Experimental results from Heavy Ion Collisions

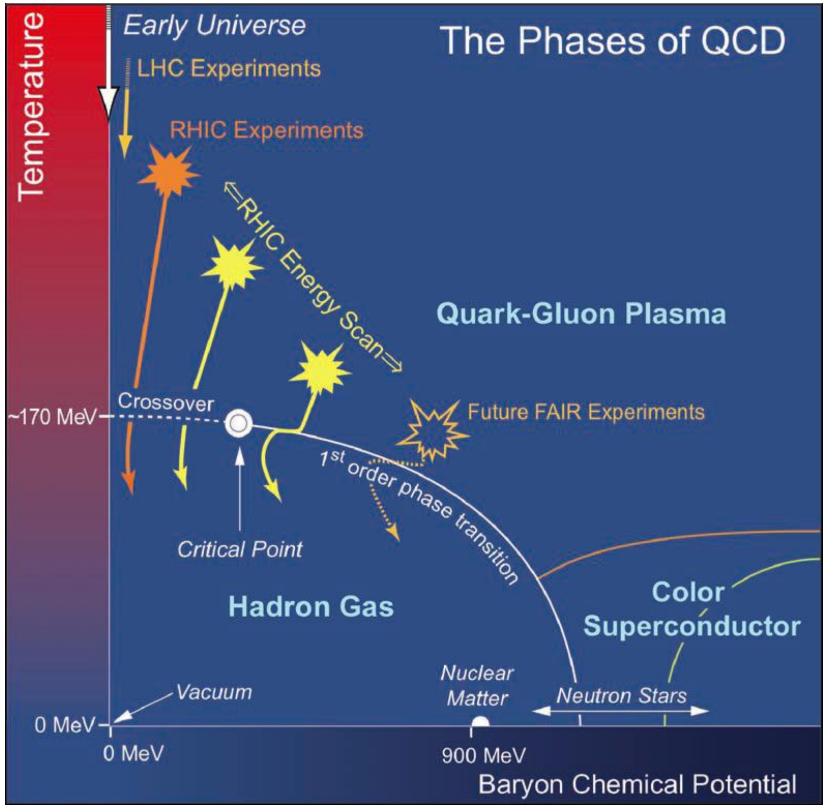
Jana Bielcikova (NPI CAS, Czech Republic)

Exploration of the QCD phase diagram

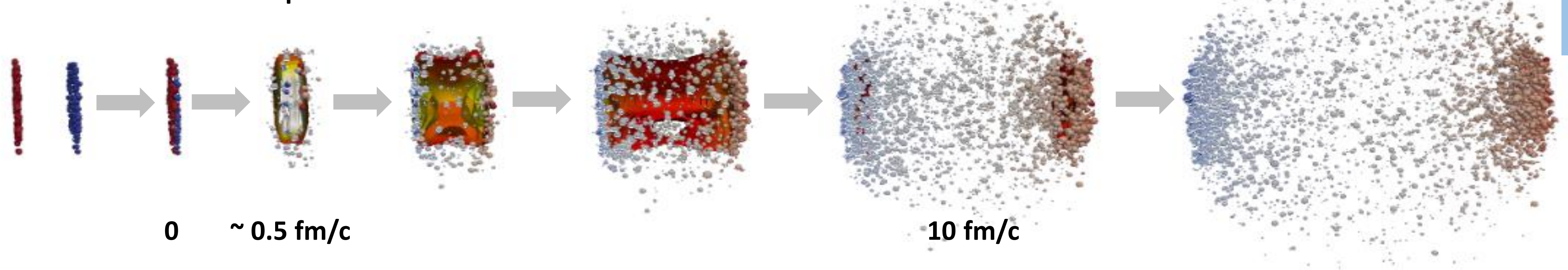
- heavy-ion collisions allow us to study QCD in laboratory
- properties of the quark-gluon plasma (QGP)
  at high temperature (RHIC/LHC)
  and large density (GSI FAIR/NICA)
- nature of the phase transition and search of critical point:

  → dedicated Beam Energy Scan (BES) program at RHIC

Reach in μ_B at RHIC:
collider mode (7-200 GeV): 20 - 420 MeV
fixed target (> 3 GeV): up to 720 MeV



Initial state | Hard collisions | QGP phase | Expansion | Hadronization and freeze-out

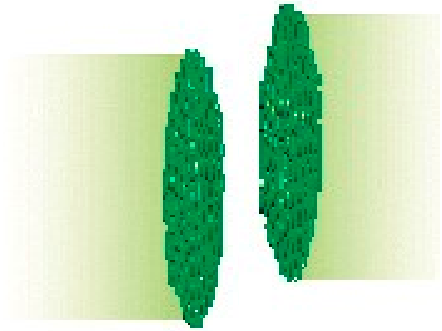


Time | 0 | ~ 0.5 fm/c | 10 fm/c

For BES results see:
H. Zbrosczyk (STAR)
Sat 17:00

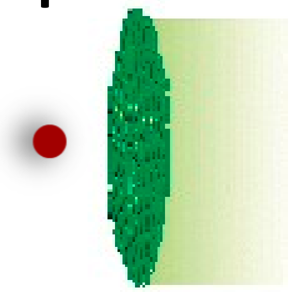
Dialing various physics phenomena: collision system

A + A



“hot/dense QCD matter”
final state effects
thermal and collective particle production (flow)

p + A



“cold nuclear matter”
initial state effects
shadowing and gluon saturation

p + p

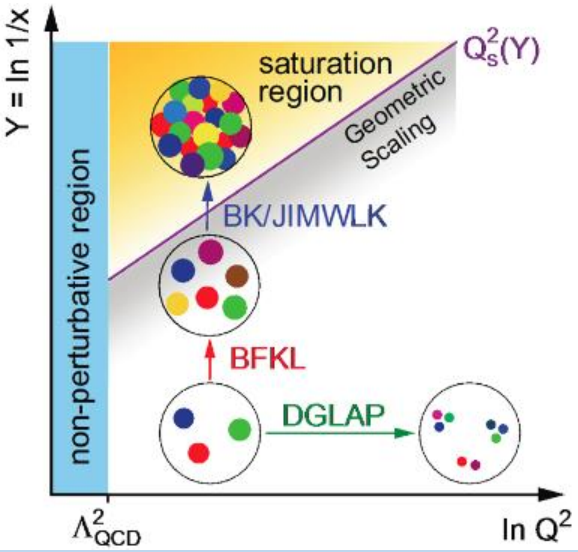
“vacuum”
reference

Centrality:
level of overlap of the colliding Lorentz contracted nuclei

A very interesting physics program on its own:
high multiplicity pp collision studies
to look for onset of QGP formation

Initial state

Constraining nPDF with LHCb data



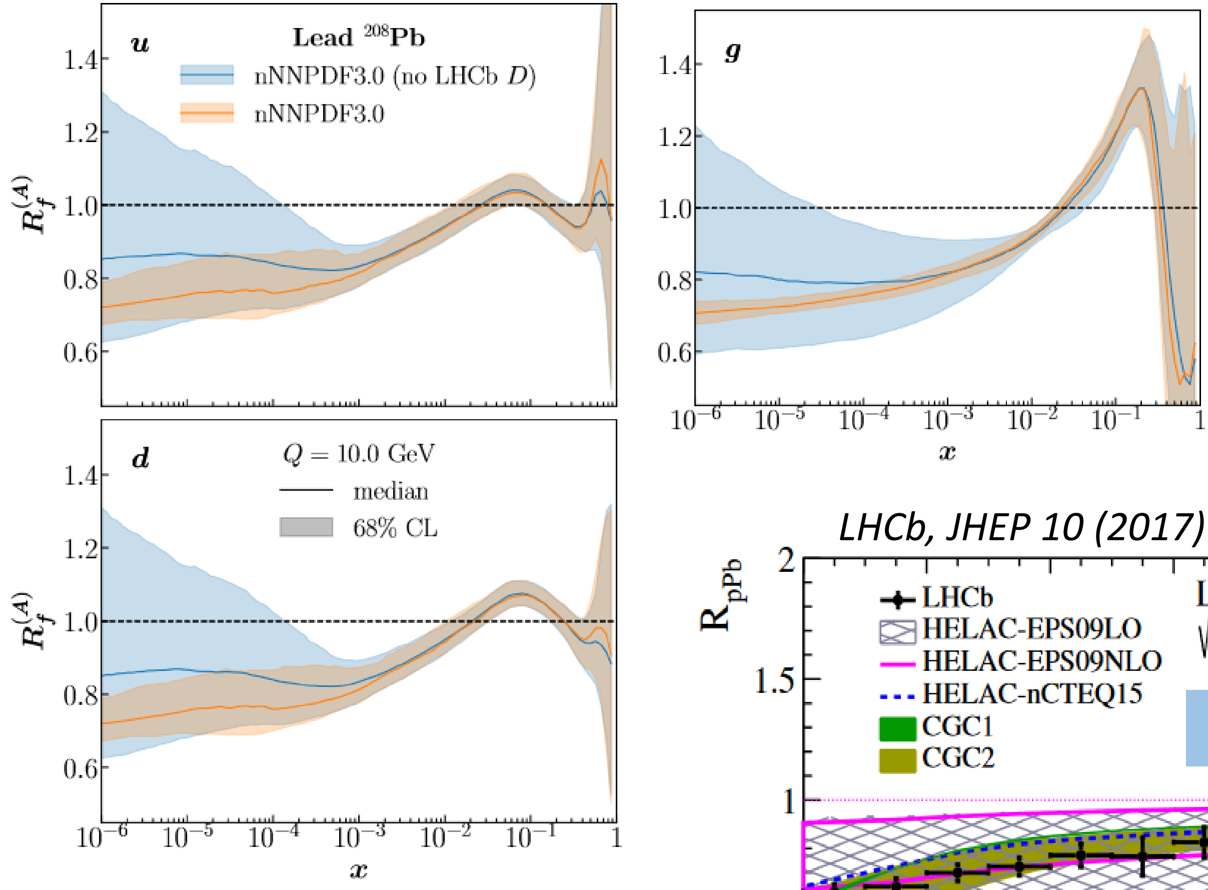
Low x region:
parton densities modified in nuclei

Shadowing:
depletion of the effective number of gluons poorly constrained from previous data

Color Glass Condensate (CGC):
large number of low-x gluons can lead to a very dense saturated wave function expected at low x and small Q^2 region

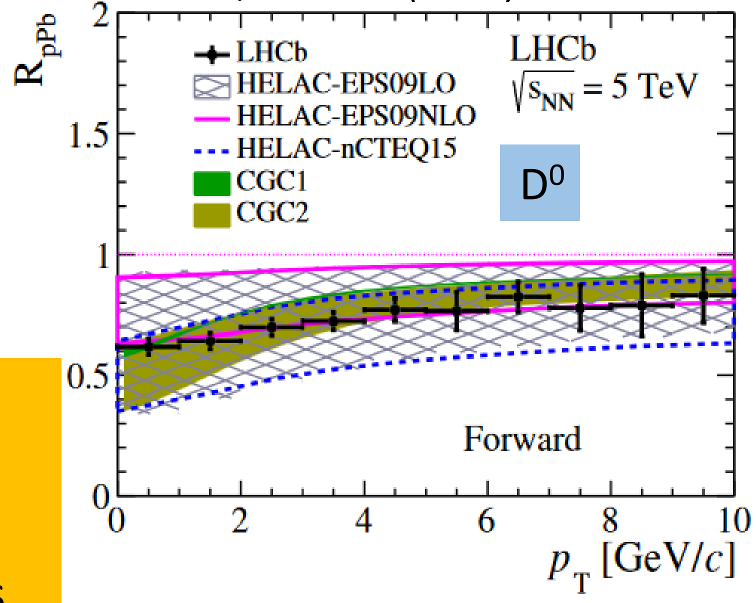
Saturation scale: $Q_s^2 \propto A^{1/3}$

Khalek et al. EPJ C 82 (2022) 6



Prompt D^0 production in pPb collisions
→ impressive impact on reducing nPDF uncertainties down to x ~ 10^{-6}!

LHCb, JHEP 10 (2017) 090

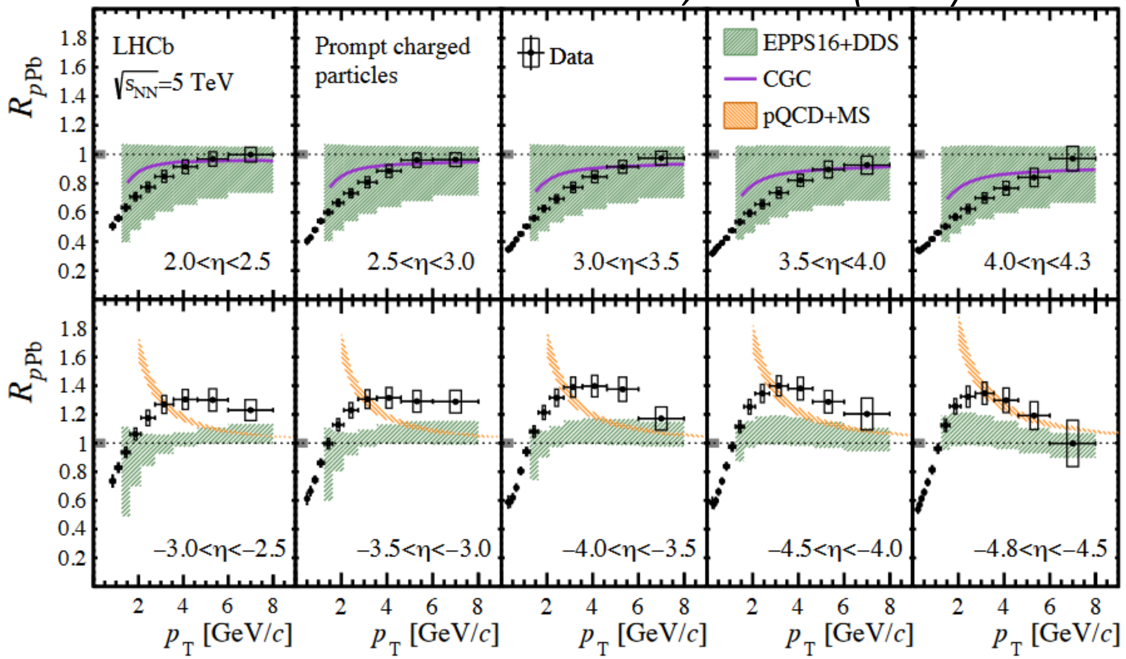


See also M. Klasen (CTEQ) Sat 10:25

Nuclear modification factor in pPb collisions

J. Sun (LHCb) Fri 17:50

LHCb, PRL 128 (2022)142004



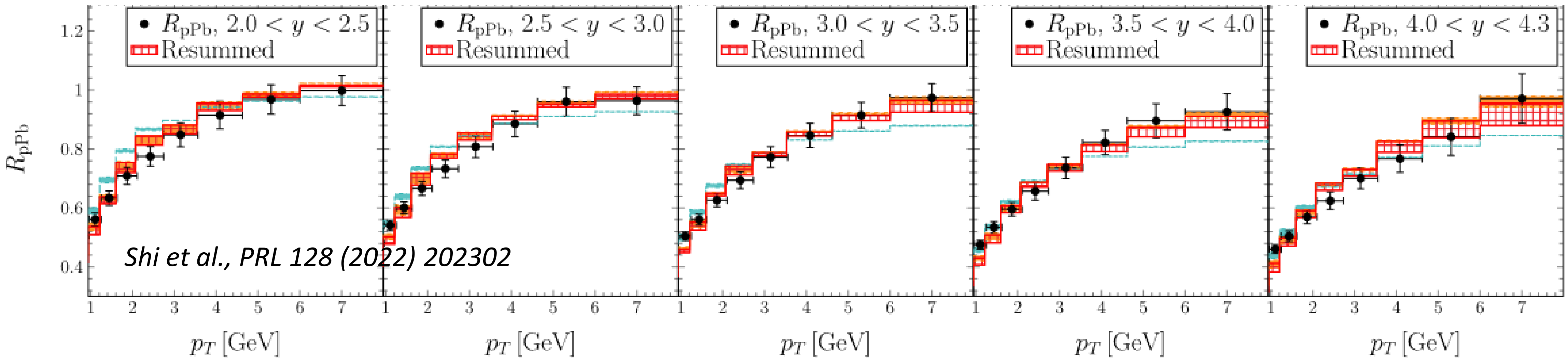
LHCb precision measurements in pPb collisions:

Strong suppression at forward rapidity and enhancement at backward rapidity.

Difficult for models to describe simultaneously data across the full rapidity range at the LHC + RHIC

New CGC NLO calculations can reproduce data from RHIC to LHC!

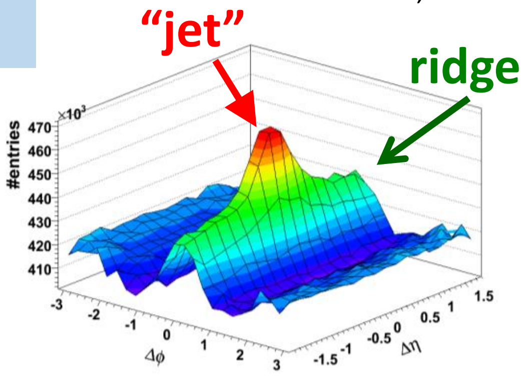
π^0 production: pPb 8.16 TeV, LHCb, arXiv:2204.10608



Shi et al., PRL 128 (2022) 202302

The ridges …

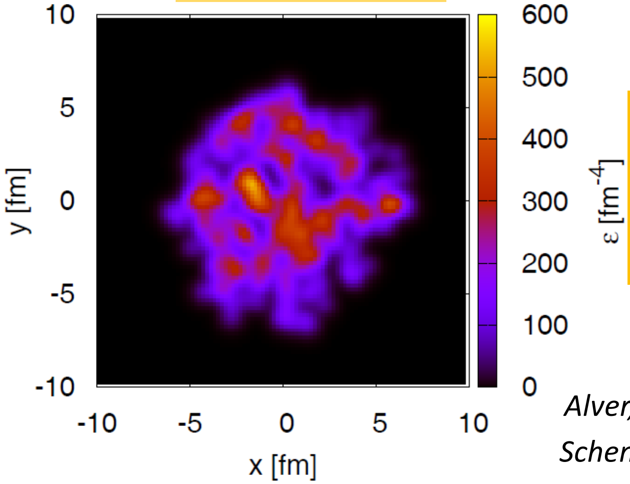
STAR



p_T^{trig}=3-4 GeV/c, 2 GeV/c <p_T^{assoc}< p_T^{trig}

The "ridge" in pseudorapidity observed in AuAu collisions at RHIC in 2004.

3+1D viscous hydrodynamics



Initial state fluctuations create the ridge (v_3) in AA collisions.

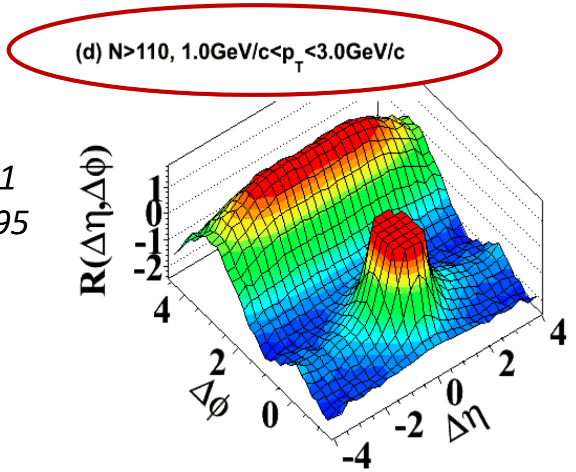
Alver, Roland, PRC81 (2010) 054905

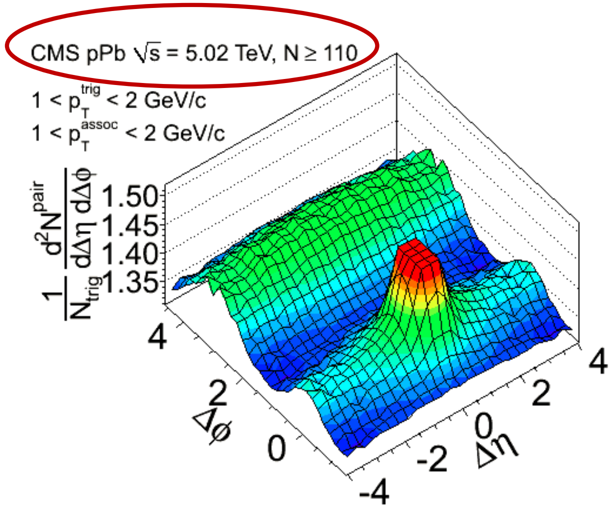
Schenke et al, PRL 106 (2011) 042301

Ridge observed in small systems at the LHC!

e.g. CMS, JHEP09 (2010) 091

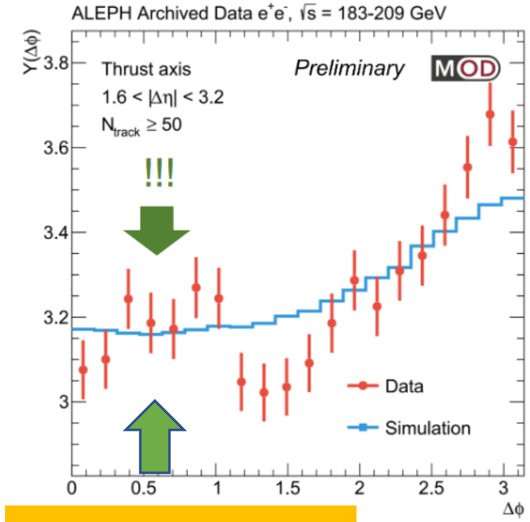
CMS, PLB 718 (2012) 795



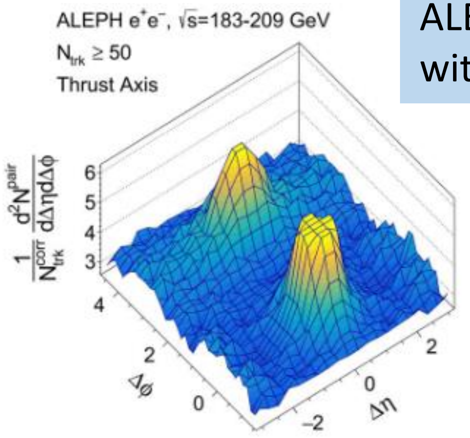


What causes the ridge in small systems: CGC, mini-QGP, … ?

→ look to e^+e^- or ep (well defined initial conditions)



Is this a ridge?



ALEPH data with (N_{trk}>50)

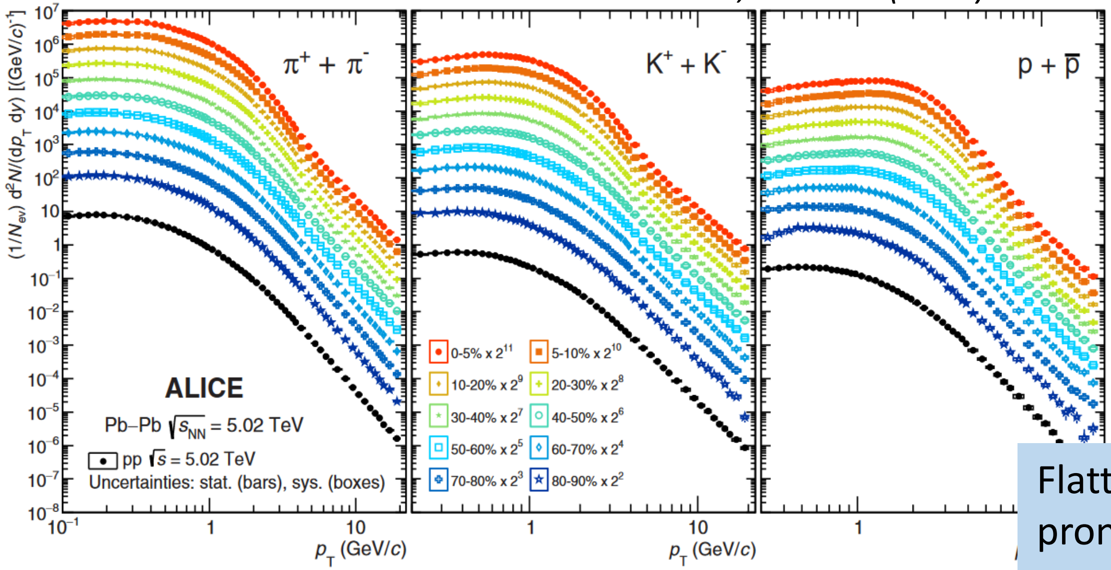
Chen (Belle), Lee (ALEPH) , Bussey (HERA) Sat 17:35-18:05

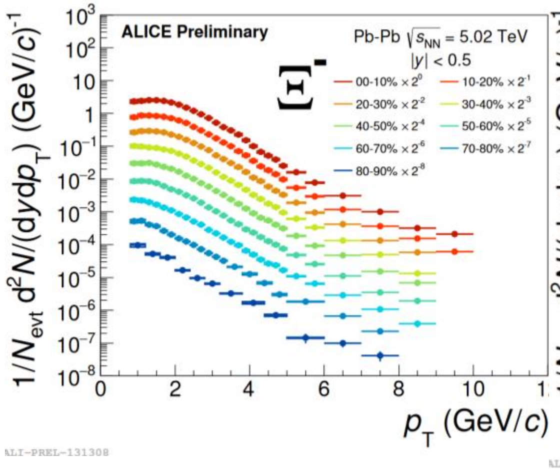
Bulk production in heavy-ion collisions

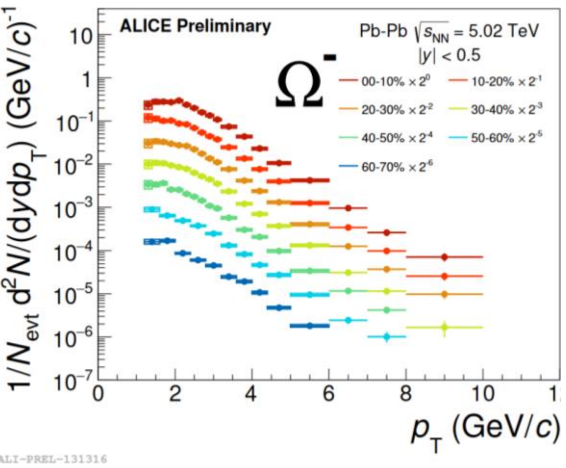
Inclusive particle production

M. Krueger (ALICE) Thu 9:00

ALICE, PRC 101 (2020) 044907

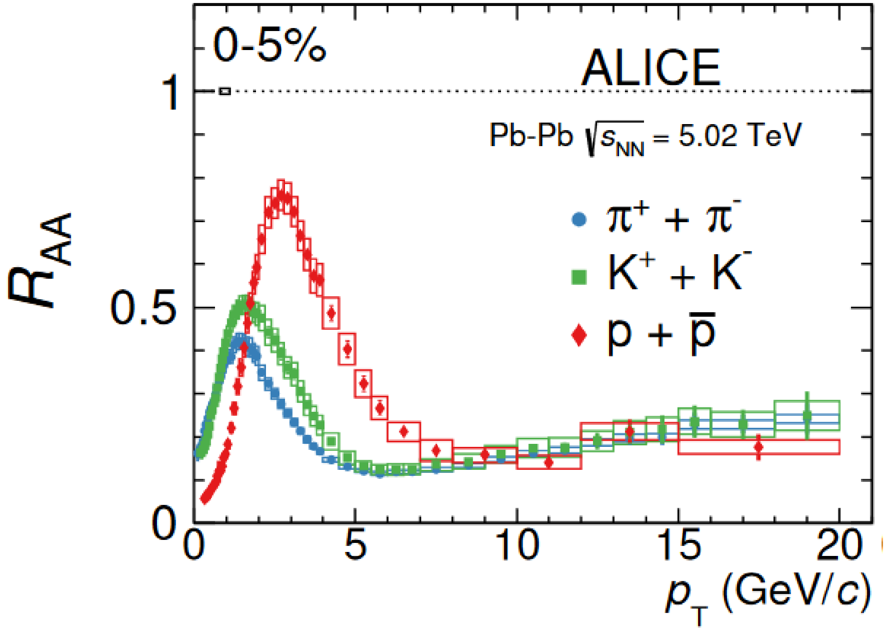






Flattening at low p_T more pronounced for heavier particles → radial flow

Particle production measured by ALICE with great precision
… just a snapshot here



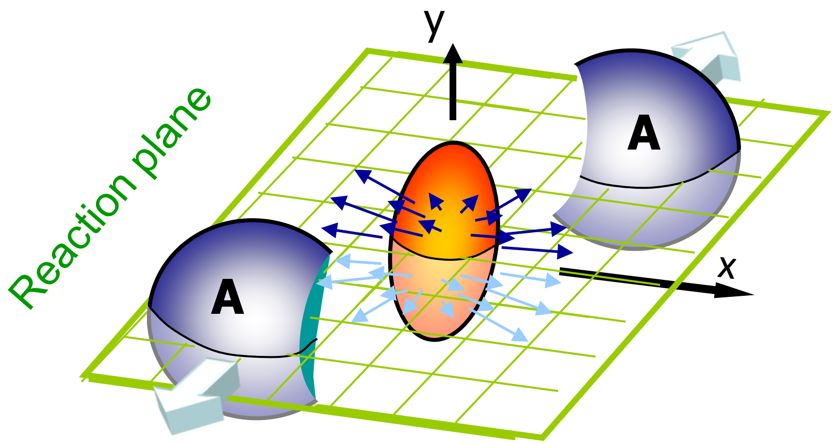
Nuclear modification factor:

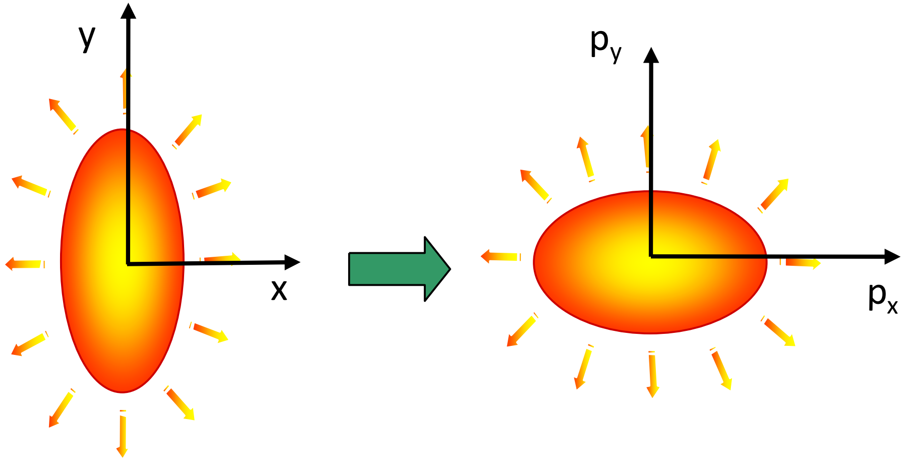
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

N_{coll} … number of binary collisions
R_{AA} = 1 AA is superposition of pp
R_{AA} < 1 suppression by medium

Central PbPb colisions: particle production is strongly suppressed by the medium

Anisotropic flow





Initial spatial anisotropy → Strong pressure gradients → Anisotropy of produced particles

Sensitivity to early expansion

Fourier analysis of particle distribution:

v_1 : directed flow

v_2: elliptic flow

v_3: triangular flow ...

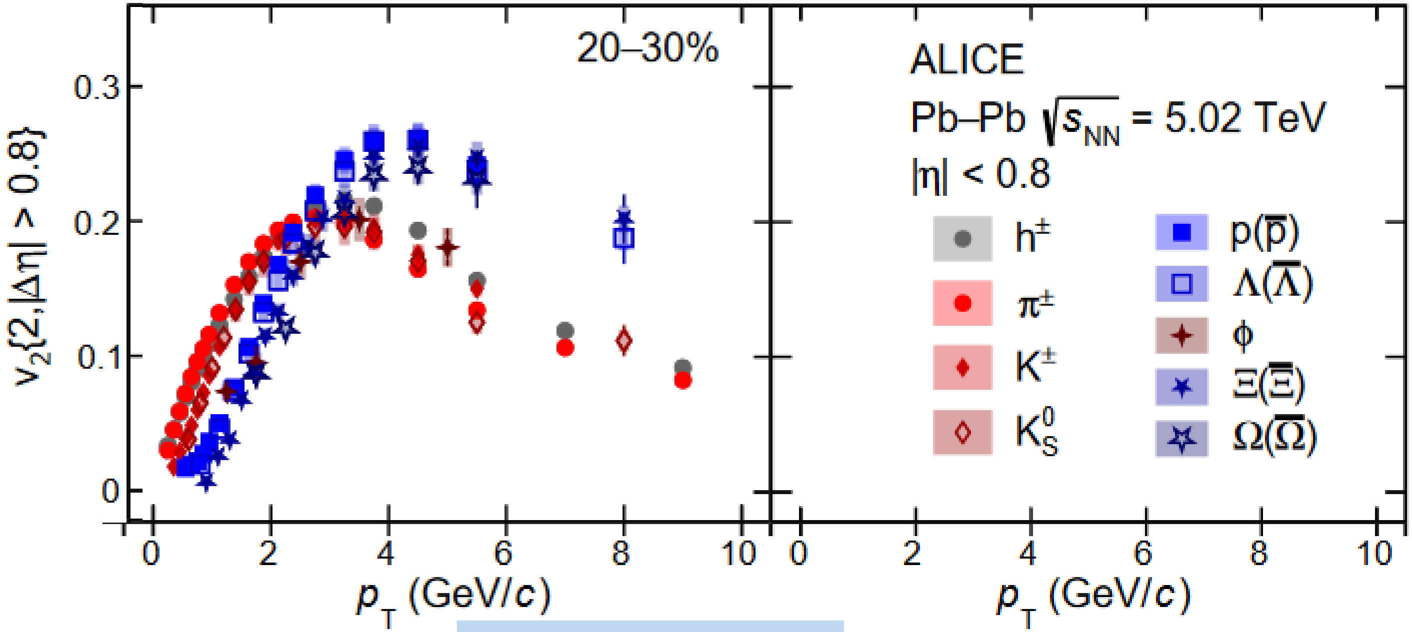
$$\frac{dN}{d(\phi - \Psi_R)} = A\left[1 + \sum_n 2\mathbf{v}_n \cos(n(\phi - \Psi_R))\right]$$

Anisotropic elliptic flow

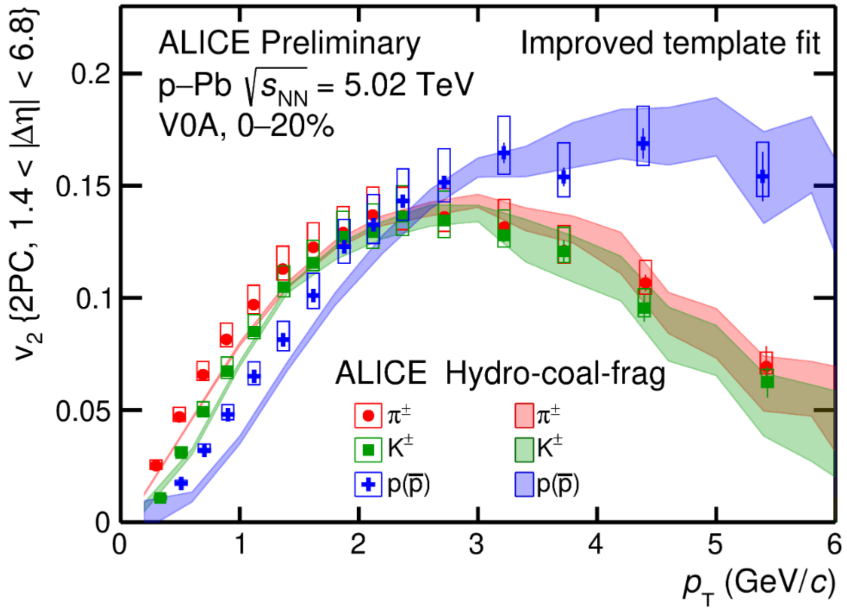
A. Dainese (ALICE) Mon 16:00
P. Dixit (STAR) Thu 9:15

ALICE, arXiv:2206.04587

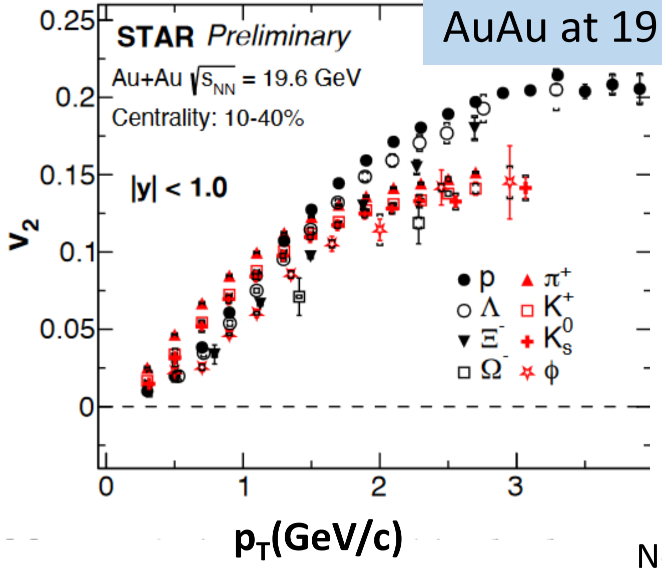
PbPb at 5.02 TeV



pPb at 5.02 TeV



AuAu at 19.6 GeV



Low p_T: mass ordering in line with hydrodynamics

High p_T: baryon and meson grouping
→ flow develops on quark level

The baryon/meson grouping is observed down to low collision energies of RHIC + similar observation also in pPb collisions at the LHC!

New method developments: Asymmetric cumulants, Symmetry plane correlations …

M. Lesch (ALICE) Fri 17:35

Hard probes: tomography of nuclear matter

Experimental challenge:
QGP lifetime is very short
→ in-situ probes needed

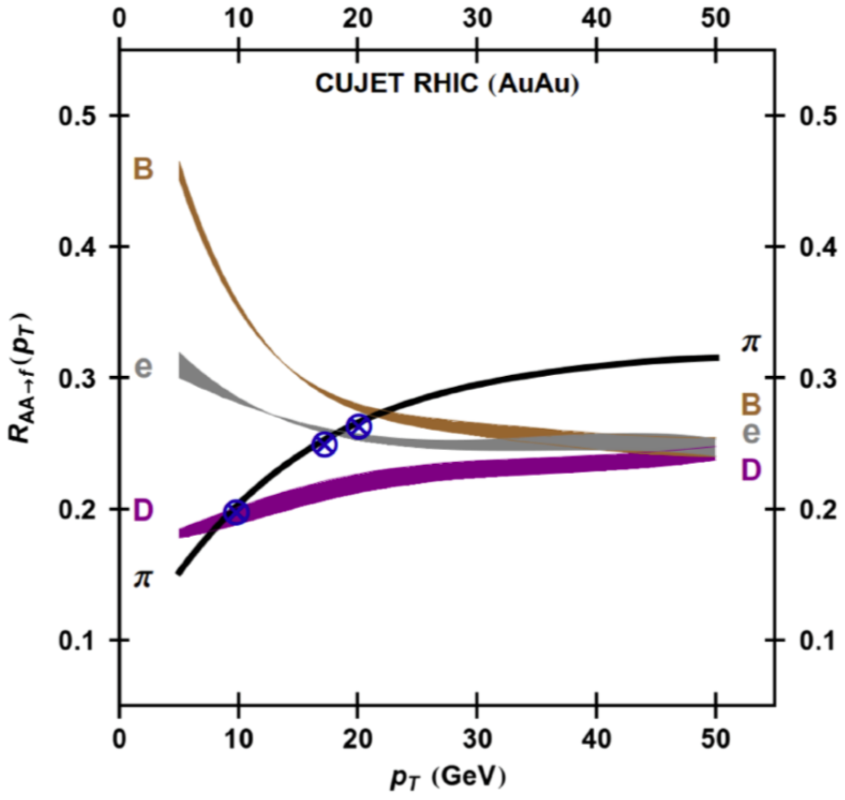
Jets, heavy quarks, quarkonia :
originate from initial hard scattering of partons which carry a color charge, interact with nuclear matter.

$\tau_b \sim 0.02$ fm/c < $\tau_c \sim 0.07$ fm/c < $\tau_{QGP} \sim 1$ fm/c

Energy loss in medium:
- elastic scatterings
- gluon radiation

Depends on:
- color charge
- quark mass (dead cone effect)
- path length in medium

Buzzatti, Gyullassy, PRL 108 (2012) 022301



Goal:
Use in-medium parton energy loss to quantify medium properties.

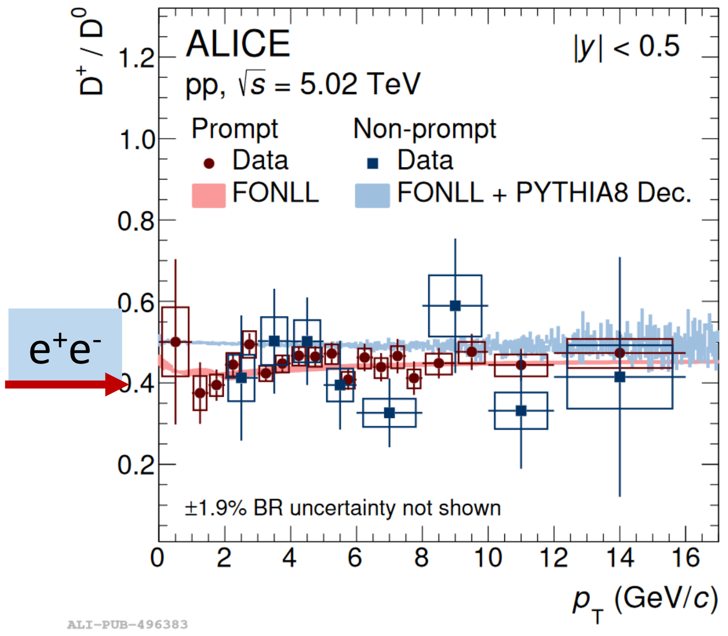
Parton interaction with medium not trivial, depends on strength of coupling, dynamics of fireball … *challenge for theorists*

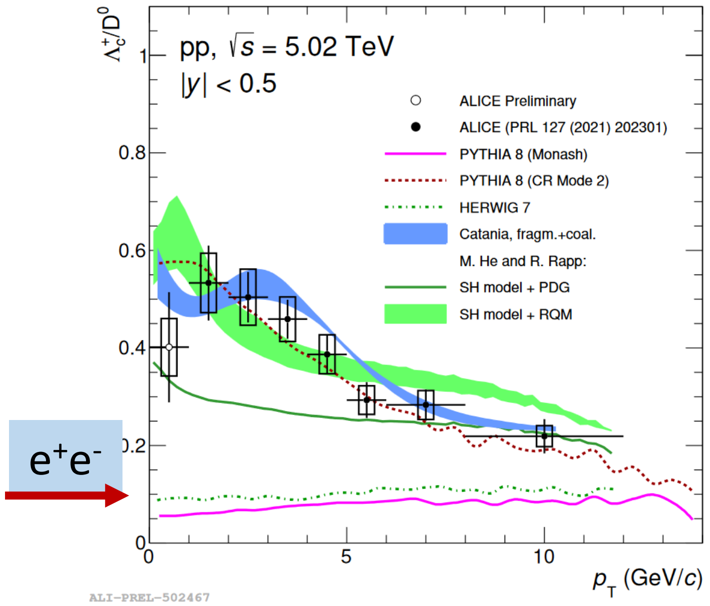
→ see talk by C. Salgado

Open heavy flavor production

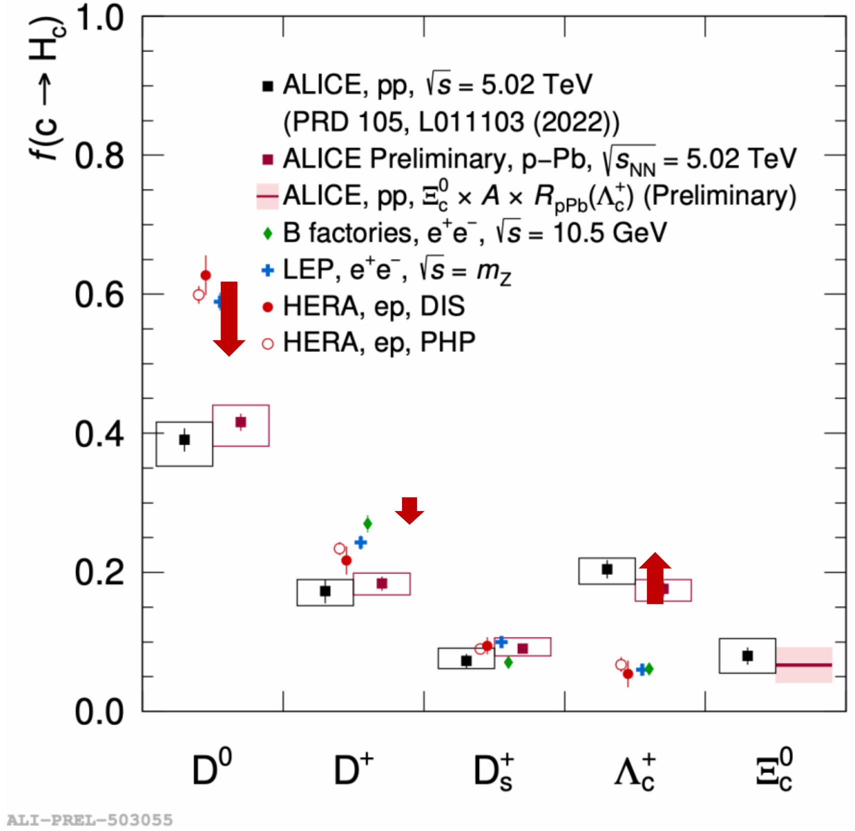
Constraining hadronization of charm quarks

J. Zhu (ALICE) Thu 11:45





ALICE, JHEP 05 (2021) 220



D meson ratios: agree with calculations based on a factorisation approach and relying on universal fragmentation functions in e^+e^-/ep

Baryon Λ_c^+/D^0 : significantly higher than in e^+e^-!

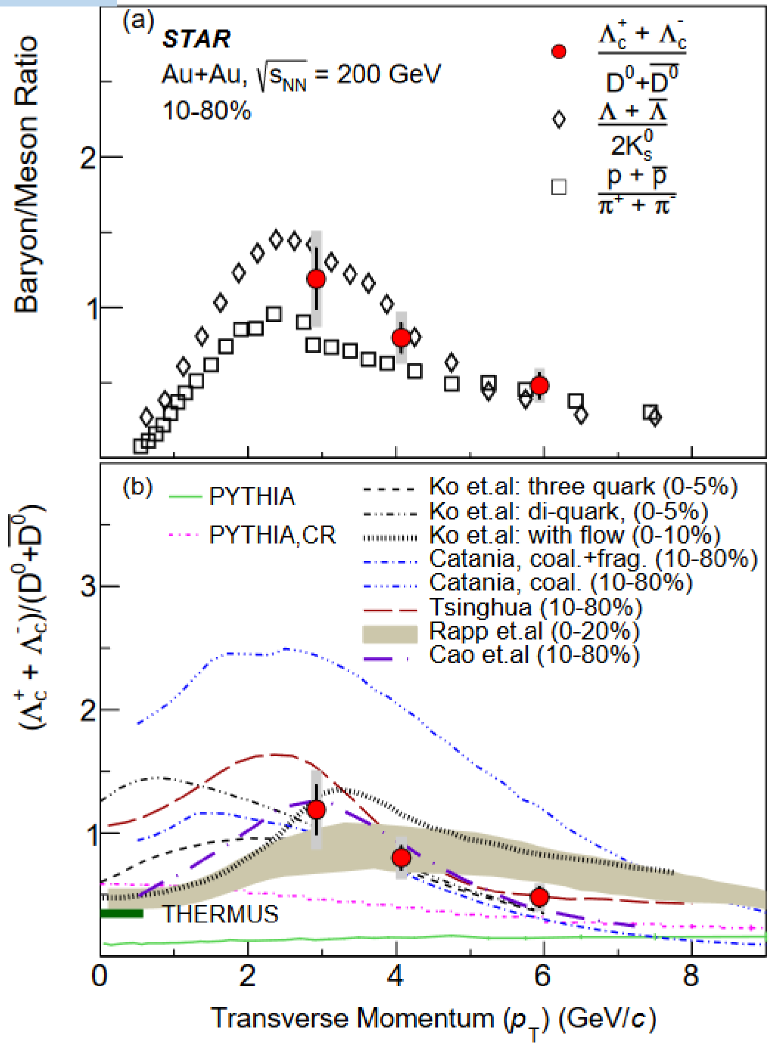
Charm-fragmentation fractions are not universal!

Hadronization of charm quarks in medium?

J. Zhu (ALICE) Thu 11:45
S. Kabana (STAR) poster
J. Wang (LHCb) Sat 12:25

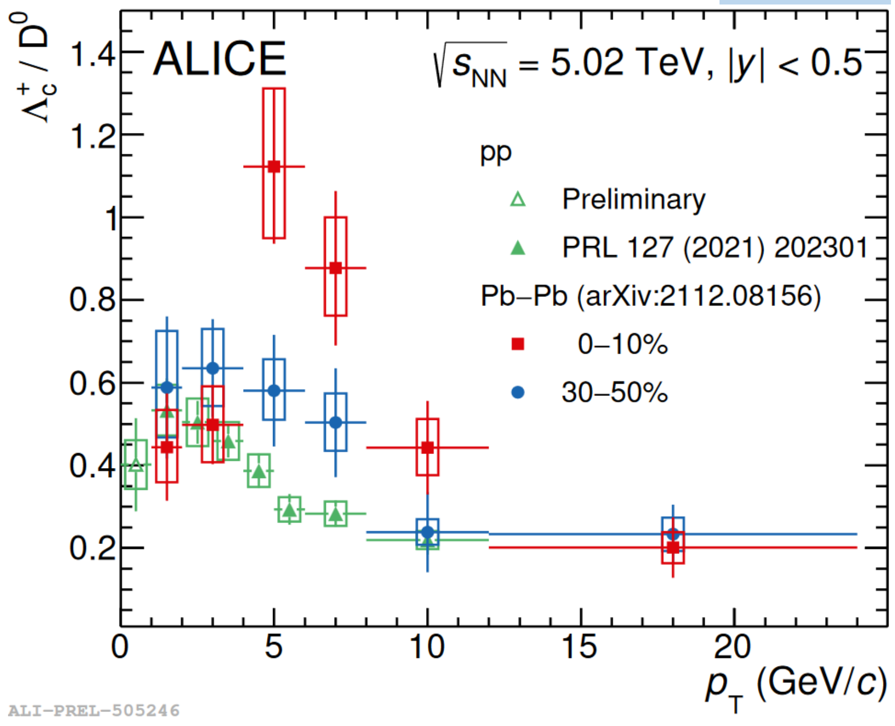
STAR

STAR, PRL 124 (2020) 17, 172301



ALICE, arXiv:2112.08156

ALICE



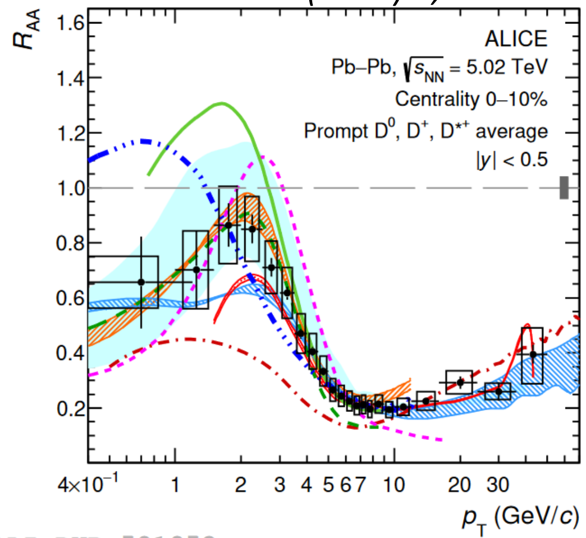
Additional dynamics in QGP:
Λ_c/D^0 enhancement at intermediate p_T relative to pp present from RHIC to LHC
→ similar to light flavor hadrons
→ parton recombination at play also for c quarks

Note: LHCb data at forward rapidity in peripheral PbPb follows a similar trend
(LHCB-PAPER-2021-04, in preparation)

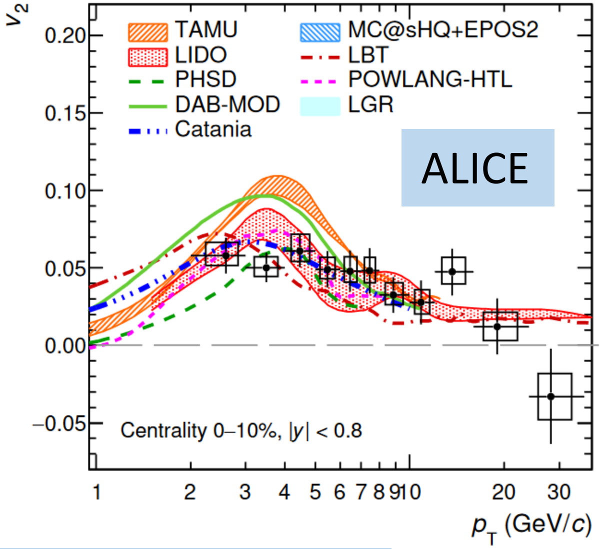
Open heavy flavor production: D^0, D^+, D^{*+}

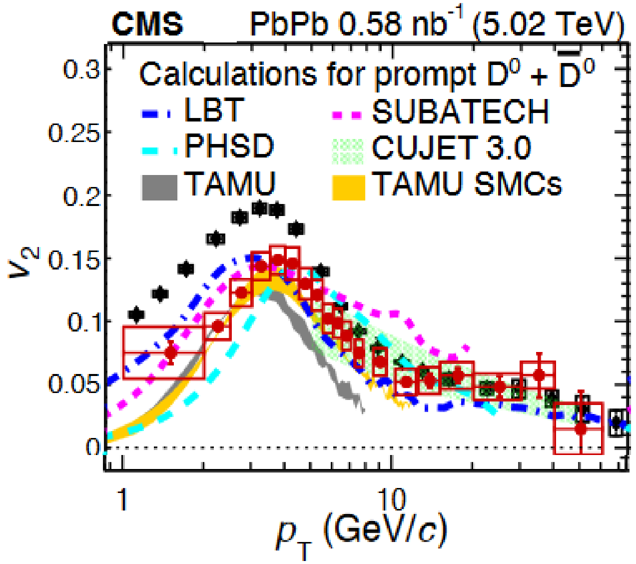
F. Catalano (ALICE) Thu 14:30
M. Stojanovic (CMS) Thu 15:00
S. Kabana (STAR) poster

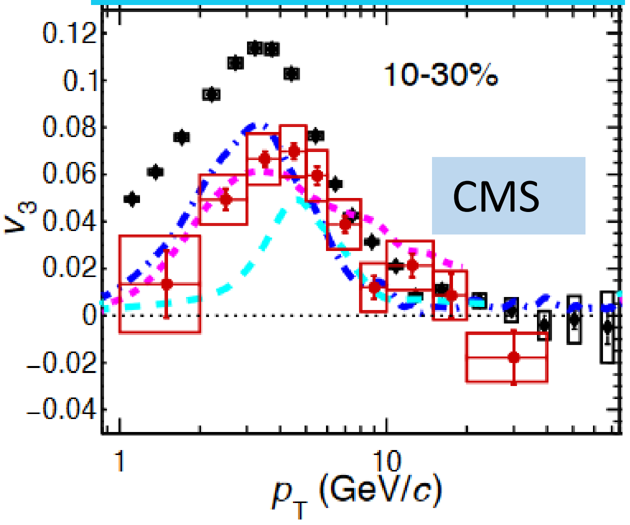
ALICE PRC 99 (2019) 3, 034908



ALI-PUB-501952



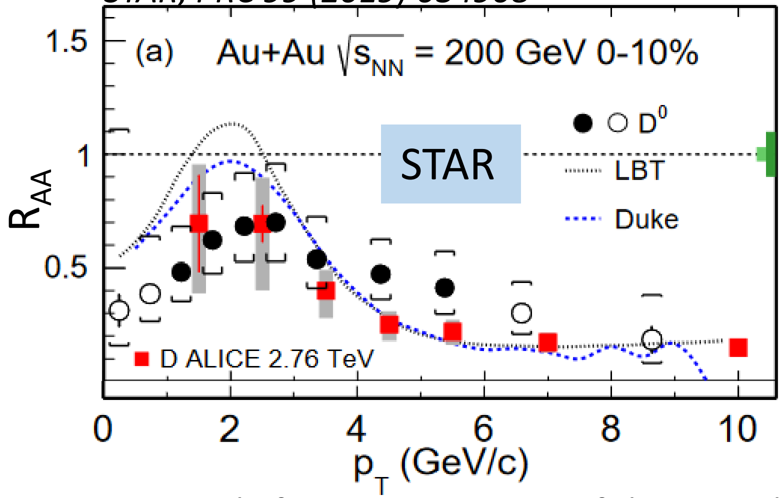




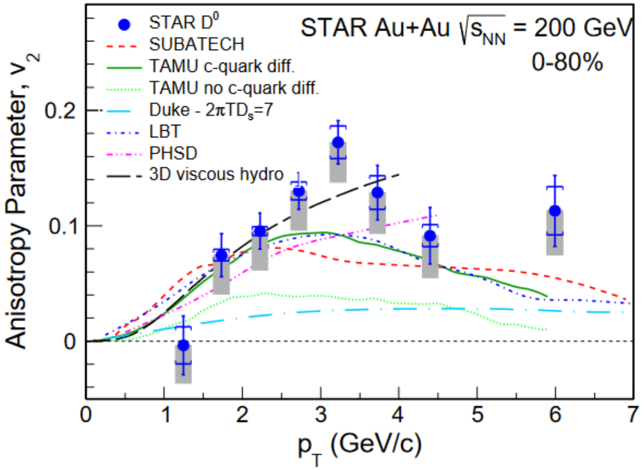
ALICE: precise D meson measurements down to low p_T

Charm production suppressed in heavy-ion collisions and charm quark flows.

STAR, PRC 99 (2019) 034908



STAR, PRL 118 (2017) 212301



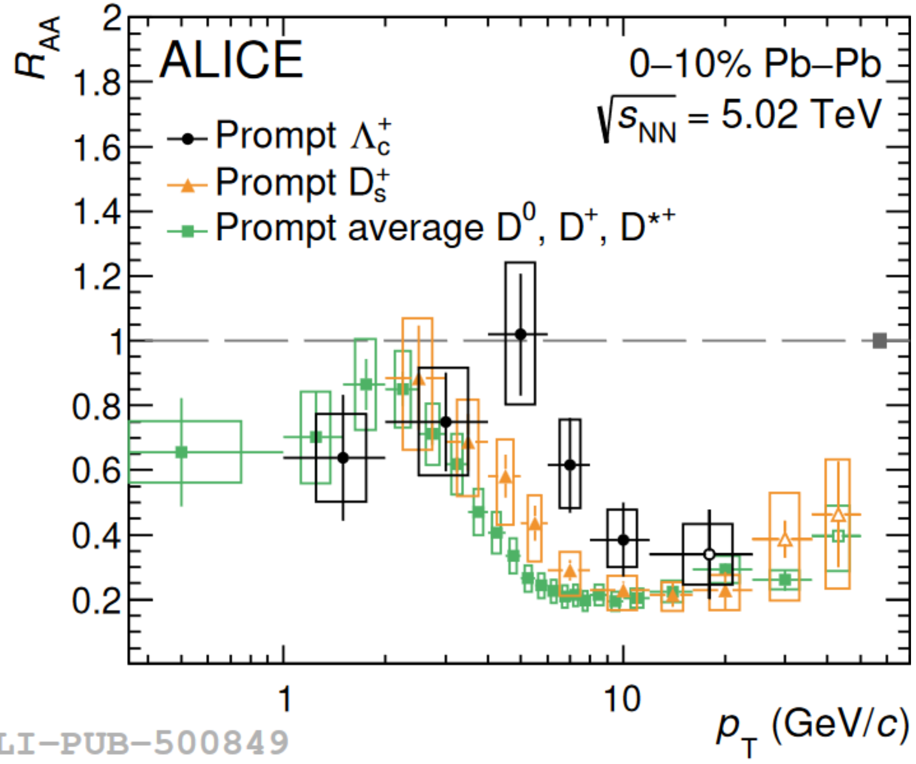
Simultaneous description of R_{AA} and v_2 challenging for c-quark transport models:
Interplay of radiative energy loss at higher p_T and recombination at lower p_T
→ D mesons acquire additional flow via c and light quark recombination

SMOG@LHCb: first measurements of charm in PbNe@68.5 GeV, S. Mariani, Thu 10:10

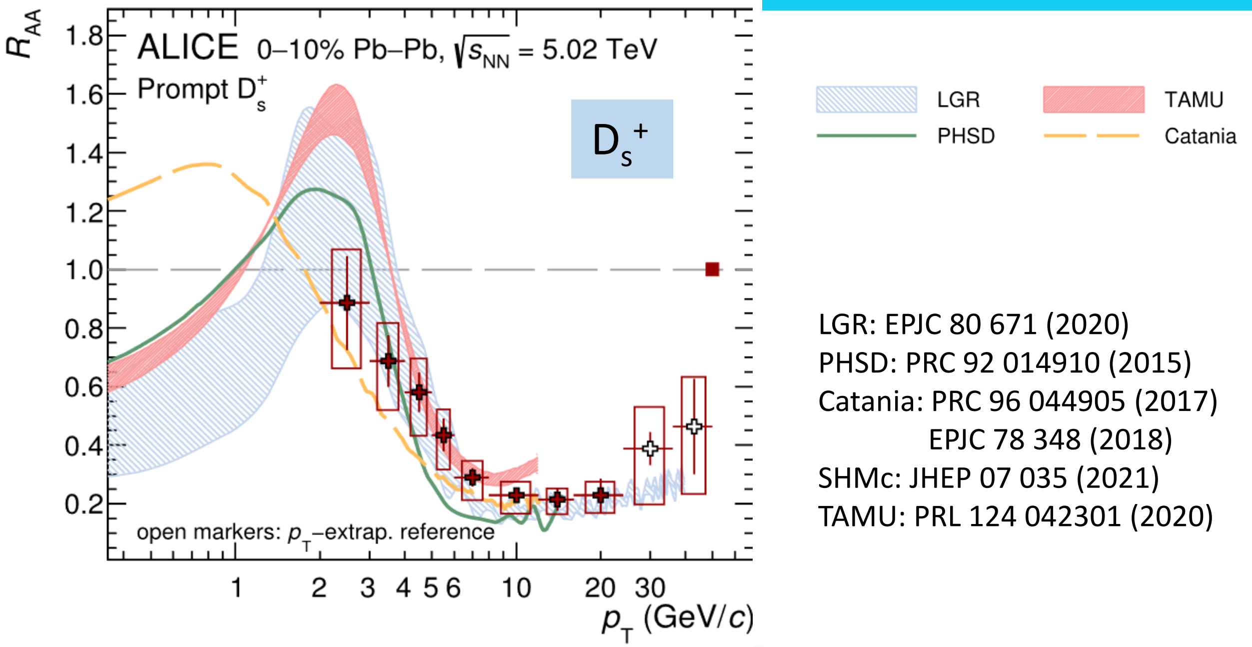
Open heavy flavor production: D_s^+, Λ_c^+

F. Catalano (ALICE) Thu 14:30
J. Zhu (ALICE) Thu 11:45

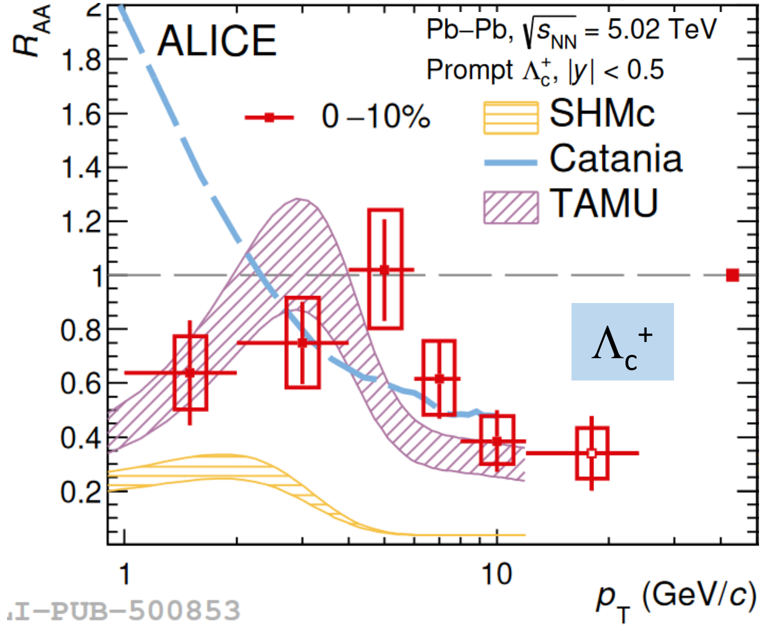
ALICE, PLB 827 (2022) 136986
ALICE, arXiv 2112.08156



Hint of hadron-mass ordering
$R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}(D)$



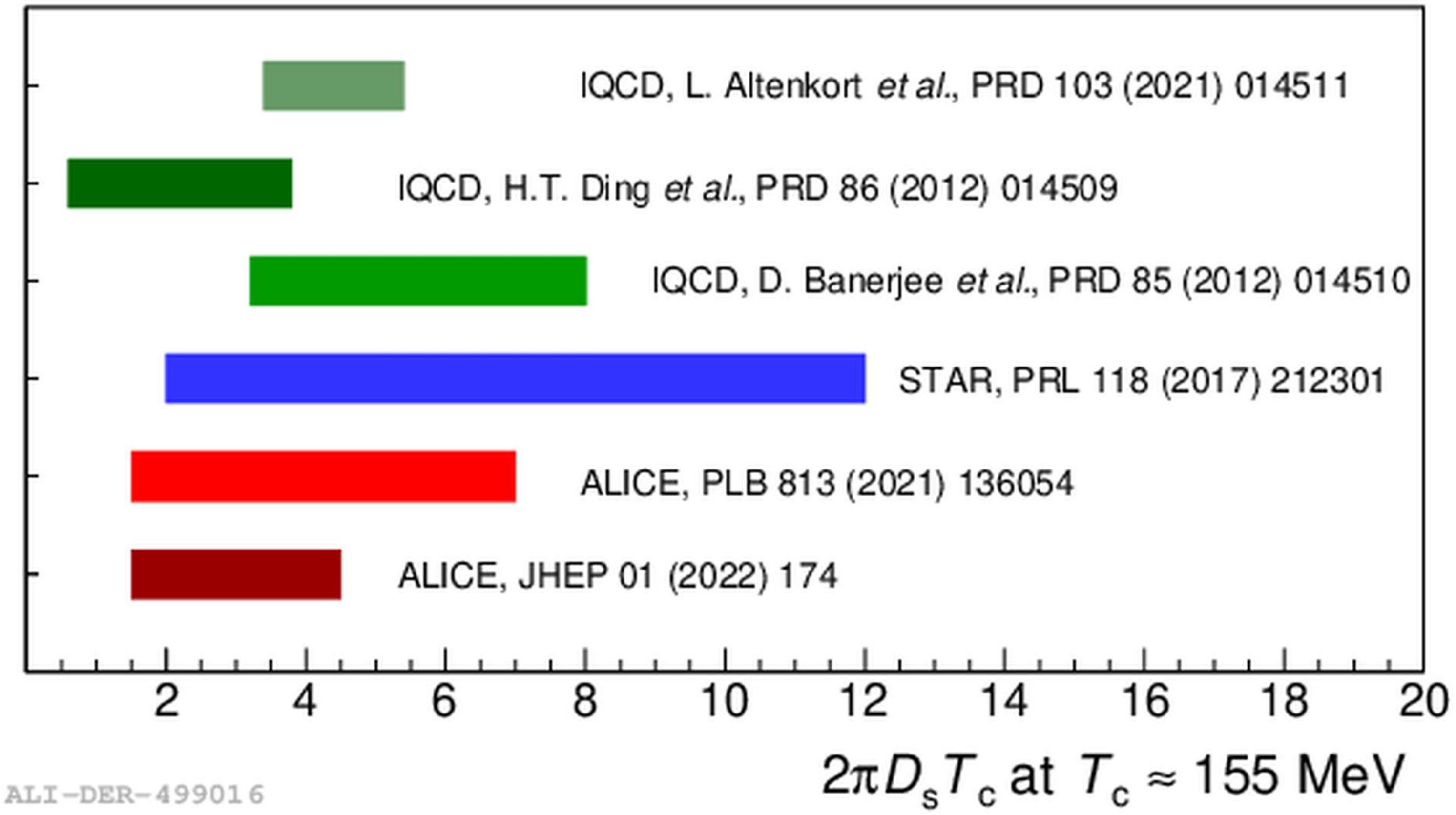
LGR: EPJC 80 671 (2020)
PHSD: PRC 92 014910 (2015)
Catania: PRC 96 044905 (2017)
EPJC 78 348 (2018)
SHMc: JHEP 07 035 (2021)
TAMU: PRL 124 042301 (2020)



c-quark transport models including hadronisation via recombination and enhanced s-quark content in QGP describe D_s^+ and also Λ_c

Charm-quark spatial diffusion coefficient

F. Catalano (ALICE) Thu 14:30



Spatial diffusion coefficient constrained from model-to-data comparison
- using R_{AA}, v_2 and v_3 of non-strange D mesons

TAMU, MC@sHQ, LIDO, LGR, and Catania models provide a reasonable description

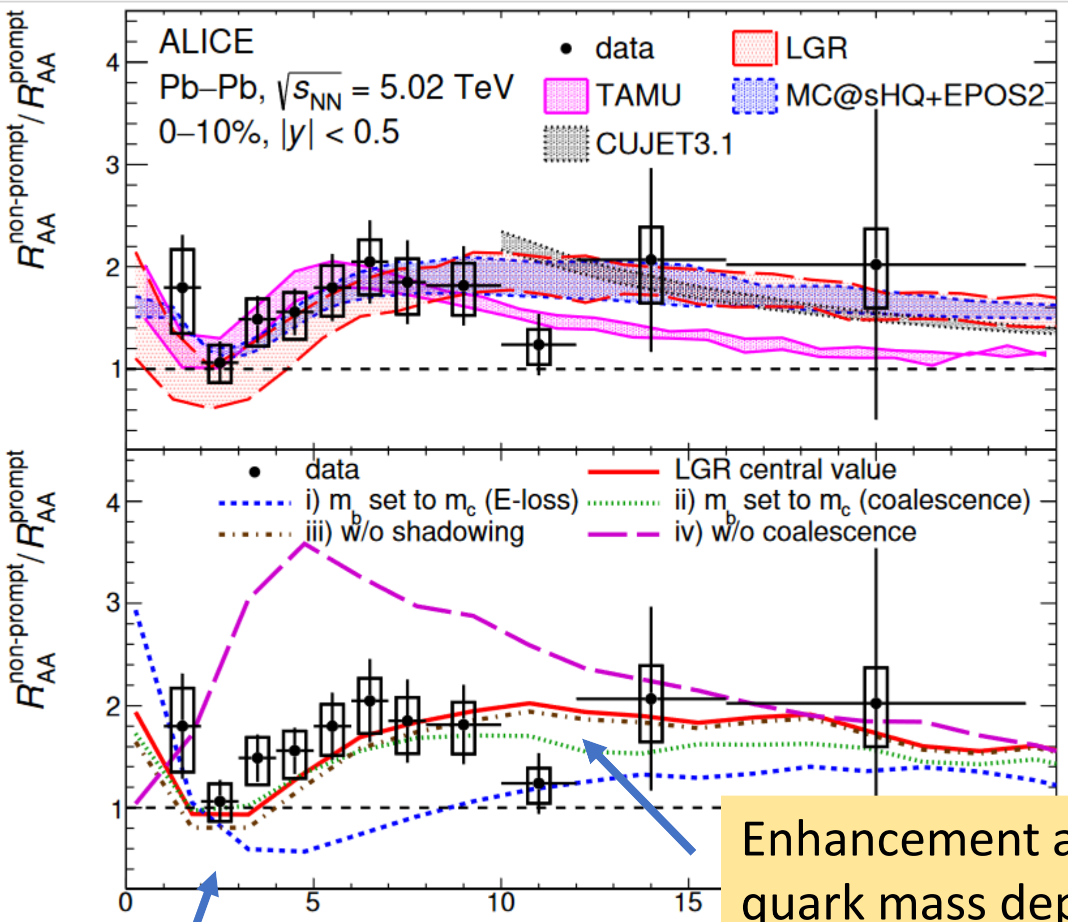
$1.5 < 2\pi D_s\, T_c < 4.5$
corresponding to a relaxation time
$\tau_{charm} \sim 3 - 8$ fm/*c*

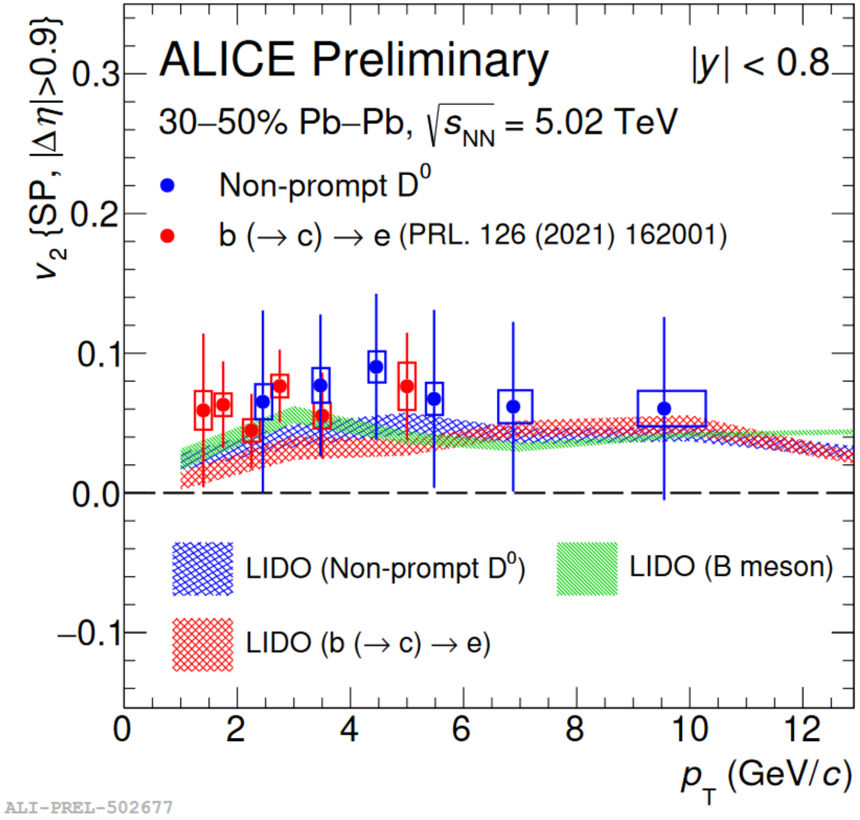
Open beauty in QGP

B. Zhang (ALICE) Thu 15:20
F. Damas (CMS) Fri 15:05

ALICE, arXiv:2202.00815

non-prompt D^0 mesons





See also
CMS PAS-HIN-21-003
for v_2 and v_3

Enhancement at high p_T: quark mass dependent energy loss:

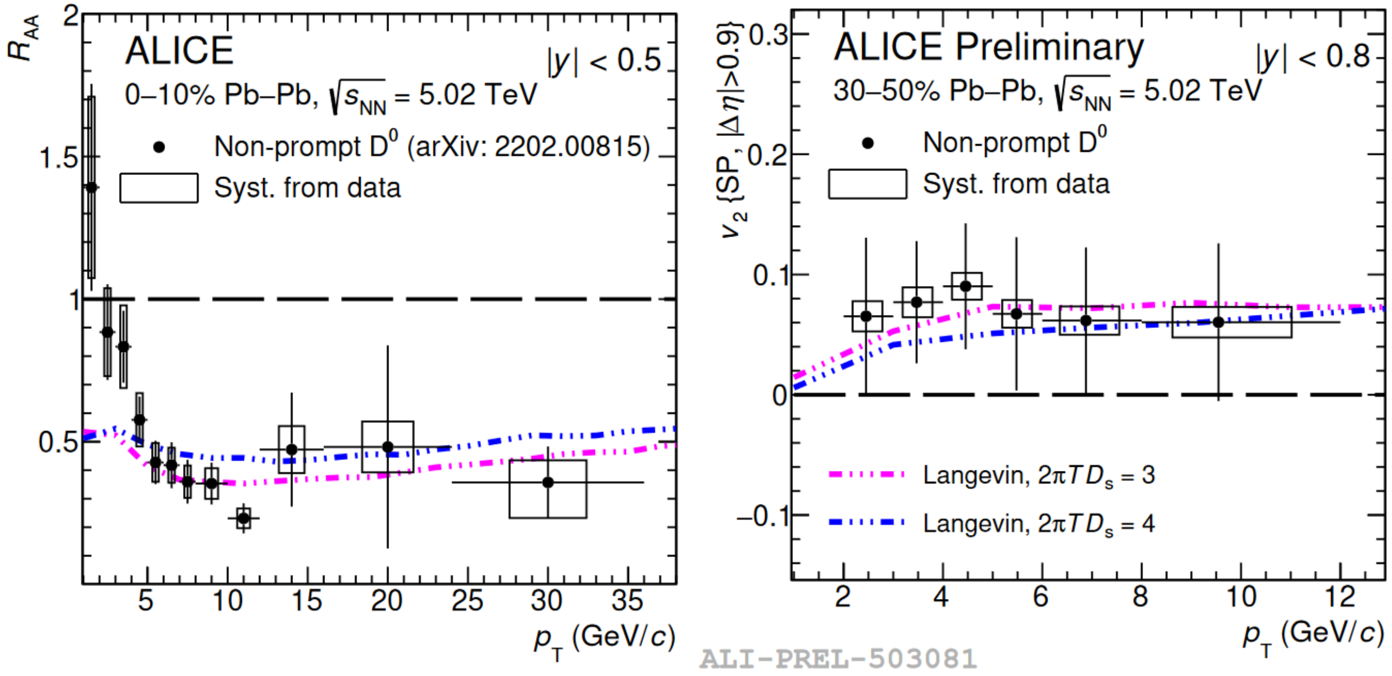
$R_{AA}(b) > R_{AA}(c)$

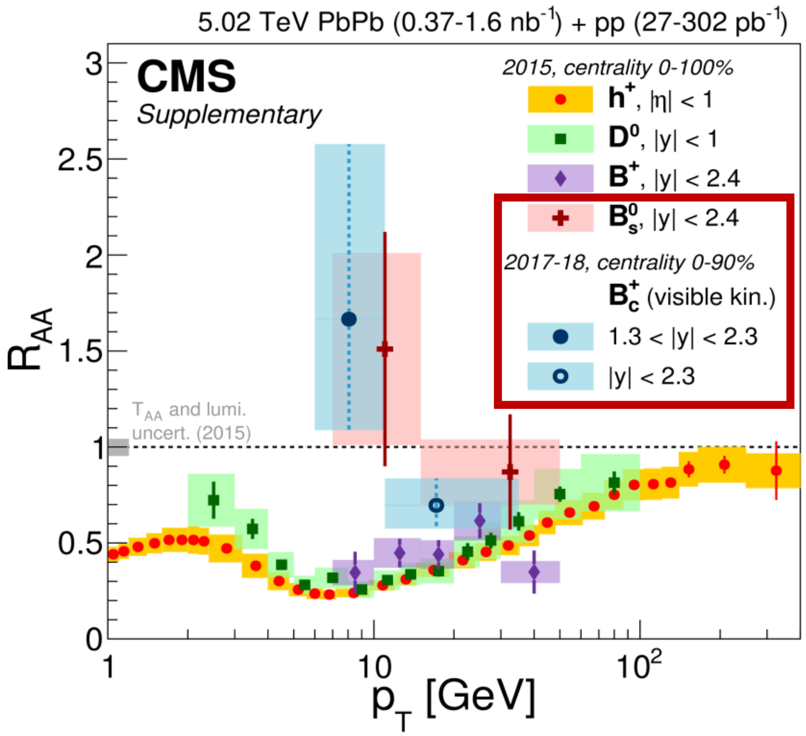
$\rightarrow \Delta E_c > \Delta E_b$

"valley": c-quark coalescence flow/decay kinematics …

Non-zero v_2 observed:
b-quarks partially thermalize in the medium or recombine with light quarks

Beauty in QGP: constraining spatial diffusion coefficient?





Can we already now constrain spatial diffusion coefficient with b measurements by comparing v_2 and R_{AA} simultaneously?

Run 3 and Run 4 data needed.

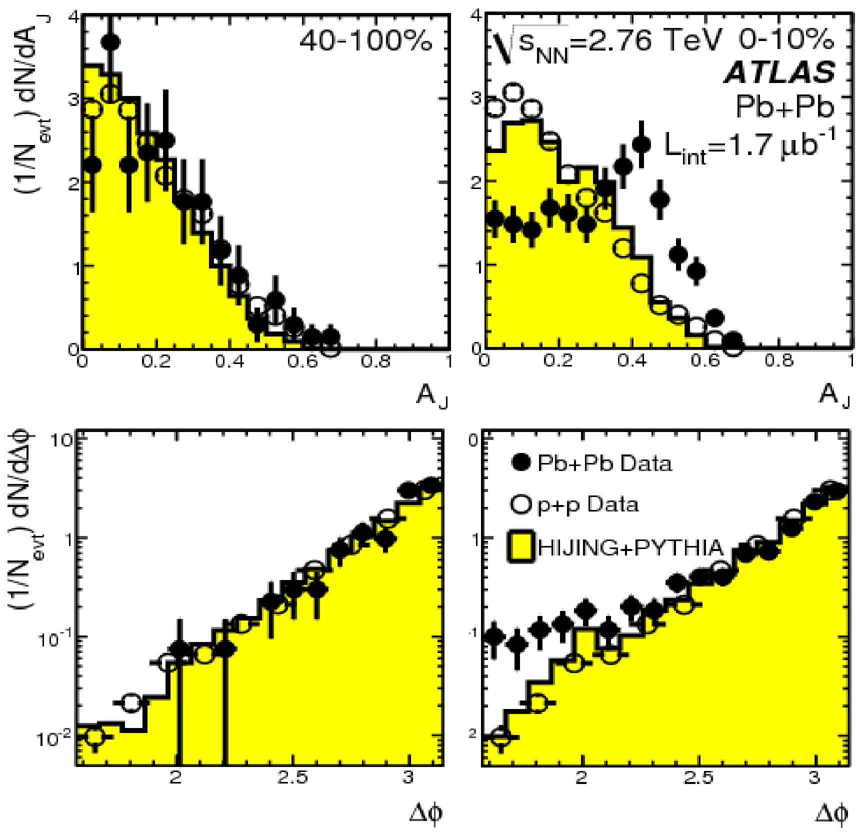
First observations of B_s^0 and B_c^+

Also here, more statistics is needed.

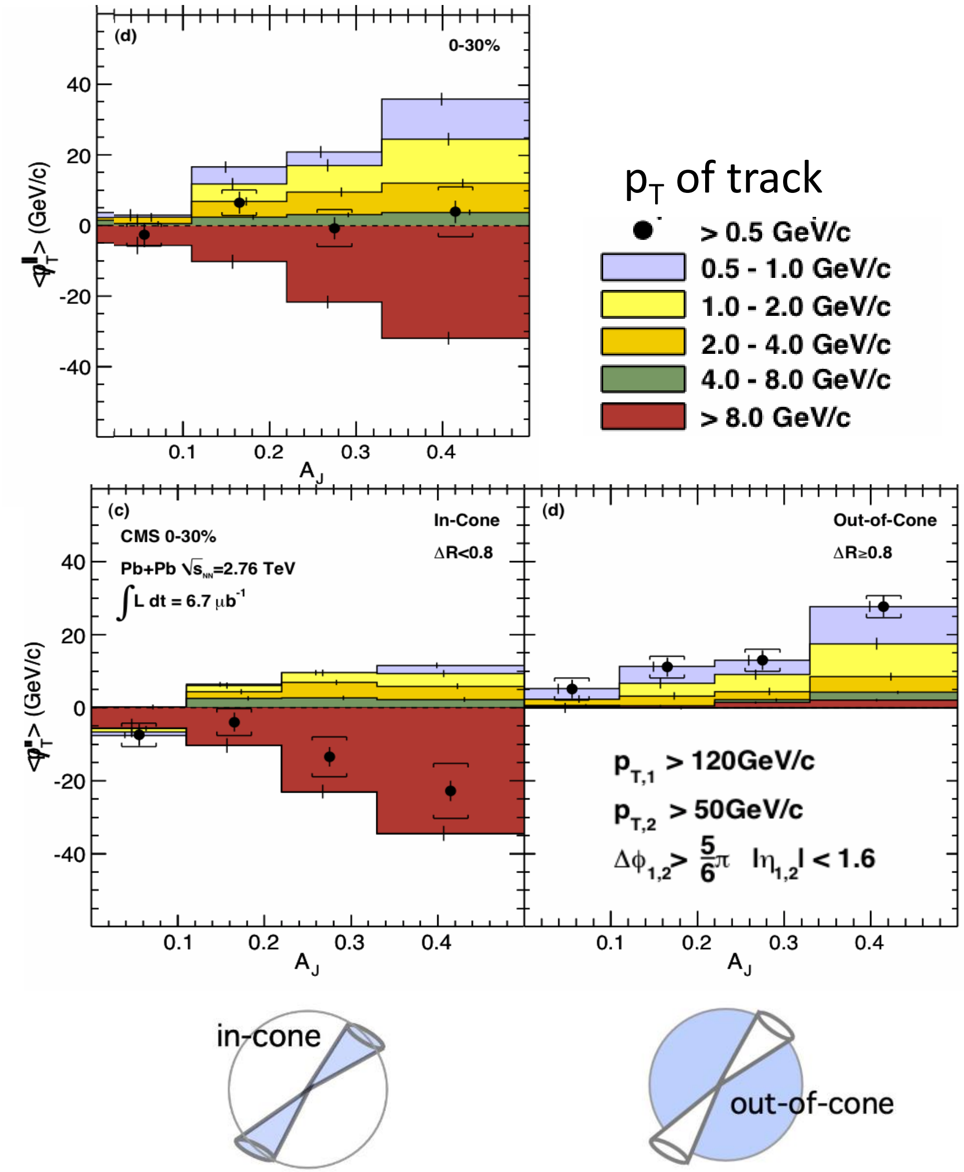
Jets

How does medium influence jets … a bit of history

ATLAS: PRL 105 (2010) 252303



CMS, PRC 84 (2011) 024906



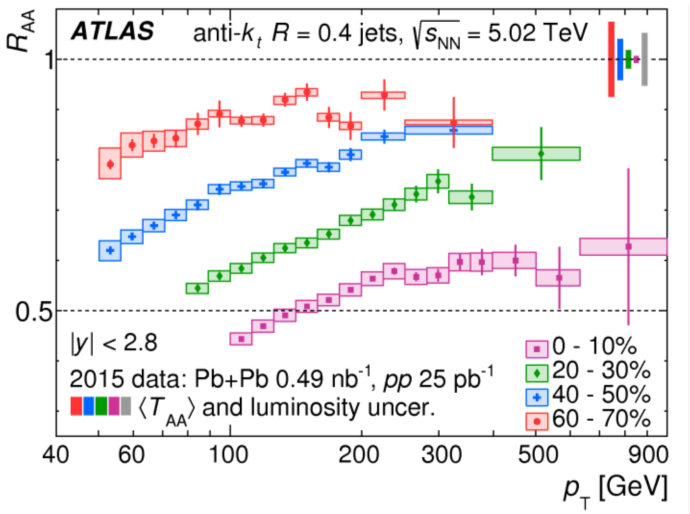
Dijet asymmetry observed in central PbPb collisions at 2.76 TeV without angular decorrelation.
Lost energy is distributed to large angles ("out-of-cone") and low-p_T particles.

Inclusive jet suppression in medium

C. Roland (CMS) Thu 11:15
B. Cole (ATLAS) Sat 16:10

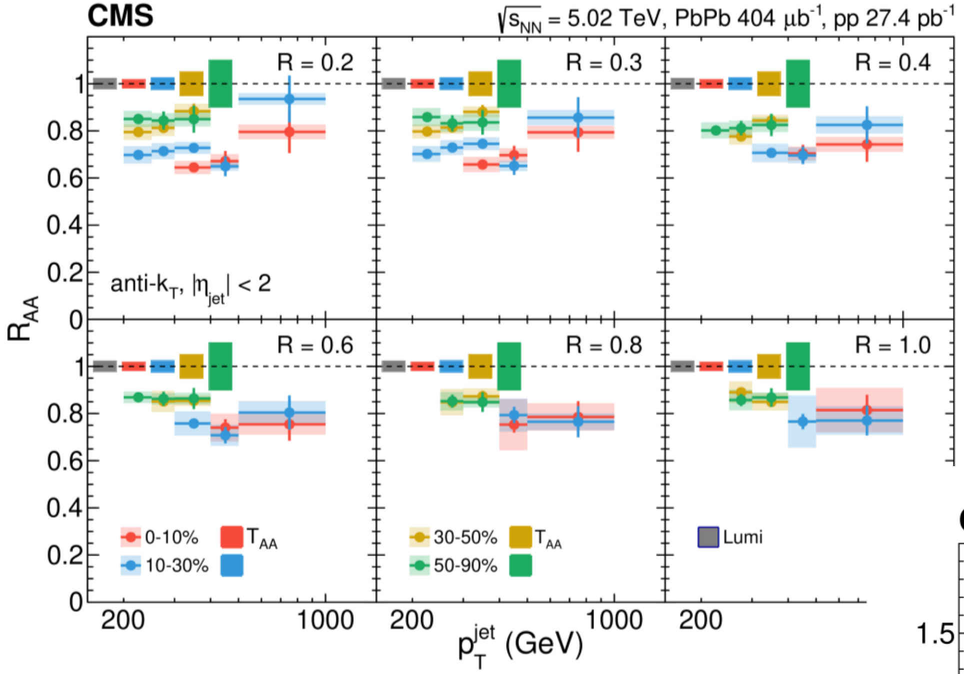
ATLAS, PLB 790 (2019) 108

R = 0.4



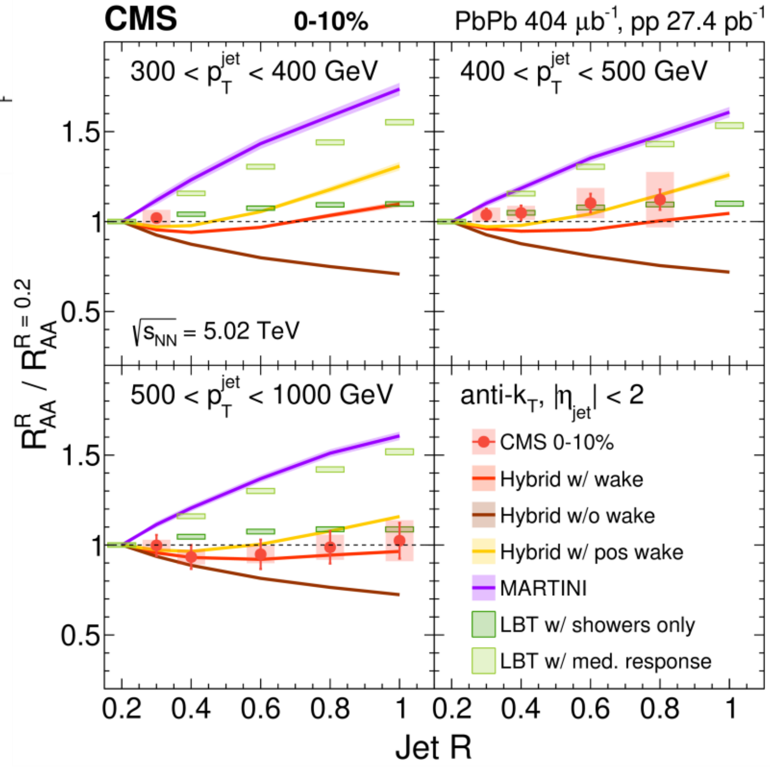
R_{AA} increases with jet p_T reaching a value of about 0.6 at p_T = 1 TeV in central PbPb collisions for R = 0.4.

Can we recover the lost energy?
→ study jets with larger radius R



Jet R_{AA} in PbPb collisions shows only a modest increase, R_{AA} never reaches unity.

CMS, JHEP 05 (2021) 284

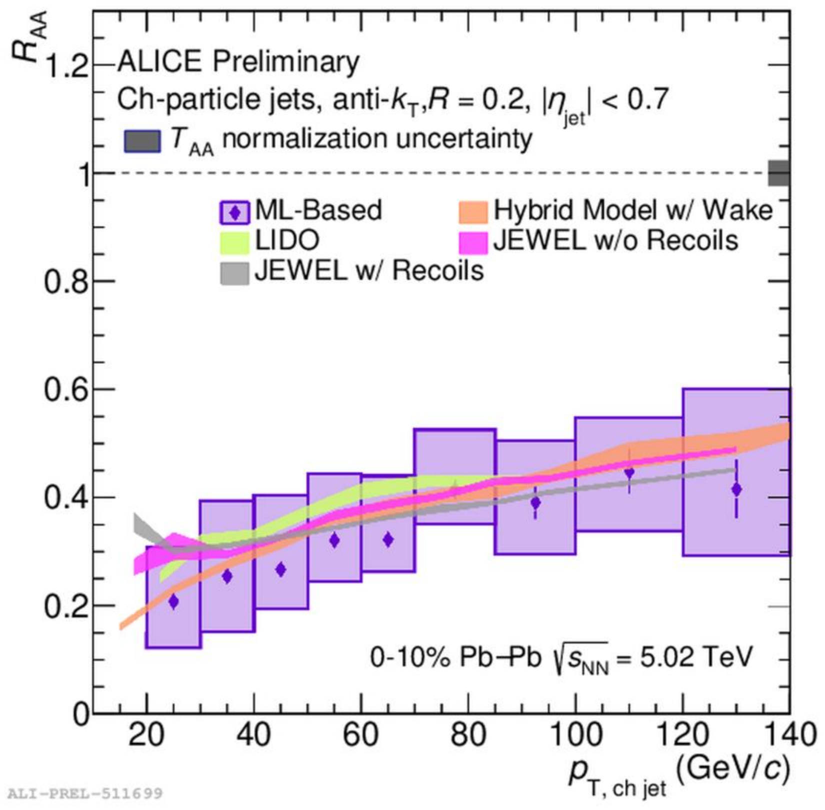


Significant constraints on models of jet quenching, medium response, wide angle radiation …

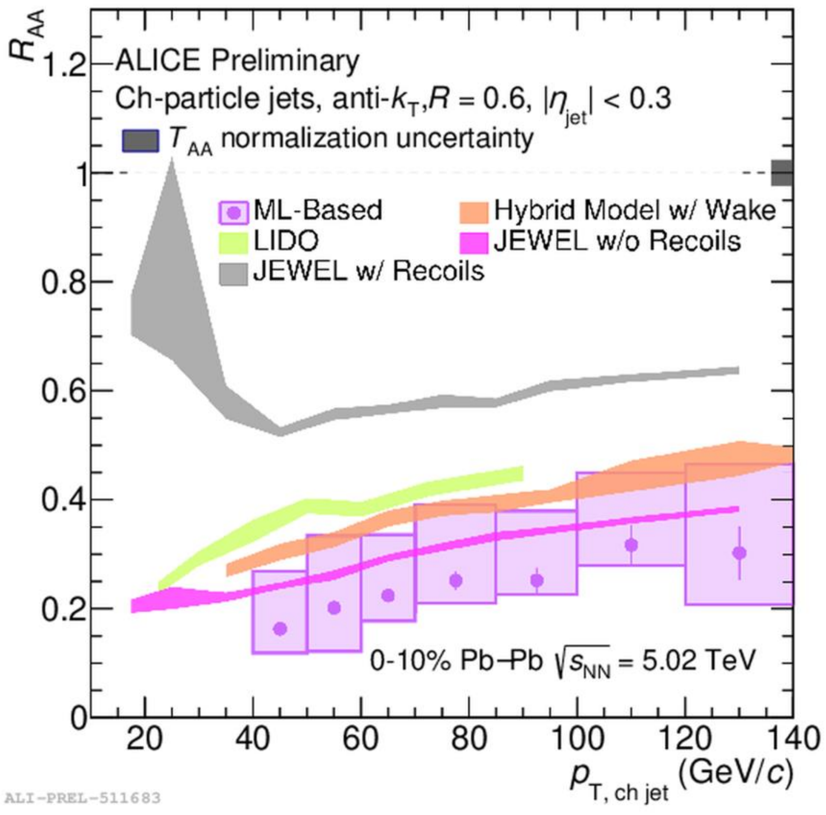
Larger R and lower jet p_T ?

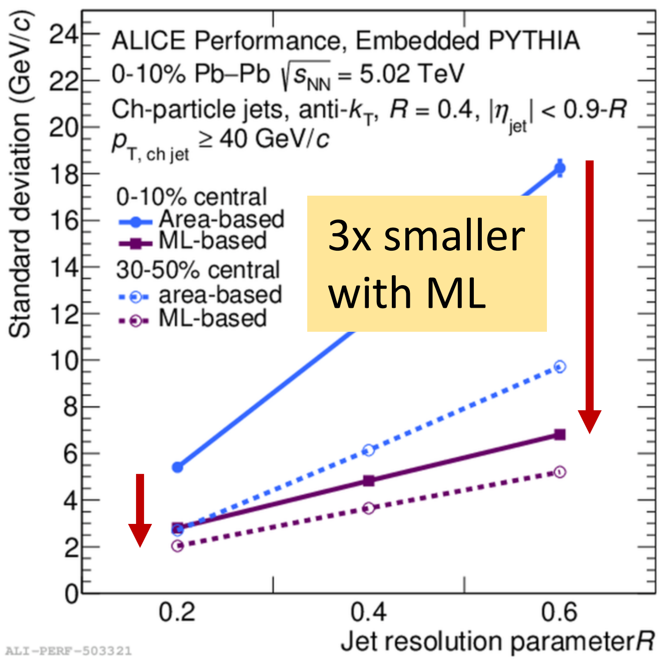
A. Dainese (ALICE) Mon 16:00

R=0.2



R=0.6



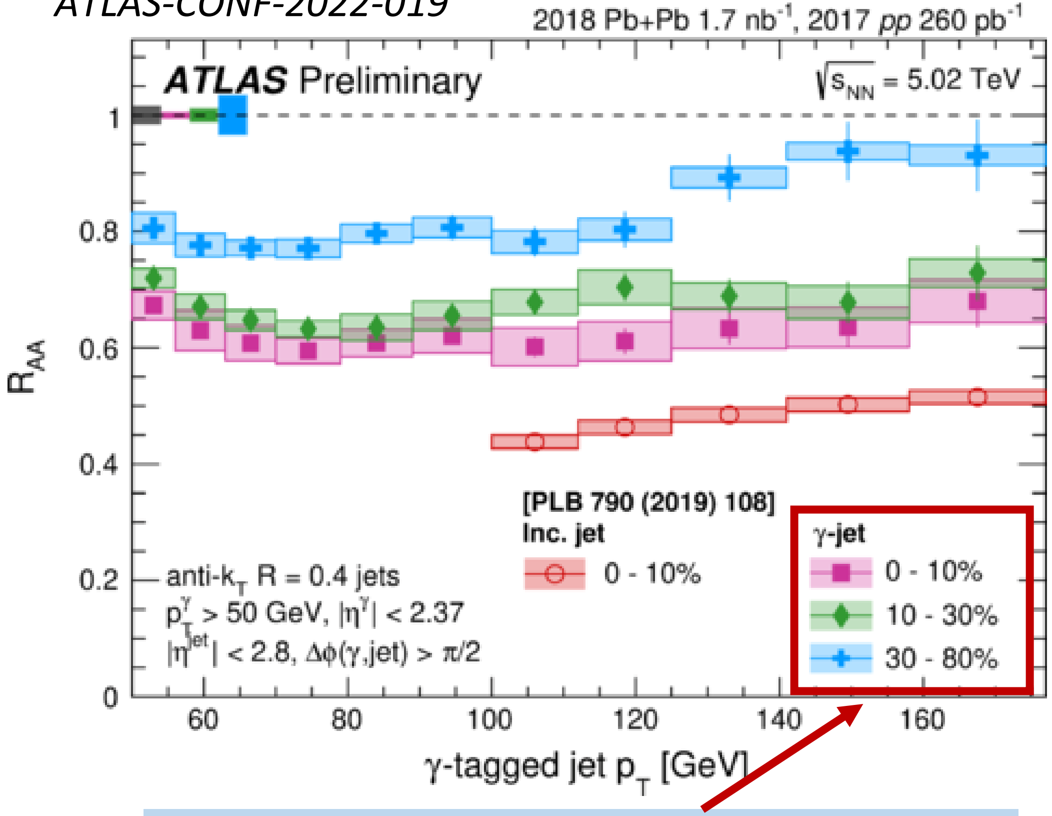


First encouraging results using ML reported by ALICE:
- improved precision and extended reach in p_T and R
- data will enable to constrain model predictions and allow for comparison with RHIC

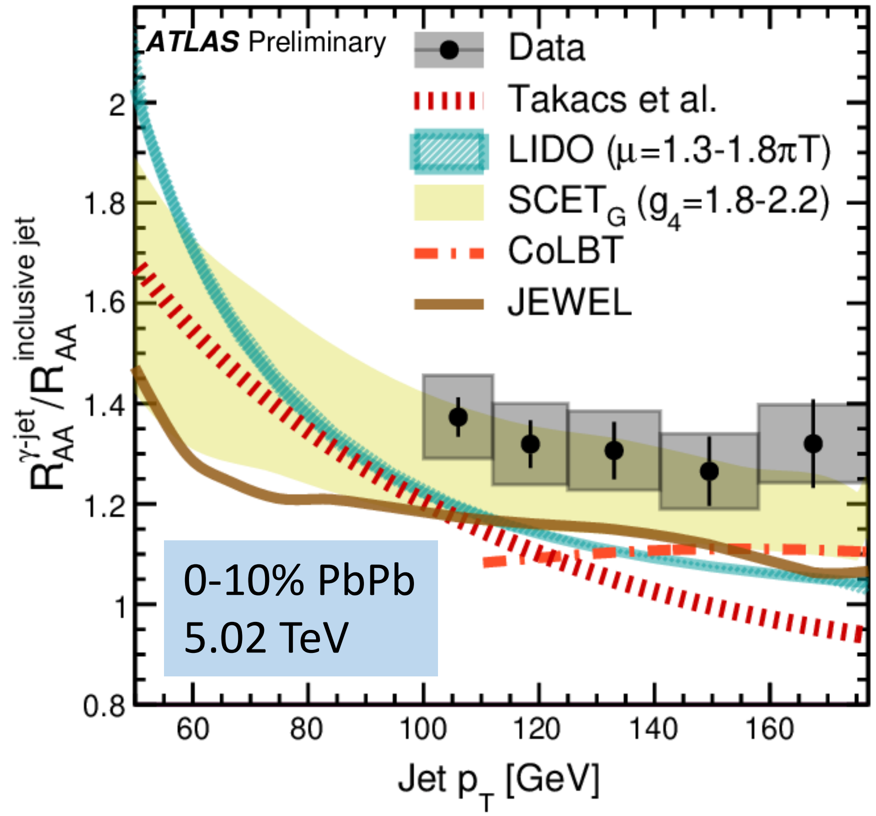
Photon-tagged jets

Dialing q/g fraction with γ-tagging:
p_T^{γ} > 50 GeV/*c* → q/g fraction ~ 80%

ATLAS-CONF-2022-019



R_{AA} for photon-tagged jets is significantly higher than that for inclusive jets
→ clear demonstration of sensitivity of energy loss to the color-charge of the initiating parton
(quarks lose less energy than gluons)



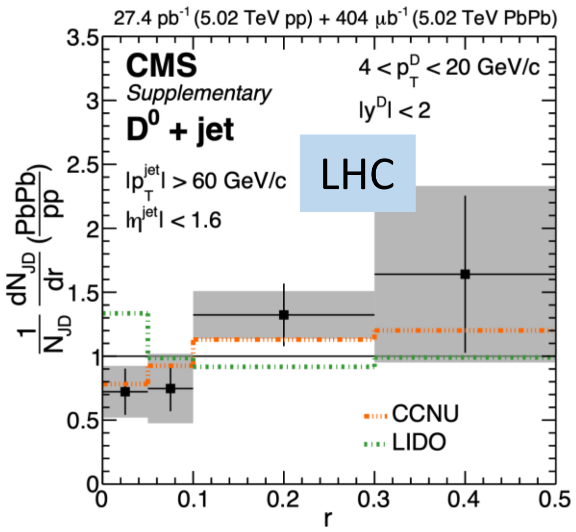
Most calculations underpredict the ratio of γ-tagged jet/inclusive jet.

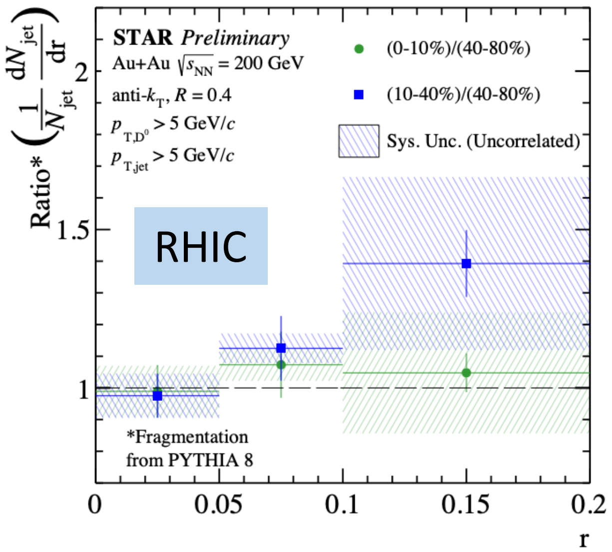
Takacs,Tywoniuk, JHEP 10 (2021) 038
Ke, Xu, Bass, PRC 100 (2019) 064911, PRC 98 (2018) 064901
Ke, Wang, JHEP 05 (2021) 041
Kang, Vitev, Xing, PRC 96 (2017) 014912,
Li, Vitev, JHEP 07 (2019) 148, PRD 101 (2020) 076020
He et al., PRC 99 (2019) 054911
Zapp, JEWEL, Eur. Phys. J. C 76 (2016) 695

Flavor dependence of jet-medium interaction

J. Wang (CMS) Thu 14:45
M. Nguyen (CMS) Thu 15:35

p_T^D = 4 - 20 GeV/c

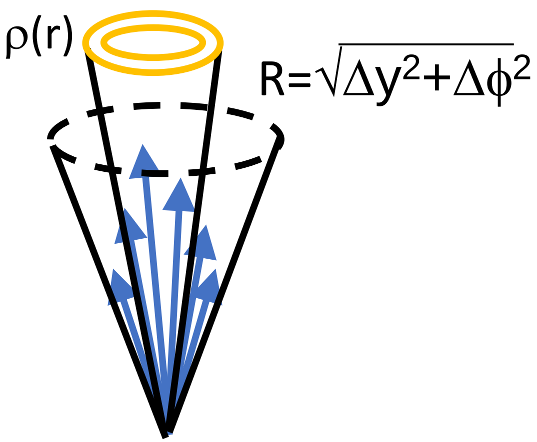


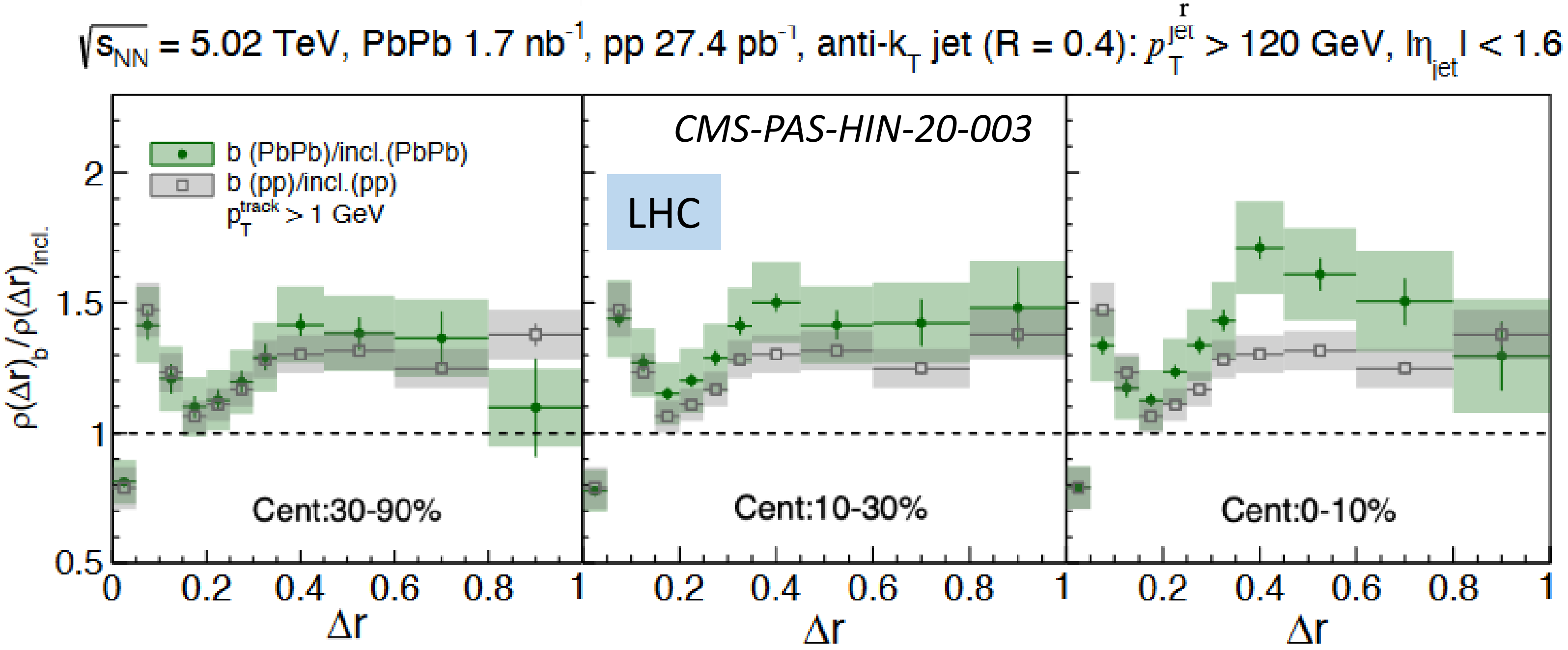


First measurements of the radial profile of heavy quarks in jets in heavy ion collisions.

Charm: hint of enhancement of D^0 at large angles and at lower p_T.

CMS, PRL 125 (2020) 102001



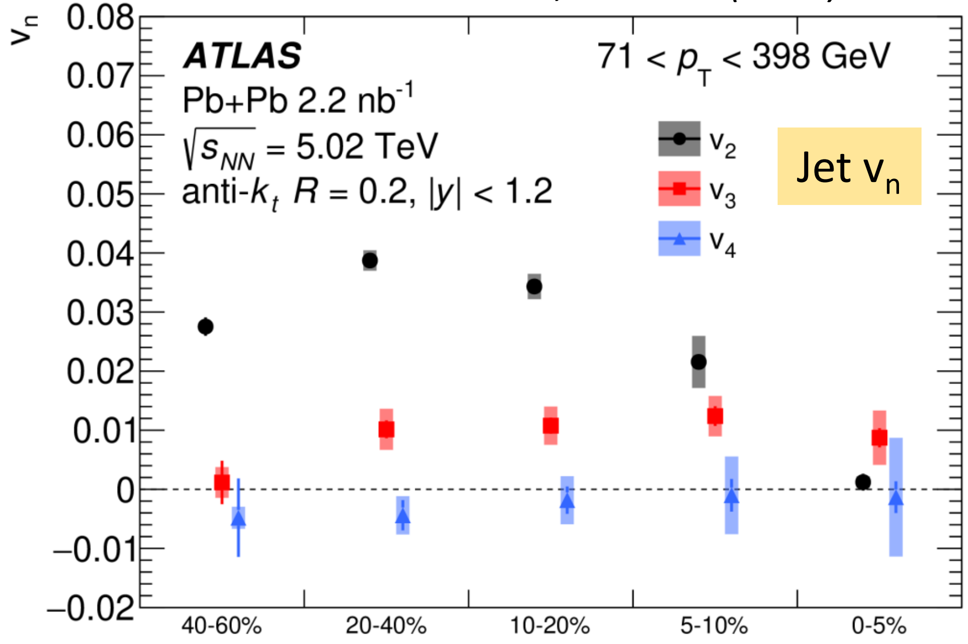


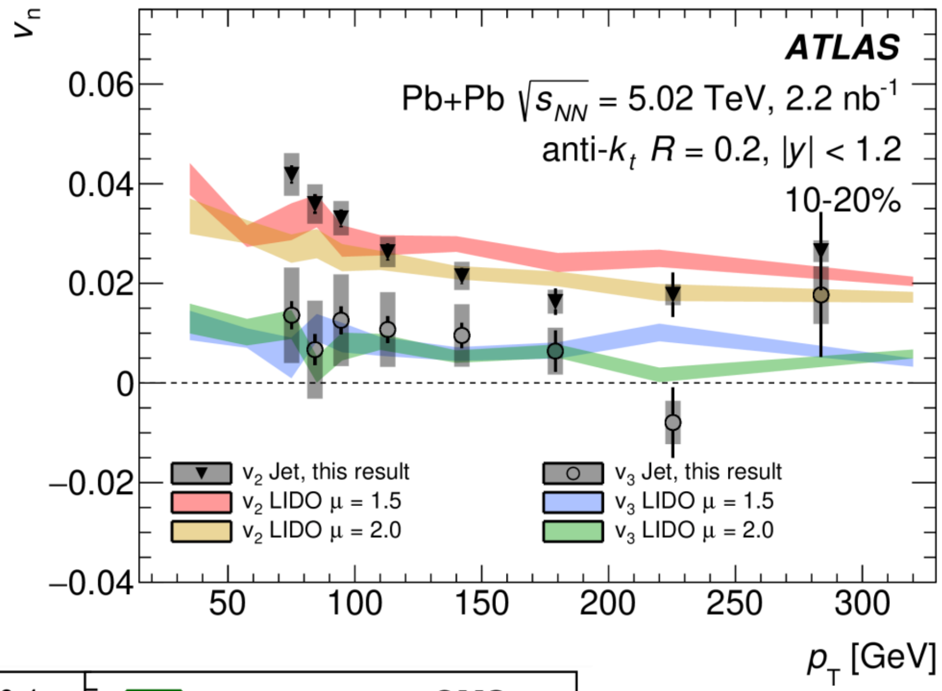
Quenching modifies b-jet shapes differently than inclusive jets:
→ relatively larger degree of transverse momentum shifted to large angles.

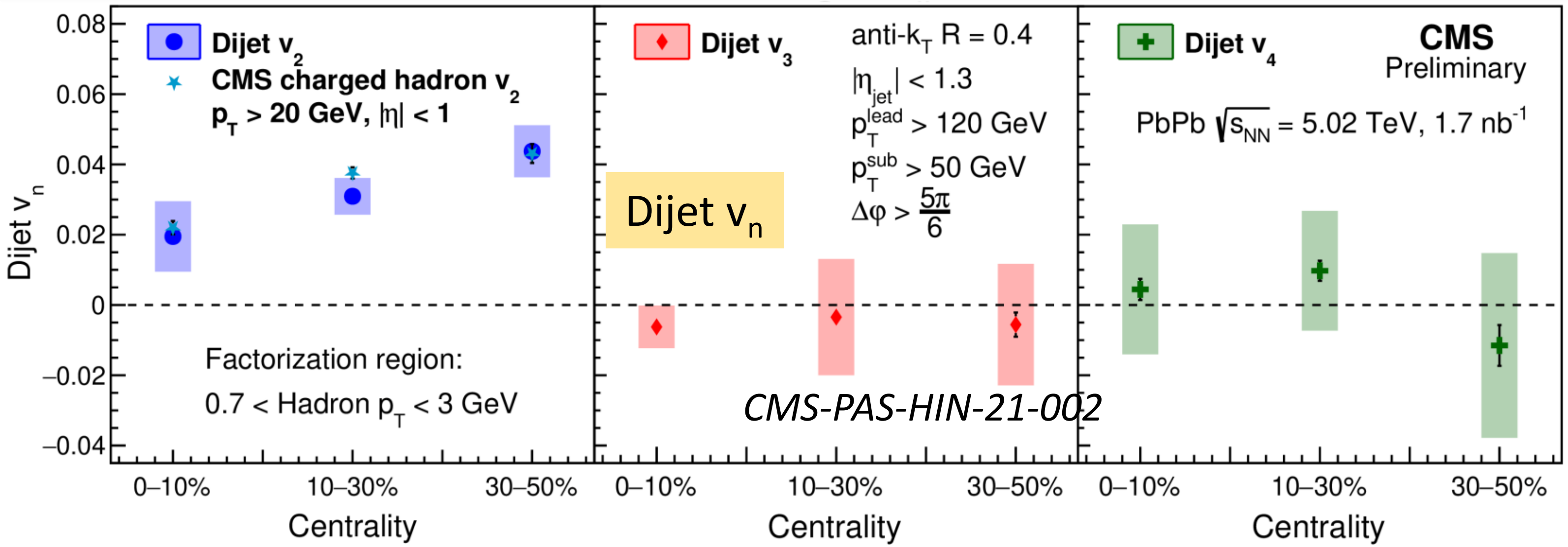
Path-length dependence of jet energy loss

B. Cole (ATLAS) Sat 16:10
S. Tuo (CMS) Fri 17:00

ATLAS, PRC 105 (2022) 064903







CMS-PAS-HIN-21-002

v_2: maximal at ~0.05 in mid-central collisions, slow decrease with p_T

v_3, v_4 measured for the first time set limits on initial-state fluctuations of energy loss

Exploring angular dependence via groomed jet substructure

R. Ehlers (ALICE) Fri 14:45

ALICE, PRL 128 (2022) 102001

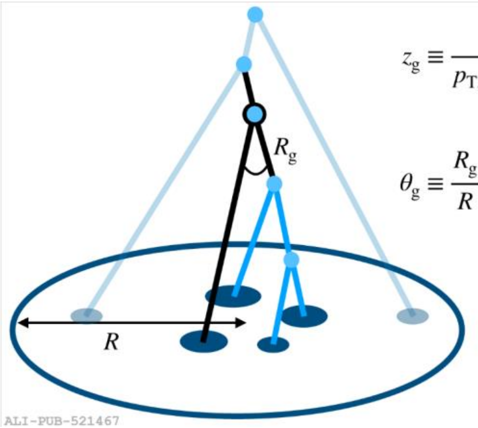
Vacuum:

Parton shower is a multi-scale process with a given momentum and angular/virtuality scale.

Medium:

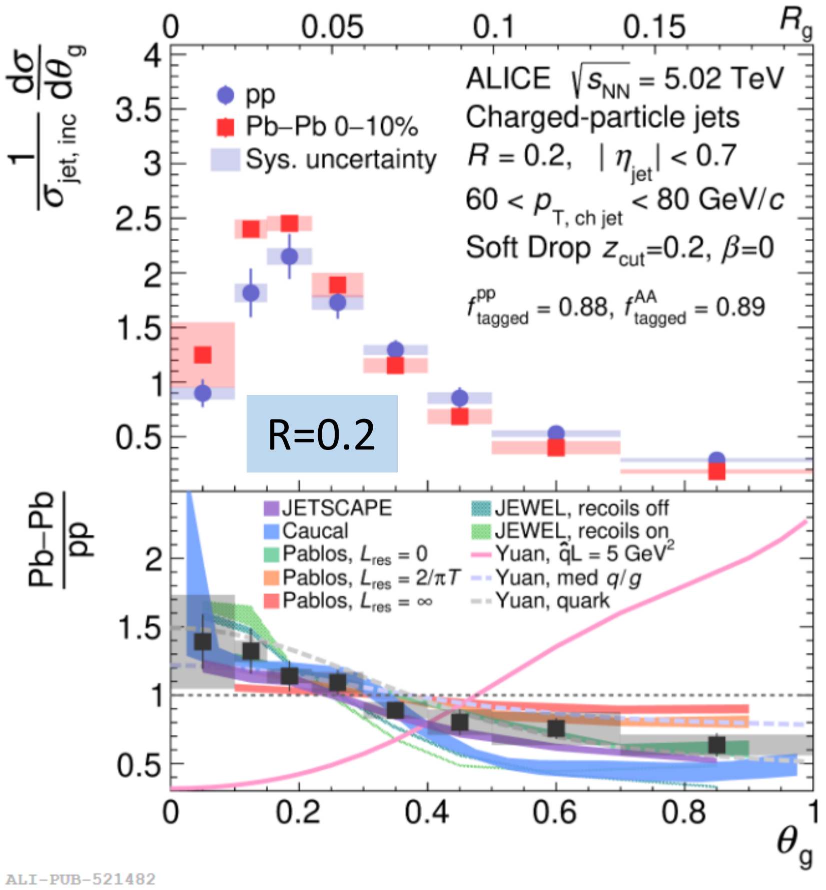
Angular/virtuality scale can be related to a "resolution scale" at which the jet probes the medium.

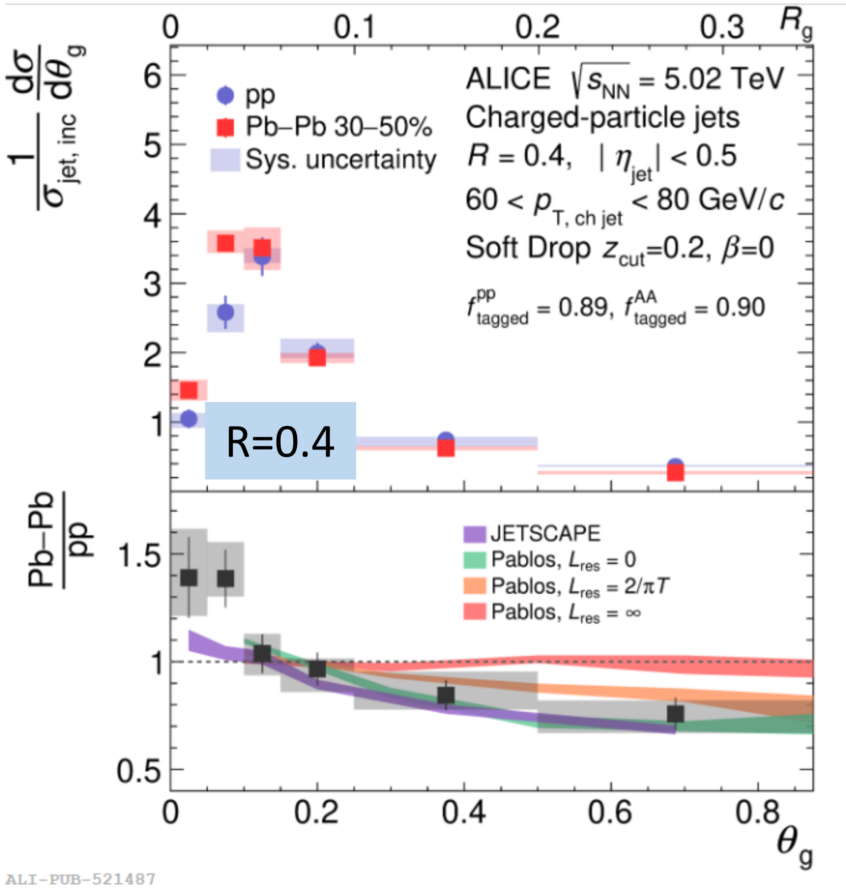
SoftDrop: Larkoski et al., JHEP 05 (2014) 146



$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$





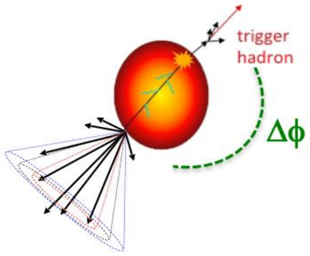
Suppression of large angles and enhancement of small angles. Medium has resolving power for splittings (promotes narrow splittings, filters out wider subjets).

See also ATLAS-CONF-2022-026

Exploring microscopic structure of QGP: acoplanarity

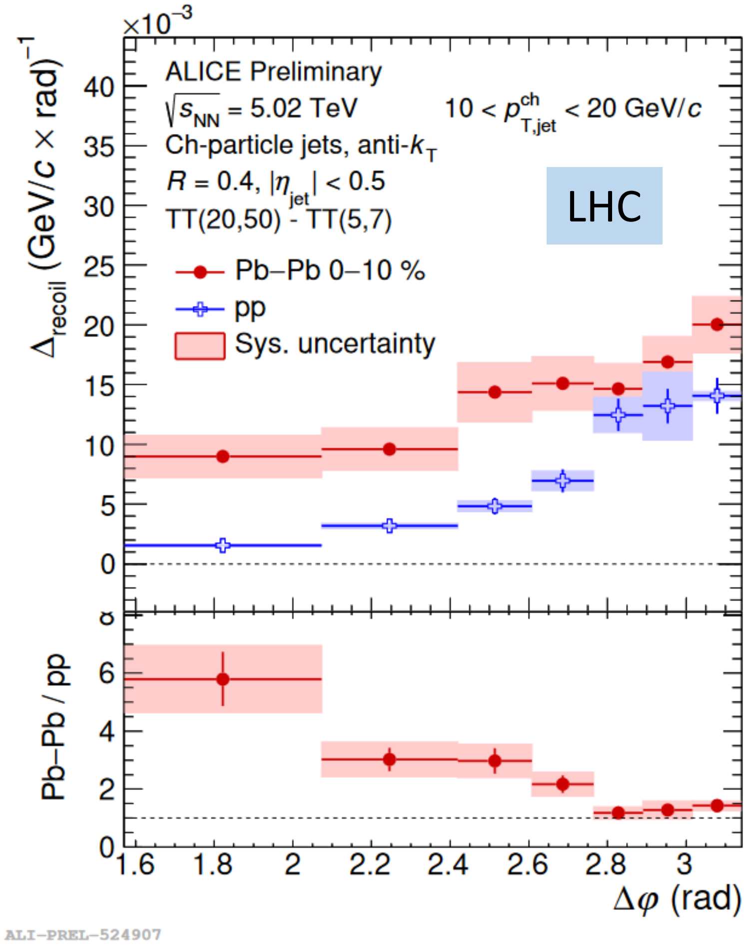
Y.Hou (ALICE) Fri 15:05
D. Anderson (STAR) Fri 15:20

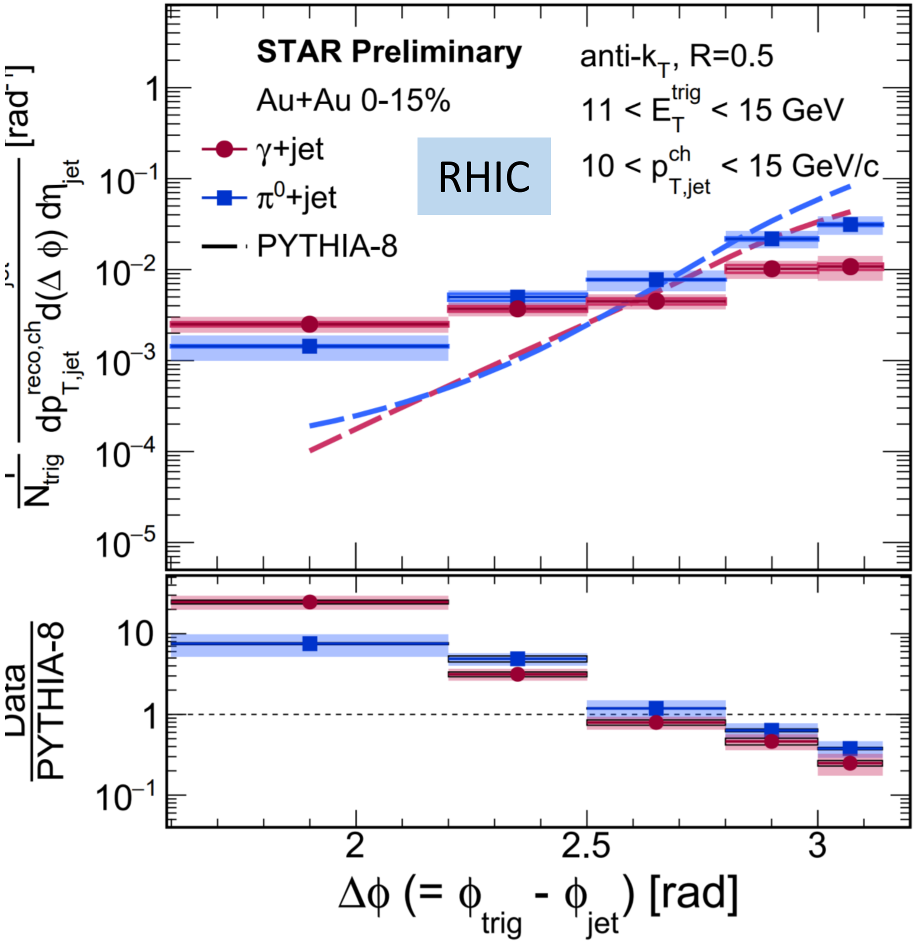
$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}_{\mathrm{Sig}}} - \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}_{\mathrm{Ref}}}$$

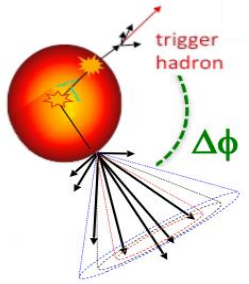


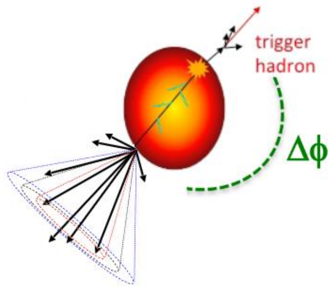
A unique observable:

- enables study of intra and inter-jet angular broadening
- large-angle jet deflection studies can probe the nature of the quasi-particles in hot QCD matter ("QCD Molière scattering")







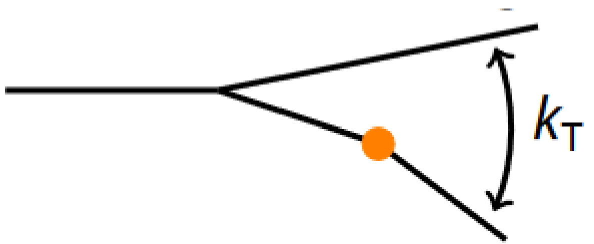


First measurements of acoplanarity down to low p_T of recoil jets.
$\Delta\phi$ broadening for larger R and small jet p_T observed at LHC and RHIC!

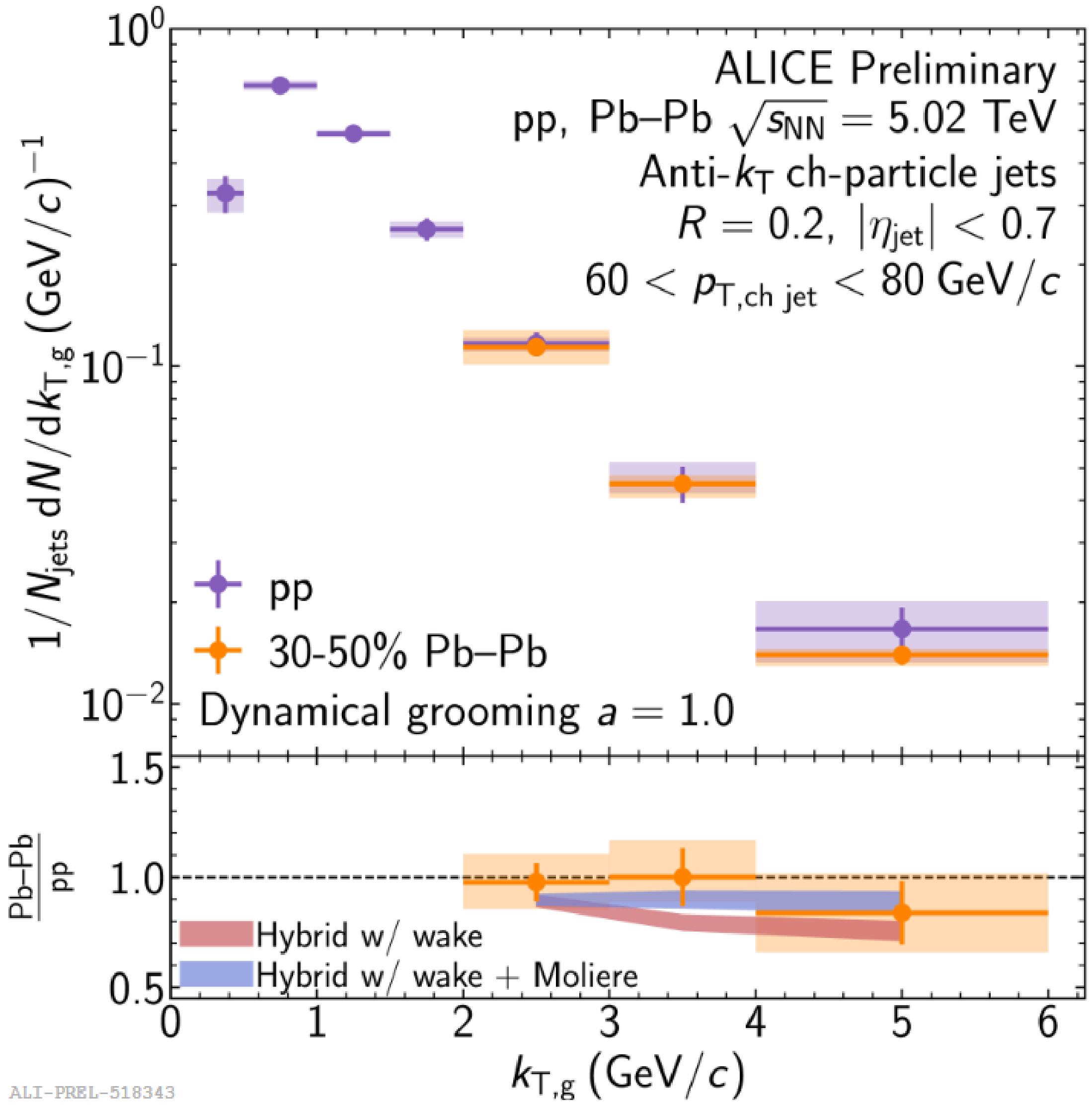
D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172

Exploring microscopic structure of QGP: hardest $k_{T,g}$ splittings

Search for high k_T emissions as signature of “Moliere” scattering



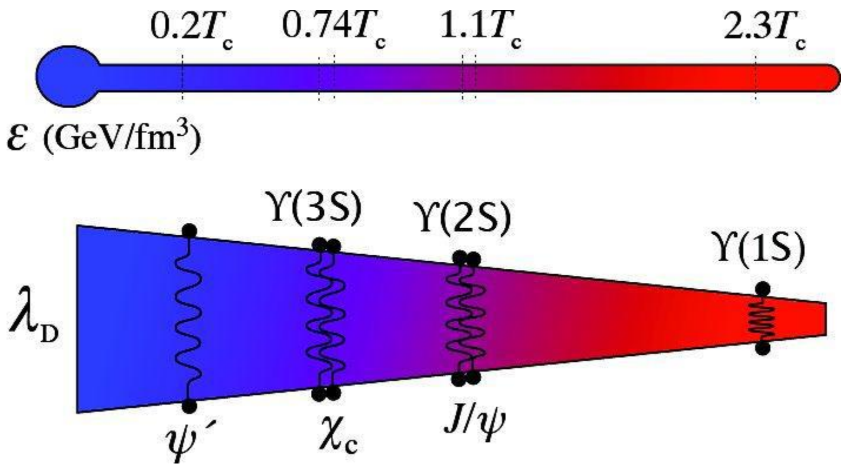
Use dynamically groomed jet substructure (1st time in PbPb collisions)
SD *zcut* = 0.2 removes soft component



Deflections off scattering centers are expected to increase the relative k_T of subjets within a jet in PbPb compared to pp collisions
→ data do not yet have the sensitivity

Quarkonia

Quarkonia as QGP thermometer



Quarkonia dissociate in QGP due to color screening of potential between heavy-quarks.

Matsui and Satz, PLB 178 (1986) 416

Lattice QCD calculations of spectral functions $\Rightarrow T_{diss}$

Sequential melting:

Differences in the binding energies lead to a sequential melting of the quarkonium states with increasing temperature of the QGP

Quarkonium recombination:

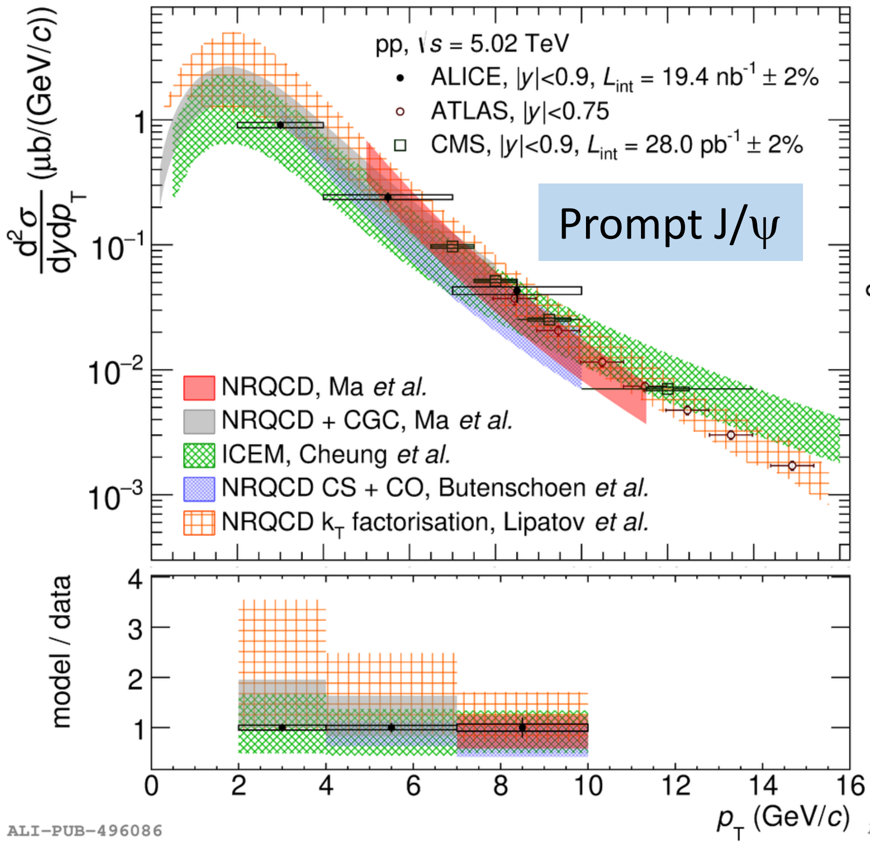
Increase of $c\bar{c}$ production cross section at the LHC enhances quarkonium production via recombination at the phase boundary or in the QGP

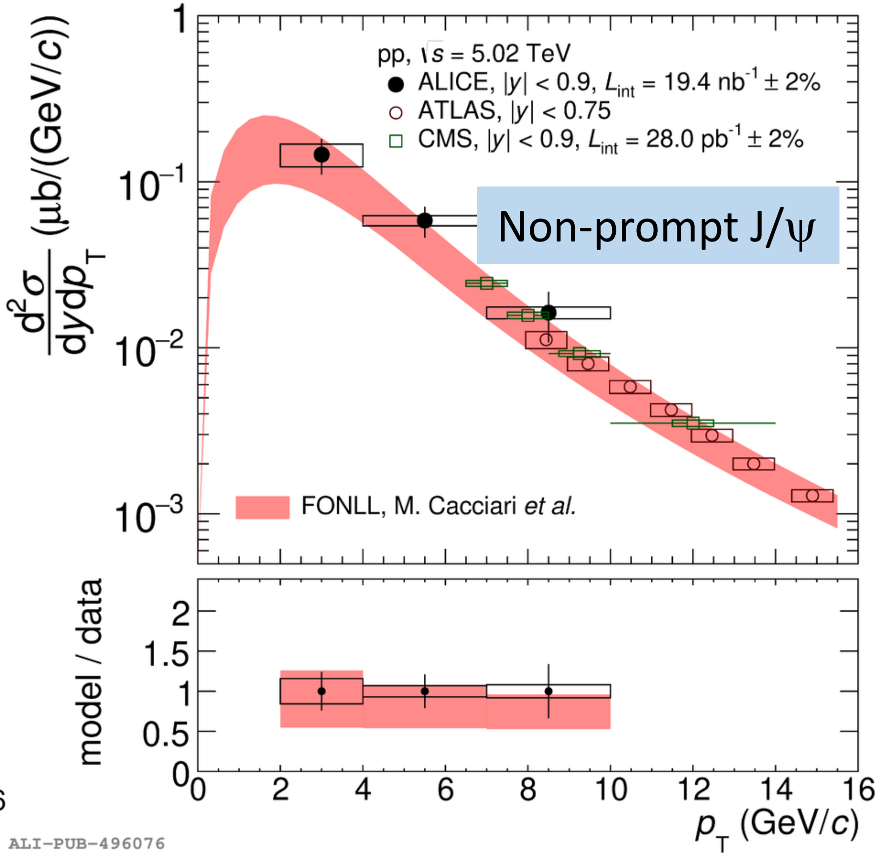
Braun-Munzinger, Stachel, PLB 490 (2000) 196

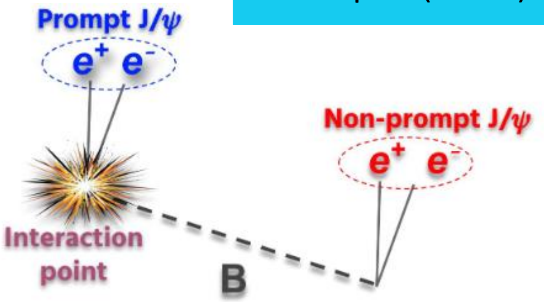
Thews et al, PRC 63 (2001) 054905

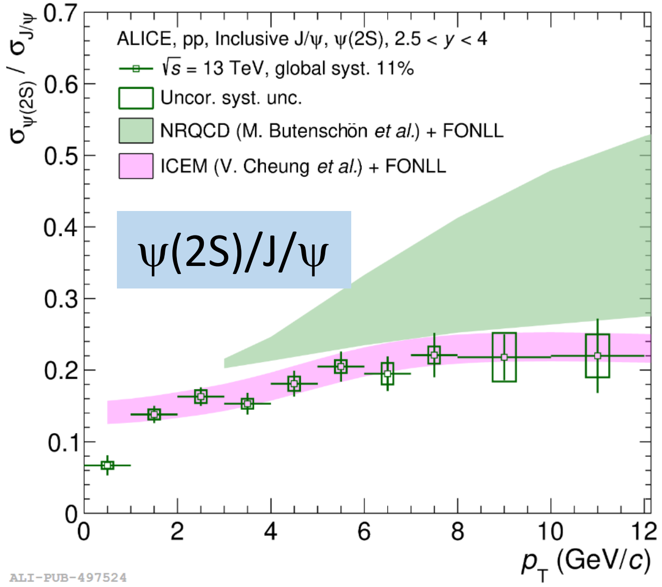
J/ψ production in pp collisions

M. Coquet (ALICE) Sat 11:15









ALICE, arXiv:2108.02523

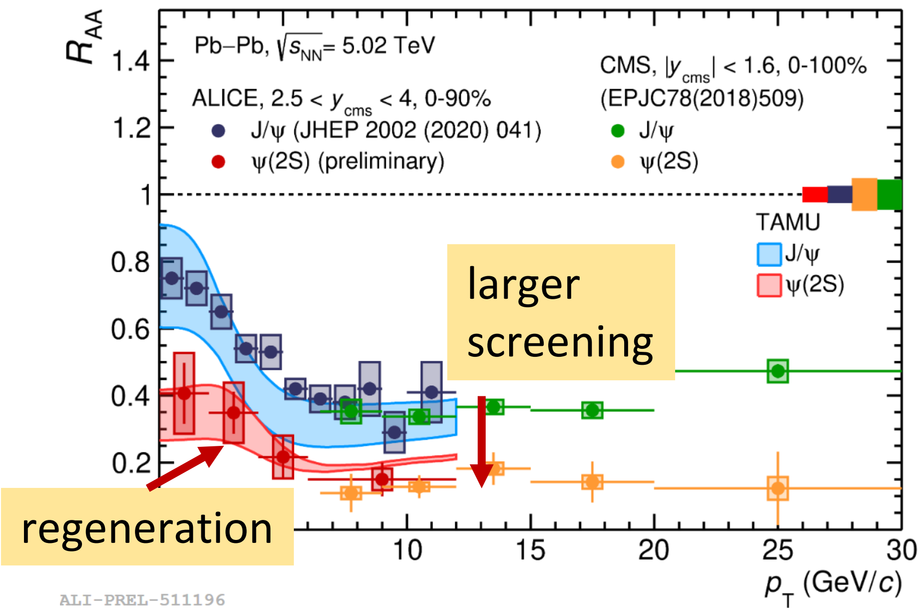
Detailed measurements exist by all experiments across LHC pp energies and rapidity, here just a snapshot …

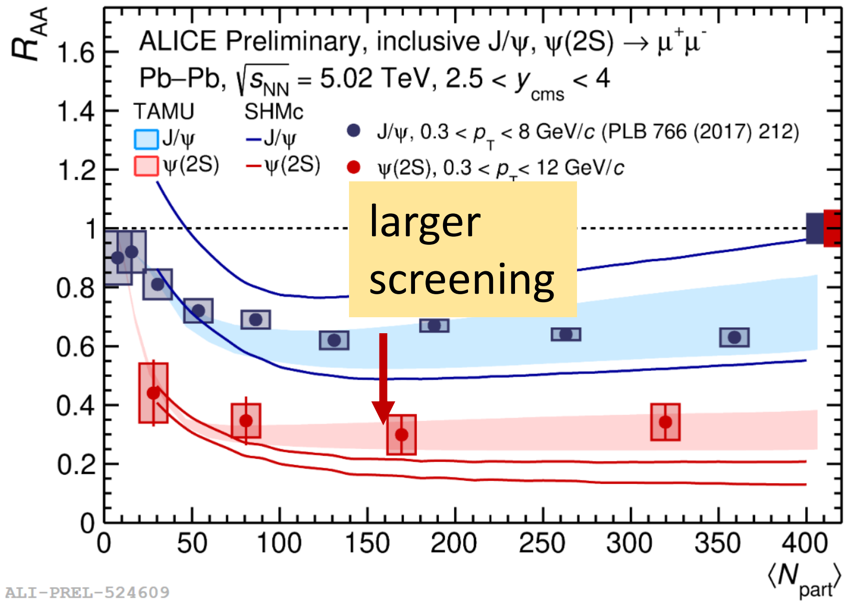
FONLL : Cacciari, JHEP 05 (1998) 007
NRQCD CS+CO : Butenschoen, PRL 106 (2011) 022003
NRQCD : Ma, PRL 106 (2011) 042002
NRQCD+CGC : Ma, PRL 113 no. 19 (2014) 192301
ICEM : Cheung, PRD 98 no. 11, (2018) 114029
NRQCD+kT fact. : Lipatov, PRD 100 no. 11, (2019) 114021

J/ψ and ψ(2S) production in pp is well described by models (although small tensions when considering cross section ratios exist)

J/ψ and ψ(2S) production in PbPb collisions

B. Paul (ALICE) Sat 9:35





ψ(2S) to J/ψ ratio weakly depends on charm production cross section
→ important constraints on models

Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage

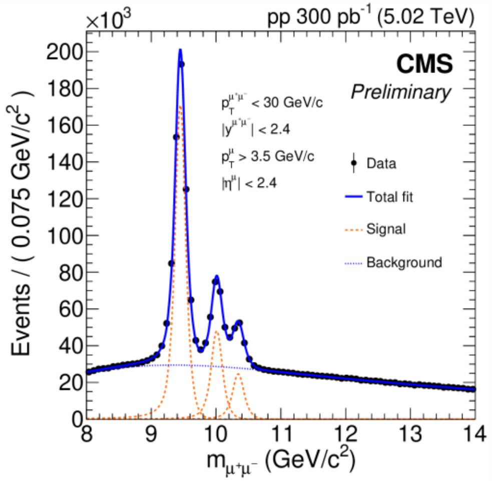
Stronger suppression for ψ(2S) compared to J/ψ

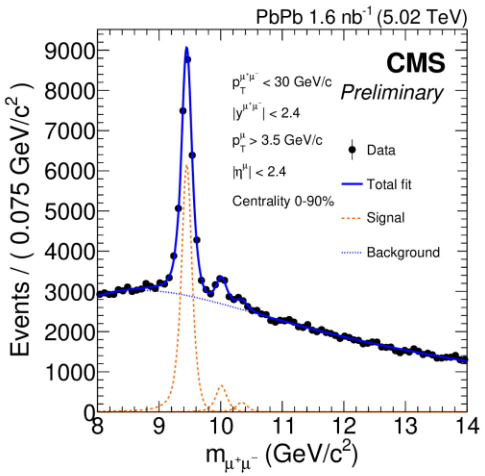
- at low p_T increase for both charmonium states
  → hint of regeneration
- data well reproduced by transport model (TAMU)
- SHM tends to underestimate the ψ(2S) result in central collisions

TAMU: Du, Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et. al., Nature 561 (2018) 321

Sequential melting of Upsilon states

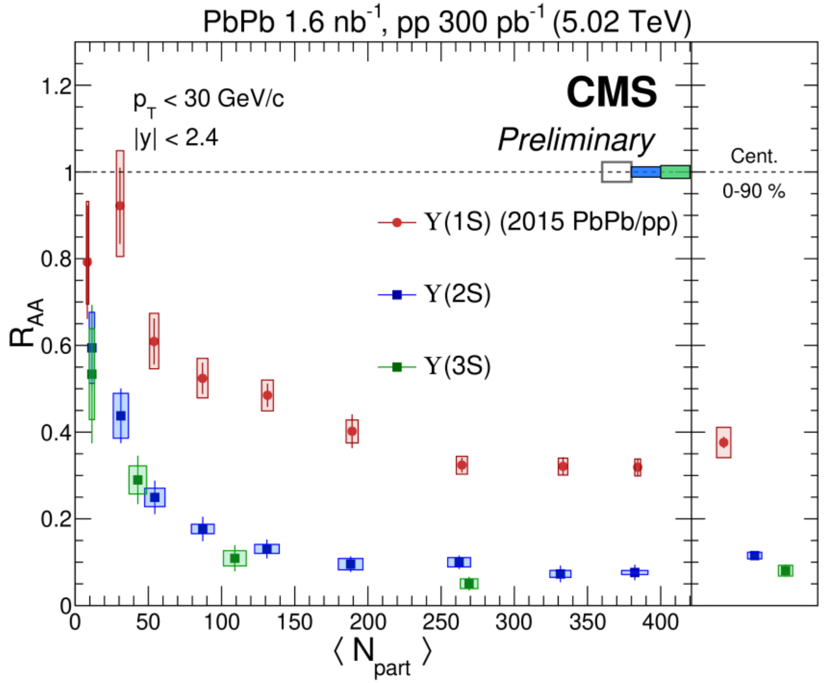
S. Lee (CMS) Sat 11:30

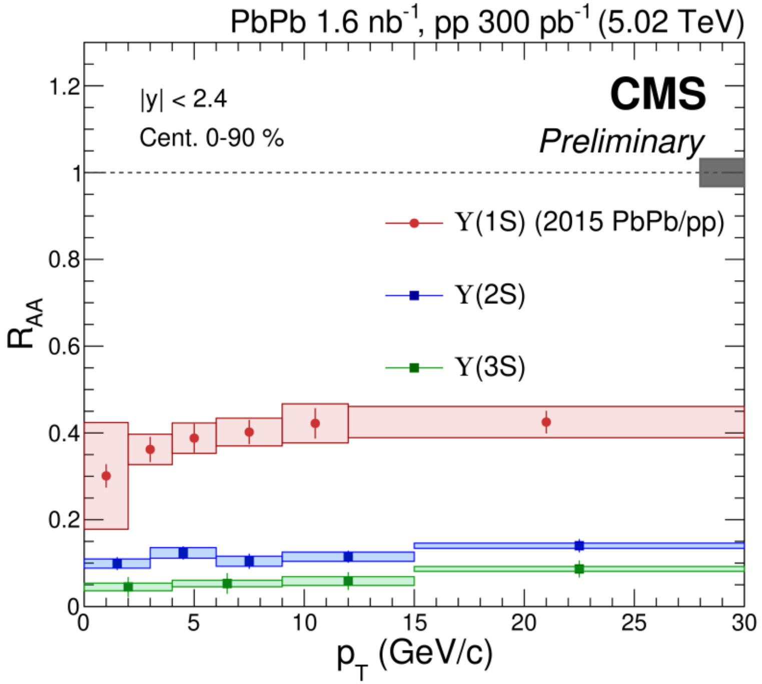




First observation of Υ(3S) state in all centrality classes in PbPb collisions and improved Υ(2S) data.

CMS HIN-21-007





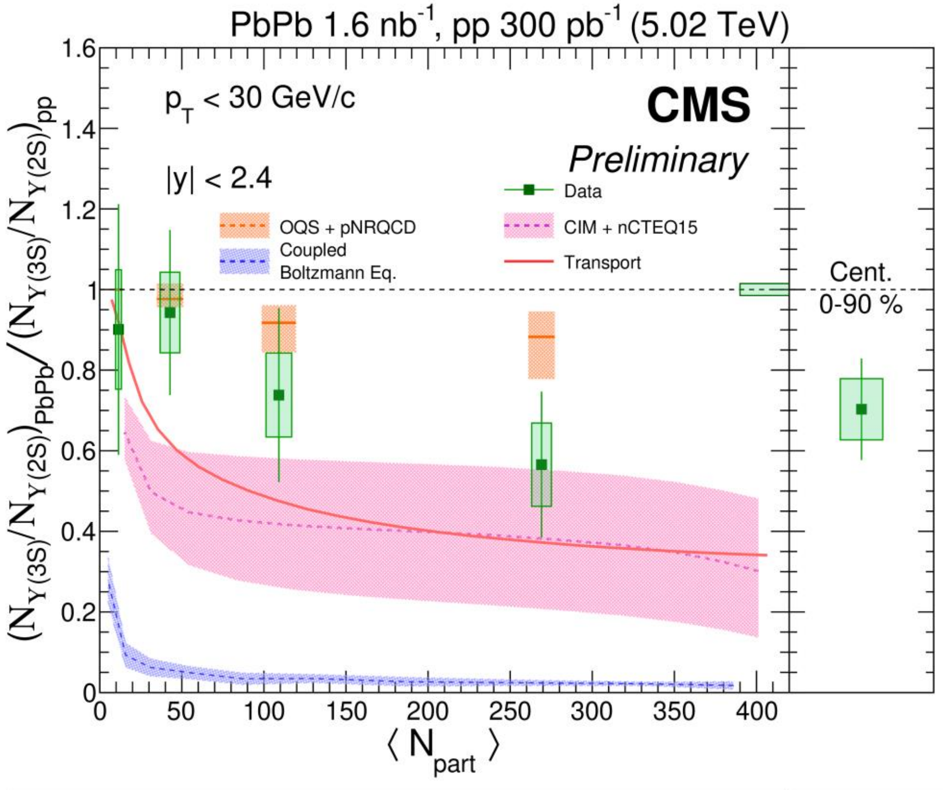
Complete picture of sequential melting of Υ states revealed!
R_{AA}(1S) > R_{AA} (2S) > R_{AA} (3S)

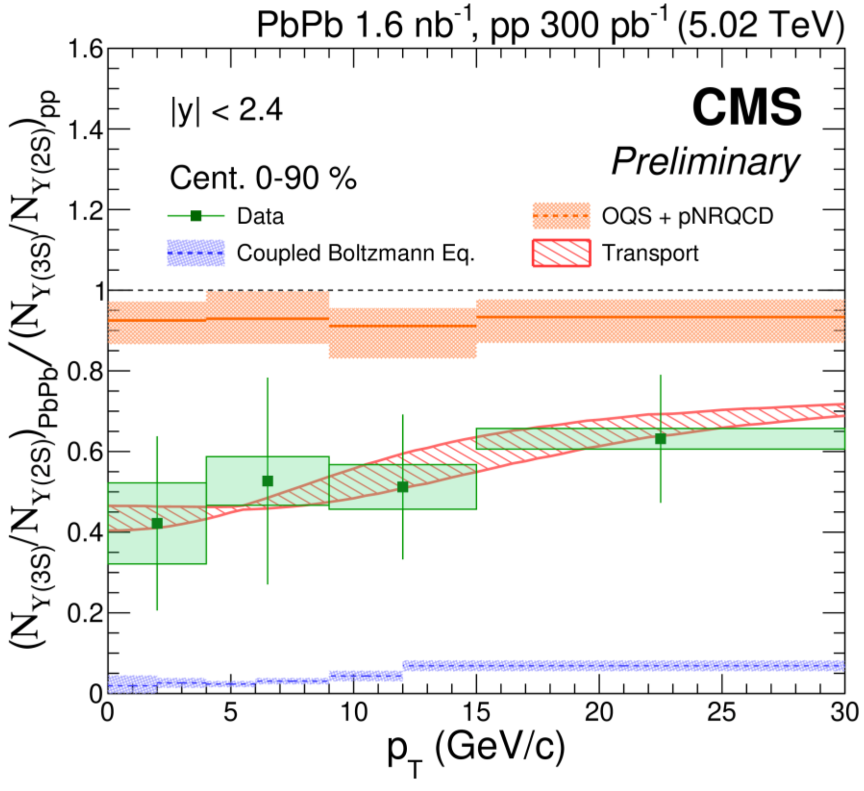
See also:
ATLAS, arXiv:2205.03042
W. Zou (ATLAS), Sat 9:00
R_{AA} Υ(1S), Υ(2S) and Υ(2S+3S)

Sequential melting of Upsilon states

S. Lee (CMS) Sat 11:30

CMS-HIN-21-007





Models expect different rate of suppression between the excited states.

Models:

Open quantum system + pNRQCD *PRD 104 094049*

Coupled Boltzmann Equation *JHEP 10(2018) 094*

Transport rate equation *PRC 96 054901*

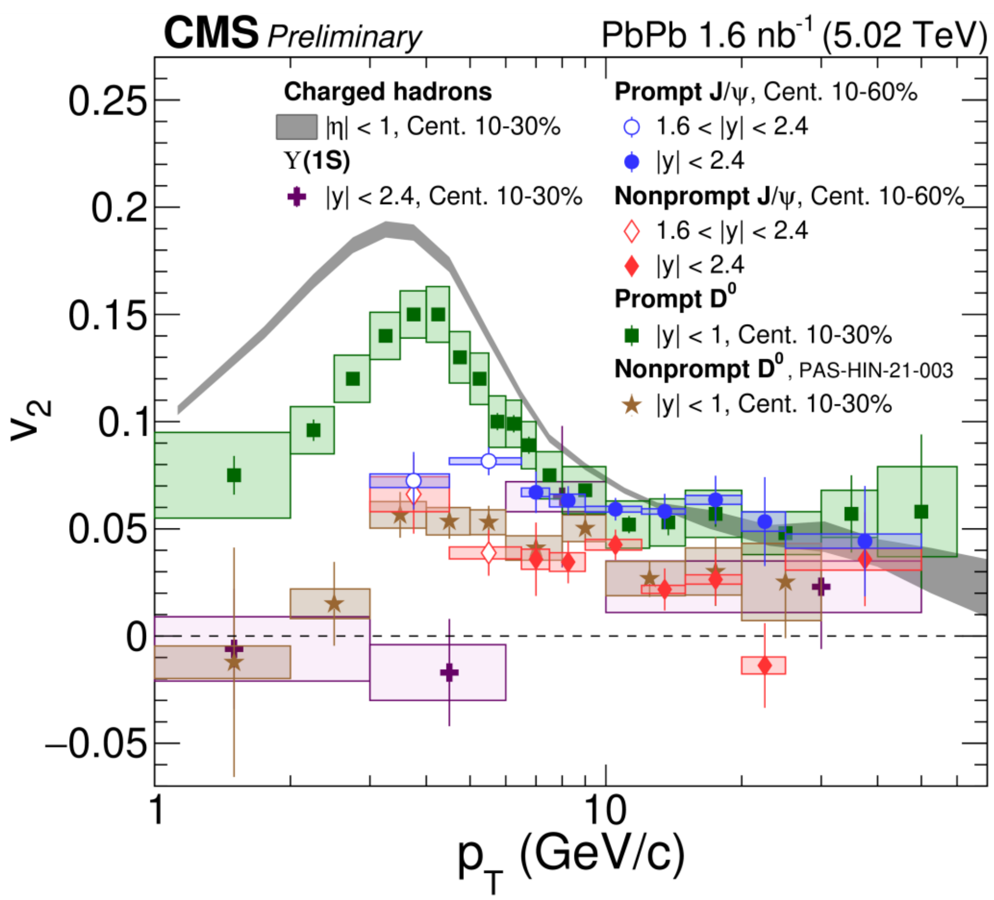
Comover interaction model *JHEP 01(2021) 046*

Strong constraints on theoretical models!
To do: need to carefully treat
individual theoretical ingredients …

Flow of heavy quarks at LHC energy

F. Damas (CMS) Fri 15:05
M. Coquet, ALICE, Sat 11:15

CMS-PAS-HIN-21-001
CMS-PAS-HIN-21-008



Comprehensive picture in PbPb collisions from Run 2 data

- low p_T: steep increase following mass hierarchy in hydrodynamic regime
  light quarks > charm > beauty

- maximum v_2 reached at $3 < p_T < 6$ GeV/*c*:
  light quarks ≳ prompt D^0 > prompt J/ψ > b→hadrons

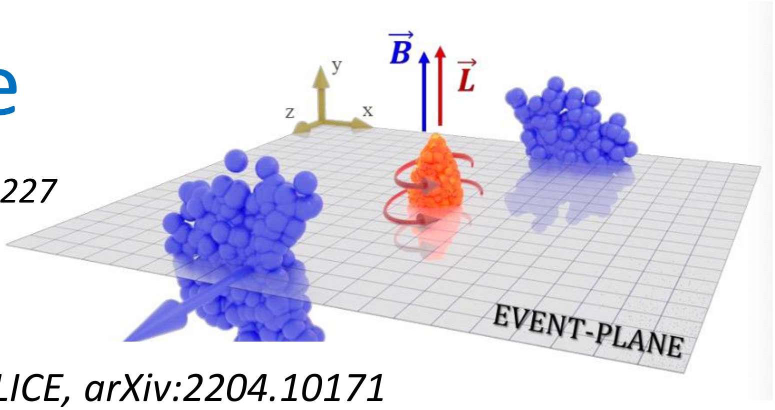
  → coalescence of heavy quarks with light quarks at play

- high p_T: convergence towards a non-zero v_2

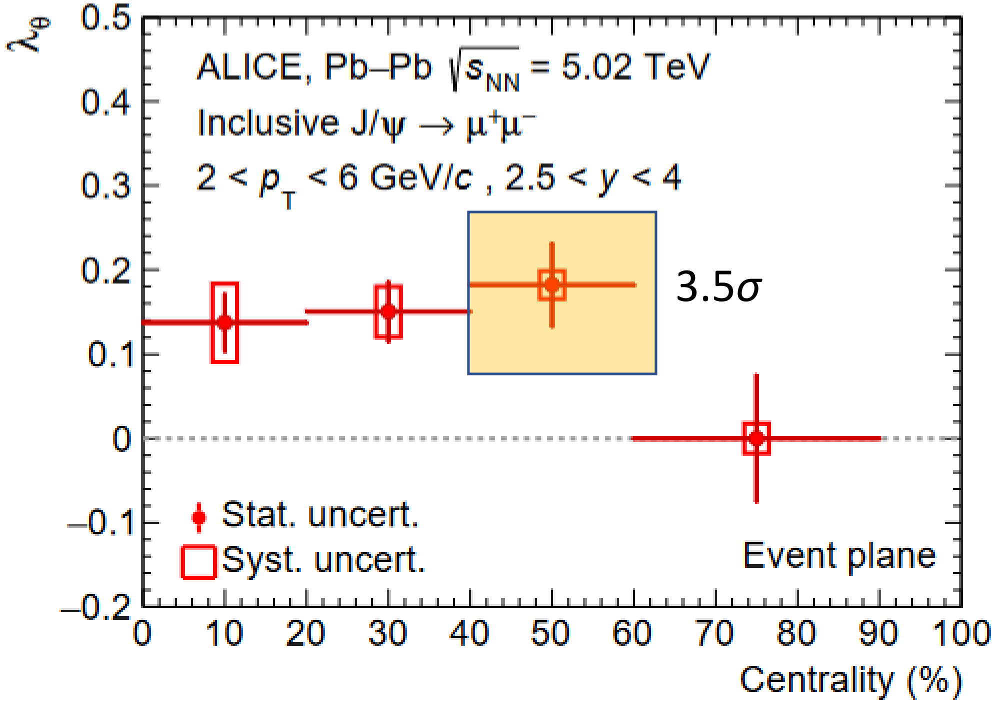
J/ψ polarization relative to the event plane

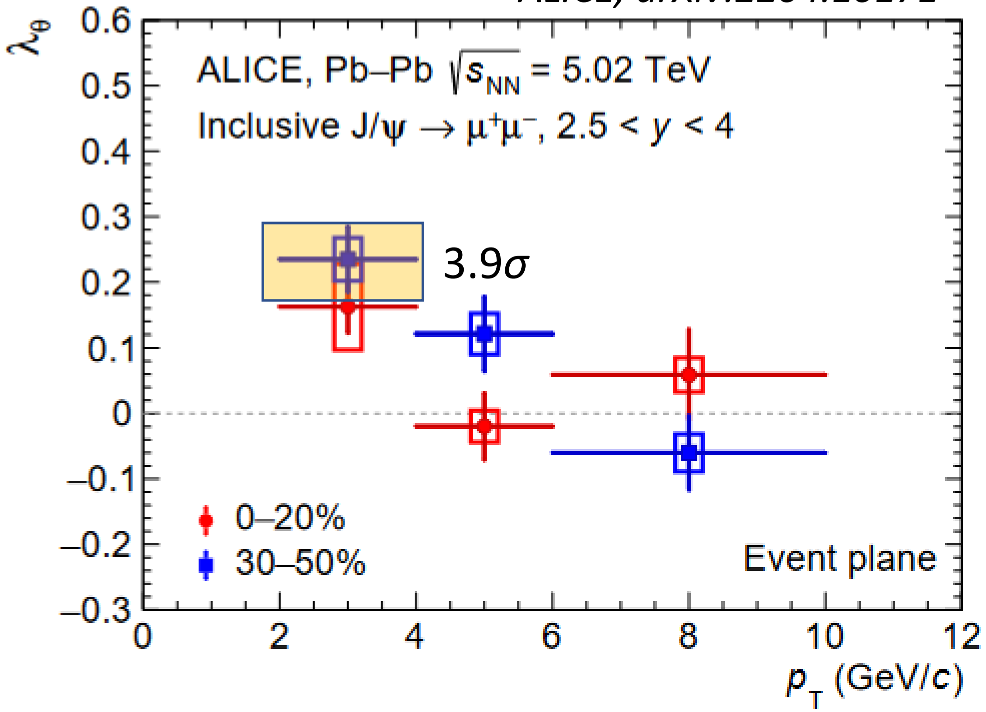
Heavy-quark pair production occurs early
→ sensitive to strong magnetic field and vorticity in non-central PbPb collisions!

Kharzeev et al., NPA 803 (2008) 227
Becattini et al., PRC 77, 024906



ALICE, arXiv:2204.10171





Non-zero polarization observed in semi-central PbPb collisions and lower p_T (2-4 GeV/*c*)

Light-flavor hadrons (K^{0*}, ϕ) "similar", but: *ALICE, PRL 125 (2020) 012301*

smaller absolute polarization: $J/\psi < \phi < K^{0*}$

opposite sign of the deviation: $J/\psi > 0$, ϕ, $K^{0*} < 0$

These require dedicated theory studies to make connection with the QGP properties at its origin

Electromagnetic probes: direct photons

Direct photons

Inclusive γ = direct γ + decay γ

Note: decay photons (from π^0, η decays) has to be removed with % precision

Sources of direct photons:

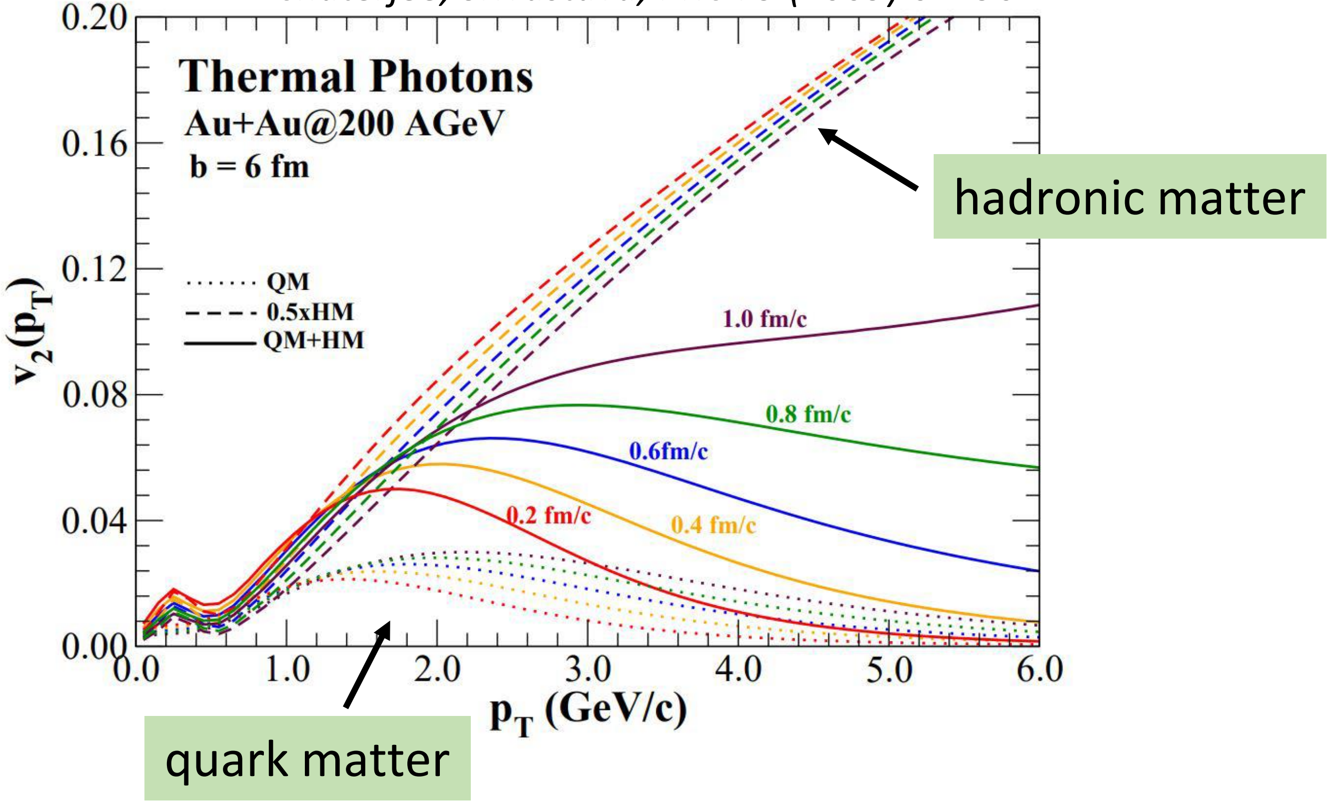
- prompt (at high p_T)

In addition in medium:

- thermal photons
- pre-equilibrium
- jet-medium interaction

→ give access to temperature and space-time evolution of the medium

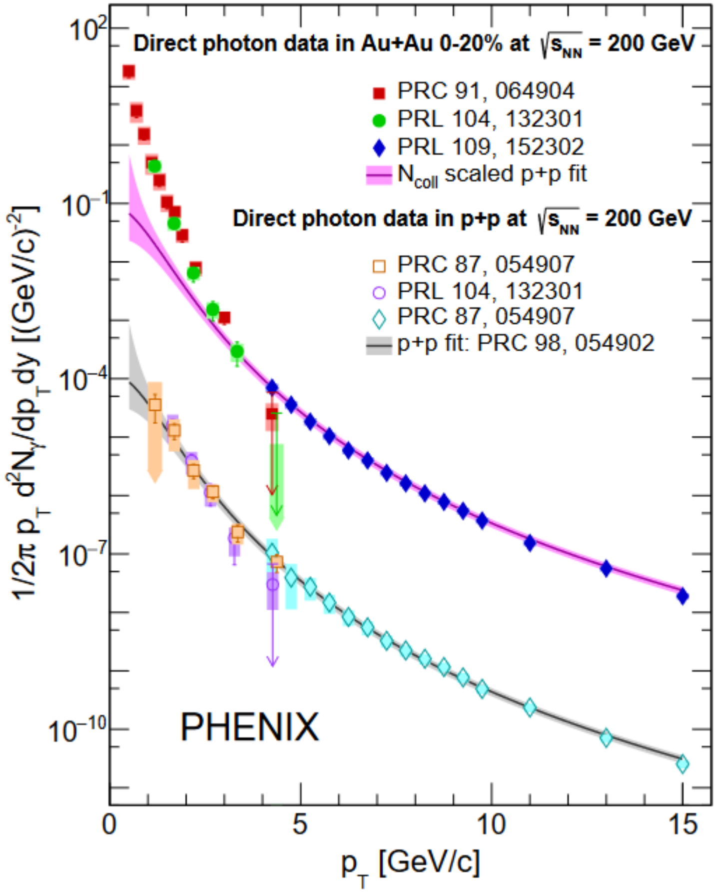
Chaterjee, Srivastava, PRC 79 (2009) 021901



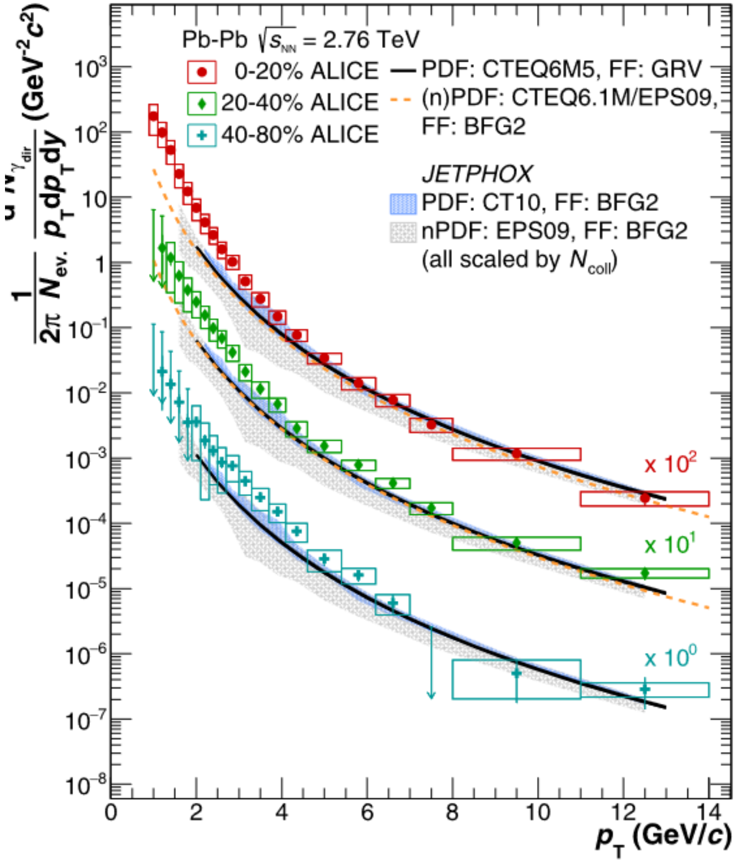
v_2 for thermal photons (solid curves) reveals a large sensitivity to formation time for p_T > 1.5 GeV/*c*

Direct photon “puzzle”

PHENIX

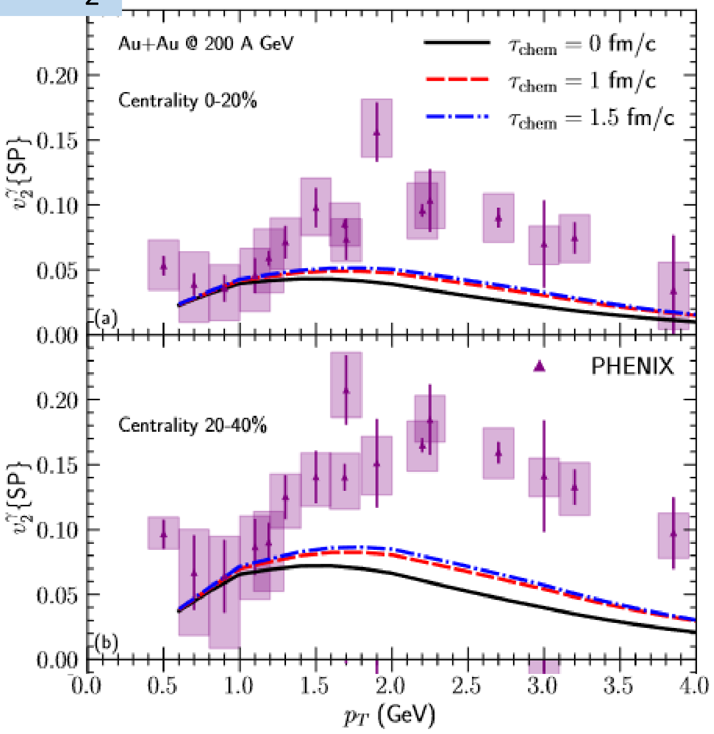


ALICE



photon v_2

PHENIX



Gale, Paquet, Schenke, Shen, PRC 105 (2022) 1, 014909

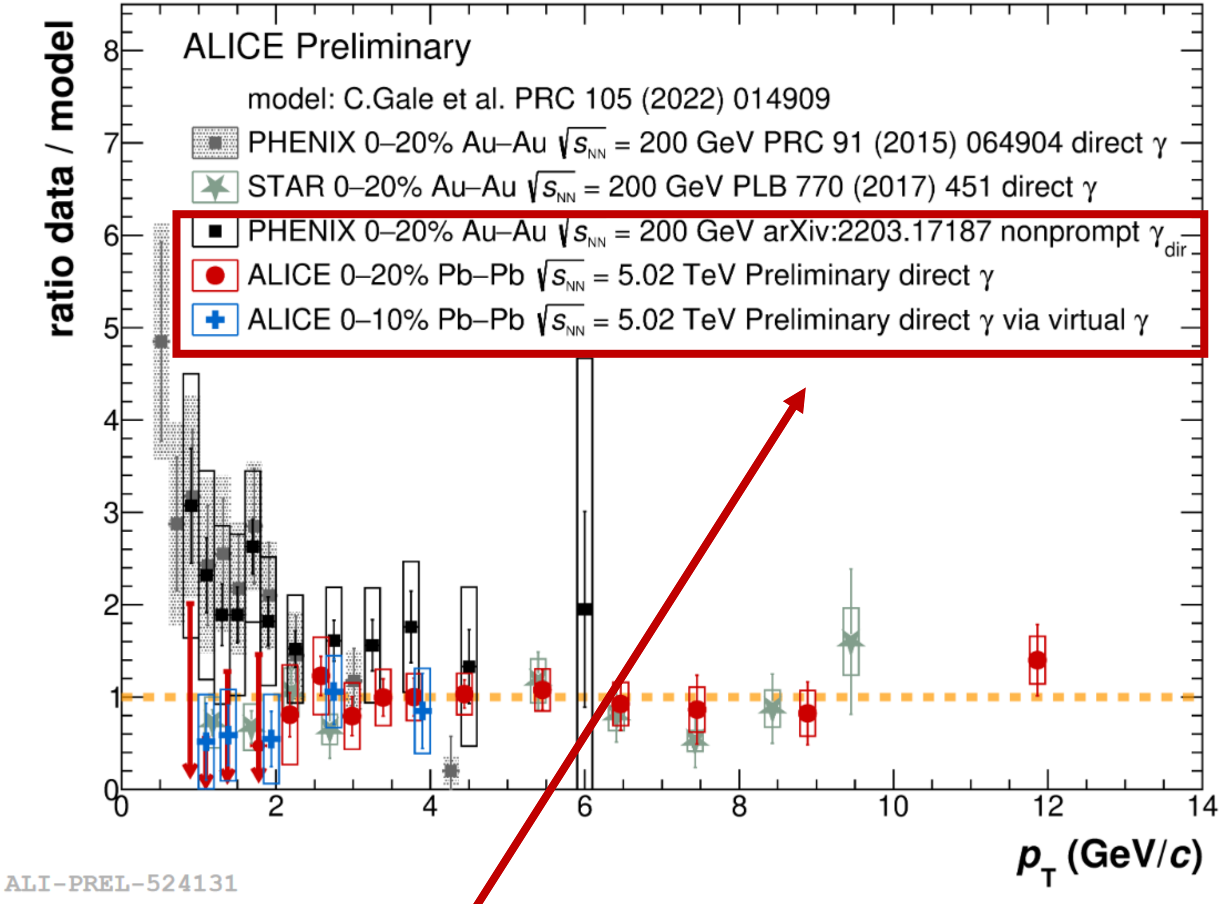
Excess of low p_T photons observed above model predictions from RHIC to LHC energy and large photon v_2.

“Puzzle”:
large yield: early emission, higher T
large v_2: late emission, lower T

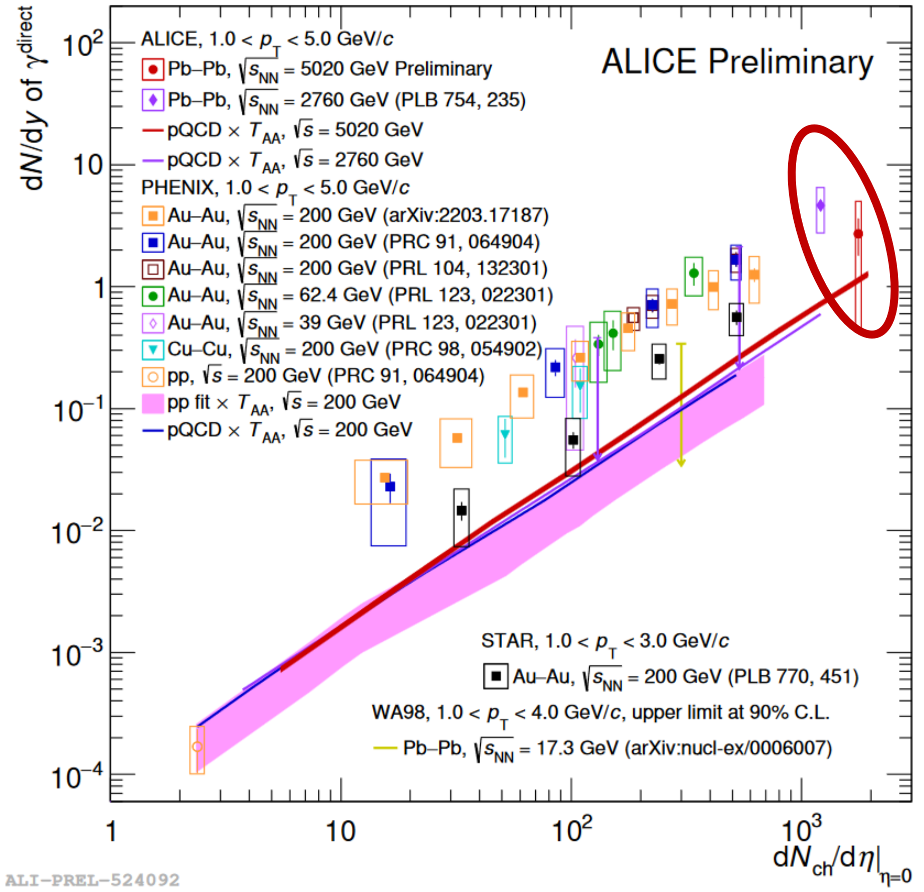
ALICE, PLB 754 (2016) 235
STAR, PLB 770 (2017) 451

Direct photon "puzzle" (almost) resolved

M. Sas (ALICE) Thu 18:40



Universal scaling of photon dN/dy with collision centrality.

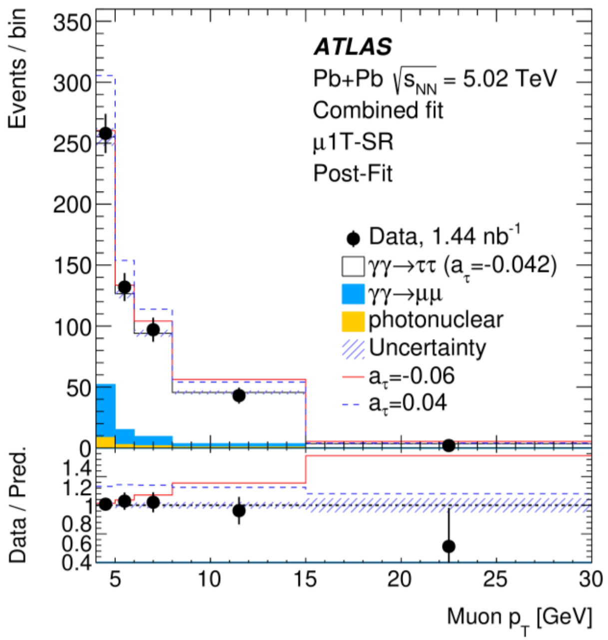


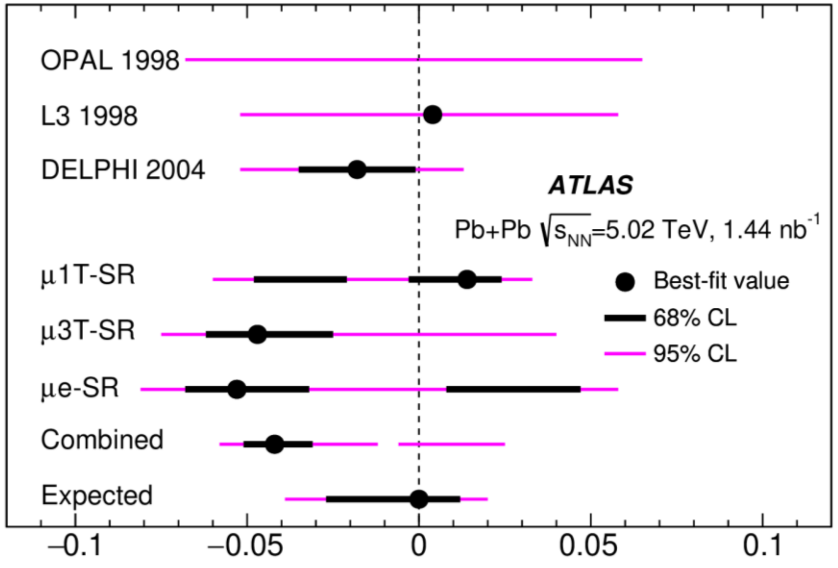
New ALICE and PHENIX data: only a slight tension at very low p_T for PHENIX data remains.

More precise photon v_2 data needed to explore the second part of the puzzle ...

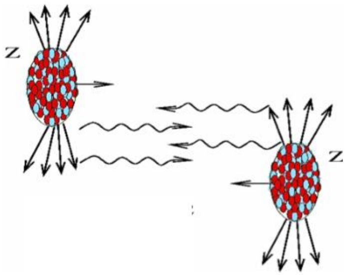
Ultraperipheral collisions: QED laboratory

C. Baldenegro Barrera (CMS) Thu 18:05
V. Lang (ATLAS) Sat 15:55

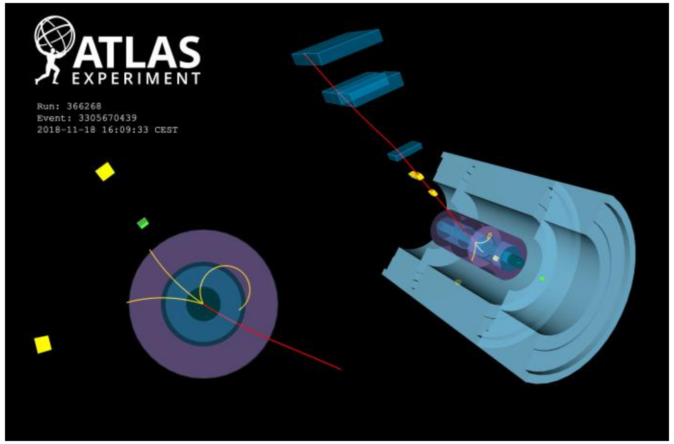


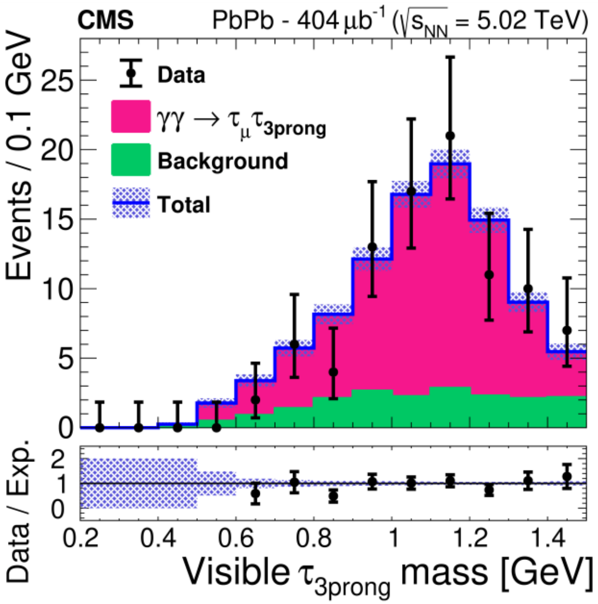


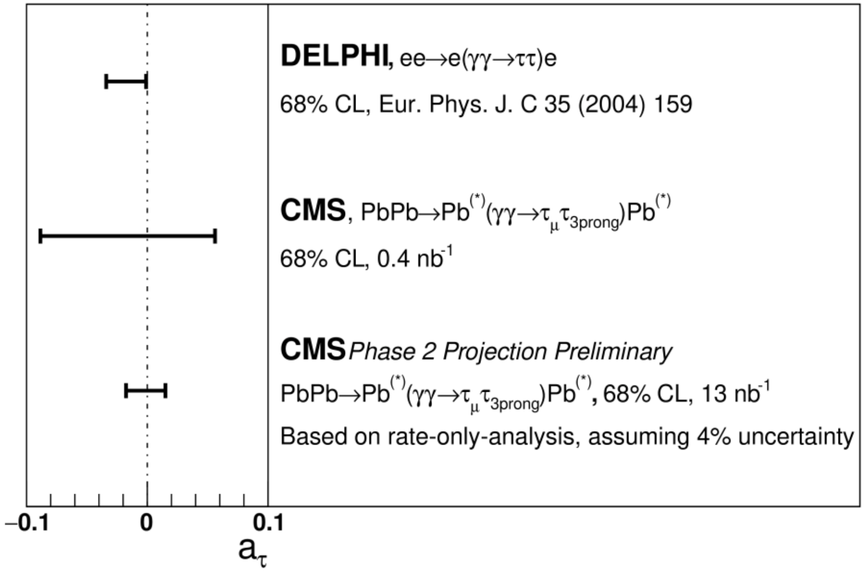
ATLAS, arXiv:2204.13478



"Particle physics with an (almost) empty detector at a hadron collider!"
V. Lang (ATLAS)







CMS, arXiv:2206.05192

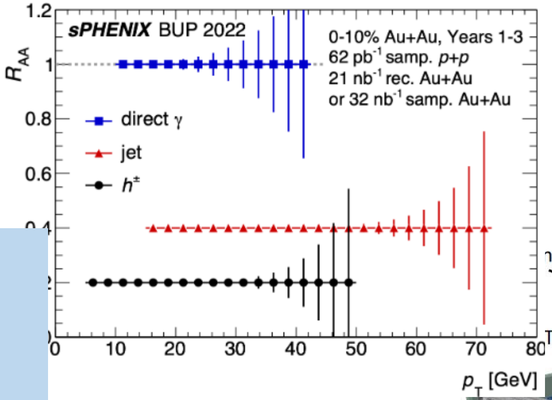
μ+3-prong decays (CMS)
μ+3-prong, μ+1-prong, μ+e (ATLAS)

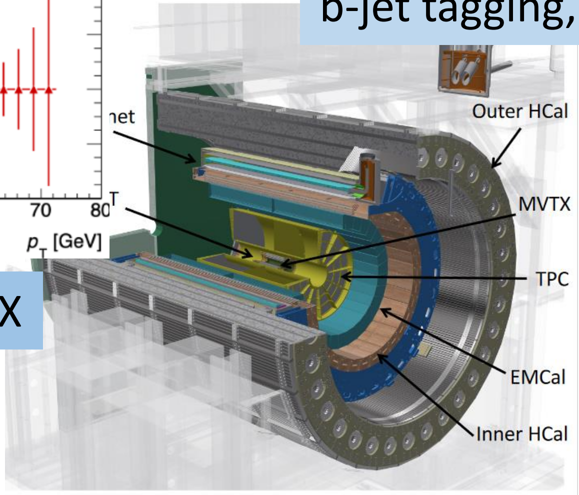
New constraints on anomalous magnetic moment of τ!

Future prospects

RHIC in 2023-2025:
Simultaneous data taking for STAR (with new forward capabilities) and a new sPHENIX experiment

- unprecedented statistics to be collected for pp, pAu and AuAu collisions at 200 GeV
  → completion of RHIC mission



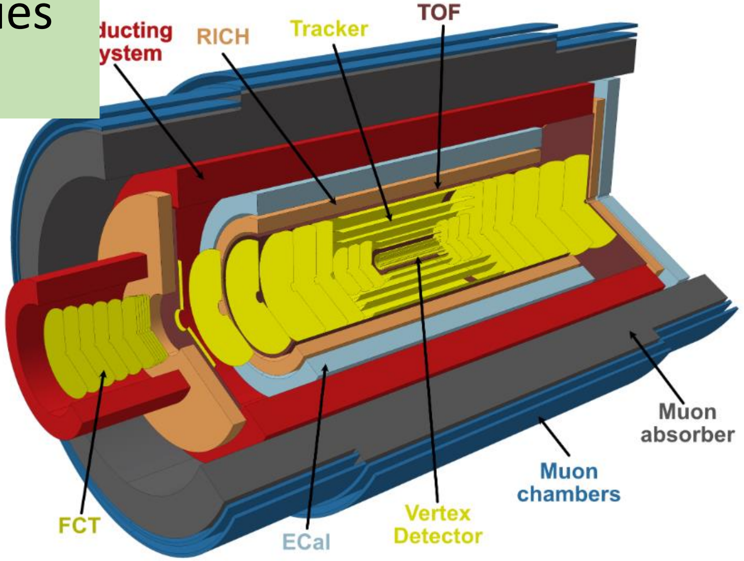


sPHENIX

full jet reconstruction, b-jet tagging, quarkonia

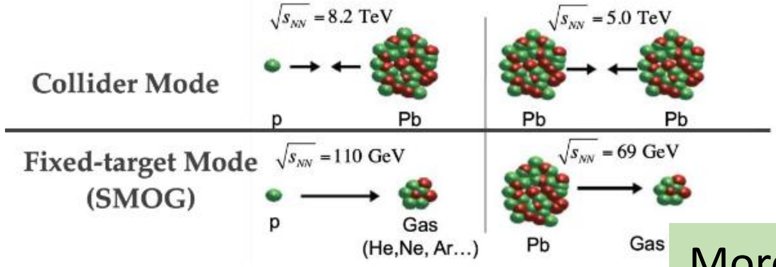
LHC:
Run 3 and Run 4 will enable to perform microscopic studies of QGP properties with upgraded LHC experiments

ALICE 3 Run5+



LoI: CERN-LHCC-2022-009

LHCb



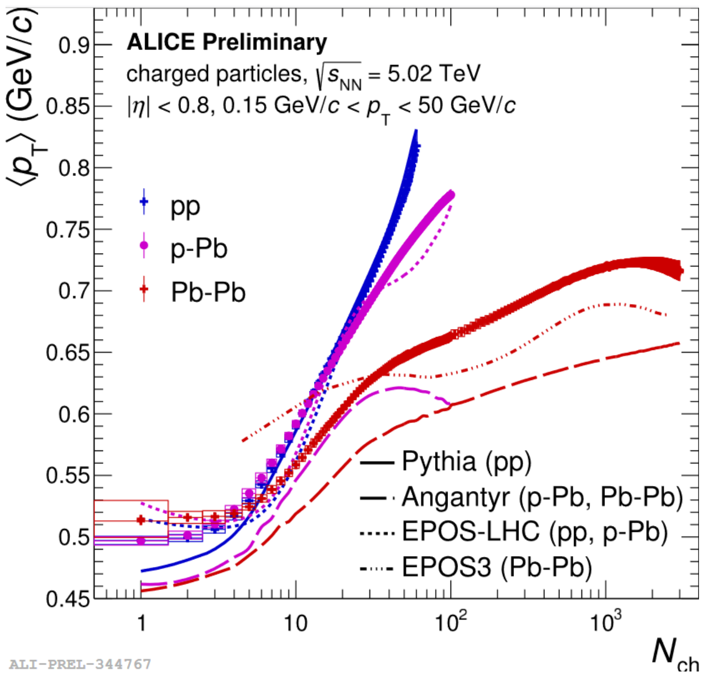
More PbPb data
+ Fixed-target mode (SMOG)

Thank you for your attention

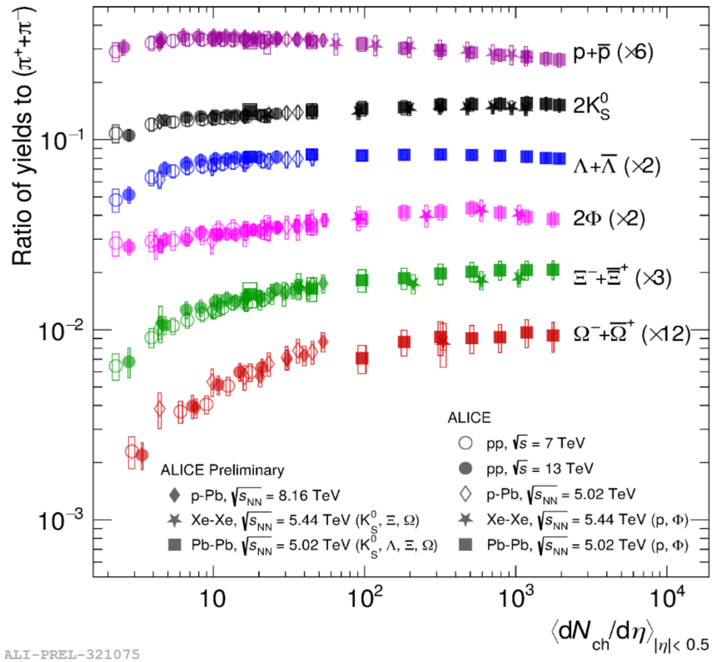
BACKUP SLIDES with more details

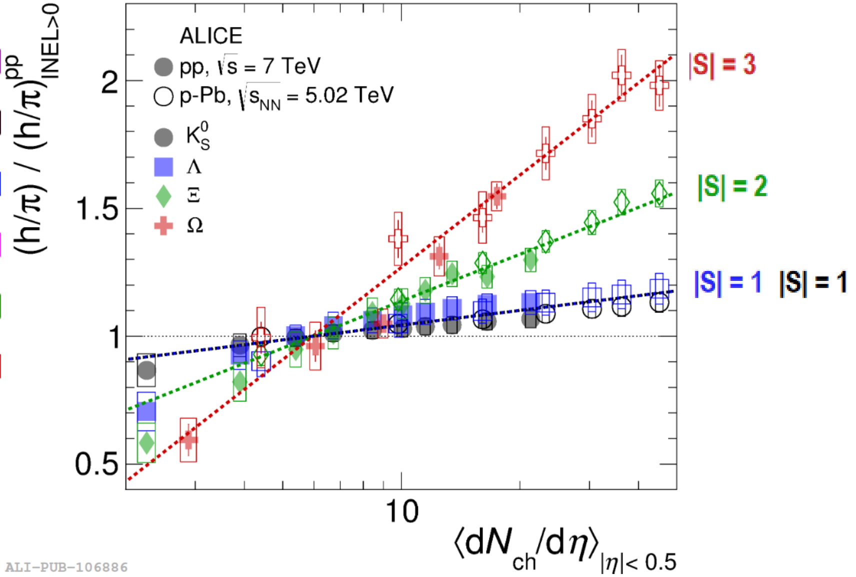
Integrated particle yields, mean p_T

M. Krueger (ALICE) Thu 9:00
F. Ercolessi (ALICE) Thu 9:55



ALICE, PRC 101 (2020) 044907





Charged hadron spectral shape evolution with highest possible granularity in multiplicity:

- steeper rise in <p_T> for small systems (pp, pPb)
- describing both large and small systems simultaneously still challenging for models

Strangeness enhancement one of the early QGP signatures

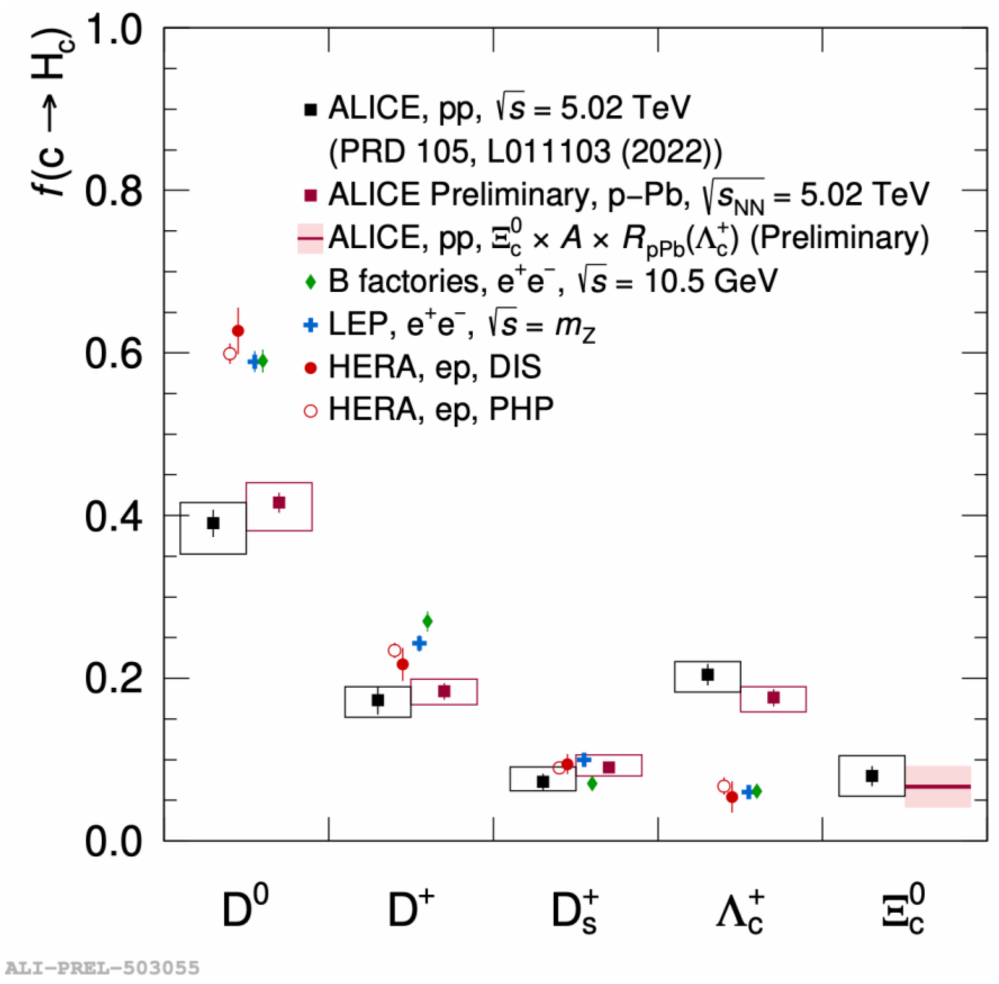
Hadron chemistry driven by multiplicity:

- continuous evolution of strangeness production across collision systems and energies
- enhancement grows with strange quark content

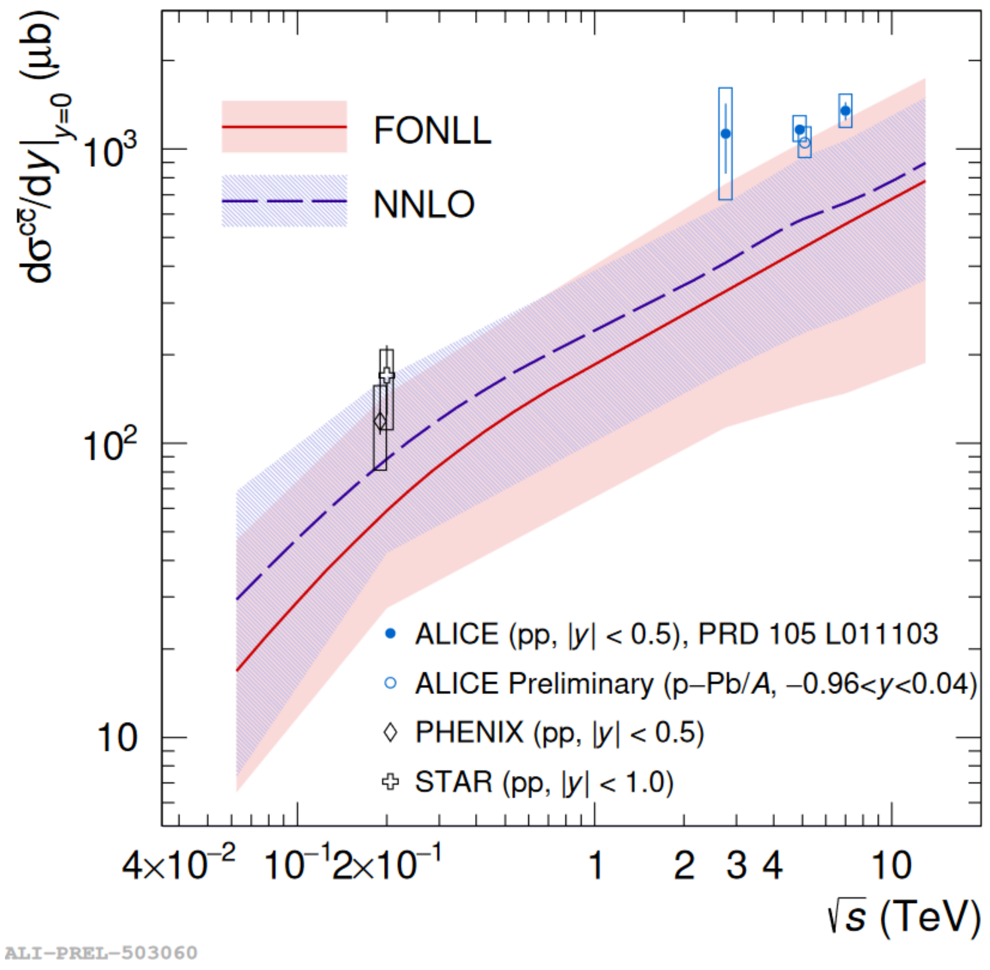
ALICE, Nature Phys 13 (2017) 535 *ALICE, EPJ C 80 (2020) 167*

Universality of charm hadronization?

J. Zhu (ALICE) Thu 11:45



STAR: PRD 86 (2012) 072013; PHENIX: PRC 84 (2011) 044905

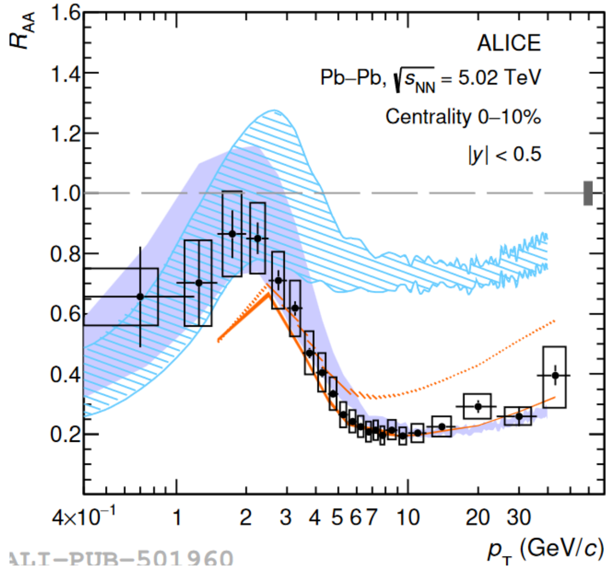


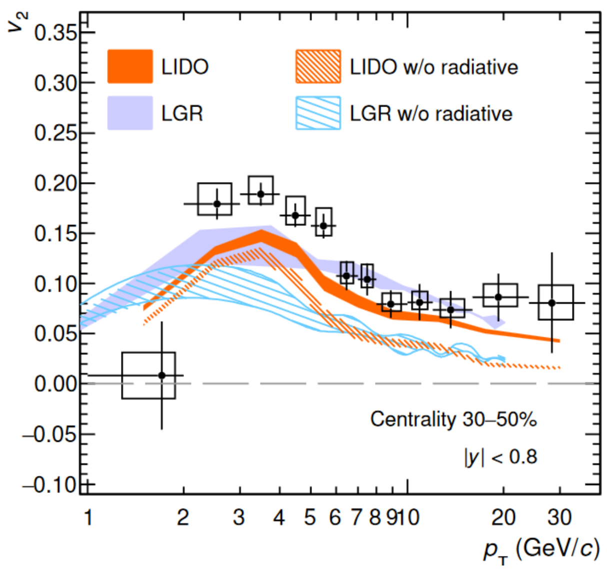
Significant baryon enhancement in pp collisions relative to e^+e^-/ep
→ c-fragmentation fractions are not universal

Data on the upper edge of FONLL and NNLO calculations

FONLL: JHEP 10 (2012) 137 NNLO: PRL 118 (2017) 12, 122001

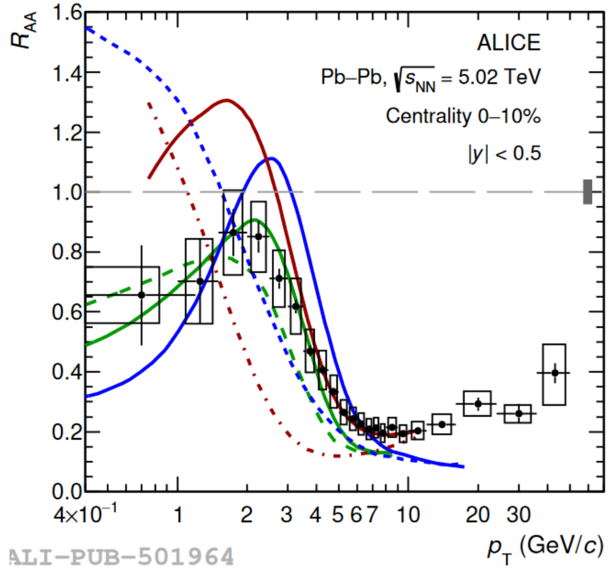
Open heavy flavor production: D^0, D^+, D^{*+}

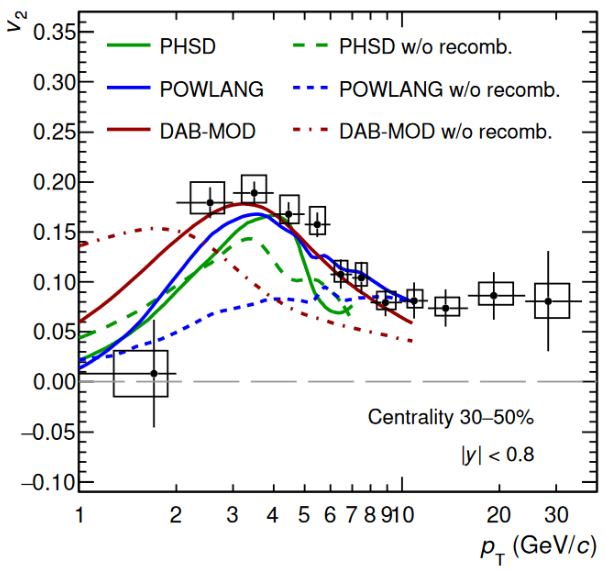




Radiative energy loss important to describe intermediate and high p_T
It has small impact on low-p_T region

LIDO: PRC 98 064901 (2018)
LGR: EPJC 807 671 (2020)





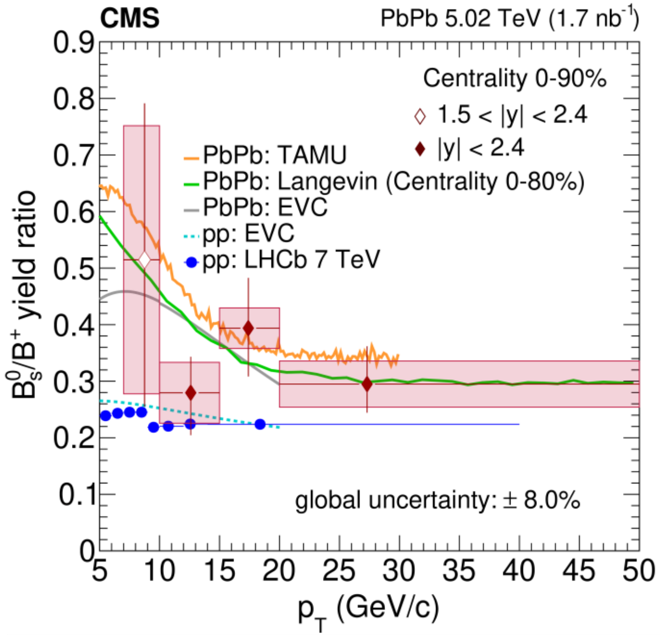
Charm-quark hadronisation via recombination essential to describe low/intermediate p_T
D mesons acquire additional flow recombining with light quarks

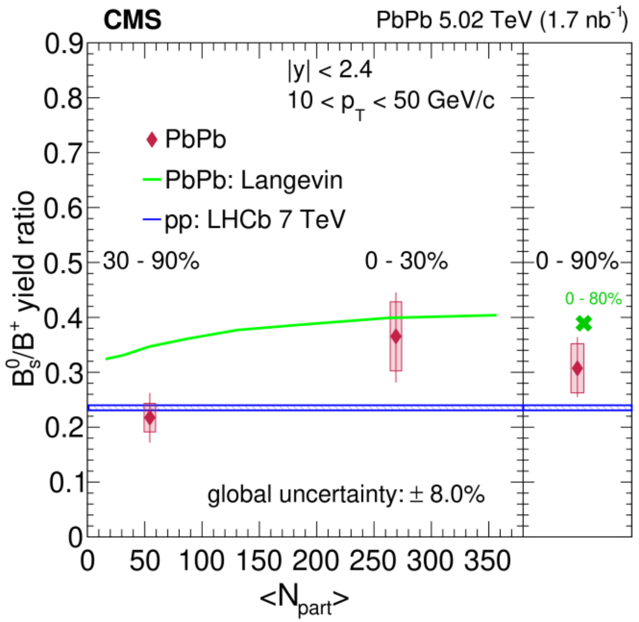
PHSD: PRC 93 034906 (2016)
DAB-MOD: PRC 96 064903 (2017)
POWLANG: EPJC 75 3 121 (2015)

Charm and Strange Beauty in QGP

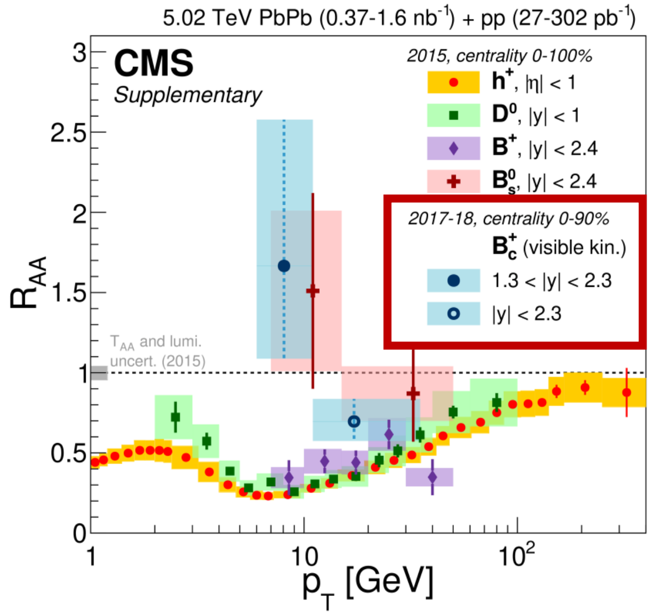
T. Sheng (CMS) Thu 15:55

CMS, PLB 829 (2022) 137062
CMS, arXiv:2201.02659





First observation of $B_s^0 > 5\sigma$ in PbPb collisions



$$B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\mu^+\nu_\mu$$

B_c^+

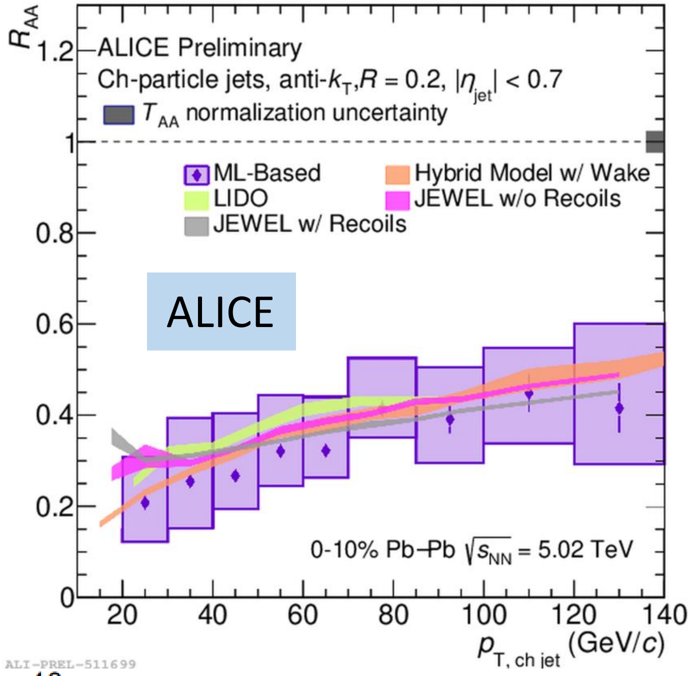
B_s and B_c can help disentangle interplay of suppression and enhancement mechanisms in the production of heavy-flavor mesons in the QGP

→ more data needed

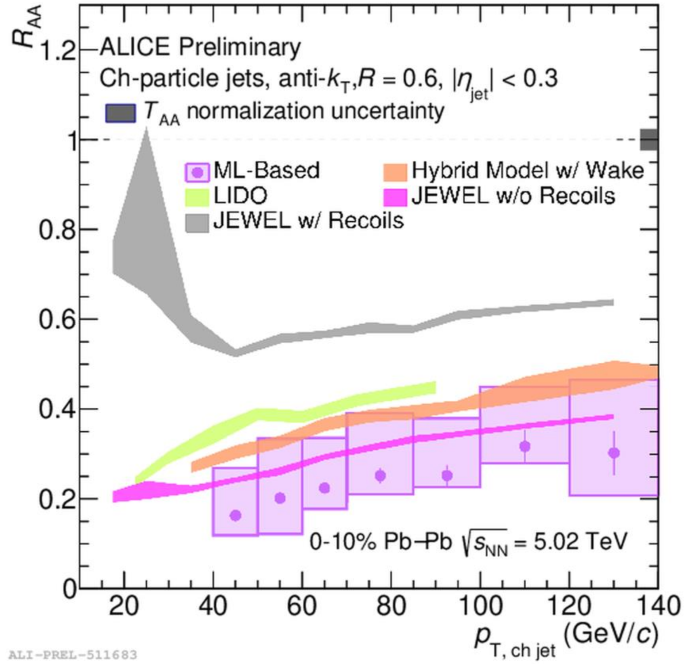
Larger R and lower jet p_T ?

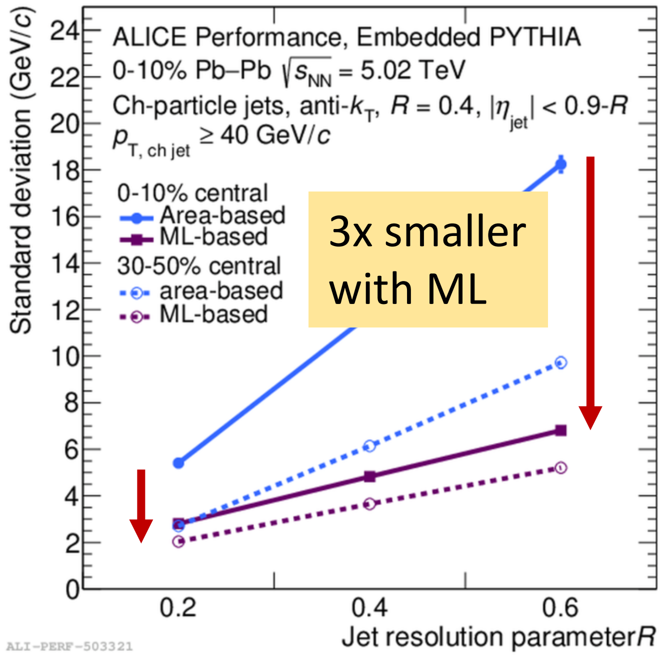
A. Dainese (ALICE) Mon 16:00

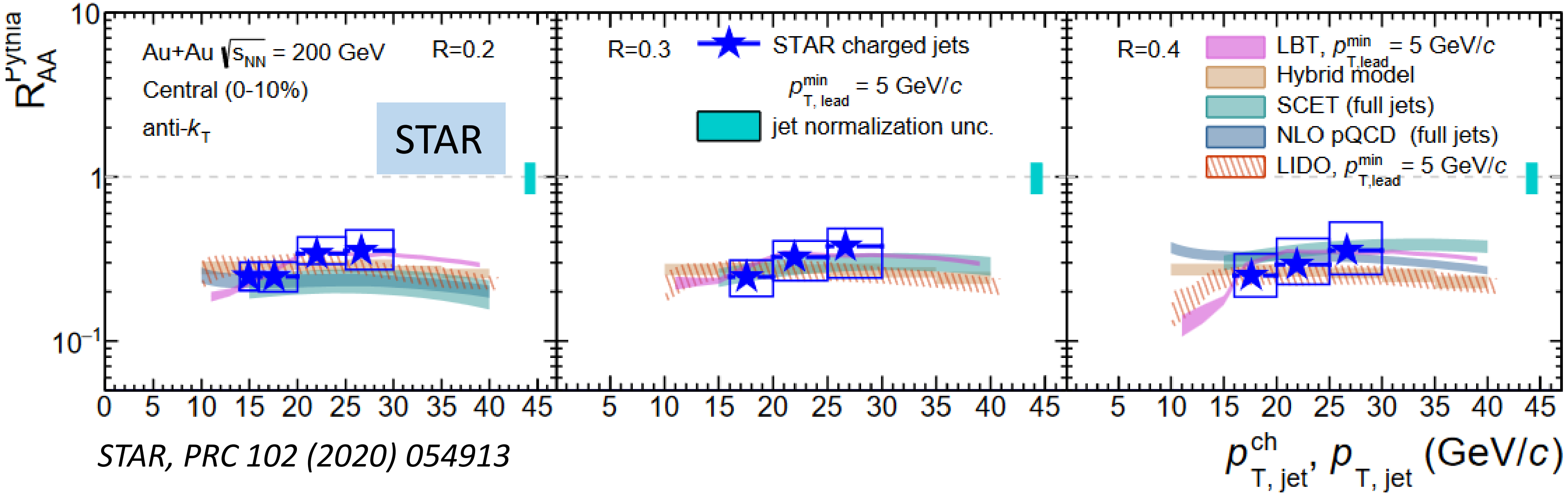
R=0.2



R=0.6







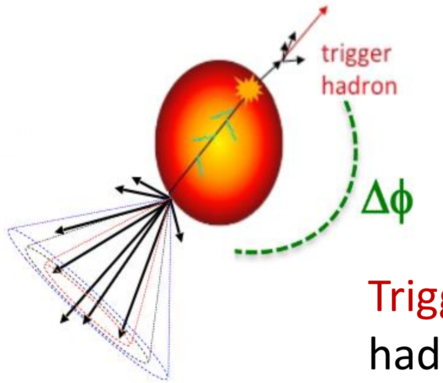
STAR, PRC 102 (2020) 054913

First encouraging results using ML reported by ALICE:

- improved precision and extended reach in p_T and R
- data will enable to constrain model predictions and allow for comparison with RHIC

Semi-inclusive recoil jet studies

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Sig}} - \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

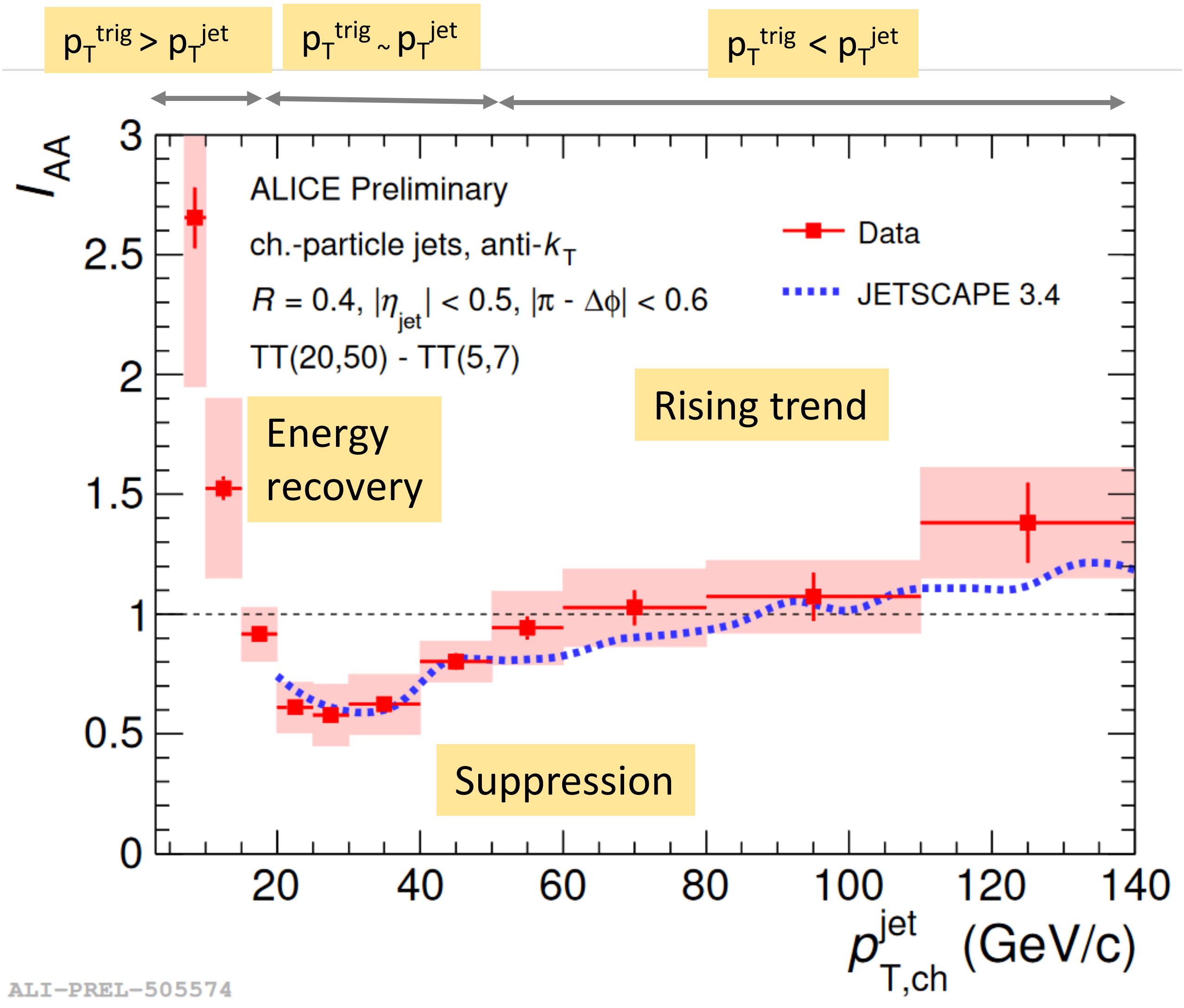


$$I_{AA} \equiv \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

Trigger particle:
hadron, π^0 , γ_{dir} …

A unique observable:
- enables study of intra and inter-jet angular broadening
- directly comparable to analytic pQCD calculation
- large-angle jet deflection studies can probe the nature of the quasi-particles in hot QCD matter ("QCD Molière scattering")

D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172

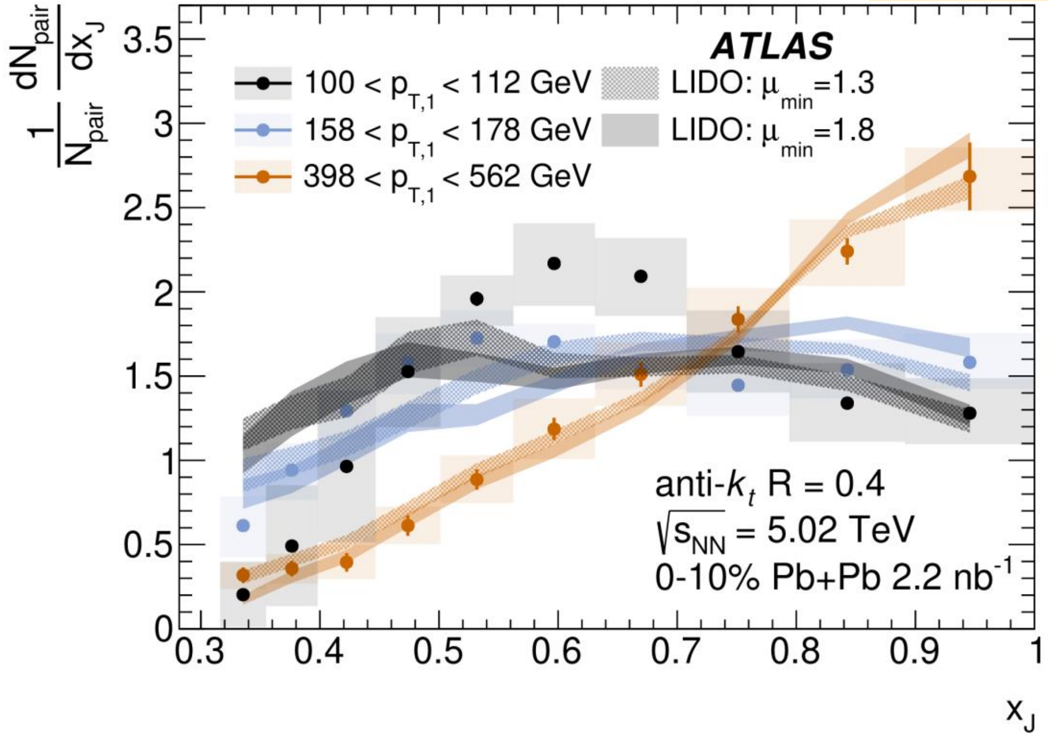


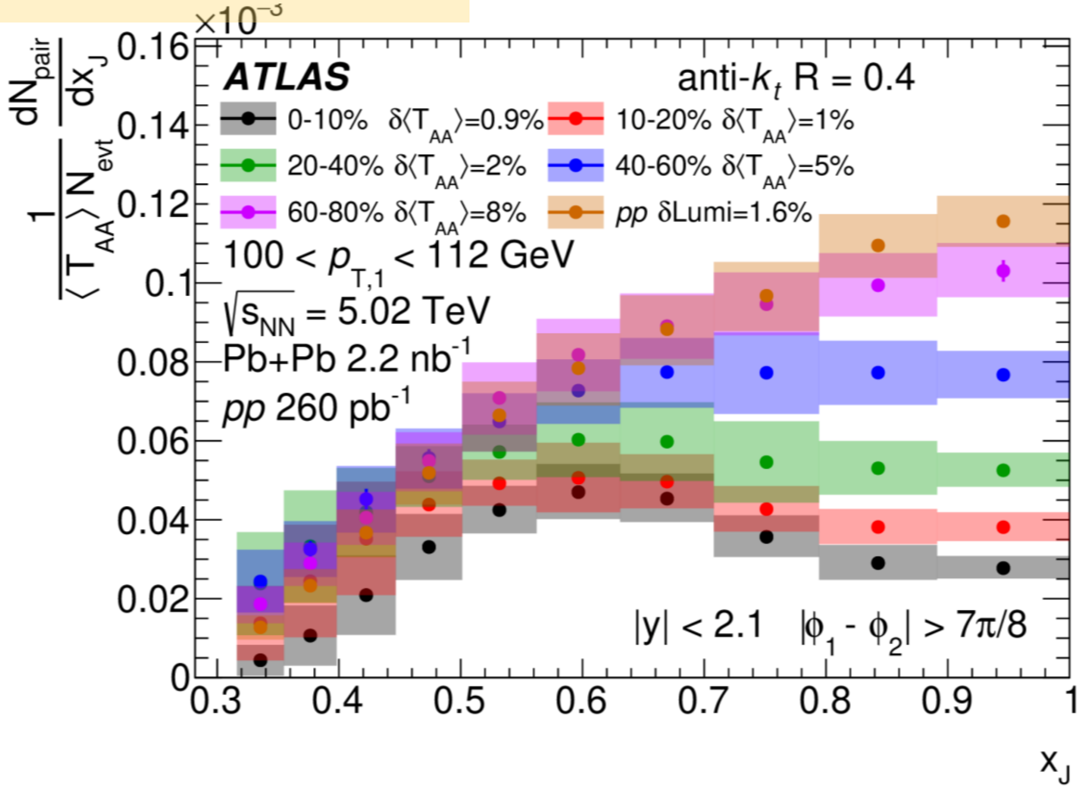
Interplay between hadron and jet energy loss?

Di-jet asymmetry

leading di-jet momentum balance
$x_J \equiv p_{T,2}/p_{T,1}$

ATLAS, arXiv:2205.00682





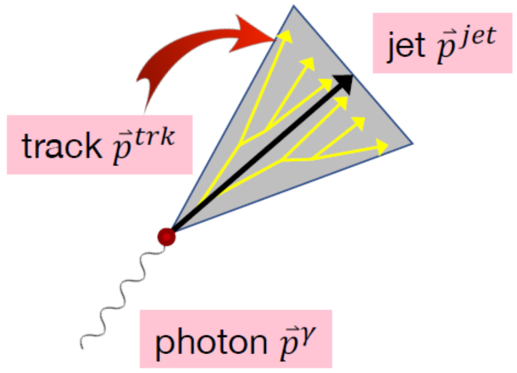
Dijet-yield-normalized x_J distributions: increased fraction of imbalanced jets in PbPb compared to pp collisions.

Absolutely-normalized dijet rates: balanced dijets are significantly more suppressed than imbalanced ones.

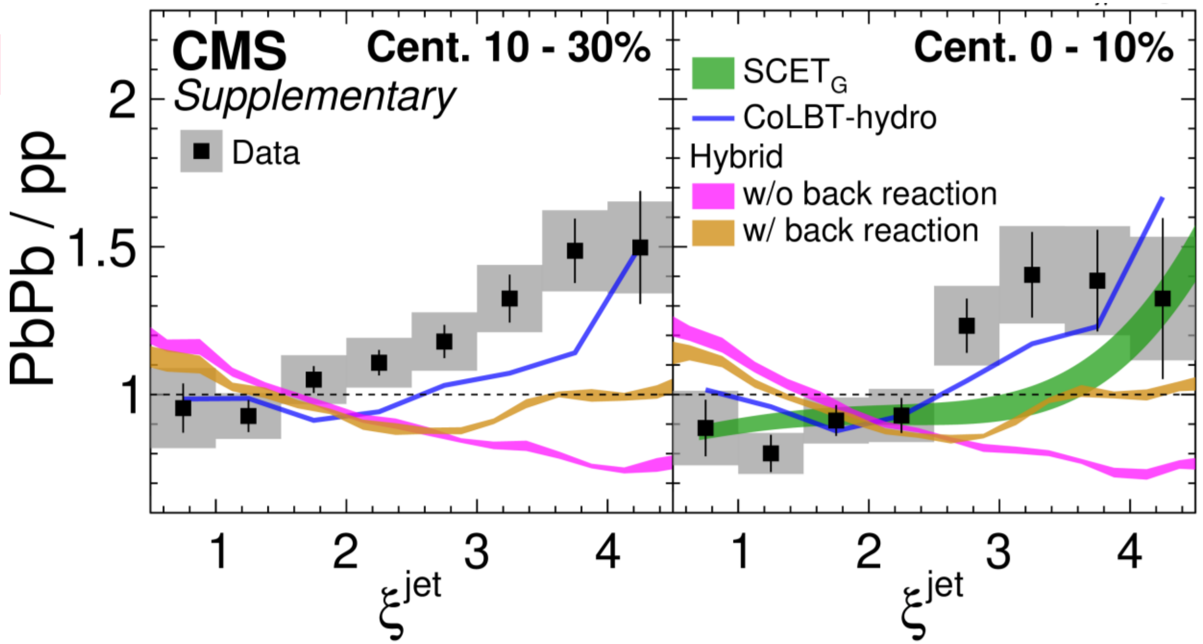
Central PbPb collisions: a broad maximum around $x_J = 0.6$ for “low” p_T = 100 -112 GeV
→ challenge for models to describe it … it would be interesting to see even lower p_T

γ-tagged jets: fragmentation, radial density

M. Taylor (CMS) Fri 15:55



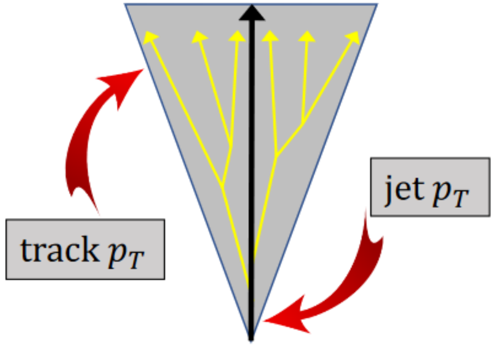
$$\xi^{jet} = \ln \frac{|\vec{p}^{jet}|^2}{\vec{p}^{trk} \cdot \vec{p}^{jet}}$$



$\sqrt{s_{NN}}$ = 5.02 TeV p_T^{trk} > 1 GeV/c, anti-k_T jet R = 0.3
PbPb 404 μb^{-1} p_T^{jet} > 30 GeV/c, $|\eta^{jet}|$ < 1.6
pp 27.4 pb^{-1} p_T^{γ} > 60 GeV/c, $|\eta^{\gamma}|$ < 1.44, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

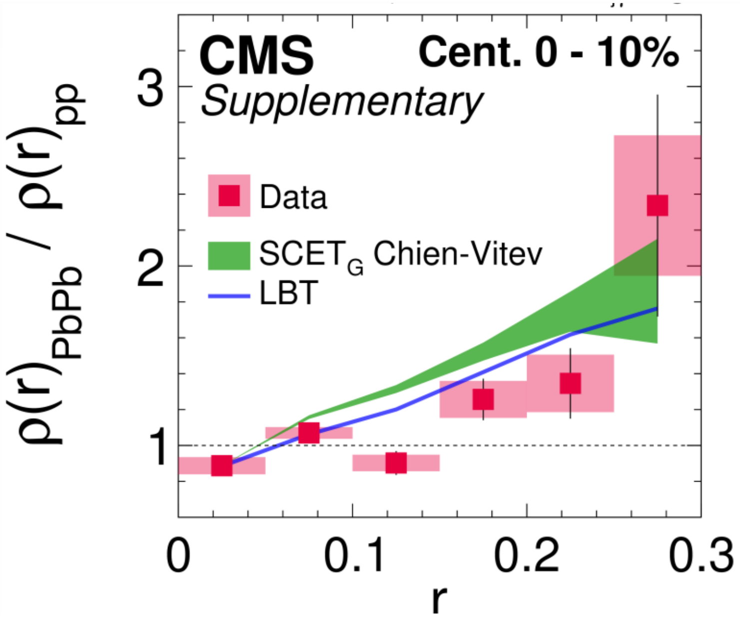
Small excess of low-p_T and depletion of high-p_T particles. Medium back-reaction in models improves data description.

CMS, PRL (2018) 242301



$$r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{jets} \sum_{r_a < r < r_b} p_T^{trk} / p_T^{jet}}{\sum_{jets} \sum_{0 < r < r_f} p_T^{trk} / p_T^{jet}}$$

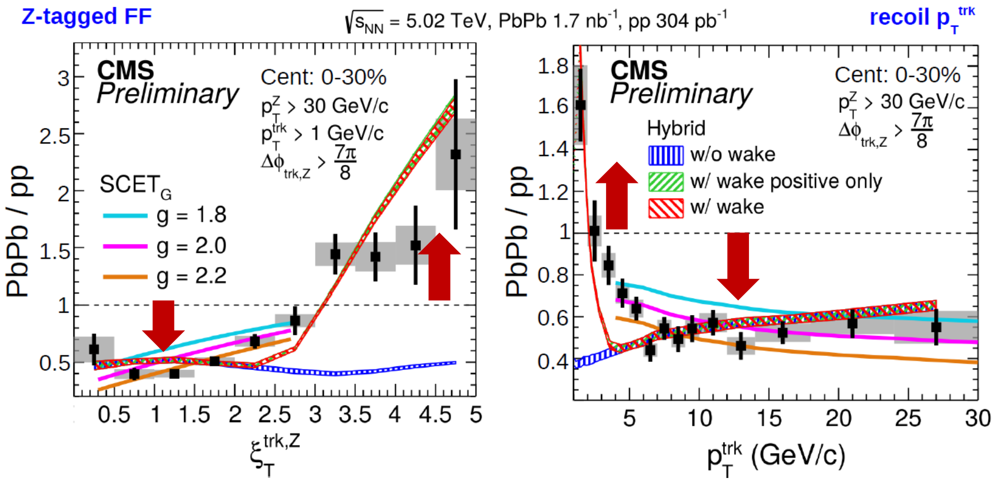


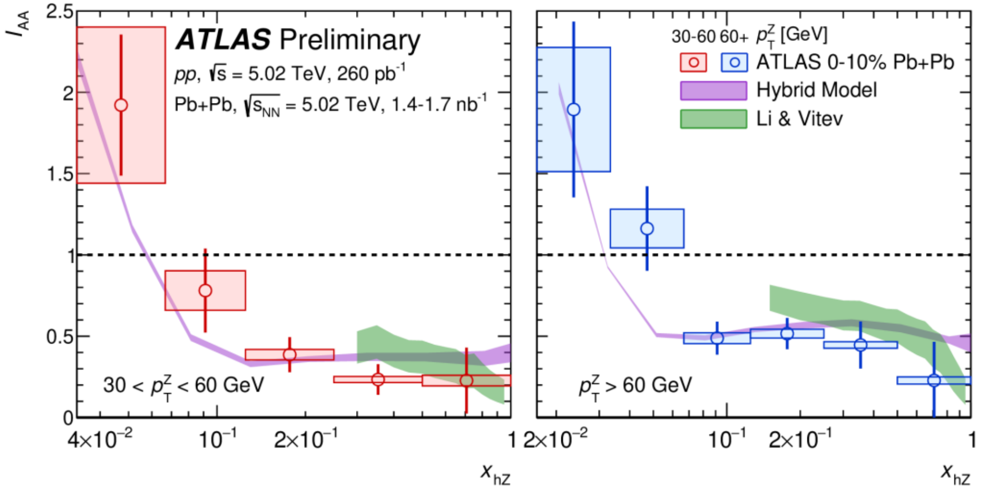
$\sqrt{s_{NN}}$ = 5.02 TeV p_T^{γ} > 60 GeV/c
PbPb 404 μb^{-1} anti-k_T jet R = 0.3
pp 27.4 pb^{-1} p_T^{jet} > 30 GeV/c, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

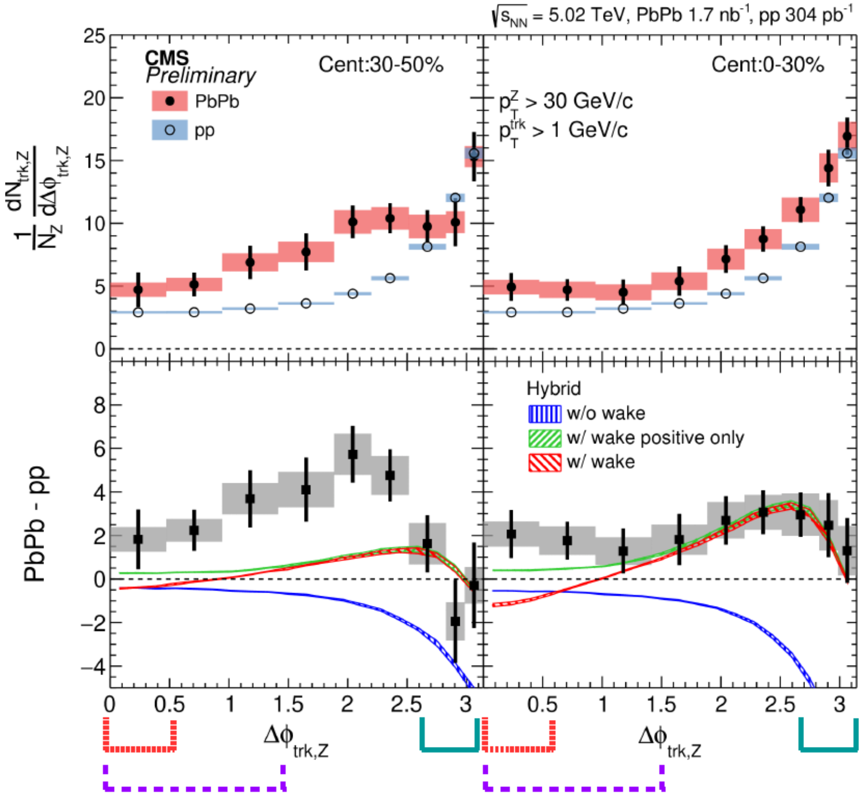
Small relative modification of jet core and enhancement of particles away from jet axis.

CMS, PRL 122 (2019) 152001

Z-tagged fragmentation







SCET$_G$ PRD 93 (2016) 074030,
PRD 101 (2020) 076020
Hybrid JHEP 1410 (2014) 019

- SCET$_G$ with g=2.0 reasonable description of data
- Hybrid model with medium wake undershoots intermediate p_T = 3-5 GeV, discrepancy even more pronounced in $\Delta\phi$ distributions

Similarly as for γ-tagged correlations excess (depletion) of low (high) momentum particles measured

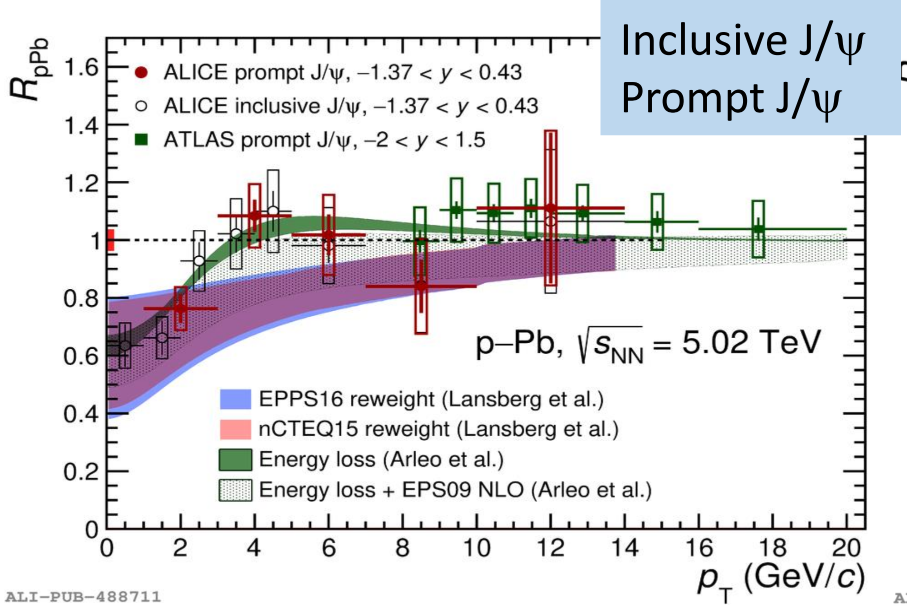
Need to improve medium response

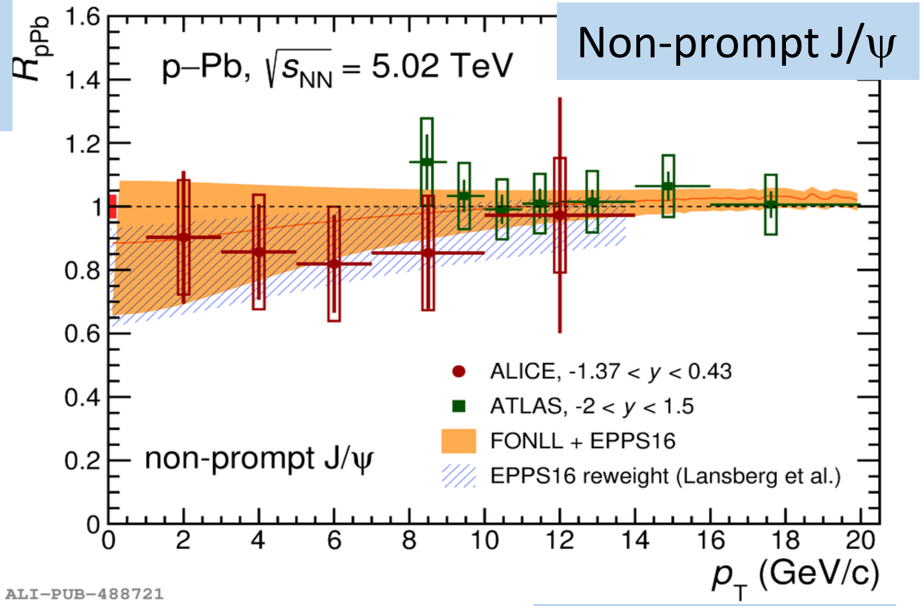
CMS-PAS-HIN-19-006, ATLAS-CONF-2019-052

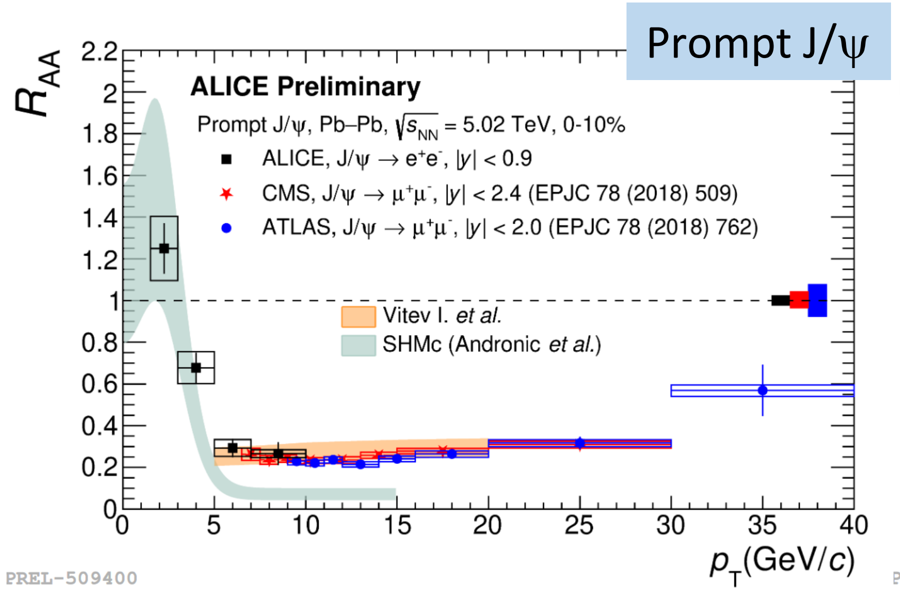
J/ψ production in pPb and PbPb collisions

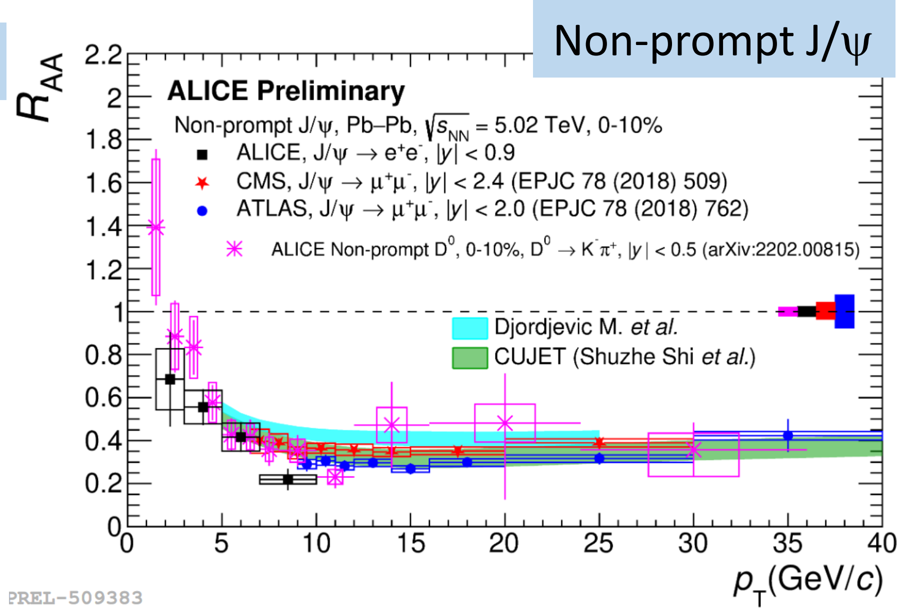
H. Sharma (ALICE) Sat 11:15

ALICE, JHEP06 (2022) 011
ATLAS, EPJ C78 (2018) 171









Cold nuclear matter effects?

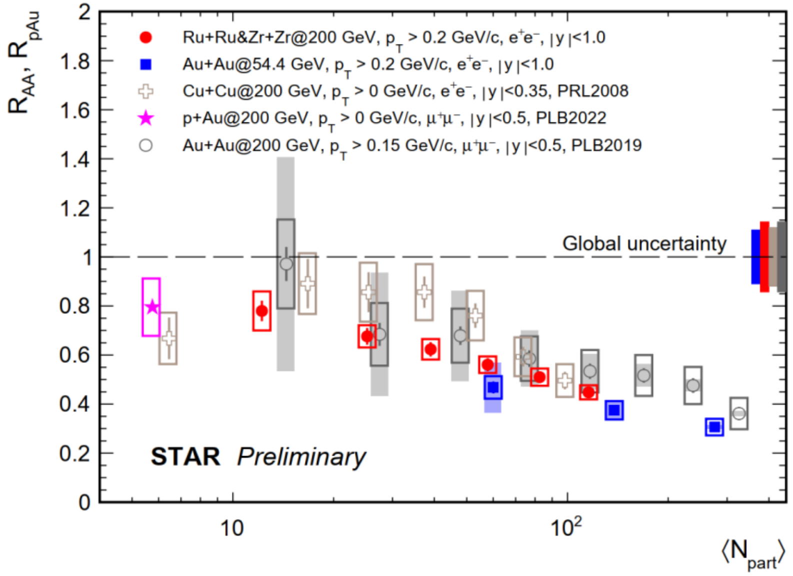
- hints of CNM for prompt compared to non-prompt J/ψ at low p_T
- models including CNM effects (E-loss and nuclear shadowing) describe the data

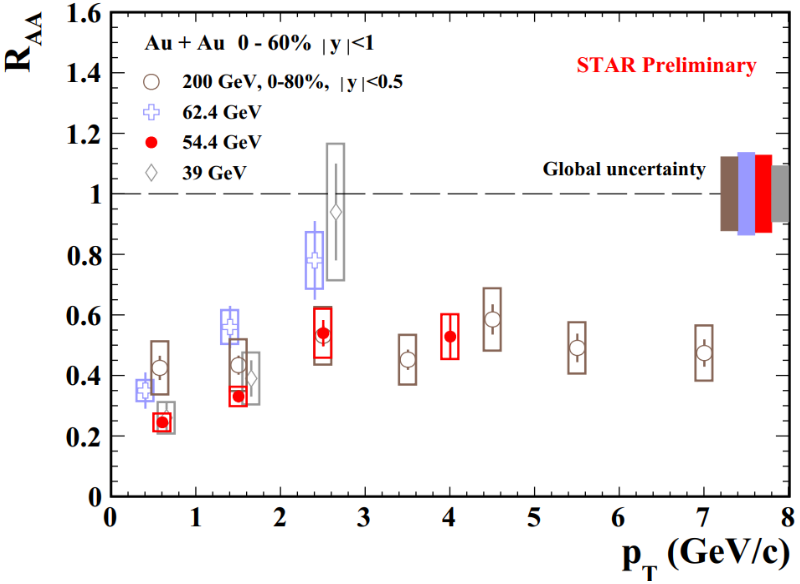
Hot medium effects?

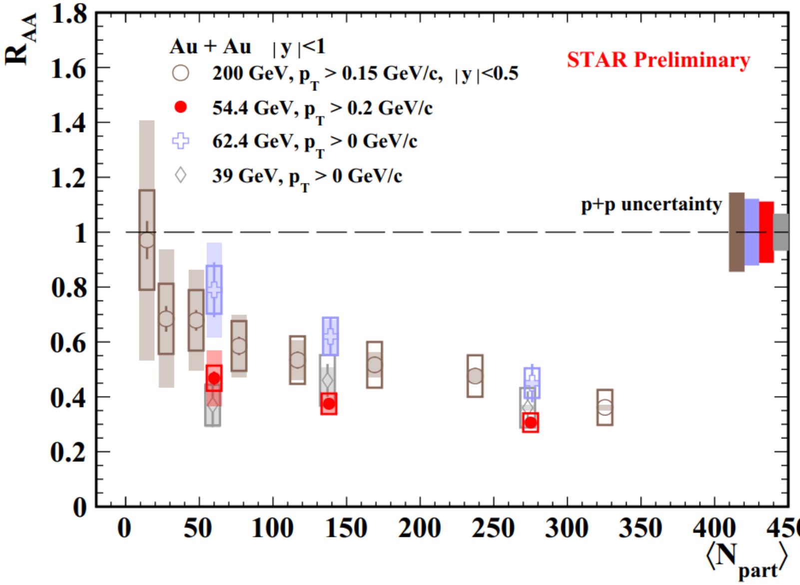
Prompt J/ψ: dissociation and regeneration of quarkonia needed to describe data

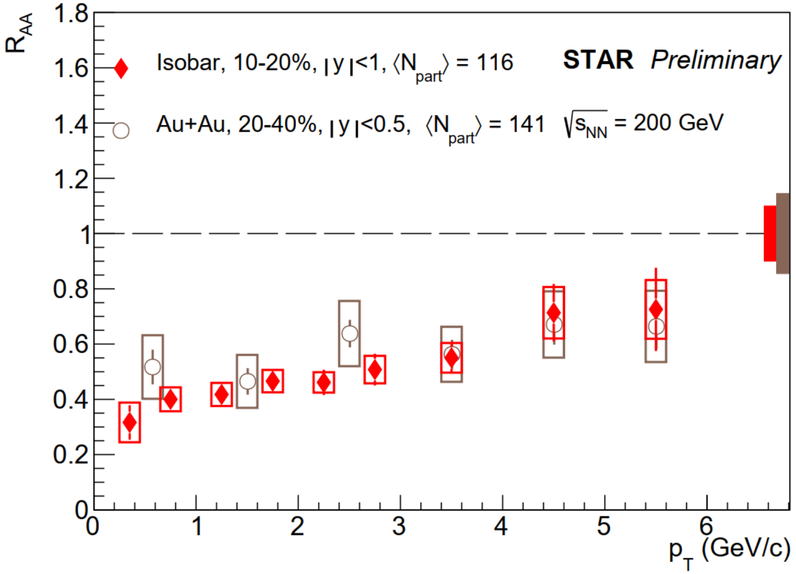
Non-prompt J/ψ:
- consistent with R_{AA} of non-prompt D^0 (b-quark E-loss)
- models implementing collisional + radiative E-loss describe data

J/ψ production at RHIC vs LHC energy





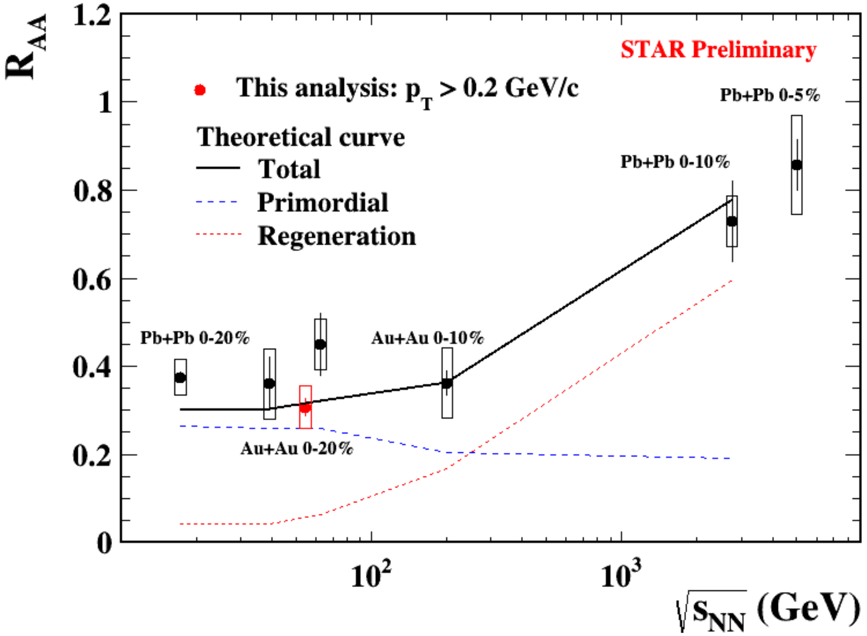




No significant energy dependence is observed from 39 - 200 GeV
54 GeV and isobar data at 200 GeV
Highest precision at RHIC to date

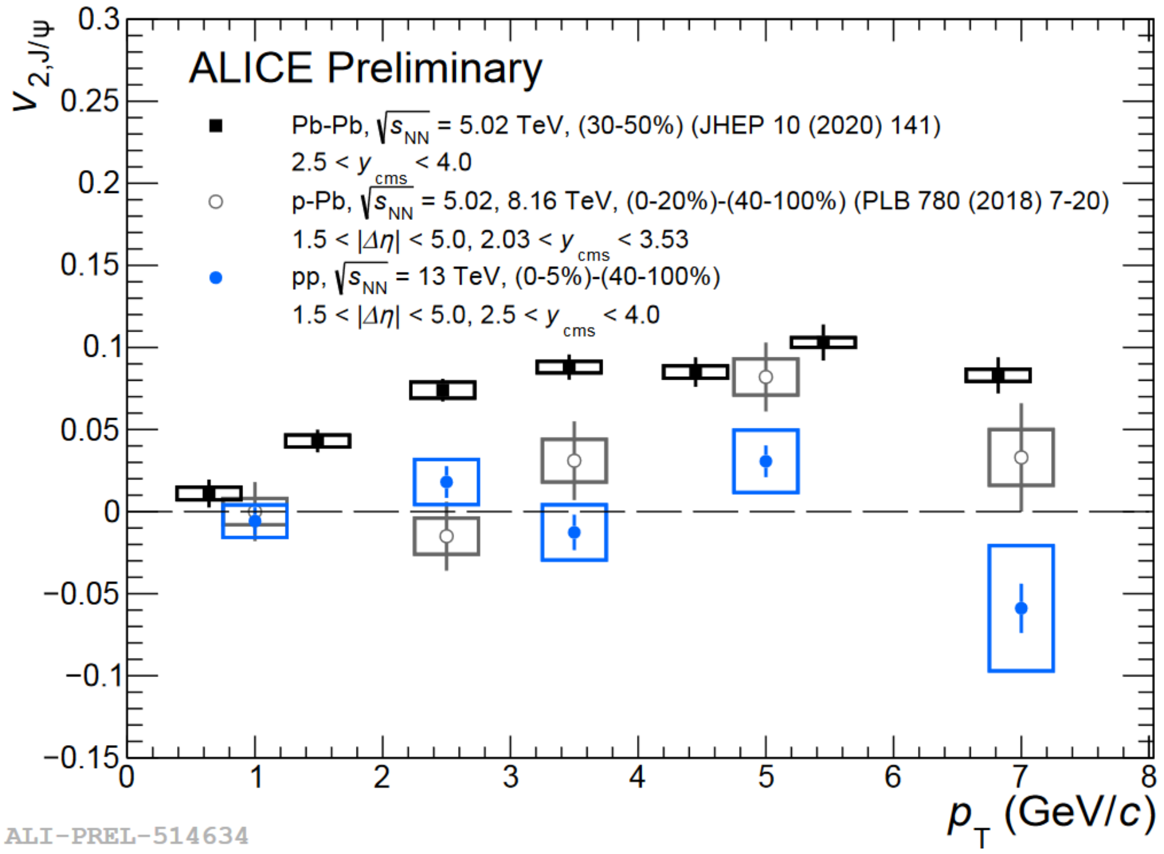
ALICE, PLB 734 (2014) 314
STAR , PLB 771 (2017) 13
STAR, PLB 797 (2019) 134917
ALICE NPA 1005 (2021) 121769

R_{AA} from RHIC to LHC



M. Coquet, ALICE, Sat 11:15

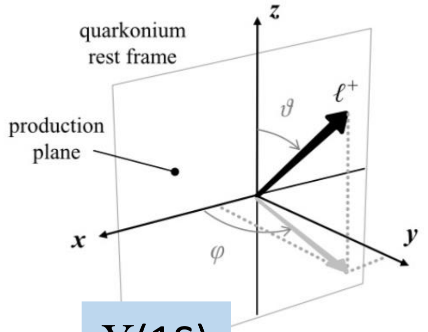
J/psi flow pp, pPb, PbPb



Polarization of quarkonia

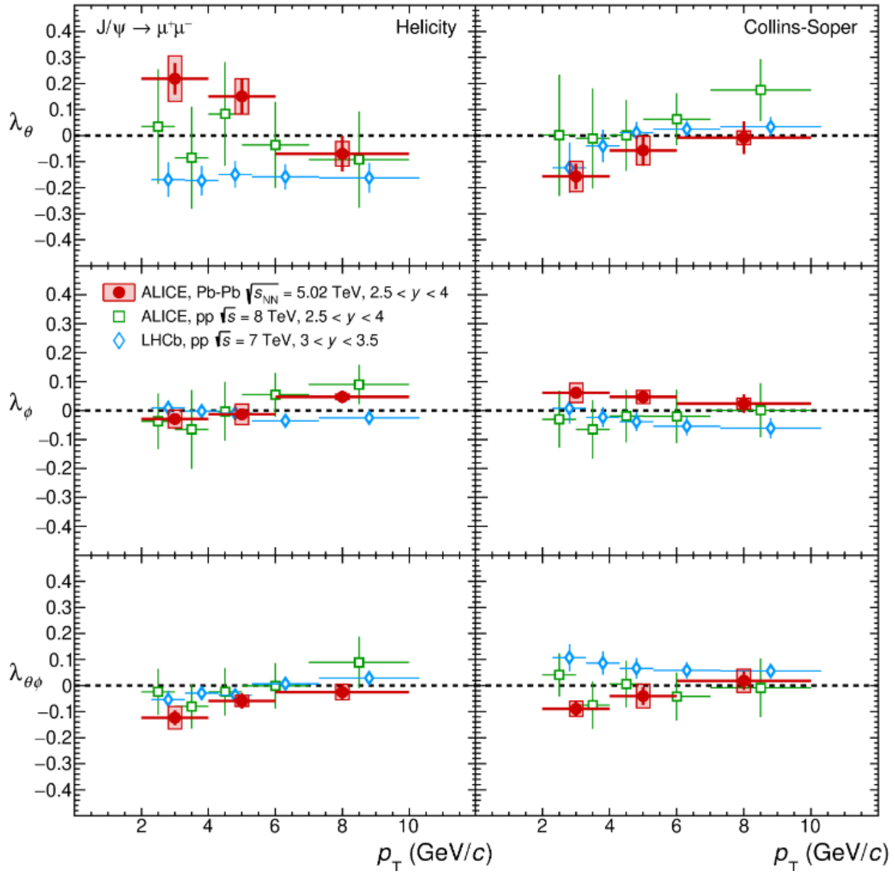
Y. Ding (ALICE)
Sat 10:10

quarkonium polarization is sensitive to its production mechanisms



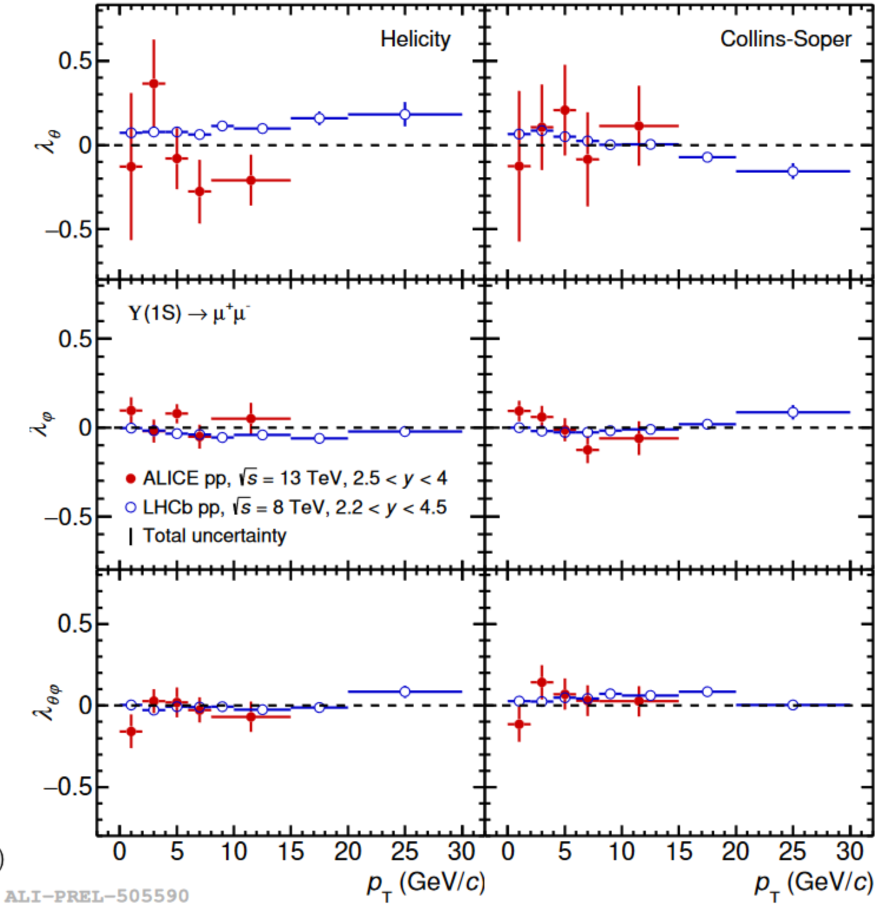
$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta} \times \left(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta\cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right)$$

J/ψ



ALICE, PLB 815 (2021) 136146

Υ(1S)



LHCb, JHEP 12 (2017) 110

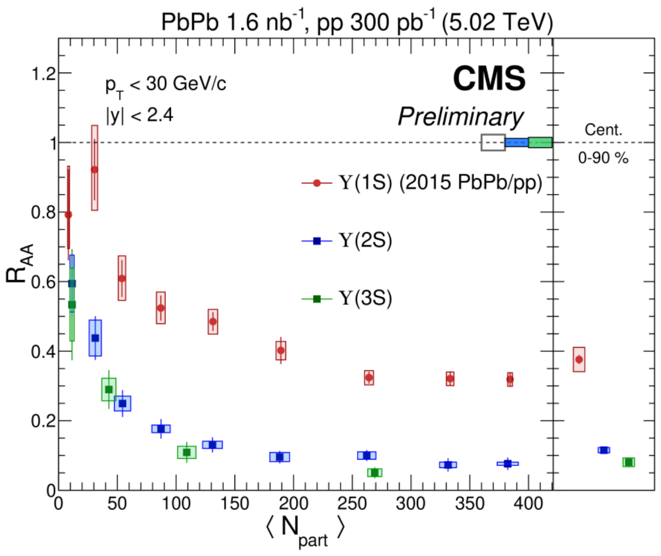
J/ψ: no sizable polarization observed in pp and PbPb collisions

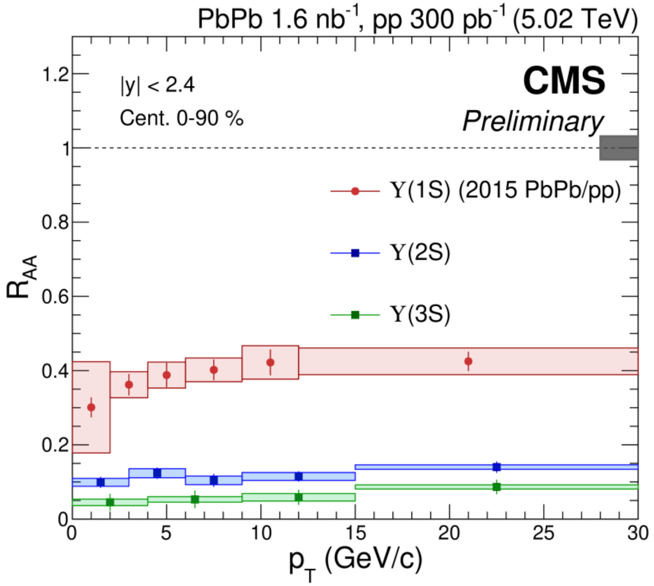
ALICE: PRL 108 (2012) 082001
EPJC 78 (2018) 562
LHCb: EPJC 73 (2013) 2631
CMS: PLB, 727 (2013) 381

First measurements of Υ(1S) in pp:
- good agreement of ALICE and LHCb
- qualitatively described by **NLO NRQCD** calculations

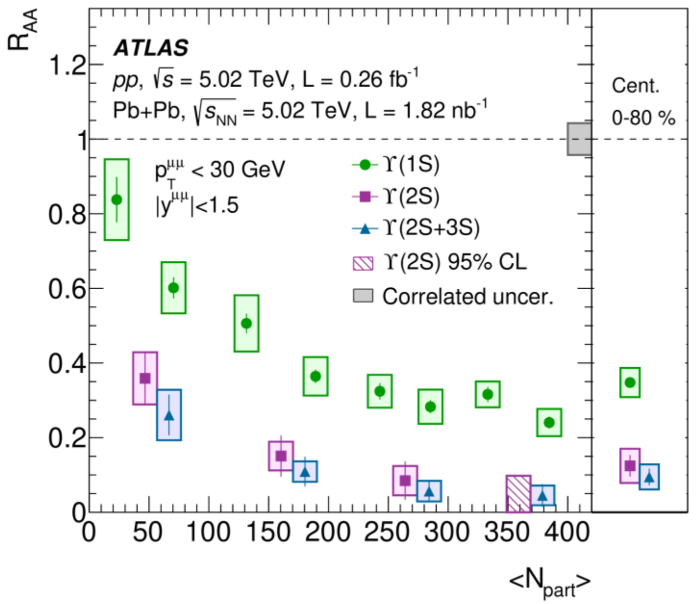
M. Butenschoen et al., PRL 108 (2012) 172002

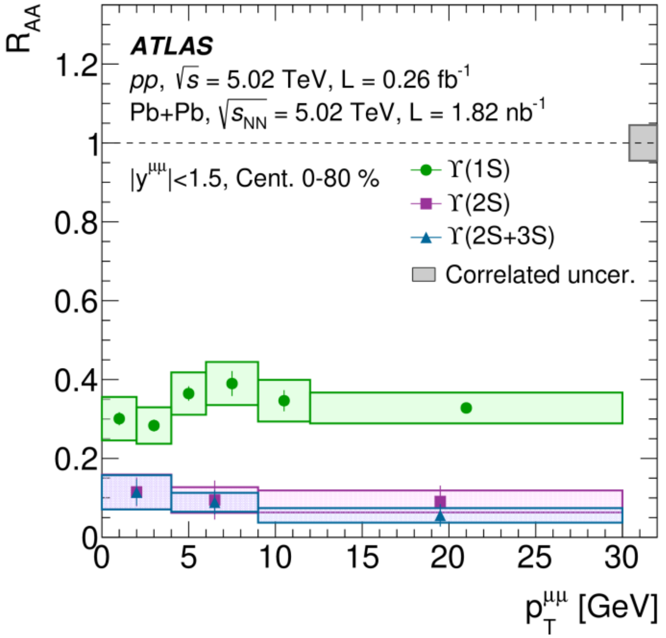
Upsilon melting: CMS vs ATLAS





CMS HIN-21-007





ATLAS, arXiv:2205.03042