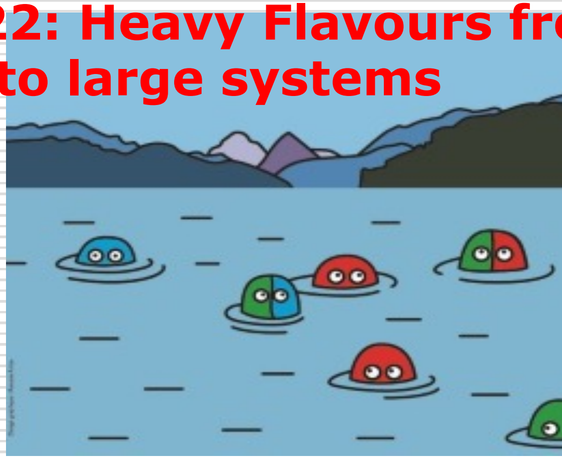
Characterization of the QGP with HF: an experimental overview

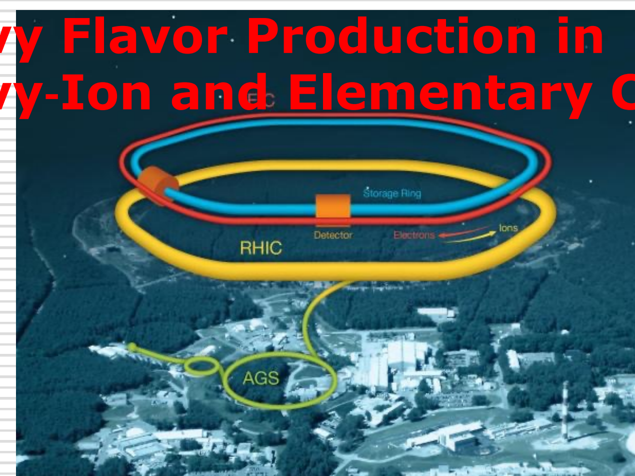
Giuseppe E Bruno
Dipartimento di Fisica and INFN – Bari –Italy

Joint seminar between
HF2022 (Inst. Pascal) and programme INT-22-3 (INT Seattle)

HF2022: Heavy Flavours from small to large systems



Heavy Flavor Production in Heavy-Ion and Elementary Collision



Orsay - October the 12th 2022

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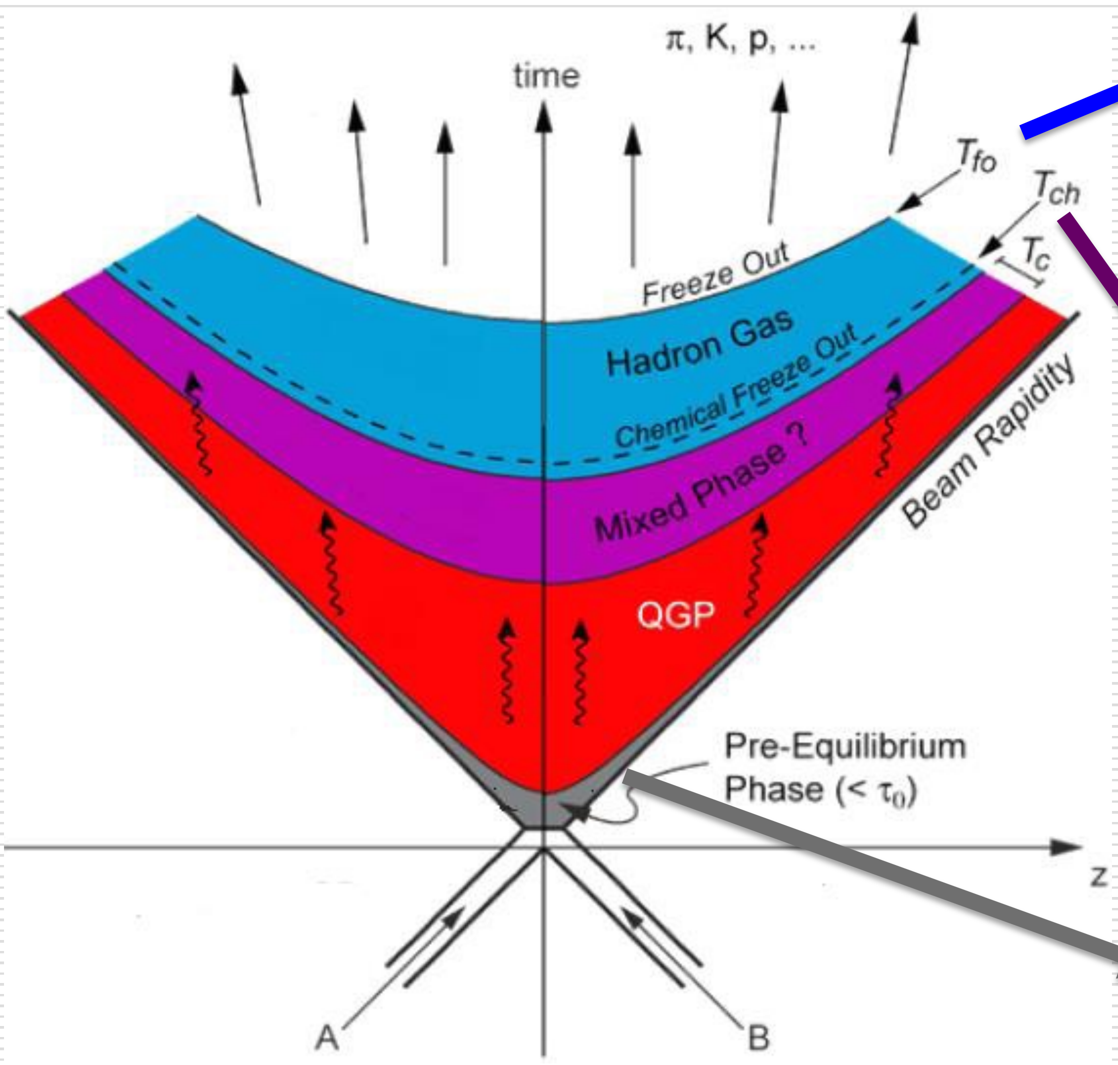
Outline:

- introduction
- overview of results in A-A collisions
  - open HF
  - quarkonium
  - HF within jets
- conclusions and outlook

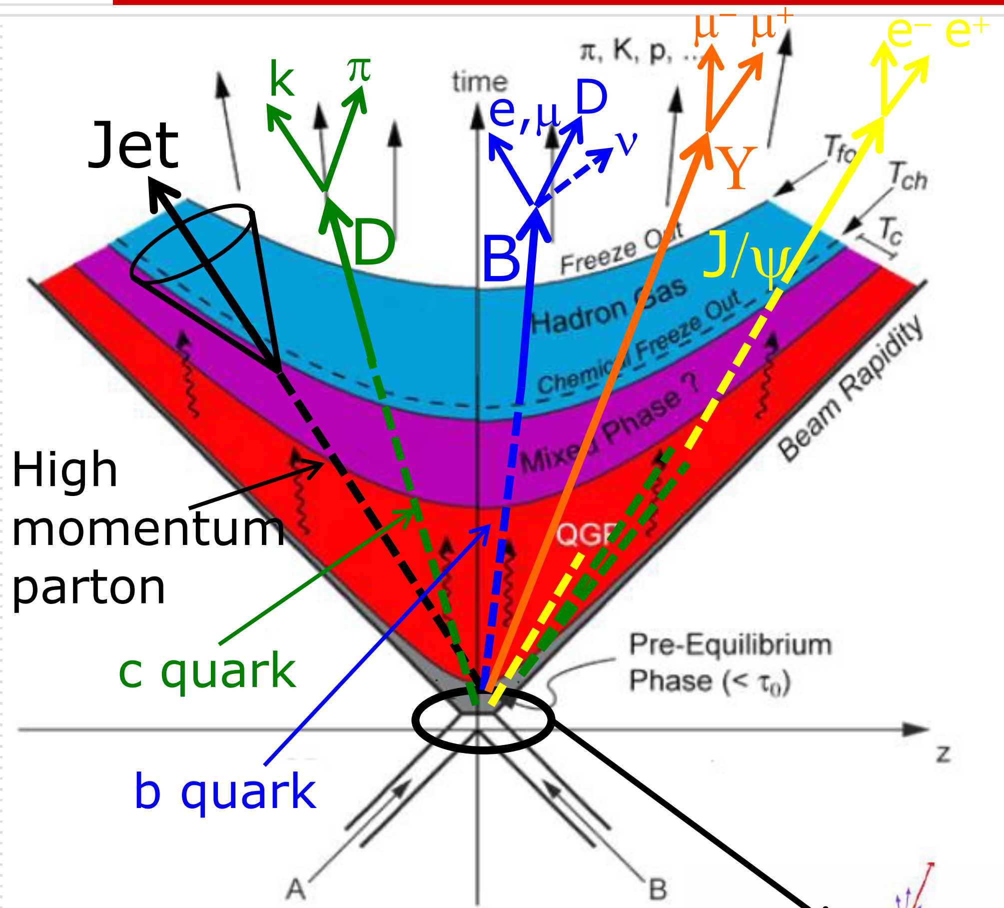
Orsay - October the 12th 2022

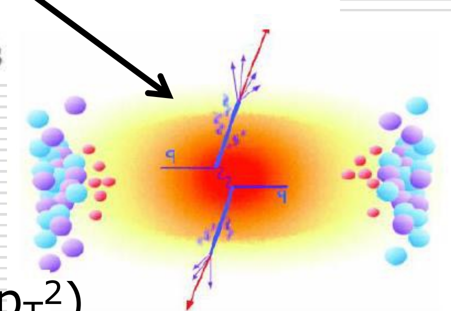
Space time evolution of A-A collision



- Thermal freeze-out
  - Elastic interactions cease
  - Particle dynamics ("momentum spectra") fixed
  - T_{fo} ~ 110-120 MeV
- Chemical freeze-out
  - Inelastic interactions cease
  - Particle abundances ("chemical composition") are fixed
  - T_{ch} ~ 155 MeV
- Thermalization time
  - System reaches local equilibrium
  - τ_{eq} ~ 0.5 fm/c

Hard probes of A-A collision





$$\tau_f = \frac{\hbar}{m_T}$$

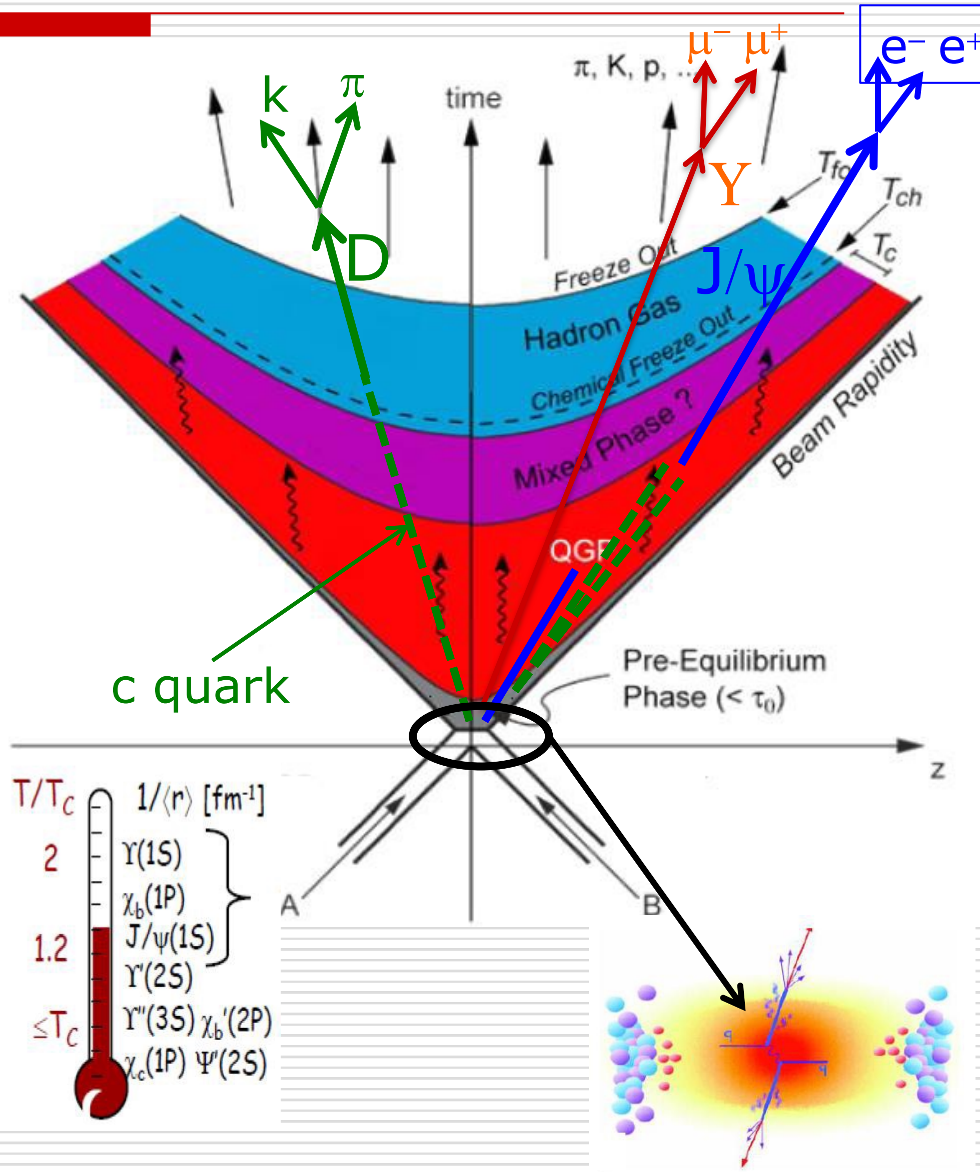
$m_T = \sqrt{(m^2 + p_T^2)}$

- Hard probes in nucleus-nucleus collisions:
  - produced at the very early stage of the collisions in partonic processes with large Q^2
  - pQCD can be used to calculate initial cross sections
  - traverse the hot and dense medium
  - can be used to probe the properties of the medium

HF quarks, due to their rest mass, are natural hard probes

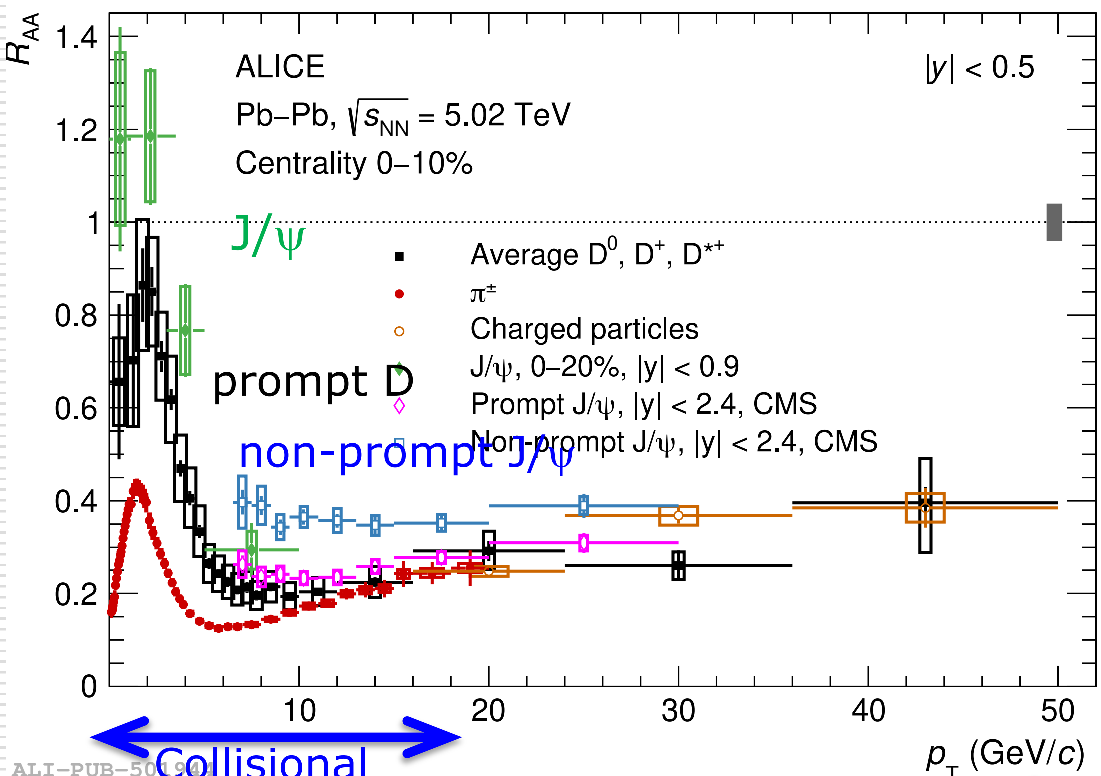
Quarkonium production

- Quarkonia are bound states of $c\bar{c}$ and $b\bar{b}$ ($Q\bar{Q}$) pairs
- $Q\bar{Q}$ pairs are produced at the very early stage of the collision in partonic processes with large Q^2
  - pQCD can be used to calculate initial partonic cross sections
- binding of the $Q\bar{Q}$ pair is a non-perturbative process
- in a QGP, the Debye screening can "melt" the less tightly bounded states [PLB 178 416]
- in a plasma with high density of Q and $\bar{Q}$, recombination of independently produced Q and $\bar{Q}$ can happen [PLB 490 196, PRC63 054905]
  - likely for charm at the LHC energy



Open heavy flavour energy loss: colour-charge and quark-mass dependence

can be studied looking ad different hadrons: exclusive channels (D,B), prompt and non-prompt D and J/ψ,



Collisional dE/dx relevant

Radiative dE/dx dominates

Bulk of production
recombination relevant (even dominant for J/ψ)

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

Energy loss depends on:
- Color charge $\Delta E_g > \Delta E_{u,d,s}$
- Parton mass $\Delta E_c > \Delta E_b$

At the parton level:
$\Delta E_g > \Delta E_{u,d,s} \gtrsim \Delta E_c > \Delta E_b$

Naive expectation:
$R_{AA}(\pi) > R_{AA}(D) > R_{AA}(B)$?

More complicated due to different production kinematics and fragmentation of light and heavy quarks

Open heavy flavour energy loss: colour-charge and quark-mass dependence

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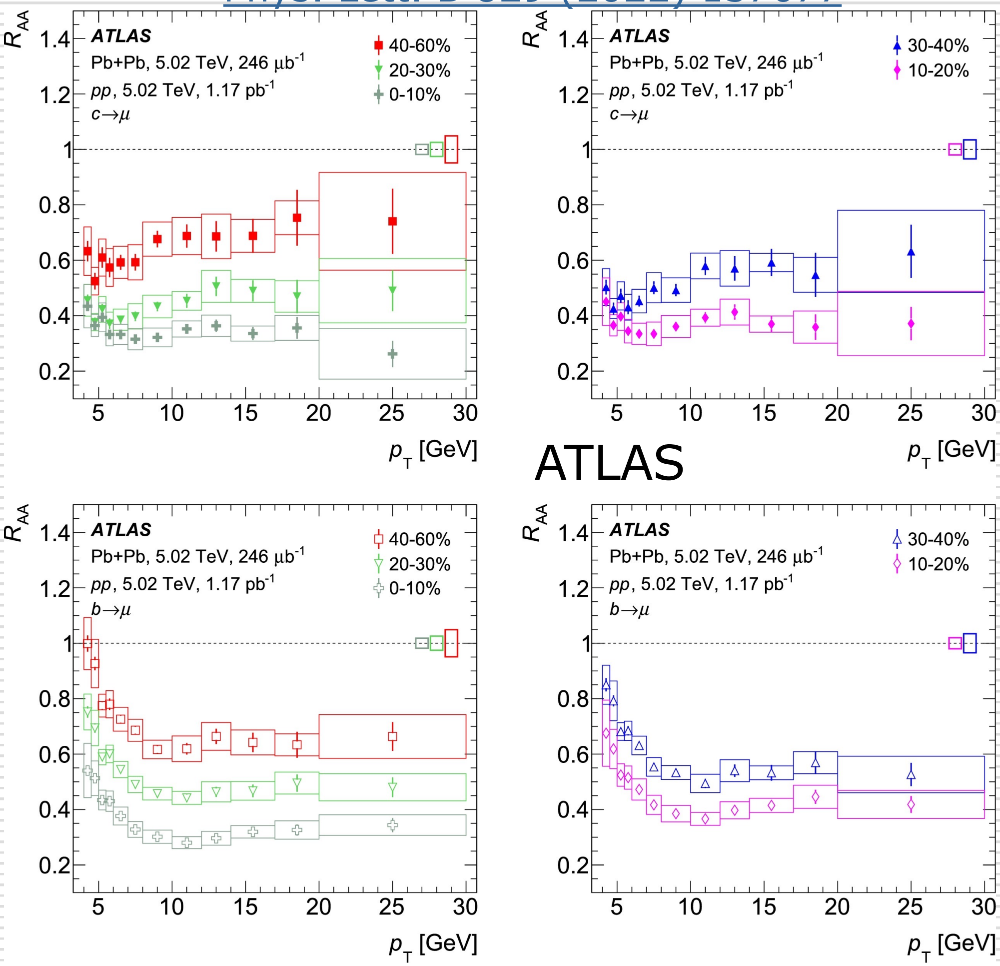
Phys. Lett. B 829 (2022) 137077



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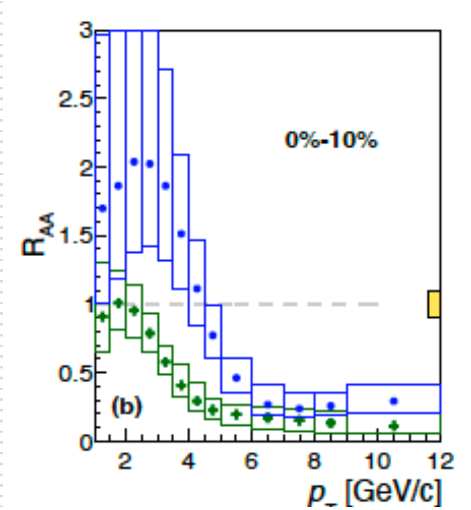
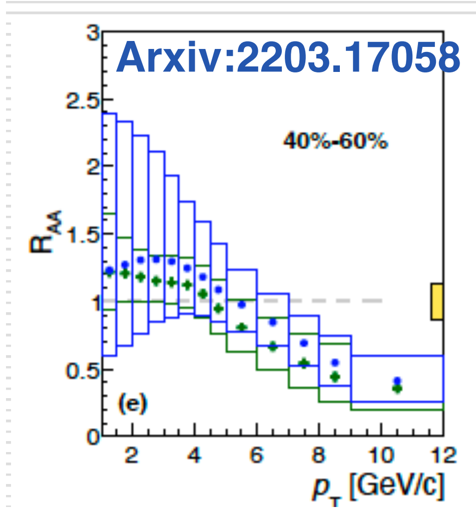
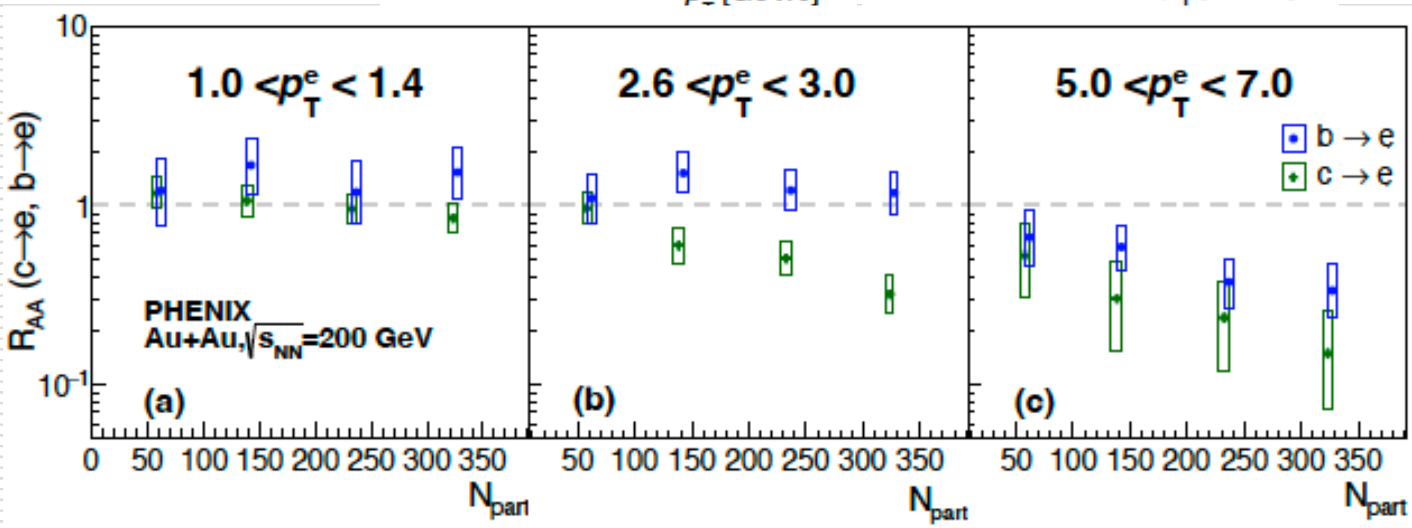
PHENIX
Au-Au √s=200 GeV







Open heavy flavour energy loss: colour-charge and quark-mass dependence

can be studied looking ad different hadrons: exclusive channels, prompt and non-prompt D and J/ψ, HF decay leptons ….

nice experimental results …

… but how to infer the properties of the QGP?

→ look at the theory models !

- comparisons to model predictions
- switch on/off ingredients of models
- fine tuning of models on data
    - Bayesian approach

Open heavy flavour energy loss: colour-charge and quark-mass dependence

can be studied looking ad different hadrons: exclusive channels, prompt and non-prompt D and J/ψ, HF decay leptons ….

Arxiv:2203.17058

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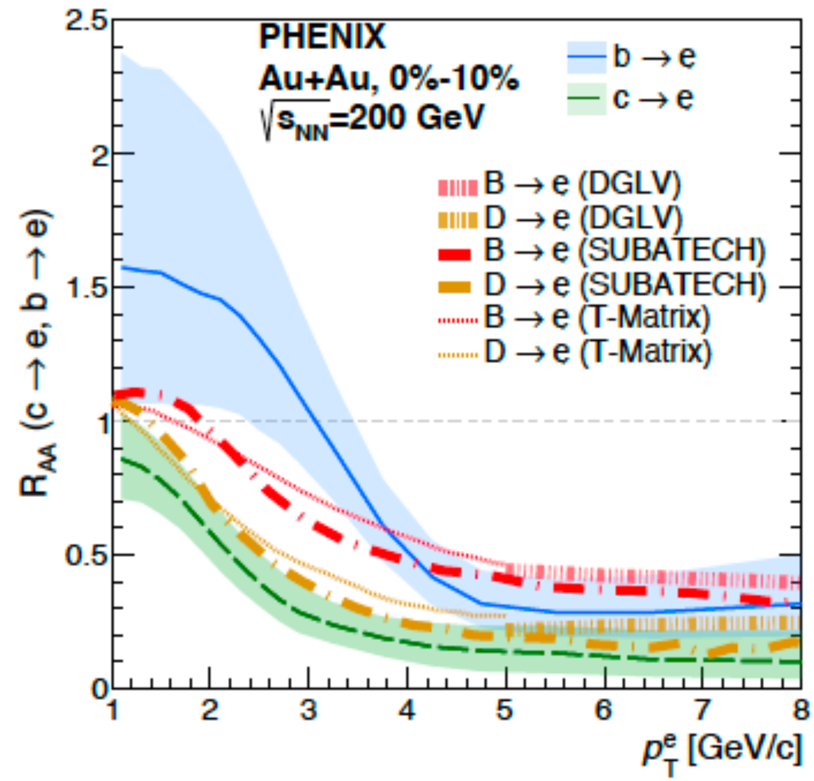

- comparisons to model predictions

Open heavy flavour energy loss: colour-charge and quark-mass dependence

ATLAS Phys. Lett. B 829 (2022) 137077

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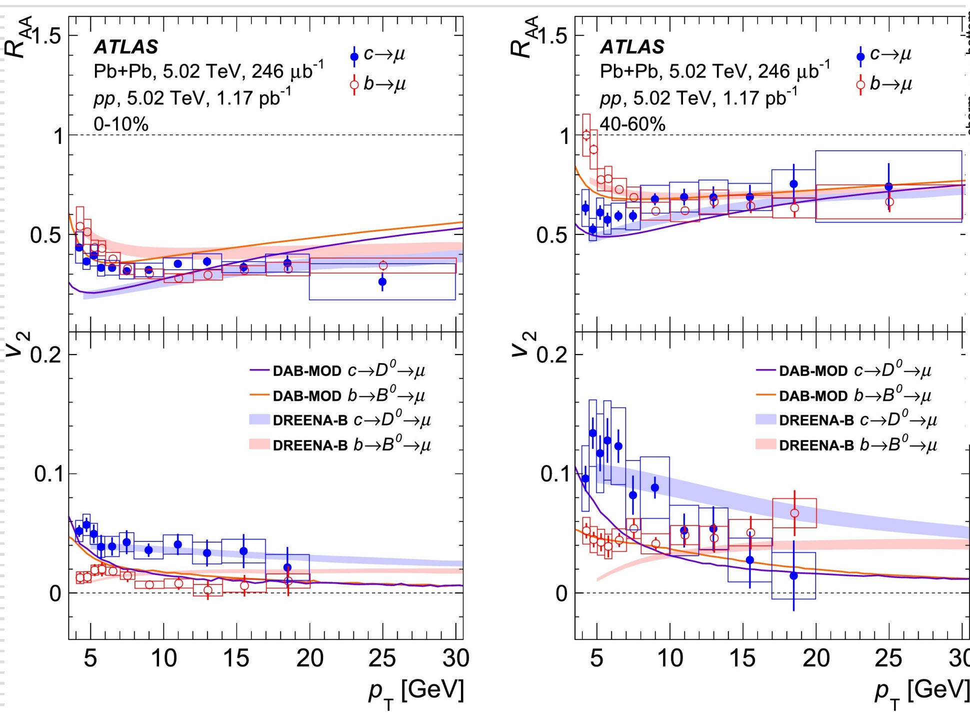
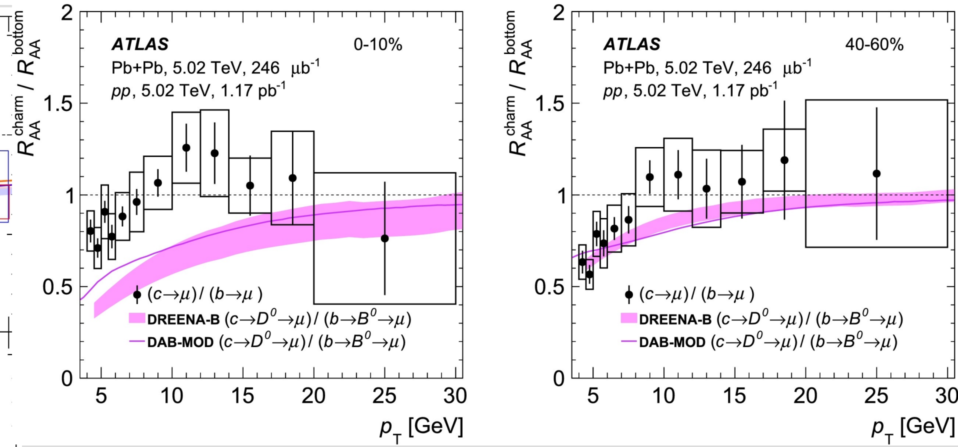


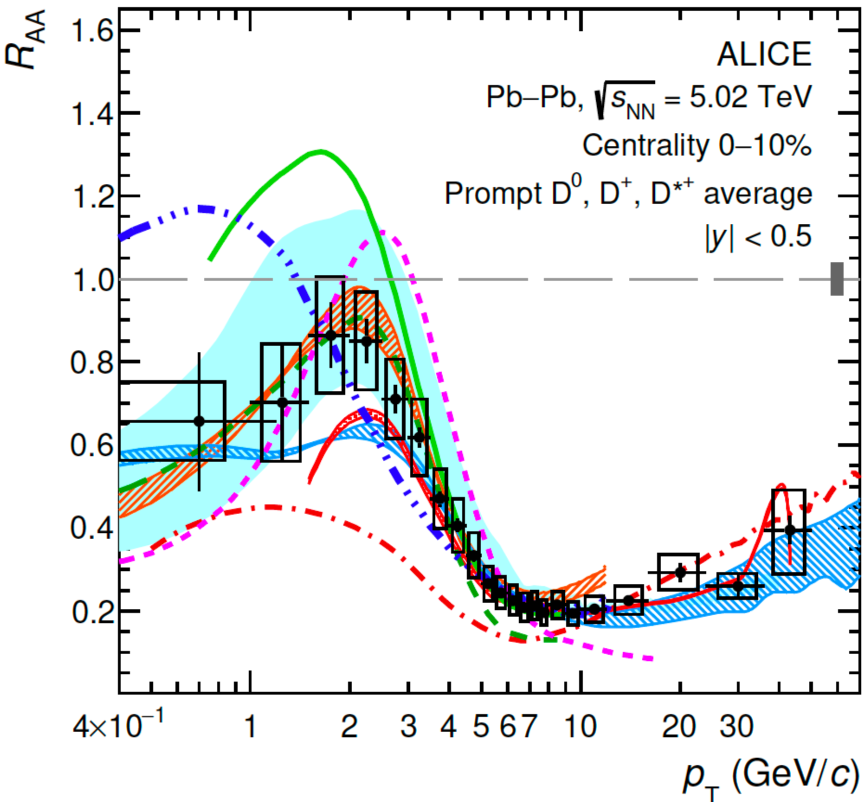


note that v_2 at high p_T also reflects path-dependent E-loss

- DREENA-B:
  - rad. and coll. E-loss
  - 1+1D Bjorken expanding QGP
  - Q->H_Q fragmentation
- DAB-MOD
  - only Langevin dynamics
  - TRENTO initial geometry
  - $D_S/2\pi T$=2.23 for c (2.79 for b)
  - decoupling at T=160 MeV
  - coalescence+fragmentation

R_{AA} of D mesons at the LHC

- comparisons to model predictions



ALI-PUB-501952

TAMU: PRL 124, 042301 (2020)
PHSD: PRC 93, 034906 (2016)
POWLANG: EPJC 75, 121 (2015)
CATANIA: PRC 96, 044905 (2017)
MC@sHQ+EPOS: PRC 91, 014904 (2015)
LIDO: PRC 98 064901 (2018)
LBT: PLB 777 (2018) 255-259
LGR: EPJC, 80 7 (2020) 671
DAB-MOD M&T: PRC 96 064903 (2017)

R_{AA} shape: interplay of parton energy loss, shadowing, radial flow, hadronization mechanisms

much better constrains when describing both R_{AA} and v_2
… I'll come later on that

A parenthesis

Control / understanding of the initial state effects and hadronization mechanism is a prerequisite to use c and b quarks as a probe of the QGP medium

Do we control properly initial state effects (shadowing at LHC)?

Are we sure that the produced c (b) quarks end up in a given charm (beauty) hadrons with the same probability as in pp?

same fragmentation fractions in pp and Pb-Pb?

total charm cross-section (i.e. integrated down to $p_T=0$) is a prime quantity to be measured with precision

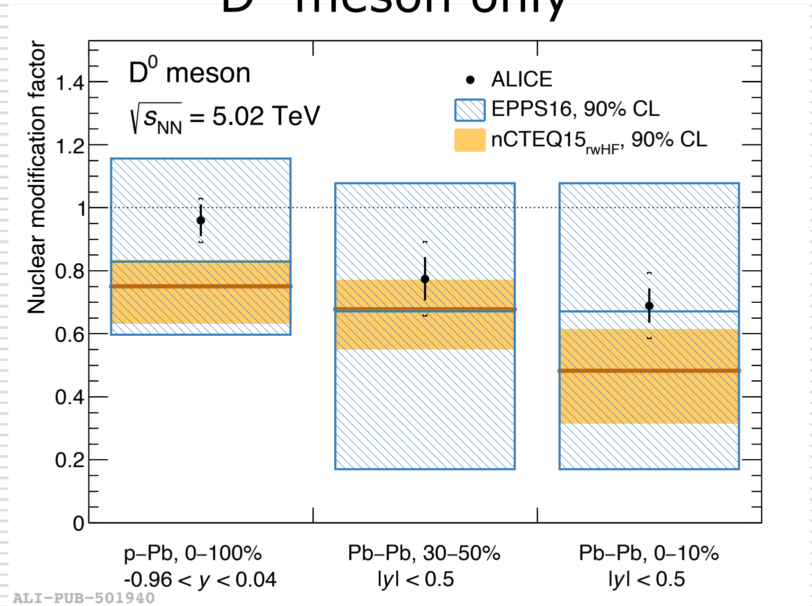
Total charm cross section

STAR in Au-Au
D mesons and Λ_C

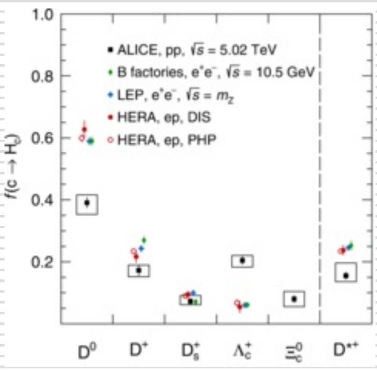
Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	$39 \pm 1 \pm 1$
	$D^\pm$	$18 \pm 1 \pm 3^*$
	D_s [2]	$15 \pm 2 \pm 4$
	Λ_c [3]	$40 \pm 6 \pm 27^{**}$
	Total	$112 \pm 6 \pm 27$
p+p at 200 GeV [4]	**Total**	$130 \pm 30 \pm 26$

~30% uncertainties

ALICE in Pb-Pb
D^0 meson only



small uncertainty for D mesons



crucial to measure all HF charm hadron ground states with high precision

as being done in pp (see, **Phys. Rev. D 105, L011103**)

Prompt D meson R_{AA} and v_2

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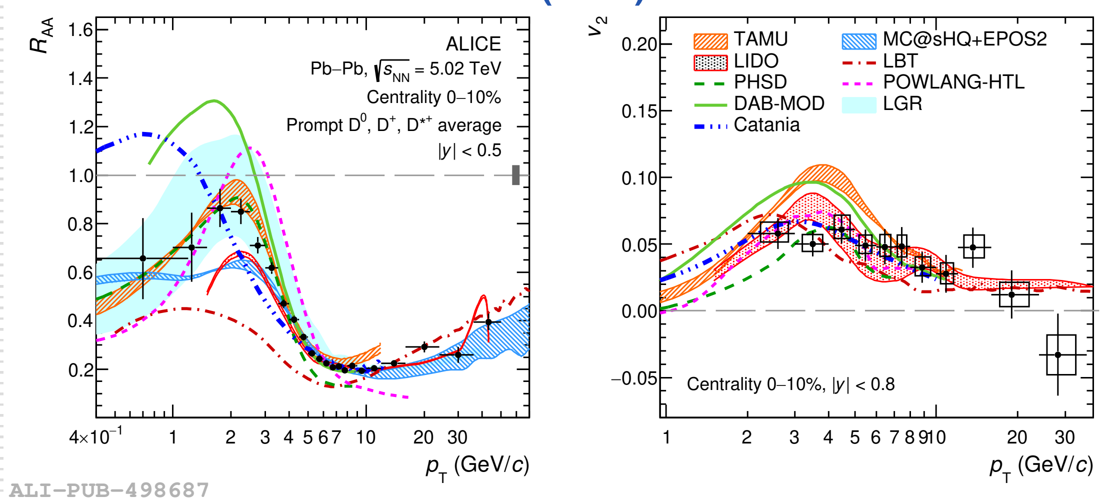

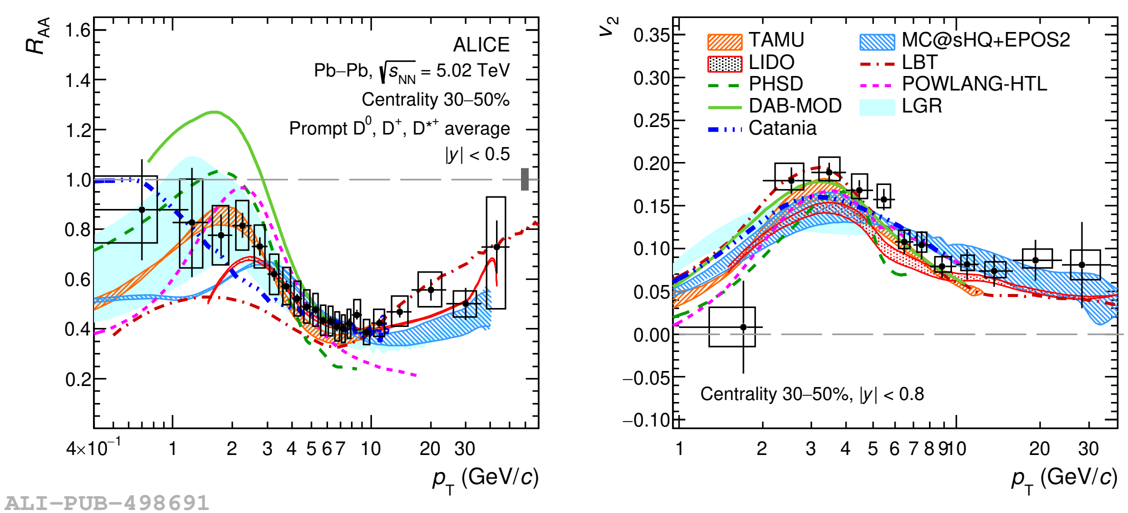

- TAMU: PRL 124 (2020) 042301
- MC@sHQ+EPOS2: PRC 89 (2014) 014905
- LGR: arXiv:1912.08965
- LIDO: PRC 98 (2018) 064901
- PHSD: PRC 93 (2016) 034906
- Catania: PLB 805 (2020) 135460
- POWLANG: EPJC (2019) 79:494
- LBT: PRC 94 (2016) 014909
- DAB-MOD: arXiv:1906.10768

Model ingredients:

- transport of c quarks in an hydrodynamically expanding medium (via Boltzmann or Langevin equations)
- c quark energy loss (elastic and/or inelastic collisions)
- c-quark hadronisation via coalescence

This is "state of the art" after LHC run1&run2

… deeper insight into models

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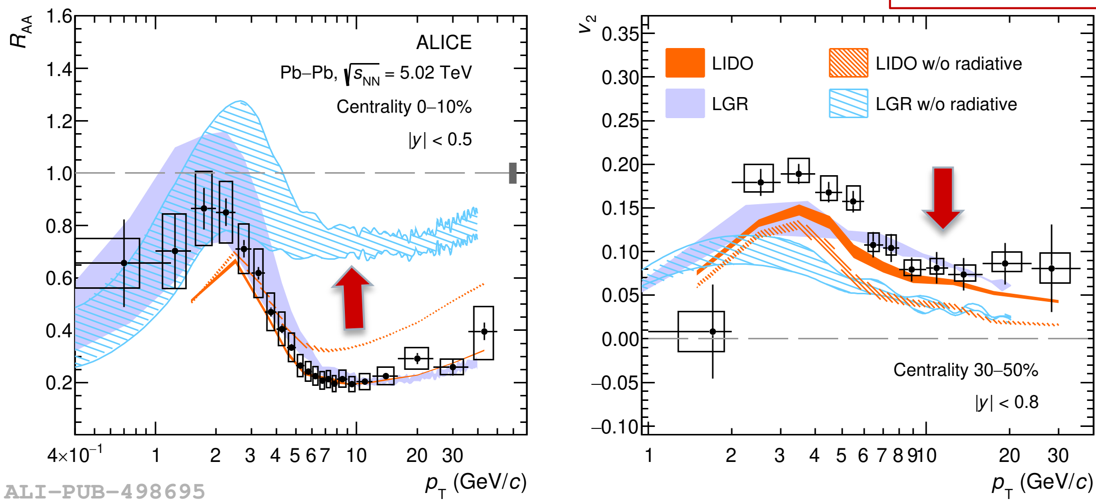
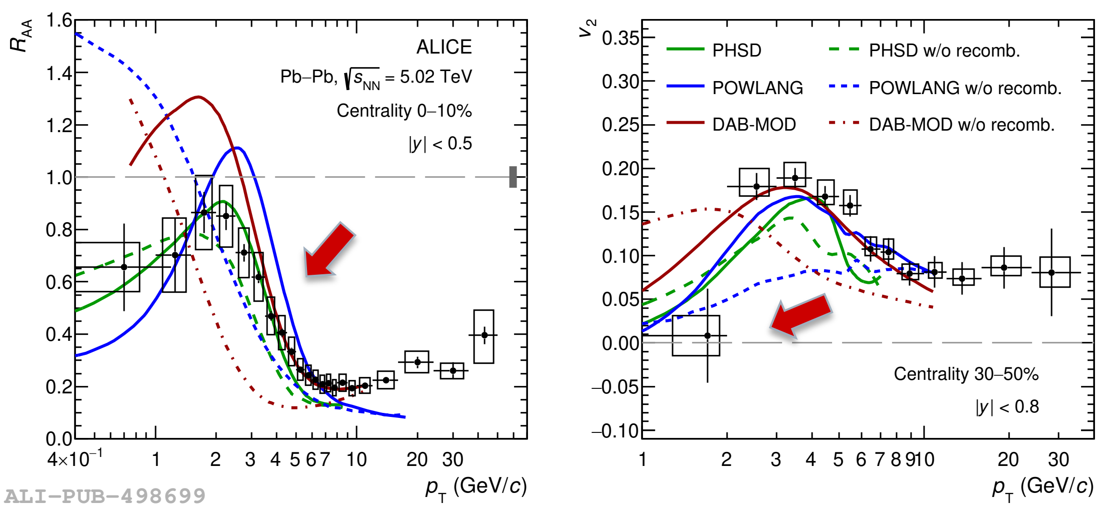
- switch on/off ingredients of models



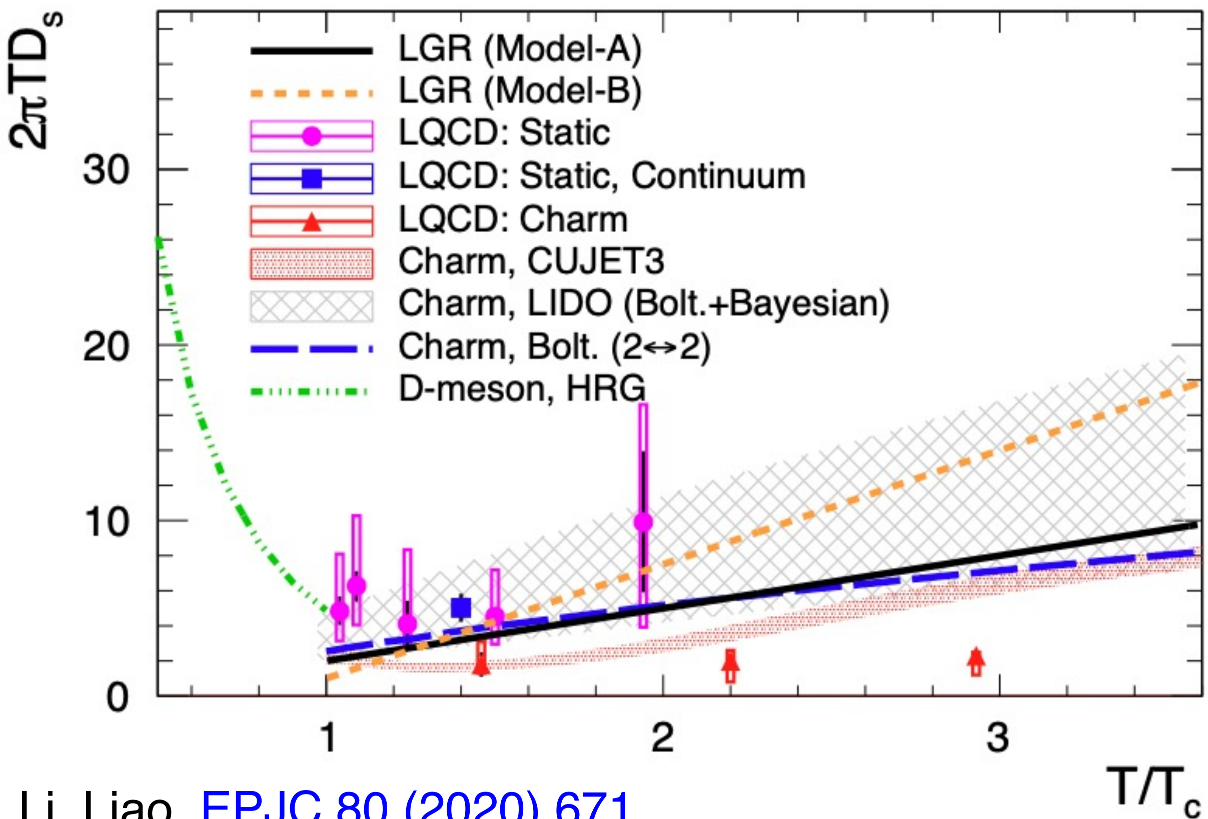
- Role of radiative dE/dx vs. elastic collisions
  - Switching off radiative E loss



- Role of hadronization
  - Switching off recombination

Charm spatial diffusion coefficient

- key transport parameter (quantifies drag, thermal, recoil forces)



Li, Liao, EPJC 80 (2020) 671

From that one derives the drag and momentum diffusion coefficients:

$$\eta_D(\vec{p}, T) = \frac{1}{2\pi T D_s} \cdot \frac{2\pi T^2}{E}$$

$$\kappa(T) = \frac{1}{2\pi T D_s} \cdot 4\pi T^3.$$

Charm spatial diffusion coefficient

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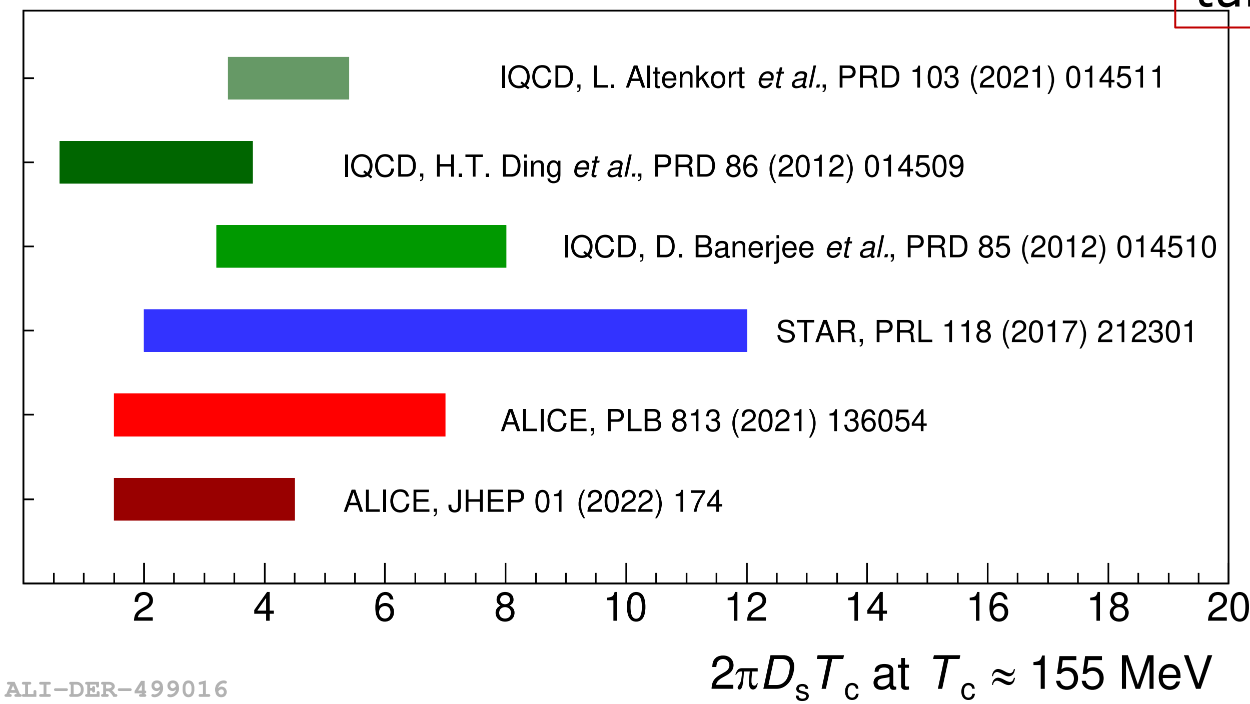
tuning of models on data?



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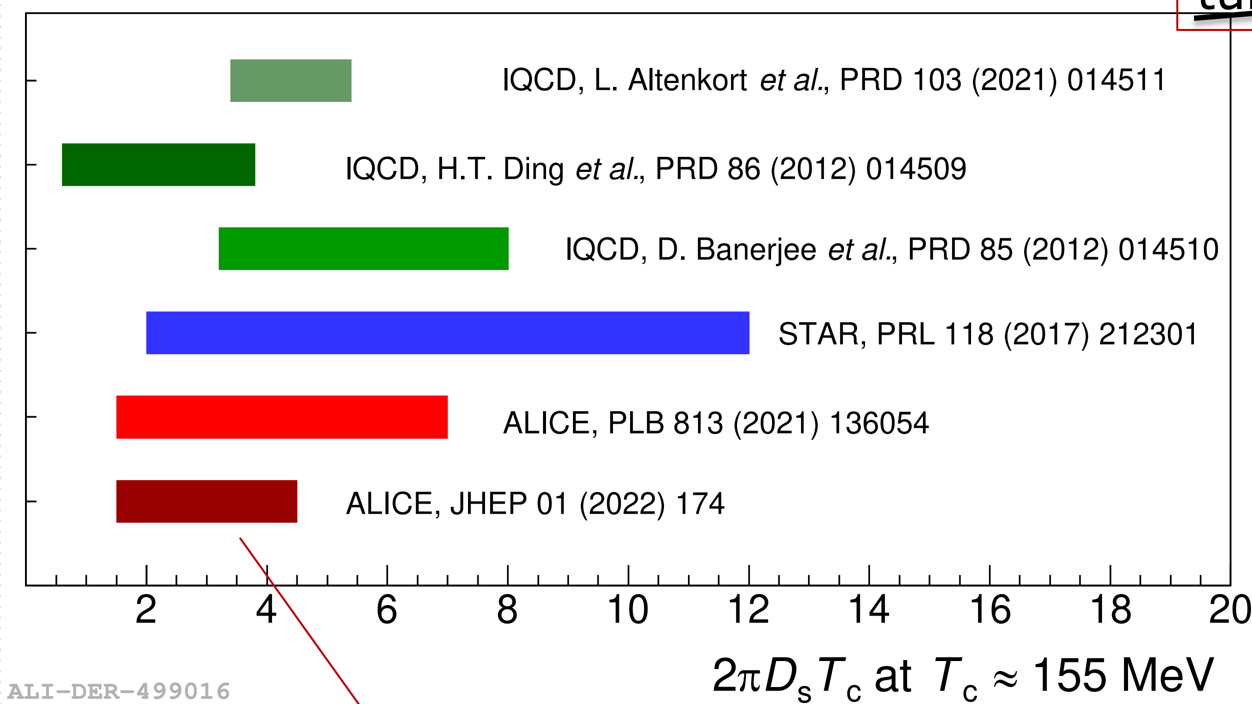

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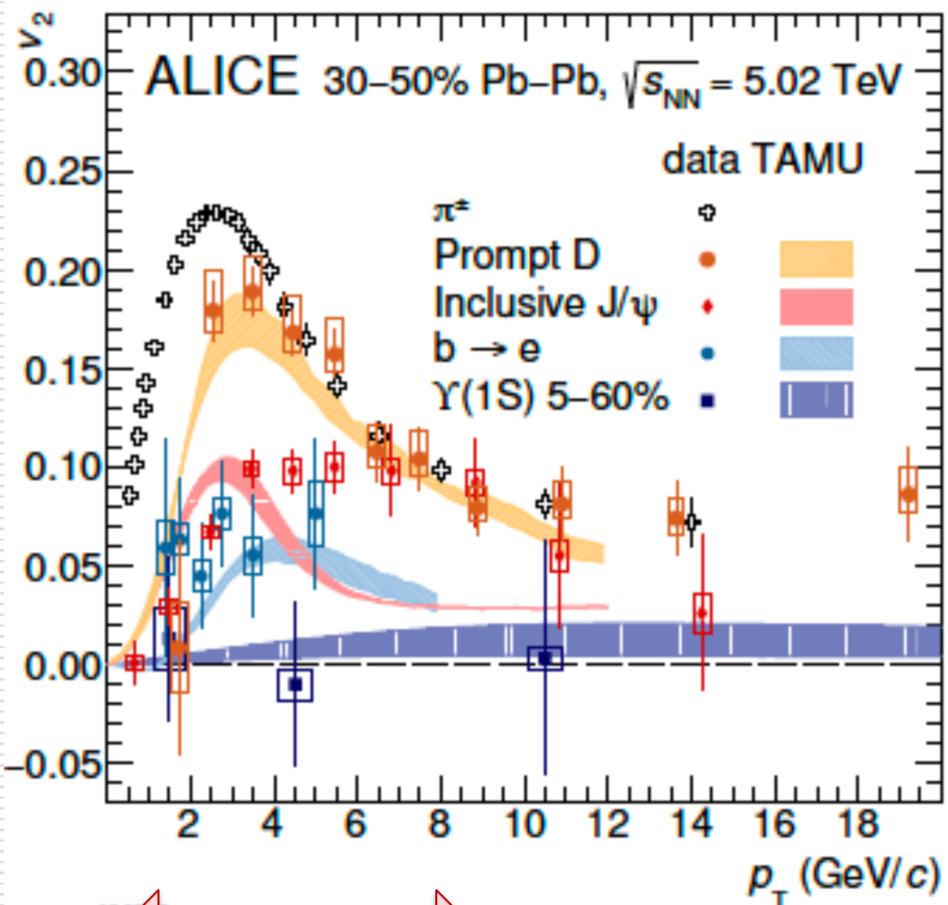
Simply obtained as the ranges of the $2\pi D_S T_C$ parameters used by a set of theory models that provides a good description of R_{AA} (χ^2/ndf<5), v_2 and v_3 (χ^2/ndf<2) experimental data

v_2 of HF hadrons

- At a glance: $0 \sim v_2^{(\Upsilon(1S))} < v_2^{(b\to e)} \sim v_2^{(\mathrm{Incl}\ J/\psi)} < v_2^{(D)} < v_2^{h}$ at low p_T



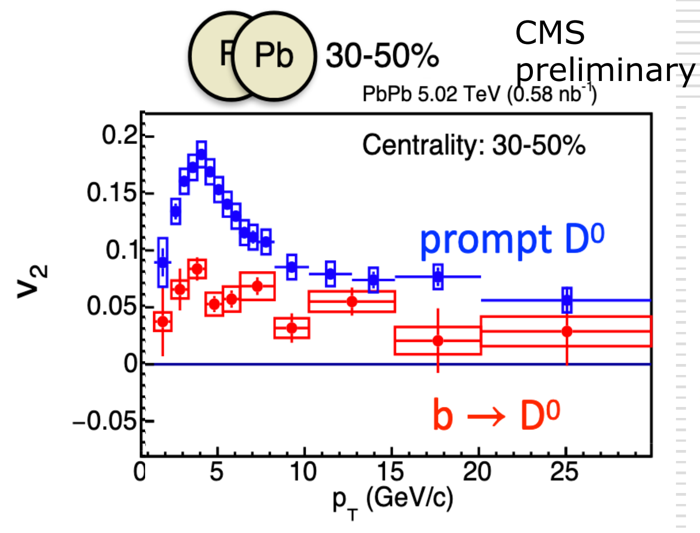
collective flow

path dependent dE/dx

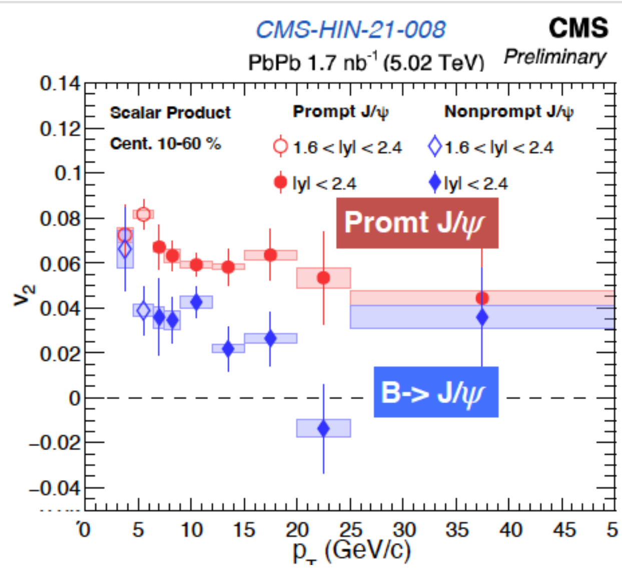
- **Open beauty-hadrons $v_2 > 0$**
  - from recombination with light quarks?
- **Bottomonia: $v_2(\Upsilon(1S)) = 0$**
  - negligible recombination. What do we learn about b quark flow?

a deeper look at beauty v_2

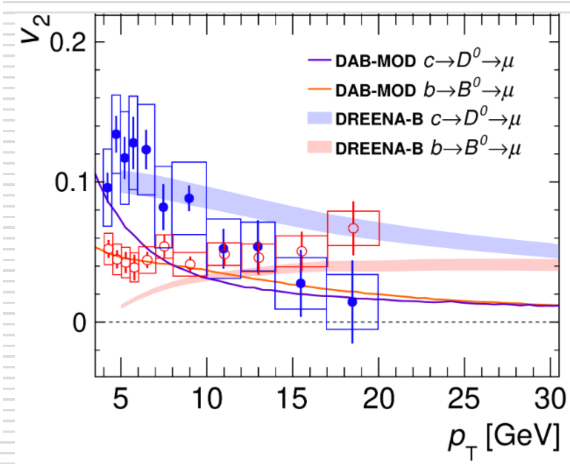
first measurement of non-prompt D^0 *v2*



non-prompt J/ψ v_2



v_2 of muons from HF hadron decays



Prompt D^0 v_2 > non-prompt D^0 v_2

Prompt J/ψ v_2 > non-prompt J/ψ v_2

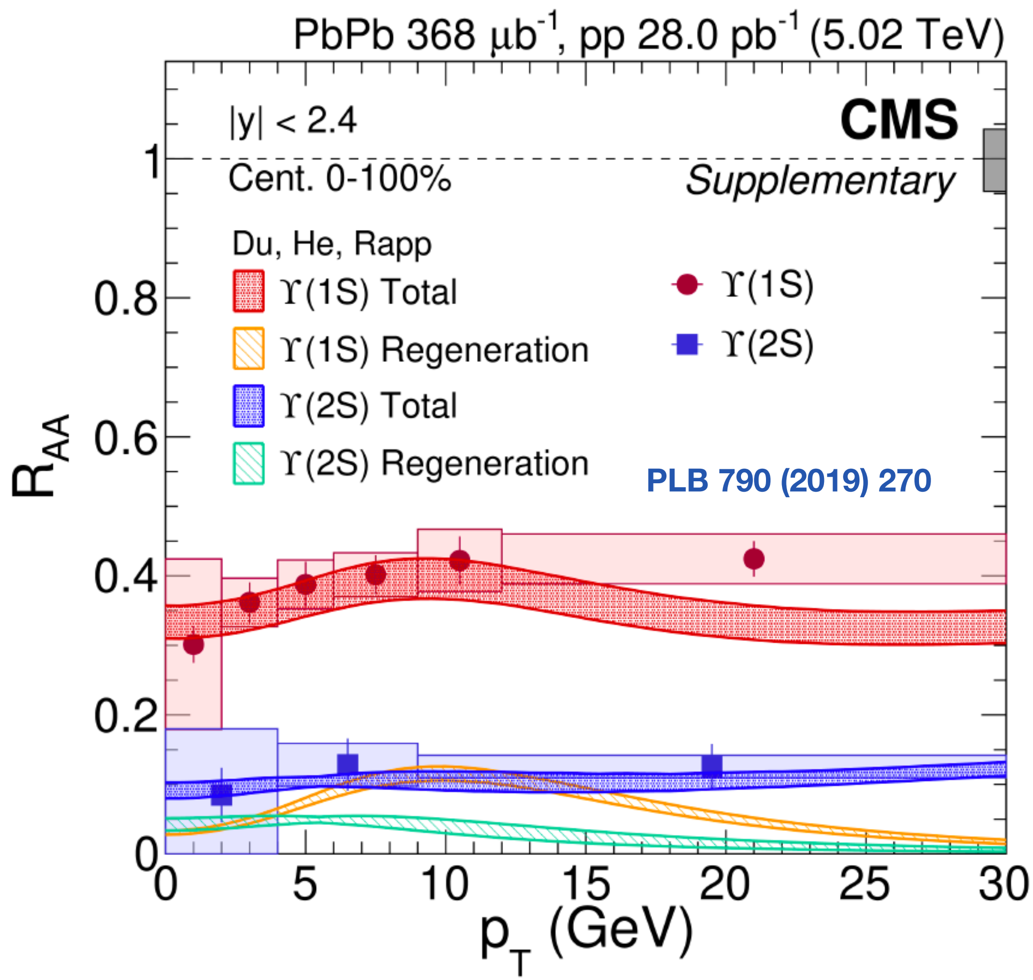
Mass splitting of **charm** and **bottom** at low p_T in v_2

Qualitative conclusion: as naively expected, b quarks less effected by collective dynamics, hence far away from thermalization

to be quantitative → theory descriptions (in synchro with that of the c sector)

Bottomonium suppression in the QGP

- **very clear ordering of R_{AA} as in the sequential melting picture**
  - transport calculation describe measurements
  - small contribution from regeneration

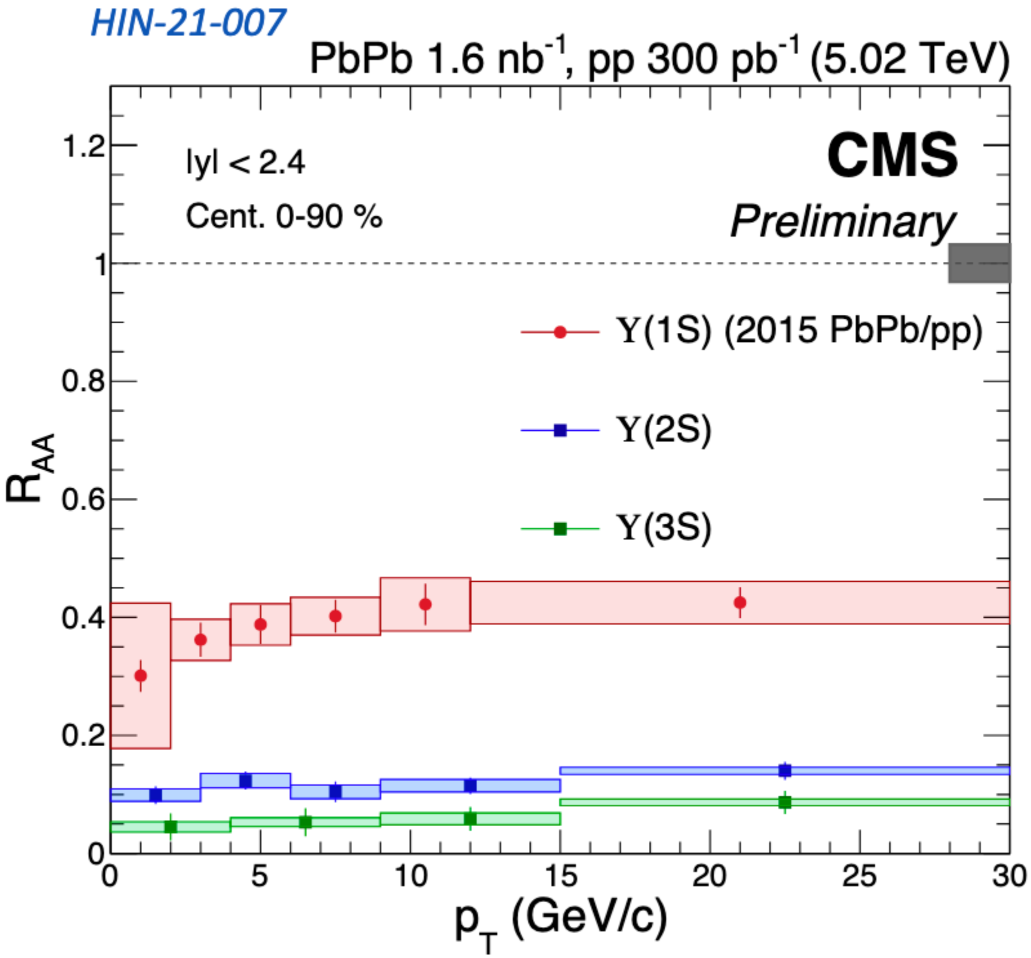


Bottomonium suppression in the QGP

- **First measurement of Υ(3S) in Pb-Pb**

$$\frac{R_{AA}^{(3S)}}{R_{AA}^{(2S)}} \approx 0.7$$

- what is the origin of those Υ(3S)?
  - from corona ?
  - from peripheral collisions ?
  - just from recombination ?



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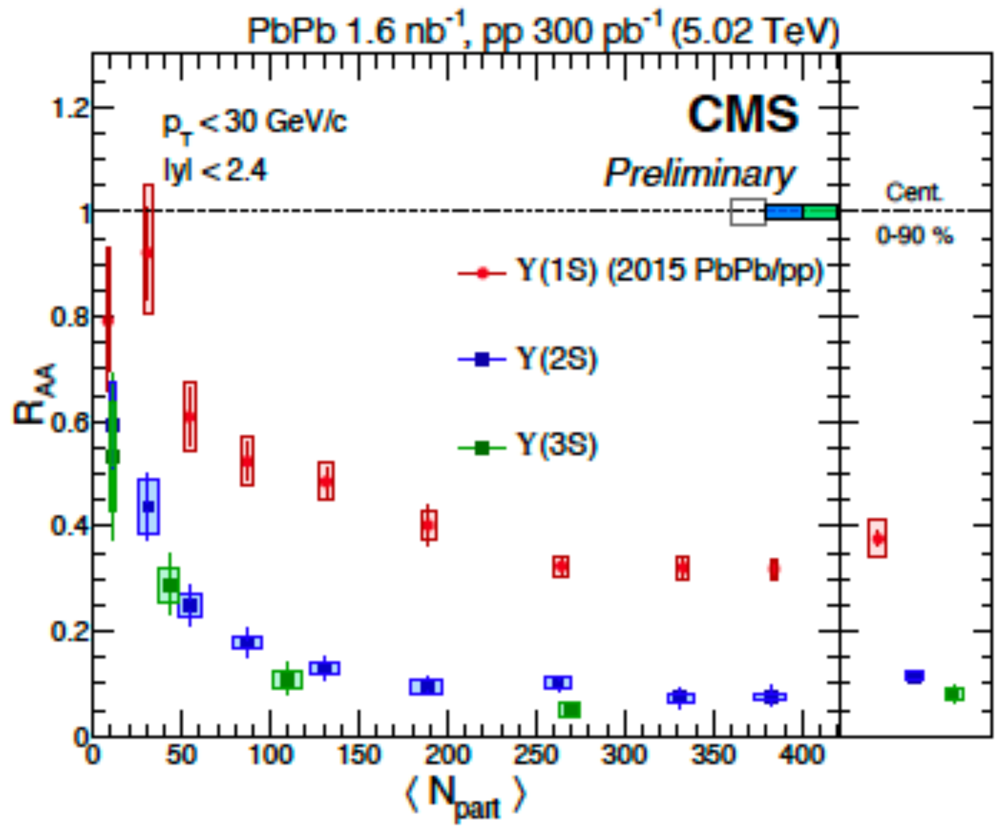
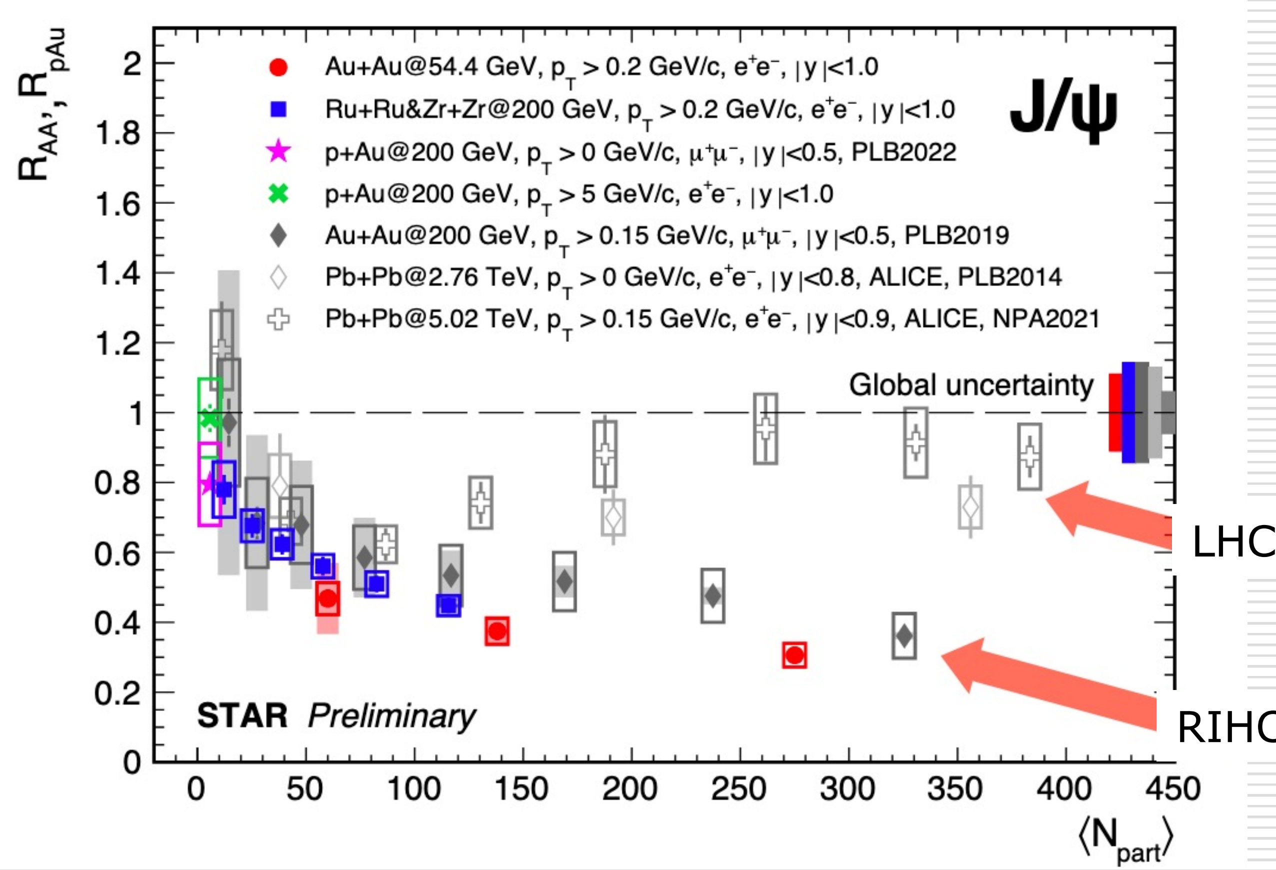


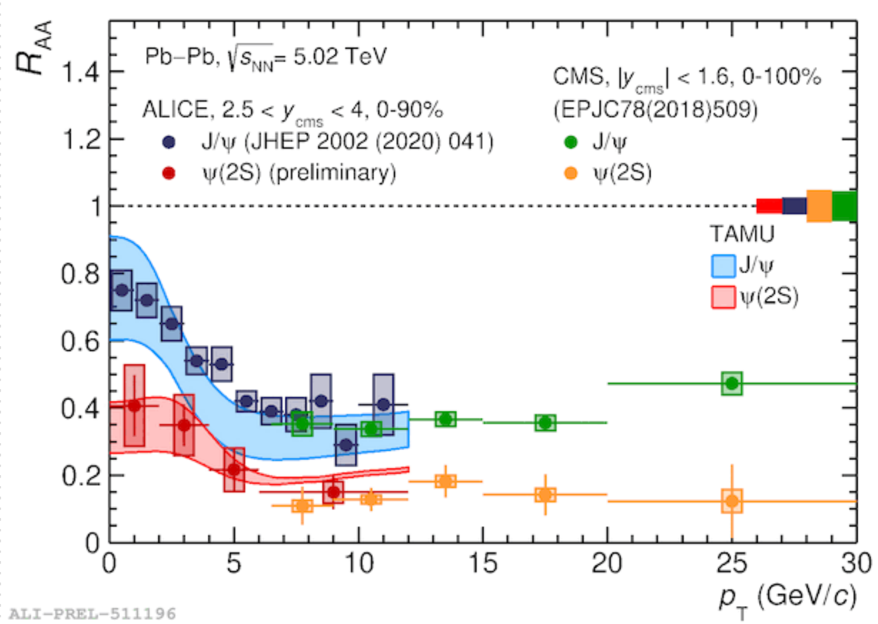
J/ψ suppression and regeneration: LHC vs. RHIC

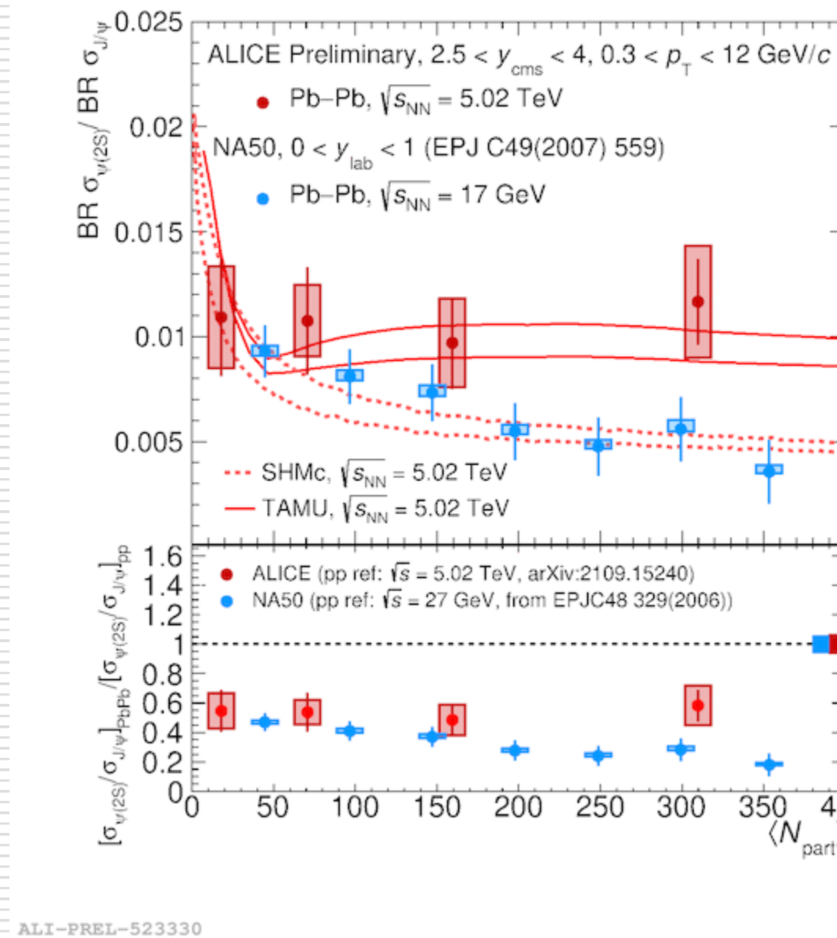
- dominant contribution from recombination at the LHC
  - bulk of production at low p_T
  - low p_T effect



Inclusive ψ(2S) production in Pb-Pb

TAMU: Nucl. Phys. A943 (2015) 147
SHMc: Nature 561 7723 (2018) 321

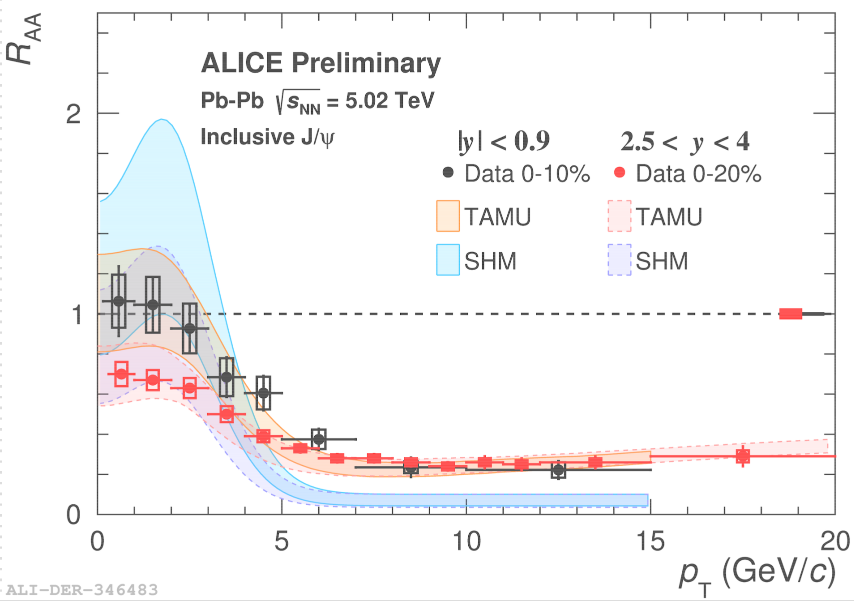


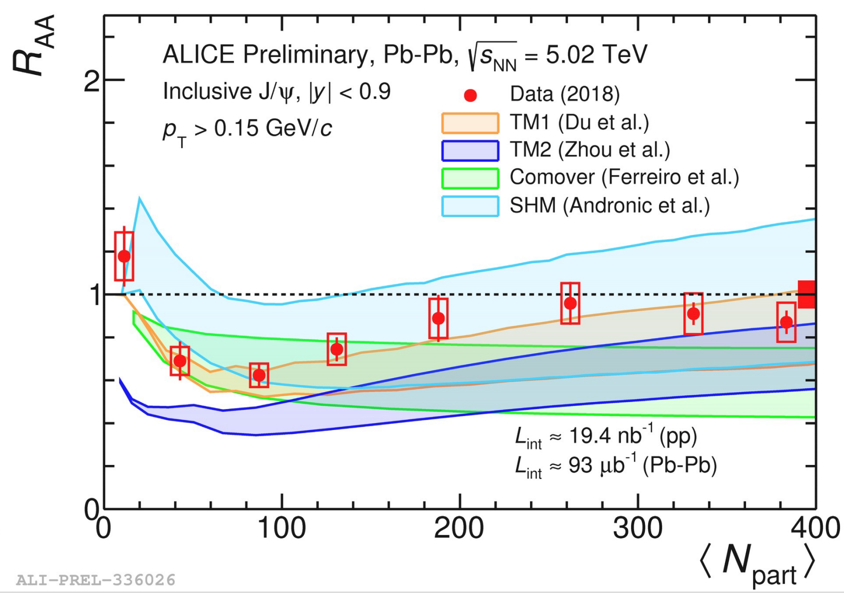


- stronger suppression of ψ(2S) than J/ψ
  - sequential suppression for charmonium?
- Increasing trend of R_{AA} towards low p_T also for ψ(2S)
  - Hint of ψ(2S) production via regeneration
- Compatible with midrapidity CMS results in the common p_T range
- TAMU reproduces the R_{AA} p_T dependence

- TAMU also compatible with the centrality dependence of the ψ(2S) / J/ψ ratio

J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

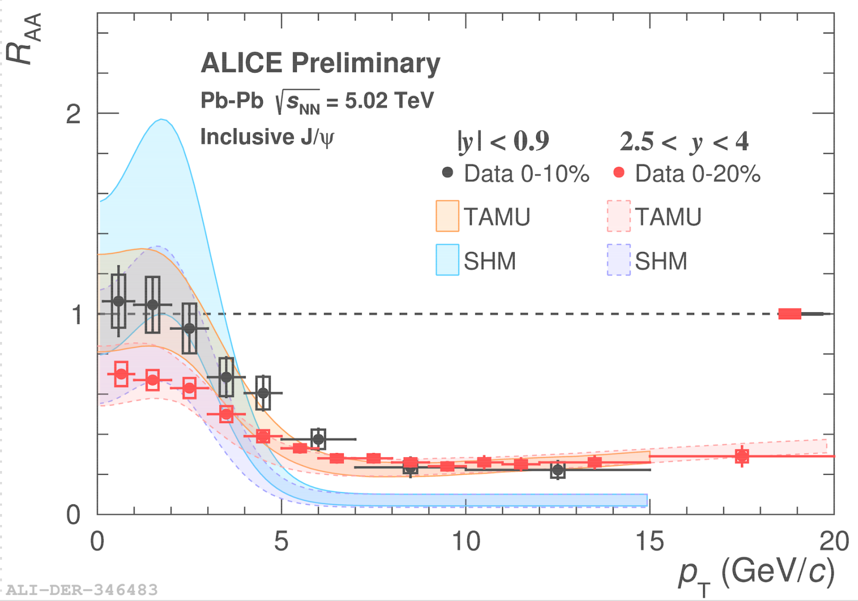


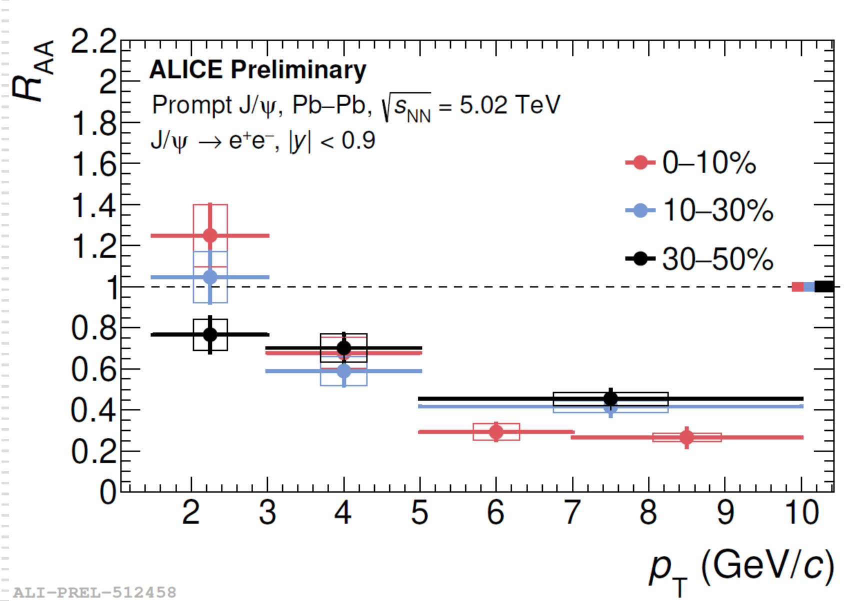


TM1: Du X. and Rapp R., NPA 943 (2015) 147-158
TM2: Zhou et al., PRC 89, 054911 (21 May 2014)
SHM: Andronic A. et al., PLB 797 (2019) 134836
Comover: Ferreiro E. et al., PLB 731 (2014) 57

- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0
  - decisive signature of recombination
- The SHM can describe the data at low p_T, while the TAMU transport model agrees with data in the whole measured p_T ranges
- Also centrality dependence qualitatively reproduced by models

J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV





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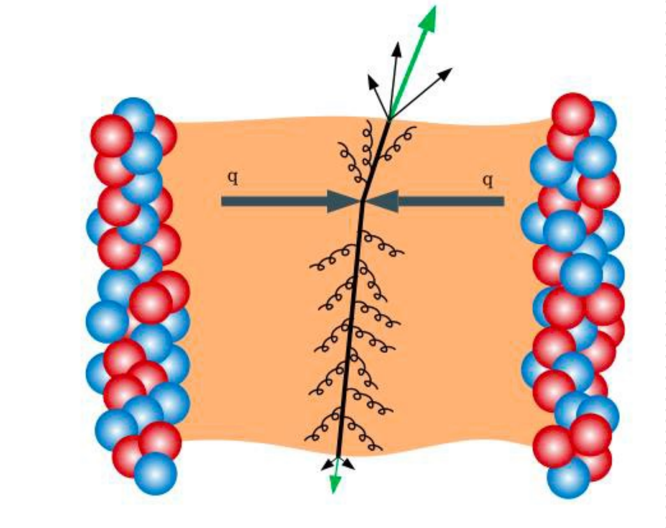
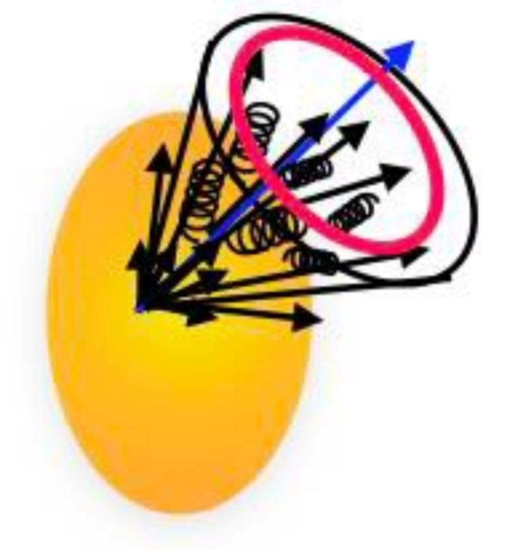
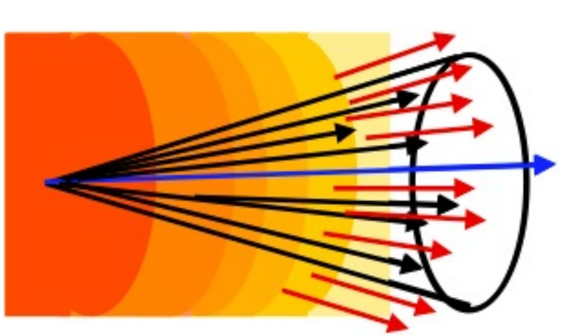
  - decisive signature of recombination
- The SHM can describe the data at low p_T, while the TAMU transport model agrees with data in the whole measured p_T ranges
- Effect confirmed when looking at prompt J/ψ production at low p_T and midrapidity, clear centrality dependence

HF jets in Heavy ion collisions







Parton energy loss

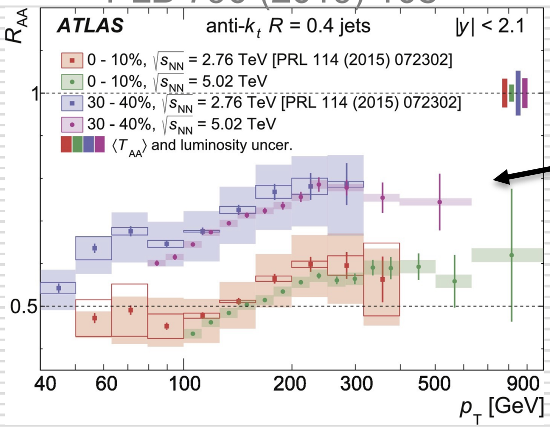
- Jet quenching
  → best control of the partonic kinematic

Momentum broadening

Medium response

Jets: what we expected and learned

PLB 790 (2019) 108

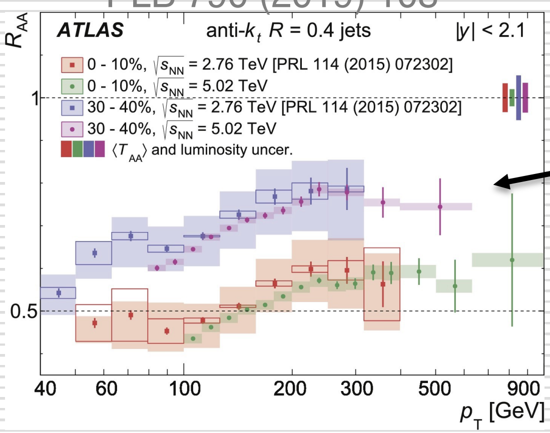


Jets are quenched in AA collisions

up to p_T =1 TeV

Jets: what we expected and learned

PLB 790 (2019) 108



Jets are quenched in AA collisions

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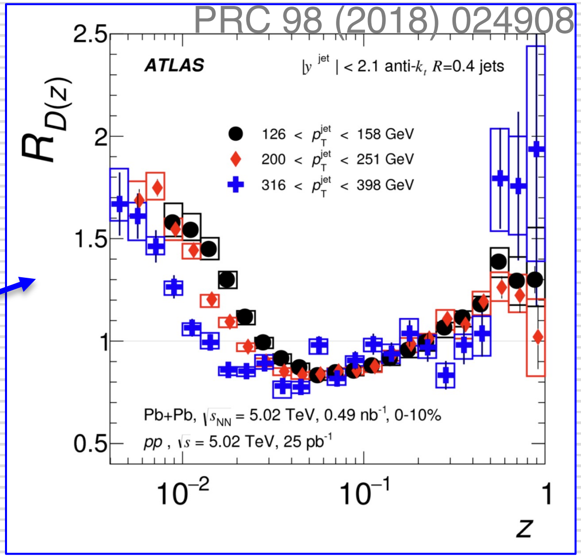
Jets in the medium appears softer

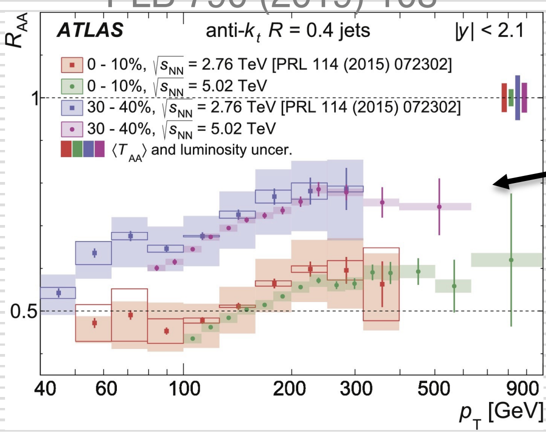
PRC 98 (2018) 024908



enhancement of particles carrying a small fraction of the jet momentum is observed in Pb-Pb w.r.t. pp, which increases with centrality and with increasing jet transverse momentum

Jets: what we expected and learned

PLB 790 (2019) 108



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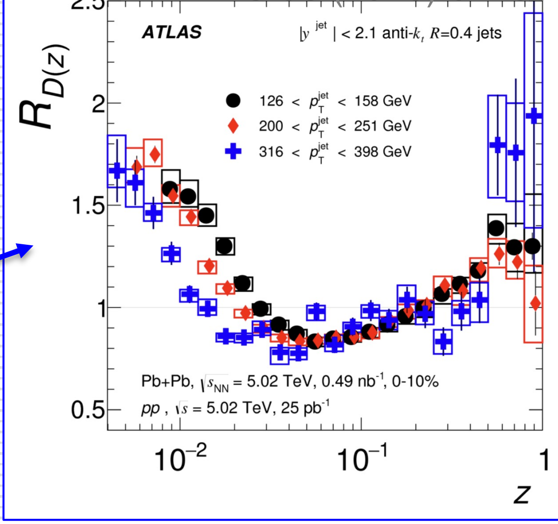
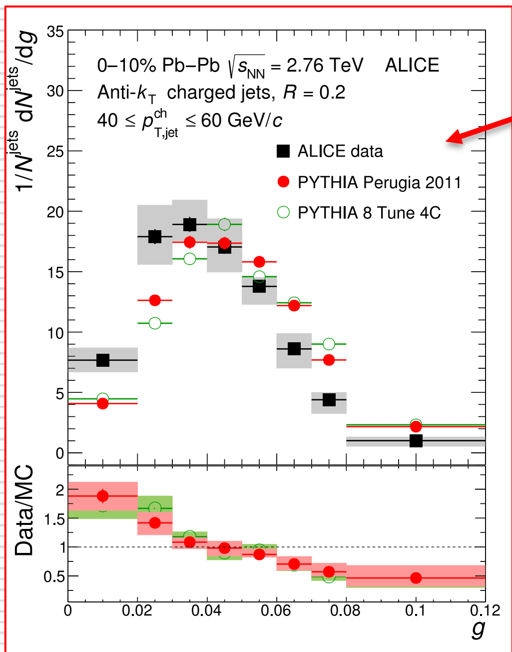


The hard core of the jets get narrower in the medium



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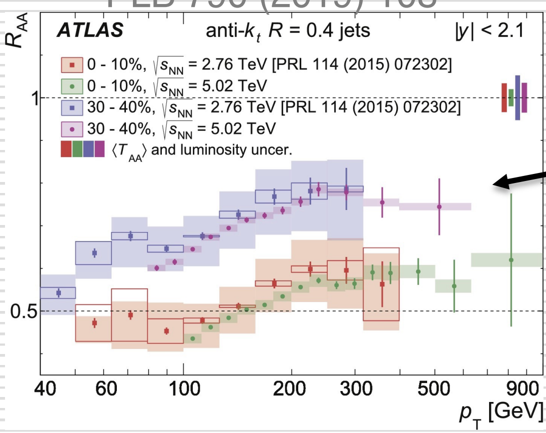
Girth = width of a jet

$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} |\Delta R_{i,jet}|$$

Jets: what we expected and learned

PLB 790 (2019) 108



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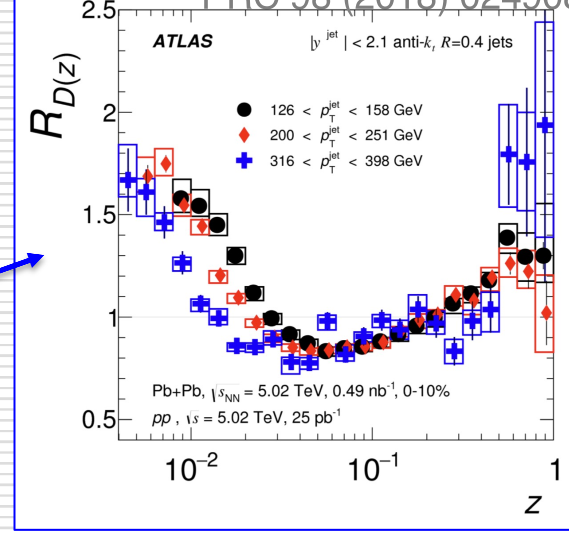

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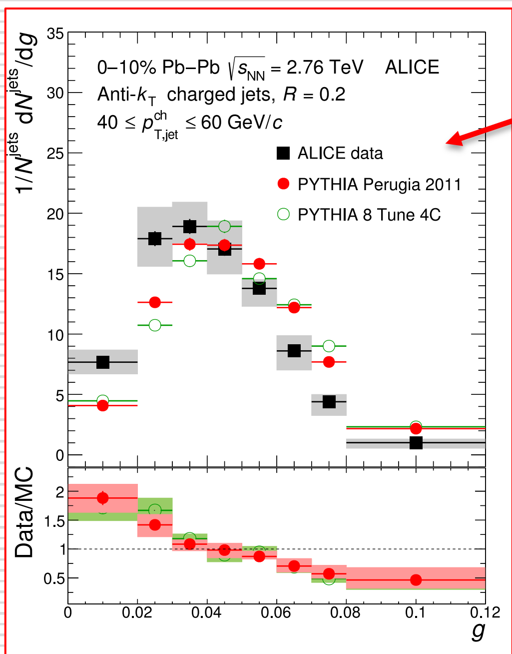
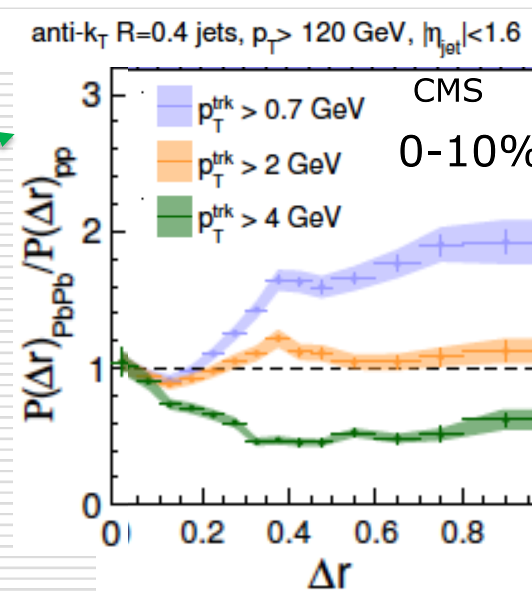


JHEP 10 (2018) 139

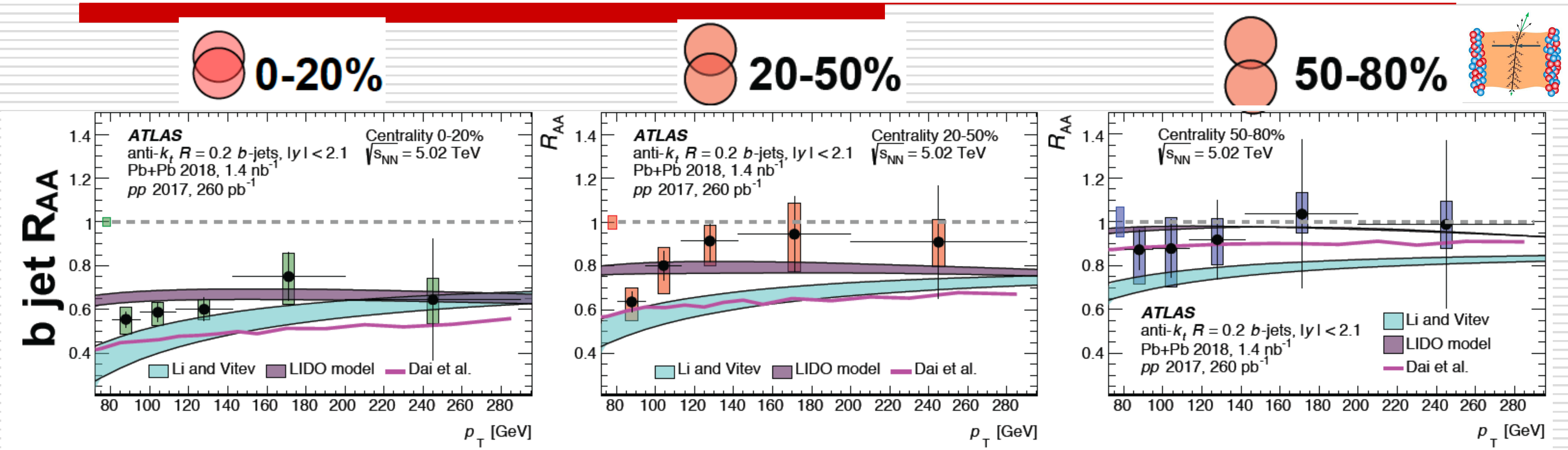
the soft part diffuses to large angles

P(Δr) distribution of ch.track (weighted by p_T^{trk}) in anular ring around the jet axis



JHEP05 (2018) 006

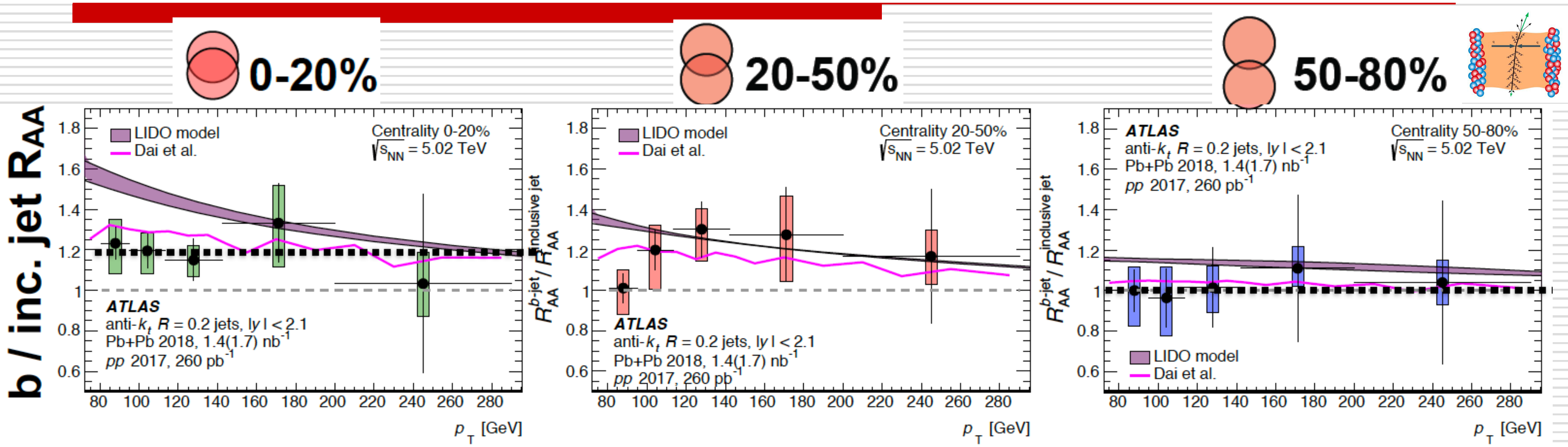
b jets in Pb-Pb at LHC



LIDO: FONLL + HF diffusion+energy loss ; **Dai et al.:** Sherpa + Langevin transport+radiation
Li&Vitev: (SCET) EFTs + medium modified splitting

- b jets suppressed in central collisions
- **LIDO** model describes well b-jet R_{AA}, while **Li&Vitev** and **Dai** underpredict the data.

b jets in Pb-Pb at LHC

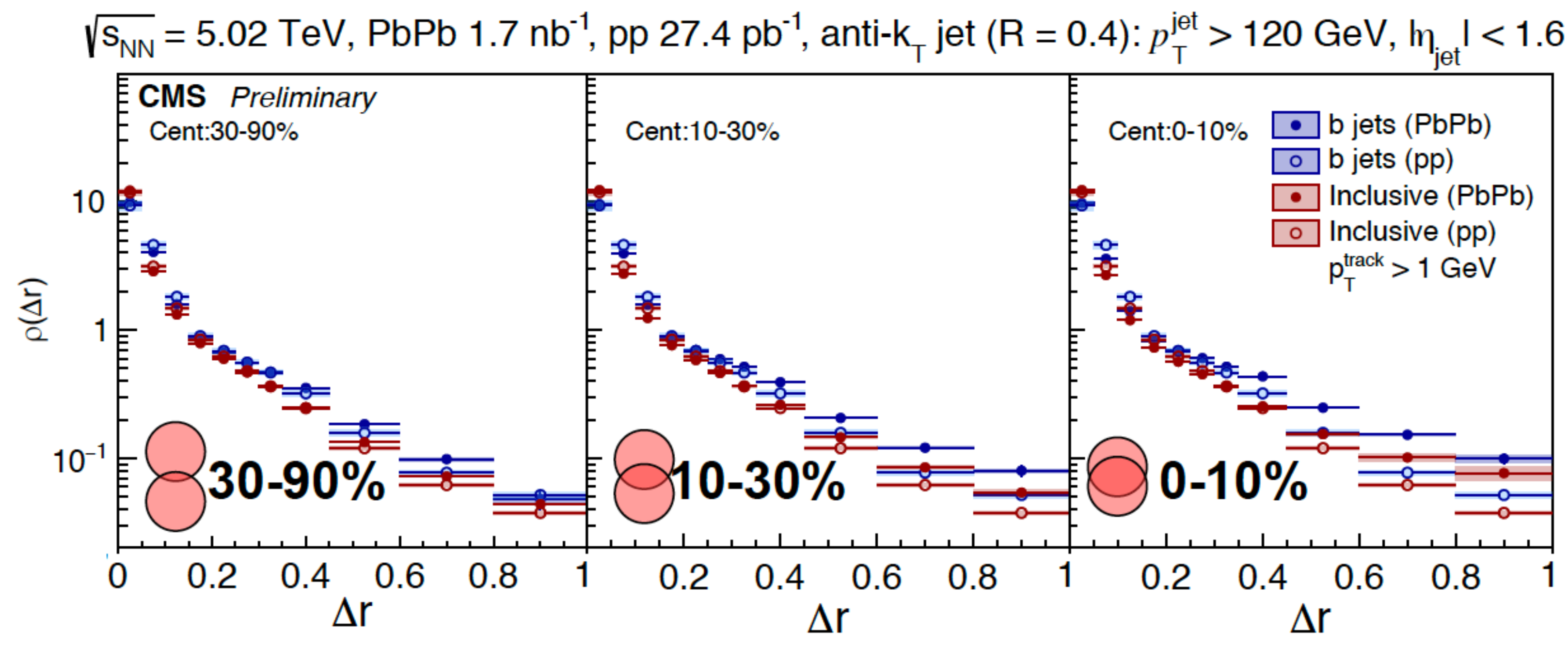


LIDO: FONLL + HF diffusion+energy loss ; **Dai et al.:** Sherpa + Langevin transport+radiation
Li&Vitev: (SCET) EFTs + medium modified splitting

- b jets suppressed in central collisions
- **LIDO** model describes well b-jet R_{AA}, while **Li&Vitev** and **Dai** underpredict the data.
- **R_{AA}(b jet) ~ R_{AA}(inc. jet)** in peripheral while **R_{AA}(b jet) > R_{AA}(inc. jet)** in central collisions.
- **Dai** calculations describe better the b / inclusive jet RAA ratio.
- Differences between b and inclusive jets dominated by quark vs gluon energy loss effects.

Radial shape modification of b-jets

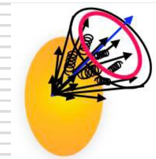
$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\Sigma_{\text{jet}} \Sigma_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_T^{\text{trk}}}{\Sigma_{\text{jet}} \Sigma_{\text{trk}} p_T^{\text{trk}}}$$

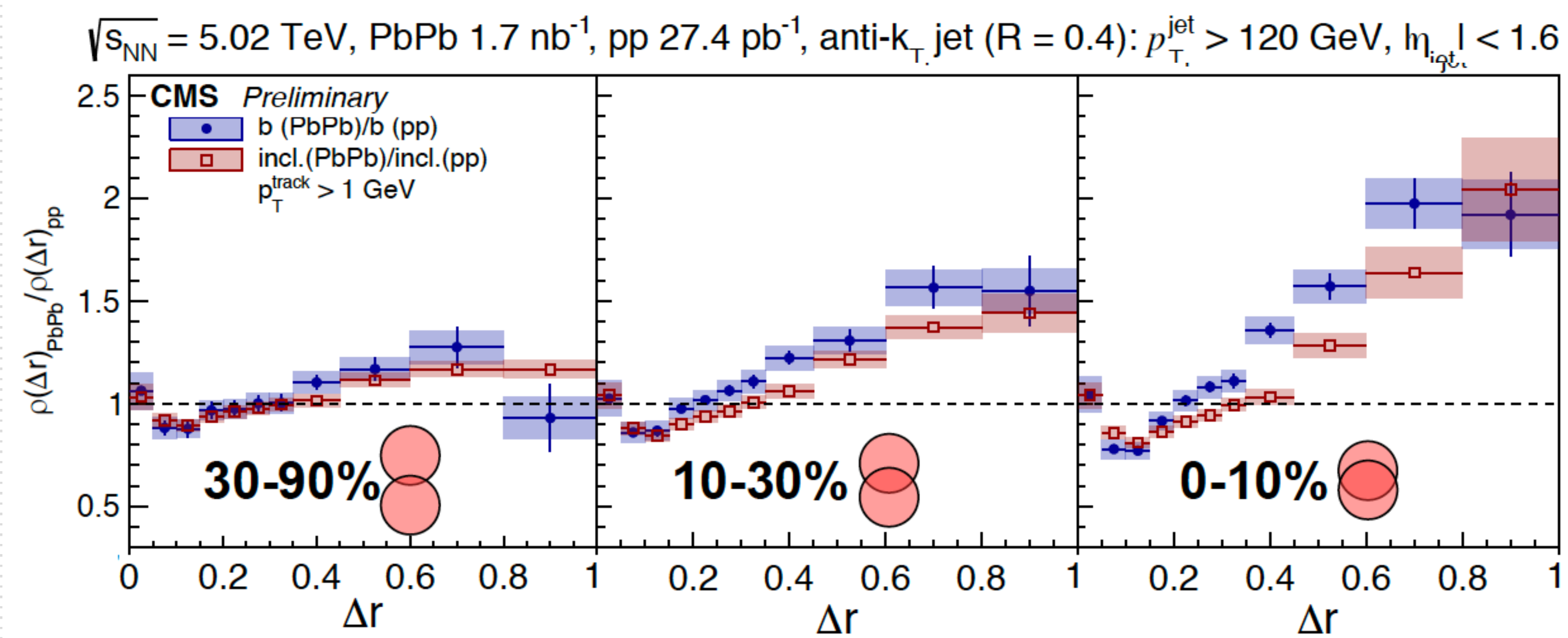


- both b and inclusive jet shapes broader than in pp

Radial shape modification of b-jets

$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\Sigma_{\rm jet} \Sigma_{{\rm trk} \in (\Delta r_a, \Delta r_b)} p_{\rm T}^{\rm trk}}{\Sigma_{\rm jet} \Sigma_{\rm trk} p_{\rm T}^{\rm trk}}$$

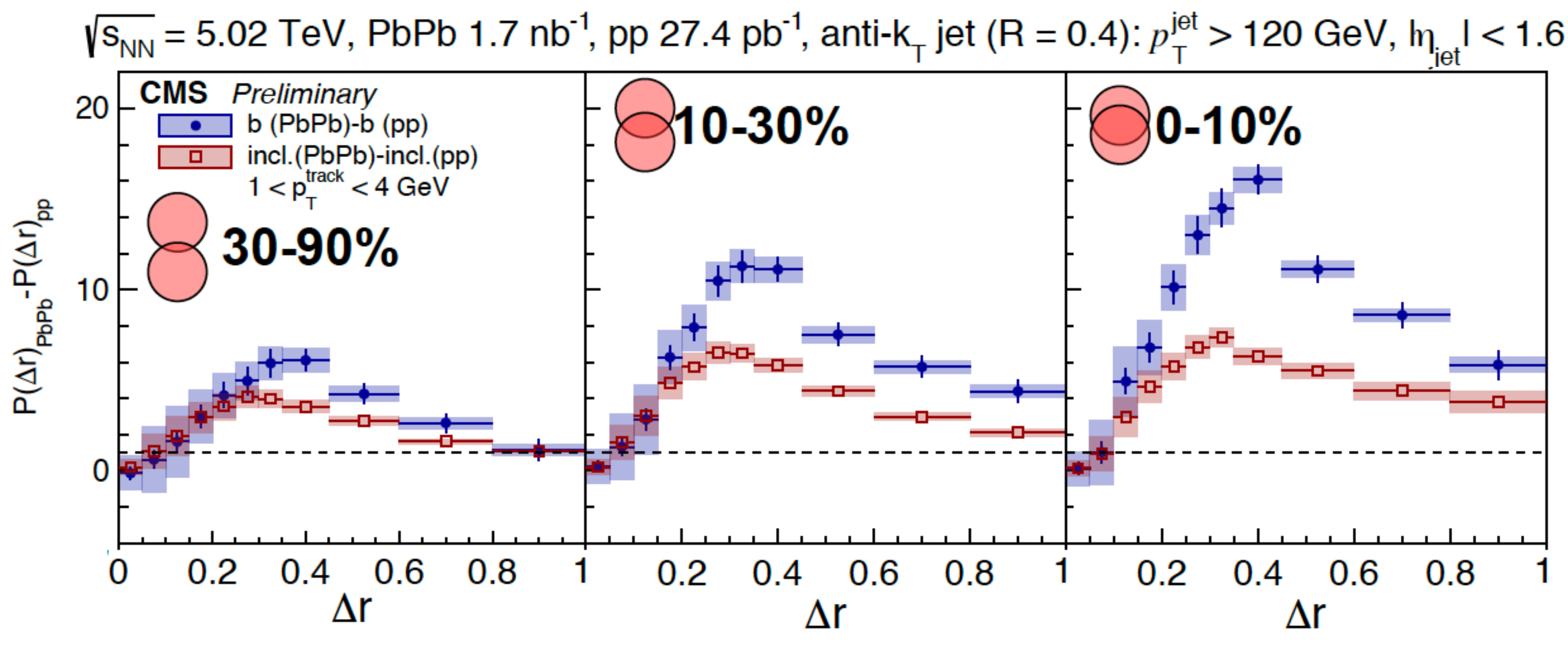




- both b and inclusive jet shapes broader than in pp
- relative modifications of b jets stronger than inclusive jets

Radial shape modification of b-jets

$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\Sigma_{\rm jets}\Sigma_{{\rm trk}\in(\Delta r_a,\Delta r_b)}p_{\rm T}^{\rm trk}$$



- both b and inclusive jet shapes broader than in pp
- relative modifications of b jets stronger than inclusive jets
- more low p_T tracks at large radius in b jets than inclusive jets

Conclusions and outlook

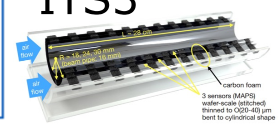
- good precision of HF experimental results reached at LHC and RHIC
  - stringent constraints to models
- quantitative properties of the QGP to be inferred from models that describe several observables at the same time
  - nice example at this workshop: approach to understand role of hadronization in HF production

Conclusions and outlook

- good precision of HF experimental results reached at LHC and RHIC
  - stringent constraints to models
- rich experimental effort on both short and long timescale

- charm and beauty mesons and baryons: v_2, R_{AA}
- low p_T regime, wider η range
- D_s constraint with beauty

ITS3



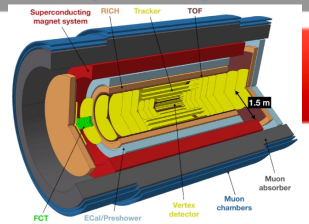
- Systematic measurements of multi-heavy-flavour hadrons
- D-$\overline{\text{D}}$ correlations
- p-wave charmonium

LHC: Run 3 (2022–2025) | LS3 (2026–2028) | Run 4 (2029–2032) | LS4 (2033–2034) | Run 5 (2035–2037)

2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037

RHIC: sPhenix

SPS: NA61 upgrade, NA60+



ALICE 3

- Υ spectroscopy
- open heavy flavor over full kinematic range: v_2, R_{AA}

- Onset of J/ψ suppression
- Hadronic decays of charmed mesons/baryons

- open charm production at SPS

Improved measurements: expected to offer new constraints to models; further insights into the hot and dense medium, origin of collectivity in small systems

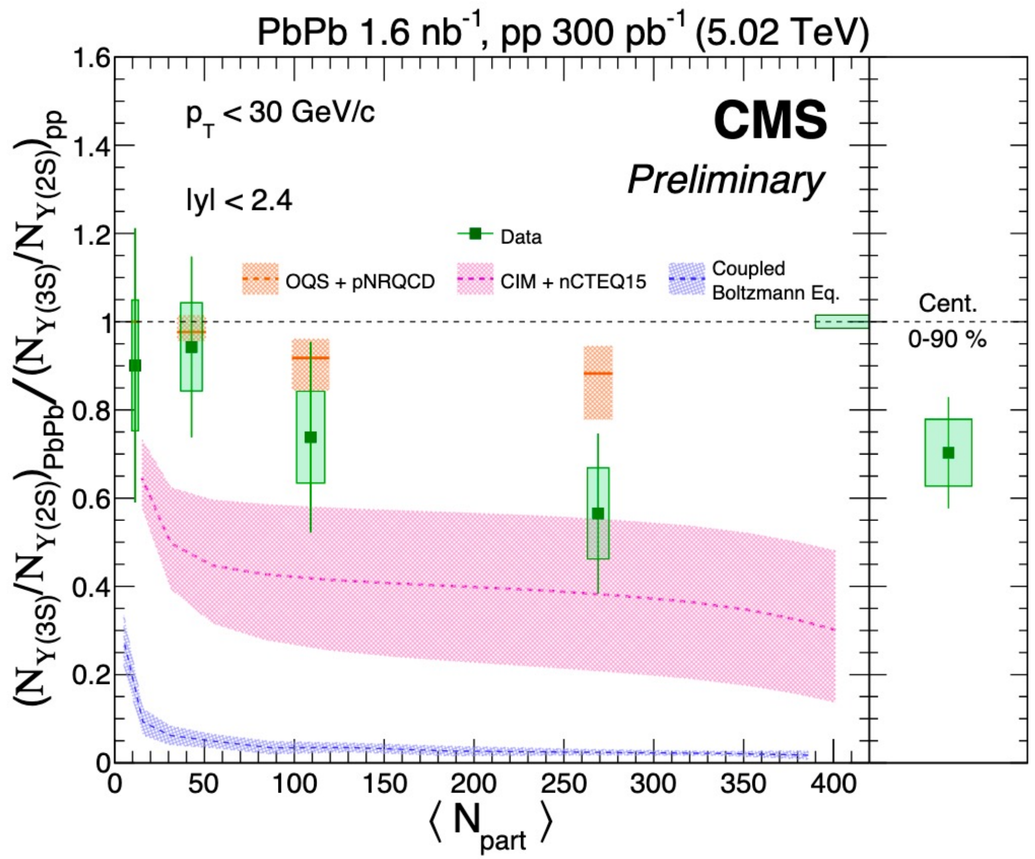
EXTRA

Bottomonium suppression in the QGP

- **First measurement of Υ(3S) in Pb-Pb**

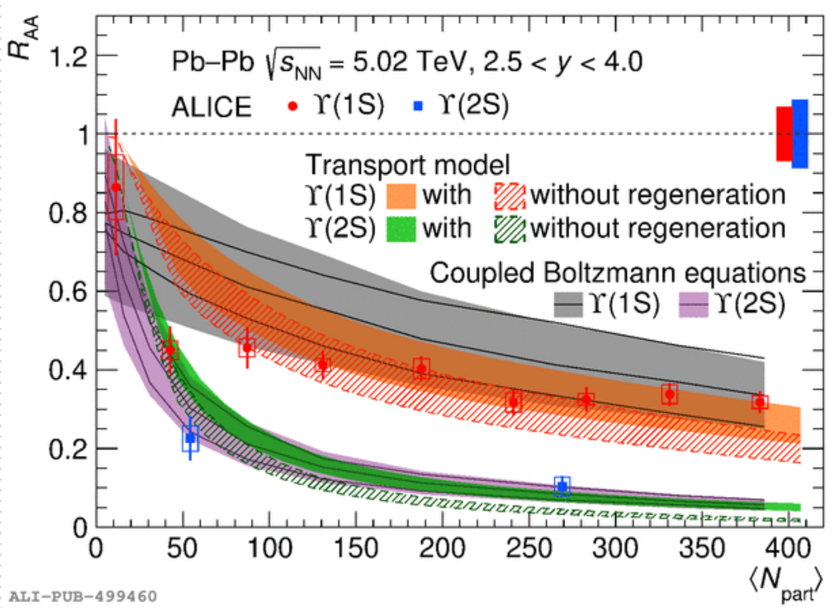
$$\frac{R_{AA}^{(3S)}}{R_{AA}^{(2S)}} \approx 0.7$$

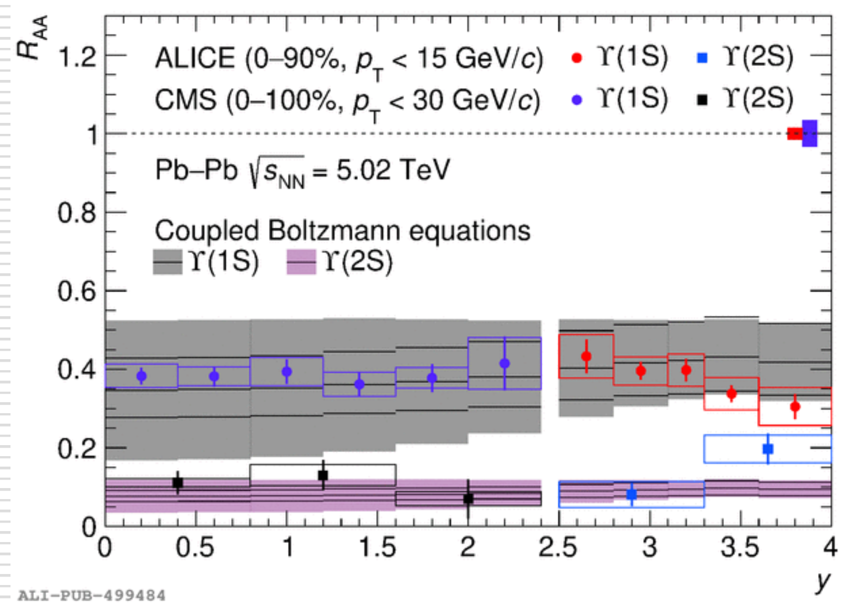
- what is the origin of those Υ(3S)?
  - from corona ?
  - from peripheral collisions ?



Υ(1S) and Υ(2S) R_{AA}

PLB 822 (2021) 136579



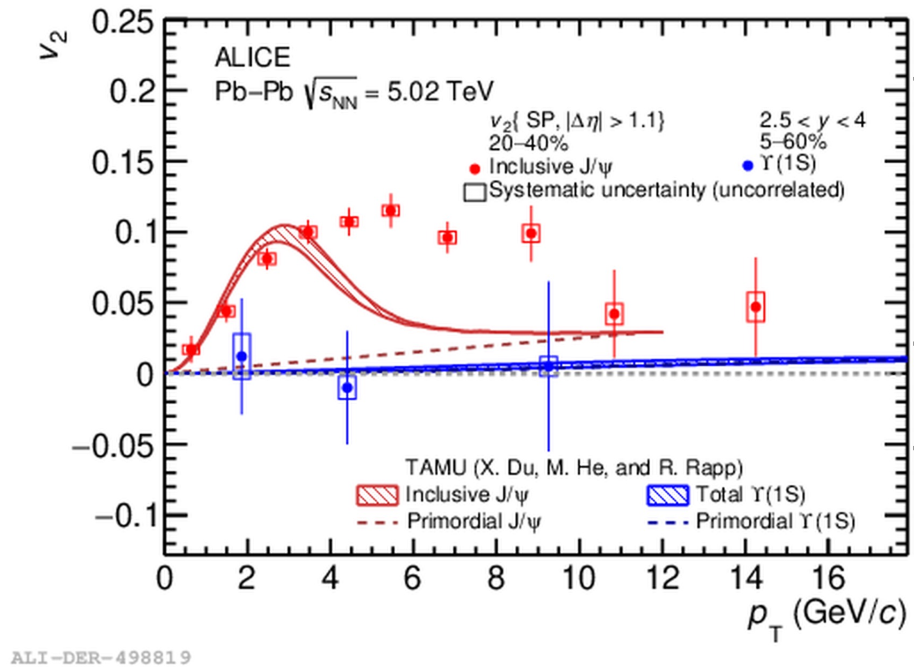


Transport Model PRC96 (2017) 054901
Coupled Boltzmann equations JHEP01 (2021) 046

- stronger suppression of Υ(2S) compared to Υ(1S)
  - confirmation at forward rapidity of the sequential suppression (CMS discovery)
- mild centrality dependence of R_{AA}
  - in agreement with models (also without including regeneration mechanism)
- rapidity dependence: hint for a decrease of Υ(1S) R_{AA} for y>3

Elliptic flow of J/ψ and Υ(1S)

JHEP 2020 (2020) 141   PRL123 (2019) 192301

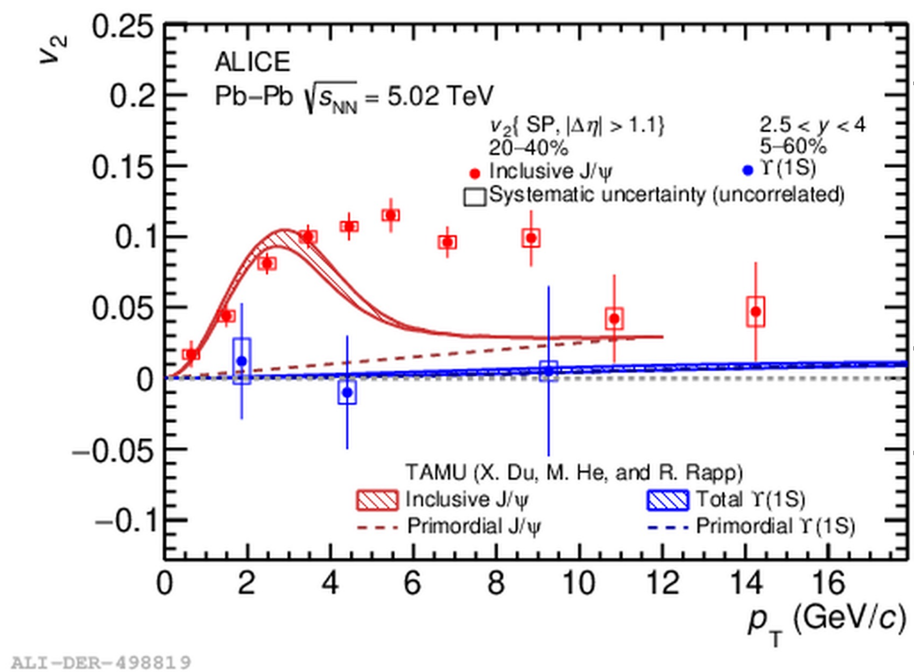


TAMU:
Nucl. Phys. A 943 (2015) 147
Phys. Rev. C 96 (2017) 054901

- large J/ψ v_2 at low p_T
  - further proof of recombination
  - suggesting also charm thermalization
- no sign of Υ(1S) flow

Elliptic flow of J/ψ and ϒ(1S)

JHEP 2020 (2020) 141 PRL123 (2019) 192301



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Nucl. Phys. A 9[illegible] (2015) 147
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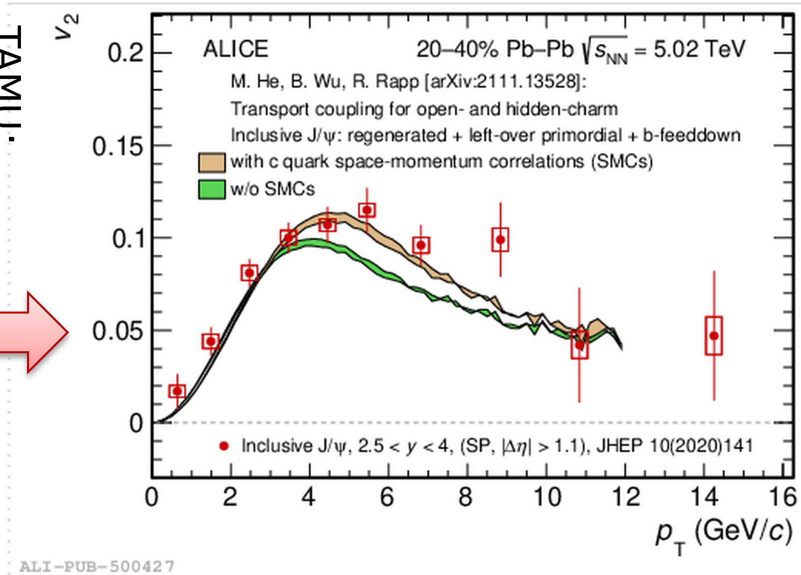


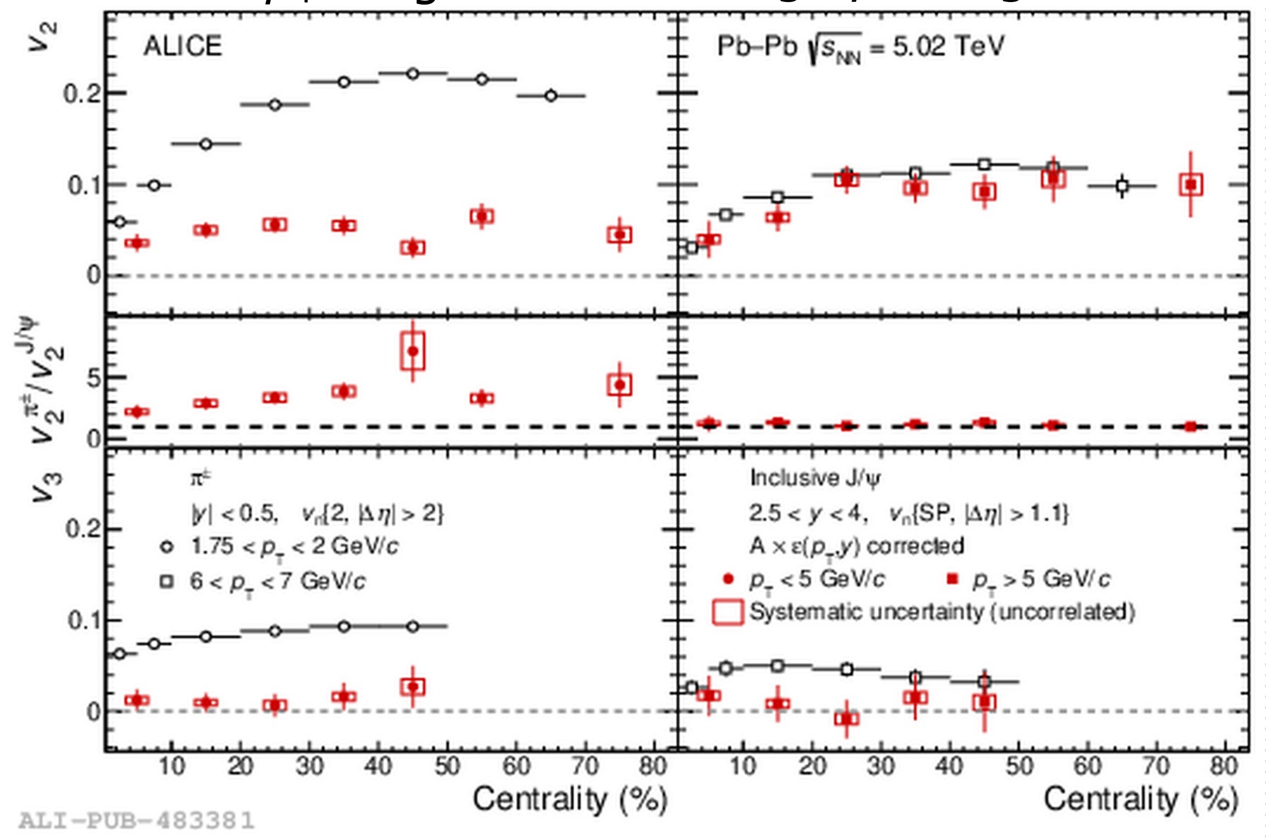
He, Wu, Rapp, PRL 128 (2022) 162301

- large J/ψ v_2 at low p_T
  - further proof of recombination
  - suggesting also charm thermalization
- models soon improved
  - accounting for the x^μ -p^μ correlation of the diffusing c and $\bar{c}$ in a hydrodynamically expanding fireball and revisiting the suppression of the primordial J/ψ component

Elliptic and triangular flow of J/ψ compared to π

low p_T range high p_T range

p_T range of the π chosen to match the $< p_T >$ of the J/ψ



JHEP 2020 (2020) 141

low p_T:

- $v_{2,3}$(J/ψ)<< $v_{2,3}$(π)
- v_2(π)/v_2(J/ψ) increasing from central to peripheral
  - increasing fraction of regenerated J/ψ or later thermalization for charm quarks than light quarks

high p_T:

- v_2(π)/v_2(J/ψ)~1
- v_3(J/ψ)< v_3(π)

Elliptic and triangular flow of J/ψ

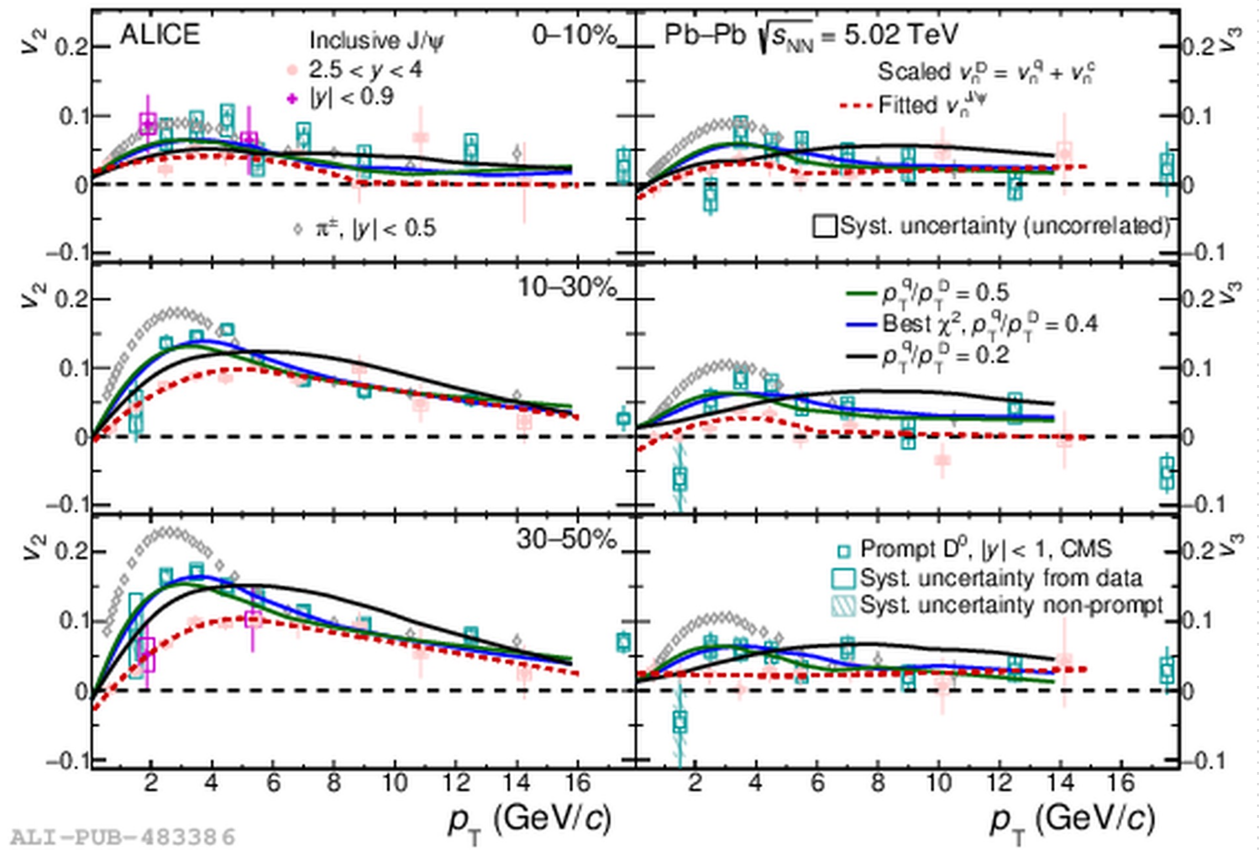
- exercise based on NCQ scaling

$$v_n^{J/\psi}(p_T^{J/\psi}) = 2 \cdot v_n^{c}(p_T^{J/\psi}/2)$$

$$v_n^{D}(p_T^{D}) = v_n^{q}(p_T^{q}) + v_n^{c}(p_T^{c})$$

$$v_n^{\pi}(p_T^{\pi}) = 2 \cdot v_n^{q}(p_T^{\pi}/2)$$

scaled D-meson flow very sensitive to the fraction of p_T carried by each of the constituent quarks



coalescence: constituent quarks have ~ same velocity → sharing of D^0 $p_T \propto$ effective m_q

$p_T^q/p_T^D = 0.2$ (black curve)	disfavoured by data
$p_T^q/p_T^D = 0.4$ (dark blue curve)	best agreement
$p_T^q/p_T^D = 0.5$ (green curve)	rather good description