The 36th Winter Workshop on Nuclear Dynamics

Summary of charm results from ALICE

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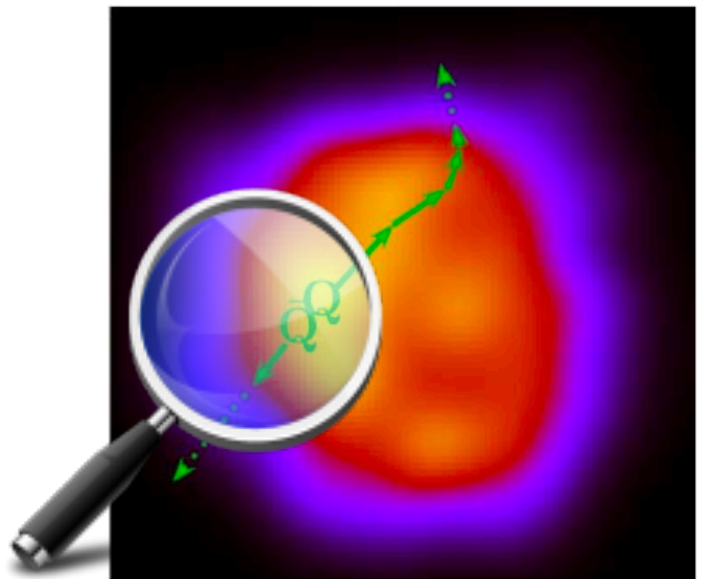
University of Houston
for the ALICE Collaboration

Puerto Vallarta, Mexico 1-7 March 2020

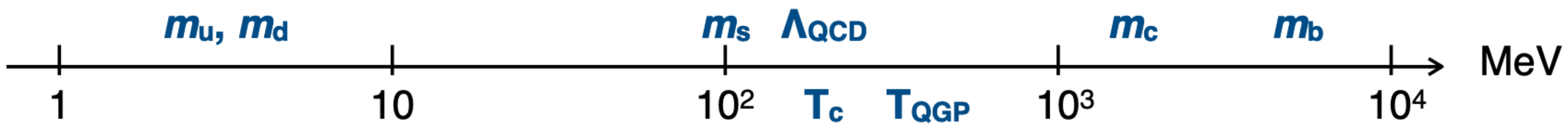
Heavy-flavour physics

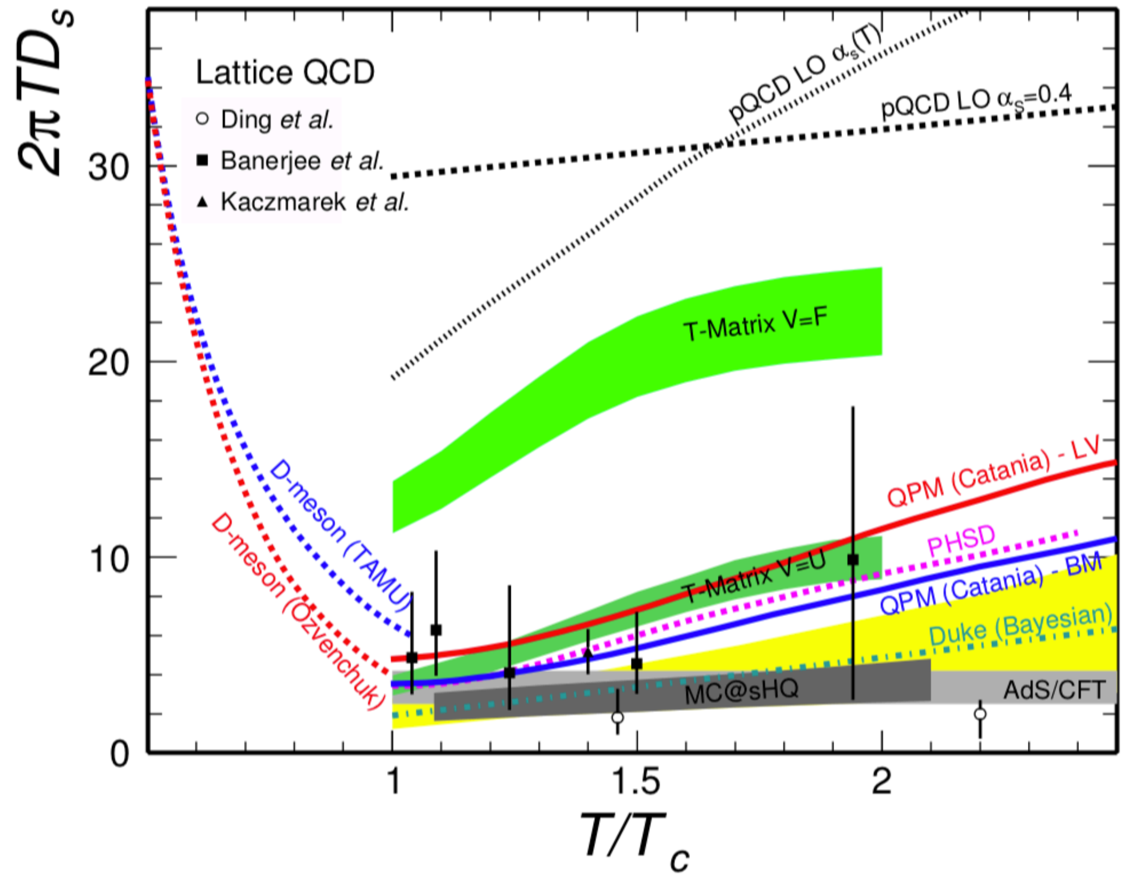
Investigate strongly interacting matter under extreme conditions of temperature and density



Heavy Quarks (HQ), **charm** and **beauty**, as probes of the QGP properties

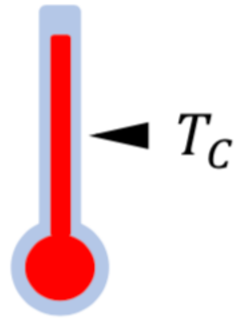
- ***$m_Q >> \Lambda_{QCD}$***
  - their production cross section calculable with pQCD
- ***$m_Q >> T_{QGP}$***
  - production restricted to initial hard scatterings (formation time 1/2 m_Q ~0.02 - 0.1 fm/*c*)
  - long relaxation time τ_Q, possibly comparable to the fireball lifetime (~ few fm/*c*)

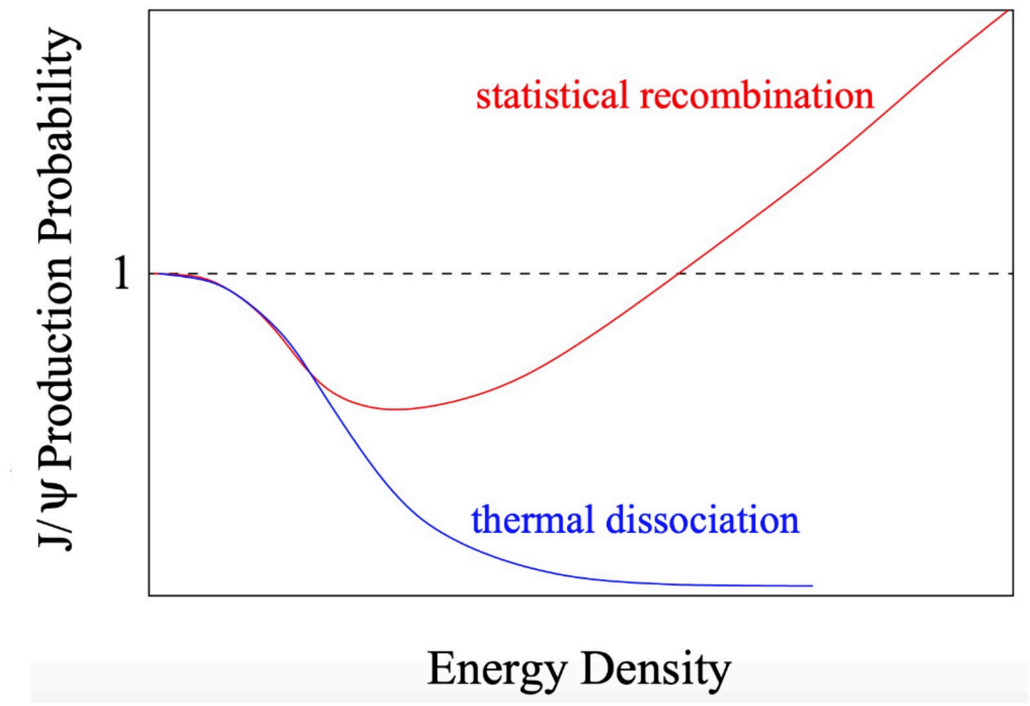




QGP investigation with HQs:

- **Open heavy flavours —> probe the opacity of the QGP**
  - **tomography via HQ energy loss at high p_T and HQ as brownian motion markers at low p_T.**
    —> spatial diffusion coefficient: $2\pi TD_s$
- **Quarkonia —> sensitive to the temperature of QGP, probe suppression of charmonia due to color screening and regeneration in medium**





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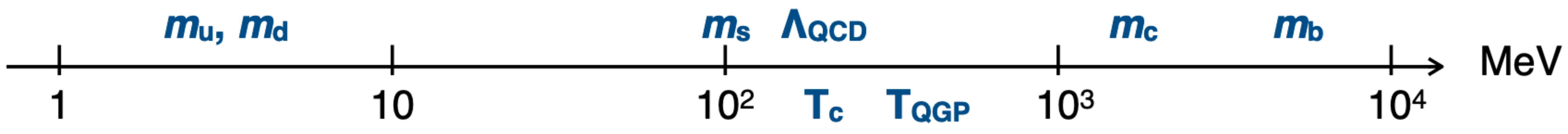

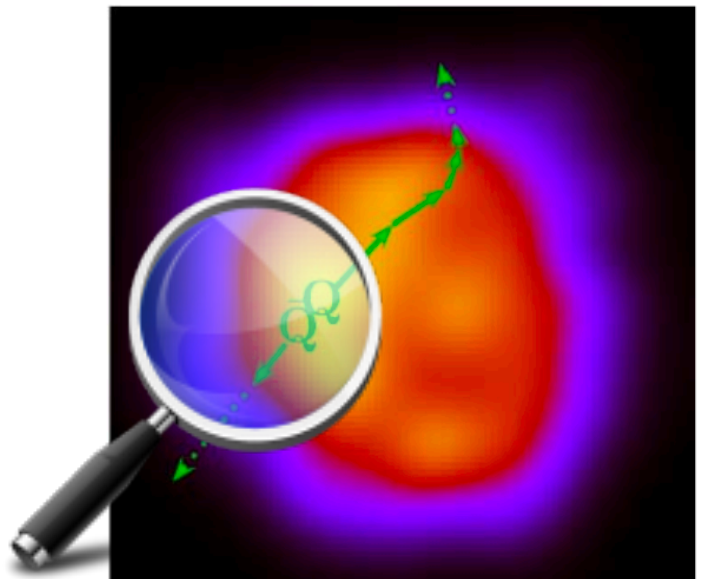

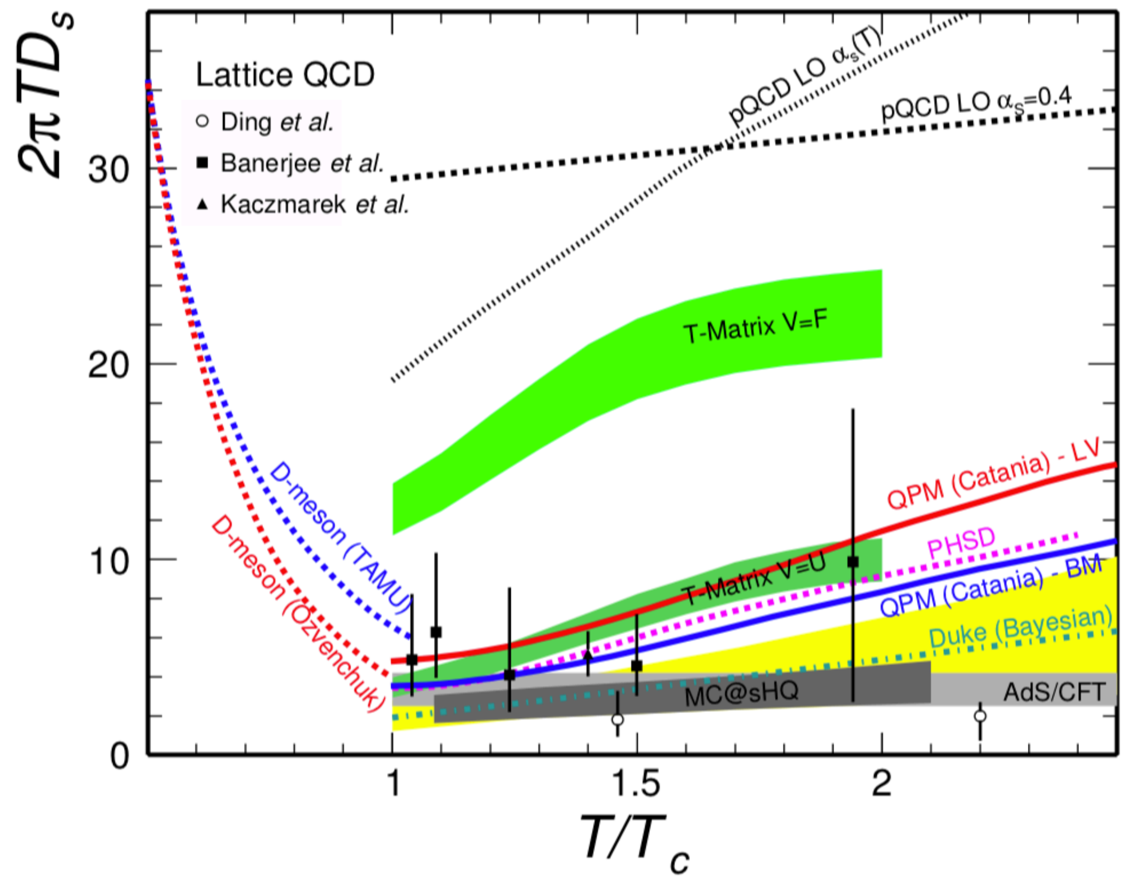

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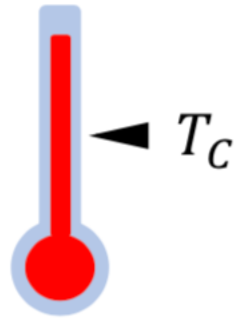
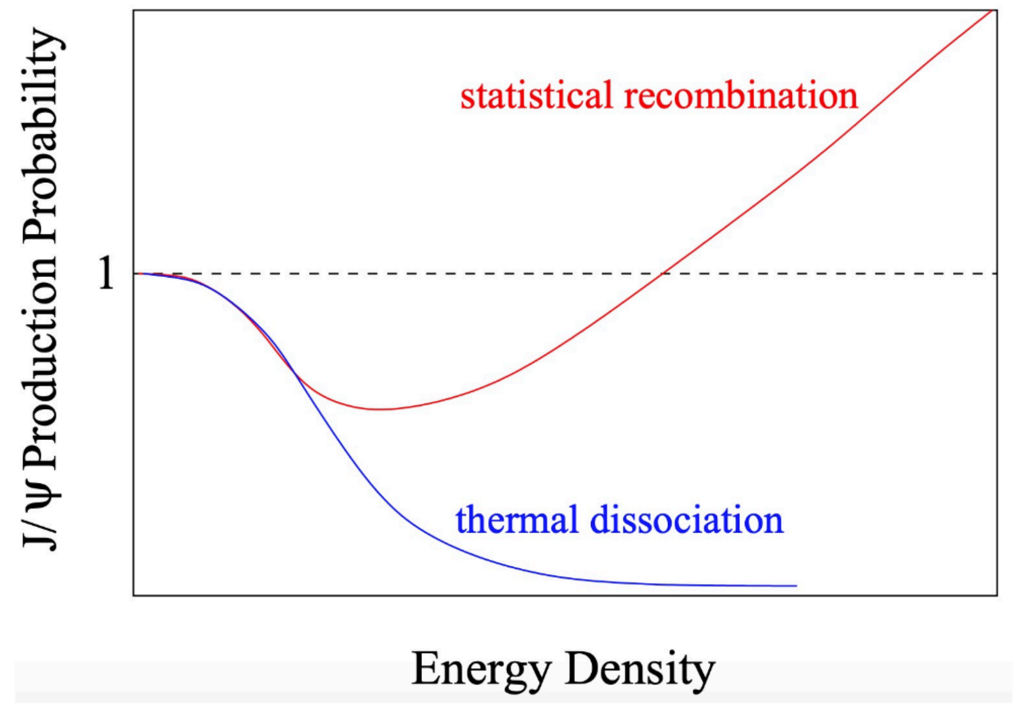




Not only Pb-Pb collisions! Heavy-flavour measurements in small systems:

- pp collisions: provide constraint to pQCD calculations
- p-Pb collisions: investigate Cold Nuclear Matter effects

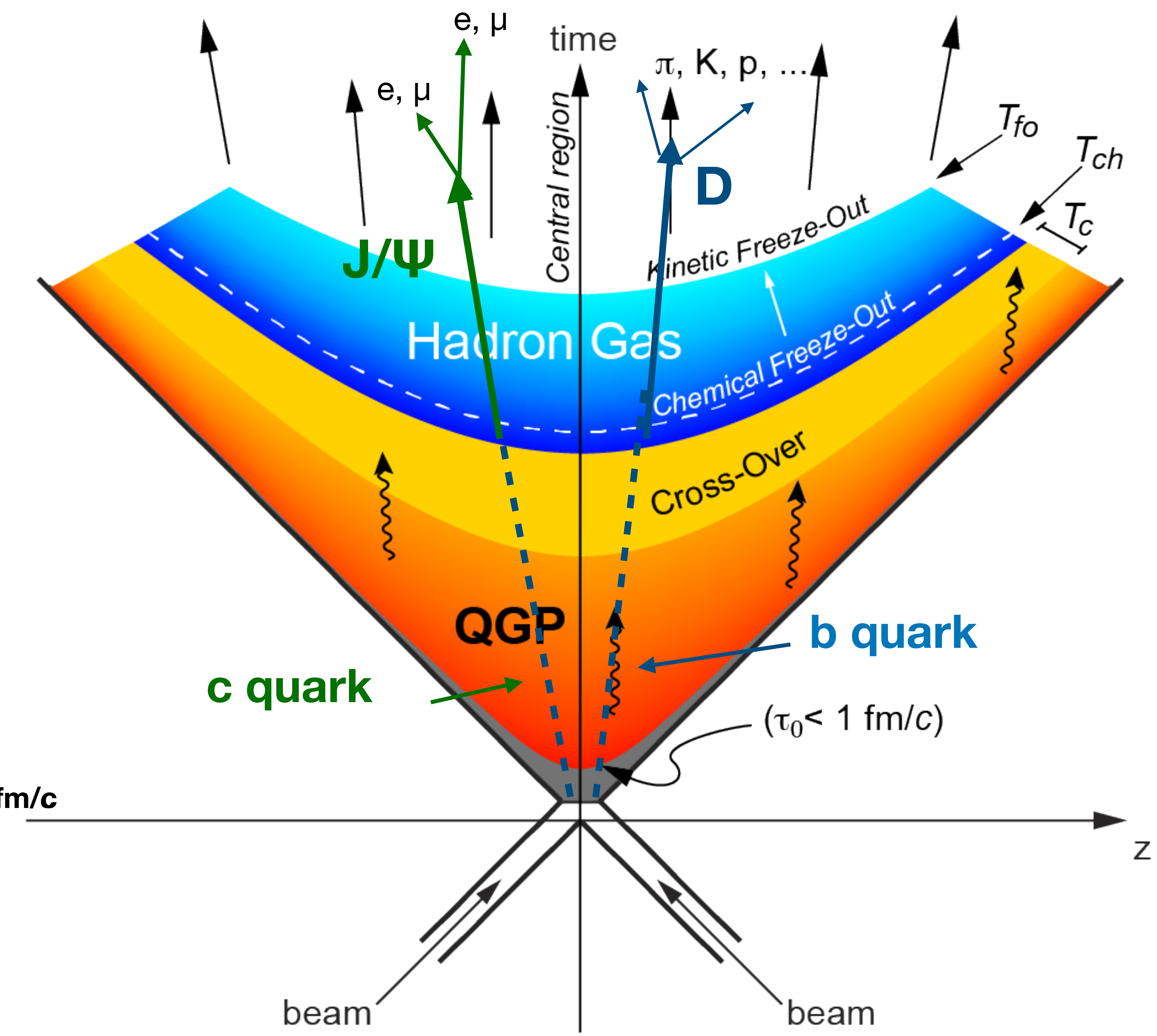
➡ High multiplicity pp and p-Pb: onset of the QGP?

Space-time evolution
From heavy-quark production to hadronization into heavy-flavour hadrons

Hadronization 5-10 fm/*c*

QGP formed at ~1 fm/*c*

HQ time formation < 0.1 fm/*c*



Hadronic final state

Expanding medium

Collision

Incoming nuclei

Space-time evolution
From heavy-quark production to hadronization into heavy-flavour hadrons

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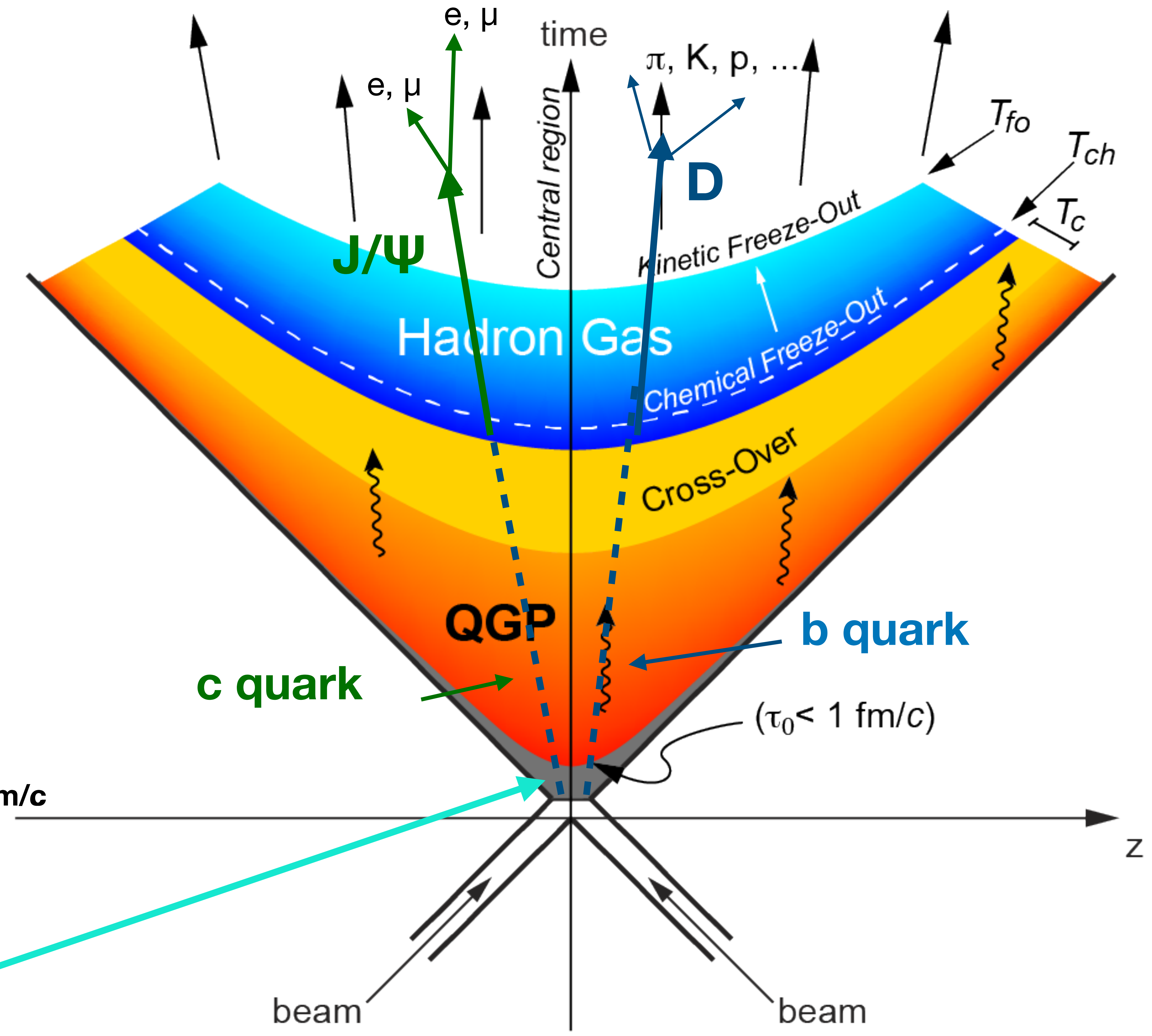

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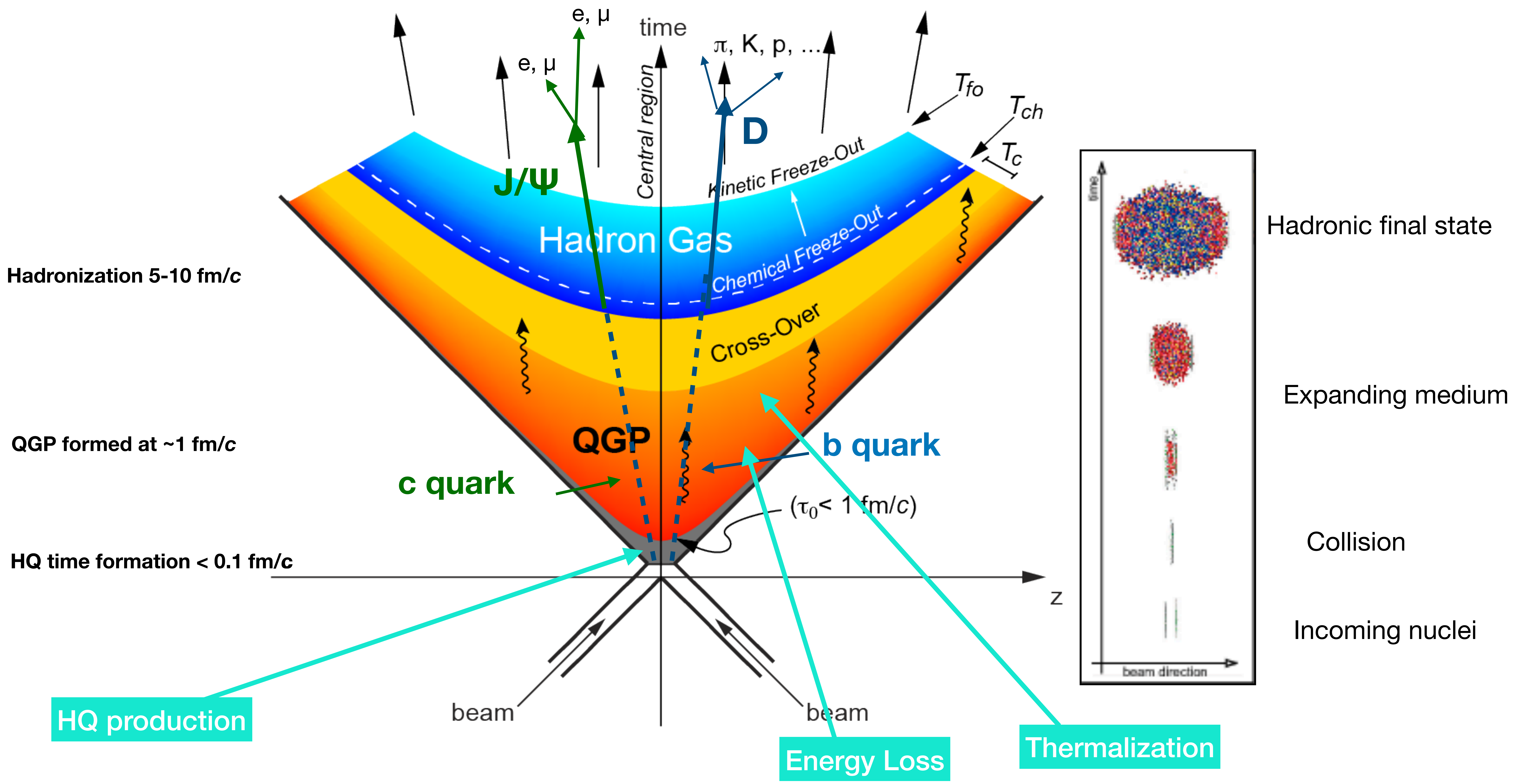

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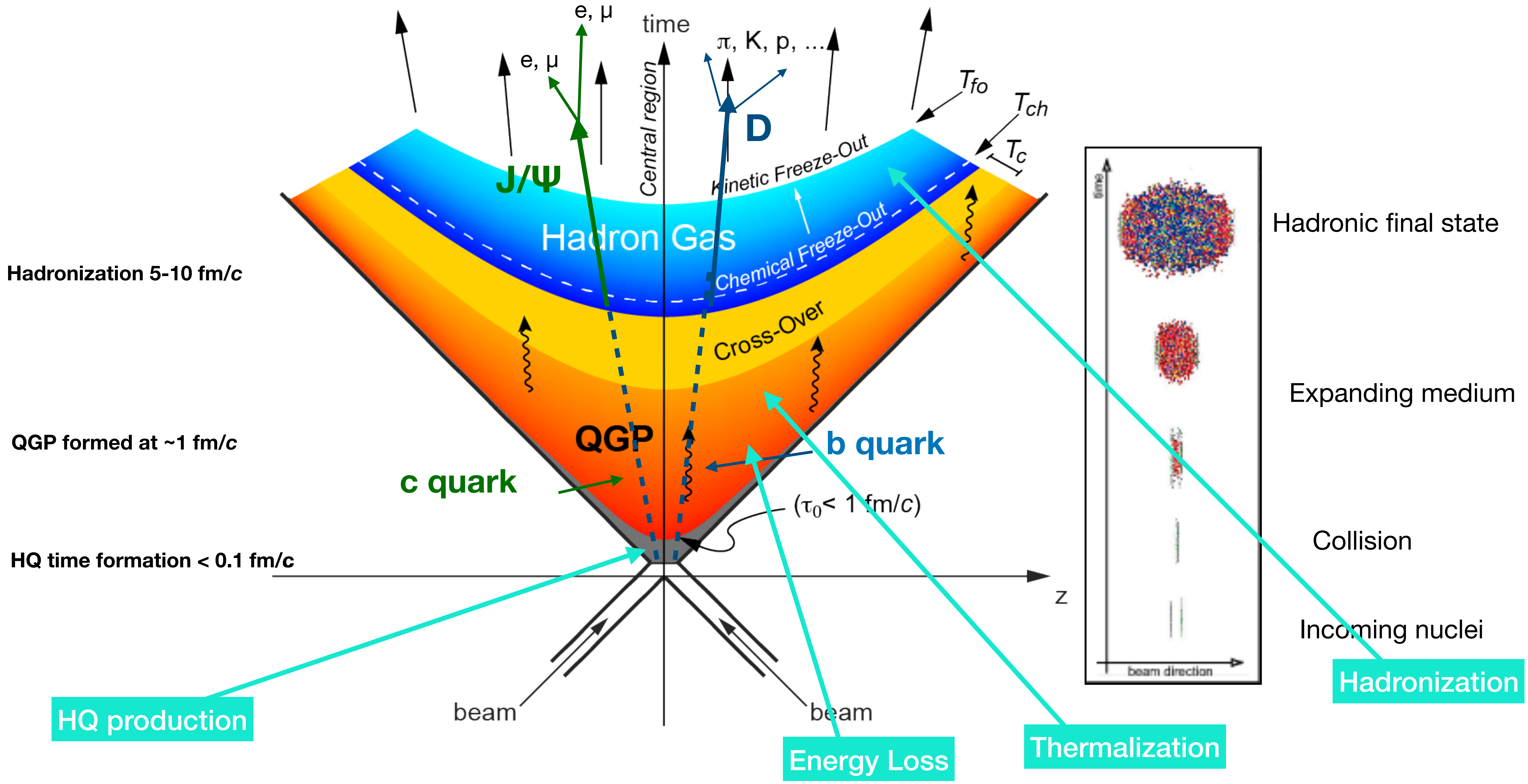
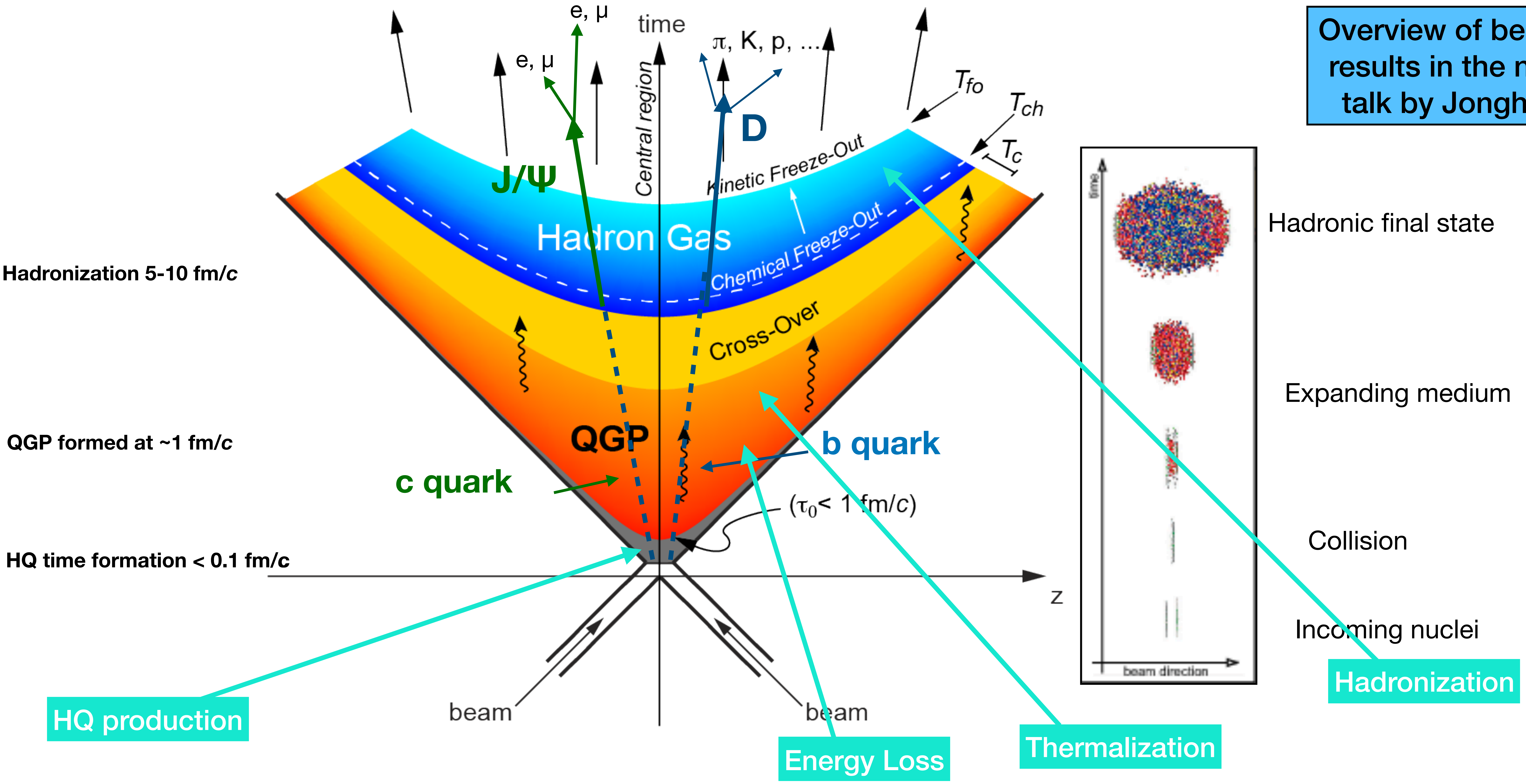


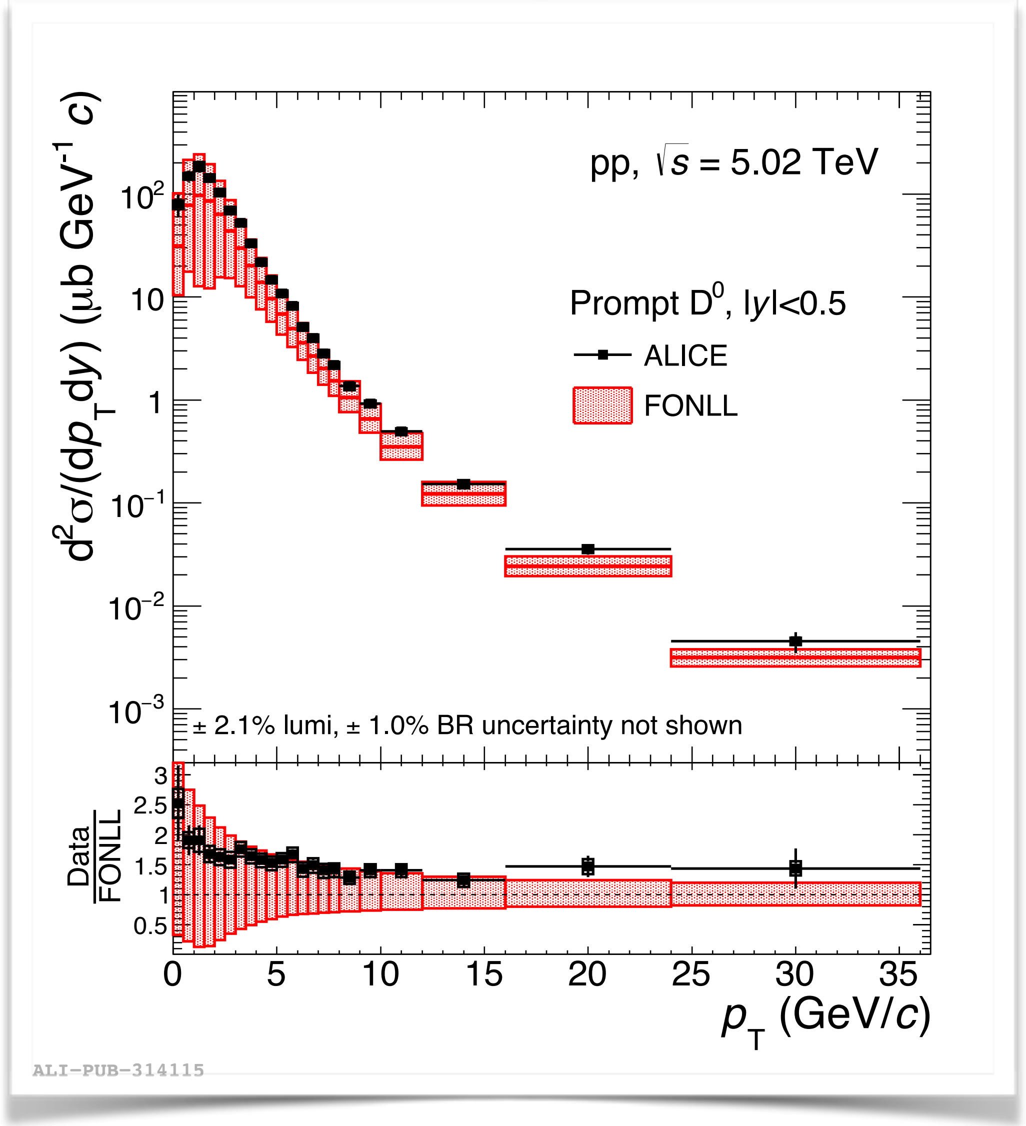
Space-time evolution
From heavy-quark production to hadronization into heavy-flavour hadrons

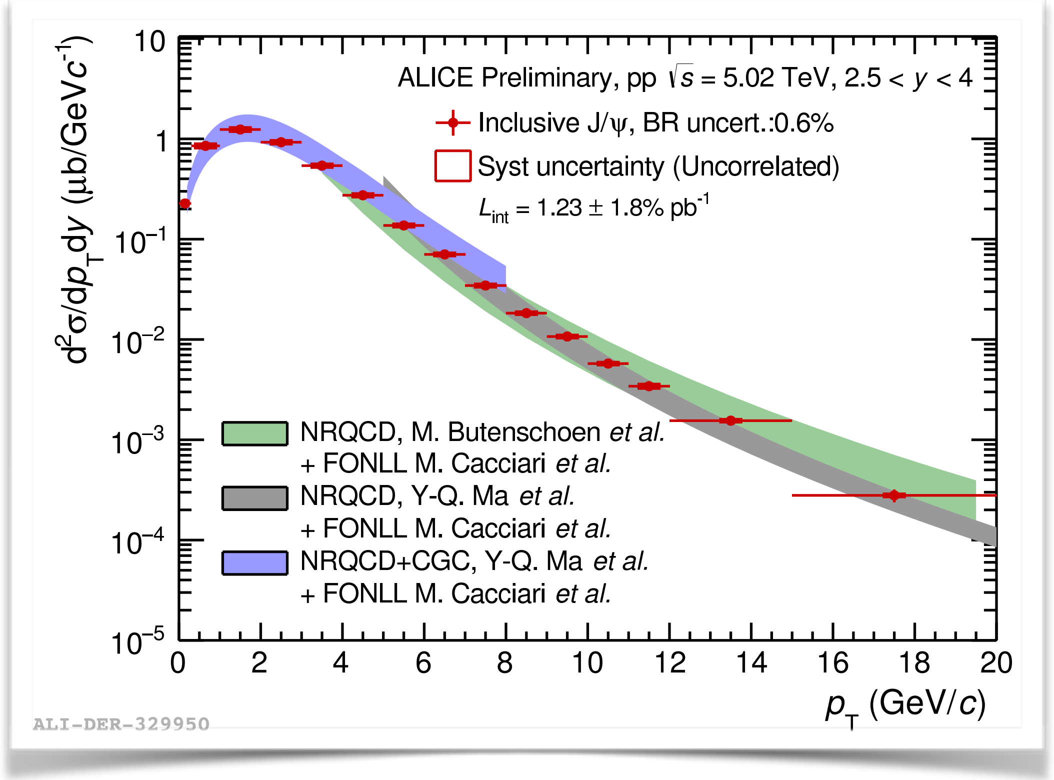
Overview of beauty results in the next talk by Jonghan



Charm production and interaction in the medium

Charm production mechanisms and test of the pQCD calculations





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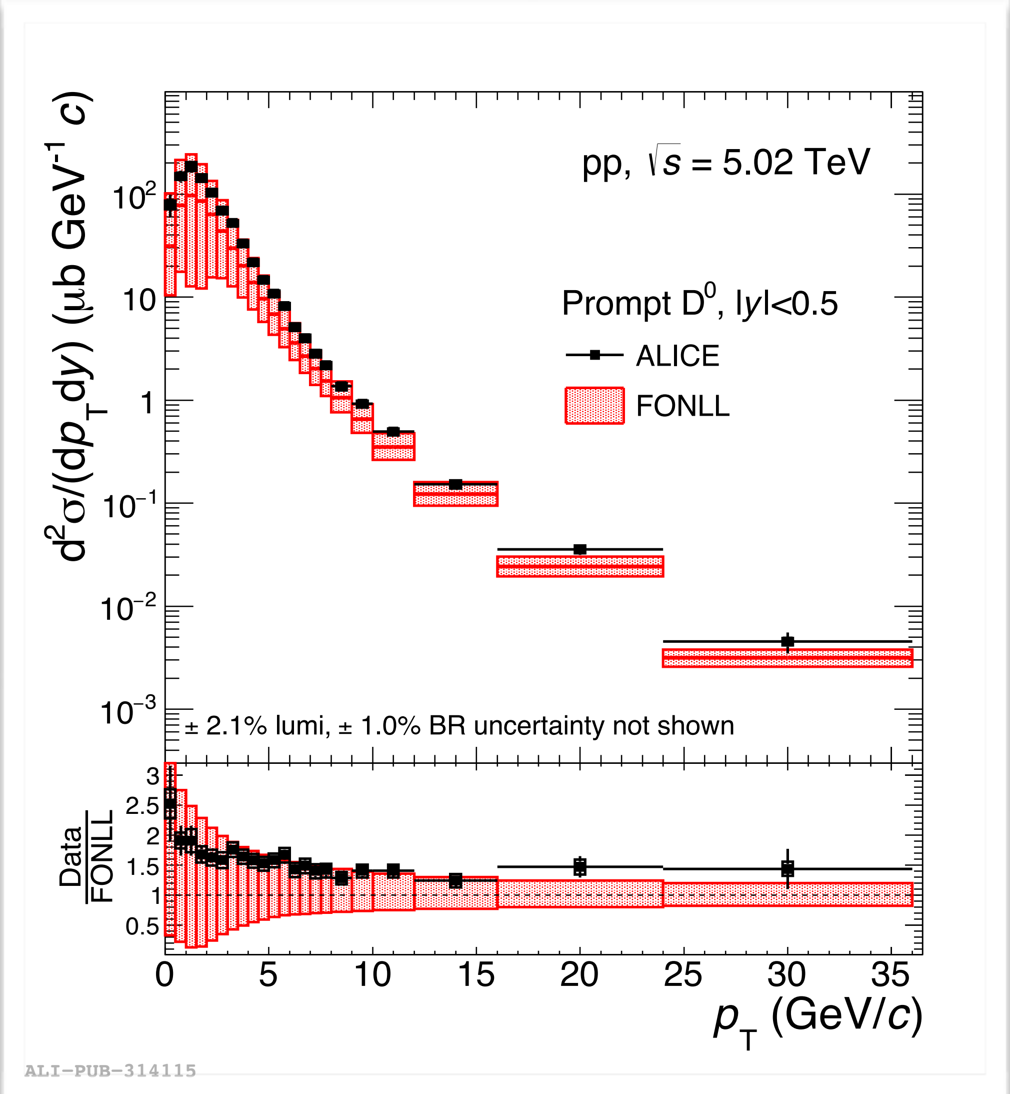
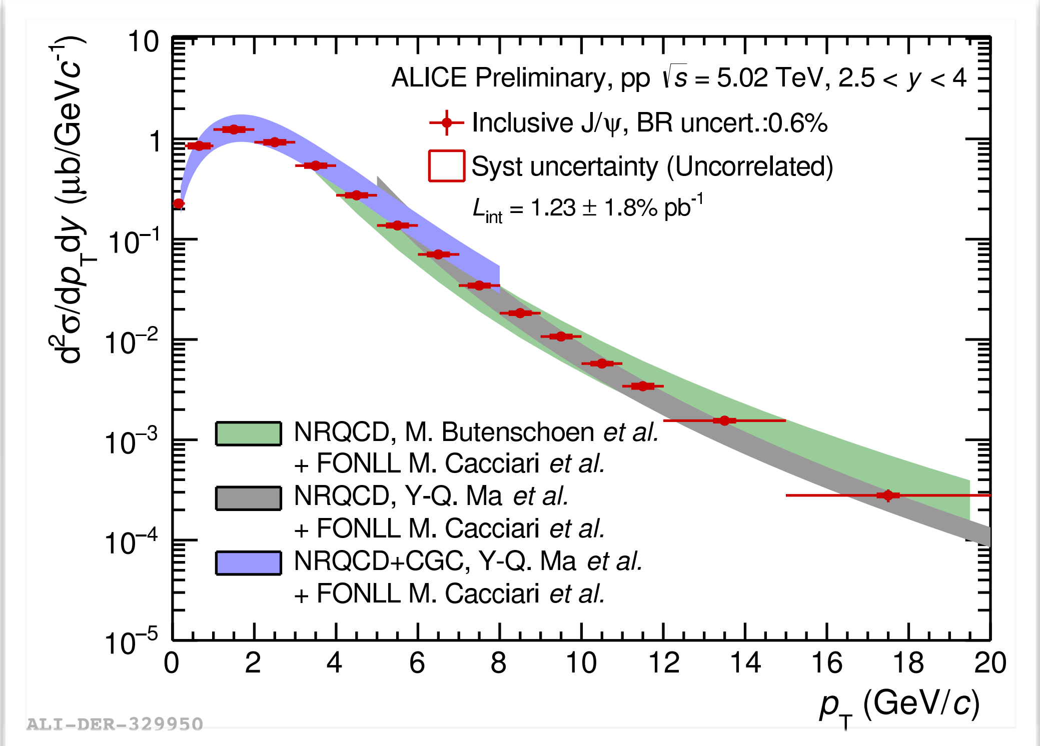
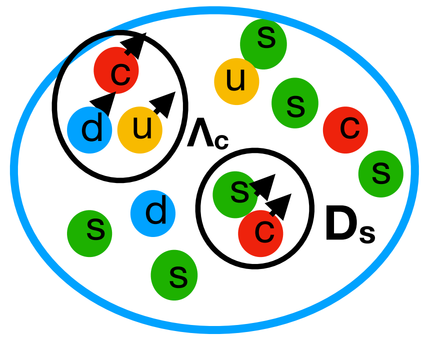
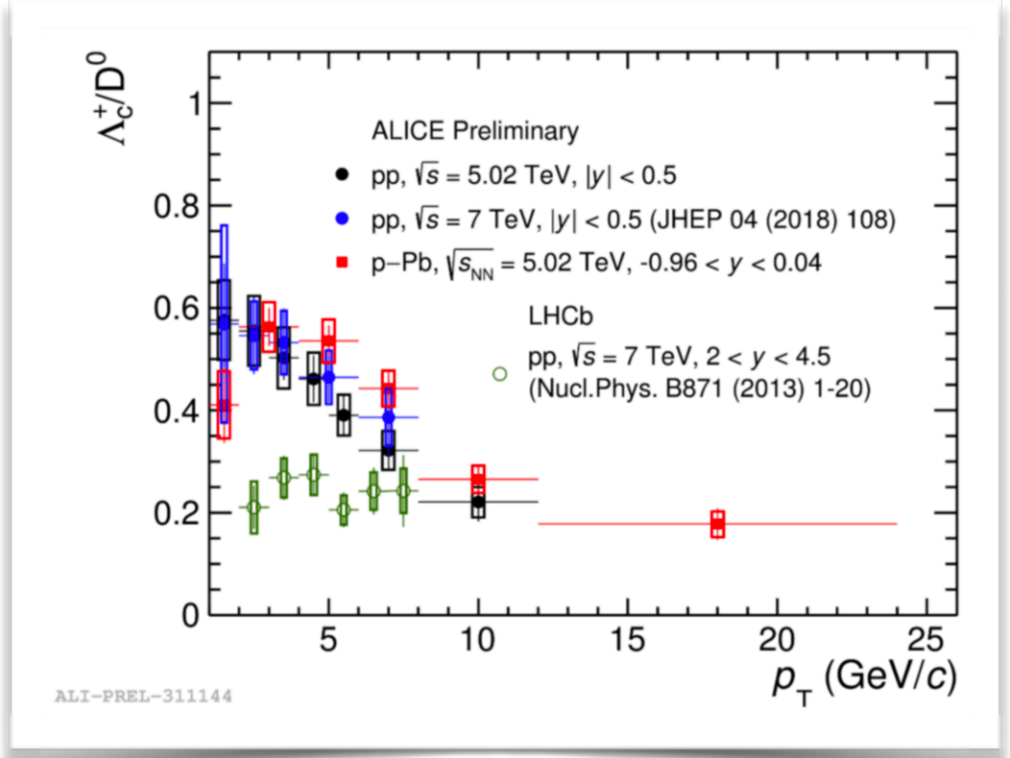




Hadronization mechanisms:
fragmentation in vacuum?
recombination with light partons?





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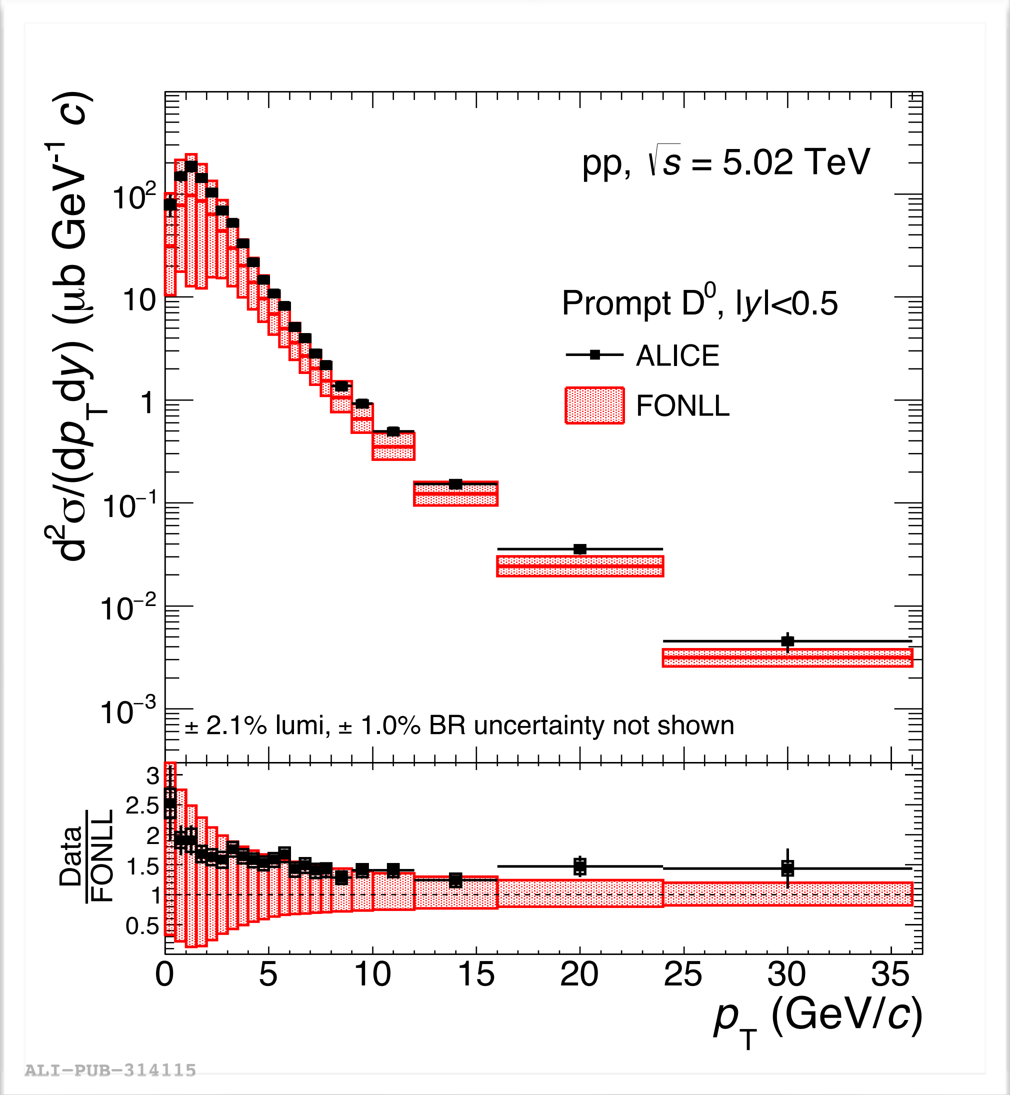
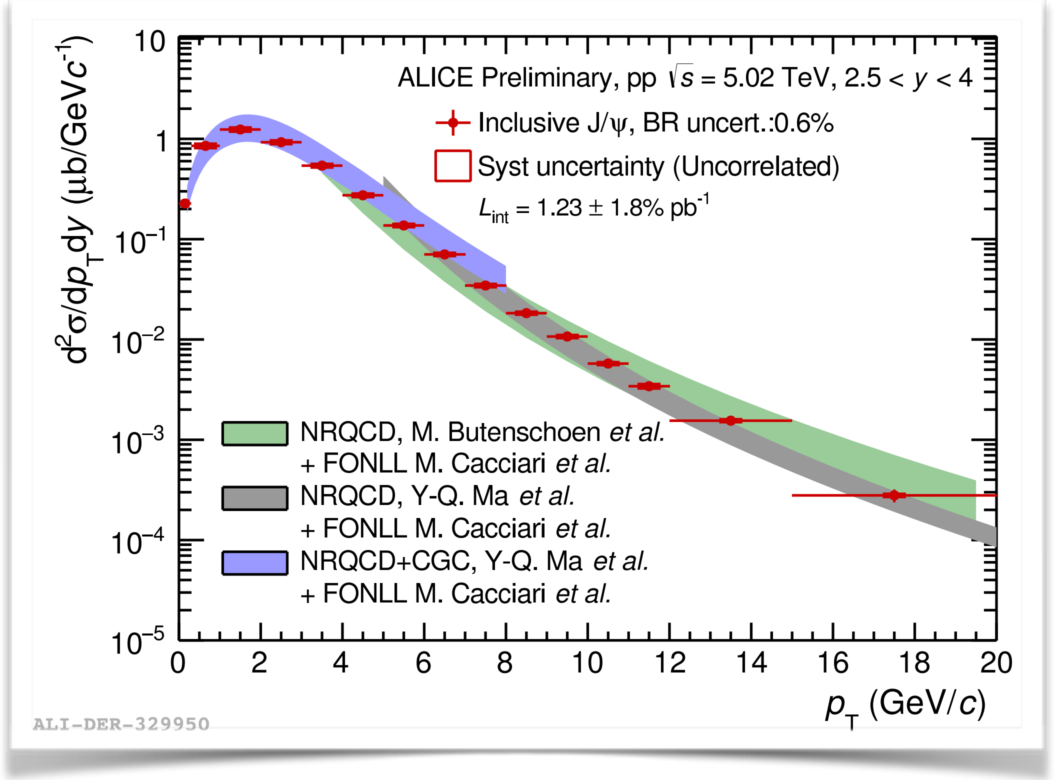
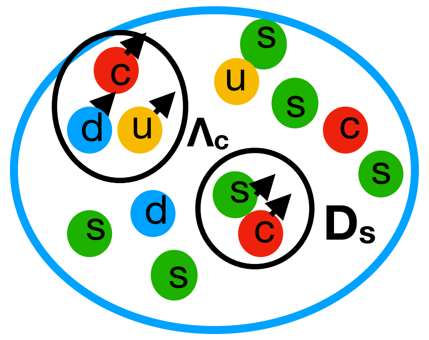
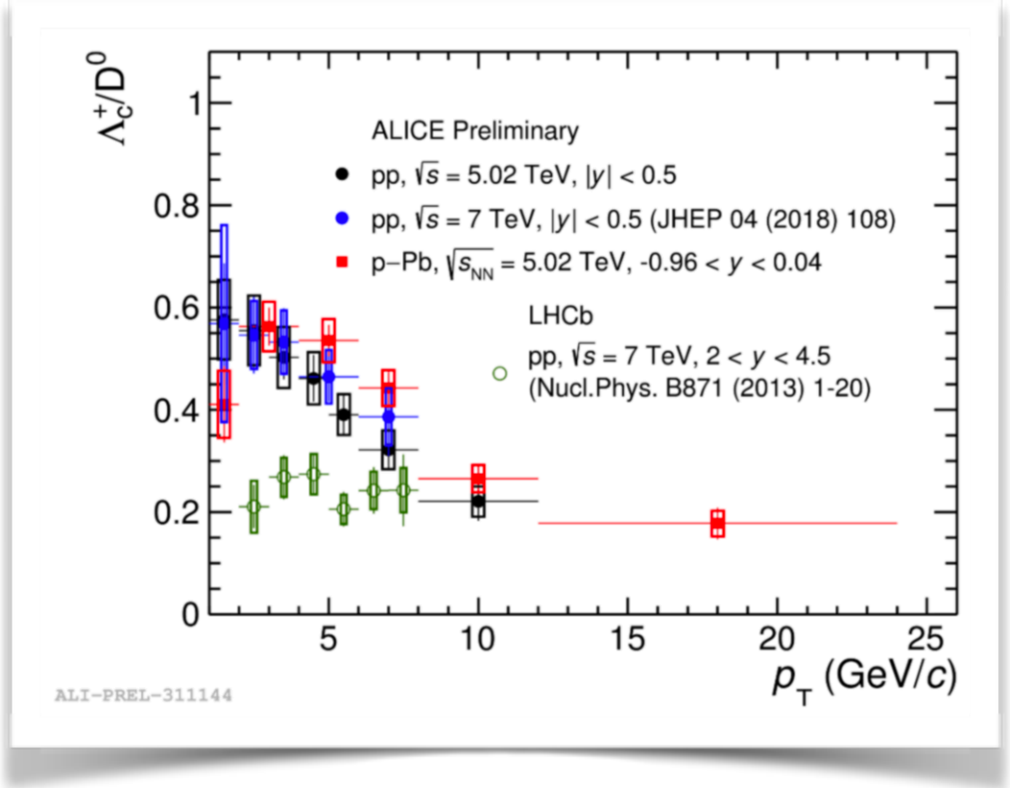


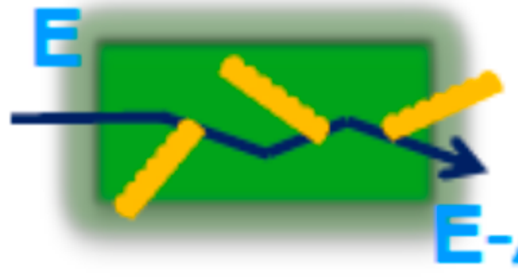


Hadronization mechanisms: fragmentation in vacuum? recombination with light partons?





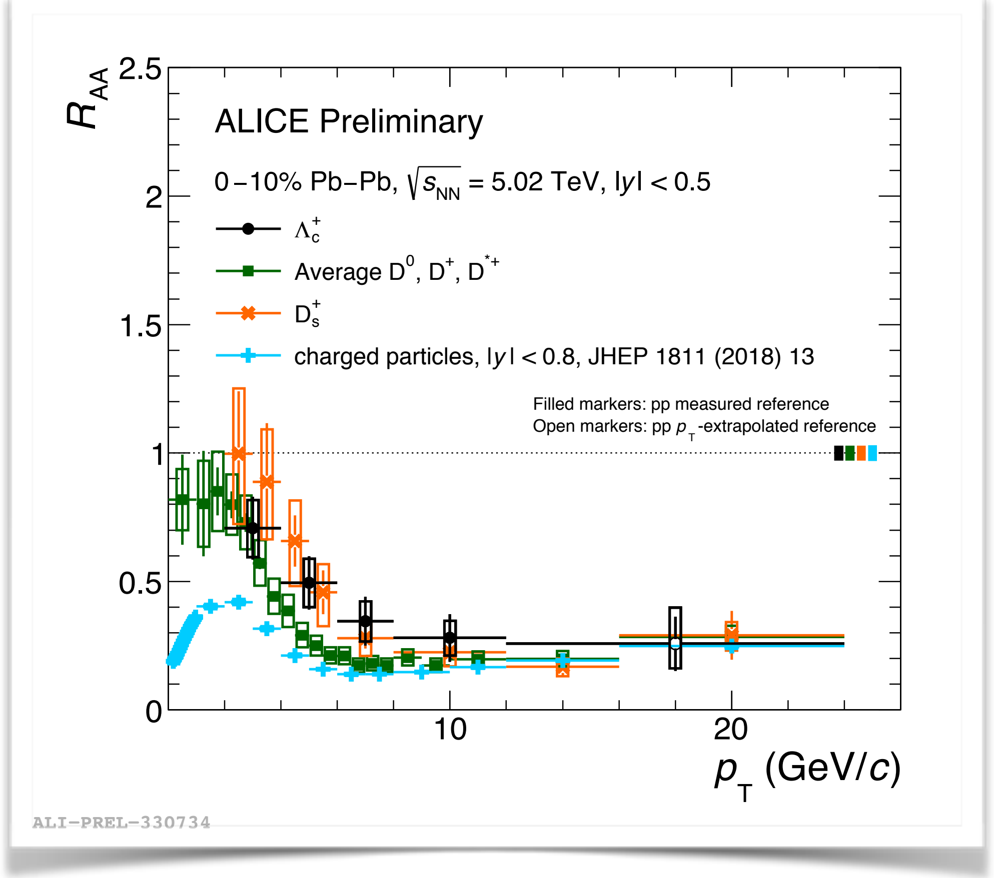
Energy loss mechanisms, flavour dependence, radiative and collisional processes, suppression and recombination



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Colour-charge and mass dependence

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



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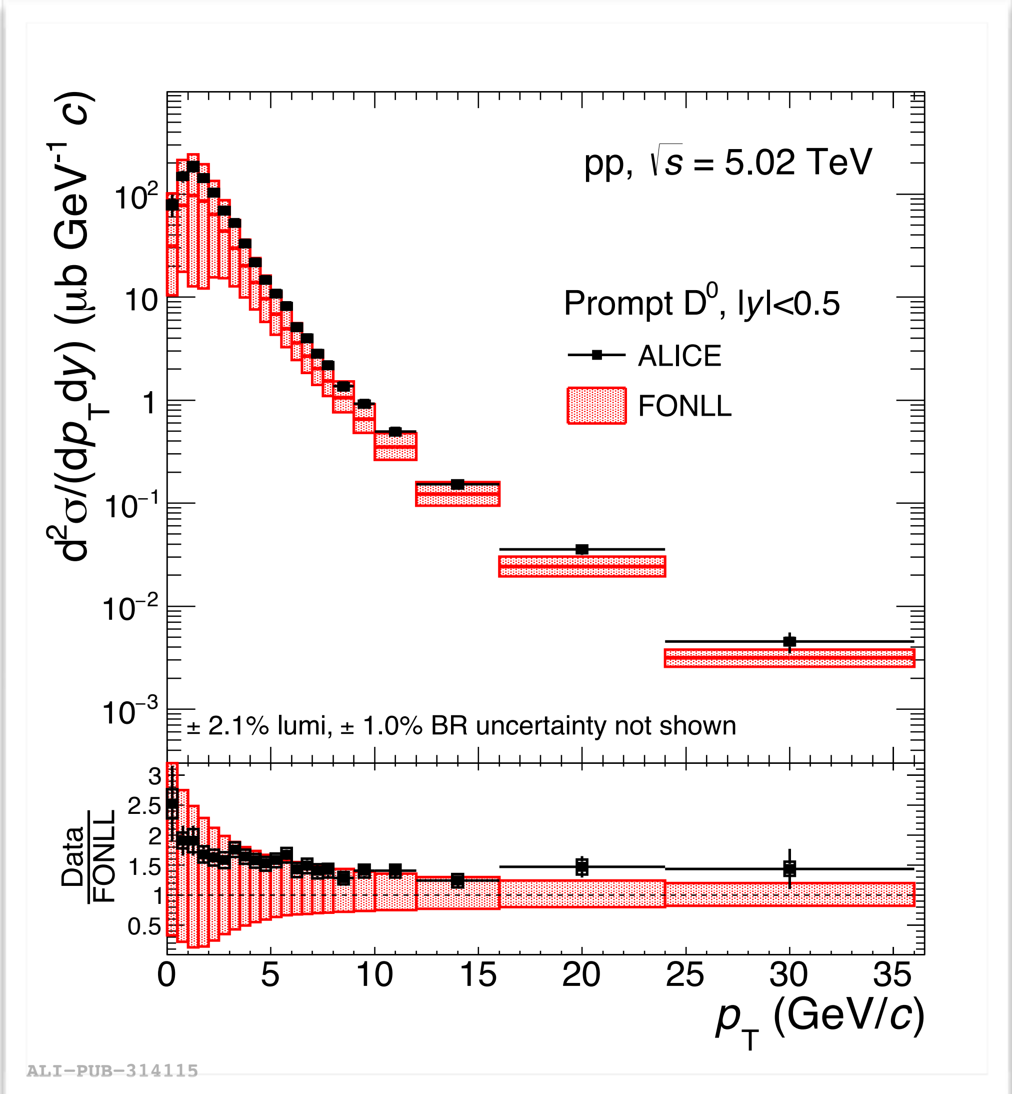

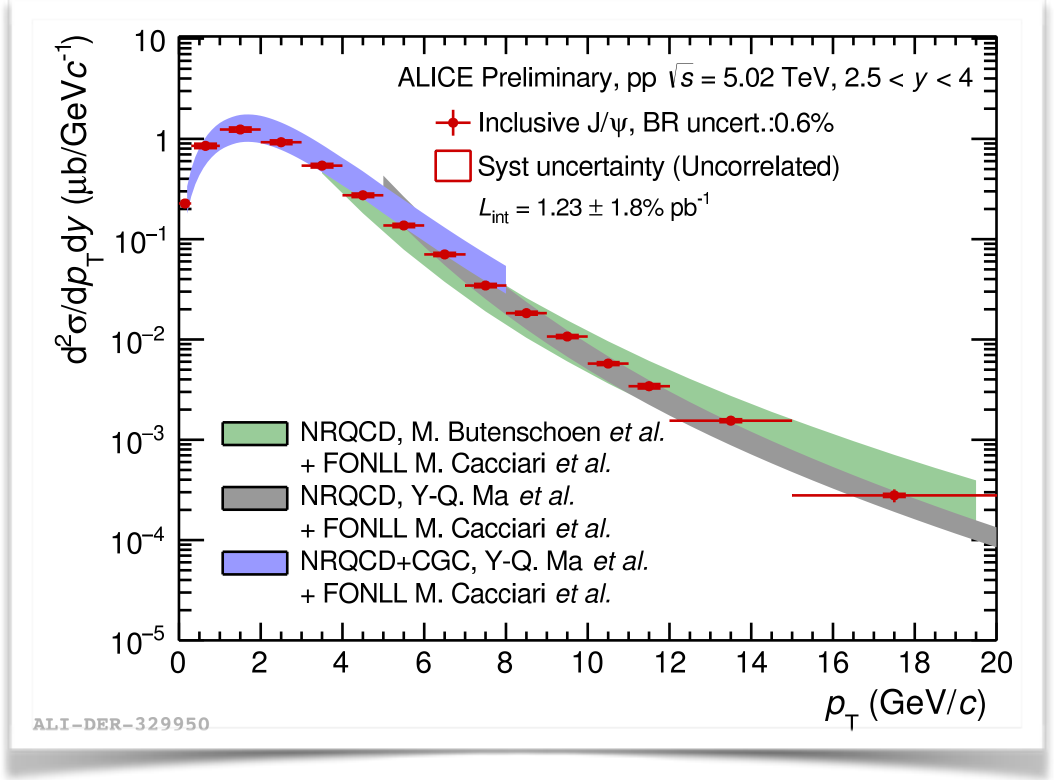

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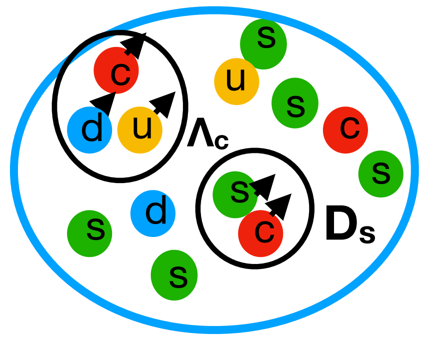

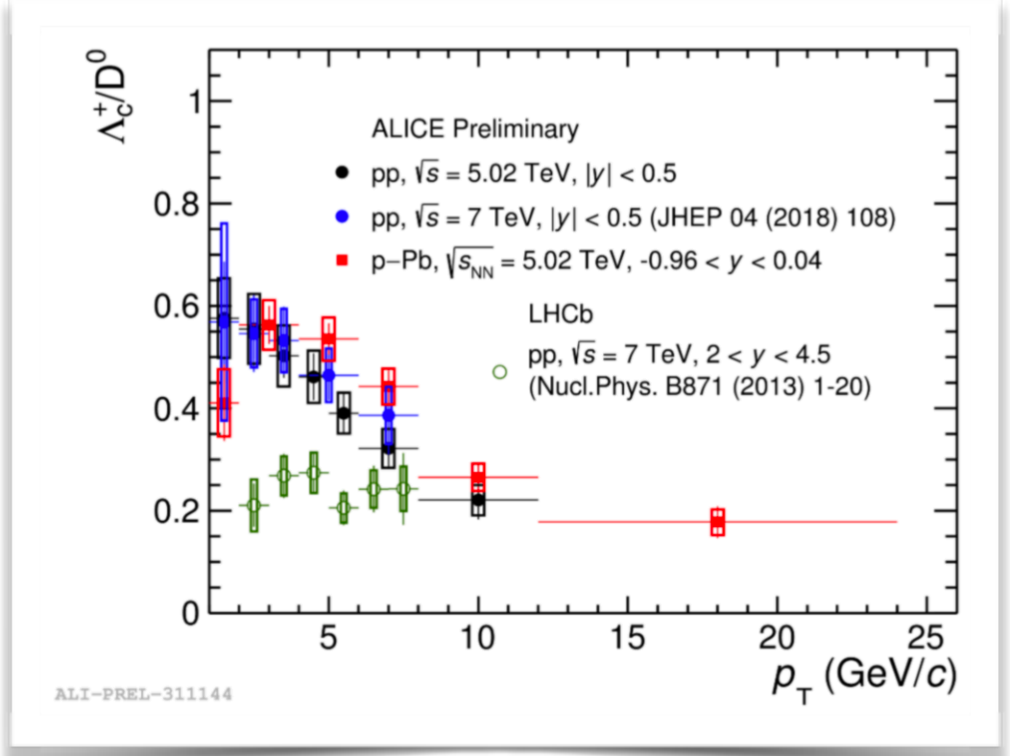

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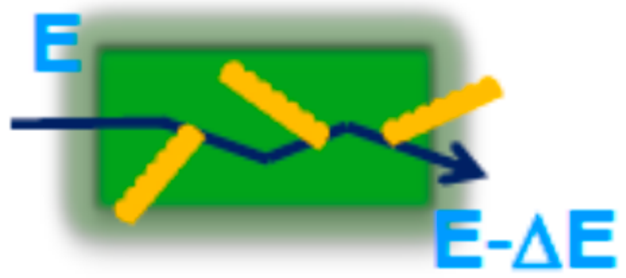

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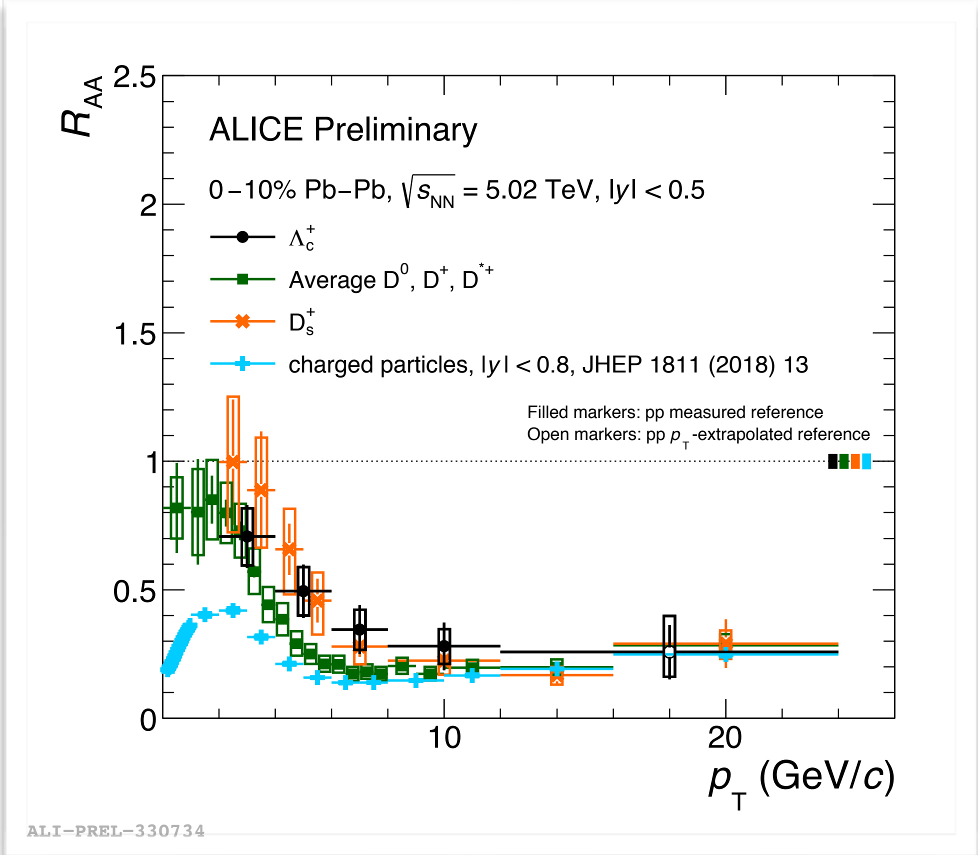
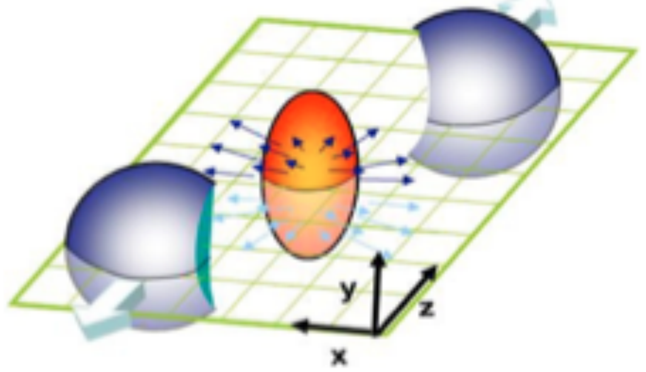
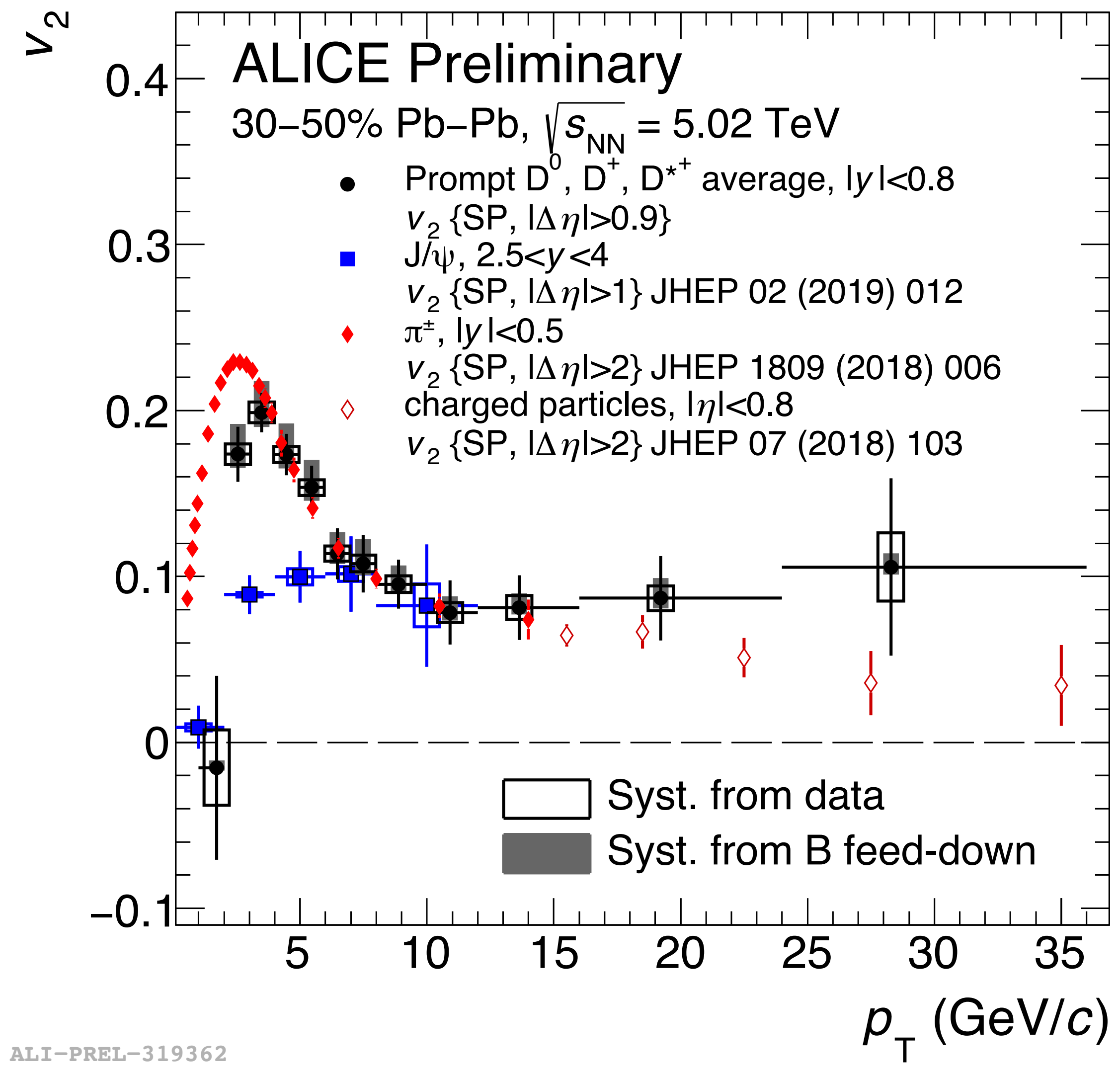


Thermalization of charm quarks

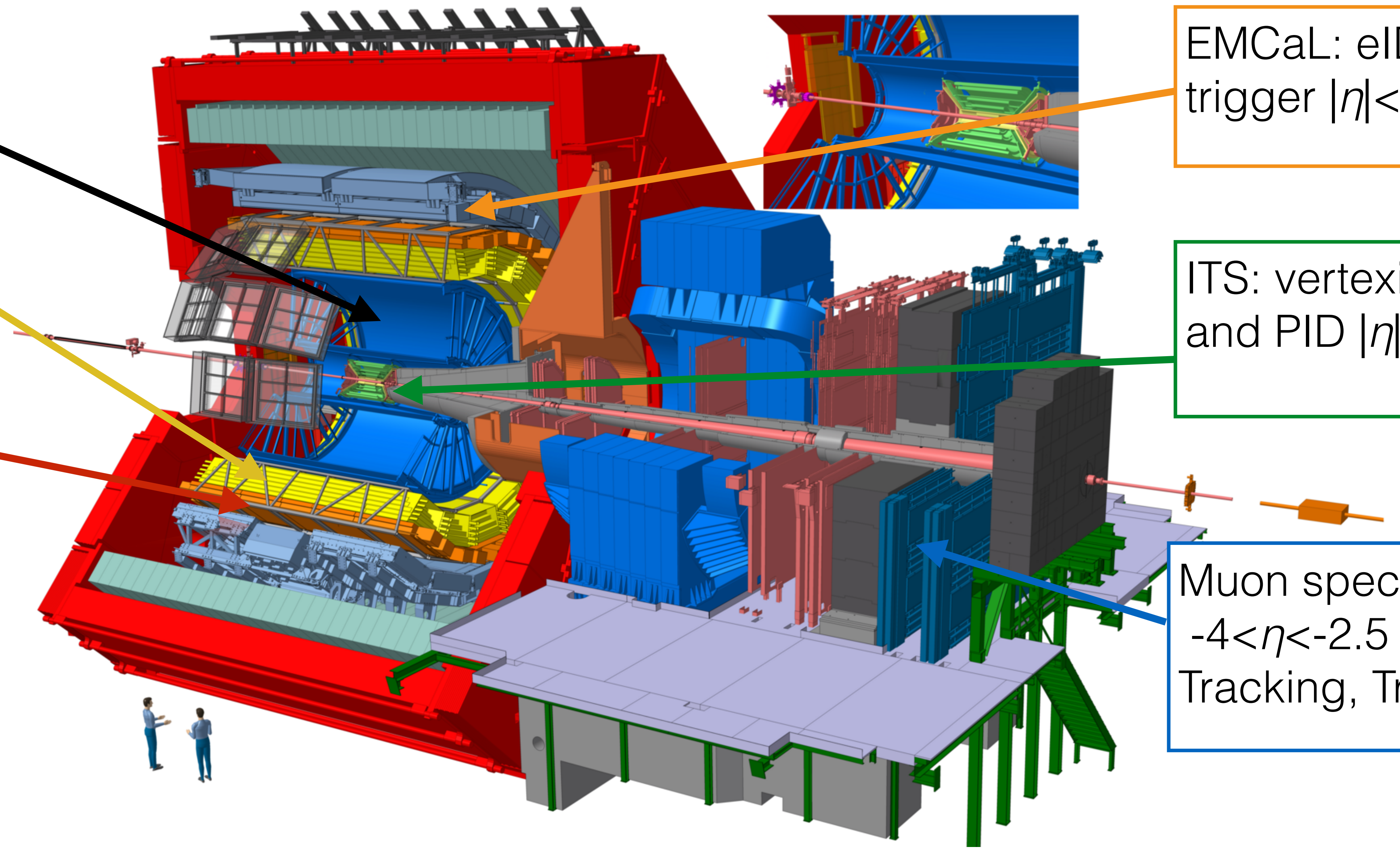


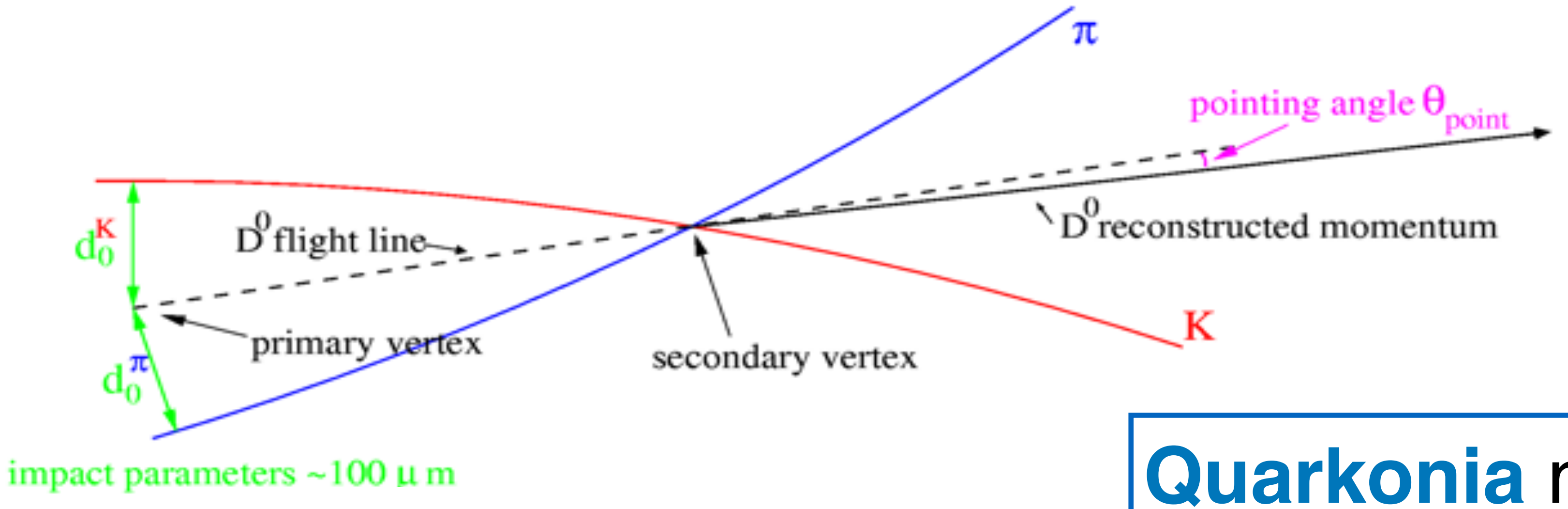
$$v_2 = \langle \cos[2(\varphi - \Psi_2)]\rangle$$

$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$



Open heavy flavour and quarkonia reconstruction





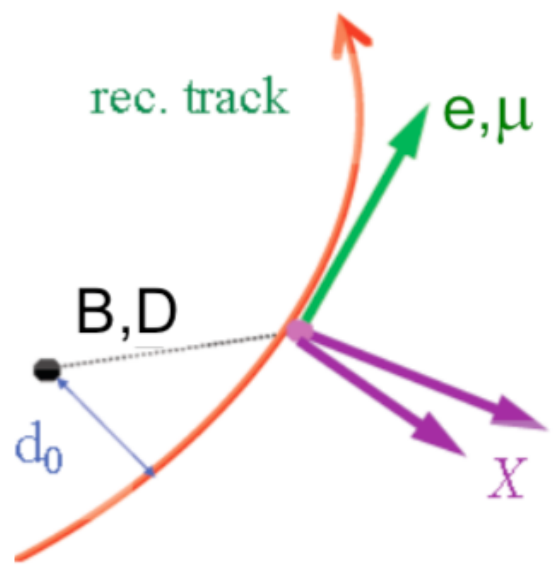
Open Heavy Flavour (HF) via fully reconstructed **D mesons, Λ_c, Ξ_c** hadronic decays: **ITS**, **TPC**, **TOF**

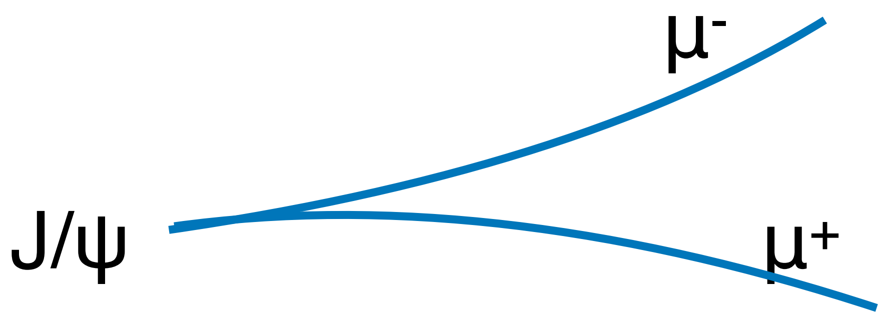
$D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+$, $D_s^+ \rightarrow \Phi\pi^+ \rightarrow K^-K^+\pi^+$, $\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow pK^0_s$, $\Xi^+_c \rightarrow \pi^+K^-p$, $\Xi^0_c \rightarrow \pi^+\Xi^-$

and partially reconstructed **semi-leptonic decays**

Muons: **forward muon spectrometer.** D, B → $\mu^\pm$ + X

Electrons: **ITS**, **TPC**, **TOF, EMCAL, TRD.** D, B → $e^\pm$ + X, and $\Xi_c^0 \rightarrow e^+ + \Xi^-$



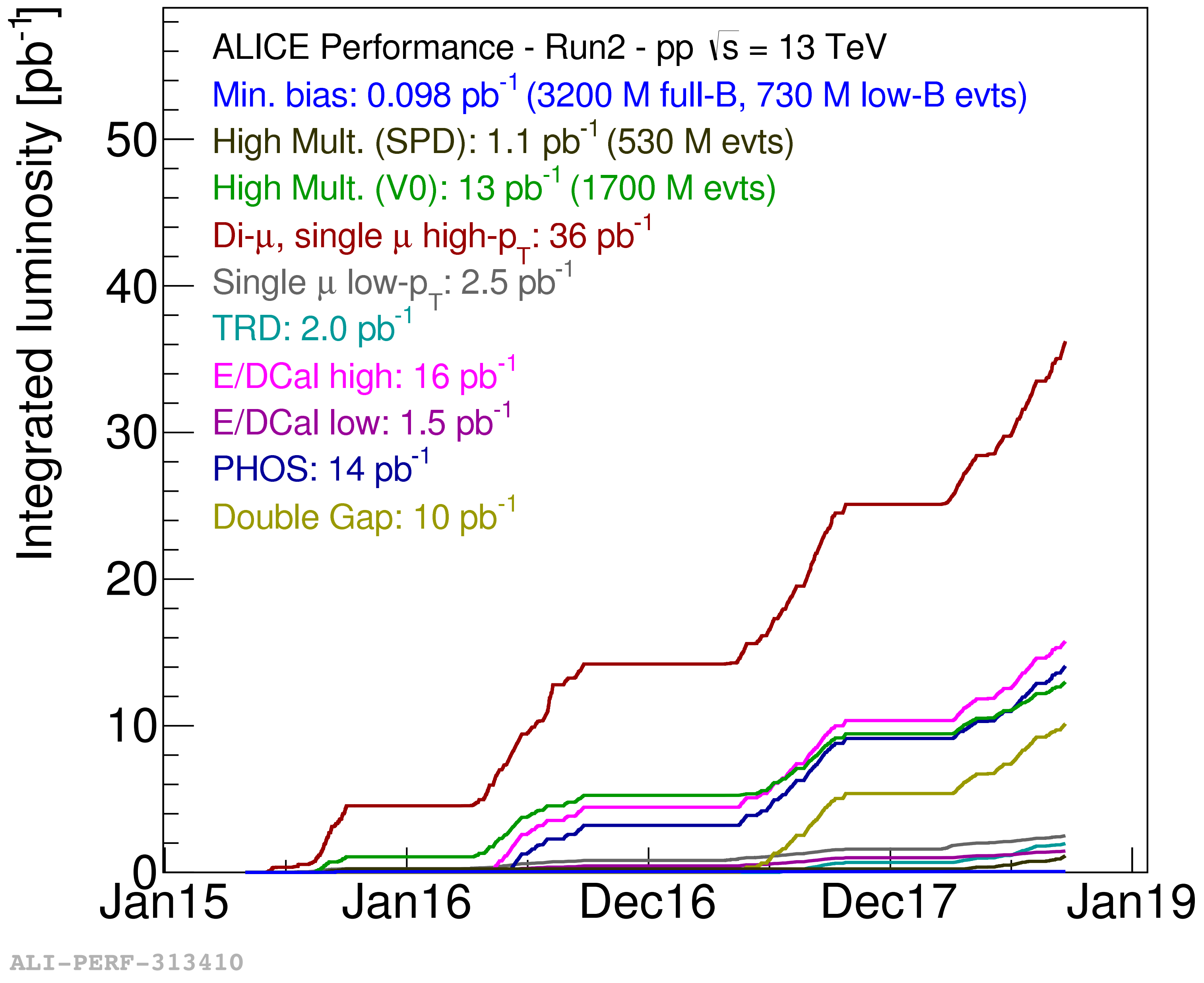


Quarkonia measurement via their dielectron (mid-y) and dimuon (forward-y, only inclusive) decay channels:

$J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$, $\psi(2S) \rightarrow \mu^+\mu^-$

Charm measurements in ALICE

selection of the most recent HF results

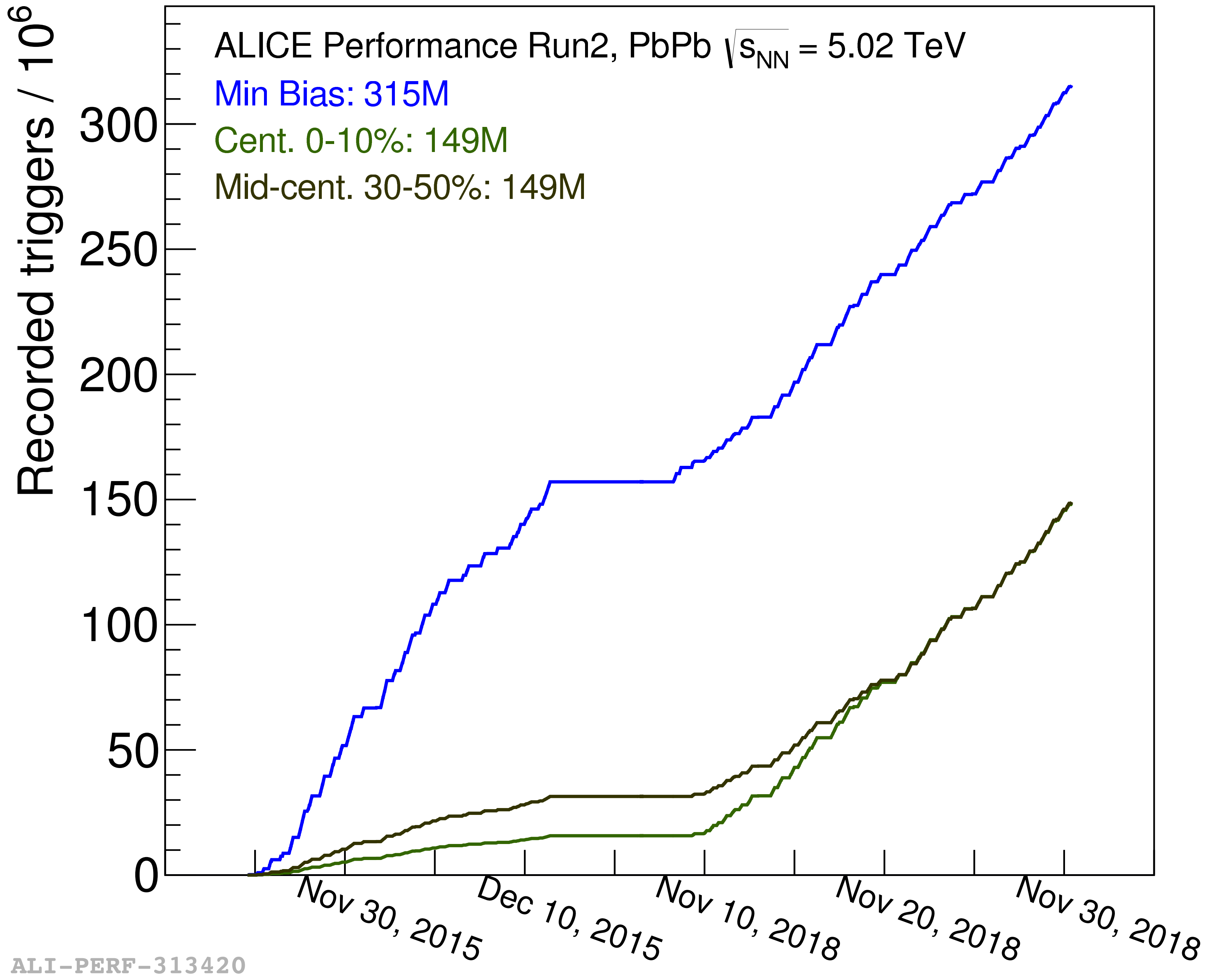


Focusing on :

- **5.02 TeV pp**
- **13 TeV pp**
- **5.02, 8.16 TeV p-Pb**
- **5.02 TeV Pb-Pb**

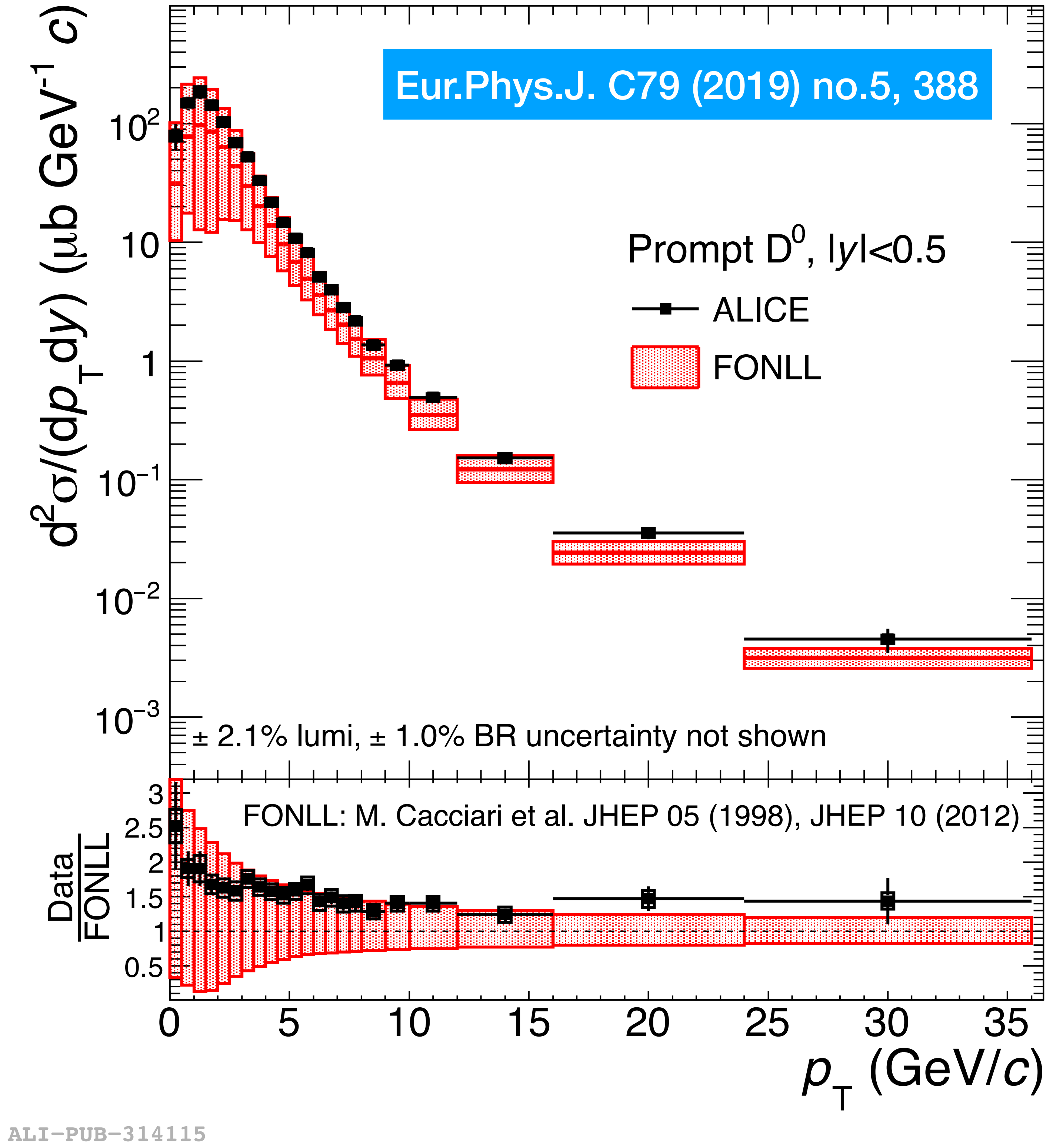
Legend

New	**New preliminary shown at QM 2019**
New	**New preliminary shown at SQM 2019**
New	**New publication**

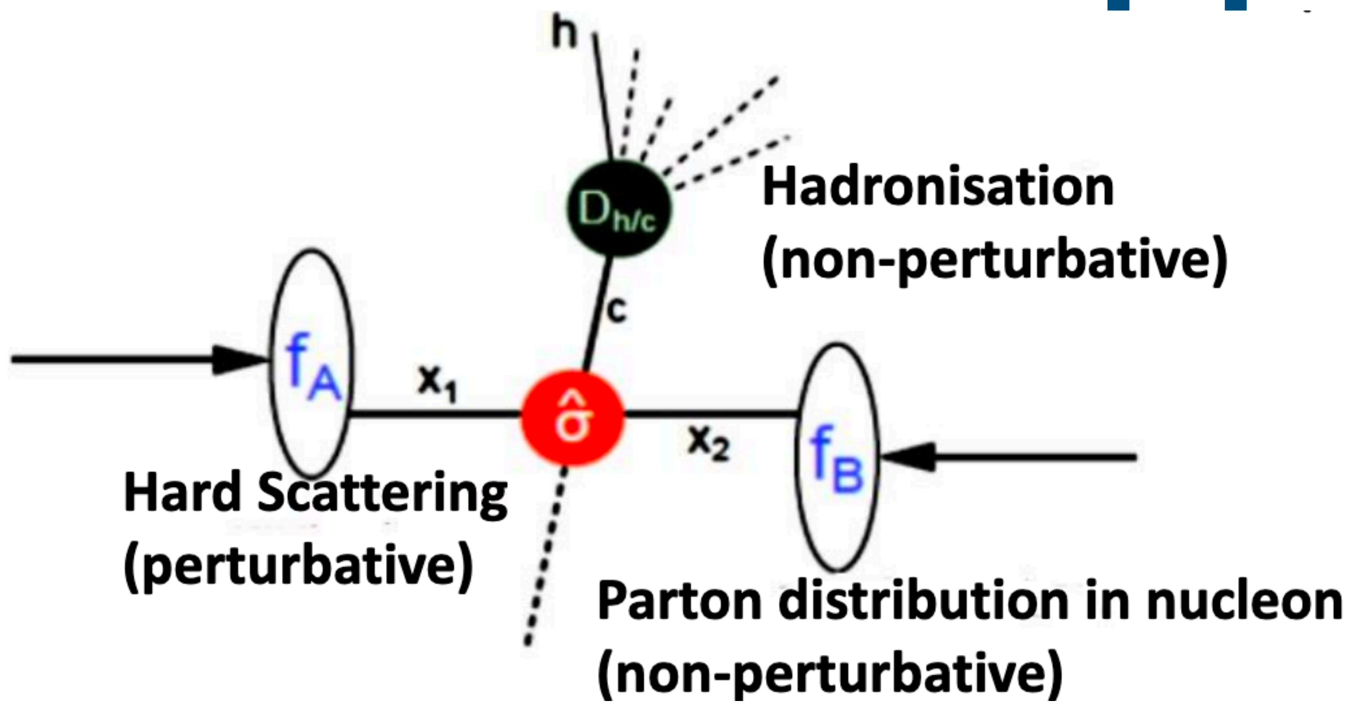


Production cross section of heavy-flavour hadrons

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F)\otimes\frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F)\otimes D_{c\to D}(z=p_D/p_c,\mu_F)$$



D meson, mid rapidity



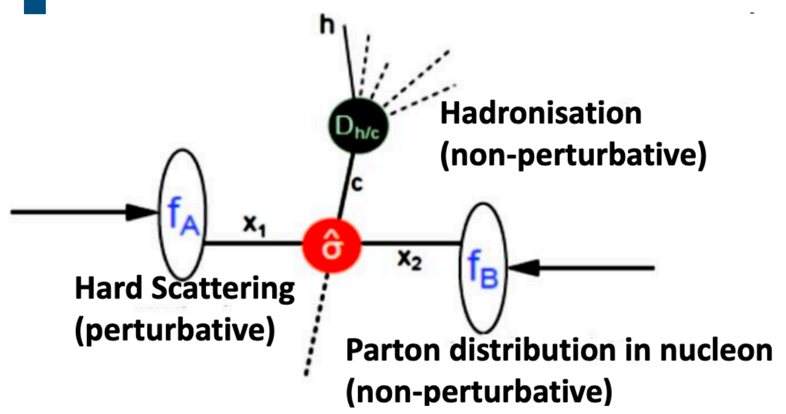
5.02 TeV pp

D-meson production cross section in pp collisions at $\sqrt{s}$= 5.02 TeV at mid rapidity

- precise reference, measured at the same energy in Pb-Pb and p-Pb
- D^0 measured down to $p_T = 0$

Open HF and quarkonia production in pp collisions

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F)\otimes\frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F)\otimes D_{c\to D}(z=p_D/p_c,\mu_F)$$

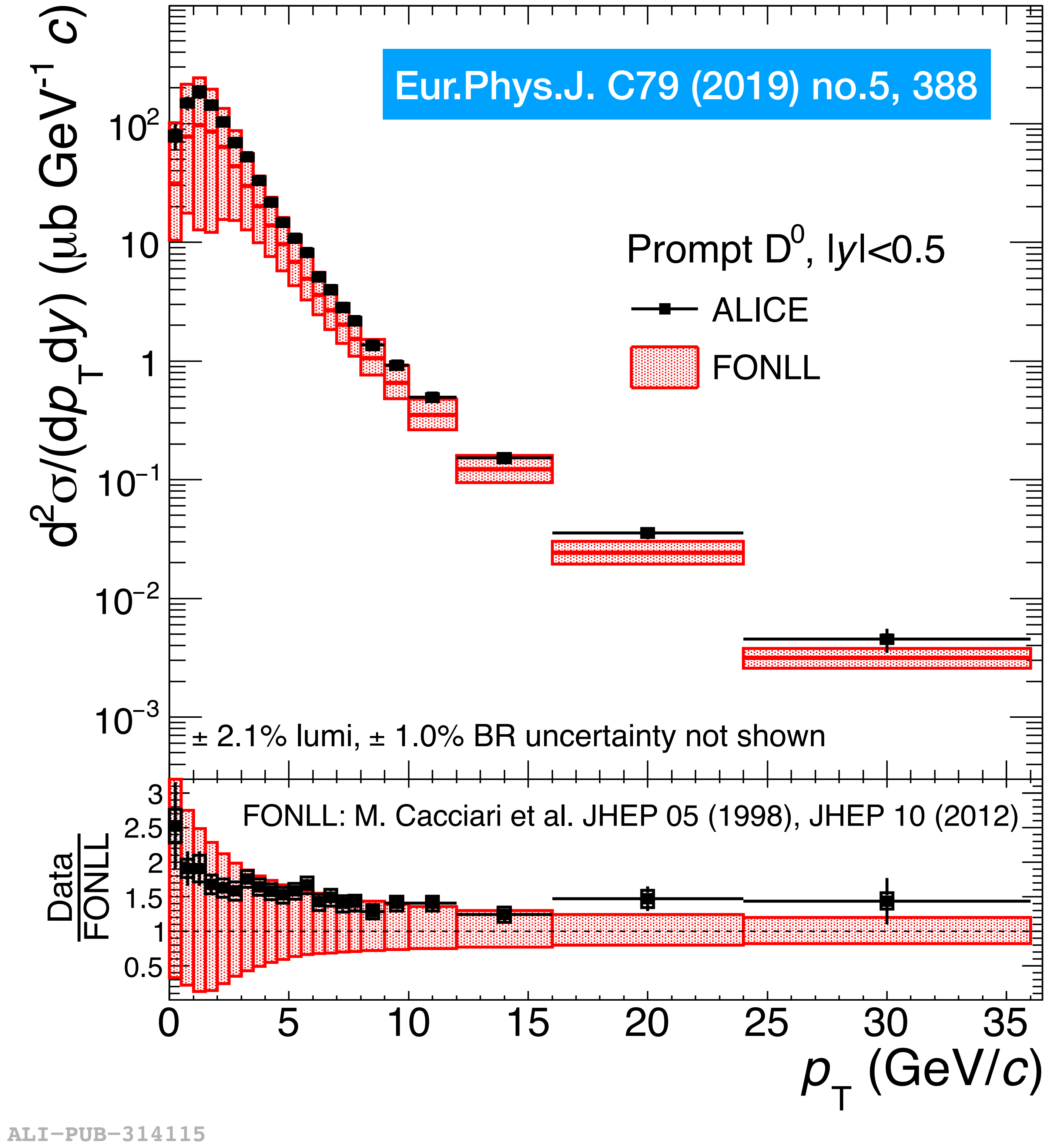


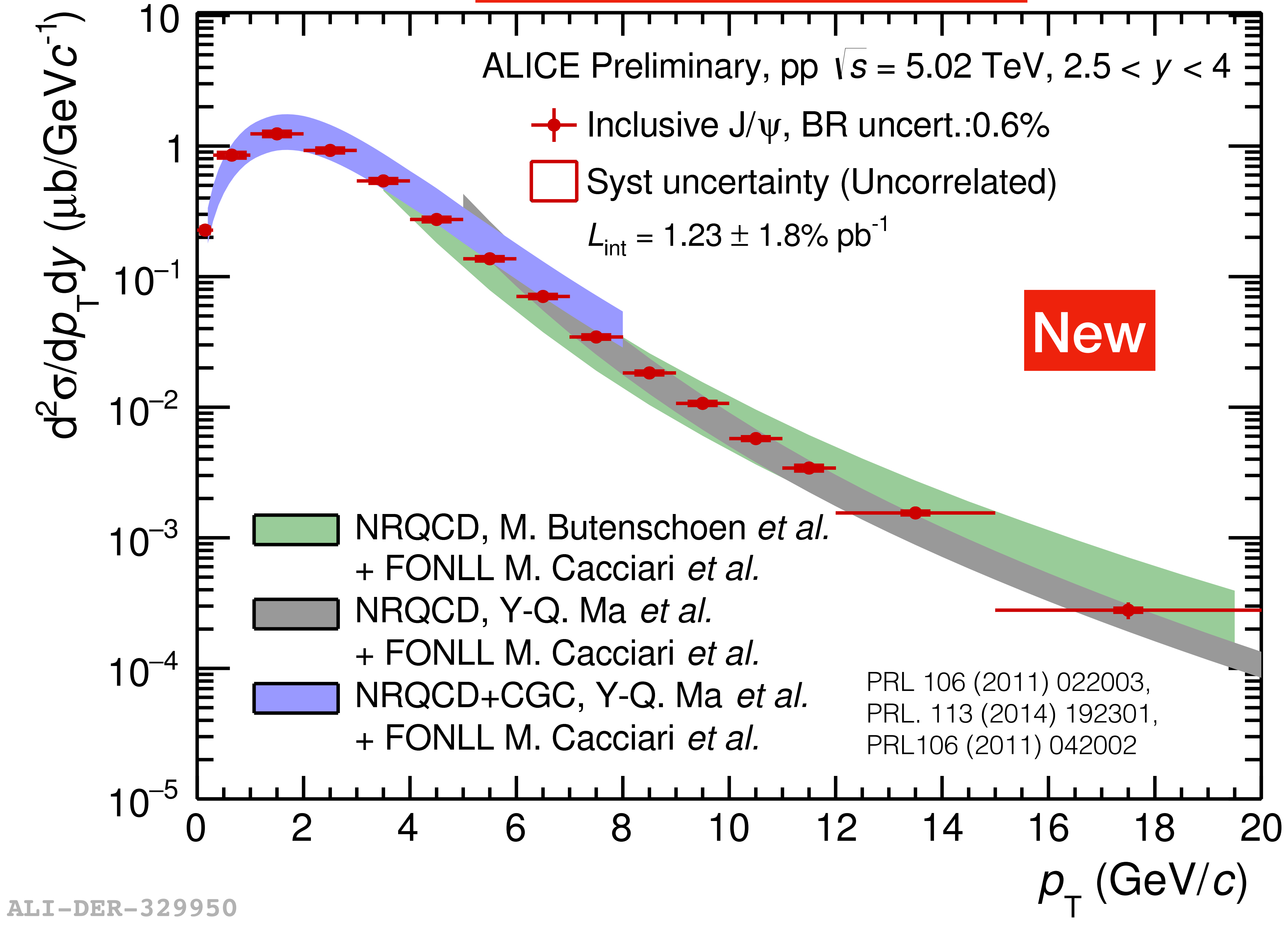
$$d\sigma^Q = f_a(x_a).f_b(x_b)\times d\hat{\sigma}_{ab}^{q\bar{q}}\times\langle O_{q\bar{q}}^Q\rangle$$

D meson, mid rapidity

5.02 TeV pp

J/Ψ, forward rapidity





D-meson production cross section in pp collisions at $\sqrt{s}$= 5.02 TeV at mid rapidity

- precise reference, measured at the same energy in Pb-Pb and p-Pb
- D^0 measured down to $p_T = 0$

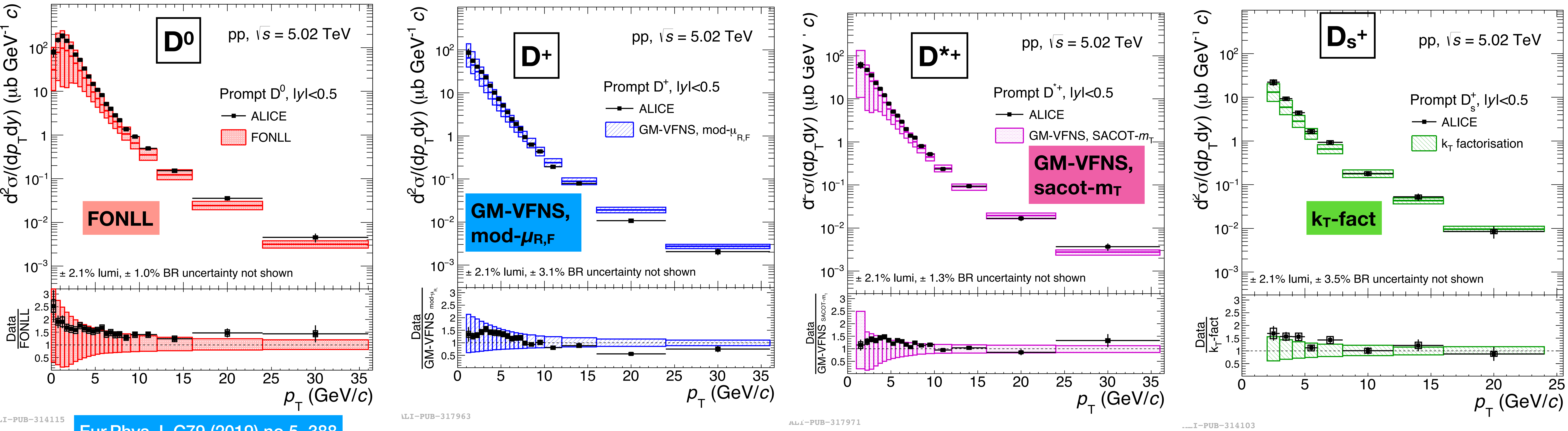
Inclusive (prompt and non-prompt) J/Ψ production cross section in pp collisions at $\sqrt{s}$= 5.02 TeV at forward rapidity

- precise reference, measured at the same energy in Pb-Pb and p-Pb
- measured down to $p_T = 0$
- well described by NRQCD+FONLL

D-meson production in pp collisions

Not only reference for Pb-Pb and p-Pb: perturbative-QCD test

$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_{T};\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$



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- **Systematic comparison with several pQCD calculations** with different schemes: agreement within uncertainties
- **Data: smaller uncertainties than theoretical ones:**
  - dominated by factorisation and renormalisation scales of the perturbative calculations

D-meson production in pp collisions

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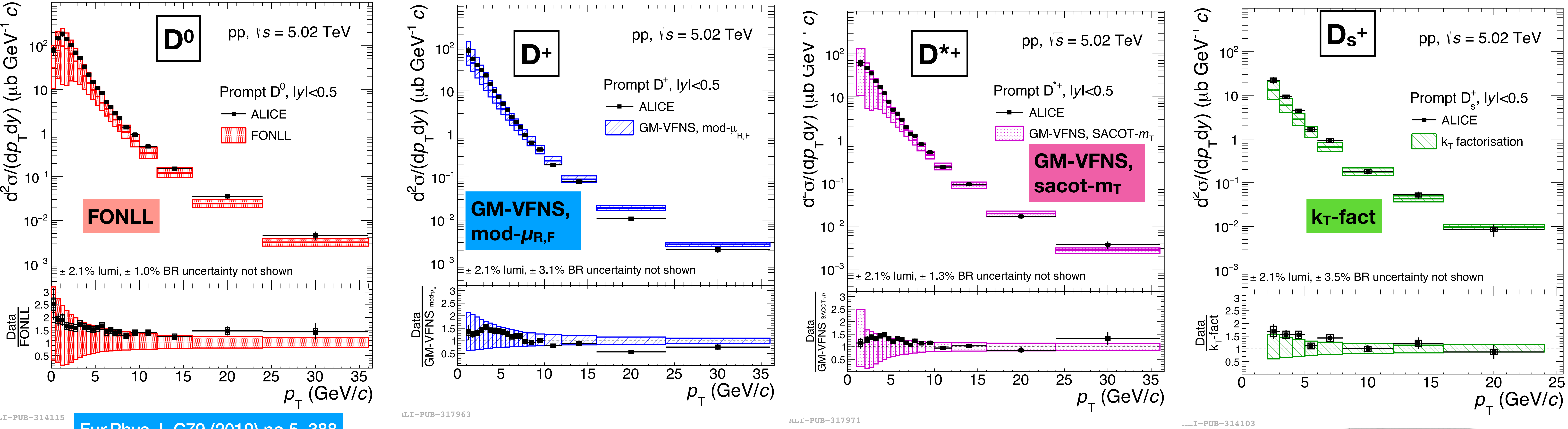
$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_{T};\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F)\otimes\frac{d\sigma^{c}}{dp_{T}^{c}}(x_1,x_2,\mu_R,\mu_F)\otimes D_{c\to D}(z=p_{D}/p_{c},\mu_F)$$



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- **Systematic comparison with several pQCD calculations** with different schemes: agreeme
- **Data: smaller uncertainties than theoretical ones:**
  - dominated by factorisation and renormalisation scales of the perturbative calculations

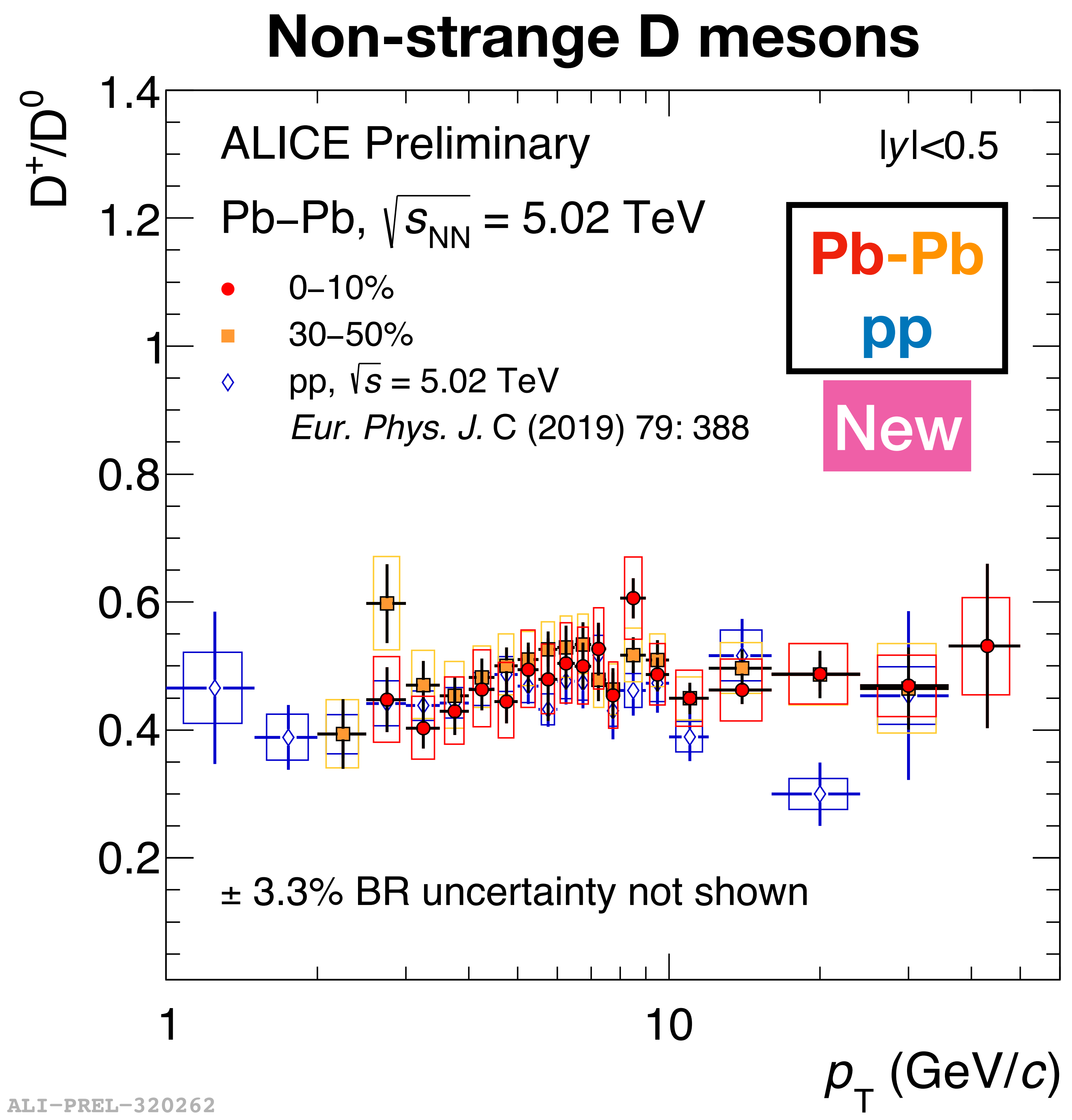
important measurement to constrain theoretical calculations and fundamental input for models to describe kinematics modification in the QGP

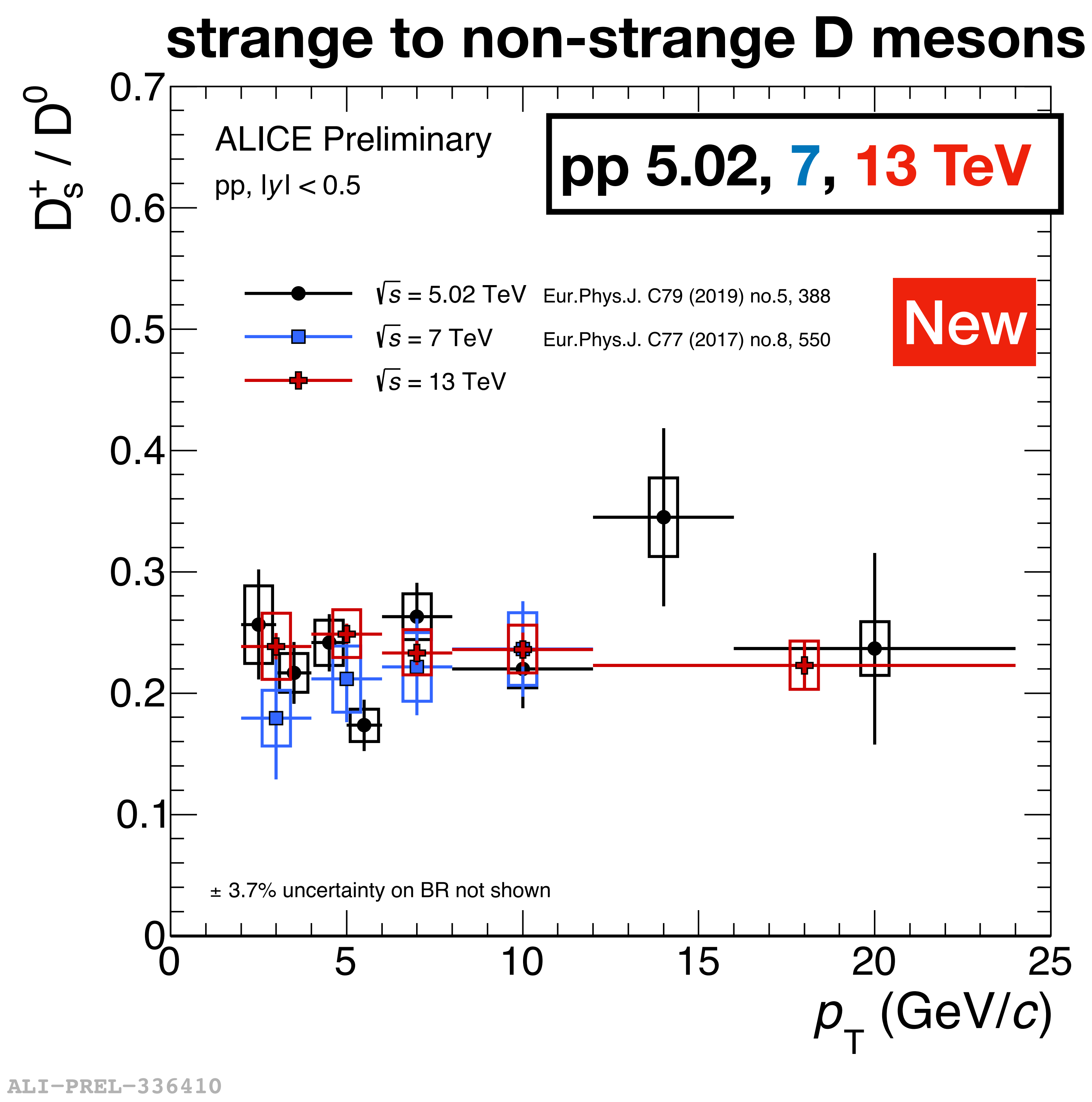
Particle ratios and hadronization mechanisms

D-meson ratios in different systems

$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_{T};\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

Sensitive to **ratio of Fragmentation Functions** for different hadronisation of charm quark



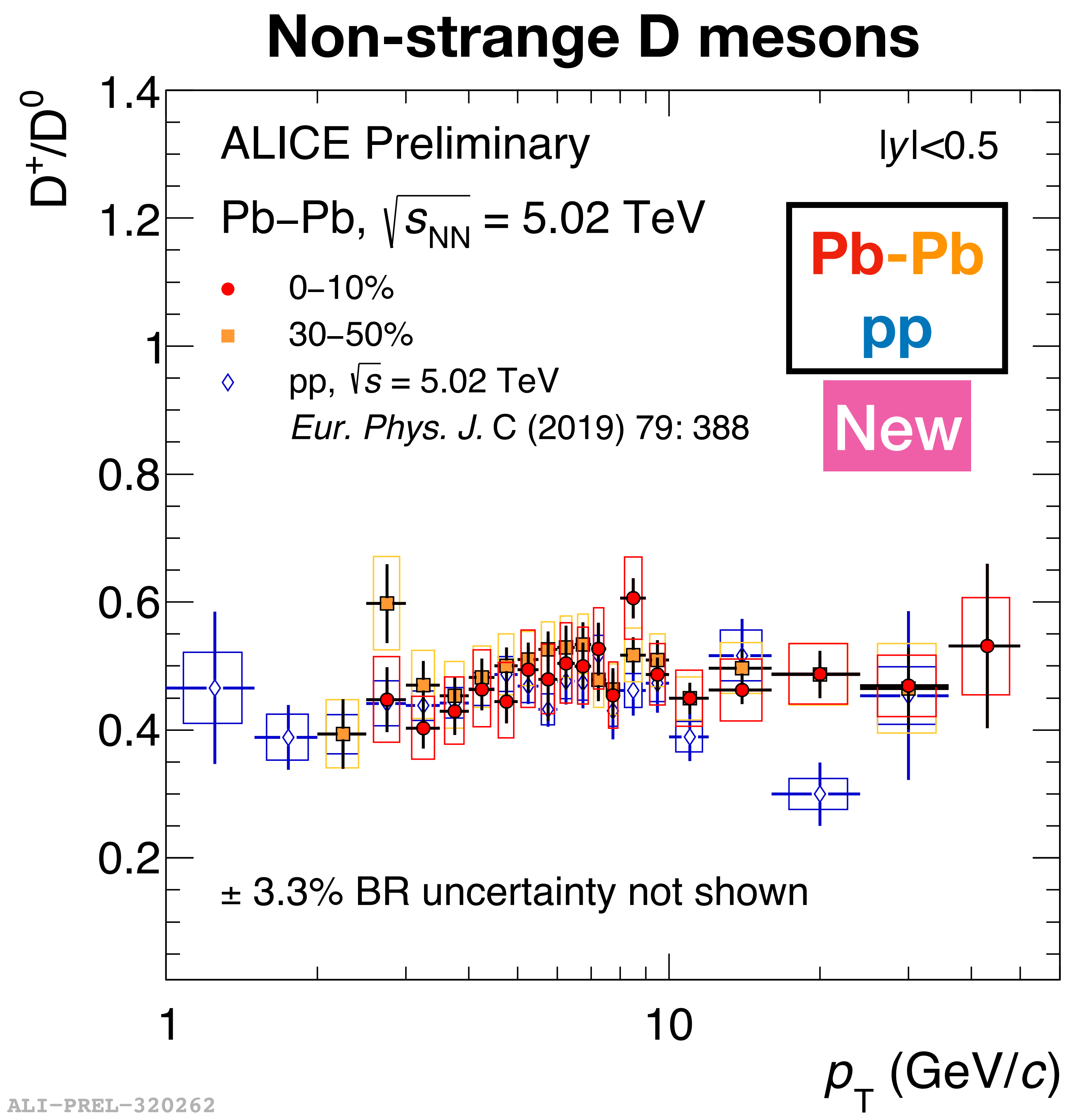


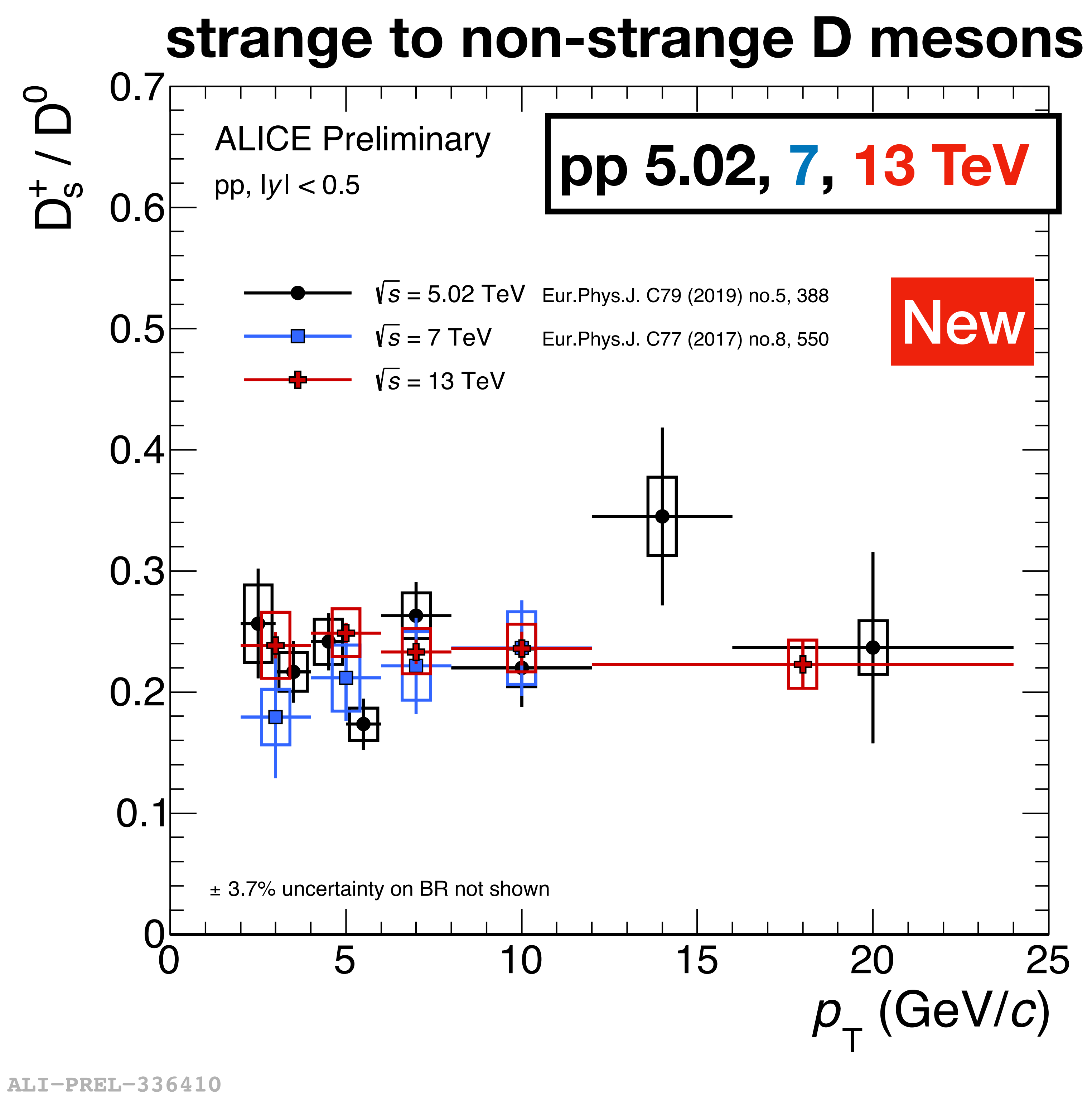
- Relative abundances of D-meson-specie ratios in different **collision systems and energies**
- Consistent with ratios measured in e^+e^- and ep collisions **Gladilin, EPJ C75 (2015) 19**
  - no dependency on **collision systems**
- **Universality of D-meson Fragmentation Functions**

D-meson ratios in different systems

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

Sensitive to **ratio of Fragmentation Functions** for different hadronisation of charm quark





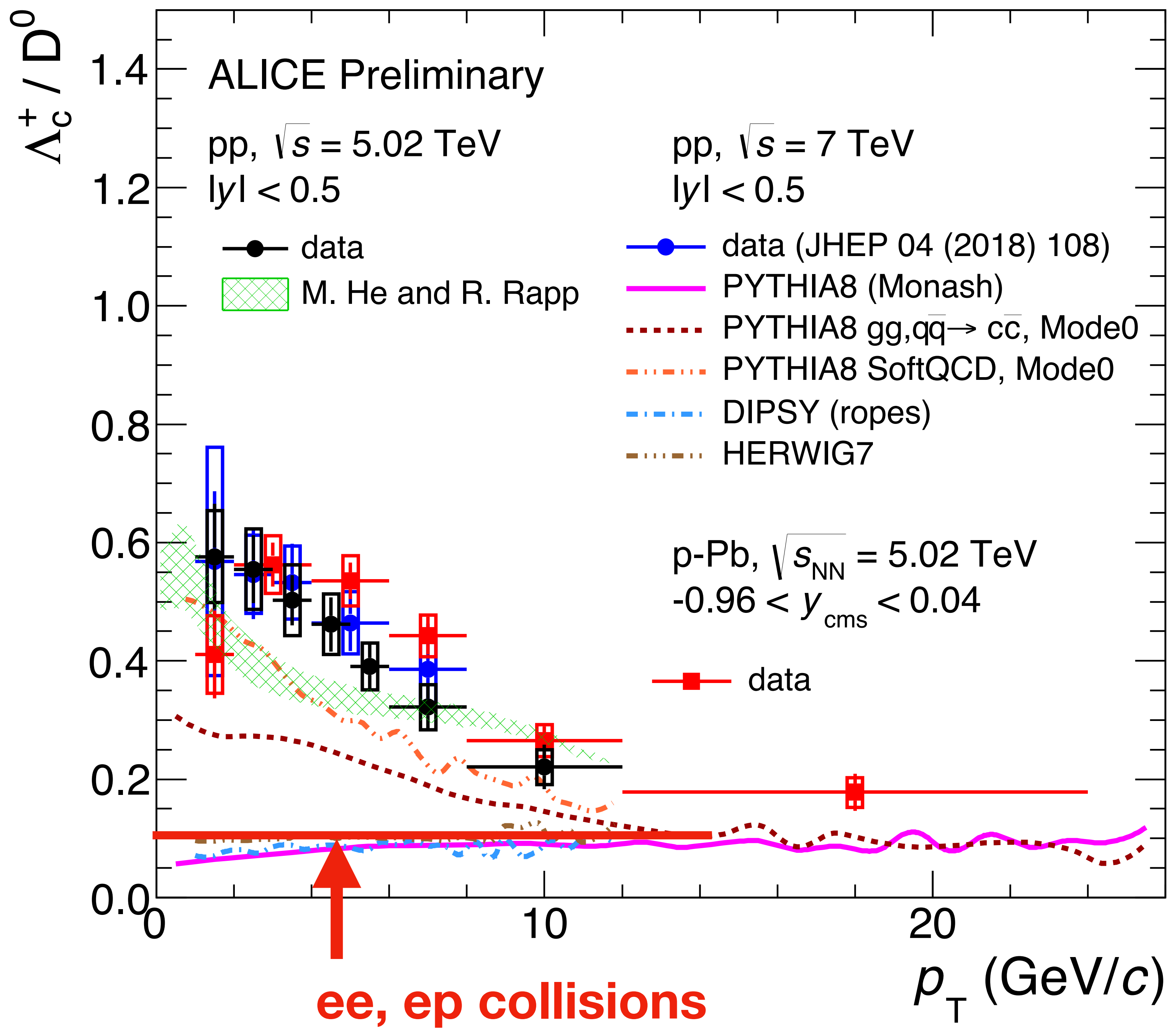
- Relative abundances of D-meson-specie ratios in different **collision systems and energies**
- Consistent with ratios measured in e^+e^- and ep collisions Gladilin, EPJ C75 (2015) 19
  - no dependency on **collision systems**
- **Universality of D-meson Fragmentation Functions**

D-meson ratios flat vs p_T and independent on the collision energy and collision system

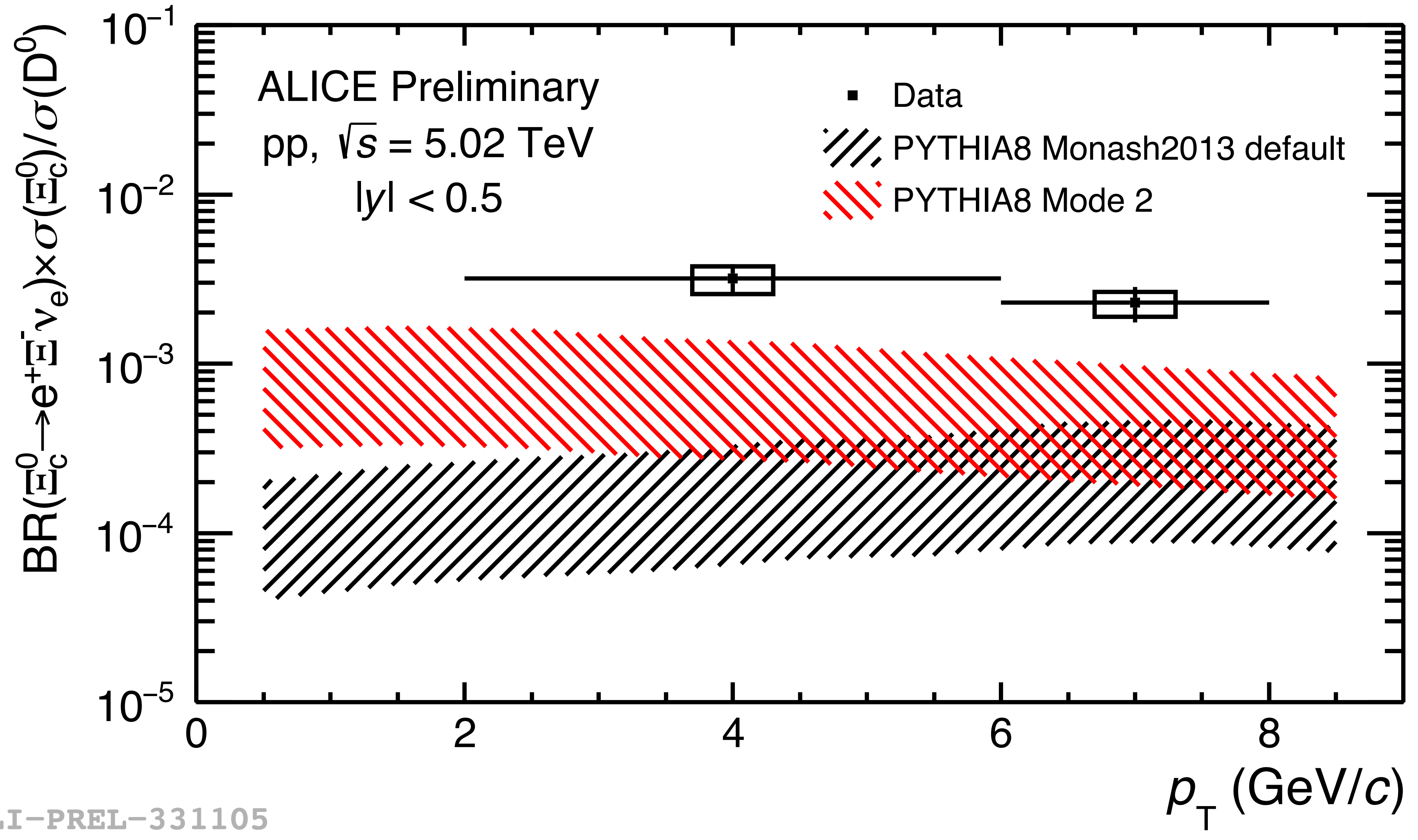
Baryon-to meson ratios in pp collisions

Λ_c/D^0

[1] J.R. Christiansen, P. Skands: JHEP 1508 (2015) 003
[2] M.He, R. Rapp: Phys.Lett. B795 (2019) 117-121



Ξ_c/D^0 New



- **Λ_c/D^0 in pp higher than in e^+e^- and ep collisions, and models tend to underestimate the ratios**
- **Also Ξ_c/D^0 ratio underestimated** by theoretical calculations
  - **Universality of charmed baryon Fragmentation Functions broken?**

Colour reconnection [1] with string formation beyond leading colour approximation (enhanced CR mechanisms with 3-leg junctions), and Statistical Hadronization Model (SHM) with **increased number of higher-mass baryon states** [2] among possible explanations for the enhancement

baryon-over-meson ratios: System dependent?

Baryon-to meson ratios in pp collisions

Λ_c/D^0 [1] J.R. Christiansen, P. Skands: JHEP 1508 (2015) 003
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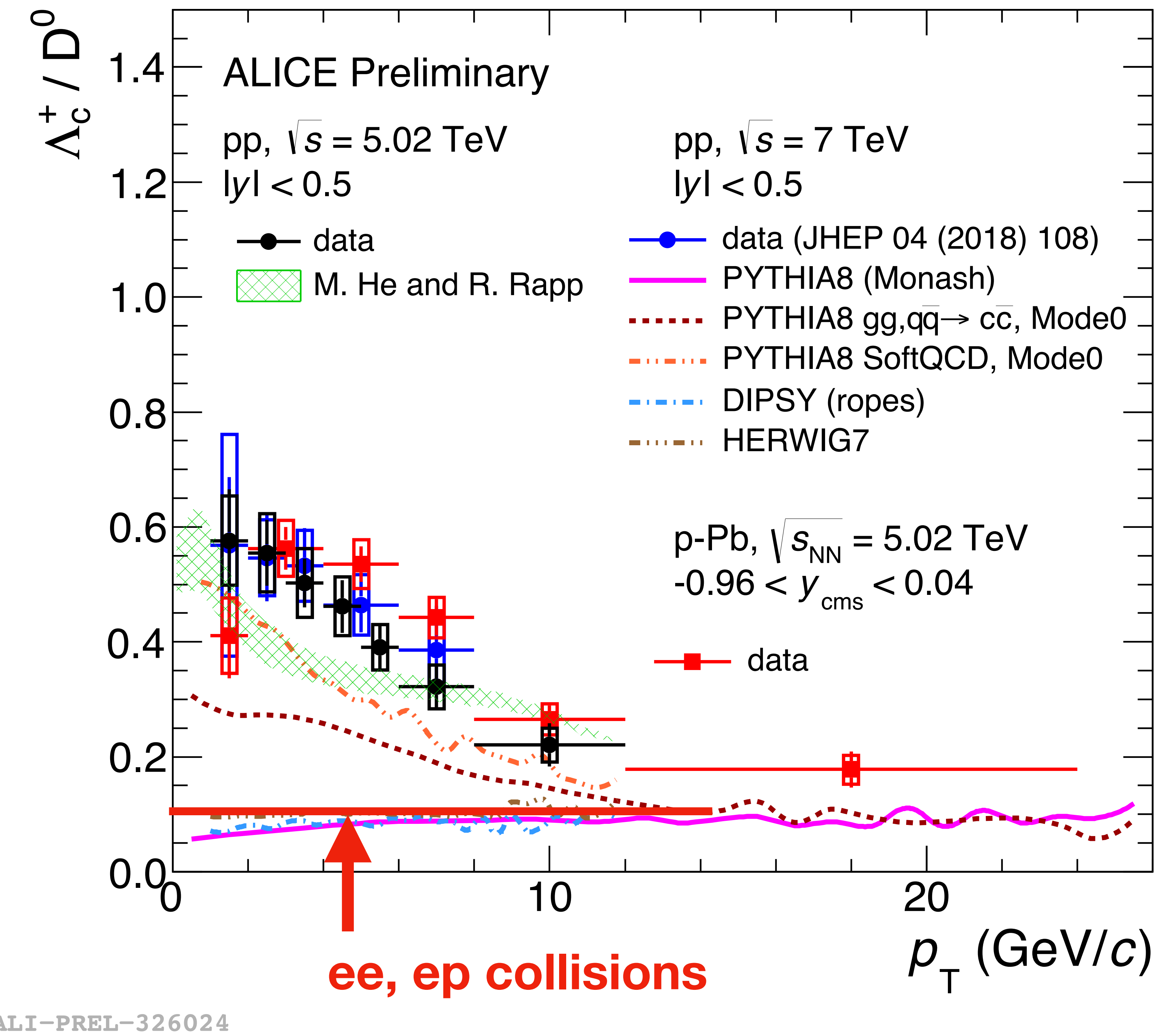
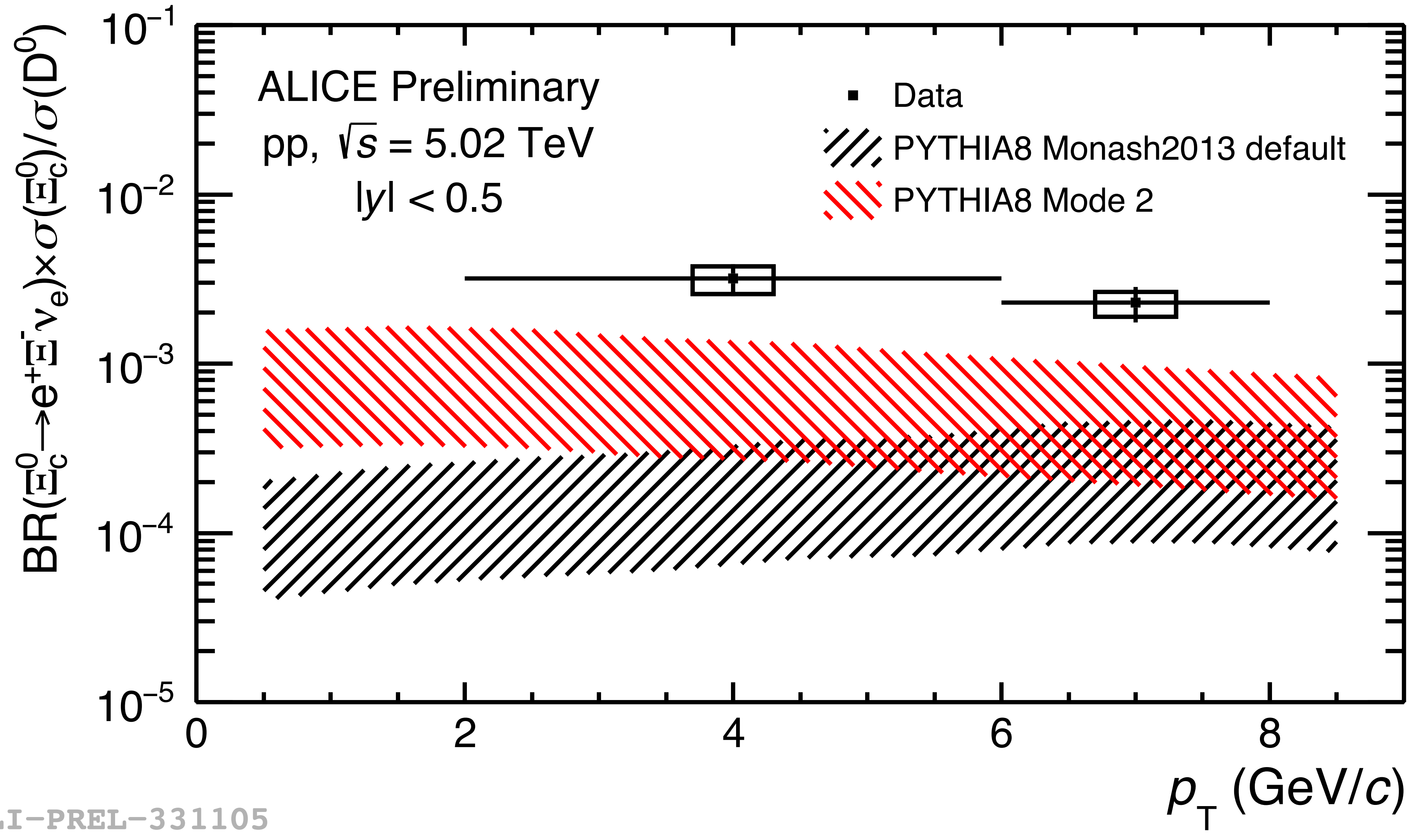
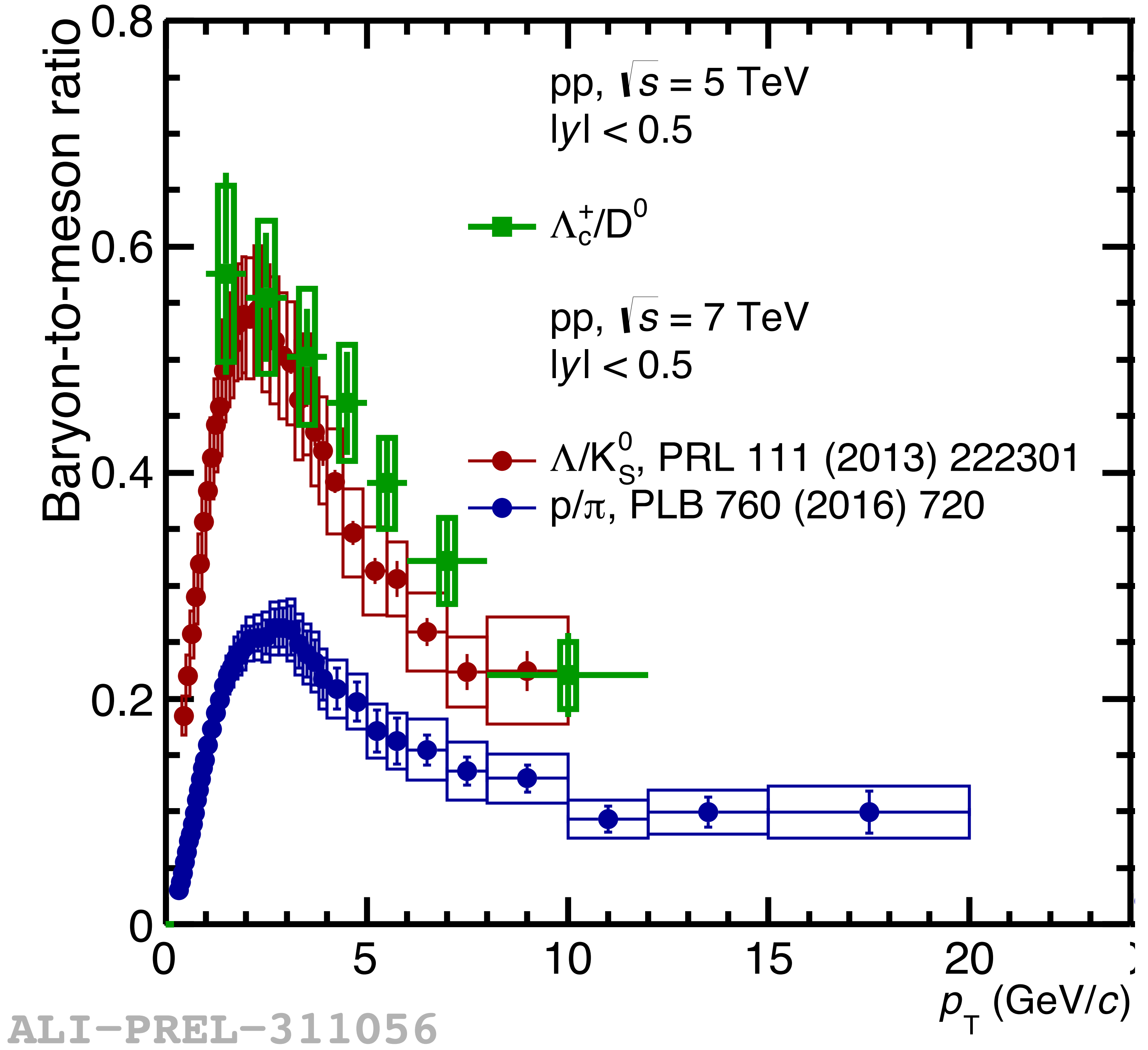


Ξ_c/D^0 New

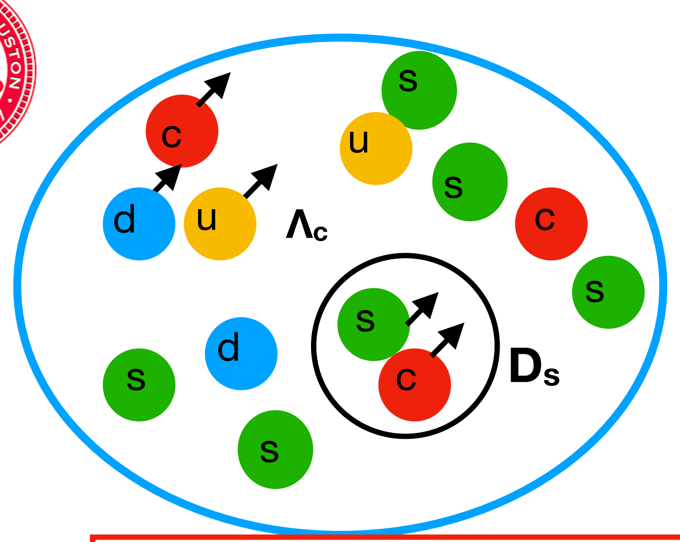


Λ_c/D^0 vs Λ/K^0_s



- **Λ_c/D^0 in pp higher than in e^+e^- and ep collisions, and models tend to underestimate the ratios**
- **Also Ξ_c/D^0 ratio underestimated** by theoretical calculations
  - **Universality of charmed baryon Fragmentation Functions broken?**
- **Similar trend of baryon-to-meson ratio in Light and Heavy Flavour sector:**
  - HF sector hadronisation is quite different due to the hard scale (the c/b quark produced in the hard scattering not in the fragmentation)

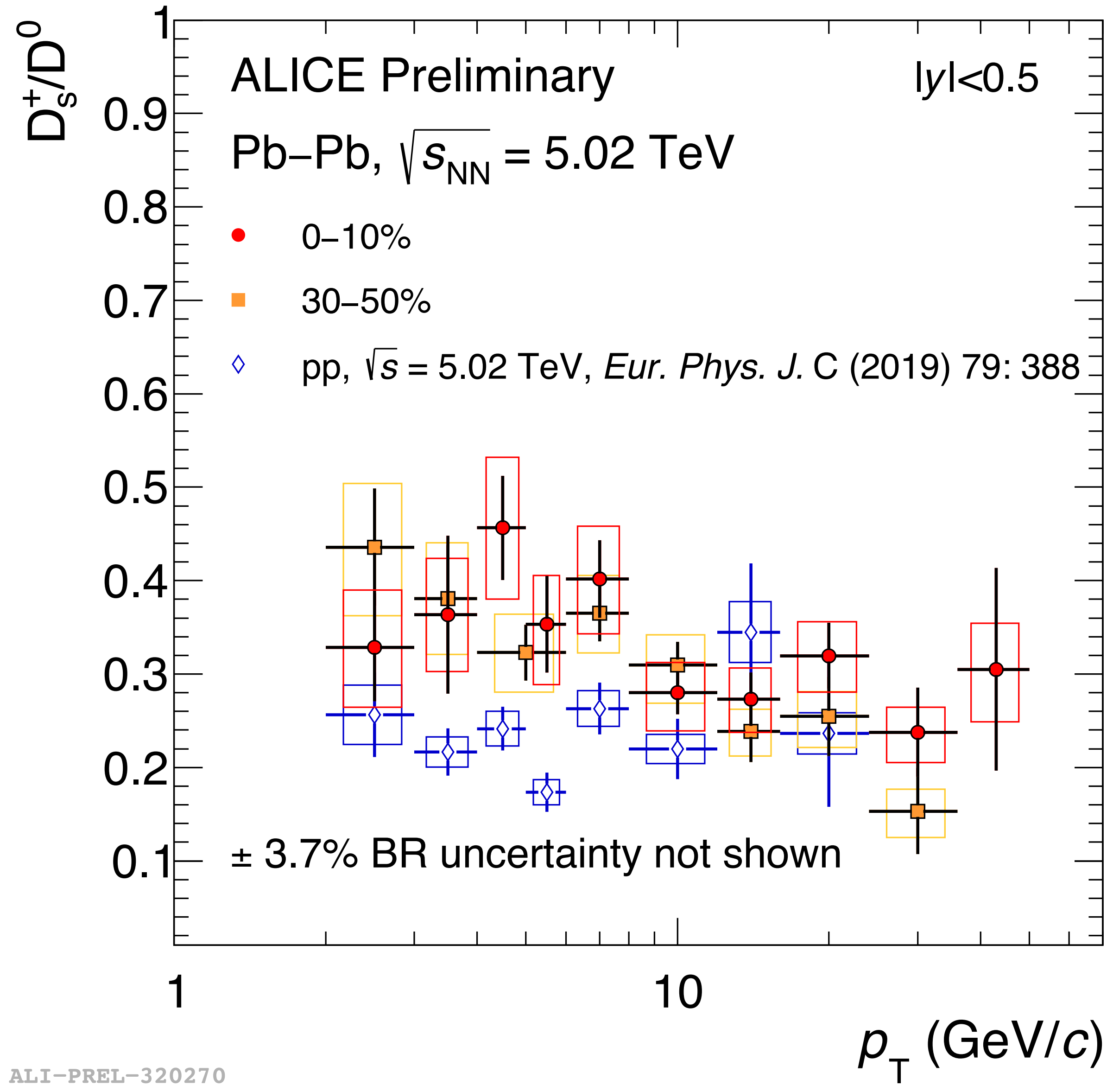
Strangeness enhancement



If coalescence plays a role, in Pb-Pb collisions, enhanced D_s over non-strange D mesons

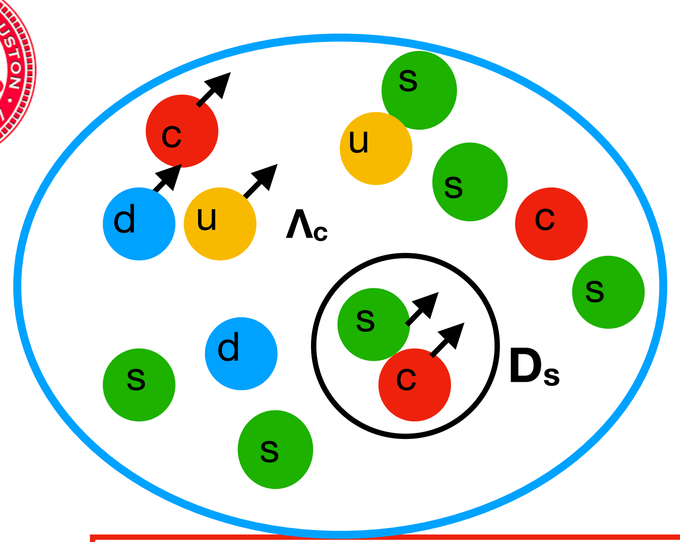
Strange - non Strange D Mesons

D_s/D^0 in Pb-Pb, pp New



- Hint of enhanced D_s/D^0 ratio at low, intermediate p_T in **Pb-Pb** with respect to **pp** collisions, measured at the same energy
- compatible measurements at high p_T

Strangeness enhancement



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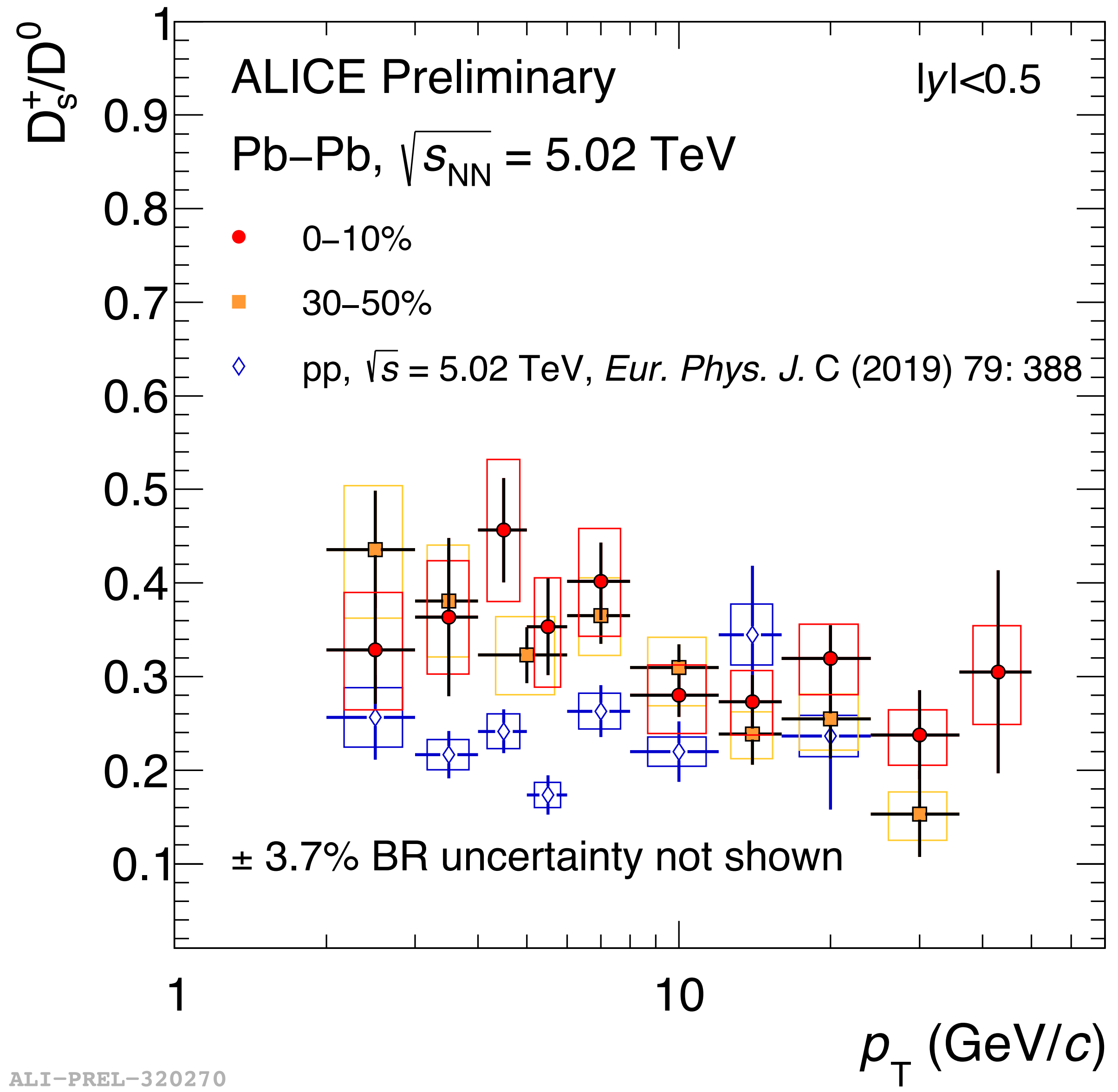
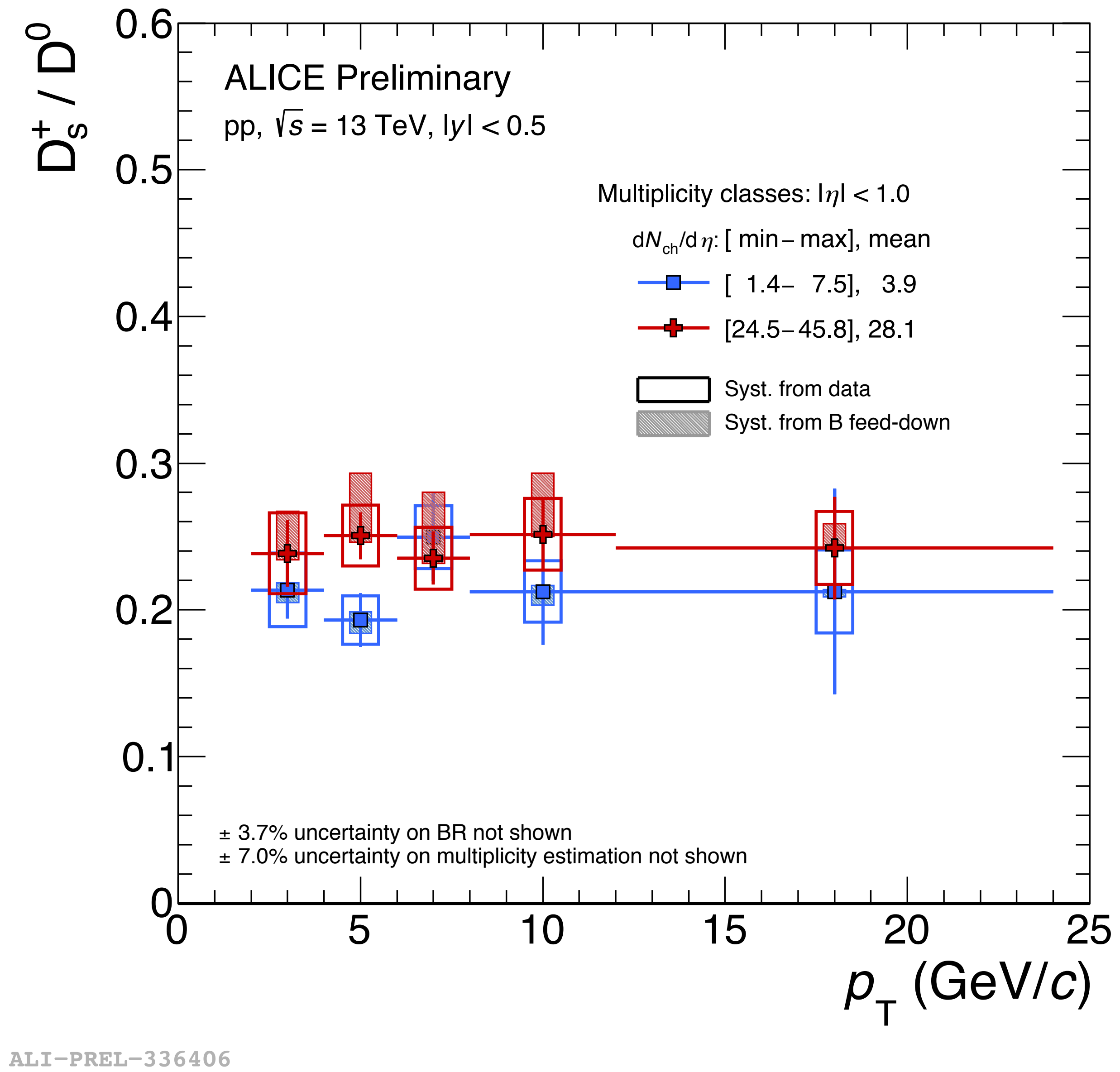
More differential Measurements: pp vs multiplicity New





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pp@13TeV, large statistics, more differential measurements: compatible ratios in pp at **high** multiplicity wrt **low** multiplicity.

$dN_{ch}/d\eta$ = 3.9
$dN_{ch}/d\eta$ = 28.1
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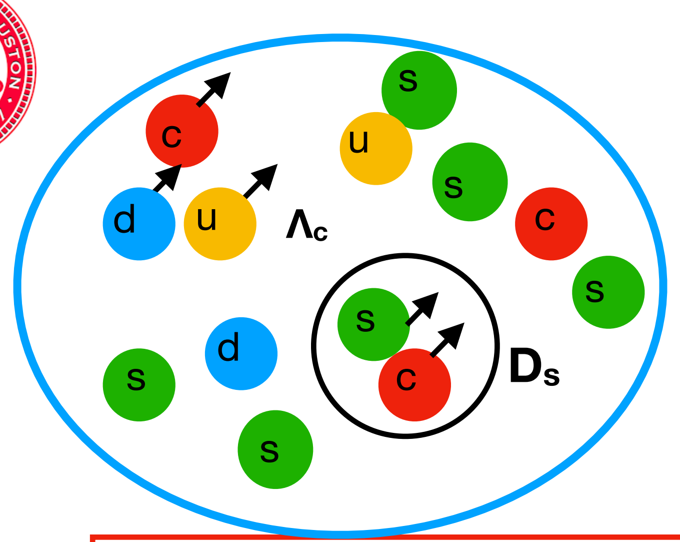
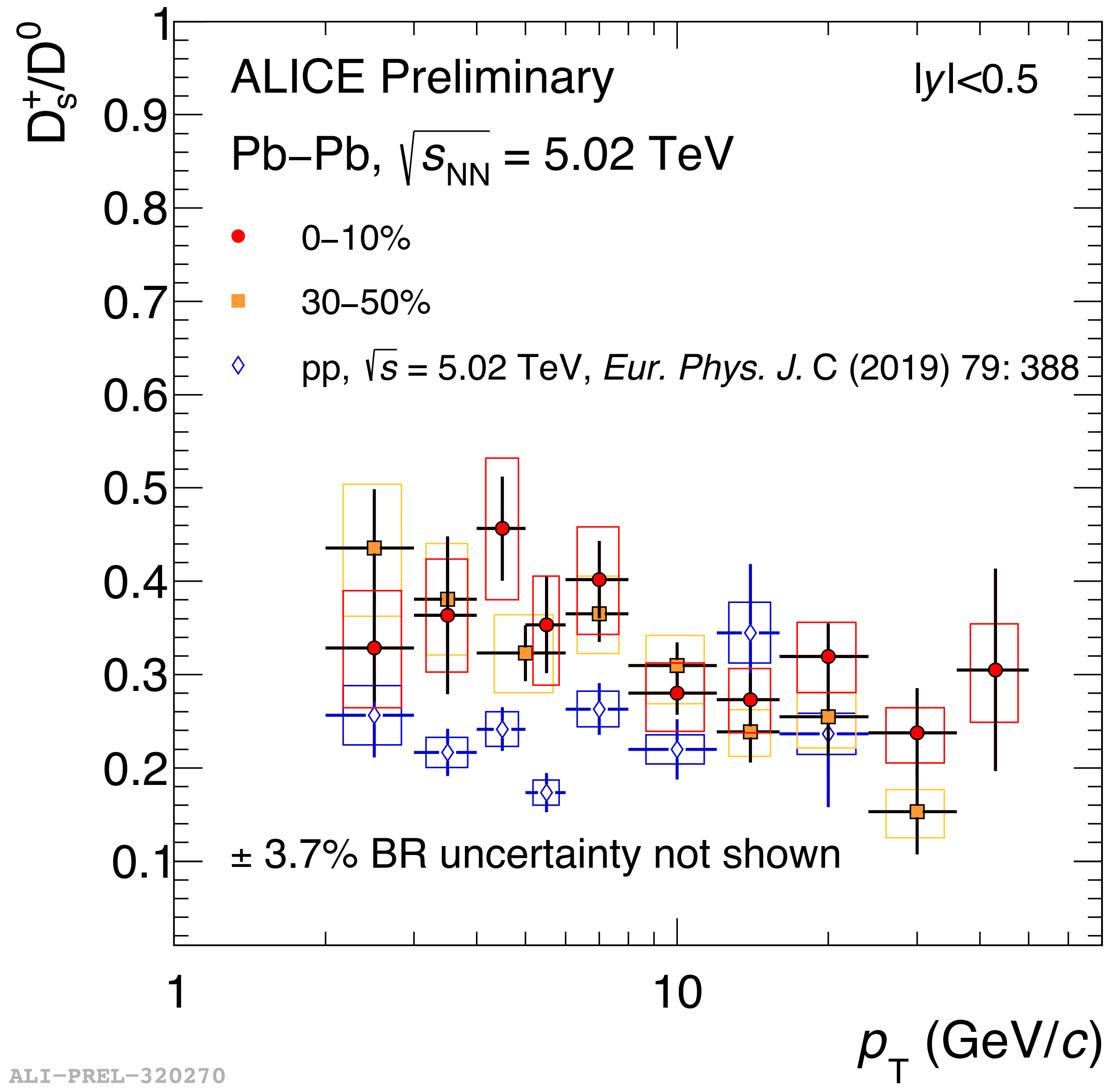


If coalescence plays a role, in Pb-Pb collisions, enhanced Ds over non-strange D mesons and enhanced baryon-over-meson ratios are expected with respect to pp collisions

Strange - non Strange D Mesons —> Charmed Baryons

D_s/D^0 in Pb-Pb, pp New



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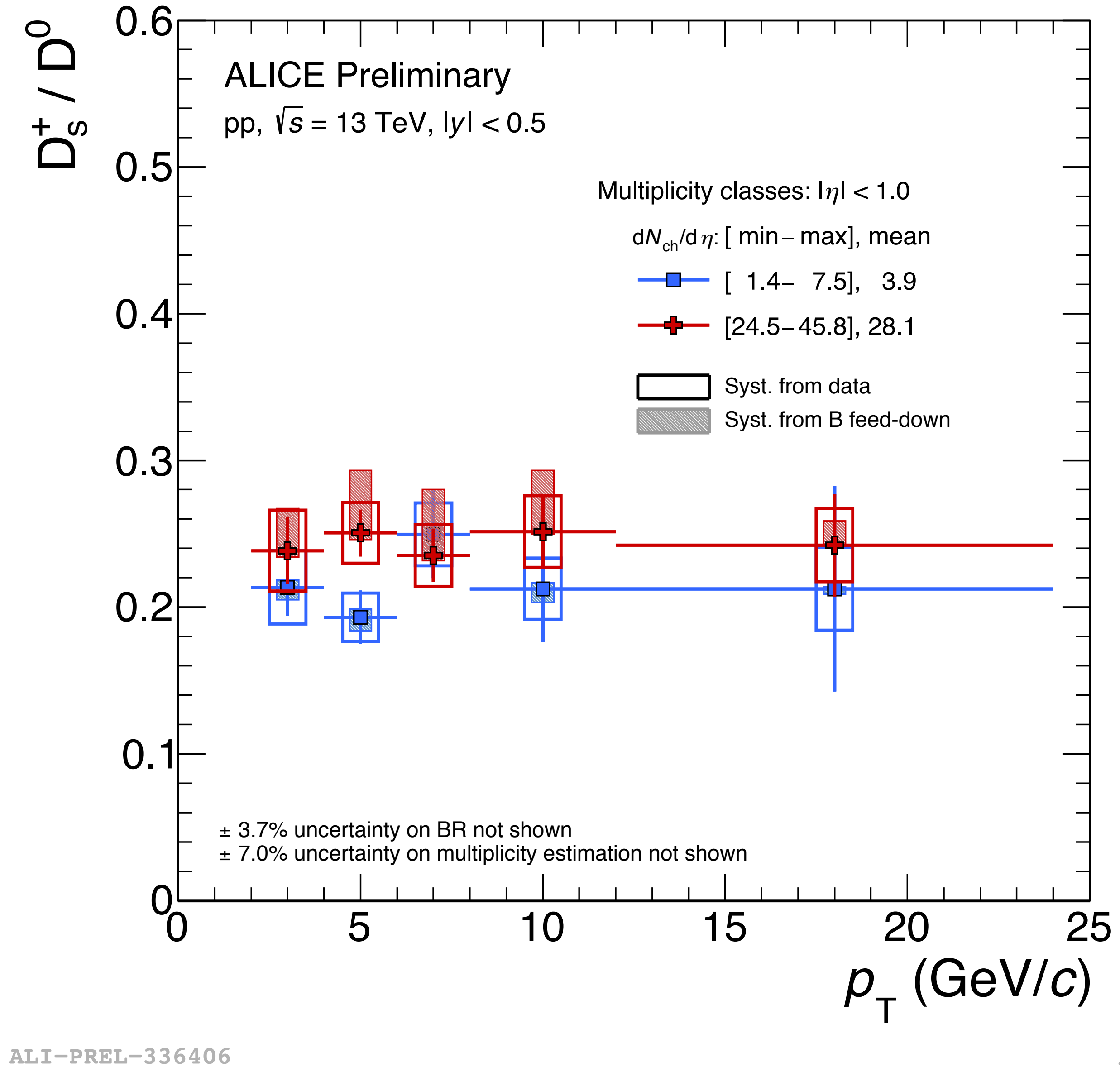
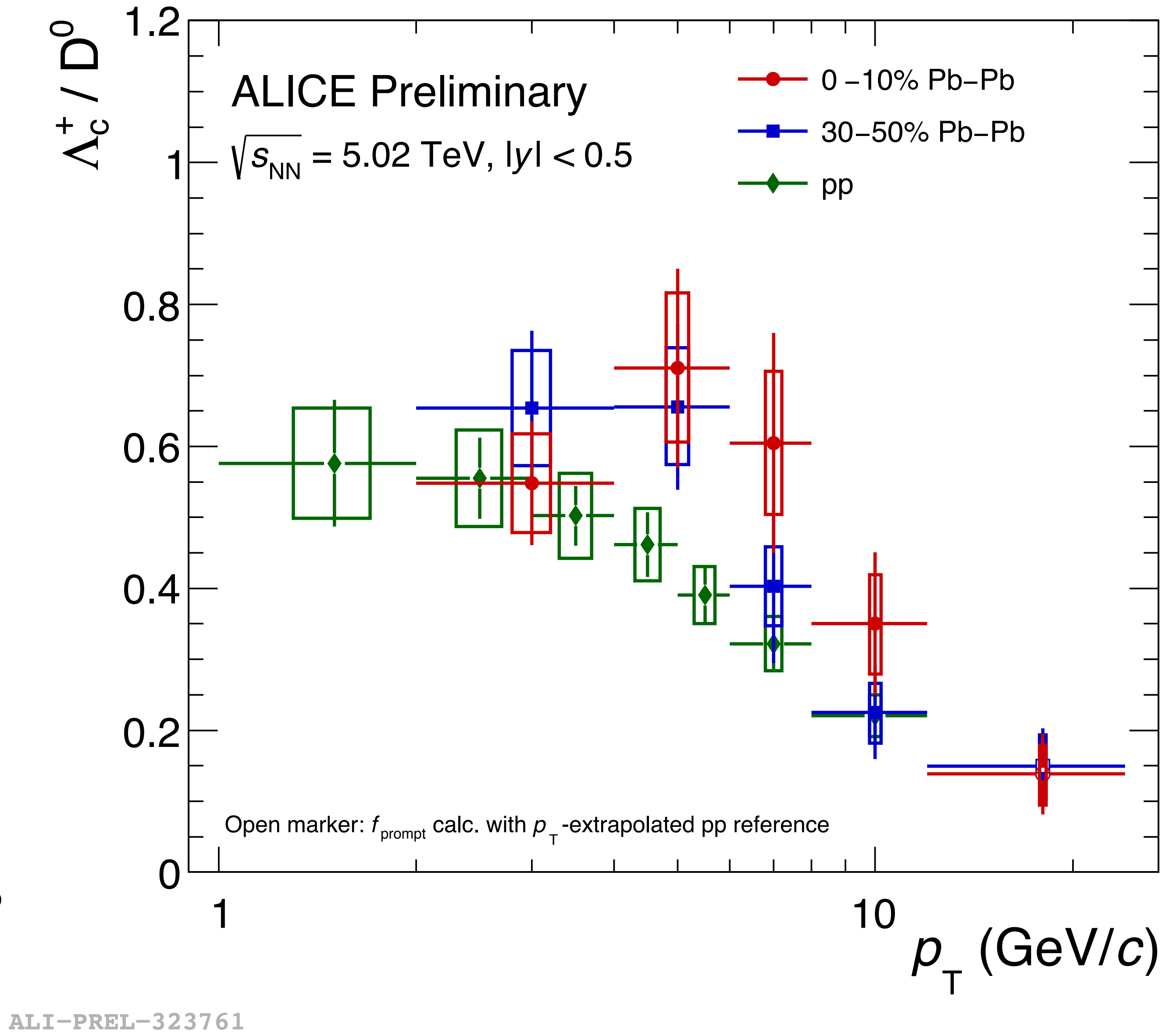


Λ_c/D^0 in Pb-Pb, pp New



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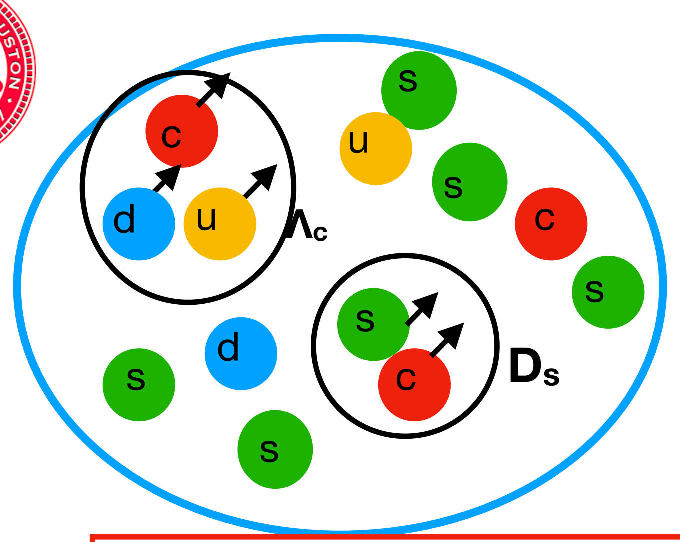
Λ_c/D^0 in **Pb-Pb** enhanced at low p_T wrt **minimum bias pp,** at the same energy.

Strangeness enhancement



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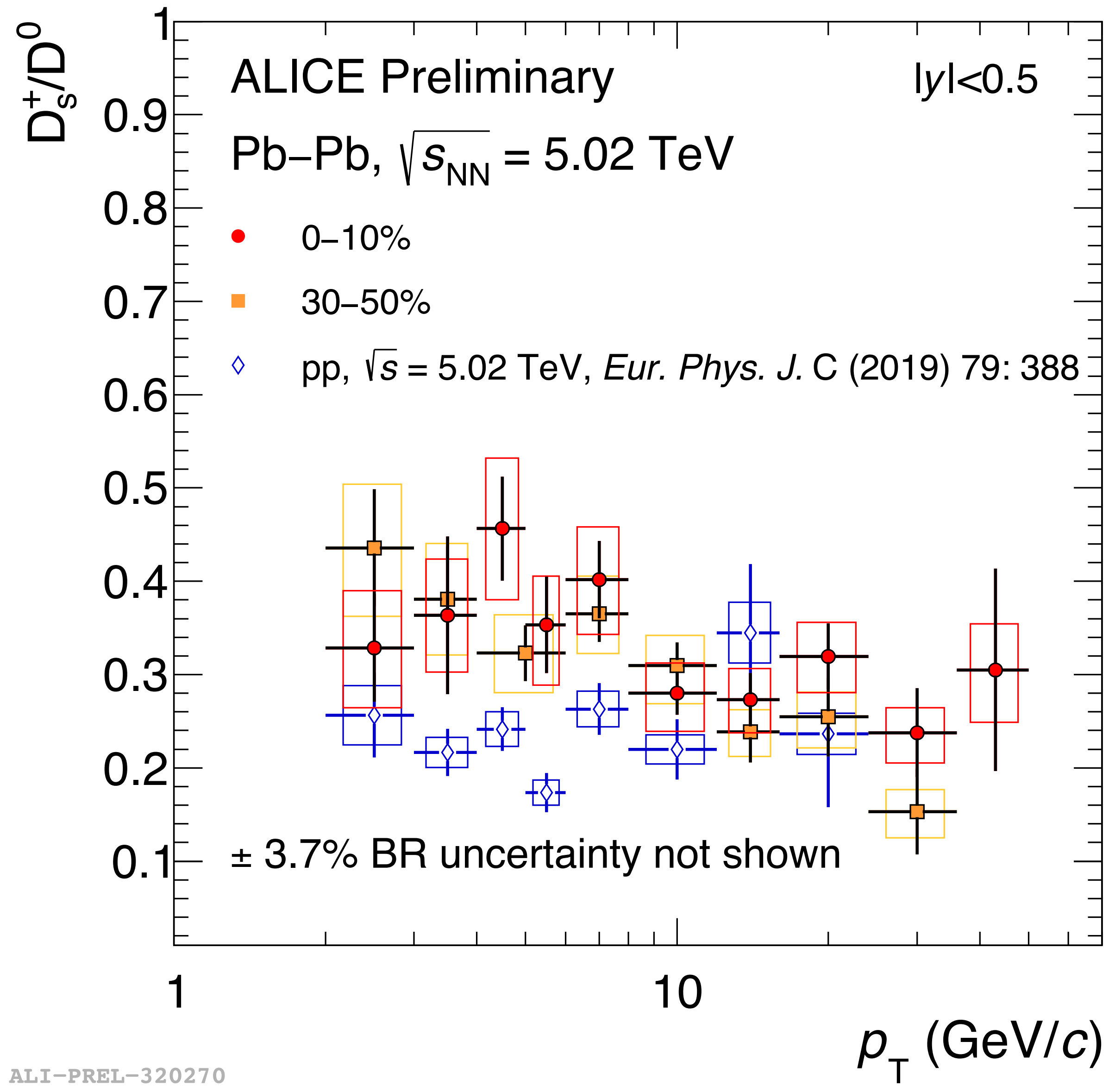
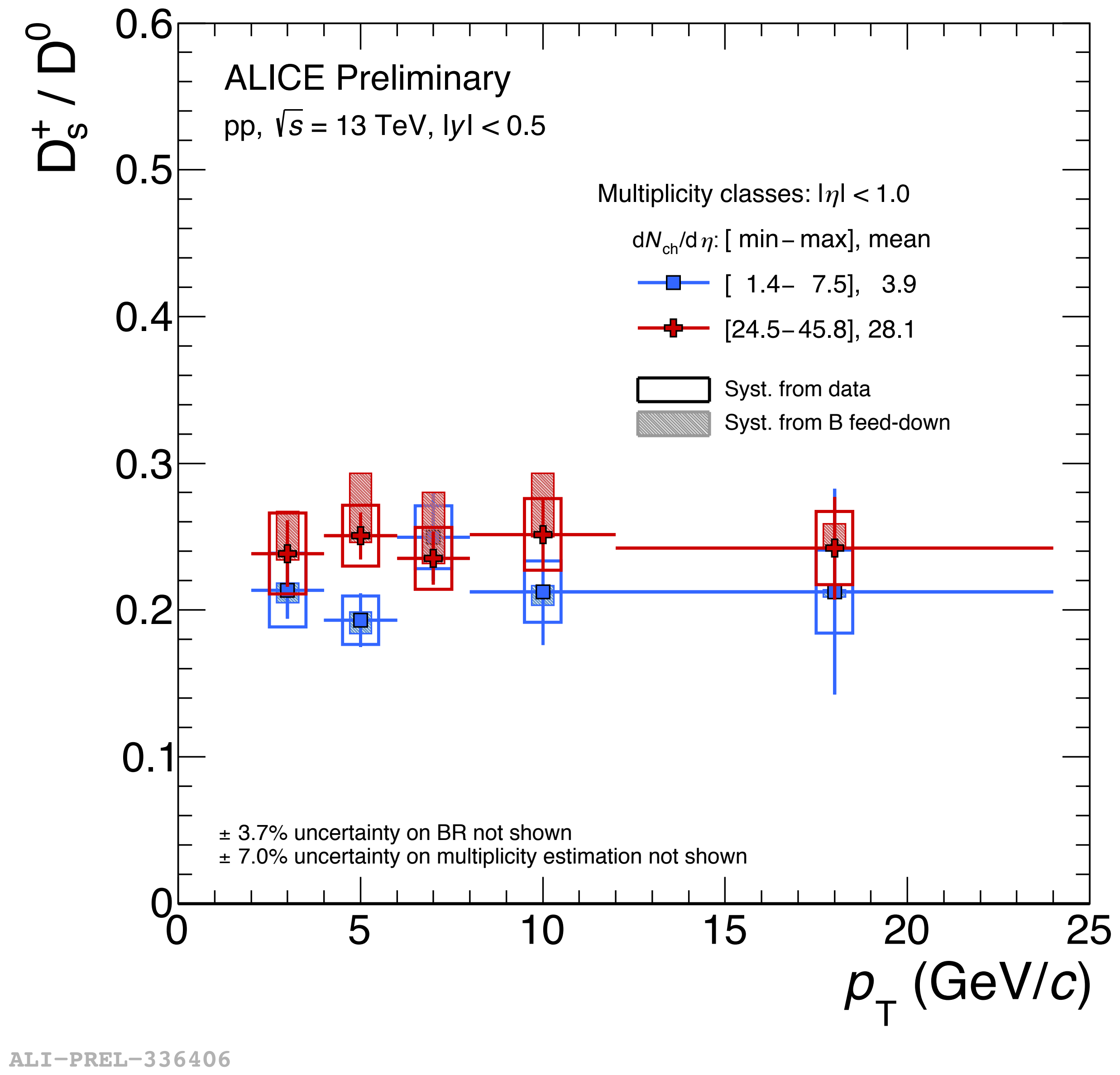
Strange - non Strange D Mesons —> Charmed Baryons

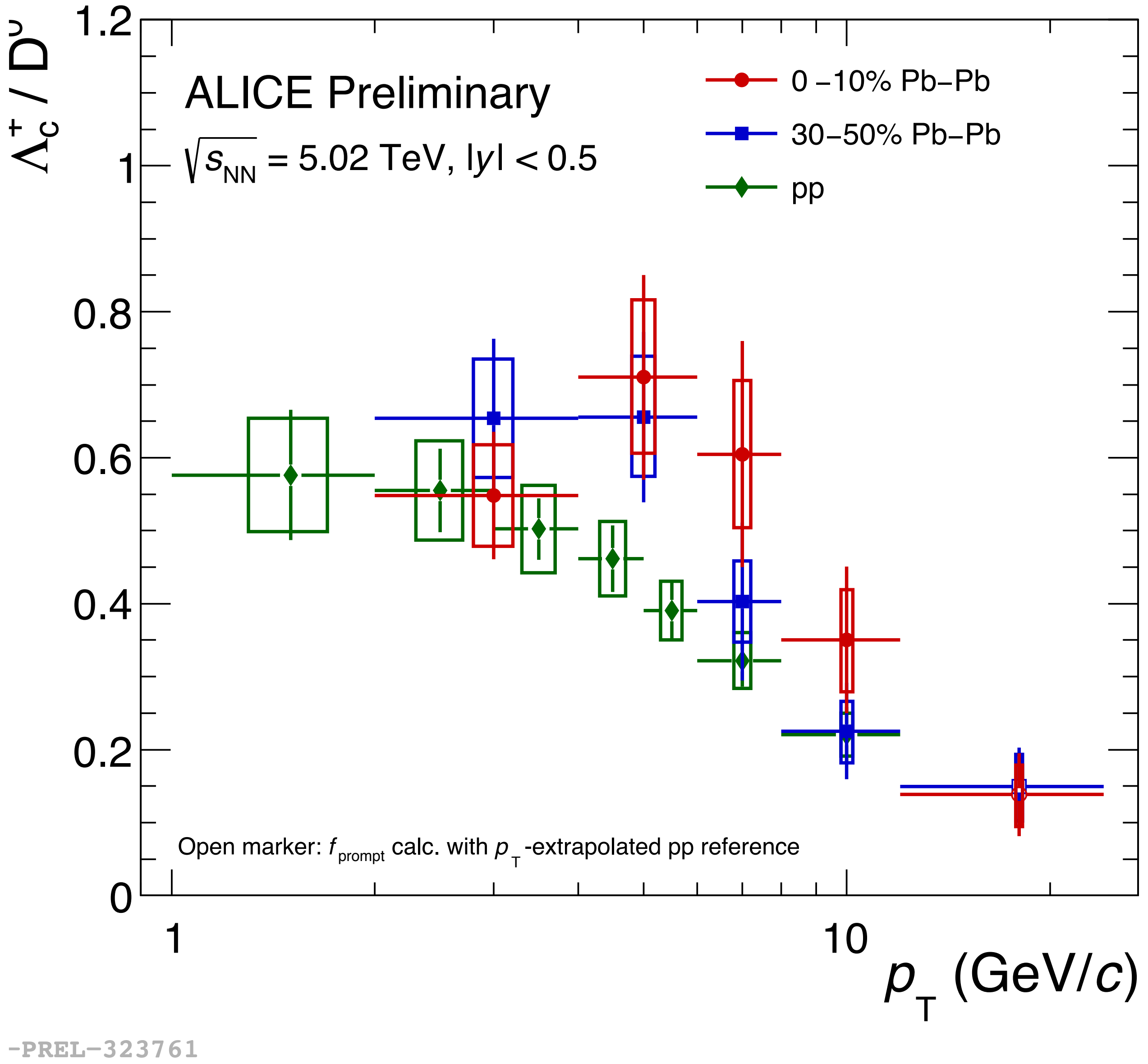
D_s/D^0 in Pb-Pb, pp New



More differential Measurements: pp vs multiplicity New



Λ_c/D^0 in Pb-Pb, pp New



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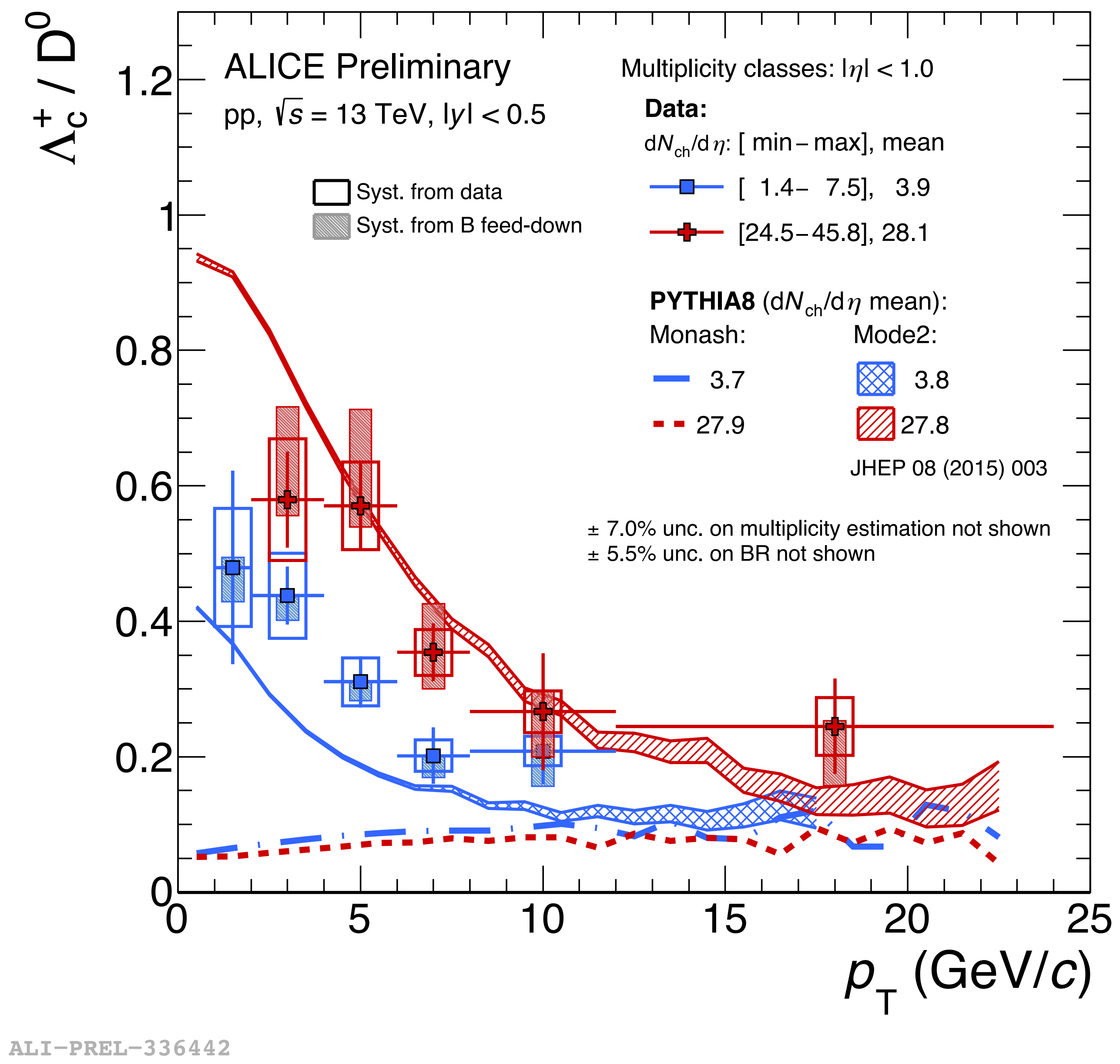

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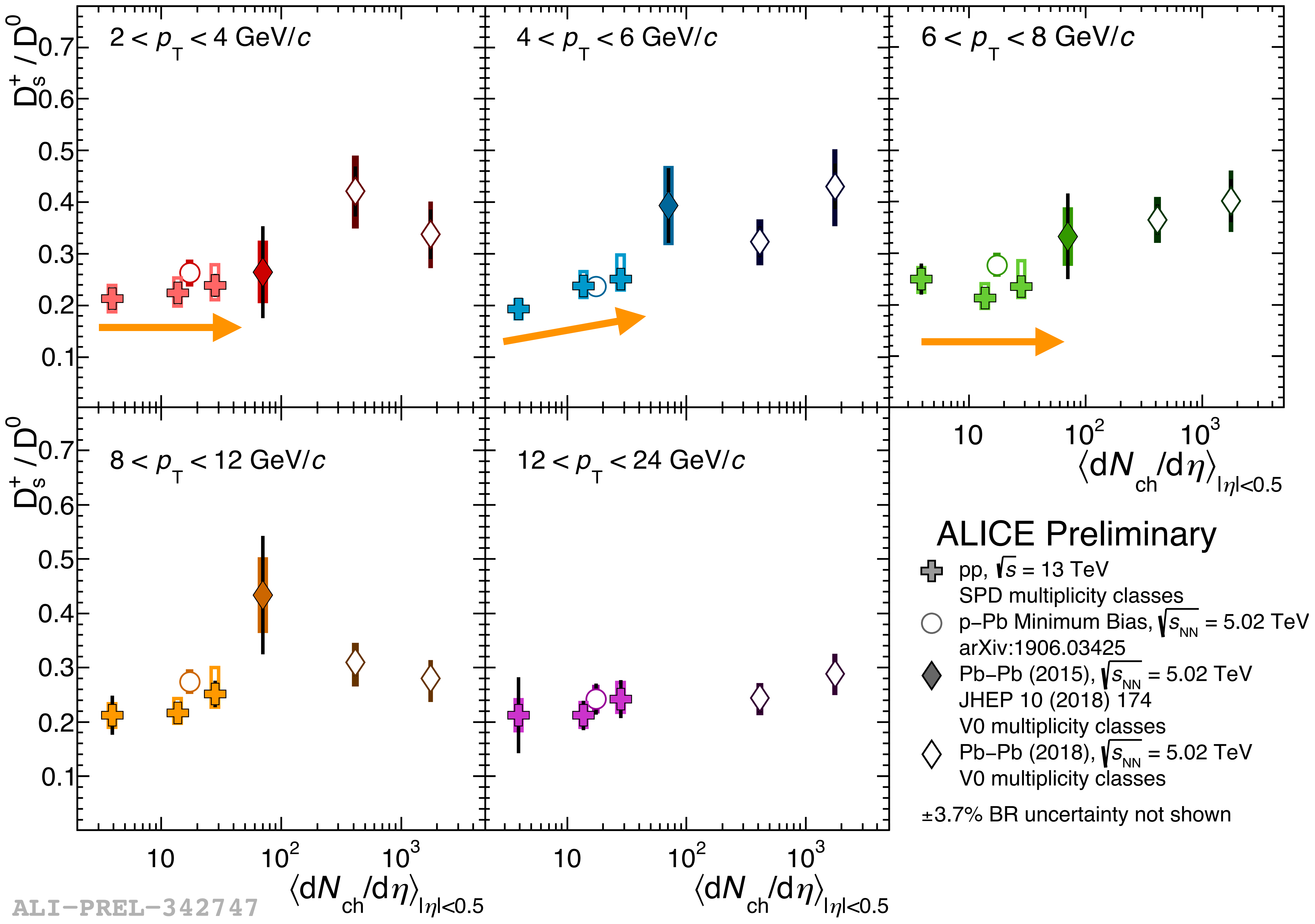
Λ_c/D^0 in **Pb-Pb** enhanced at low p_T wrt **minimum bias pp,** at the same energy.

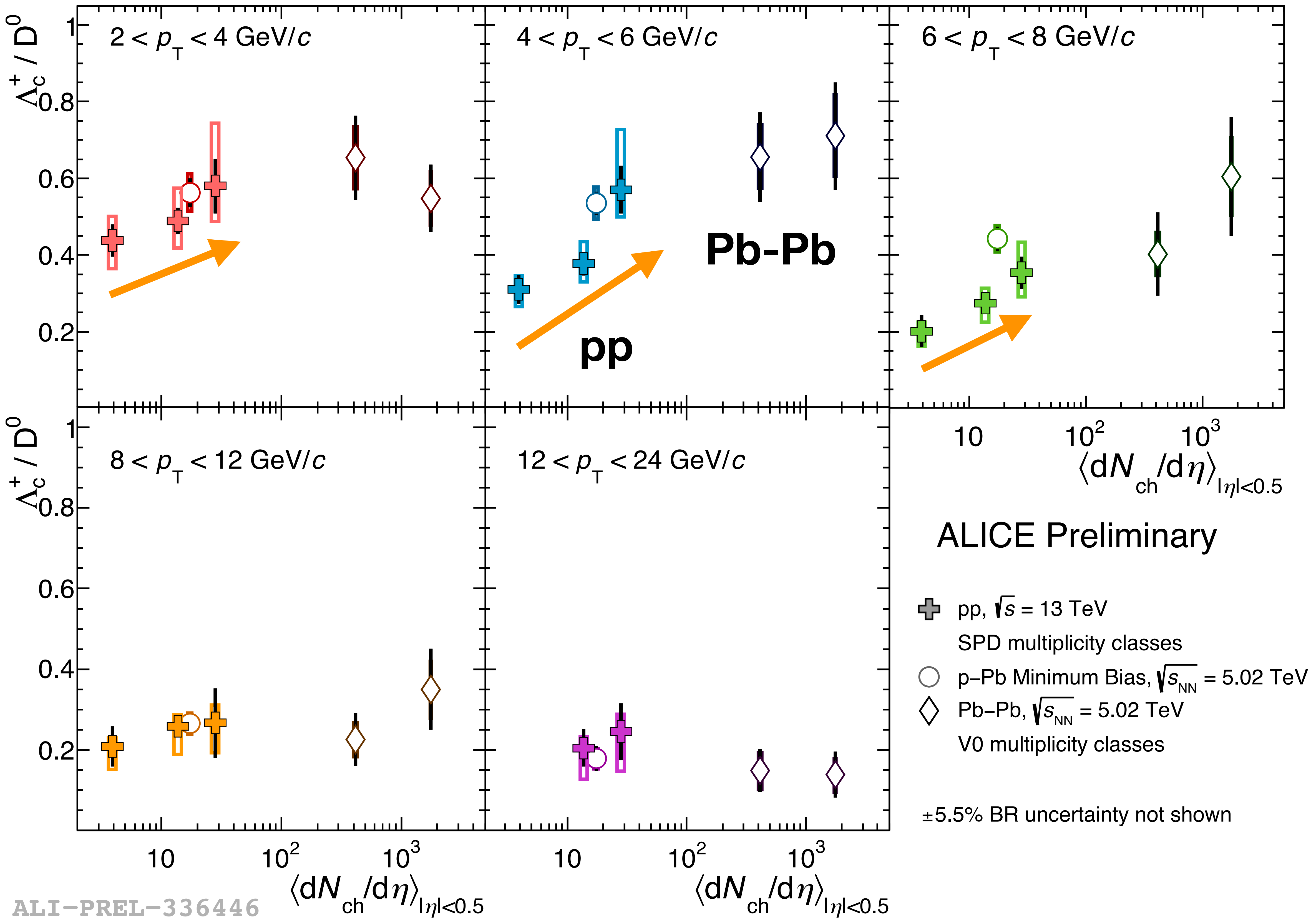
- Λ_c/D^0 enhancement in **high** vs **low** multiplicity pp collisions
- Enhancement over default Pythia
- Color reconnection models with junctions describe data

Strangeness and baryon-to-meson enhancement
from pp, p-Pb to Pb-Pb

New



New

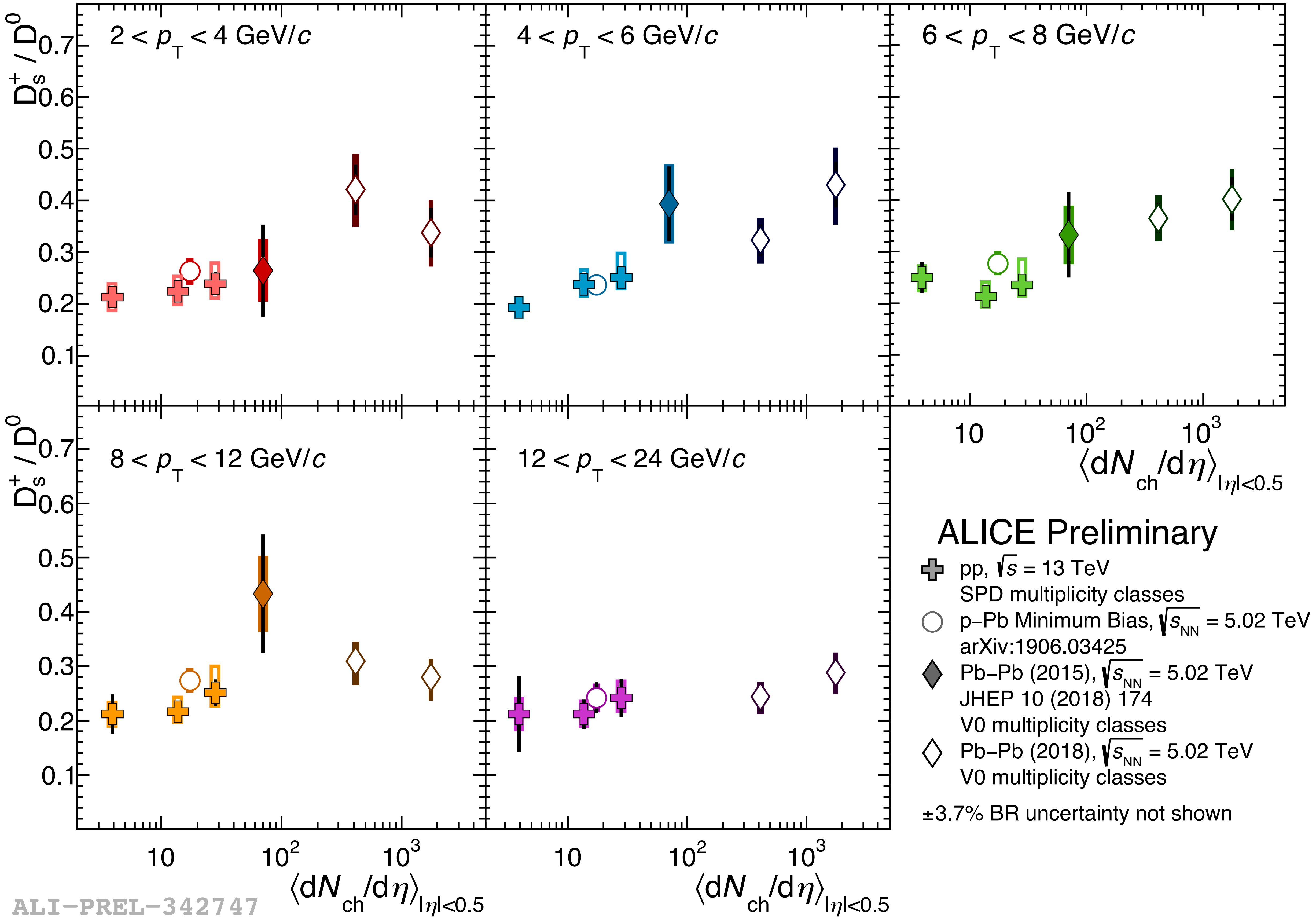


- More pronounced increasing trend from low towards higher multiplicities, in pp collisions for Λ_c/D^0 at low-intermediate p_T, than D_s/D^0

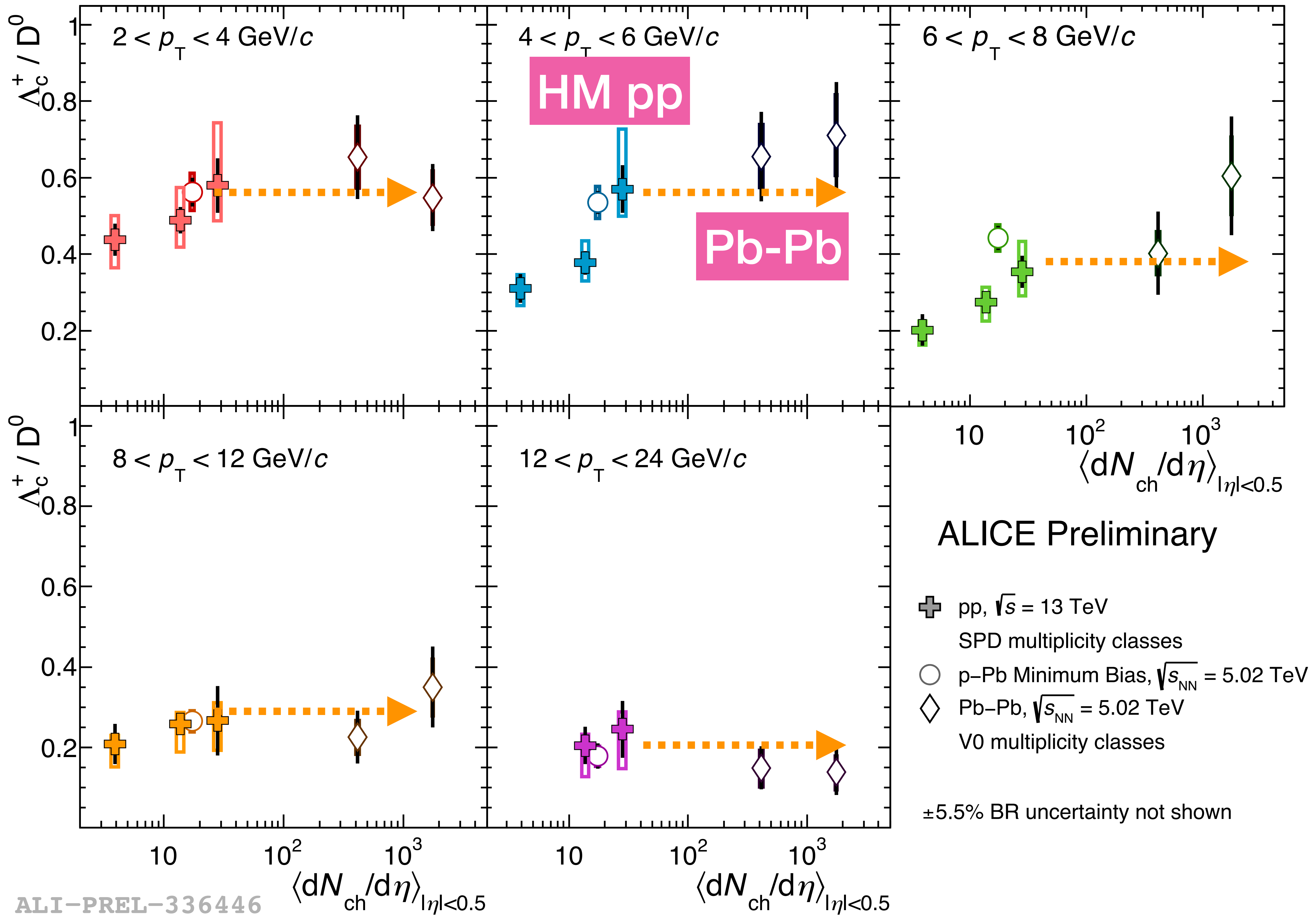
Strangeness and baryon-to-meson enhancement

from pp, p-Pb to Pb-Pb

New

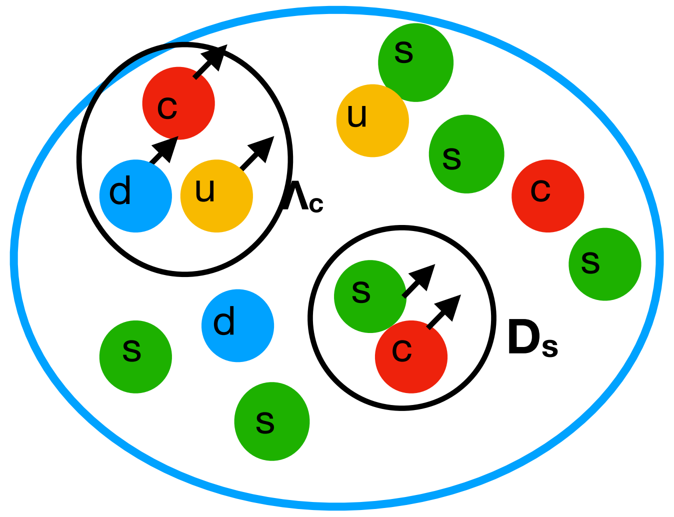


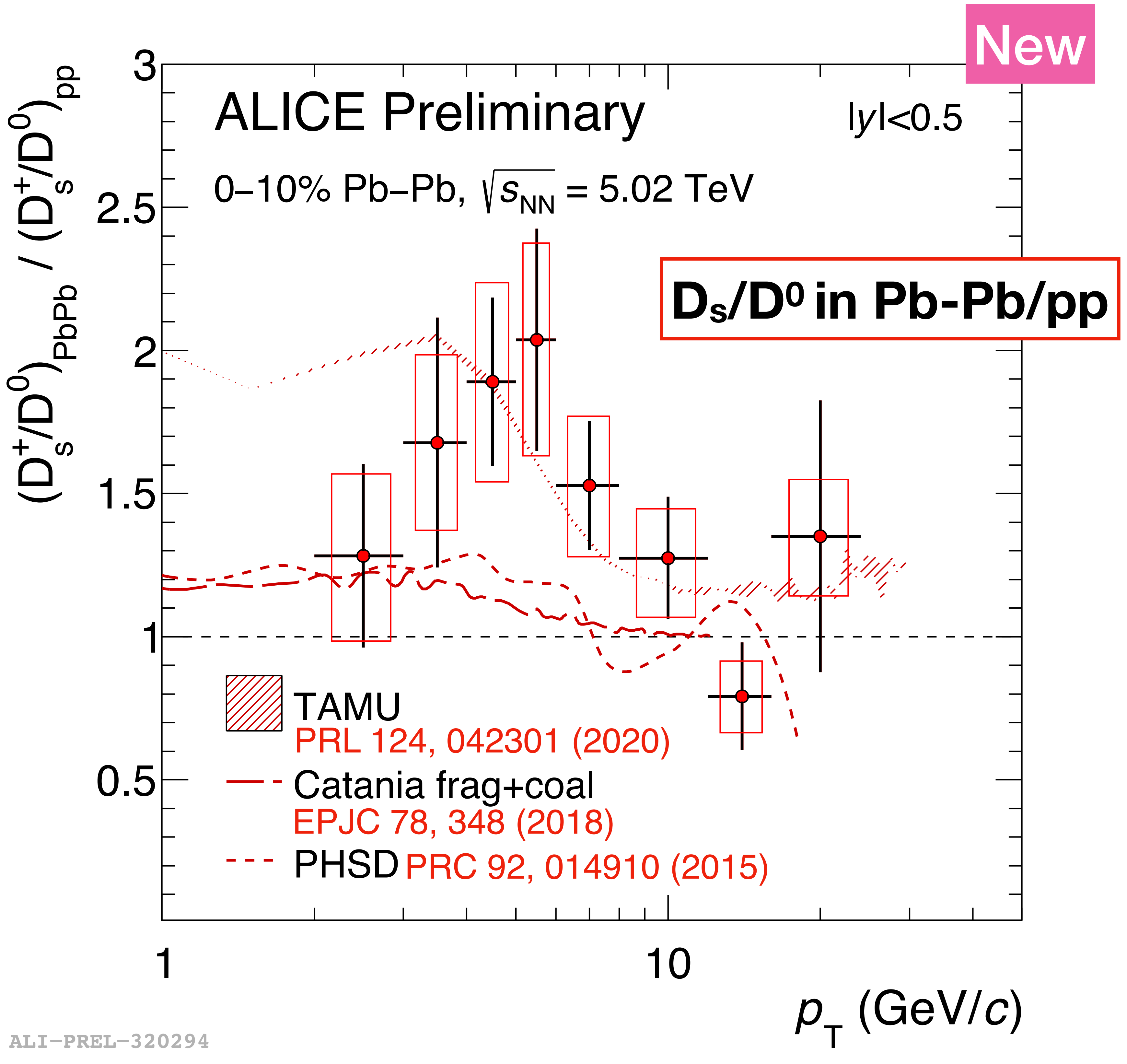
New

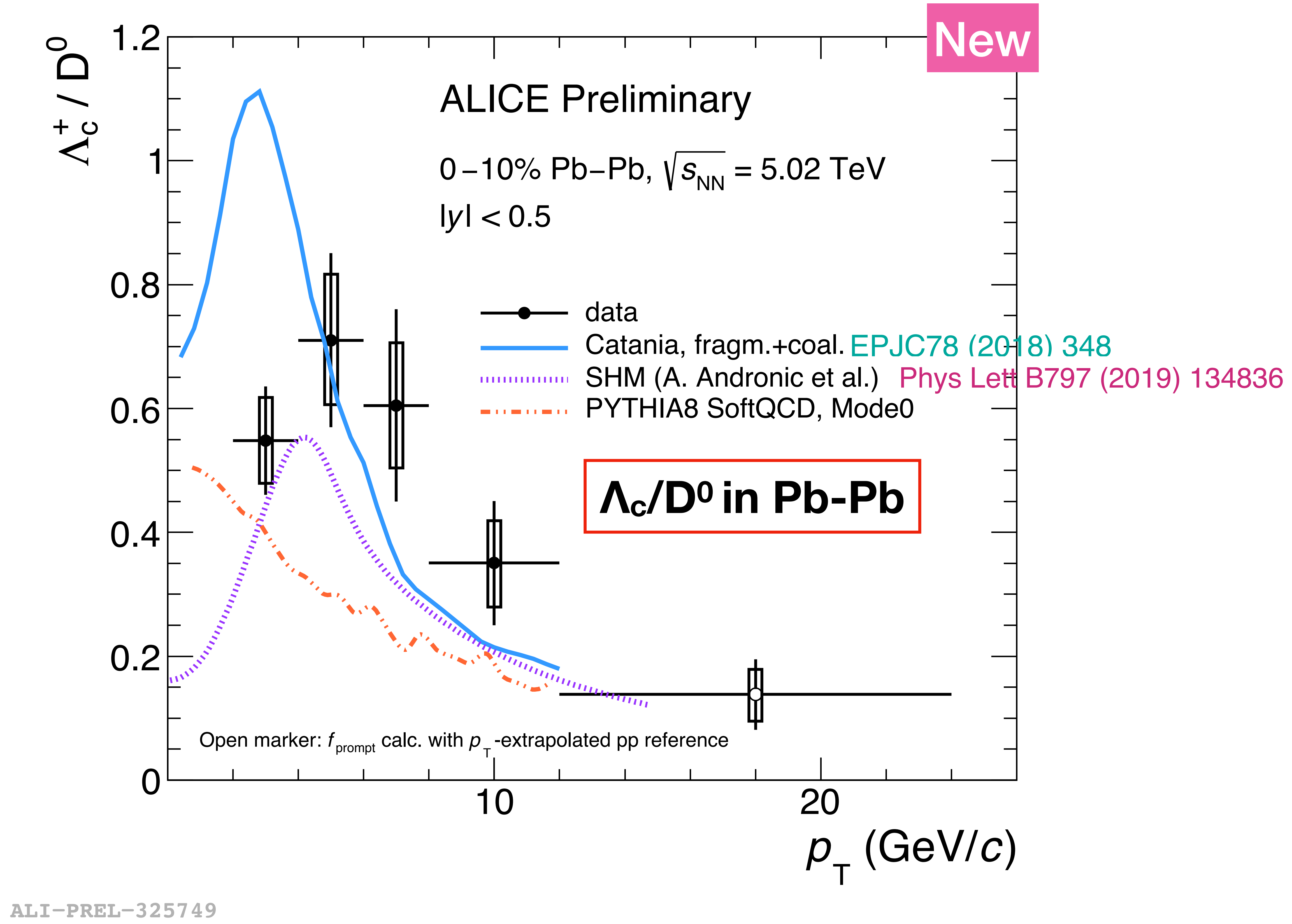


- More pronounced increasing trend from low towards higher multiplicities, in pp collisions for Λ_c/D^0 at low-intermediate p_T, than D_s/D^0
- Λ_c/D^0: high-multiplicity pp and minimum bias p-Pb, and semicentral and central Pb-Pb: measurements in agreement

Strangeness and baryon-to-meson: comparison with models in Pb-Pb



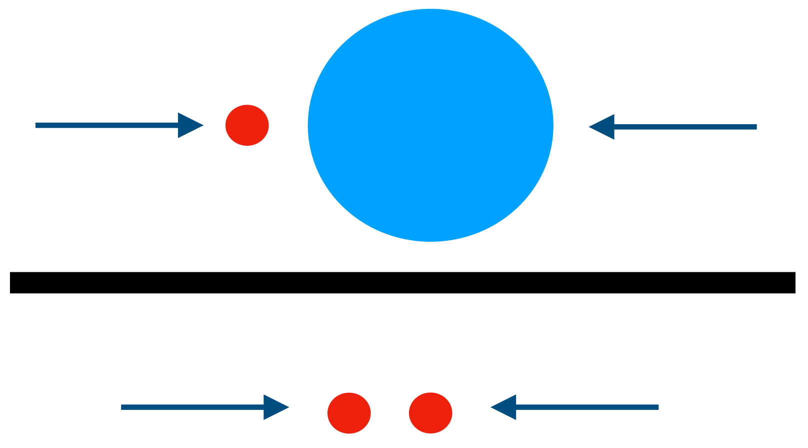




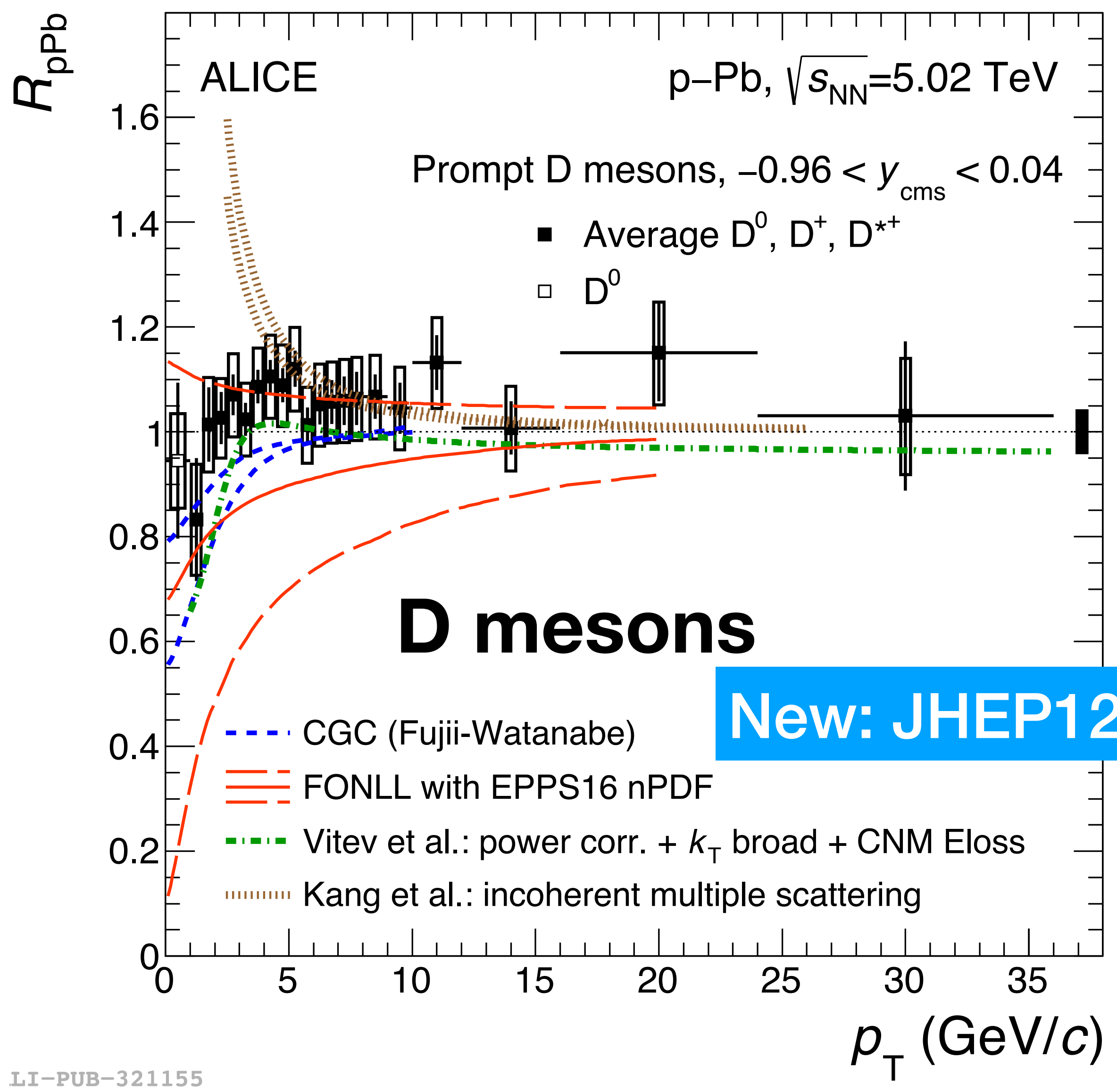
- Theoretical models that include charm quark hadronization via coalescence + fragmentation describe the D_s enhancement in Pb-Pb wrt pp and the Λ_c/D^0 measurements in Pb-Pb
- Statistical Hadronization Model describes the Λ_c/D^0 in Pb-Pb

Nuclear modification factor

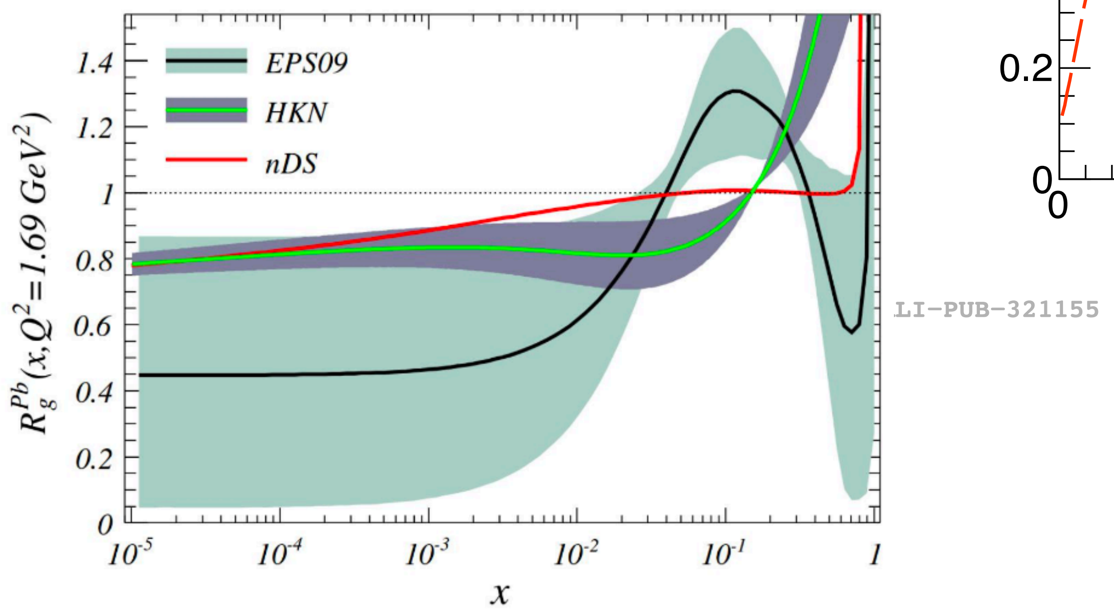
Nuclear modification factor in p-Pb



Mid-rapidity

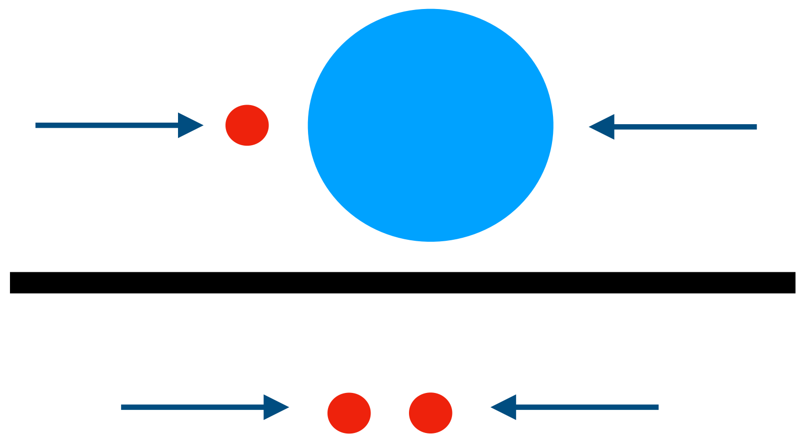


New: JHEP12(2019)092



$$R_{pPb} = \frac{1}{A} \frac{d^2\sigma^{prompt\,D}_{pPb}/dp_T dy}{d^2\sigma^{prompt\,D}_{pp}/dp_T dy}$$

Nuclear modification factor in p-Pb



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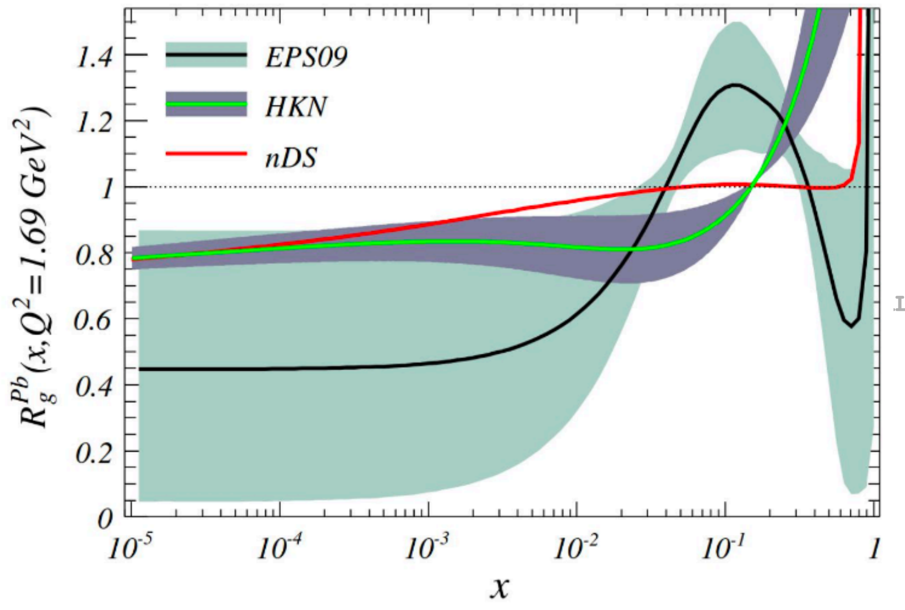

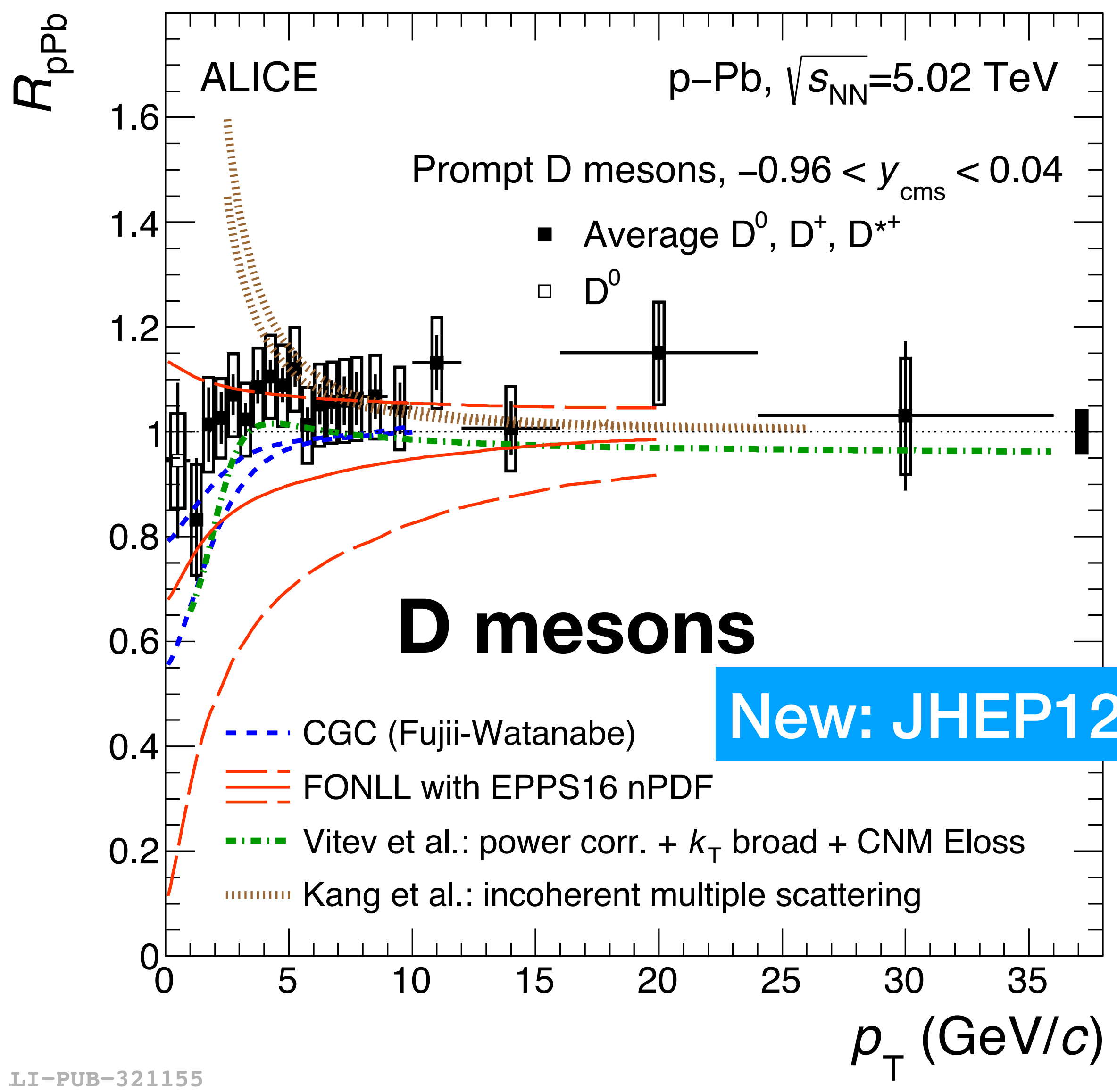

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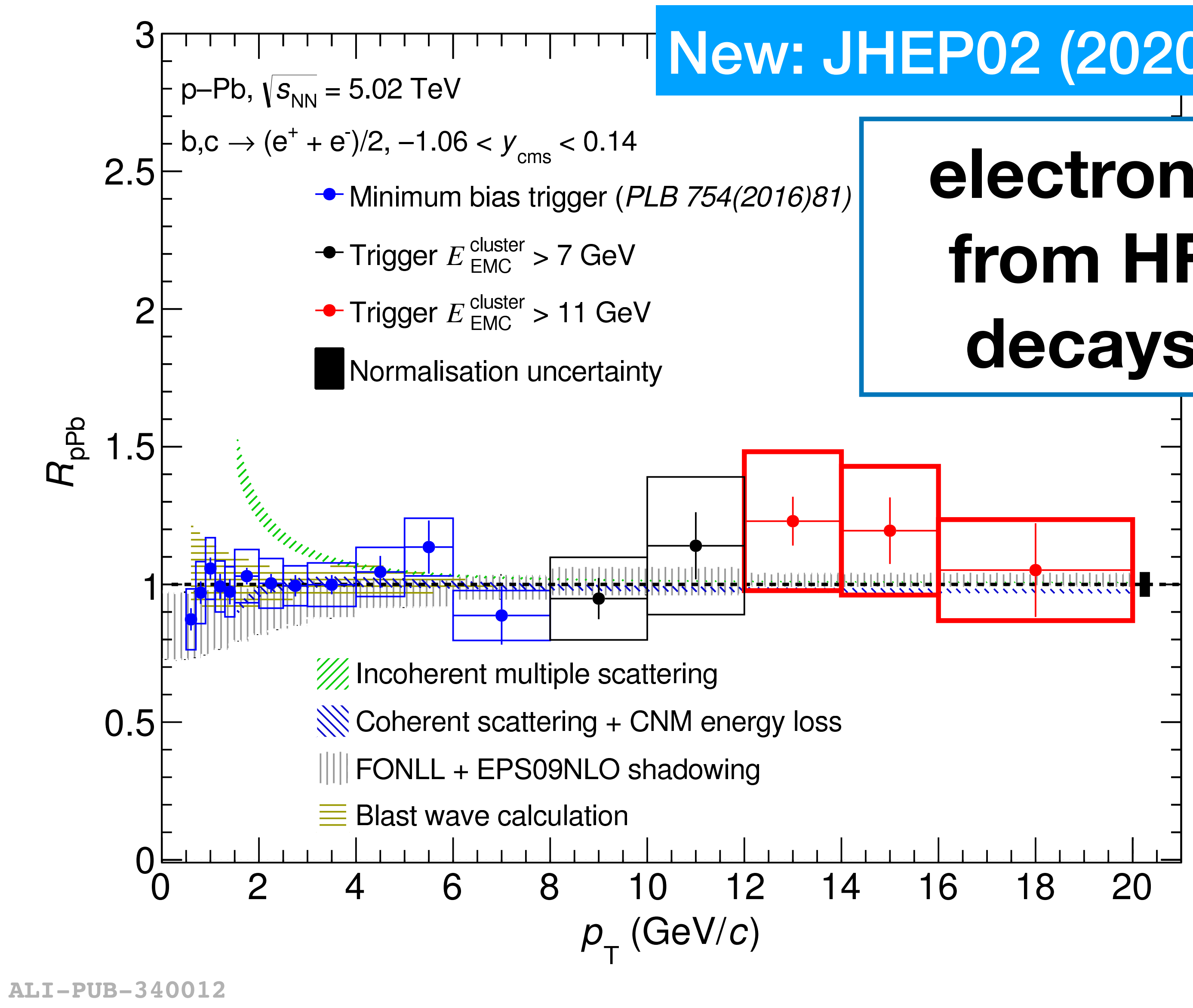
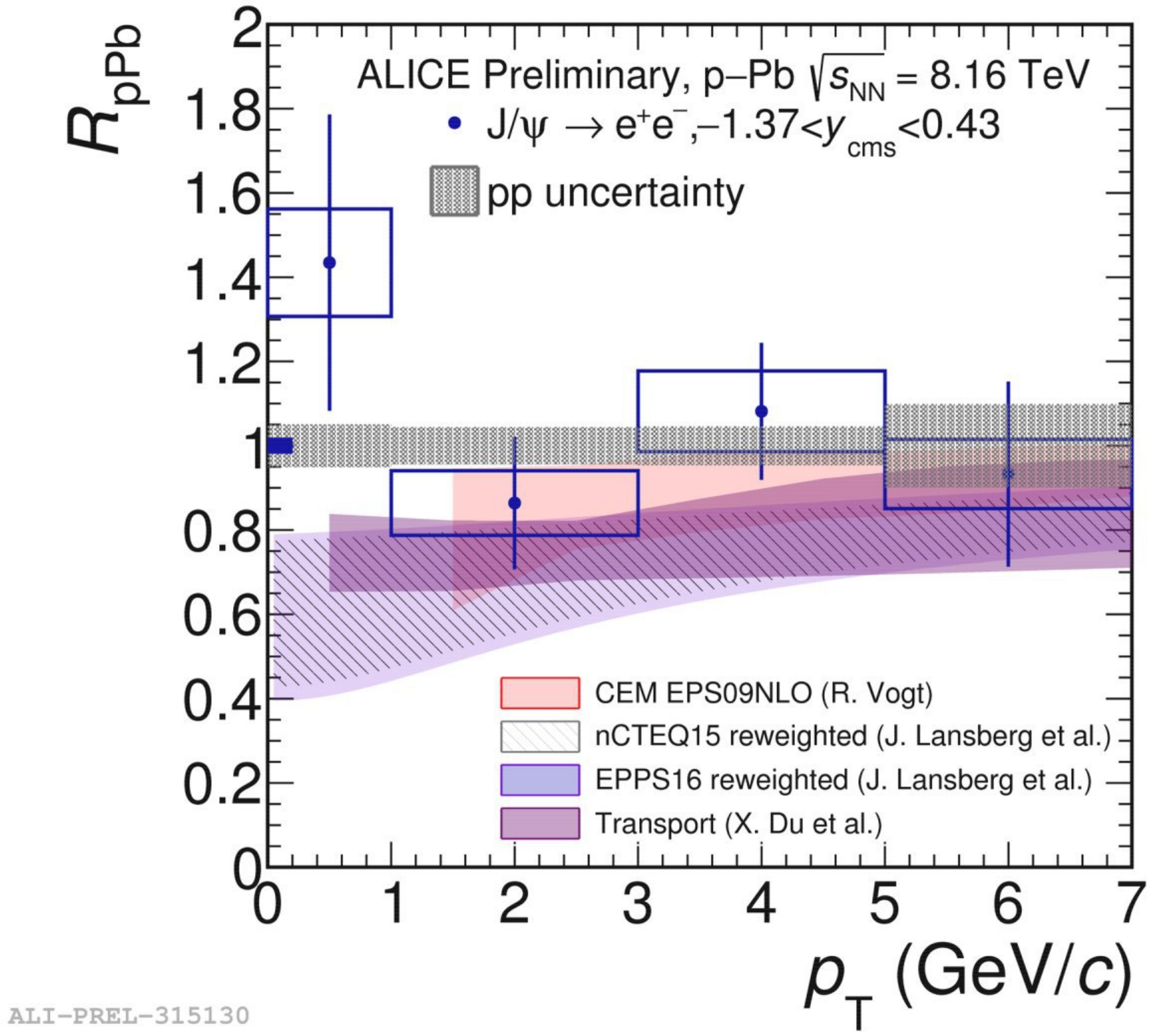
New: JHEP02 (2020) 077

electrons from HF decays

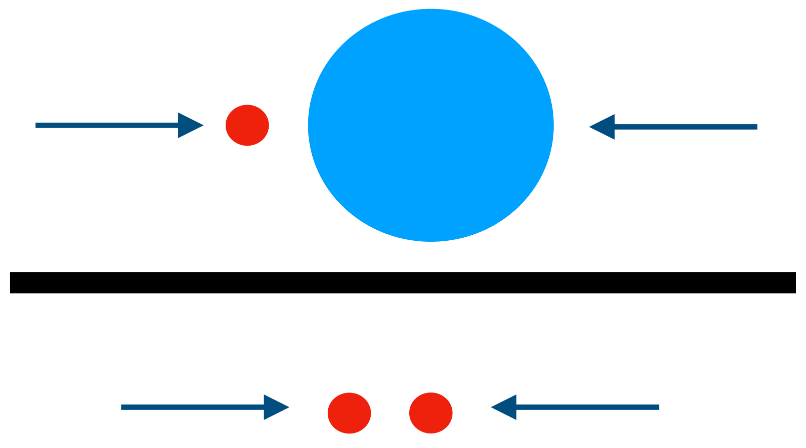




J/Ψ→e^+e^-

***R_{pPb}* of D-meson, electrons from HF, J/Ψ at mid rapidity is compatible with unity** within uncertainties
and compatible with **models that include Cold Nuclear Matter Effects**

Nuclear modification factor in p-Pb



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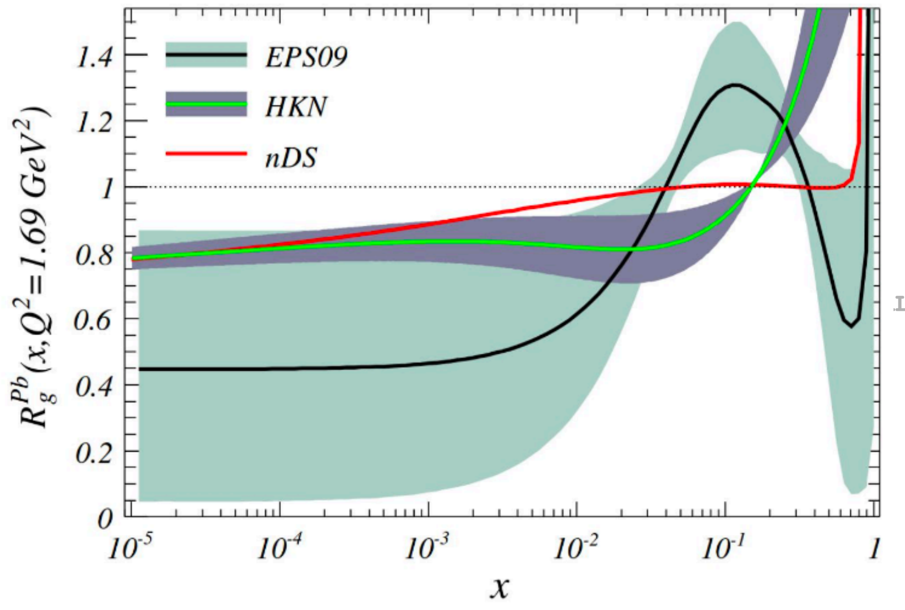

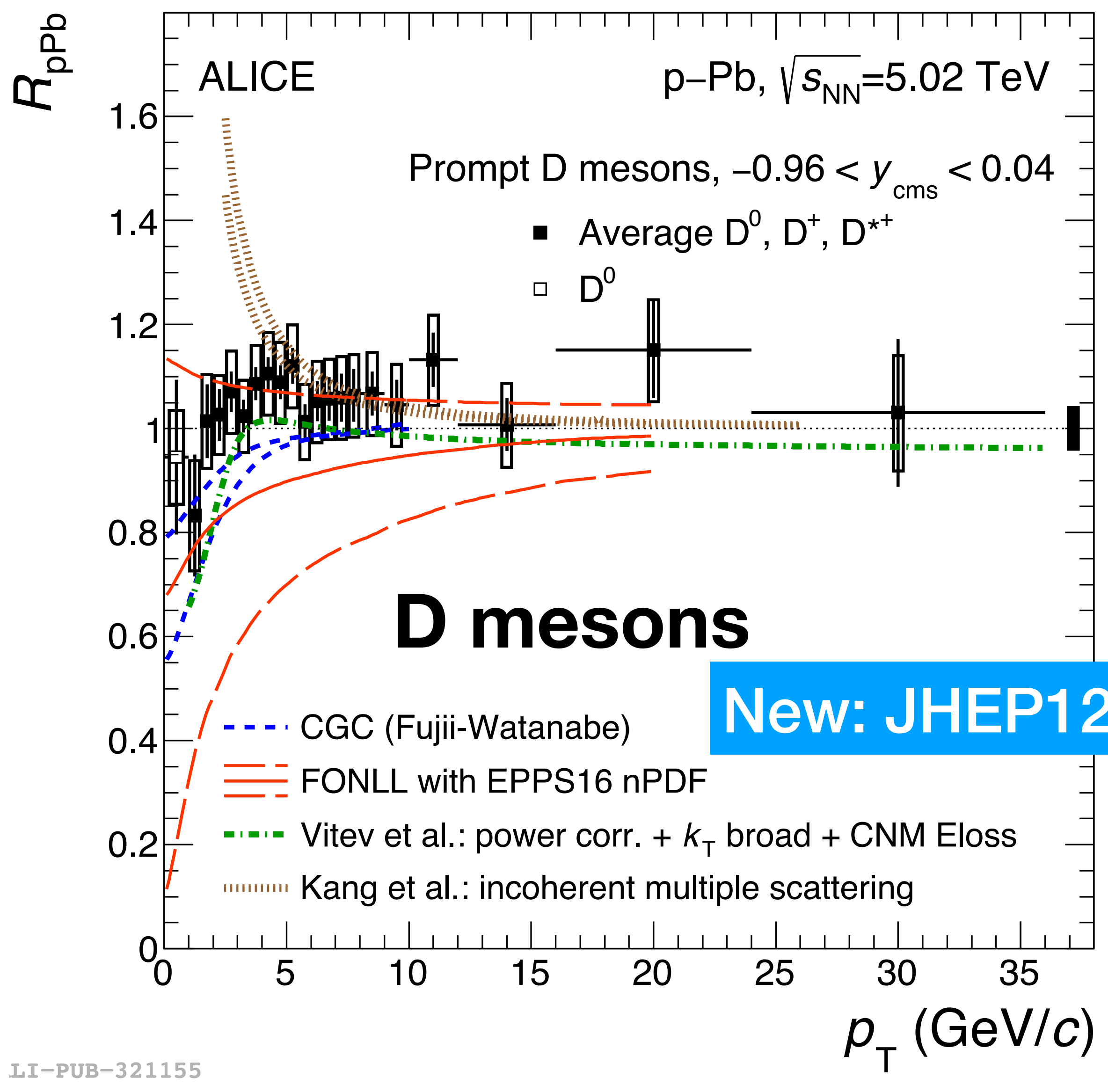

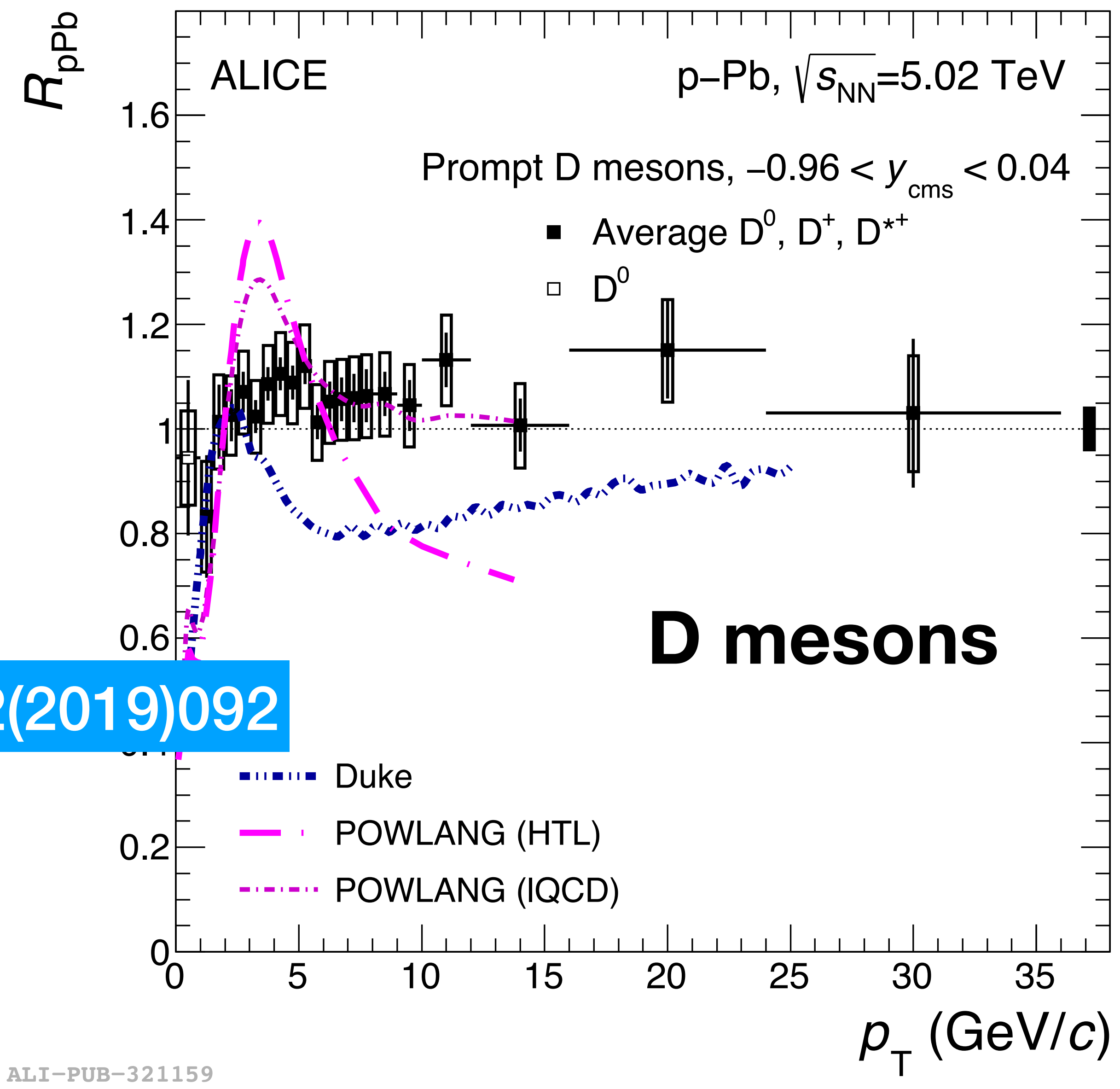

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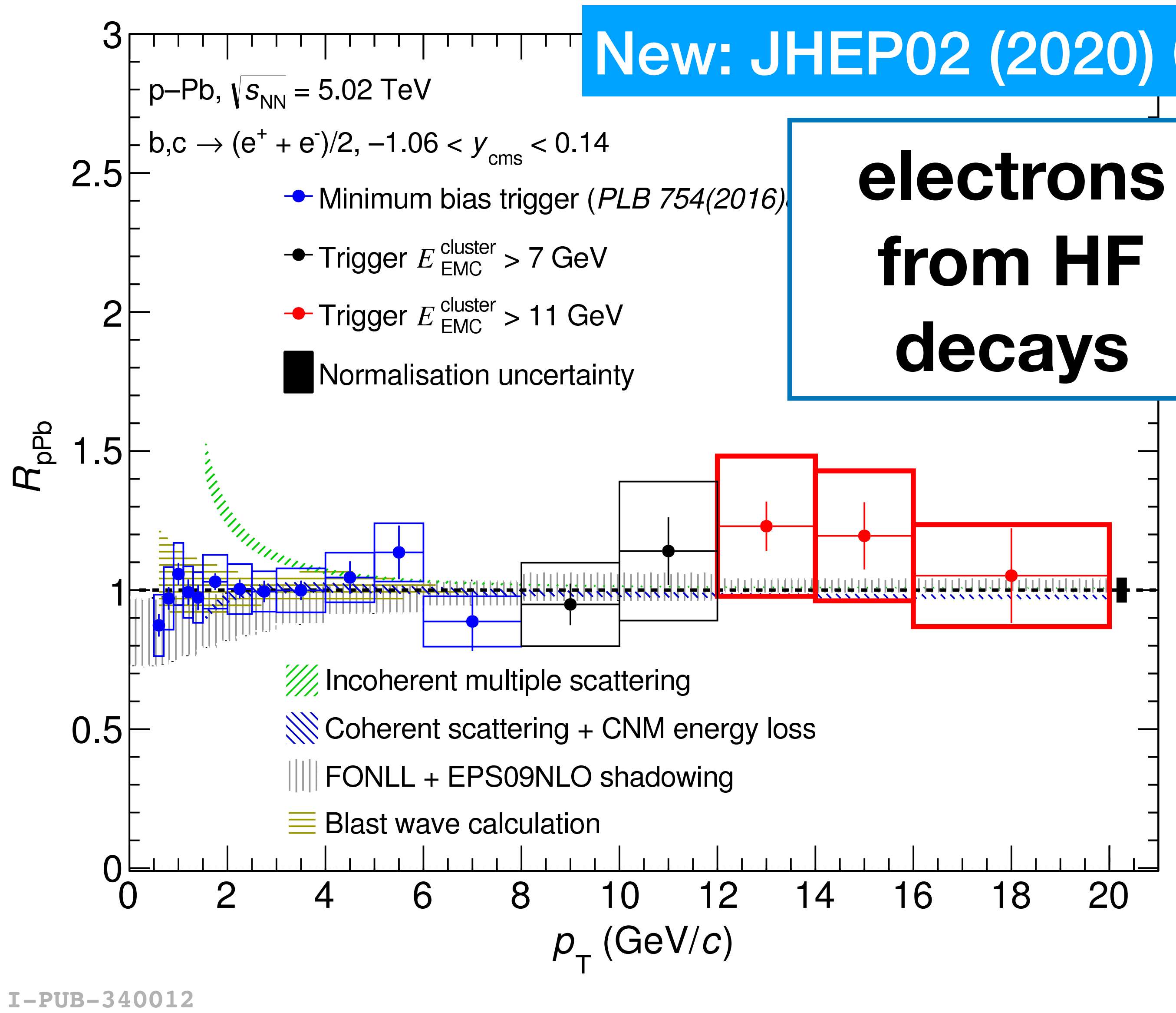

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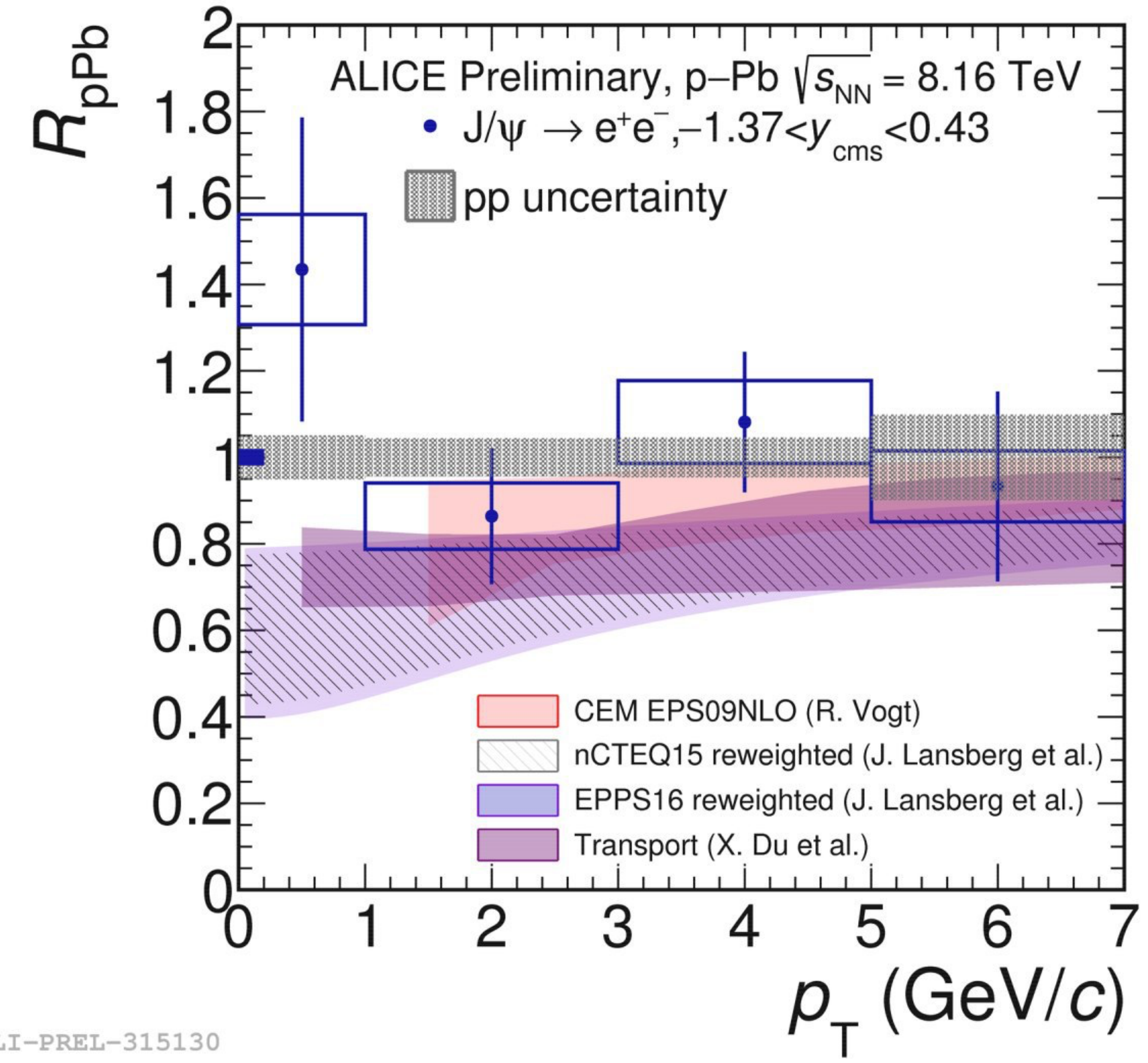
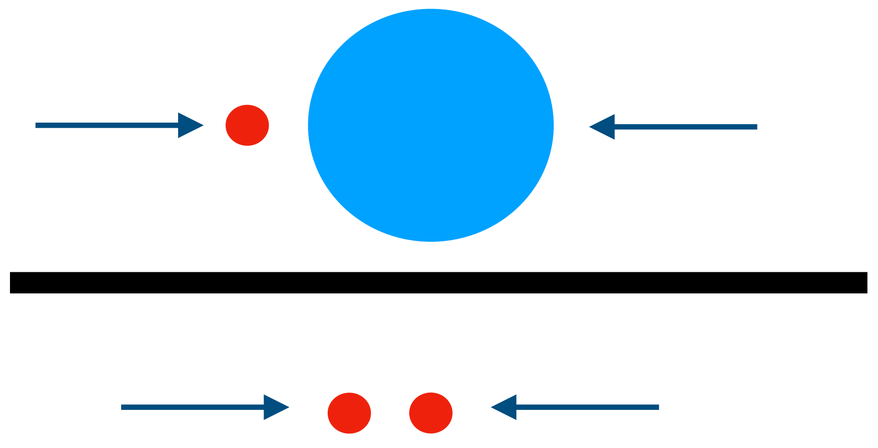


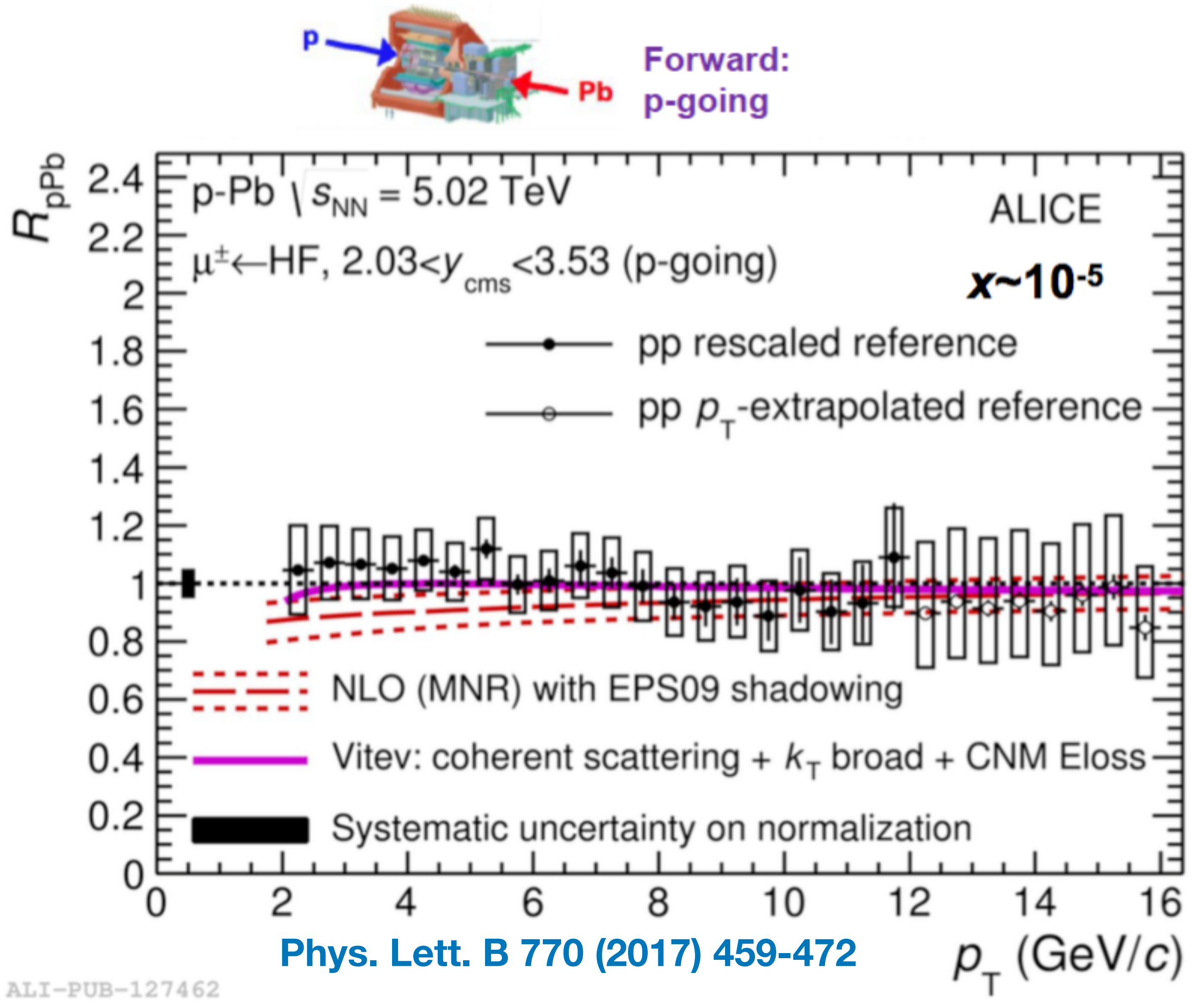
J/Ψ→e⁺e⁻

***R*pPb of D-meson, electrons from HF, J/Ψ at mid rapidity is compatible with unity** within uncertainties
and compatible with **models that include Cold Nuclear Matter Effects**
- Ex. for D-mesons: data do not favour a suppression larger than 10-15% for $5<p_T<12$ GeV/*c*: models that include **QGP in p-Pb**, are disfavored by the data

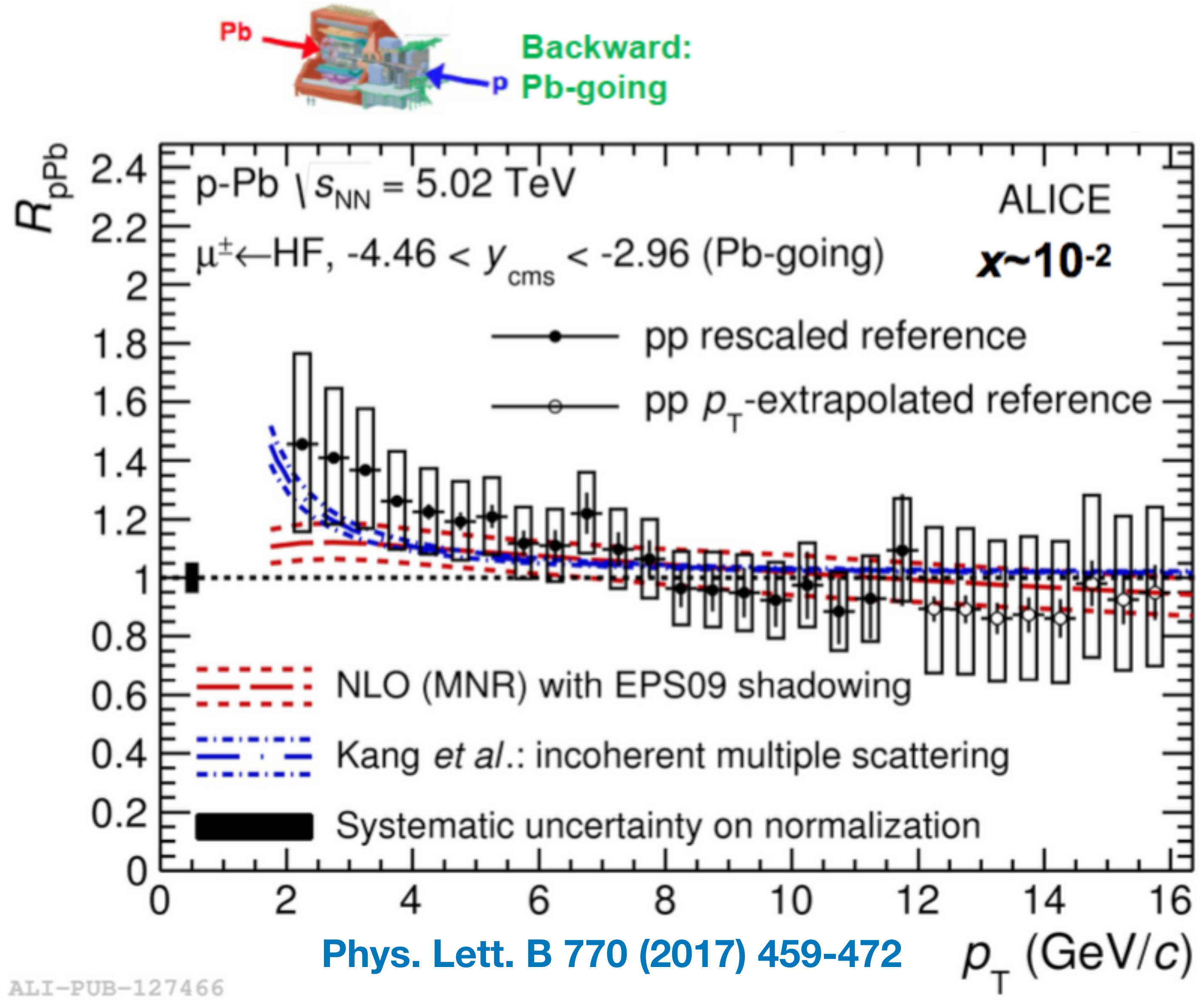
Nuclear modification factor in p-Pb



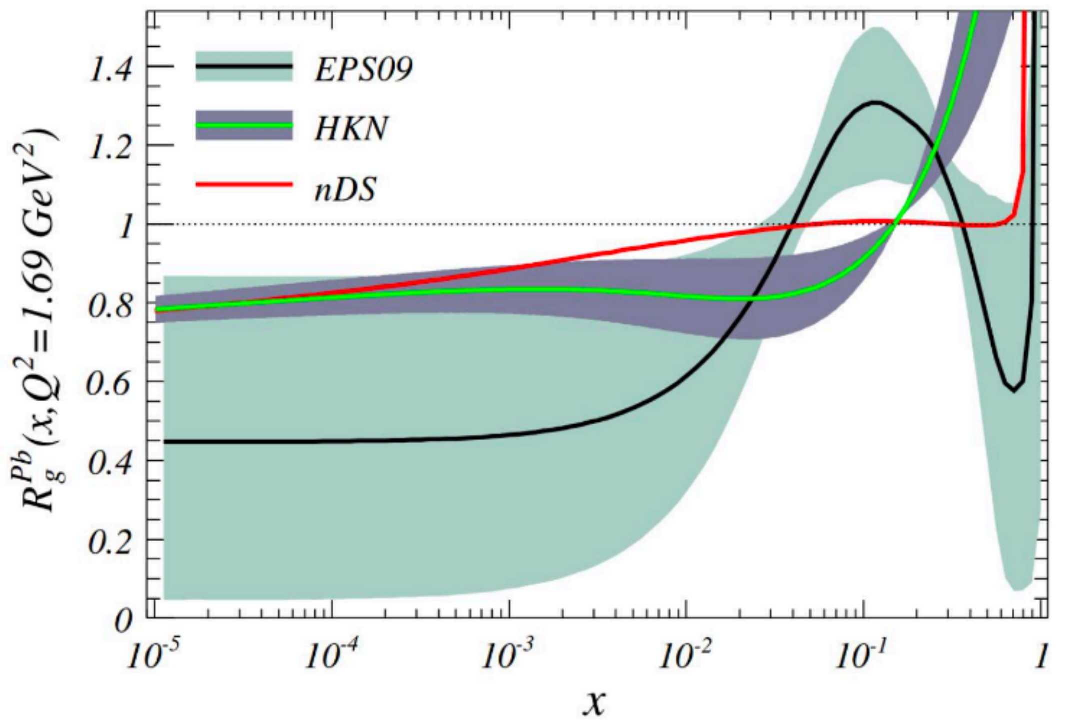
Forward and backward rapidity



Phys. Lett. B 770 (2017) 459-472



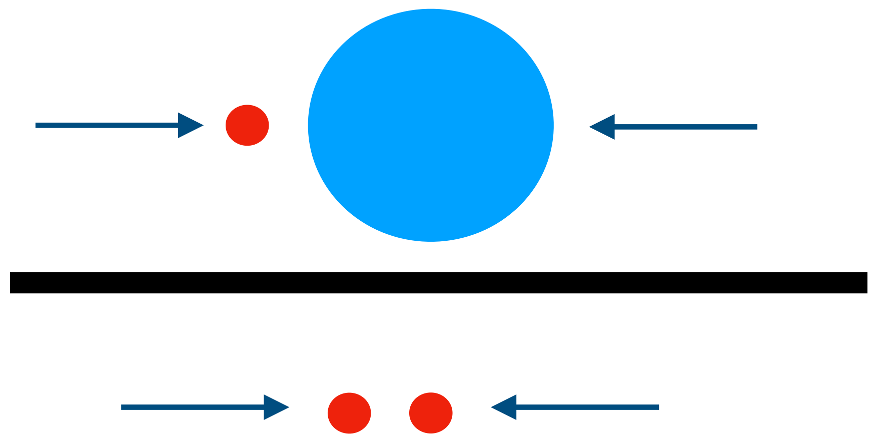
Phys. Lett. B 770 (2017) 459-472



Different rapidity ranges allow access to different Bjorken-*x* regimes

- The shadowing calculations describe well the y_{cms} dependence of the R_{pPb} at forward-y and backward-y
- hint of enhancement at backward rapidity at low p_T
  - described by models including CNM effects

Nuclear modification factor in p-Pb



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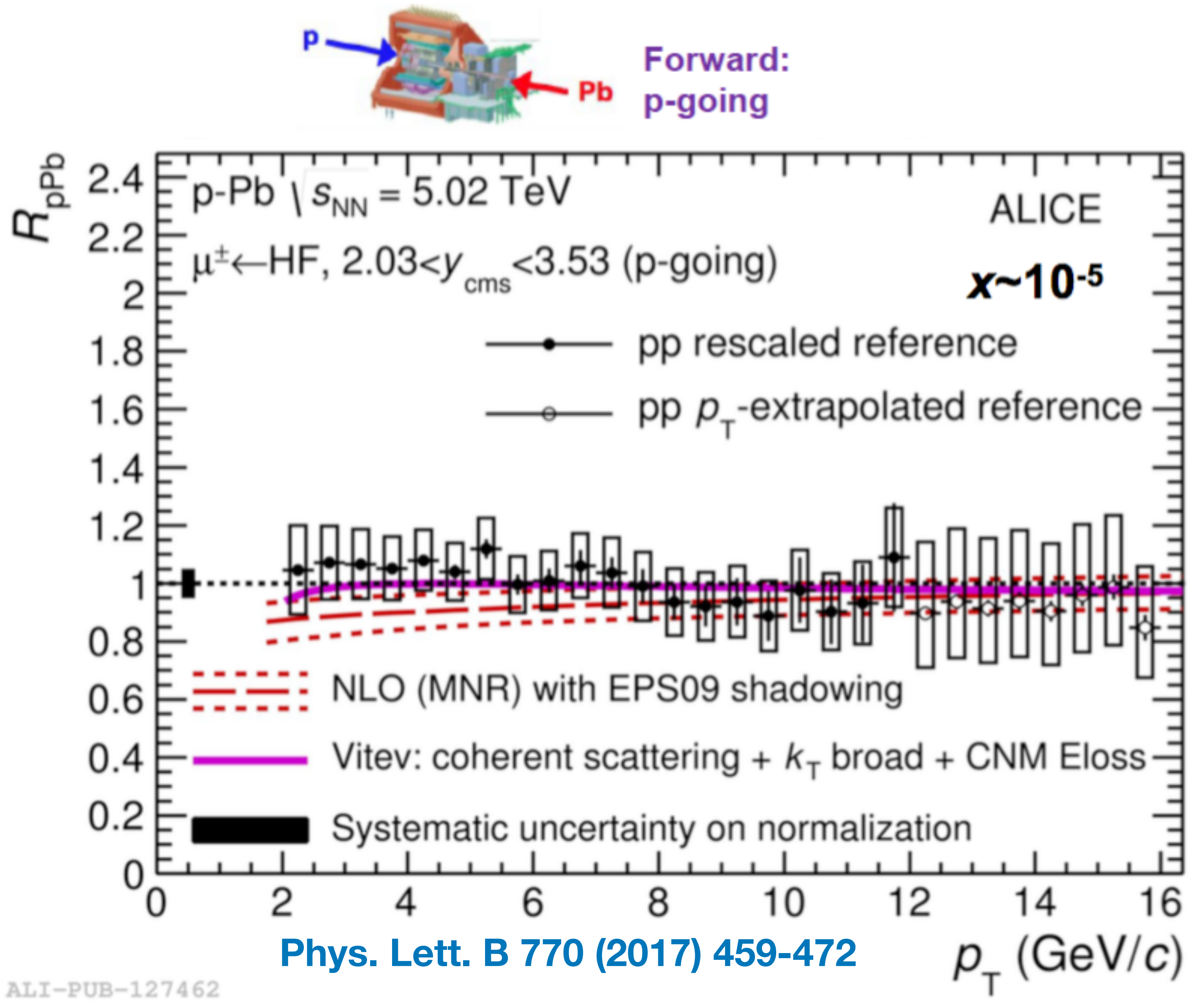

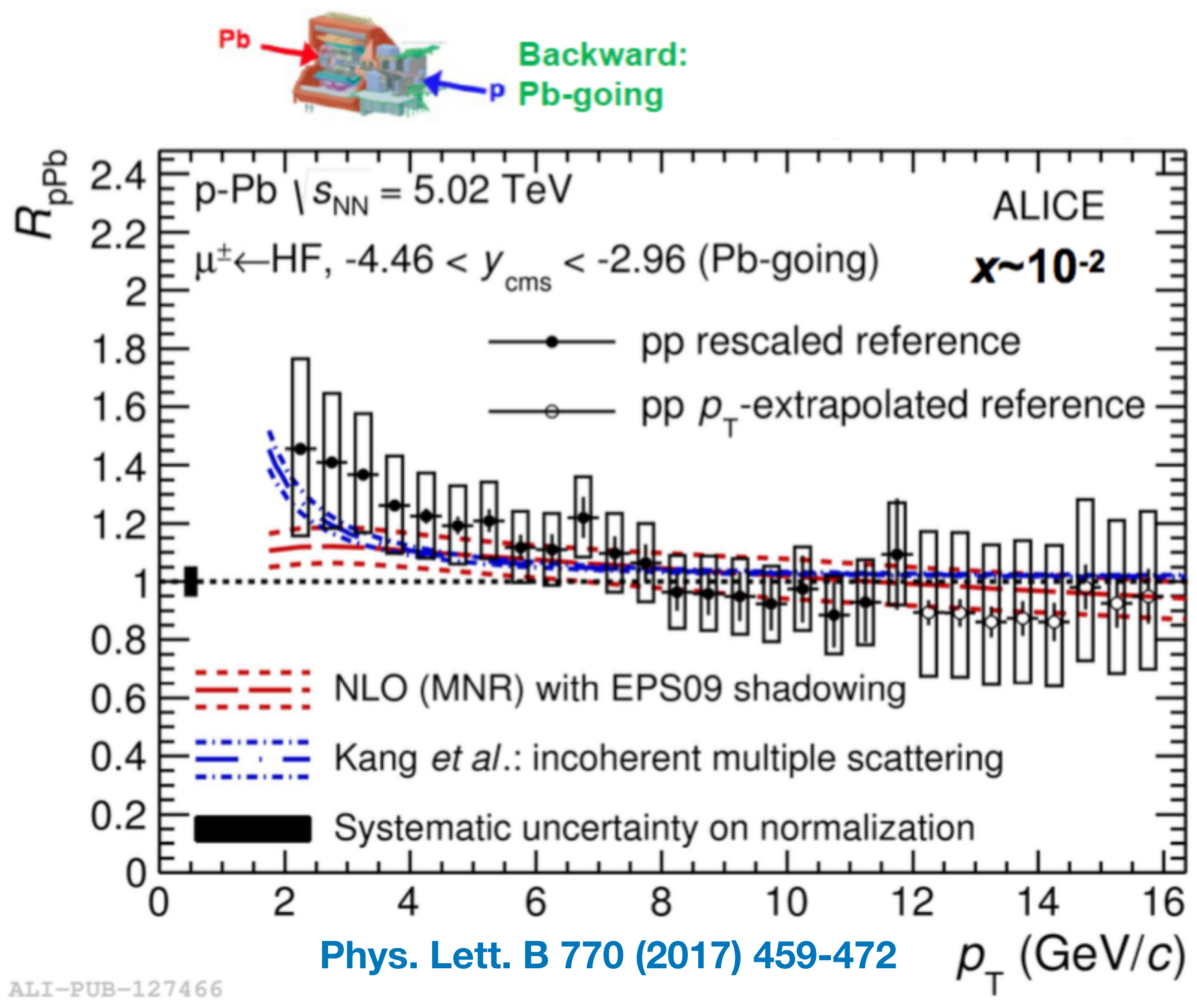

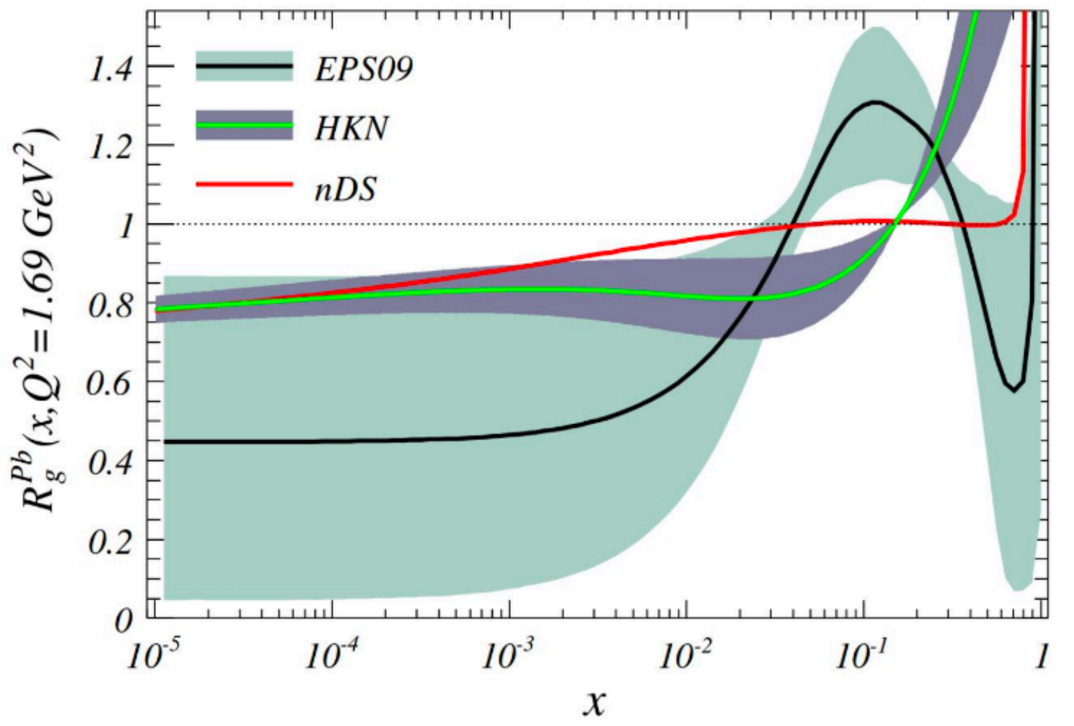

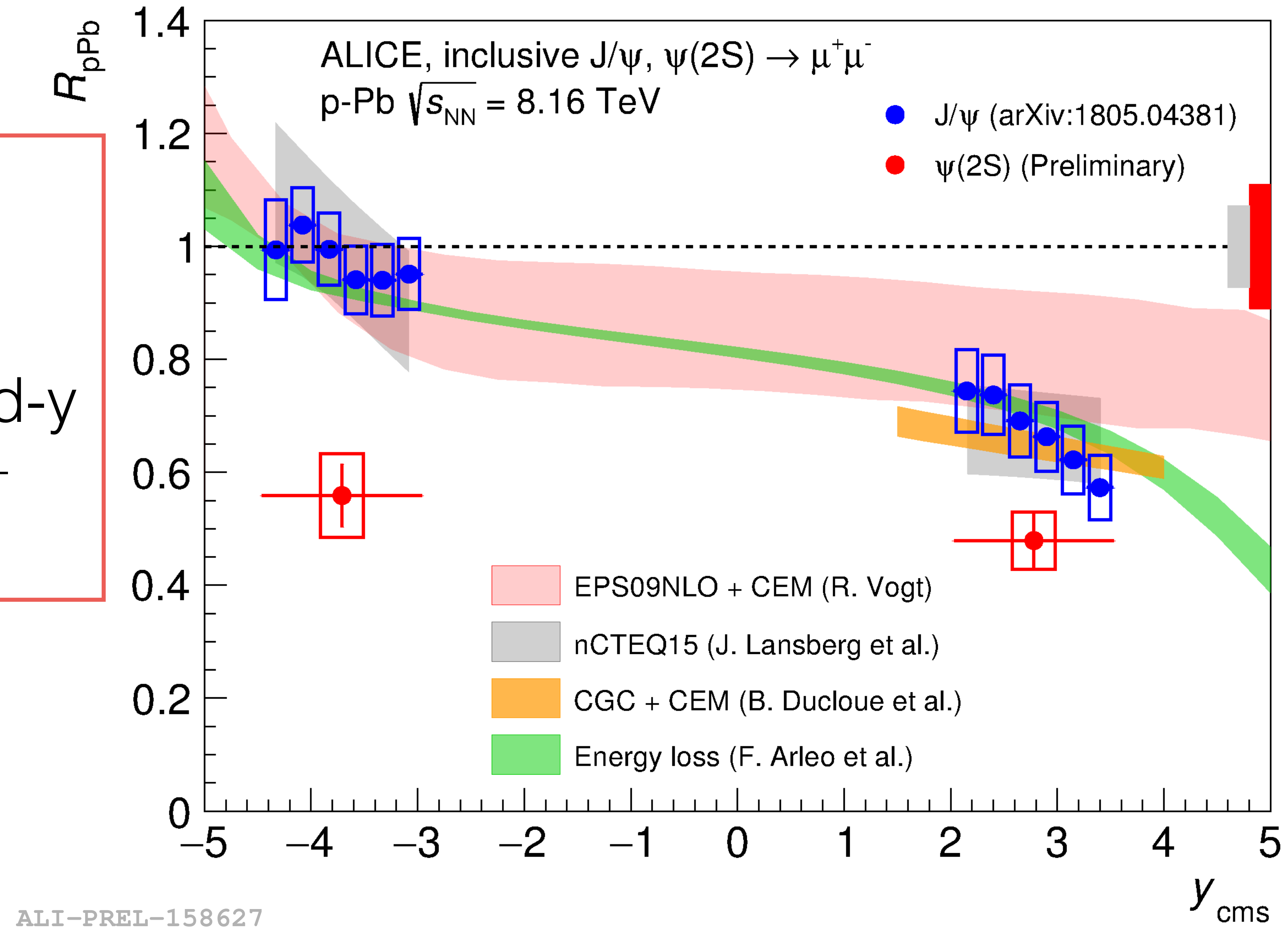

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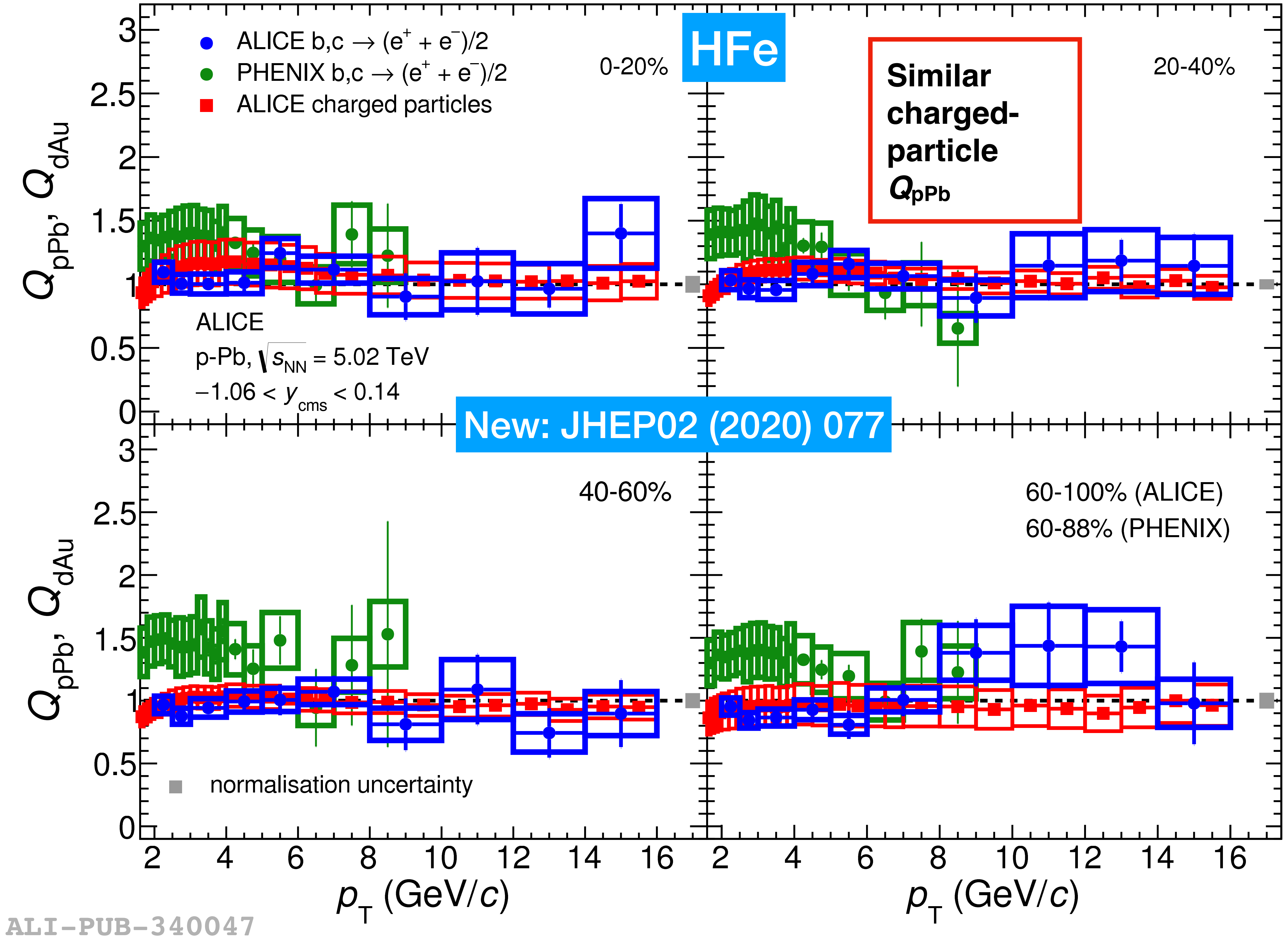
J/Ψ and Ψ(2S)→$\mu^+\mu^-$

- Strong CNM effects on J/Ψ at forward rapidity
- Strong CNM effects on Ψ(2S) at forward and backward rapidity, more suppressed than J/Ψ
  - ➡ described by models that include effect of shadowing and comover dissociation

HF production in p-Pb vs multiplicity

$$Q_{\mathrm{pPb}} = \frac{1}{\langle T_{\mathrm{pPb}}^{\mathrm{mult}} \rangle} \frac{\mathrm{d}N_{\mathrm{mult}}^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

Centrality classes: slicing the distribution of the energy deposited in the neutron calorimeter in the Pb-going side (ZNA)



ALI-PUB-340047

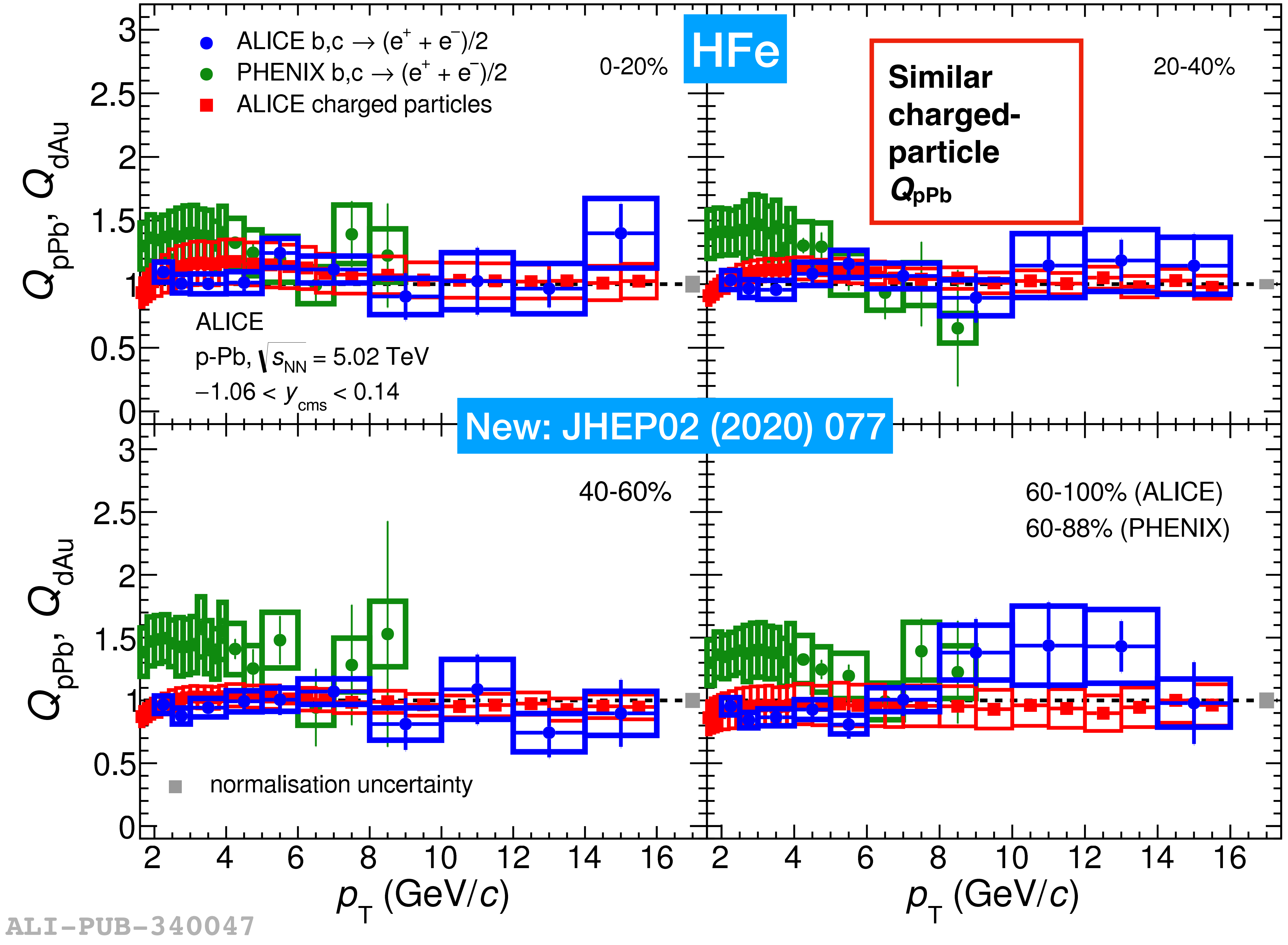
Q_{pPb} **consistent with unity** within uncertainties
More radial flow in RHIC d–Au than at the LHC?

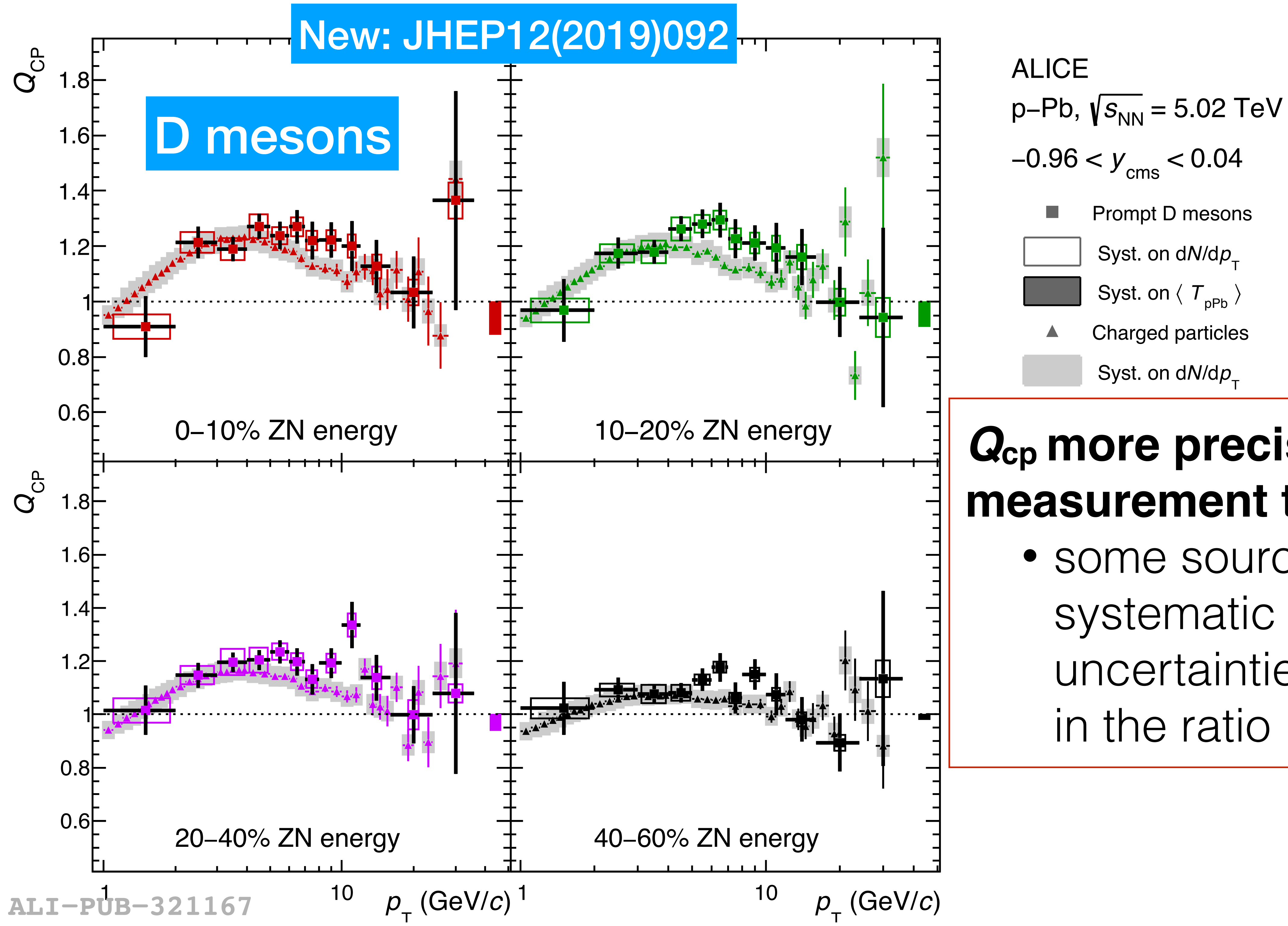
HF production in p-Pb vs multiplicity

$$Q_{\mathrm{pPb}} = \frac{1}{\langle T^{\mathrm{mult}}_{\mathrm{pPb}} \rangle} \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{mult}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

Centrality classes: slicing the distribution of the energy deposited in the neutron calorimeter in the Pb-going side (ZNA)

$$Q_{\mathrm{CP}} = \frac{(\mathrm{d}^2N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{0-10}_{\mathrm{pPb}} / \langle T_{\mathrm{pPb}} \rangle^{0-10}}{(\mathrm{d}^2N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{60-100}_{\mathrm{pPb}} / \langle T_{\mathrm{pPb}} \rangle^{60-100}}$$





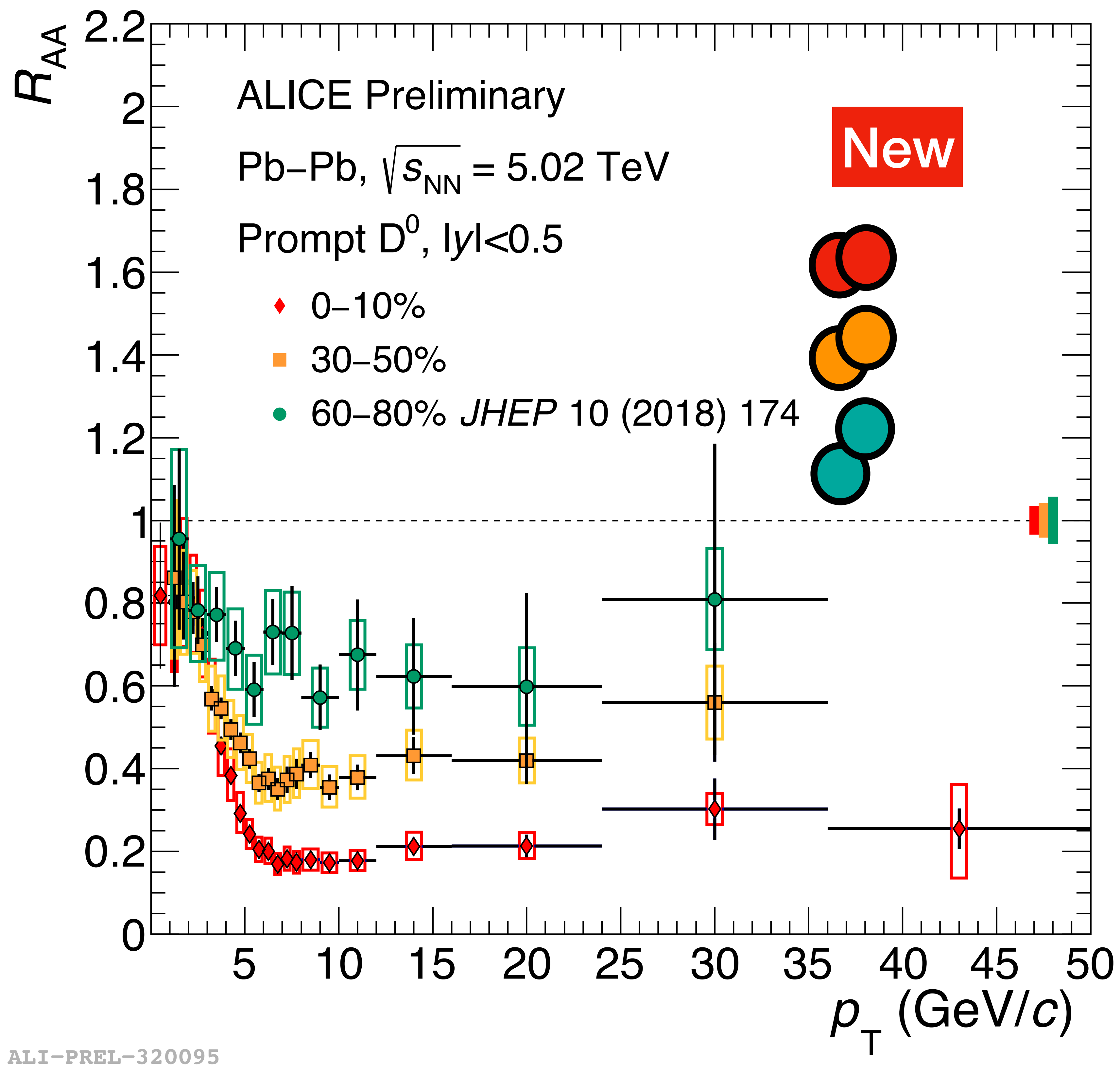
Q_{cp} more precise measurement than Q_{pPb}
- some sources of systematic uncertainties cancel in the ratio

Q_{pPb} consistent with unity within uncertainties
More radial flow in RHIC d–Au than at the LHC?

Hint of $Q_{\mathrm{cp}} > 1$ in $3 < p_{\mathrm{T}} < 8$ GeV/c **for D mesons with 3σ** significance.
Similar trend as for charged particles. Shifted mean?
➡Radial flow? Initial or final-state effect?

Nuclear modification factor: R_{pPb} vs R_{AA}

Strong suppression in 0-10% central Pb-Pb collisions



First measurement of HF in Pb-Pb down to p_T = 0 at LHC

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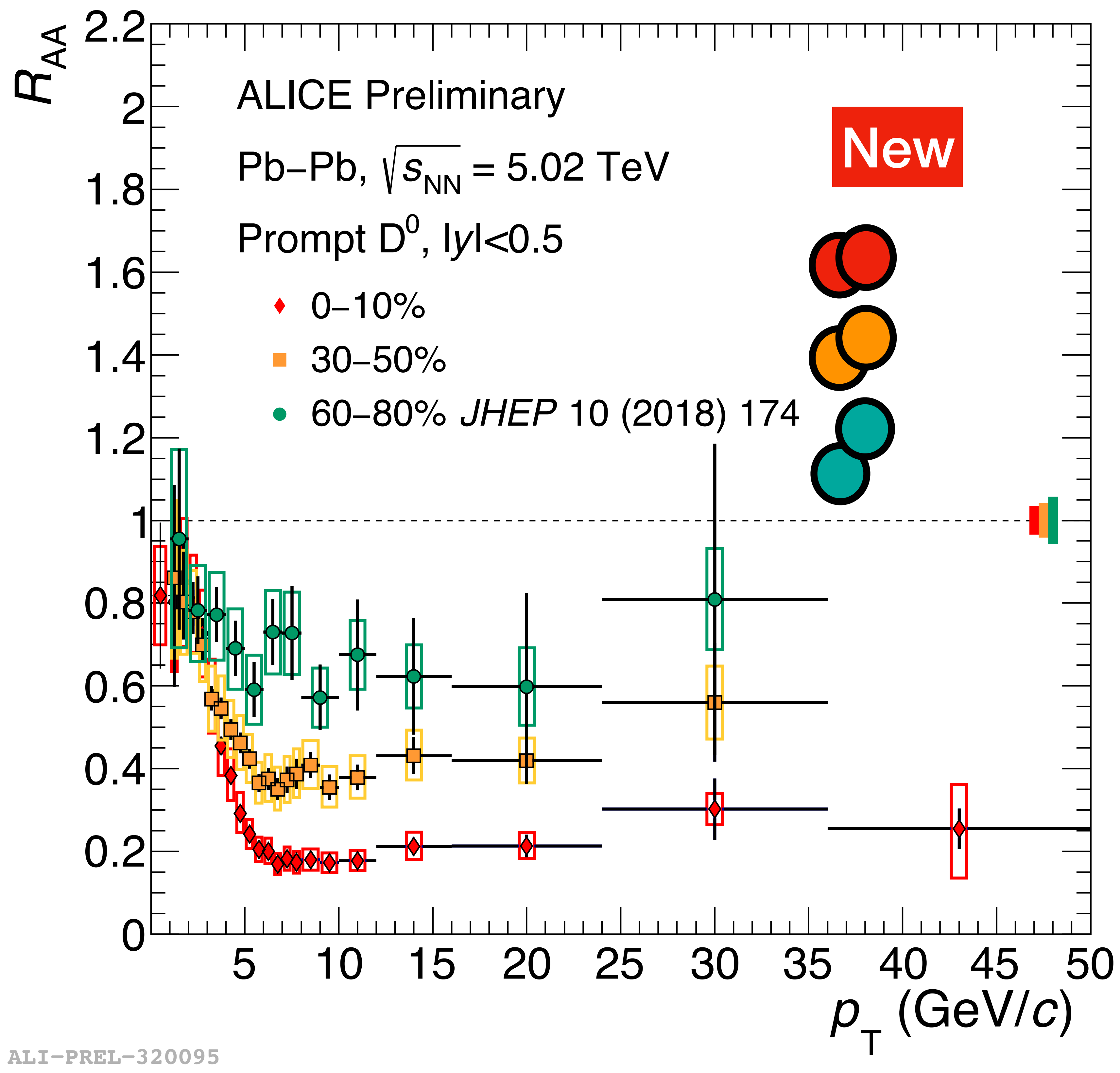
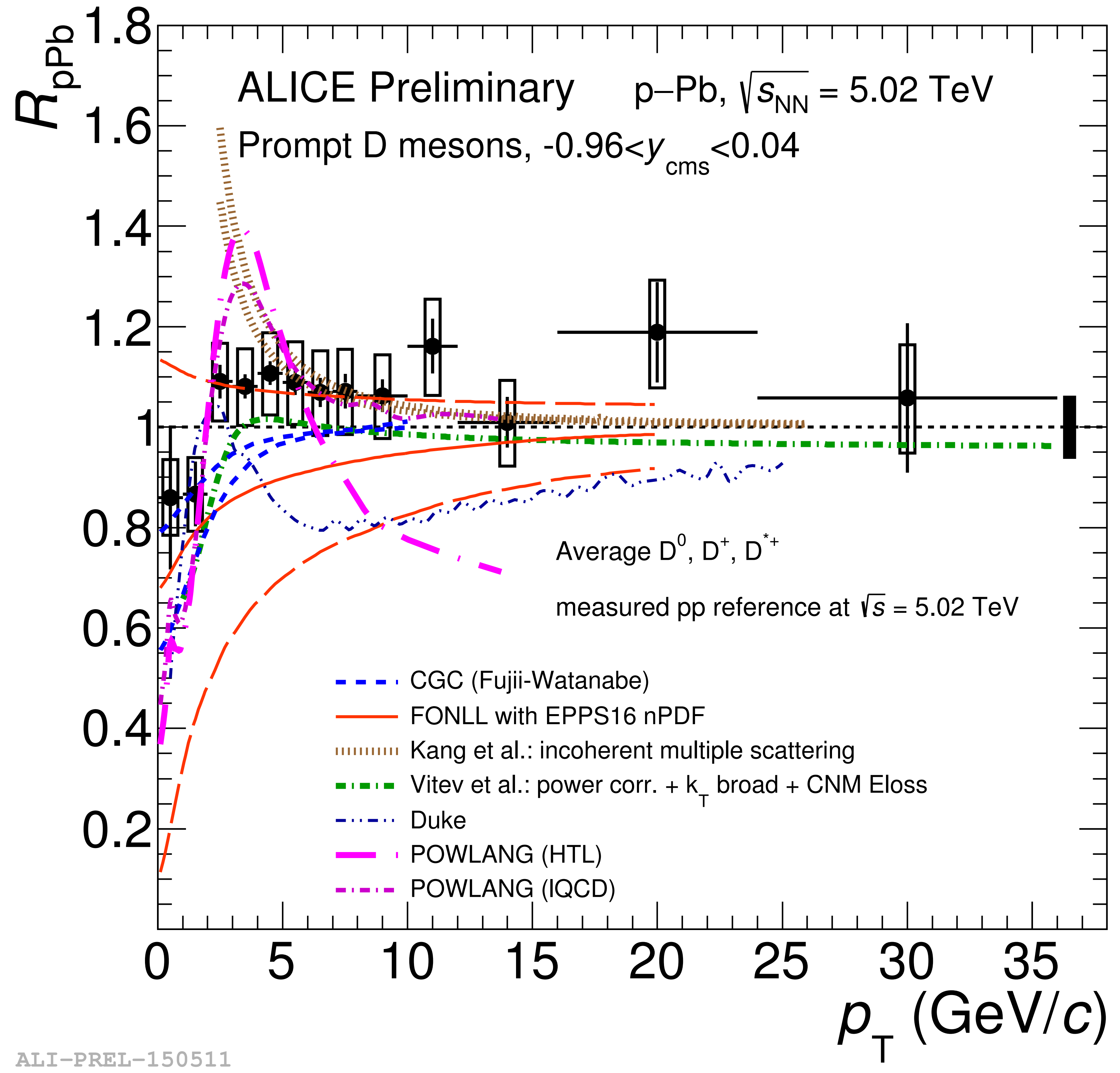


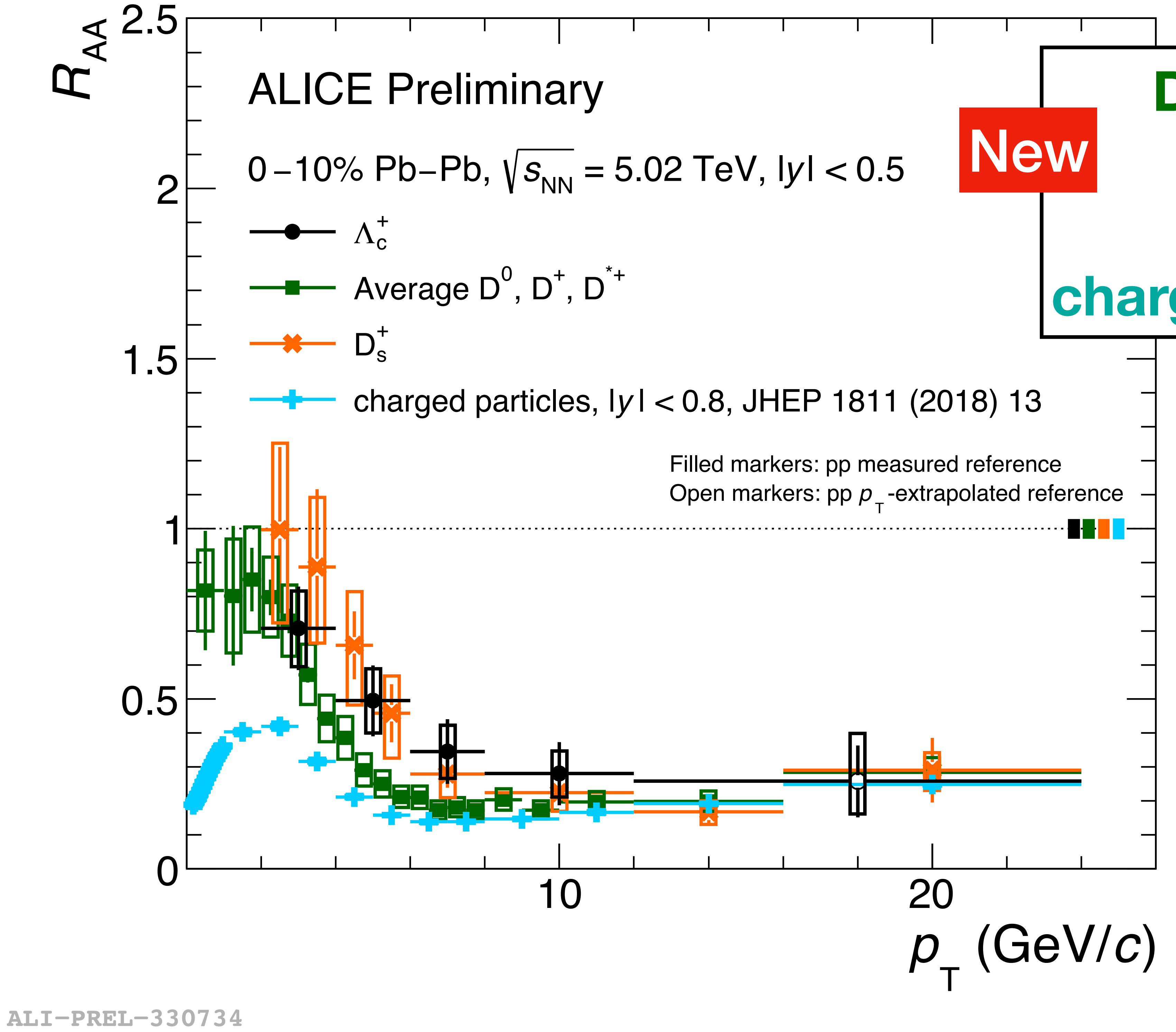


First measurement of HF in Pb-Pb down to p_T = 0 at LHC

R_{pPb} compatible with unity for p_T>3 GeV/c
➡ Strong suppression in Pb-Pb is due to final state effects!

Open HF nuclear modification factor R_{AA}

Energy loss mechanisms, flavour dependence, radiative and collisional processes, suppression and recombination



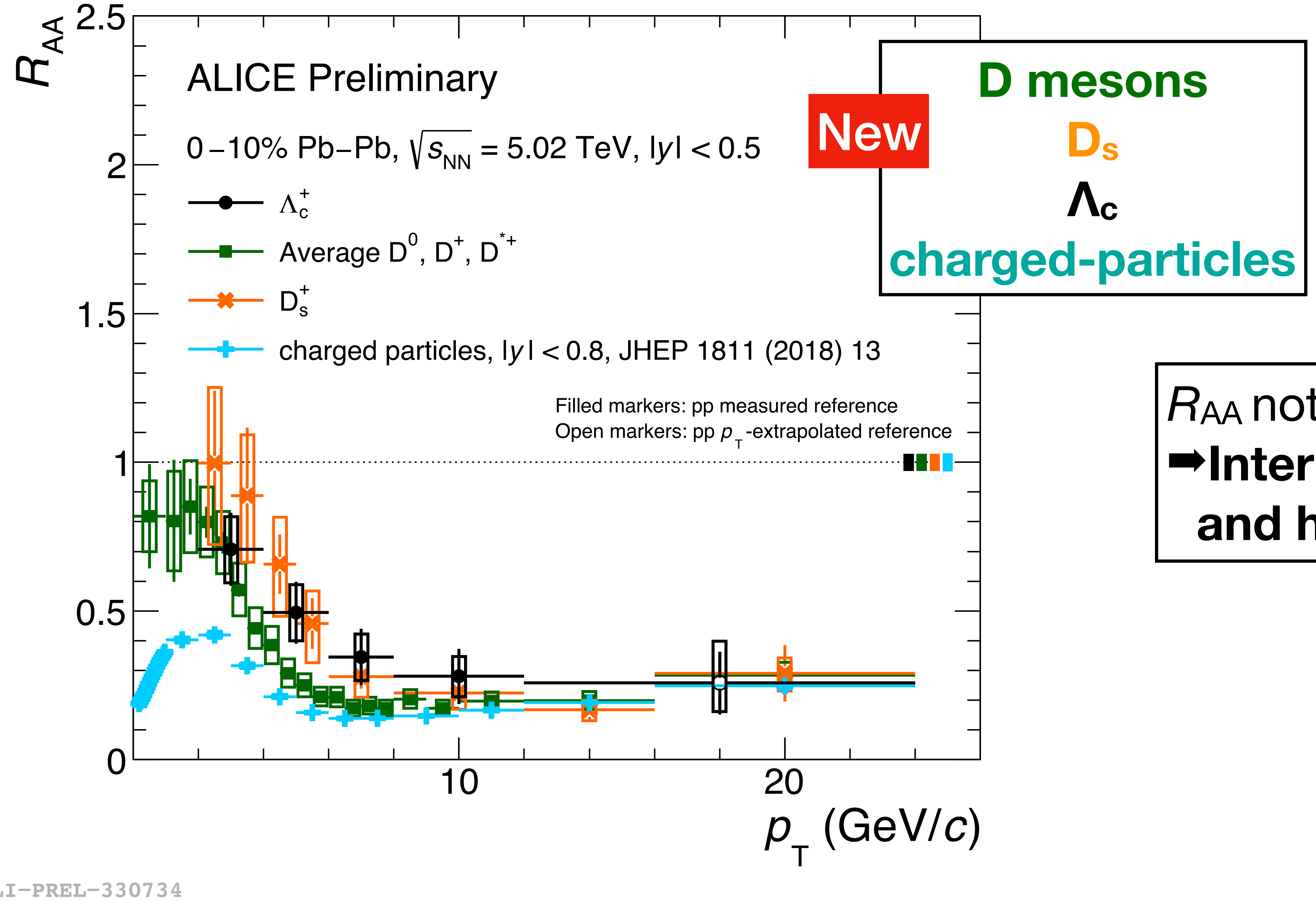
New

D mesons
D_s
Λ_c
charged-particles

- Similar suppression of **D mesons** and **charged particles** at high p_T
- **less suppression for D at low/intermediate p_T**
  - Interplay of harder charm p_T distributions and different fragmentation functions w.r.t. light quarks and gluons
- **Bump at low p_T:** charm quarks gain collective motion in the medium evolution?
  - **Hint of less suppressed D_s** and **Λ_c**

Open HF nuclear modification factor R_{AA}

Energy loss mechanisms, flavour dependence, radiative and collisional processes, suppression and recombination



R_{AA} not determined just by 'energy loss'
➡**Interplay of energy loss, collective motion and hadronization mechanisms**

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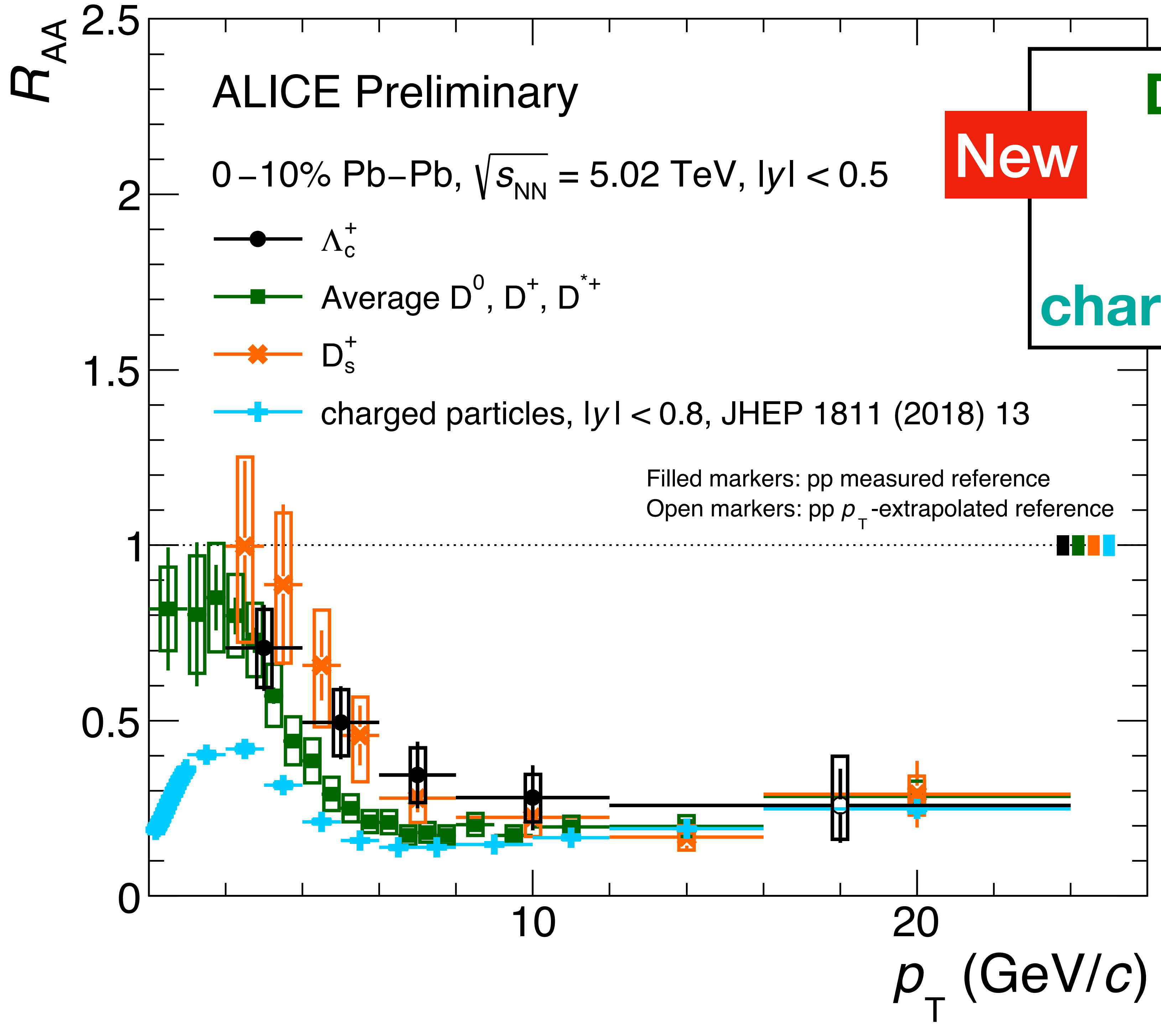

New

D mesons
D_s
Λ_c
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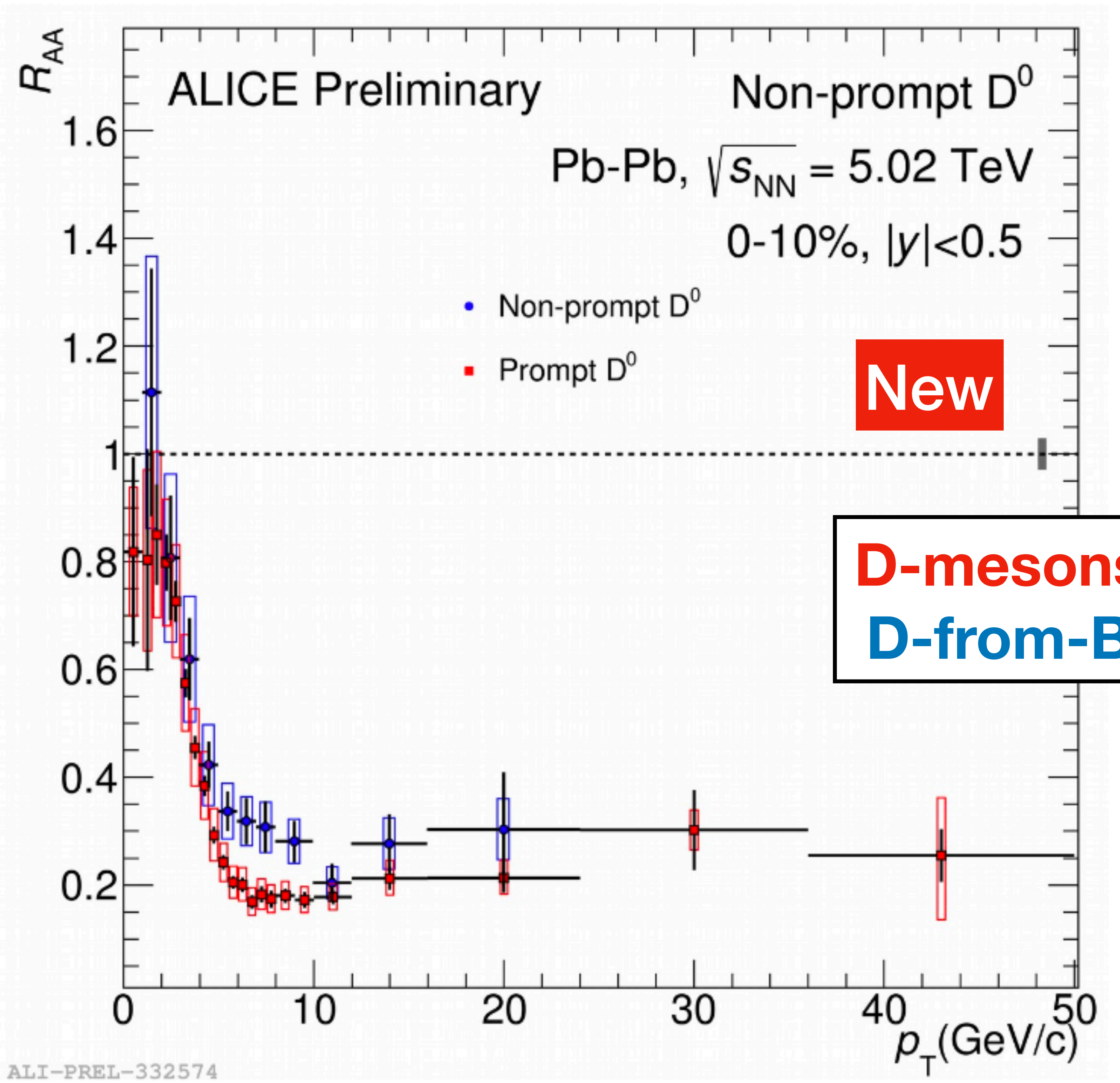

New

D-mesons
D-from-B

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- **less suppression for D at low/intermediate p_T**
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- **Bump at low p_T:** charm quarks gain collective motion in the medium evolution?
  - **Hint of less suppressed D_s** and **Λ_c**

- Larger suppression for prompt **D^0 mesons** wrt **D^0 from B** in 5 < p_T <10 GeV/c
  - Hint of **m_Q ordering from B w.r.t. D at low p_T**

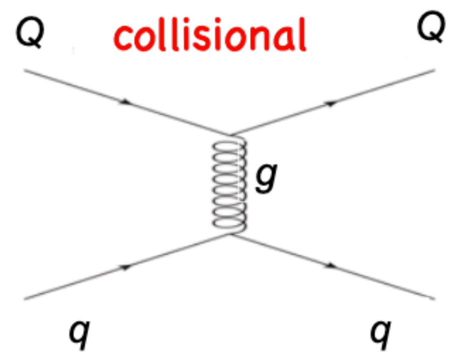
Hint of hierarchy observed ad low-p_T $R_{AA}(\pi)<R_{AA}(D)<R_{AA}(B)$

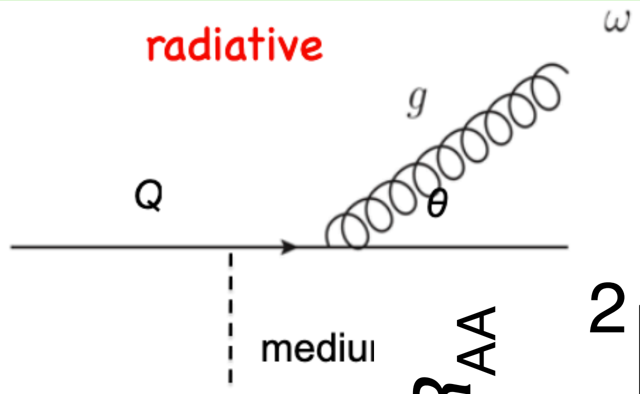
Color charge and mass dependence of R_{AA}

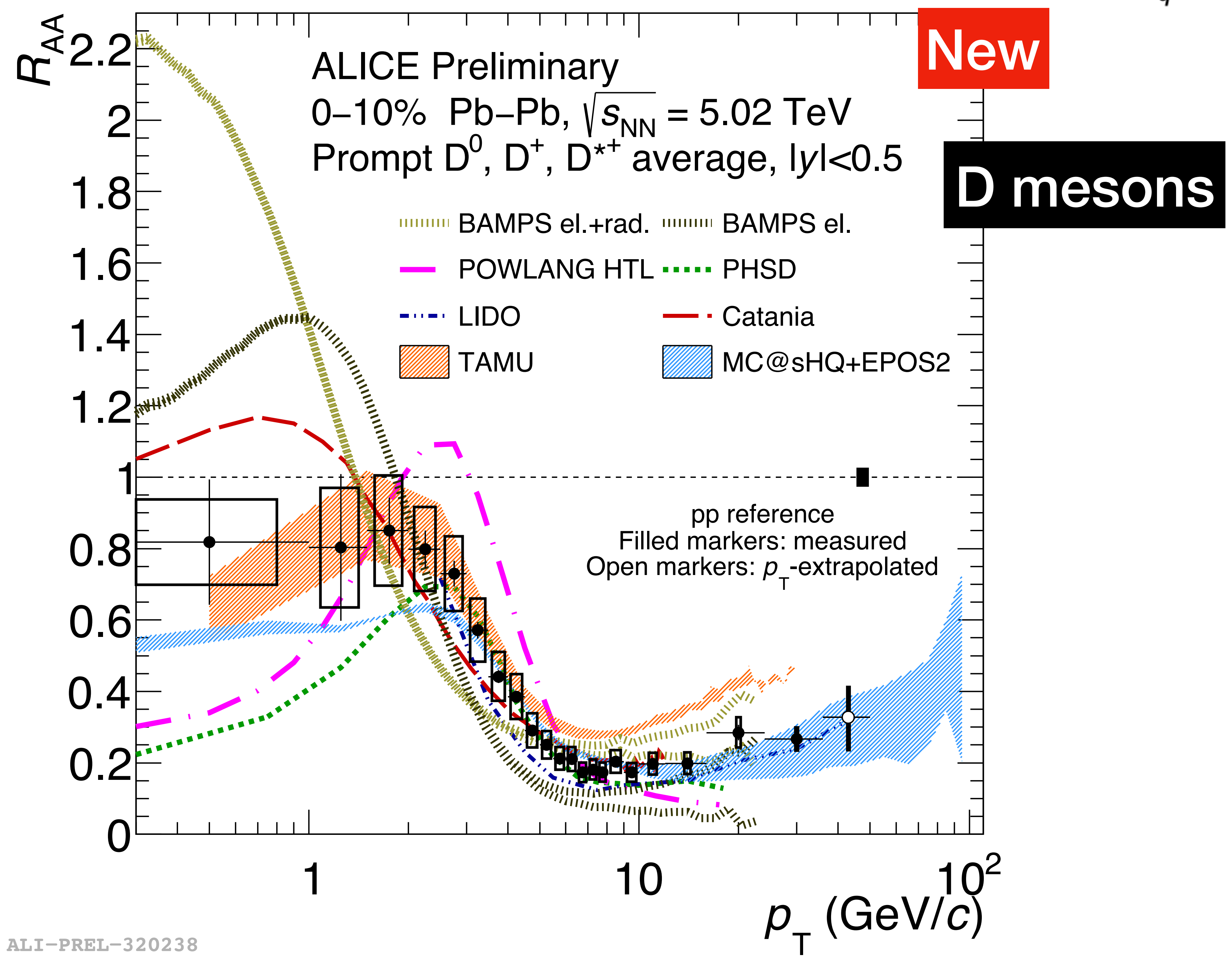
Open HF hadron R_{AA}: theoretical model comparison

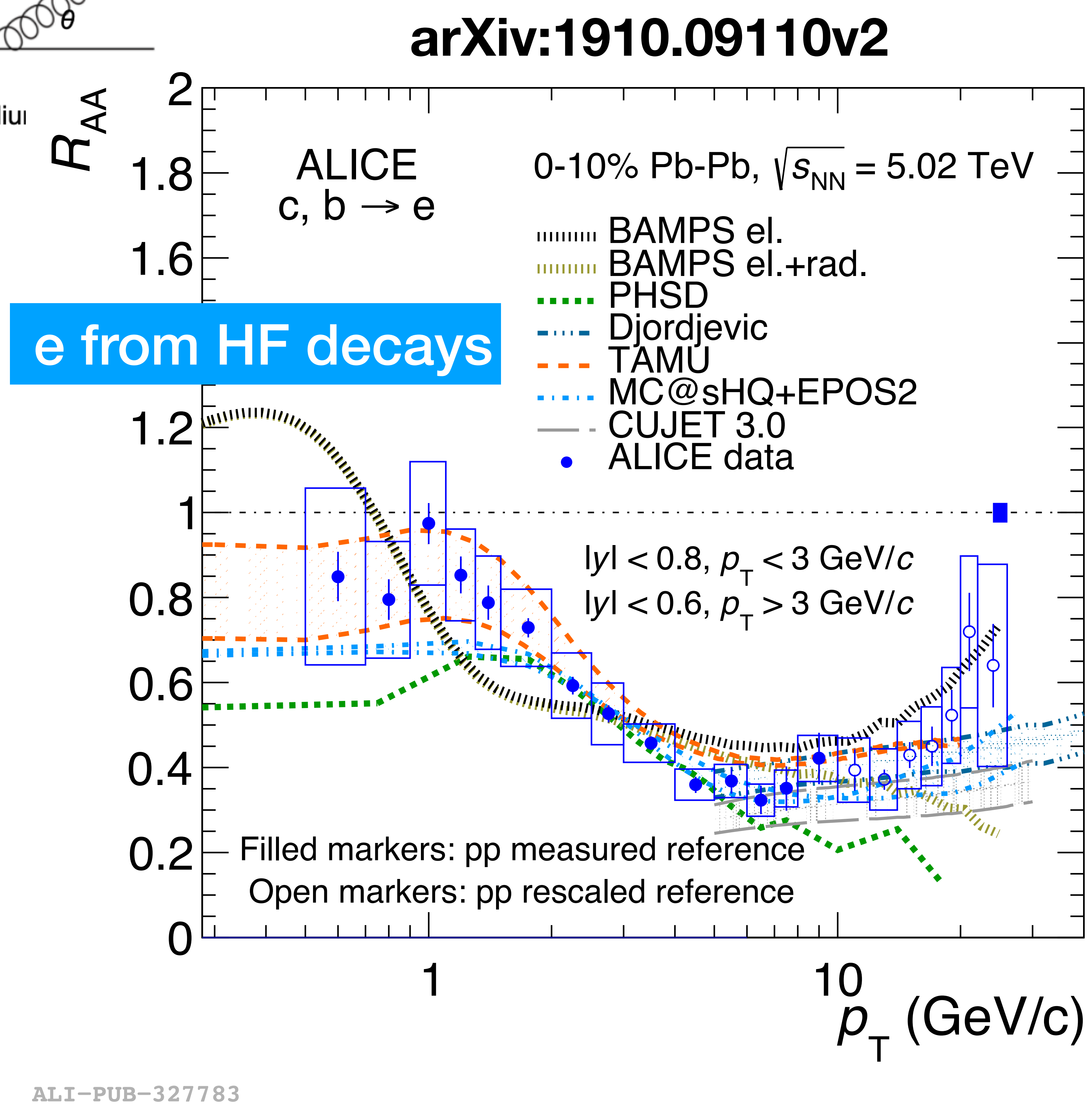
Energy loss mechanisms, flavour dependence, radiative and collisional processes, suppression and recombination

quarks are expected to lose energy via **collisional** (dominant at low p_T) and **radiative** (dominant at high p_T) energy loss









- **POWLANG**, **BAMPS el**, **TAMU**: do not include radiative energy loss

➡determination of onset of radiative contributions by deviations from experimental data at a certain p_T

- **PHSD**, **MC@sHQ+EPOS2**, BAMPS el.rad, **Djordjevic**: **both elastic and radiative** contributions are included
- **Quark recombination: in TAMU, POWLANG, PHSD, MC@sHQ, LBT, Catania**

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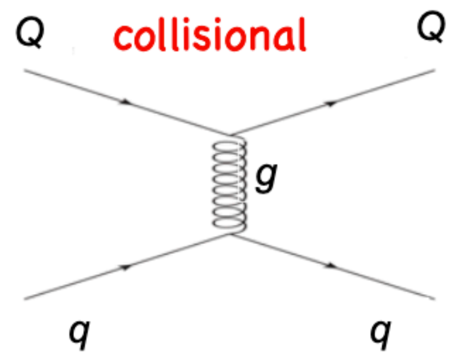
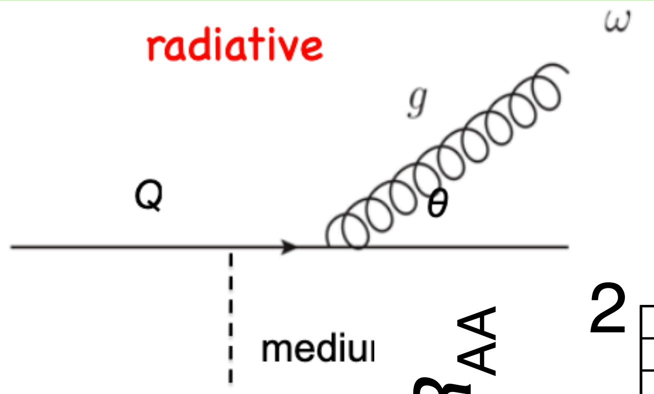
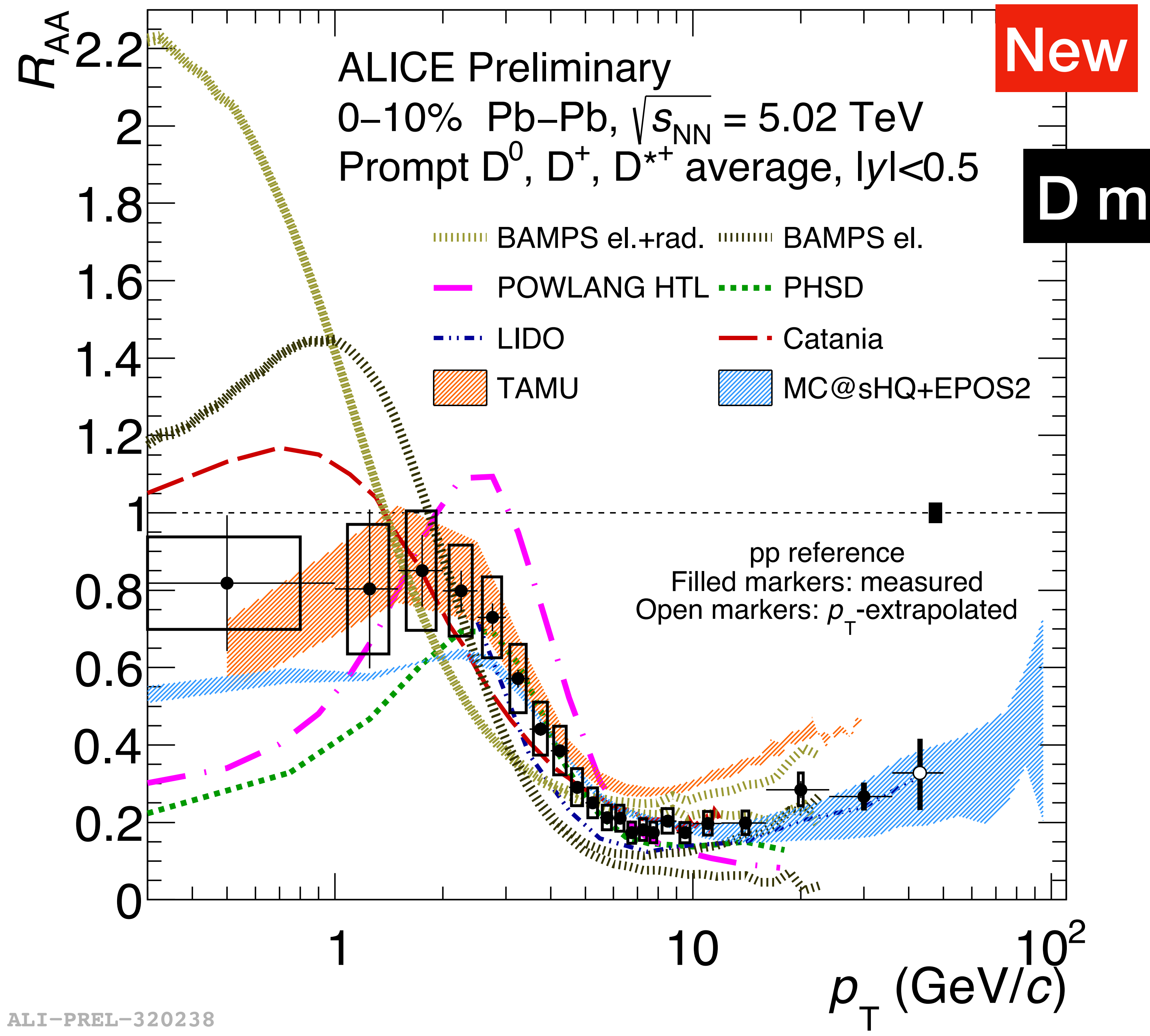




New

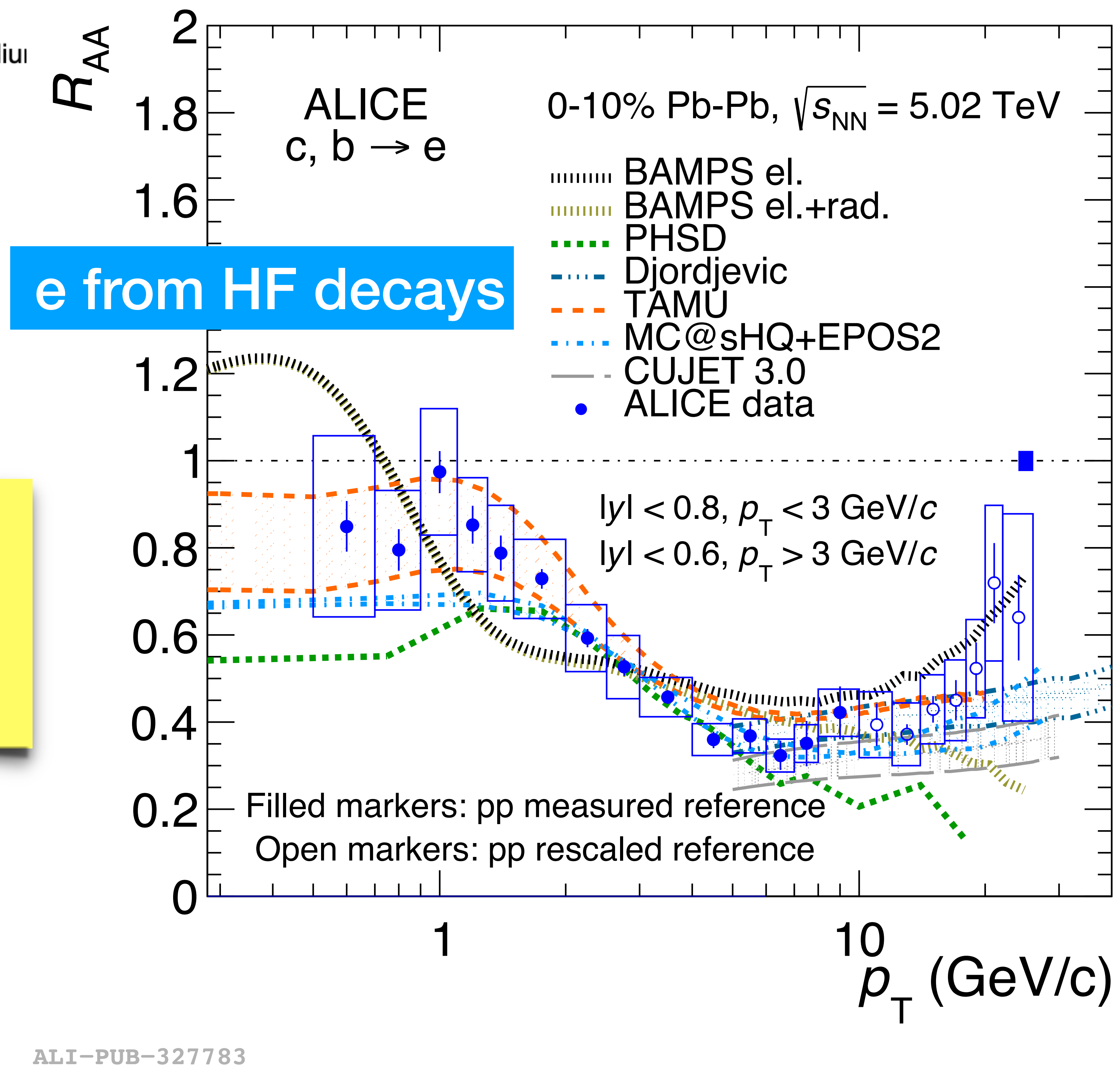
D mesons



Interplay with **coll + rad energy loss**, **hadronization via coal+frag**, **hydrodynamic expansion** of medium **needed**

arXiv:1910.09110v2

e from HF decays



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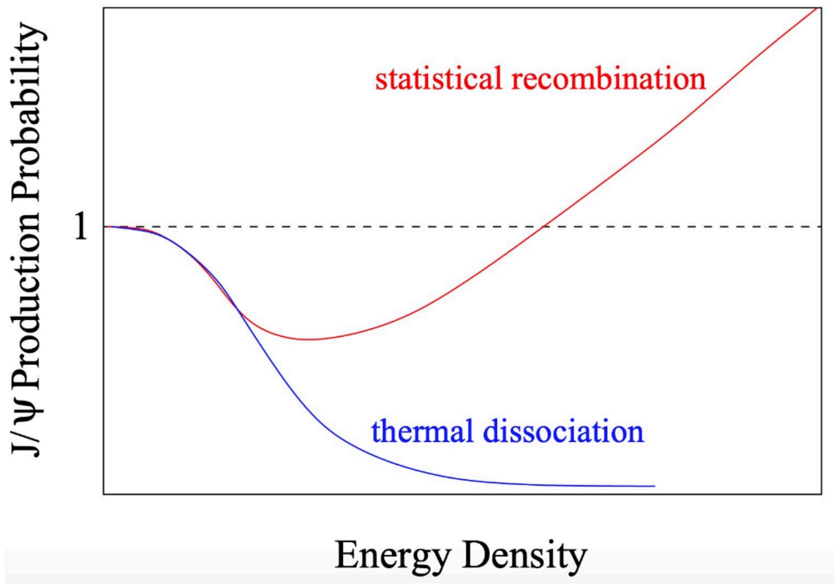
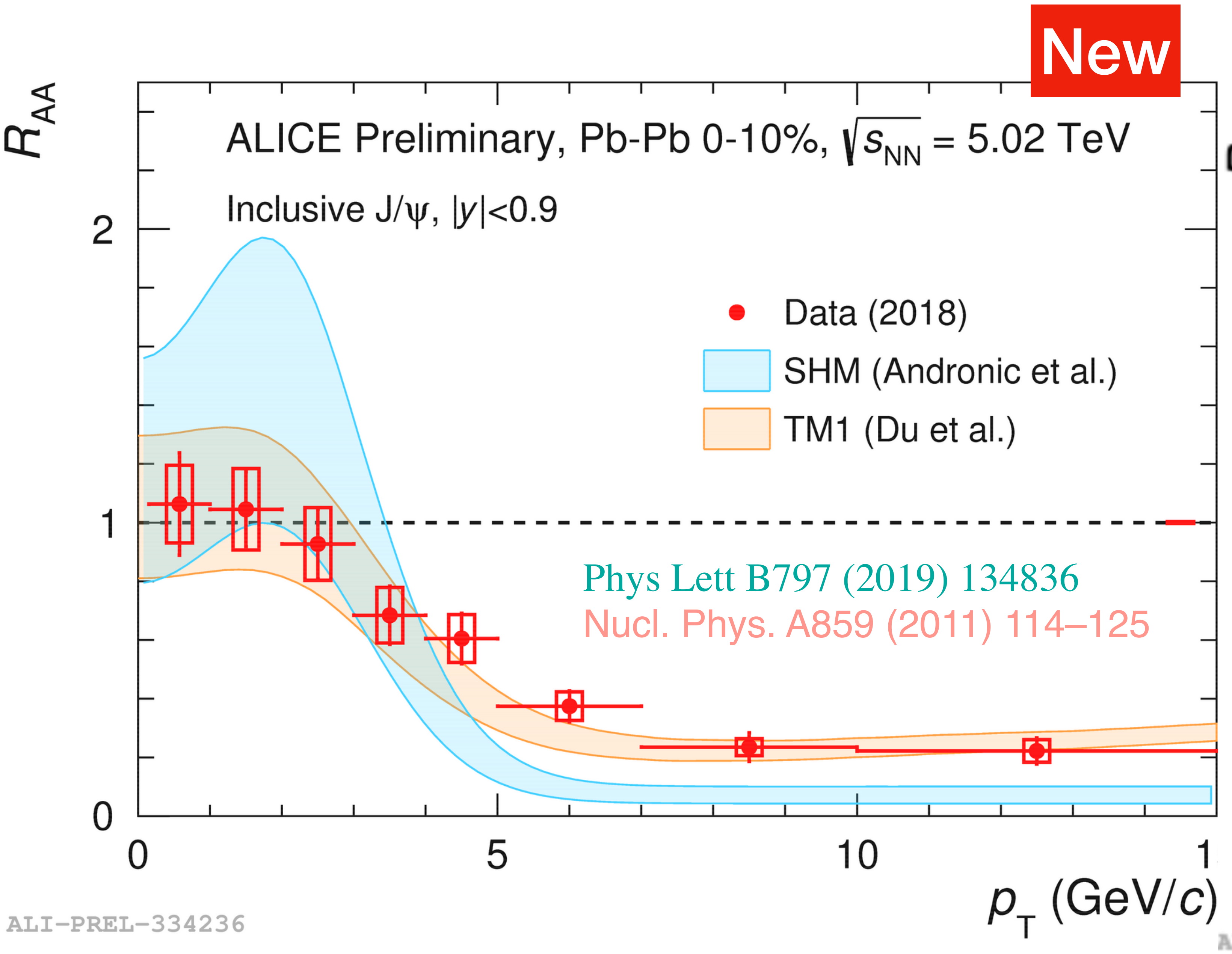
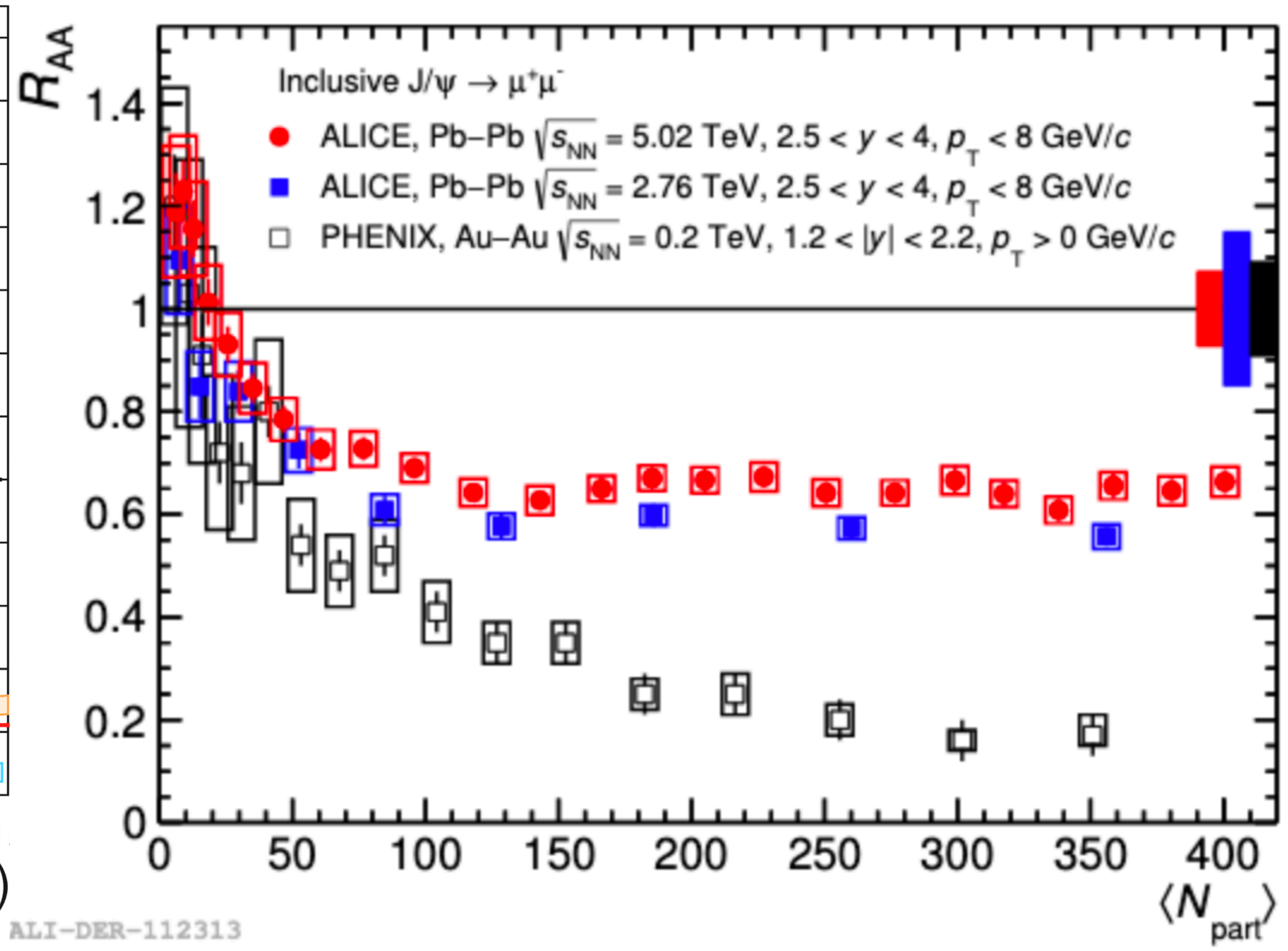
Quarkonia: J/Ψ R_{AA}







Statistical hadronization model describes the measurement at low p_T, while **the transport model** agrees with data for all p_T

Suppression and **regeneration** of quarkonia

- less suppressed J/Ψ at **ALICE** than at **Phenix**: larger amount of regeneration in medium at LHC
- Small dependence of R_{AA} at the LHC energies

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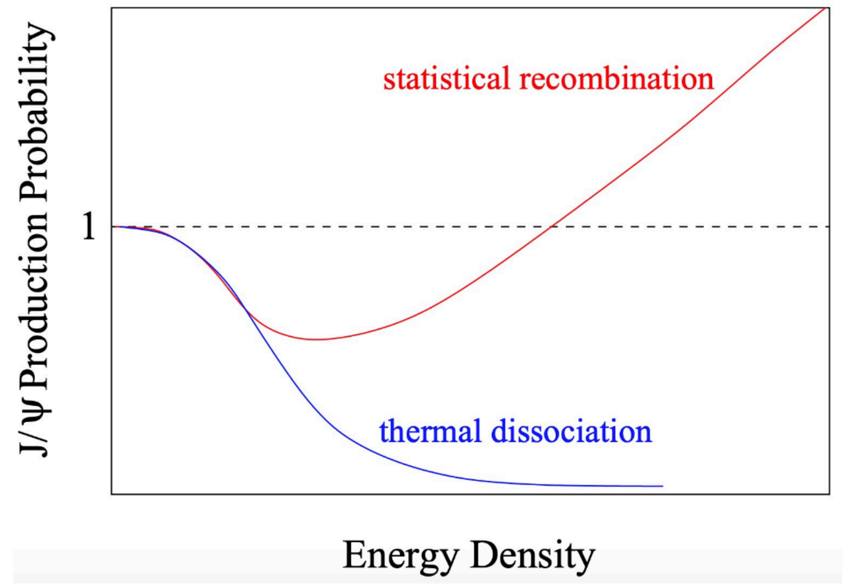

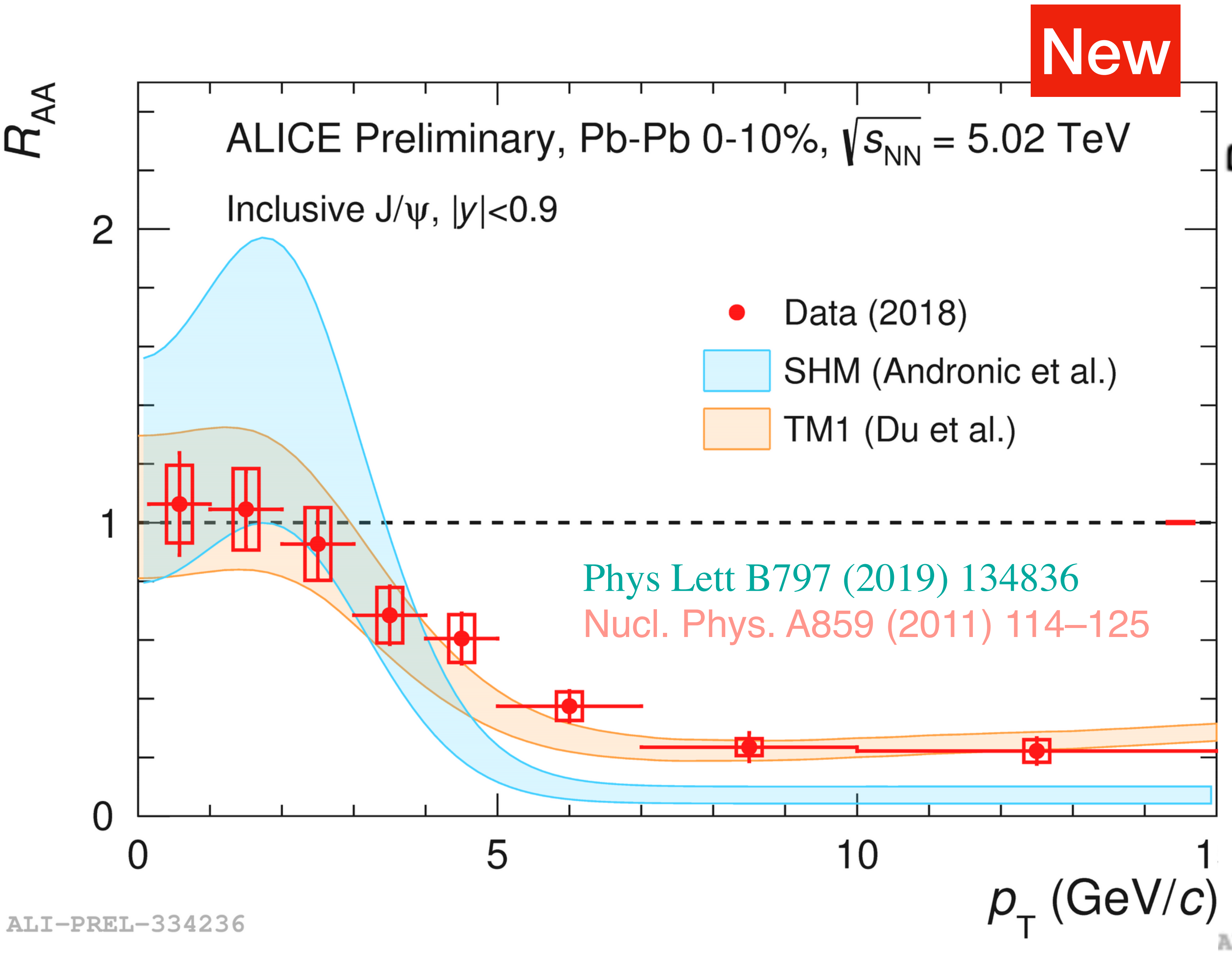

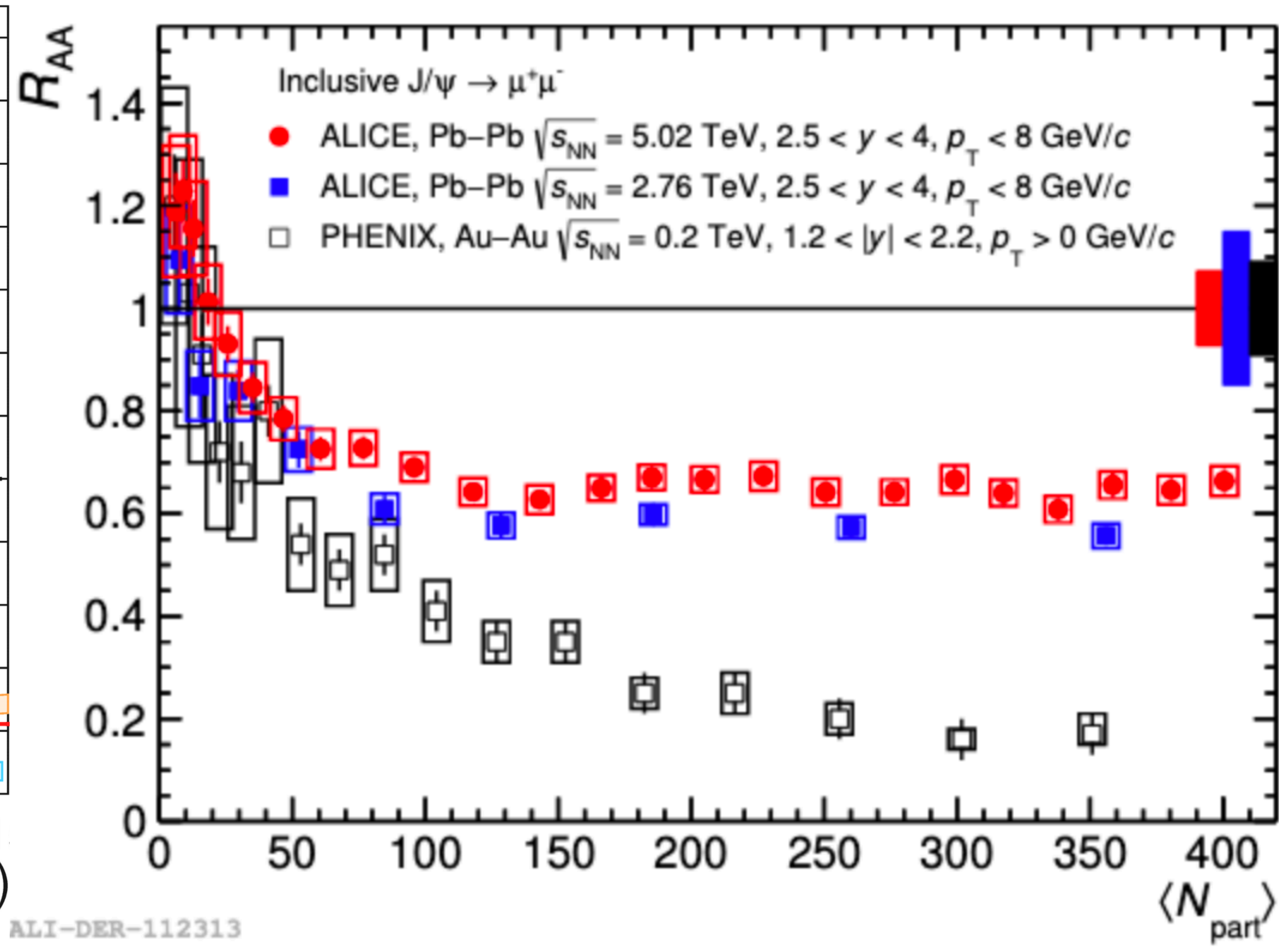

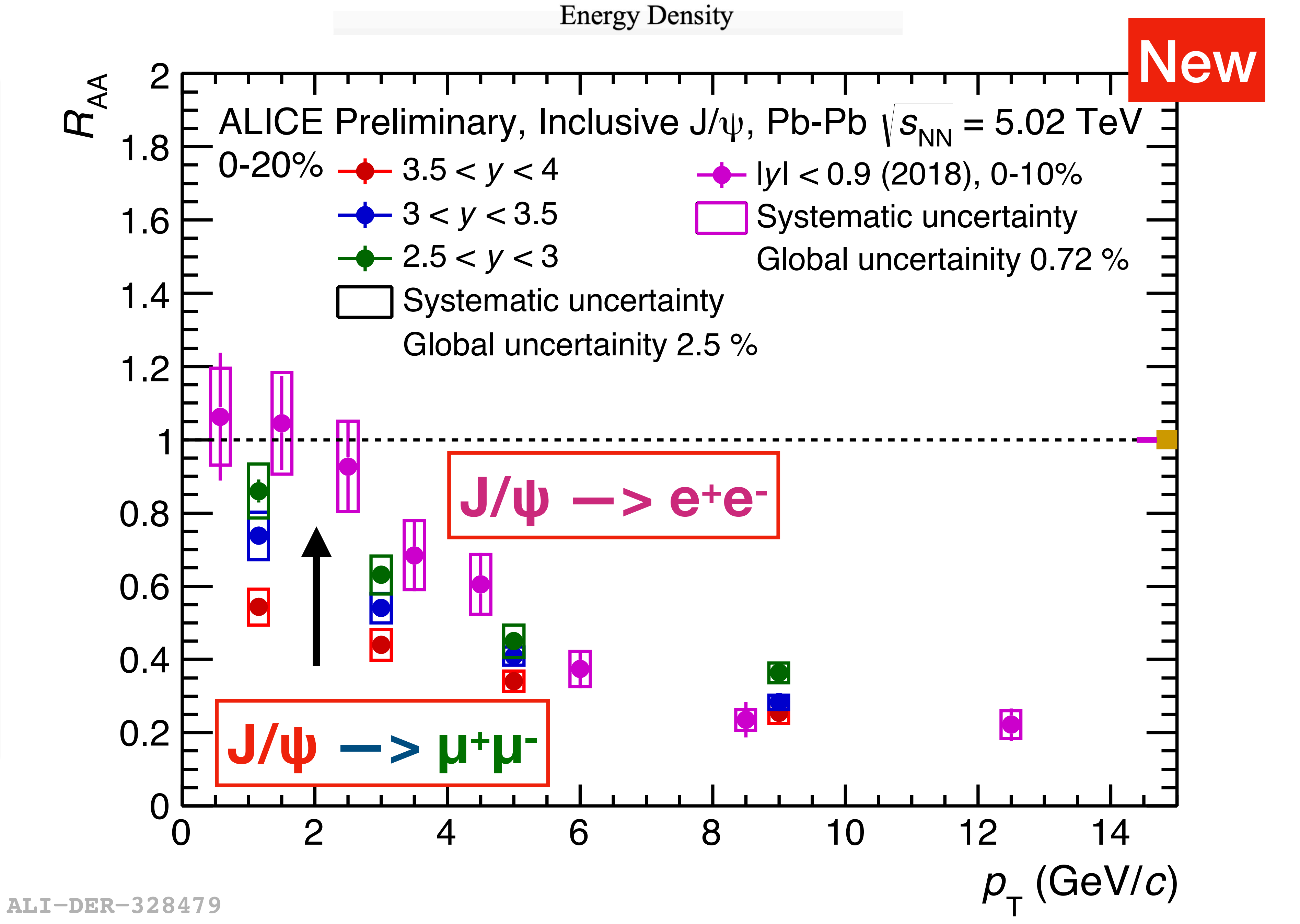

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- **Rapidity dependence of J/ψ R_{AA} at low p_T**
- Consistent with regeneration models:
  - charm quark density increases towards mid rapidity
  - rise of R_{AA} at low p_T as a further sign of regeneration

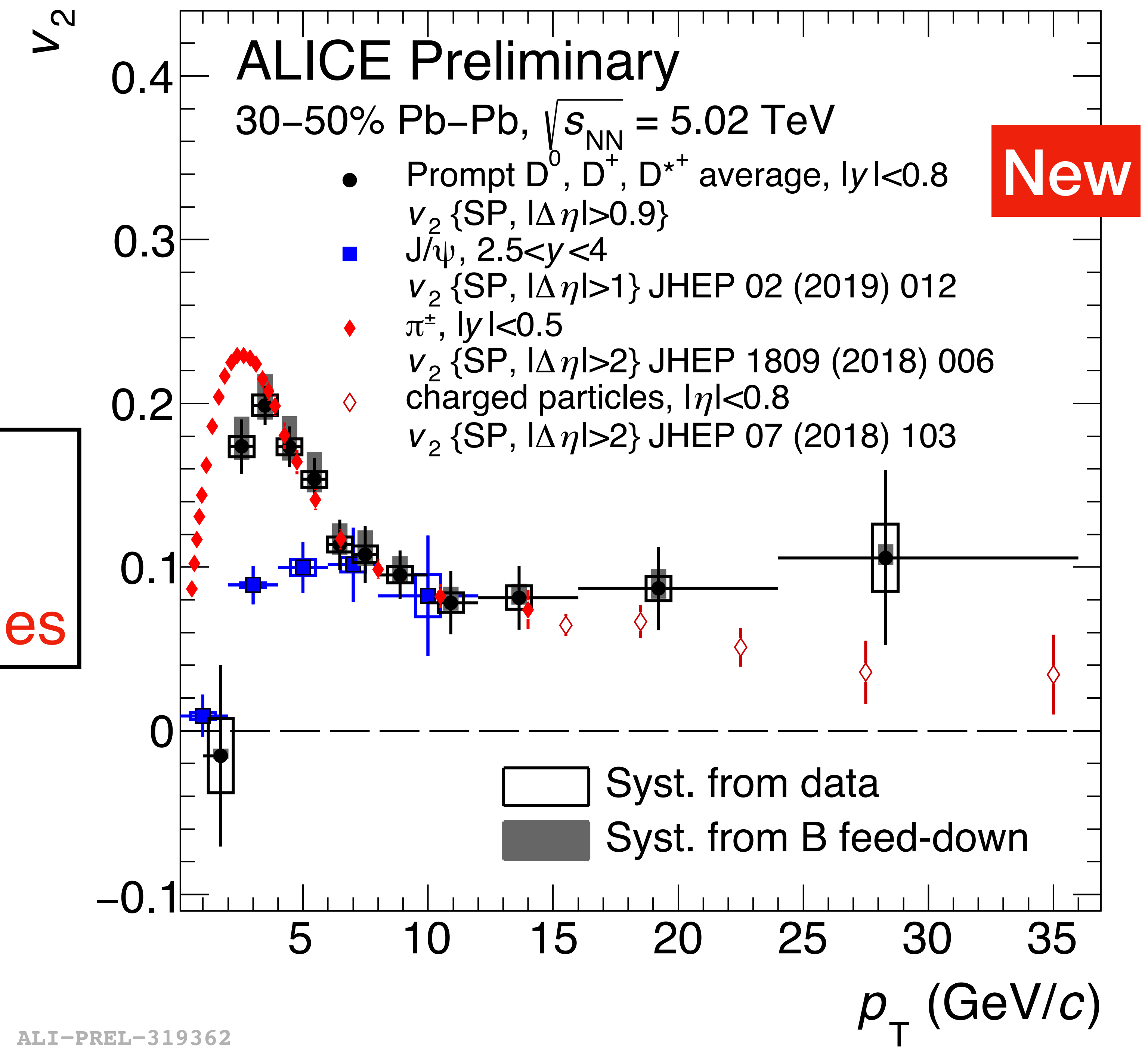
charm v_2

Thermalization
as a consequence of HQ coupling with medium

➡Positive charm hadrons v_2 observed
- charm quarks largely thermalize in QGP until hadronization

Pb-Pb

D mesons
J/Ψ
Charged particles



- **Similar** v_2 for **charged particles** and **D mesons** for $p_T > 3$ GeV/c
- **Slightly higher** v_2 for **charged particles** than **D mesons** at low p_T
  - indication of radial flow? mass scaling also in charm sector?
- similar v_2 for **J/Ψ for $p_T > 6$ GeV/c and v_2(D)>v_2(J/Ψ) at low p_T** (different y-interval though)
  - non-zero J/Ψ v_2 is likely dominated at low and intermediate p_T by J/Ψ from recombination that should inherit charm quark flow

Charm is strongly coupled in QGP.

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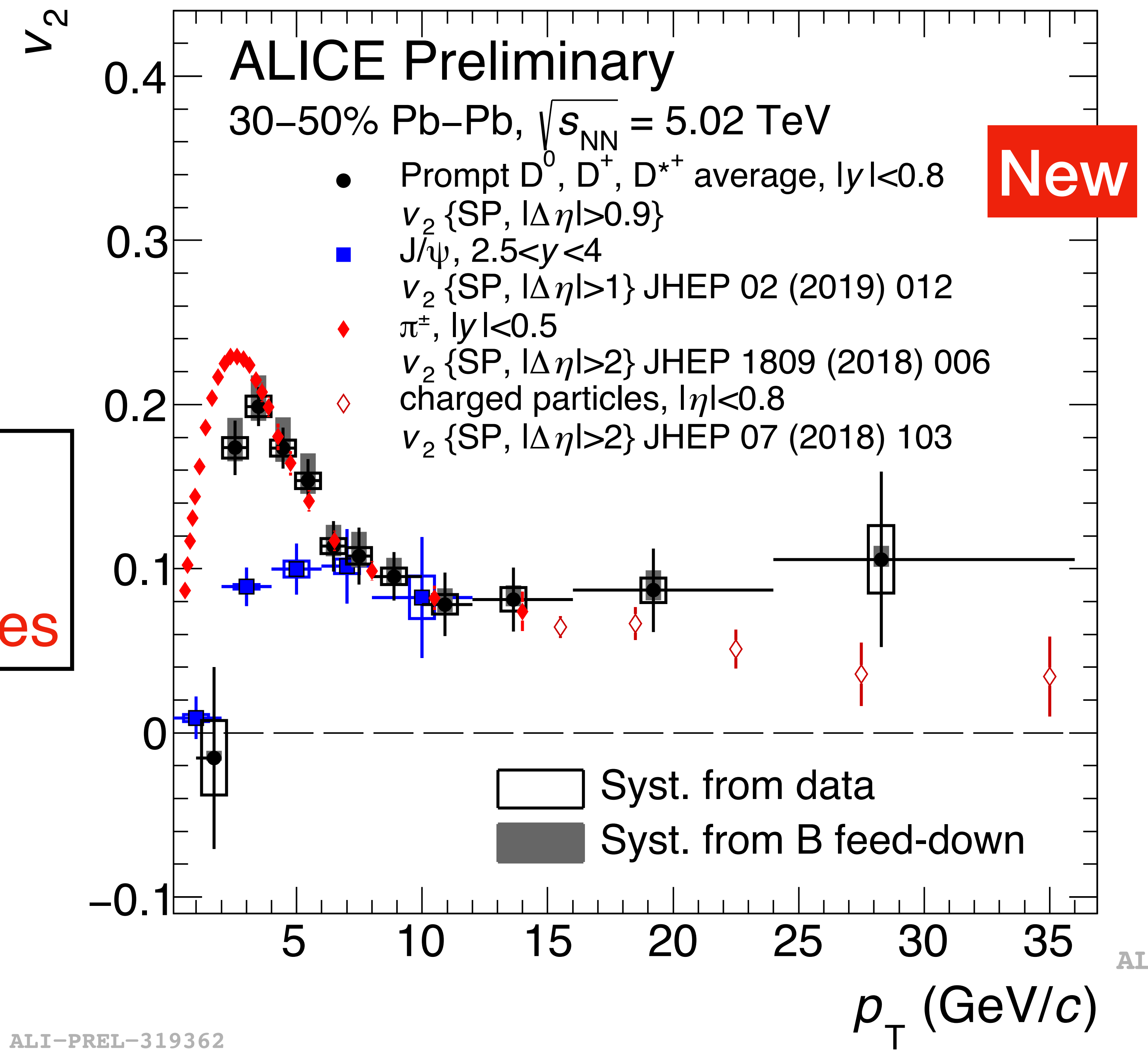

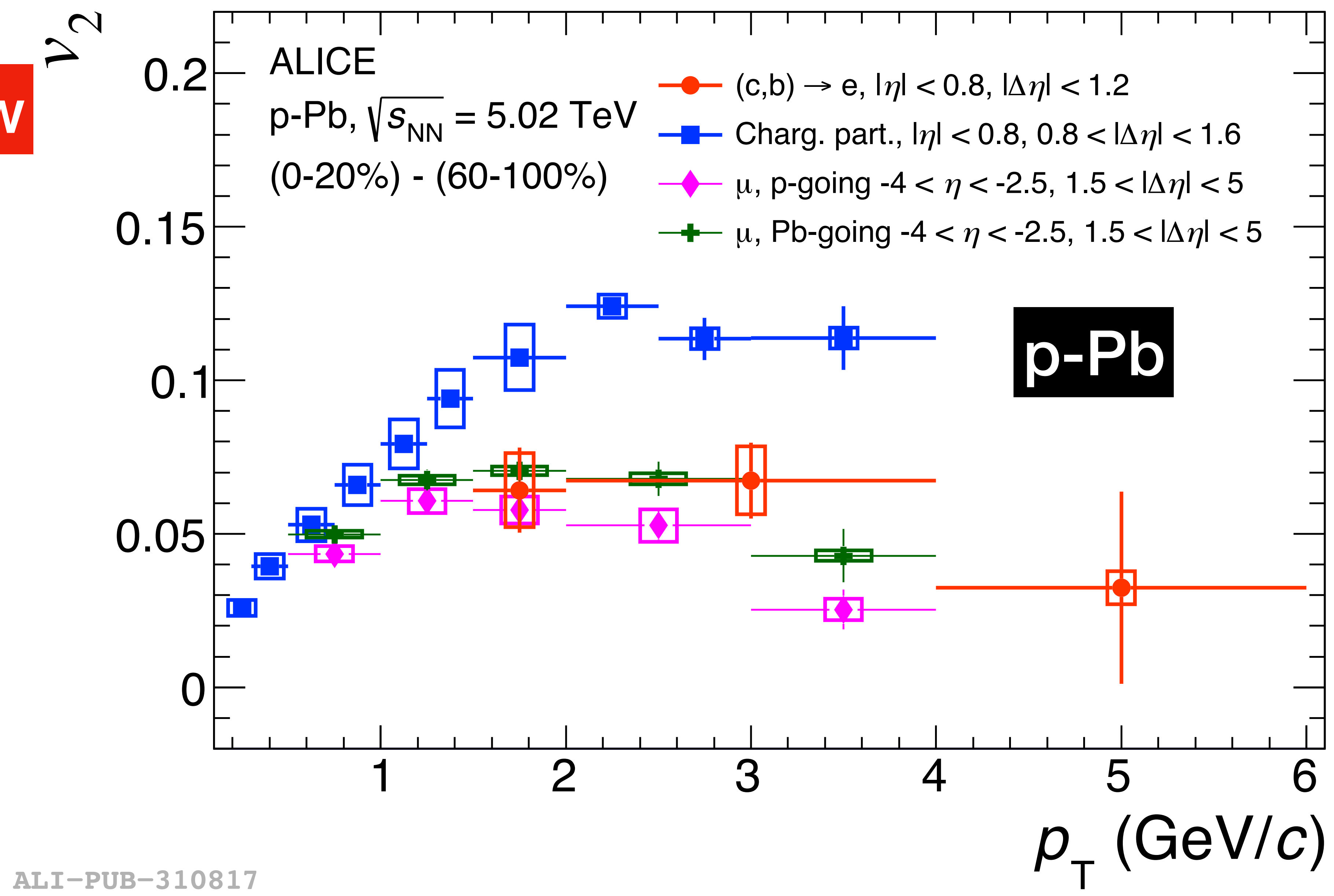

HFe, **HFμ**, **charged particles**

Phys.Rev.Lett. 122 (2019) no.7, 072301

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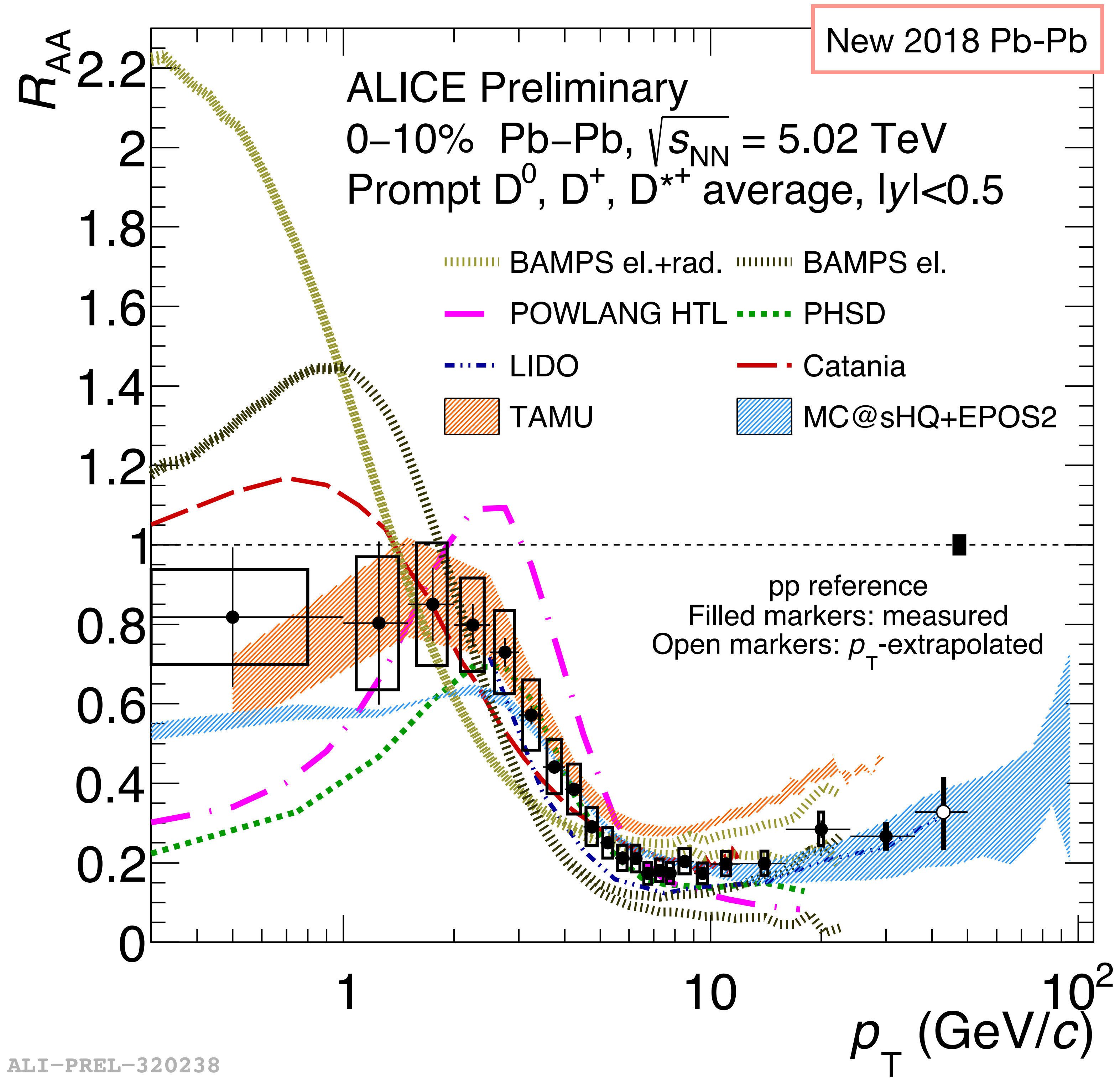
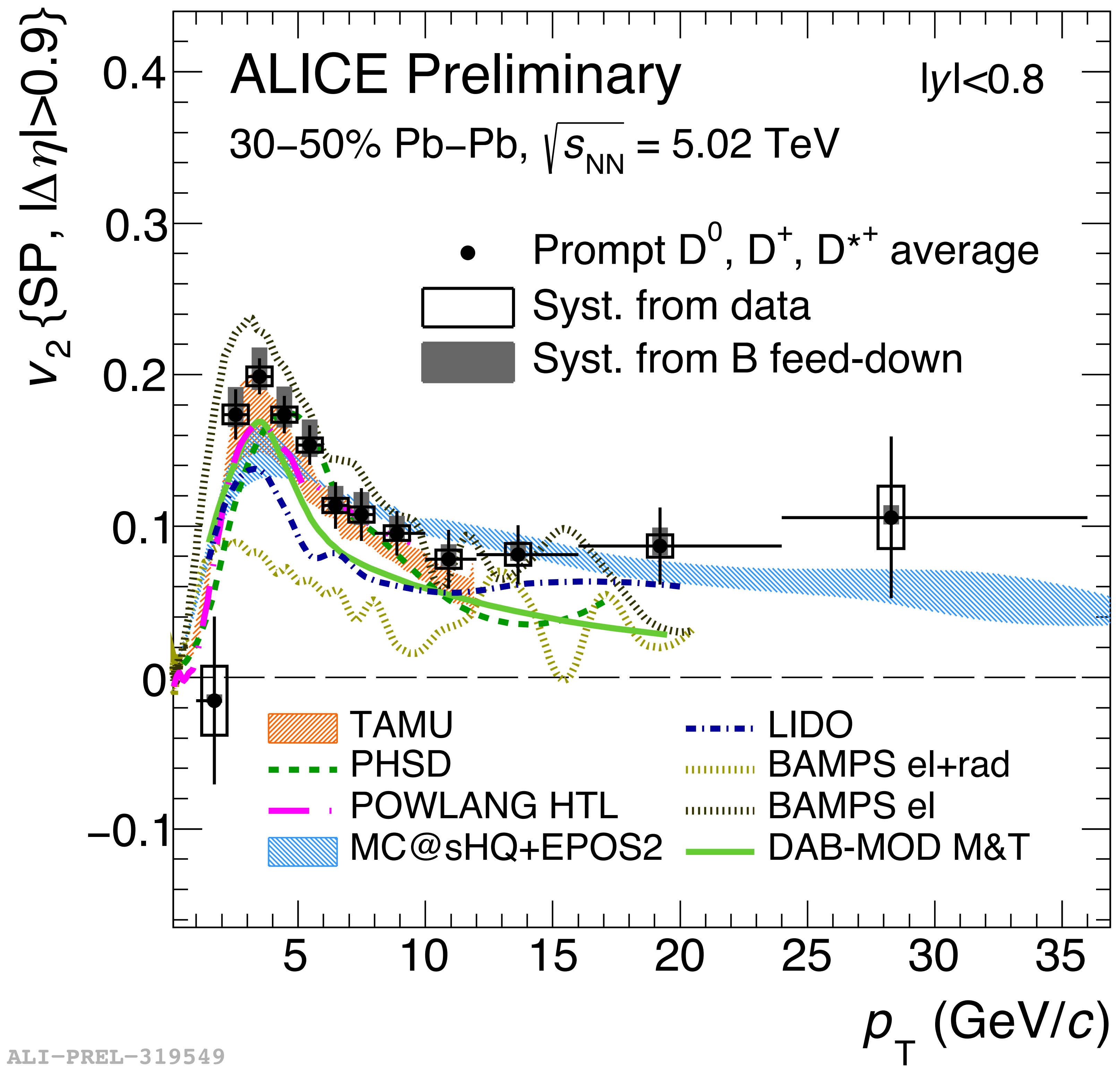
- **Non zero v_2 for HFe and HFμ in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV: collectivity in p-Pb?**

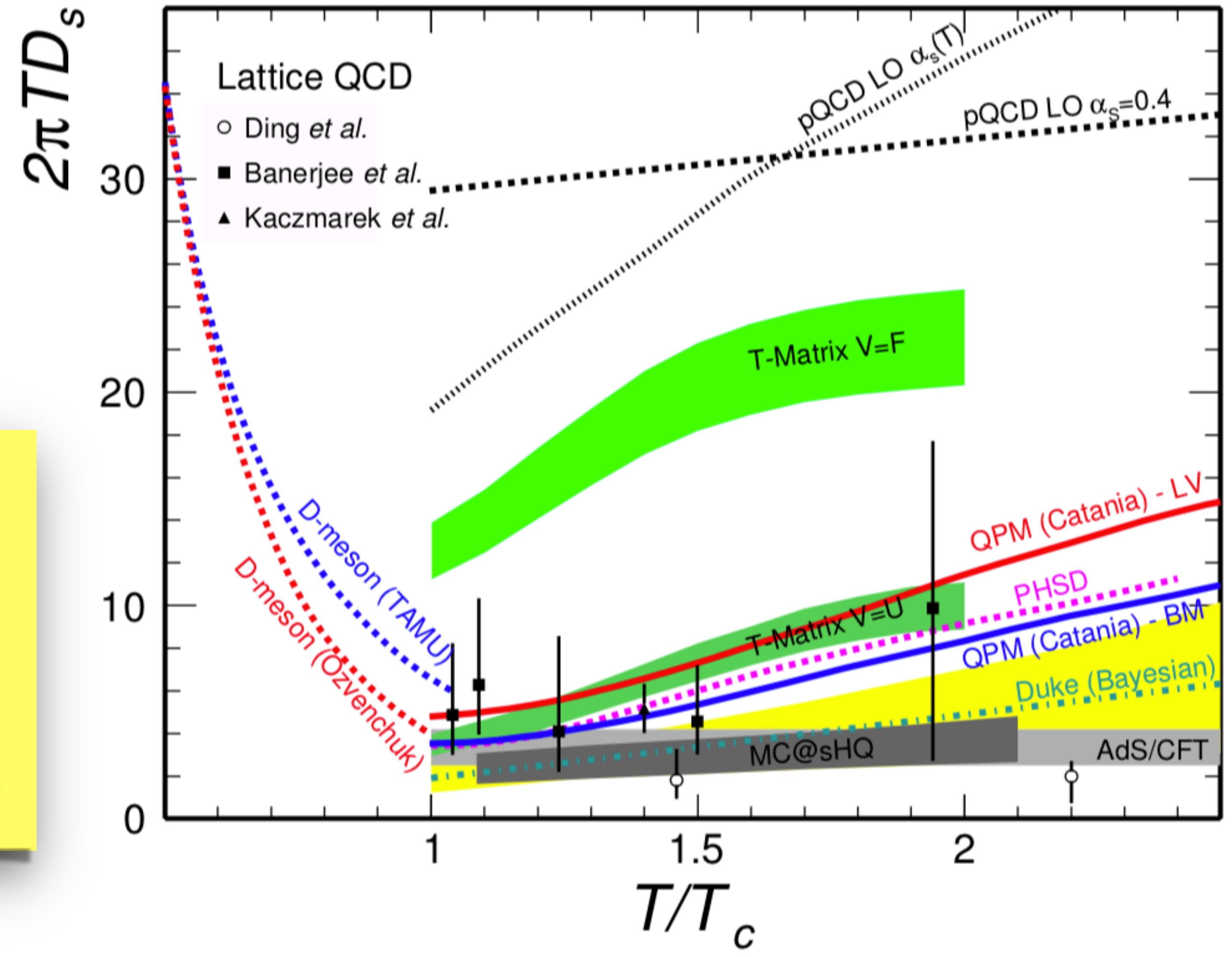
Charm is strongly coupled in QGP.
Onset of collectivity motion in p-Pb?

R_{AA} and v_2
Comparison with models





TAMU: PLB 735,445-450(2014), arXiv:1905.09216
PHSD: PRC 92, 014910 (2015), PRC 93, 034906 (2016)
POWLANG: EPJC 75,121(2015)
MC@sHQ+EPOS2: PRC 89 014905 (2014)
LBT: PLB 777 (2018) 255-259
LIDO: arXiv:1810.08177
BAMPS: JPG 42, 115106 (2016)
Djordevic: PRC 92, 024918 (2015)
CUJETS3.0: JHEP 02 (2016) 169
SCET: JHEP 03 (2017) 146
DAB-MOD: PRC 96 (2017) 064903
Catania: Eur. Phys. J. C (2018) 78: 348



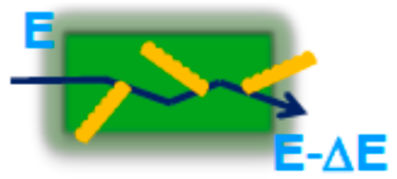
- ➡ Simultaneous description of ***R_{AA}* and *v_2* is challenging** in the whole measured p_T range!
- ➡ Experimental measurements start to **provide constraint to the models** for the characterization of the charm and beauty interaction with the medium
  - ➡**constraints on plasma transport parameters**, such as the heavy-quark diffusion coefficient

Future physics goals for charm

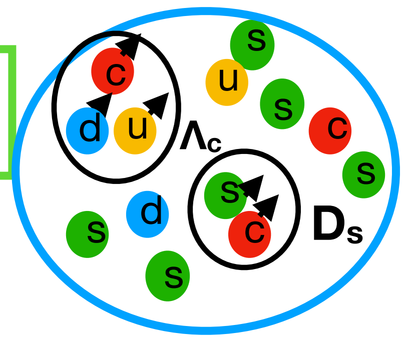
The improved measurements are expected to offer new constraints to models and help gain further insights into the hot and dense medium created

With the help of improved precision and statistics

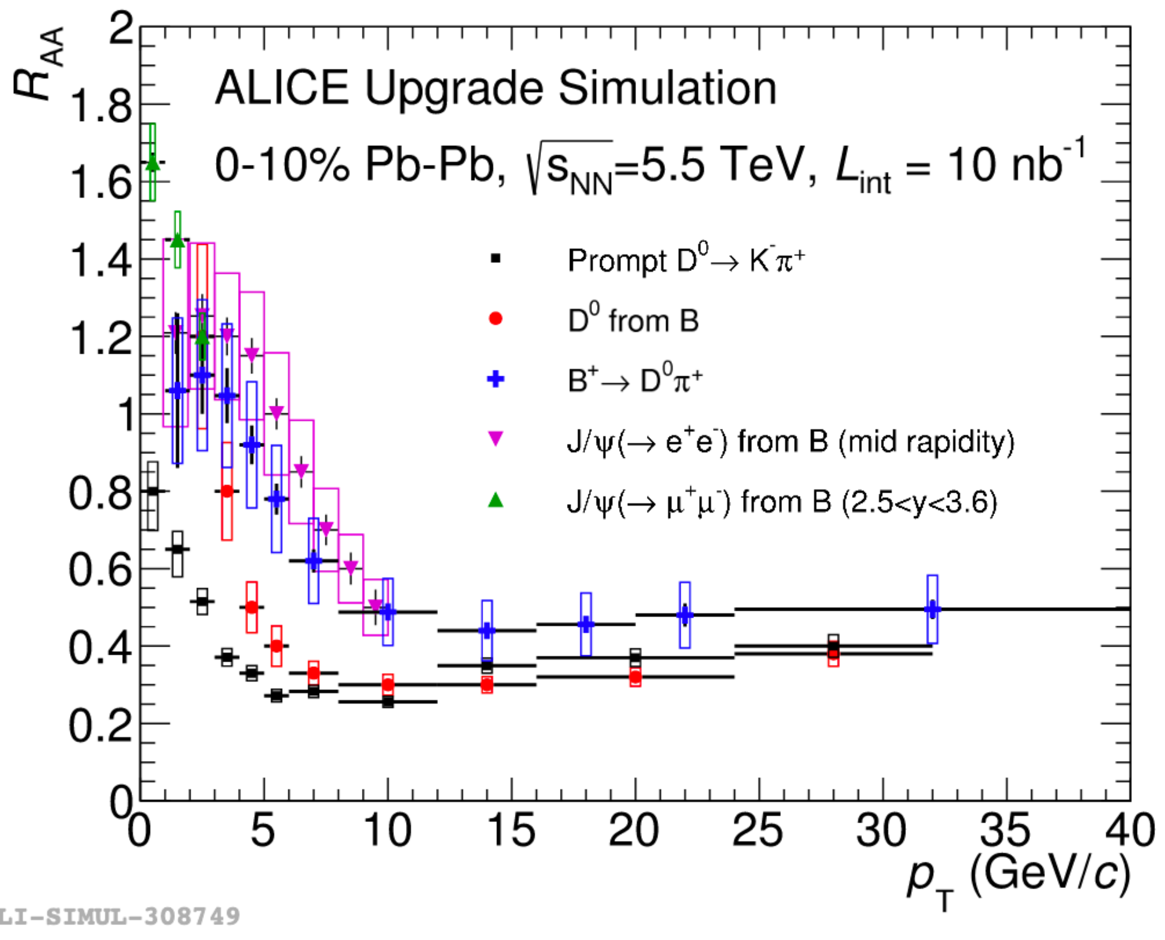
Further insights into the energy loss mechanisms

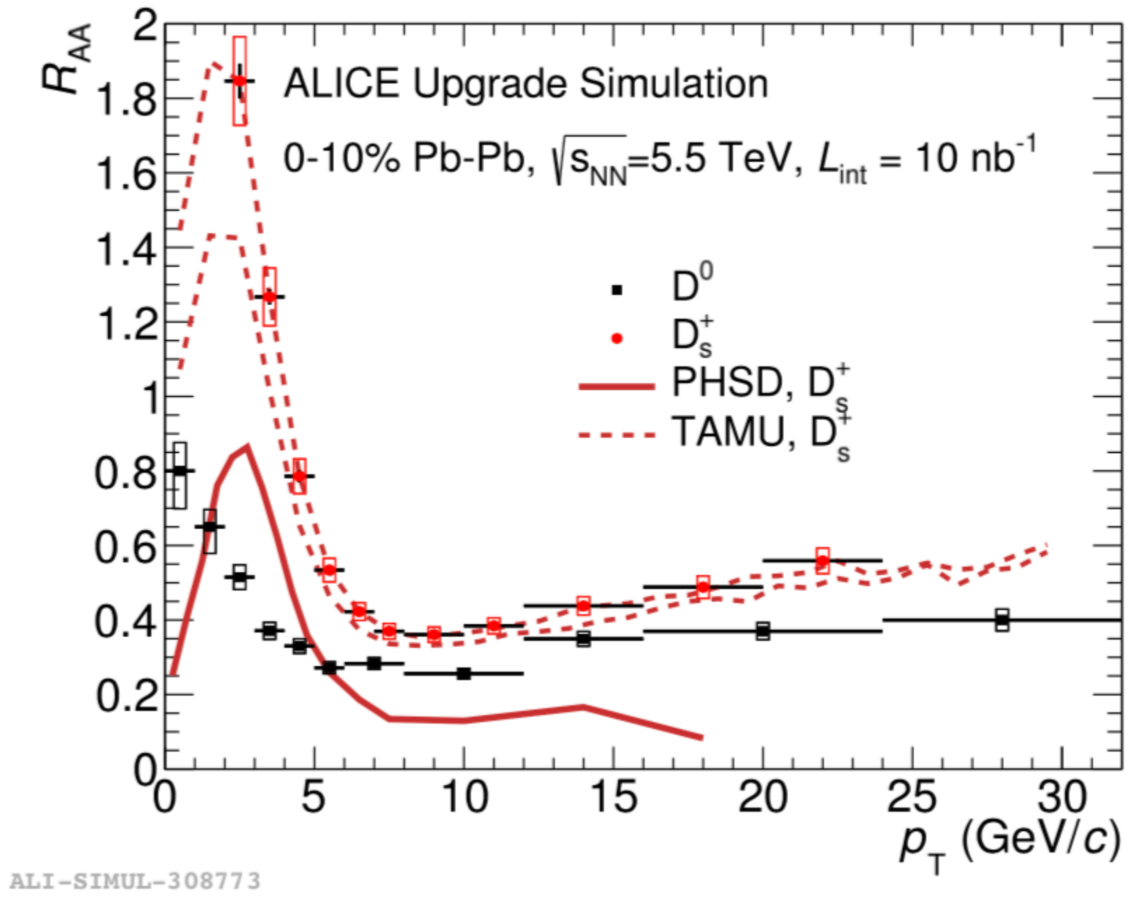


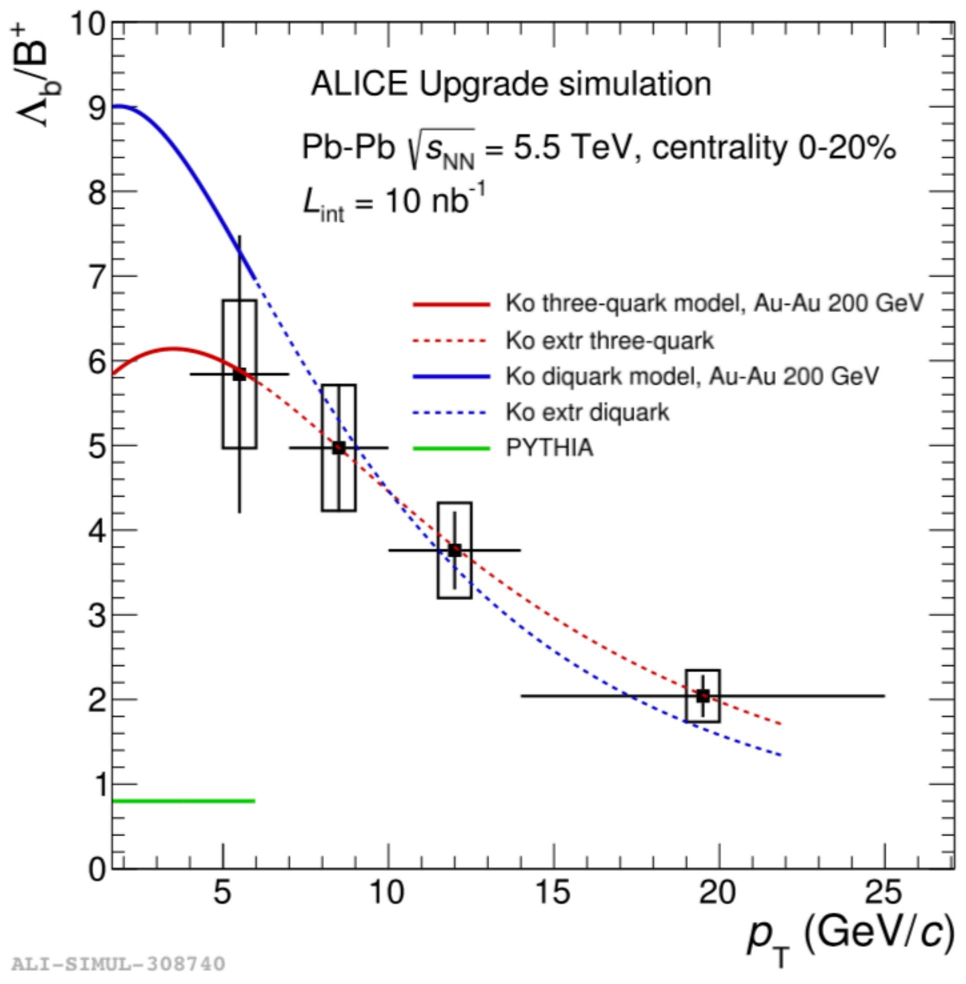
Role of recombination in hadronization?

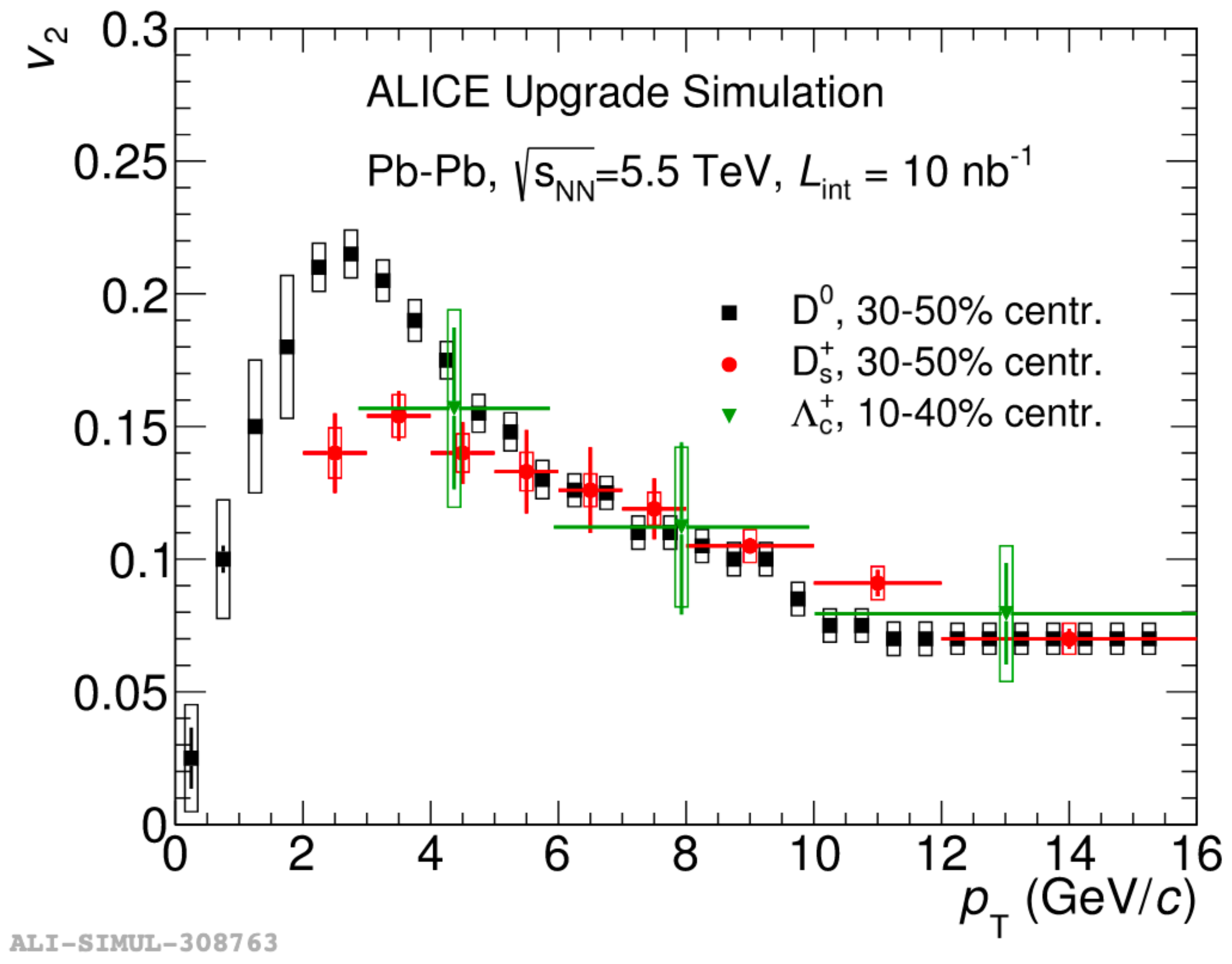


baryon v_2, precise measurement of D_s and J/Ψ v_2



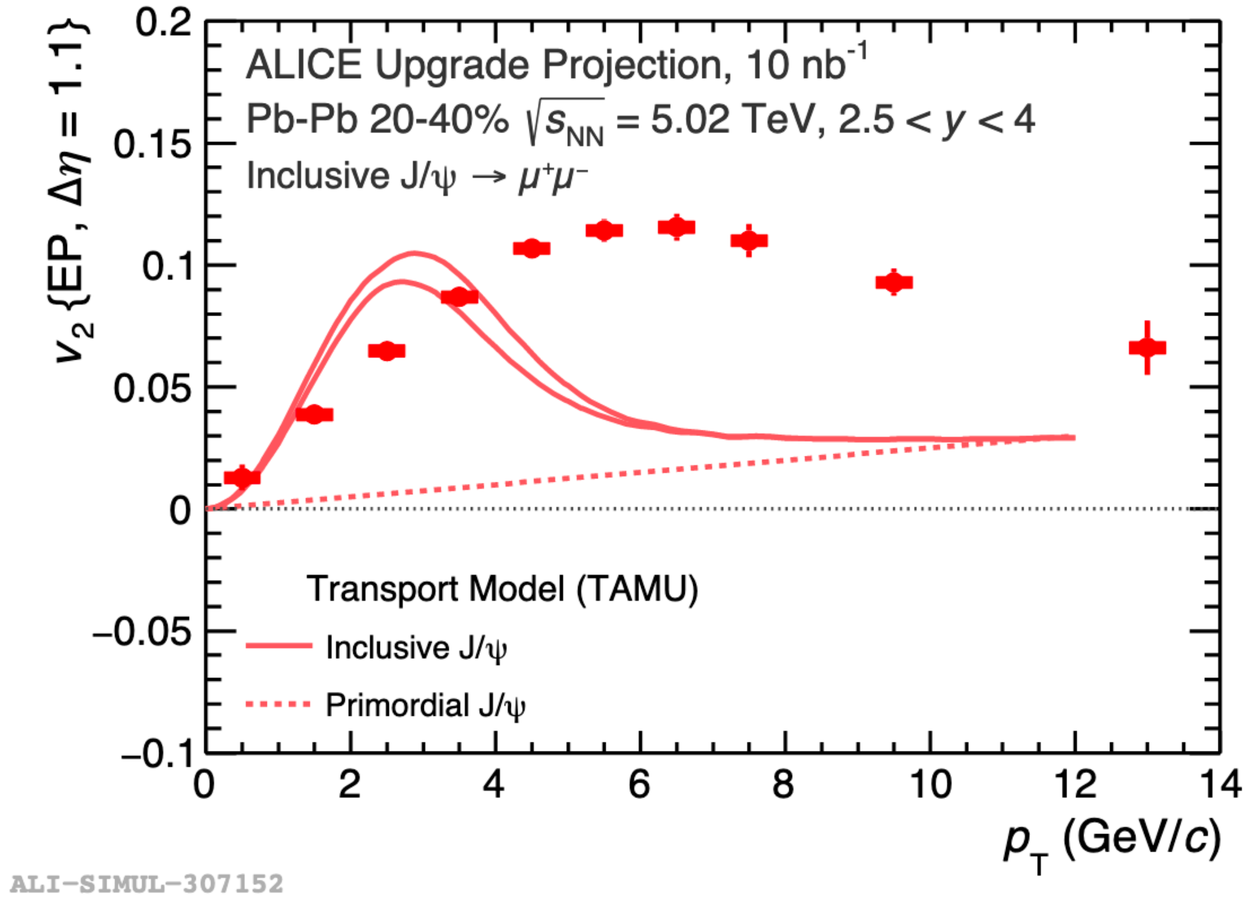






- Investigate deeper the **low p_T regime**
- **Charm and beauty baryons**
- More **differential measurements**

➡ Precise measurements of the QGP properties



arXiv:1812.06772v2

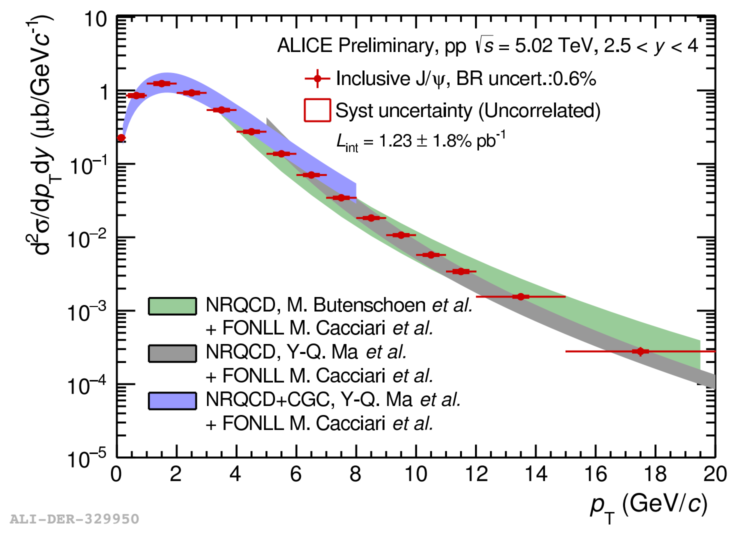
Summary and conclusions

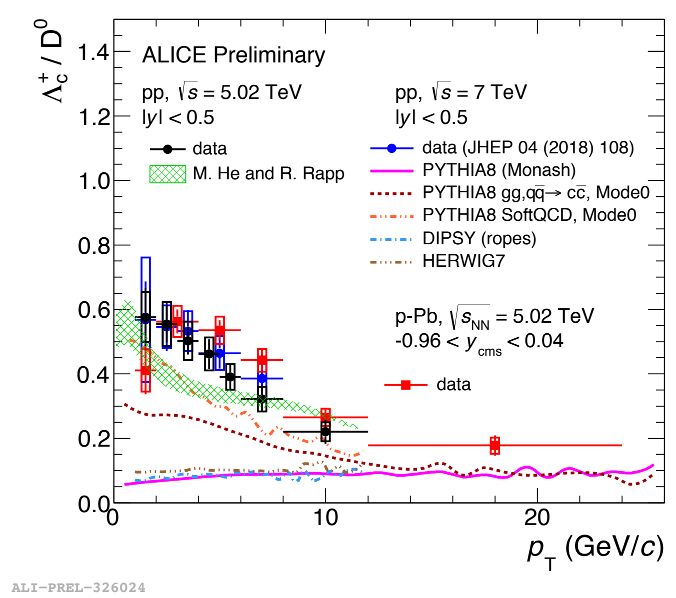
Investigation of **heavy quark interaction with the hot and dense medium** created in heavy-ion collisions, from the production to their "journey" into the medium until the formation of heavy-flavour hadrons

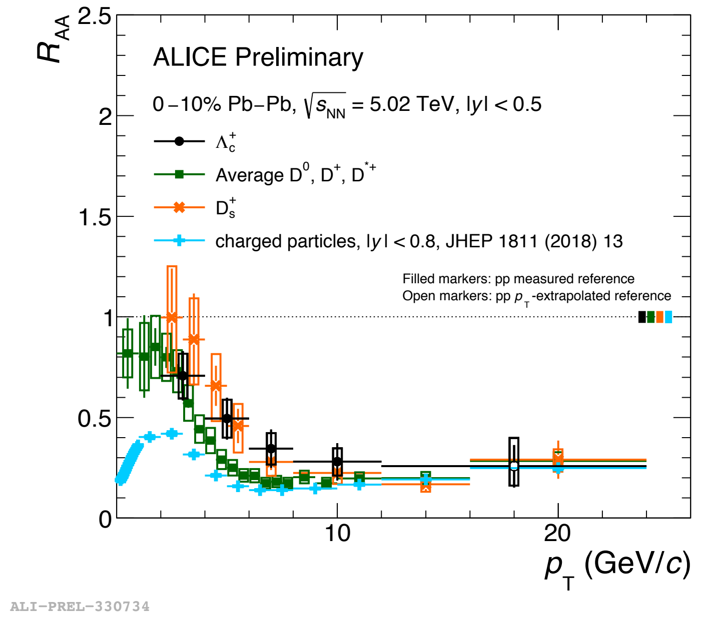
Recent charm measurement presented

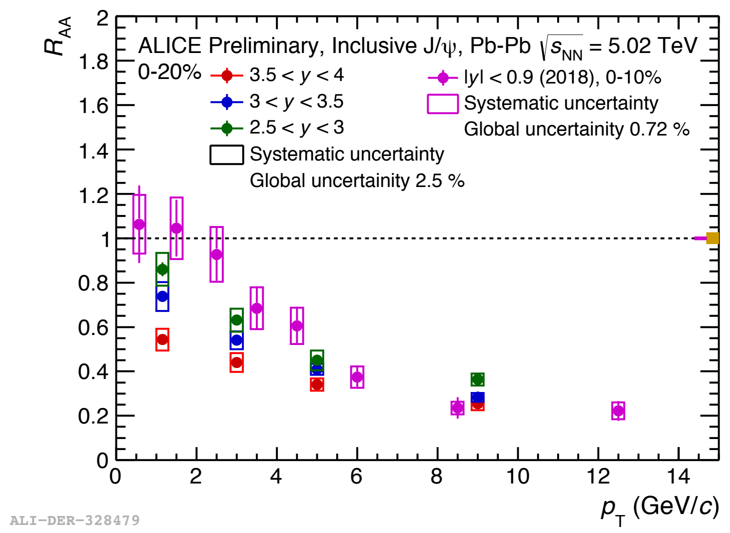
- **Production cross section measurements:**
  - constrain theoretical calculations and input for models to describe kinematics modification in the QGP
- **Particle ratios: sensitive to hadronization**
  - meson-to-meson ratios: universality of FF
  - baryon-over-meson ratios: system dependent?
  - coalescence+fragmentation and SHM describe data in Pb-Pb
- **Nuclear modification factor:**
  - Mass ordering of R_{AA} and interplay of recombination, fragmentation, collisions and radiative energy loss, collectivity to describe R_{AA}
  - J/psi R_{AA}: recombination and suppression needed to explain the measurements
- **Elliptic flow:** thermalization of charm quark in the medium, onset of QGP in p-Pb?

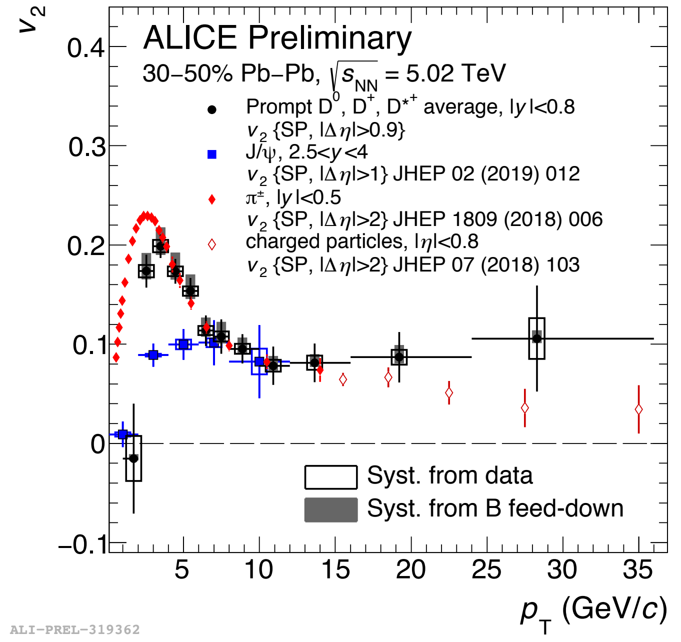
Run3: ready for the precision era of the QGP characterization:
improved precision and new measurements to fully characterize the QGP
and to further constrain theory



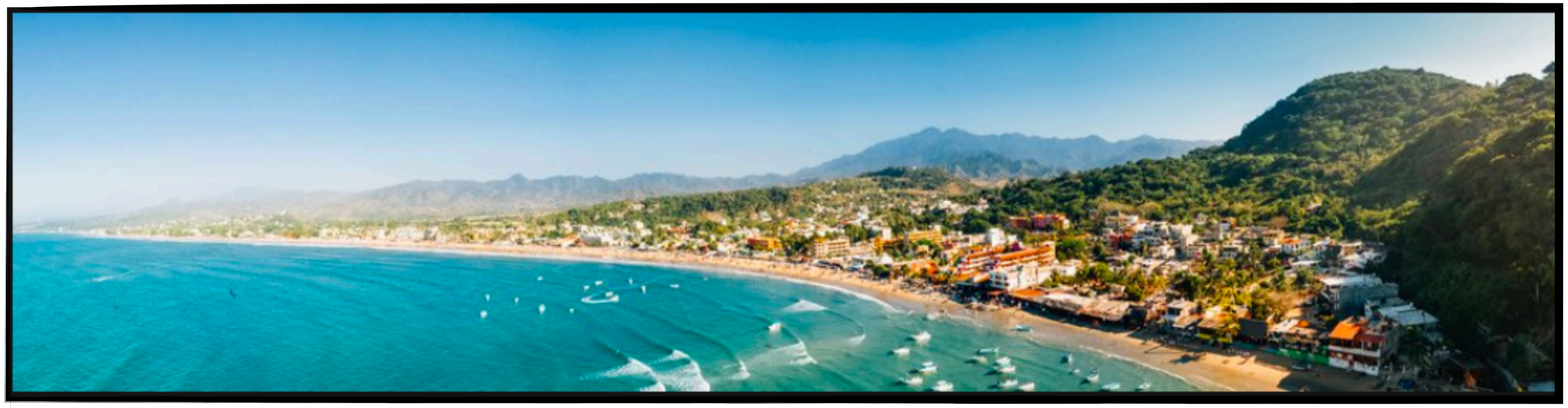








Thanks !

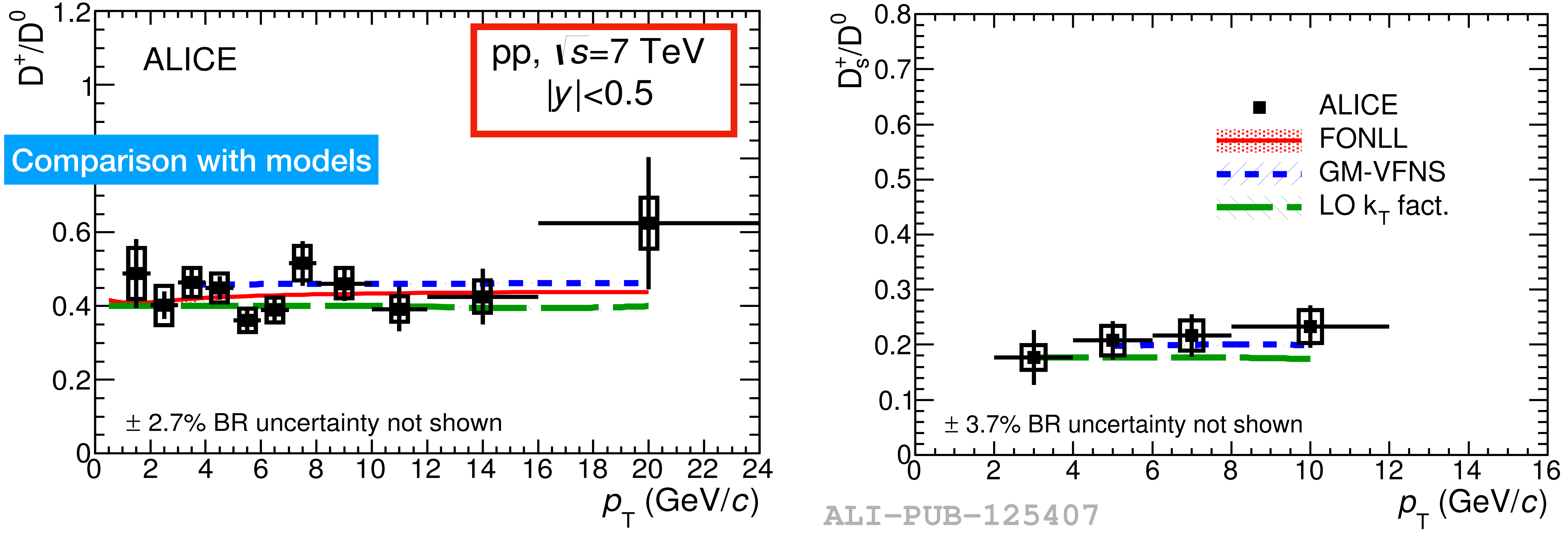


Heavy-flavour production: particle ratios

Particle species ratio at different energies: $\sqrt{s}$ = 5.02, 7 TeV

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F)\otimes\frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F)\otimes D_{c\to D}(z=p_D/p_c,\mu_F)$$

Sensitive to **ratio of Fragmentation Functions** for different hadronisation of charm quark

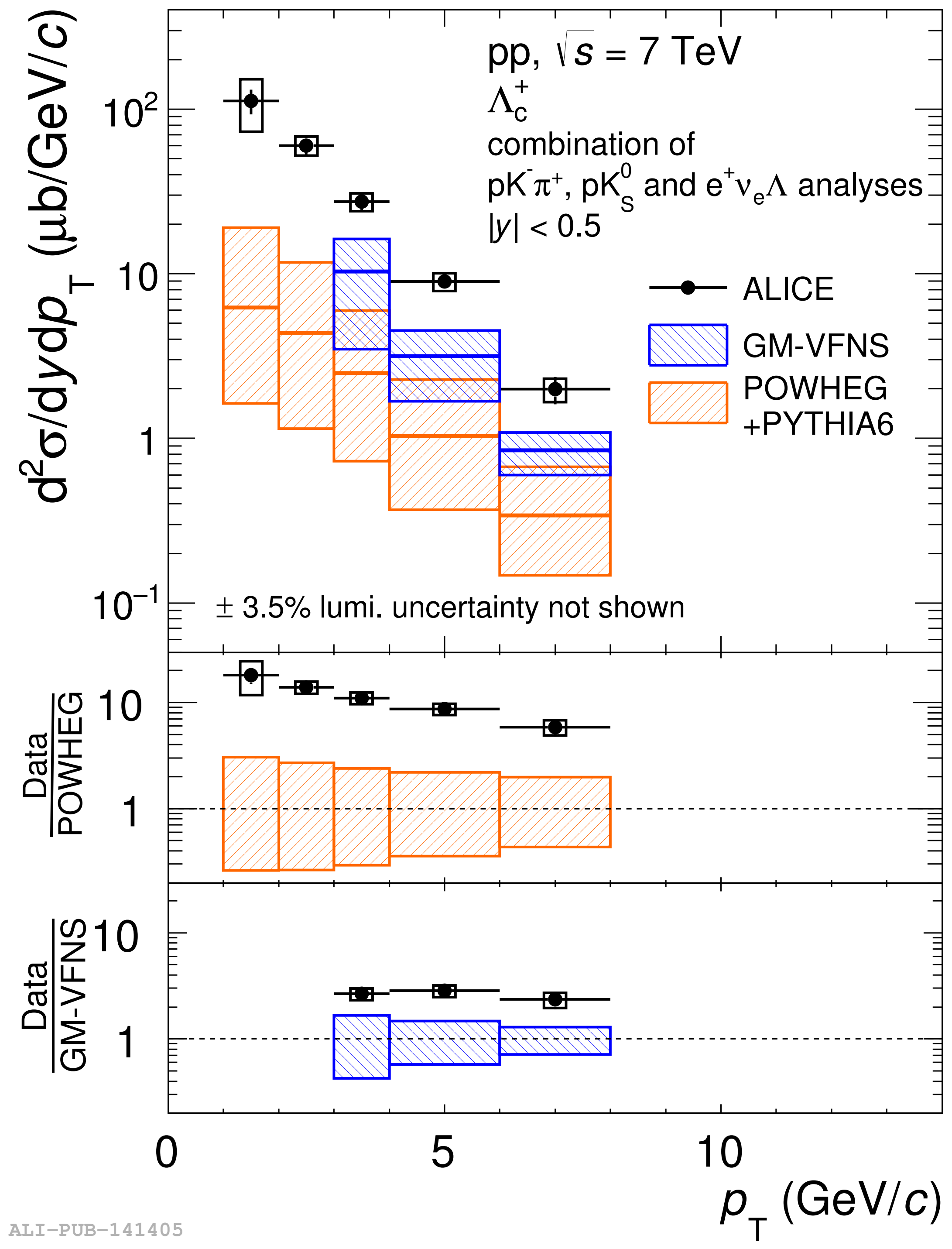


- no differences between D-meson ratios in different collision energies
- compatible with ratios measured in e+e- and ep collisions
  - no dependency on collision systems
- agreement with models
- **Universality of D-meson Fragmentation Functions**

D-meson ratios flat vs p_T and independent on the collision energy and collision system

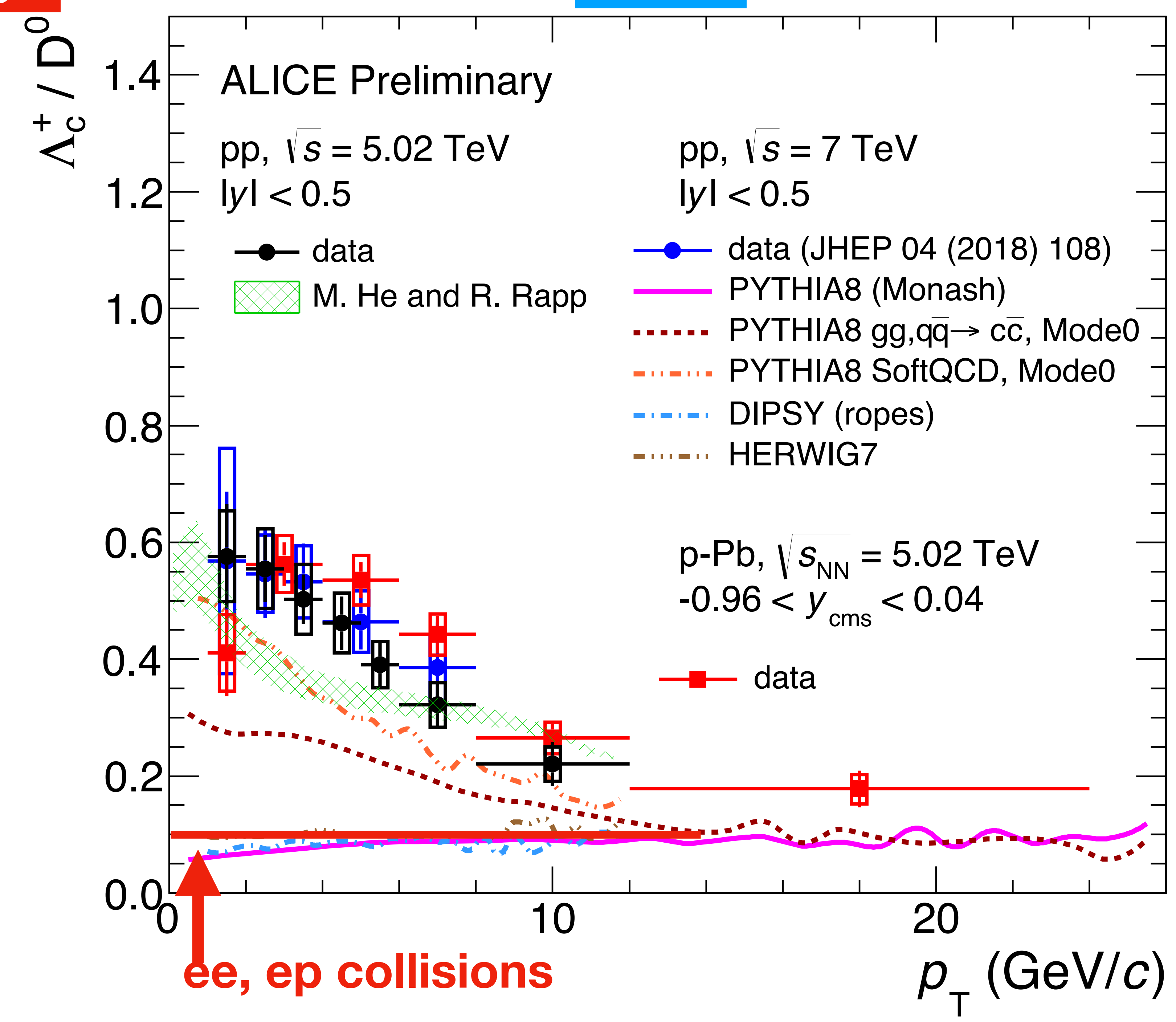
Baryon-to meson ratios in pp collisions

Λ_c baryon, mid rapidity



Λ_c/D^0

GM-VFN
Eur. Phy
POWHE



ALI-PREL-326024

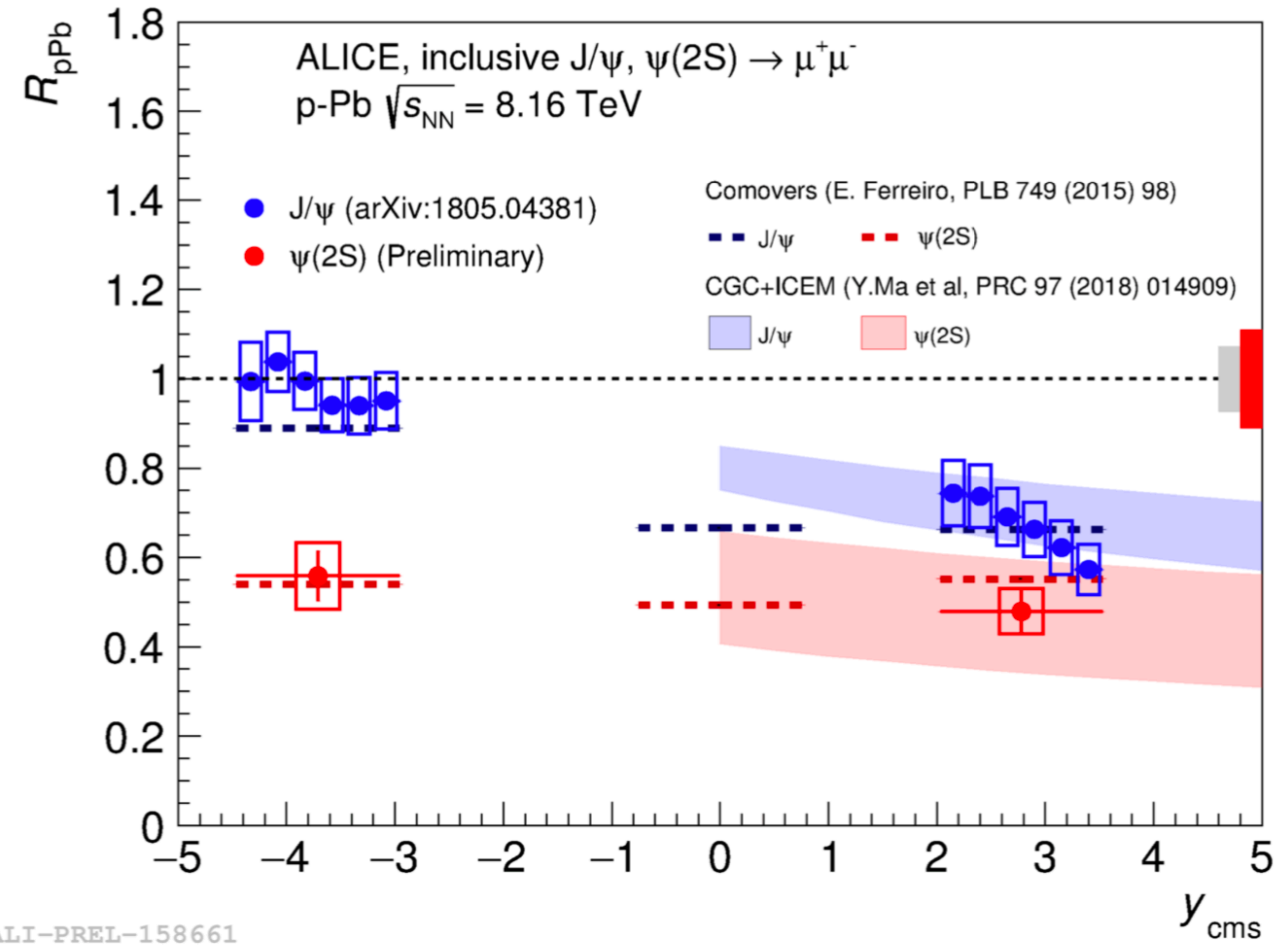
[1] J.R. Christiansen, P. Skands: JHEP 1508 (2015) 003
[2] M.He, R. Rapp: Phys.Lett. B795 (2019) 117-121

Cross section of charmed baryons: not described by pQCD-based models:
fragmentation in models from ee/ep:
baryon fragmentation non-universal?

Λ_c/D^0 in pp higher than in e^+e^- and ep collisions, and models tend to underestimate the ratios

Colour reconnection [1] (reconnection between uncorrelated interactions), and increased number of higher-mass baryon states [2] among possible explanations for the enhancement

$\psi(2S)$ R_{pPb} vs y and p_T : theoretical models



ALICE

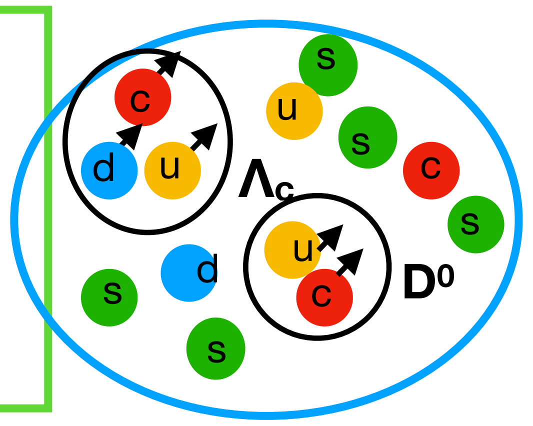
- $R_{pPb}^{\psi(2S)}(y_{cms}) < 1$
- $R_{pPb}^{\psi(2S)}[8.16\ \text{TeV}] \sim R_{pPb}^{\psi(2S)}[5.02\ \text{TeV}]$
- $R_{pPb}^{\psi(2S)} < R_{pPb}^{J/\psi}$

Comovers: particles produced in the interaction which move with the hadronizing cc pair

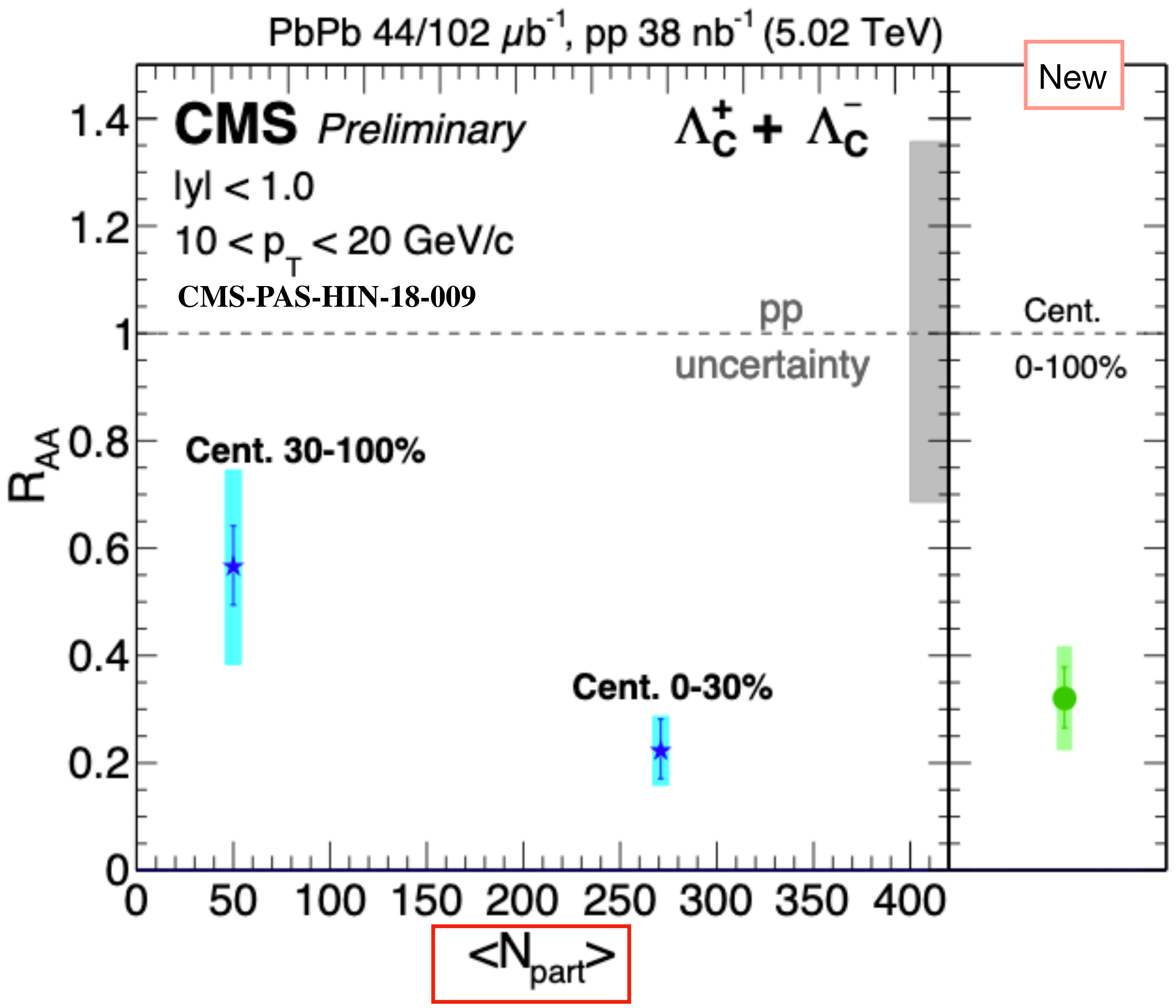
“CGC+ iCEM”: soft color exchanges between cc hadronizing pair and comoving partons
“Comovers": final-state interactions with the comoving medium

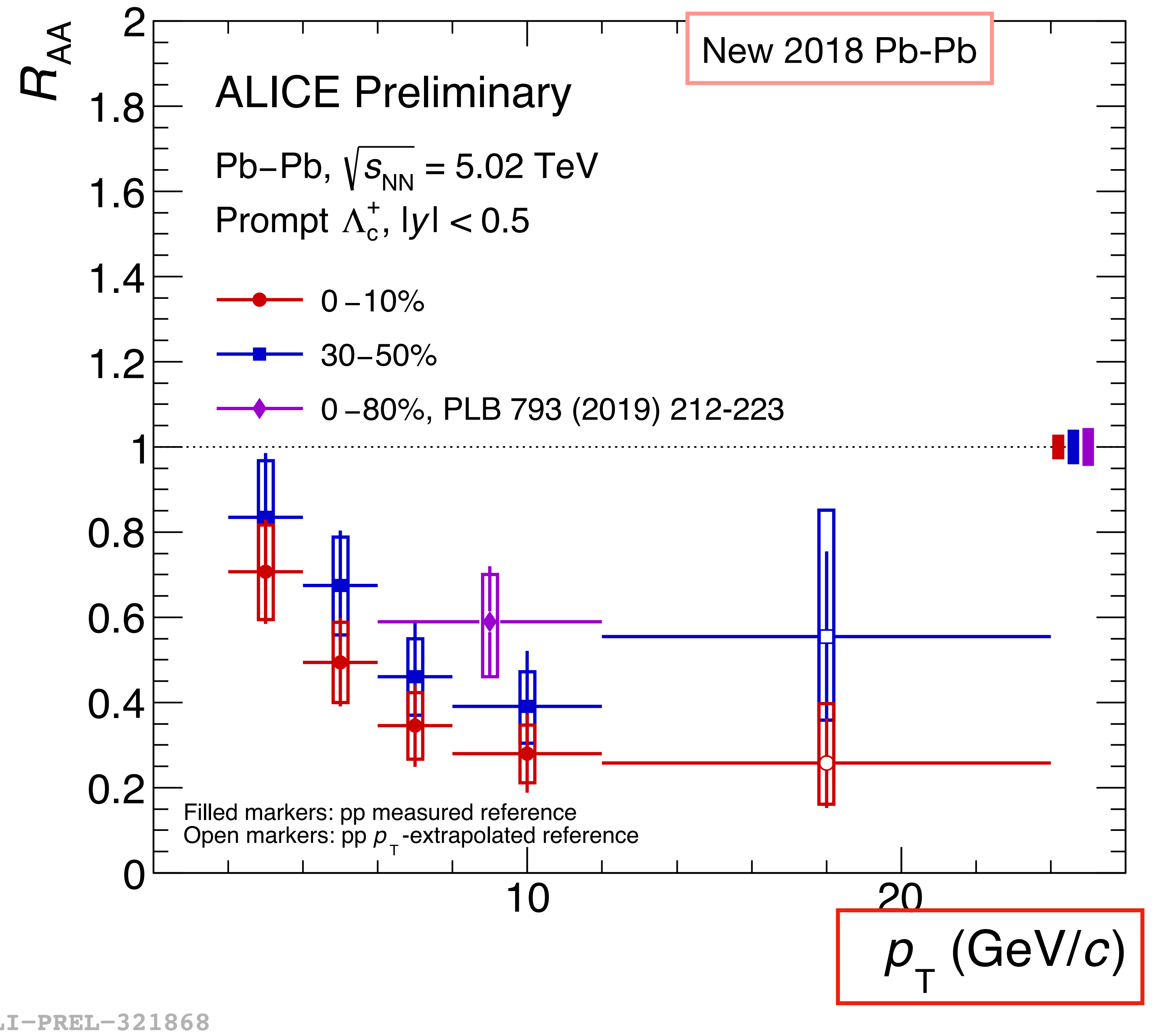
Charmed baryon nuclear modification factor: Λ_c

Further Investigation: Charmed baryon energy loss



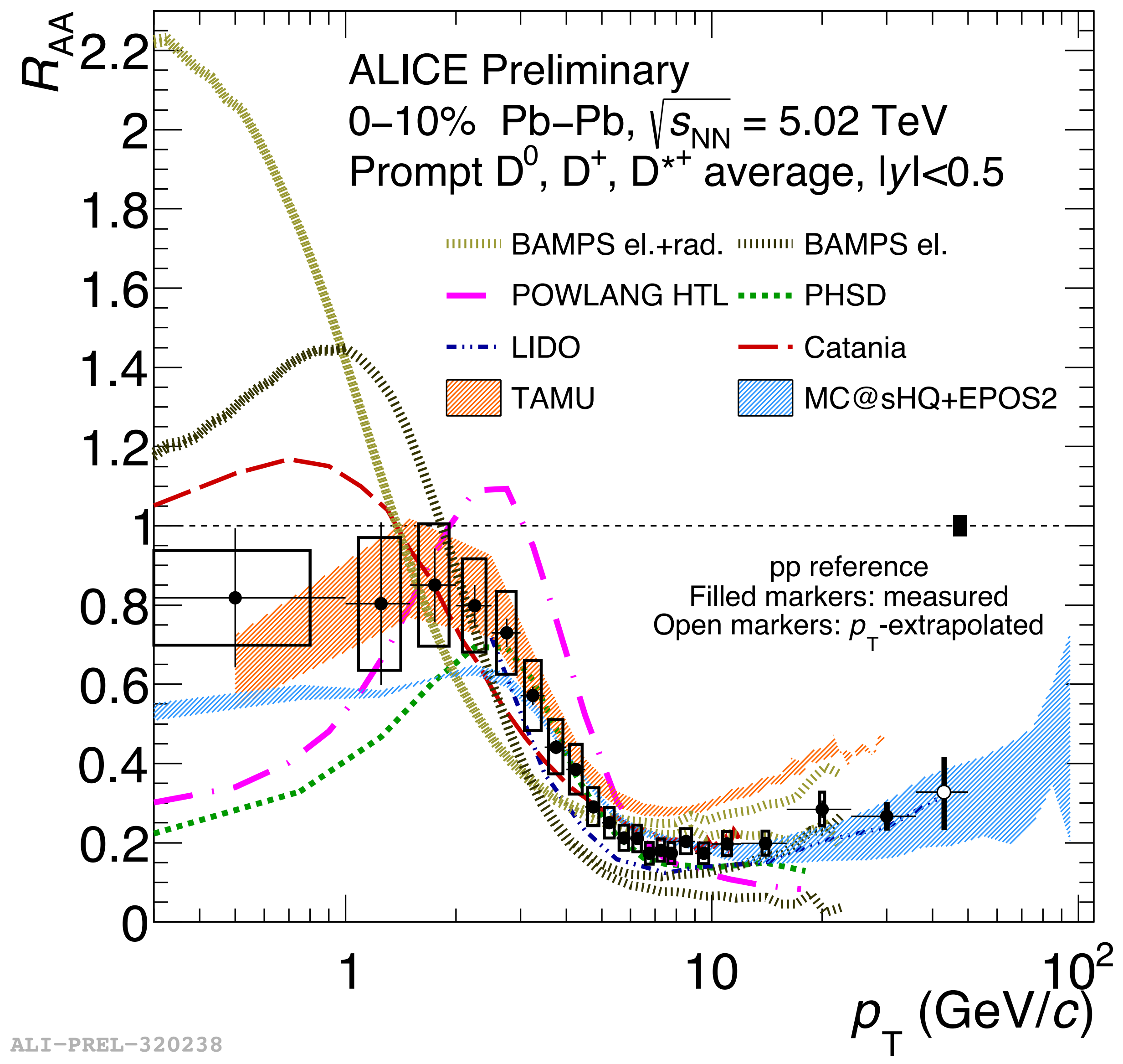
arXiv:1906.03322

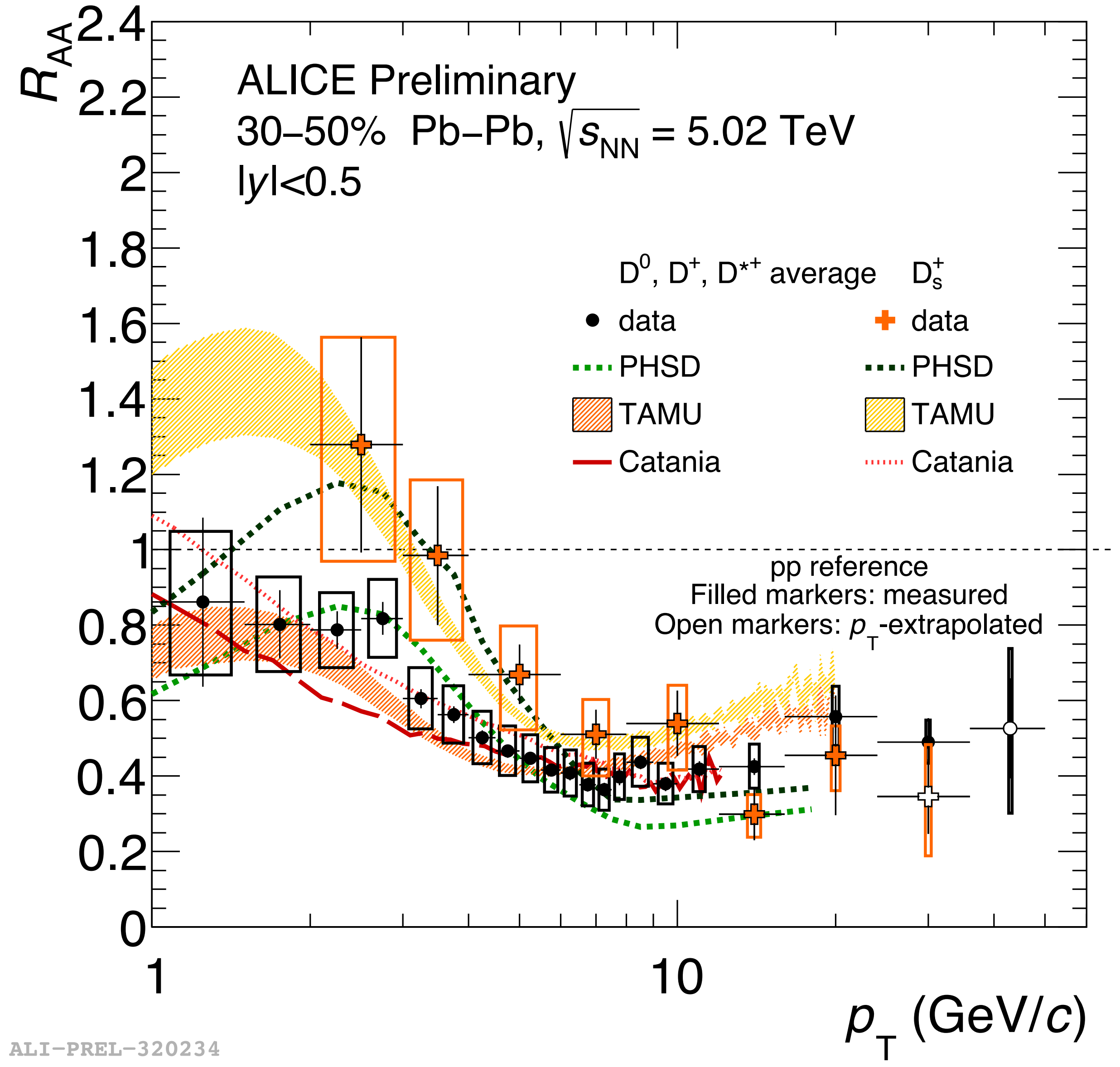




- Large Λ_c suppression observed up to a factor of 5 at high p_T both in ALICE and CMS
  - compatibility of CMS and ALICE results (slightly different p_T and centrality ranges)
- Hint of smaller R_{AA} in semicentral collisions

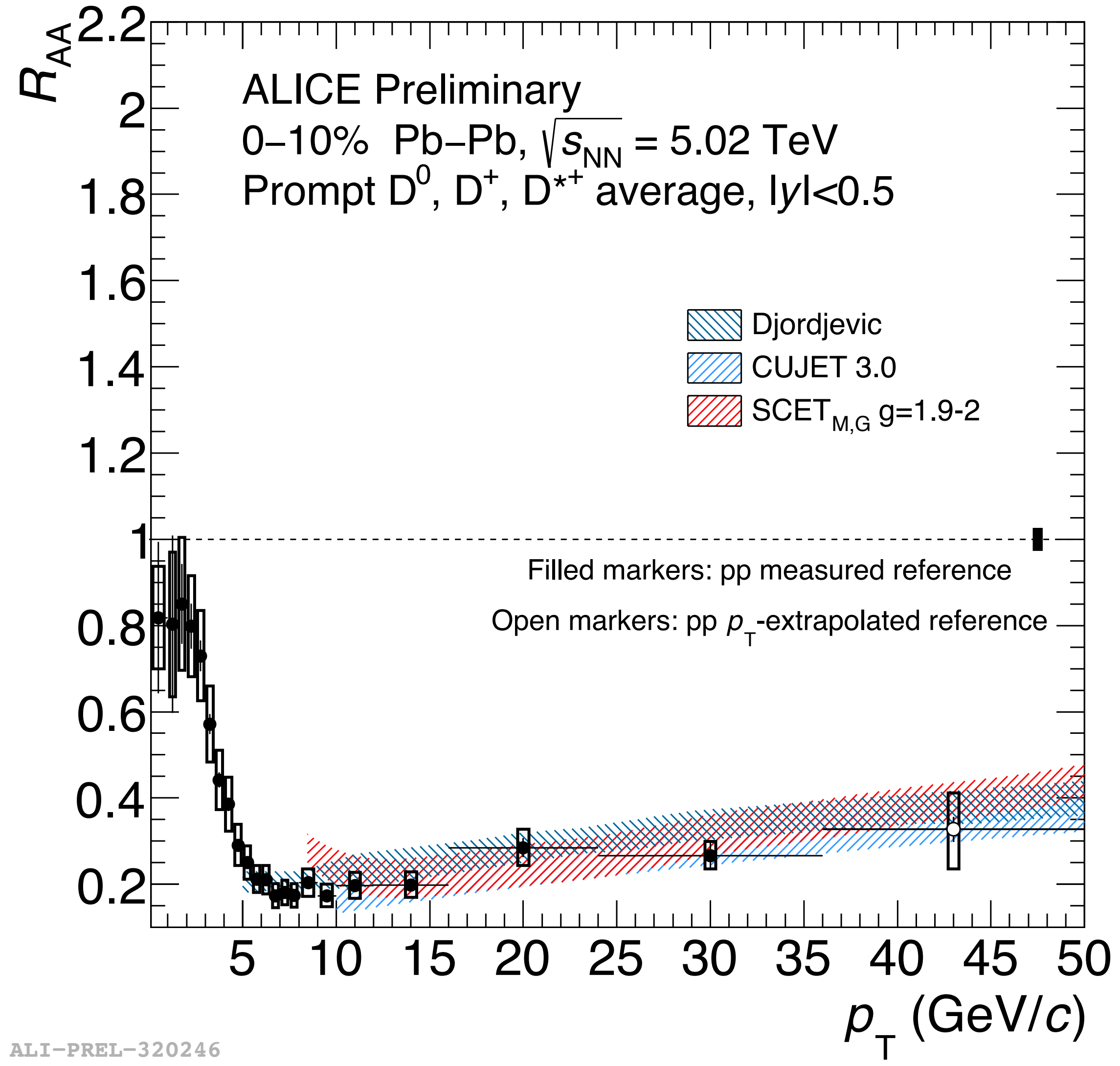
R_{AA} and models

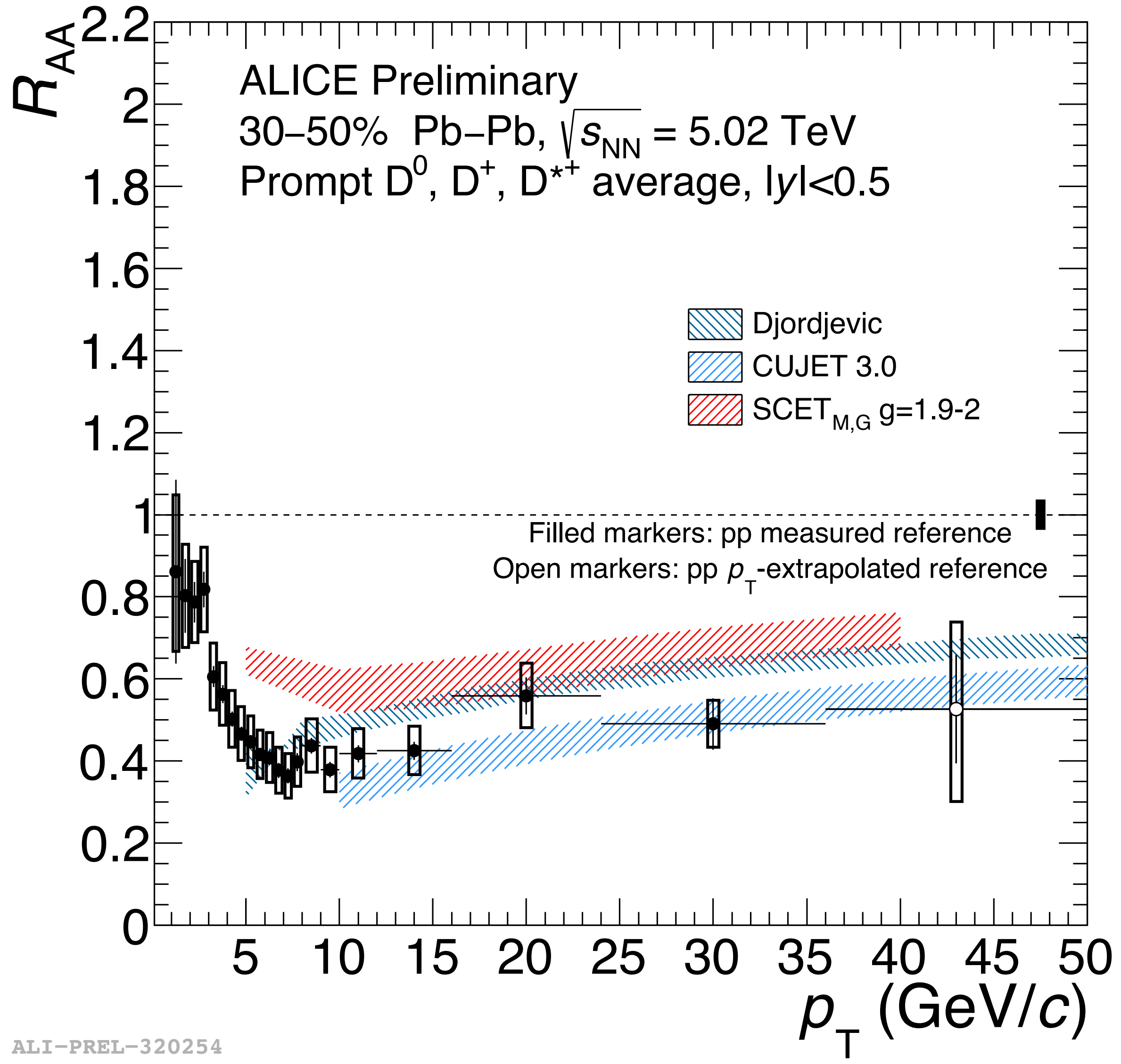




"Transport models" based on Boltzmann/Fokker-Plank/Langevin equations

TRANSPORT MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro/ dynamics	nPDF
BAMPS J. Phys. G42 (2015) 115106	✔	✔	✗	✔	✗
LBT arXiv:1703.00822	✔	✔	✔	✔	✔
PHSD PRC 93 (2016) 034906	✔	✗	✔	✔	✔
POWLANG EPJC 75 (2015) 121	✔	✗	✔	✔	✔
TAMU Phys. Lett. B735 (2014) 445	✔	✗	✔	✔	✔





pQCD based models

pQCD e-loss MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro	nPDF
CUJET3.0 JHEP 02 (2016) 169	✔	✔	✗	✗	✗
Djordjevic PRC 92 (2015) 024918	✔	✔	✗	✗	✔
MC@sHQ+EPOS PRC 89 (2014) 014905	✔	✔	✔	✔	✔
SCET JHEP 03 (2017) 146	✔	✔	✗	✗	✔

Table 11: Comparative overview of the models for heavy-quark energy loss or transport in the medium described in the previous sections.

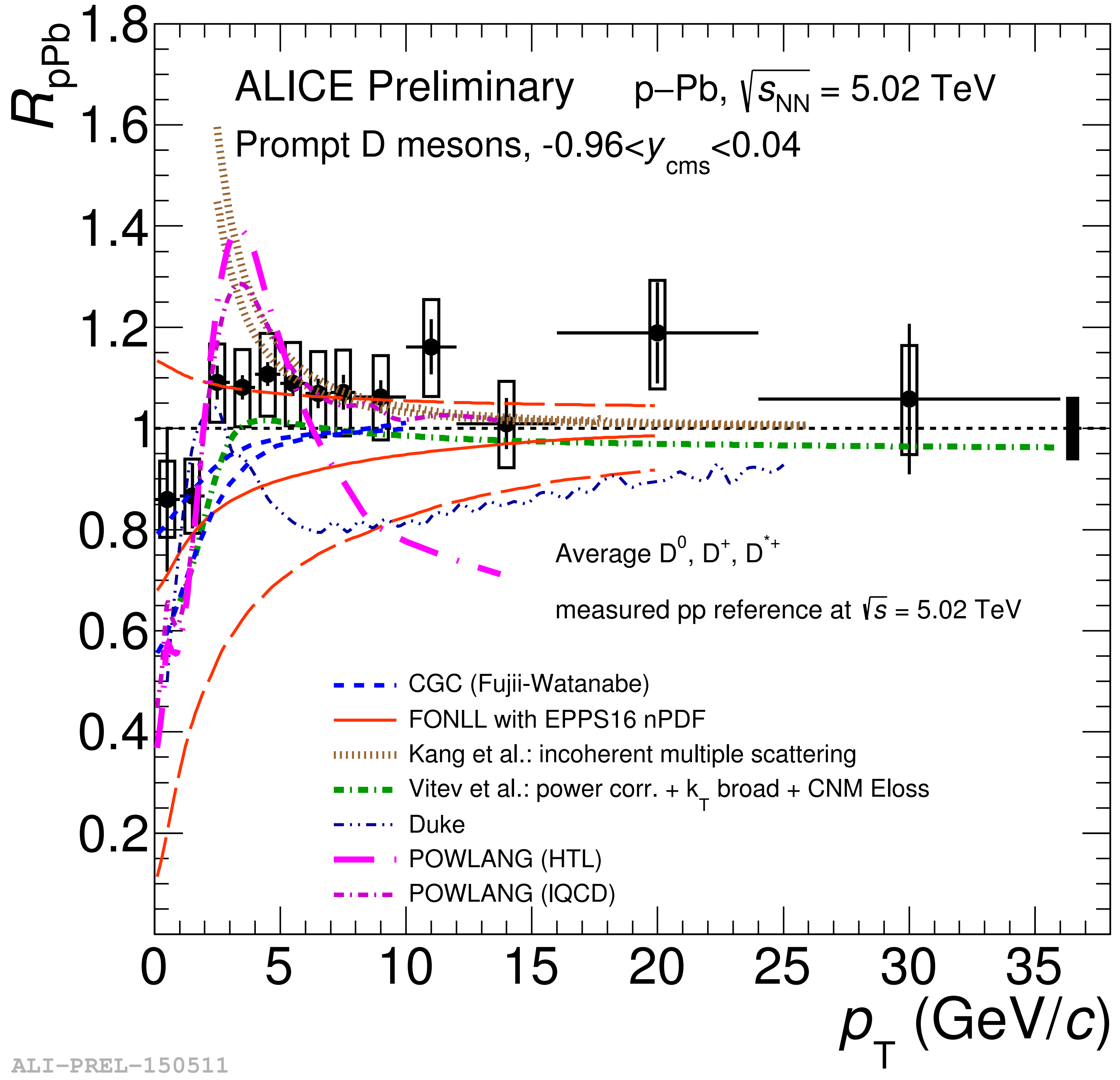
Model	*Heavy-quark production*	*Medium modelling*	*Quark–medium interactions*	*Heavy-quark hadronisation*	*Tuning of medium-coupling (or density) parameter(s)*
Djordjevic *et al.* [511–515]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss finite magnetic mass	fragmentation	Medium temperature fixed separately at RHIC and LHC
WHDG [459, 519]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
Vitev et al. [422, 460]	non-zero-mass VFNS no PDF shadowing	Glauber model nuclear overlap ideal fl. dyn. 1+1d Bjorken expansion	radiative energy loss in-medium meson dissociation	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
AdS/CFT (HG) [624, 625]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	AdS/CFT drag	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
POWLANG [507–509, 585, 586]	POWHEG (NLO) EPS09 (NLO) PDF shadowing	2+1d expansion with viscous fl. dyn. evolution	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume pQCD (or l-QCD *U* potential)
MC@$_s$HQ+EPOS2 [528–530]	FONLL EPS09 (LO) PDF shadowing	3+1d expansion (EPOS model)	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at LHC, slightly adapted for RHIC
BAMPS [537–540]	MC@NLO no PDF shadowing	3+1d expansion parton cascade	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
TAMU [491, 565, 606]	FONLL EPS09 (NLO) PDF shadowing	2+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss diffusion in hadronic phase	fragmentation recombination	assume l-QCD *U* potential
UrQMD [608–610]	PYTHIA no PDF shadowing	3+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume l-QCD *U* potential
Duke [587, 628]	PYTHIA EPS09 (LO) PDF shadowing	2+1d expansion viscous fl. dyn.	transport with Langevin eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at RHIC and LHC (same value)

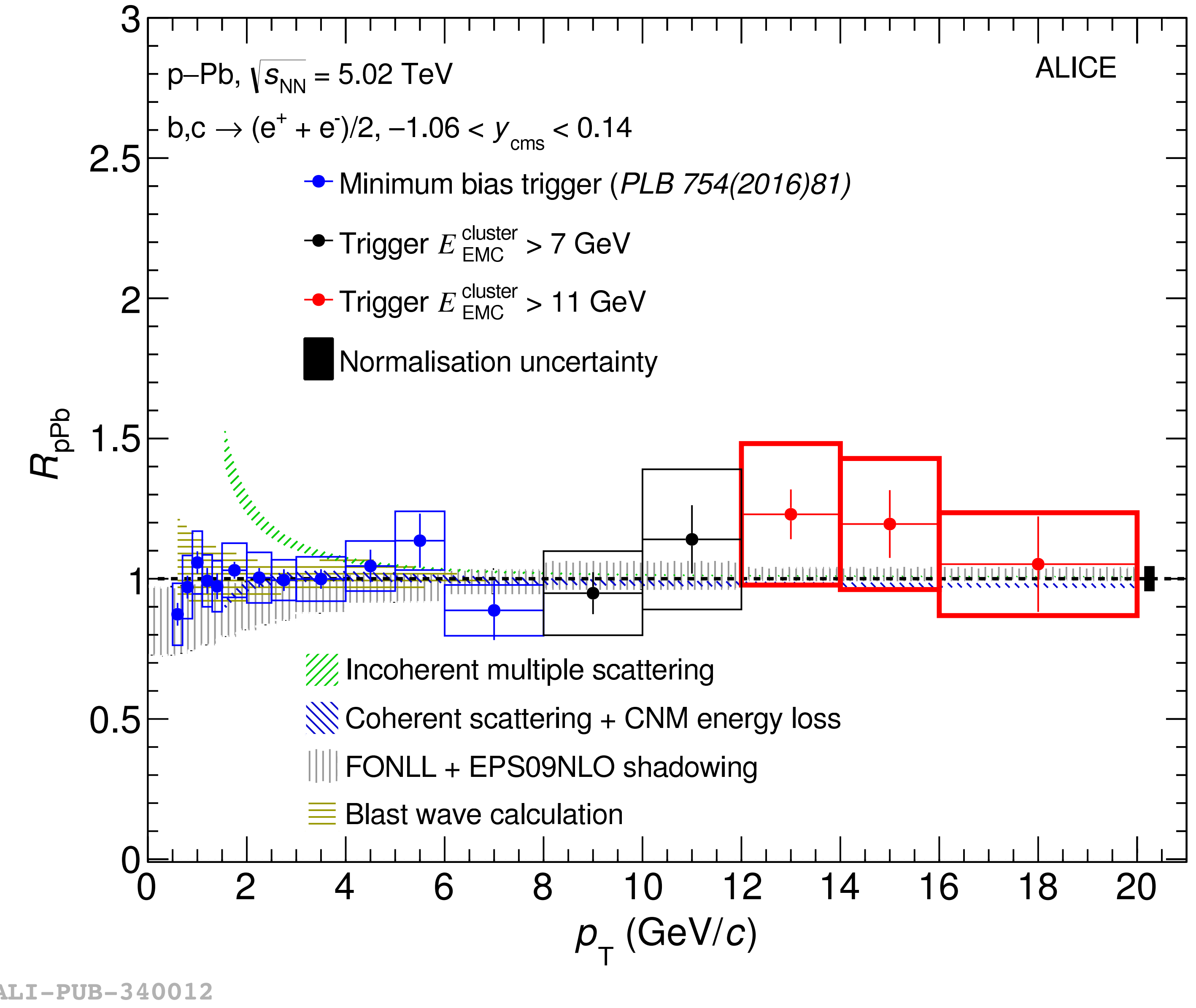
MODELS Pb-Pb

From:
J. Phys. G43 no. 9 093002 (2016)

R_{pPb} models

- **CGC**: arXiv:1706.06728
- **FONLL** (JHEP 1210 (2012) 137, arXiv:1205.6344) **with EPPS16 nPDFs** (Eur. Phys. J. C77 no. 3, (2017) 163, arXiv:1612.05741).
- **Vitev et al**: Phys.Rev. C80 (2009) 054902, arXiv: 0904.0032.
- **Kang et al.**: Phys. Lett. B740 (2015) 23–29, arXiv: 1409.2494.
- **Duke**: Nucl. xPart. Phys. Proc. 276-278 (2016) 225–228, arXiv:1510.07520.
- **POWLANG**: JHEP 03 (2016) 123, arXiv:1512.05186.
- **FONLL** (JHEP 1210 (2012) 137, arXiv:1205.6344 [hep- ph]) with **EPS09NLO** (JHEP 04 (2009) 065, arXiv:0902.4154)
- **Blast wave calculation:** Phys. Lett. B 728 (2014) 25, arXiv:1307.6796
- **Sharma et al:** Phys. Rev. C 80 (2009) 054902, arXiv: 0904.0032

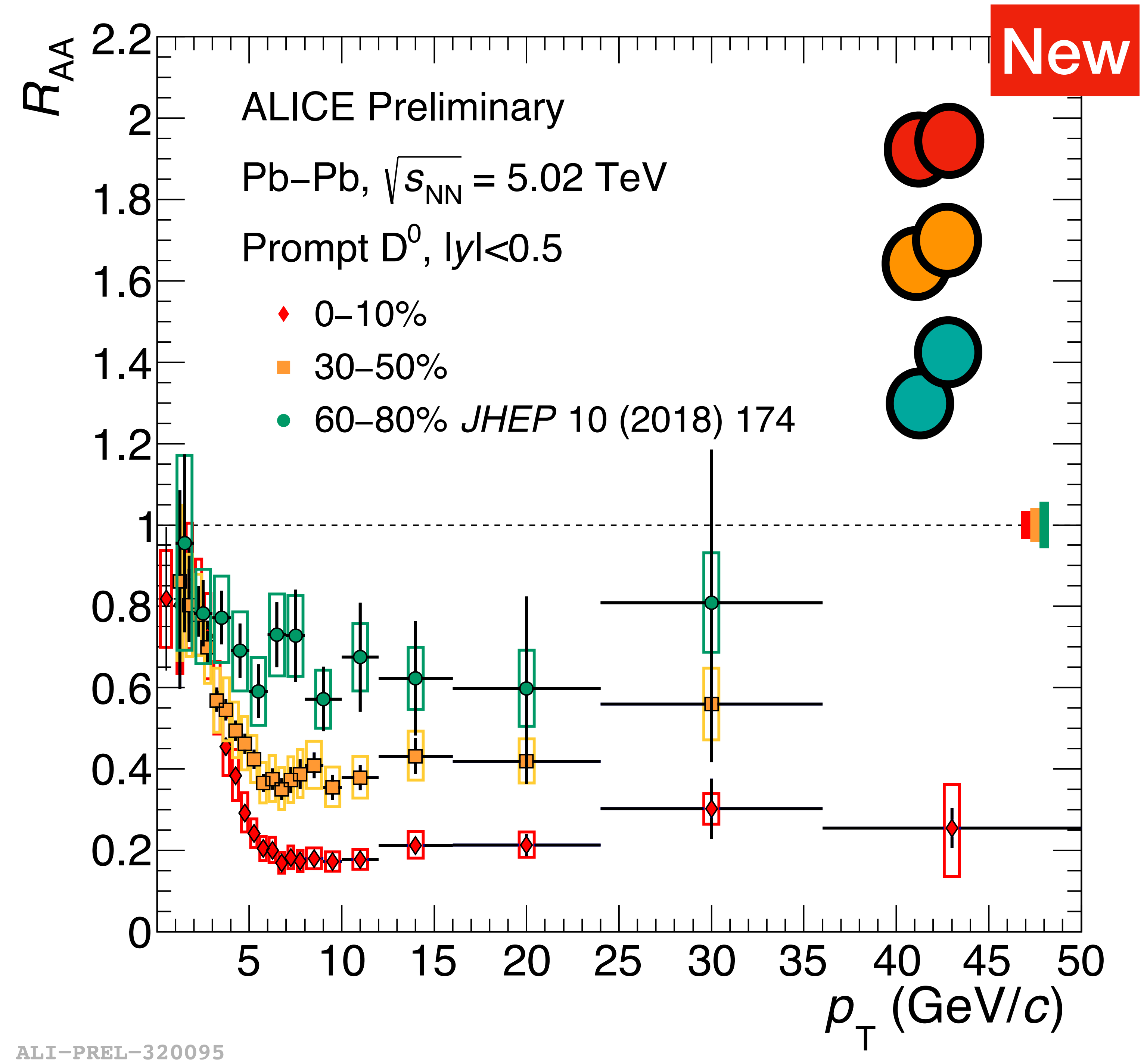


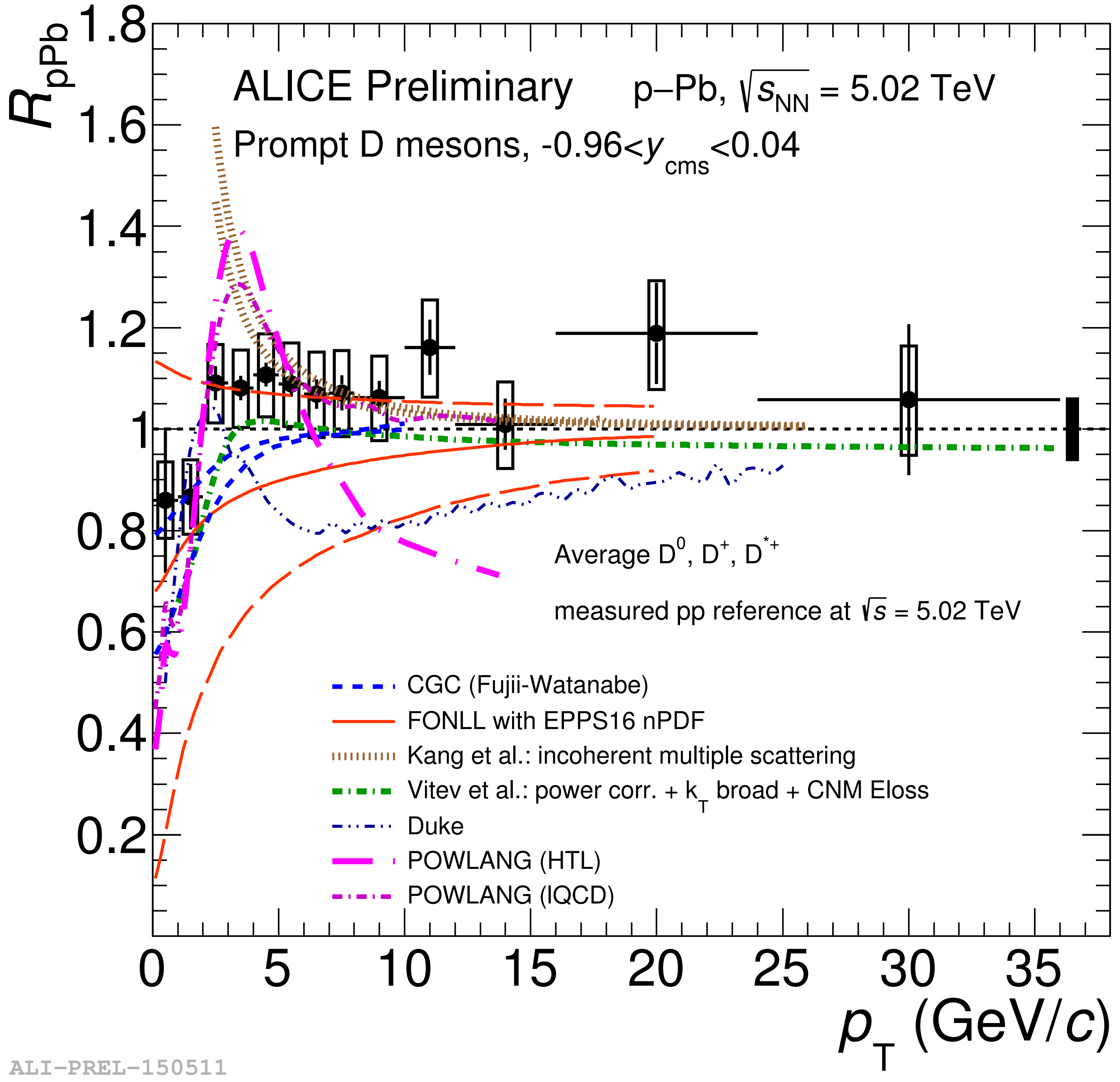


Nuclear modification factor: R_{pPb} vs R_{AA}

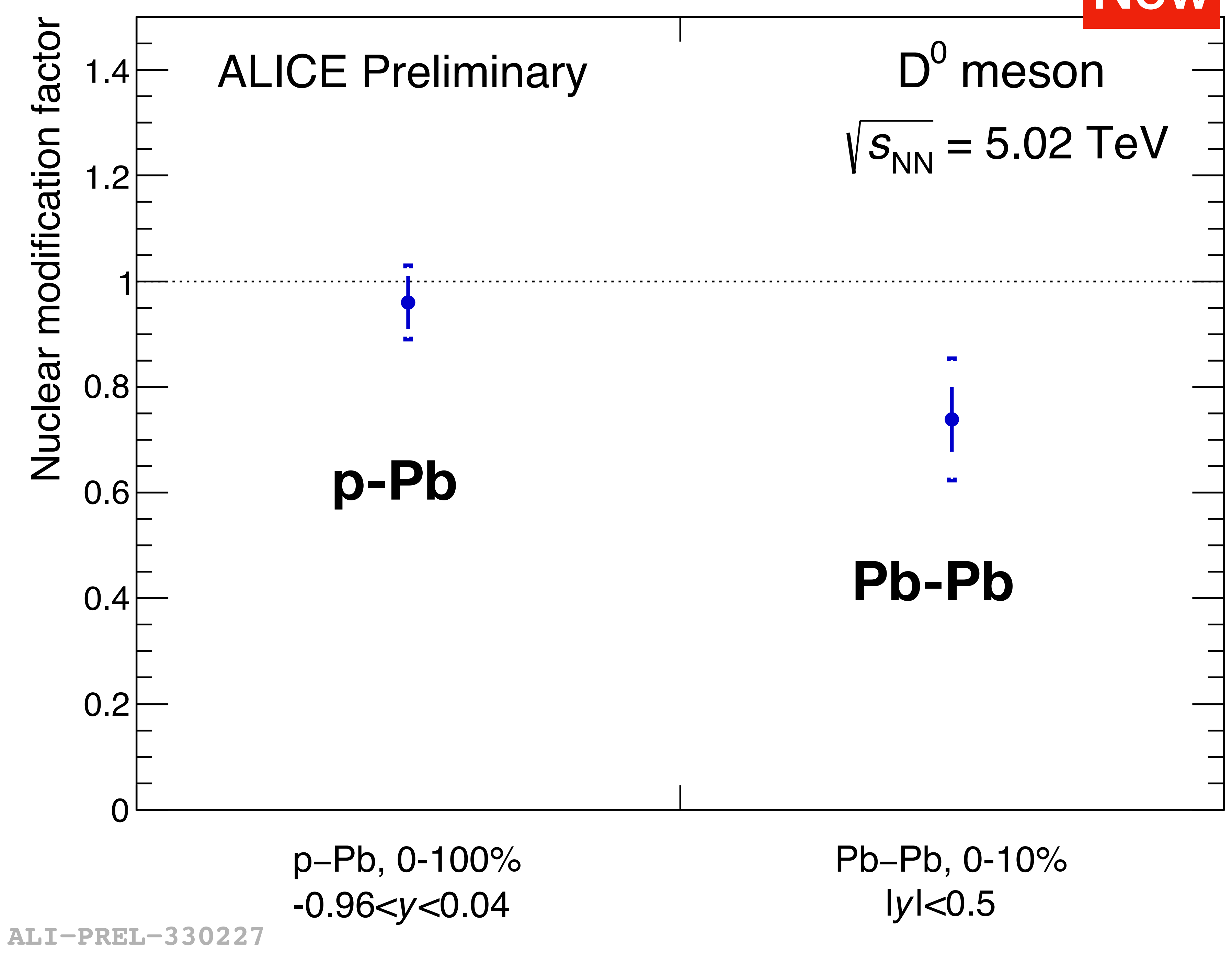
Strong suppression in 0-10% central Pb-Pb collisions

New





New



First measurement of HF in Pb-Pb down to p_T = 0 at LHC

D⁰ meson p_T integrated R_{AA} in Pb-Pb collisions, 0-10% centrality, and p-Pb collisions (0-100% centrality)

R_{pPb} compatible with unity for p_T>3 GeV/c

➡ Strong suppression in Pb-Pb is due to final state effects!