ZOOM room for discussions

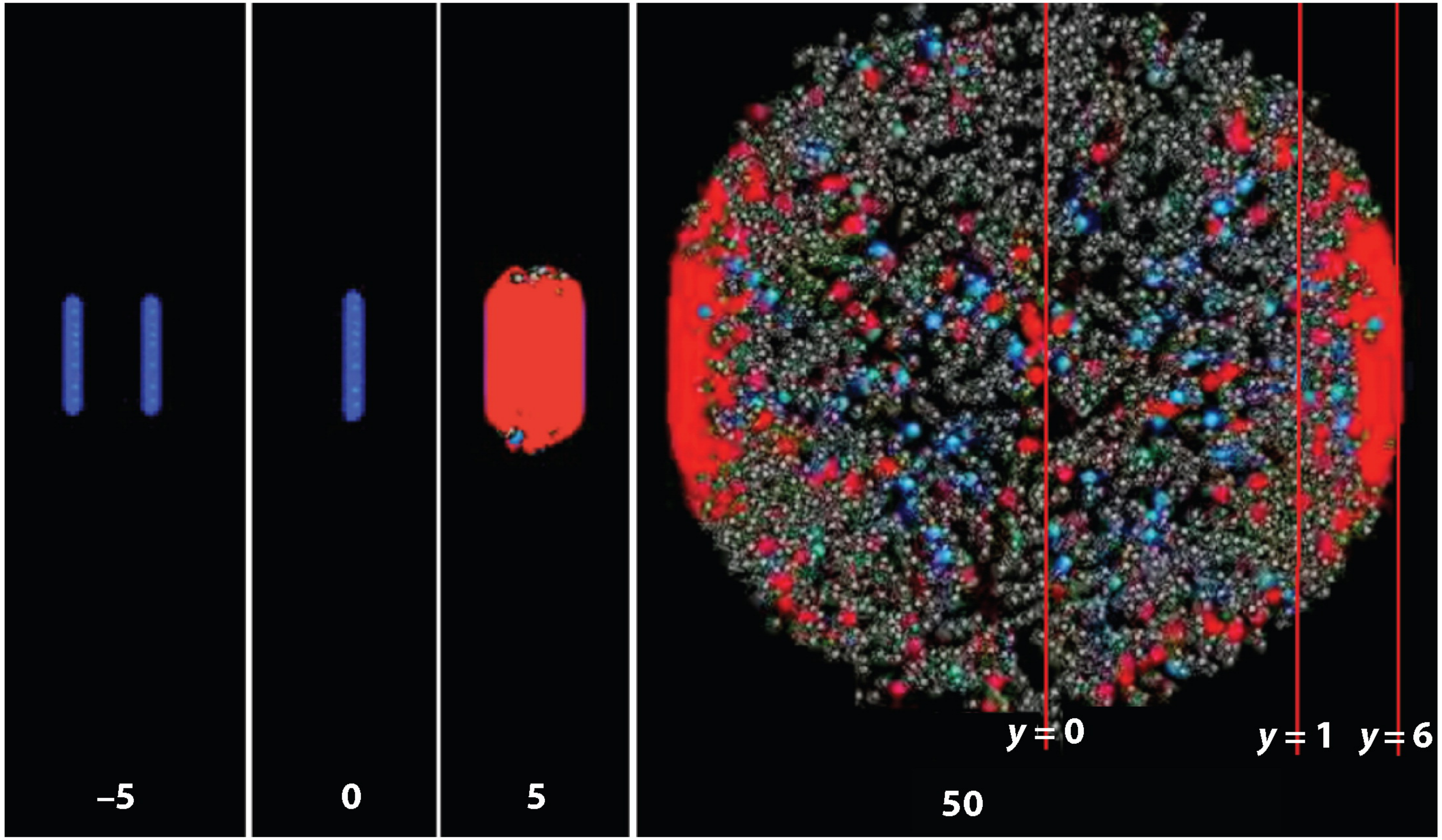
Overview of heavy flavour and quarkonia

8th Large Hadron Collider Physics Conference
May 25-30 2020

Gian Michele Innocenti (CERN)
on behalf of the ALICE, ATLAS, CMS and LHCb collaborations

Quark-gluon plasma (QGP) with heavy quarks

Busza W, et al. 2018.
Annu. Rev. Nucl. Part. Sci. 68:339–76



Time (fm/c)

Quark-gluon plasma (QGP) with heavy quarks

- $m_Q >> \Lambda_{QCD}$ → early pQCD production
- $m_Q >> T_{QGP}$ → no thermal production
- **charm/beauty content is conserved!**

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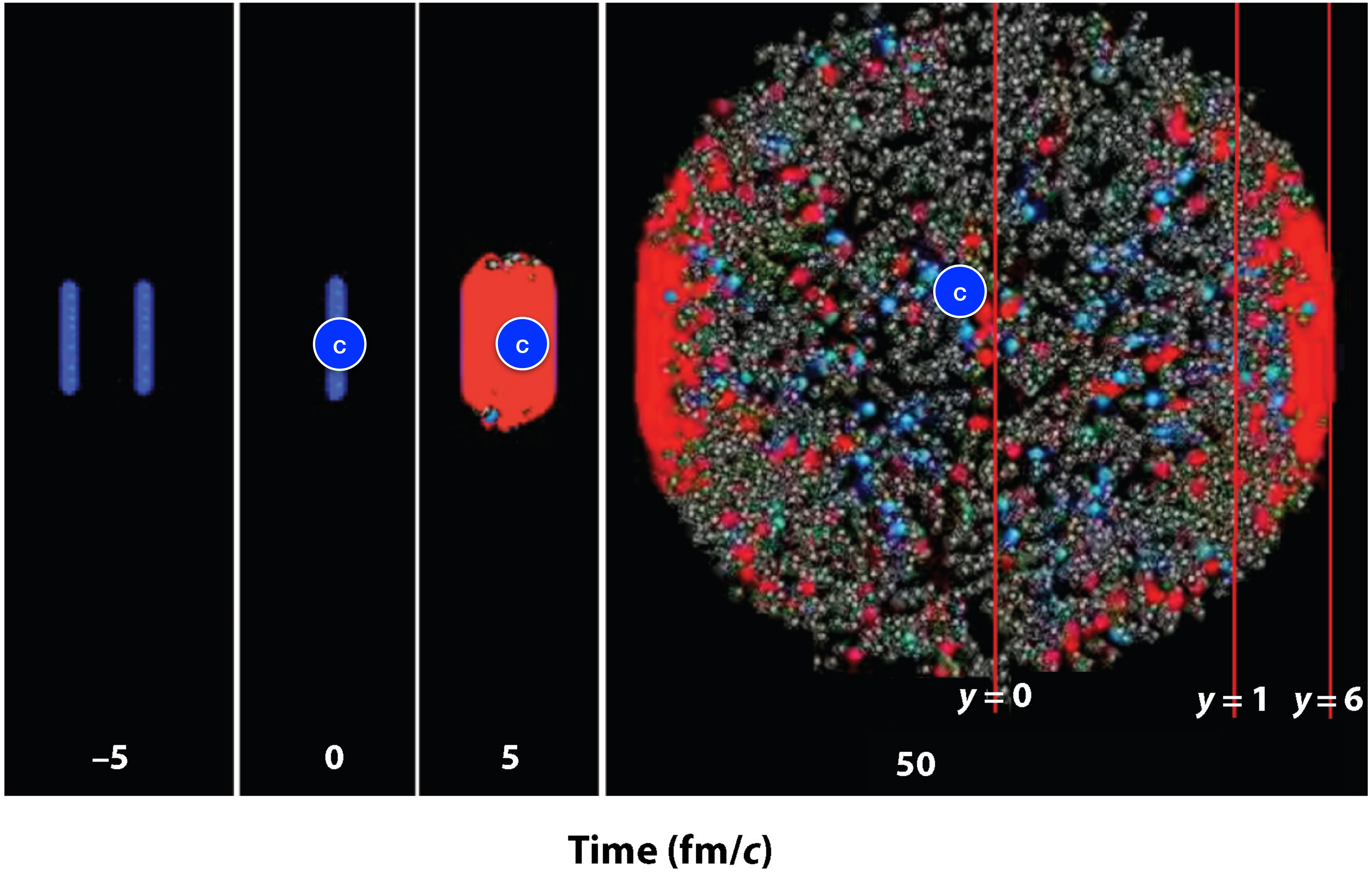
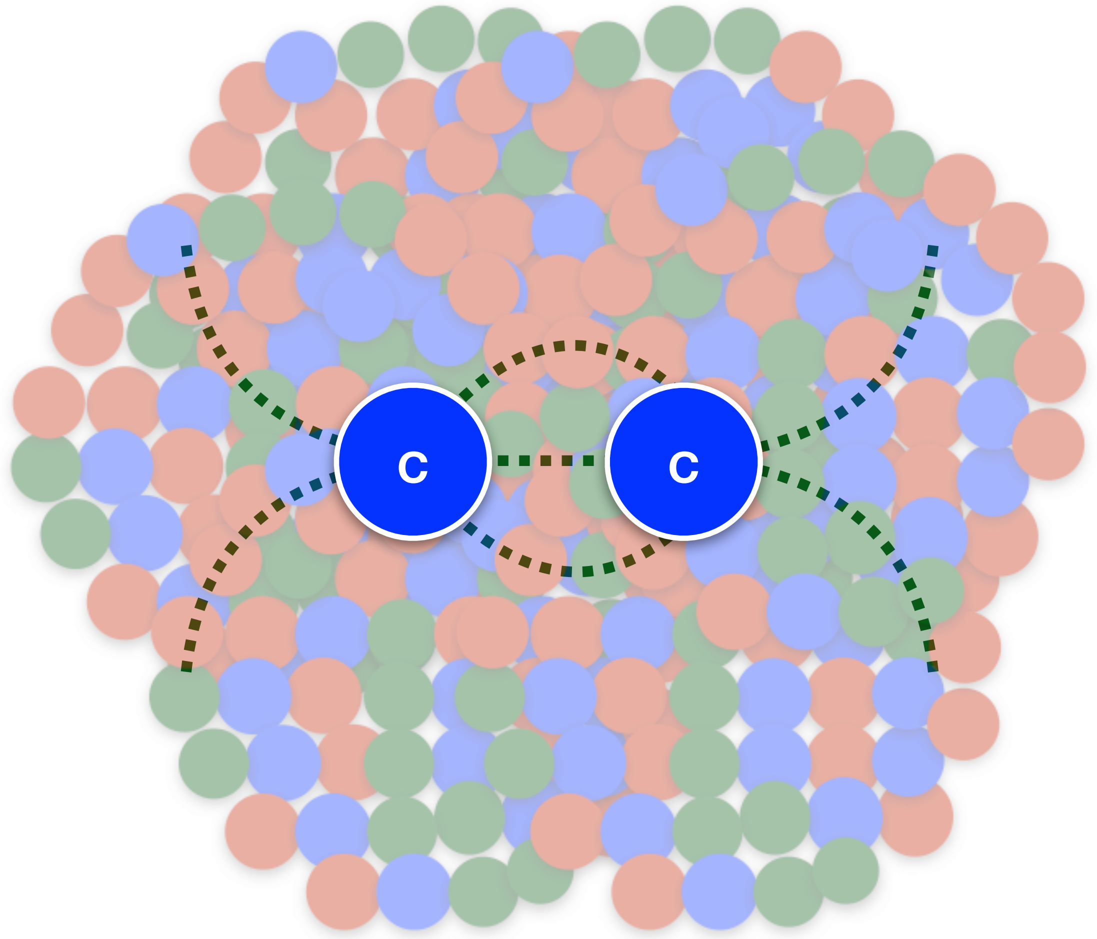
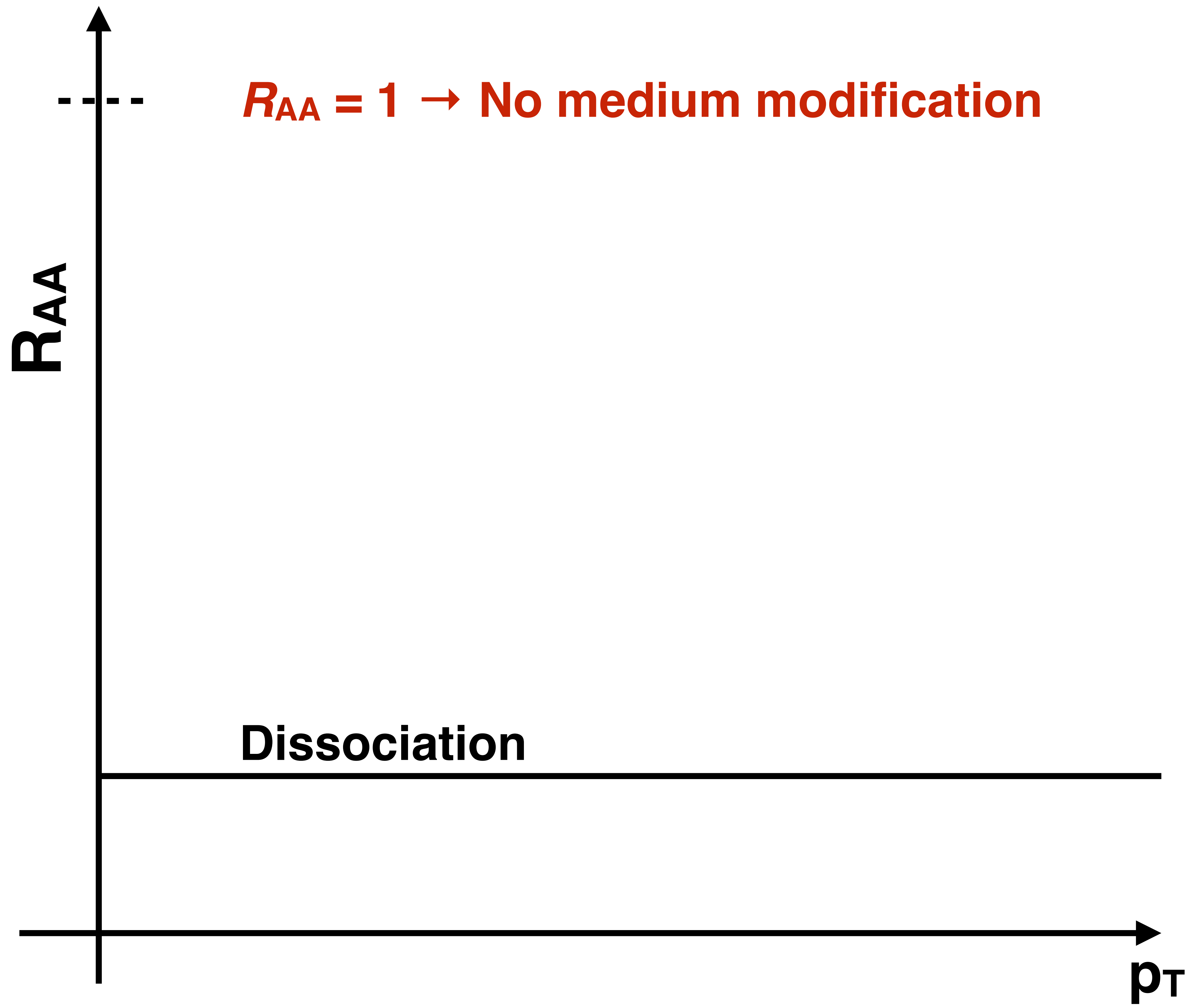


Quarkonia suppression in heavy-ion collisions

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$



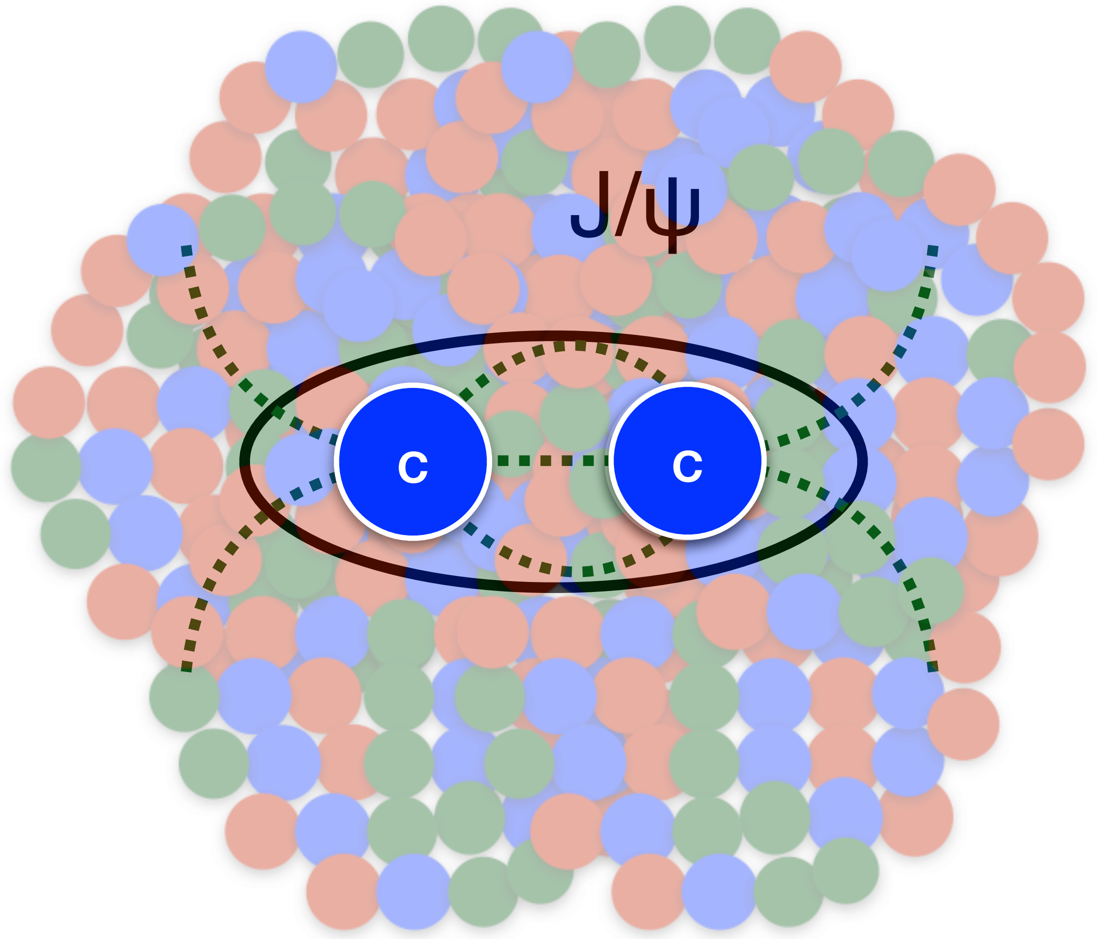


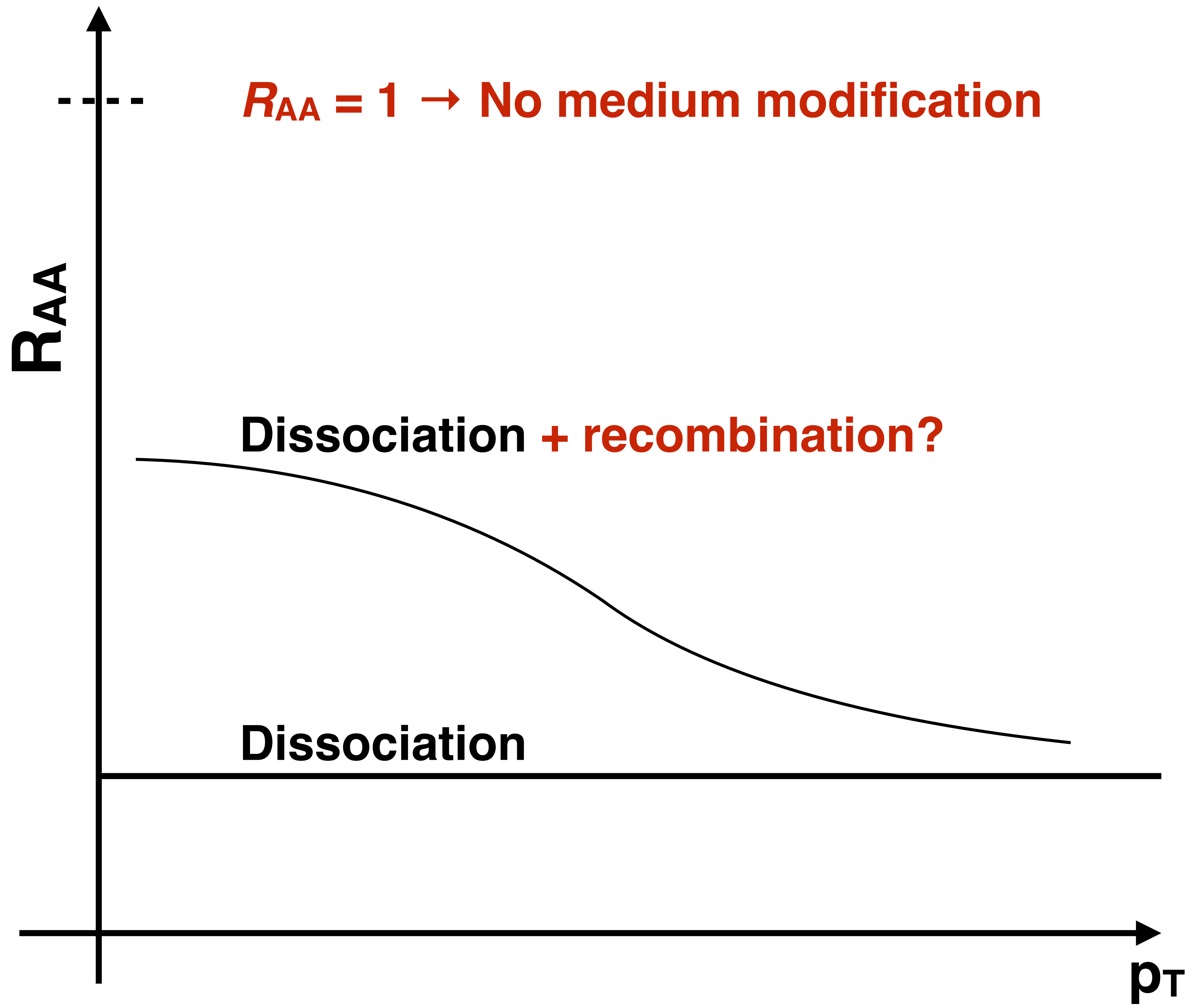
- **Dissociation:**
  - J/ψ melt inside the medium **(colour screening)**

Phys.Lett.B 178 (1986) 416-422

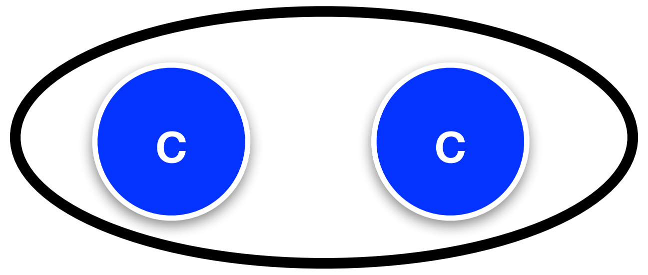
J/ψ in the QGP: suppression vs recombination

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$





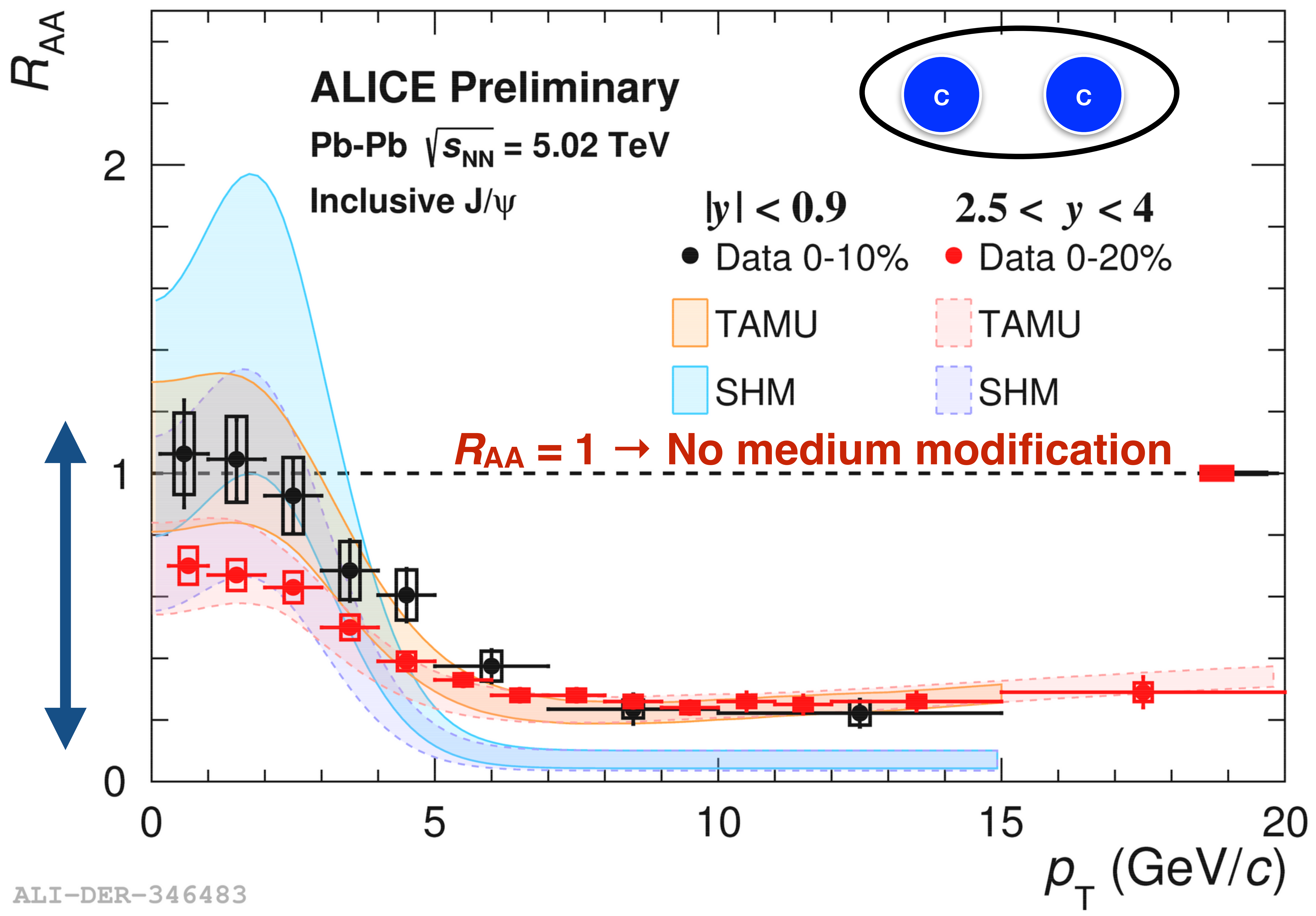
- **Dissociation:**
  - J/ψ melt inside the medium **(colour screening)**
- **Recombination:**
  - J/ψ created in the QGP by combination of c-cbar pairs



Charmonium recombination

Effects of recombination:

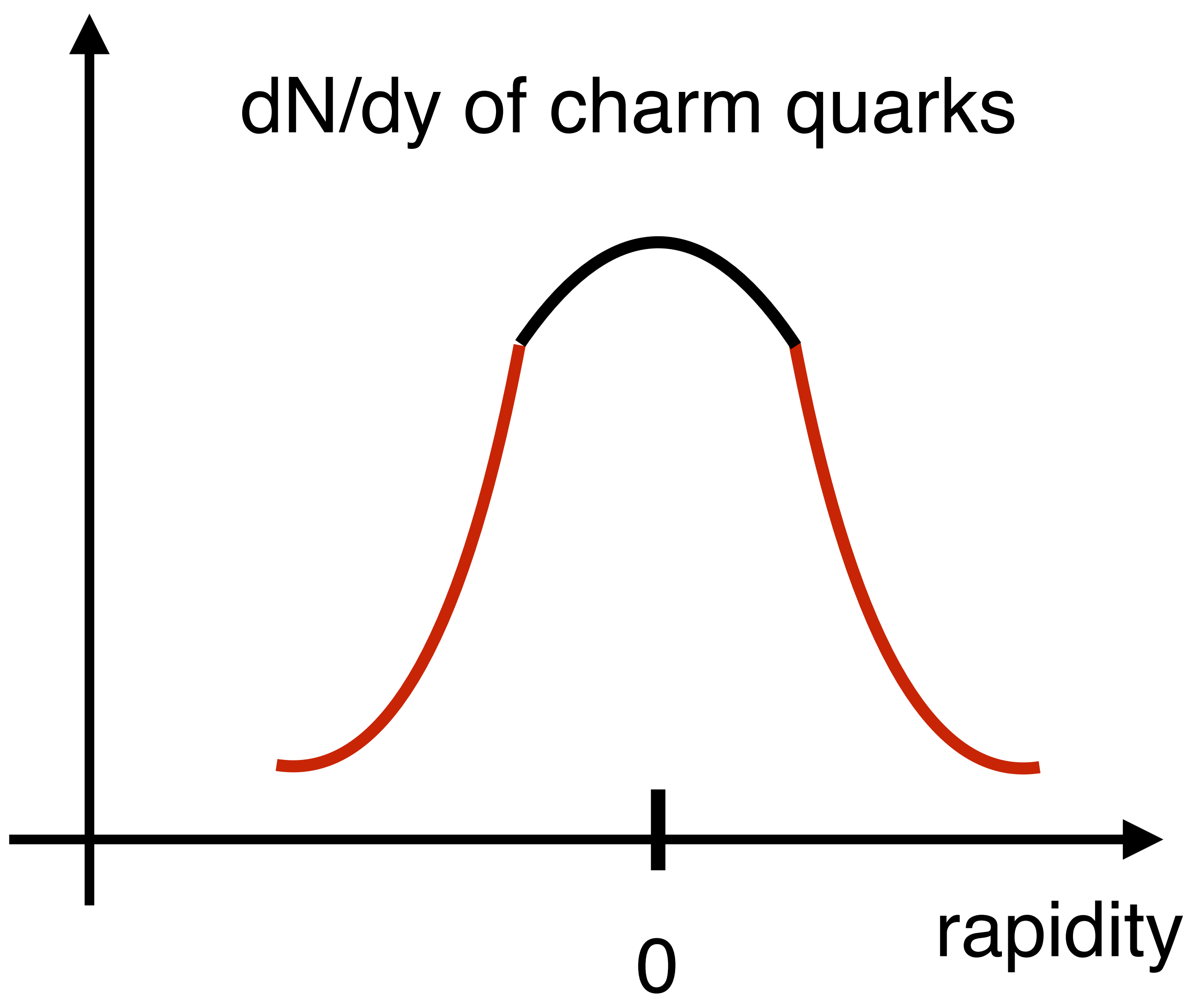
- overall **enhancement of the R_{AA} at low p_T**

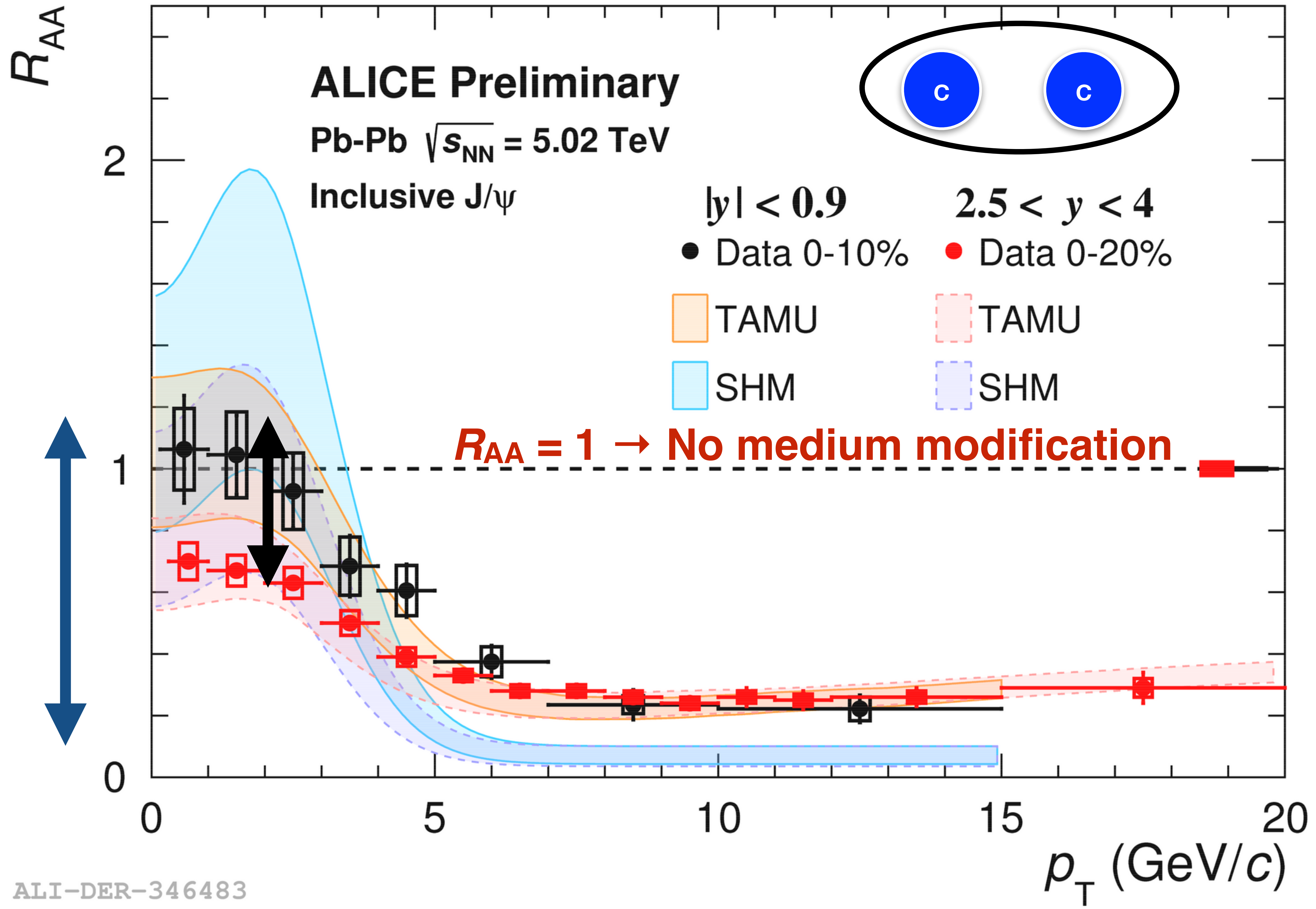


Charmonium recombination

Effects of recombination:

- overall **enhancement of the R_{AA} at low p_T**
- more J/ψ at **central rapidities** than at **forward rapidities:**



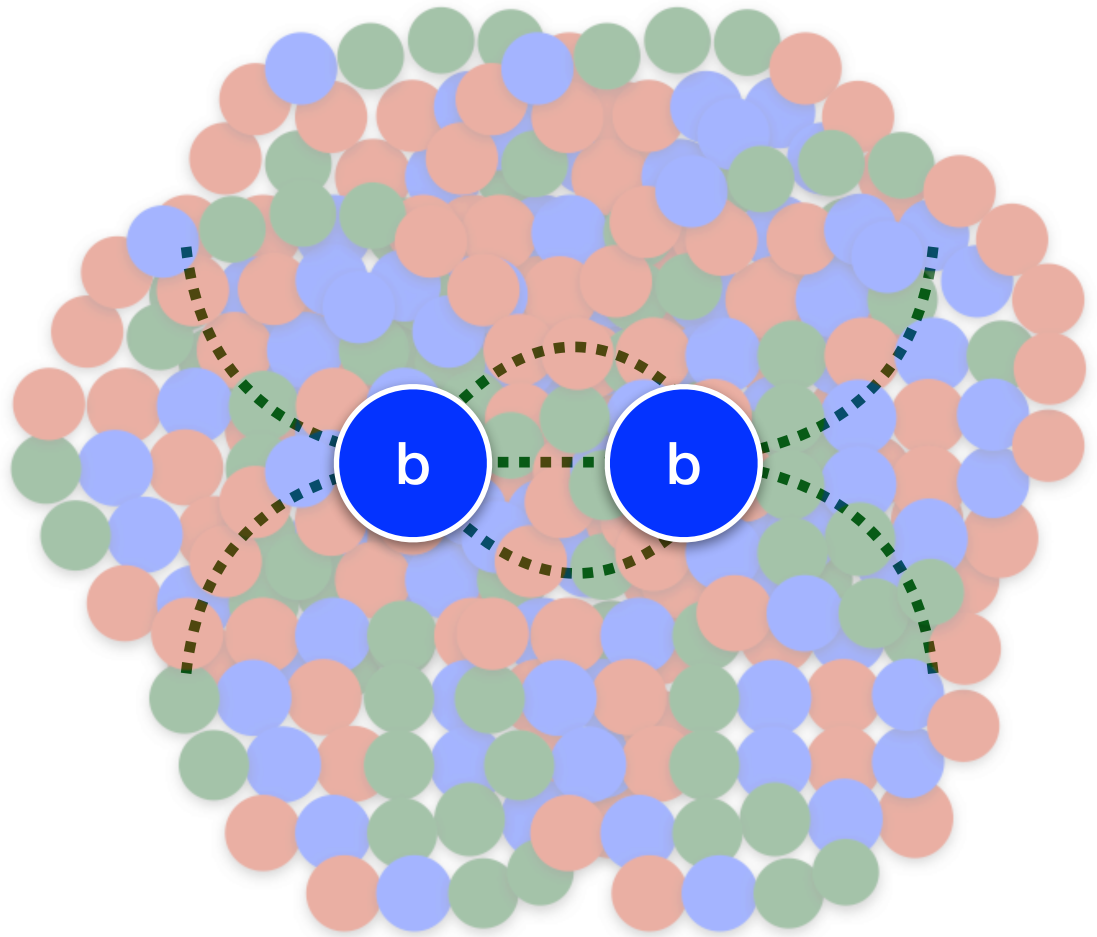


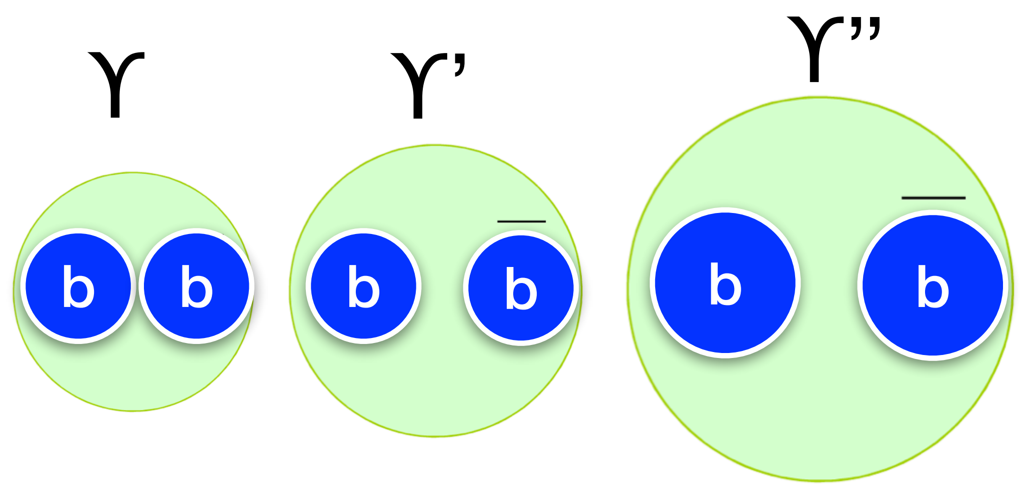
→**Recombination allows for a coherent description of the data!**

→model uncertainty dominated by total c-cbar cross section uncertainty, need for measurements down to p_T = 0

Bottomonium suppression in PbPb collisions

Bottomonia less affected by recombination due to lower b-bbar cross section!





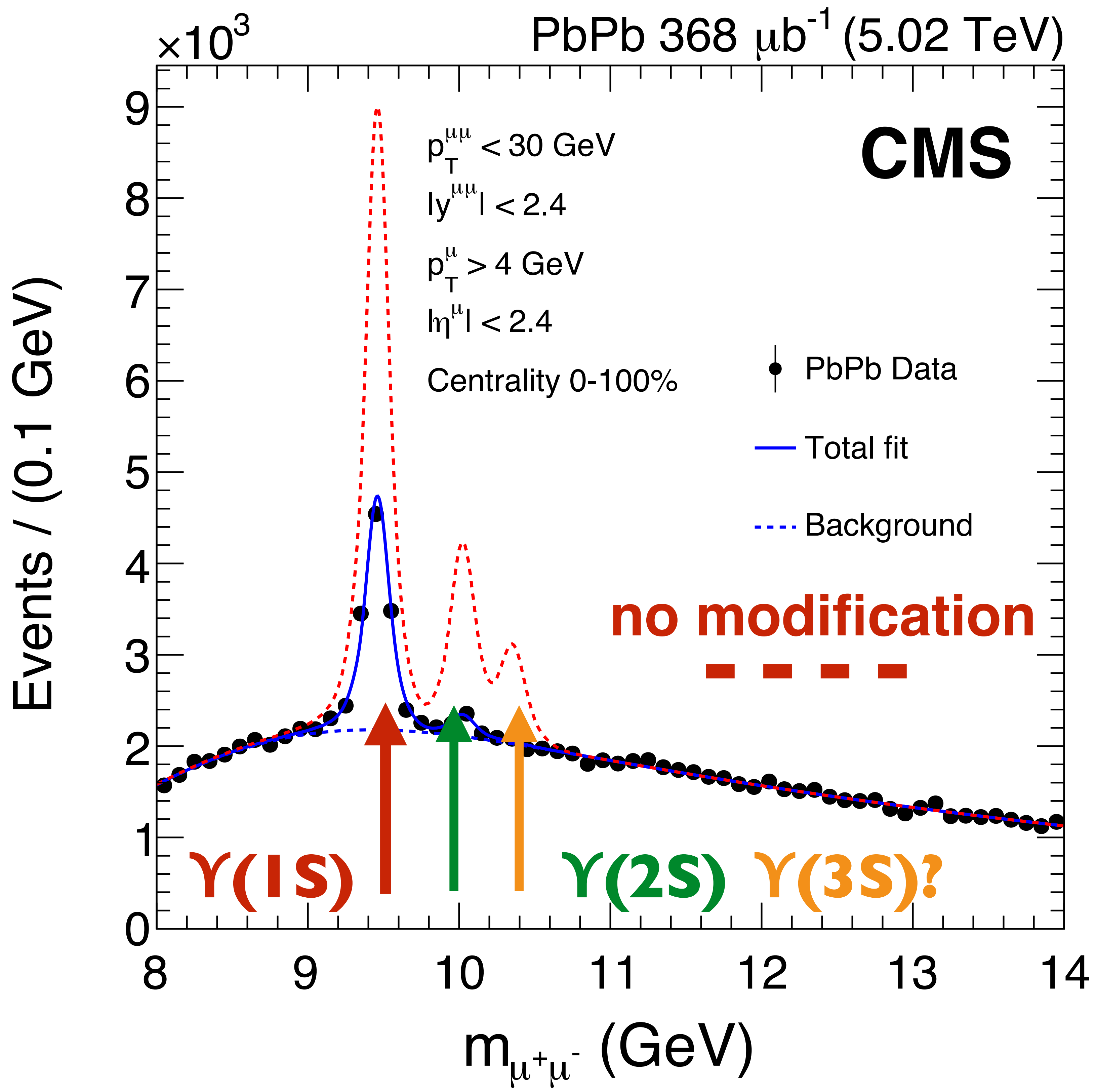
different radii/binding energies
→ **different suppression**

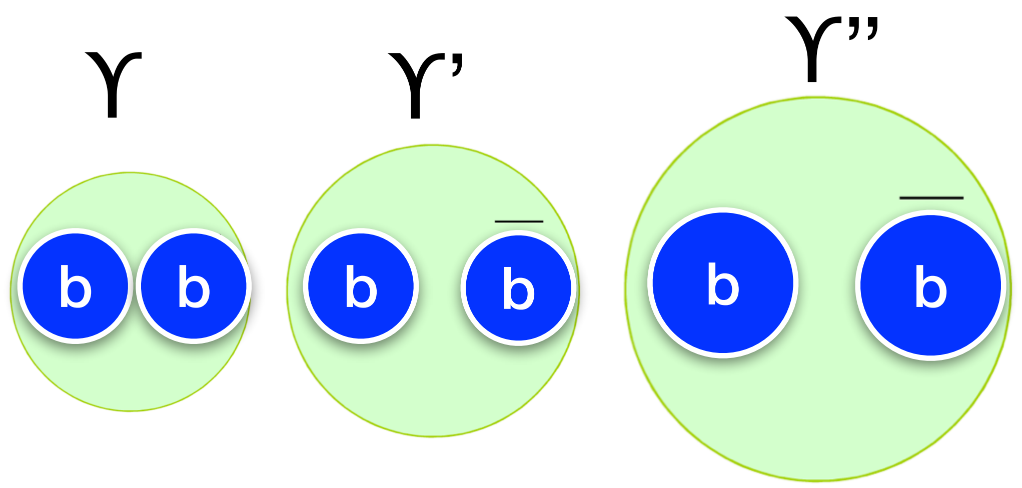
- **Dissociation:**
  - Bottomonia melt inside the medium **(colour screening)**

Bottomonium suppression in PbPb collisions

Bottomonia less affected by recombination due to lower b-bbar cross section!

CMS-PAS-HIN-18-005

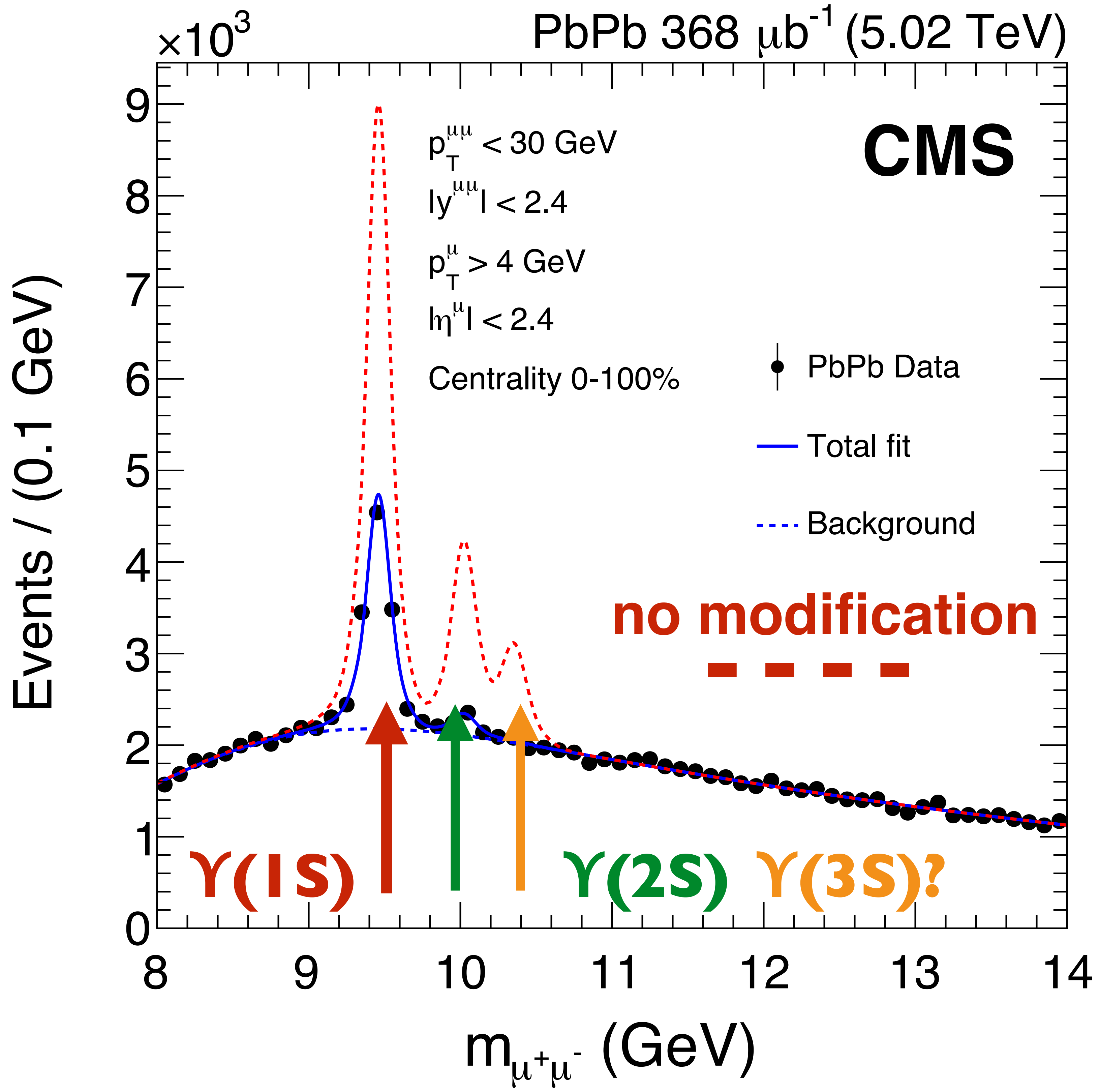


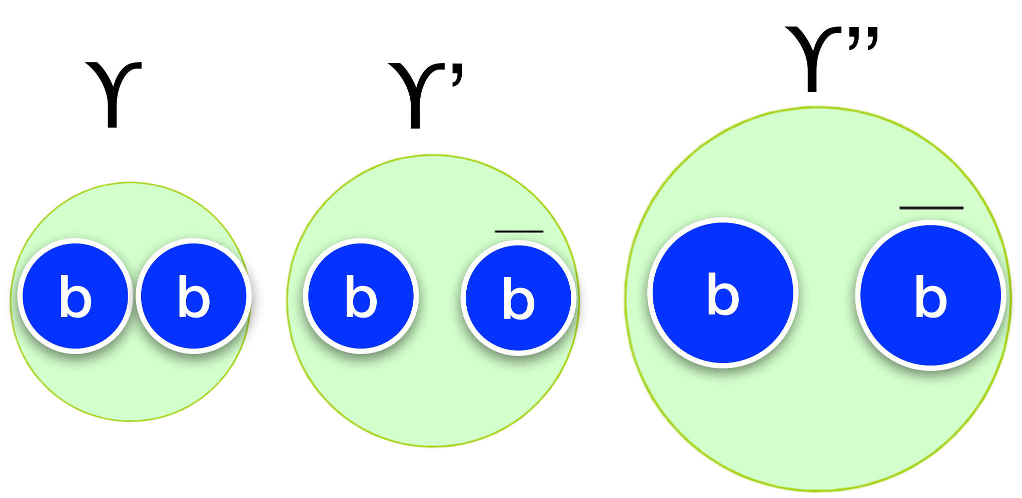


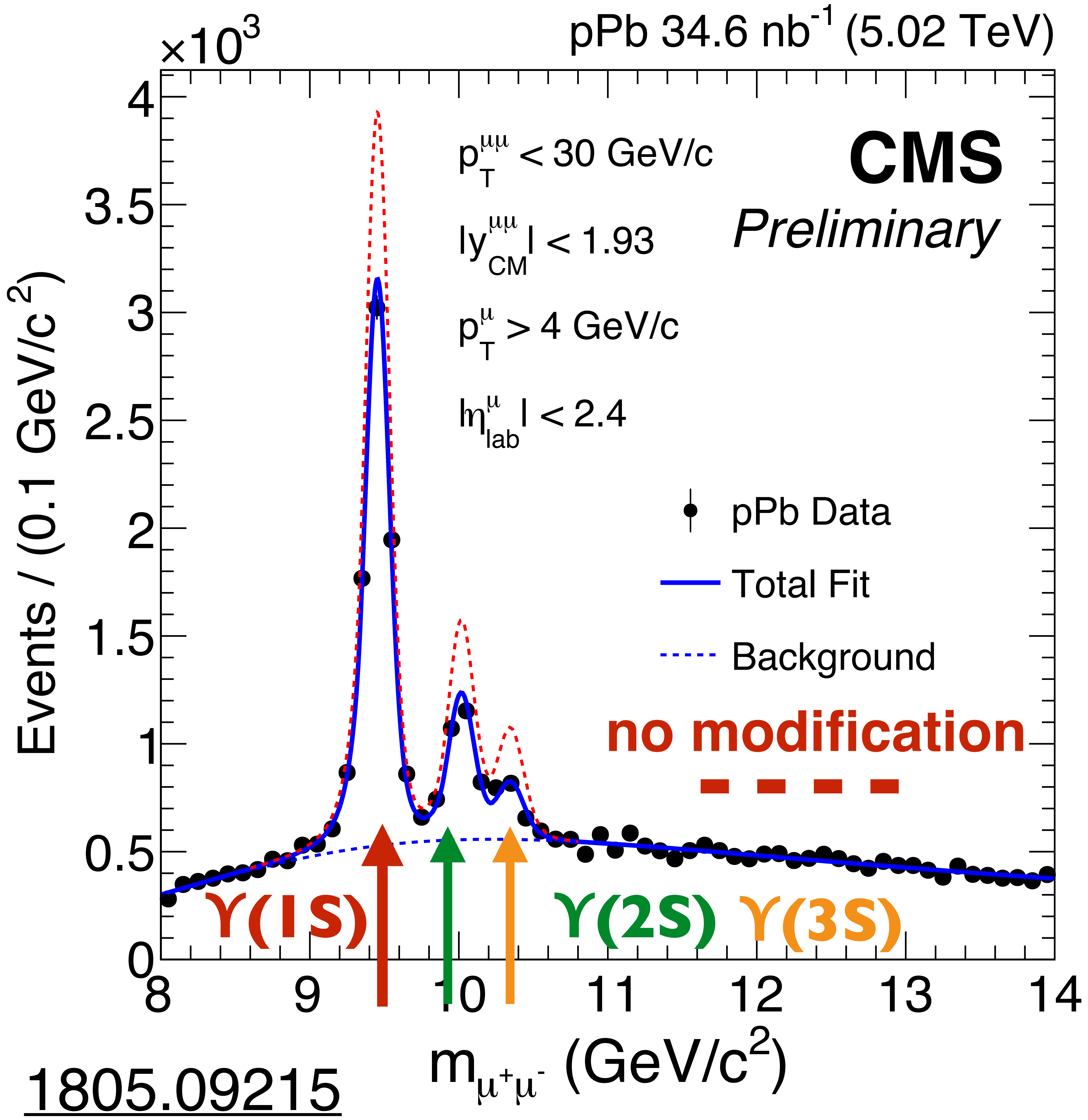
- Strong suppression w.r.t. to pp collisions in PbPb collisions!
- Loosely bound states more suppressed

Bottomonium suppression in PbPb and pPb collisions

Bottomonia less affected by recombination due to lower b-bar cross section!







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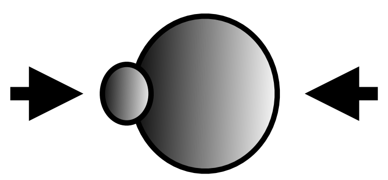
pPb



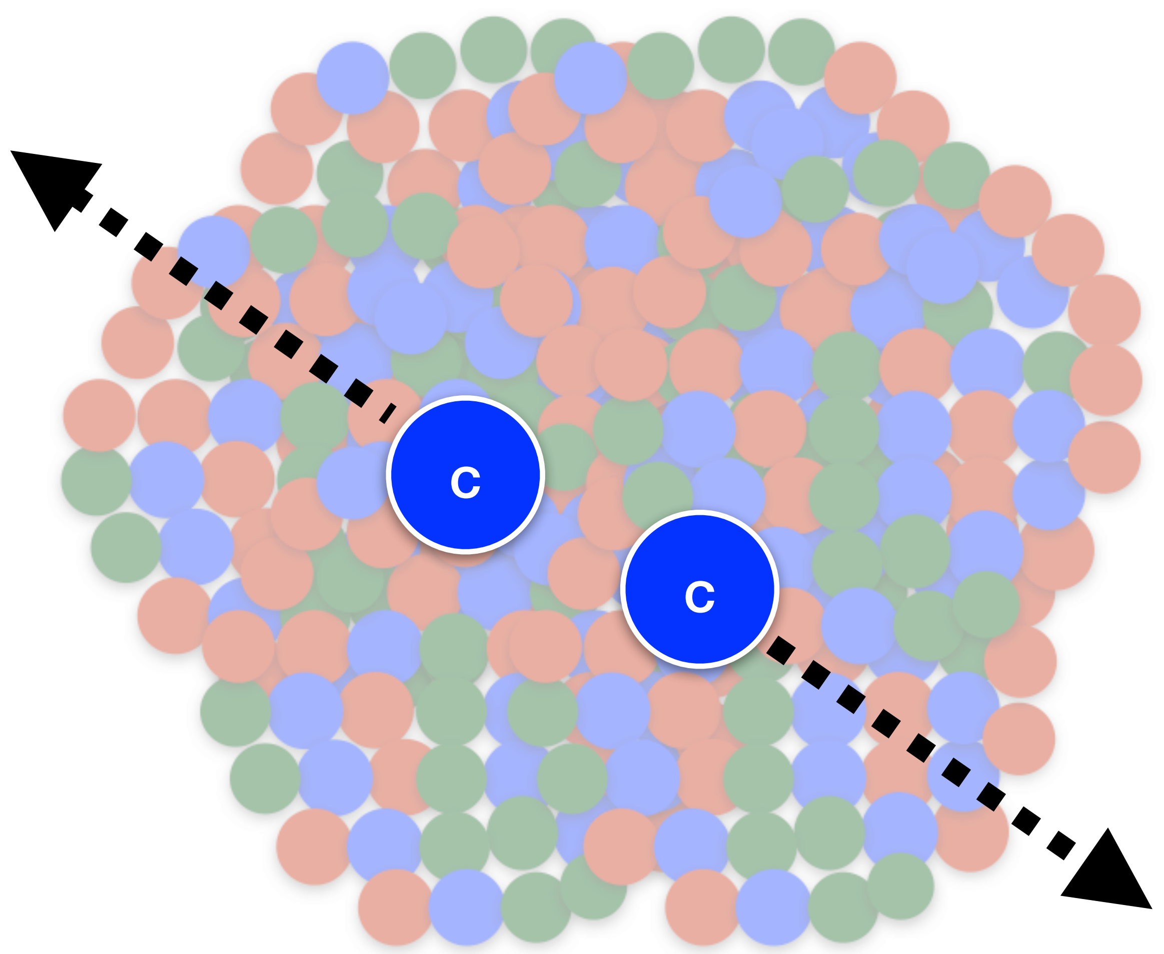
- Strong suppression w.r.t. to pp collisions in PbPb collisions!
- Loosely bound states more suppressed

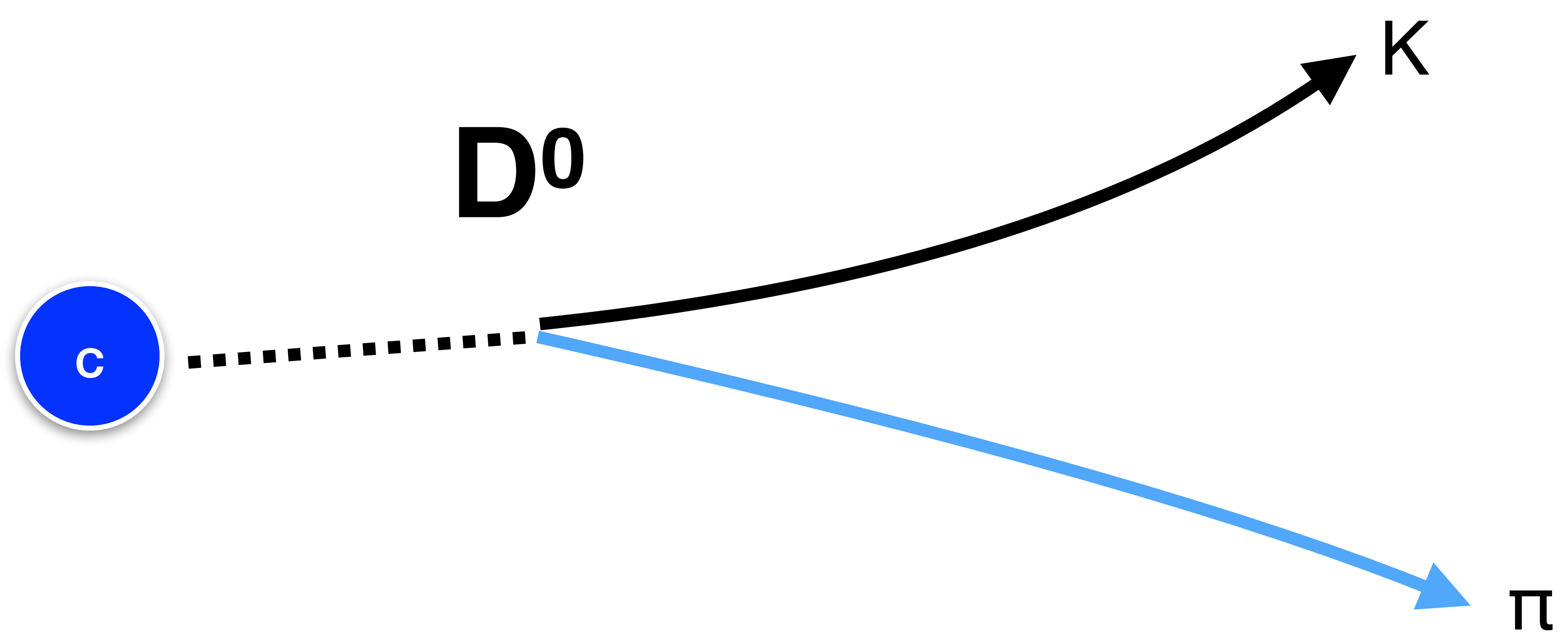
- (Milder)Υ suppression of loosely bound states
- Need for **final state effects in pPb collisions (e.g. hadronic rescattering**)

How much of the PbPb suppression can be explained by "cold" final state processes?

JHEP10 (2018) 094

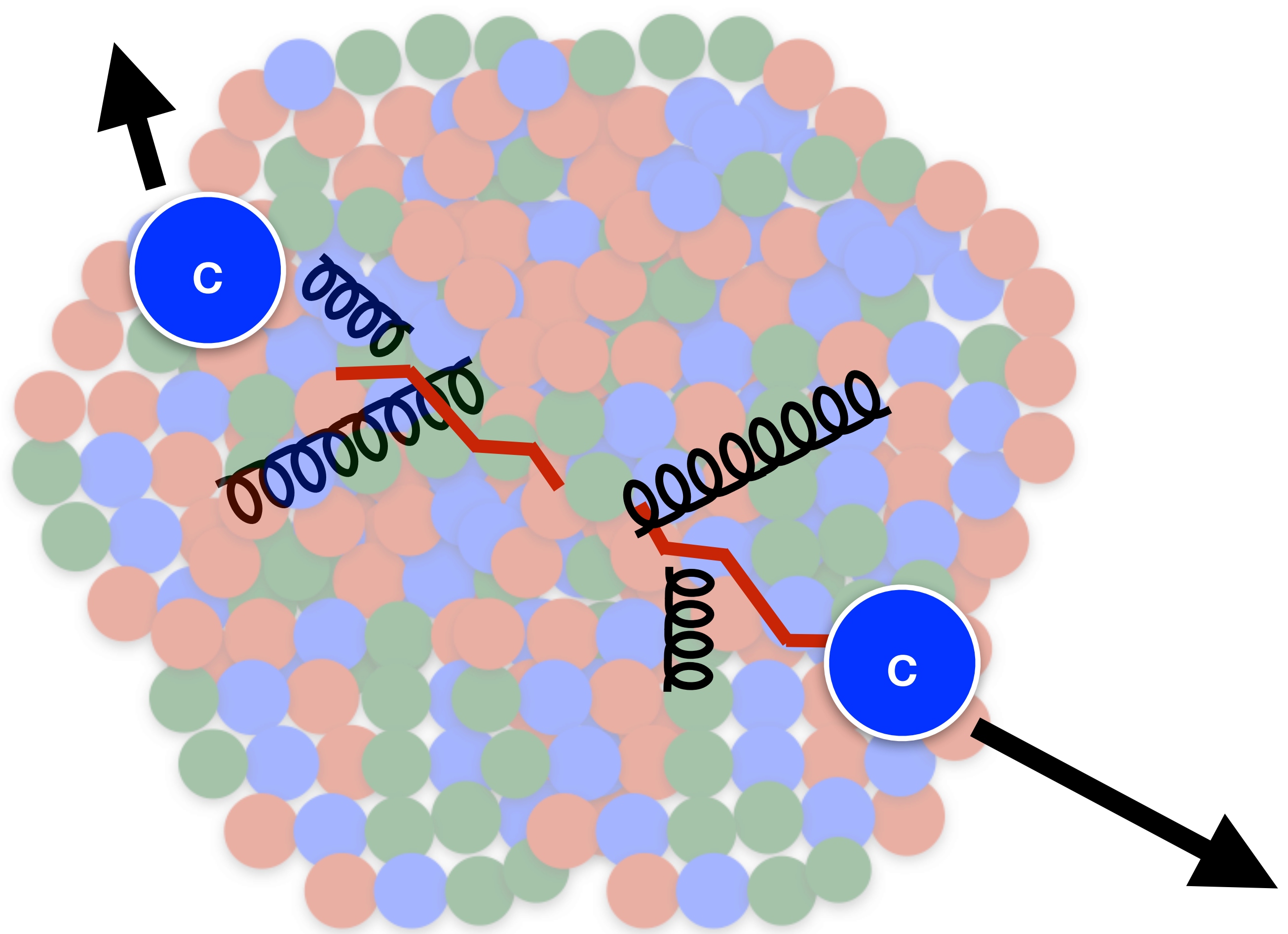
Open heavy flavour in PbPb collisions





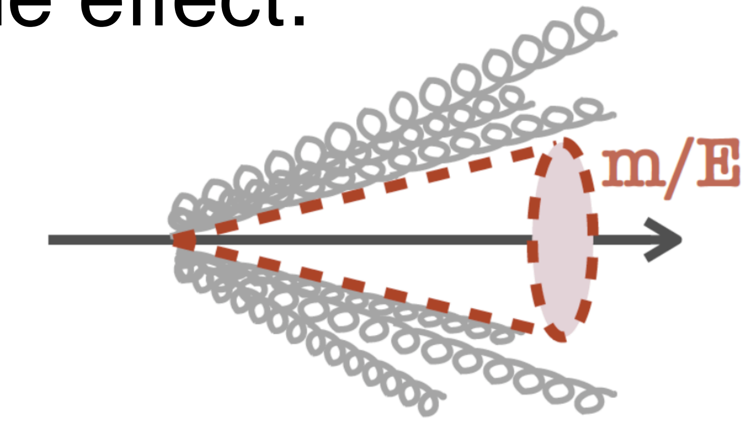
Flavour dependence of E_{loss} in PbPb

In-medium energy loss as a consequence of **radiative** and **collisional** processes.

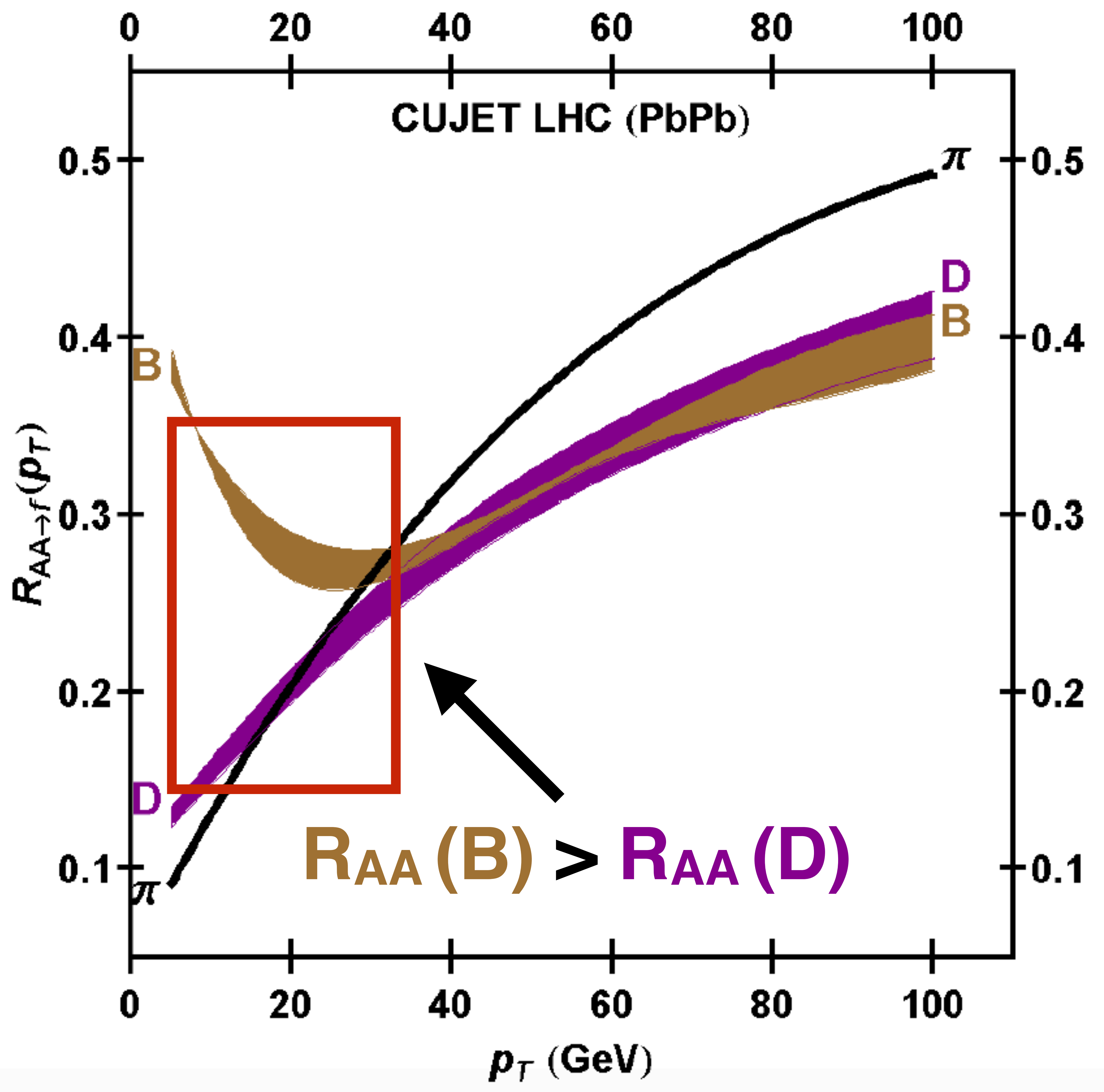


QCD predicts modifications in the presence of QGP due to:

- different Casimir factors for quarks vs gluons
- dead cone effect:



→ **E_{loss} (gluon) > E_{loss} (charm) > E_{loss} (beauty)**



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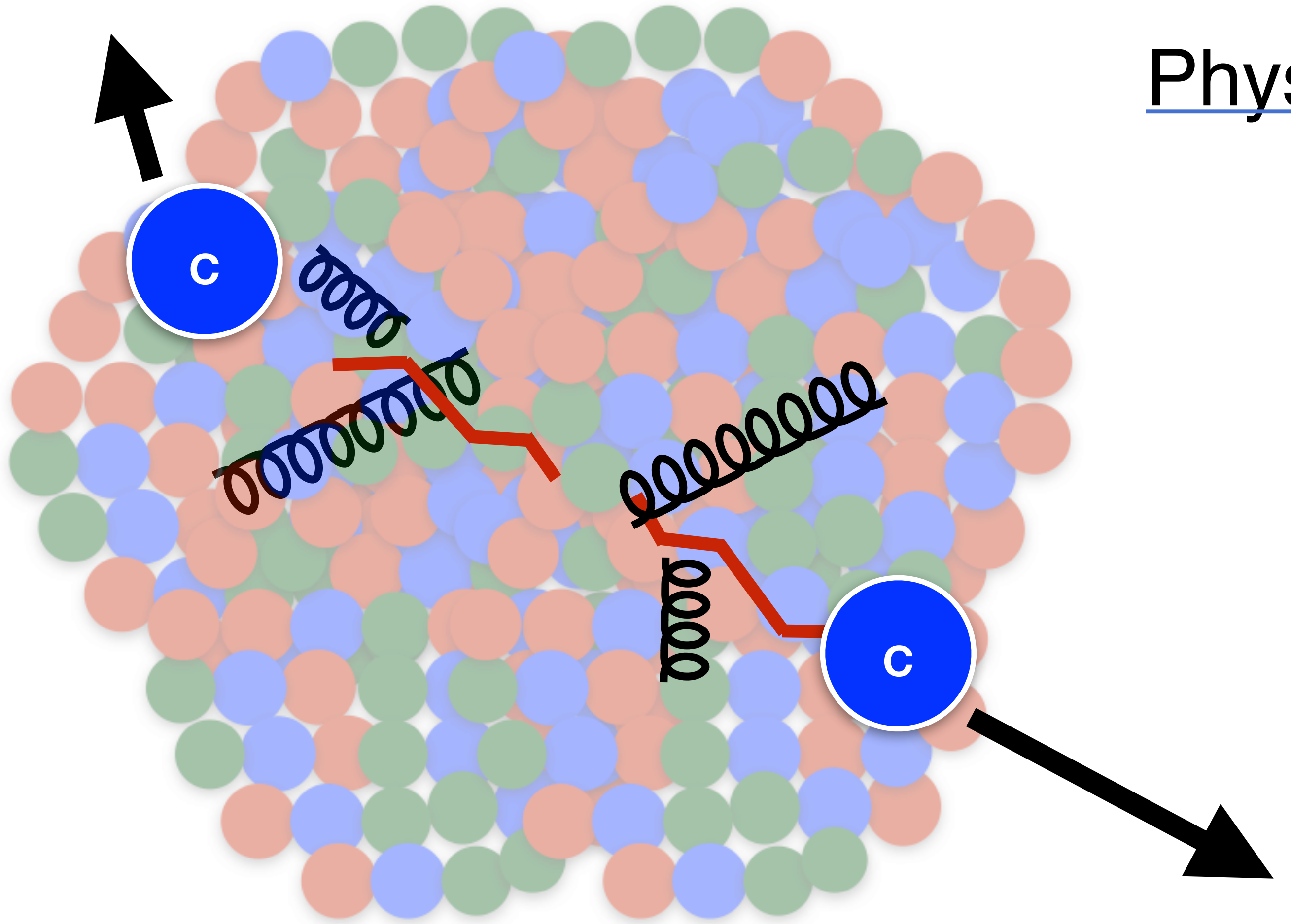
Phys. Lett. B 782 (2018) 474 et al.



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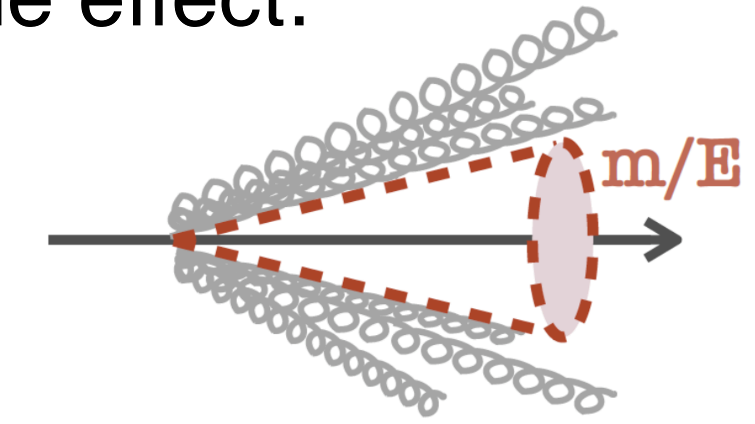

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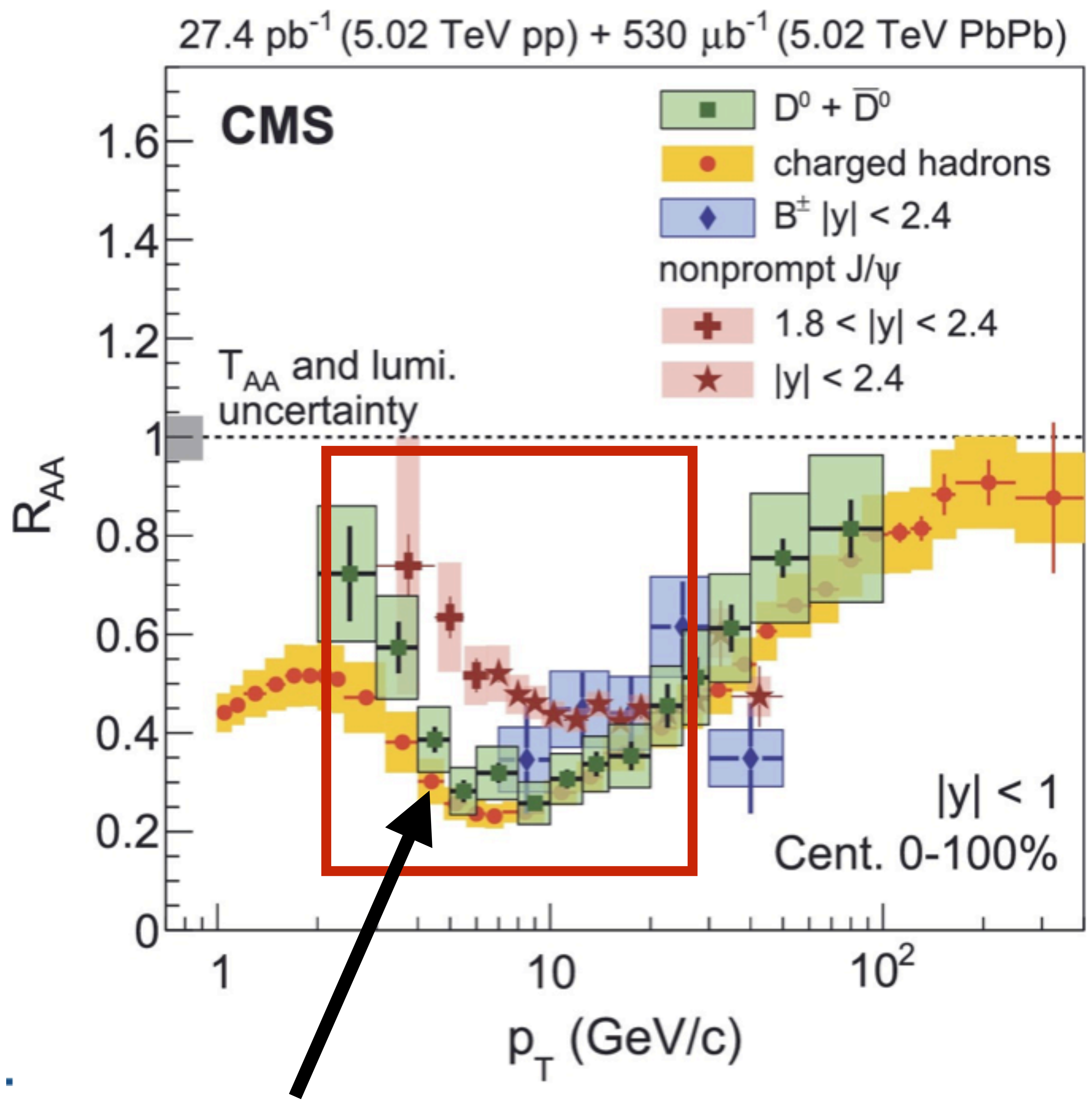


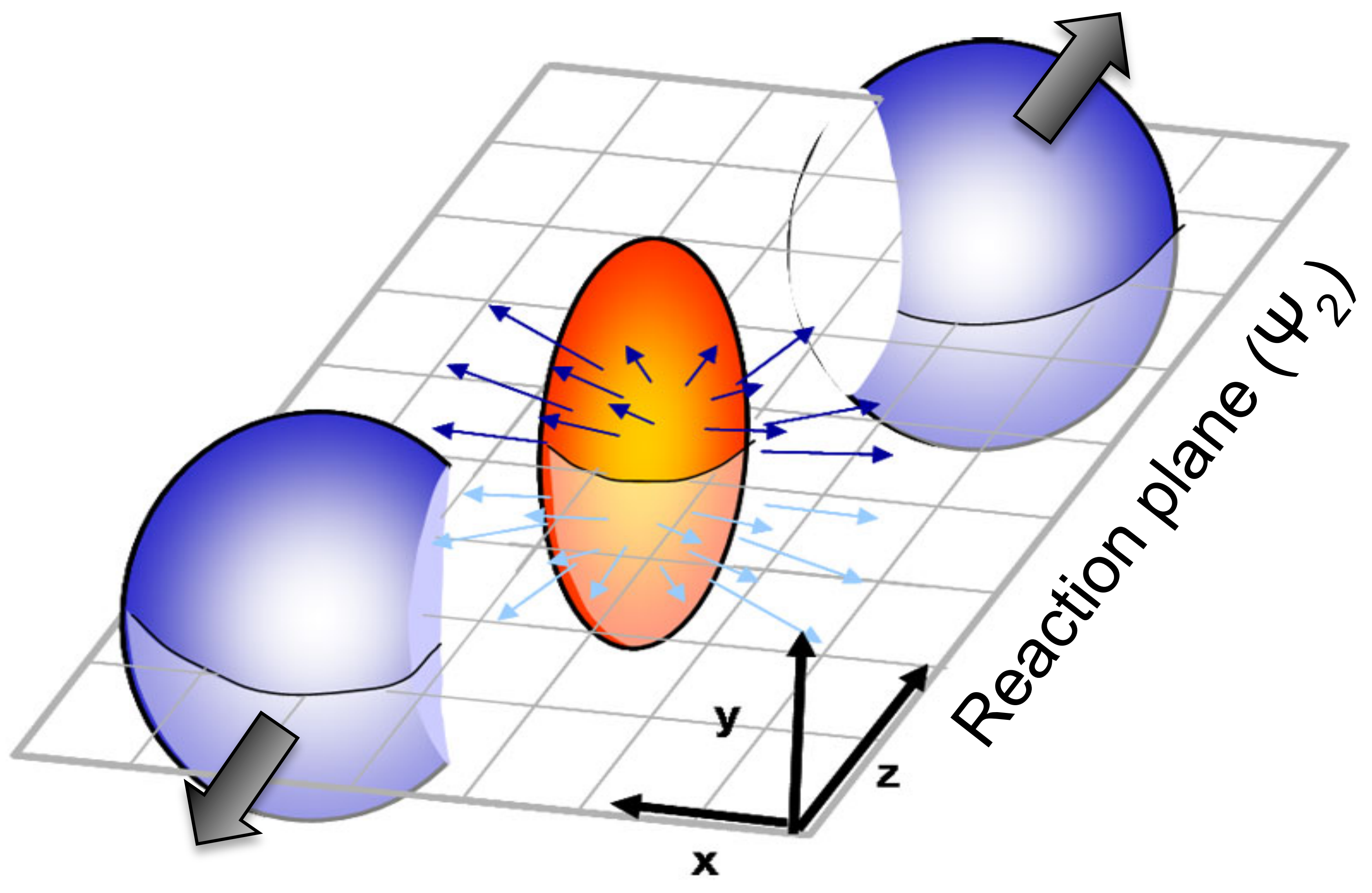
R_{AA} (b→J/ψ) > D meson

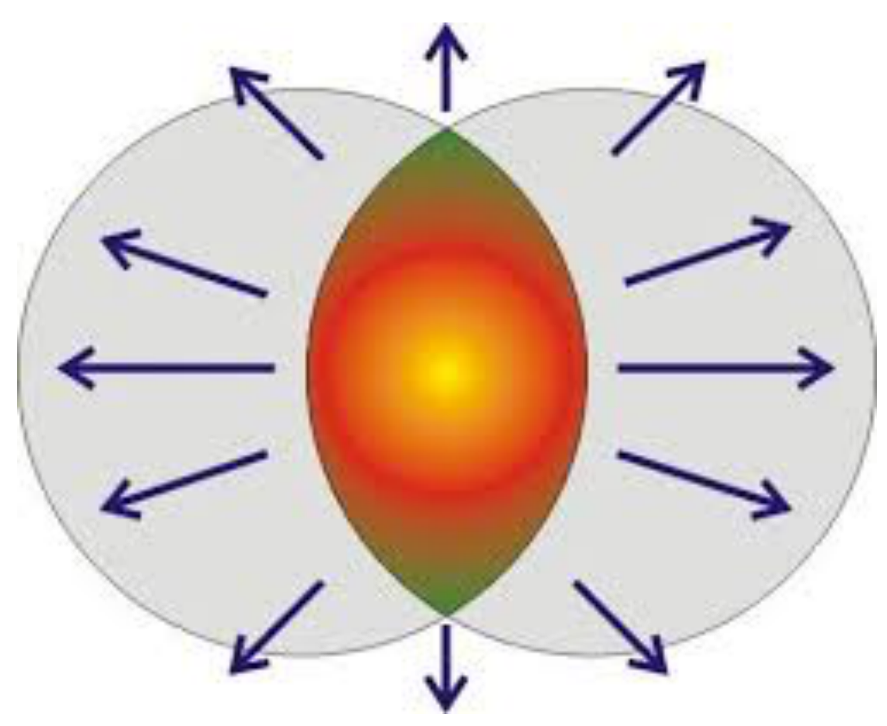
→ Hint of flavour dependence of in-medium energy loss

Collectivity in PbPb collisions:

Testing the collective behaviour of the medium

“Elliptic” flow (v_2) in PbPb collisions



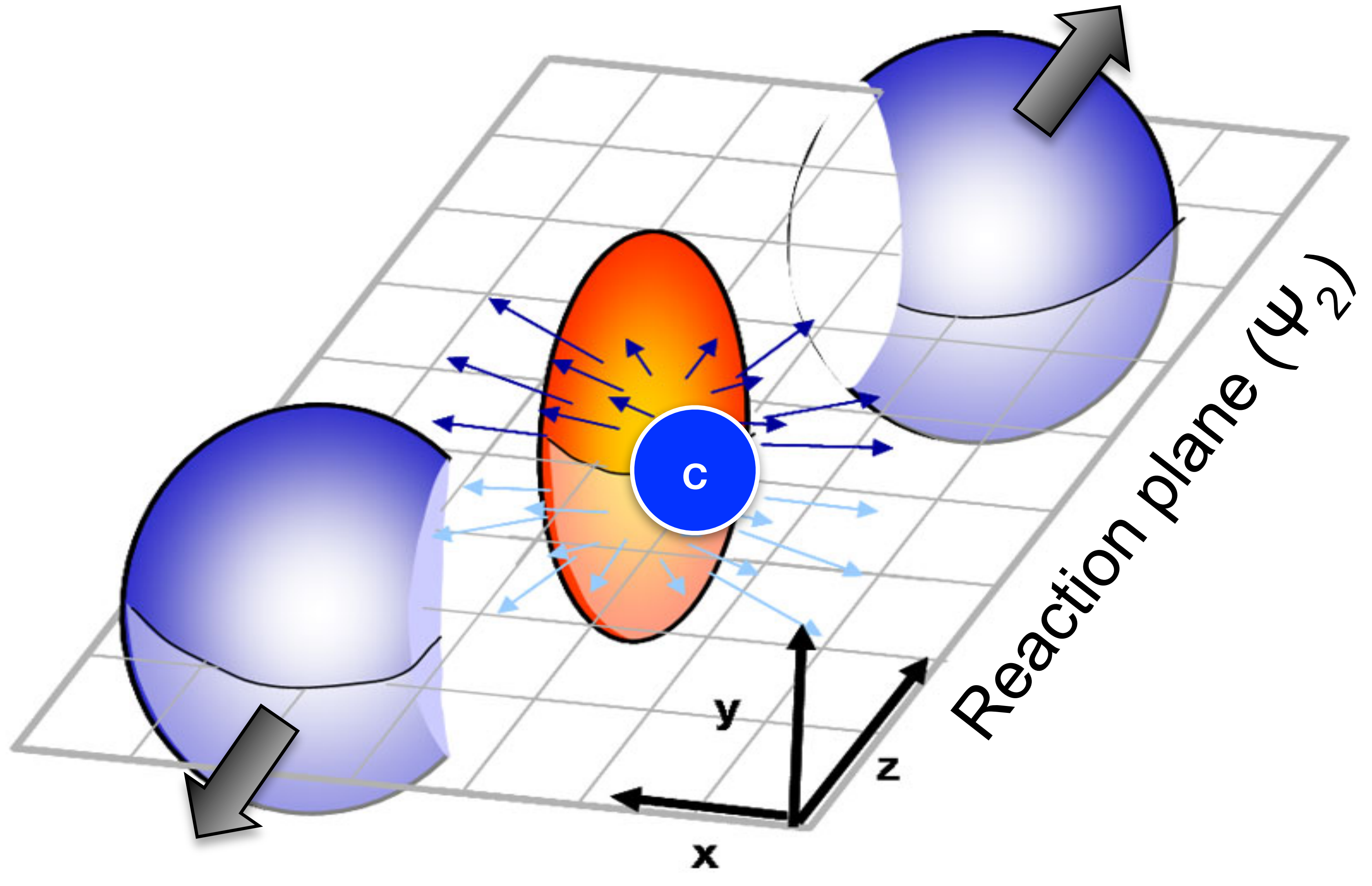


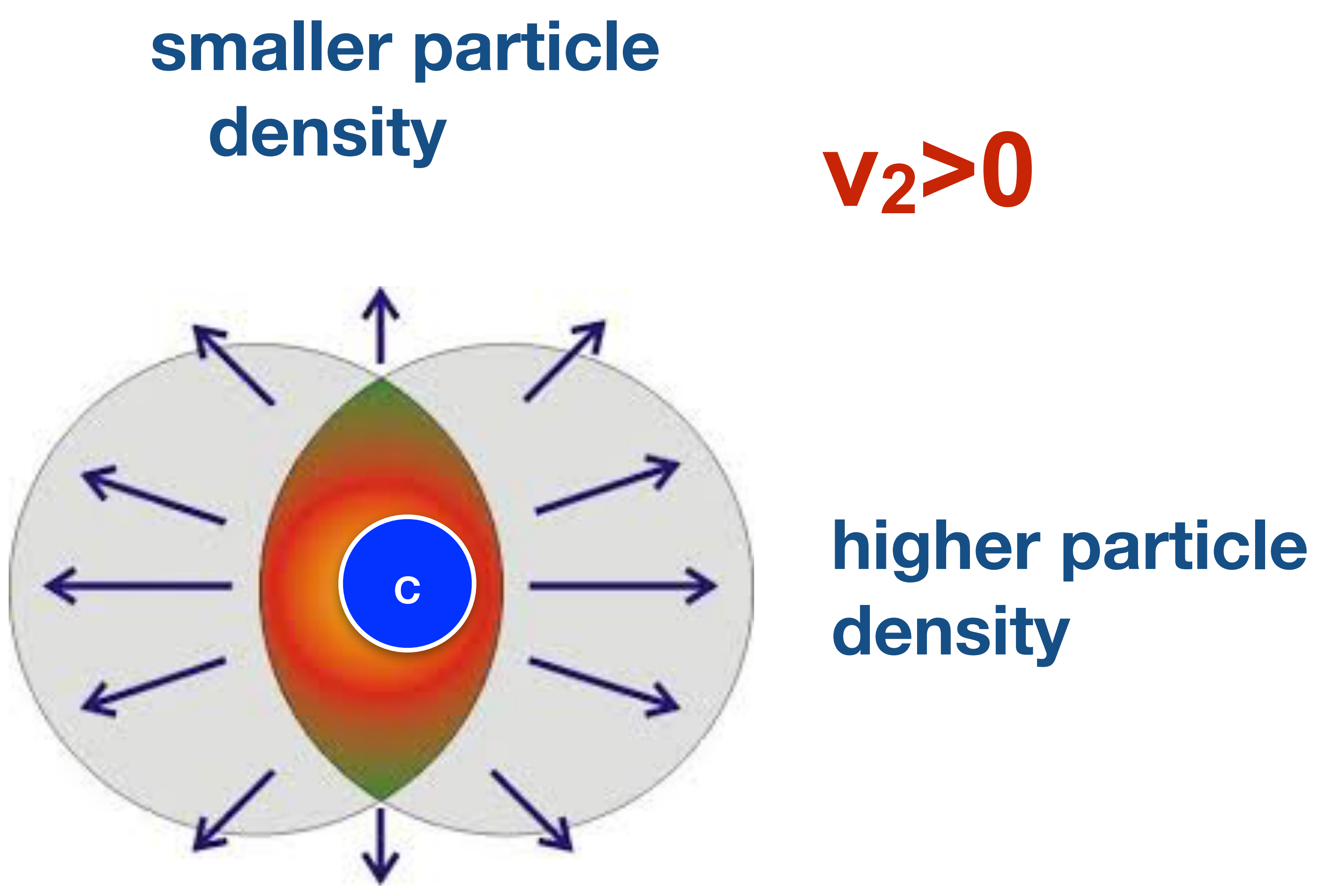
In the presence of a strongly interacting medium:

initial azimuthal asymmetry of the fireball → **azimuthal particle momentum anisotropy**

→Large v_2 at low p_T suggests collective expansion of the medium

“Elliptic” flow (v_2) in PbPb collisions





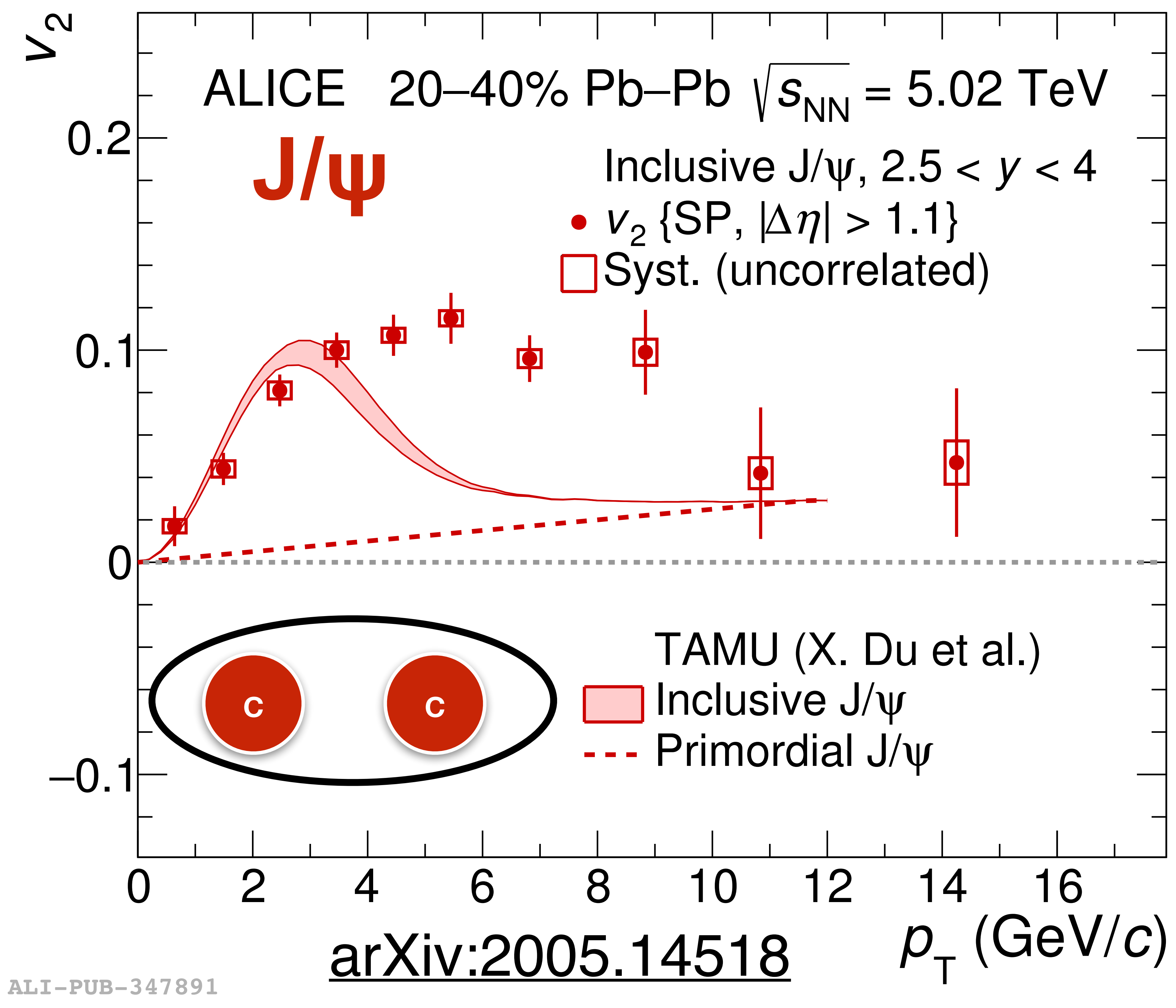
In the presence of a strongly interacting medium:

initial azimuthal asymmetry of the fireball → **azimuthal particle momentum anisotropy**

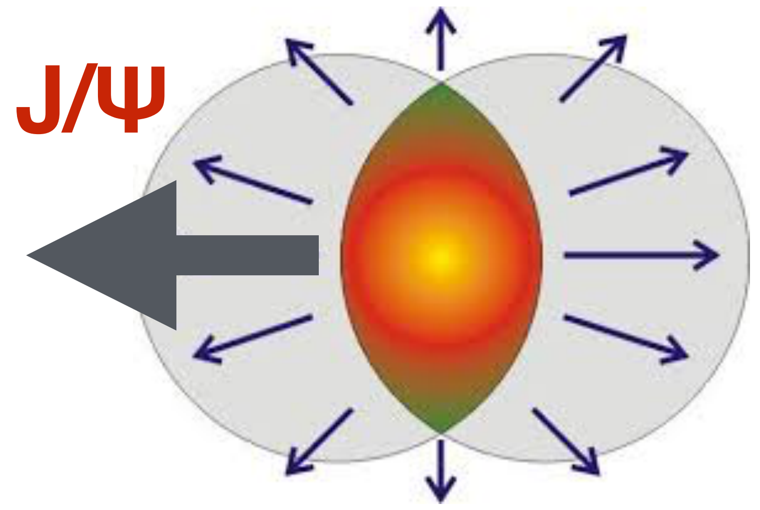
→Large v_2 at low p_T suggests collective expansion of the medium
→Are heavy quarks sensitive to the medium espansion?

Quarkonia flow in PbPb collisions

A. Lebedev

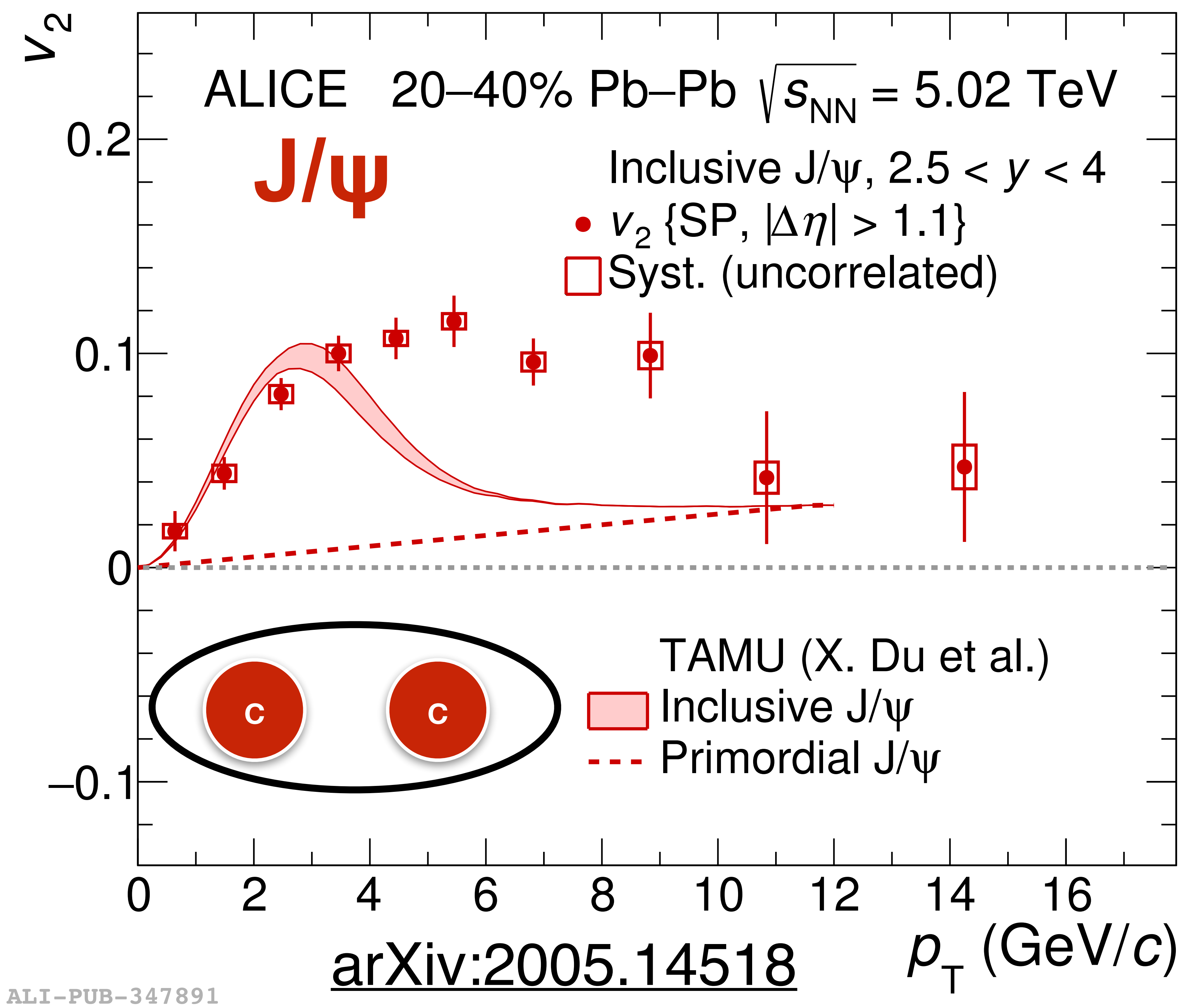


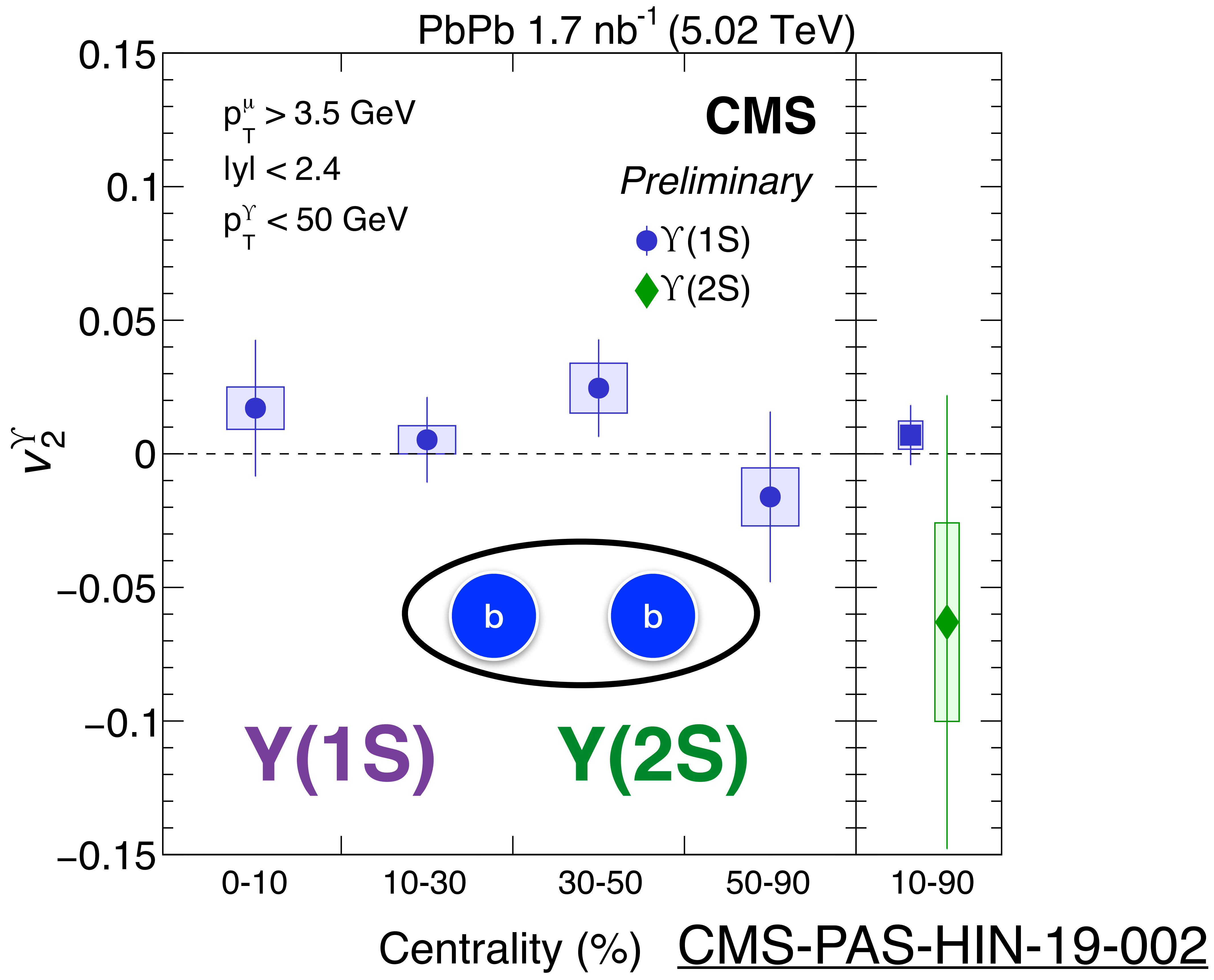
arXiv:2005.14518

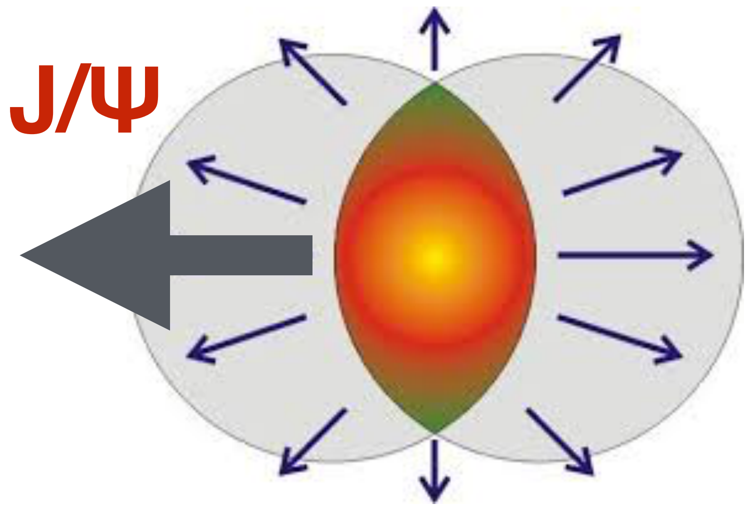


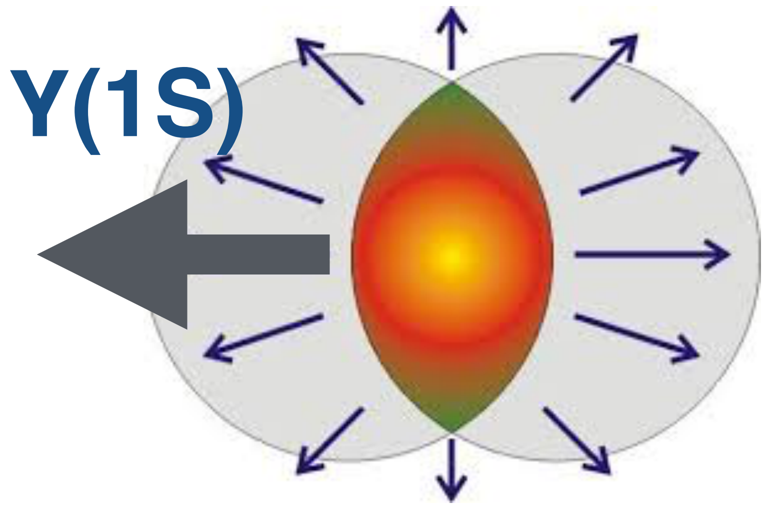
- **$v_2 > 0$**
- positive v_2 at high-p_T? charm energy loss?

Quarkonia flow in PbPb collisions





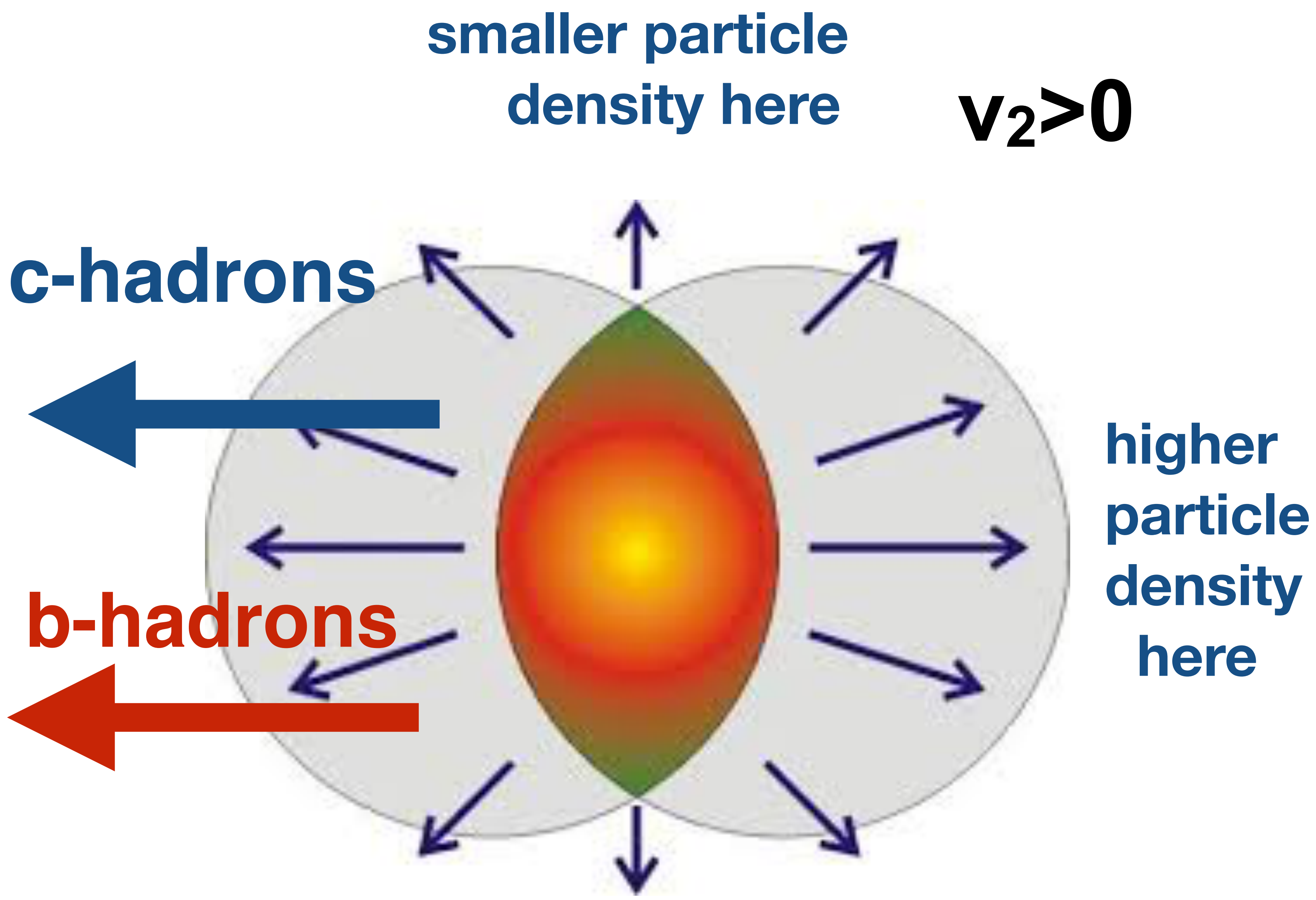


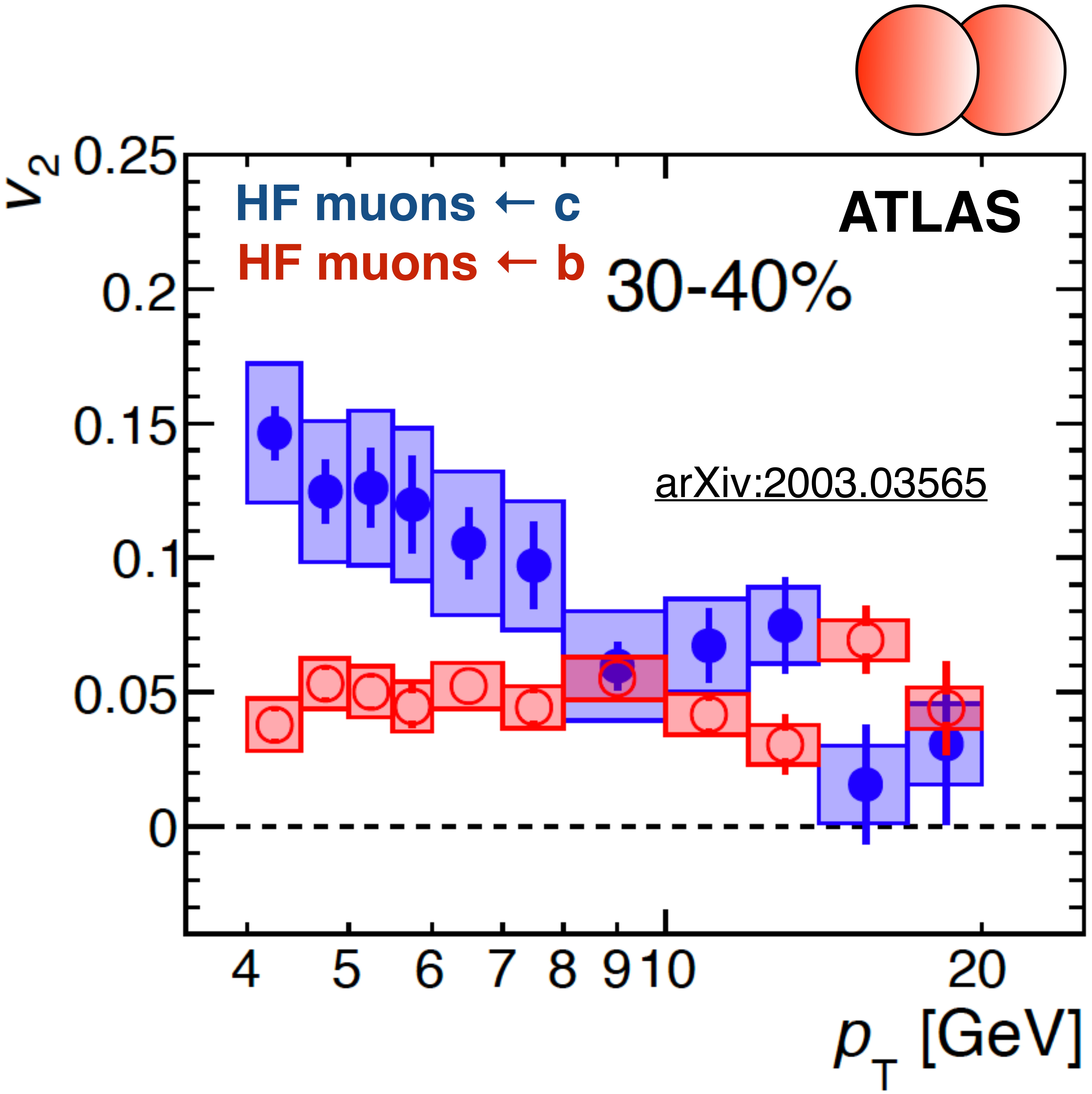


- **$v_2 > 0$**
- positive v_2 at high-p_T? charm energy loss?

- $v_2 \sim 0$ for both Y(1S) and Y(2S)

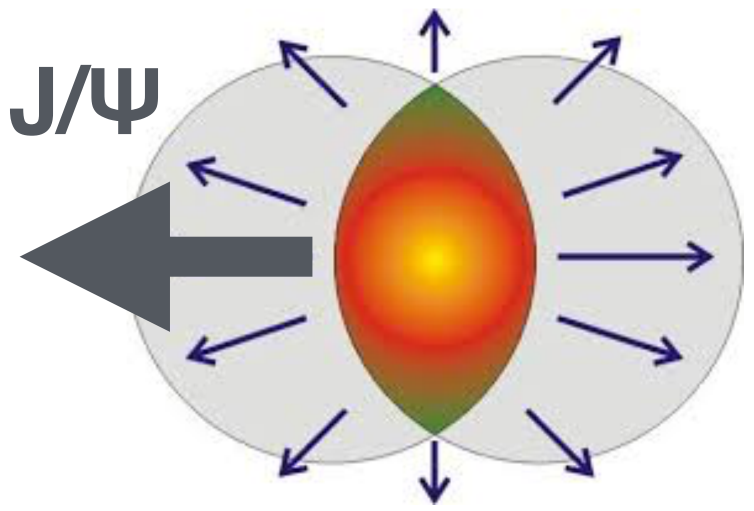
Charm and beauty "flow" in PbPb collisions

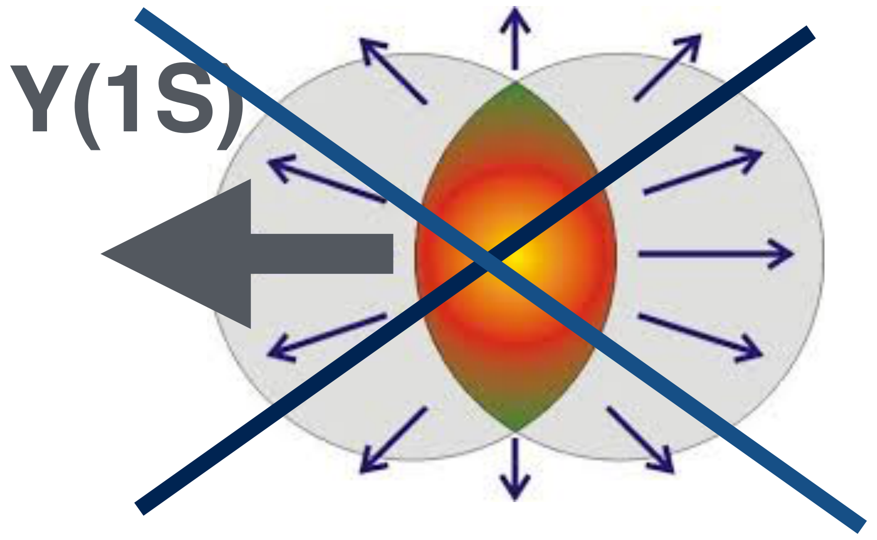


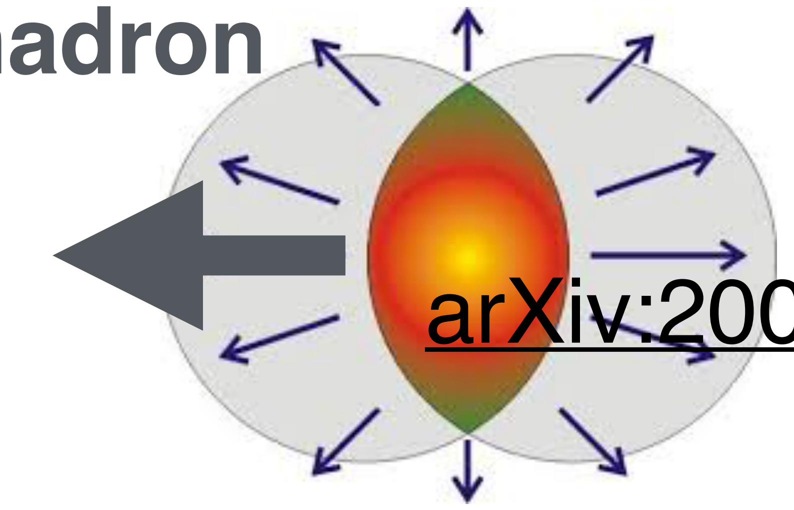


- v_2 significantly > 0 for HF muons ← c
- v_2 smaller but still > 0 for HF muons ← b

Charm and beauty "flow" in AA collisions







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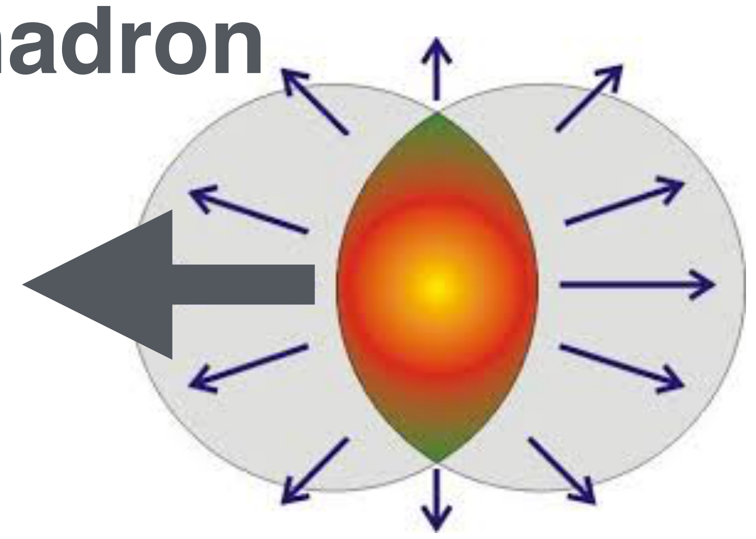
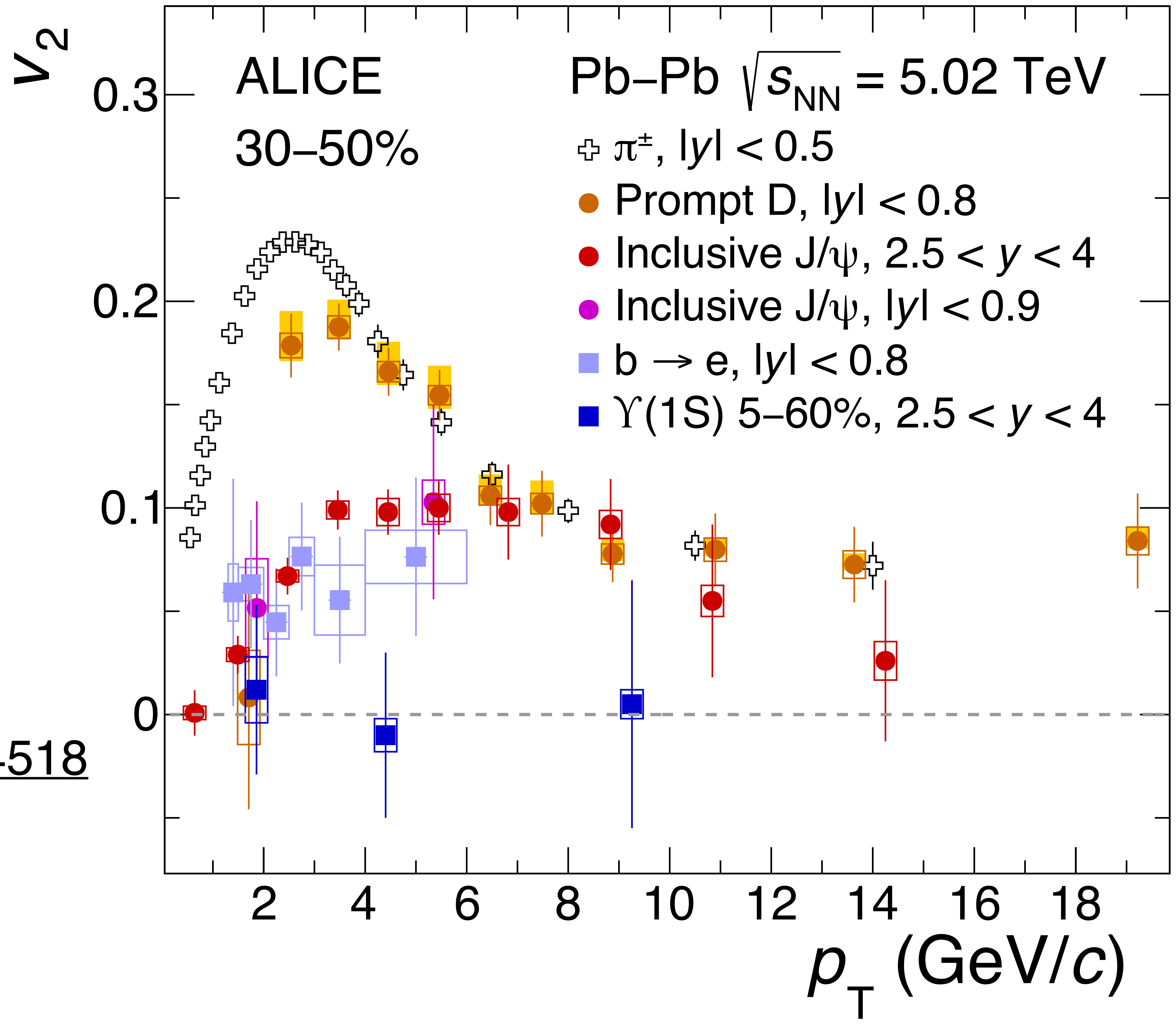
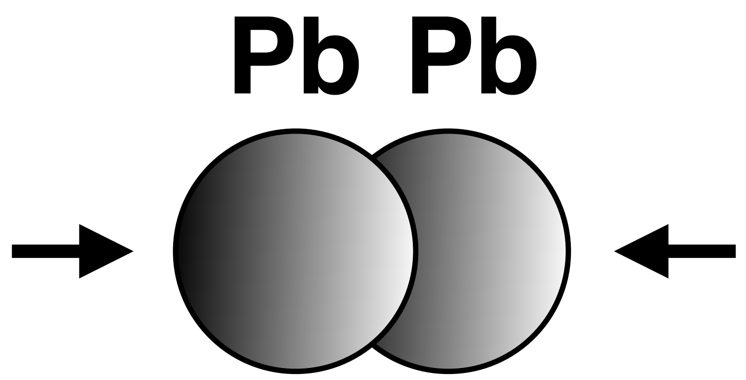
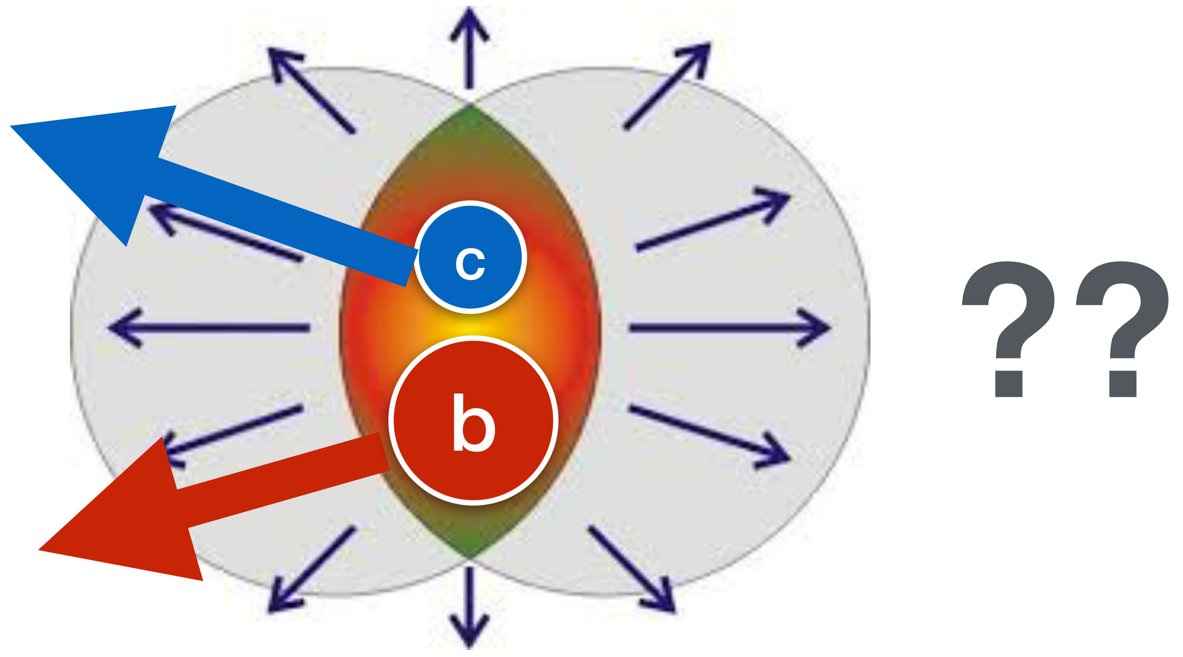


arXiv.2005.11130







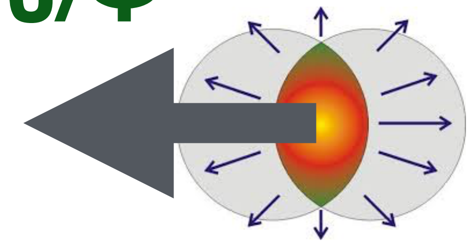
→ seems likely that the charm quarks are "flowing"

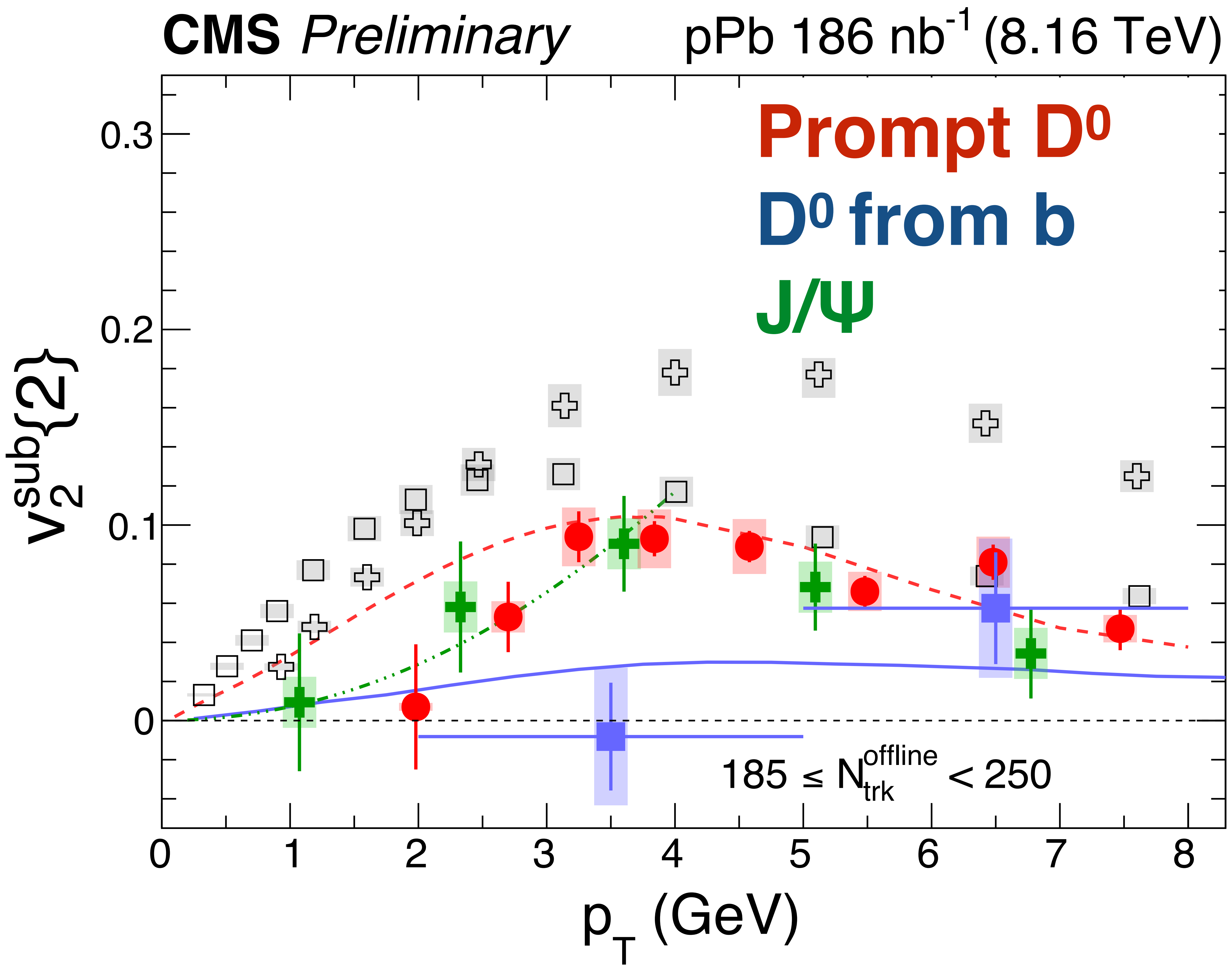
→ v_2> 0 for open beauty and ~ 0 for bottomonium! **Effect of recombination processes**?

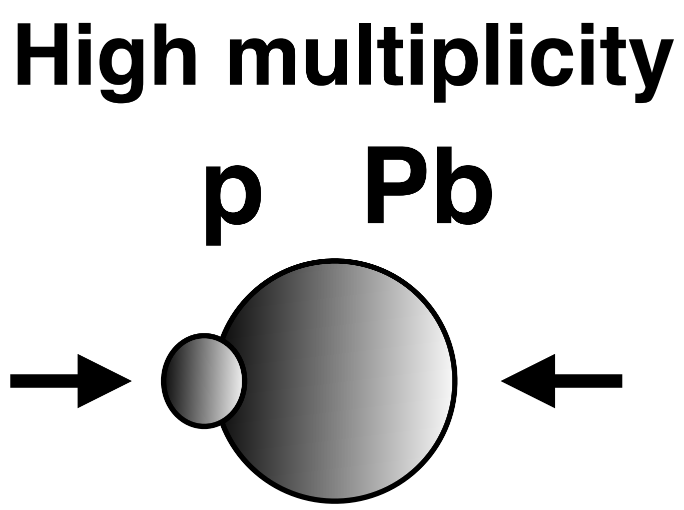
Charm and beauty "flow" in pPb collisions

CMS-PAS-HIN-19-009

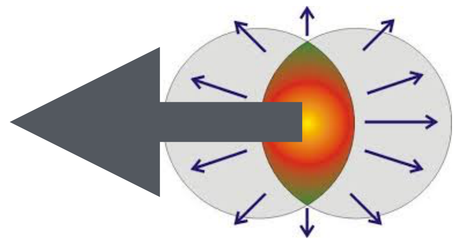
J/Ψ



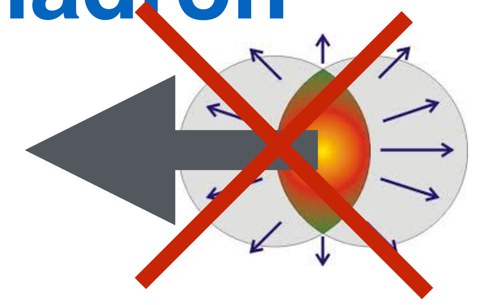




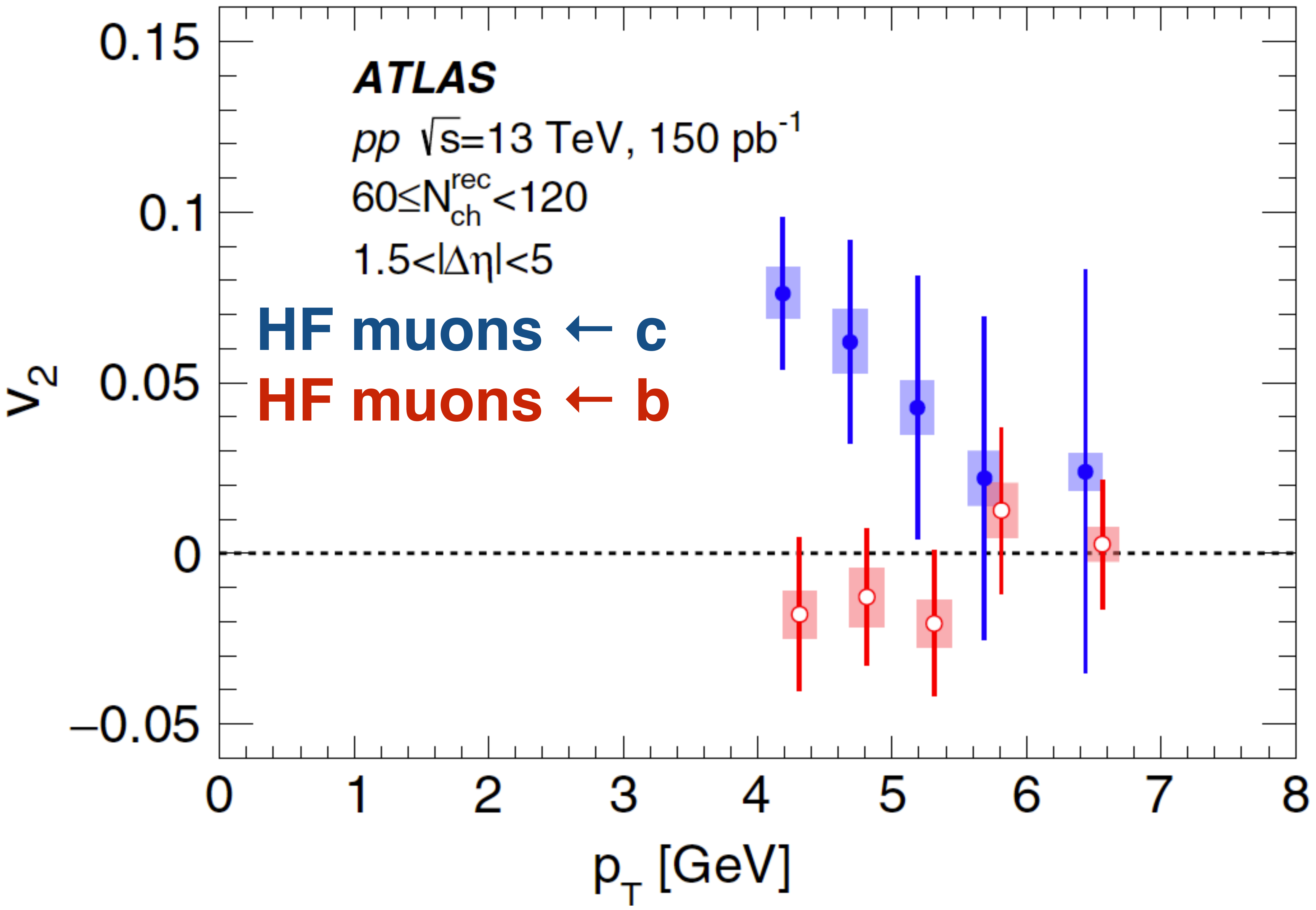
c-hadron



b-hadron

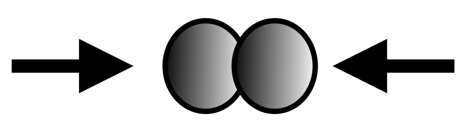


Charm and beauty "flow" in pp collisions

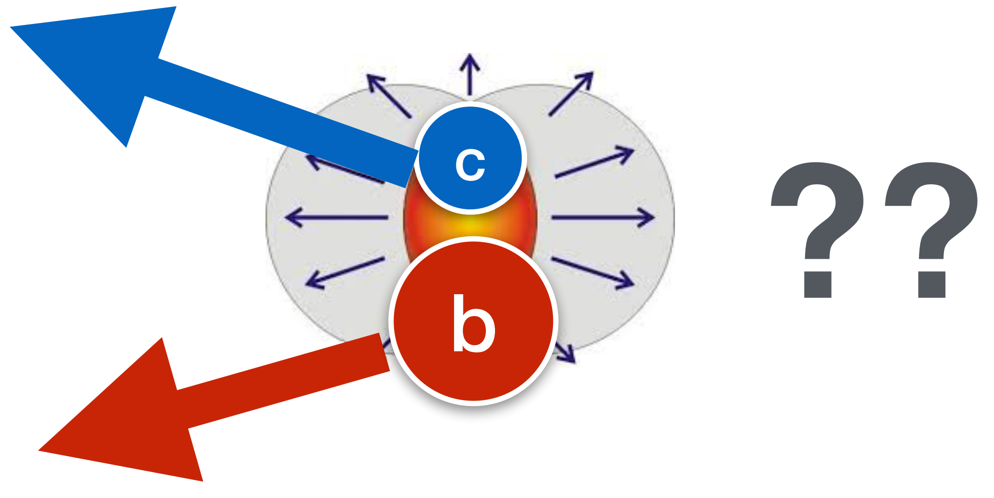


PRL 124, 082301 (2020)

pp



High multiplicity



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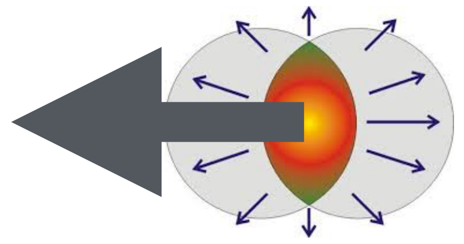
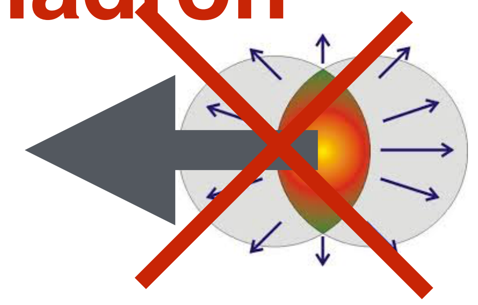
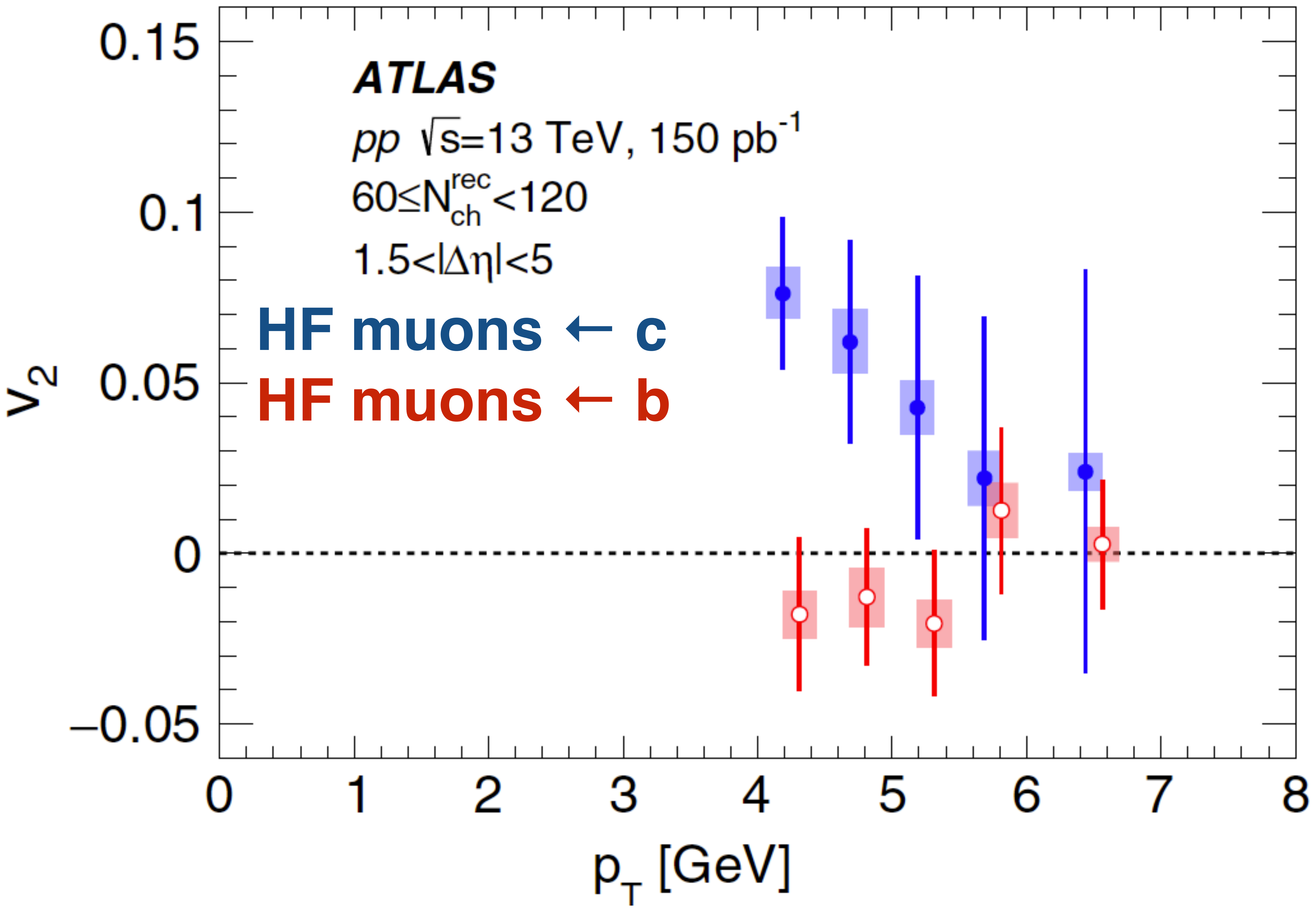


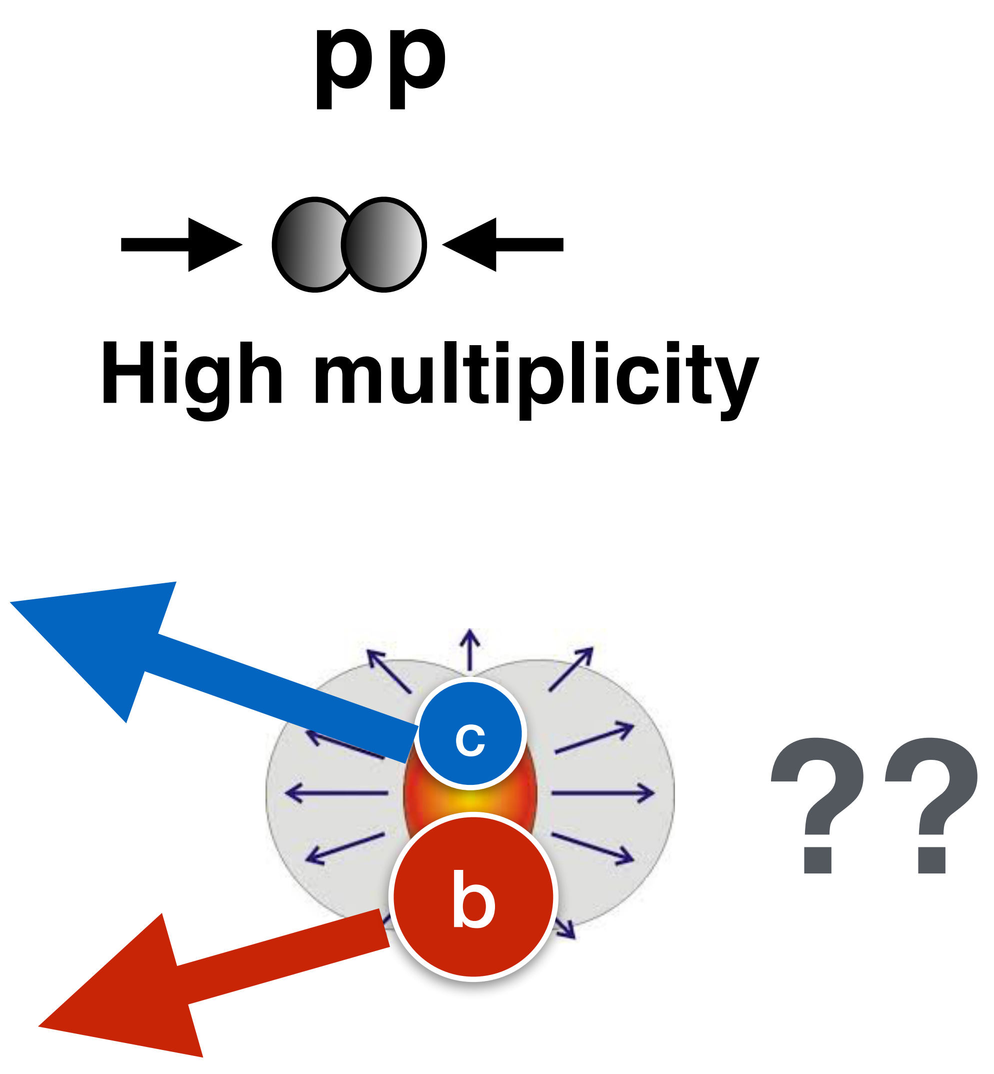
b-hadron

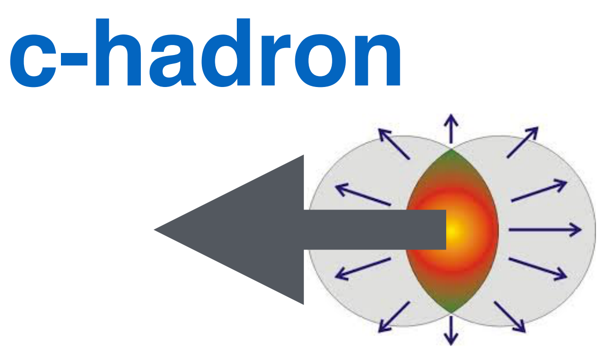


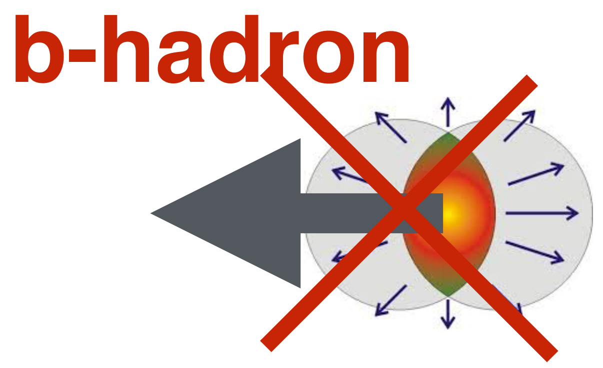
Charm and beauty "flow" in pp collisions

CMS-PAS-HIN-19-009
PRL 124, 082301 (2020)









- **indication of charm quark flow**
- b-hadron flow $v_2 \sim 0$. **Is beauty too heavy to flow?**

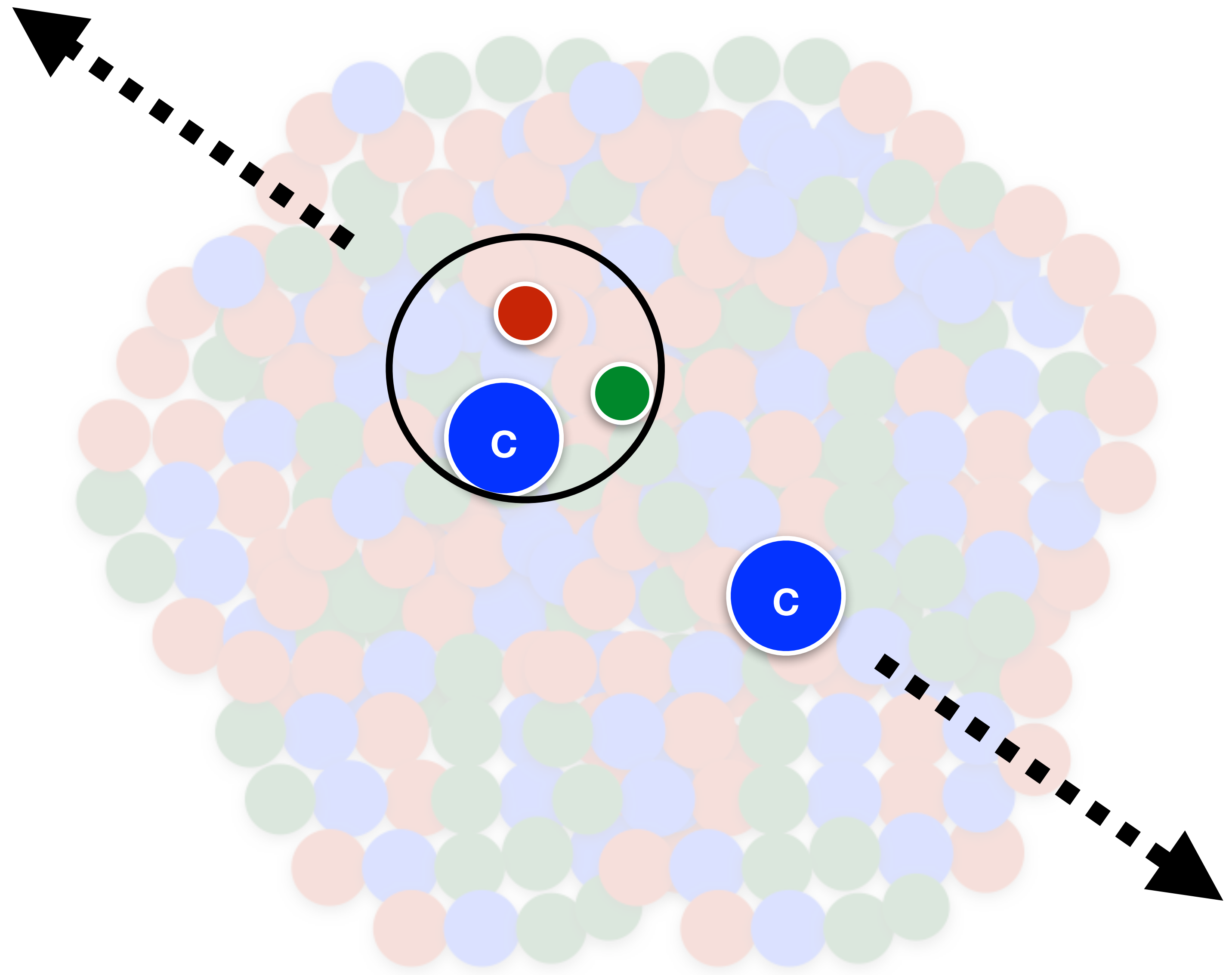
→ **suggest the presence of final state interactions in pp and pPb collisions**

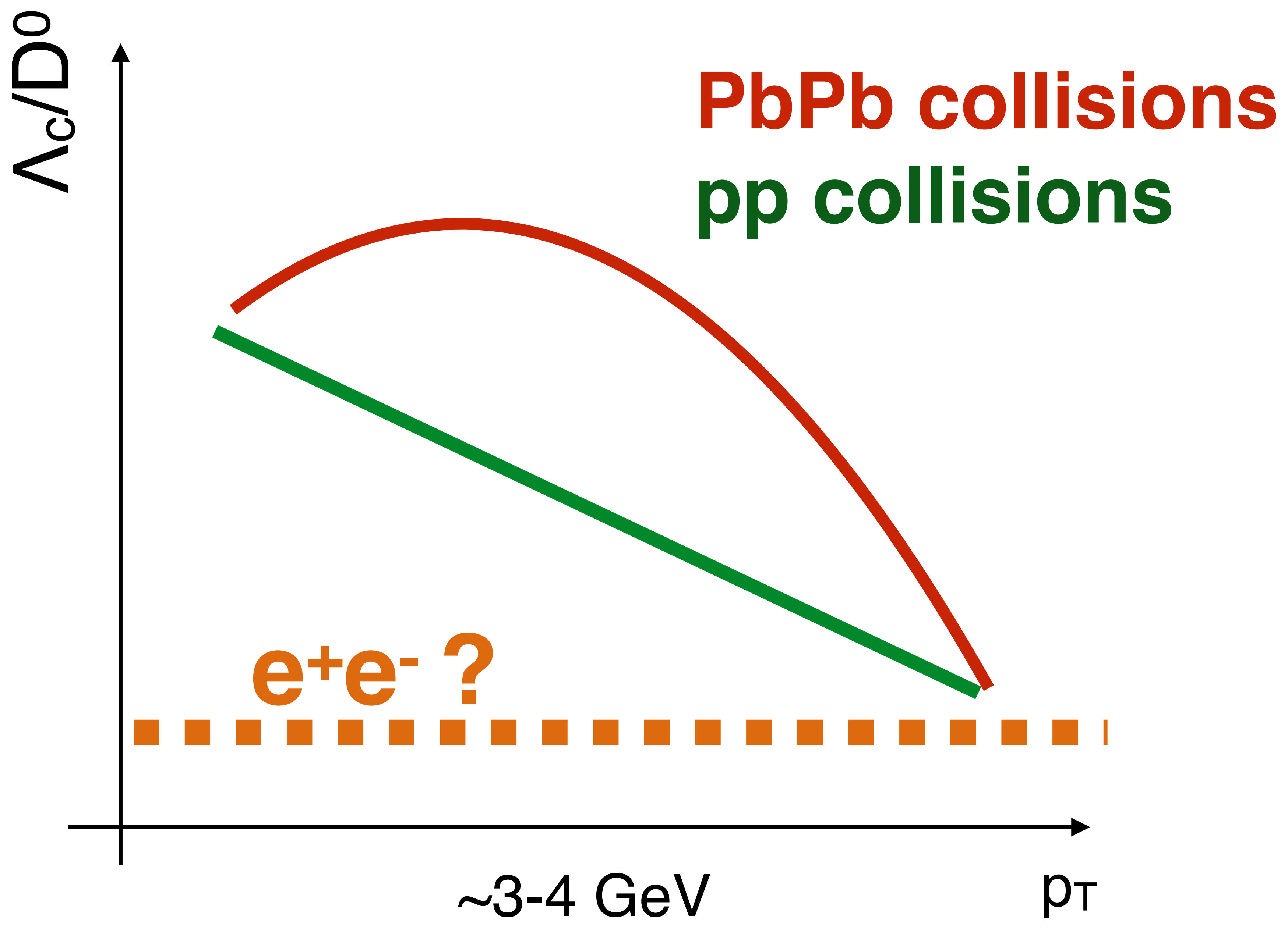
Open heavy flavour:

probing hadronisation mechanisms

In-medium hadronisation for charmed hadrons

Λ_c/D^0 (baryon/meson) ratio is also **expected to increase in the presence of charm recombination** in the QGP





C.-L. Huang
C. Terrevoli

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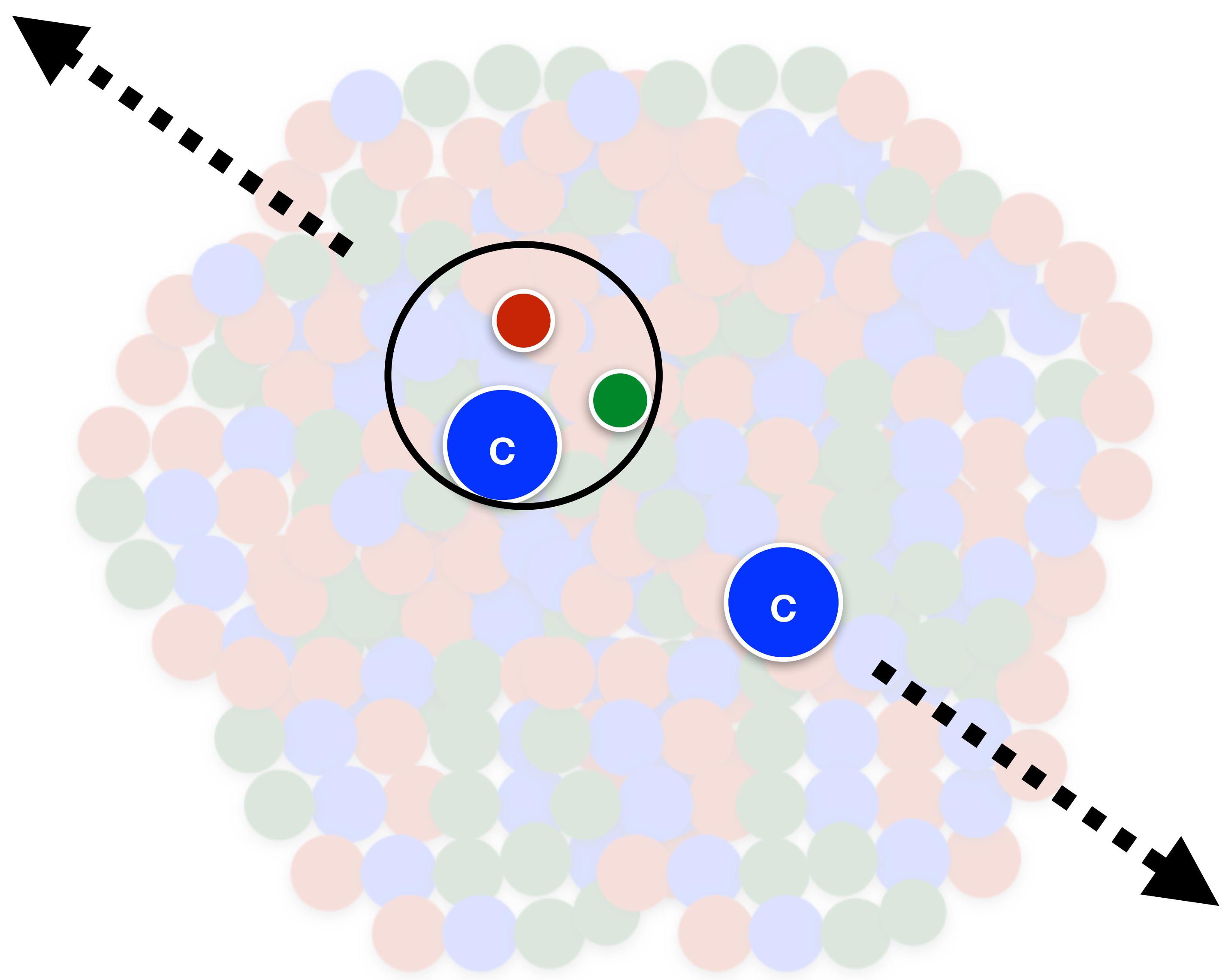
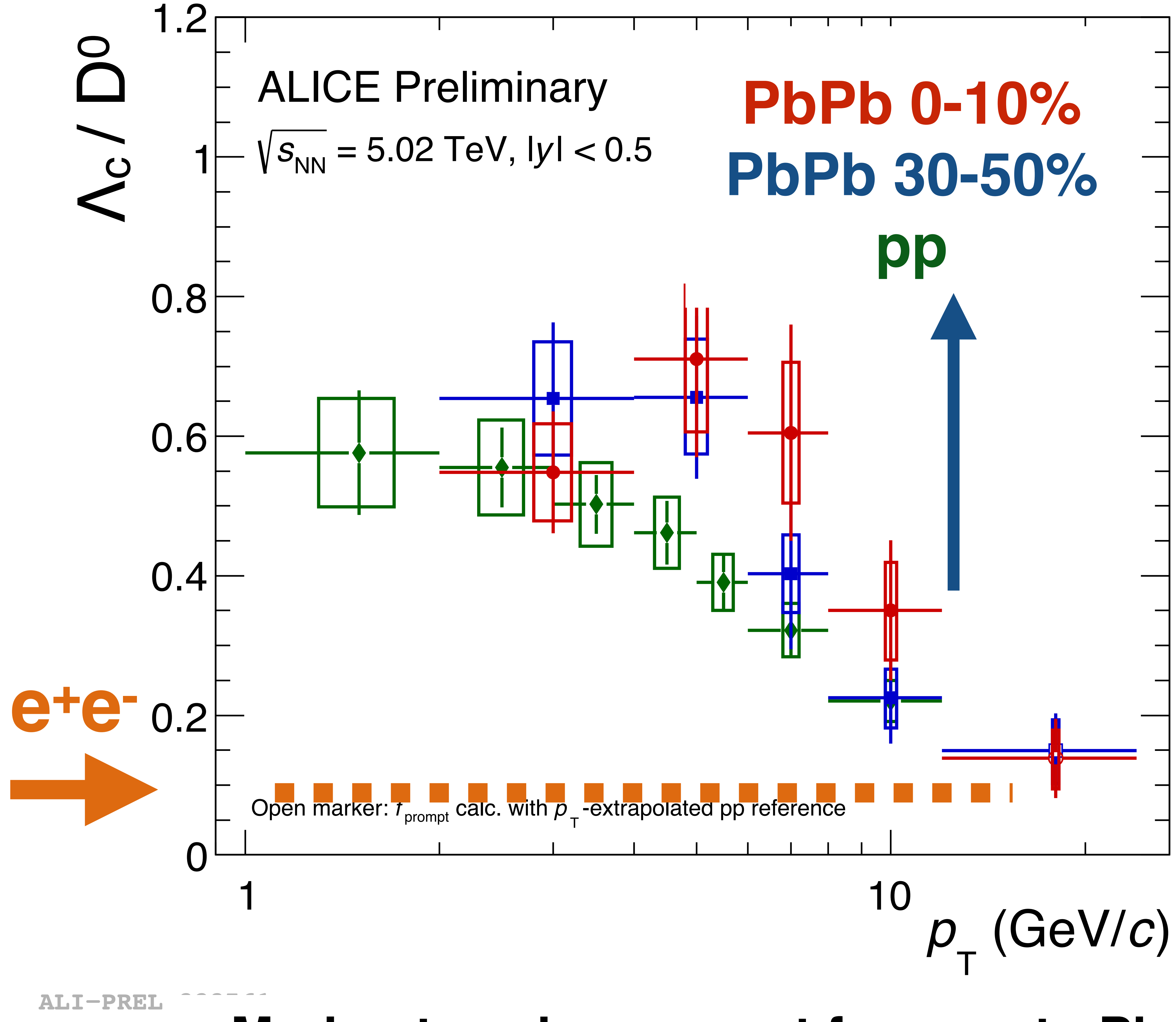
Λ_c/D^0 (baryon/meson) ratio is also **expected to increase in the presence of charm recombination** in the QGP



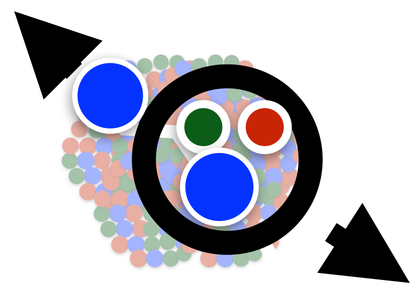


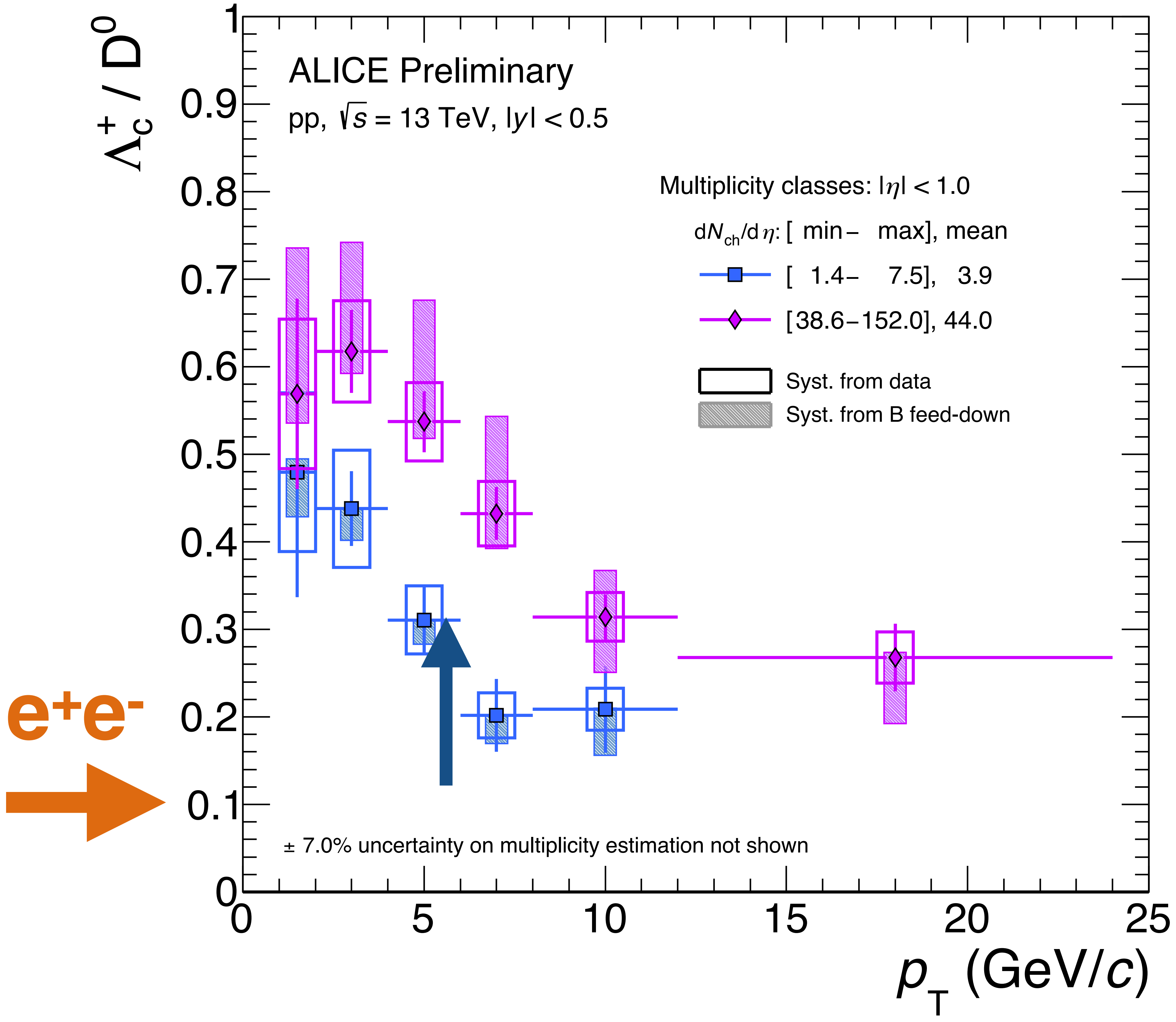
- **Moderate enhancement from pp to Pb-Pb** at intermediate p_T within uncertainties

→ **Hadronization is modified already in pp collisions?**

C.-L. Huang
C. Terrevoli

Modification of hadronisation in pp collisions?

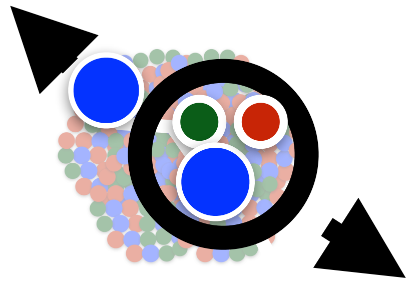


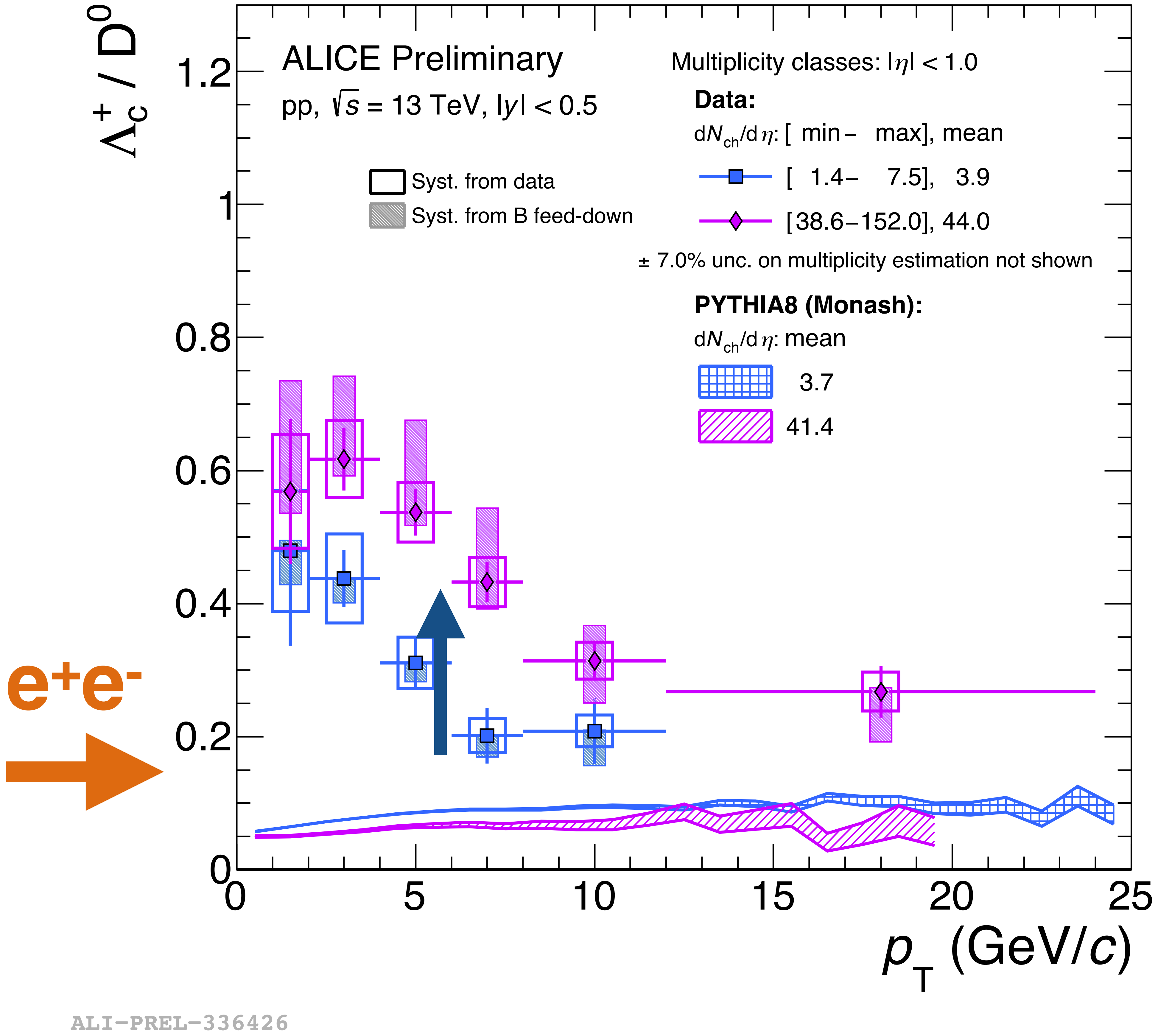


- Λ_c/D^0 shows an increase from **low pp multiplicity** to **high pp multiplicity**
- **large increase from e^+e^- to pp**

C.-L. Huang
C. Terrevoli

Modification of hadronisation in pp collisions?



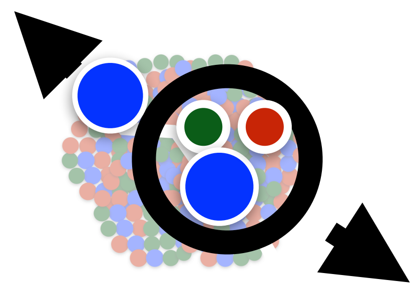


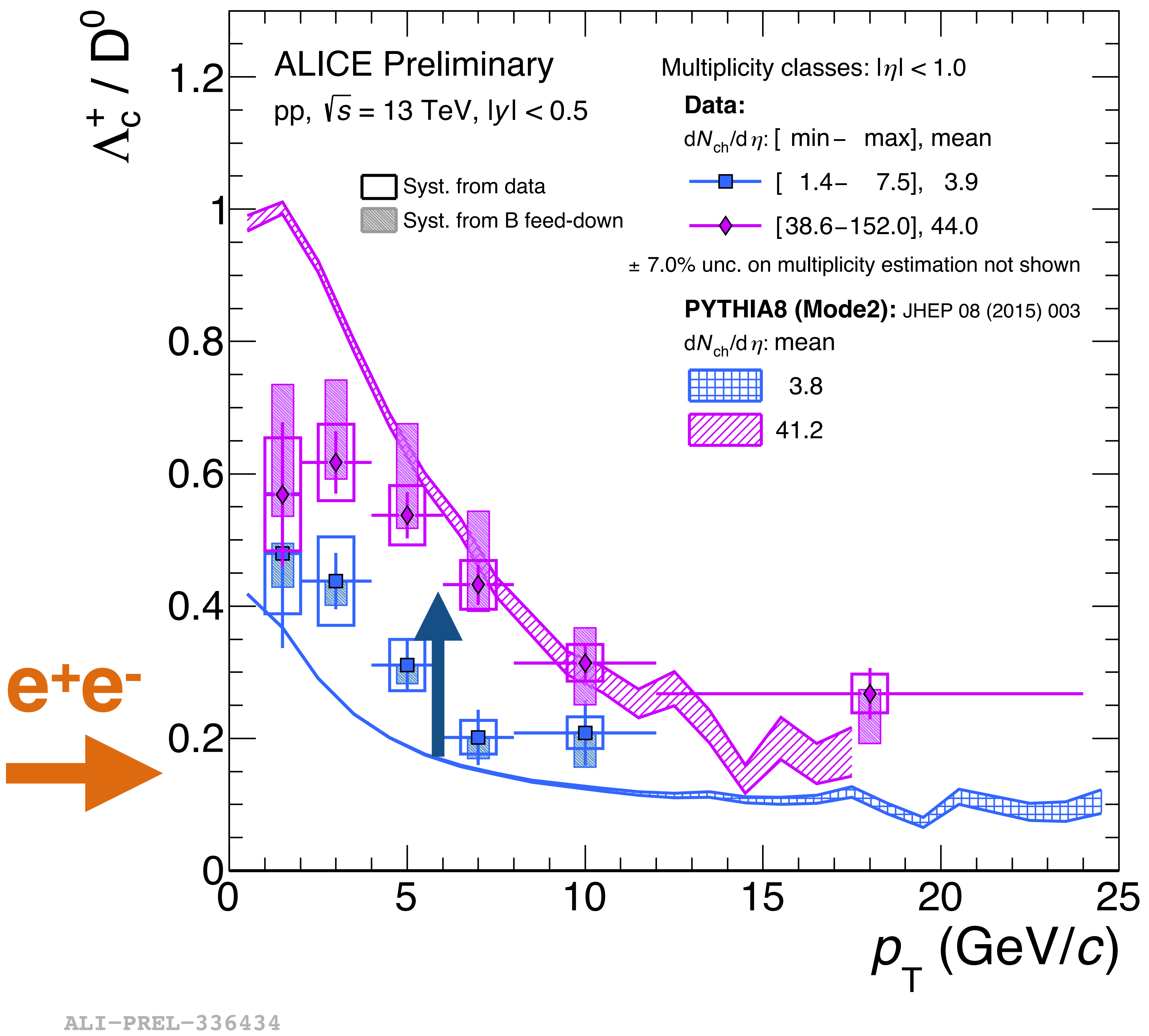
LHCP NEW 2020

- **Standard Pythia calculation** (tuned on e+e-) do not describe the observed ratios

C.-L. Huang
C. Terrevoli

Modification of hadronisation in pp collisions?



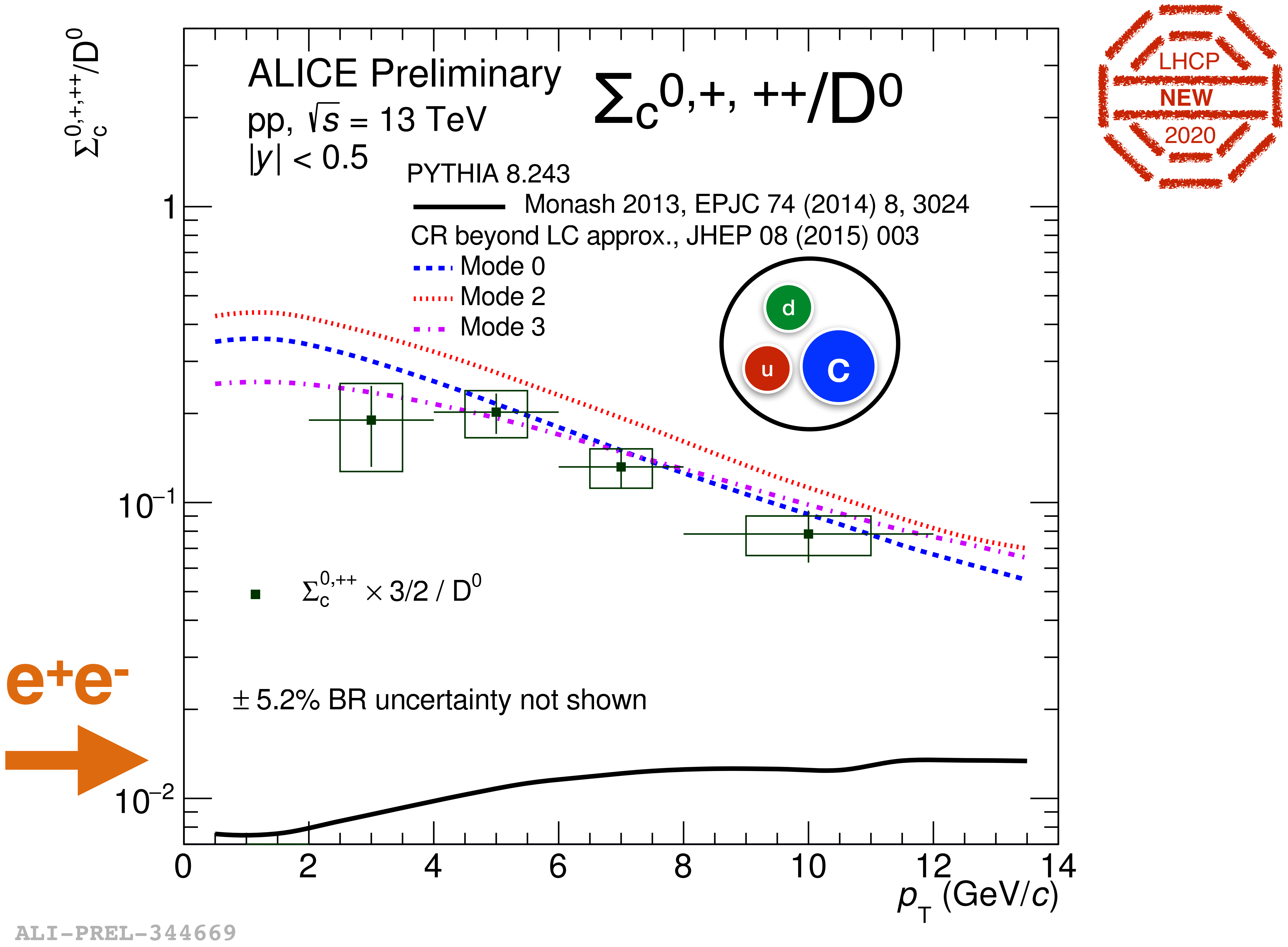


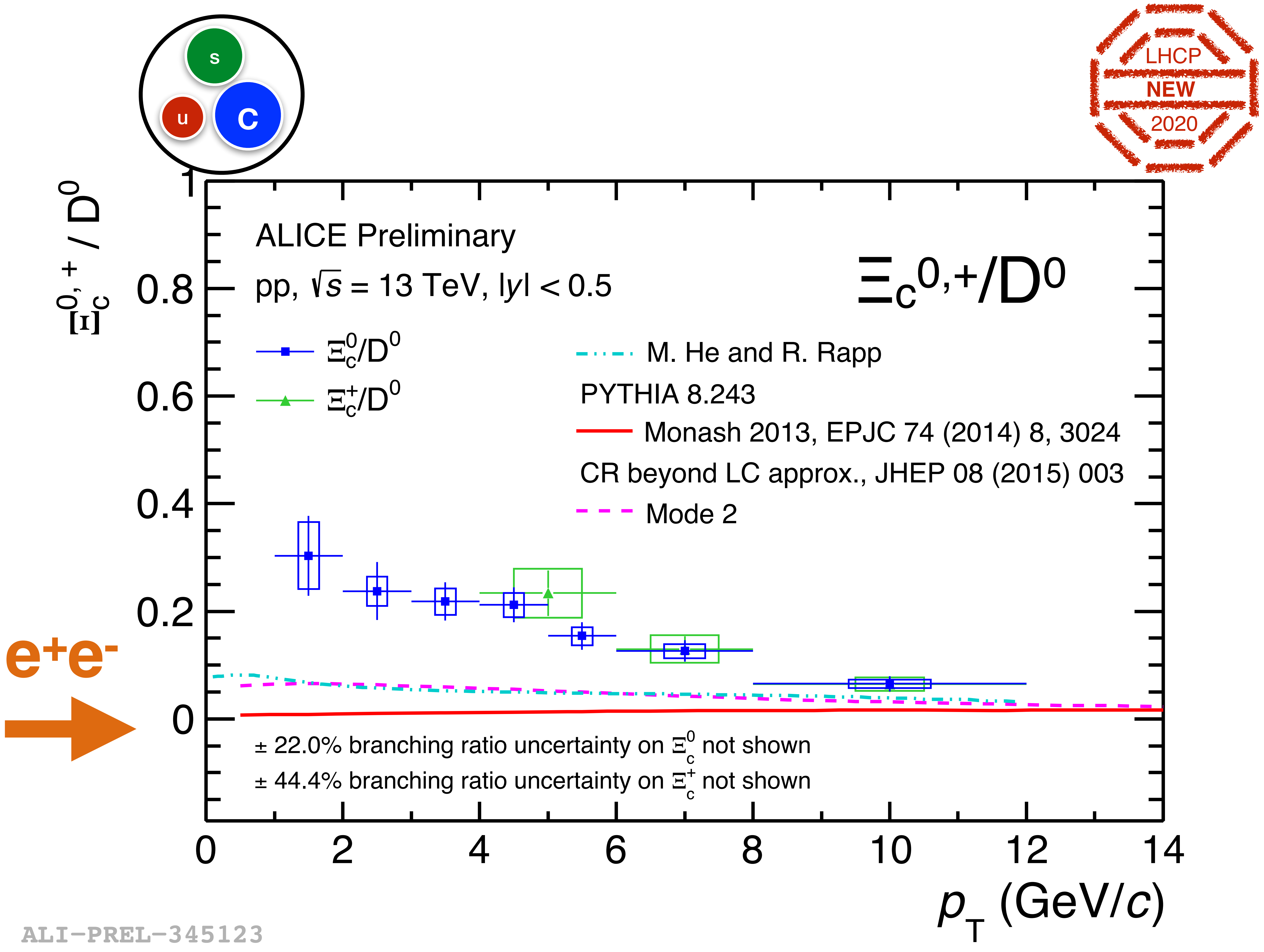
- **Pythia tunes including color "junction" formation + MPI** can describe the measurements

→ Significant modification of the fragmentation process already in pp collisions **driven by multiplicity**
→ **Alternative mechanisms without hot medium can explain the observed enhancement?**

A. Harlenderova
C.-L. Huang

Heavier charmed/beauty baryons in pp collisions





- Indication of large **enhancement** w.r.t e^+e^- fragmentation ratios for $\Sigma_c^{0,+,++}$ and $\Xi_c^{0,+}$
  →More constraints on the microscopic description of the enhancement

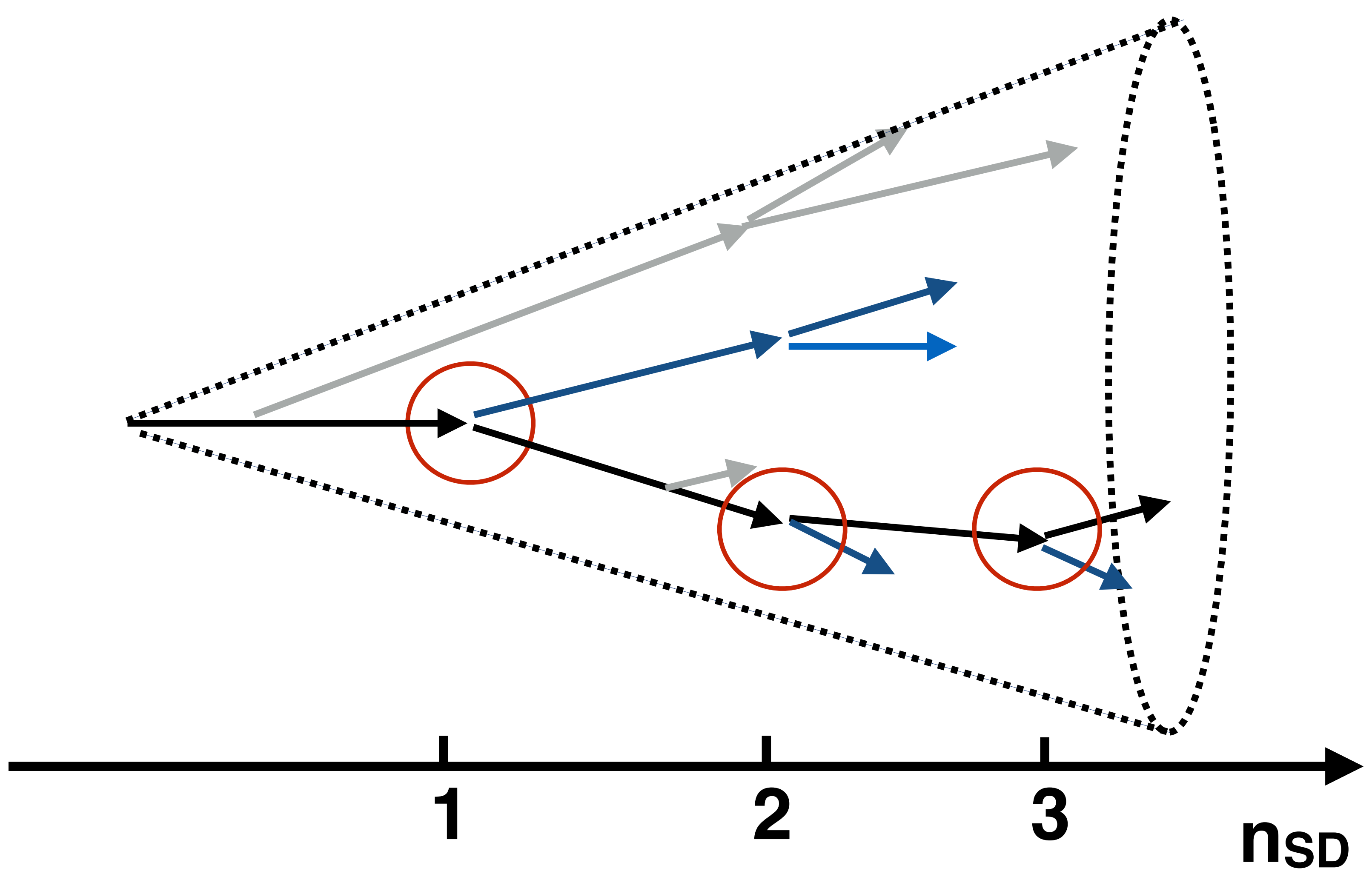
New experimental probes for HF studies

Substructure of soft charm jet

D^0-tagged jets with **$15 < p^{Jet}_T < 30$ GeV/c** (track-based)

→ testing QCD in an unexplored kinematic region

JHEP 05 (2014) 146



Number of Soft-Dropped splittings n_{SD}:

- sub-leading prong carries > 10% of splitting p_T

Substructure of soft charm jet

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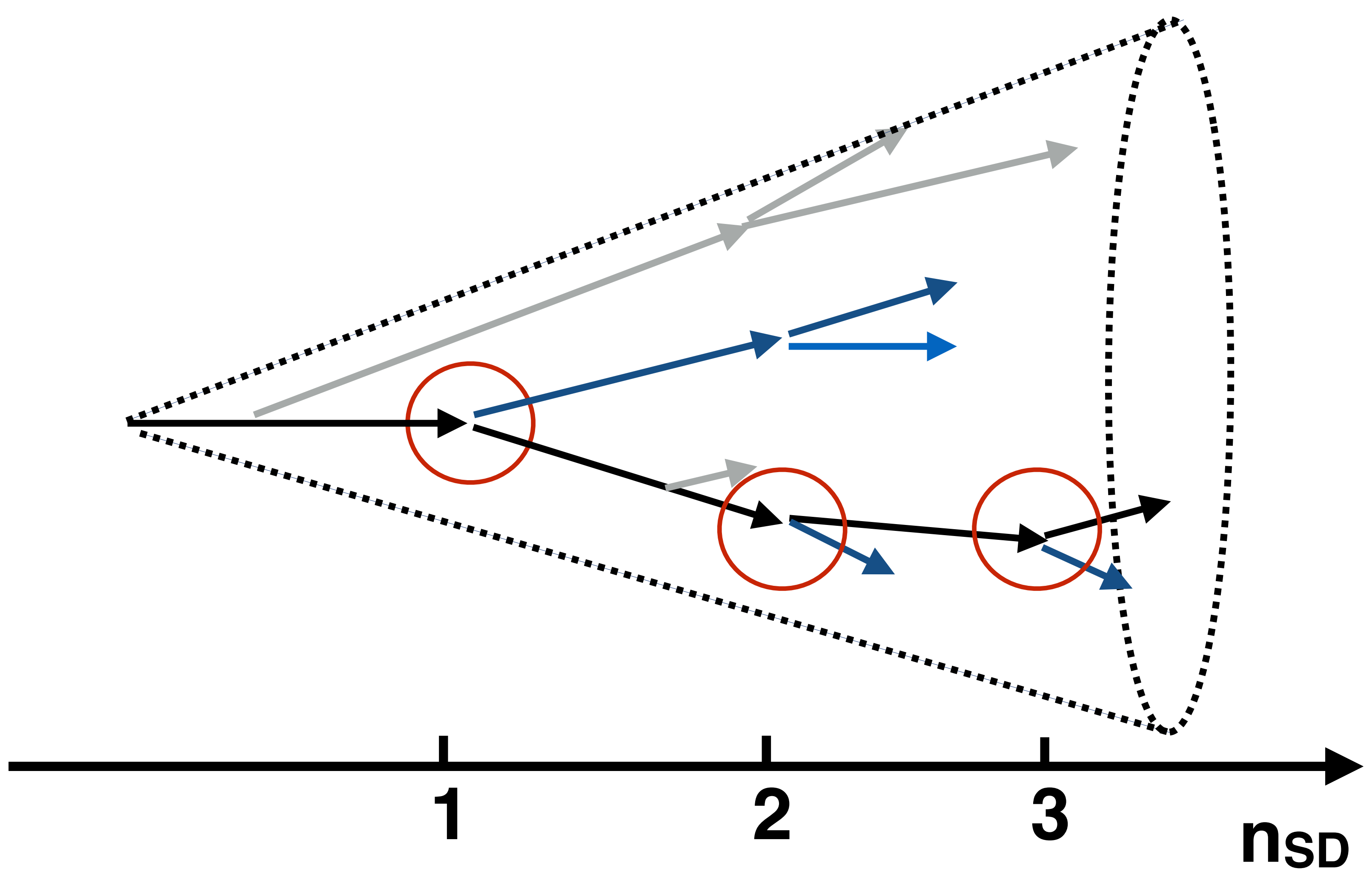
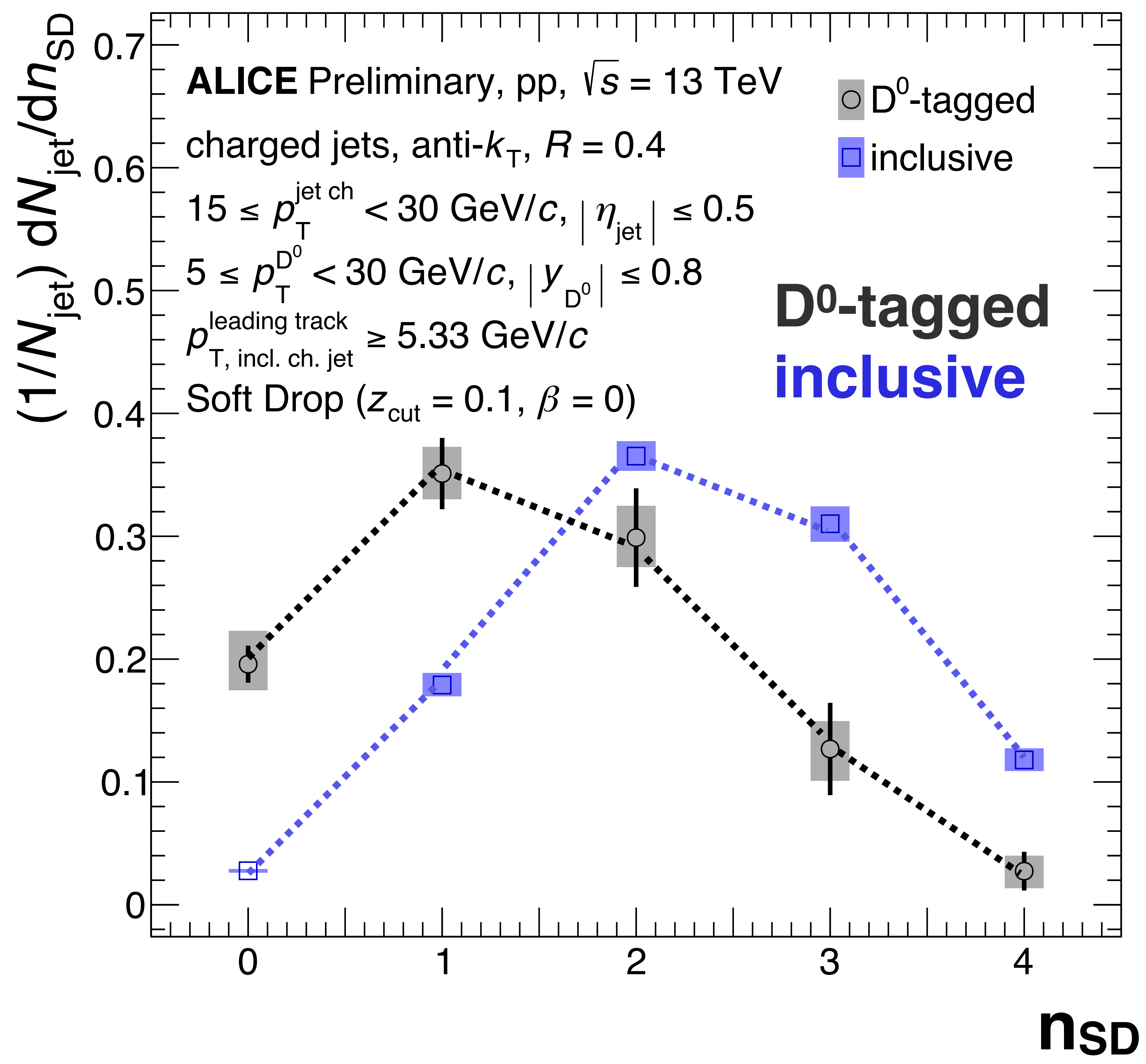
JHEP 05 (2014) 146





Number of Soft-Dropped splittings n_{SD}:

- sub-leading prong carries > 10% of splitting p_T

- **charm** jets have fewer "hard" splittings than **inclusive jets**
- **described by PYTHIA**

→ **Consistent with harder fragmentation of HF jets (quark) w.r.t. inclusive jets (gluon)**

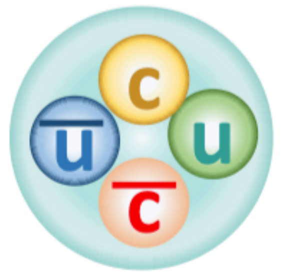
→ New technique for studying quark/gluon jet quenching in PbPb collisions

X(3872) particle

X(3872) observed for the first time by Belle in 2003 ($M_{X(3872)} \sim 2\ M_D$) BELLE PRL 91, 262001 (2003)

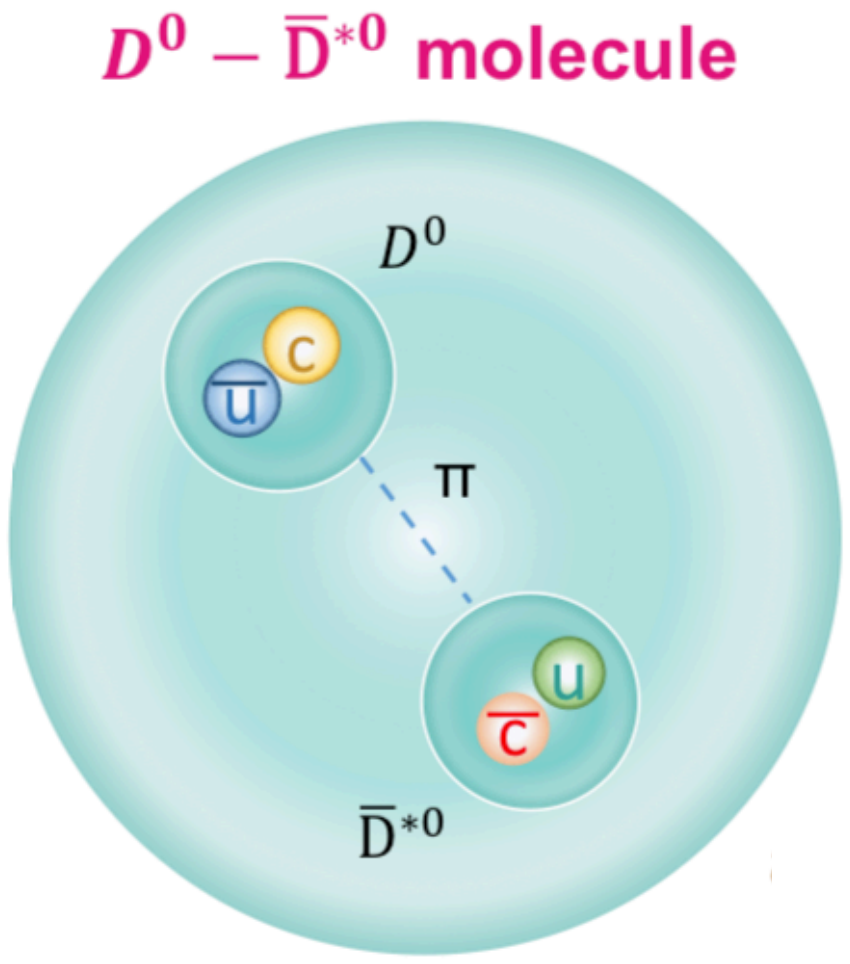
X(3872) → J/ψ $\pi^+\pi^-$ as ψ(2S)

Tetraquark (4q)



$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

VS



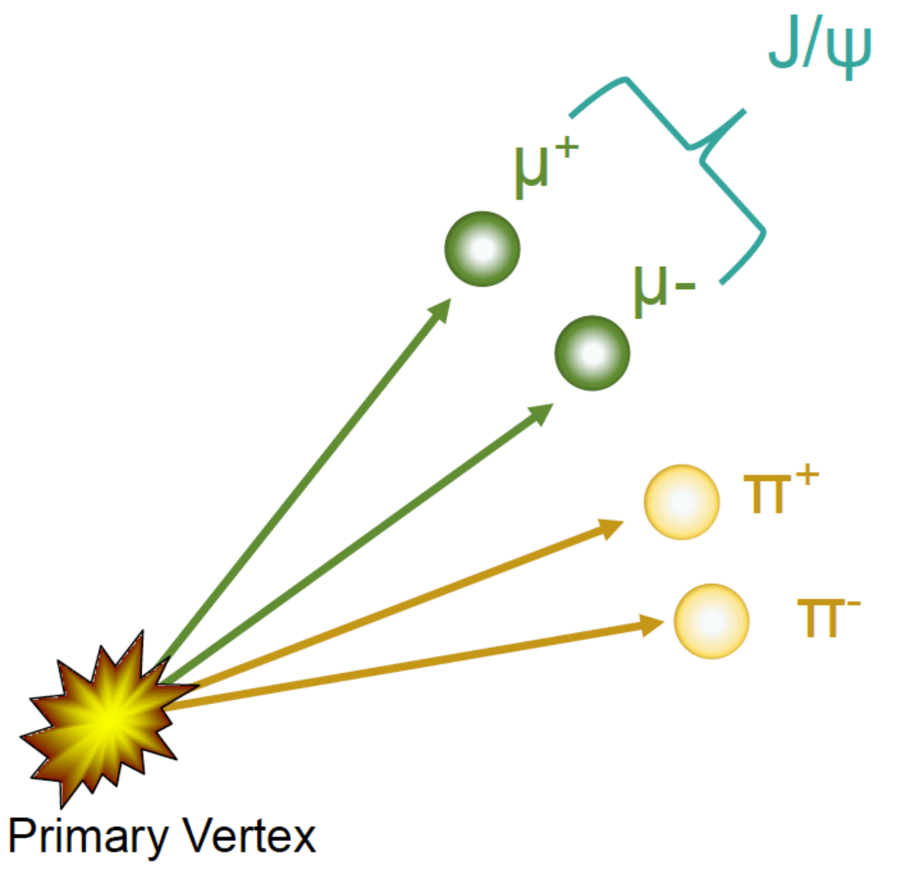
$r_{molecule}$
as large as 5 fm

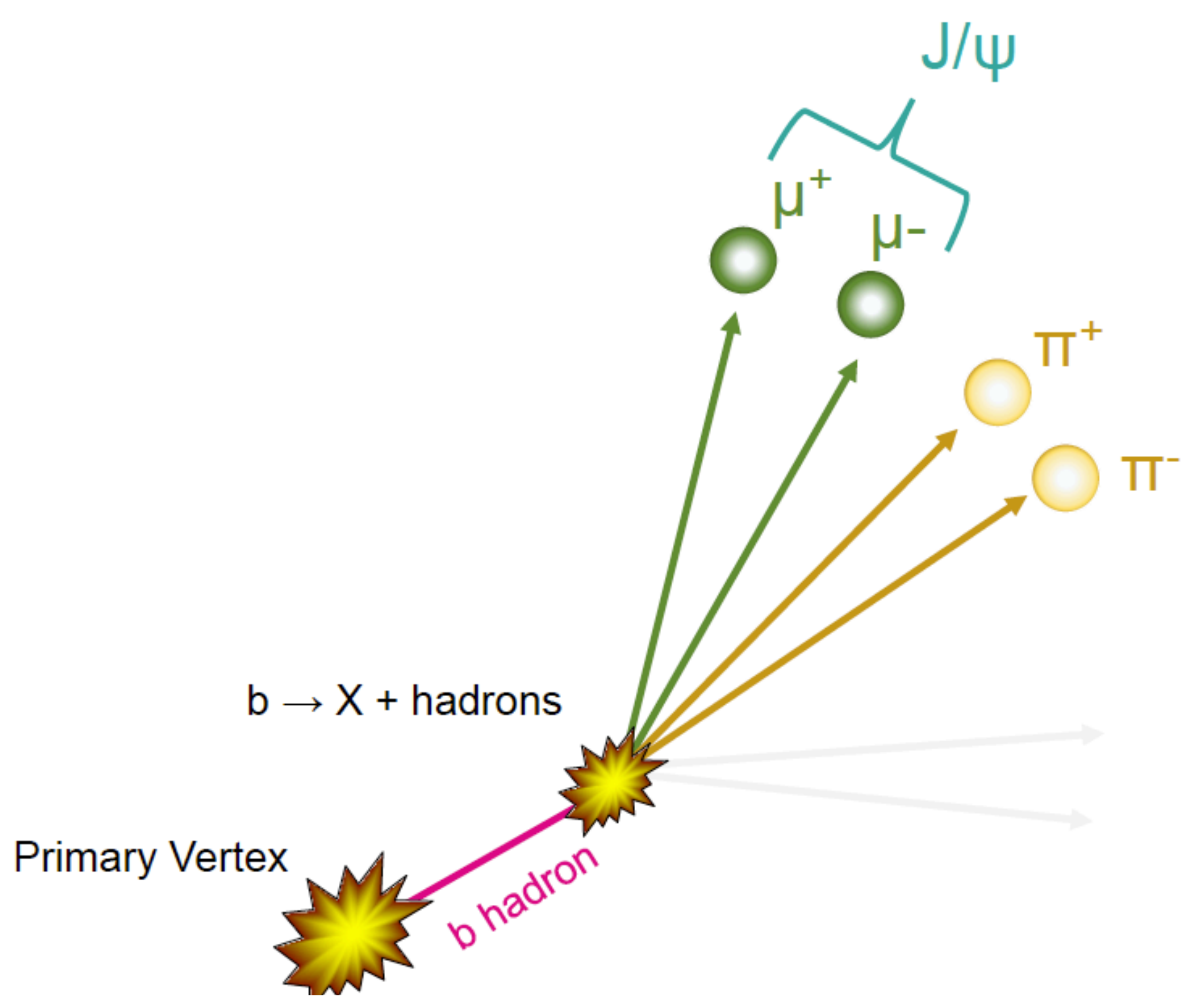
How does it interact with a "hadronic" environment and in presence of QGP?

X(3872) in pp collisions

X(3872) observed for the first time by Belle in 2003 ($M_{X(3872)} \sim 2\ M_D$) LHCb-CONF-2019-005

X(3872) → J/ψ $\pi^+\pi^-$ as ψ(2S)

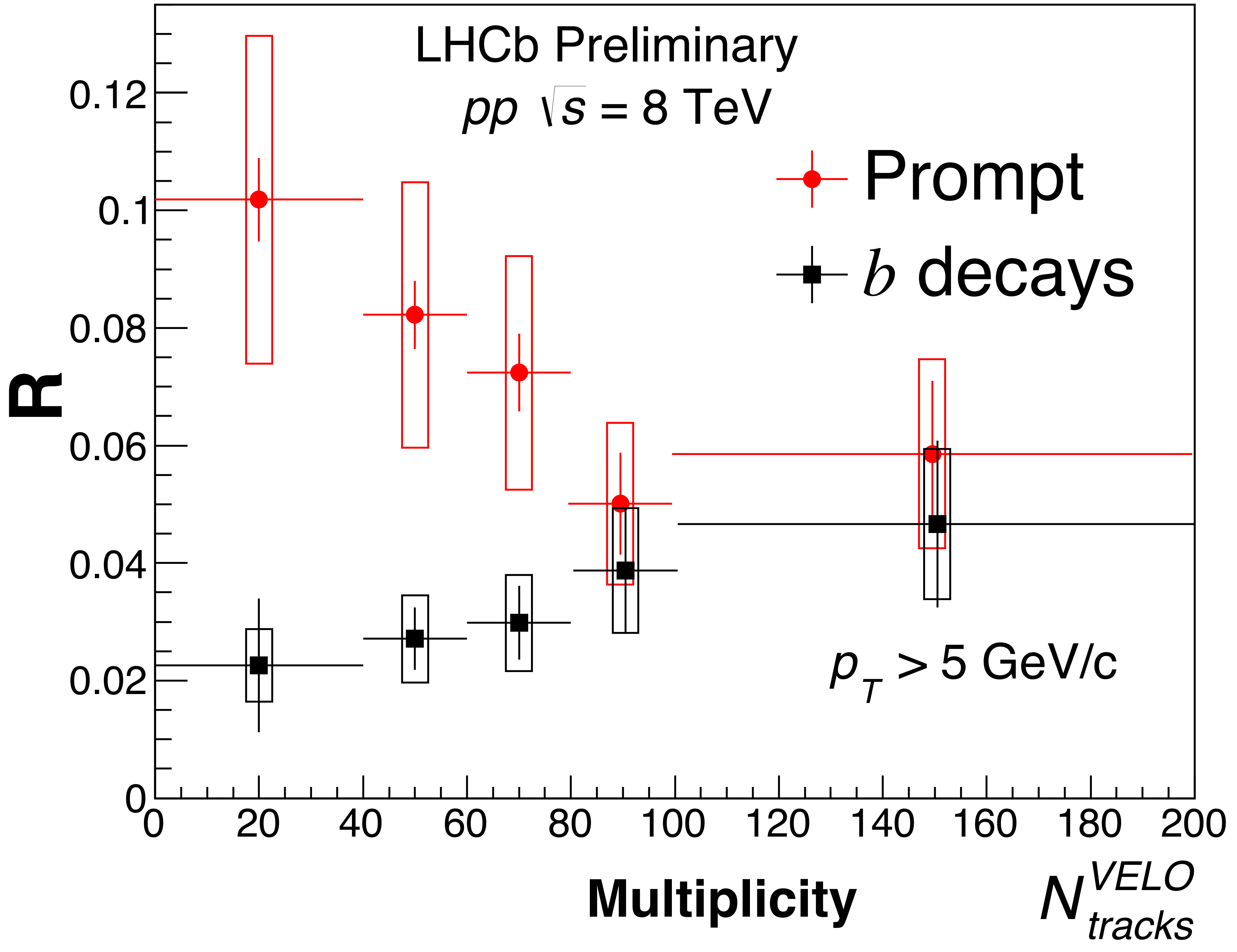




Prompt:
interact with the medium as a X(3872)

b-feeddown:
interact with the medium as a b-hadron

R = $N_{X(3872)}$ / $N_{\psi(2S)}$



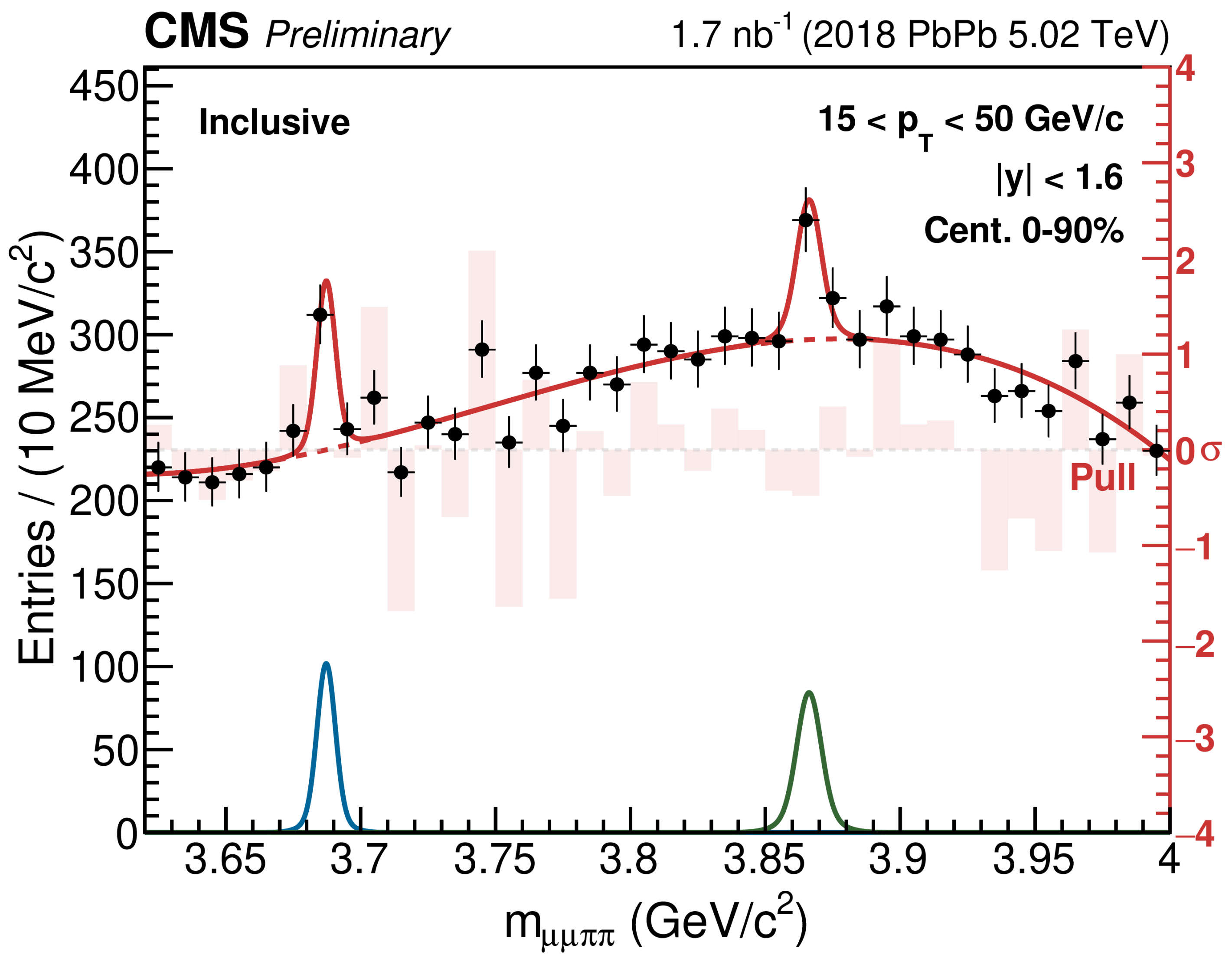
Prompt $N_{X(3872)}$ / $N_{\psi(2S)}$ decreases as a function of multiplicity:
→ loosely bound states destroyed by hadronic interactions?

Phys. Rev. D 81, 114018

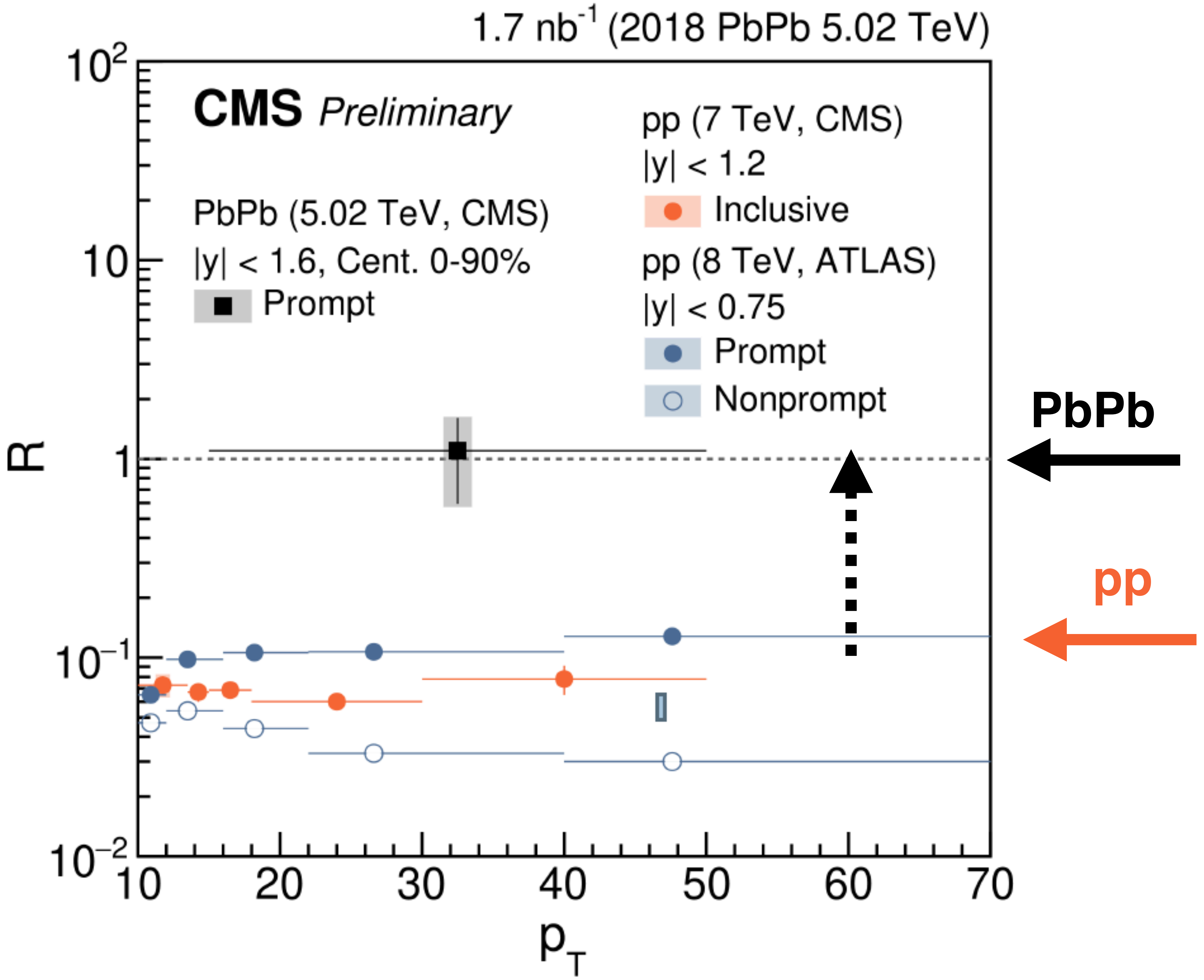
Prompt X(3872) in PbPb collisions

X(3872) observed for the first time by Belle in 2003 ($M_{X(3872)} \sim 2\ M_D$)

X(3872) → J/ψ $\pi^+\pi^-$ as ψ(2S)



R = $N_{X(3872)}$ / $N_{\psi(2S)}$



Prompt:
interact with the medium as a X(3872)

Prompt $N_{X(3872)}$ / $N_{\psi(2S)}$ in PbPb significantly enhanced with respect to pp:

→ sensitive to mechanisms of recombination in the QGP?

→ **more statistics is needed**

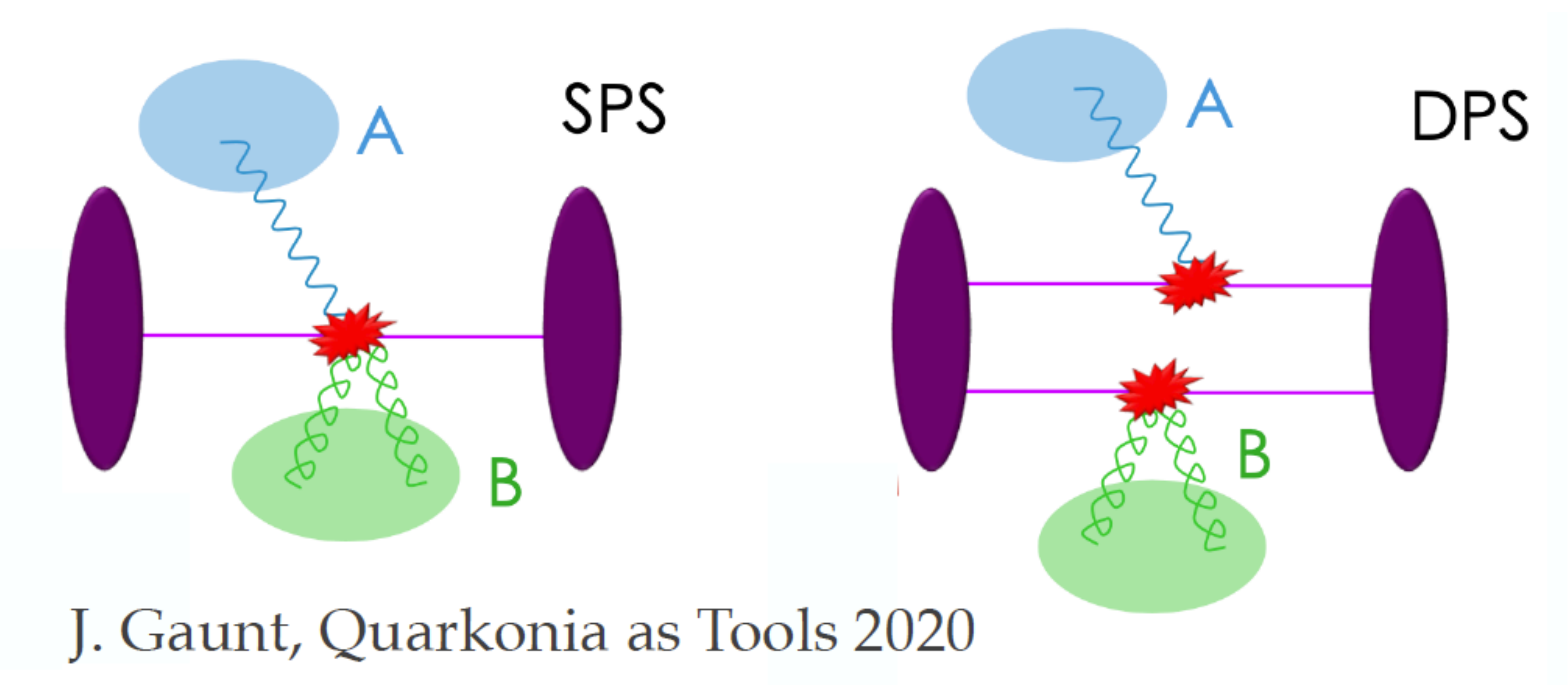
Phys. Rev. D 81, 114018

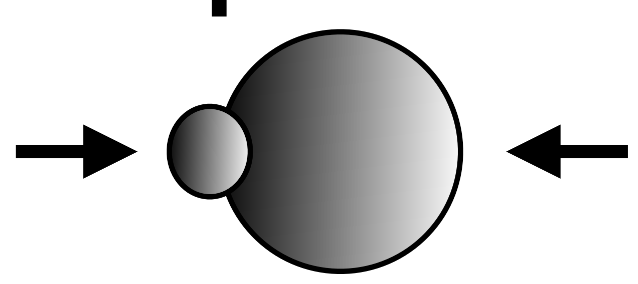
Double charm production in pPb collisions

Fresh result from LHCb!

Double Parton Scattering (DPS):
two independent scatterings in one pp collisions
→ transverse parton density and correlations

LHCB-PAPER-2020-010

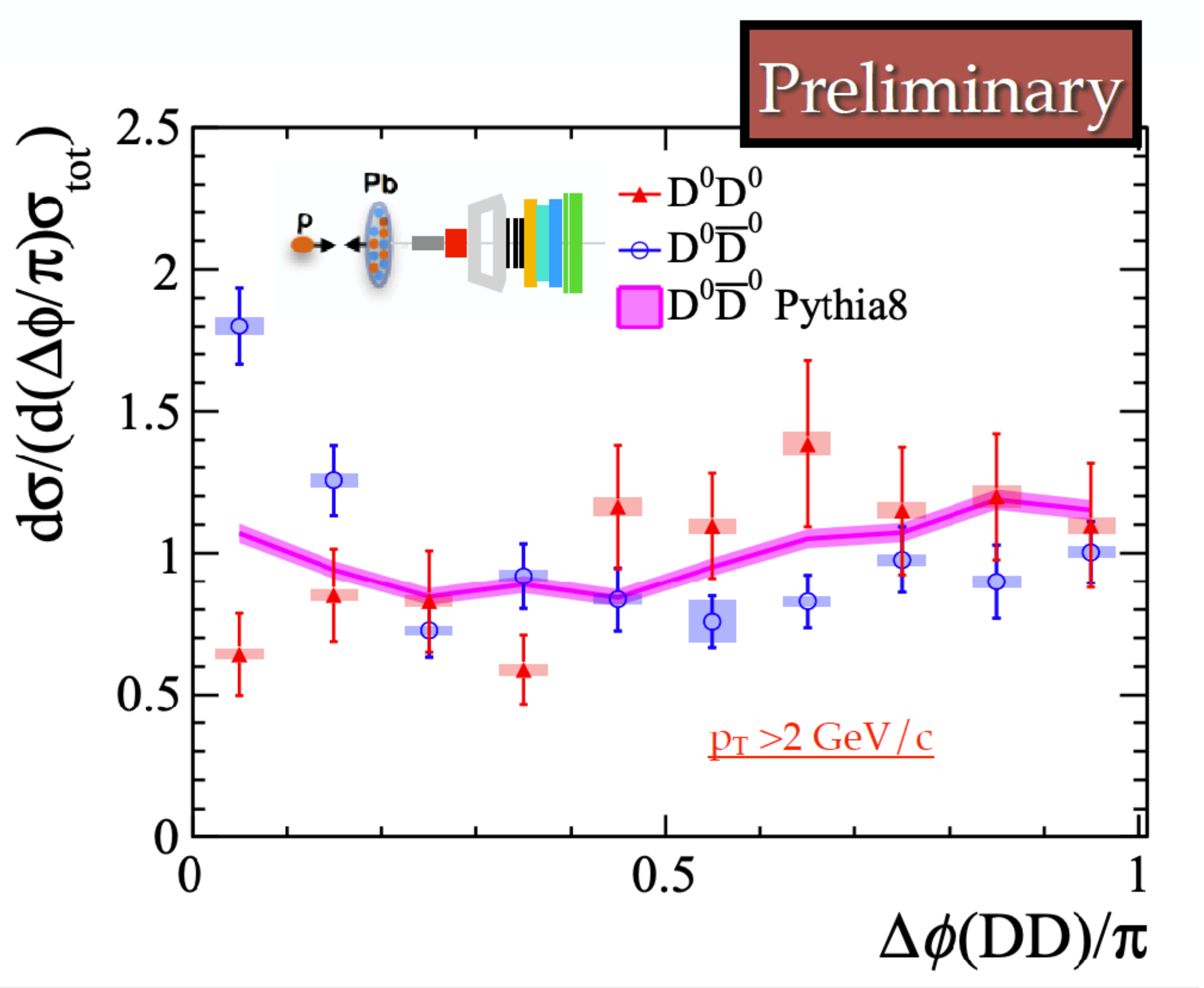




In pA collisions:

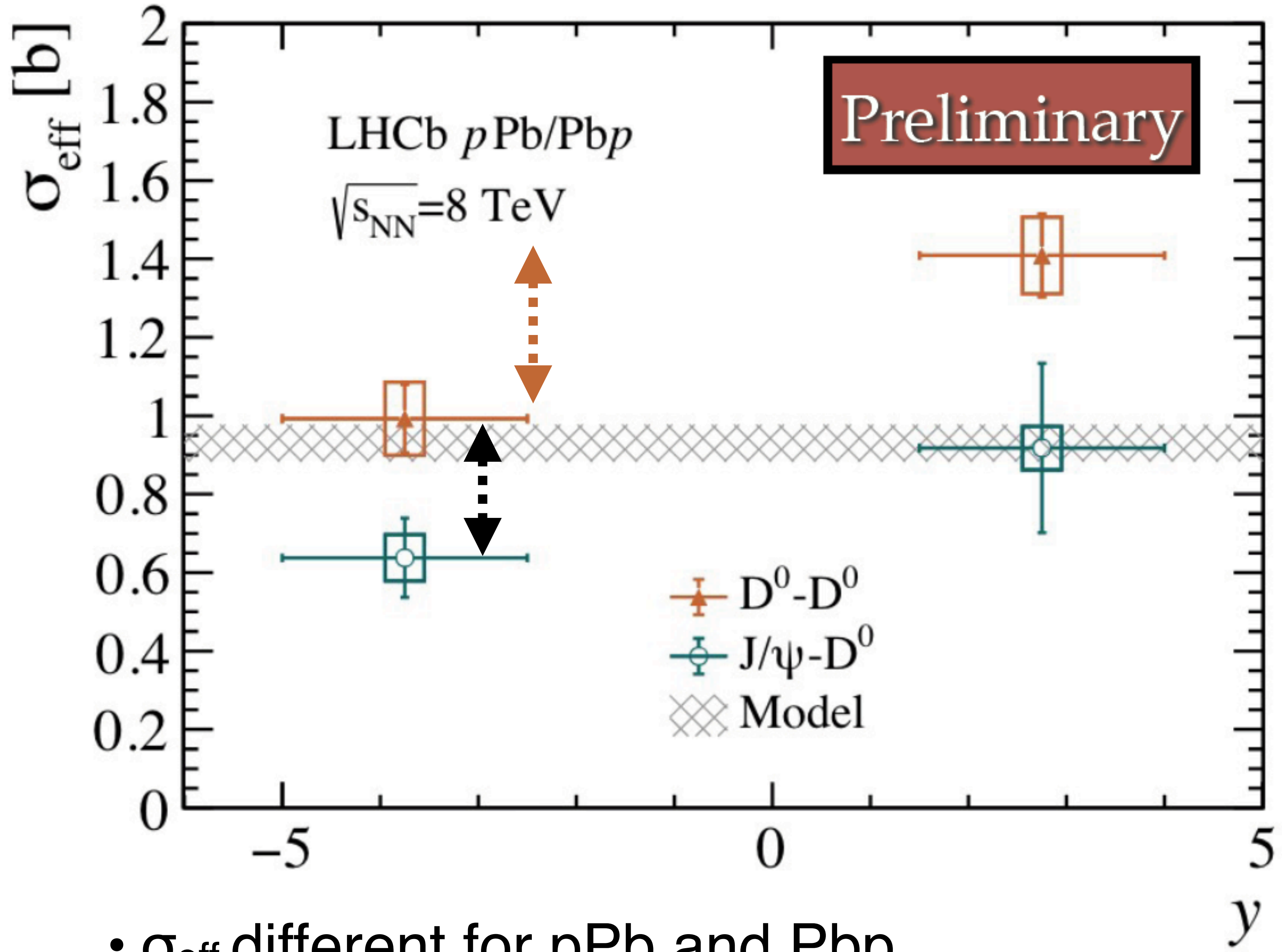
- enhanced DPS cross section due to larger transverse parton density

arXiv:1708.07519



- General good agreement with Pythia 8

$$\sigma^{AB}_{DPS} = \frac{\sigma^A \sigma^B}{\sigma_{eff}}$$



- σ_{eff} different for pPb and Pbp
- σ_{eff} different for D^0-D^0 and J/ψ-D^0

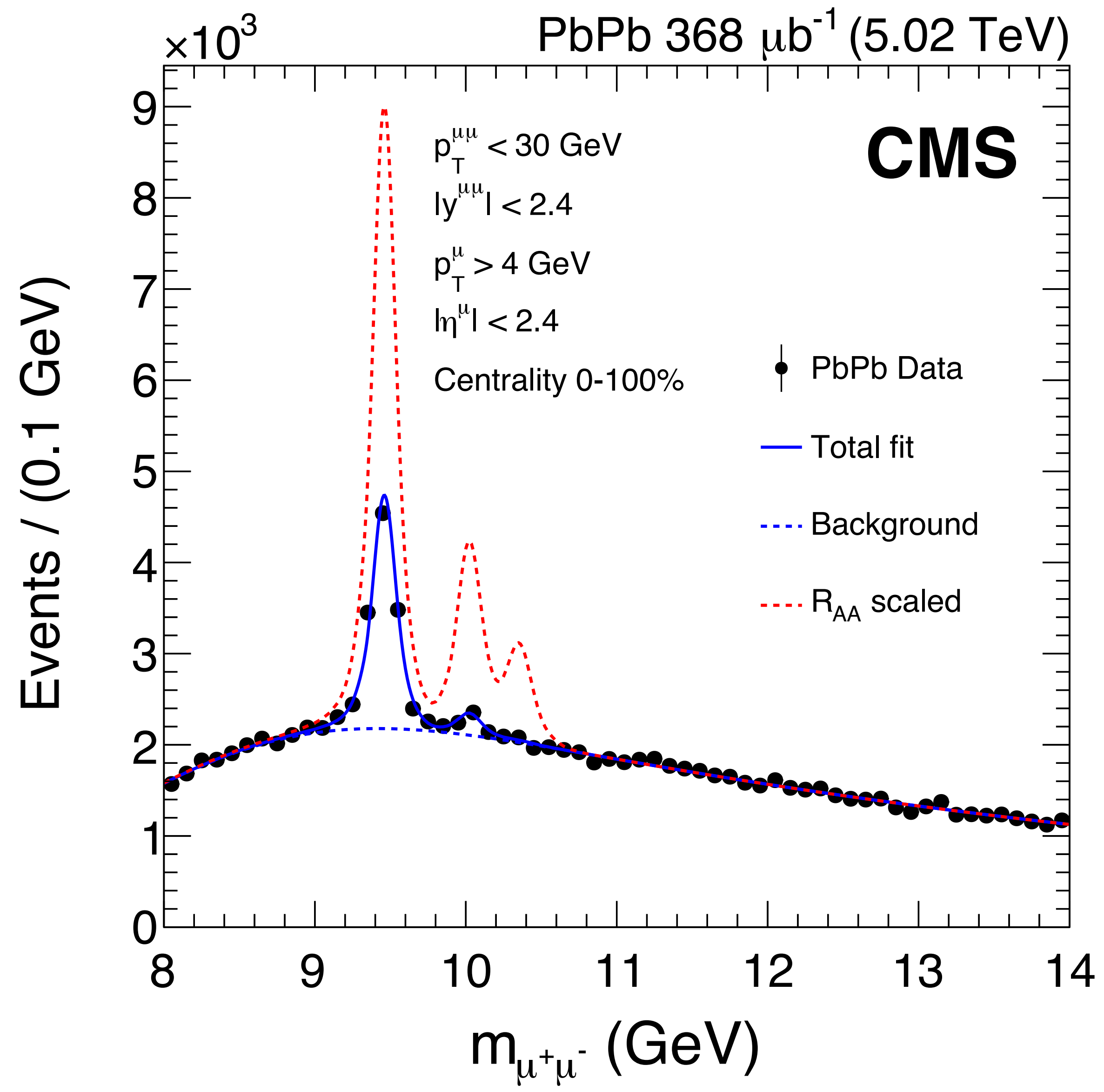
Conclusions

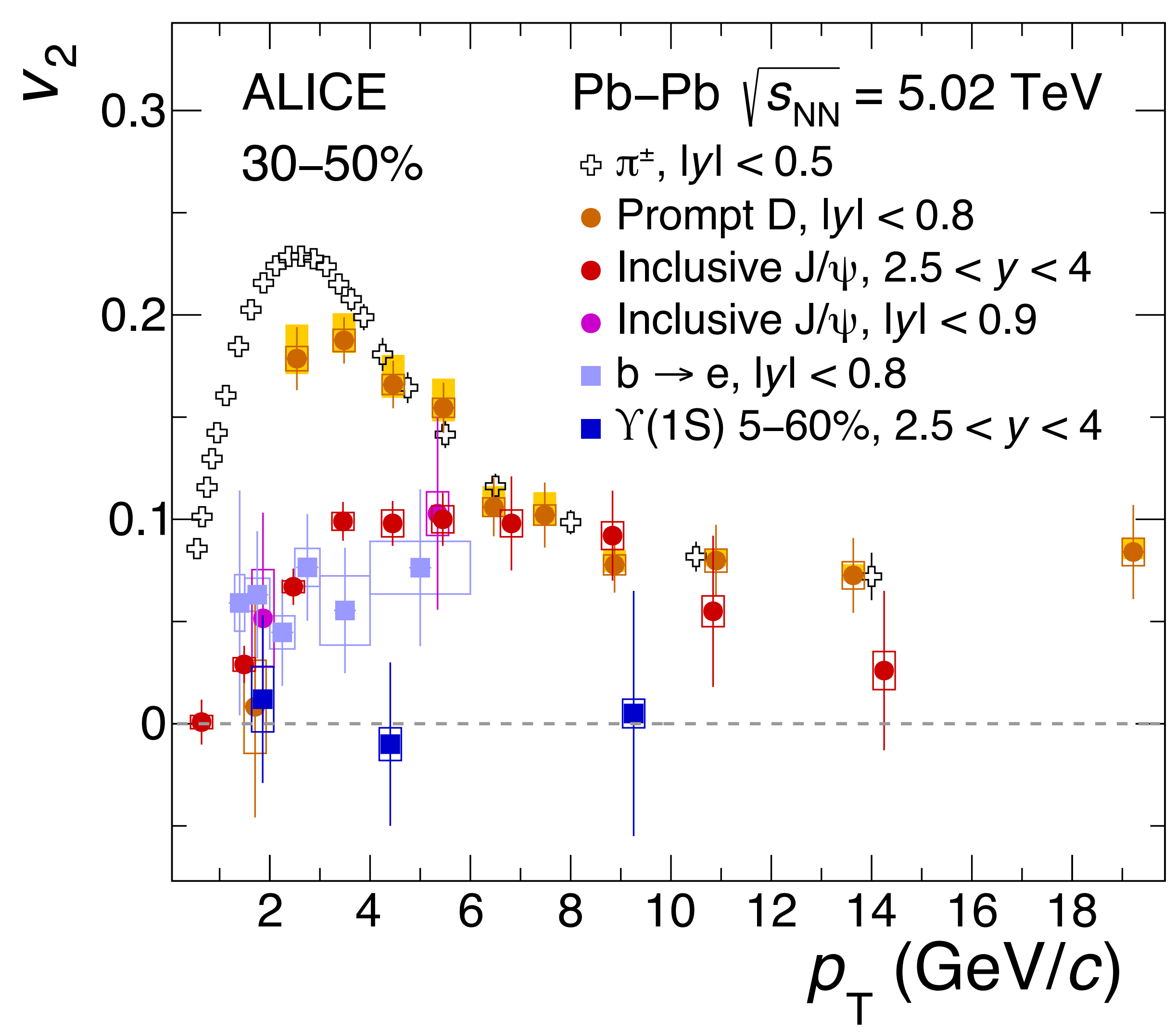
New insights into QCD matter in large systems:

• quarkonia dissociation
• energy loss measurements
• “flow” observables
→heavy quark interactions, QCD fluid-dynamic properties

Constraints on the properties of pp, pPb collisions:

→insights into the small system collective properties
→modification of hadronisation mechanisms
→indication of final state interactions in small systems





Conclusions

New insights into QCD matter in large systems:
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Constraints on the properties of pp, pPb collisions:
→insights into the small system collective properties
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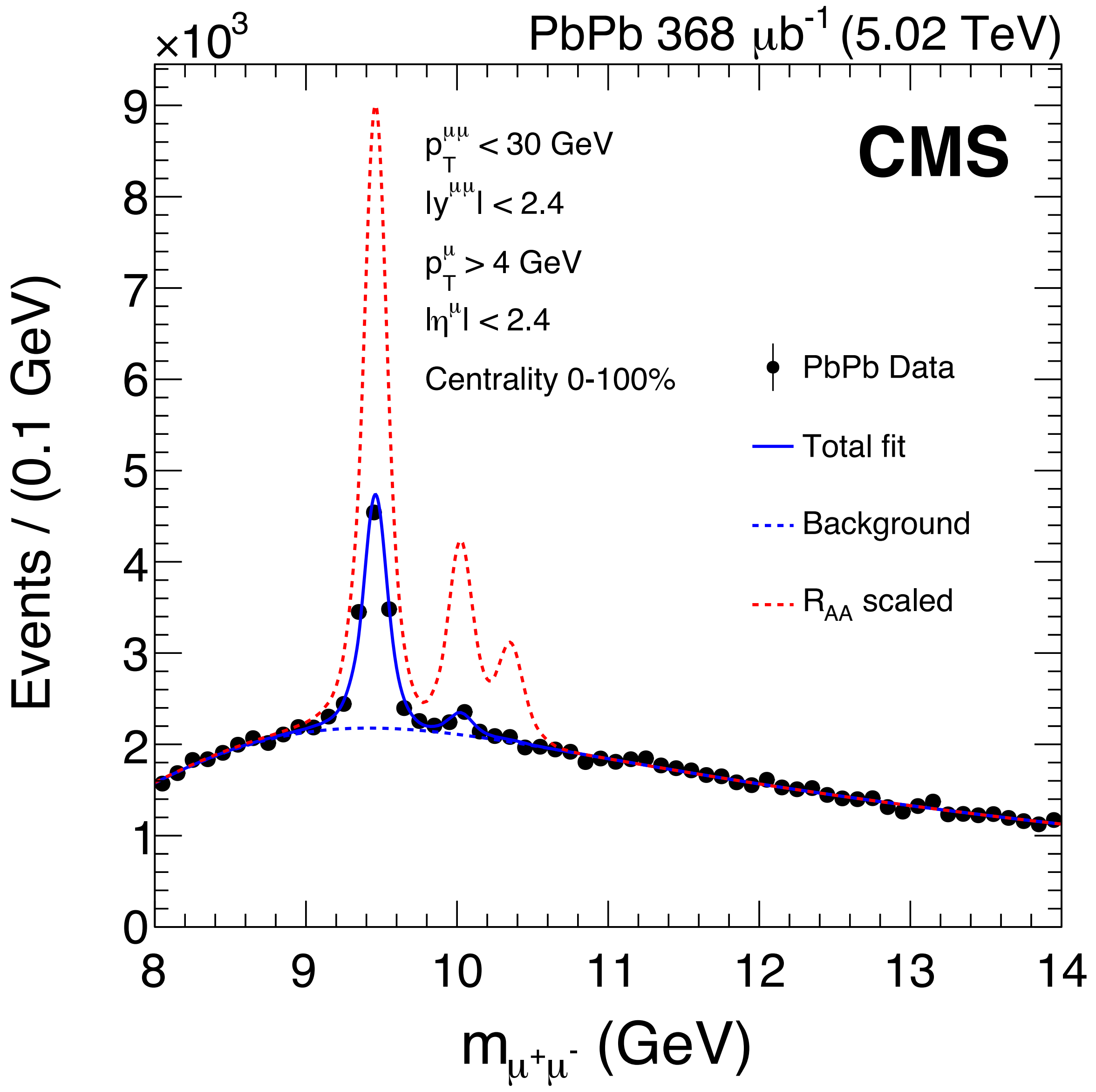
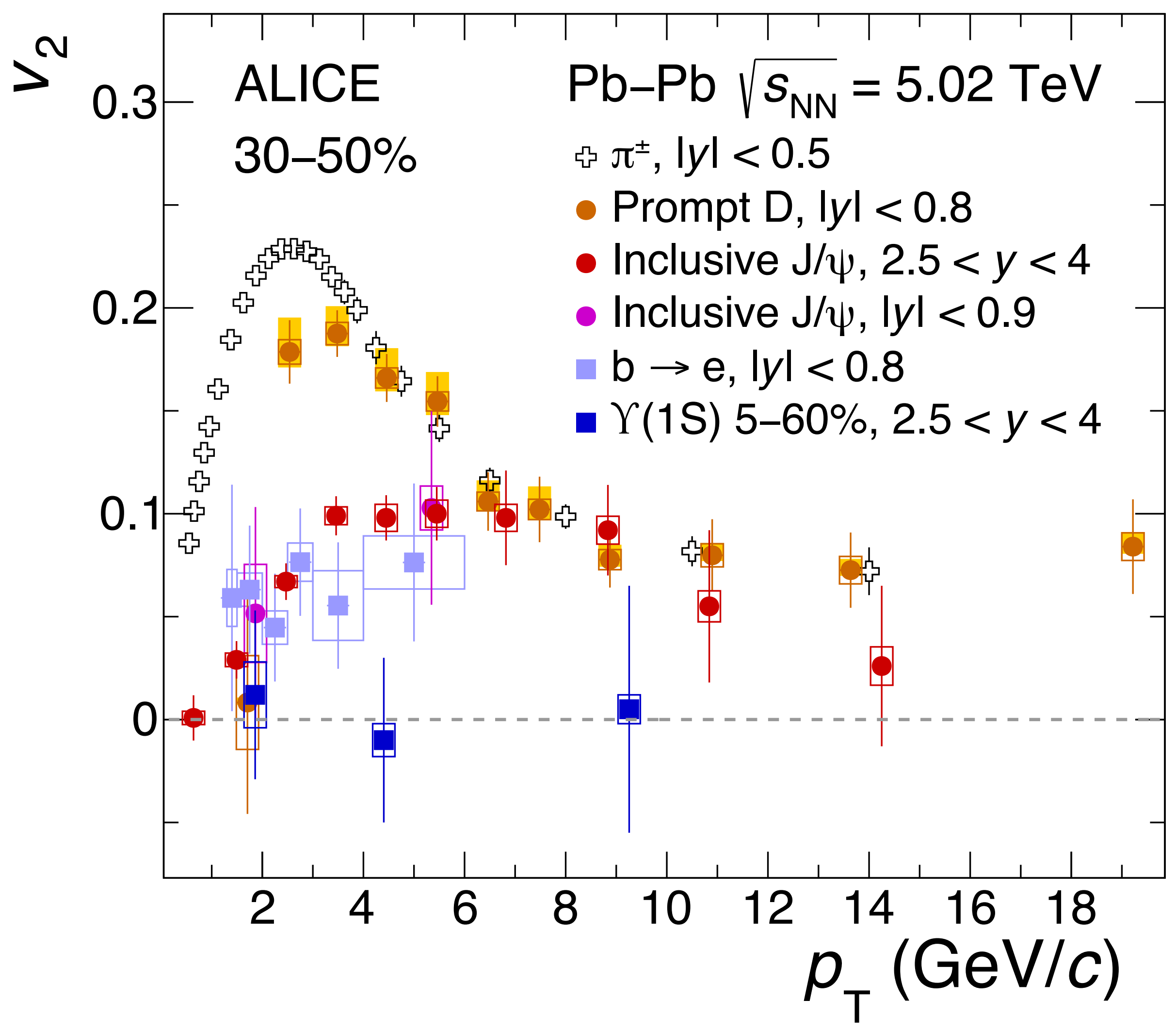
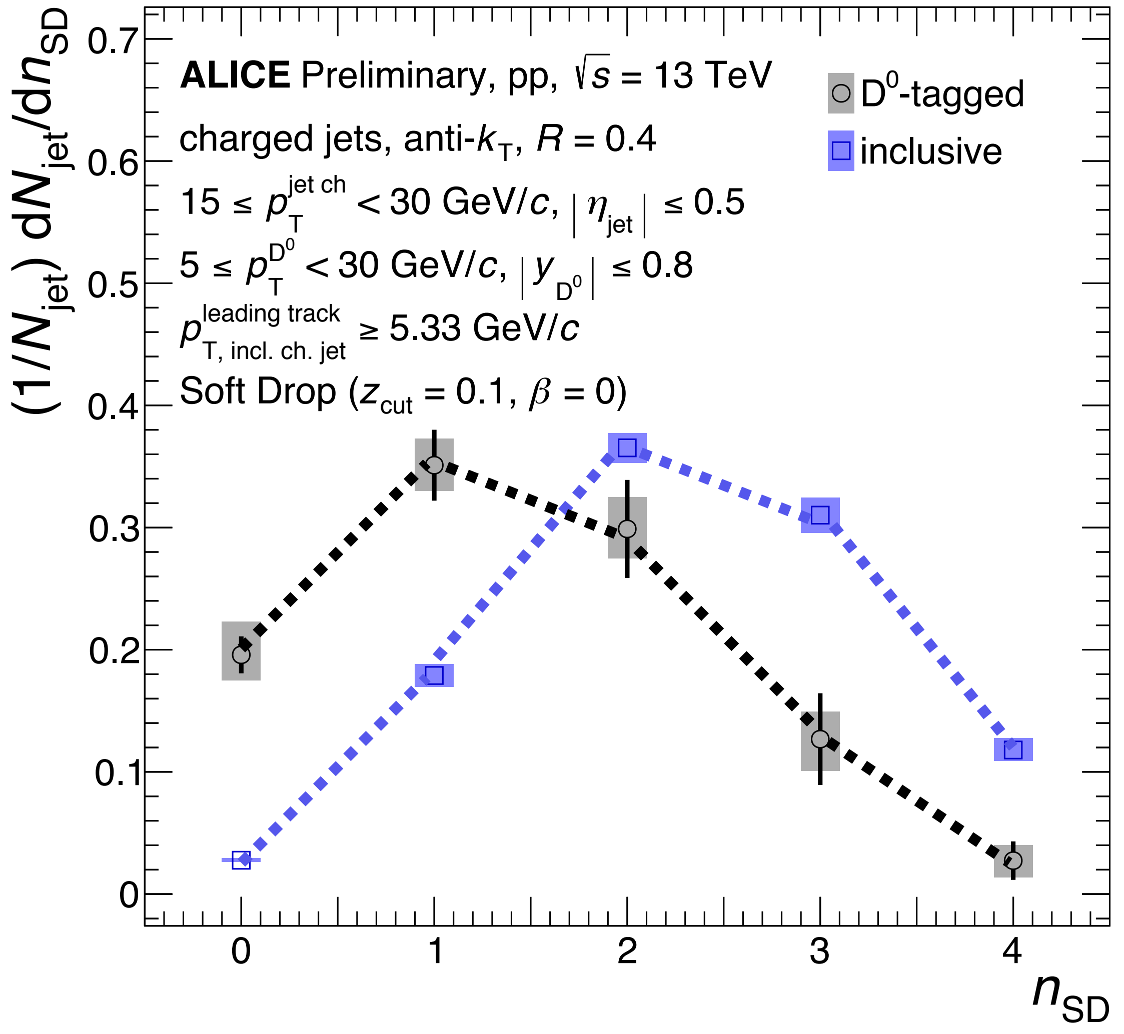
→indication of final state interactions in small systems

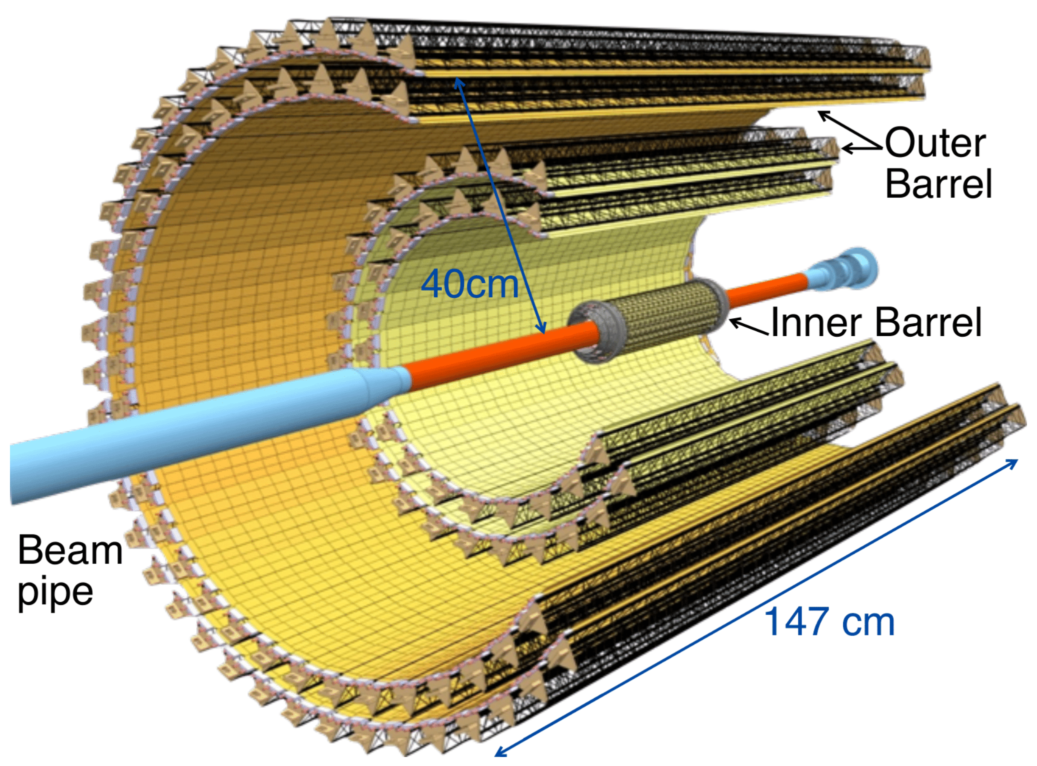
Opening new fields of exploration:
- soft jet measurements in pp/PbPb collisions with HF-jets
- Exotic states
- …

Run3/4 are approaching:
- extensive upgrade projects in various experiments
- high-precision large statistics pp/pPb/PbPb datasets









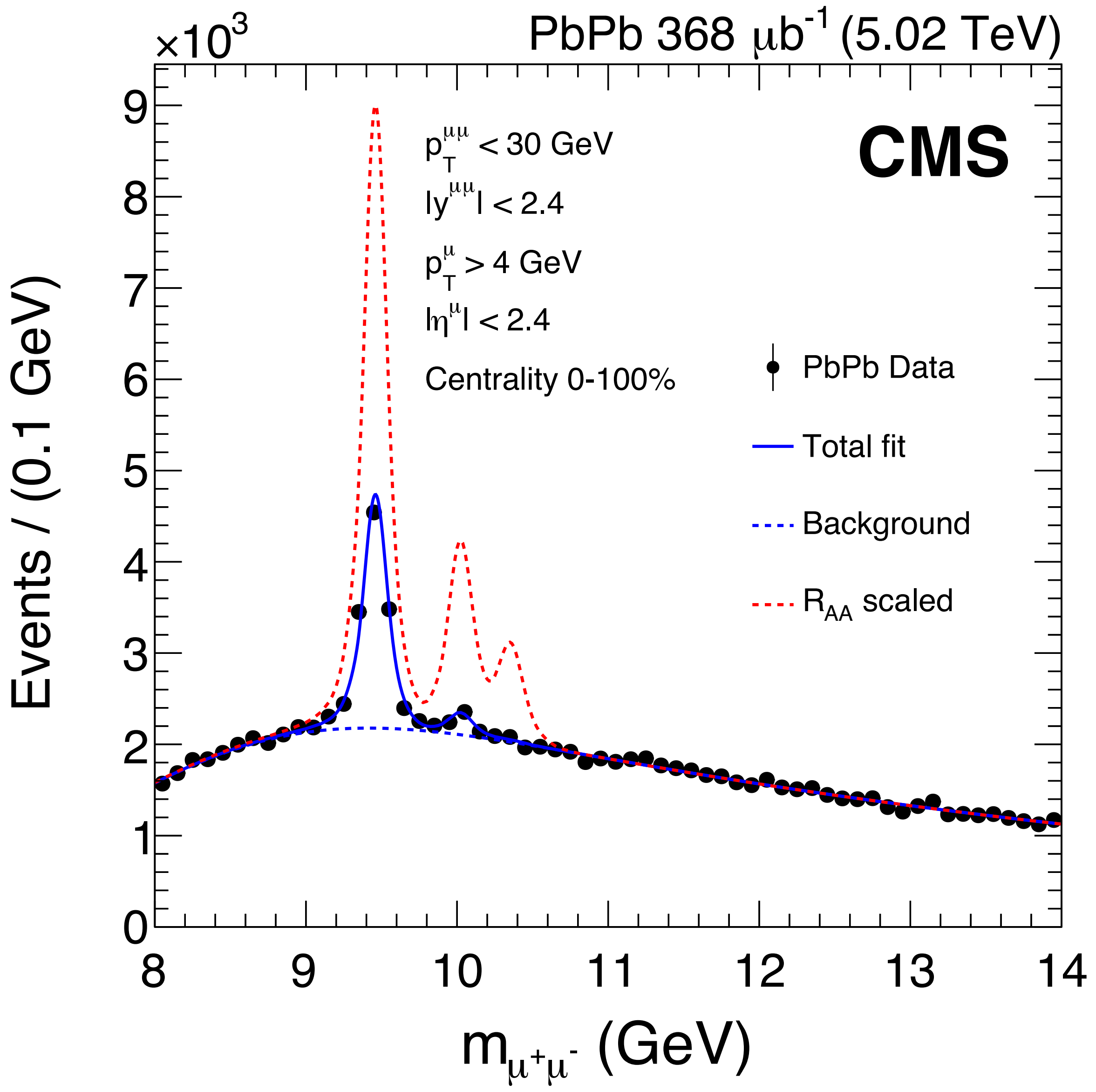
New ALICE full-pixel Inner Tracker (ITS2) for Run3

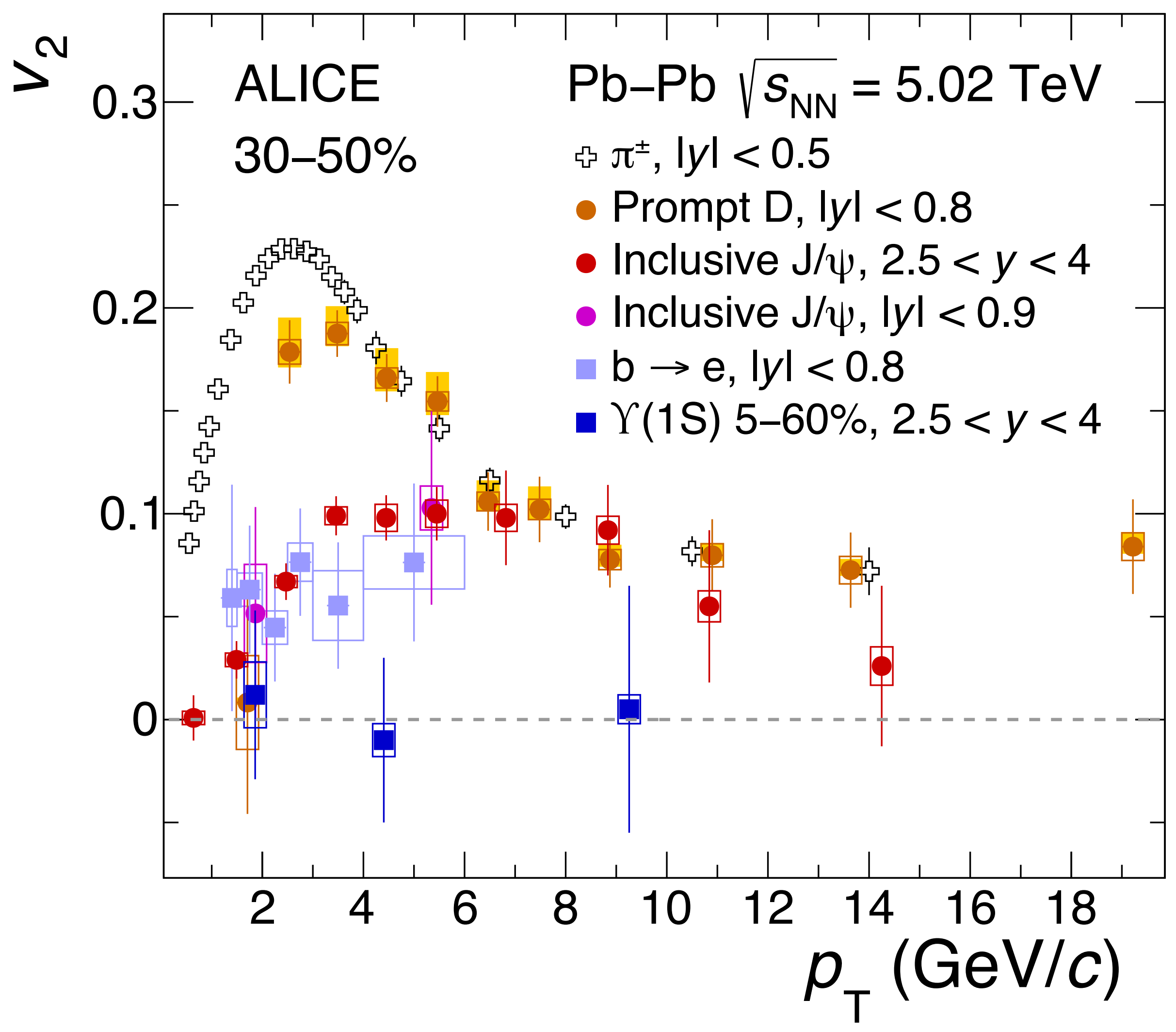
Conclusions

New insights into QCD matter in large systems

- quarkonia dissociation
- energy loss measurements
- “flow” observables

→heavy quark interactions, QCD fluid-dynamic properties





Constraints on the properties of pp, pPb collisions

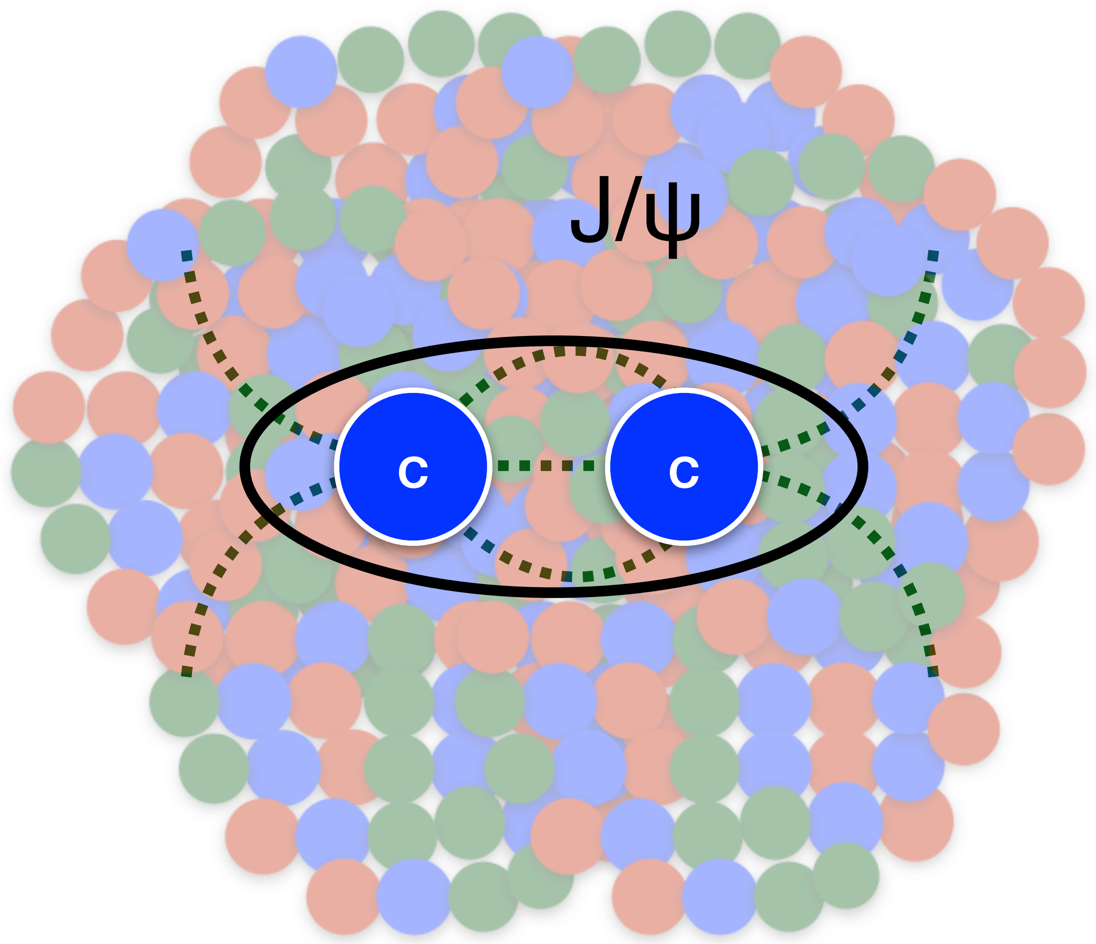
→insights into the small system collective properties
→modification of hadronization mechanisms
→indication of final state interactions in small systems

Thank you for your attention!

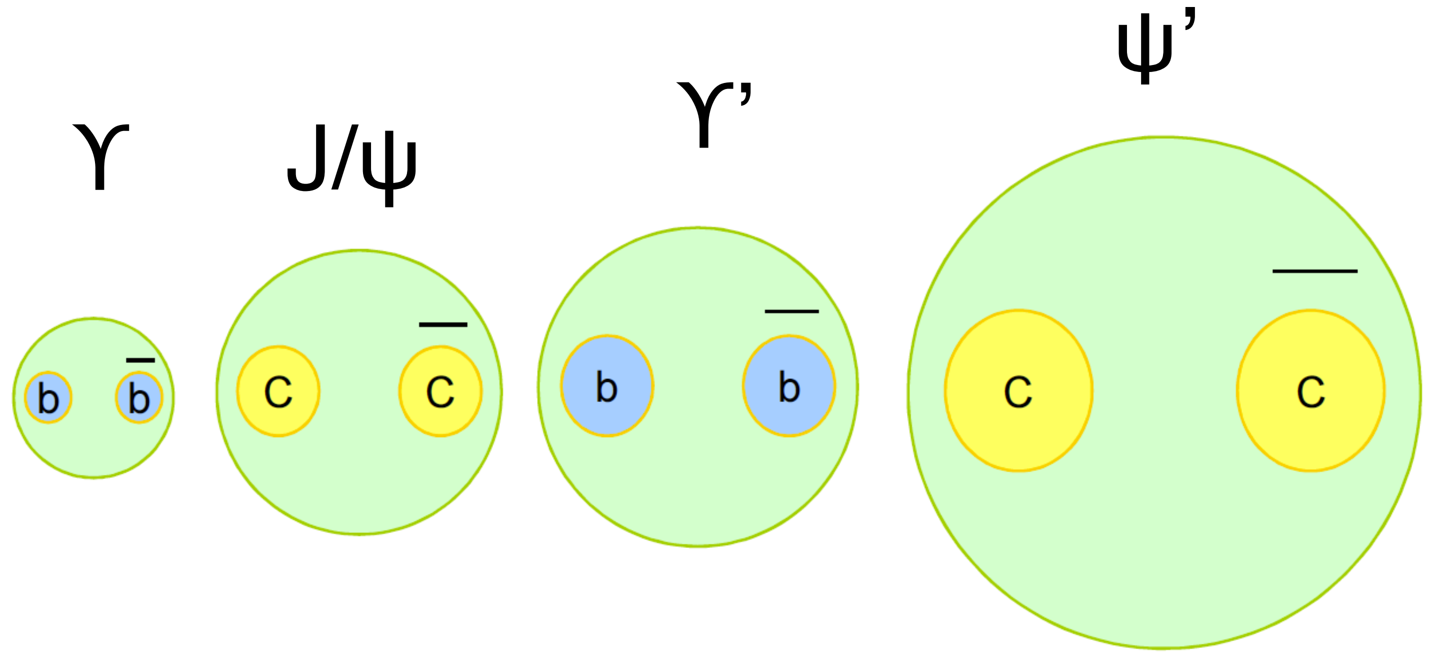
BACKUP

J/ψ suppression from RHIC to LHC

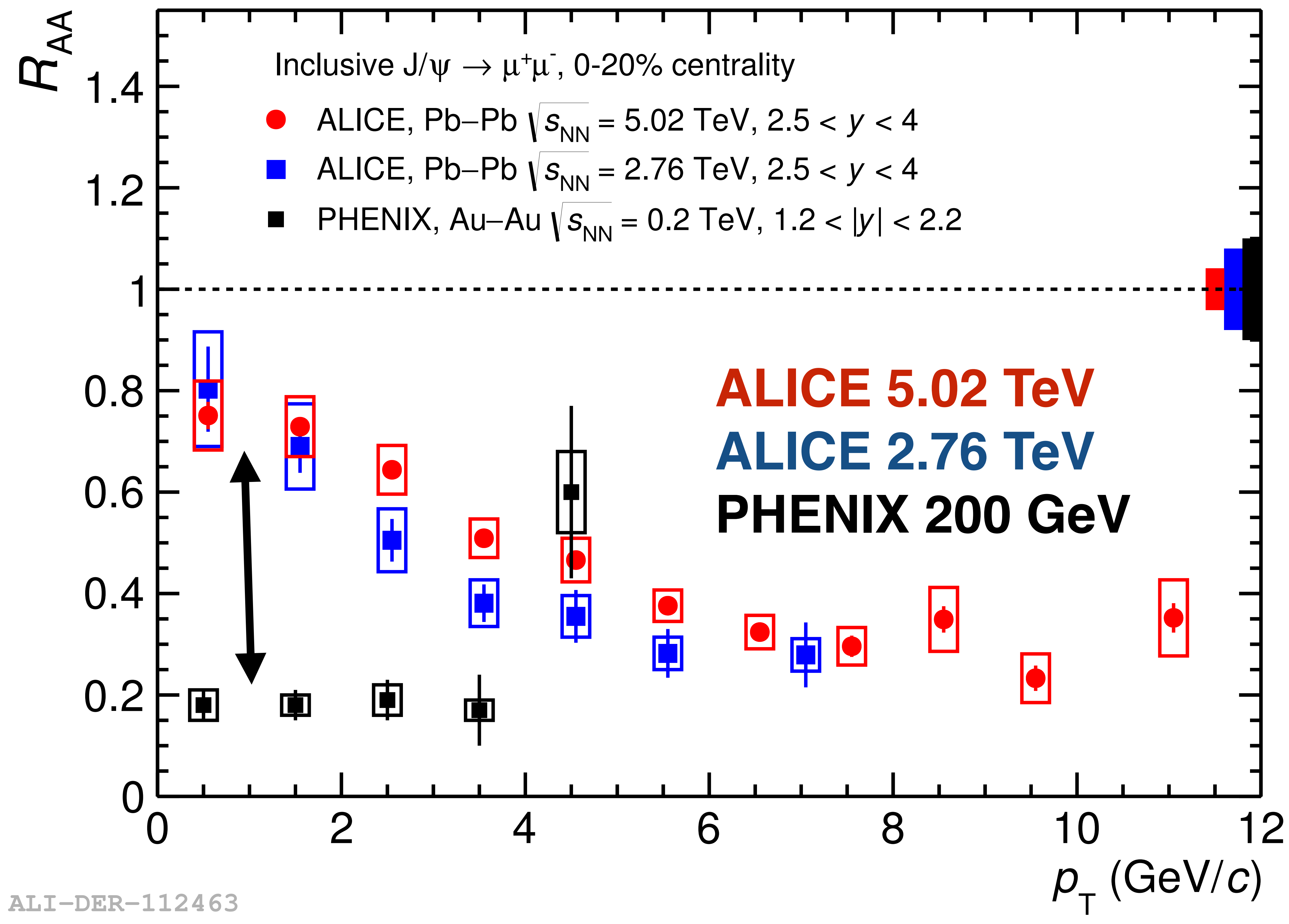
The historic "static" picture



$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$



R_{AA} = 1 → No medium modification



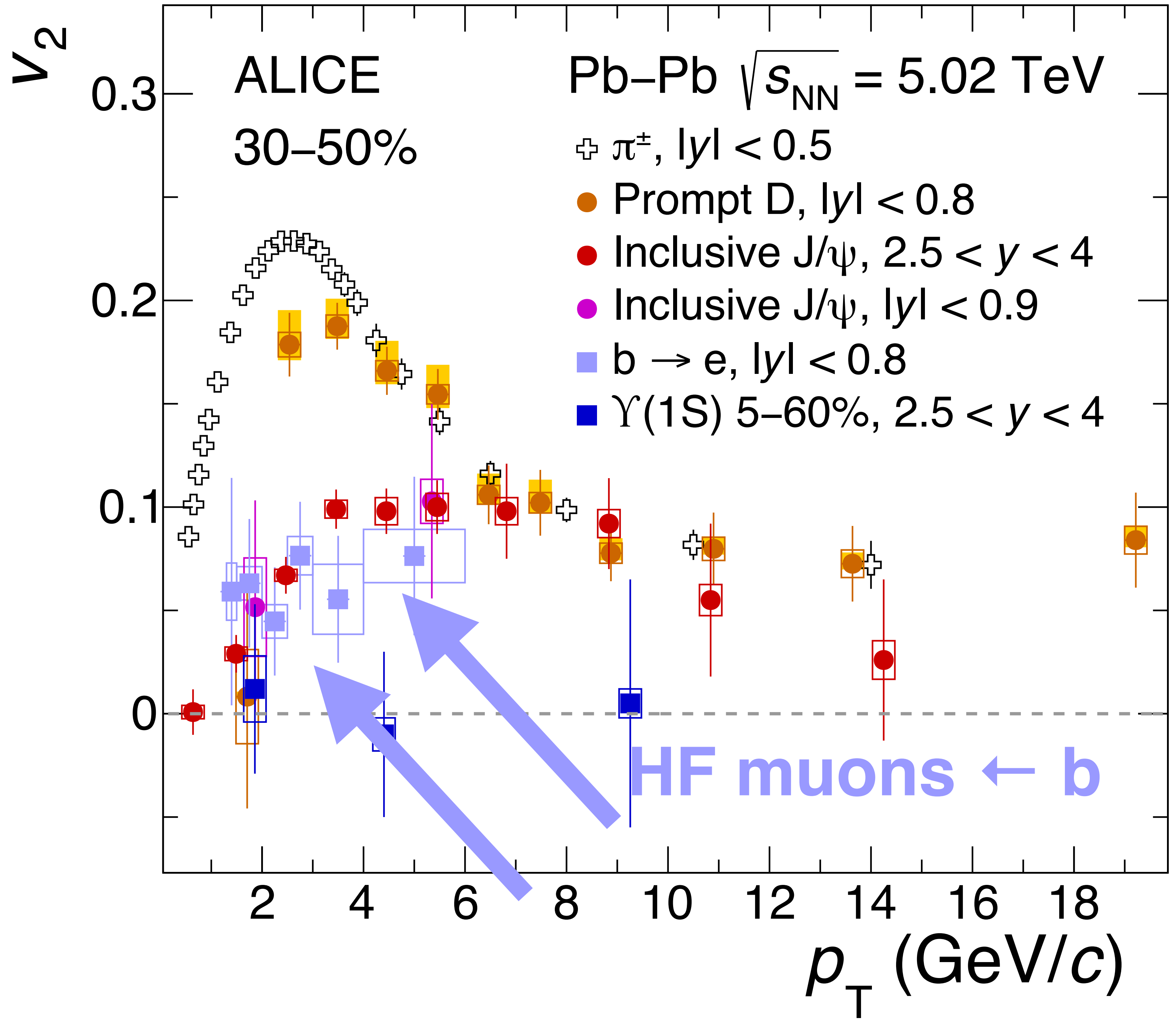
- J/ψ AA/pp production **larger at LHC** than at **RHIC, even in the presence of a hotter medium**

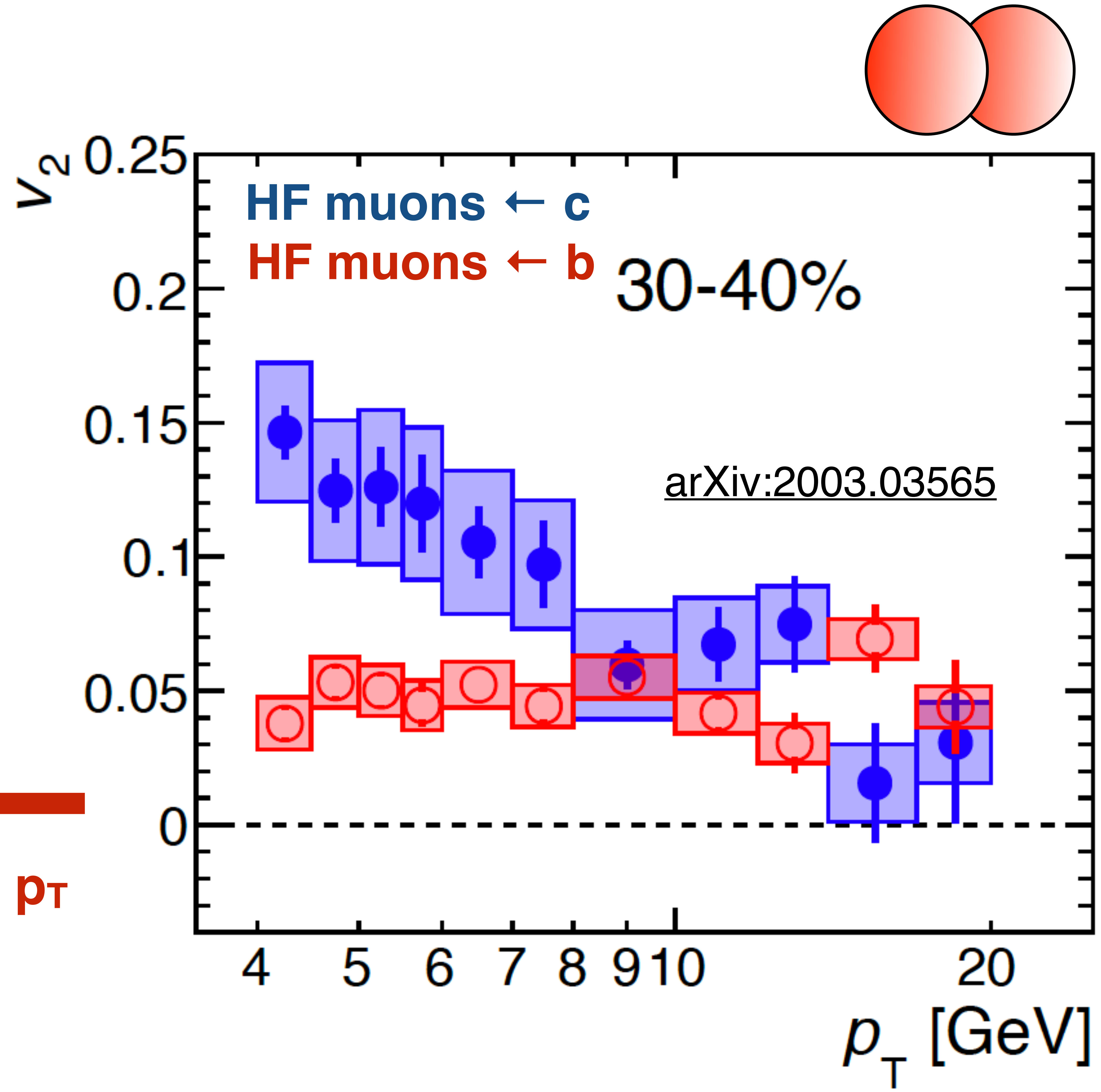
→Hadronisation by recombination:

J/ψ created in the QGP by combination of c-cbar pairs, more abundant at LHC w.r.t. RHIC

Charm and beauty “flow” in PbPb collisions

arXiv.2005.11130





Lower p_T

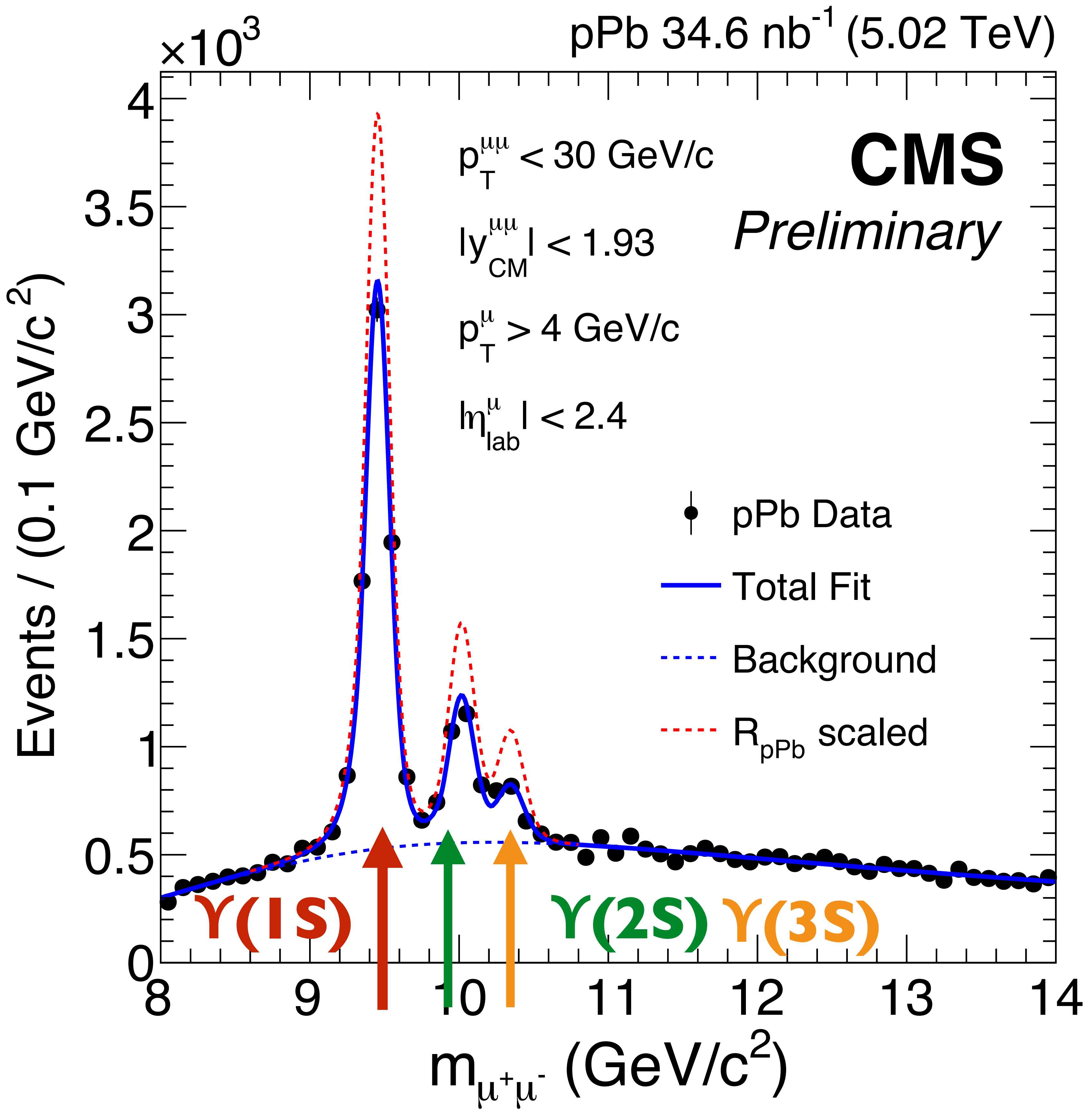
- **v_2 significantly > 0 for HF muons ← c**
- **v_2 smaller but still > 0 for HF muons ← b**

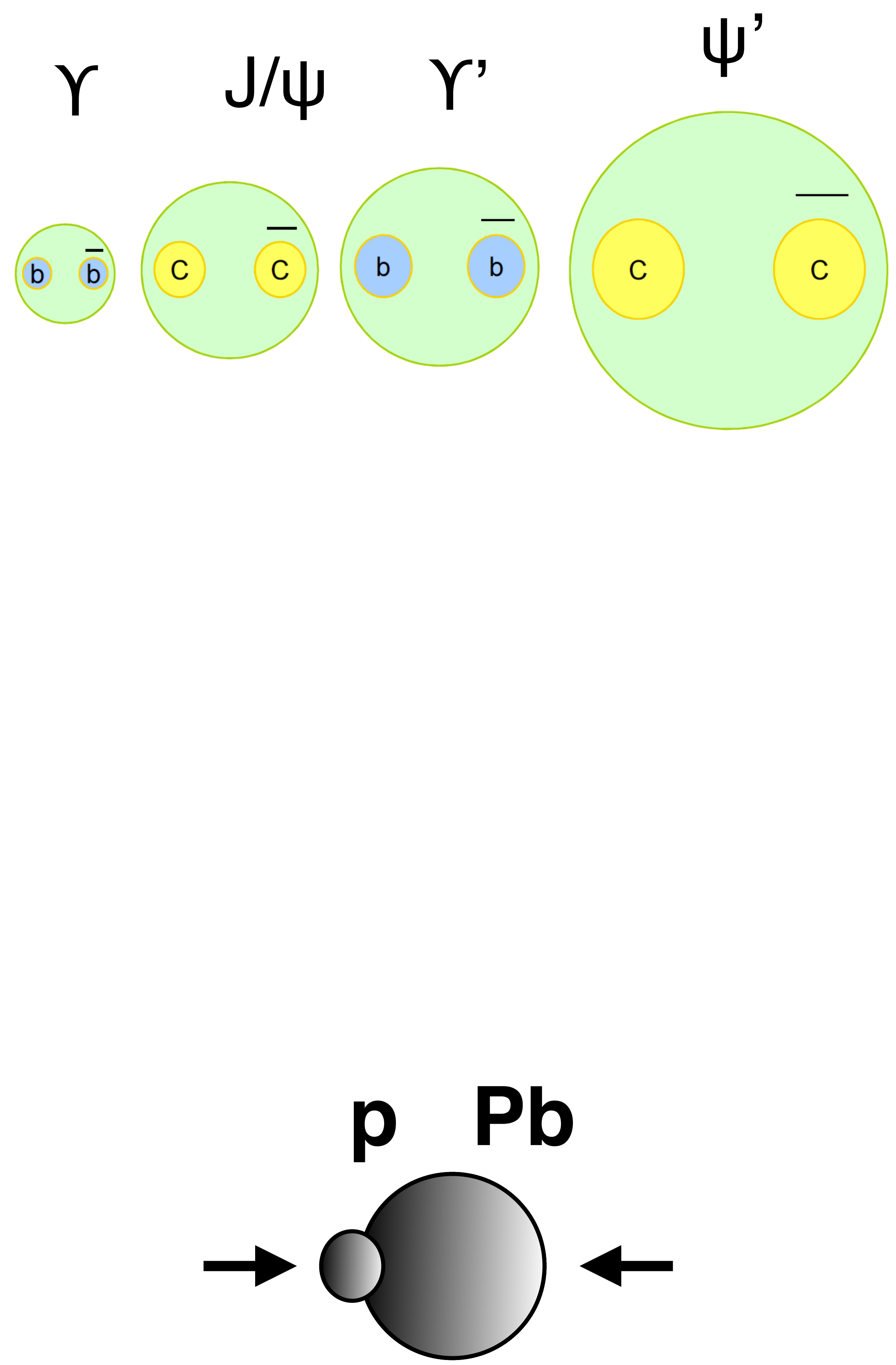
→ **Both charm and beauty quarks take part in the collective expansion of the medium**

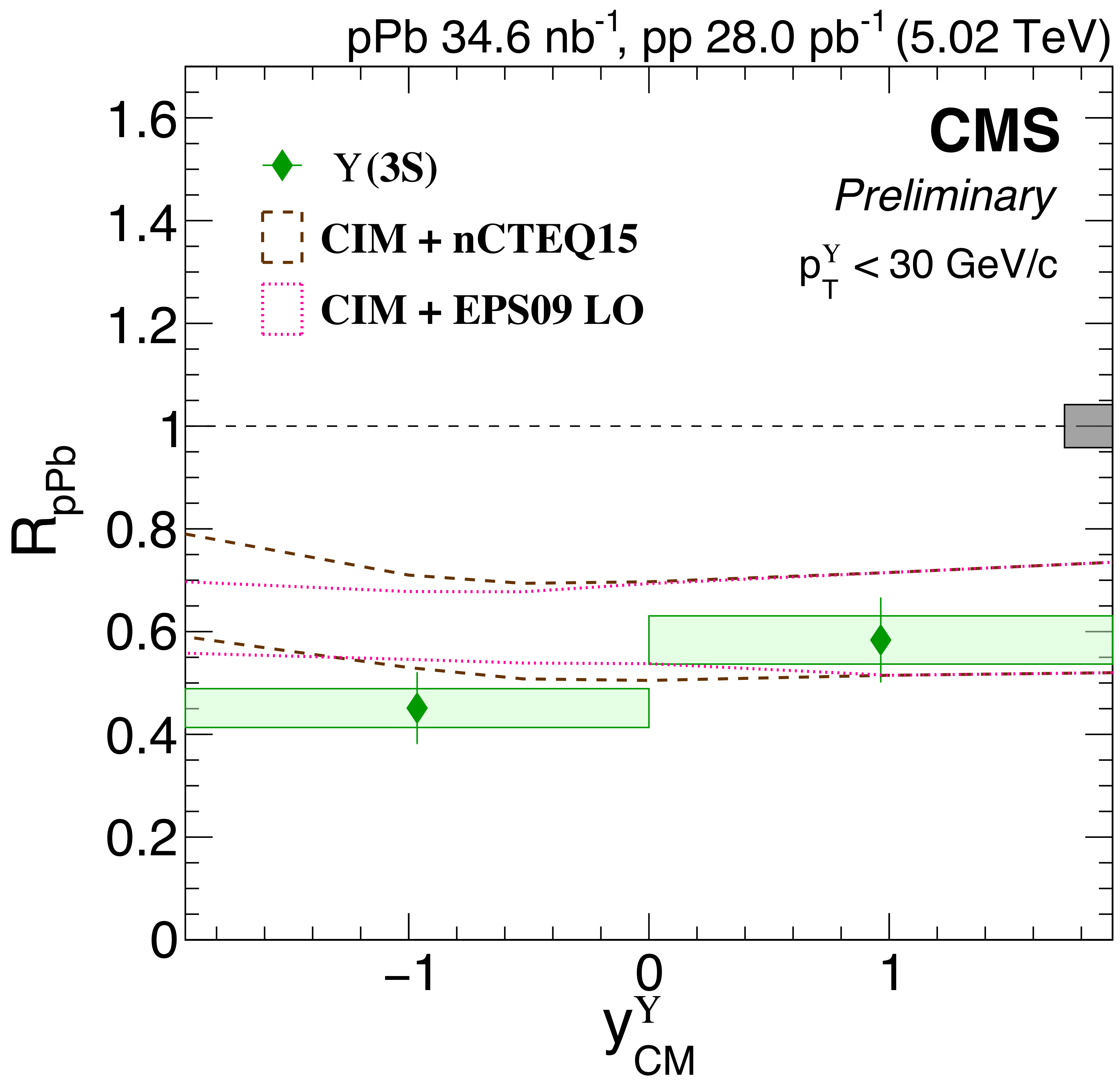
→ $v_2(\Upsilon)$ consistent with zero! Mass effect?

Bottomonium suppression in pPb collisions

CMS-PAS-HIN-18-005







- Υ suppression observed in pPb collisions!
- **Milder suppression w.r.t. Υ(1S)**

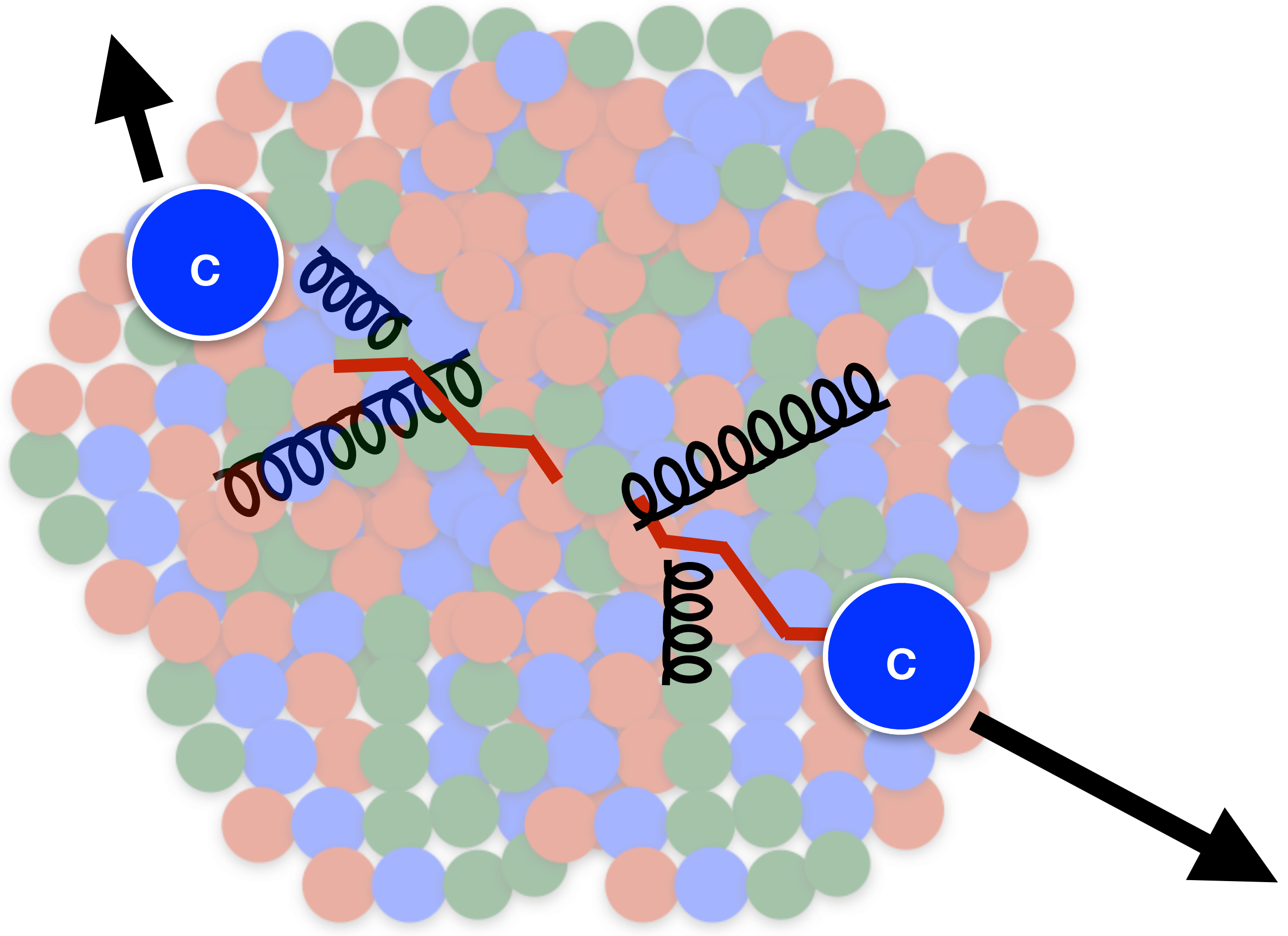
- **"cold" final state interaction** in pPb collisions probably **needed** to describe suppression of Υ states

How much of the PbPb suppression can be explain with "cold" final state processes?

JHEP10 (2018) 094

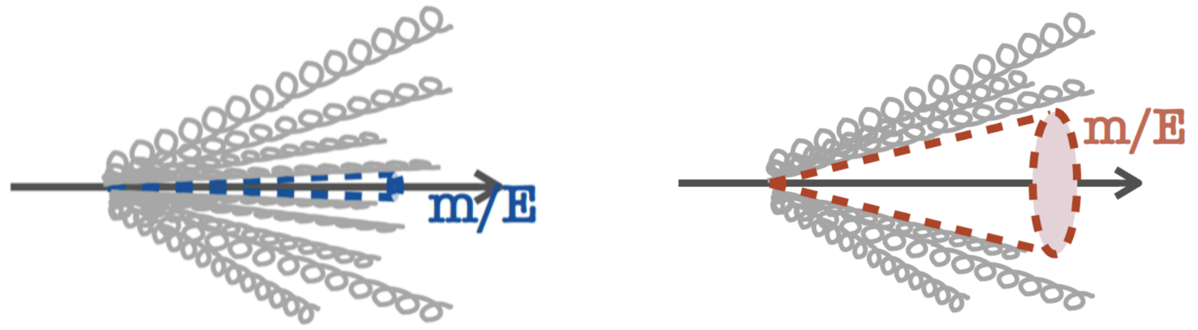
Flavour dependence of E_{loss}

In-medium energy loss as a consequence of **radiative** and **collisional** processes.

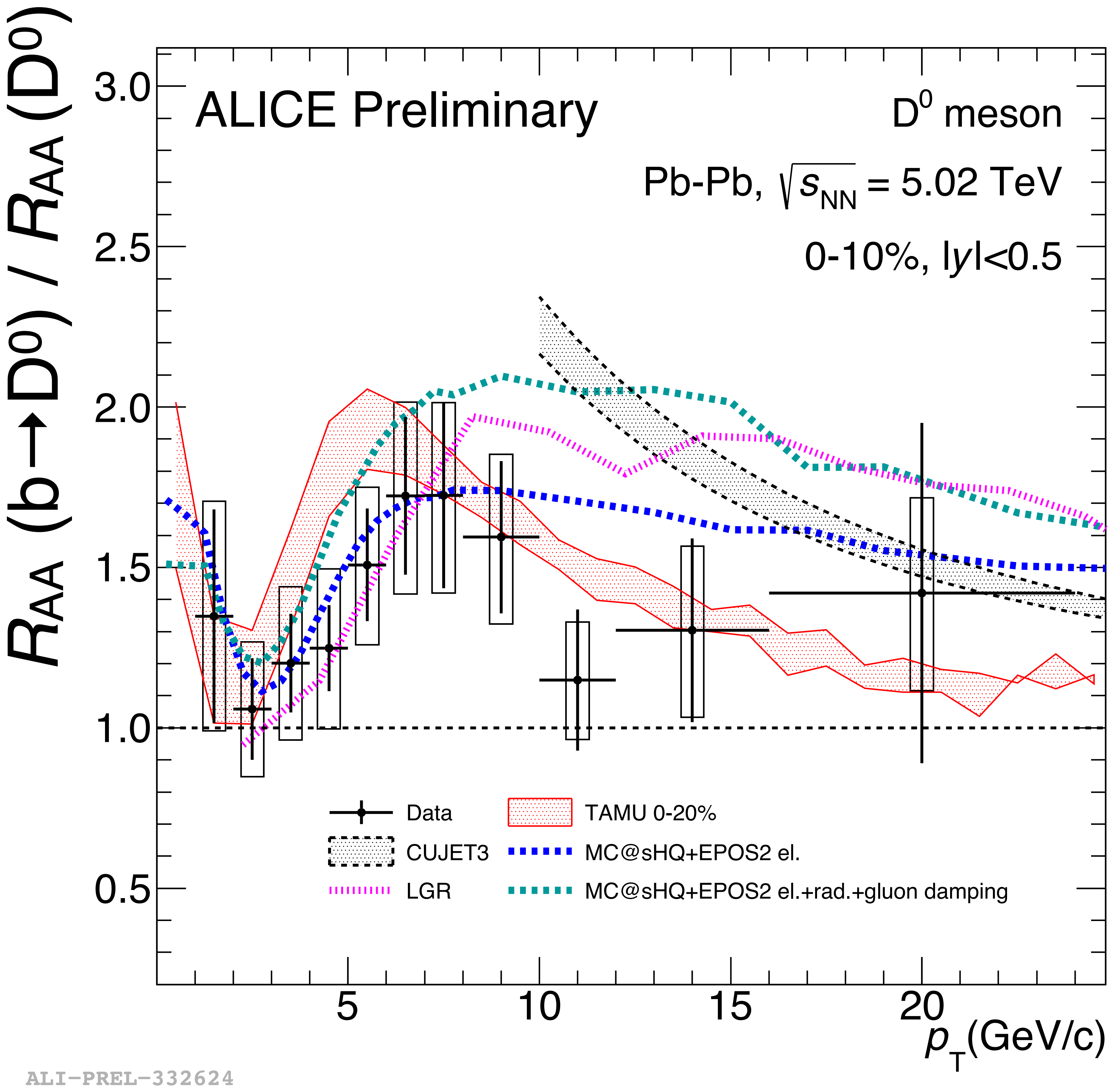


<u>Flavour dependence of radiative E_{loss}:</u>

- **different Casimir factors** for quark and gluons
  $C_R = 3$ for gluons, $C_R = 4/3$ for quarks
- **dead cone effect:**



→ **E_{loss} (gluon) > E_{loss} (charm) > E_{loss} (beauty)**



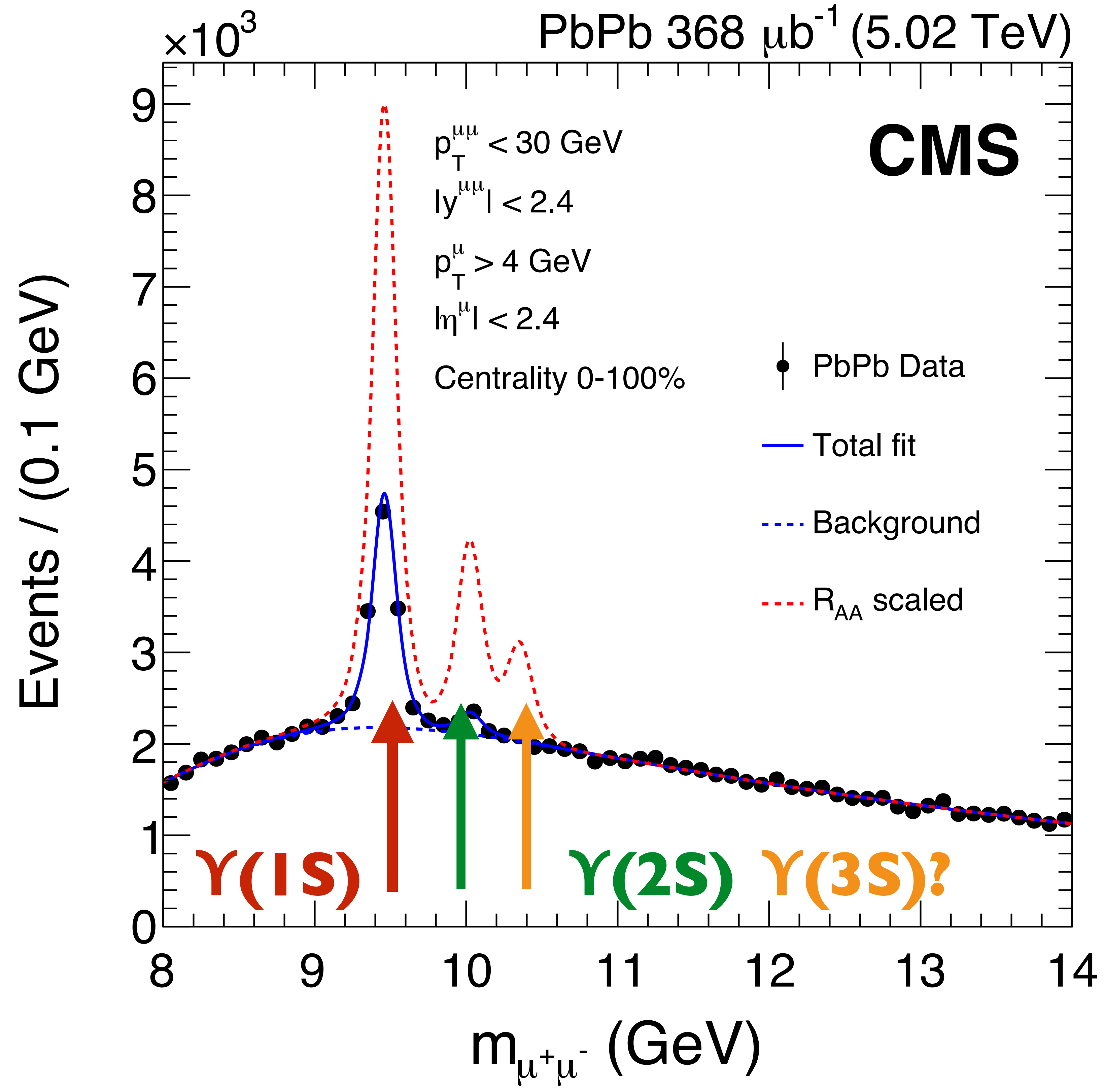
- Described by theoretical calculations that include different E_{loss} for charm and beauty quarks

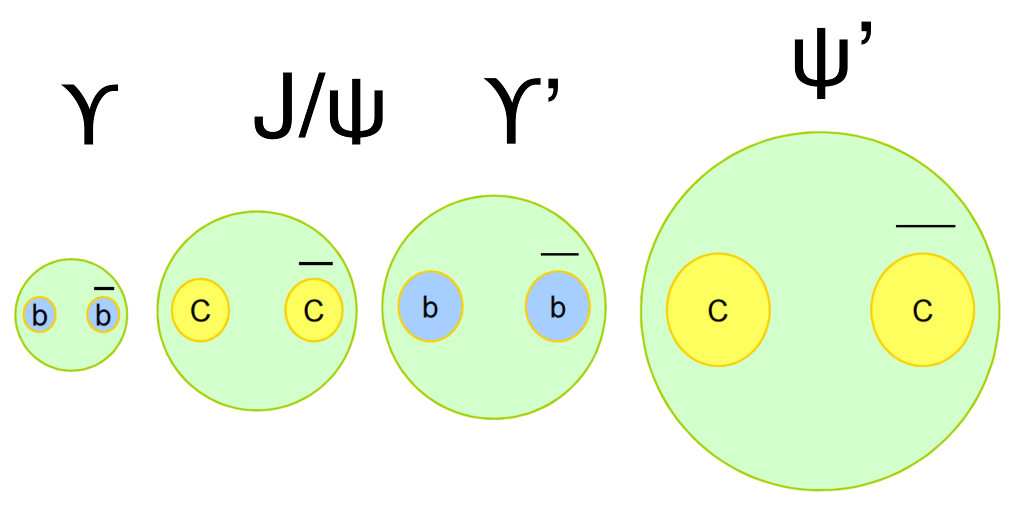
→ Quantitive indication of flavour dependence of E_{loss} as predicted by pQCD calculations

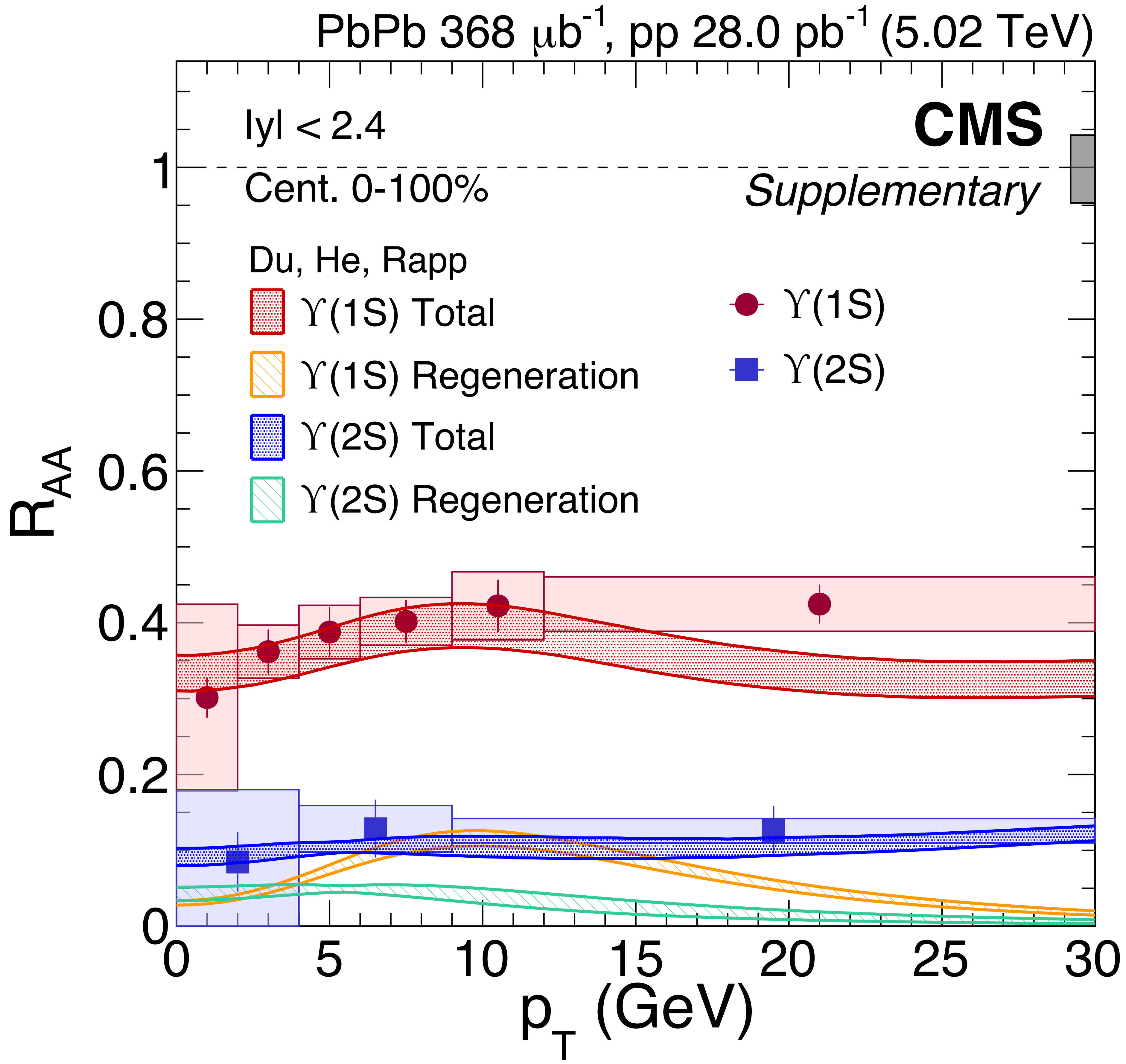
Bottomonium suppression in PbPb

Bottomonia less affected by recombination due to lower b-bar cross section!

1805.09215





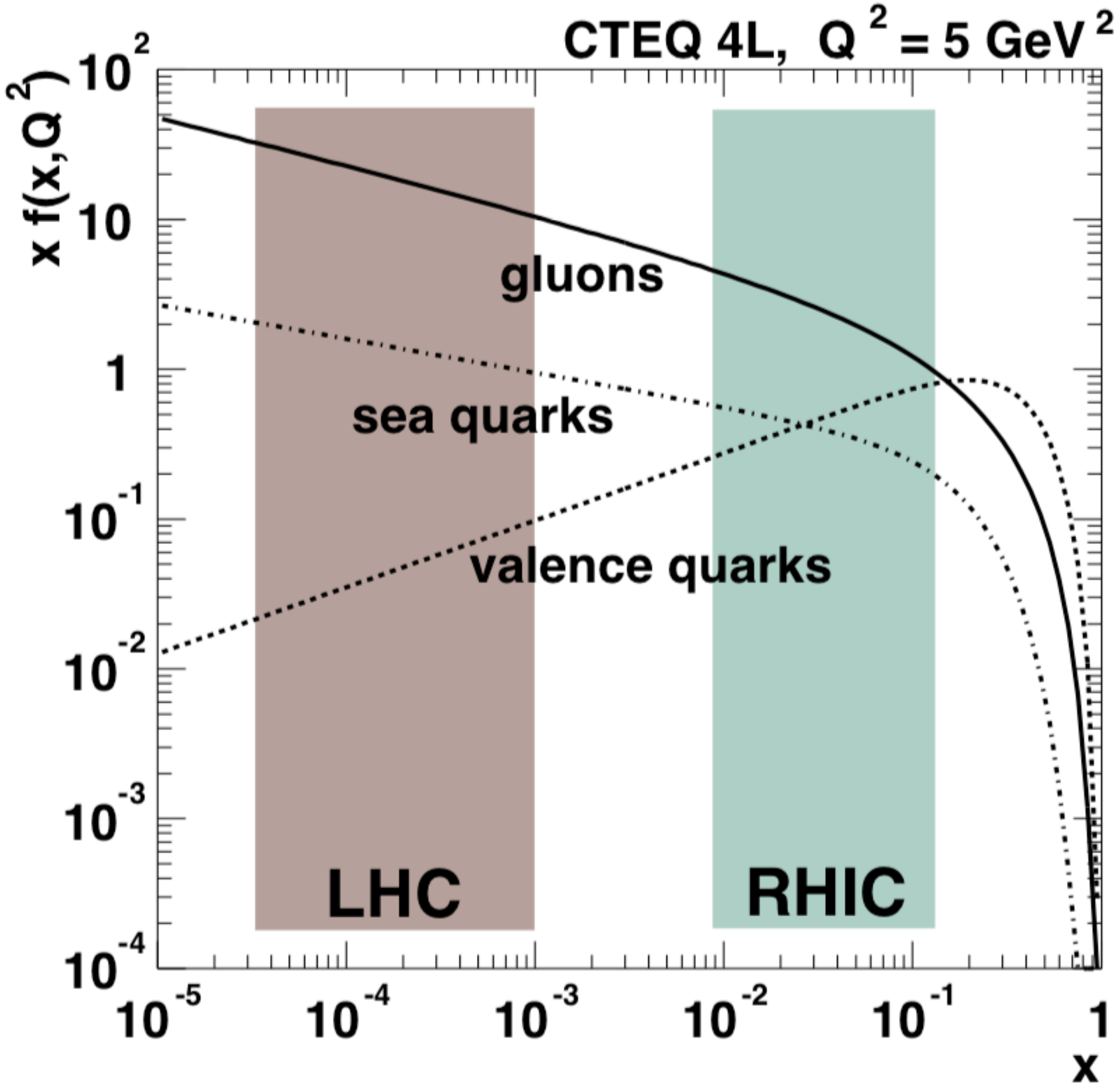


- Looser bound ϒ states more suppressed!

- Suppression pattern well described by models with melting + recombination

→ Unambiguous indication of sequential suppression?

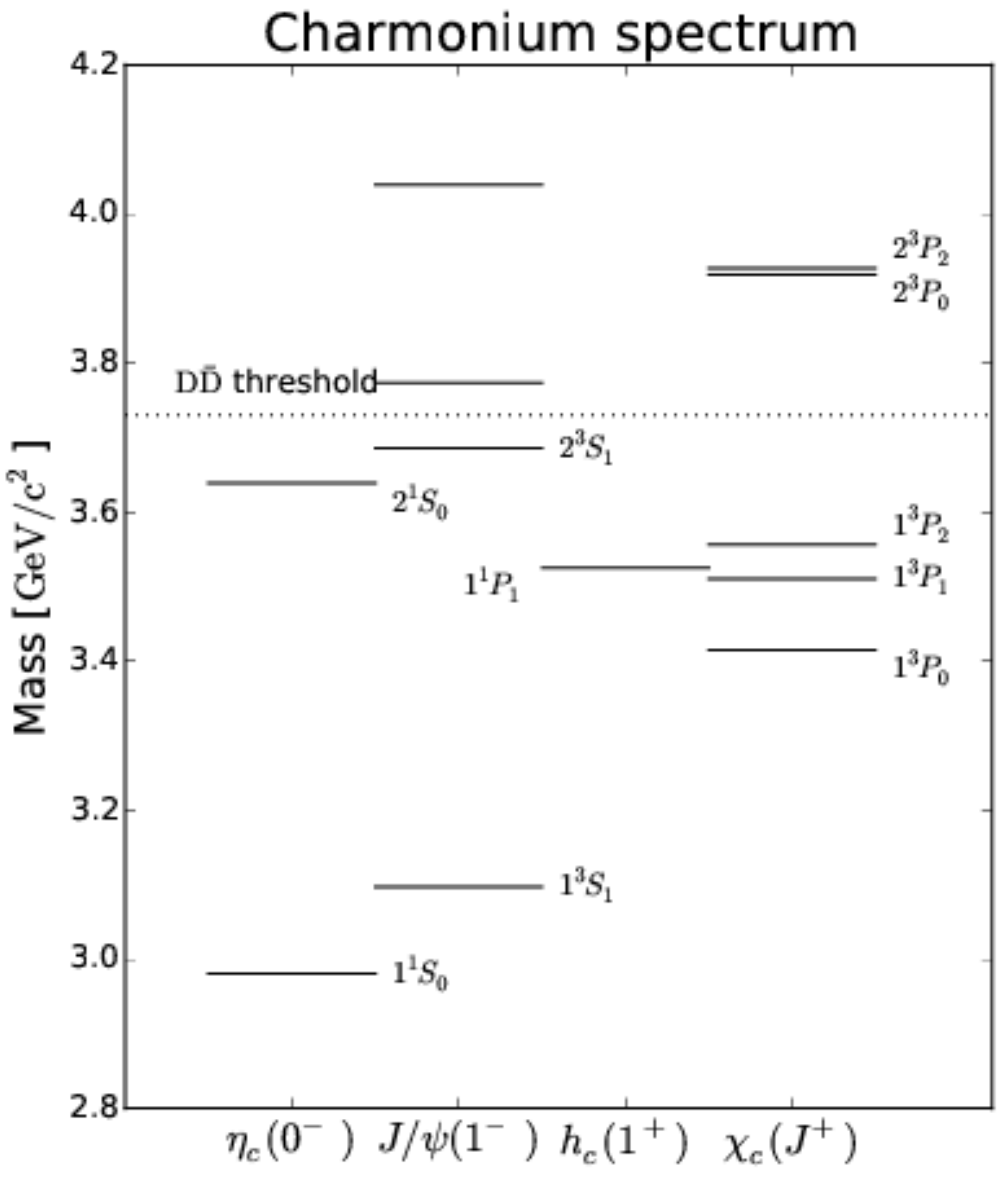
PDF in nuclei

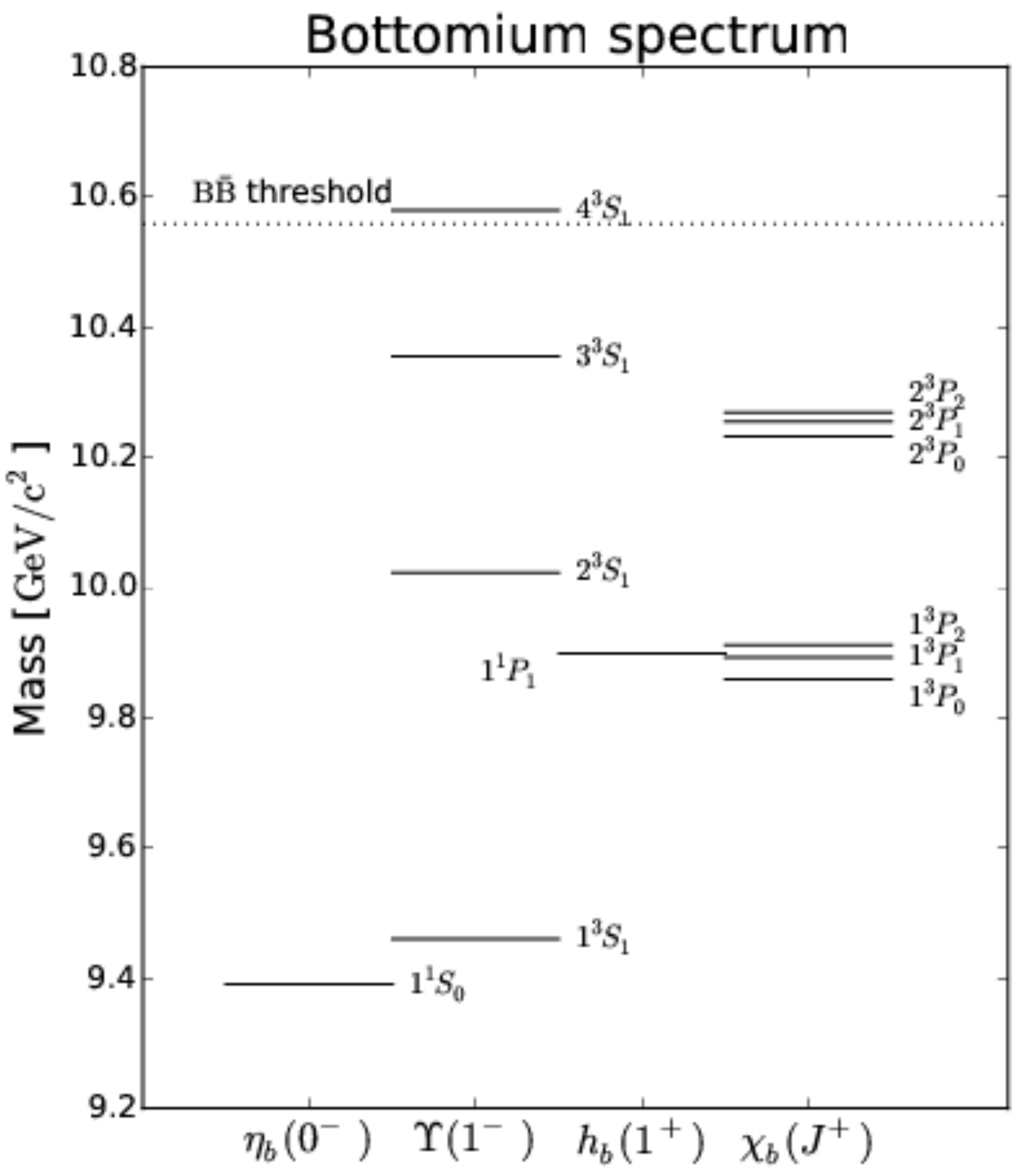


$$x_1 = \frac{M_{Q\overline{Q}}}{\sqrt{s_{\rm NN}}} \exp\left(+y_{Q\overline{Q}}\right)$$

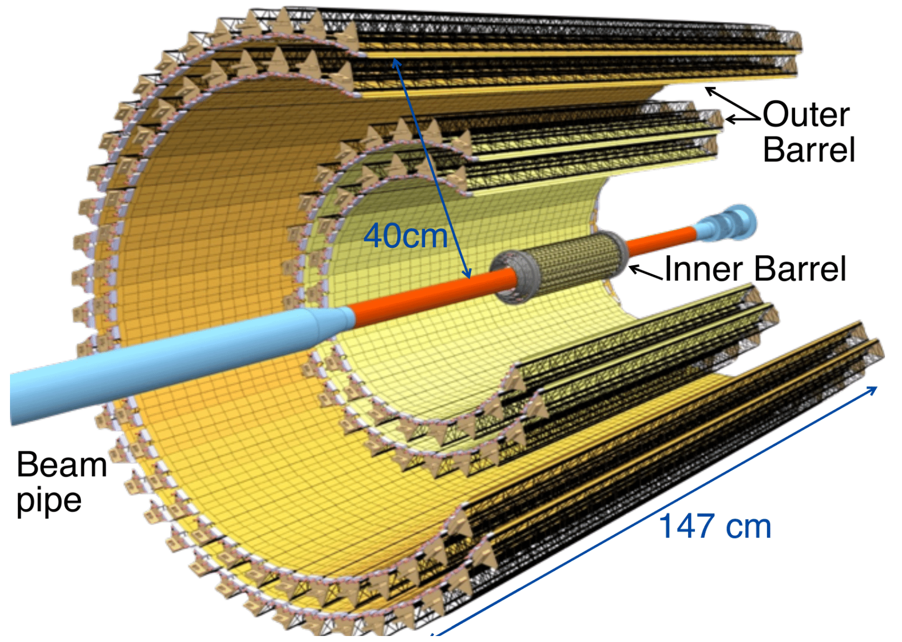
Machine	SPS	RHIC	LHC	LHC
System	Pb–Pb	Au–Au	Pb–Pb	pp
$\sqrt{s_{\rm NN}}$	17 GeV	200 GeV	5.5 TeV	14 TeV
$c\overline{c}$	$x \simeq 10^{-1}$	$x \simeq 10^{-2}$	$x \simeq 4 \cdot 10^{-4}$	$x \simeq 2 \cdot 10^{-4}$
$b\overline{b}$	–	–	$x \simeq 2 \cdot 10^{-3}$	$x \simeq 6 \cdot 10^{-4}$

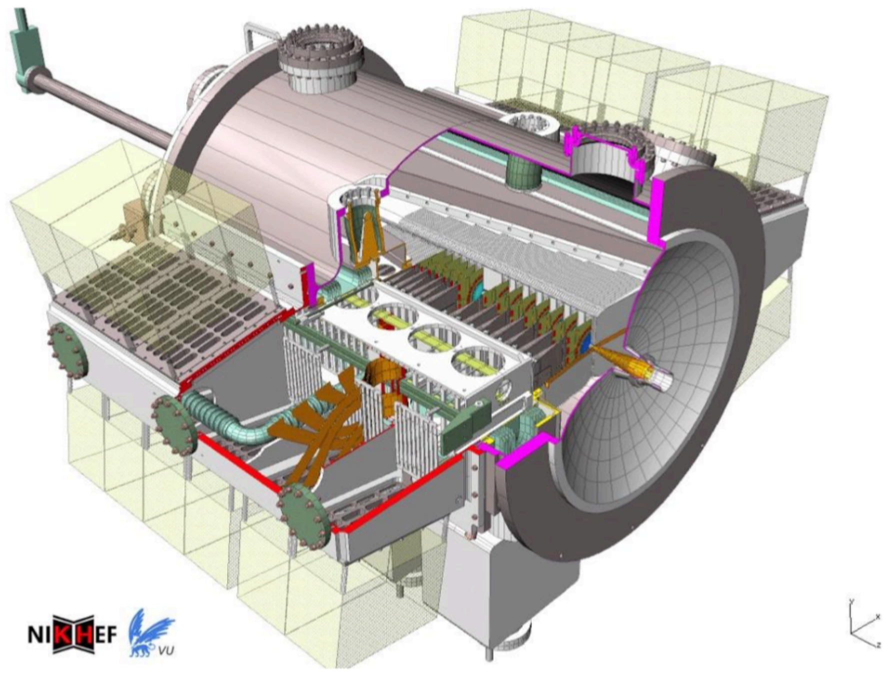
Quarkonia family

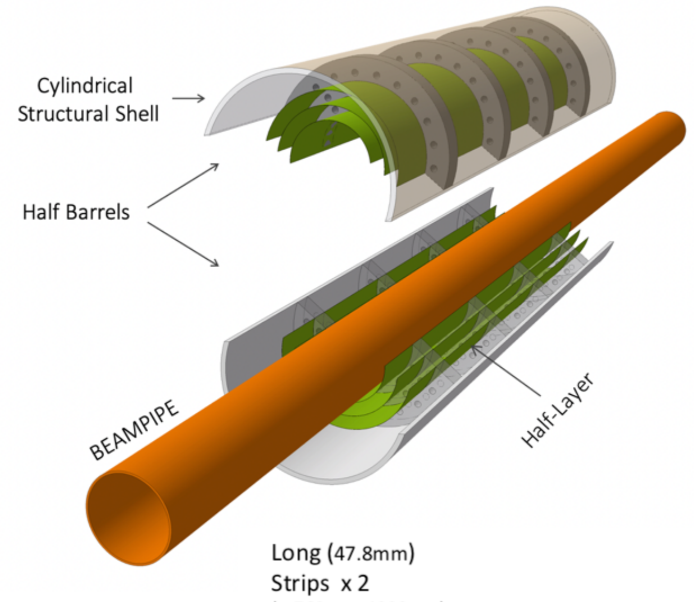


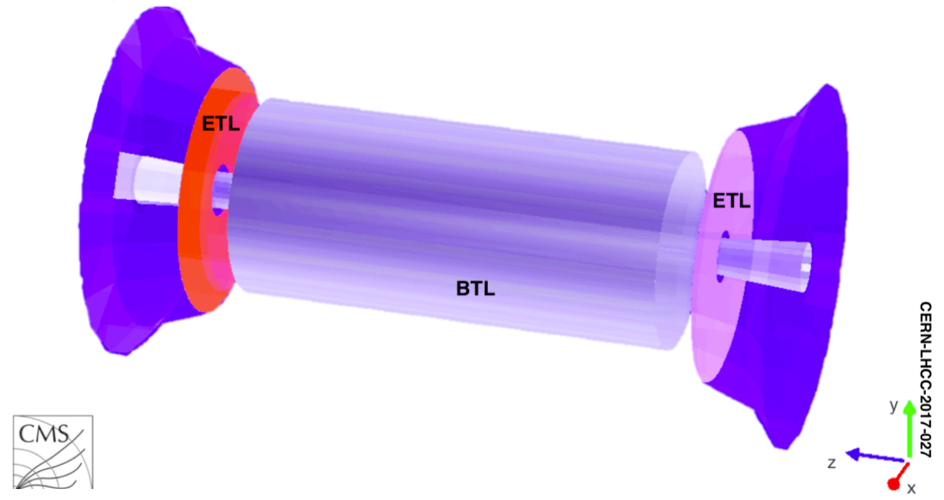


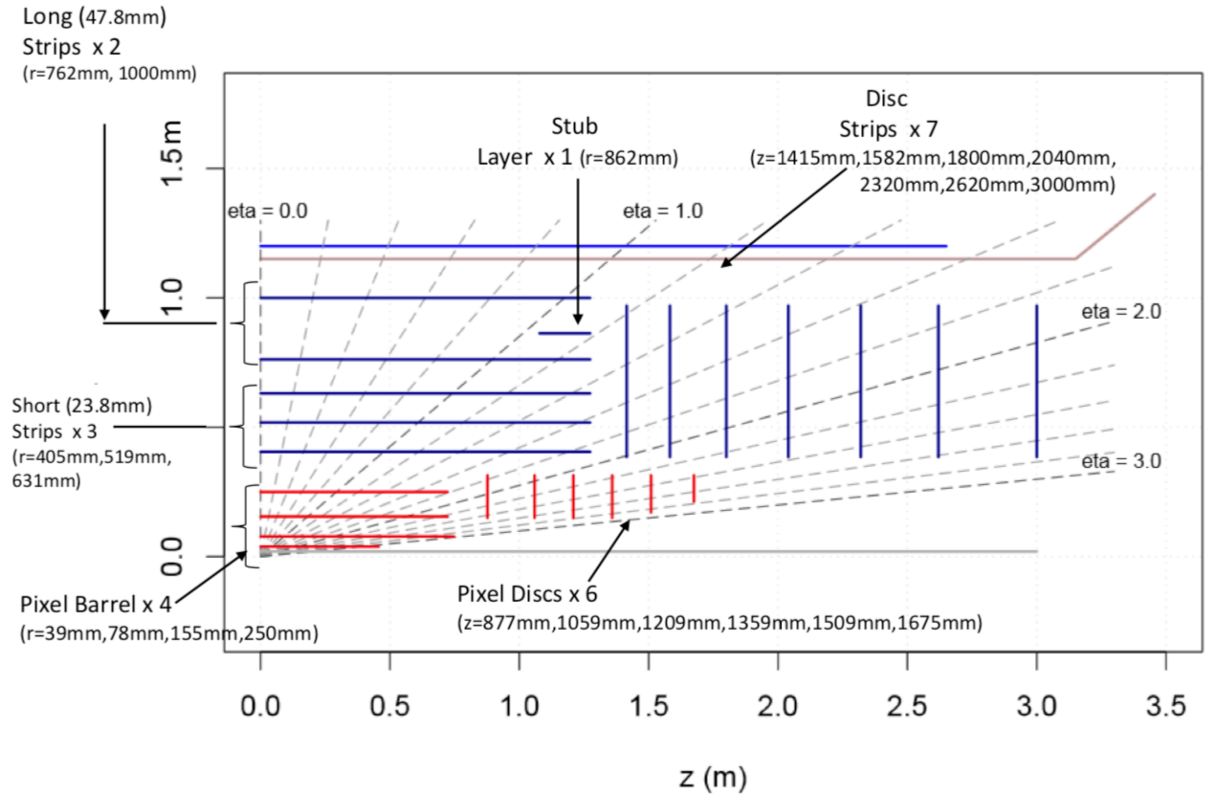
HF/Quarkonia for Run3 and beyond

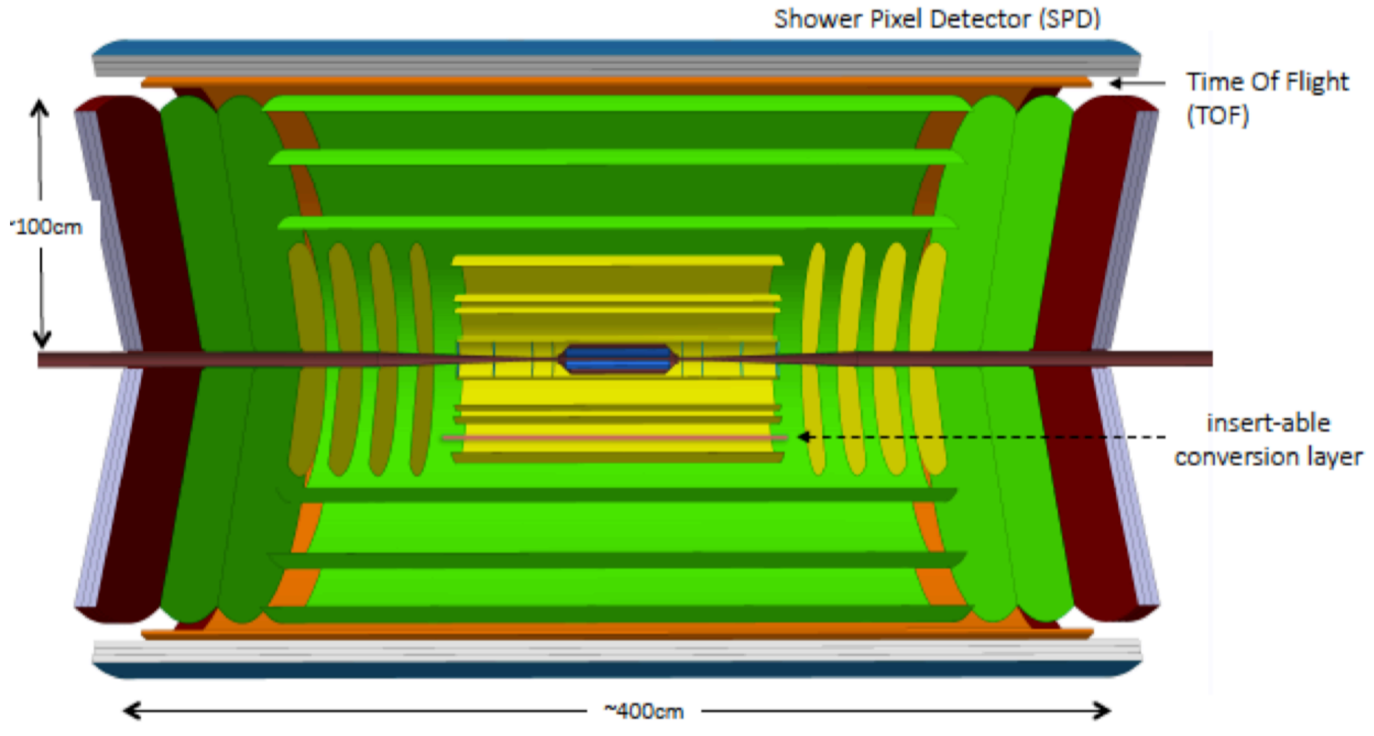












Run 3:

- ALICE
  - Inner Tracking system (ITS2) + new TPC readout (x100 more stats)
  - Muon Forward Tracker
- LHCb:
  - VELO detector
  - push to more central HI collisions!

Run 4:

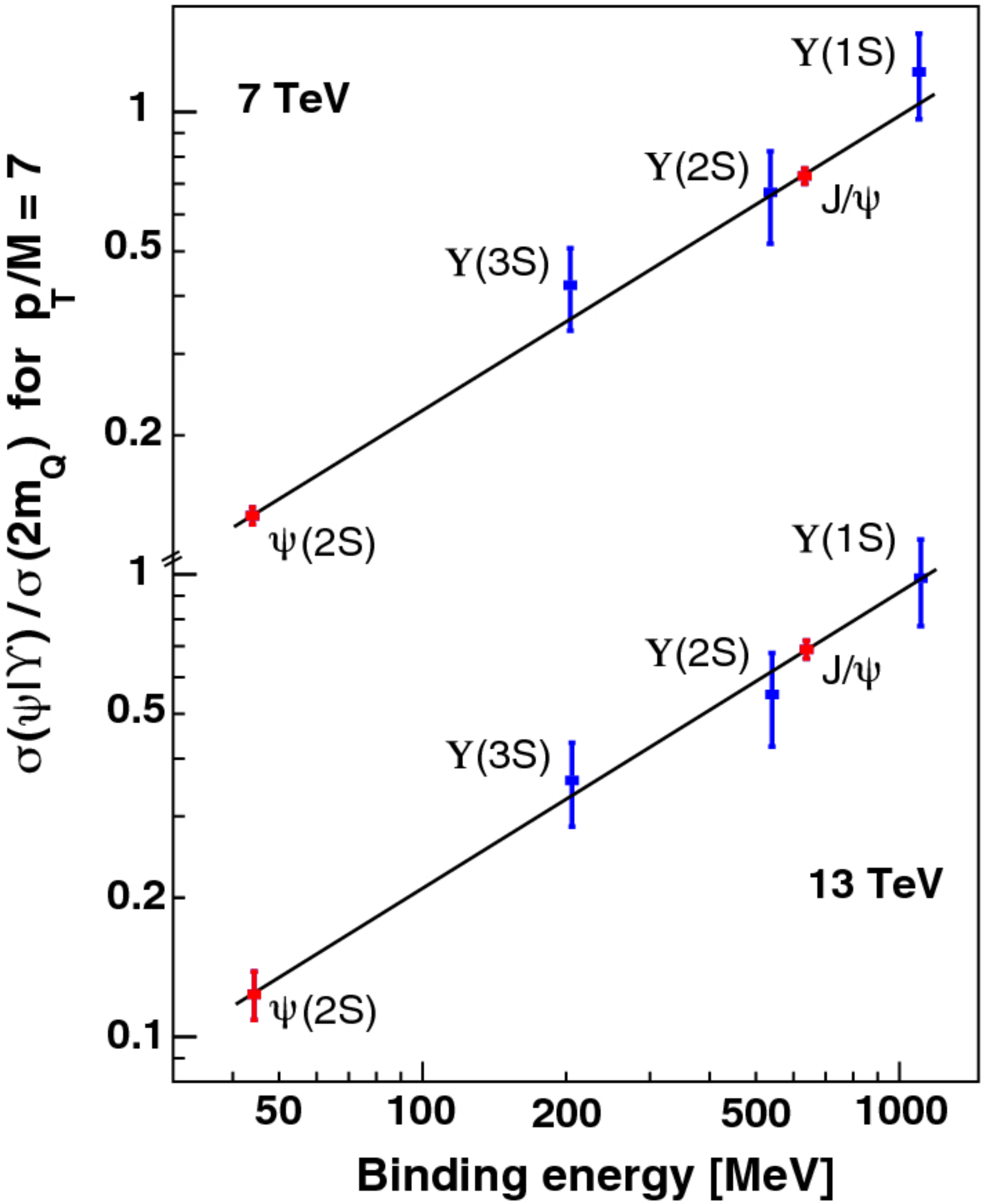
- ALICE: “massless” full pixel inner barrel (ITS3)
- CMS:
  - new tracker and calorimetry
  - Time-of-Flight detector
- ATLAS:
  - new tracker and calorimetry

Run 5

- new full pixel HI experiment!

Upgrade sessions Monday Afternoon

Quarkonia family

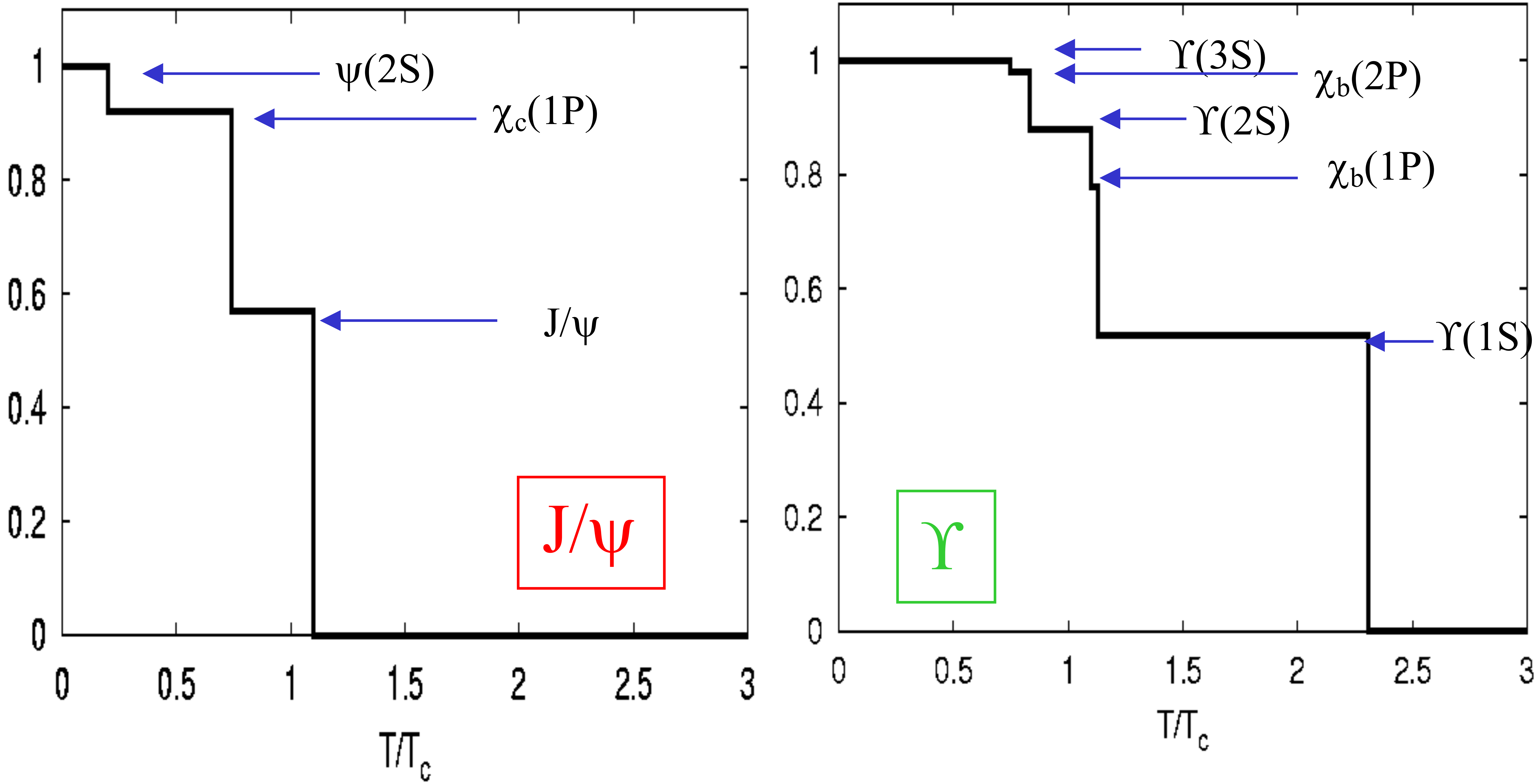


state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Table 3: Quarkonium Spectroscopy from Non-Relativistic Potential Theory [9]

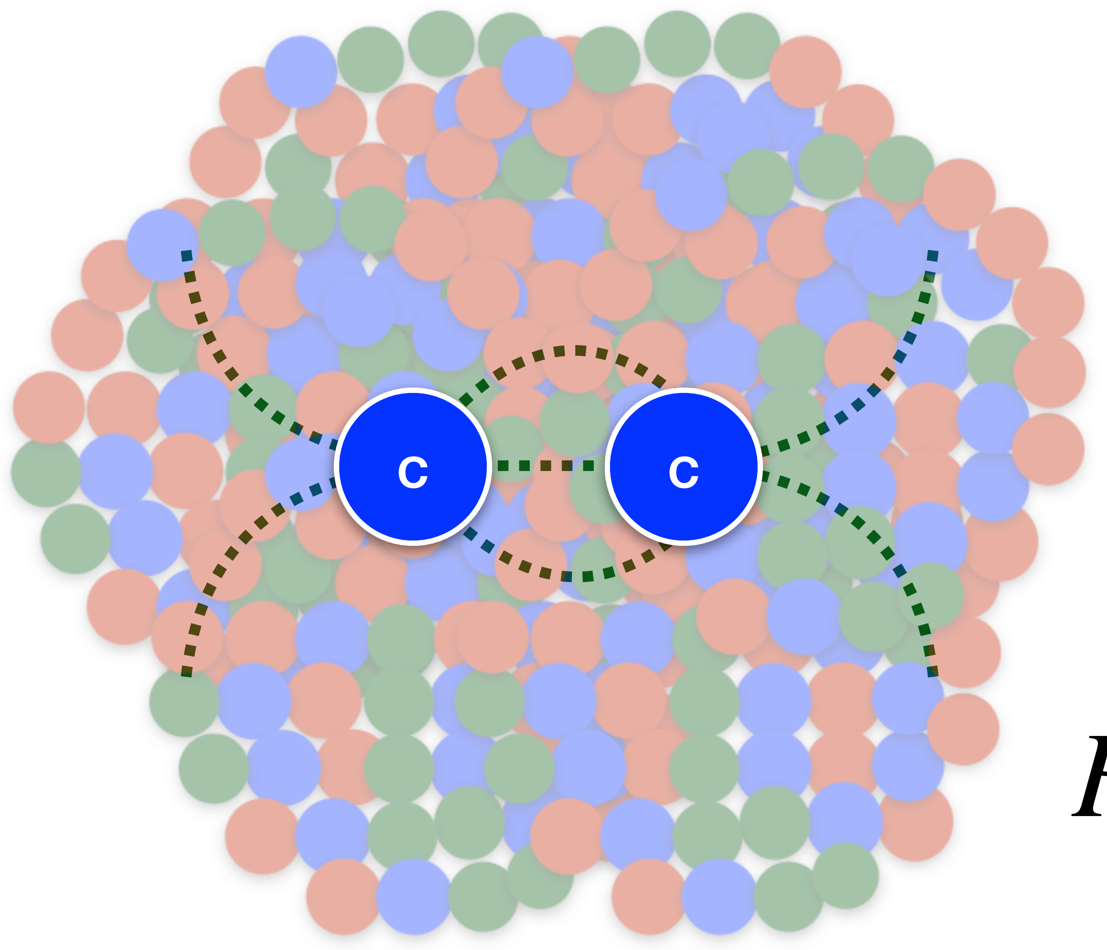
https://link.springer.com/article/10.1140/epjc/s10052-018-6216-z
https://arxiv.org/pdf/0901.3831.pdf

Sequential suppression and medium T

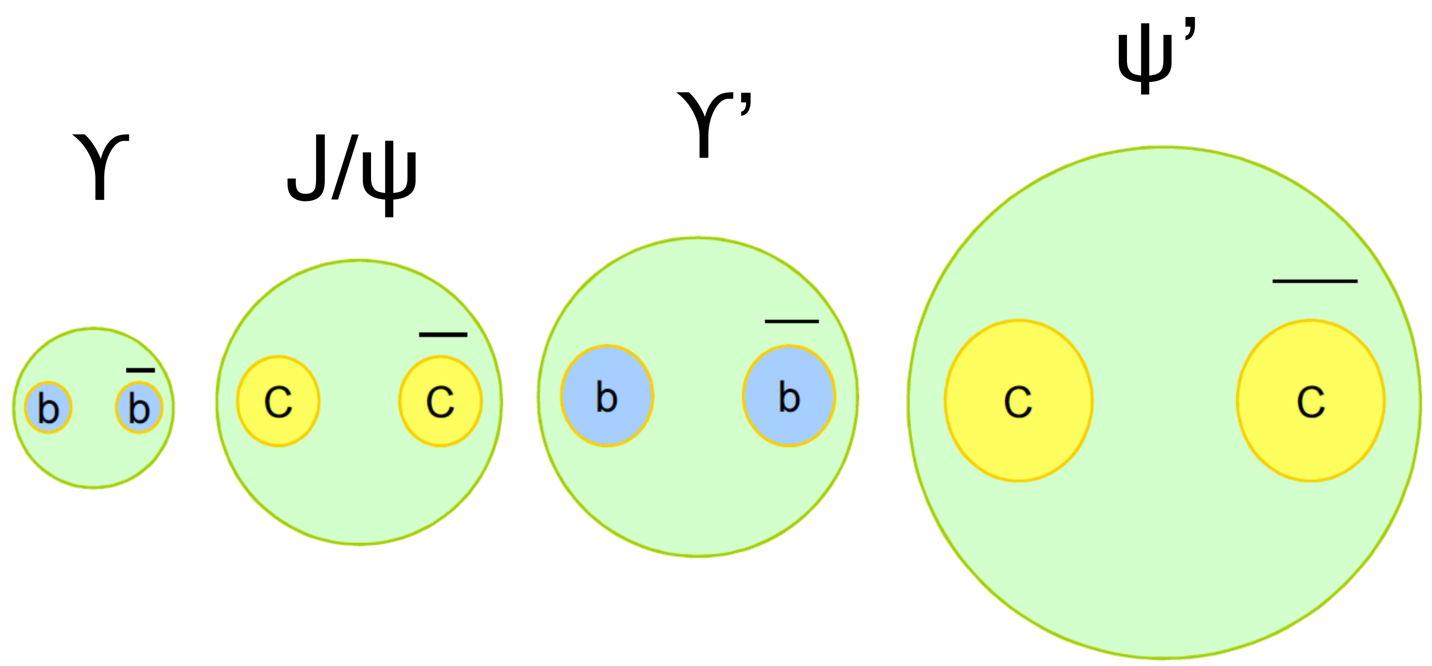


J/ψ suppression from RHIC to LHC

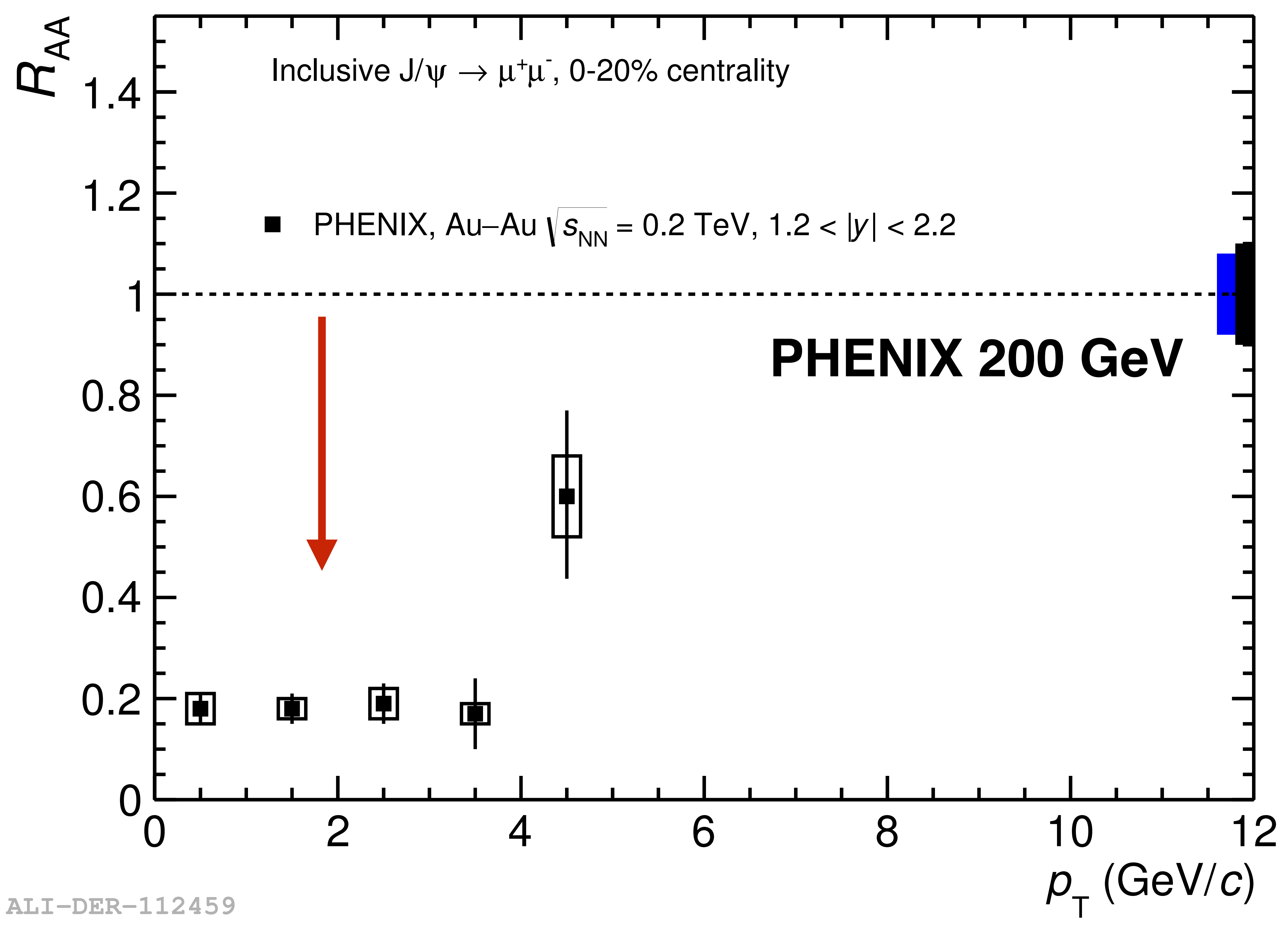
The historical "static" picture



$$R_{AA} = \frac{1}{N_{coll}} \frac{AA}{pp}$$



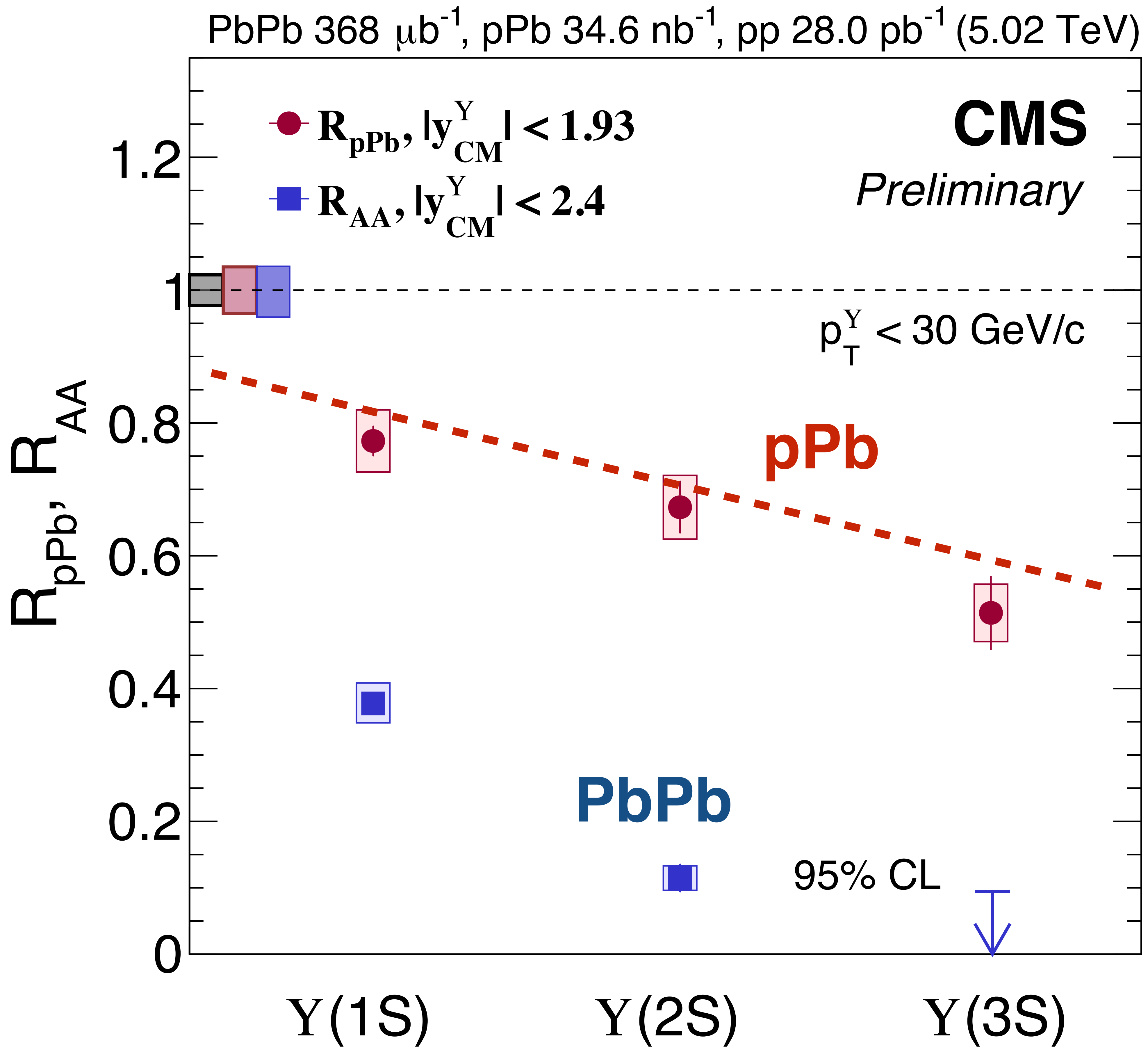
$R_{AA} = 1$ → No medium modification



- Different states have different binding energies
- loosely bound melt first
- **From suppression pattern → QGP temperature**

Bottomonium sequential suppression in PbPb?

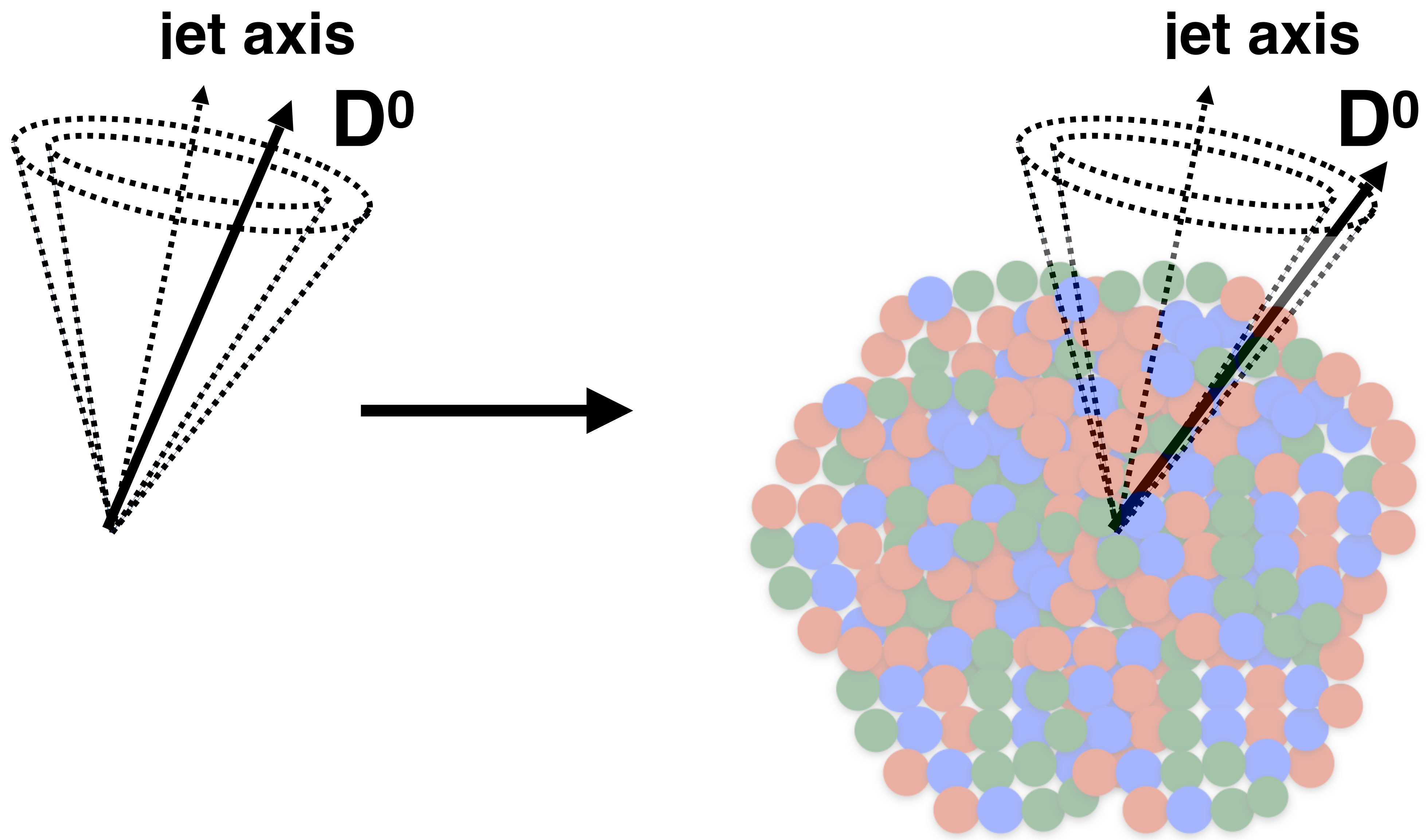
CMS-PAS-HIN-18-005

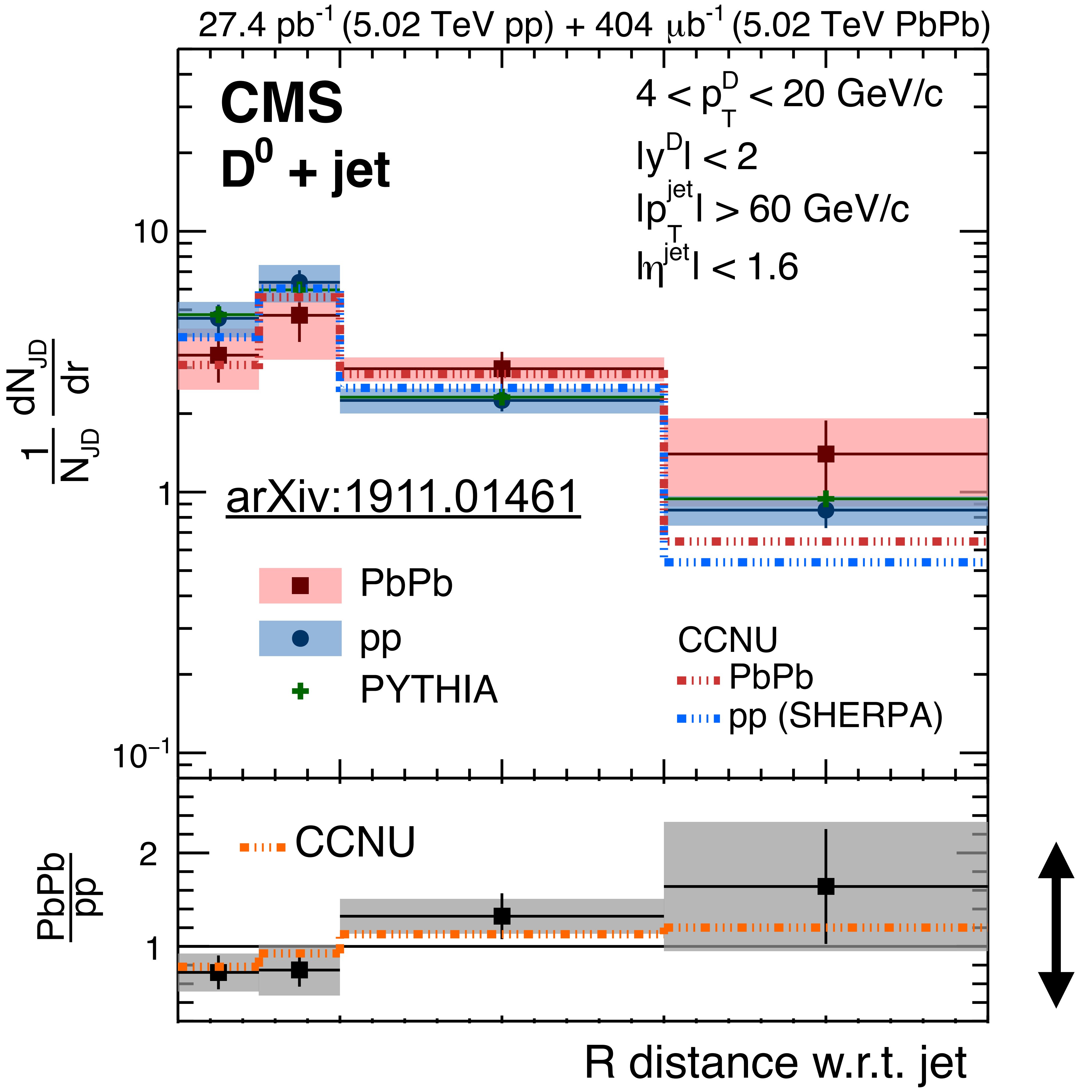


- **suppression in pPb** can be explained by "cold" final state effects
- **Suppression in PbPb:**
  - due to remnant sequential melting
  - cold state effect sufficient to describe the data?
    JHEP10 (2018) 094

D⁰-jet radial distance in PbPb collisions

→ Measure the radial distribution of D⁰ inside a jet with respect to the jet axis





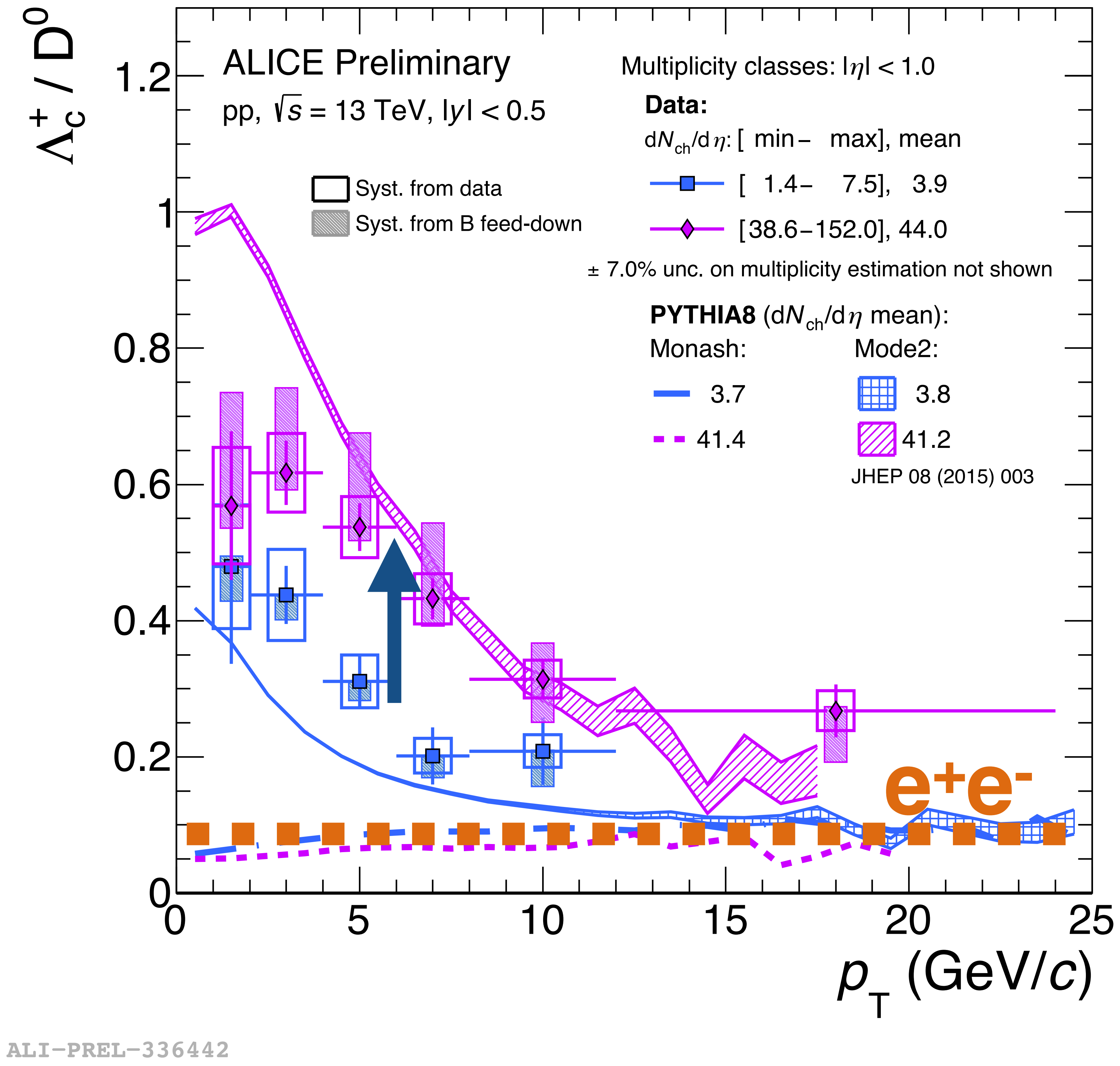
→ Sensitive to mechanism of charm diffusion inside the QGP medium

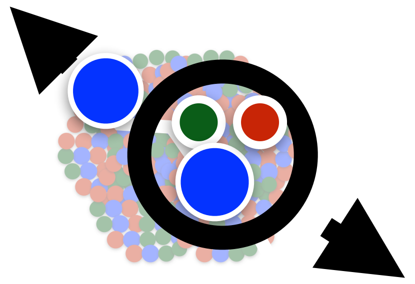
→ **First insights into the inner structure of HF jets**

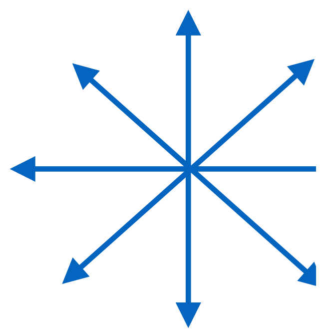
- In PbPb D⁰ "pushed" far from the jet cone

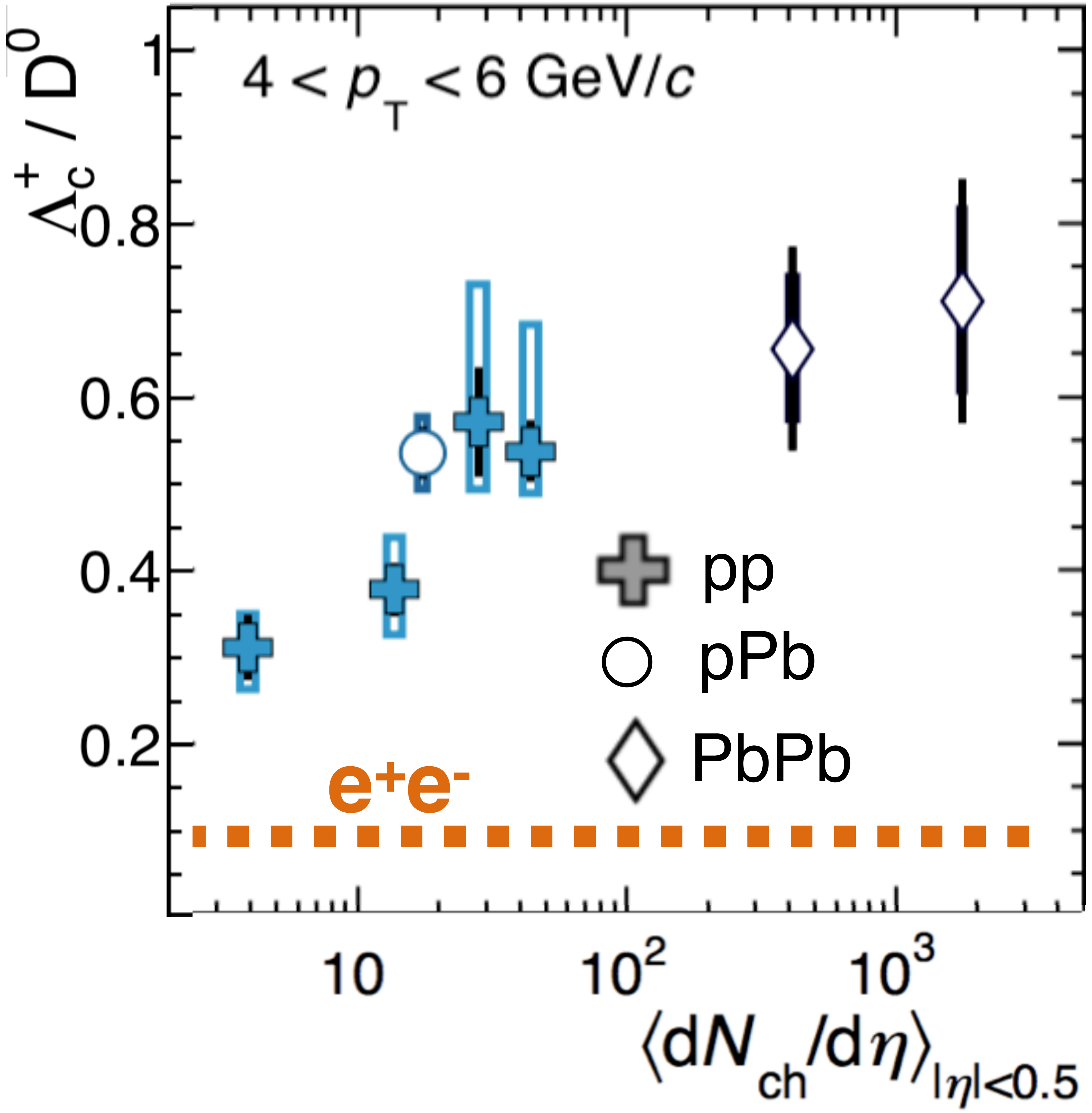
→to be confirmed by future measurement

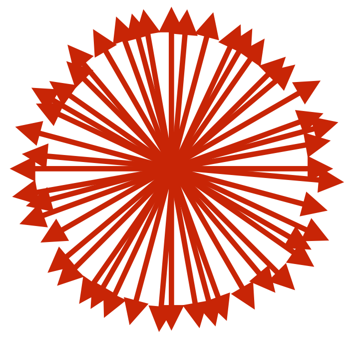
Modification of hadronisation in pp collisions?







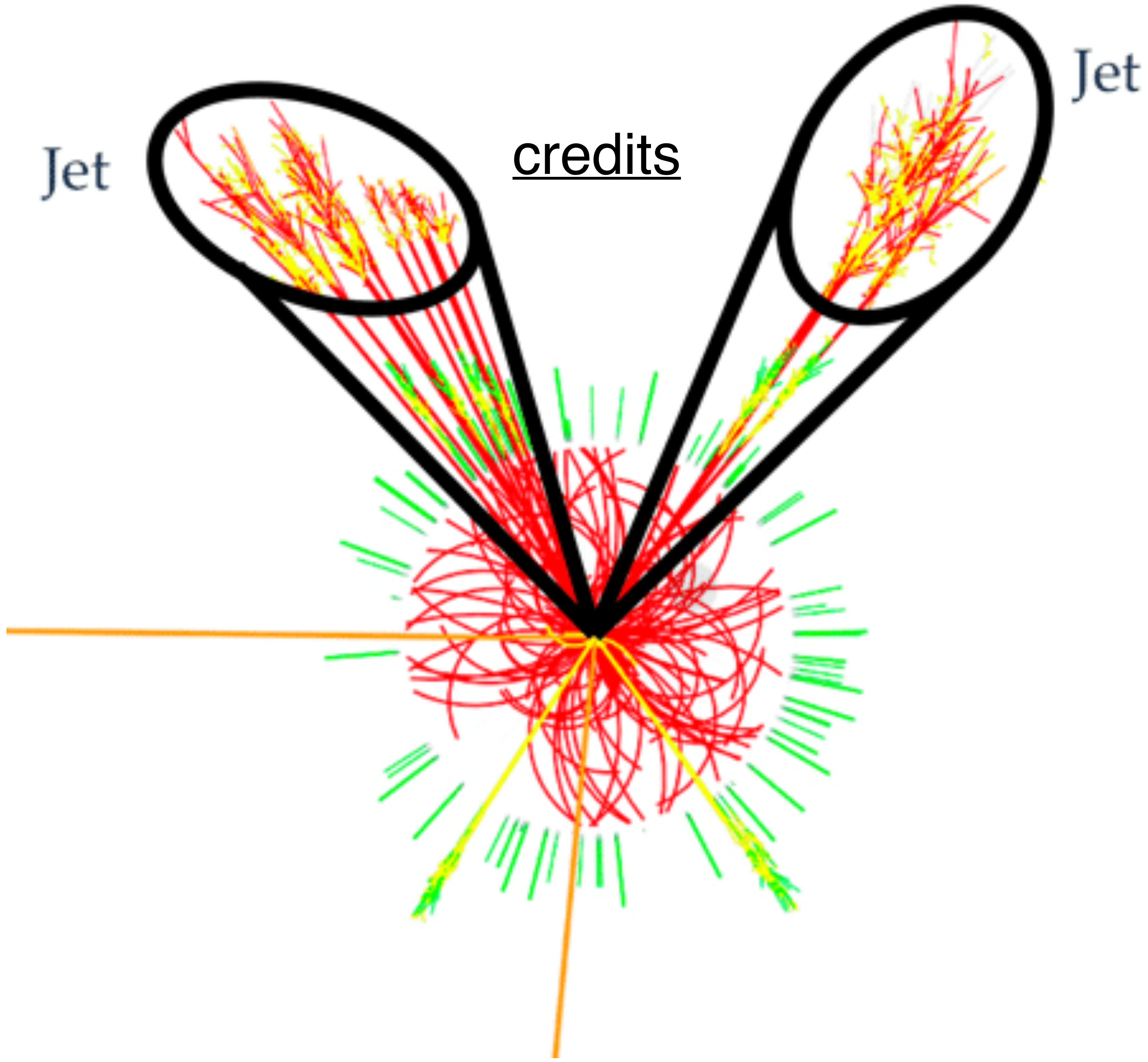




- Λ_c/D^0 shows an increase from **low multiplicity** to **high multiplicity**
- **large increase from e^+e^- to pp**

→ Significant modification of the fragmentation process already in pp collisions **driven by multiplicity**

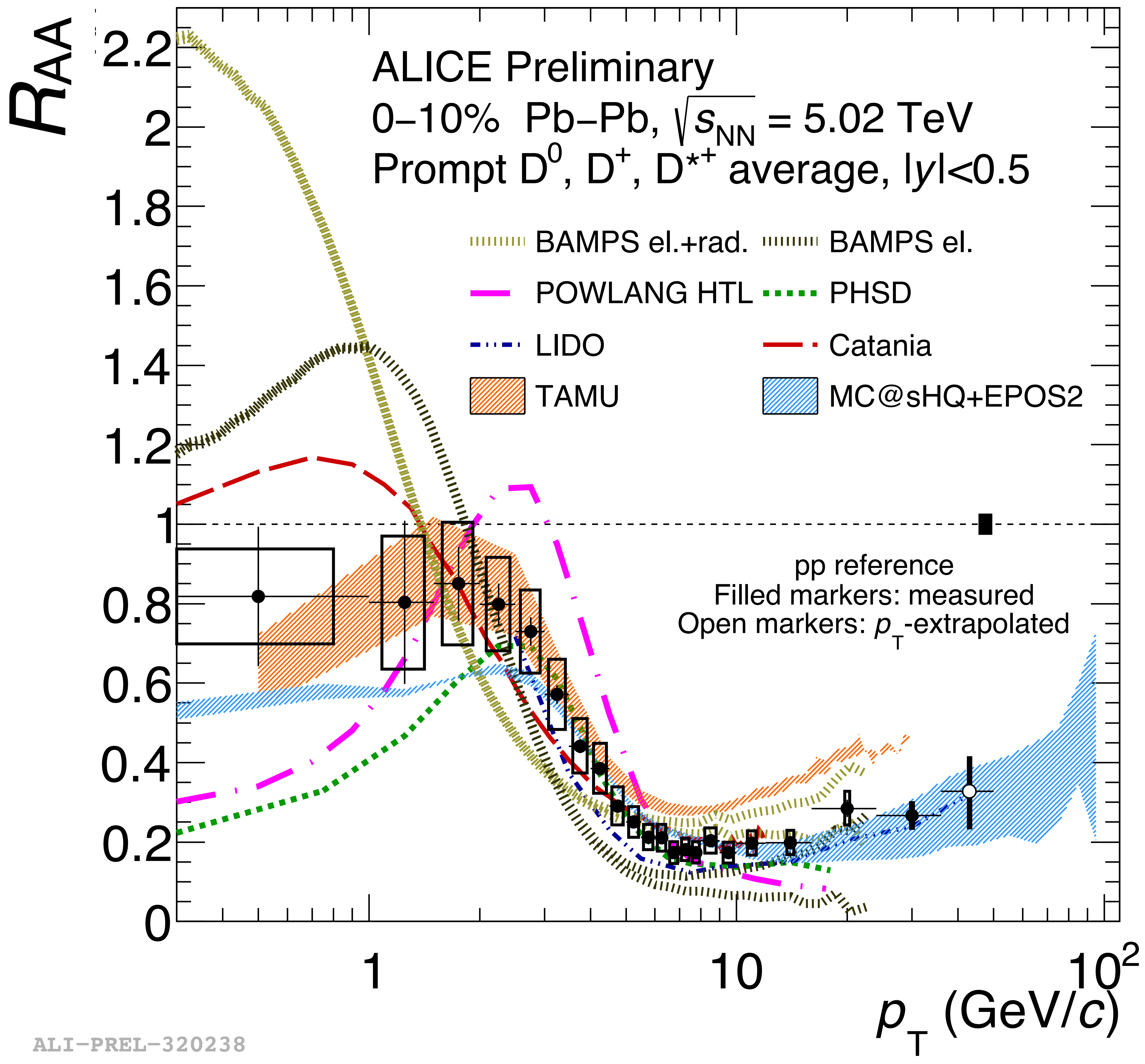
HF jets: a new dimension for HF studies



- More differential studies of quenching mechanisms in AA collisions
- Study hadronisation mechanisms with fragmentation functions
- **Substructure techniques** to study HF parton shower in vacuum and inside the QGP

D^0 R_{AA} in central Pb-Pb collisions

First measurement of charm production down to 0 GeV/*c*!

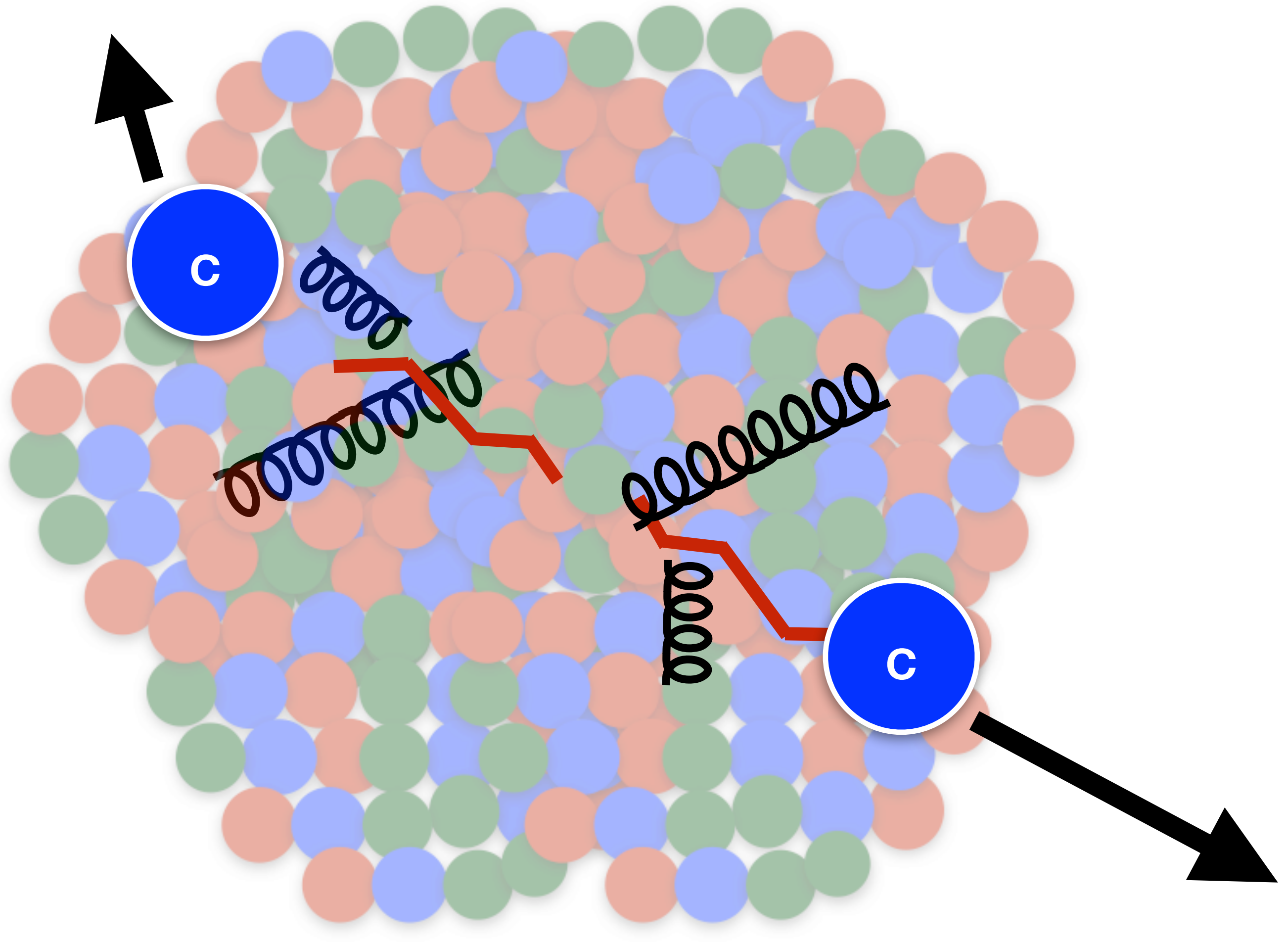


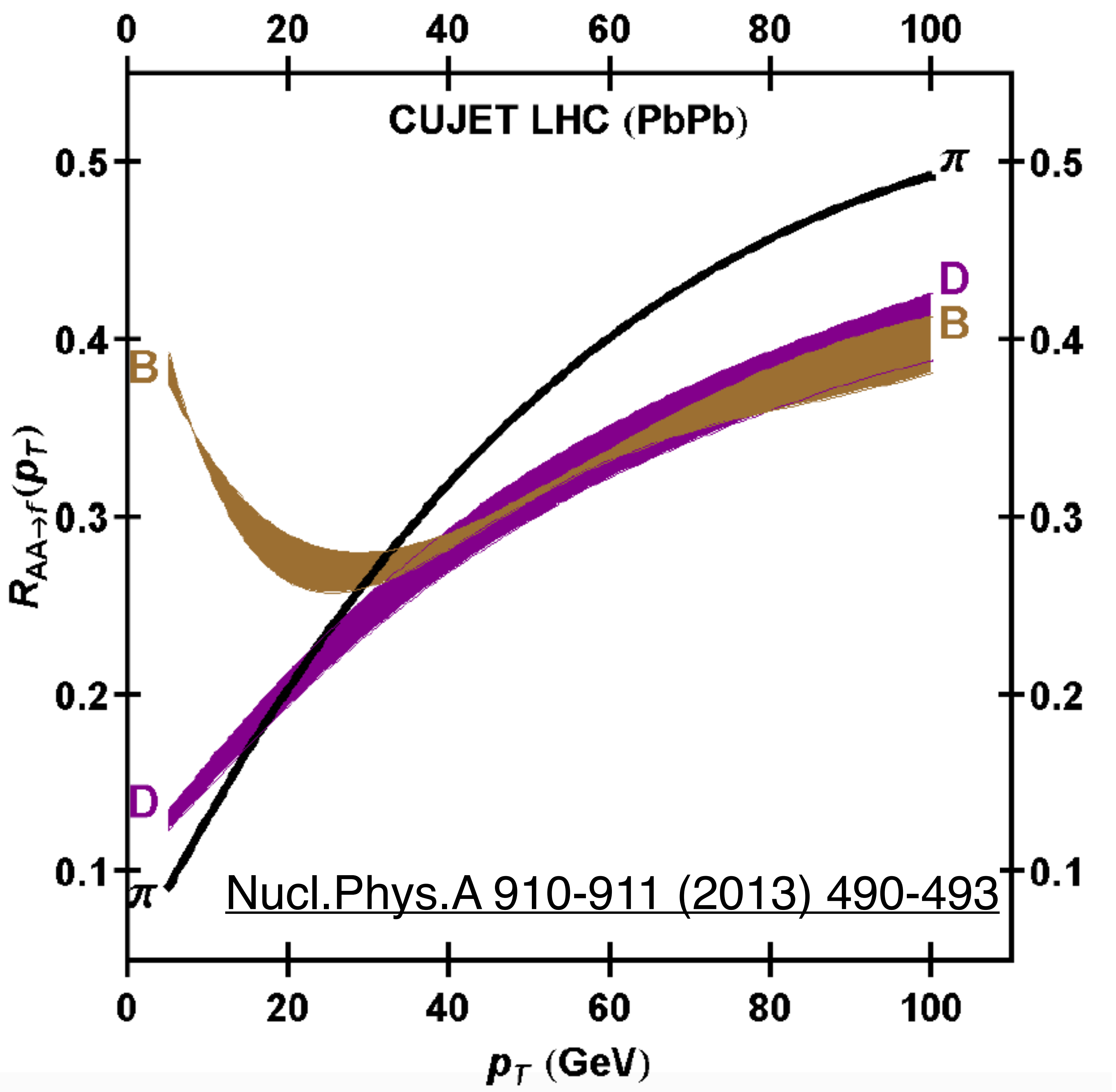
→ Strong experimental constraints on charm E_{loss} and initial state effects (e.g. shadowing)

→ New constraints on the total charm cross section at the LHC!

Flavour dependence of E_{loss}

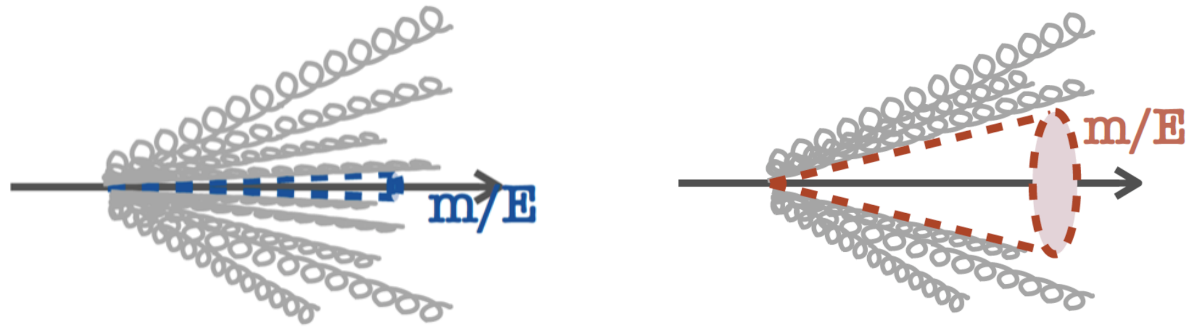
In-medium energy loss as a consequence of **radiative** and **collisional** processes.





Flavour dependence of radiative E_{loss}:

- **different Casimir factors** for quark and gluons
  $C_R = 3$ for gluons, $C_R = 4/3$ for quarks
- **dead cone effect:**

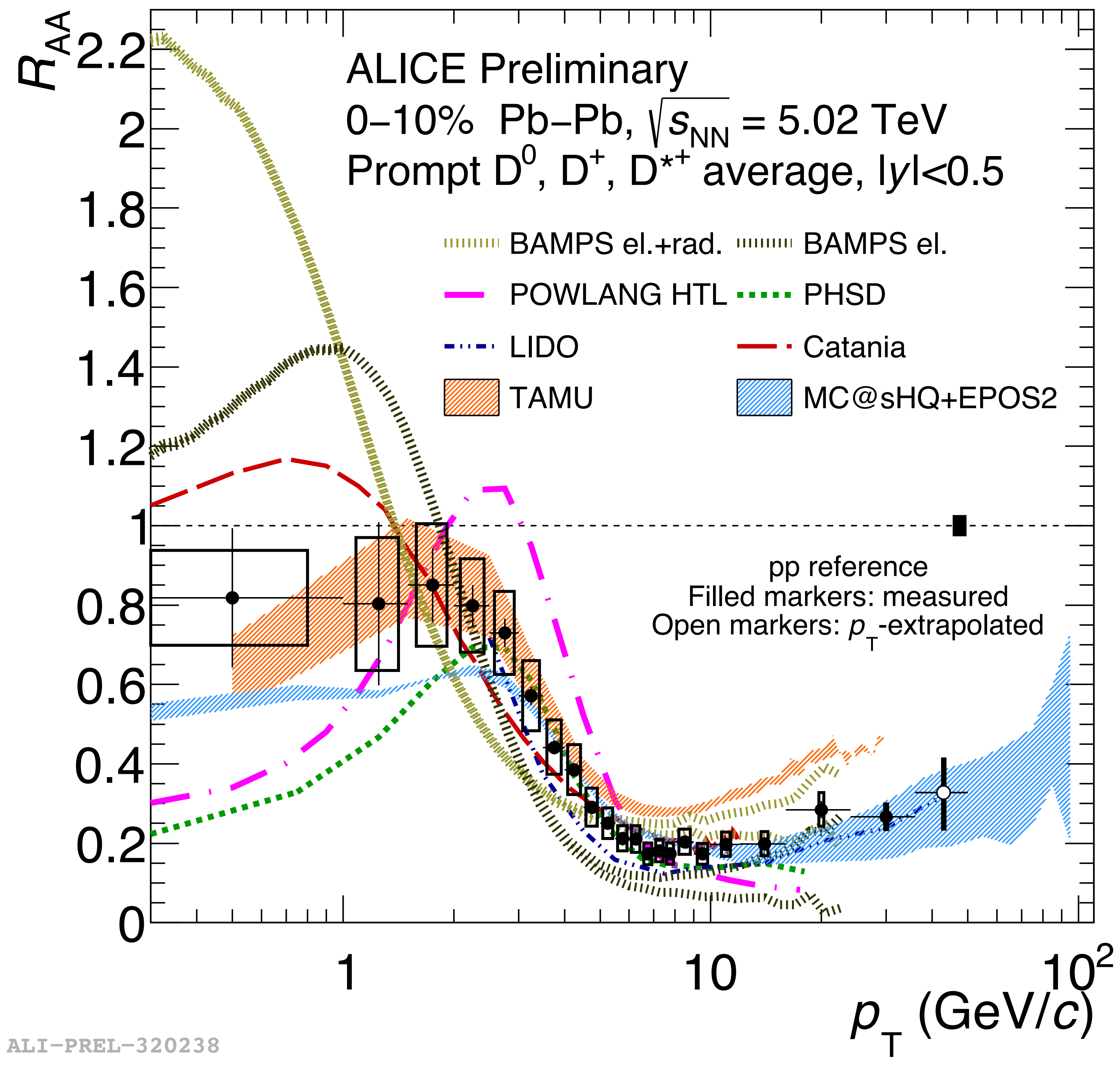


→ **E_{loss} (gluon) > E_{loss} (charm) > E_{loss} (beauty)**

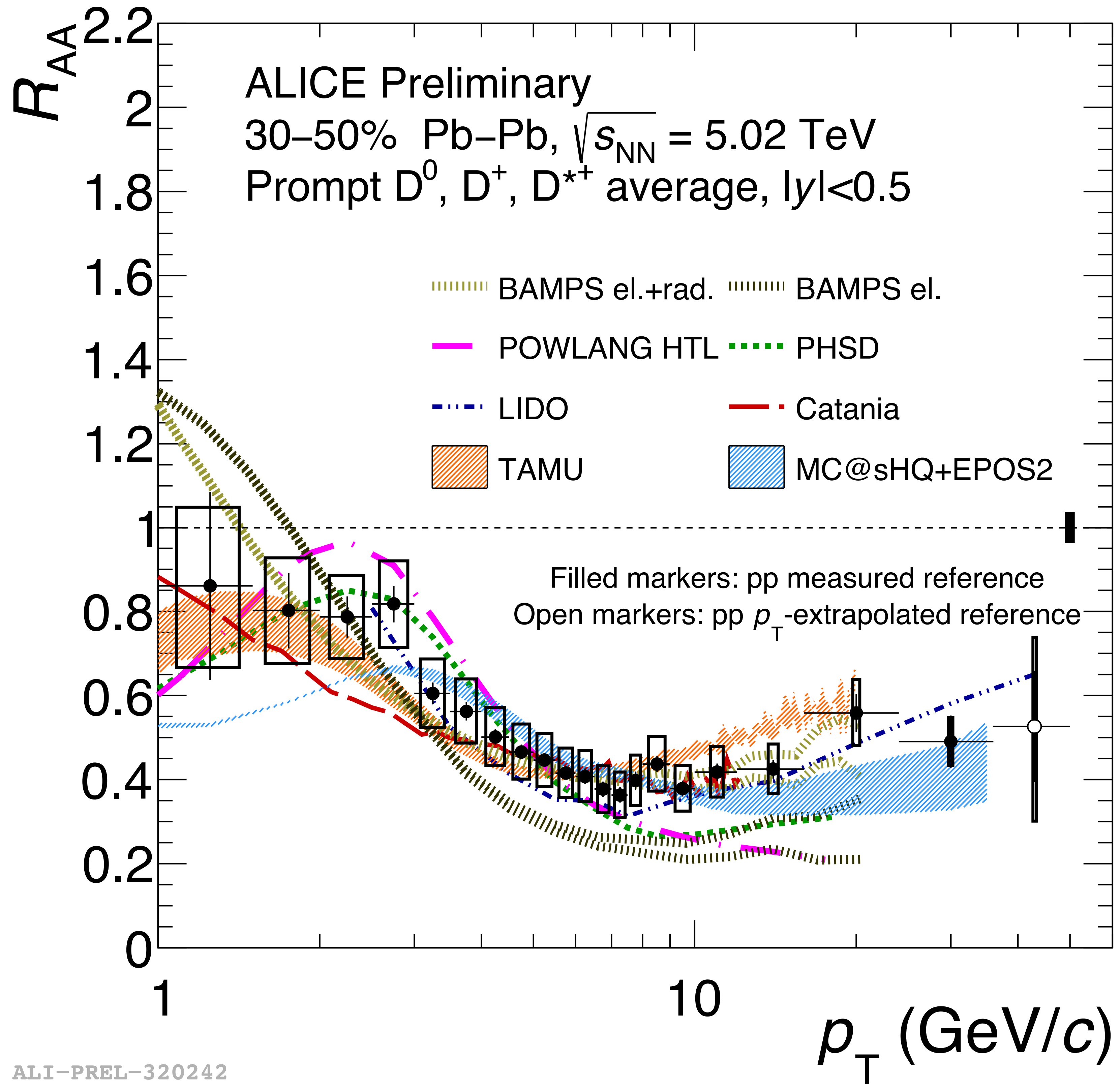
→ **R_{AA} (π) > R_{AA} (light) > E_{loss} (beauty)?**

D meson R_{AA} : comparison to models

Centrality 0-10%



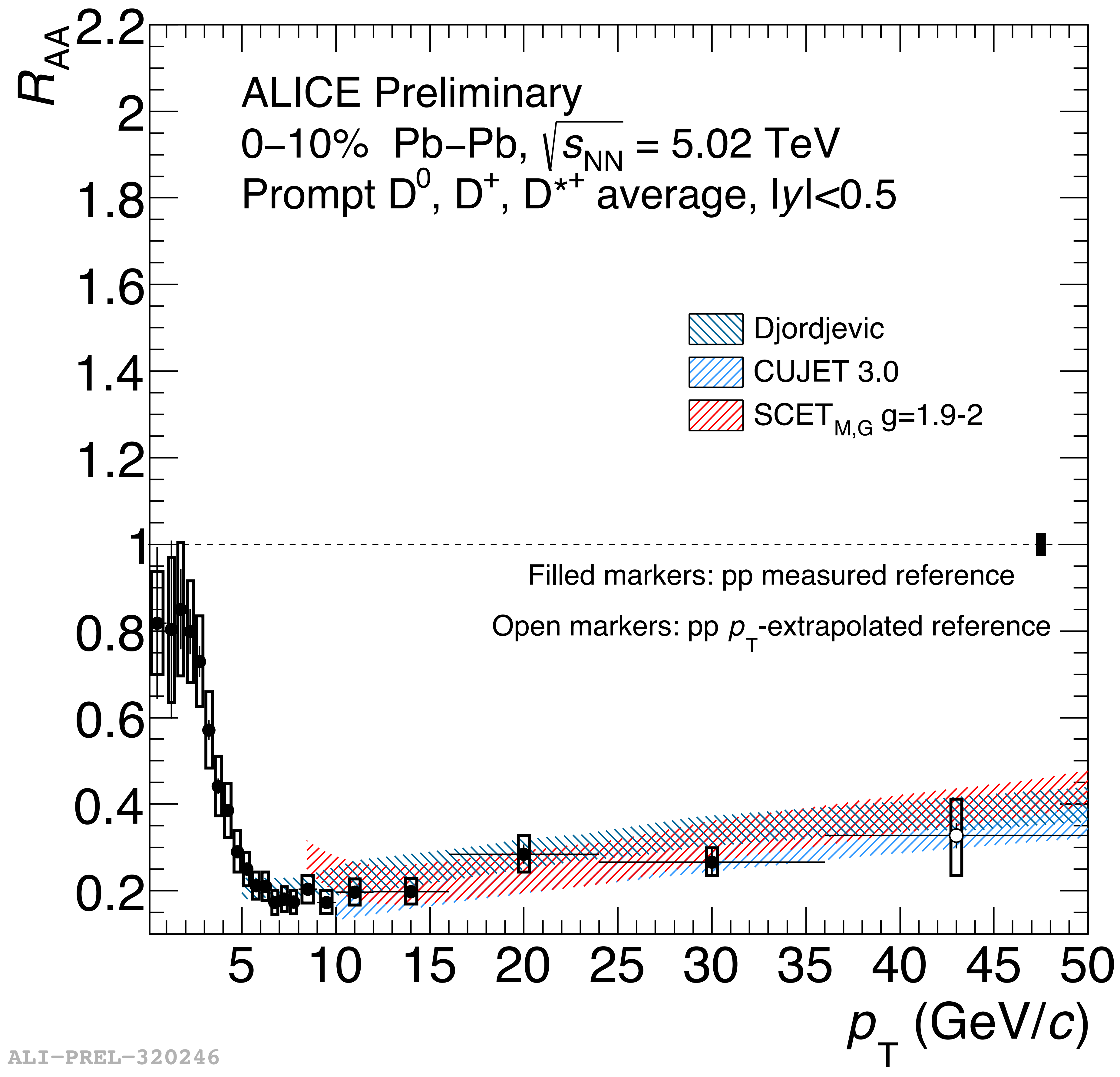
Centrality 30-50%

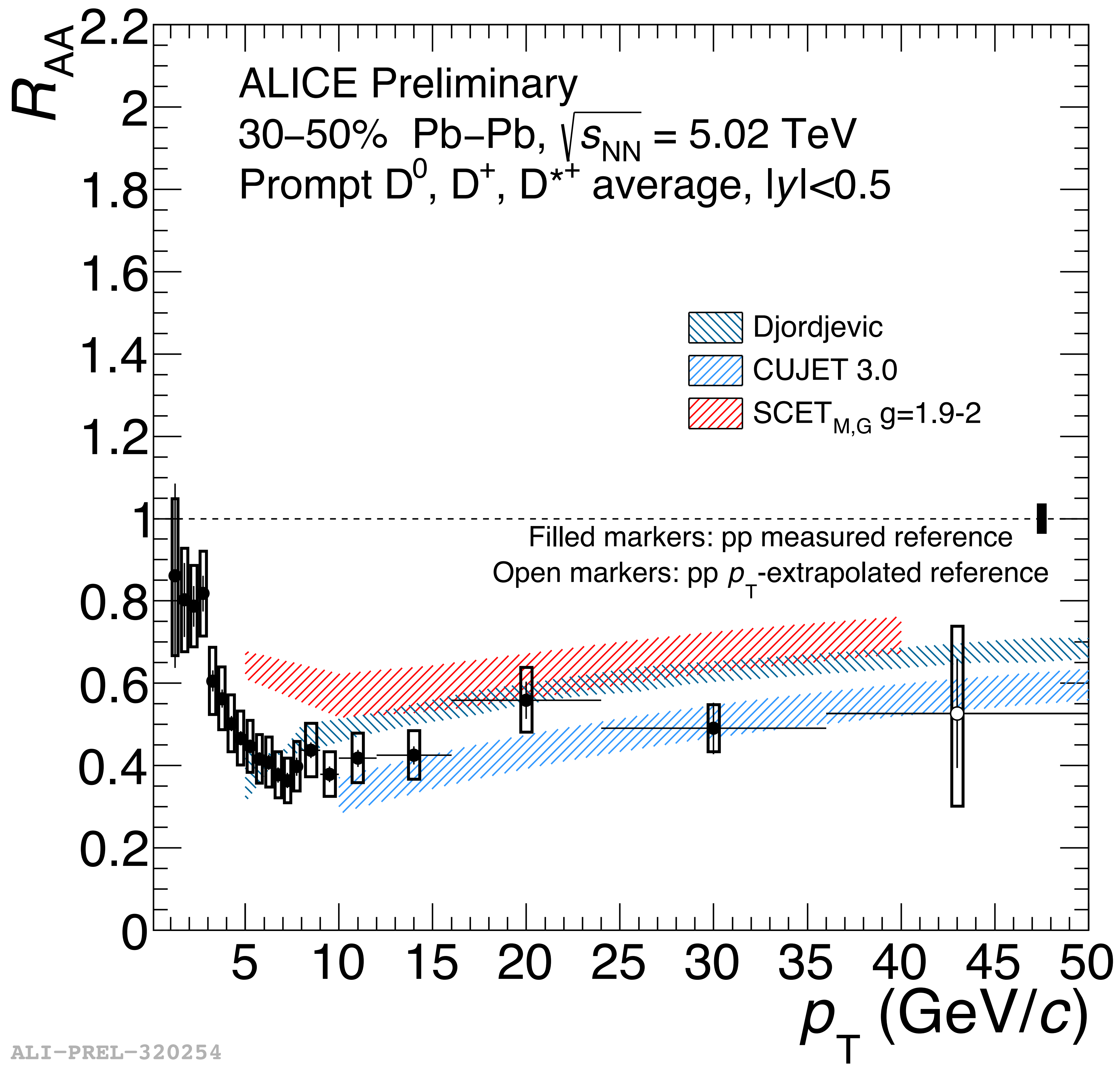


- Strong discrimination power at 0-1 GeV/c
- TAMU (Langevin) well describes the data from low to high p_T

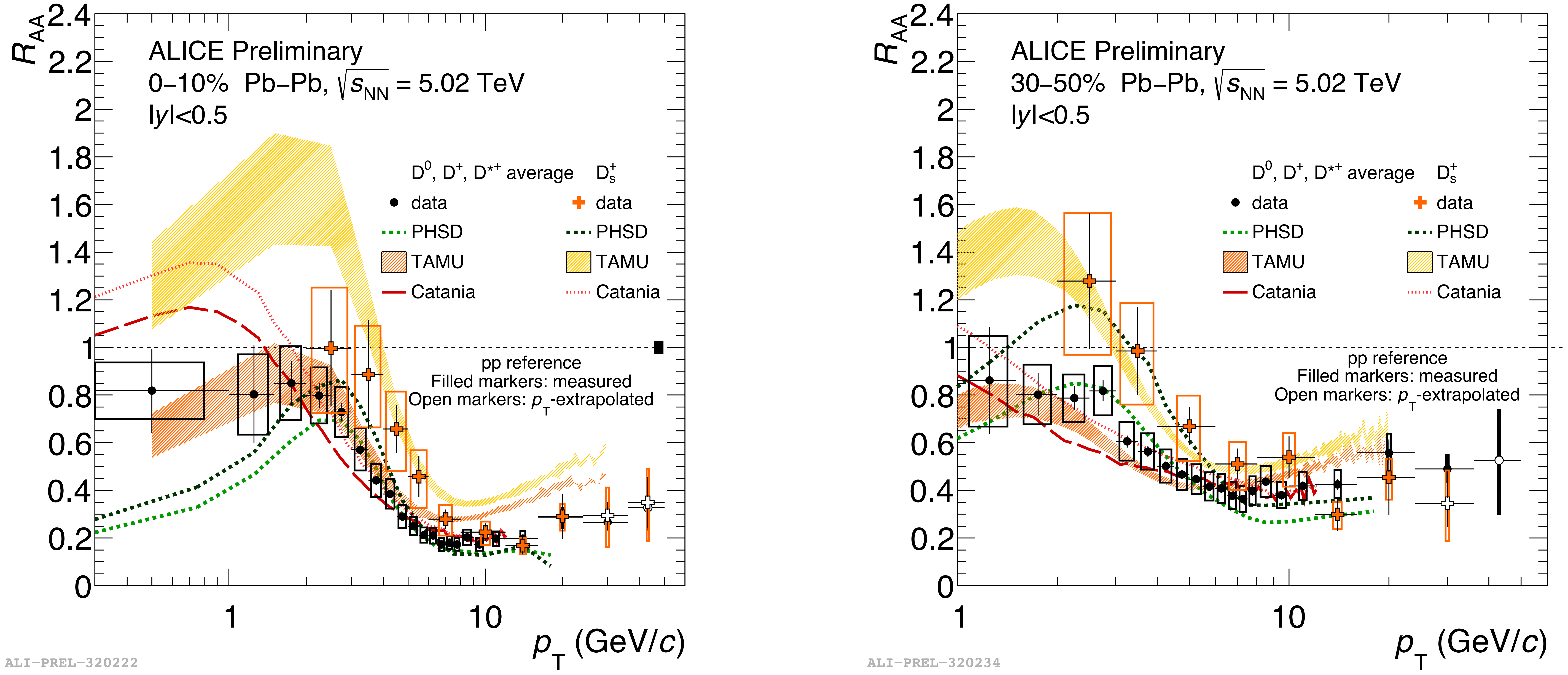
- In semi- peripheral events, most of the models show a good agreement with the data

D meson R_{AA} : comparison to models

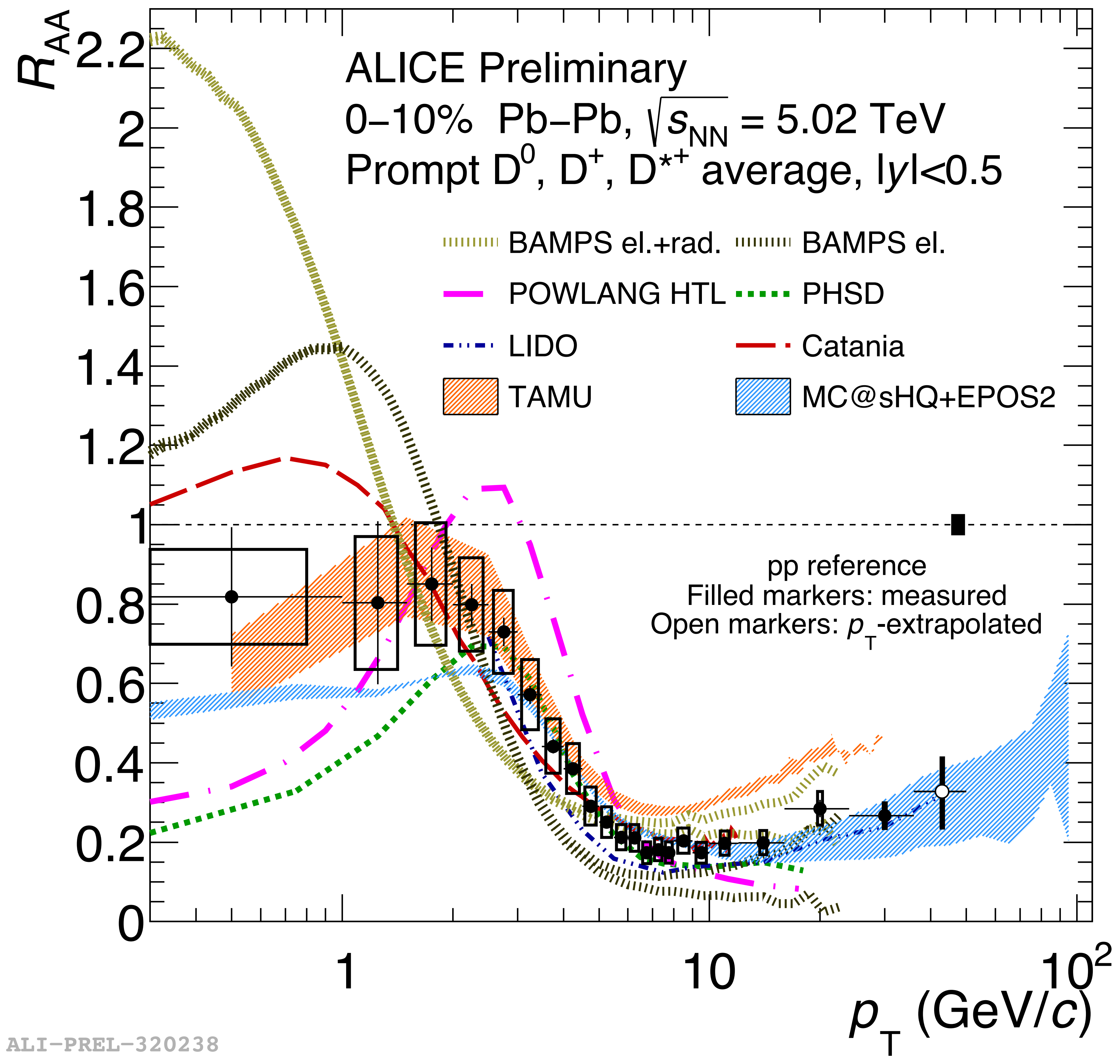




R_{AA} of D_s vs D^0 in central and peripheral Pb-Pb



D meson R_{AA} : comparison to models



BAMPS el. + rad., BAMPS el.:
- overestimate the low p_T region probably because of absence of PDF modification in nuclei (shadowing)
- In presence of radiative energy loss the Pb-Pb is pushed more at lower momenta and therefore the R_{AA} goes higher

TAMU:
- Good description of the low p_T region including very low p_T intervals thanks to EPS09 + shadowing.
- FONLL as production mechanisms helps having a proper initial p_T shape
- Description at high p_T suffers from missing radiative component

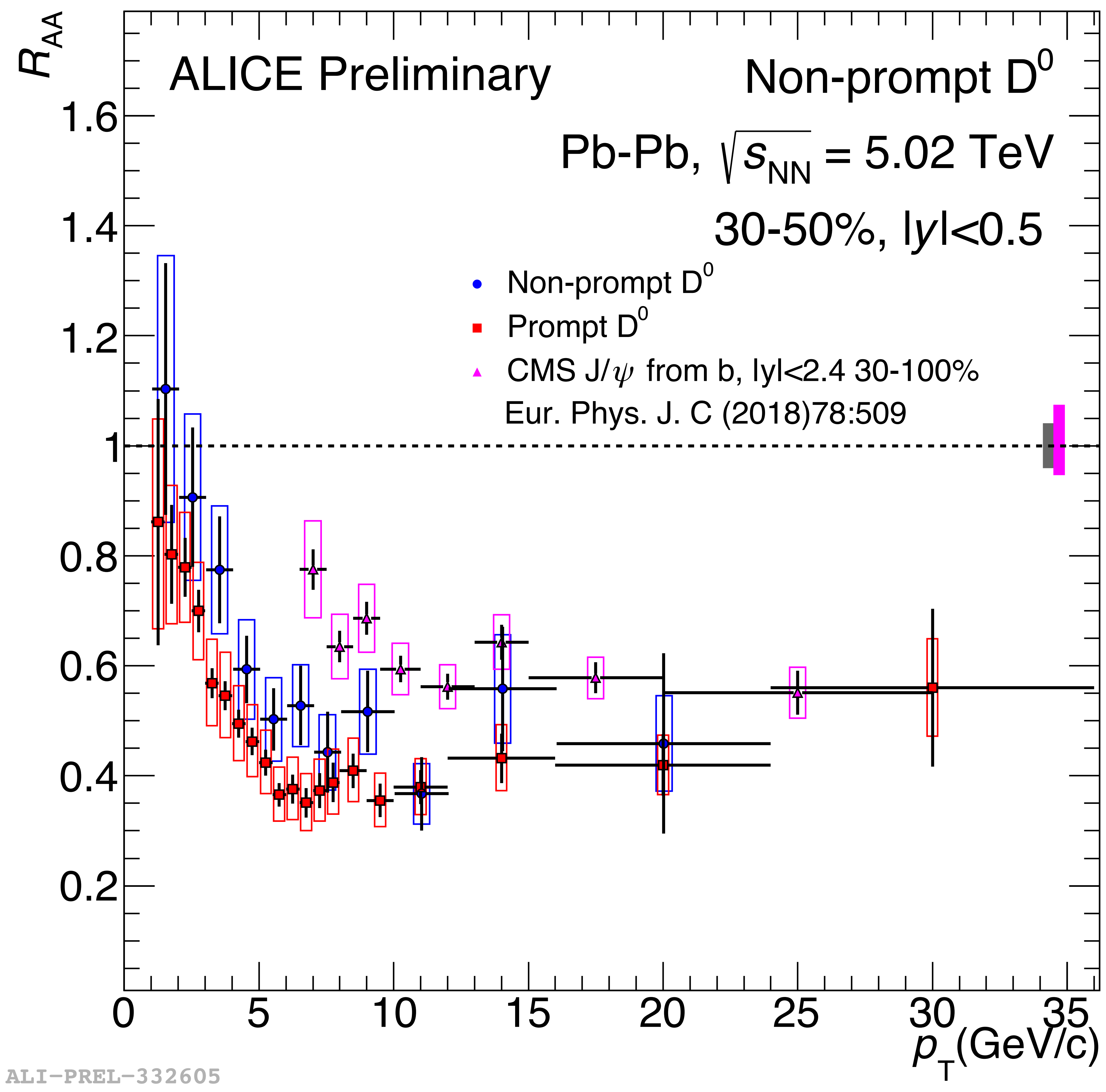
POWLANG:
- The R_{AA} shape is shifted at high p_T . Effect of different HQ production mechanisms?
- The effect of PDF modification is visible at low momenta where the R_{AA} decreases significantly, more than in TAMU
- At high p_T . The R_{AA} is smaller than data, which is surprising given that there is no radiative energy loss

Catania:
- Results similar to TAMU, but with a shift of the p_T spectrum (or R_{AA}) at lower p_T . Effects of the different recombination?

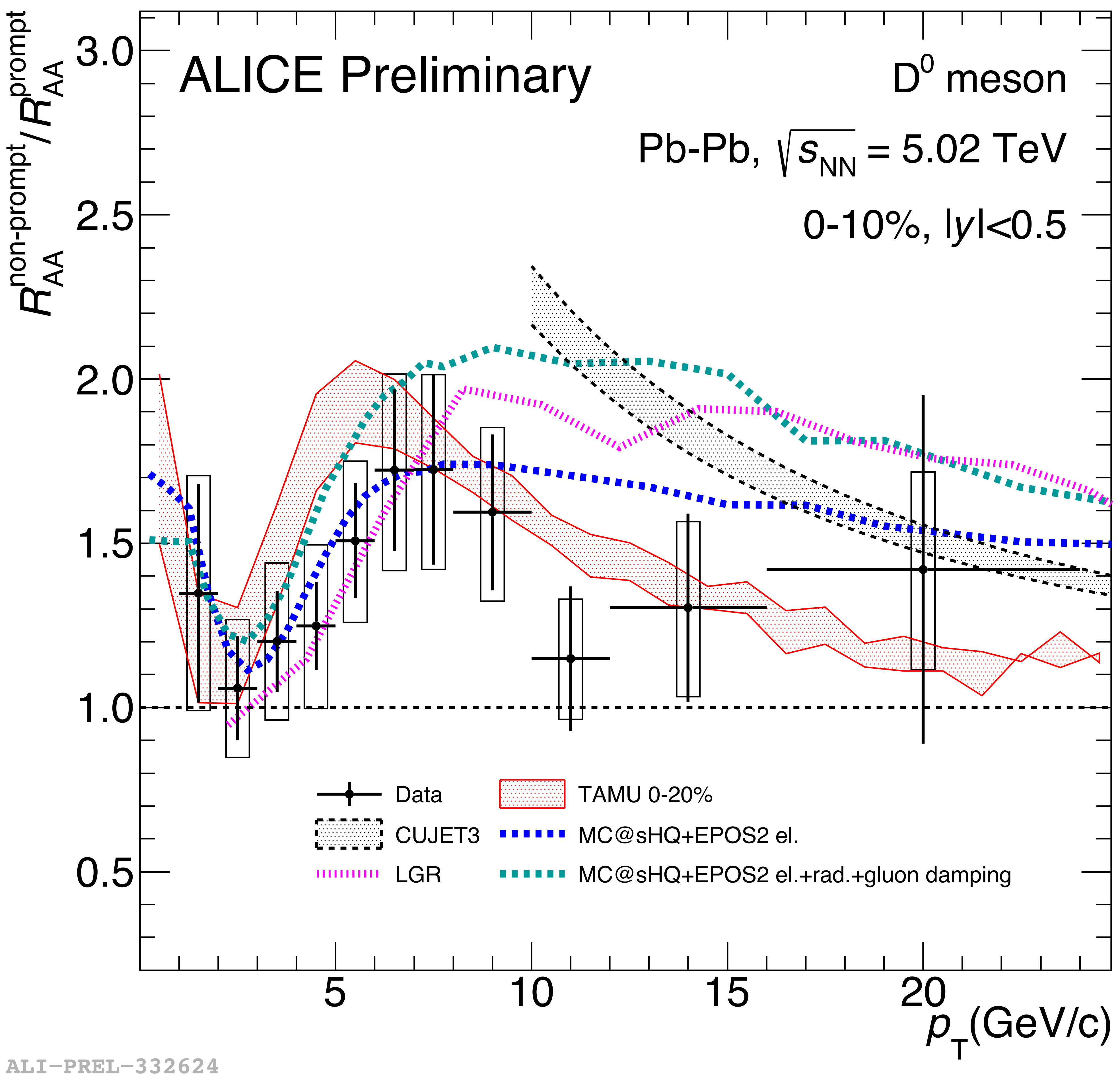
LIDO:
- Results similar to TAMU. Not available for the very low p_T region

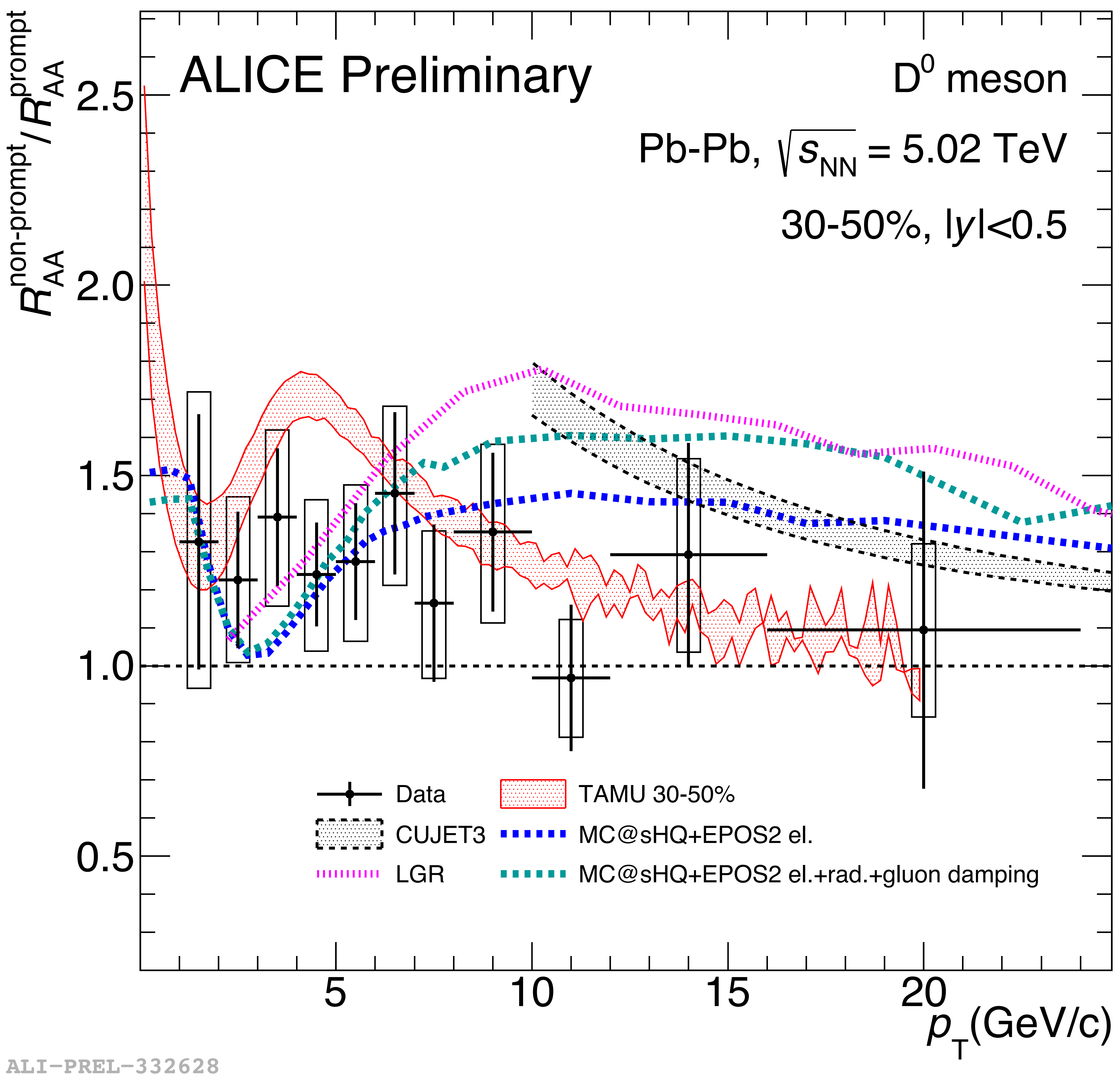
MC@sHQ+EPOS2:
- Pretty good agreement at high pT.
- Underestimate the low p_T region

non-prompt D^0 R_{AA} : comparison to CMS b→J/ψ



R_{AA} (prompt D^0) / R_{AA} (non-prompt D^0)

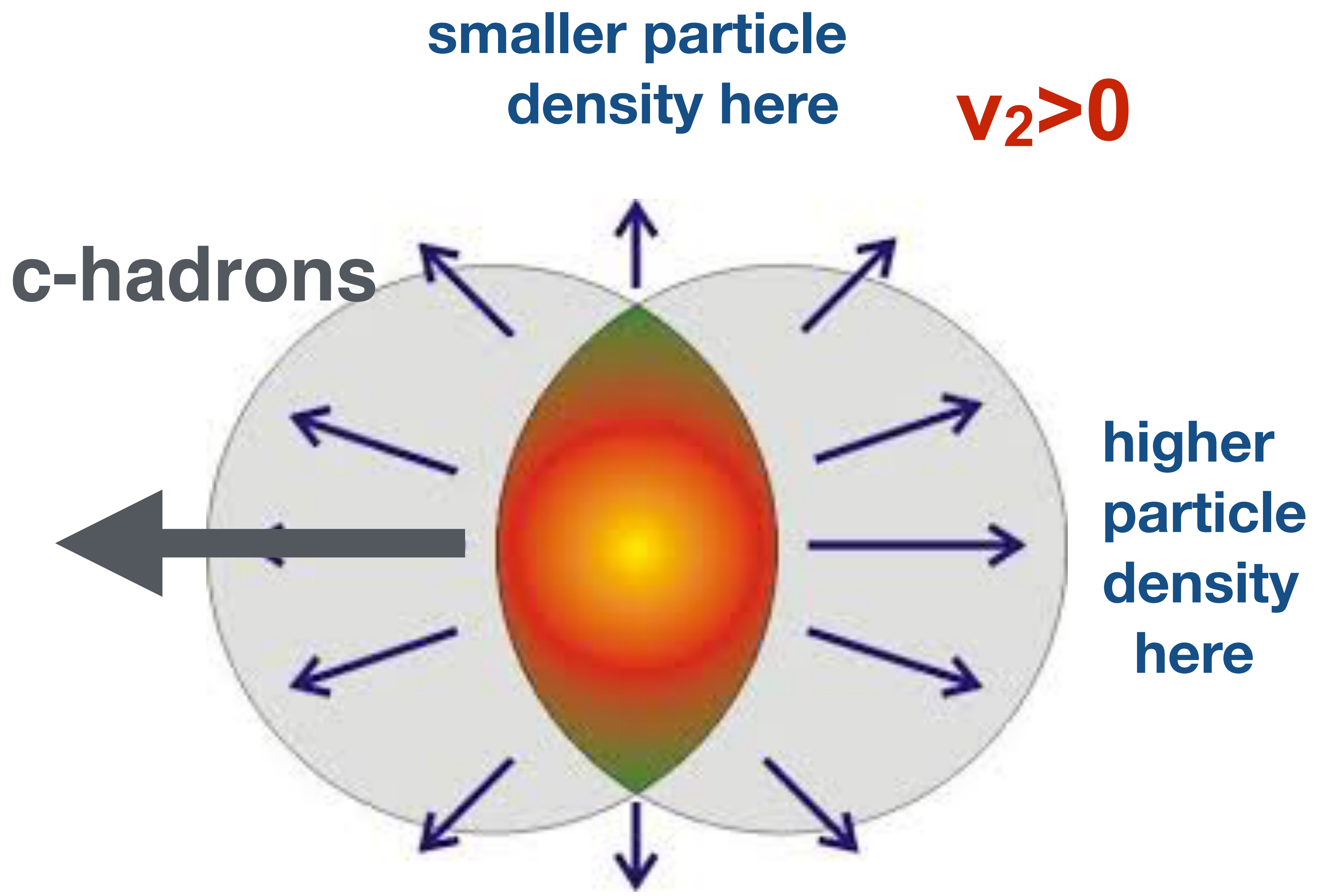


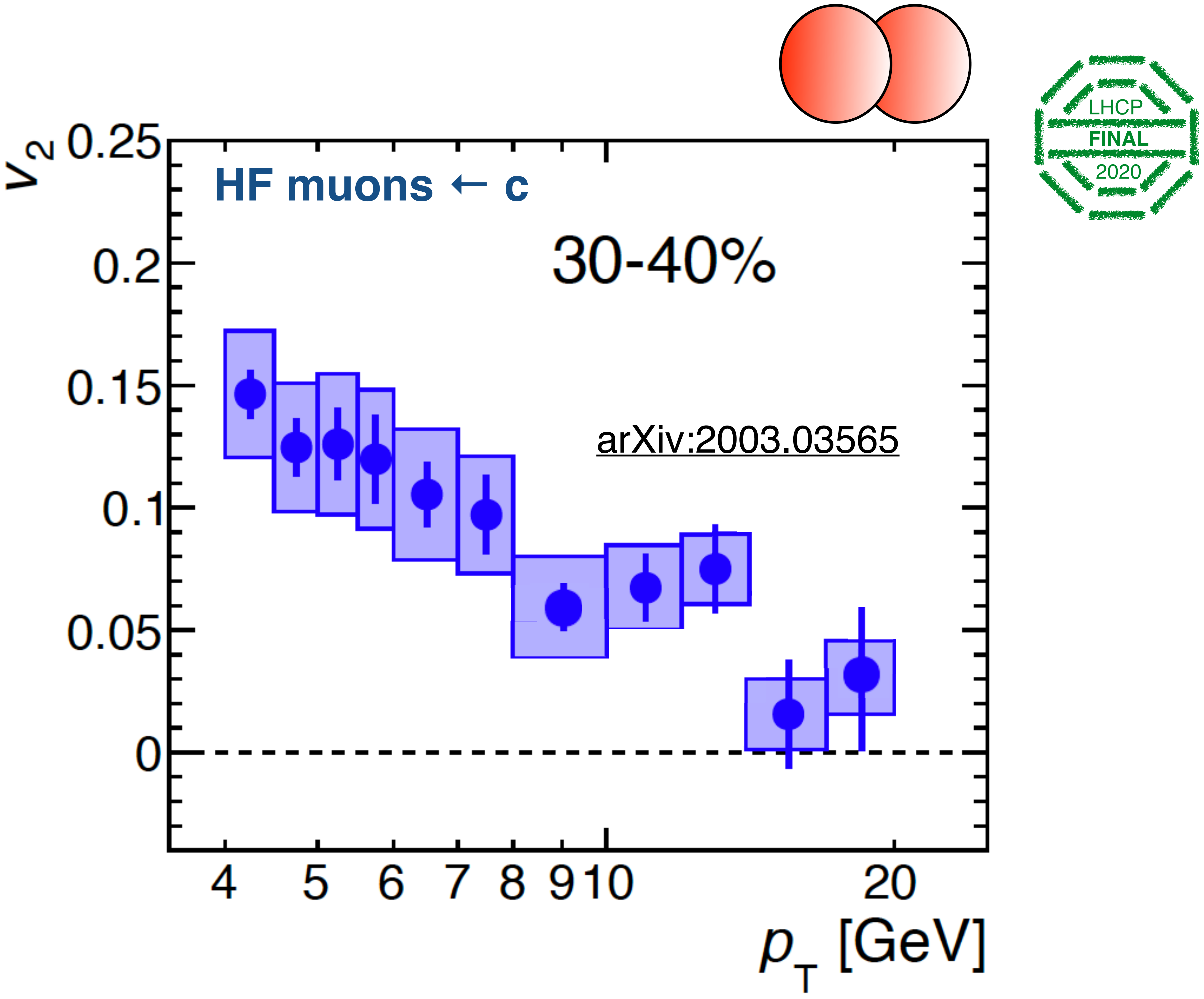


Overview of theoretical calculations

Model	HQ production	Medium modelling	Quark-medium interaction	HQ hadronisatio n	Tuning of medium coupling	References
BAMPS el.	MC@NL0 No PDF shadowing	3d+1 expansion parton cascade	Transport with Boltzmann rad. + coll.	Frag.	RHIC (then scaled by dN/ dη	https://arxiv.org/abs/1408.2964
TAMU	FONLL EPS09 (NLO) PDF shadowing	2d+1 expansion parton cascade	Transport with Langevin coll. only Diffusion in hadronic phase Improved space-mom correlation	Frag. + Rec.	Assume 1-QCD U potential	https://arxiv.org/abs/1401.3817
POWLANG	POWLANG EPS09 (NLO) PDF shadowing	2d+1 expansion with viscous fluido-dyn evolution	Transport with Langevin coll. only	Frag. + Rec.	Assume 1-QCD U potential	https://arxiv.org/abs/1410.6082
Catania	FONLL EPS09 (NLO) PDF shadowing	2d+1 expansion parton cascade	Transport with Langevin coll. only	Frag. + Rec. (different from TAMU?)	Assume 1-QCD U potential	https://arxiv.org/pdf/1712.00730.
LIDO	FONLL EPS09 (NLO) PDF shadowing	2d+1 rel. fluido-dynamics	Transport with Langevin + empirical transport coefficients to capture the non-perturbative part. (Boltzmann)	Frag. + Rec.	Coefficients fixed with Bayesian analysis to LHC D and B results	https://arxiv.org/pdf/1806.08848.

Charm and beauty “flow” in PbPb collisions





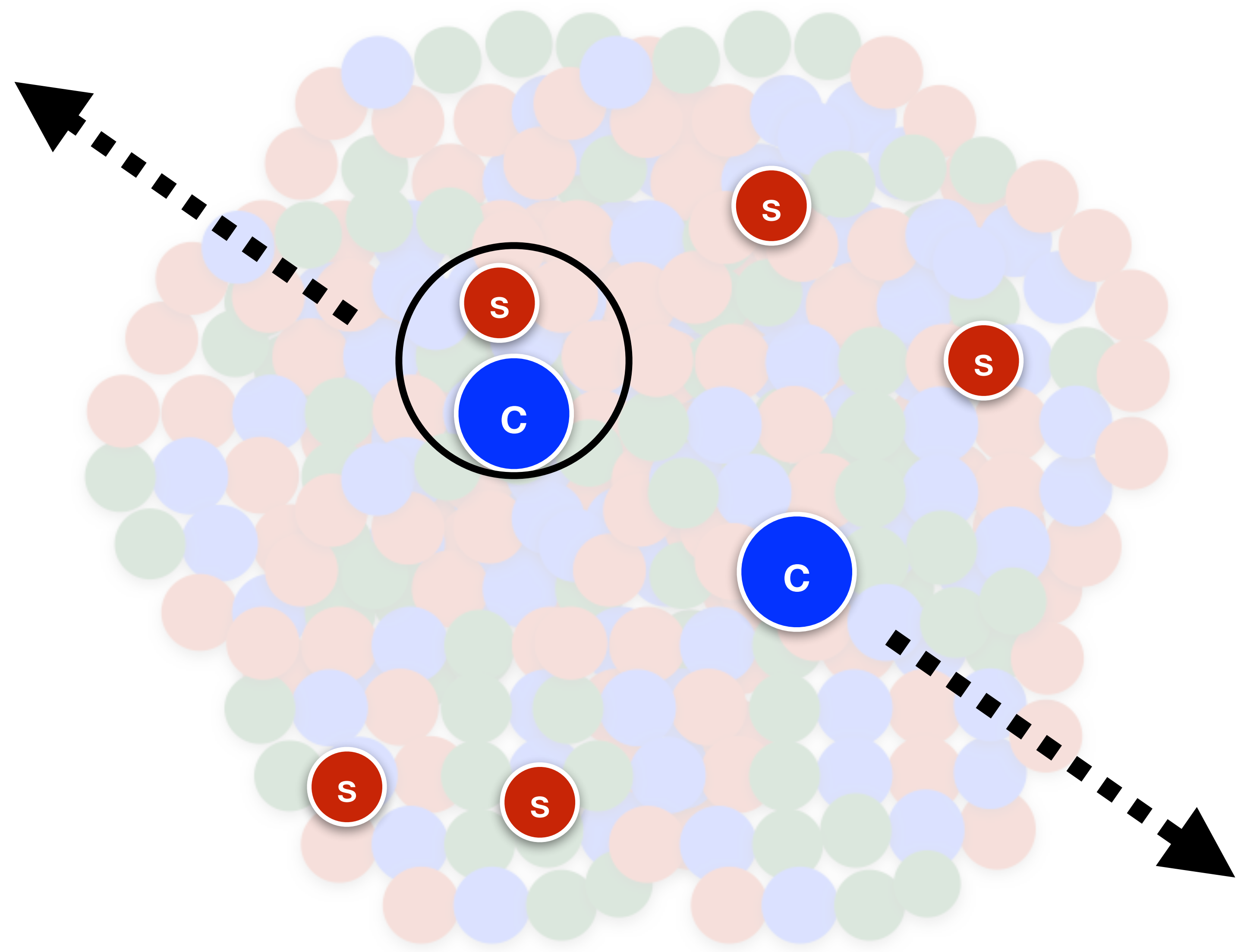
- v_2 significantly > 0 for HF muons ← c

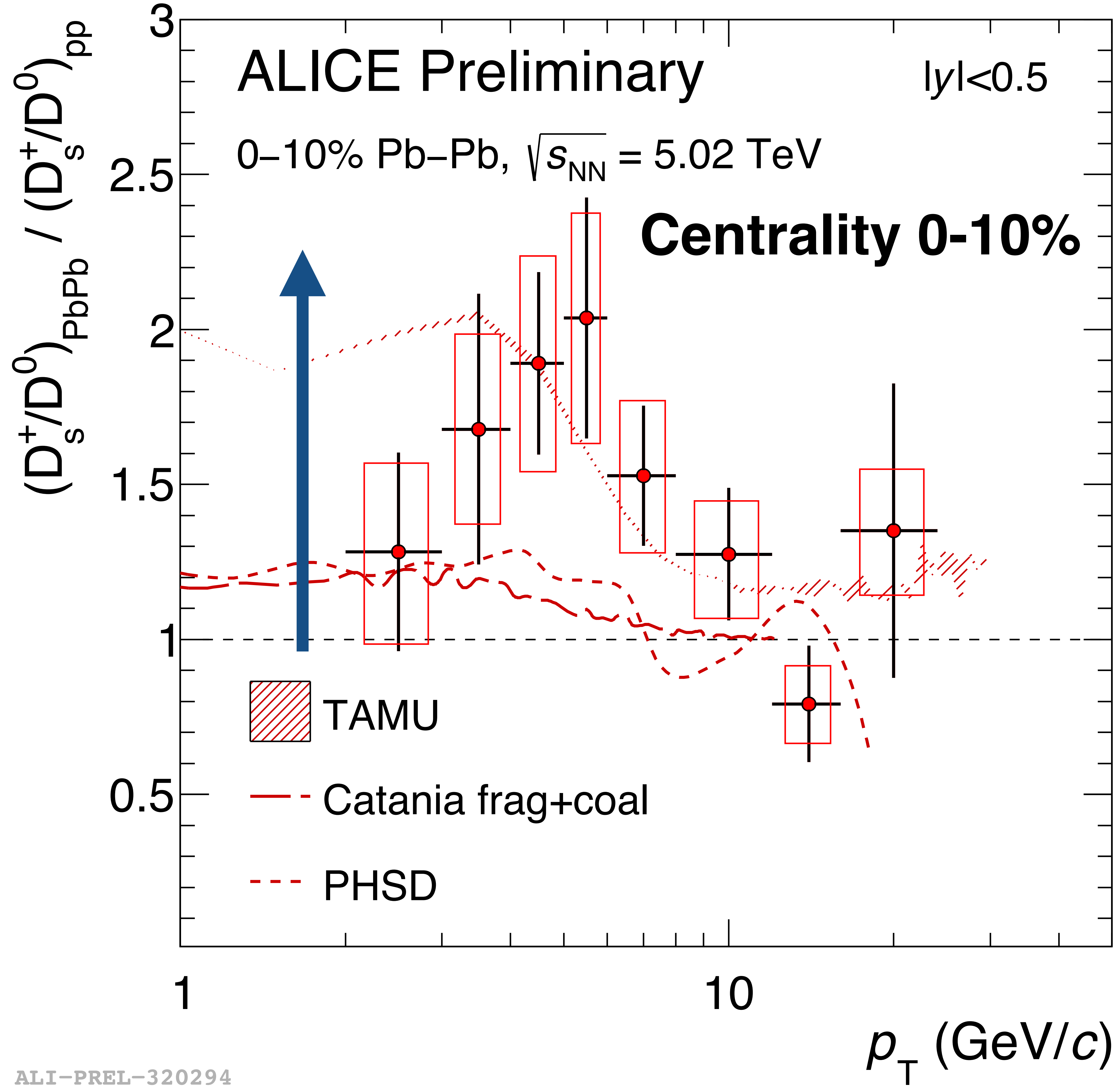
Overview of theoretical calculations

Model	HQ production	Medium modelling	Quark-medium interaction	HQ hadronisation	Tuning of medium coupling	References
PHSD	Pythia + string melting		Microscopic covariant transport Dynamical Quasiparticle Model	Local covariant transition rates		https://arxiv.org/pdf/1908.00451.
MC@ sHQ+ EPOS2	FONLL EPS09 (NLO) PDF shadowing	3d+1 expansion (EPOS model)	Transport with Boltzmann coll. (+rad when mentioned)	Frag. + Rec.	QGP transport coefficients fixed at LHC, adapted for RHIC	https://arxiv.org/abs/1305.6544
WHDG	FONLL no PDF shadowing	Glauber model nuclear overlap No fluido-dyn evol.	rad. + coll.	Frag.	RHIC (then scaled by dN/dη	
Vitev et al.	Non-zero mass VFNS no PDF shadowing	Glauber model nuclear overlap Ideal fluido-dyn Bjorken expansion	rad. + coll. In medium meson dissociation	Frag.	RHIC (then scaled by dN/dη	
CUJET3		Semi quark gluon monopole plasma	rad.	Frag.	Model parameters tuned on light flavour data	https://arxiv.org/abs/1704.04577

D_s/D^0 as a test for recombination

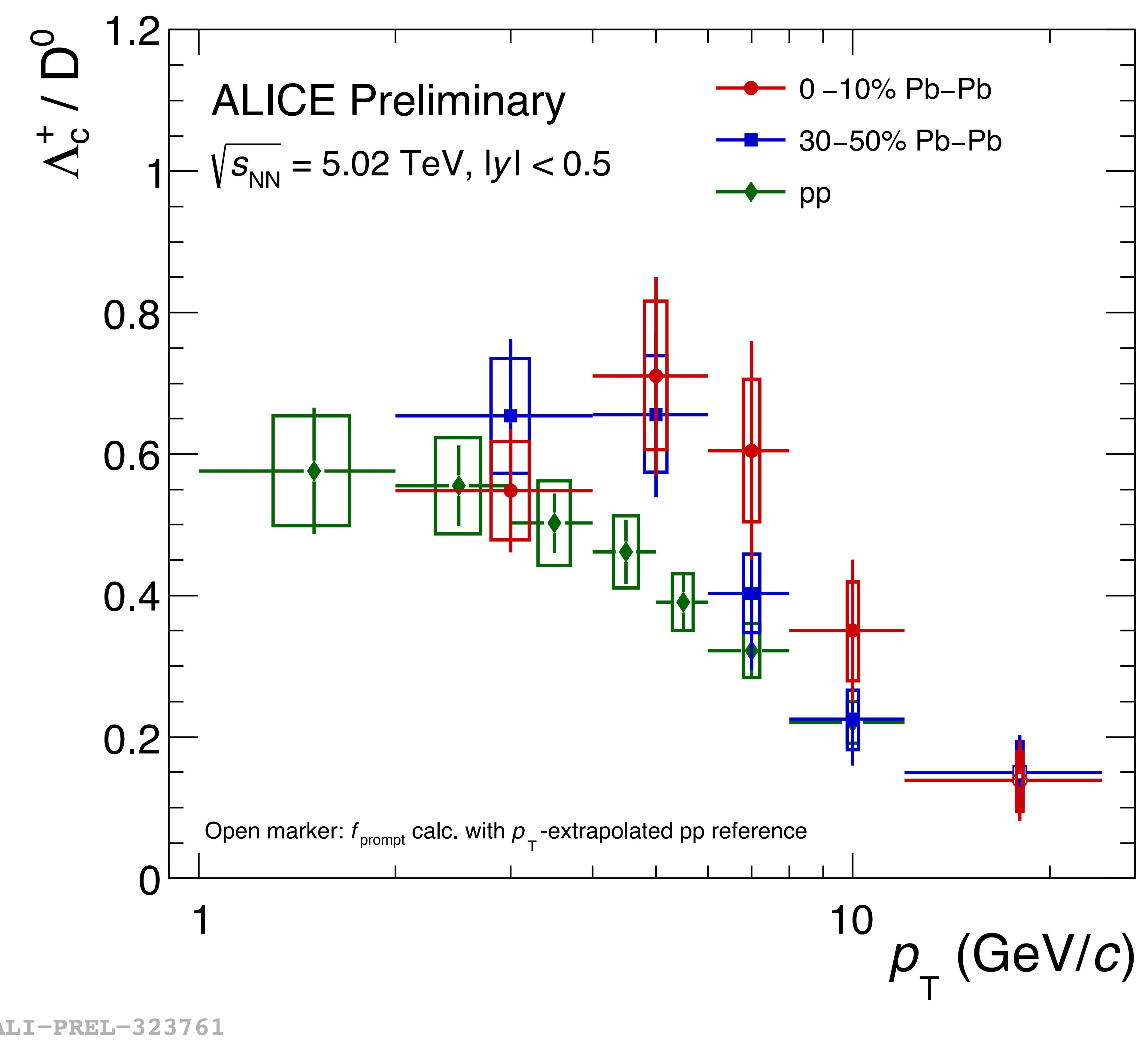
D_s/D^0 to be enhanced in Pb-Pb vs pp in presence of charm recombination and strangeness enhancement

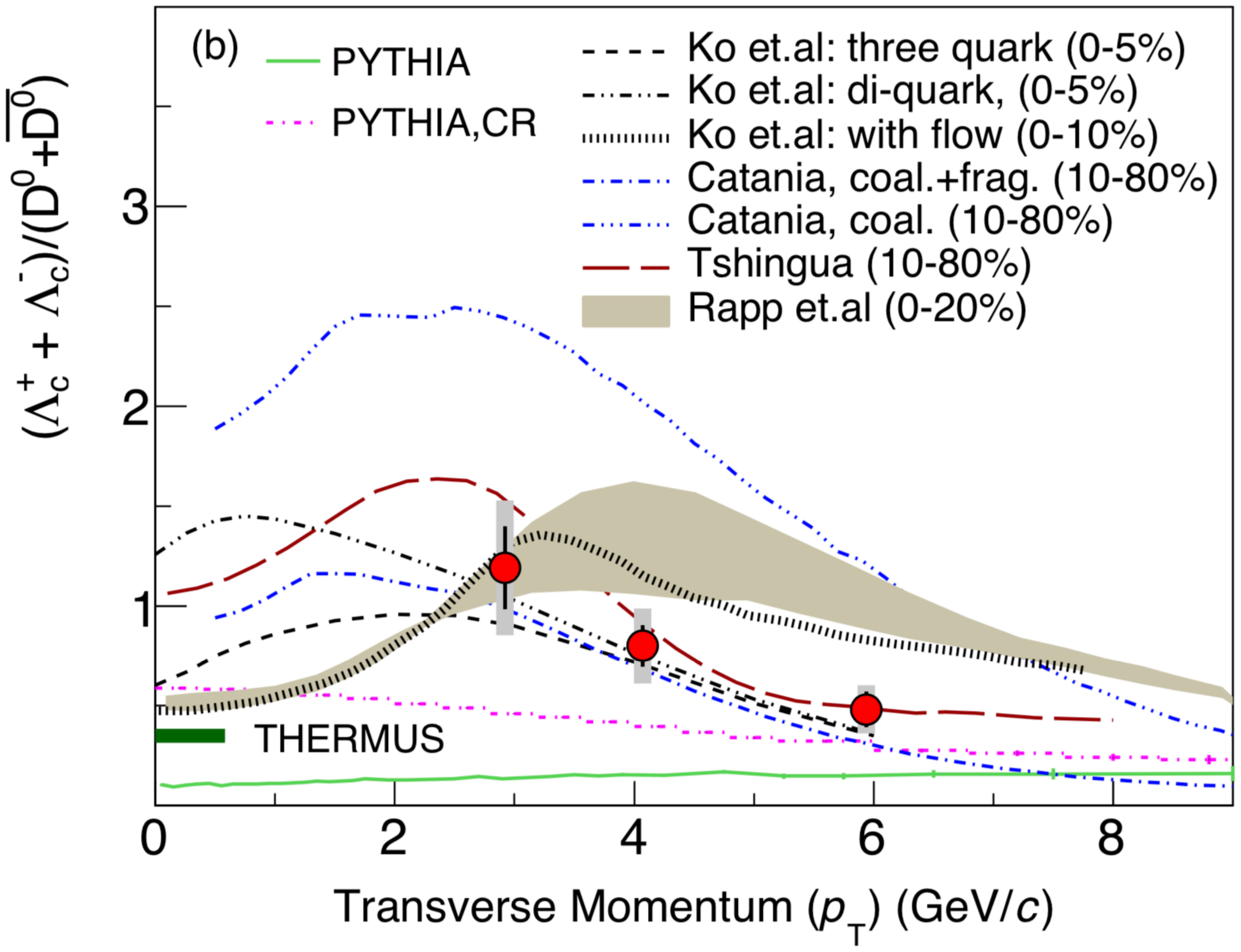




→ Relevant contribution of coalescence in charm hadronisation in Pb-Pb

Comparison to Λ_c/D^0 ratio from STAR

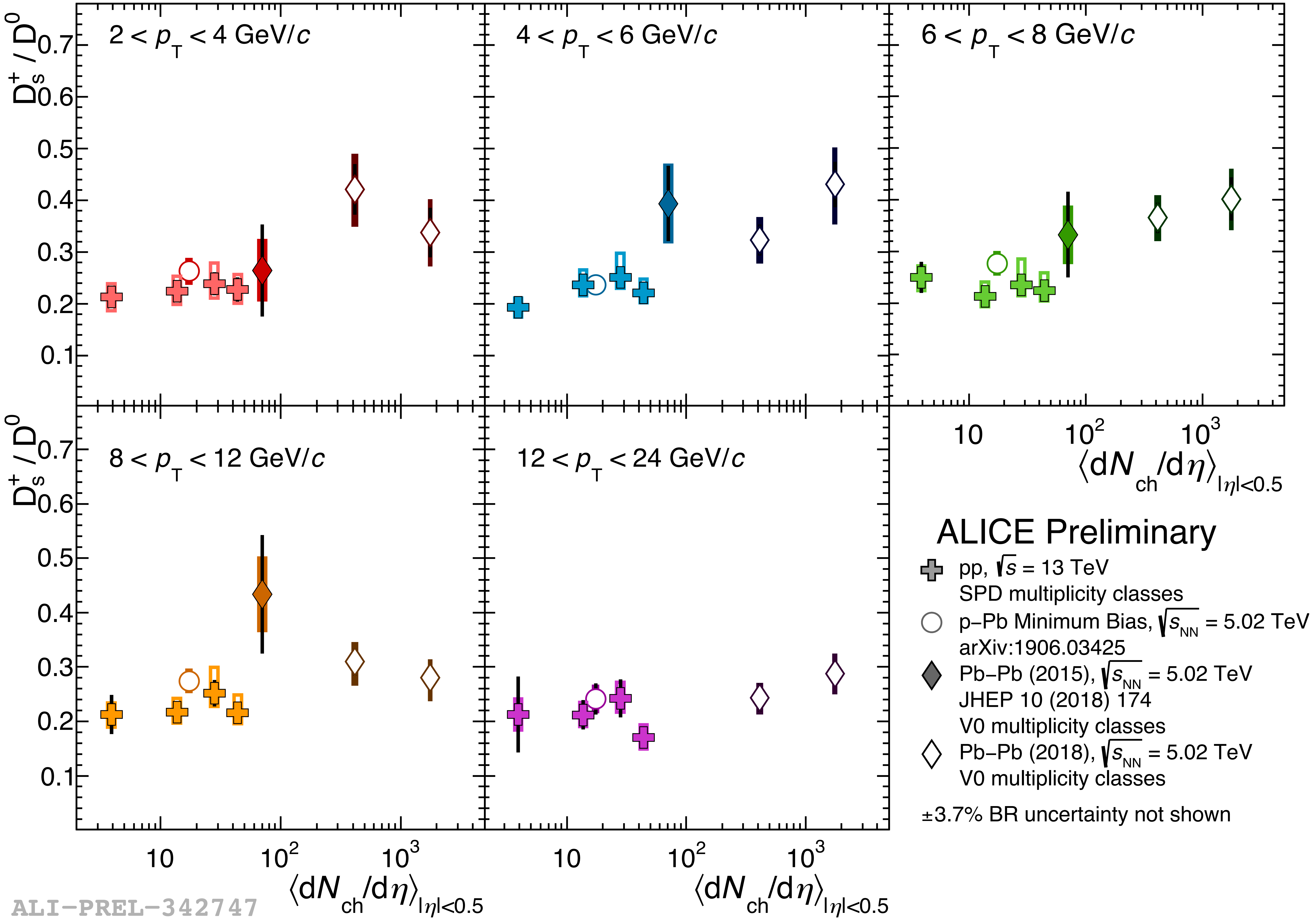




arXiv 1910.14628v1

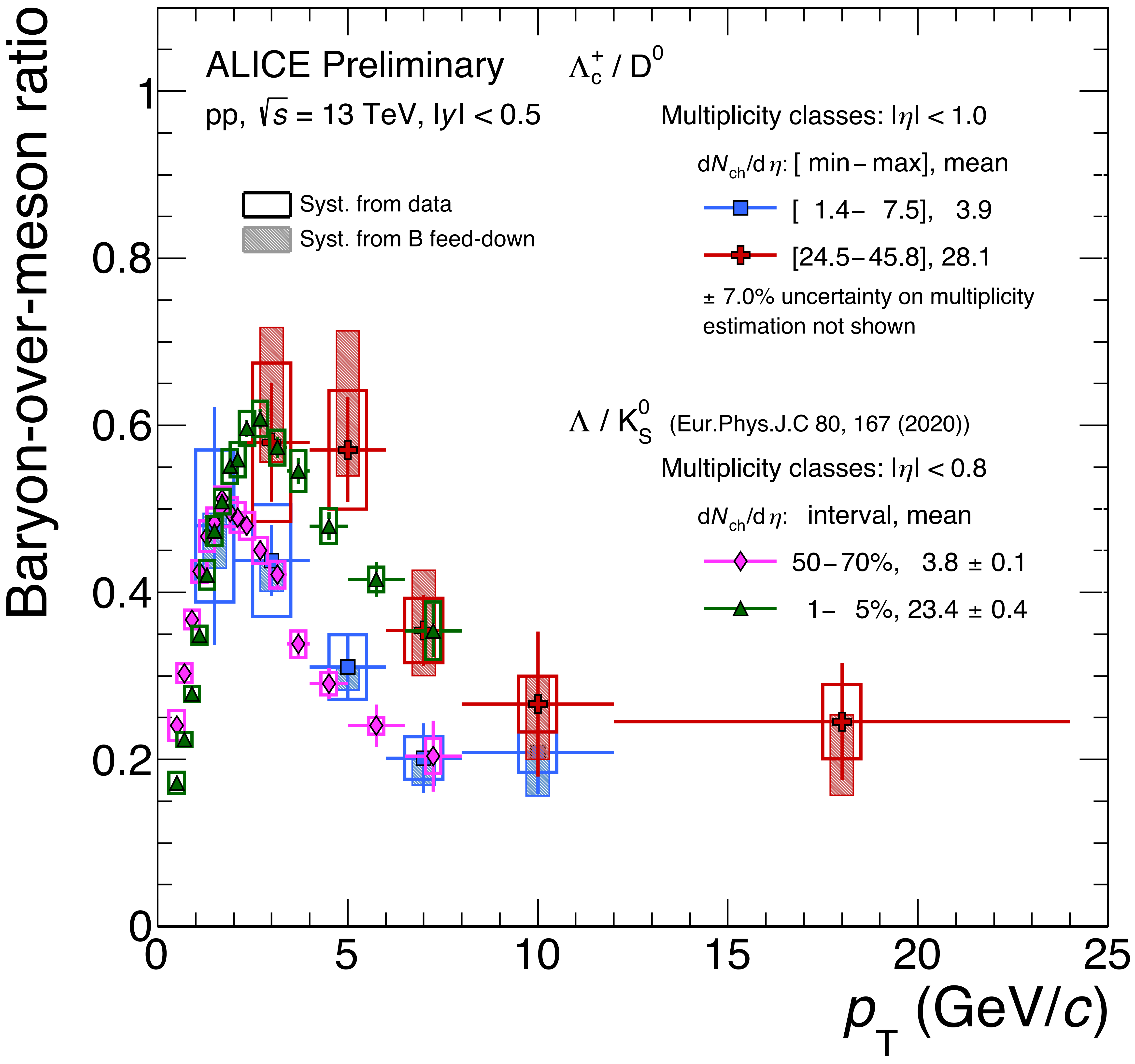
D_s/D^0 in pp collisions vs multiplicity

Can we observe D_s/D^0 enhancement in high multiplicity collisions?

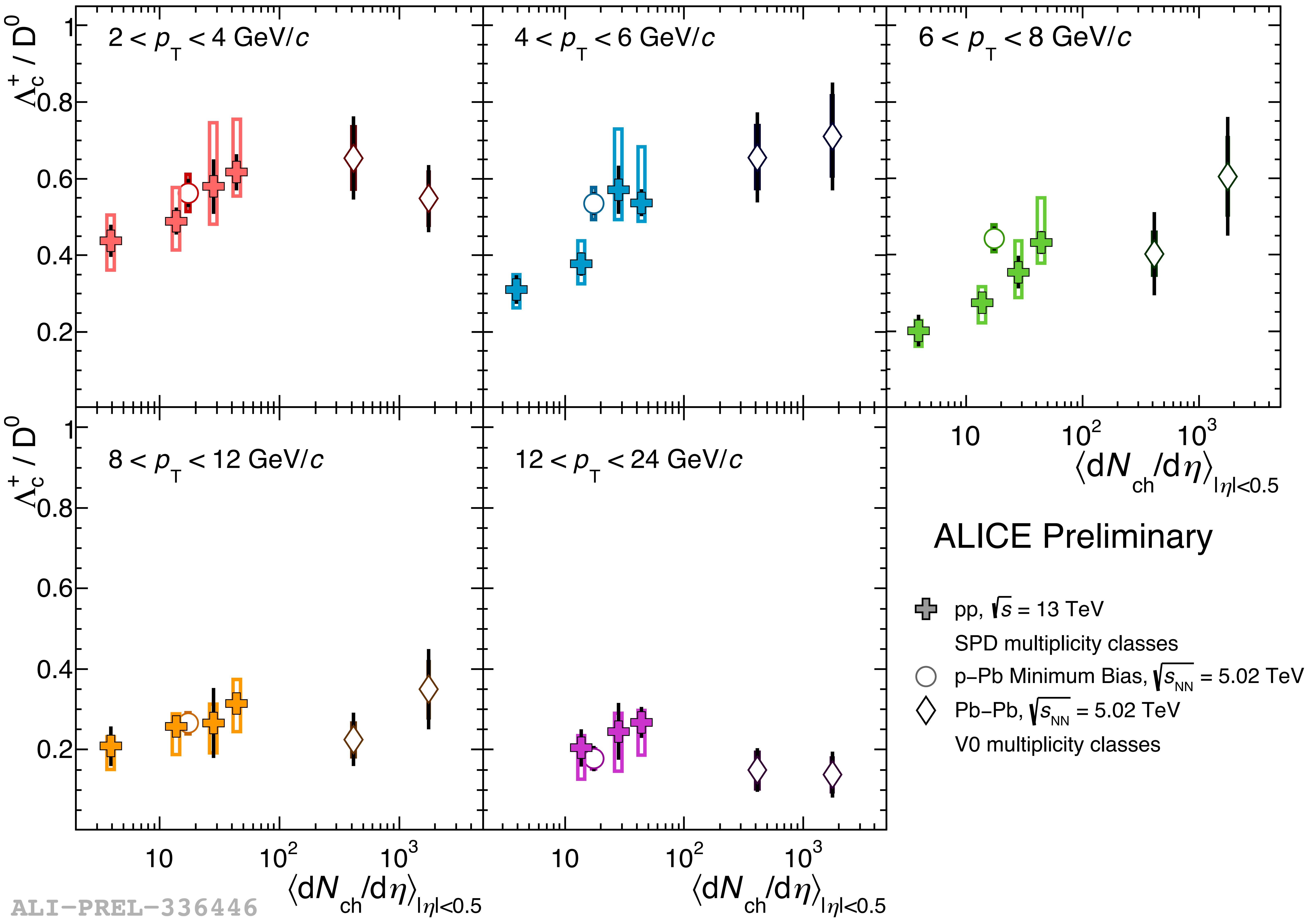


→ D_s/D^0 shows a hint of enhancement from low to high pp multiplicities

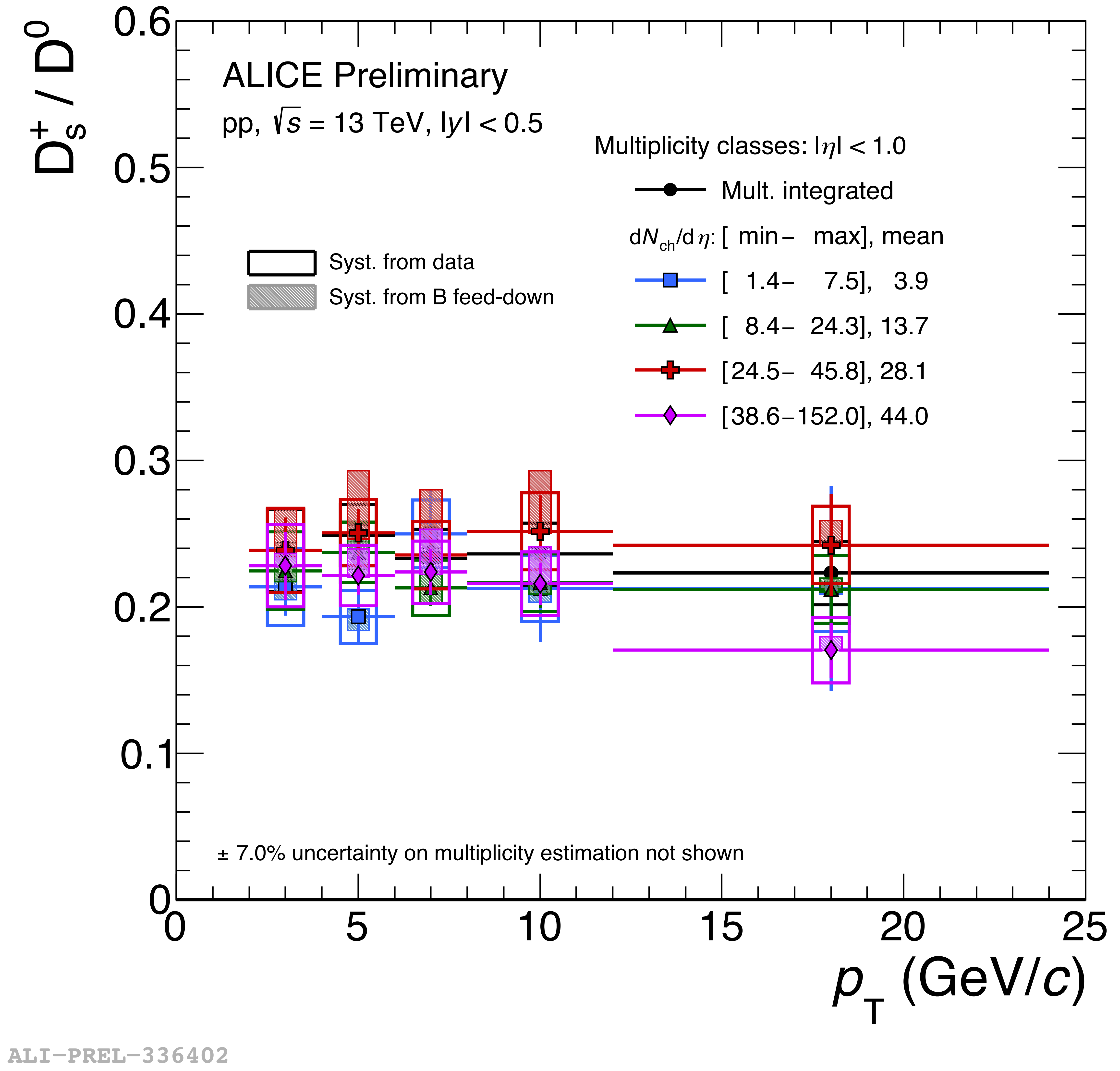
Baryon/meson zoo



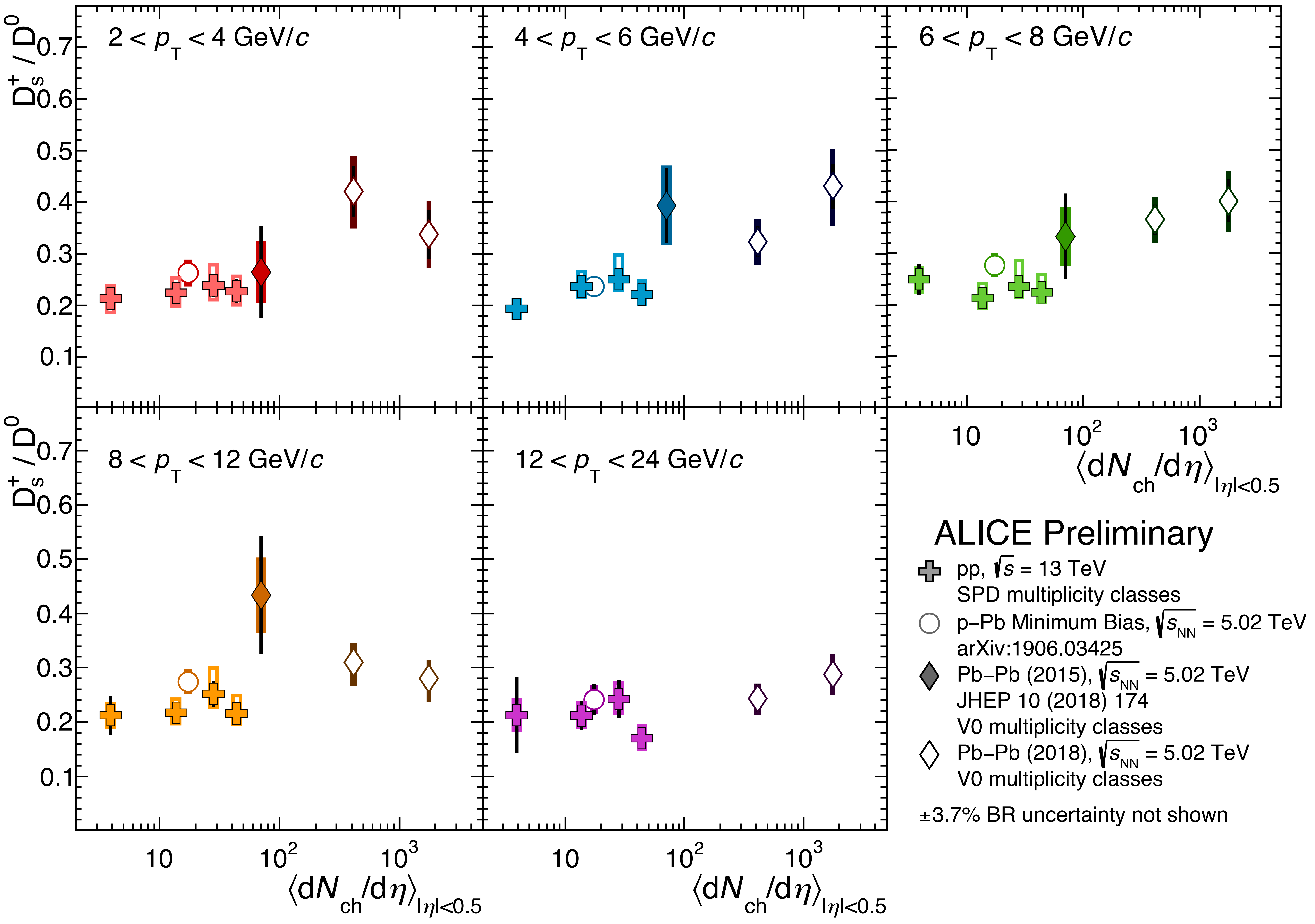
Λ_c/D^0 vs multiplicity in pp, pPb, PbPb



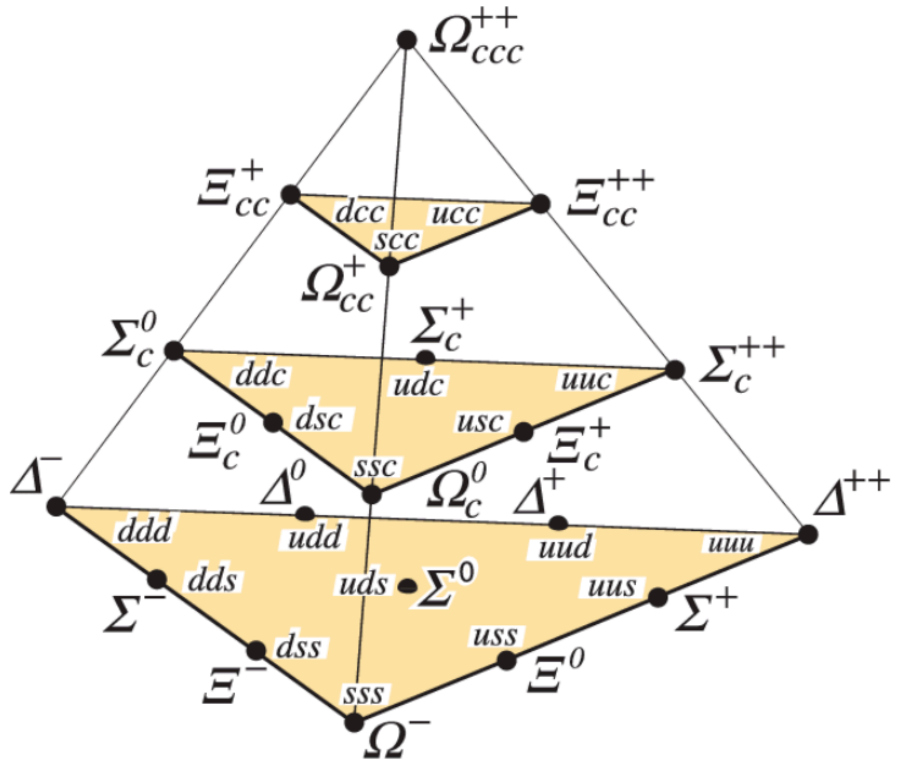
D_s/D^0 vs multiplicity in pp, pPb, PbPb

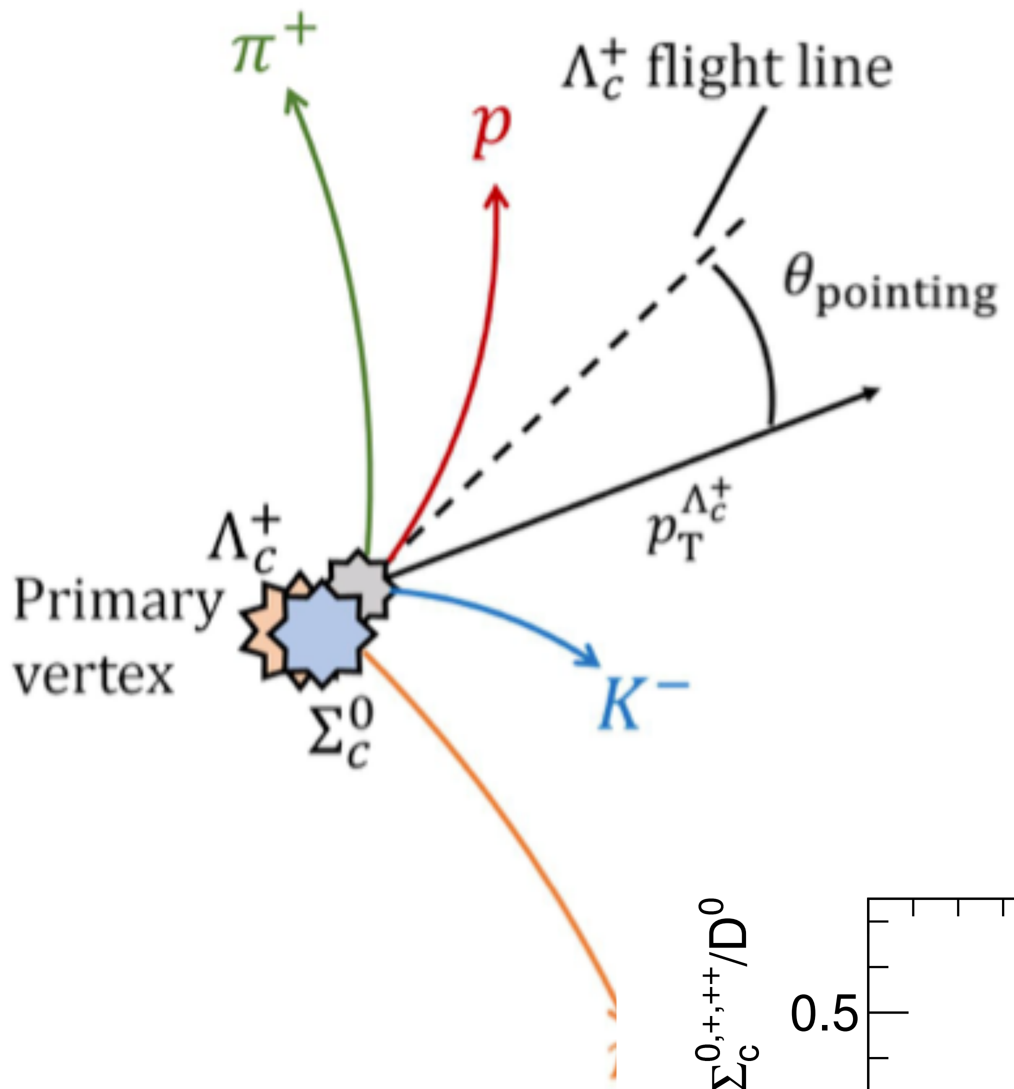


D_s/D^0 vs multiplicity in pp, pPb, PbPb

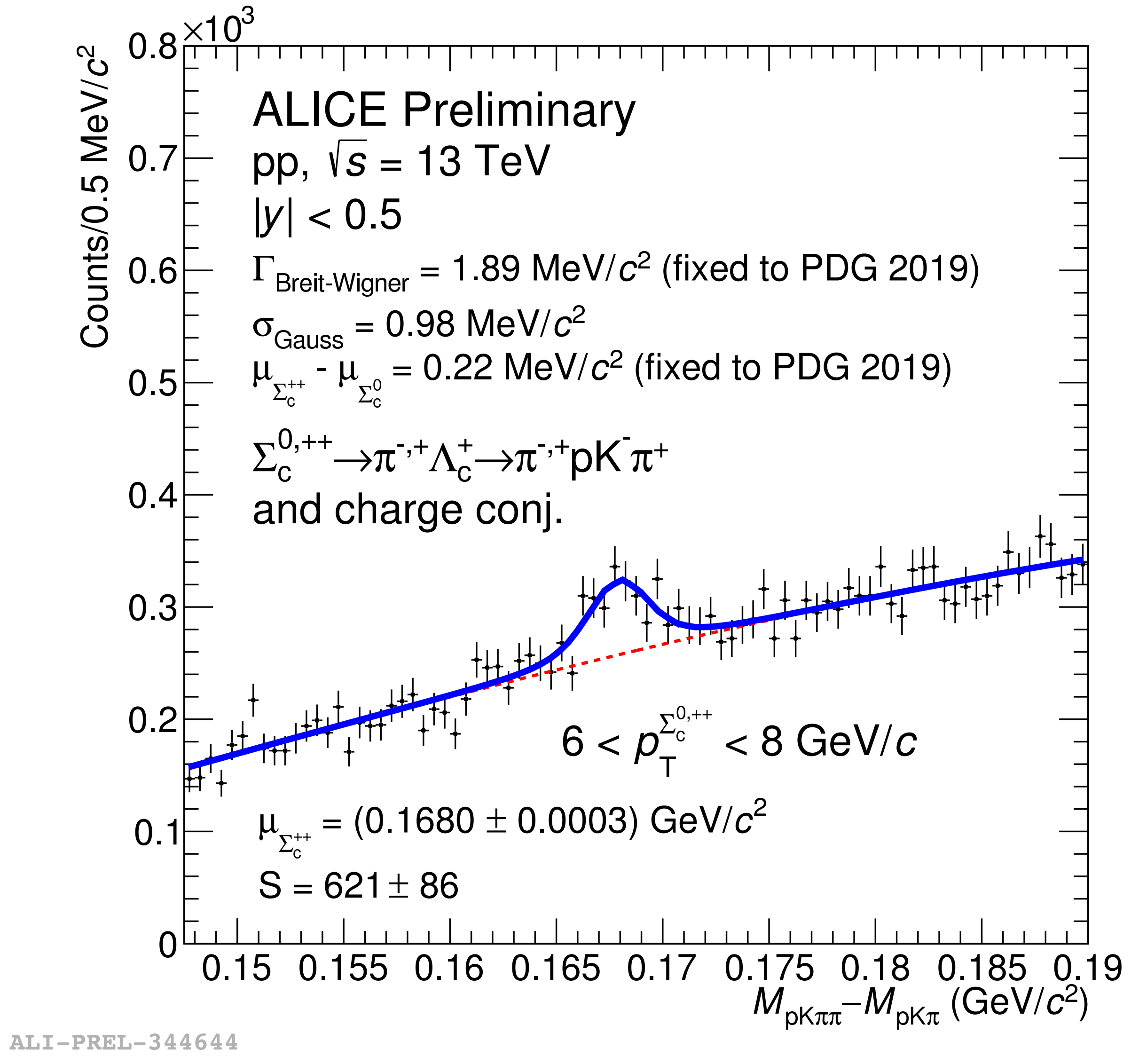


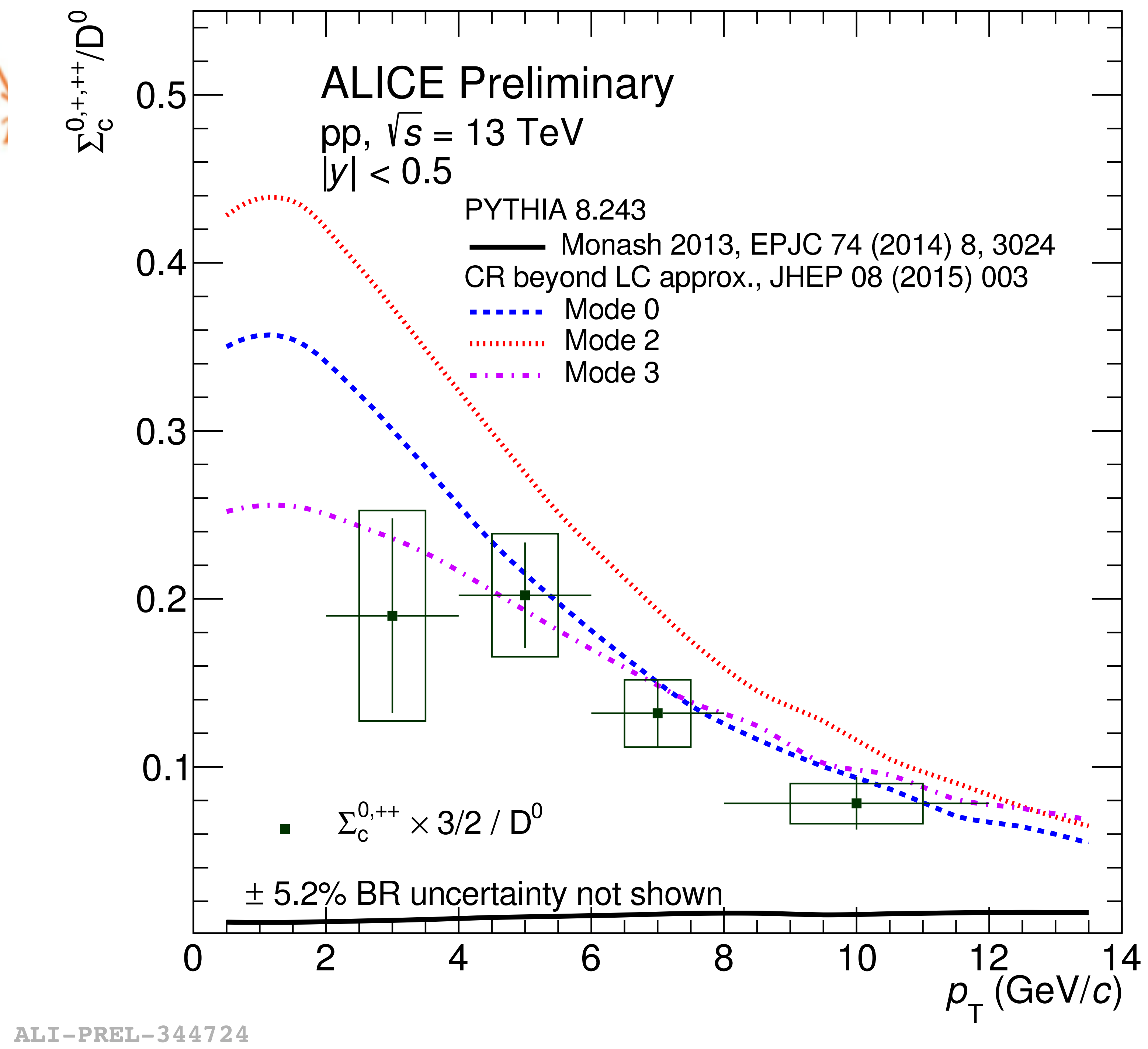
$\Lambda_c \leftarrow \Sigma_c^{0,+,++}$ and $\Sigma_c^{0,+,++}$ in pp collisions

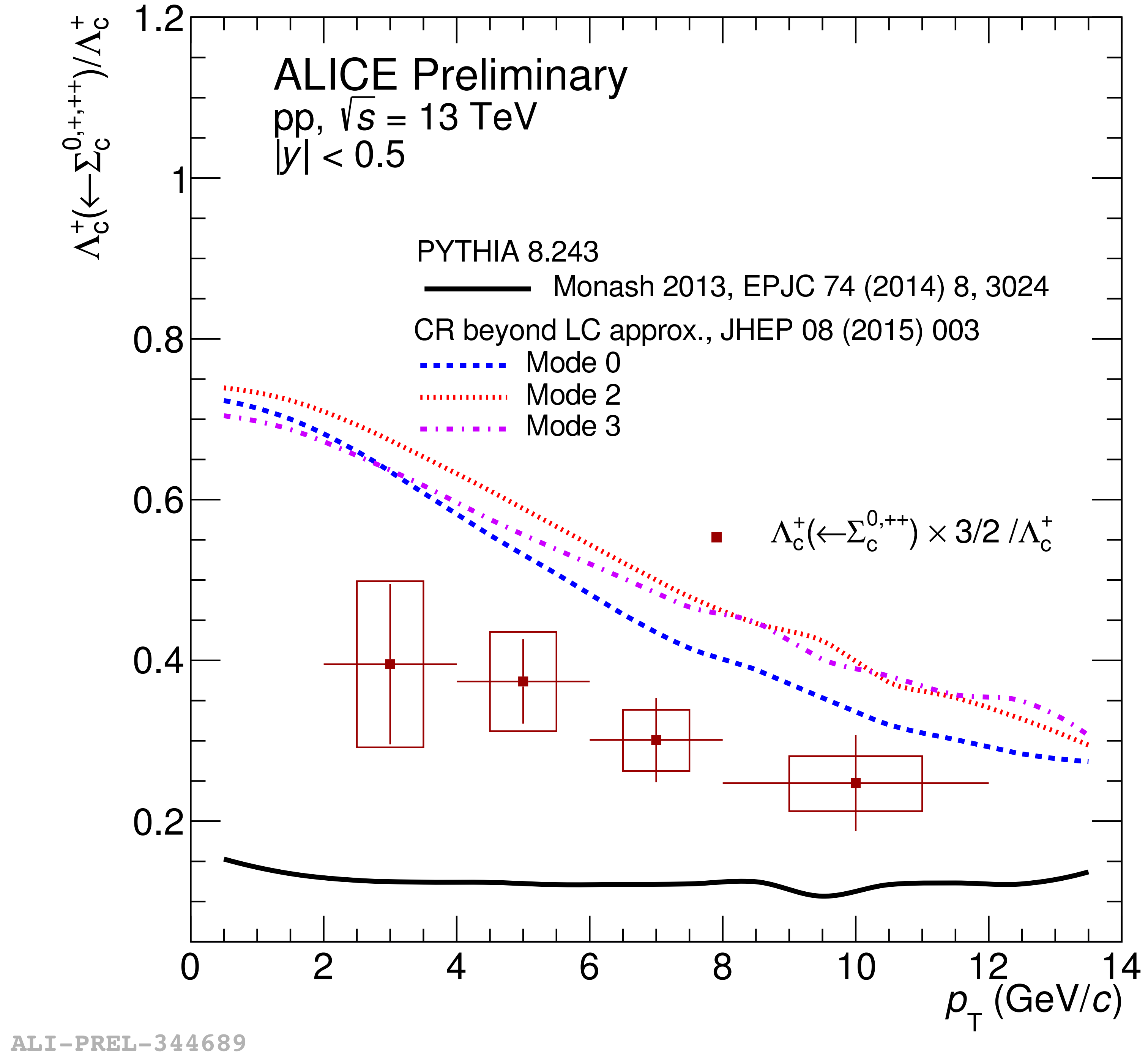




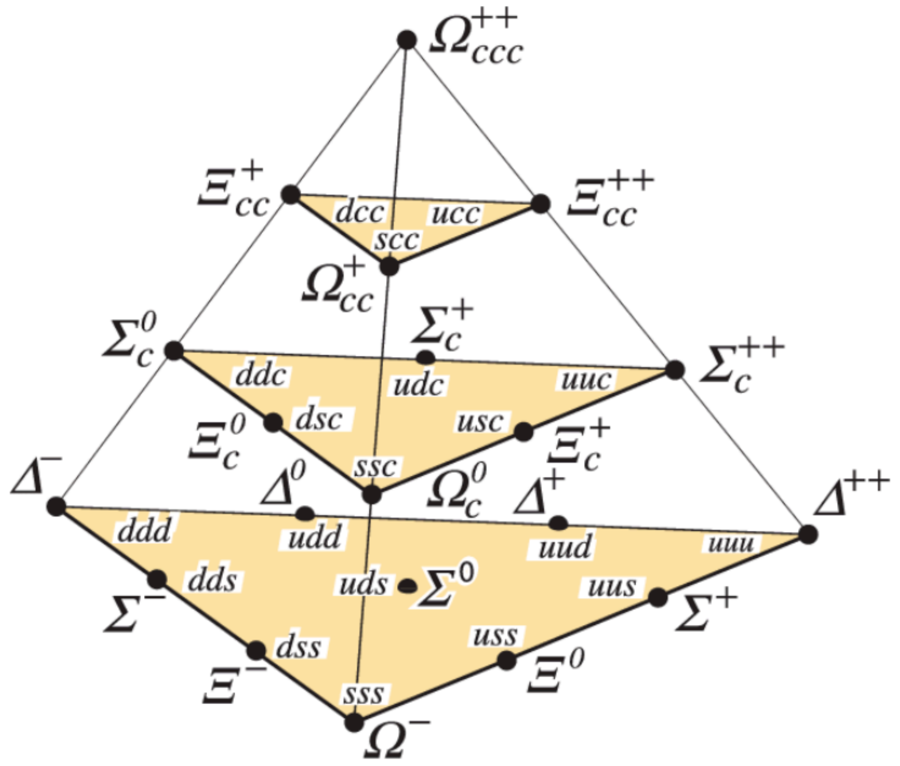
- Λ_c measurement largely underestimated by PYTHIA calculations with different tunes like Monash, DIPSY (rope hadronisation) and do not describe p_T shape.
- Feed-down from higher baryon states in presence of large enhancement (PLB 795 117-121 (2019)) was suggested as a possible explanation
- Further test for PYTHIA tunes with string formation beyond Leading Color (SU3 weights, string-length minimization and junction reconnections)





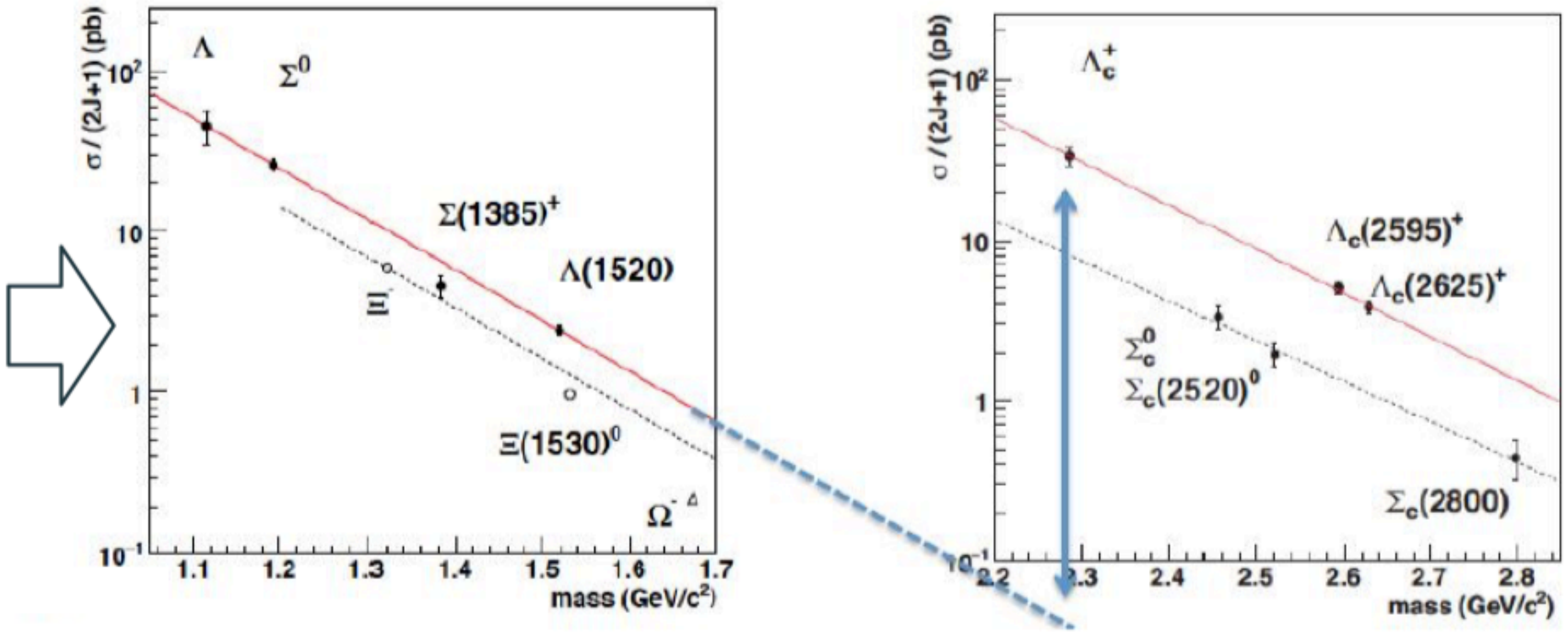


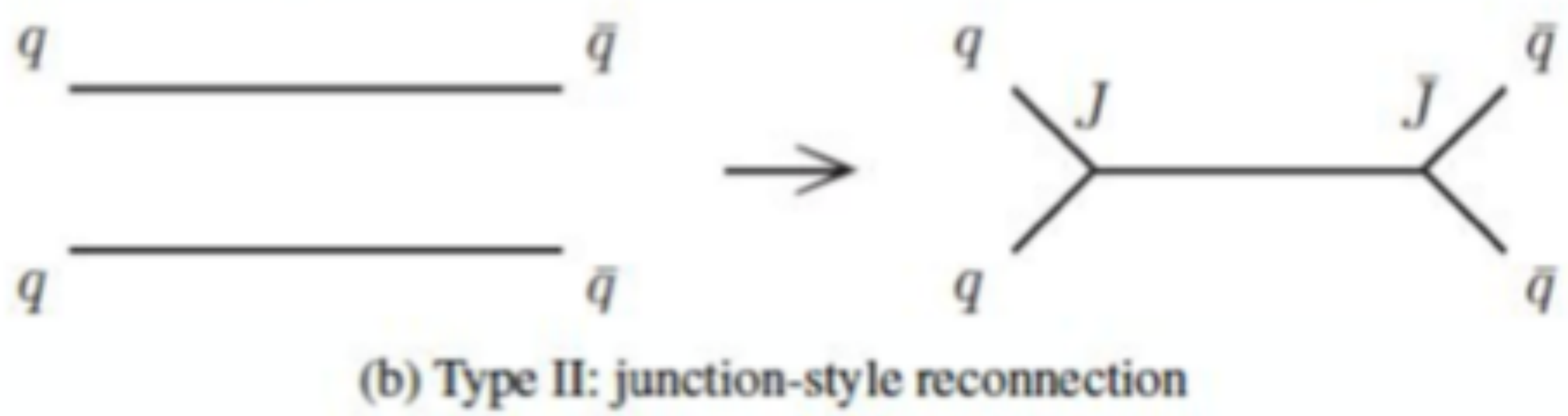
Σ_c enhancement and di-quark states



- Only way to produce Σ_c states in ordinary string fragmentation is via the production of dd or uu di quark states which must be in state spin-1 and combine with c quark
- But spin-1 di-quarks are suppressed!

Supported by e^+e^- data Belle, PRD 97, 072005 (2018)

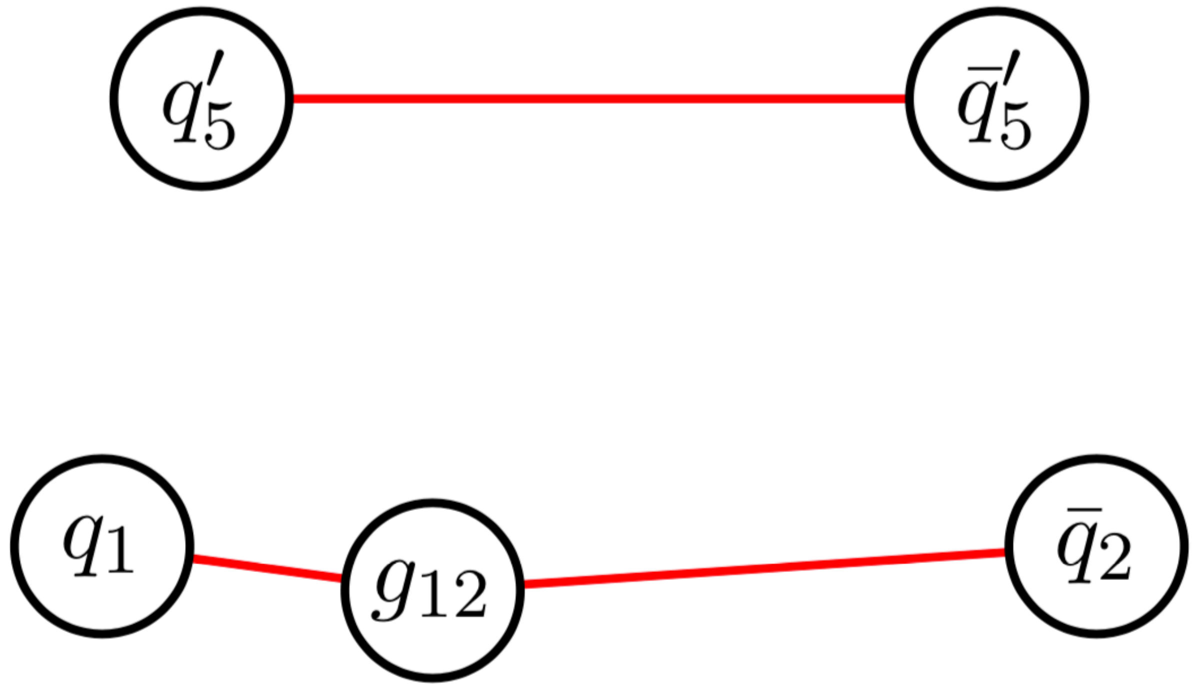




- With junctions recombination, there is no penalty for having two legs with the same flavour.
- uu, ud, dd have ~ same probability, simply combinatorial effect

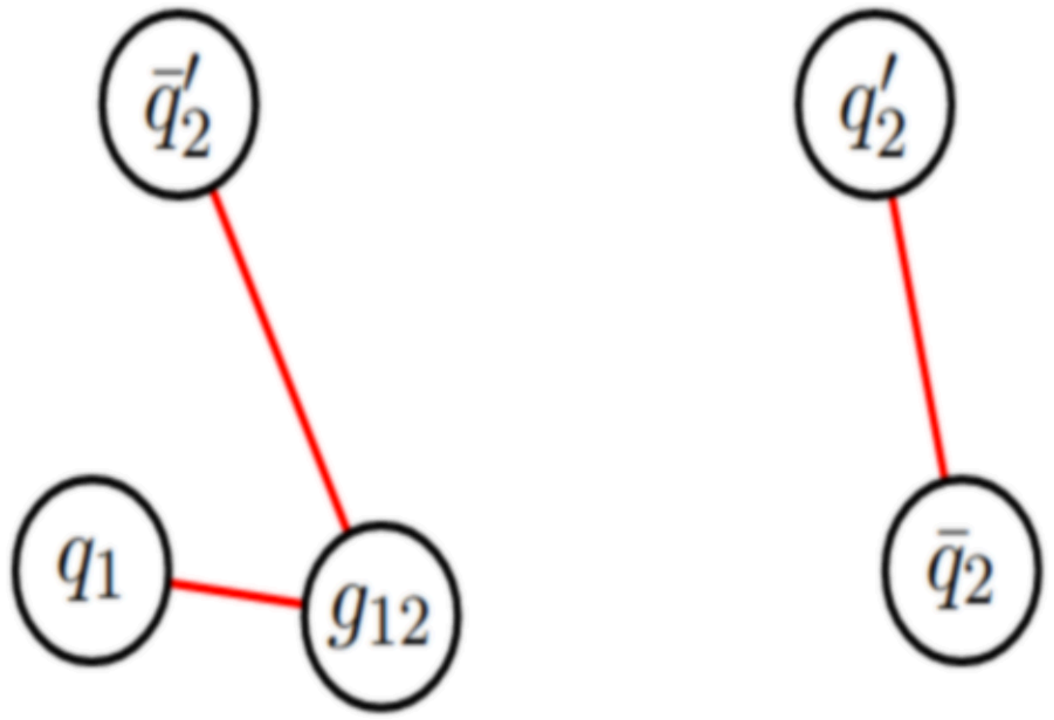
Overview of color reconnection in PYTHIA

No CR



- partons created in different MPIs do not interact

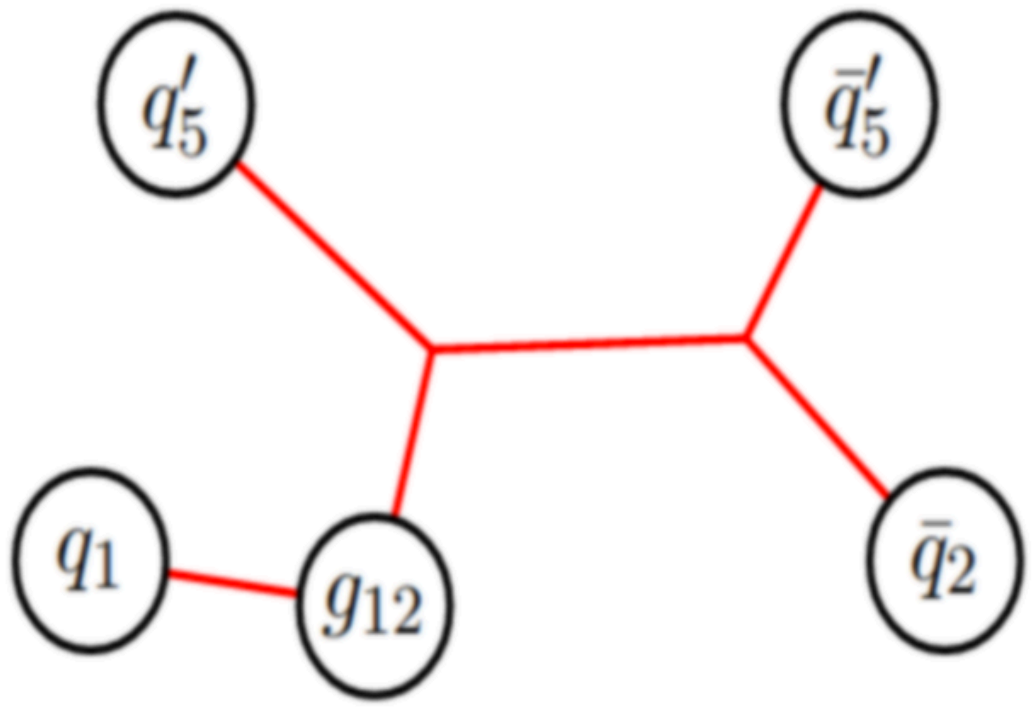
MPI-based CR



- Color reconnection allowed between partons from different MPIs to minimize string length

- As implemented in Monash
- ColorReconnection:mode =0

More-QCD CR



- Uses a simple model of the colour rules of QCD to determine the formation of strings and introduce junctions
- Minimization of the string length over all possible configurations

- Include CR with MPIs and with beam remnants

- ColorReconnection:mode = 1

JHEP 08 (2015) 003, arXiv:1505.01681v1

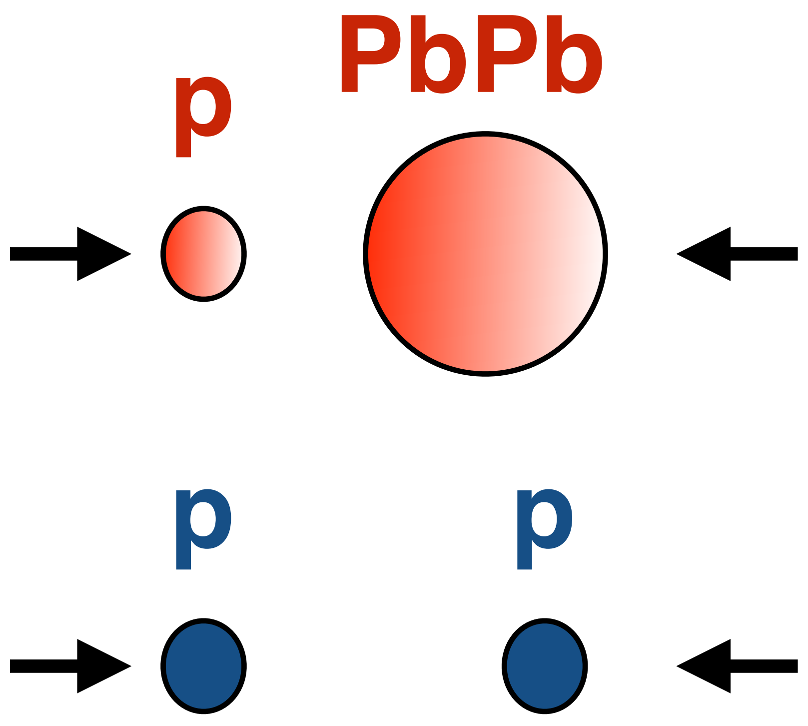
PYTHIA color reconnection parameters

Parameter	Monash	Mode 0	Mode 2	Mode 3
StringPT:sigma	= 0.335	= 0.335	= 0.335	= 0.335
StringZ:aLund	= 0.68	= 0.36	= 0.36	= 0.36
StringZ:bLund	= 0.98	= 0.56	= 0.56	= 0.56
StringFlav:probQQtoQ	= 0.081	= 0.078	= 0.078	= 0.078
StringFlav:ProbStoUD	= 0.217	= 0.2	= 0.2	= 0.2
StringFlav:probQQ1toQQ0join	= 0.5, 0.7, 0.9, 1.0	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275
MultiPartonInteractions:pT0Ref	= 2.28	= 2.12	= 2.15	= 2.05
BeamRemnants:remnantMode	= 0	= 1	= 1	= 1
BeamRemnants:saturation	-	= 5	= 5	= 5
ColourReconnection:mode	= 0	= 1	= 1	= 1
ColourReconnection:allowDoubleJunRem	= on	= off	= off	= off
ColourReconnection:m0	-	= 2.9	= 0.3	= 0.3
ColourReconnection:allowJunctions	-	= on	= on	= on
ColourReconnection:junctionCorrection	-	= 1.43	= 1.20	= 1.15
ColourReconnection:timeDilationMode	-	= 0	= 2	= 3
ColourReconnection:timeDilationPar	-	-	= 0.18	= 0.073

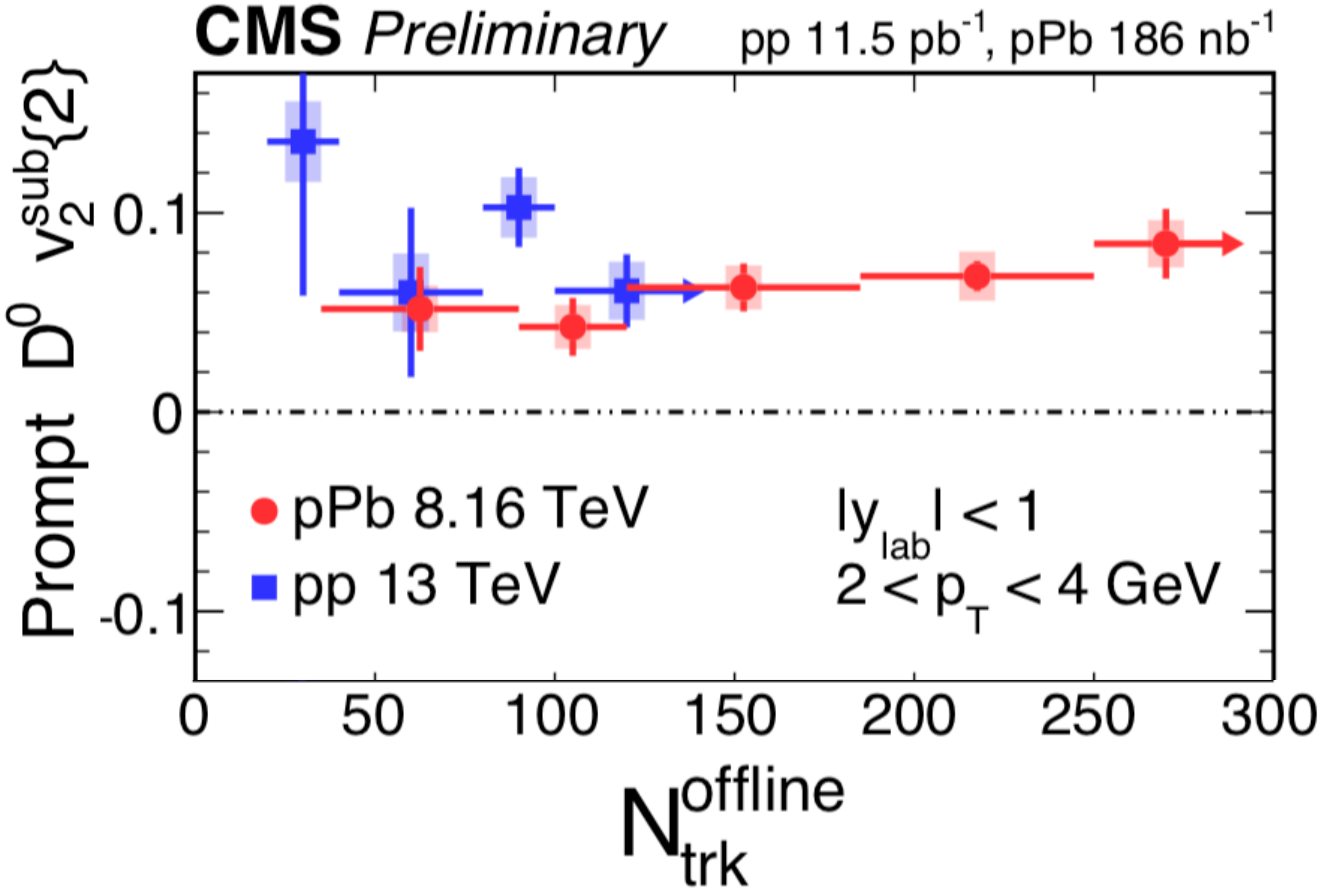
JHEP 08 (2015) 003, arXiv:1505.01681v1

Charm and beauty flow in small systems

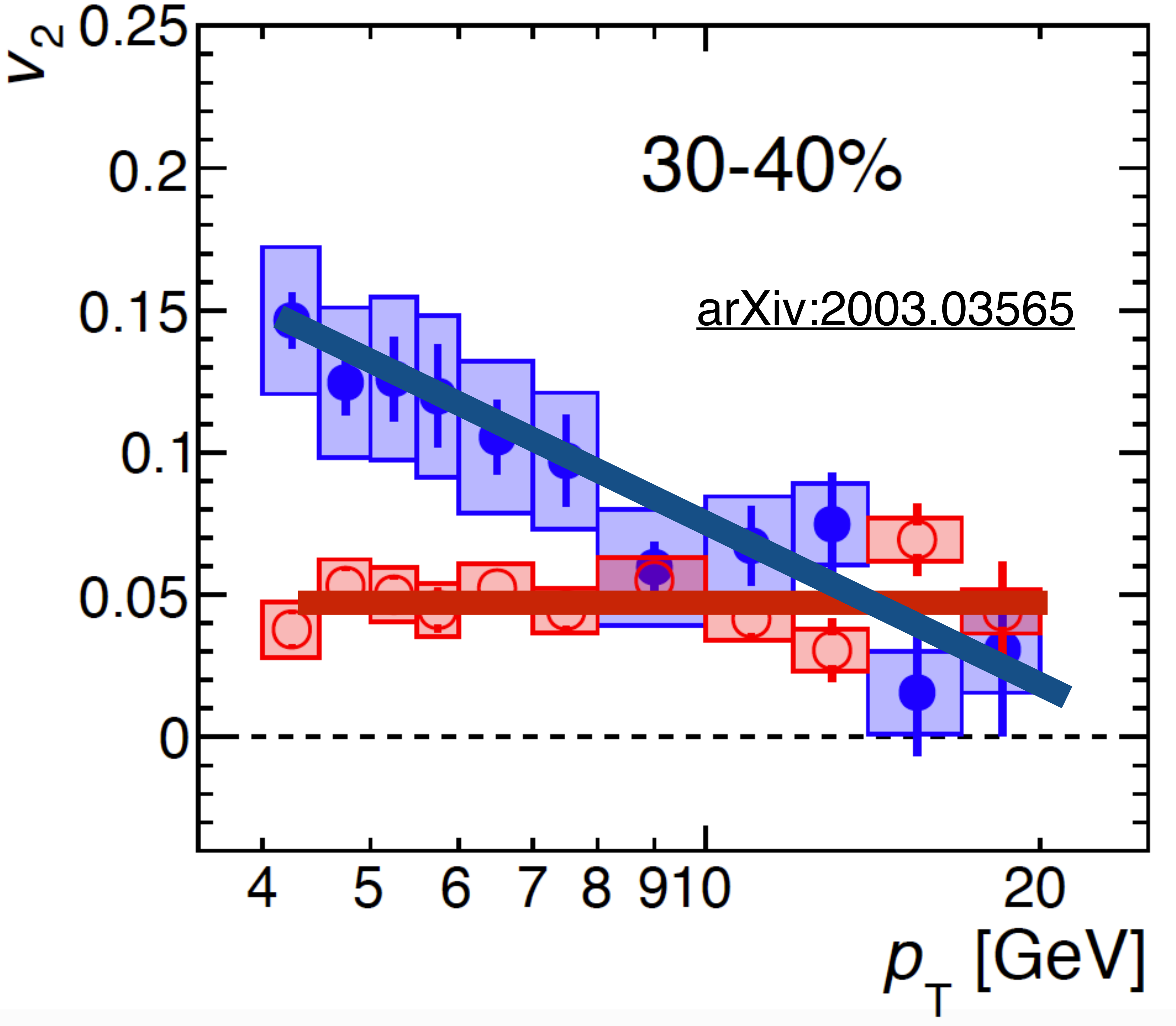
CMS-PAS-HIN-19-009

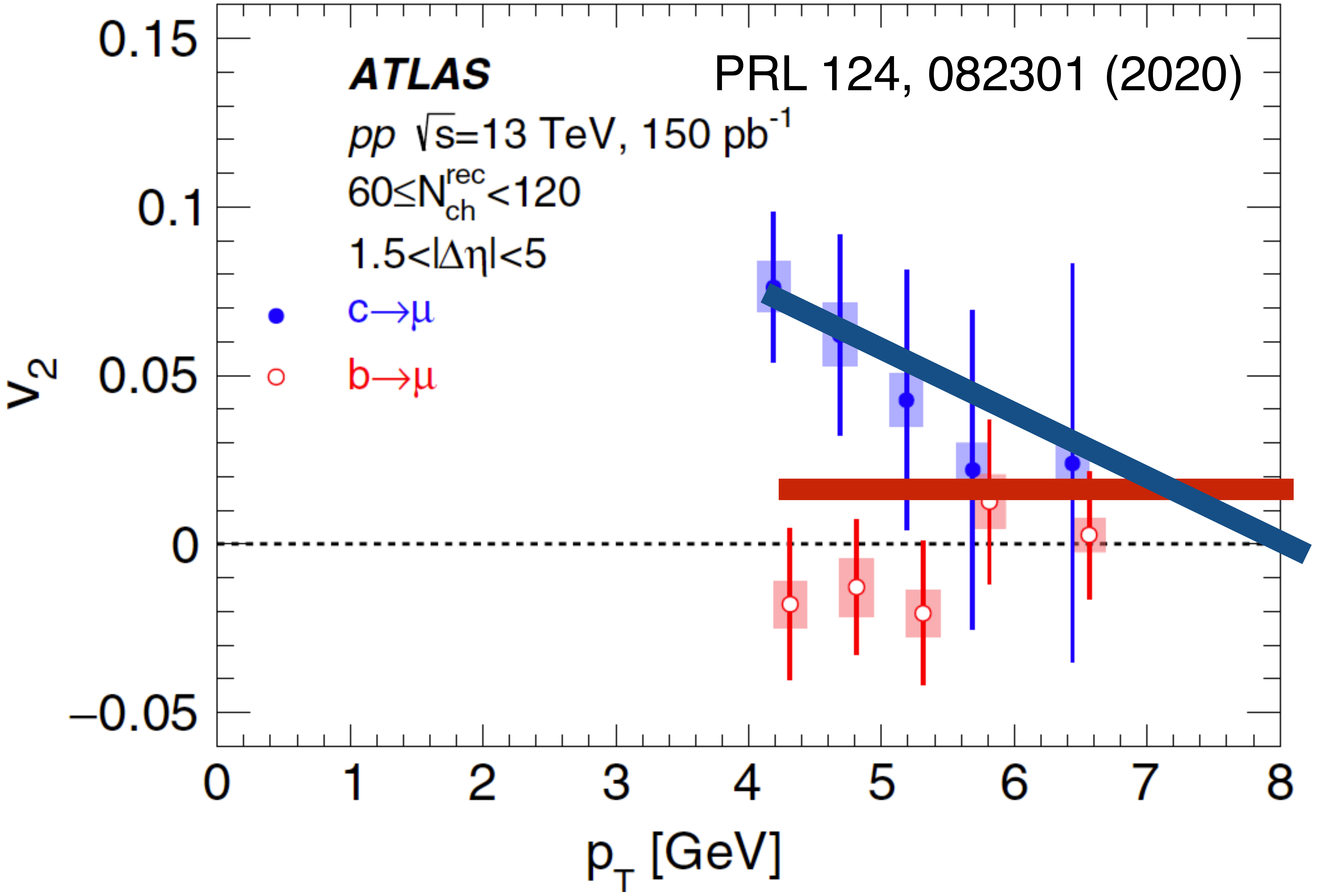


→ Same D^0 v_2 in **pp** and **pPb** at same multiplicities

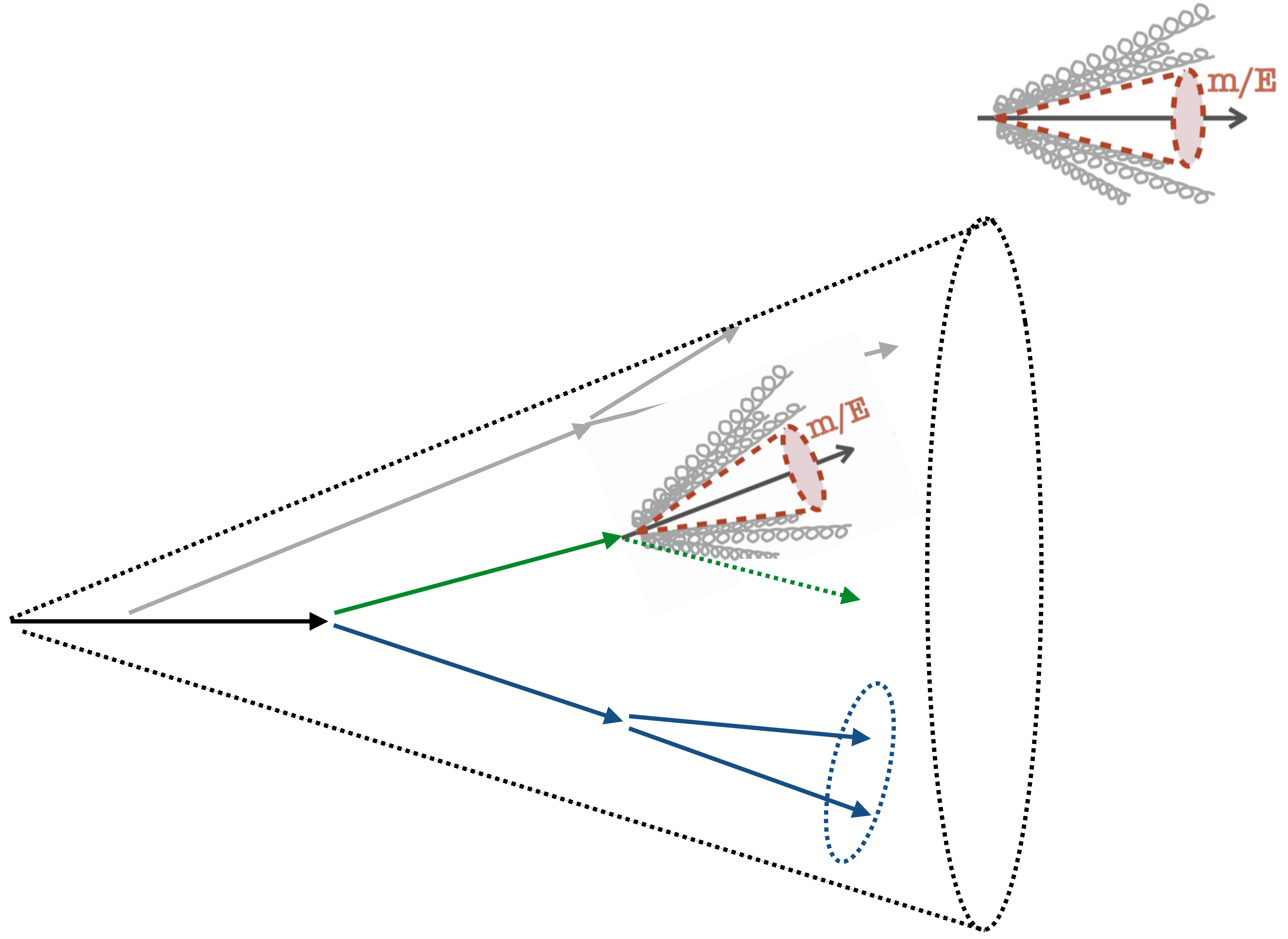


Beauty flow in pp collisions?

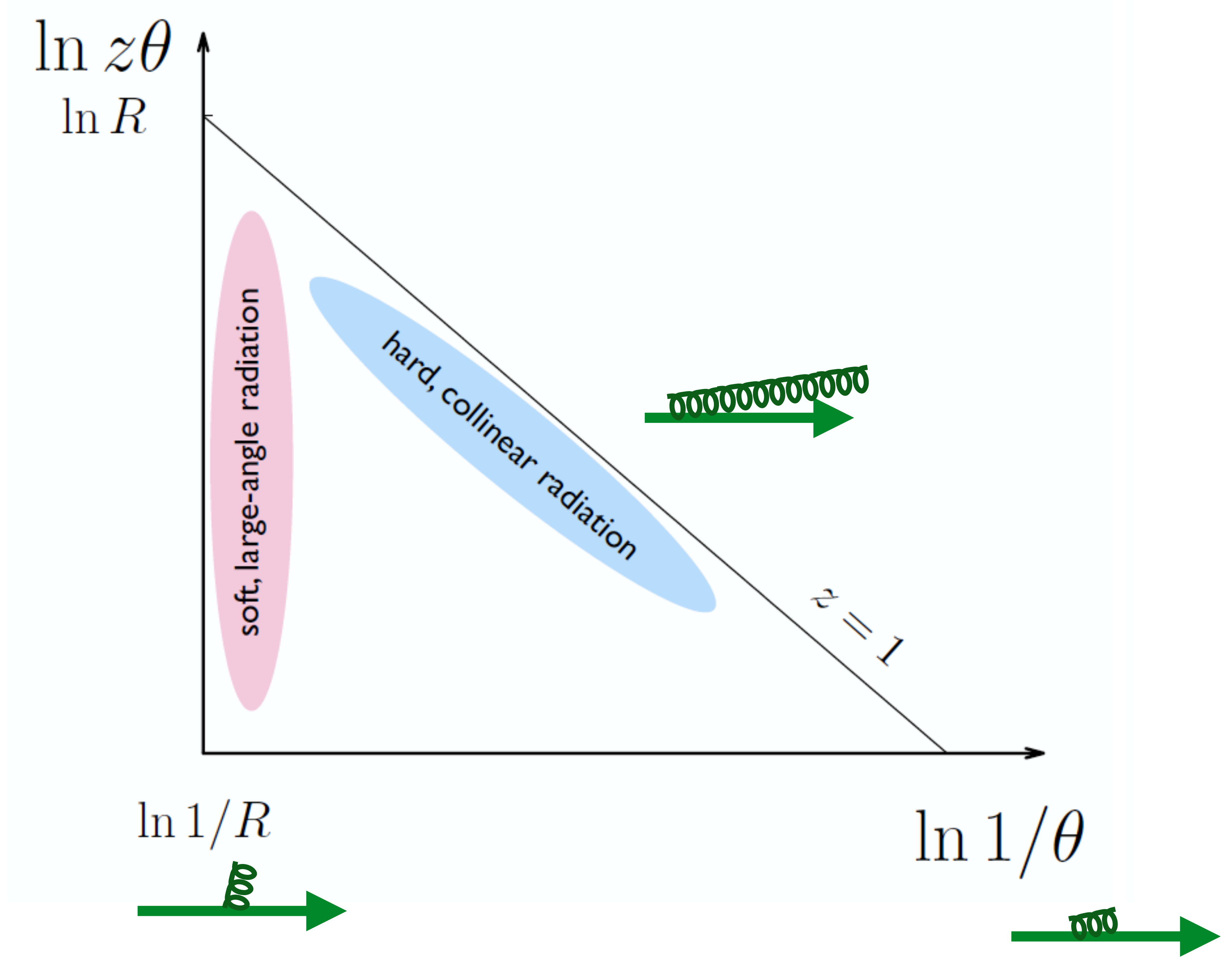




HF jets to test QCD predictions: dead cone effect

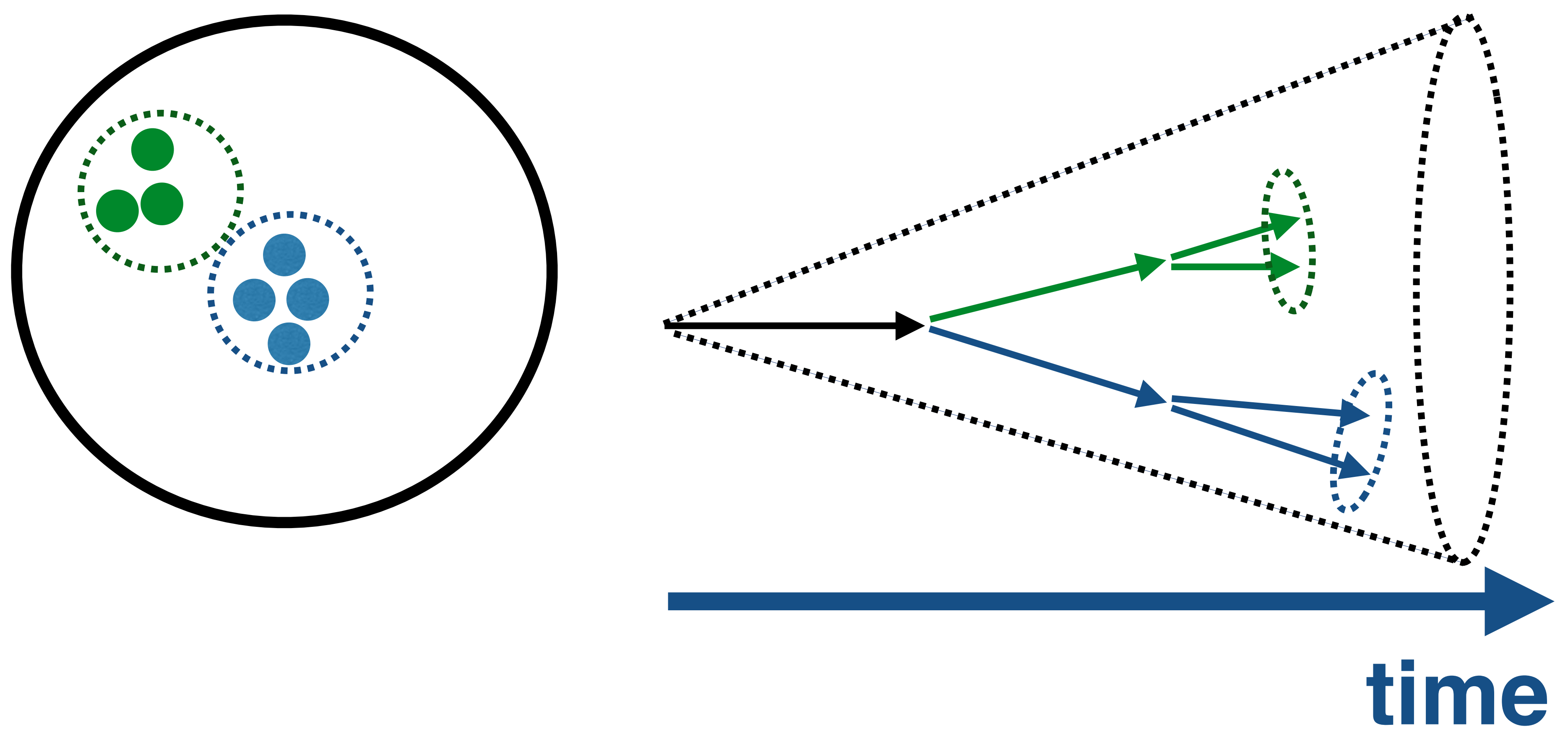


Dead cone: suppression of small angle radiation for heavy quarks.
→**Fundamental QCD effect never observed directly**



Grooming techniques

Remove soft radiation at large angles to isolate largest hard structures in the jets:
→ study the coherent vs incoherent behaviour of jets inside the medium



"Soft drop":
Iteratively test the soft drop condition at each splitting.

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

remove softer subjet if soft drop is not satisfied. Can be tuned for sensitivity to:

- large p_T unbalance ($p_{T2} < p_{T1}$)
- large angle between subjects

Considering the two main sub-jets j_1, j_2

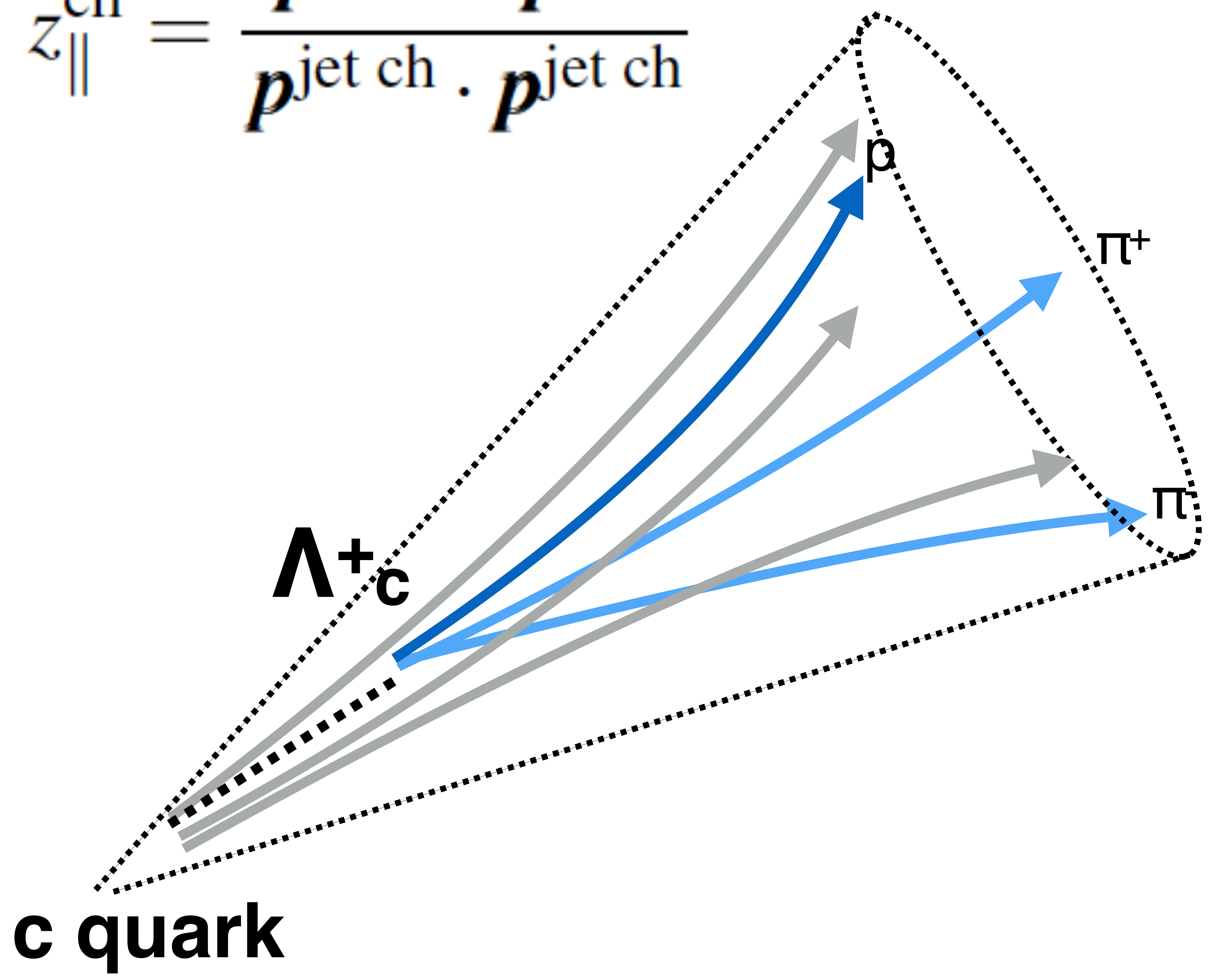
- Momentum asymmetry: $z_g = \frac{p_{T,2}}{p_{T,2} + p_{T,1}}$
- Radial distance R_g
- Groomed mass M_g

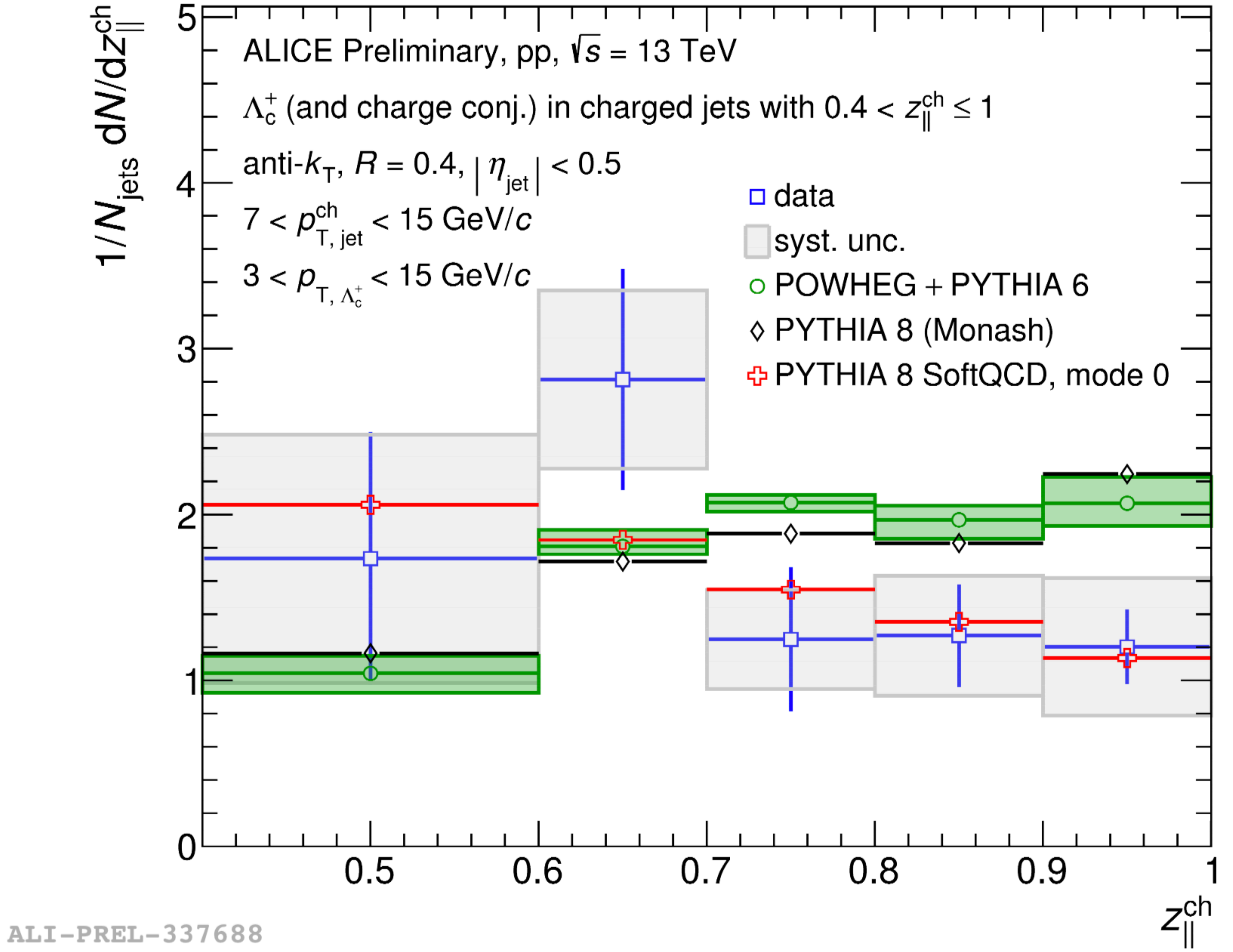
First measurement of Λ_c fragmentation at the LHC

~Fraction of the momentum of the jet carried by the heavy flavour particle:

- **directly linked to the hadronisation mechanism!**

$$z_{||}^{ch} = \frac{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{HF}}}{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{jet ch}}}$$

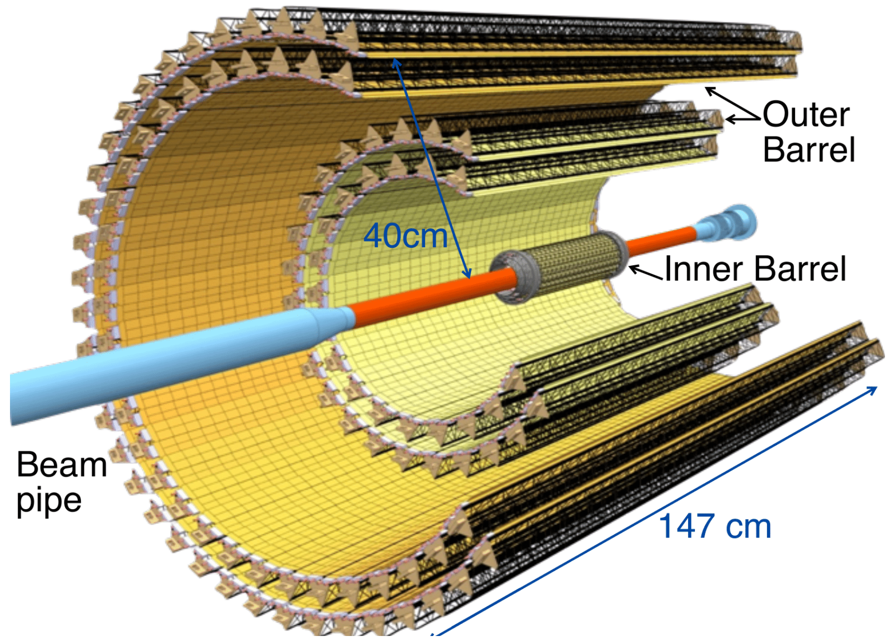


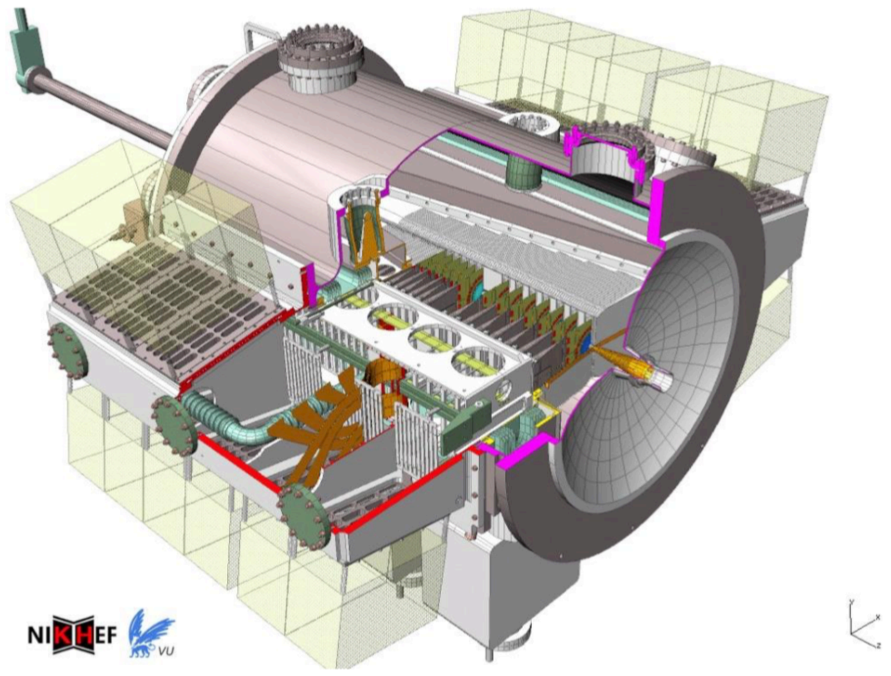


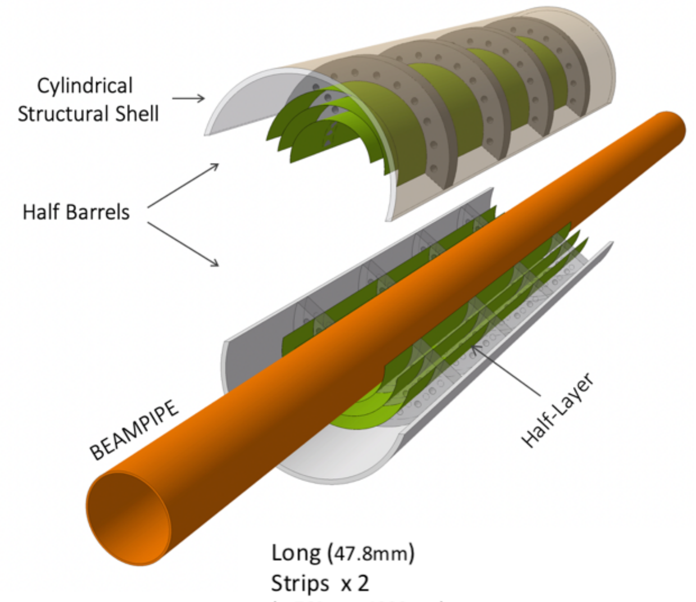
HF fragmentation studies and jet hadrochemistry:

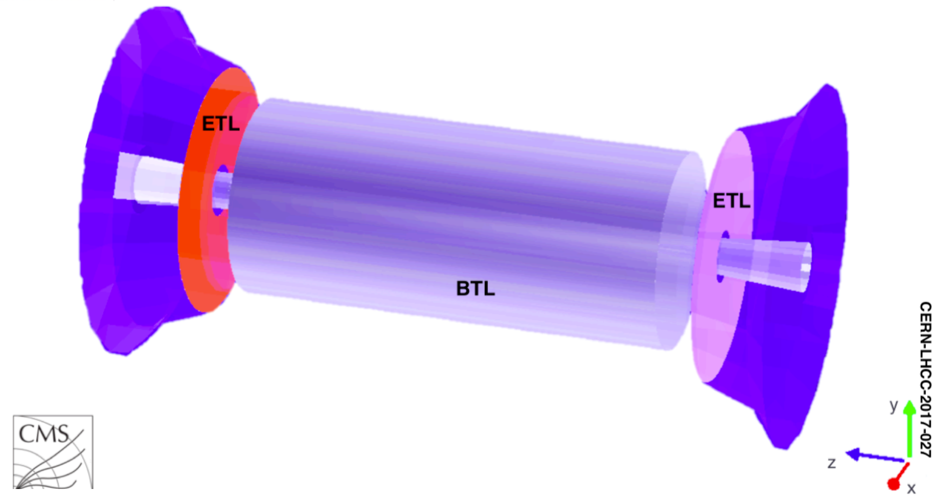
→ New constraints into the mechanisms of charm hadronisation in small and large systems

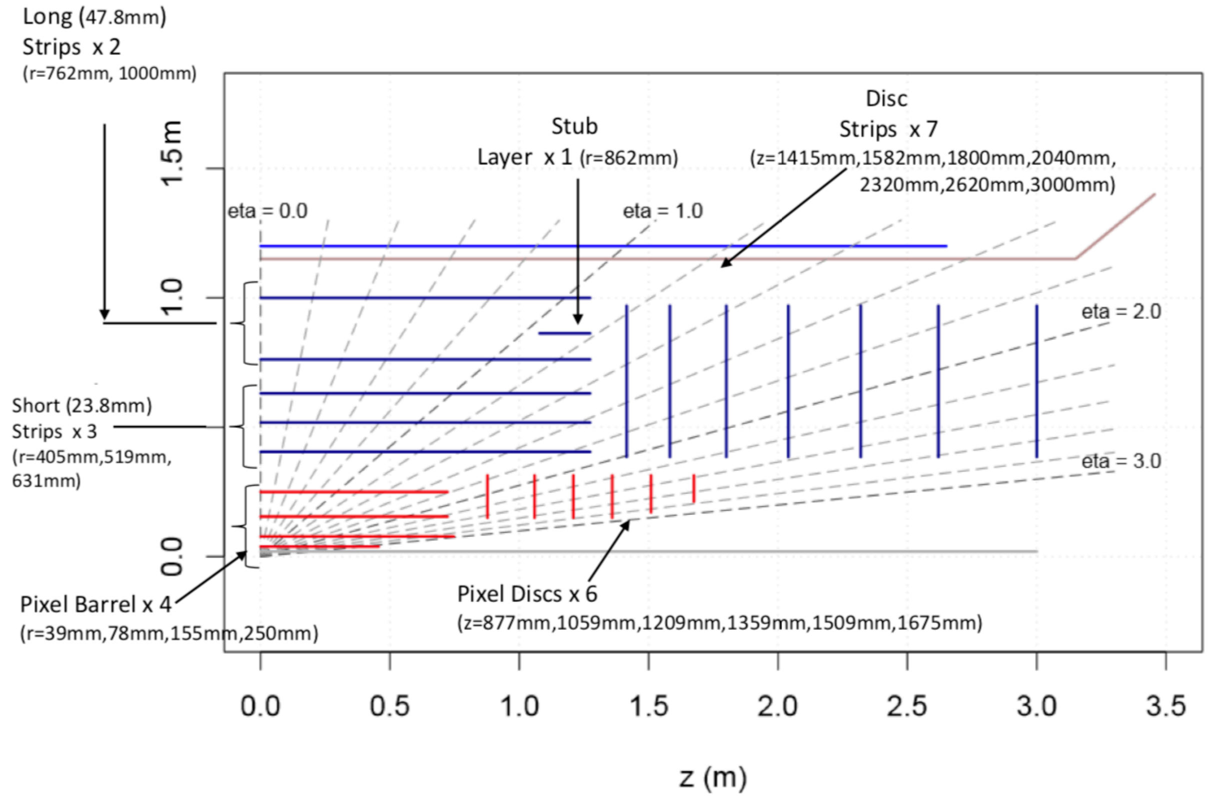
HF/Quarkonia for Run3 and beyond

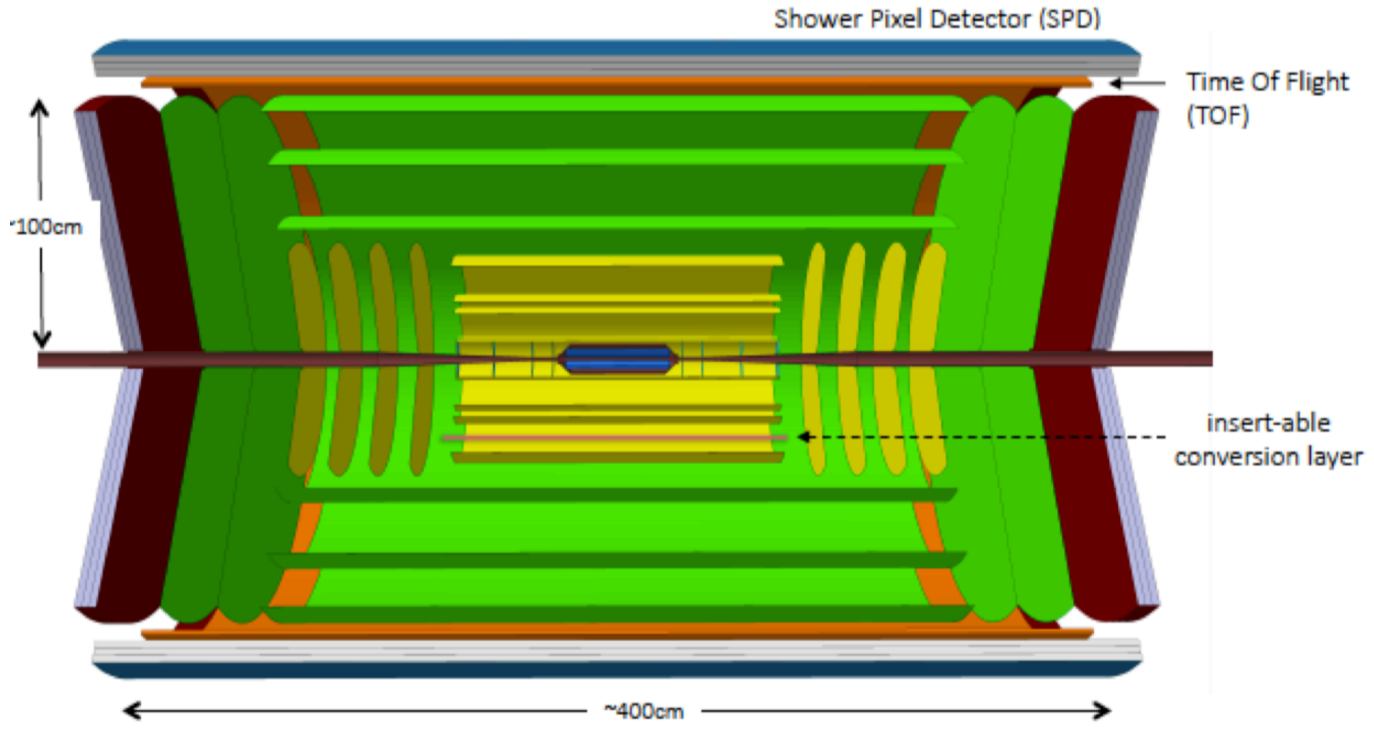






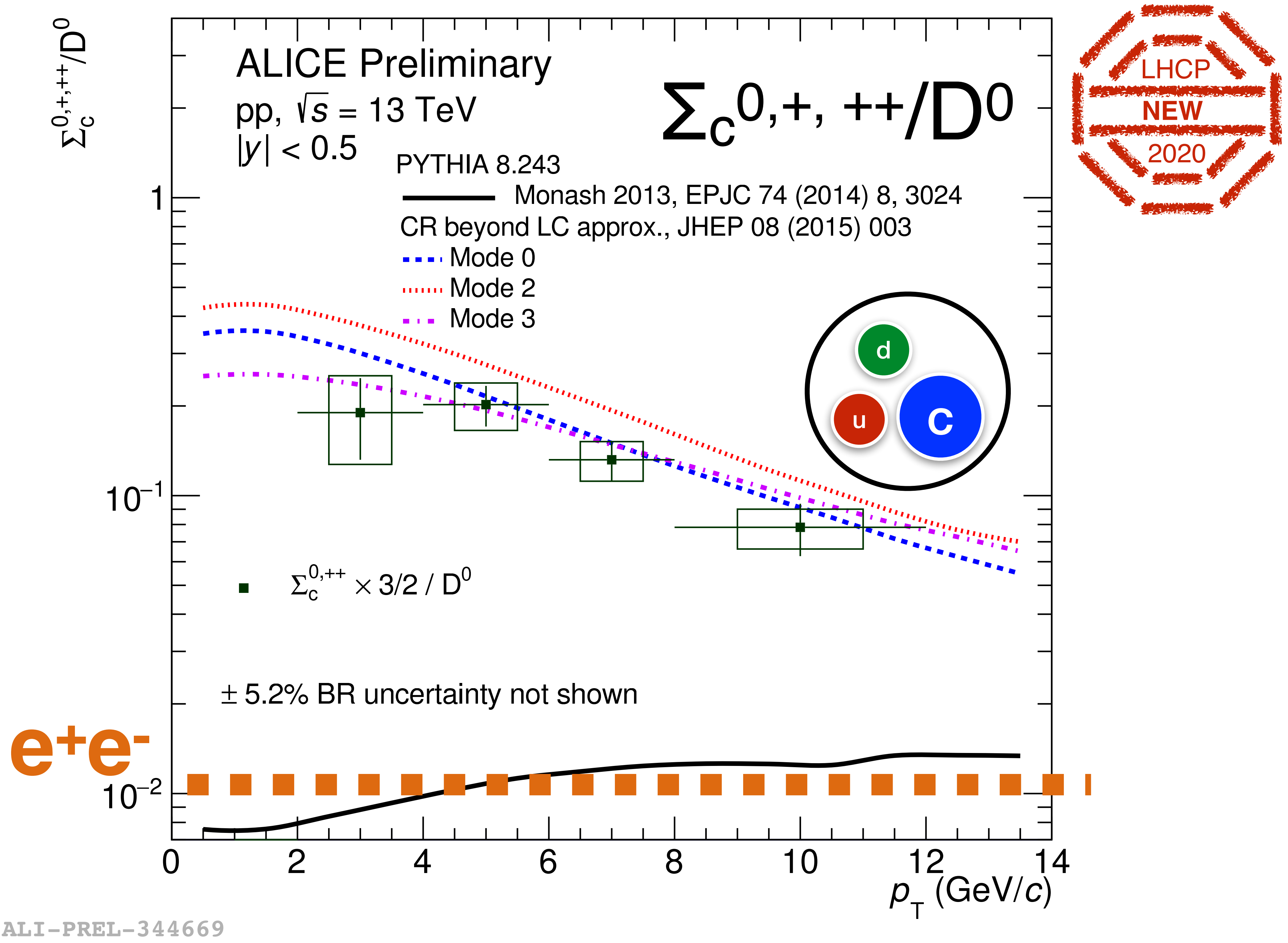


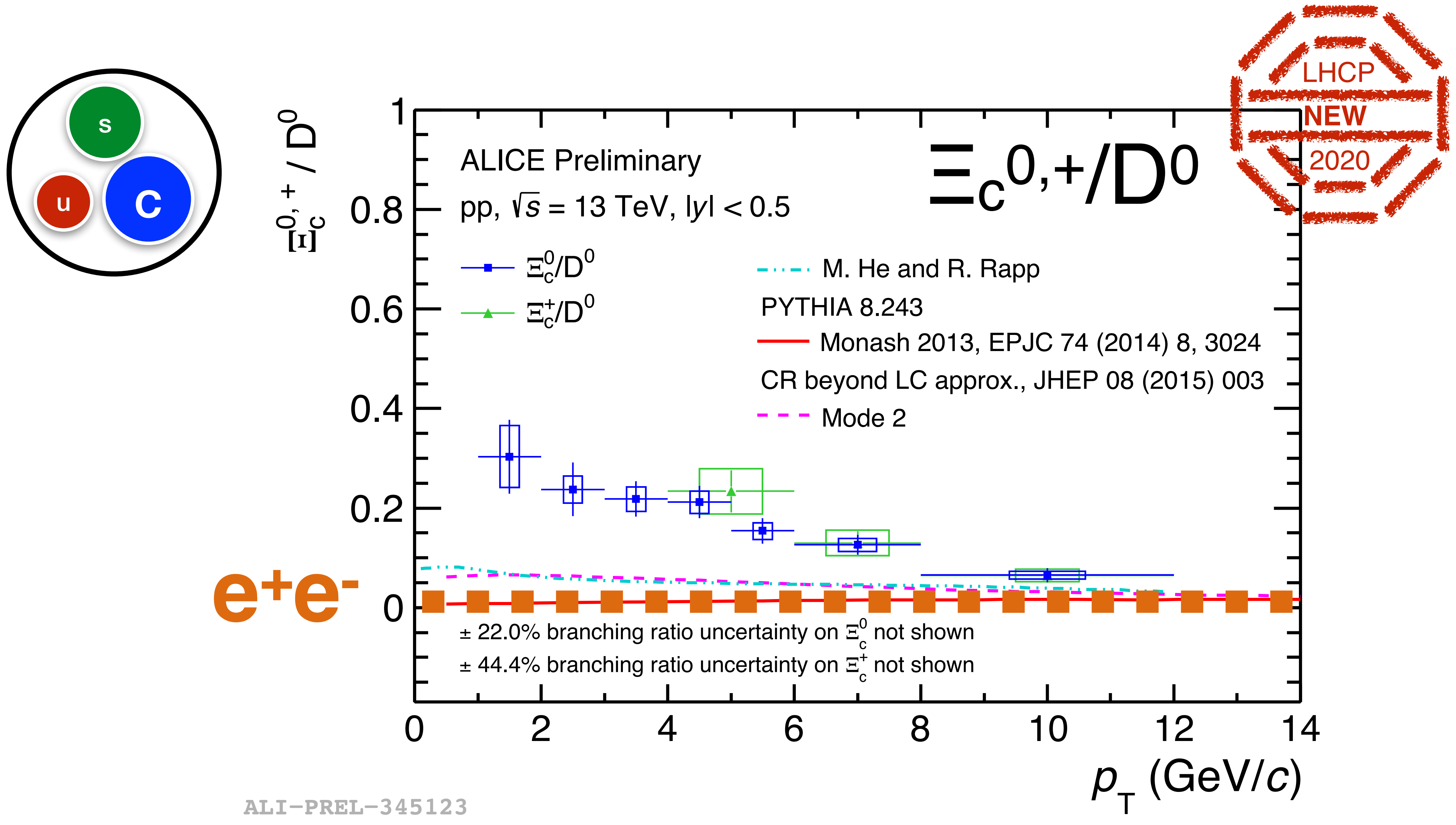


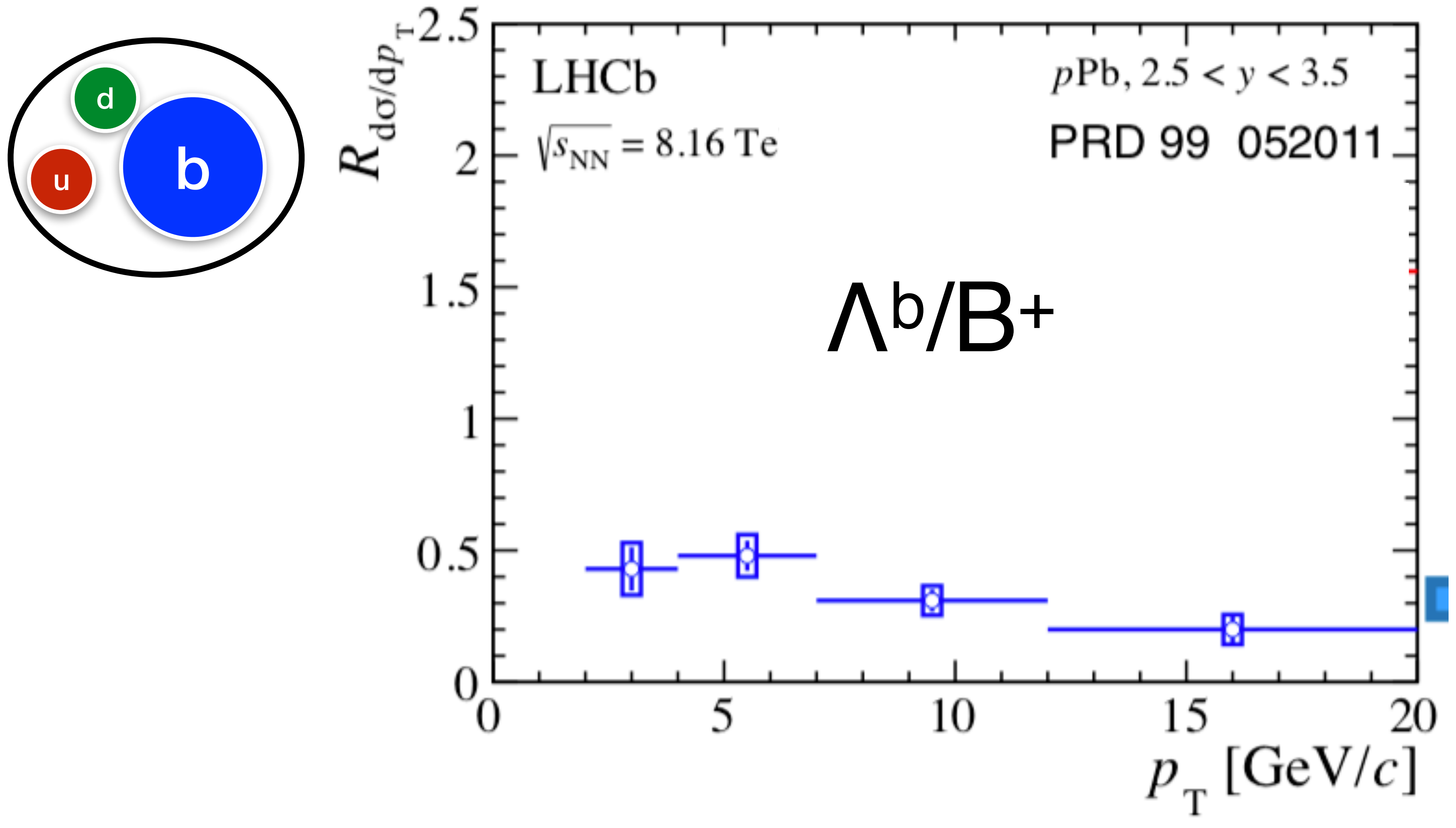


Thank you for your attention!

Heavier charmed/beauty baryons in pp collisions





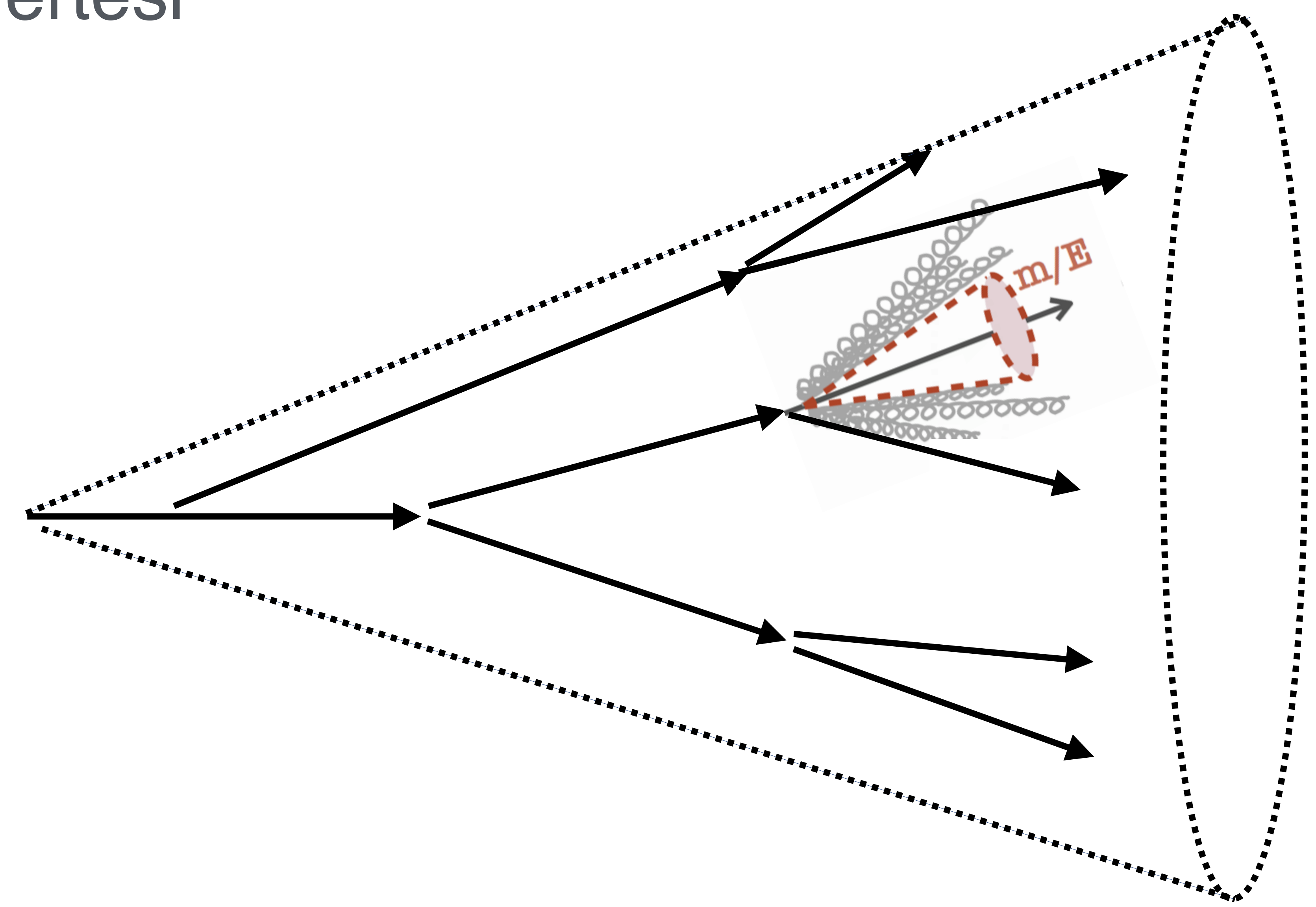


- Indication of large **enhancement** w.r.t e^+e^- fragmentation ratios for $\Sigma_c^{0,+,++}$ and $\Xi_c^{0,+}$
- Modification of baryon/meson ratio in the beauty sector

→ Stronger constraints on the microscopic mechanisms responsible for baryon/meson modifications in pp collisions

HF jets to test QCD predictions: dead cone effect

R. Vertesi



$\theta_c < M_q/E_q$ suppressed

Dead cone: suppression of small angle radiation for heavy quarks.
→**Fundamental QCD effect never observed at colliders directly**

J. Phys. G17, 1602–1604 (1991).
Phys. Rev. D 99, 074027 (2019)

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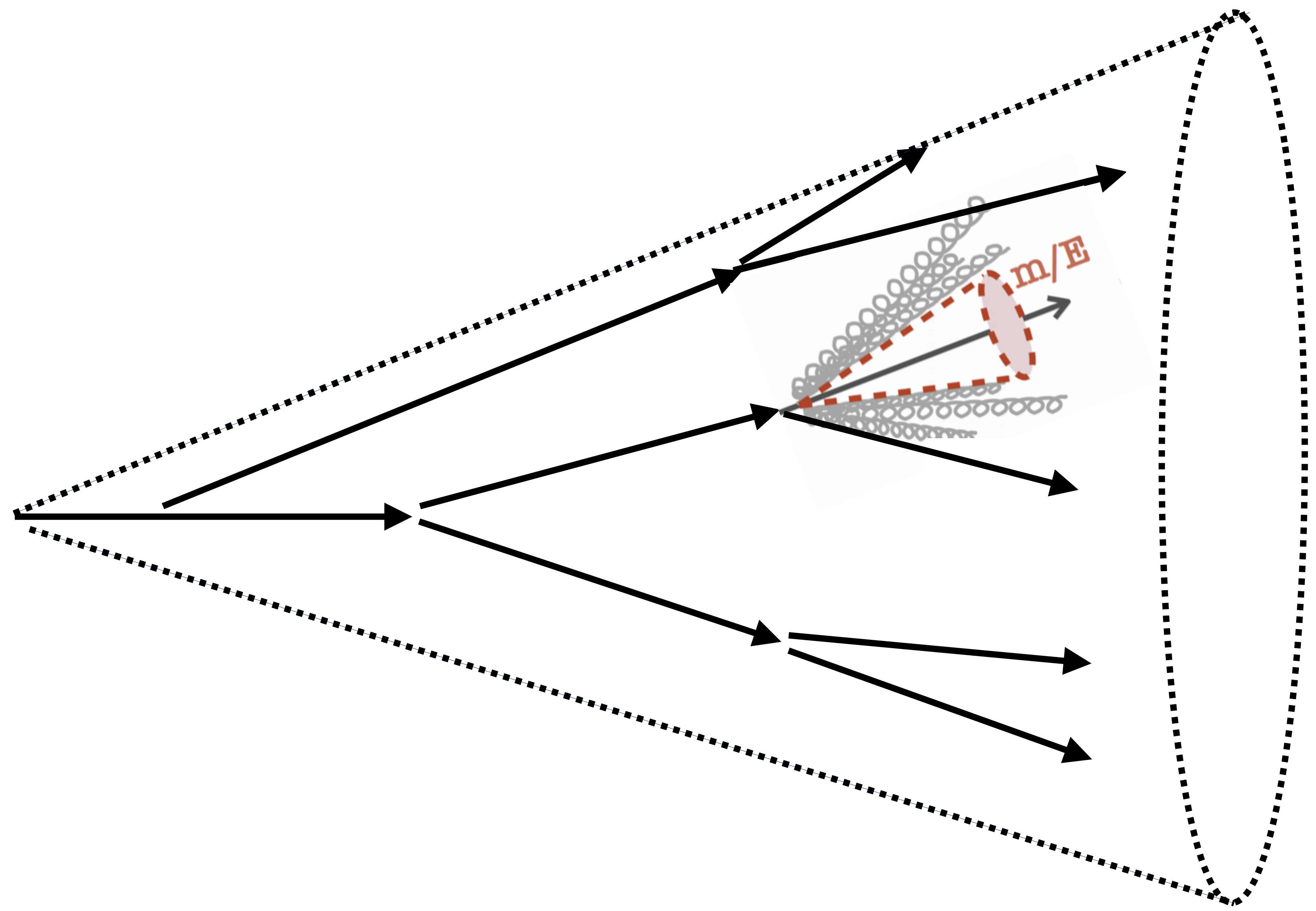

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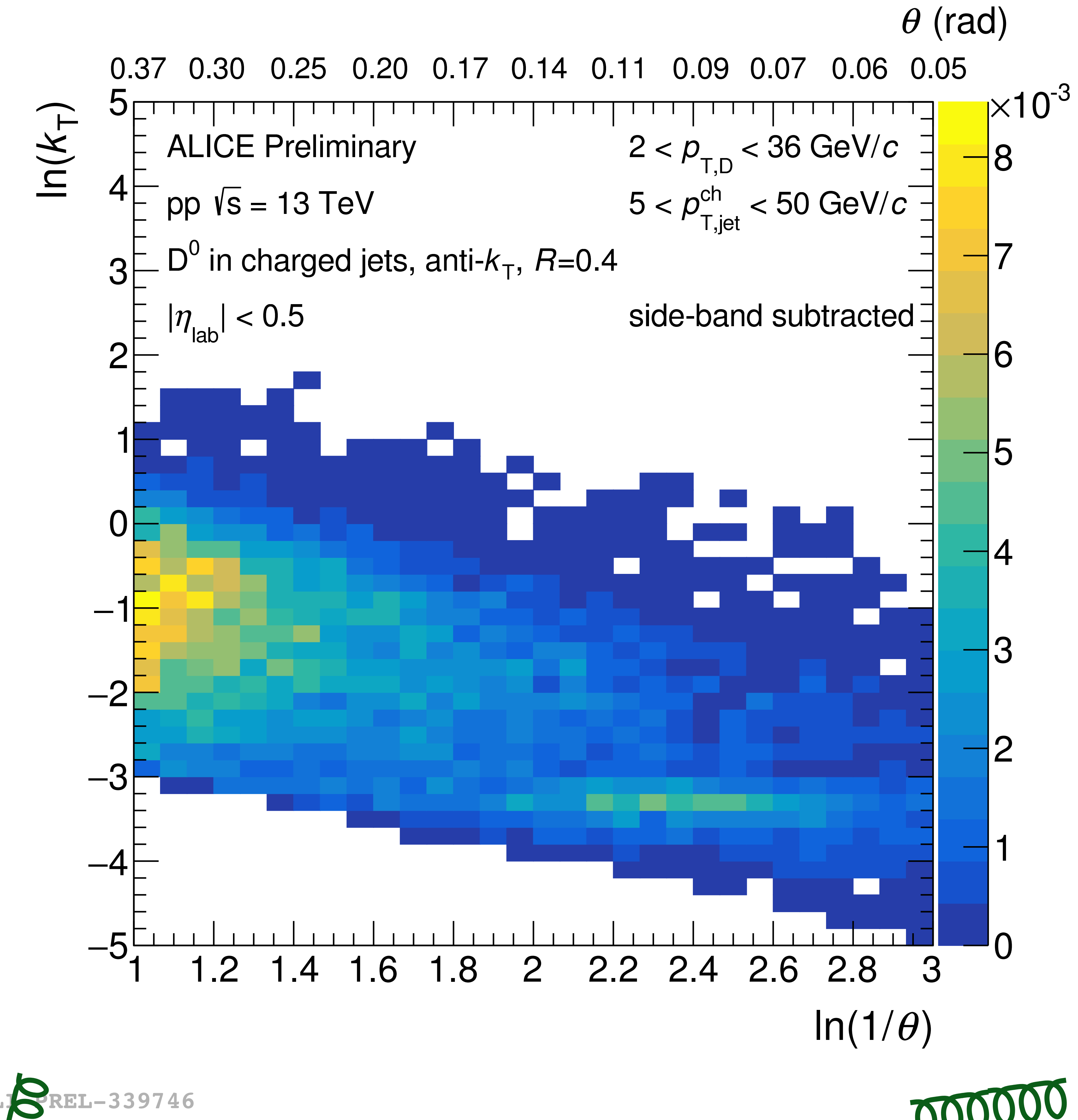
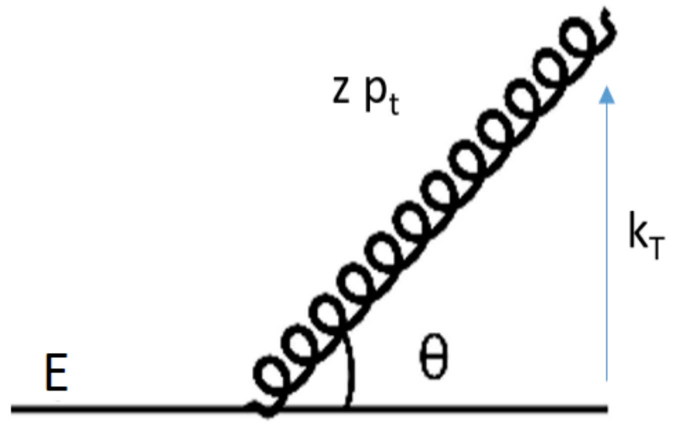
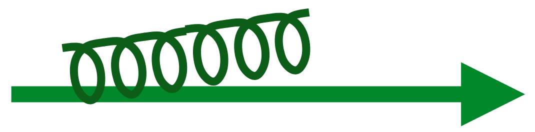


For both inclusive and charm jets:

- Iterative declustering with C/A - access to each splitting
- Fill a Lund plane with θ, k_T of each splitting
- project in θ



$\theta \sim k_T/zp_t$



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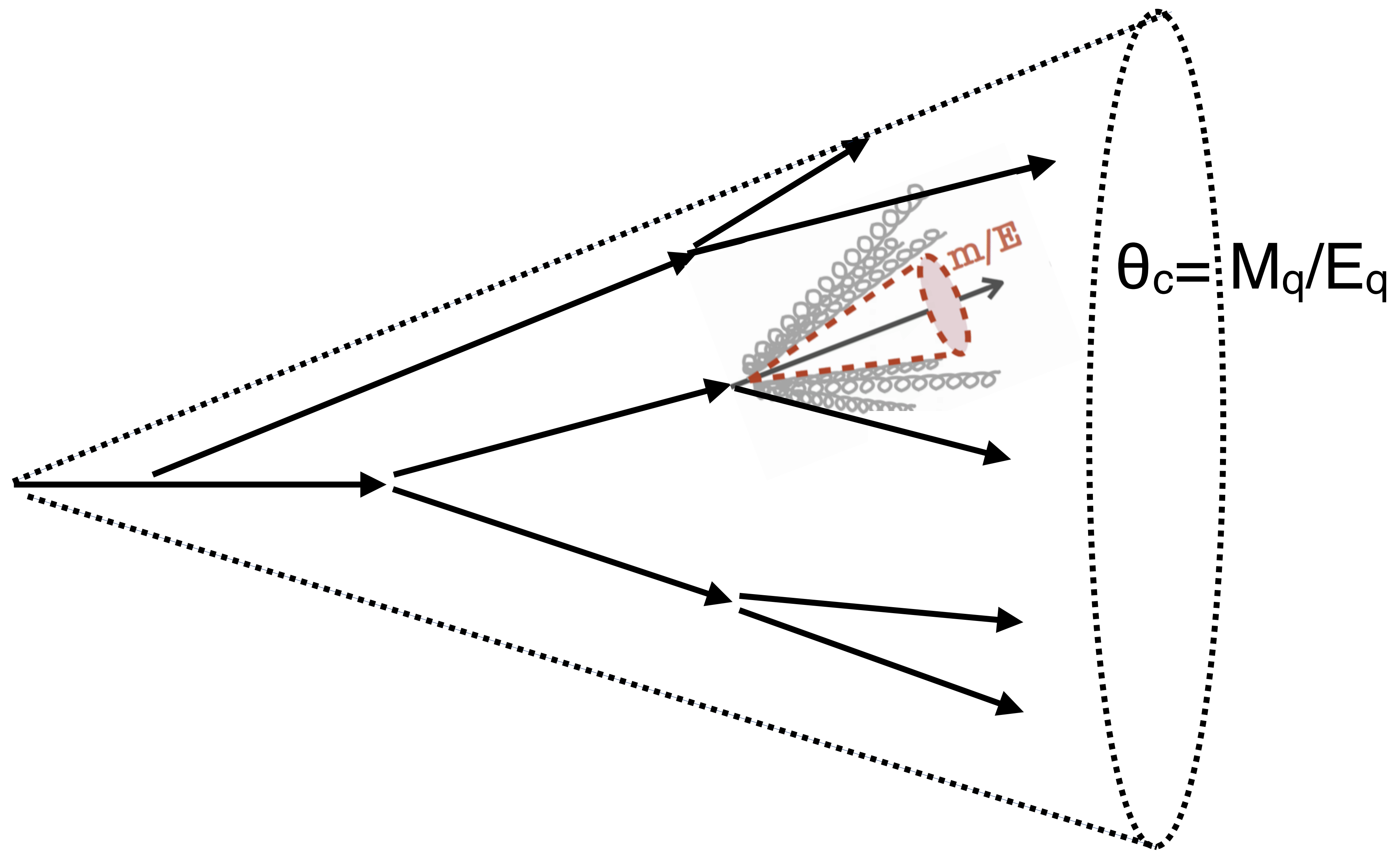

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- Iterative declustering with C/A - access to each splitting
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- project in θ

→Evidence of suppression of small angle radiation for D^0-tagged jets
"dead cone effect"

ratio of D^0-tagged / inclusive jet distributions