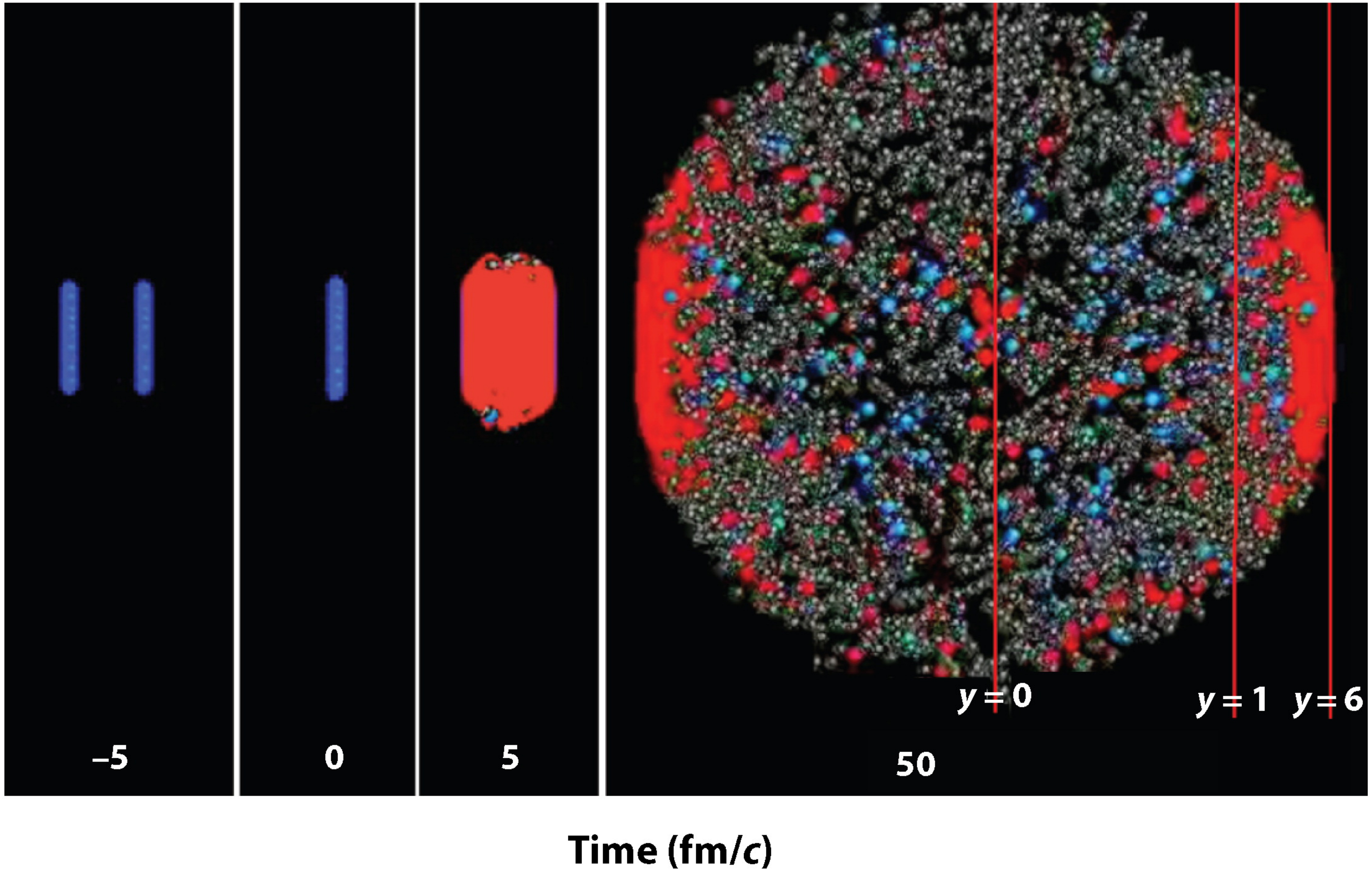
Heavy Flavour Physics with ALICE in pp and PbPb collisions

Snowmass 2021 Energy Frontier (EF07 group)

G.M. Innocenti (CERN) on behalf of the ALICE Collaboration

Quark-gluon plasma (QGP) with heavy quarks

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



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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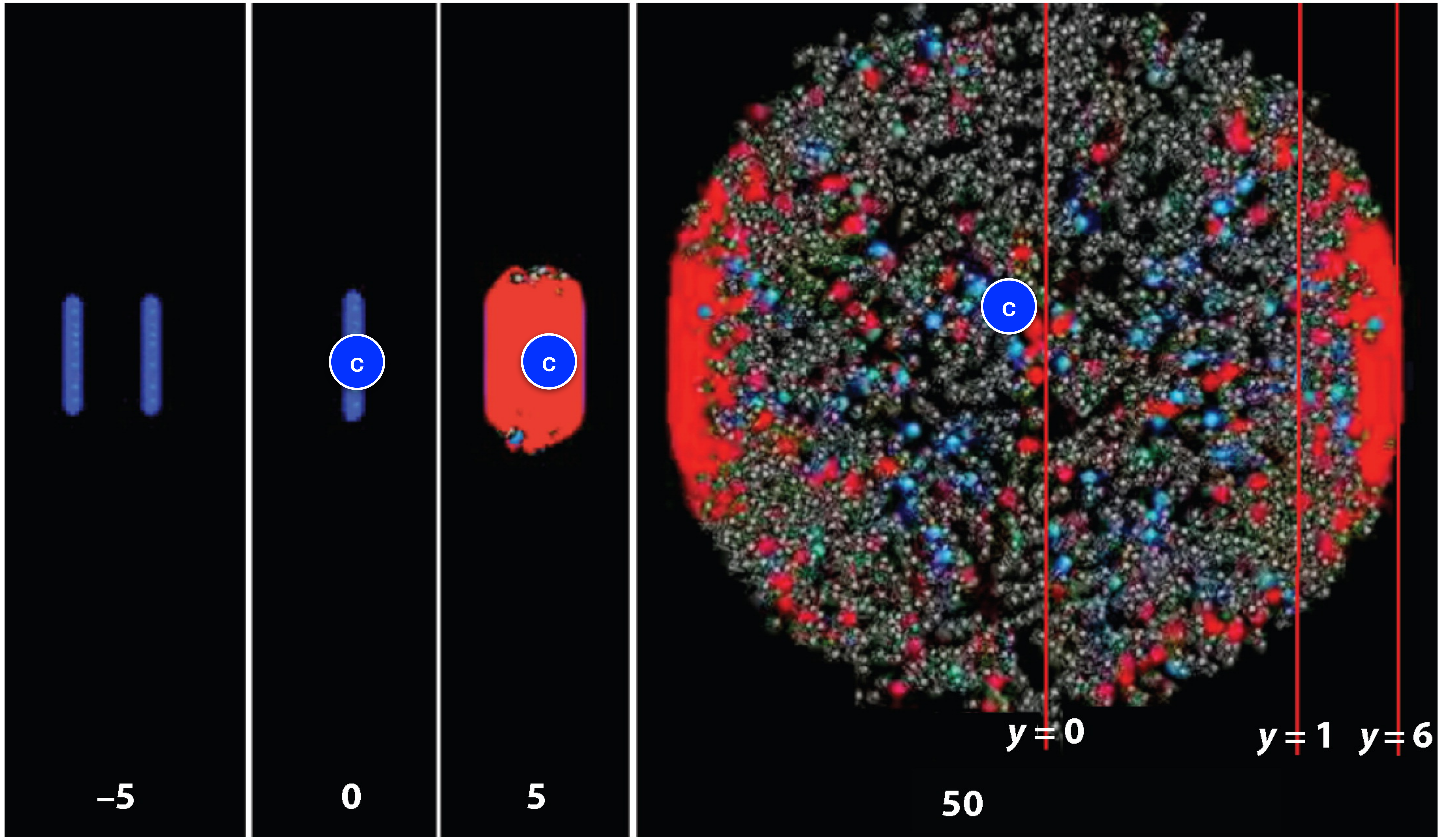
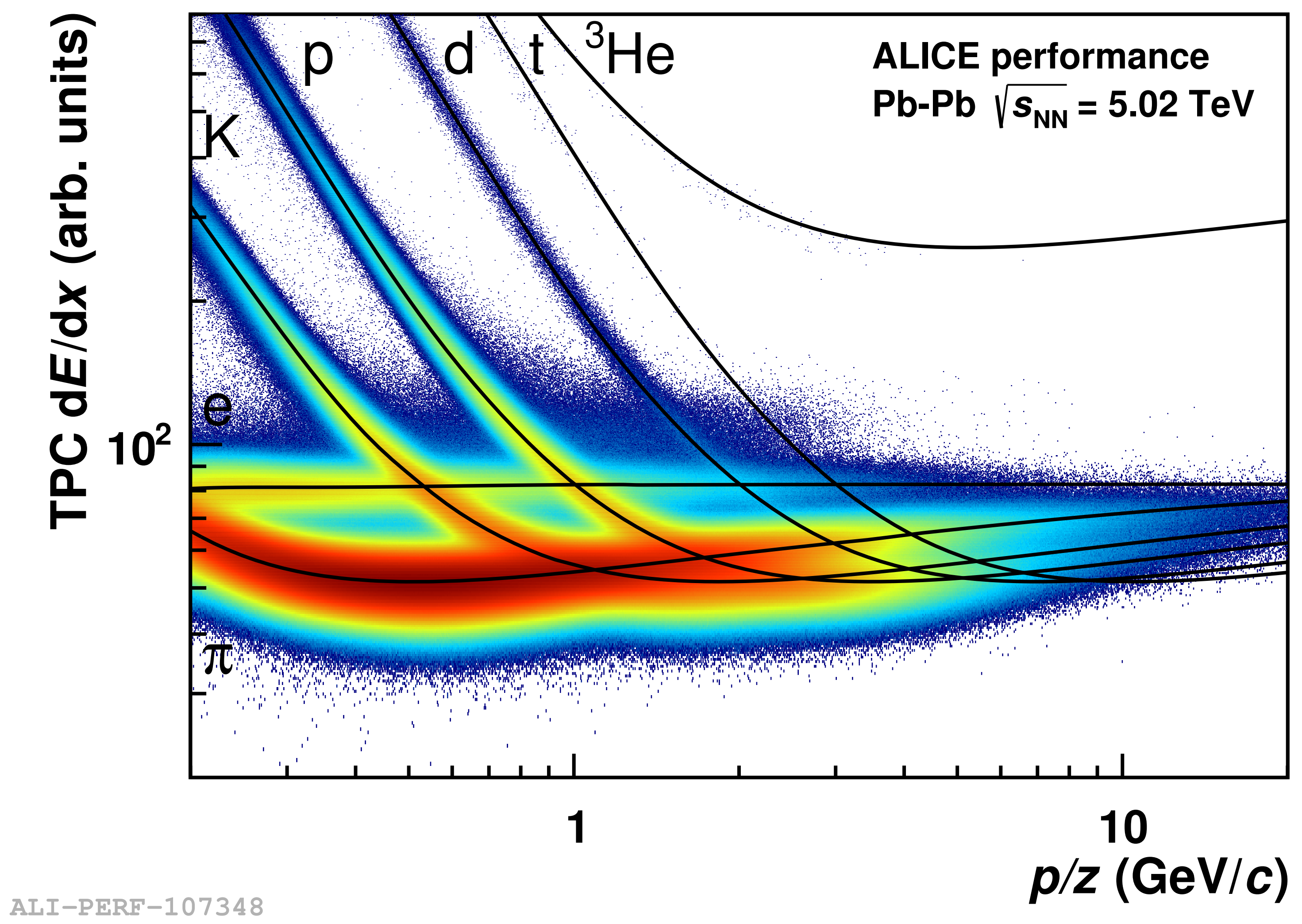
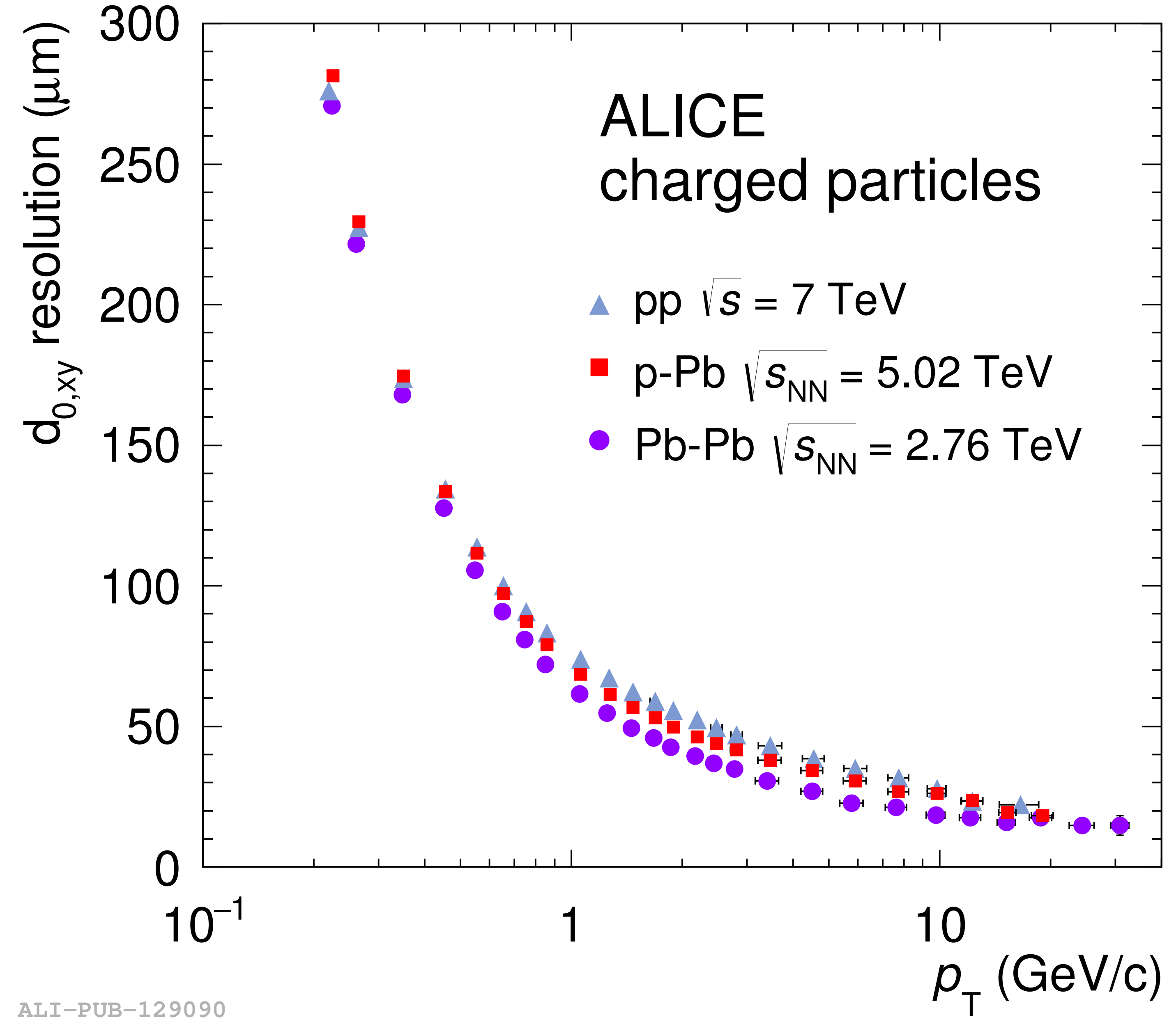


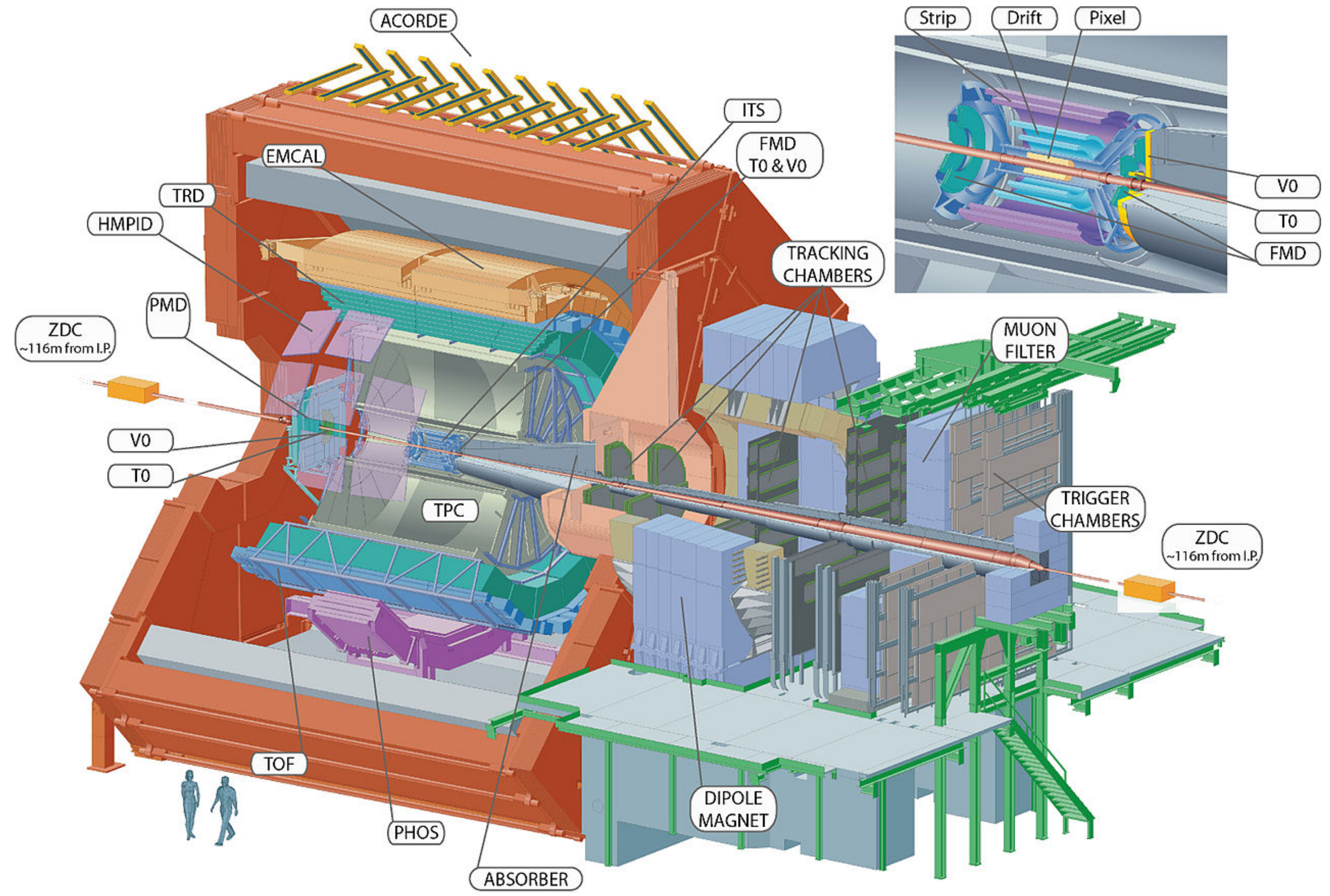
Time (fm/c)

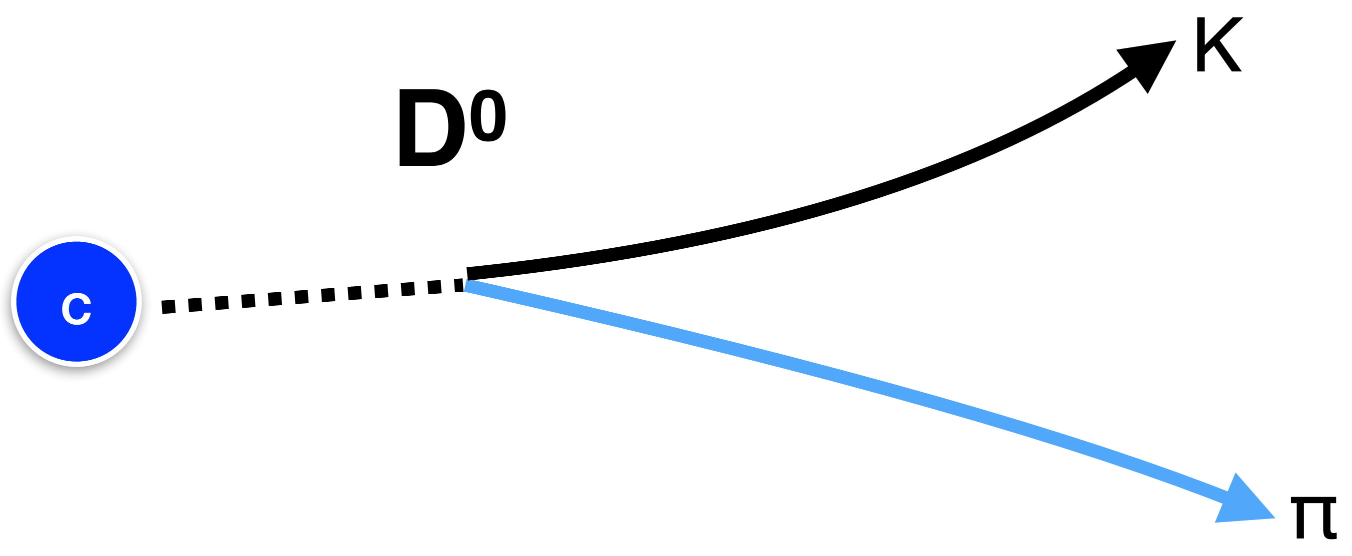
The ALICE experiment at CERN





- **High precision tracking** down to low p_T~150 MeV
- **Particle Identification** with TPC dE/dx and Time-of-Flight

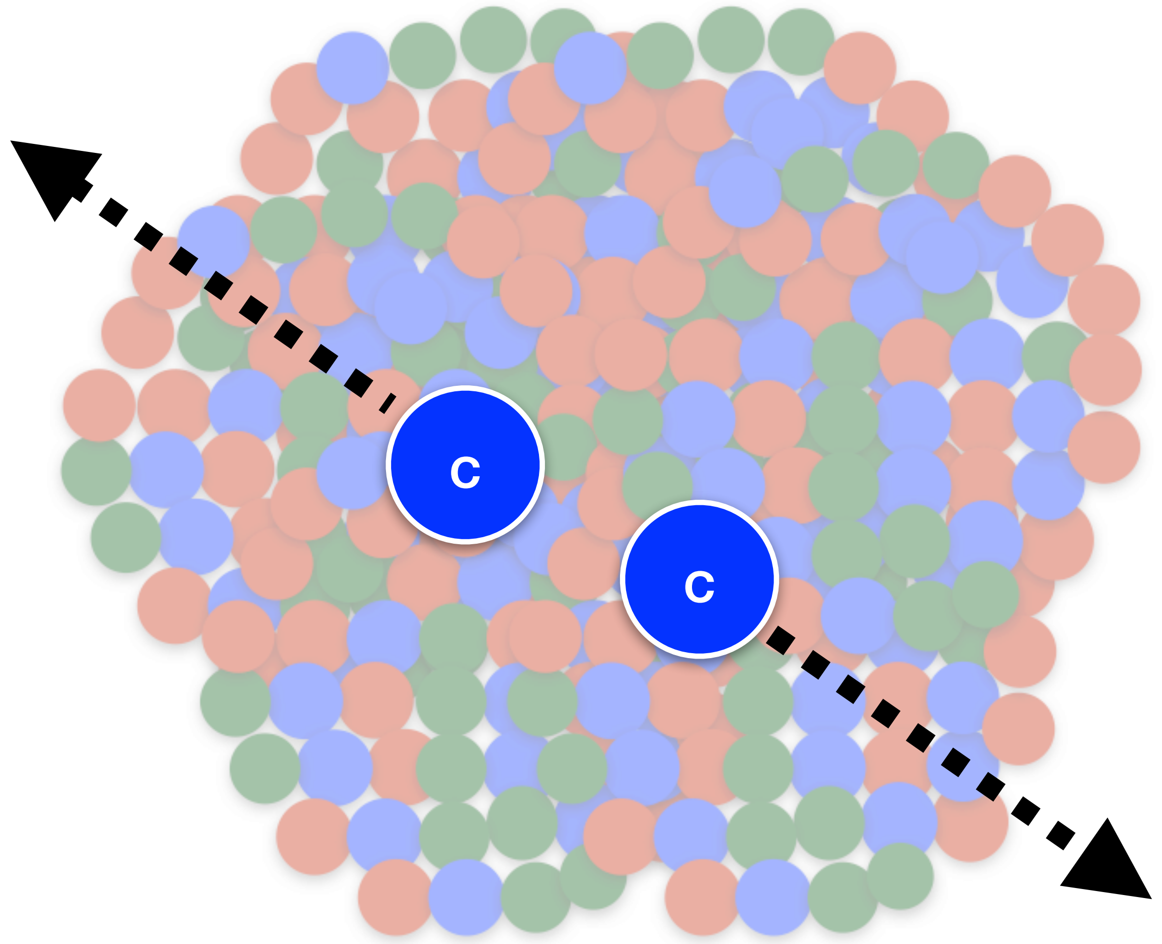




Energy loss in the medium

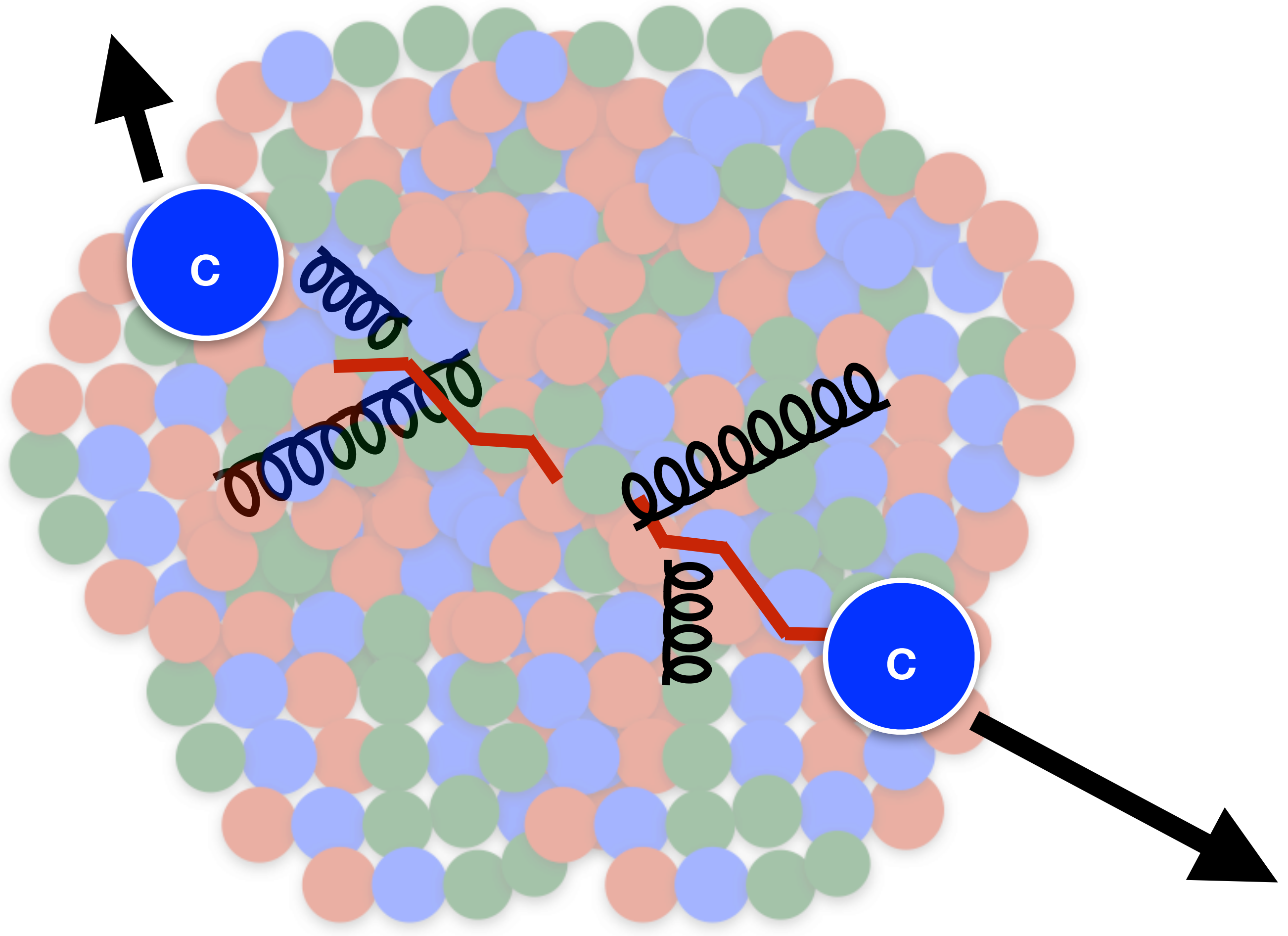
Testing the medium properties and the mechanism of quark-QGP interaction

Energy loss of heavy quarks in the QGP

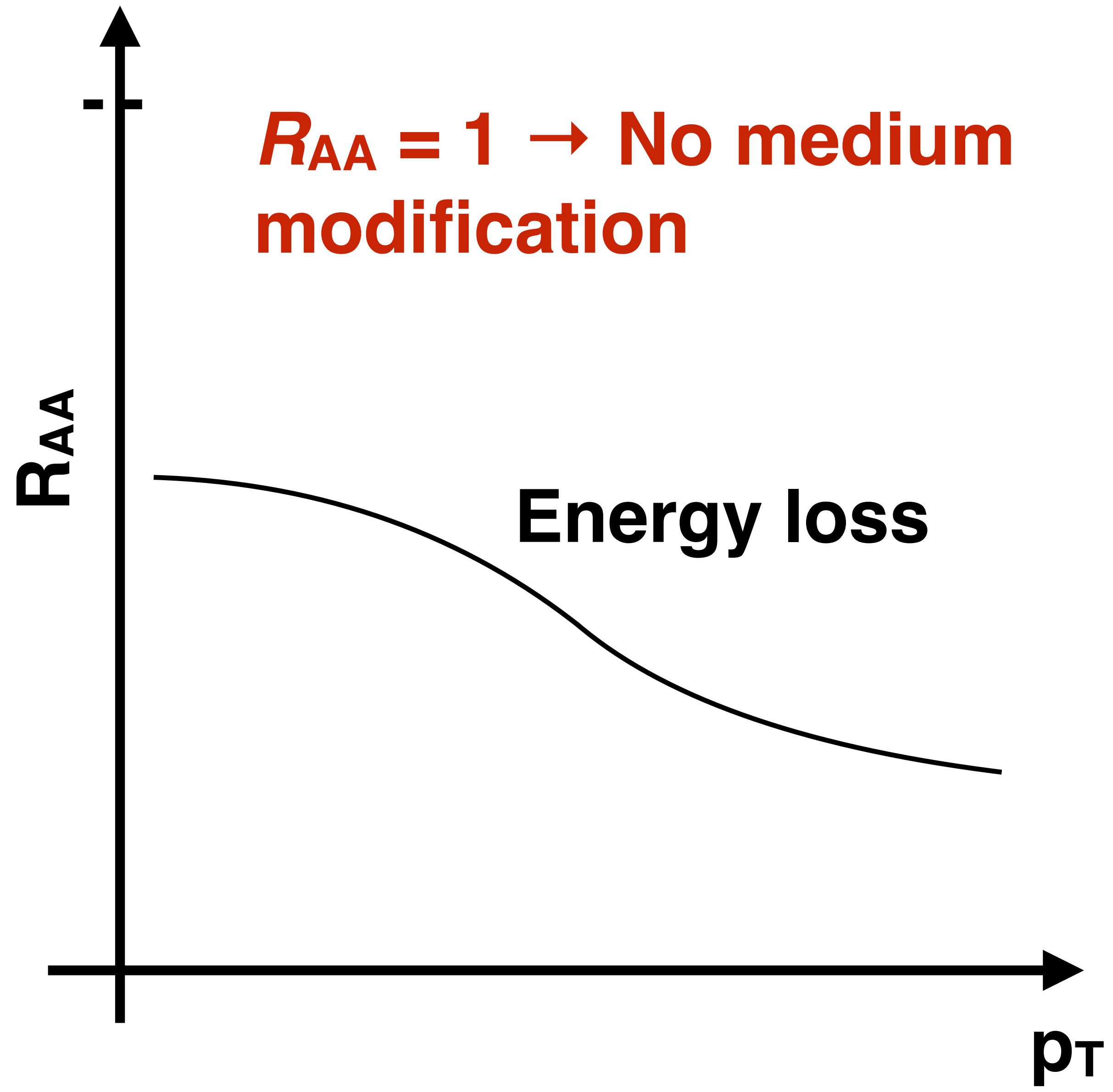


Energy loss of heavy quarks in the QGP

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



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



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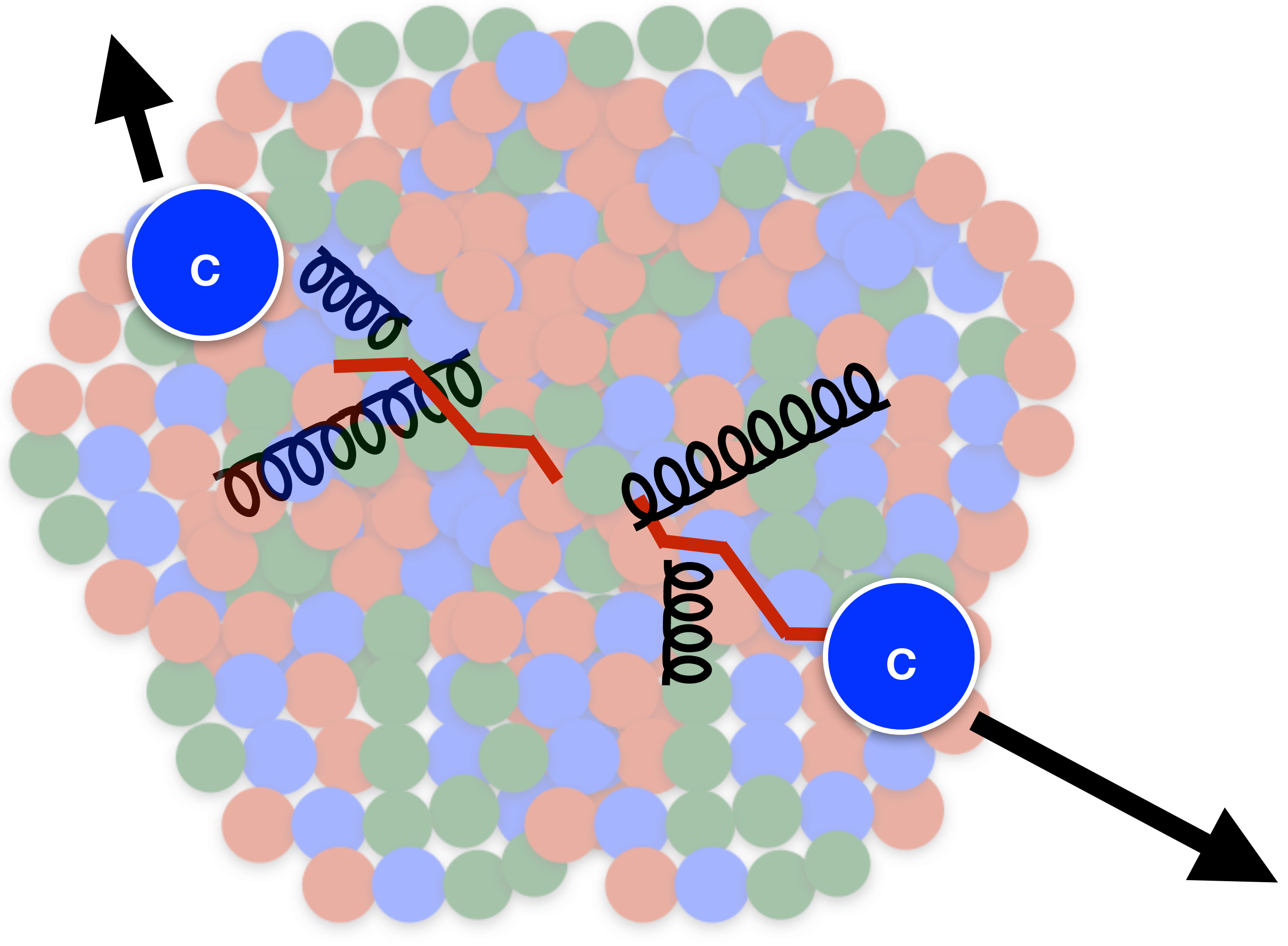

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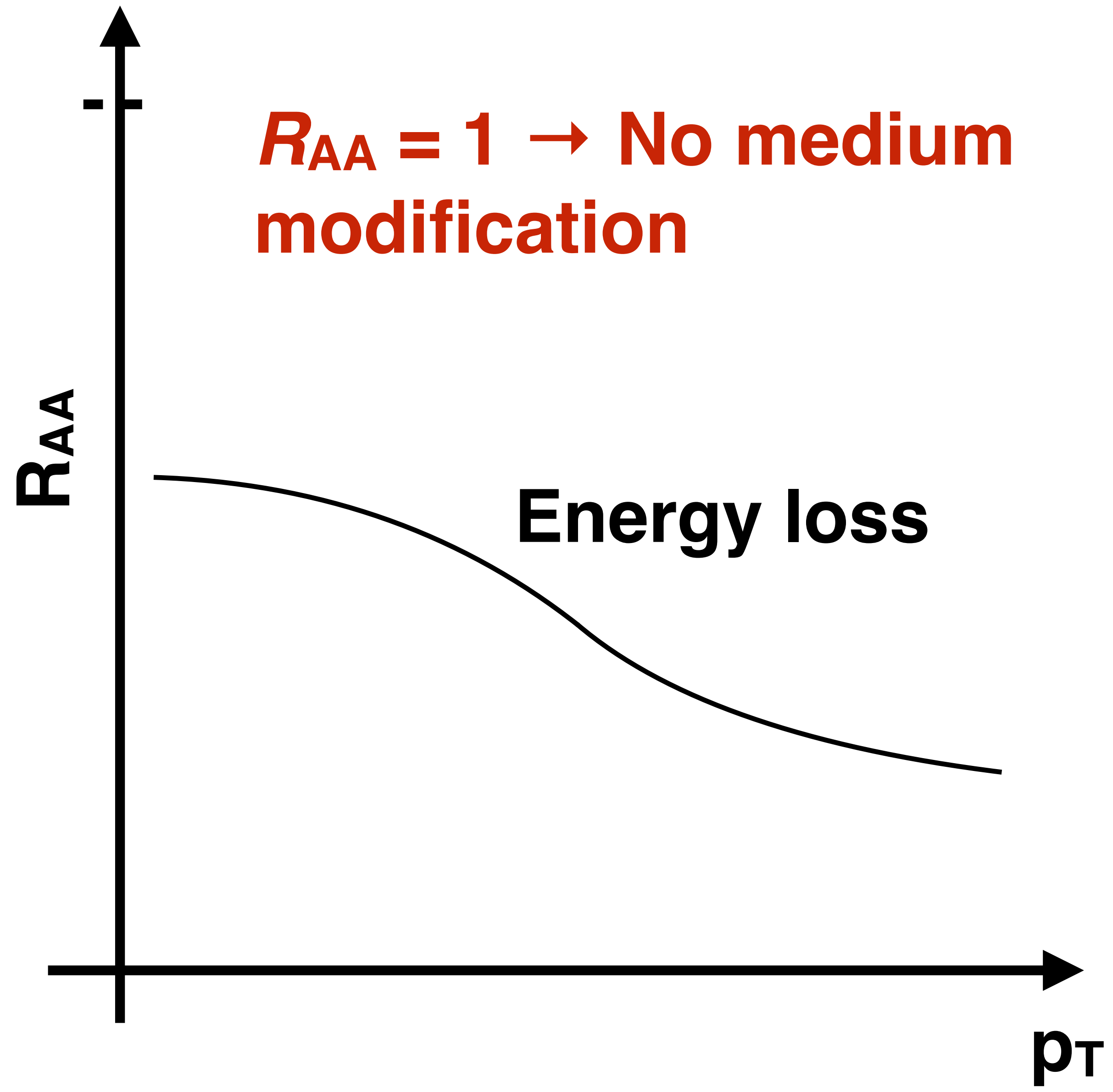
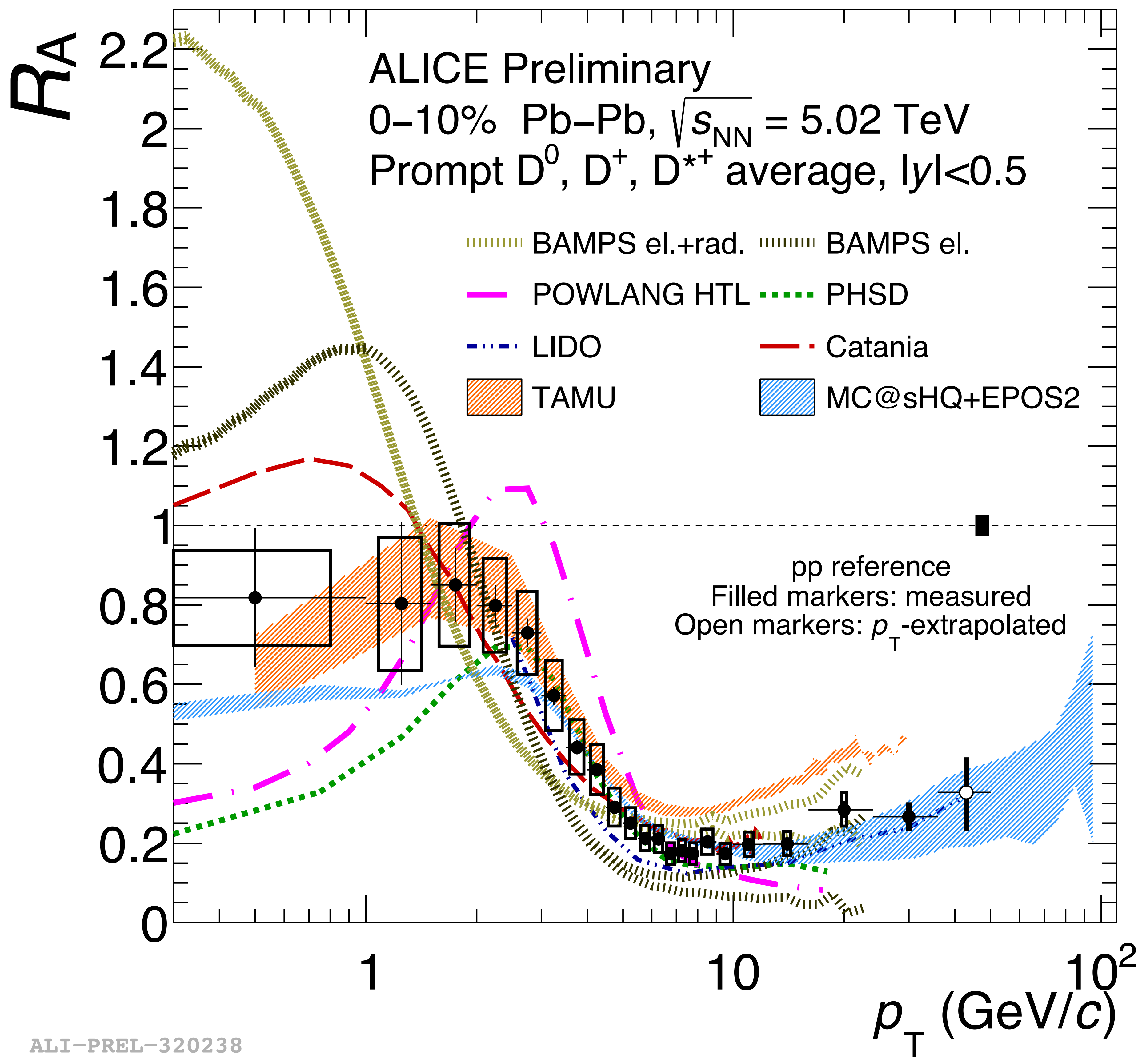
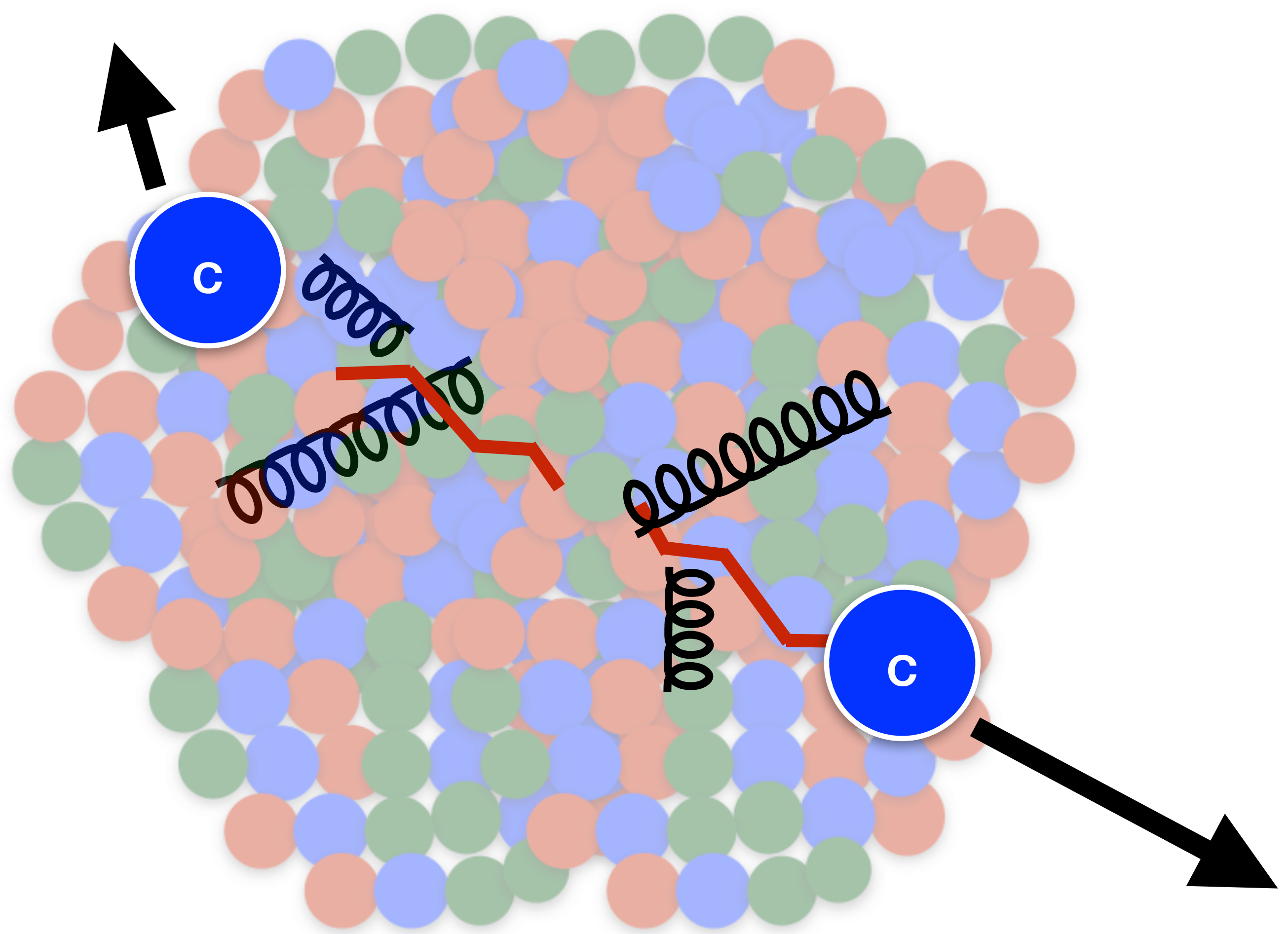


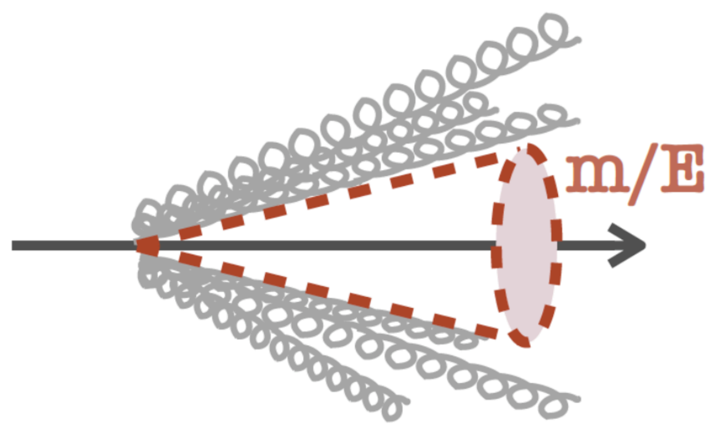


- Quantitative constraints on E_{loss} mechanisms and medium coefficients (e.g. charm diffusion Ds)
- First measurement of charm R_{AA} to 0 at LHC

Flavour dependence of E_{loss} in PbPb

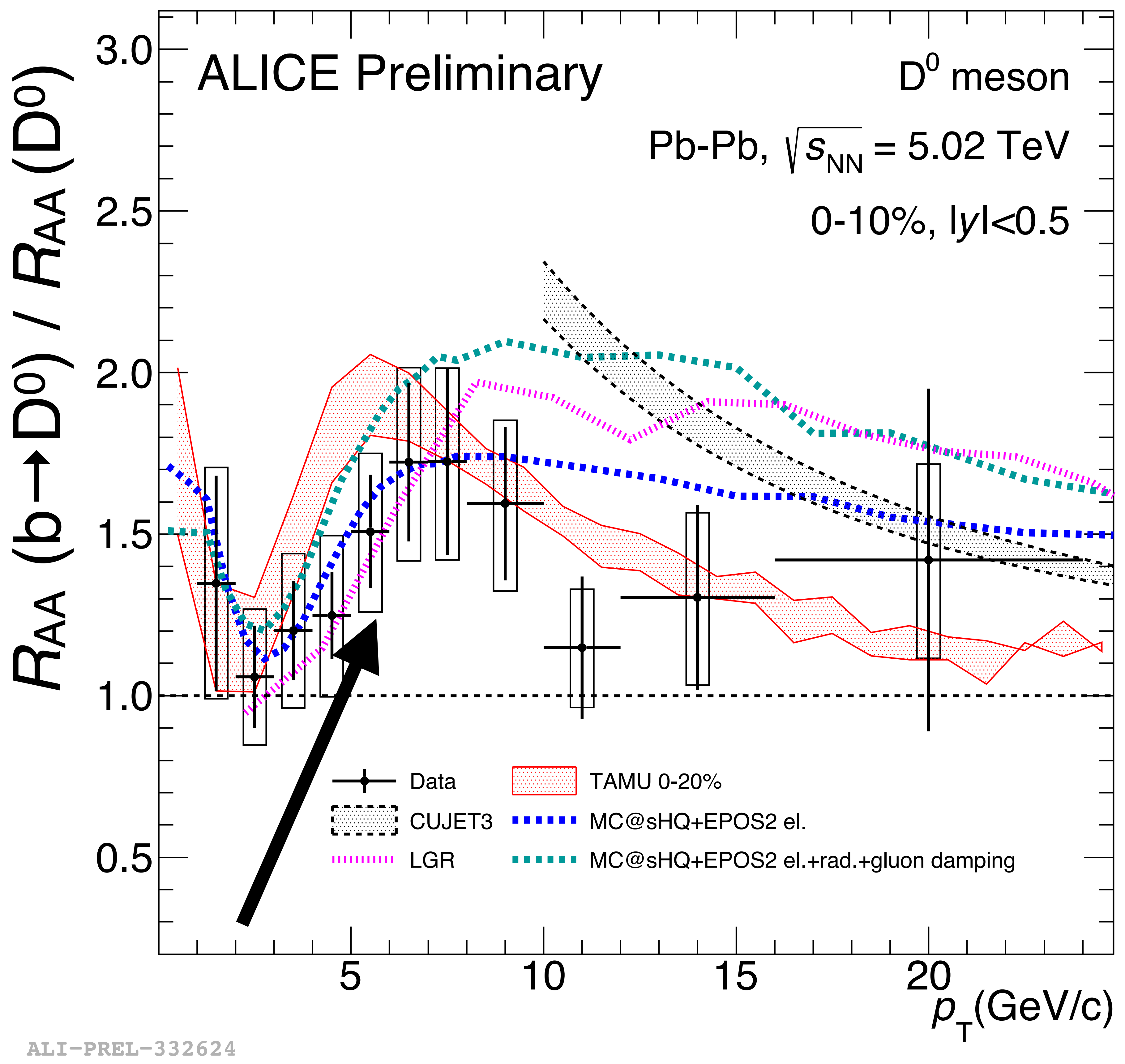


- **different Casimir factors** for quarks vs gluons
- **“dead” cone** effect:



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

R_{AA} (b→D) > D meson



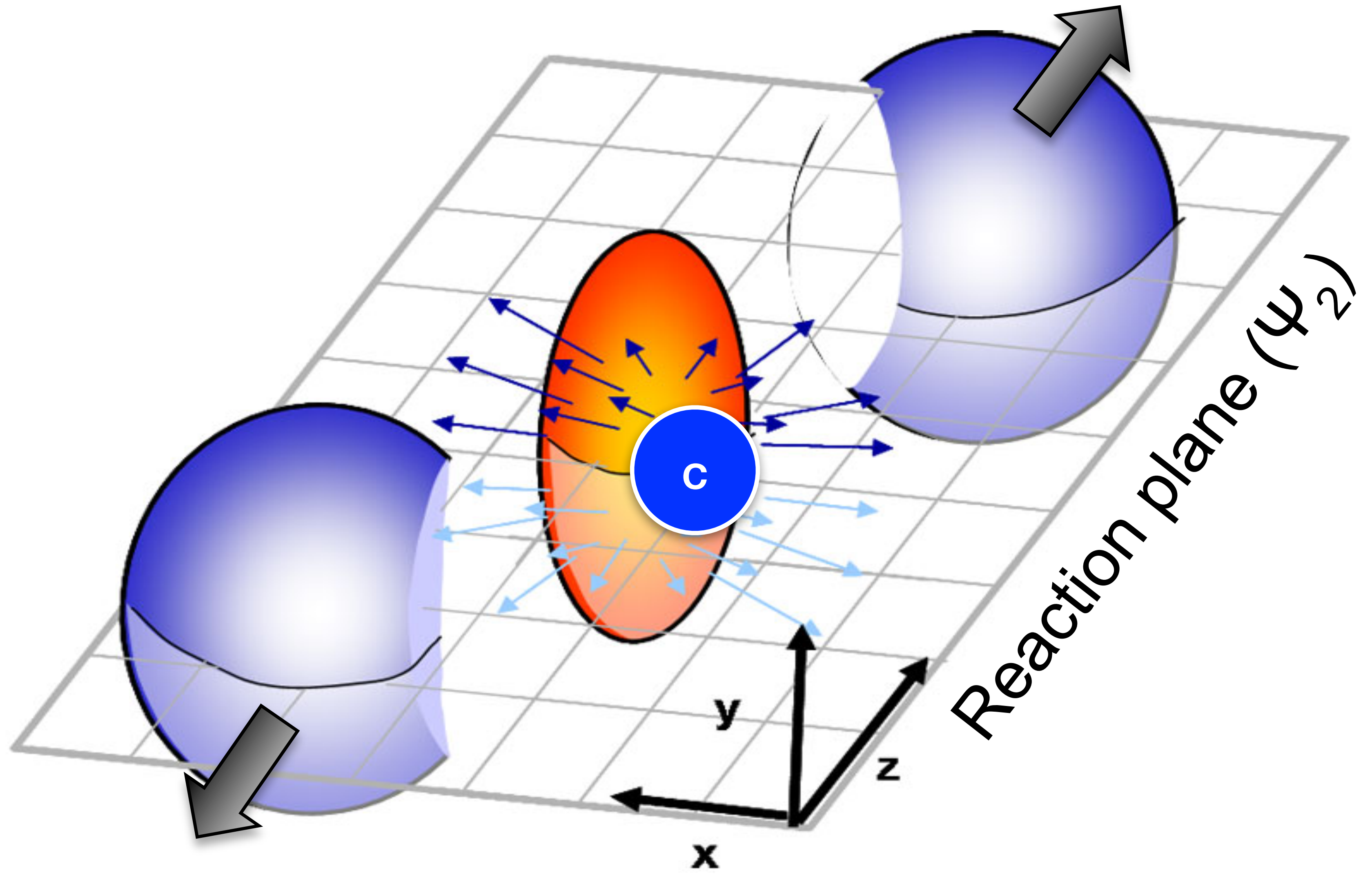
- Described well by calculations that include different E_{loss} for beauty and charm quarks

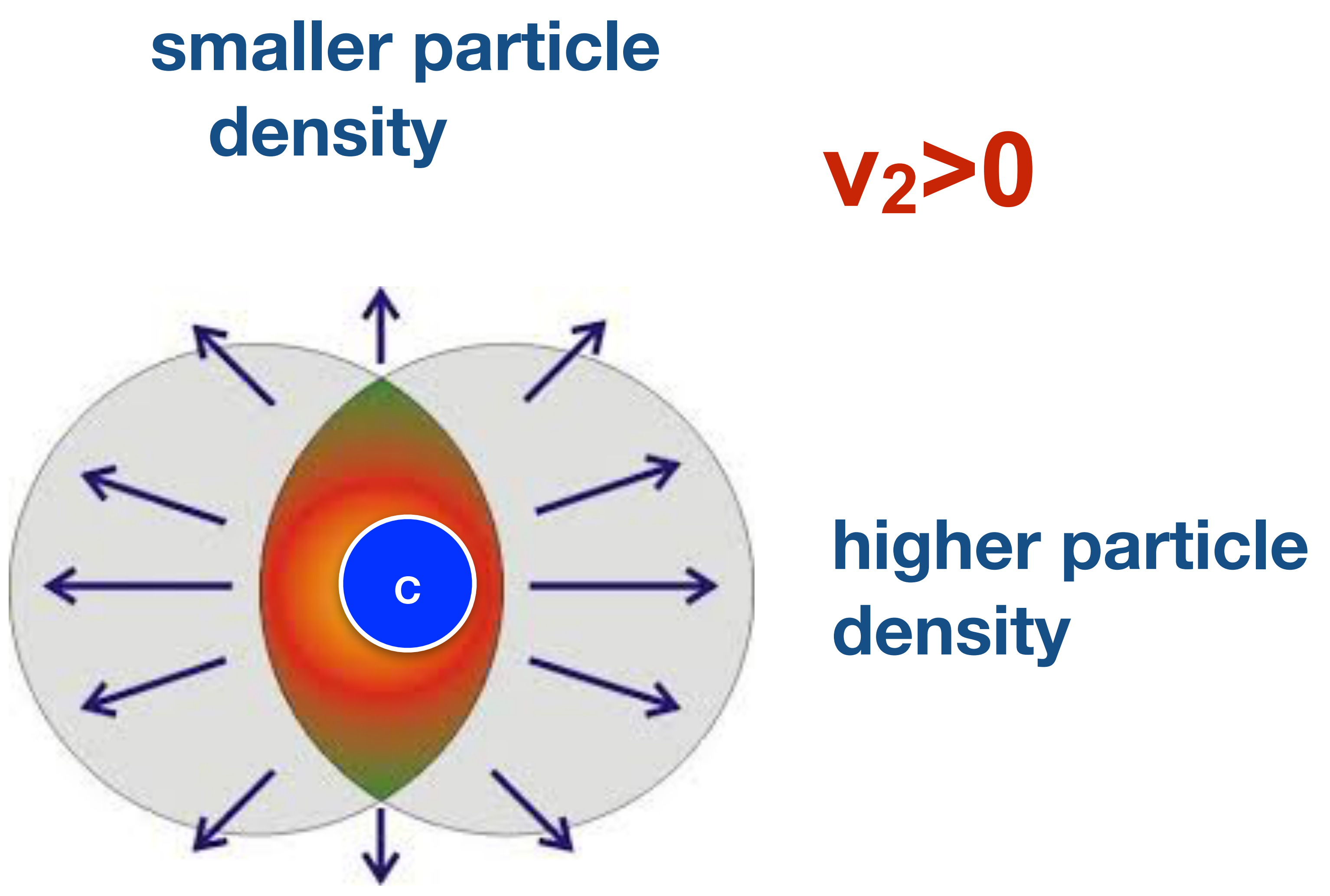
→ Hint of flavour dependence of in-medium energy loss

Collectivity in PbPb collisions:

Testing the collective behaviour of the medium

Heavy-flavor “flow” in PbPb collisions





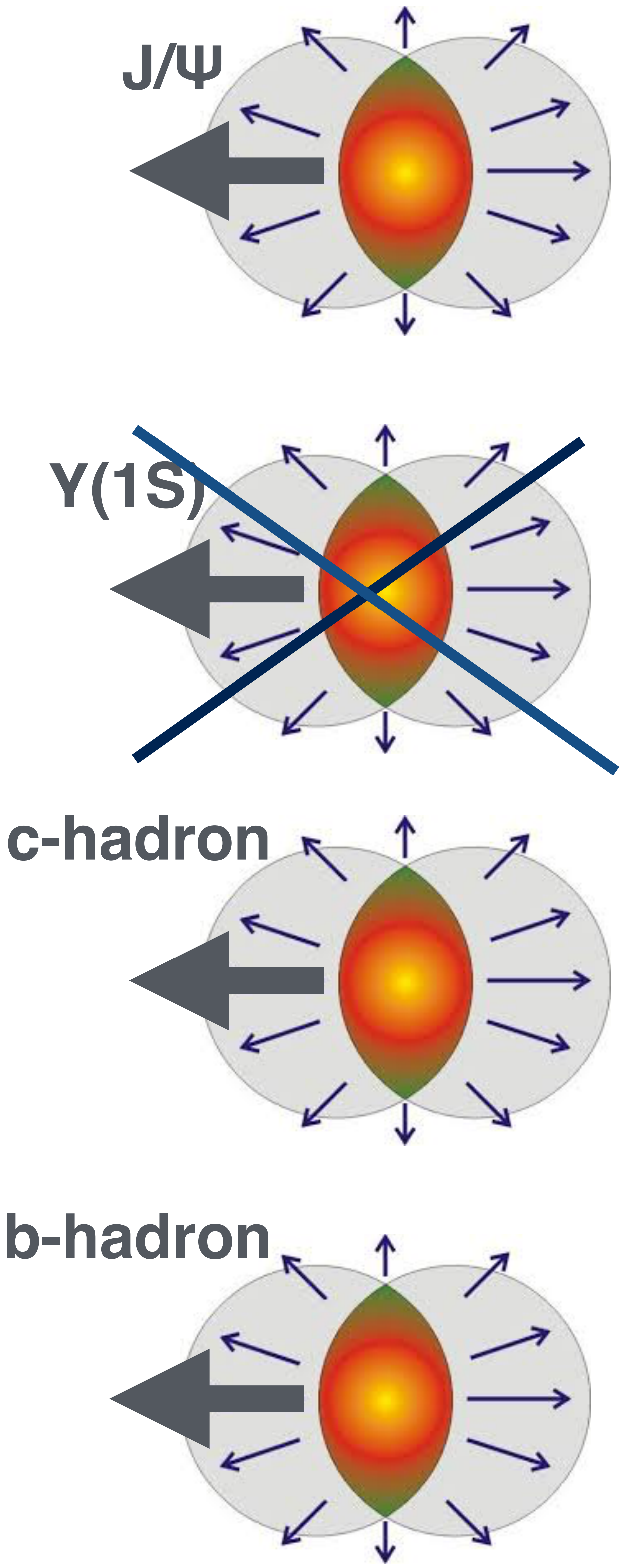
In the presence of a strongly interacting medium:

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

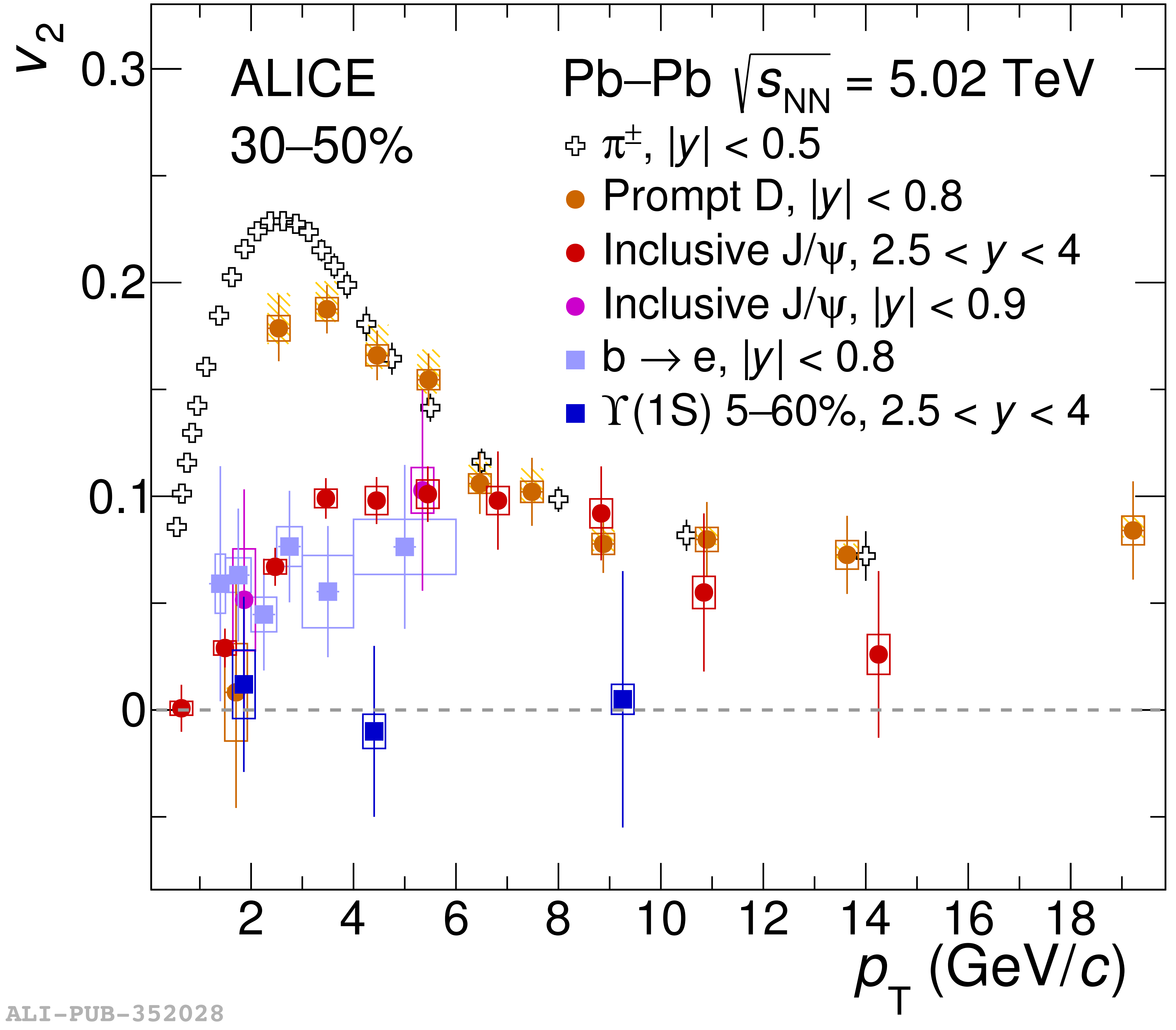
→Large v_2 at low p_T suggests collective expansion of the medium

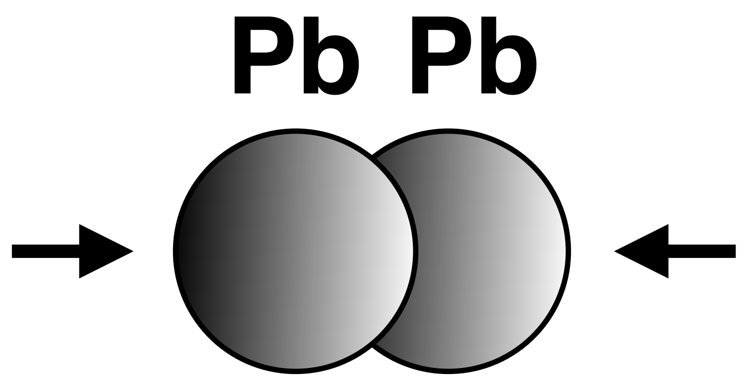
→Are heavy quarks sensitive to the medium expansion?

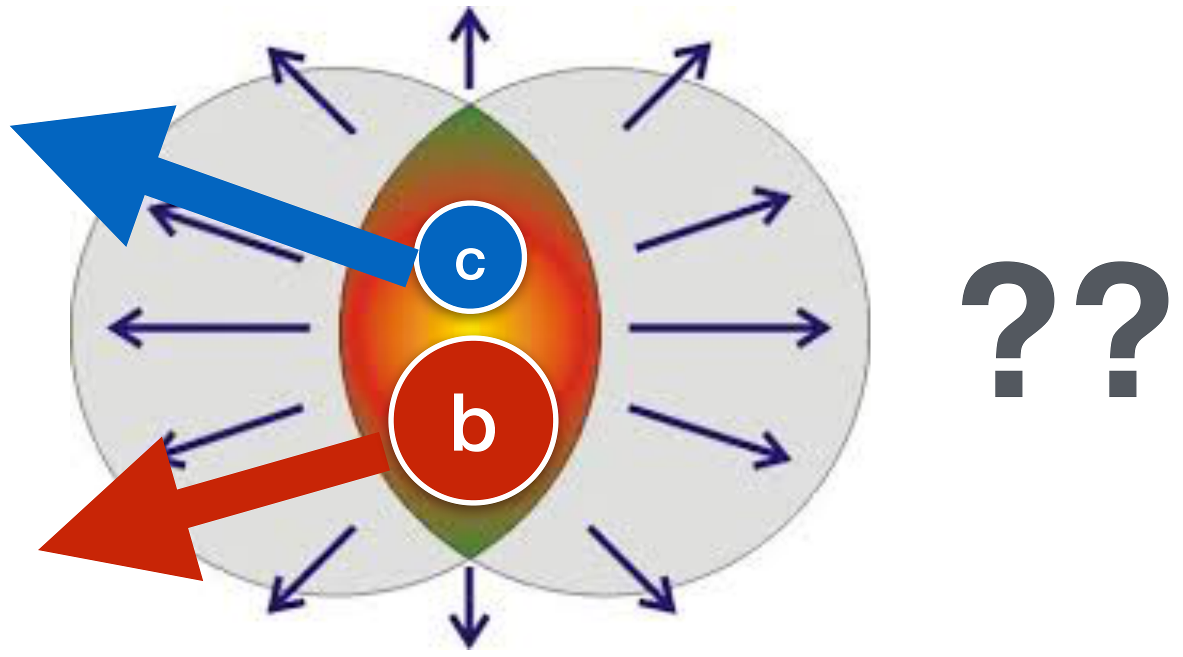
Charm and beauty "flow" in AA collisions



arXiv.2005.11130







New v_3 measurements recently presented!

→ seems likely that the charm quarks are "flowing"

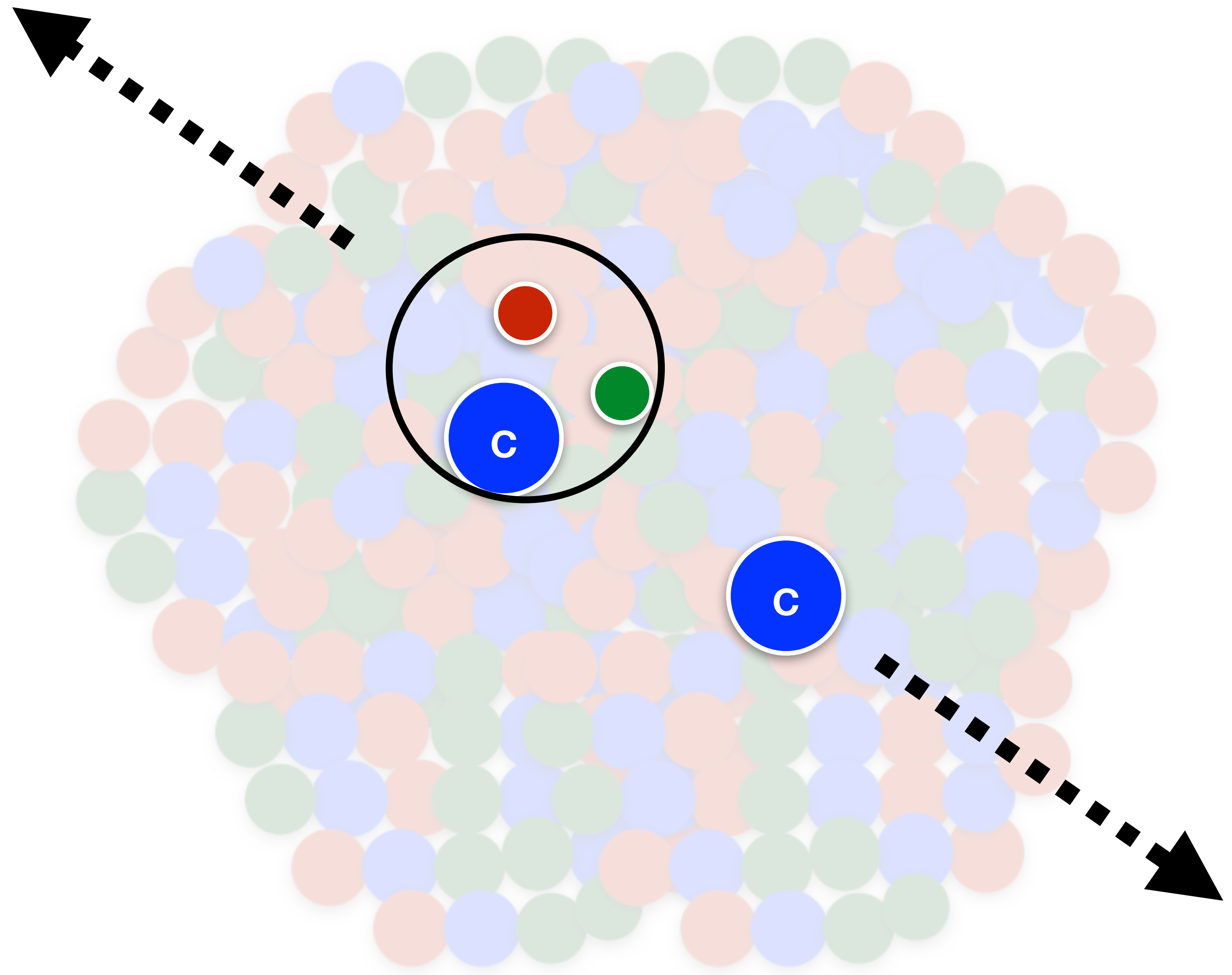
→ v_2> 0 for open beauty and ~ 0 for bottomonium! More high precision data from low to high p_T needed!

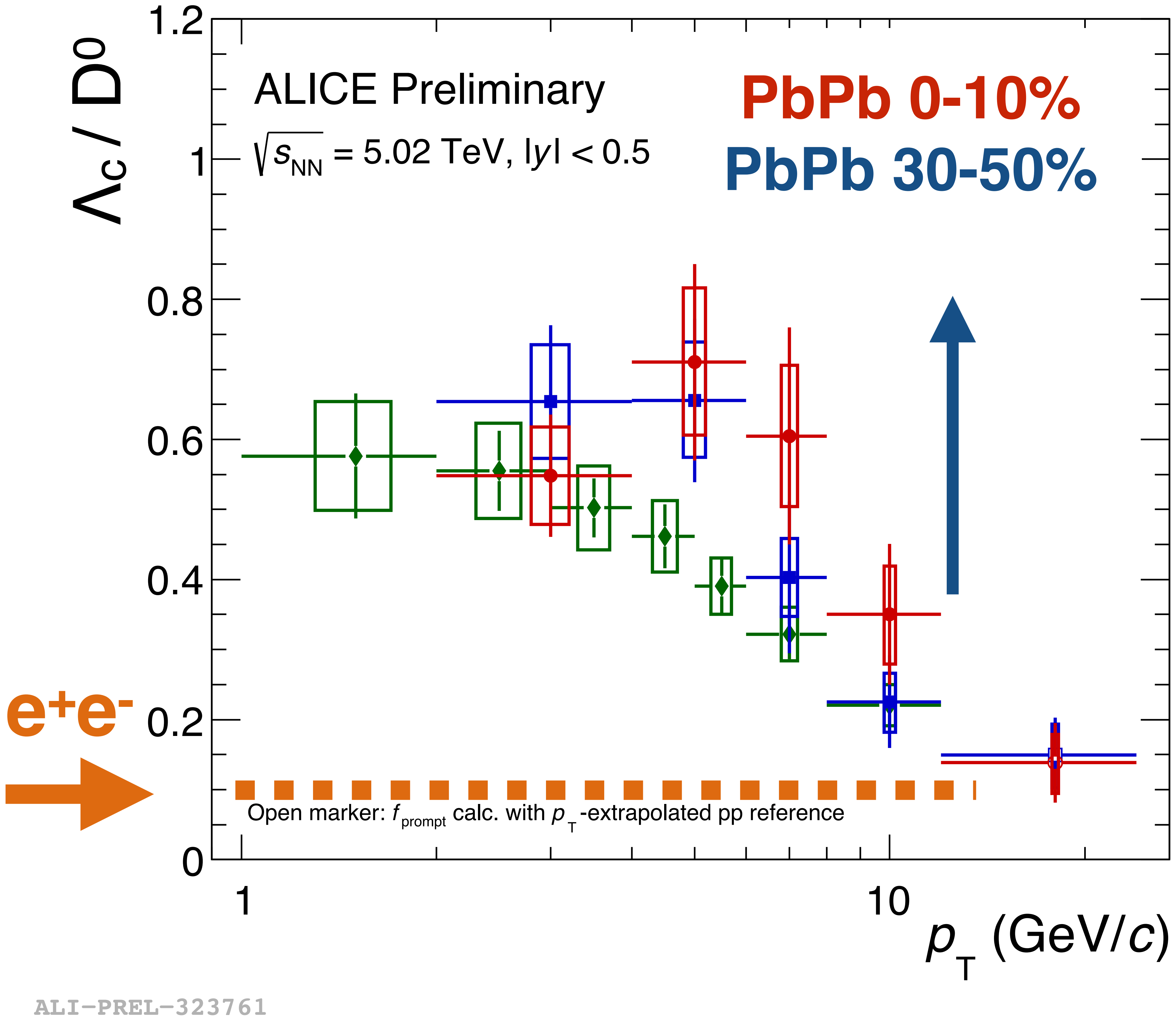
HF particle ratios:

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

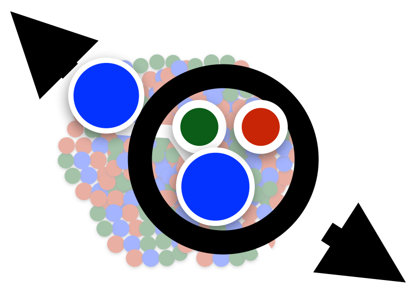


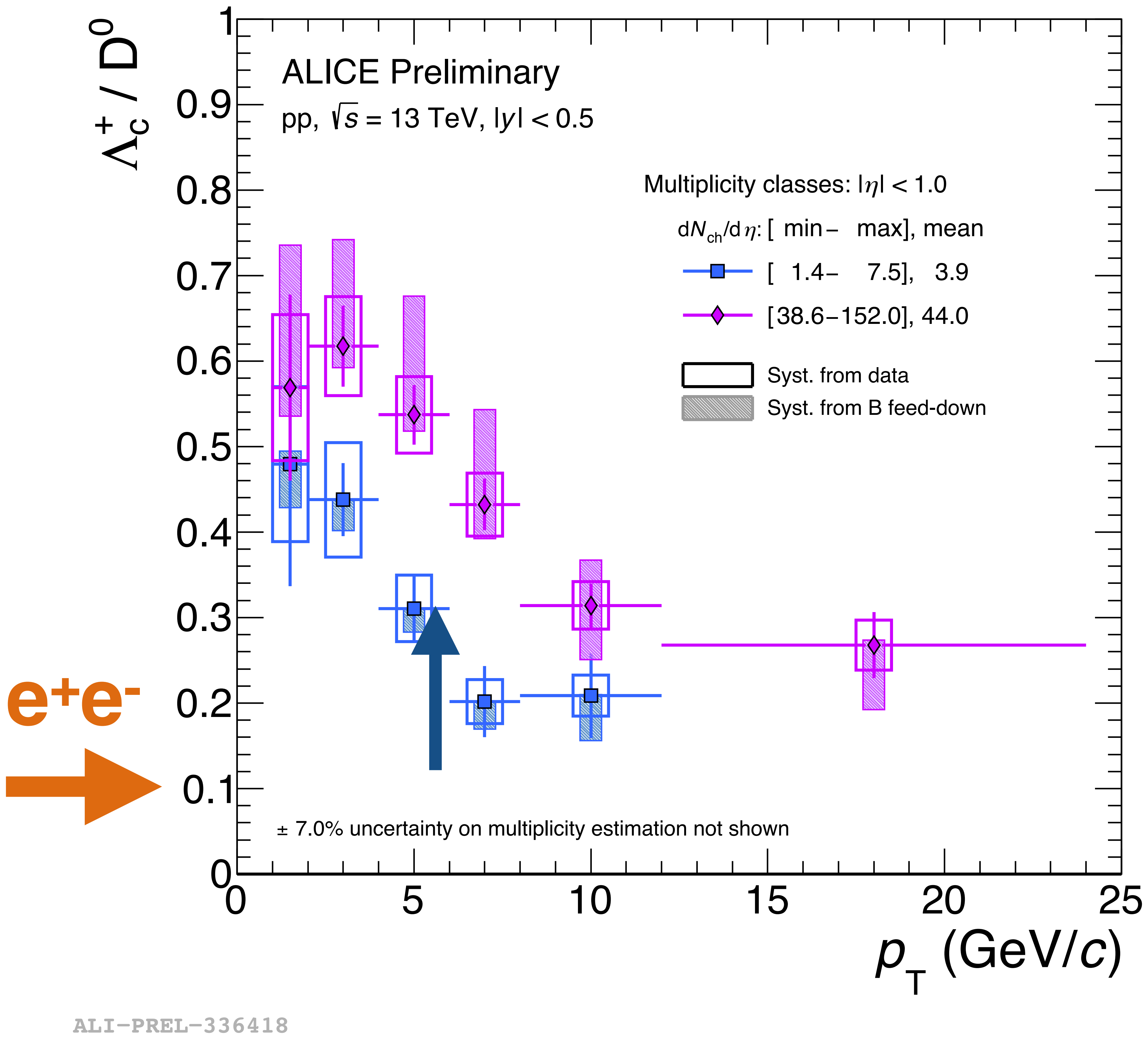


- **Moderate enhancement from pp to Pb-Pb** at intermediate p_T within uncertainties

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

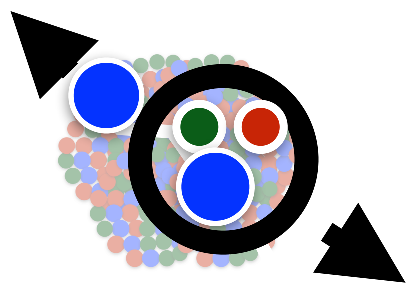
Modification of hadronisation in pp collisions?

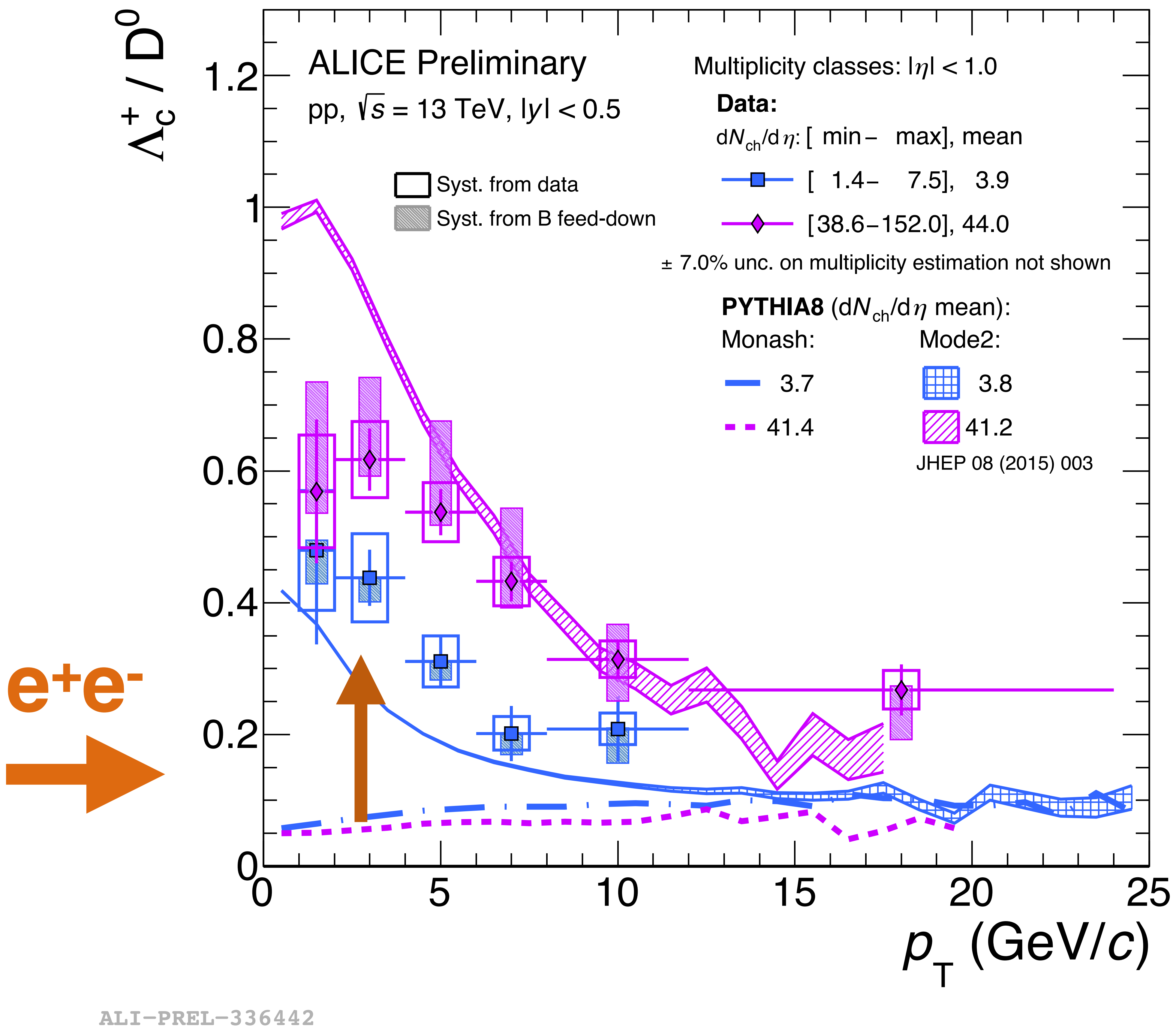




- Λ_c/D^0 shows an increase from **low multiplicity pp** to **high multiplicity pp**
- **large increase from e^+e^- to pp**

Modification of hadronisation in pp collisions?





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

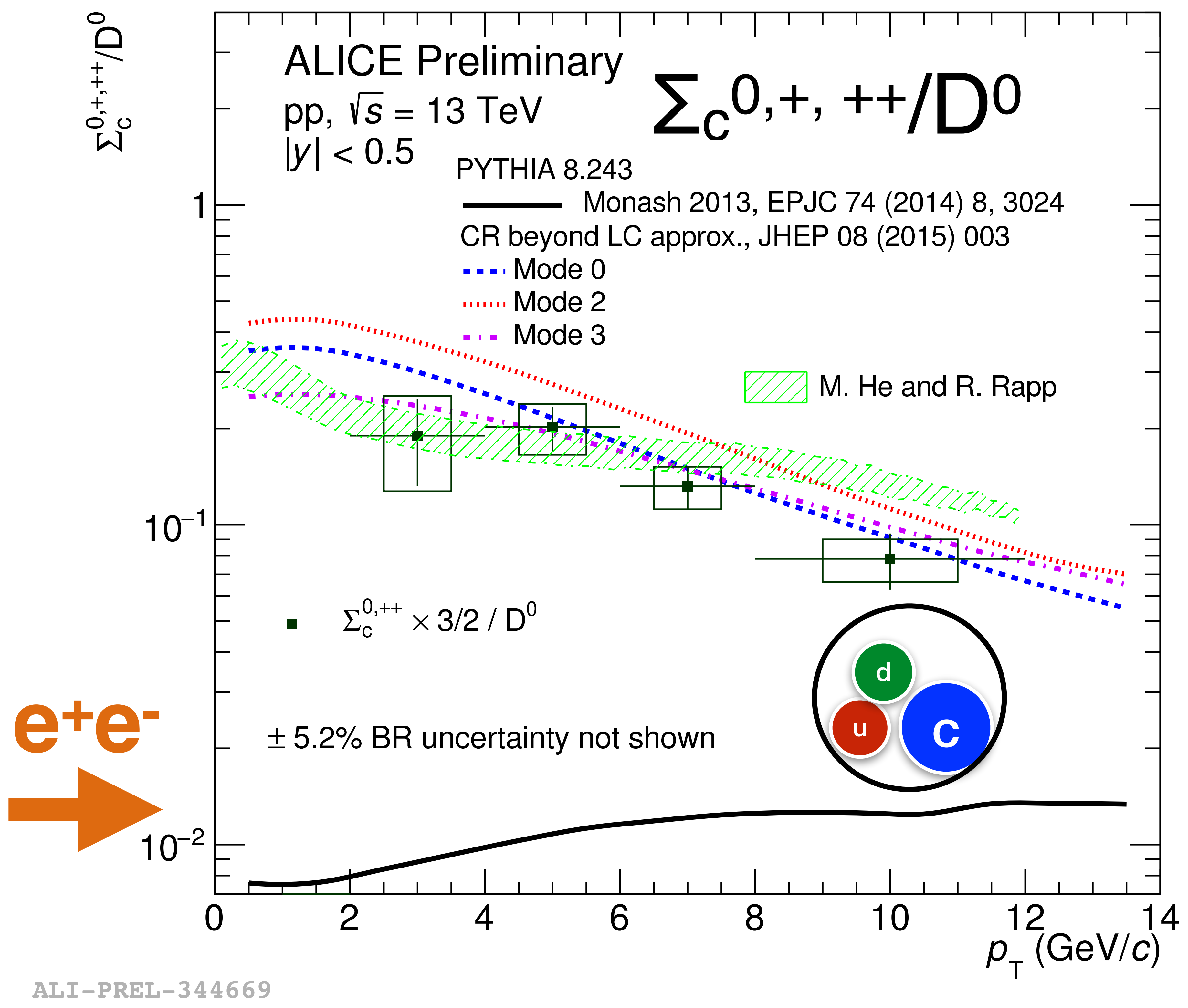
→ Significant modification of the hadronisation process already in pp collisions **driven by multiplicity**

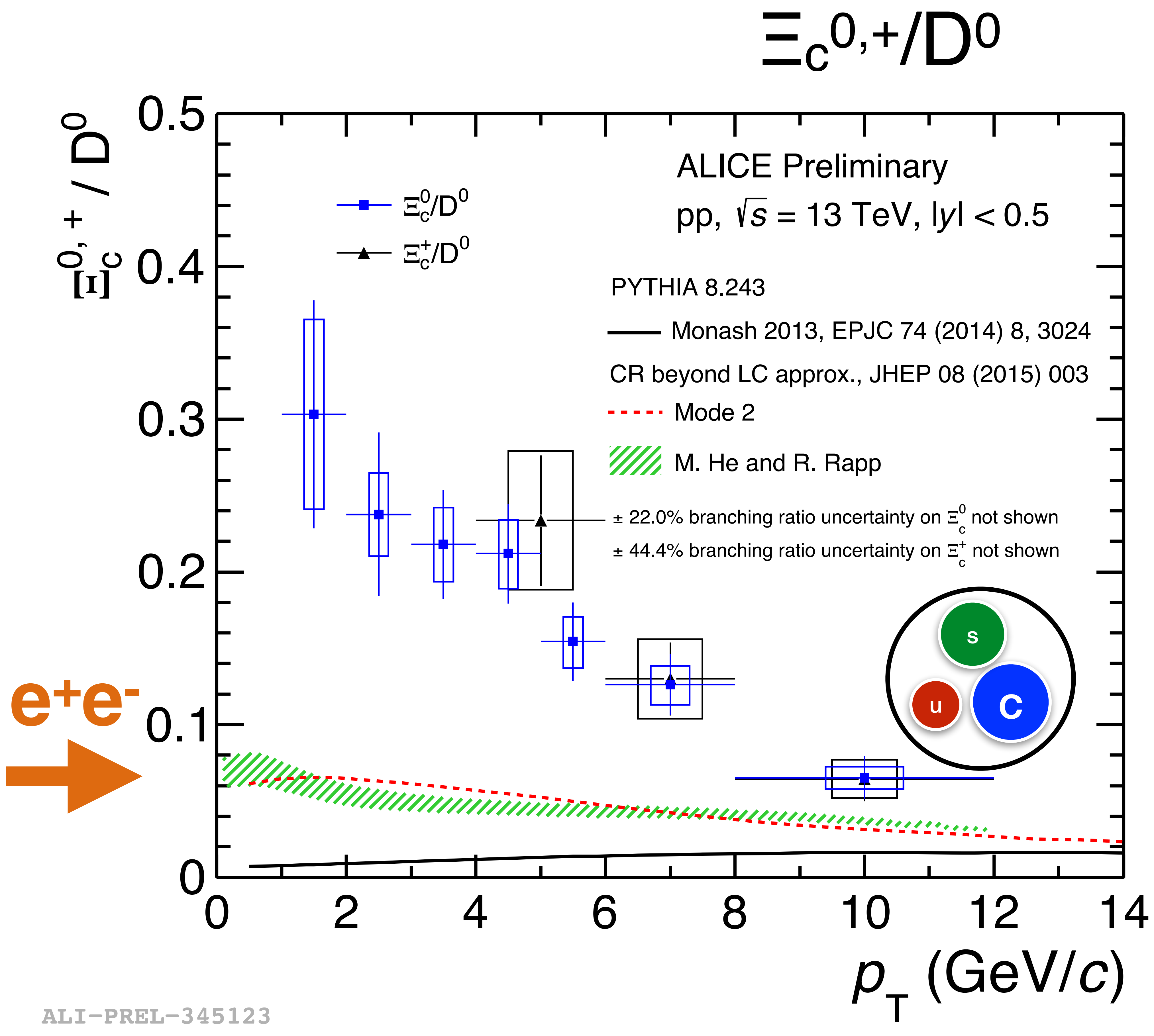
→ **Alternative mechanisms without hot medium can explain the observed enhancement?**

New experimental probes for HF studies

Stronger constraints with heavier baryons

First studies being carried out in **pp collisions** with Σ_c^0 and Ξ_c^0





- 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 insights into PbPb system with Run3 measurements!**

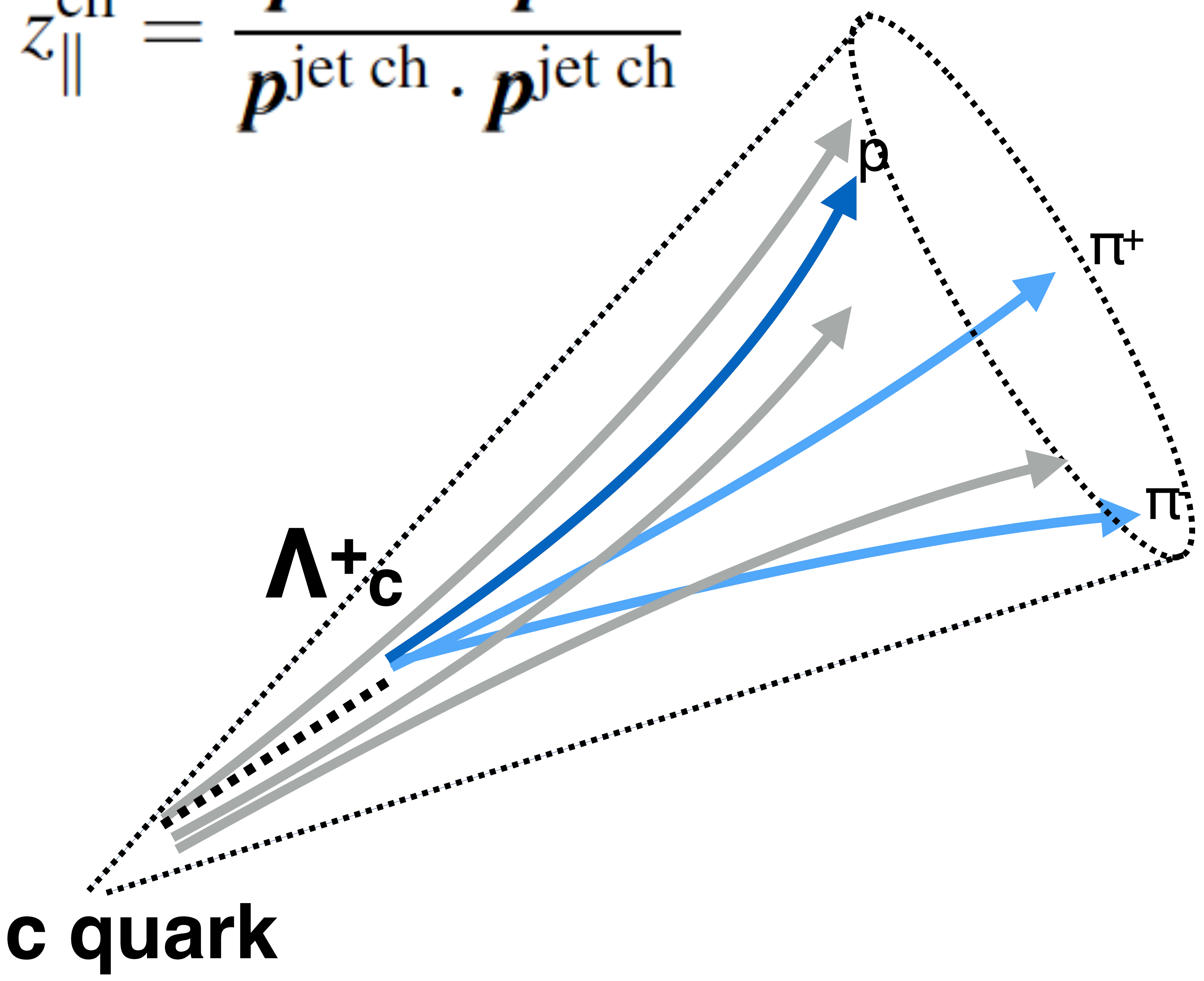
HF-chemistry in-jet for hadronisation studies

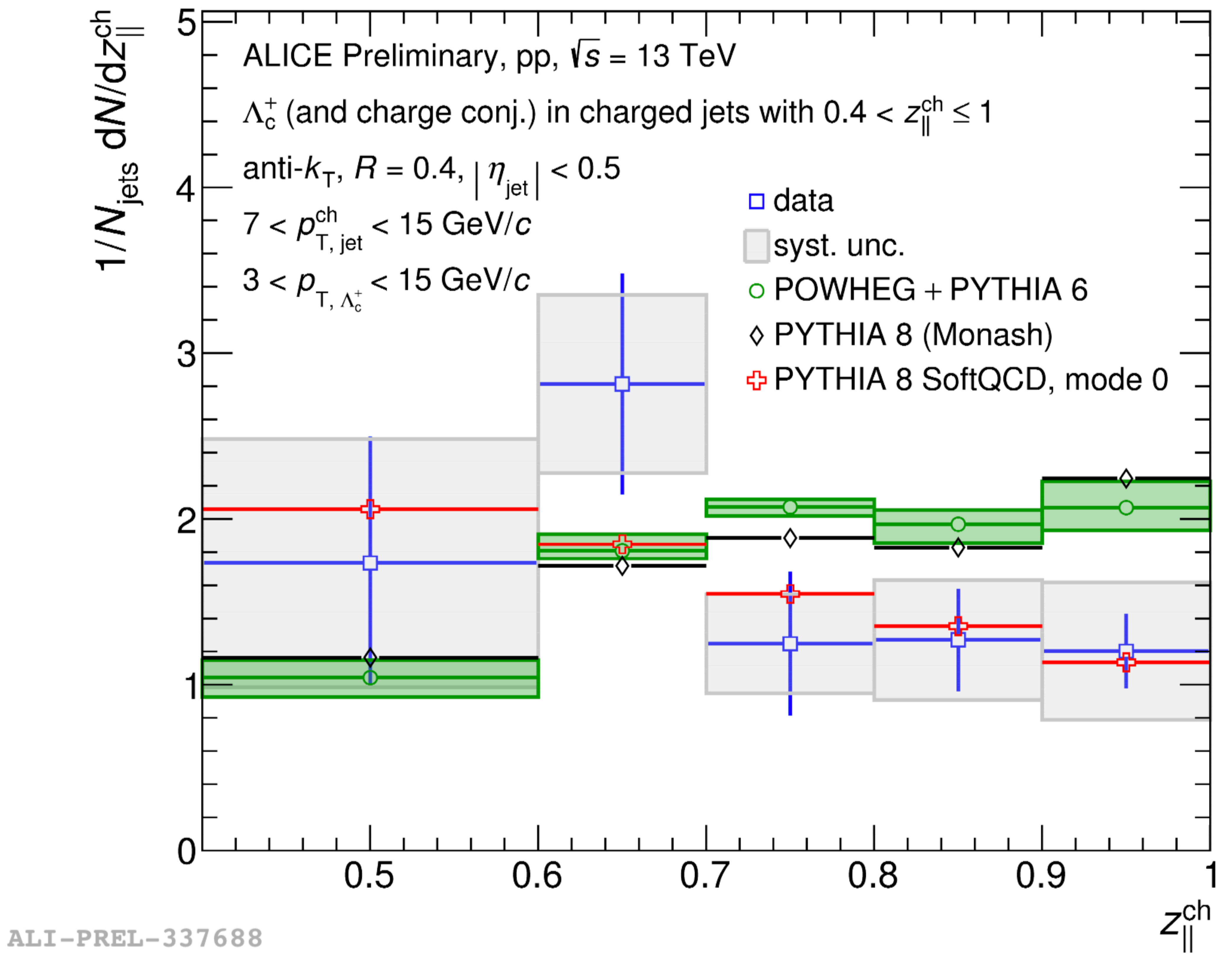
HF-tagged jet provide a reference for the energy and direction of the initial charm quark

• stronger constraints of the hadronisation process!

First measurement of Λ_c fragmentation at LHC

$$z_{\parallel}^{\rm ch} = \frac{\boldsymbol{p}^{\rm jet\ ch} \cdot \boldsymbol{p}^{\rm HF}}{\boldsymbol{p}^{\rm jet\ ch} \cdot \boldsymbol{p}^{\rm jet\ ch}}$$



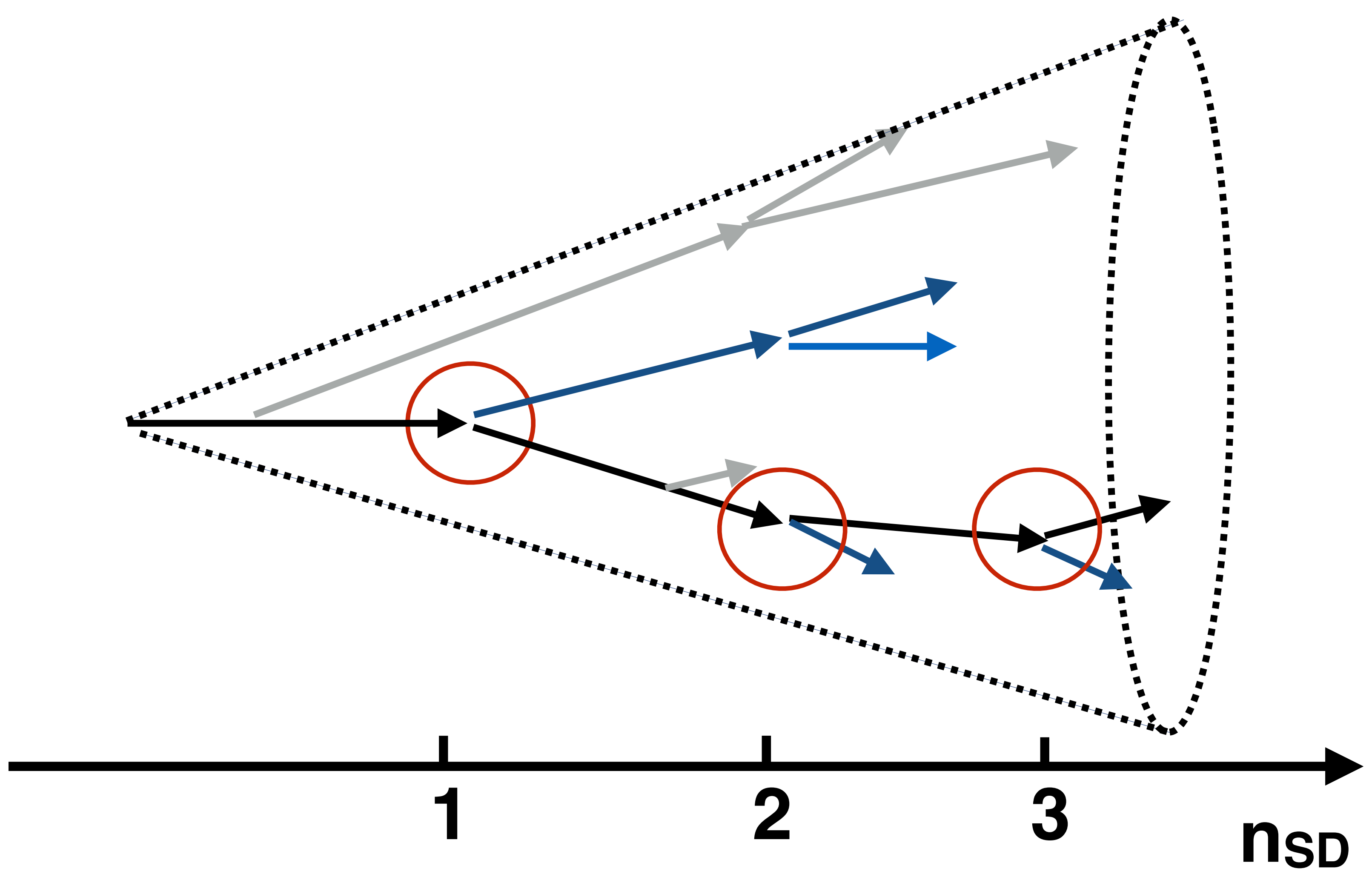


→ **More differential studies possible in pp and PbPb in Run3/Run4**

Substructure of charm jets in pp

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

→ testing QCD in an unexplored kinematic region



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Number of splittings passing Soft-Dropped n_{SD}:

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

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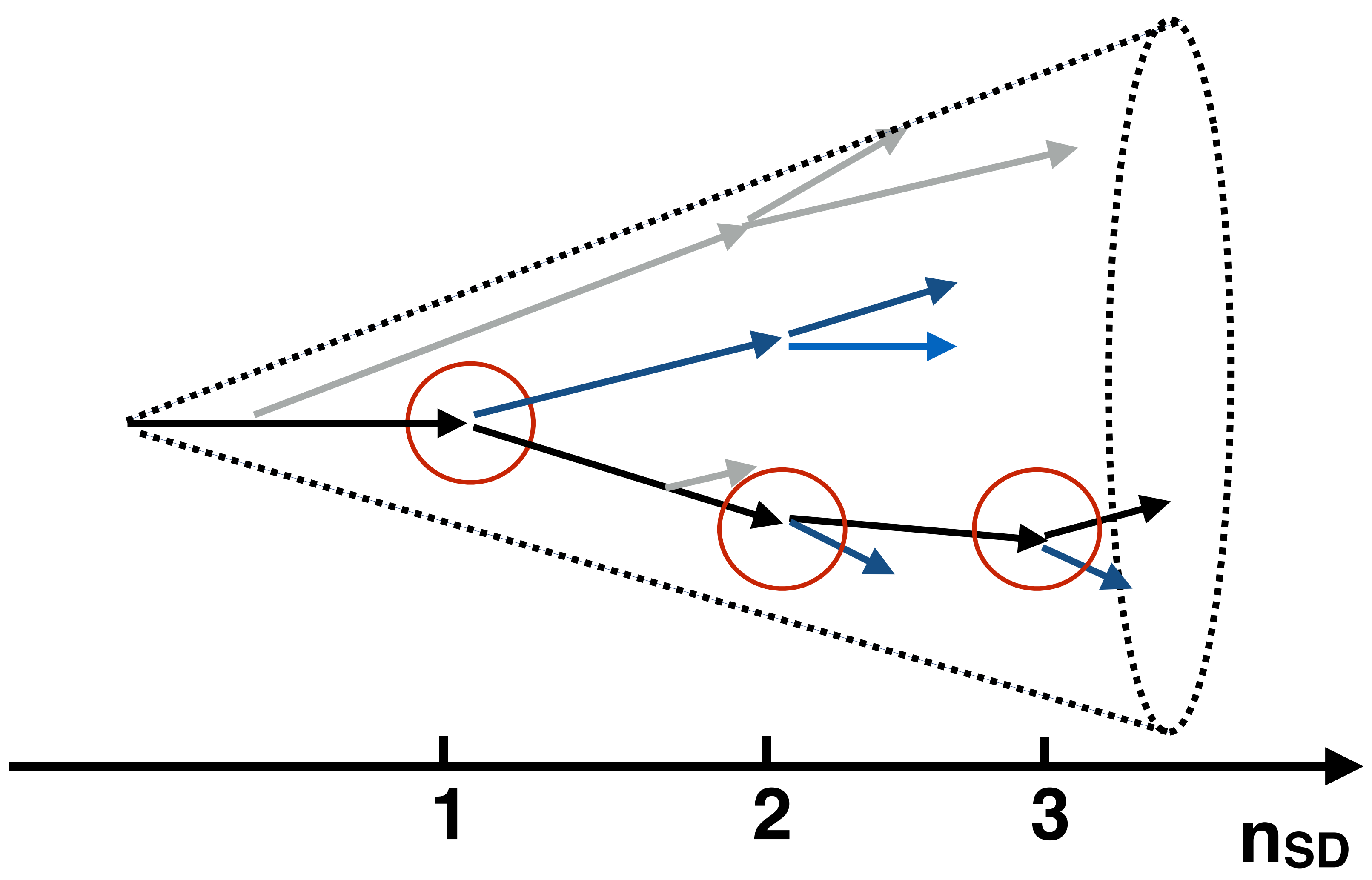

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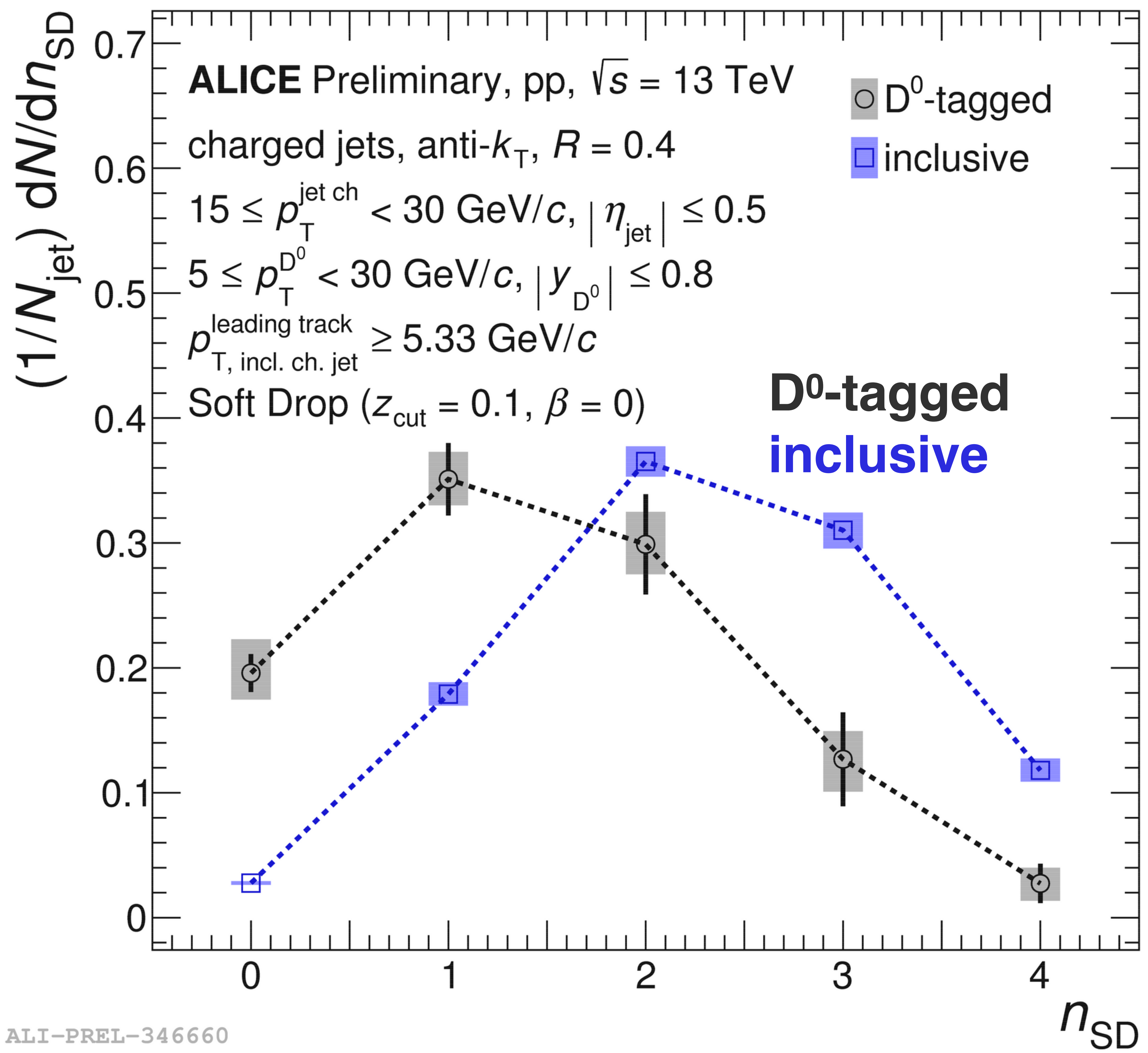


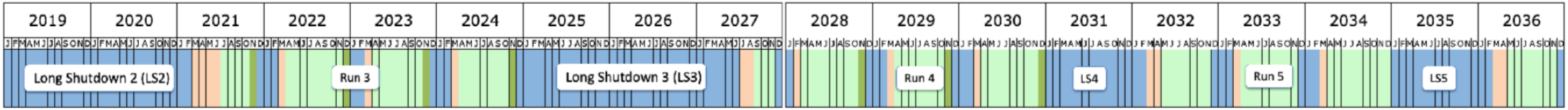
- **charm** jets have fewer "hard" splittings than **inclusive jets**
- **described by PYTHIA**

→ **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

(Some) ALICE plans for Run3/4

HF in ALICE during Run3/Run4

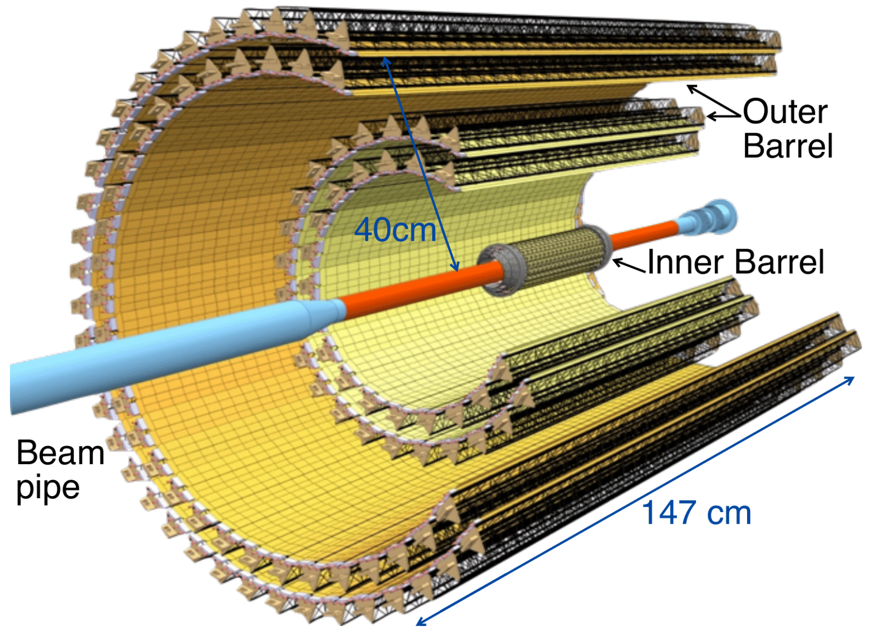


Shutdown/Technical stop
Protons physics
Commissioning
Ions

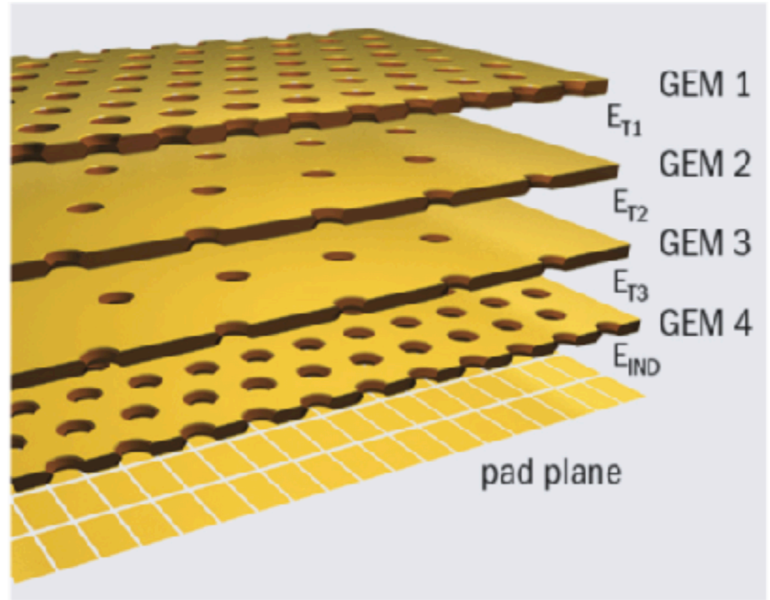
$\mathscr{L}_{\mathrm{Pb-Pb}} \approx 6\ \mathrm{nb}^{-1}$

$\mathscr{L}_{\mathrm{Pb-Pb}} \approx 7\ \mathrm{nb}^{-1}$

Schedule pre-COVID:
- Run3 start could be shifted to March 2022



Time Projection Chamber



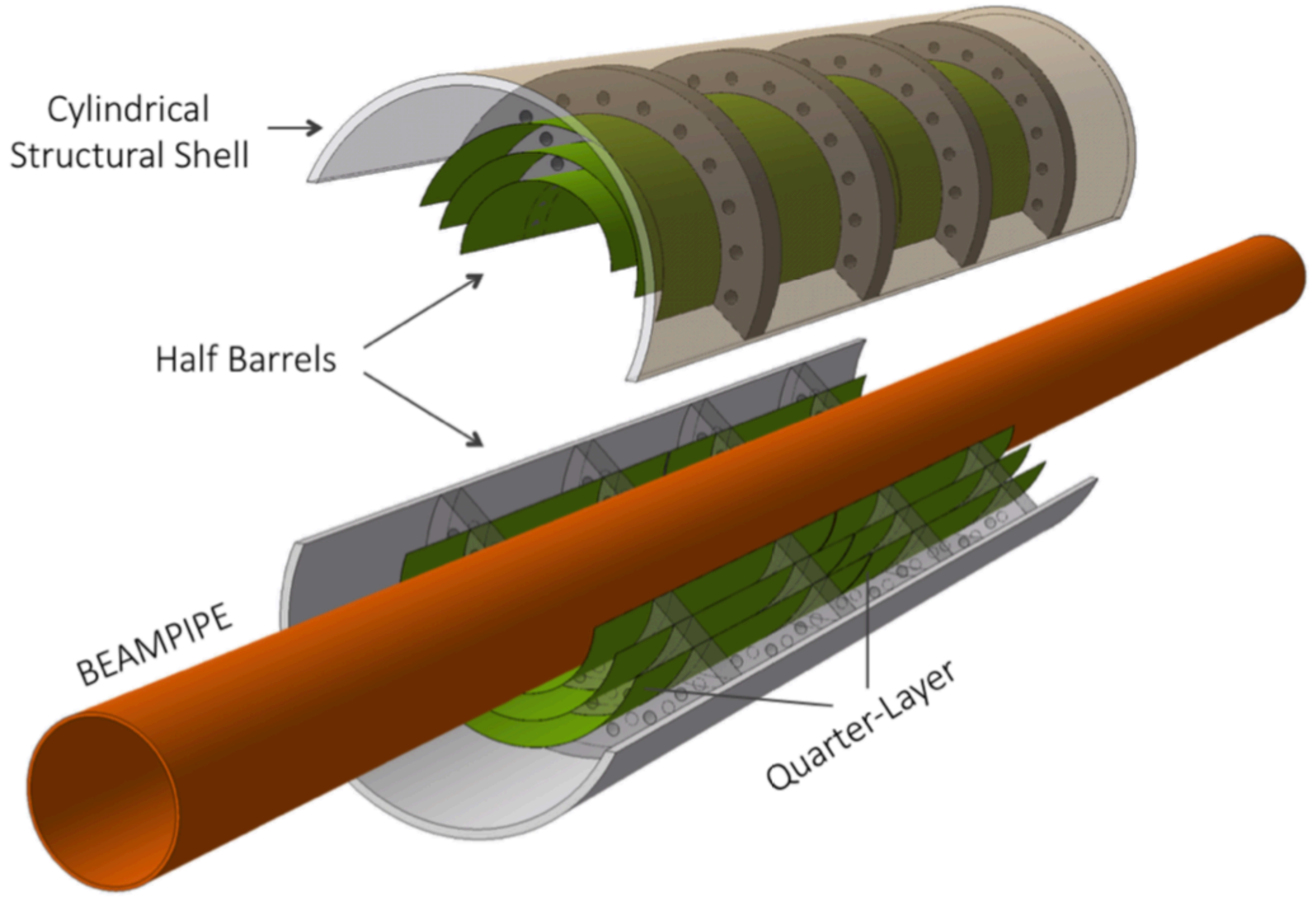
J. of Phys. G: Vol. 41, Num. 8

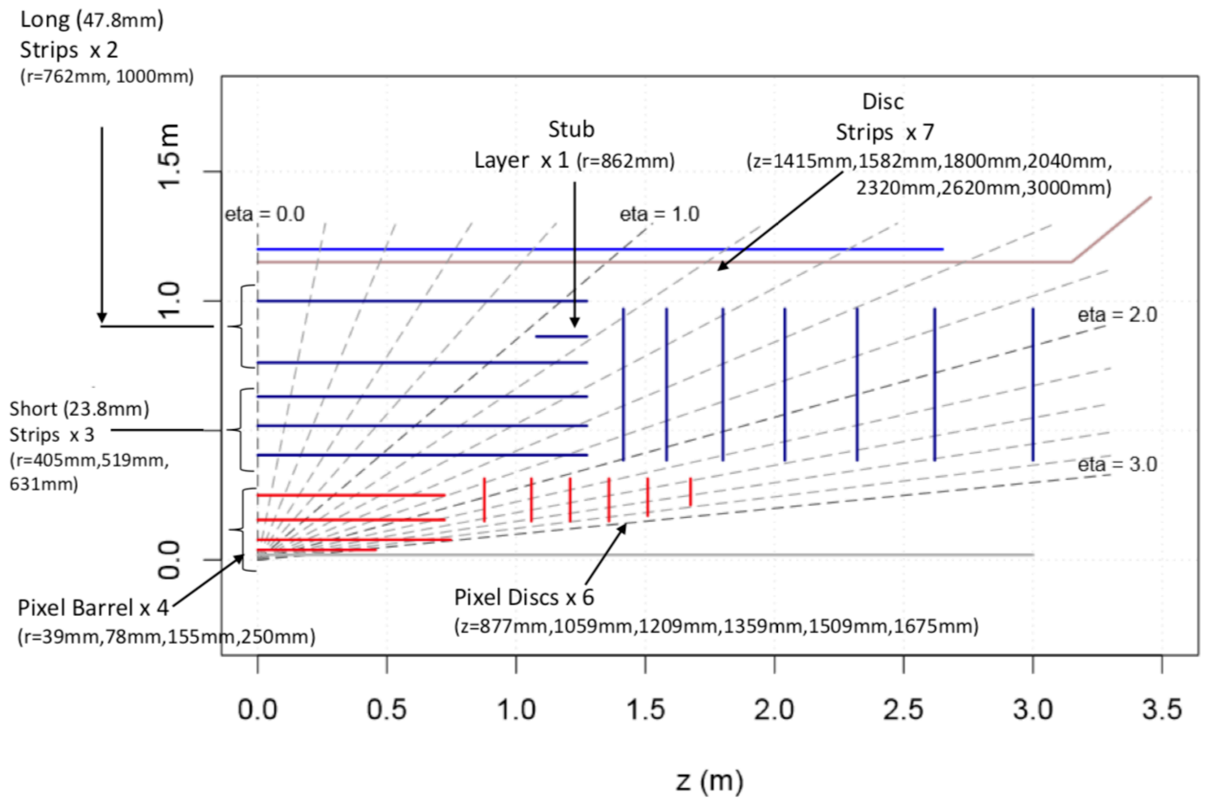
ALICE in Run3:
- improved primary and secondary vertex resolution with new ITS (ITS2)
- Up to 50kHz of interaction rate with new TPC readout

→ **100x more statistics compared to Run1+2**

Run 4:
- ALICE: “massless” full pixel inner barrel (ITS3)
- extremely low material budget for improved tracking resolution

Nucl. Part. Phys. 41 087001

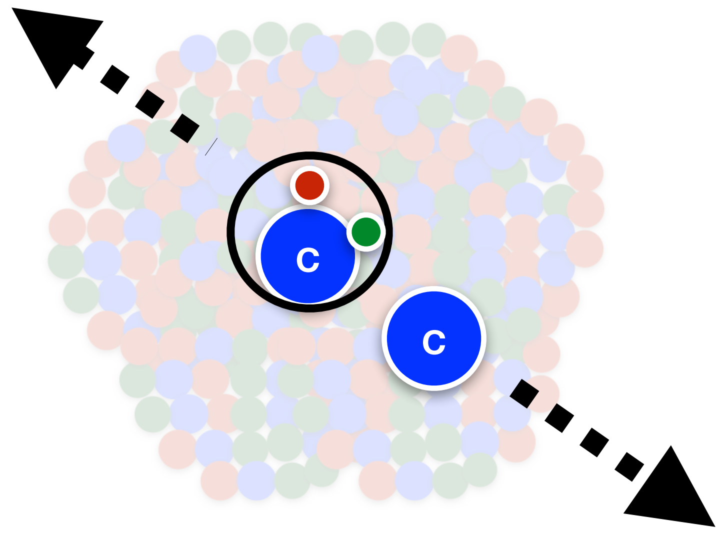


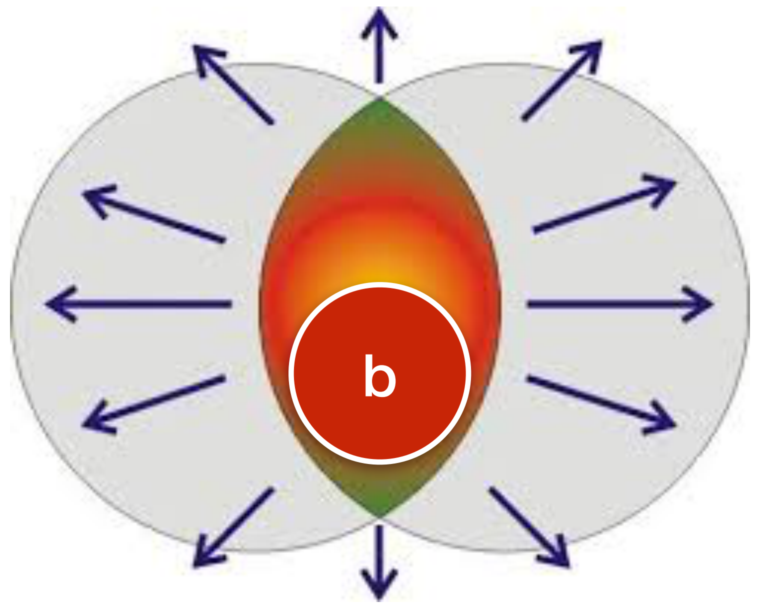


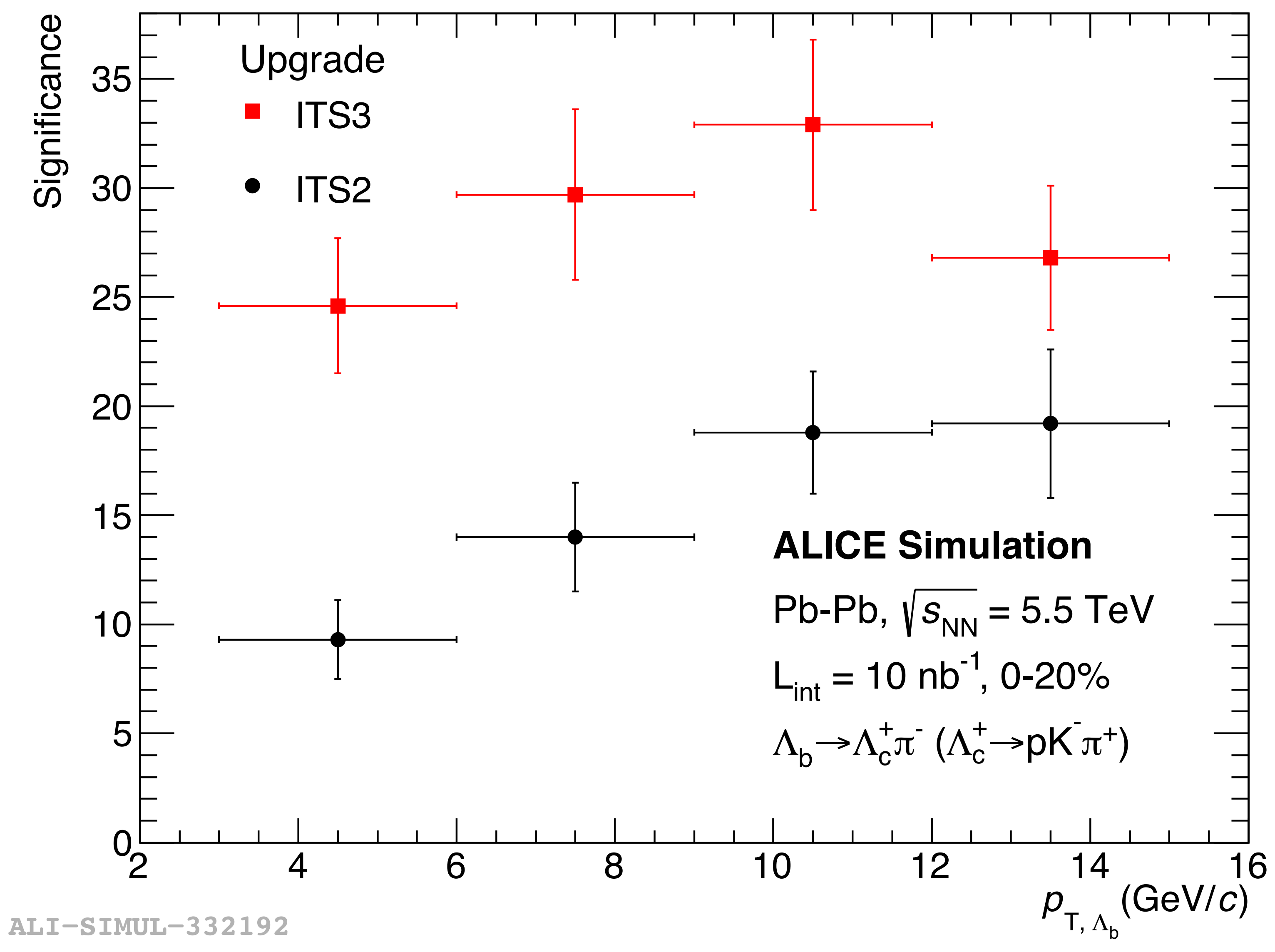
Run3/4: ALICE in large systems

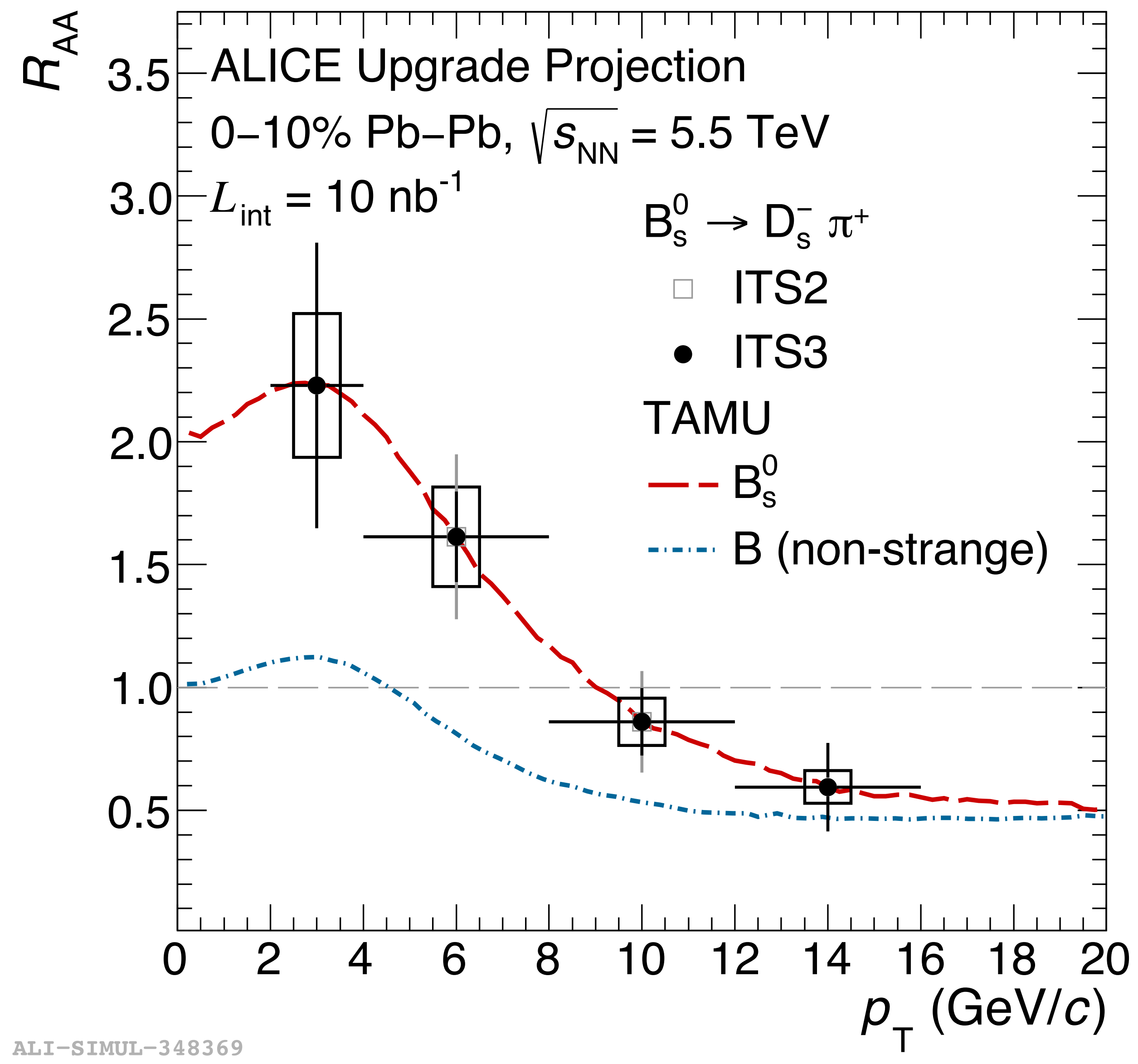
Study of quenching, hadronisation and collectivity in central PbPb collisions will be the core ALICE activities:

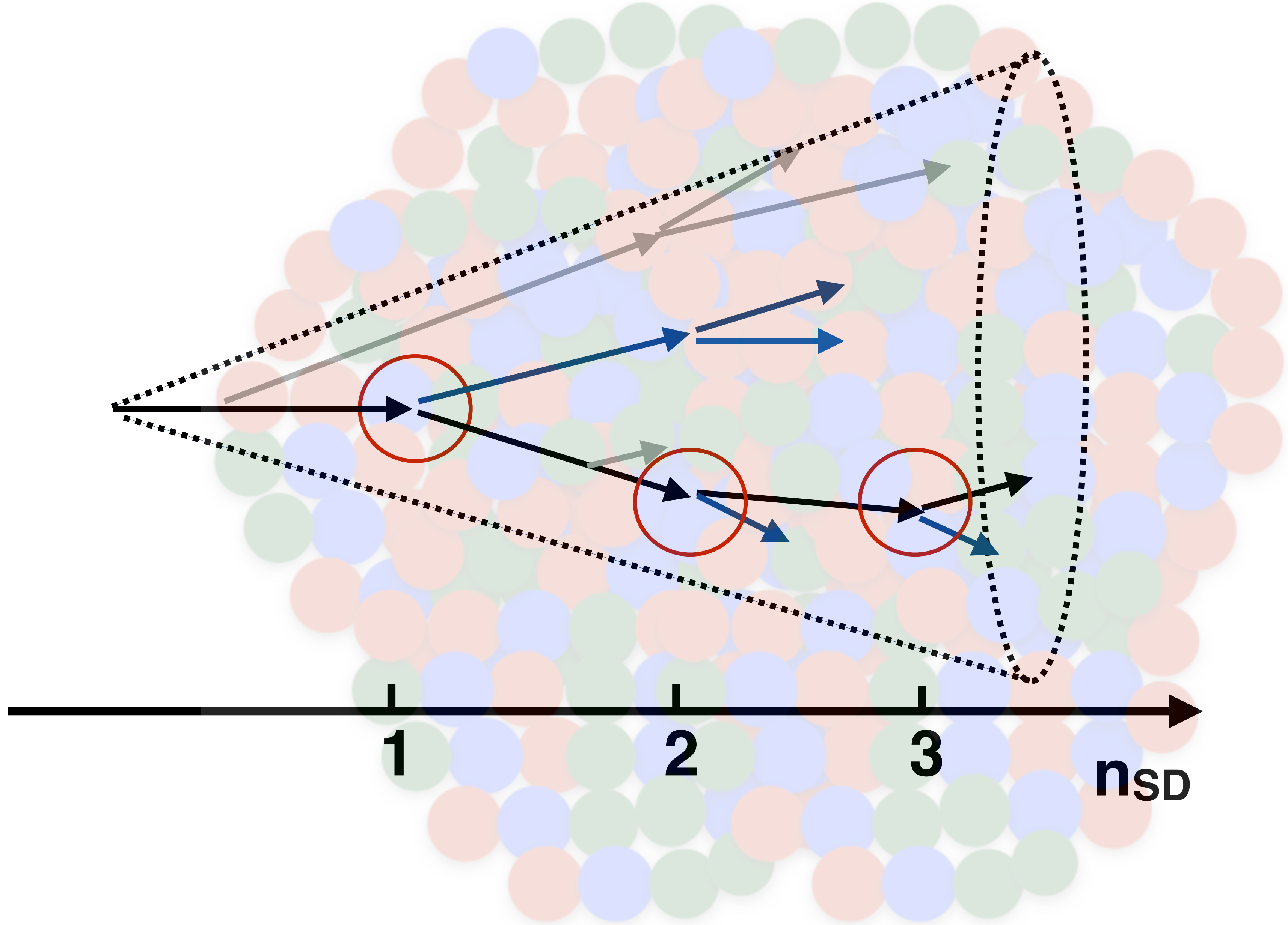
- traditional observables (R_{AA}, v_2, particle ratios) for charm and beauty down to very low p_T
- HF-jet chemistry and HF-jet substructure from low to intermediate/high p_T







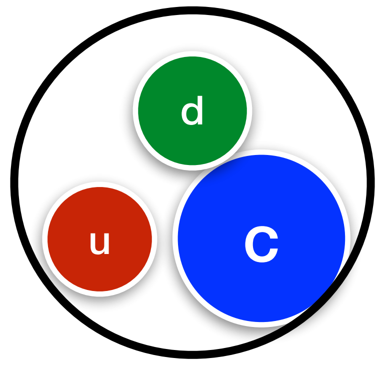


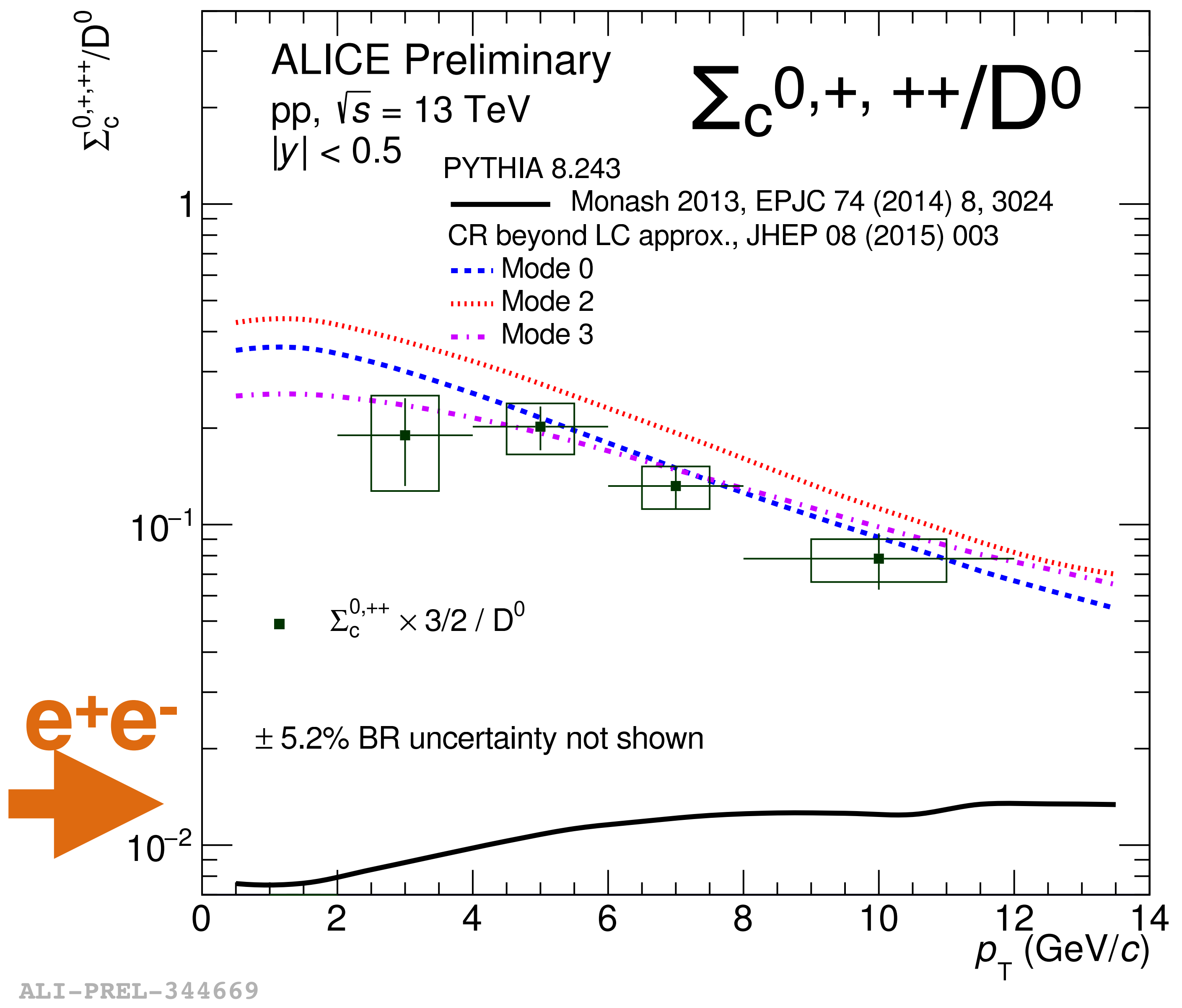


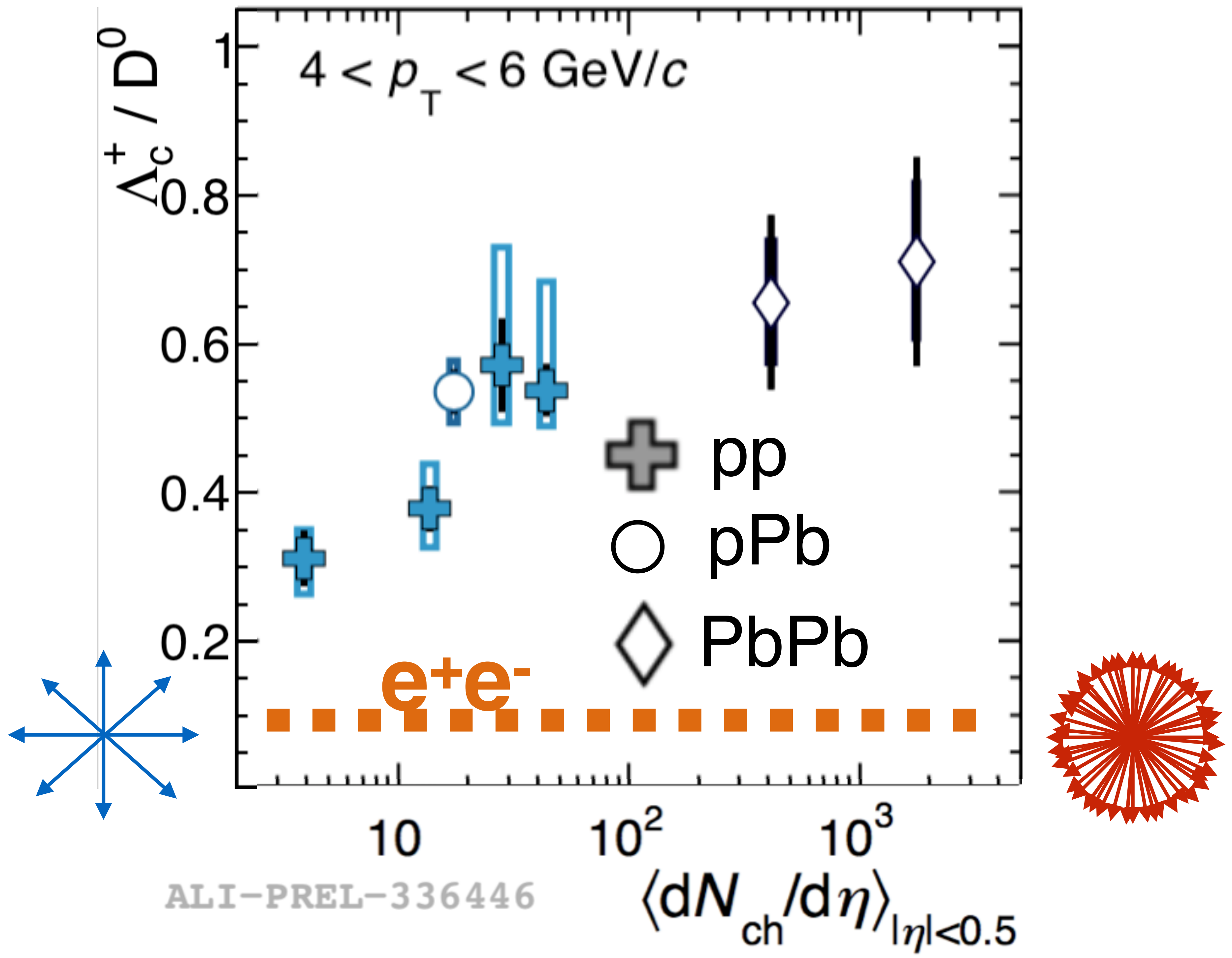
Run3/4: from low to high multiplicity pp/pPb

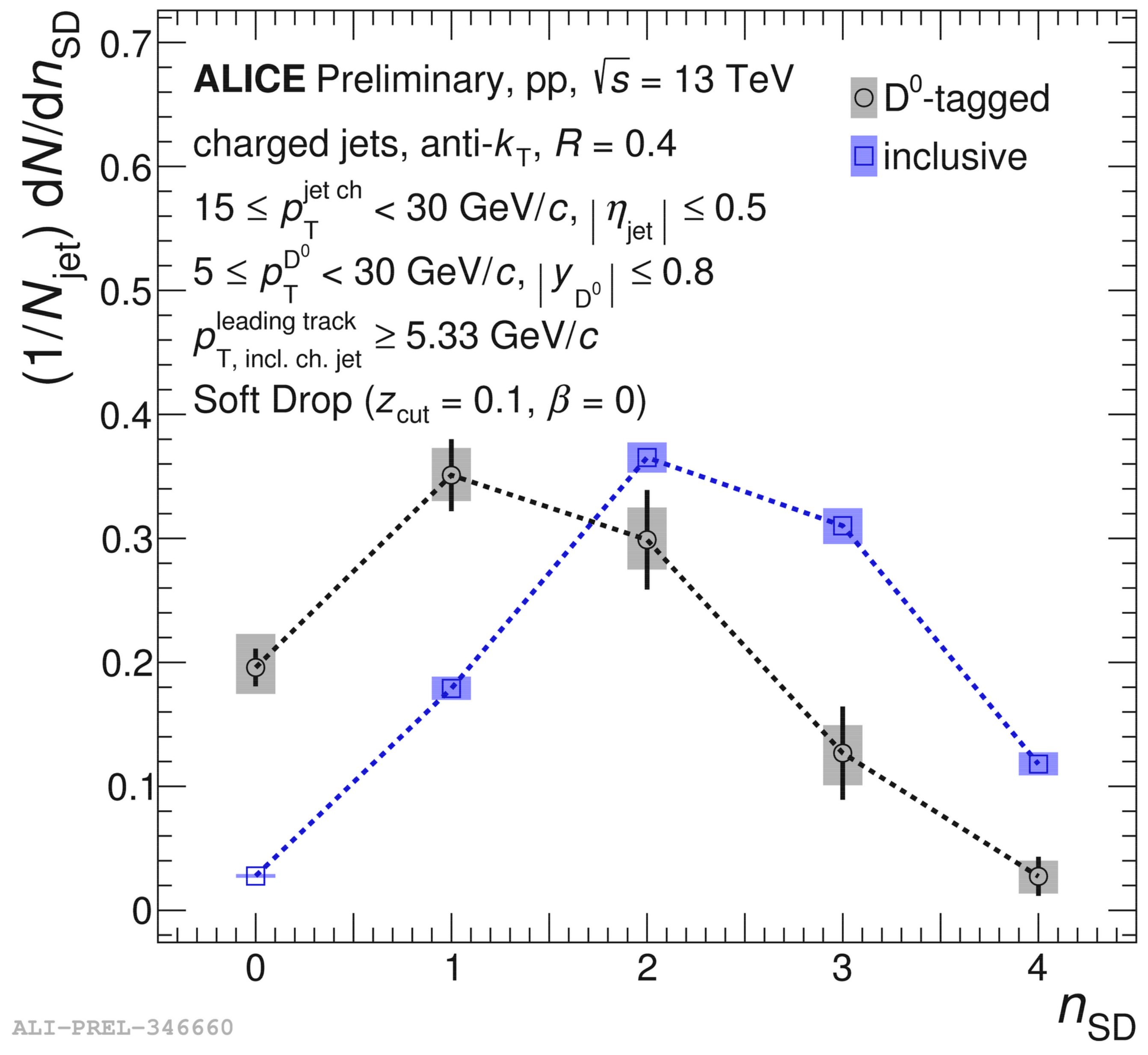
Expand the successful pp program to study pQCD and hadronisation mechanisms in small systems :

- low multiplicities are probably as interesting as high multiplicities!
- heavier baryonic states, more differential analyses vs multiplicities and event shapes, HF-jets









→ towards a quantitative understanding of hadronisation mechanisms

→new insights into pQCD

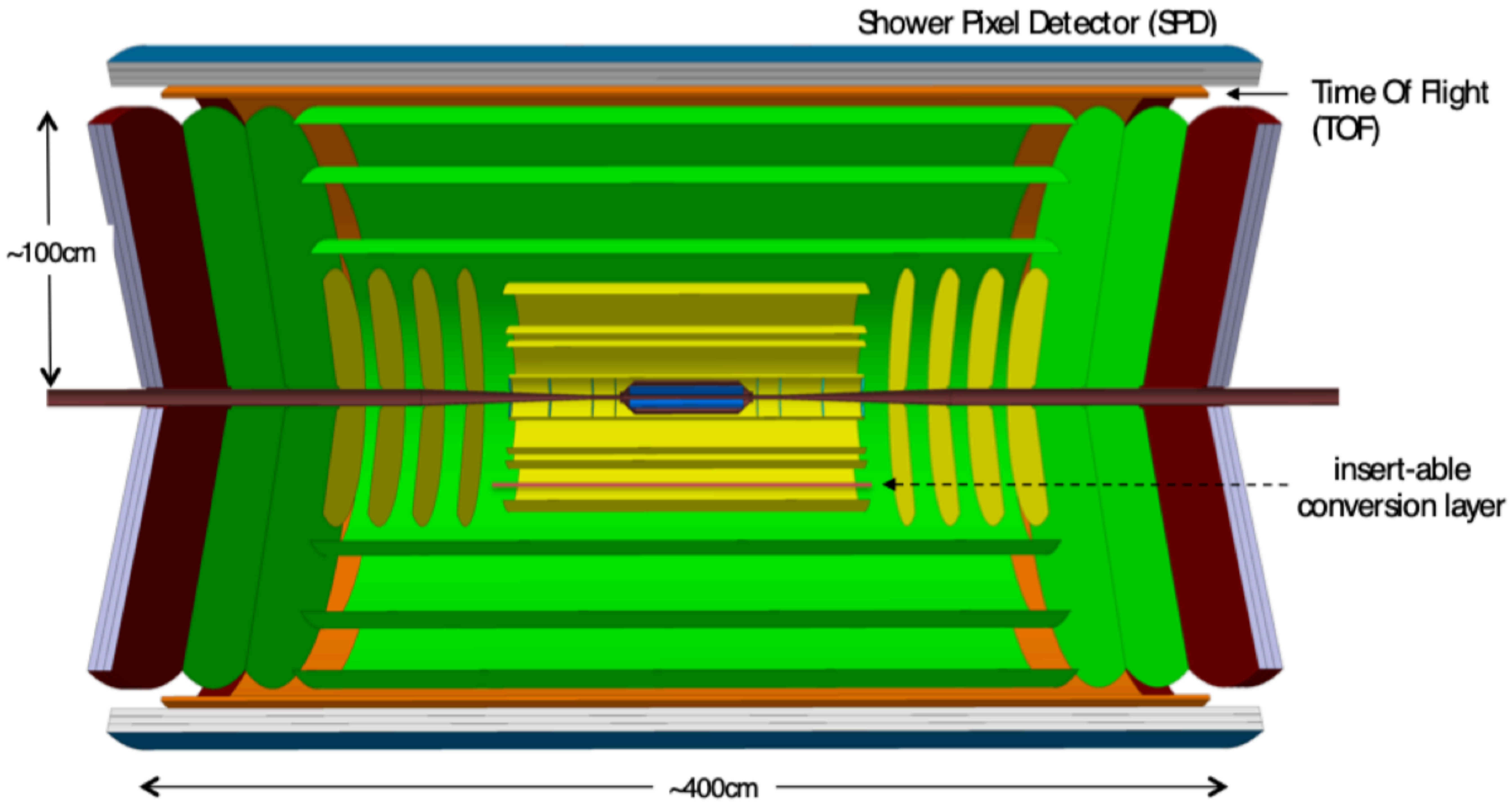
Beyond Run4!

A completely new detector at point 2: low-material, high-rate, all-Si

Could be installed in LS4 (2031)

arXiv1902.01211

High-resolution tracking à la ITS3
Extremely good pointing resolution
10 layers for tracking
Forward coverage up to $\eta \approx 4$



Time-of-flight layer(s) for
particle identification:
electrons, hadrons

Shower Pixel Detector:
electron ID at higher momentum

Additional capabilities for photons
via conversions

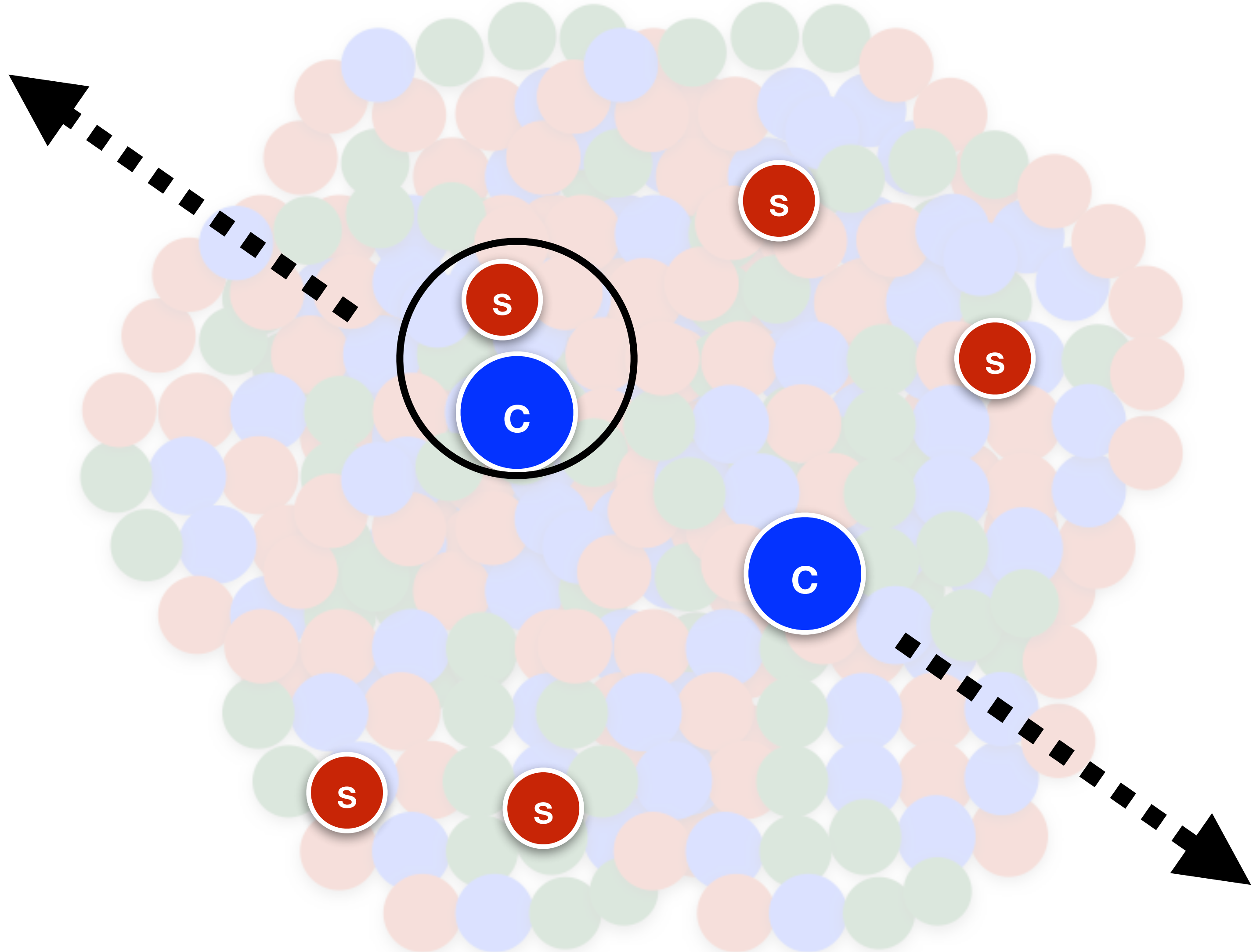
M. Van Leeuwen, LHCP2020

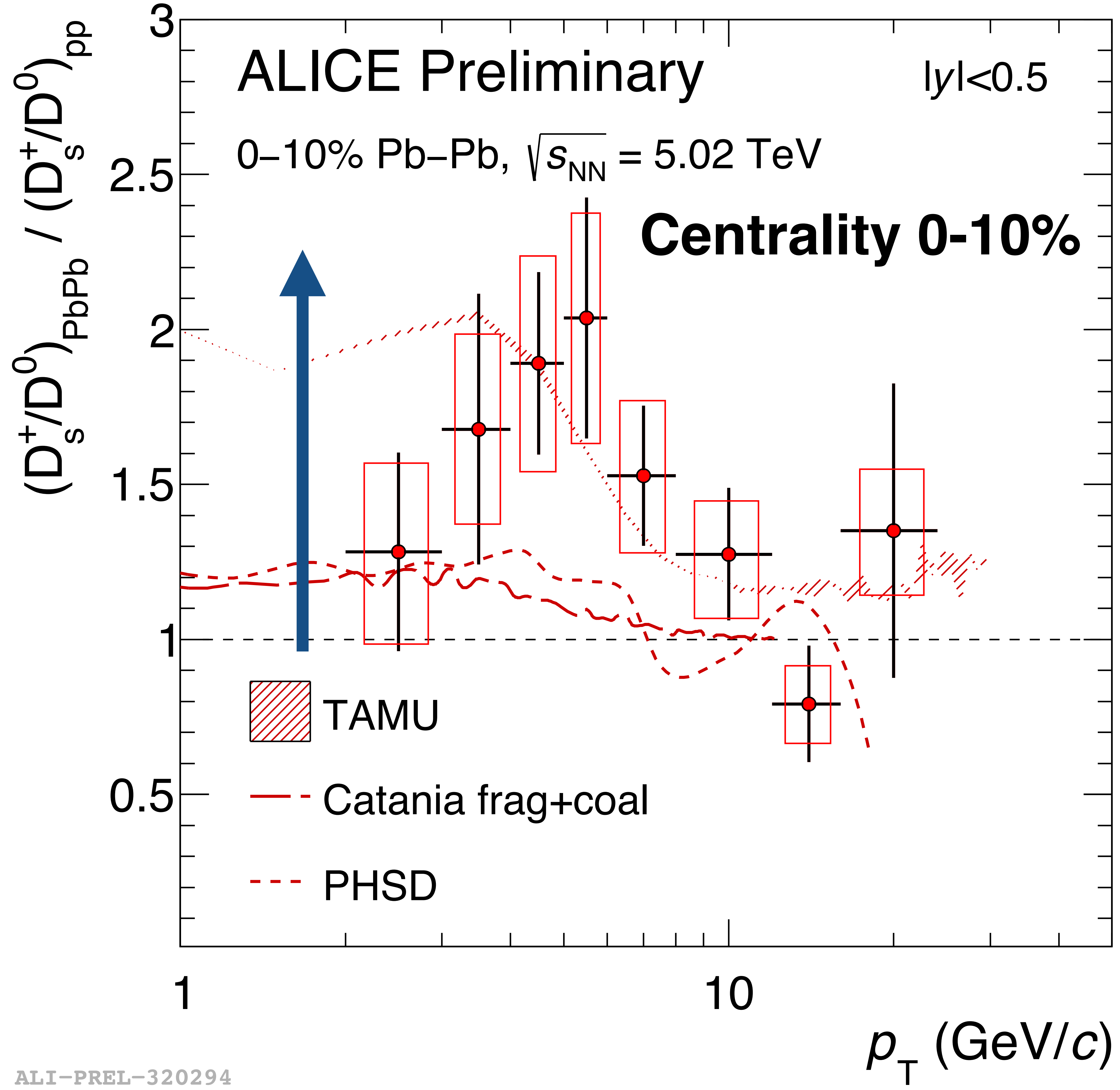
Thank you for your attention!

BACKUP

D_s/D^0 as a test for recombination

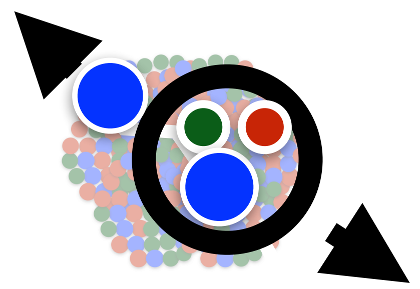
D_s/D^0 to be enhanced in Pb-Pb vs pp in presence of charm recombination and strangeness enhancement

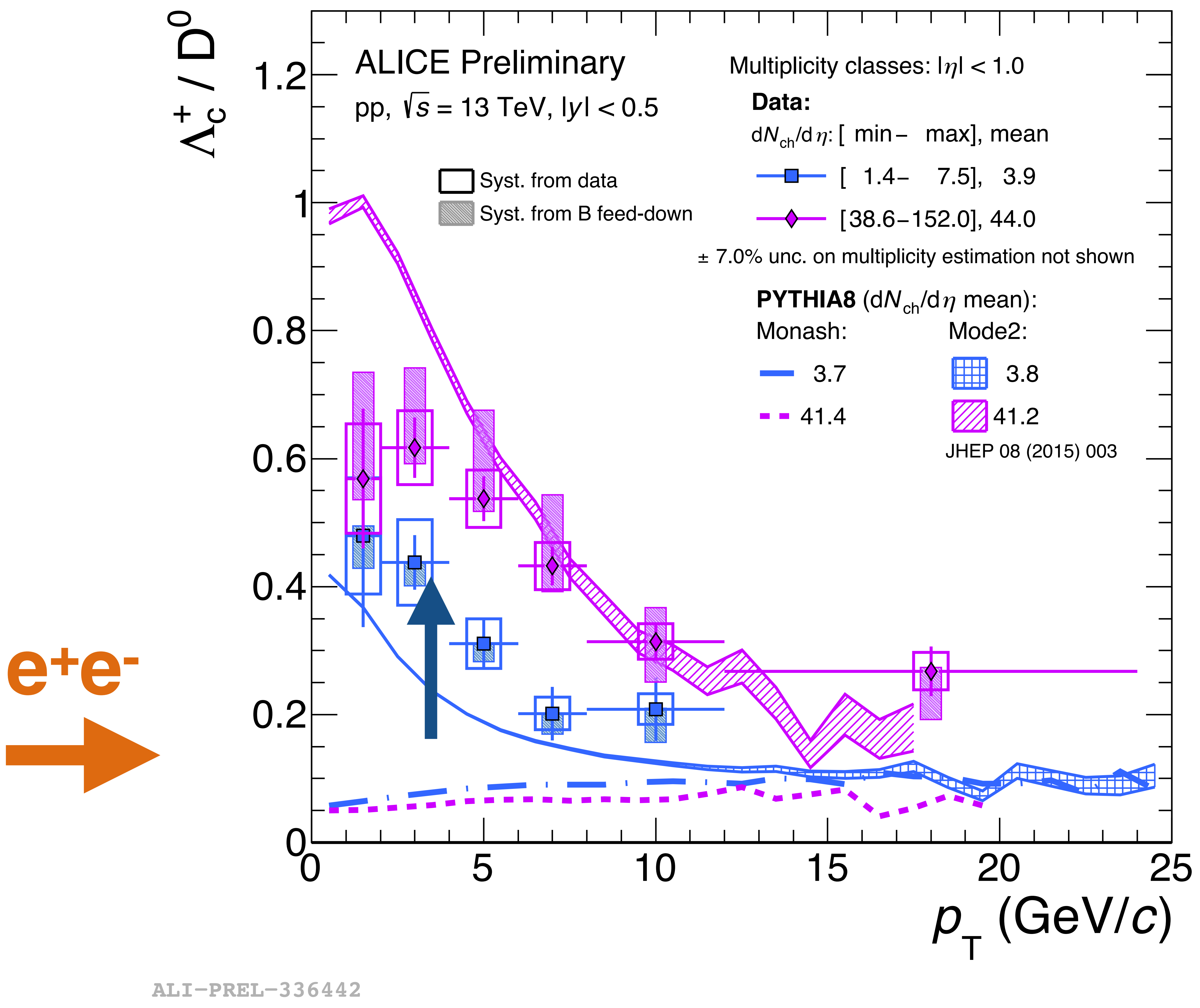




→ Relevant contribution of coalescence in charm hadronisation in Pb-Pb

Modification of hadronisation in pp collisions?

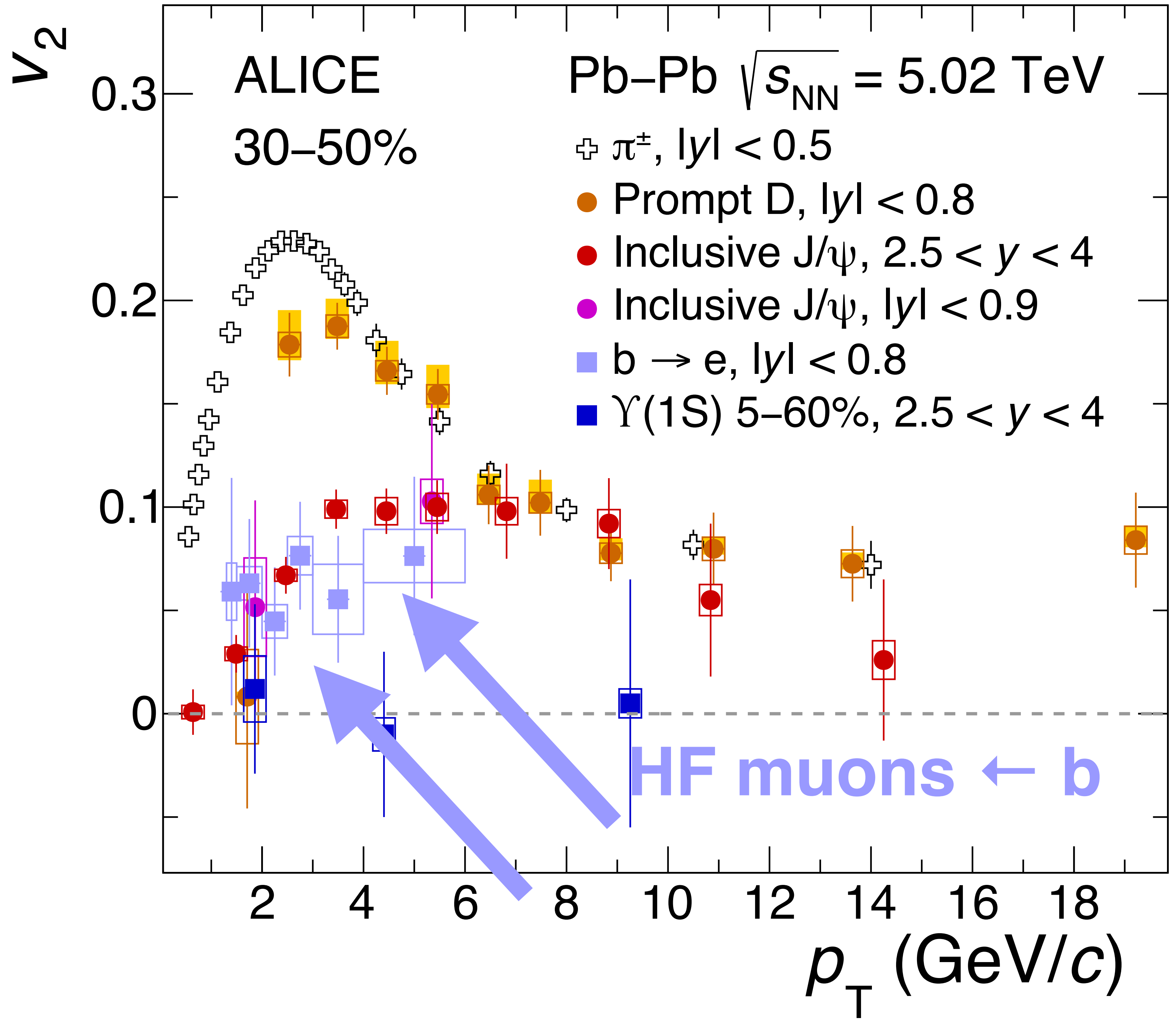




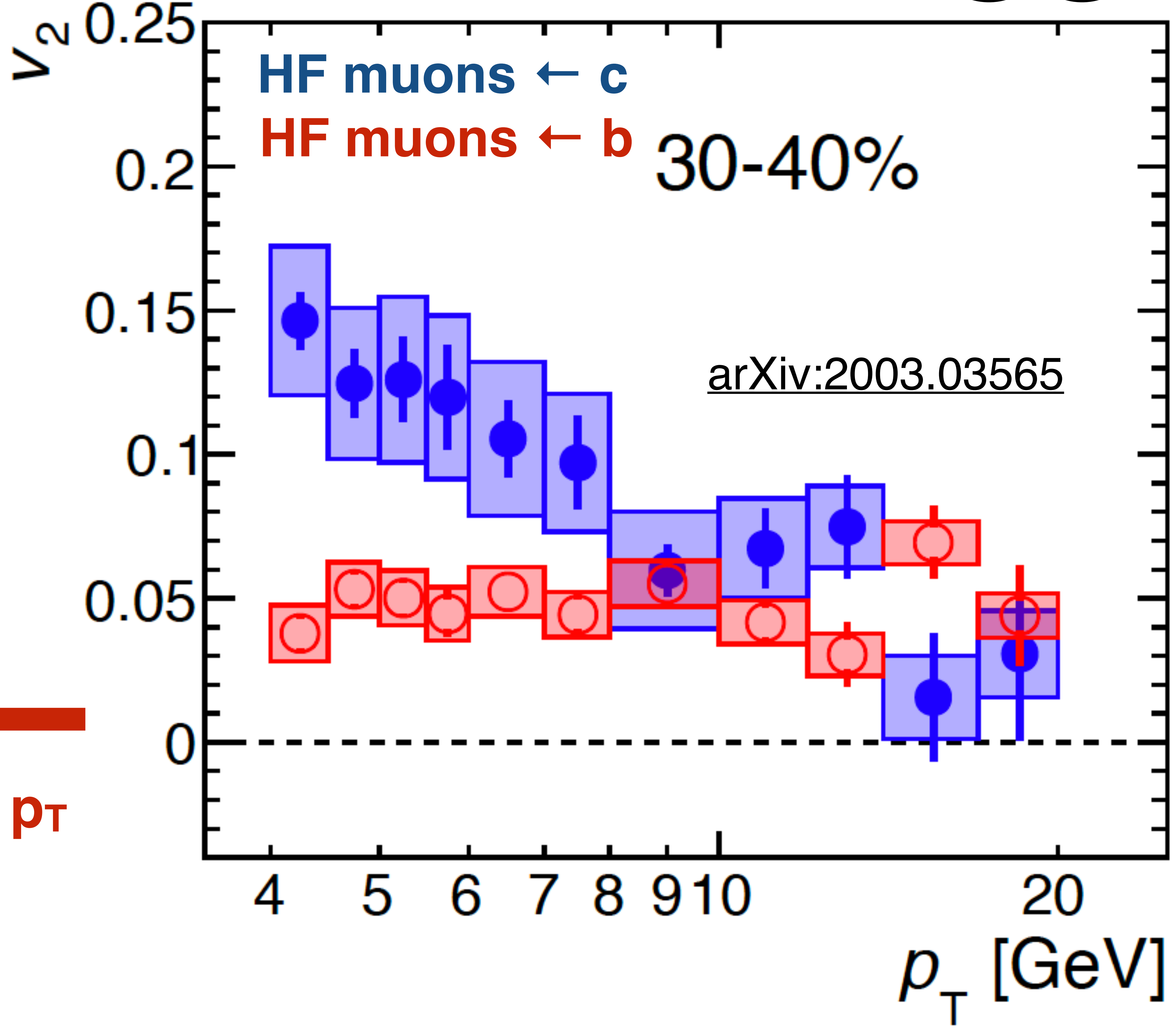
- **Standard Pythia calculation** (tuned on e^+e^-) do not describe the observed ratios

Charm and beauty "flow" in PbPb collisions

arXiv.2005.11130



Lower p_T



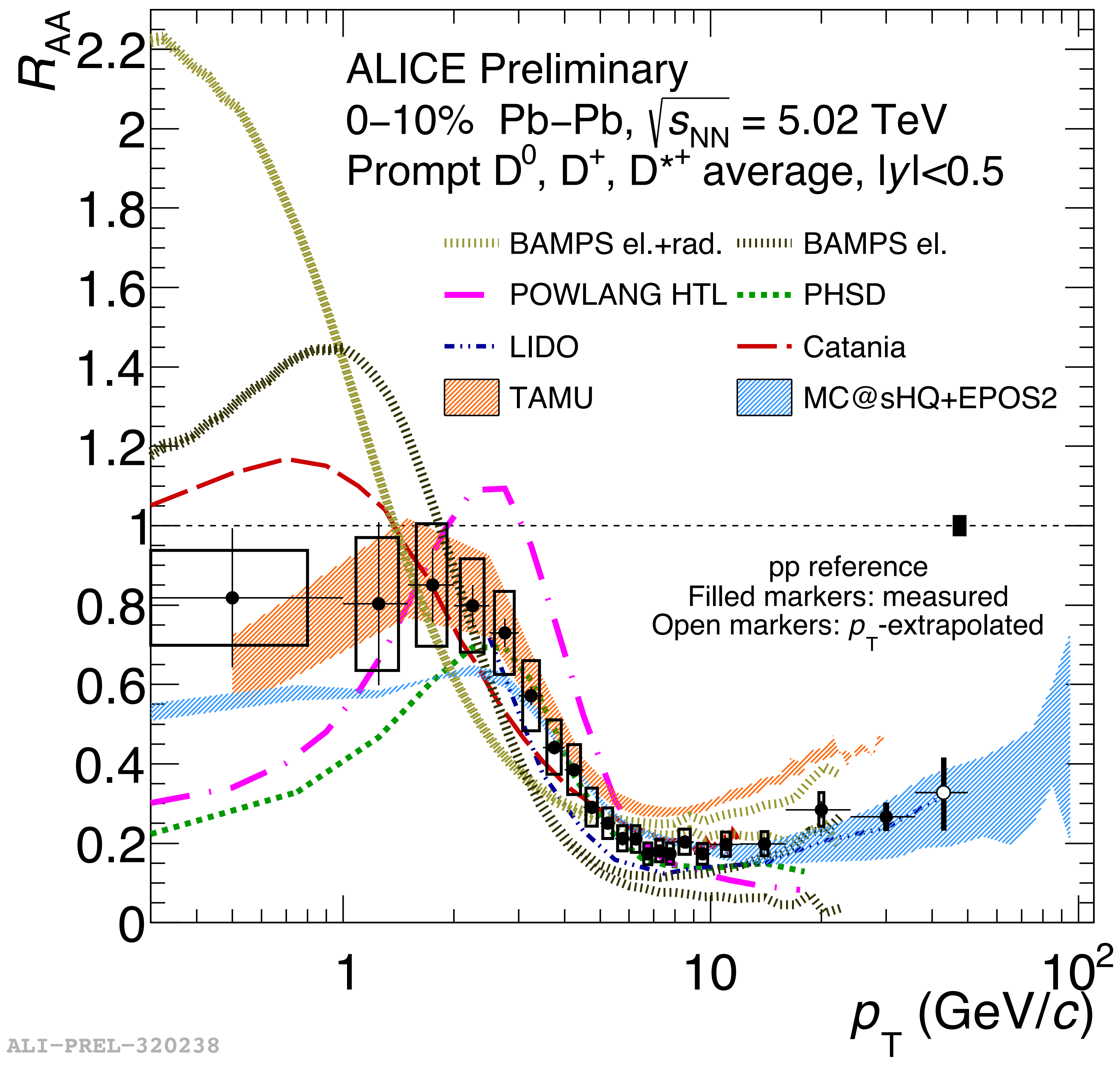
- v_2 significantly > 0 for HF muons ← c
- v_2 smaller but still > 0 for HF muons ← b

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

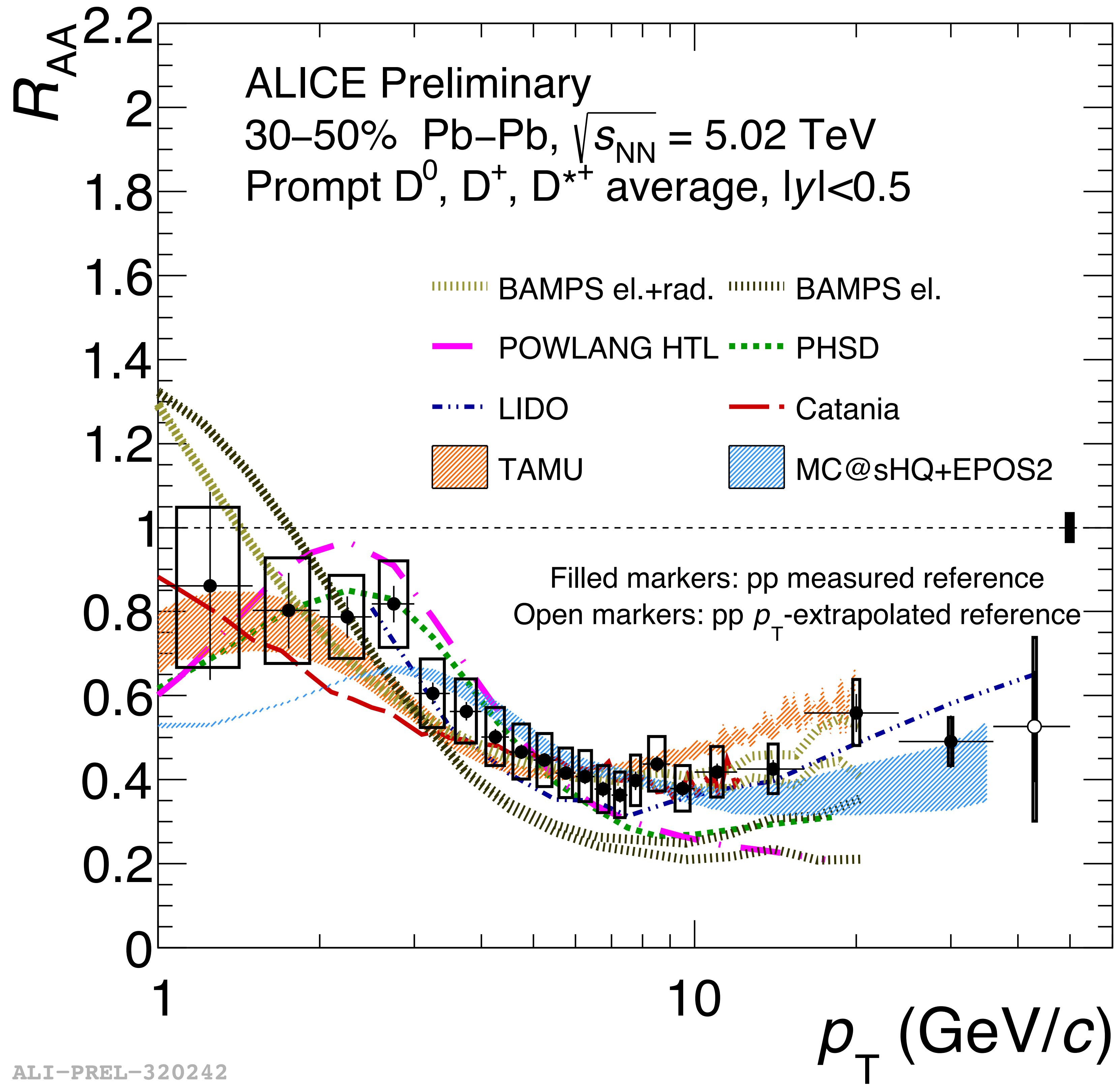
→ v_2(ϒ) consistent with zero! Mass effect?

D meson R_{AA} : comparison to models

Centrality 0-10%



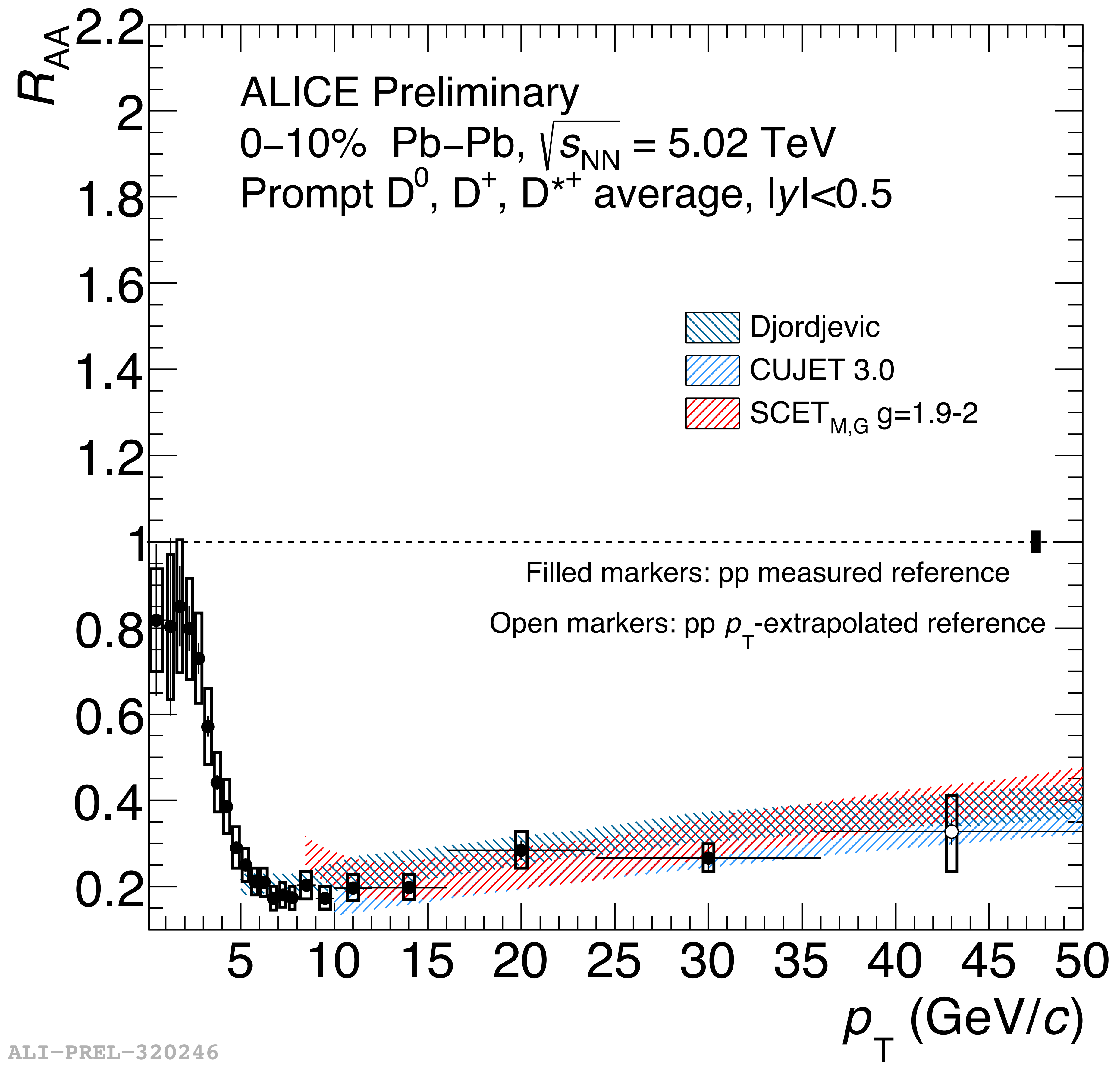
Centrality 30-50%

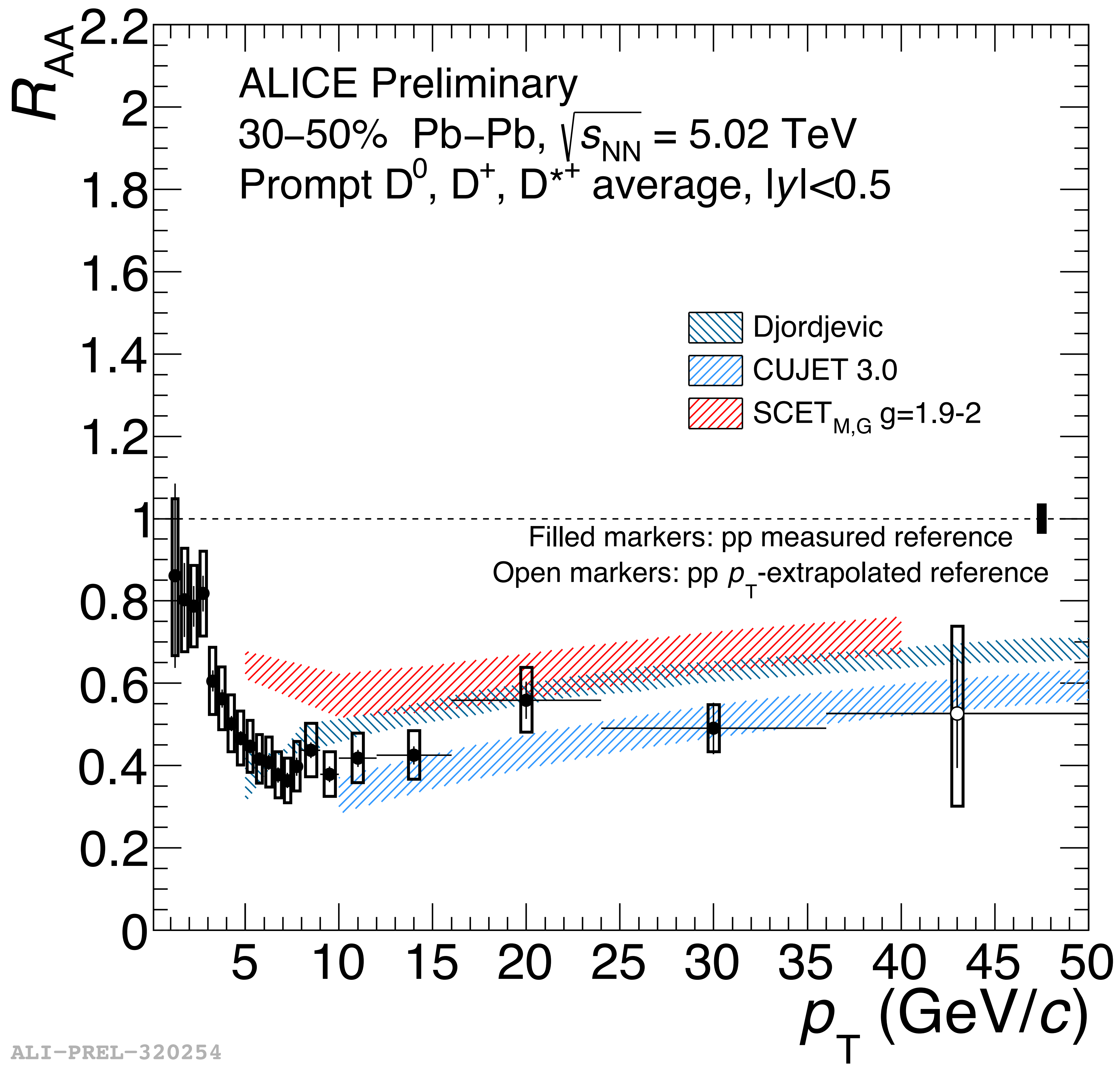


- Strong discrimination power at 0-1 GeV/c
- TAMU (Langevin) well describes the data from low to high p_T

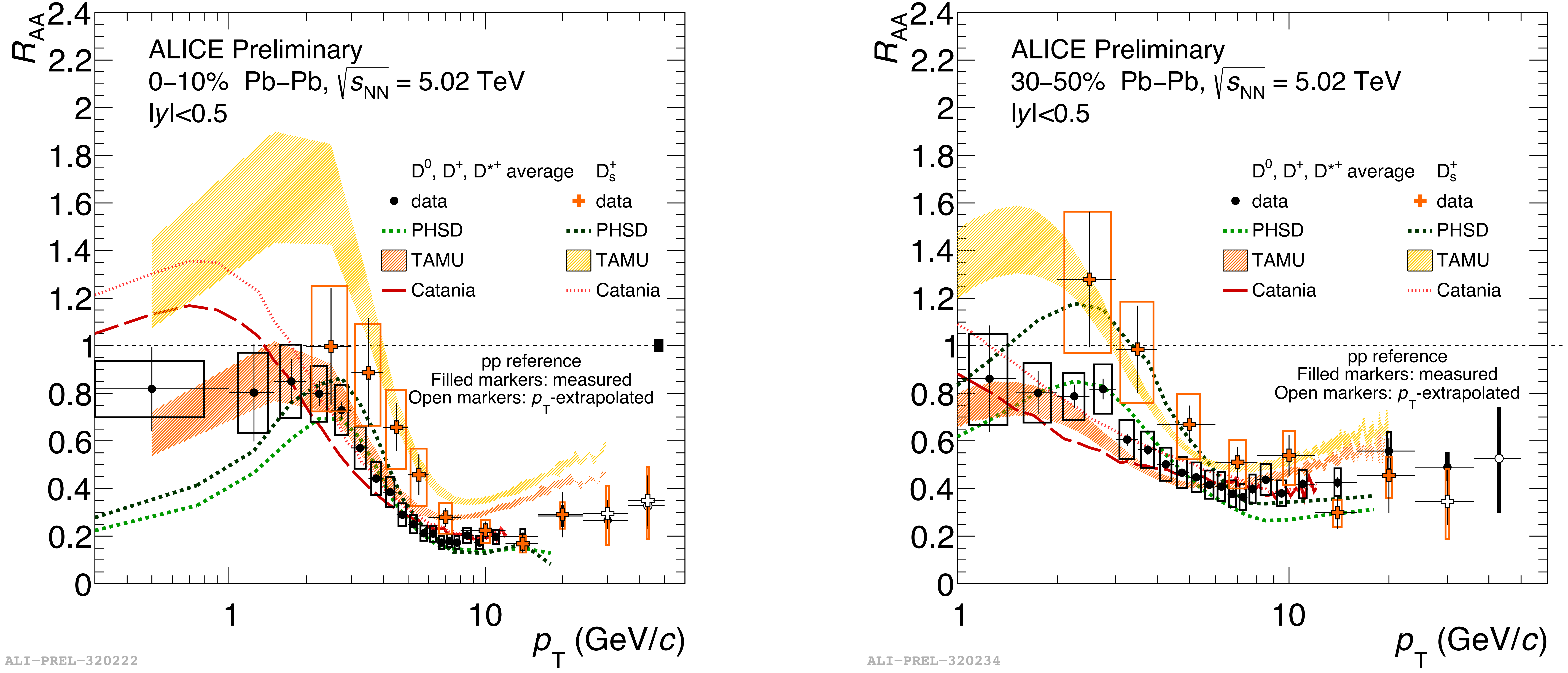
- In semi- peripheral events, most of the models show a good agreement with the data

D meson R_{AA} : comparison to models

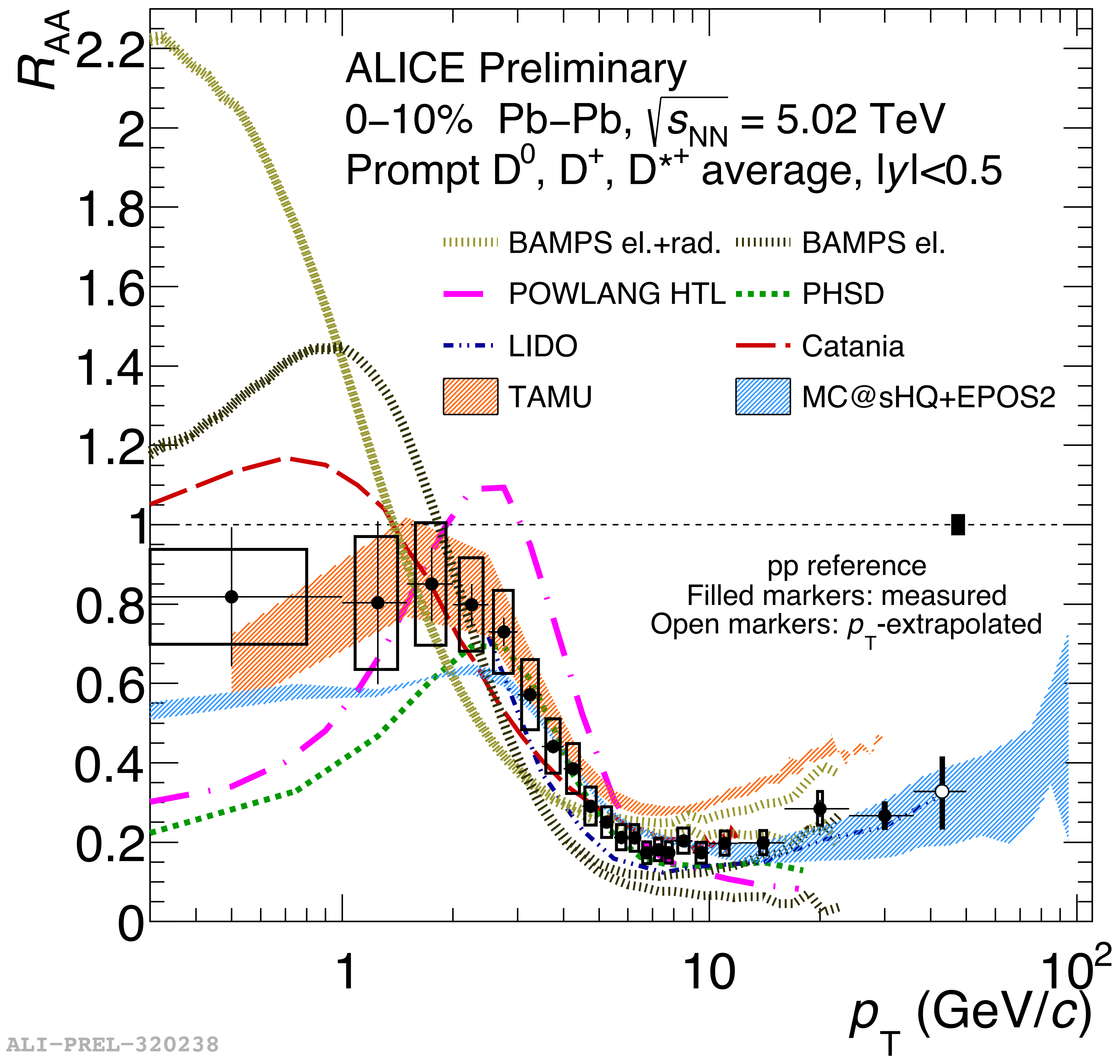




R_{AA} of D_s vs D^0 in central and peripheral Pb-Pb



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?

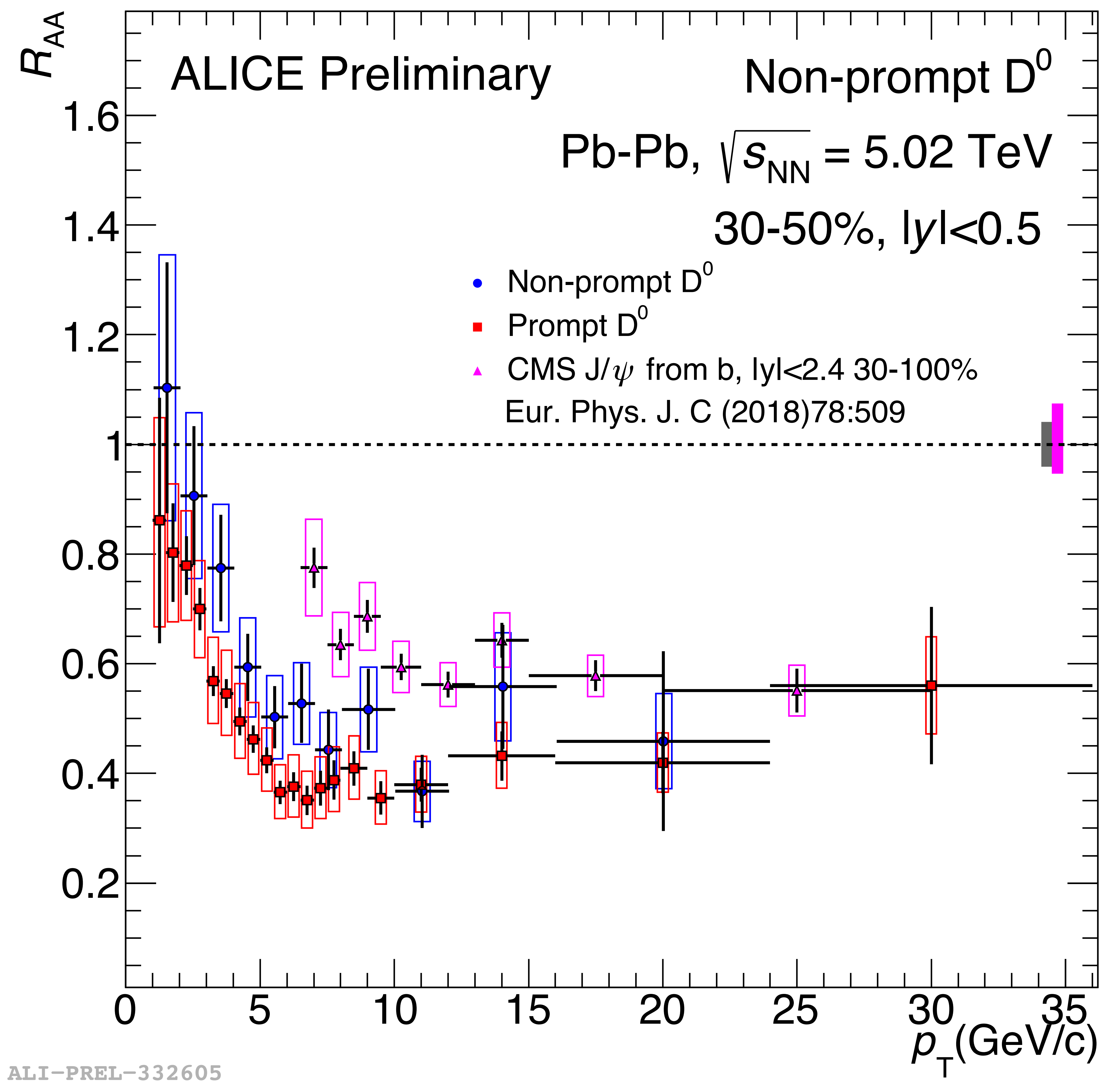
LIDO:

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

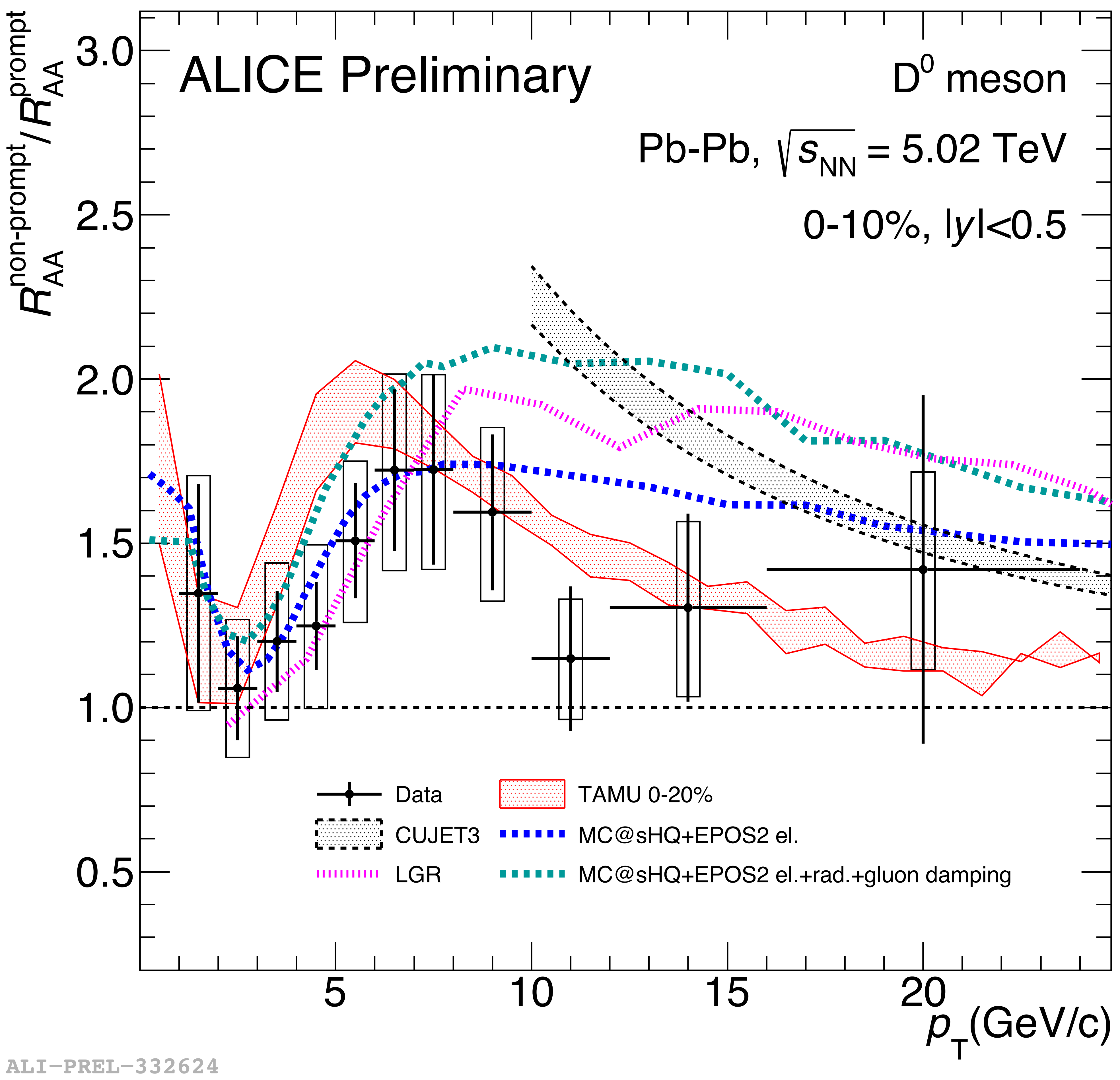
MC@sHQ+EPOS2:

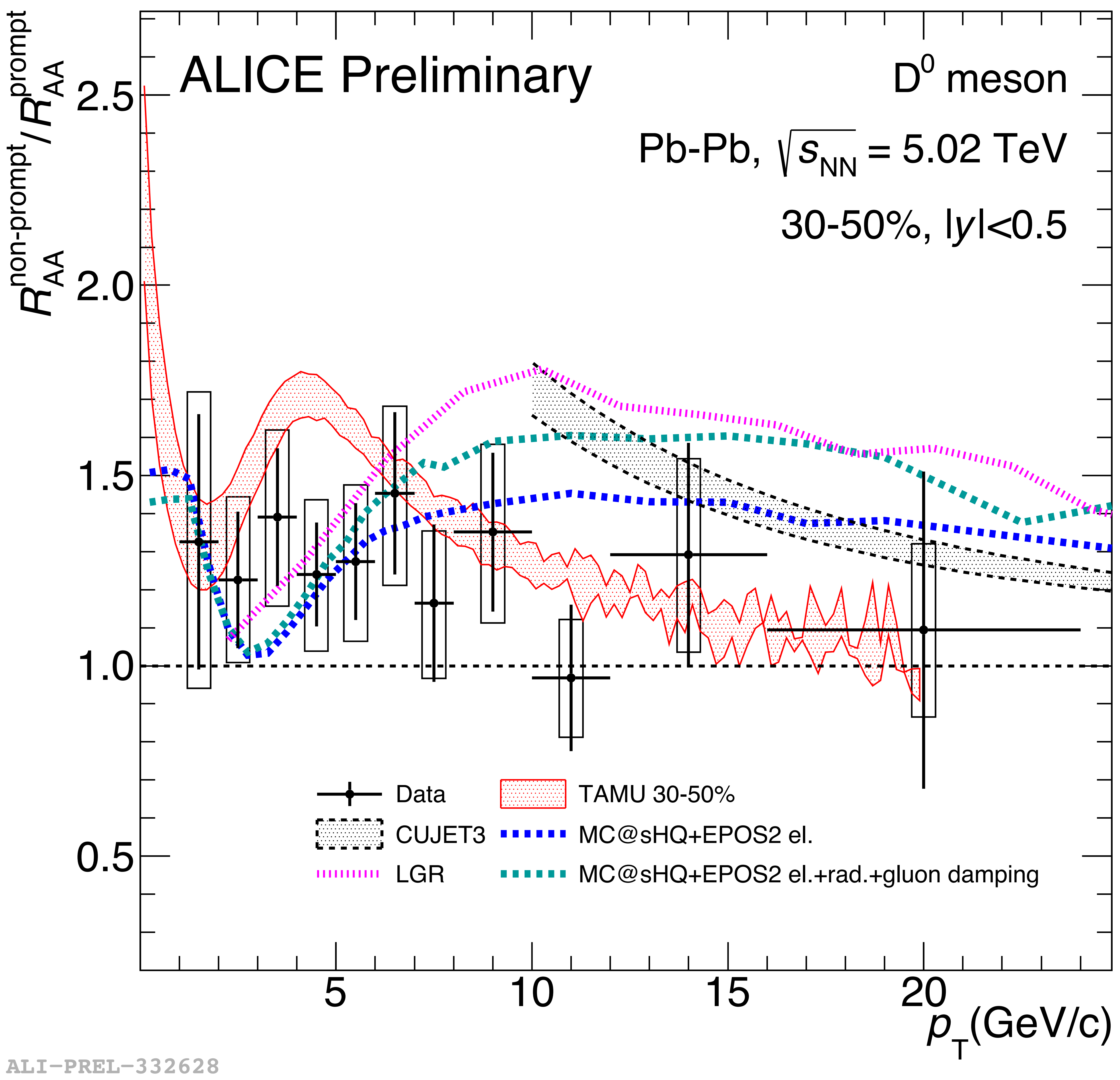
- Pretty good agreement at high pT.
- Underestimate the low p_T region

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



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





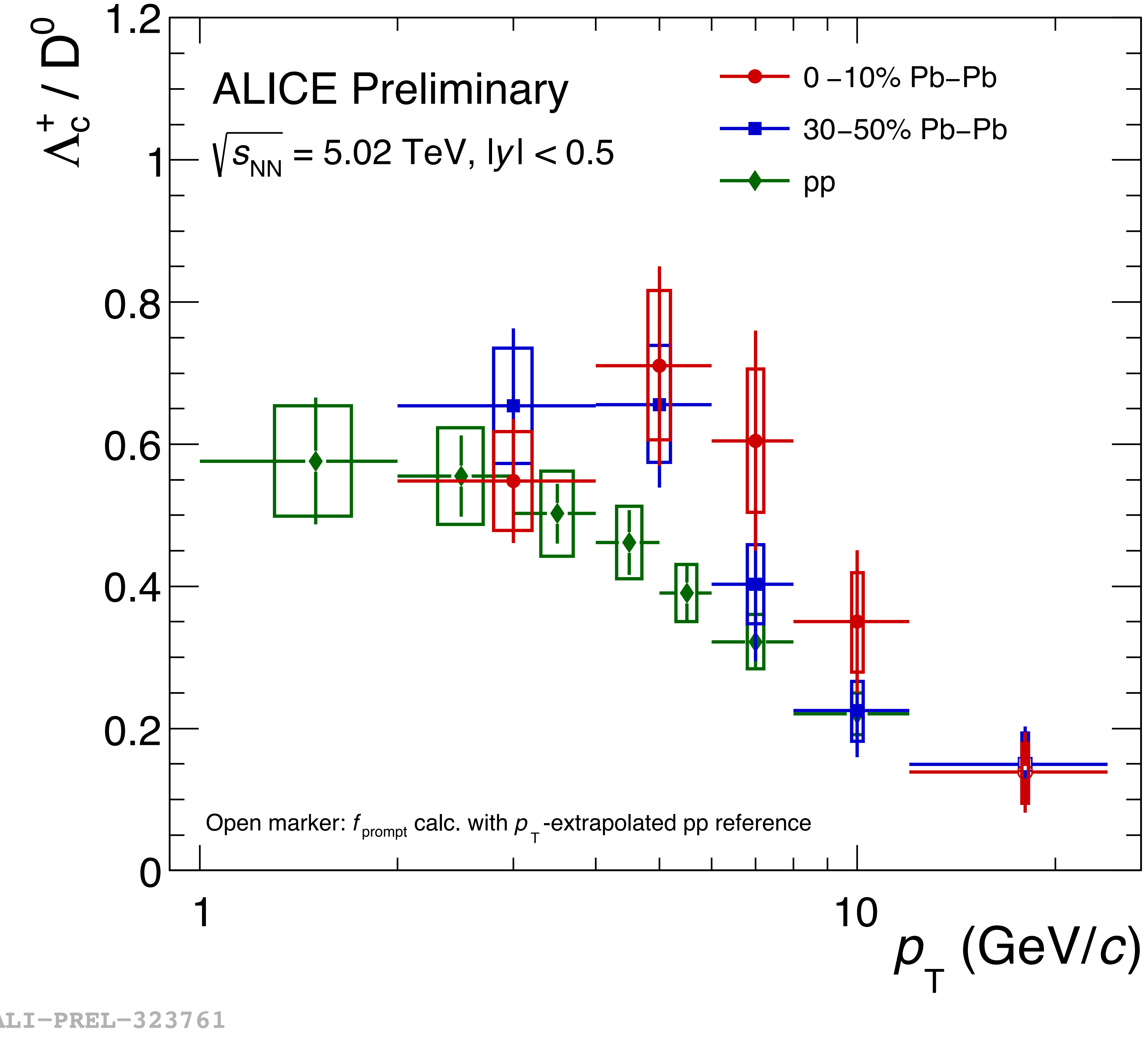
Overview of theoretical calculations

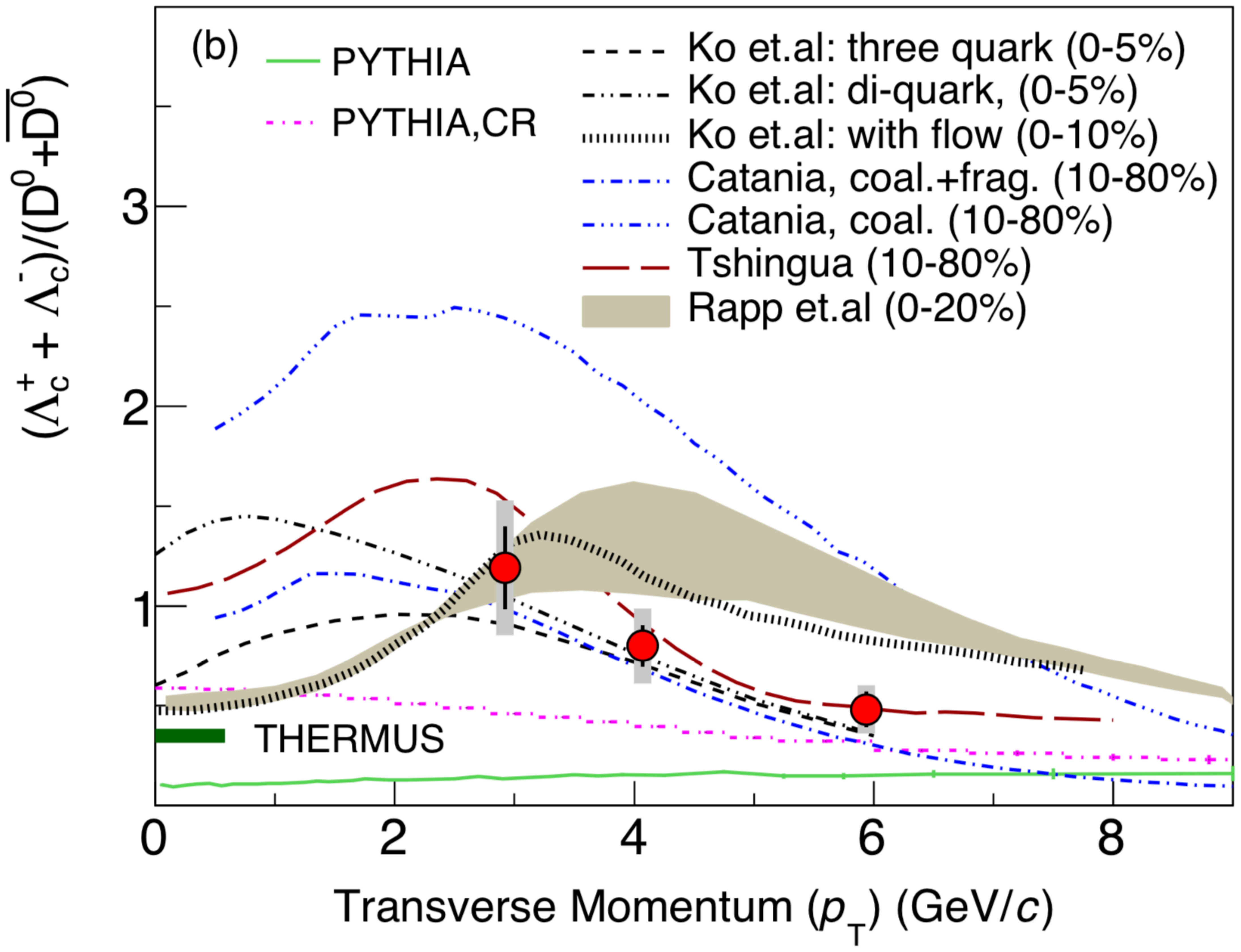
Model	HQ production	Medium modelling	Quark-medium interaction	HQ hadronisatio n	Tuning of medium coupling	References
BAMPS el.	MC@NL0 No PDF shadowing	3d+1 expansion parton cascade	Transport with Boltzmann rad. + coll.	Frag.	RHIC (then scaled by dN/dη	https://arxiv.org/abs/1408.2964
TAMU	FONLL EPS09 (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.

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

Comparison to Λ_c/D^0 ratio from STAR

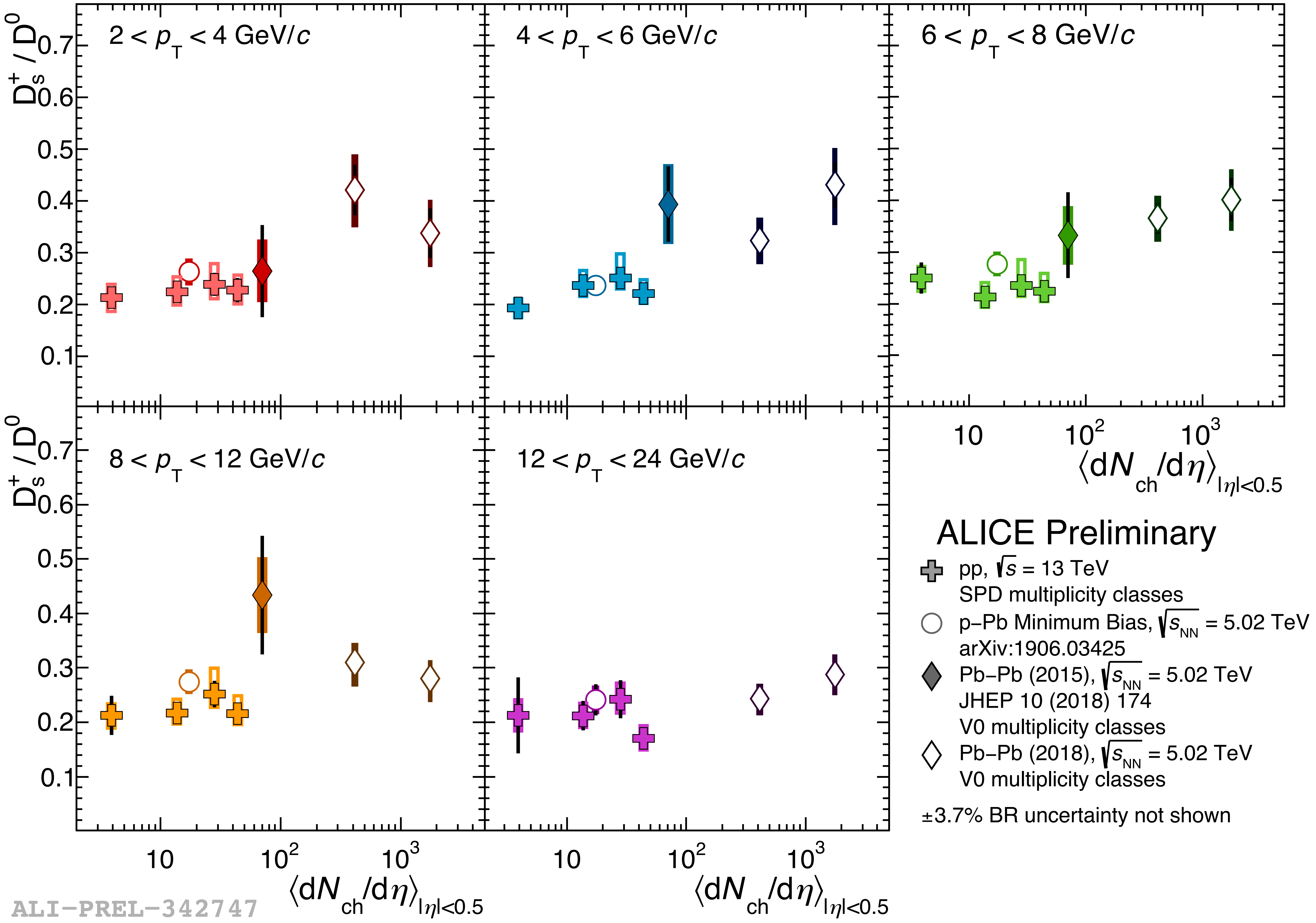




arXiv 1910.14628v1

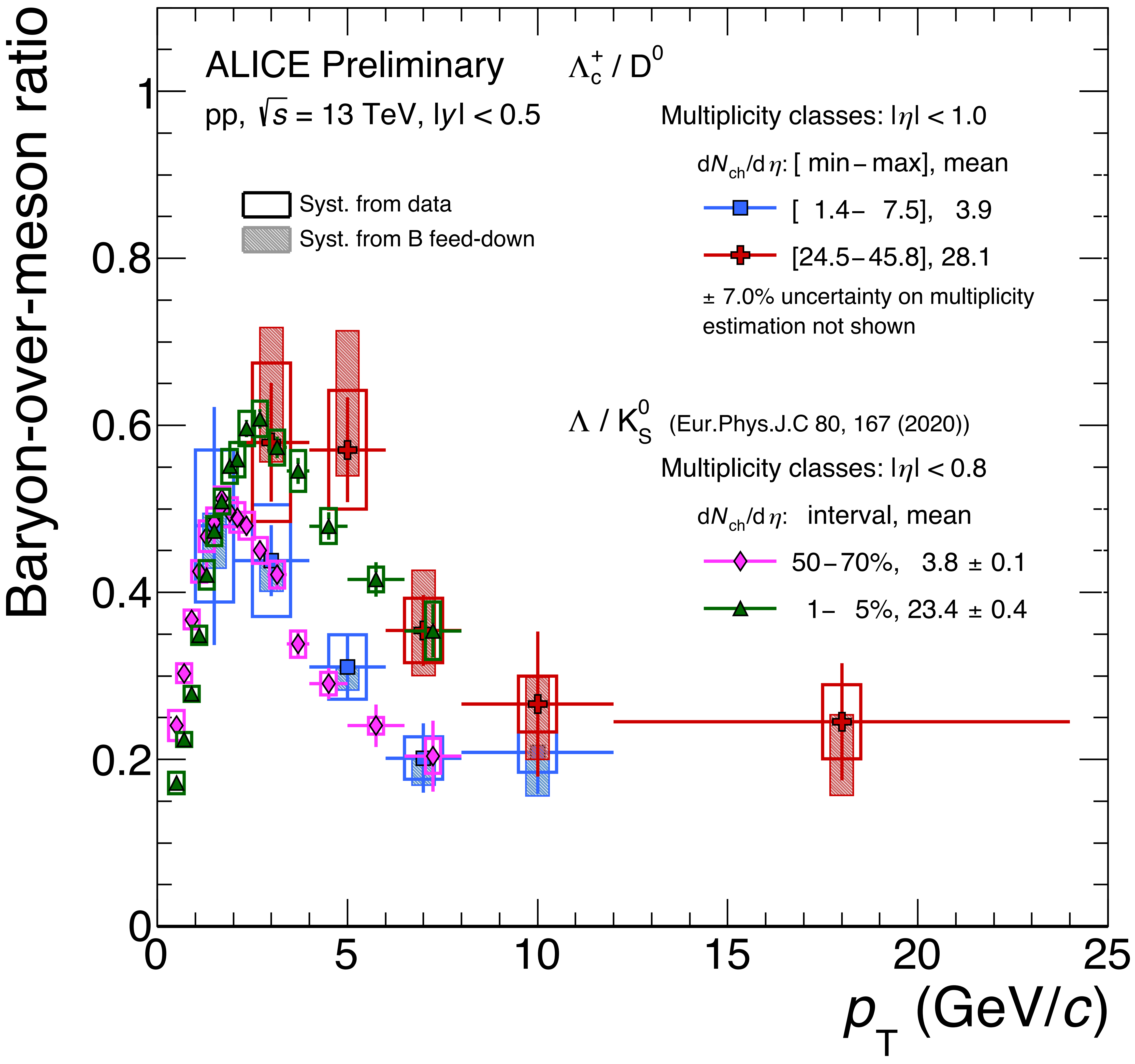
D_s/D^0 in pp collisions vs multiplicity

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

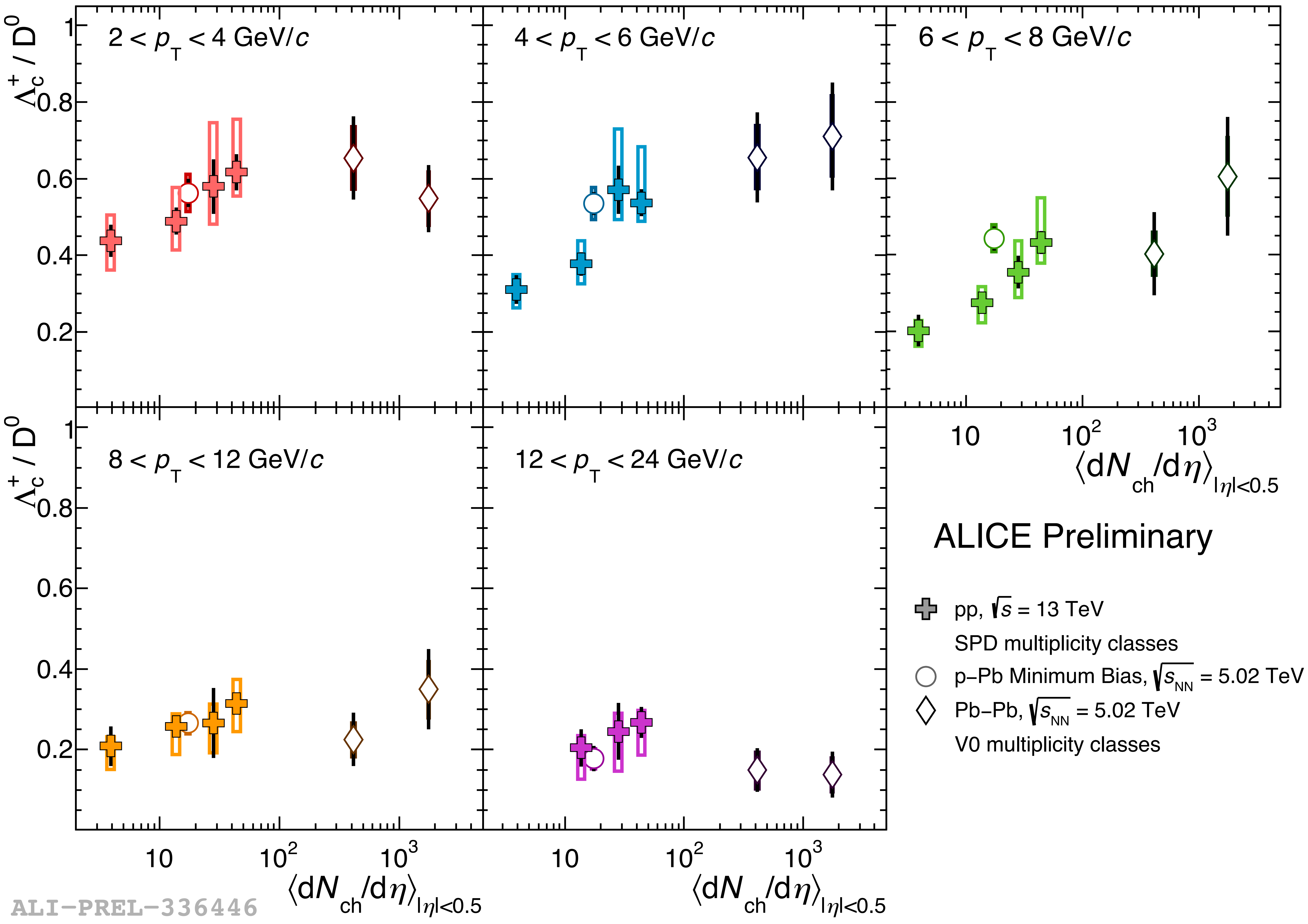


→ D_s/D^0 shows a hint of enhancement from low to high pp multiplicities

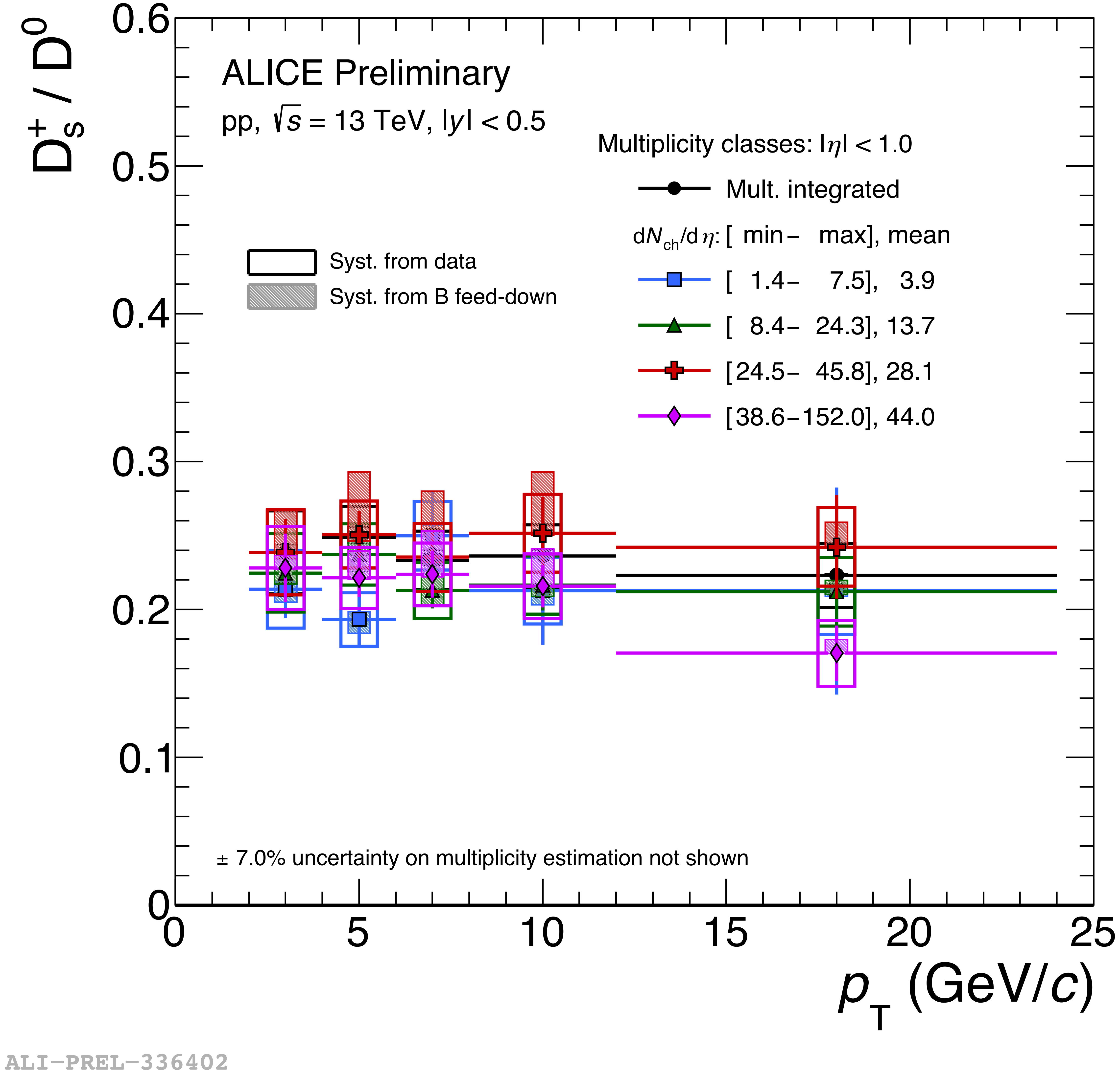
Baryon/meson zoo



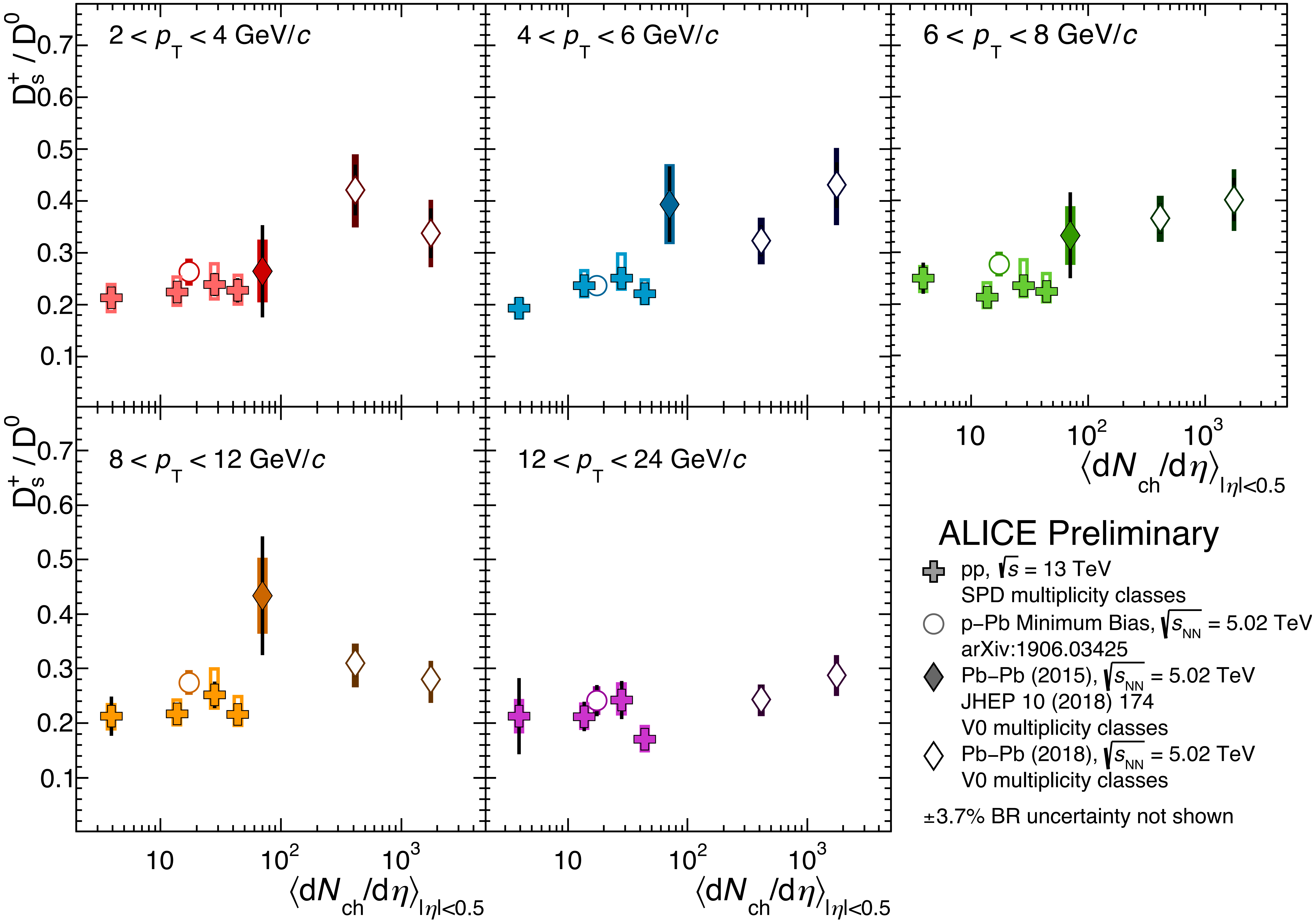
Λ_c/D^0 vs multiplicity in pp, pPb, PbPb



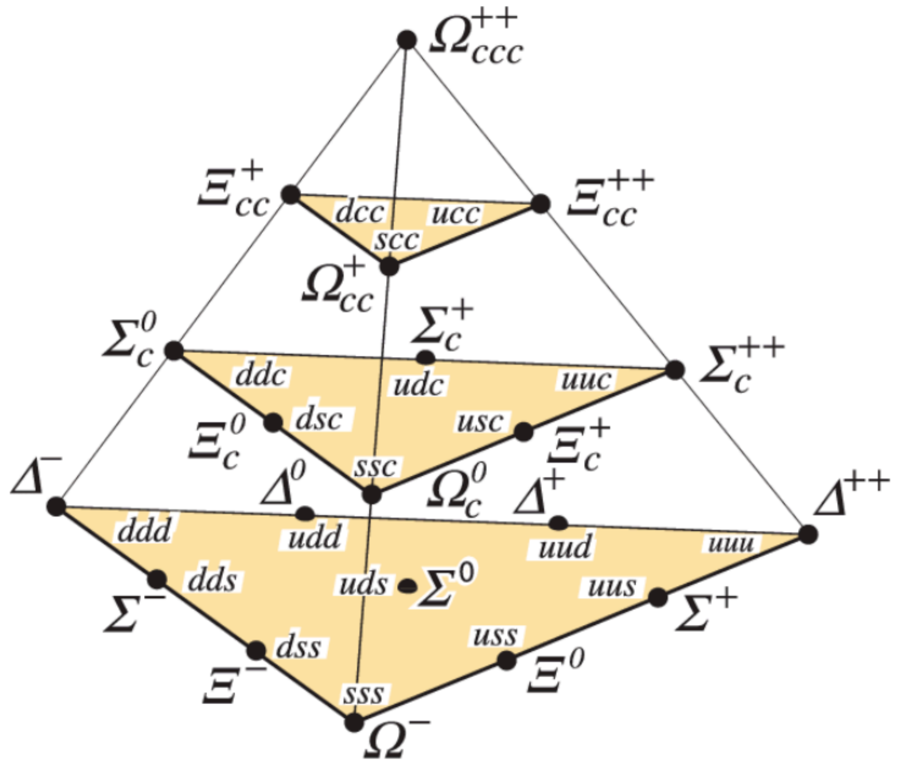
D_s/D^0 vs multiplicity in pp, pPb, PbPb

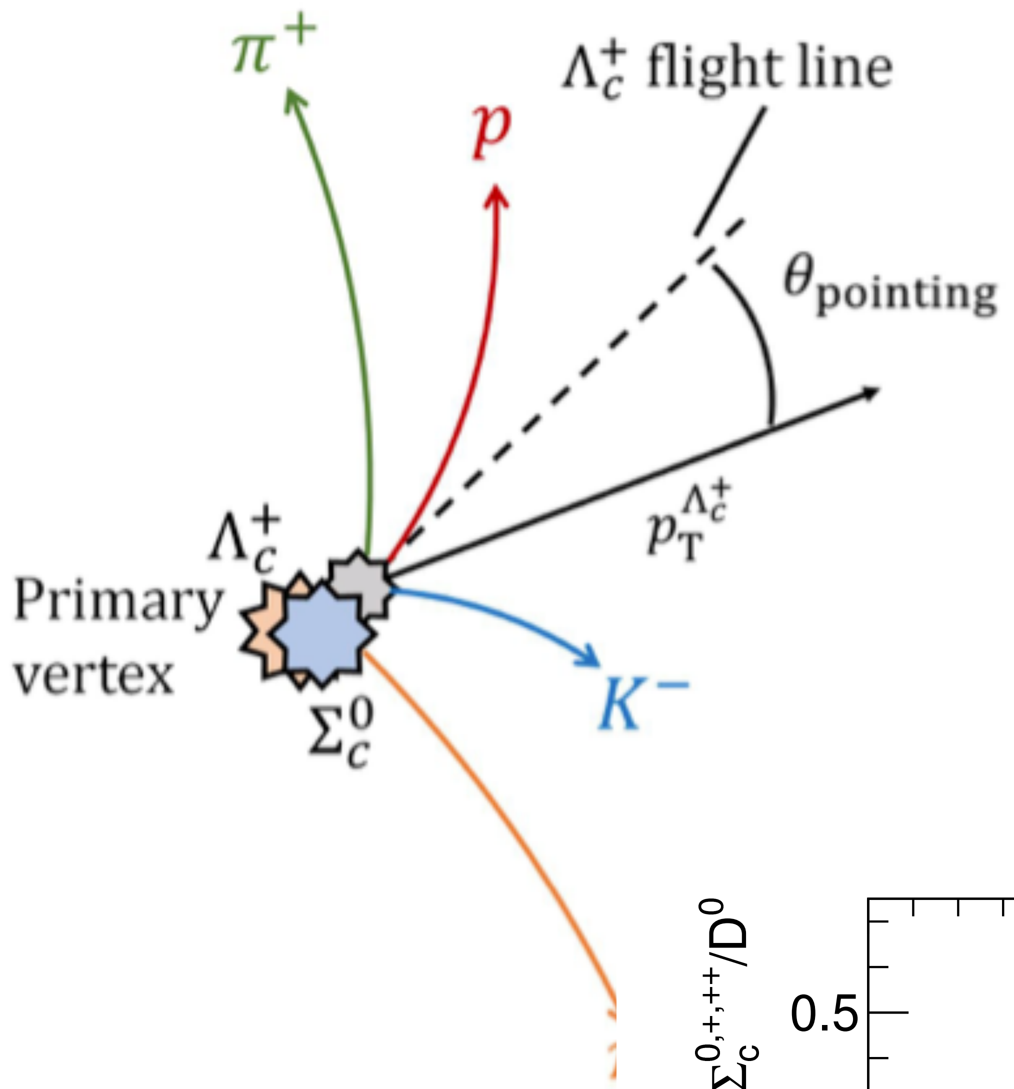


D_s/D^0 vs multiplicity in pp, pPb, PbPb

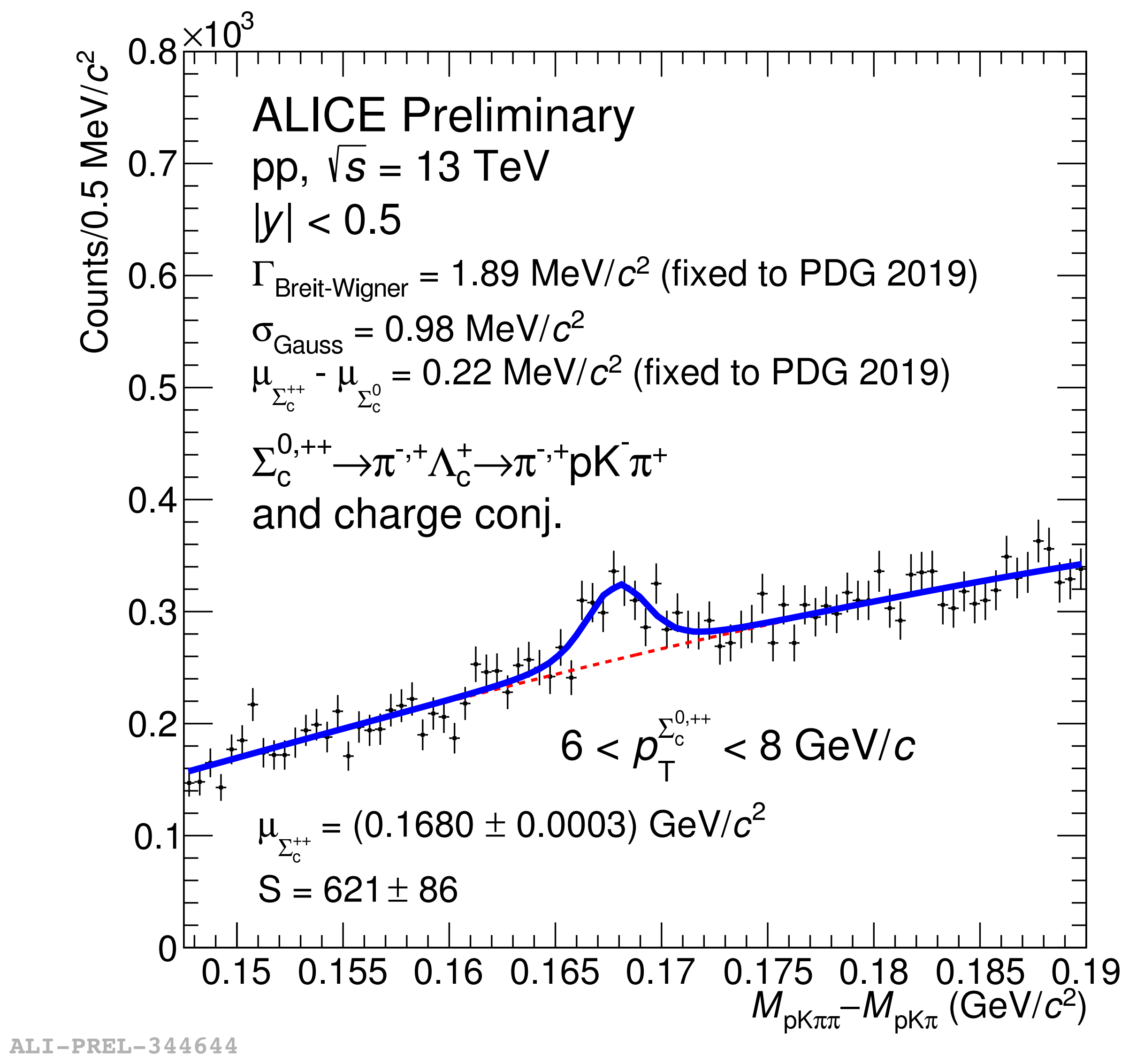


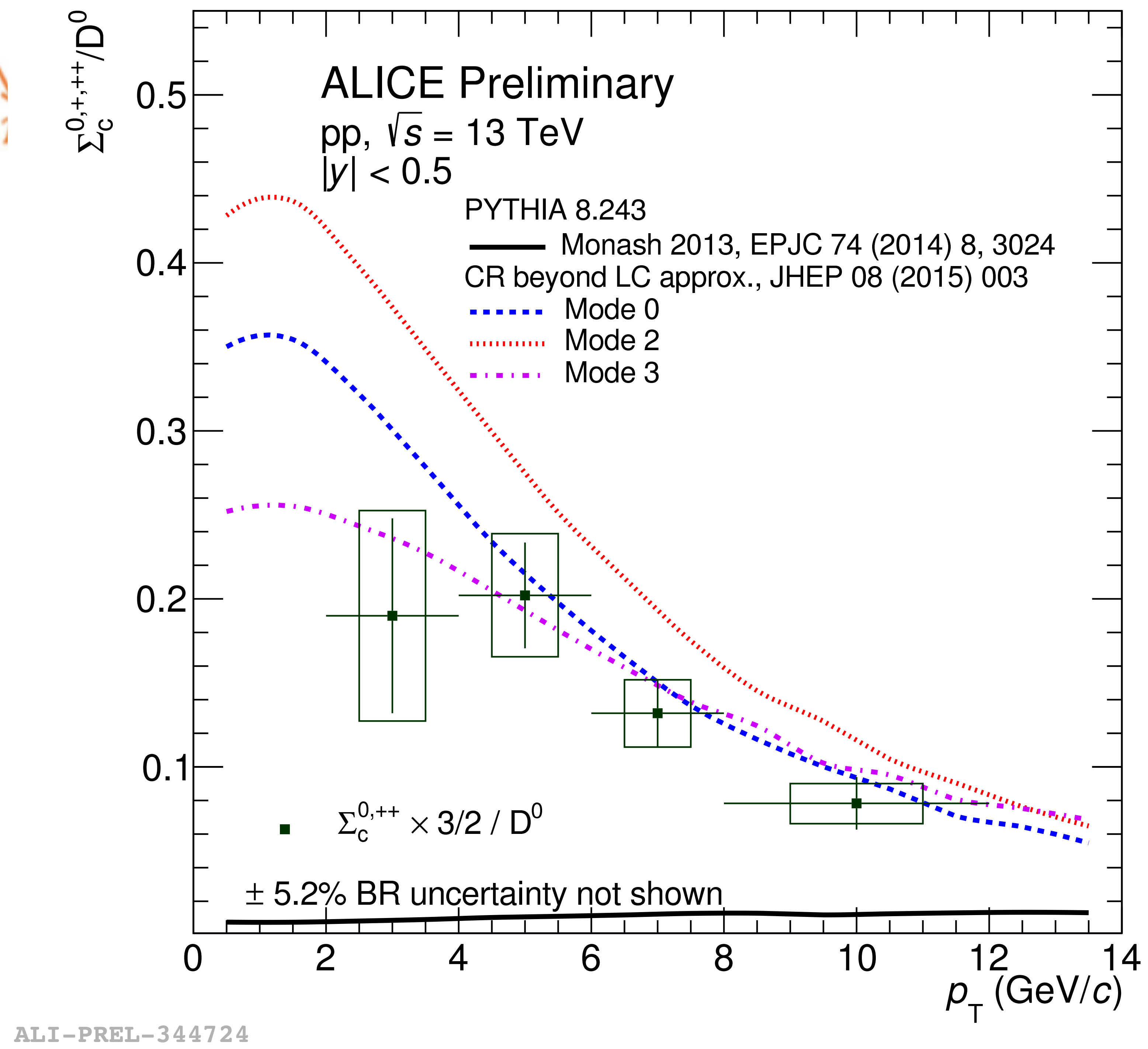
$\Lambda_c \leftarrow \Sigma_c^{0,+,++}$ and $\Sigma_c^{0,+,++}$ in pp collisions

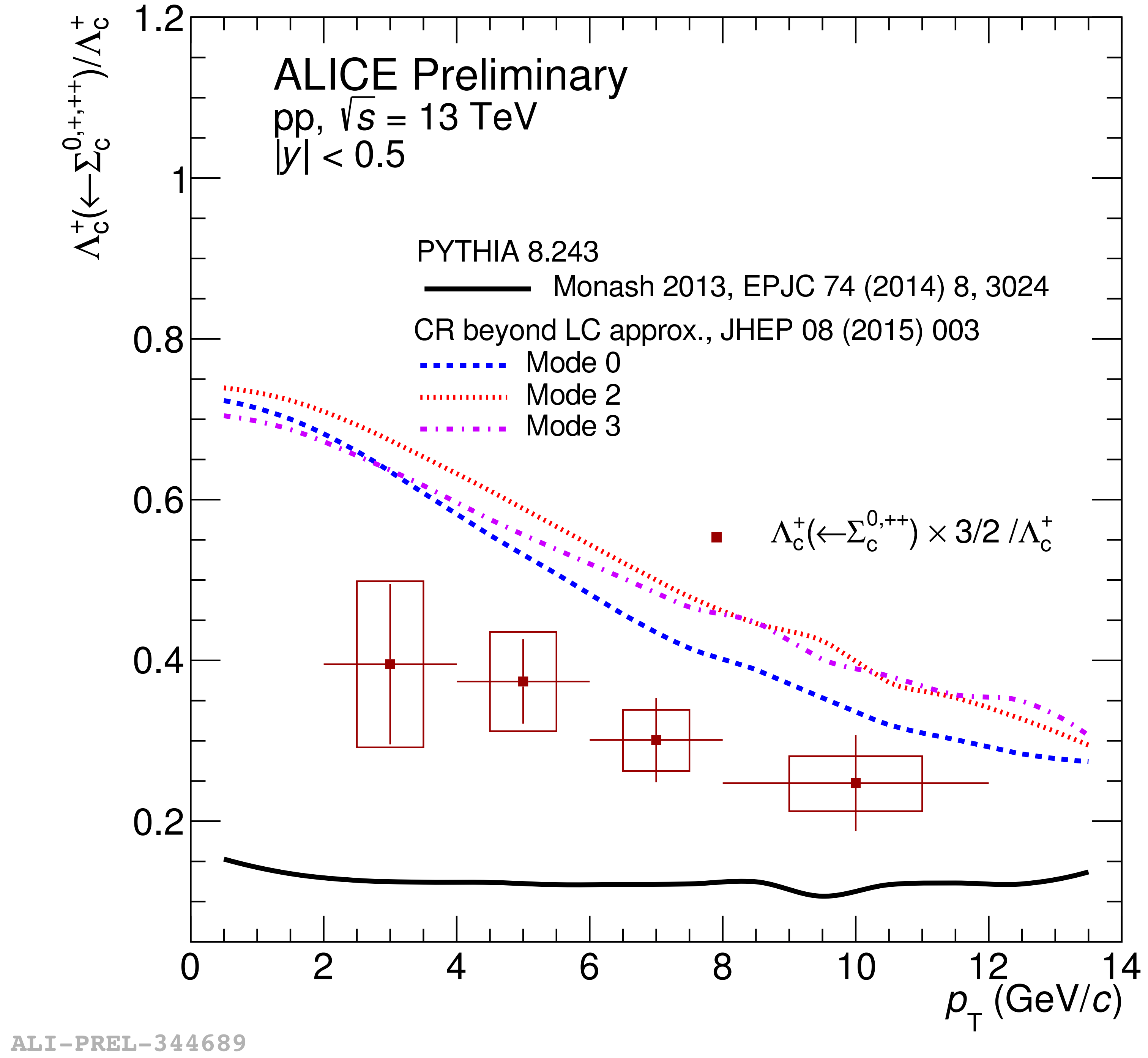




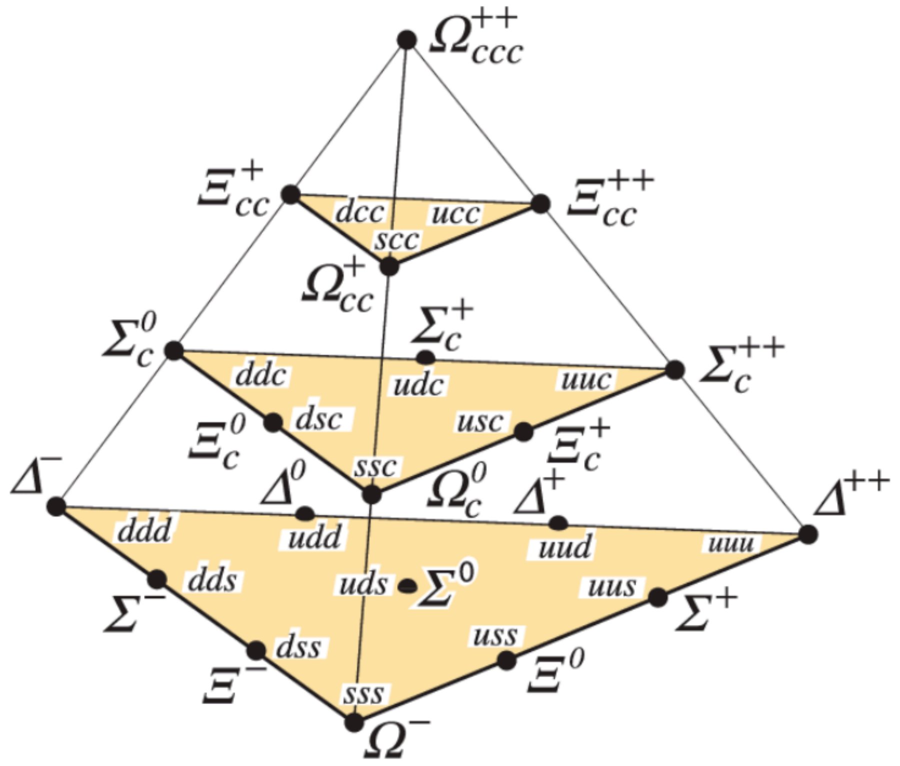
- Λ_c measurement largely underestimated by PYTHIA calculations with different tunes like Monash, DIPSY (rope hadronisation) and do not describe p_T shape.
- Feed-down from higher baryon states in presence of large enhancement (PLB 795 117-121 (2019)) was suggested as a possible explanation
- Further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





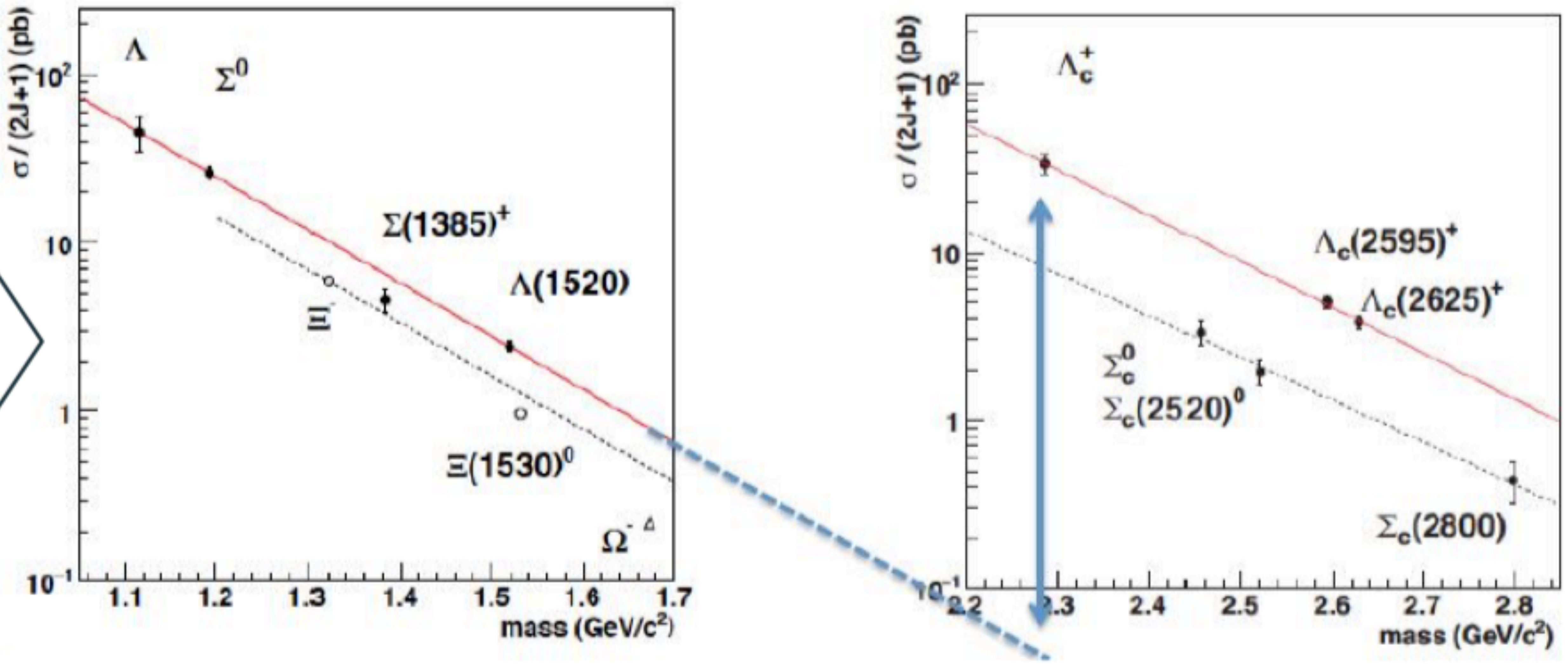


Σ_c enhancement and di-quark states



- 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)

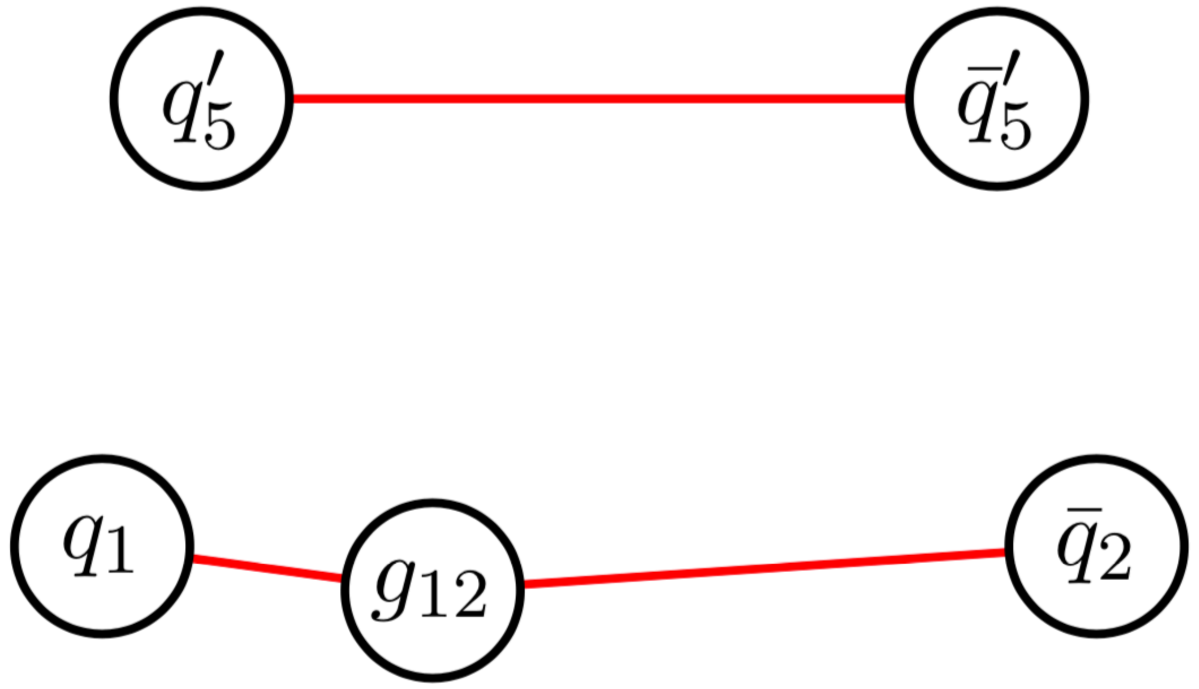


(b) Type II: junction-style reconnection

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

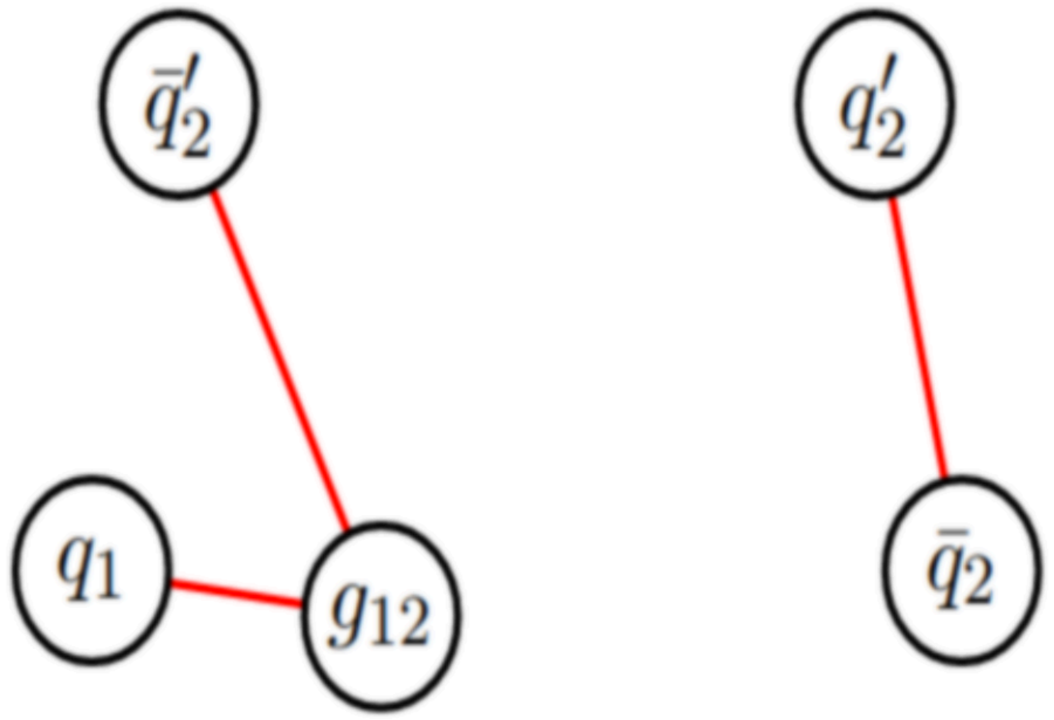
Overview of color reconnection in PYTHIA

No CR



- partons created in different MPIs do not interact

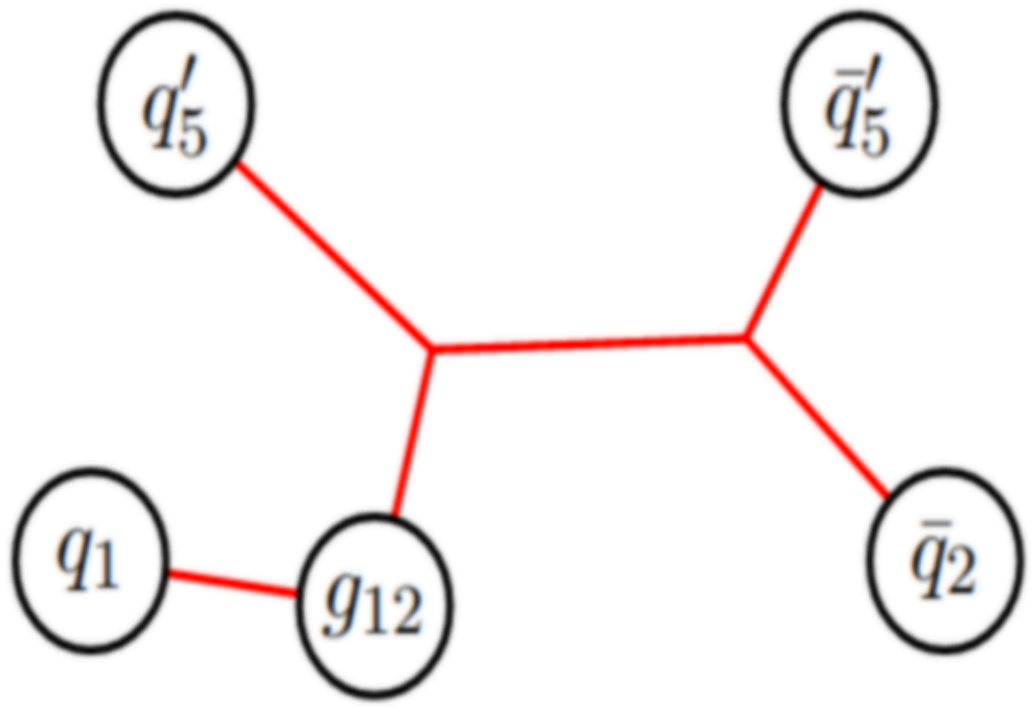
MPI-based CR



- 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

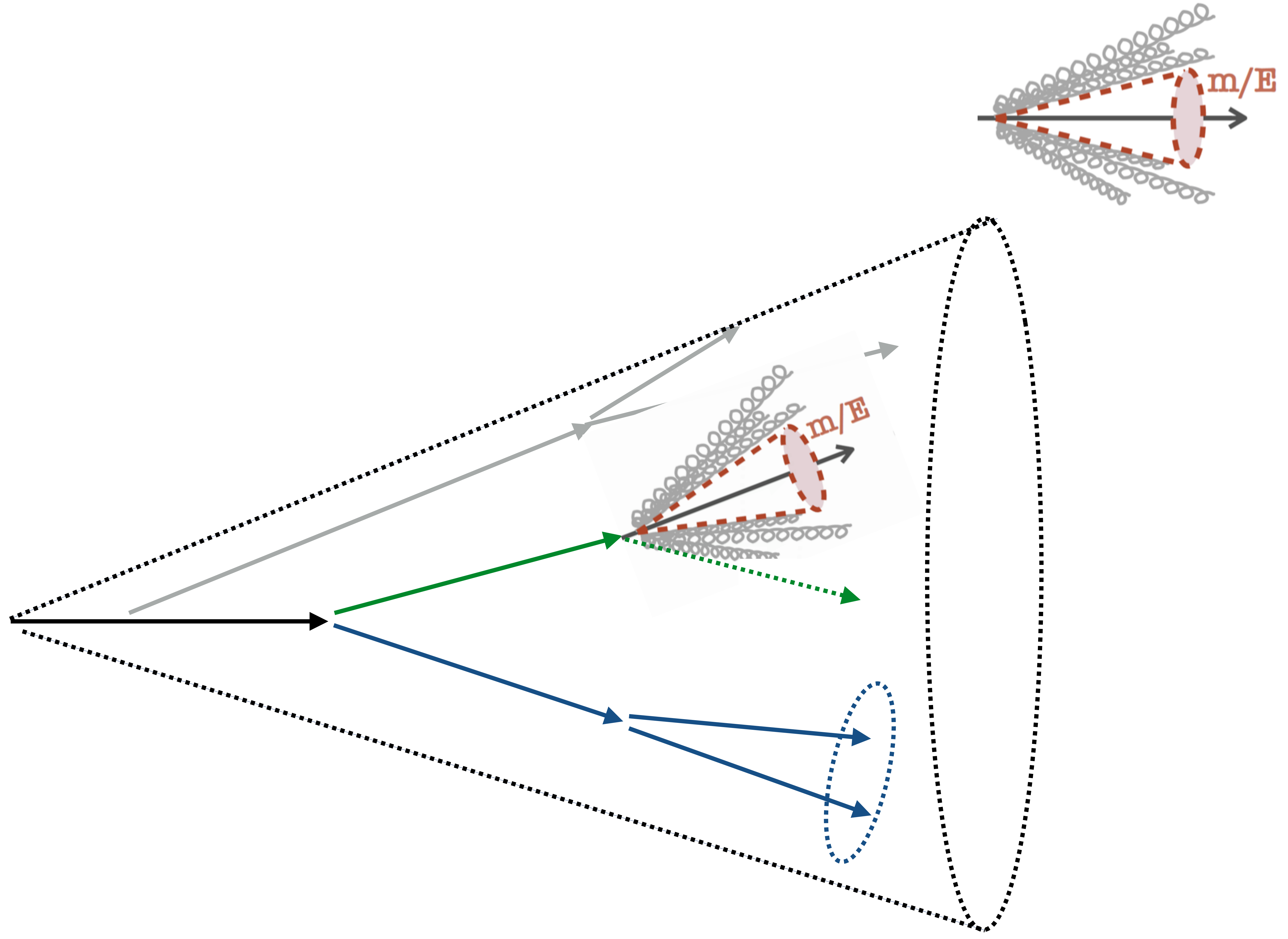
JHEP 08 (2015) 003, arXiv:1505.01681v1

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

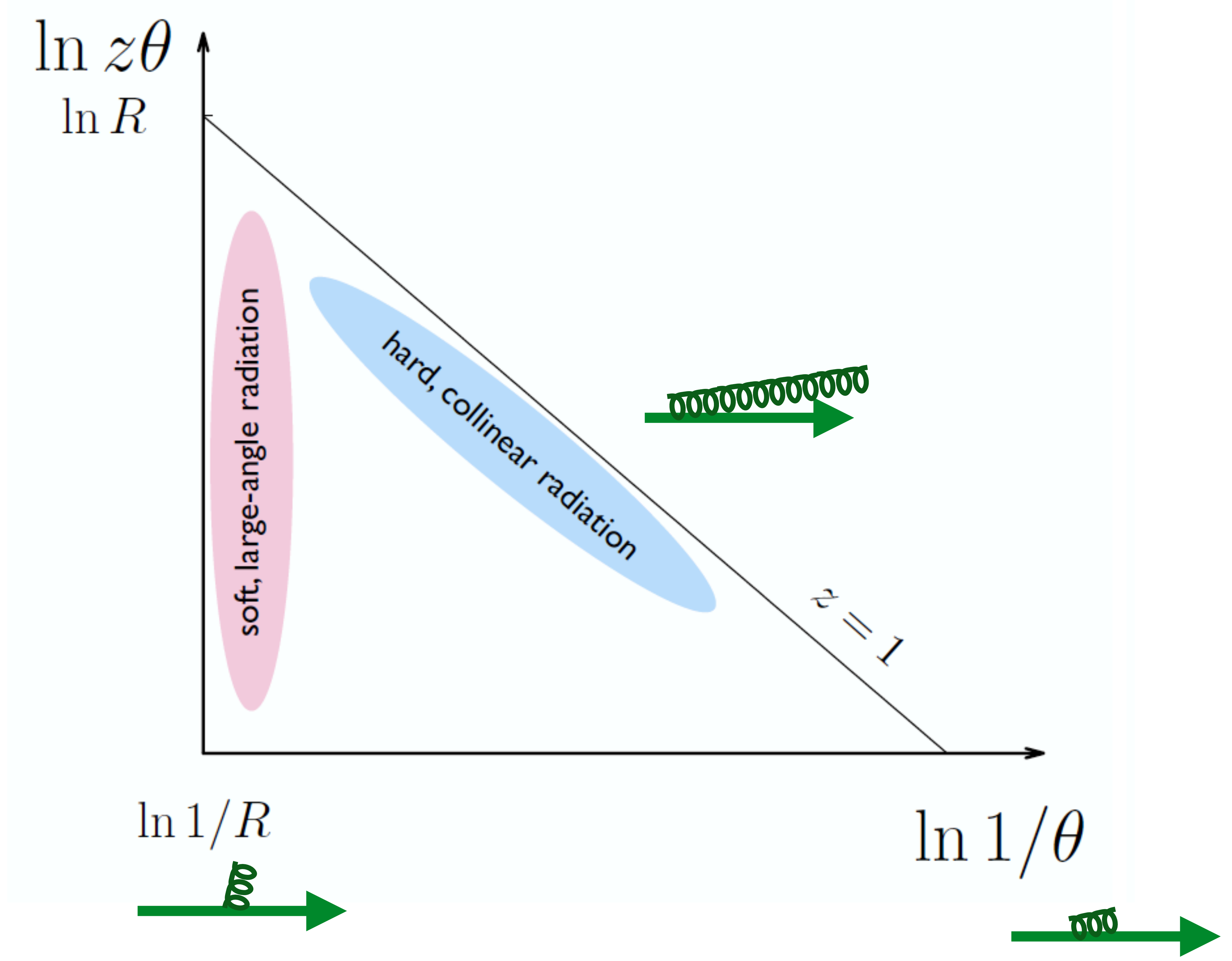
JHEP 08 (2015) 003, arXiv:1505.01681v1

HF jets to test QCD predictions: dead cone effect



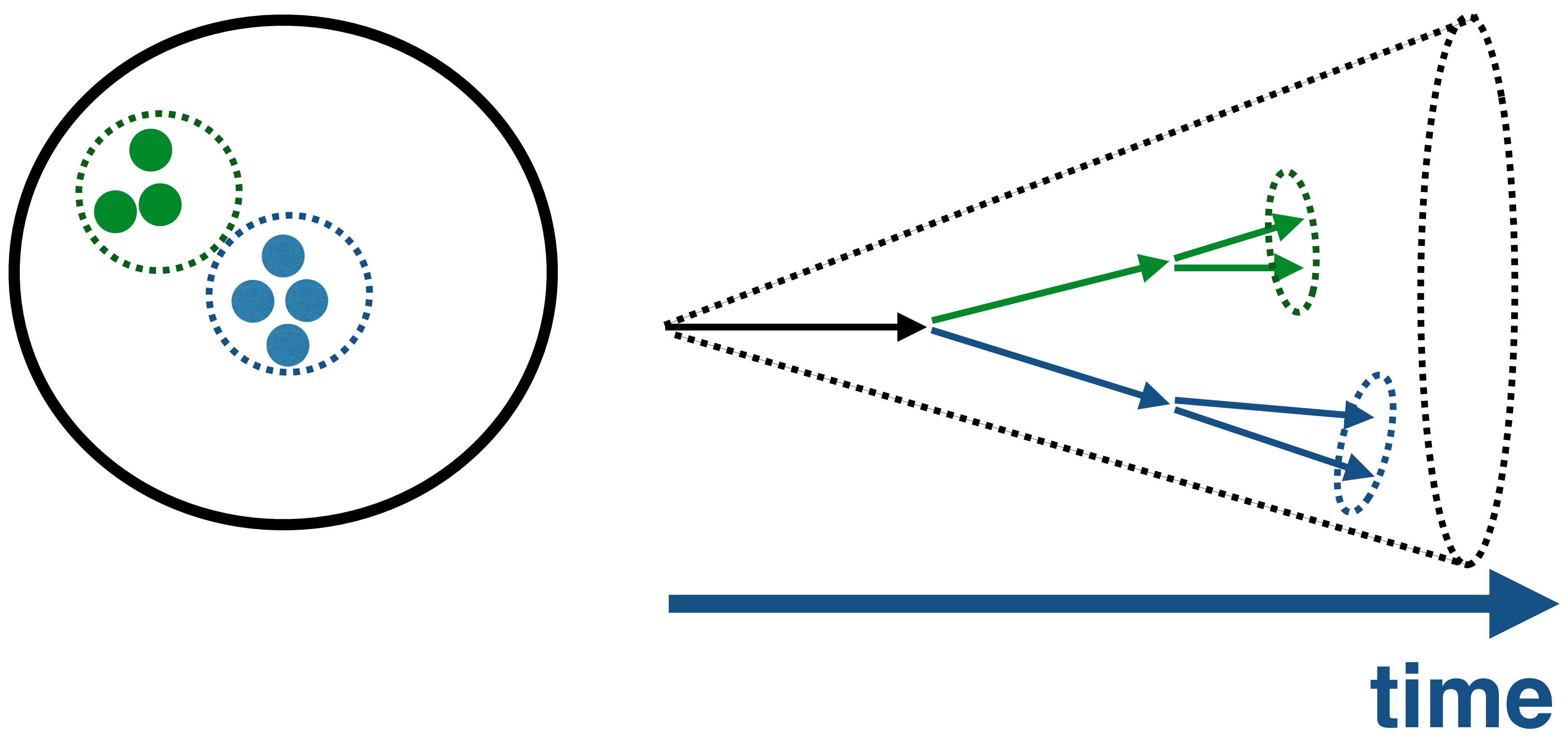
Dead cone: suppression of small angle radiation for heavy quarks.

→**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



Considering the two main sub-jets j_1, j_2

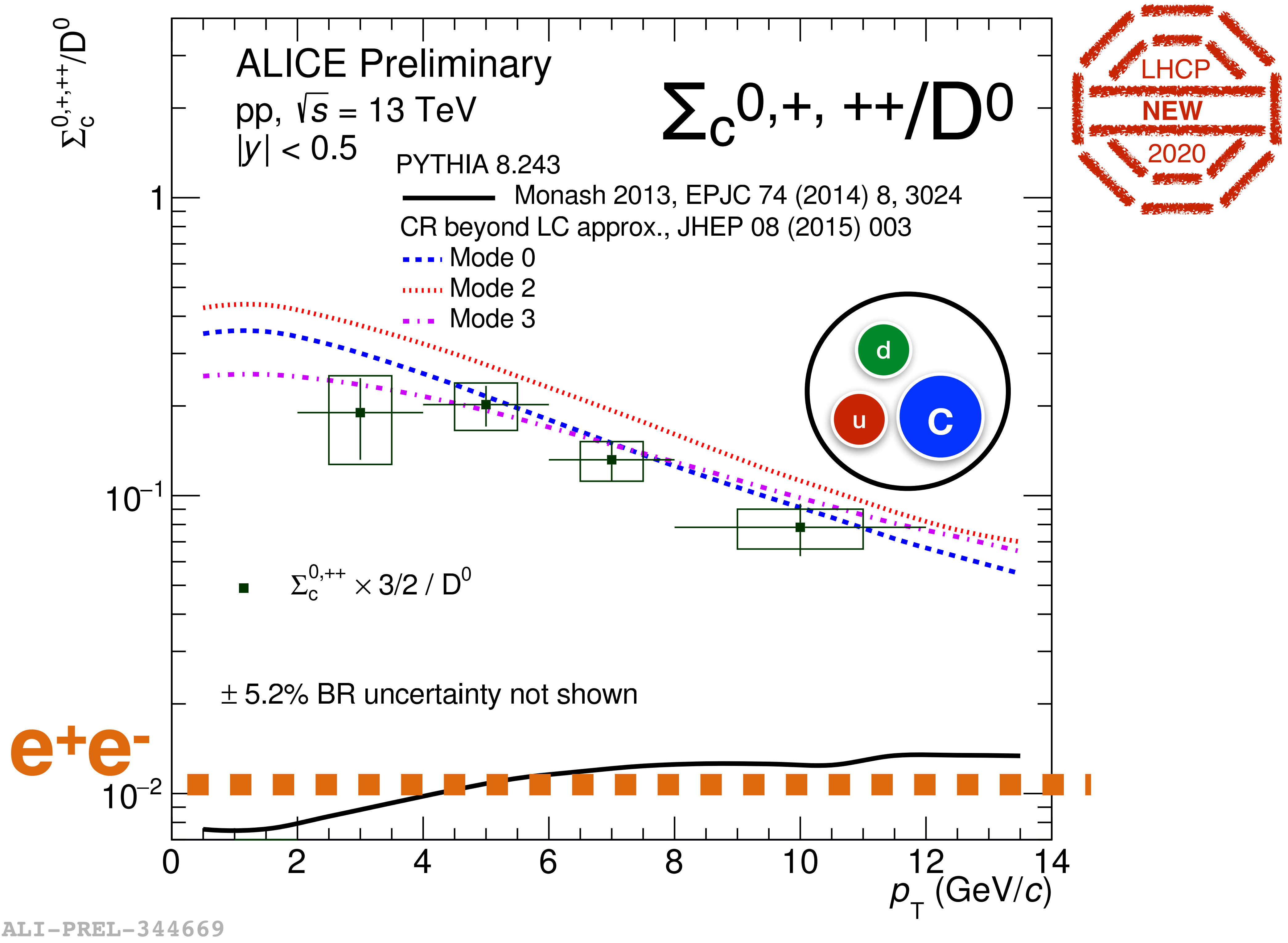
- Momentum asymmetry: $z_g = \frac{p_{T,2}}{p_{T,2} + p_{T,1}}$
- Radial distance $\mathbf{R_g}$
- Groomed mass $\mathbf{M_g}$

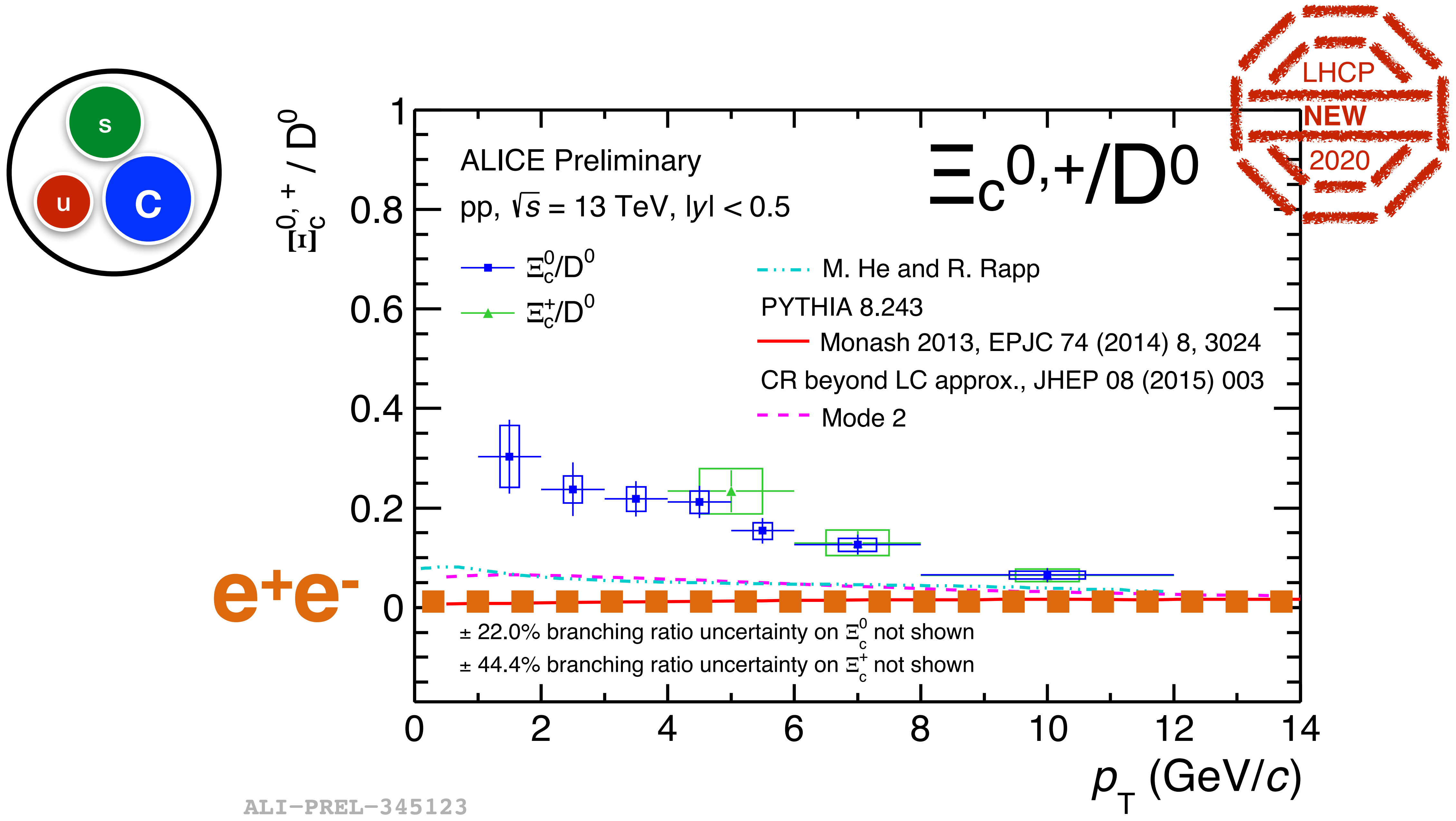
"Soft drop":
Iteratively test the soft drop condition at each splitting.

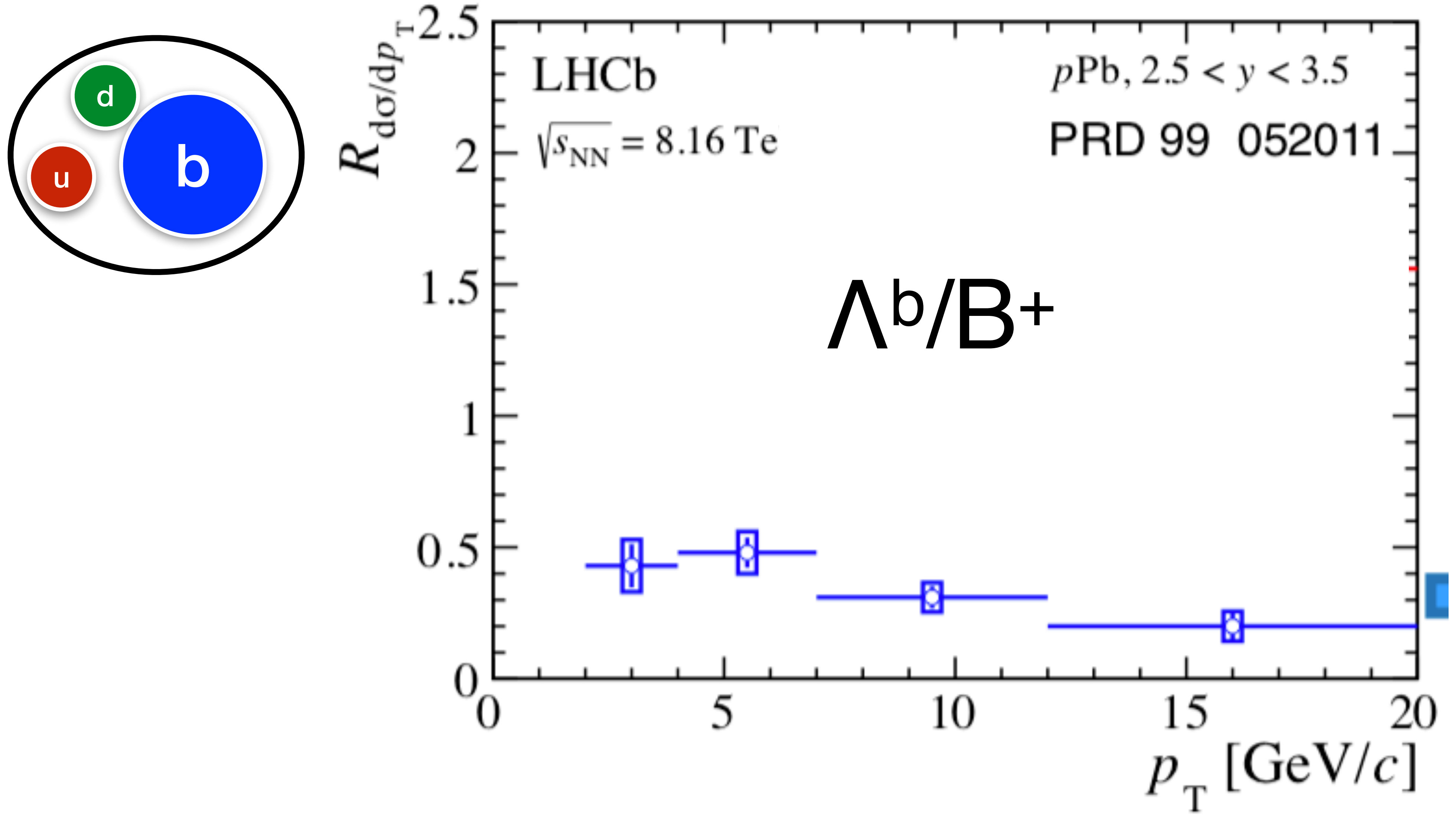
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

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

Heavier charmed/beauty baryons in pp collisions





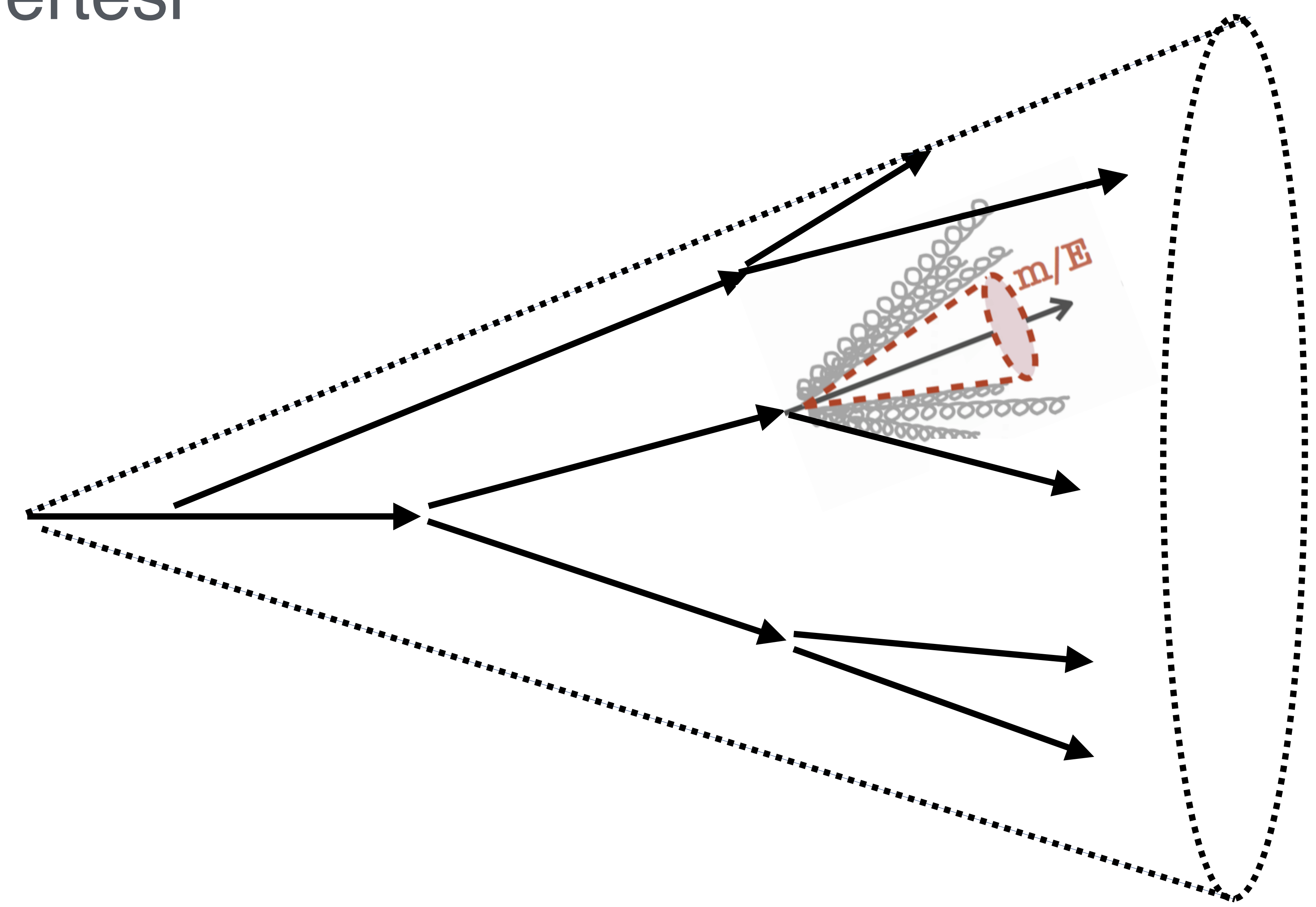


- Indication of large **enhancement** w.r.t e^+e^- fragmentation ratios for $\Sigma_c^{0,+,++}$ and $\Xi_c^{0,+}$
- Modification of baryon/meson ratio in the beauty sector

→ 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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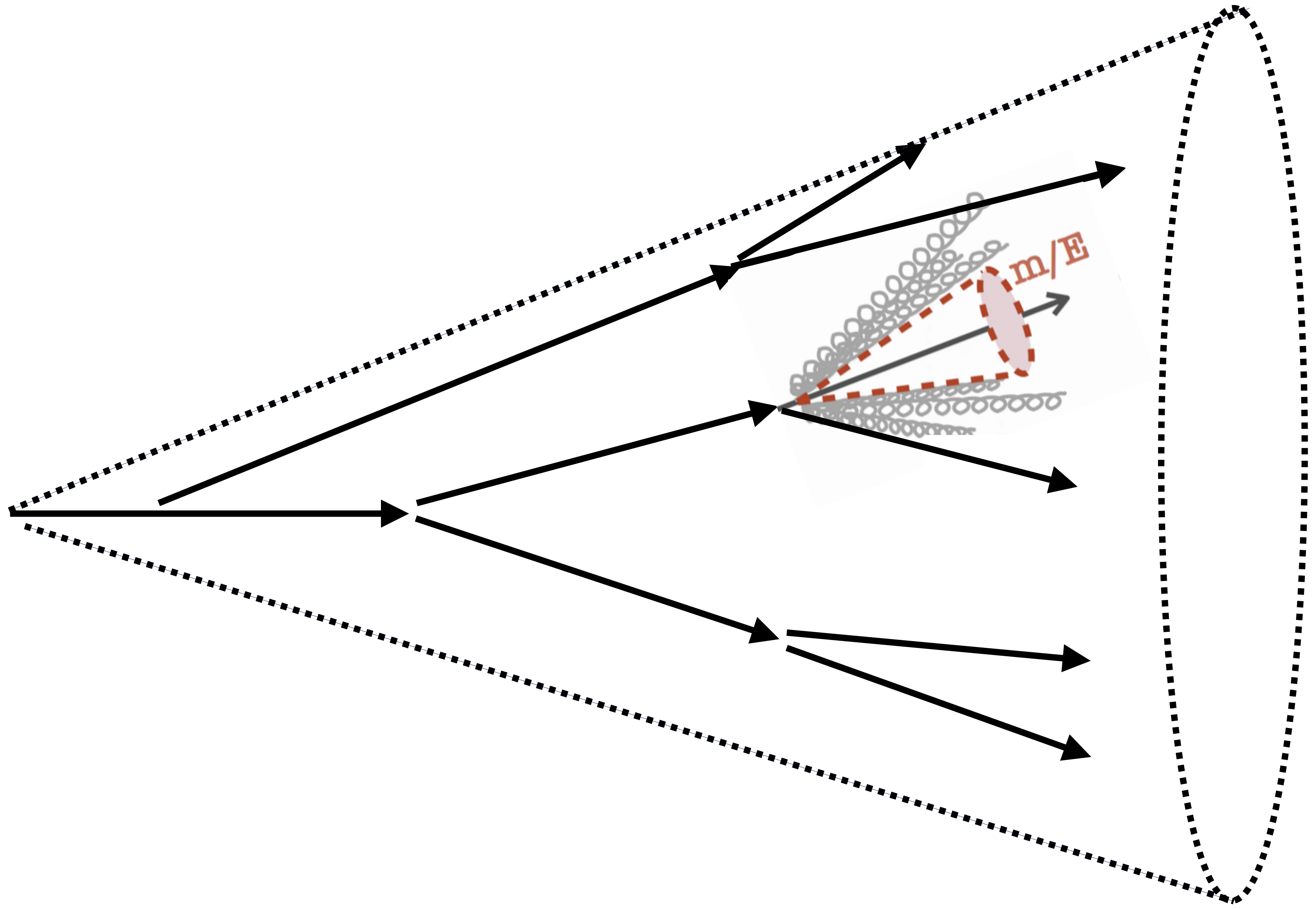

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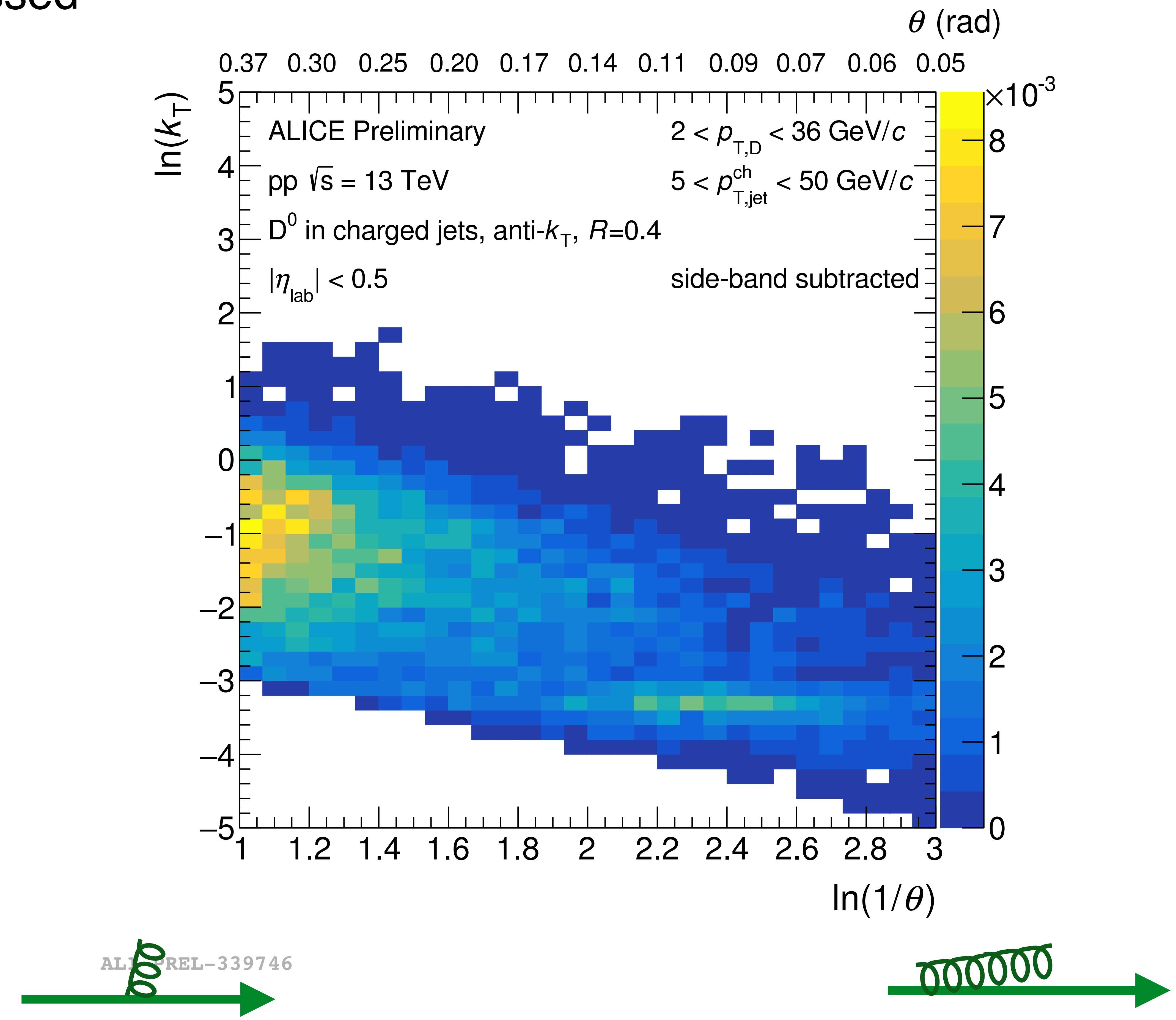
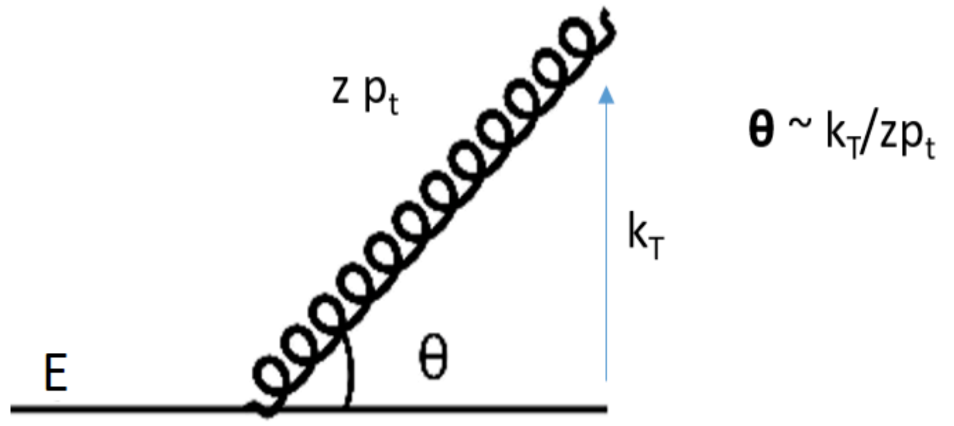
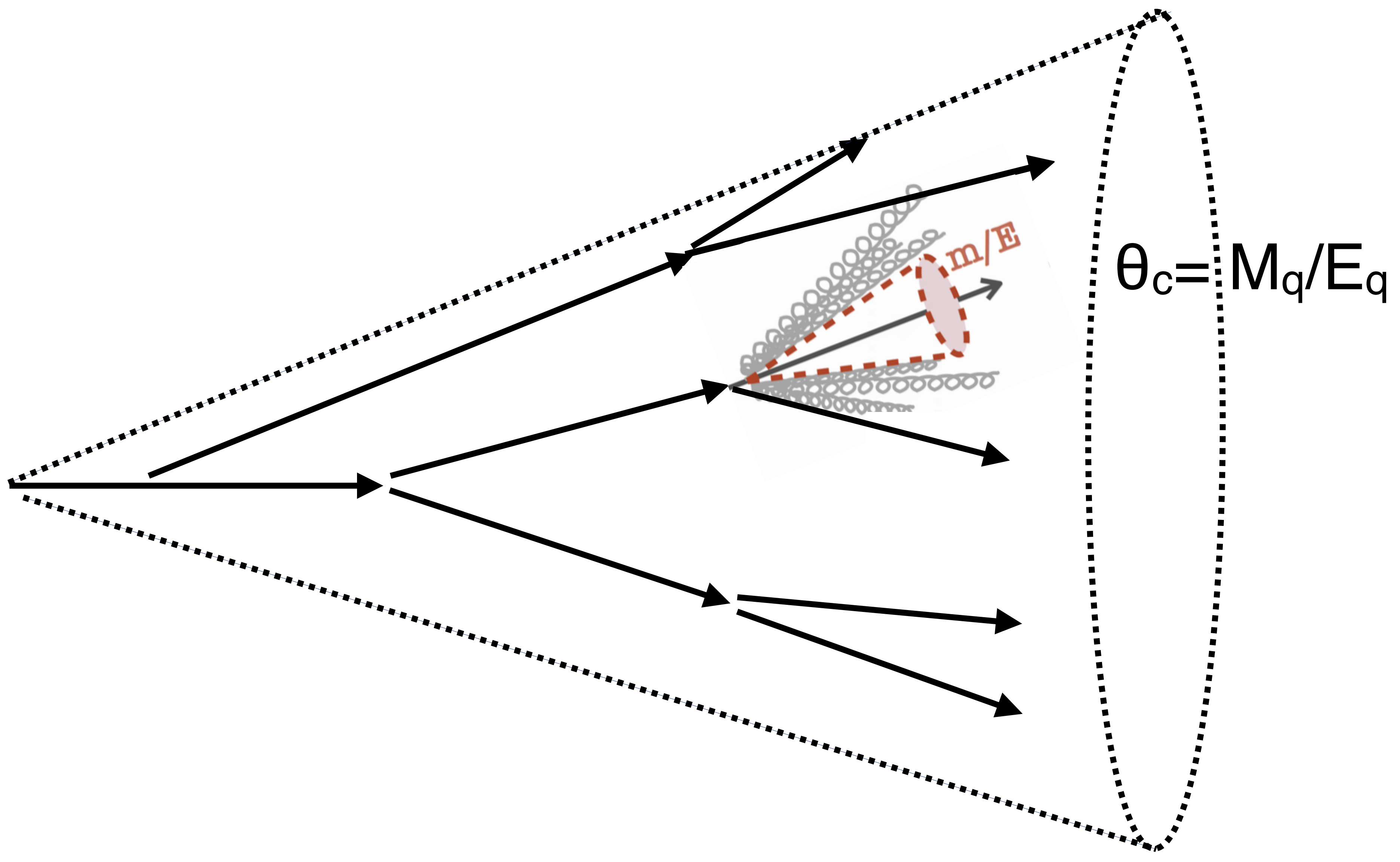


For both inclusive and charm jets:
- Iterative declustering with C/A - access to each splitting
- Fill a Lund plane with θ, k_T of each splitting
- project in θ



HF jets to test QCD predictions: dead cone effect



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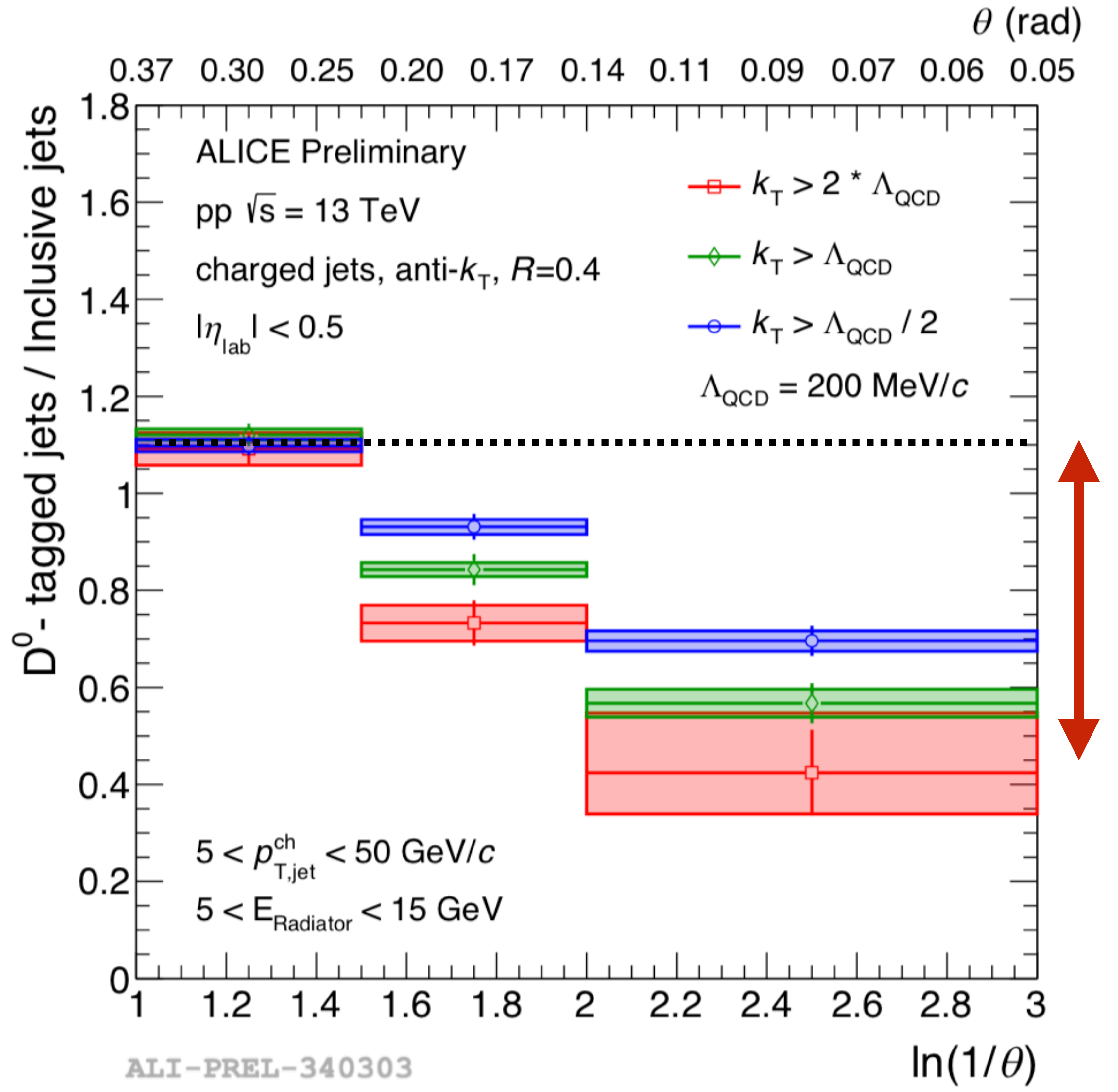
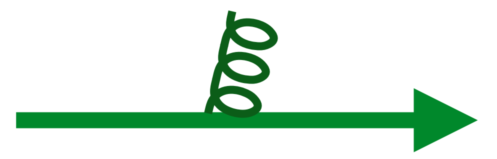
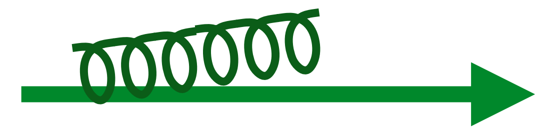
ratio of D⁰-tagged / inclusive jet distributions







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