Heavy ion physics: experimental review

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Manchester - January the 13th 2022

Heavy ion physics: experimental review

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Outline:
- Introduction
    - what can we learn from ultra-relativistic HI collisions?
    - space time evolution of HI collisions
- Observables in HI collisions
    - initial stage
    - soft probes: the bulk of the produced particles
    - hard probes: the rarest observables
- Outlook

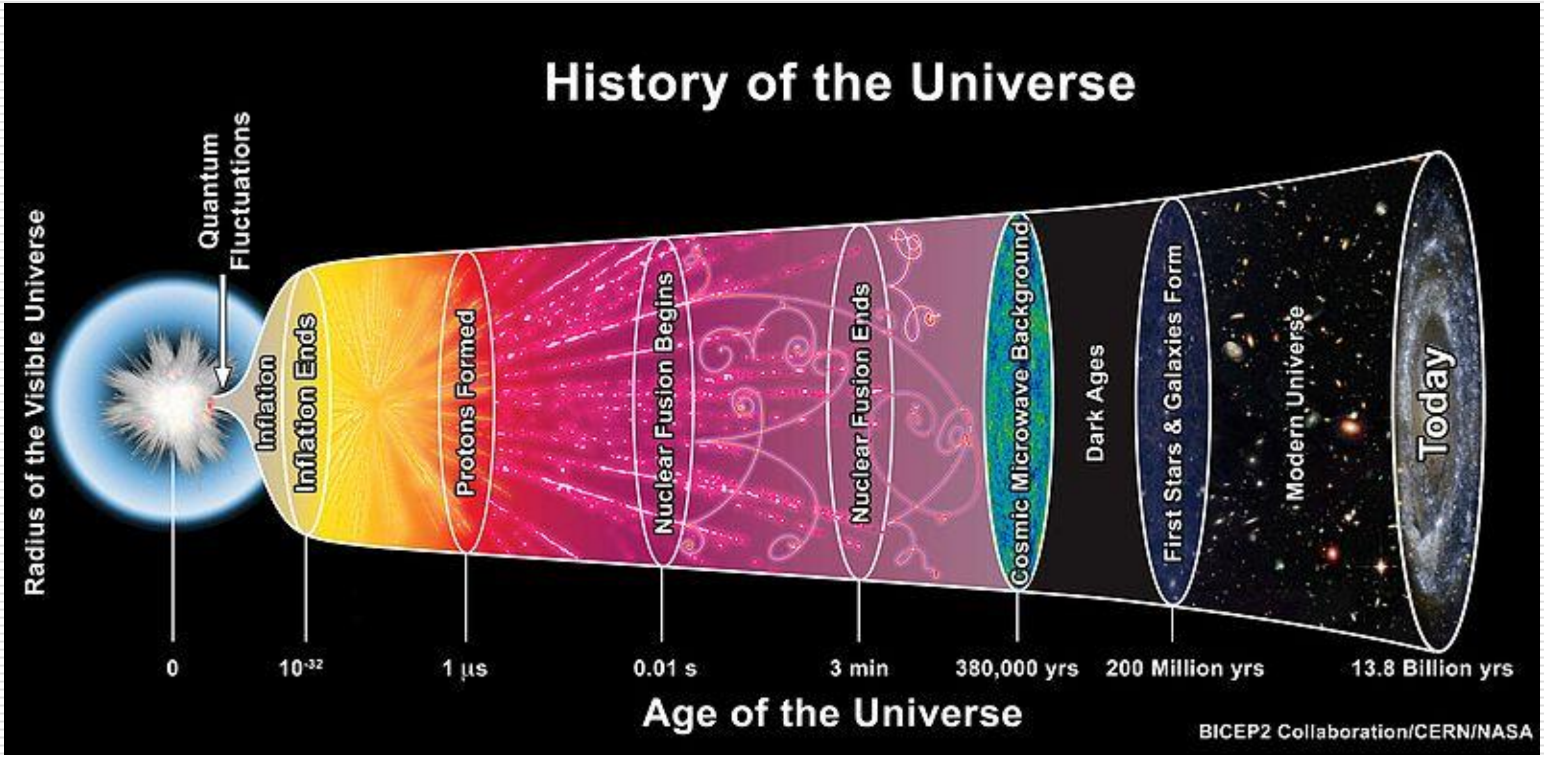
Manchester - January the 13th 2022

What can we learn from HI collisions ?

Credits: W. Busza et al. Annu. Rev. Nucl. Part. Sci. 2018.68:339-376

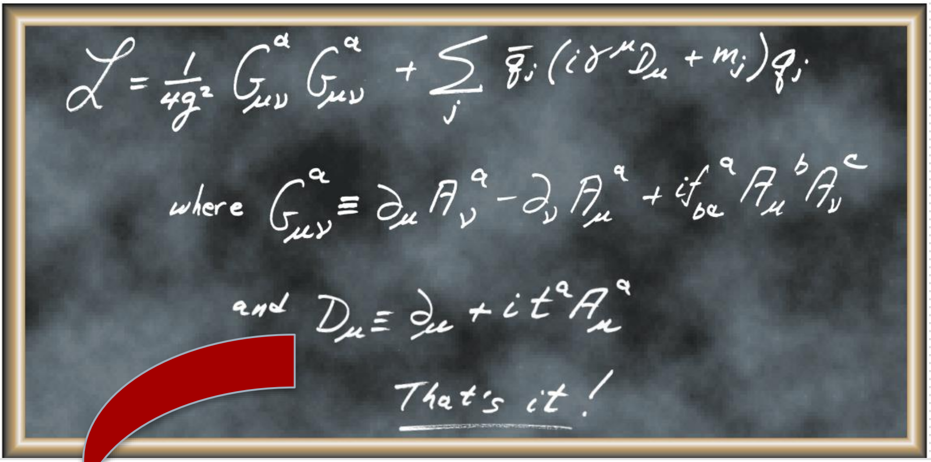
QCD in Cosmology

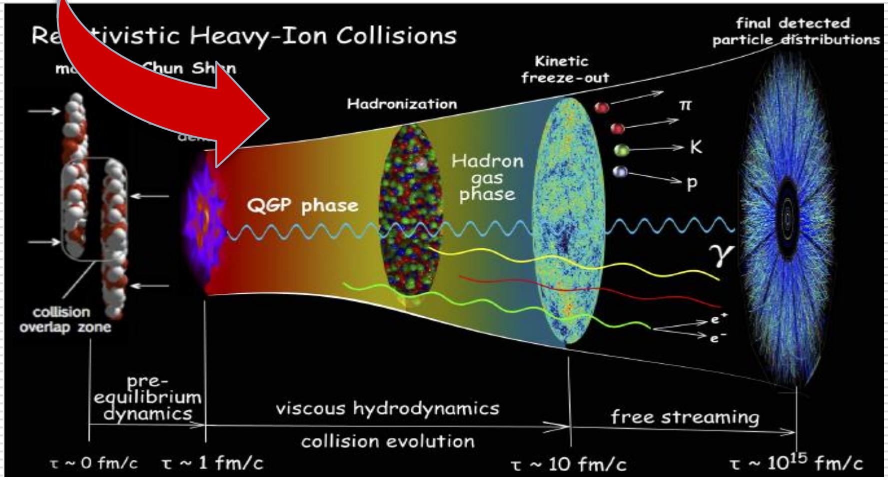
- heavy ion collisions recreate droplets of the state of matter of our Universe 1μs after the Big Bang
  - state at this time and its evolution to hadronic phase (cross-over vs. 1st order phase transition) had severe influence on the entire history of our Universe



What can we learn from HI collisions ?

Emergence of Complex Quantum Matter



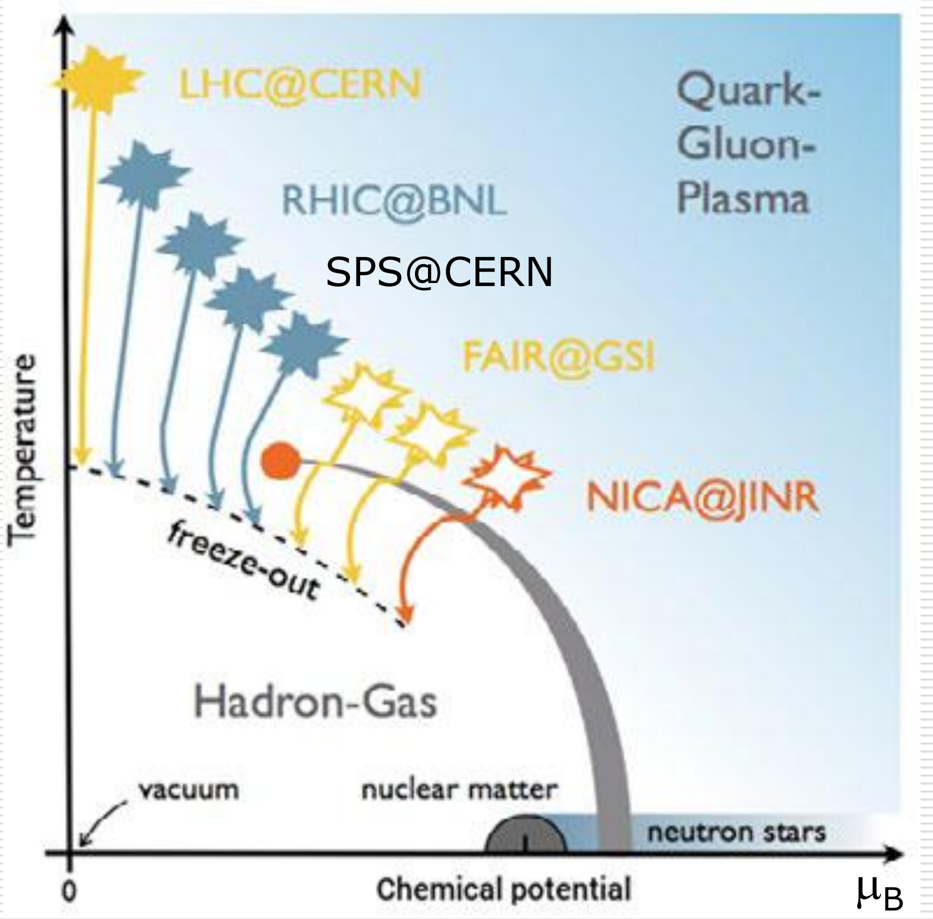


What can we learn from HI collisions ?

Phase Diagram of QCD

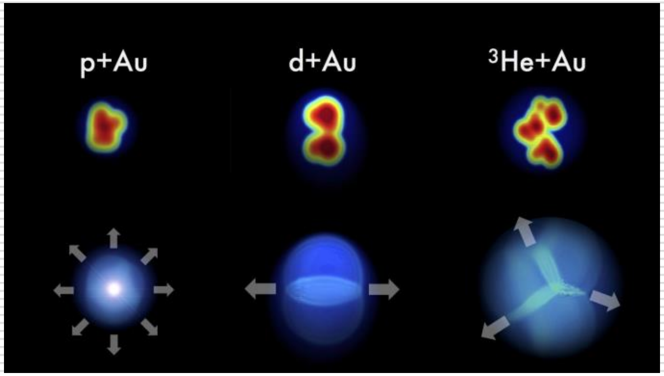
understanding the nature of any complex material needs mapping its full phase diagram

- μ_B=0 describes matter with equal densities of quarks and antiquarks.
  - early Universe and HI collisions at LHC and top RHIC energy in the central rapidity region
- μ_B>0, QGP doped with a significant excess of quarks over antiquarks
  - in highest-energy HI collisions, where QGP forms from the compressed remnants of the incident nuclei, looking at debris produced at very high rapidity
    - not yet detectors that can do that
  - scan the QCD phase diagram of QCD with HI collisions with lower and lower collision energies
    - RHIC BES, SPS, FAIR, NICA, J-PARC



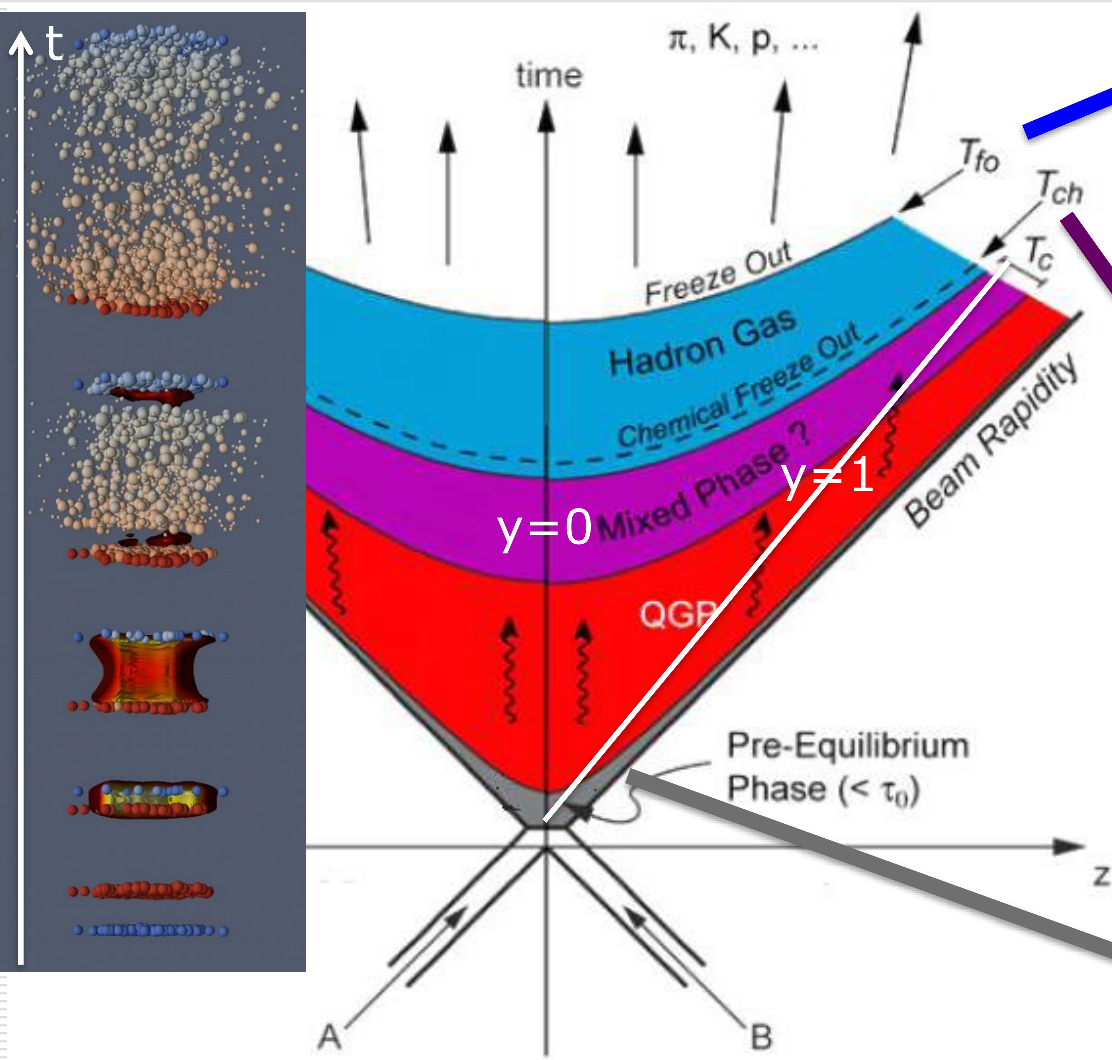
not just HI…

- study of “reference” colliding systems like pp and d-Au is a fundamental part of any HI programme



At the LHC, not just “reference”: extreme pp and p-Pb events have revealed unexpected features

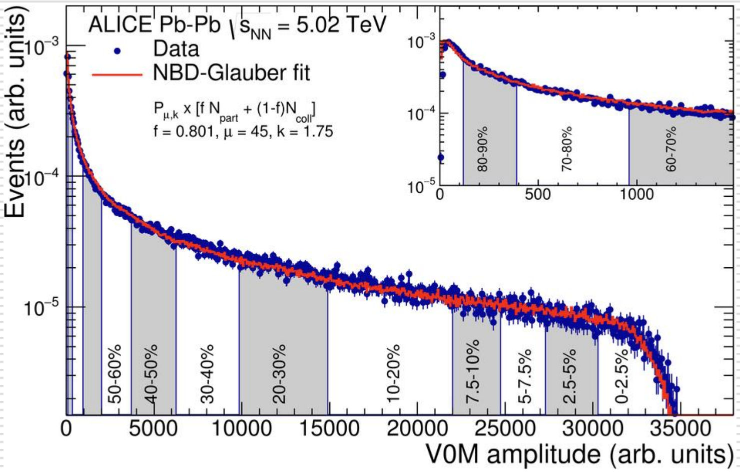
Space time evolution of A-A collision

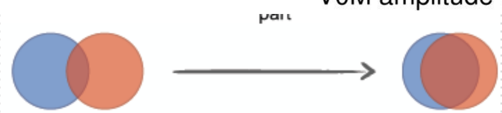


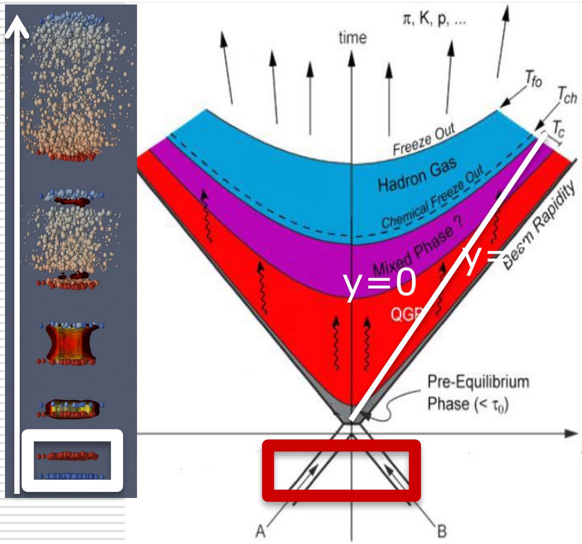
- Thermal freeze-out
  - Elastic interactions cease
  - Particle dynamics ("momentum spectra") fixed
  - T_{fo} ~ 110-120 MeV
- Chemical freeze-out
  - Inelastic interactions cease
  - Particle abundances ("chemical composition") are fixed
  - T_{ch} ~ 155 MeV
- Thermalization time
  - System reaches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

Initial stage

The geometry of HI collisions can be determined precisely







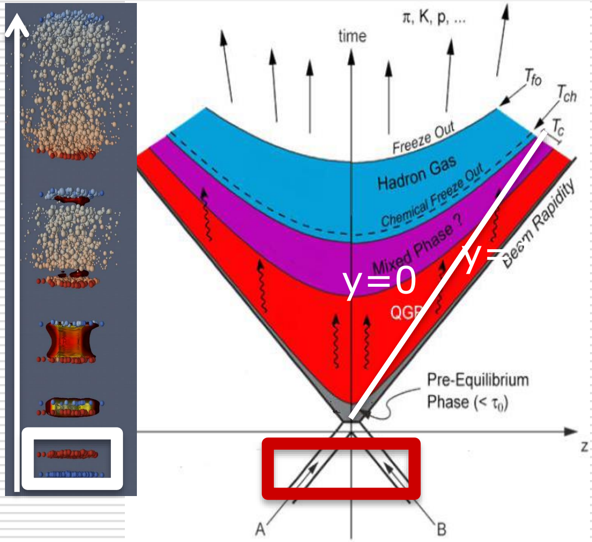
Centrality variables:

- $\boldsymbol{N_{coll}}$: number of binary nucleon-nucleon collisions ($\boldsymbol{N_{bin}}$)
- $\boldsymbol{N_{part}}$: number of nucleons participating to the collisions ($\boldsymbol{N_{wound}}$)
- Percentile of hadronic cross-section:
  - 0-5% → most central collisions ; 80-90% → peripheral collisions

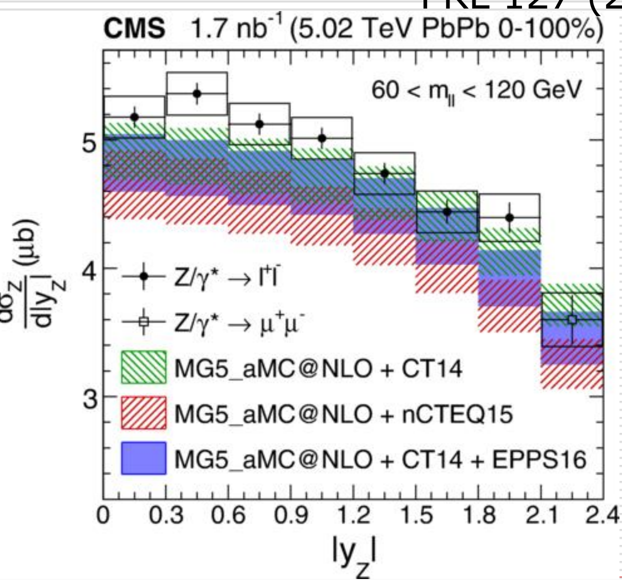
Initial stage

Distributions of partons in the nucleons are affected by the presence of other nucleons:

- nuclear PDFs (nPDFs)
  - determined studying p-A collisions, ultra-peripheral AA collisions, or even AA collisions with probes unaffected by the strong interactions (EW bosons)



PRL 127 (2021) 102002



current nPDFs underestimate the CMS Z^0 measurement

Soft probes

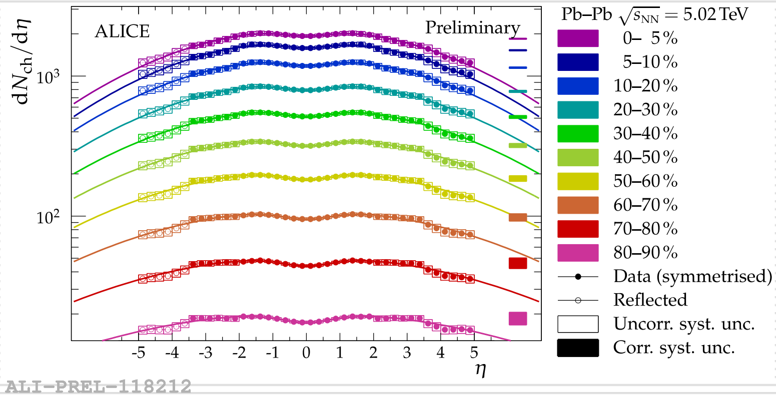
- several observables, e.g.
  - total multiplicity → estimate of initial energy density
  - kinematic distributions of identified particles
    - p_t or y differential distribution, double differential distributions (in y, p_t and azimuthal angle ϕ)

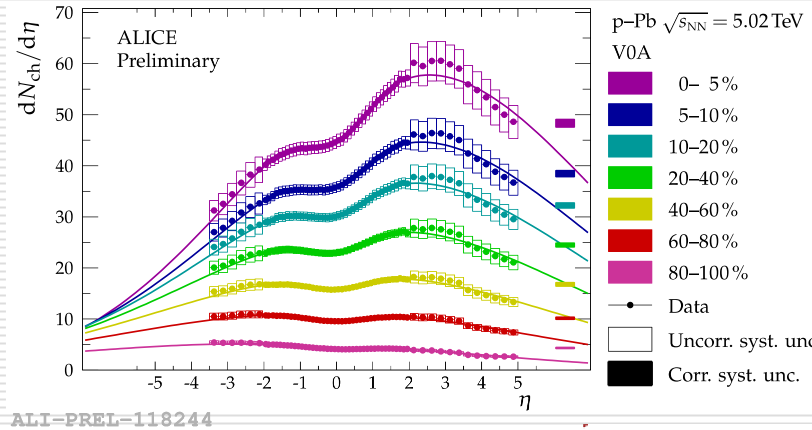
      → collective dynamics of the medium
  - hadrochemistry: (relative) abundancies of different species
    - statistical models, in the grand-canonical limit (where **local** conservation of quantum numbers is not imposed), work very well

      → T_{ch} and μ_B
  - two-particle momentum correlations → system sizes, strong interaction between hadrons
  - event by event fluctuations → critical point

Total multiplicity

- charged particle multiplicity density $dN/d\eta$ at $\sqrt{s_{NN}}$=5.02 TeV for different centralities





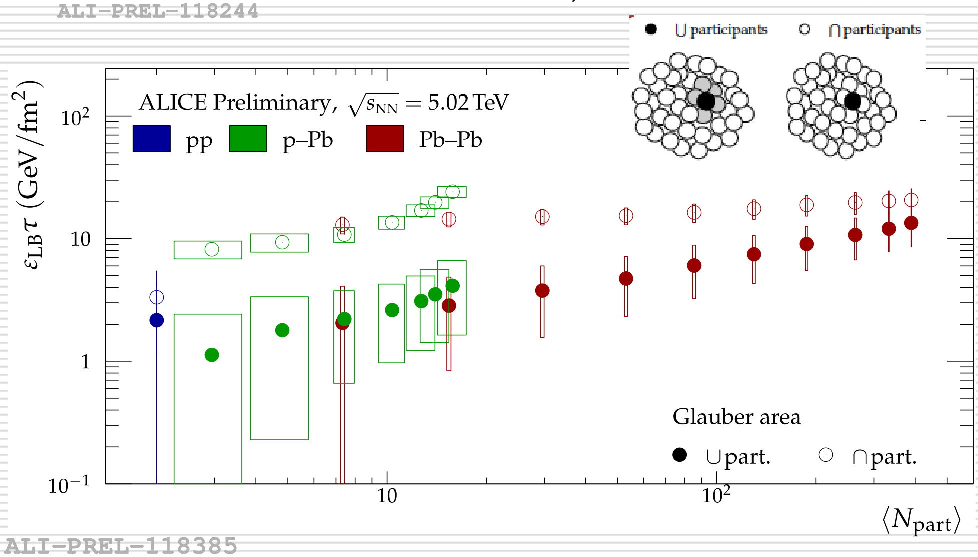
J.D. Bjorken PRD **27** (1983) 140

$$\boxed{\varepsilon_{Bj} = \frac{1}{c\tau}\frac{1}{S_T}\left\langle\frac{dE_T}{dy}\right\rangle}$$

$$S_T \approx \pi R^2 \approx \pi N_{part}^{2/3}$$

$$f_{total} = 0.55 \pm 0.01$$

$$\left\langle\frac{dE_T}{dy}\right\rangle \approx \langle m_T\rangle \frac{1}{f_{total}}\frac{dN_{ch}}{dy}$$



<u>lower bound</u> on the energy density times τ_{eq} larger than 10 GeV/fm²

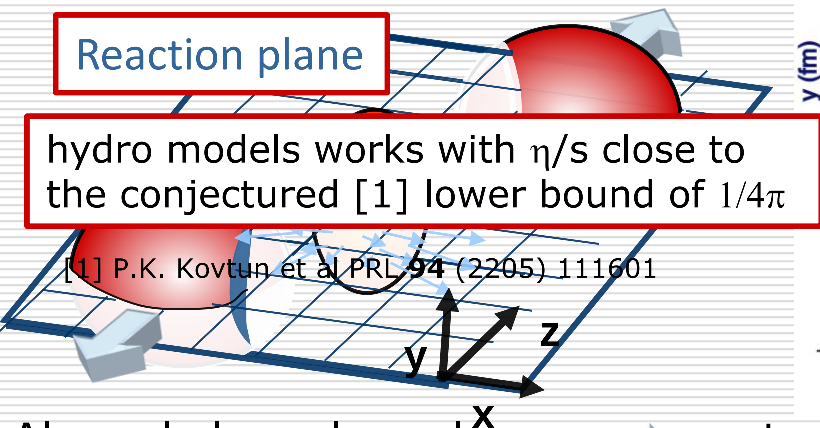
Kinematic distributions of identified particles

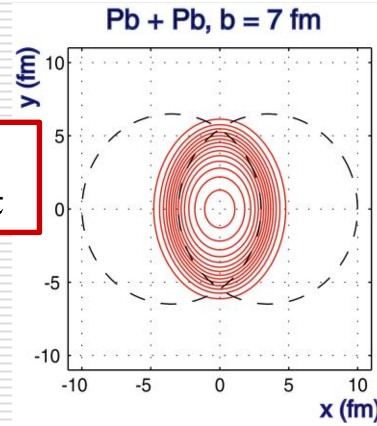
□ Azimuthal anisotropy

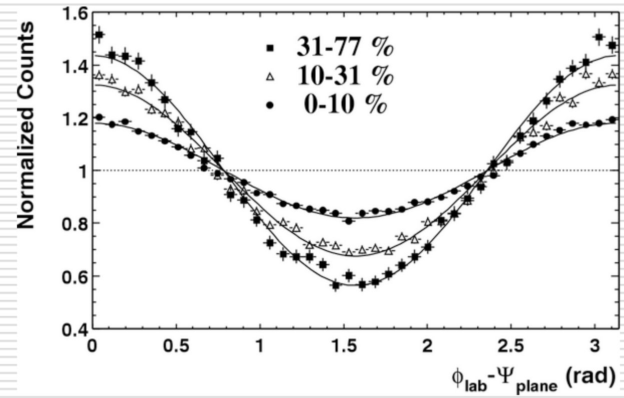
Reaction plane

hydro models works with η/s close to the conjectured [1] lower bound of $1/4\pi$

[1] P.K. Kovtun et al PRL **94** (2205) 111601







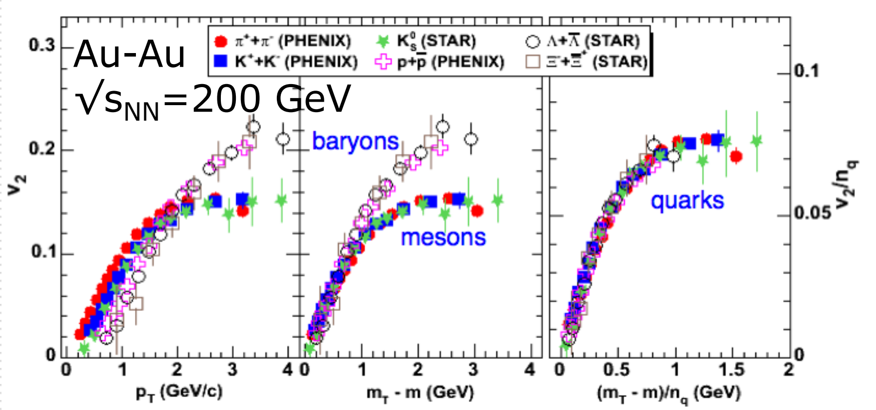
STAR, PRL **90** (2003) 032301

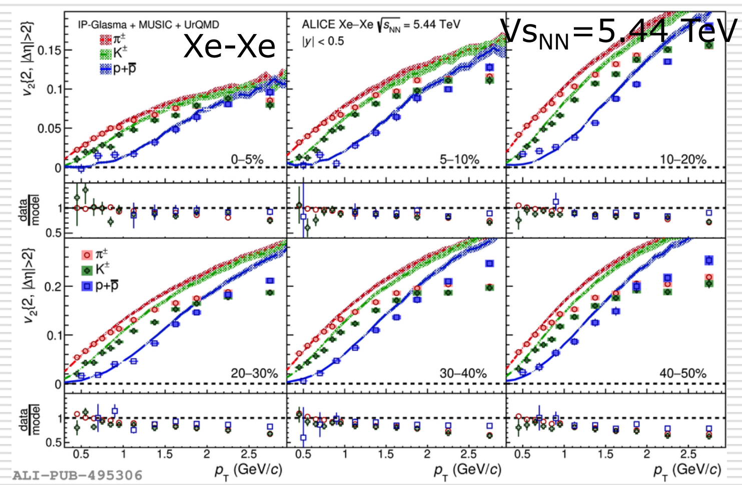
Almond shaped overlap region in geom. space → strong in-plane expansion due to pressure gradients → anisotropy in momentum space

$$\frac{dN}{d(\varphi-\psi_{RP})} \propto 1+2\sum_{n=1} v_n \cos\left(n[\varphi-\psi_{RP}]\right)$$

$$v_2 = \left\langle \cos\left[2(\varphi-\psi_{RP})\right]\right\rangle$$

arXiv:0809.2949 and references therein





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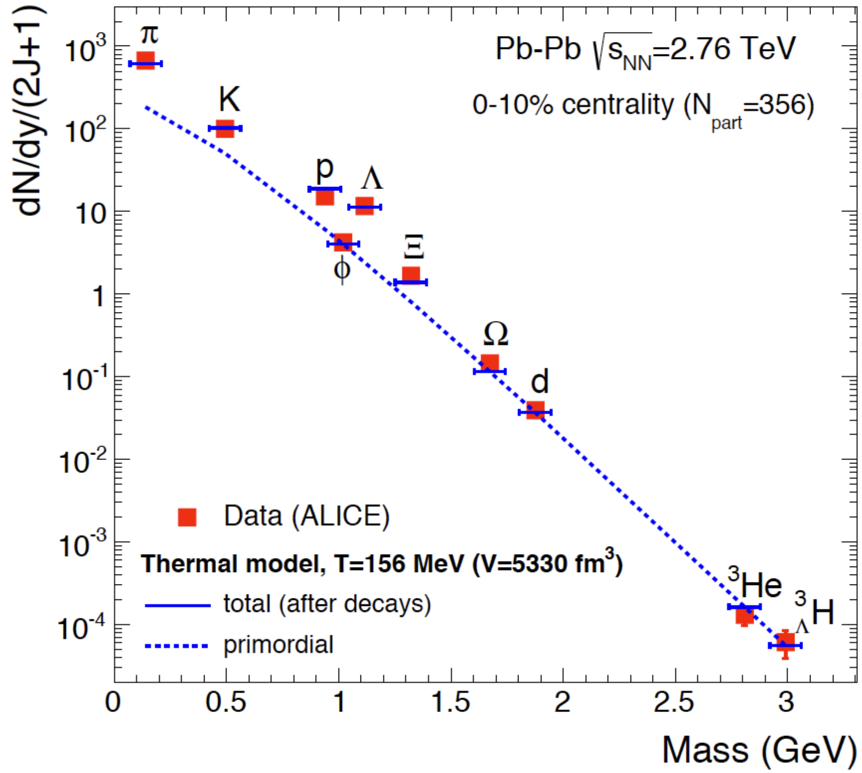
Hadrochemistry

Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models

- In Pb-Pb collisions at LHC, particle yields of light flavor hadrons are described over 7 orders of magnitude with a common chemical freeze-out temperature of $T_{ch} \approx 155$ MeV
- This includes hadrons with strange quarks which are rarer than u,d quarks.
  - Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).



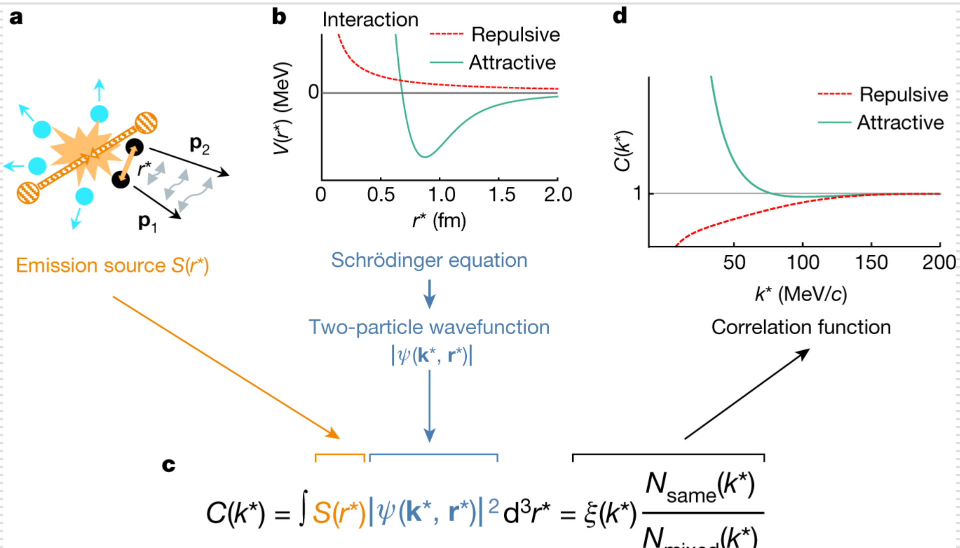
Light (anti-)nuclei are also well described despite their low binding energy ($E_b << T_{ch}$).

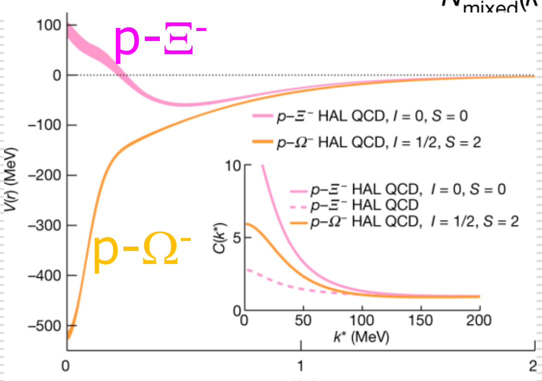
Fit works equally well at SPS and RHIC energies

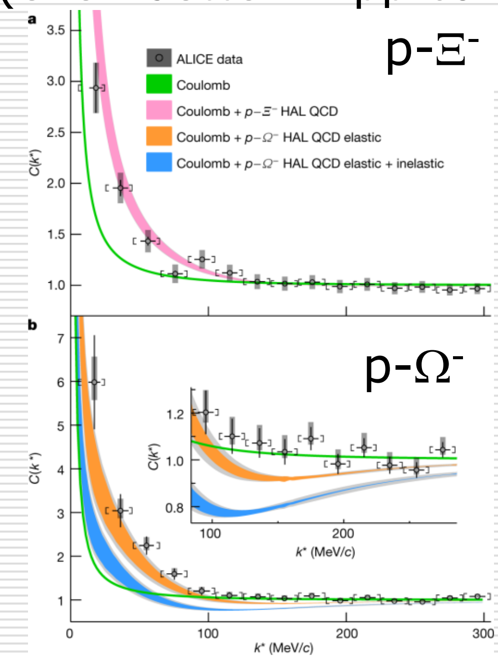
Two particle correlation

- identical particle (HBT)→ evolution of system sizes (month-1 measurement)
- hadron1-hadron2 correlation→ strong interaction (even better in pp collisions)

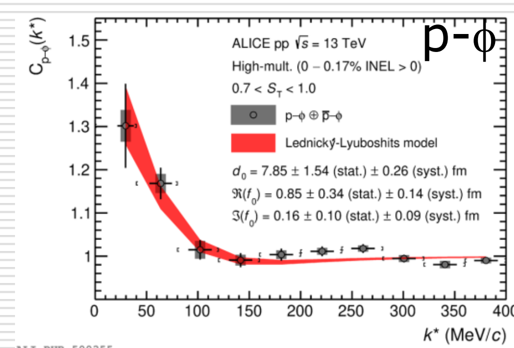
ALICE, *Nature* **588** (2020) 232







ALICE *Nature* **588** (2020) 232



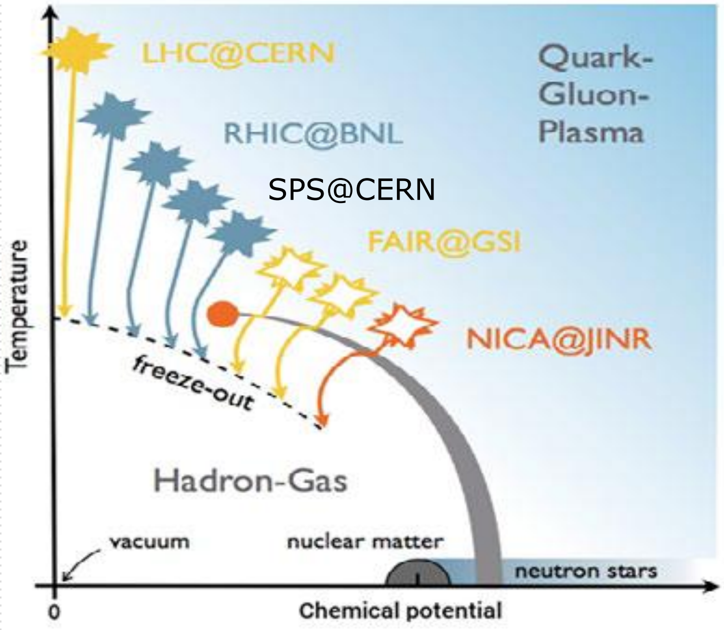
PRL 127 (2021) 172301

Event by event fluctuations

- Higher order **cumulants** of conserved quantities (B, Q, S) are sensitive to the QCD critical point and the 1-order phase transition
- STAR (BES at RHIC) and NA61/SHINE (SPS) have broad programmes which include fluctuations

$$\delta N = N - \langle N \rangle$$
$$C_1 = \langle N \rangle,\ C_2 = \langle (\delta N)^2 \rangle,\ C_3 = \langle (\delta N)^3 \rangle$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$
$$S = C^3/(C^2)^{3/2},\ \kappa = \frac{C^4}{(C^2)^2},$$
$$\frac{C_2}{C_1} = \frac{\sigma^2}{M},\qquad \frac{C_3}{C_2} = S\sigma,\qquad \frac{C_4}{C_2} = \kappa\sigma^2$$

$\boxed{C_1 = M}$ $\boxed{C_2 = \sigma^2}$ $\boxed{C_3 = S\sigma^3}$ $\boxed{C_4 = \kappa\sigma^4}$



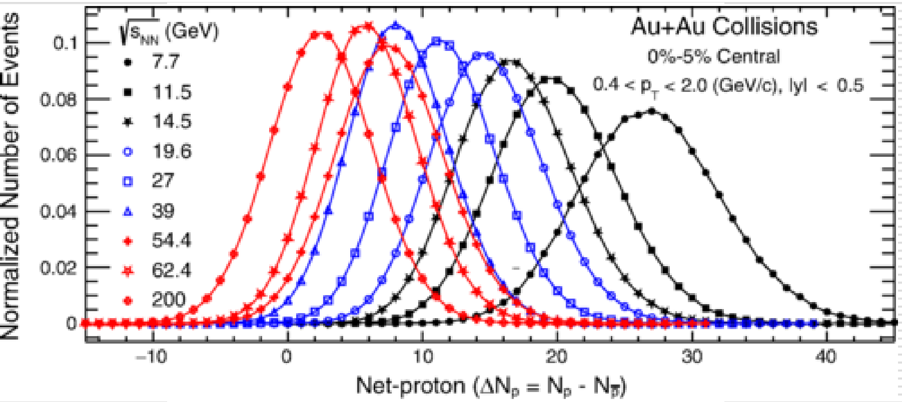
Non-monotonic variations with $\sqrt{s_{NN}}$ expected around the critical point

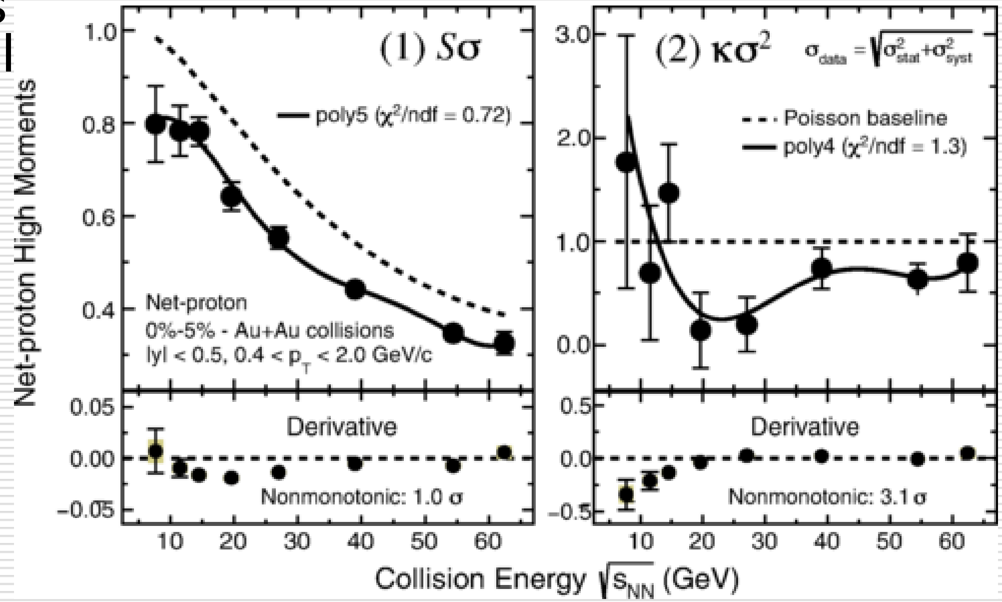
Event by event fluctuations

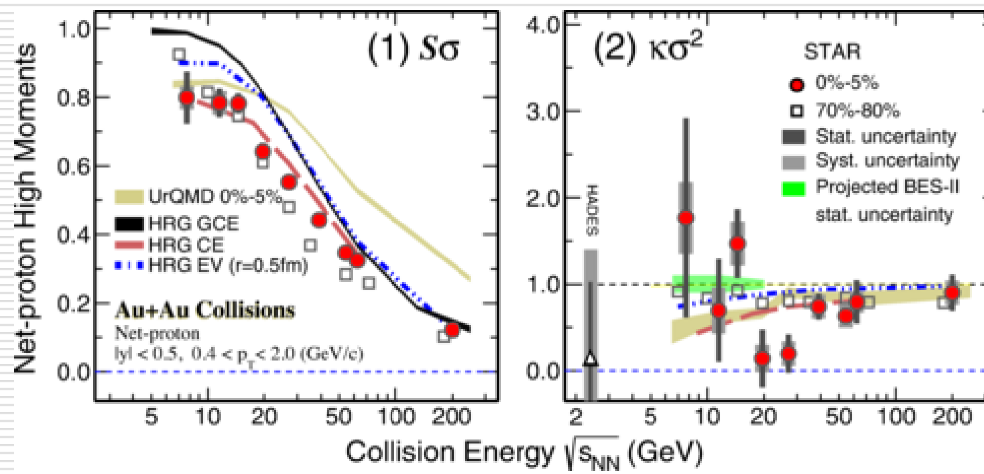
STAR PRL. 126 (2021) 092301

- Ratio of **net-proton** cumulants as a function of $\sqrt{s_{NN}}$ for central Au-Au collisions

$$\frac{C_3}{C_2} = S\sigma, \qquad \frac{C_4}{C_2} = \kappa\sigma^2$$



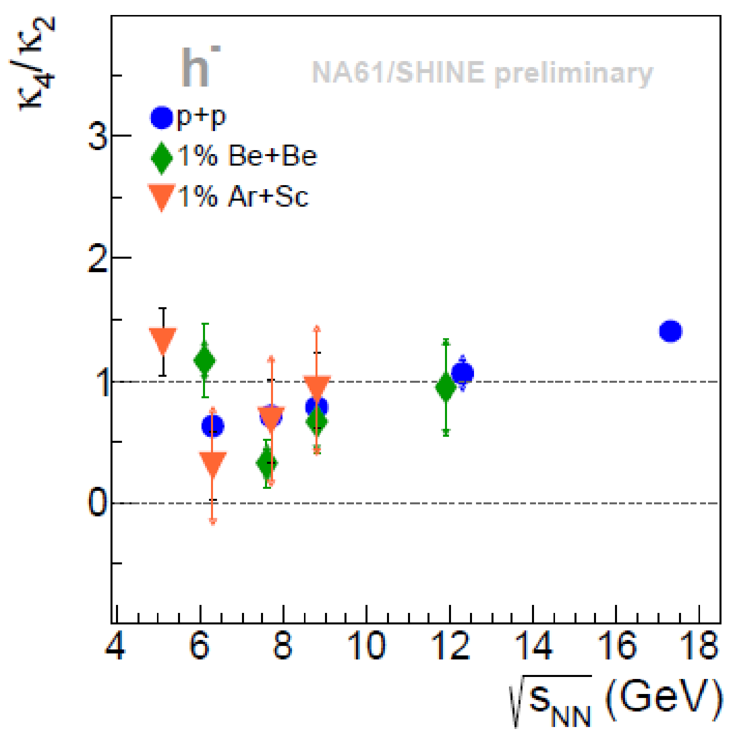




- Observation of non-monotonic dependence of $\kappa\sigma^2$ (3.1σ)
- Data in peripheral collisions and models without critical point show a monotonic dependence
- further results expected from BES-II (2023-25) data

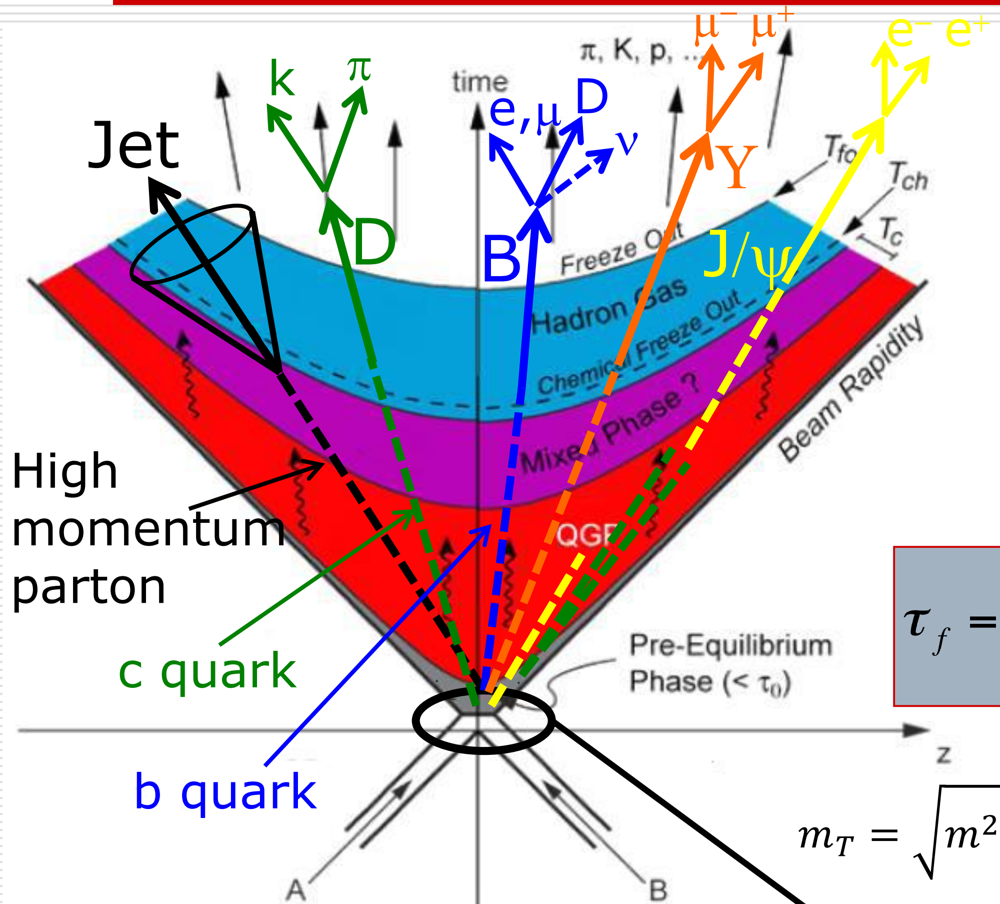
Event by event fluctuations

- but the critical point is still eluding experimental evidence



No indication of the critical point based on higher order moments of h⁻ nor proton intermittency
→Need more data, a new programme confirmed for >2022, after shutdown

Hard probes of A-A collision



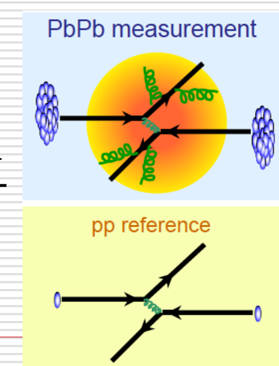
$$\tau_f = \frac{\hbar}{m_T}$$

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

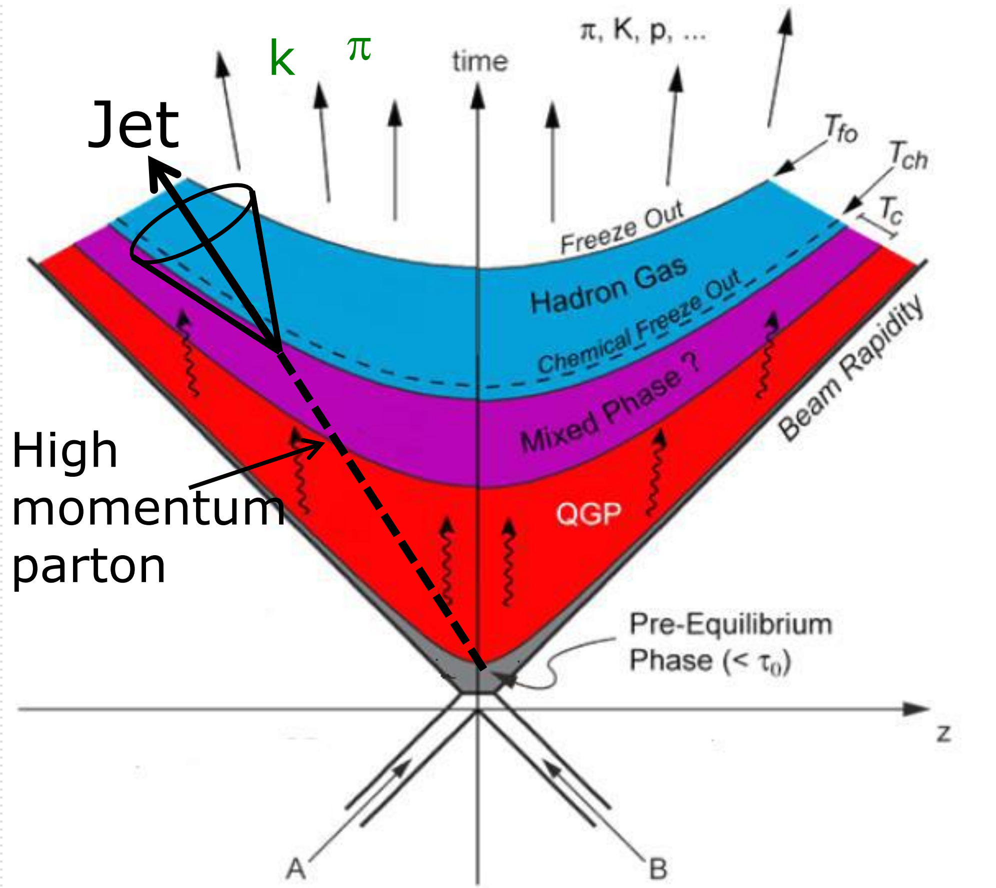
Hard probes in nucleus-nucleus collisions:

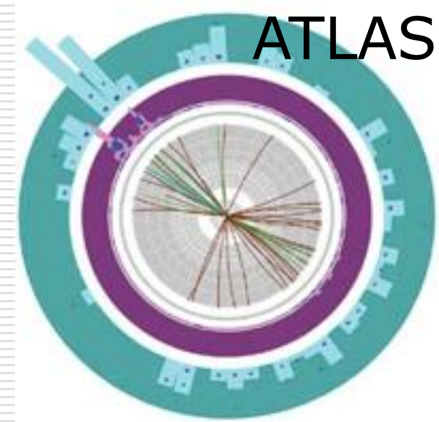
- produced at the very early stage of the collisions in partonic processes with large Q^2
- pQCD can be used to calculate initial cross sections
- traverse the hot and dense medium
- can be used to probe the properties of the medium

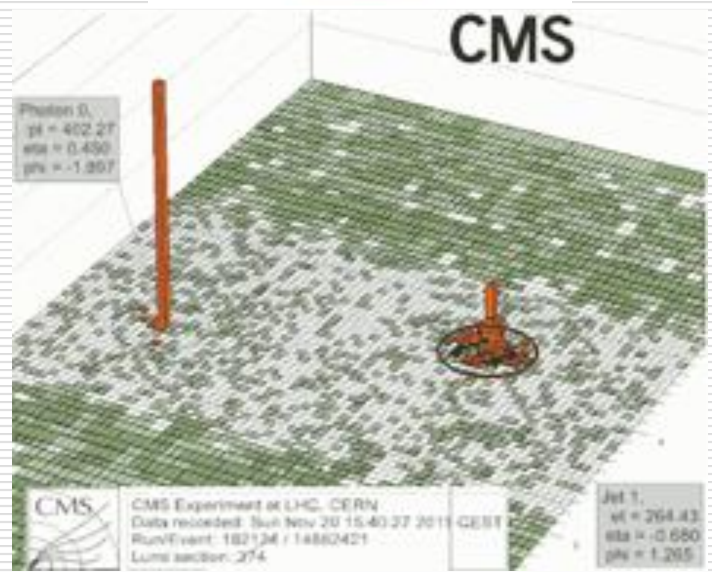
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$



JETS

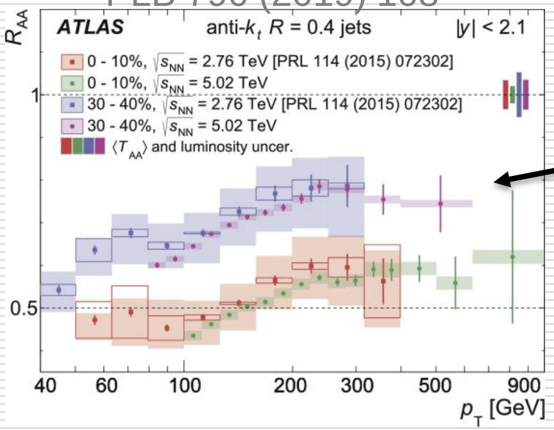

Jet
k
π
time
π, K, p, ...
T_{fo}
T_{ch}
T_c
Freeze Out
Hadron Gas
Chemical Freeze Out
Mixed Phase ?
Beam Rapidity
QGP
High momentum parton
Pre-Equilibrium Phase ($< \tau_0$)
z
A
B


ATLAS


CMS

Jets: what we expected and learned

PLB 790 (2019) 108

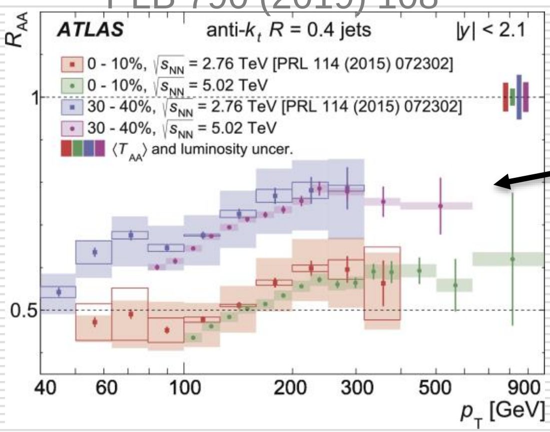


Jets are quenched in AA collisions

up to p_T =1 TeV

Jets: what we expected and learned

PLB 790 (2019) 108



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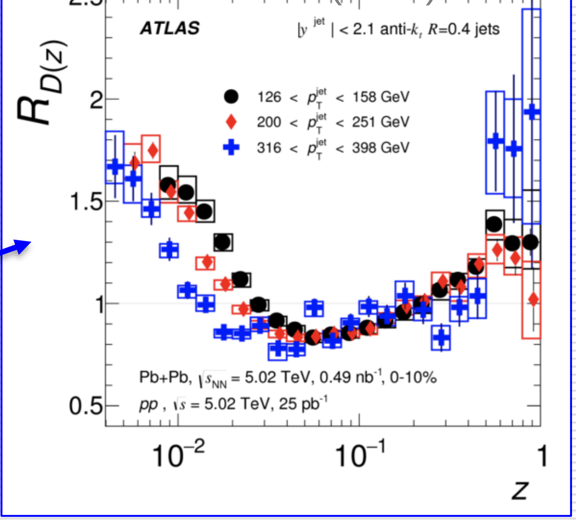
Jets in the medium appears softer

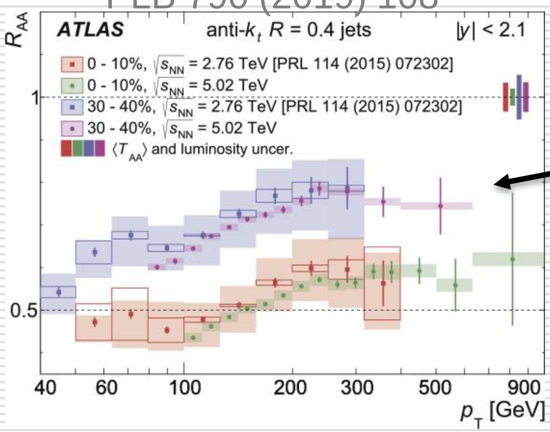
PRC 98 (2018) 024908



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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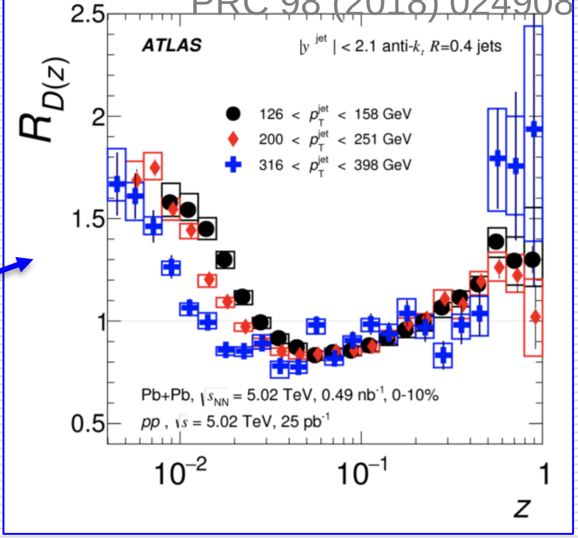
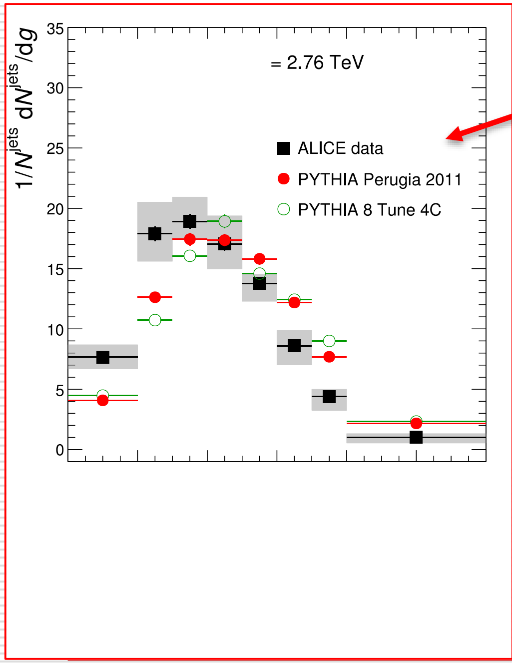




JHEP 10 (2018) 139

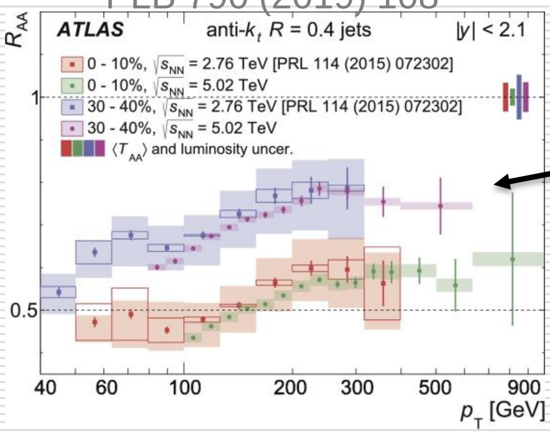
The hard core of the jets get narrower in the medium

Girth = width of a jet

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

Jets: what we expected and learned

PLB 790 (2019) 108



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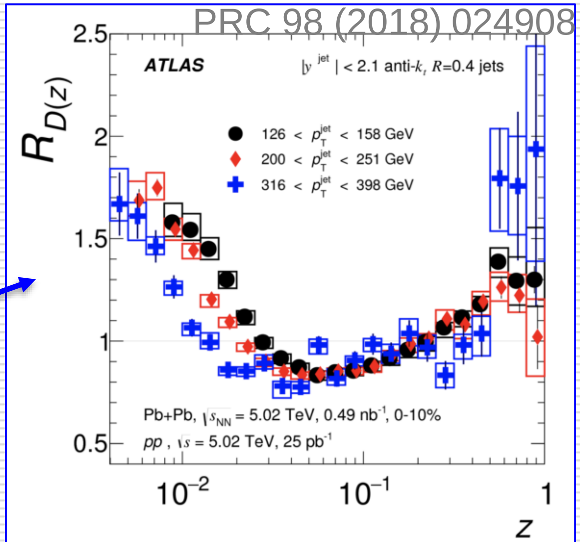

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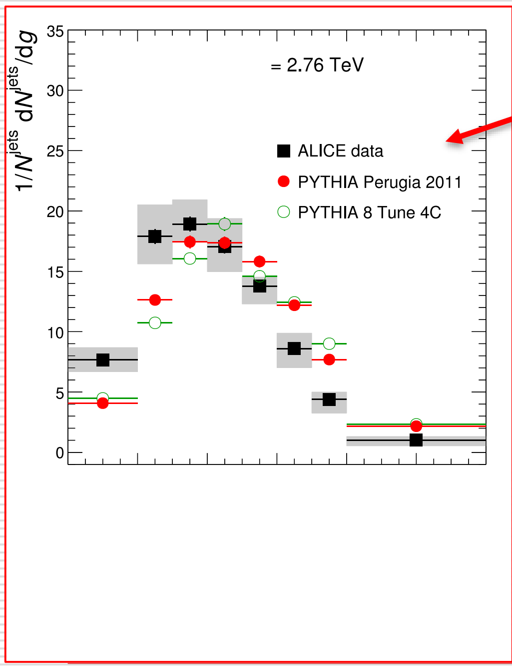
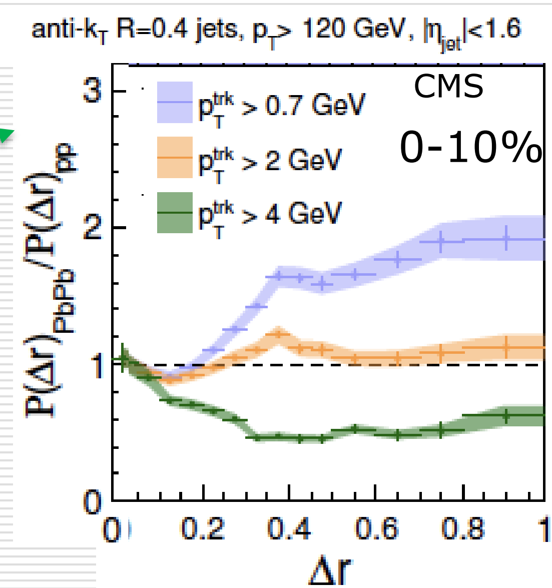


JHEP 10 (2018) 139

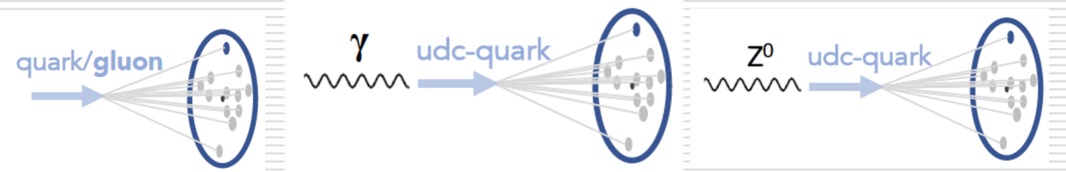
the soft part diffuses to large angles

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



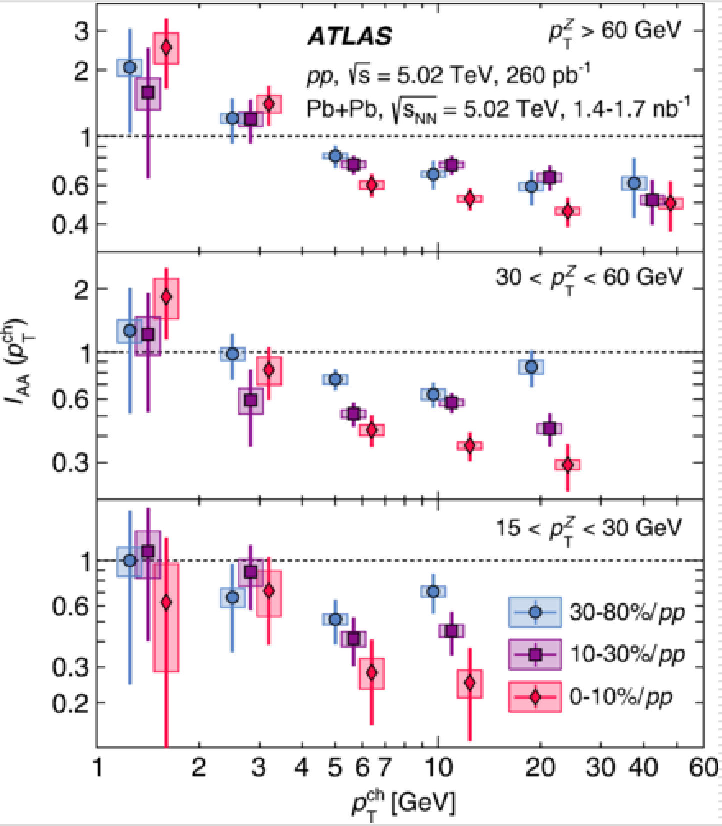
JHEP05 (2018) 006

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

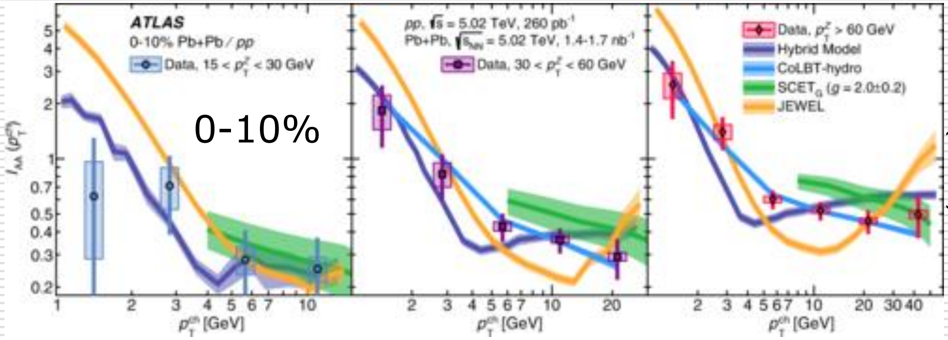


Z vs γ -tagged jets:

- 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

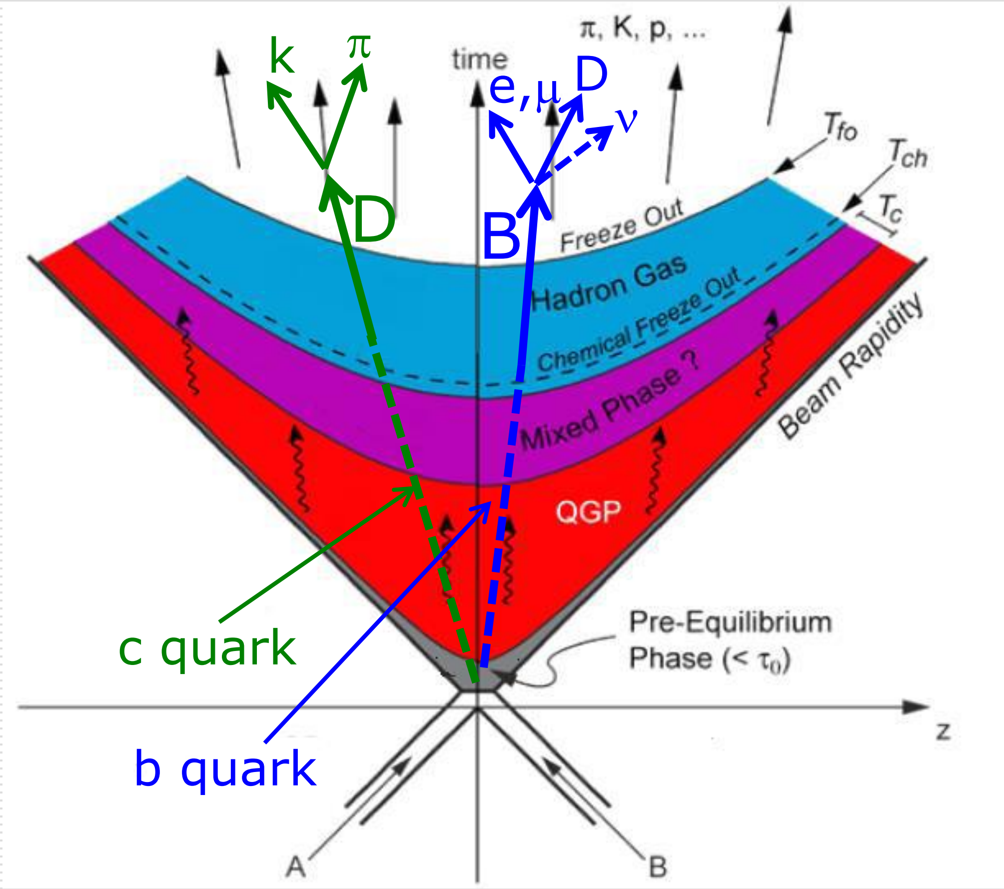
The per-Z yields modified in PbPb compared to pp

- 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)



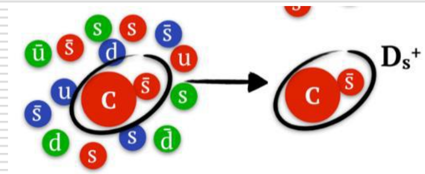
PRL 126 (2021) 072301

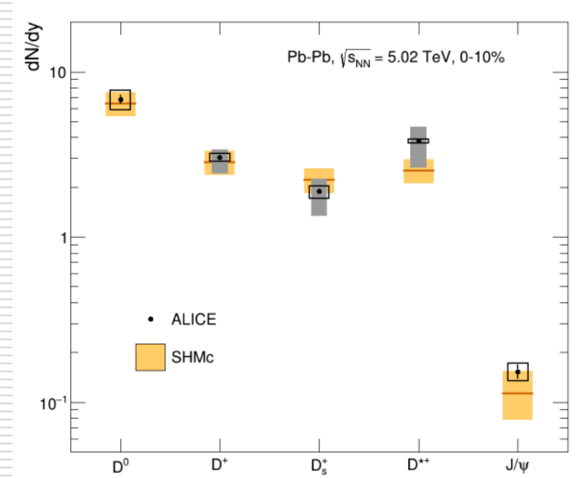
Heavy Flavour: open HF



Heavy flavour: charm hadro-chemistry

$$\tau_f = \frac{\hbar}{m_T} \qquad m_T = \sqrt{m^2 + p_T^2}$$

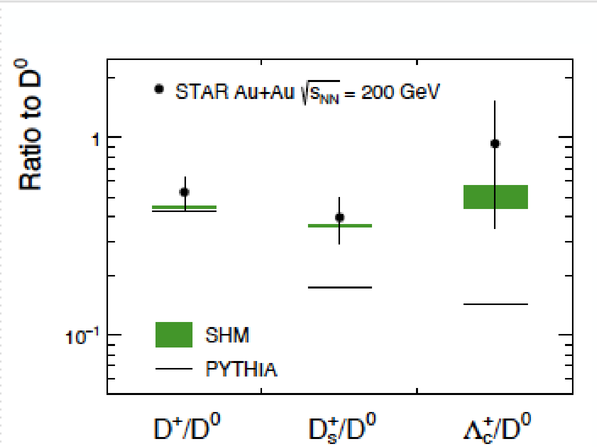




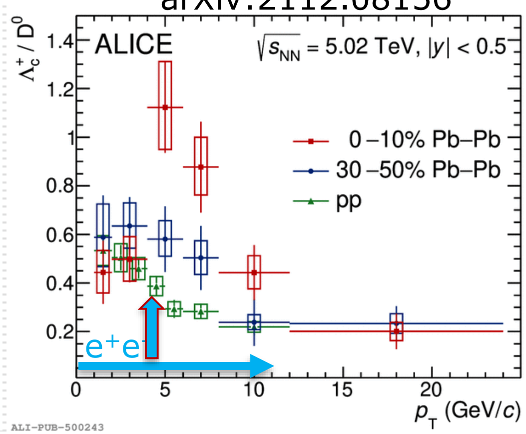
(relative) abundancies of charmed <u>mesons</u> reproduced by thermal models

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

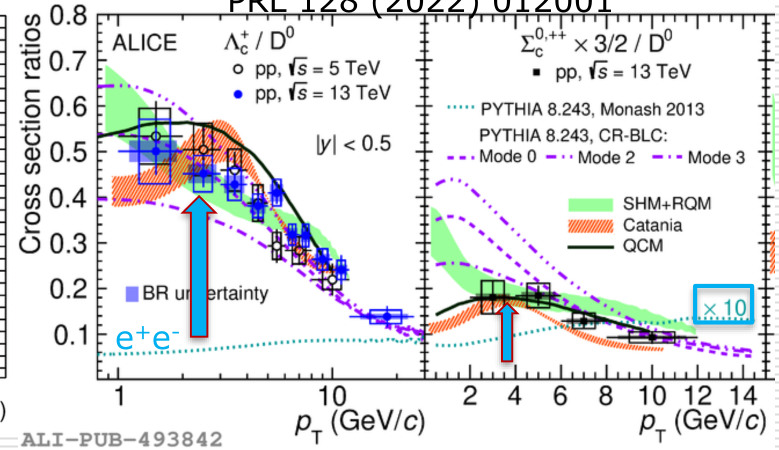
-> hadro-chemistry at the freeze-out reflects **how** these **quarks** have “**dressed**” while escaping from the fireball



arXiv:2112.08156



PRL 128 (2022) 012001



universality of charm (and beauty) fragmentation **broken** at the LHC

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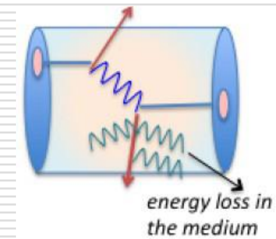
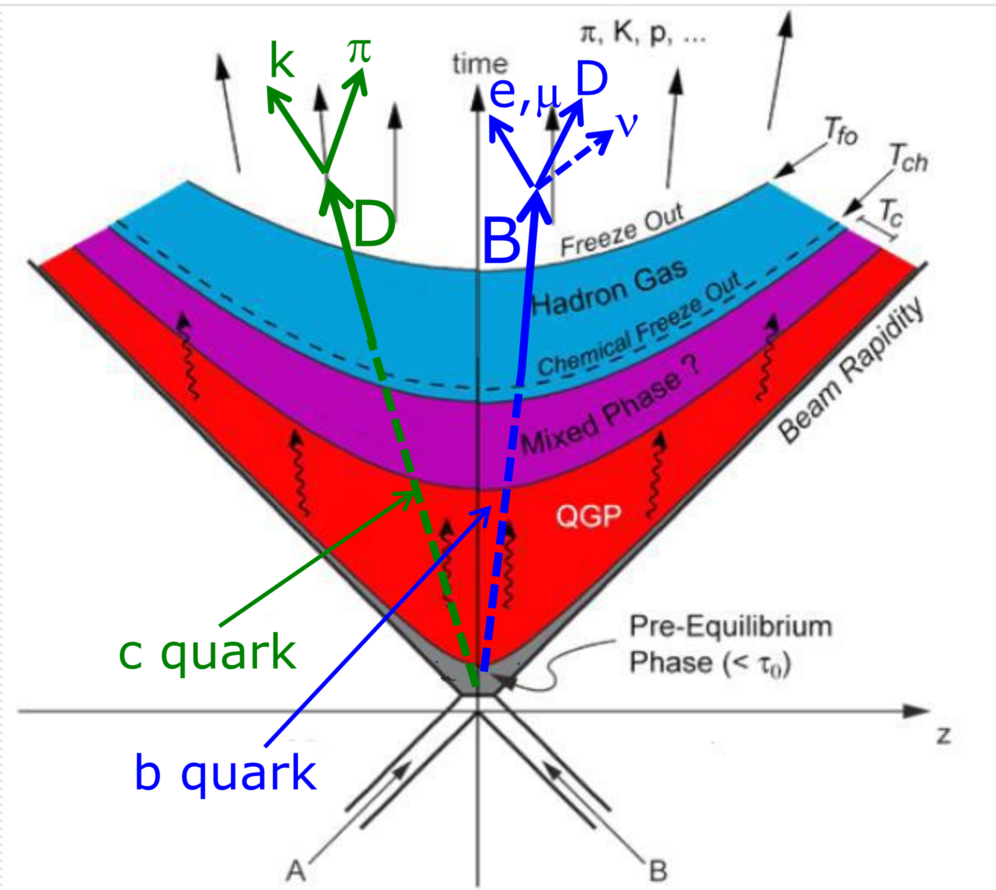




Energy loss depends on:

- Color charge $\Delta E_g > \Delta E_{u,d,s}$
- Parton mass $\Delta E_c > \Delta E_b$

At the parton level:

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

Naive expectation:

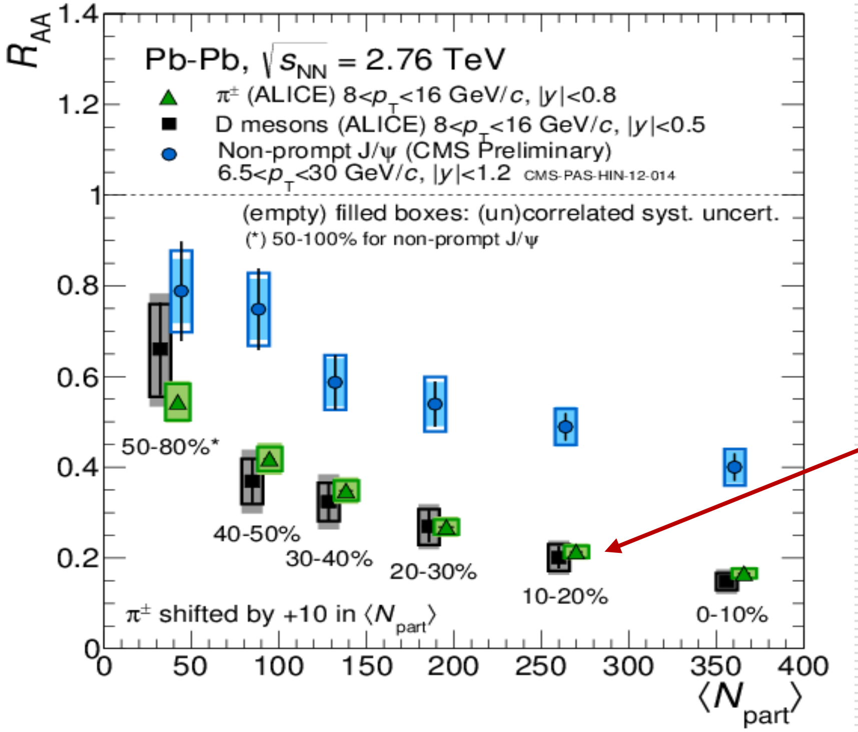
$R_{AA}(\pi) > R_{AA}(D) > R_{AA}(B)$?

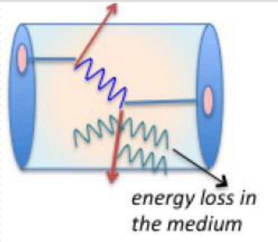
More complicated due to different production kinematics and fragmentation of light and heavy quarks

Heavy Flavour: open HF

Soon understood with LHC run1 data

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





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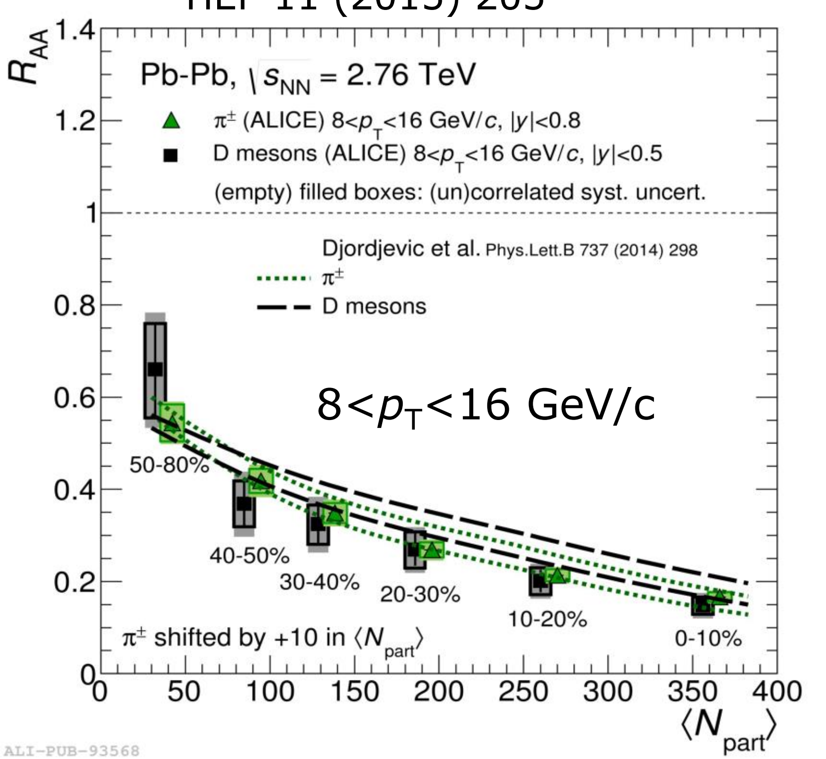

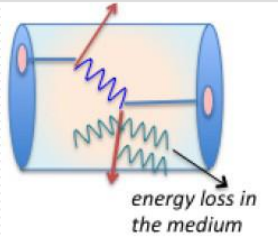

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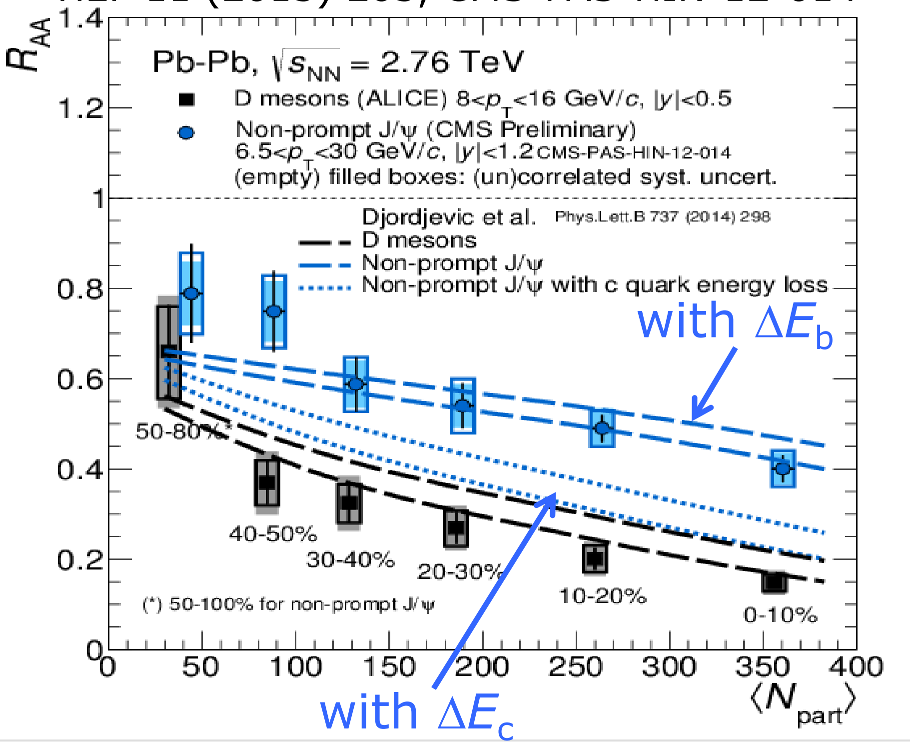

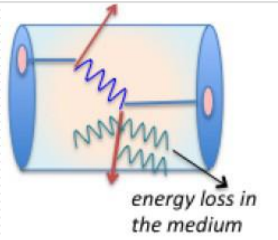

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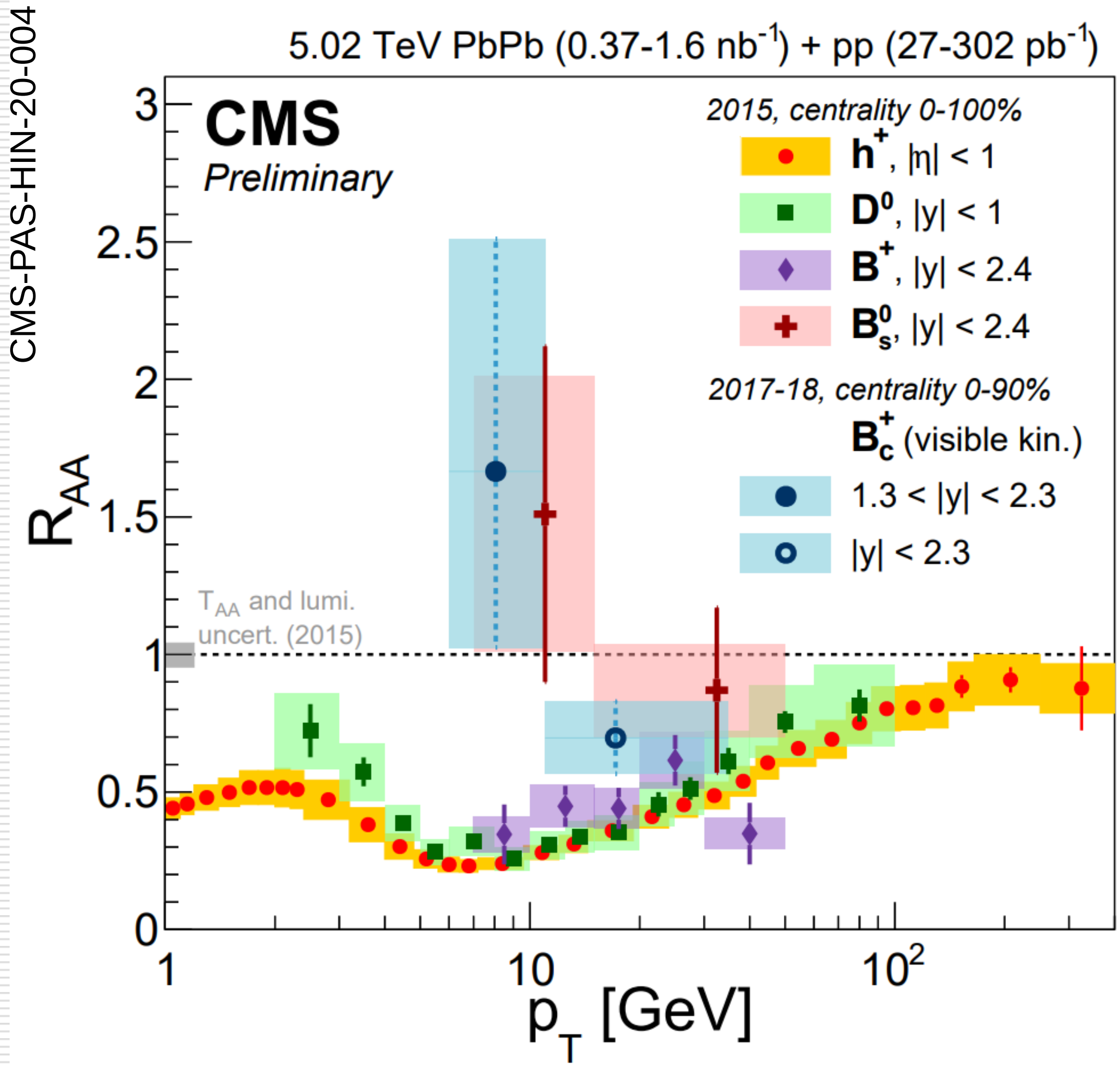
$R_{AA}(\pi) \approx R_{AA}(D) > R_{AA}(B)$?

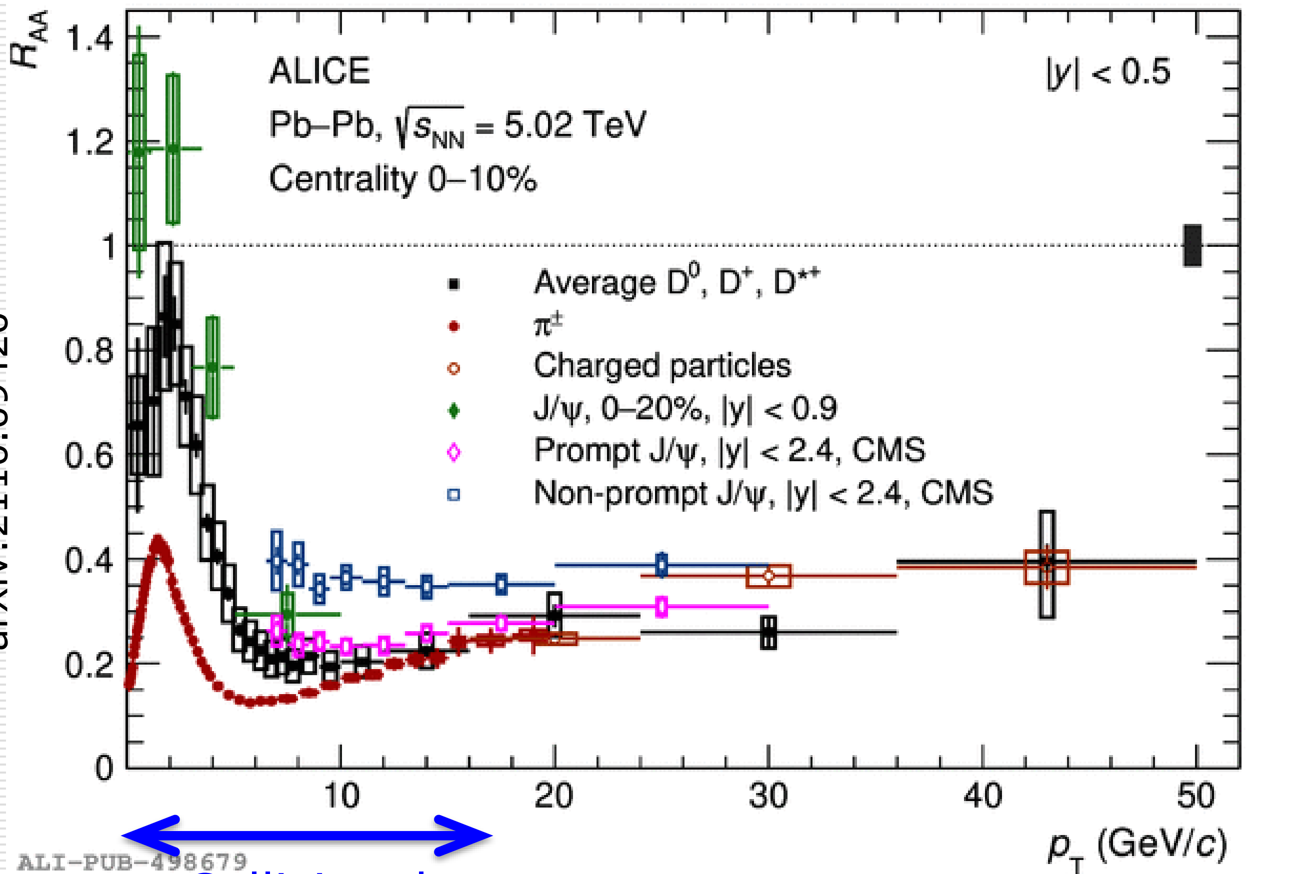
More complicated due to different production kinematics and fragmentation of light and heavy quarks

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



… p_T range still drives the physics



arXiv:2110.09420

also for the v_2 observables

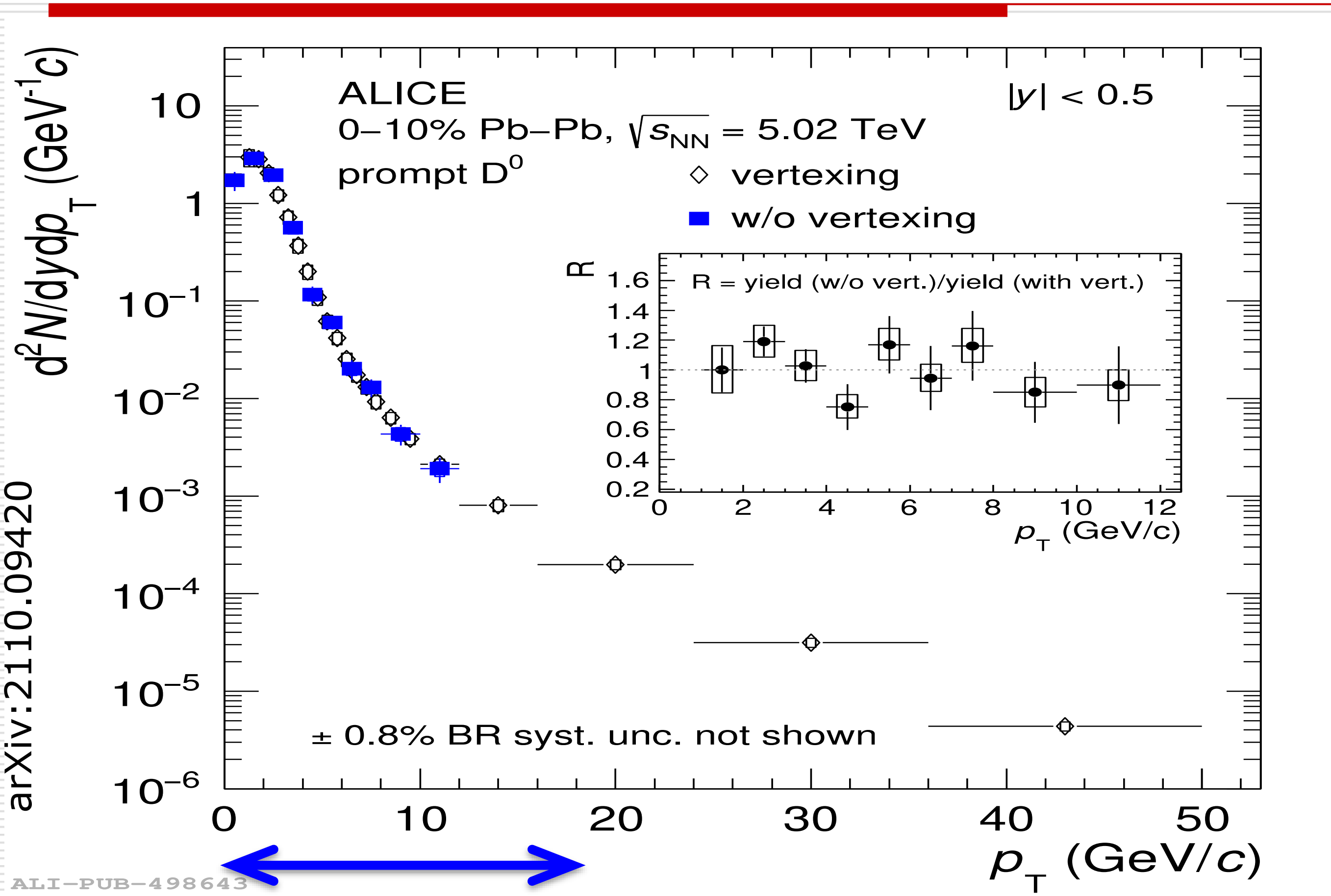
the lower the better !

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



also for the v_2 observables

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Collisional dE/dx relevant

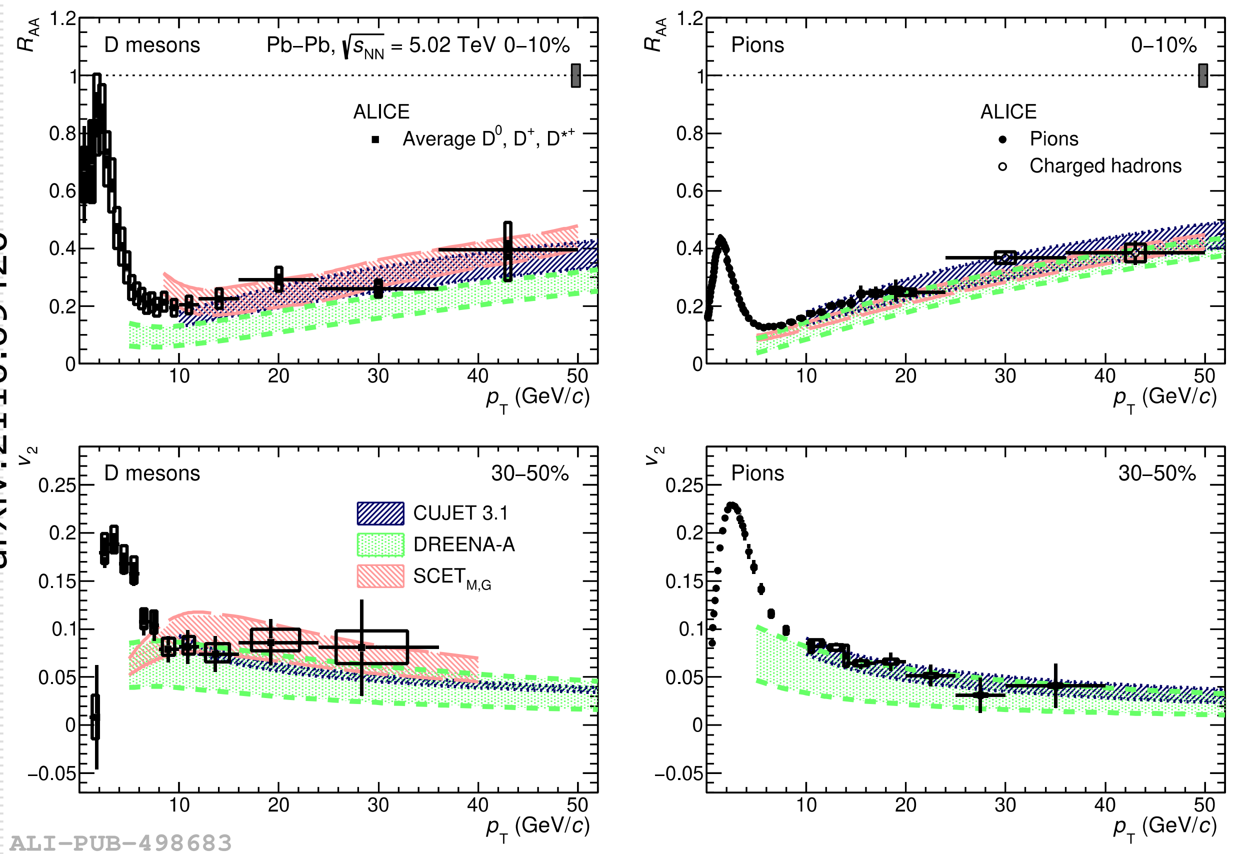
Radiative dE/dx dominates

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

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

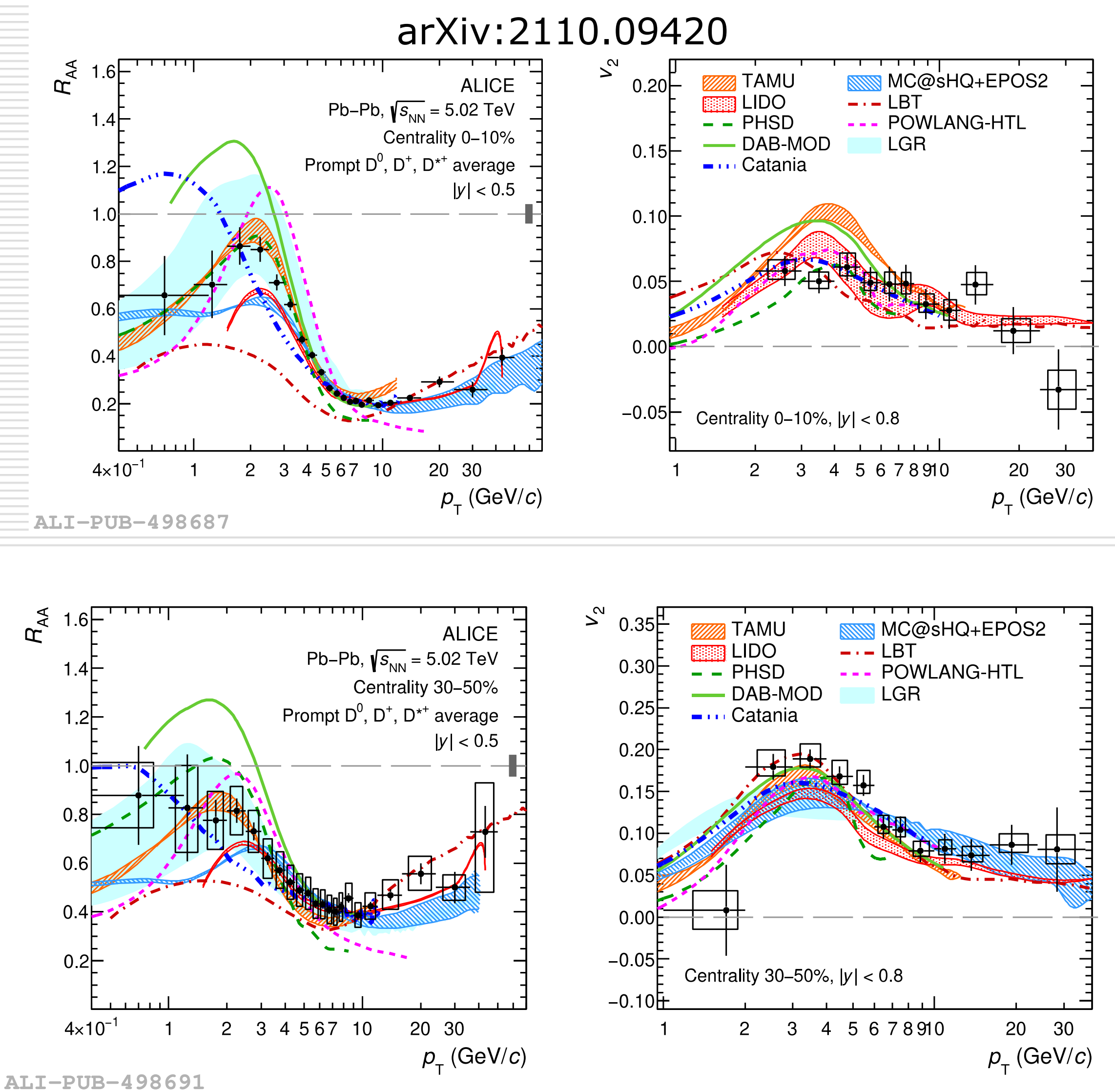


The three models have different implementations of radiative energy loss with dependence on color charge, parton mass and path length in the medium

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

Prompt D meson R_{AA} and v_2

arXiv:2110.09420



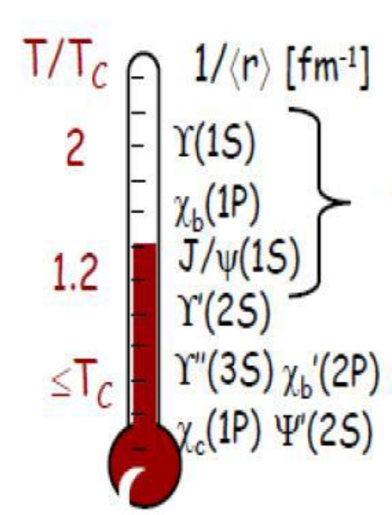
TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: arXiv:1912.08965
LIDO: PRC 98 (2018) 064901
PHSD: PRC 93 (2016) 034906
Catania: PLB 805 (2020) 135460
POWLANG: EPJC (2019) 79:494
LBT: PRC 94 (2016) 014909
DAB-MOD: arXiv:1906.10768

Model ingredients:

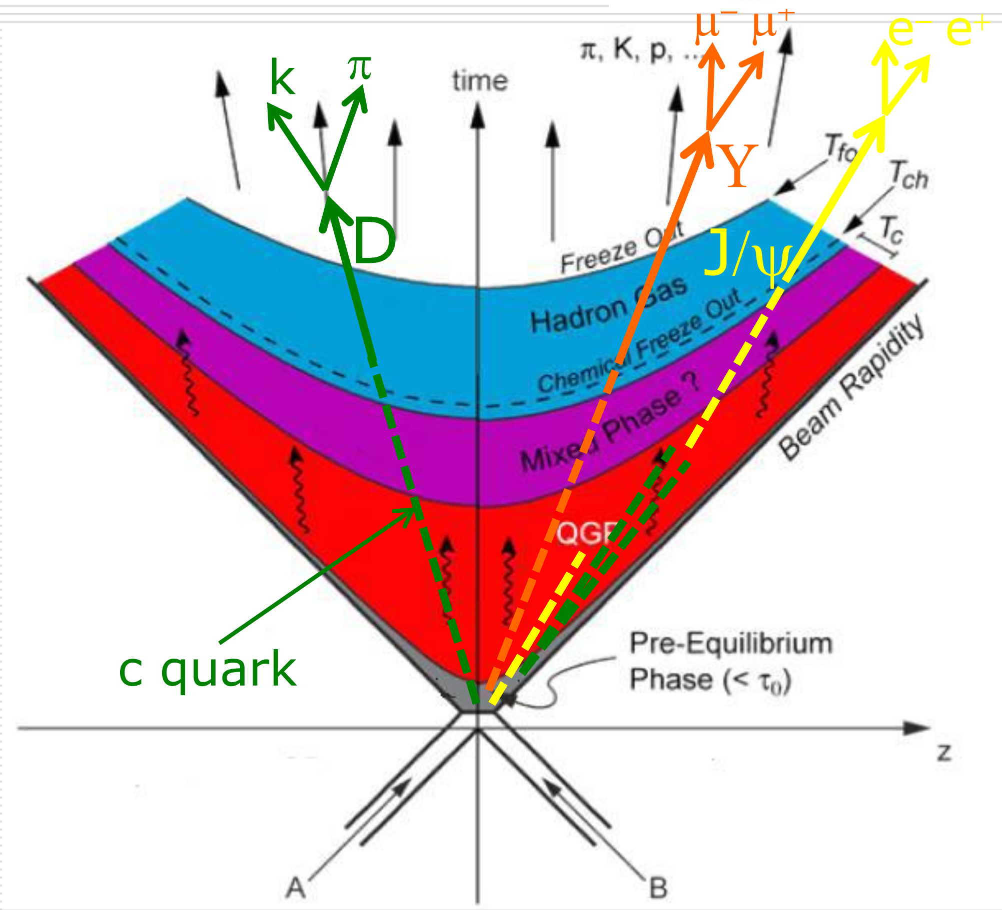
- transport of c quarks in an hydrodynamically expanding medium (via Boltzmann or Langevin equations)
- c quark energy loss (elastic and/or inelastic collisions)
- c-quark hadronisation via coalescence

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

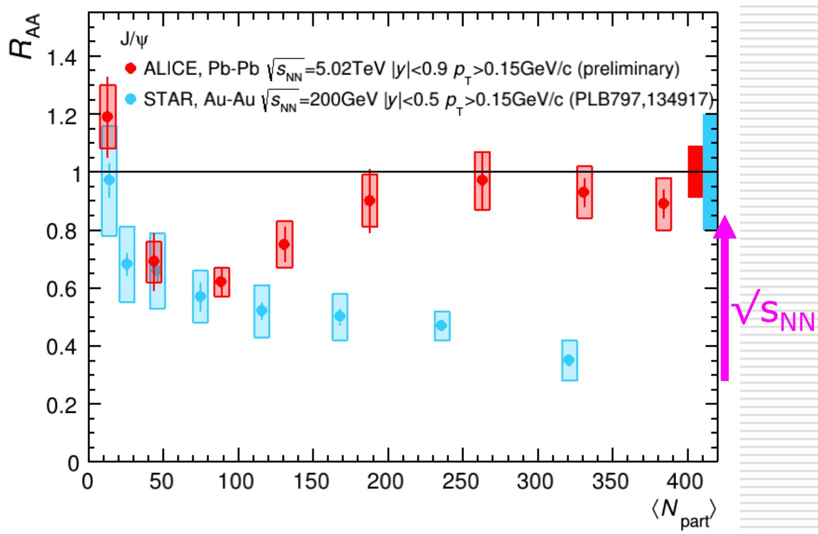
Quarkonium

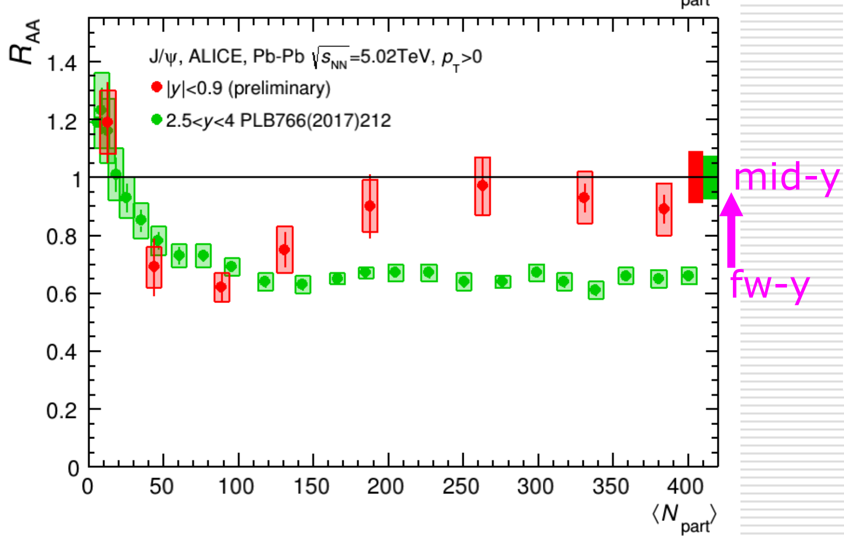


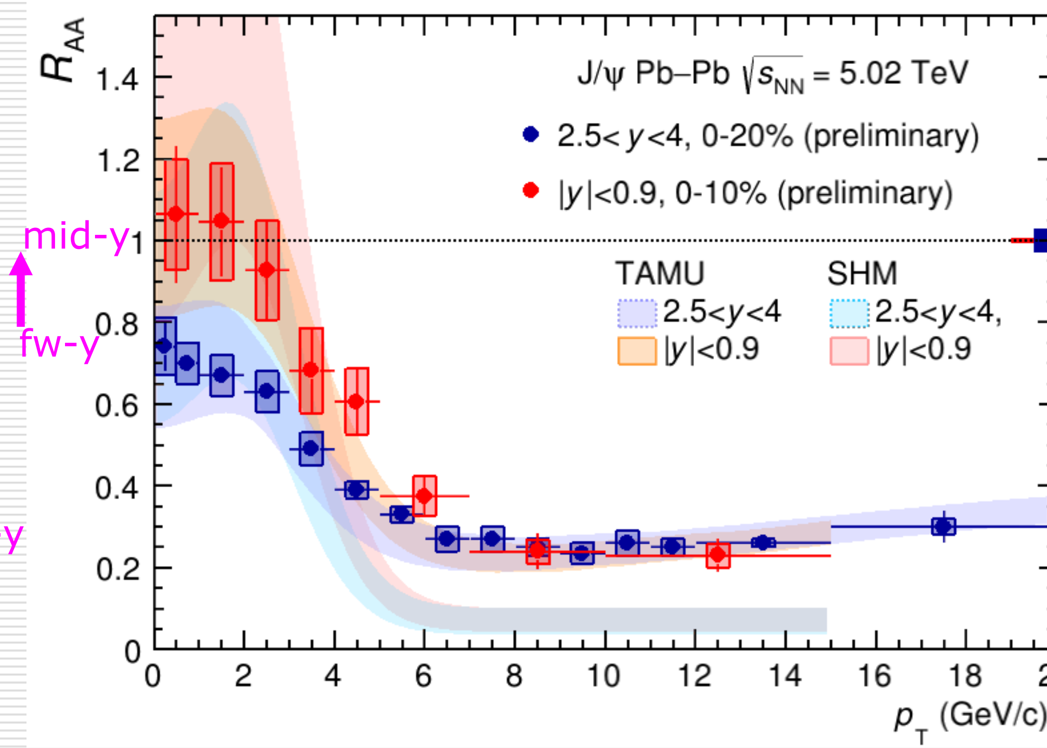
I'll discuss a few results



J/ψ R_{AA}





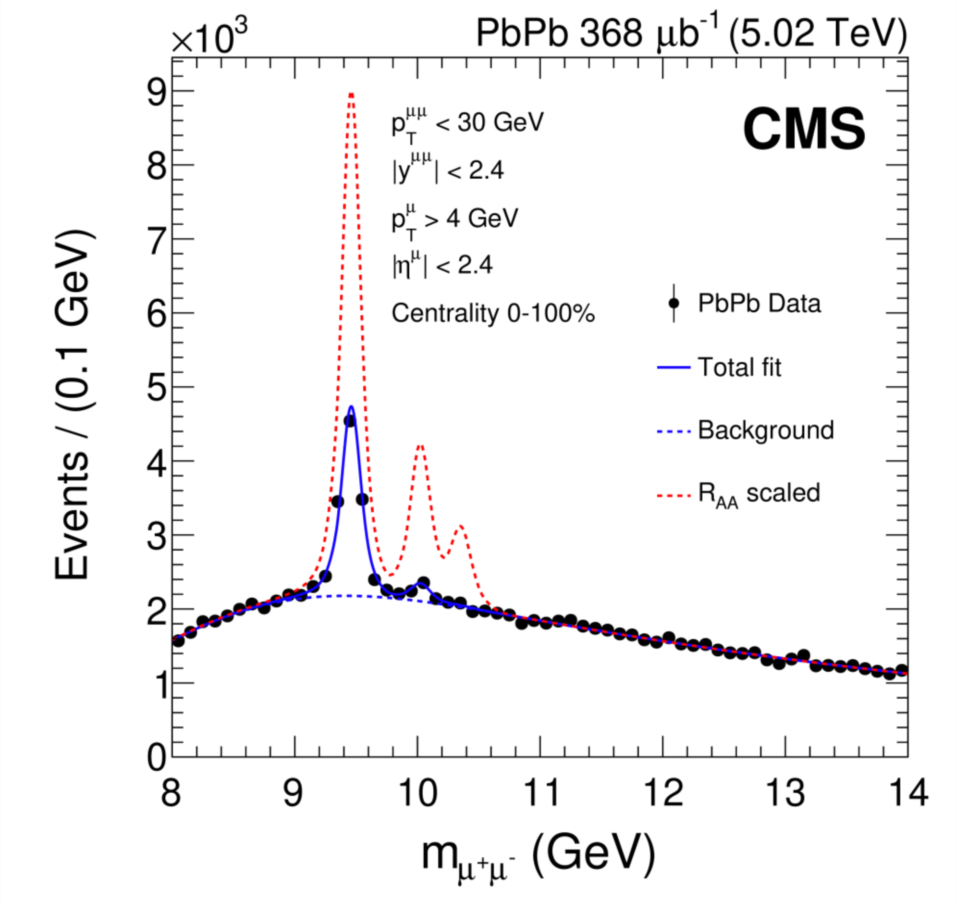


Recombination of $c\bar{c}$ quarks dominant effects at the LHC (at low p_T)

Upsilon

CMS, PLB 790 (2019) 270

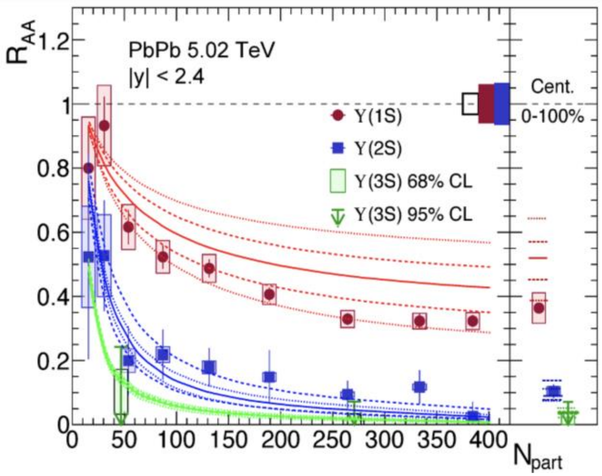
- Spectacular signature of the “sequential” dissociation
  - Υ(1S) suppression as due to suppression of its feed-down components

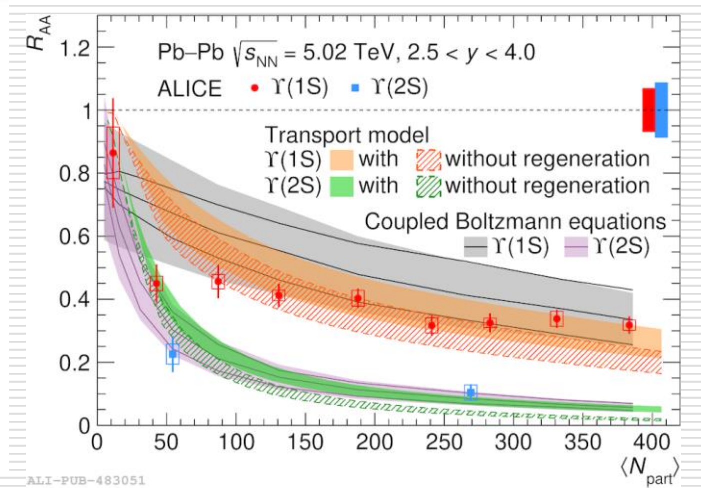


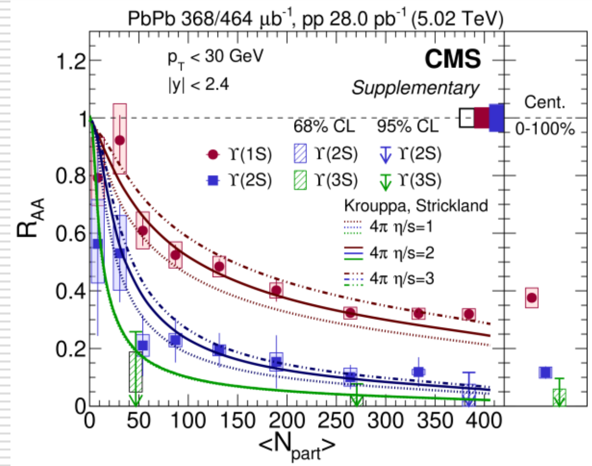
Υ R_{AA} versus models

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**







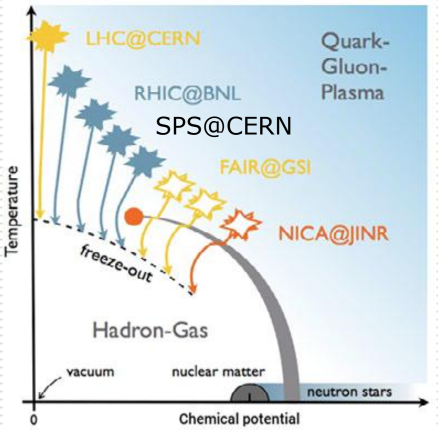
Break-up by **comover interaction** + nCTEQ15 parametrisation

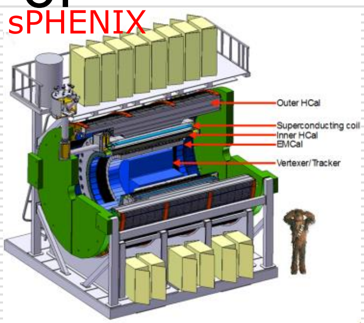
Transport description in-medium dissociation and recombination + nPDF sets

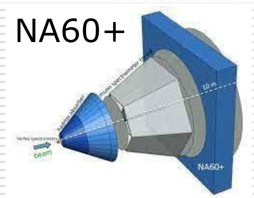
Hydrodynamic framework modification of the heavy-quark potential

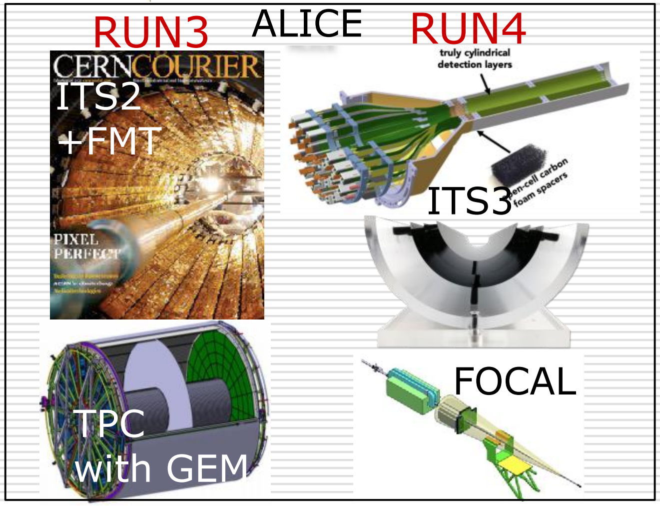
Outlook

- Broad programme to scan the QCD phase diagram
  - BES-II at RHIC
  - SPS: NA61/SHINE, proposal of NA60+
  - FAIR@GSI
  - NICA@JINR
- At very high energies:
  - sPHENIX at RHIC, prior of EIC
  - Run3 and Run4 of the LHC, with the major upgrades of ALICE
  - in the HL-LHC phase: proposal of a new experiment ALICE3 (>2032)
  - HI physics part of FCC@CERN



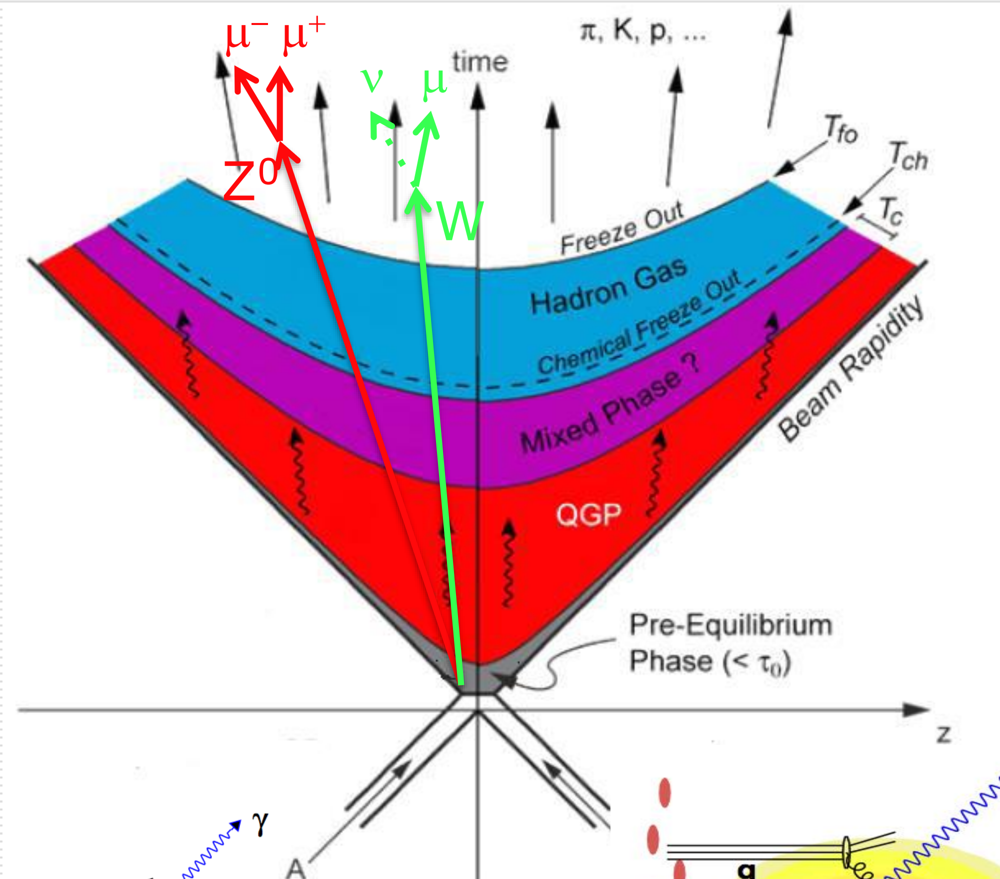


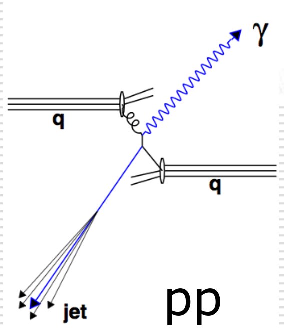


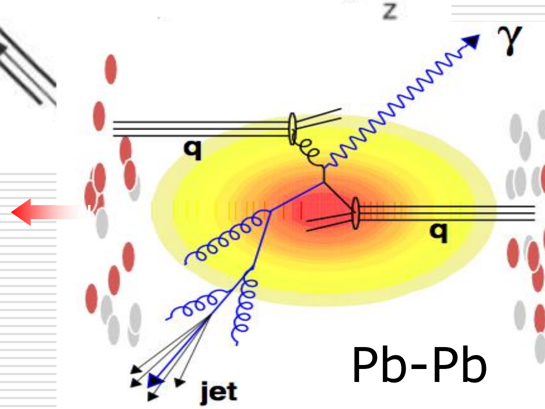


Extra

Electromagnetic probes



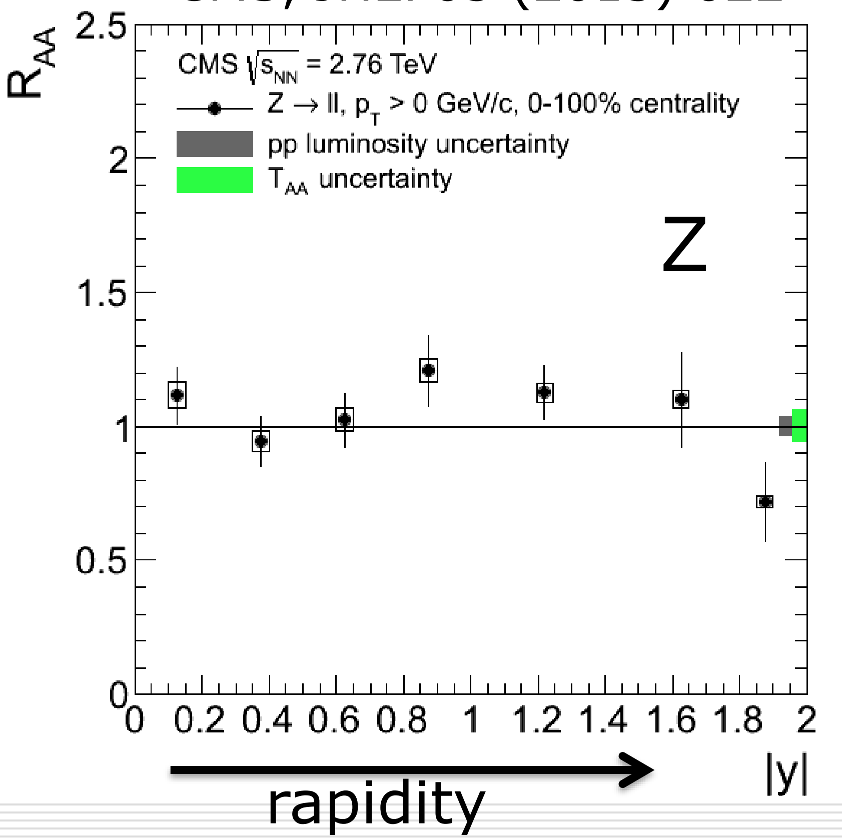




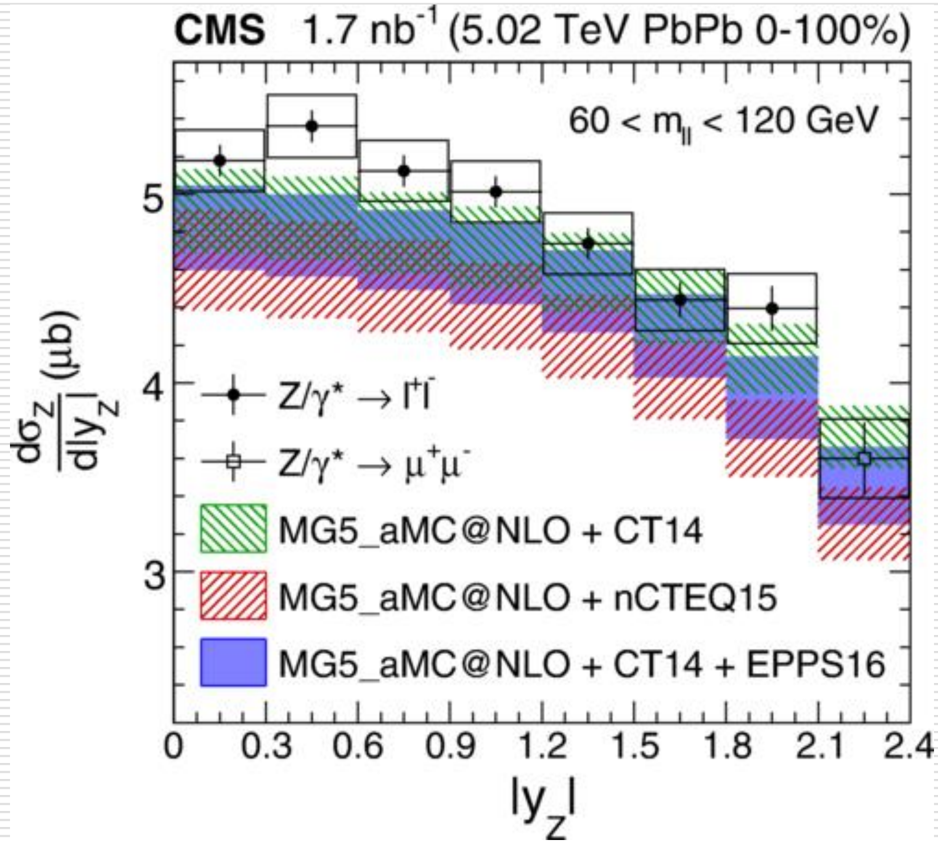
- Electromagnetic probes in nucleus-nucleus collisions
  - photons, W and <u>Z bosons</u>, ~~dileptons~~
  - do not carry a color charge
  - provide information about initial state / nuclear PDFs
- Also, prompt photons or Z^0 to study the medium suppression:
  - Prompt photon and jet production follow 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



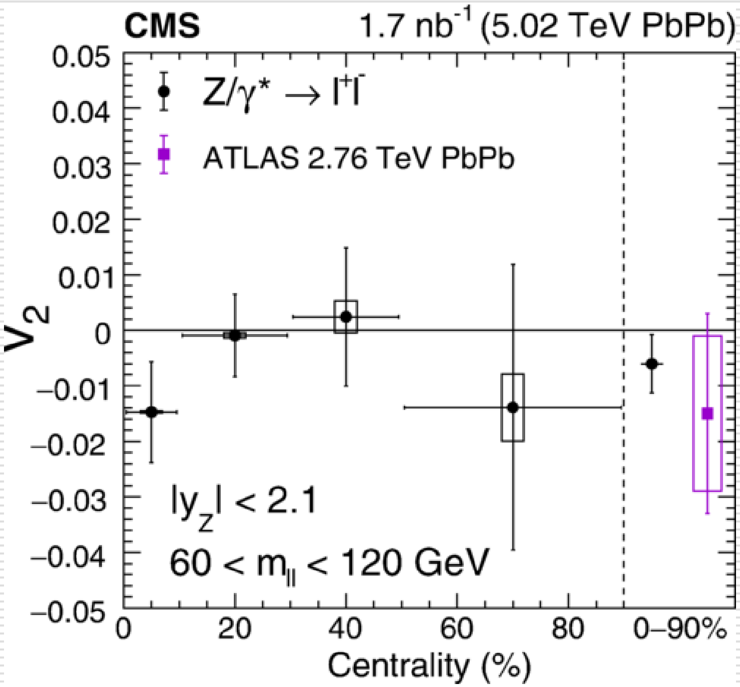
PRL 127 (2021) 102002

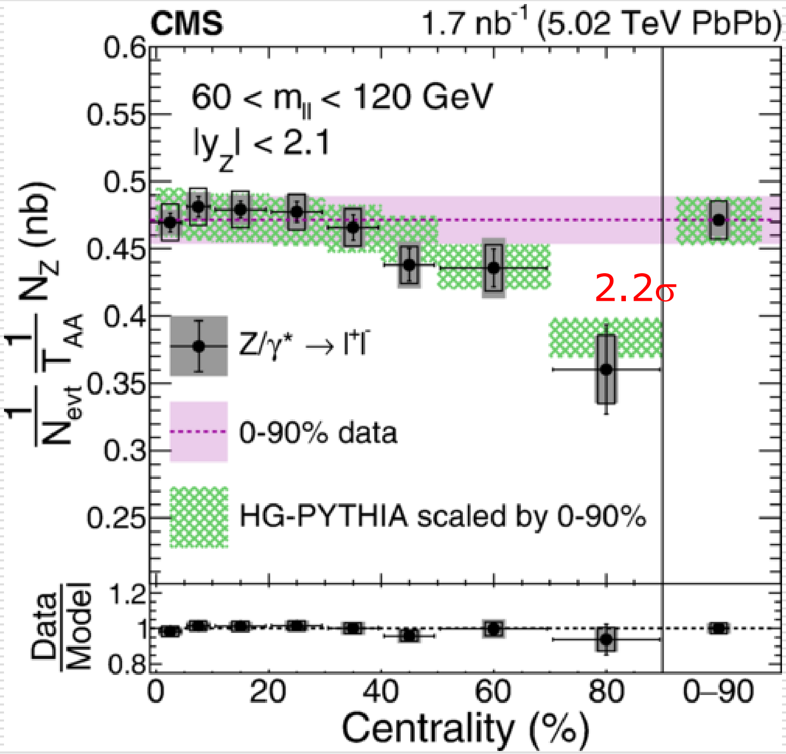


MadGraph5_aMC@NLO

Z^0 boson in Pb-Pb

PRL 127 (2021) 102002





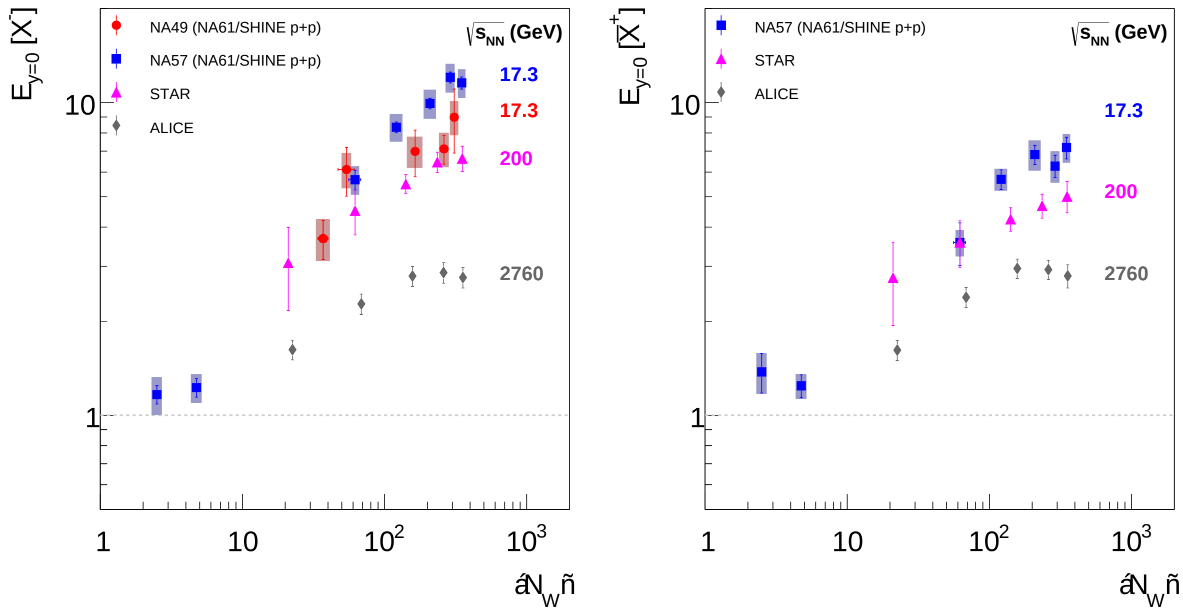
- V$_2$ consistent with 0 → unaffected by final-state effects such as hydrodynamic flow and energy loss

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

Strangeness enhancement

- historical signature of the QGP formation
- maximum enhancement at the SPS energy
- if A-A would be a superposition of elementary pp collisions, then E=1
- Statistical model approach:
  lifting of local strangeness conservation in Pb-Pb, i.e. from canonical (pp) to grand-canonical (Pb-Pb) ensembles
  → the QGP becomes the "reservoir" of $s\bar{s}$ quarks

$$E = \frac{2}{\langle N_{part} \rangle} \frac{\frac{dN}{dy}(A+A)}{\frac{dN}{dy}(p+p)}$$



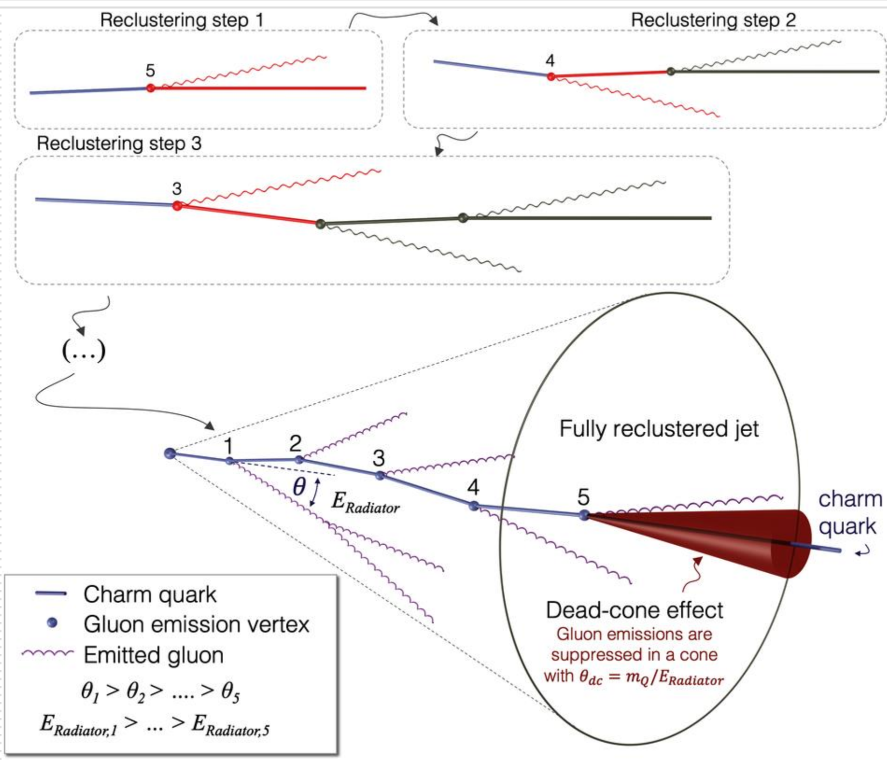
new pp reference from NA61/SHINE for the SPS energy, *Eur. Phys. J. C* 80 (2020) 833

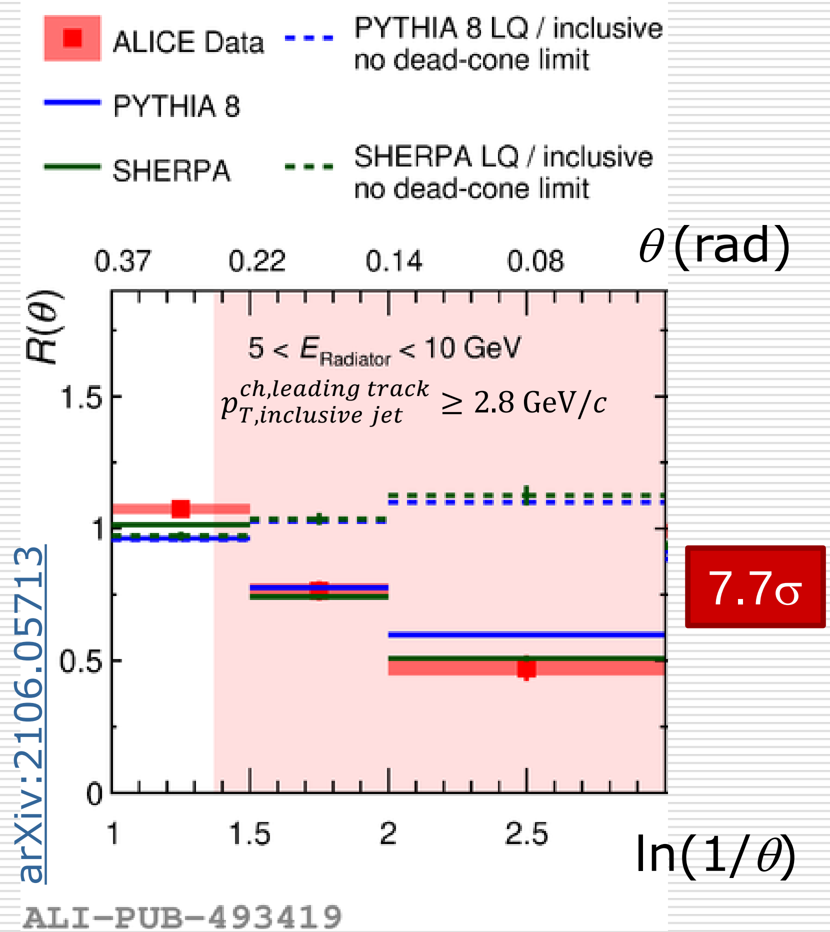
HF jets in pp

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

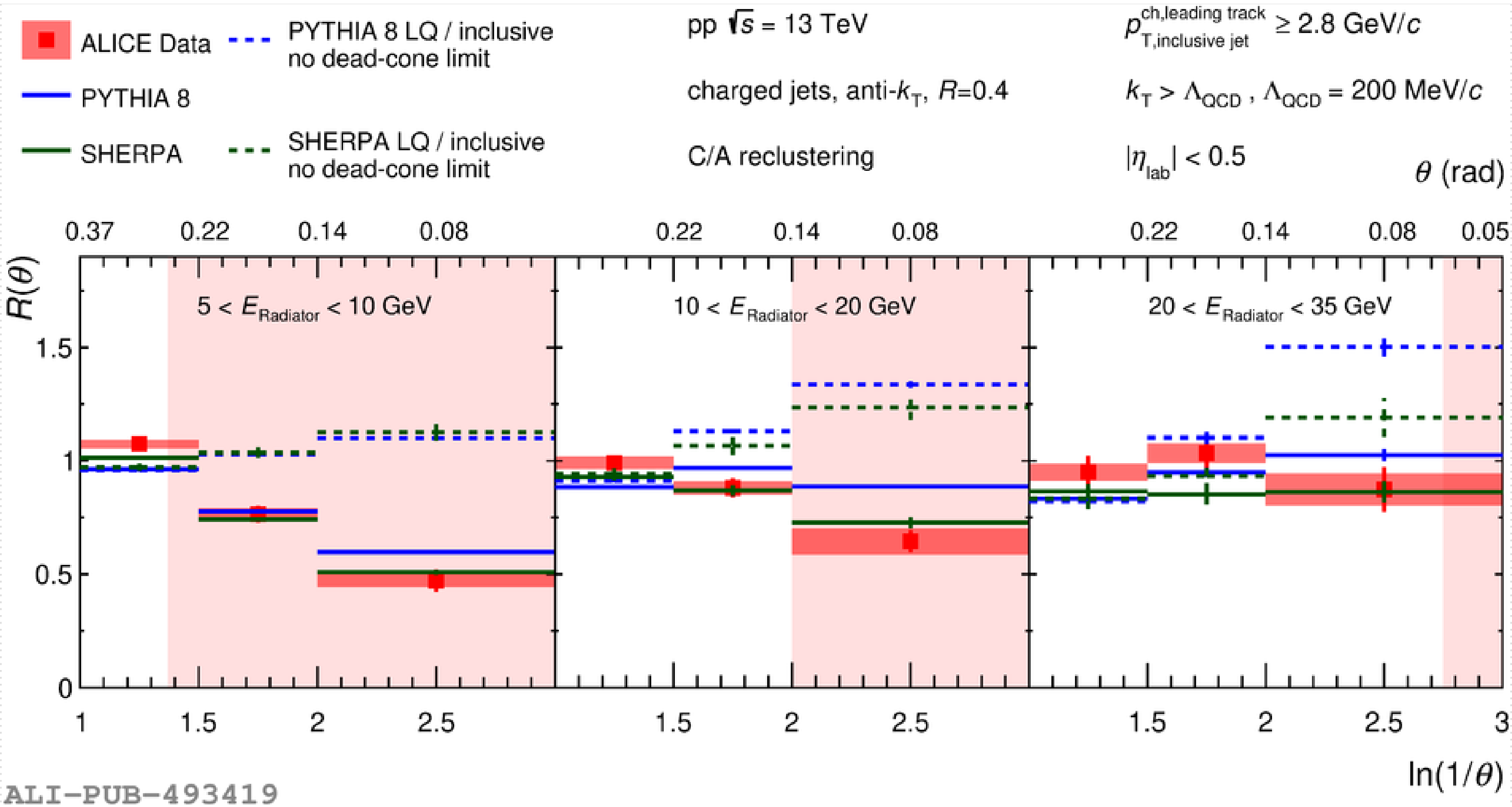
QCD vacuum is not transparent → Expectation: radiation suppressed for $\theta_c < \frac{m_Q}{E}$

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





Dead cone effect in pp

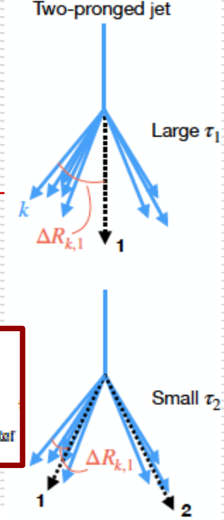


7.7σ

3.5σ

1.0σ

First measurements of N-subjettiness in AA



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

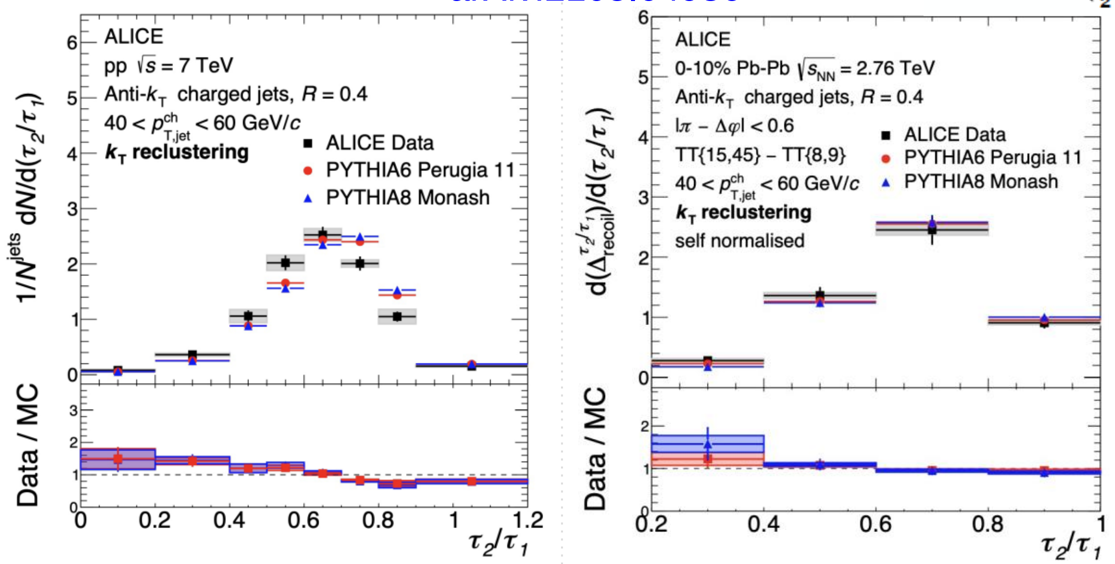
Suppression of combinatorial jets with data driven method

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

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

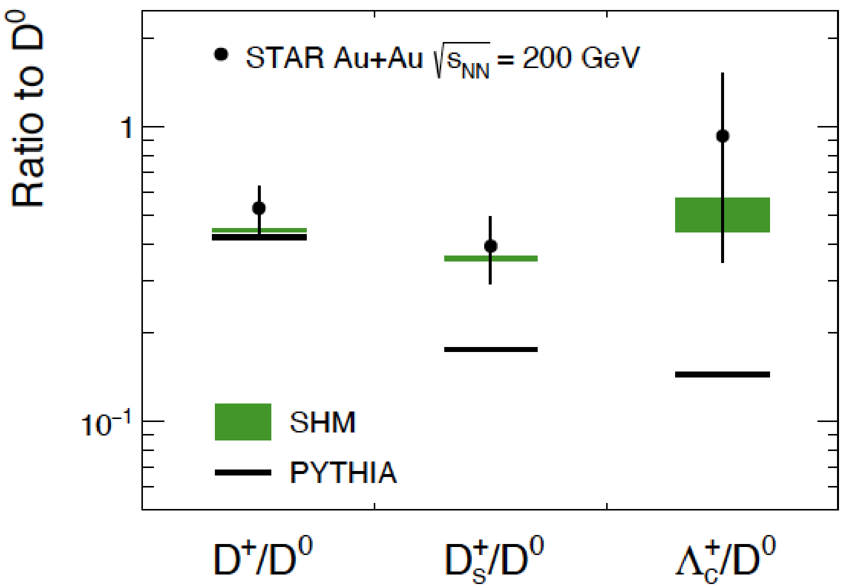
arXiv:2105.04936



- ☐ 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

Charm Hadrochemistry



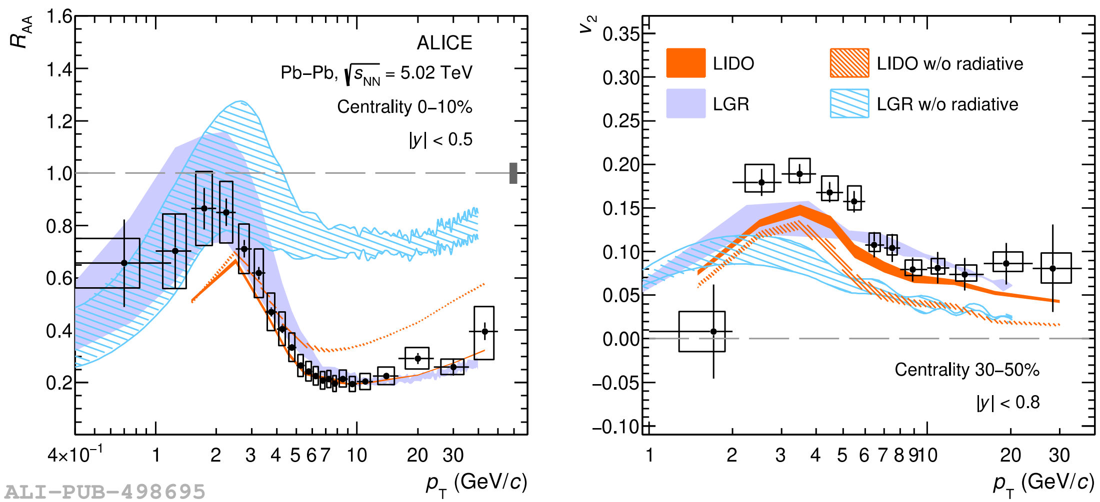
SHM: THERMUS calculations
chemical FO parameters from the fit to light/strange hadrons

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

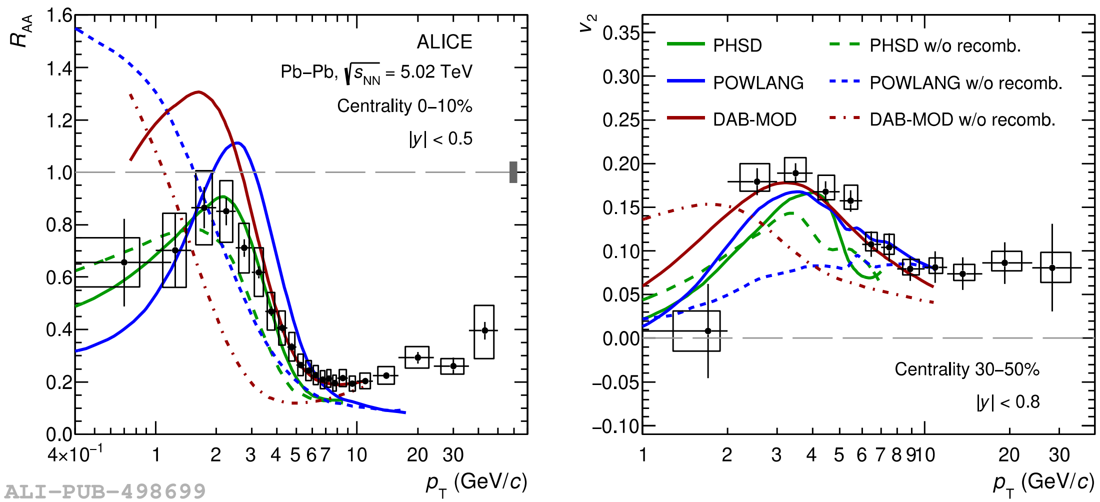
** extracted from 10-80%*

… deeper insight into models

arXiv:2110.09420



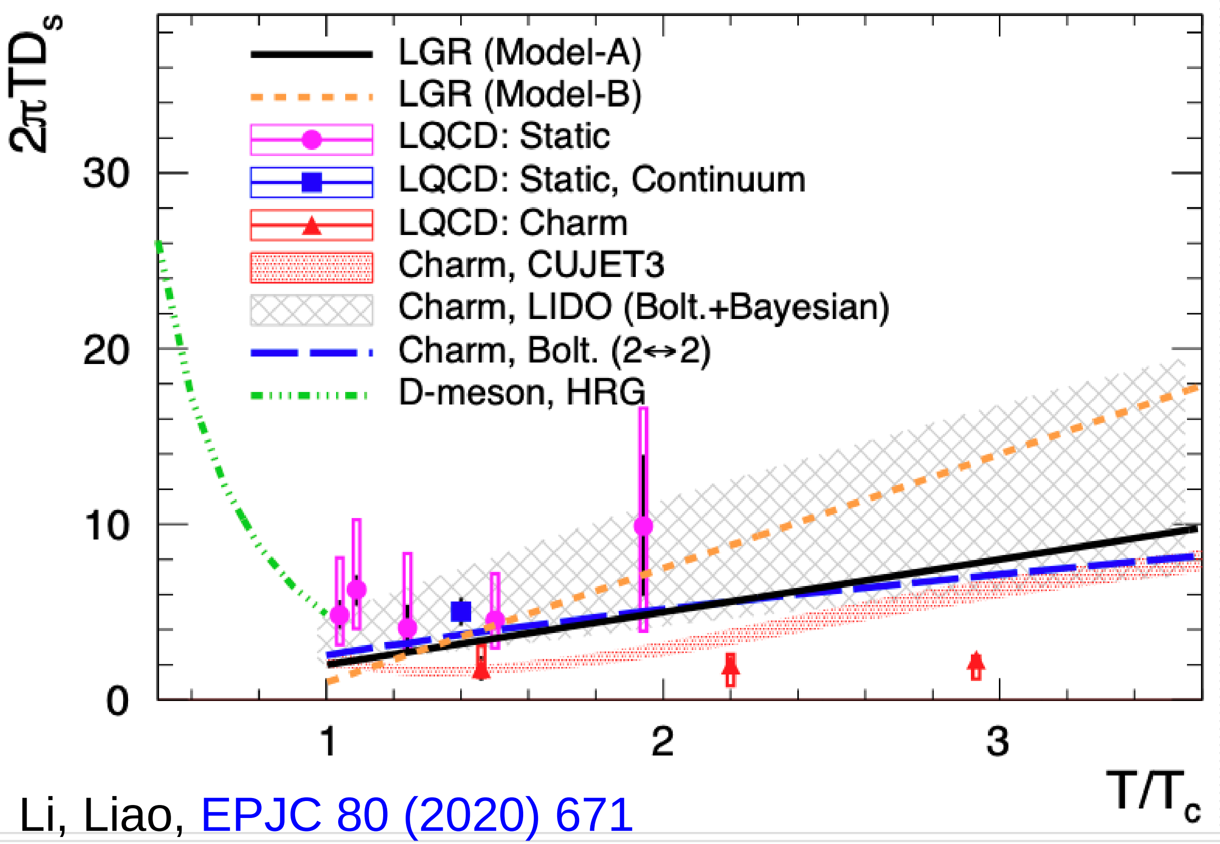
- Role of radiative dE/dx vs. elastic collisions
  - Switching off radiative E loss



- Role of hadronization
  - Switching off recombination

Charm spatial diffusion coefficient

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



Li, Liao, EPJC 80 (2020) 671

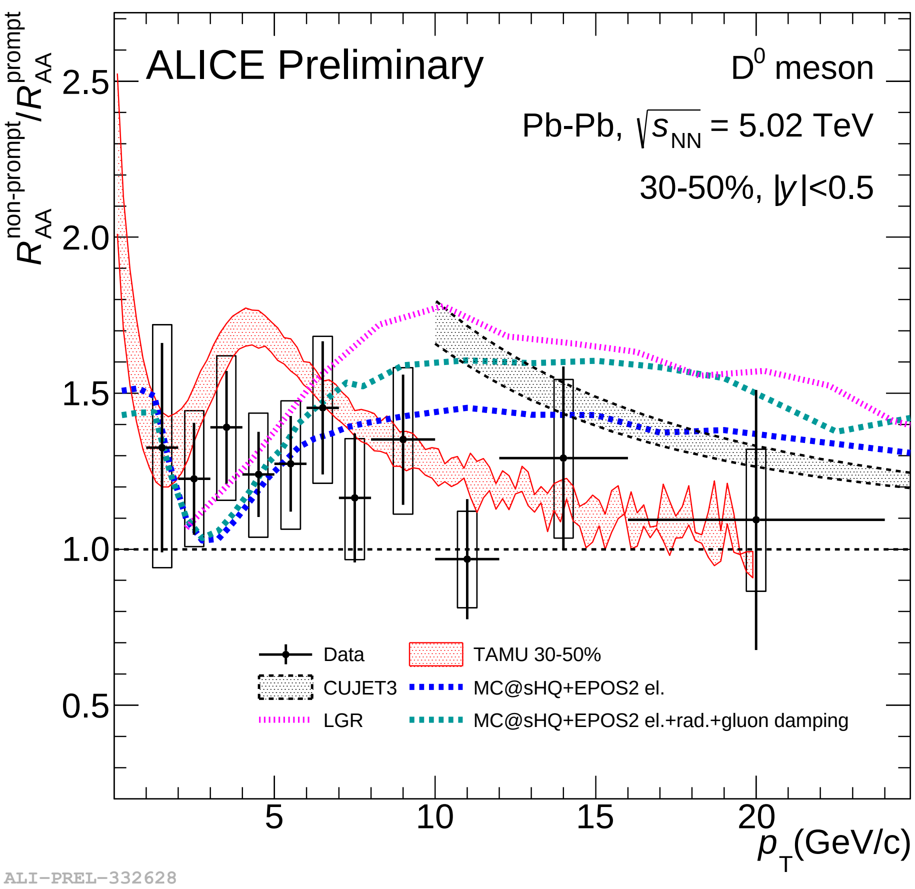
From that, one derives the drag and momentum diffusion coefficients:

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

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

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

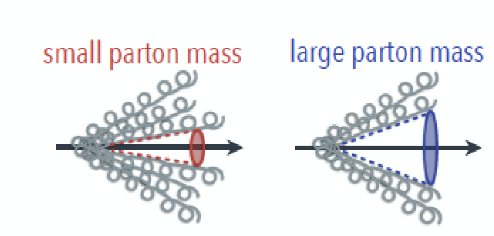
Prompt vs. non-prompt D mesons



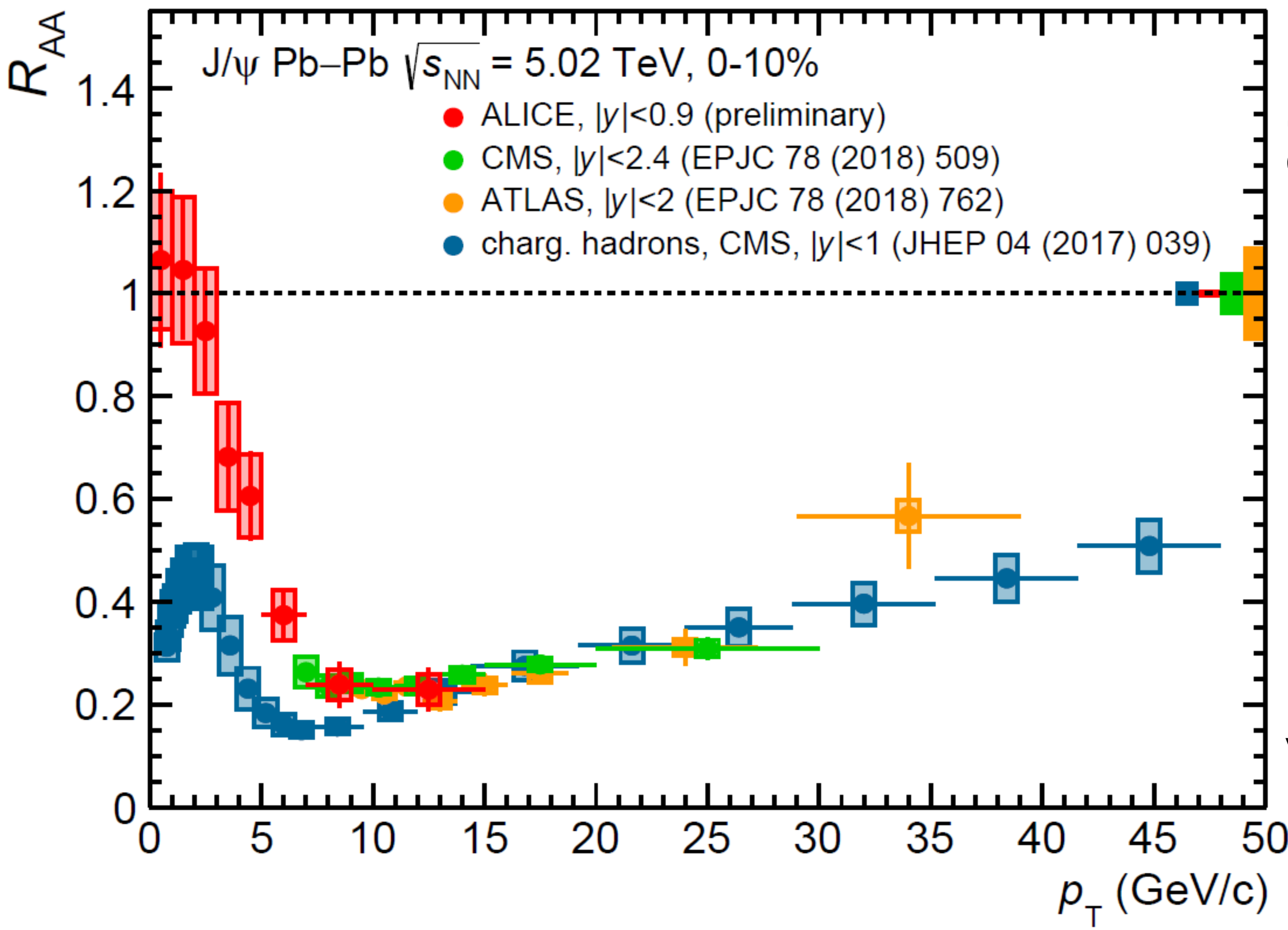
CUJET3.0: JHEP02 (2016) 169
LGR: EPJC **80** (2020) 671
TAMU: PLB **735** (2014) 445
MC@sHQ+EPOS2: PRC 89(2014)014905

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



J/ψ R_{AA} vs. p_T at the LHC



Strong R_{AA} p_T dependence

low p_T

- strong y dependence

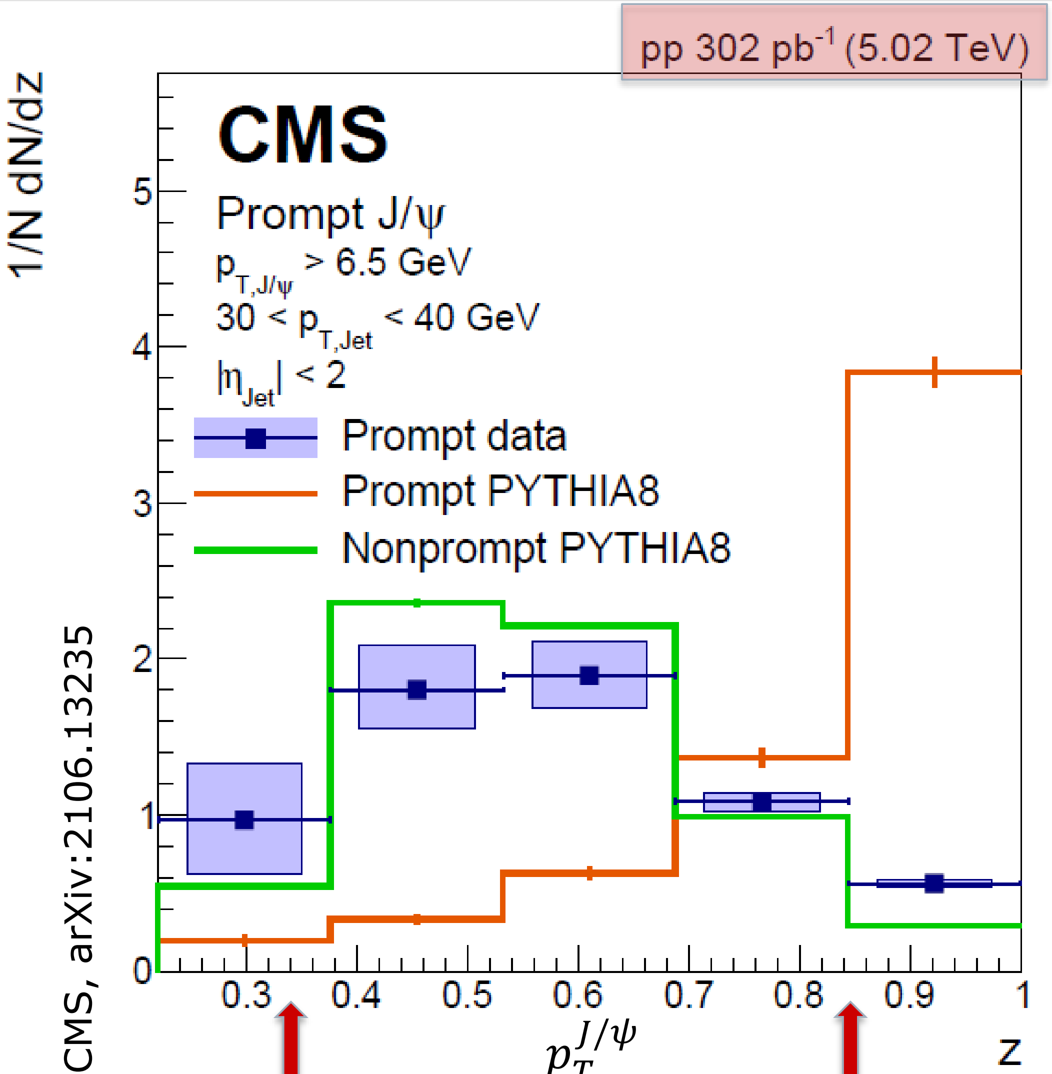
high p_T

- 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

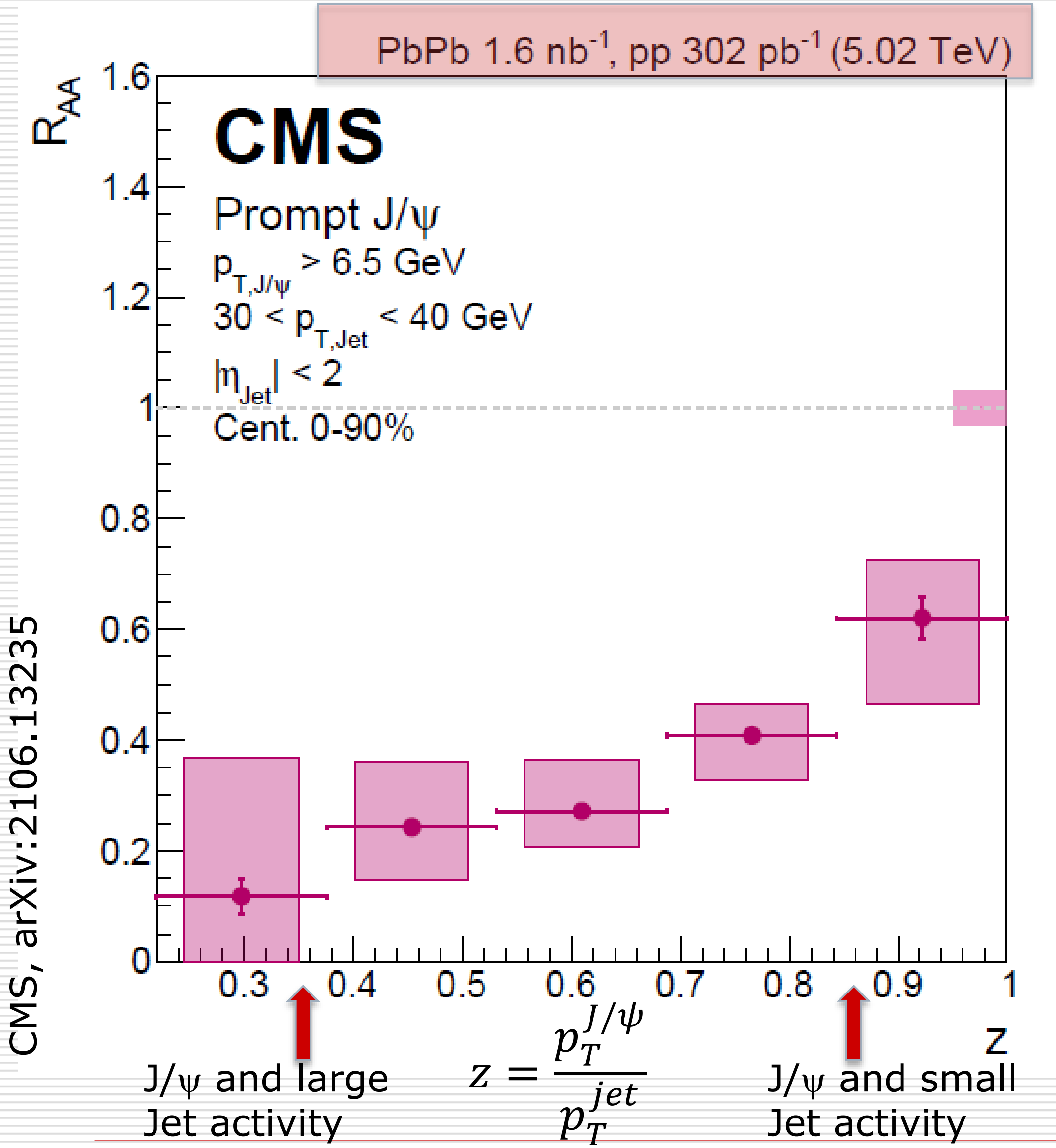
$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

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



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

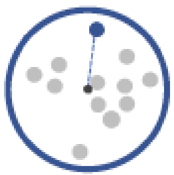
- J/ψ production later in parton showers underestimated

In Pb-Pb

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

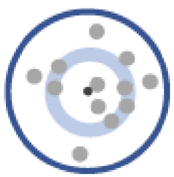
Tagged Jets - EW Boson Recoil

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

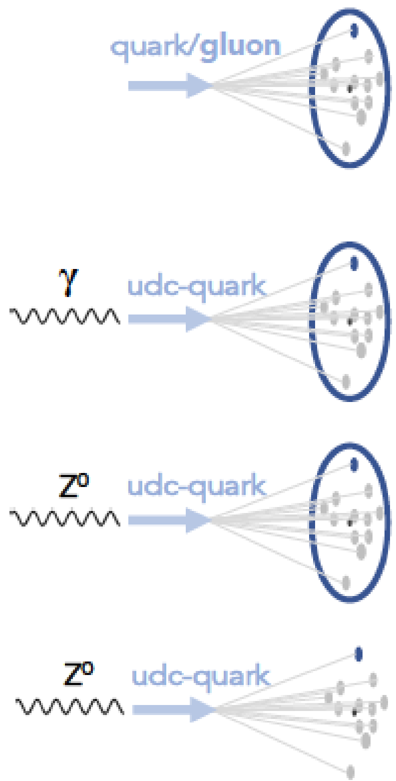


$$D(r) = \frac{dN}{dr}$$

$$r = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$



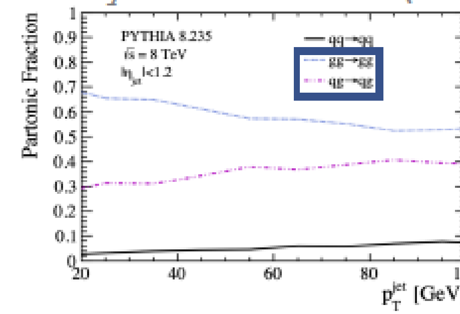
$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{Tr \in (r, r+\delta r)} p_T^{Tr}}{p_T^{jet}}$$

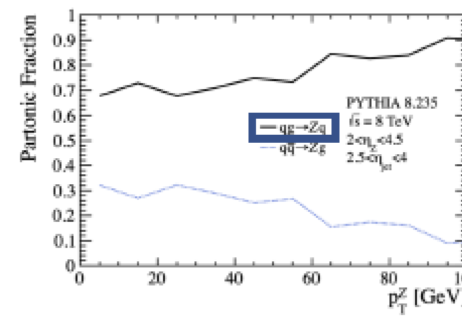


Inclusive jets dominated by gluons

Jets recoiling against an EW-Boson dominated light quarks

LHCb collaboration
Phys. Rev. Lett. 123(2019)

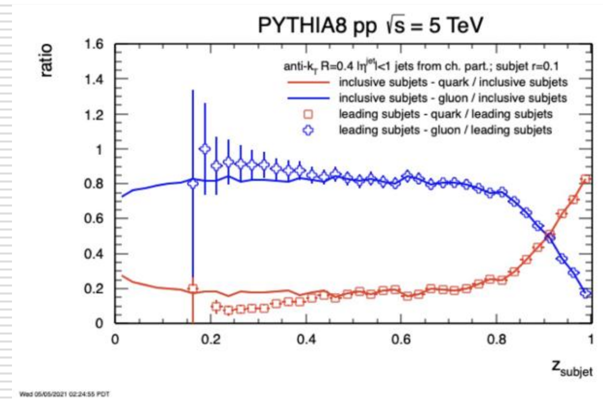




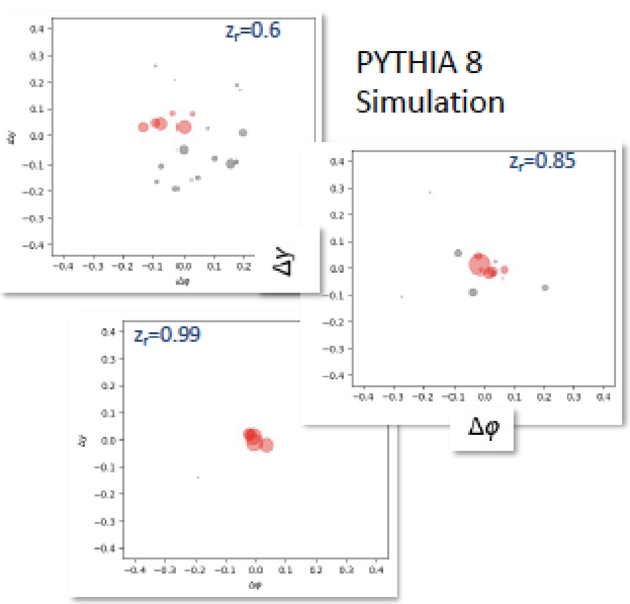
Modifications of jet substructure in the QGP

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

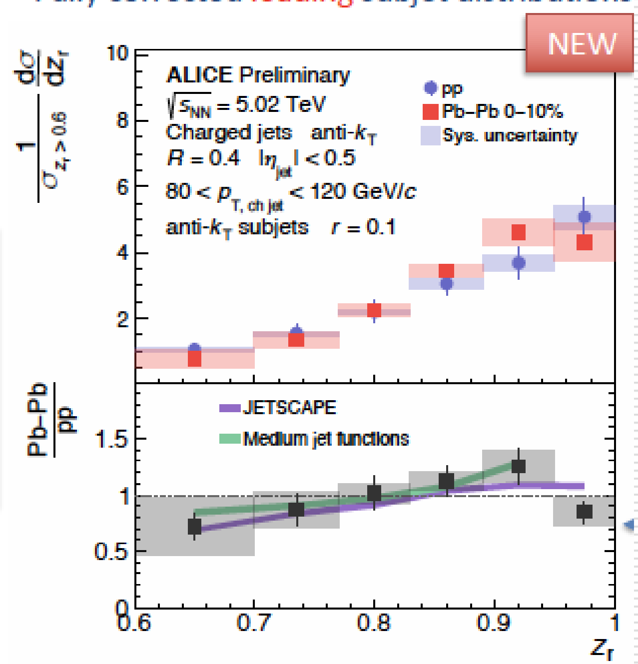
motivations:
- investigate redistribution of energy from the leading subjet (at different r<R) – collimation and z≈1 suppression
- sensitivity to quark vs. gluon jet in-medium energy loss?



$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$



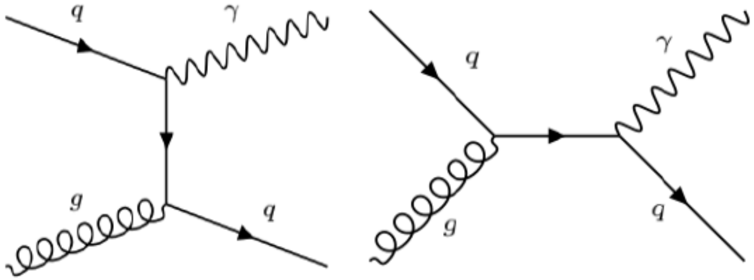
Fully corrected leading subjet distributions



γ + jet in Pythia 8

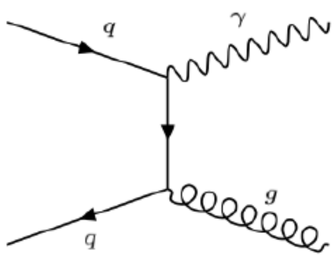
γ+quark

dominantly via QCD Compton scattering

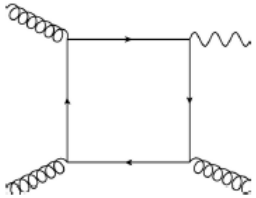


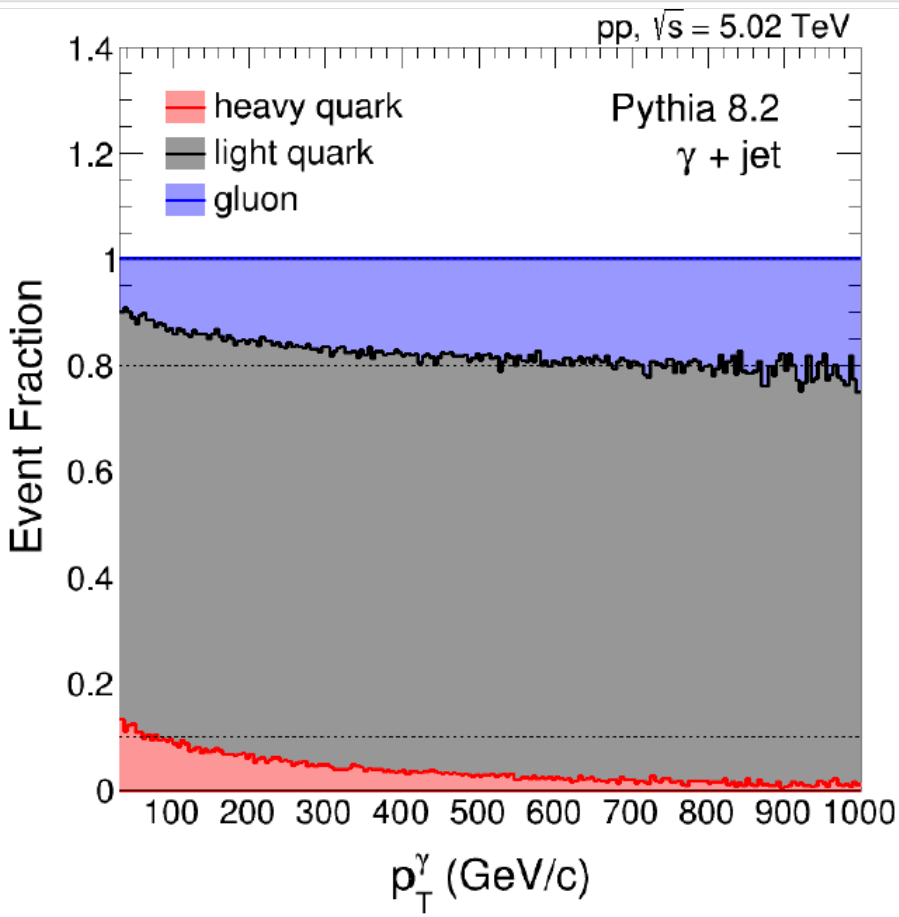
γ+gluon

dominantly via qqbar annihilation



subdominantly via





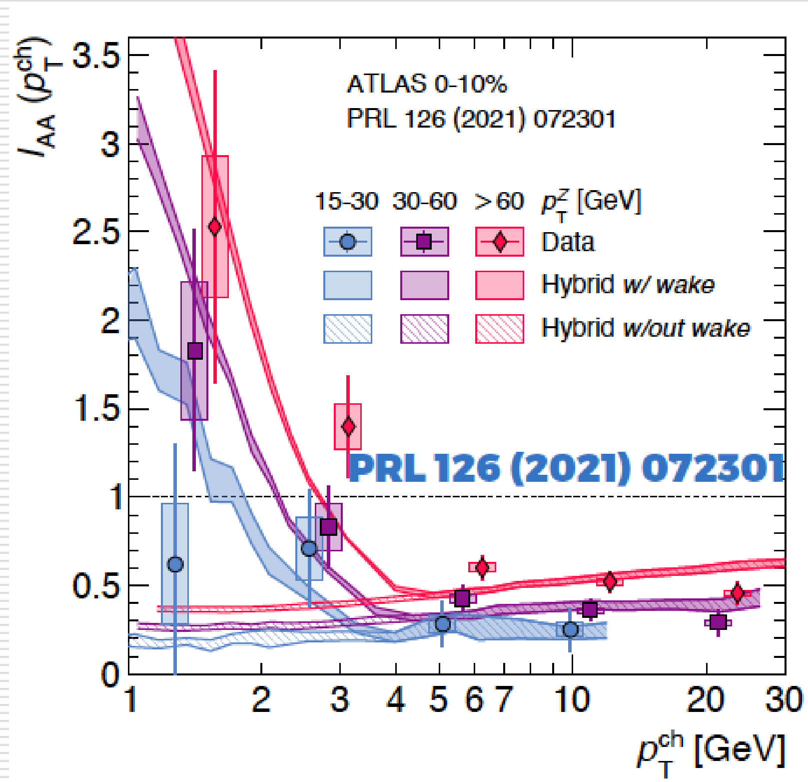
Process here is prompt photon (not isolated photon)
Quark dominated across the spectrum
80-90% from p_T ~ 50 GeV to ~ 1 TeV

Z-tagged Jets – comparison to models

Does a jet in medium leave a wake?

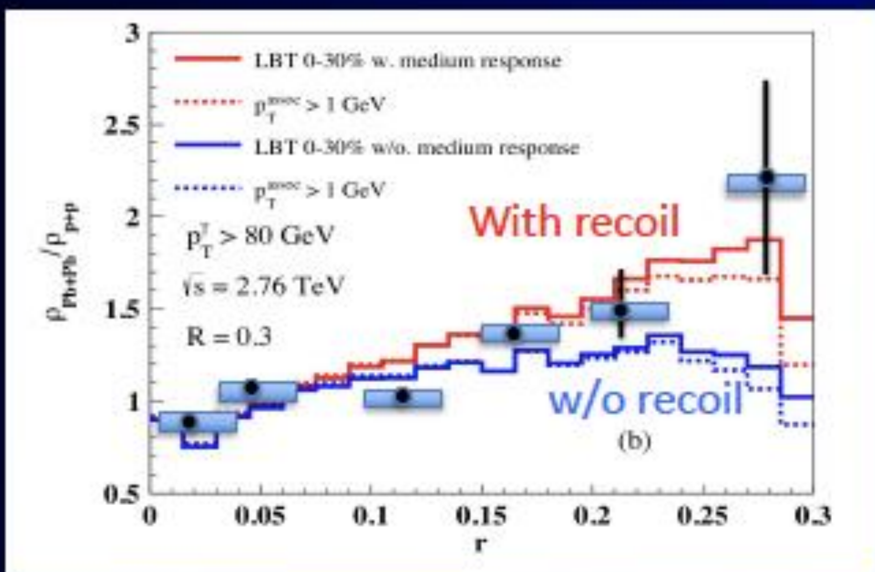
- Check in Hybrid model - jet quenching theory with strong-coupling

- Hybrid model does not describe low-p_T excess in data without such a back-reaction

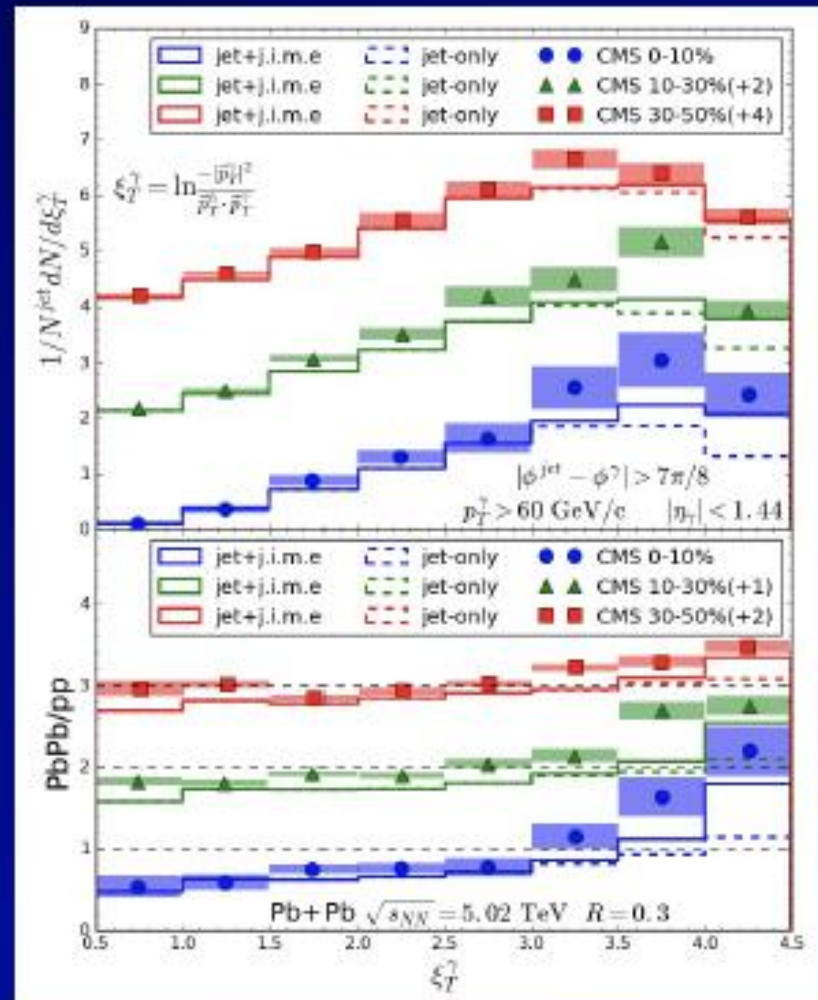


Medium modification of γ-jets

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

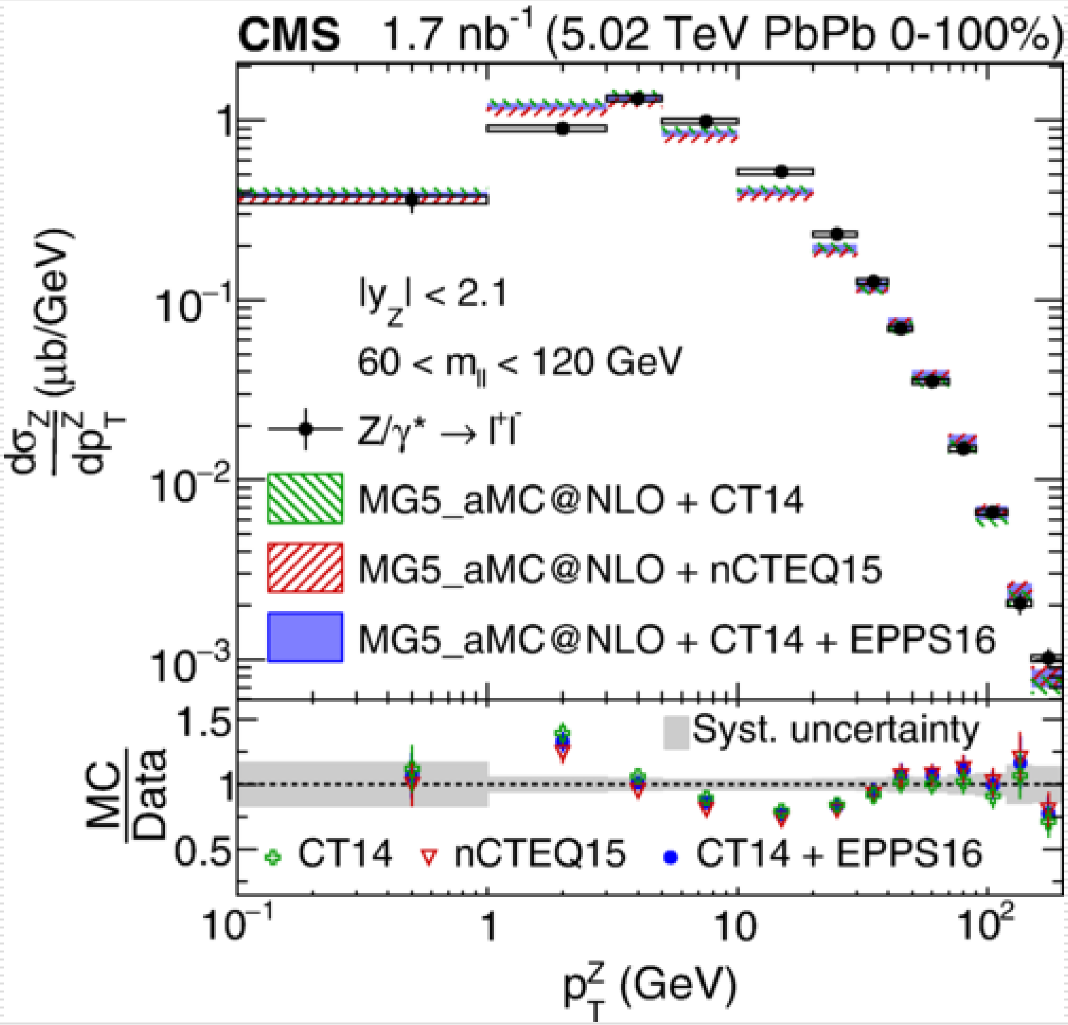
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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.

Z^0 boson as a function of p_T



MadGraph5_aMC@NLO calculations with different (n)PDF

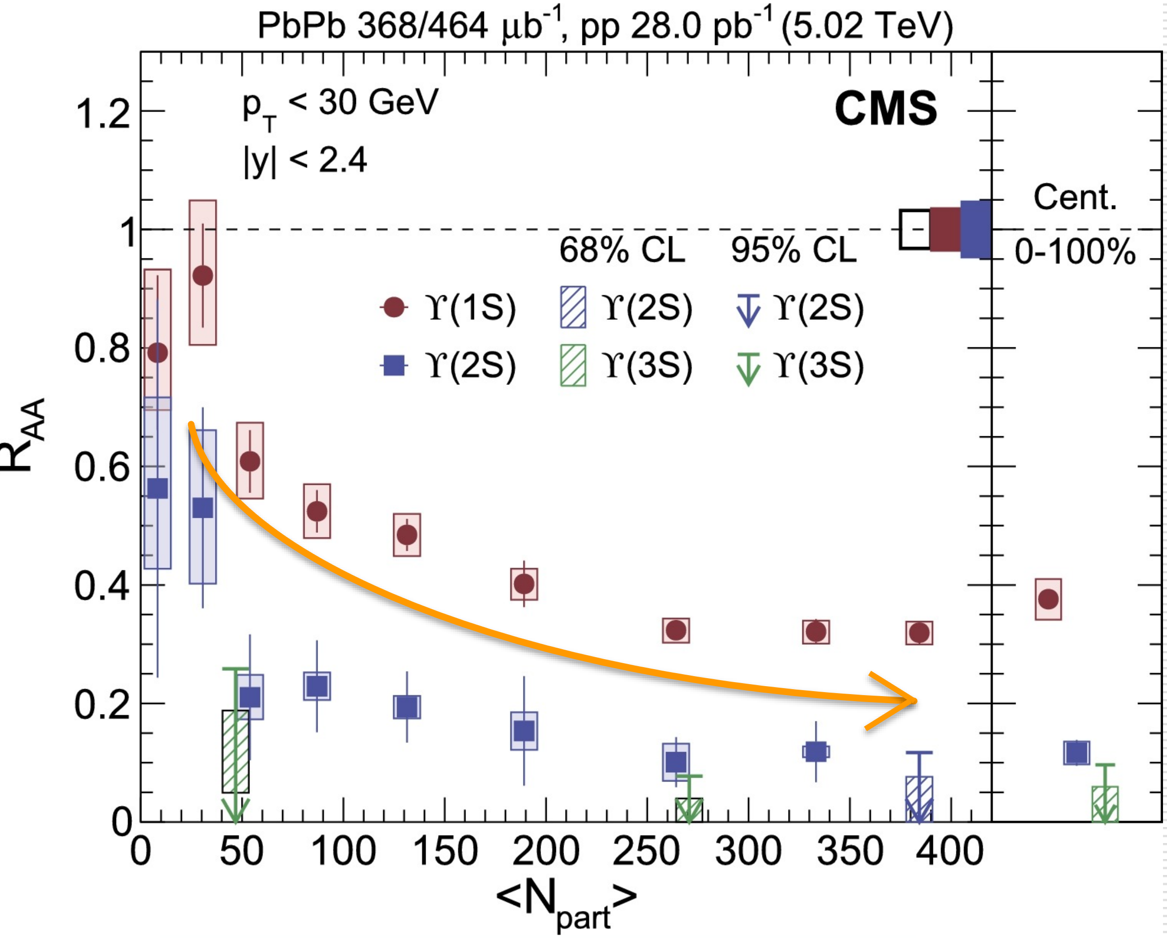
general trend correctly reproduced by the simulation, but

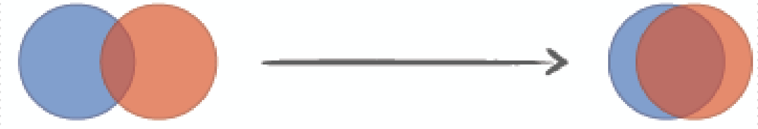
- Low p_T: lack of soft g resummation in the model (also in pp)
- nPDF sets 10% lower then free PDF at low pt, trend reversed for p_T >50 GeV/c
- Differences between two nPDF sets smaller than deviations of model from data

→modelling improvements more urgent

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

Semi-classical calculations based on transport or rate equations

nuclear effects / nPDF
regeneration term

- **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.

<u>All account for the suppression of feed-down contributions</u> but with different treatments.

Total multiplicity

- Two assumptions for the transverse overlap area

$$\boxed{\varepsilon_{\mathrm{Bj}} = \frac{1}{c\tau}\frac{1}{S_{\mathrm{T}}}\left\langle\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y}\right\rangle}$$

$$S_{\mathrm{T}} \approx \pi R^2 \approx \pi N_{\mathrm{part}}^{2/3}$$

$$\left\langle\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y}\right\rangle \approx \langle m_{\mathrm{T}}\rangle \frac{1}{f_{\mathrm{total}}}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

$$f_{\mathrm{total}} = 0.55 \pm 0.01$$