Open Heavy Flavor: Experiment

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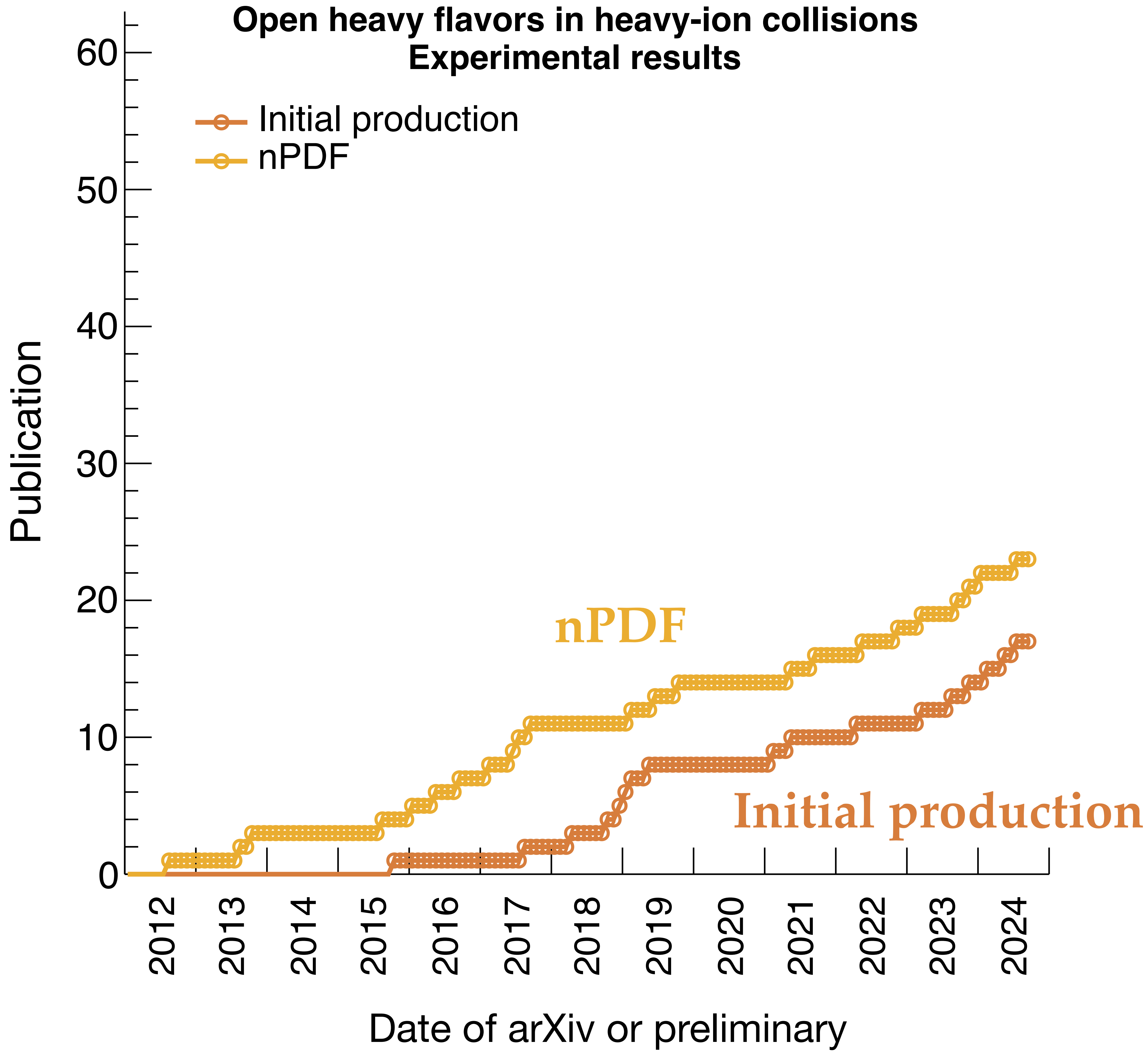
Why Open Heavy Flavors and Fun Stats

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

- Produced early $\tau \sim 1/m_Q$
  - Unique access to high temperature stage

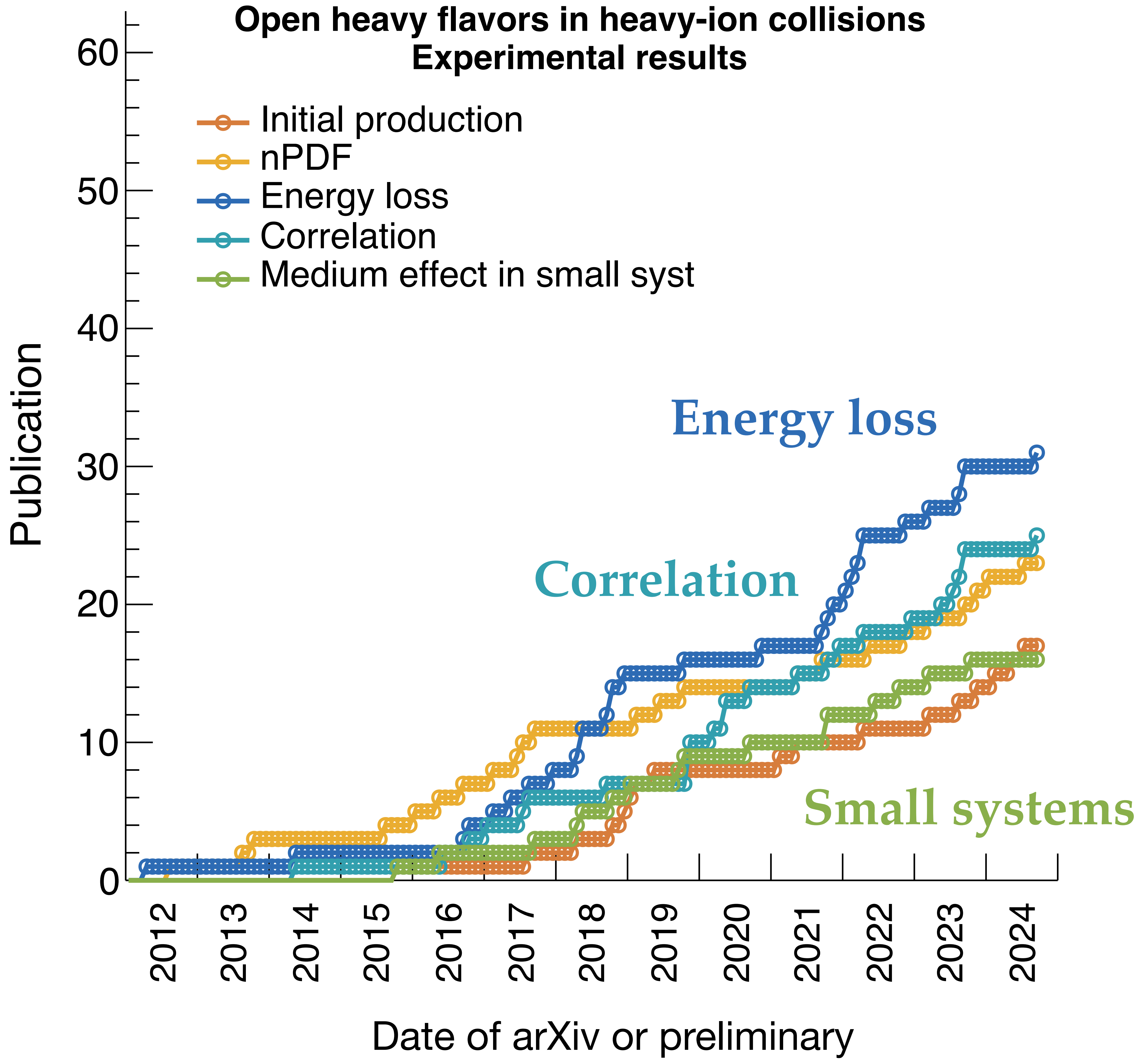
- **Hard scattering quark production** can be calculated with perturbative QCD even at zero p_T $m_Q \gg \Lambda_{QCD}$
  - Different length scale structure by varying p_T
  - No significant deviation found in data so far
    Theoretical uncert » experimental uncert now
  - Good probe to constrain gluon nuclear PDF with easy control of production and wide $(x, 1/Q^2)$



Why Open Heavy Flavors and Fun Stats

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

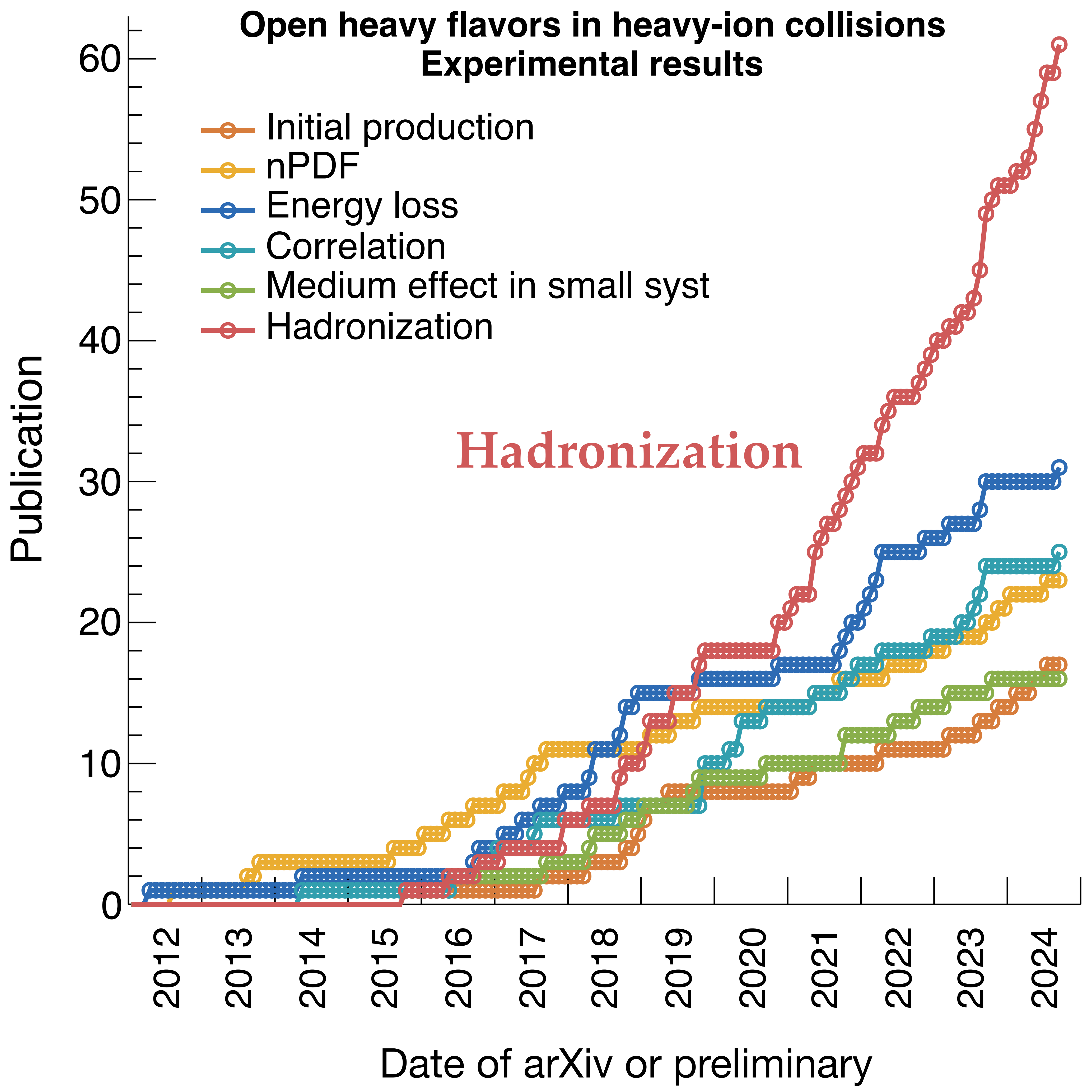
- Small momentum transfer with medium $\mathbf{m_Q \gg T_{QGP}}$
  - Brownian motion diffusion → Can trace transport individual partons with Langevin* framework
  - If momentum exchange sufficiently → **collectivity**
- Different **energy loss** behaviors $\mathbf{m_Q \gg m_q}$



*or Boltzmann framework

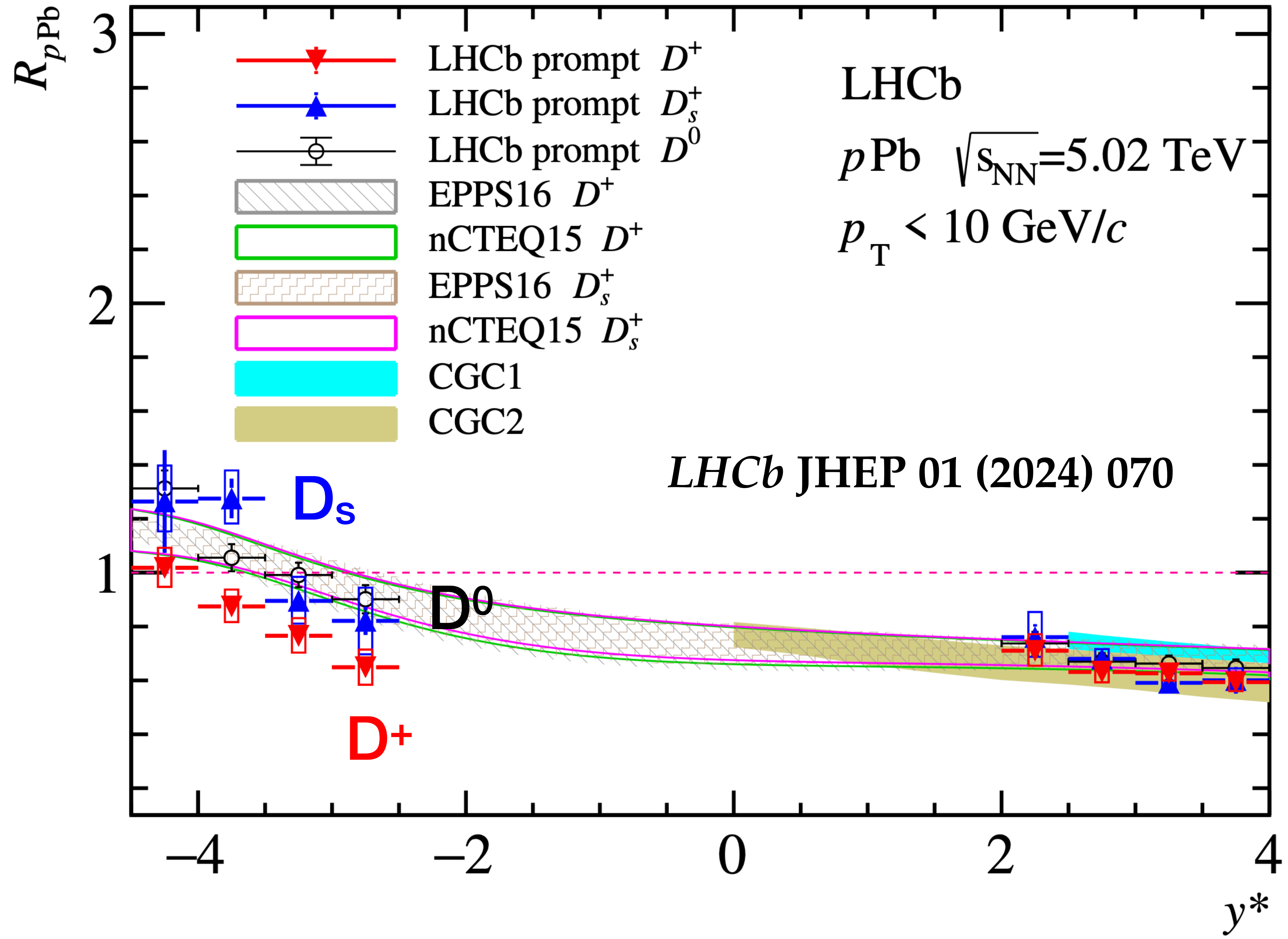
Why Open Heavy Flavors and Fun Stats

Big monster recently…



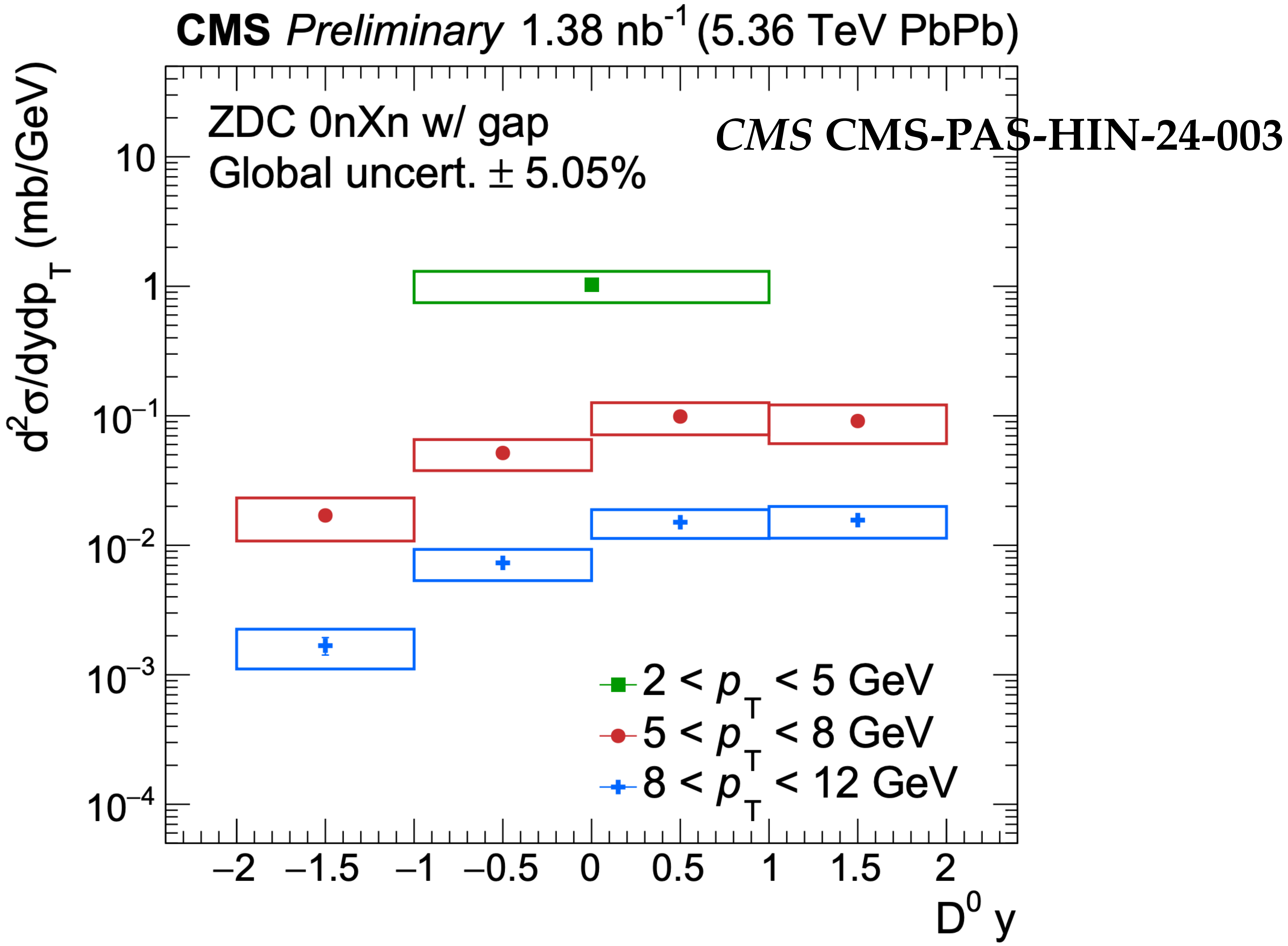
Gluon nPDF Constrained by Heavy Flavors

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

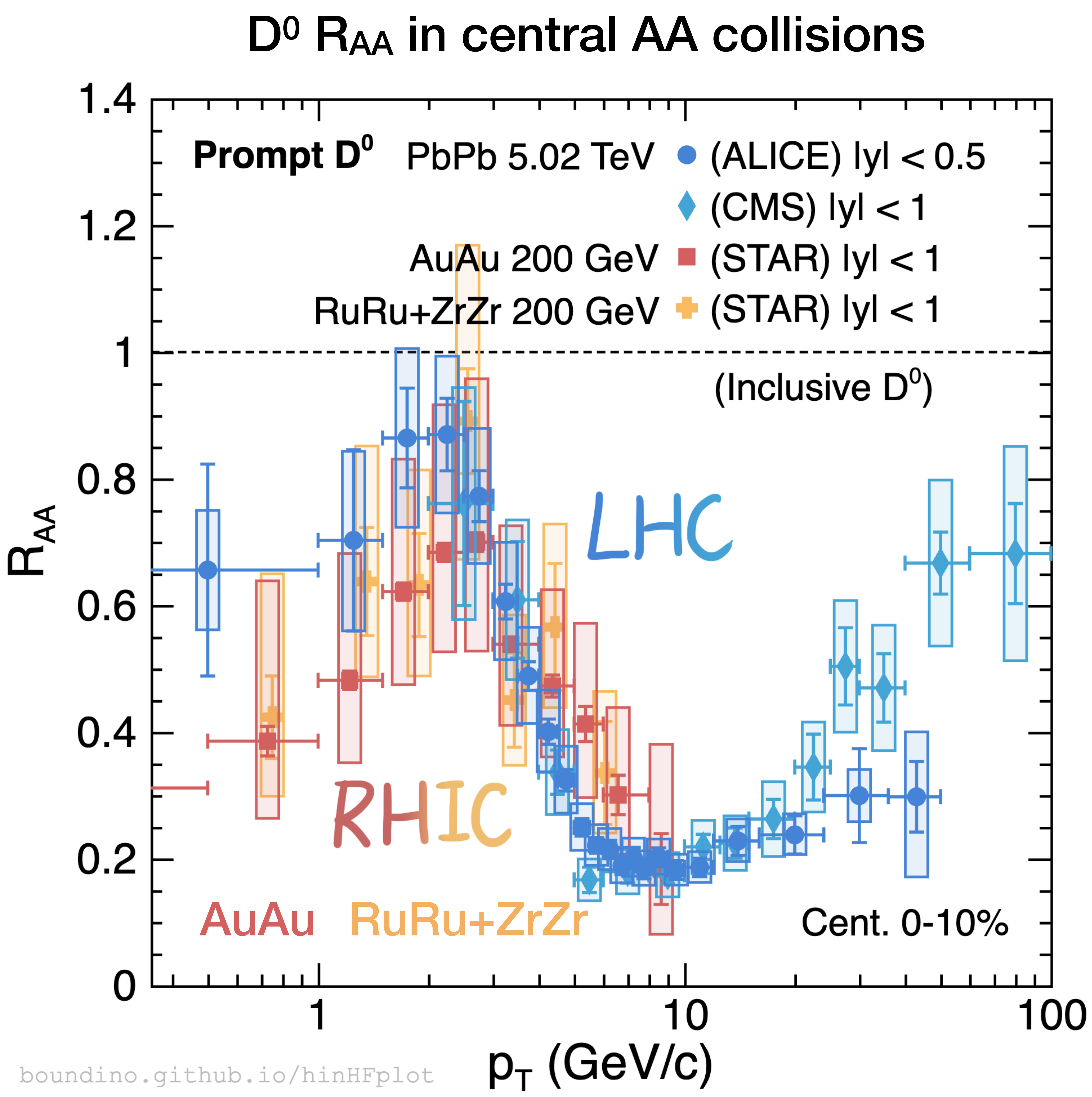


- Very clean final states and potential for large y
  → Open up a new collision system at LHC

LHCb Yiheng L.

CMS Christopher M.

Nuclear Modification R_{AA} D^0 Mesons



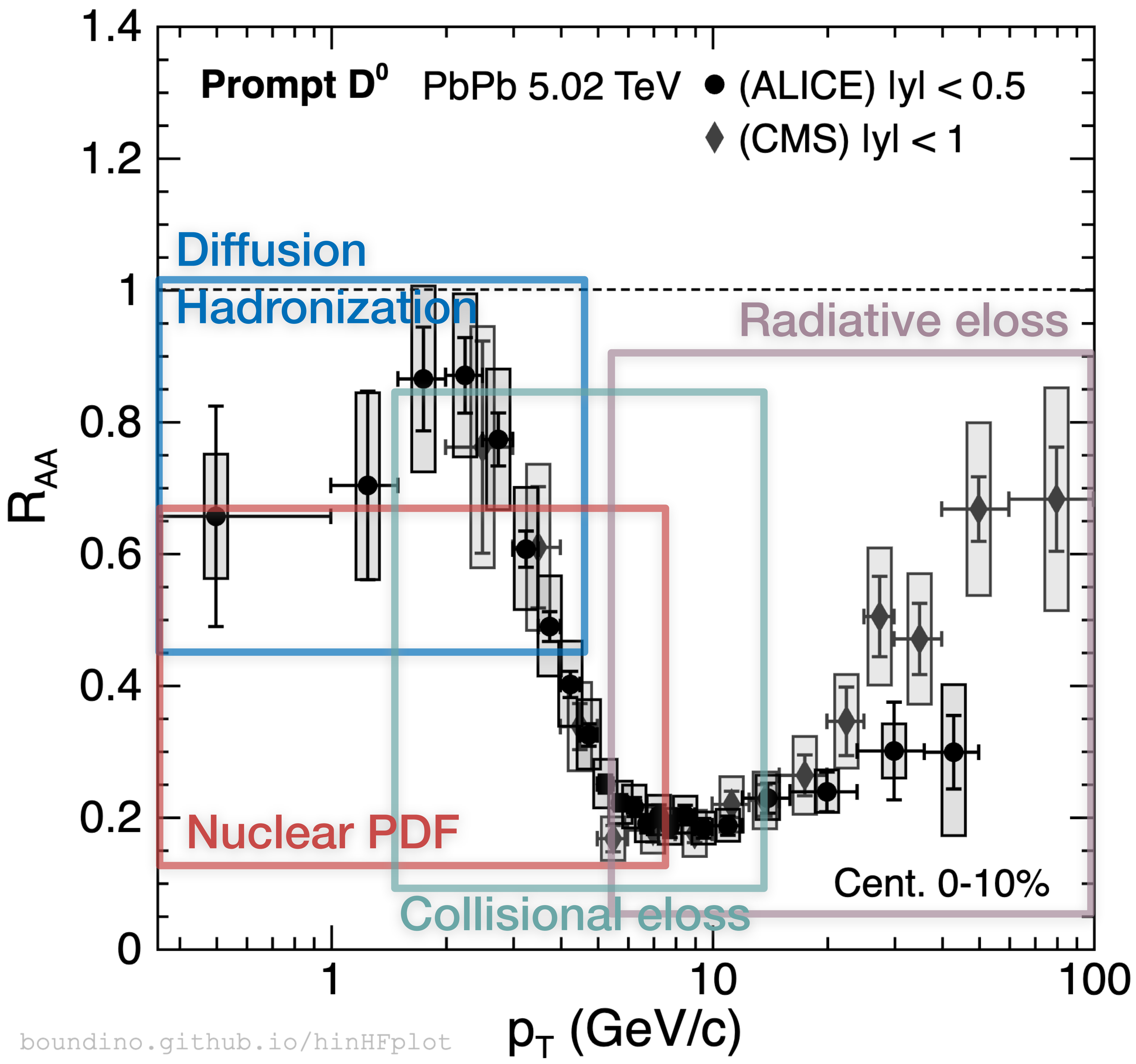
- Prompt D^0 suppression in wide kinematics
  pQCD picture:
  - Quenching in charm sector: medium induced radiative energy loss high p_T
  - Collisional energy loss low p_T plays a more important role for heavy quarks

- 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 sPHENIX

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

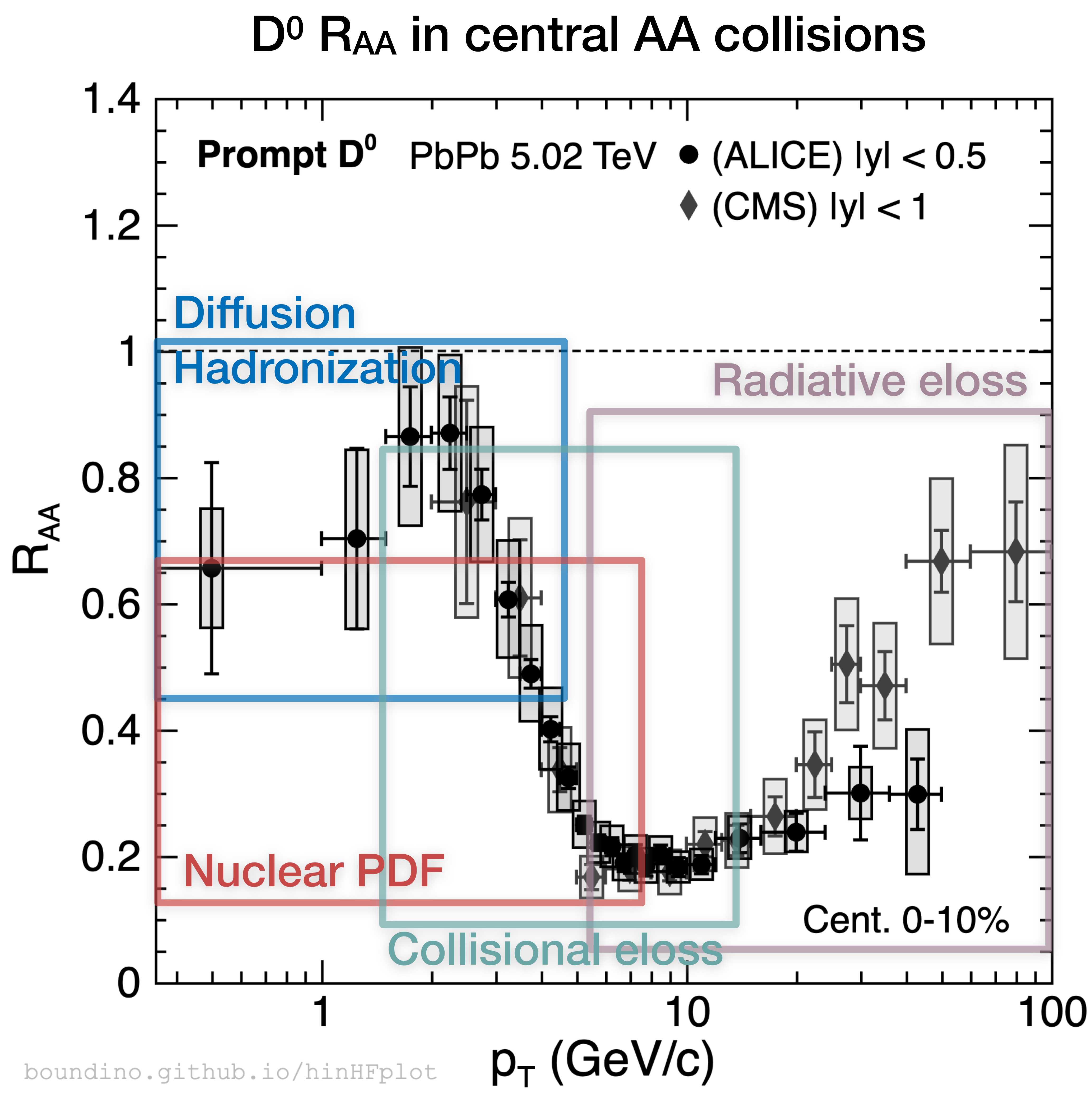


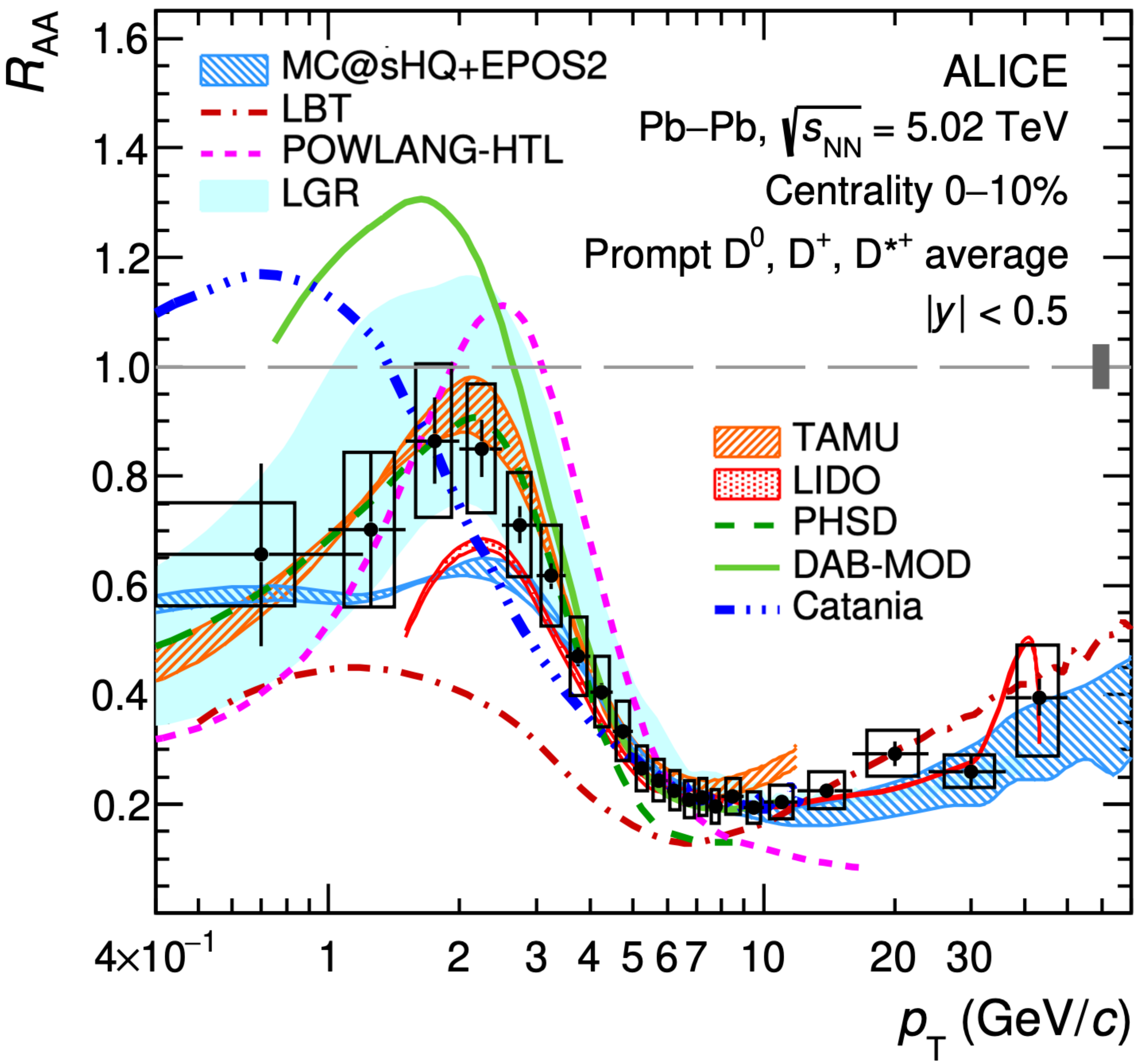
If I would build a toy model…

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

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

D^0 R_{AA} Understanding the Shape





- Transport models are fairly successful

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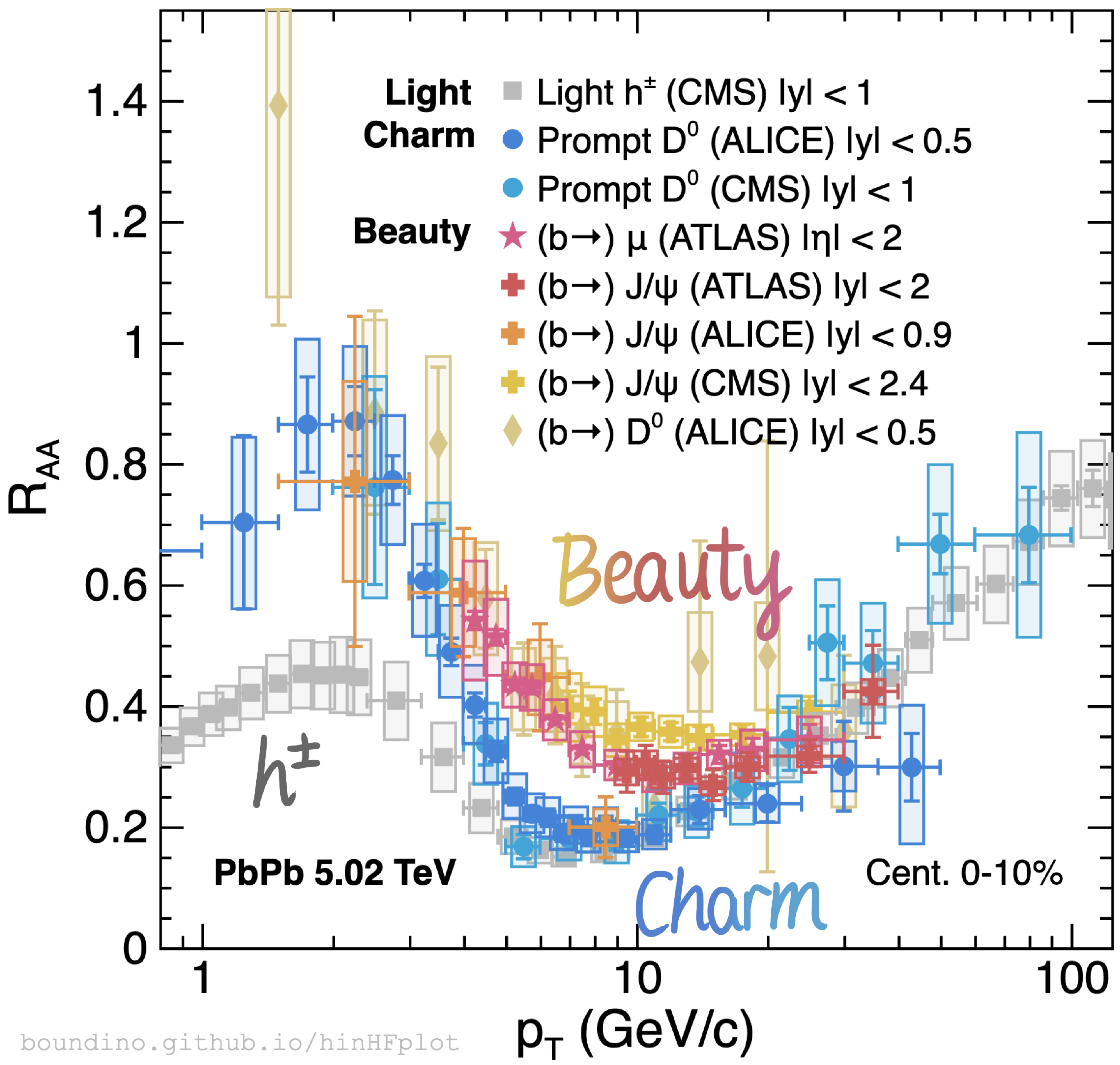
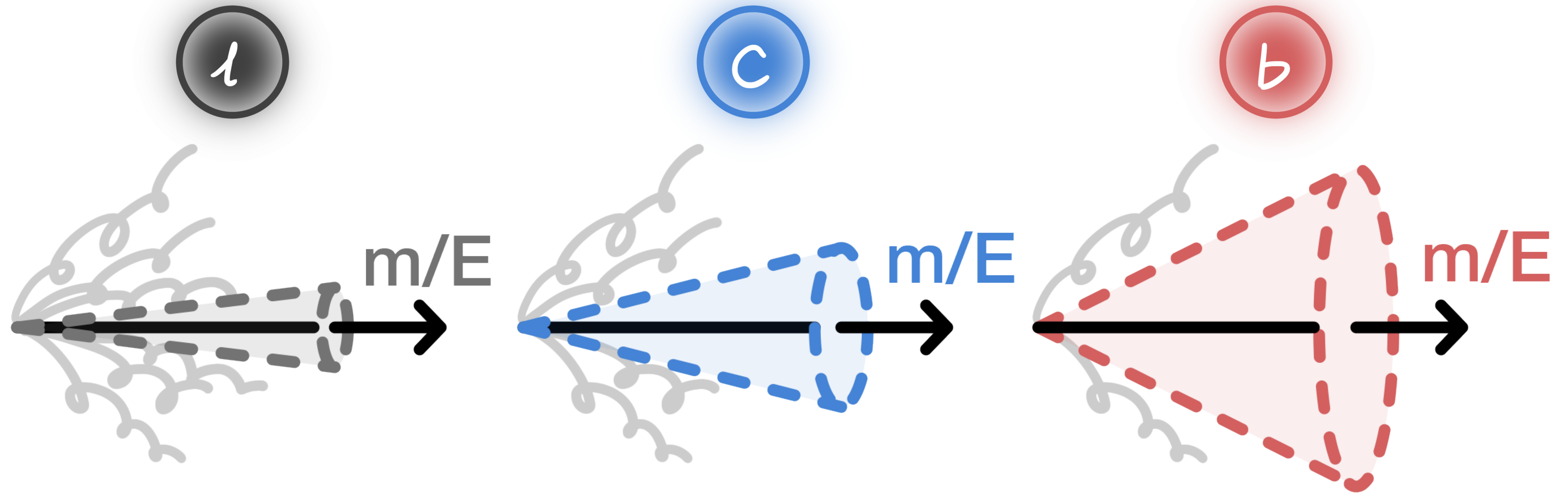
R_{AA} Mass Dependence of Energy Loss

R_{AA} for different flavors



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



Larger energy loss ➜ Smaller energy loss

Wonder if there really is dead cone effect? See:

CMS Jelena M. *CMS* Lida K. *ALICE* Nature 605 (2022) 440

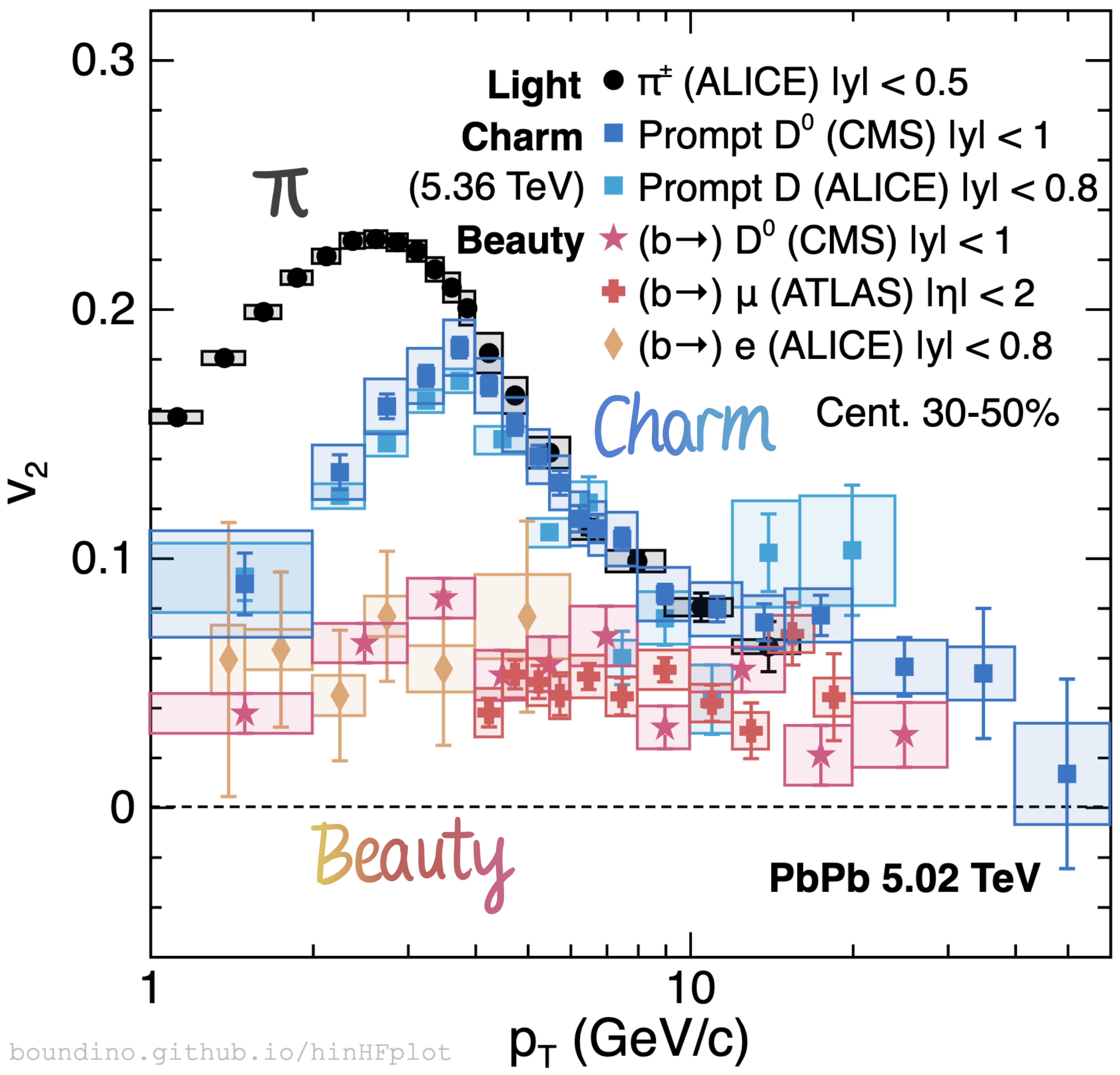
- Flavor dependent R_{AA} ← **Interplay of effects**
  - Significant: dead cone, coalescence
  - Not significant: nPDF

ALICE Biao Z.
ALICE Yuan Z.
CMS Tzu-An S.

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

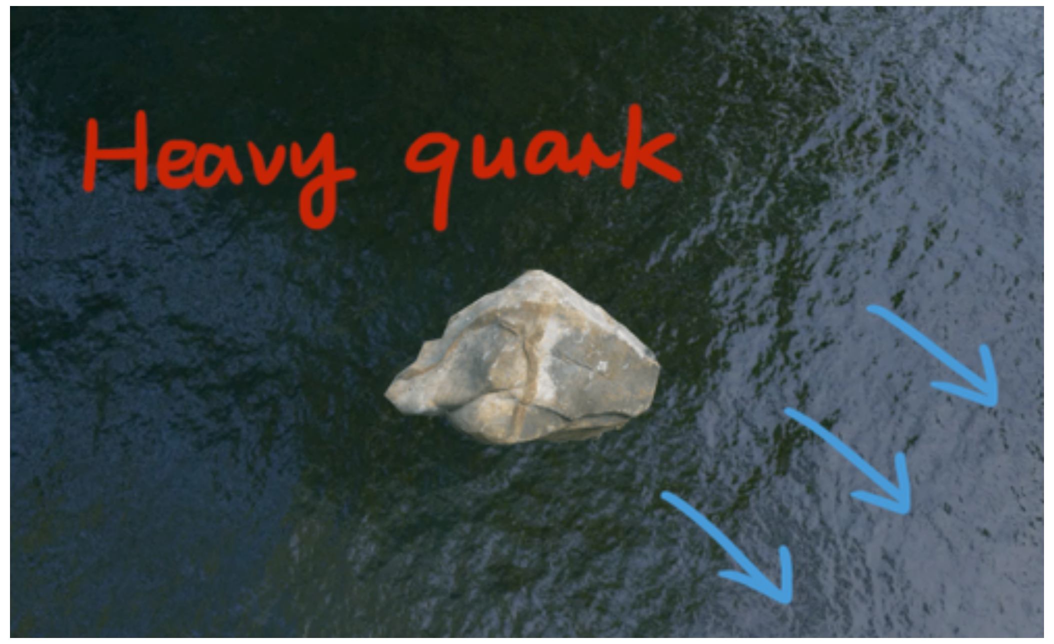
Collective Flow Flavor Dependence

v_2 for different flavors

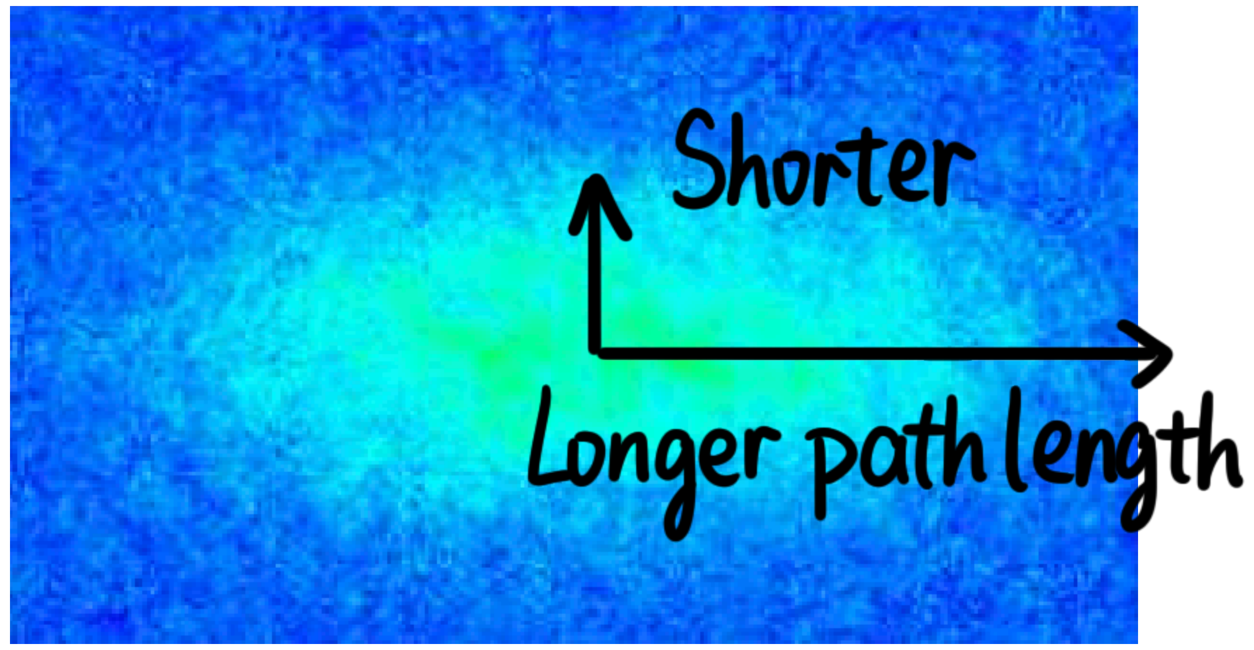


- Charm quarks explicitly take part in **collective motion**
  - Strong coupling
- Non-zero beauty flow signal is significant
- **Thermalization** degree varies vs flavors

Low p_T: elliptic flow



High p_T: path-length dependence of energy loss

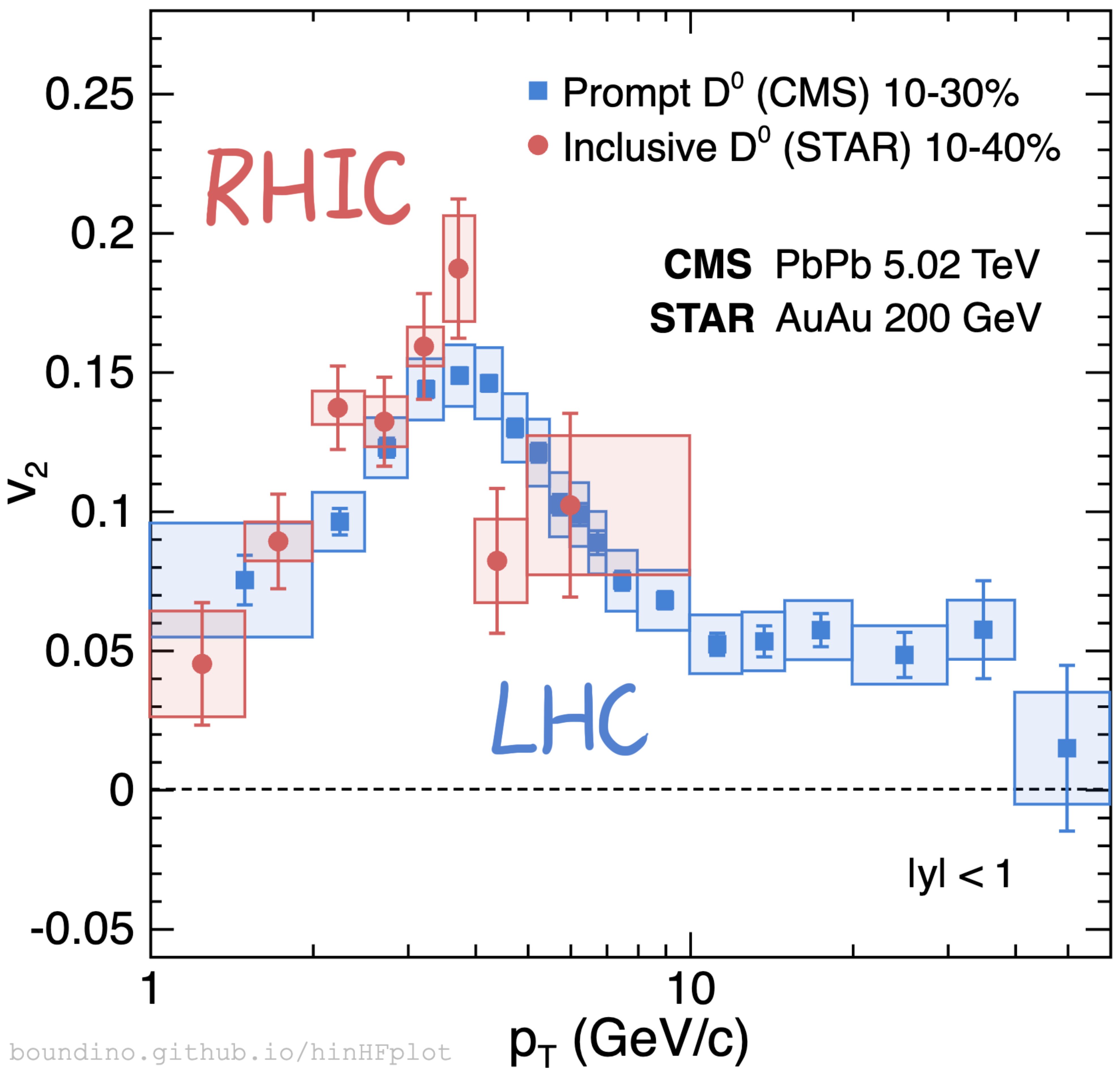


ALICE Biao Z.
CMS Nihar S.
PHENIX Julia V.

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

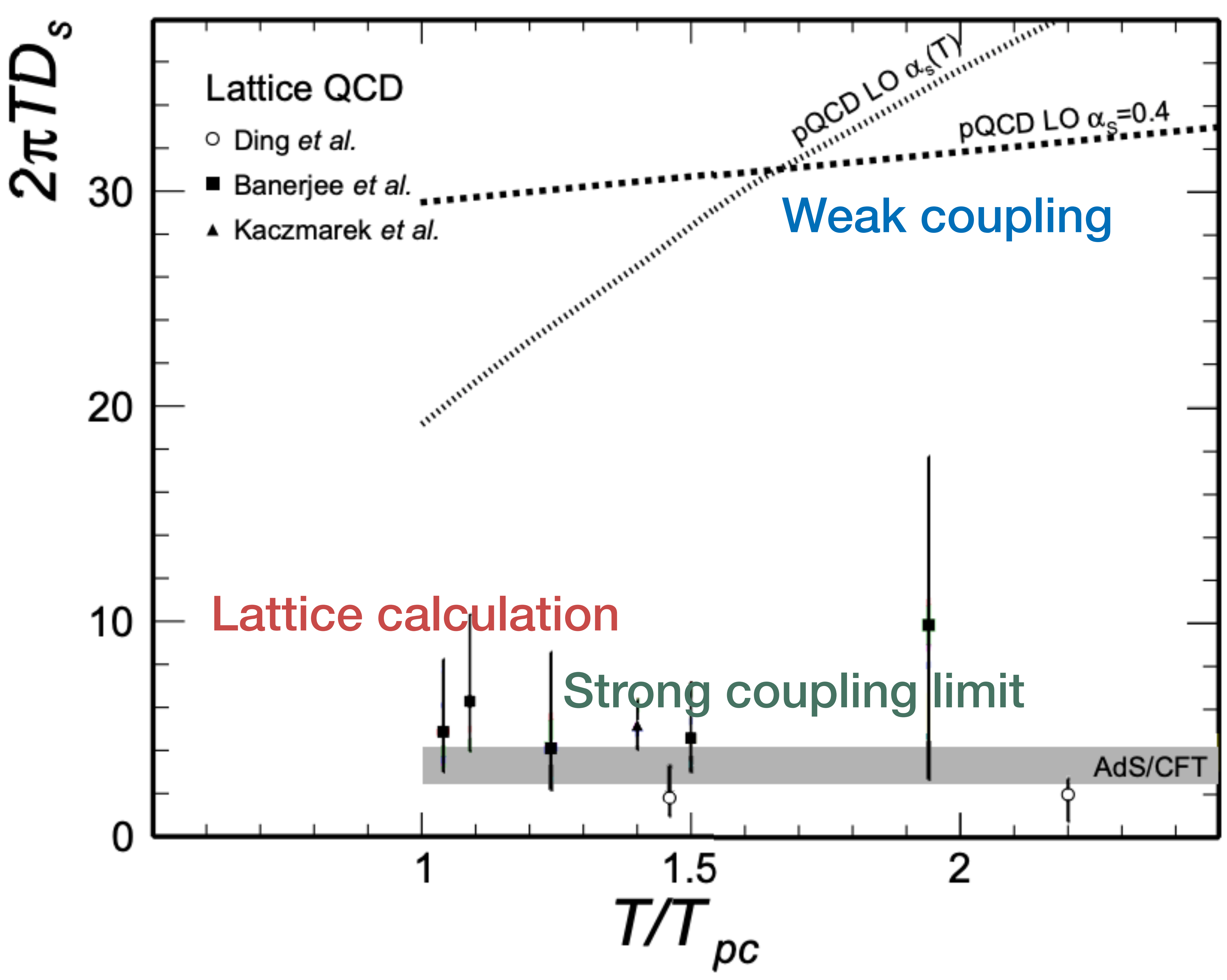


- **Similar** D v_2 between LHC and RHIC
  - Indicate similar flow strength despite different temperature & size?
  - Hope for better precision from sPHENIX

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

Diffusion Spatial Diffusion Coefficient D_S

Spatial diffusion coefficient D_S(T, p=0)



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

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

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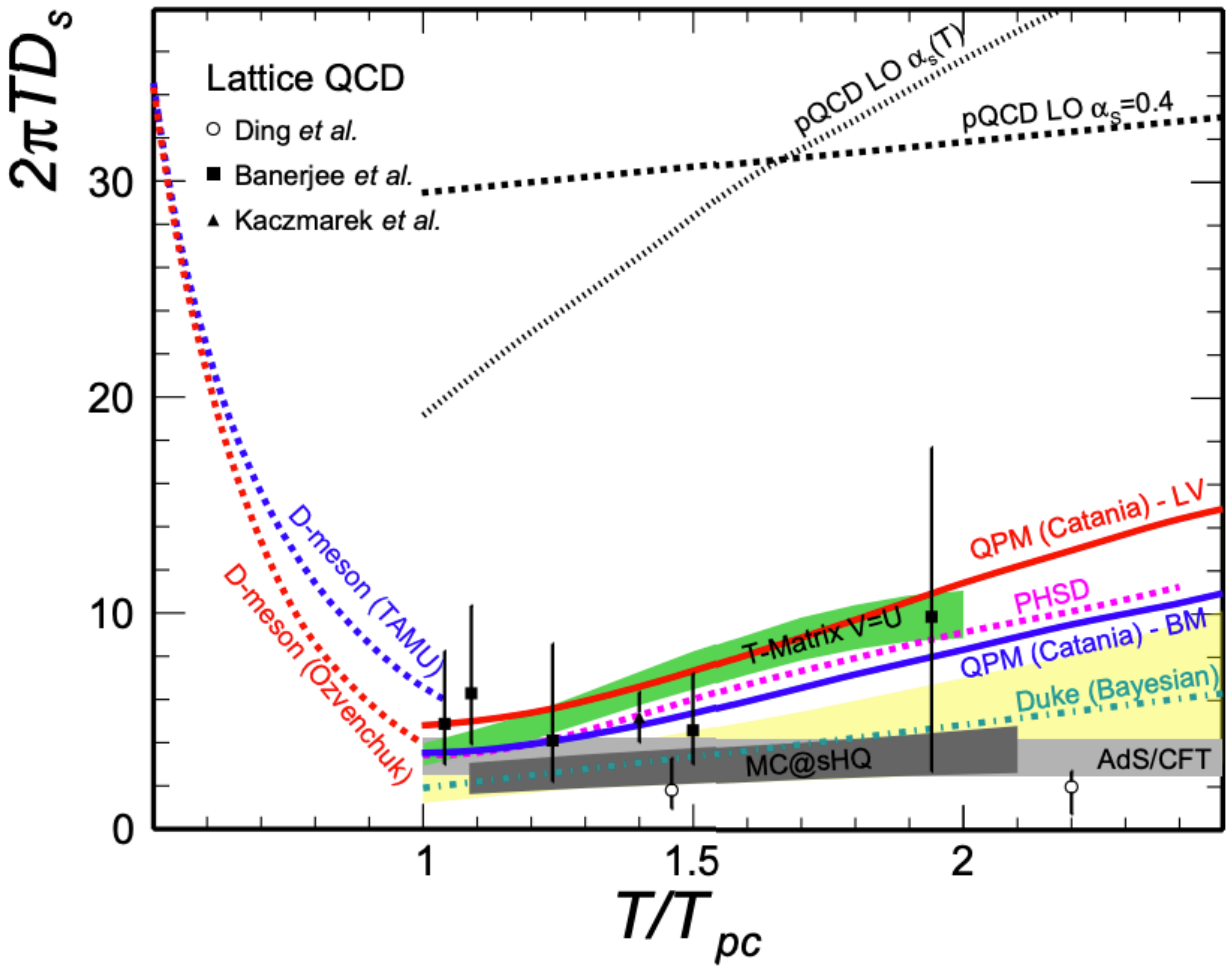


- First principle calculation
  - **LO pQCD** Weak coupling
  - **AdS/CFT** Strong coupling limit
  - **Lattice QCD** Not accessible at finite momentum
    Need **phenomenological models**

- **Models** that can describe data R_{AA} & v_2 have
  - D_S close to AdS/CFT strong interaction limit
  - Different momentum dependence of coefficients

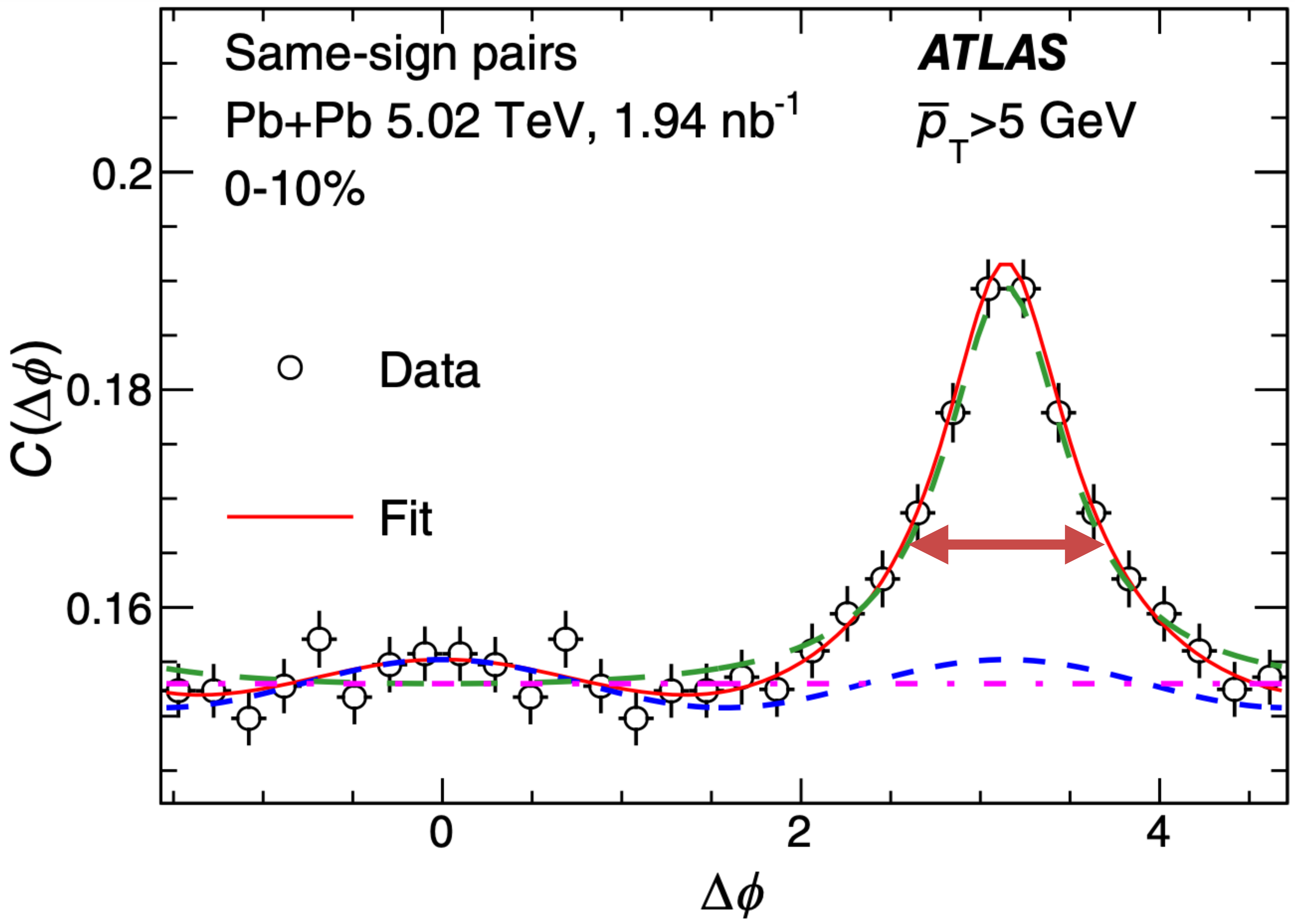
- **Next!**
  - Observables beyond R_{AA} and v_2: Correlation
    - Also constrain other coefficients beyond D_S
  - Reduce theoretical uncertainty: **especially on Hadronization**

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

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

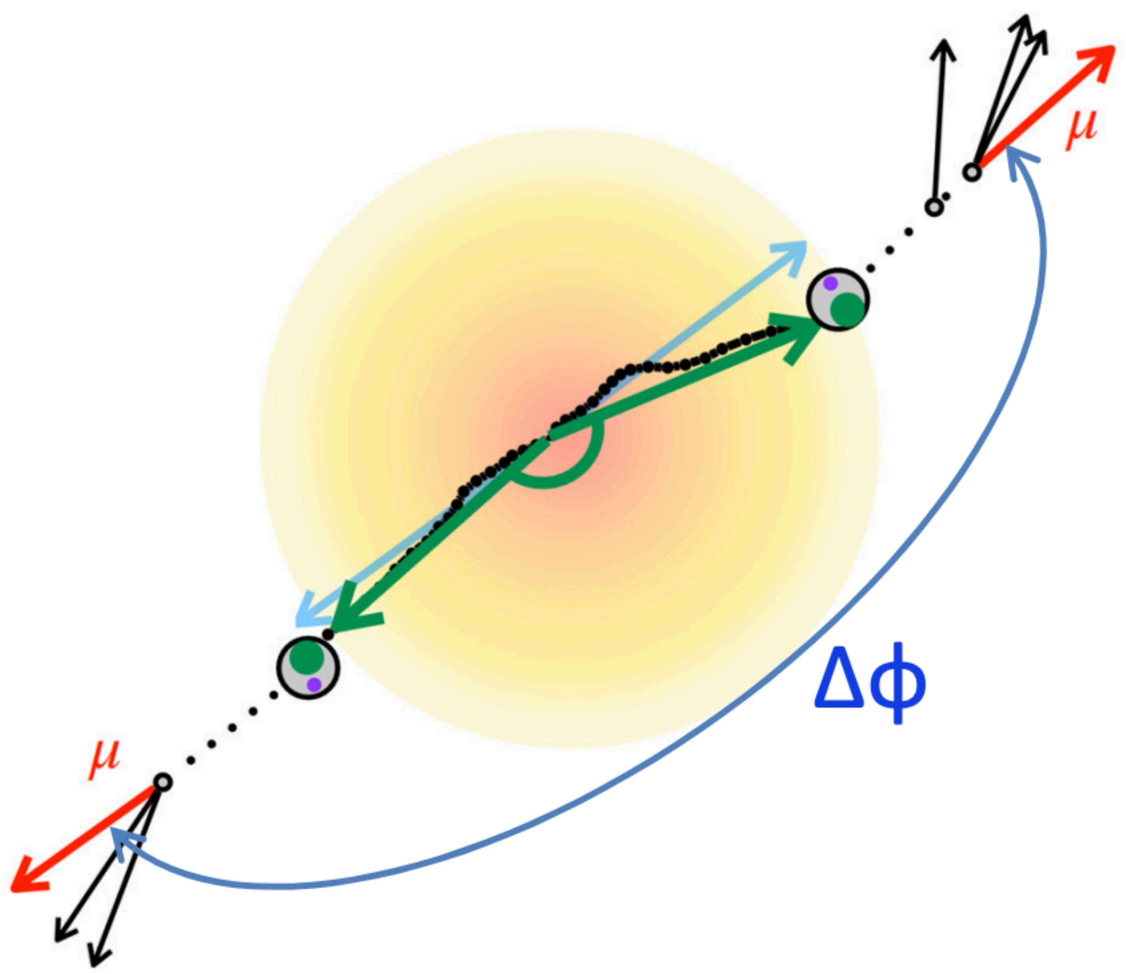
Diffusion Correlation with Hard Probes

(HF→)μ - (HF→)μ correlation



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

- 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



ATLAS **Soumya M.**
STAR **Diptanil R.**

ATLAS **PRL 132 (2024) 202301**

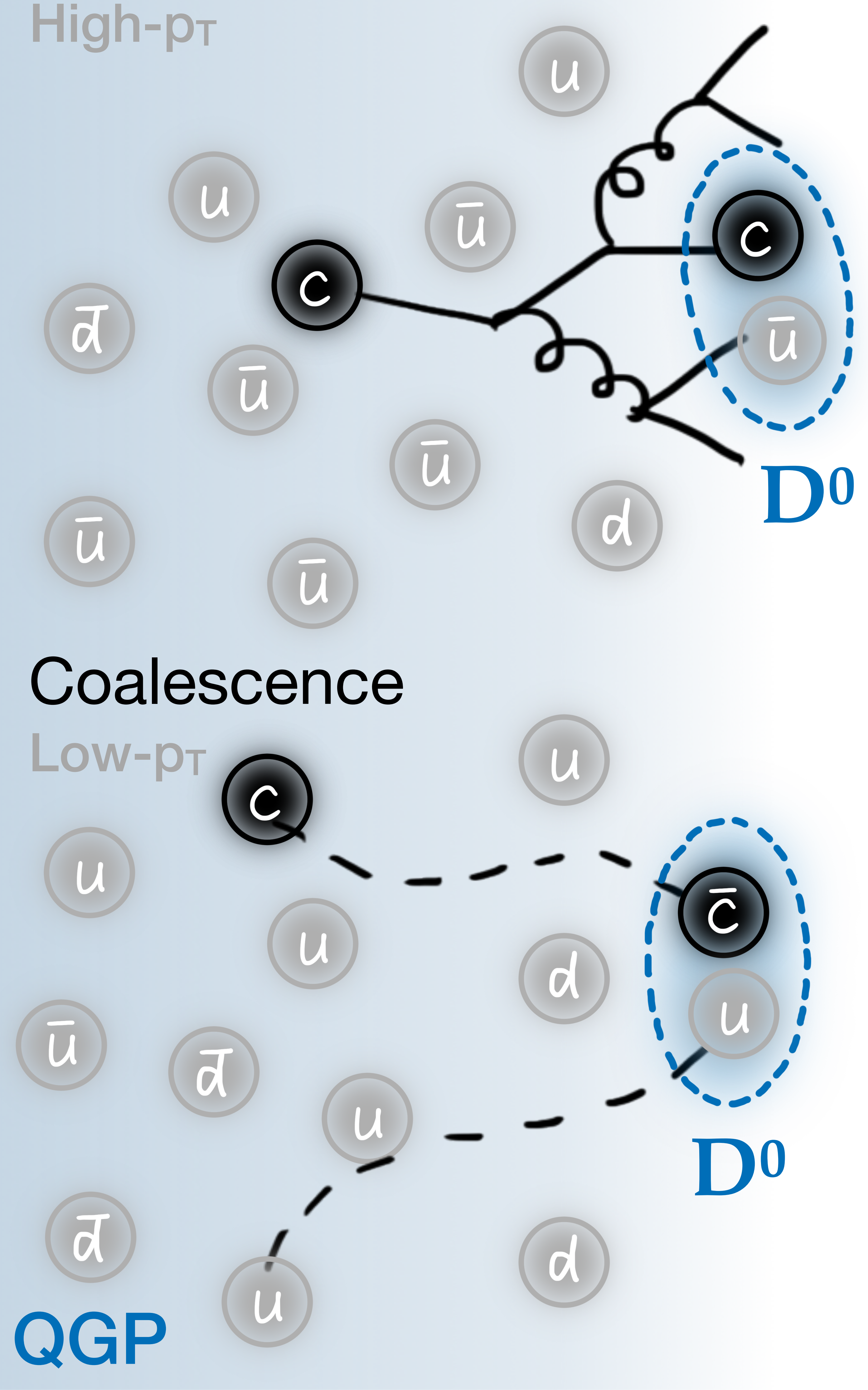
Hadronization Modification In Medium

Fragmentation

High-p_T

Coalescence

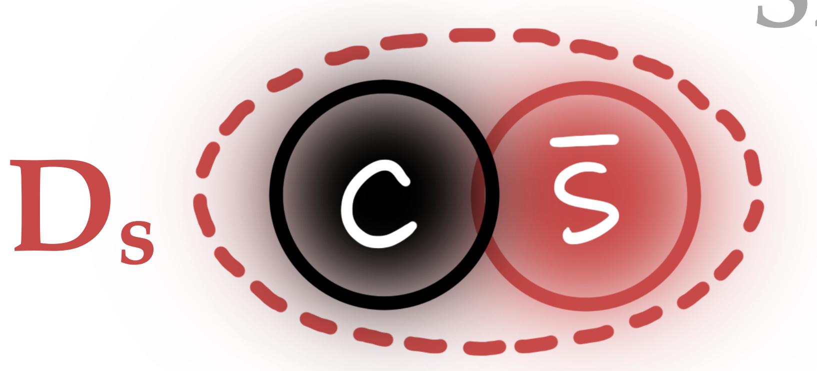
Low-p_T



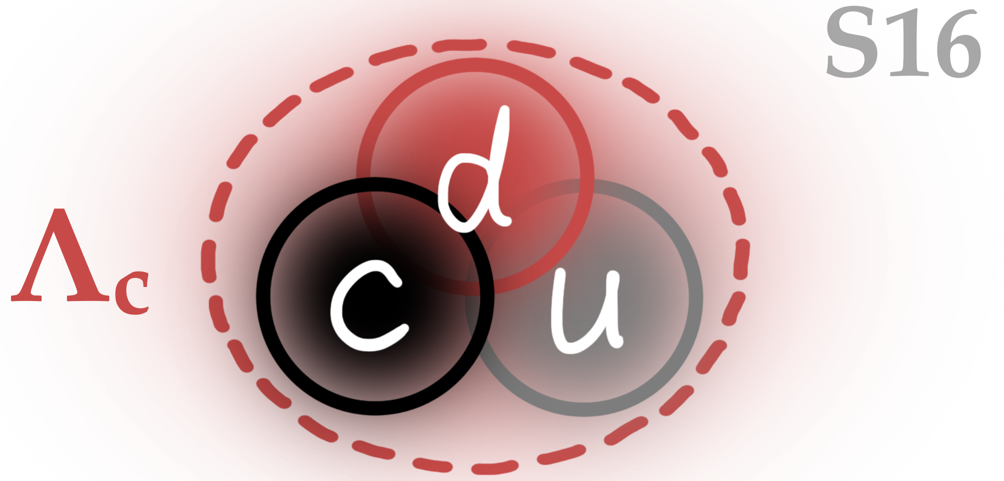
- Fragmentation universality assumed across collision systems
  - Successful in HF meson production in pp
  - **Lesson from LF** Additional coalescence (recombined with light quarks in medium) to describe in-medium modification in AA collisions

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

S24



S16



If there is coalescence

Higher **D_s / D^0** expected

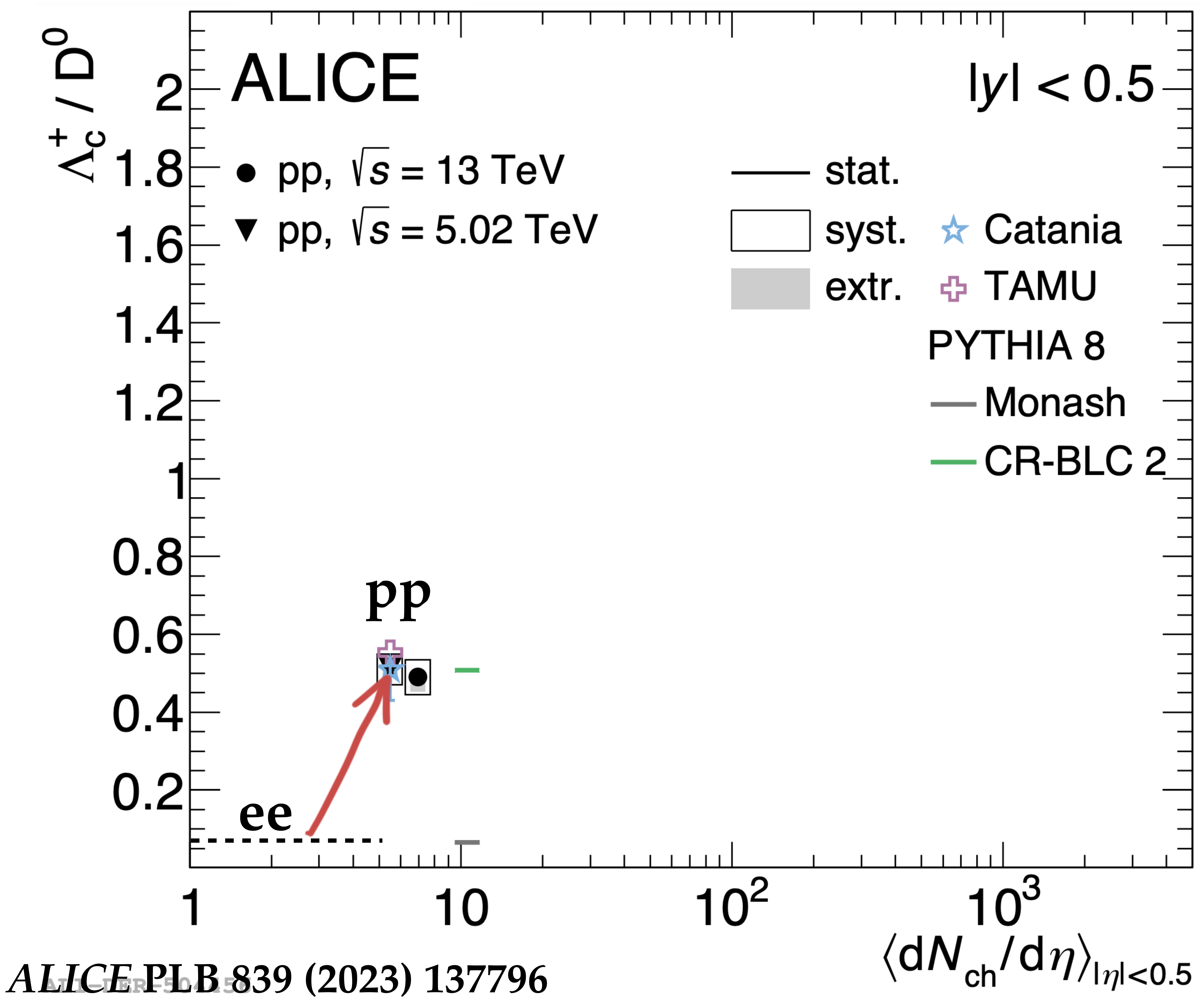
strangeness enhancement

Higher **Λ_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

Was a surprising news: p_T-Integrated yield ratio Λ_c / D^0

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

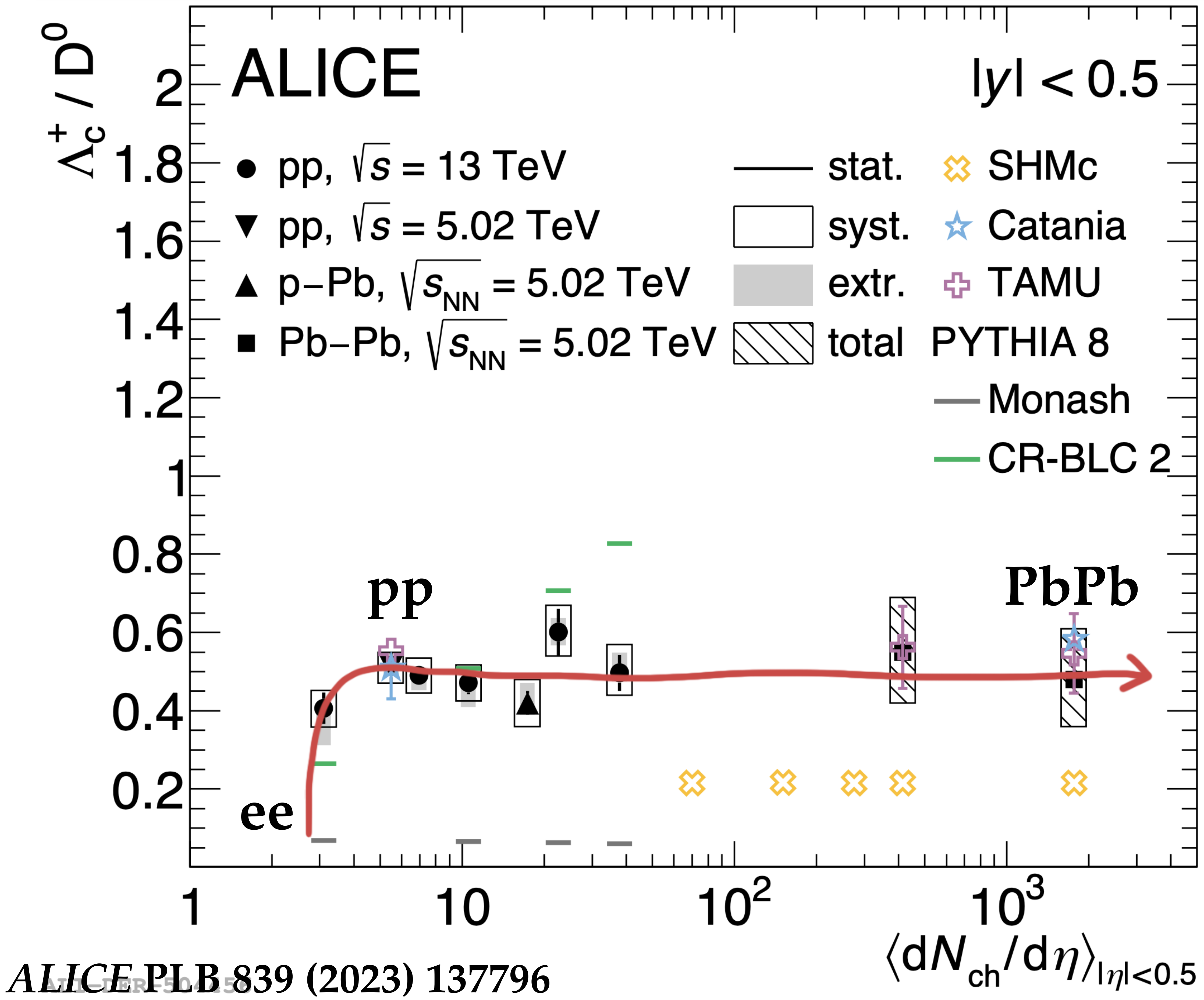
Most microscopic → Most static

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 Across Collision Systems

Λ_c / D^0 vs Multiplicity



ALICE PLB 839 (2023) 137796

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- **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

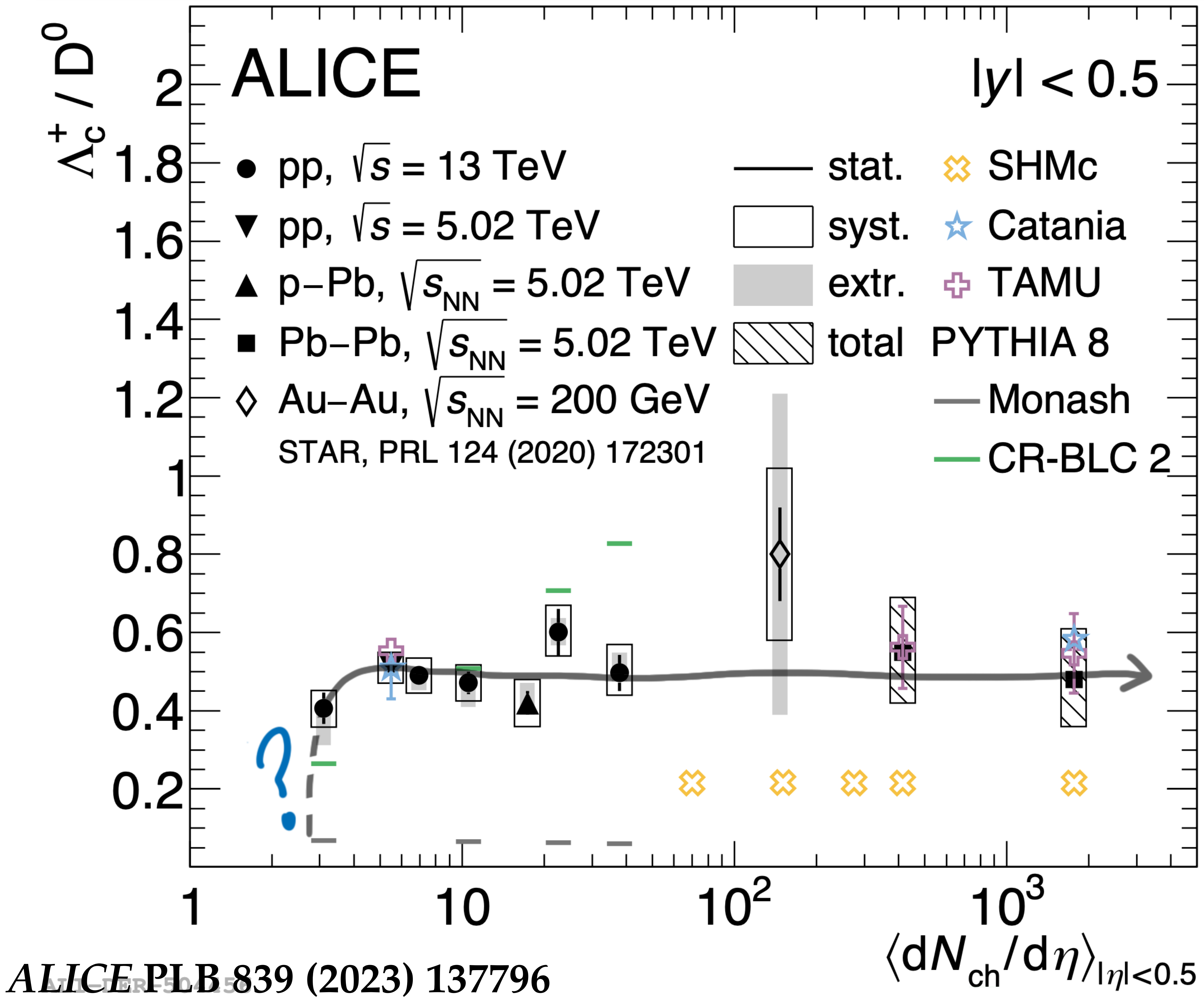
- **Saturated**: pp to central PbPb (~0.5)

No saturation mechanisms	Chemical equilibrium / similar T_{QGP}	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



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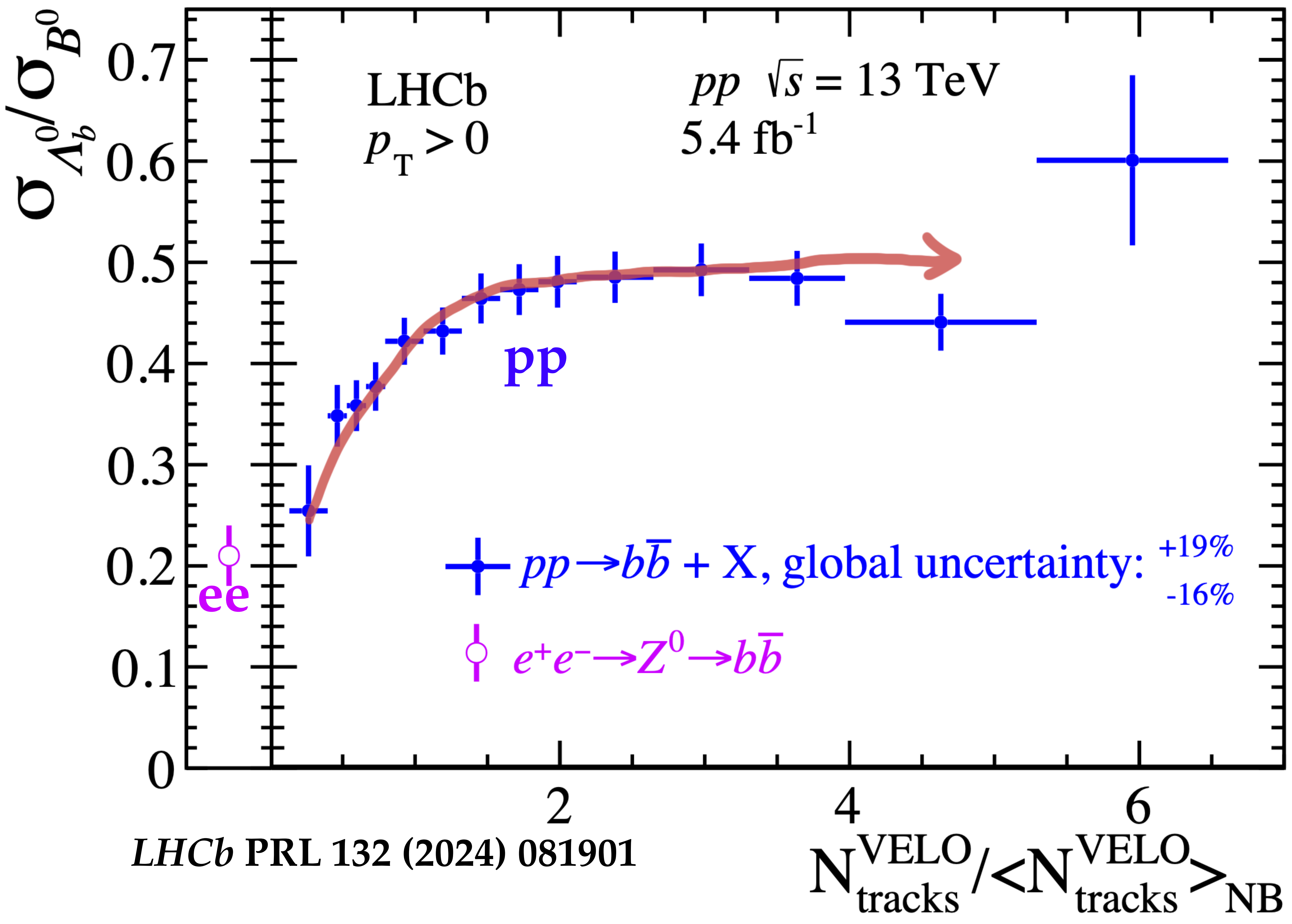
Integrated p_T Λ_b / B^0



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?

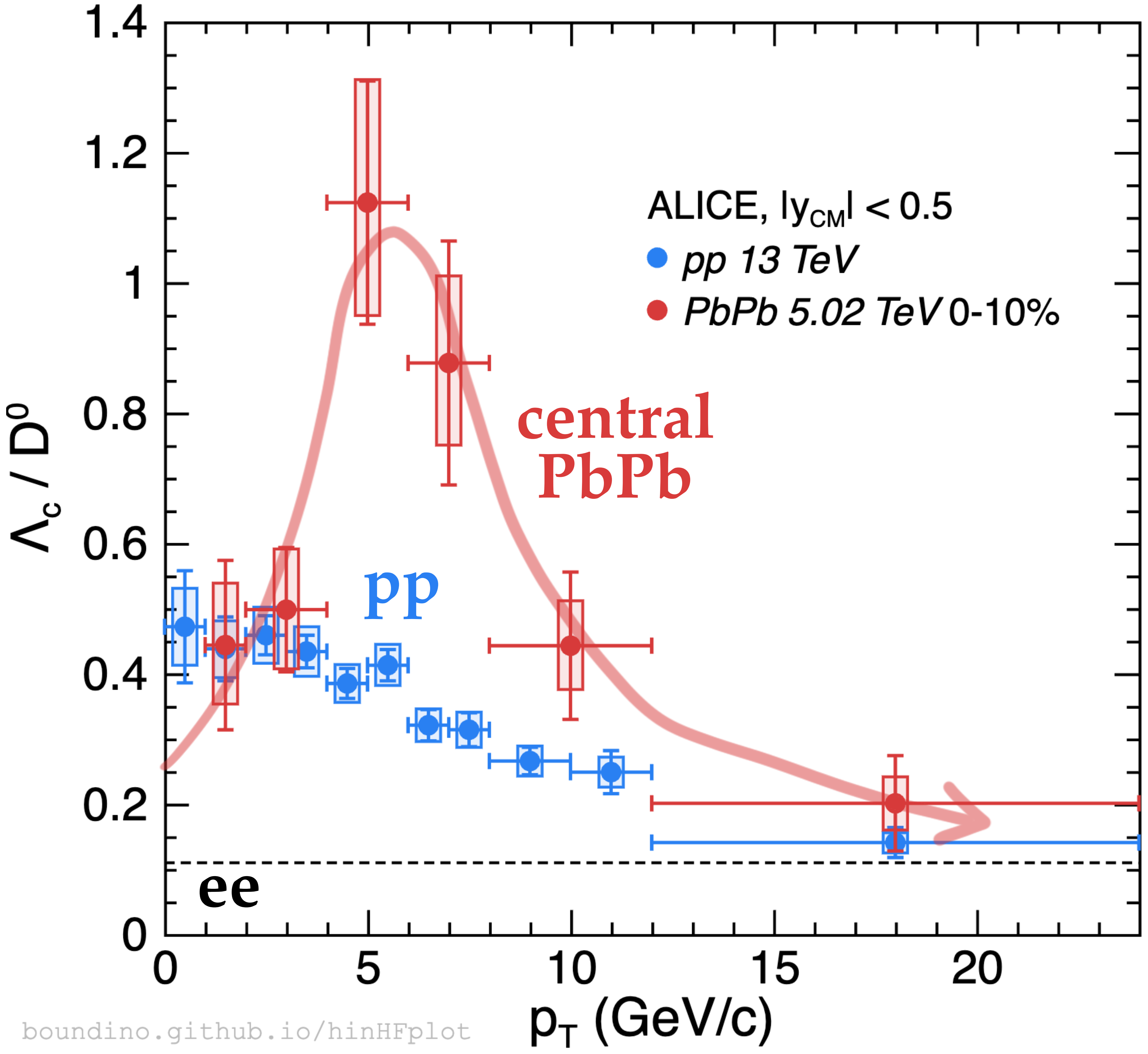
LHCb Julie B.
ALICE Federica Z.

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

Λ_c / D^0 vs. p_T



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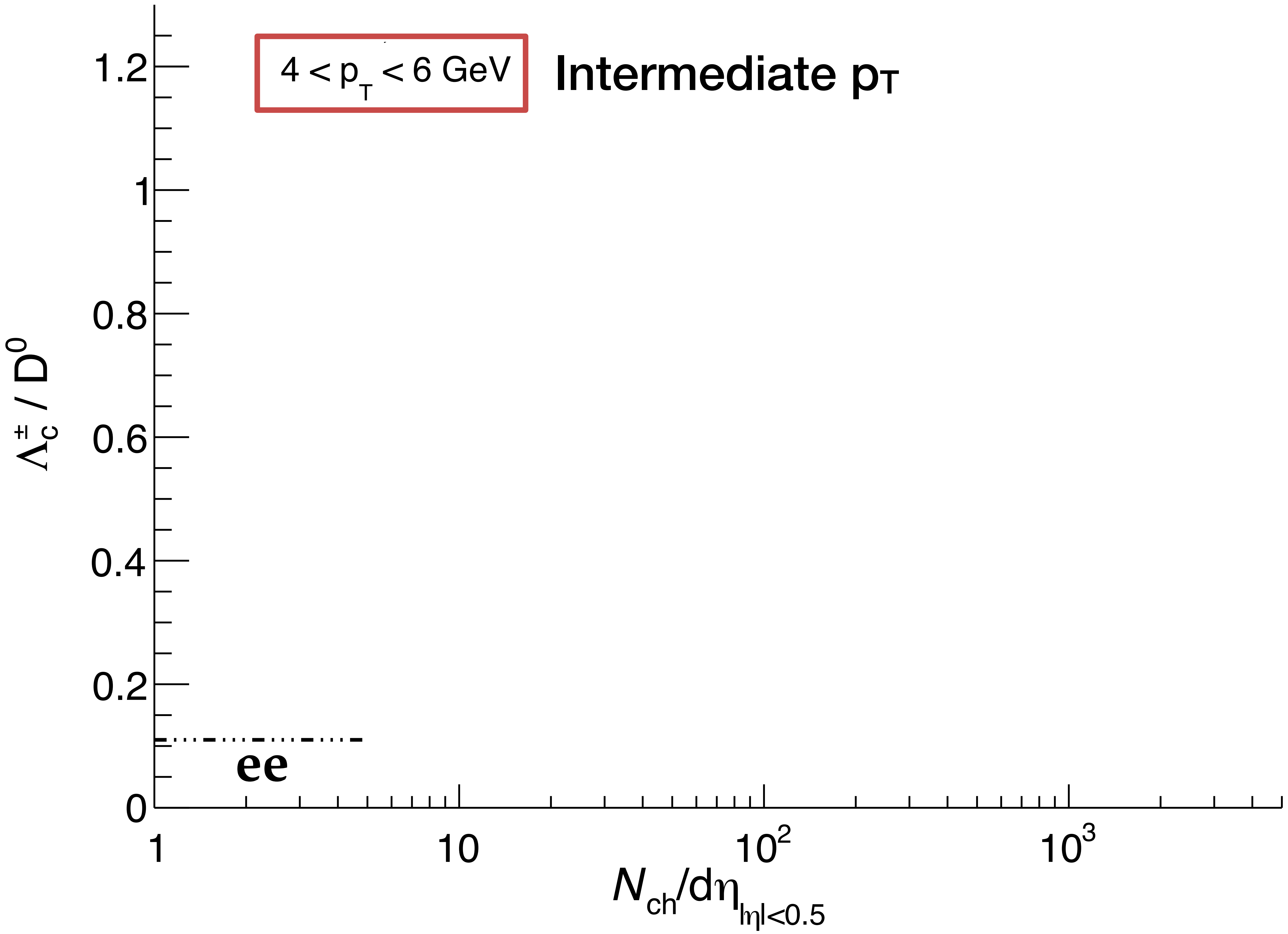
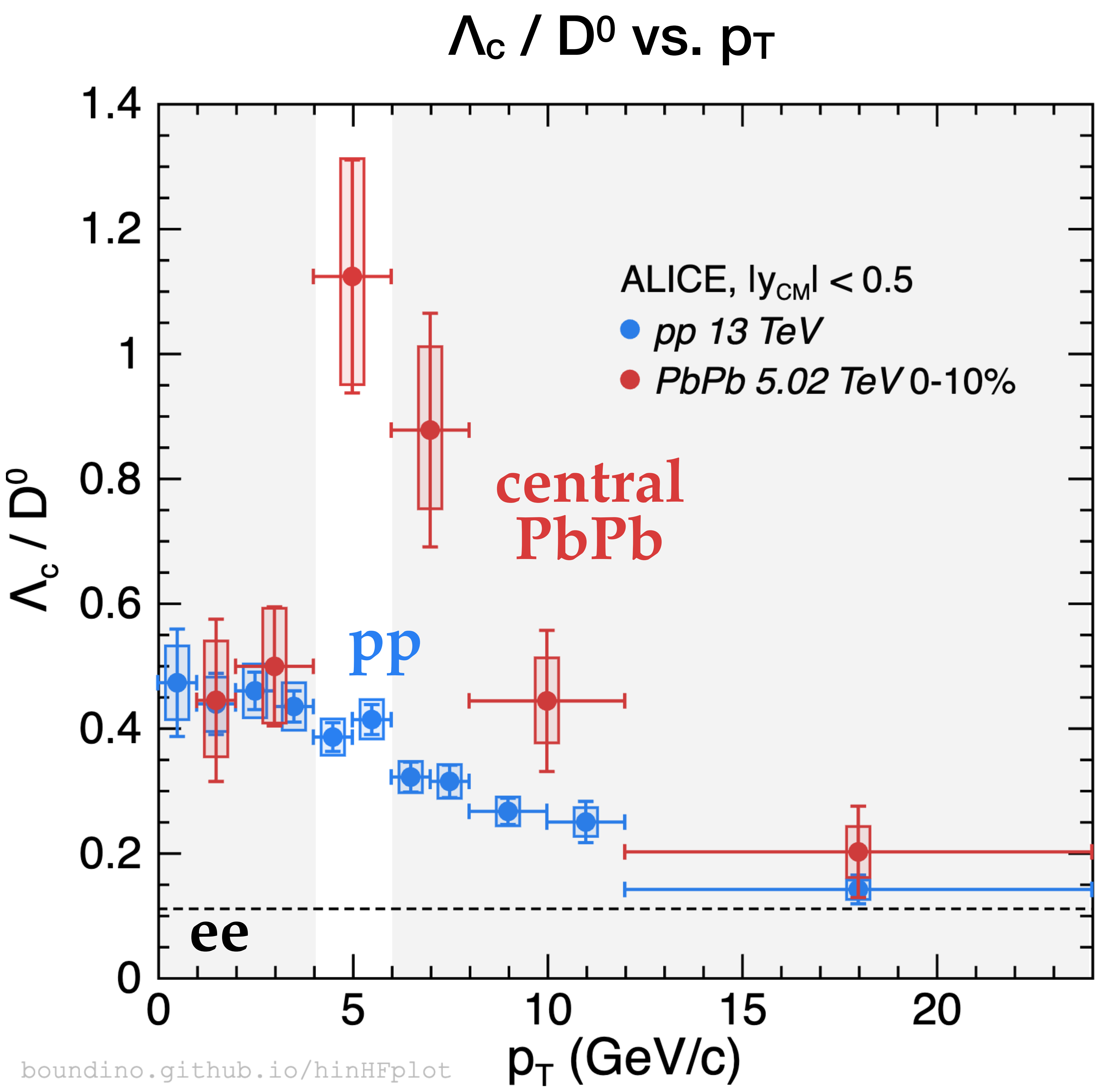
ALICE JHEP 12 (2023) 086

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

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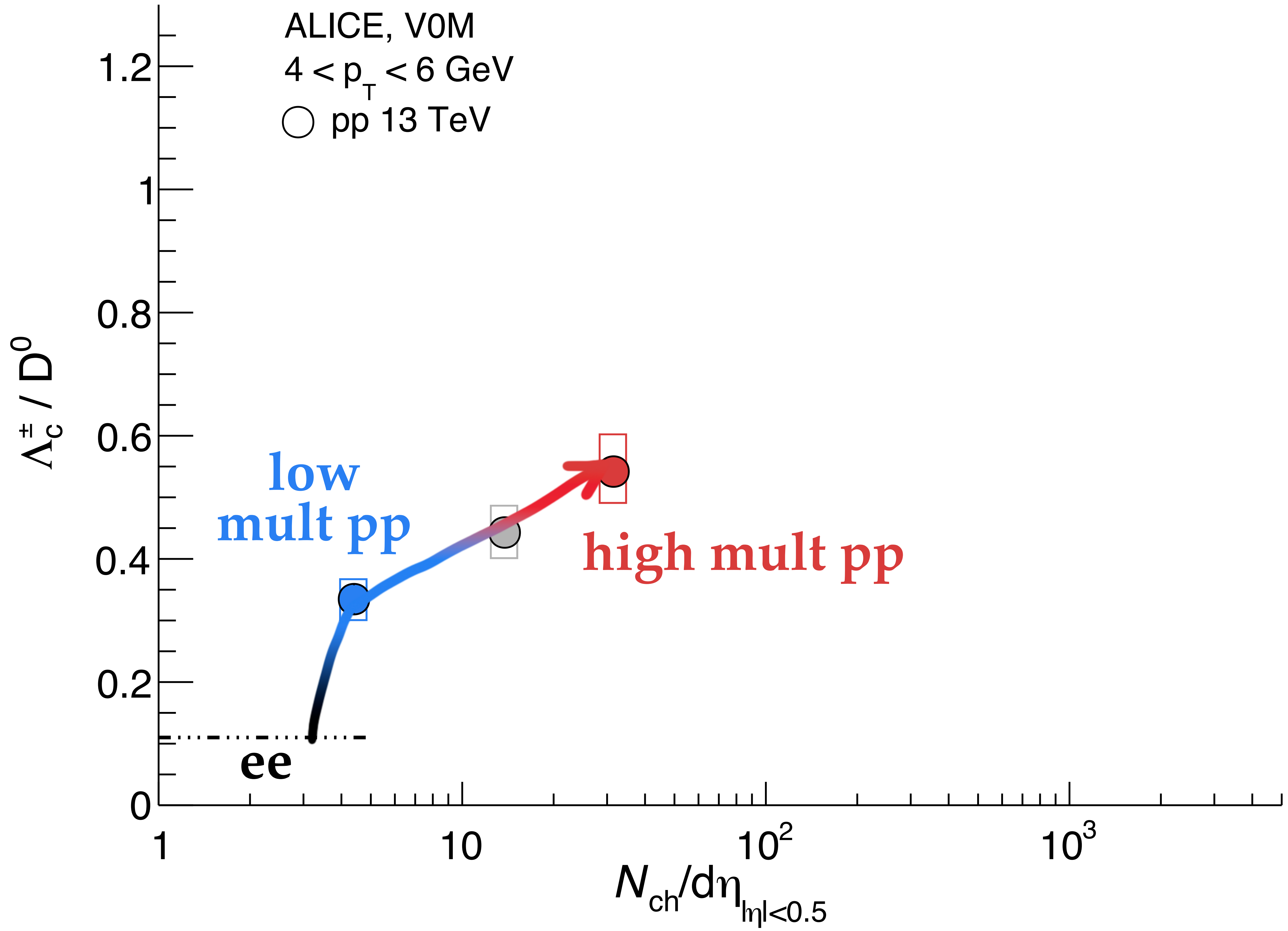
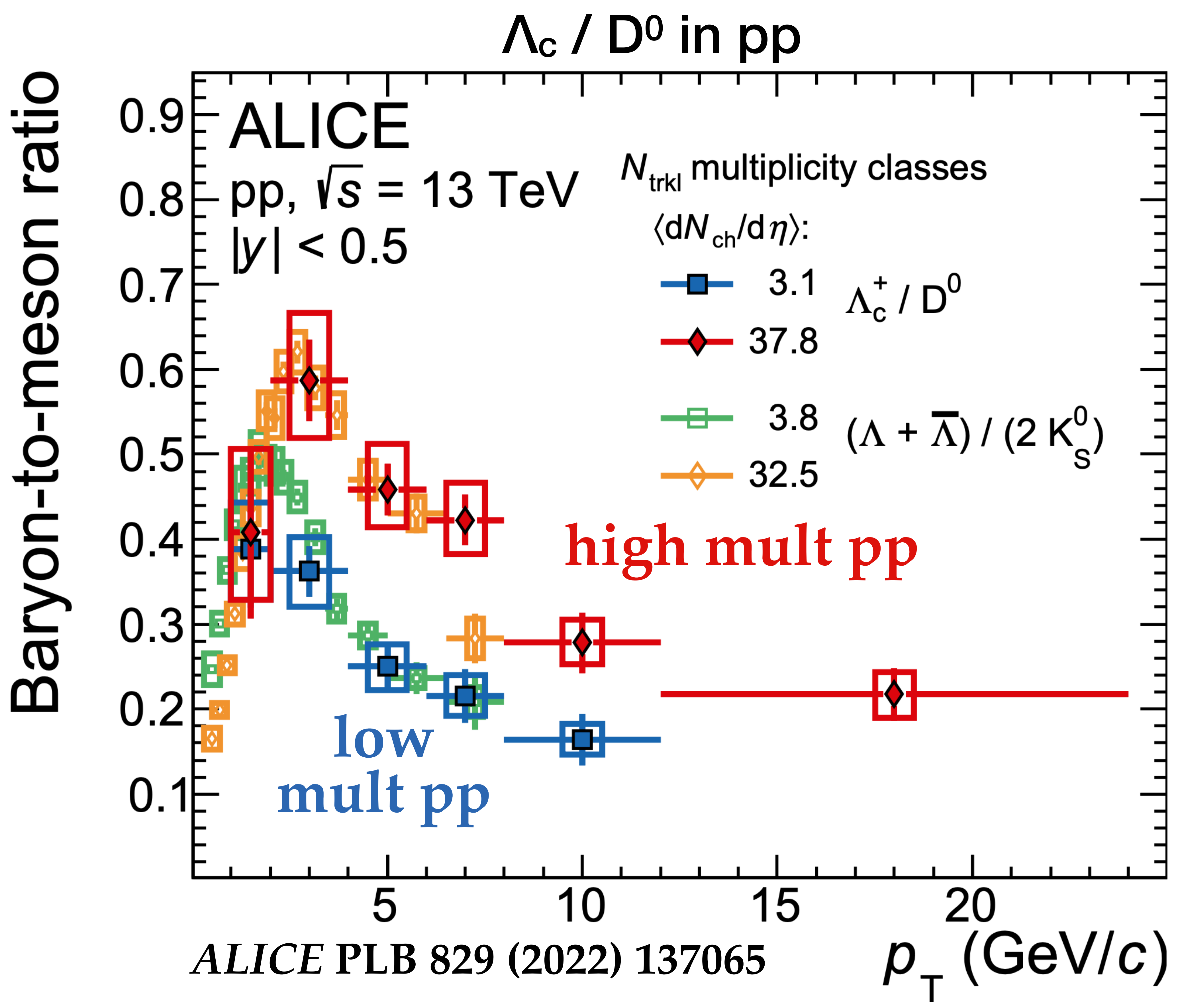
Λ_c p_T Redistribution Across Collision Systems

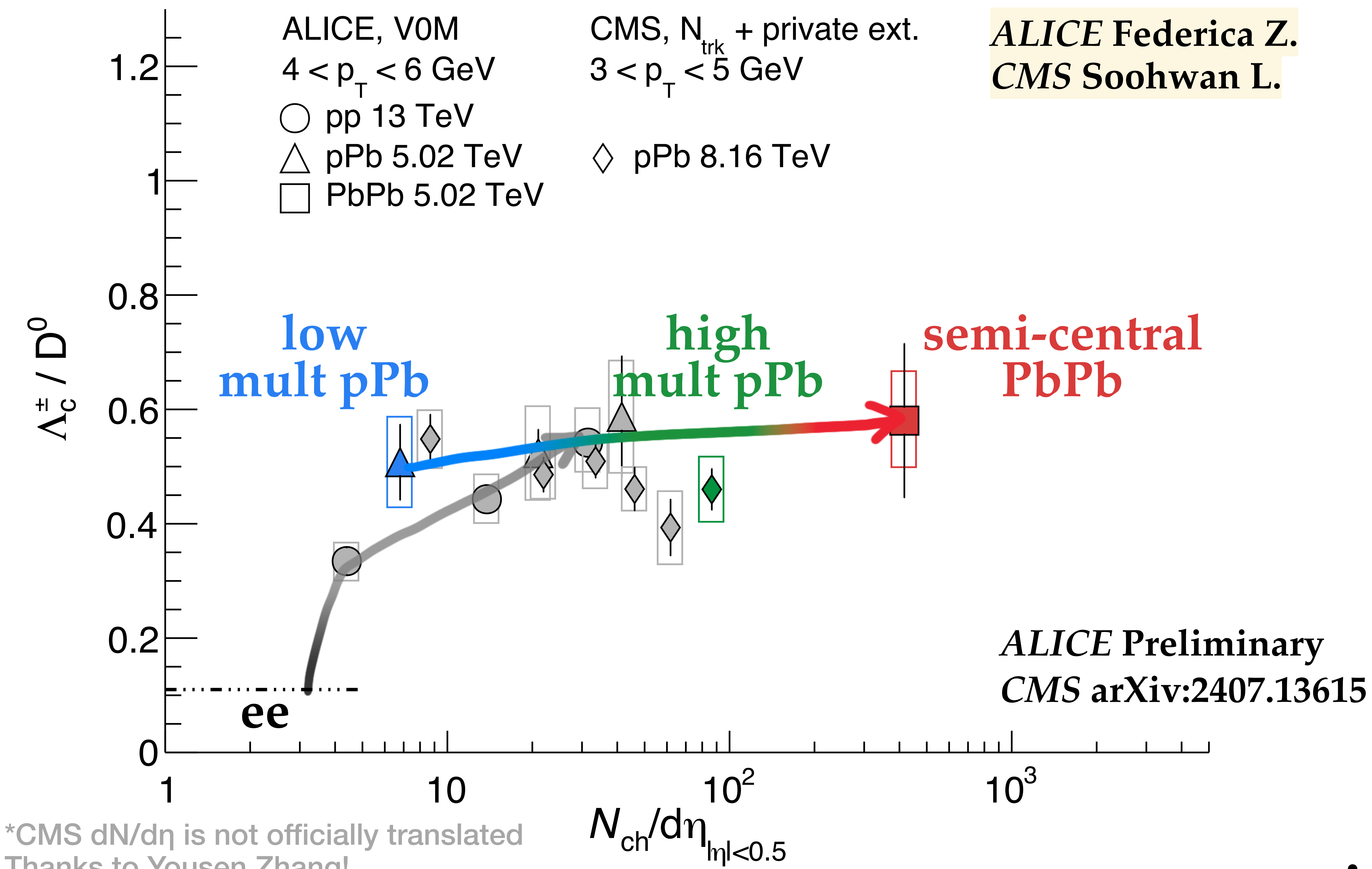




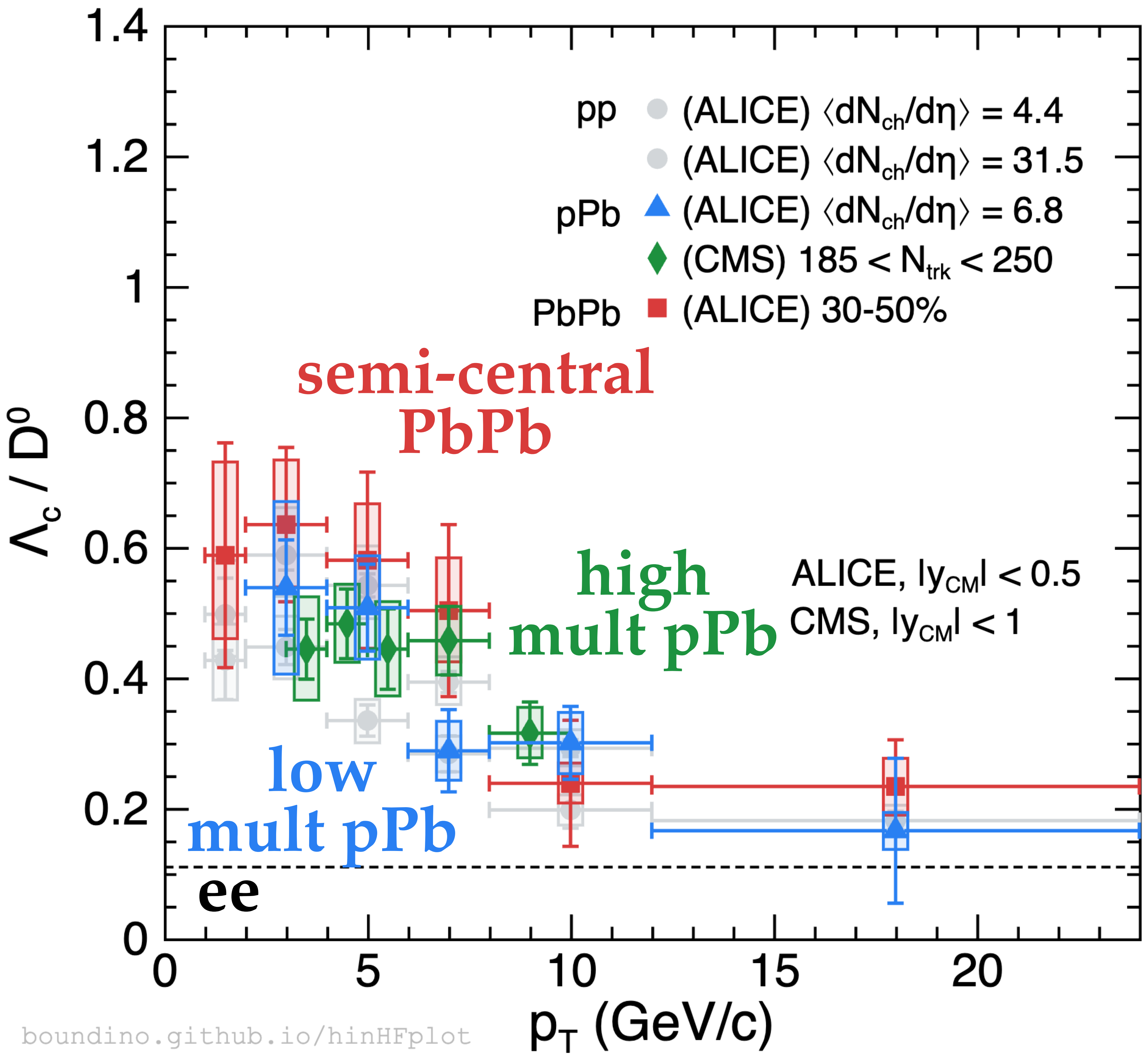
- Momentum redistribution already happens in high-multiplicity pp

- Similarity between strange and charm
- **Puzzling** to me: not likely to have *same* flow strengths of charm and strange?

Λ_c p_T Redistribution Across Collision Systems

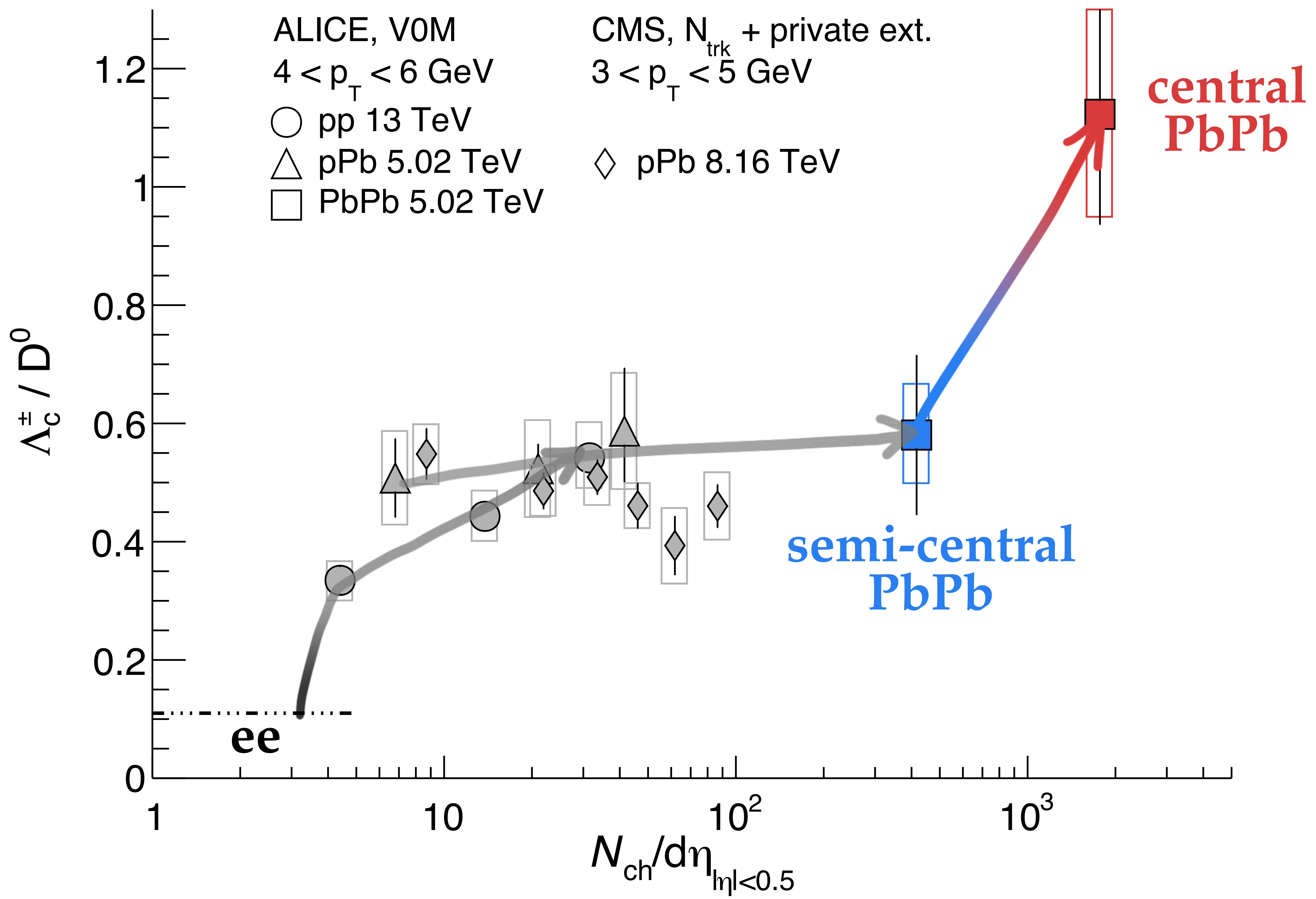


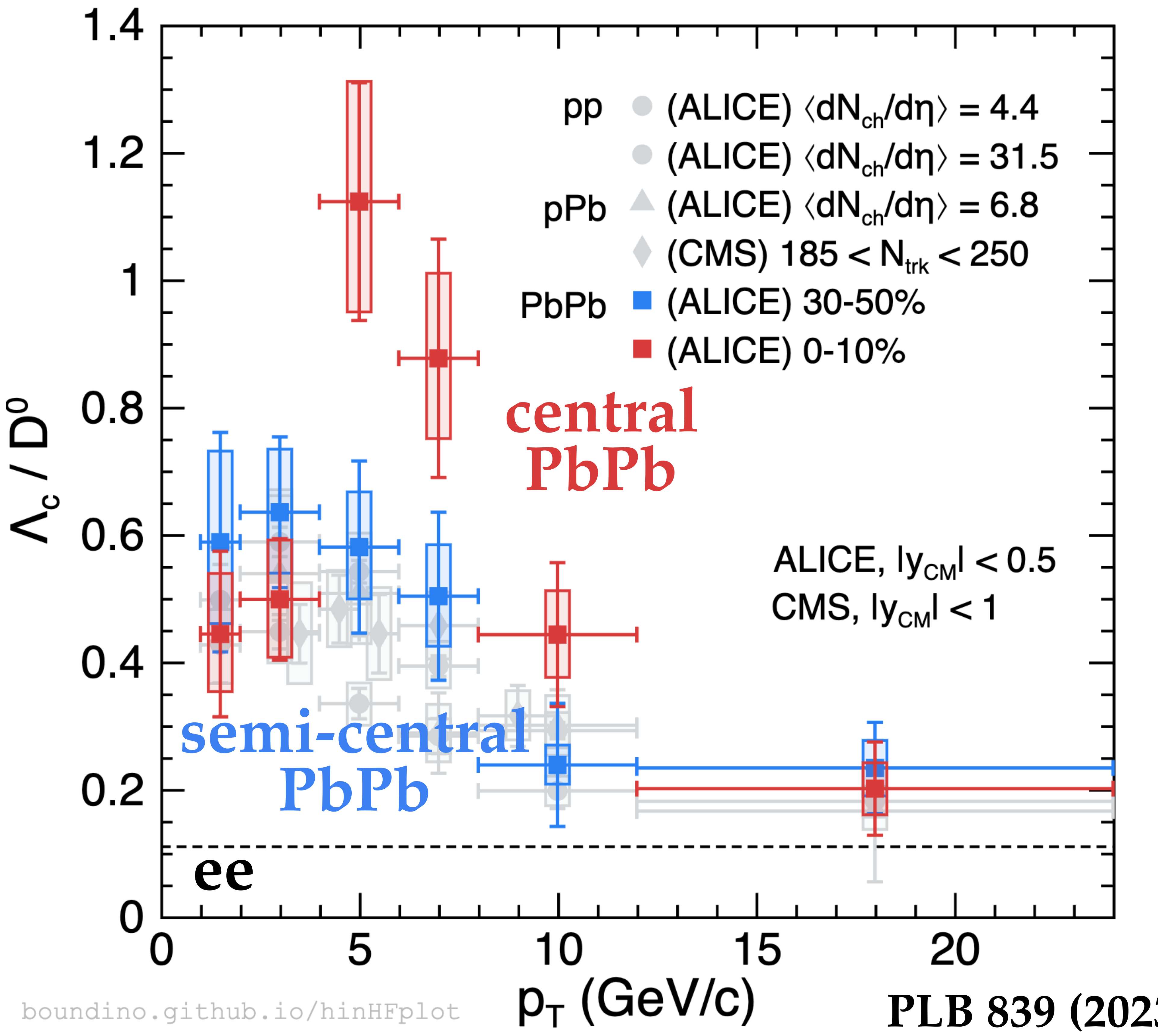
*CMS dN/dη is not officially translated
Thanks to Yousen Zhang!



- 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





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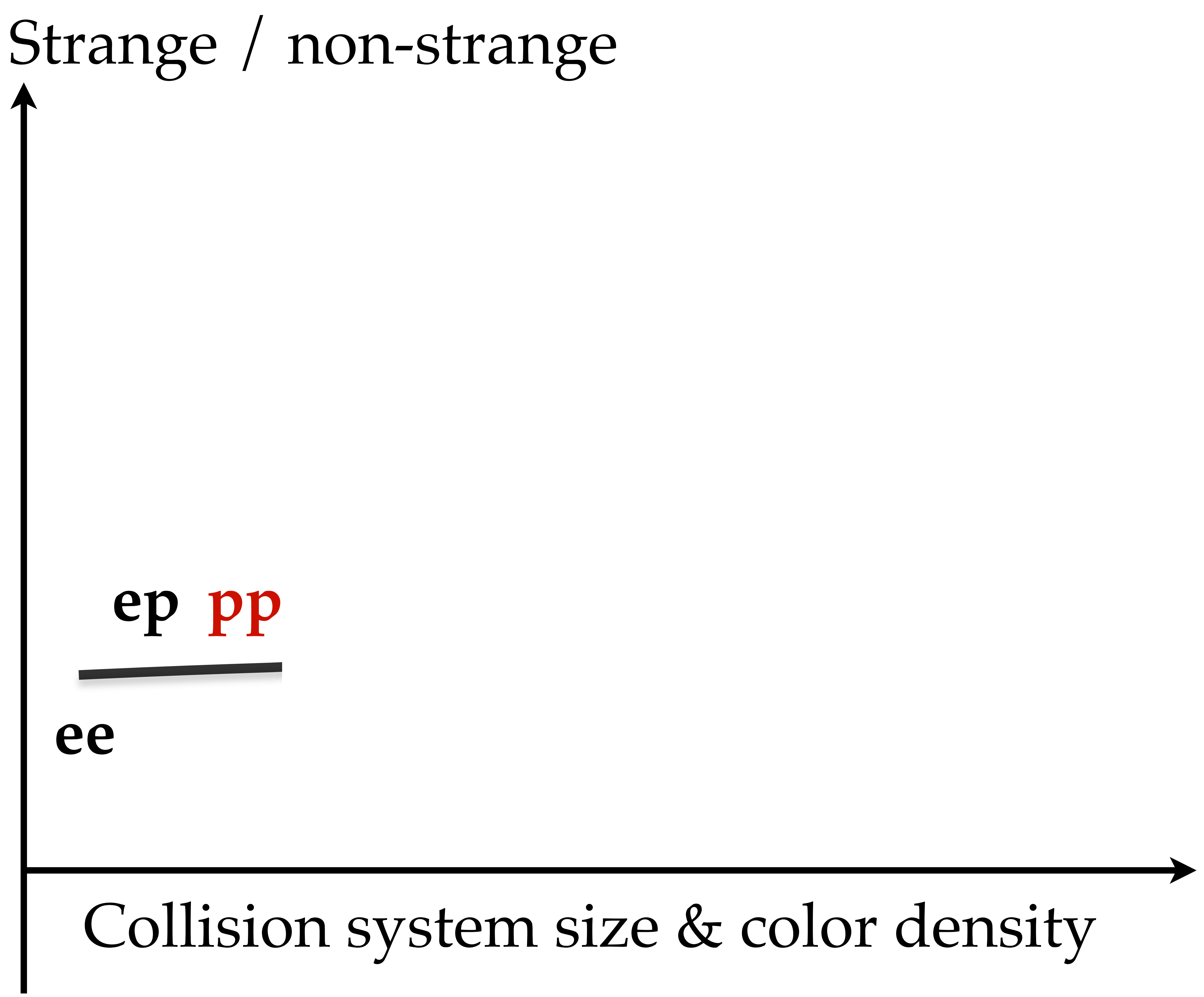
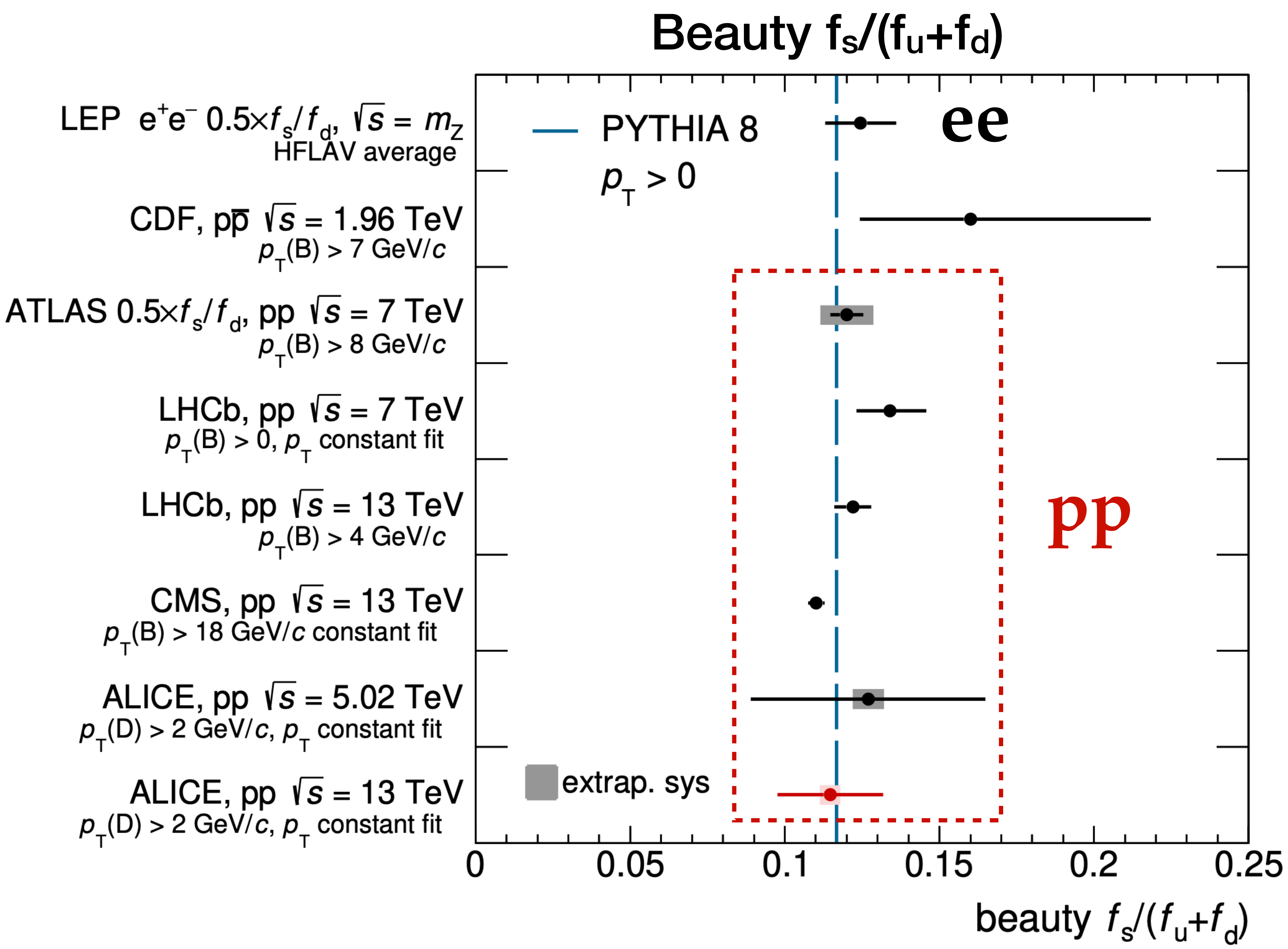
- The shape changes dramatically in central PbPb → Strongest radial flow
- Hope for better precision with Run 3 data

Strangeness Across Collision Systems



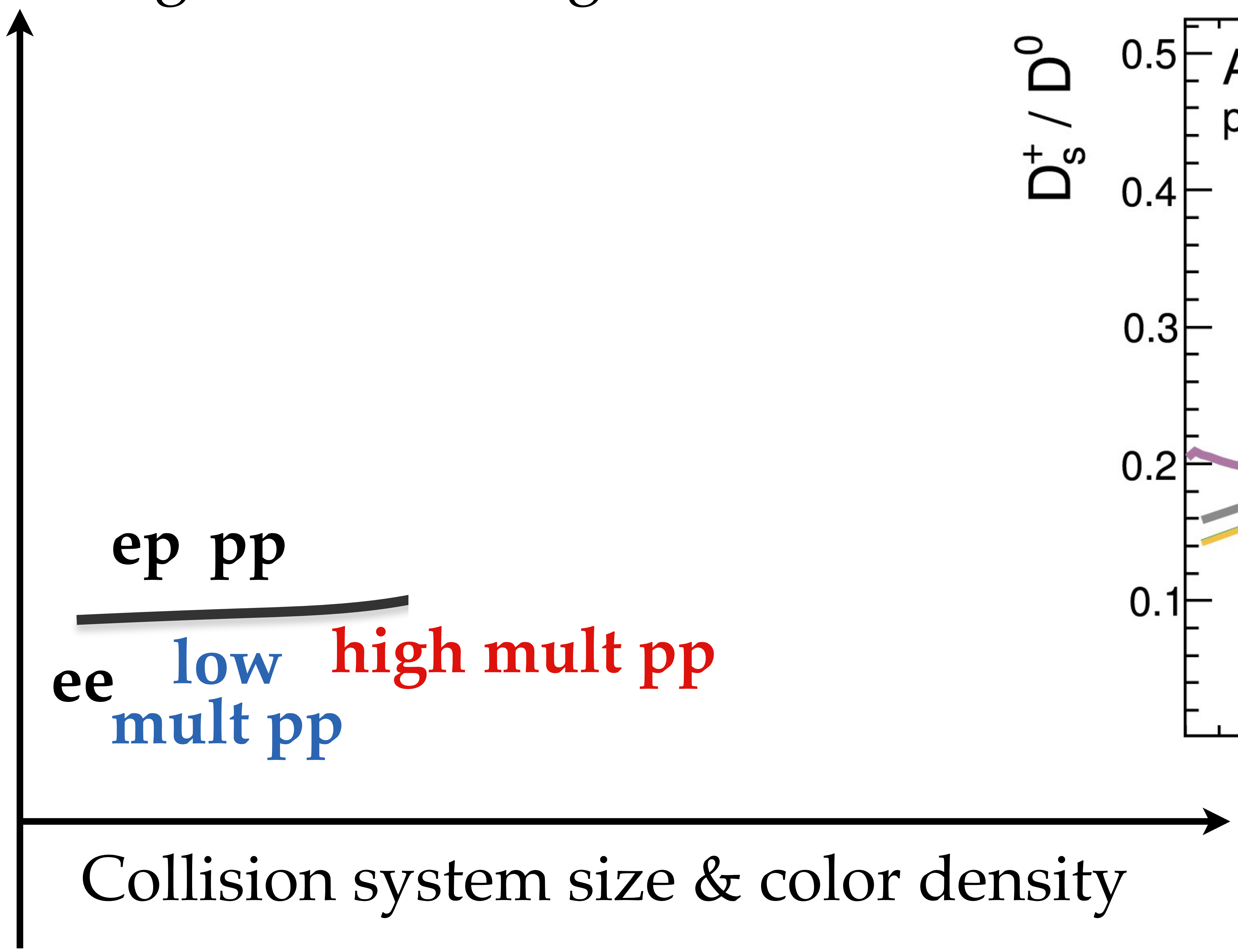


- Keep fragmentation universality
- $f_s/(f_u+f_d)$ consistent between e^+e^-, ep and pp for both **charm** and **beauty**

ALICE Andrea G.

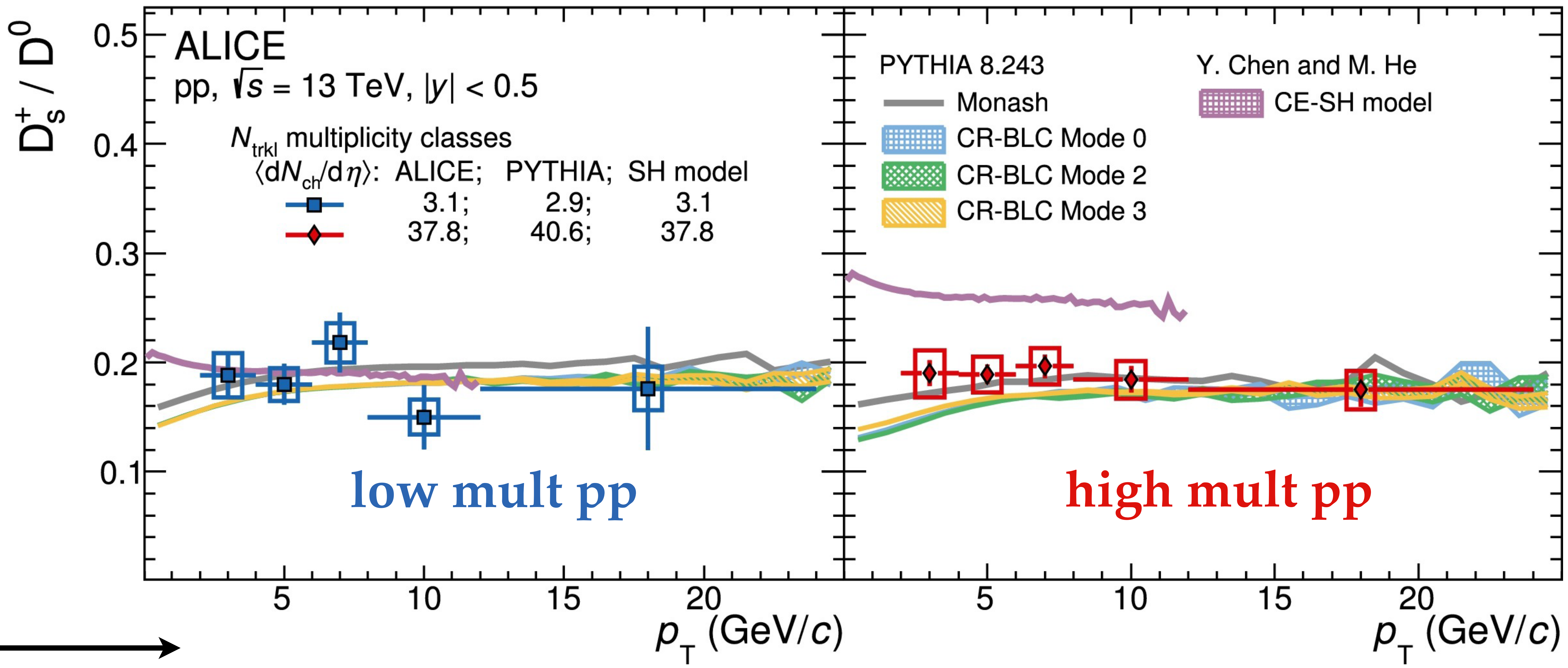
ALICE arXiv:2402.16417

Strangeness Across Collision Systems



Ds / D0 in pp

ALICE PLB 829 (2022) 137065

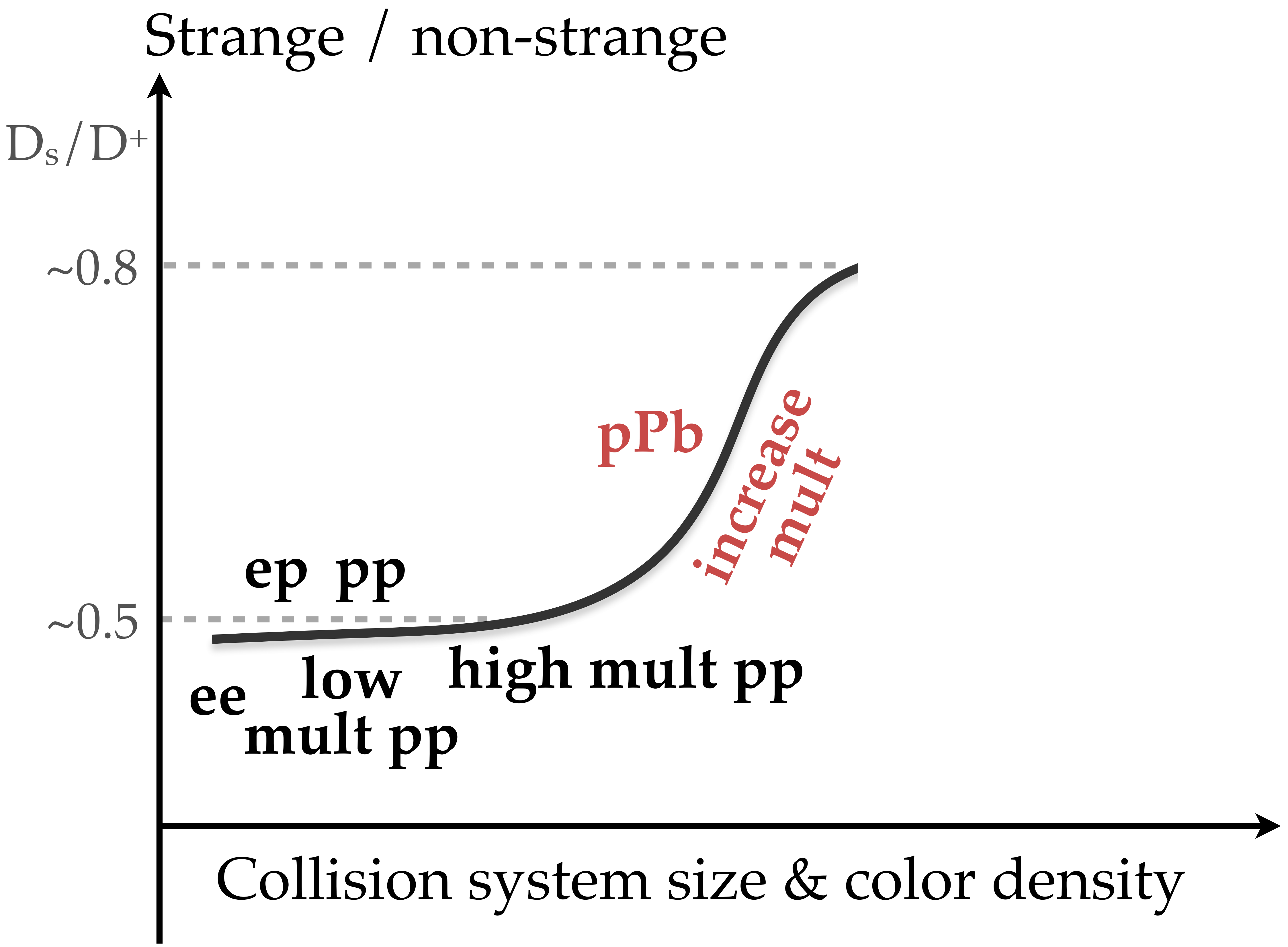


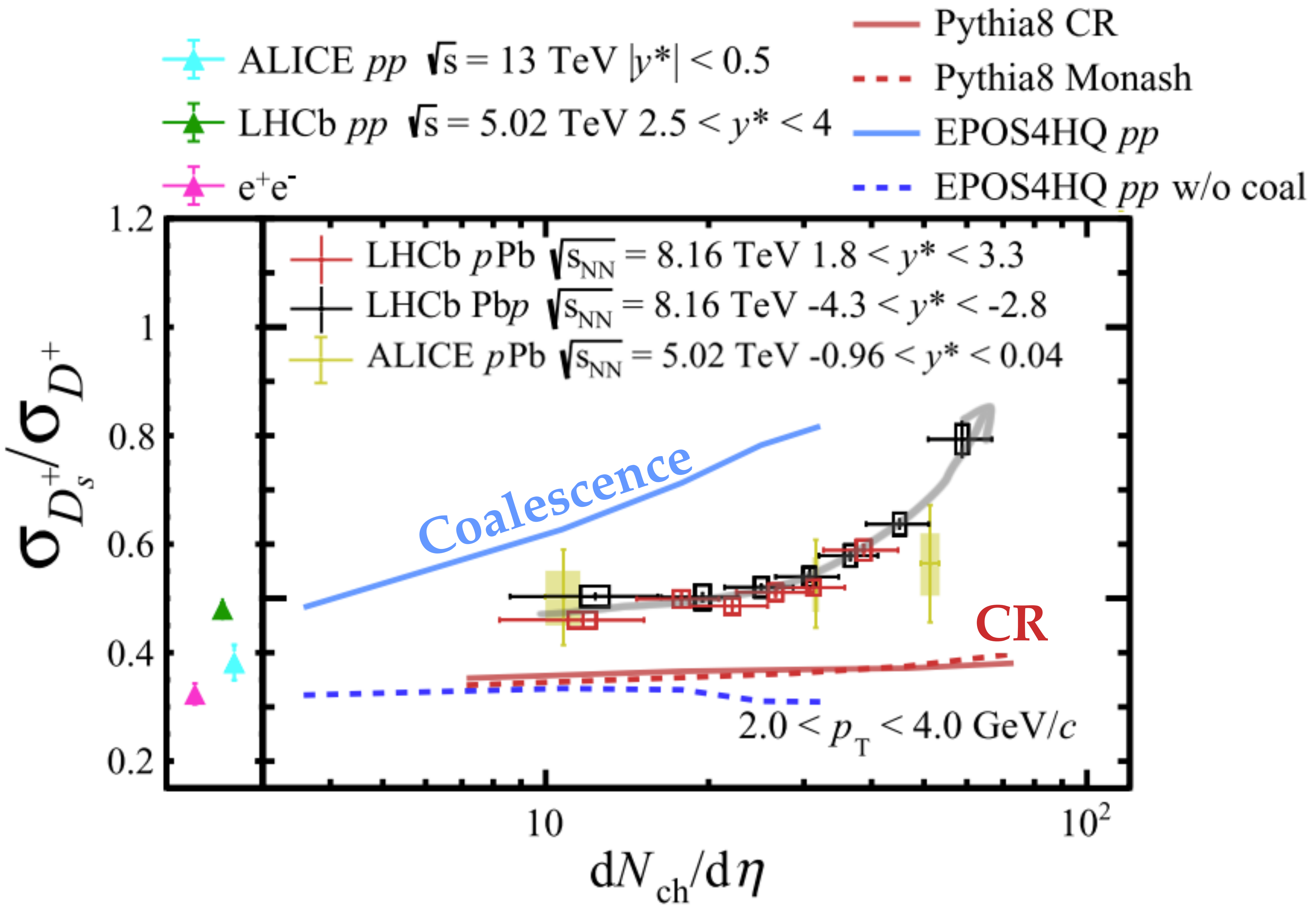
- No multiplicity dependence in pp

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

ALICE Fabio C.

Strangeness Across Collision Systems





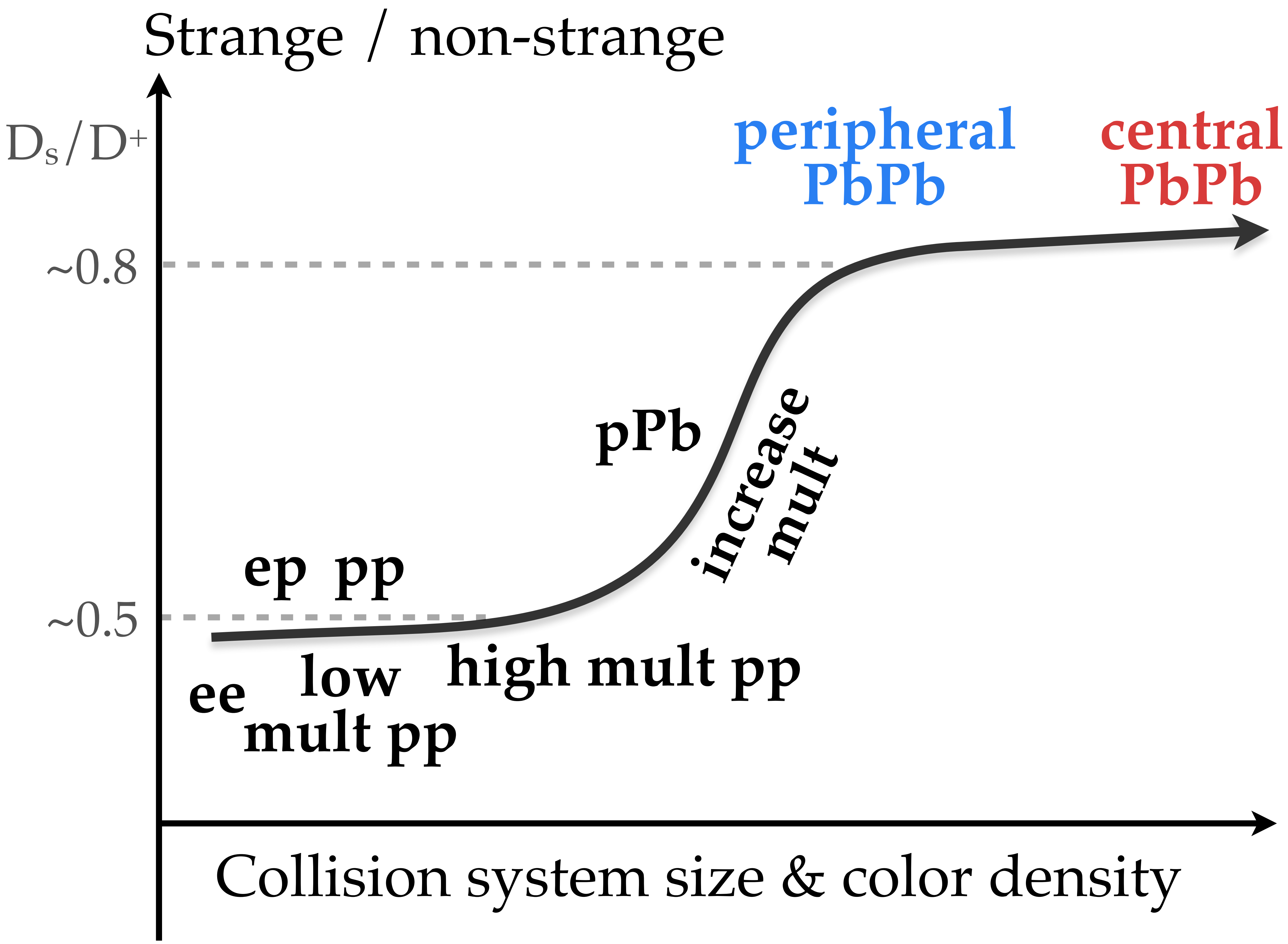
- Significant multiplicity dependence in pPb
- Coalescence models increases the ratio
  - **But** conflicting to pp results in this case

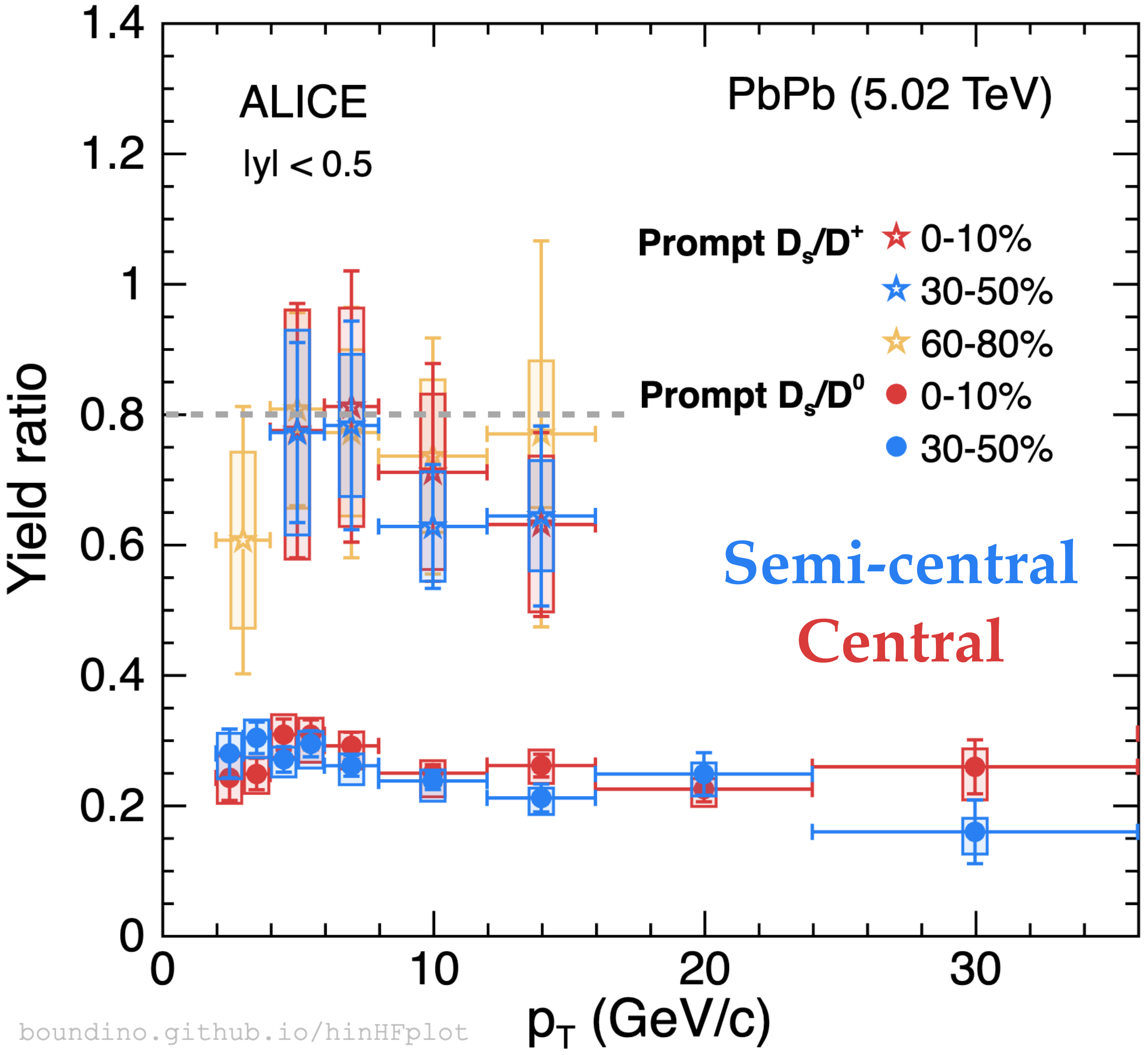
- **CR** has small effects → Models **e.g. Rope** describing LF can enhance strangeness by increasing string tension
  - **Curious** if it can describe the multiplicity dependence

LHCb Yiheng L.

LHCb PRD 110 (2024) L031105

Strangeness Across Collision Systems

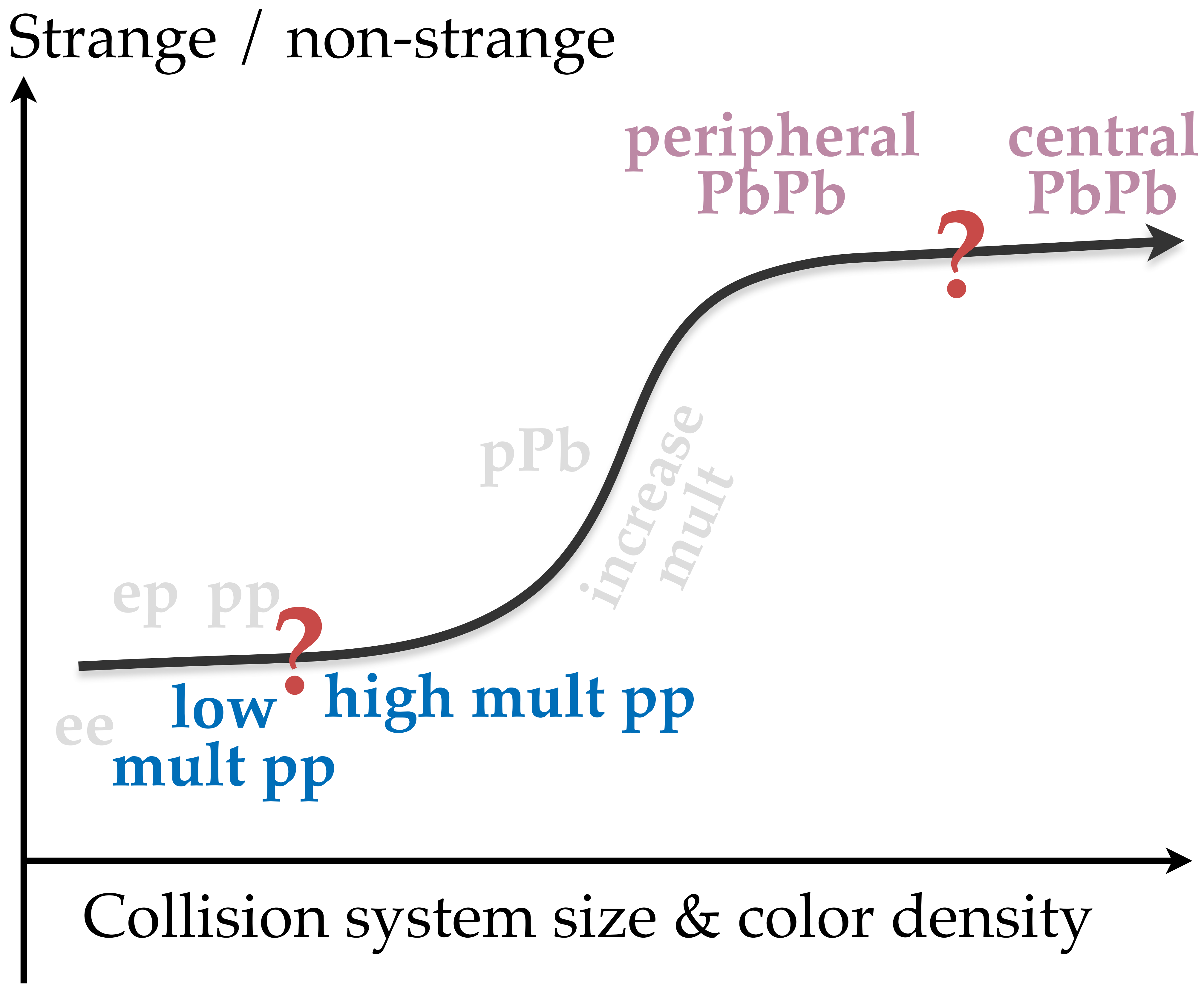




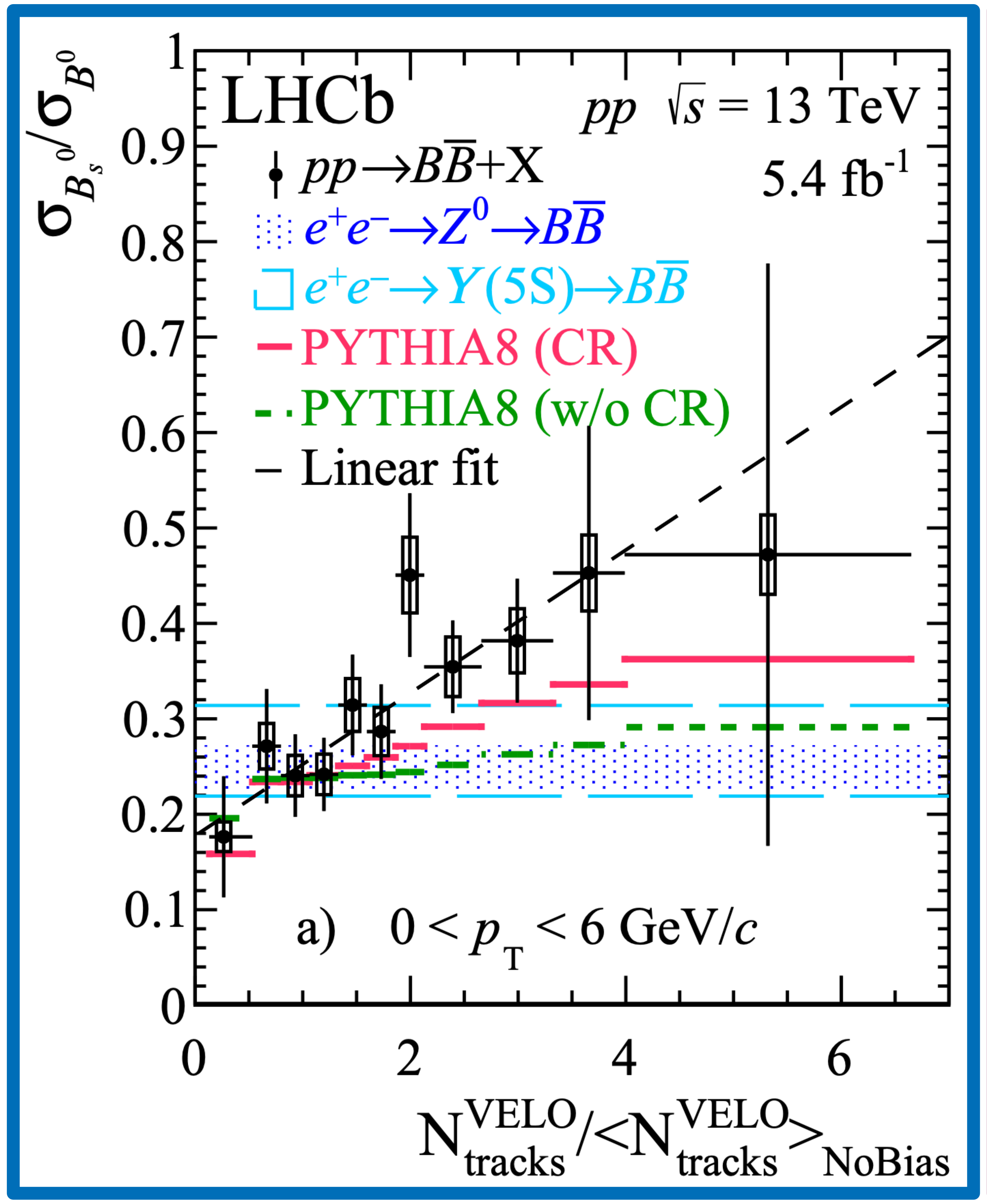
- No significant multiplicity dependence in PbPb
- Smoothly connected to high-multiplicity pPb

PLB 827 (2022) 136986
JHEP 10 (2018) 174
ALICE Fabio C.

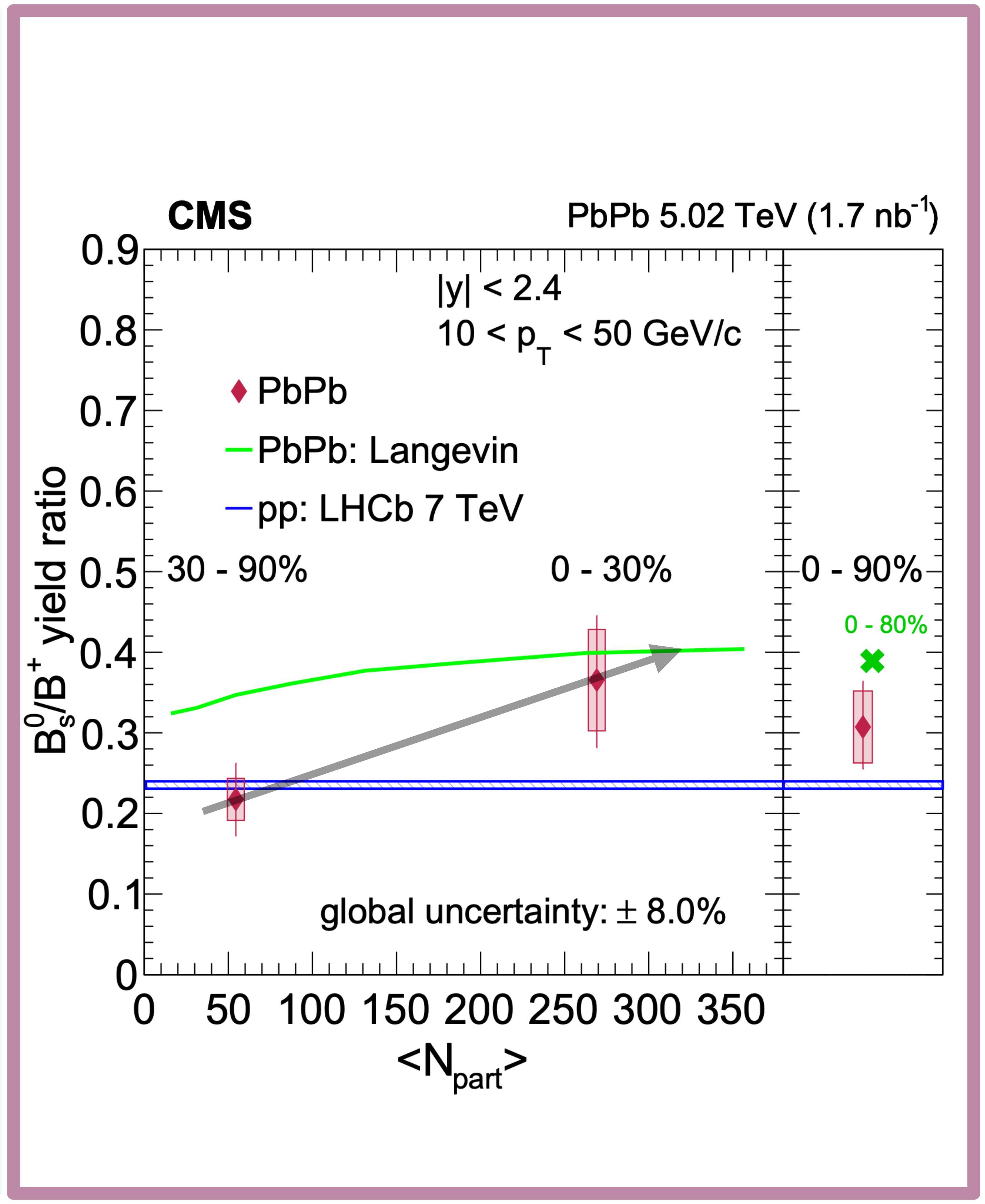
Strangeness Consistent Between D_s & B_s?



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 Julie B.

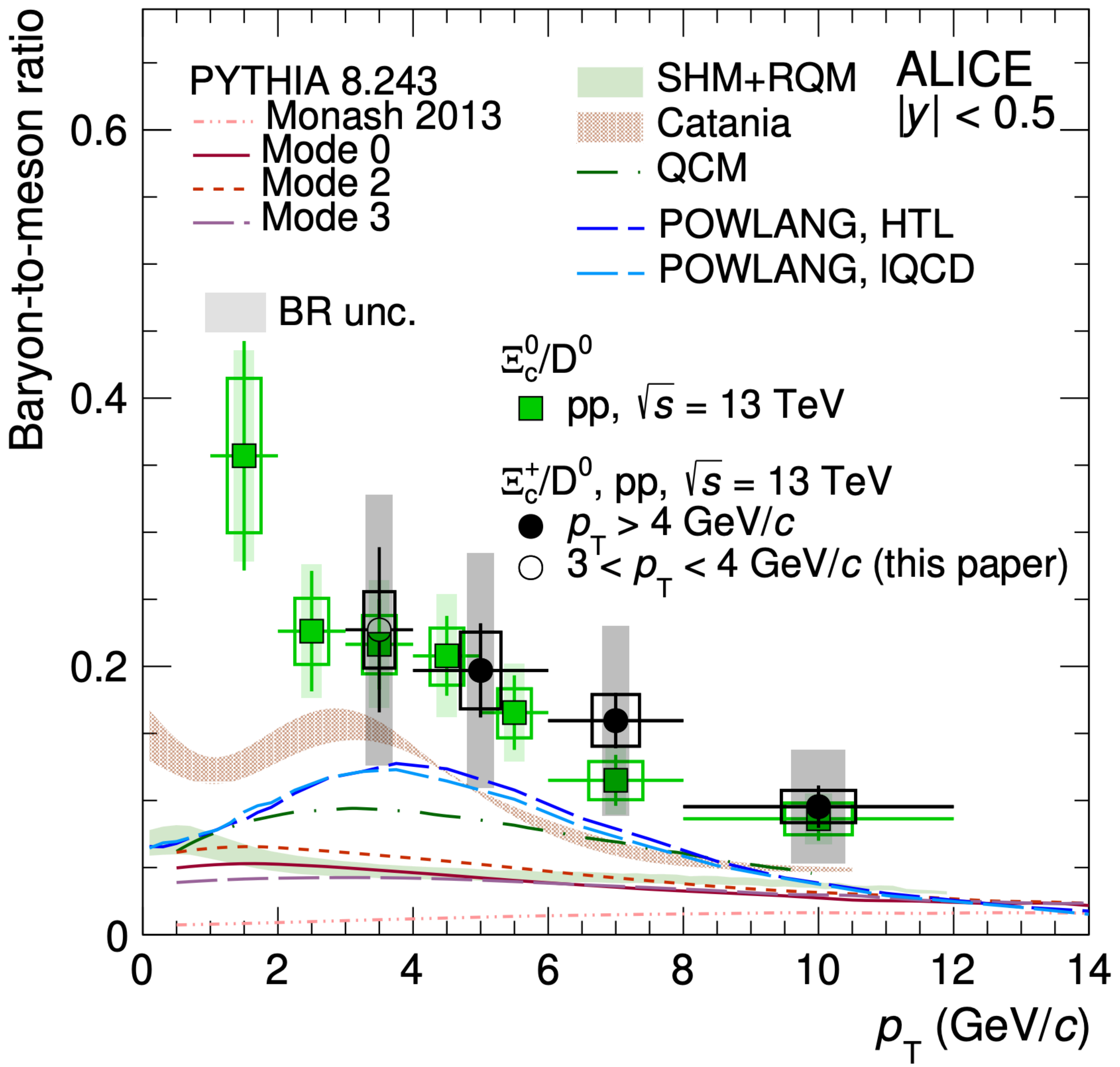
CMS Tzu-An S.

LHCb PRL 131 (2023) 061901

CMS PLB 829 (2022) 137062

More Challenges Strange Charm Baryons

Ξ_c / D^0 in pp



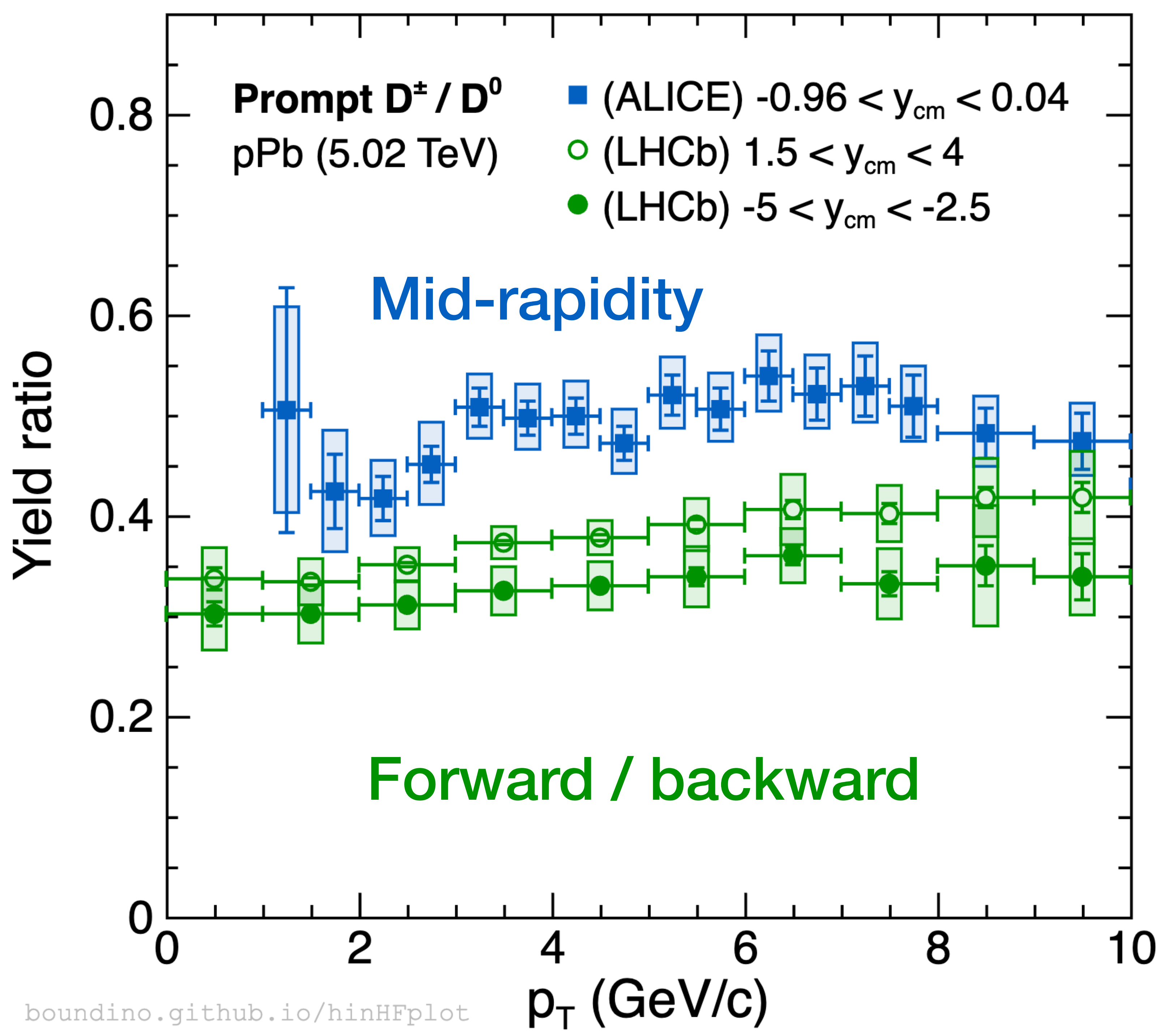
ALICE JHEP 12 (2023) 086

- 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

ALICE Federica Z.

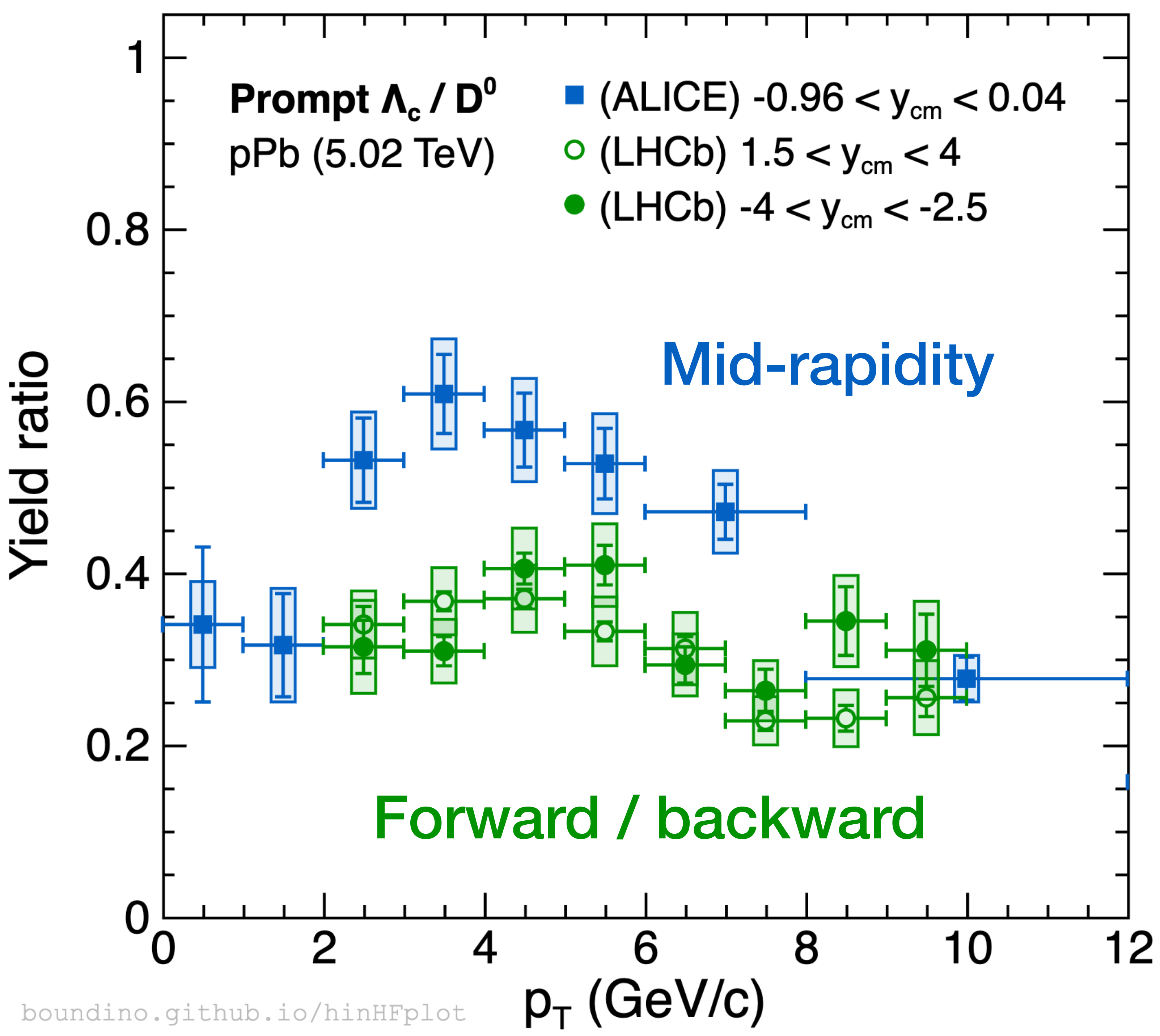
More Challenges Rapidity Dependence

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



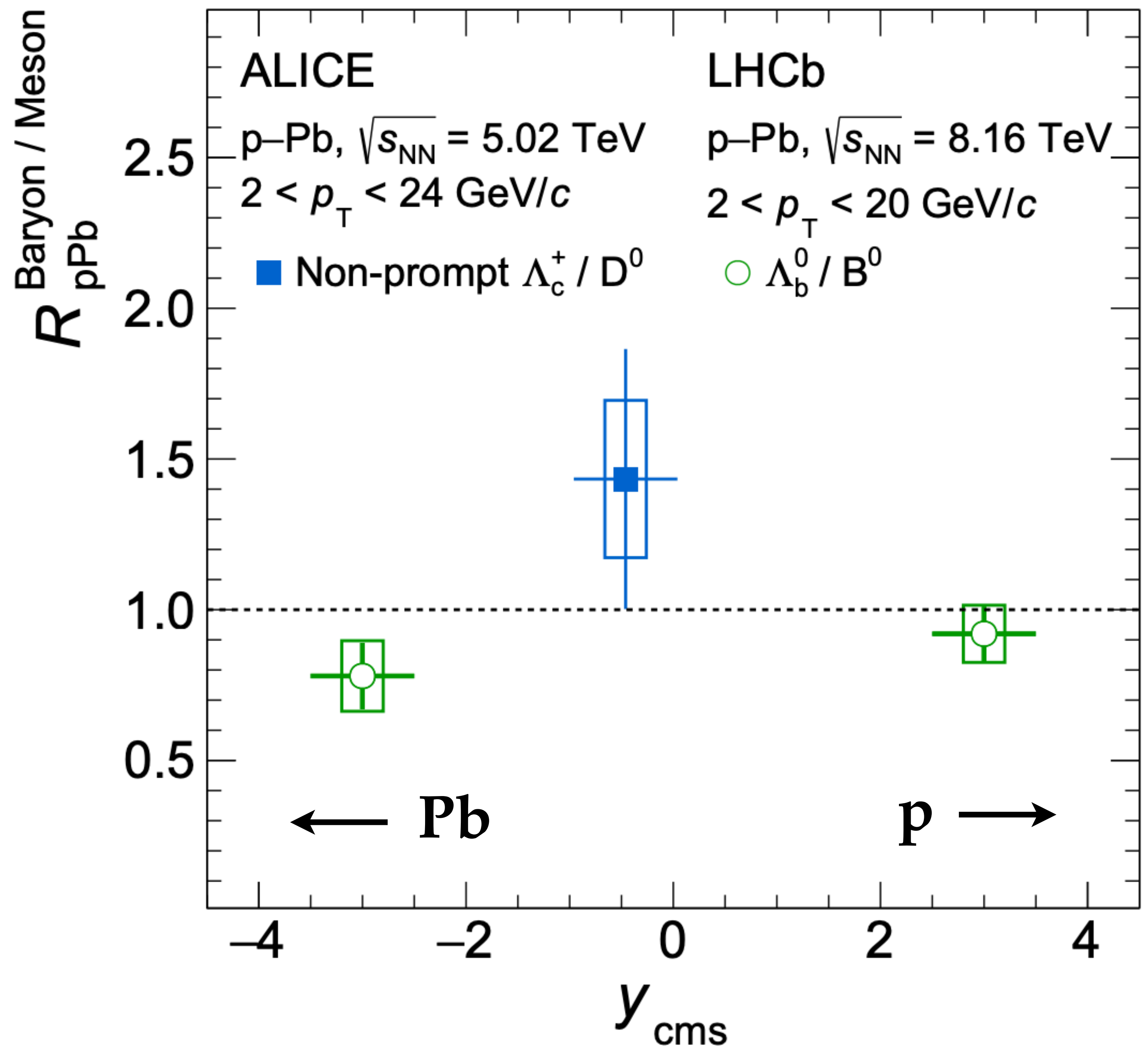
ALICE JHEP 12 (2019) 092
LHCb JHEP 01 (2024) 070

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

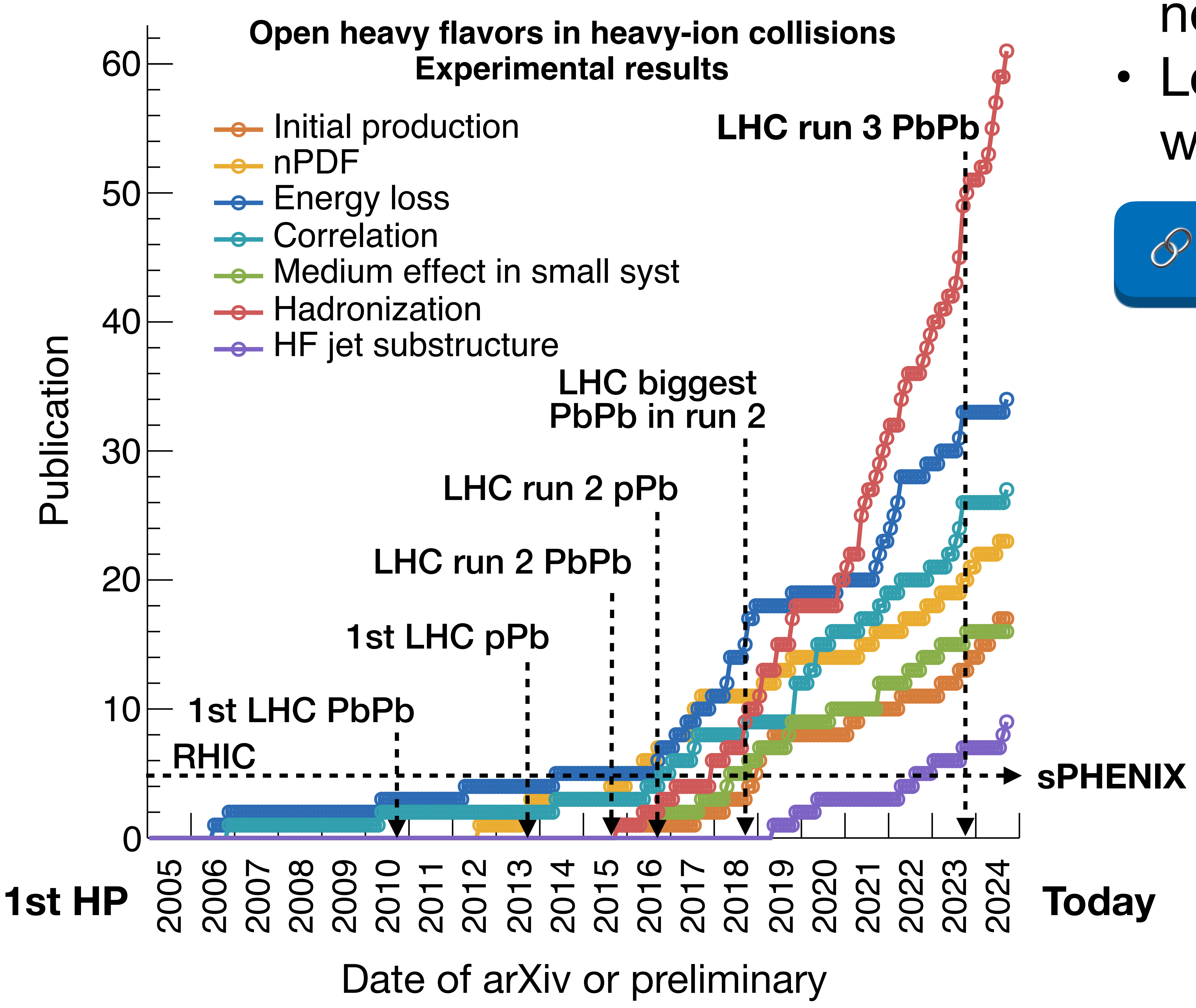


ALICE arXiv:2407.10593
LHCb PRD 99 (2019) 052011

- **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!

ALICE Andrea G.
LHCb Yiheng L.

Enjoy!

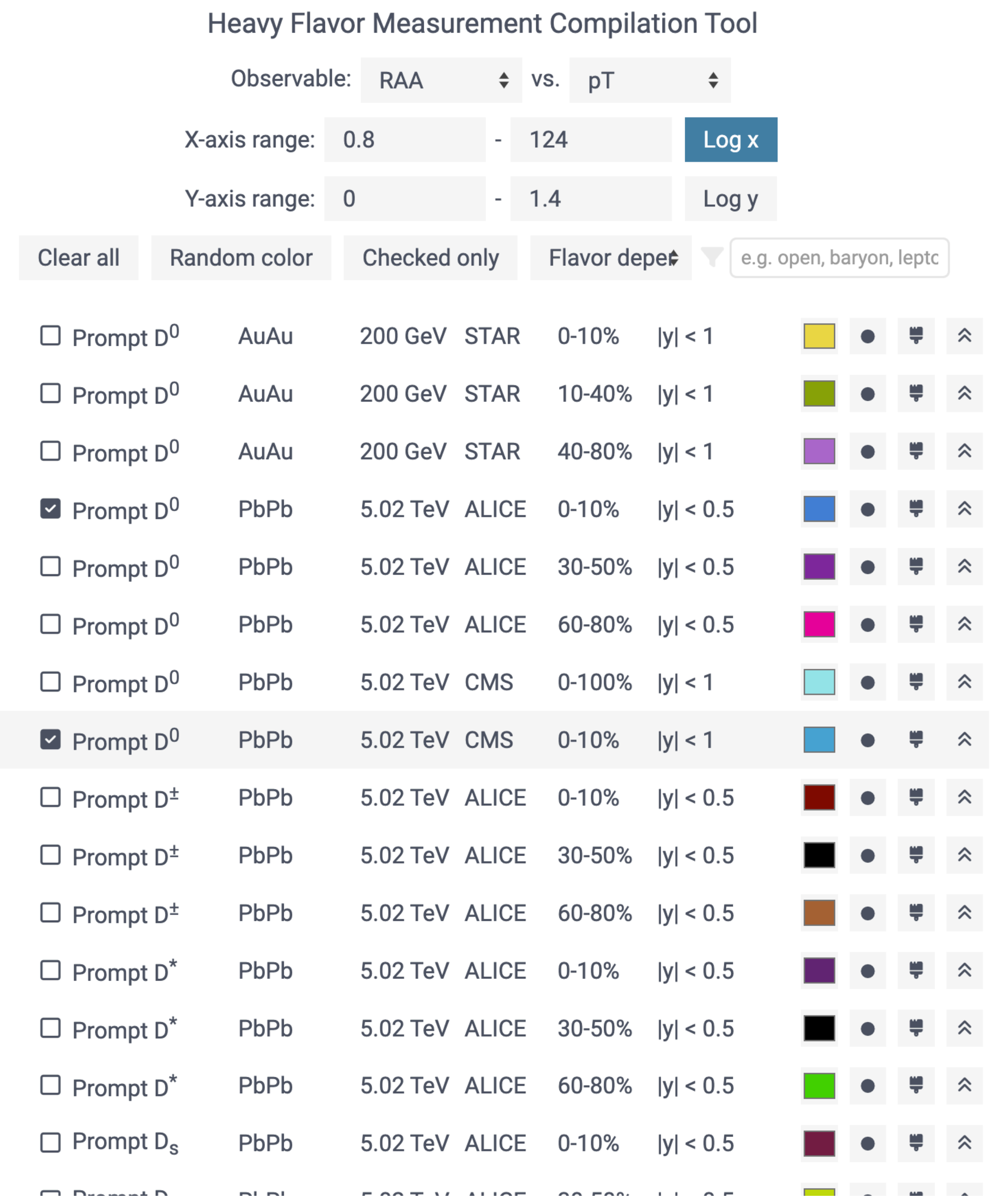


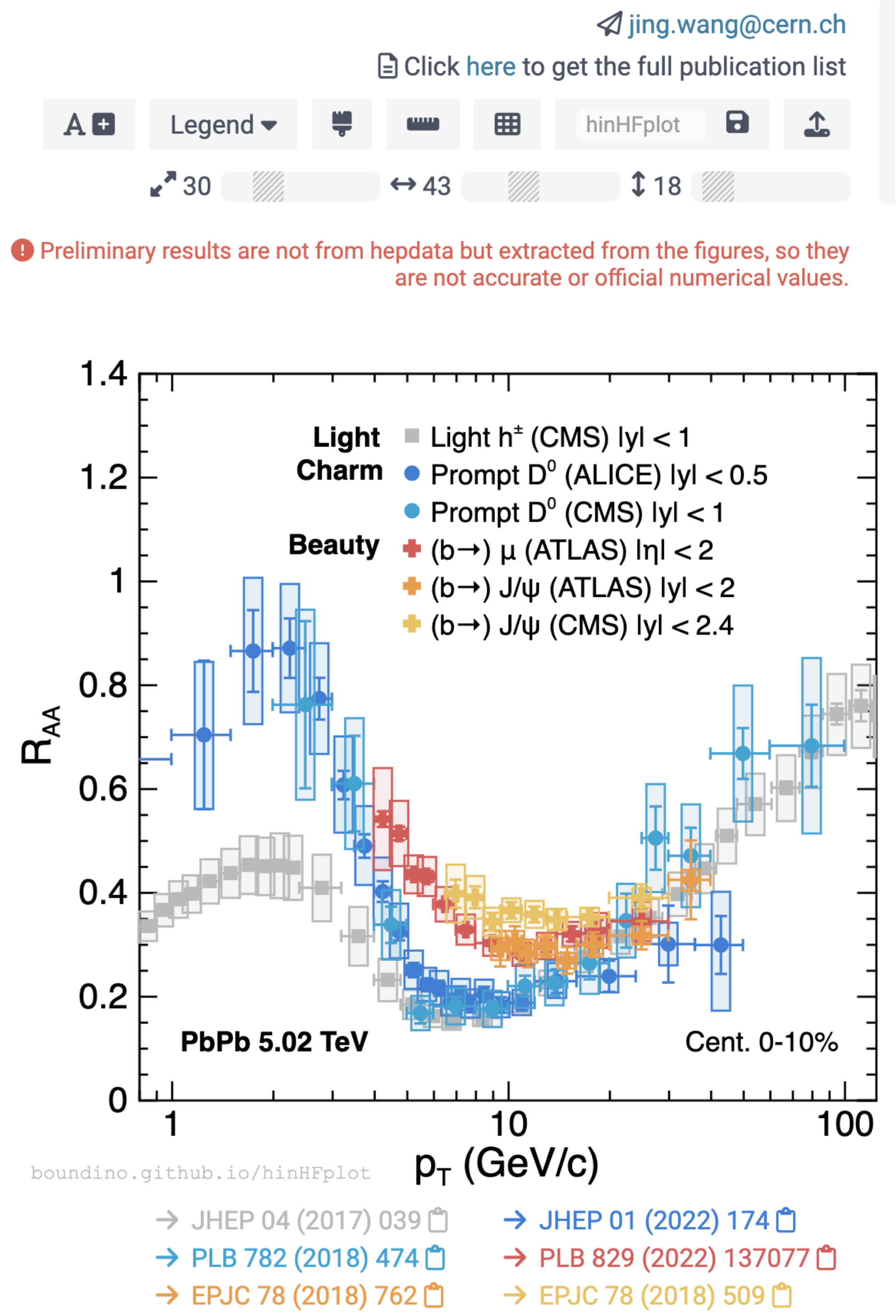
*The earlier the more inaccurate, apologies…

- Clearly see new data triggered new analysis techniques, new physics topics, and surges in measurements
- Look forward to seeing a lot of more exciting HF physics with **LHC Run 3** and **sPHENIX**!

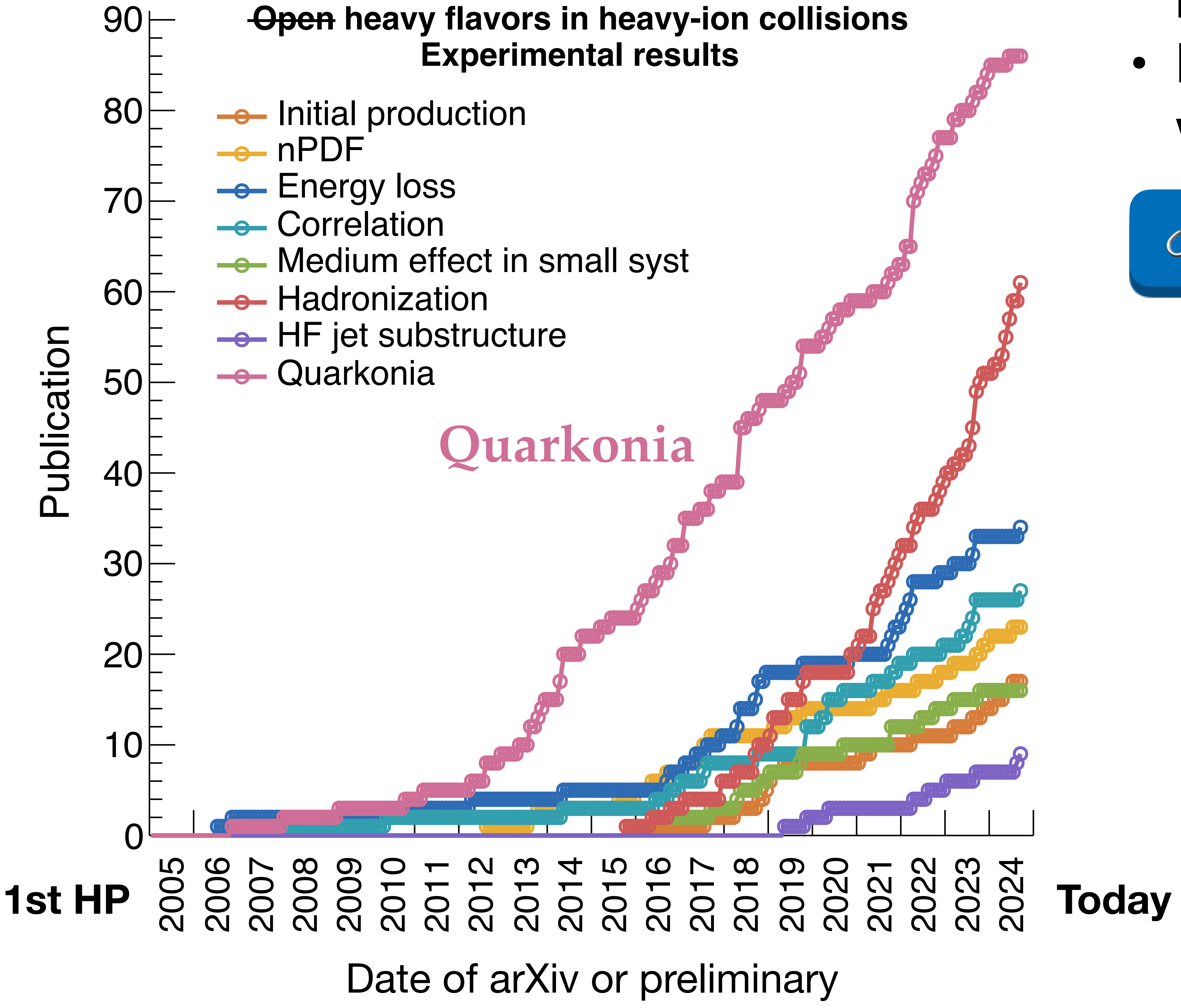
🔗 Heavy flavor result playground

🔗 Open HF results in HP'2024





Enjoy More!



- Clearly see new data triggered new analysis techniques, new physics topics, and surges in measurements
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🔗 Heavy flavor result playground

🔗 Open HF results in HP'2024

Next talks!

*The earlier the more inaccurate, apologies…

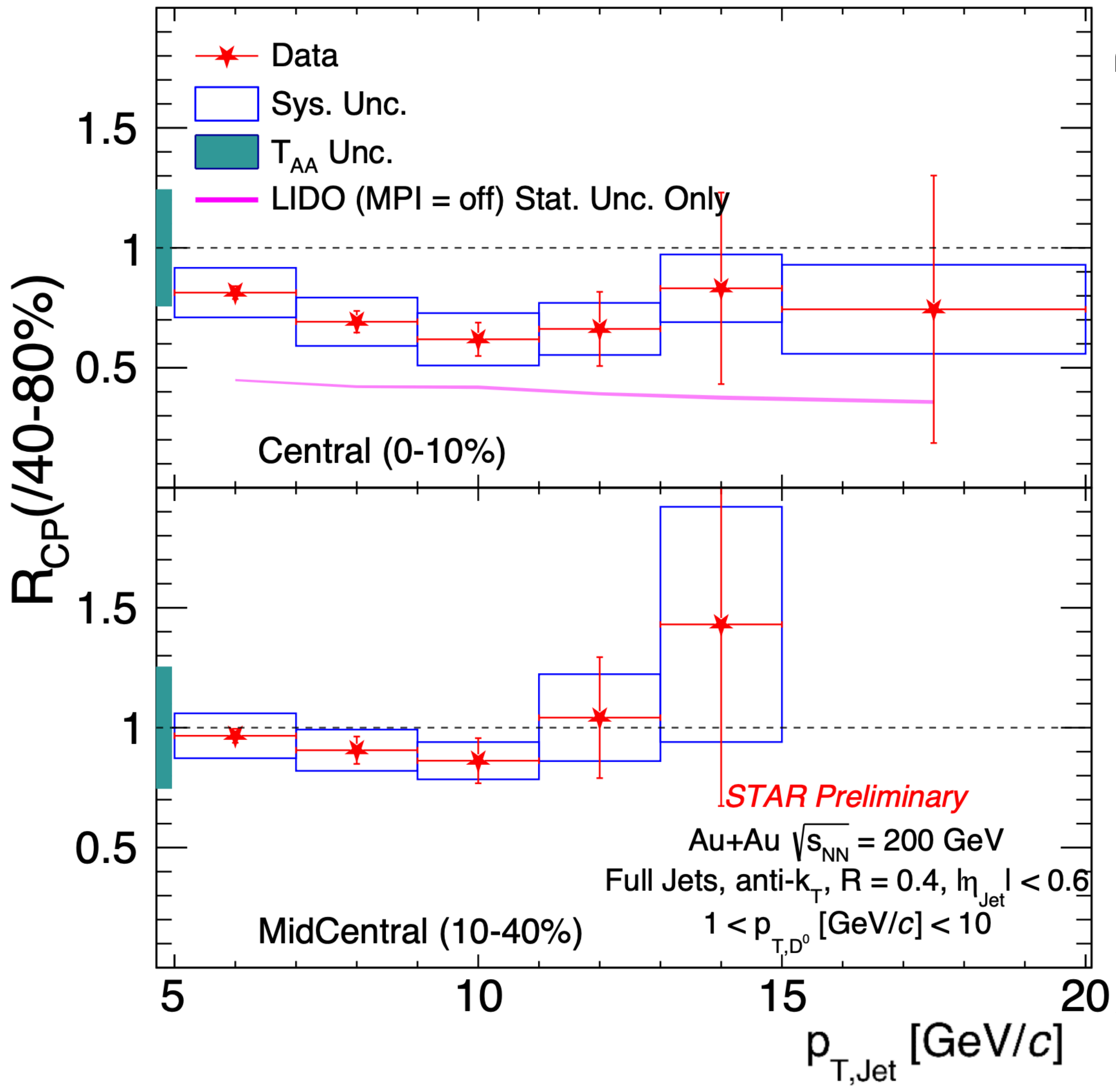

Isabelle
Thanks for your attention!

Hadronization My Thoughts

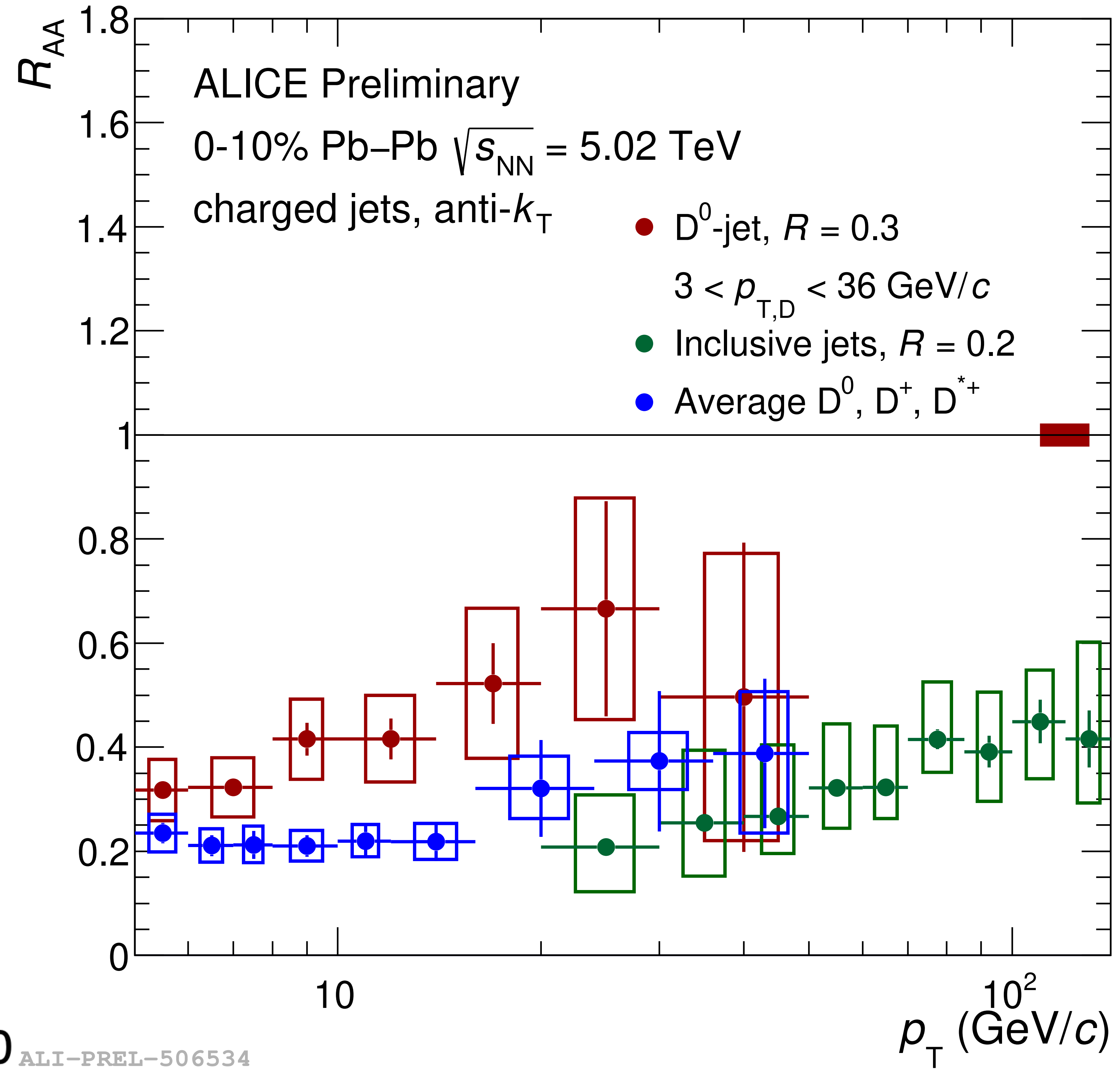
- Multiplicity is not the best scale for system scan
- Hope models can calculate all the different systems simultaneously

Quenching Heavy-Flavor Tagged Jets

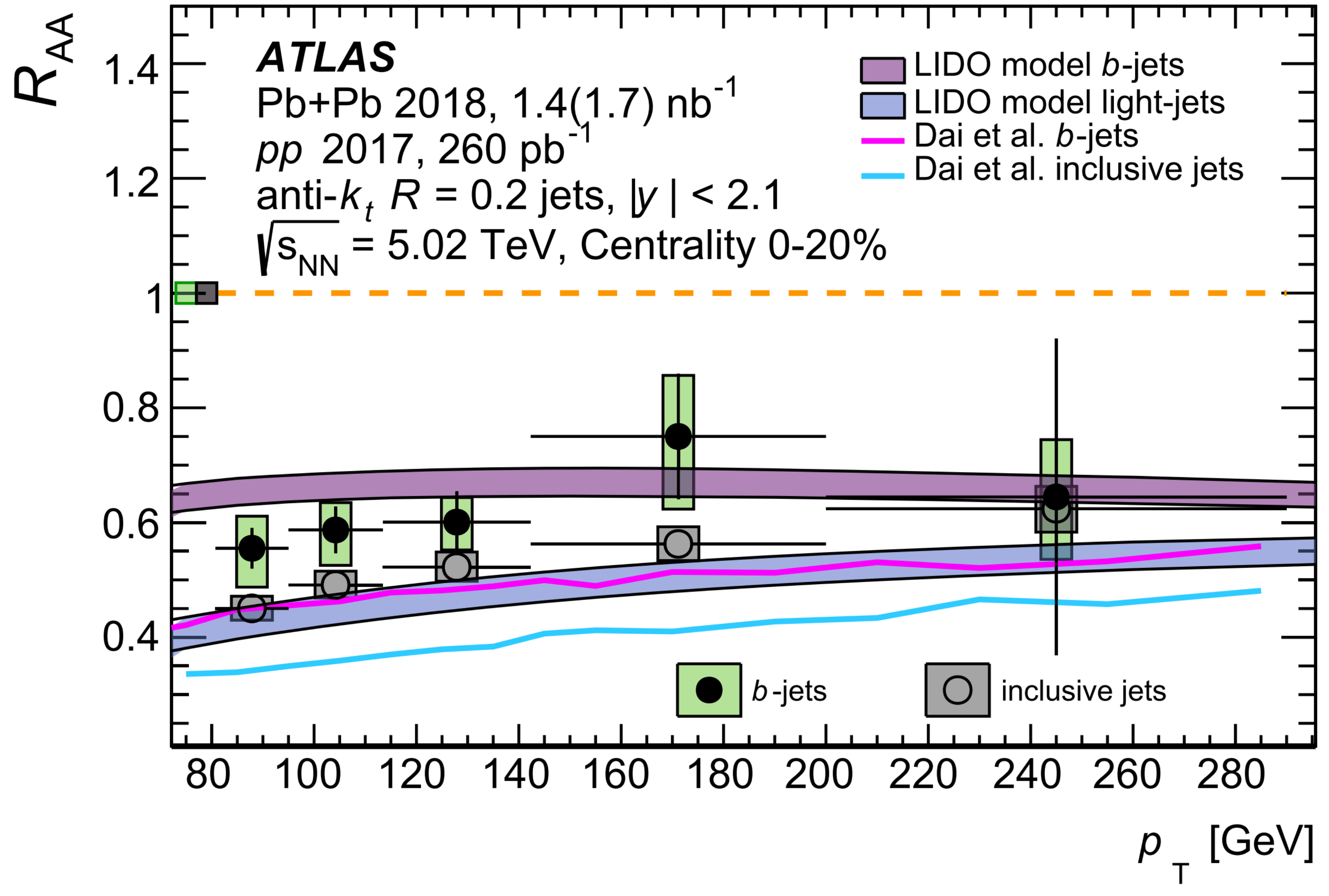
D-tagged jet R_{CP} AuAu



D-tagged jet R_{AA} PbPb



b-tagged jet R_{AA} PbPb



ATLAS EPJC 83 (2023) 438

ATLAS Soumya M.
STAR Diptanil R.
ALICE Jochen K.

PYTHIA Color Reconnection Modes

3 Constraints and Tuning

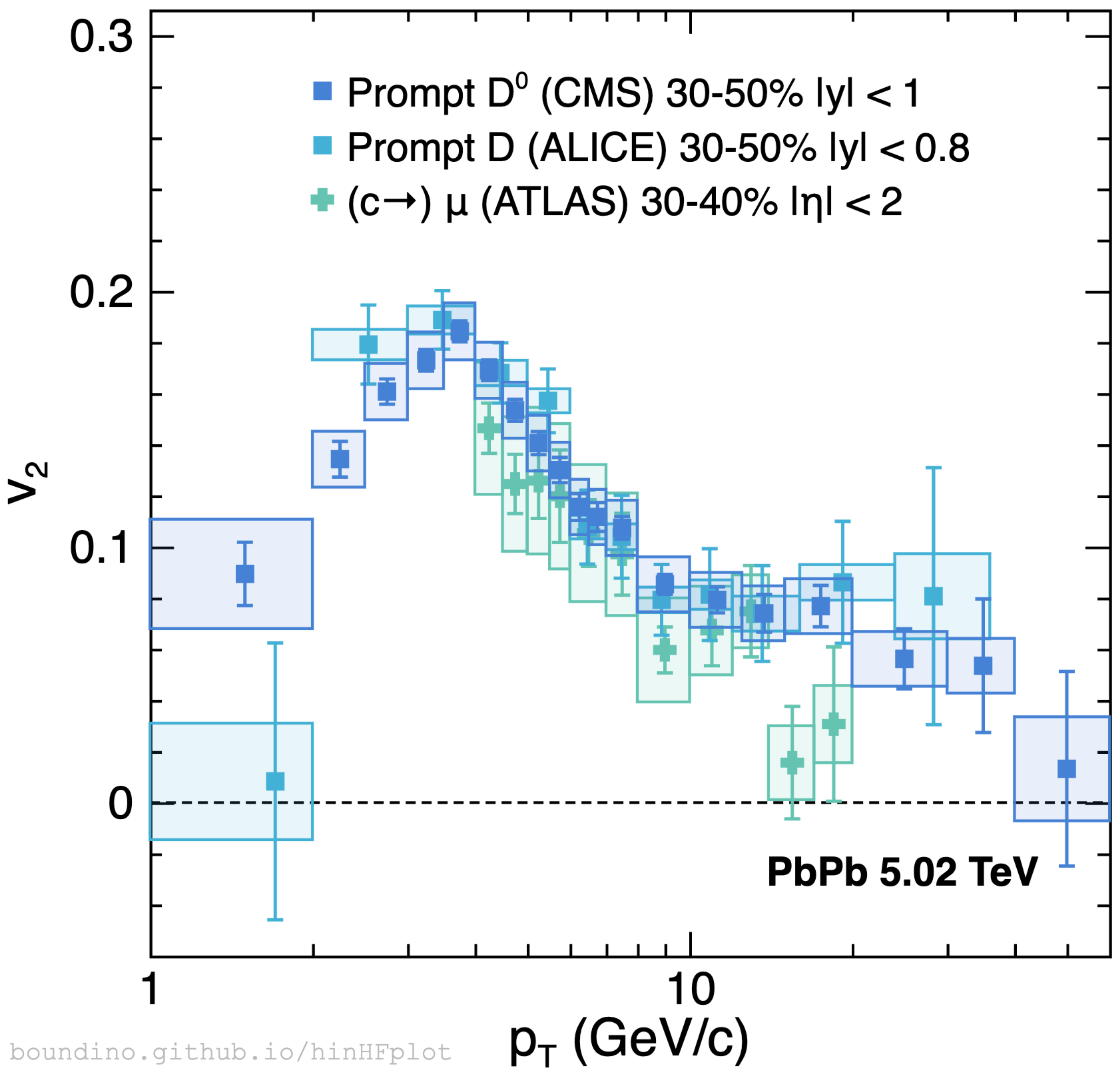
The tuning scheme follows the same procedure as for the Monash 2013 tune [34]. However at a more limited scope, since only CR parameters, and ones strongly correlated with them, are tuned. As a natural consequence of this, the Monash tune was chosen as the baseline. As discussed in section 2.3.4, several 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:

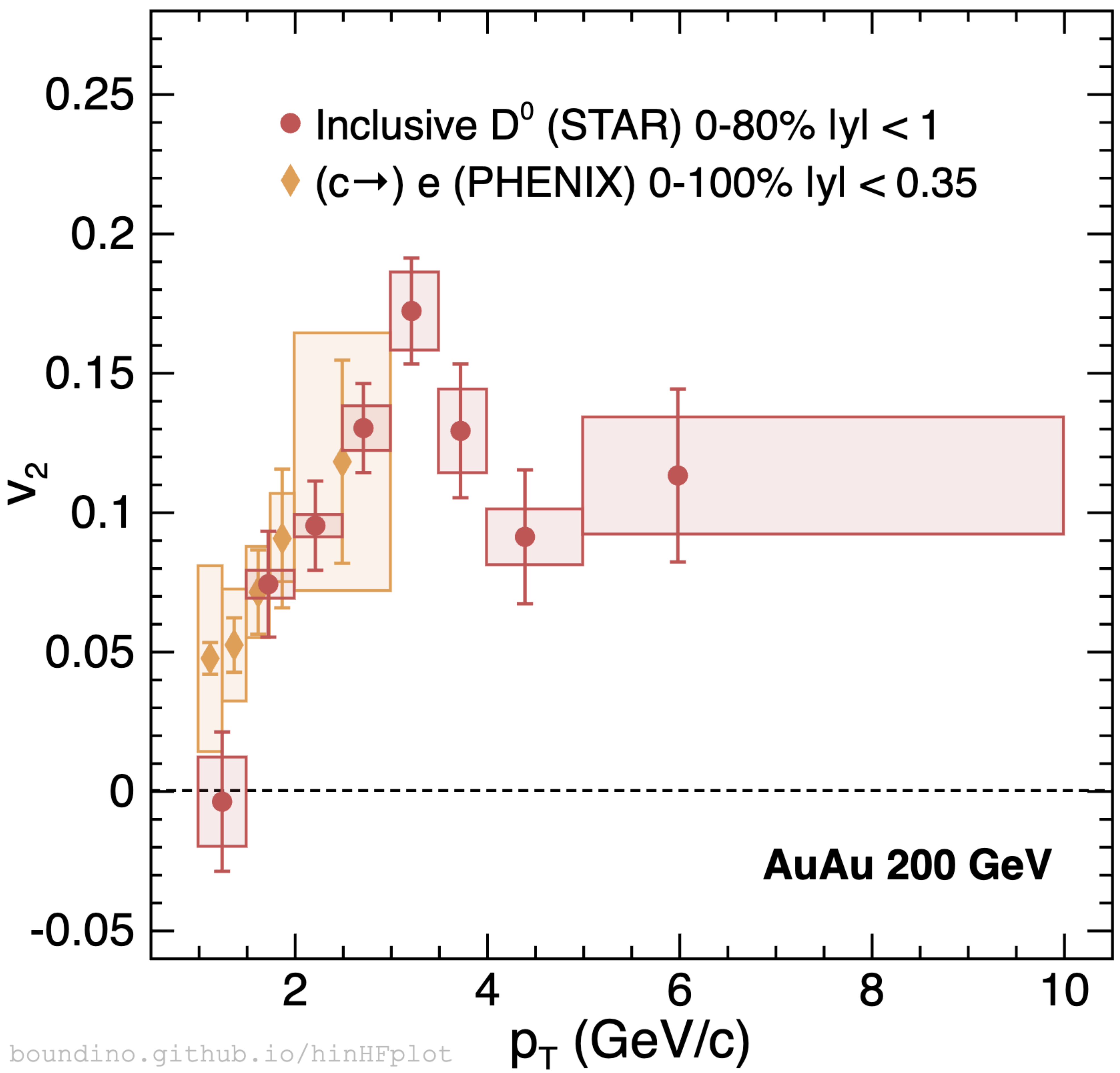
- Mode 0: no time-dilation constraints. m_0 controls the amount of CR (mode 0);
- Mode 2: time dilation using the boost factor obtained from the final-state mass of the dipoles, requiring all dipoles involved in a reconnection to be causally connected (strict);
- Mode 3: time dilation as in Mode 2, but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

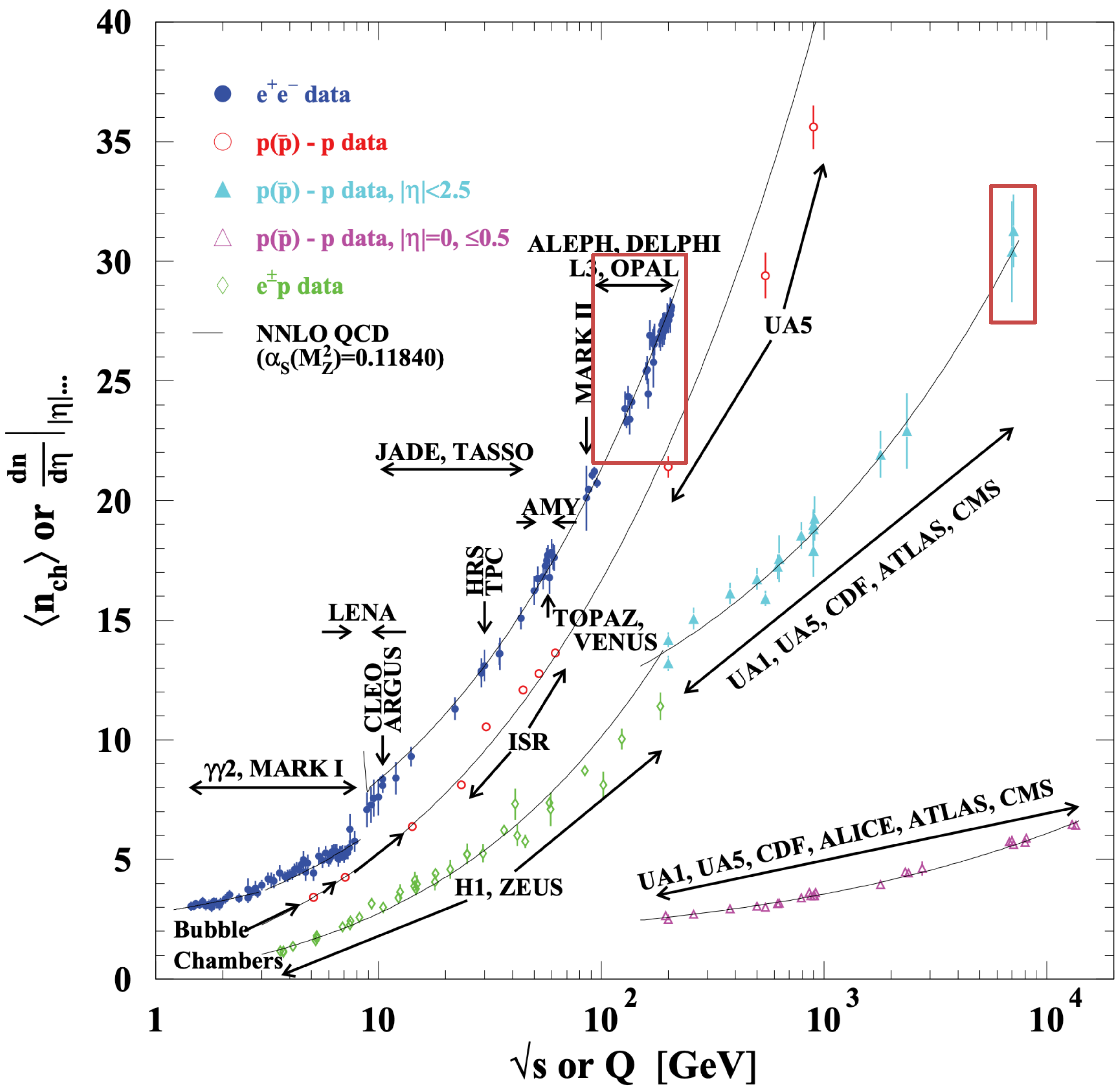




PHENIX **Julia V.**

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

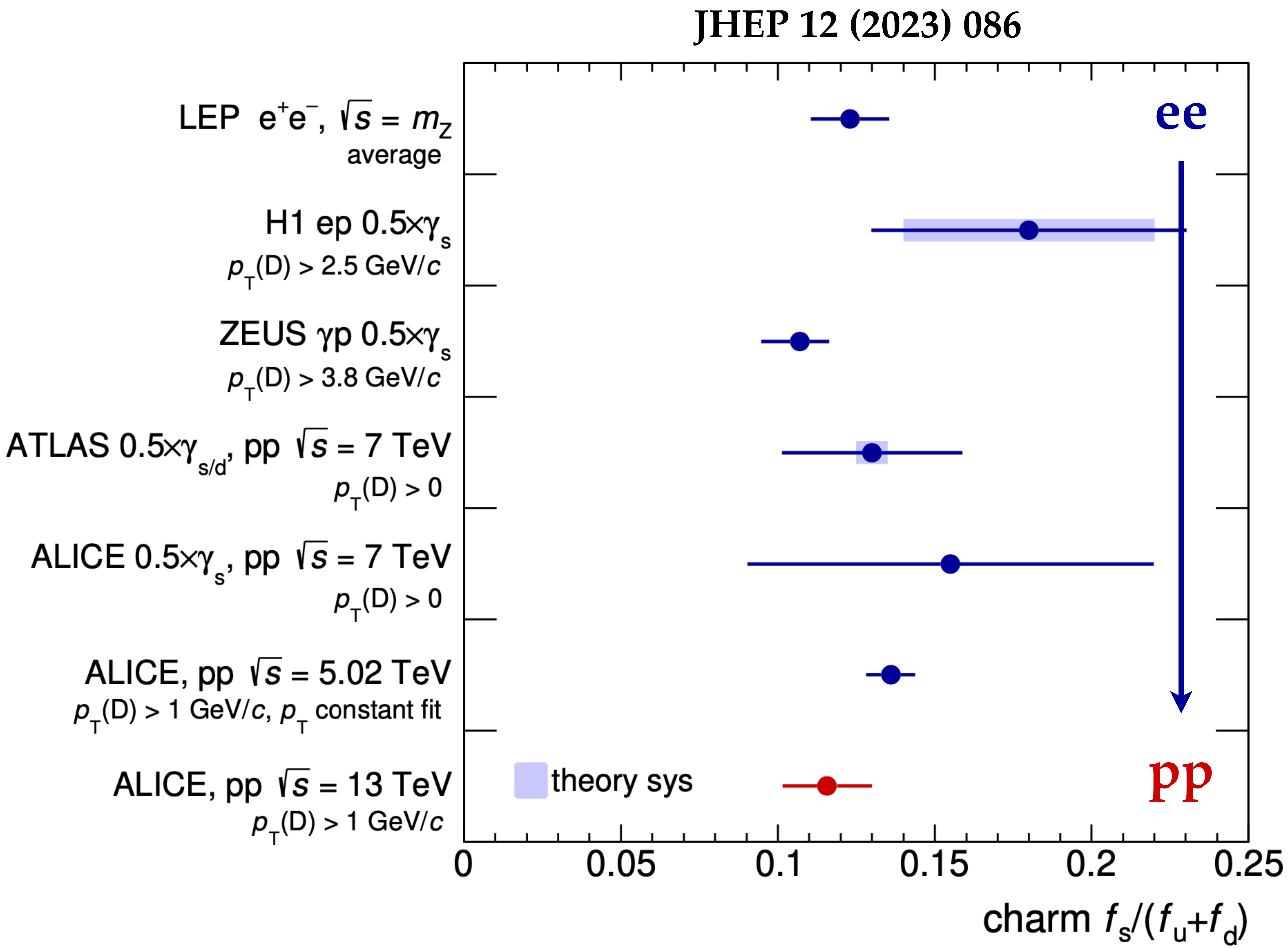
Multiplicity LEP vs LHC

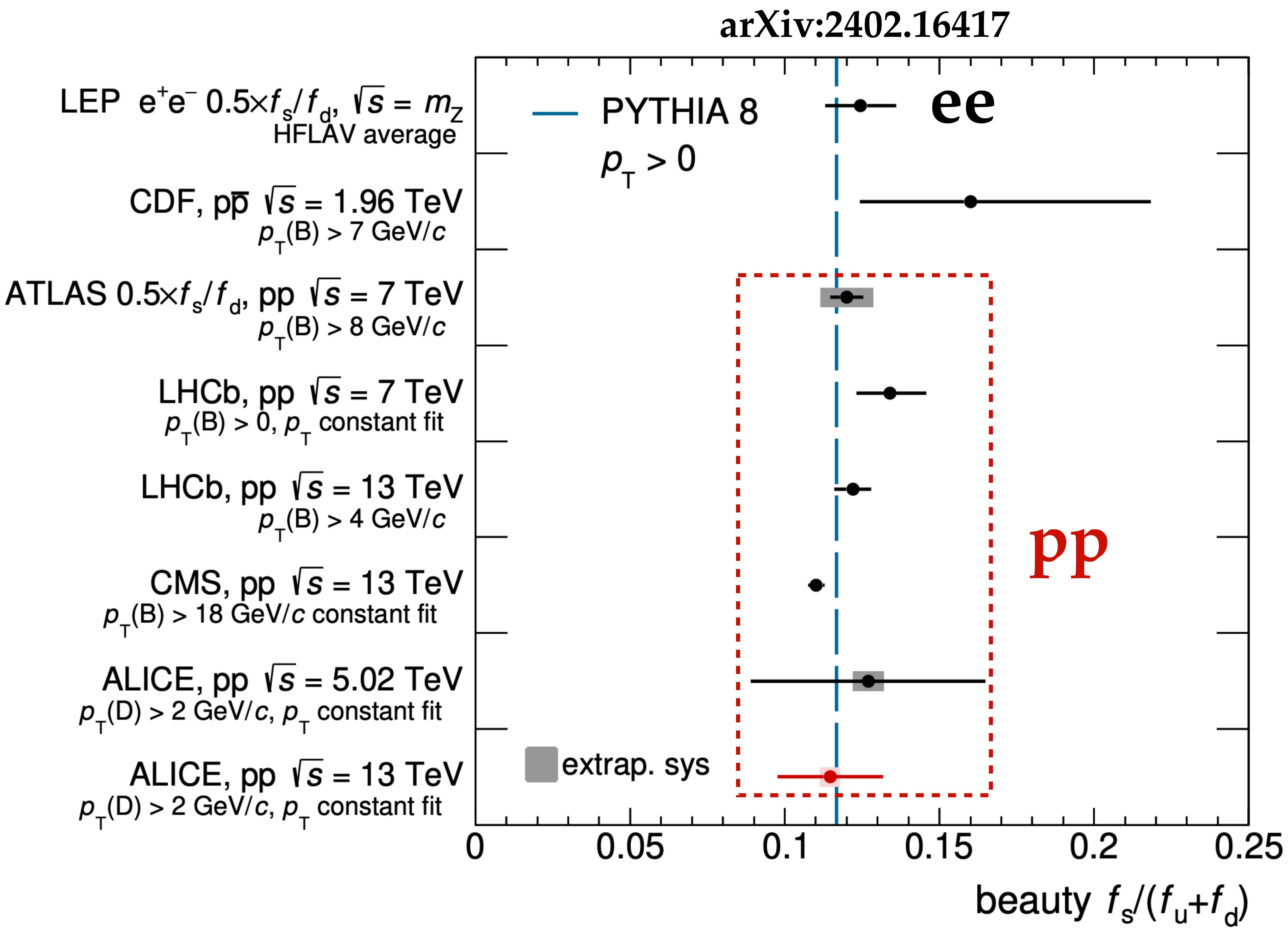


- Multiplicity is not much different between LEP ee and LHC pp

PDG PTEP 2022, 083C01

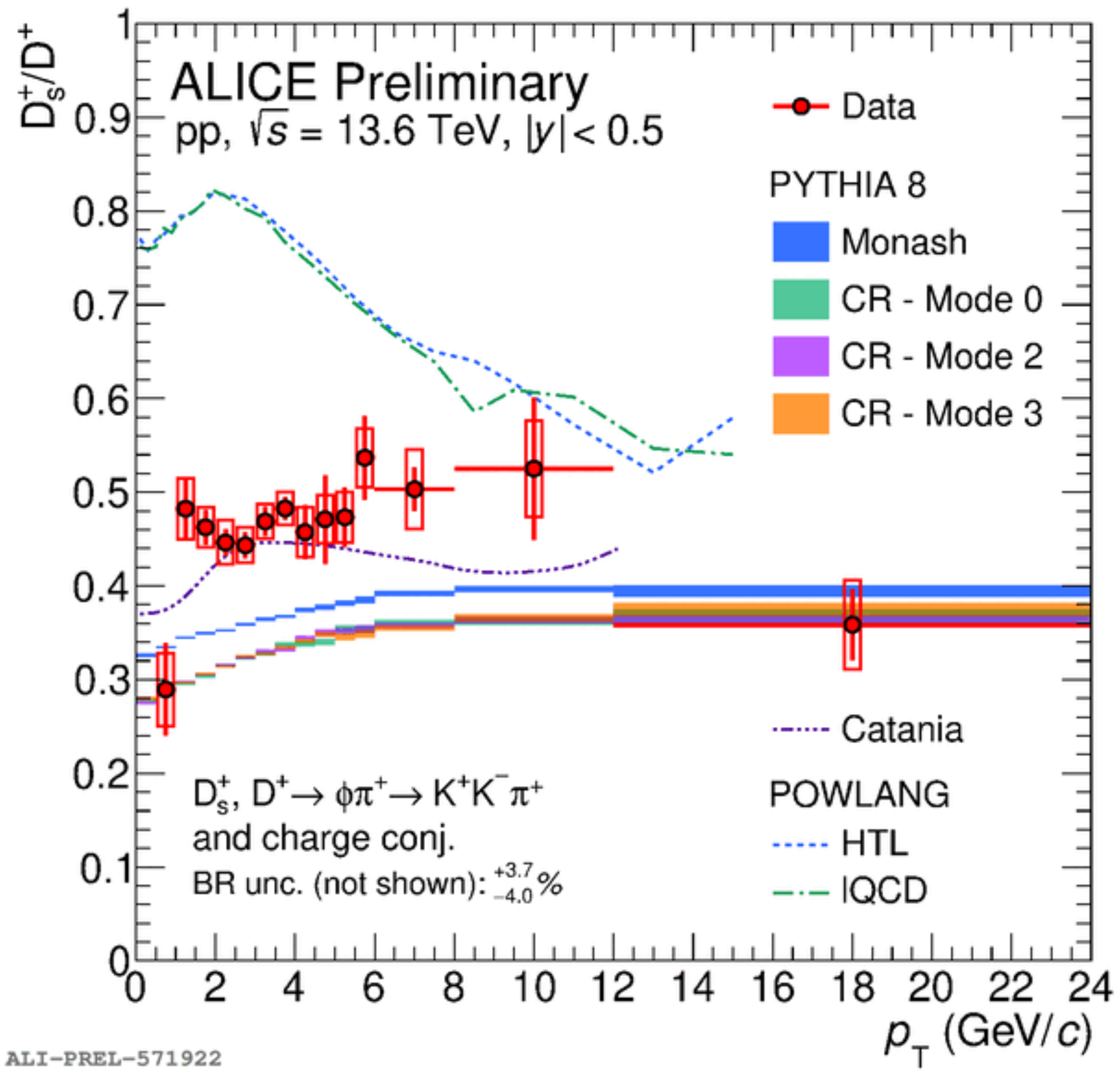
Strangeness LEP vs LHC





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

Strangeness Across Collision Systems

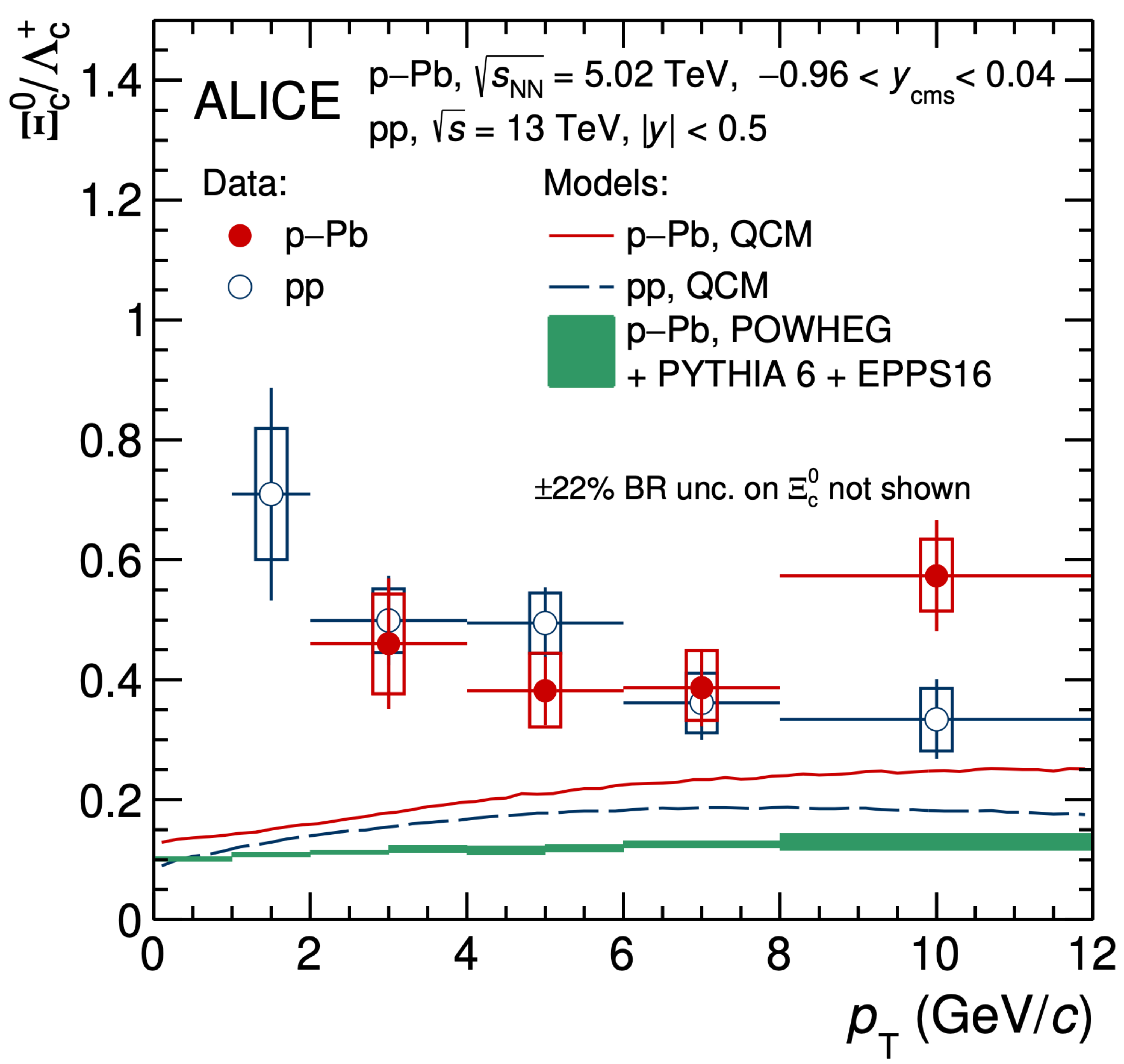


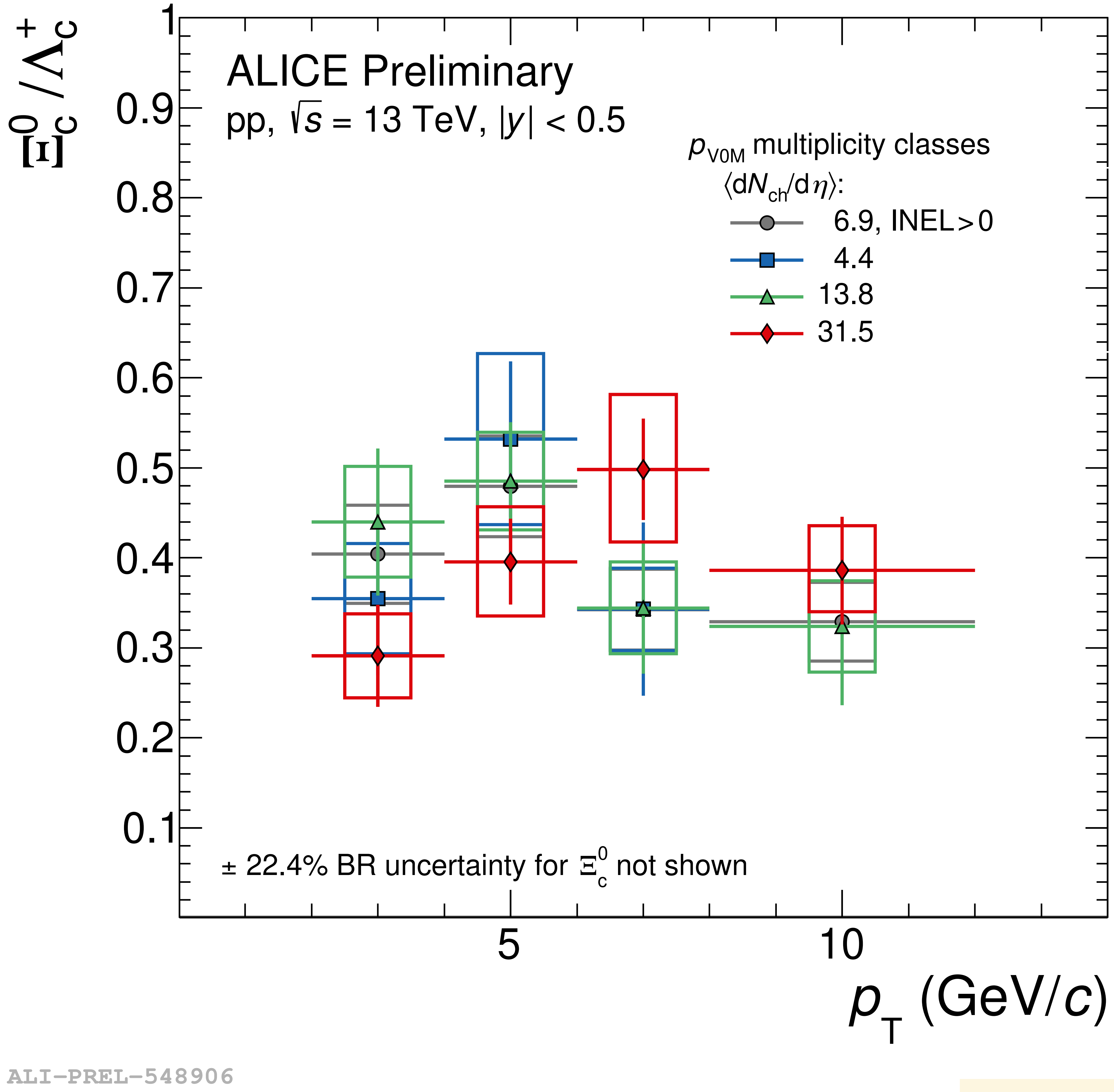
- p_T dependence is not flat when going to very low p_T?
- Why PYTHIA CR can describe D_s/D^0 in pp but not D_s/D^+?
  - Why CR reduces D_s/D^+?

ALICE **Fabio C.**

Ξ_c / Λ_c In pPb and Multiplicity Dependence

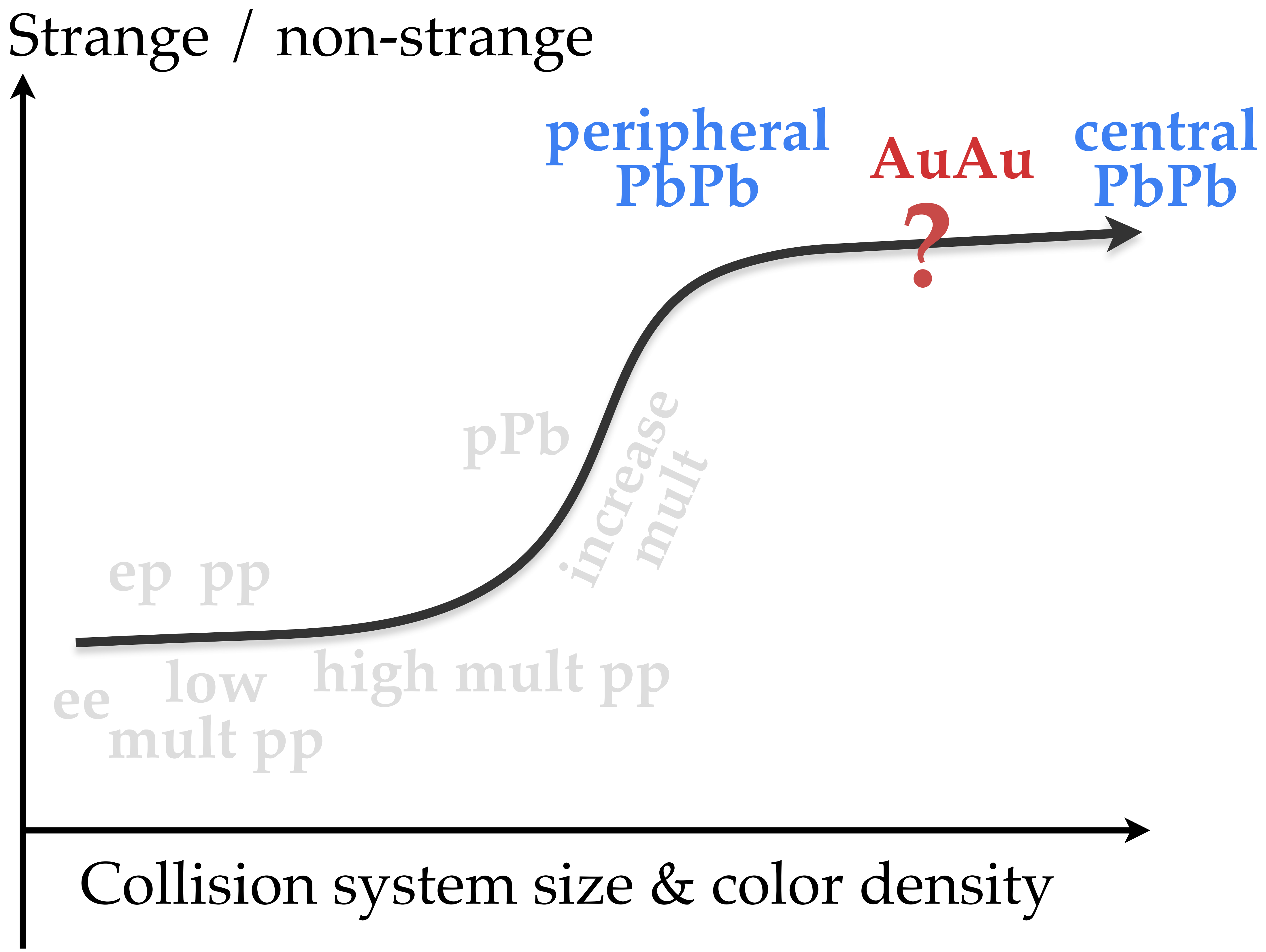
arXiv:2405.14538

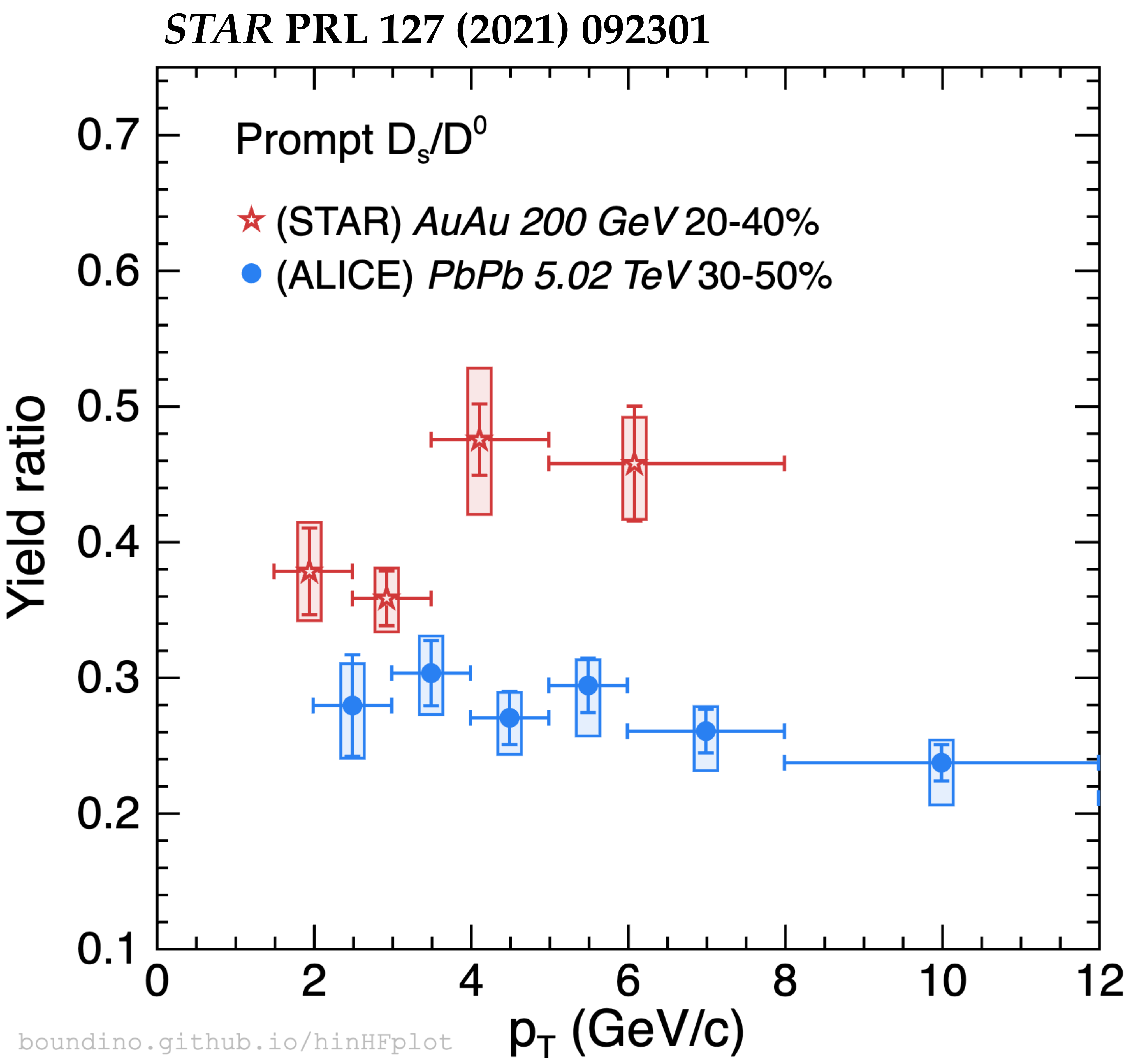




ALICE Fabio C.

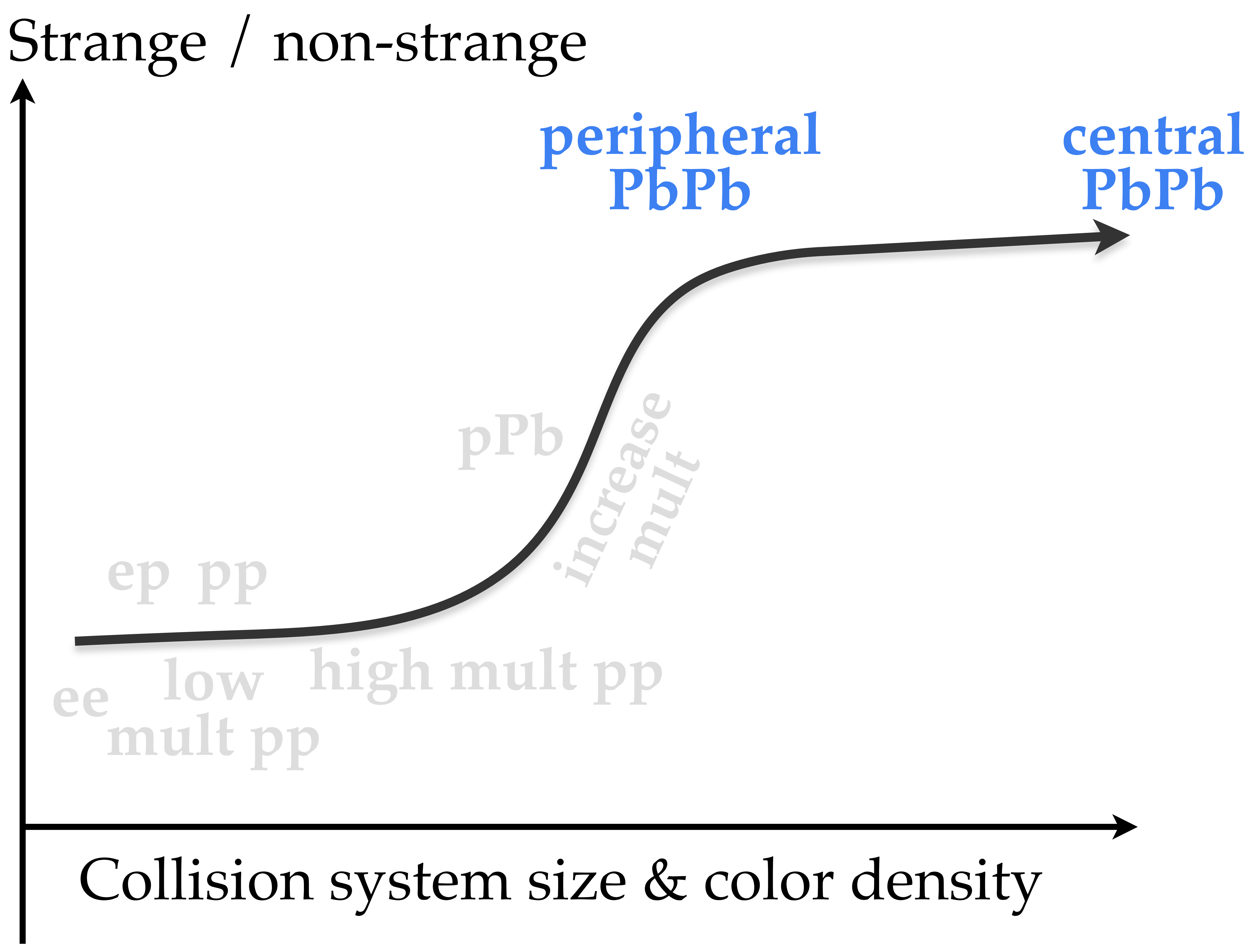
Strangeness Across Collision Systems

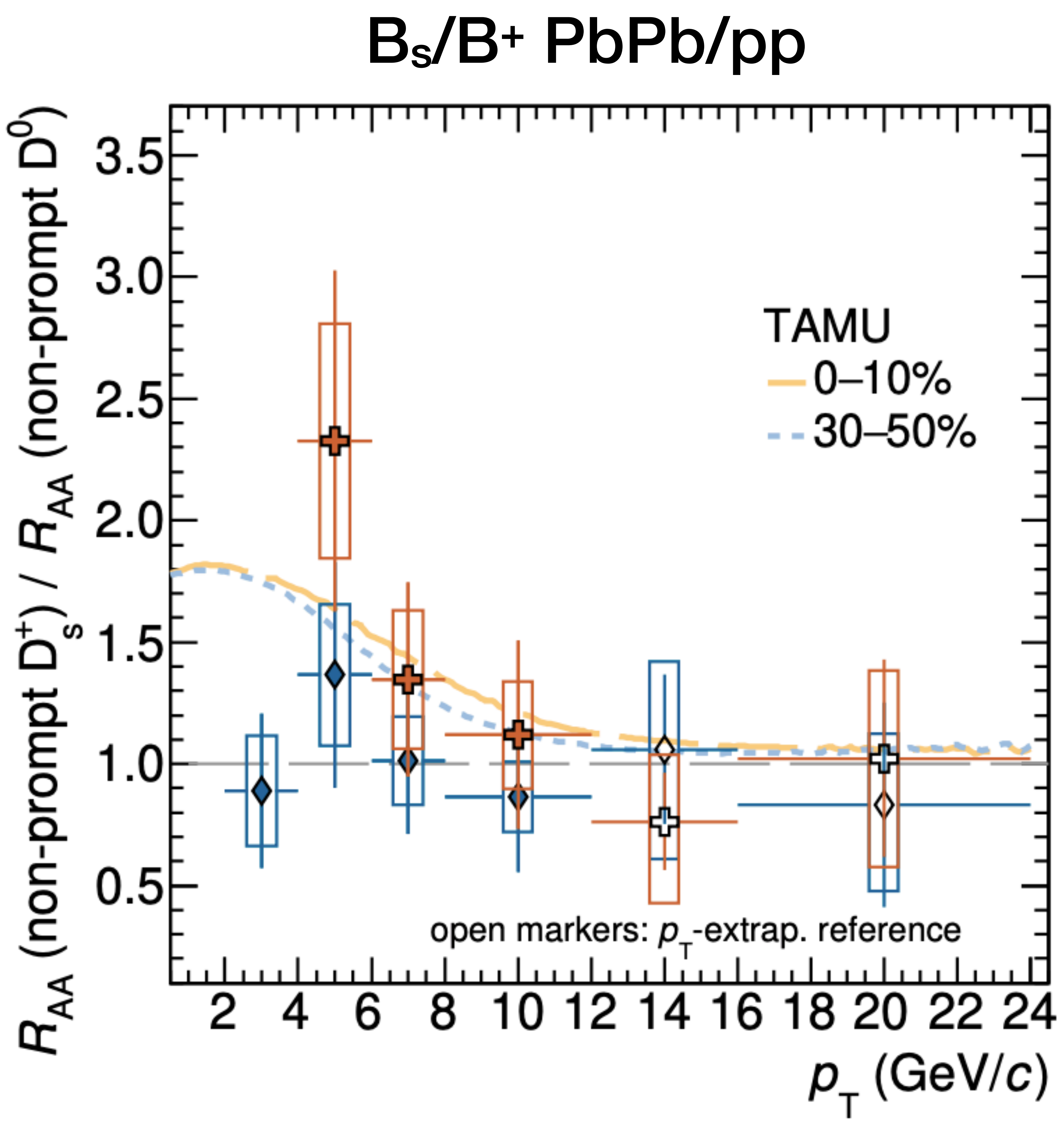




- **Why?**

Strangeness Across Collision Systems



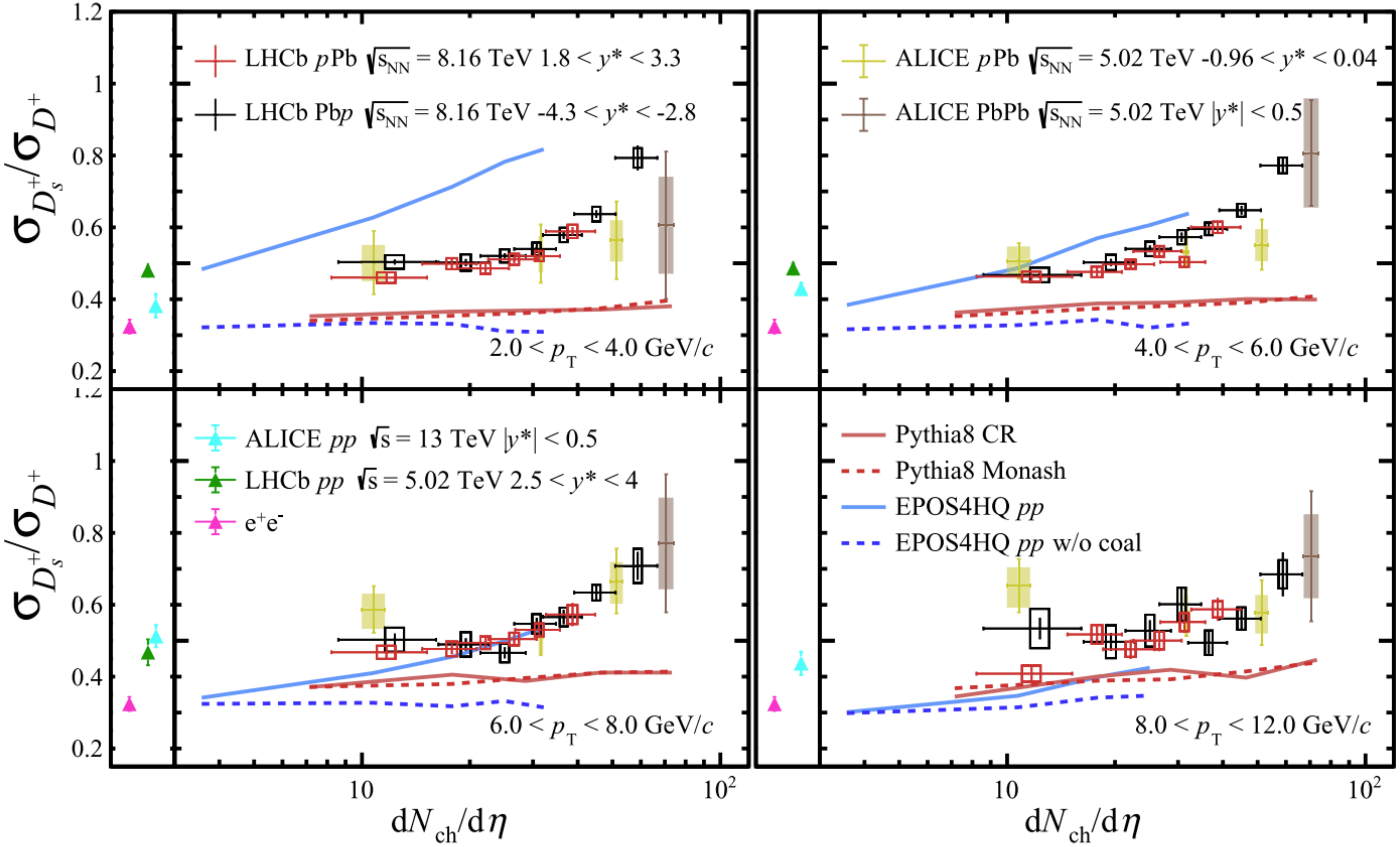


- Model does not predict significant centrality dependence

ALICE Fabio C.

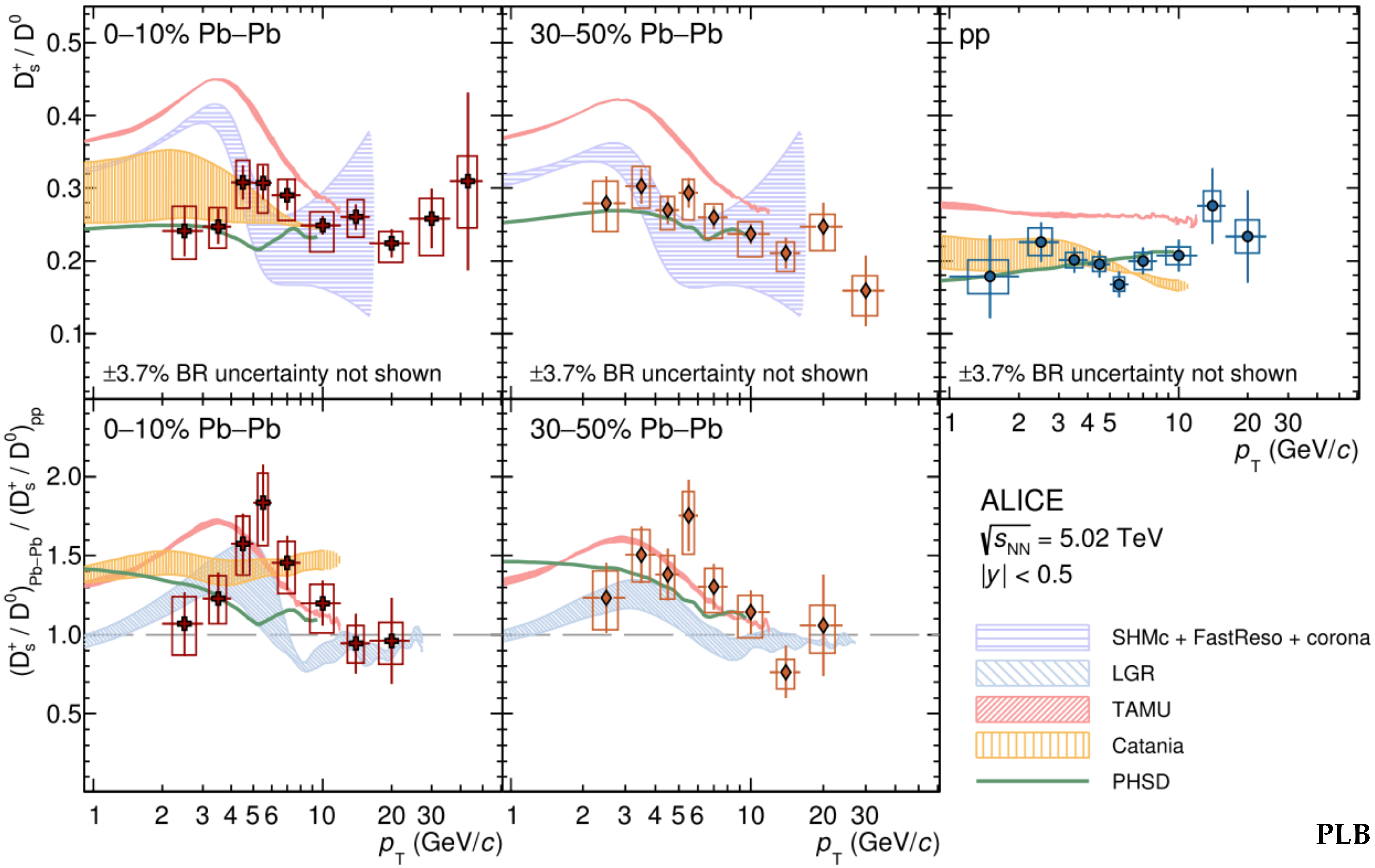
ALICE PLB 846 (2023) 137561

Strangeness Across Collision Systems



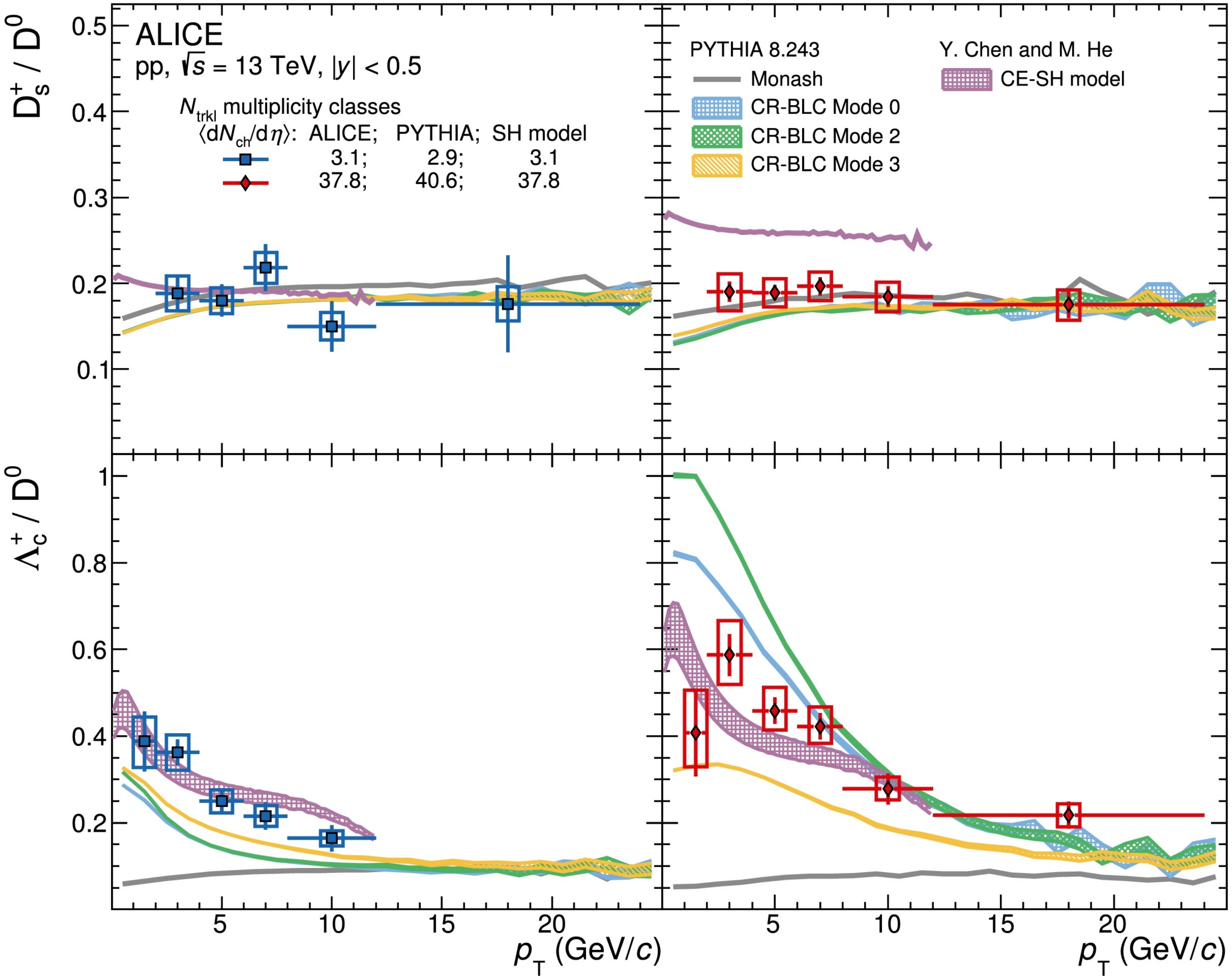
PRD 110 (2024) L031105

Strangeness Across Collision Systems

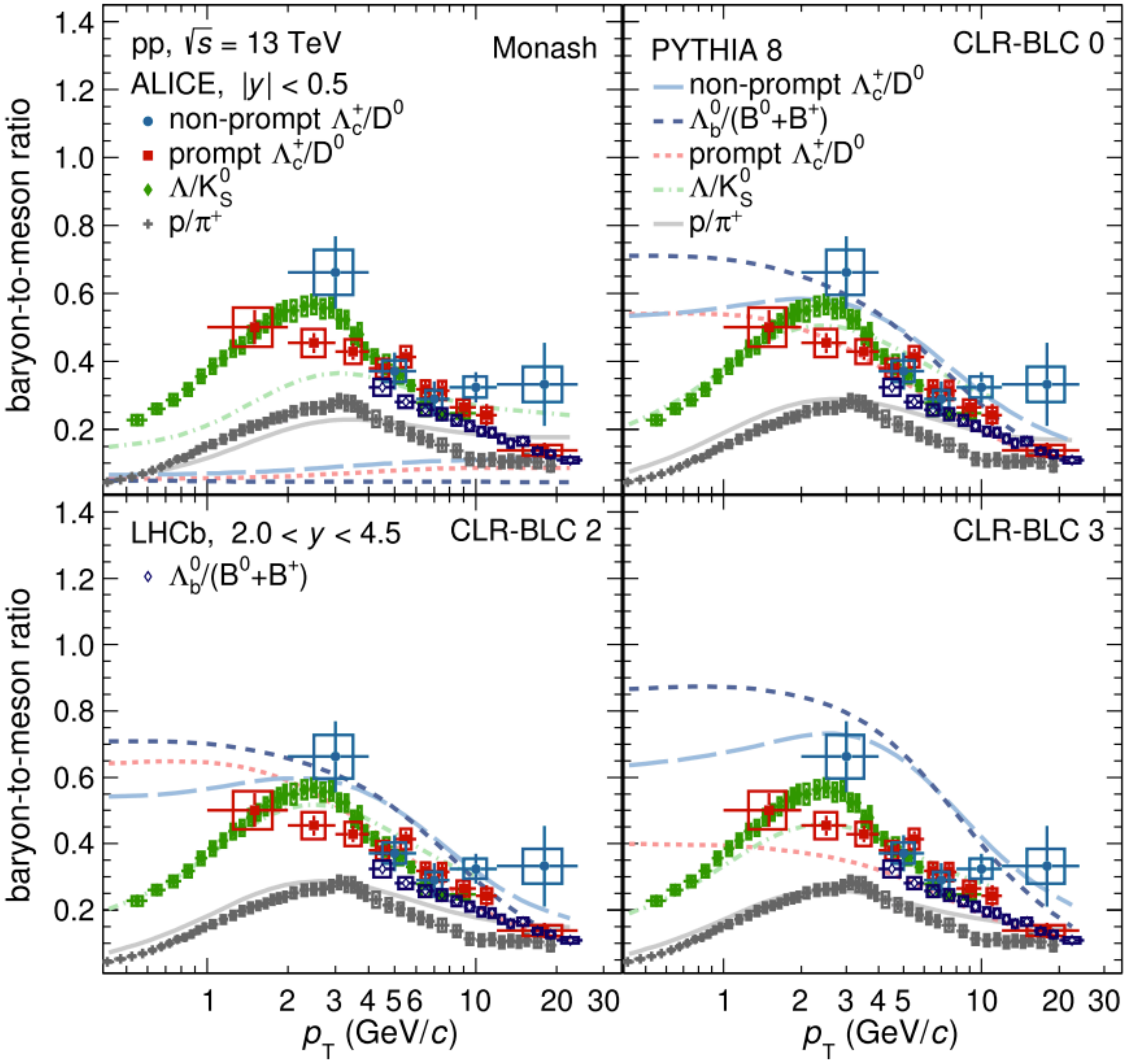


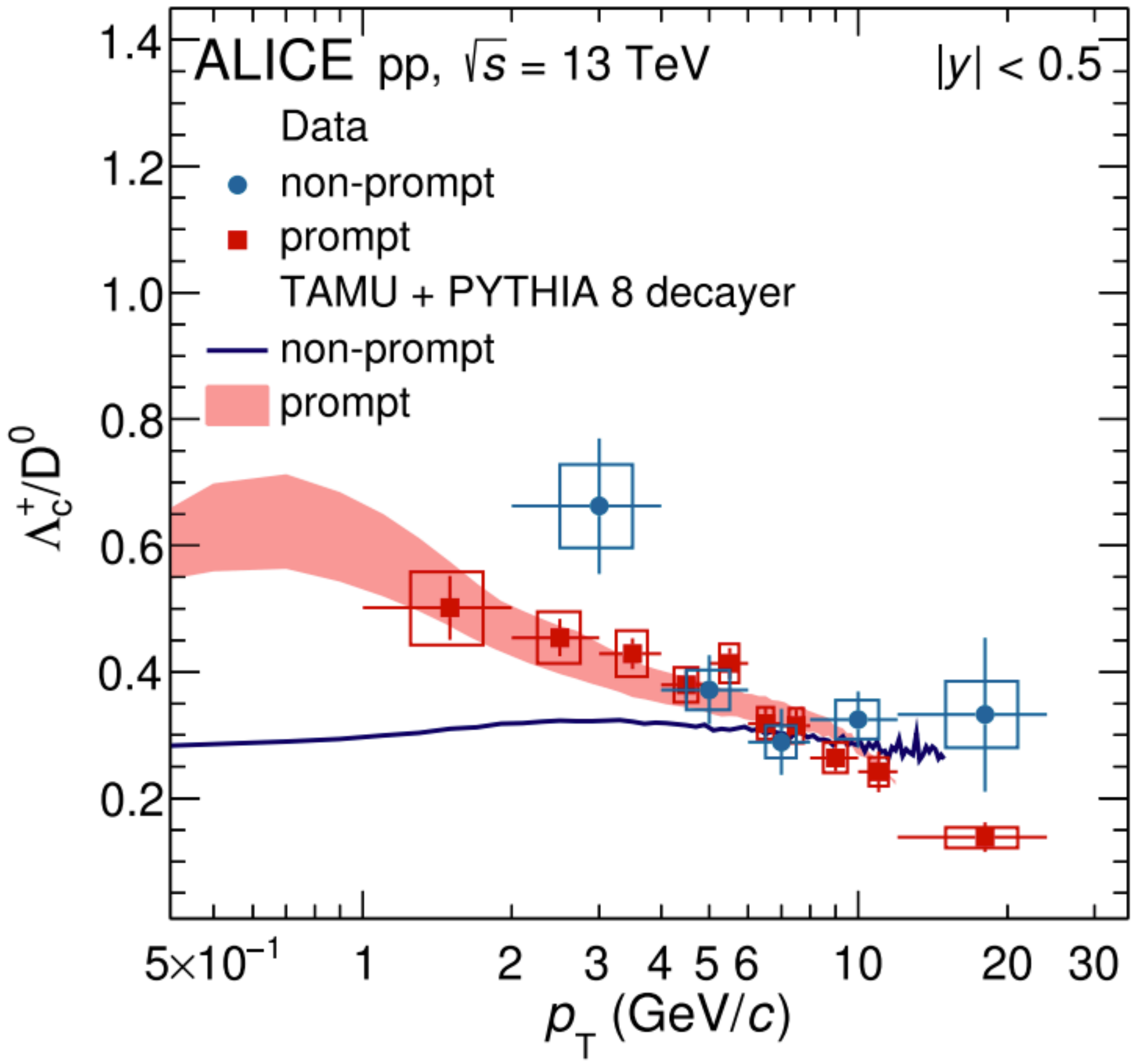
PLB 827 (2022) 136986

Charm Strangeness Across Collision Systems

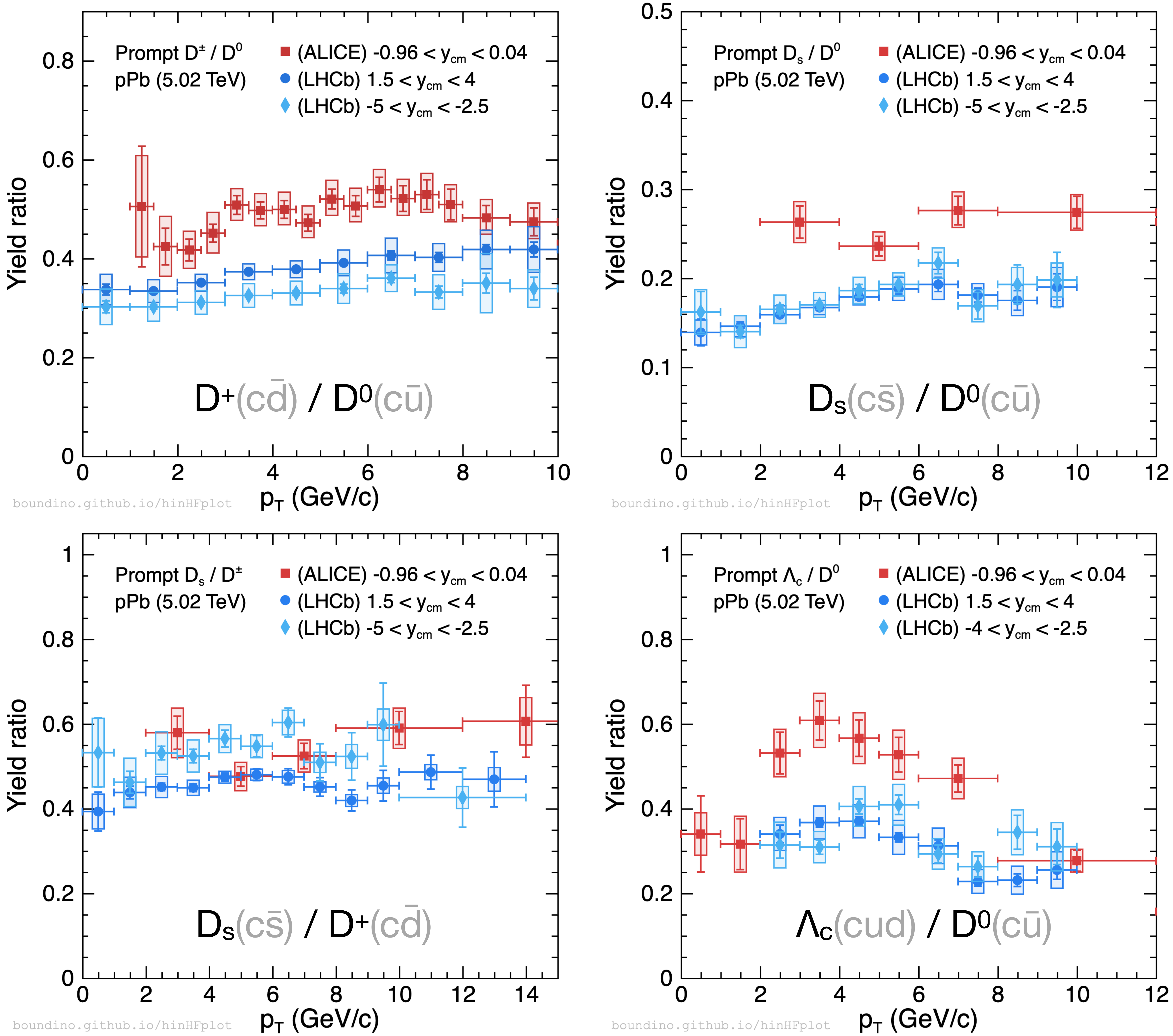


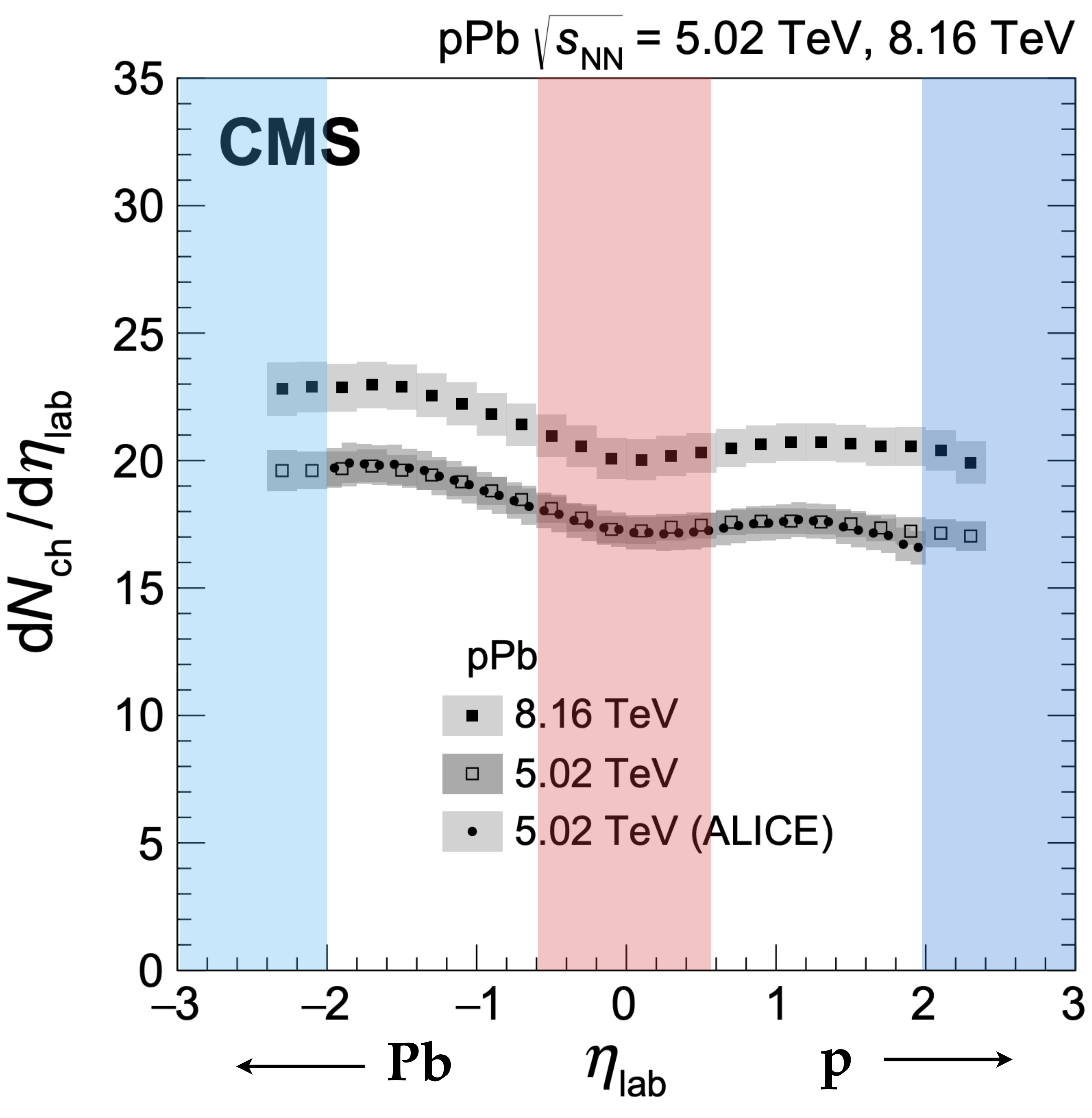
Baryon p_T Redistribution Flavor Dependence





Rapidity Dependence pPb Collisions

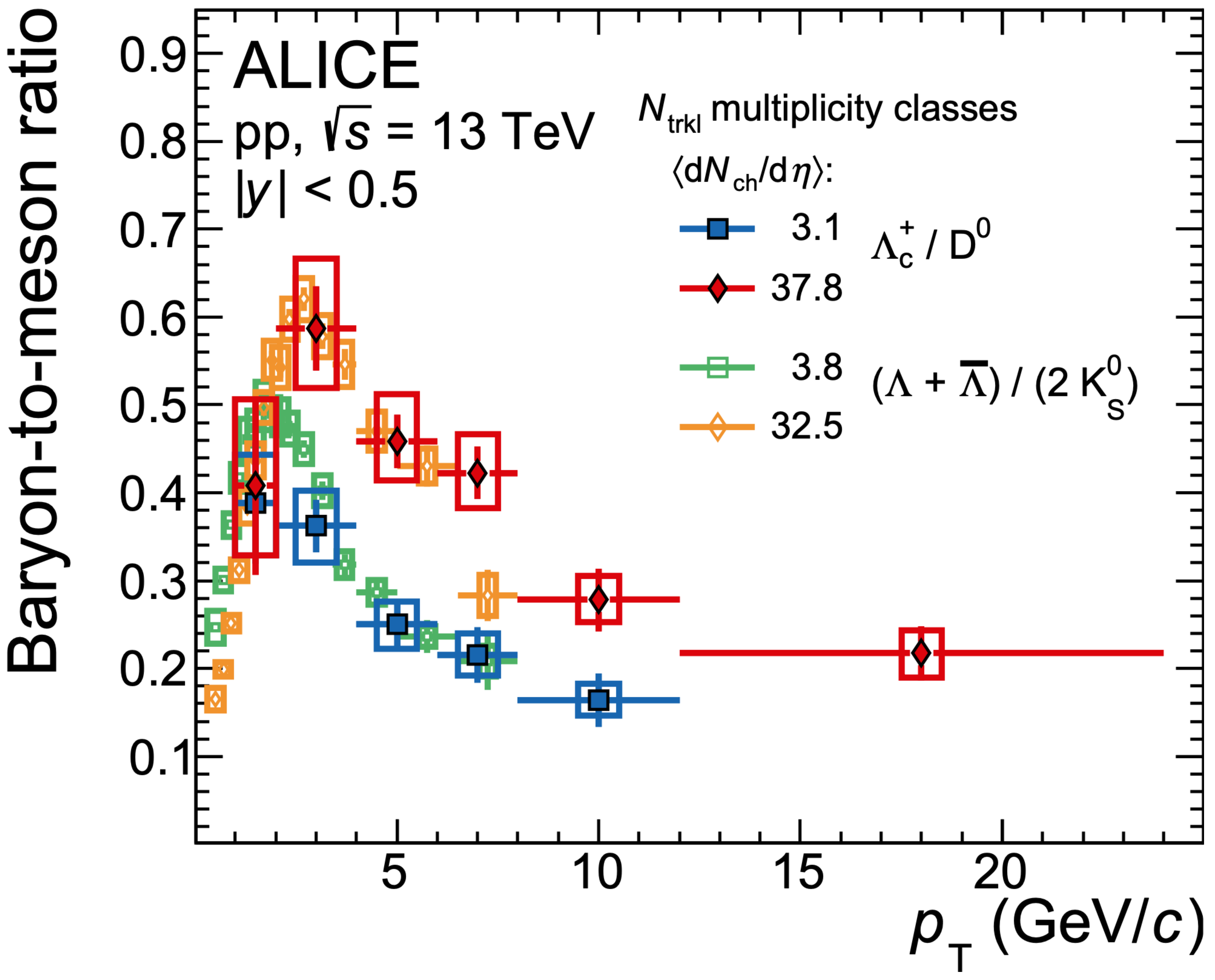




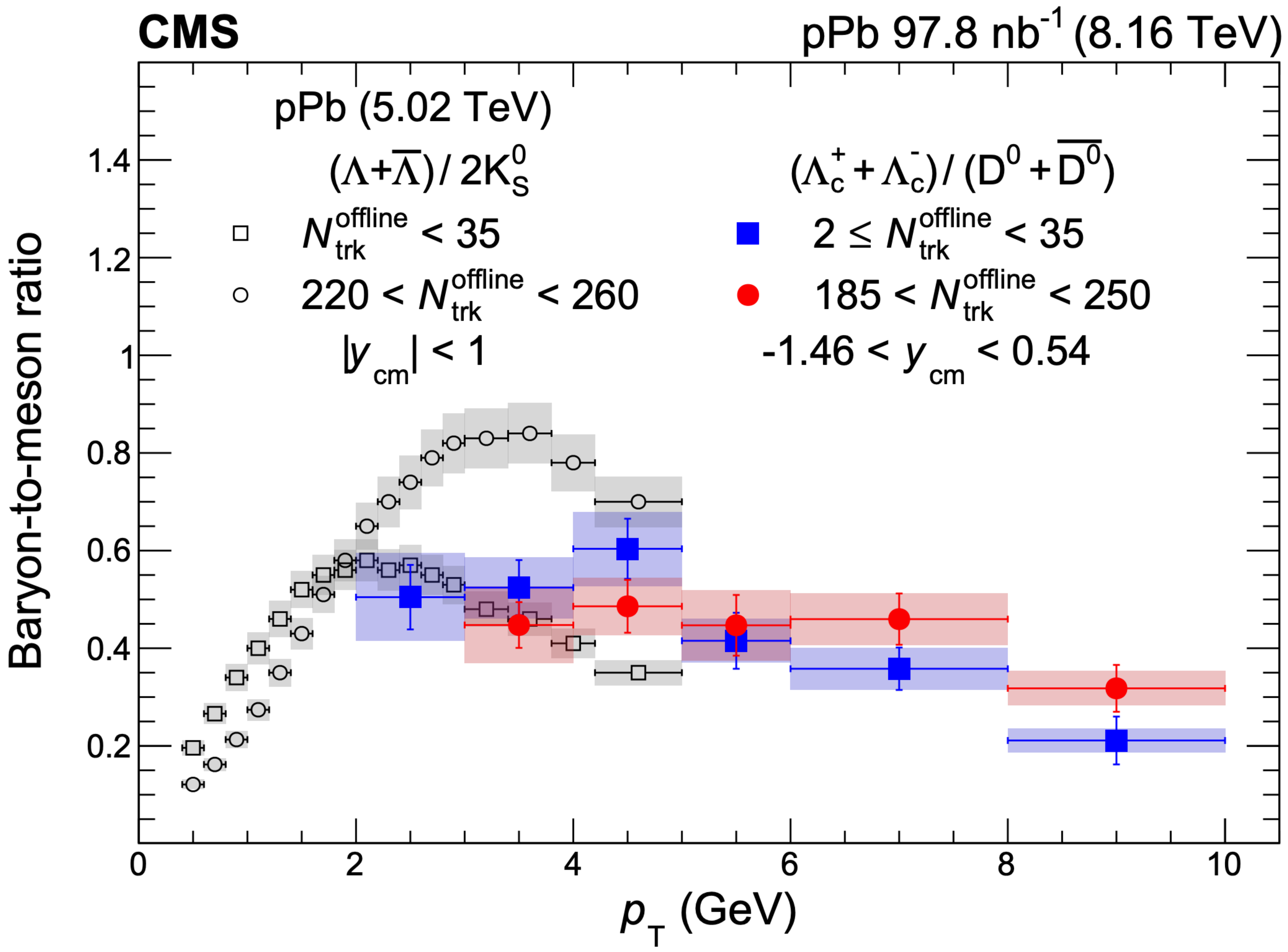
of R_{pPb} and R_{FB} for D^+ versus other D mesons. On average, the multiplicity value at backward rapidity is 1.6 times higher than that at forward rapidity in terms of the backward-forward production ratio of charged particles at the same center-of-mass energy from LHCb [80]. As some contributions 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

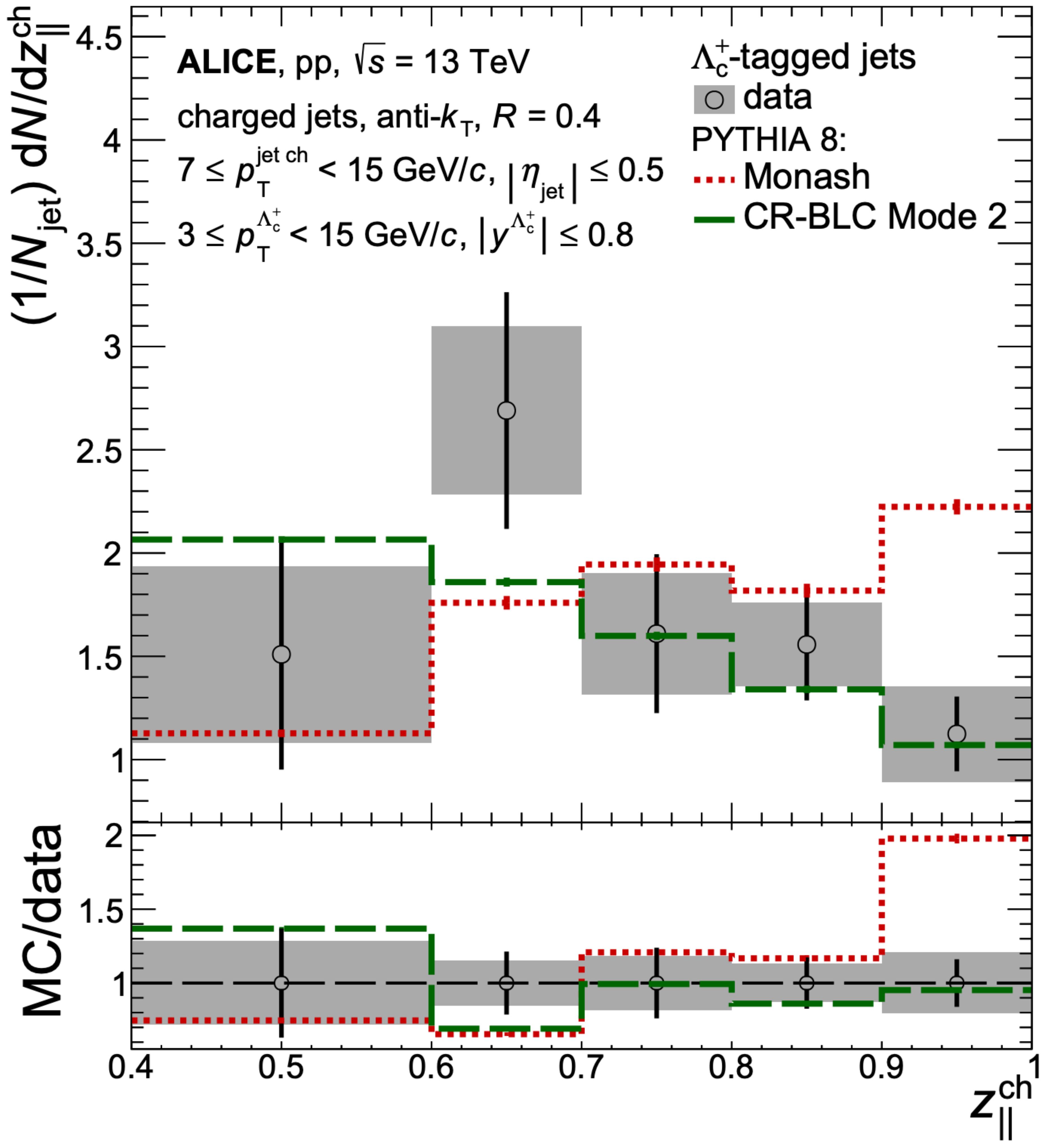


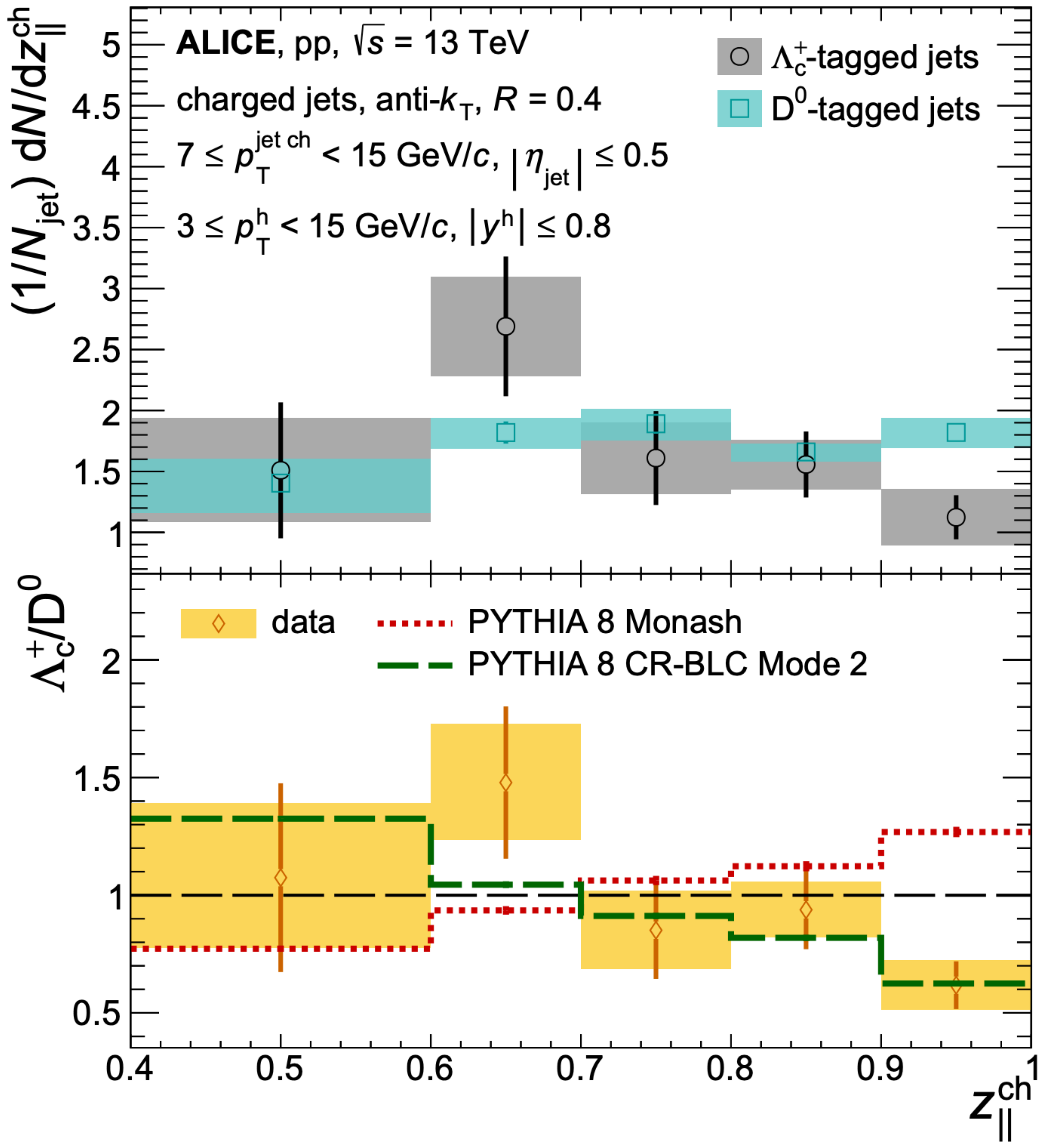
pPb



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

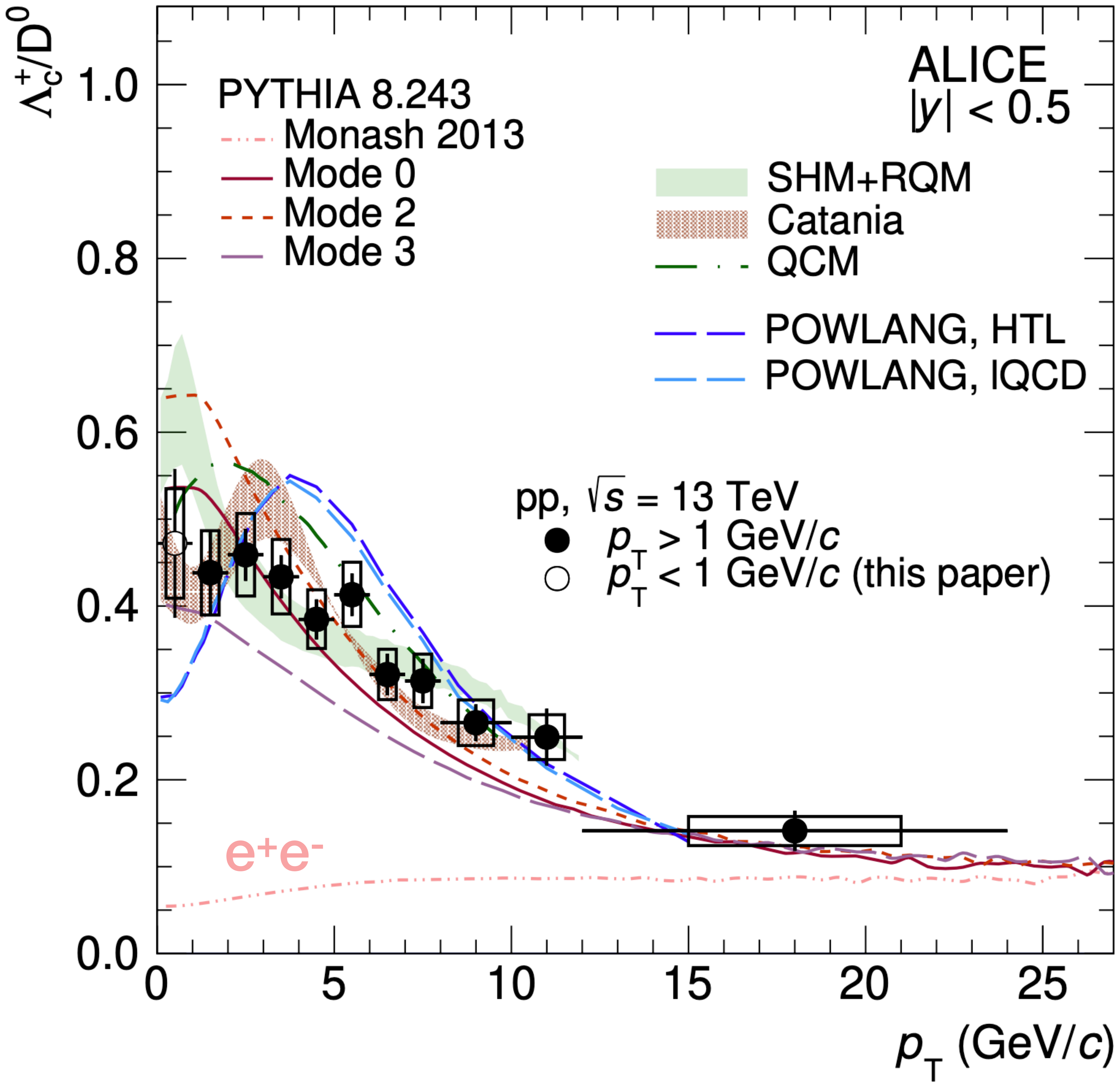
Jet Fragmentation Fraction New Info?





ALICE **Jochen K.**

Charm Baryon Λ_c Hadronization in pp

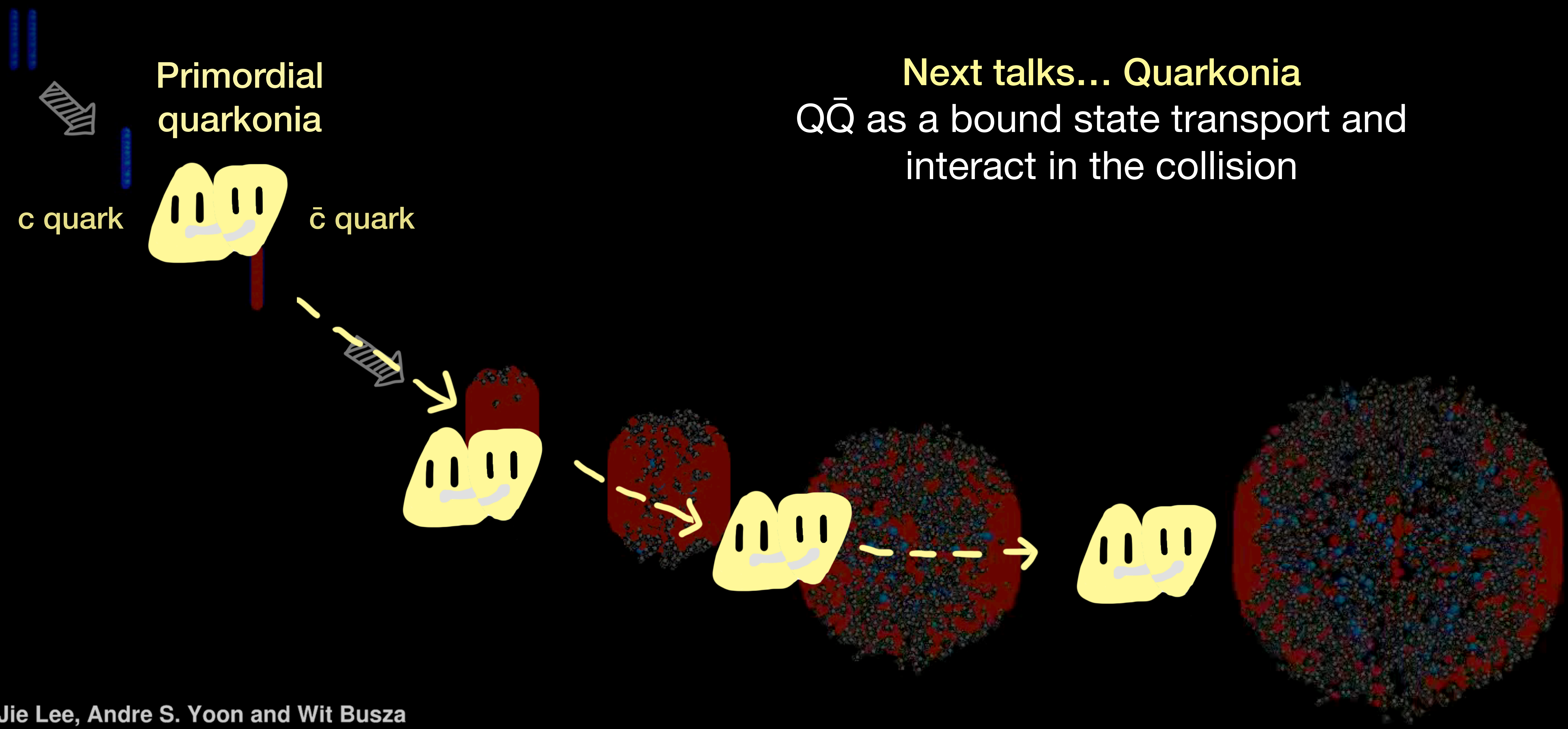


JHEP 12 (2023) 086

- 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

Life of a Heavy Quark Open Heavy Flavor

Life of a Heavy Quark Quarkonia



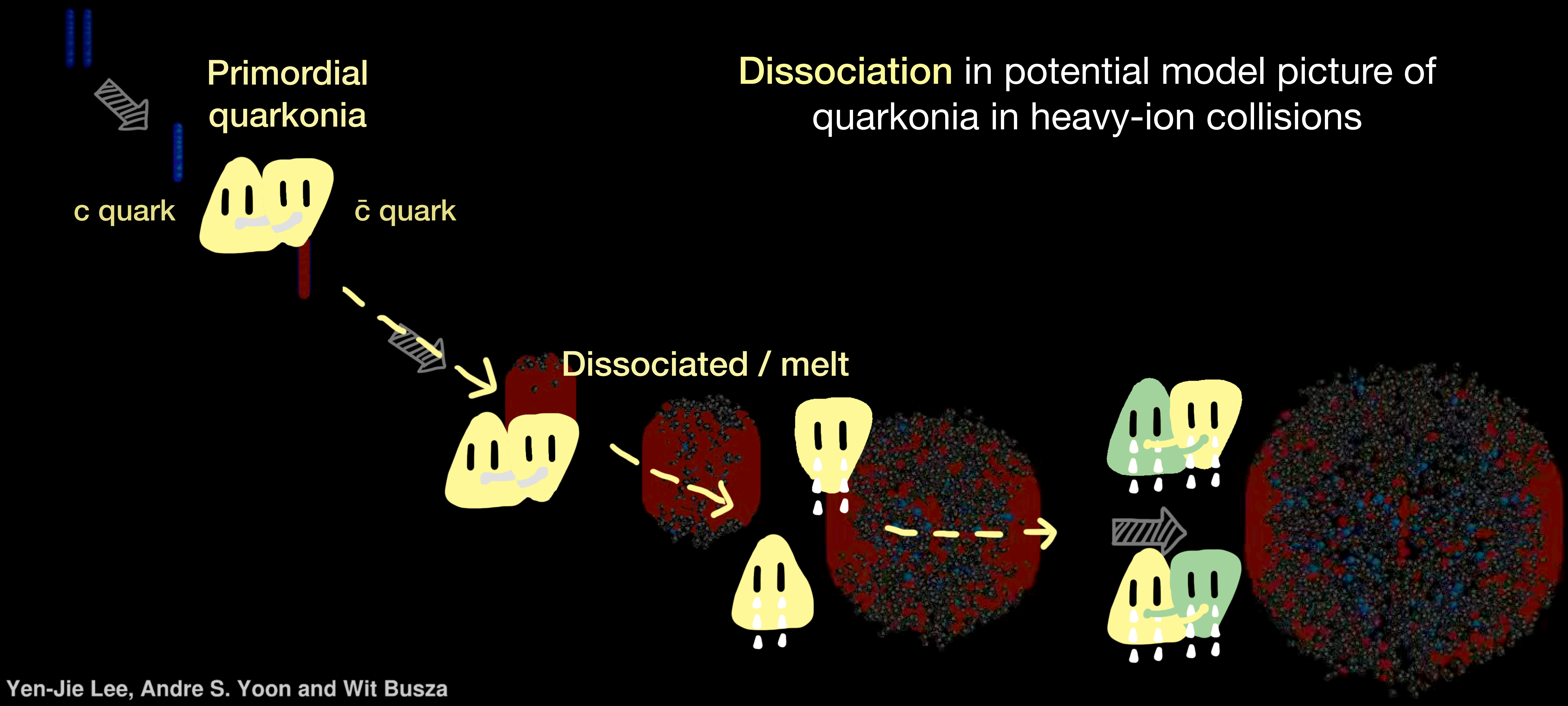
Next talks… Quarkonia

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

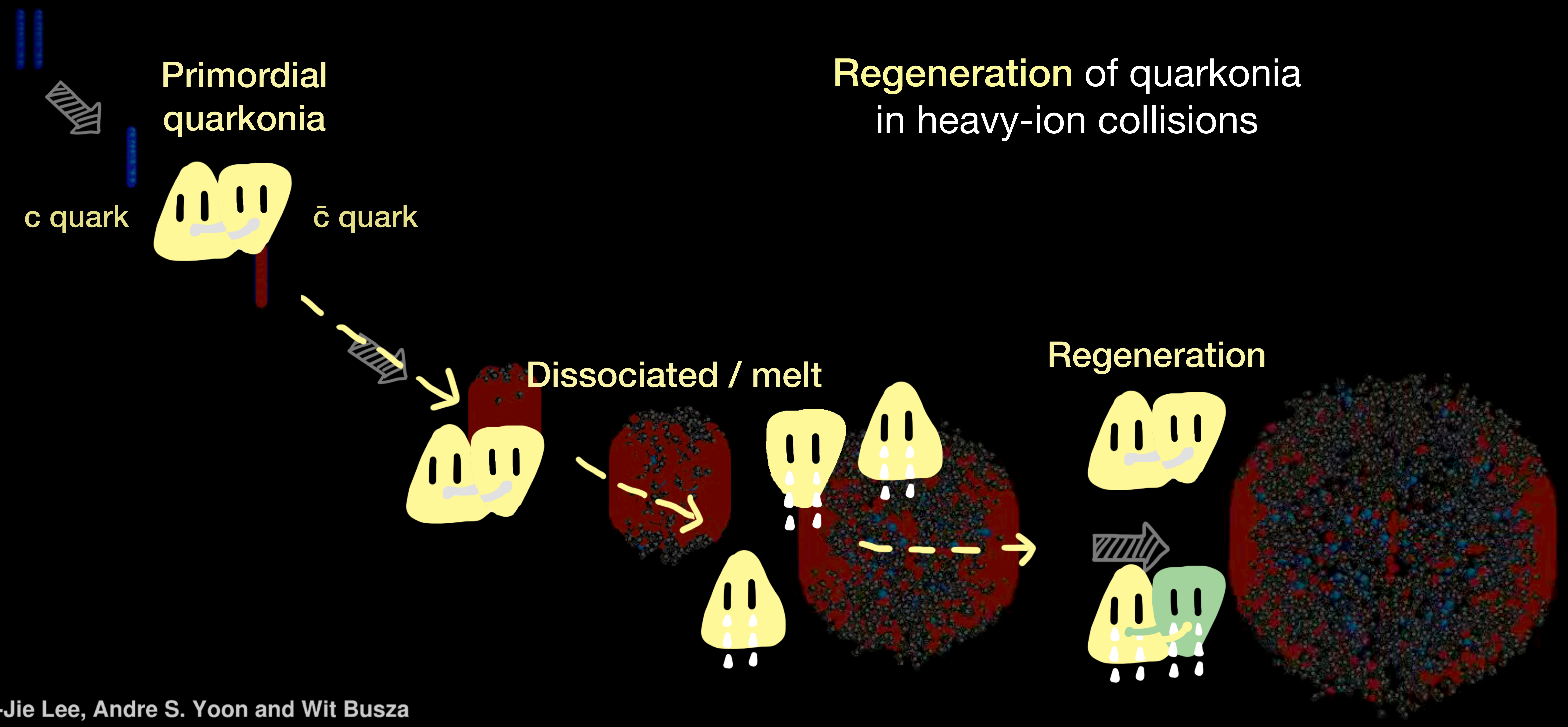
Yen-Jie Lee, Andre S. Yoon and Wit Busza

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



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%).