Experimental overview on hard probes and quarkonium

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Terzo Incontro di Fisica con Ioni Pesanti alle Alte Energie 2021

Padova - November the 25th 2021

Experimental overview on hard probes (including quarkonium)

Dipartimento Interateneo di Fisica
Michelangelo Merlin

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INFN

Outline:
- introduction
- hard probes
  - electromagnetic (EM) probes
  - jets
  - open and hidden heavy flavour (HF)
- conclusions/outlook

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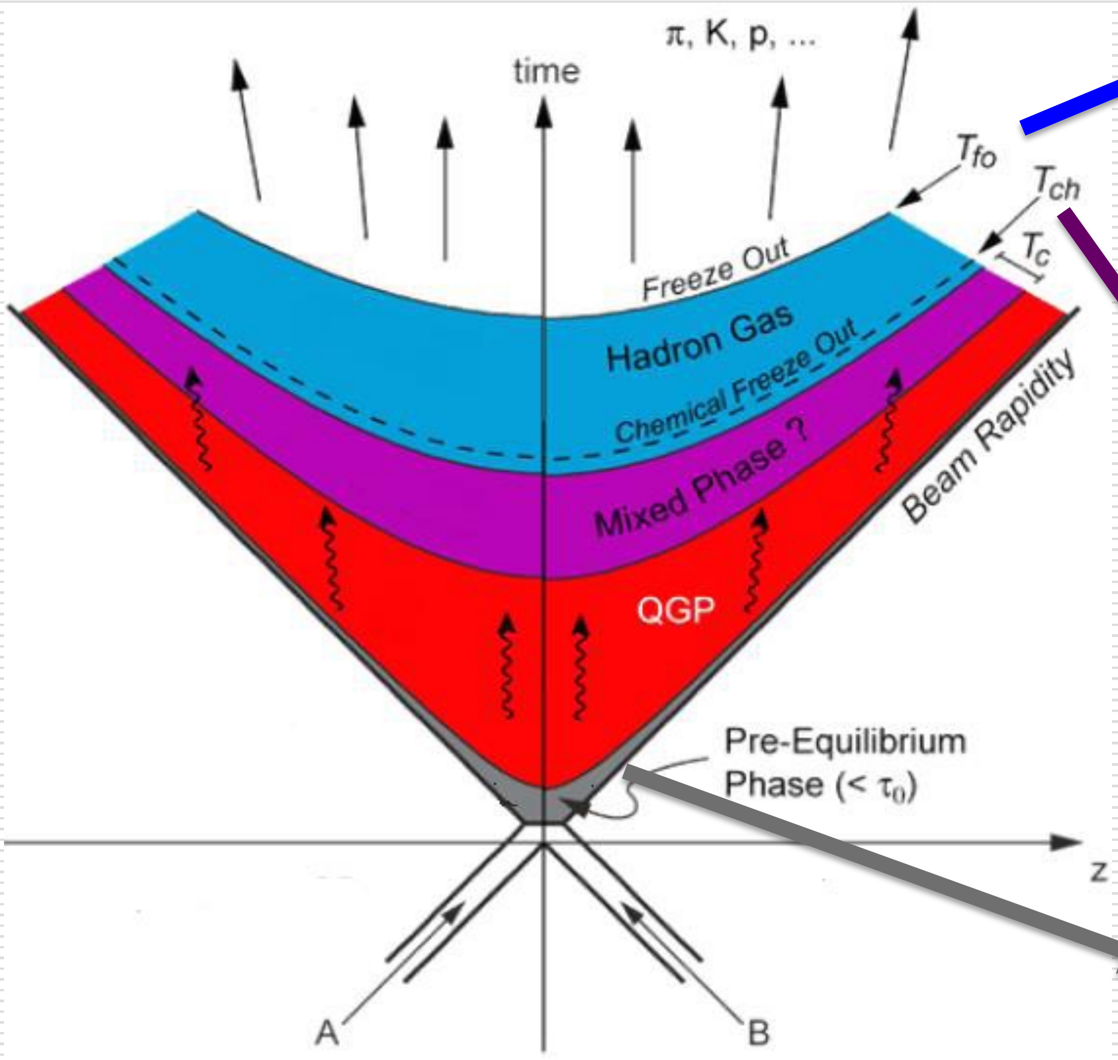
- hard probes
  - electromagnetic (EM) probes
  - jets
  - open and hidden heavy flavour (HF)
- conclusions/outlook

Very broad list

→ Personal selection on a few items likely not discussed in other talks

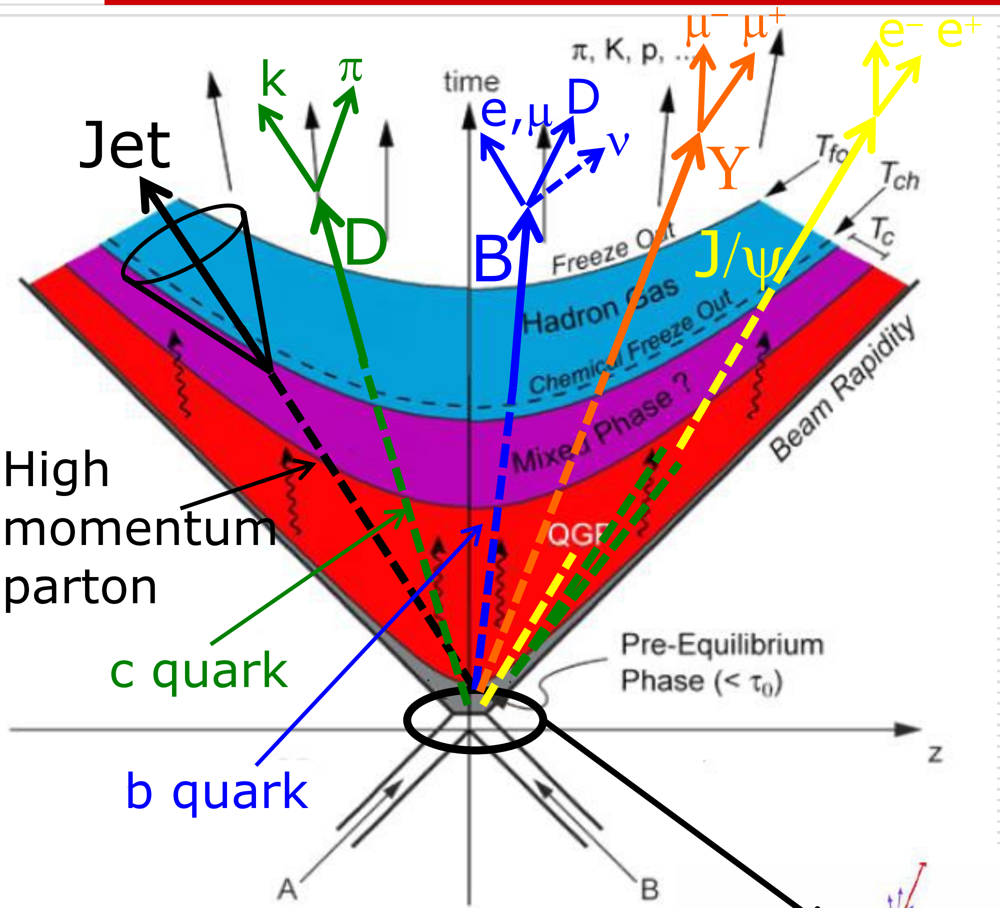
Padova - November the 25th 2021

Space time evolution of A-A collision

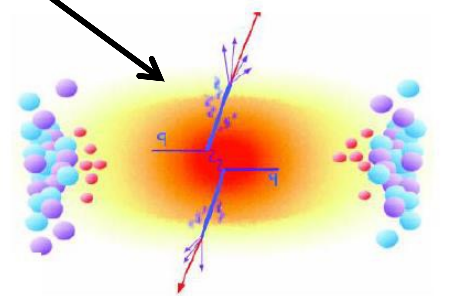


- Thermal freeze-out
  - Elastic interactions cease
  - Particle dynamics ("momentum spectra") fixed
  - T_{fo} ~ 110-120 MeV
- Chemical freeze-out
  - Inelastic interactions cease
  - Particle abundances ("chemical composition") are fixed
  - T_{ch} ~ 155 MeV
- Thermalization time
  - System reaches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

Hard probes of A-A collision

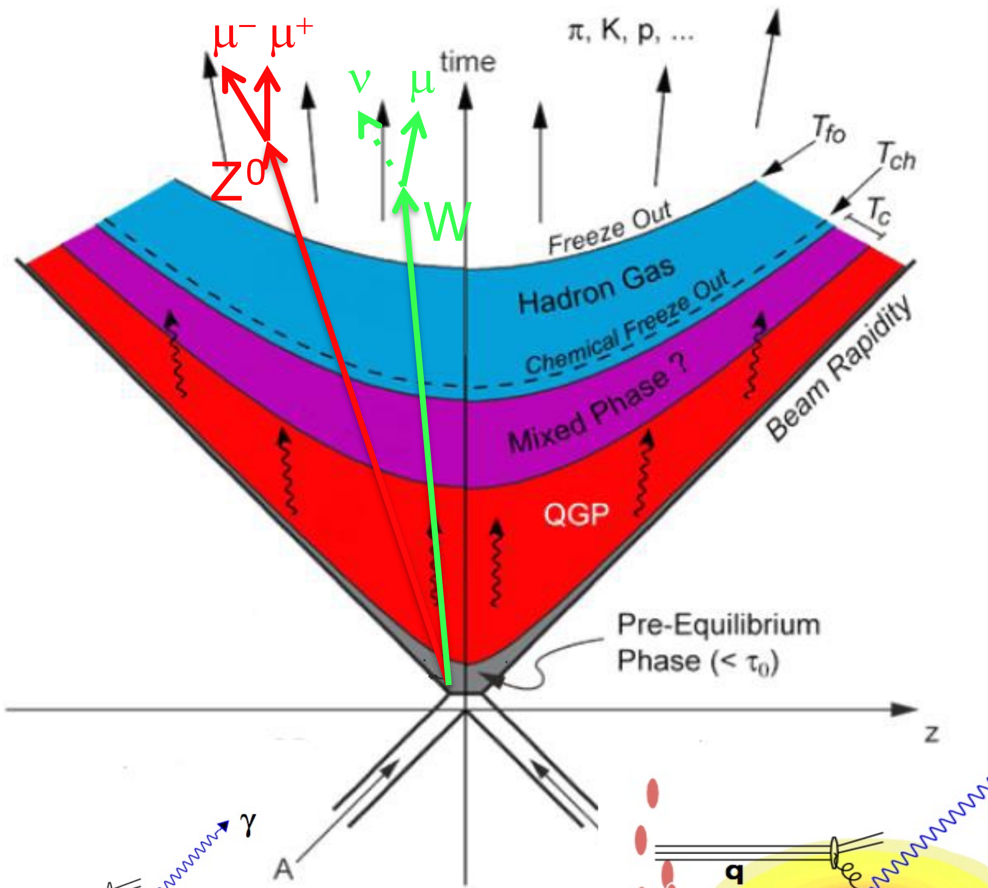


$$\tau_f = \frac{\hbar}{m_T}$$



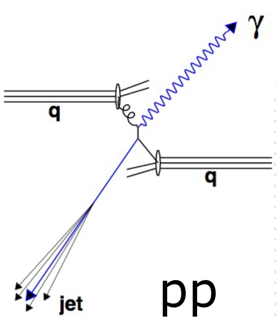
- Hard probes in nucleus-nucleus collisions:
  - produced at the very early stage of the collisions in partonic processes with large Q^2
  - pQCD can be used to calculate initial cross sections
  - traverse the hot and dense medium
  - can be used to probe the properties of the medium

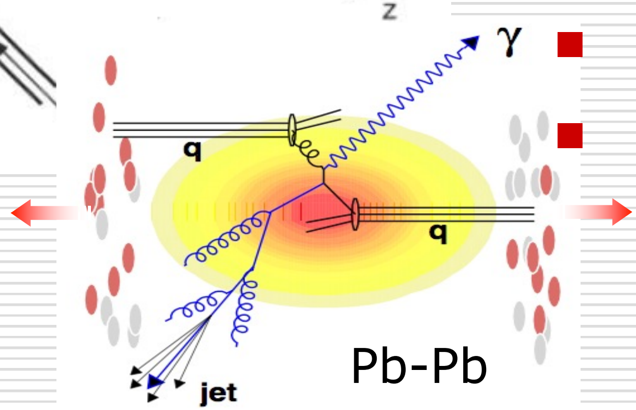
Electromagnetic probes



- Electromagnetic probes in nucleus-nucleus collisions
  - photons, W and <u>Z bosons</u>, ~~dileptons~~
  - do not carry a color charge
  - provide information about initial state / nuclear PDFs

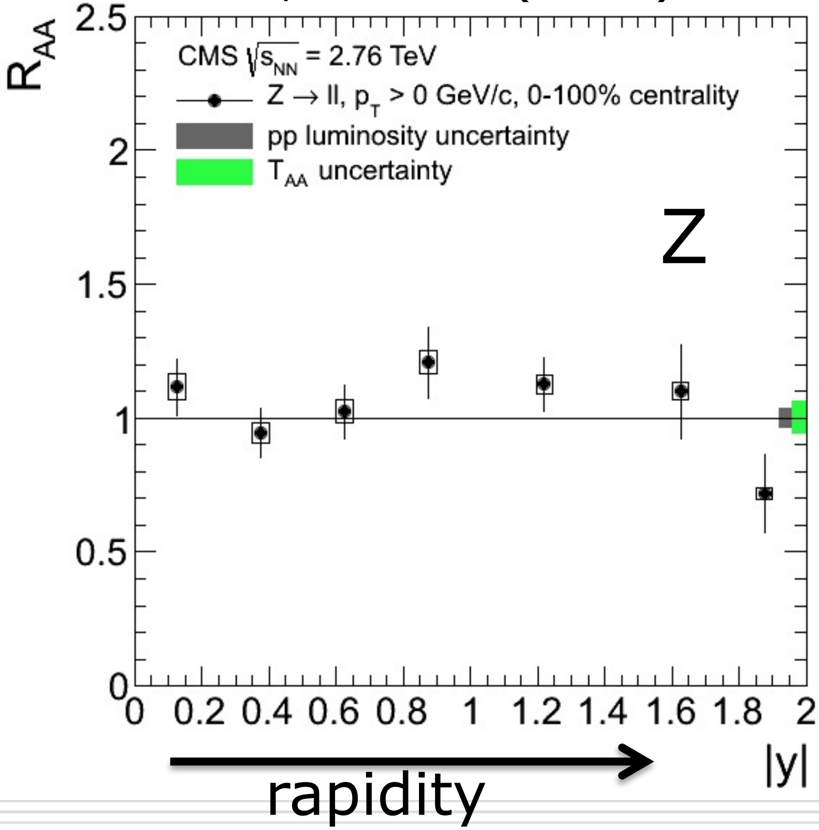
- Also, prompt photons or Z^0 to study the medium suppression:
  - Prompt photon and jet production follow the **pQCD**
  - Photons do not interact with the created medium (mfp~100 fm)
  - Jets (hadrons) are sensitive to final state effects also.
  - Very precise measurement of the energy of the outgoing parton from the hard scattering



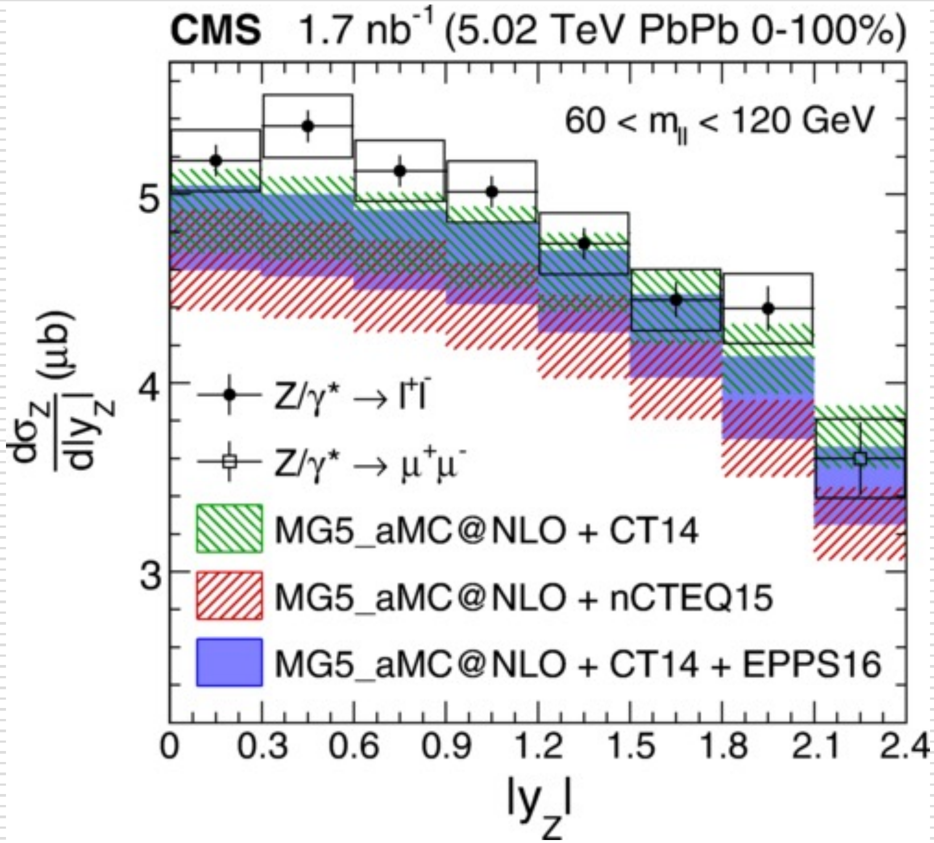


EM probes: from “control experiment” to “constrainer” of initial conditions

CMS, JHEP03 (2015) 022



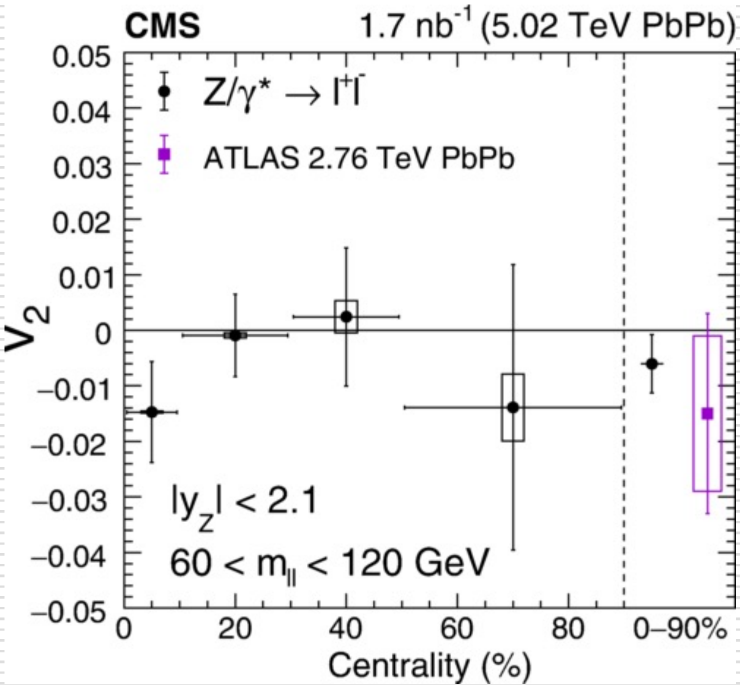
PRL 127 (2021) 102002

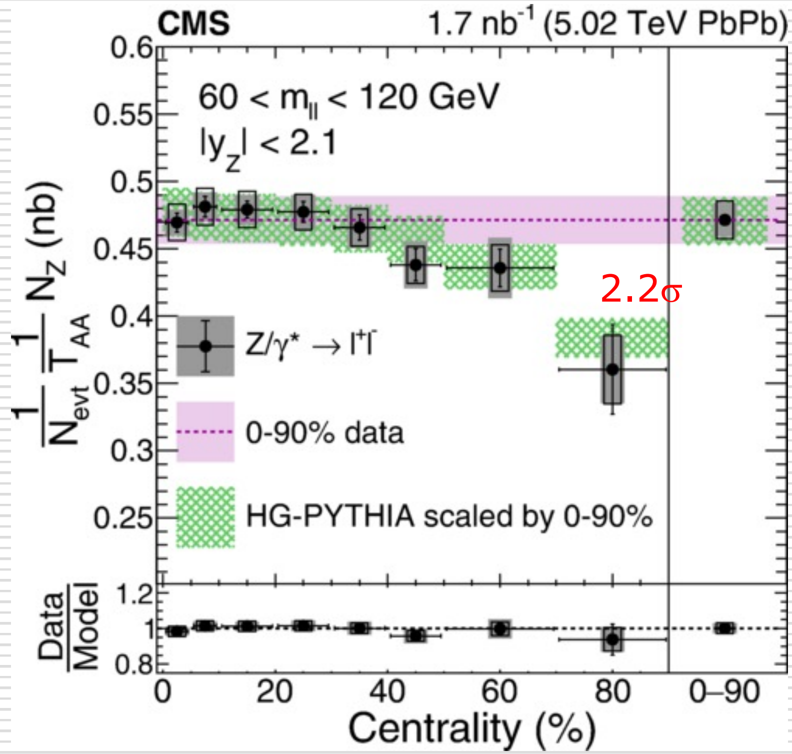


MadGraph5_aMC@NLO

Z^0 boson in Pb-Pb

PRL 127 (2021) 102002

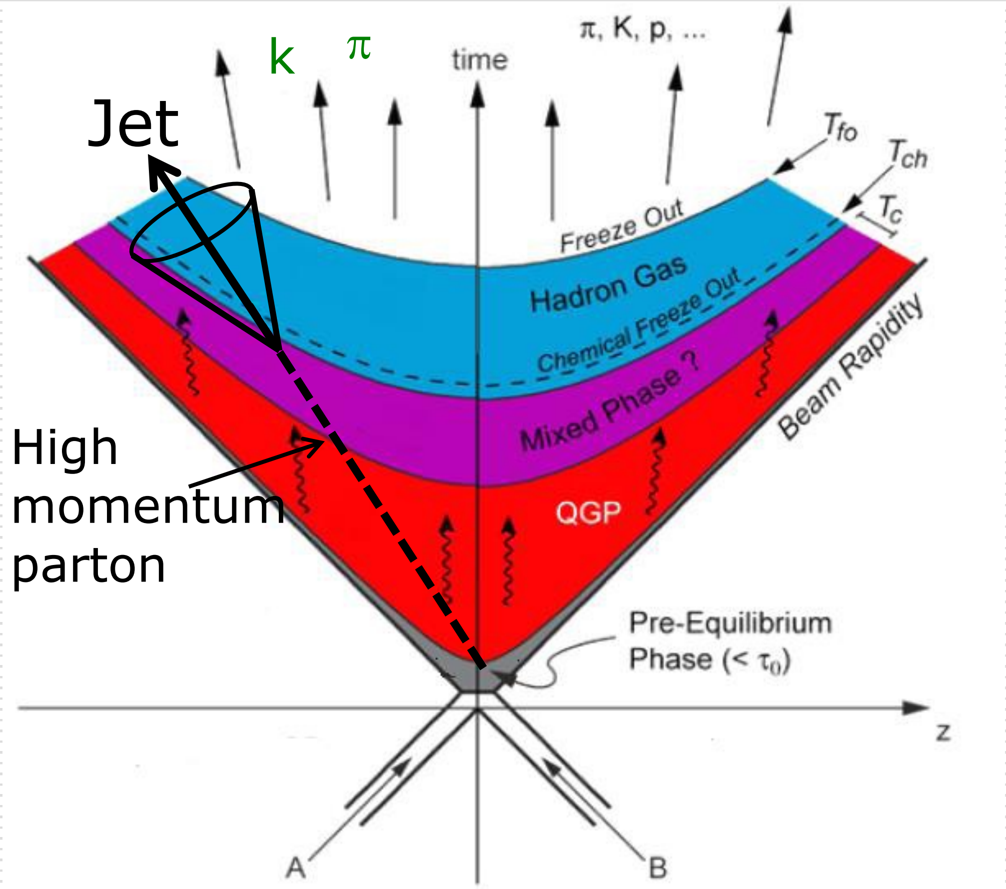


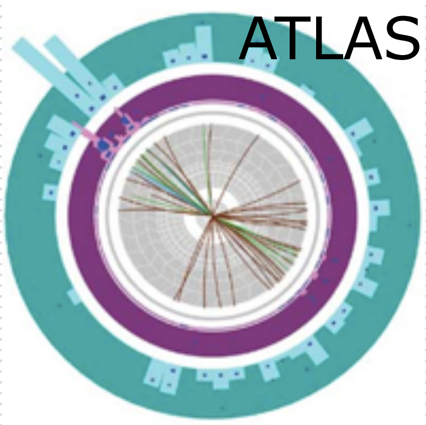


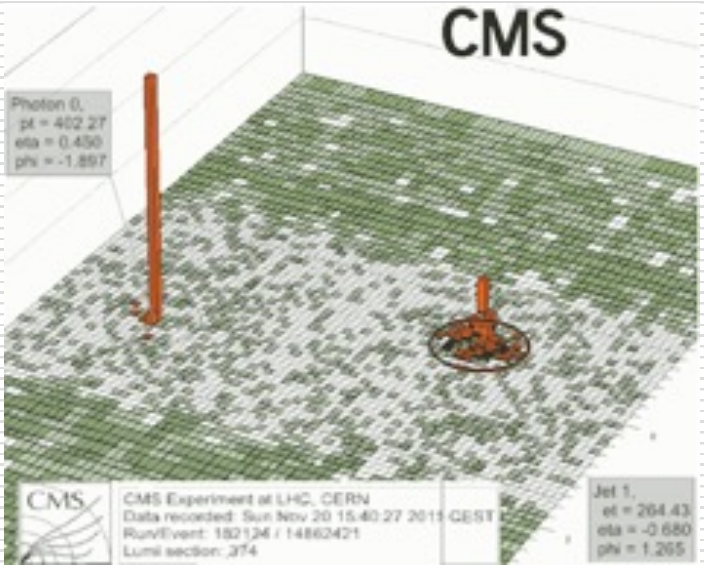
- V_2 consistent with 0
→ unaffected by final-state effects such as hydrodynamic flow and energy loss

- Depletion not expected by final state interactions
→ Initial-state geometry ?
→ centrality selection in peripheral collisions ?

JETS

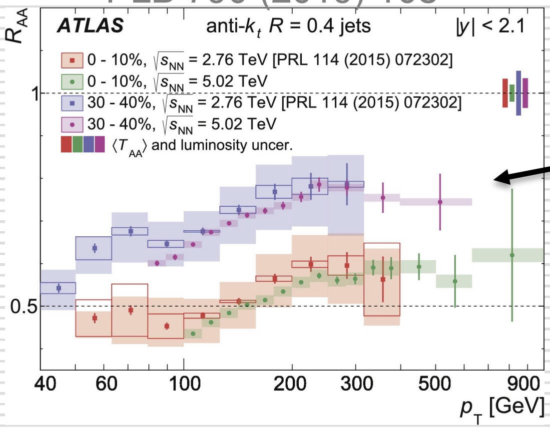

Jet
k
π
time
π, K, p, ...
T_{fo}
T_{ch}
T_c
Freeze Out
Hadron Gas
Chemical Freeze Out
Mixed Phase ?
QGP
Beam Rapidity
High momentum parton
Pre-Equilibrium Phase (< τ_0)
z
A
B


ATLAS


CMS
Photon 0,
pt = 402.27
eta = 0.450
phi = -1.897
CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 20 15:40:27 2011 CEST
Run/Event: 182124 / 14862421
Lumi section: 374
Jet 1,
et = 264.43
eta = -0.680
phi = 1.265

Jets: what we expected and learned

PLB 790 (2019) 108

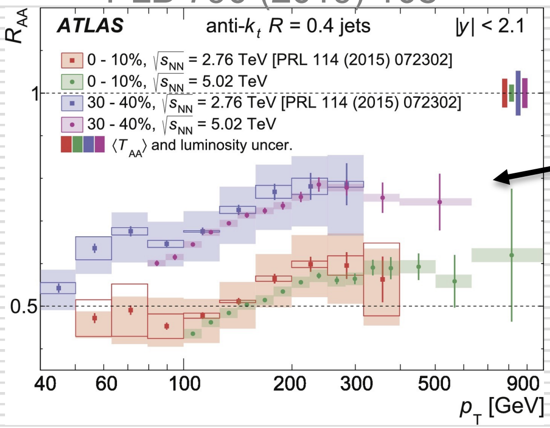


Jets are quenched in AA collisions

up to p_T =1 TeV

Jets: what we expected and learned

PLB 790 (2019) 108



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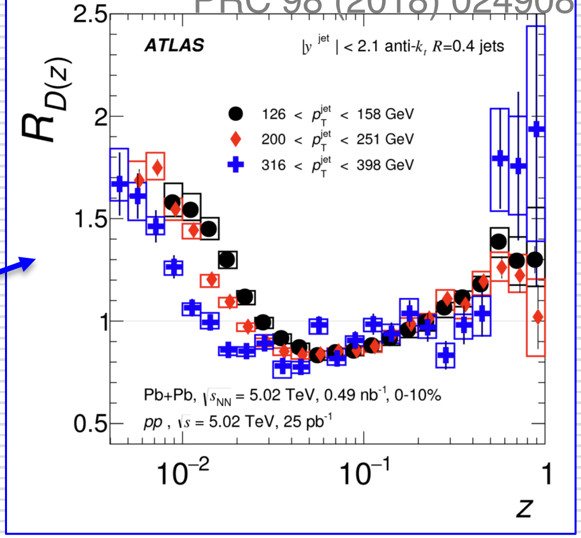
Jets in the medium appears softer

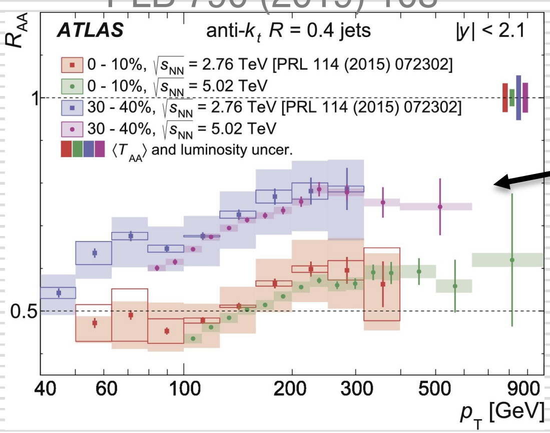
PRC 98 (2018) 024908



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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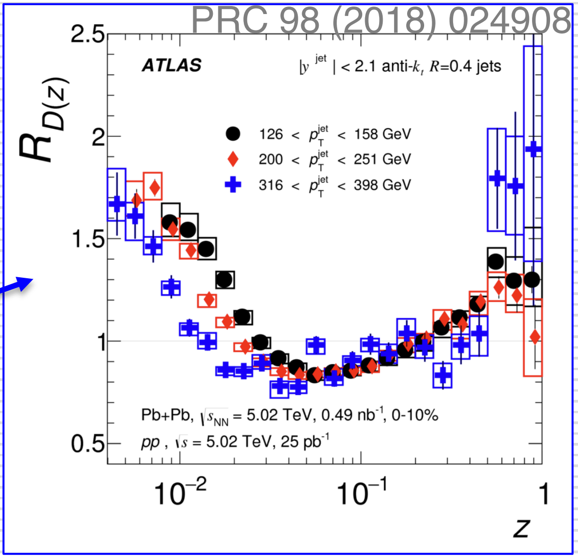
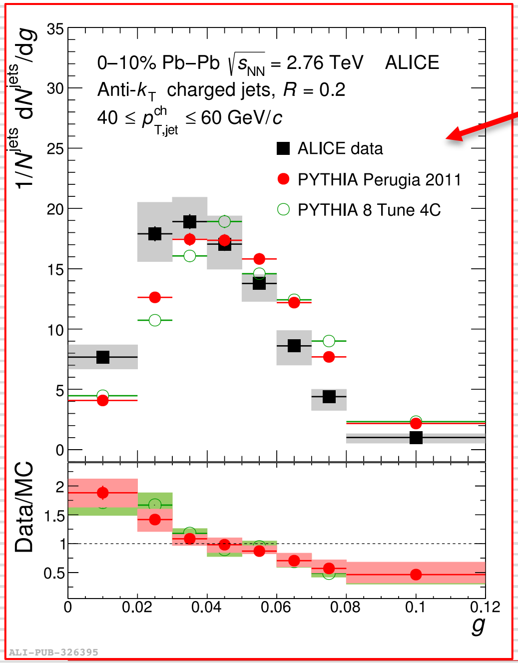




JHEP 10 (2018) 139

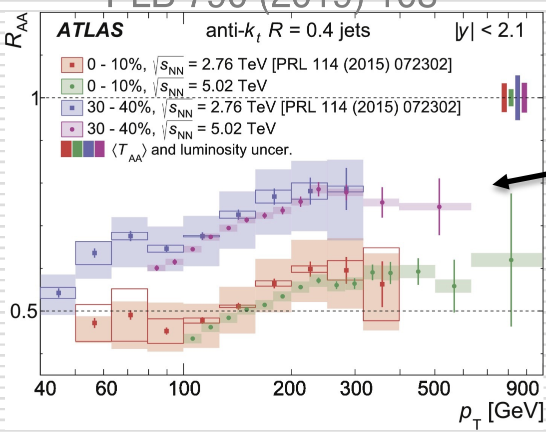
The hard core of the jets get narrower in the medium

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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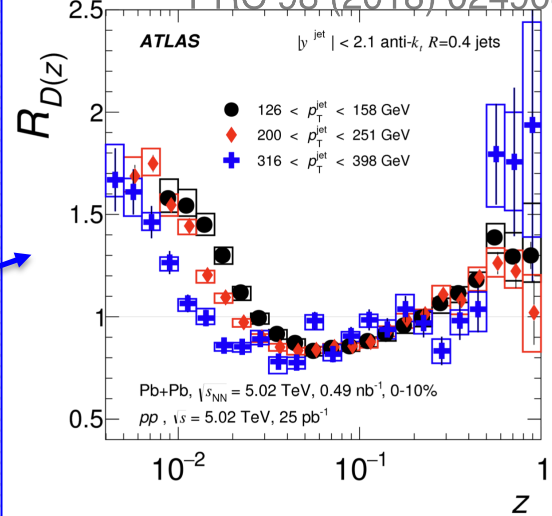

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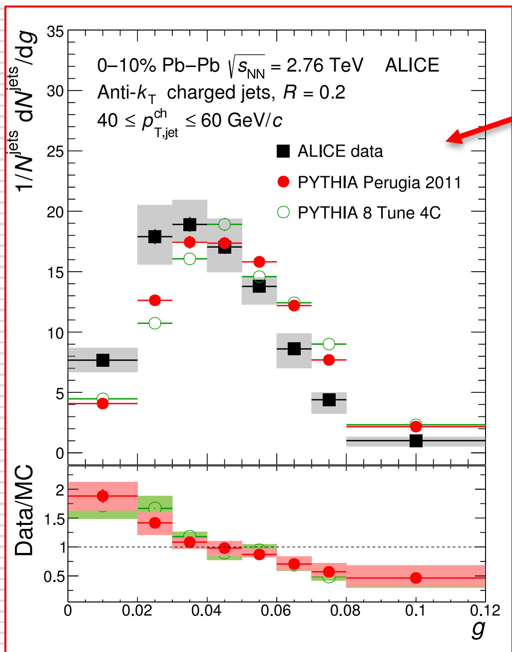
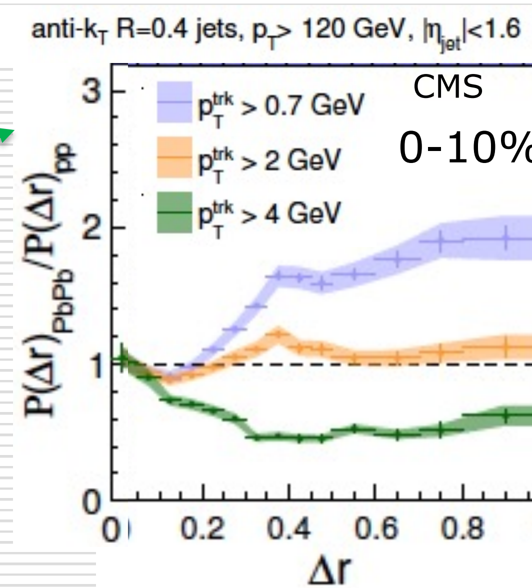


JHEP 10 (2018) 139

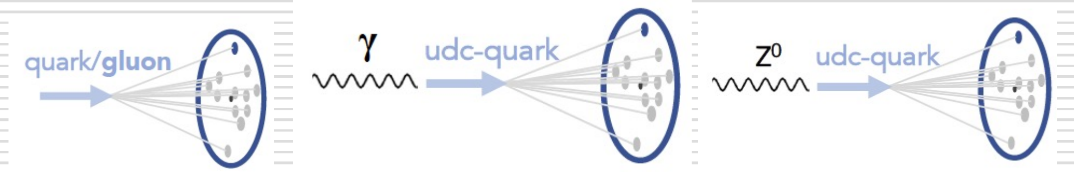
the soft part diffuses to large angles

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



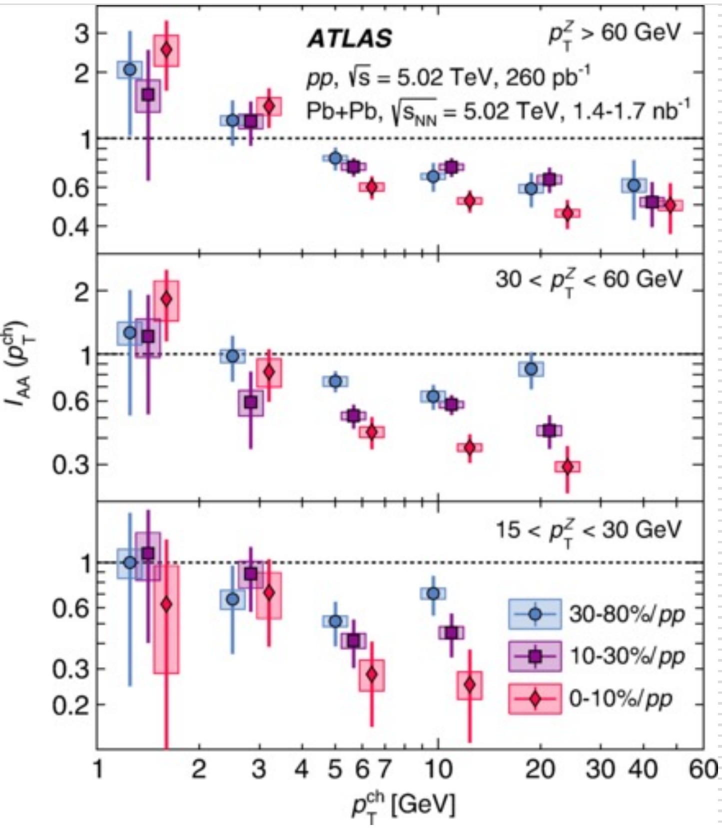
JHEP05 (2018) 006

Z tagged jets



$$I_{AA} = \frac{\left(1/N_Z\right)\left(d^2N_{ch}/dp_T^{ch}\Delta\phi\right)^{PbPb}}{\left(1/N_Z\right)\left(d^2N_{ch}/dp_T^{ch}\Delta\phi\right)^{pp}}$$

PRL 126 (2021) 072301

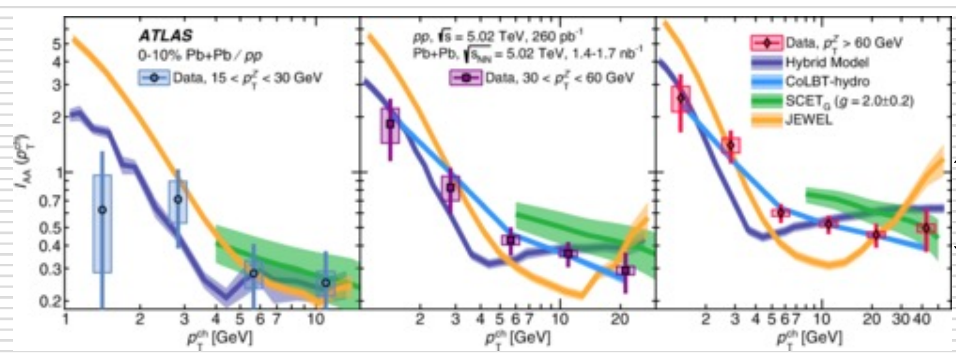


Z vs γ -tagged jets:

- both provide (@LO) the p_T and azimuthal direction of the partner hard-scattered parton
- At fixed p_T jets balancing Z and γ arise from different Q^2 values
  → sensitivity of the energy loss process to parton virtuality

The per-Z yields modified in PbPb compared to pp

- Softer p_T^{ch} distribution with suppression at high p_T^{ch} and enhancement at low p_T^{ch}
  - significant centrality dependence
- Hybrid model, JEWEL and COLBT catch the low p_T^{ch} increase only by including back-reaction, medium recoils, and jet-induced medium excitations (details in the back-up)



PRL 126 (2021) 072301

Jets with heavy flavour

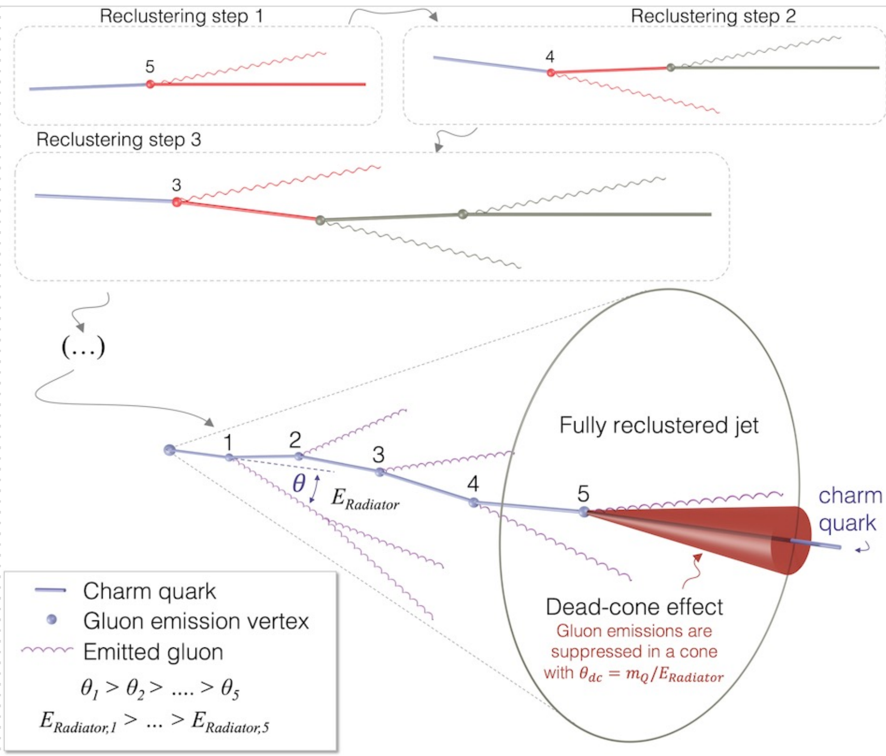
- ALICE quite competitive; covered by Marianna

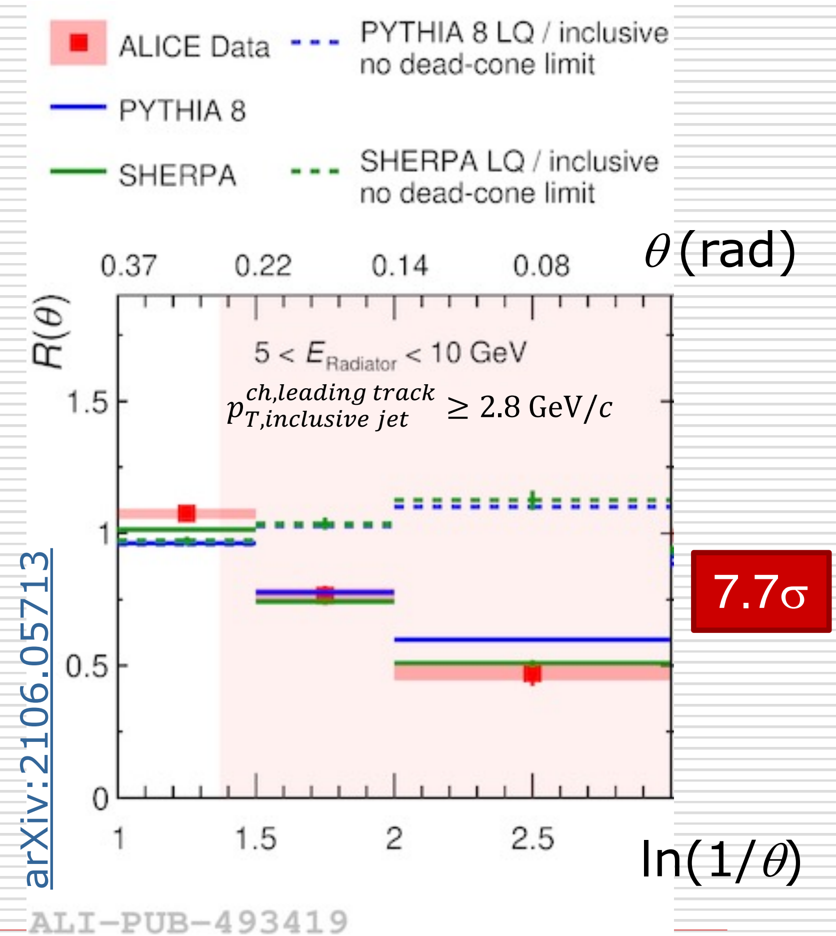
First direct observation of dead-cone effect in QCD (in pp)

QCD vacuum is not transparent →

Expectation: radiation suppressed for $\theta_c < \frac{m_Q}{E}$

$$R(\theta) = \frac{1}{N^{D^0 jets}} \frac{\mathrm{d}n^{D^0 jets}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{inc.jets}} \frac{\mathrm{d}n^{inc.jets}}{\mathrm{d}\ln(1/\theta)}$$





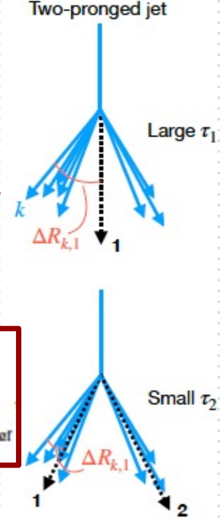
7.7σ

First measurements of N-subjettiness in AA

$$\tau_N = \frac{1}{p_{\mathrm{T,jet}} \times R} \sum_k p_{\mathrm{T},k} \, \mathrm{minimum}(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{\mathrm{N},k})$$

Suppression of combinatorial jets with data driven method

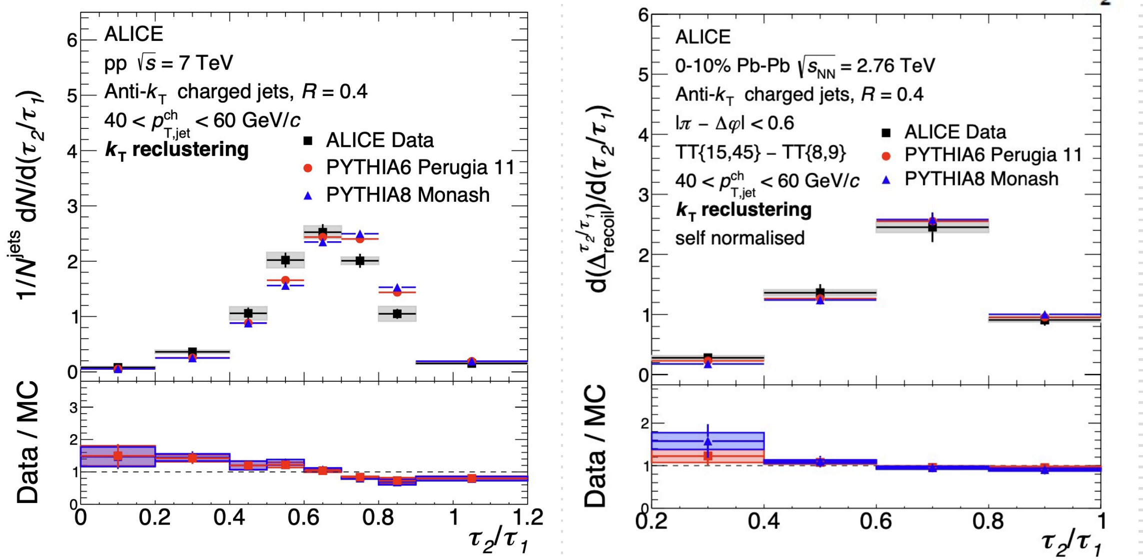
$$\Delta_{\mathrm{recoil}}^{\tau_2/\tau_1} = \frac{1}{N_{\mathrm{trig,Sig}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\tau_2/\tau_1}\bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT_{Sig}}} - \frac{1}{N_{\mathrm{trig,Ref}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\tau_2/\tau_1}\bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT_{Ref}}}$$



motivations:

- τ_2/τ_1 sensitive to the rate of two-pronged jet substructure
- two-prongness of jets might be sensitive to coherence effects in the QGP
  - if resolved by the medium, these jets should lose more energy than jets with energy flow in a single core

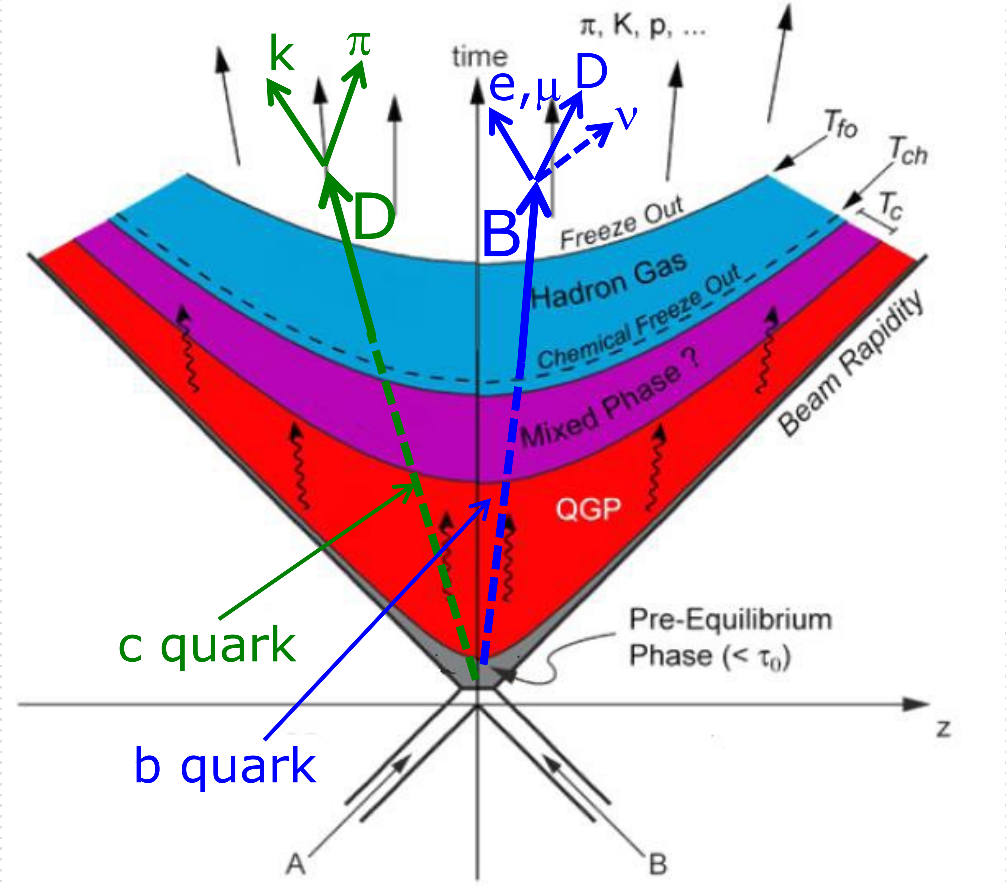
arXiv:2105.04936



- ☐ pp: important input for MC generators (observed a syst. shift)
- ☐ Pb-Pb: not yet <u>direct</u> indication of modifications in central collisions

→ Medium induced radiation may have slightly modified the structure

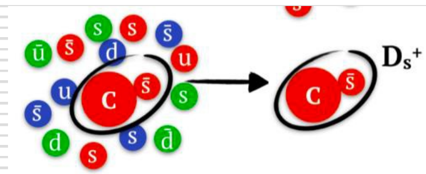
Heavy Flavour: open HF

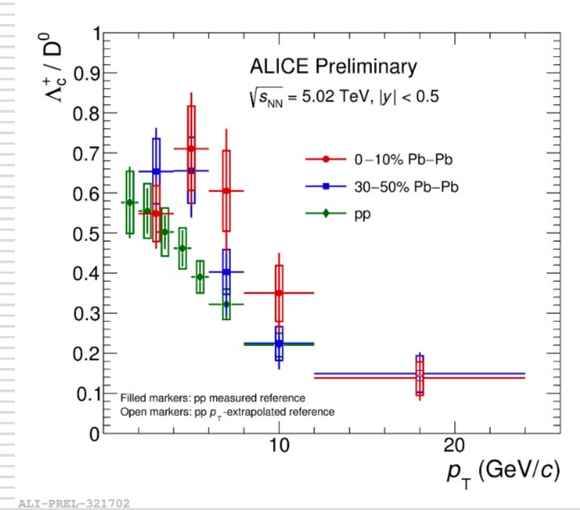


Heavy flavour: charm hadro-chemistry

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

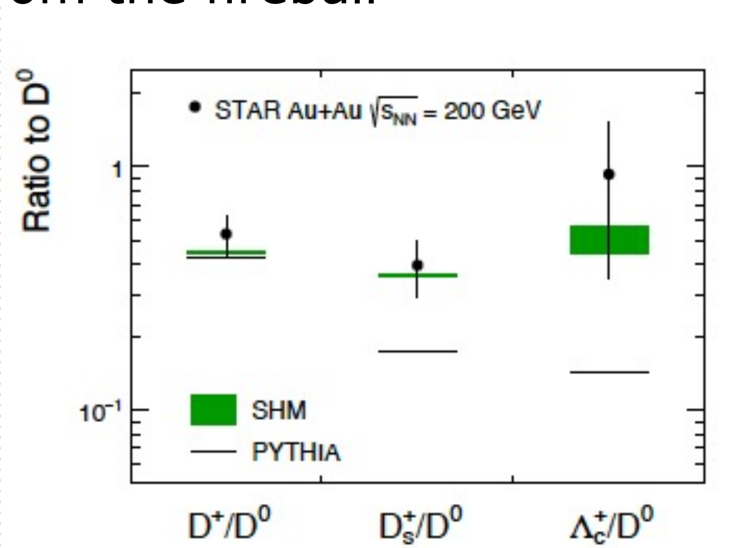
$$m_T = \sqrt{m^2 + p_T^2}$$

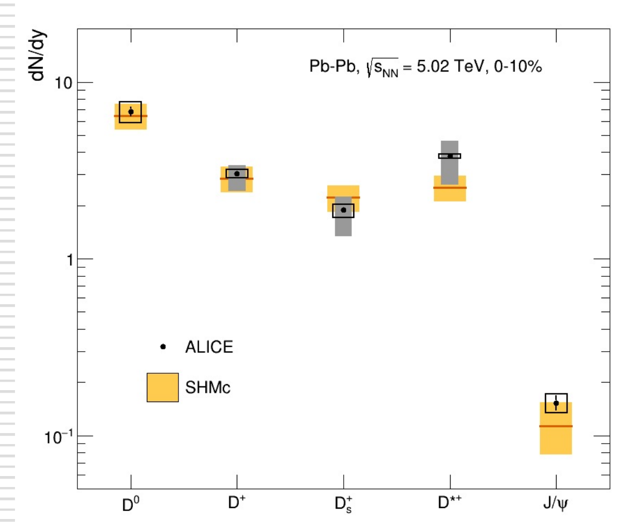




- $c\bar{c}$ (and $b\bar{b}$) pairs produced only initially in hard partonic scatterings (pQCD)
  - no sizeable thermal production at the LHC

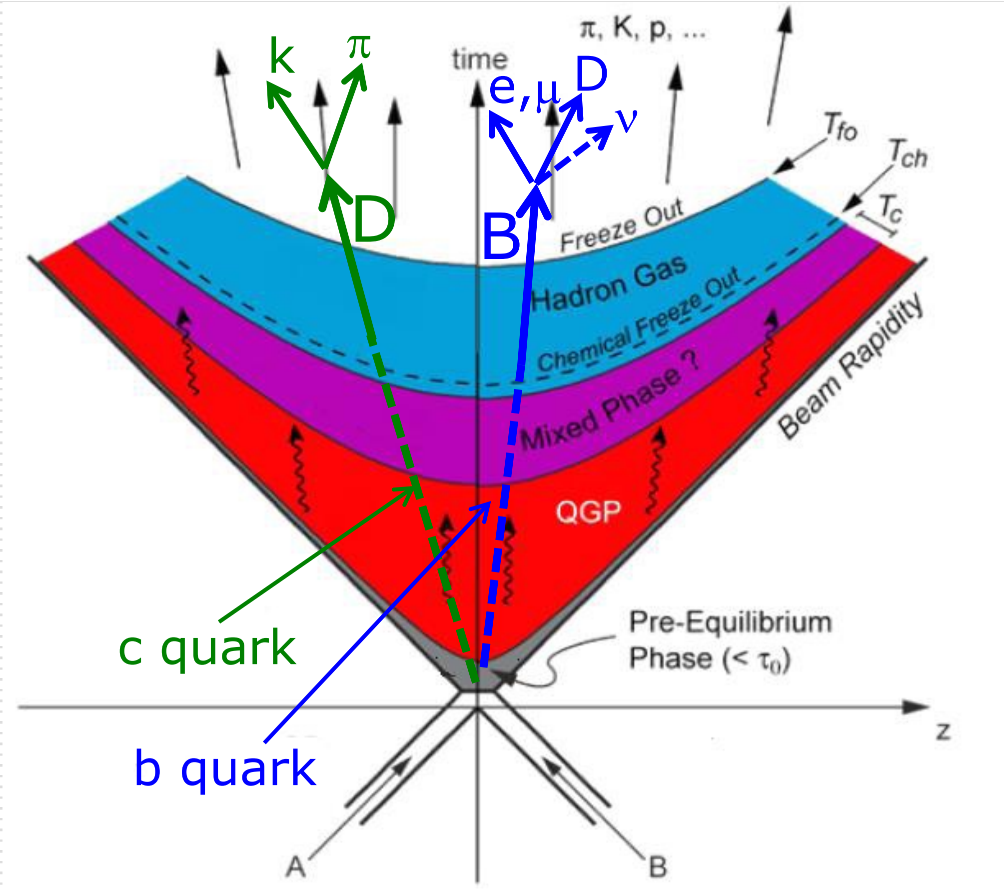
-> hadro-chemistry at the freeze-out reflects **how** these **quarks** have "**dressed**" while escaping from the fireball

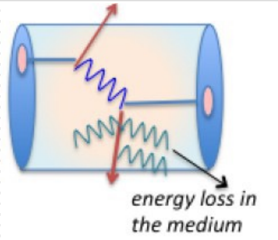




Discussed at length tomorrow

Heavy Flavour: open HF





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

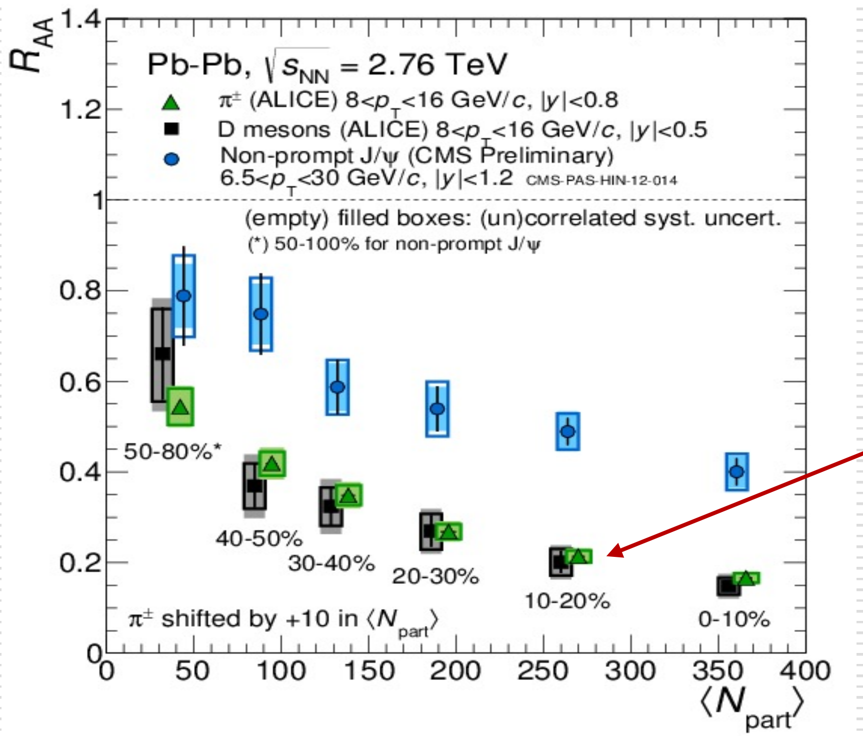
Naive expectation:
$R_{AA}(\pi) > R_{AA}(D) > R_{AA}(B)$?

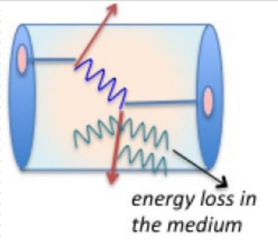
More complicated due to different production kinematics and fragmentation of light and heavy quarks

Heavy Flavour: open HF

Soon understood with LHC run1 data

HEP 11 (2015) 205, CMS-PAS-HIN-12-014





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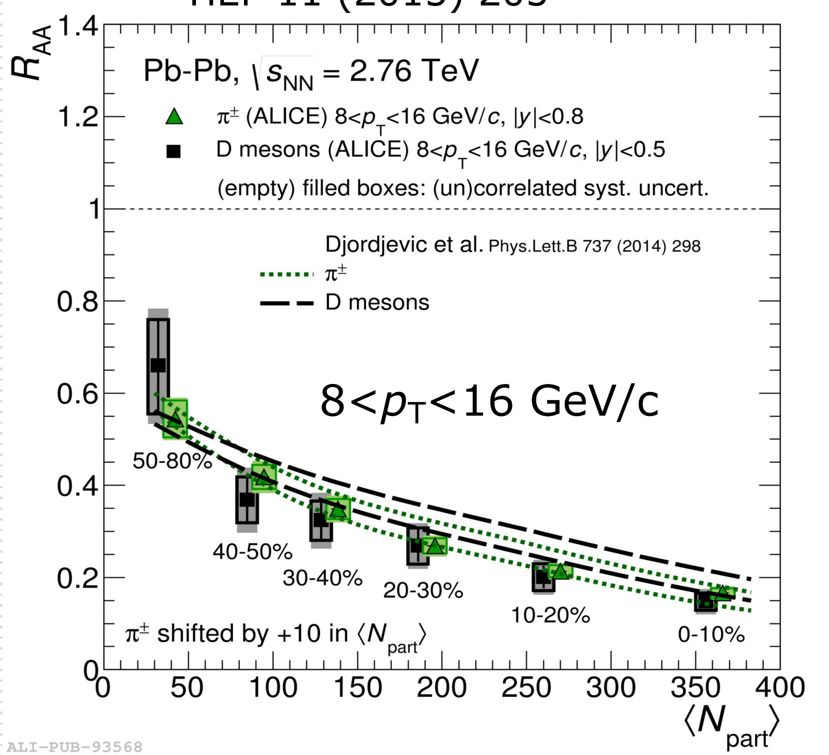

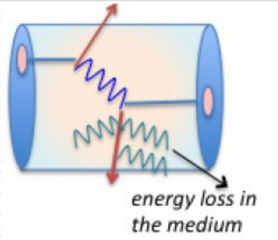

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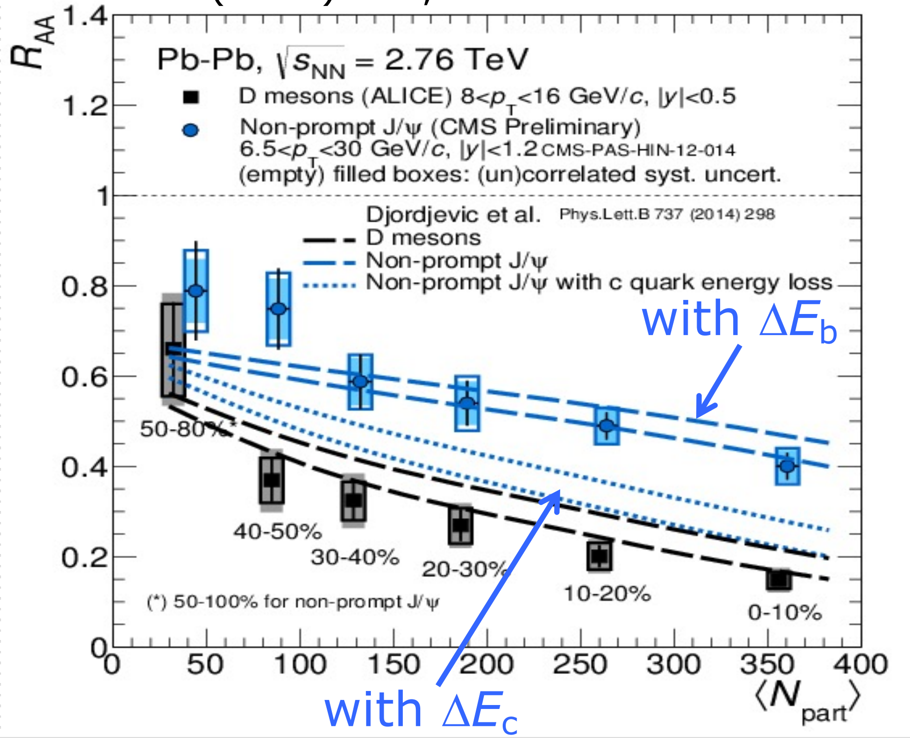

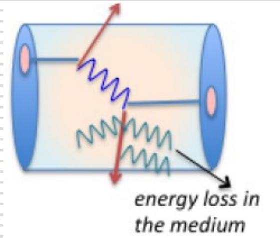

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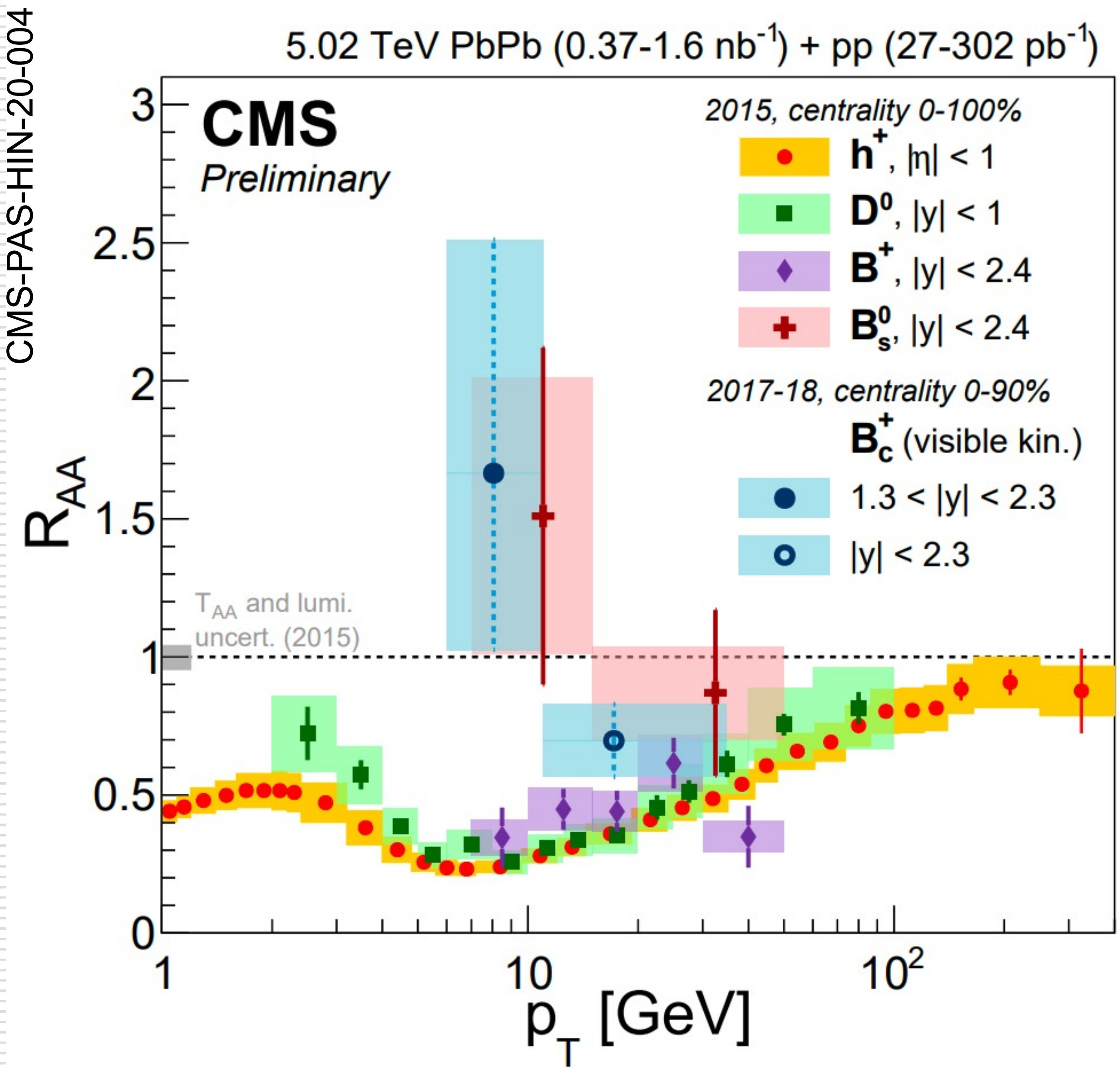
More complicated due to different production kinematics and fragmentation of light and heavy quarks

Spectacular performance of CMS

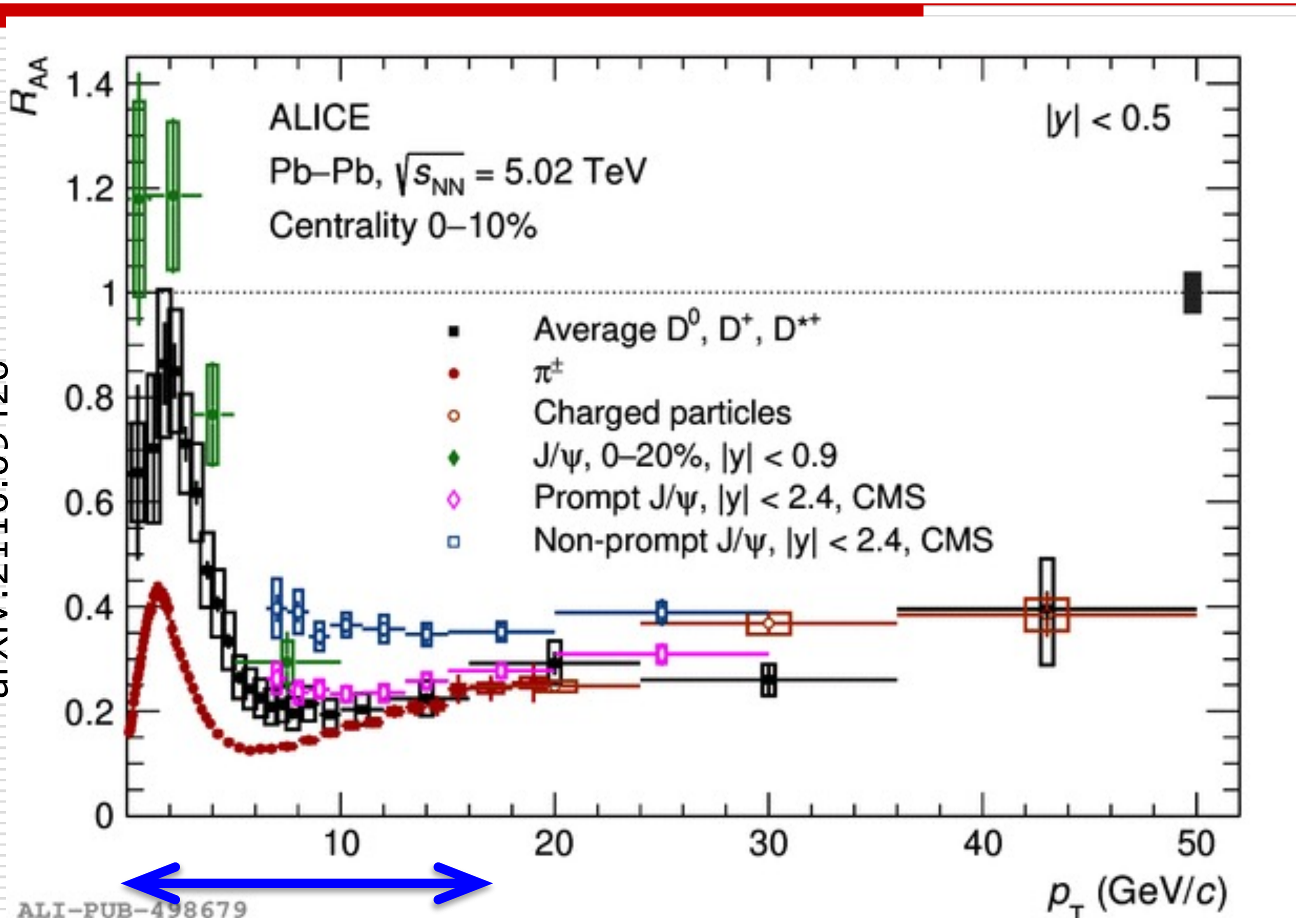
- First observation of B_c^+ production in heavy ion collisions!
- Similar suppression for B_s and B_c^+
  - B_c^+ p_T is partially reconstructed (tri-muon)
- At high p_T: R_{AA} of all flavor identified hadrons seem to converge above ~ 20-30 GeV

but …



… p_T range still drives the physics

arXiv:2110.09420



also for the v_2 observables

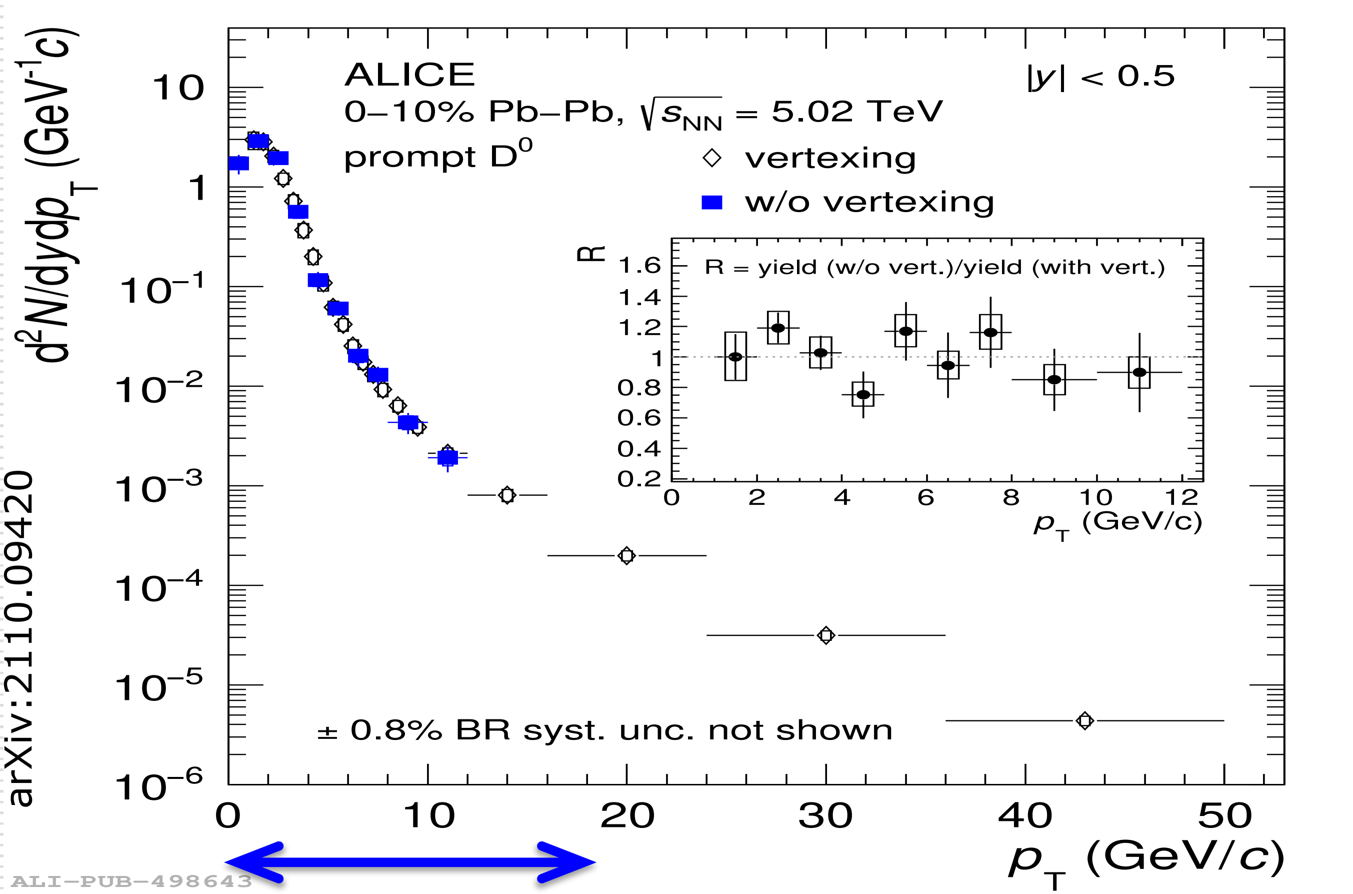
the lower the better !

Collisional dE/dx relevant

Radiative dE/dx dominates

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

… p_T range still drives the physics



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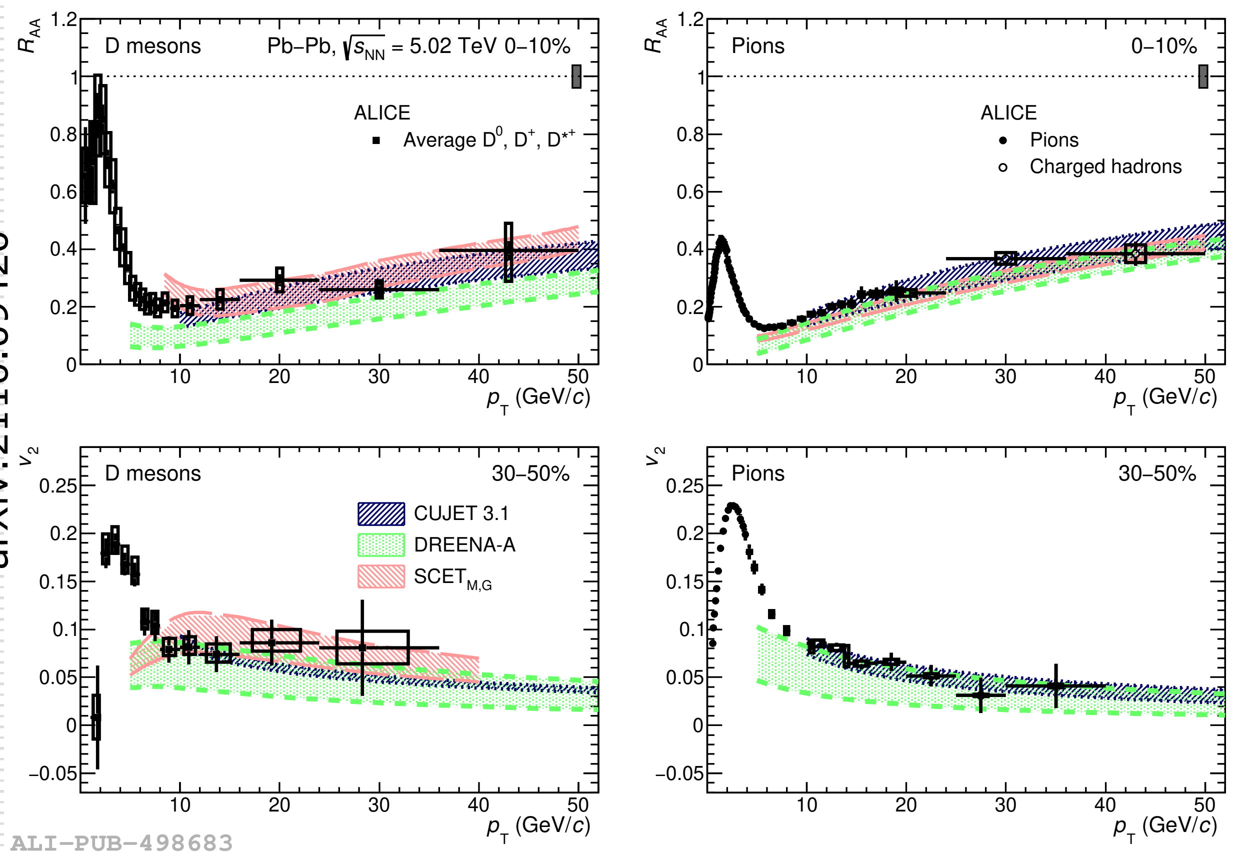
Prompt D mesons at high p_T

- Gluon radiation dominant energy loss mechanism
- Collective flow effects and modification to the hadronization mechanism negligible

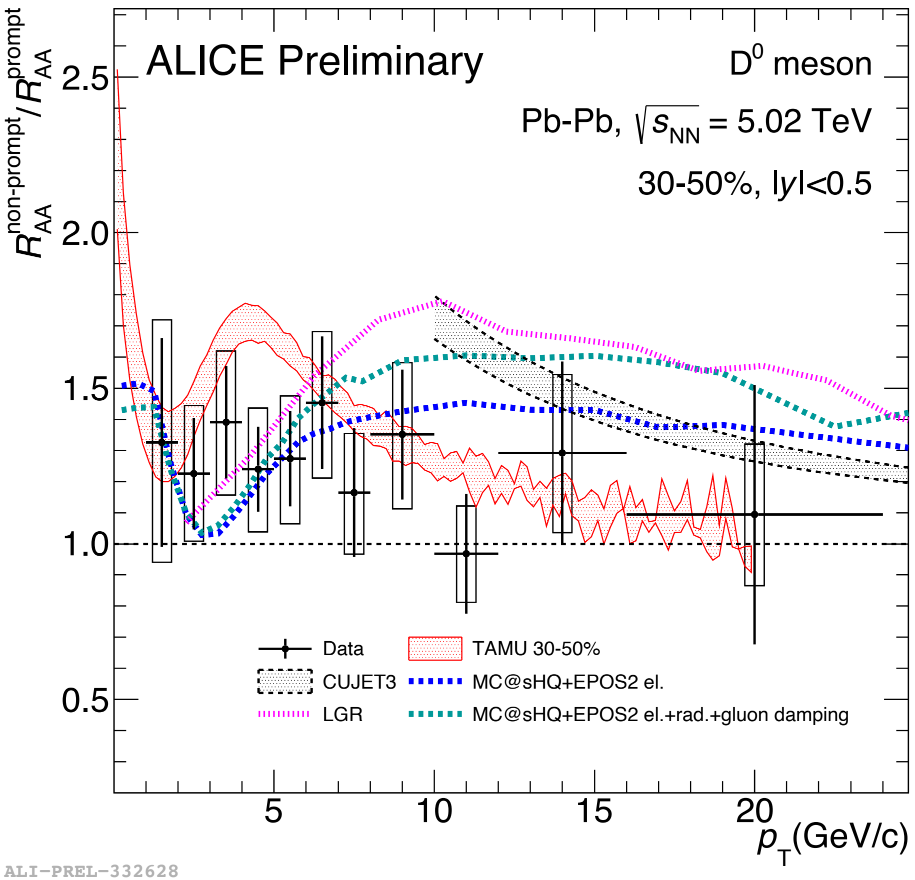
arXiv:2110.09420



The three models have different implementations of radiative energy loss with dependence on color charge, parton mass and path length in the medium

This is “state of the art” after LHC run1&run2

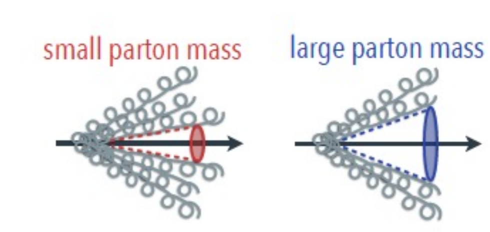
Prompt vs. non-prompt D mesons



CUJET3.0: JHEP02 (2016) 169
LGR: EPJC **80** (2020) 671
TAMU: PLB **735** (2014) 445
MC@sHQ+EPOS2: PRC 89(2014)014905

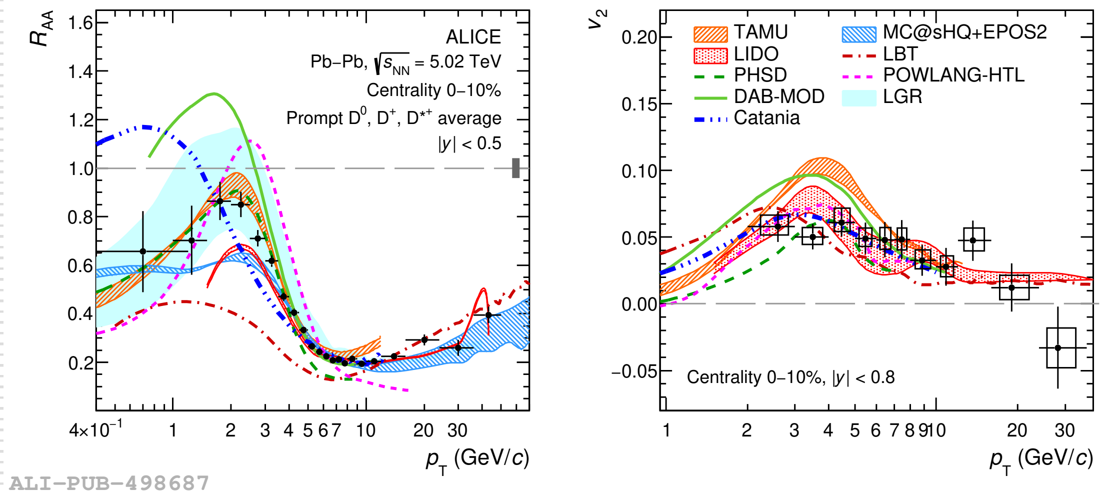
R_{AA}(prompt D) > R_{AA}(non-prompt D)

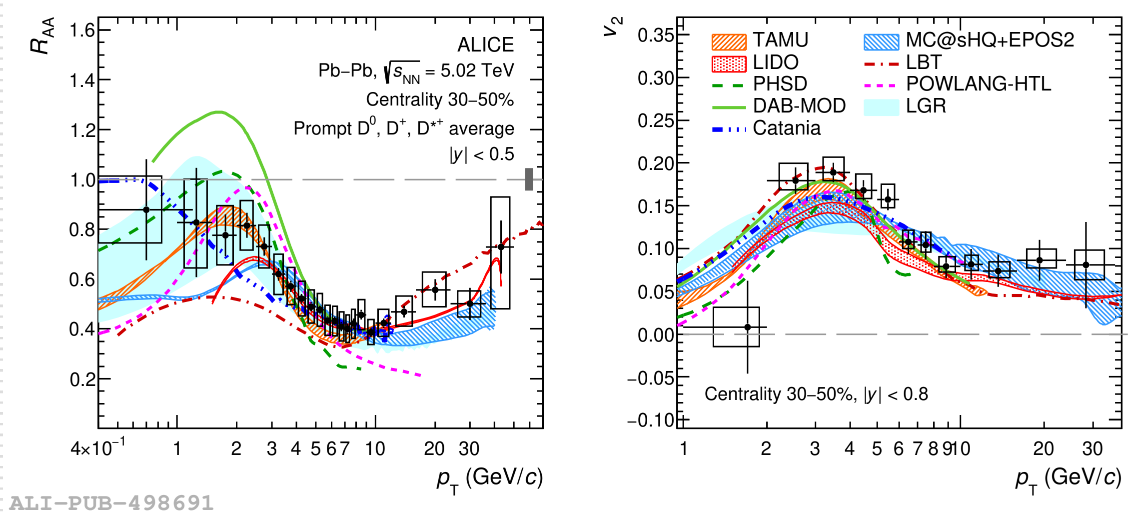
- p_T< 5 GeV/c different decay kinematics / radial flow
- p> 5 GeV/c smaller energy loss for B
- Described by models including collisional and radiative energy losses



Prompt D meson R_{AA} and v_2

arXiv:2110.09420





- 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

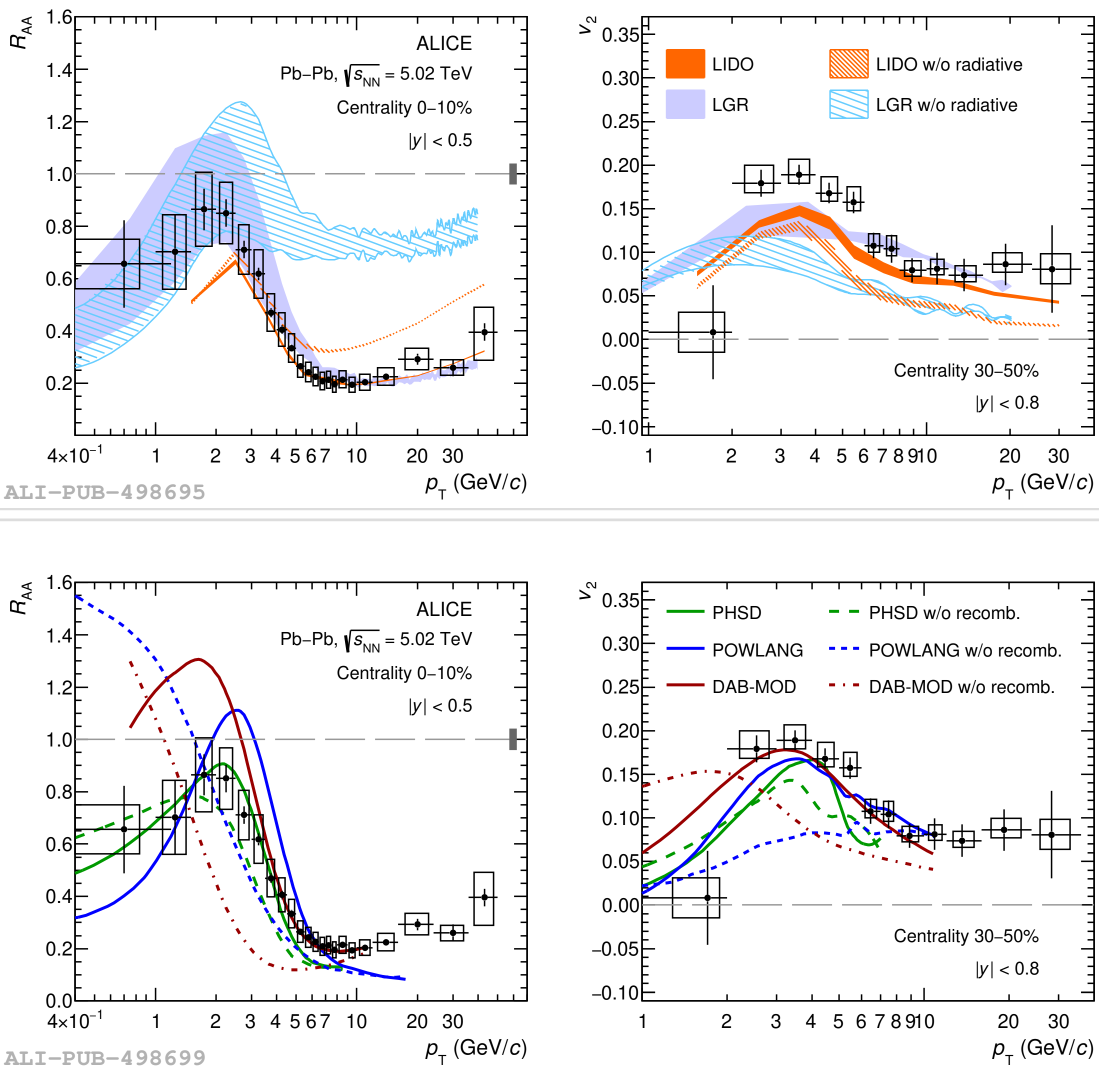
Model ingredients:

- 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

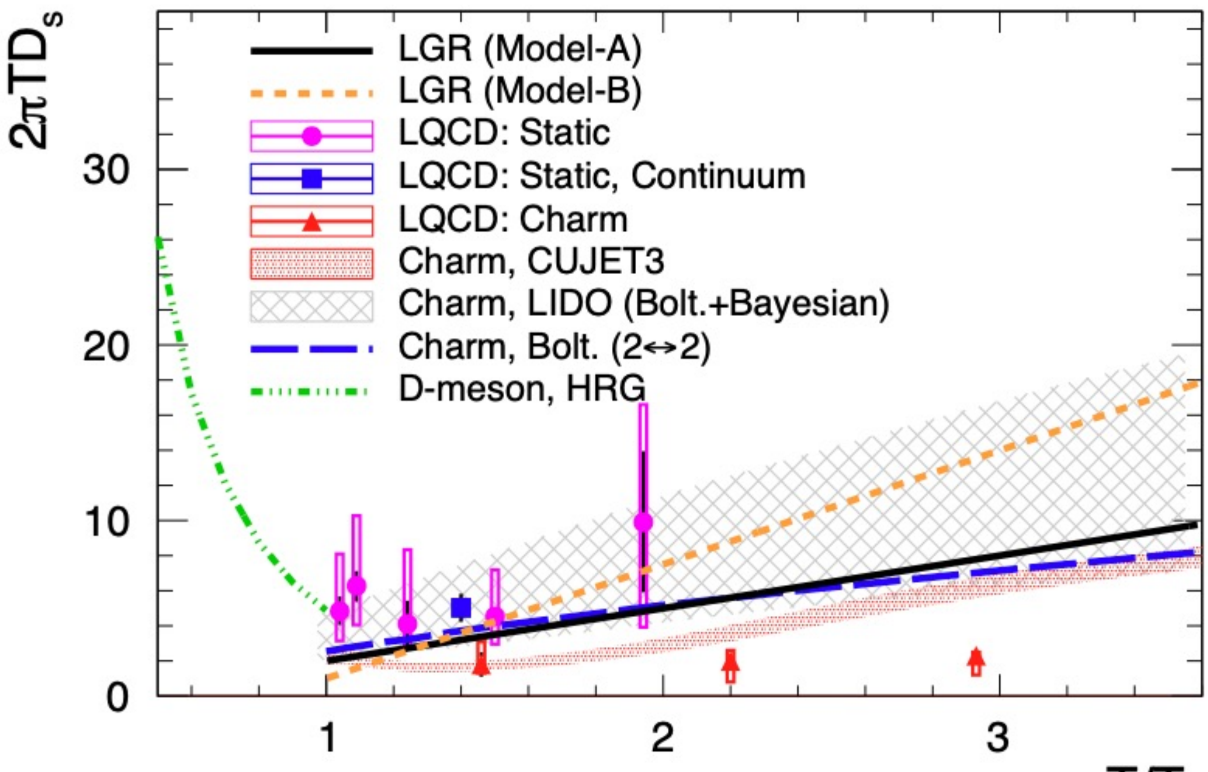
arXiv:2110.09420



- 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

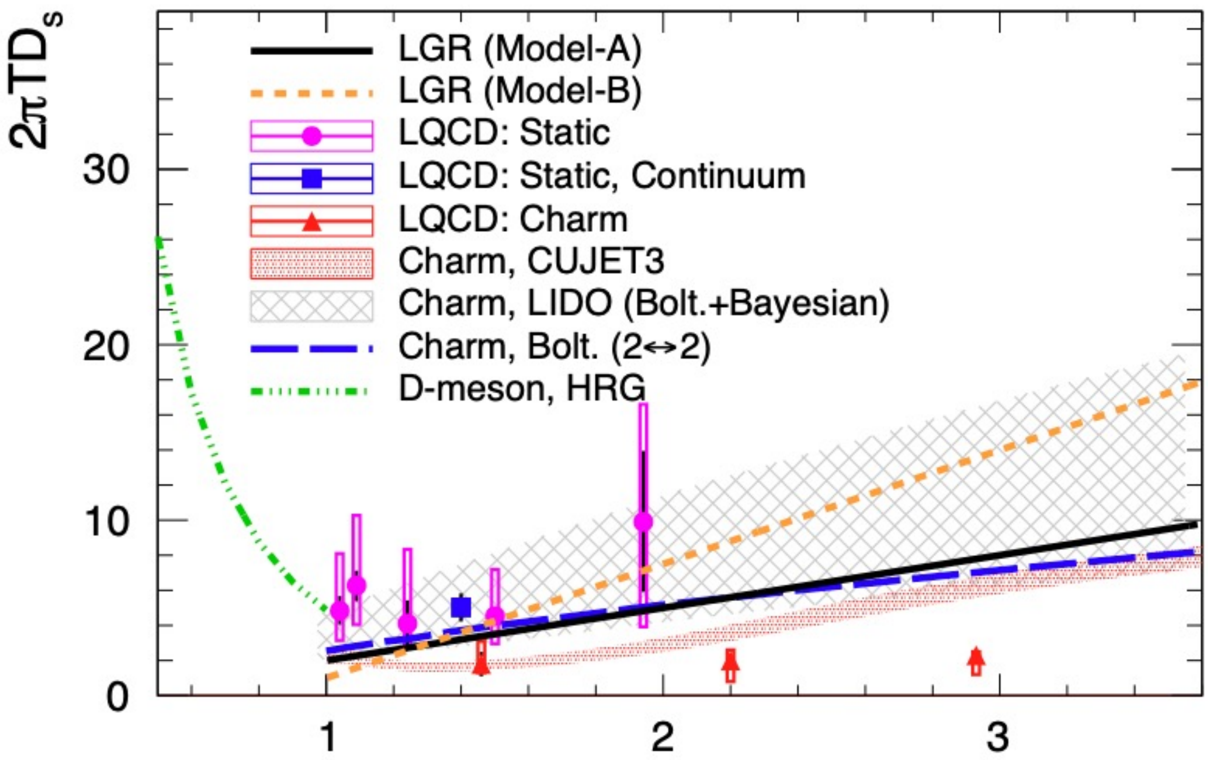
From that one derives the drag and momentum diffusion coefficients:

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

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

Charm spatial diffusion coefficient

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



Li, Liao, EPJC 80 (2020) 671

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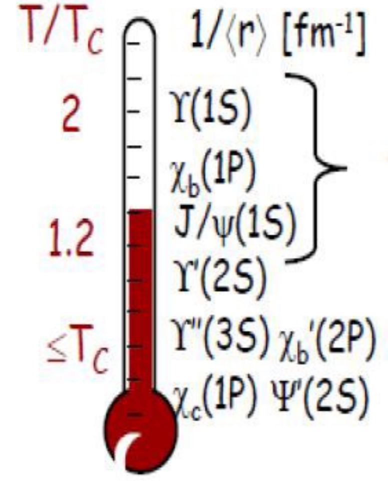
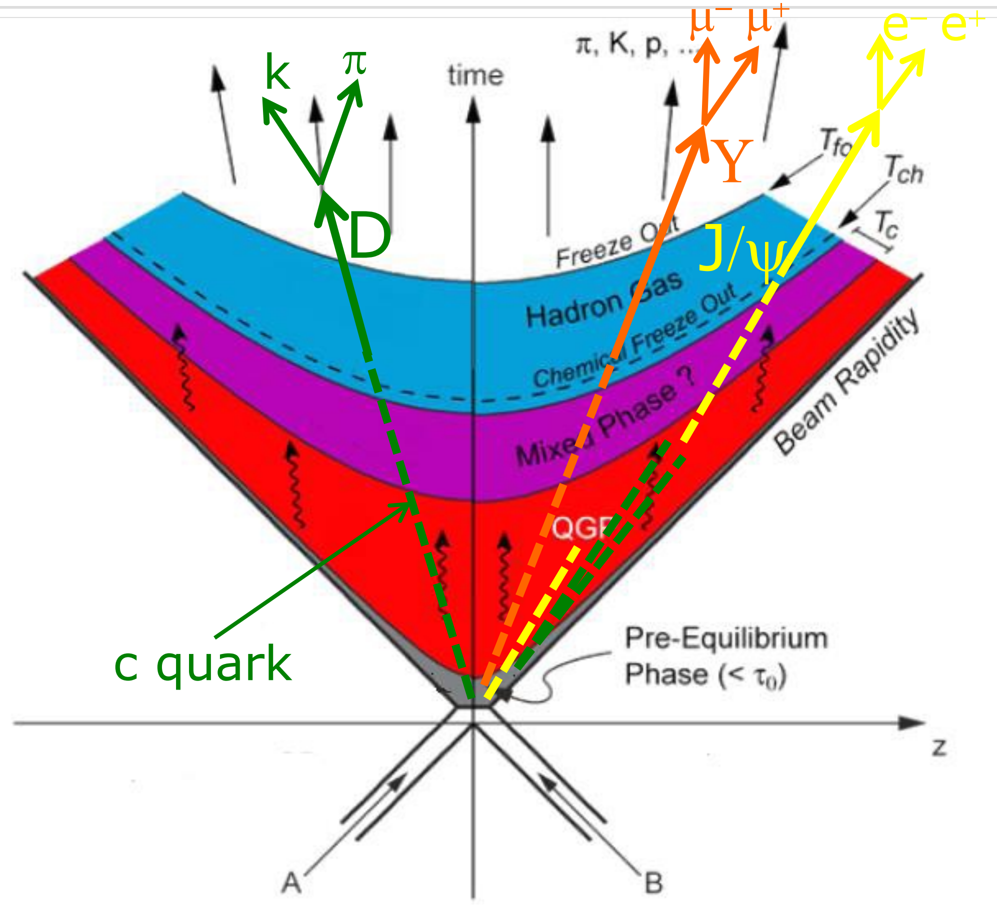
latest ALICE data (including v_2), arXiv:2110.09420: $1.5 < 2\pi T_c D_s < 4.5$

Quarkonium

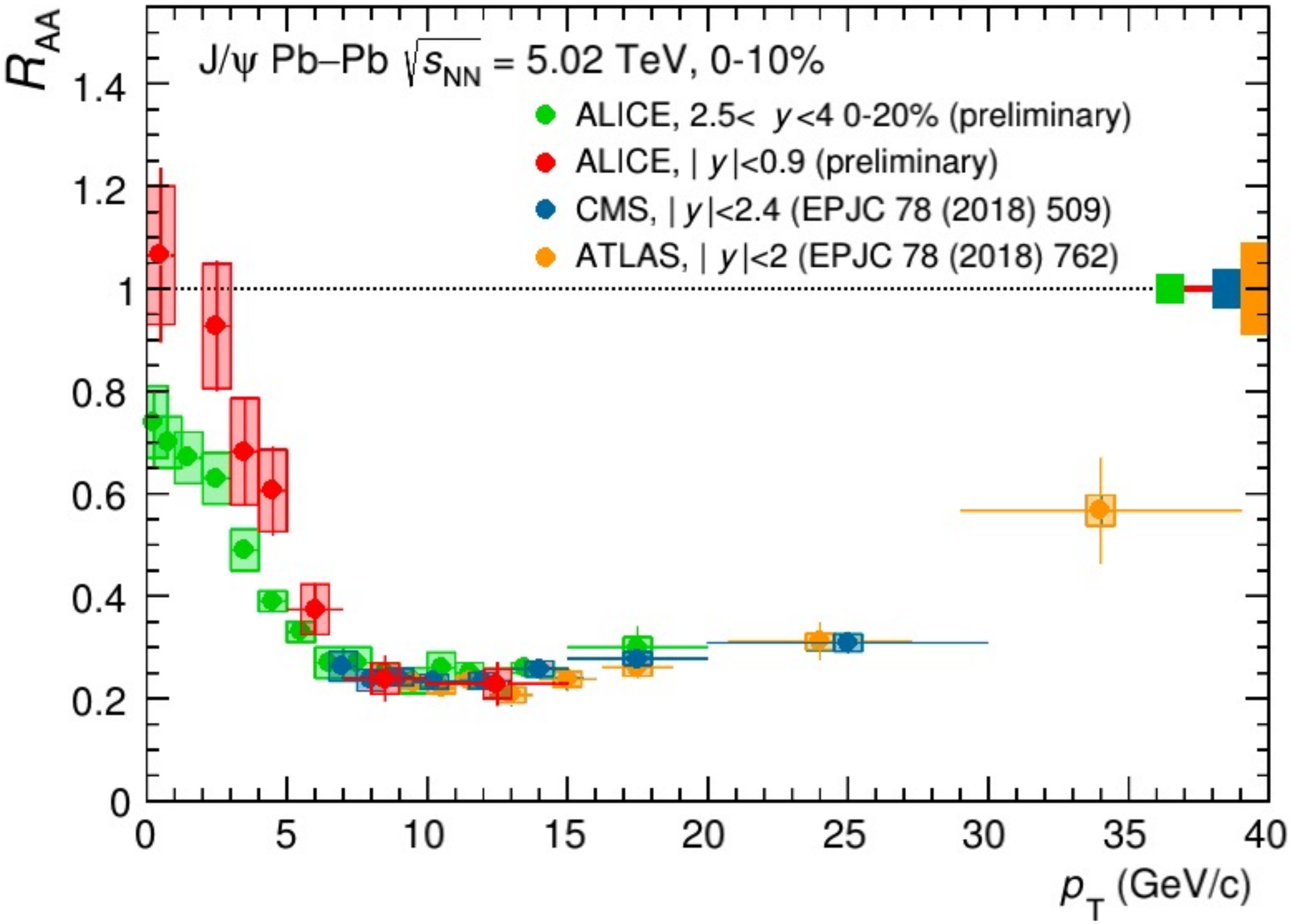


I'll discuss a few results

Detailed experimental review covered by Fiorella this morning



J/ψ R_{AA} vs. p_T



Strong R_{AA} p_T dependence

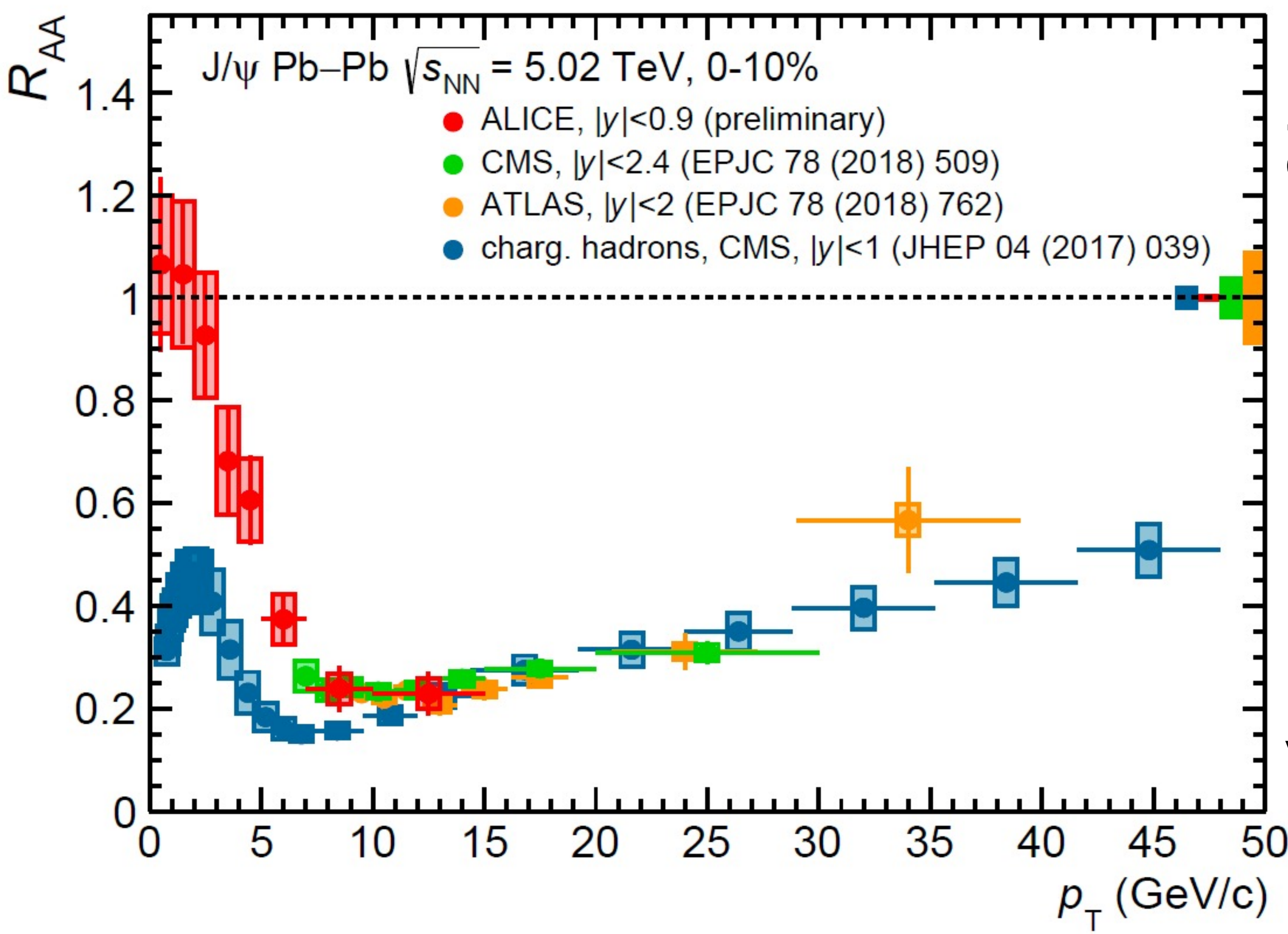
low p_T

- strong y dependence

high p_T

- common behavior, independent on y
- nice compatibility of results from different experiments

J/ψ R_{AA} vs. p_T



Strong R_{AA} p_T dependence

low p_T

- strong y dependence

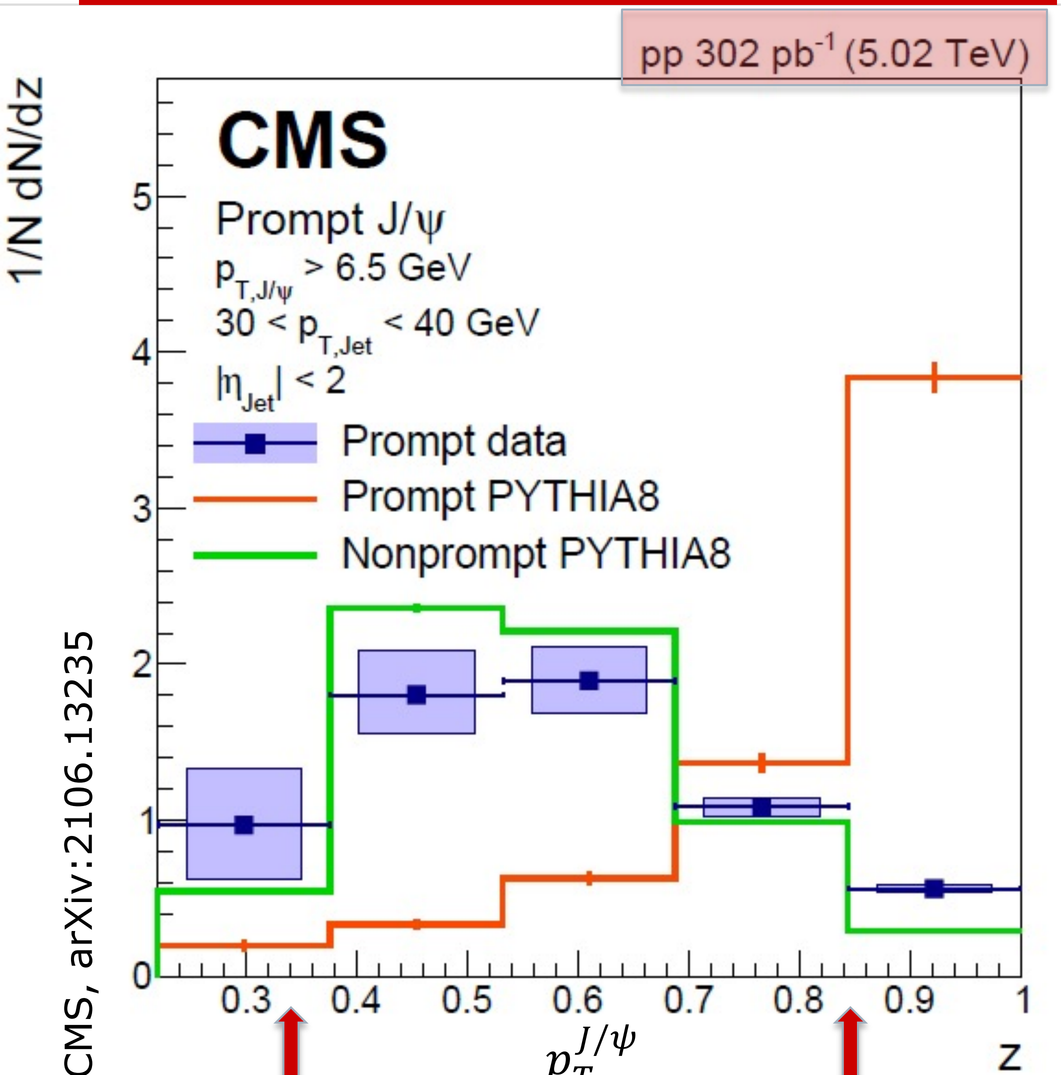
high p_T

- common behavior, independent on y
- nice compatibility of results from different experiments

very high p_T

- R_{AA} rise due to partonic energy loss mechanisms observed for hadrons?

J/ψ in jets



J/ψ and large Jet activity

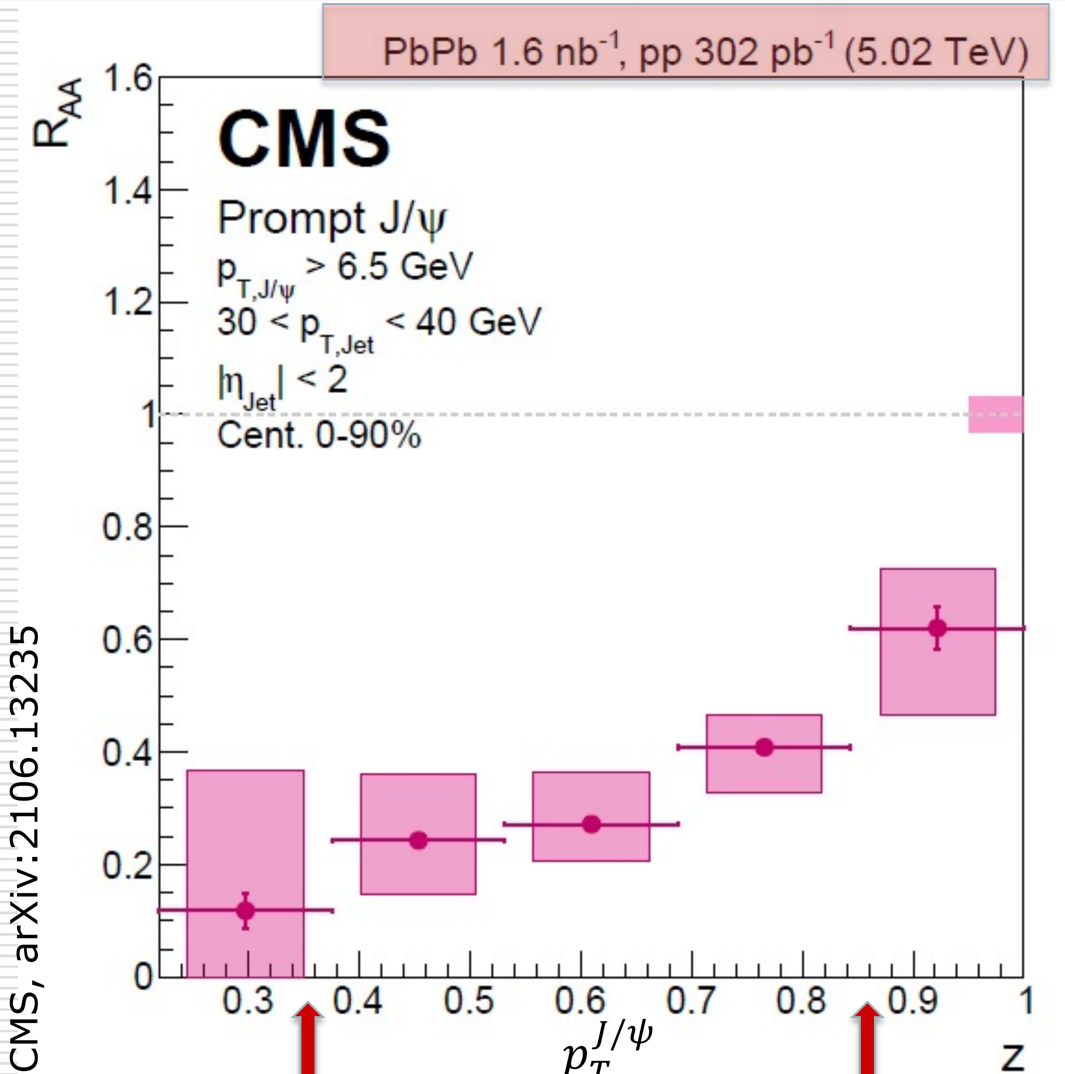
$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

J/ψ and small Jet activity

In pp prompt J/ψ are produced less isolated than predicted by event generator (PYTHIA)

- J/ψ production later in parton showers underestimated

J/ψ in jets



J/ψ and large Jet activity

$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

J/ψ and small Jet activity

In pp prompt J/ψ are produced less isolated than predicted by event generator (PYTHIA)

- J/ψ production later in parton showers underestimated

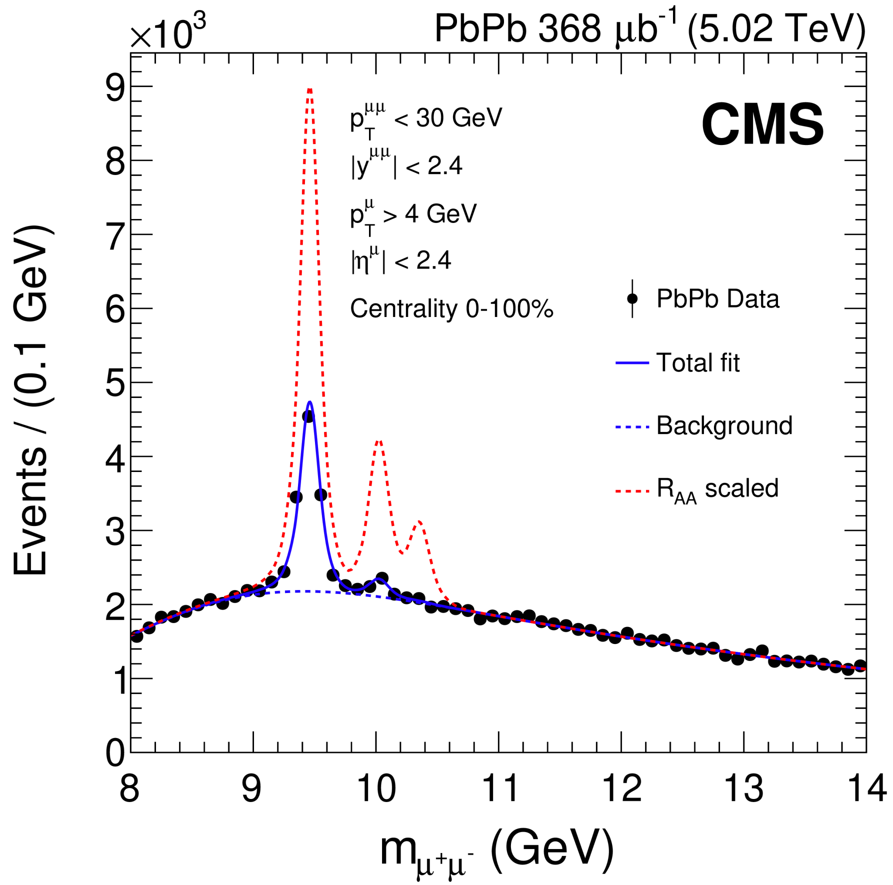
In Pb-Pb

- J/ ψ produced with a large degree of surrounding jet activity more suppressed than those isolated

Upsilon

CMS, PLB 790 (2019) 270

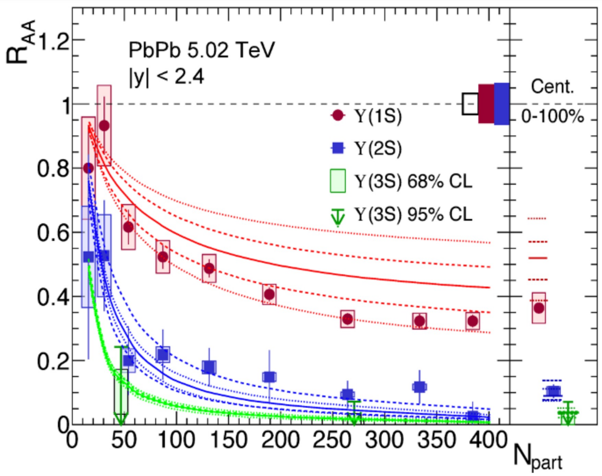
- Spectacular signature of the "sequential" dissociation
  - Υ(1S) suppression as due to suppression of its feed-down components

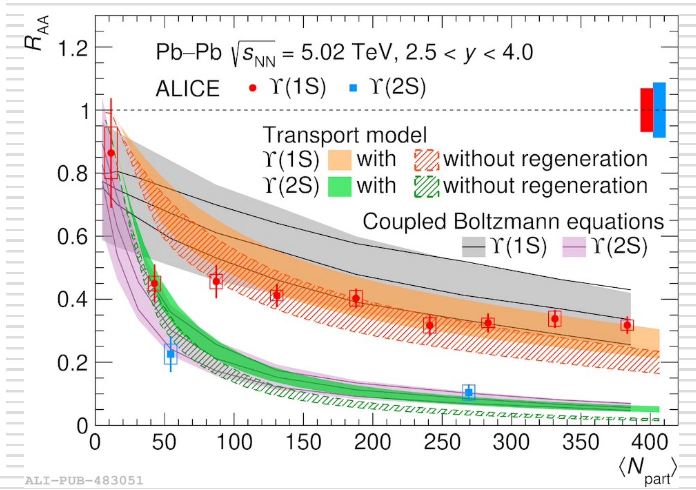


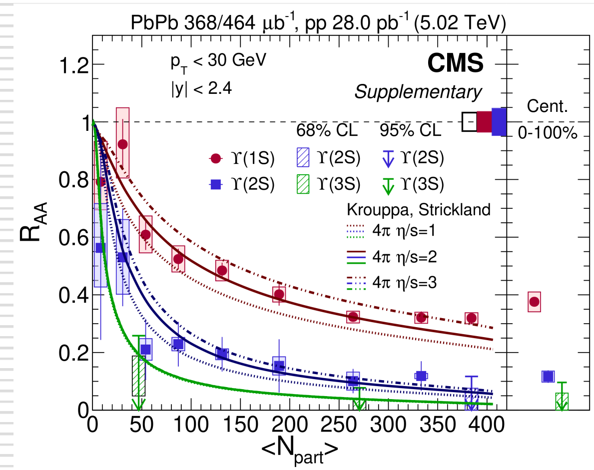
Υ R_{AA} versus models

CMS, PLB 790 (2019) 270
ALICE, PLB 822 (2021) 136579

Many calculations with different approaches and ingredients (detailed in backup)
Globally reproducing the experimental trends sometimes **within large uncertainties**







Break-up by **comover interaction** + nCTEQ15 parametrisation

Transport description in-medium dissociation and recombination + nPDF sets

Hydrodynamic framework modification of the heavy-quark potential

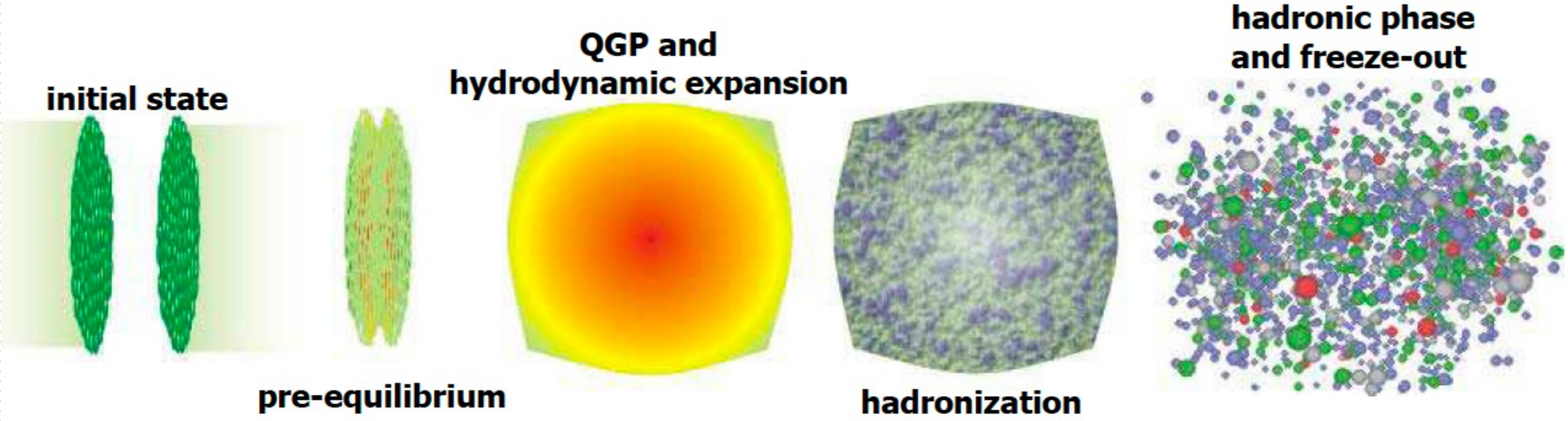
Conclusions / outlook

- Hard probes allow us to infer the properties of the fireball since the very **early stage** of the collisions all along its evolution

- Hard probes are **rare** probes
  - a lot to come with LHC run3 & run4 data, and beyond

Extra

Moments of a heavy ion collision



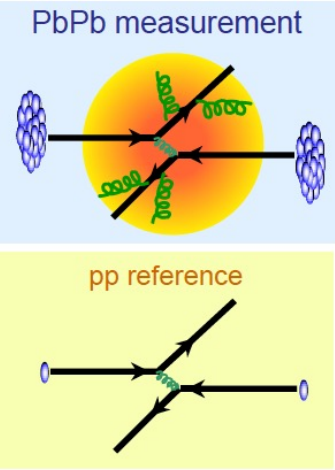
t ≈ 10^{-23} s, V ≈ 10^{-40} m^3

1. initial collisions ($t \leq t_{coll} \simeq \frac{2R}{\gamma_{cm}c}; R_{Pb} \simeq 7\ fm$)
2. thermalization: equilibrium is established ($t \lesssim 1\frac{fm}{c} = 3\ 10^{-24}s$)
3. expansion ($\langle v \rangle \simeq$) and cooling (t < 10-15 fm/c) ...deconfined stage
4. hadronization (quarks and gluons form hadrons)
5. chemical freeze-out: inelastic collisions cease; particle identities (yields) frozen
6. kinetic freeze-out: elastic collisions cease; spectra are frozen

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

Nuclear modification factor

- Production of hard probes in A-A expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor**

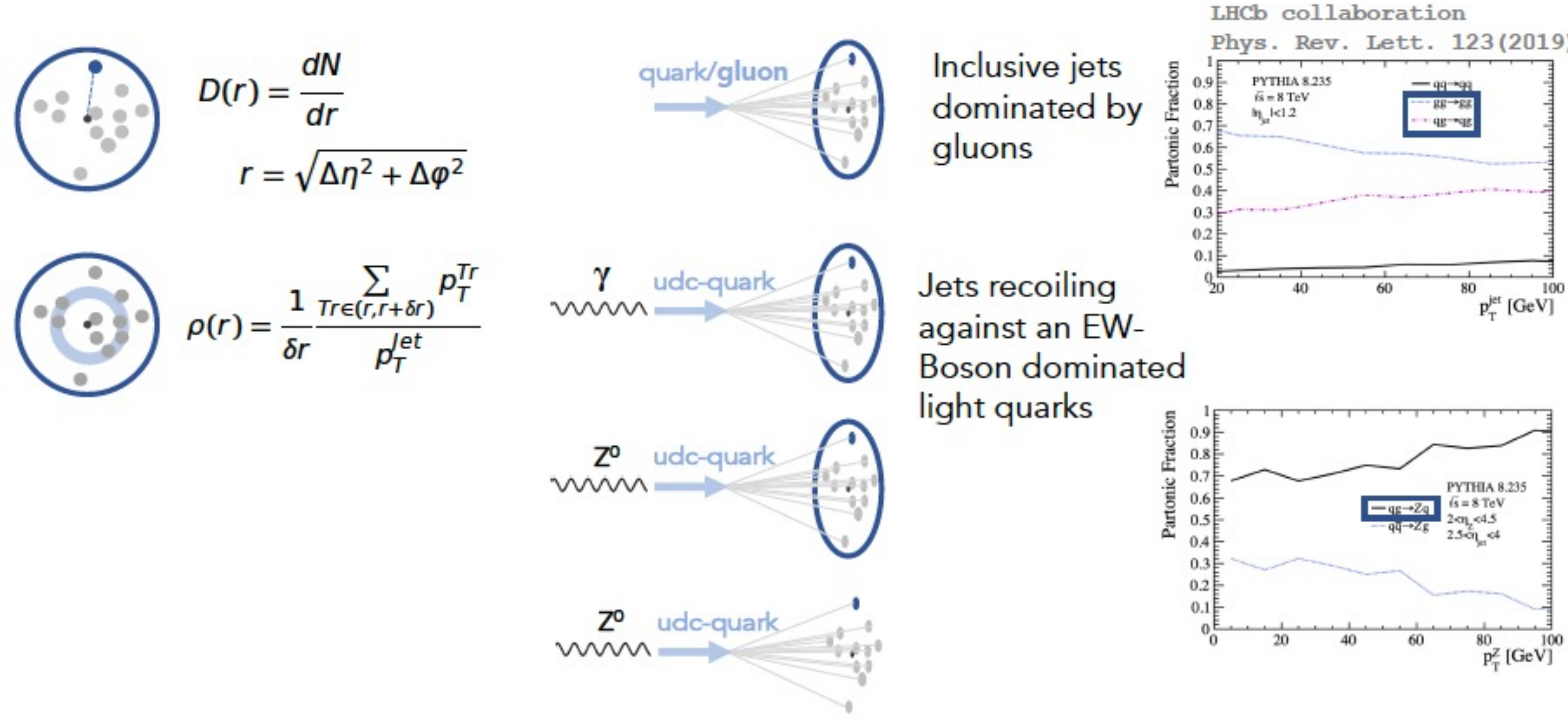


$$R_{\text{AA}} = \frac{1}{N_{\text{coll}}} \frac{\mathrm{d}N_{\text{AA}} / \mathrm{d}p_{\text{T}}}{\mathrm{d}N_{\text{pp}} / \mathrm{d}p_{\text{T}}} = \frac{1}{T_{\text{AA}}} \frac{\mathrm{d}N_{\text{AA}} / \mathrm{d}p_{\text{T}}}{\mathrm{d}\sigma_{\text{pp}} / \mathrm{d}p_{\text{T}}} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

- If no nuclear effects are present → $R_{\text{AA}}=1$
- Effects from the hot and deconfined medium created in the collision → breakup of binary scaling → $R_{\text{AA}} \neq 1$
  - **Parton energy loss** via gluon radiation and collisions in the medium
  - **Quarkonium melting** in the QGP
- But also initial state effects (e.g. nuclear modification of PDFs) may lead to $R_{\text{AA}} \neq 1$
  - Need control experiments: medium-blind probes (photons, W, Z) + p-A collisions

Tagged Jets - EW Boson Recoil

- At leading order, the boson and the jet are produced back to back in the azimuthal plane, with equal p_T

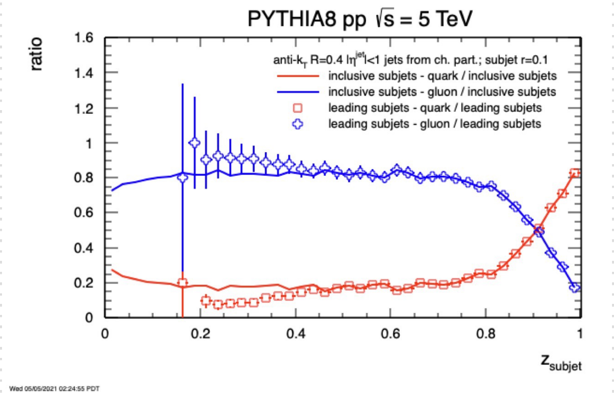


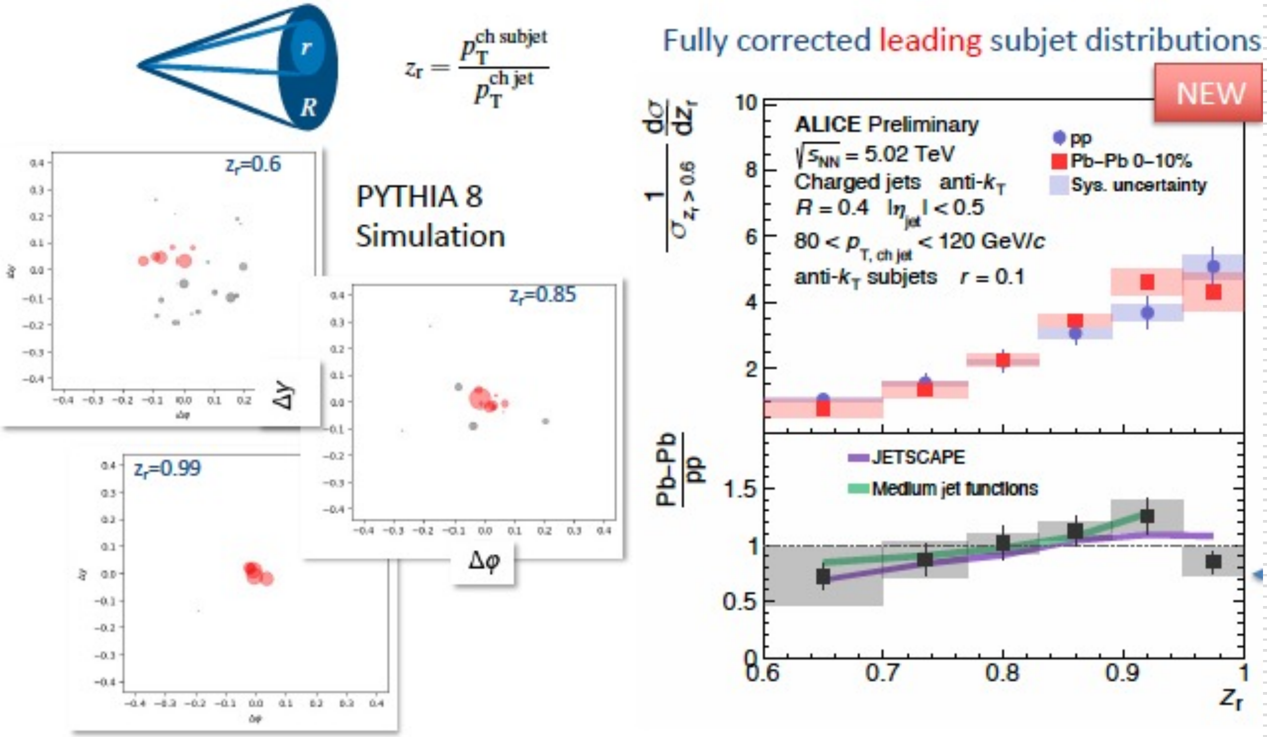
Modifications of jet substructure in the QGP

Follow up on groomed jet substructure in AA => subjet tagging – quark vs. gluon

motivations:

- investigate redistribution of energy from the leading subjet (at different r<R) – collimation and z≈1 suppression
- sensitivity to quark vs. gluon jet in-medium energy loss?

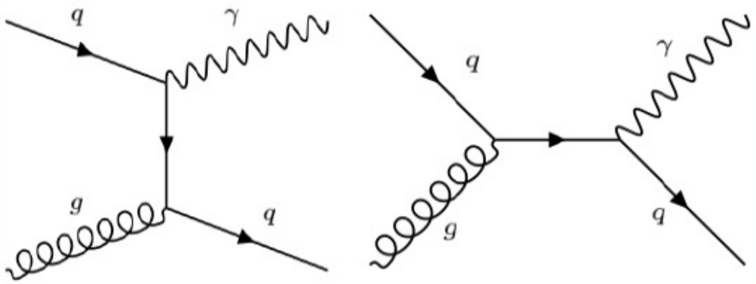




γ + jet in Pythia 8

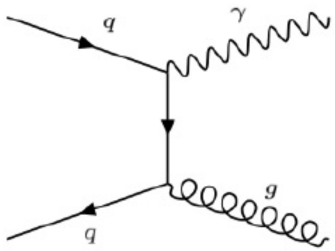
γ+quark

dominantly via QCD Compton scattering

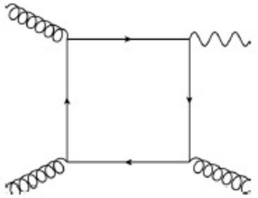


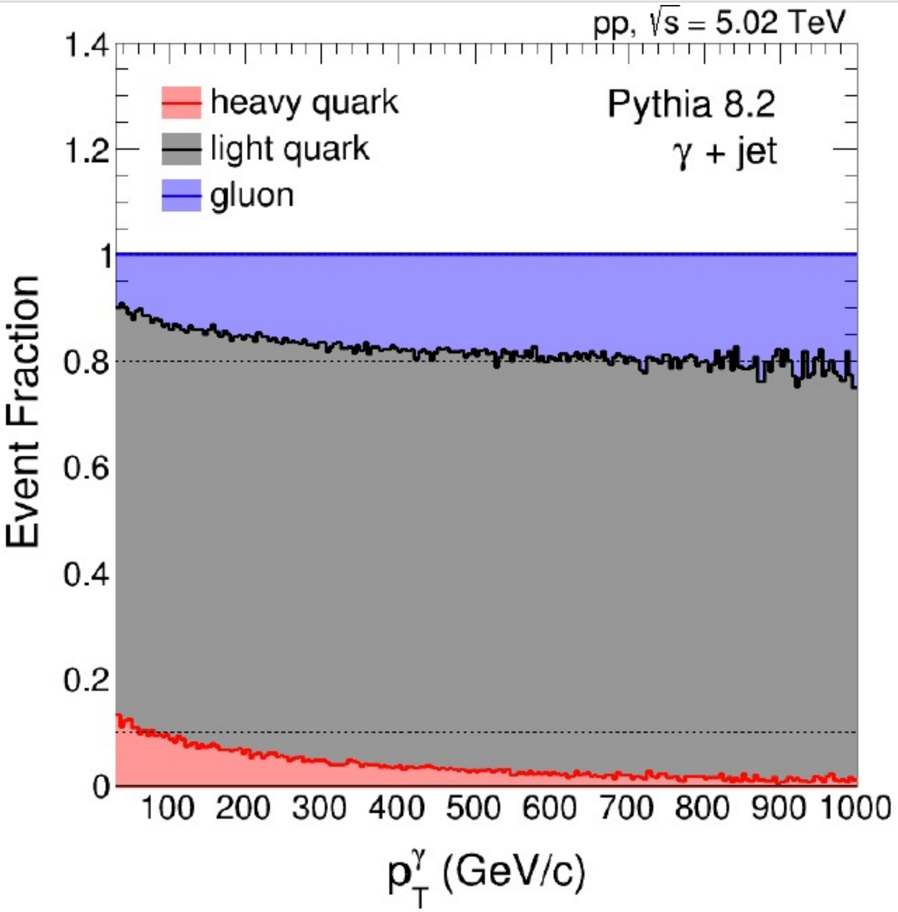
γ+gluon

dominantly via qqbar annihilation



subdominantly via



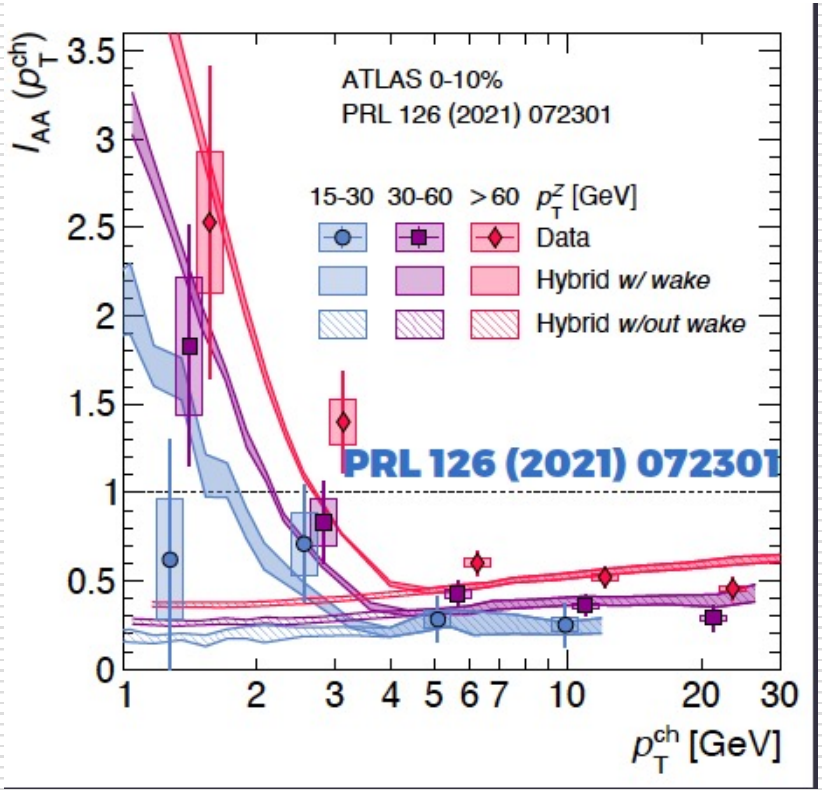


Process here is prompt photon (not isolated photon)
Quark dominated across the spectrum
80-90% from p_T~ 50 GeV to ~ 1 TeV

Z-tagged Jets – comparison to models

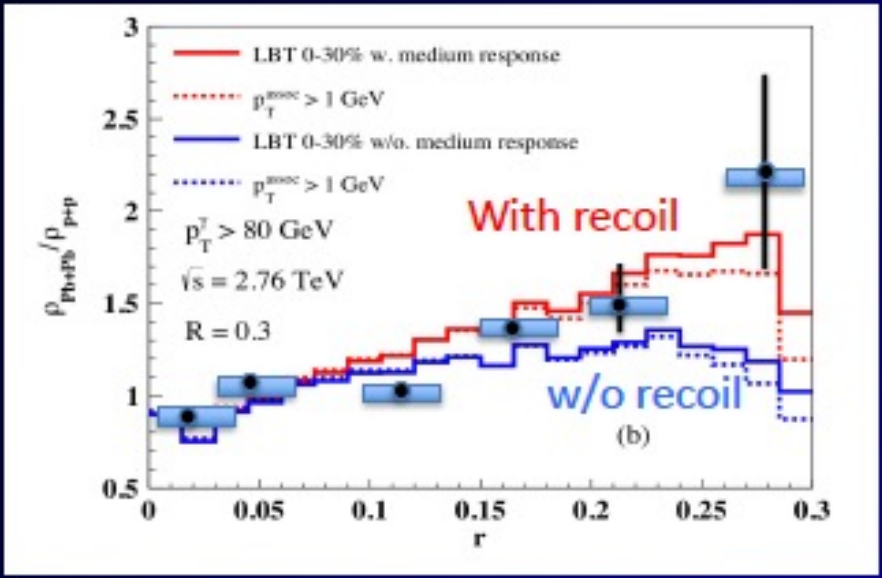
Does a jet in medium leave a wake?

- Check in Hybrid model - jet quenching theory with strong-coupling
- Hybrid model does not describe low-p_T excess in data without such a back-reaction

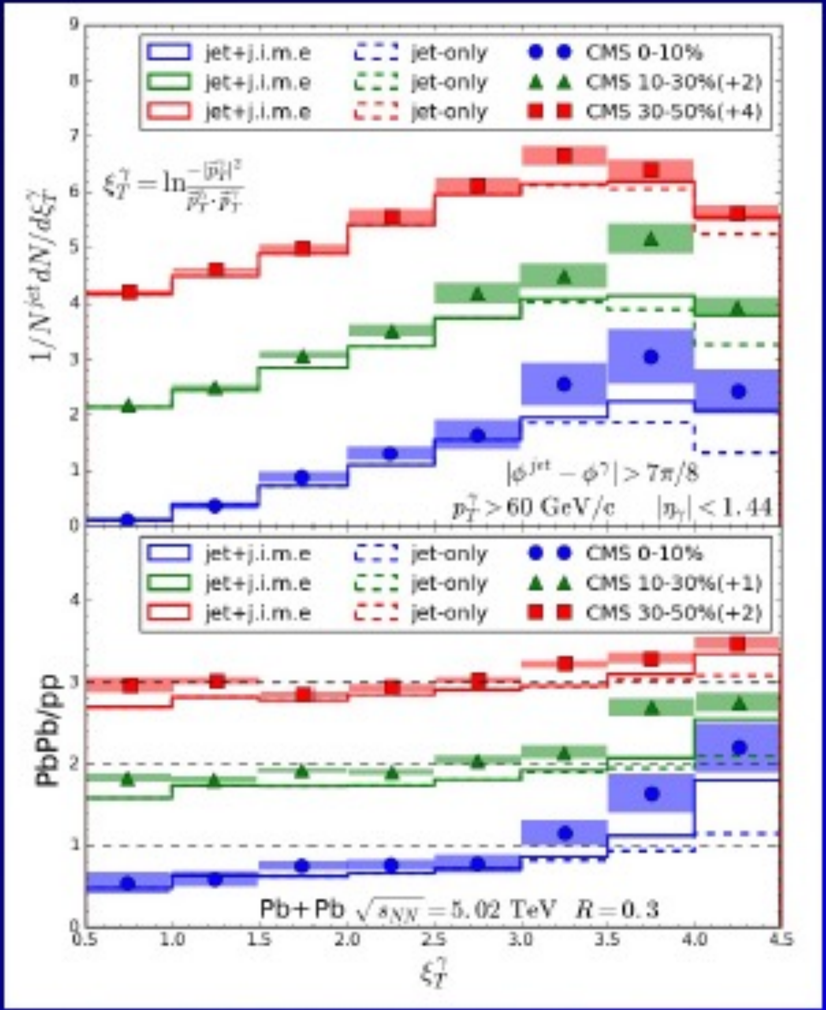


Medium modification of γ-jets

Enhancement of soft hadrons in large angles



Luo, Cao, He & XNW, arXiv:1803.06785



Chen, Cao, Luo, Pang & XNW, 2005.09678

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

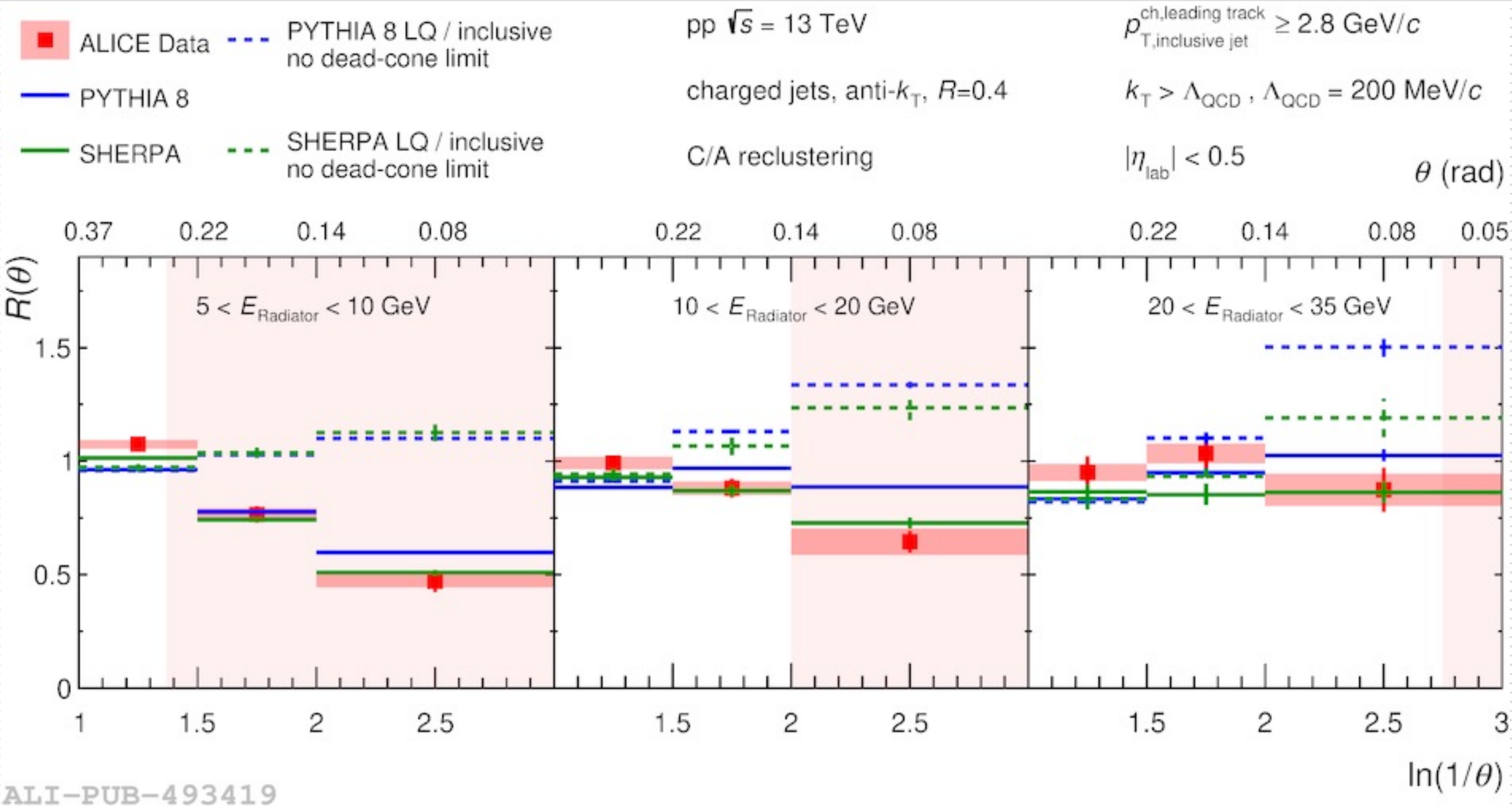
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

should be made to look for it. In particular, it should be interesting to carefully study all jet phenomena as function of associated multiplicity. In addition, one might anticipate, even in the presence of quark-gluon plasma and "extinction," special classes of events associated with particular collision geometries (Fig. 3). Most spectacular would be events (Fig. 3b) containing one clean observable high-p_T jet, with no sign whatsoever of a recoiling jet, and where the p_T of the observed jet is (visibly) balanced by a large aggregation of low p_T particles.

We also note that, while "extinction" may be an important phenomenon, it should not be dominant for hadron-jets from the anticipated W and Z electroweak bosons. And as one enters the high-p_T region of hundreds of GeV, it would require an increase in the height of the central-plateau by an order of magnitude to extinguish or greatly modify the produced jets.

Dead cone effect in pp



7.7σ

3.5σ

1.0σ

N-subjetiness

Quantifies to which degree a jet has N (or fewer)-pronged structure

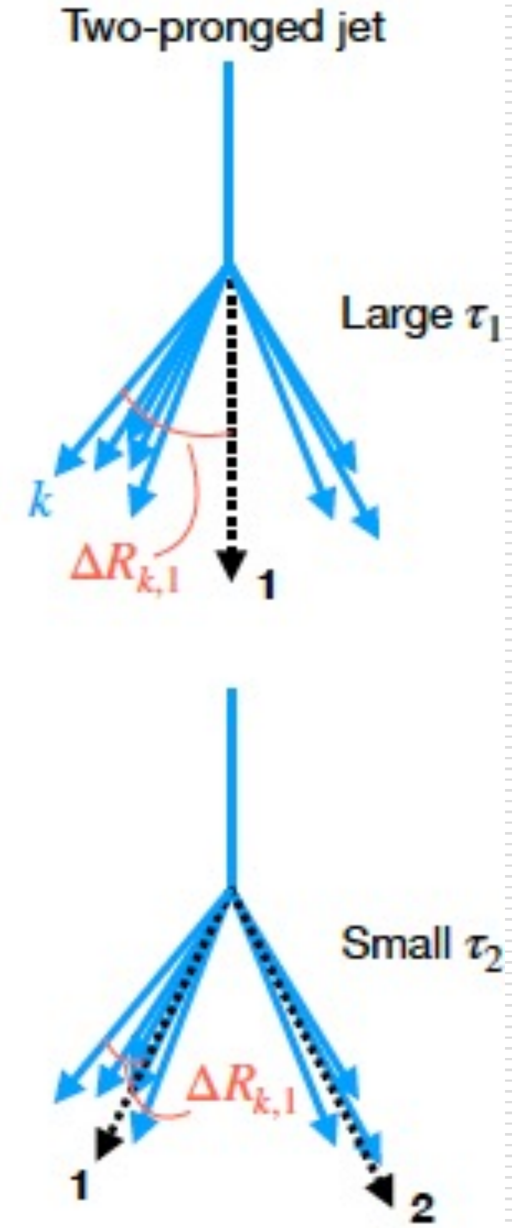
$$\tau_N = \frac{1}{p_{\mathrm{T,jet}} \times R} \sum_k p_{\mathrm{T},k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})$$

N axes determined by declustering jet by N-1 steps

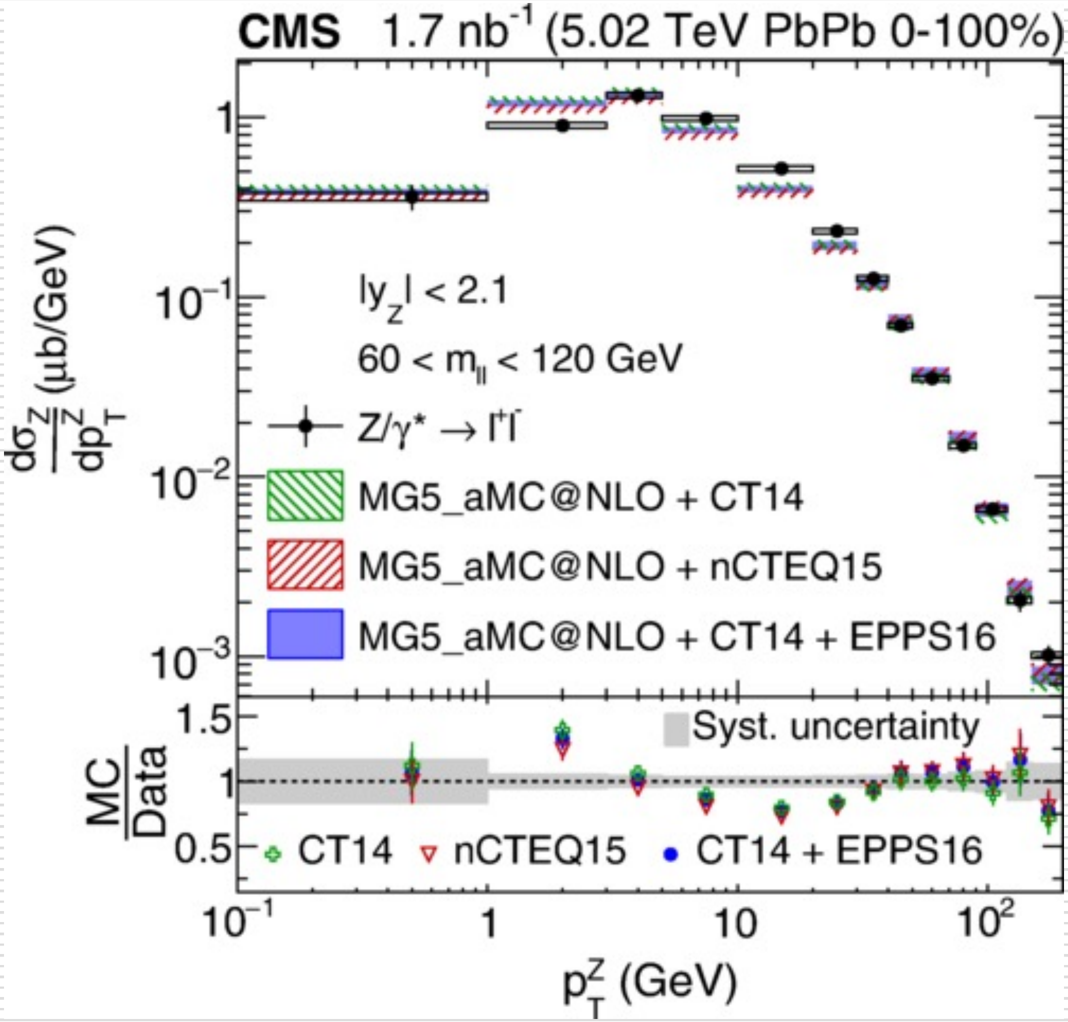
Axes depend on reclustering algorithm
(different reclustering algorithms -> axes sensitive to different regions of splitting phase space)

1) k_{T} reclustering: first splitting exposes hardest two subjets
2) C/A: first splitting exposes largest-angle subjets
3) Soft-drop (C/A, $z_{\mathrm{cut}} = 0.1$, $\beta = 0$): first accepted structure correlated to earliest hard splitting in jet

τ_2/τ_1 sensitive to exactly 2-prongs in a jet



Z^0 boson as a function of p_T



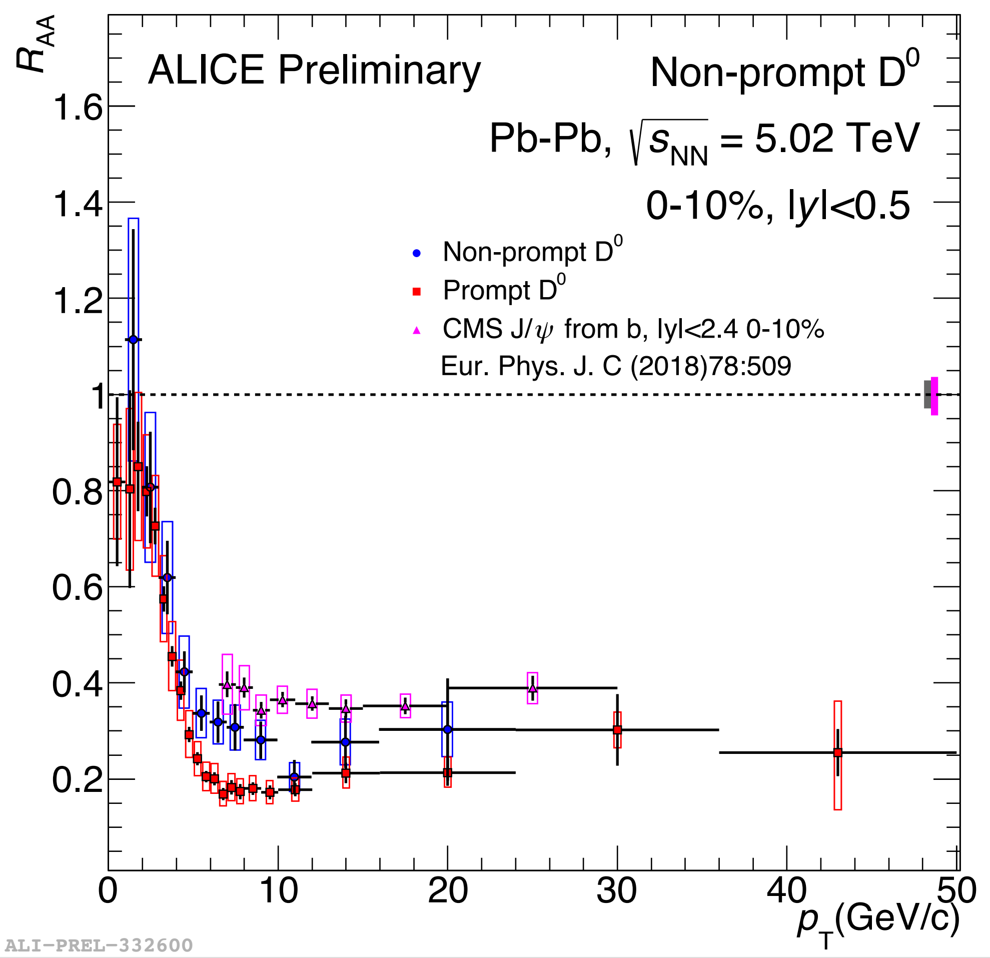
MadGraph5_aMC@NLO calculations with different (n)PDF

general trend correctly reproduced by the simulation, but

- Low p_T: lack of soft g resummation in the model (also in pp)
- nPDF sets 10% lower then free PDF at low pt, trend reversed for p_T >50 GeV/c
- Differences between two nPDF sets smaller than deviations of model from data

→modelling improvements more urgent

In-medium energy loss: charm vs. beauty



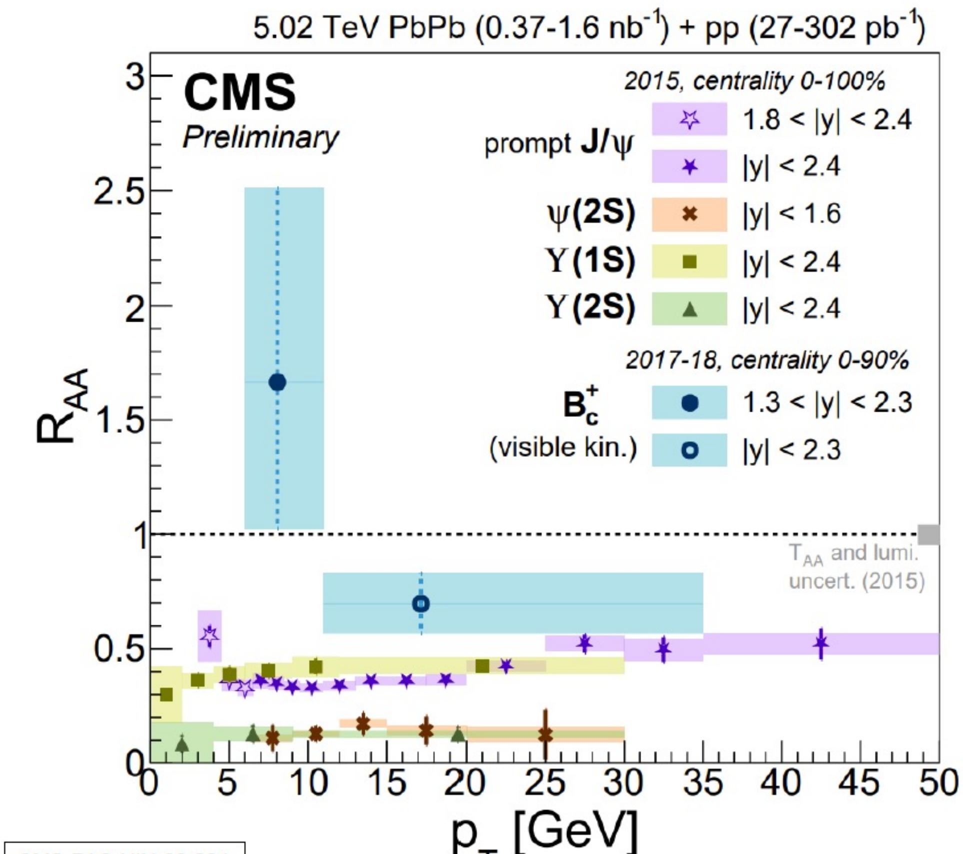
- ALICE: prompt and non-prompt D mesons, CMS: non-prompt J/ψ

B_c^+ R_{AA} Compared to Quarkonia at CMS

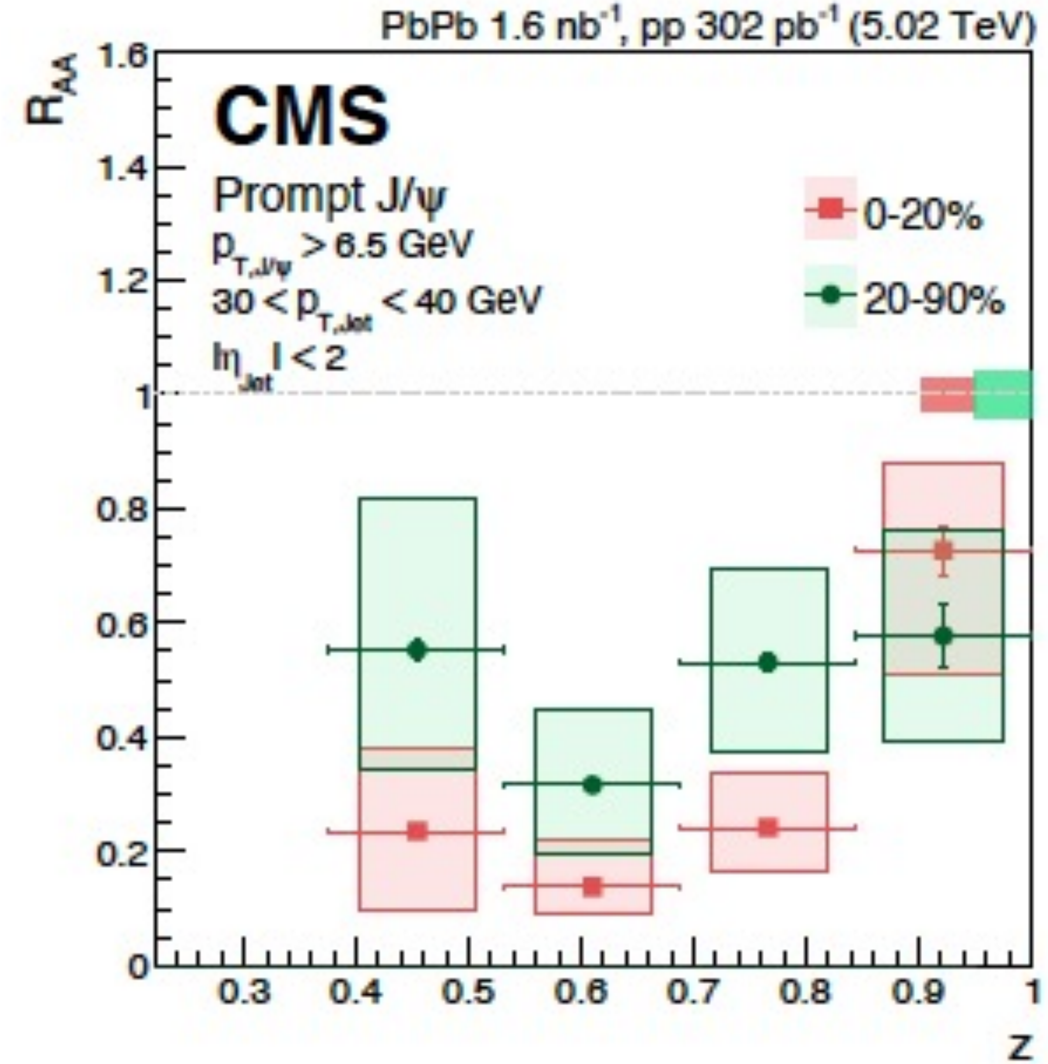
State	Ψ(2S)	Υ(2S)	J/ψ	B_c^+	Υ(1S)
Mass (GeV)	3.68	10.02	3.10	6.27	9.46
Δ E (GeV)	0.05	0.54	0.64	0.87	1.10

Small binding energy → Large binding energy

- B_c^+ R_{AA} is higher than Quarkonia
  - Binding energy between J/ψ and Υ(1S)
  - Large experimental uncertainties prevent a firm conclusion
- Recombination of charm and beauty could increase the B_c^+ R_{AA}
- Would be interesting to go to low p_T < 5 GeV with future CMS and ALICE data in Run 3+4



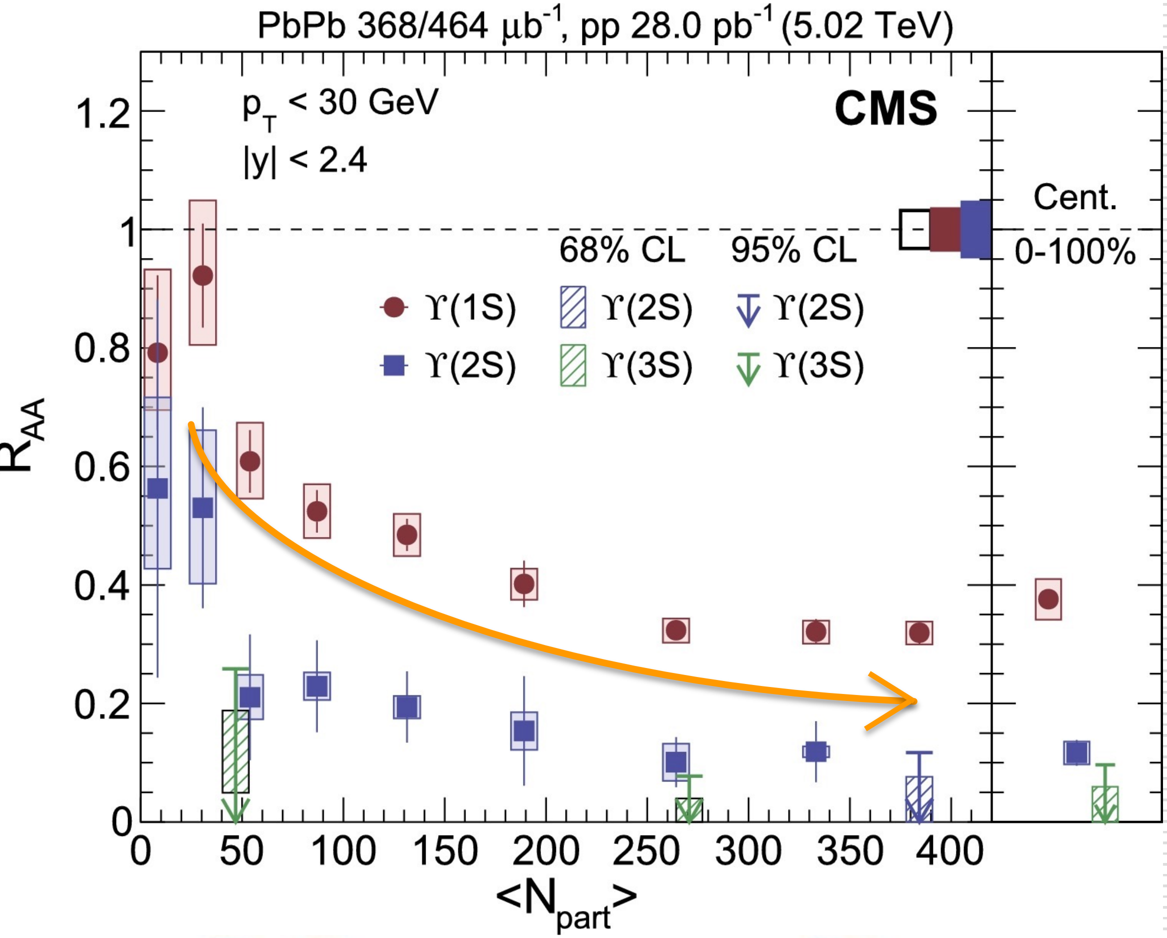
CMS-PAS-HIN-20-004

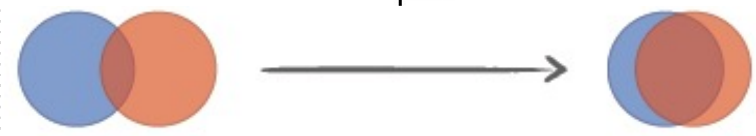


CMS, arXiv:2106.13235

Υ R_{AA} versus centrality

CMS, PLB 790 (2019) 270





Strong suppression of Υ production increasing with the centrality

- Down to a plateau of R_{AA} = 0.3–0.4 for Υ(1S)
  → Is the direct contribution even affected?
- Υ(2S) production suppressed by a factor 10 for the most central collisions
- No evidence yet for Υ(3S) production to date (R_{AA} < 0.096 at 95% CL)

→ Ordering like sequential melting picture

Phenomenological models for Υ

nuclear effects / nPDF
regeneration term

Semi-classical calculations based on transport or rate equations

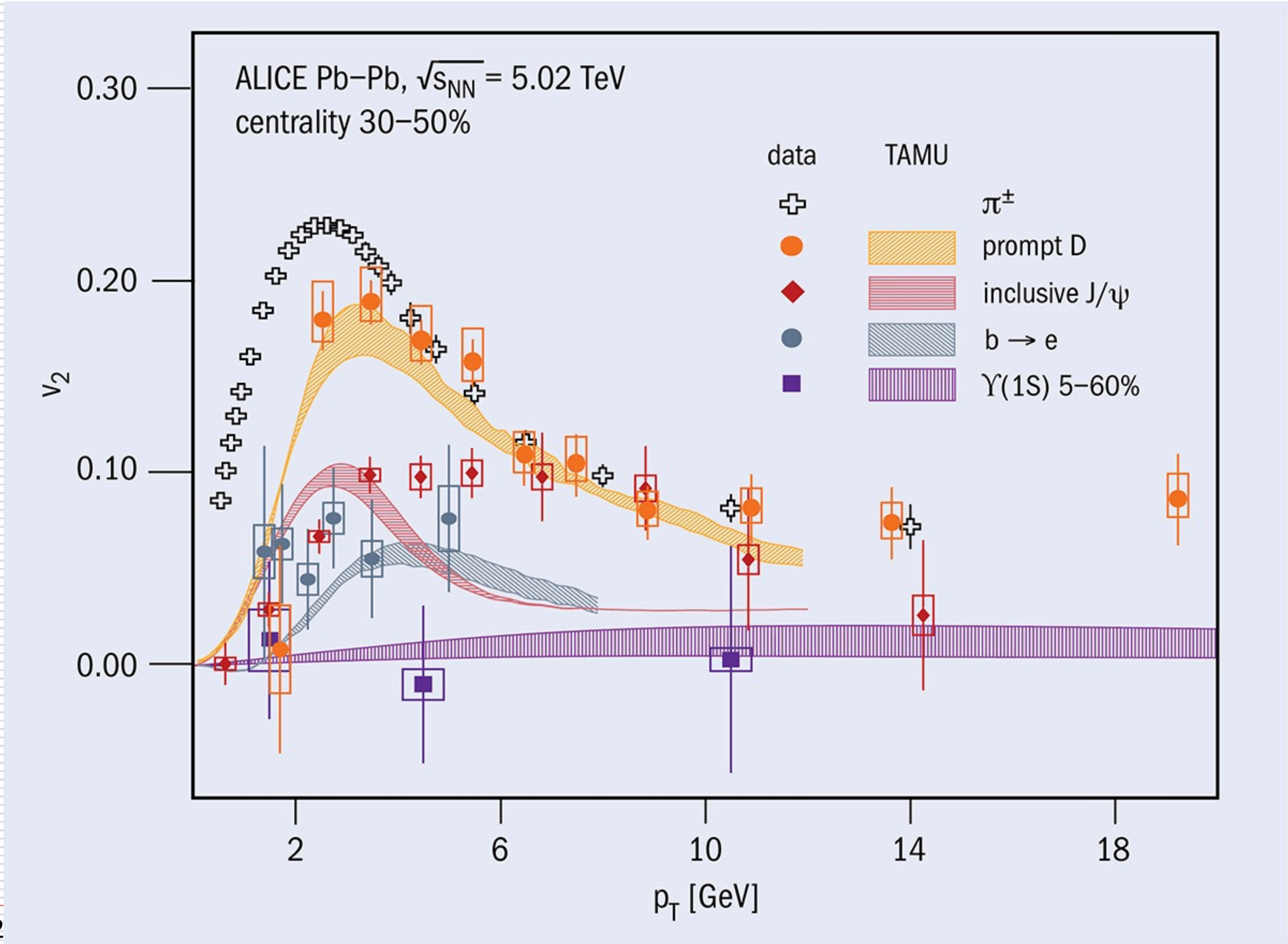
- **Comover interaction model** [JHEP 10 (2018) 094]
  Final-state suppression by interaction with *comoving* particles + nCTEQ15 parametrisation

- **Transport descriptions**: in-medium dissociation and recombination processes
  - « transport model » a.k.a TAMU = isotropic fireball + effective absorbtion [PRC 96 (2017) 054907]
  - « coupled Boltzmann equations » = 2+1d viscous hydrodynamics + EPPS16 parametrisation [JHEP 01 (2021) 046]

- **Hydrodynamic calculations** [Universe 2 (2016) 3]
  Thermal modification of the heavy-quark potential inside a 3+1d anisotropic medium.
  No nPDF parametrisation nor regeneration mechanism.

All account for the suppression of feed-down contributions but with different treatments.

ALICE HF v_2 results (ALICE) vs TAMU



Open charm v_2 compilation