Study on charmed-baryon production with the ALICE experiment at the LHC

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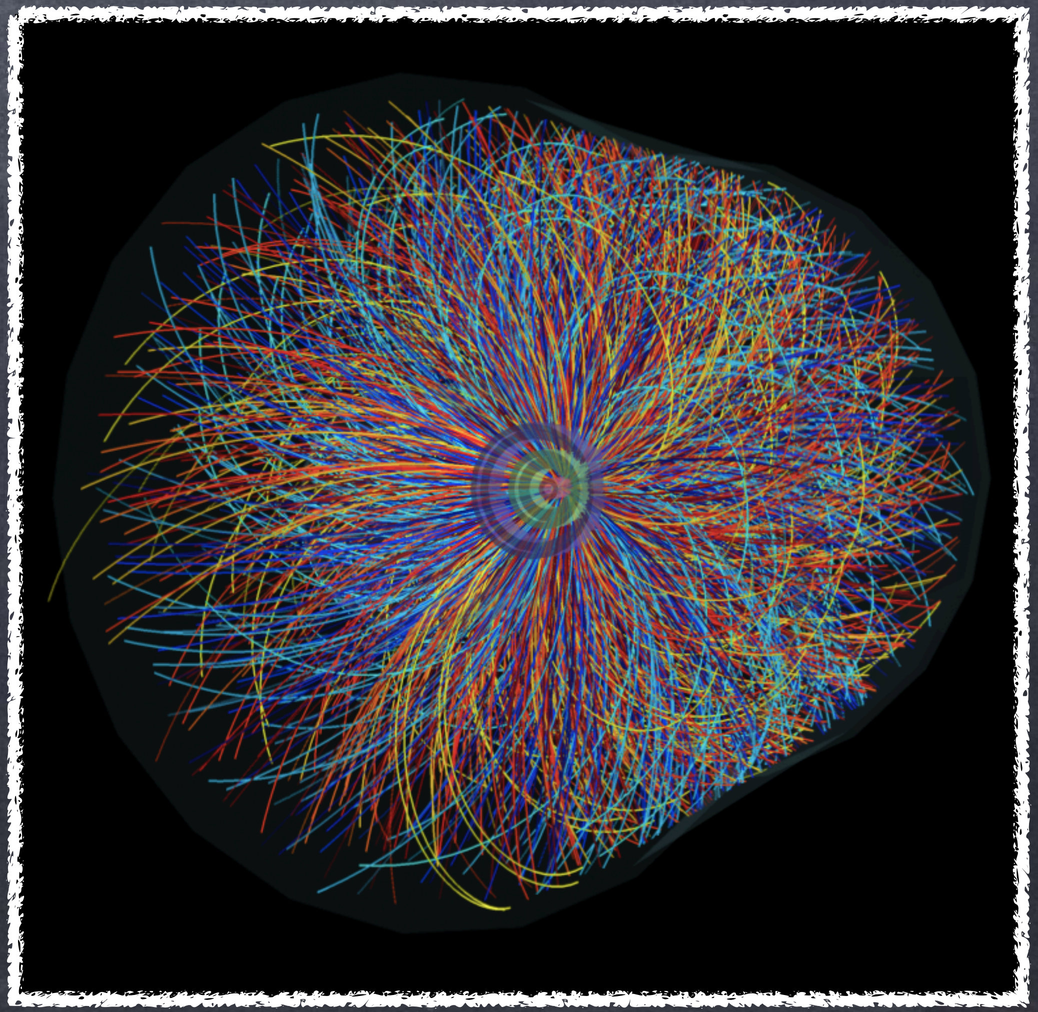
17th Chinese Nuclear Physics Conference

CCNU, Wuhan, 08. - 12.10.2019

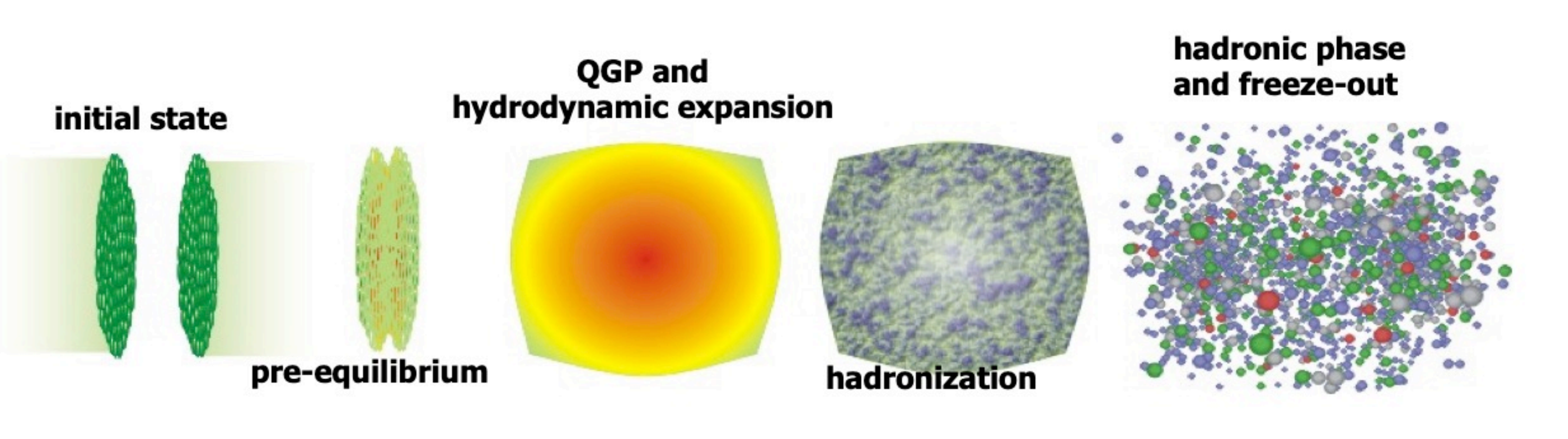


Outline

- Introduction
- The ALICE detector
- Reconstruction strategy
- Results on Λ_c^+
- Summary and outlook

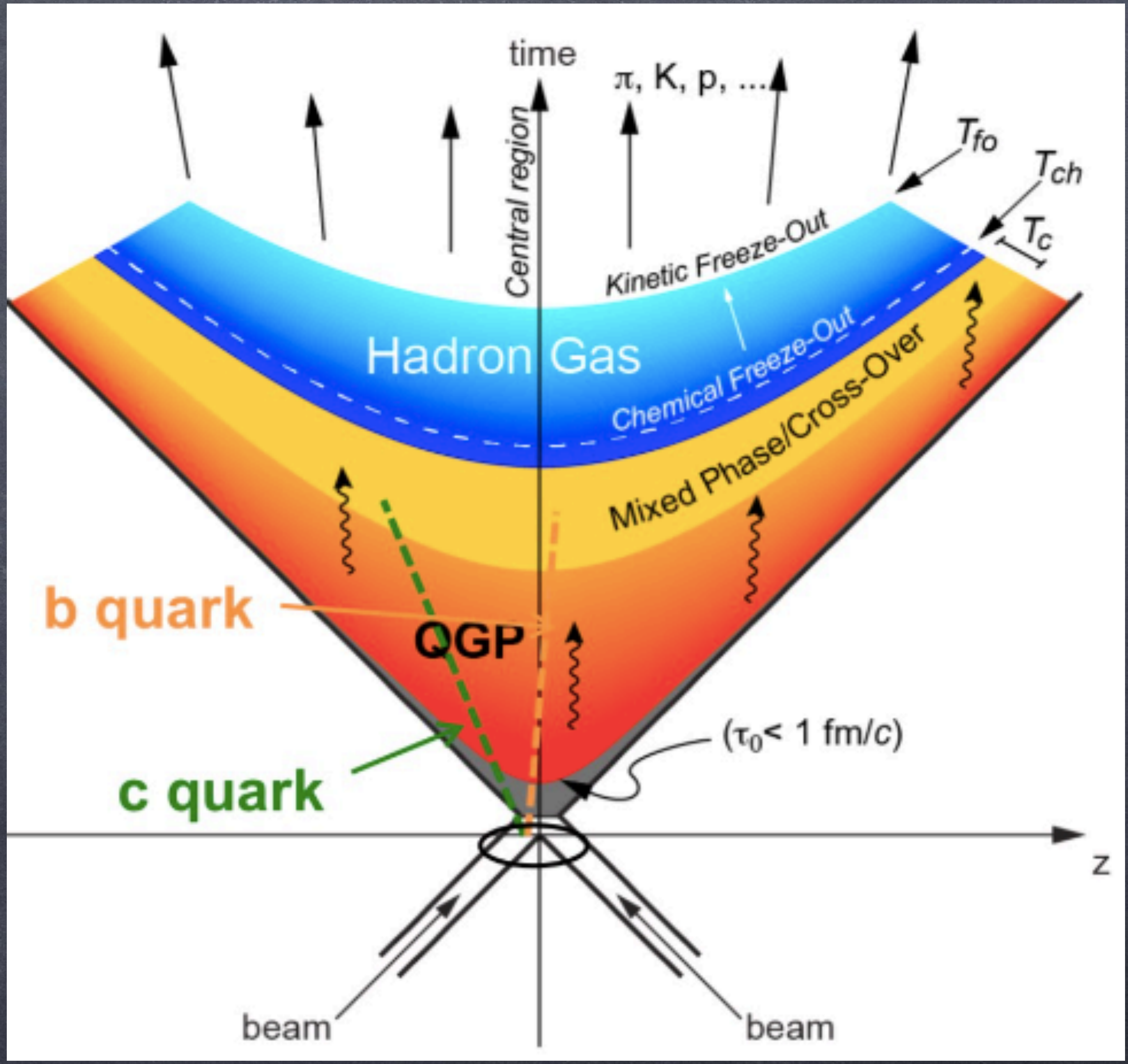
Motivations: Probing the Quark-Gluon Plasma

- The aim of heavy-ion collisions is to study the properties of the colour-deconfined medium, Quark-Gluon Plasma(QGP).



Motivations :Heavy quarks in pp, p-Pb and Pb-Pb collisions

- Heavy quarks are excellent probes to characterise QGP medium.
  - -> Early production in hard-scattering processes at the early stage of heavy-ion collisions.
  - -> Experience the entire evolution of the medium.
  - -> Strongly interacting with QGP.



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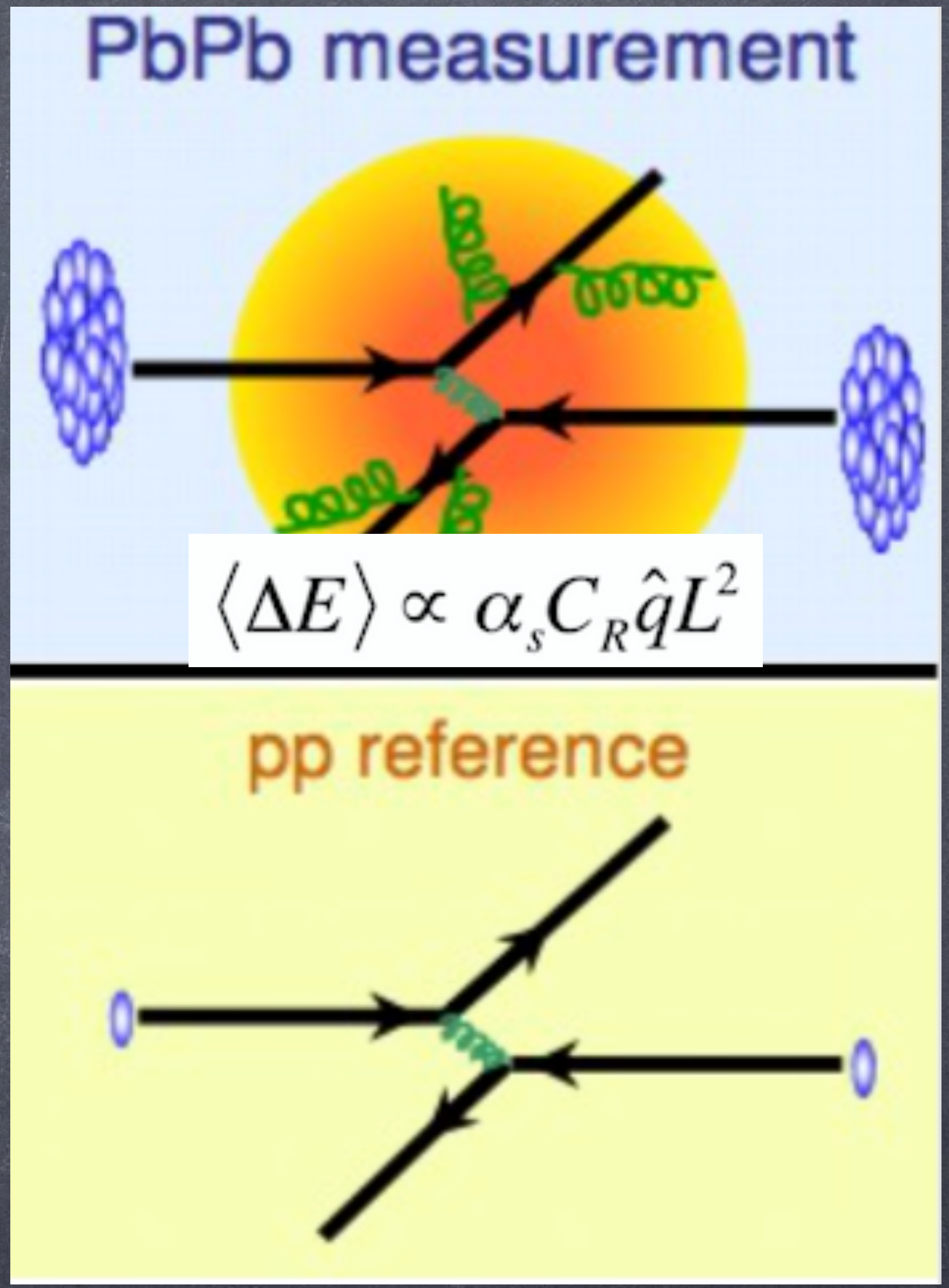

Energy loss

Mechanisms: gluon radiation, elastic collisions

Key Observables: $$R_{\rm AA}(p_{\rm T}) = \frac{1}{<T_{\rm AA}>}\frac{{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}}{{\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm T}}$$

- R_{AA} = 1, if there is no medium modification

$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ → R_{AA}(light hadron)<R_{AA}(D)<R_{AA}(B)?

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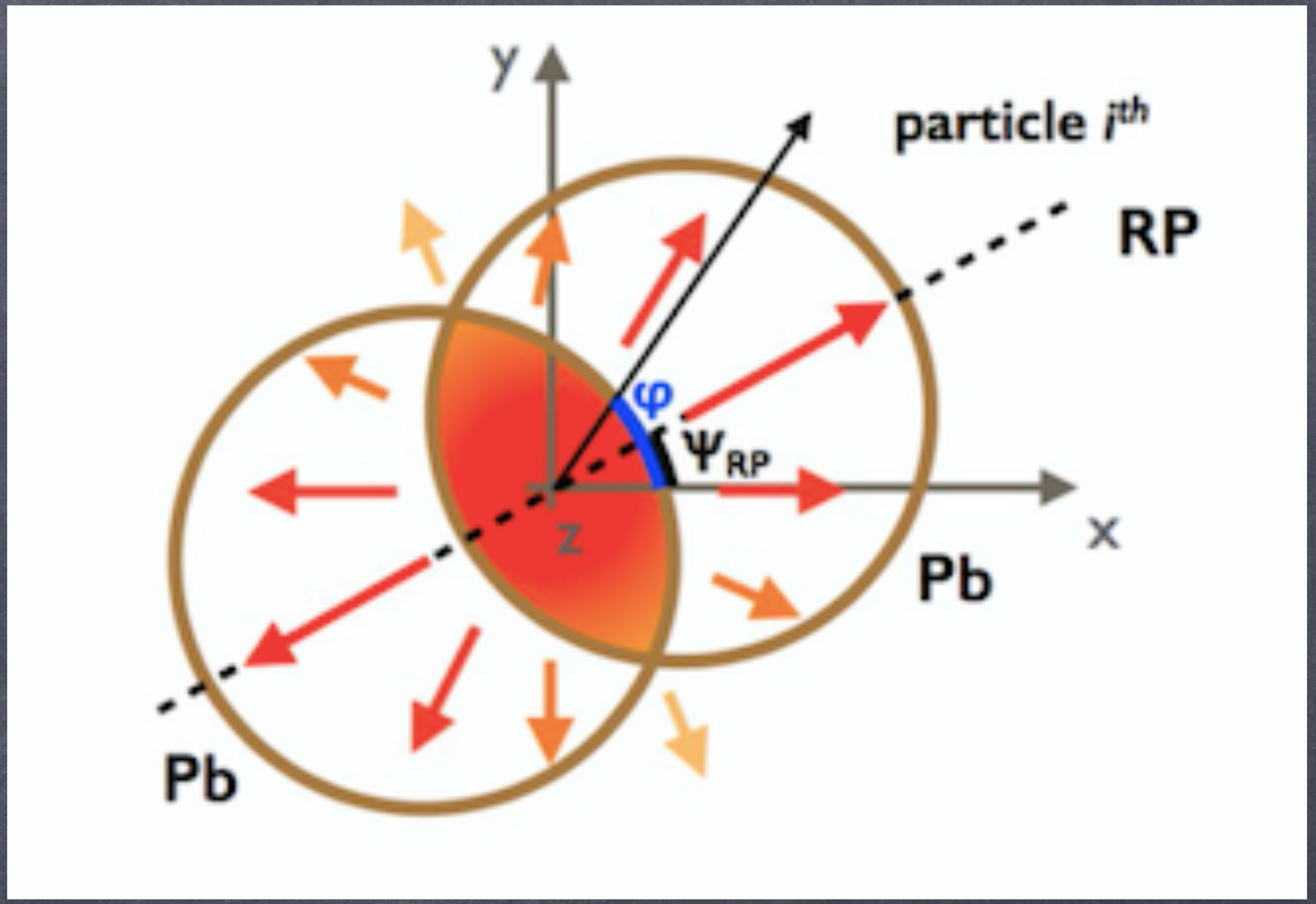

Energy loss

Collectivity

- Azimuthal anisotropy of produced particles.
- At low p_T —> information on the transport properties of the medium, collectivity and thermalisation of heavy quarks.

Key Observables: $v_2 =< \cos 2(\varphi - \psi_2) >$

Motivations :Heavy quarks in pp, p-Pb and Pb-Pb collisions

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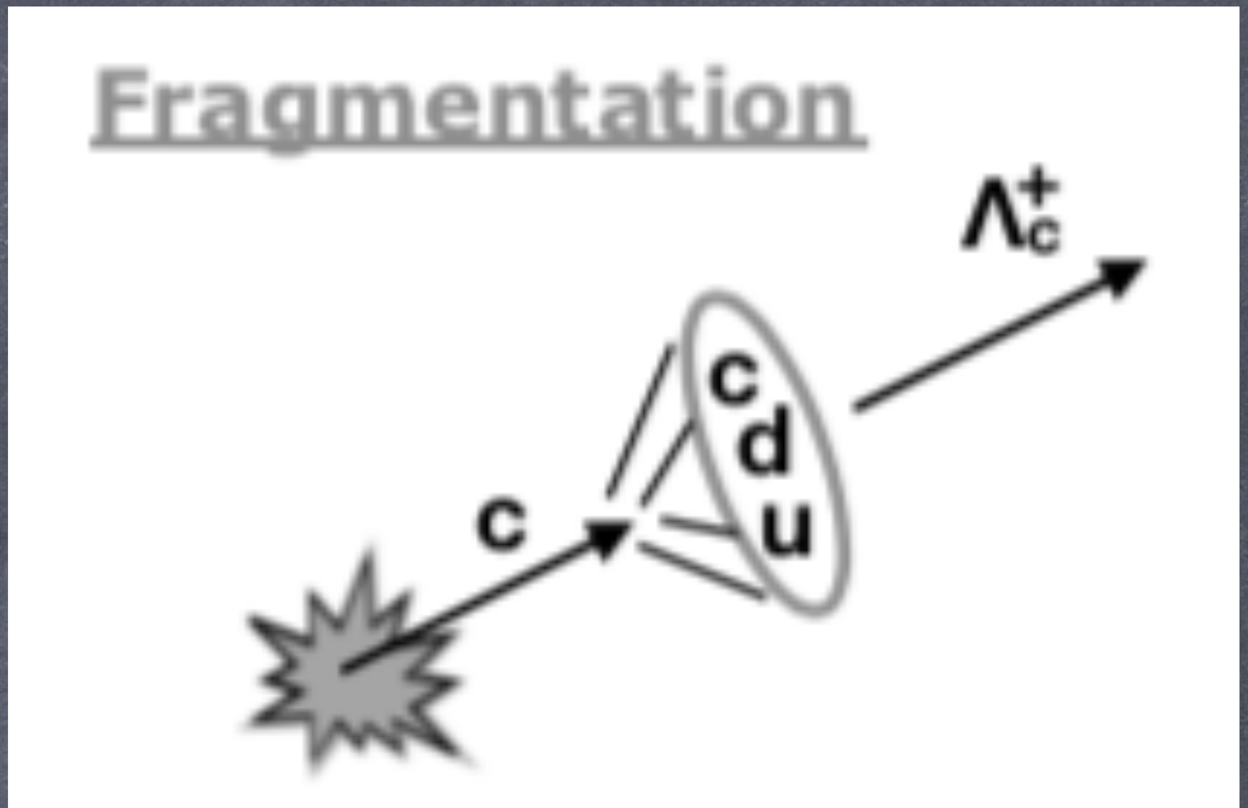
  - -> Strongly interacting with QGP.

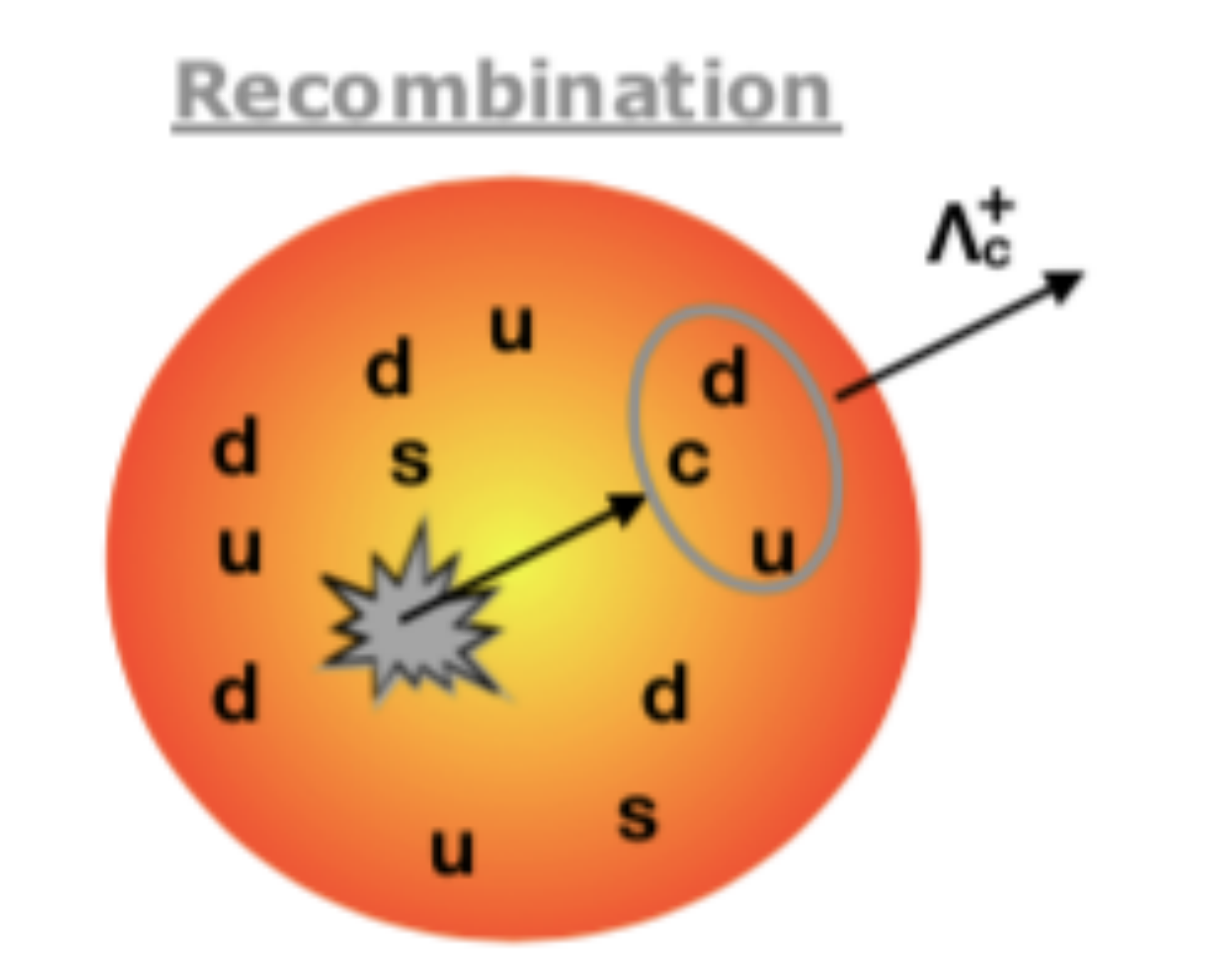
Energy loss

Collectivity

Modification to hadron formation

- Hadronisation via quark coalescence.





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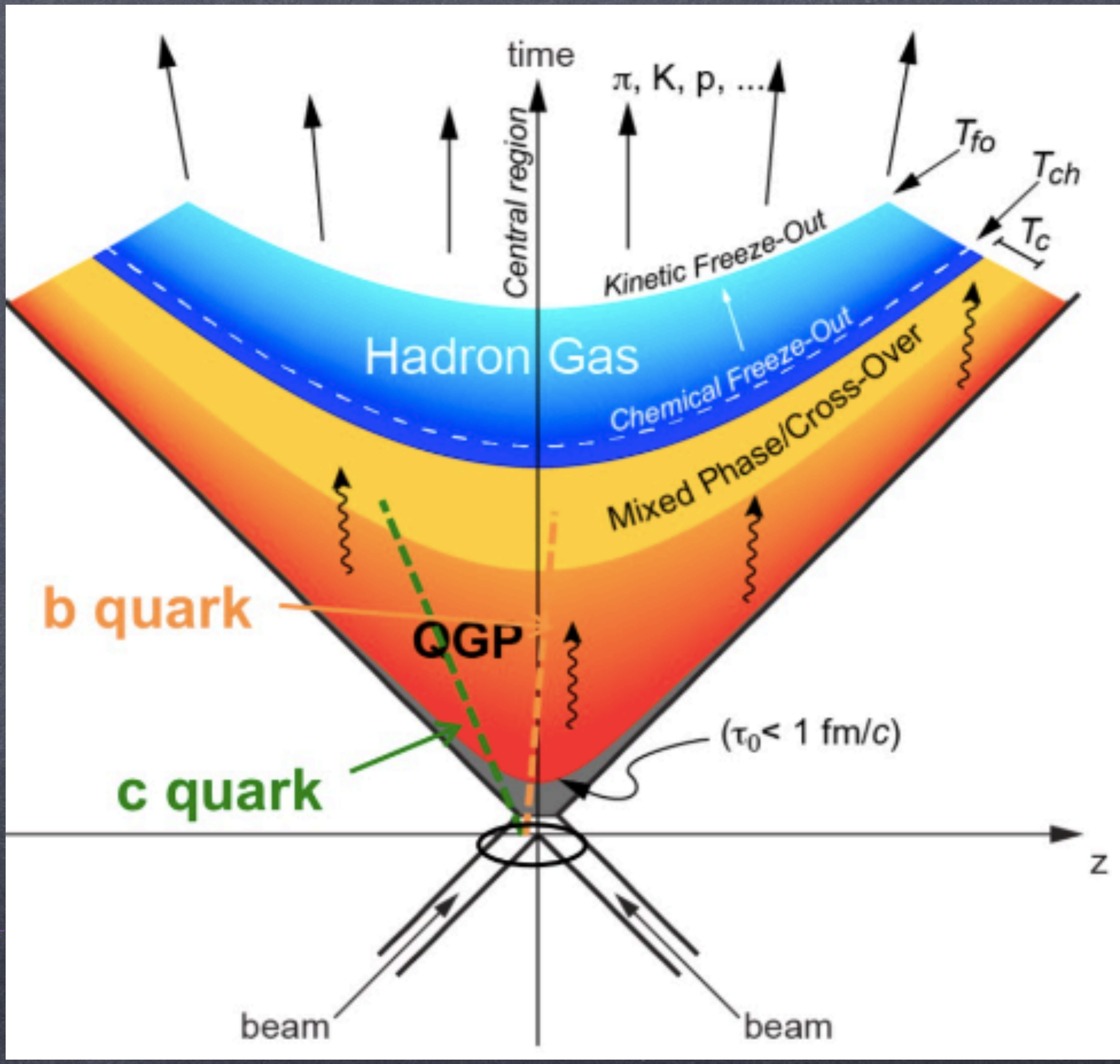


Energy loss

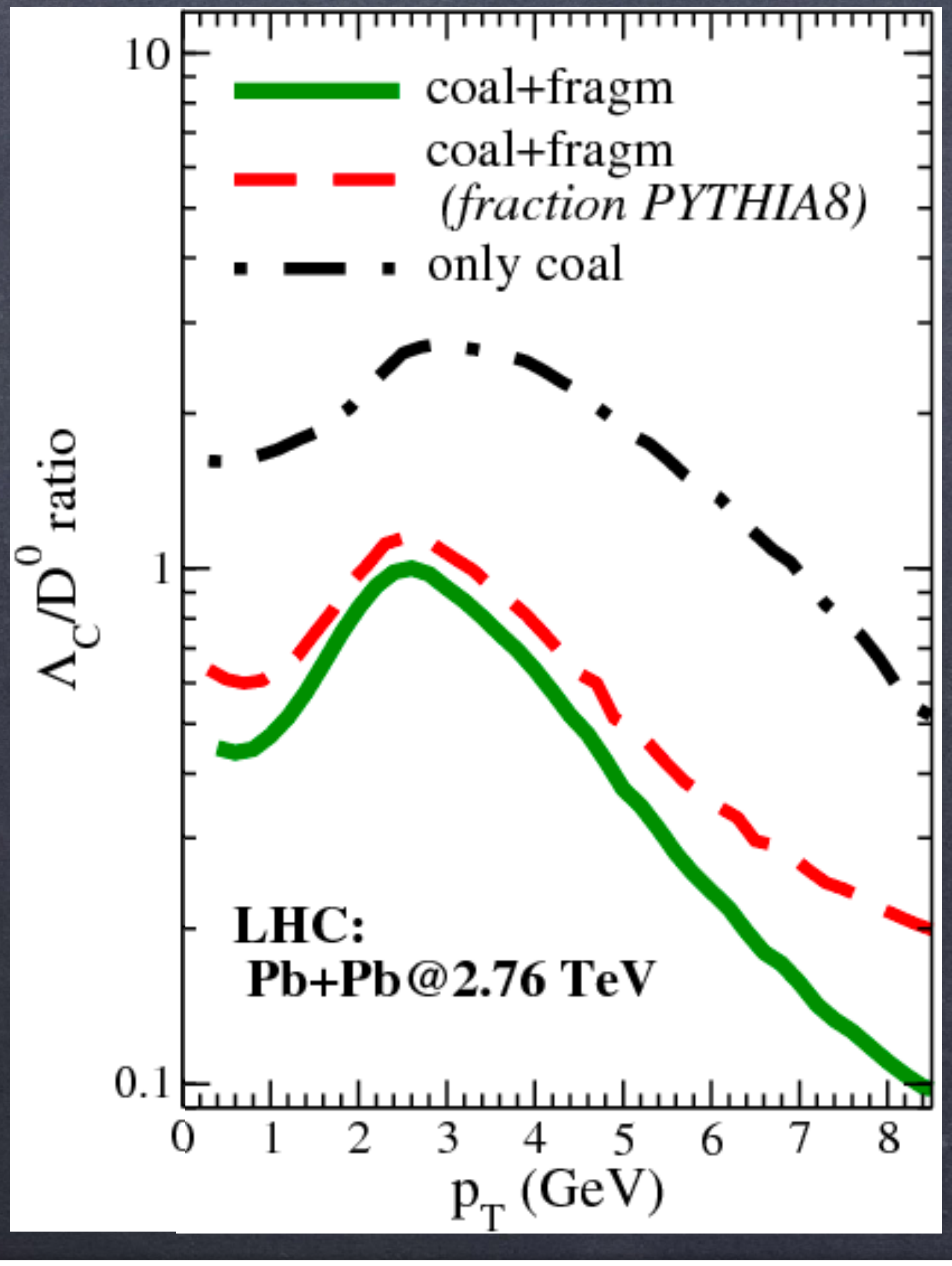
Collectivity

Modification to hadron formation

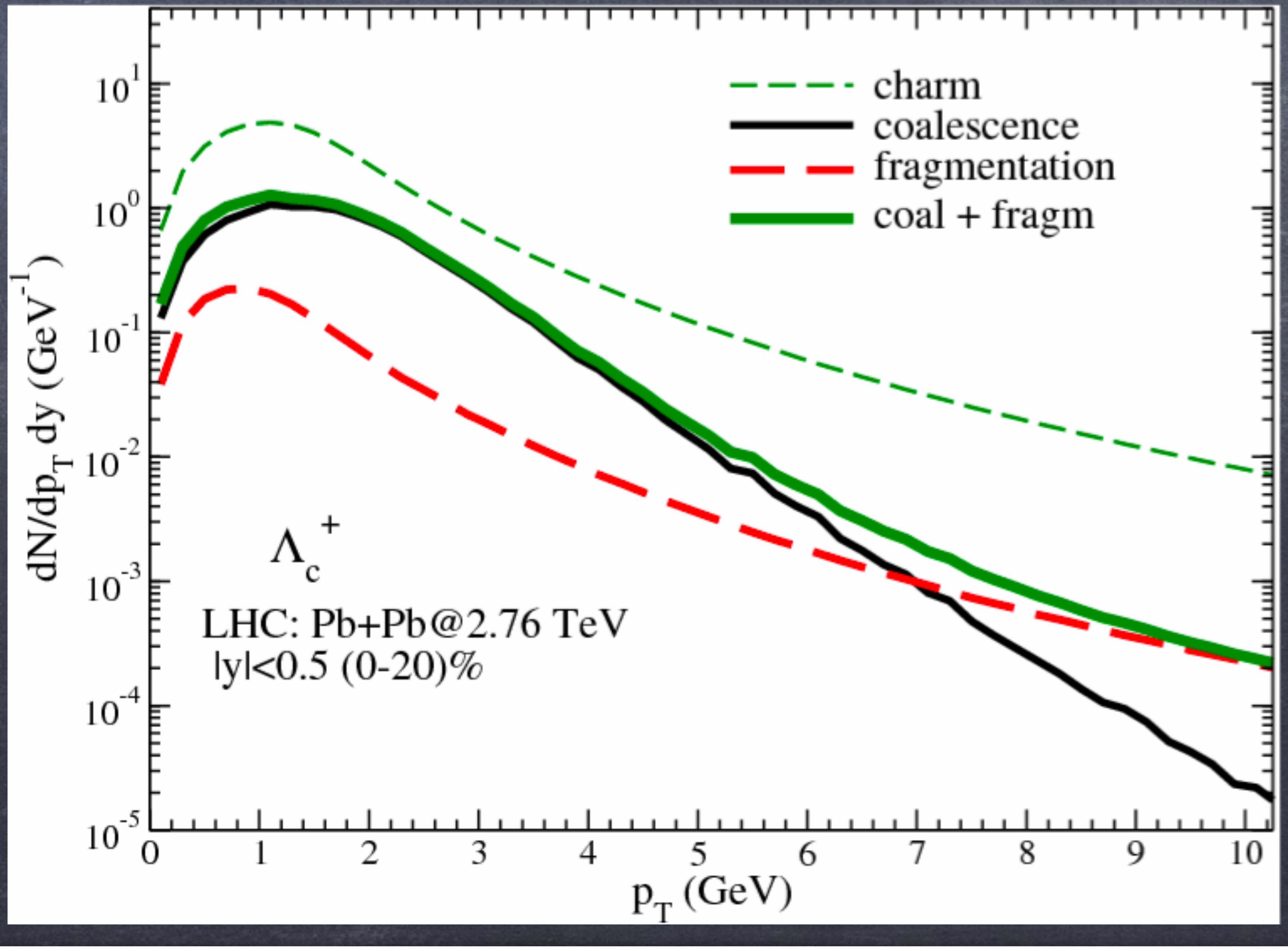
- pp collisions:
  - ✓ Study hadronization mechanism
  - ✓ Set a reference for p-Pb and Pb-Pb
- p-Pb collisions:
  - ✓ Study cold nuclear matter(CNM) effects
  - ✓ reference for Pb-Pb measurements

Motivations: Charm-baryon measurements

- Charm-baryon measurements could provide unique insights into hadronisation in the QGP.
  - ✓ Enhancement of baryon-to-meson(Λ_c^+/D^0) ratio is predicted in coalescence models
  - ✓ Further enhancement of baryon-to-meson ratio is expected if light di-quark states exist in the QGP
  - ✓ Λ_c^+/D^0 is a good tool to disentangle different hadronization mechanisms.

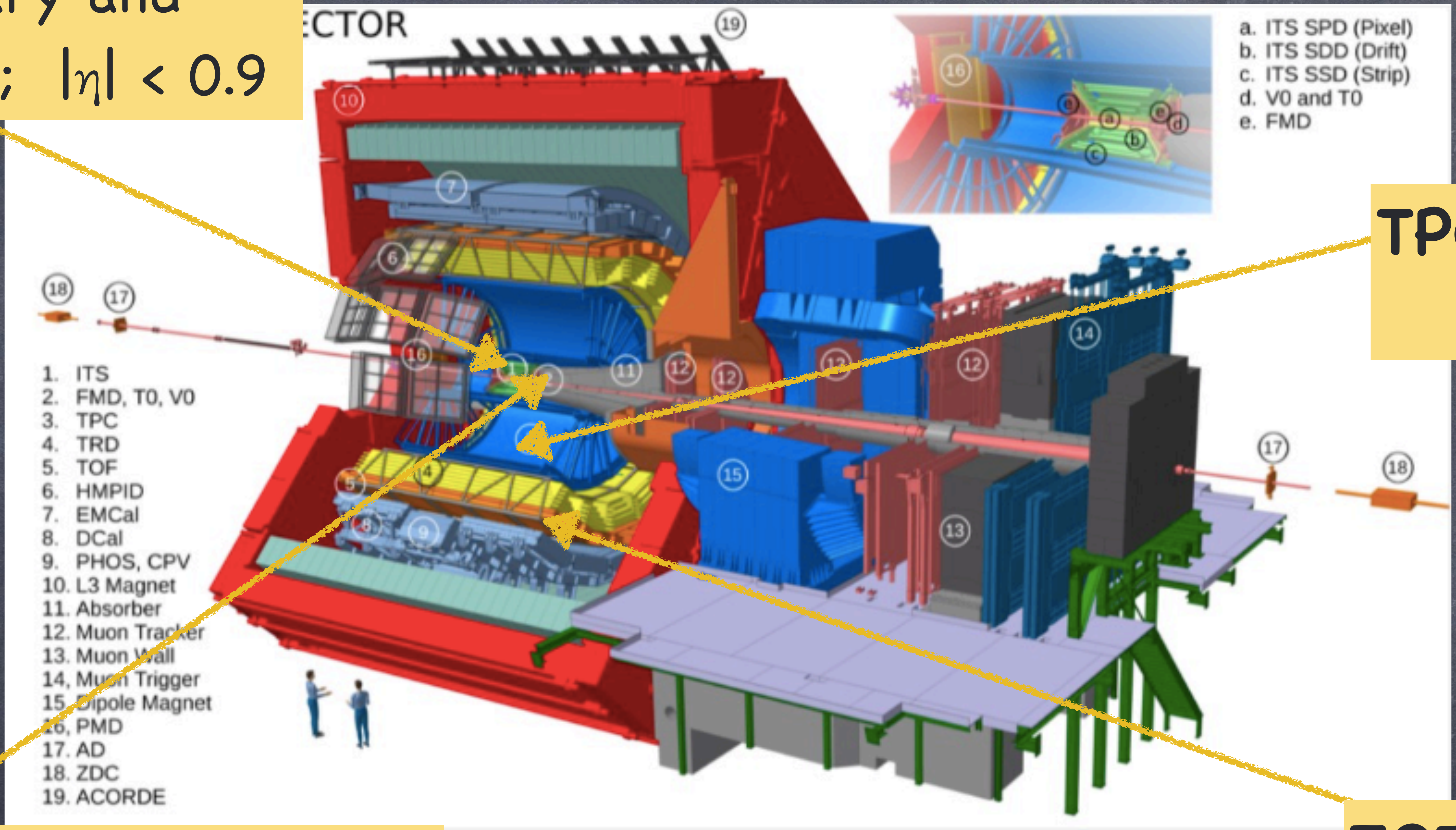


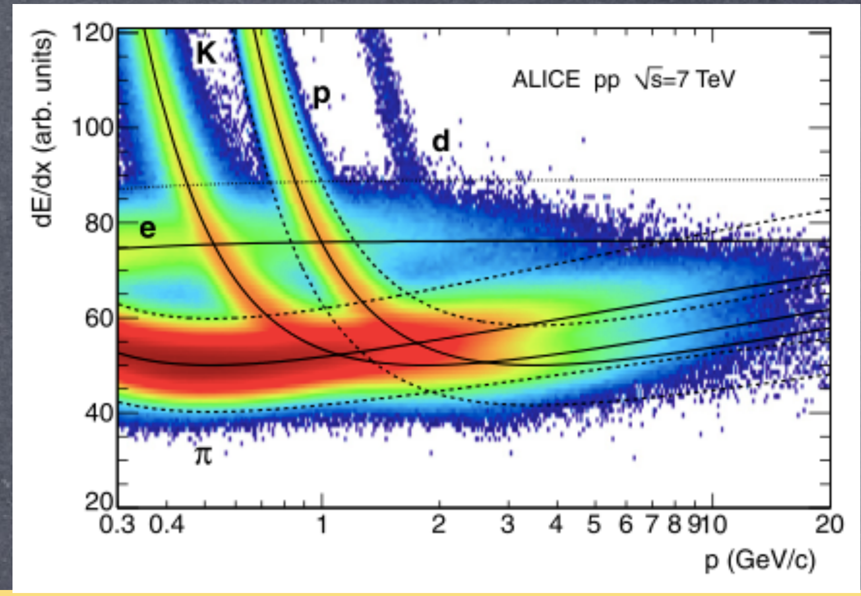
[1]Eur. Phys. J. C (2018) 78:348



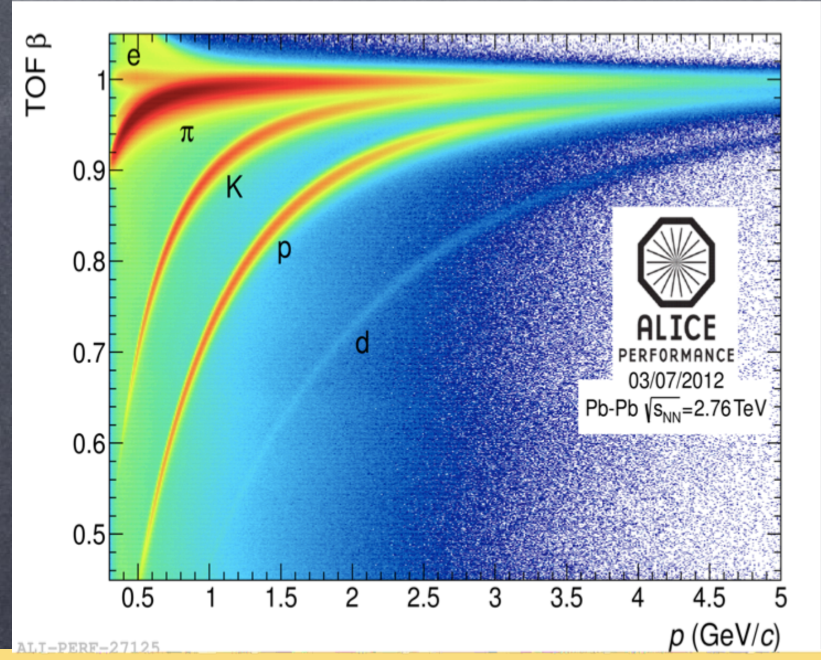
A Large Ion Collider Experiment

ITS: tracking; primary and secondary vertexing; $|\eta| < 0.9$





TPC: tracking and PID via dE/dx; $|\eta| < 0.9$



V0,T0: trigger and centrality

TOF: PID(time of flight); $|\eta| < 0.9$

High precision tracking, good vertexing capabilities and excellent particle identification

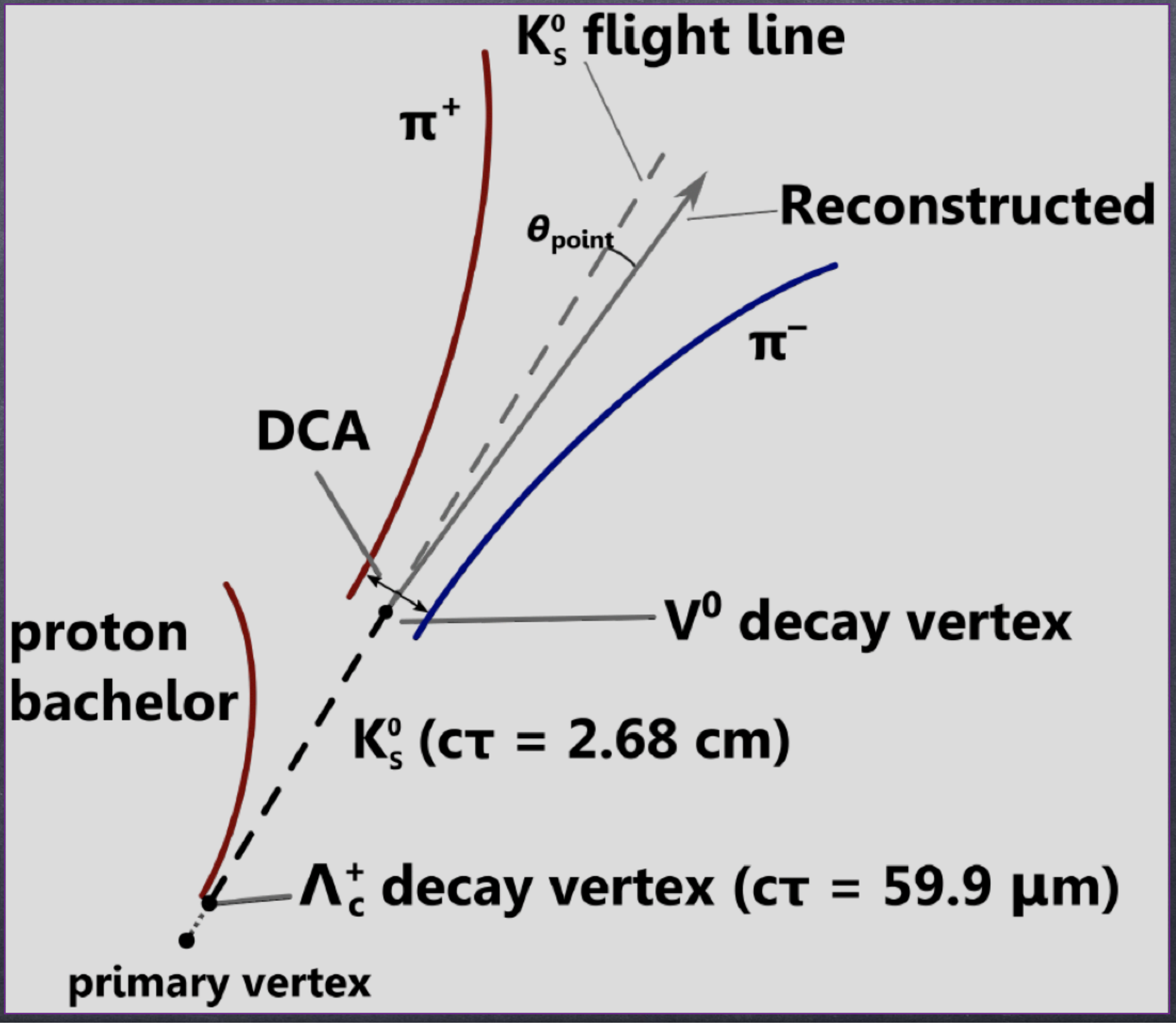
Reconstruction of Λ_c^+

- Invariant mass analysis of the decays
  - ✓ $\Lambda_c^+ \to pK^-\pi^+$ (BR=6.3%)
  - ✓ $\Lambda_c^+ \to pK_s^0 \to \pi^+\pi^- p$ (BR=1.1%)

- Candidates build combining triplets of tracks reconstructed at mid-rapidity ($|\eta| < 0.8$) with proper charge.

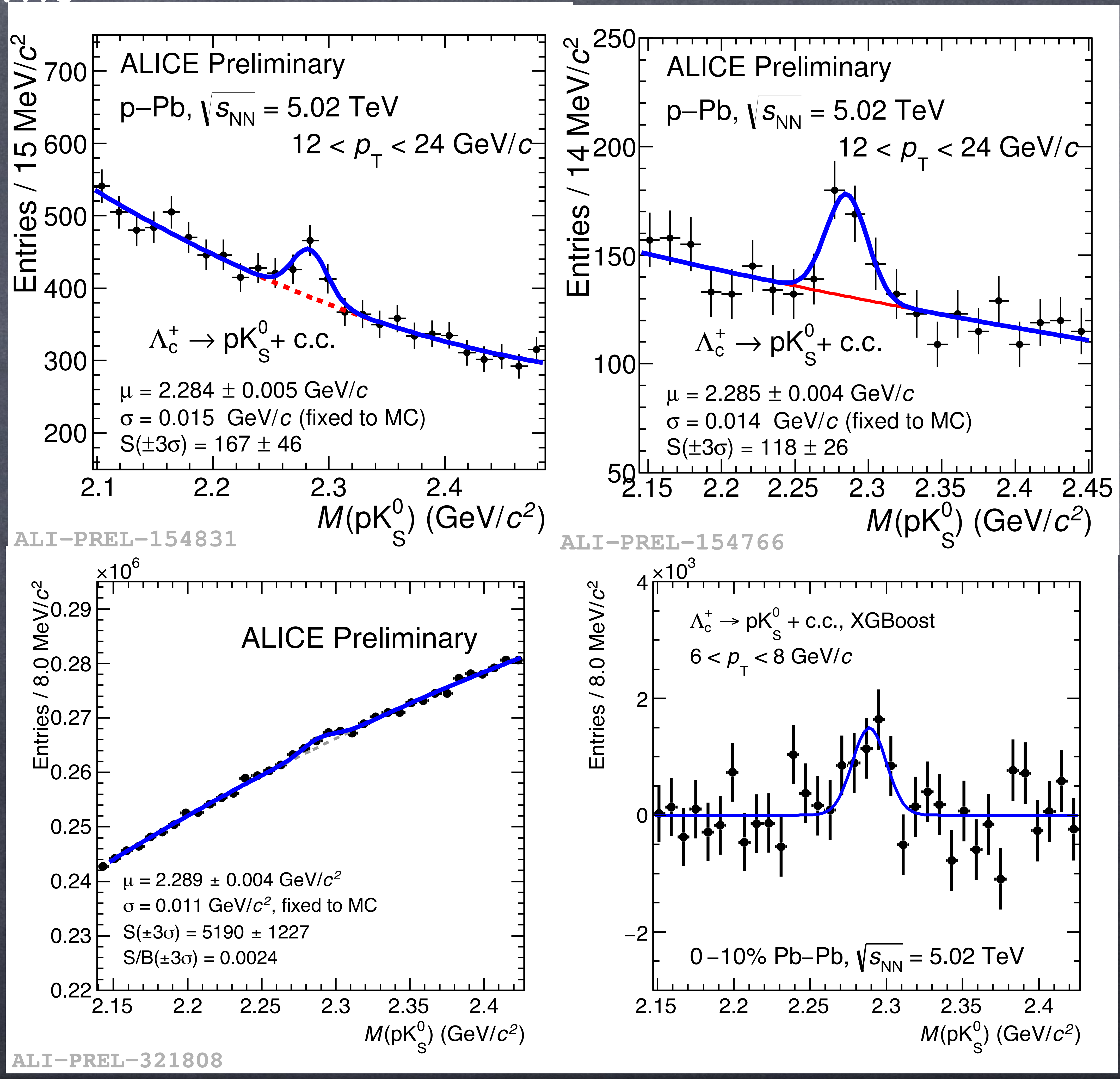
- Reduction of the combinatorial background

- Different method for signal selection of the decay topological variables:
  - ✓ Rectangular topological cuts.
  - ✓ BDT based TMVA method used for cut optimization.

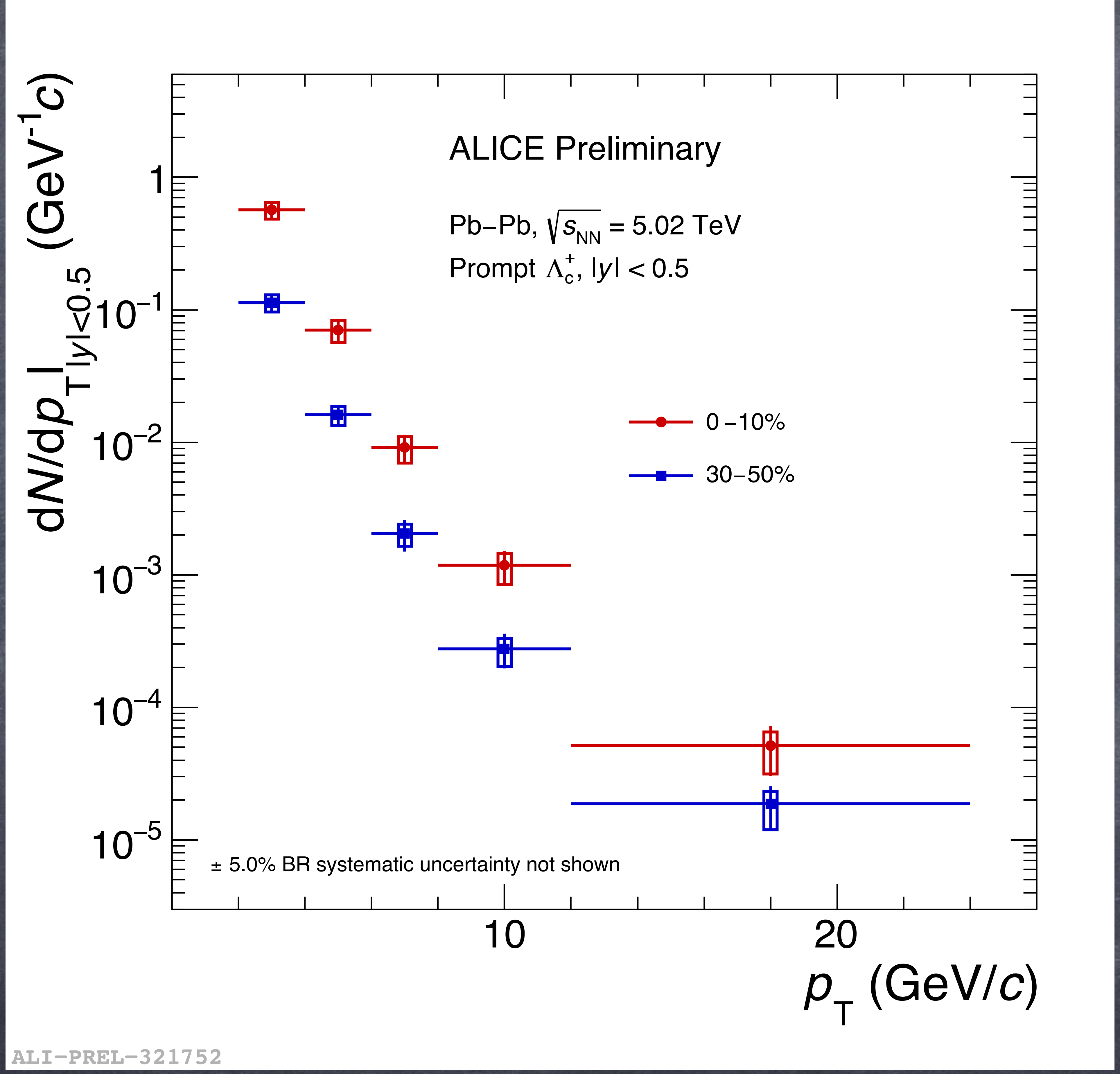


ML to extract Λ_c^+ in p-Pb and Pb-Pb

- For the Λ_c^+, different machine-learning algorithms were exploited in p-Pb and Pb-Pb analyses.
- Training variables.
- Background used for training taken from side-bands in data.
- The invariant mass distribution was obtained after selecting on the ML algorithm response.

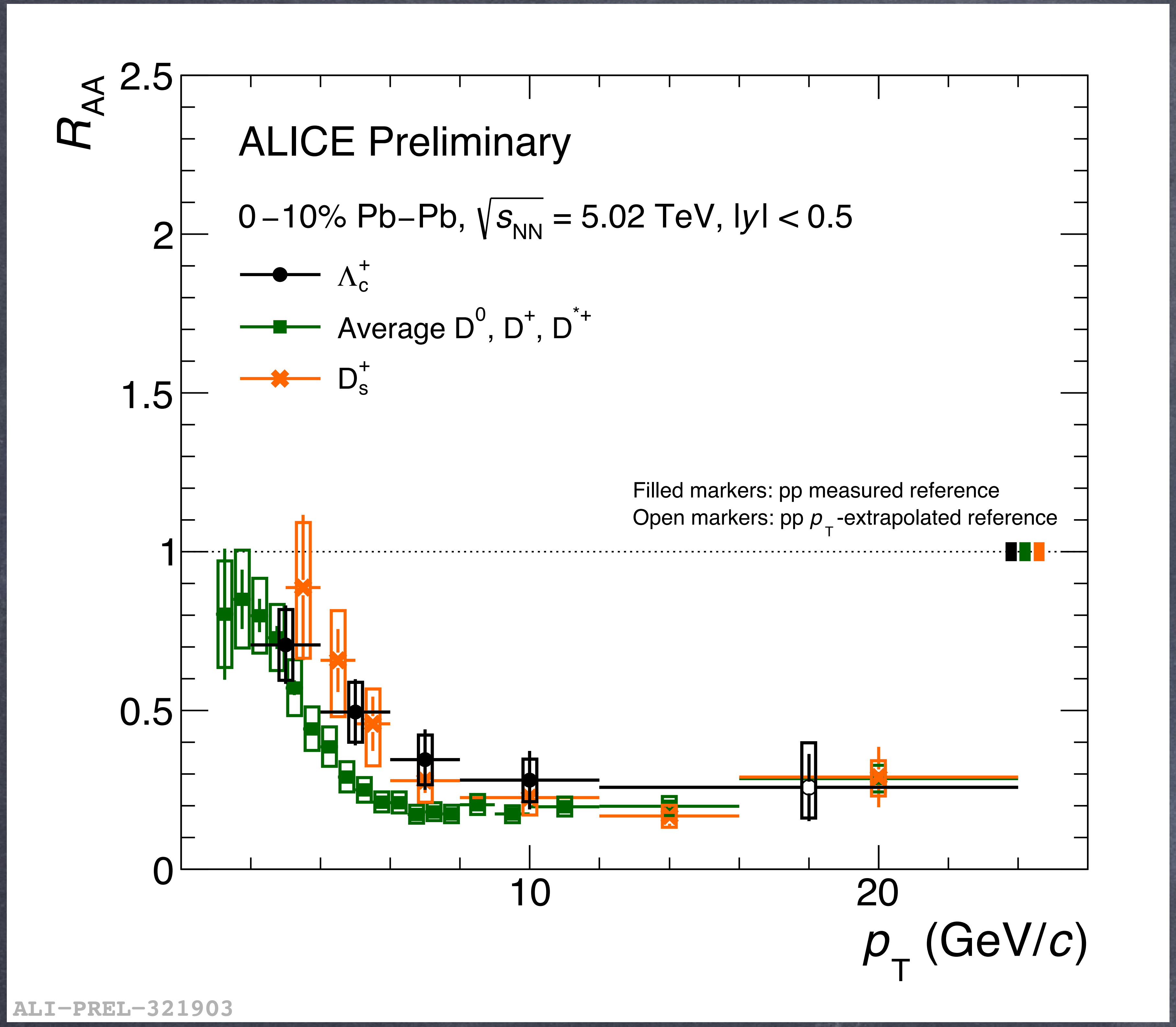


Λ_c^+ cross section in Pb-Pb collisions (2018)



✓ Λ_c^+ are measured in the range 2 < p_T < 24 GeV/c for the 0-10% and 30-50% most central Pb-Pb collisions at 5.02 TeV.

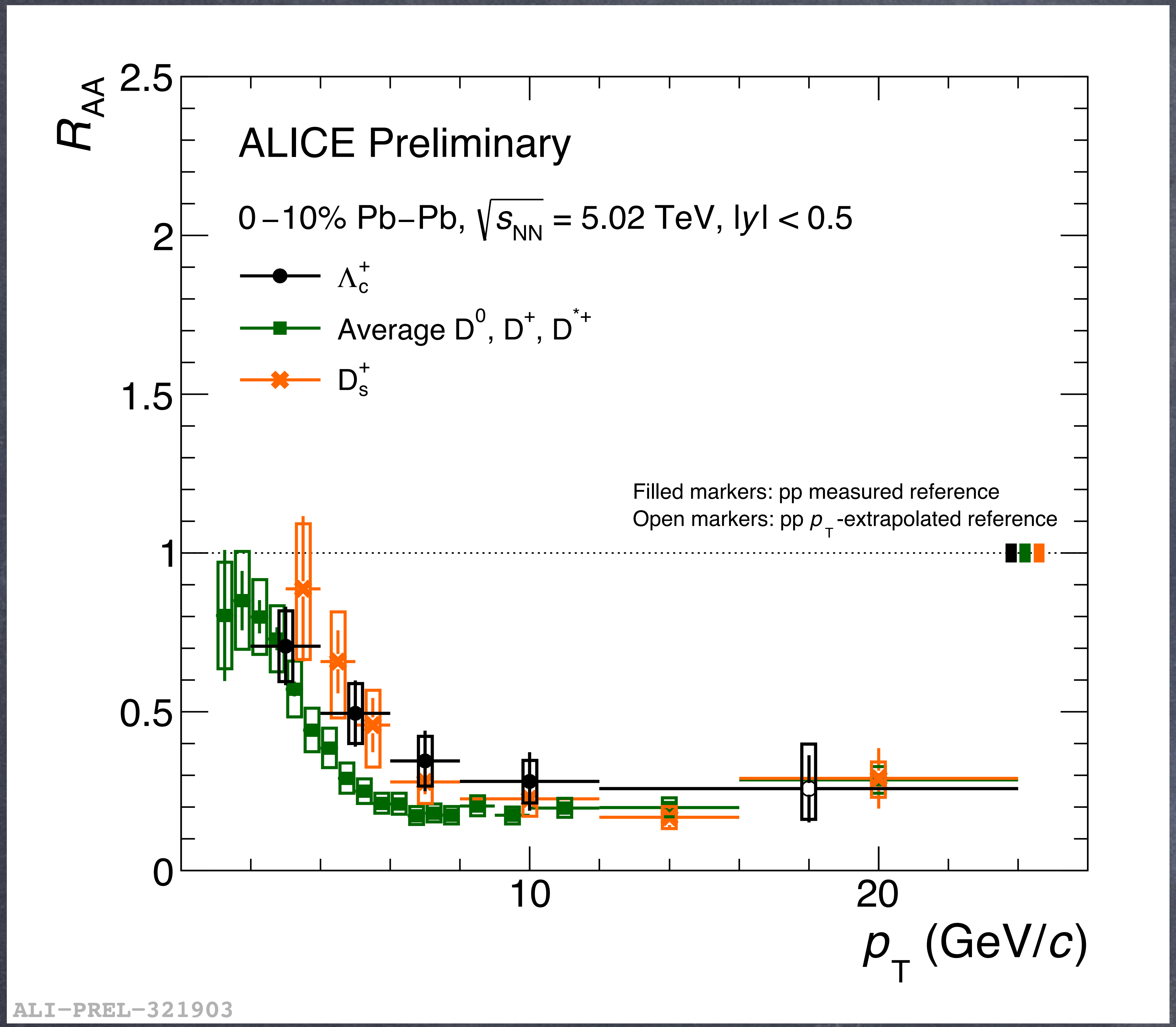
Λ_c^+ nuclear modification factor R_{AA} (2018)

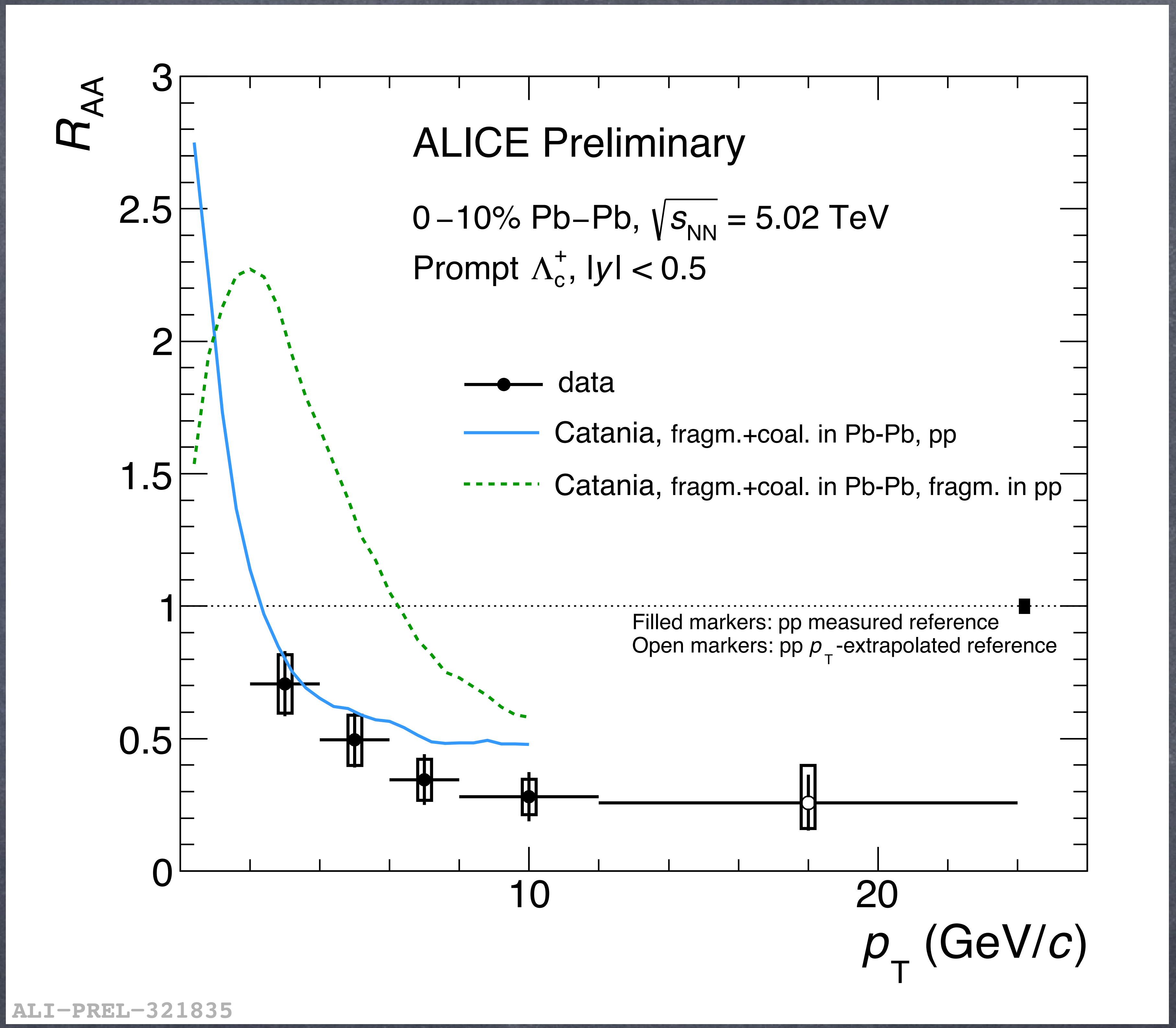


$$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

✓ Suppression observed for the Λ_c^+ baryon in Pb–Pb collisions.

Λ_c^+ nuclear modification factor R_{AA} (2018)

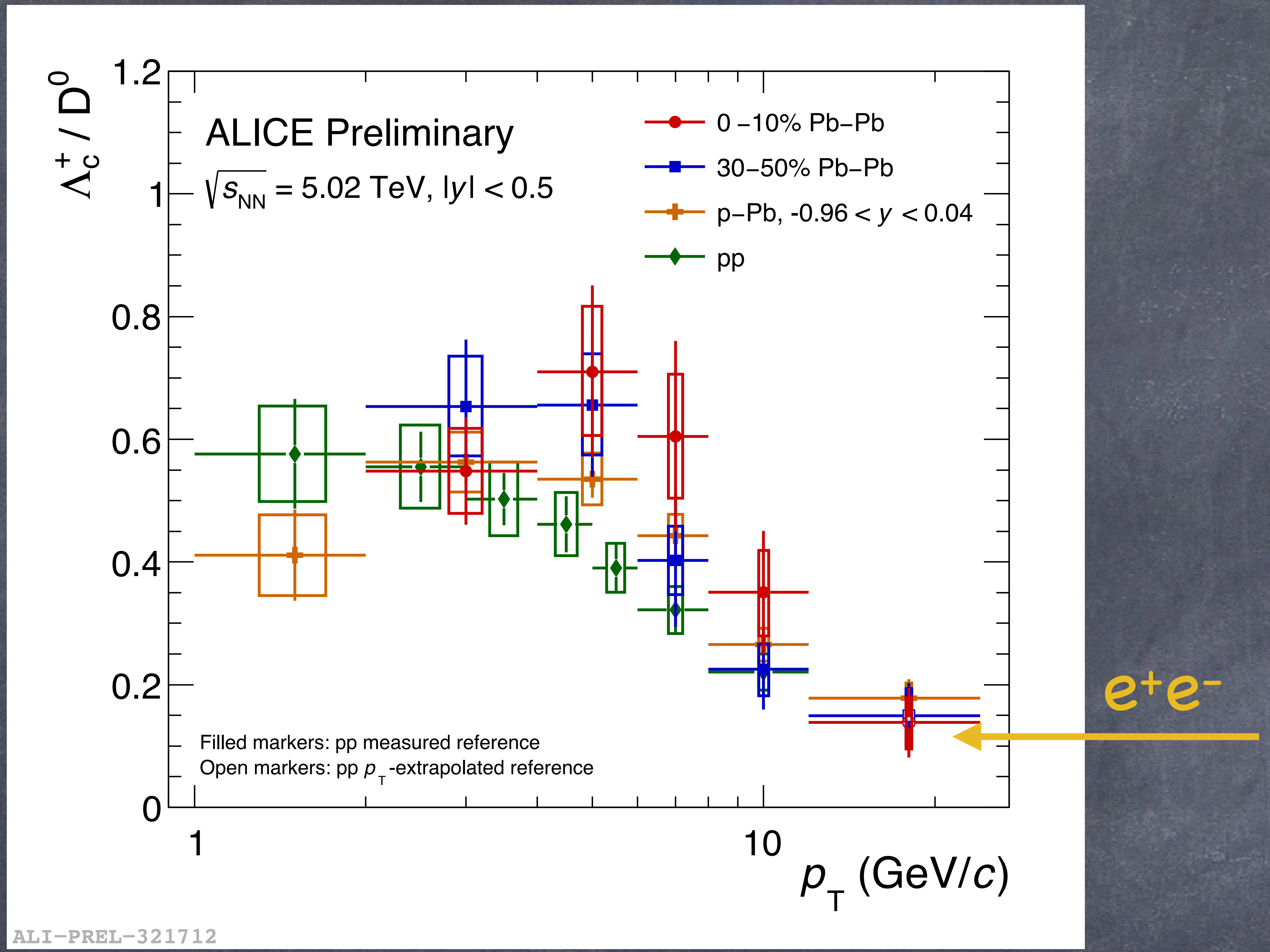




- ✓ Suppression observed for the Λ_c^+ baryon in Pb–Pb collisions.
- ✓ Comparison to theory favours[4] a scenario where both fragmentation and recombination are present in Pb–Pb and pp collisions, for both centrality ranges.
- ✓ The same conclusion for semi-central collisions see backup.

[4]Catania: Eur. Phys. J. C (2018) 78: 348

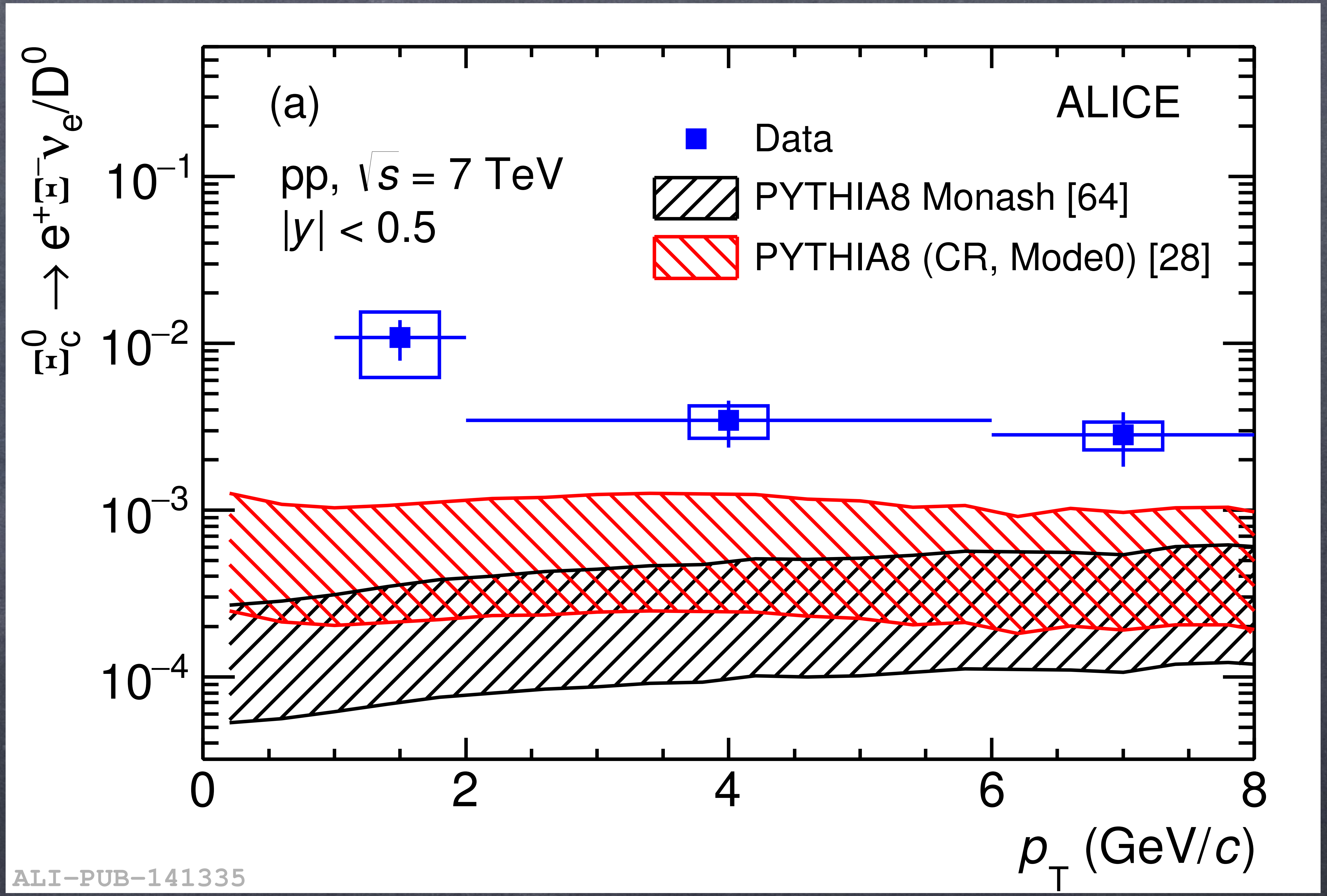
Baryon-to-meson ratio: Λ_c^+/D^0 (2018)



- ✓ Hint to a higher Λ_c^+/D^0 ratio in Pb–Pb (0–10% and 30%–50%) collisions w.r.t. pp collisions.
  - -> Understanding of pp data is fundamental. Ratio is underestimated by models with fragmentation parameters derived from e^+e^- collision data.
- ✓ More precision needed to investigate a pp -> p–Pb -> Pb–Pb trend.

Outlook: Ξ_c^0 production

- First measurement of Ξ_c^0 production in pp collisions at $\sqrt{S_{NN}}$= 7 TeV[6]
  - ✓ $\Xi_c^0 \to e^+\Xi^-\nu$ $(\Xi^- \to \pi^-\Lambda)$
  - ✓ Event generators PYTHIA8[7][8] underestimate data.
  - ✓ The same conclusion with DIPSY[9] and HERWIG7[10] models see backup.



- The investigation under Ξ_c^0 with hadronic decay and the Σ_c work in processing.

[6] Phys. Lett. B 781 (2018) 8-19
[7] PYTHIA8 CR: JHEP 08 (2015) 003
[8] PYTHIA8: Eur. Phys. J. C (2014) 74:3024
[9] DIPSY: JHEP 08 (2011) 103
[10] HERWIG7: Eur. Phys. J. C58 (2008) 639-707

Summary

- Λ_c^+/D^0 and Λ_c^+ R_{AA} are measured in the range $2 < p_T < 24$ GeV/c for the 0–10% and 30–50% most central Pb–Pb collisions.
  - ✓ Different machine-learning algorithms are used for the Λ_c^+ analysis.
  - ✓ Λ_c^+/D^0 Compatible with p–Pb within statistical uncertainties.
  - ✓ The Results of R_{AA} in agreement with models that foresee both fragmentation and recombination.

Upgrate:

- ALICE upgrade for Run3+4: (new ITS and TPC)
  - ✓ It will offer the opportunity to explore, with more precision, a wide p_T range of open HF measurements.

Back up

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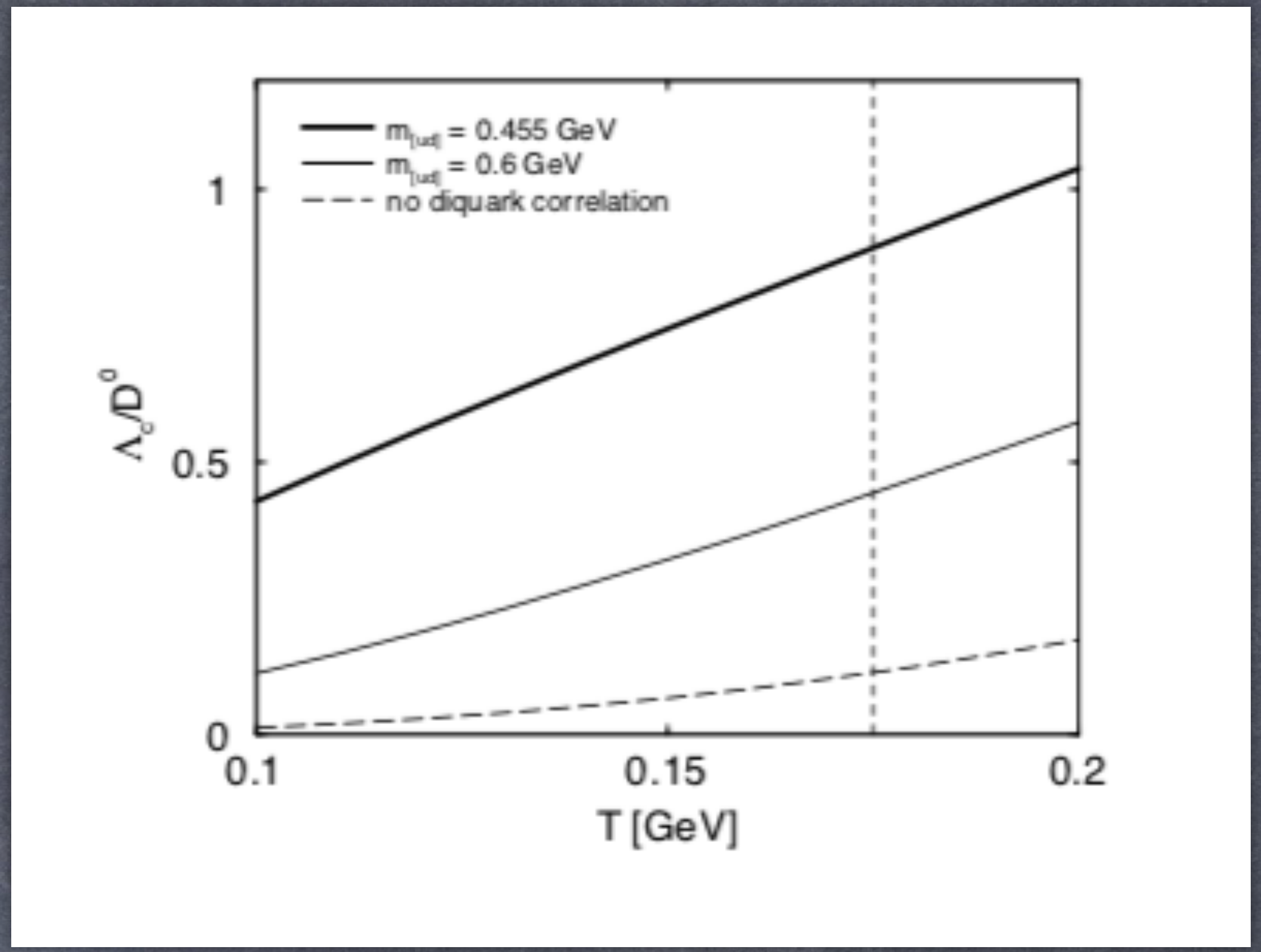
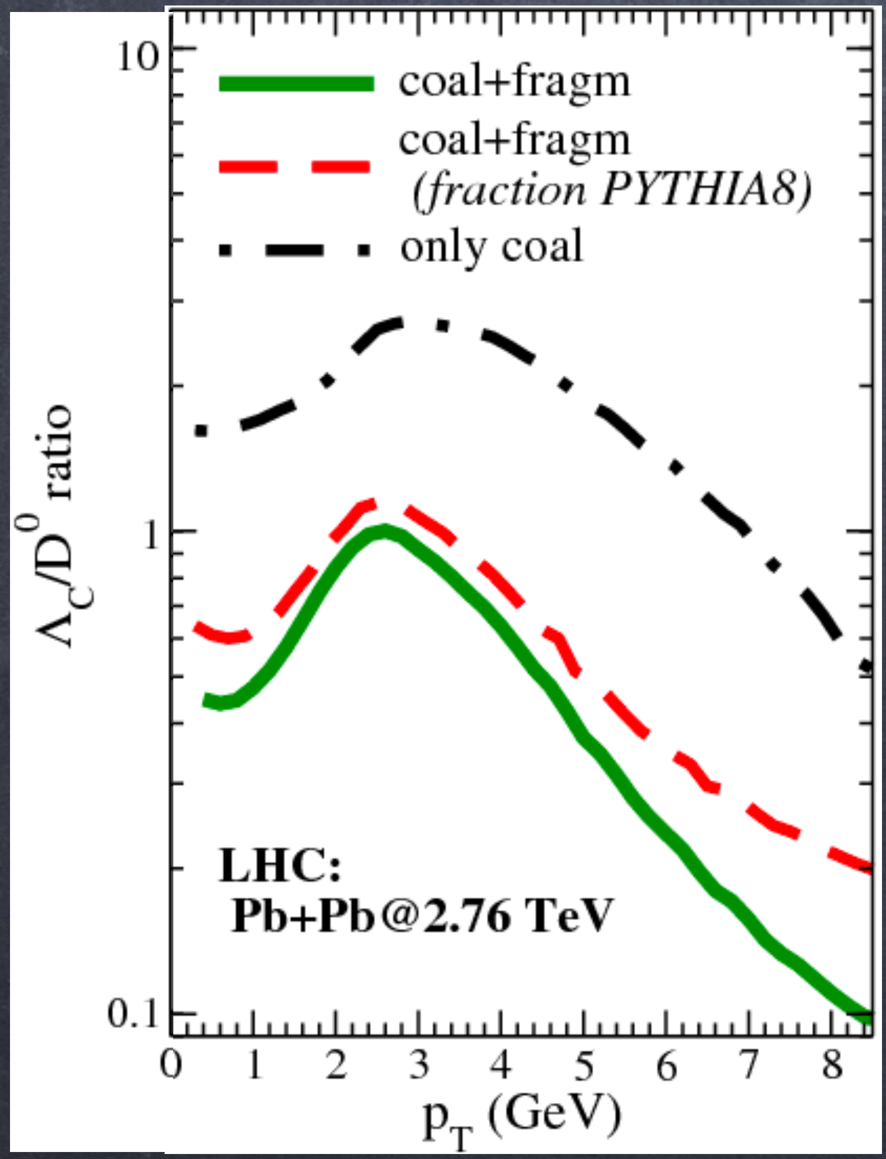
Motivations: Charm-baryon measurements

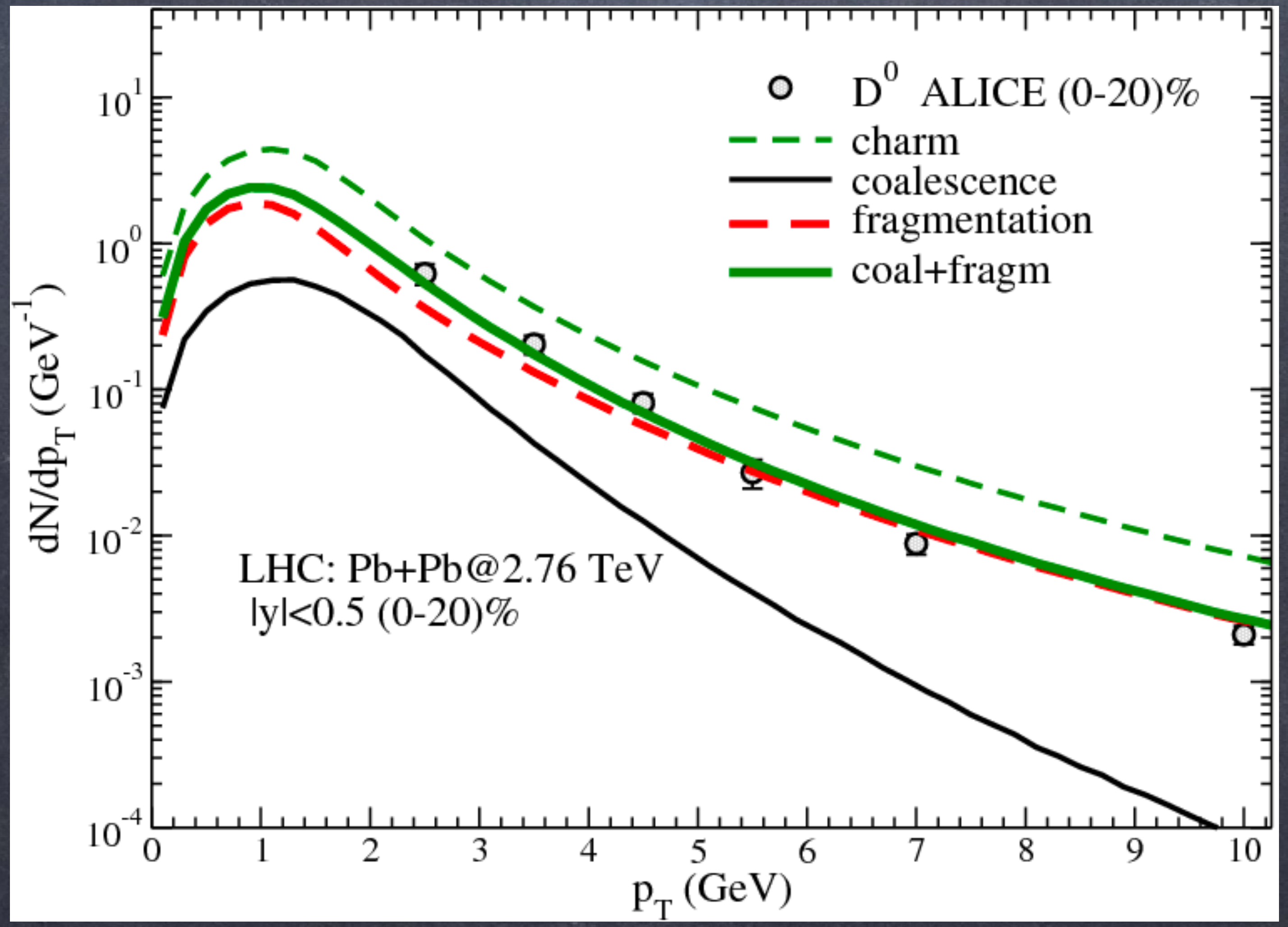
- ✓ Enhancement of baryon-to-meson(Lc/D0) ratio is predicted in recombination (or coalescence models)
- ✓ Further enhancement of baryon-to-meson ratio is expected if light di-quark states exist in the QGP

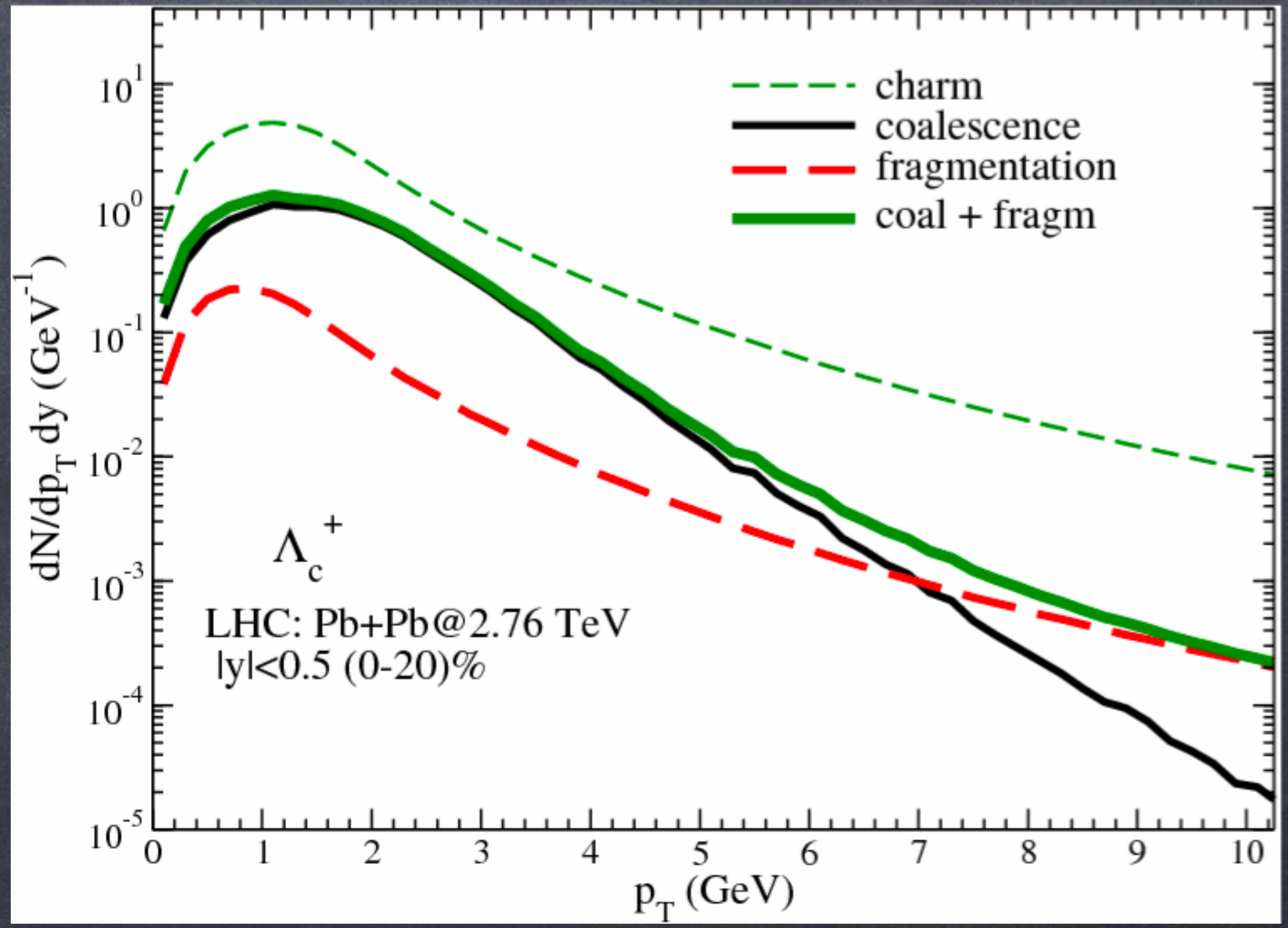
PRL 100, 222301 (2008)



- ✓ The baryon-to-meson ratio is expected to be enhanced if charm quarks hadronise via recombination with the surrounding light quarks in the QGP.





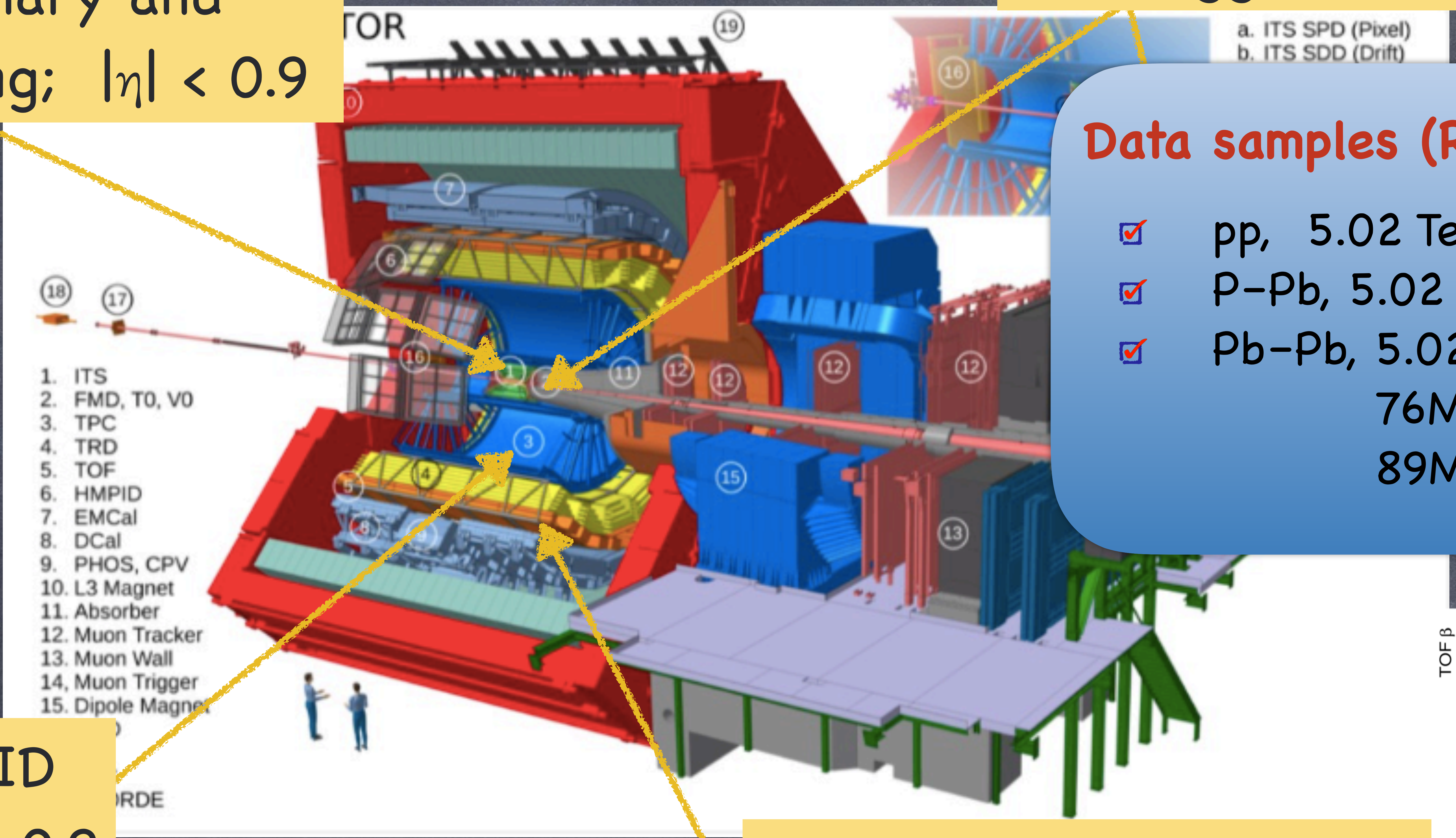


Eur. Phys. J. C (2018) 78:348

A Large Ion Collider Experiment

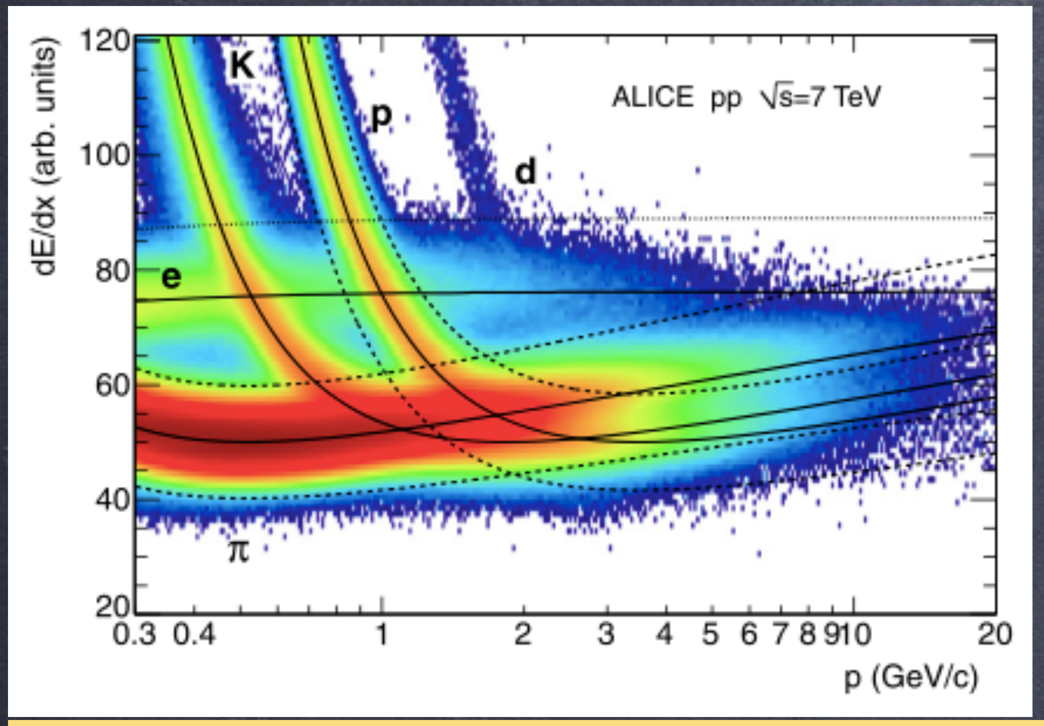
ITS: tracking; primary and secondary vertexing; $|\eta| < 0.9$

V0: trigger and centrality



Data samples (Run-2):

- pp, 5.02 TeV: 980M MB events.
- P-Pb, 5.02 TeV: 600M MB events.
- Pb-Pb, 5.02TeV: 100M MB events.
  76M 30-50% events
  89M 0-10% events



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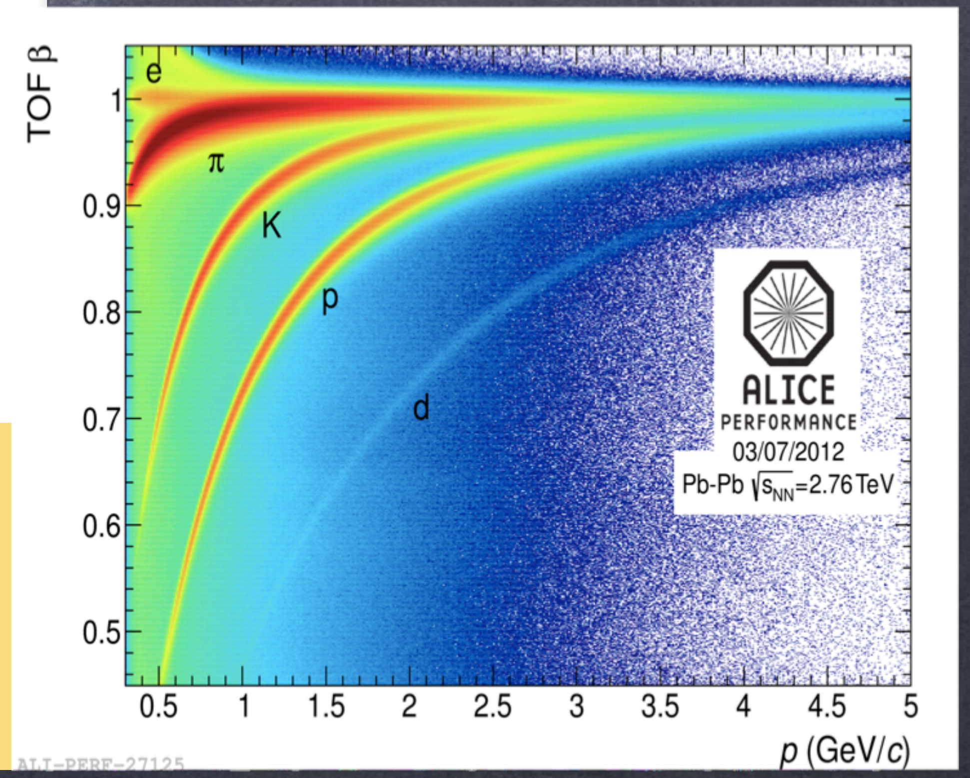
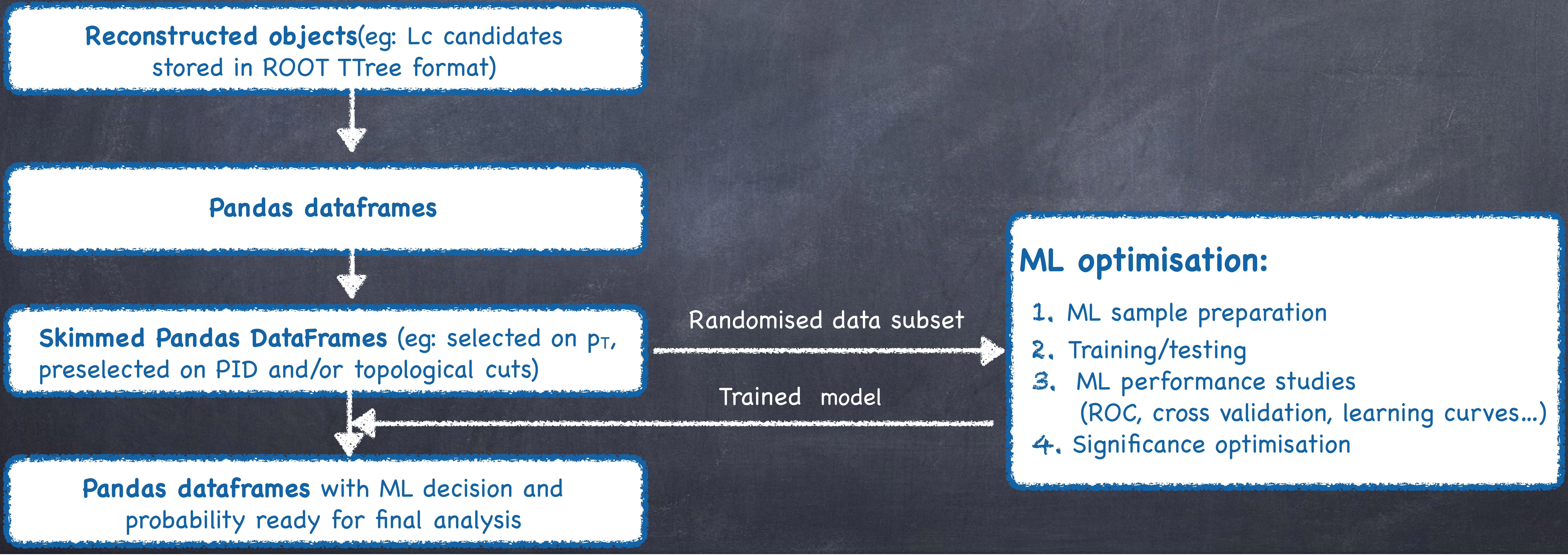


TOF: PID(time of flight); $|\eta| < 0.9$

High precision tracking, good vertexing capabilities and excellent particle identification

MLHEP python-based package

- General purpose Python package for performing parallelised analysis over large datasets and Machine Learning (ML) optimisation with Scikit, Keras, and XGBoost.



Merging strategy: introduction

- Similar strategy as analyses that were statistically correlated (other Lc analysis: BDT/ standard)
  - ✓ Treat statistical uncertainties as fully correlated.
  - ✓ Weighted average according to the uncorrelated uncertainties (in this case, assumed to just be the yield extraction systematic)

    -> Ok assumption given different background shape, cut on response, etc.
  - ✓ Corrected yield given weight

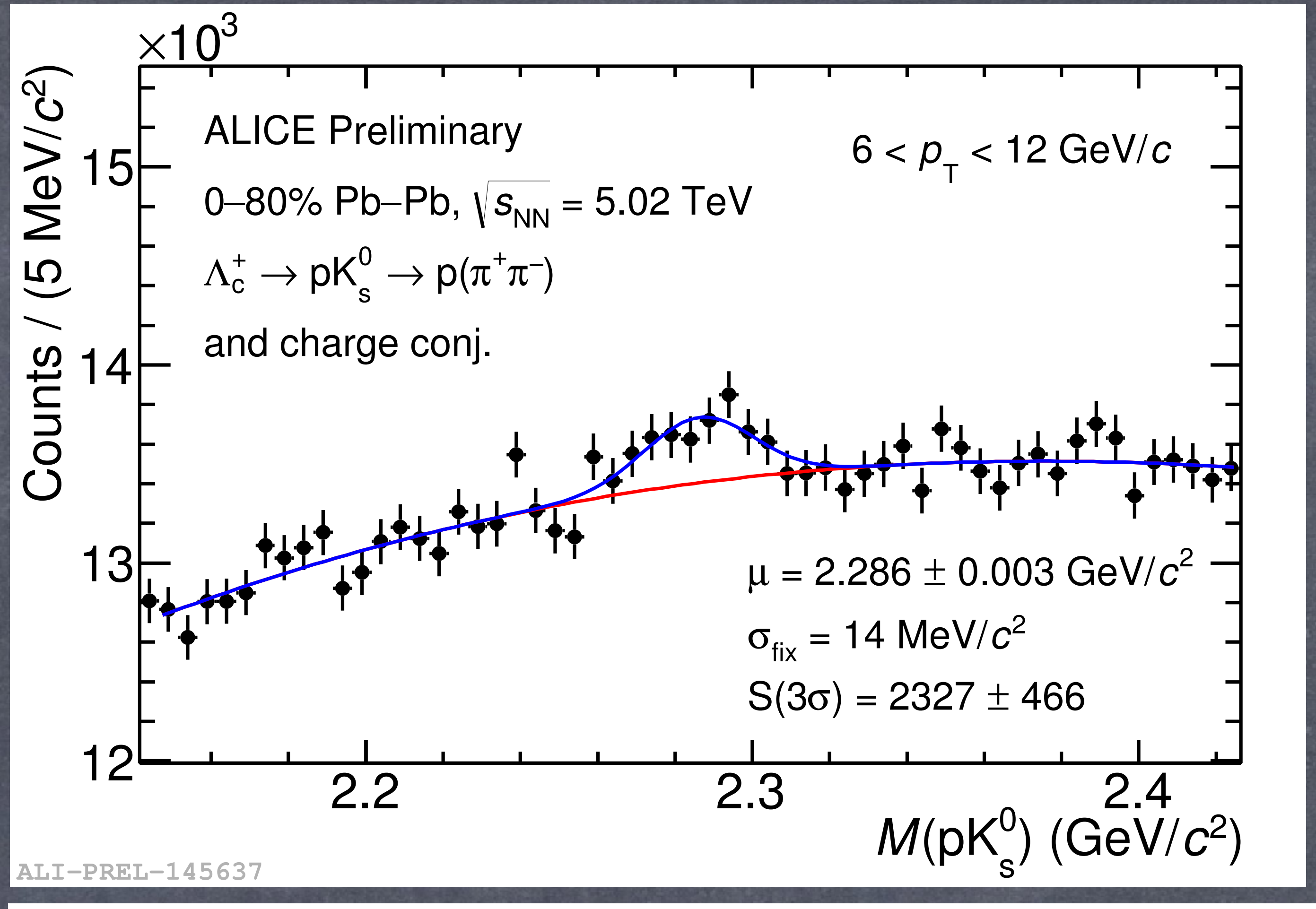
    -> $1/a^2$ where $a = \Delta\sigma_{uncor.sys.}/\sigma$ (σ = yield)
  - ✓ So yield and uncertainties are worked out as follows:

$$\sigma_{averaged} = \frac{\Sigma\, w_i \sigma_i}{\Sigma\, w_i} \qquad \Delta\sigma_{corr} = \frac{\Sigma\, w_i \Delta\sigma_i}{\Sigma\, w_i} \qquad \Delta\sigma_{nucorr} = \frac{(\Sigma\, w_i^2 \Delta\sigma_i^2\,)^{1/2}}{\Sigma\, w_i}$$

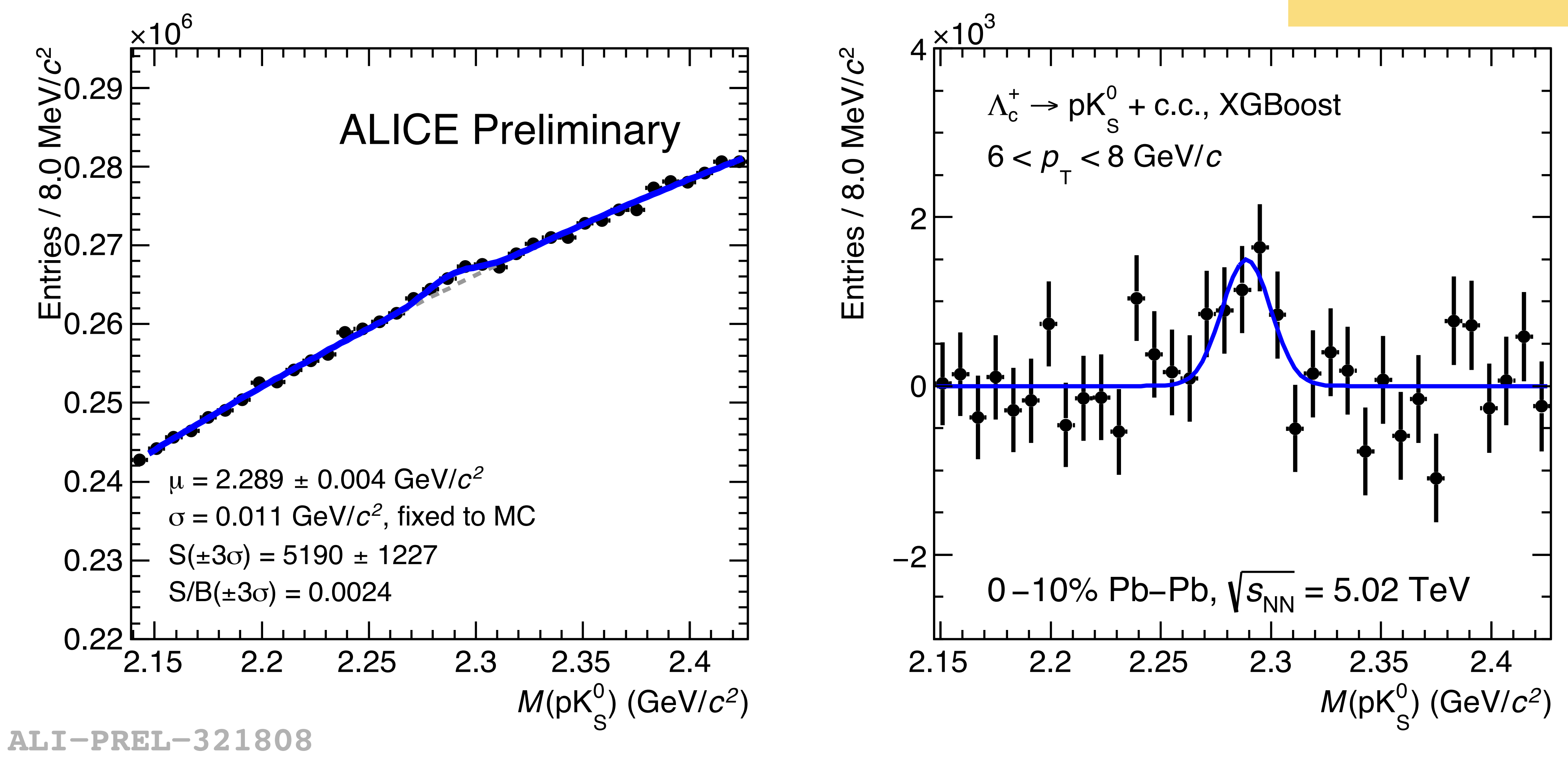
  - ✓ Note - this averaging does not reduce uncertainties expect for yield extraction uncertainties - but means not 1 analysis is favoured.

Reconstruction of Λ_c^+

- Invariant mass analysis of the decays
  - ✓ $\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR=6.3%)
  - ✓ $\Lambda_c^+ \rightarrow pK_s^0 \rightarrow \pi^+\pi^- p$ (BR=1.1%)
- Candidates build combining triplets of tracking reconstructed at Mid-rapidity ($|\eta| < 0.8$) with proper charge.
- Reduction of the combinatorial background by:
  - ✓ Kinematical and geometrical selection of displaced decay-topology ($c\tau \sim 60$ μm).
  - ✓ Particle identification of decay tracks.



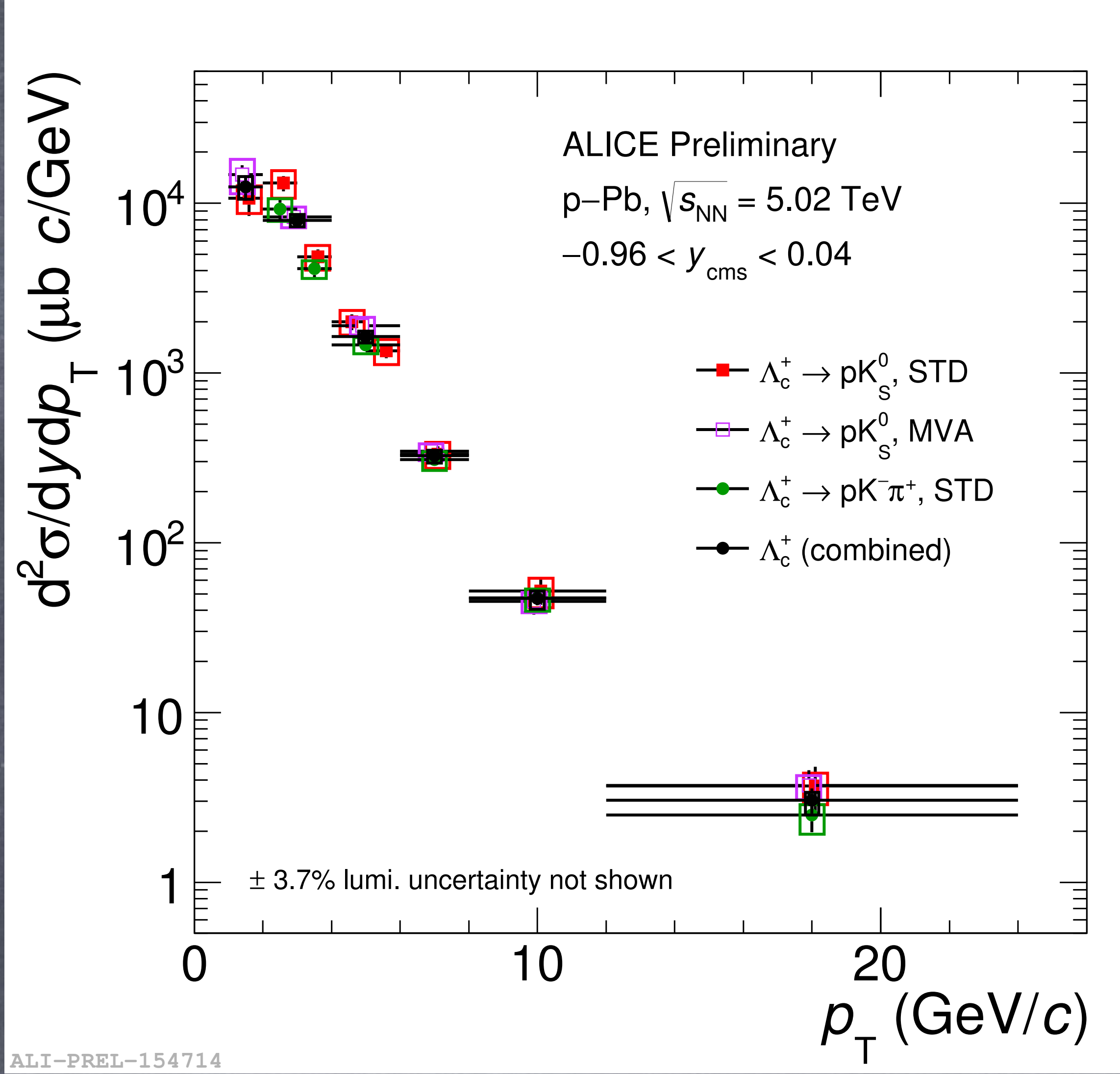
New



- Corrected for :
  - ✓ Selection efficiency using MC simulations.
  - ✓ Feed-down subtraction using FONLL predictions.
- Two analysis methods used :
  - ✓ Rectangular topological cuts.
  - ✓ Multivariate analysis exploiting **BDT's**

ML to extract Λ_c^+ in p-Pb and Pb-Pb

- For the Λ_c^+, different machine-learning algorithms were exploited in p-pb and Pb-Pb analyses.
  - ✓ The TMVA package using AdaBoost.
  - ✓ New developed MLHEP (python-based fast analysis framework) using XGBoost. ->(more details in the backup)
- Topological, kinematical and PID training variables.
- Background used for training taken from side-bands in data.
- The invariant mass distribution was obtained after selecting on the ML algorithm response.
- Average results obtained by weighting the different results by the inverse of the sum in quadrature of the relative uncorrelated systematics.



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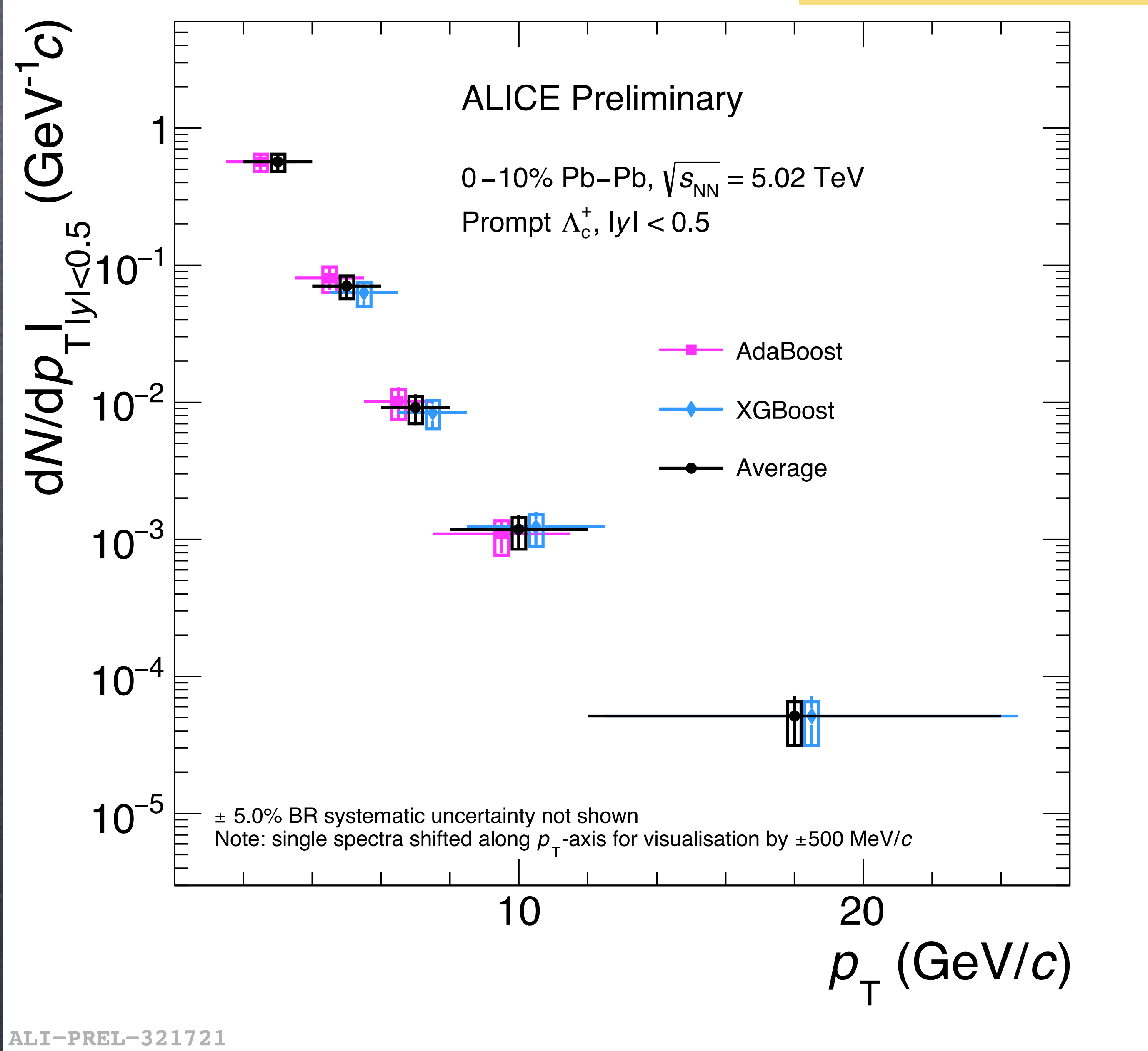
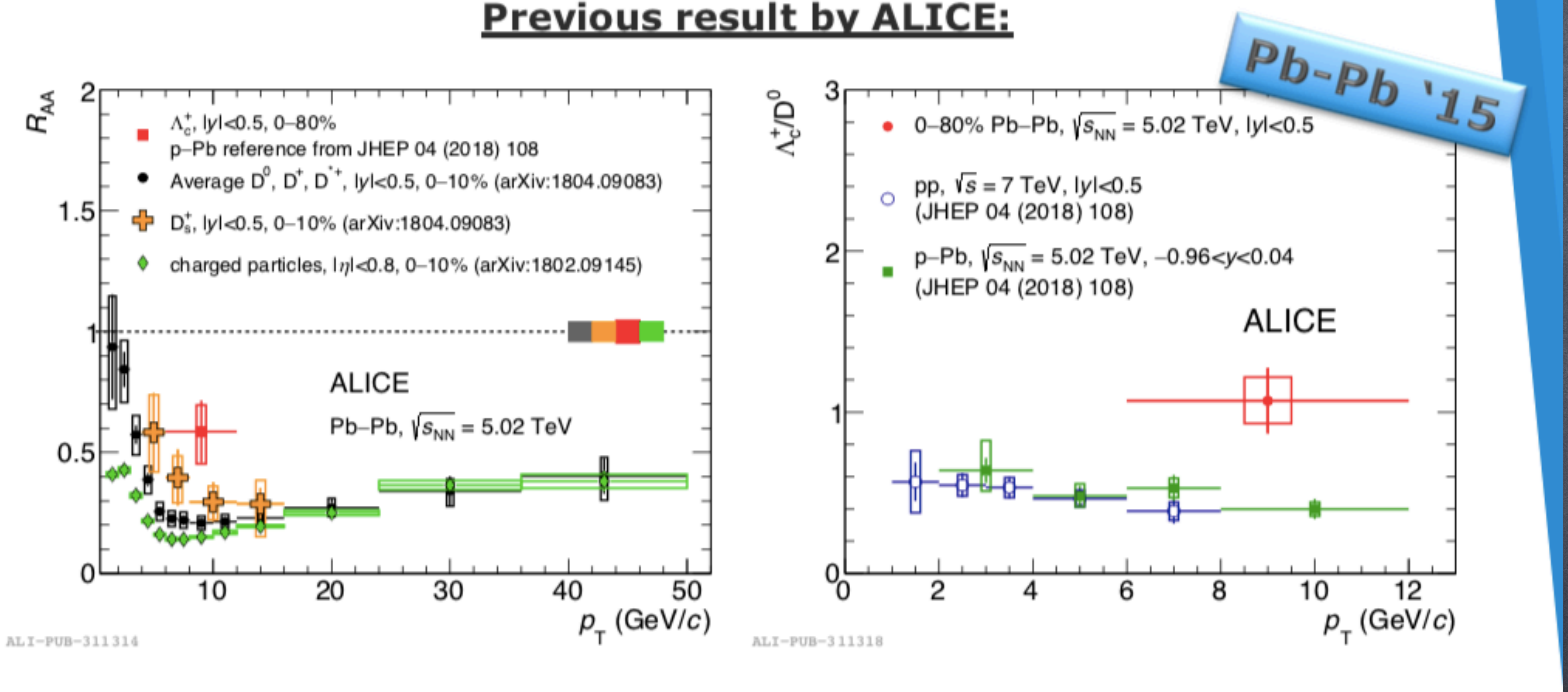
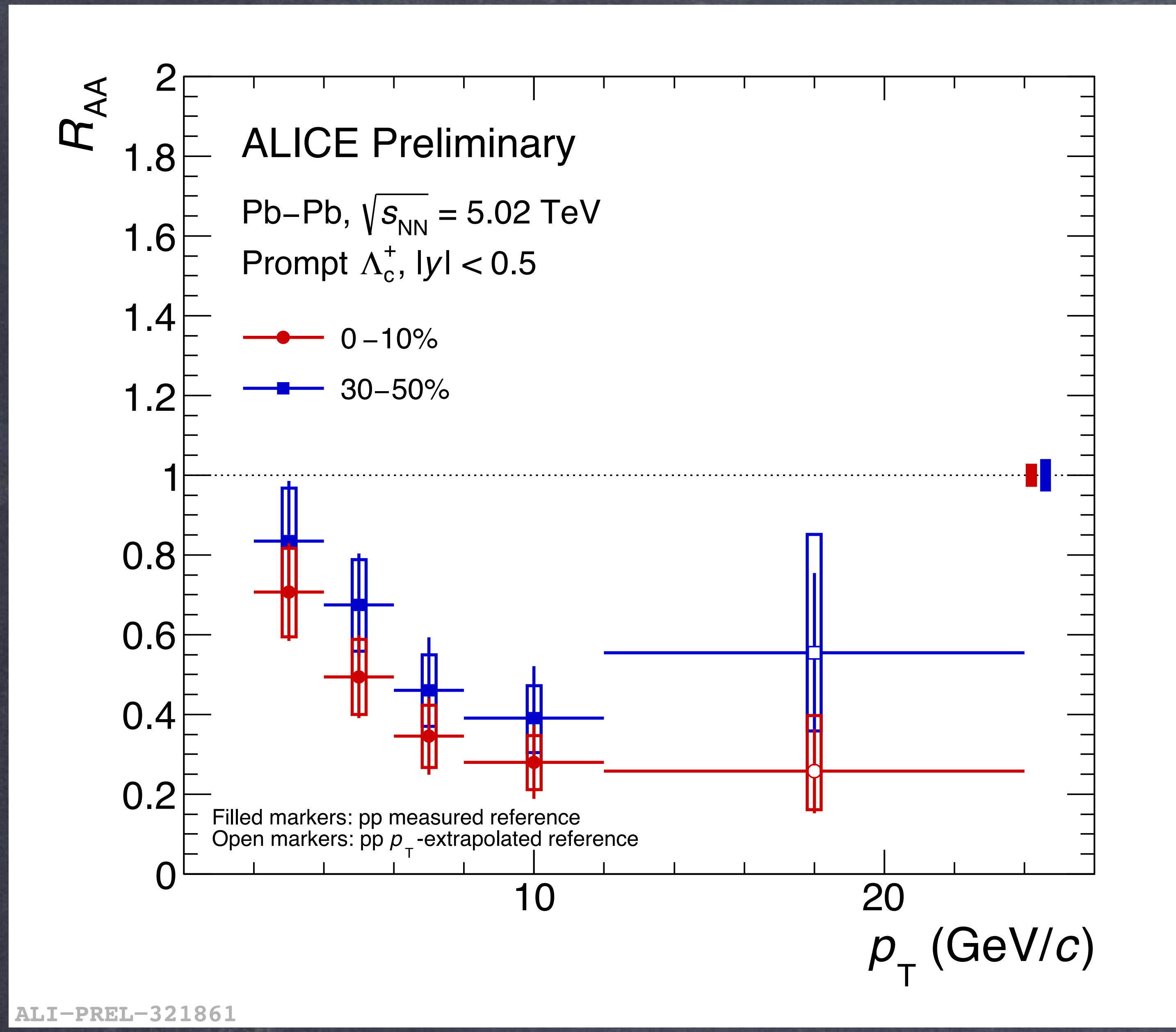


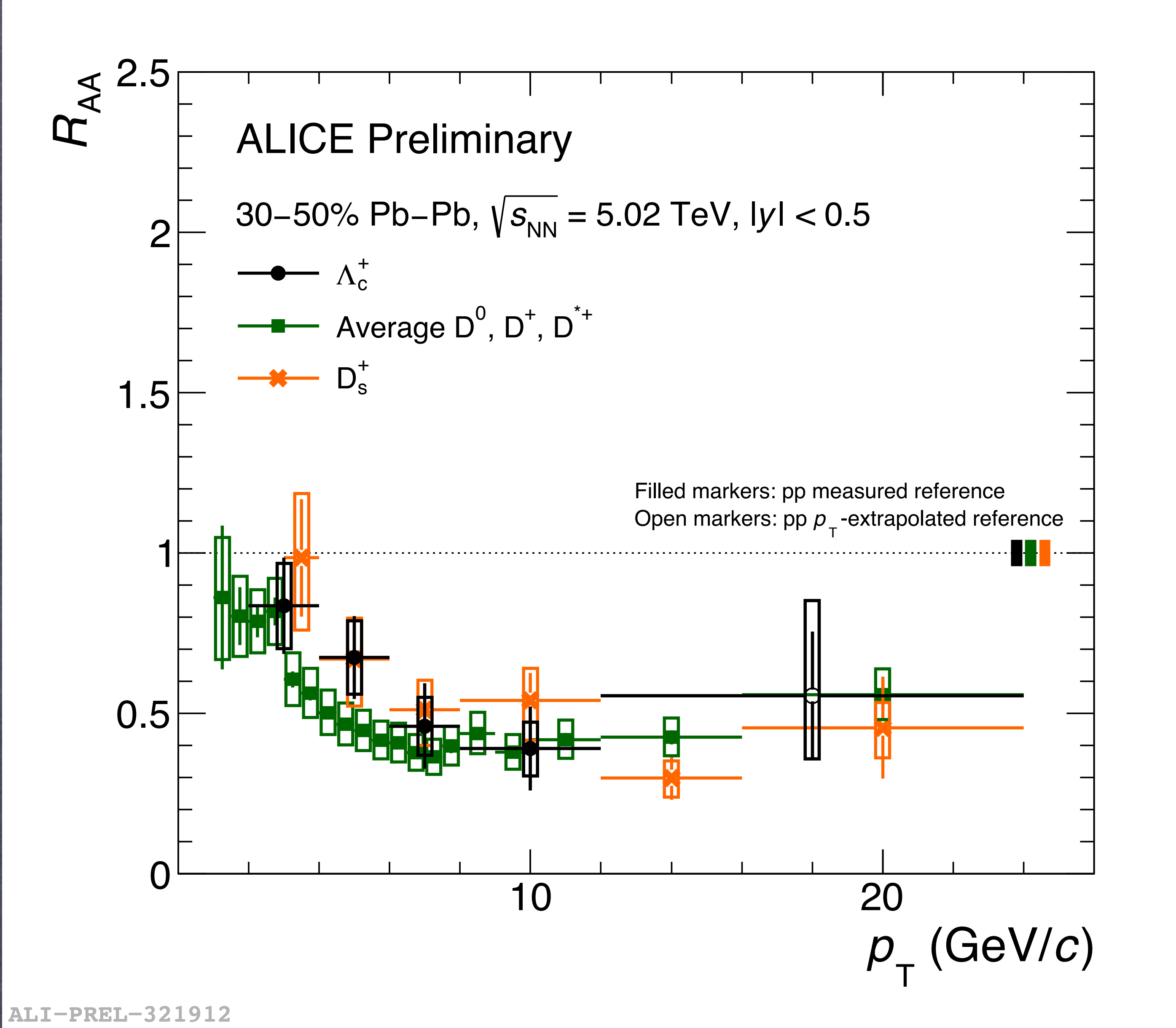
Previous result by ALICE:

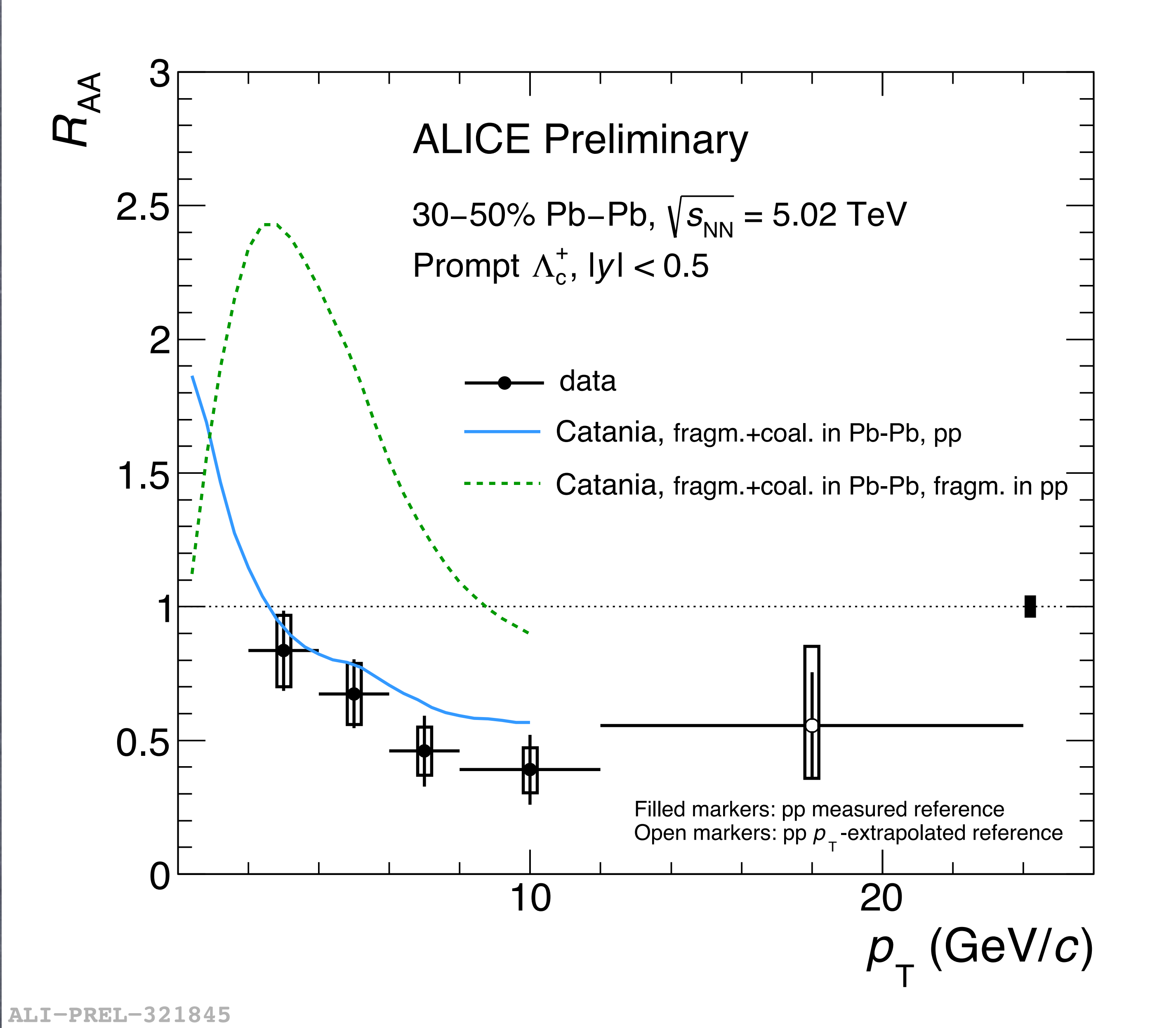


[3]Phys. Lett. B793 (2019) 212-223

Λ_c^+ nuclear modification factor R_{AA} (2018)



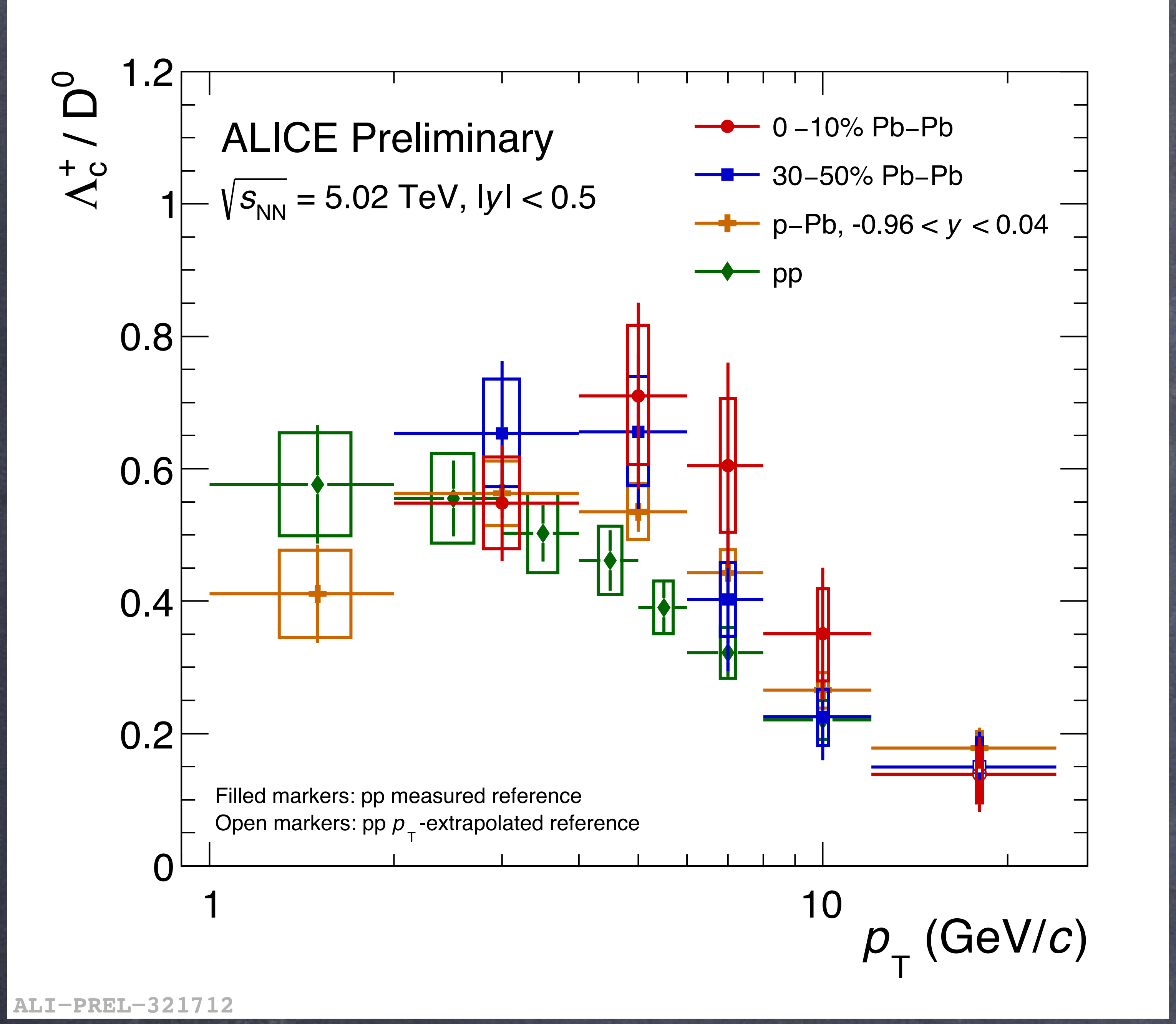


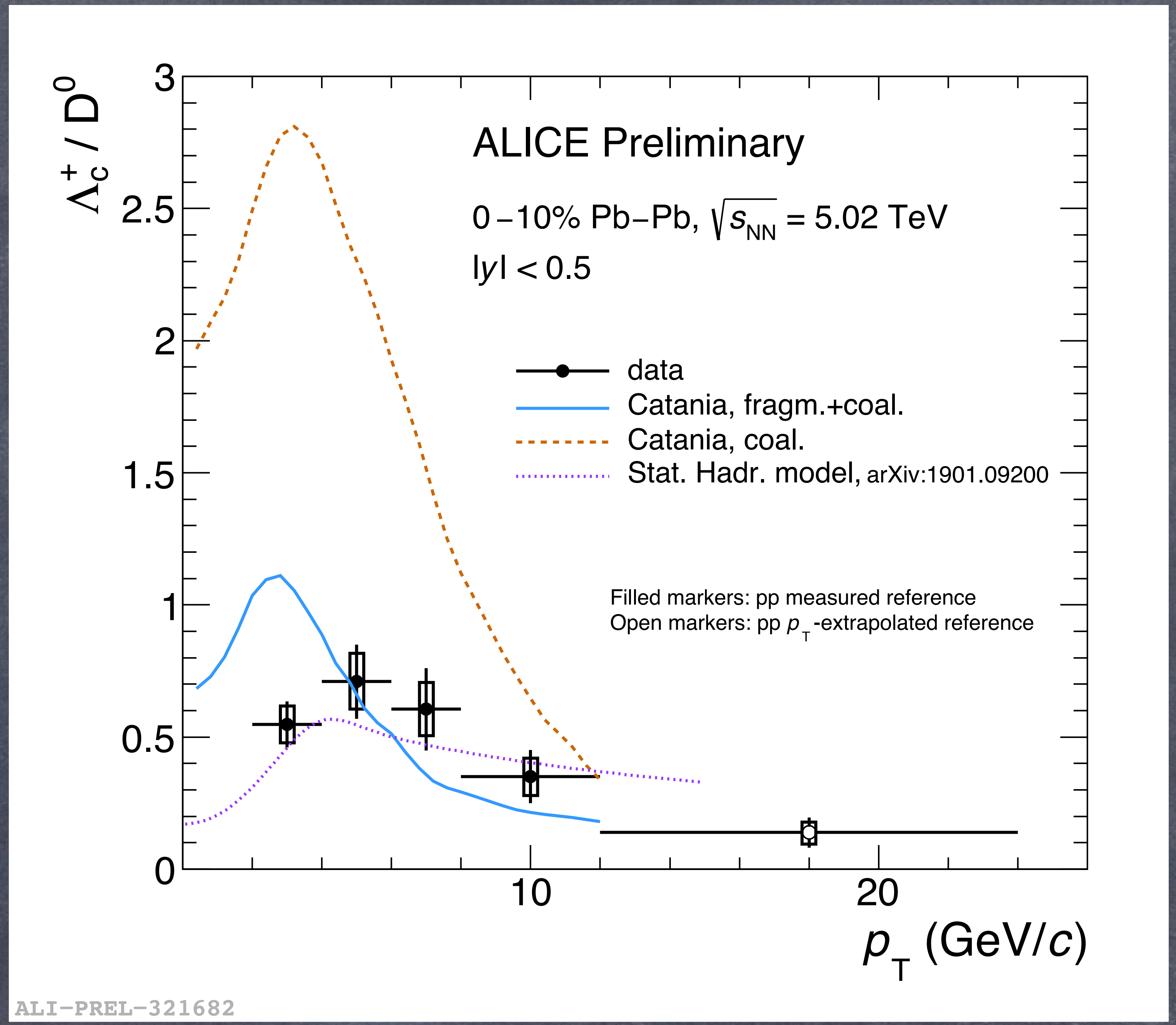


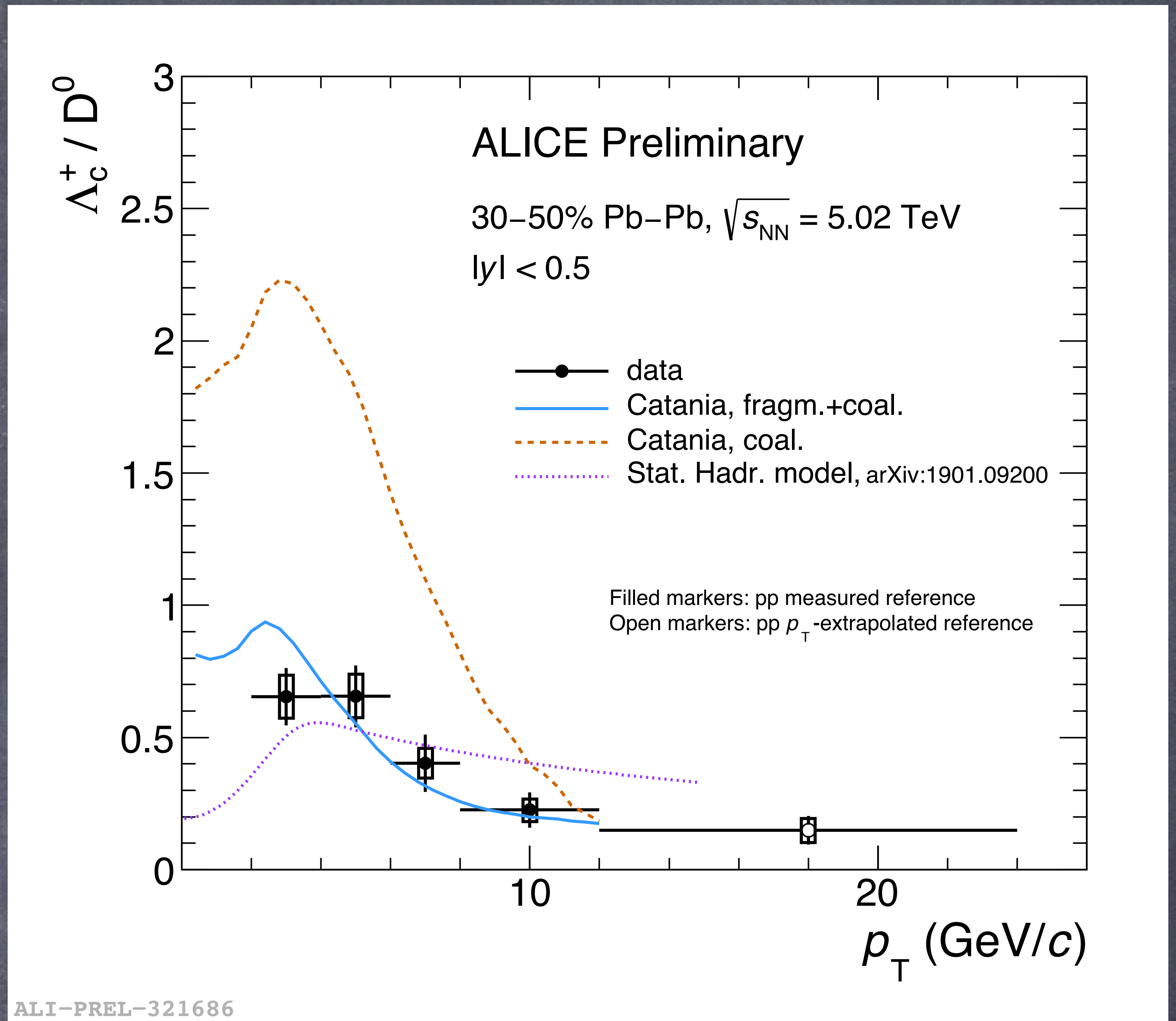
- ✓ Despite the compatibility within uncertainties, hint of larger suppression for central collisions by ~1.5x up to p_T = 12 GeV/c.
- ✓ Suppression observed for the Λ_c^+ baryon in Pb-Pb collisions.
- ✓ Comparison to theory favours[4] a scenario where both fragmentation and recombination are present in Pb-Pb and pp collisions, for both centrality ranges.

[4]Catania: Eur. Phys. J. C (2018) 78: 348

Baryon-to-meson ratio: Λ_c^+/D^0 (2018)





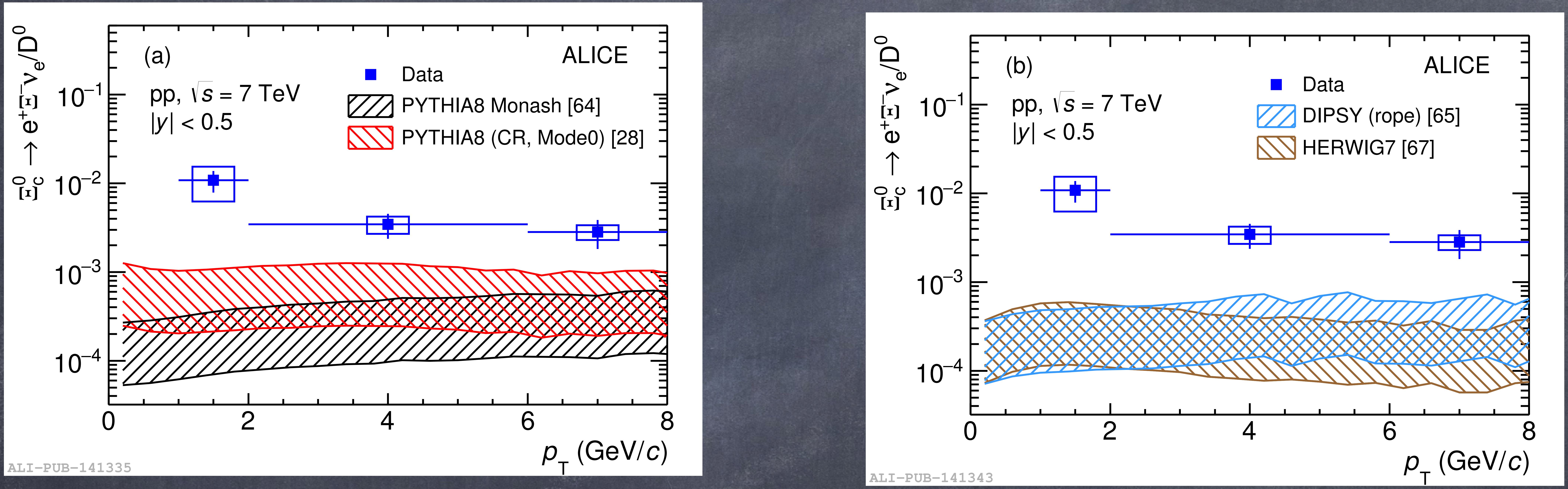


- ✓ Hint to a higher Λ_c^+/D^0 ratio in Pb-Pb (0-10% and 30%-50%) collisions w.r.t. pp collisions.
- ✓ Same behaviour w.r.t. p-Pb collisions
- ✓ More precision needed to investigate a pp -> p-Pb -> Pb-Pb trend.
- ✓ Comparison to Catania theory favours[4] a scenario where both fragmentation and recombination are present, for both centrality ranges.
- ✓ Good agreement with statistical hadronization model[5].

[4]Catania: Eur. Phys. J. C (2018) 78: 348
[5]SHM: arXiv: 1901.09200

Results on Ξ_c^0

- First measurement of Ξ_c^0 production in pp collisions at $\sqrt{s_{NN}}$= 7 TeV[6]



✓ $\Xi_c^0 \to e^+\Xi^-\nu\,(\Xi^- \to \pi^-\Lambda)$ BR currently unknown, and can not measure neutrino.

✓ Event generators PYTHIA8[7][8], DIPSY[9] and HERWIG7[10] underestimate data.

[6] Phys. Lett. B 781 (2018) 8-19

[7] PYTHIA8 CR: JHEP 08 (2015) 003

[8] PYTHIA8: Eur. Phys. J. C (2014) 74:3024

[9] DIPSY: JHEP 08 (2011) 103

[10] HERWIG7: Eur. Phys. J. C58 (2008) 639-707