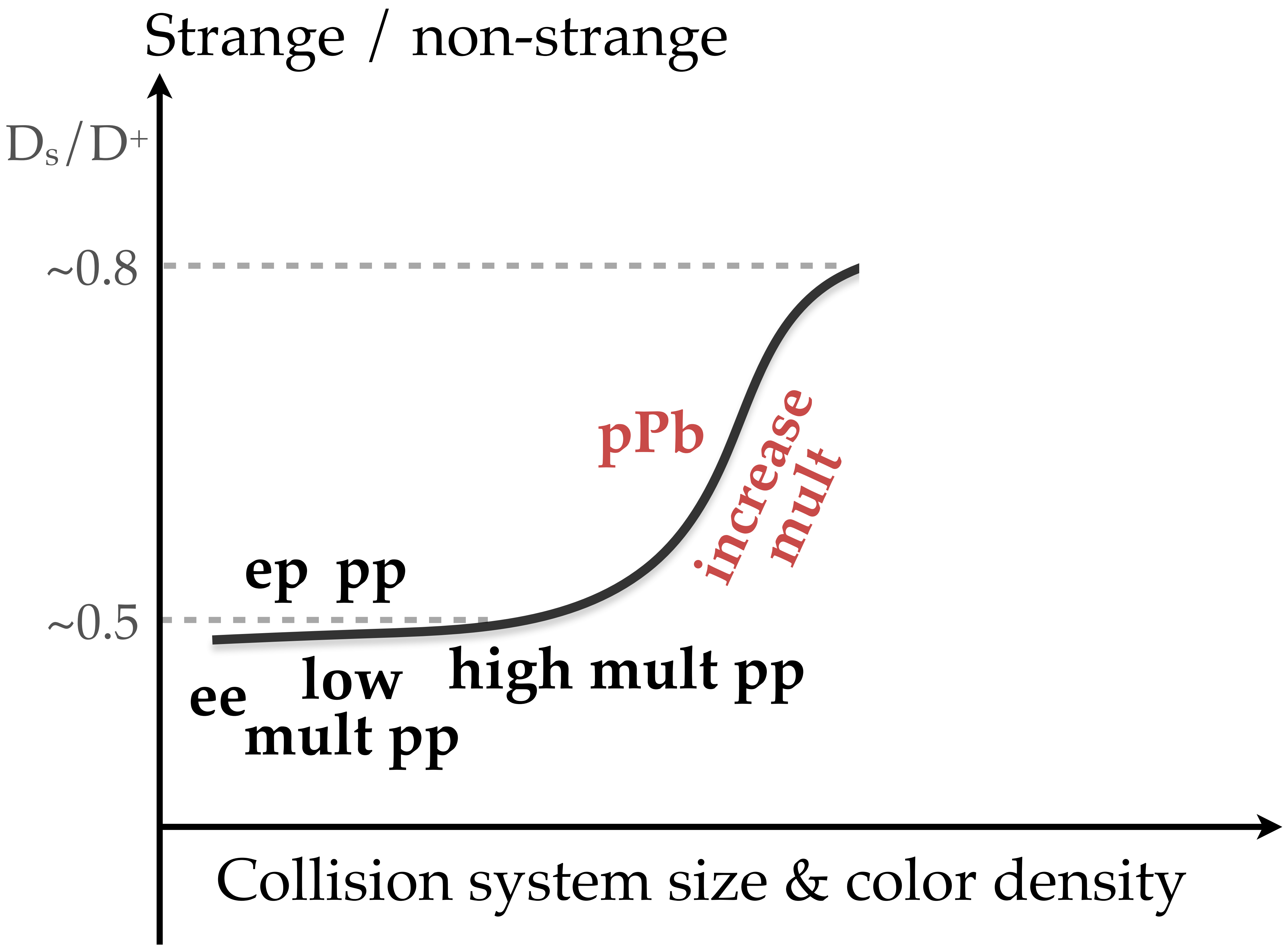
ALICE PLB 829 (2022) 137065

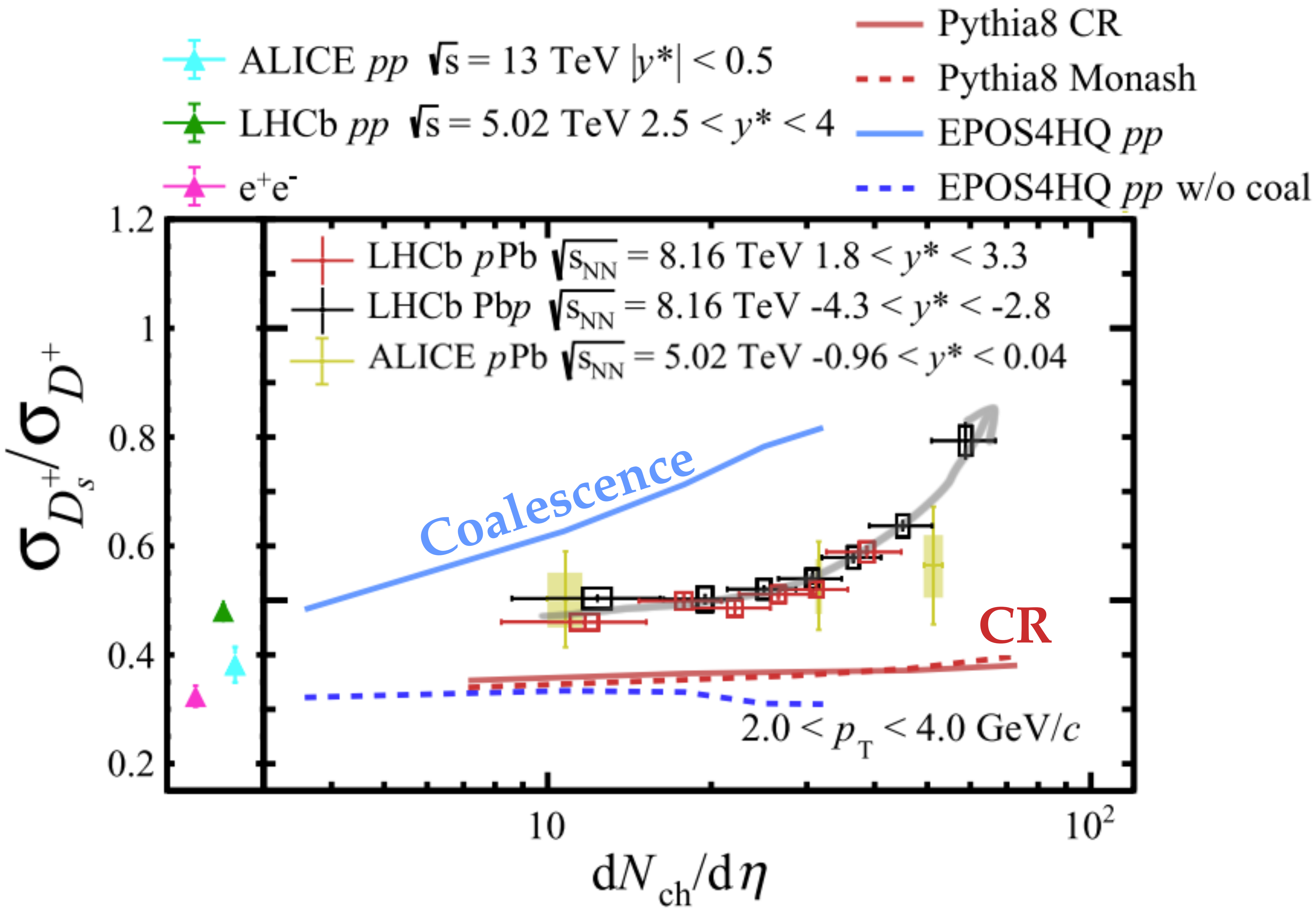


- No multiplicity dependence in pp

- Contrary to baryon / meson
- Color reconnection has small effects as it has similar impacts on D_s and D^0 simultaneously

Strangeness Across Collision Systems



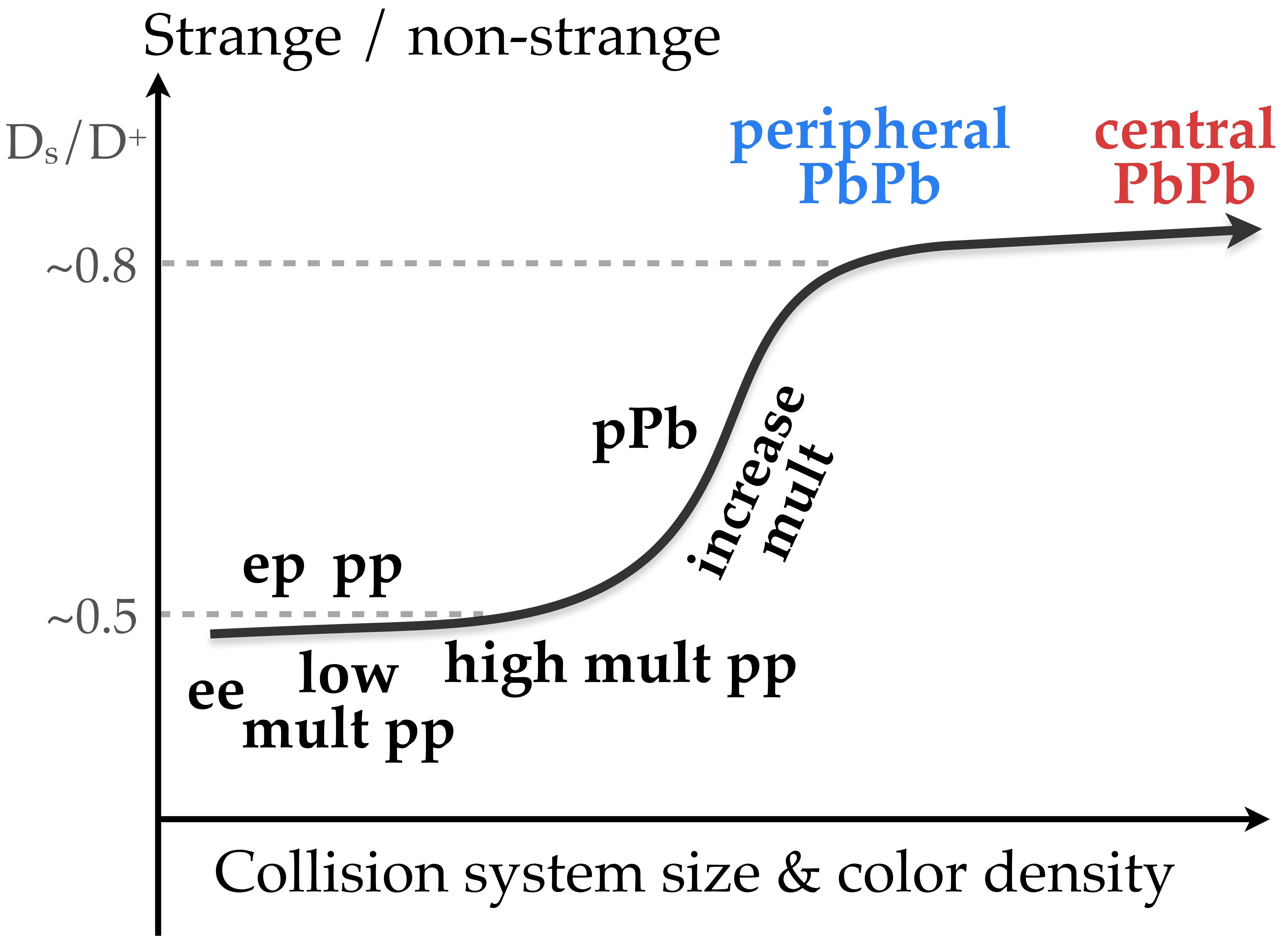


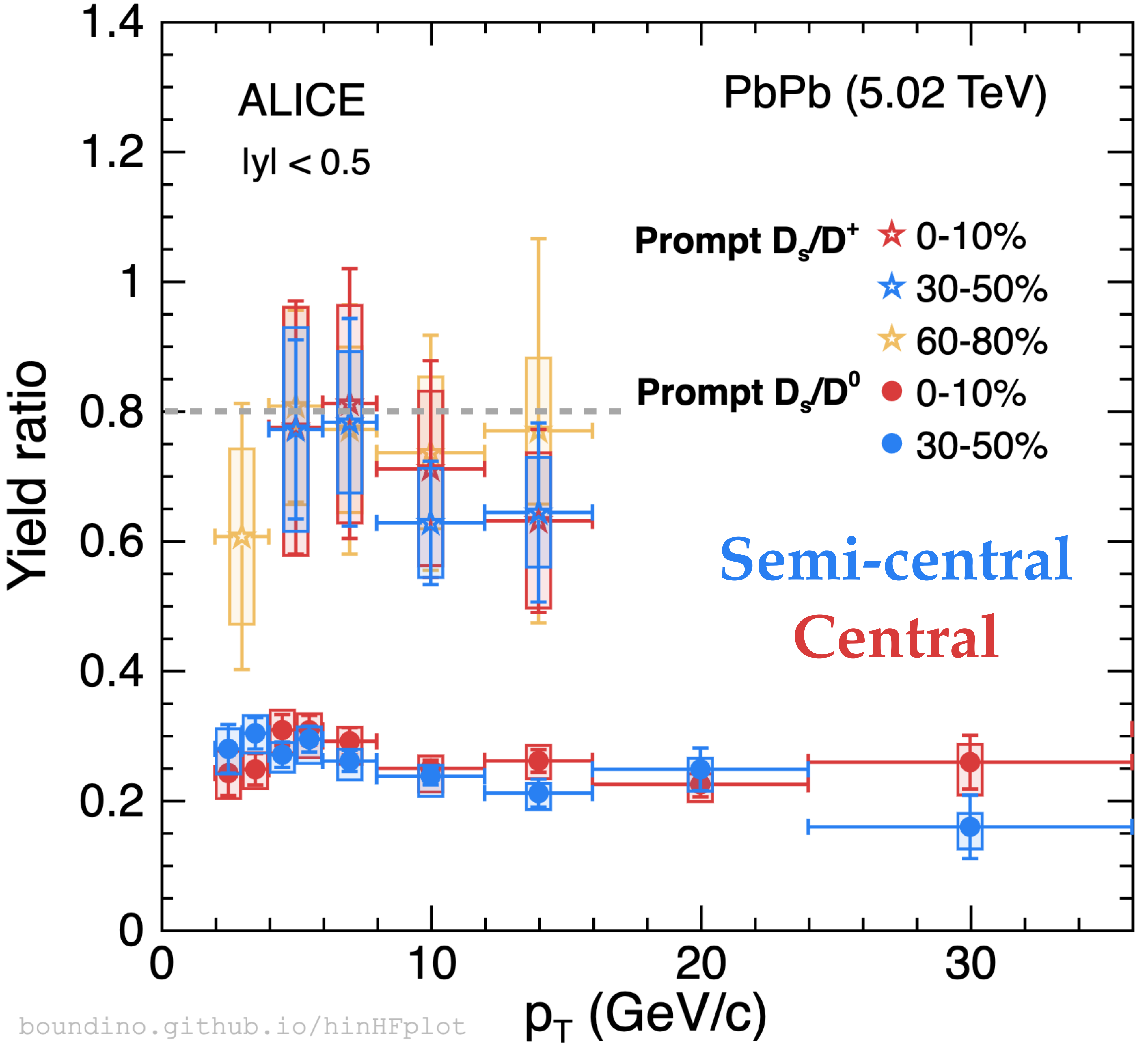
- Significant multiplicity dependence in pPb
- Coalescence models increases the ratio
  - **But** conflicting to pp results in this case

- **CR** has small effects → Models **e.g. Rope** describing LF can enhance strangeness by increasing string tension
  - **Curious** if it can describe the multiplicity dependence

***LHCb* PRD 110 (2024) L031105**

Strangeness Across Collision Systems

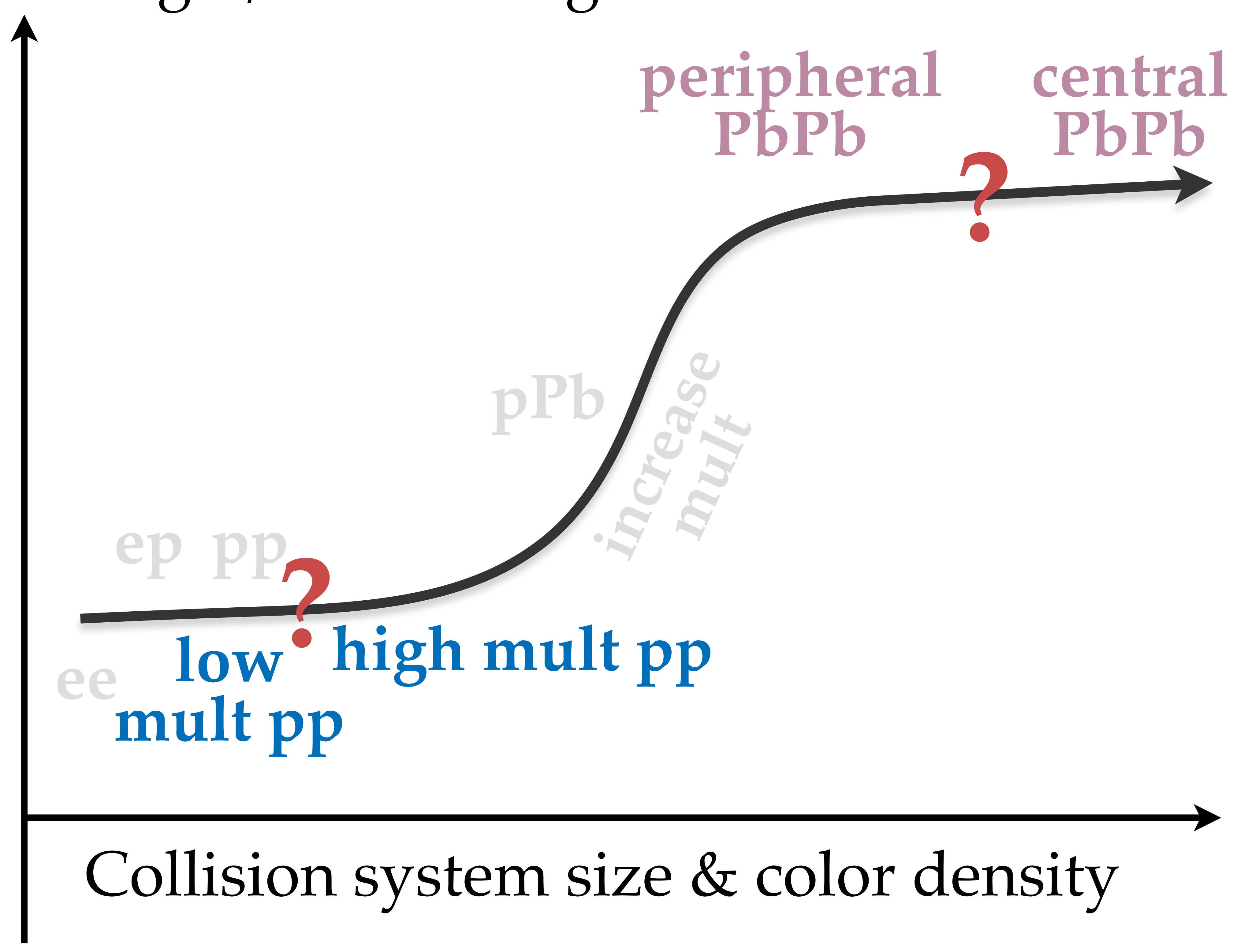




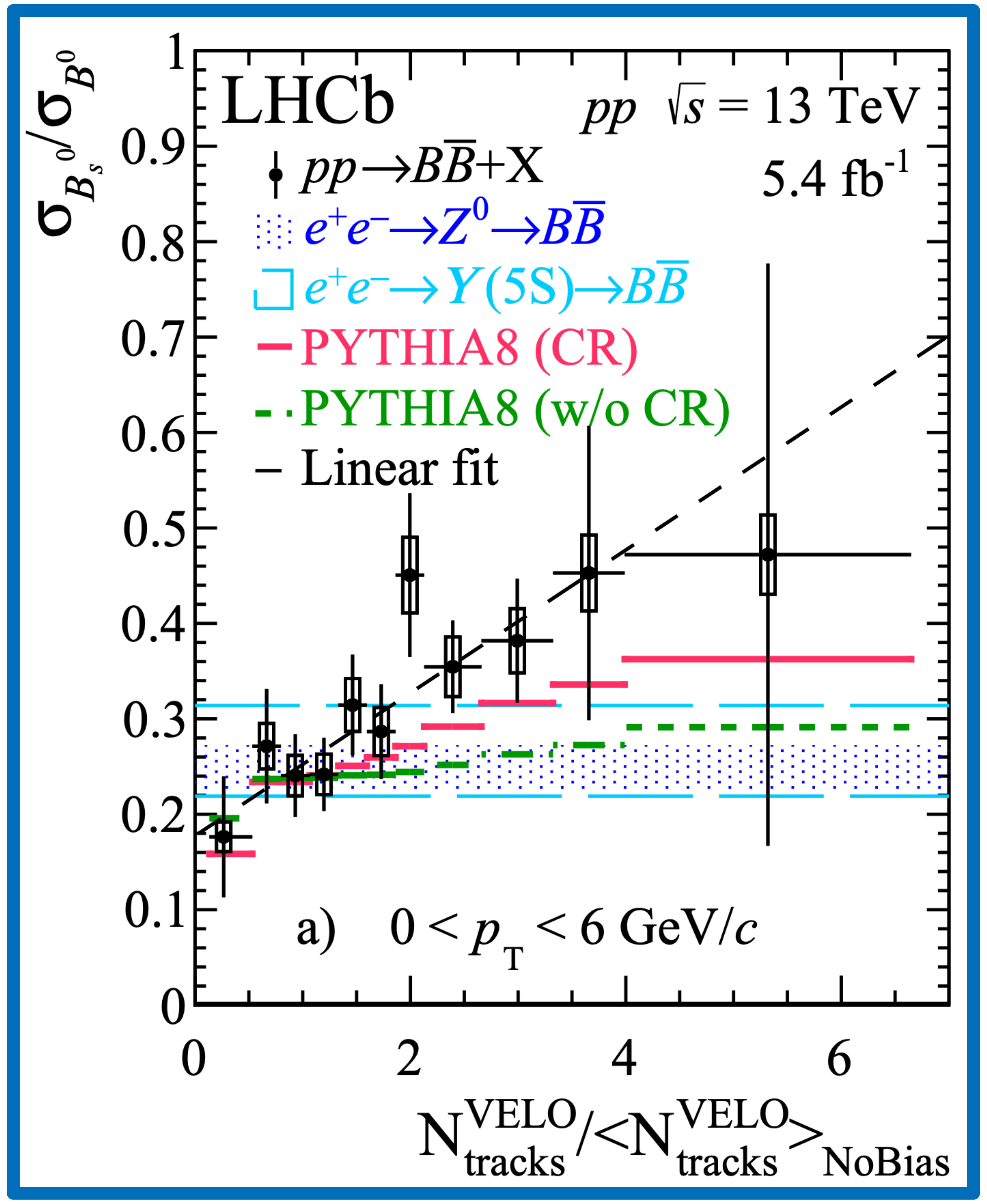
- No significant multiplicity dependence in PbPb
- Smoothly connected to high-multiplicity pPb

PLB 827 (2022) 136986
JHEP 10 (2018) 174

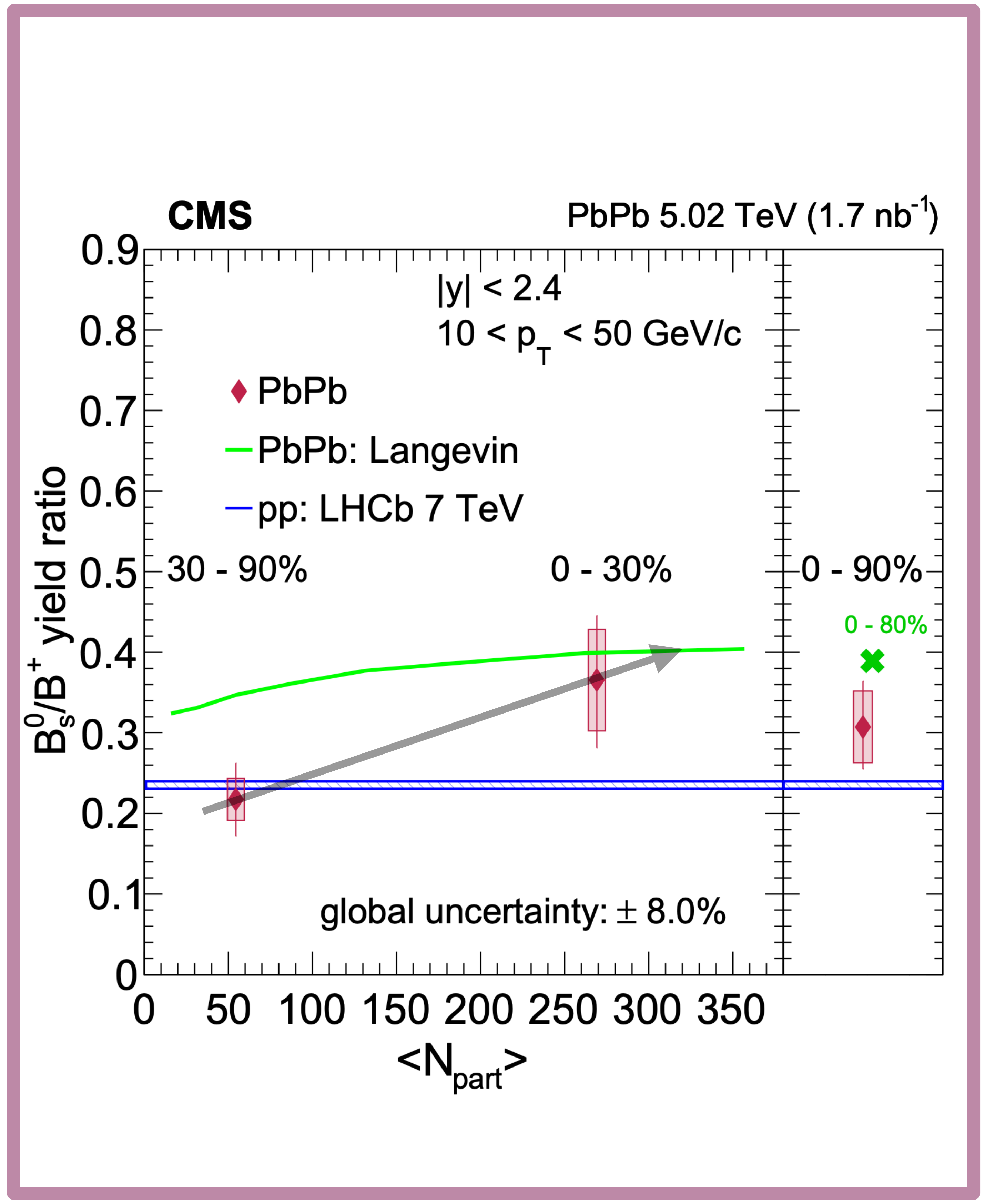
Strangeness Consistent Between D_s & B_s?



B_s/B^0 vs. mult in pp



B_s/B^+ vs. PbPb centrality

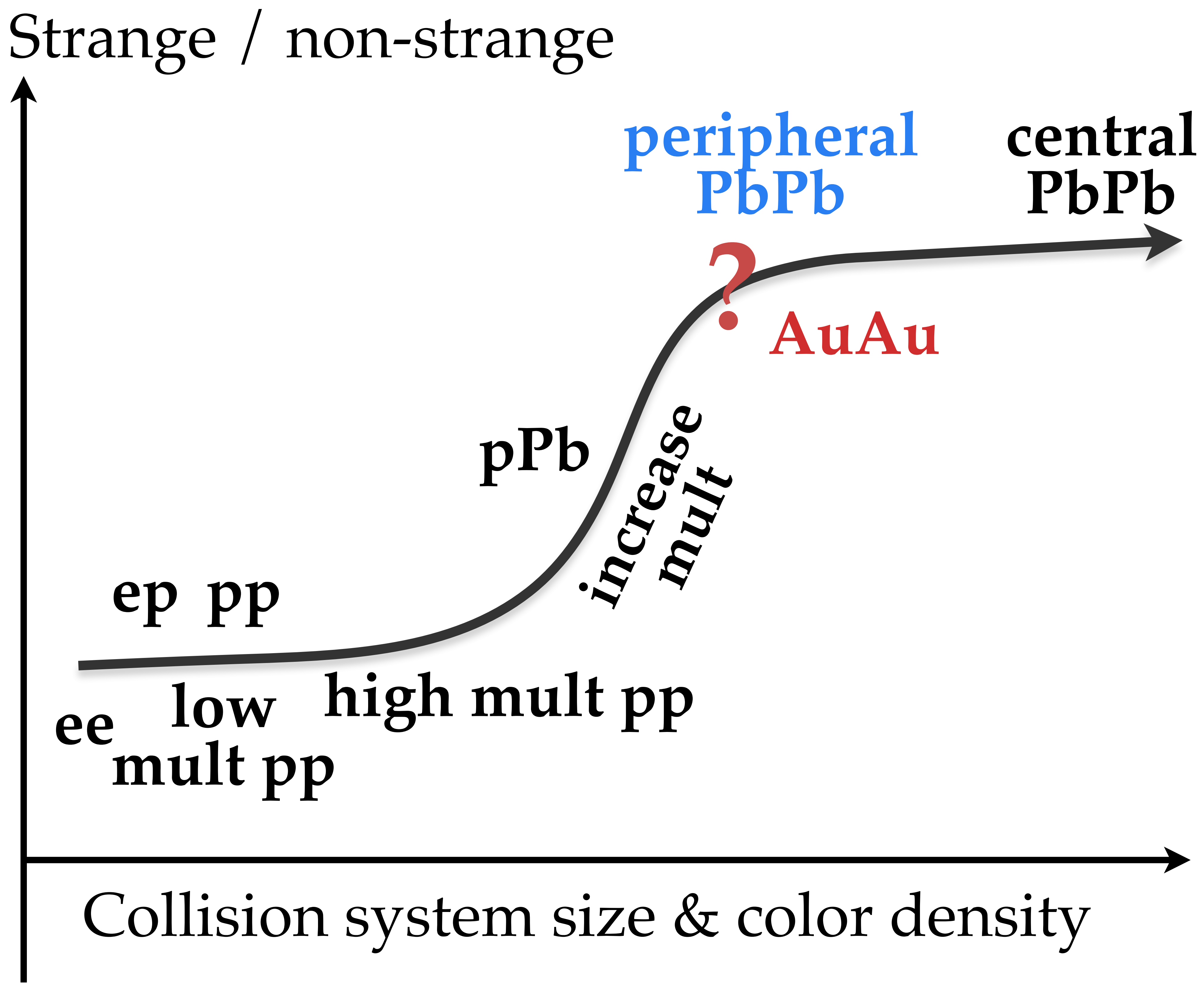


- Hint of different behaviors of beauty from charm
- Need better precision

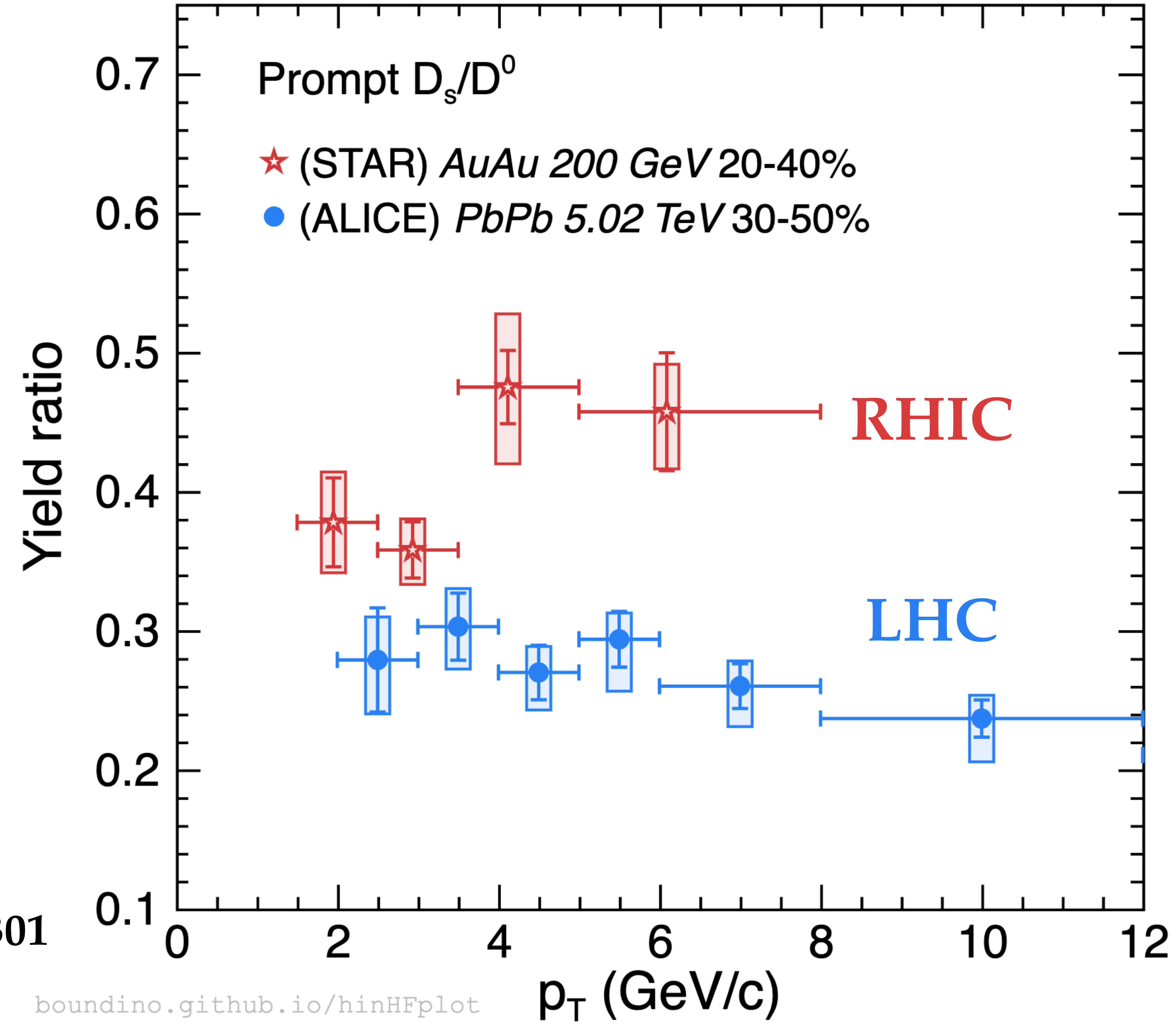
LHCb **PRL 131 (2023) 061901**

CMS **PLB 829 (2022) 137062**

Strangeness RHIC vs LHC



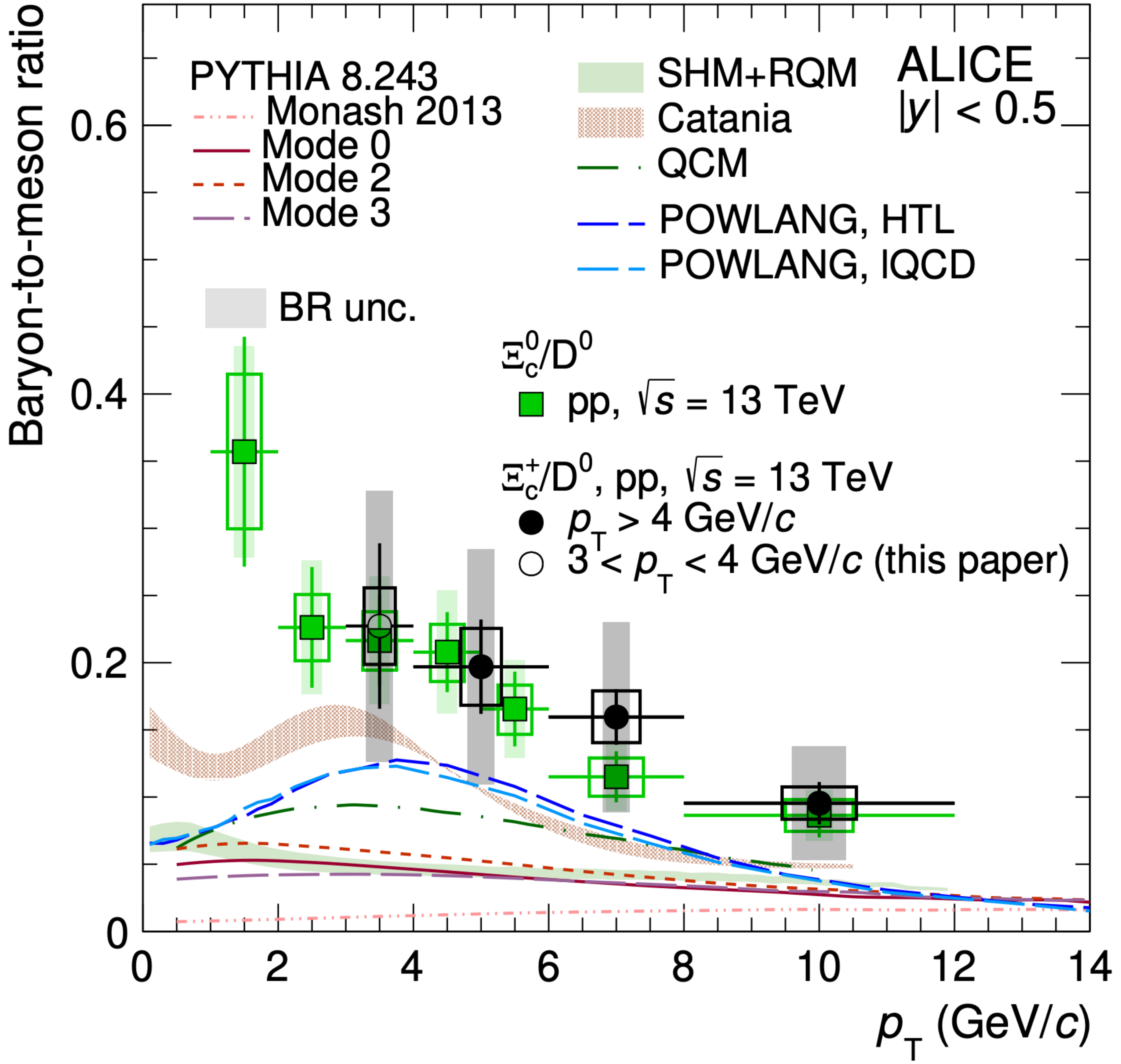
STAR PRL 127 (2021) 092301



- **Puzzling** to me that D_s/D^0 is larger in RHIC
- Need better precision

More Challenges Strange Charm Baryons

Ξ_c / D^0 in pp



ALICE **JHEP 12 (2023) 086**

- Ξ_c(c**s**d) / Λ_c(c**u**d) enhanced in pp compared to ee
  - Contrary to meson D_s($c\bar{s}$) / D^0($c\bar{u}$)
  - Models that can describe Λ_c underestimate Ξ_c
- Different roles of strangeness in mesons and baryons might be a challenge to theory
  - Maybe related to diquark production

Lesson #3

Is hadronization a very interesting topic by itself?

Maybe

Is establishing a reliable hadronization description important?

YES

Is there consistent picture behind different models?

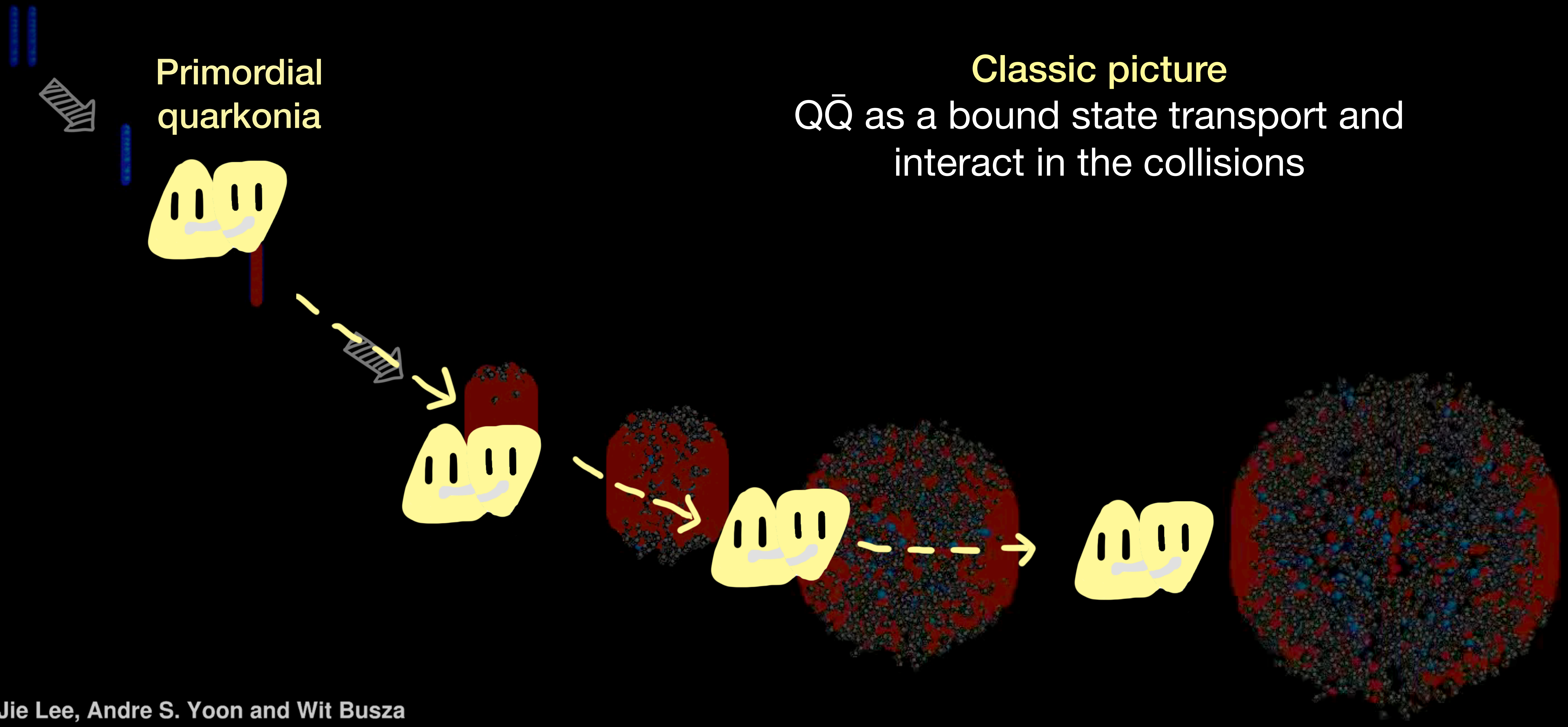
Open HF - Life of a Heavy Quark in HIC

Life of a Lucky Heavy Quarkonium in HIC

Primordial quarkonia

Classic picture

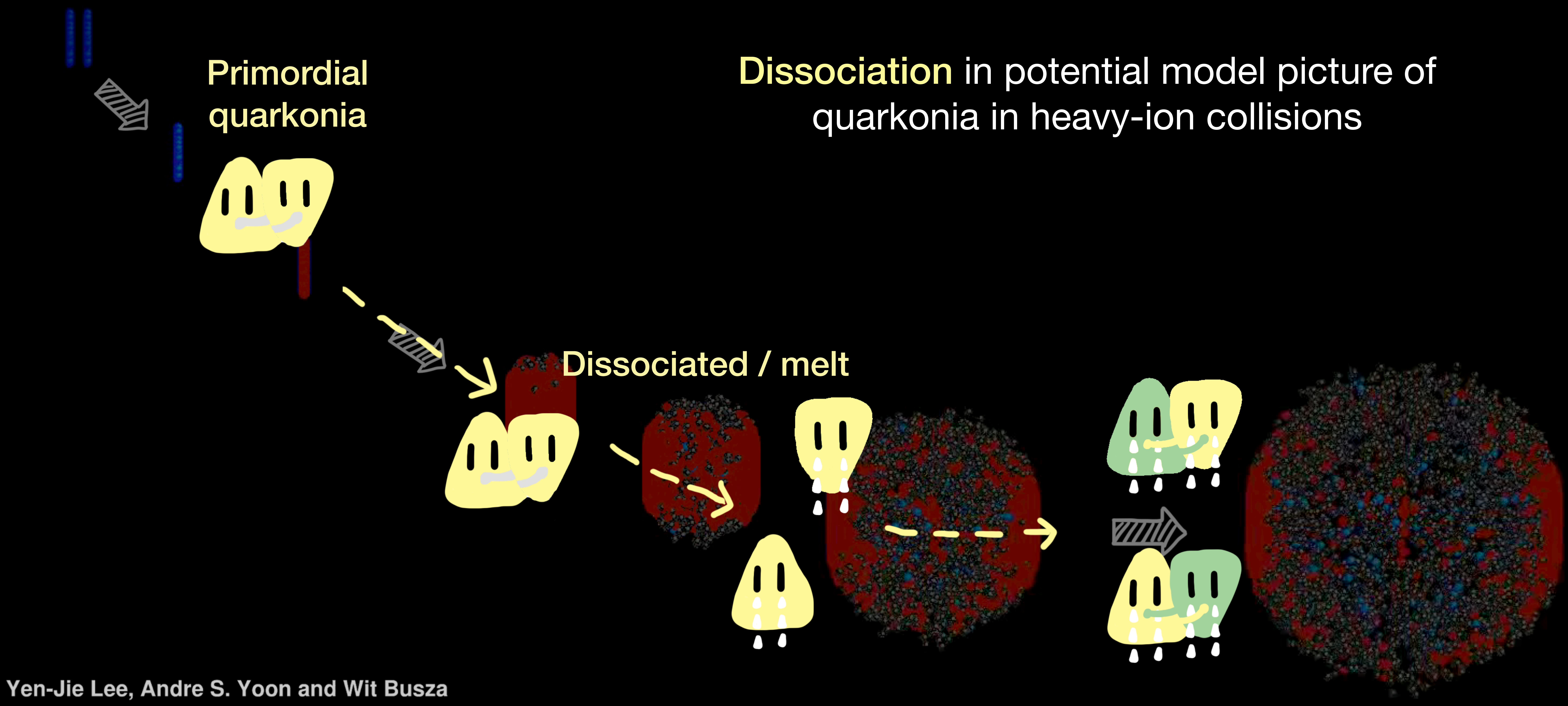
$Q\bar{Q}$ as a bound state transport and interact in the collisions



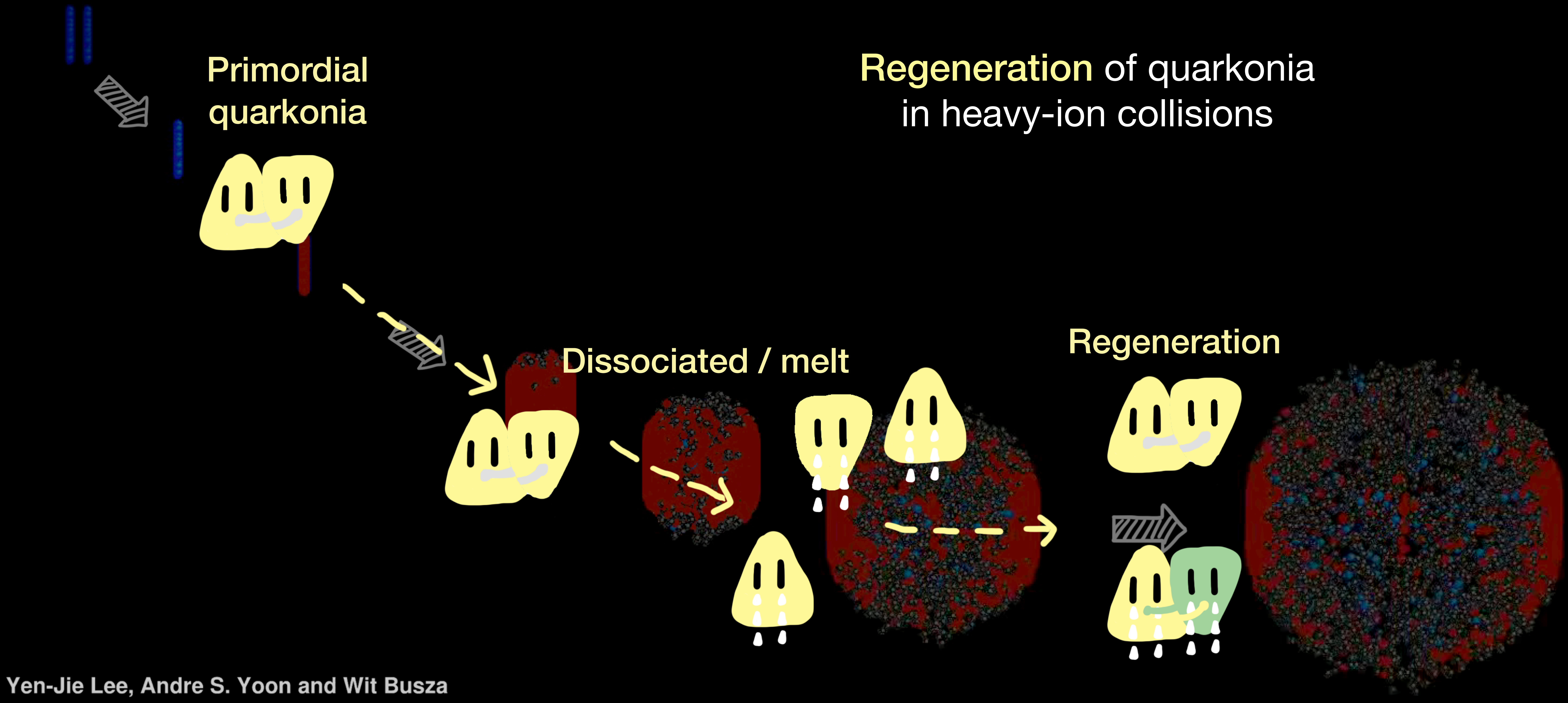
Yen-Jie Lee, Andre S. Yoon and Wit Busza

Life of a Weak Unlucky Quarkonium in HIC

Dissociation in potential model picture of quarkonia in heavy-ion collisions

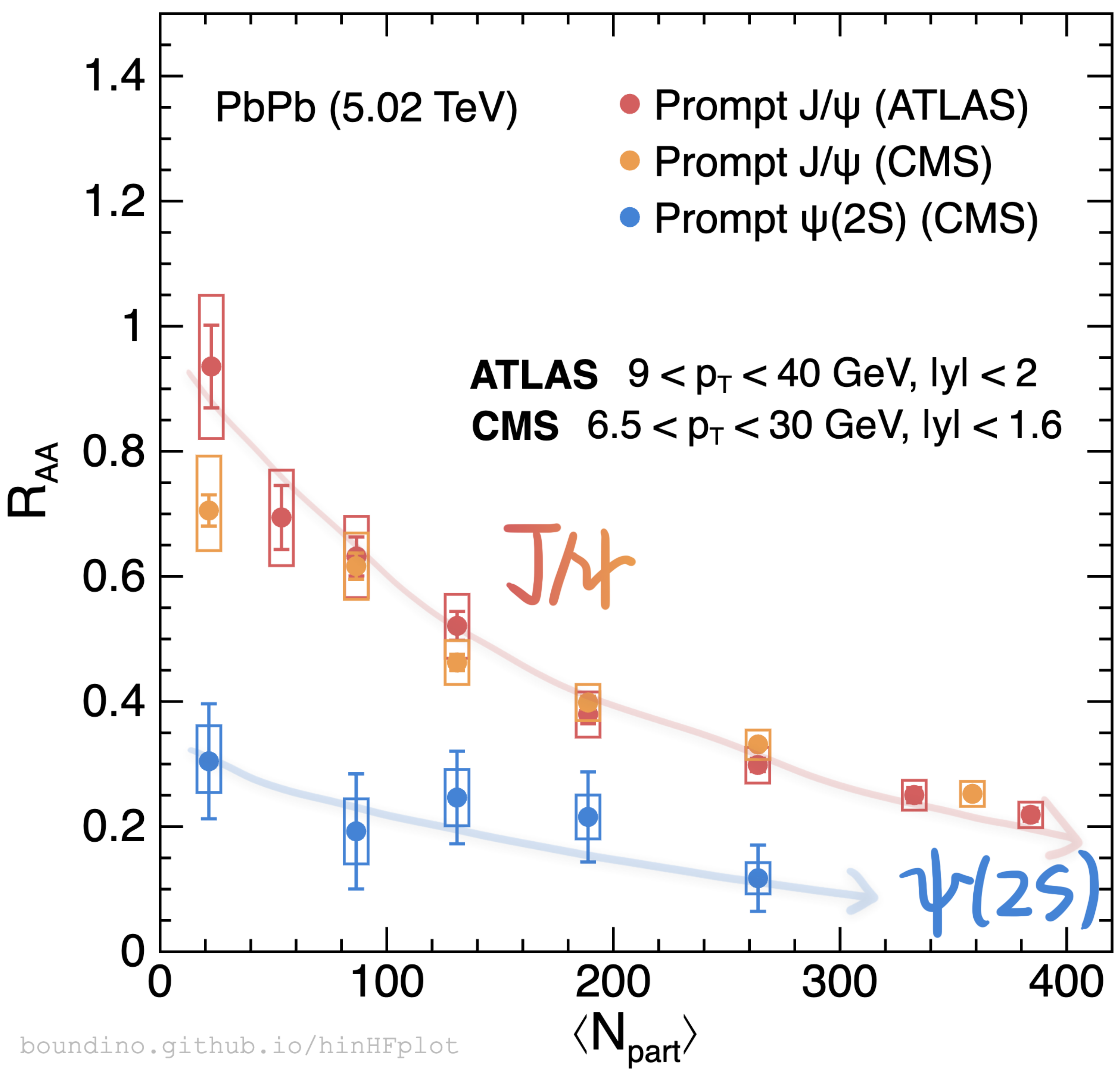


Life of a Weak Lucky Quarkonium in HIC



Charmonia in QGP Sequential Melting

Charmonium R_{AA} vs N_{part}



Sequential melting

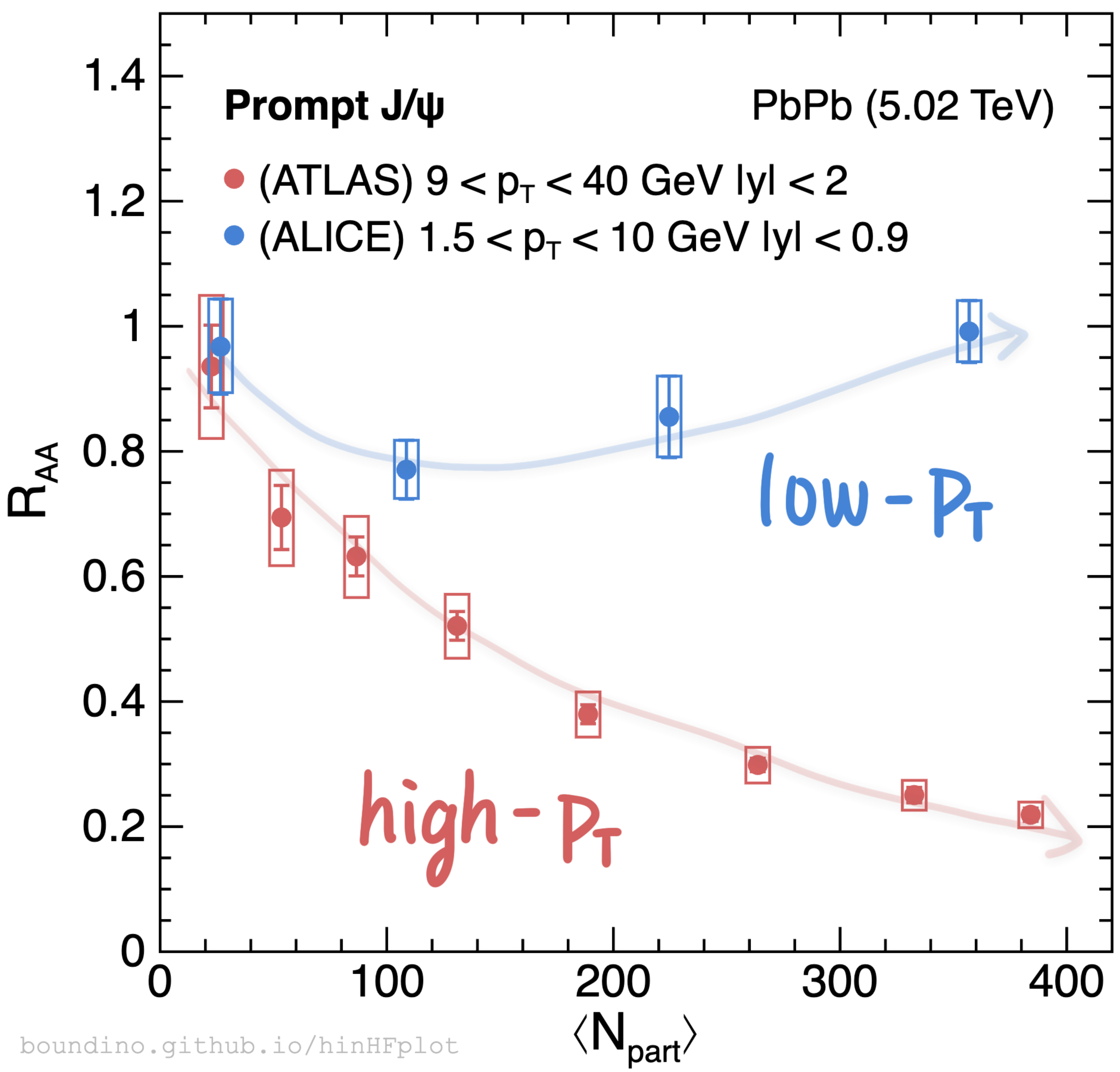
- Charmonia strongly suppressed in PbPb collisions
- Binding energy hierarchy
  - weaker bound state easier to be dissociated
- Stronger suppression in central events

  *Central: large participant nucleon number N_{part}
  - higher temperature and larger size

ATLAS EPJC 78 (2018) 762 *CMS* EPJC 78 (2018) 509 *CMS* EPJC 78 (2018) 509

Charmonia in QGP Regeneration

Charmonium R_{AA} vs N_{part}



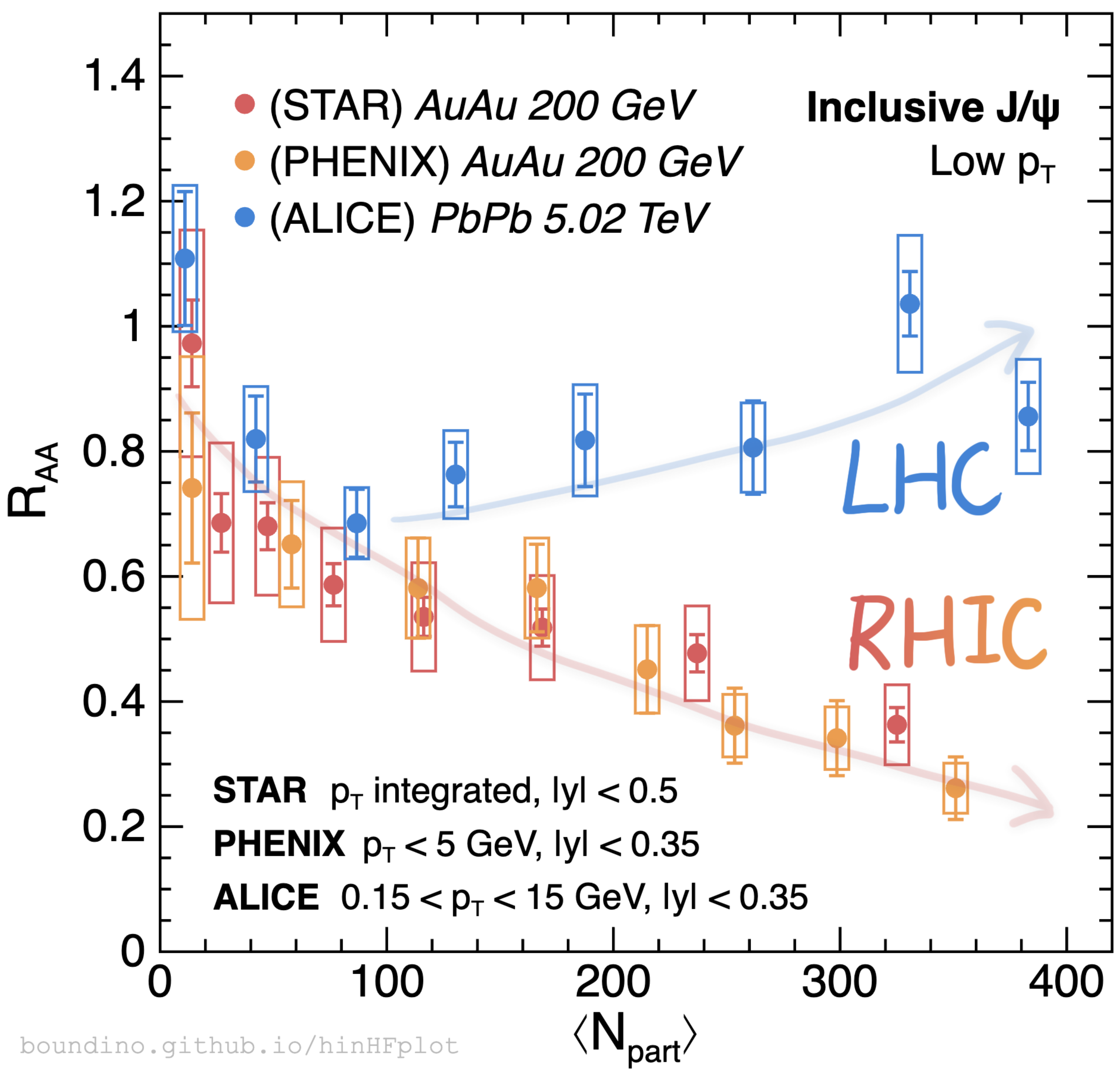
Significant regeneration

- Uncorrelated $Q\bar{Q}$ in QGP regenerate quarkonia
- Increasing R_{AA} at low p_T towards central events
  - central events have larger $\sigma_{c\bar{c}}$

ATLAS EPJC 78 (2018) 762 *ALICE* JHEP 02 (2024) 066

Charmonia in QGP Regeneration

Charmonium R_{AA} vs N_{part}

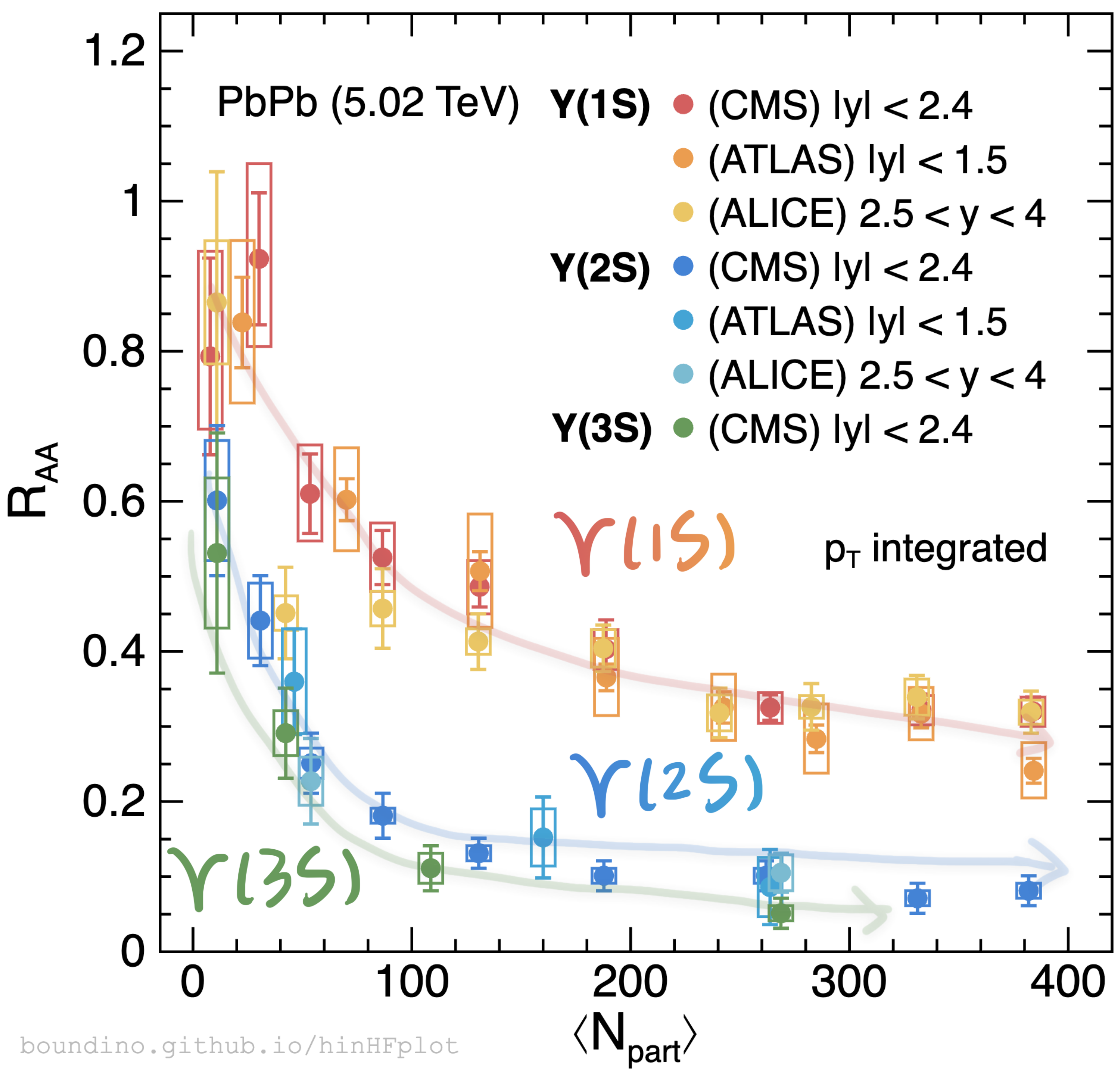


Significant regeneration

- Uncorrelated $Q\bar{Q}$ in QGP regenerate quarkonia
- Increasing R_{AA} at low p_T towards central events
  - central events have larger $\sigma_{c\bar{c}}$
- More significant in LHC than RHIC
  - higher collision energy has larger $\sigma_{c\bar{c}}$

STAR PLB 797 (2019) 134917 *PHENIX* PRL 98 (2007) 232301 *ALICE* PLB 849 (2024) 138451

Bottomonia in QGP Sequential Melting



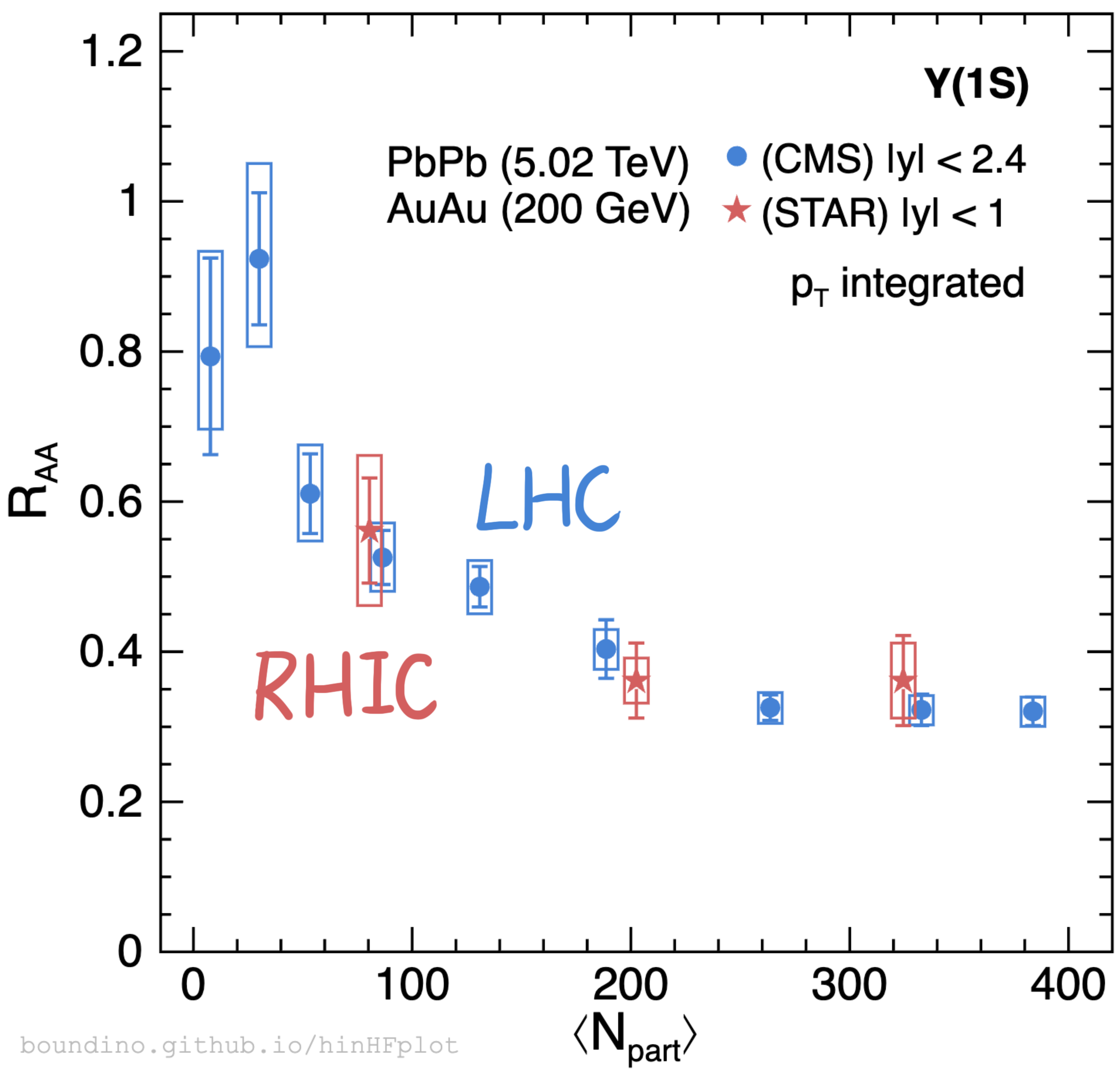
Sequential melting

- Bottomonia strongly suppressed in PbPb collisions
- Binding energy hierarchy
  - weaker bound state easier to be dissociated
- Weak (if any) uncorrelated recombination expected for Υ(nS)
  - smaller $\sigma_{b\bar{b}}$ than $\sigma_{c\bar{c}}$

CMS PRL 133 (2024) 022302 *ATLAS* PRC 107 (2023) 054912 *ALICE* PLB 822 (2021) 136579

Quarkonium Production Challenges

Υ(1S) R_{AA} vs N_{part}

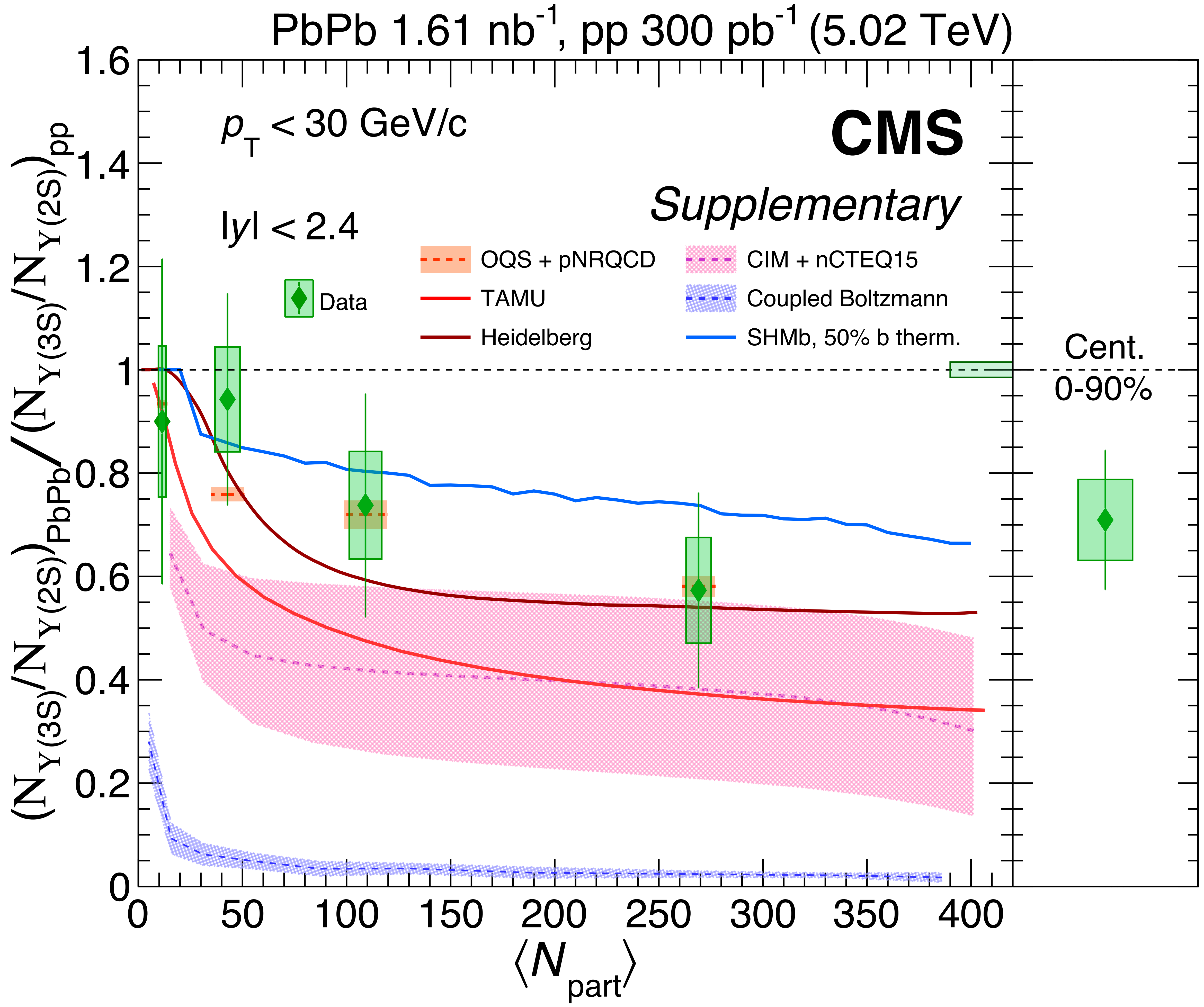


CMS PLB 790 (2019) 270 *STAR* PRL 130 (2023) 112301

Happy with dissociation + regeneration picture?

- Why is Υ(1S) suppression degree so similar in LHC and RHIC?
  - even if they have different initial temperatures
- Why does Υ(1S) not continue decreasing in most central events?
  - models with regeneration still don't describe it
- Feed-down contribution not well constrained

Quarkonium Production Challenges

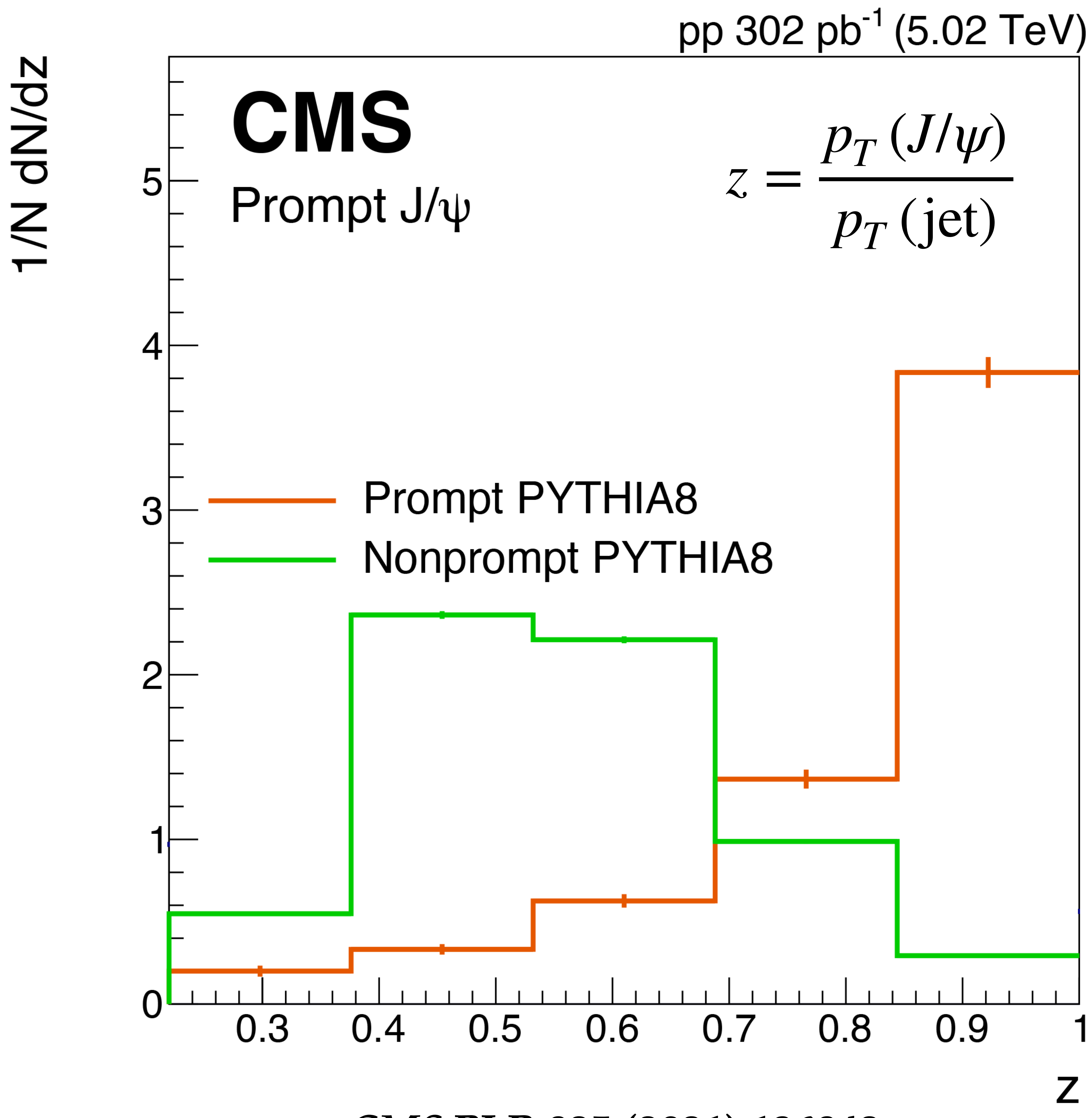


CMS **PRL 133 (2024) 022302**

More excited states Υ(3S) observation

- Challenging for theoretical models
  - Particle ratio cancels nPDF effect
- Crucial to constrain feed-down contribution

Revisit J/ψ Really Primordial?



CMS **PLB 825 (2021) 136842**

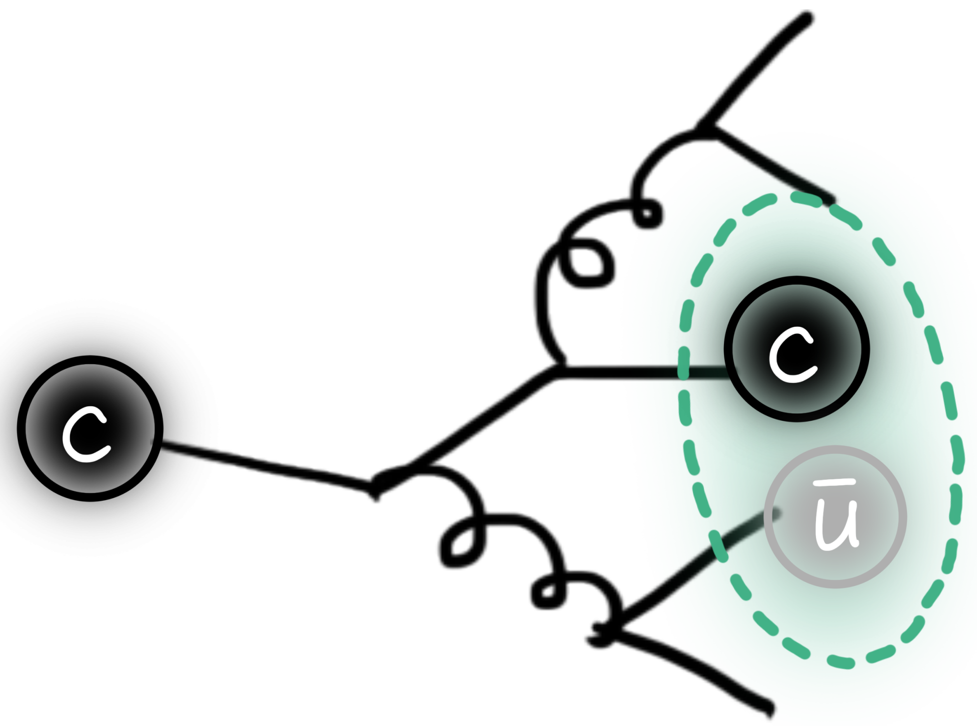
Early bound state picture

- Few surrounding jet activities

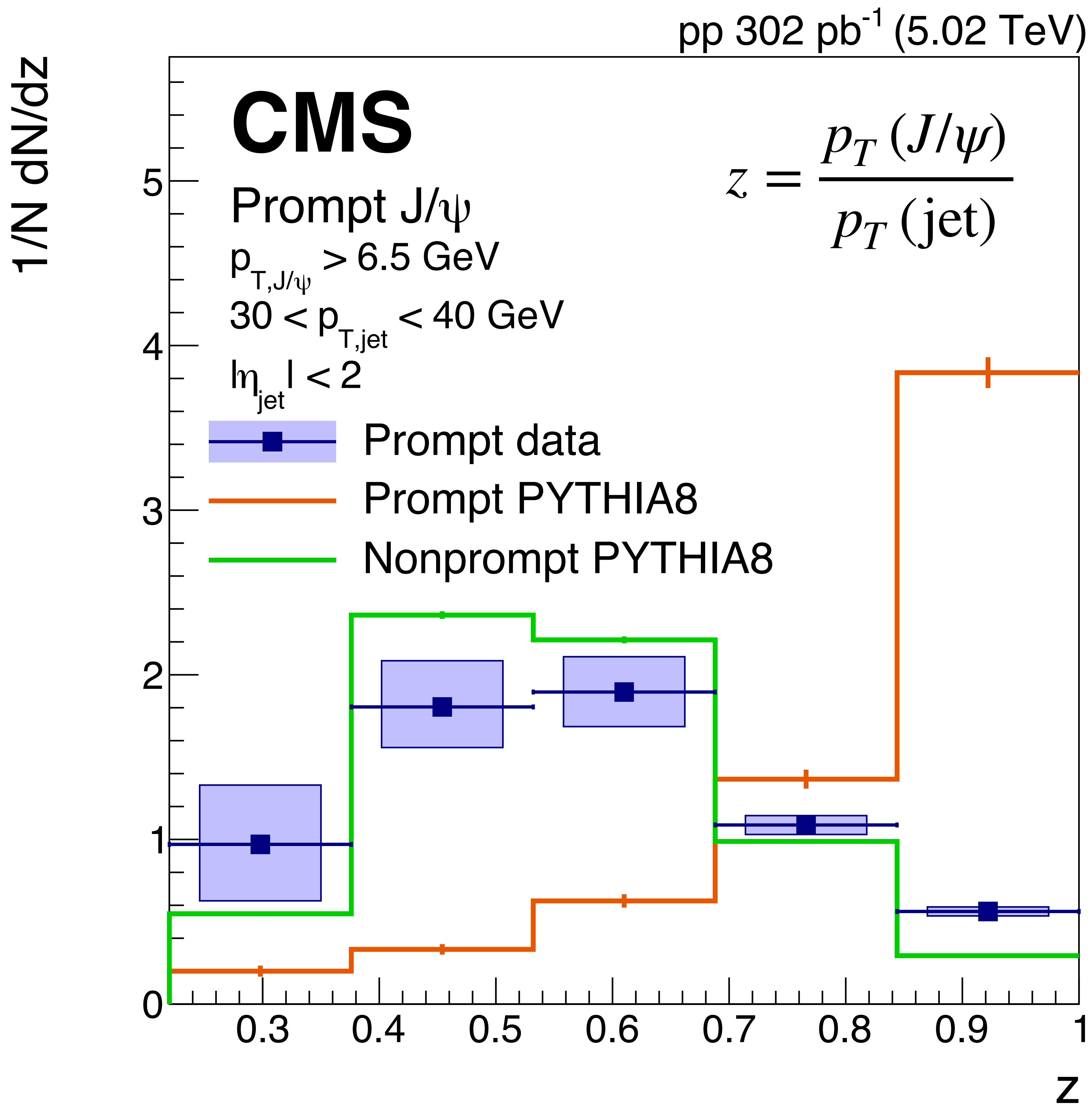
Late jet fragmentation picture

How open heavy flavors are formed

- J/ψ only carries partial transverse momentum in the jet shower



J/ψ Production Jet Fragmentation



CMS **PLB 825 (2021) 136842**

Early bound state picture
Late jet fragmentation picture

- J/ψ have more surrounding jet activities than (model) expected in pp
  - Similar to open heavy flavors
  - Parton energy loss may also play an important role in J/ψ suppression in HIC

Lession #4

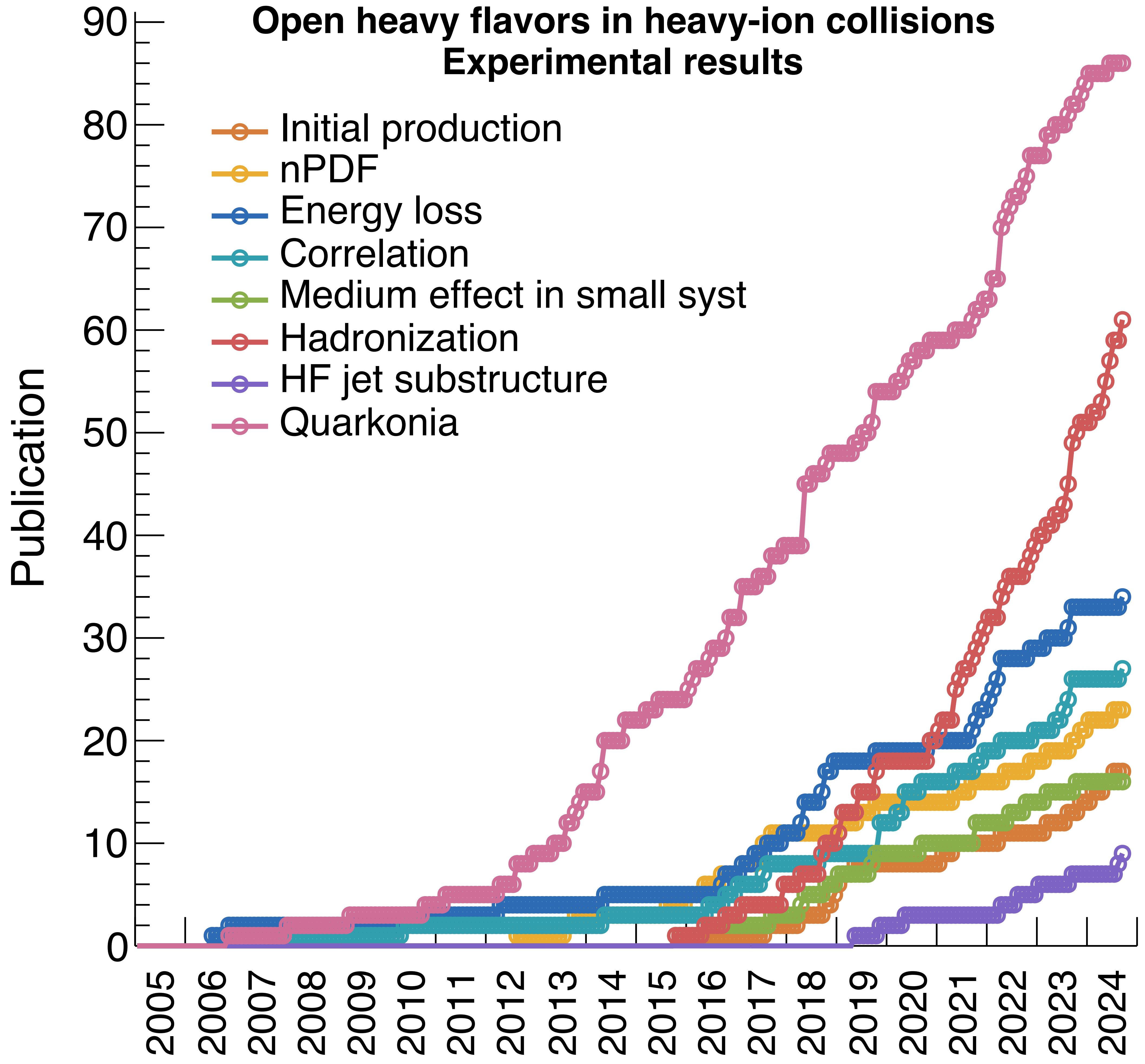
Dissociation + regeneration picture qualitatively works

QQ transport is more complicated than single parton transport
2-body quantum features, complex potential, poorly constrained dissociation rate, …

Need better control of feeddown and CNM effects

What are the experimental paths to the answers
polarization, high-precision flow, …?

(Not a) Summary



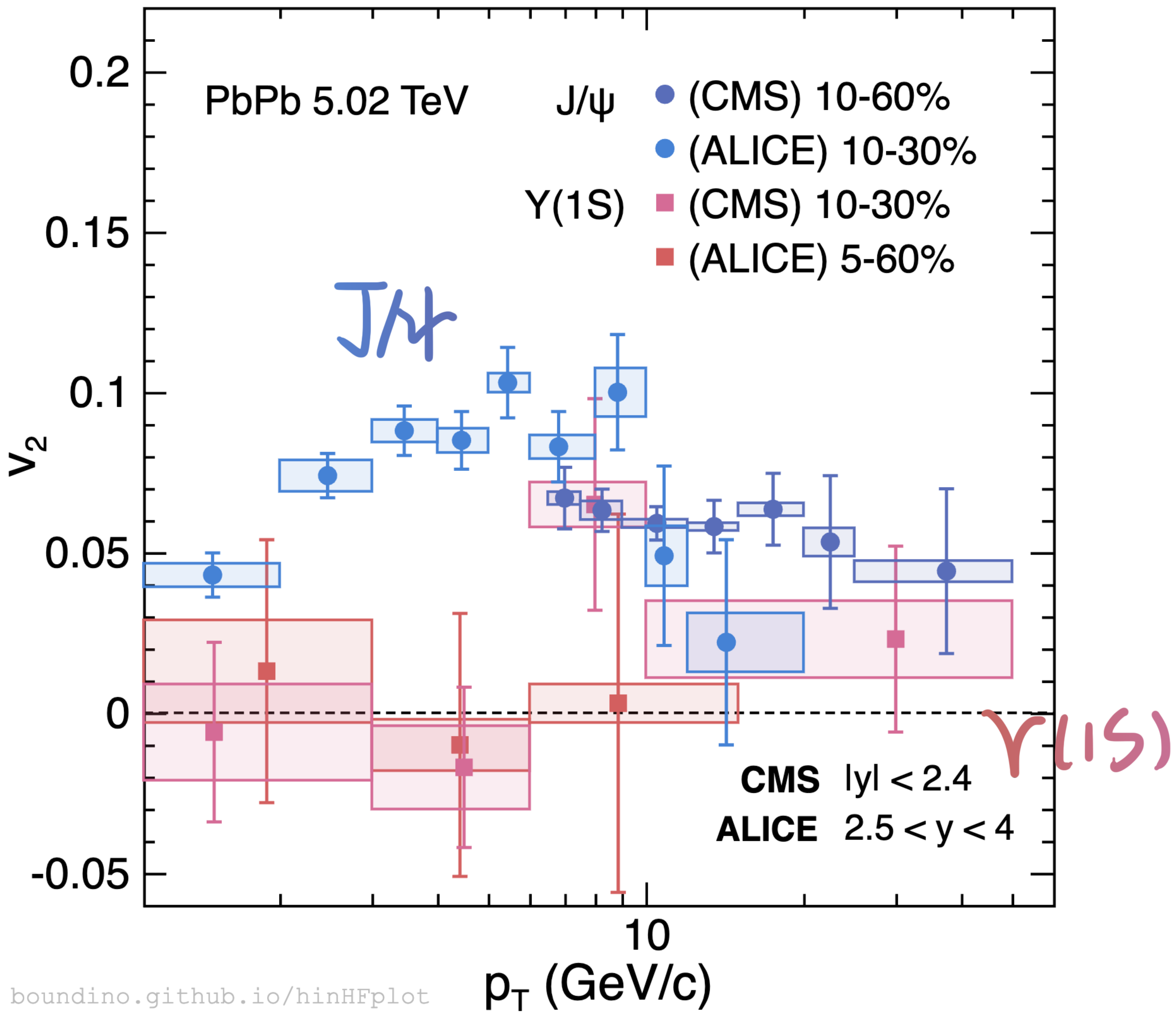
- Fruitful experimental results on heavy flavors
  - Many clear physics messages
  - Many challenges
- Hope to see new ideas in this workshop!

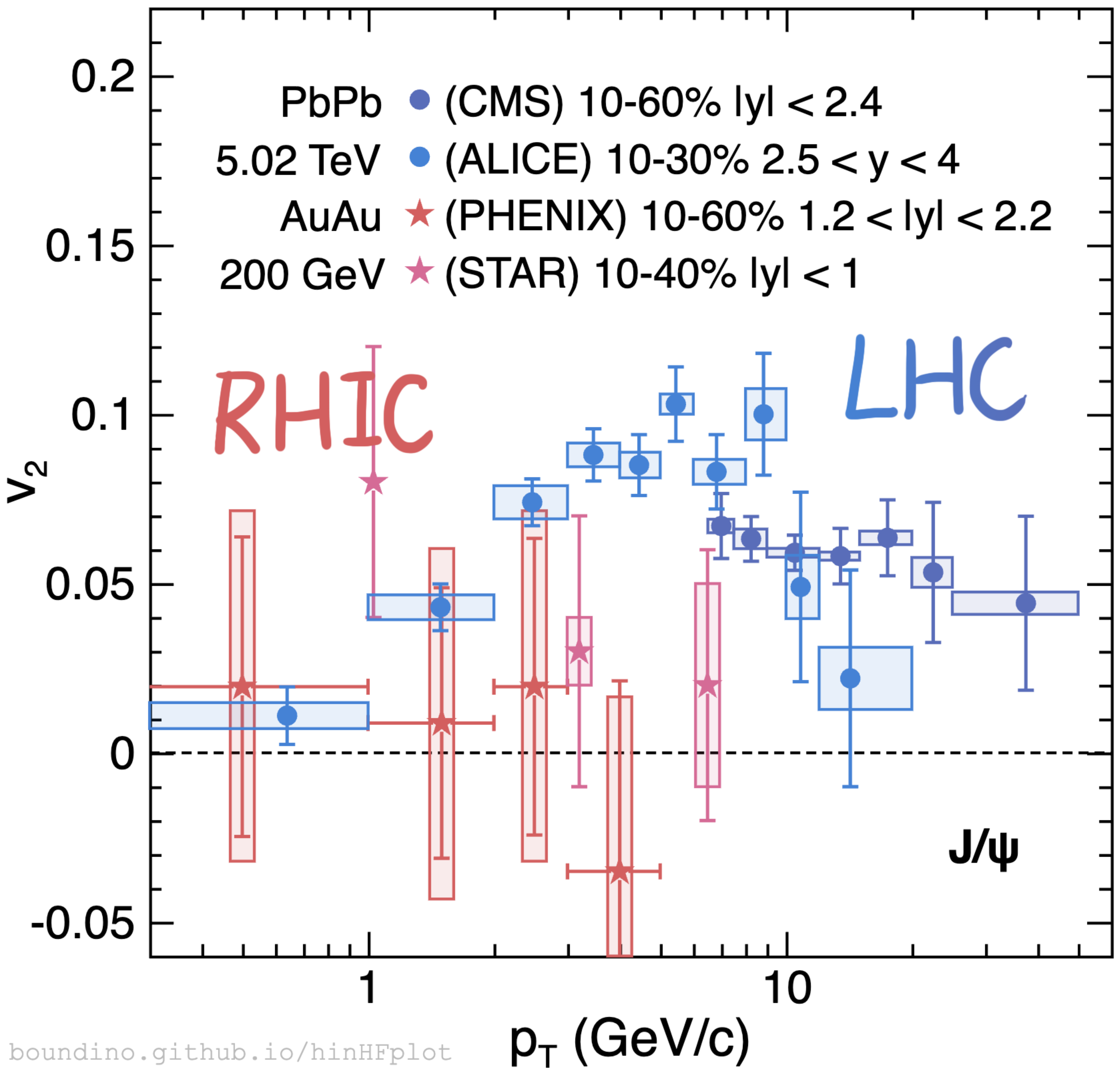
🔗 Heavy flavor result playground


Isabelle
Thanks for your attention!

Examine Regeneration Azimuthal Anisotropy

- Significant non-zero J/ψ v_2 → Indicate significant contribution from uncorrelated regeneration

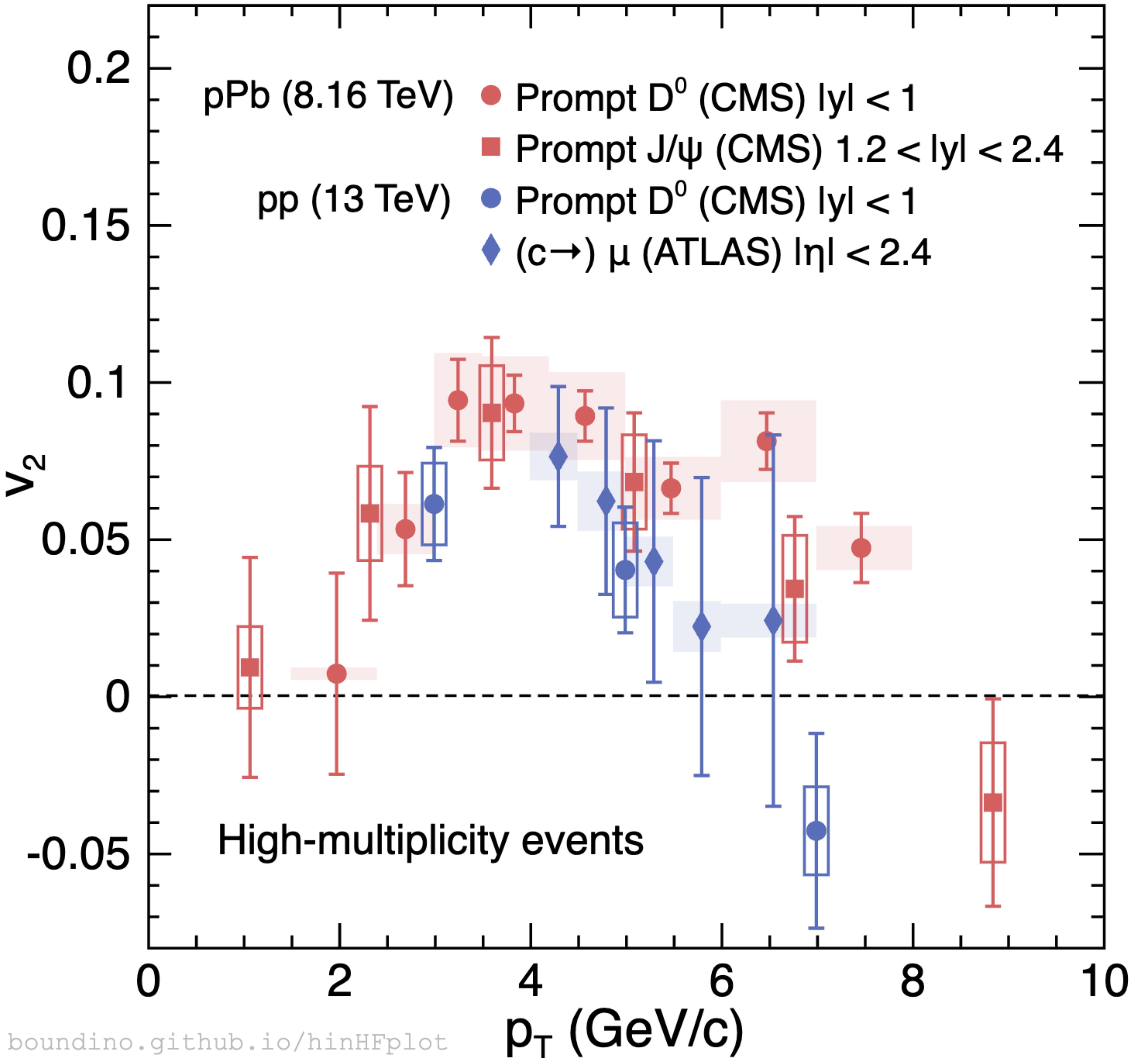




- Υ(1S) v_2 ~ 0 → small regeneration
- J/ψ v_2 at RHIC ~ 0 → small regeneration

CMS JHEP 10 (2023) 115 PLB 819 (2021) 136385 *ALICE* JHEP 10 (2020) 141 PRL 123 (2019) 192301 *STAR* PRL 111 (2013) 052301 *PHENIX* Prelim

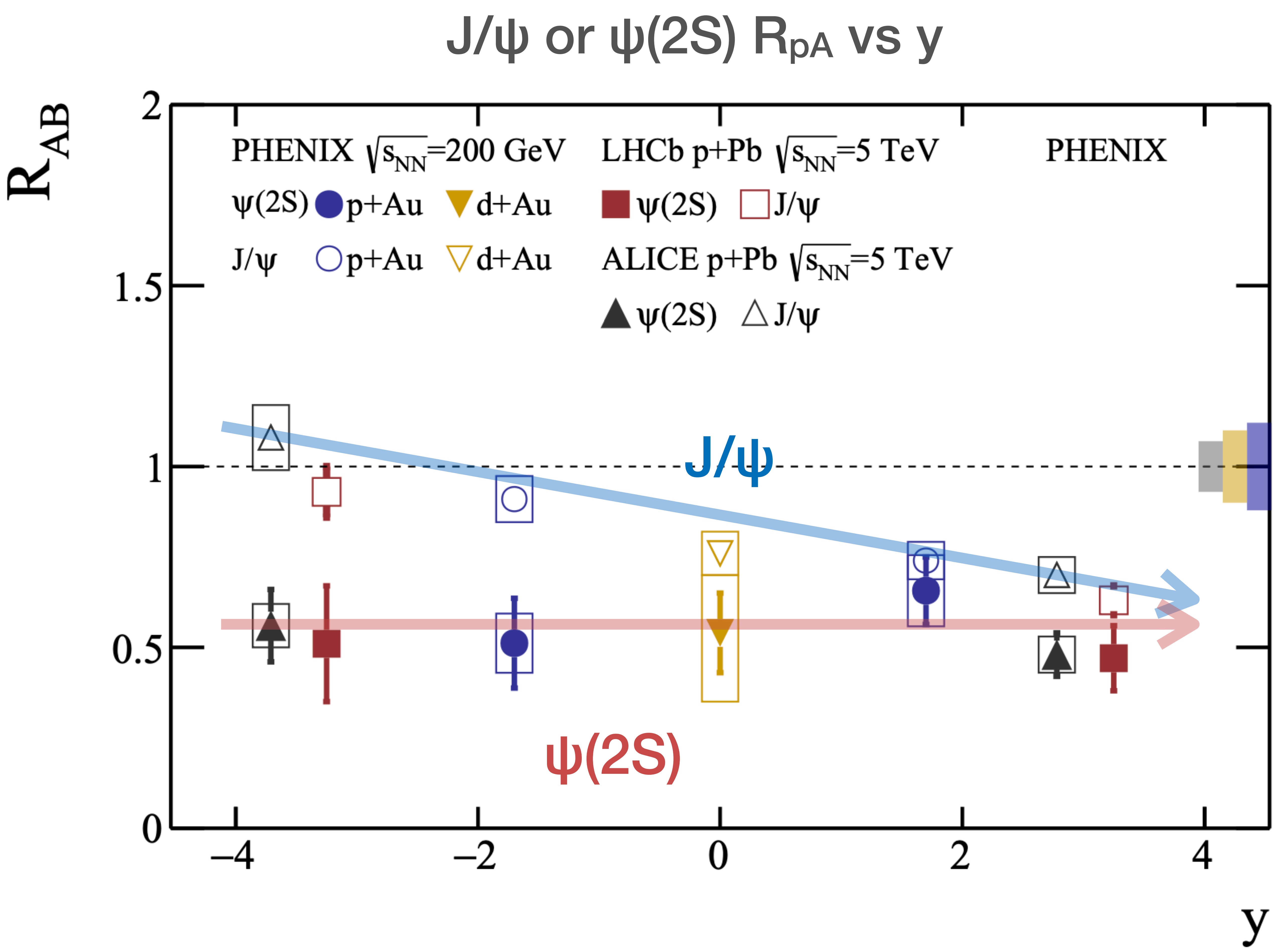
Small Systems Collective Behaviors



- Non-zero v_2 of charm hadrons in high-multiplicity pp and pPb collisions
- Source of flow signals not decisive
  - Maybe initial transverse momentum correlation in CGC framework
  - Maybe small QGP medium in final states

PRL 121 (2018) 082301 PLB 813 (2021) 136036 PLB 791 (2019) 172 PRL 124 (2020) 082301

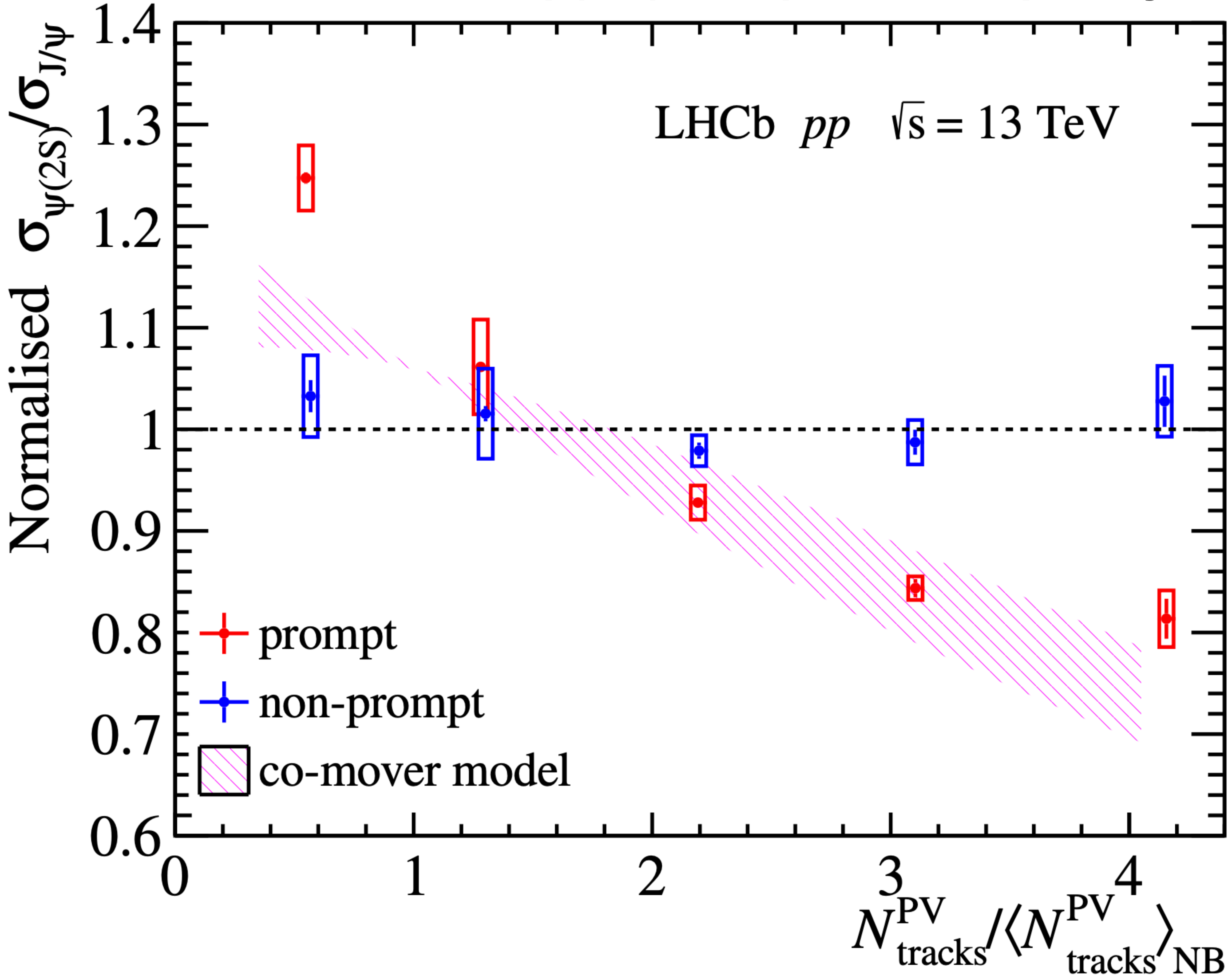
Small Systems Quarkonia Sequential Suppression



- Not surprising J/ψ R_{pA} is not unity
  - Nuclear PDF
  - Initial coherent energy loss
- These initial state effects cannot explain different R_{pA} of J/ψ and ψ(2S)

Small Systems Quarkonia Sequential Suppression

Normalized ψ(2S) / J/ψ vs multiplicity



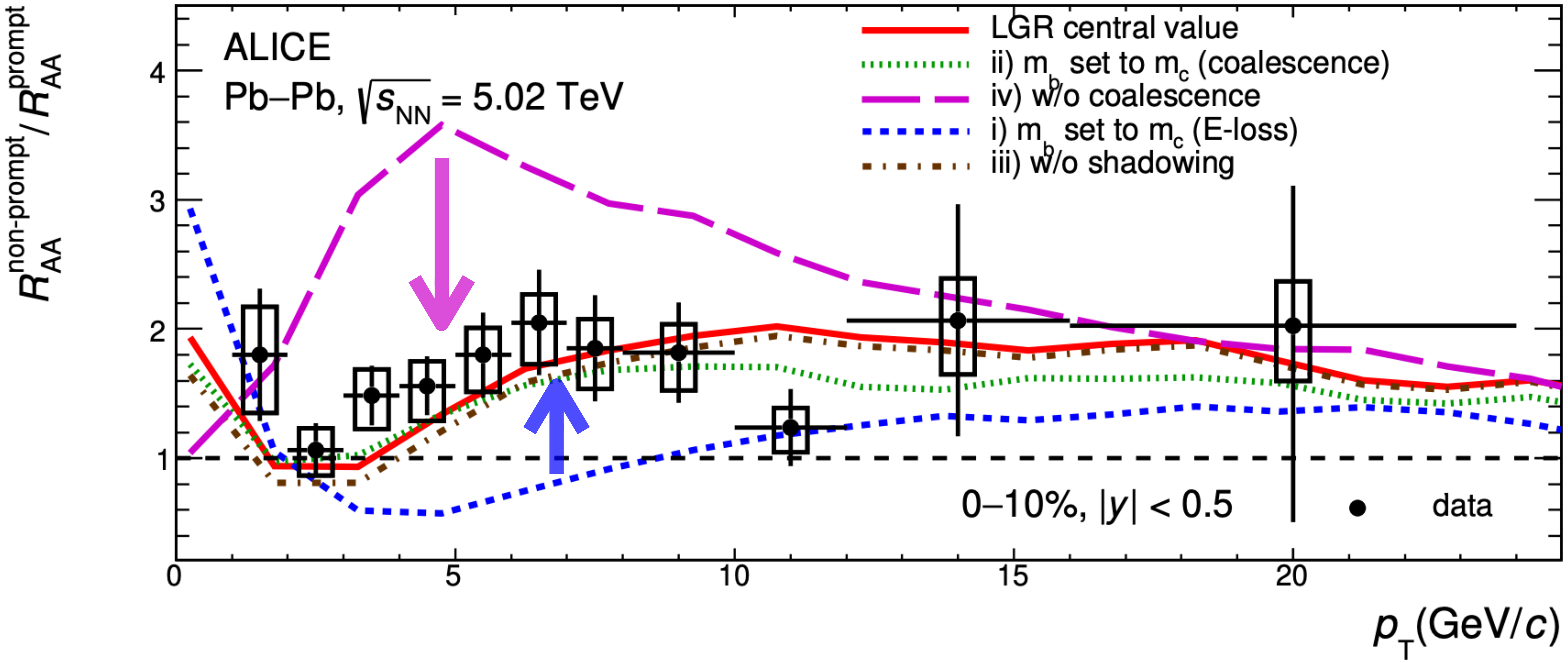
[JHEP 05 (2024) 243]

- Double ratio of ψ(2S) to J/ψ
  - Cancel initial state effects
- Vary multiplicities
  - Examine potential final state effects
    - comover dissociation
    - small medium droplet created

R_{AA} Flavor Dependence

Non-prompt D R_{AA} / Prompt D R_{AA}

Beauty / charm



[JHEP 12 (2022) 126]

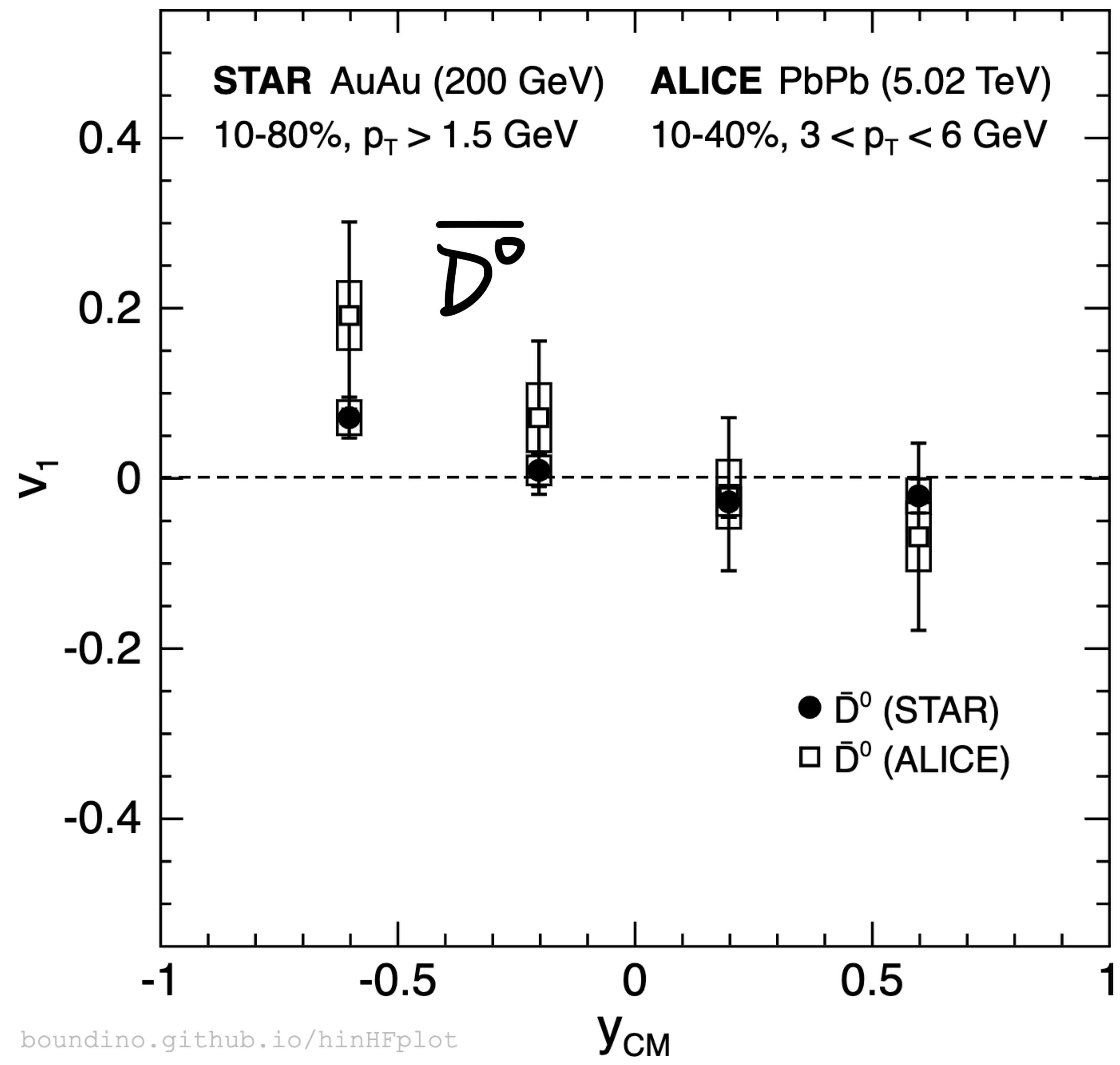
nPDF *small effect*
- Simultaneous effect on charm and beauty

Mass dependent energy loss
significant effect
- Enhance difference between c and b

Hadronization
significant effect
- Reduce diff between c and b

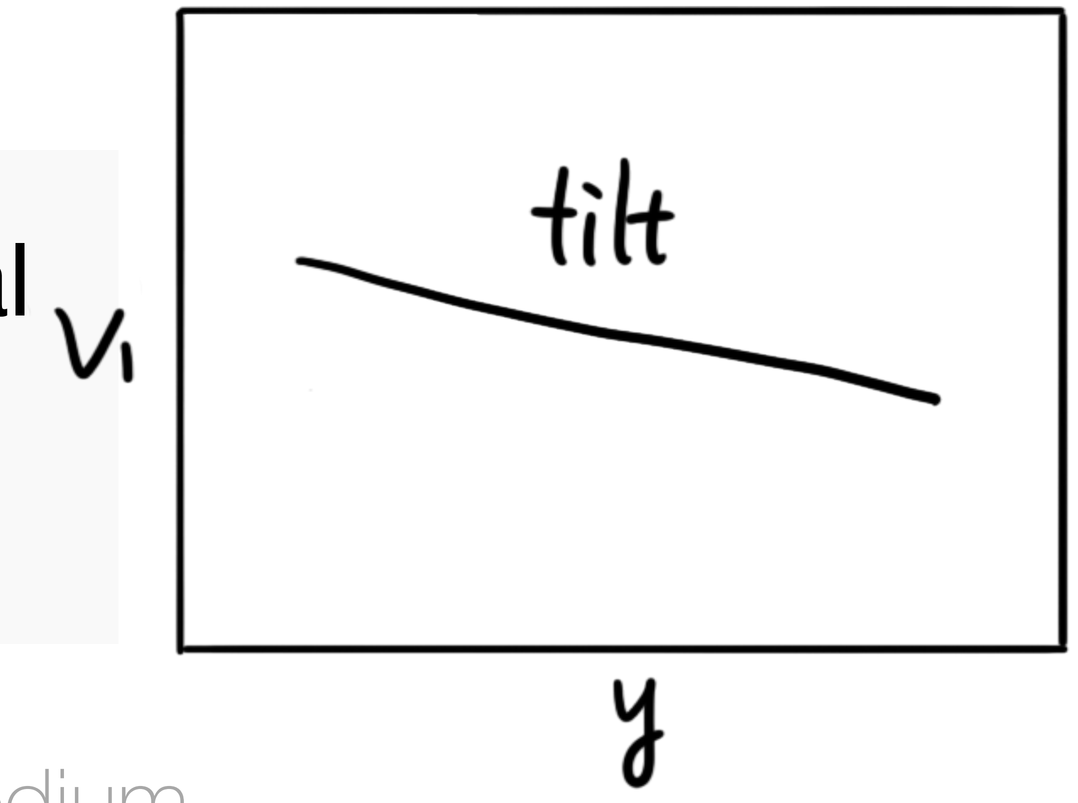
HF Probe Initial Condition Tilt of Medium

v_1 vs. y in PbPb, AuAu

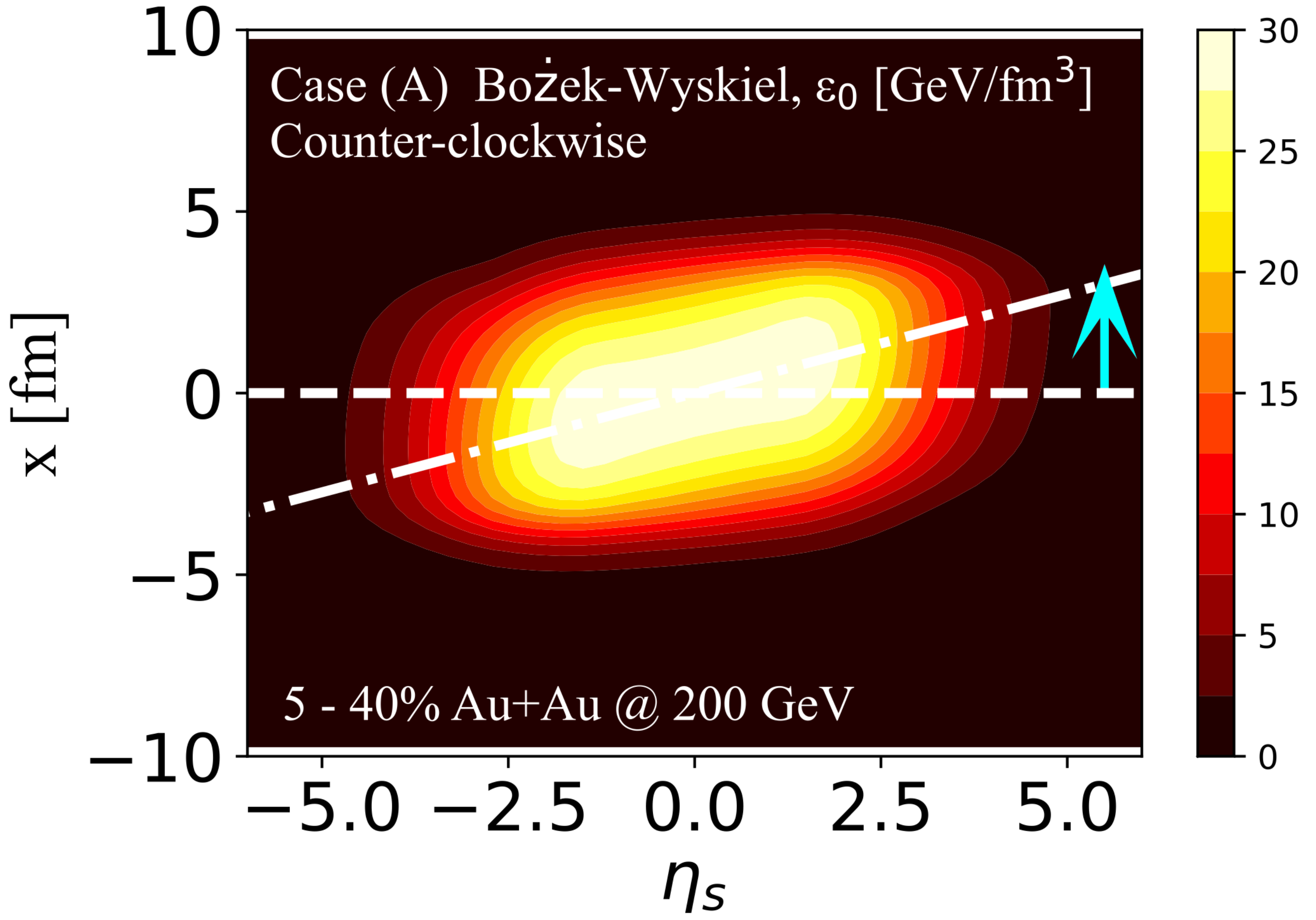


PRL 125 (2020) 022301
PRL 123 (2019) 162301

- Tilt → Longitudinal structure of initial energy density distribution
  ➡ Non-zero (rapidity-dependent) v_1



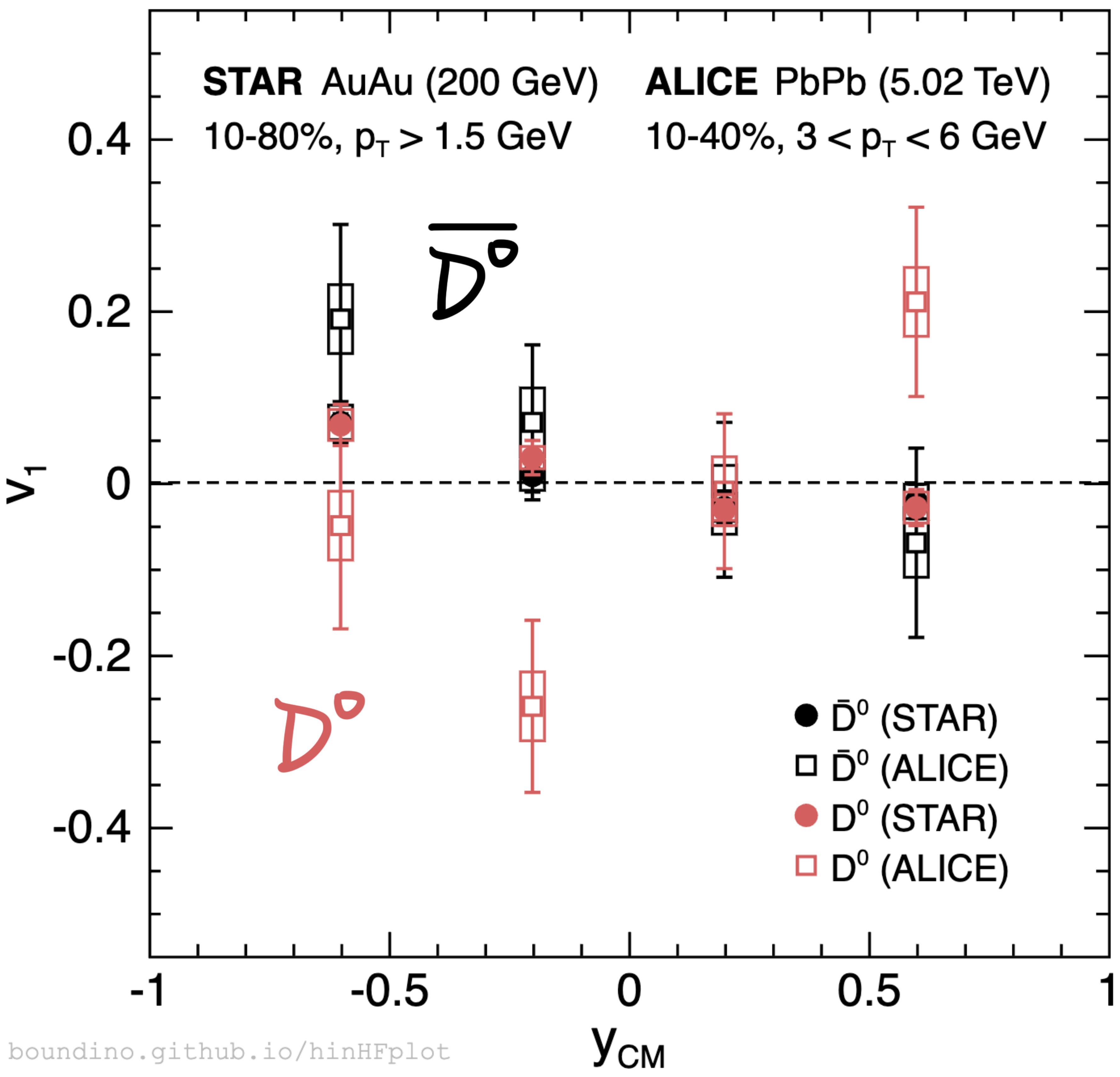
Counter clockwise tilt of the medium



PRC 105 (2022) 034901

HF Probe Initial Condition Strong EM Field

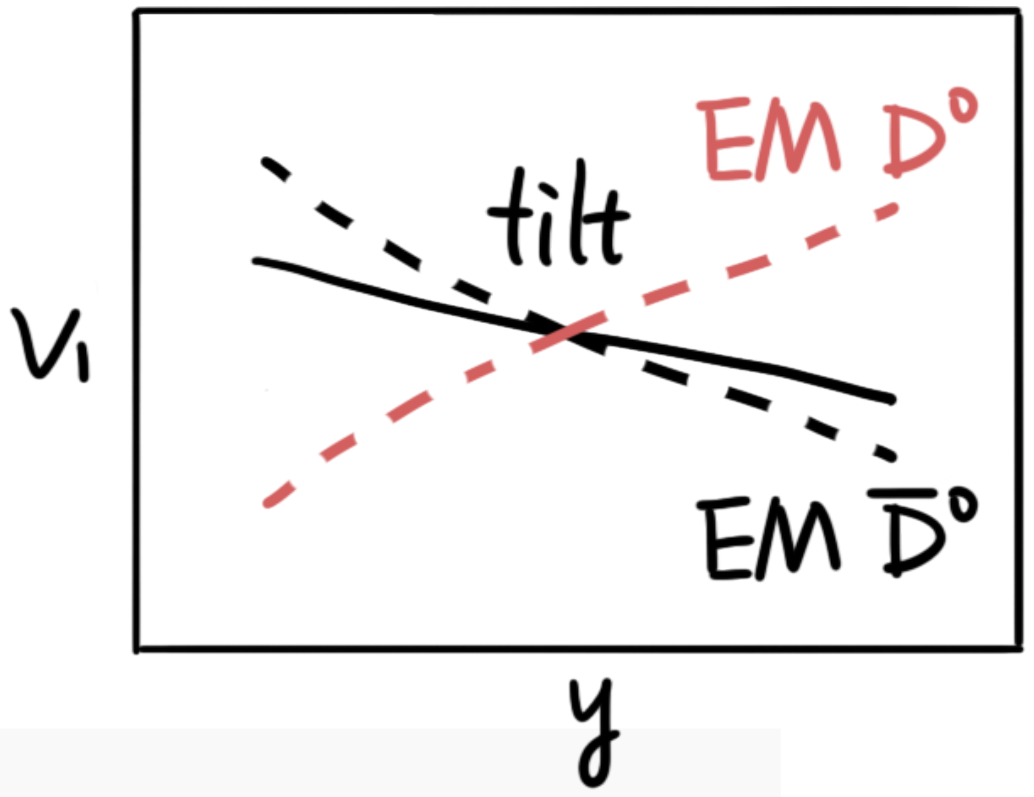
v1 vs. y in PbPb, AuAu



PRL 125 (2020) 022301

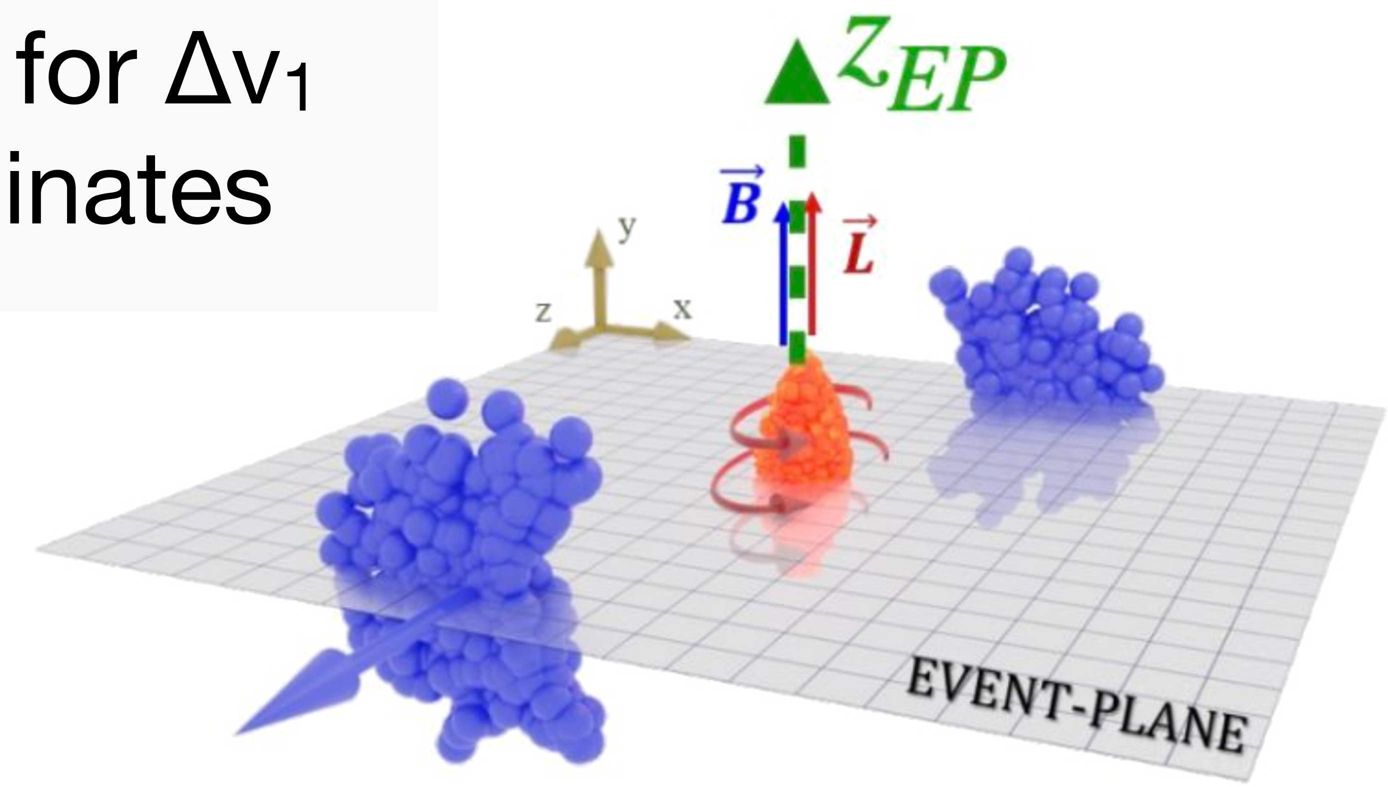
PRL 123 (2019) 162301

- Tilt → Longitudinal structure of initial energy density distribution
  ➡ Non-zero (rapidity-dependent) v_1



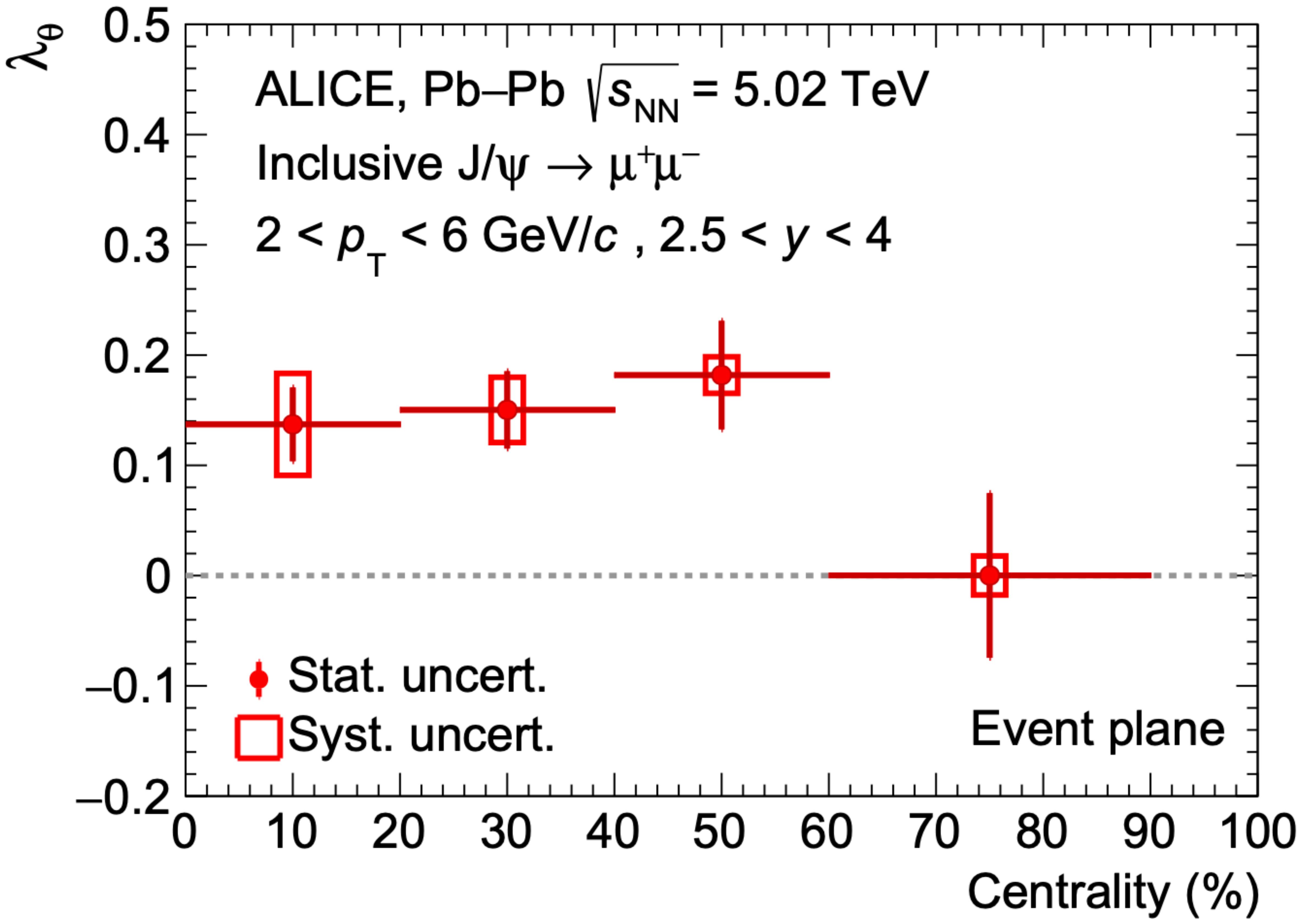
- Strong EM field emerges at early stage
  - Decays quickly → unique chance for heavy flavors
  ➡ Split v_1 of c and c̄ → non-zero (rapidity-dep) Δv_1

- Difference b/w LHC and RHIC for Δv_1
  - Possibly different effect dominates



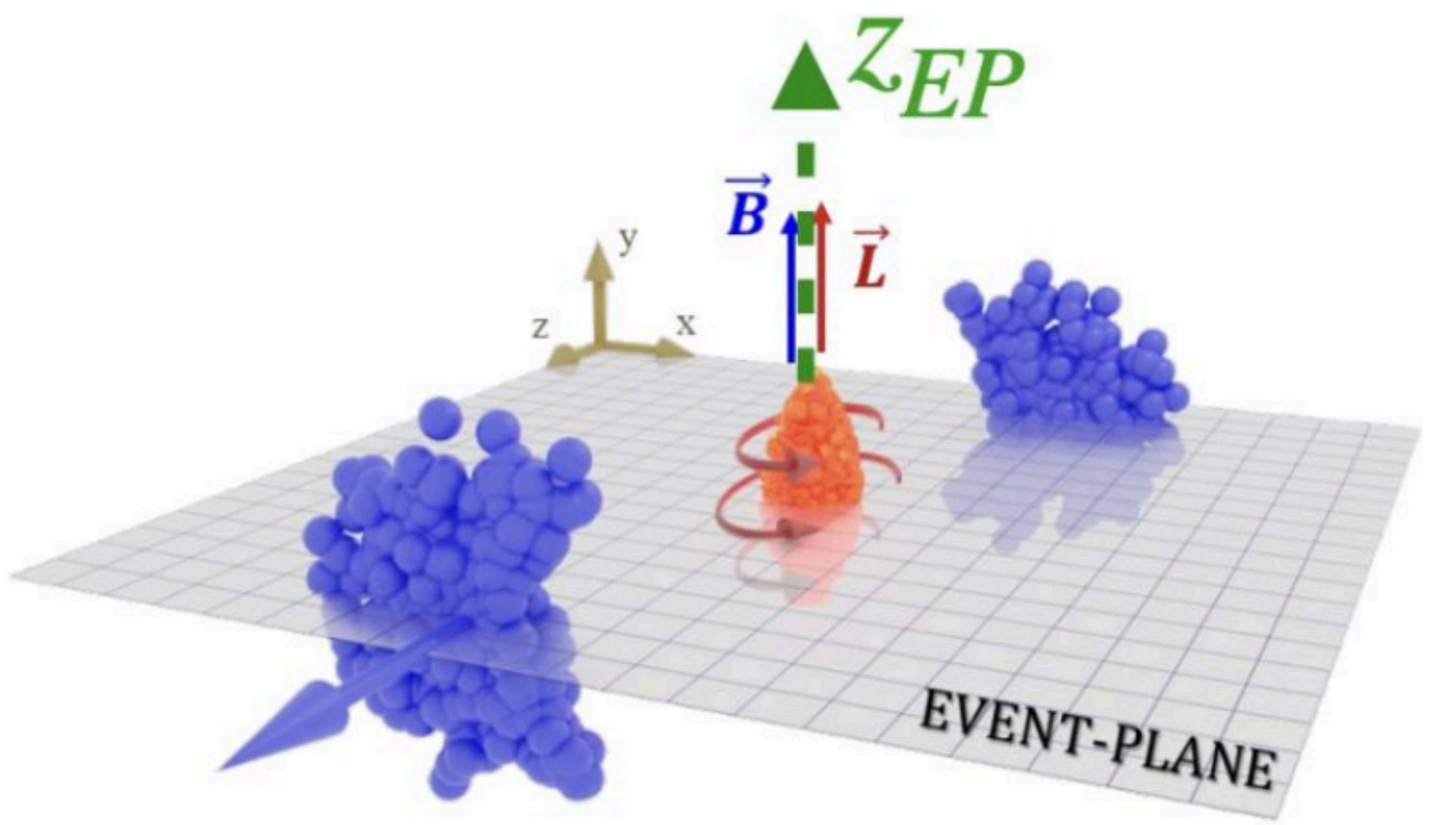
J/ψ Polarization Initial B Field, Vorticity

J/ψ Polarization

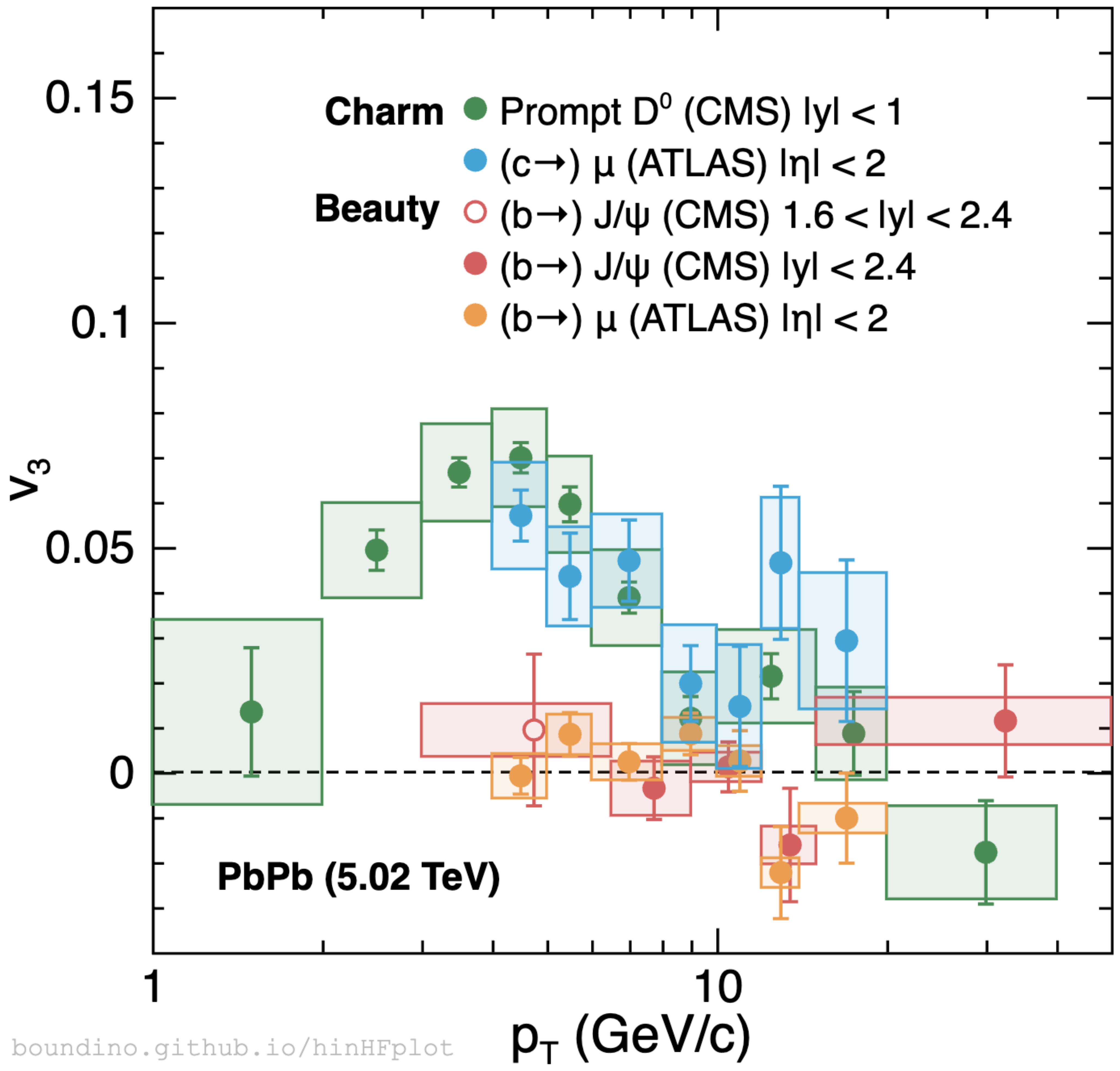


arXiv:2204.10171

- $\lambda_\theta > 0$ → Transverse polarization in the direction perpendicular to the reaction plane
  ➜ connected with
  - Strong magnetic field
  - Rotation at early stage via spin-orbit coupling



HF Probe Fluctuations Initial Geometry

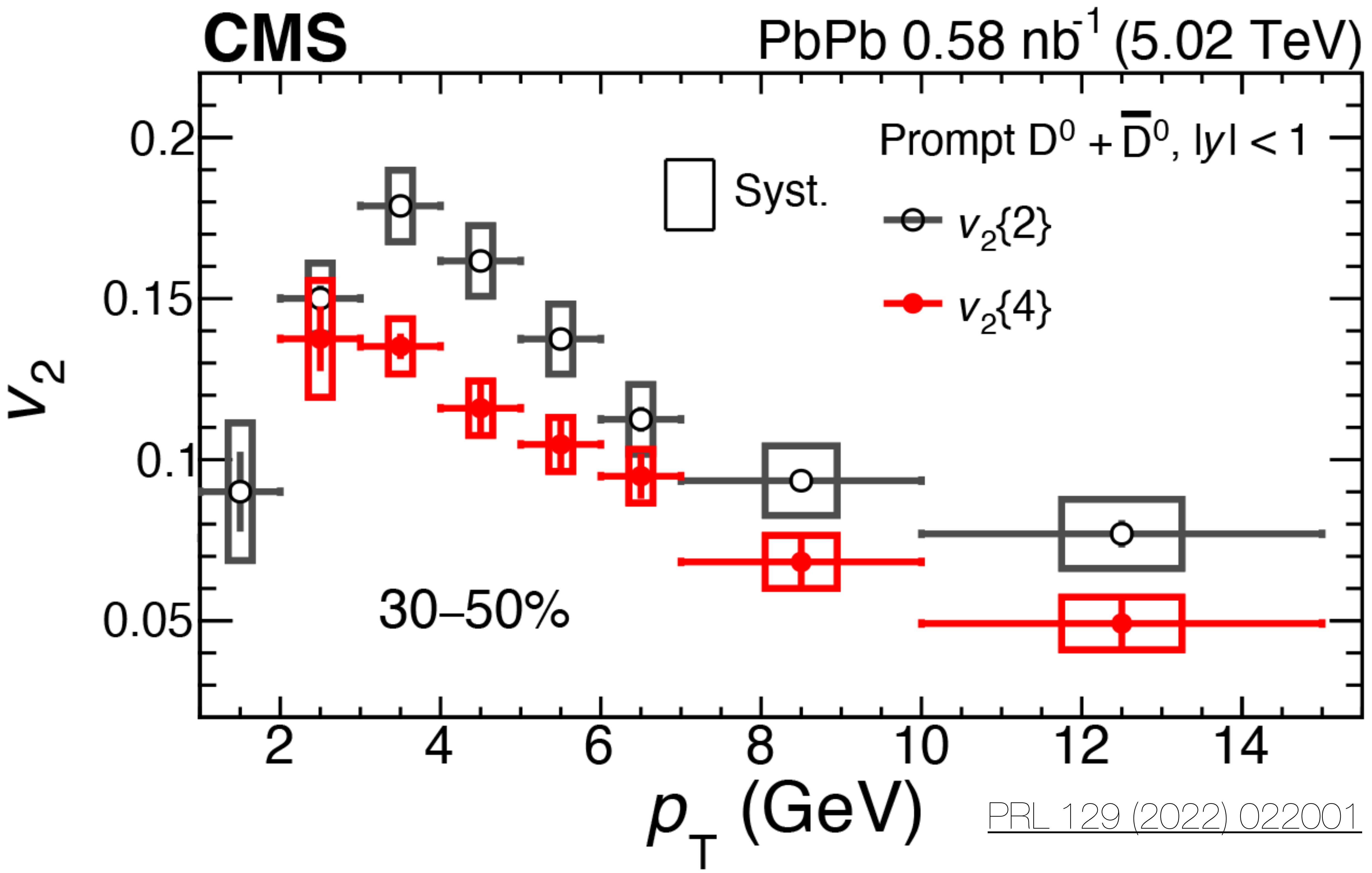


- High-order v_n probes event-by-event fluctuation of initial geometry
  - Similar to soft probes but different length-wave probes

PLB 816 (2021) 136253 CMS-PAS-HIN-21-008
PLB 807 (2020) 135595 PLB 807 (2020) 135595

HF Probe Fluctuations Energy Loss

D^0 4-particle correlation $v_2\{4\}$



PRL 129 (2022) 022001

- Probe event-by-event fluctuation
  - $v_2\{2\}^2 \approx \langle v \rangle^2 + \sigma^2$
  - $v_2\{4\}^2 \approx \langle v \rangle^2 - \sigma^2$

  flow fluctuation

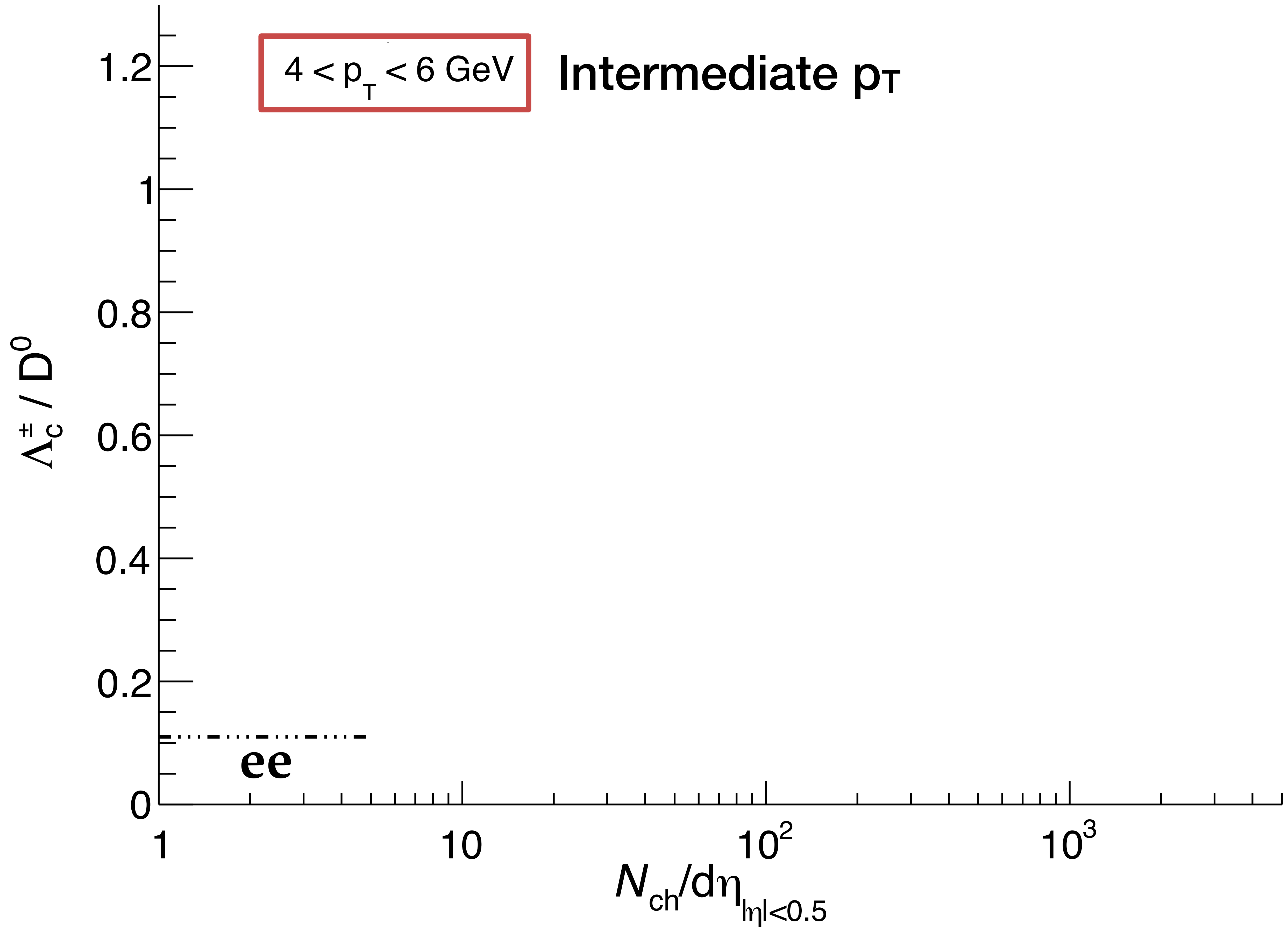
- Indeed $v_2\{4\} < v_2\{2\}$ for D^0
  - Provide additional constraints

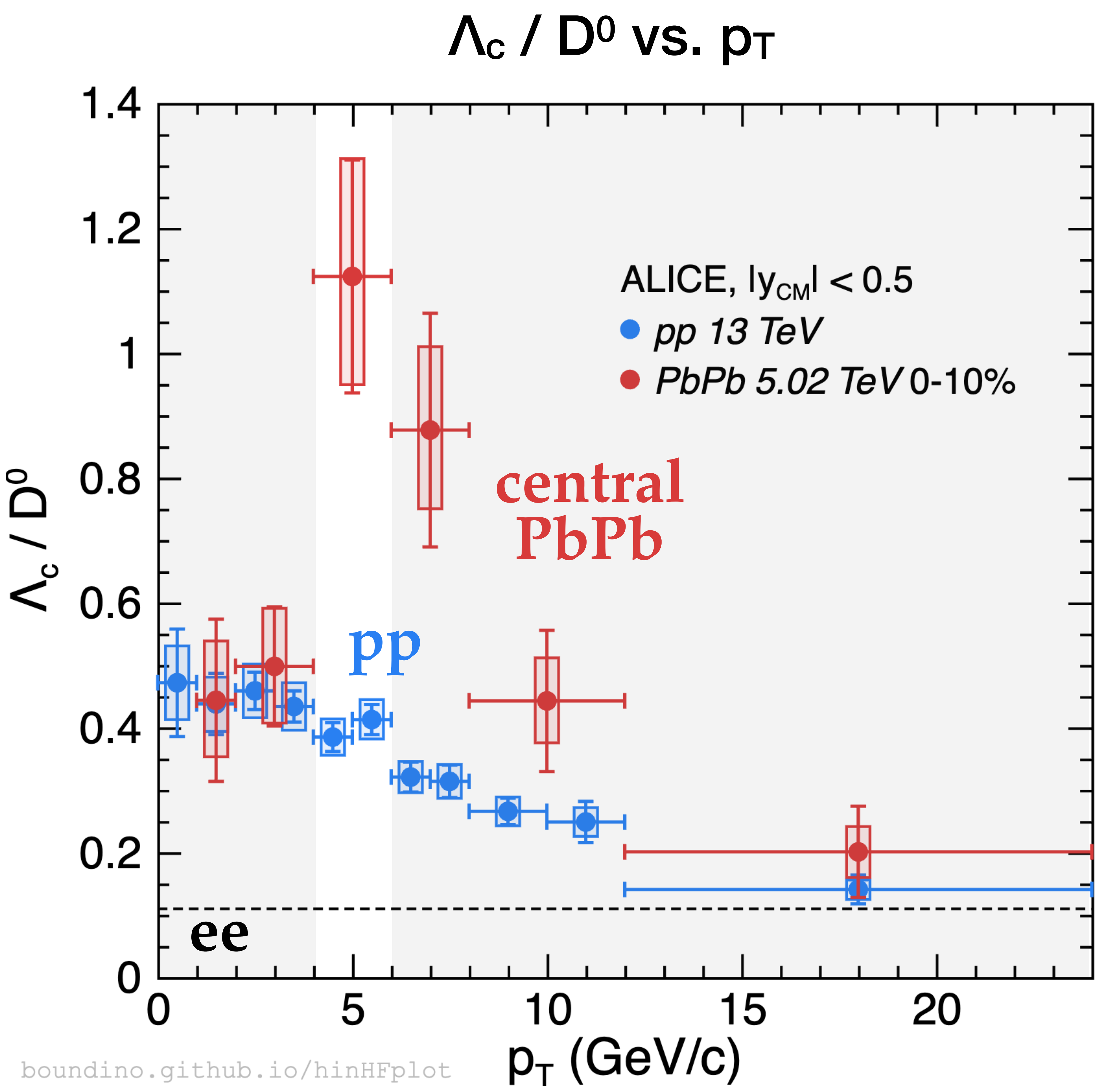
- v_2 fluctuations from both initial geometry (soft) and energy loss (hard)

Hadronization My Thoughts

- Multiplicity is not the best scale for system scan
- Hope models can calculate all the different systems simultaneously

Λ_c p_T Redistribution Across Collision Systems





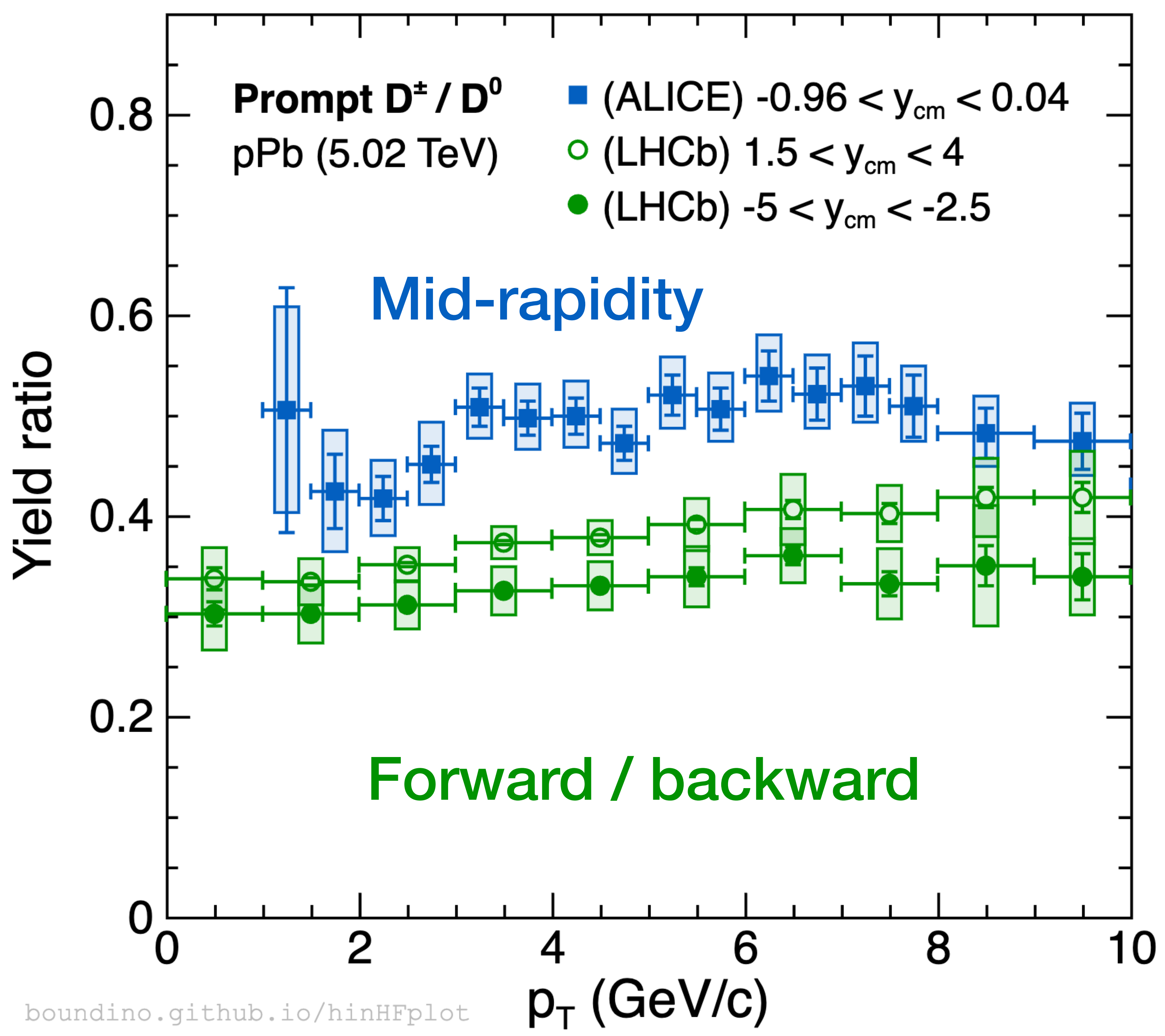
- **How does it evolve from ee to PbPb?**
- Use intermediate p_T as a proxy to the p_T redistribution

ALICE PLB 839 (2023) 137796

ALICE JHEP 12 (2023) 086

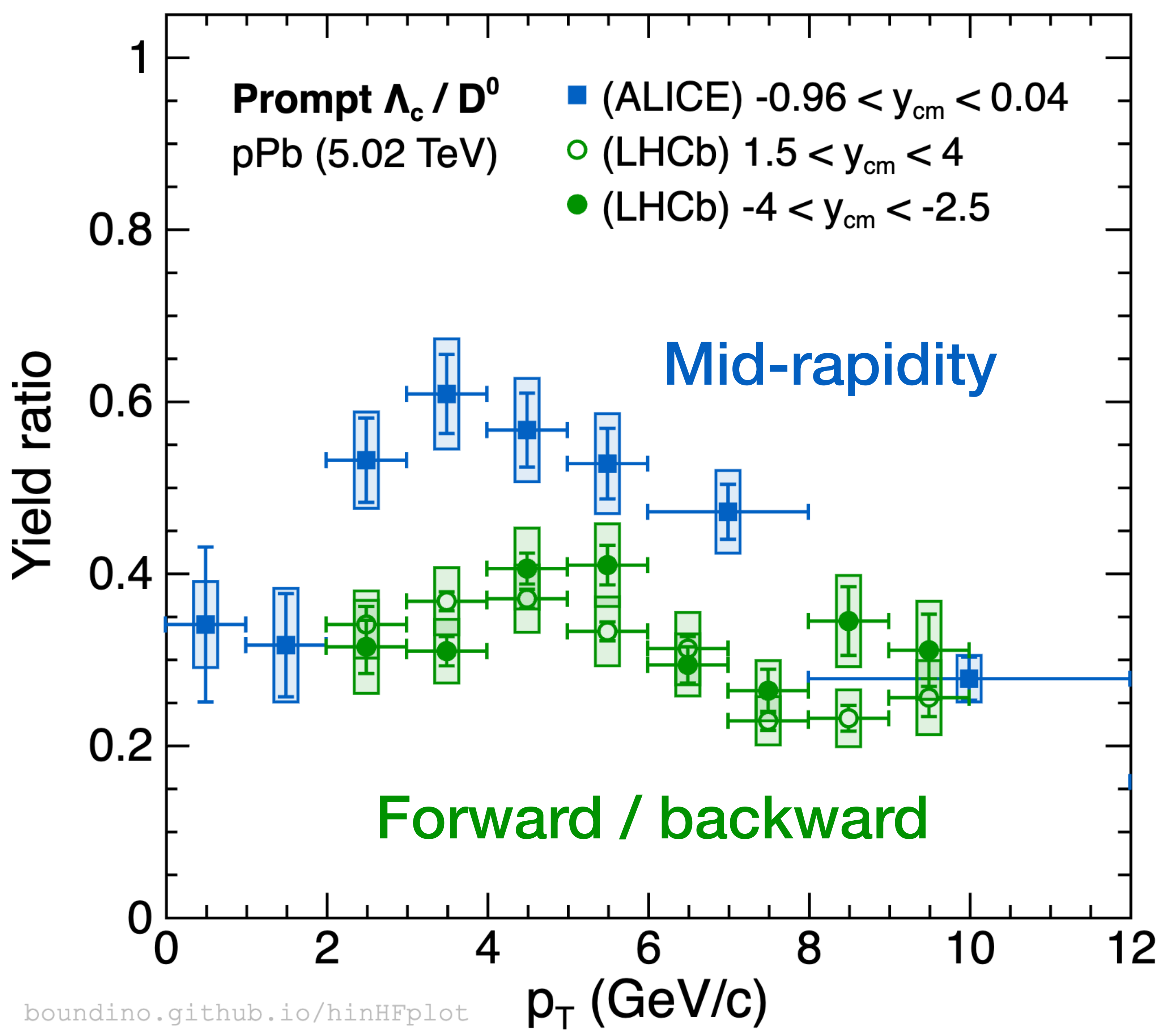
More Challenges Rapidity Dependence

D^+ ($c\bar{d}$) / D^0 ($c\bar{u}$)



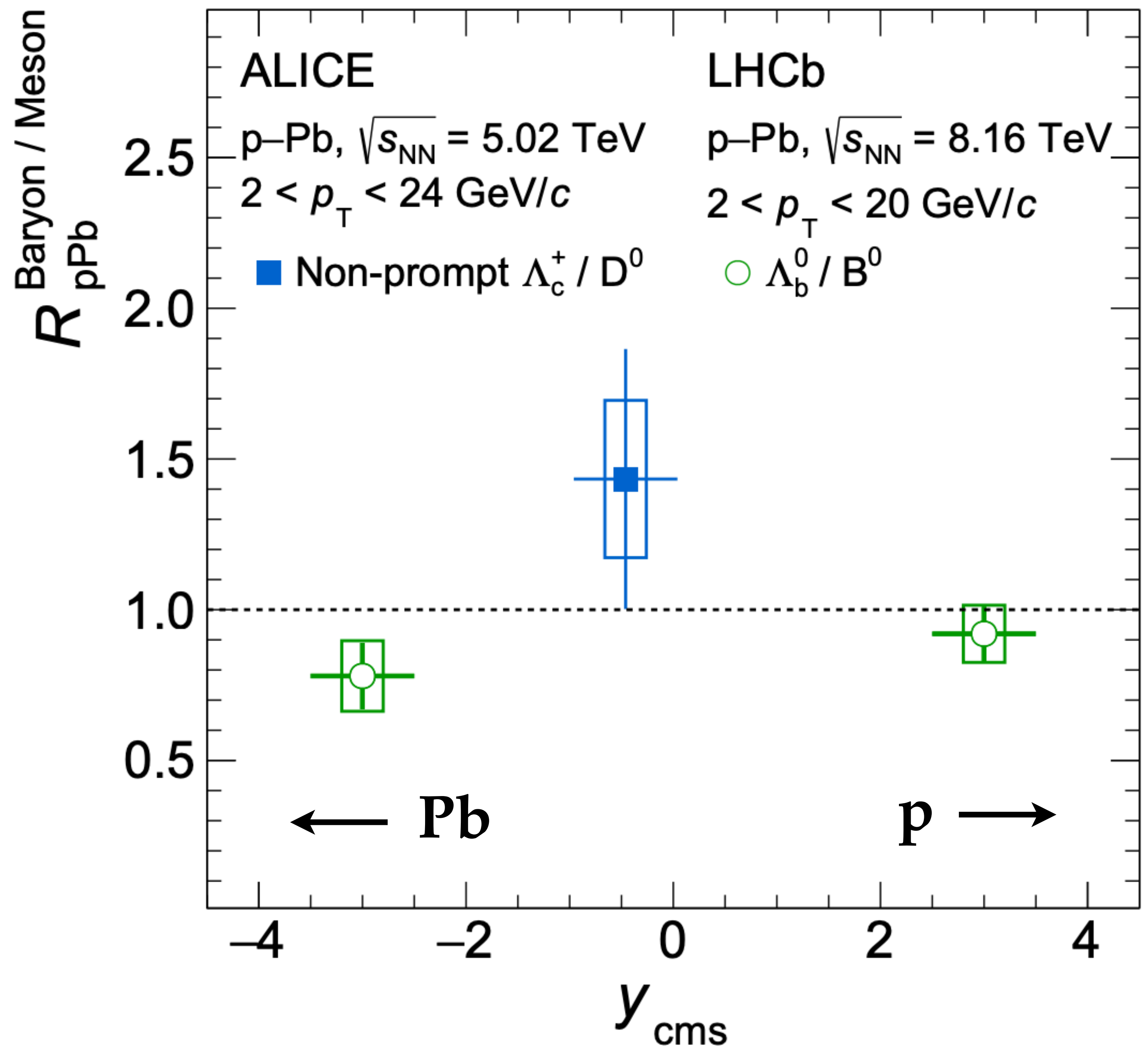
ALICE JHEP 12 (2019) 092
LHCb JHEP 01 (2024) 070

Λ_c (cud) / D^0 ($c\bar{u}$)



ALICE PRC 107 (2023) 064901
LHCb JHEP 02 (2019) 102

Λ_b (bud) / B^0 ($b\bar{d}$) double ratio

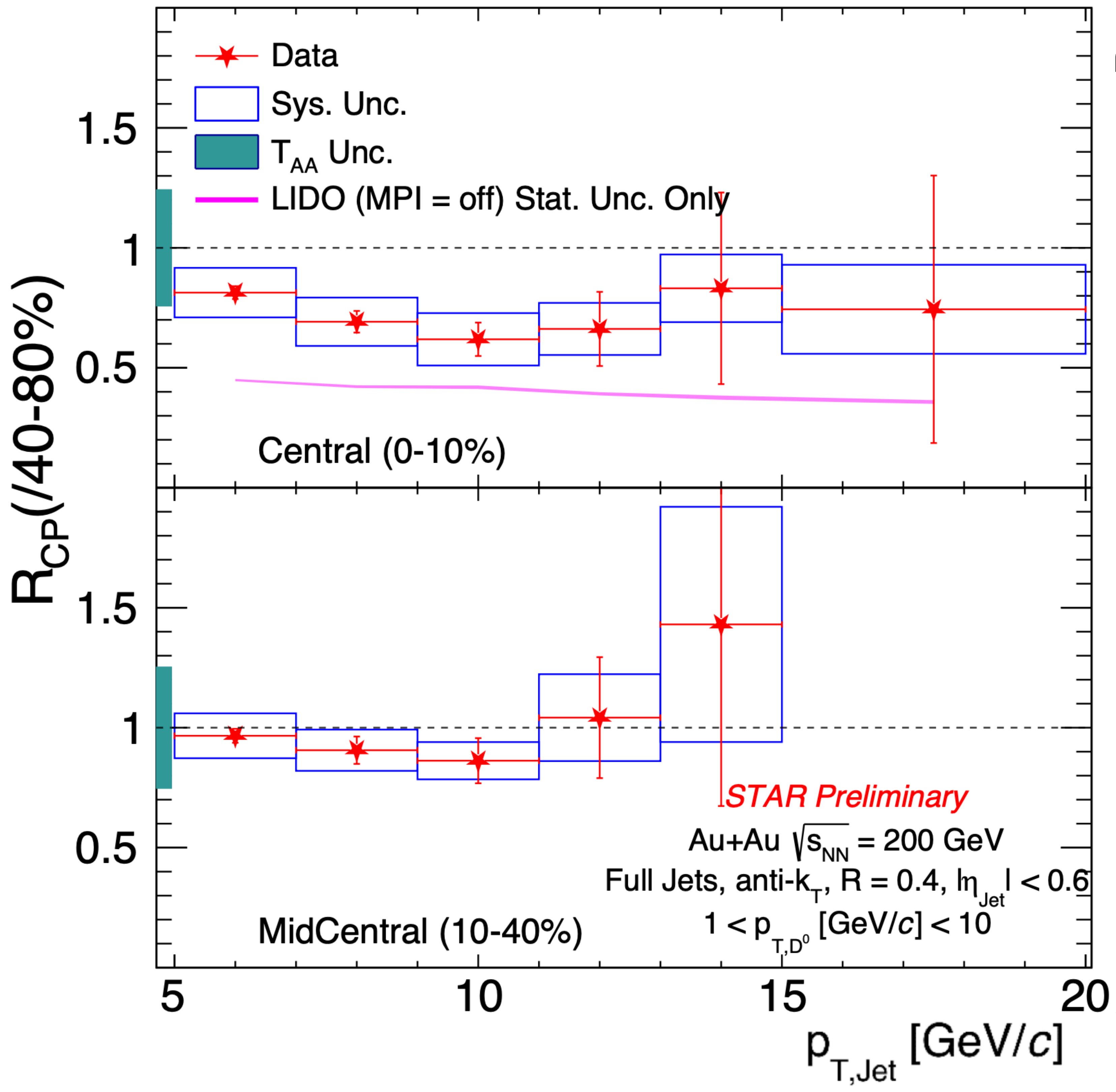


ALICE arXiv:2407.10593
LHCb PRD 99 (2019) 052011

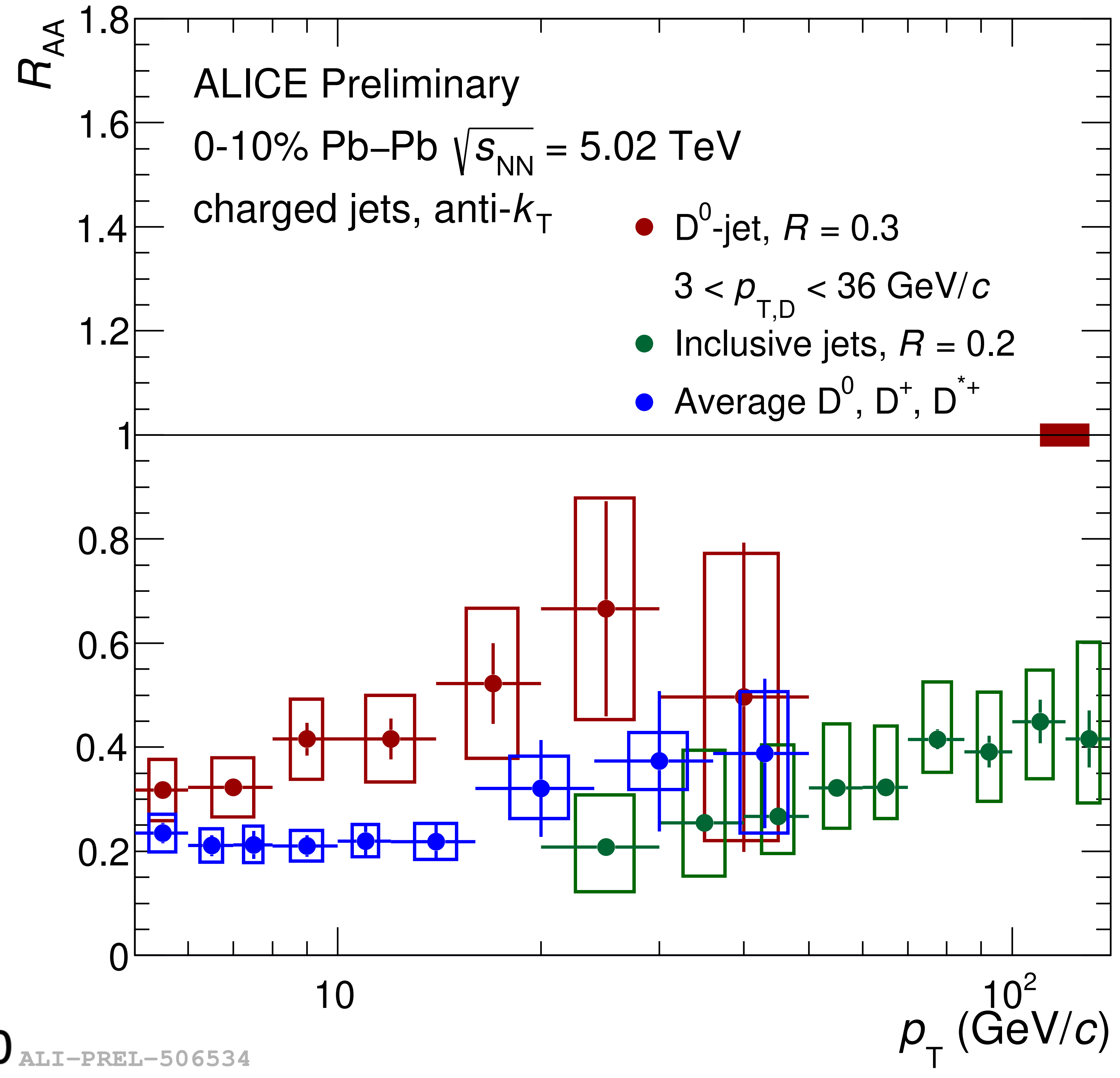
- **Rapidity dependence** in both mesons and baryons, in both charm and beauty sectors
- Models do not expect rapidity dependence
- Wider tracker of CMS and ATLAS after Phase II upgrade and ALICE3!

Quenching Heavy-Flavor Tagged Jets

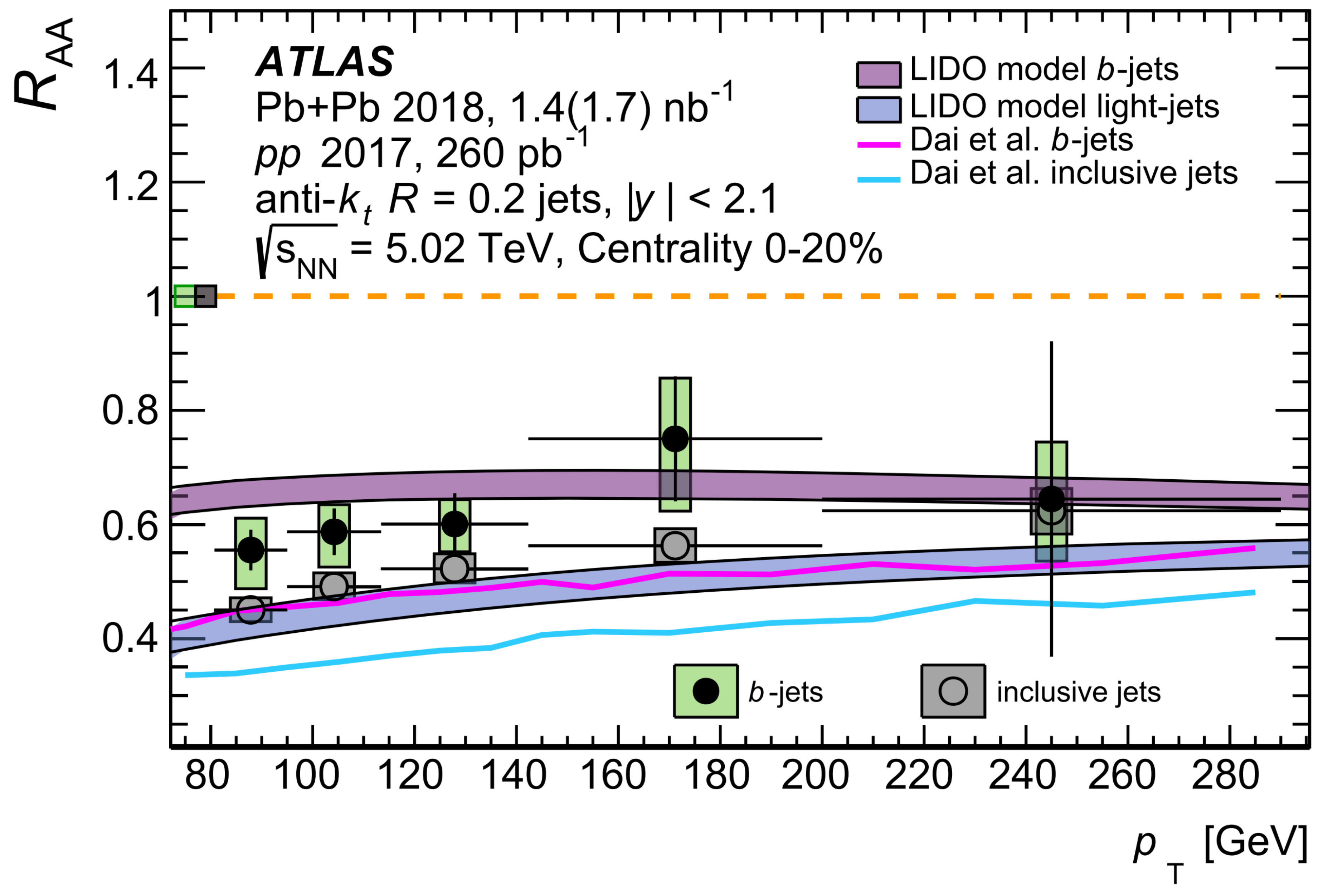
D-tagged jet R_{CP} AuAu



D-tagged jet R_{AA} PbPb



b-tagged jet R_{AA} PbPb



ATLAS **EPJC 83 (2023) 438**

PYTHIA Color Reconnection Modes

3 Constraints and Tuning

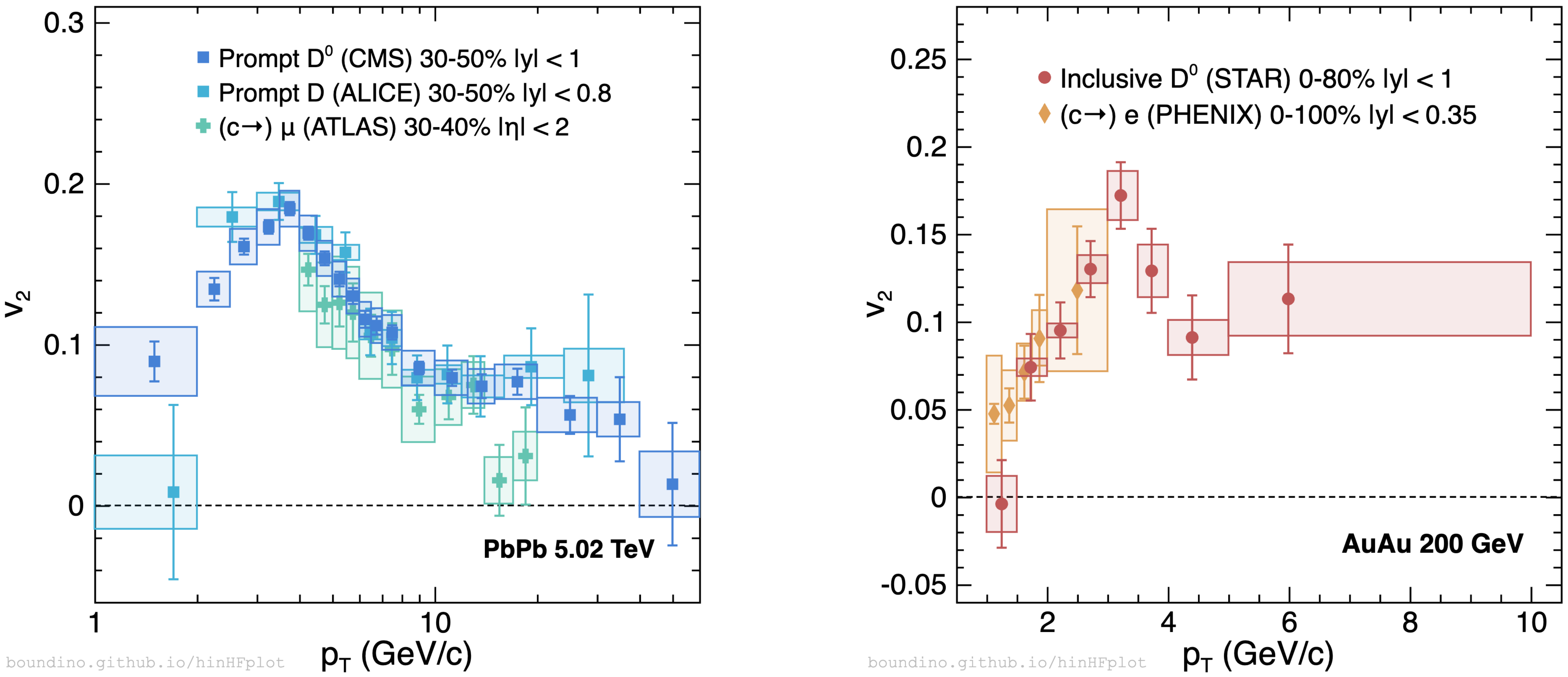
The tuning scheme follows the same procedure as for the Monash 2013 tune [34]. However at a more limited scope, since only CR parameters, and ones strongly correlated with them, are tuned. As a natural consequence of this, the Monash tune was chosen as the baseline. As discussed in section 2.3.4, several options are available for the choice of CR time-dilation method, which naturally results in slightly different preferred parameter sets. Here, we consider the following three modes:

- Mode 0: no time-dilation constraints. m_0 controls the amount of CR (mode 0);
- Mode 2: time dilation using the boost factor obtained from the final-state mass of the dipoles, requiring all dipoles involved in a reconnection to be causally connected (strict);
- Mode 3: time dilation as in Mode 2, but requiring only a single connection to be causally connected (loose).

This allows to investigate the consequences of some of the ambiguities in the implementation of the model. For the purpose of later studies that may want to focus on a single model, we suggest to use mode 2 as the "standard" one for the new CR. The parameters described in this section will therefore correspond to that particular model, with parameters for the others given in appendix A. Note that this section only contains the main physical parameters; for a complete list we again refer to appendix A.

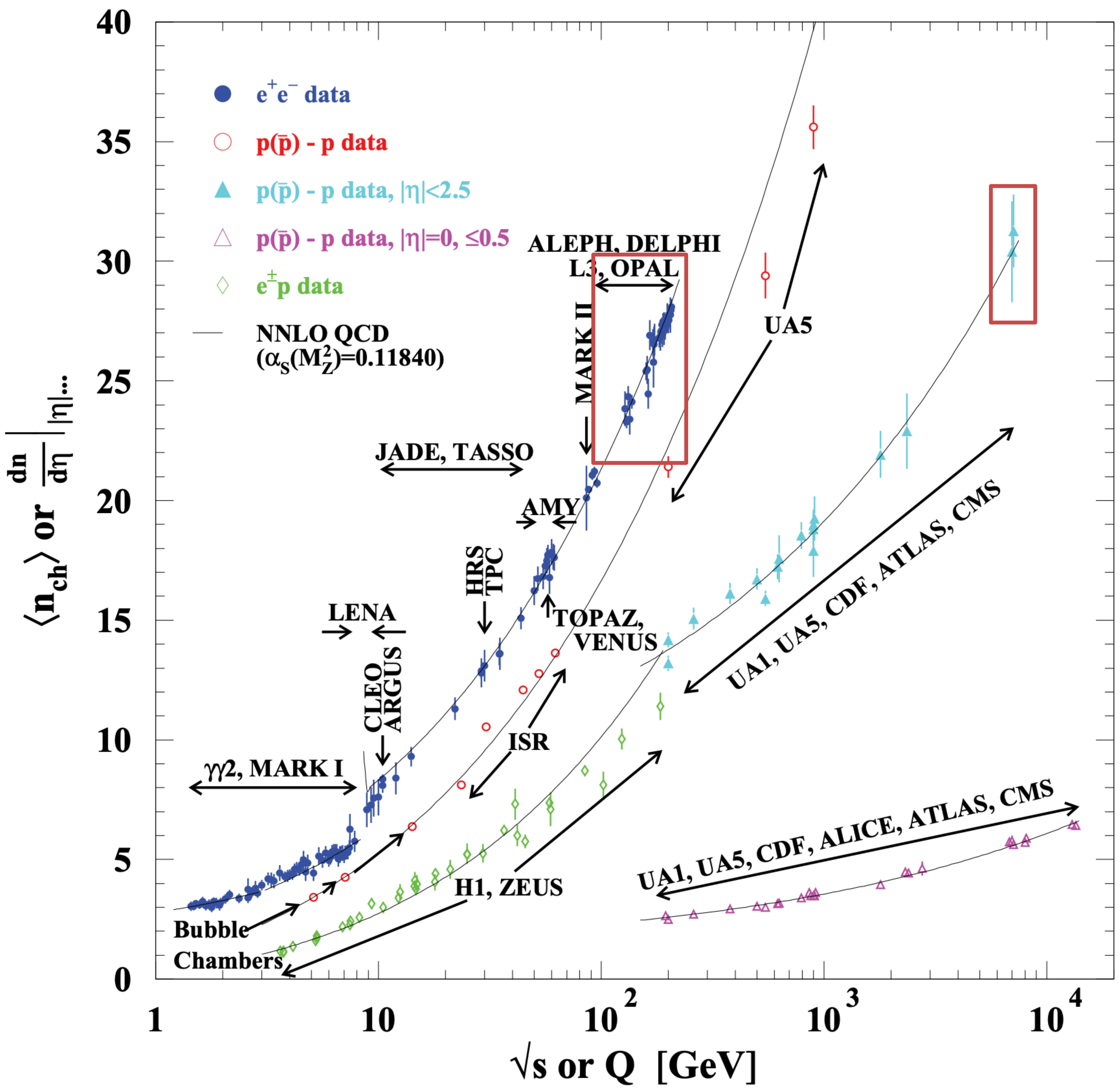
J. *Christiansen, P. Skands* **JHEP 08 (2015) 003**

Collective Flow Experiment Agreements



CMS **PLB 816 (2021) 136253** *ALICE* **PLB 813 (2021) 136054** *ATLAS* **PLB 807 (2020) 135595** *STAR* **PRL 118 (2017) 212301** *PHENIX* **Preliminary**

Multiplicity LEP vs LHC

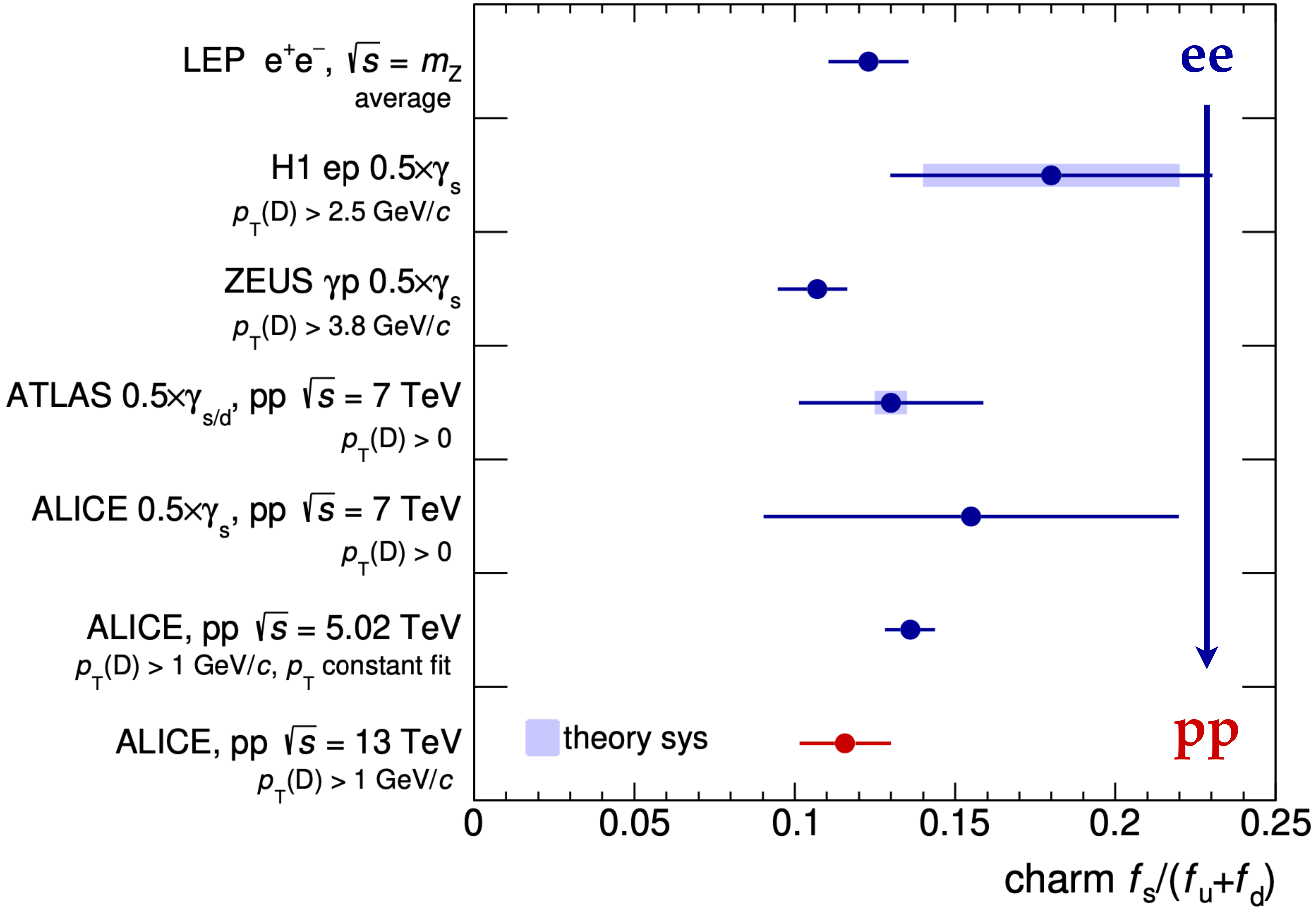


- Multiplicity is not much different between LEP ee and LHC pp

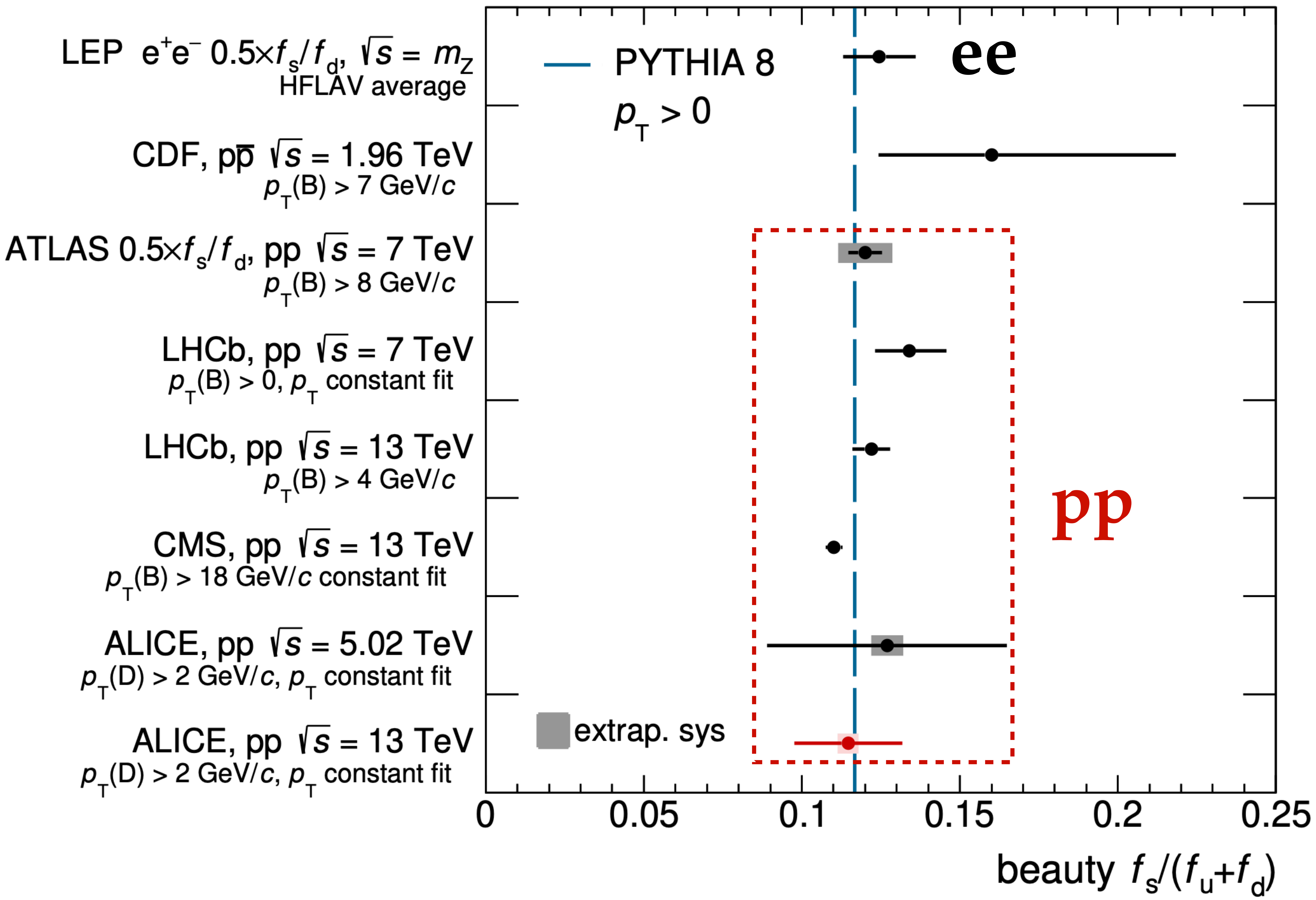
PDG PTEP 2022, 083C01

Strangeness LEP vs LHC

JHEP 12 (2023) 086

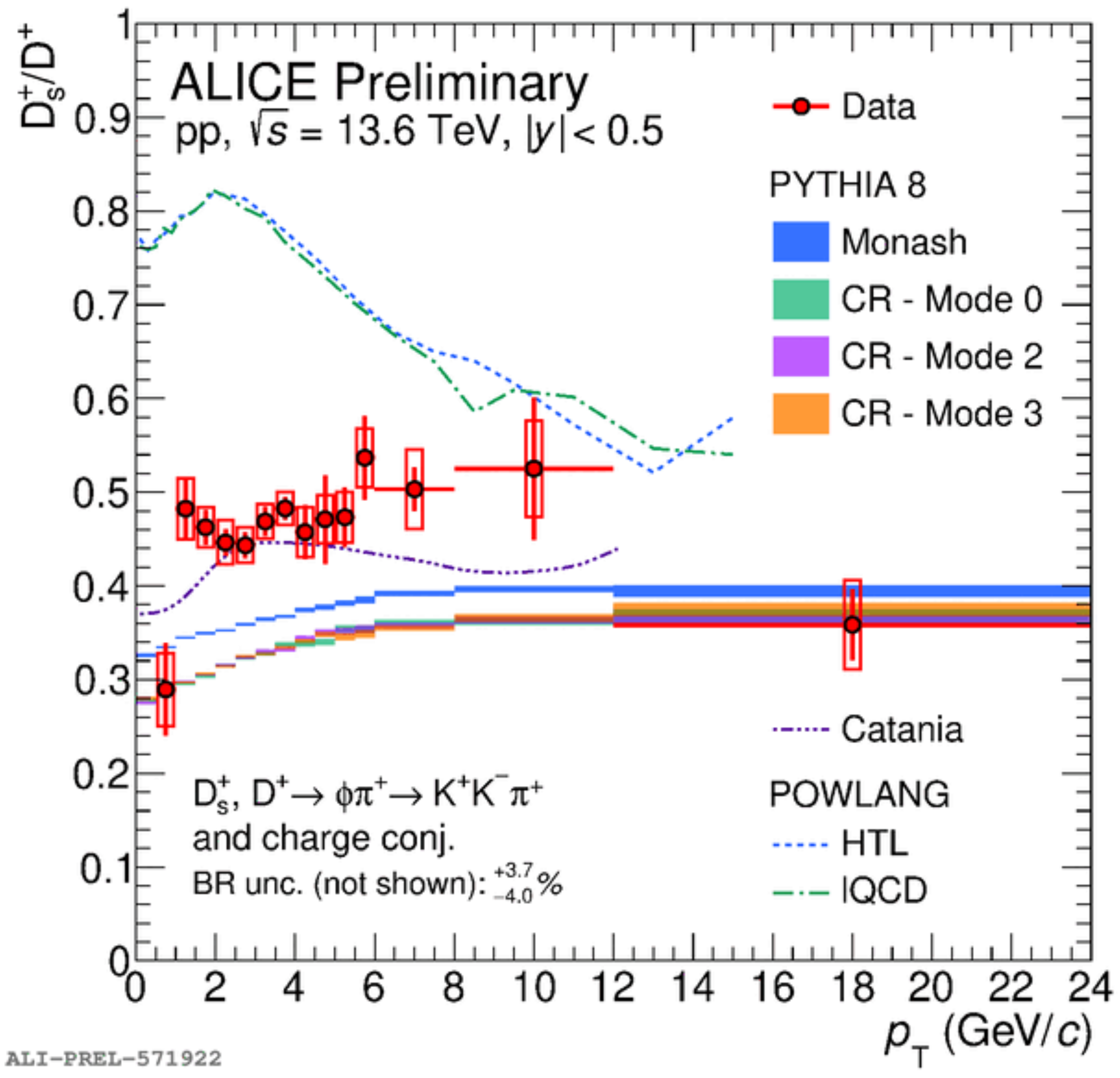


arXiv:2402.16417



- $f_s / (f_u+f_d)$ consistent between ee and pp for both charm and Beauty

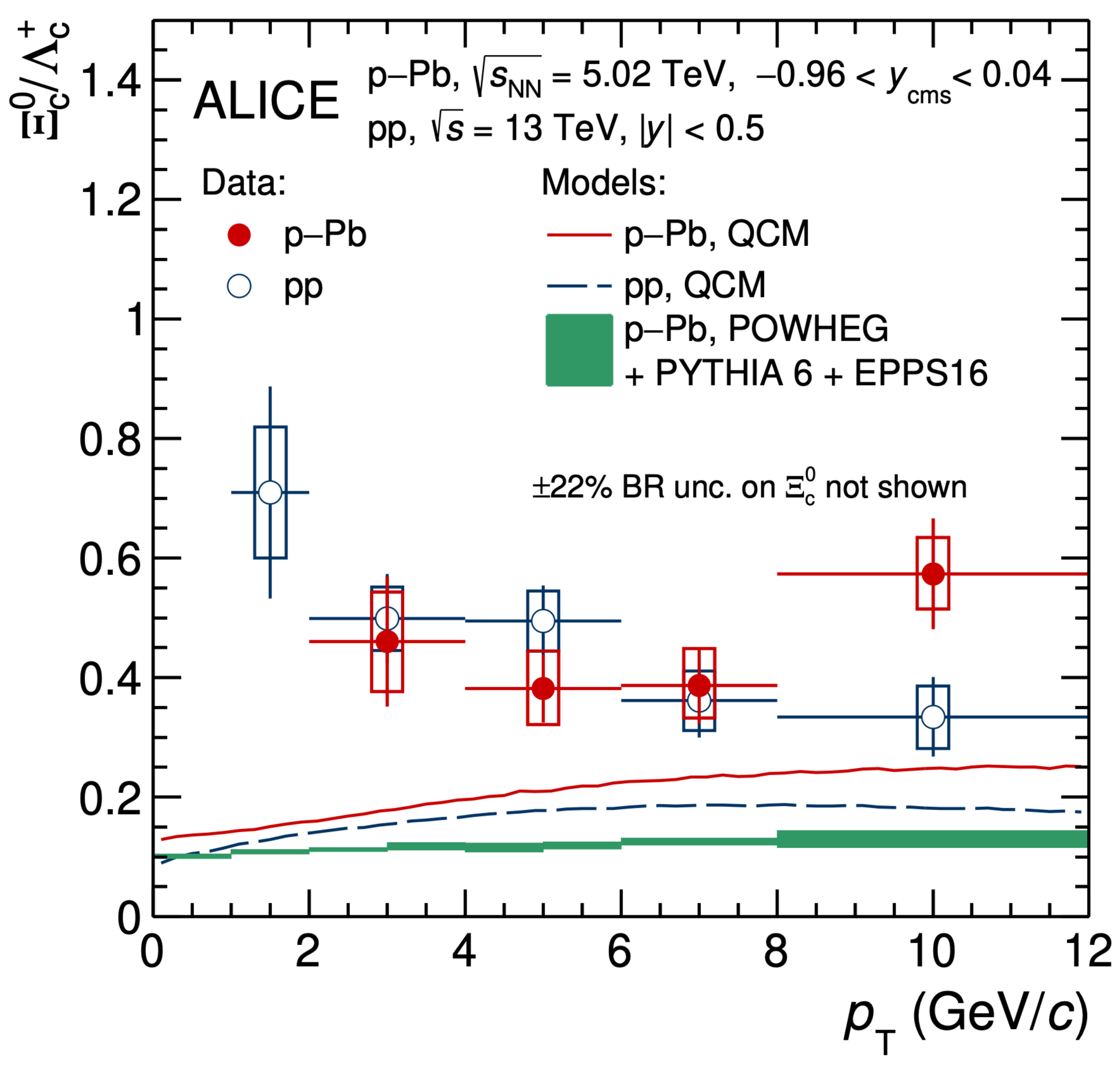
Strangeness Across Collision Systems

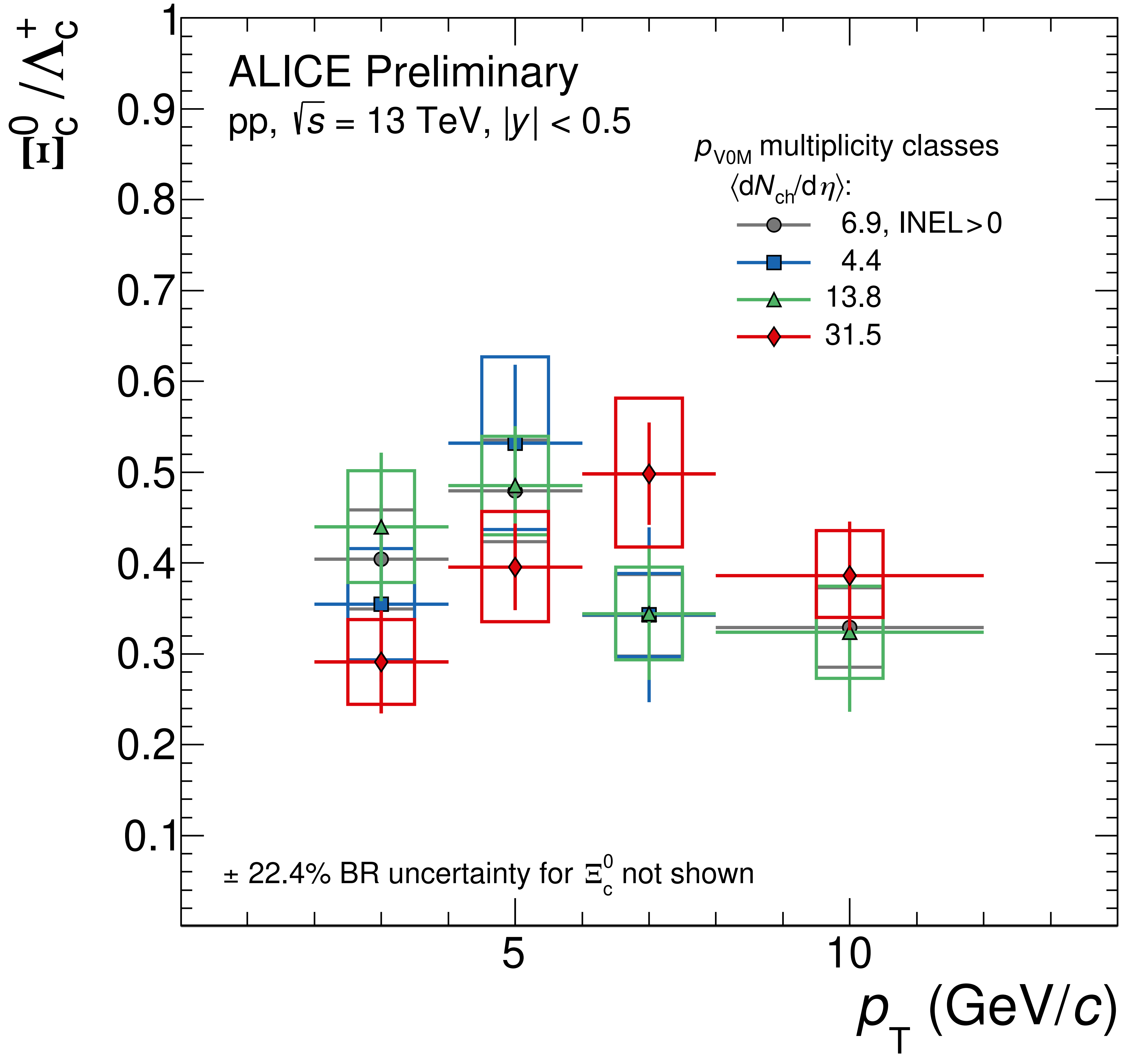


- p_T dependence is not flat when going to very low p_T?
- Why PYTHIA CR can describe D_s/D^0 in pp but not D_s/D^+?
  - Why CR reduces D_s/D^+?

Ξ_c / Λ_c In pPb and Multiplicity Dependence

arXiv:2405.14538





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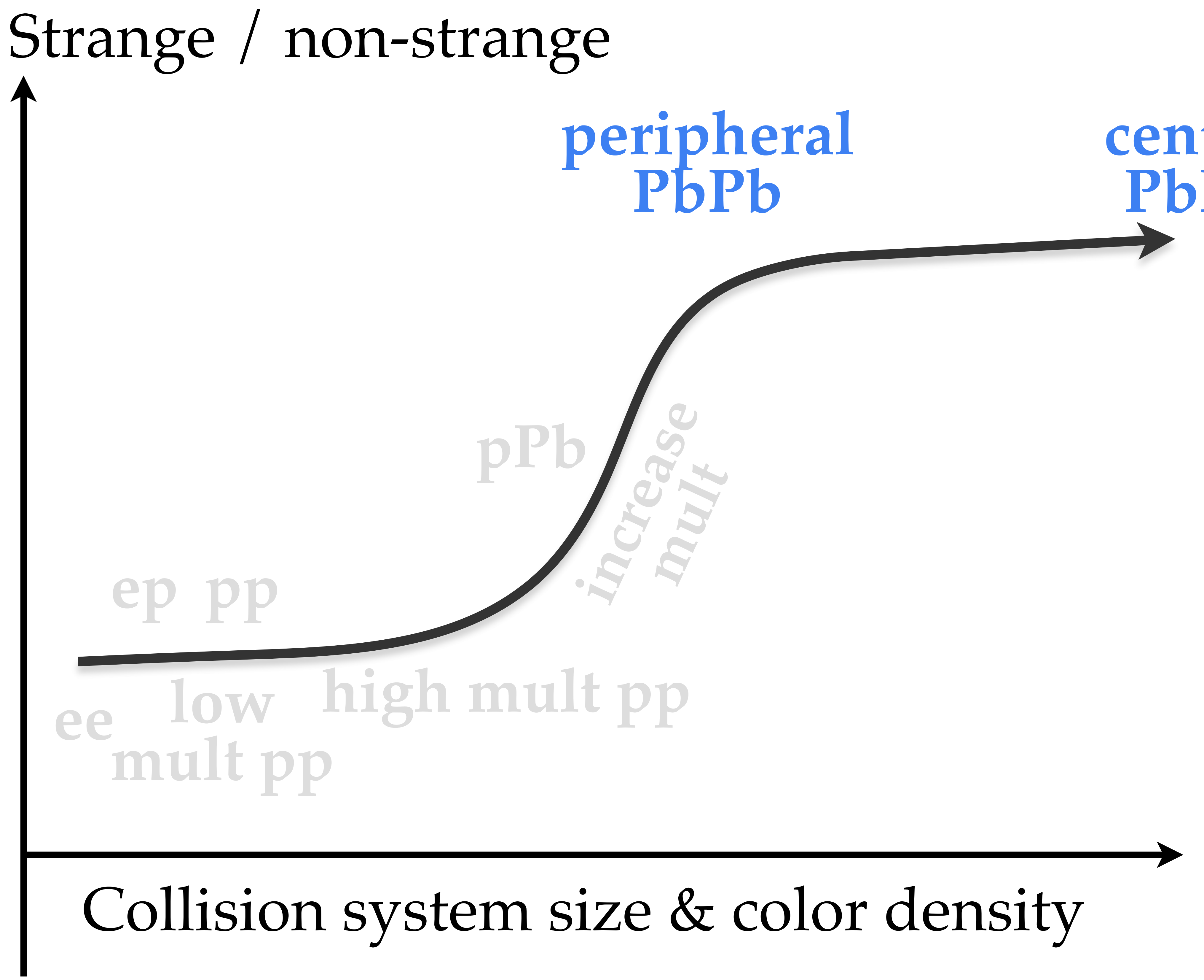
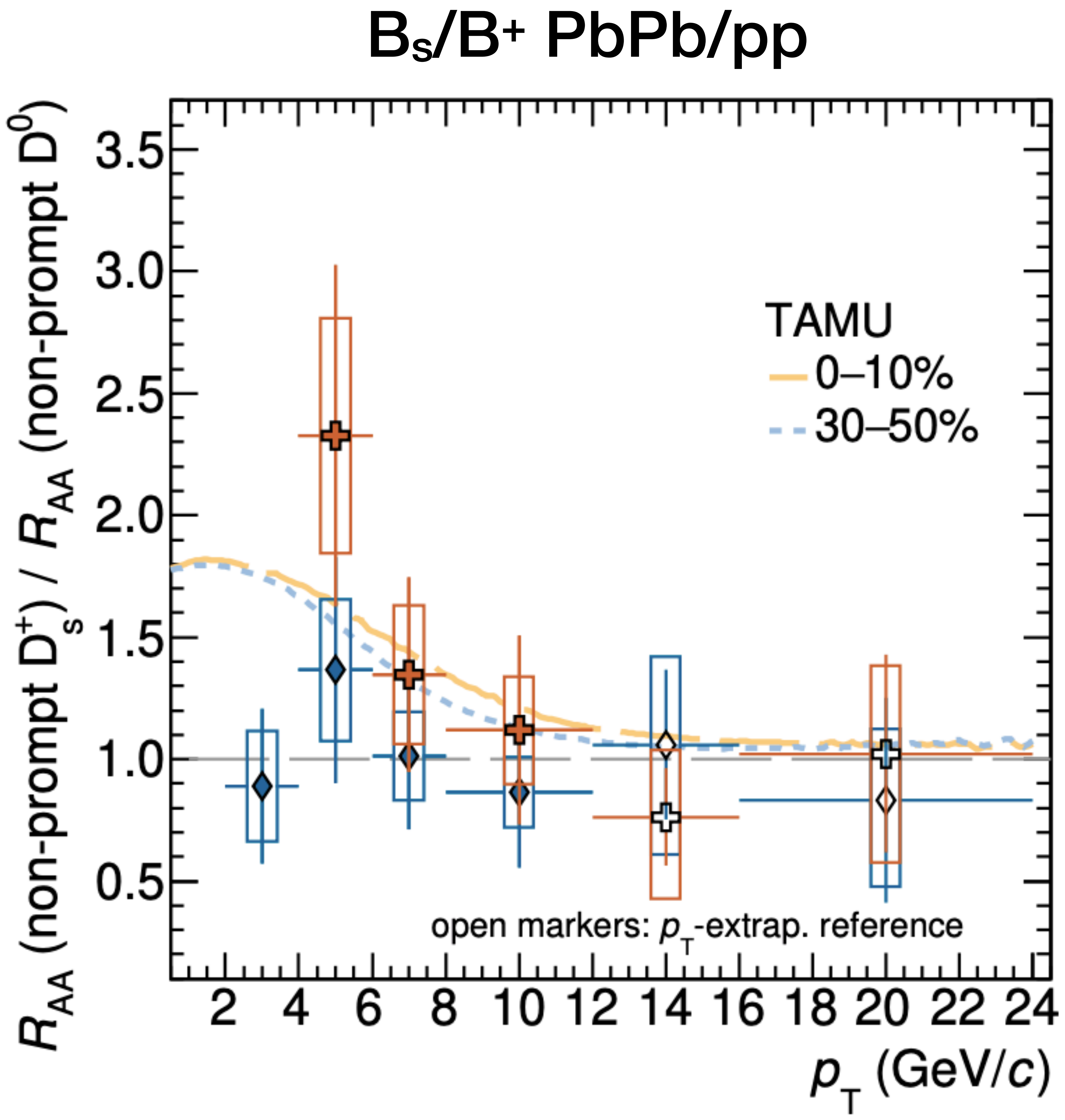
Strangeness Across Collision Systems



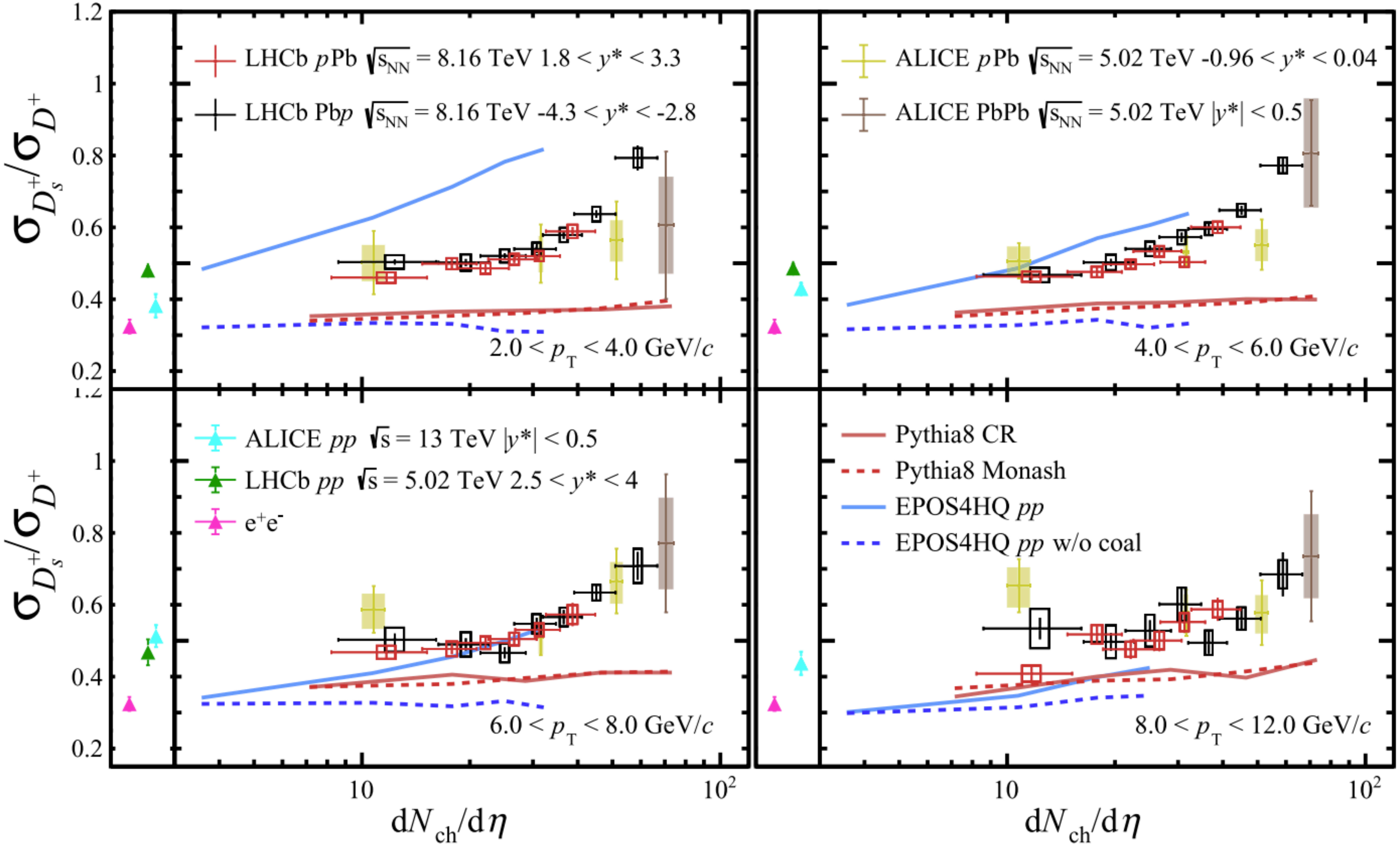


- Model does not predict significant centrality dependence

ALICE **Fabio C.**

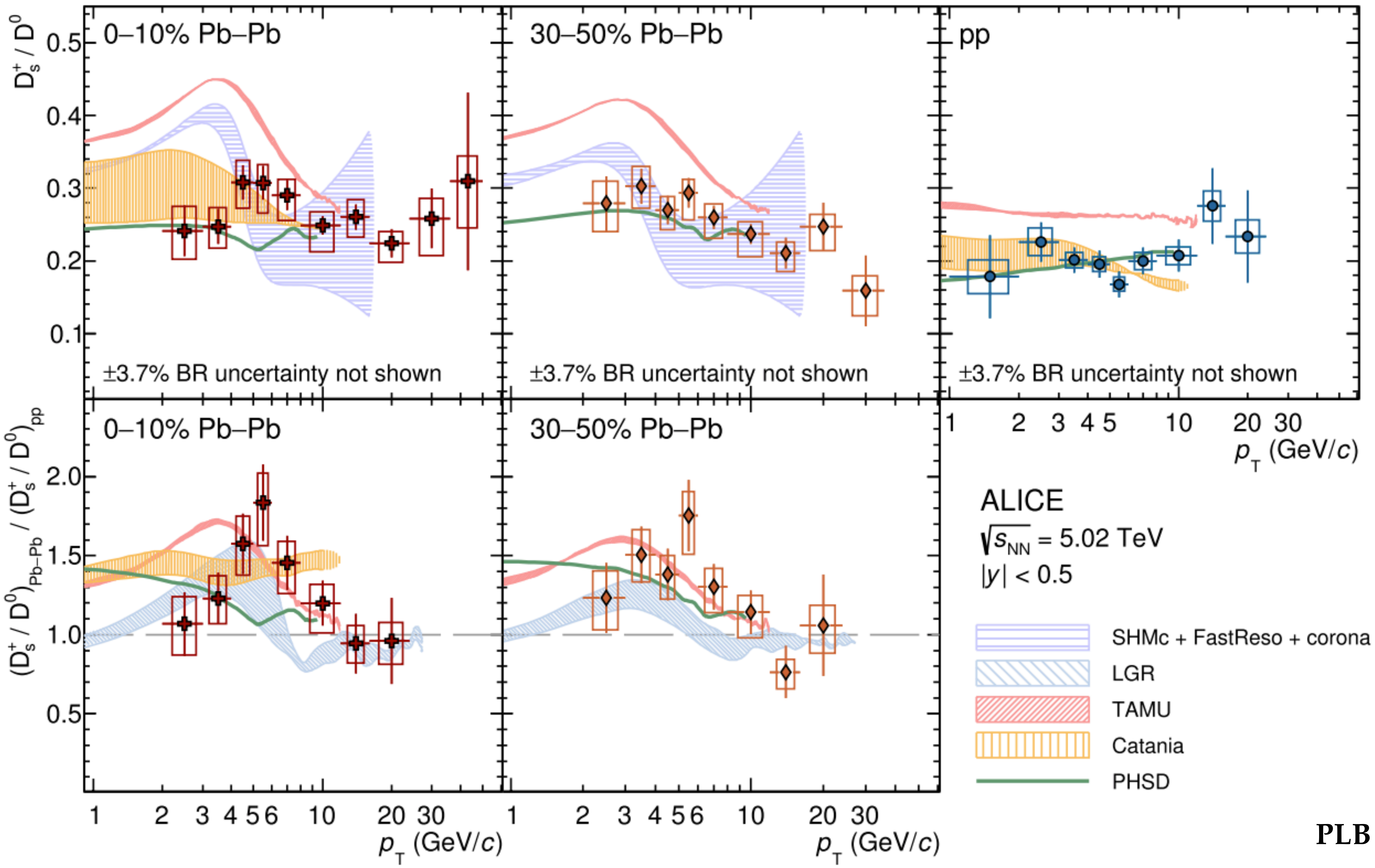
ALICE **PLB 846 (2023) 137561**

Strangeness Across Collision Systems



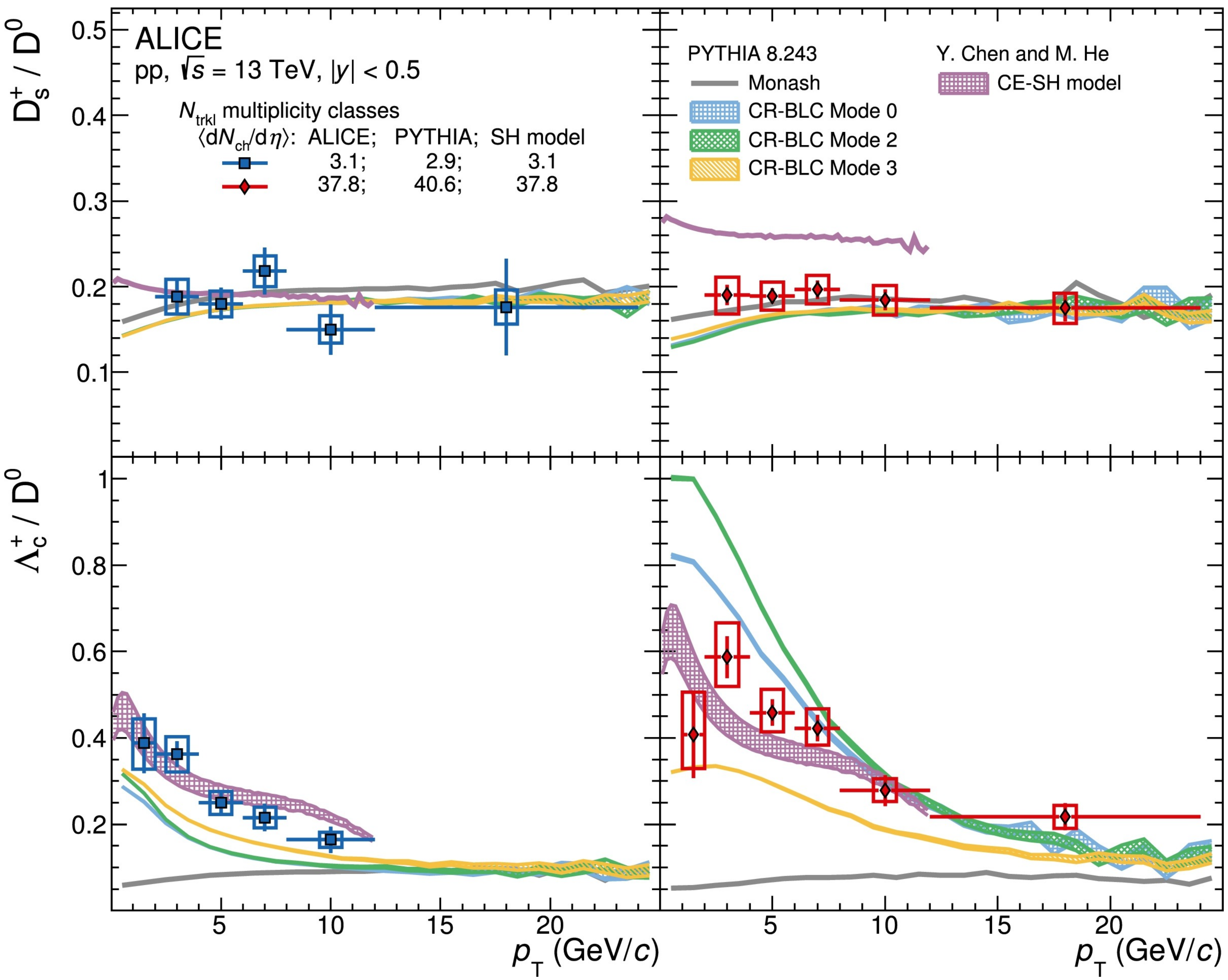
PRD 110 (2024) L031105

Strangeness Across Collision Systems

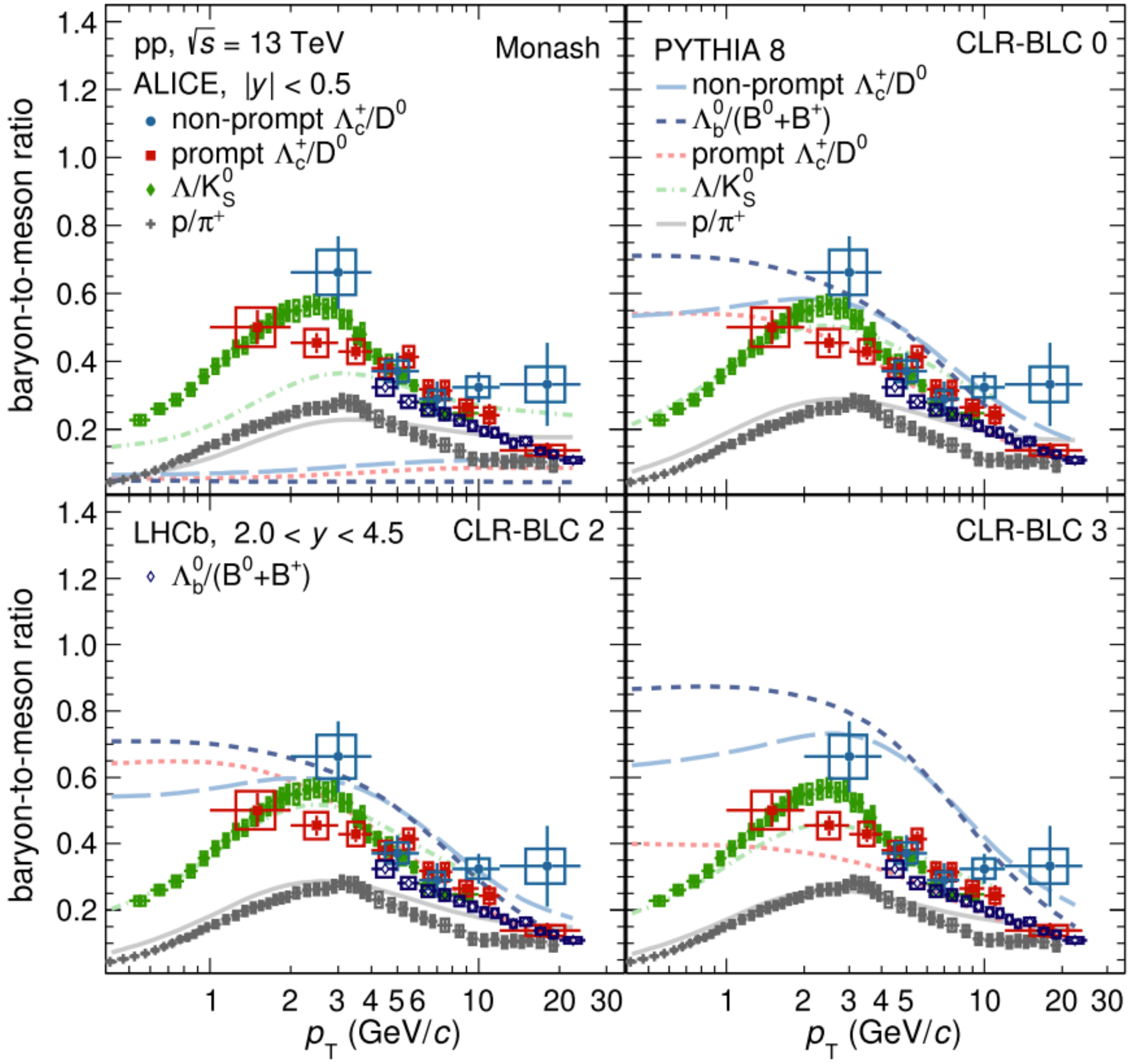


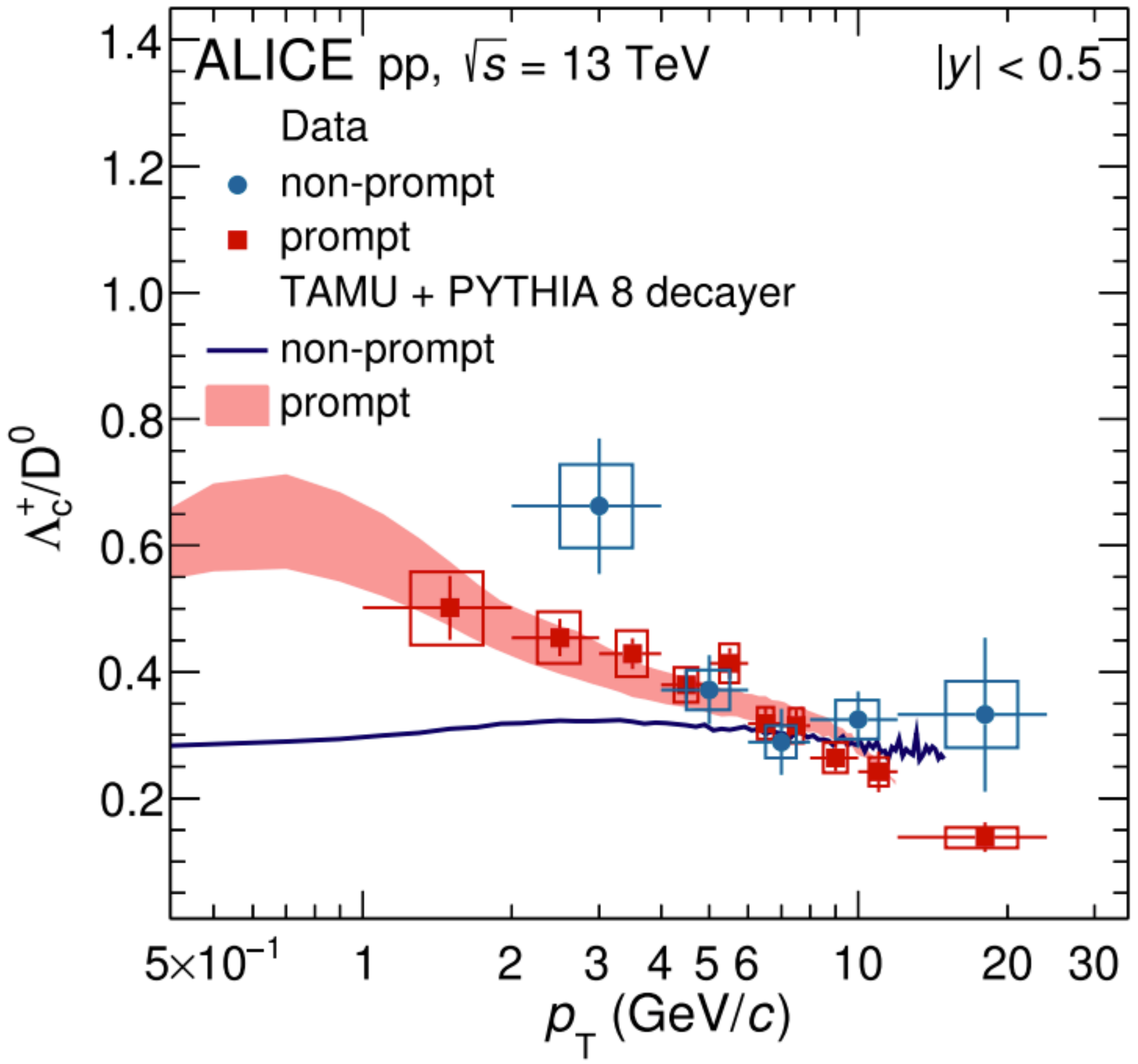
PLB 827 (2022) 136986

Charm Strangeness Across Collision Systems

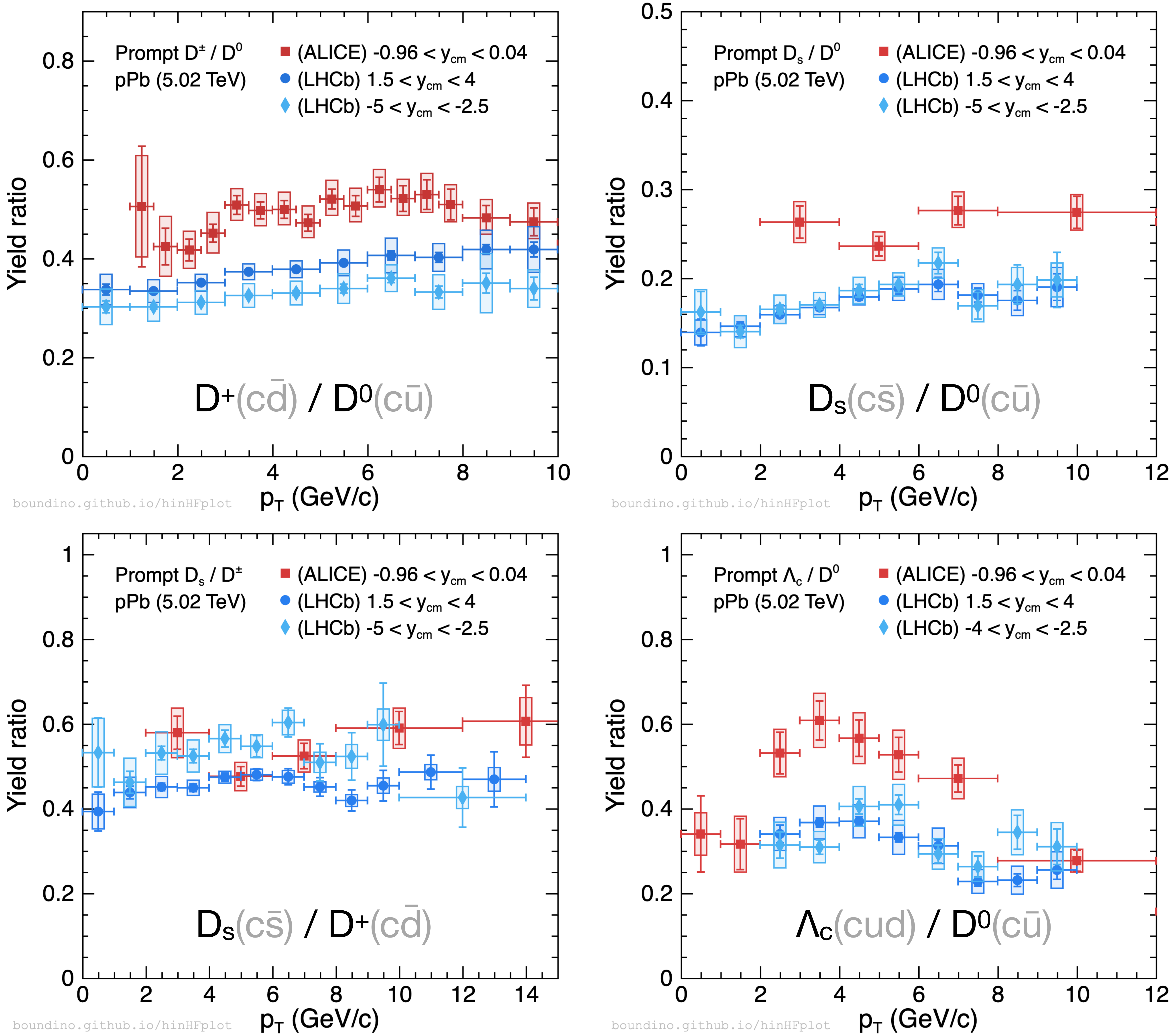


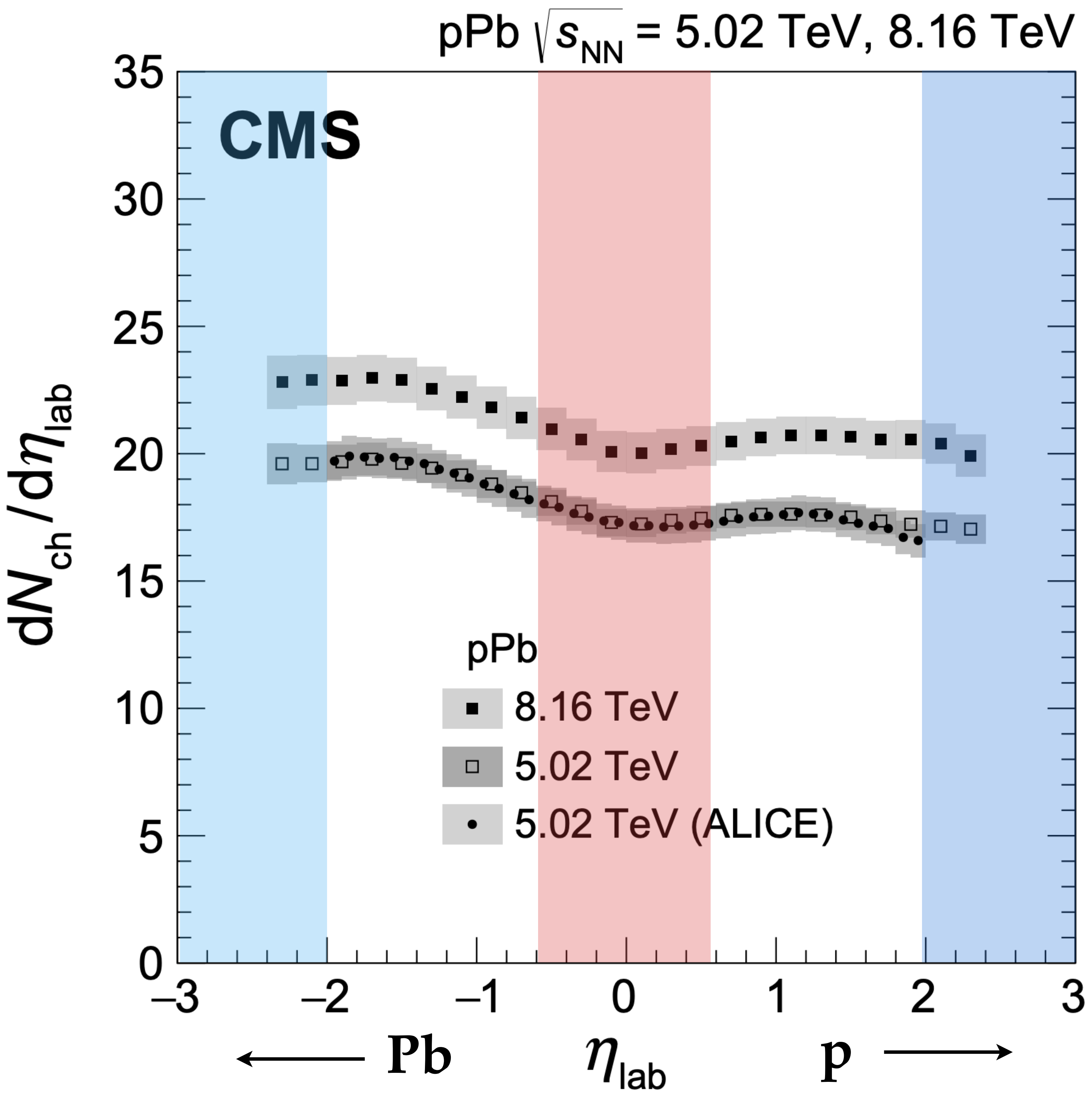
Baryon p_T Redistribution Flavor Dependence





Rapidity Dependence pPb Collisions

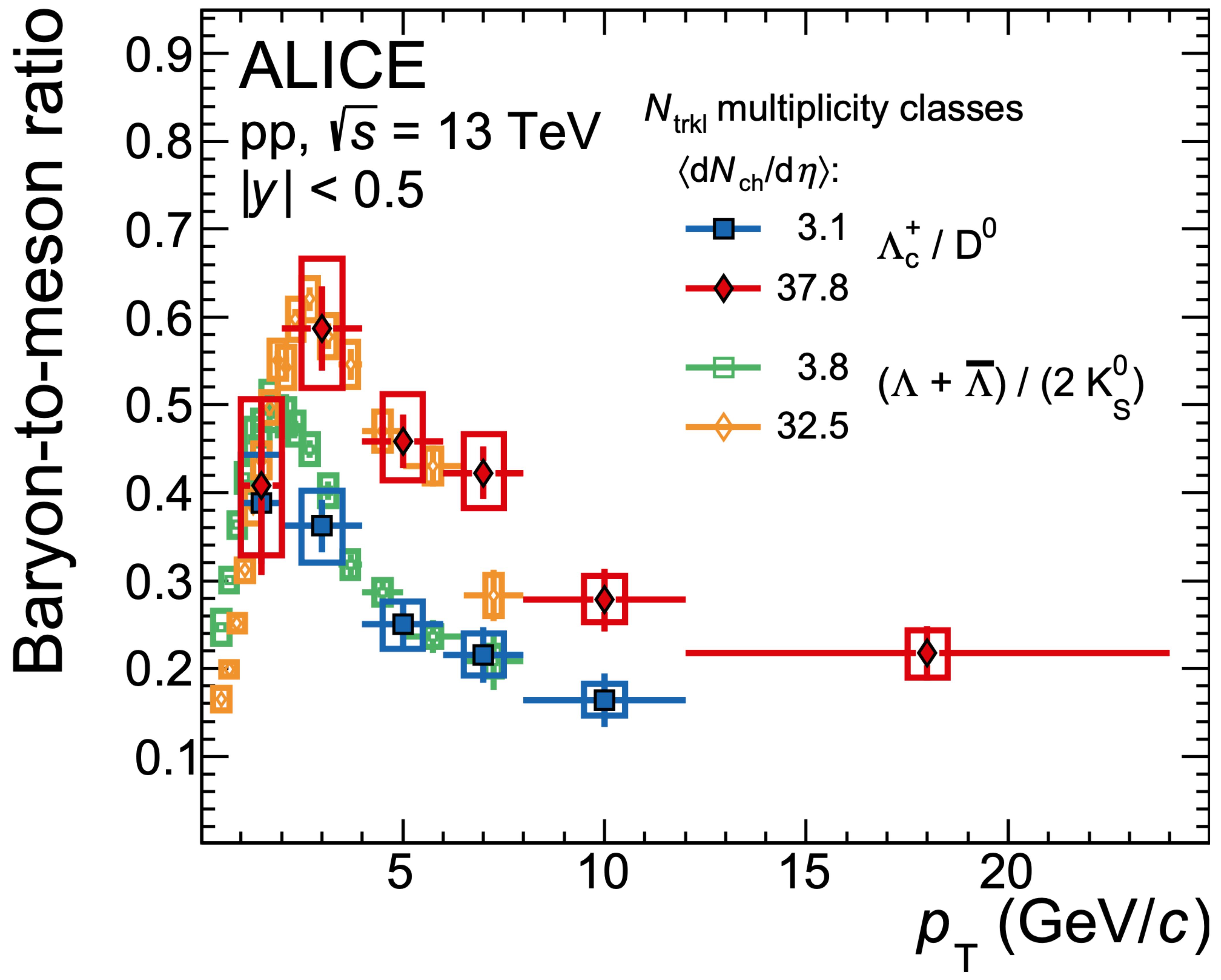




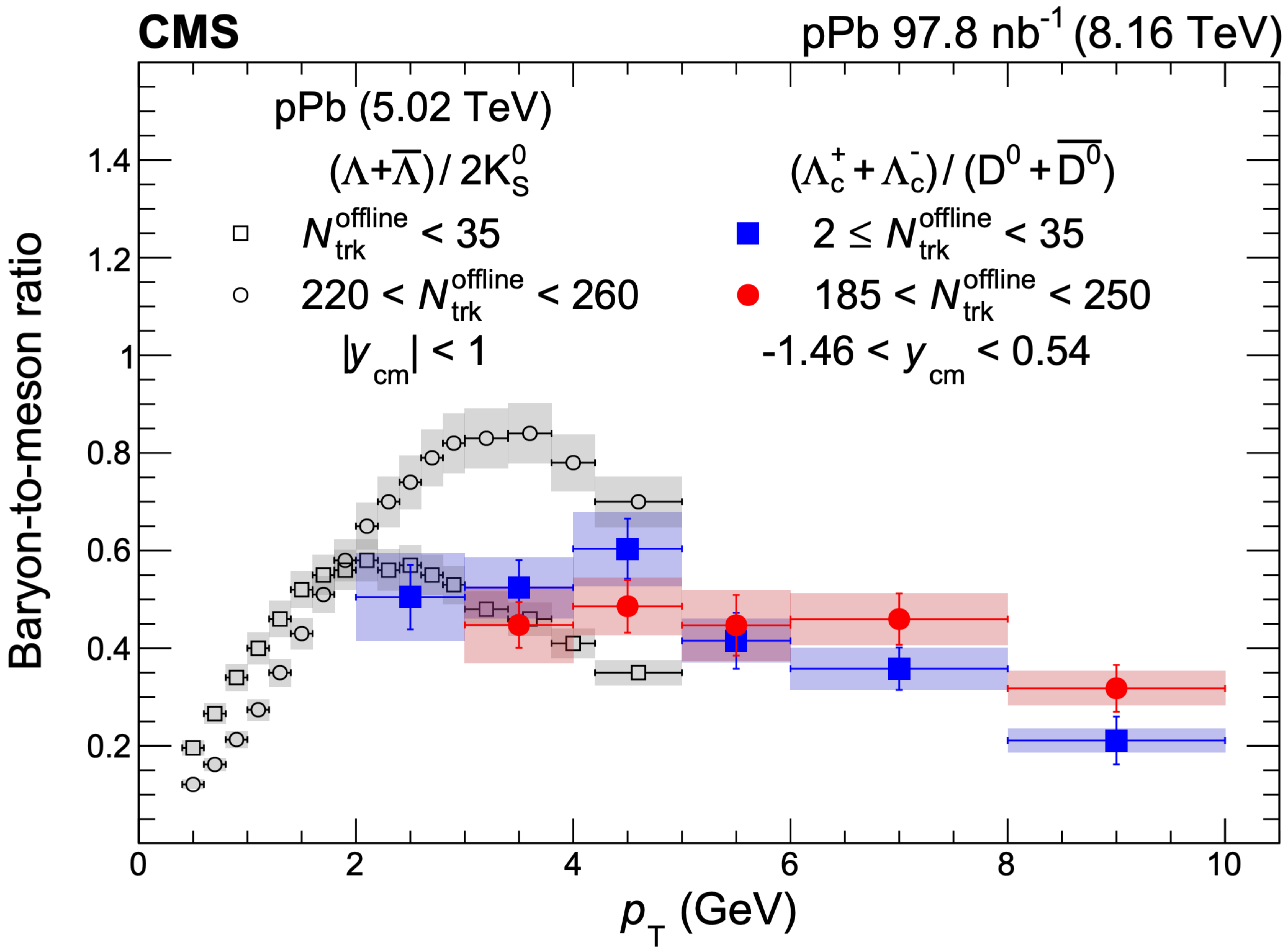
of $R_{p\mathrm{Pb}}$ and R_{FB} for D^+ versus other D mesons. On average, the multiplicity value at backward rapidity is 1.6 times higher than that at forward rapidity in terms of the backward-forward production ratio of charged particles at the same center-of-mass energy from LHCb [80]. As some contributions of D^+ and D^0 mesons come from the decay of the excited charm resonance, the D^{*+} meson [64, 81], it may be possible to further understand this phenomenon by investigating the production of D^{*+} mesons in high multiplicity pPb events.

Baryon p_T Redistribution Flavor Dependence

pp

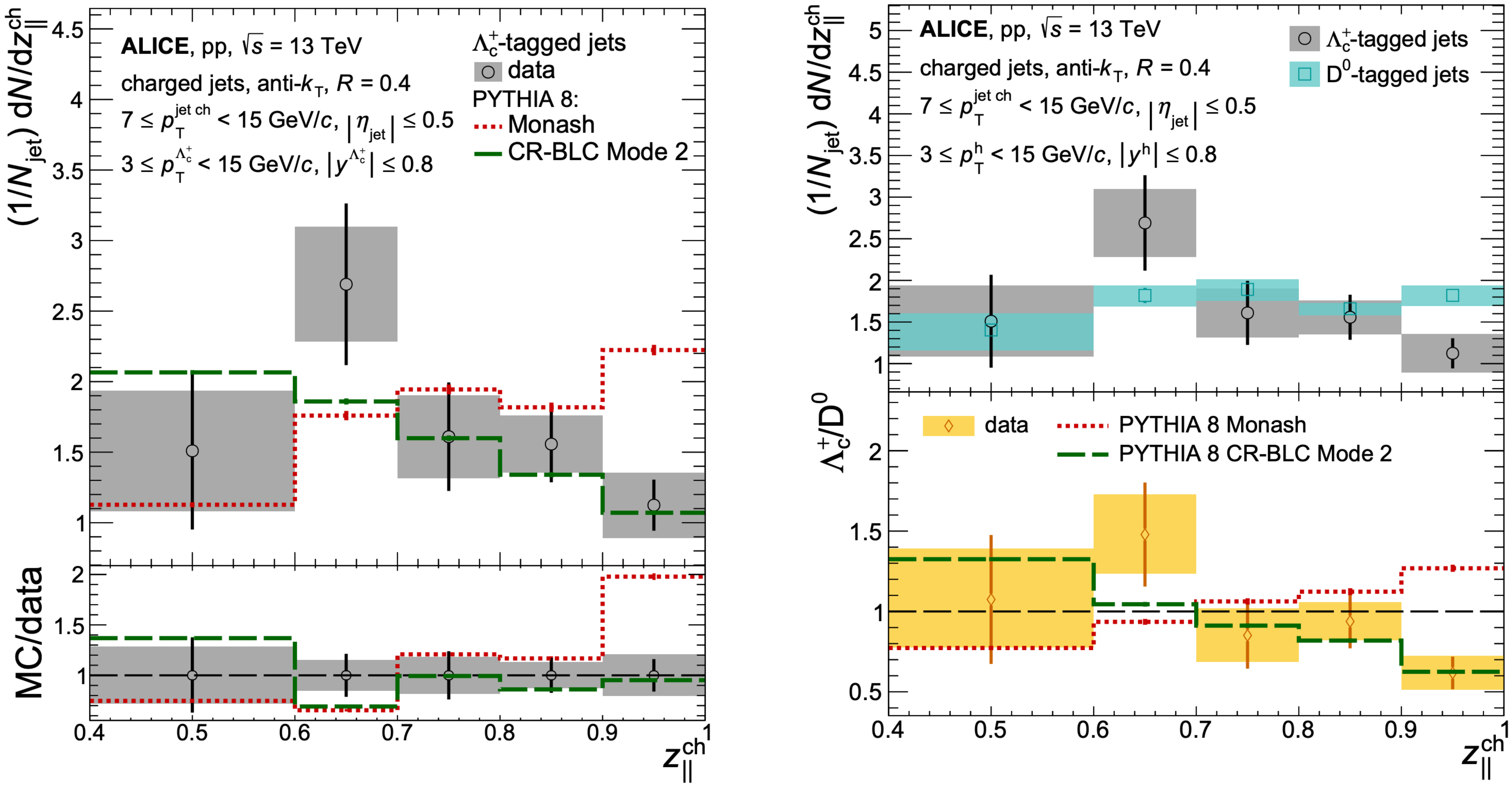


pPb

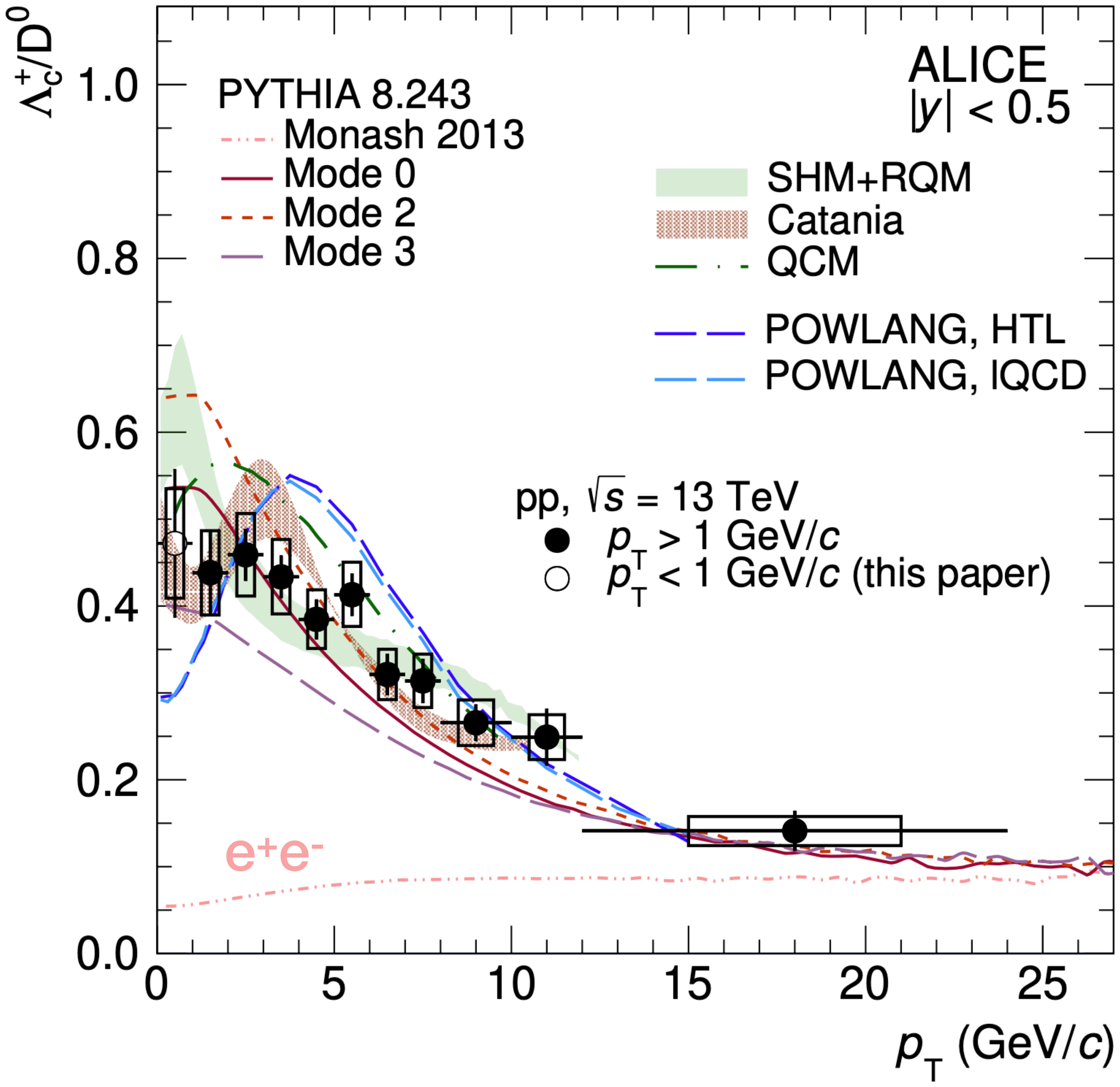


- Charm and strange are consistent in pp
- Significant difference at higher multiplicity in pPb

Jet Fragmentation Fraction New Info?



Charm Baryon Λ_c Hadronization in pp



JHEP 12 (2023) 086

- Significant larger Λ_c / D^0 observed in pp
  - Stronger enhancement at low p_T compared to e^+e^-
- Theoretical efforts to describe it
  - More excited baryons
  - Color reconnection
  - Coalescence also in pp

Luminosity Projection Conservative

Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA}\rangle$ ($cm^{-2}s^{-1}$)	3.0×10^{32}	9.5×10^{29}	2.0×10^{29}	1.9×10^{29}	5.0×10^{28}	2.3×10^{28}	1.6×10^{28}	3.3×10^{27}
$\mathscr{L}_{AA}^{month}$ (nb^{-1})	5.1×10^{5}	1.6×10^{3}	3.4×10^{2}	3.1×10^{2}	8.4×10^{1}	3.9×10^{1}	2.6×10^{1}	5.6
$\mathscr{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
	at $R = 0.5$ cm							
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	1.8×10^{14}	1.0×10^{14}	8.6×10^{13}	7.9×10^{13}	6.0×10^{13}	3.3×10^{13}	4.1×10^{13}	1.9×10^{13}
TID (Rad)	5.8×10^{6}	3.2×10^{6}	2.8×10^{6}	2.5×10^{6}	1.9×10^{6}	1.1×10^{6}	1.3×10^{6}	6.1×10^{5}
	at $R = 100$ cm							
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	4.9×10^{9}	2.5×10^{9}	2.1×10^{9}	2.0×10^{9}	1.5×10^{9}	8.3×10^{8}	1.0×10^{9}	4.7×10^{8}
TID (Rad)	1.4×10^{2}	8.0×10^{1}	6.9×10^{1}	6.3×10^{1}	4.8×10^{1}	2.7×10^{1}	3.3×10^{1}	1.5×10^{1}

Table 1: Projected LHC performance: For various collision systems, we list the peak luminosity L_{AA}, the average luminosity $\langle L_{AA}\rangle$, the luminosity integrated per month of operation $\mathscr{L}_{AA}^{month}$, also rescaled to the nucleon–nucleon luminosity $\mathscr{L}_{NN}^{month}$ (multiplying by A^2). Furthermore, we list the maximum interaction rate R_{max}, the minimum bias (MB) charged particle pseudorapidity density $dN/d\eta$, and the interaction probability μ per bunch crossing. For the radii 0.5 cm and 1 m, we also list the particle fluence, the non-ionising energy loss, and the total ionising dose per operational month (assuming a running efficiency of 65%).