The 18th International Conference on

Strangeness in Quark Matter (SQM 2019)

10-15 June 2019, Bari (Italy)

Open Heavy-Flavour review

Cristina Terrevoli
University of Houston

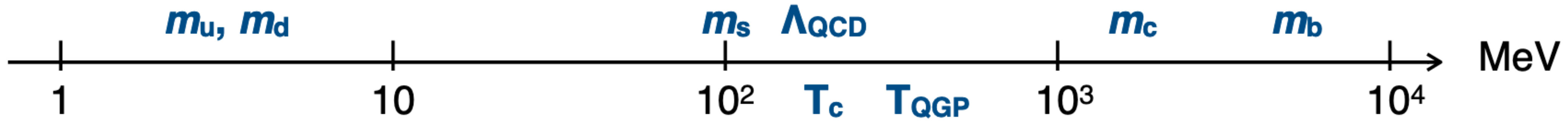
Heavy Quarks: unique probes of the QGP

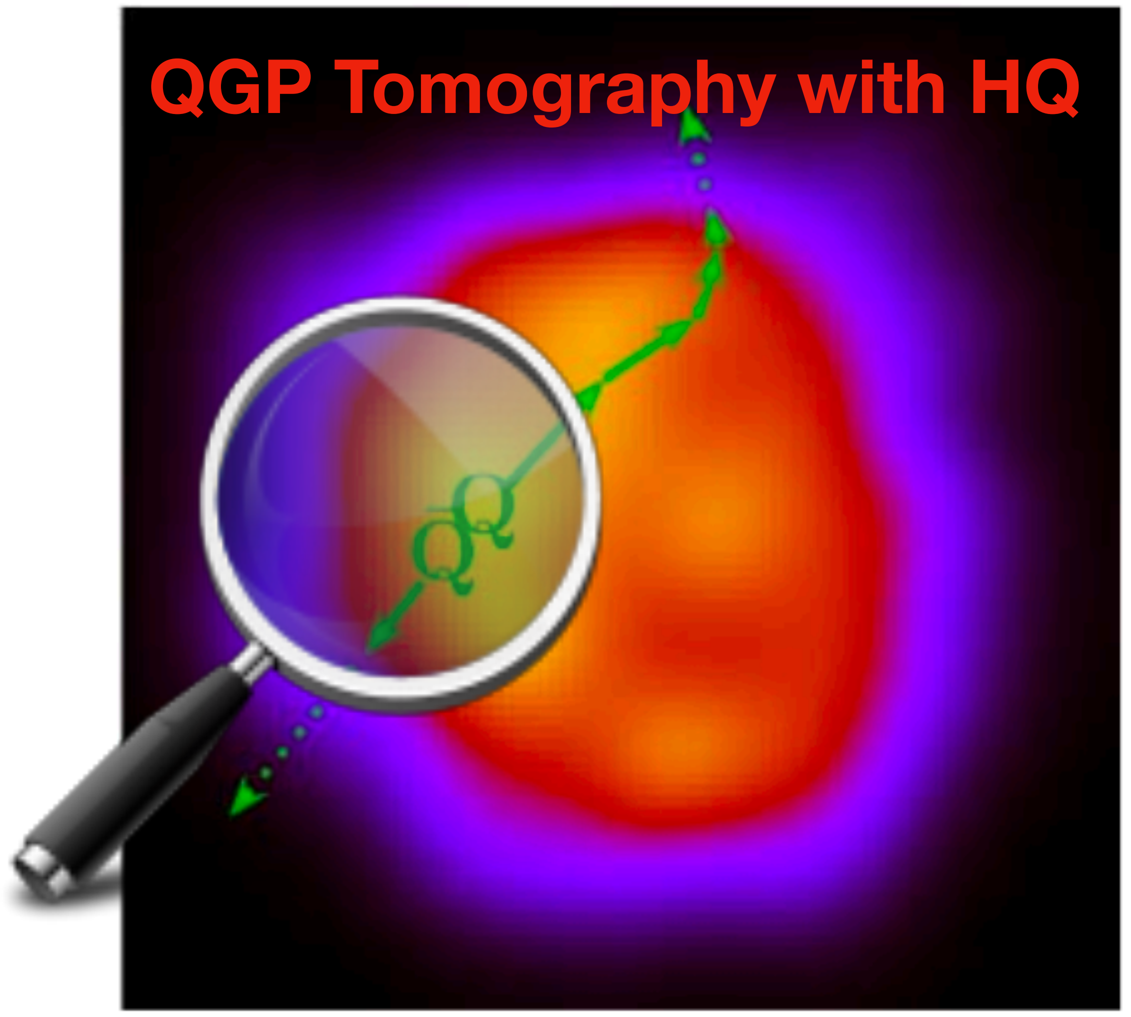
GOAL
Investigate strongly interacting matter under extreme conditions of temperature and density

charm and **beauty** quarks as probes of the QGP properties

Why "heavy"?

- **$m_Q >> \Lambda_{QCD}$**
  - 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, possible comparable to the fireball lifetime (~ few fm/c)





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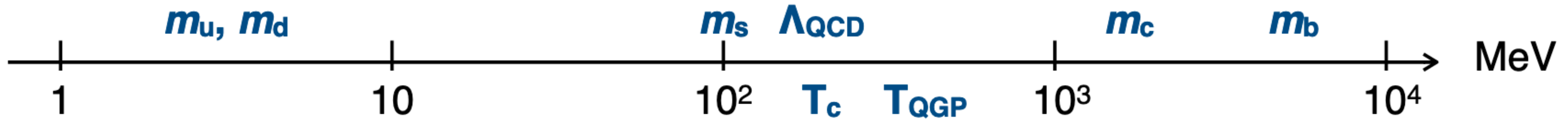
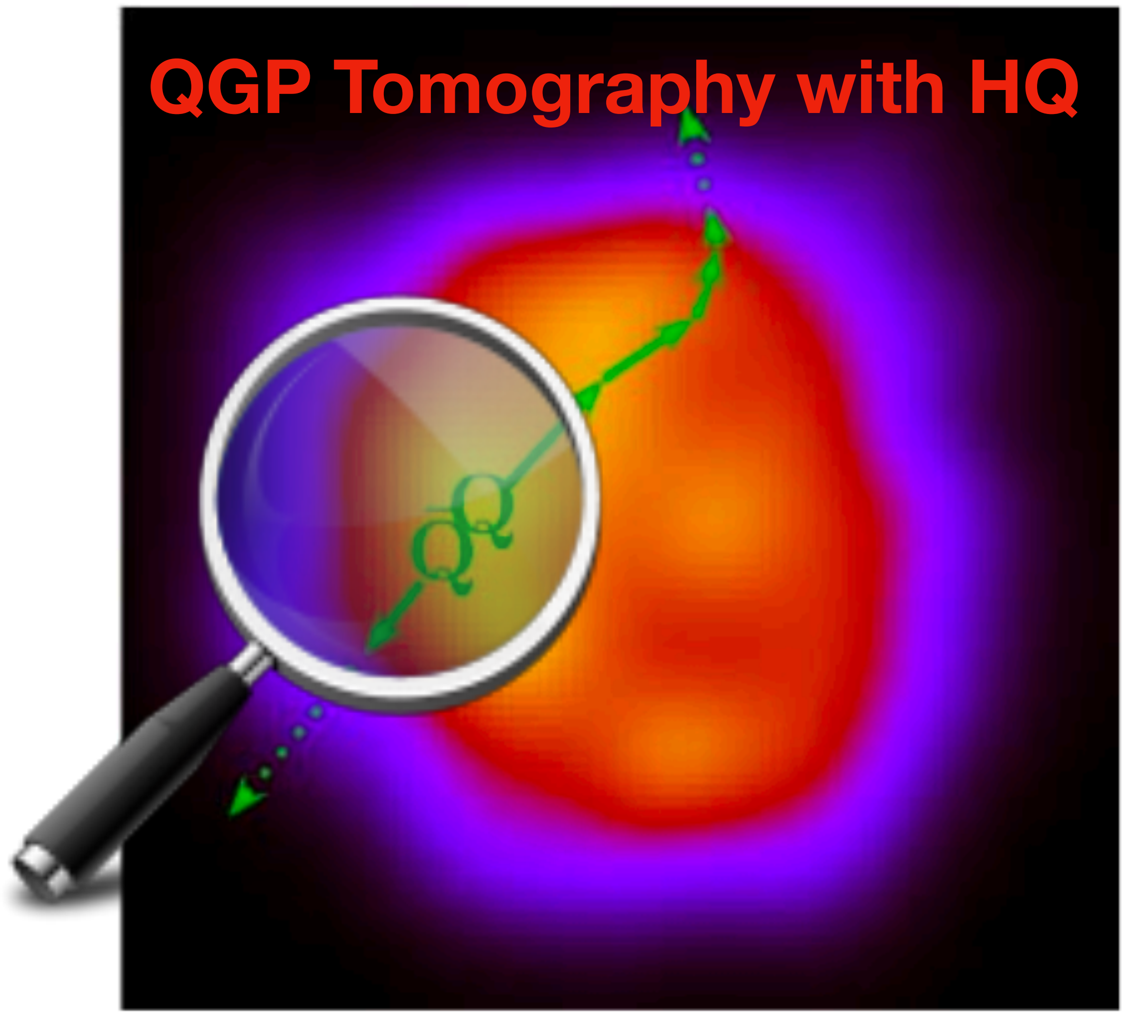
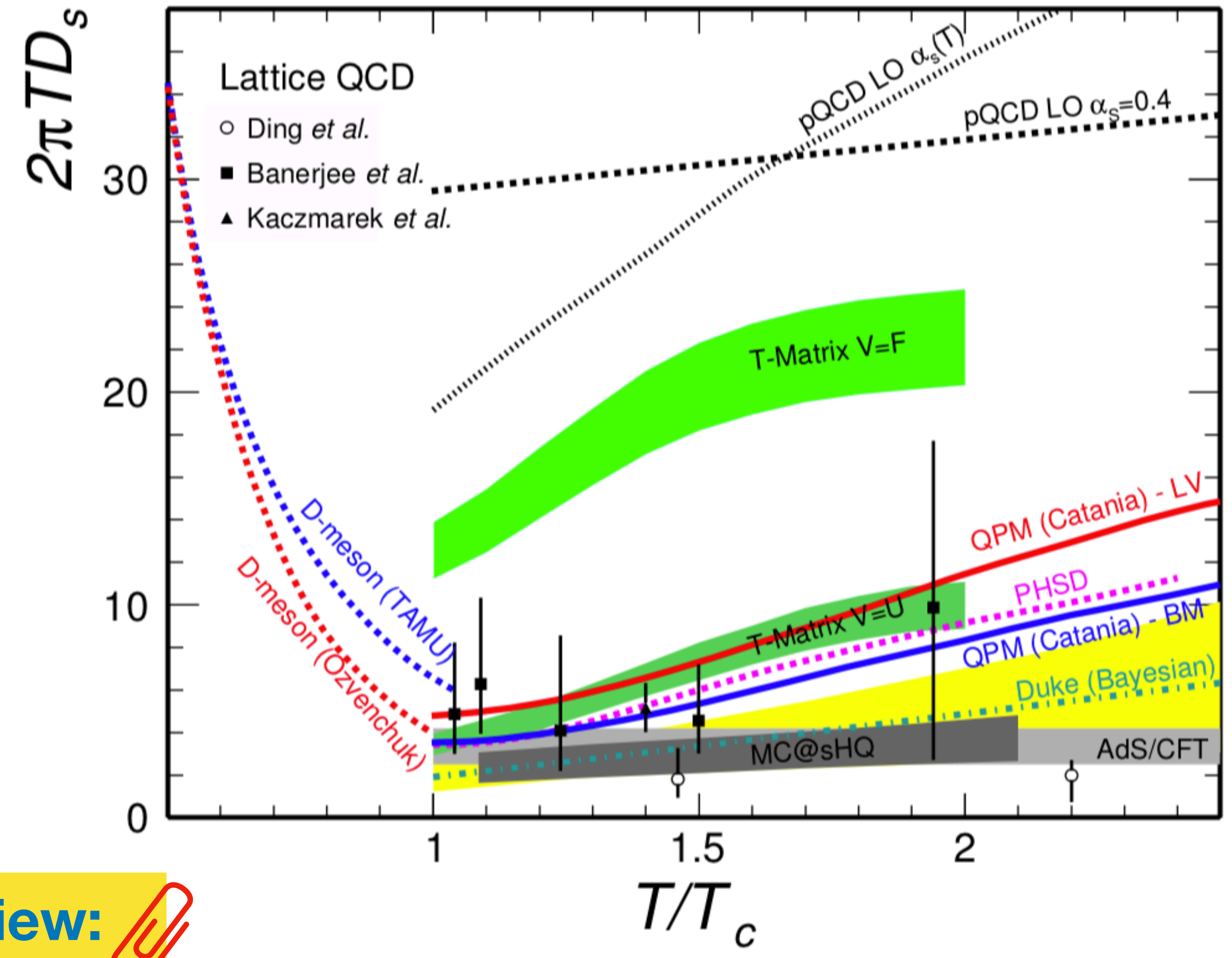




QGP investigation with HQs:

- **High p_T —> tomography via study of HQ energy loss**
- **Low p_T —> HQs as brownian motion markers**
  - **spatial diffusion coefficient: $2\pi TD_s = 2 - 6$**
  - **related to the relaxation time $\tau_Q = (m_Q/T)D_s$; T dependence?**

X. Dong and V. Greco, Progr. Part. Nucl. Phys. (2018)



Not only A-A collisions! Heavy Flavour measurements in small systems:

- pp collisions: provide constraint to pQCD calculations
- pPb/dAu collisions: investigate Cold Nuclear Matter effects

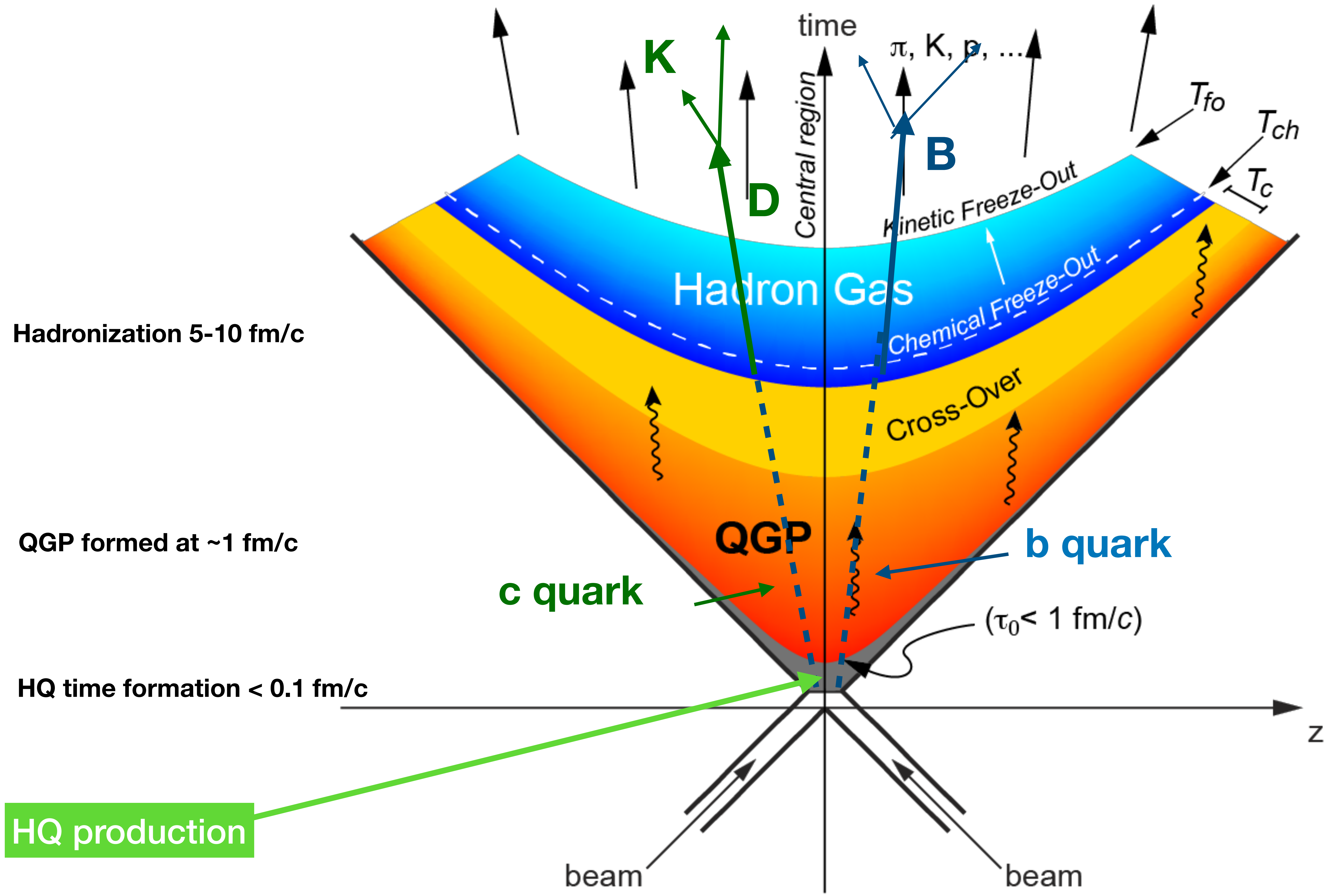
High multiplicity pp and pPb: onset of QGP?

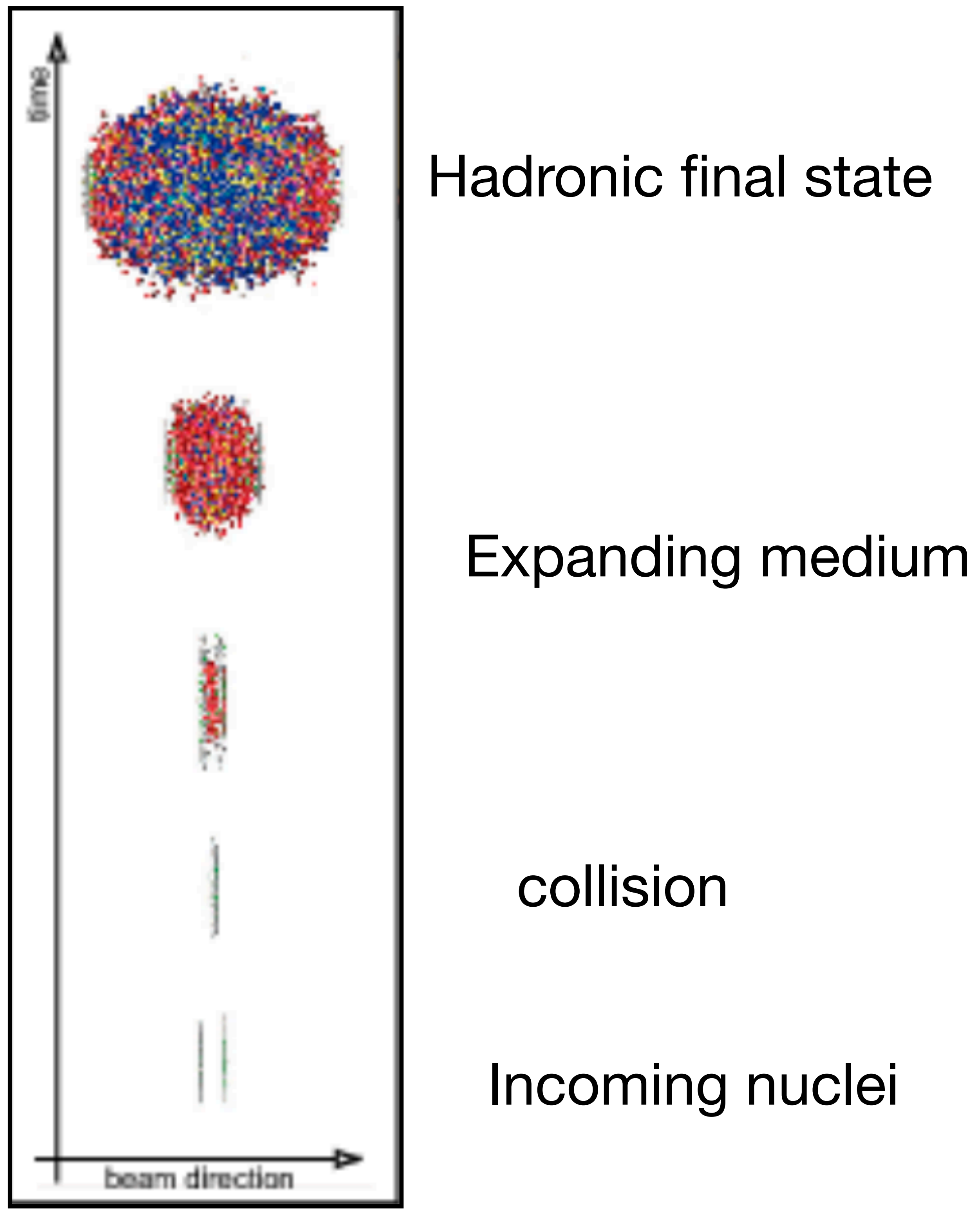
This talk: focus on A-A collisions with some incursions from small systems

Small System Overview:
Talk on Fri. by E. Chapon

Space-time evolution

From heavy-quark production to hadronization into heavy-flavour hadrons





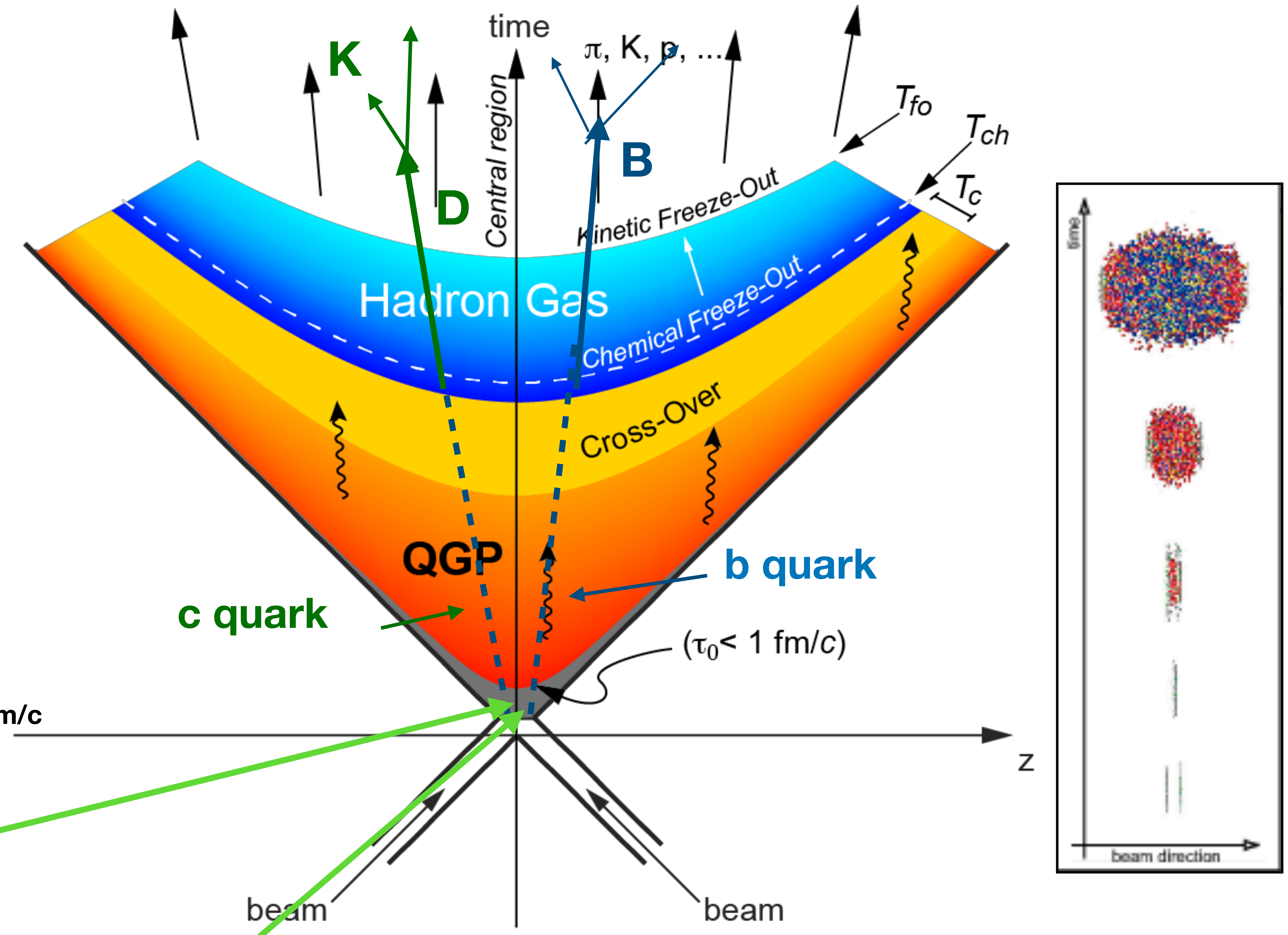
Space-time evolution

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

HQ production

Sensitivity to strong B field

Space-time evolution

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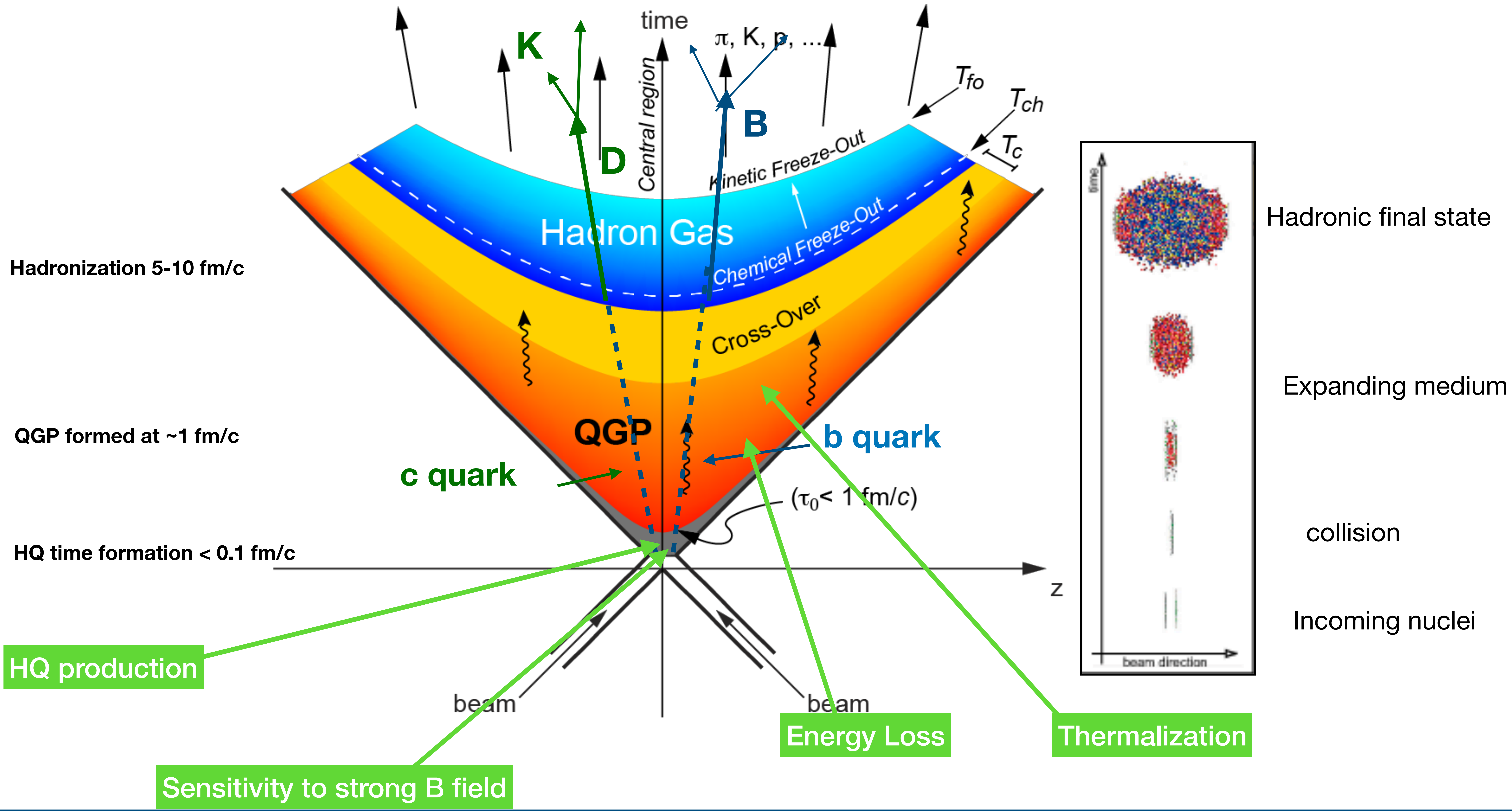

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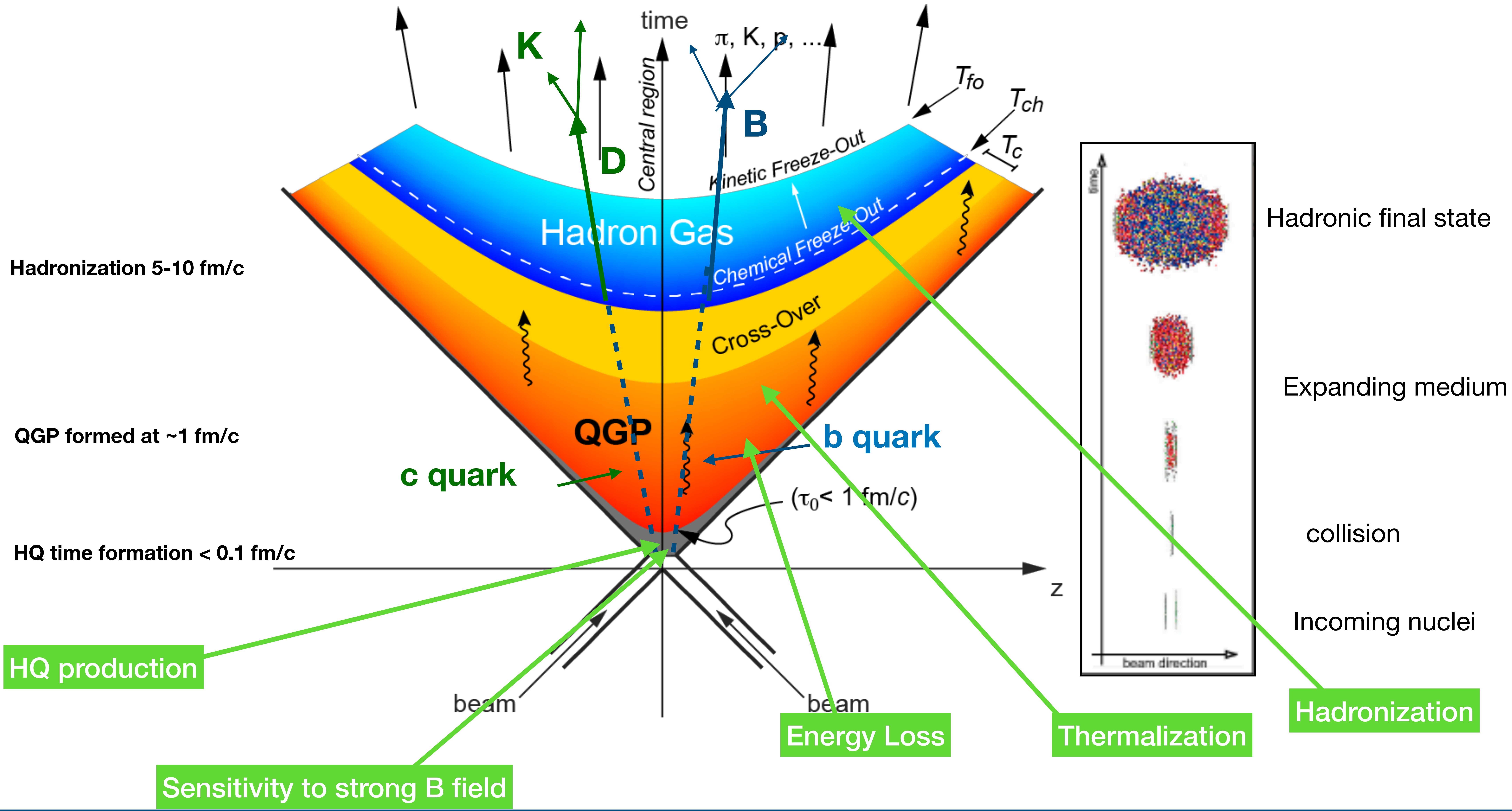

Some (open) questions discussed in this talk

charm and beauty production and interaction in the medium

selection of the most recent HF results

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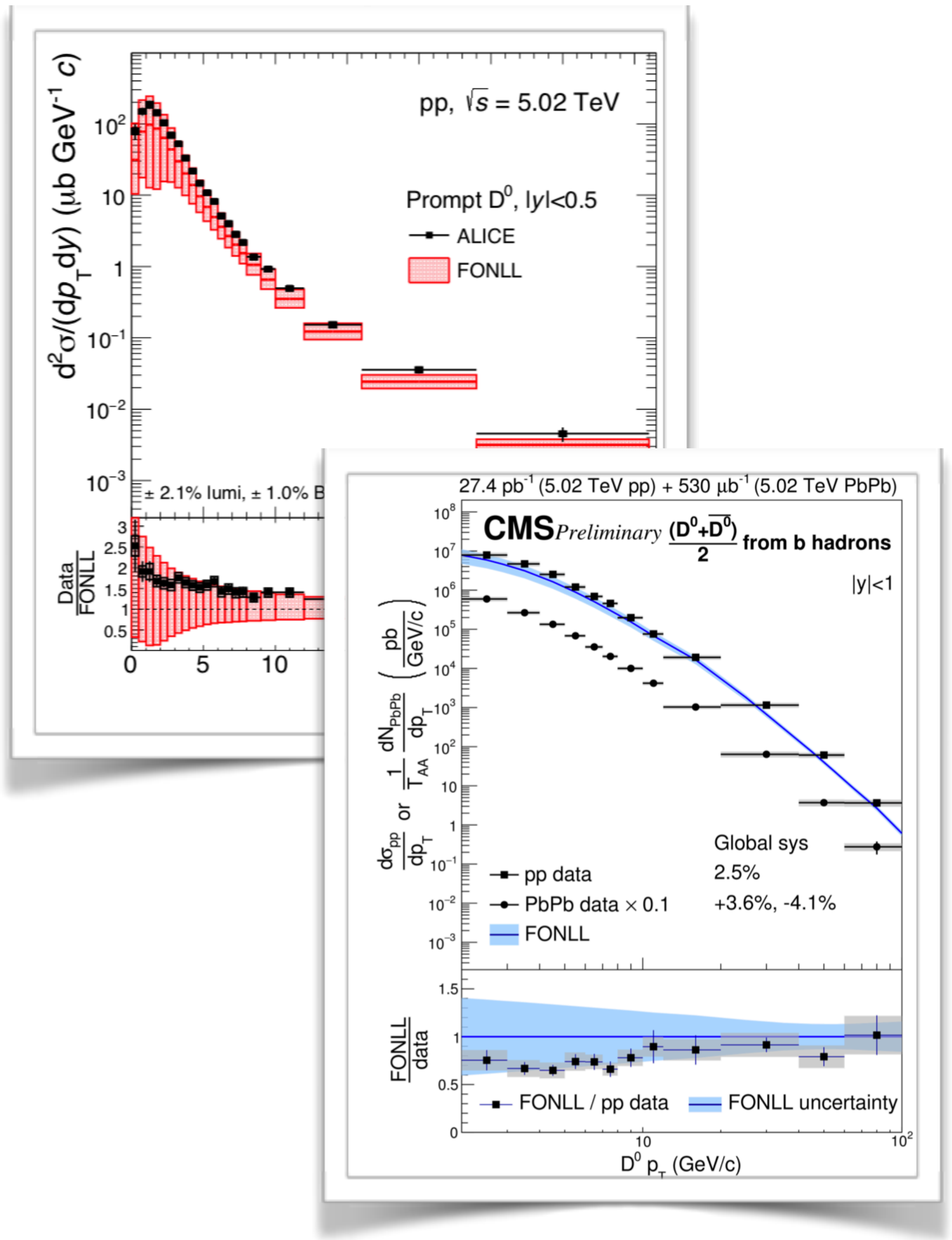
Do we understand the charm and beauty production mechanisms?



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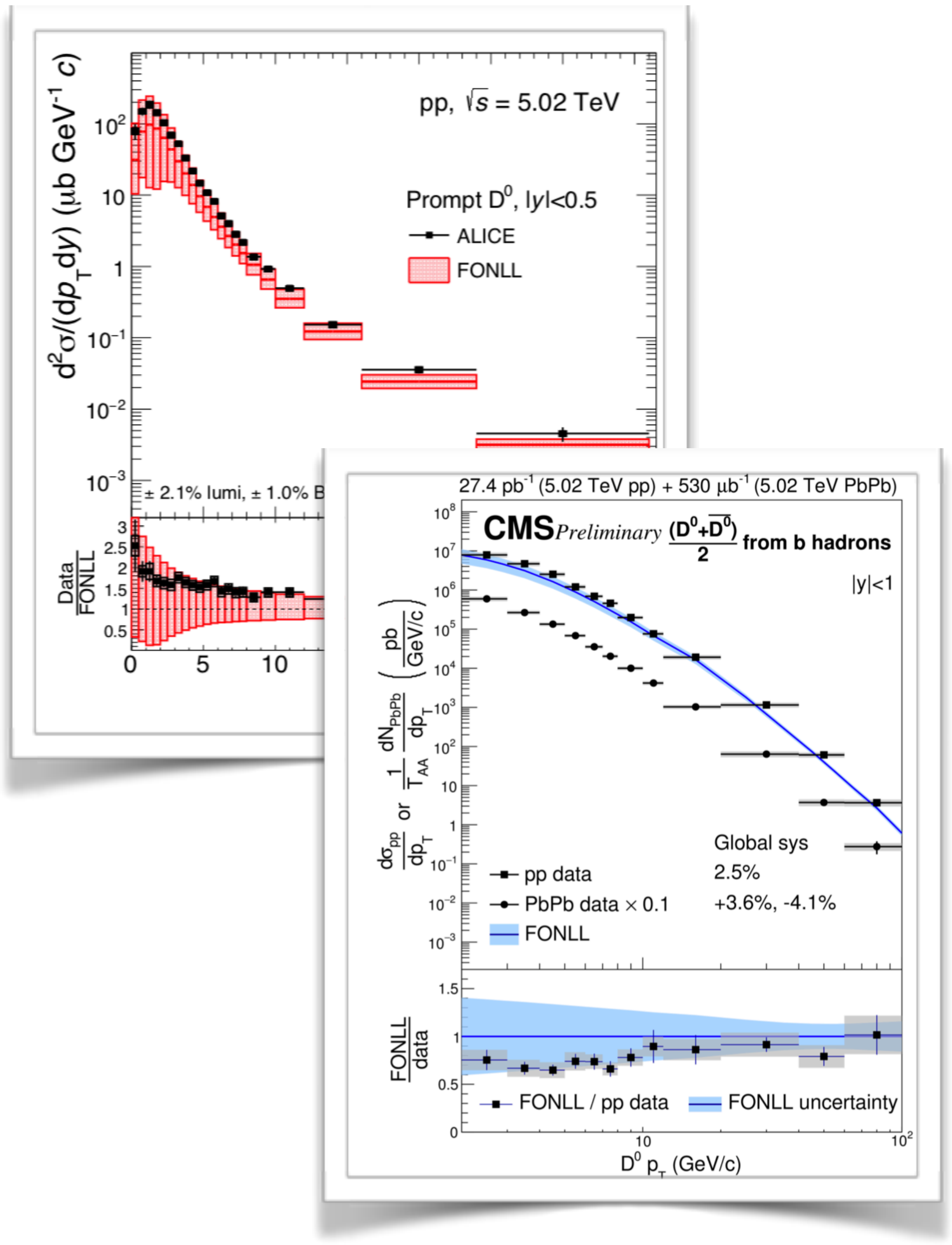
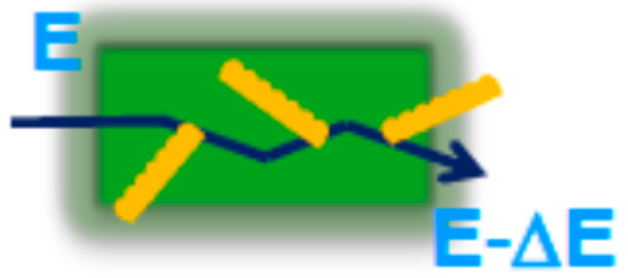
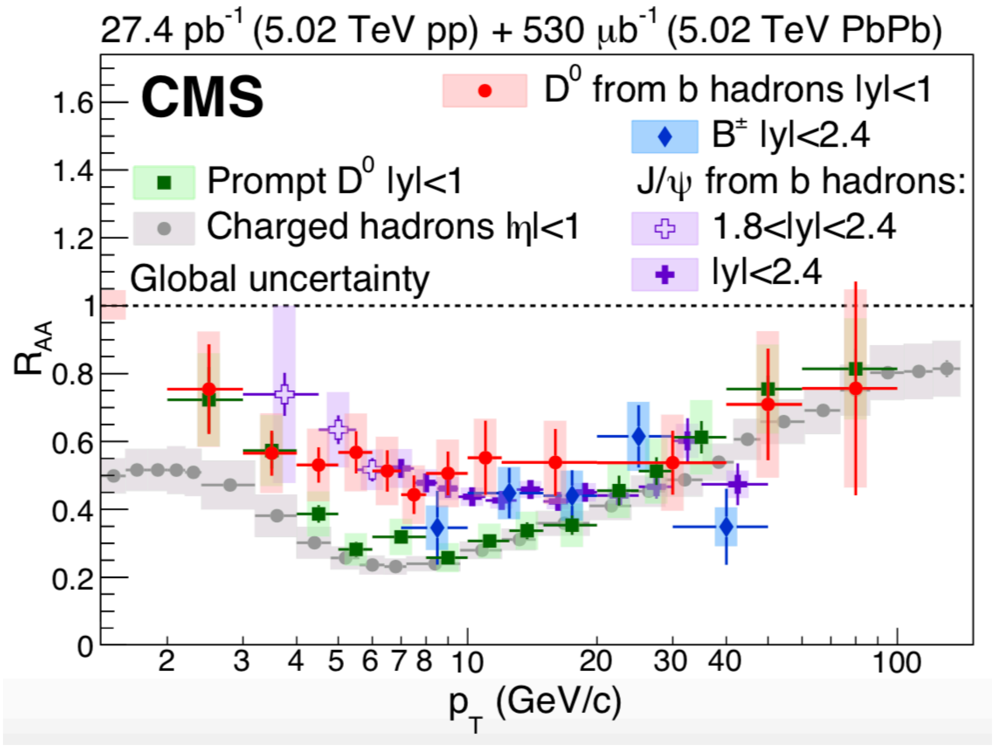


What are the relevant energy loss mechanisms?
Is there a flavour dependence?
When radiative processes start to become predominant on collisional processes?





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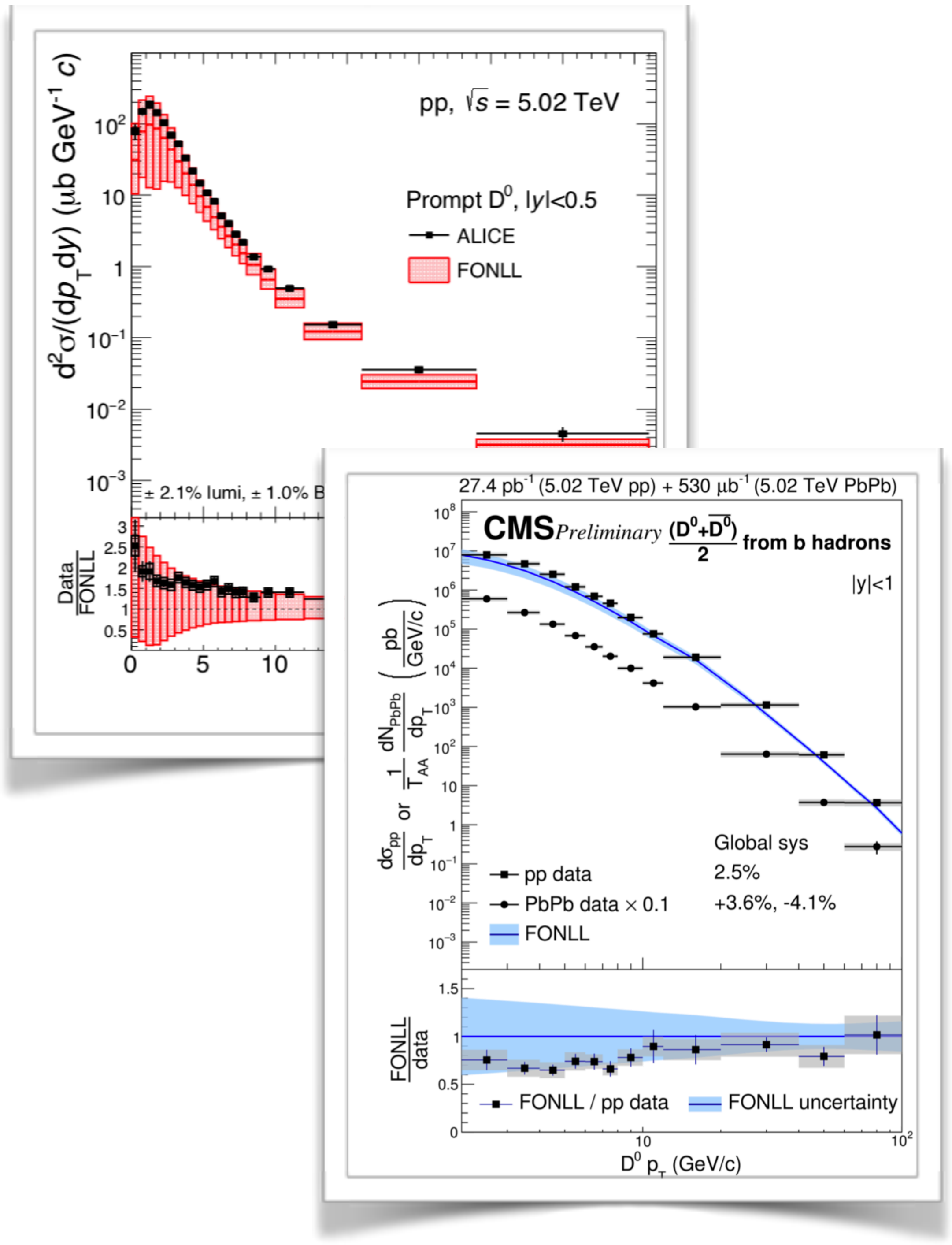

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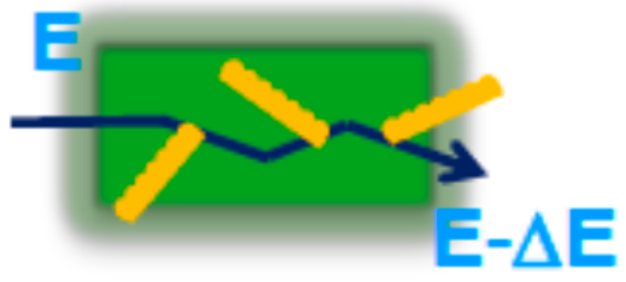
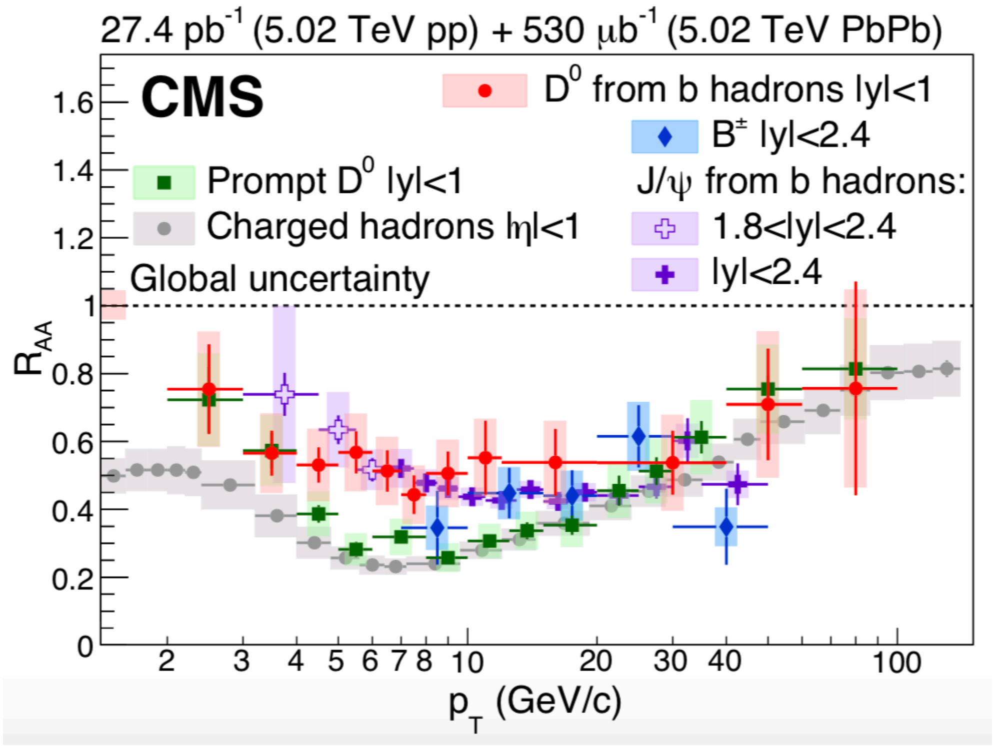
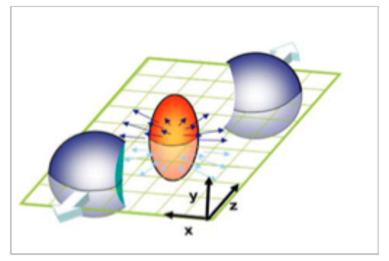
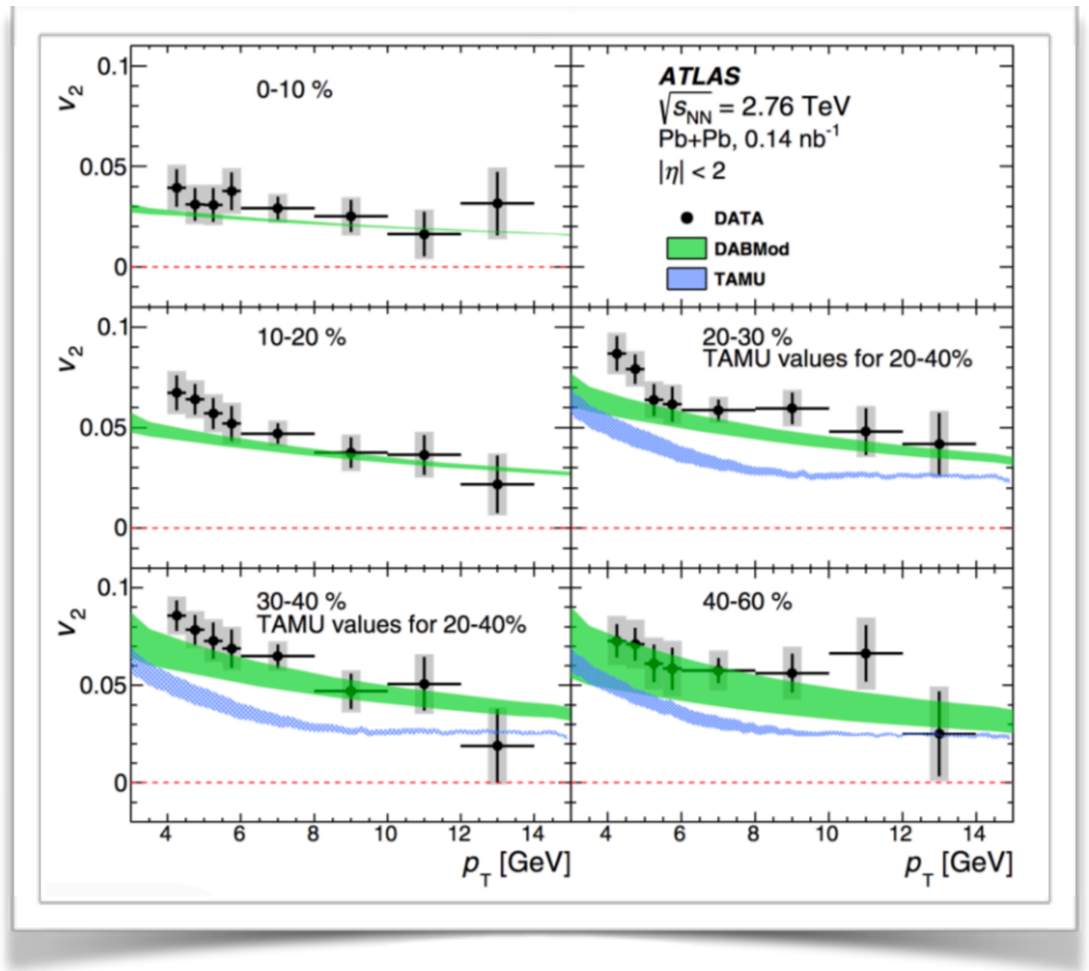




Charm and beauty quarks thermalise?





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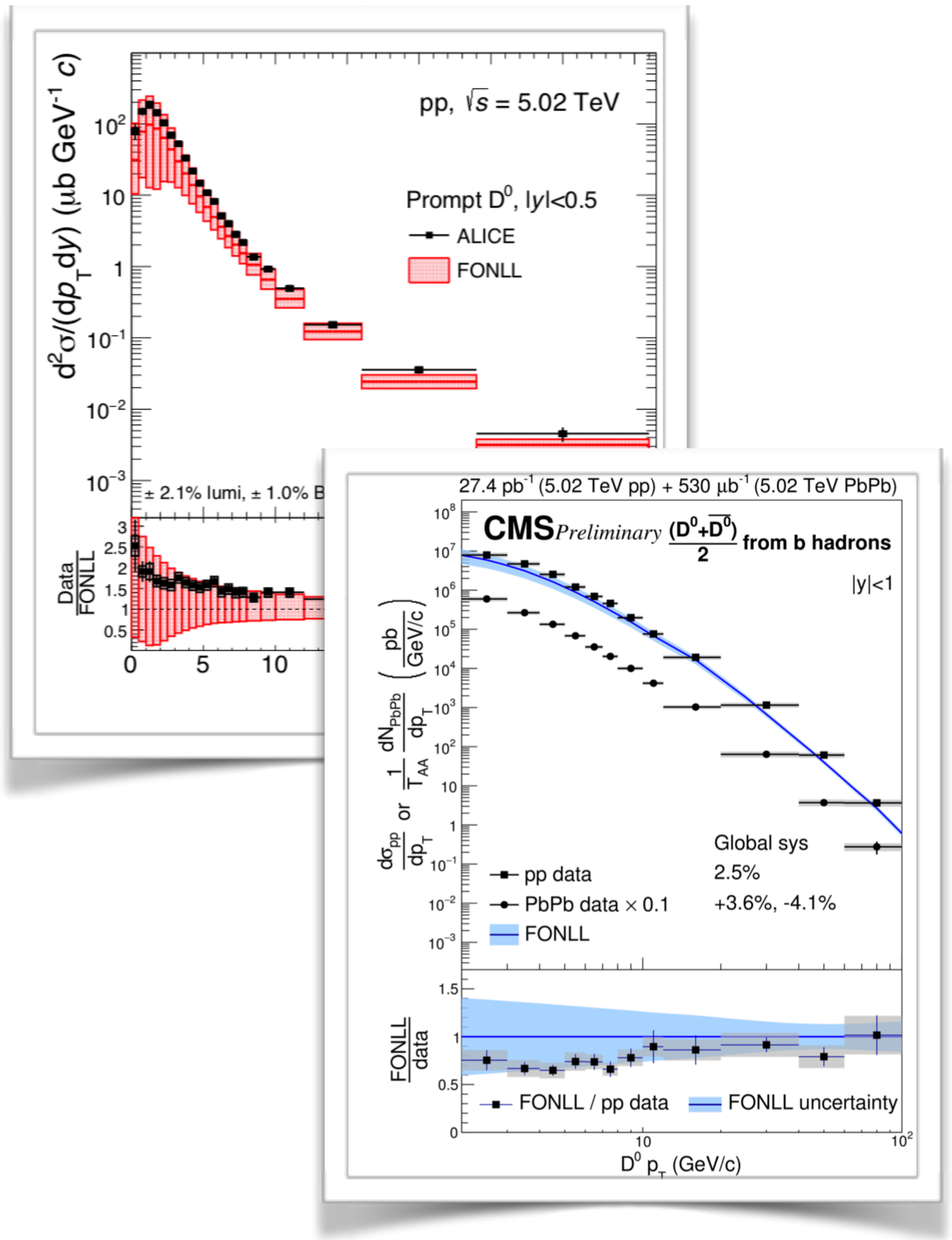

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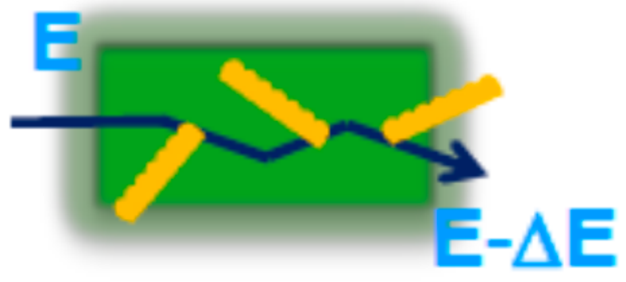

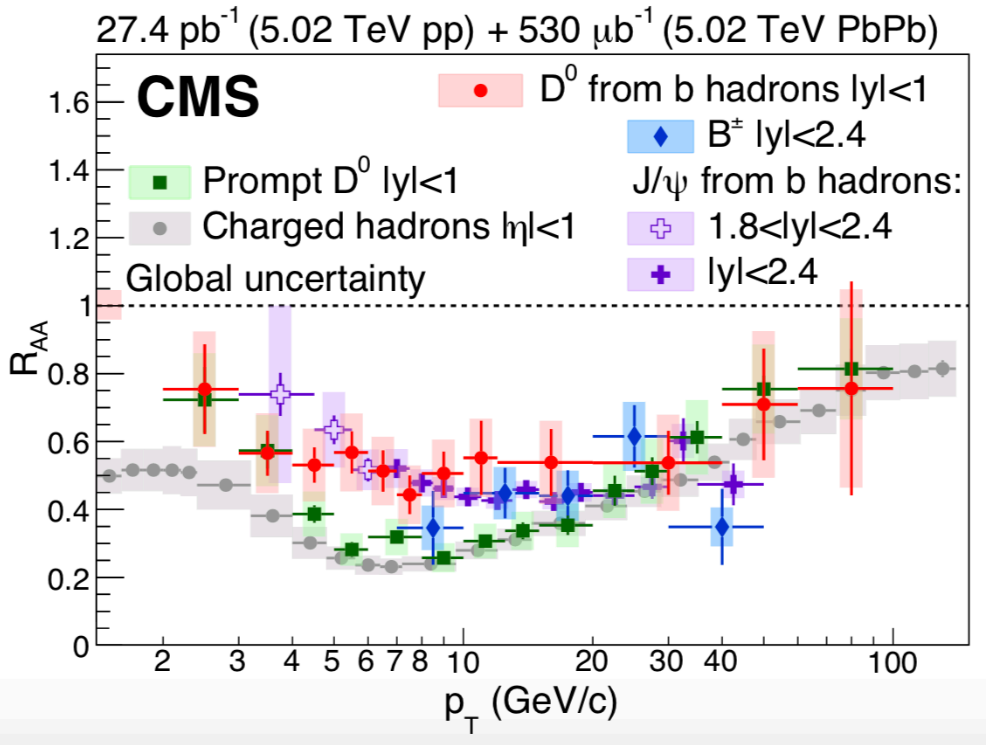

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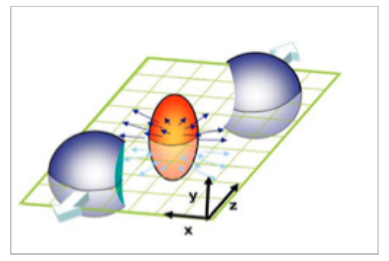
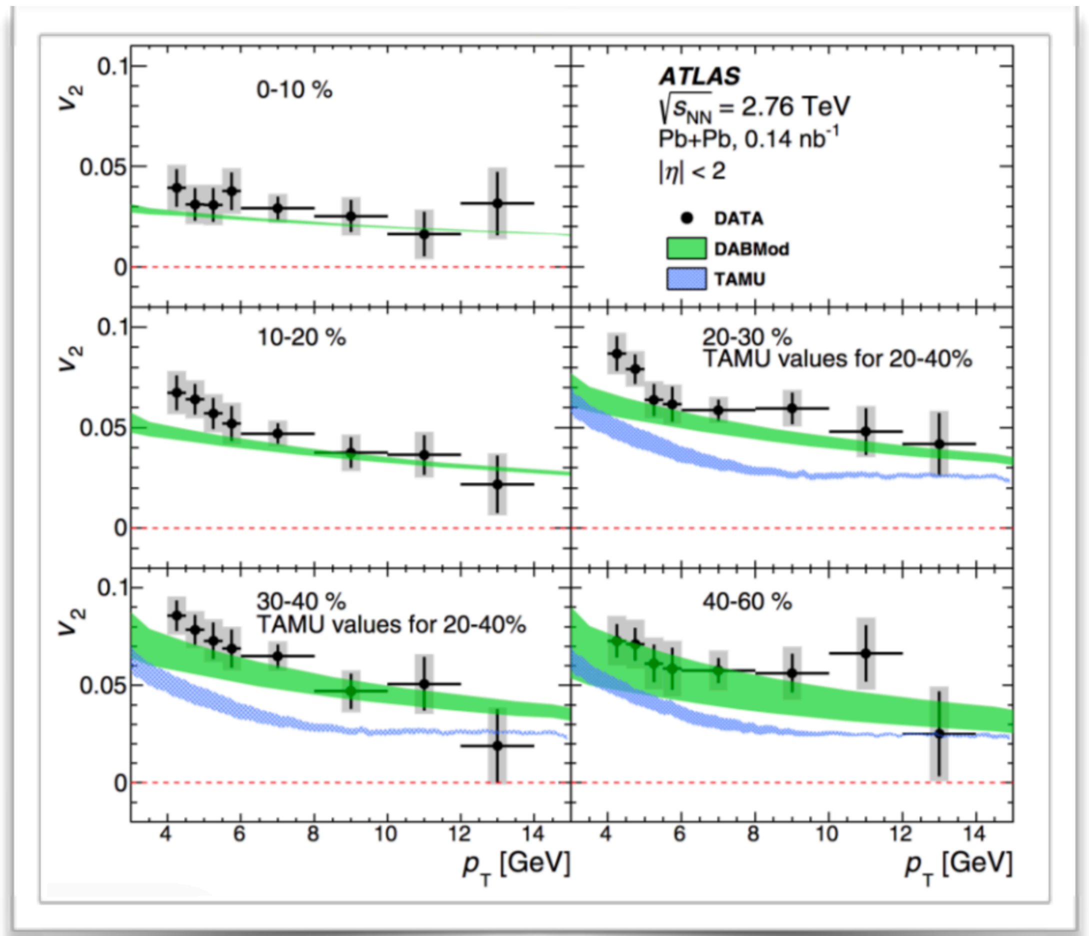
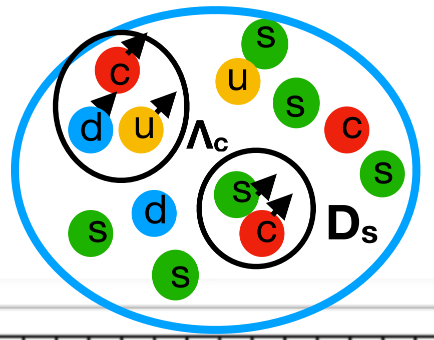
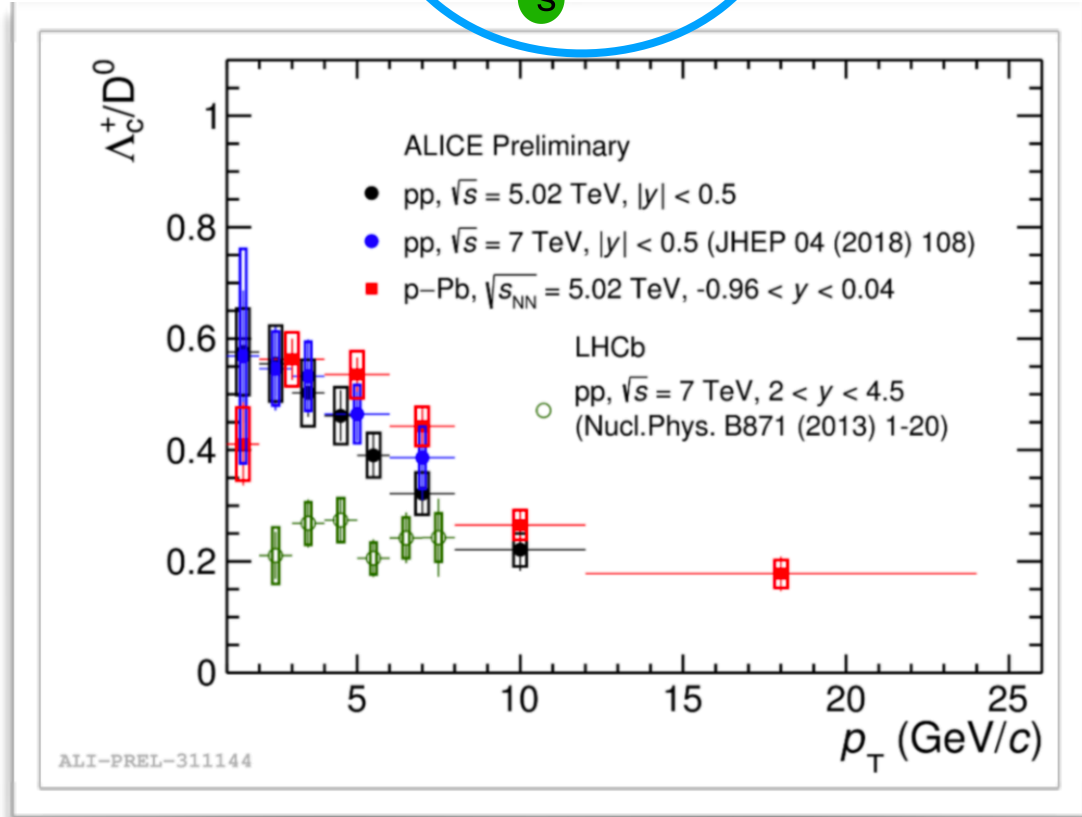


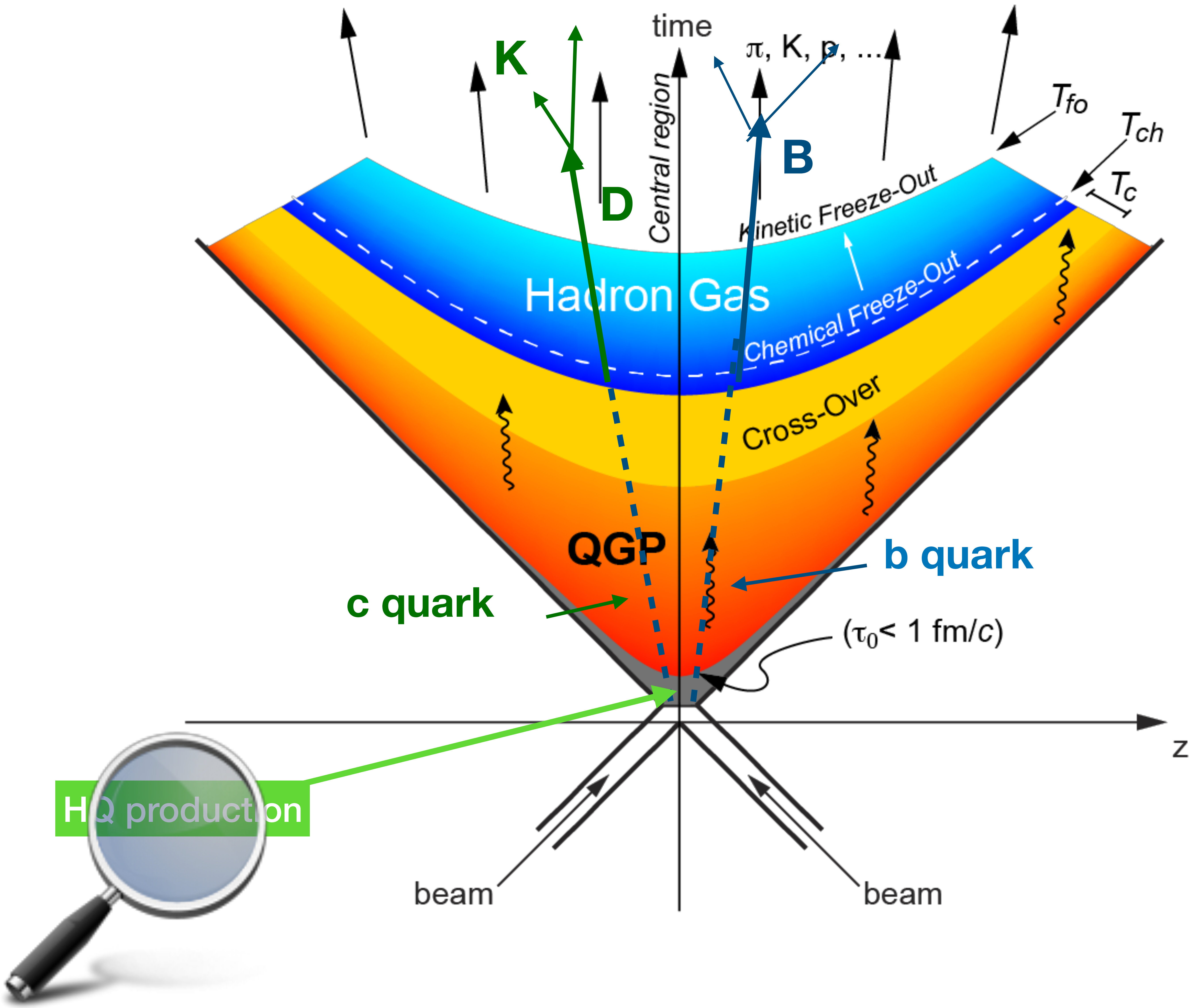


What are the hadronization mechanisms: fragmentation in vacuum? recombination with thermal partons?





Space-time evolution
Production of heavy quarks



Hadronic final state

Expanding medium

collision

Incoming nuclei

Heavy-flavour production in pp collisions

pp collisions as test for perturbative-QCD

Do we understand the charm and beauty production mechanisms?

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

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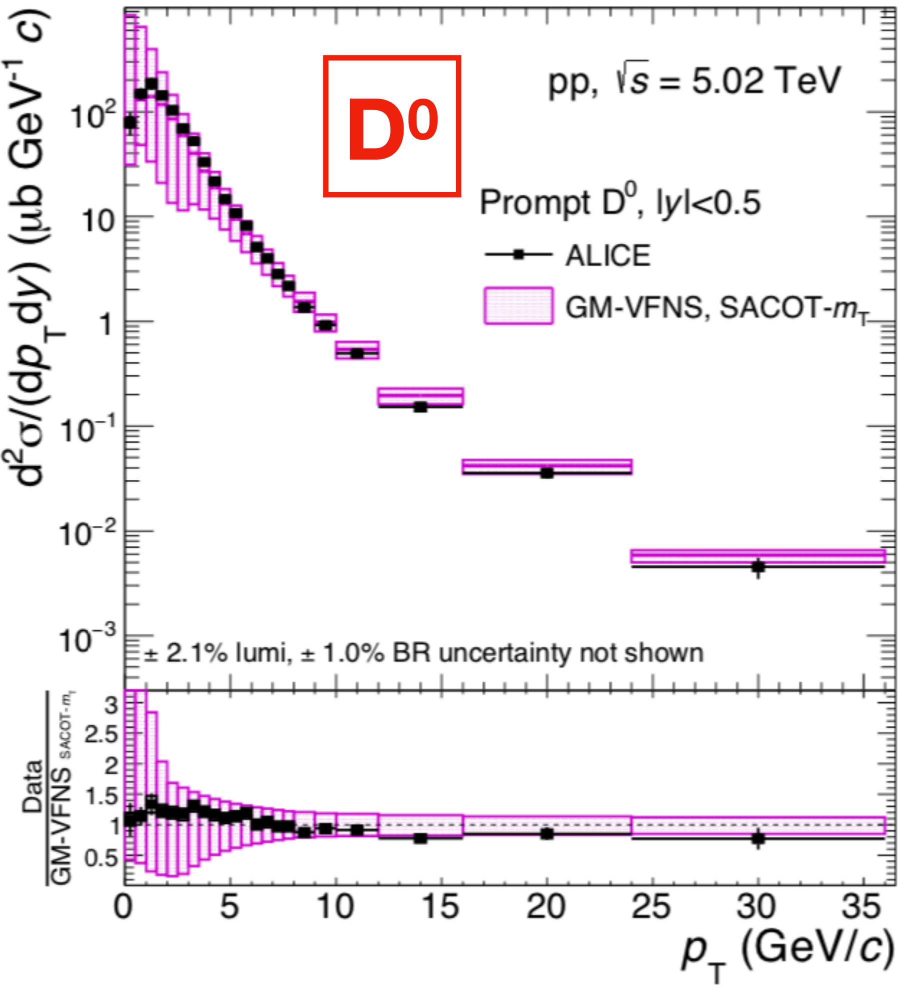
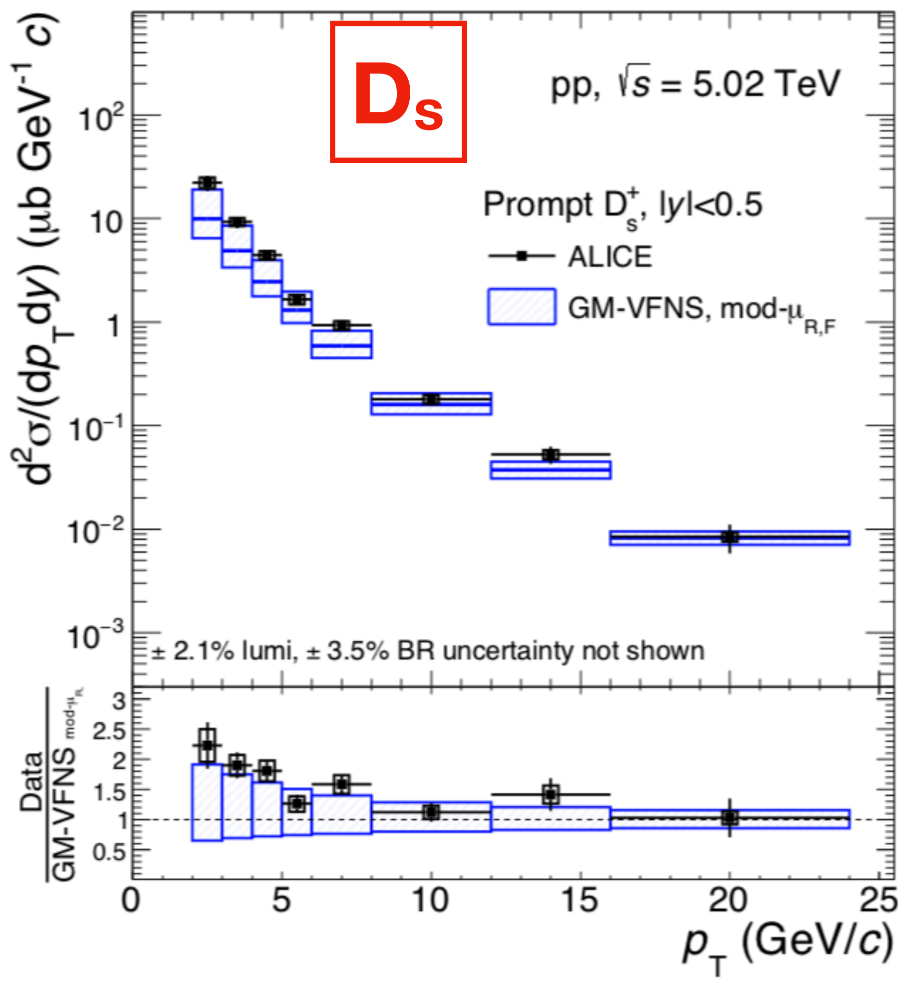
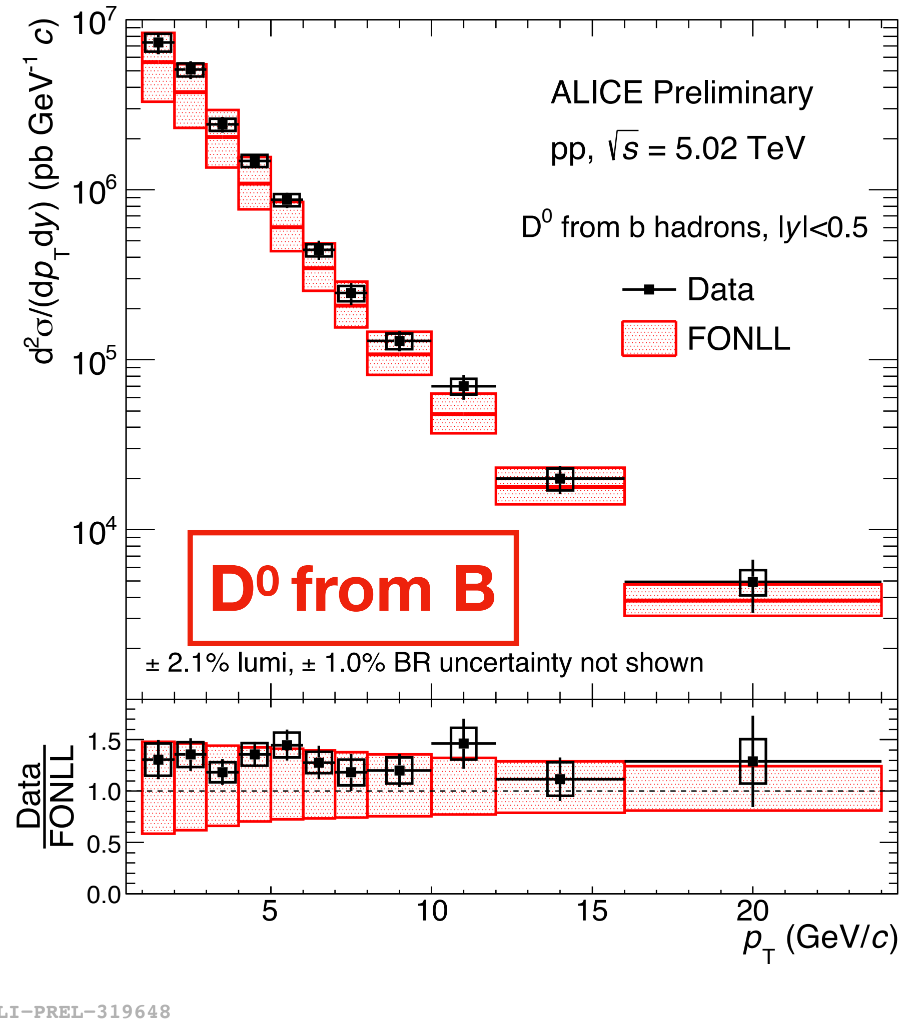
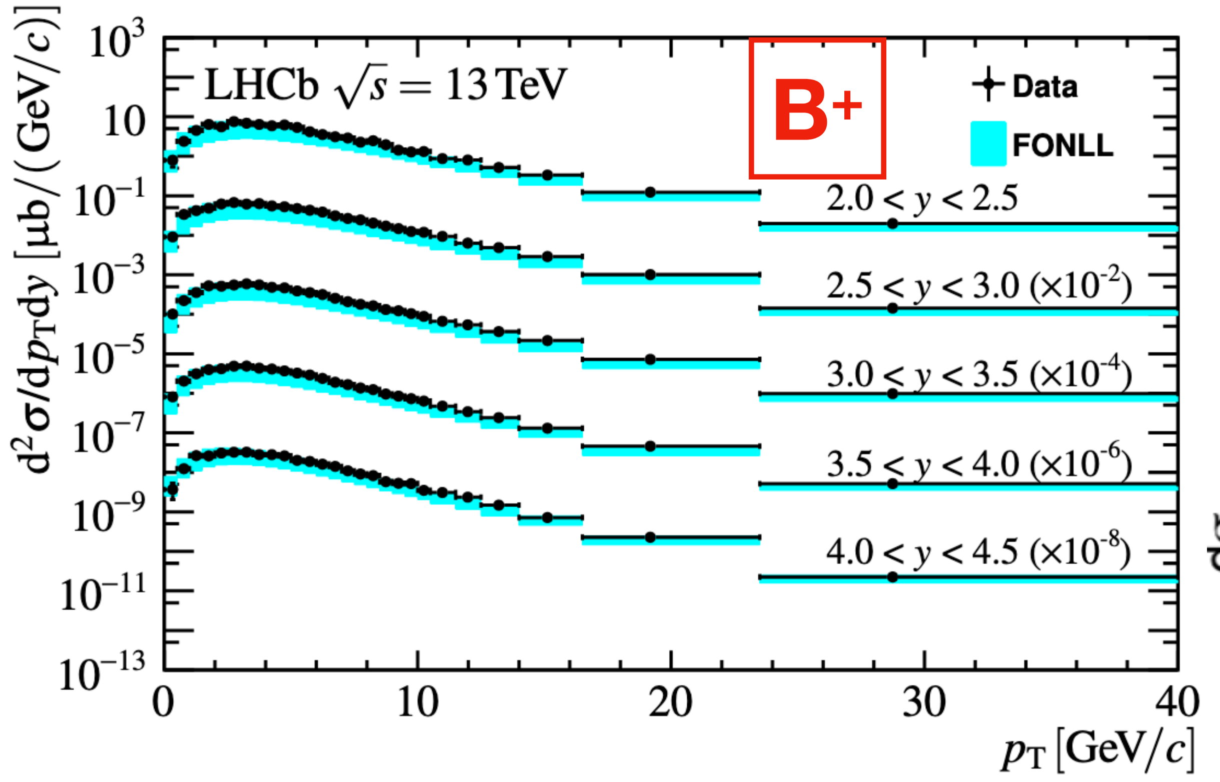
Eur.Phys.J. C79 (2019) no.5, 388



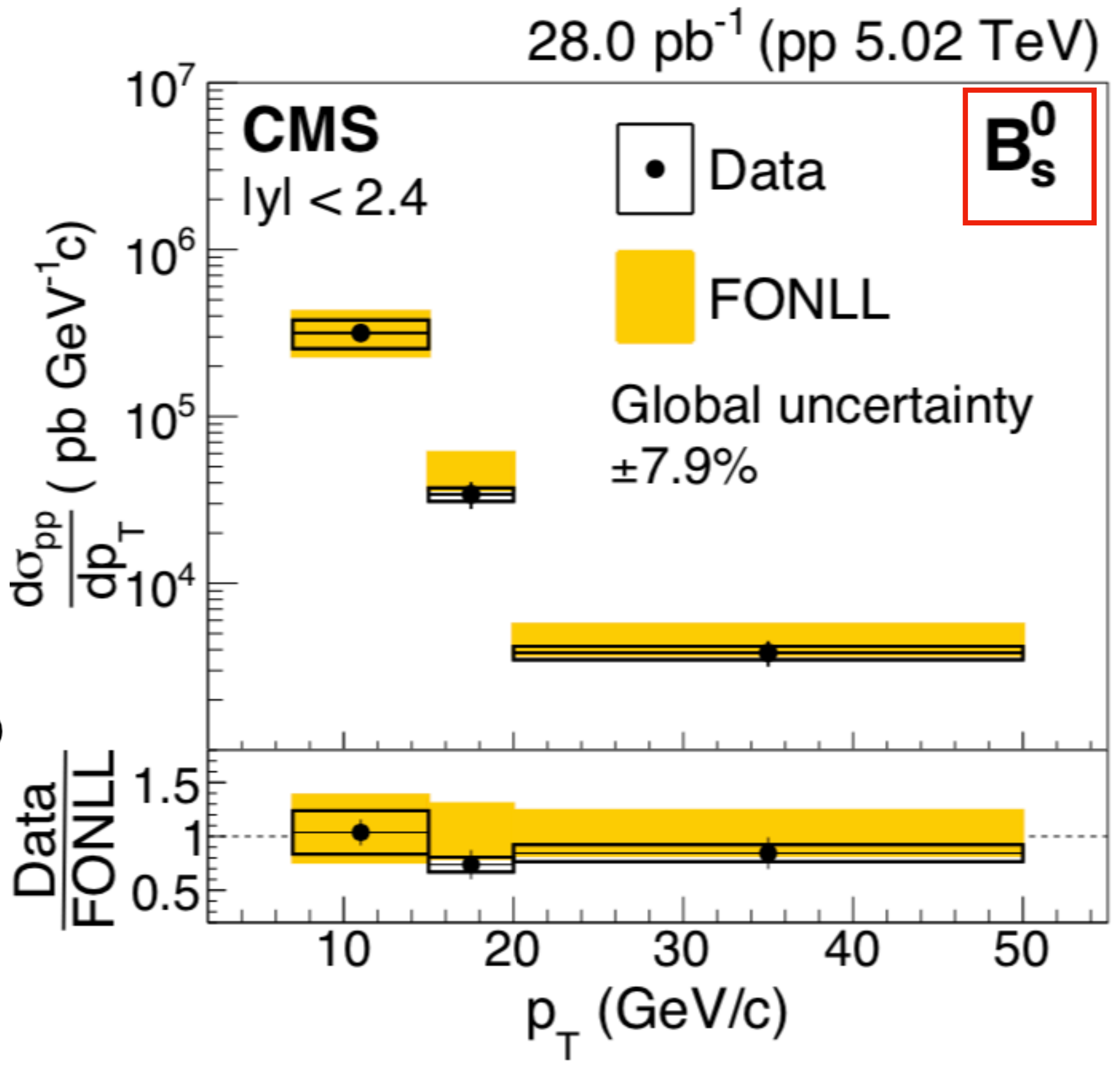




JHEP12 (2017) 026



arxiv:1810.03022



Systematic comparison with several pQCD calculations with different schemes: agreement within uncertainties

Talks/Posters:
D. Yang
P. Dhanker
M. Cai
F. Gauger
F. Wang

Heavy-flavour production in pp collisions

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$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\text{-}}$$

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

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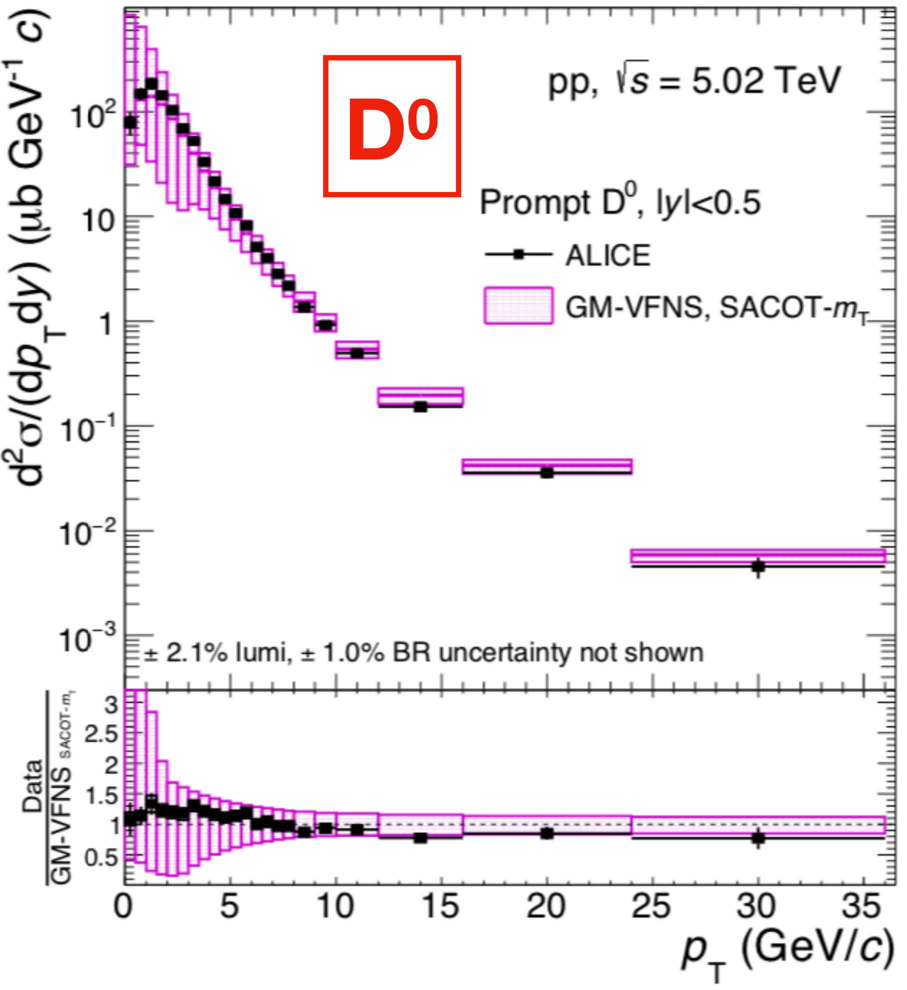

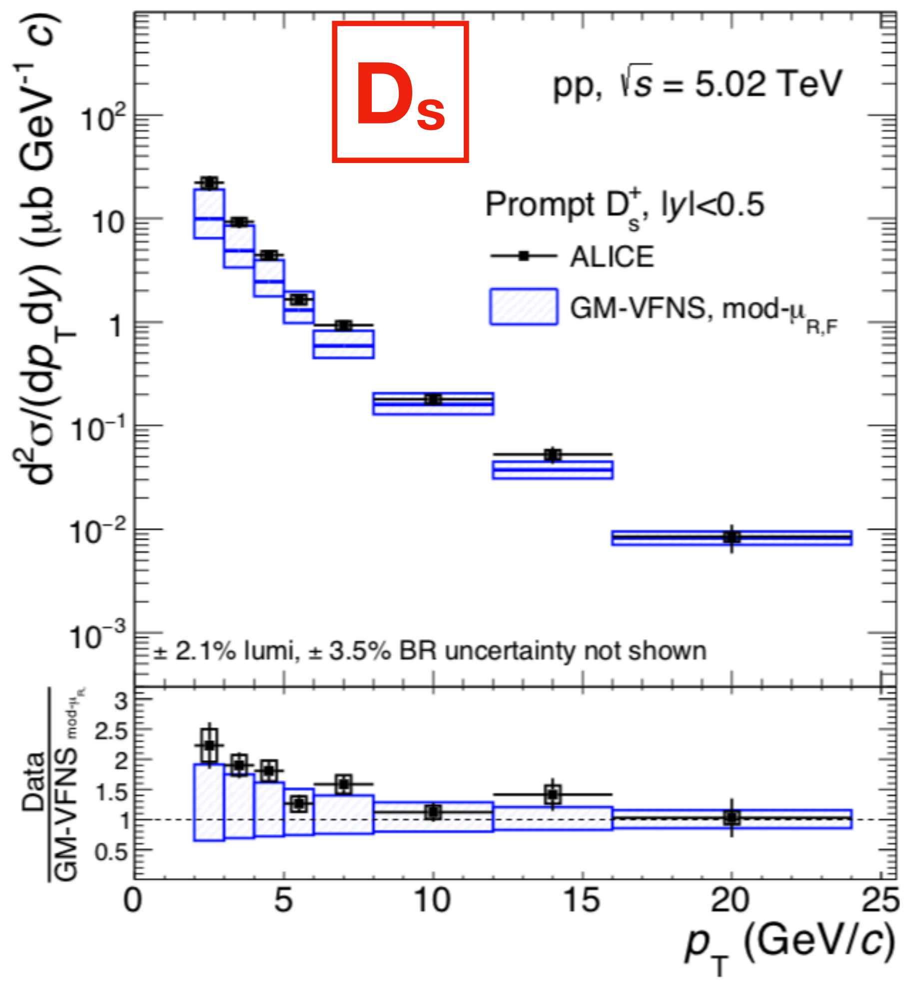

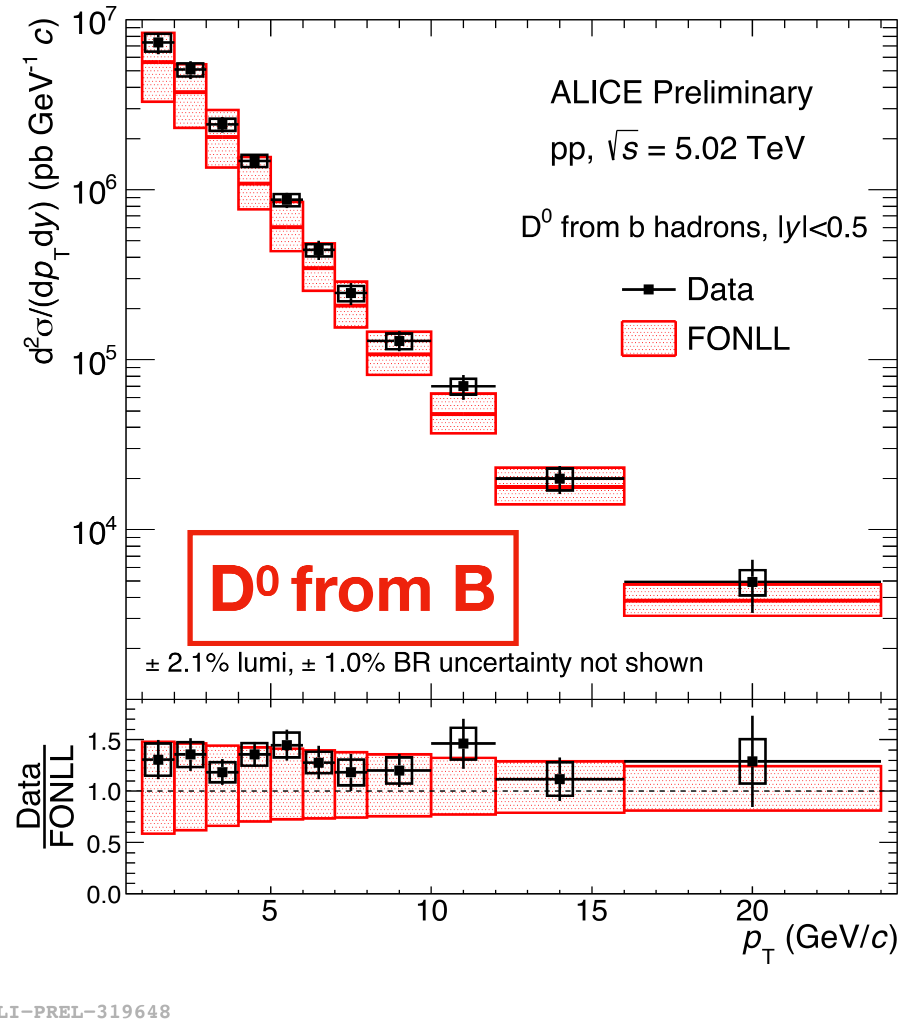

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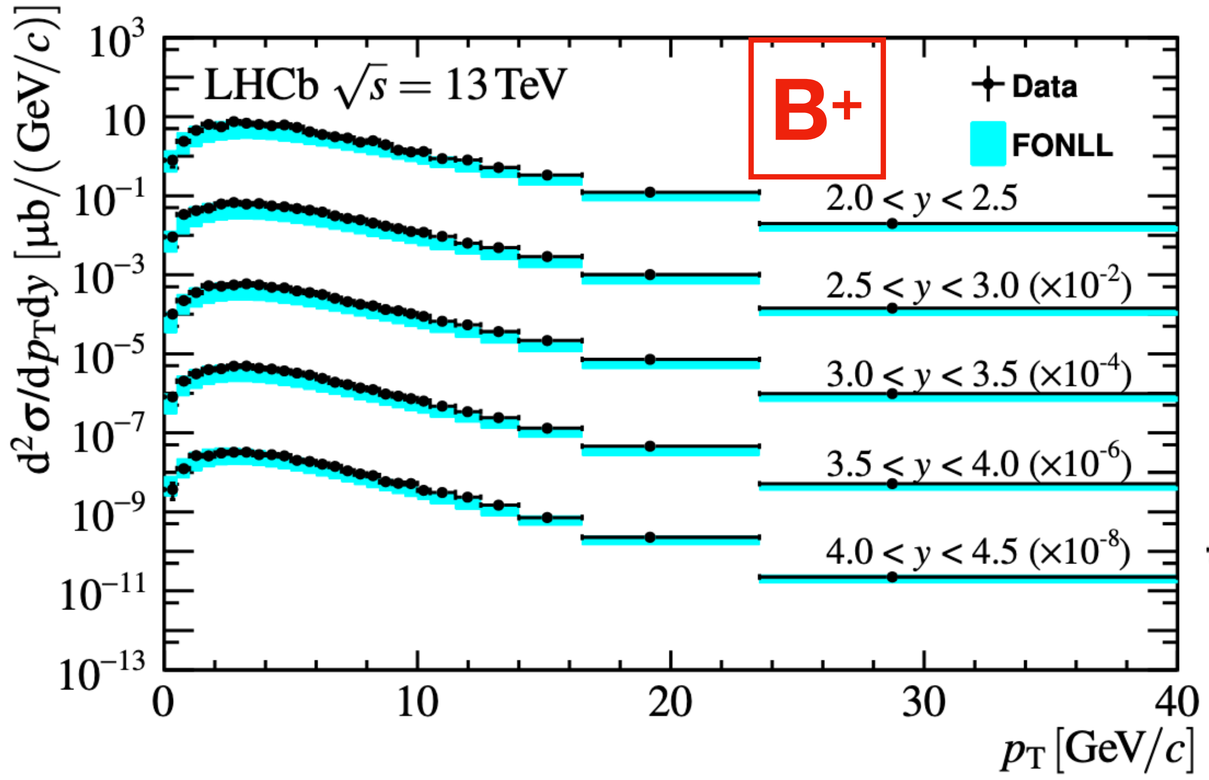
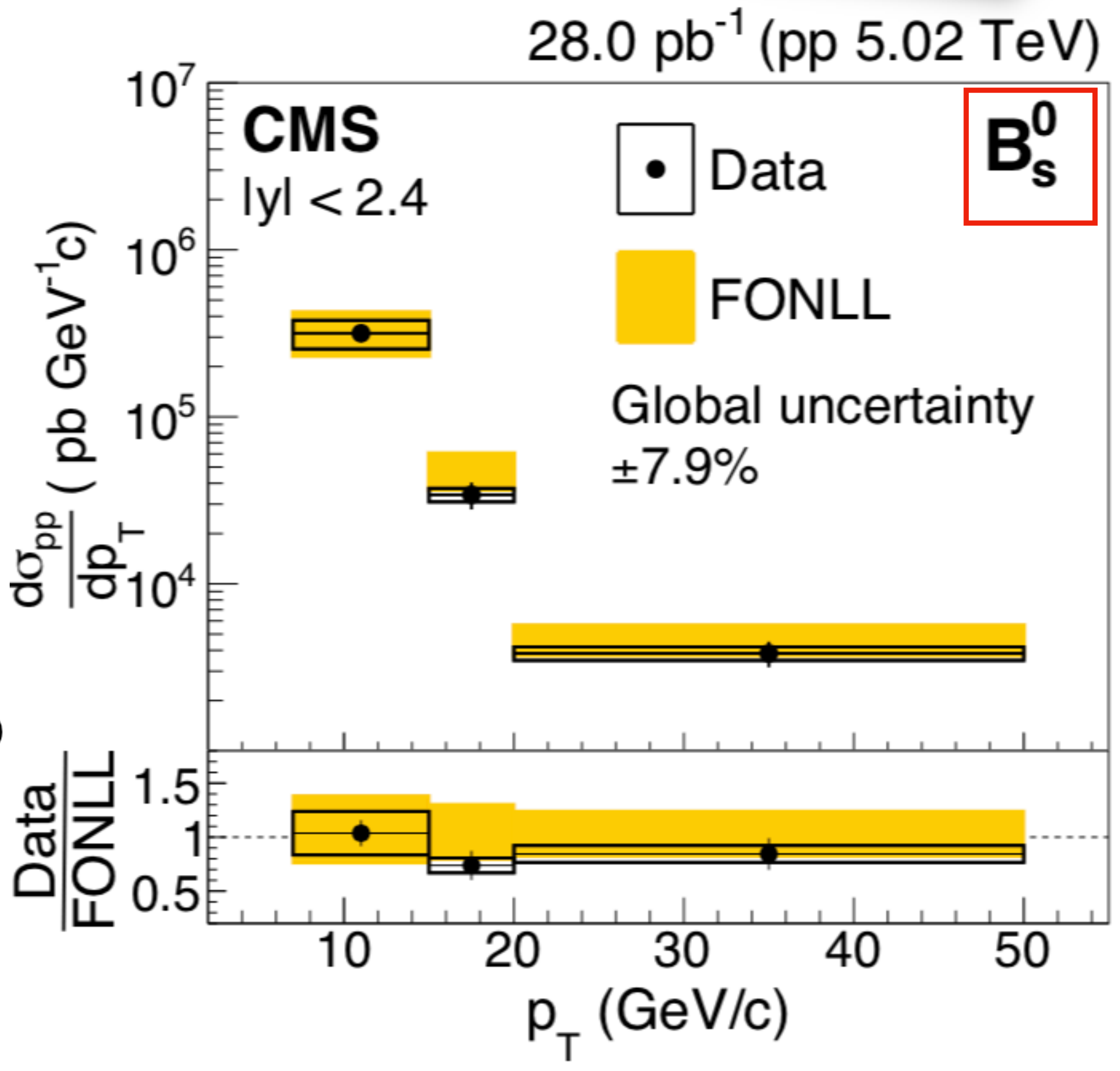


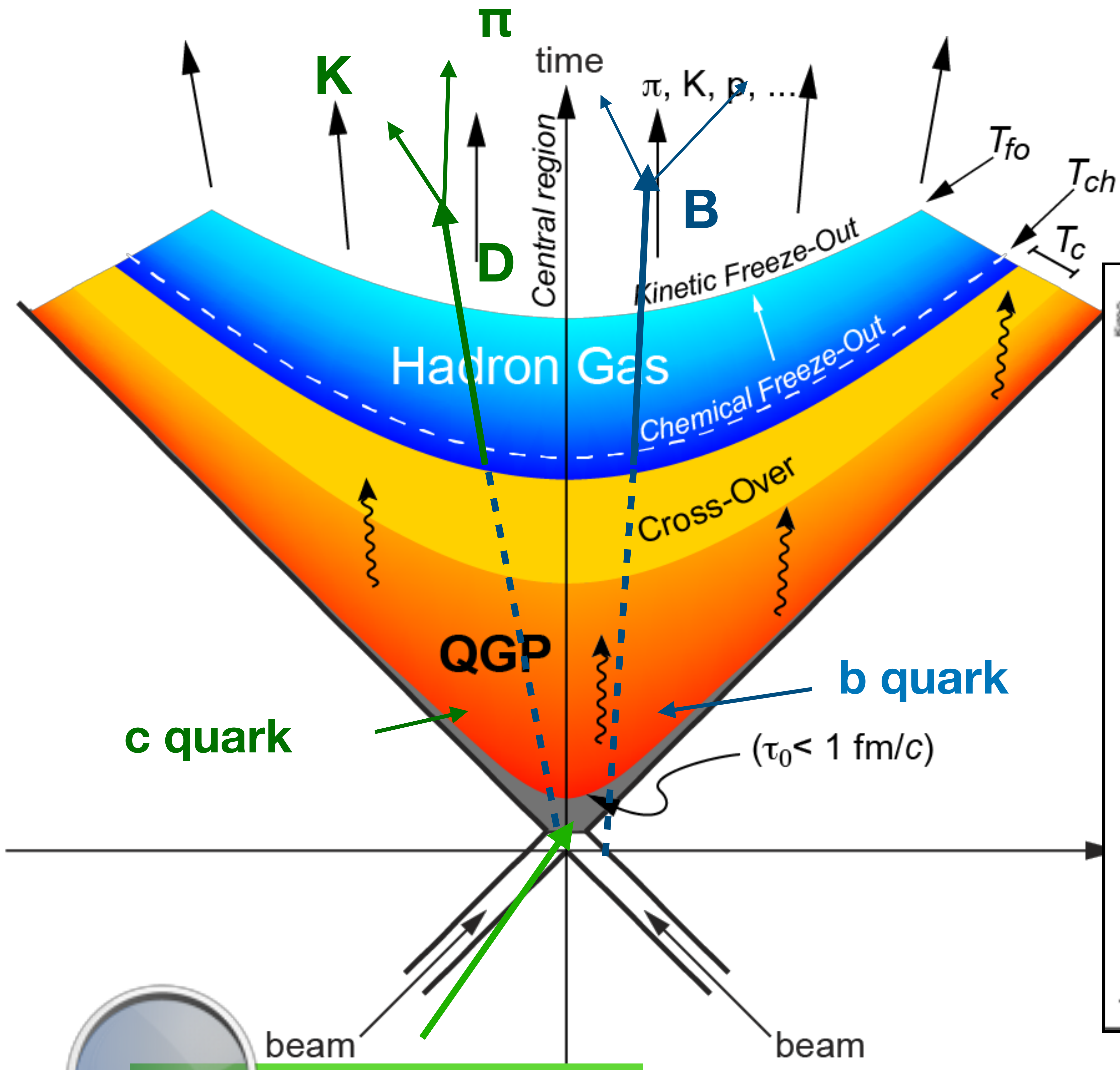


Systematic comparison with several pQCD calculations with different schemes: agreement within uncertainties

Data: smaller uncertainties than theoretical ones

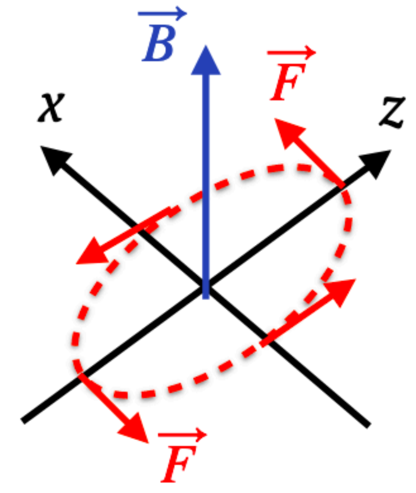
dominated by factorisation and renormalisation scales of the perturbative calculations and PDF uncertainties

Space-time evolution

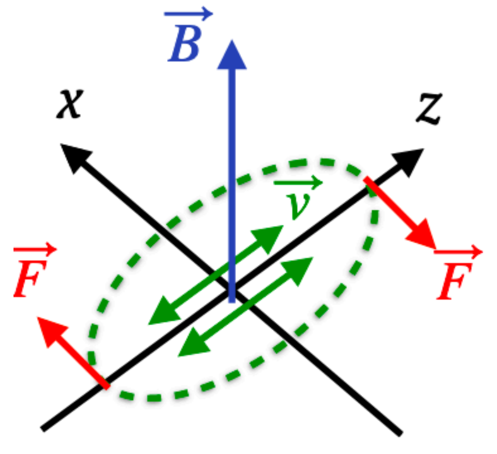


Sensitivity to strong B field

charm **formation time** ~ 0.1 fm/c
→ comparable to the time scale when B is maximum
➡ Probes of the strong B field in the early state of the collision



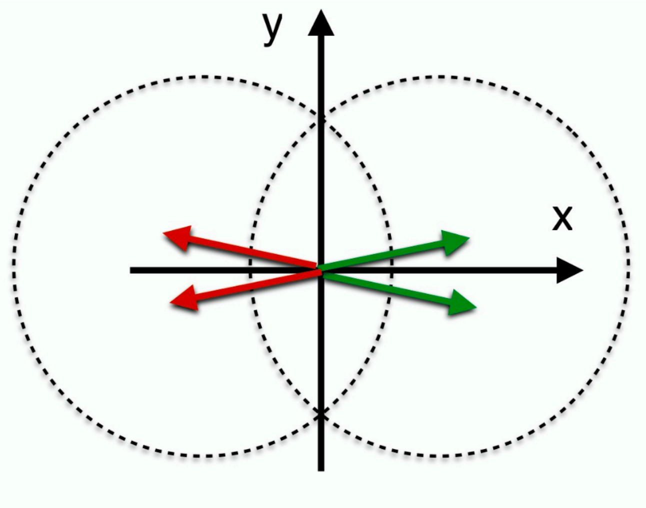
➡ Faraday effect
Electric field induced by decreasing $\vec{B}$



➡ Hall effect
Lorentz force induced by moving charges
$\vec{F} = q\vec{v} \times \vec{B}$

Observable

Direct flow v_1



$$v_1 = \langle cos(\phi_p) \rangle = \langle p_x/p_T \rangle$$

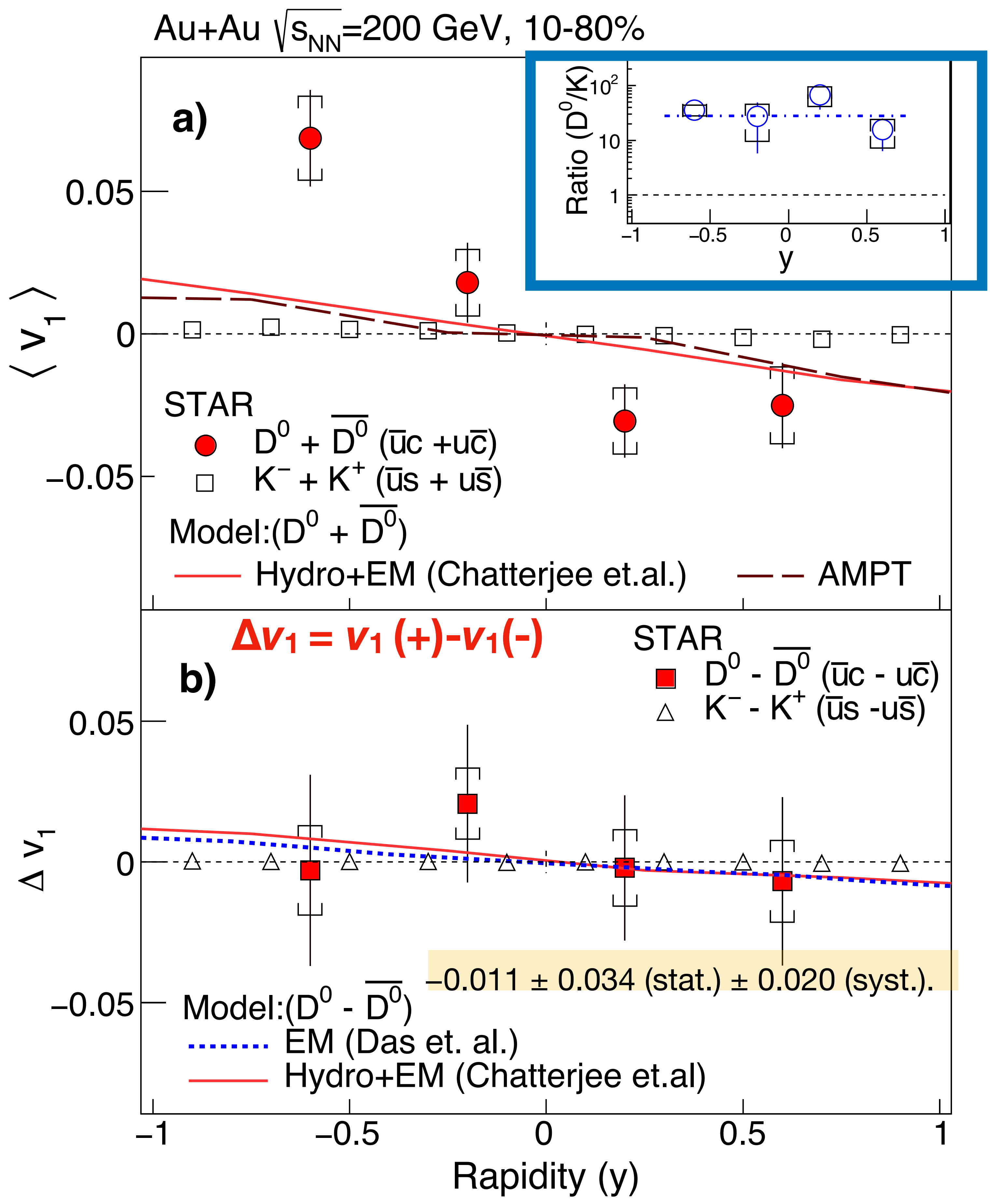
Heavy quarks directed flow v_1

Probe the effect of the **strong electro-magnetic field** and the **initial vorticity**

q and $\bar{q}$ feel an opposite Lorentz force

Effect **depend** on the **quark mass** and **formation time** —> charm more sensitive than light quarks

arXiv:1905.02052



Large difference between v_1 slopes of **kaons** and $D^0/\bar{D}^0$ (~ factor 25) different sensitivity to the early time dynamics

Heavy quarks directed flow v_1

Probe the effect of the strong electro-magnetic field and the initial vorticity

Talks
Jan Vaněk
S. Jaelani
S. Plumari

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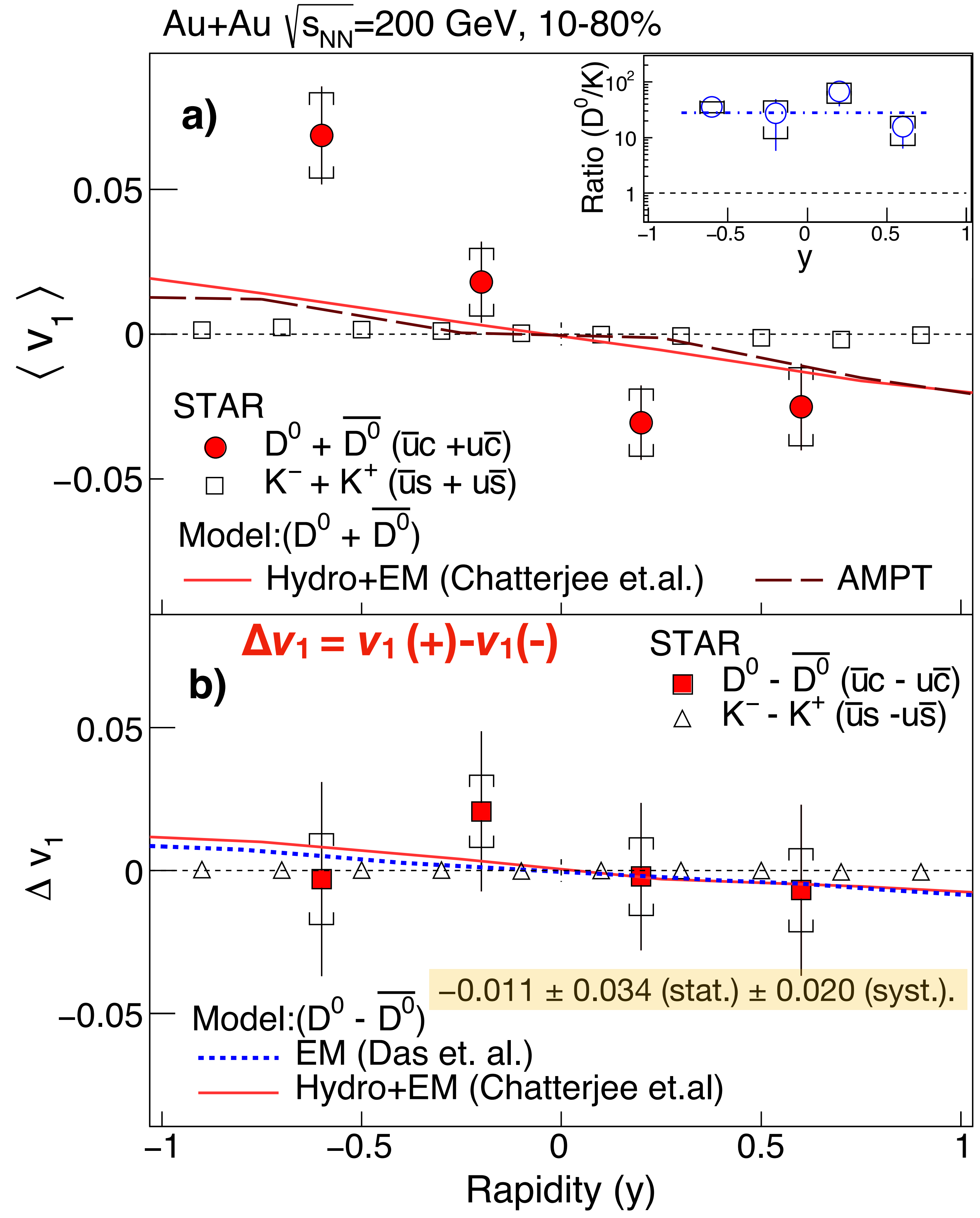
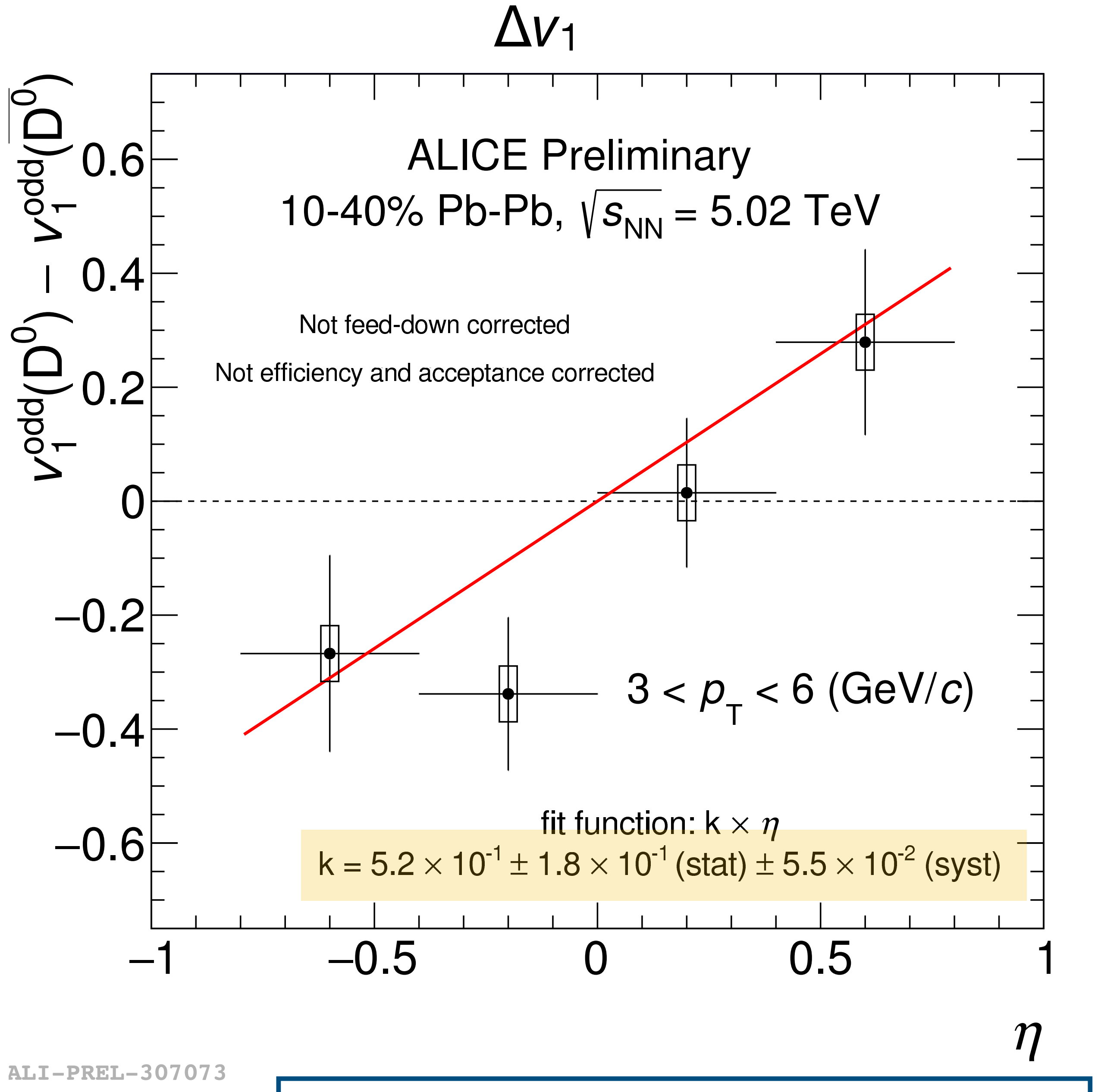
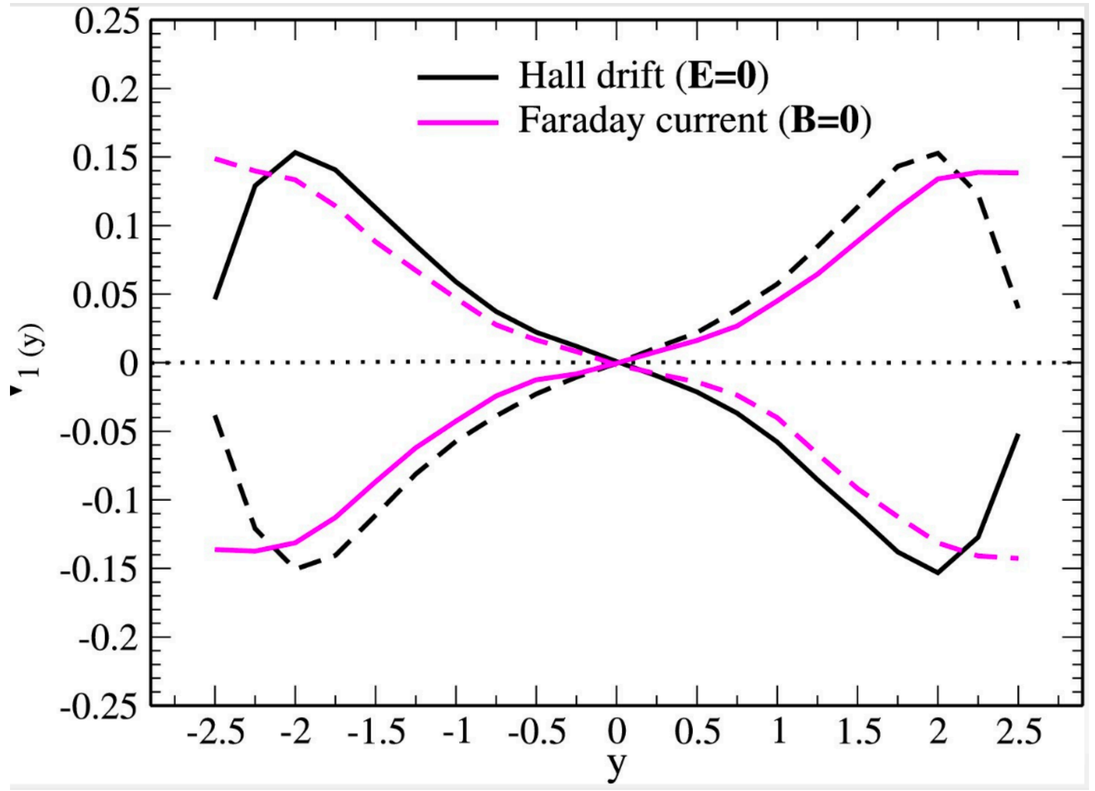


ALICE: opposite slope w.r.t. RHIC, effect due to larger B than the induced E, or different initial tilted bulk at LHC?



Slope ≠ 0 significance 2.7σ



PLB768 (2017) 260-264

Intriguing measurement: starting to provide inputs to theoretical calculations

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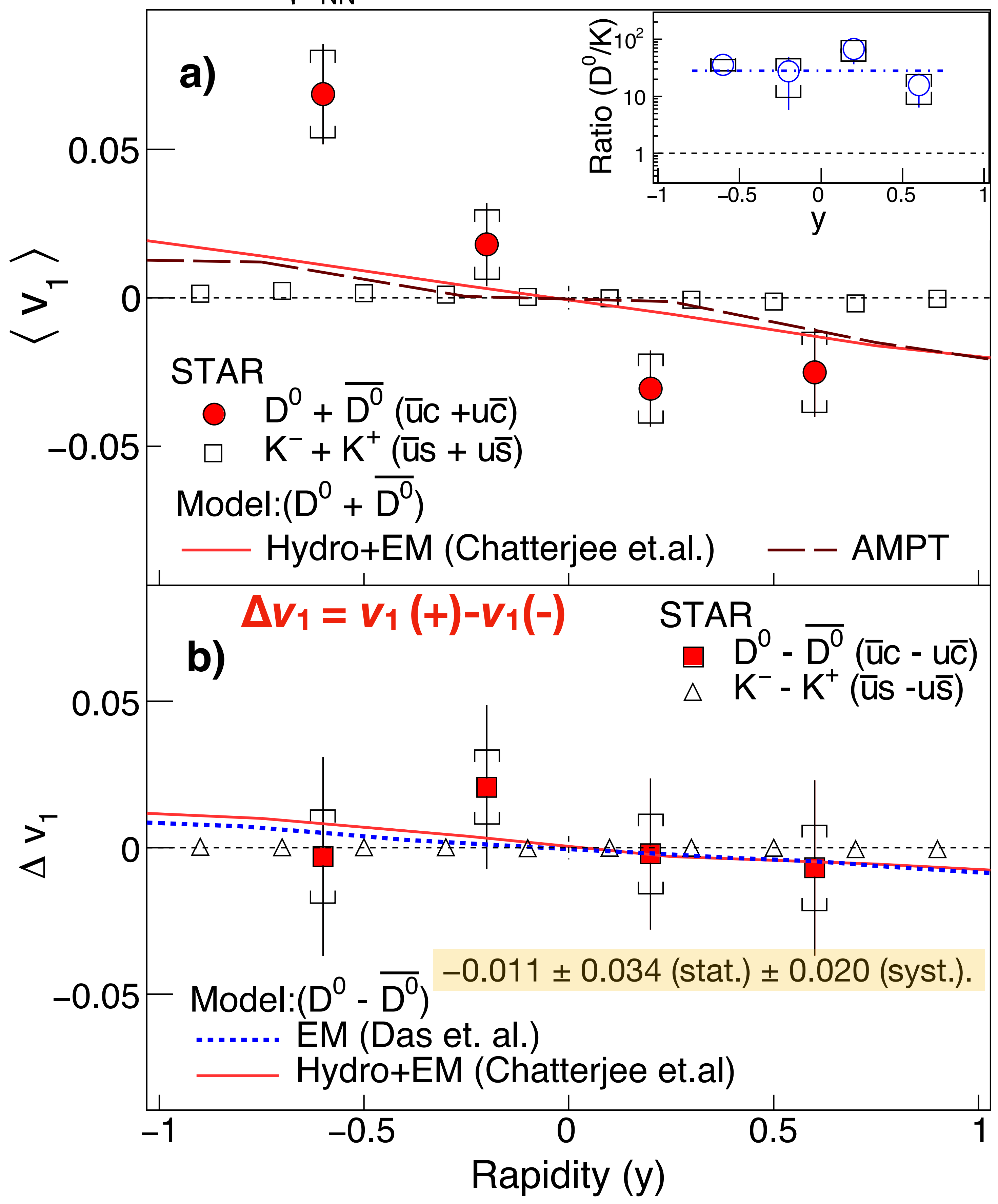
Au+Au $\sqrt{s_{NN}}$=200 GeV, 10-80%



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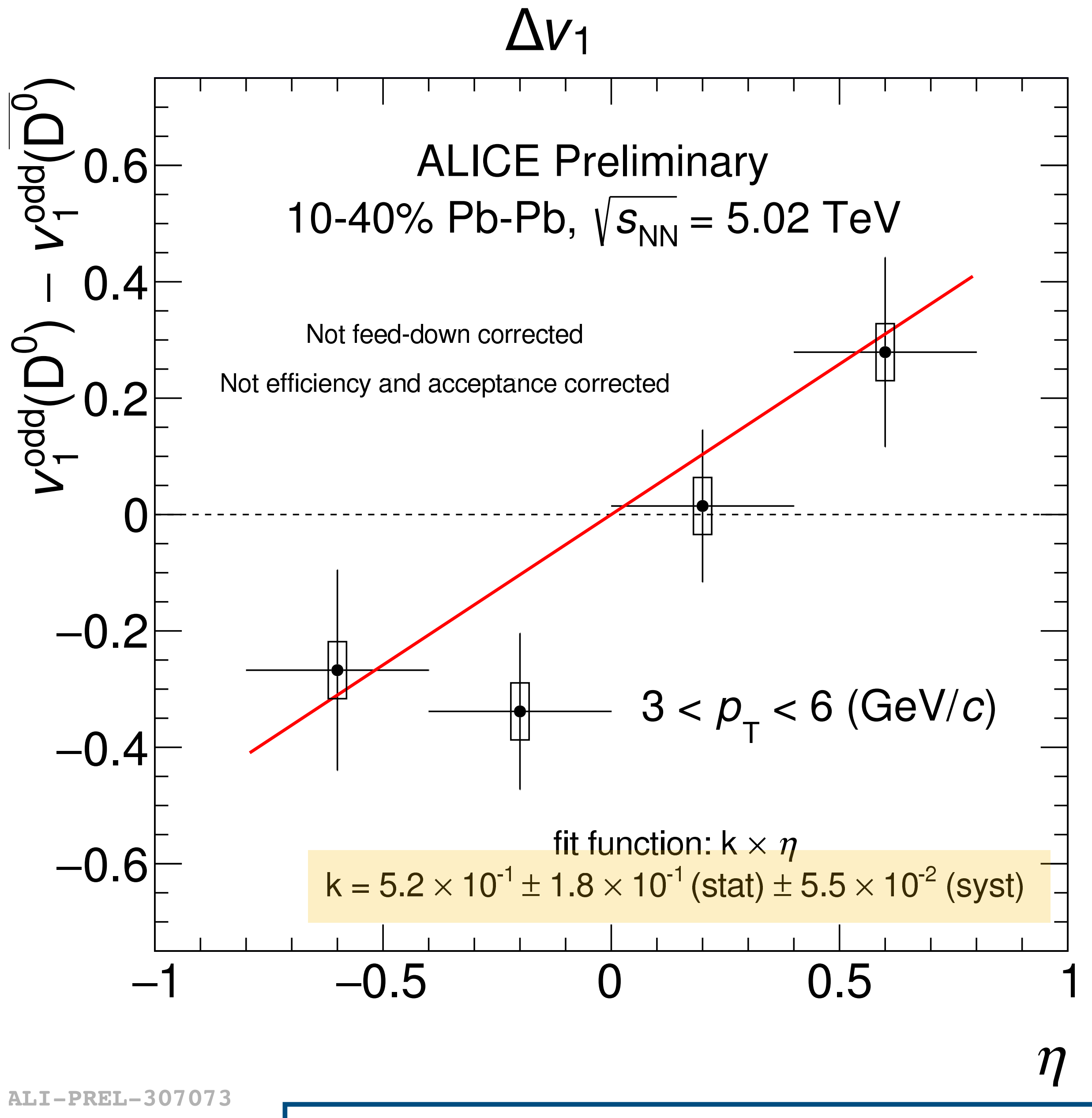
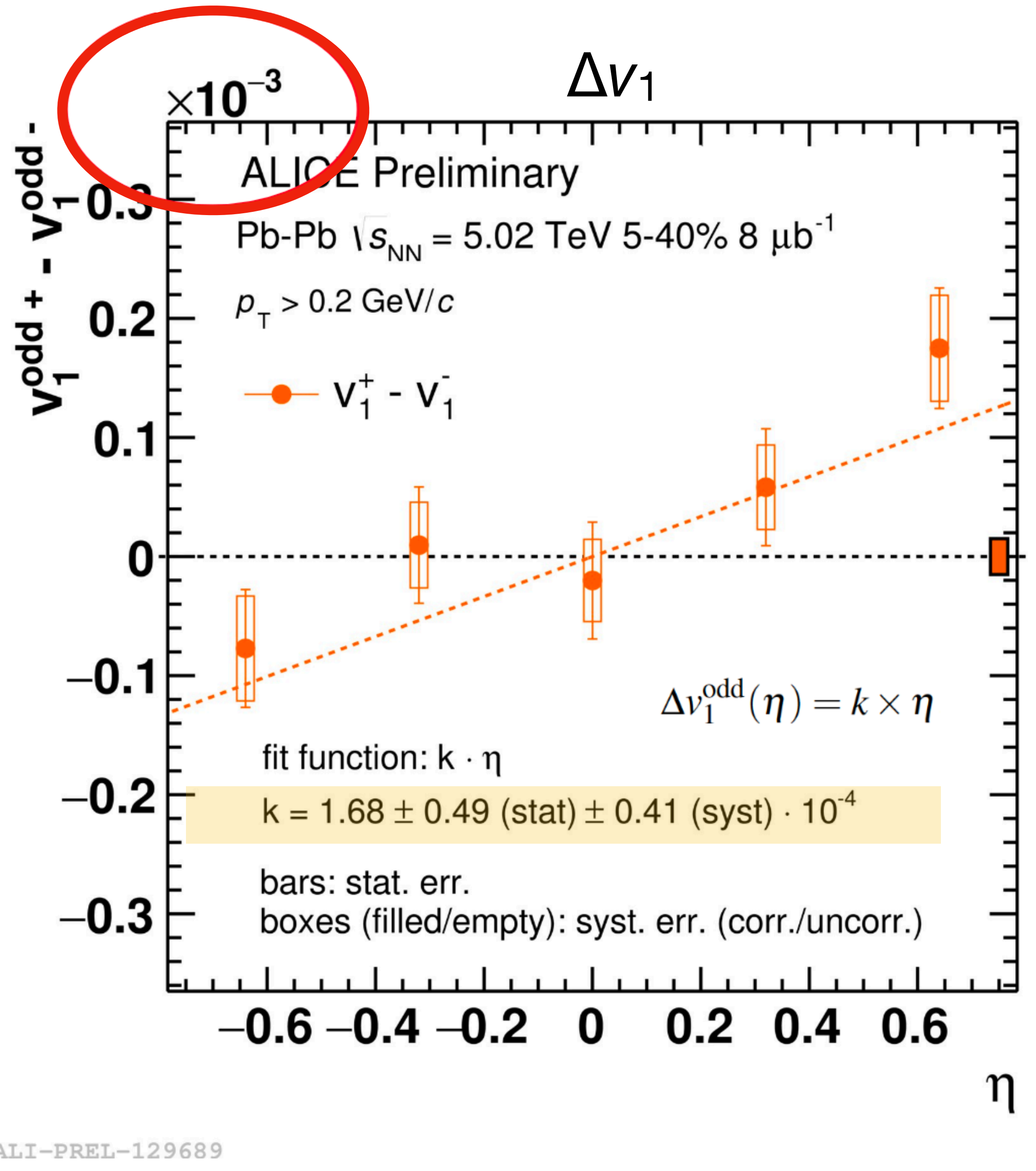
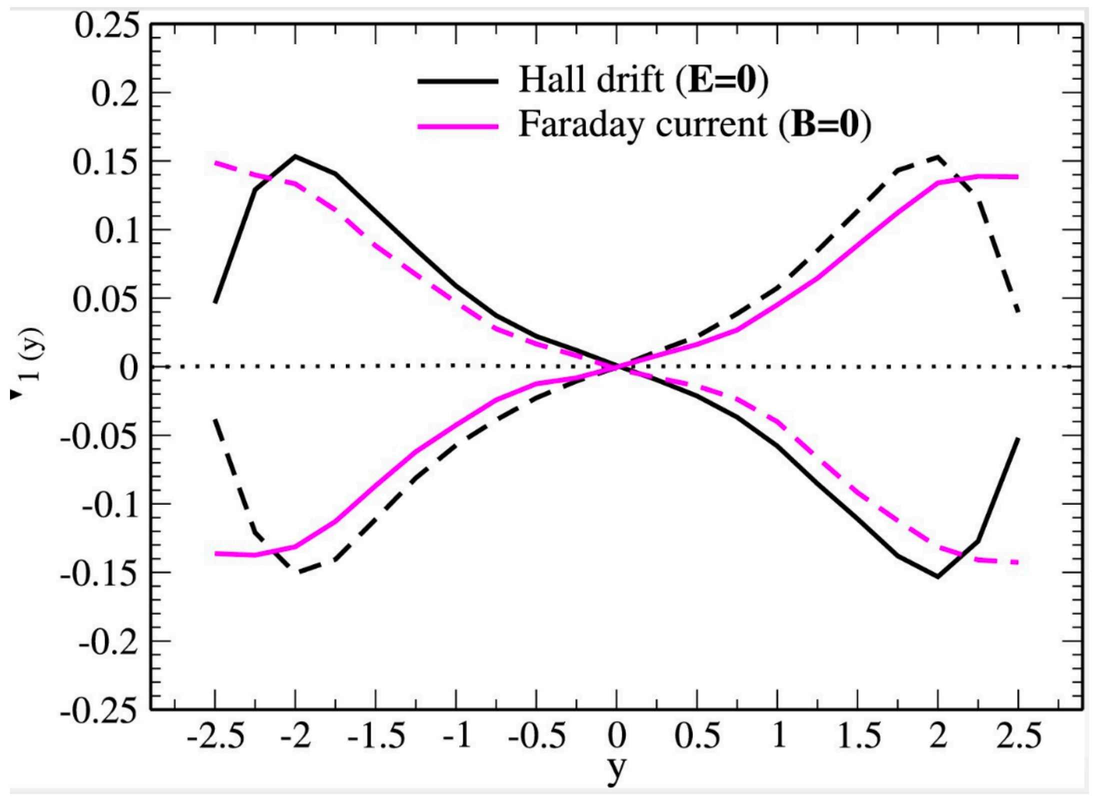






PLB768 (2017) 260-264

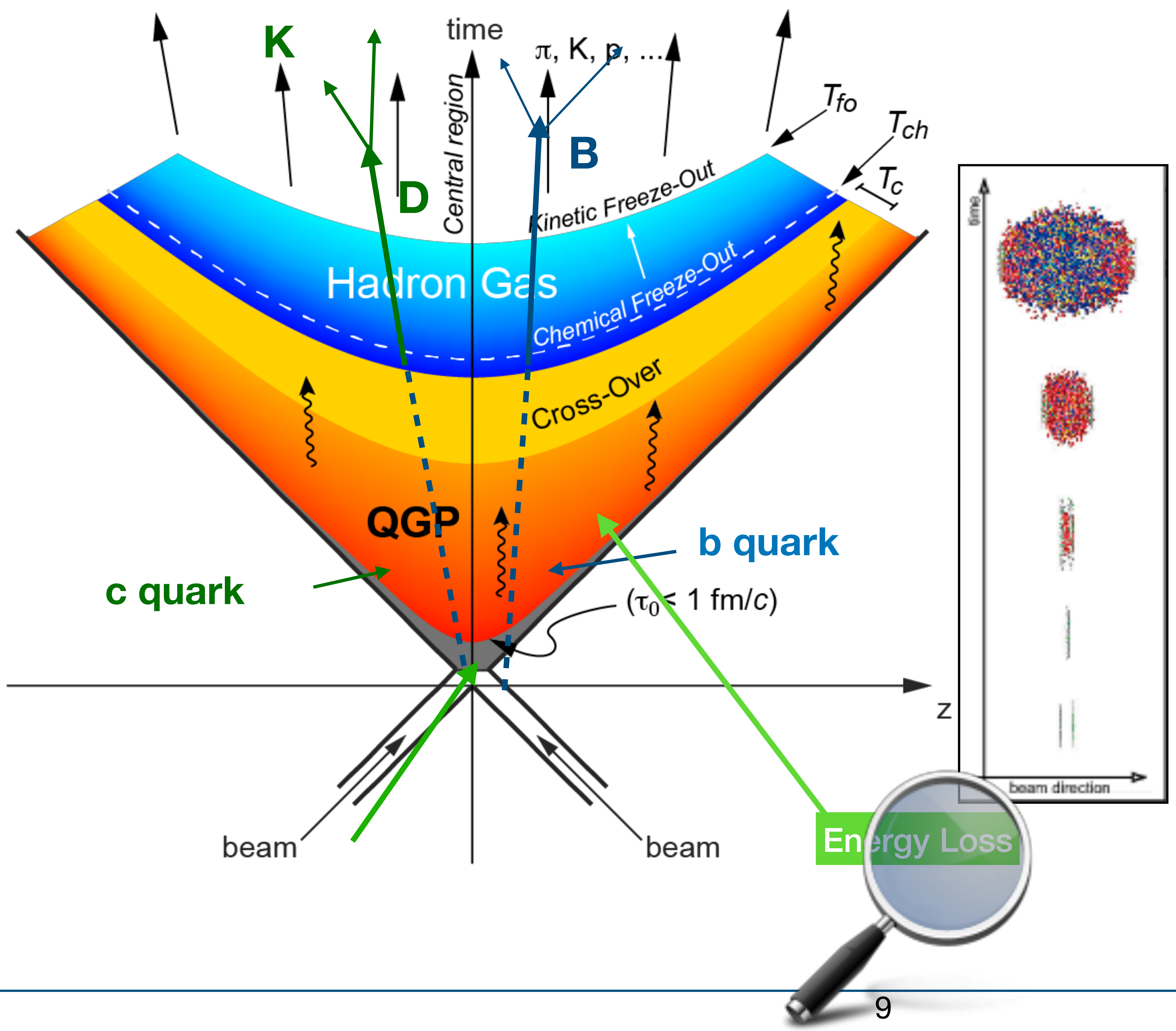
Slope ≠ 0 significance 2.7σ

3 order of magnitude larger slopes w.r.t. **charged hadrons**

Intriguing measurement: starting to provide inputs to theoretical calculations

Space-time evolution

Energy Loss in medium: elastic and inelastic interactions of HQ with the opaque fluid



What are the relevant energy loss mechanisms?
Is there a flavour dependence?
When radiative processes starts to become predominant on collisional processes?

Observable

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

Colour-charge and mass dependence

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

Expected hierarchy

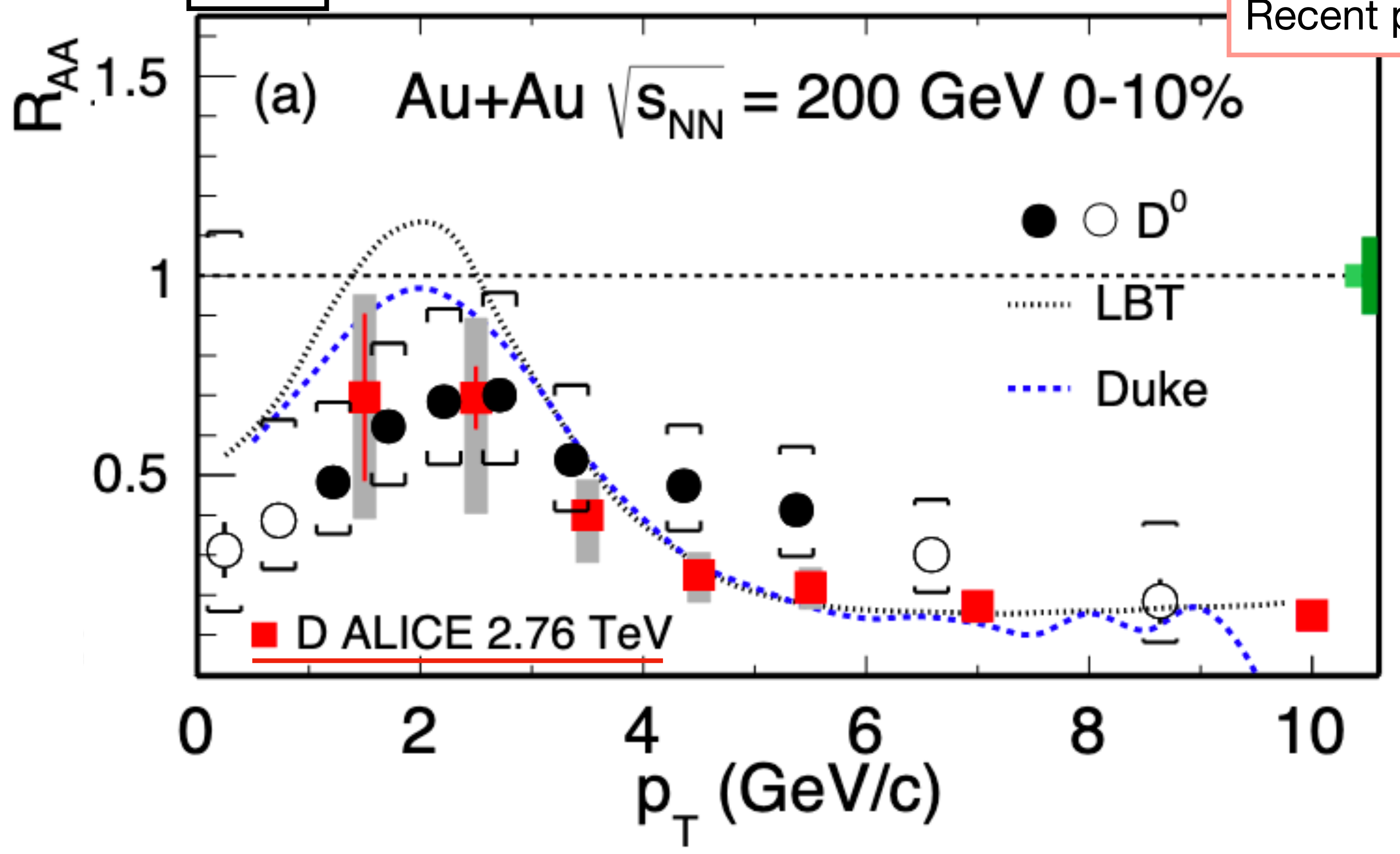
$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

Open HF Nuclear Modification Factor R_{AA}

D^0

STAR: Phys. Rev. C 99, 034908 (2019)
ALICE: JHEP 03 (2016) 081

Recent publication



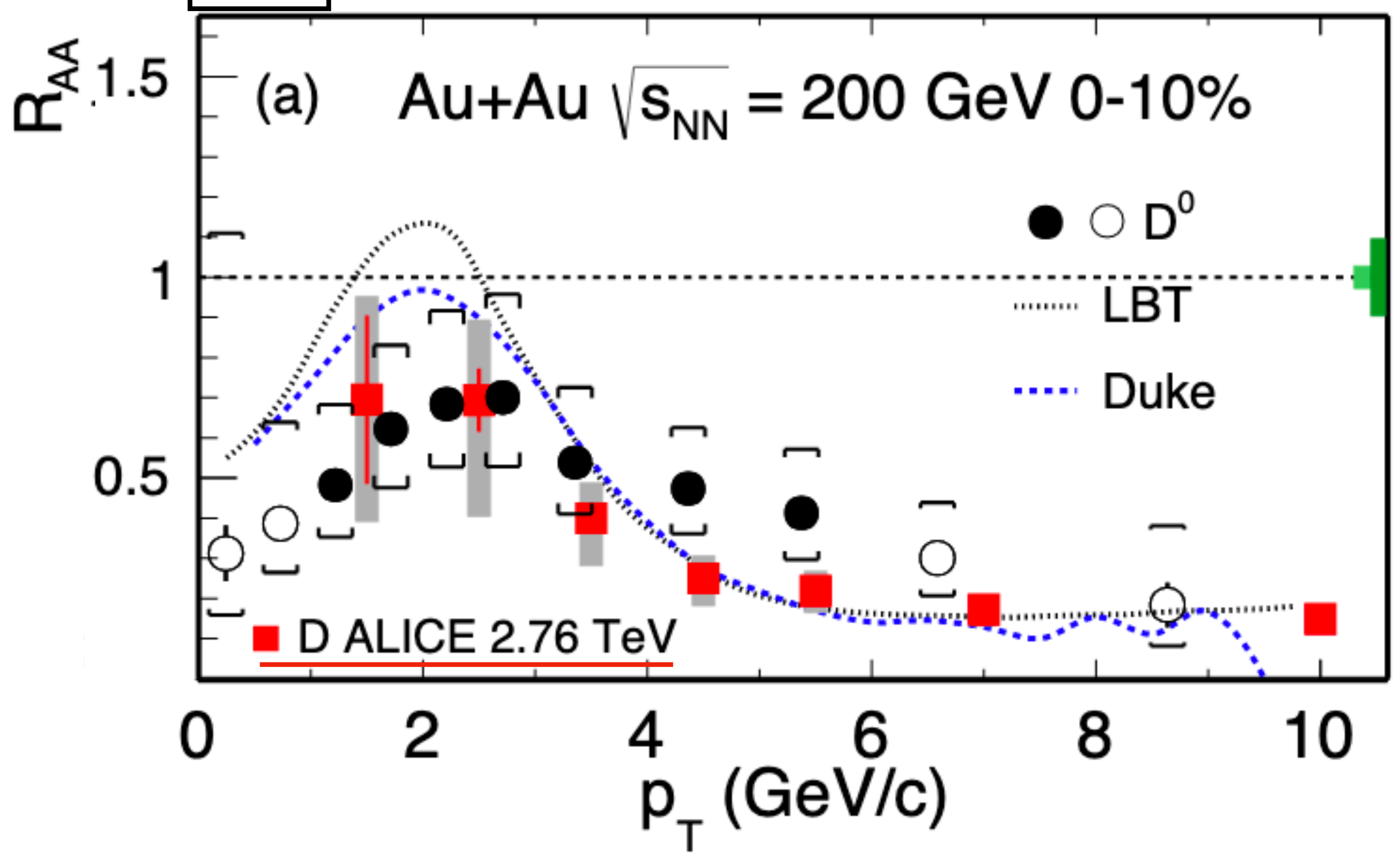
- **strong suppression in 0-10% A-A collisions**
  - similar R_{AA} in **STAR** and **ALICE**

- **Bump at low-p_T:** charm quarks gain collective motion in the medium evolution?
  - qualitatively described by models that include fragmentation+coalescence and hydrodynamic evolution

Open HF Nuclear Modification Factor R_{AA}

D^0

STAR: Phys. Rev. C 99, 034908 (2019)
ALICE: JHEP 03 (2016) 081



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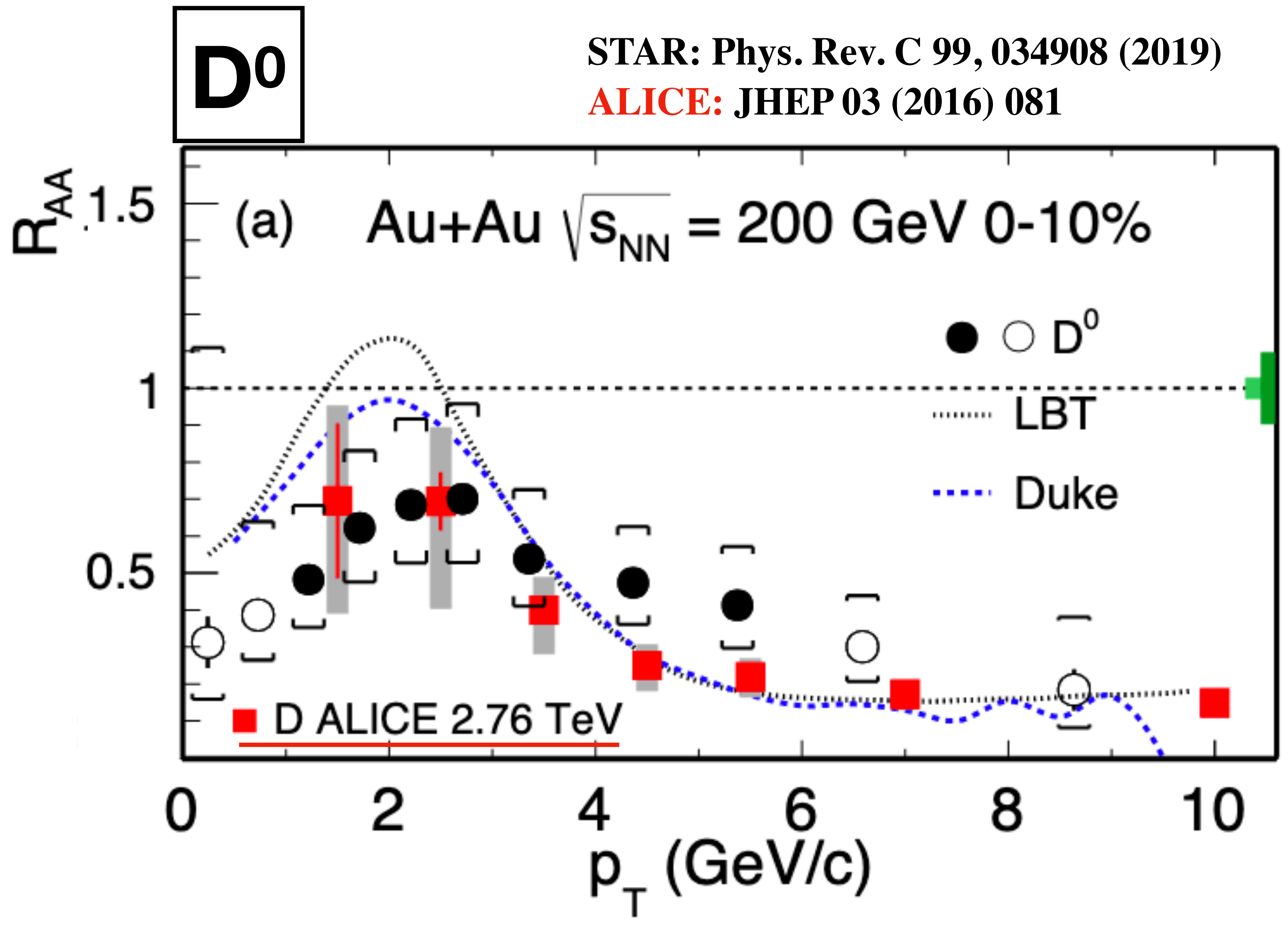
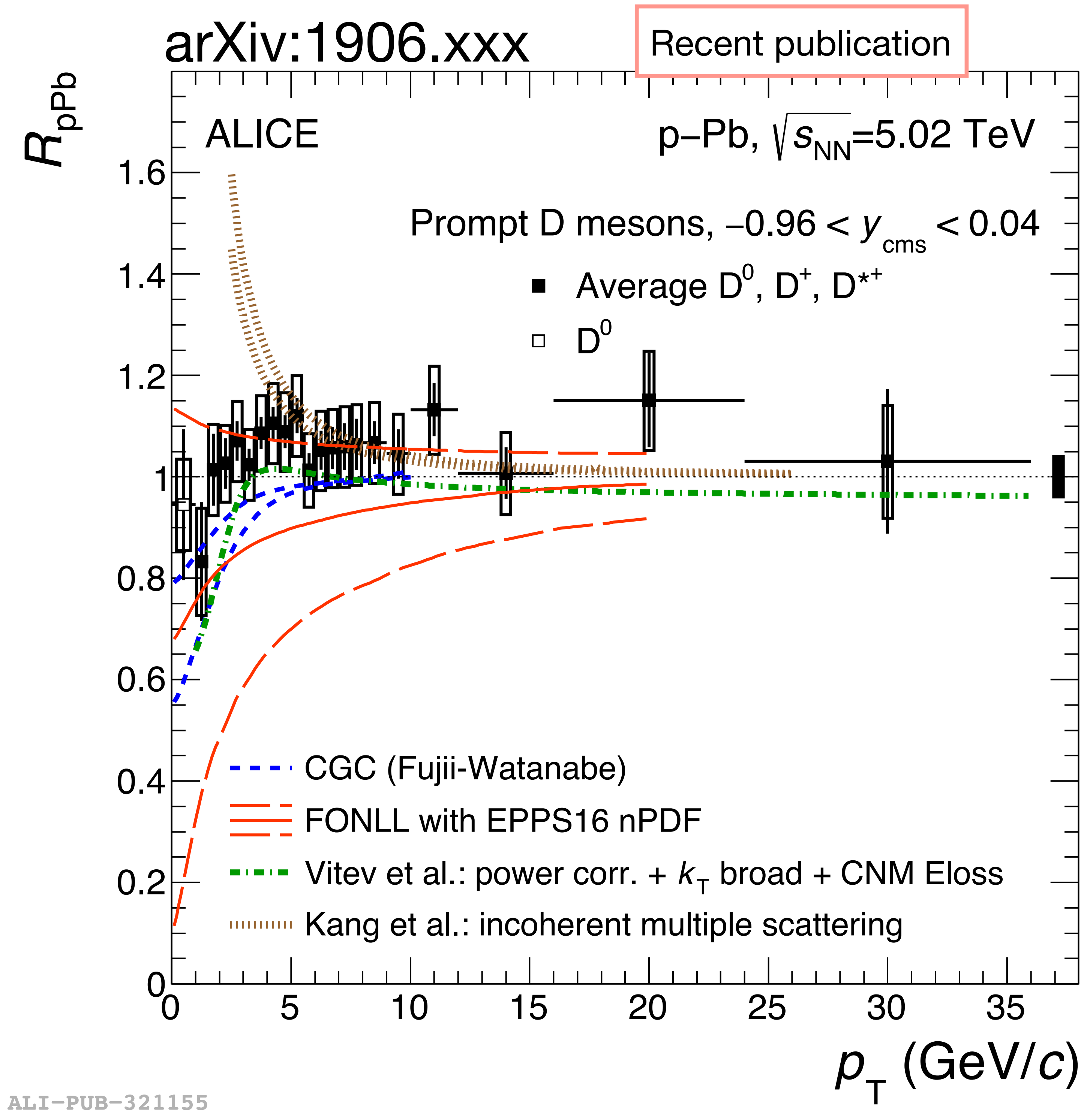
Caveat: R_{AA} not determined just by 'energy loss'
➡Interplay of energy loss, collective motion and hadronization mechanisms

Open HF Nuclear Modification Factor R_{AA}





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

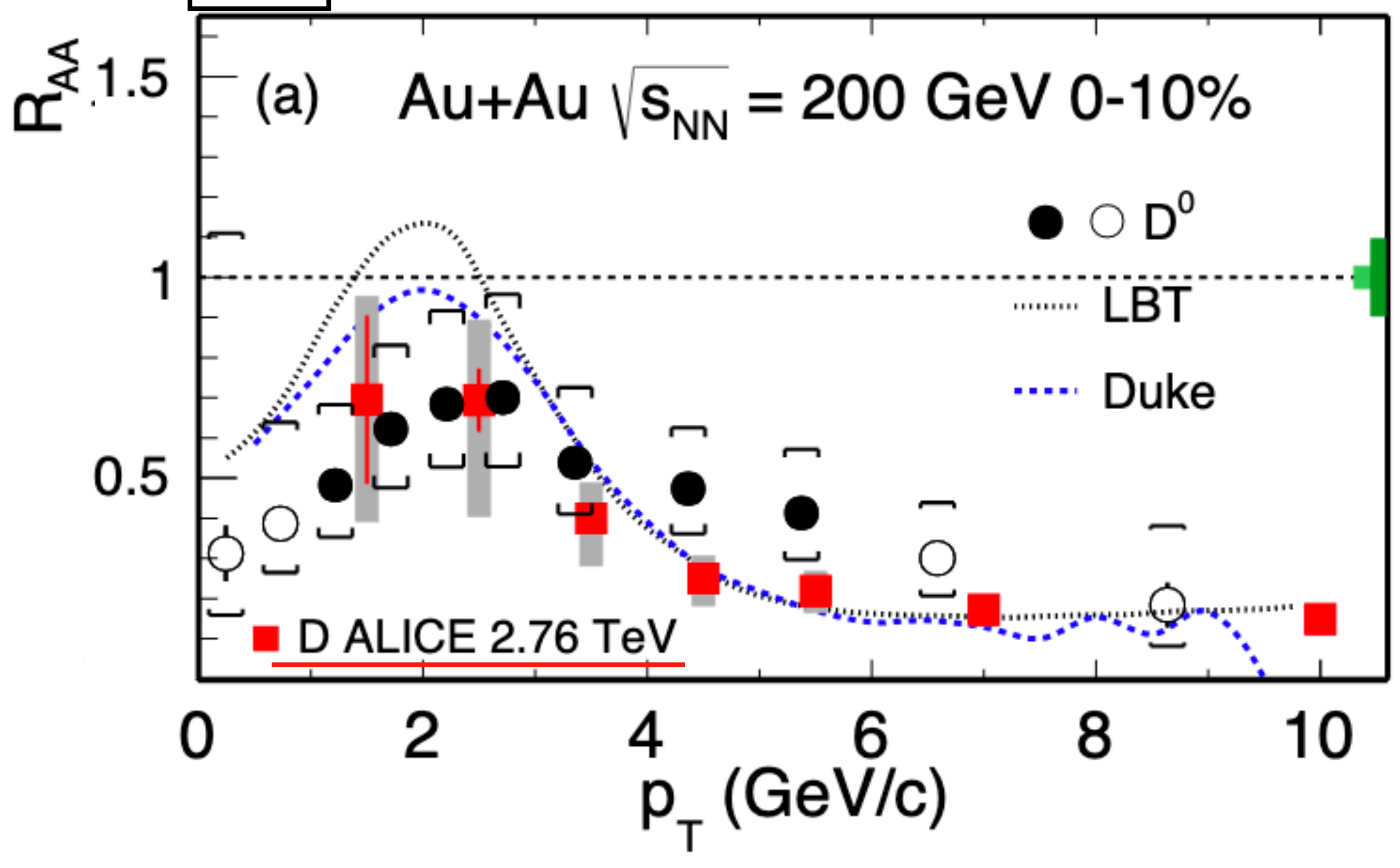
Caveat: R_{AA} not determined just by 'energy loss'
➡Interplay of energy loss, collective motion and hadronization mechanisms

Open HF Nuclear Modification Factor R_{AA}

Is there a flavour dependence?

D0

STAR: Phys. Rev. C 99, 034908 (2019)
ALICE: JHEP 03 (2016) 081



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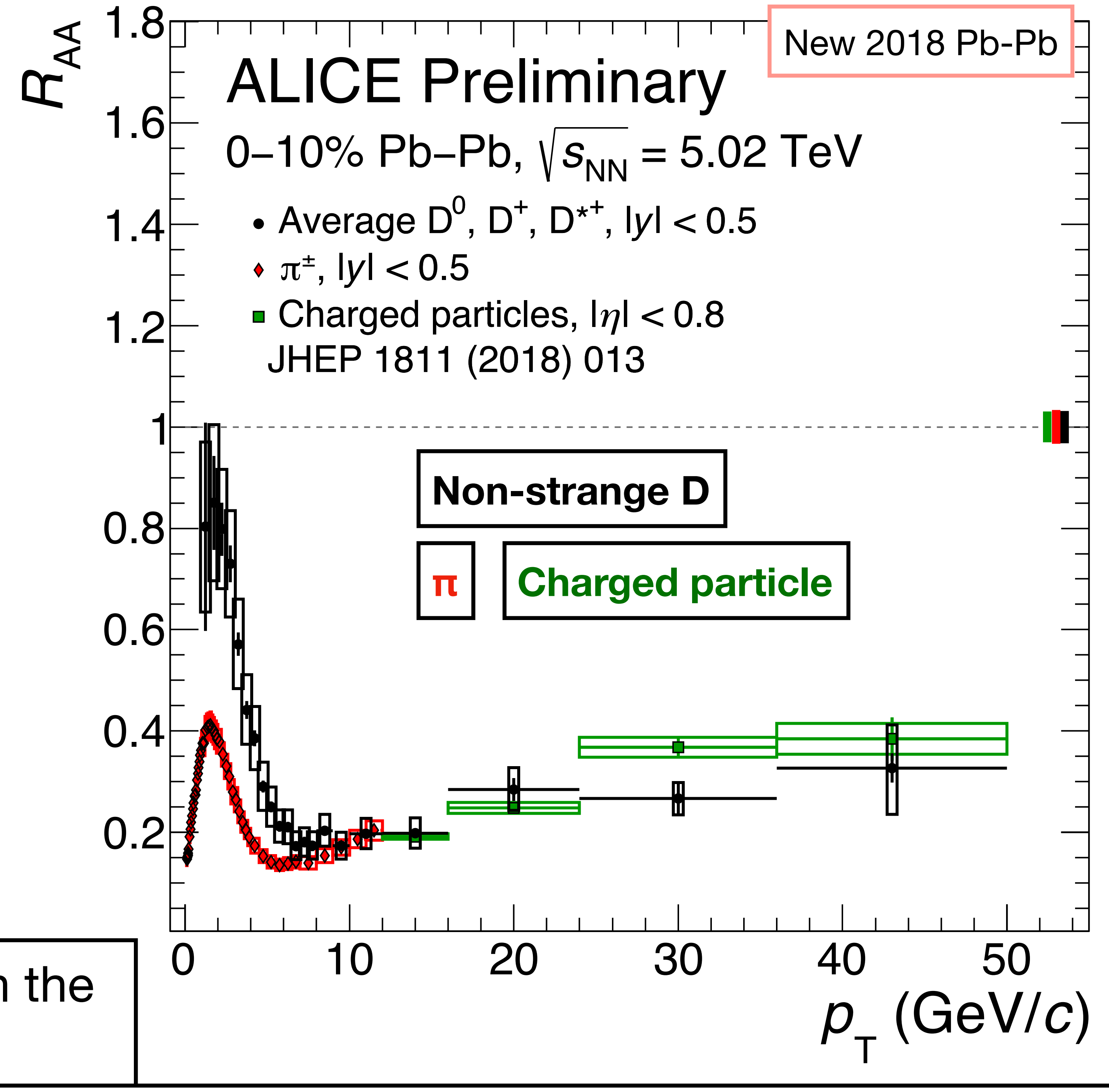

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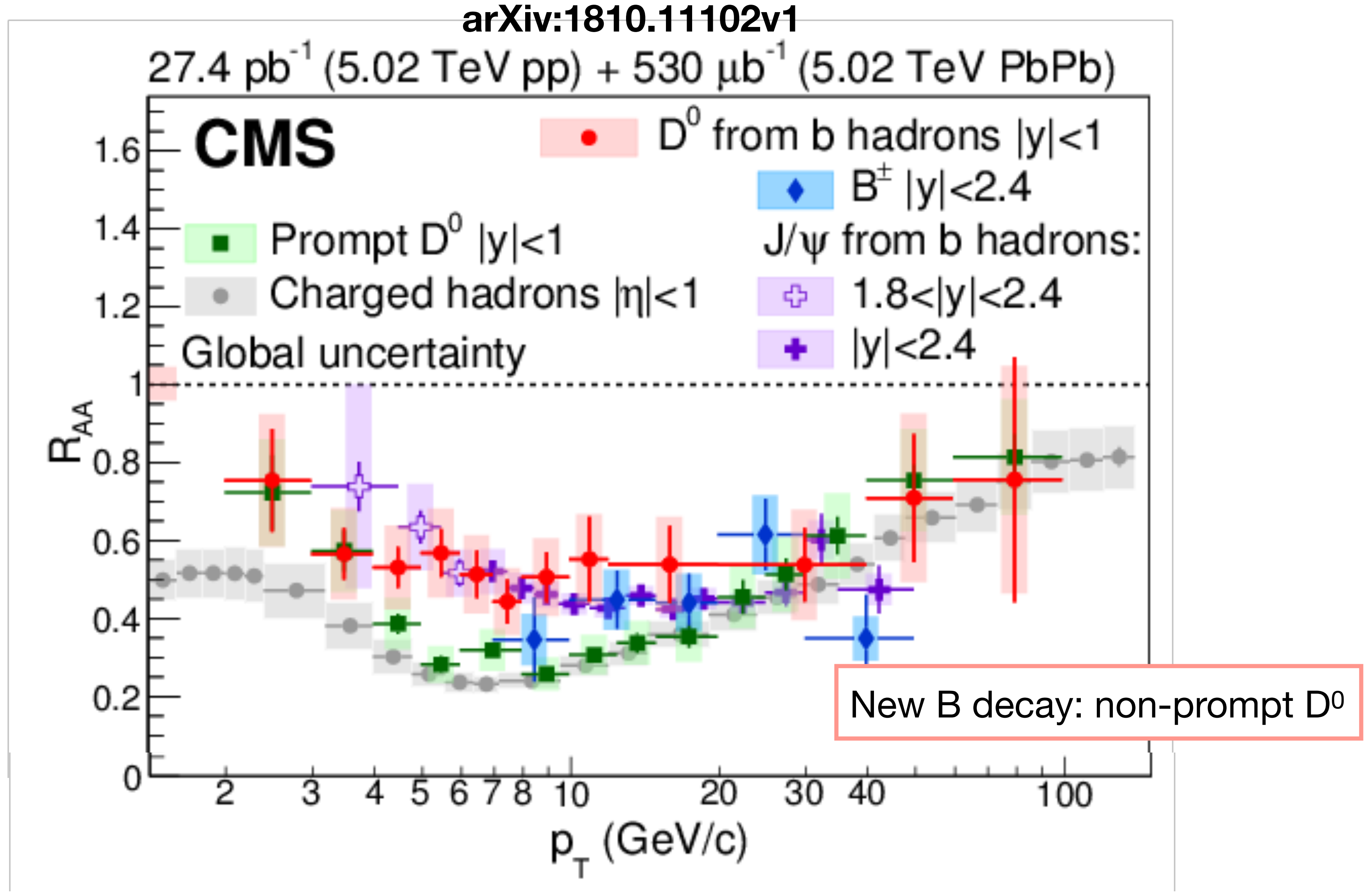
- less suppression for D at low/intermediate p_T
  - Interplay of harder charm p_T distributions and different fragmentation functions w.r.t. light quarks and gluons

Ch. hadrons, D^0, D^0 from B, J/Ψ from B, B^+



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

Open HF Nuclear Modification Factor R_{AA}

Is there a flavour dependence?

strong suppression of high-pt yield. Color charge and mass dependence of R_{AA}

D⁰

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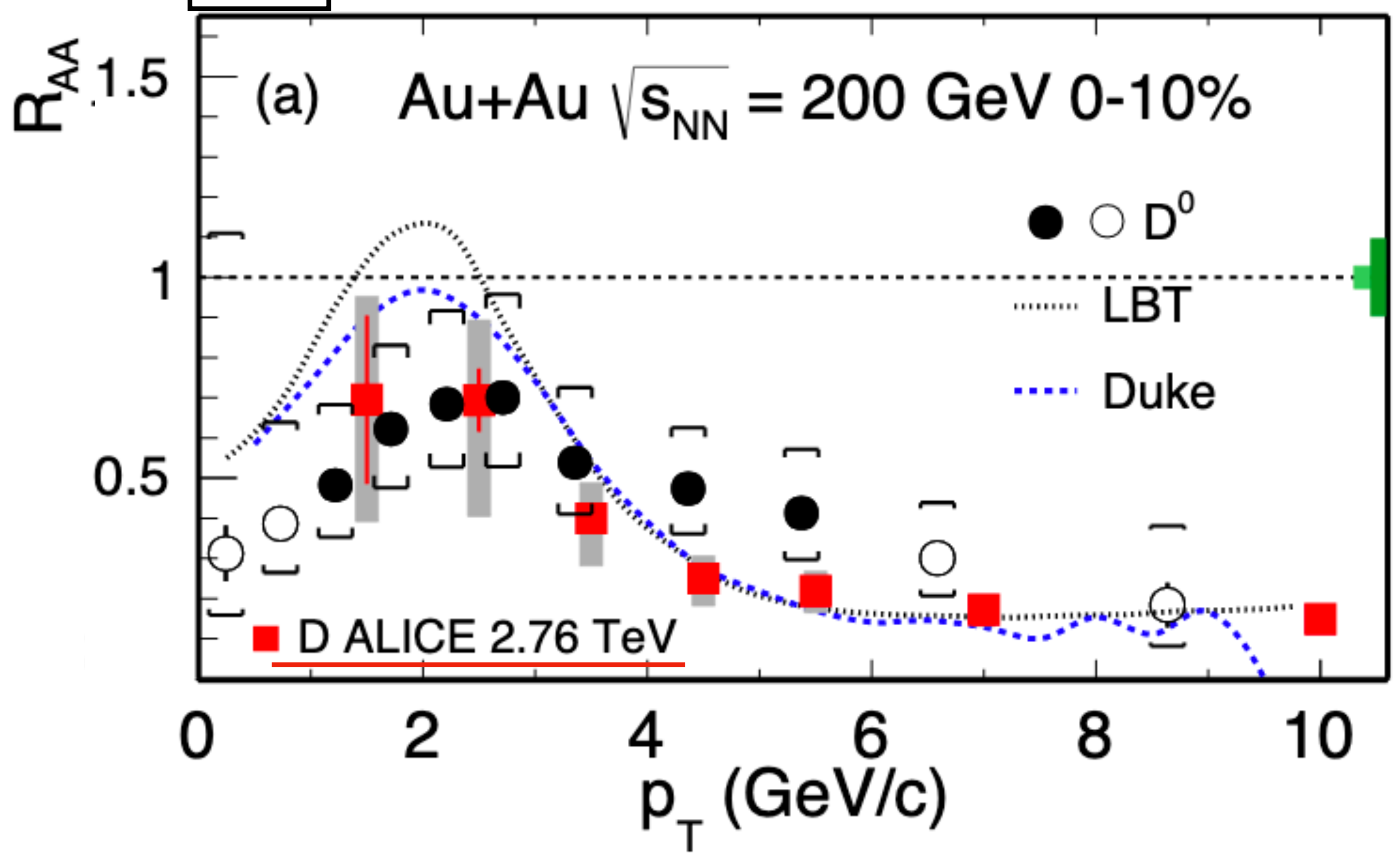

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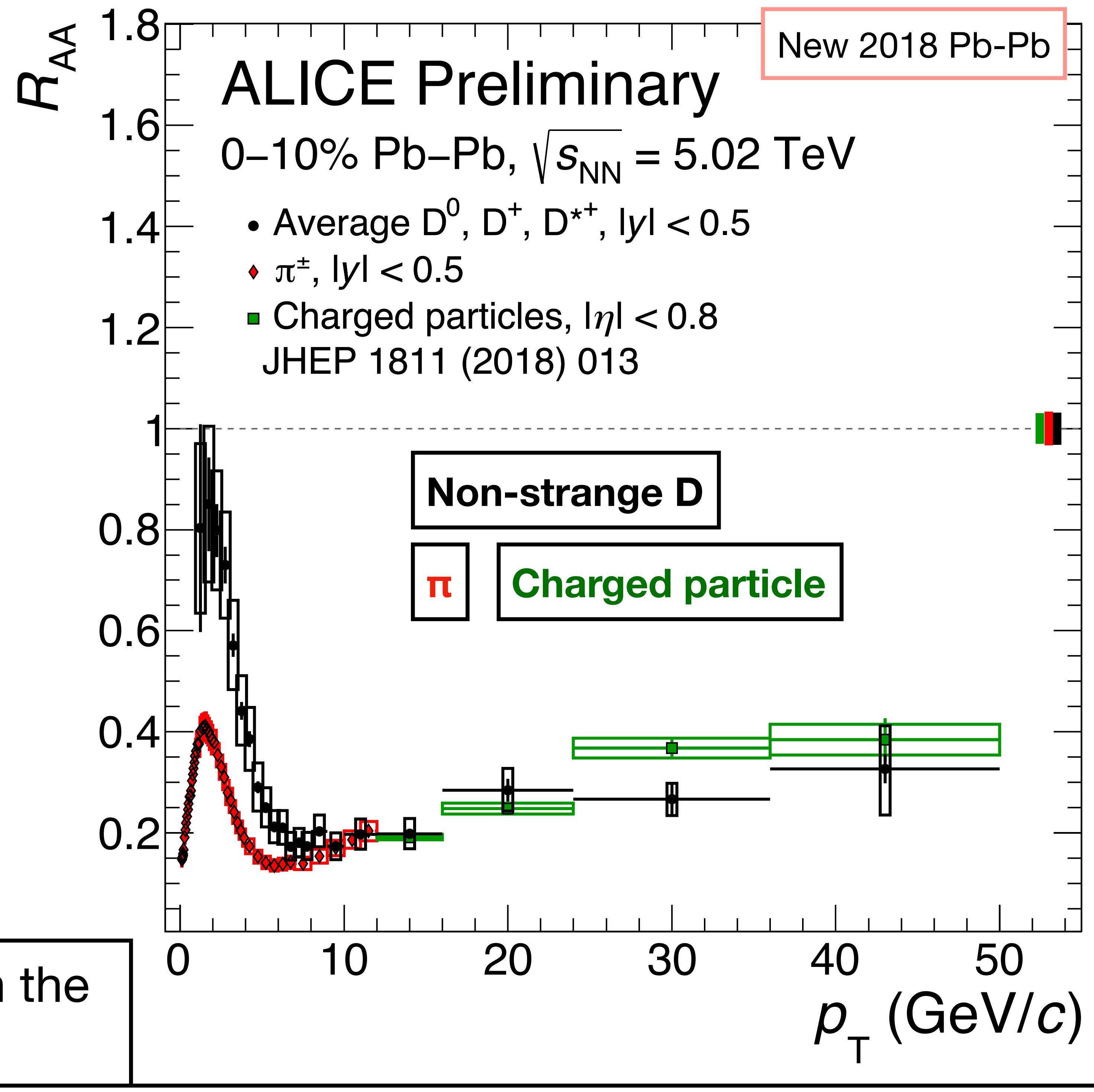
Talks:
J. Vaněk
S. Jaelani
C Peng
F. Wang



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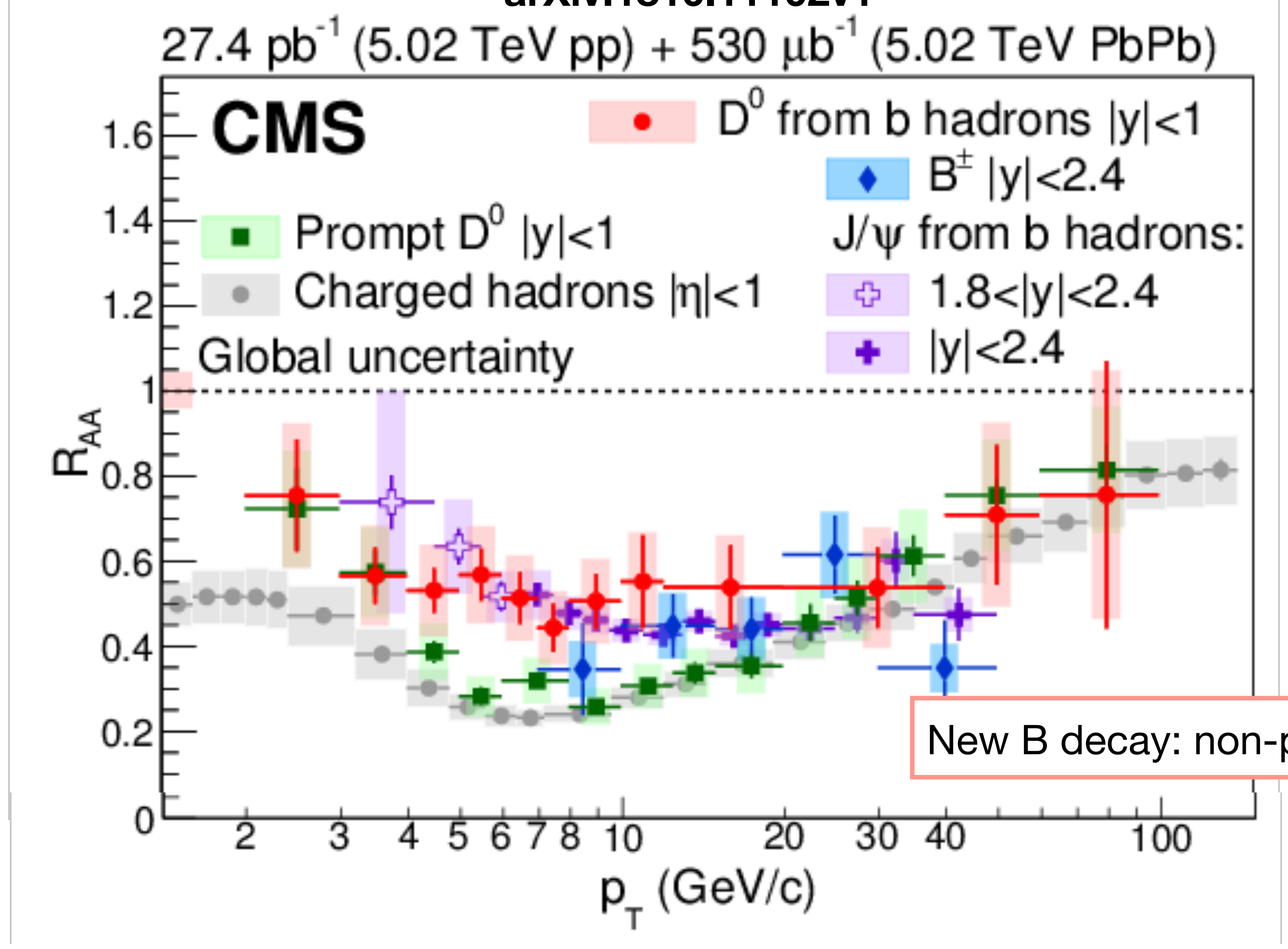
arXiv:1810.11102v1



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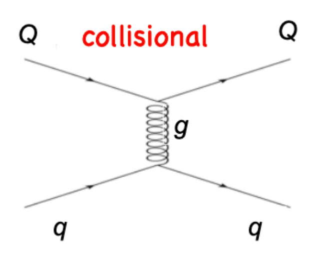
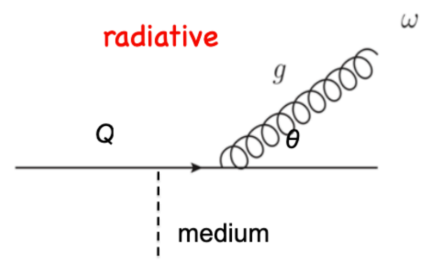
D and B R_{AA}: Theoretical model comparison

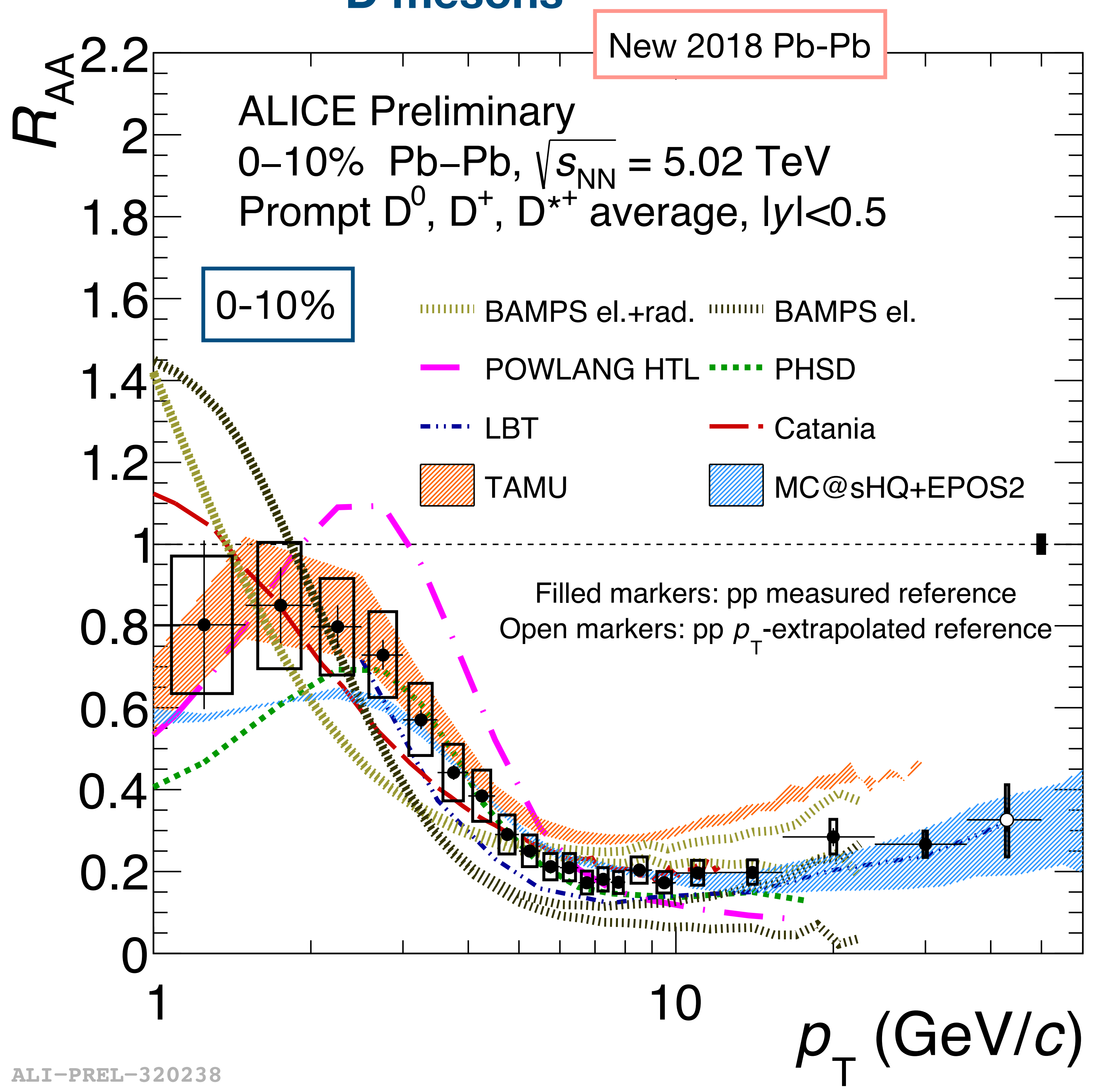
quarks are expected to lose energy via collisional (dominant at low p_T) and radiative (dominant at high p_T) energy loss





Energy loss:
At which p_T radiative dominates on collisional?

D mesons



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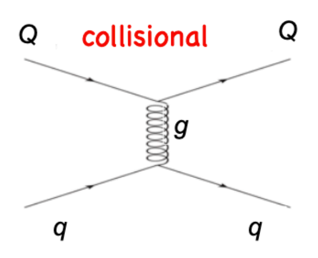

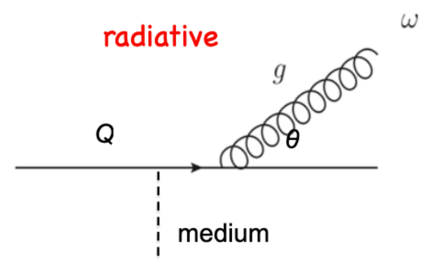

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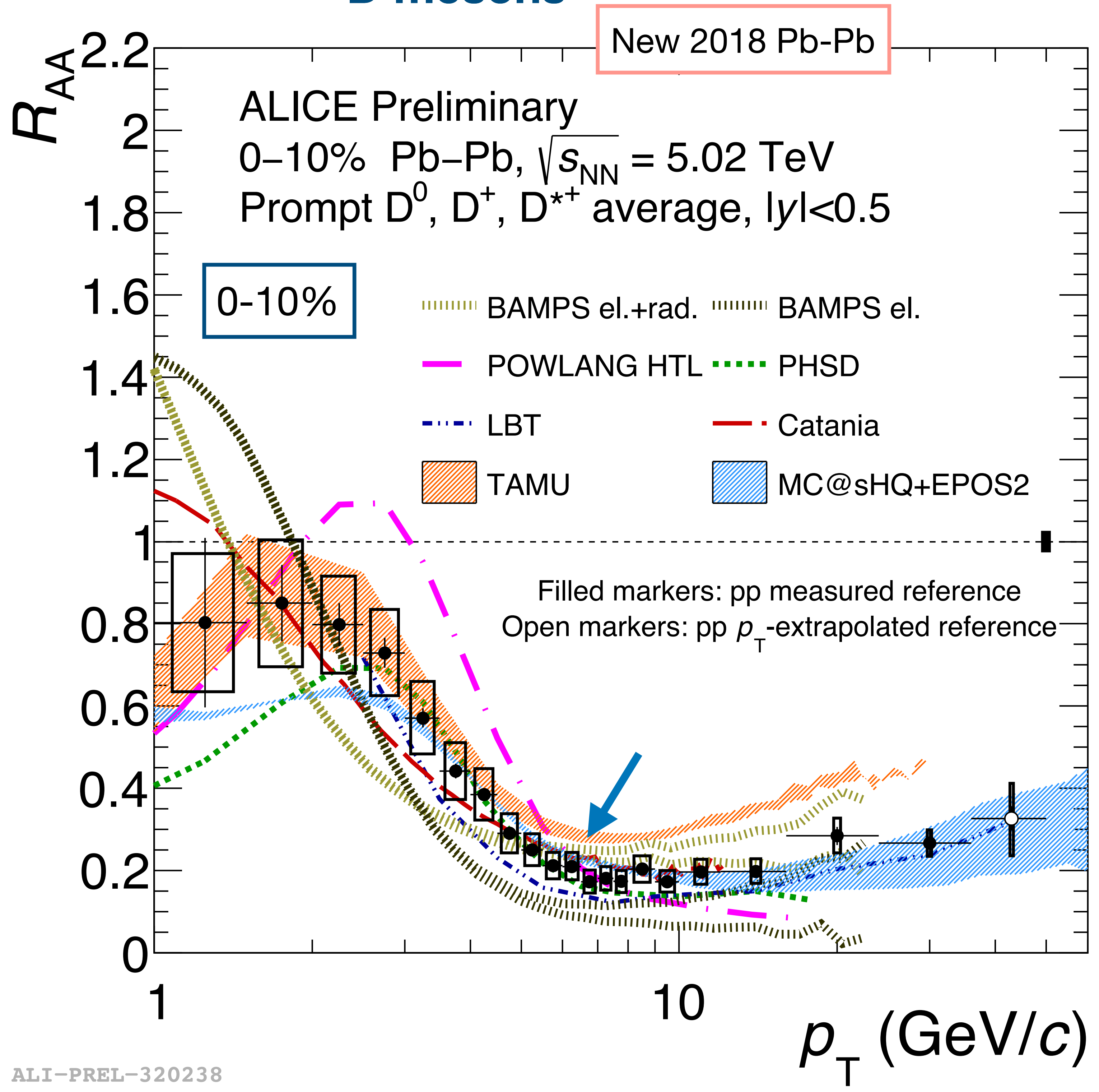

• **POWLANG**, **BAMPS el**, **TAMU**: do not include radiative energy loss
➡**determination of onset of radiative contributions by deviations from experimental data at a certain p_T**

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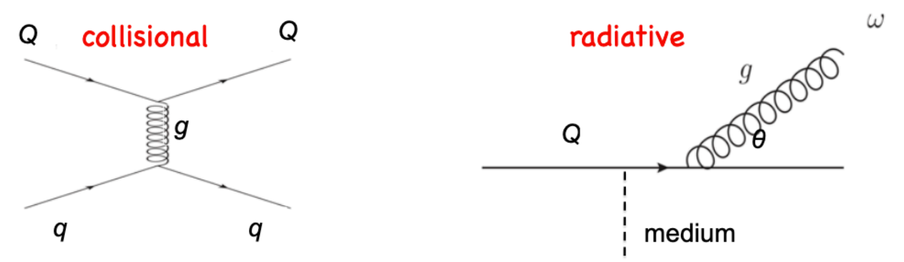
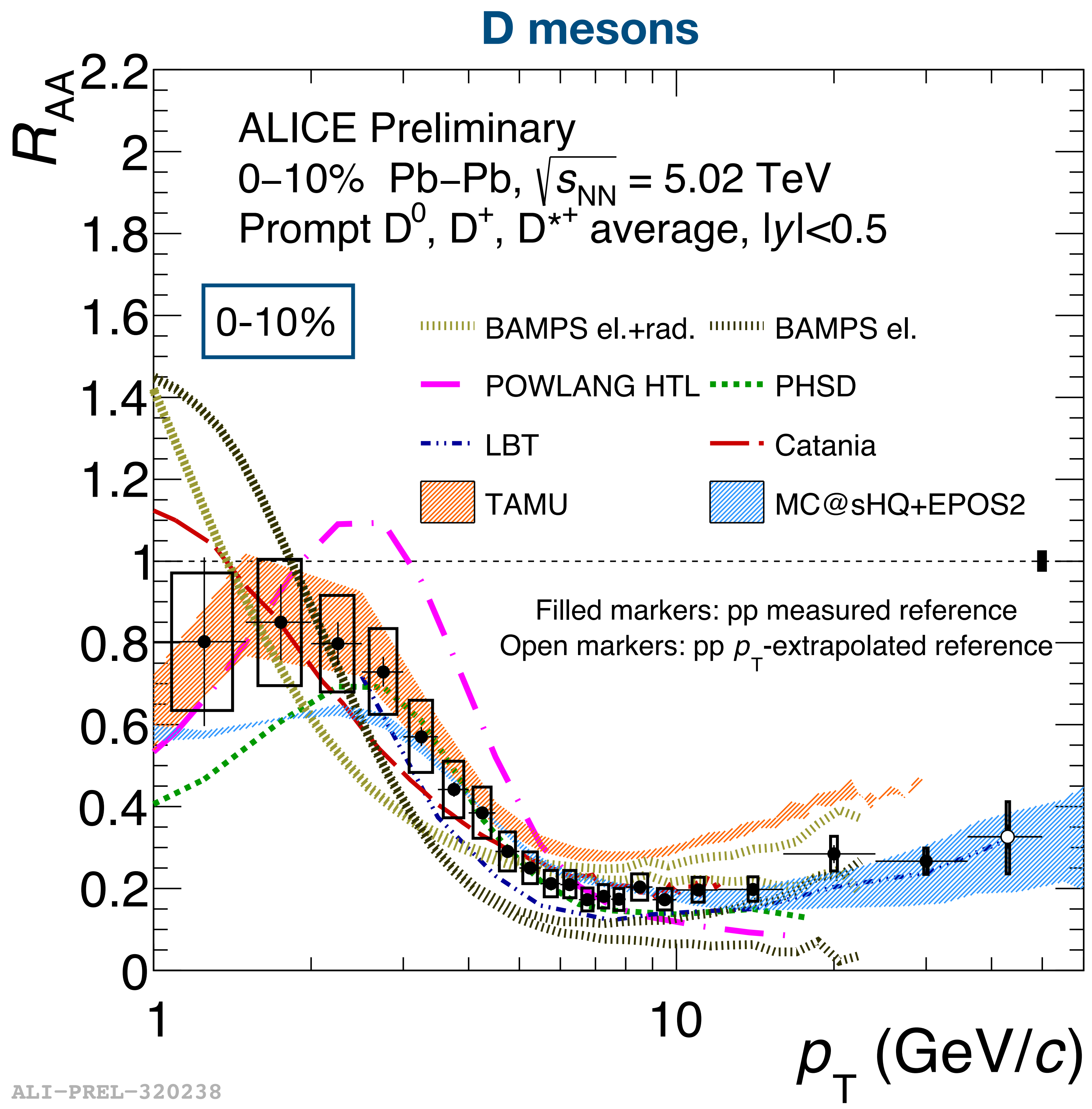
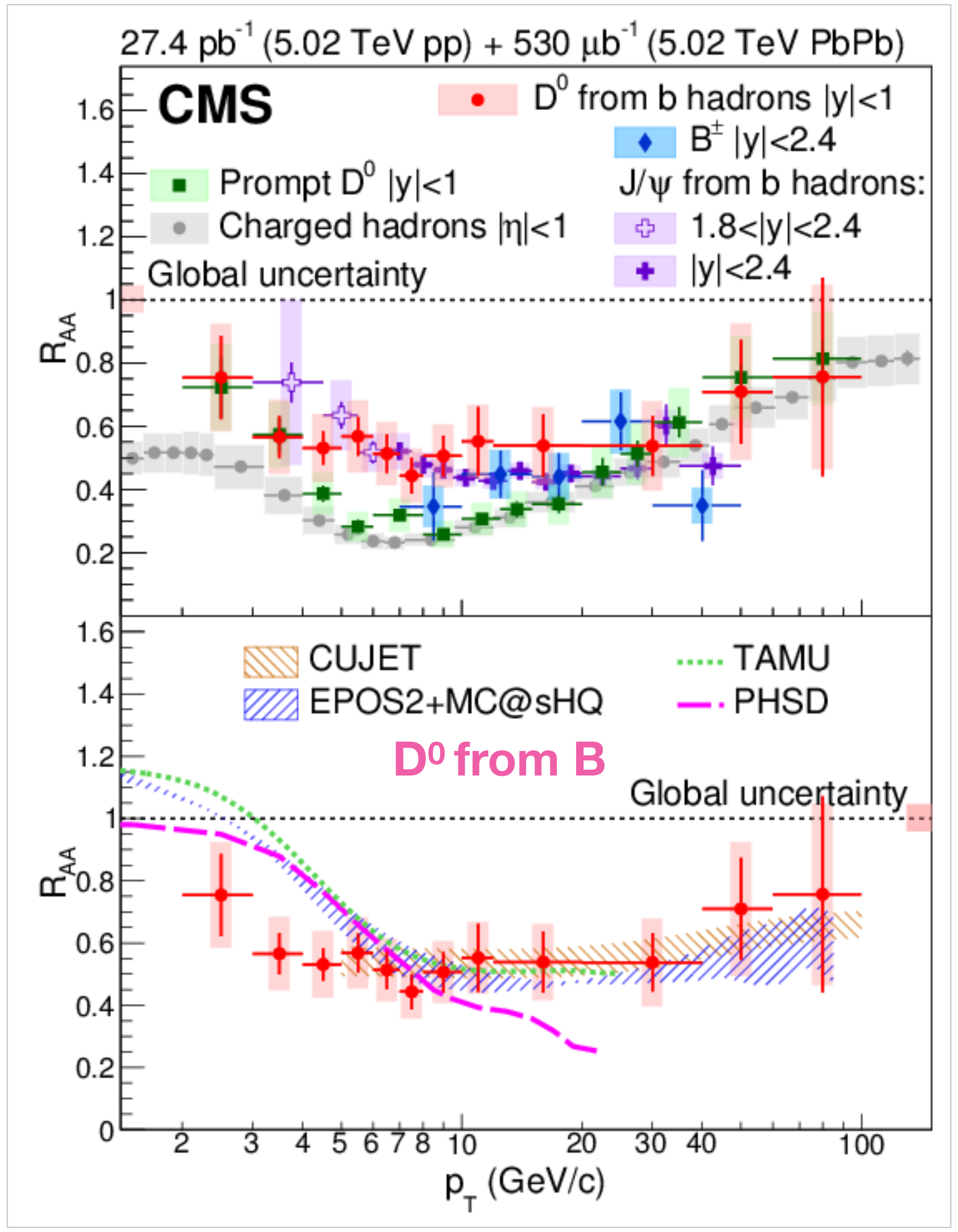


Energy loss:
Do we understand all the involved processes?

?





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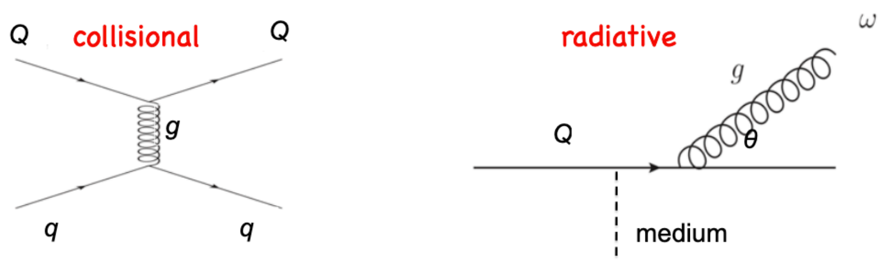

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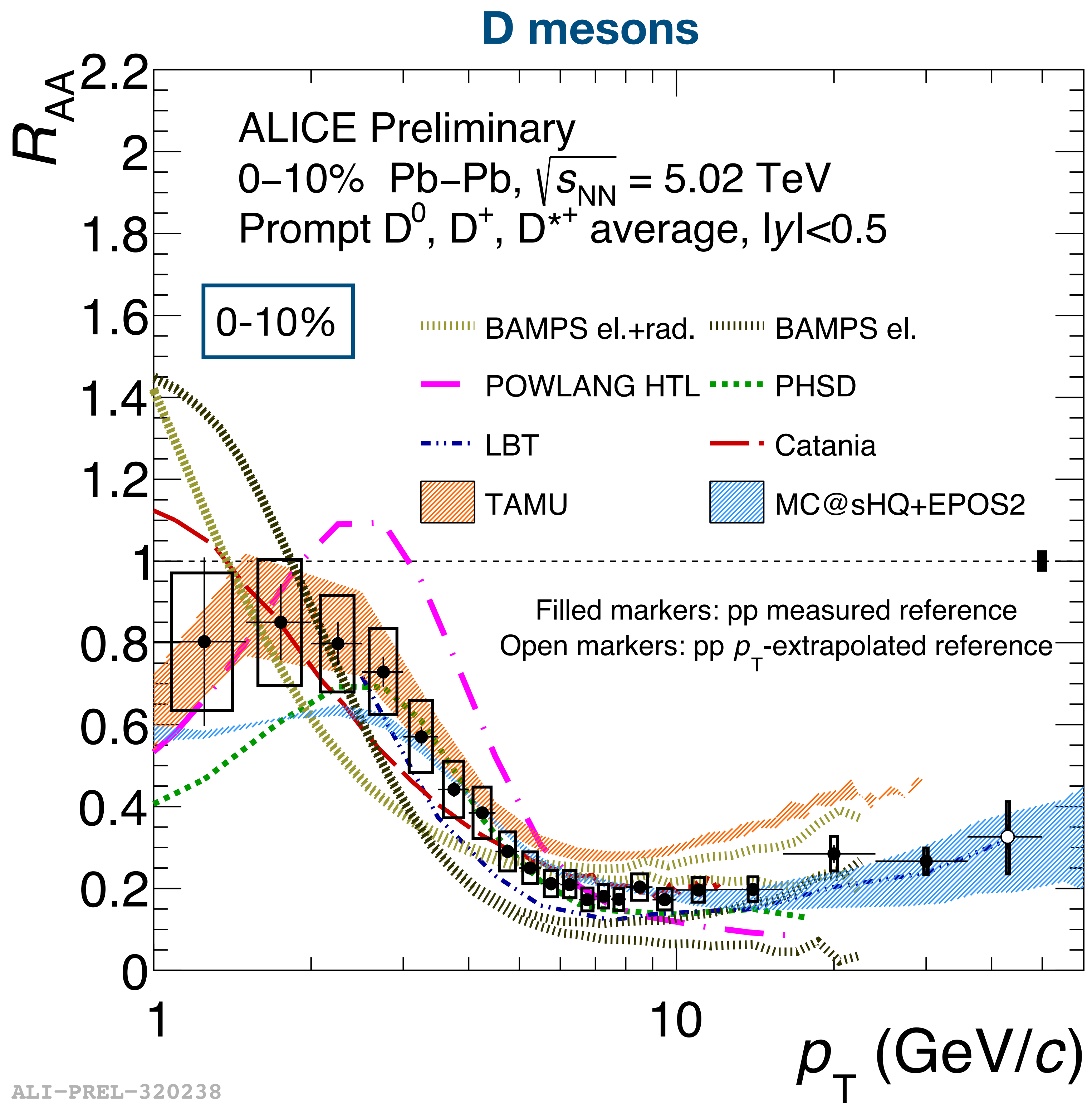

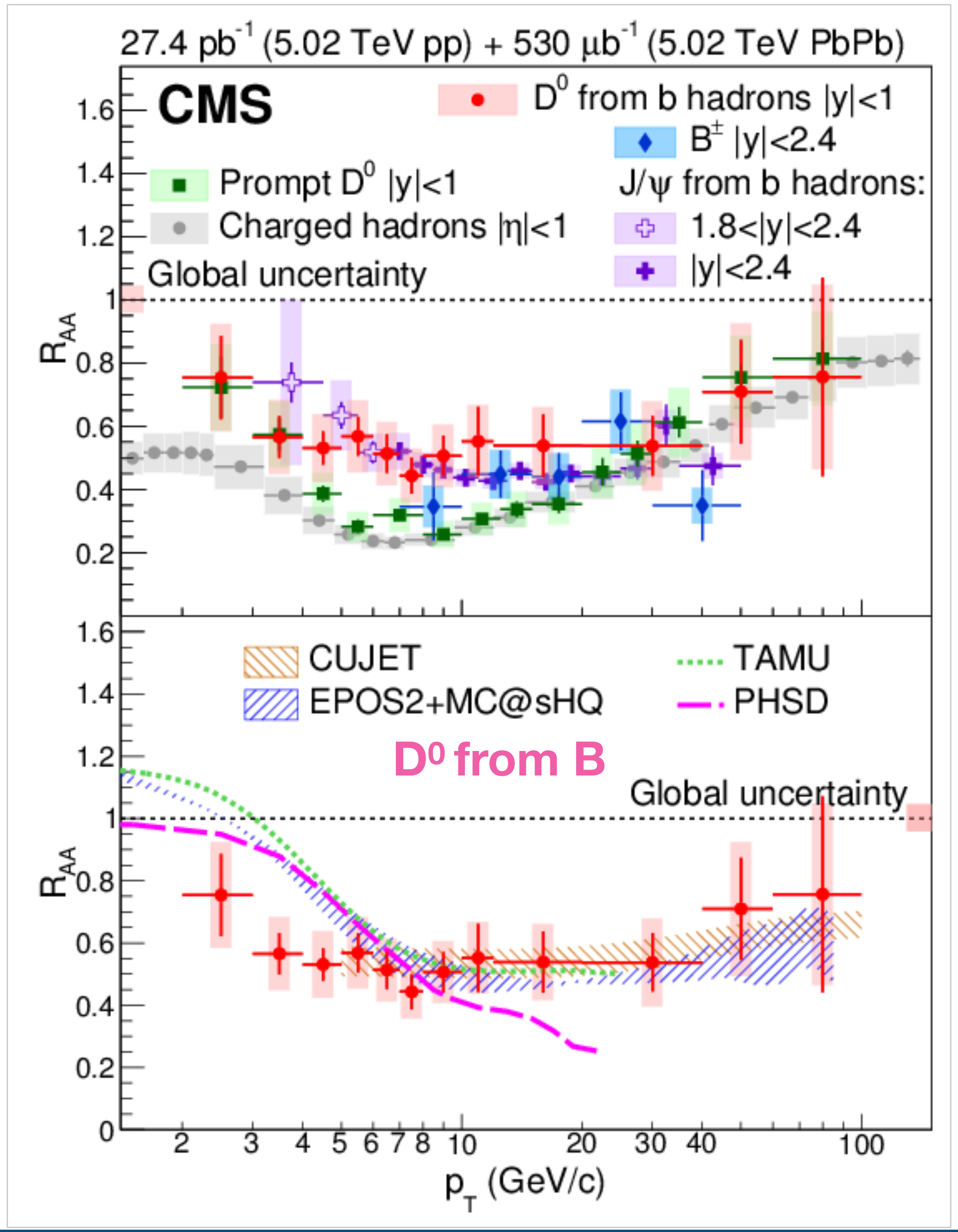

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- **PHSD**, **MC@sHQ+EPOS2**, BAMPS el.rad, **LBT**: **both elastic and radiative** contributions are included
- **Quark recombination: in TAMU, POWLANG, PHSD, MC@sHQ, LBT, Catania**

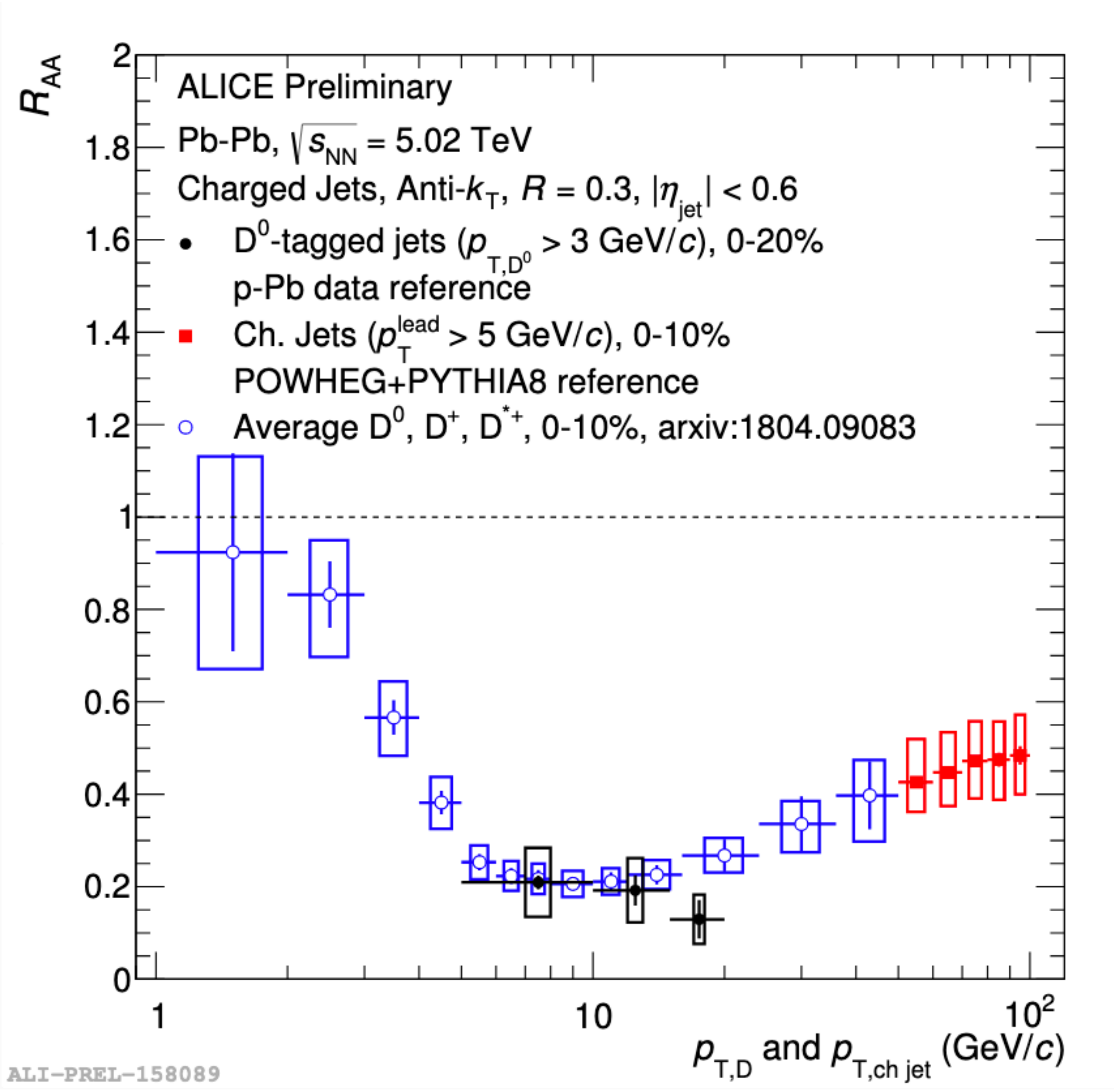
Interplay with **coll + rad energy loss**, **hadronization via coal+frag**, **hydrodynamic expansion** of medium **needed**

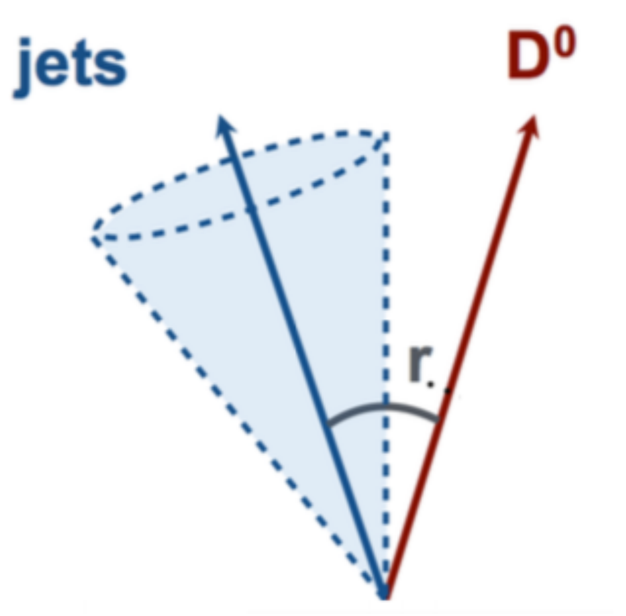
D^0-Jet R_{AA}

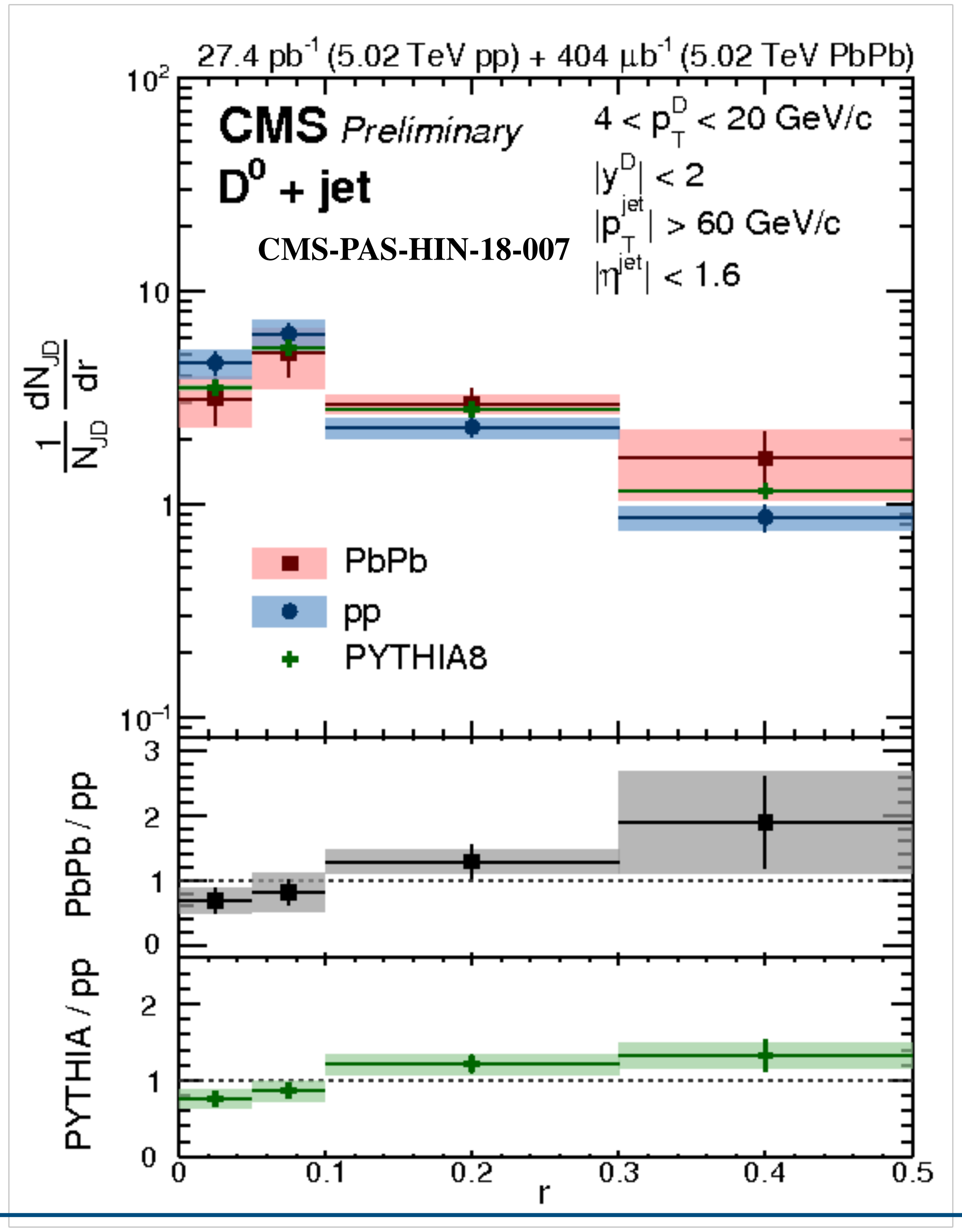
Further Investigation with D-tagged jets

How is the **jet structure and kinematics** modified in the medium?

Study in-medium color/mass dependent energy loss and modification of internal jet sub-structure with heavy-flavour jets







Talks:
A. Mohanty
X Wang

- D-meson tagged jets R_{AA} consistent with inclusive D-mesons
- Hint of larger suppression for low p_T D-jets than high p_T charged jets

Slightly different radial distribution of D^0 meson in jets in Pb-Pb with respect to pp at low D^0-meson p_T: redistribution of the D^0 mesons with respect to the jet axis

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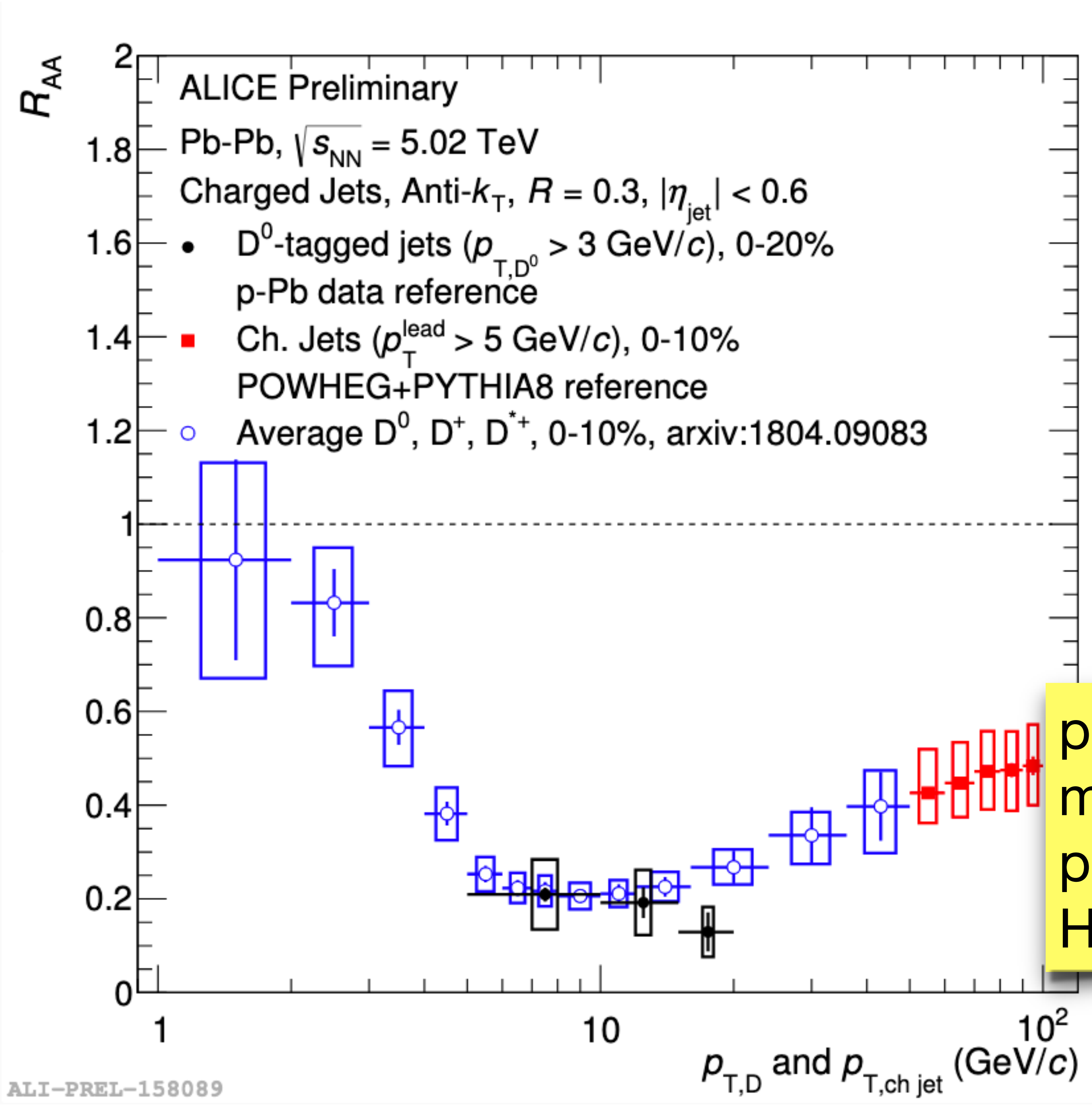

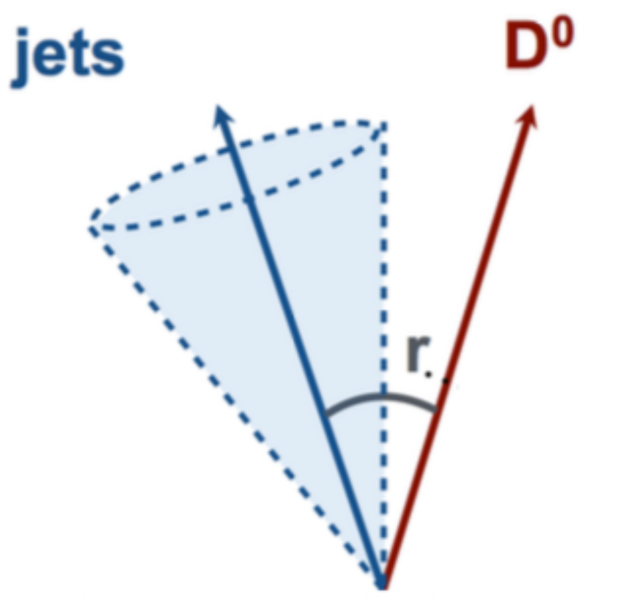

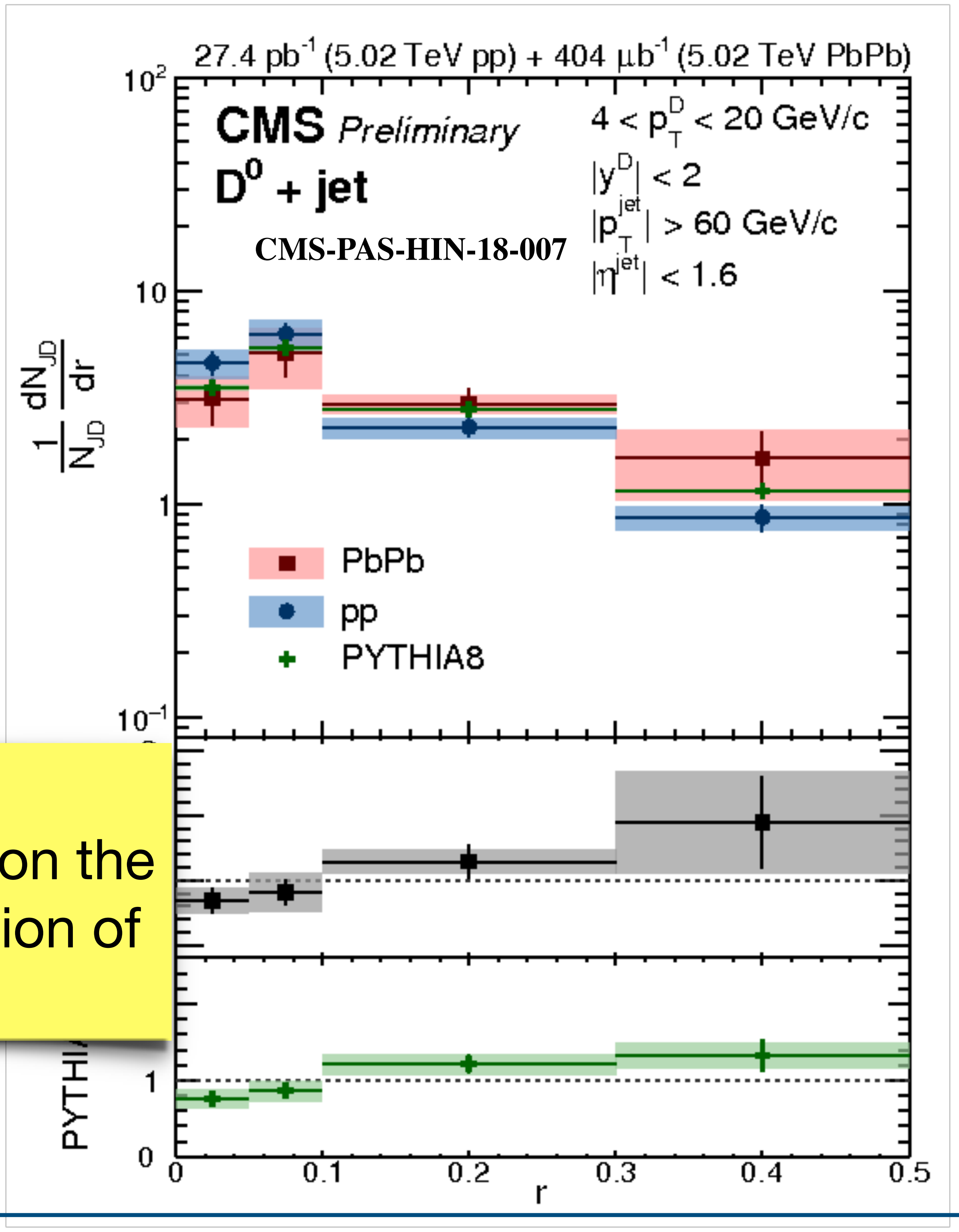

promising observable on the mechanisms of HF production and on the processes of energy loss and diffusion of HQ inside the medium

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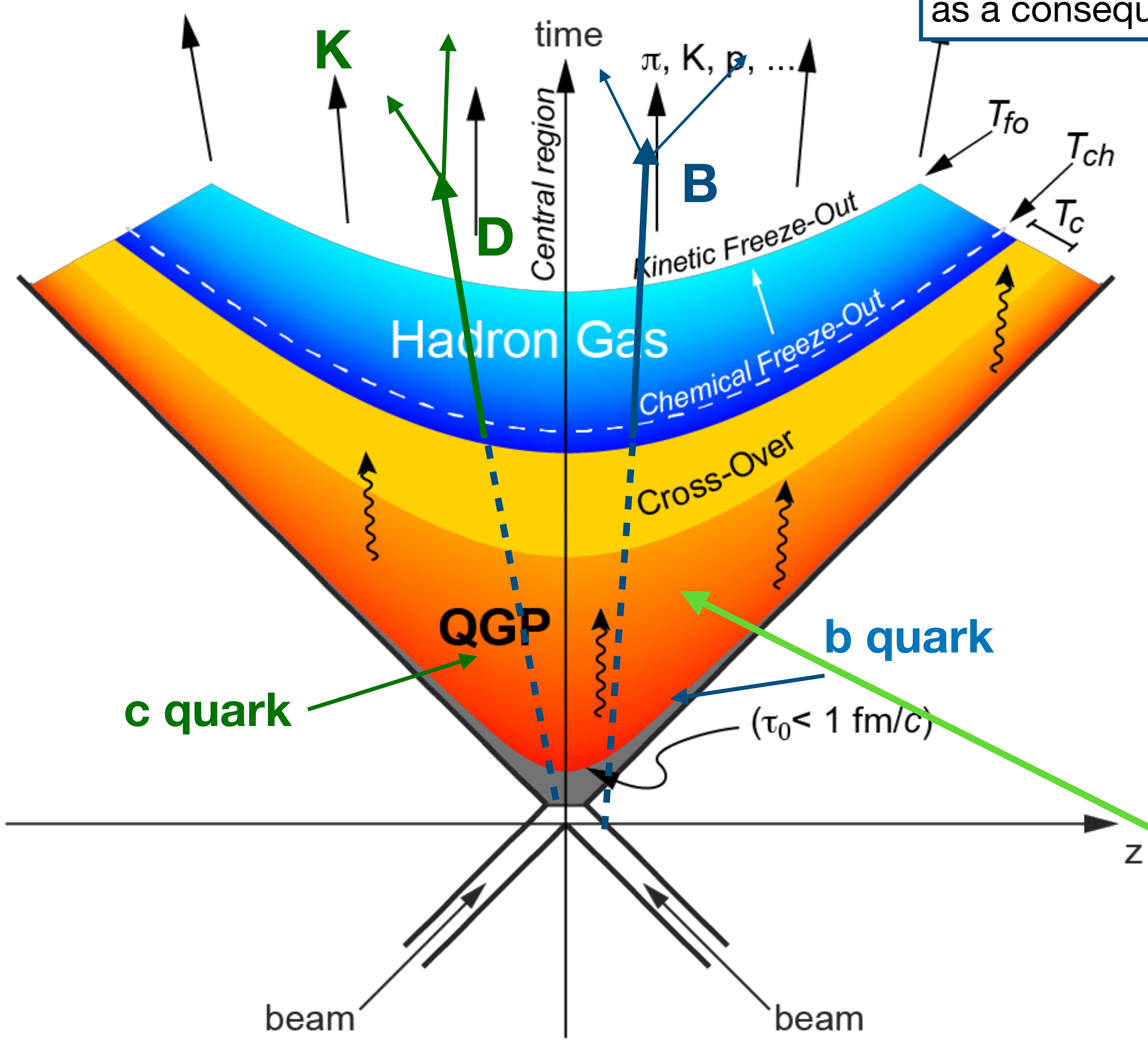
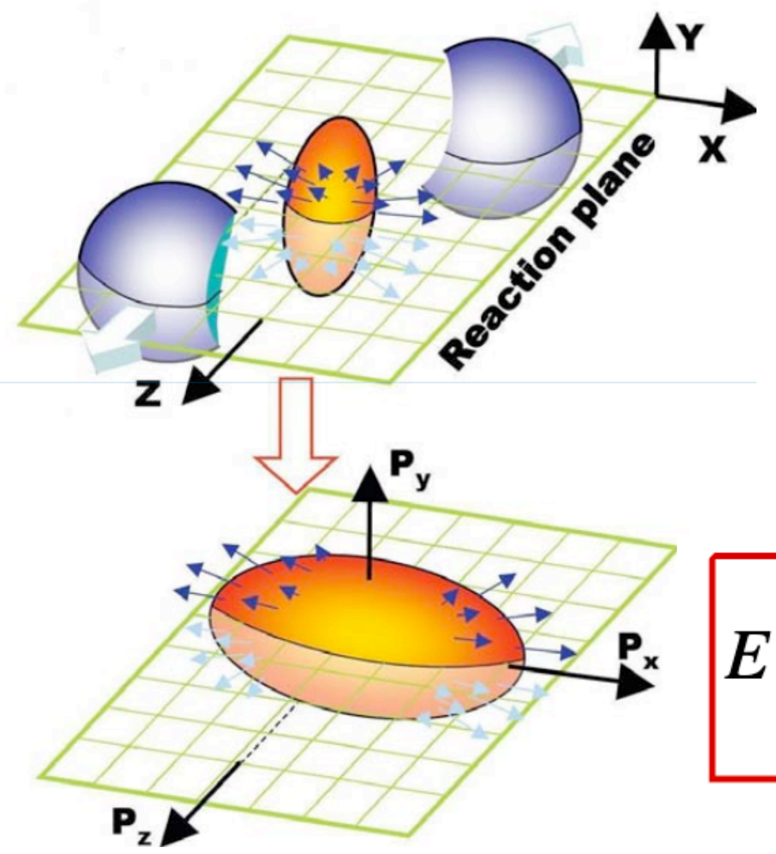
Space-time evolution



Thermalization
as a consequence of HQ coupling with medium



Which is the degree of thermalization of HQs in the medium?
Do charm/beauty flow?

Observable

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

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

Thermalization

charm v_2

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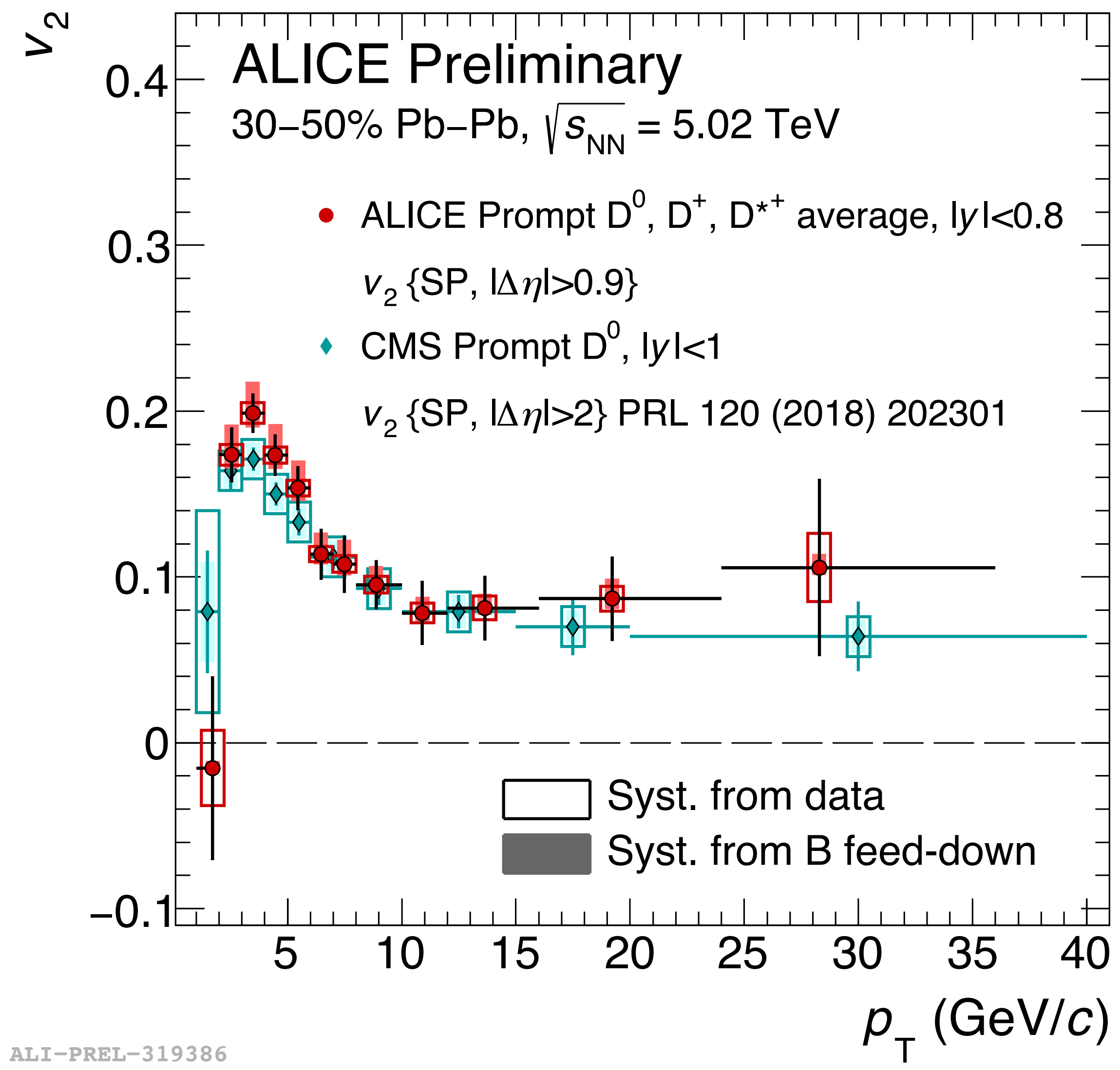
➡Positive D v_2 observed at RHIC and LHC
- charm quarks largely thermalize in QGP until hadronization

ALICE - CMS



- positive **D mesons** v_2
  - Compatible results measured by **CMS** and **ALICE** in Pb-Pb@5.02TeV

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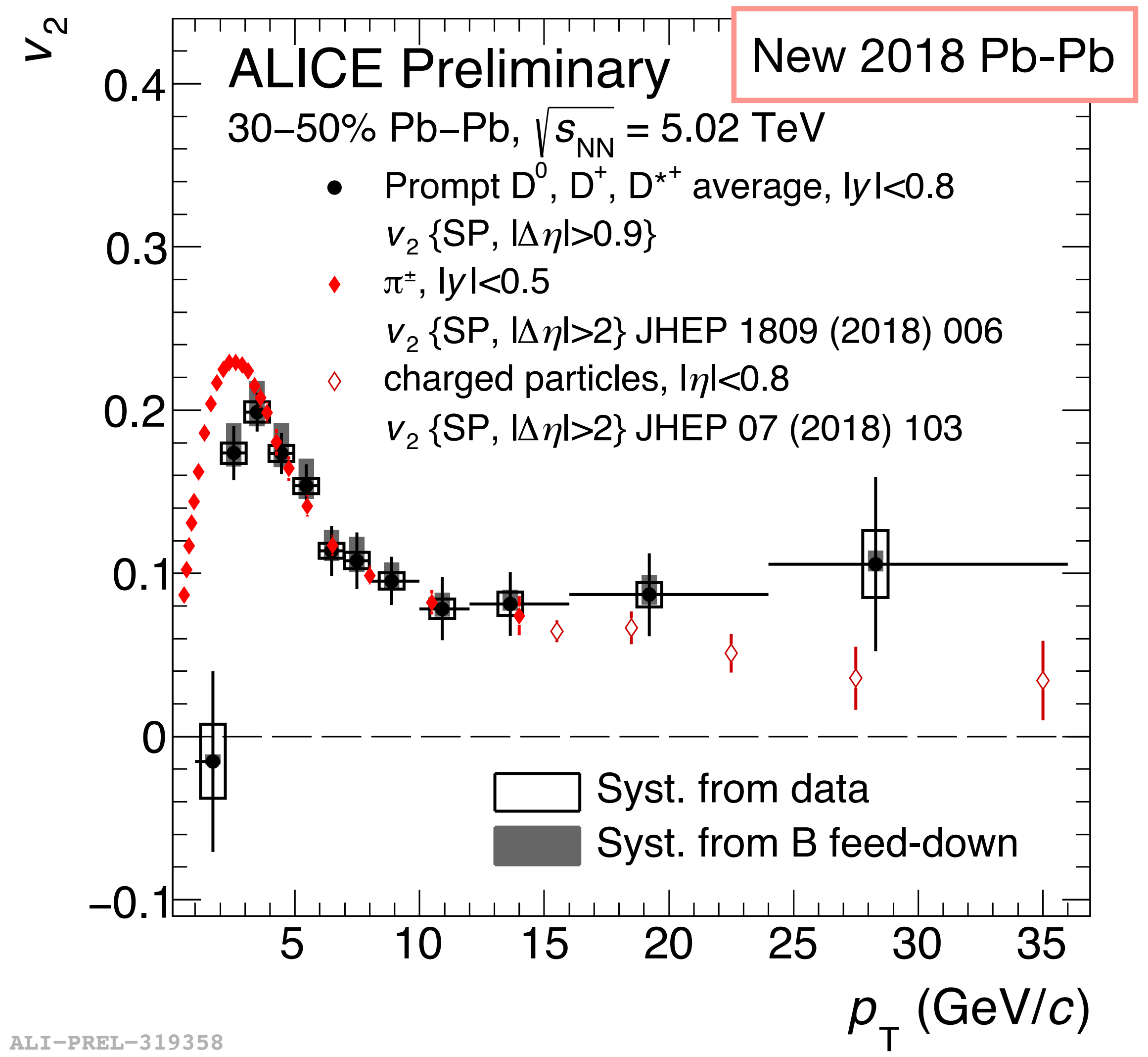
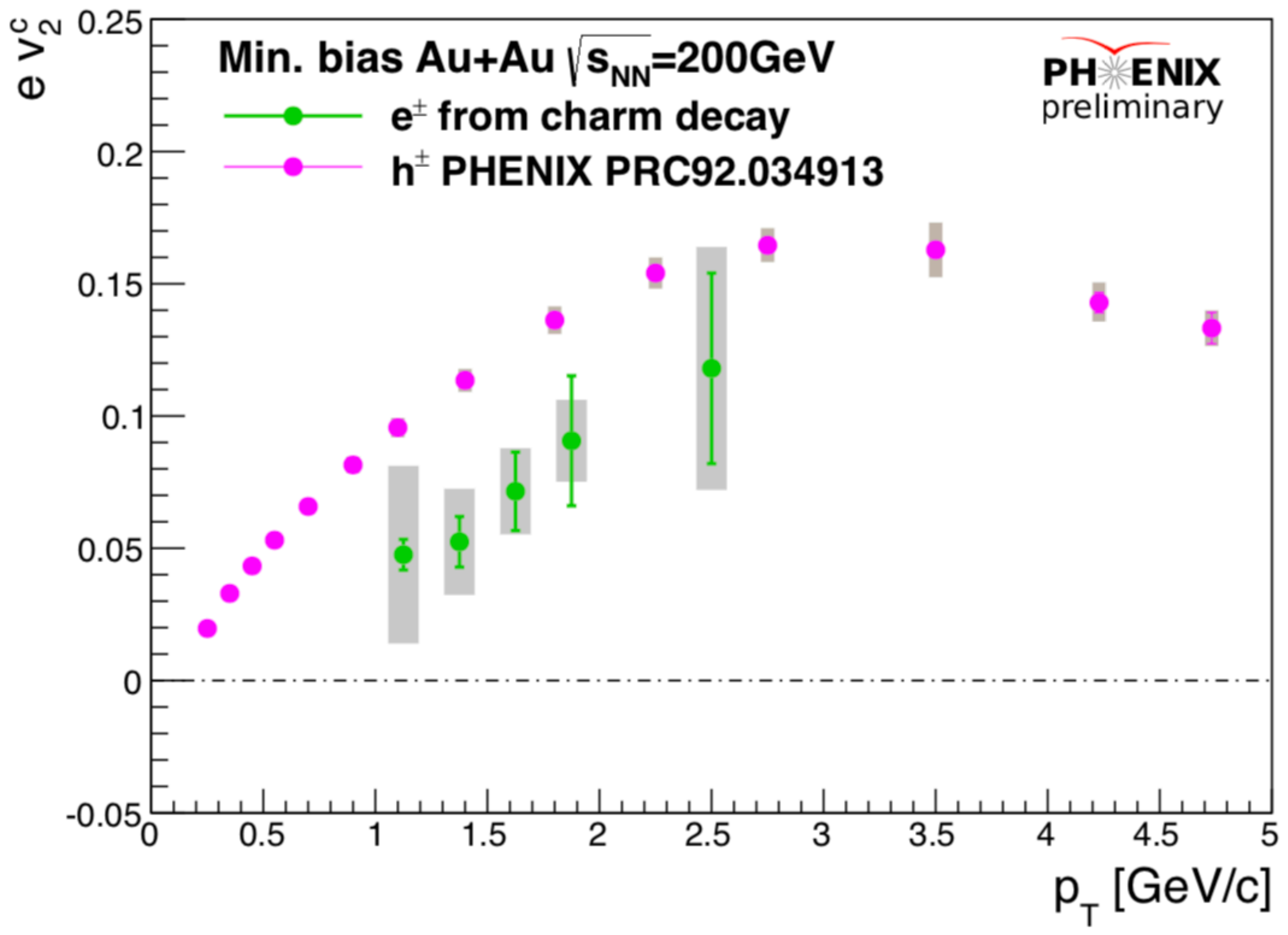


charged hadrons and c—>e v_2



- **Similar** v_2 for **charged particles** and **D mesons** for p_T > 3GeV/c
- **Slightly higher** v_2 for **charged particles** than **D mesons** and **c—>e-** at low p_T
  - indication of radial flow?

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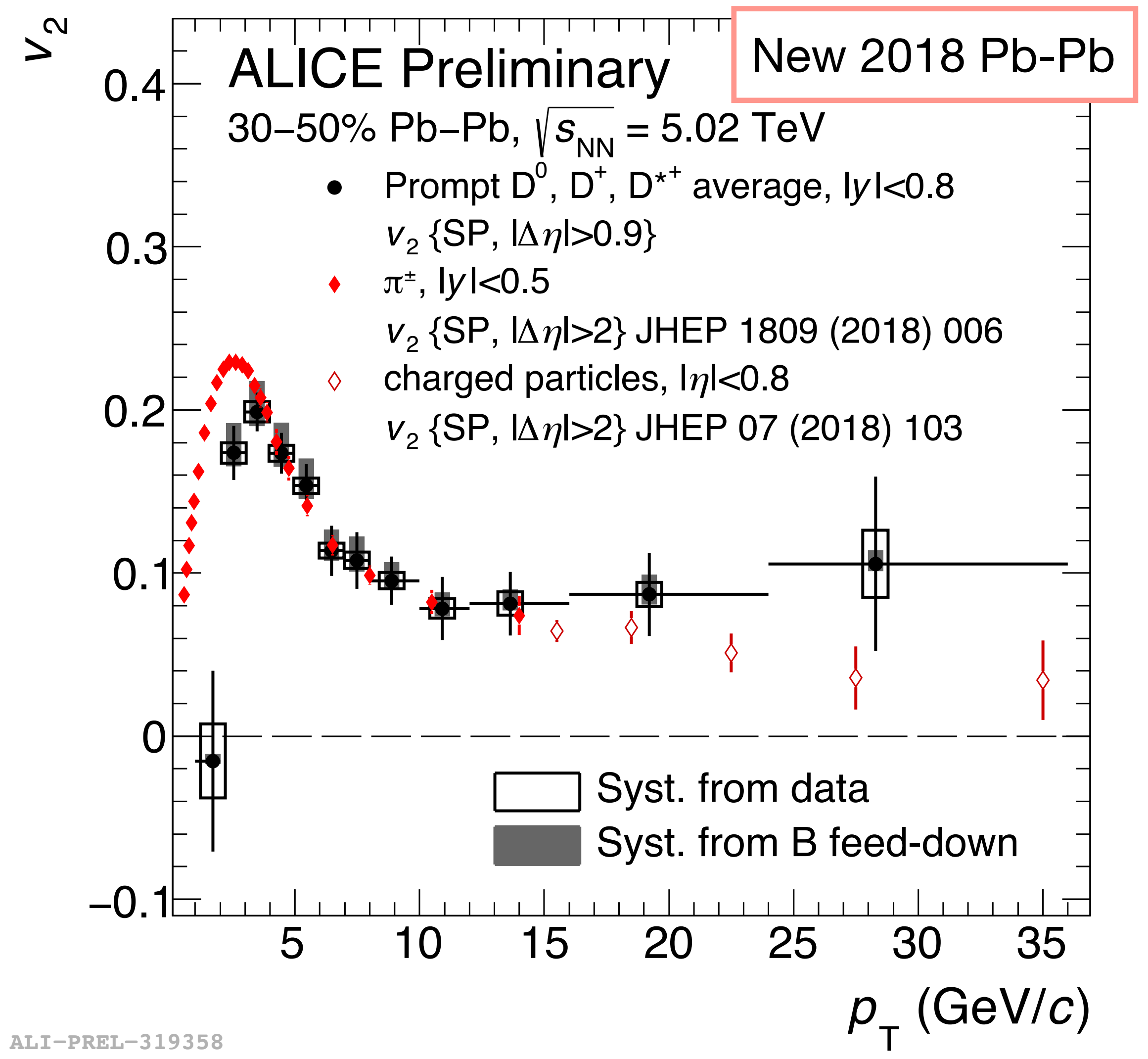
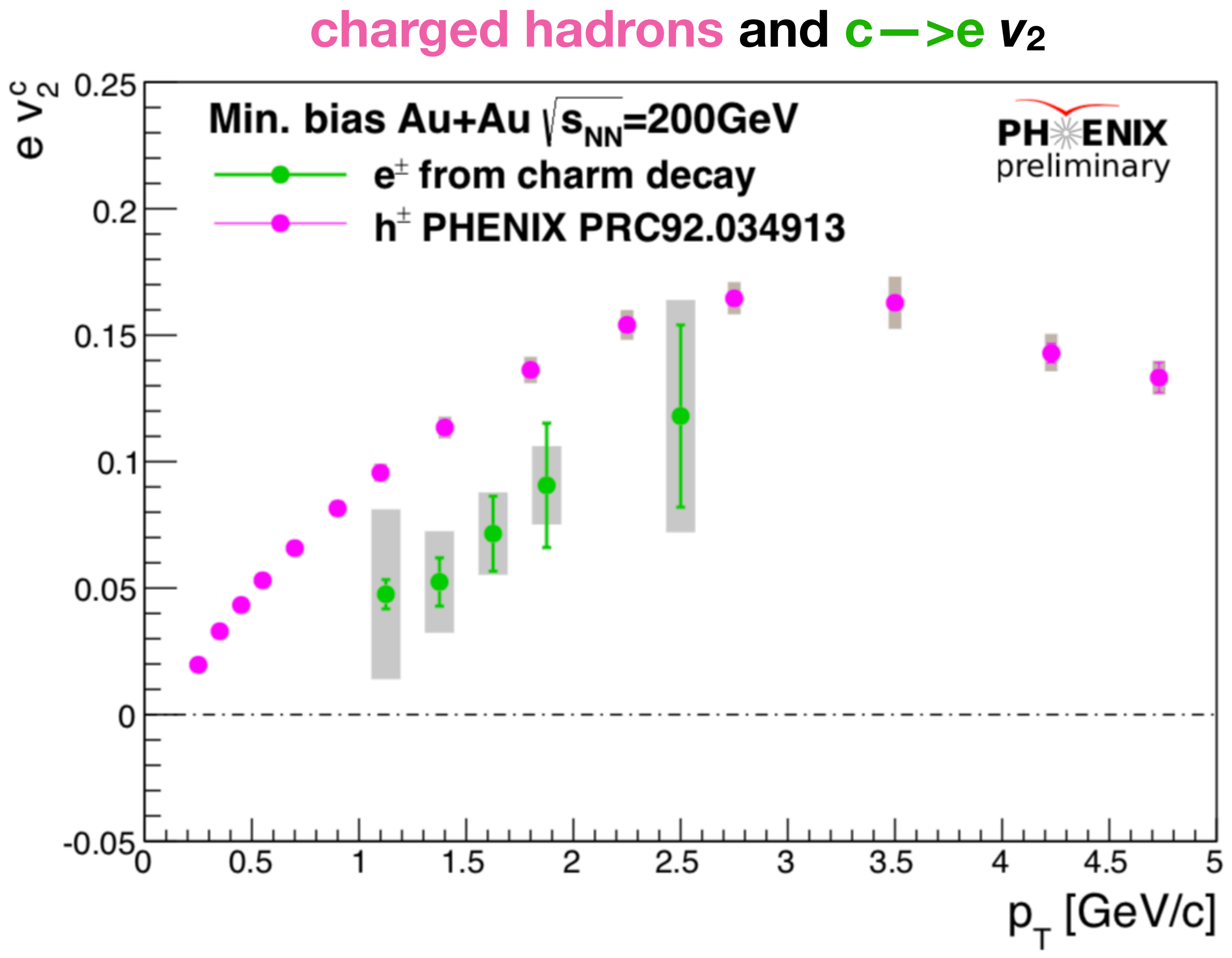
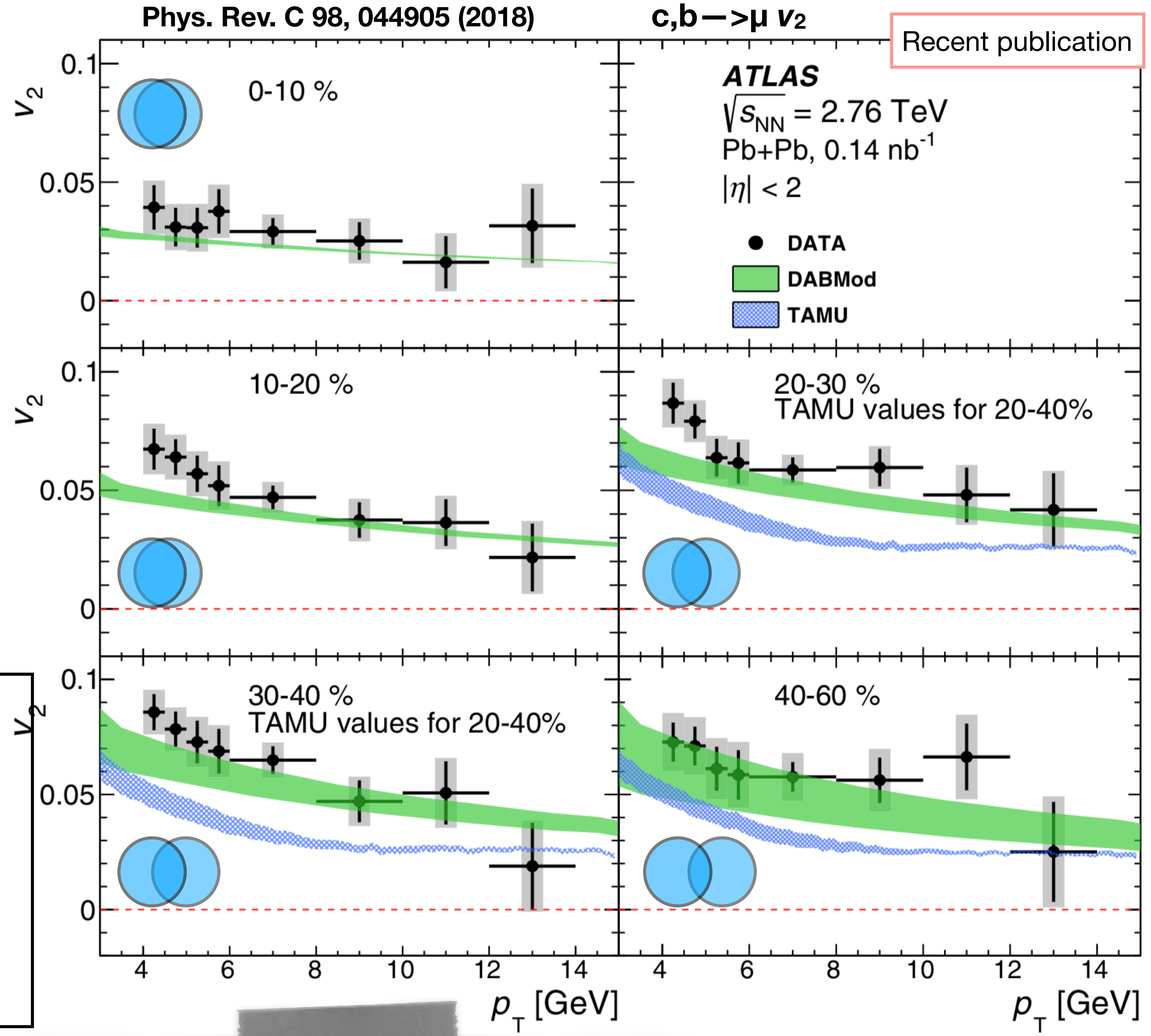
Talk:
S. Jaelani
M. Rosati





TAMU transport model
DABMod energy loss model



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  - indication of radial flow?
- centrality dependence: larger v_2 in semi-central collisions:
  - v_2 increases going from central to peripheral —> sensitive to the initial geometry of the overlap A-A region

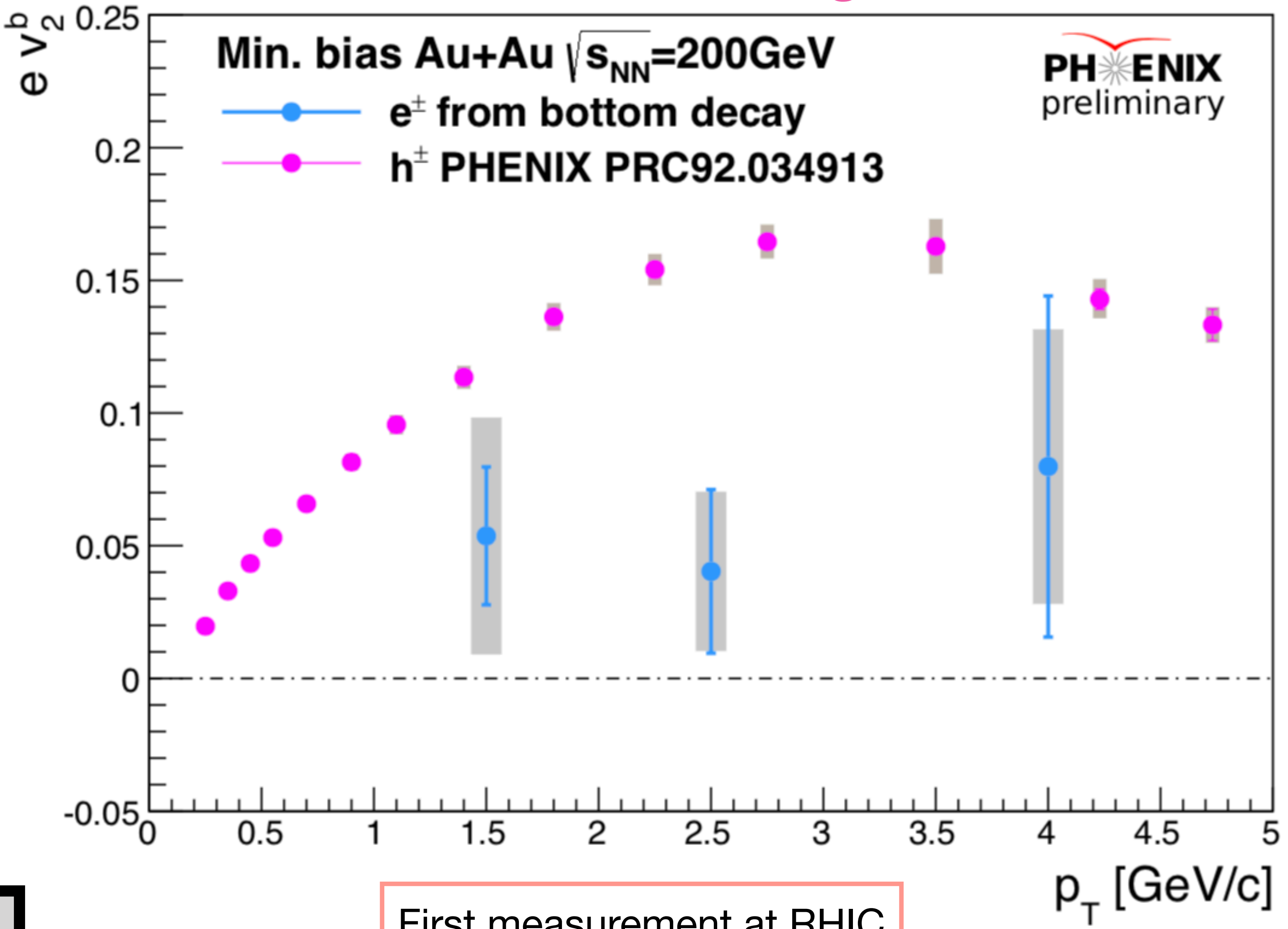
Charm is strongly coupled in QGP

...and beauty v_2

Which is the degree of thermalization of HQs in the medium?
Do charm/beauty flow?

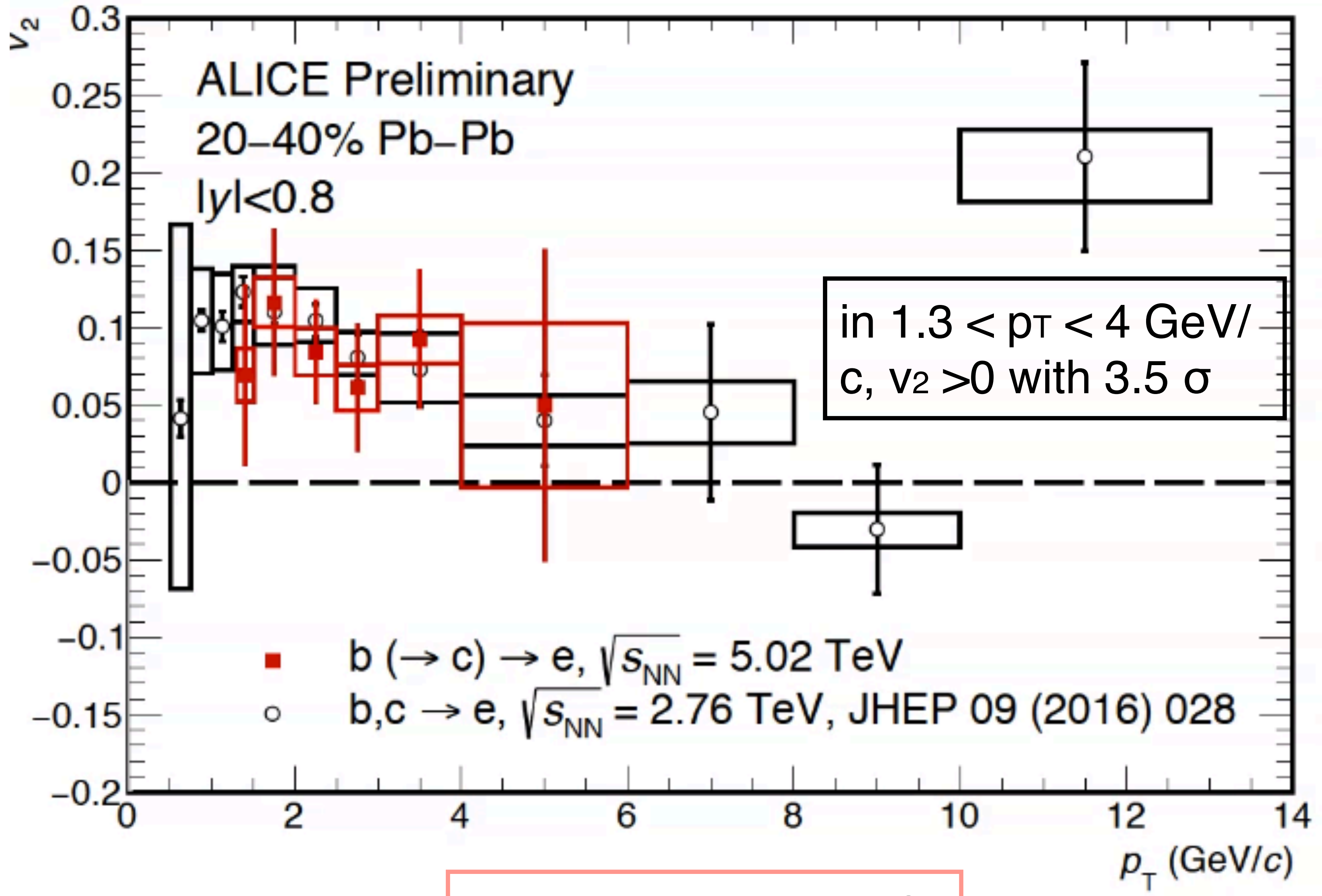
➡Positive D v_2 observed at RHIC and LHC
- charm quarks largely thermalize in QGP until hadronization
- **much less known about beauty!**

v_2 of b—>e, v_2 of charged hadrons



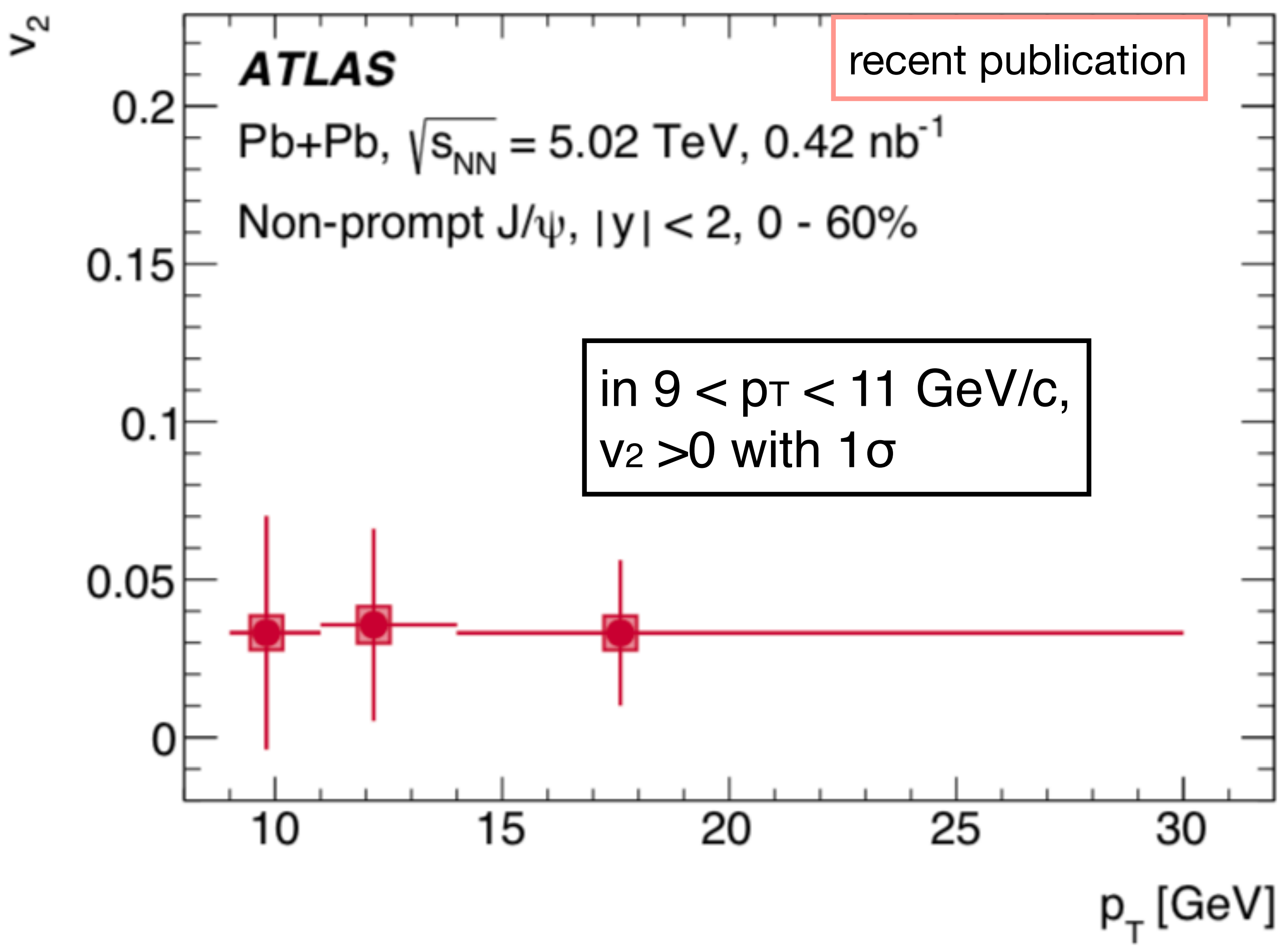
First measurement at RHIC

v_2 of b—>e, v_2 of b,c—>e



First measurement at ALICE

Eur. Phys. J. C 78 (2018) 784



Talks:
M.Rosati
E. Gauger
M. Spousta

- beauty v_2 measured via electrons from HF hadron decays and non-prompt J/Ψ
- Smaller v_2 for beauty, as expected, but hint of v_2>0 at low p_T
- compatible v_2 for **non-prompt** and prompt **J/Ψ** at high p_T

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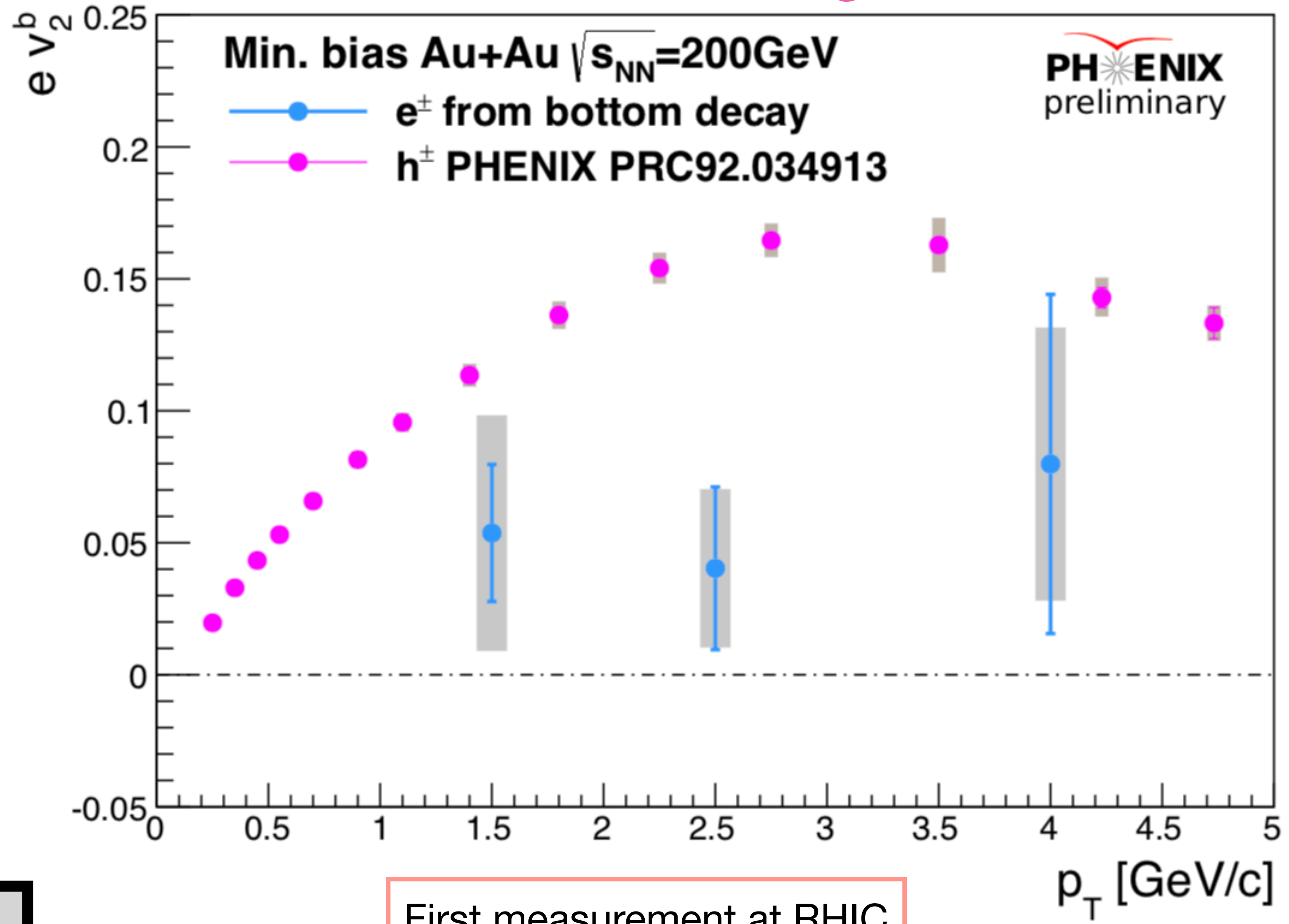

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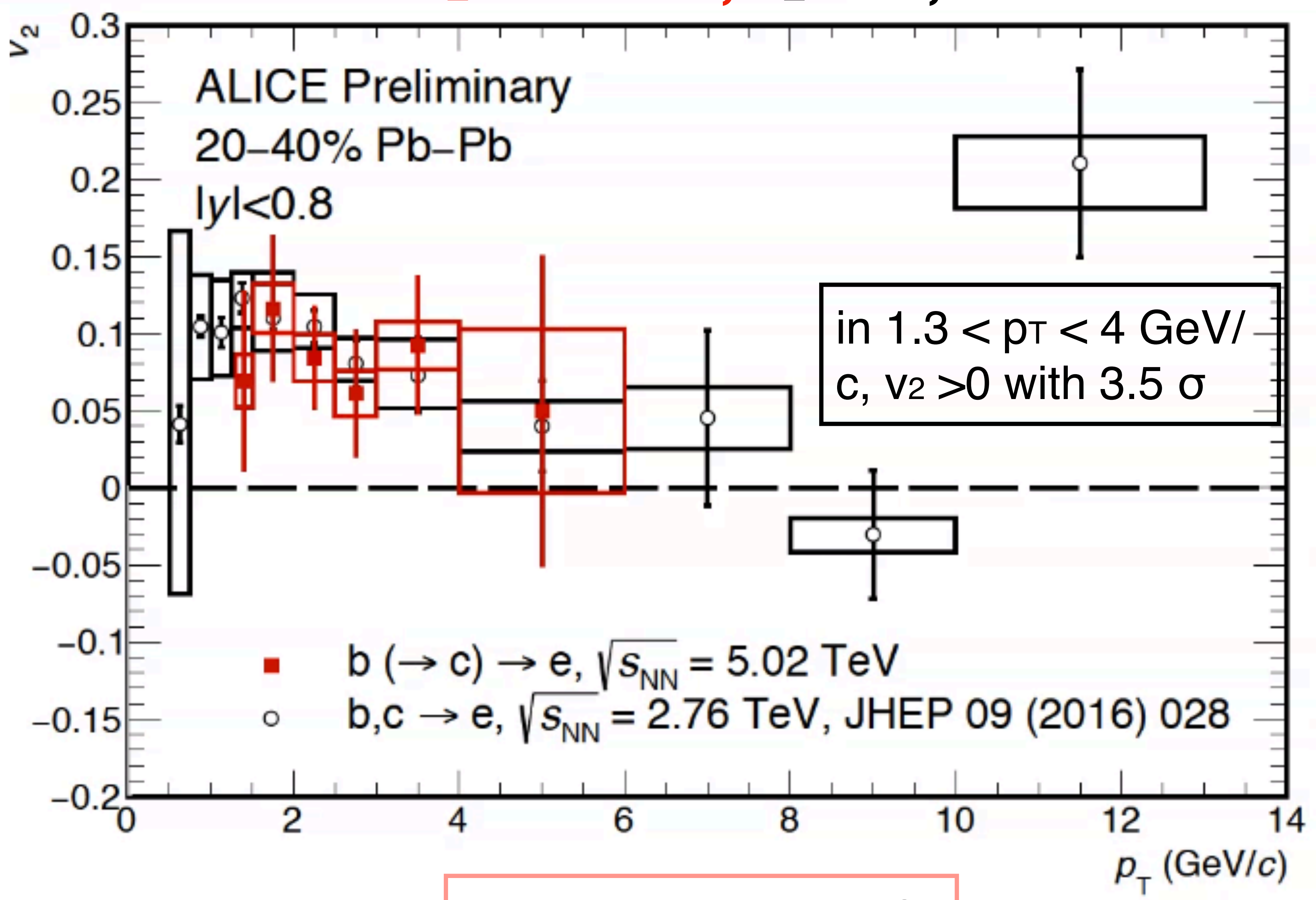

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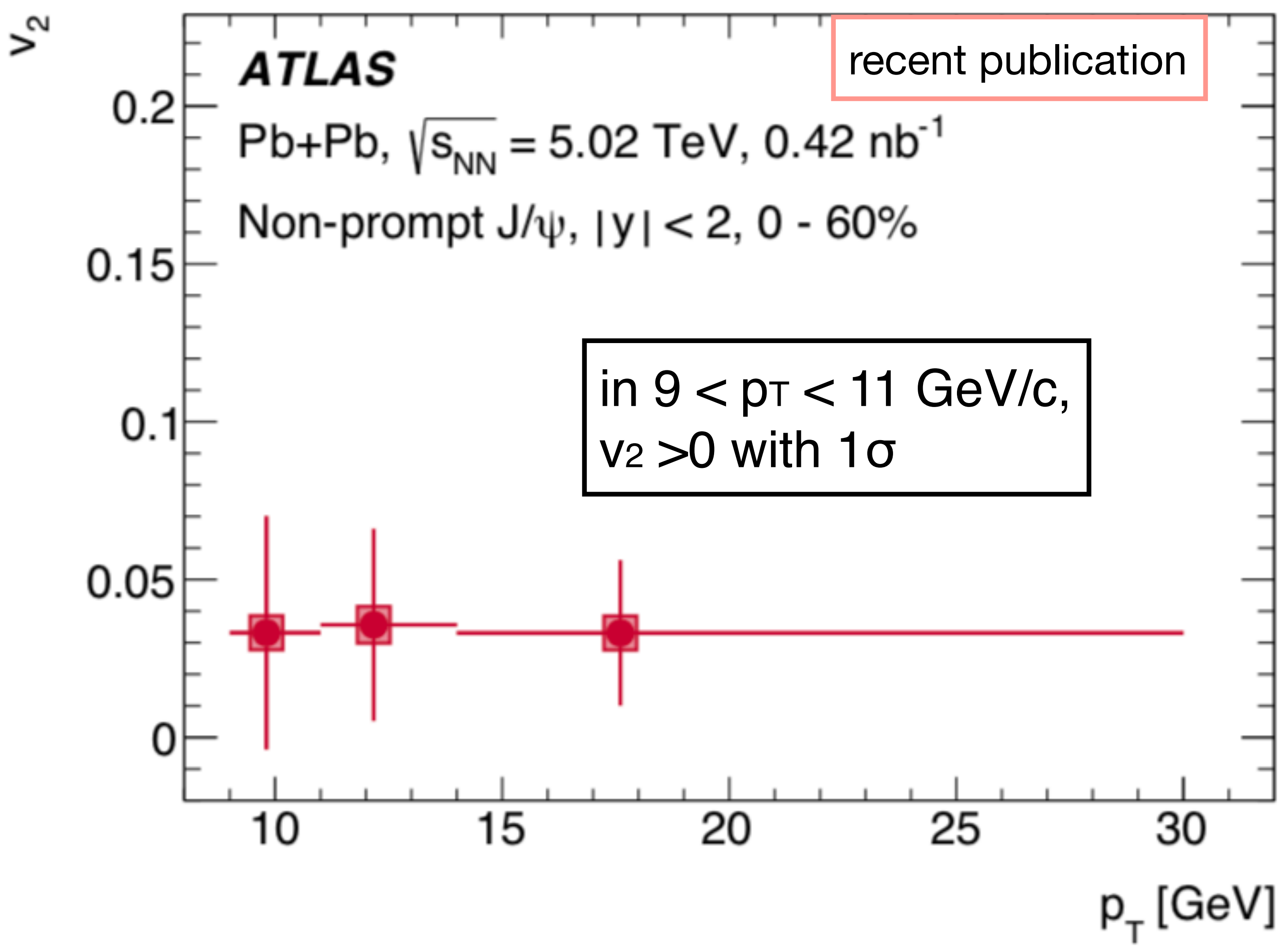

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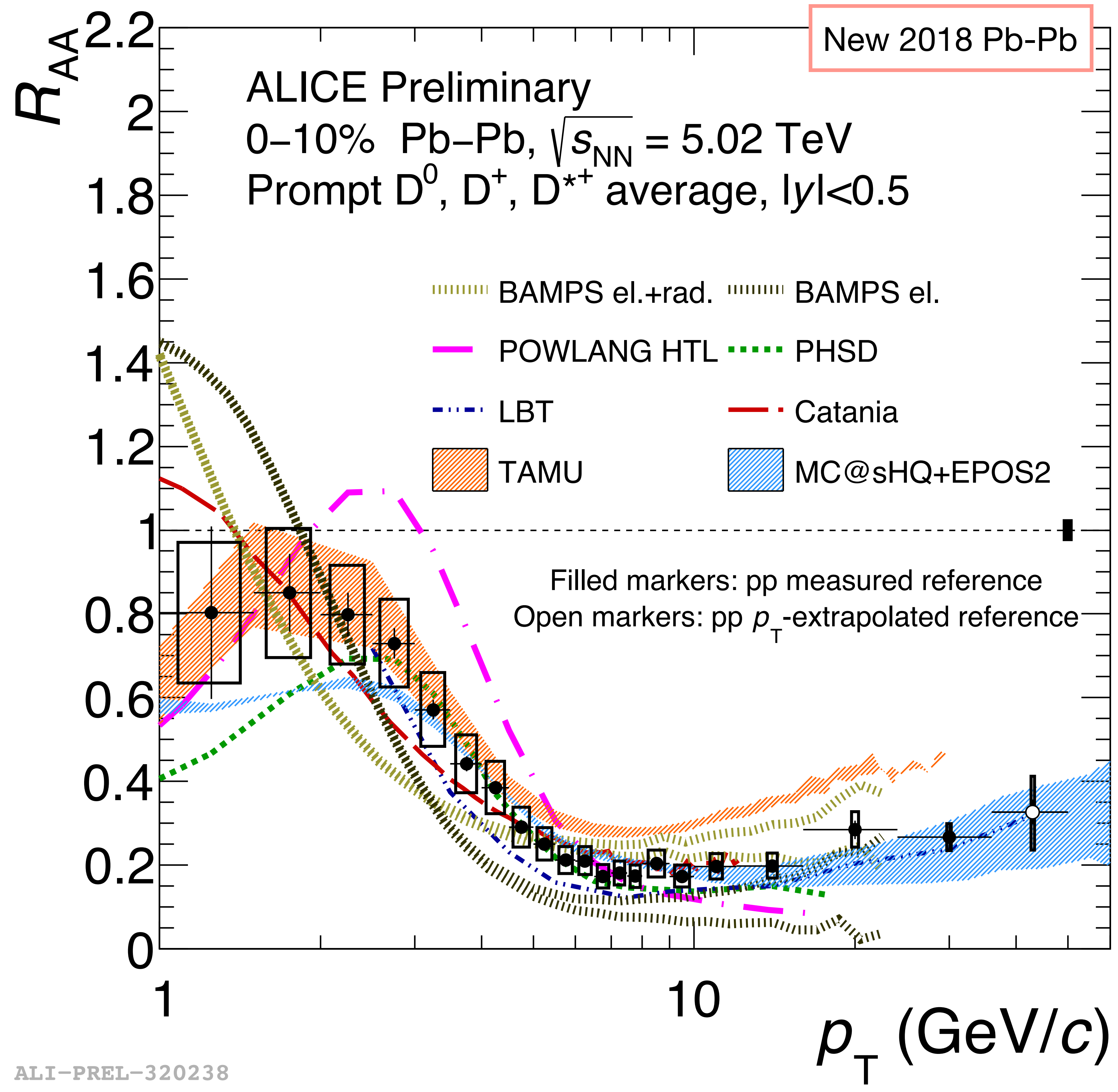
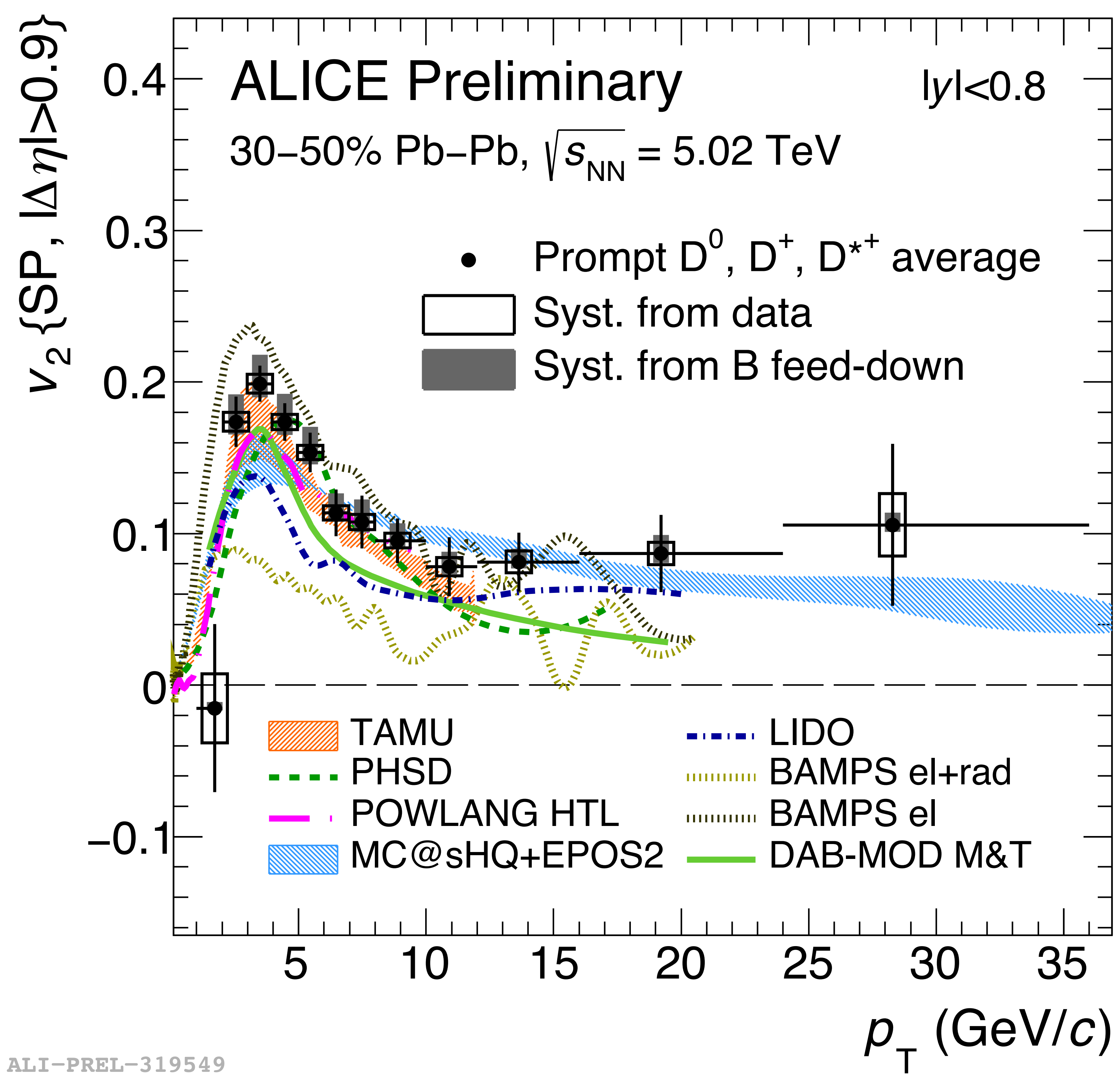
Hint of $0<v_2^b<v_2^c<v_2^h$ at low p_T? but large uncertainties, different p_T explored by b,c—>e, non-prompt J/Ψ and D mesons
Smaller energy loss—> longer relaxation time —> smaller thermalization for beauty?
Positive v_2 from path-length dependence of energy loss?

Beauty participates to the collective motion in the medium ? Does it partially thermalize?

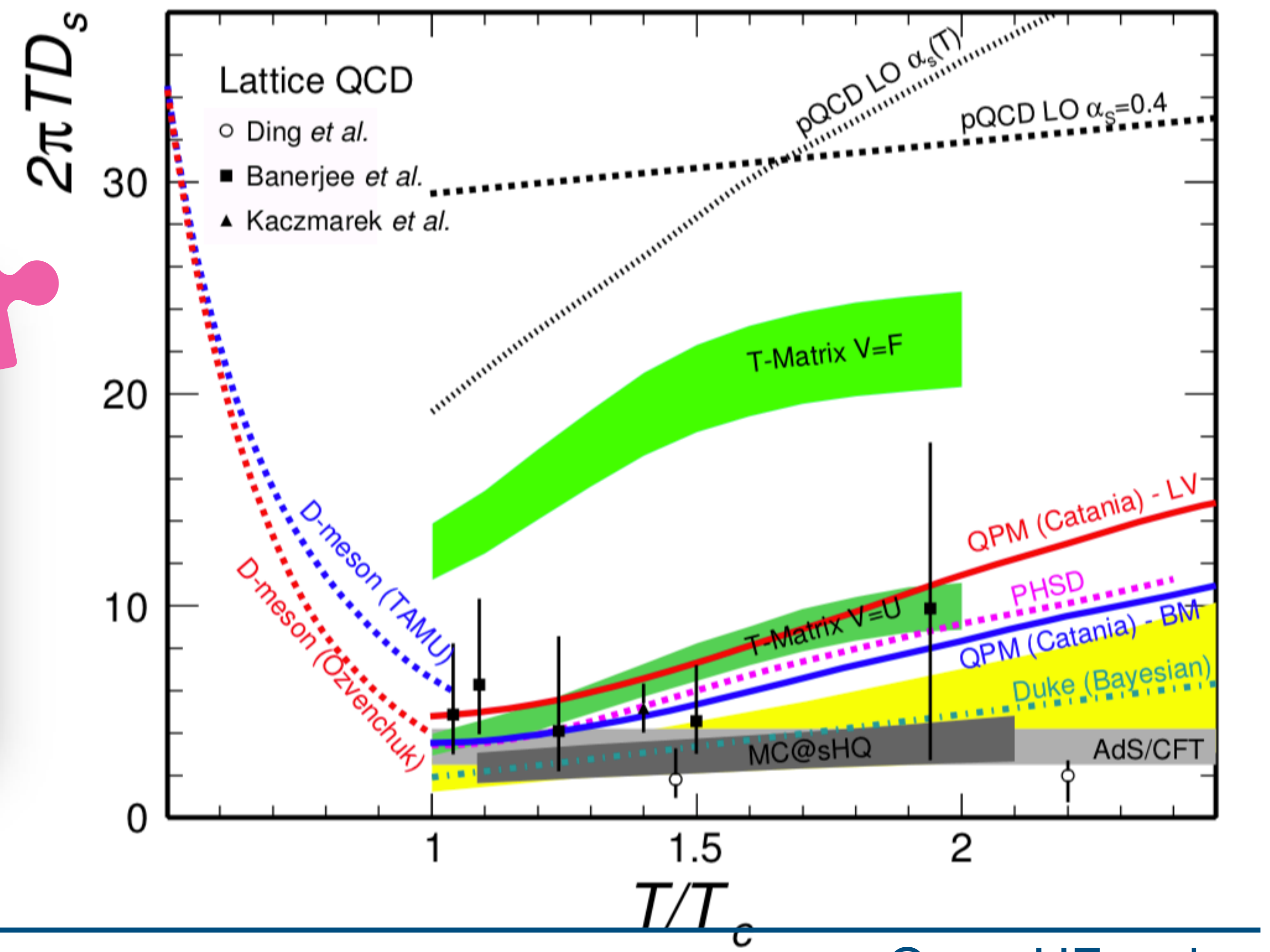
R_{AA} and v_2
Comparison with models





TAMU: PLB 735,445-450(2014), arXiv:1905.09216
PHSD: PRC 92, 014910 (2015)
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

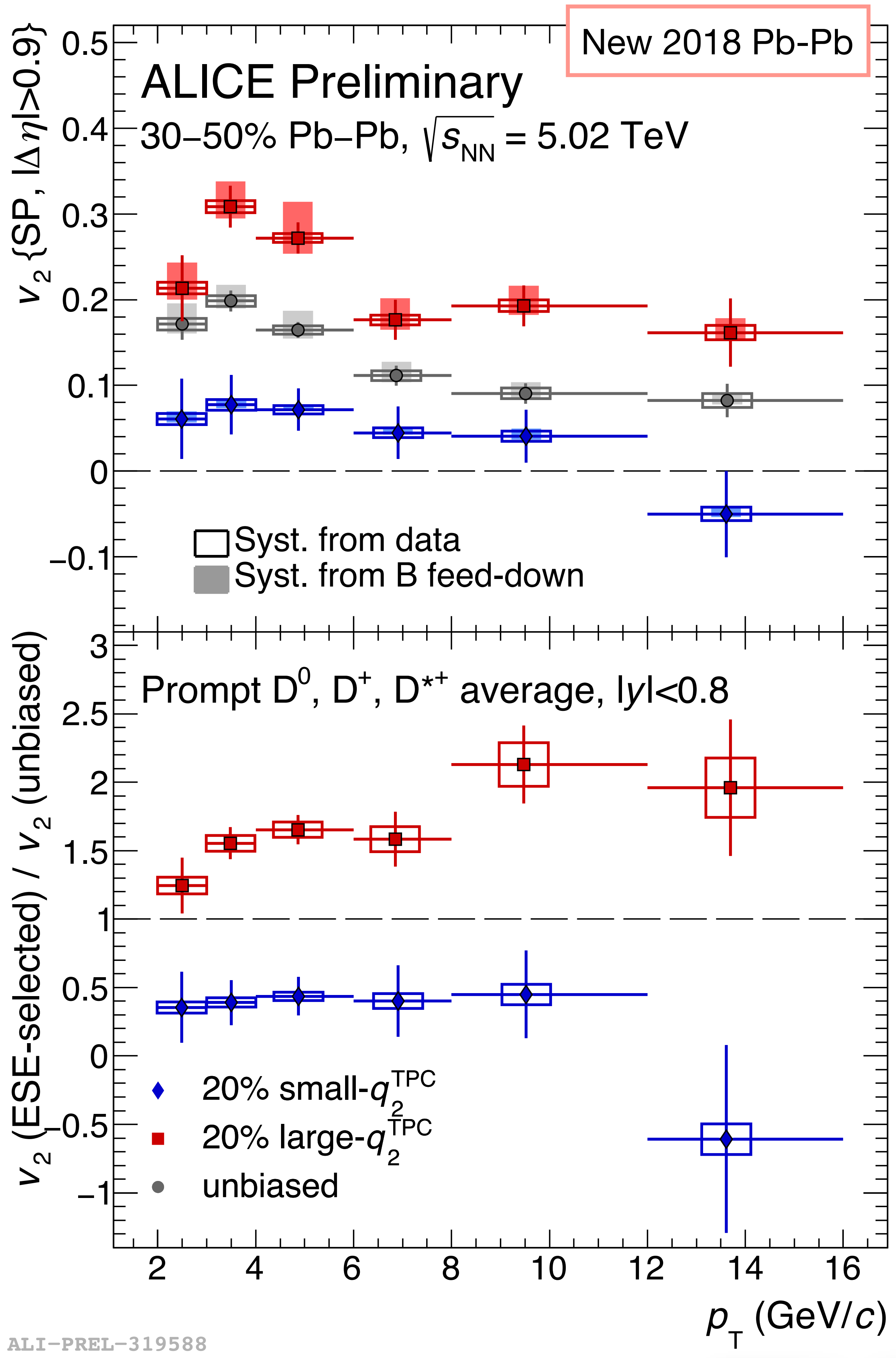
- ➡ Simultaneous description of ***R_{AA}* and *v_2* is challenging** in the whole measured p_T range!
- ➡ Experimental measurements start to **provide constraint to the models** for the characterization of the charm and beauty interaction with the medium
  - ➡**constraints on plasma transport parameters**,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



Event Shape Engineering with D-mesons

Further investigate the dynamics of hq in the medium

Initial-condition fluctuations and event eccentricity: event-by-event variation of the flow coefficients at fixed centrality can be large



v_2 in classes of events selected in 30-50% with different initial geometrical shape eccentricity

'reduced flow vector' q_2 to quantify the eccentricity of the event

20% largest q_2: **v_2 increased**

20% smallest q_2: **v_2 reduced**

2018 data improve measurement reported in **JHEP1902 (2019) 150**

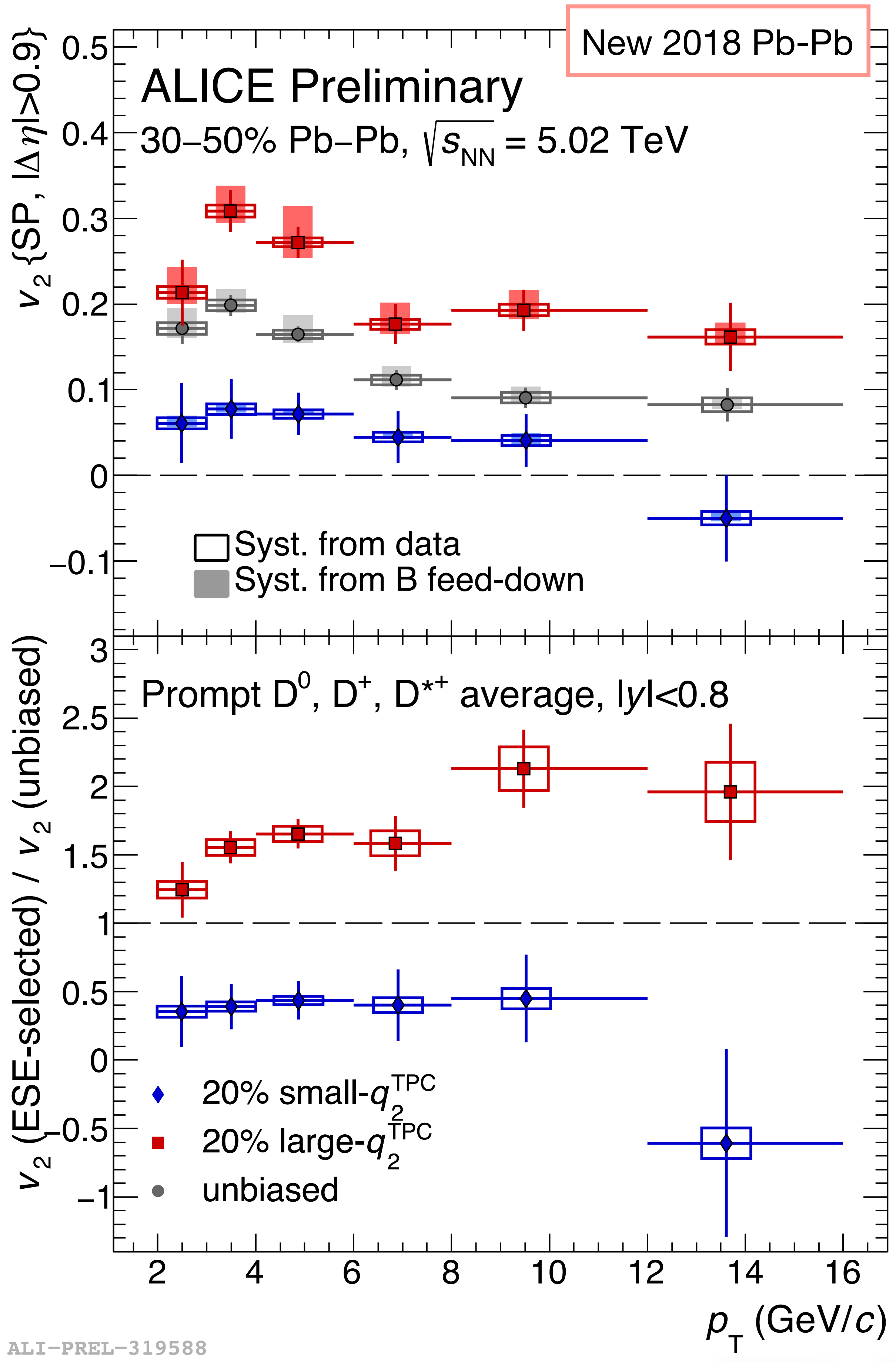
D-meson v_2 sensitive to event shape selection confirming a correlation with the collective expansion of the bulk matter

Talk: S. Jaelani

Event Shape Engineering with D-mesons

Further investigate the dynamics of hq in the medium

Initial-condition fluctuations and event eccentricity: event-by-event variation of the flow coefficients at fixed centrality can be large



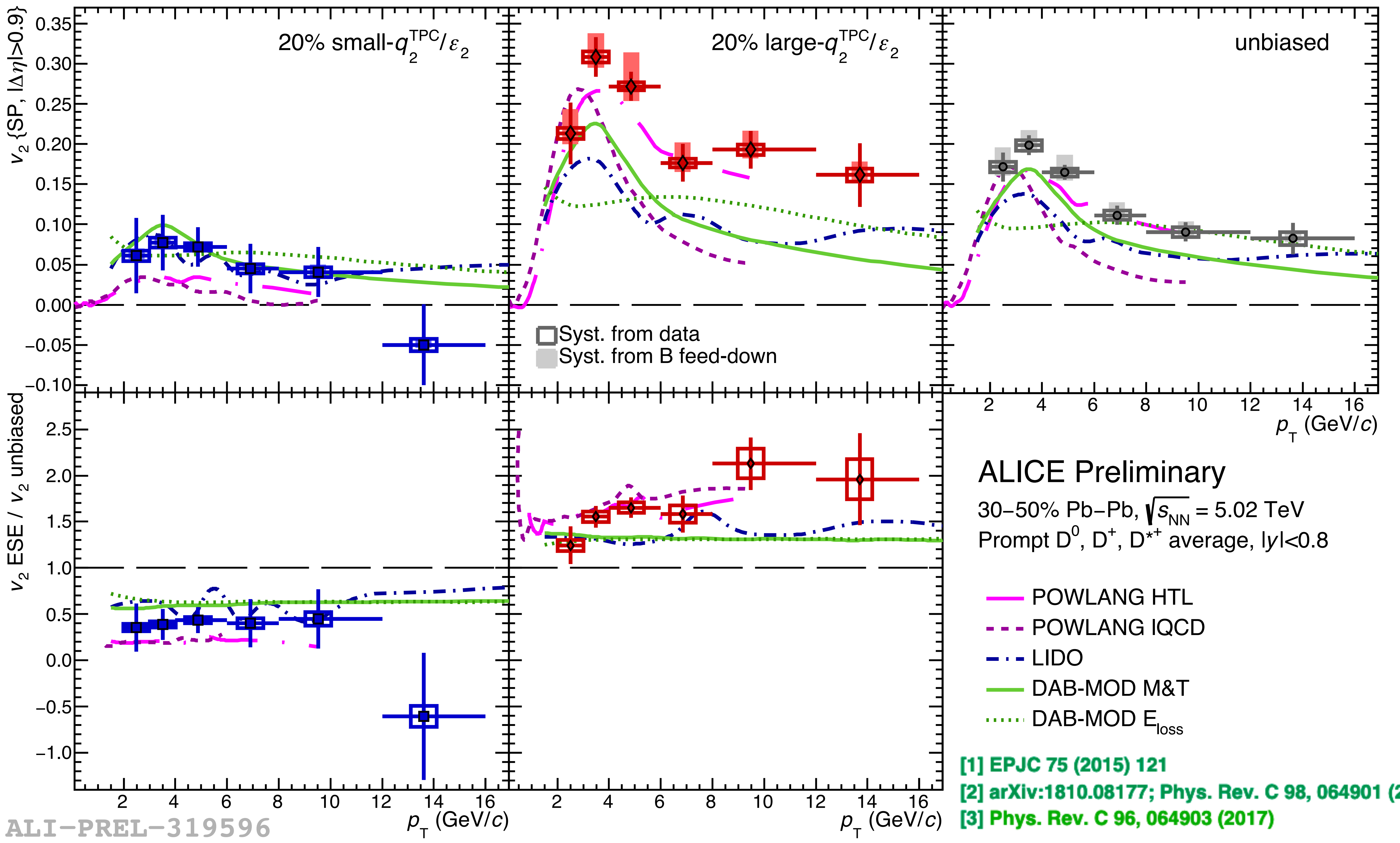
v_2 in classes of events selected in 30-50% with different initial geometrical shape eccentricity

'reduced flow vector' q_2 to quantify the eccentricity of the event

20% largest q_2: **v_2 increased**

20% smallest q_2: **v_2 reduced**

2018 data improve measurement reported in **JHEP1902 (2019) 150**



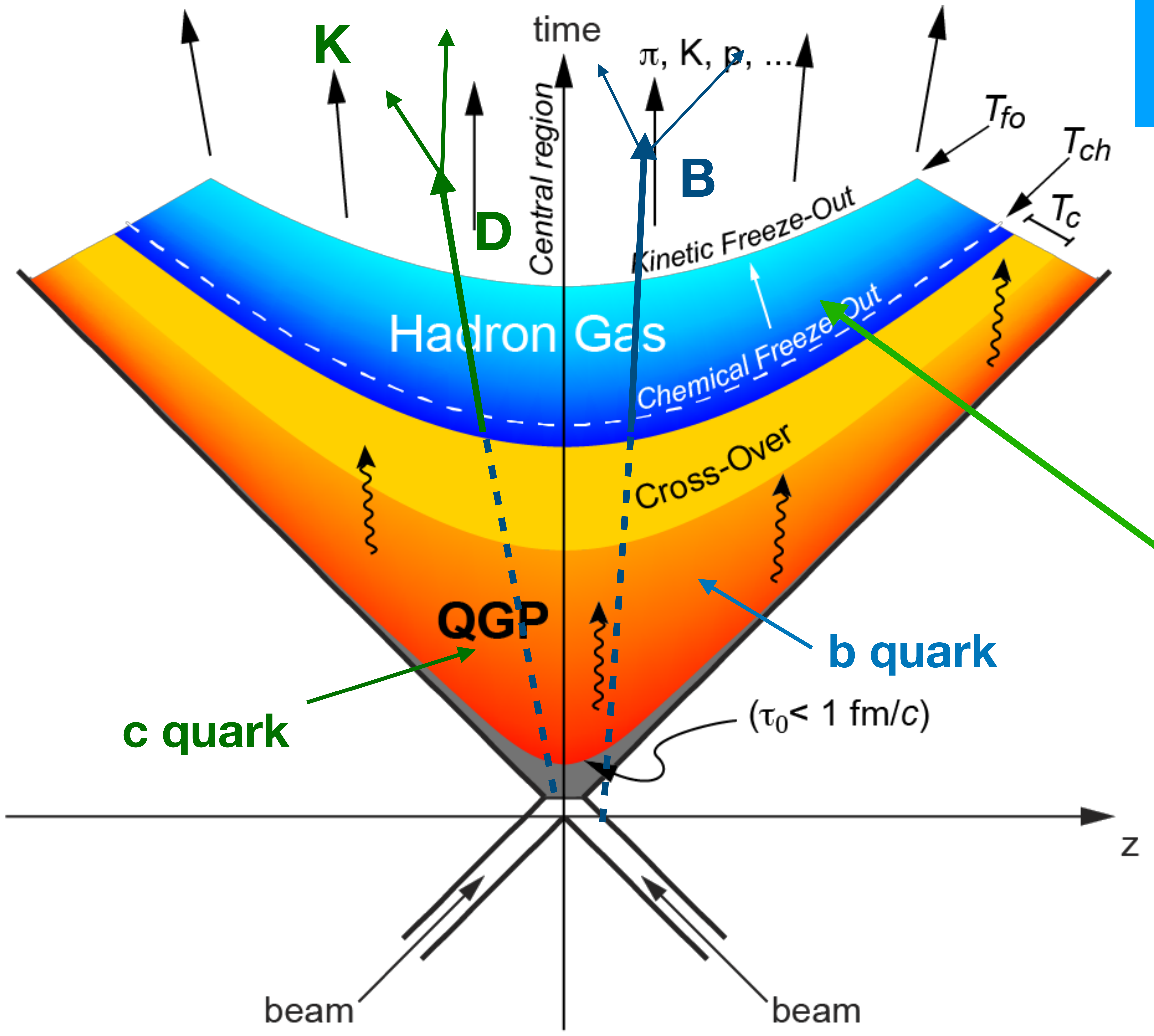
[1] EPJC 75 (2015) 121
[2] arXiv:1810.08177; Phys. Rev. C 98, 064901 (2018)
[3] Phys. Rev. C 96, 064903 (2017)

D-meson v_2 sensitive to event shape selection confirming a correlation with the collective expansion of the bulk matter

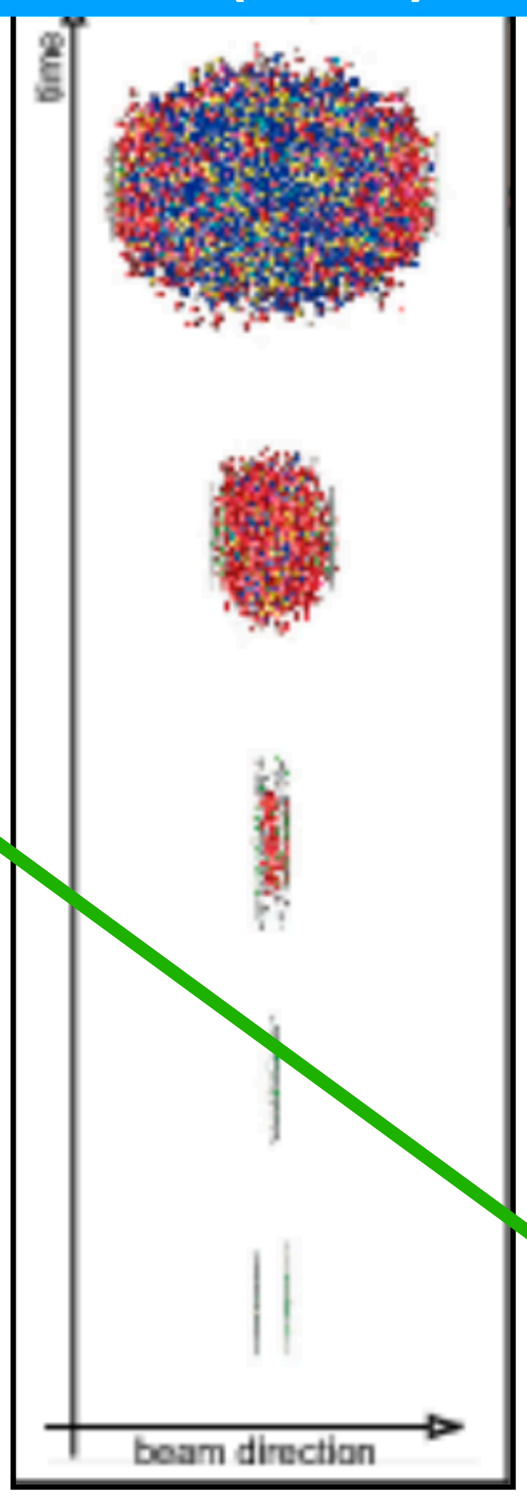
Models with different transport parameters (ex. POWLANG HTL and lQCD) describe large-q_2/unbiased in similar way:
- v_2 sensitive to initial condition or to underlying bulk processes?

Talk: S. Jaelani

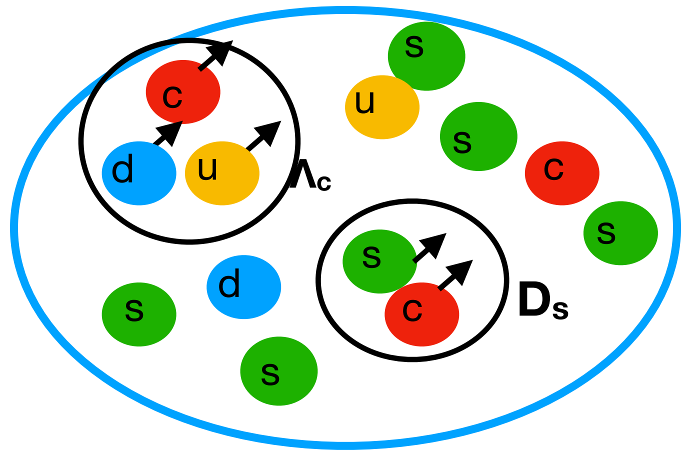
Space-time evolution



Hadronization in F. Prino review (Wed)



What are the hadronization mechanisms:
fragmentation in vacuum?
recombination with thermal partons?

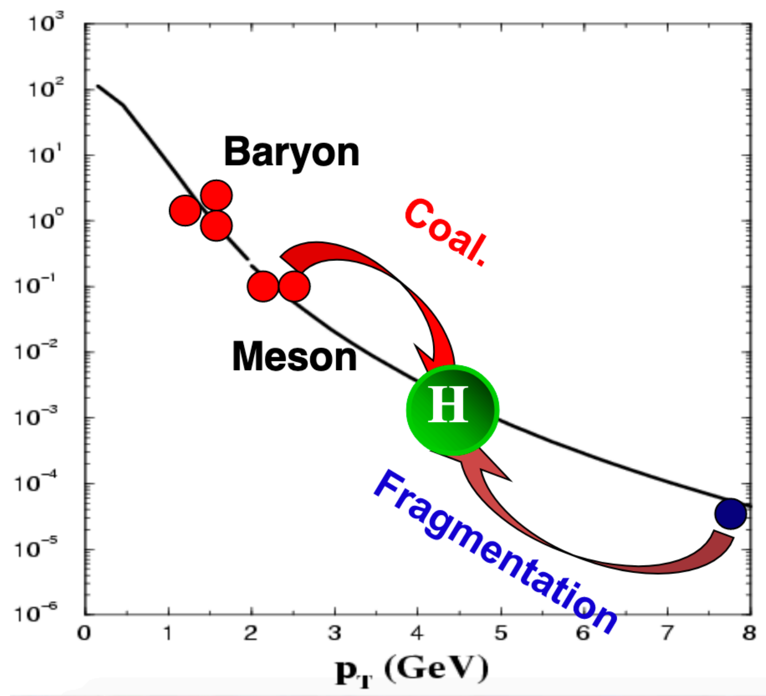


- **Recombination** at low-intermediate p_T of c and b with light quark in the medium

➡ **Baryon over meson enhancement**

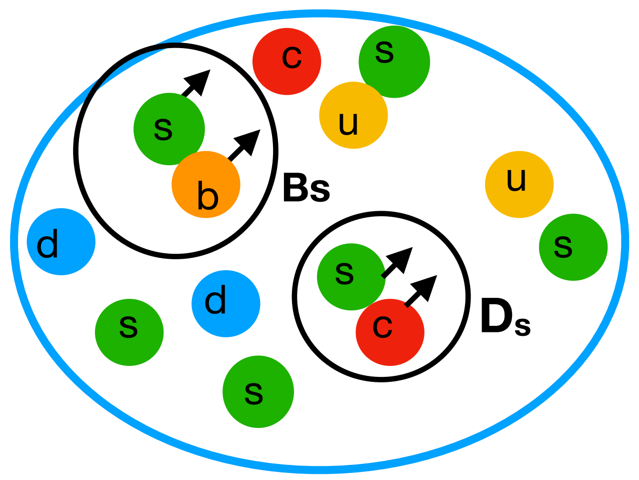
- \+ **Strangeness enhancement**

➡ **Strange/non-Strange heavy mesons enhancement**

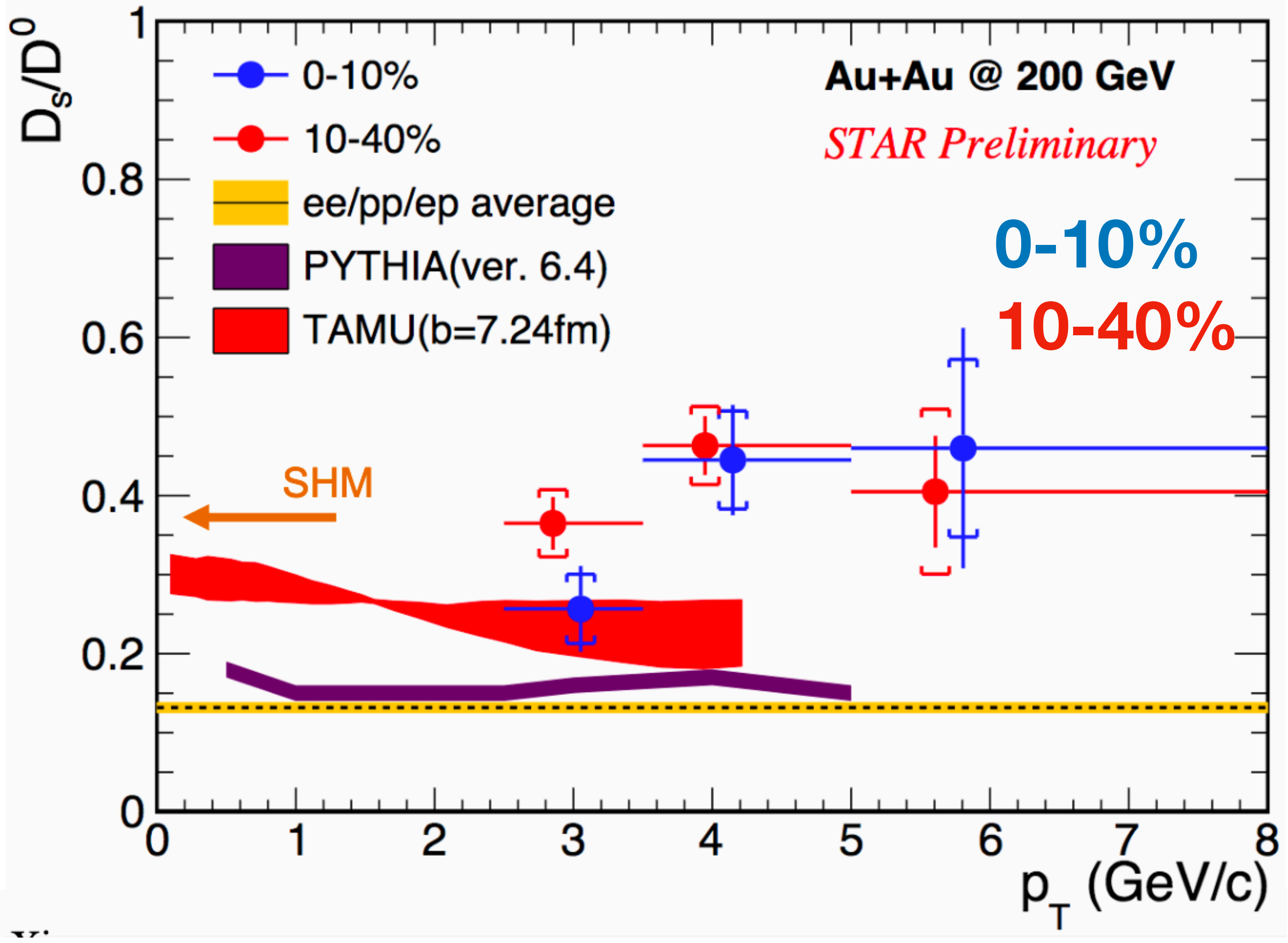


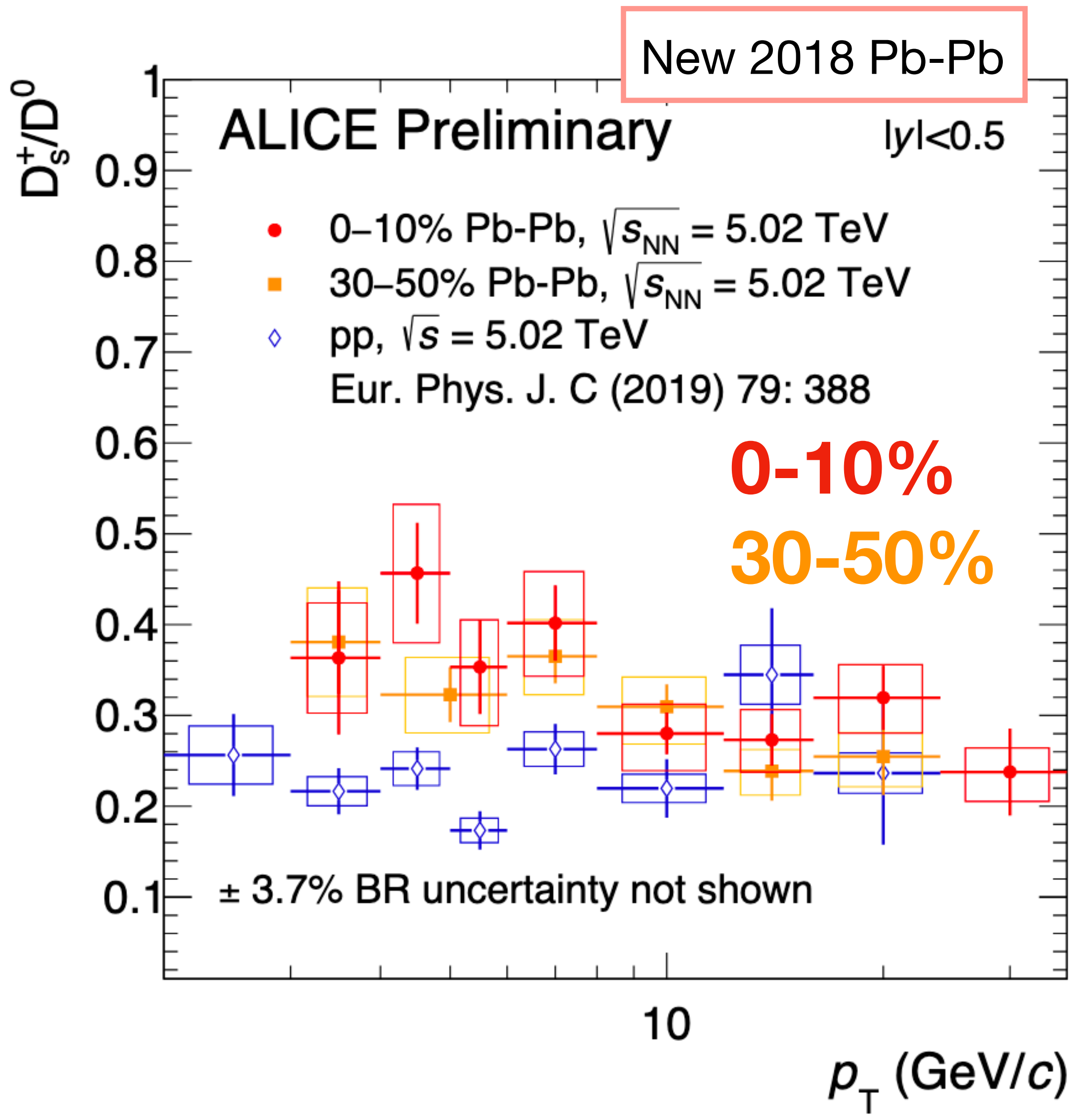
D_s and B_s

Hadronization in F. Prino review (Wed)



Recombination + **Strangeness enhancement** in the QGP
—> enhancement of strange heavy mesons in AA w.r.t. pp?

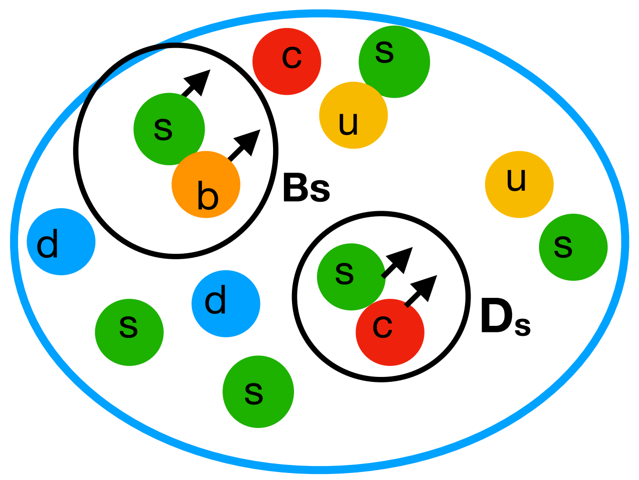




D_s/D^0 measured in Au-Au by STAR and in Pb-Pb by ALICE
- Compatible results at low-intermediate p_T: $D_s/D^0 \sim 0.4$
- No evident centrality dependence
- Hint of enhancement w.r.t pp measurements

Ds and Bs

Hadronization in F. Prino review (Wed)



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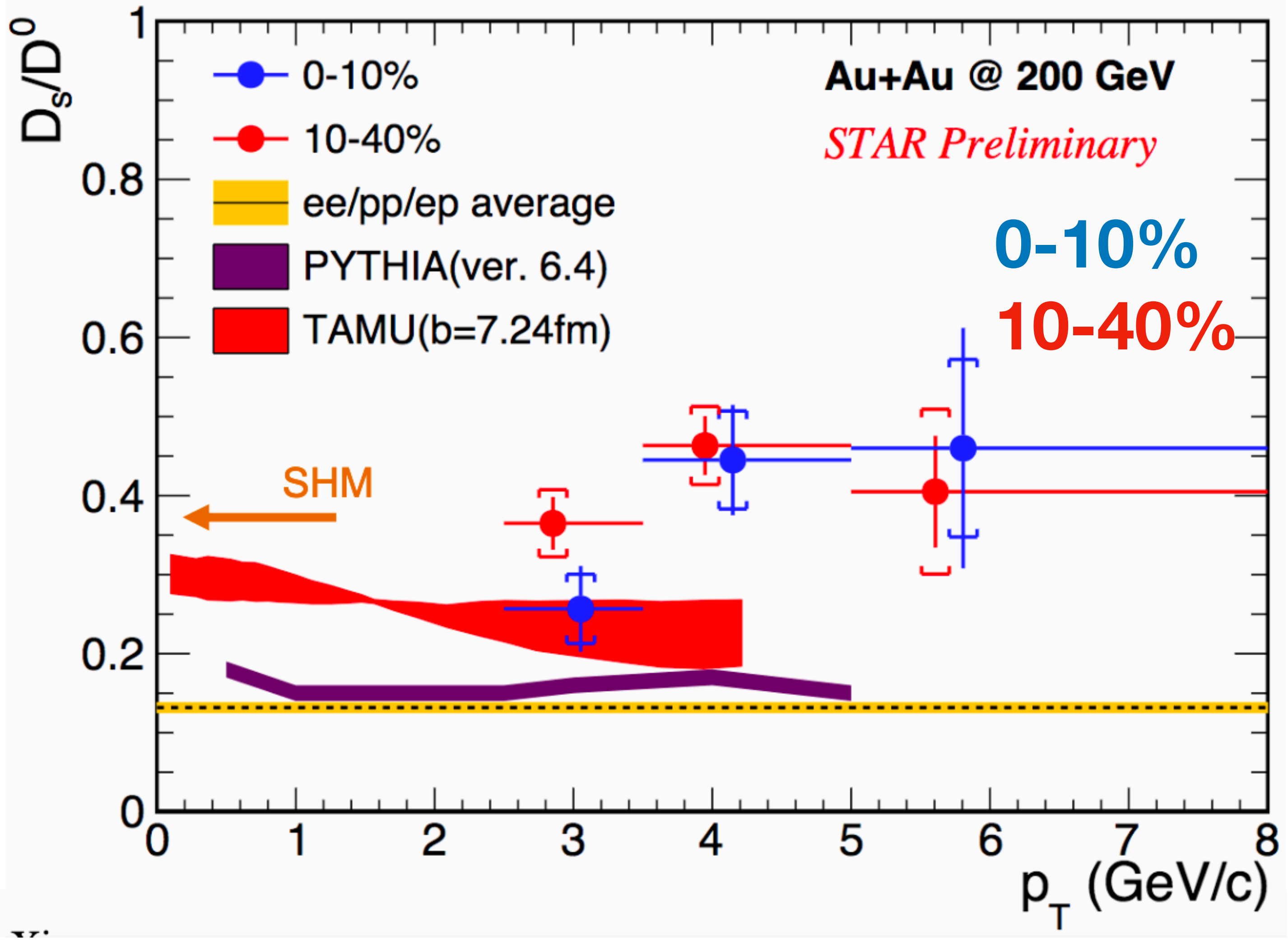

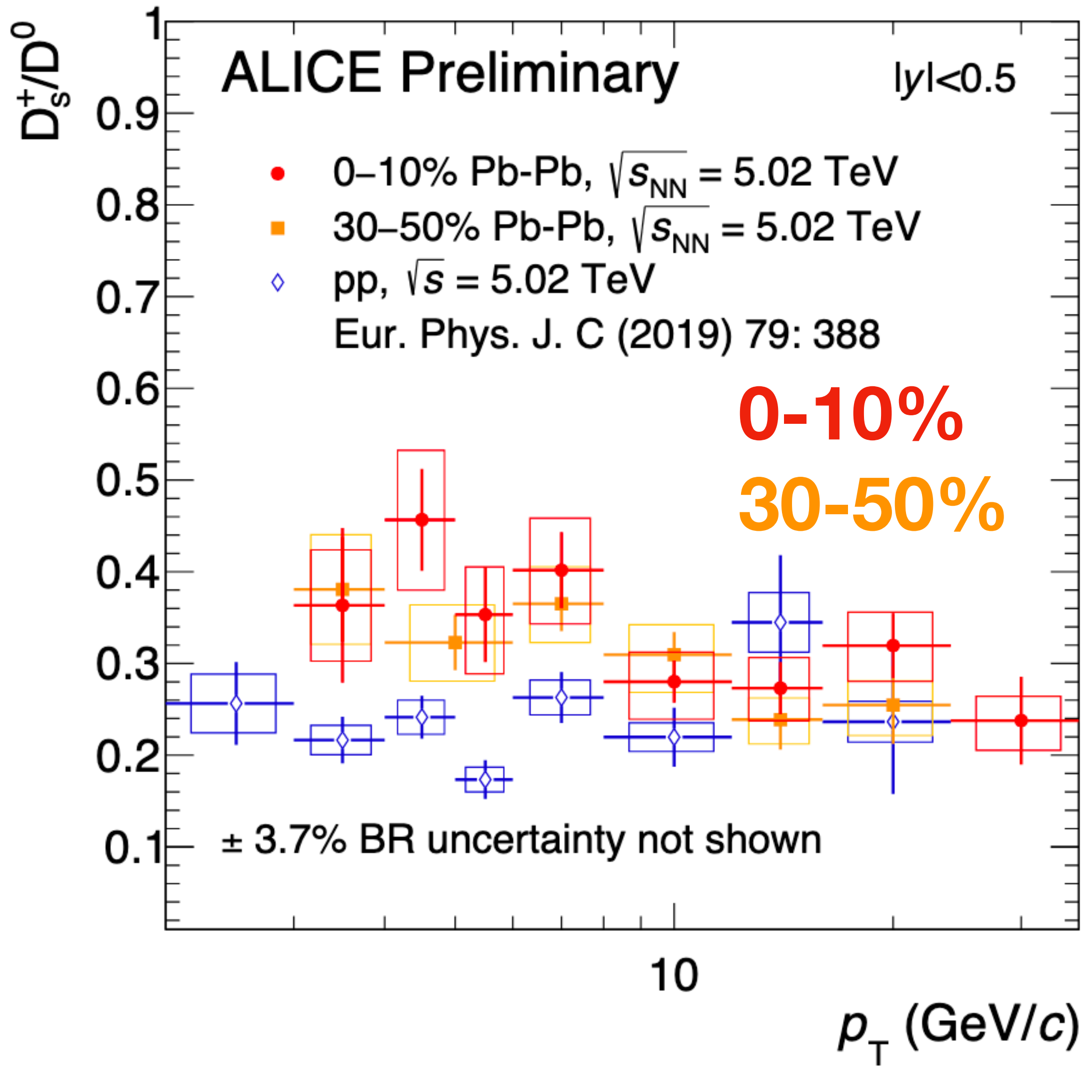

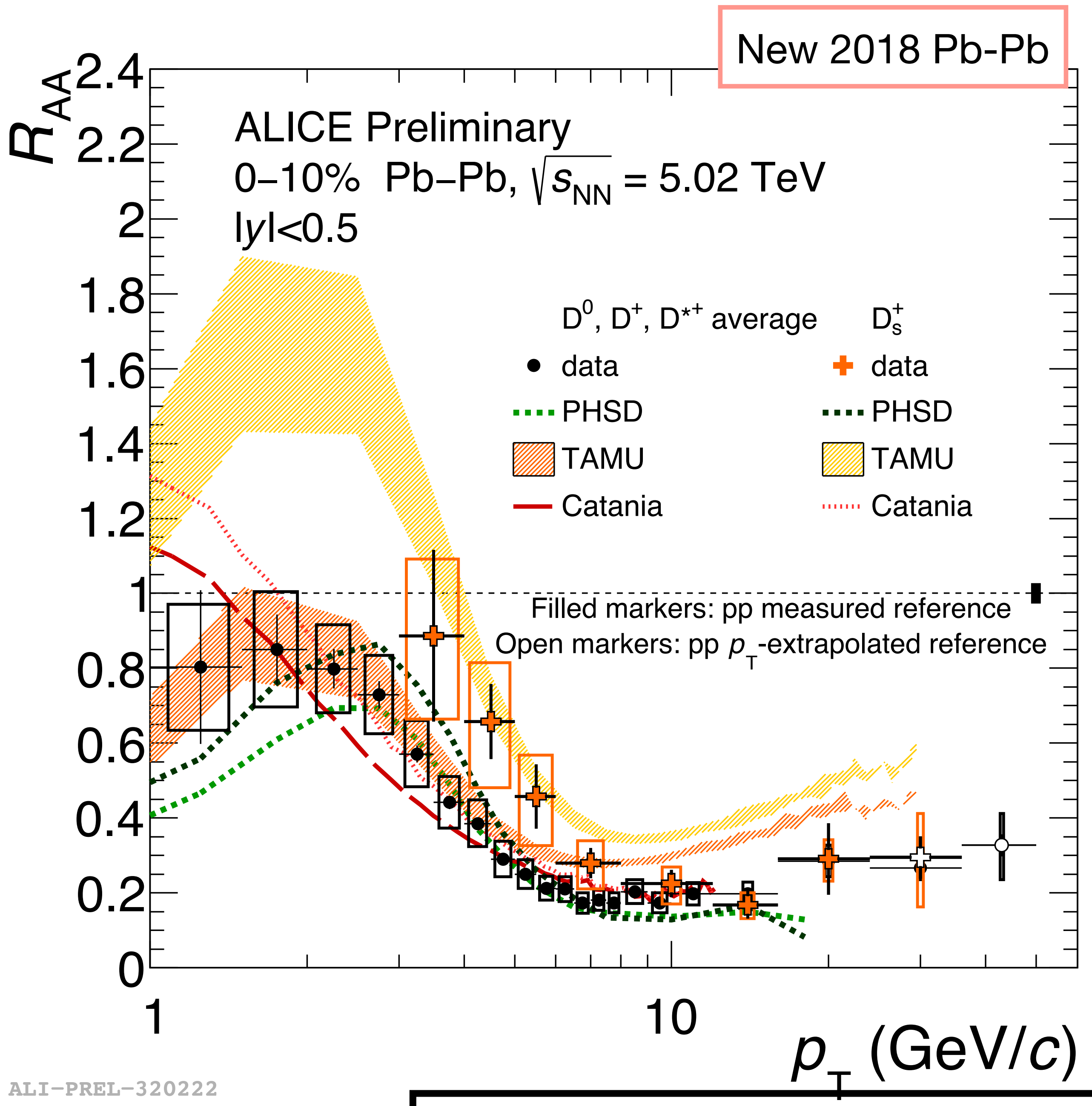

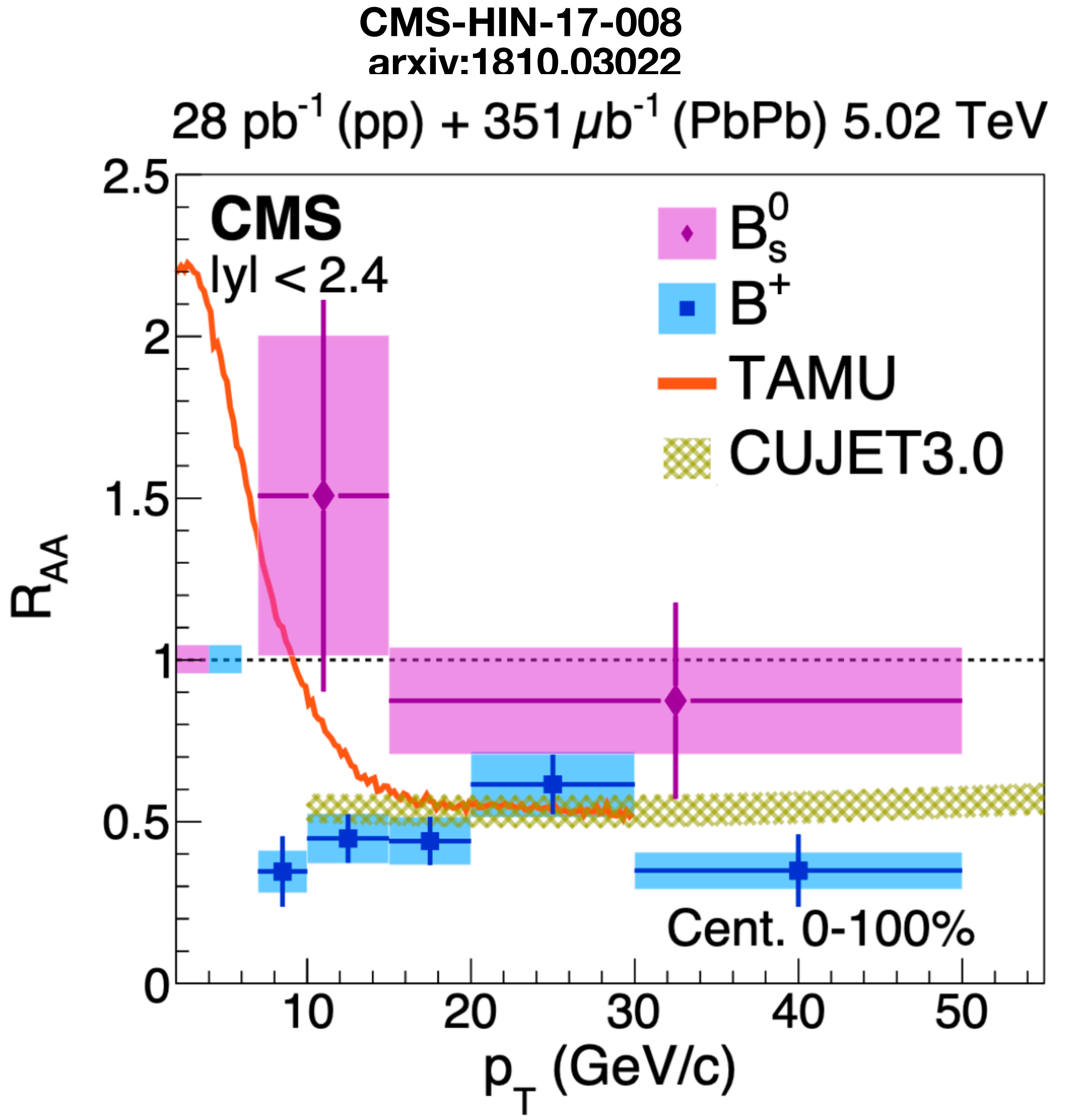

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- Compatible results at low-intermediate p_T: $D_s/D^0 \sim 0.4$
- No evident centrality dependence
- Hint of enhancement w.r.t pp measurements

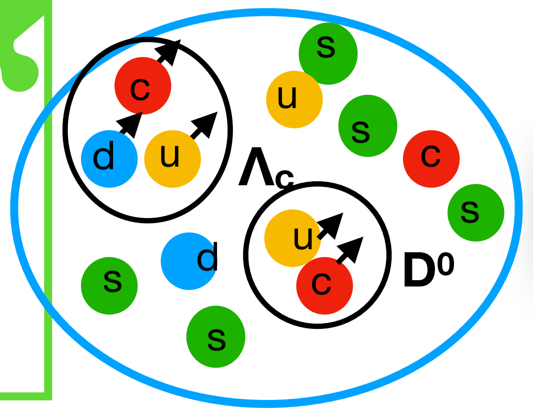
Small differences in mass: splitting in their R_{AA} due to collective flow would be a small effect —> other causes: recombination?
Hint of $R_{AA}(D_s) > R_{AA}(D)$ and $R_{AA}(B_s) > R_{AA}(B)$

Talks:
Wang
Zampolli
C.Peng

Promising measurements with higher statistics!

Charmed baryon: Λ_c/D^0

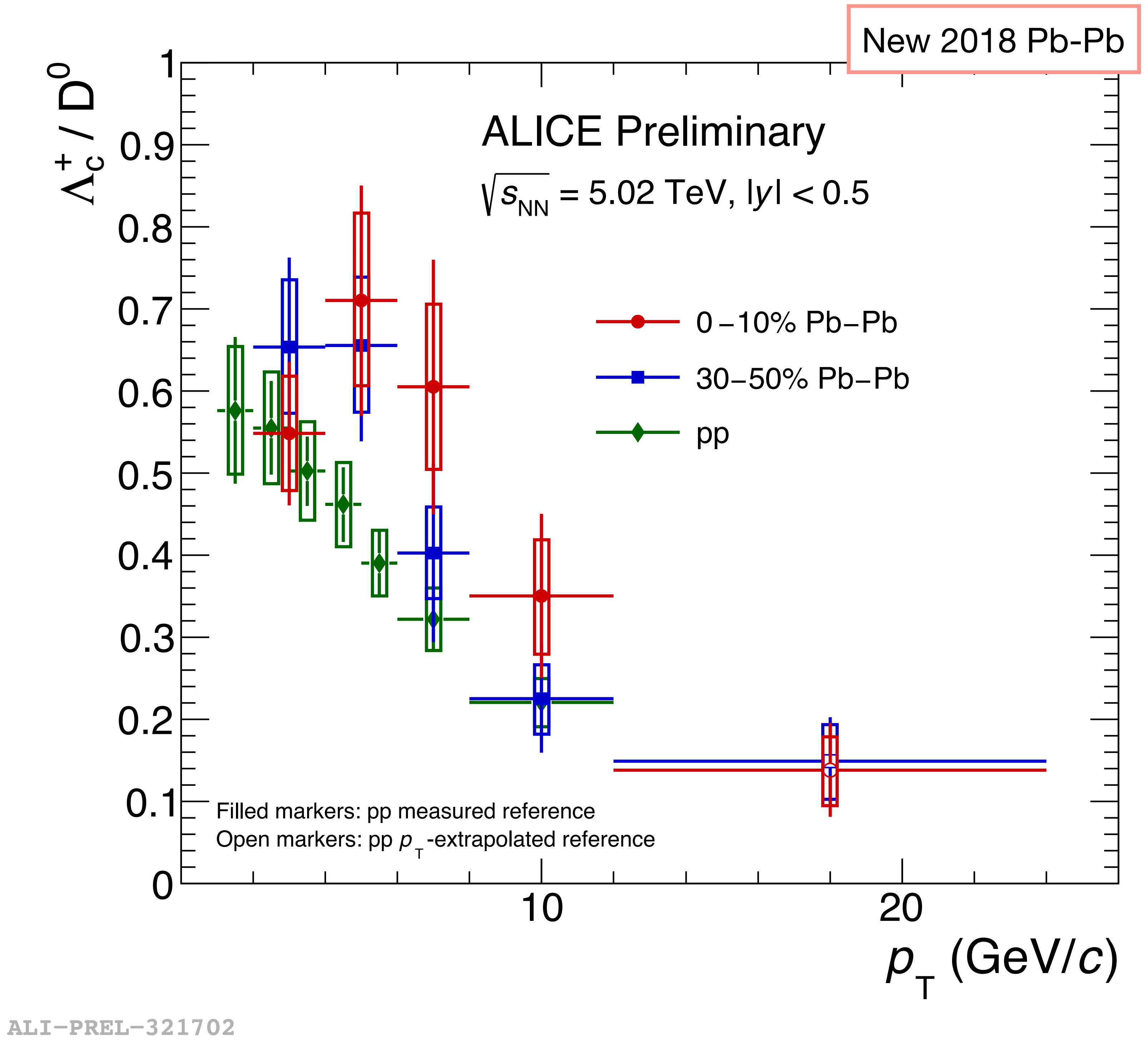
Further Investigation: Charmed baryon hadronization



If recombination is effective: Λ_c/D^0 enhanced in AA relative to pp

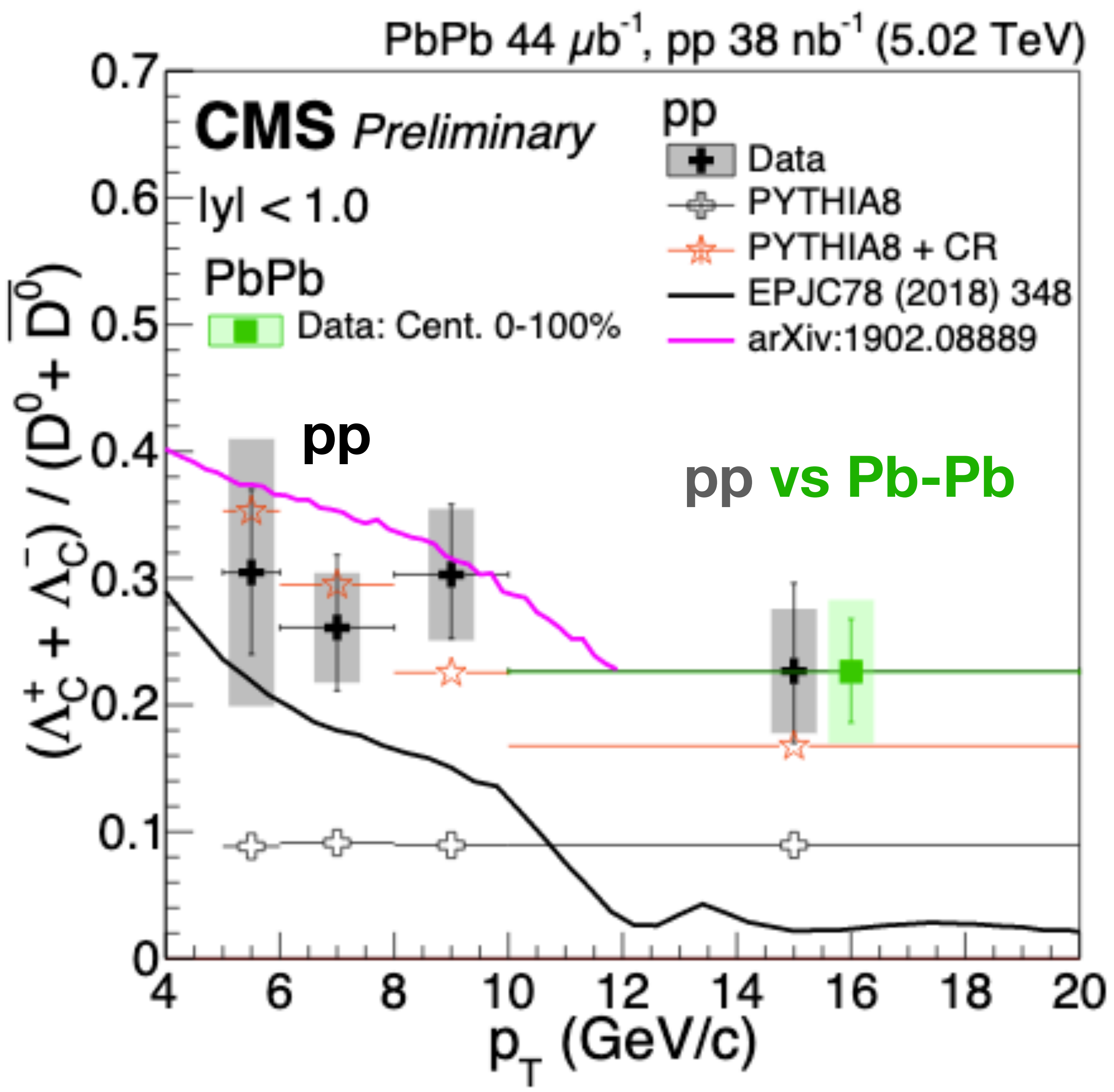
Hadronization in F. Prino review (Wed)

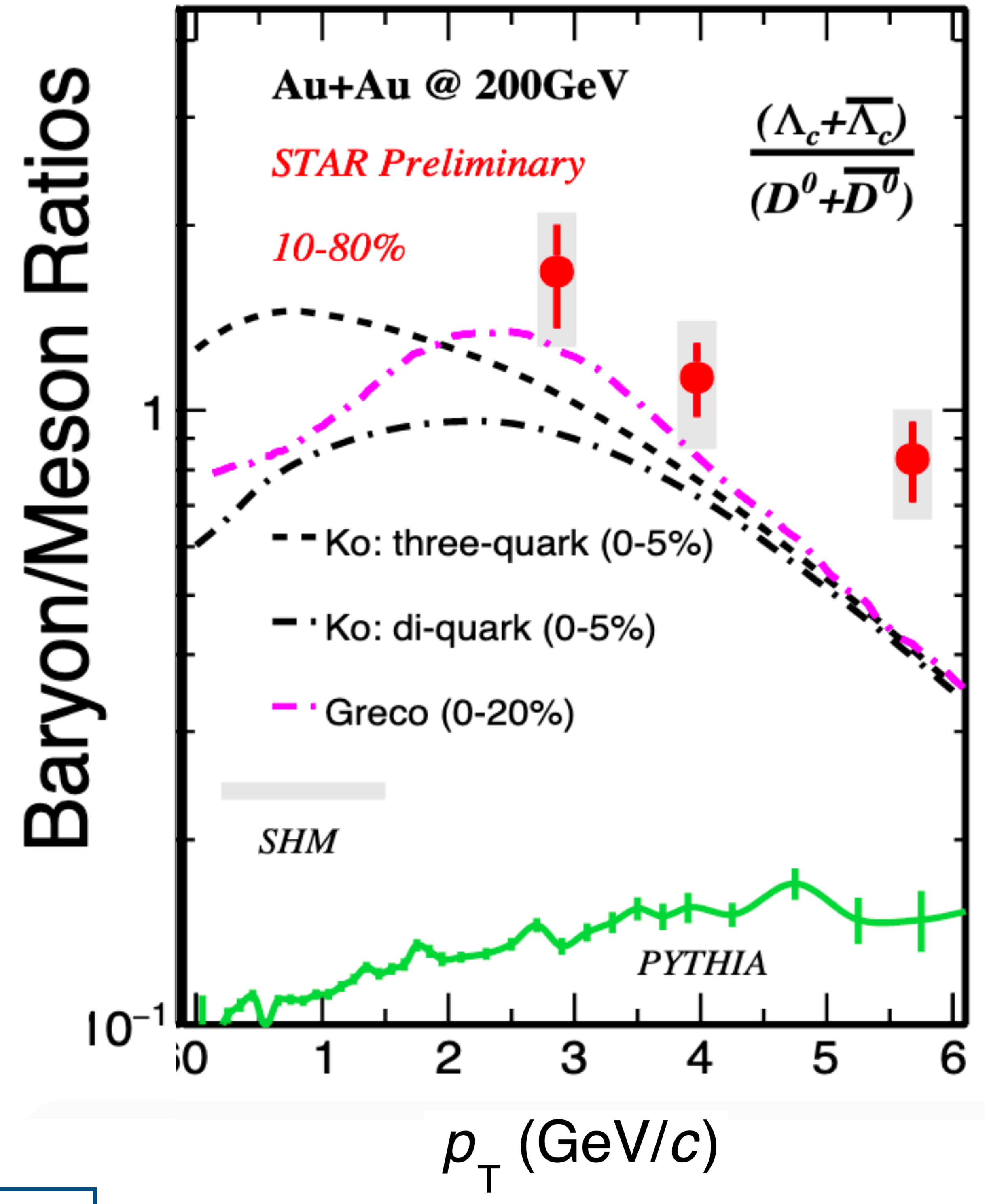
New 2018 Pb-Pb



arXiv:1906.03322

New





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- **CMS: similar Λ_c/D^0 in Pb-Pb** and **pp at high p_T**
- **CMS** and **ALICE** agreement in pp and Pb-Pb (slightly different p_T and centrality ranges)

STAR shows higher value for Λ_c/D^0 ~1 in Au-Au at low p_T (3-6 GeV/c)

Talks:
C. Zampolli
J. Vaněk
R. Xiao

Charmed baryon: Λ_c/D^0

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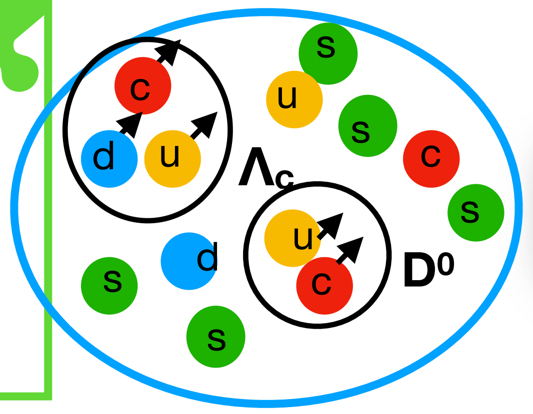

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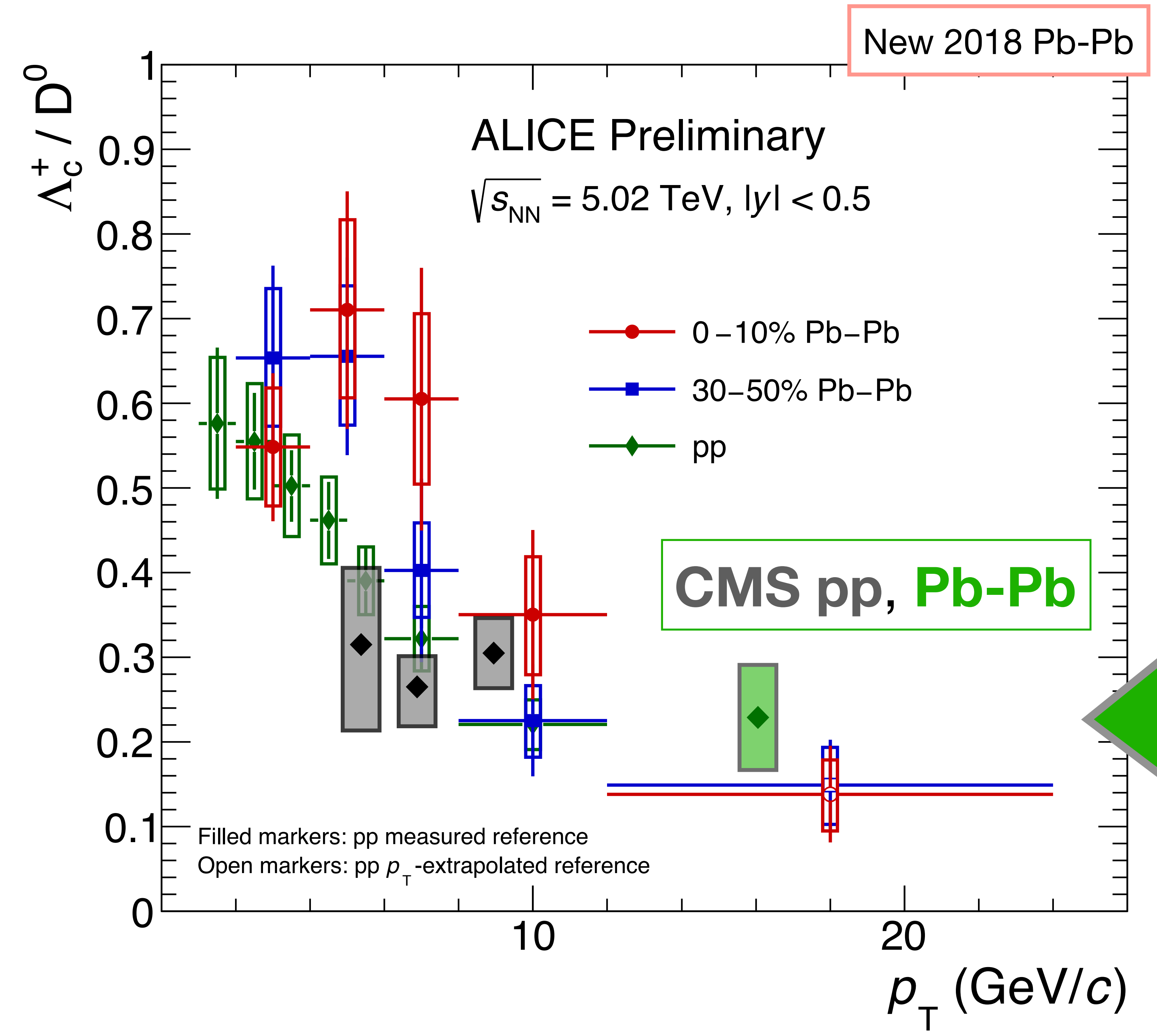
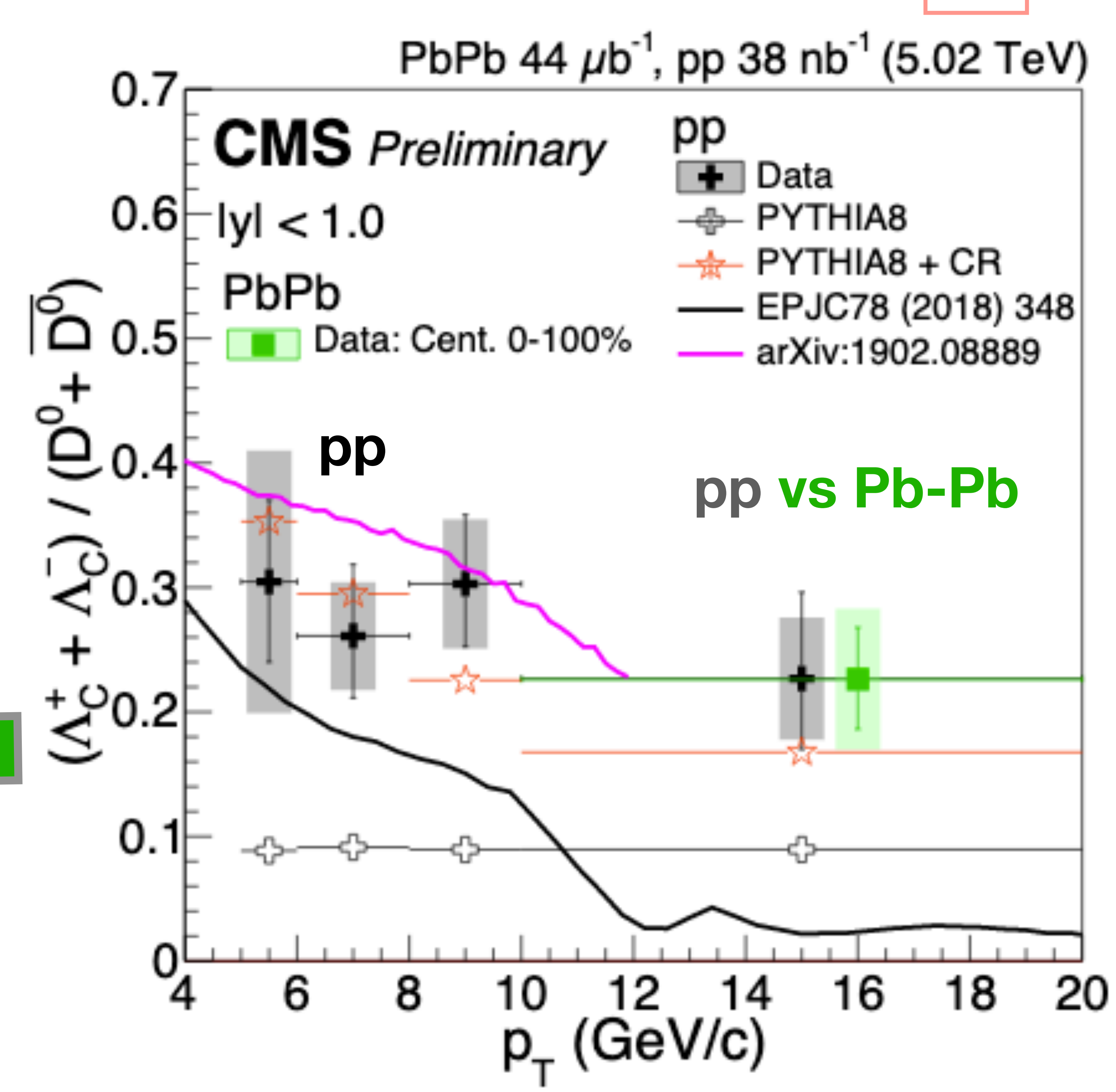
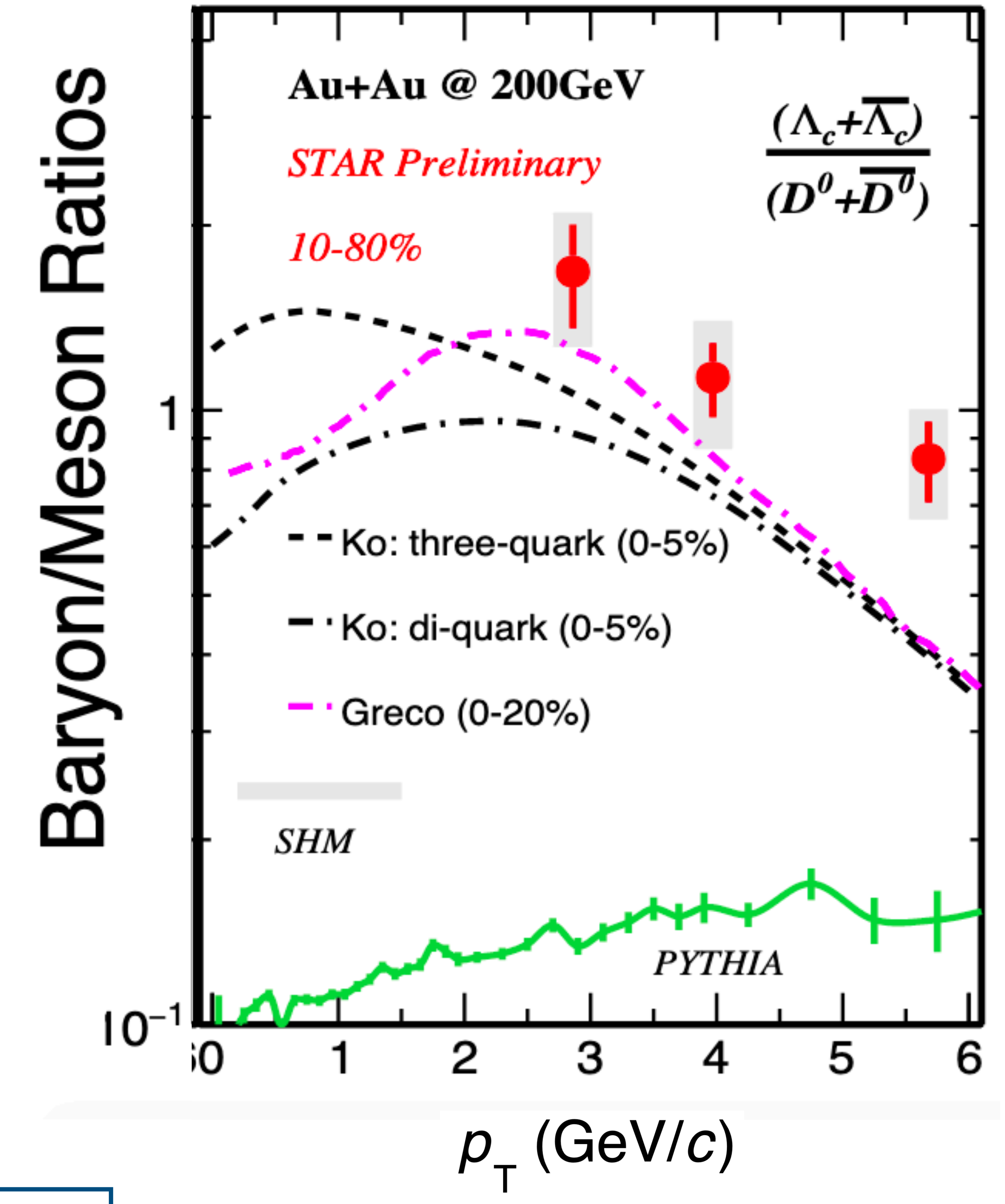
Hadronization in F. Prino review (Wed)



arXiv:1906.03322 New





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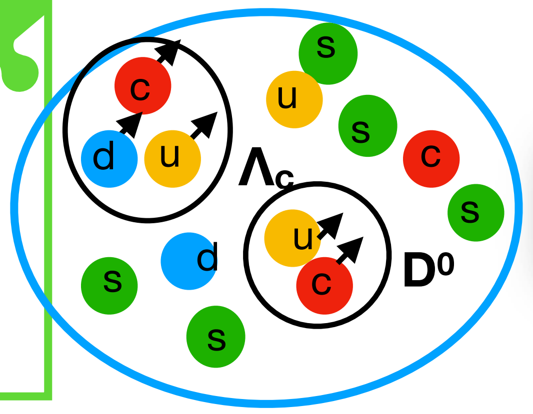
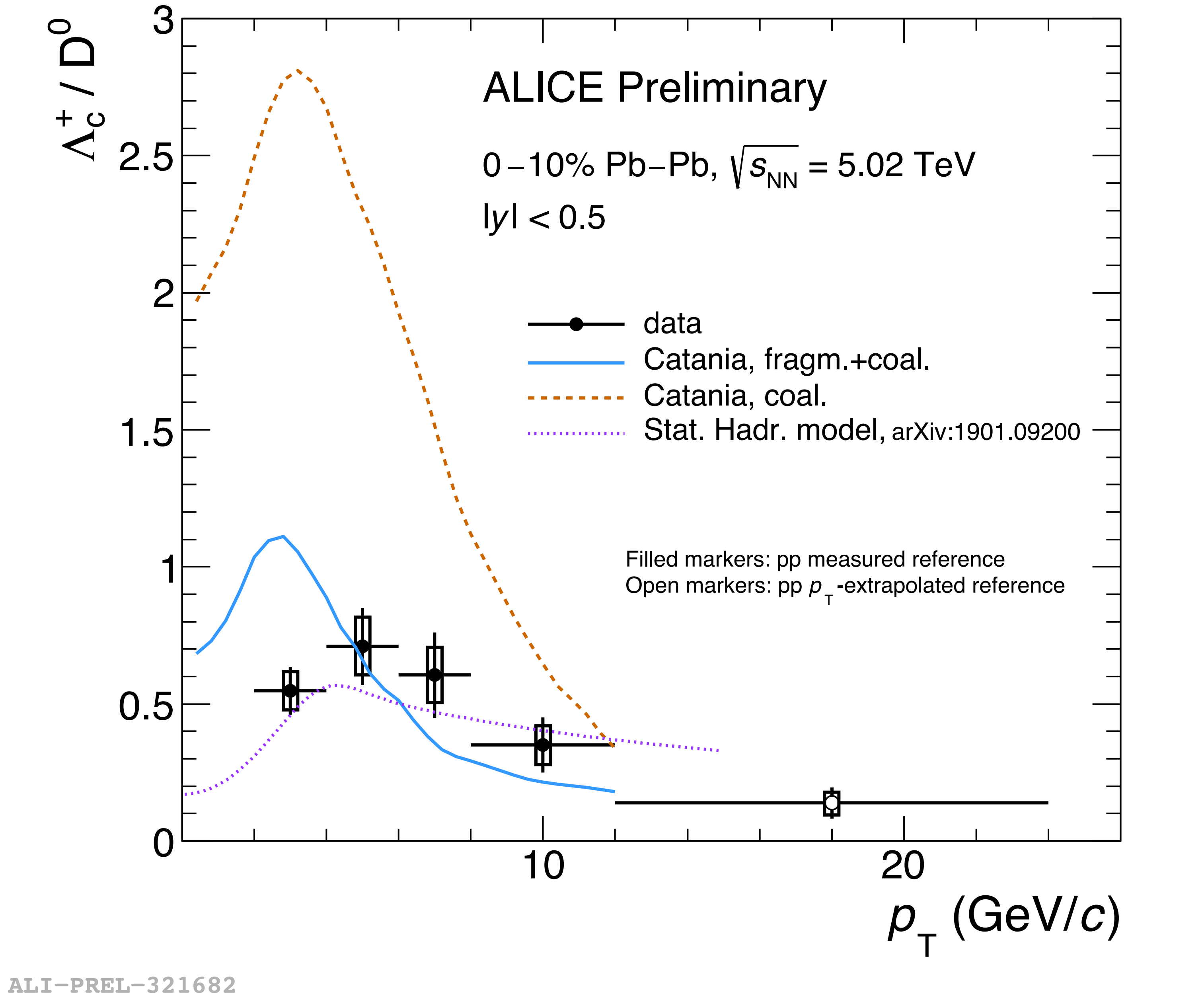


If recombination is effective: Λ_c/D^0 enhanced in AA relative to pp

Hadronization in F. Prino review (Wed)

New 2018 Pb-Pb



arXiv:1906.03322

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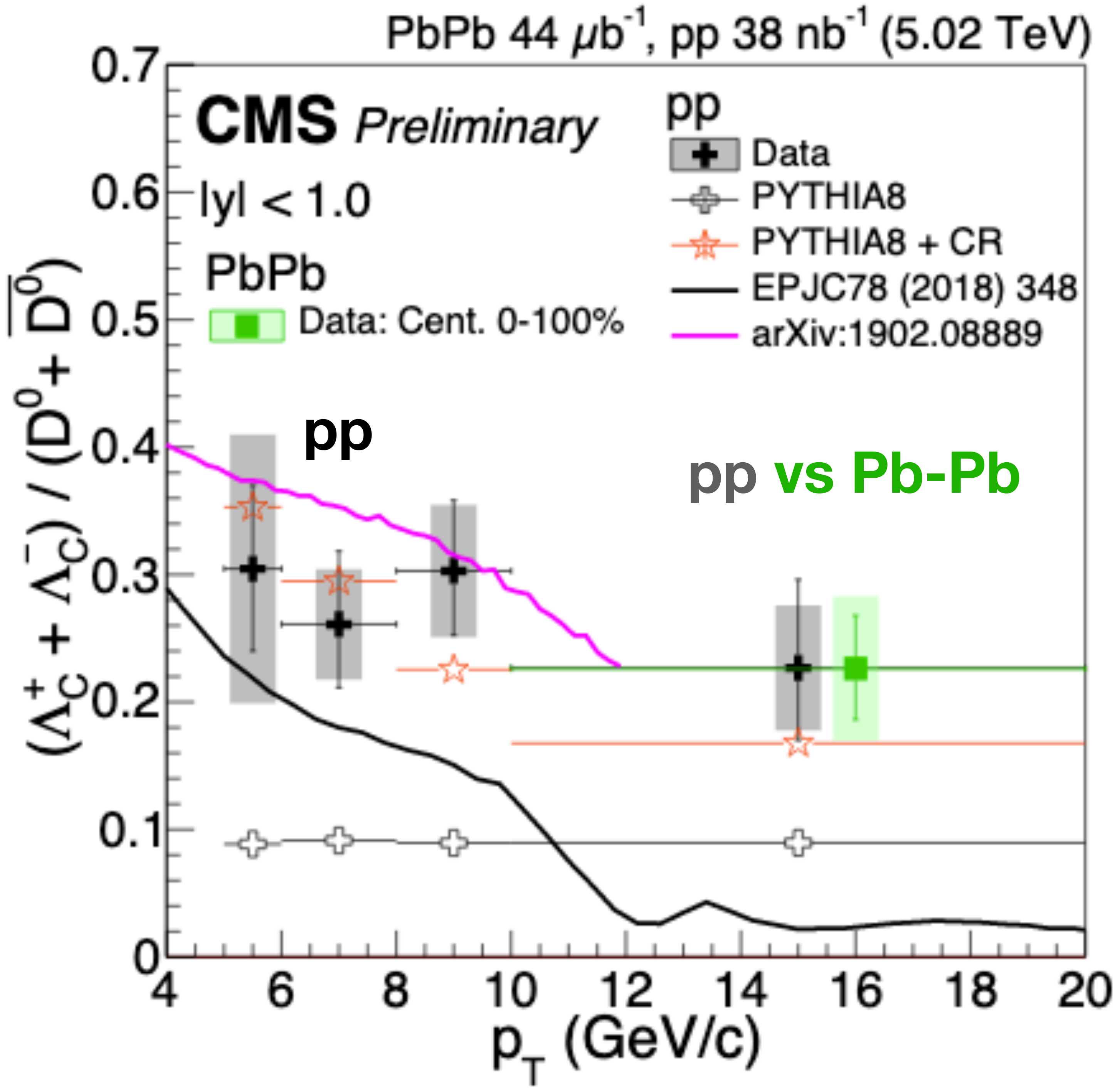

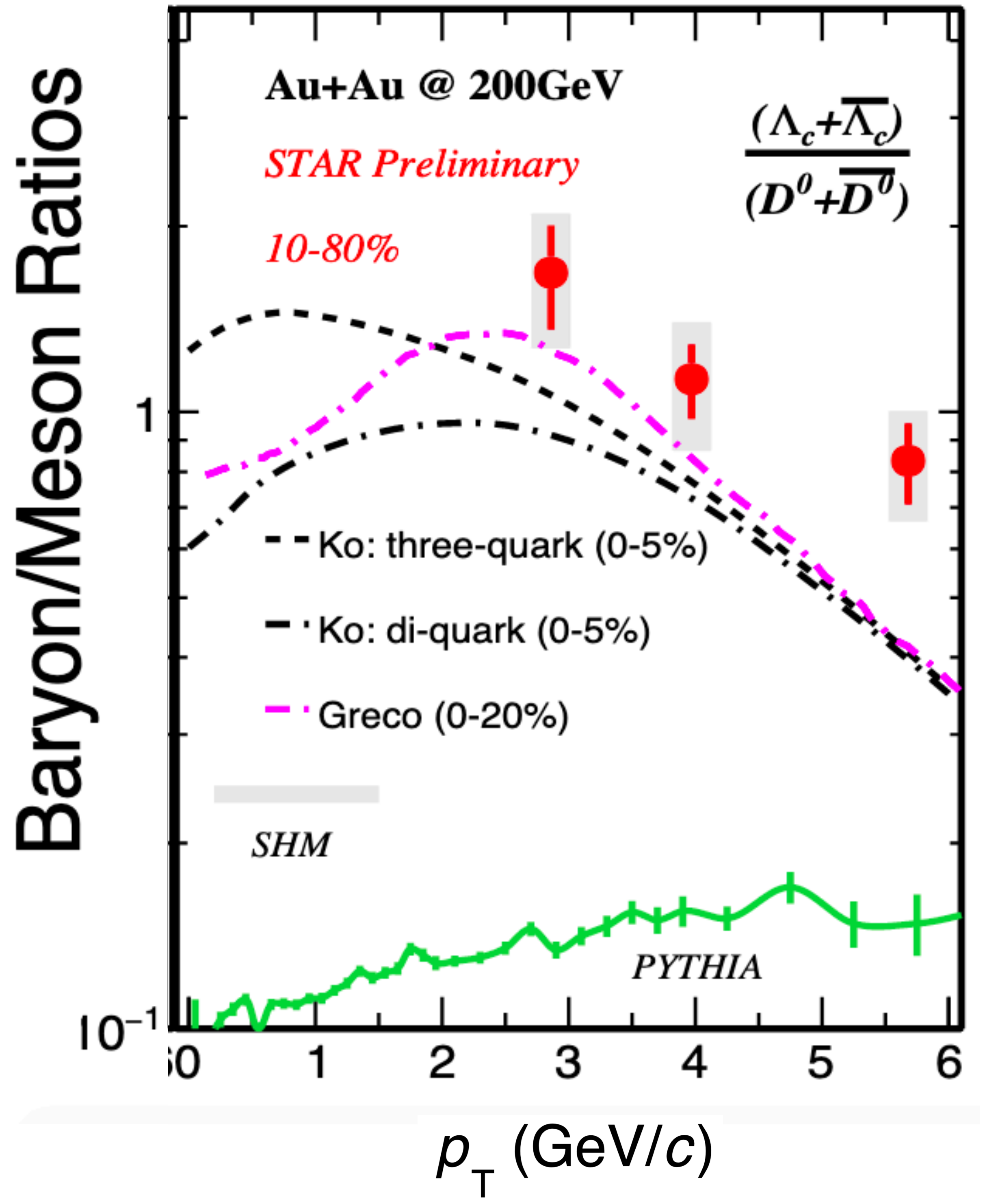

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STAR shows higher value for Λ_c/D^0 ~1 in Au-Au at low p_T (3-6 GeV/c)

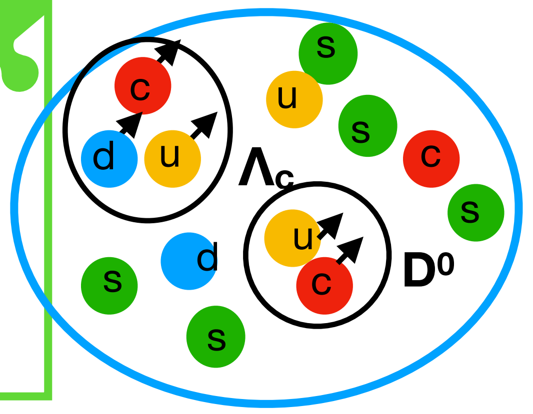
Λ_c/D^0 in Pb-Pb consistent with charm quark hadronization via coalescence and with Stat. Hadr. Model

Talks: S. Plumari

How do we interpret higher Λ_c/D^0 ratio at RHIC than LHC? Smaller recombination probability due to different initial spectra shapes?

Charmed baryon nuclear modification factor: Λ_c

Further Investigation: Charmed baryon energy loss



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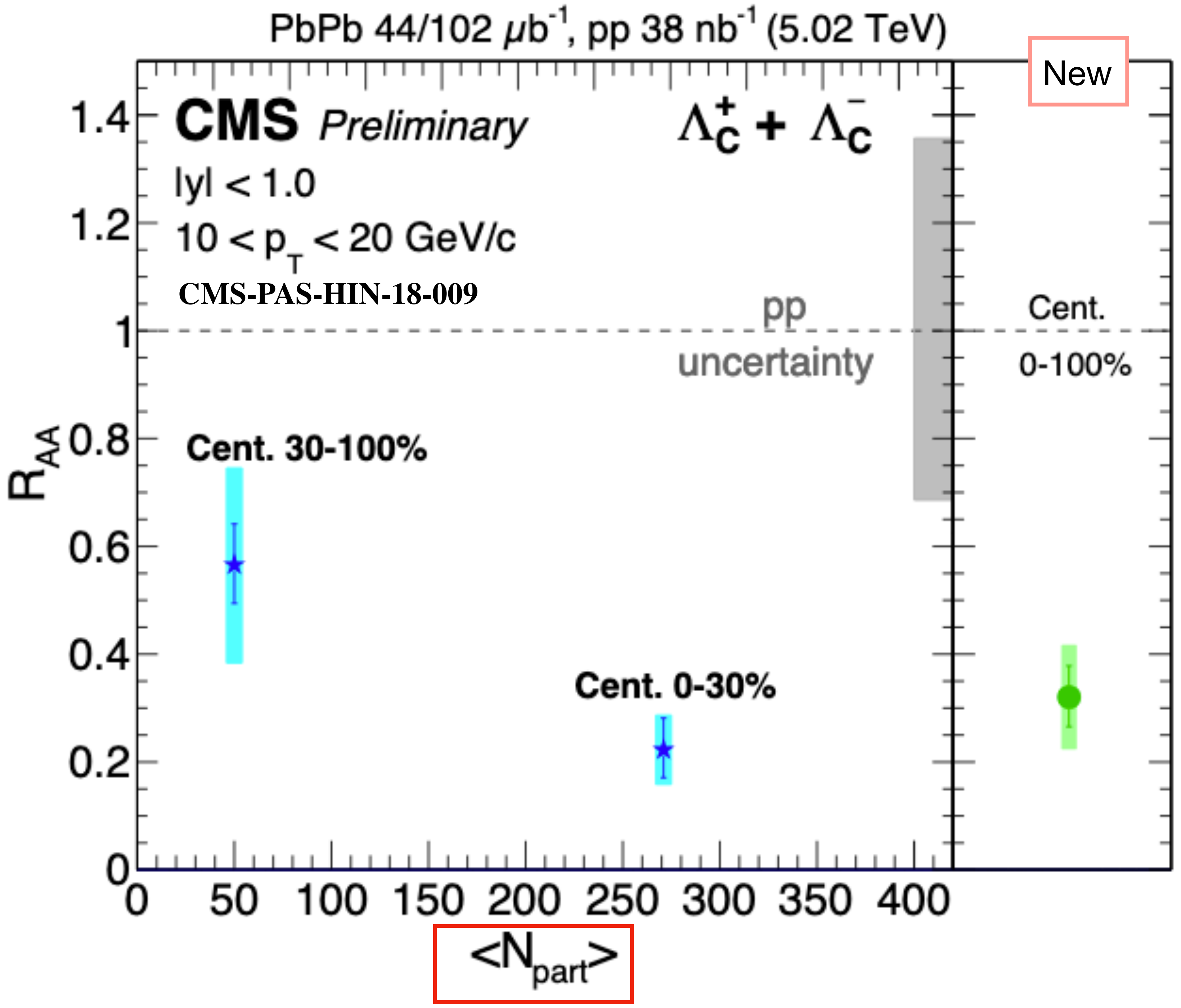
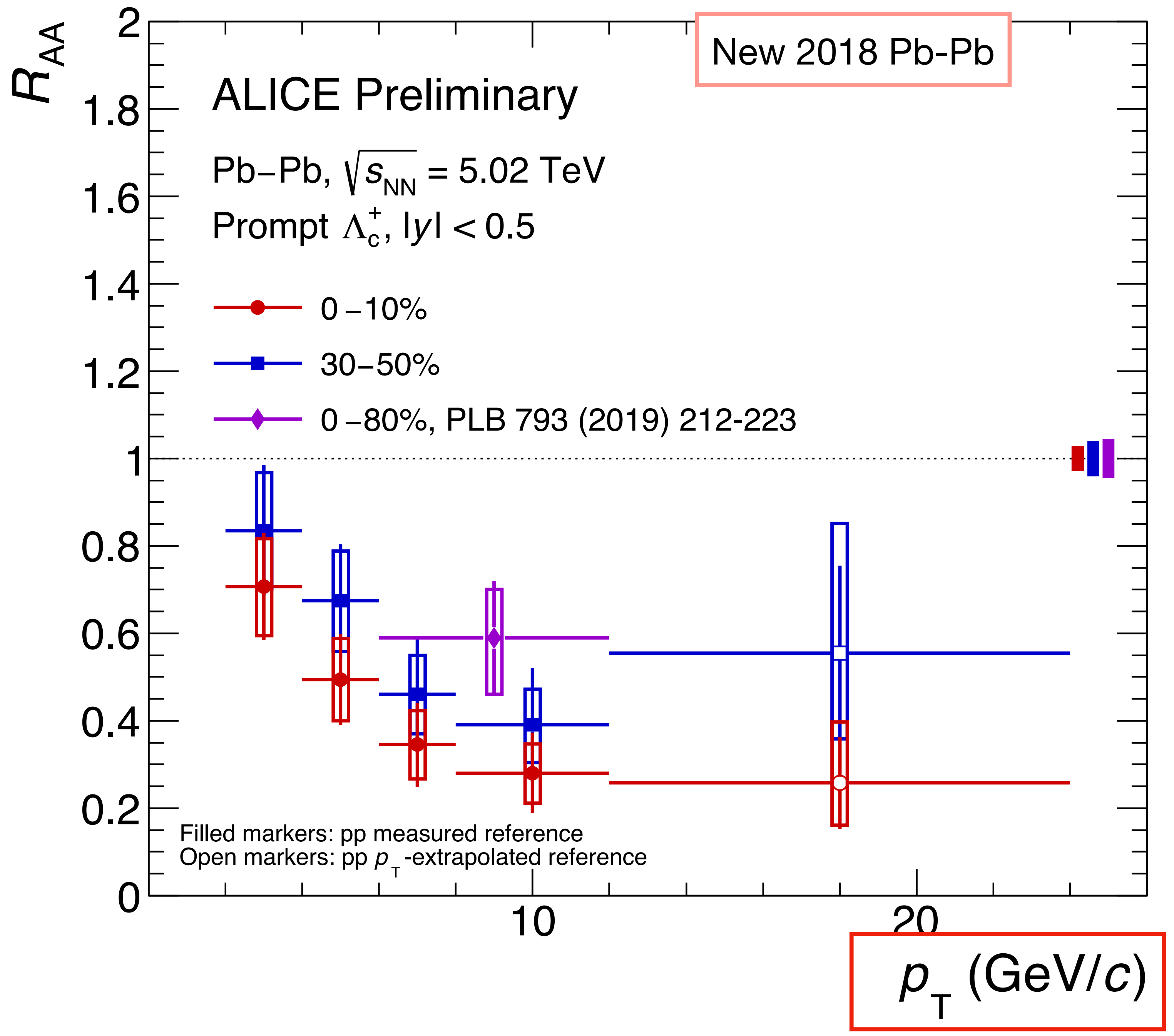




- Large Λ_c suppression observed up to a factor of 5 at high p_T both in ALICE and CMS
  - compatibility of CMS and ALICE results (slightly different p_T and centrality ranges)
- Hint of smaller R_{AA} in semicentral collisions

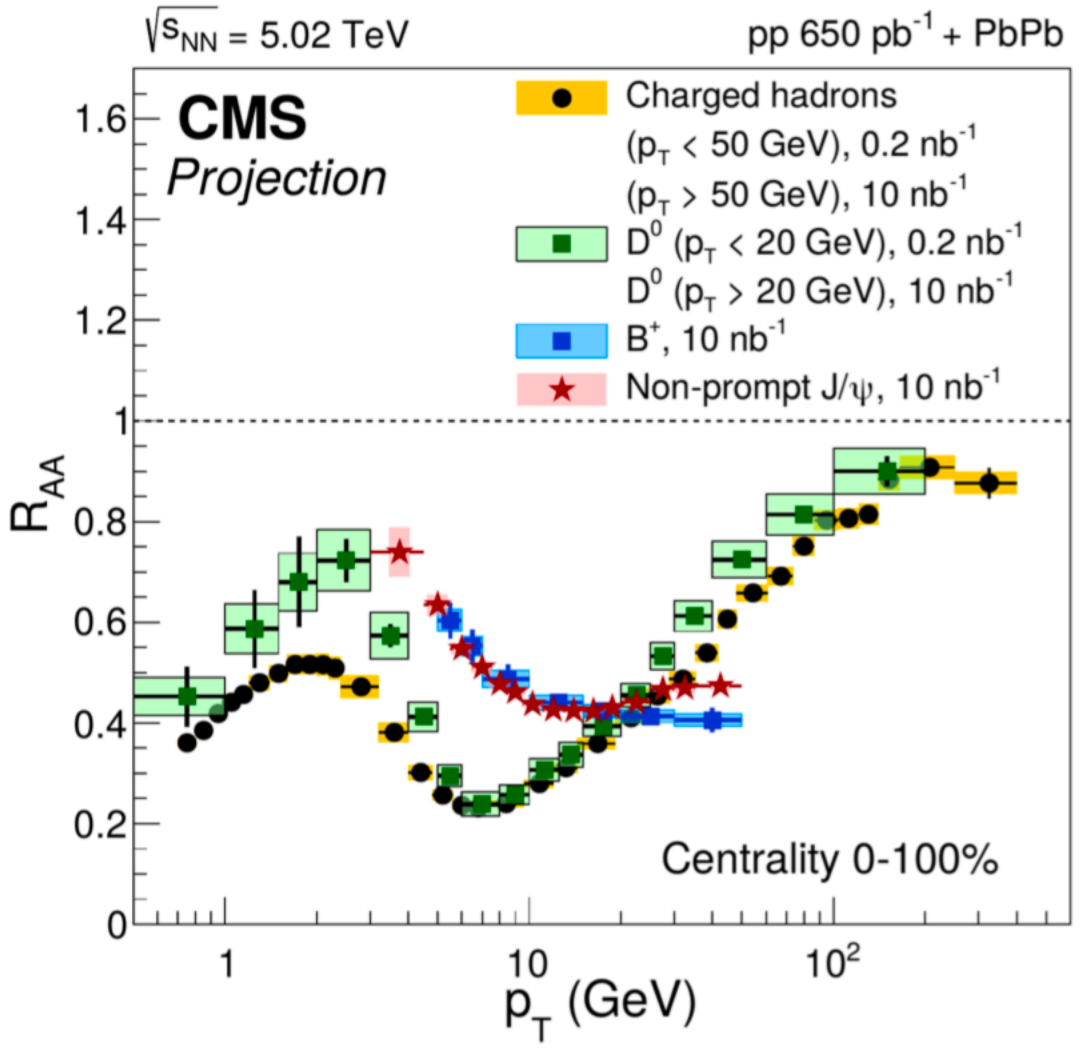
Future Physics Goals

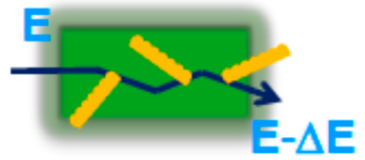
Talks:
L Musa
M. Weber

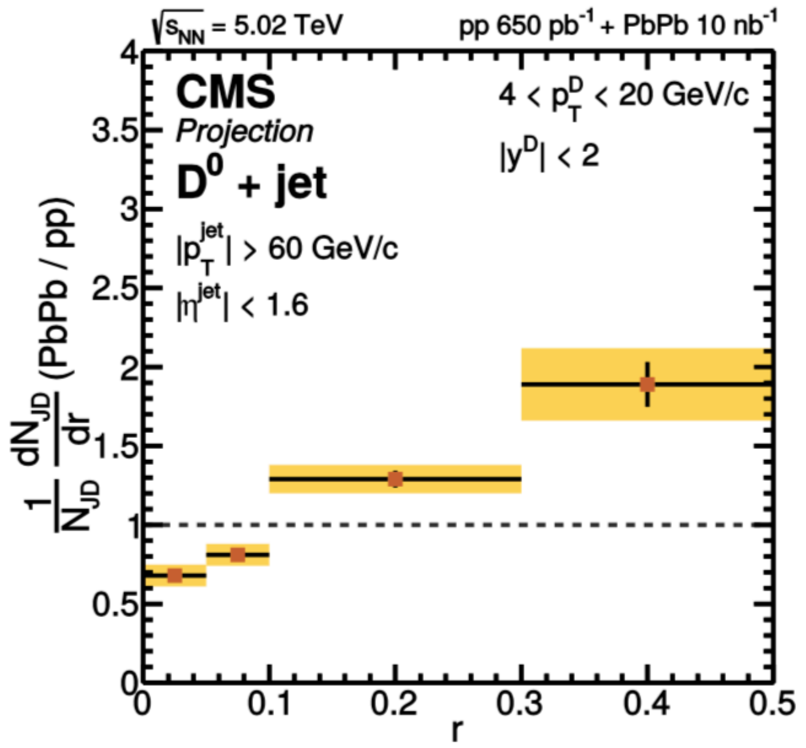
The improved measurements are expected to offer new constraints to models and help gain further insights into the hot and dense medium created

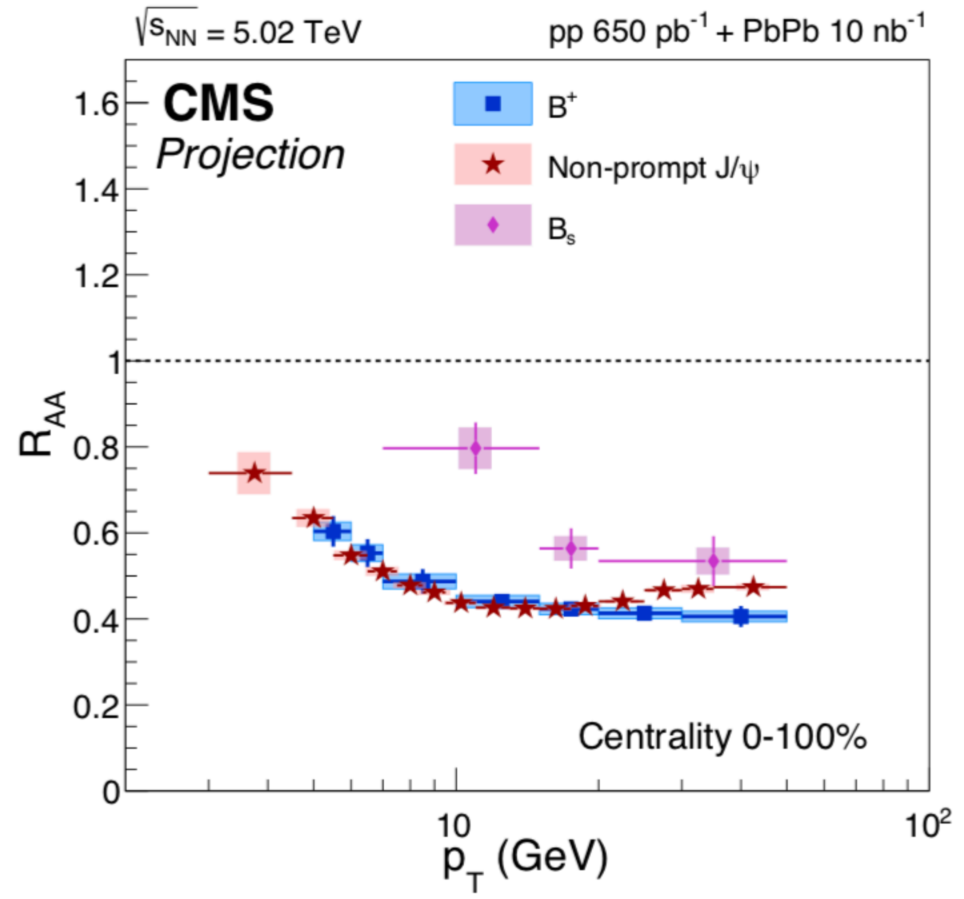
With the help of improved precision and statistics

Further insights into the energy loss mechanisms

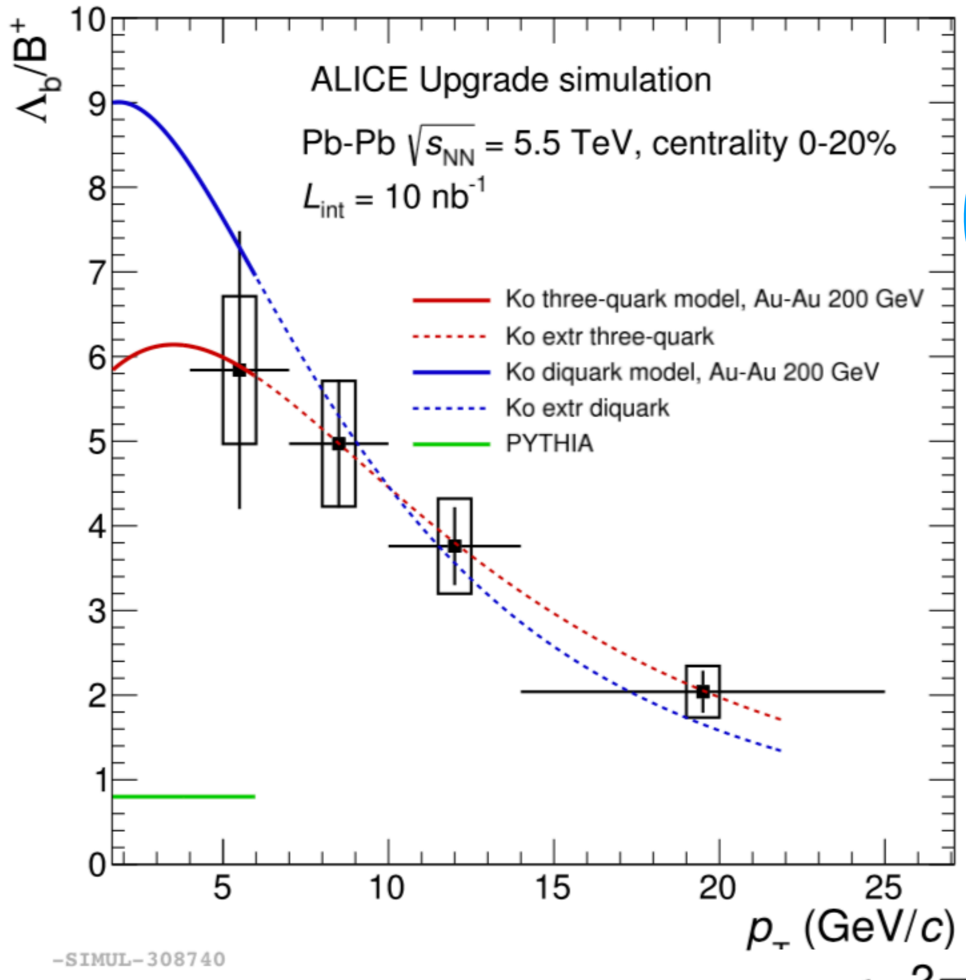


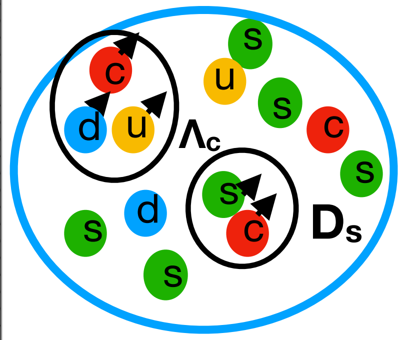




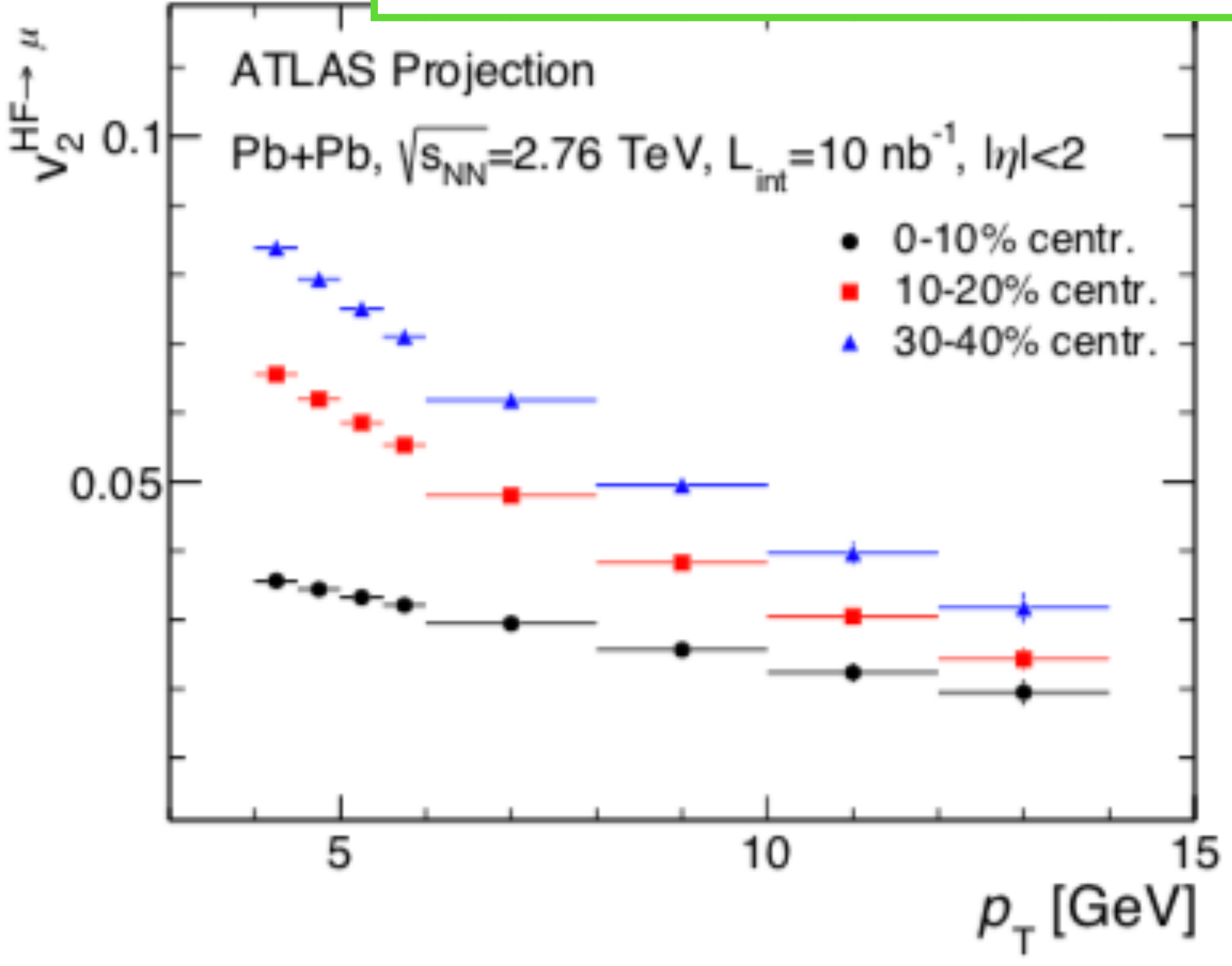


Role of recombination in hadronization?



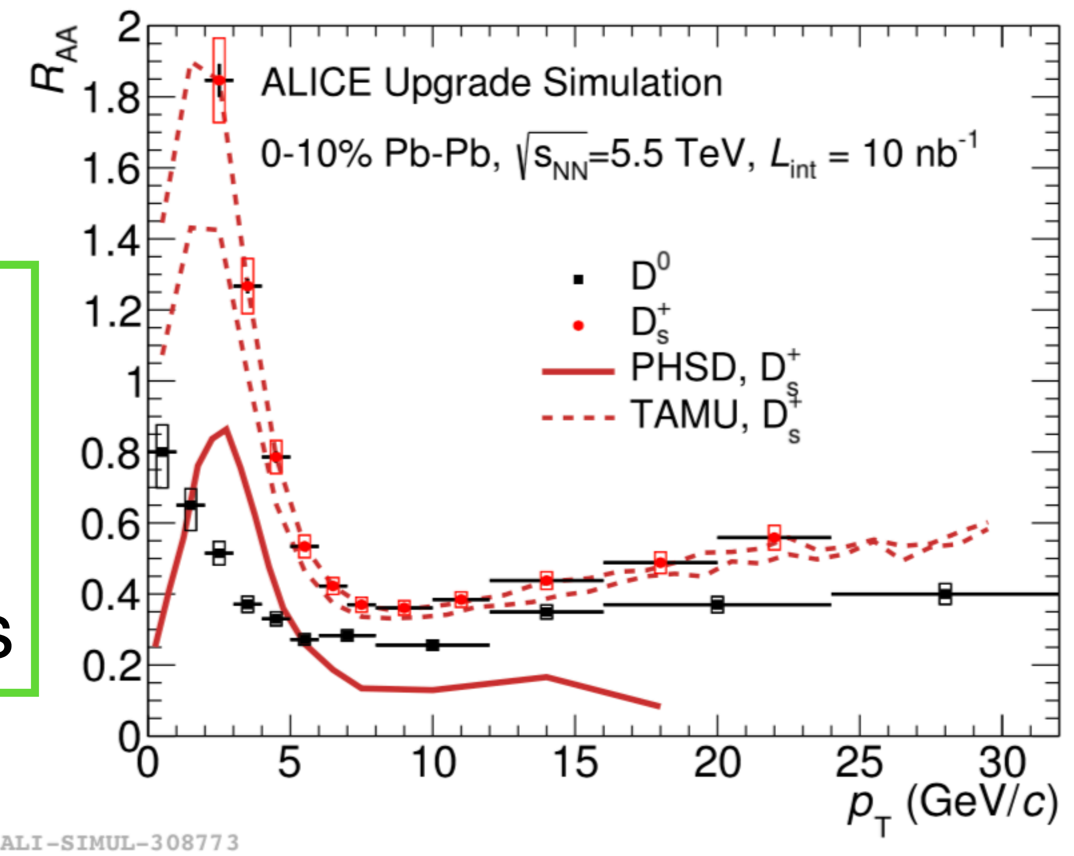


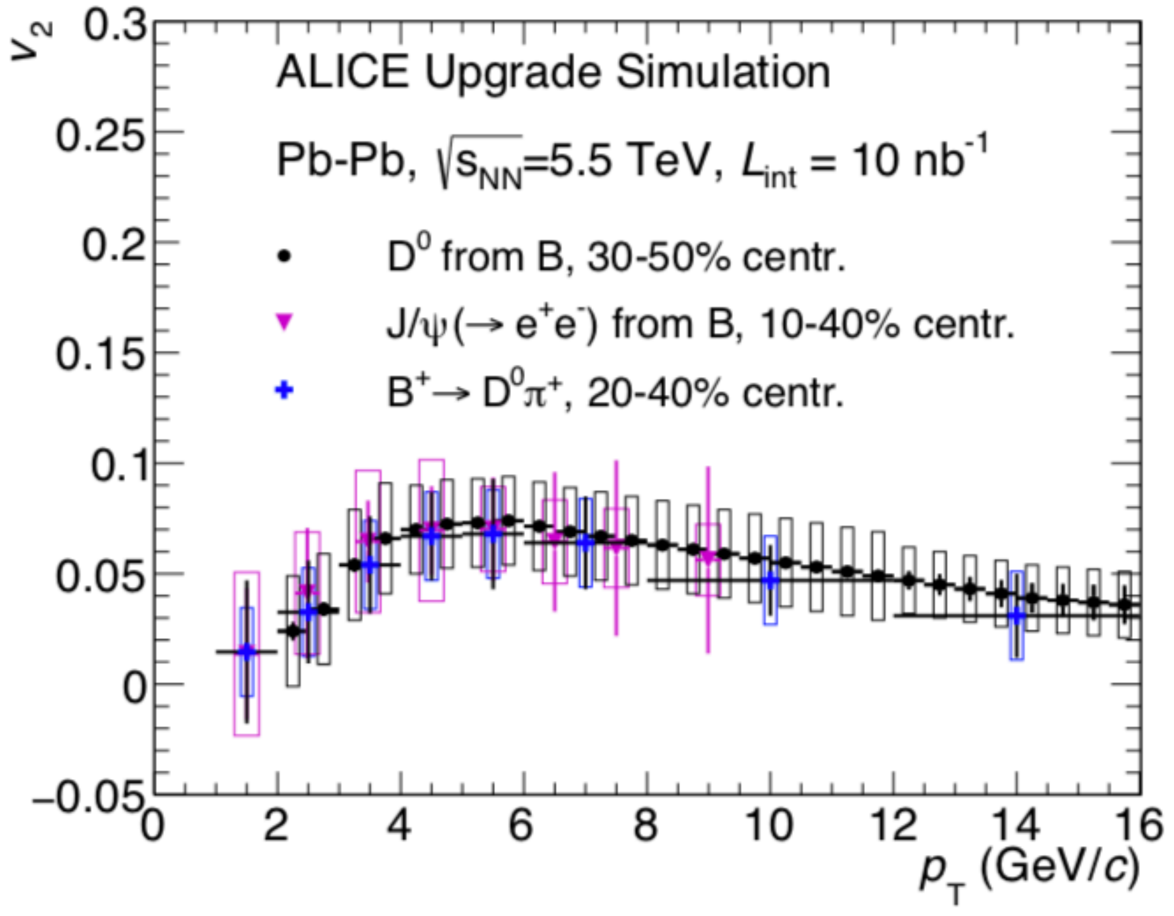
Beauty participates to the collective motion in the medium ?



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

➡ Precise measurements of the QGP properties





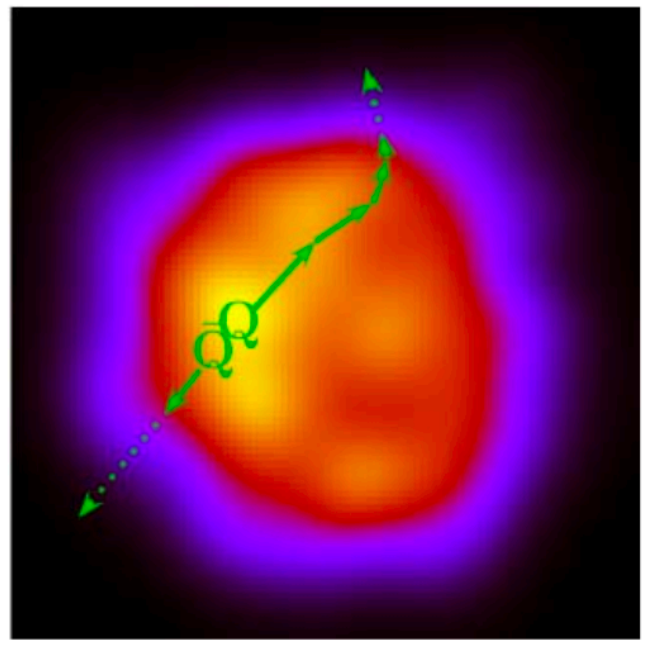
arXiv:1812.06772v2

Summary and conclusions

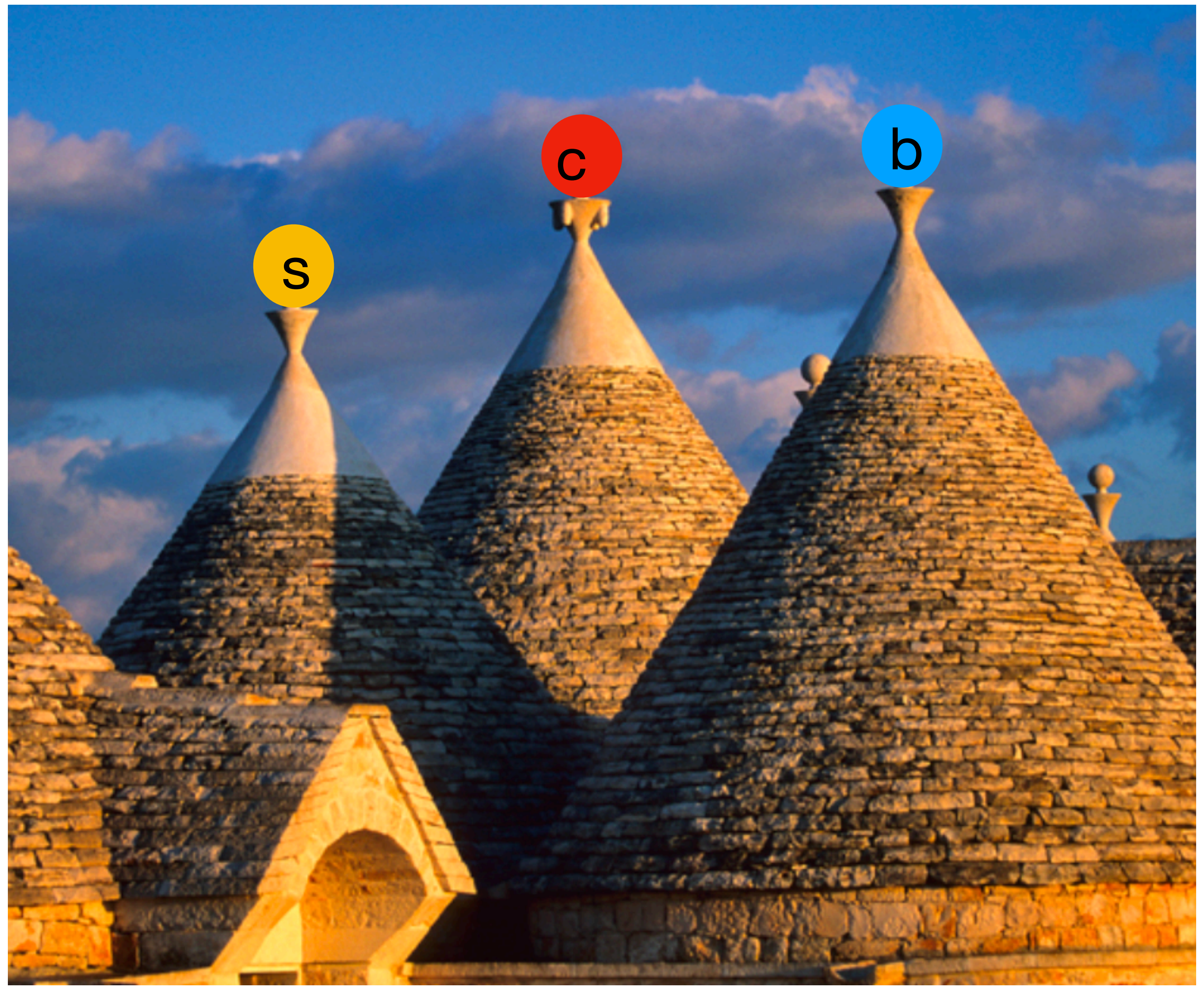
- **Deep investigation** of **heavy quark interaction with the hot and dense medium** created in heavy-ion collisions
    - from the production to their “journey” into the medium until the formation of heavy-flavour hadrons

- **Interesting new results presented**
    - improved precision and extended p_T range of charm hadrons measurements
    - charmed baryons and more beauty hadrons accessible also in Pb-Pb/Au-Au collisions

- **Need improved precision and new measurements to fully characterize the QGP** and to further constrain theory
    - all experiments are ready for the precision era of the QGP characterization
        - combine results from all the experiments: large phase space coverage (p_T, y)



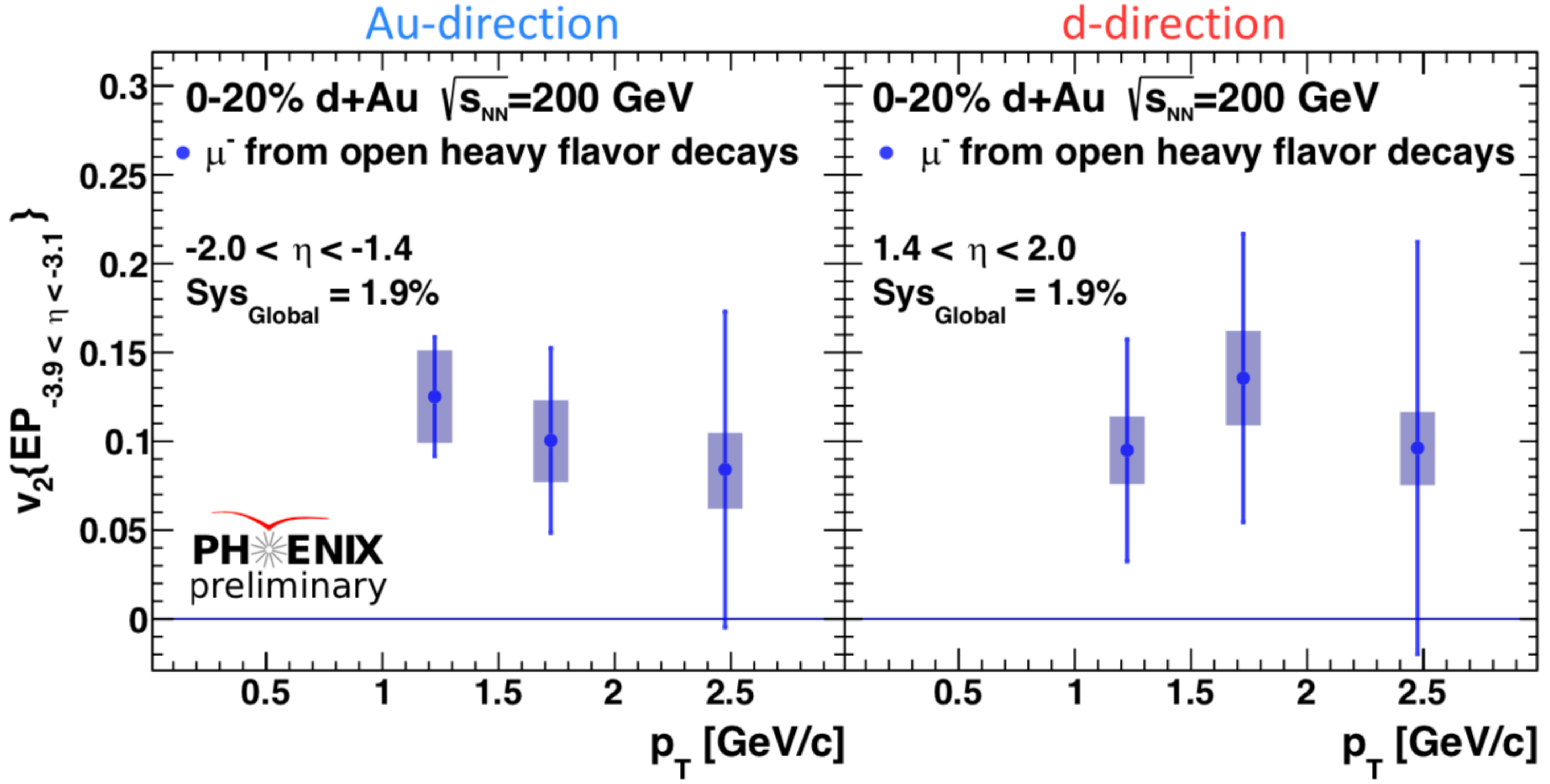
Thanks!



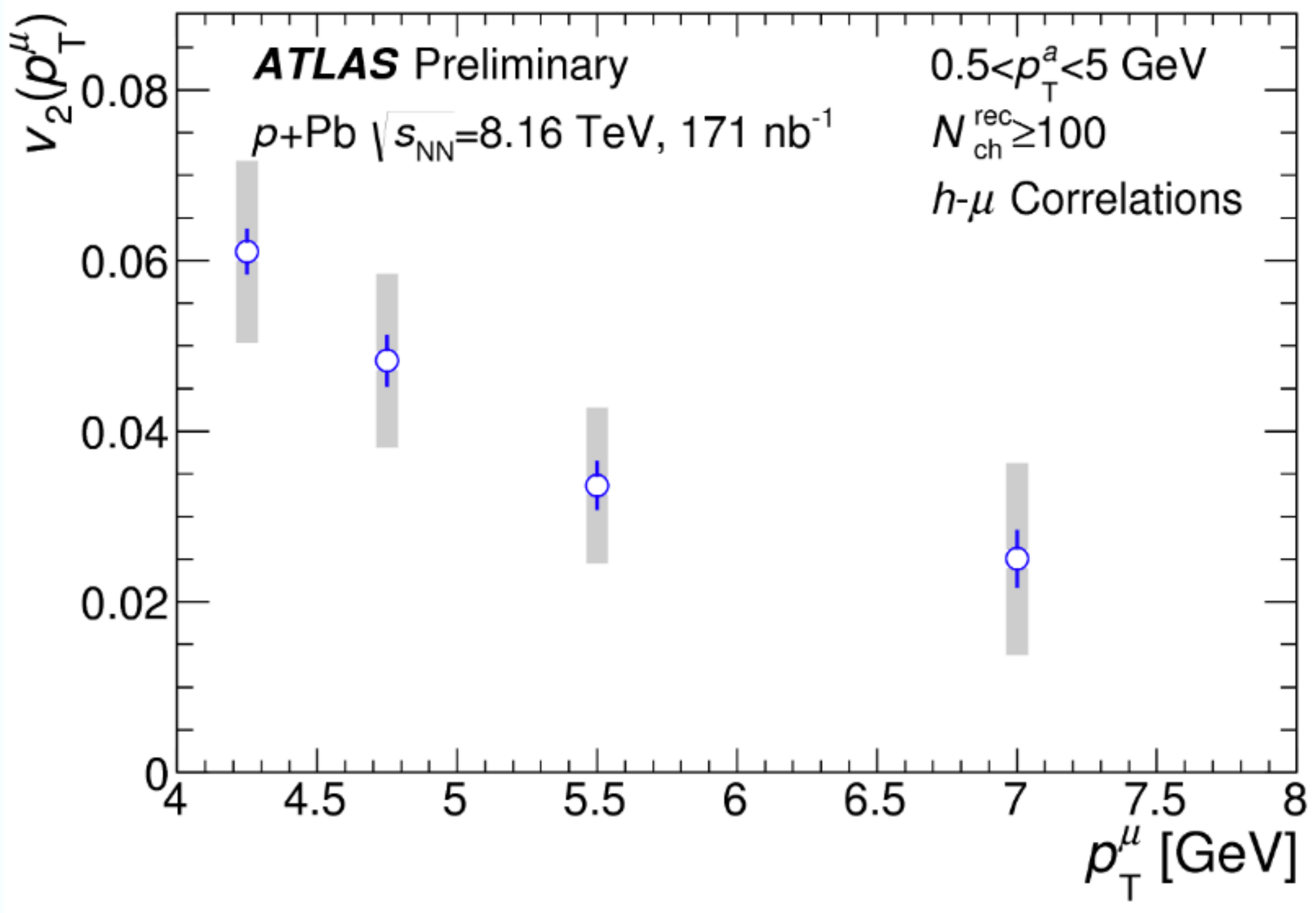
and thanks to: E. Chapon, A. Dainese, A. Festanti, F. Fleuret, GM. Innocenti, F. Prino, S. Plumari, M. Rosati, A. Rossi, L. Ruan, M. Spousta, A.M Sickles, Z. Ye, for the input provided and the fruitful discussions

Collectivity in small system?

HFμ, d-Au 200 GeV



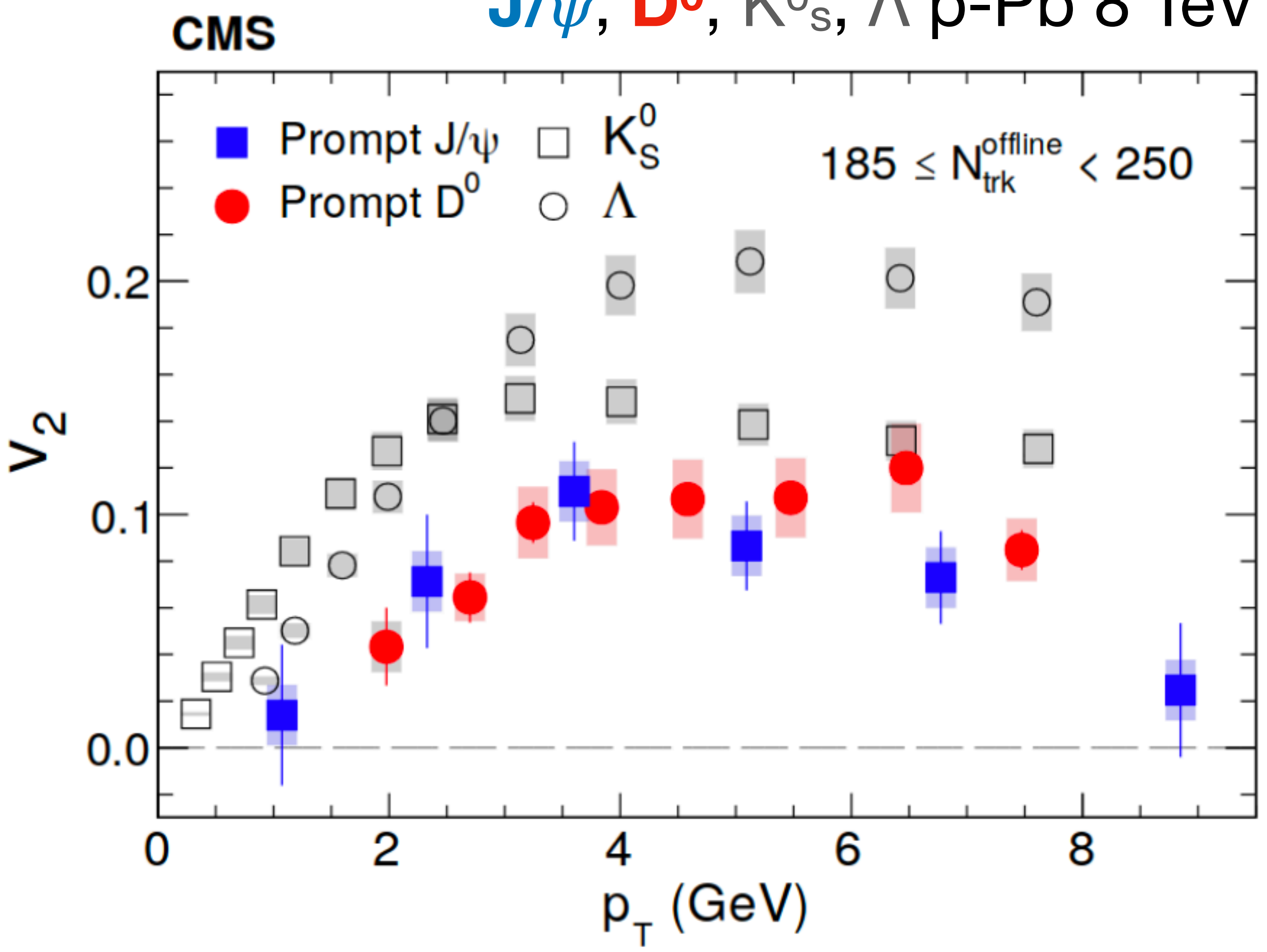
HFμ, p-Pb 8 TeV



Positive v_2 for $e^{\pm}$ and $\mu^{\pm}$ from HF decays and D^0

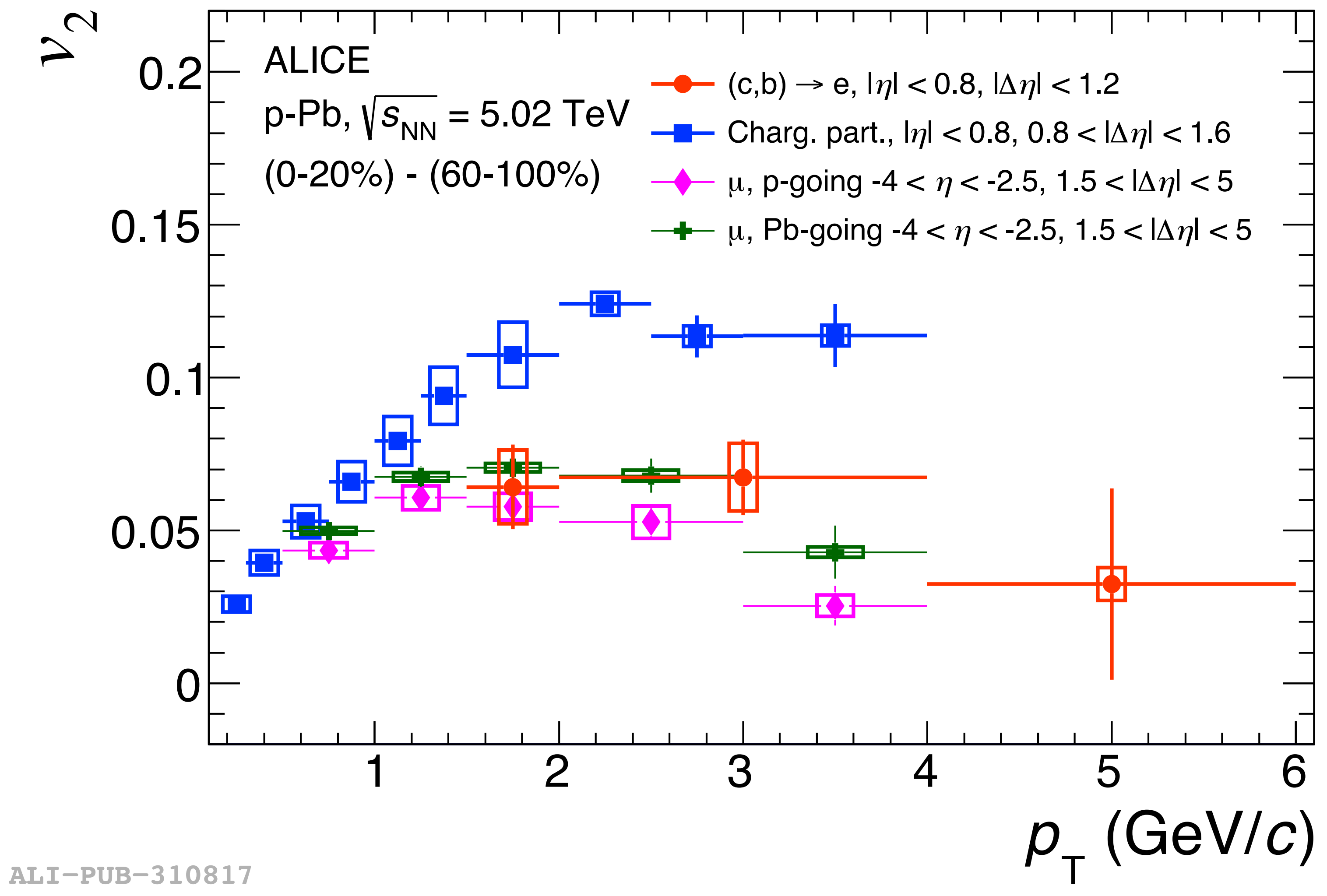
- Analysis with 2-particle correlations in **high-multiplicity p-Pb/d-Au collisions in different c.m. energies $\sqrt{s}$= 200 GeV, 5.02TeV, 8.16 TeV**
- sizeable effect, possibly lower than **charged-particles maximum**

J/ψ, D⁰, K^0_S, Λ p-Pb 8 TeV



Phys. Lett. B 791 (2019) 172

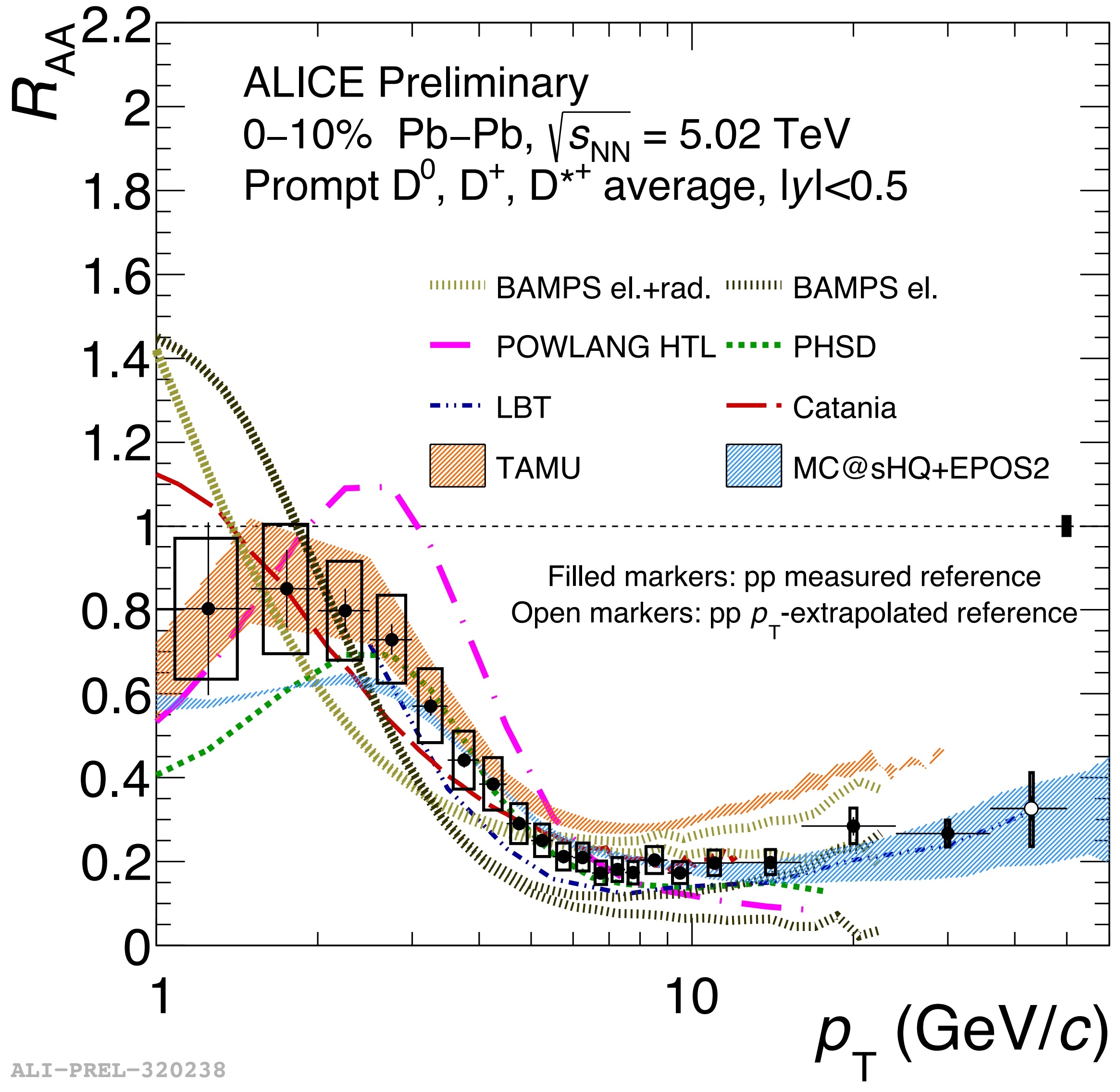
h±, **HFe**, **HFμ** p-Pb 5 TeV

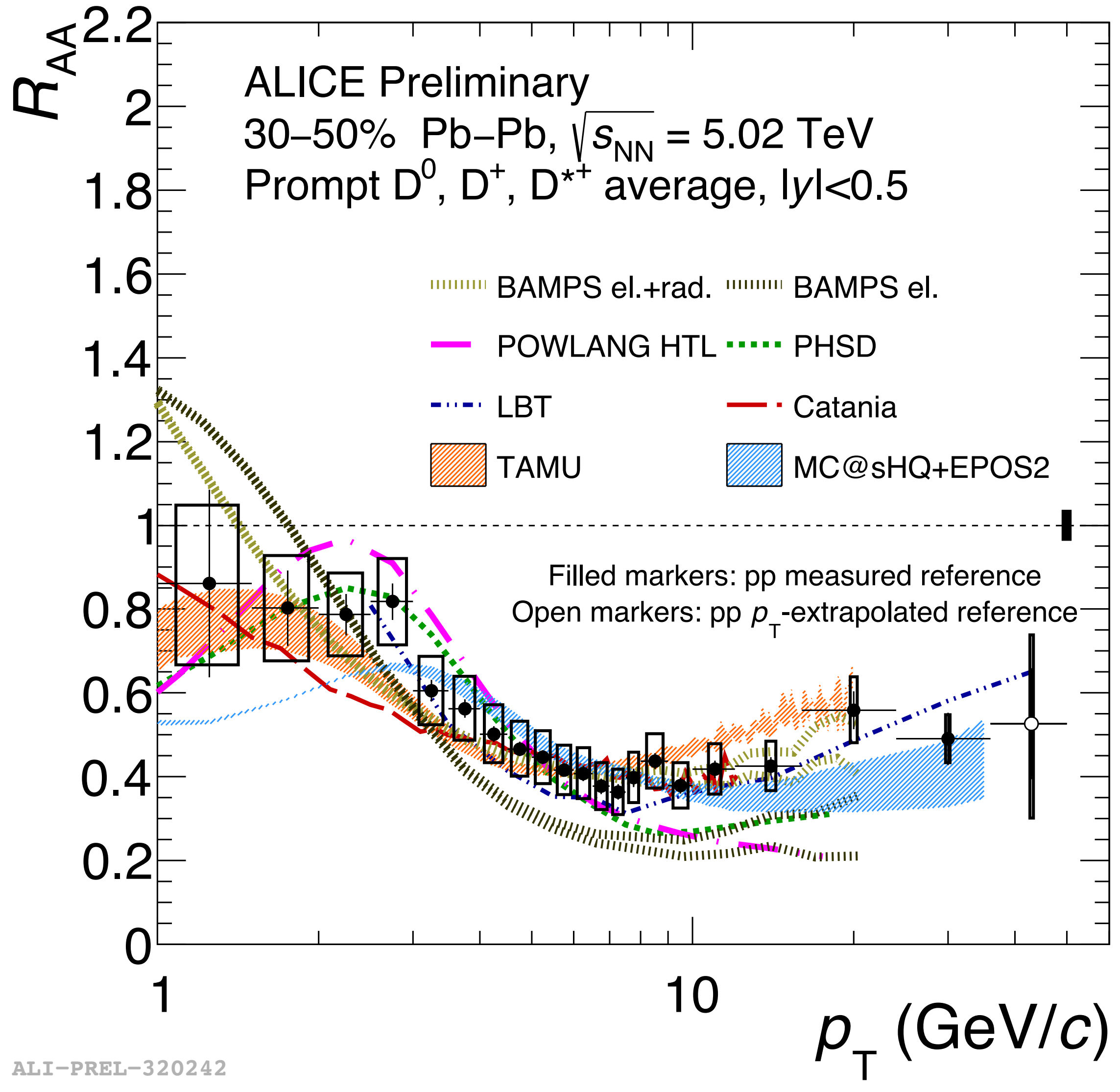


Collective effects in p-Pb/d-Au system?
Initial- or final-state effects?
Which is the origin?

More on small systems
E. Chapon (Fri)

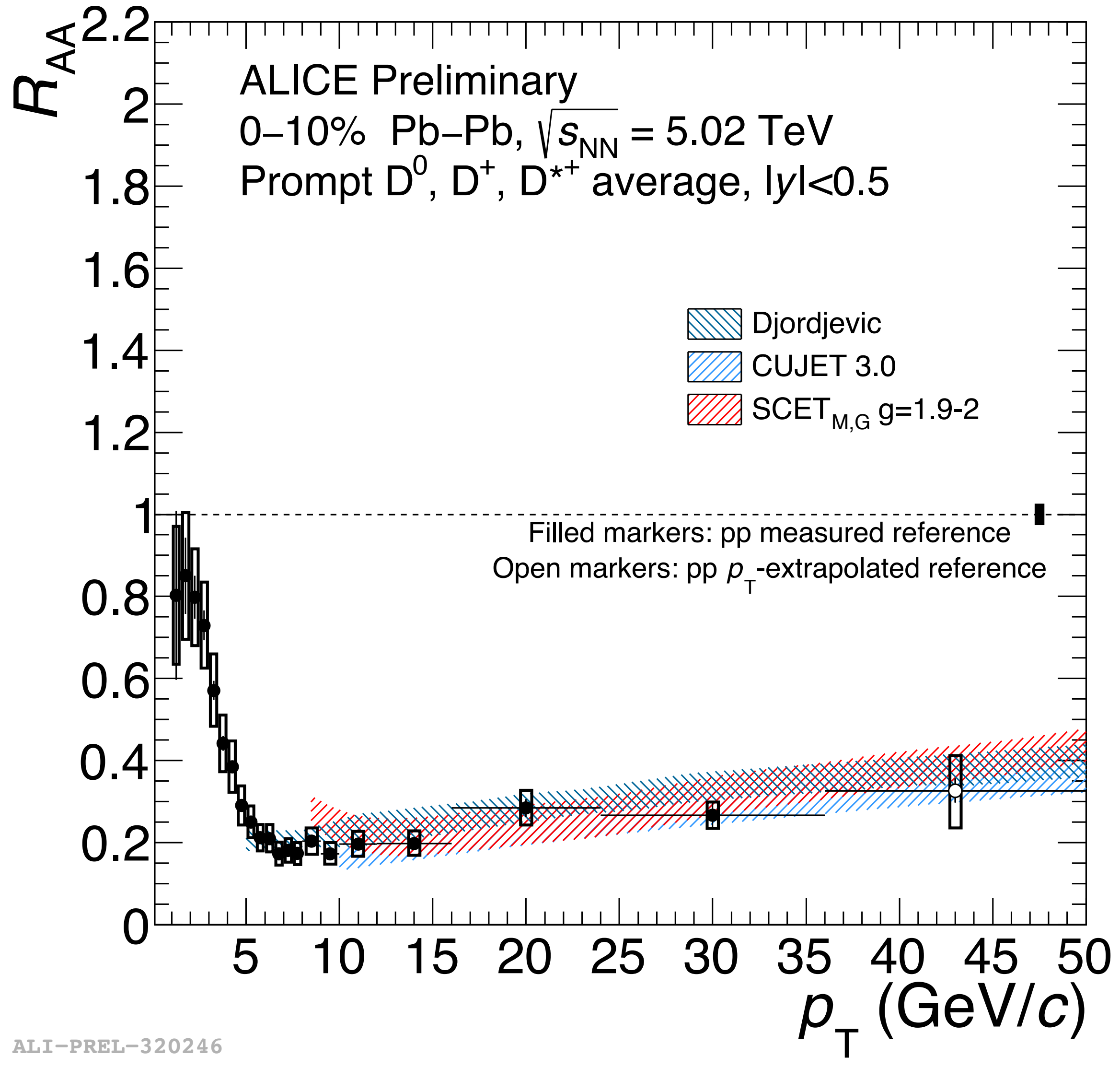
R_{AA} and models

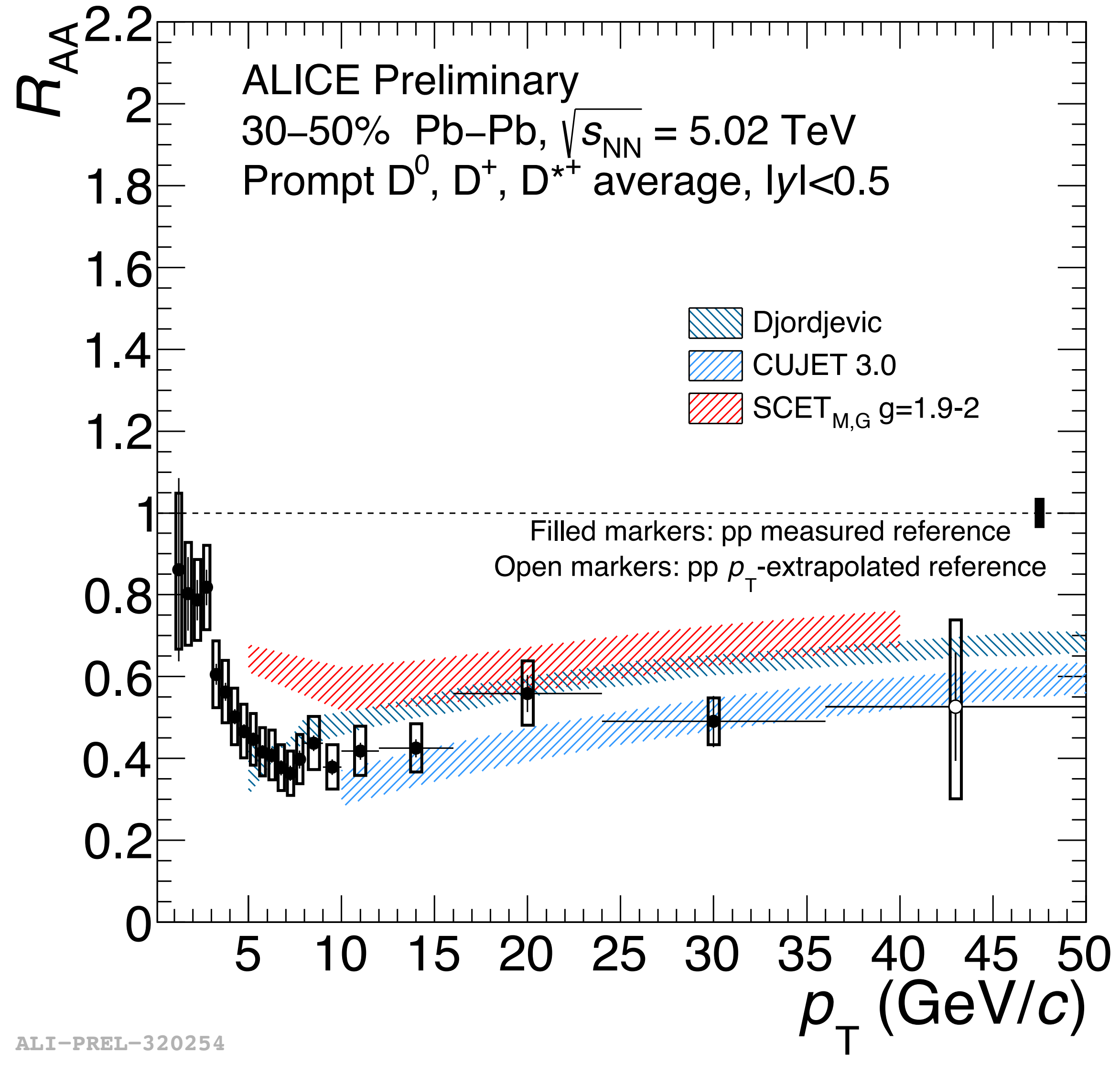




"Transport models" based on Boltzmann/Fokker-Plank/Langevin equations

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	✔	✔	✘	✘	✔

MODELS Pb-Pb

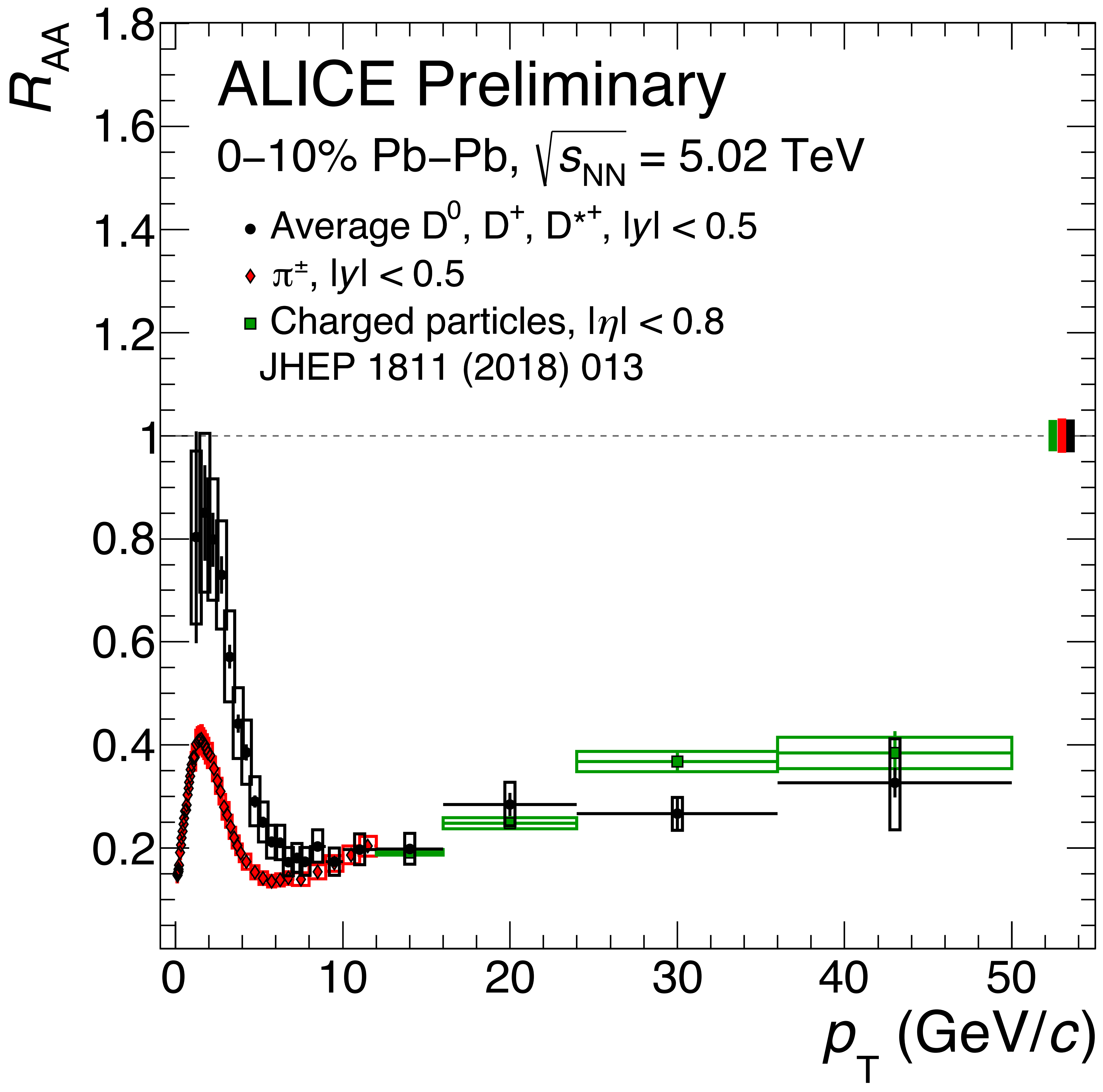
From:

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

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)

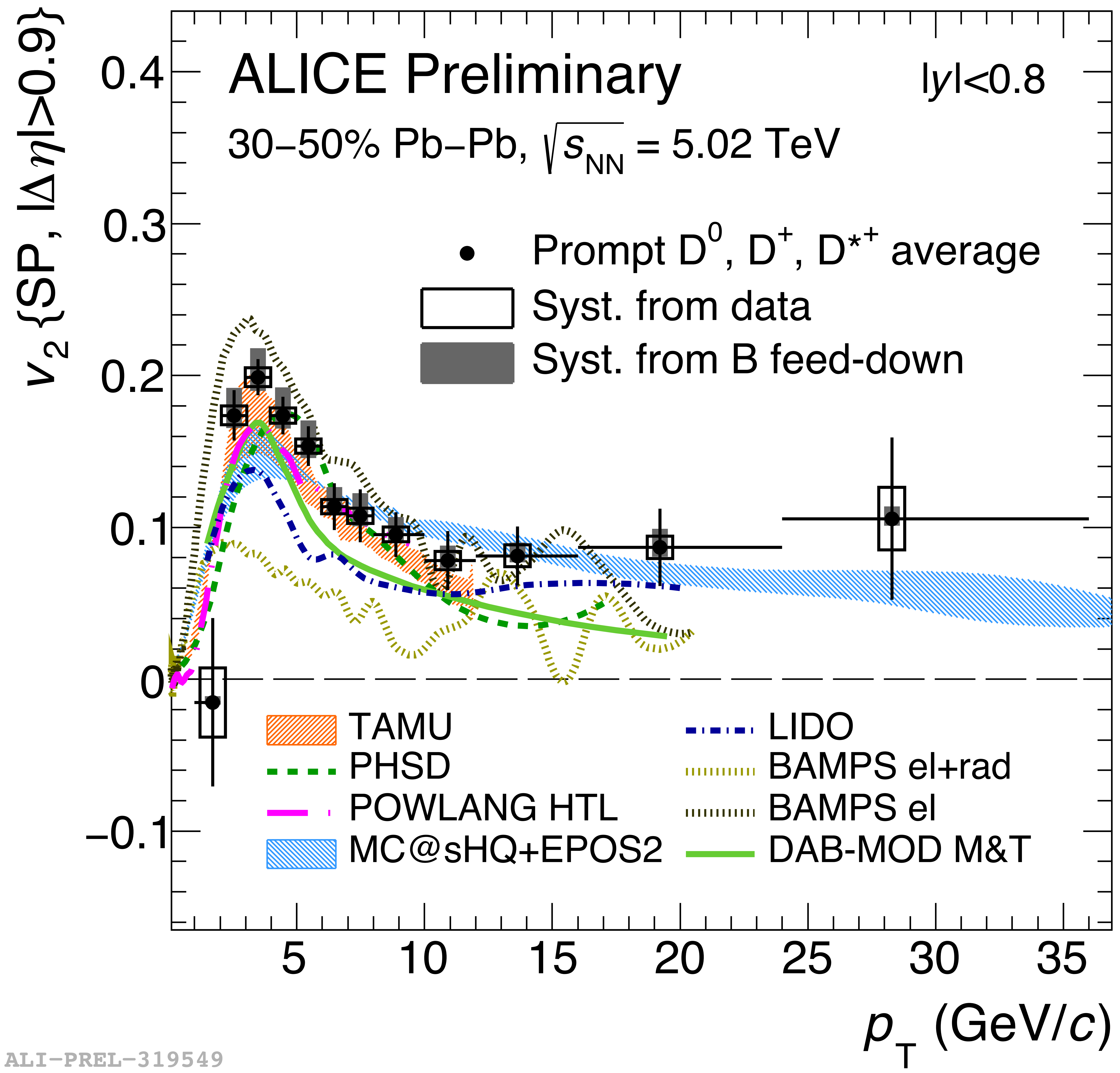
R_{AA} vs charged particles at low p_T



Indication of $R_{AA}(D)>R_{AA}(\pi)$ but interpretation not trivial:

- soft-particle production not expected to scale with N_{coll} with down to p_T=0 (while binary scaling + energy loss could lead to Raa>1 at low pt, if no shadowing)
- Different impact of shadowing (nPDF)
- Different initial spectra and fragmentation
- Different impact of collisional energy loss, radial flow, modification of particle-species abundances

v_2 and models



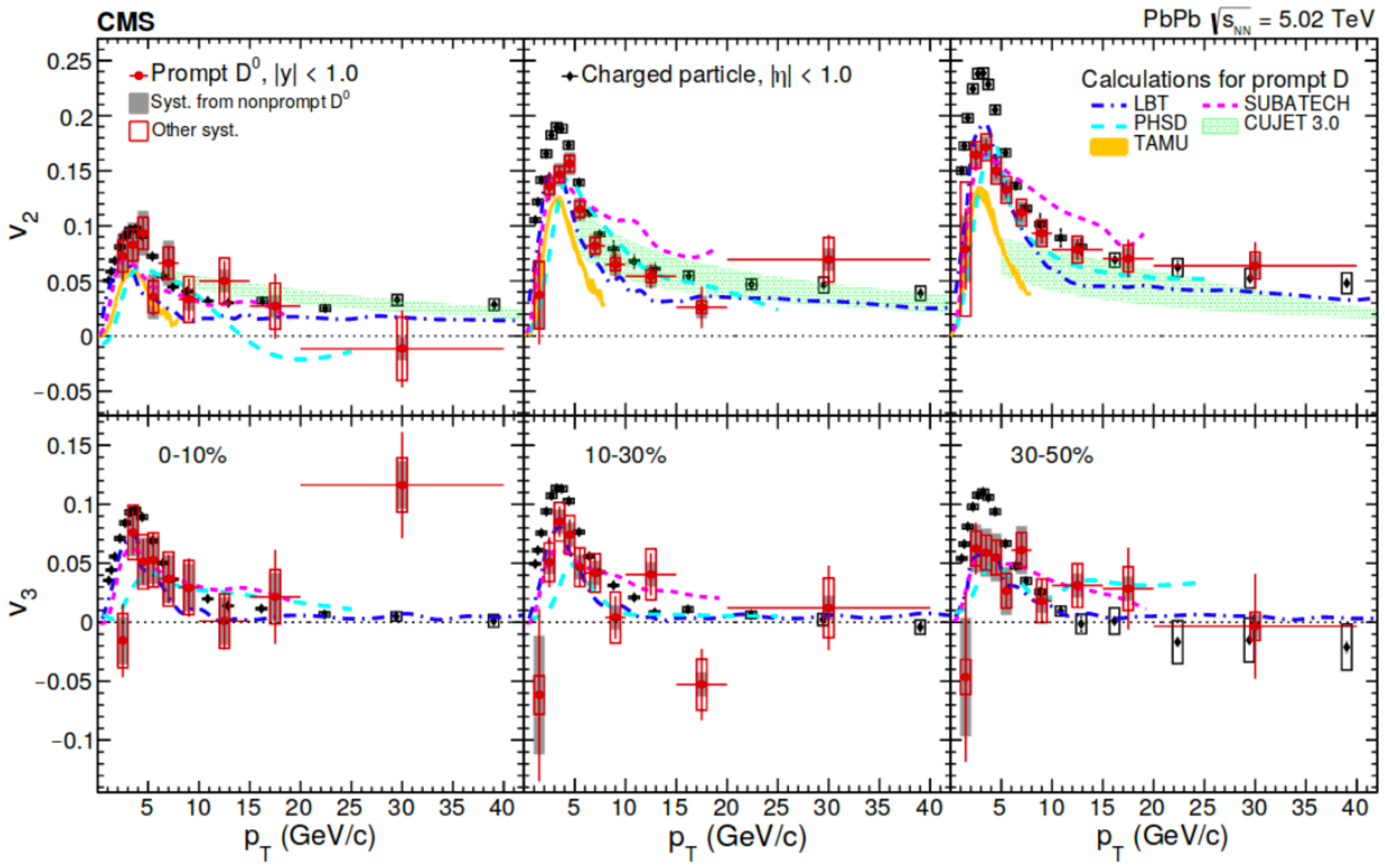
- Compared with theoretical calculations that include a hydrodynamical model for the QGP expansion
  - models that lack this expansion underestimated the range
- **BAMPS-el, POWLANG**, **TAMU** include only collisional interaction processes,
- **BAMPS-el+rad**, **LIDO**, **MC@sHQ**, and **PHSD** also include energy loss via gluon radiation.

All calculations, with the exception of BAMPS, **include hadronization via quark recombination**, in addition to independent fragmentation.

All calculations provide a fair description of the R_{AA}

Other armonics: v_3

Higher order flow coefficient —> sensitive probe of the degree of charm- and beauty-quark thermalization.
v_3 shows an incomplete coupling of hq to the bulk medium as week as the expected mass hierarchy



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