Overview of heavy flavour and quarkonia

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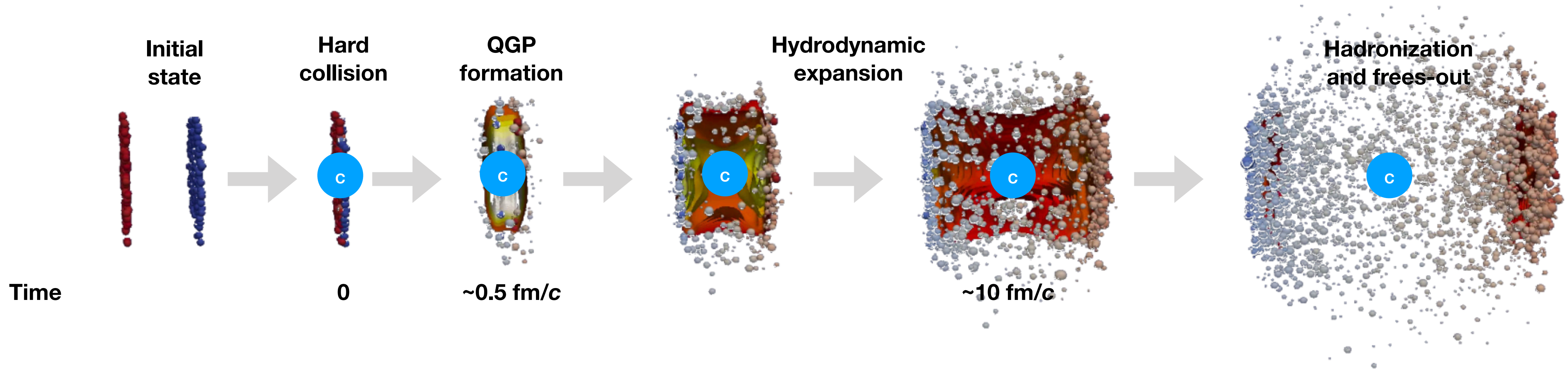
RHIC & AGS Annual Users' Meeting 2020

Probing quark-gluon plasma (QGP) with heavy flavour

- Goal: Explore the deconfined phase of QCD matter →quark-gluon plasma



Visualization by J.E Bernhard arXiv:1804.06469

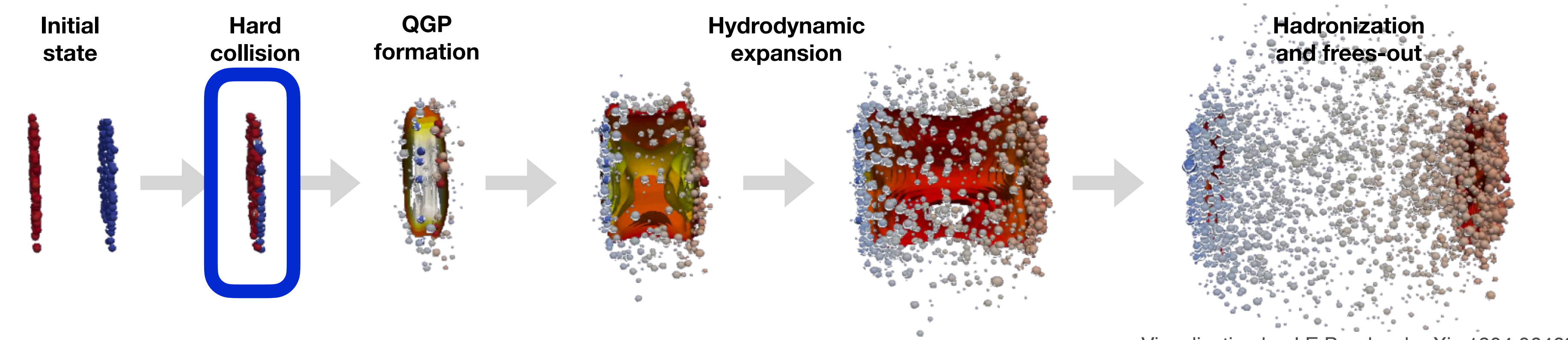
Why heavy flavour?

- $m_Q >> \Lambda_{QCD}$
  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)

Studies from their production to their “journey” into the medium until the formation of heavy-flavour hadrons!

Heavy-flavour production in pp collisions



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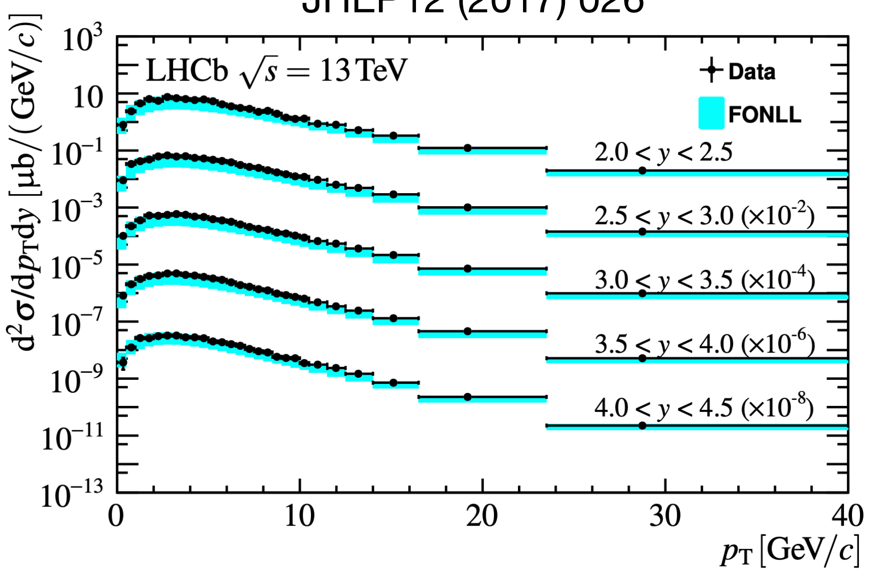
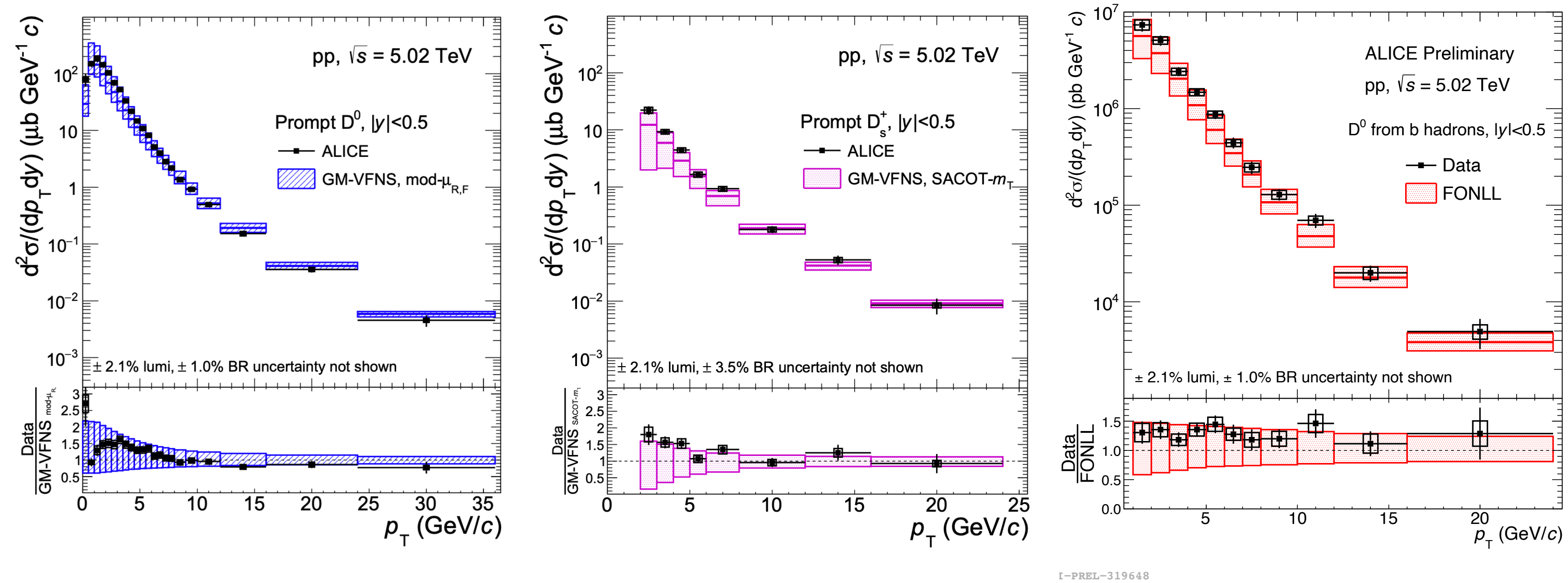
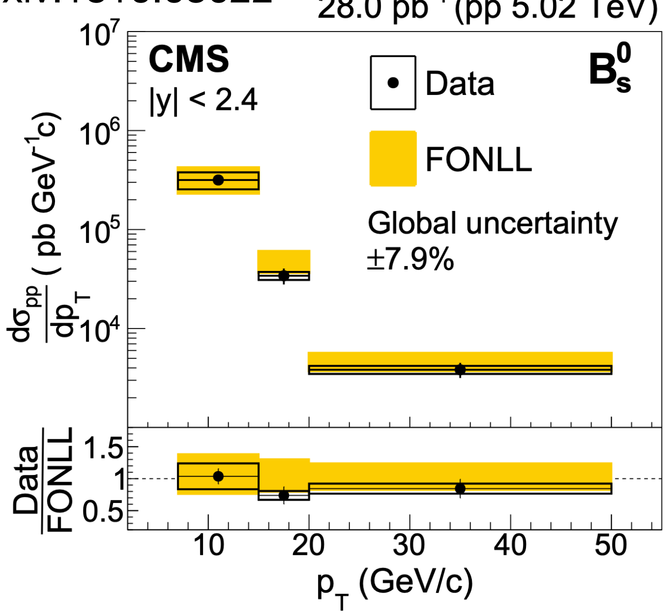
JHEP12 (2017) 026



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



arxiv:1810.03022



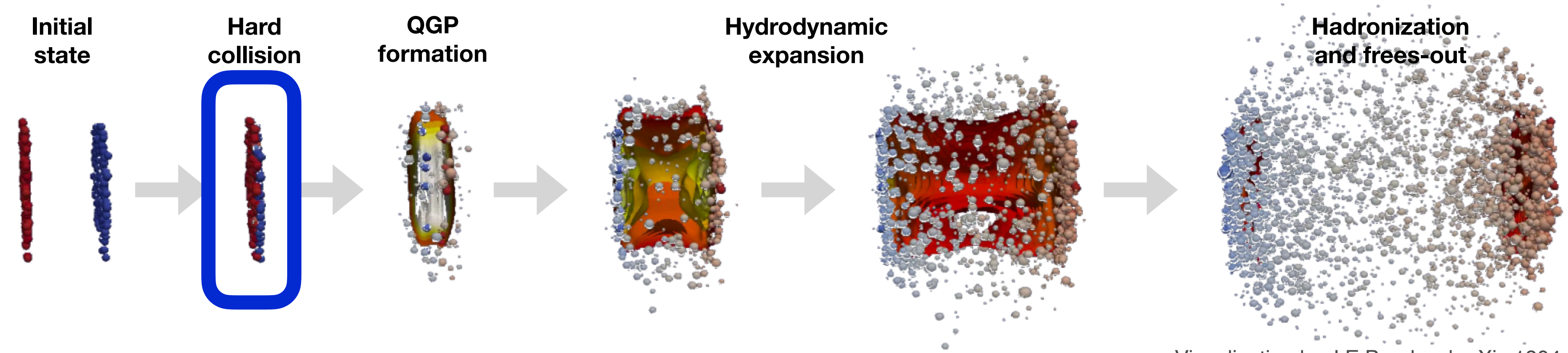
- Precise production measurement in pp down to low p_T (~ 0 with D^0).

Comparison with models:

- Data **described by pQCD** calculations.
- Data is more precise than the model prediction. Need to constrain the model prediction.

Heavy-flavour directed flow v_1

Talk by Lucia Oliva



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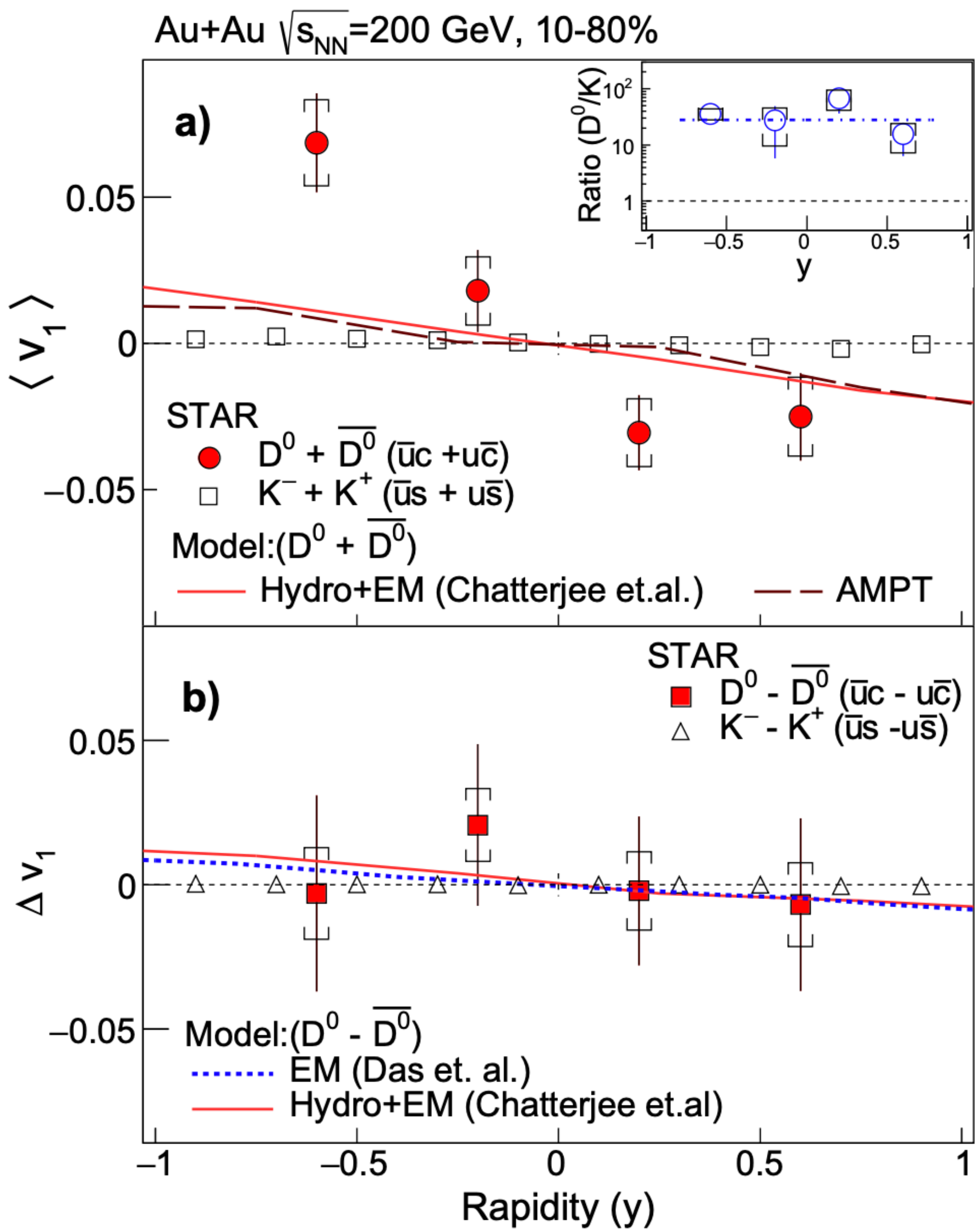
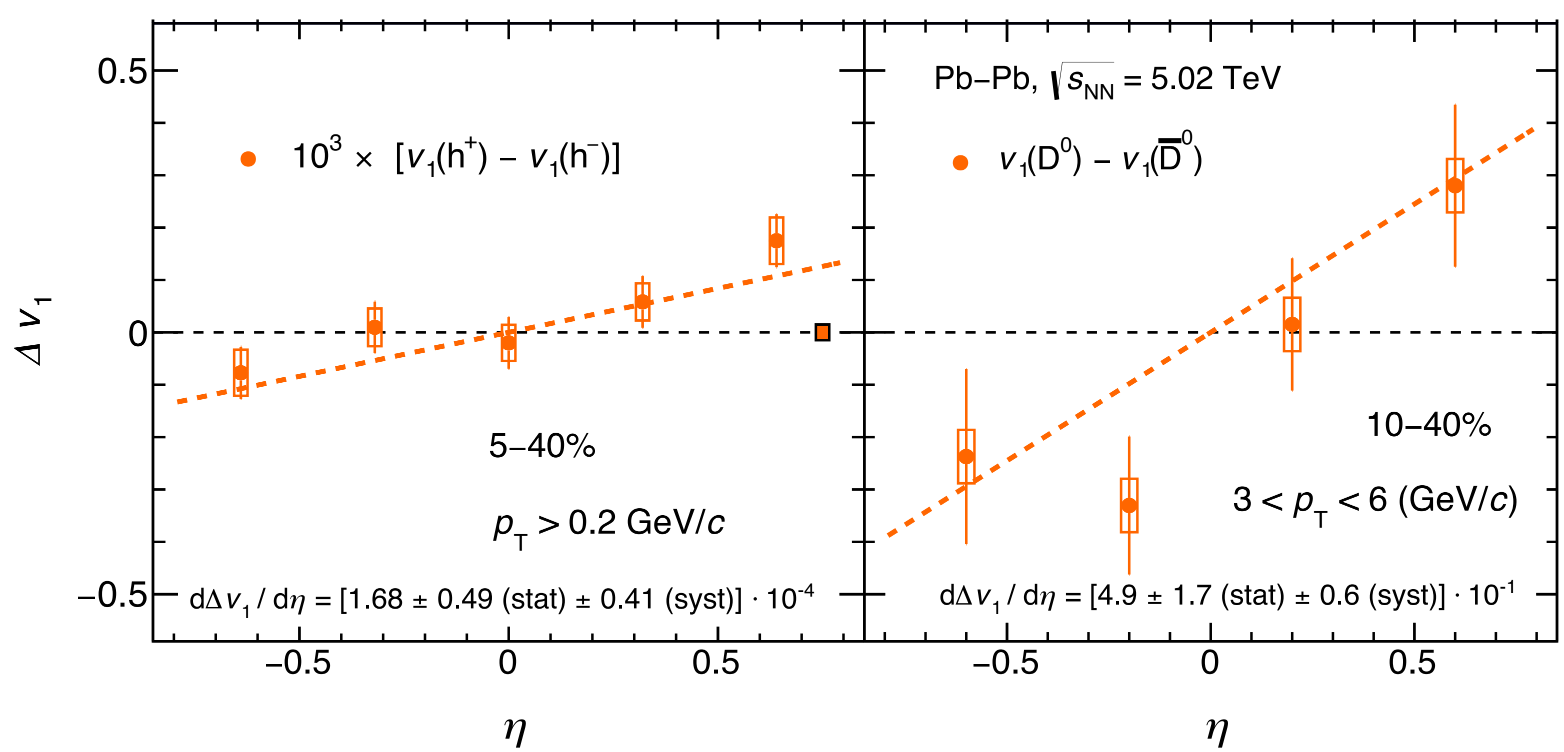
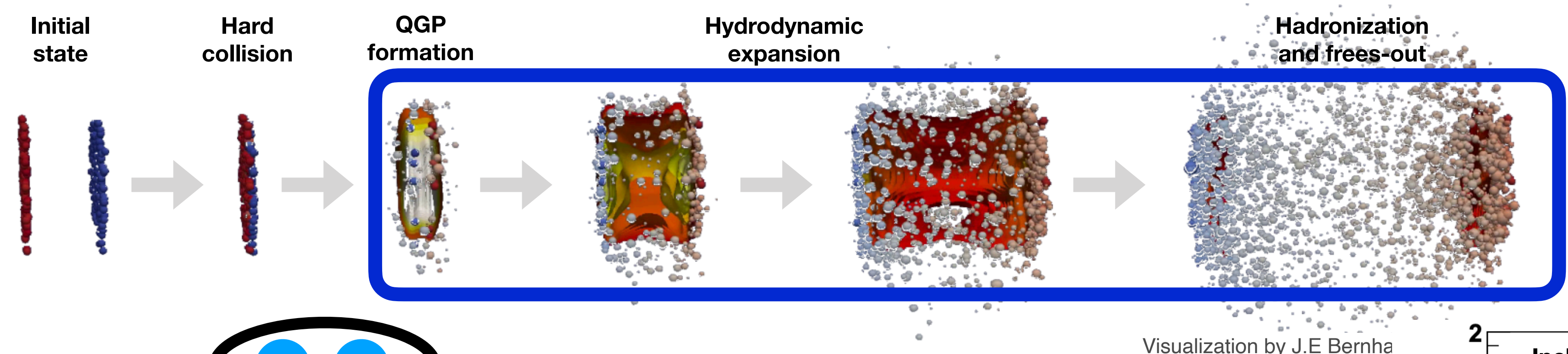
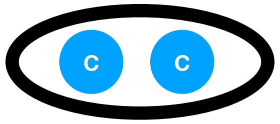




- ALICE: opposite slope w.r.t. RHIC, effect due to larger B than the induced E?

Quarkonium: dissociation and re-generation

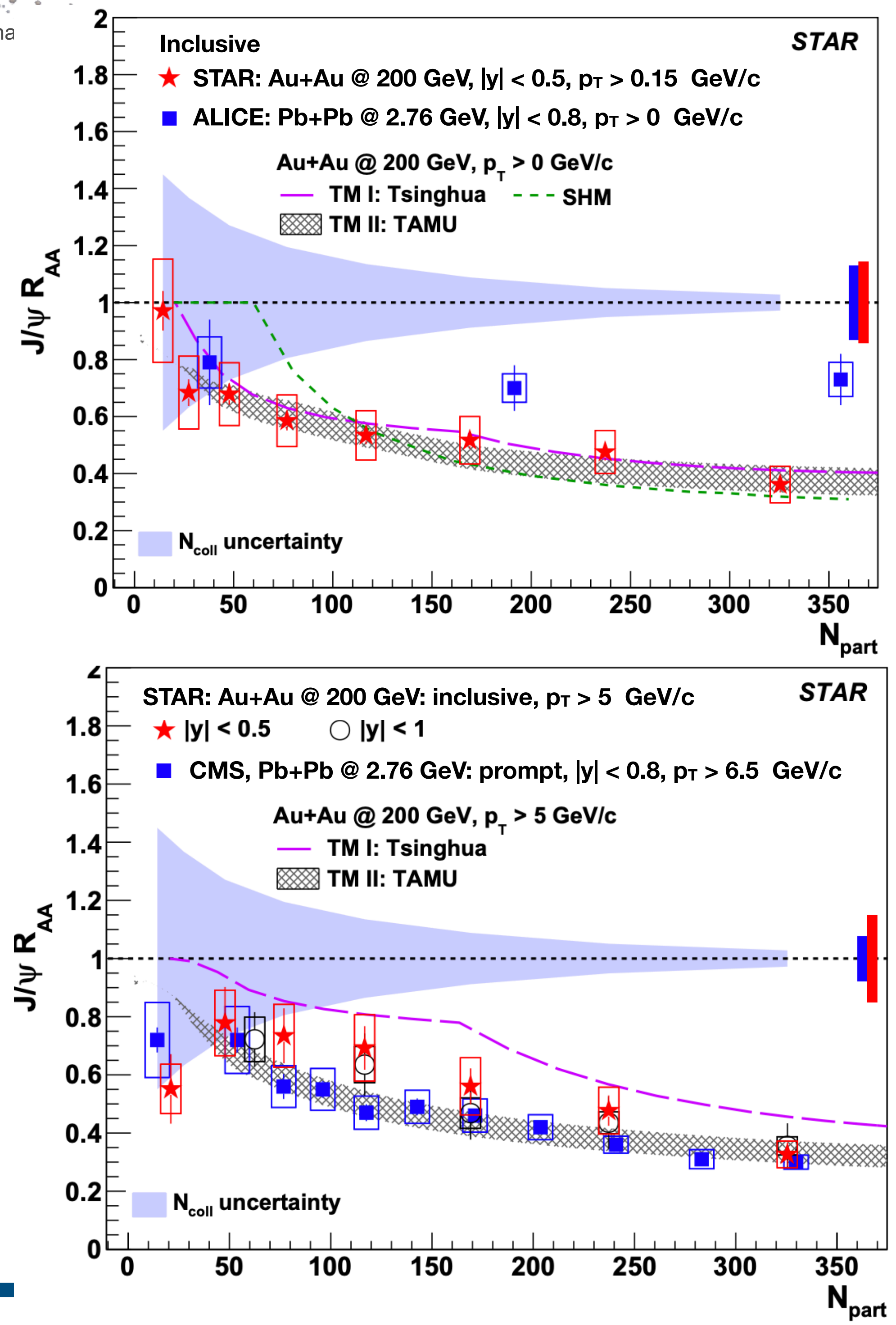




arxiv:1905.13669v1

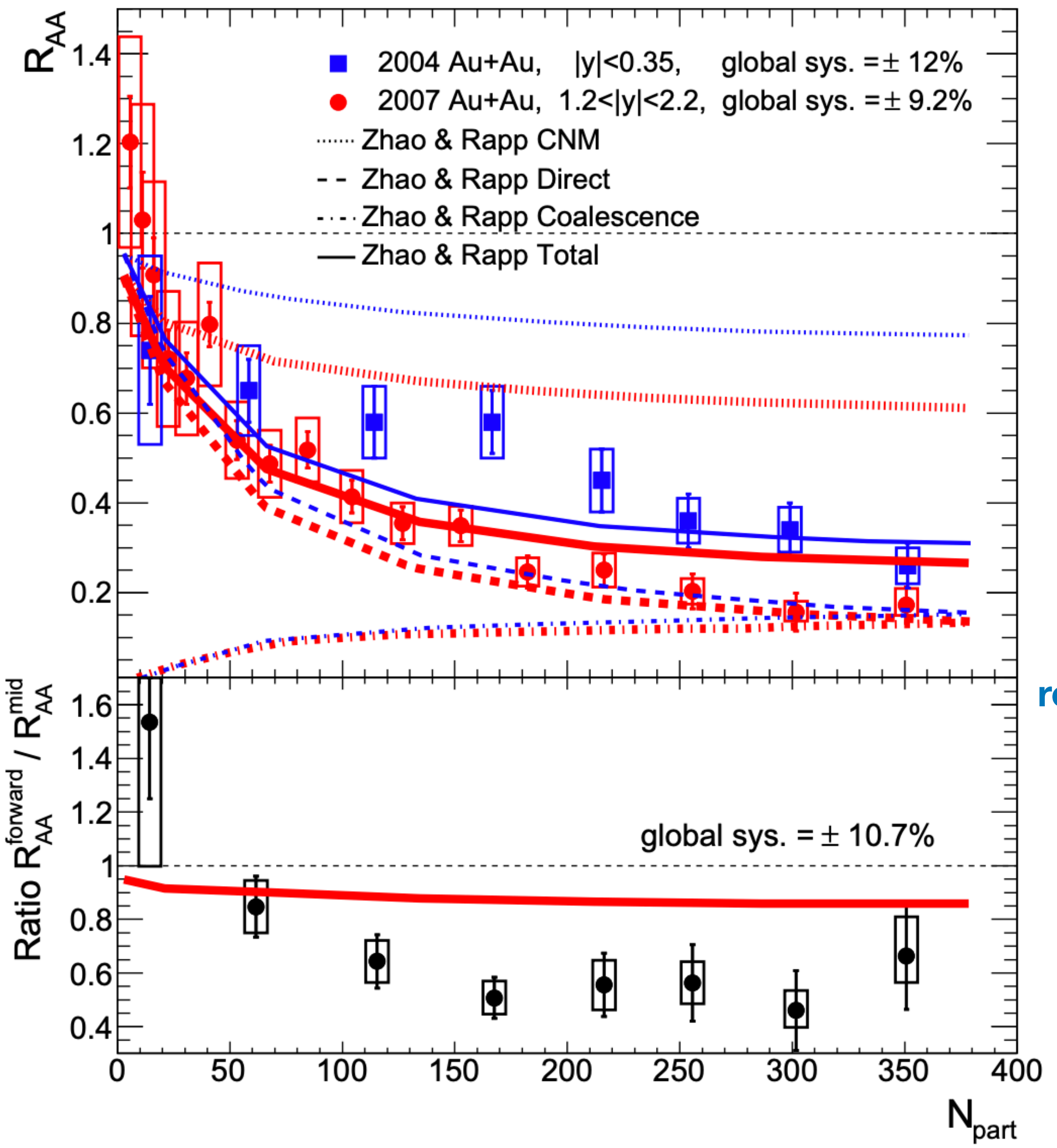
- **Dissociation:**
  - J/ψ cannot exit inside the medium **(colour screening)**
- **Recombination**:
  - J/ψ created in the QGP by combination of $c\bar{c}$ pairs.

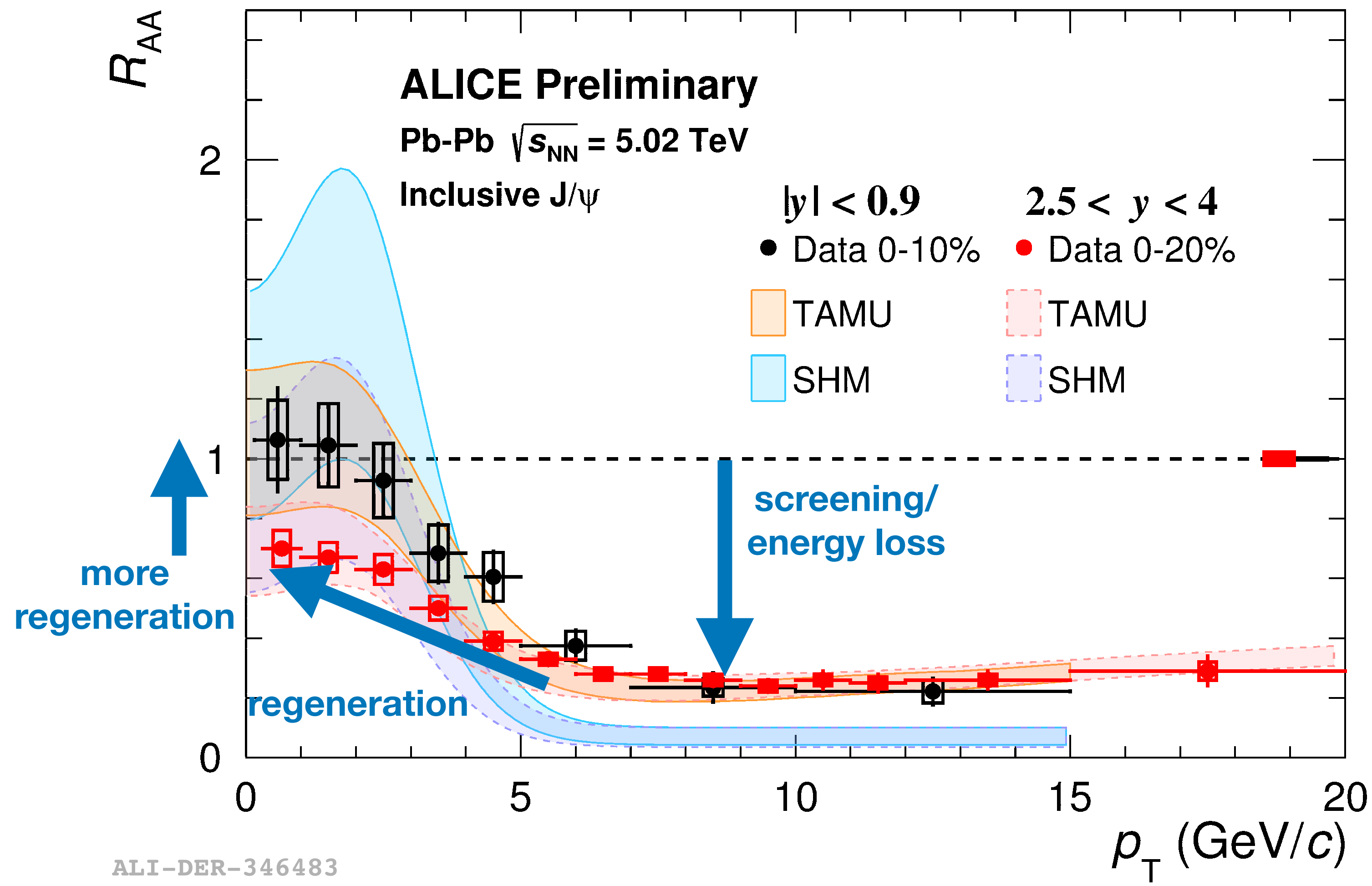
- Low p_T: In most central collision J/ψ is less suppressed at LHC than RHIC→ regeneration balancing the screening in the QGP
- High pT: J/ψ is strongly suppressed at both LHC and RHIC due to color screening.



Quarkonium: dissociation and re-generation

arxiv:1103.6269



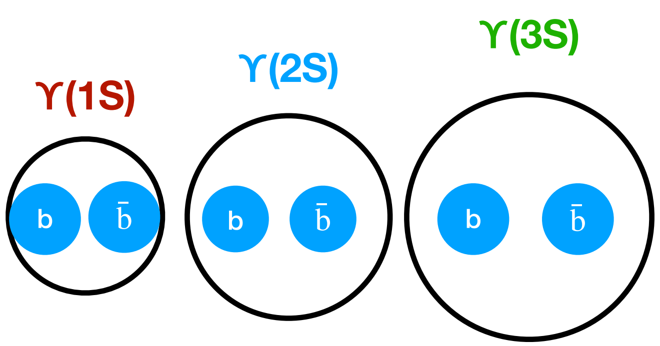


- modification decreases from **forward** to **central** rapidity.

  Reflects rapidity dependence of the $c\bar{c}$ cross-section regeneration probability.

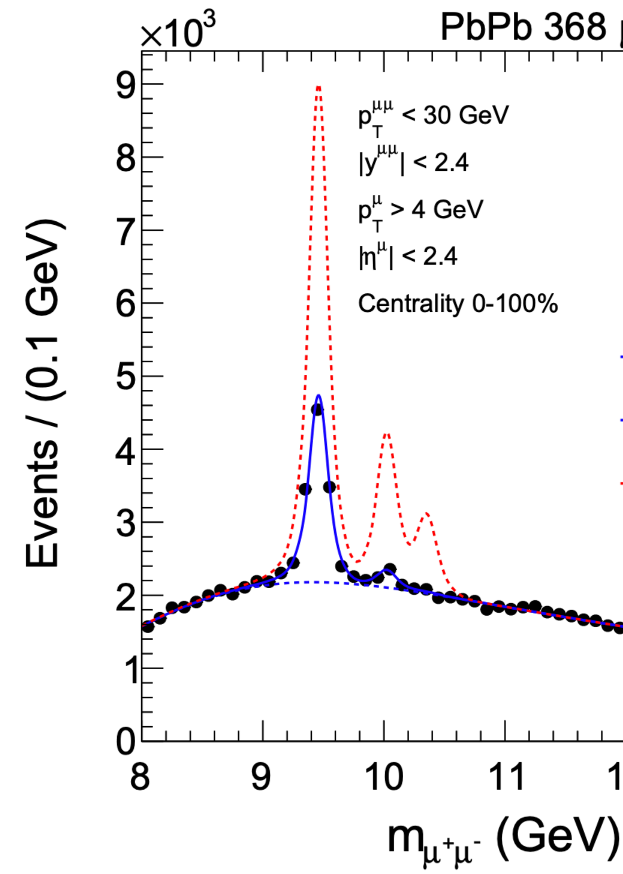
Bottomonium suppression

- **Dissociation:**
  - Bottomonia cannot exit inside the medium **(colour screening).**
  - **Sequential suppression**:
    different radii/binding energies → different suppression

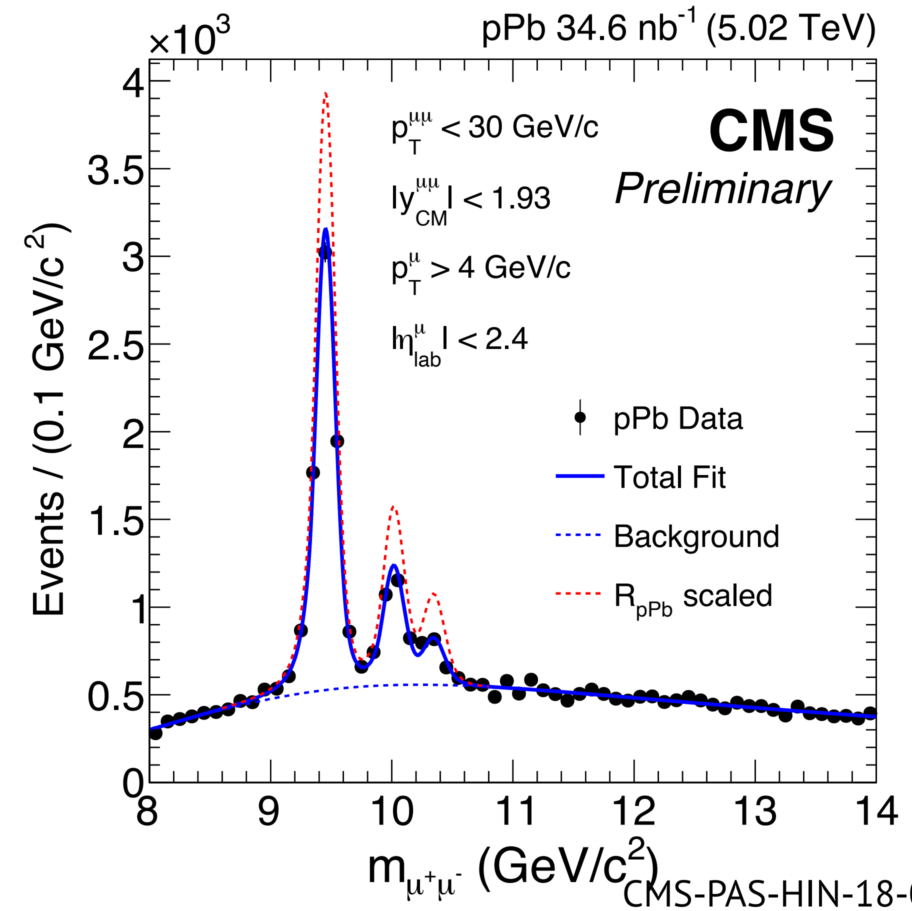


- **Recombination**:
  - Bottomonia created in the QGP by combination of $b\bar{b}$ pairs.
  - Less affected due to lower $b\bar{b}$ cross section at both RHIC and LHC.

- Strong suppression in PbPb collisions w.r.t to pp collisions.



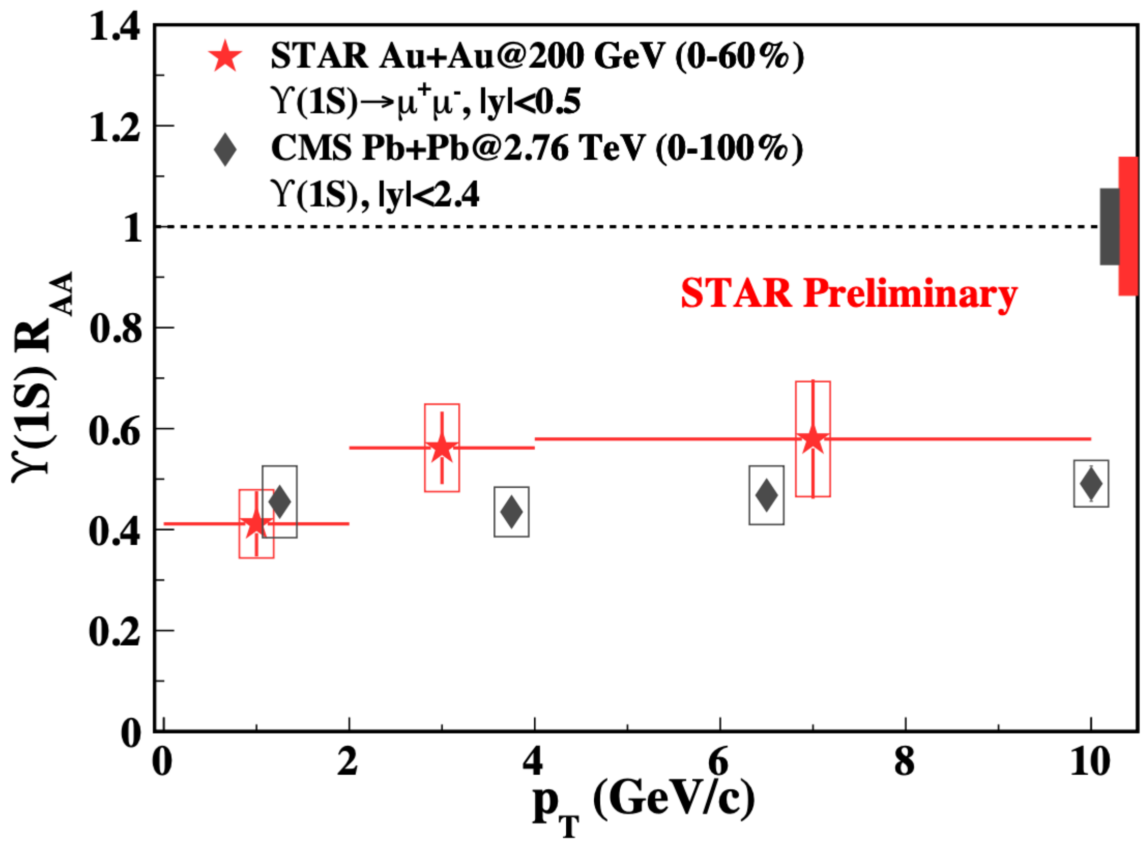
arxiv:1805.09215

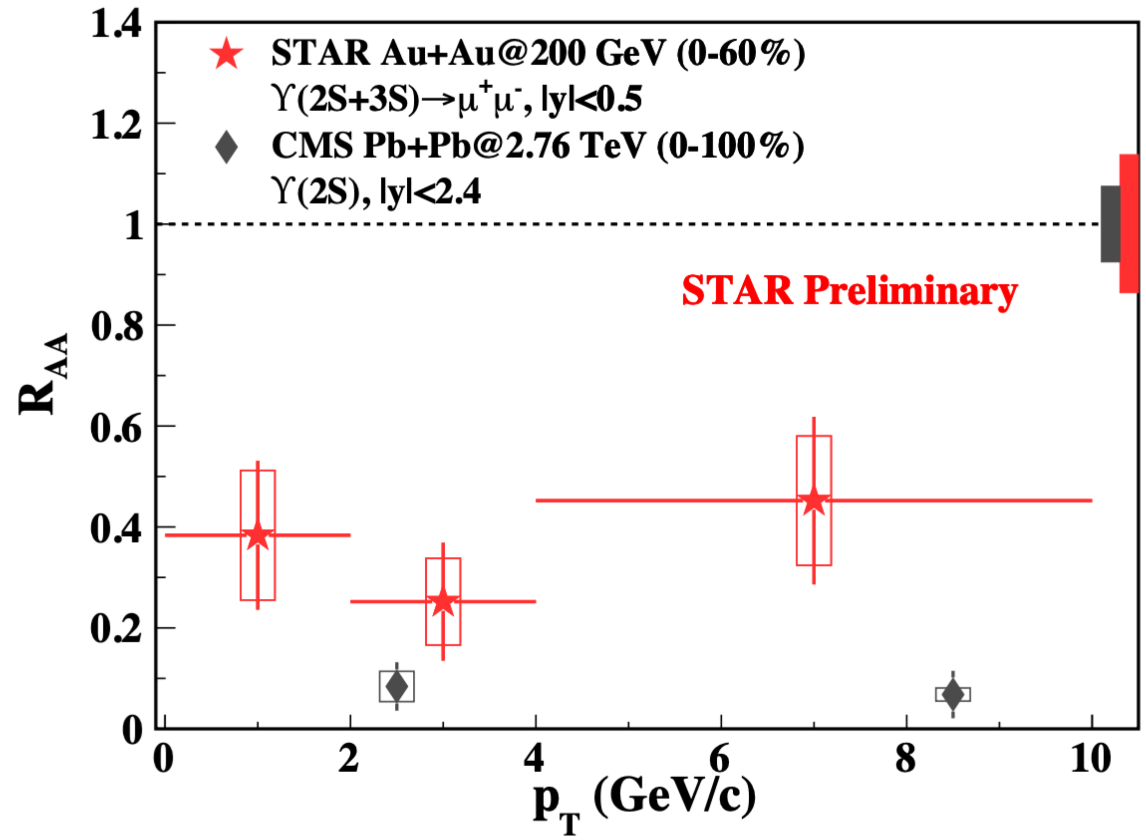


CMS-PAS-HIN-18-005

Bottomonium suppression

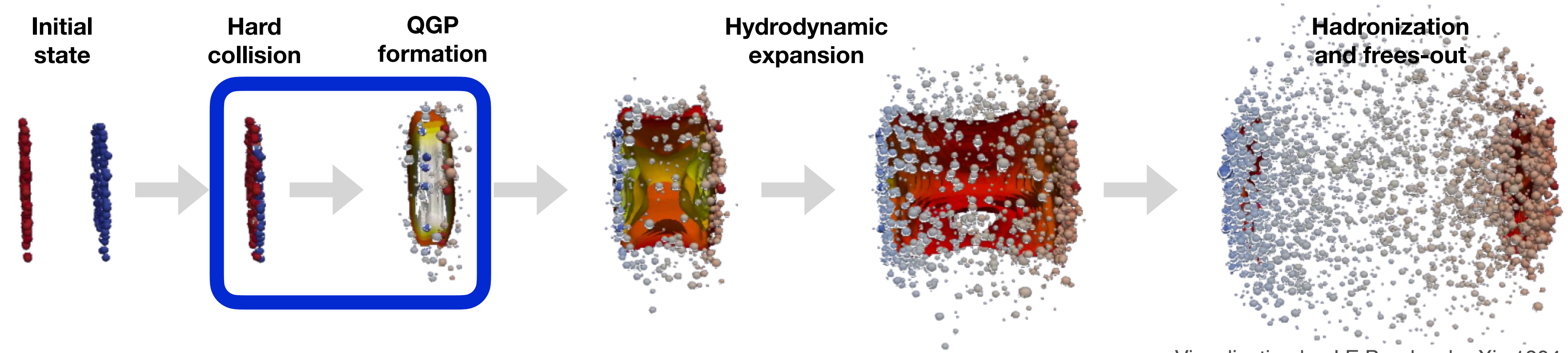
CMS: PLB 770, 357 (2017)





- ϒ (1S): Shows similar suppression at RHIC and LHC.
- ϒ (2S+3S): Hint of more suppression at LHC than RHIC.

Heavy flavour energy loss



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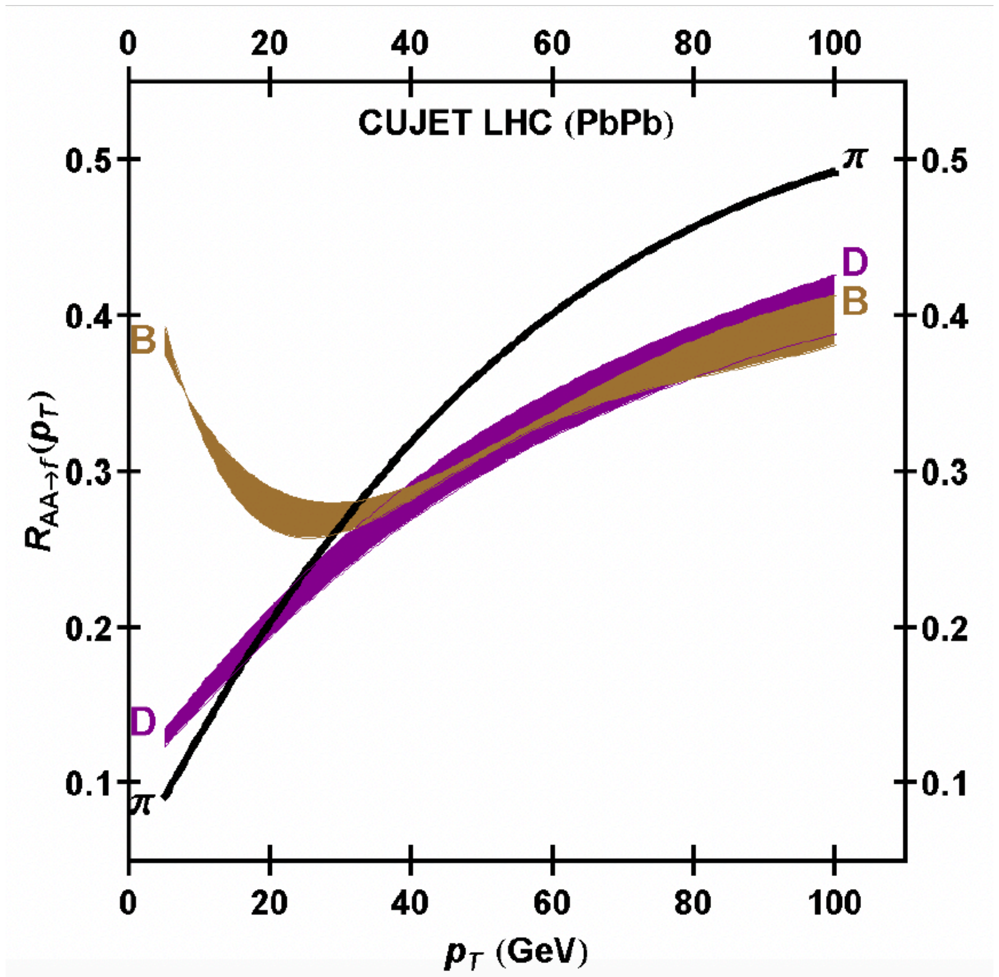
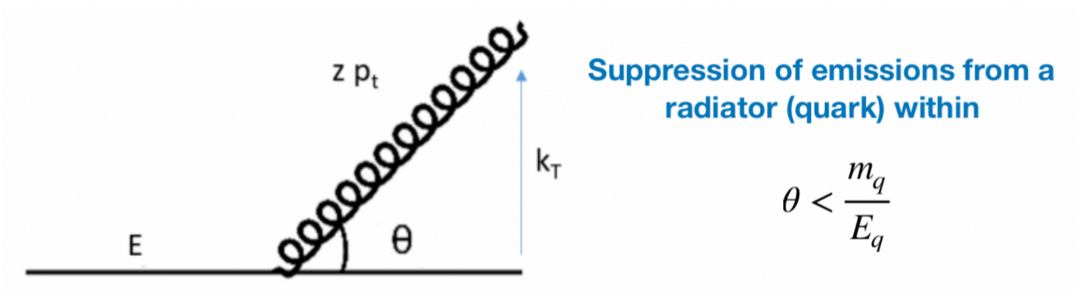
In-medium energy loss as a consequence of **radiative** and **collisional** processes.



Energy loss in the medium due to.

- Color charge (Casimir factor): $\Delta E_q < \Delta E_g$
- Dead cone effect (radiative energy loss): Reduction of gluon radiation from heavy quarks at small angles. It depends on the mass of the radiator quark.
  $\Delta E_b < \Delta E_c < \Delta E_{u,d,s,g}$



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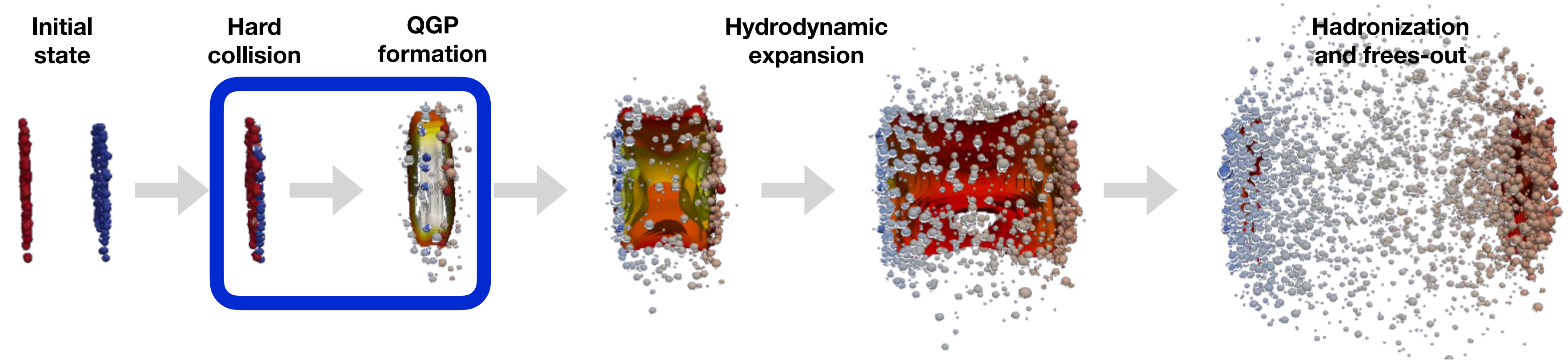

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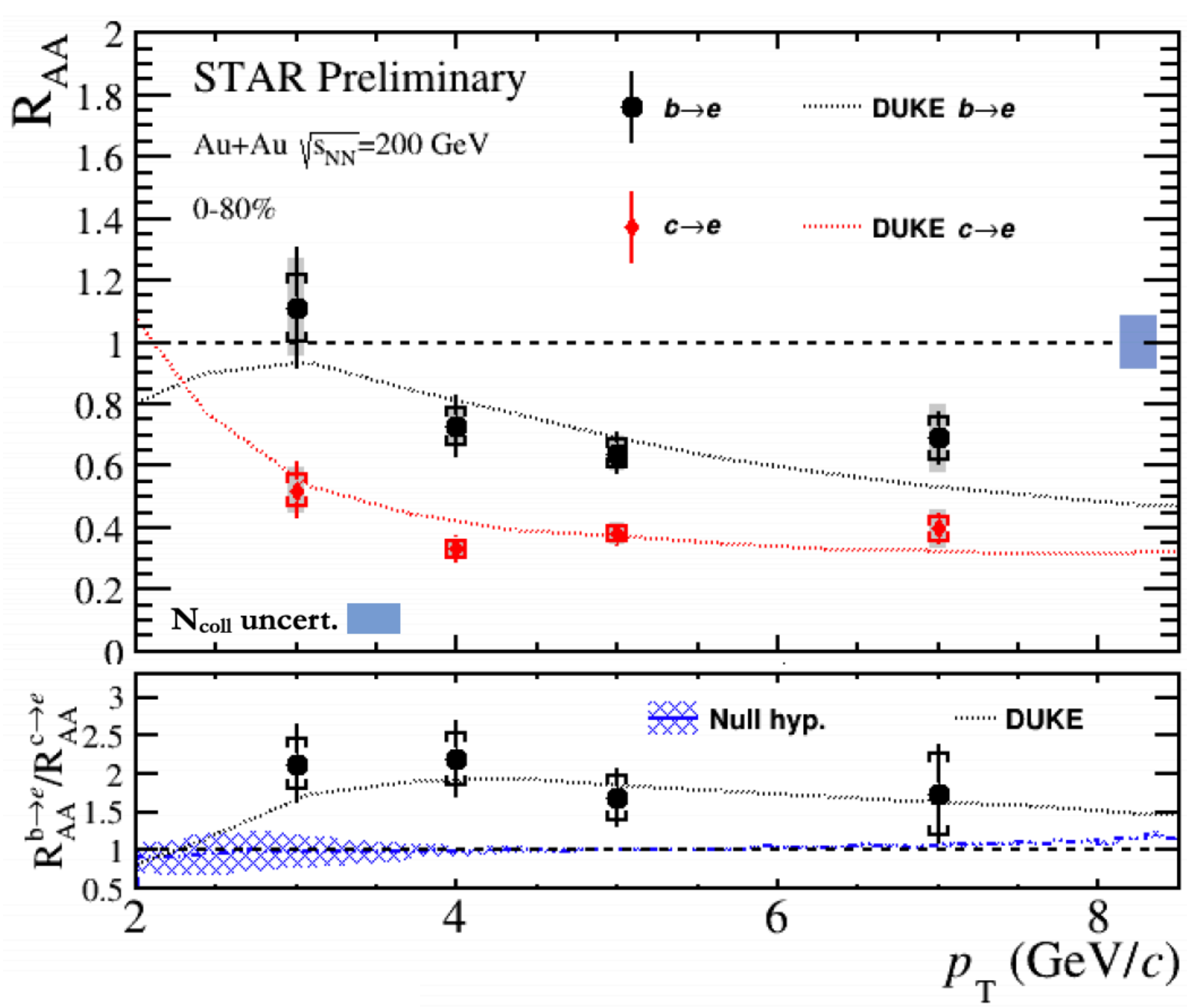

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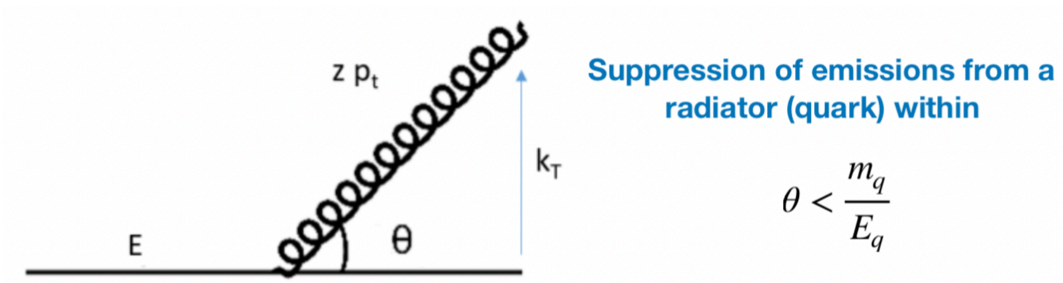
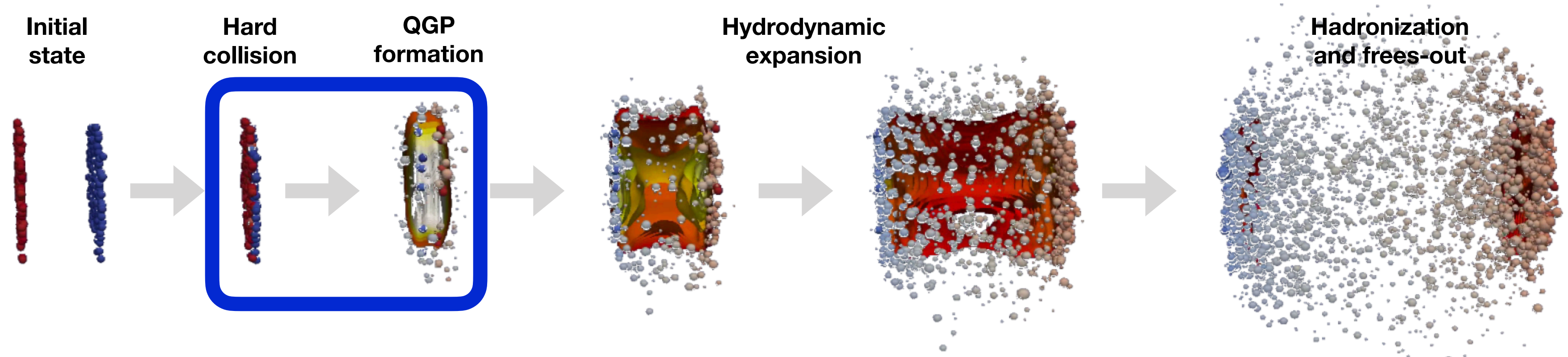


Hint of flavour dependence of in-medium energy loss

Heavy flavour energy loss



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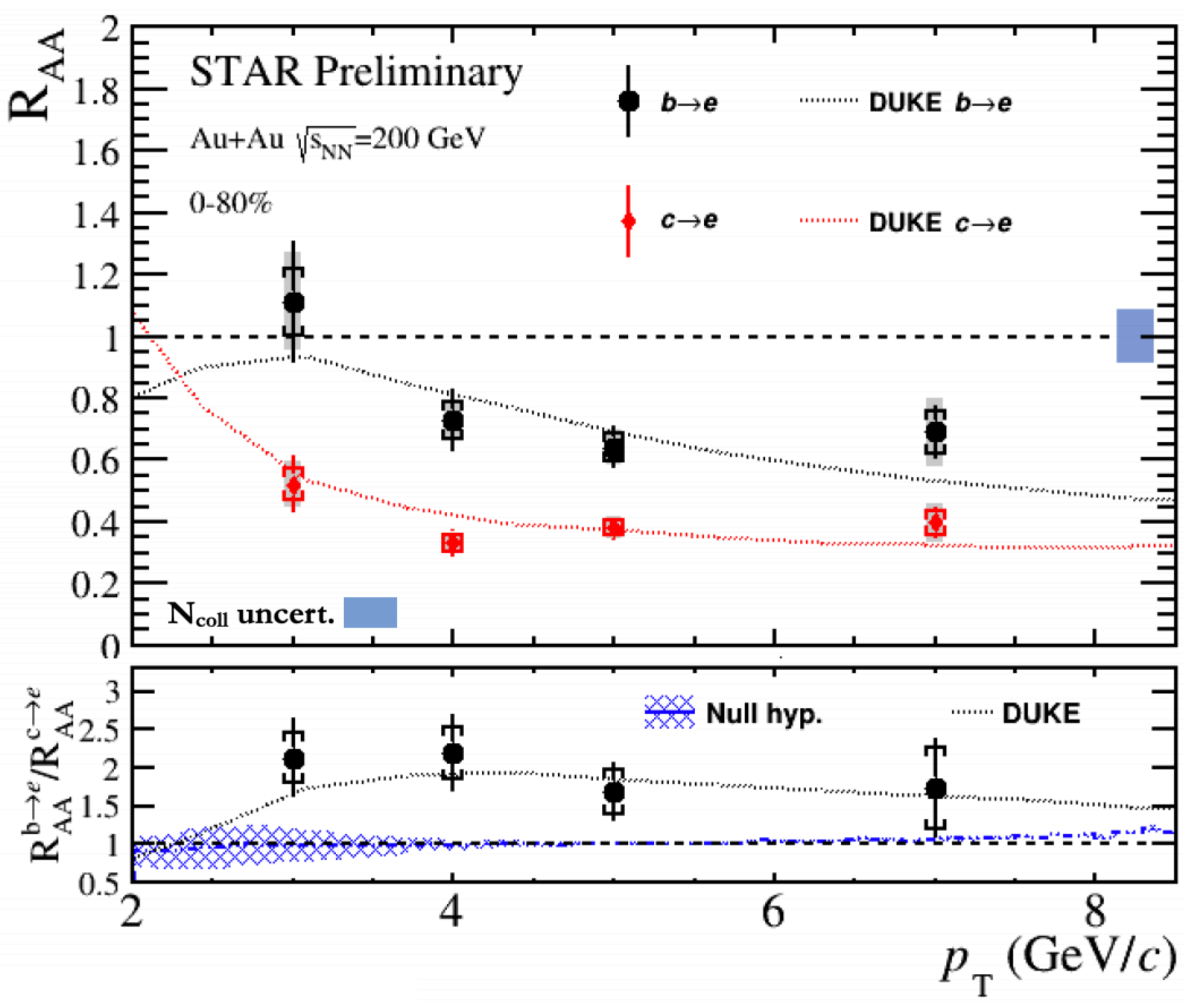
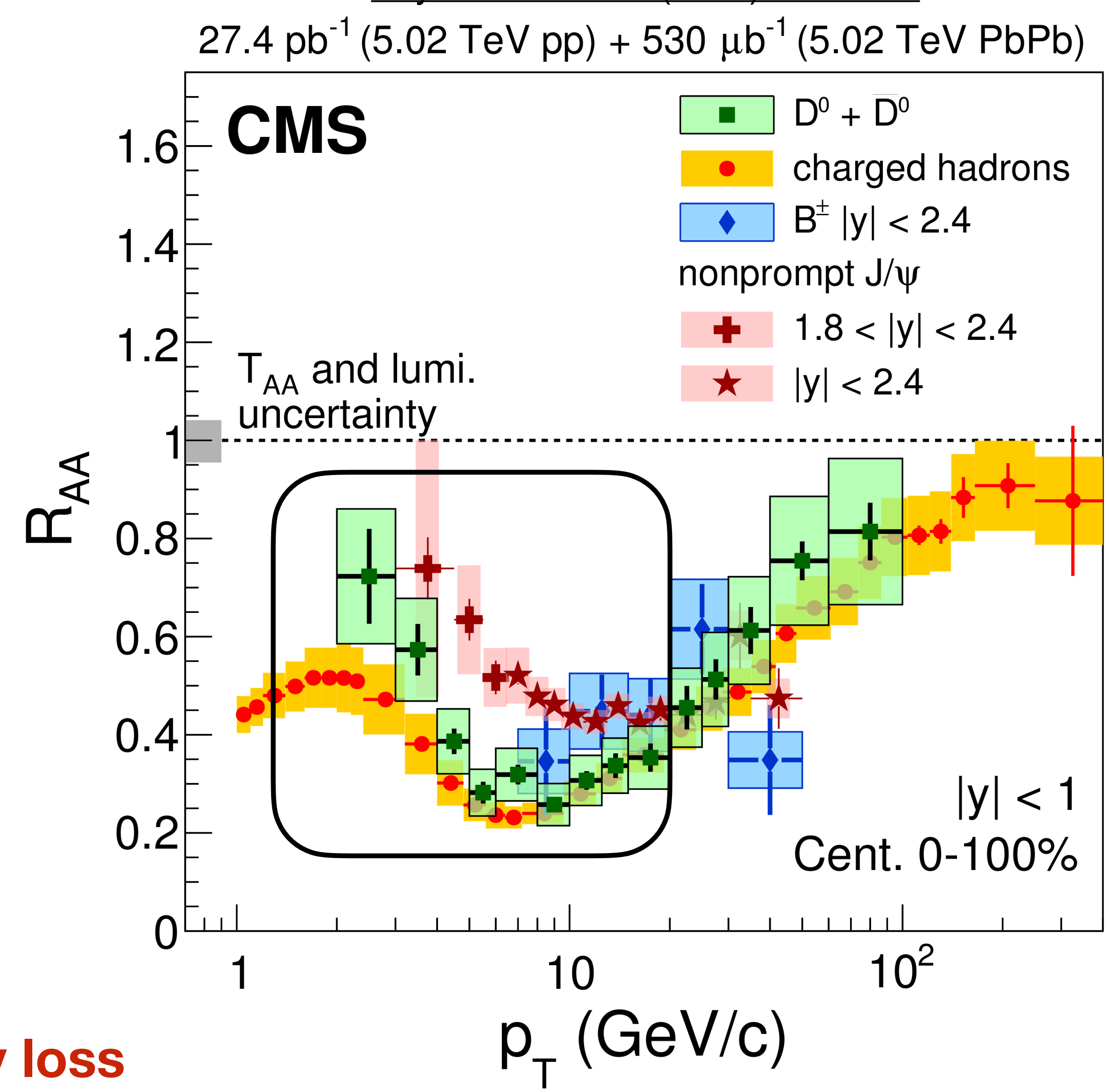


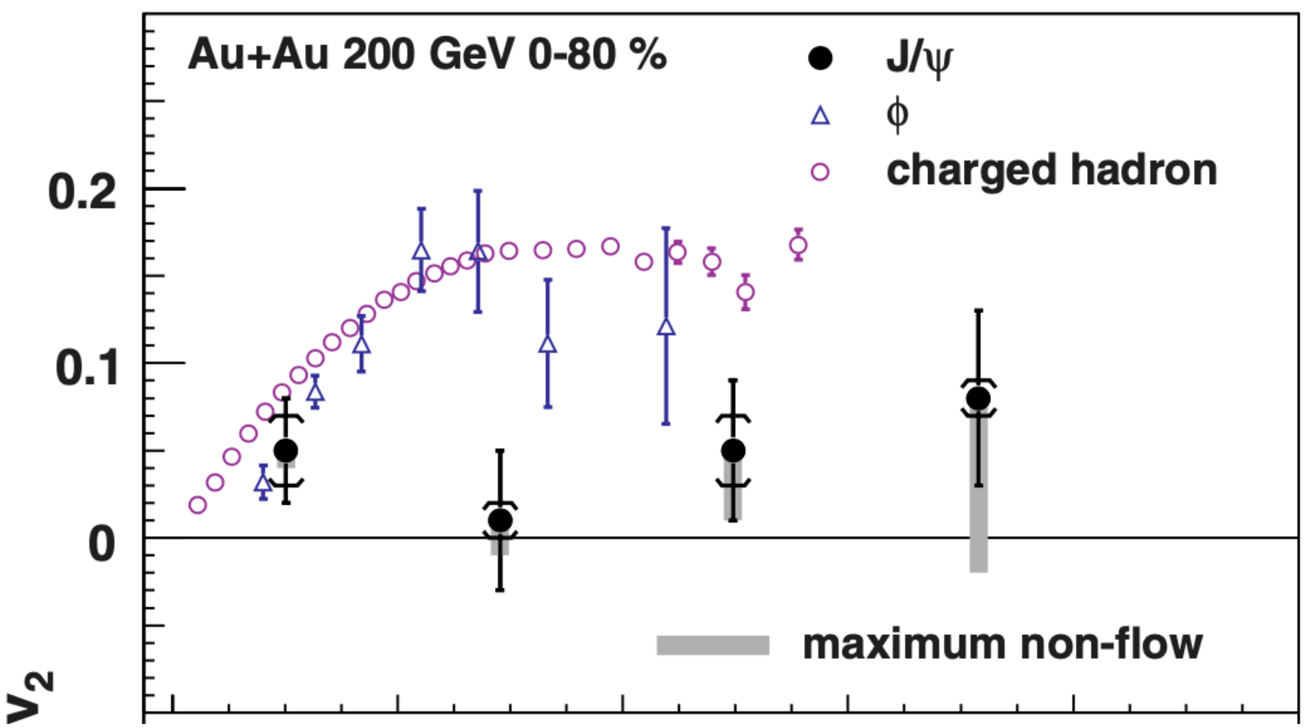
Phys. Lett. B 782 (2018) 474 et al.

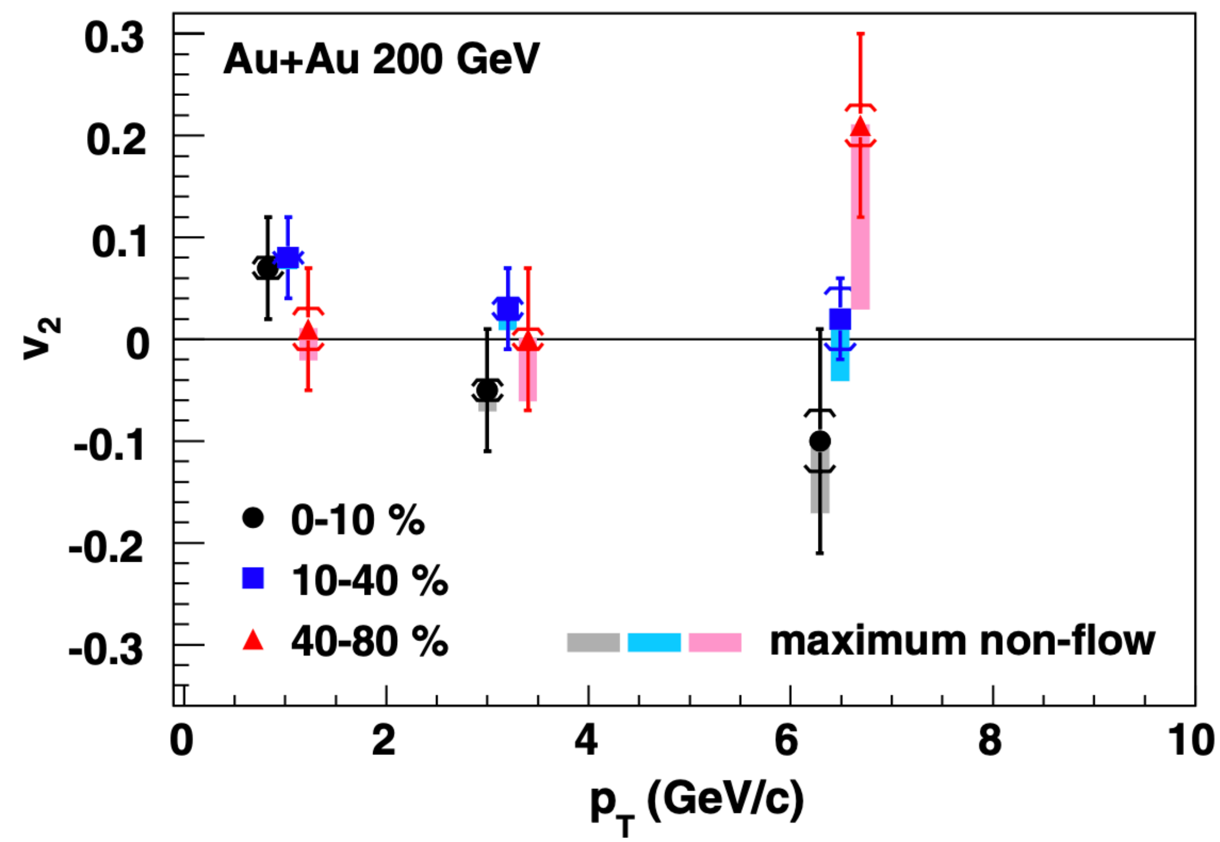


Hint of flavour dependence of in-medium energy loss

Elliptic flow in heavy-ion collision

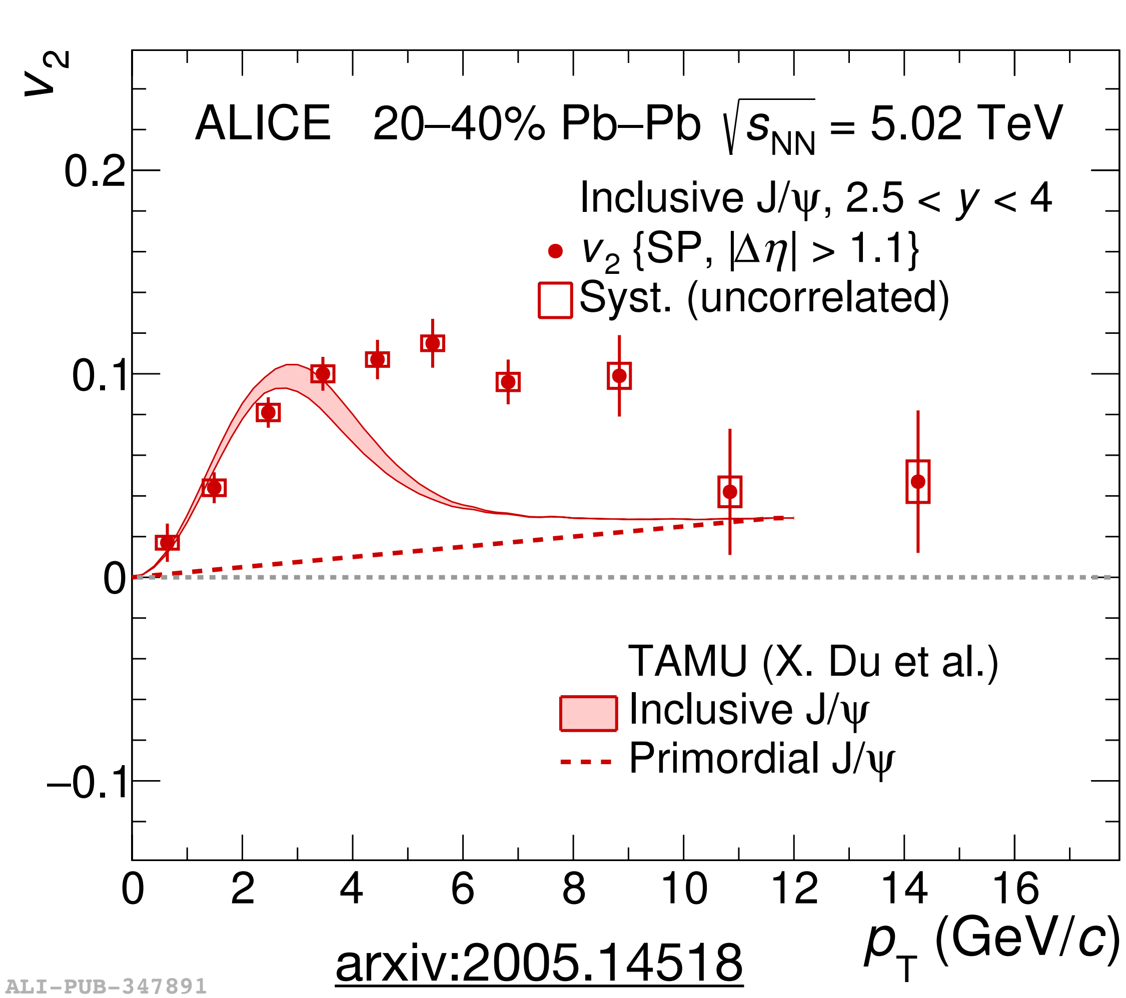
PRL 111, 052301 (2013)



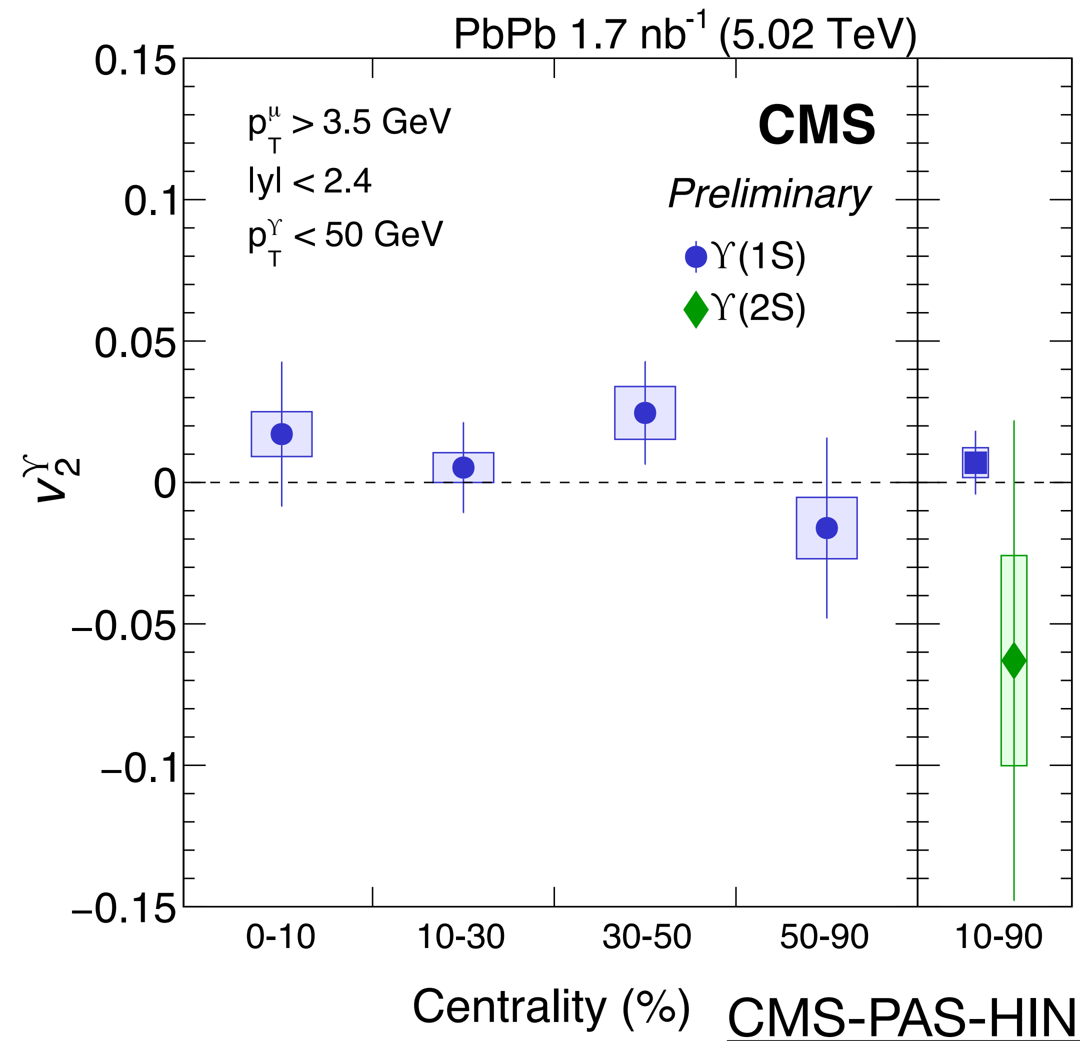


- v_2 ~ 0 for Charmonium state unlike charged hadrons.
- Consistent in all centrality bins → Hints charmonium doesn't flow at all.

Elliptic flow in heavy-ion collisions



arxiv:2005.14518

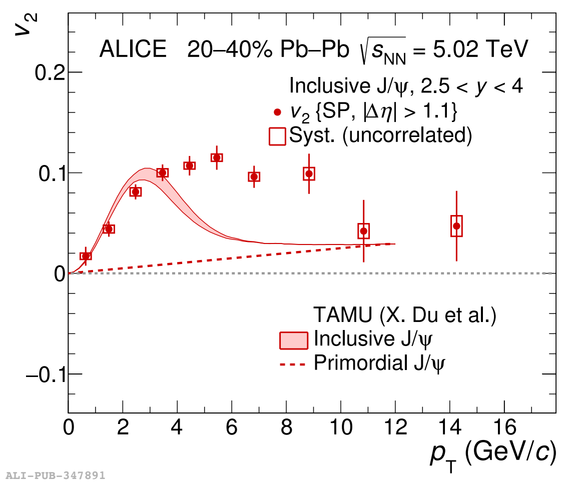


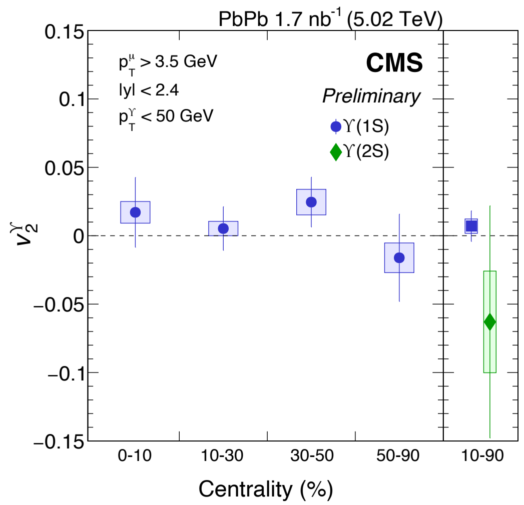
CMS-PAS-HIN-19-002

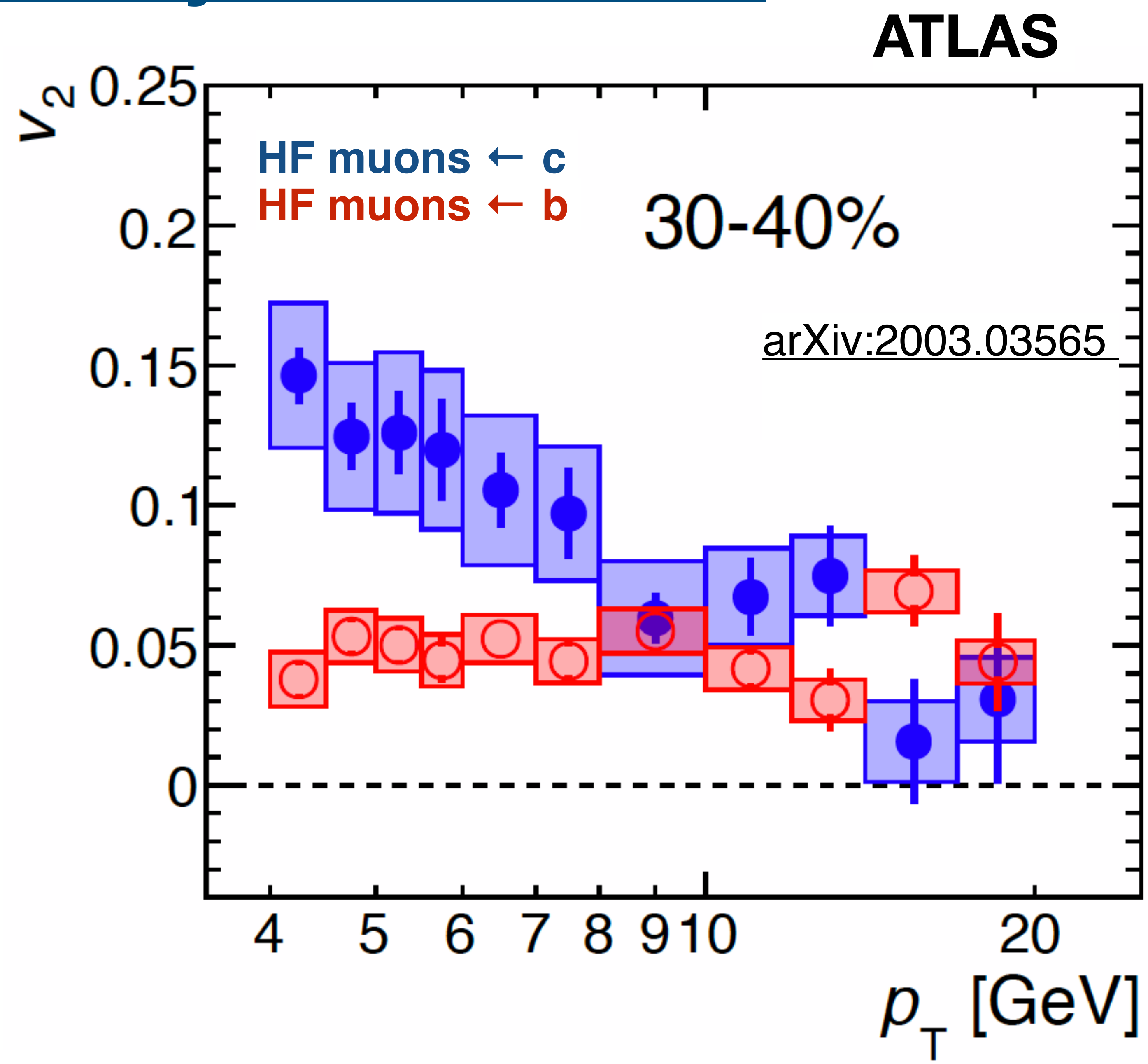
- Charmonium state exhibit large flow.
- v_2 ~ 0 for bottomonium states. Both ϒ(1S) and ϒ(2S) shows negligible flow.

→ charm flows but not beauty?

Elliptic flow in heavy-ion collisions







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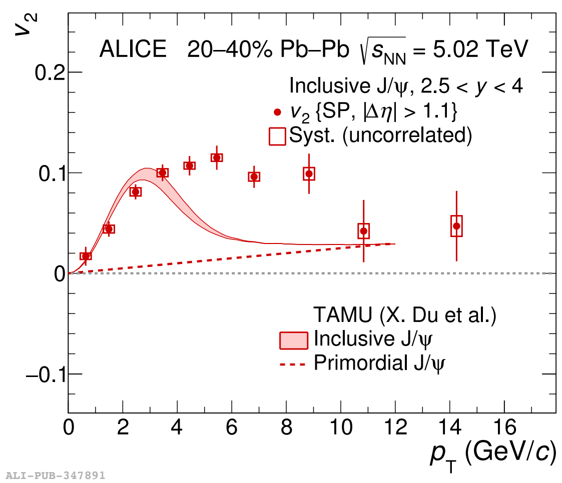
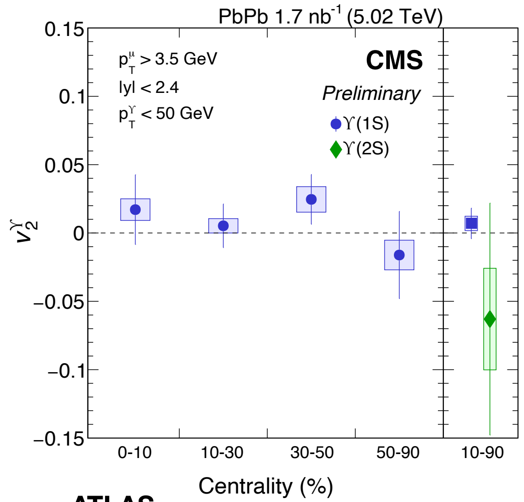
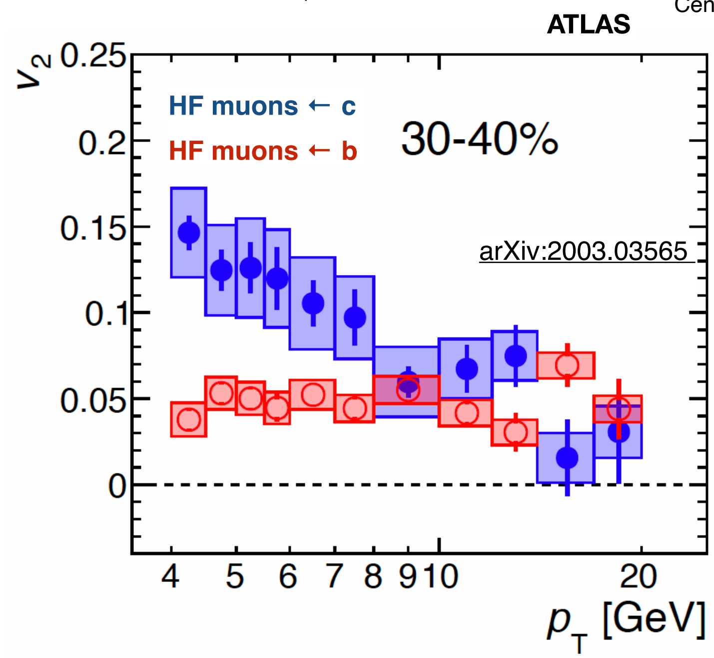
- **v_2 significantly > 0 for HF muons ← c.**
- **v_2 smaller but still >0 for HFmuons ← b.**

} → open charm and open beauty both flow

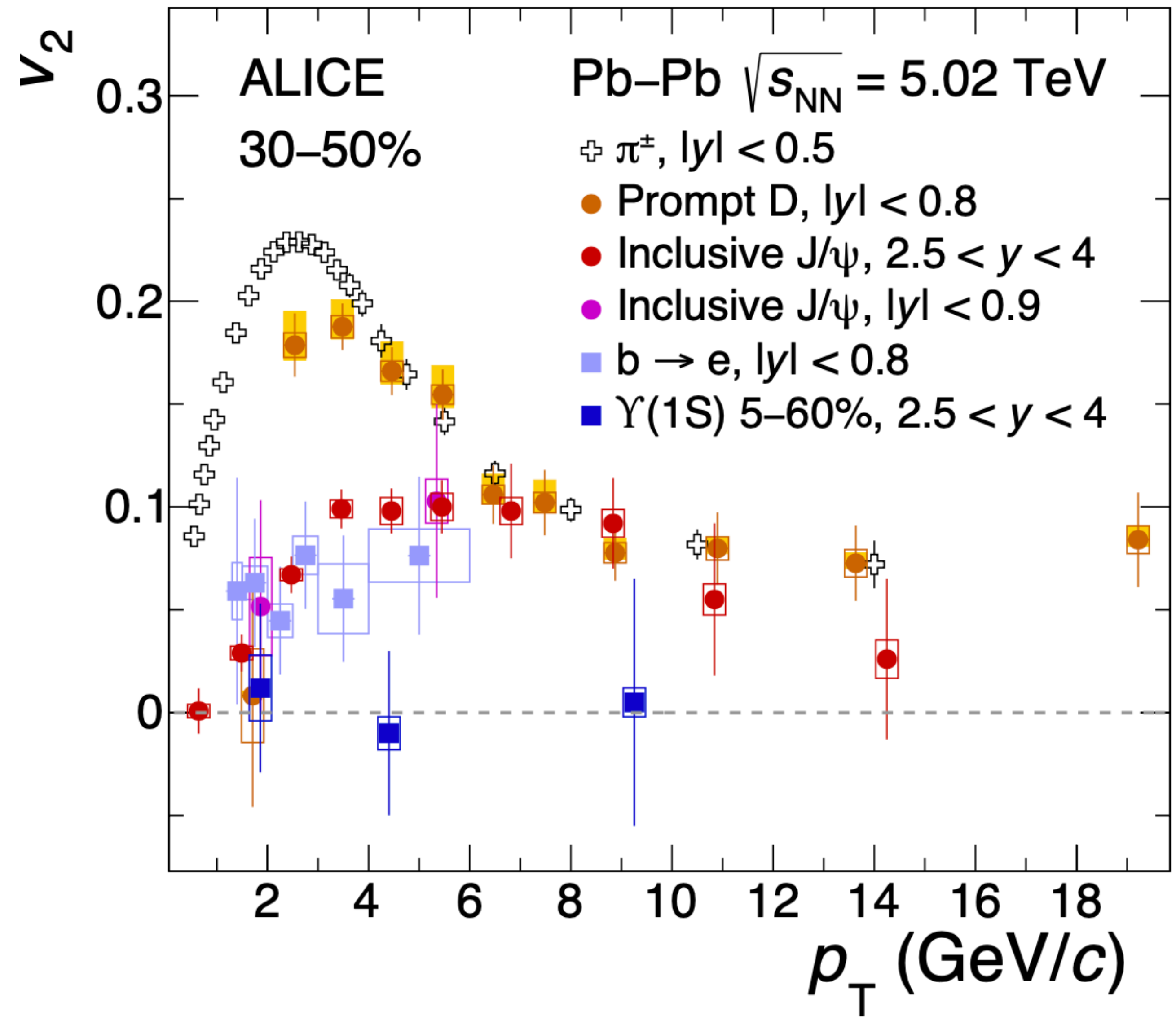
Elliptic flow in heavy-ion collisions







arXiv.2005.11130



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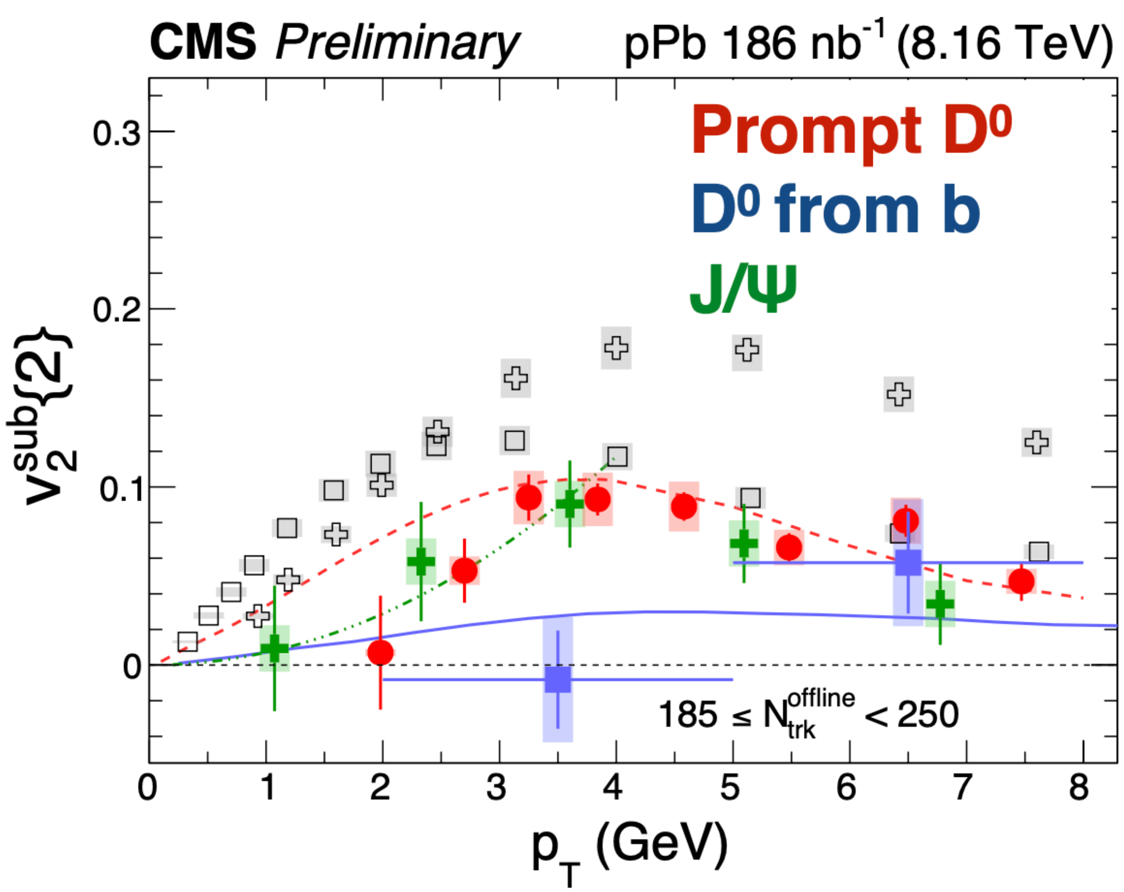
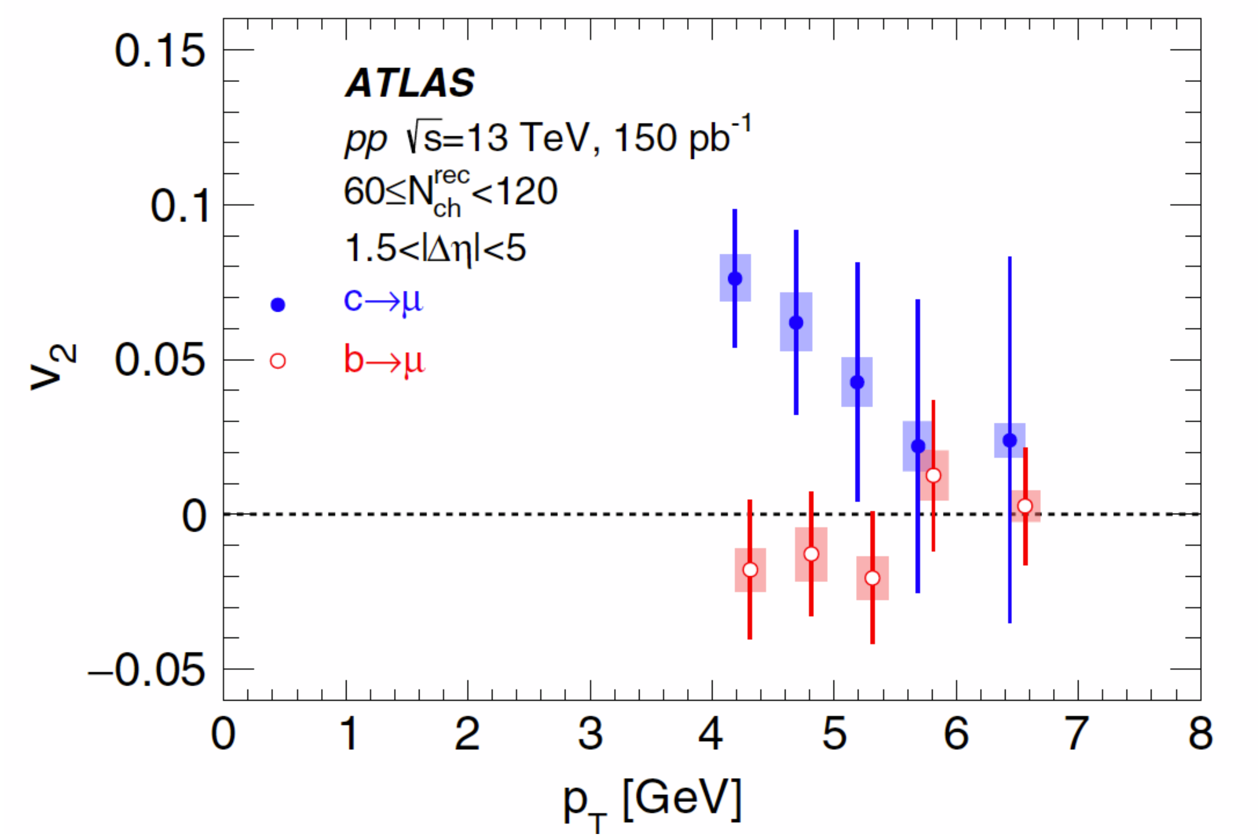
Inheriting the flow from the light quark forming the HF hadron?

Elliptic flow in small system

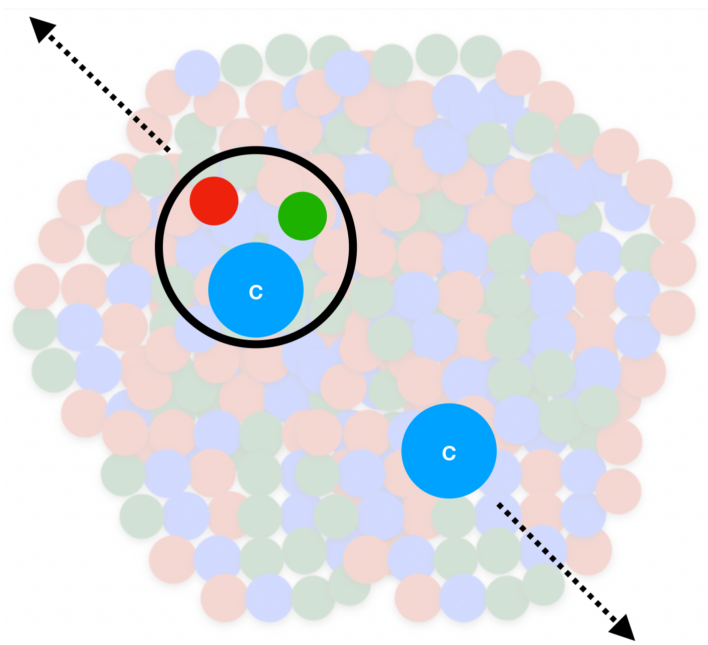


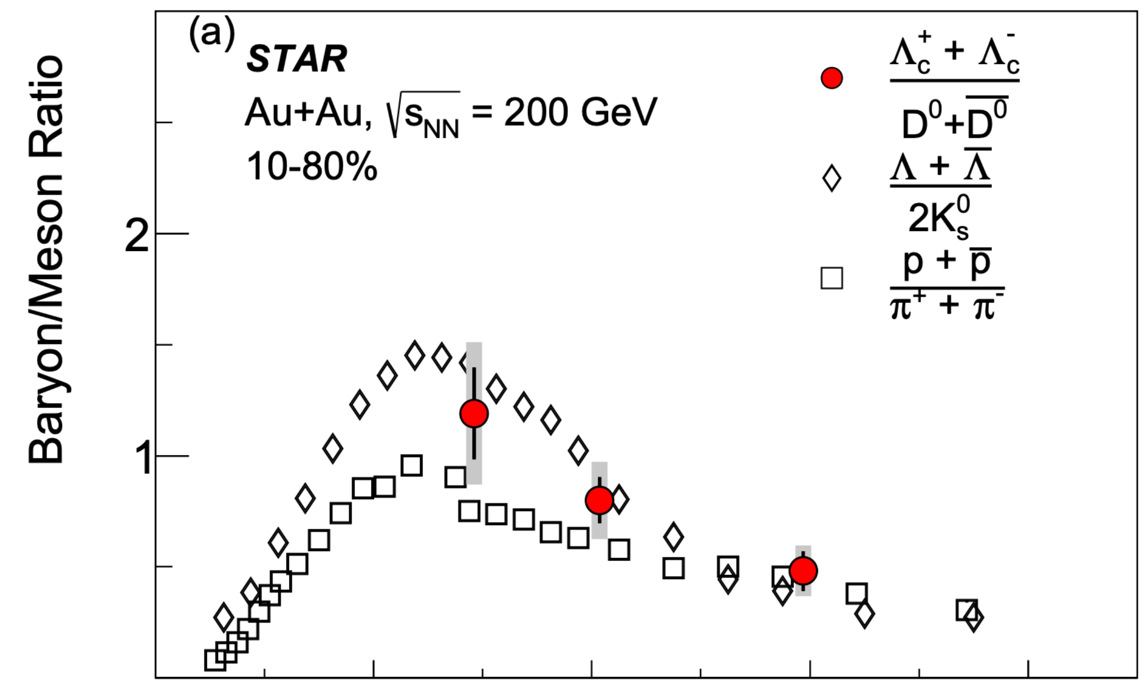
PRL 124, 082301 (2020)



- indicate charm open and bound state positive v_2 also in small system.
- b-hadron flow v_2 ~ 0 . Is beauty too heavy to flow?

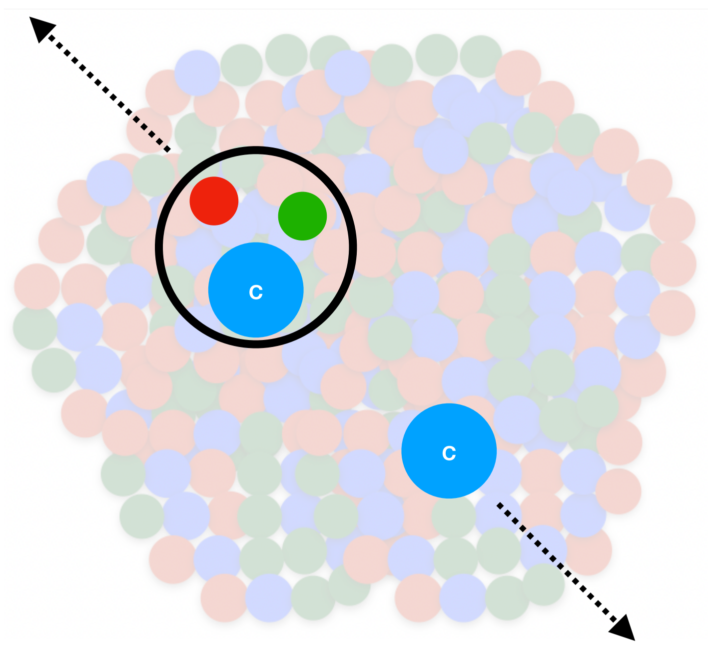
Hadronisation of charmed hadrons

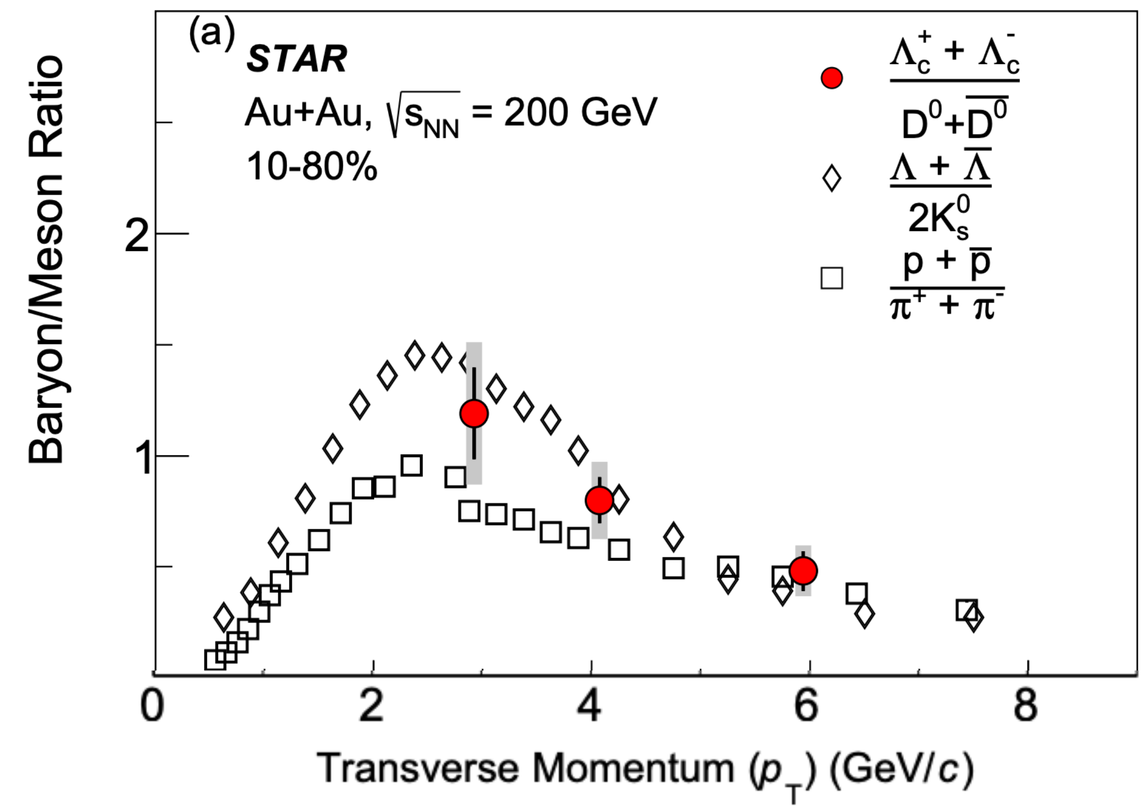


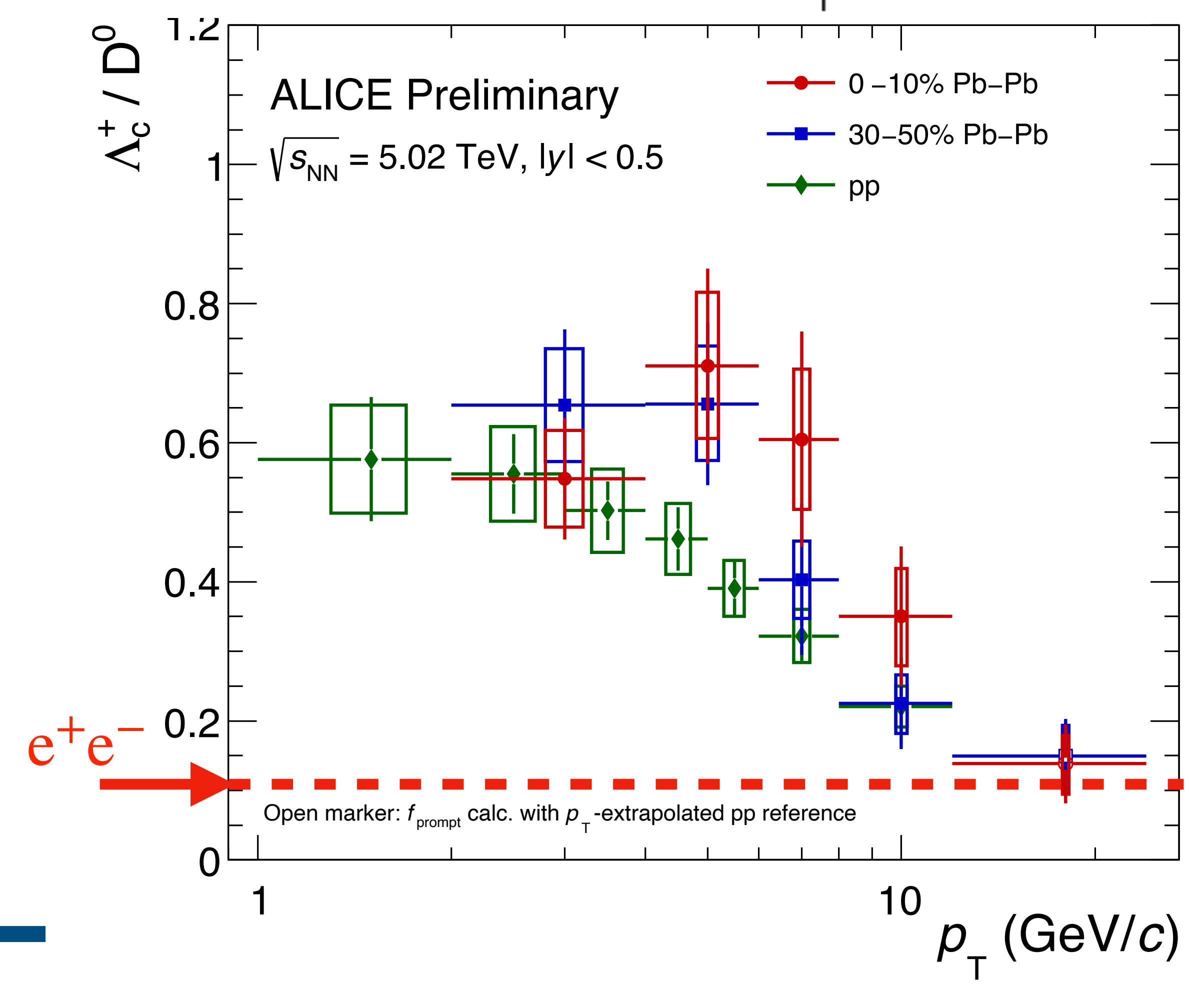


- Λ_c^+/D^0 ratio is expected to increase in the presence of charm recombination in the QGP
- Λ_c^+/D^0 ratio in PbPb shows moderate enhancement from pp at intermediate pT within uncertainties
  - Hadronization is modified already in pp collisions?

Hadronisation of charmed hadrons







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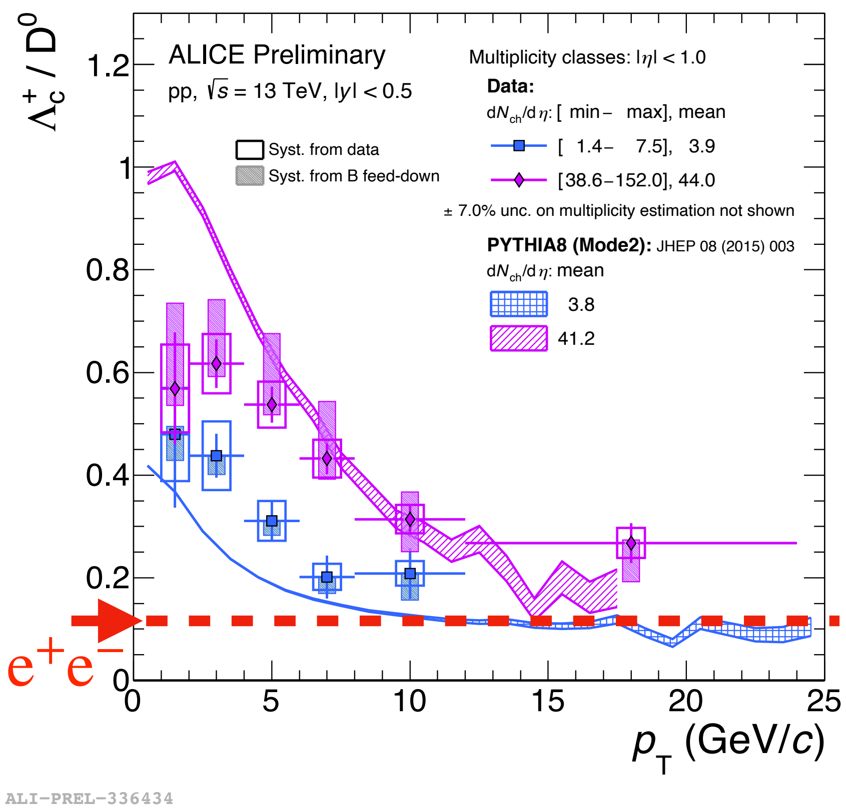
Hadronisation of charmed hadrons

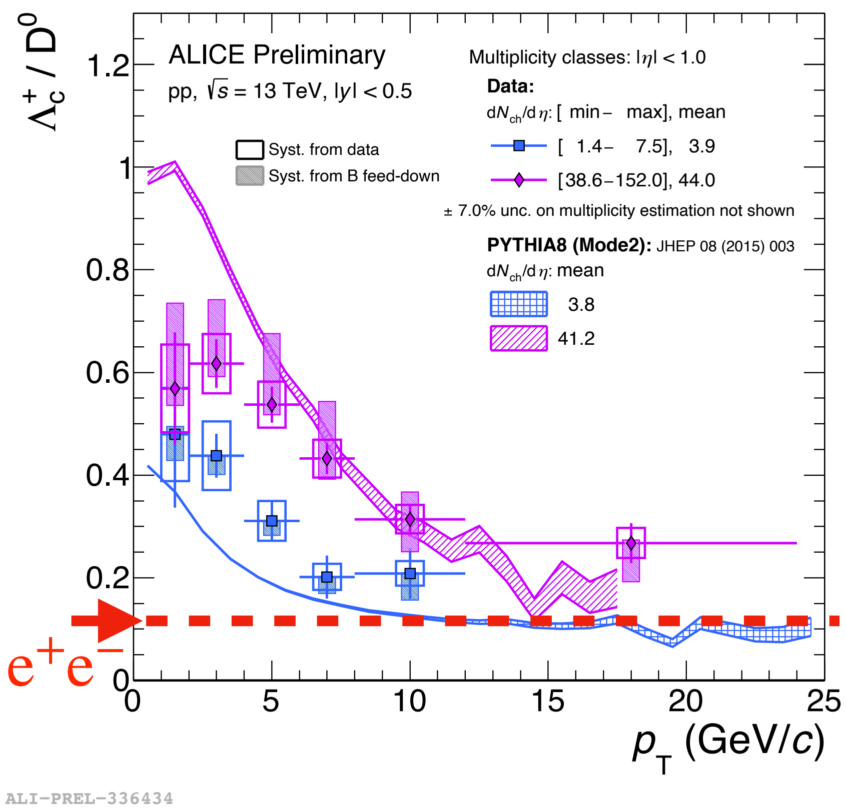
Hadronisation in pp very different than in e^+e^- and depends on multiplicity

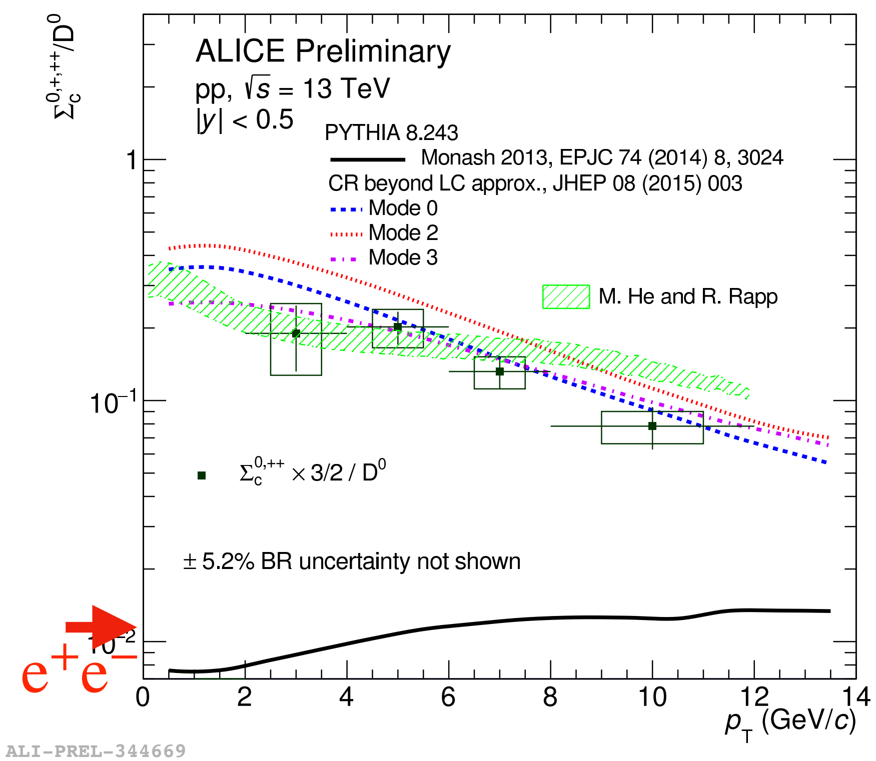


- Λ_c^+/D^0~ x10 larger than in e^+e^-
- PYTHIA color reconnection tune Mode 2.

Hadronisation of charmed hadrons

Hadronisation in pp very different than in e$^+$e$^-$ and depends on multiplicity



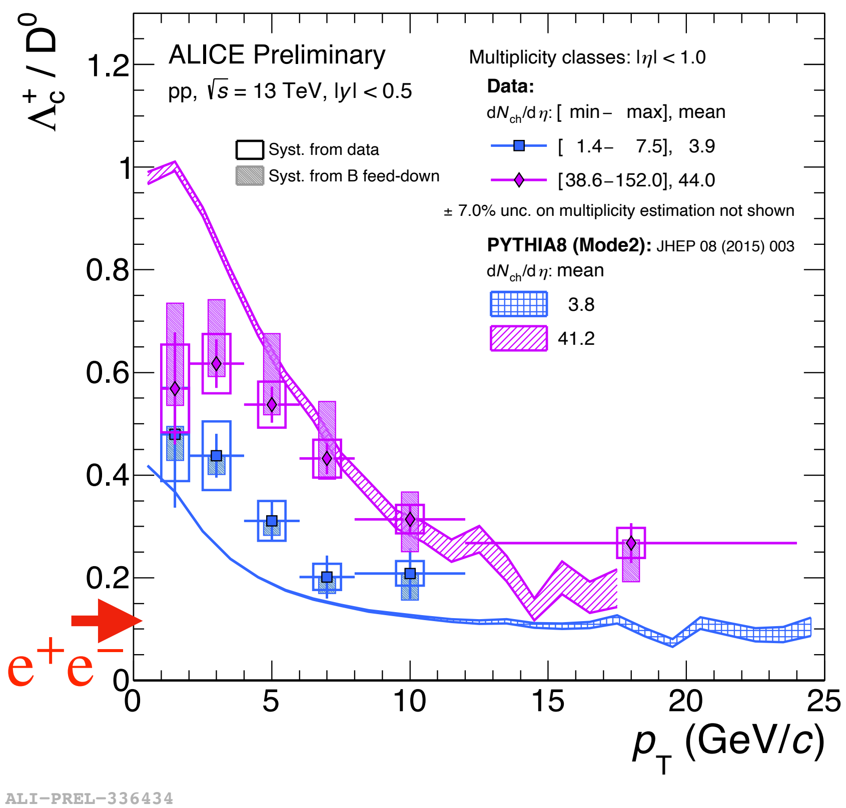


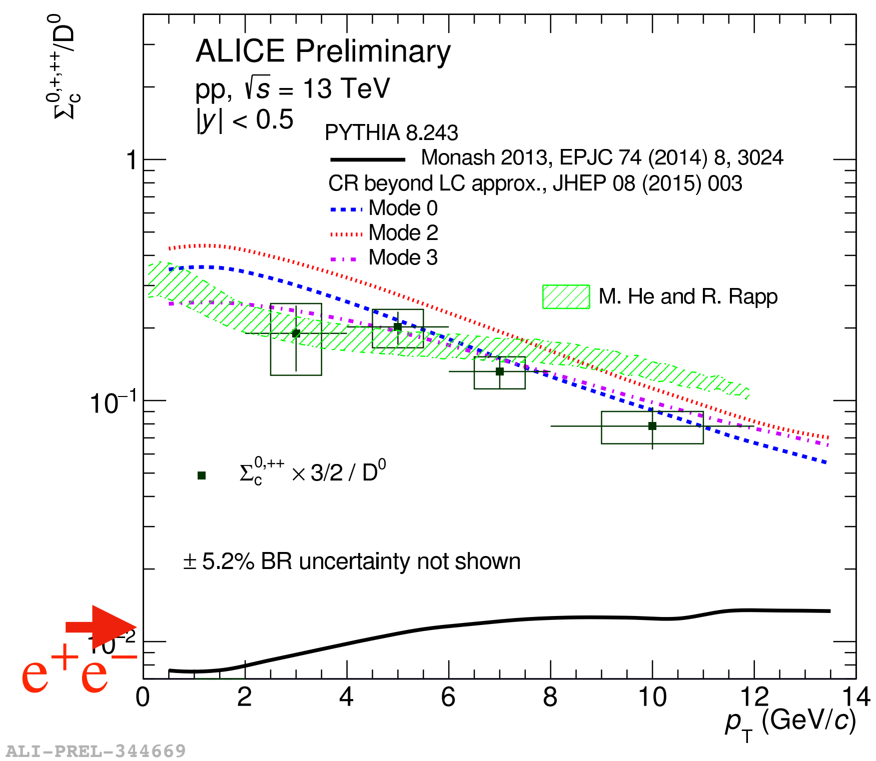
- ☑ Λ_c^+/D^0~ x10 larger than in e$^+$e$^-$
- ☑ PYTHIA color reconnection tune Mode 2.

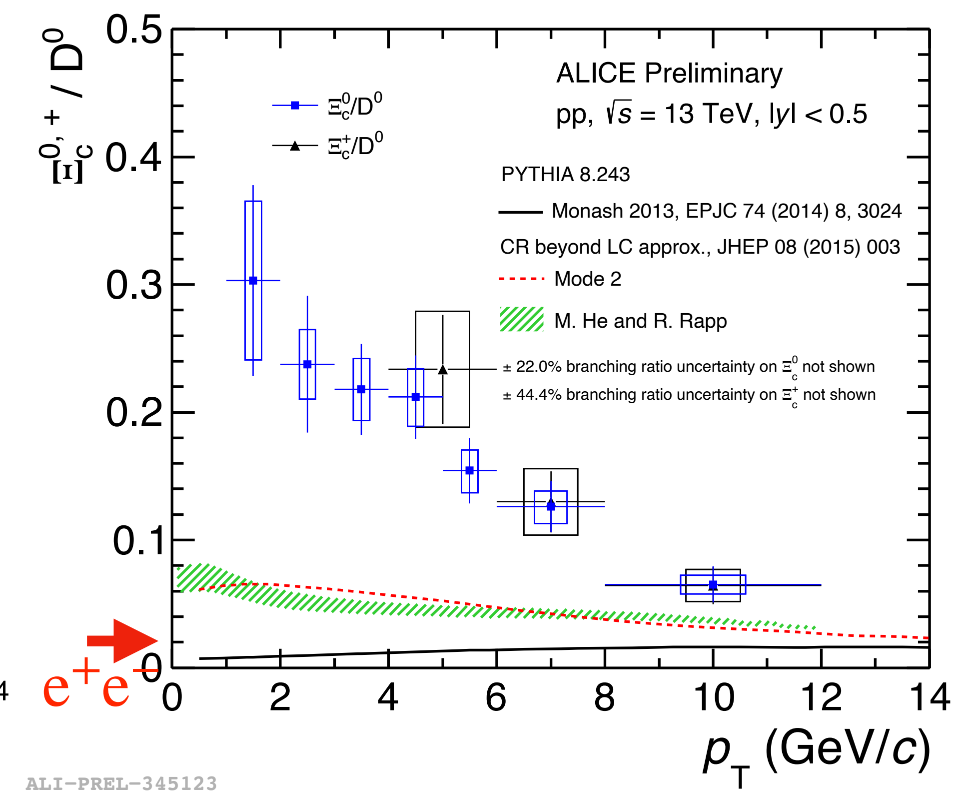
- ☑ Σ_c/D^0~ x20-30 larger than in e$^+$e$^-$
- ☑ PYTHIA color reconnection tune Mode 2.

Hadronisation of charmed hadrons

Hadronisation in pp very different than in e^+e^- and depends on multiplicity







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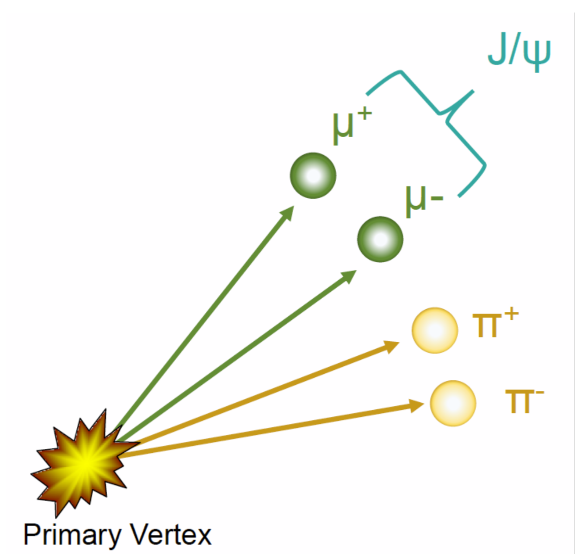
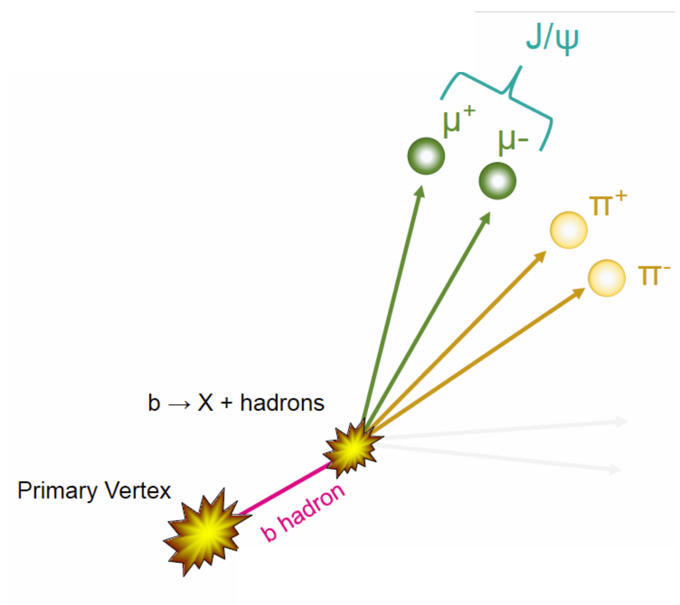
New experimental probe: X(3872) particle

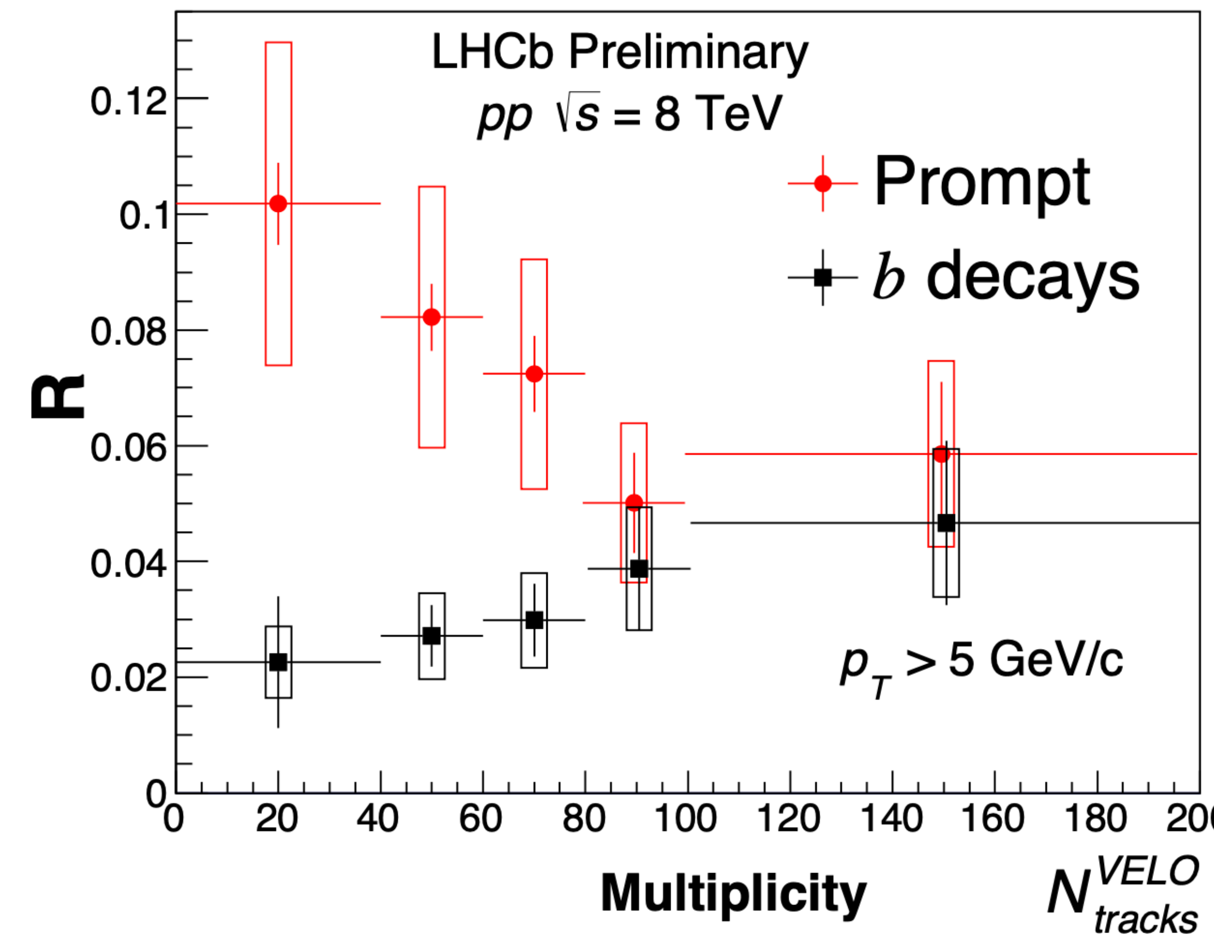
Observed first time by Belle in 2003 ($M_{X(3872)} \sim 2\ M_D$)





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

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



LHCb-CONF-2019-005

Prompt $N_{X(3872)}$ / $N_{\psi(2S)}$ decreases as a function of multiplicity:

→ loosely bound states destroyed by hadronic interactions?

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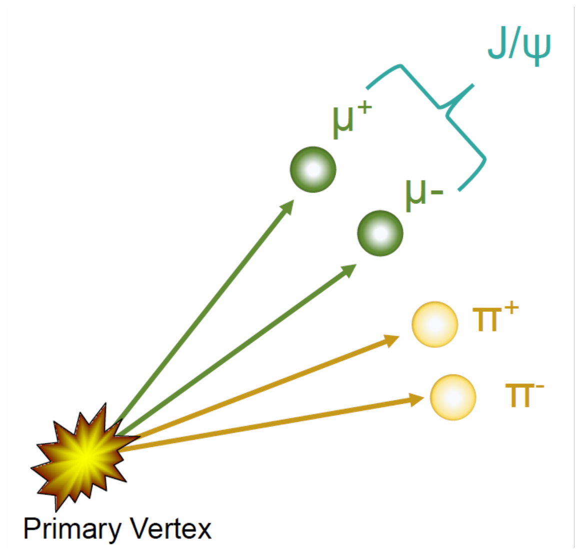

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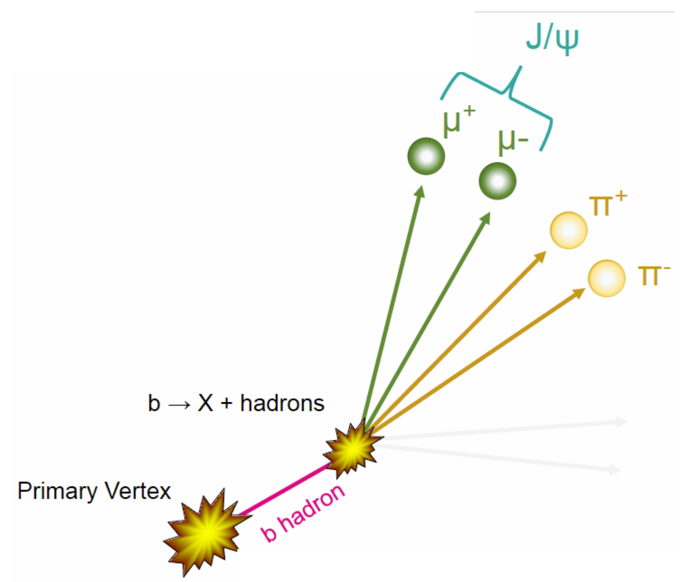
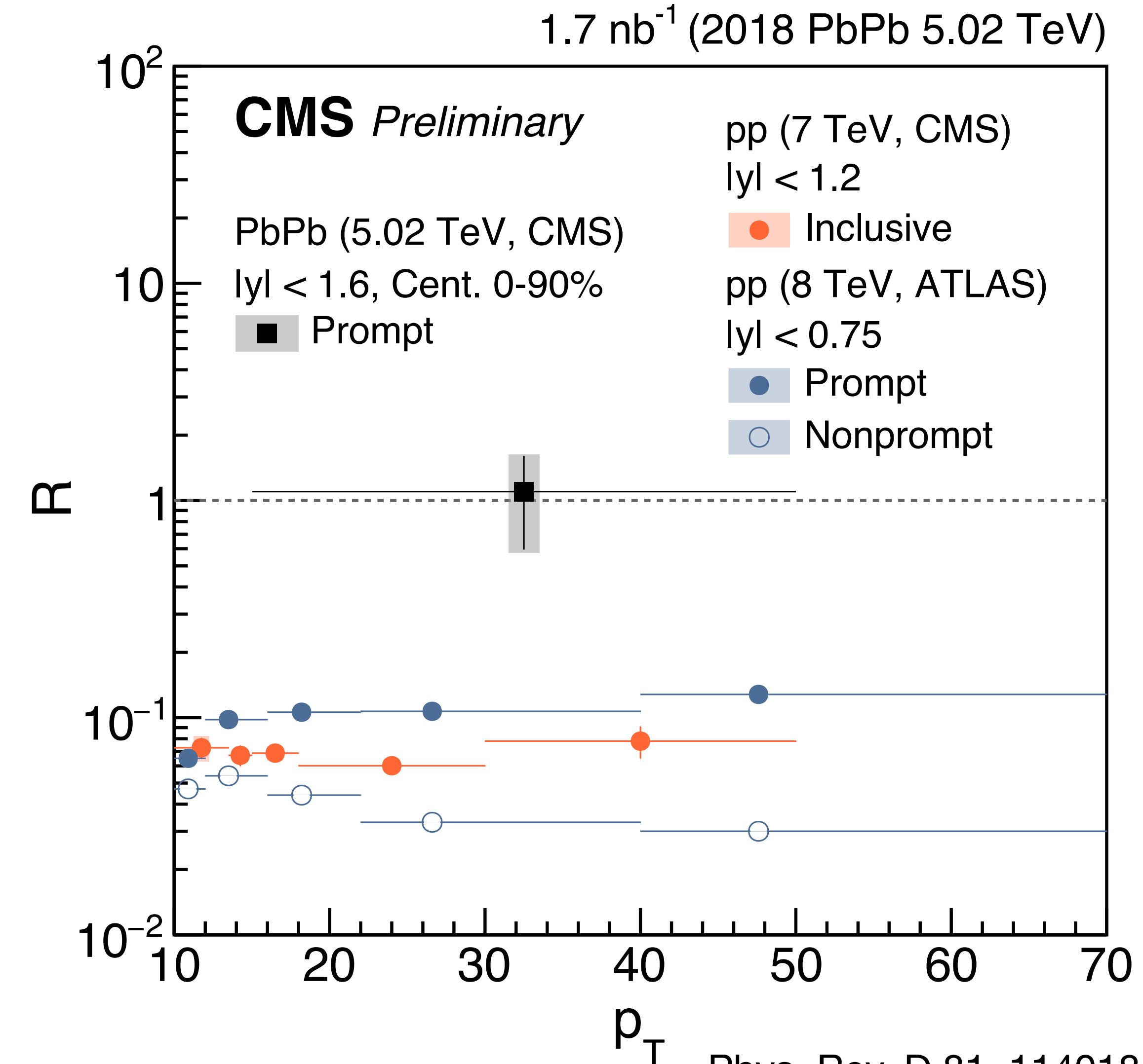


b-feeddown: interact with the medium as a b-hadron



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

→ sensitive to mechanisms of recombination in the QGP? → **more statistics is needed**

Summary

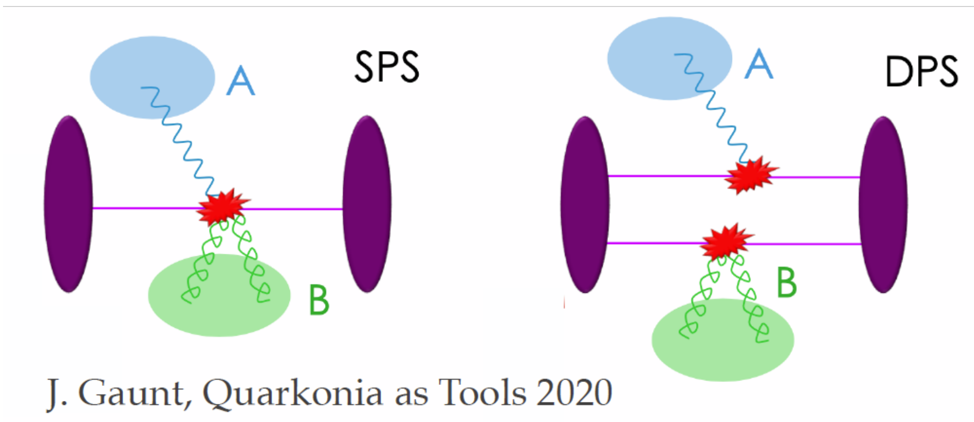
- Detailed insight on the QGP in heavy ion system using heavy quark from their production to their “journey” into the medium until the formation of heavy-flavour hadrons.
  - Heavy quark interaction.
  - quarkonia dissociation
  - Energy loss measurement.
  - Flow measurement.

- Heavy flavours used to constraint the properties of the small system
  - insights into the small system collective properties.
  - modification of hadronization mechanisms.

Thank you!

Backup slides

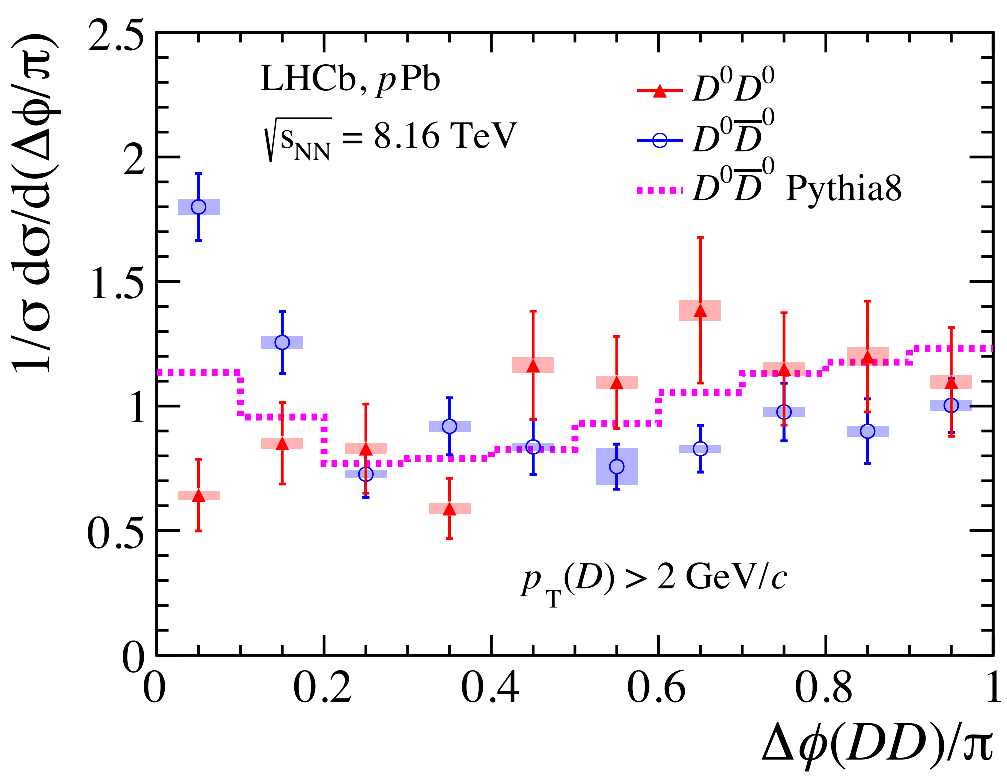
New experimental probe: Double charm

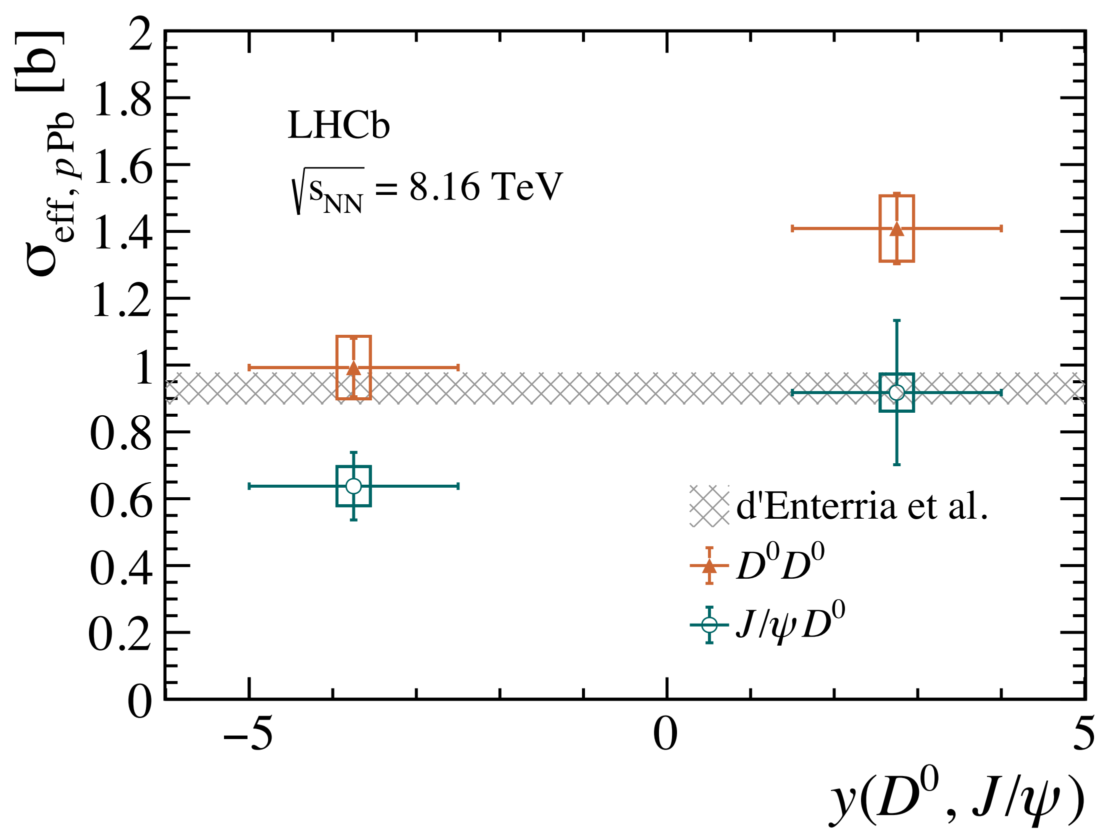


Double Parton Scattering (DPS): two independent scatterings in one pp collisions
→ transverse parton density and correlations

In pA collisions: enhanced DPS cross section due to larger transverse parton density.

arxiv::2007.06945v1

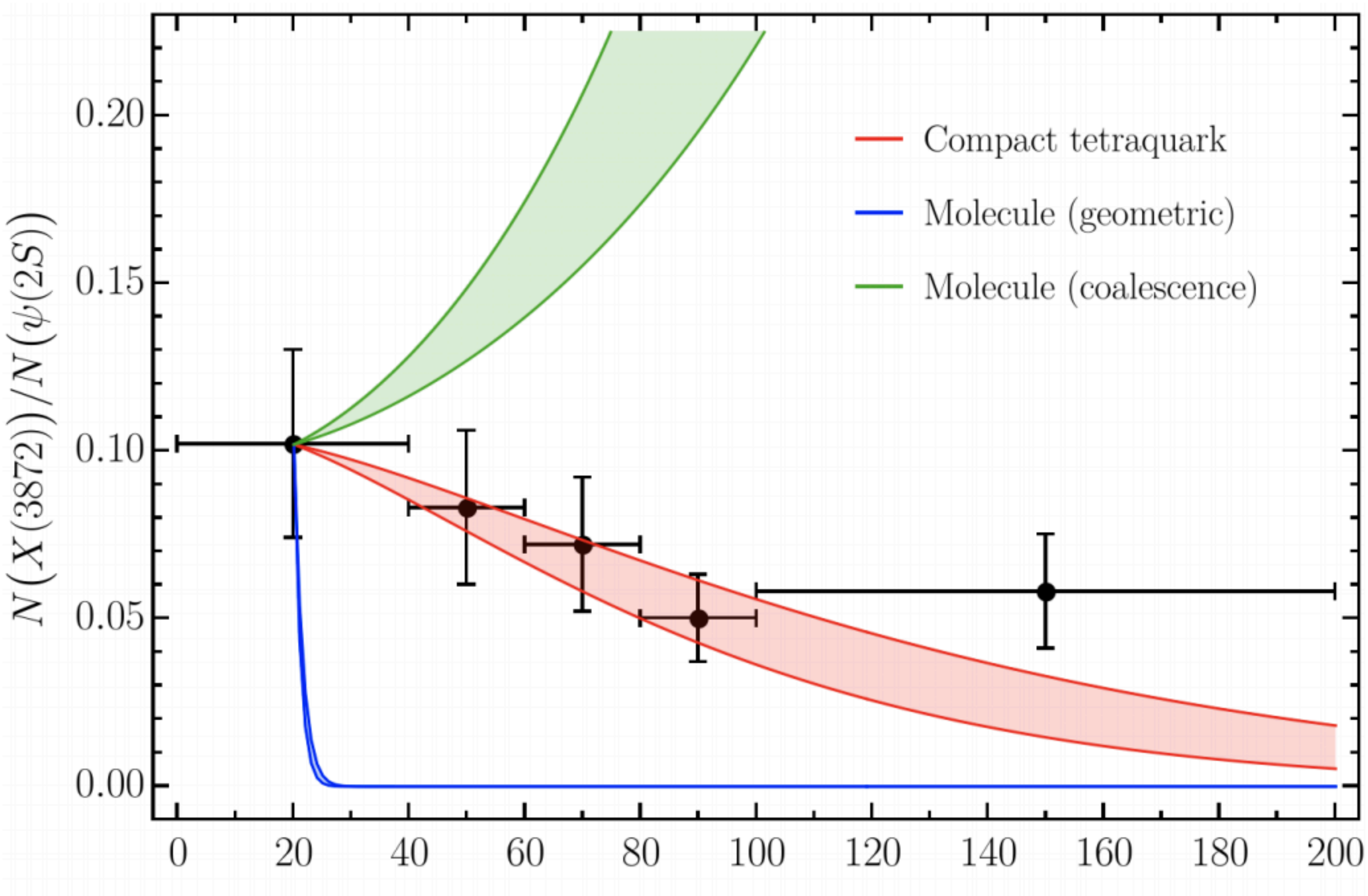




General good agreement with Pythia 8

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

arxiv:2006.15044

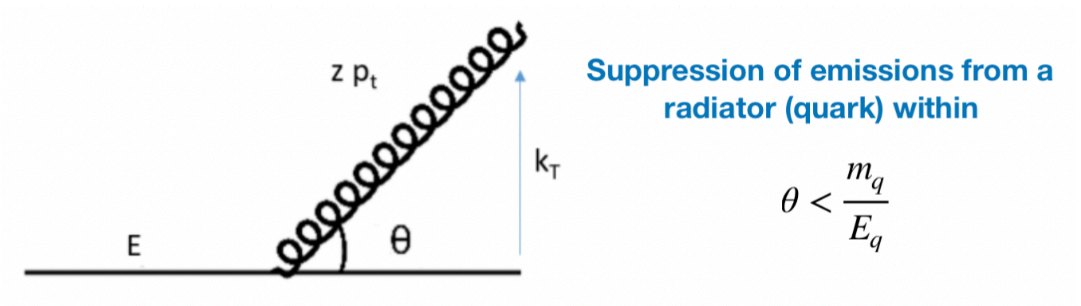


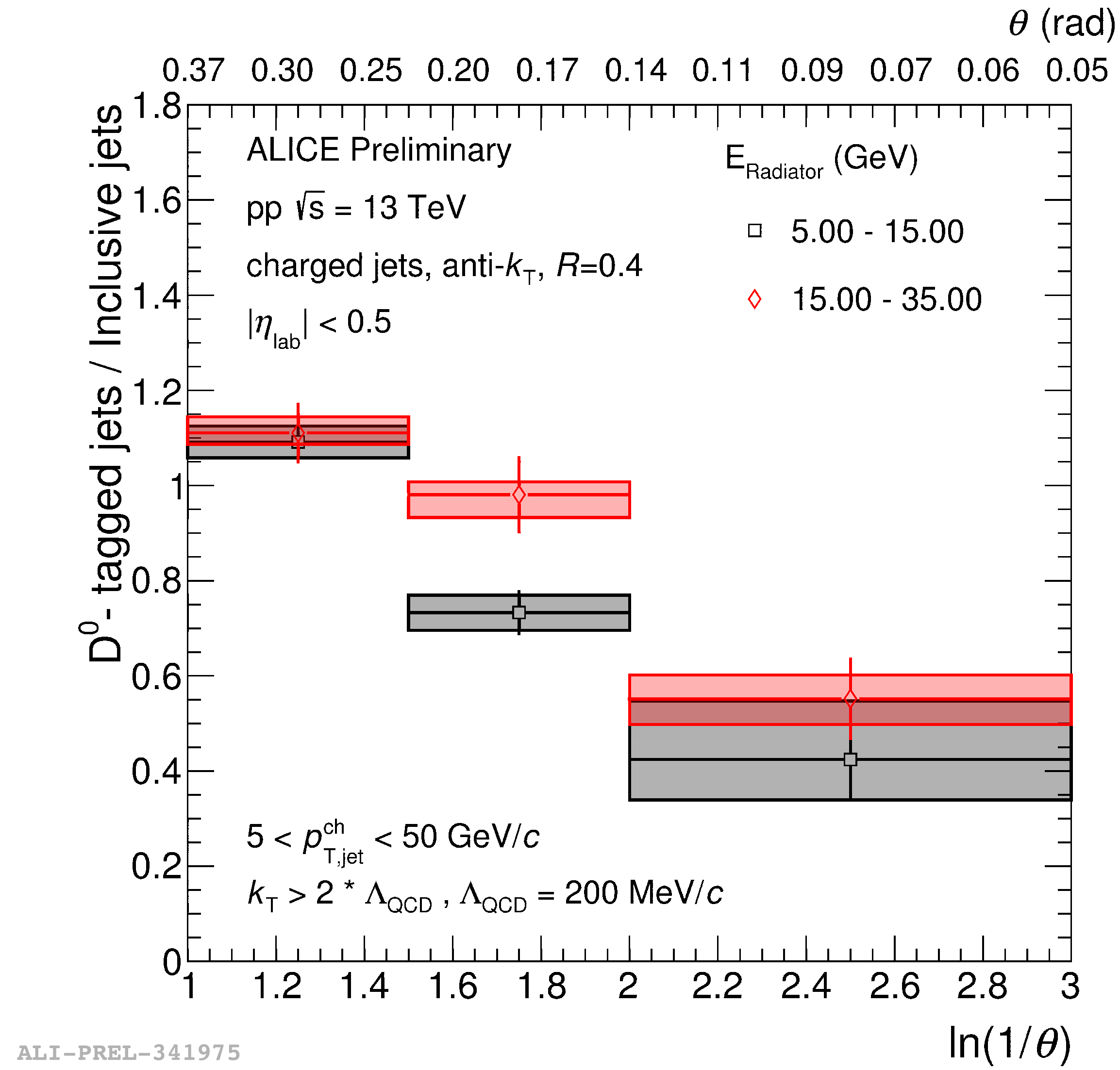
- The assumption of a tetraquark of size 1.3 fm reproduces well the experimental data.
- Extending the CIM to a molecular state via its geometrical cross section predicts a very sharp suppression.
- The coalescence picture predicts a qualitatively different behavior, still in clear contradiction with data

Heavy flavour energy loss: dead cone effect in pp

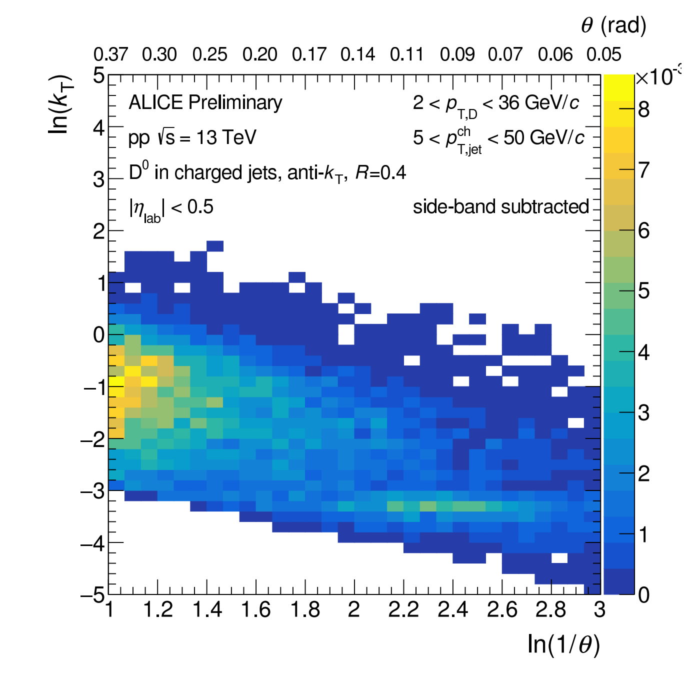
Energy loss in the medium due to.

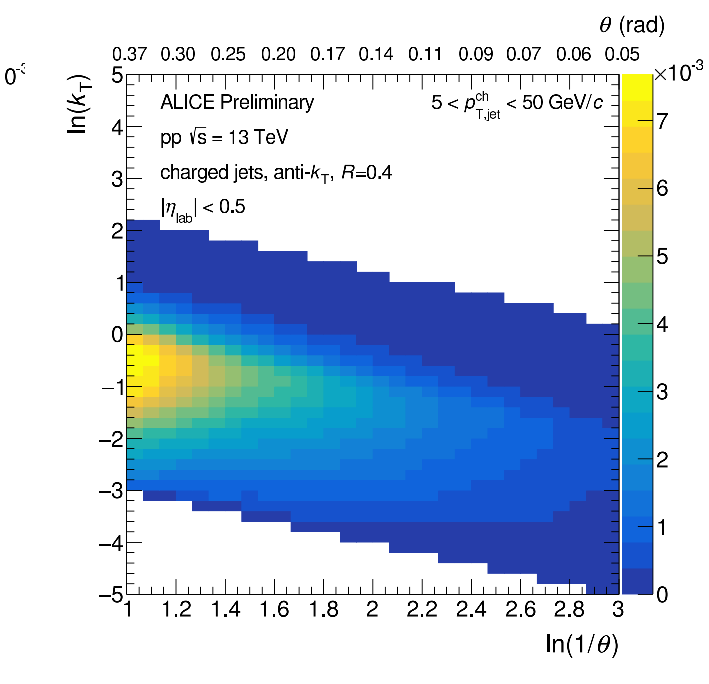
- Color charge (Casimir factor): $\Delta E_q < \Delta E_g$
- Dead cone effect (radiative energy loss): $\Delta E_b < \Delta E_c < \Delta E_{u,d,s,g}$





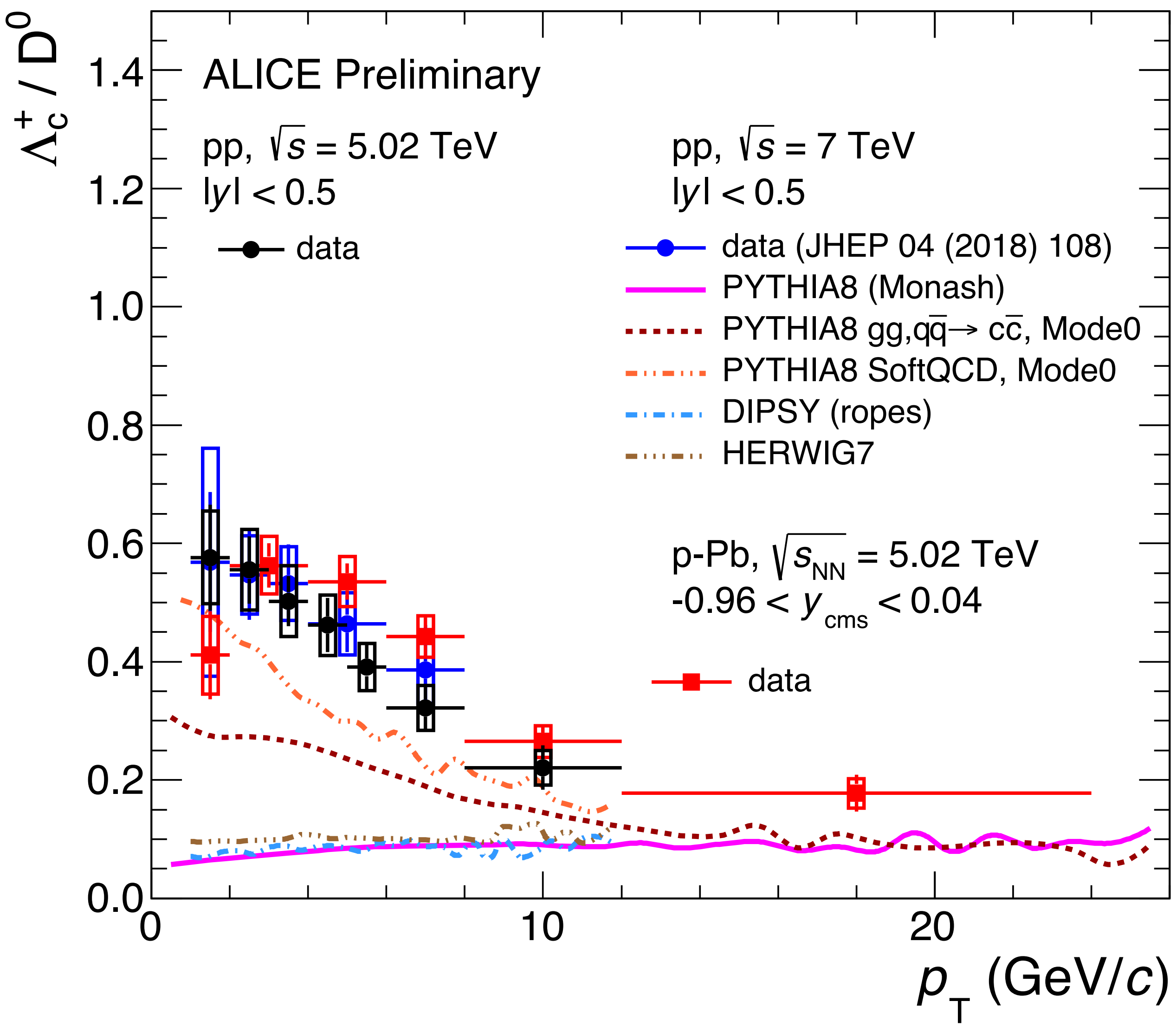
Lund plane:





First direct observation using jet iterative declustering and **Lund plane** analysis of jets that contain a soft D^0 meson

Charm baryon production in small systems



ALI-DER-314626

- Λ_c^+/D^0 significantly higher than expectation from e^+e^- collisions.
- Measurement in pp and pPb is compatible with each other with current uncertainty level.