PROBING THE QUARK-GLUON PLASMA WITH HARD PROBES

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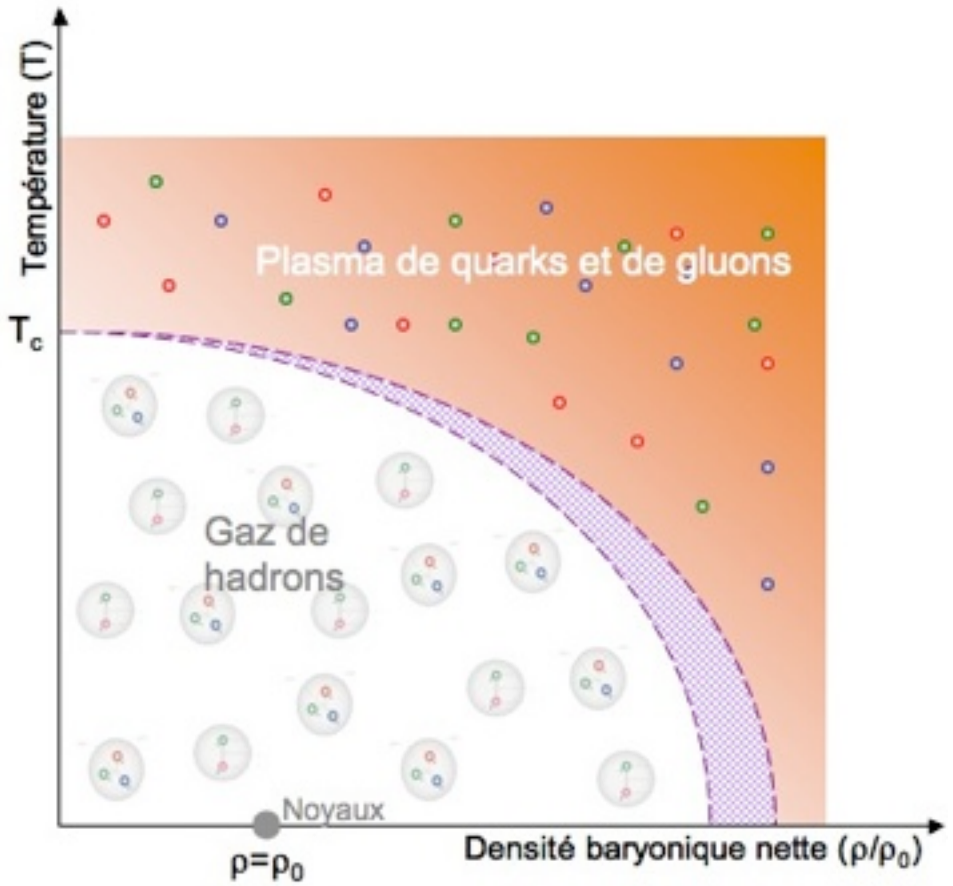
25e Congrès Général de la Société Française de Physique SFP
(Nantes, 8—12 of July 2019)

QCD matter under extreme conditions

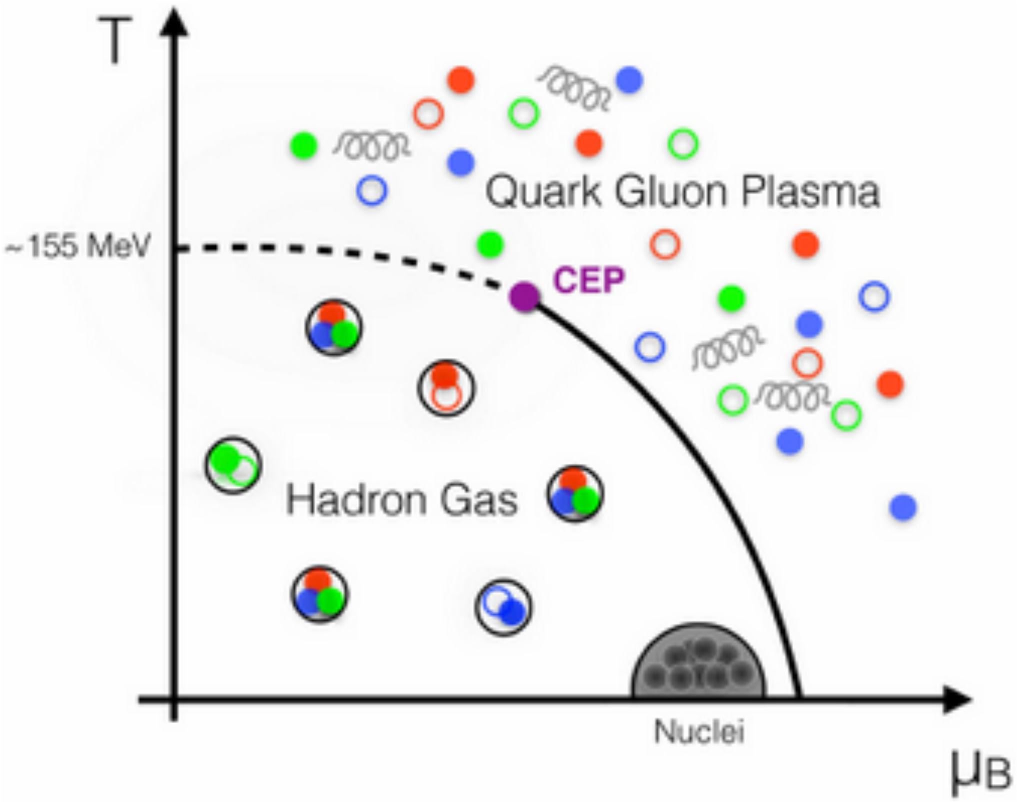


- ρ_B = 1, T ~ 0
  - Nuclei
- ρ_B ↑ , T ~ 0
  - Neutron star cores
- ρ_B = 0, T↑
  - T_c~ 150-170MeV, ε_c~ 0.3-0.8GeV/fm^3
  - Cross-over transition
  - Quark gluon plasma

"When the energy density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), matter no longer exists of separate hadrons (protons, neutrons, etc), but as their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or Quark Gluon) plasma."
E.V. Shuryak, Phys. Rept. 61 (1980) 71

"Above T_c, the medium consists of deconfined quarks and gluons. We emphasize that deconfinement does not imply the absence of interaction – it is only the requirement to form color neutral bound states that has been removed." H. Satz, J.Phys.G32:R25 (2006)

The Quark-Gluon Plasma (QGP)



- $\rho_B = 1$, T ~ 0
  - Nuclei
- $\rho_B \uparrow$, T ~ 0
  - Neutron star cores
- $\rho_B = 0$, T$\uparrow$
  - T_c~ 150-170MeV, ε_c~ 0.3-0.8GeV/fm^3
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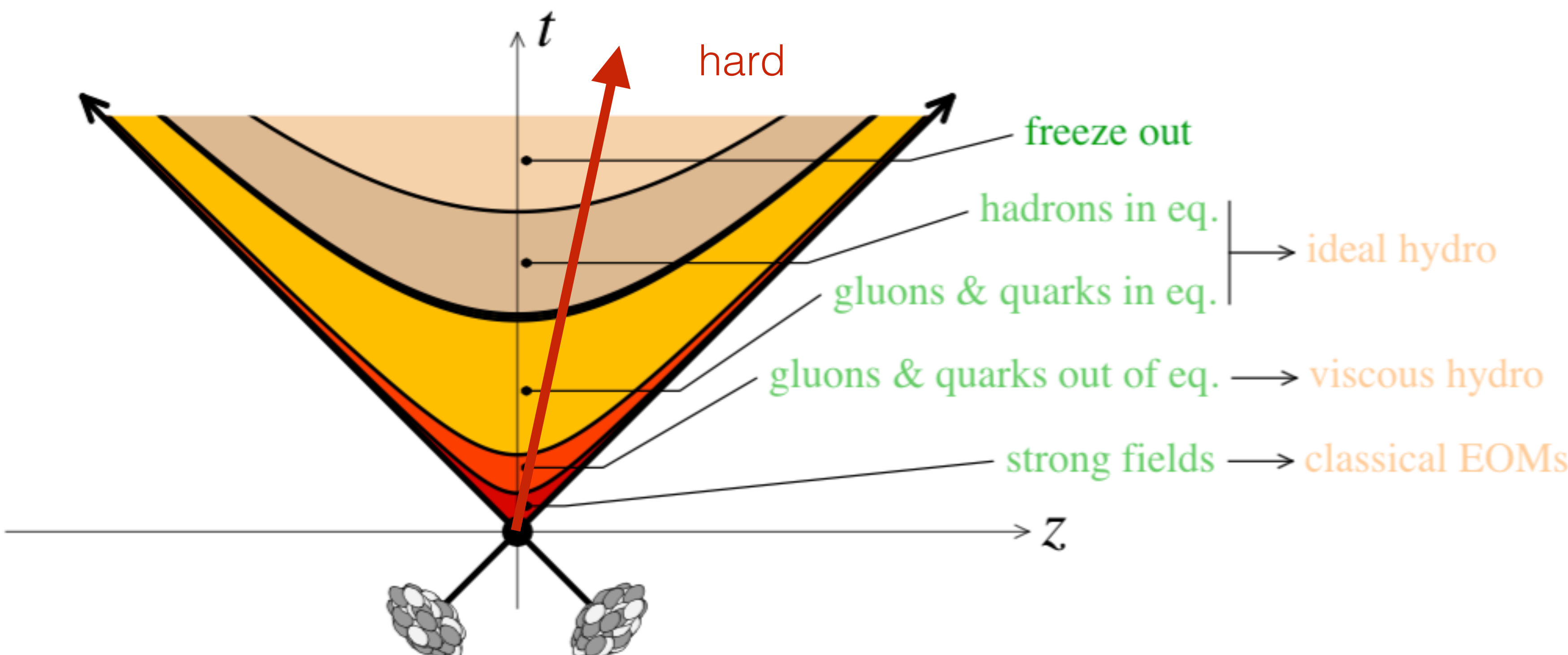
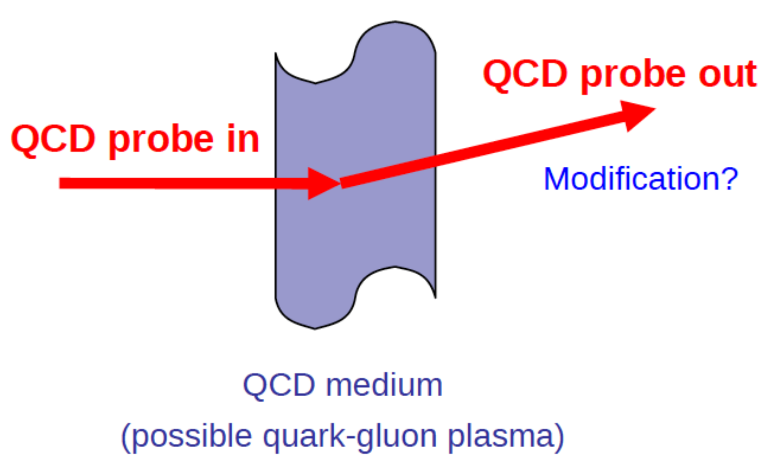
In (2+1) lattice-QCD calculations: **$T_c = (154 \pm 9)$ MeV, $\varepsilon_c = (0.34 \pm 0.16)$ GeV/fm^3**,
Ordinary matter: $\varepsilon_{\text{nuclear matter}} \simeq 0.15$ GeV/fm^3, $\varepsilon_{\text{nucleon}} \simeq 0.45$ GeV/fm^3 if $R_{\text{nucleon}} \simeq 0.8$ fm
[Bazavov et al, Phys.Rev.D 90 (2014) 094503; Ding et al, Quark-Gluon Plasma 5 (2015)]

Hard probes in heavy-ion collisions

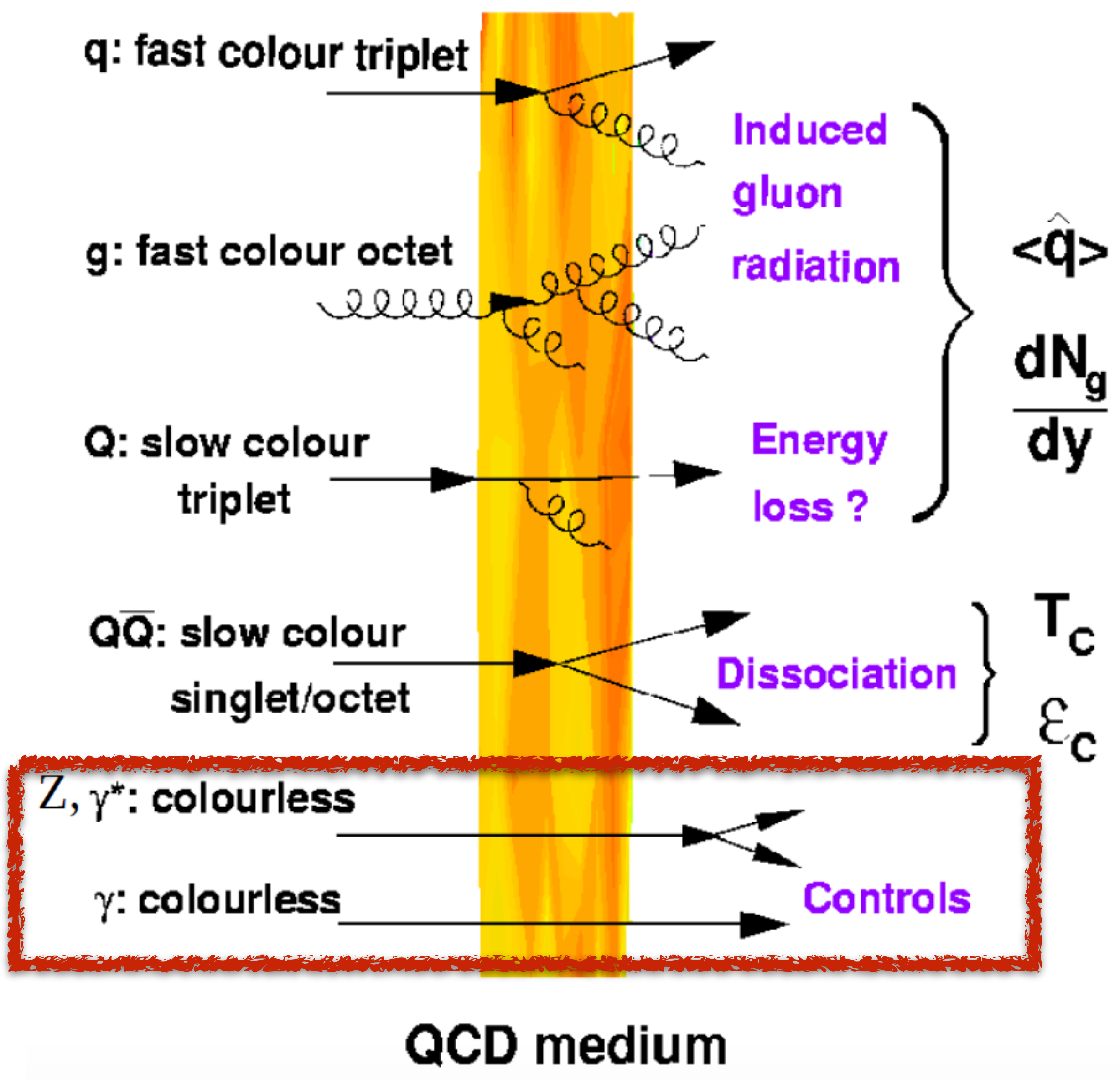
- Hard (large Q^2) probes **production in vacuum is well controlled** experimentally and theoretically (pQCD)
- **Produced early** (short formation time t~1/Q~0.1fm/c), before the QGP is formed, they experience the full evolution of the system
- **"tomographic" probes** of the hottest and densest phase of the collision





Hard probes as control experiment.

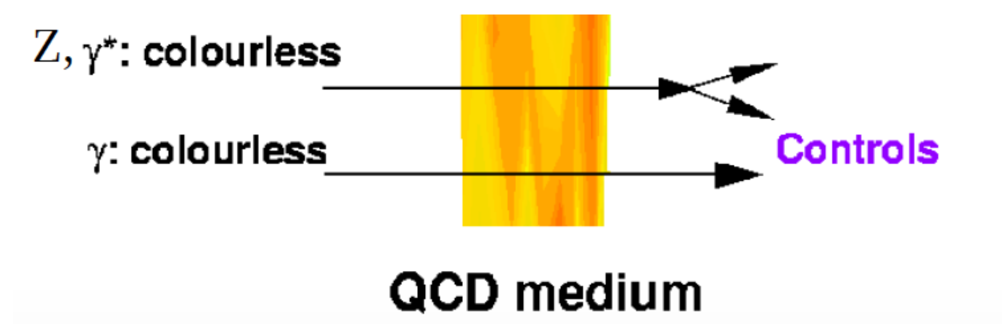
A look at W and Z boson production.



E. Masson talk later (photons)

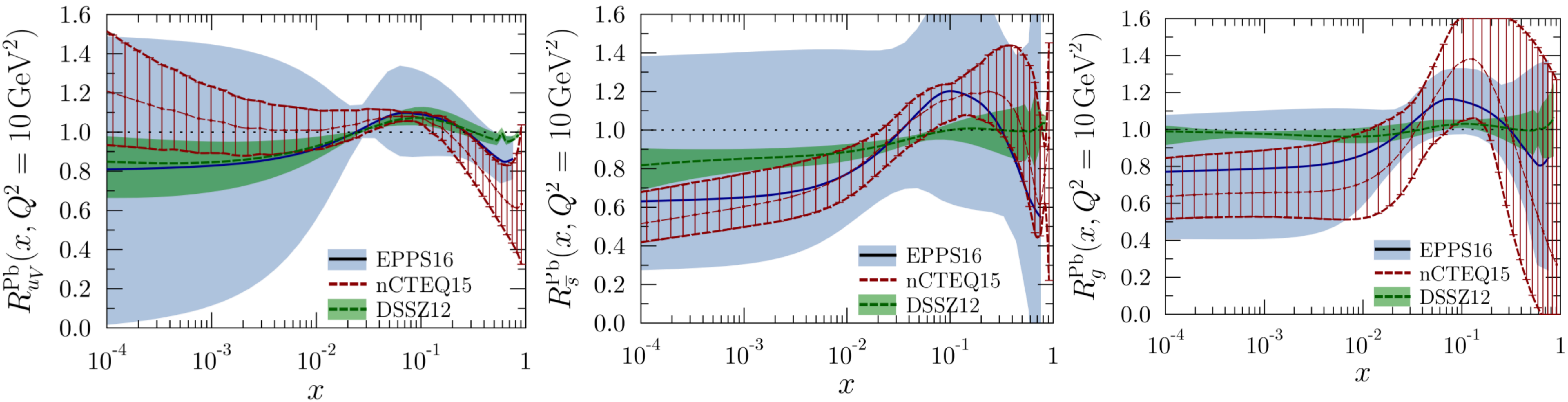
W/Z as medium-blind references

- The standard model allows precise calculations involving electroweak bosons,
  - sensitive to quark (u,d,s) PDF
  - large enough abondance at the LHC
- **Medium-blind references in a QGP:**
  - they do not interact strongly, allow **binary scaling test**
  - bremsstrahlung of their decay leptons by interaction with the medium is negligible
  - **sensitive to nuclear Parton Distribution Functions (nPDFs)**



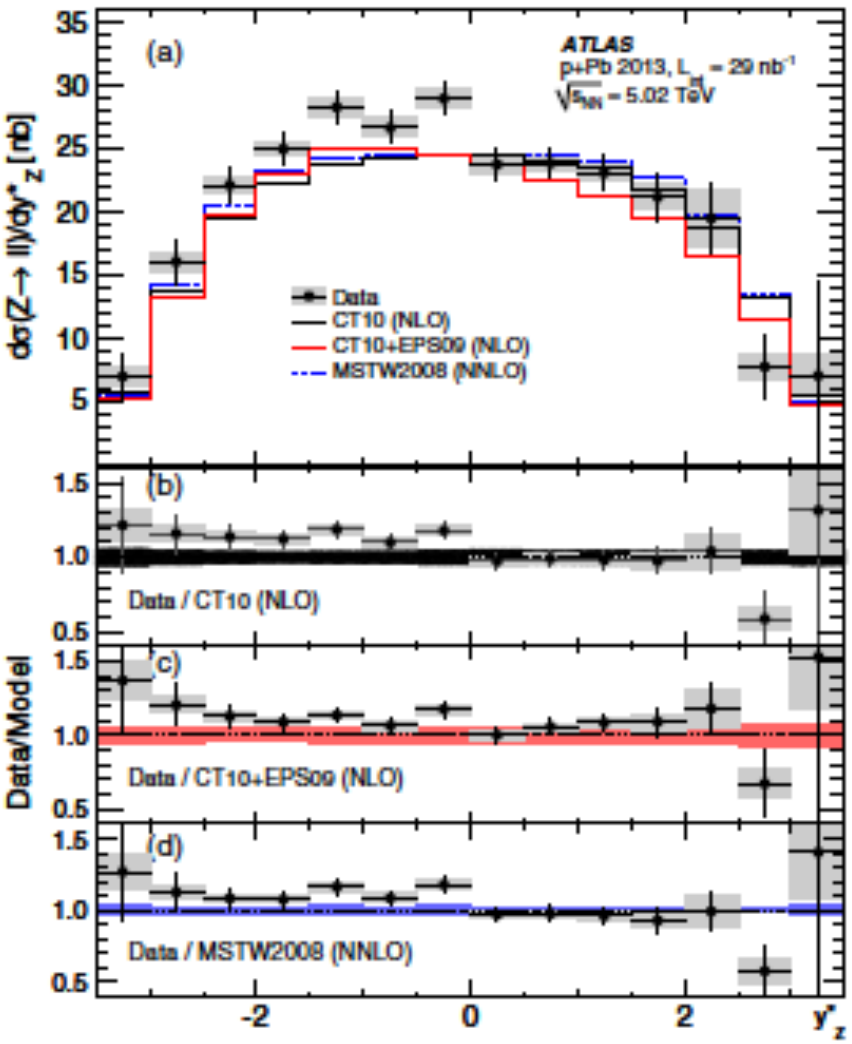
$$R_i^A(x,\mu_f) = \frac{f_i^A(x,\mu_f)}{A f_i^{nucleon}(x,\mu_f)}, \quad f_i = q, \bar{q}, g$$

EPPS16: Eur. Phys. J. C (2017) 77: 163
nCTEQ15: PRD 93 (2016) 085037
nDSSZ'11: PRD85 (2012) 074028
KA15 (NNLO): PRD 93 (2016) 014026
HKN'17: PRC 76 (2007) 065207
NNPDF: arXiv:1811.05858

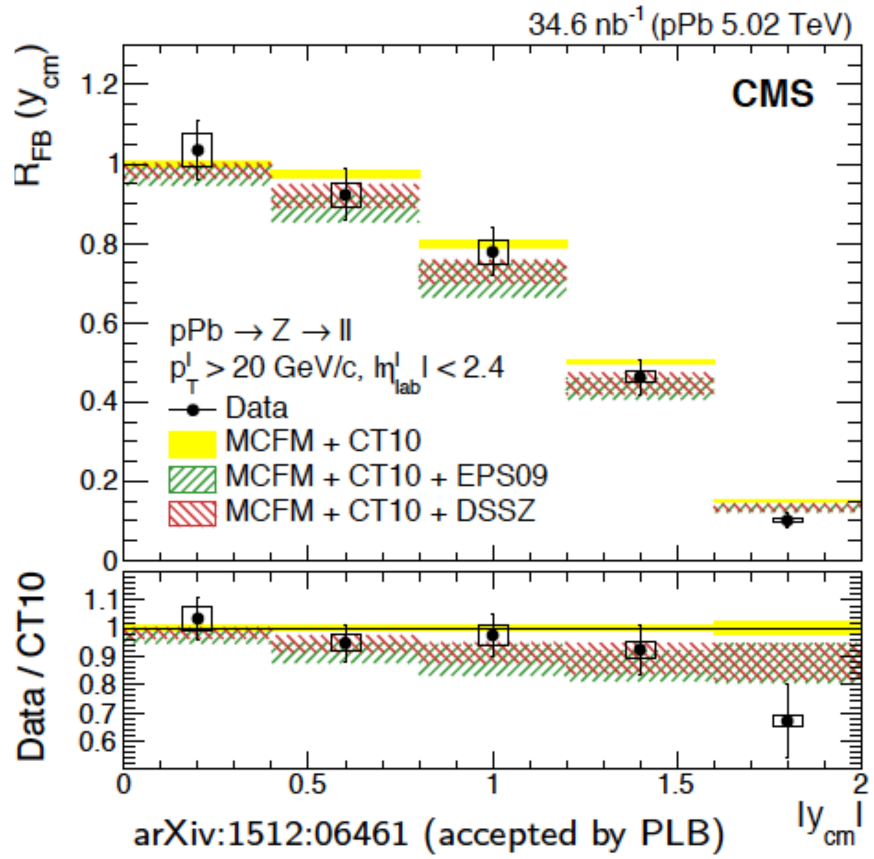


W/Z in pPb collisions

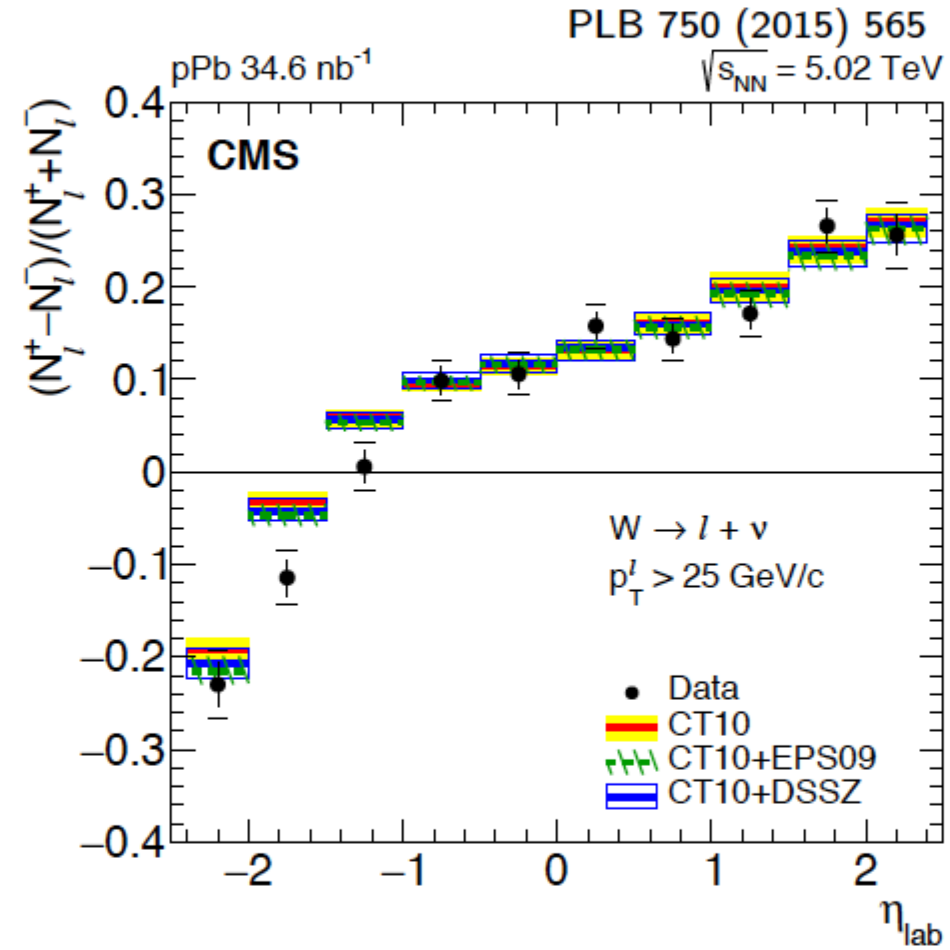
Z boson y dependence



Z boson
forward to backward ratio



W-decay lepton charge asymmetry

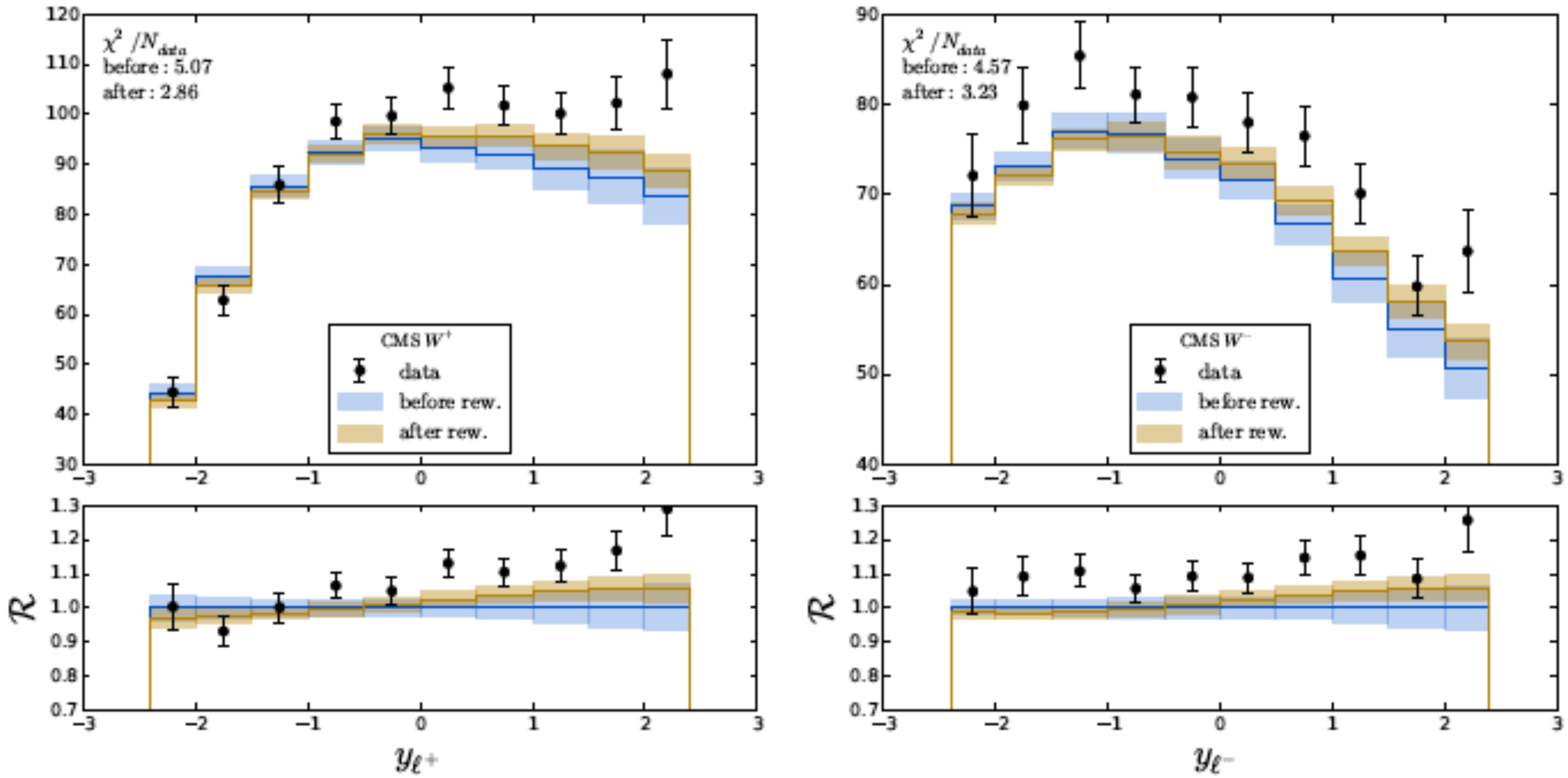


ATLAS, ATLAS-CONF-2017-010, ATLAS-CONF-2015-056
ALICE, JHEP 02 (2017) 077
CMS, Phys. Lett. B 759 (2016) 36, PLB 750

- Good sensitivity to quark nPDFs
- Z results show some tension appearing at large rapidities
- W-decay lepton charge asymmetry: deviation from expectations, scaling properties
  - Excess of W^- in backwards hemisphere (Pb-going): well beyond EPS09.
  - Requires weakening of assumed isospin symmetry?

Including W/Z pPb LHC data on nPDFs

W boson y distribution from CMS

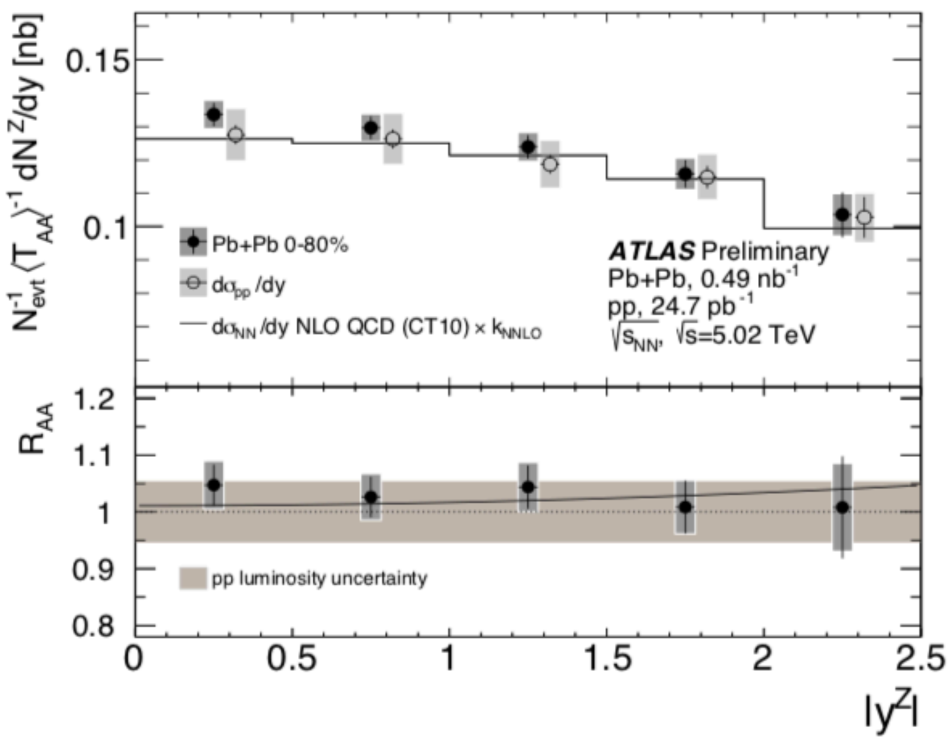


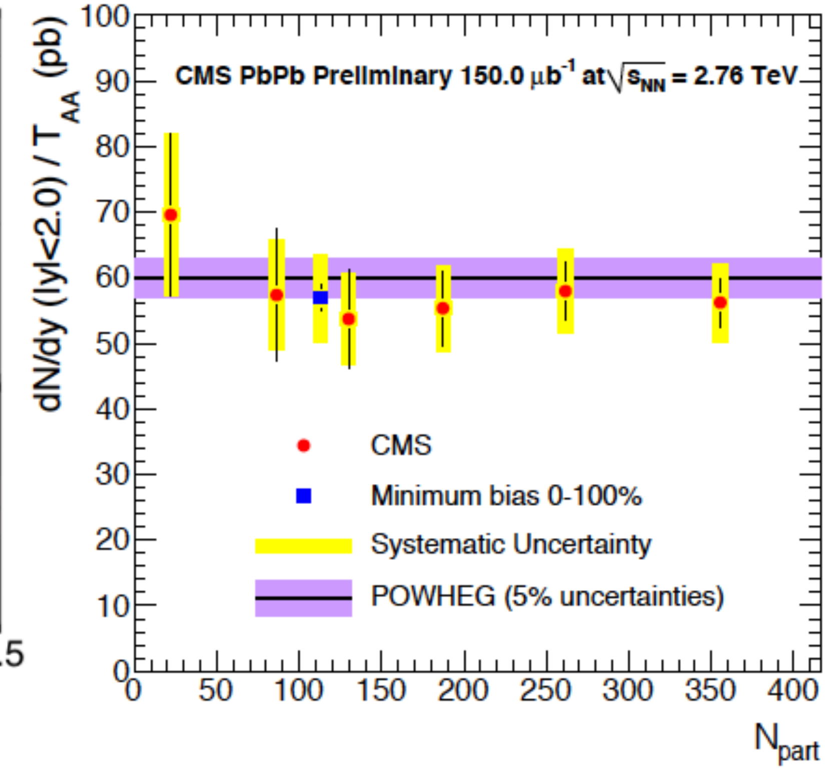
- Reweighting procedure used to include W/Z pPb data on nCTEQ15
    - Improvements after reweighting
    - However, strange PDF not fitted independently in nCTEQ15
    - Need to include data in global analysis and open up strange PDF

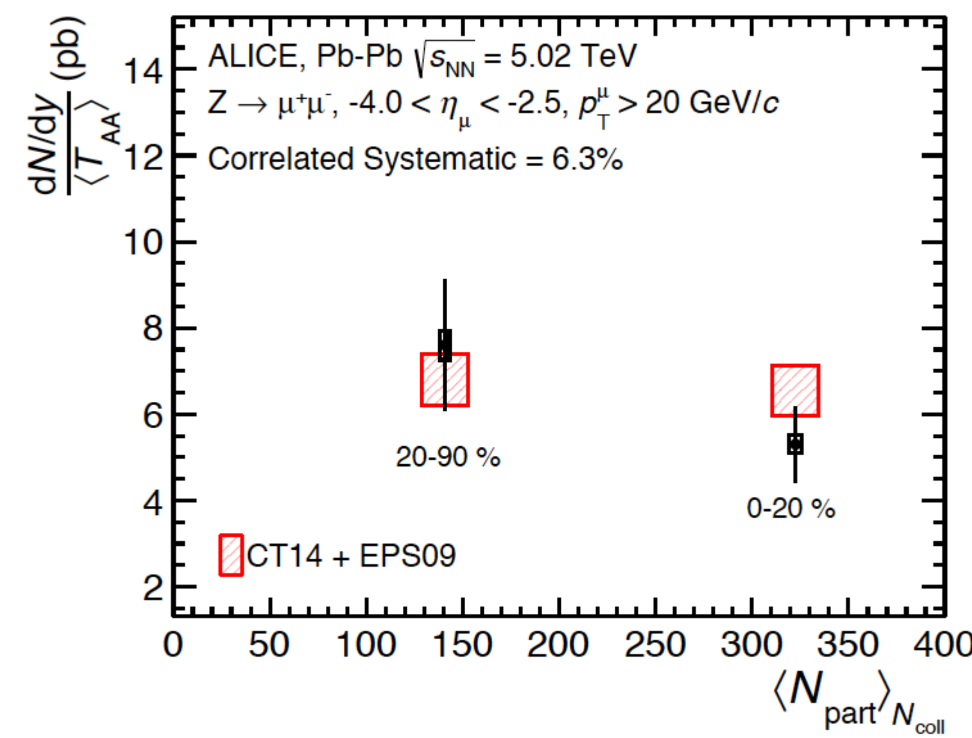
Kusina et al, Eur.Phys.J. C77 (2017) no.7, 488

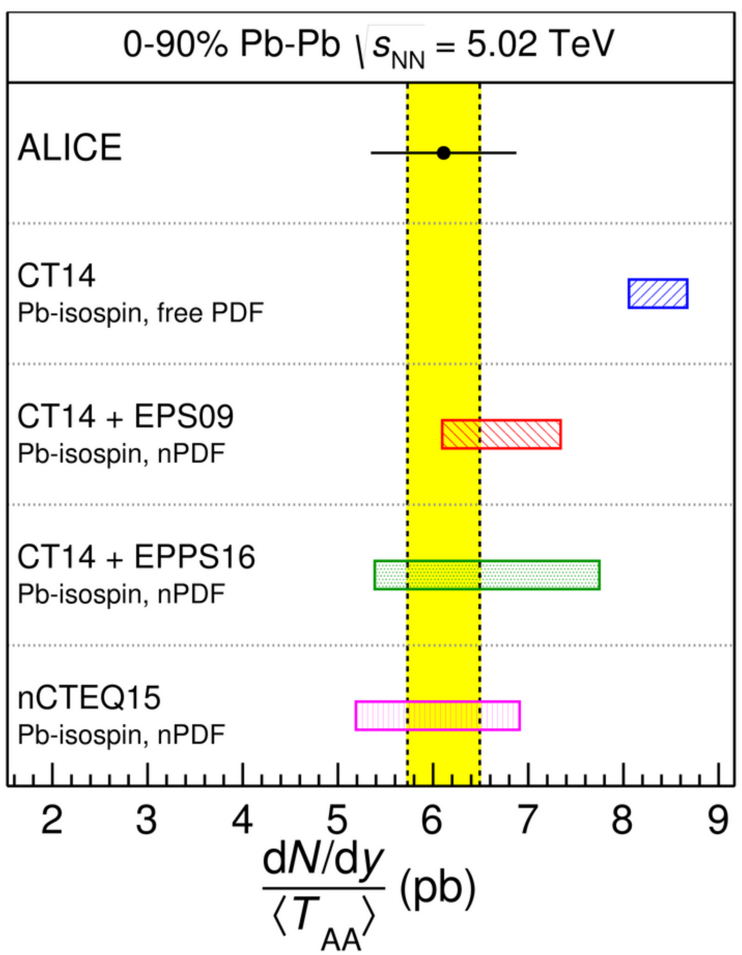
- W/Z data are **sensitive** to the heavier quark flavours (specially s PDF) ⇨ information on **flavour decomposition**
- Improving the nuclear corrections with heavy-ion data can help to reduce proton PDF uncertainties (flavours)

Constraints from PbPb data?







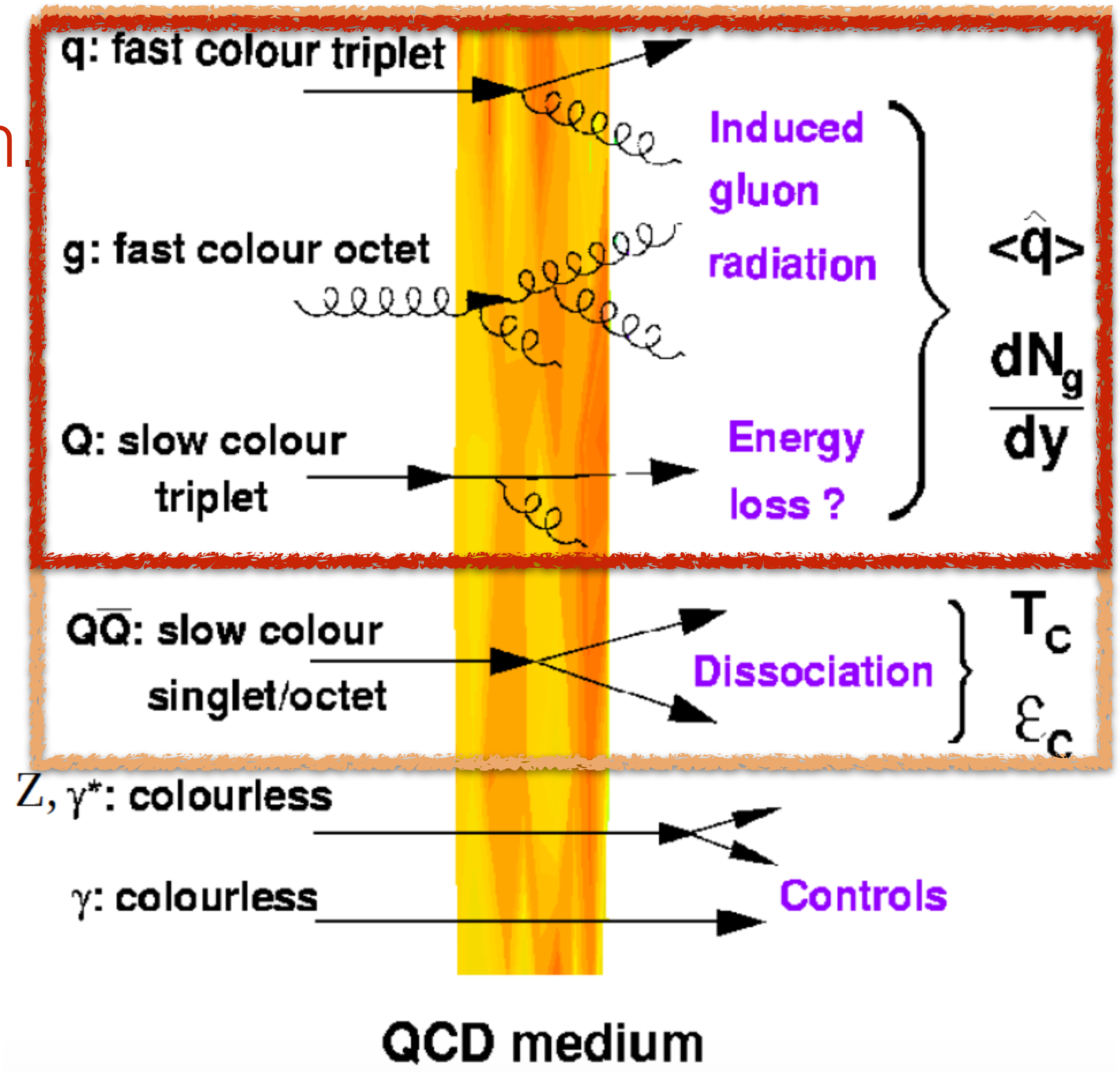


ALICE, Phys. Lett. B 780 (2018) 372–383
ATLAS, ATLAS-CONF-2017-010, ATLAS-CONF-2017-067
CMS, PRL 106 (2011) 212301, JHEP 03 (2015) 022
EPS09s: Helenius et al, Nucl.Phys. A904-905 (2013) 999c-1002c

- **Average integrated yield per nucleon collision well described considering nPDFs** (not with only PDFs)
- Impact parameter (centrality) dependence:
  - No deviation measured at mid-rapidity (binary scaling), whereas forward rapidity data there are hints of a suppression in more central events.
  - nPDF centrality dependence seemingly weaker than data
- **More precise data required to constrain the nPDF**

Hard probes
as medium sensitive observables.

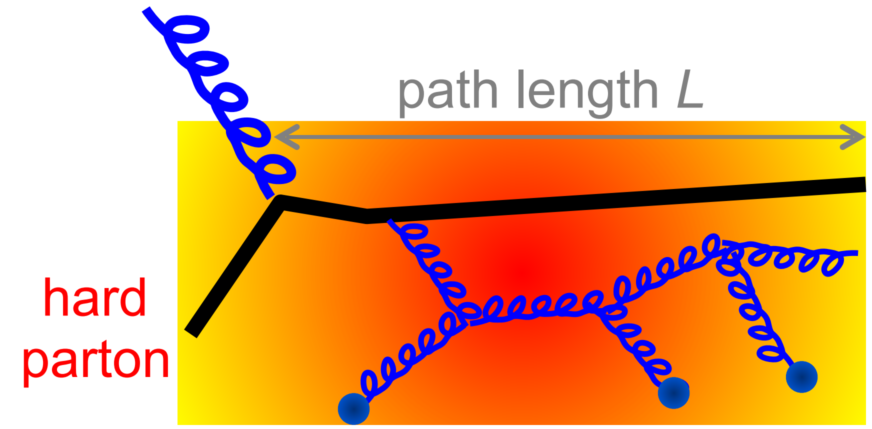
A look at charged-particle
and heavy-flavour production.



R. Katz talk later (quarkonia)

Parton energy loss in the QGP

- In heavy-ion collisions, partons that traverse the QGP can lose energy in the QGP:
  - **radiative** energy loss
  - **collisional** energy loss



$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

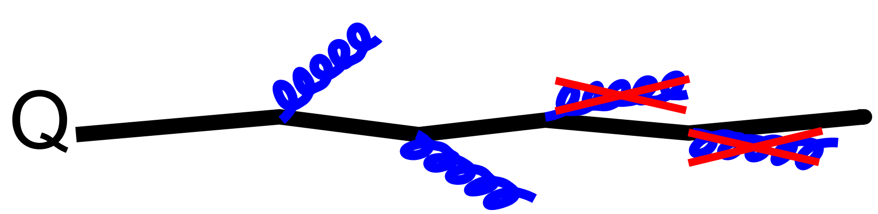
Cassimir factor, transport coefficient

[R.Baier et al(BDMPS), Nucl. Phys. B483 (1997) 291.]

$$\hat{q} \equiv m_D^2 / \lambda = m_D^2 \, \rho \, \sigma$$

Debye mass ~ gT, ρ medium density, σ cross section

- Medium-induced gluon radiation
  - Depends on:
    - Casimir (**colour**) coupling factor: 4/3 for quarks, 3 for gluons
    - Medium **transport coefficient** ∝ gluon density and momenta
    - In-medium **path length**
  - Dead cone (**mass**) effect: in vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

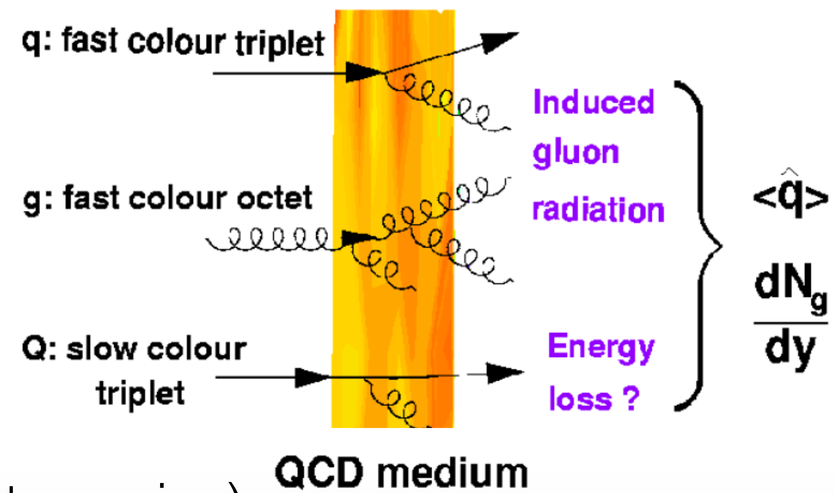


[Dokshitzer and Kharzeev, Phys. Lett. B519 (2001) 199]

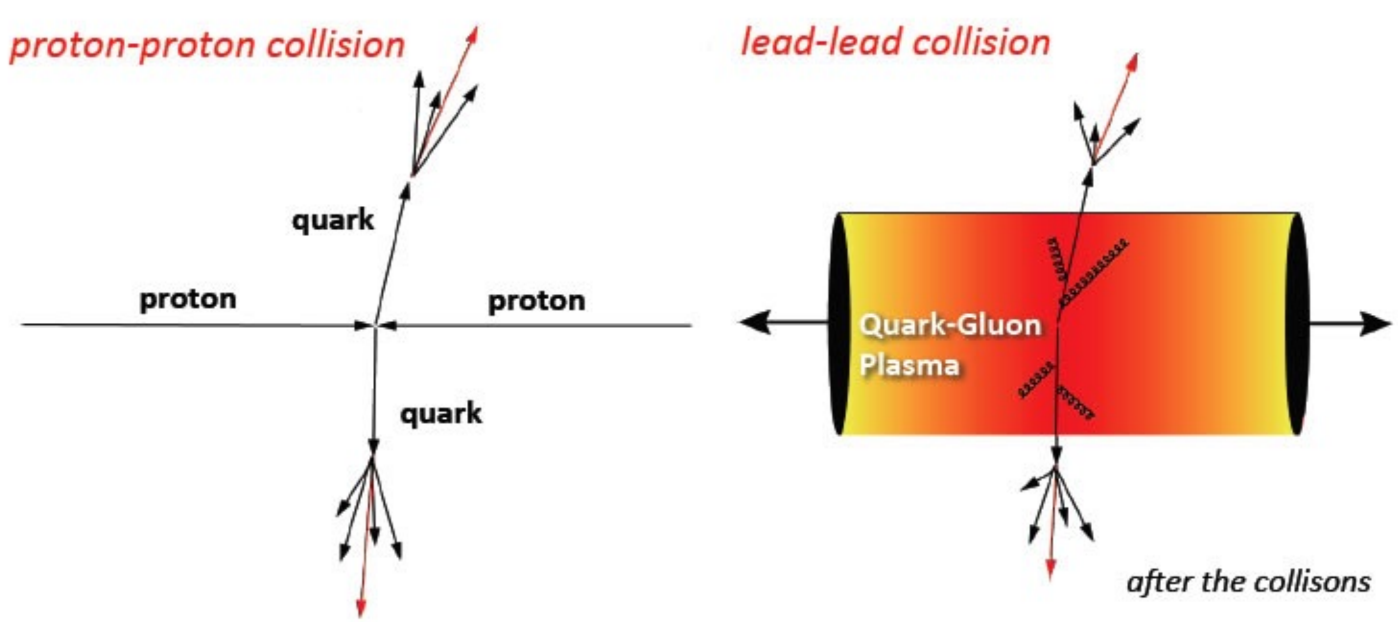
- **Parton energy loss is:**
  - **Sensitive to the energy density of the system**
  - **Different partons may have different energy loss**
    - $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$

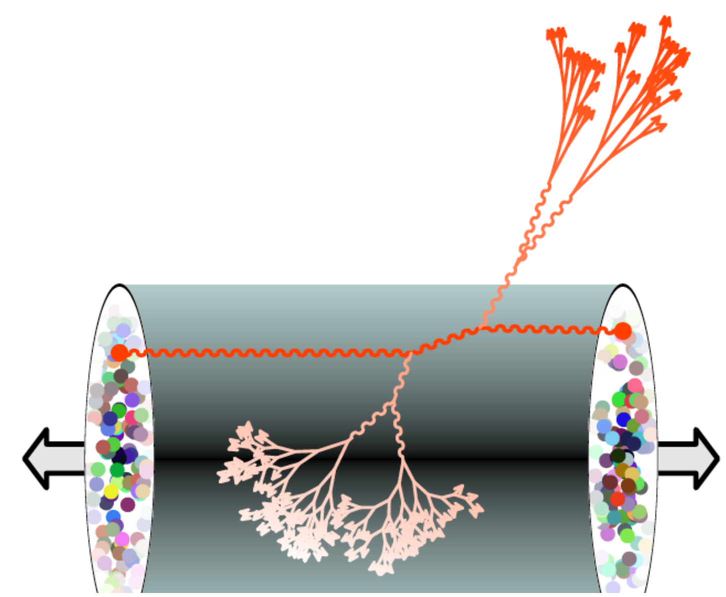
Jet quenching

- Hard probes (high momentum particles, jets, heavy flavours) originate from the fragmentation of high momentum partons (large Q^2) produced by the initial hard scatterings
  - well controlled experimentally & theoretically (pQCD),
  - back-to-back correlation in vacuum.

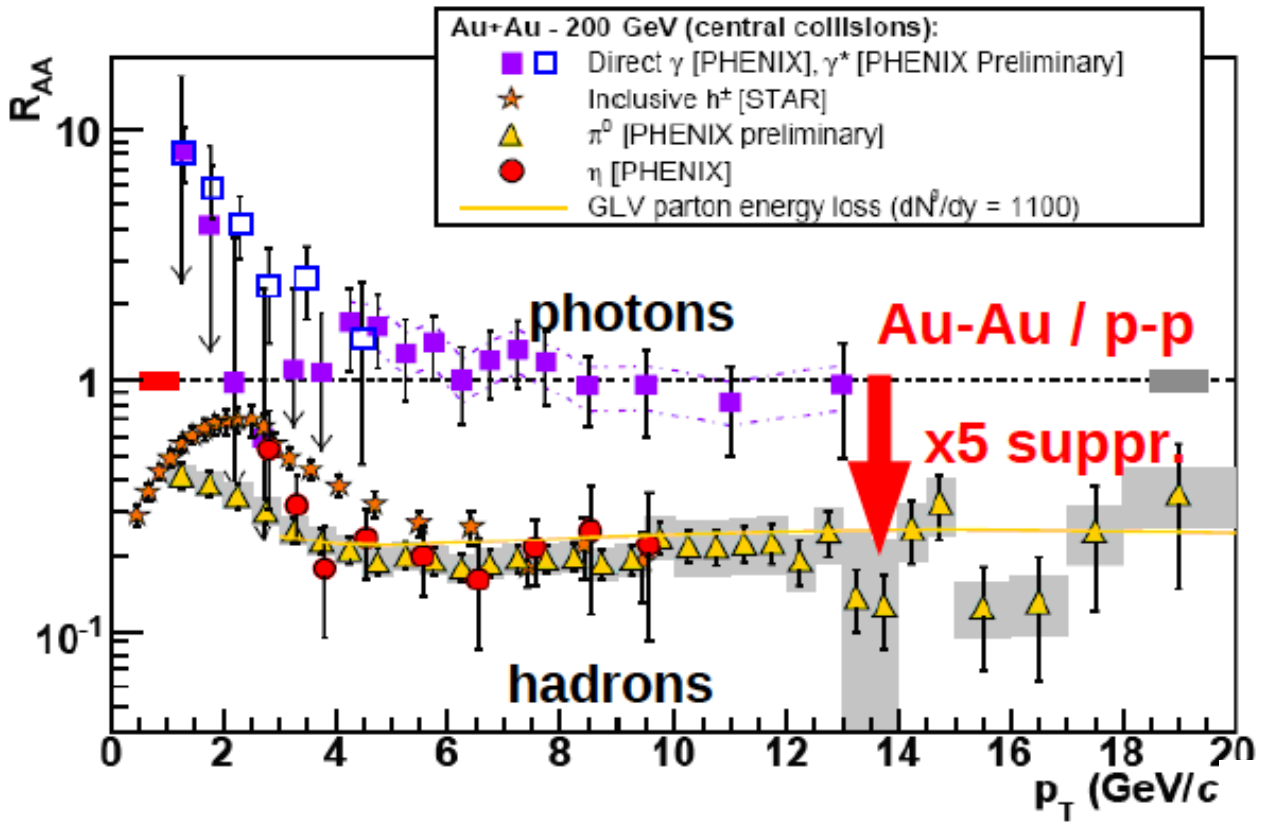


- In a QGP: **jet quenching:**
  - **Suppression of high momentum hadrons**,
  - **Color** and **mass** dependent suppression (look at different species),
  - Modification of **azimuthal correlations**; jets escape only if they are produced near the edge and are directed outwards.





Suppression of high-p_T hadrons at RHIC



$$R_{AA} = \frac{\left(dN/dp_T\right)_{AA}}{\langle N_{coll}\rangle_{AA}\ \left(dN/dp_T\right)_{pp}}$$

- **Suppression of all high-p_T hadrons (but not photons!) observed first at $\sqrt{s_{NN}}$=200 GeV**

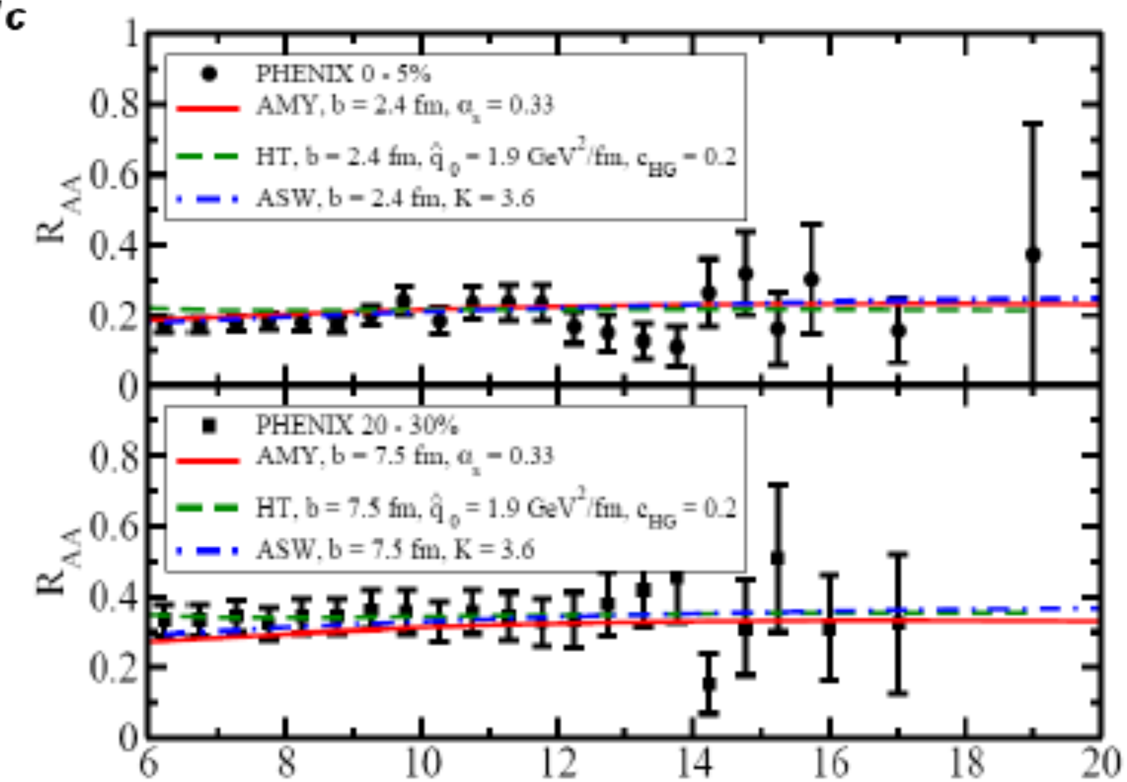
- Derived medium properties (within 3-D hydro model):

QGP very dense & opaque to coloured particles!

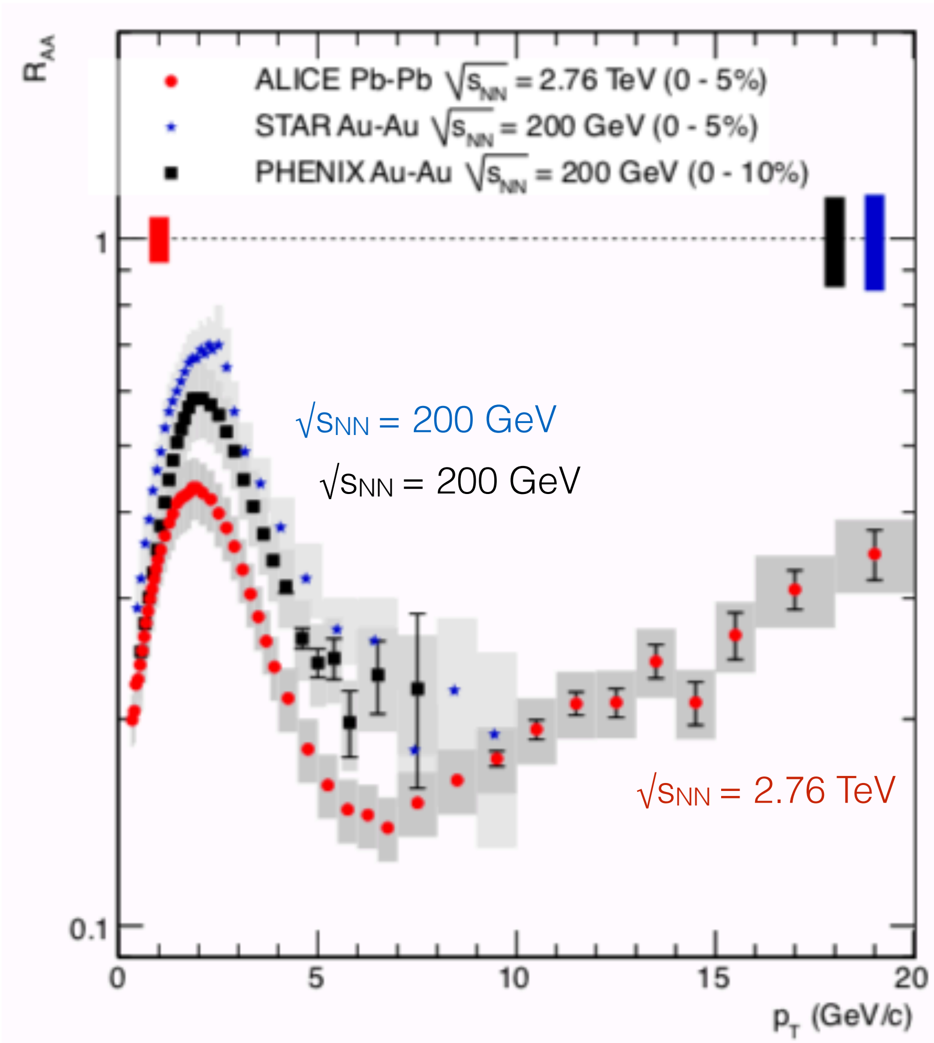
$$\langle \hat{q} \rangle = 4 - 13\ \mathrm{GeV}^2/\mathrm{fm}$$

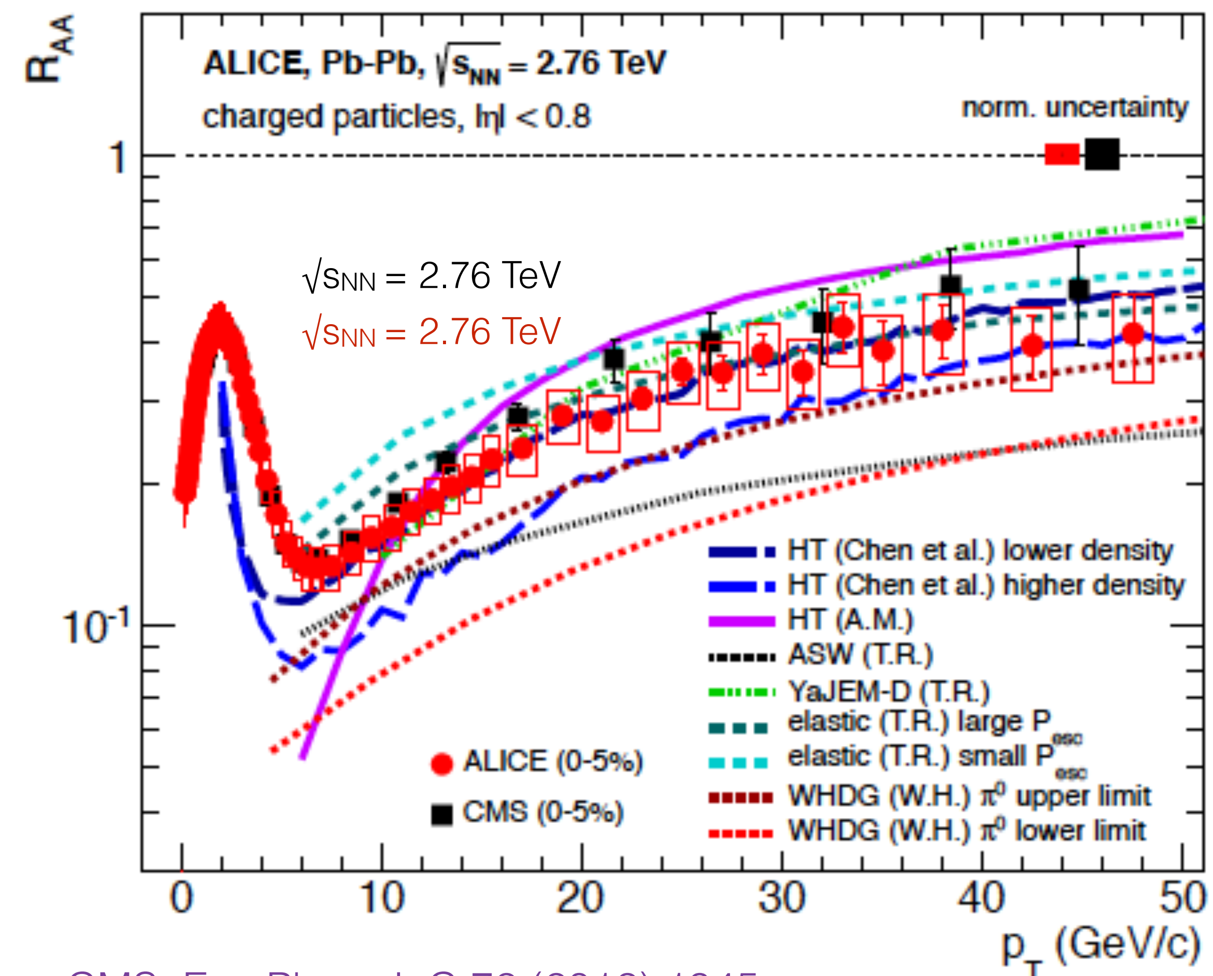
$$dN^g/dy \sim 1400 \pm 200$$

Bass et al, PRC79 (2009) 024901



Suppression of high-p_T hadrons

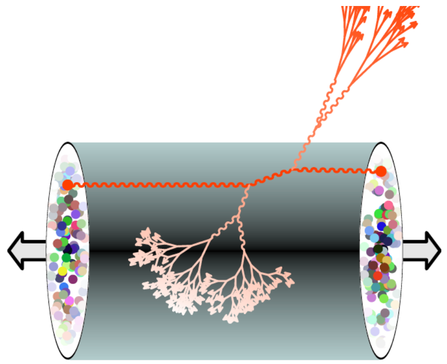


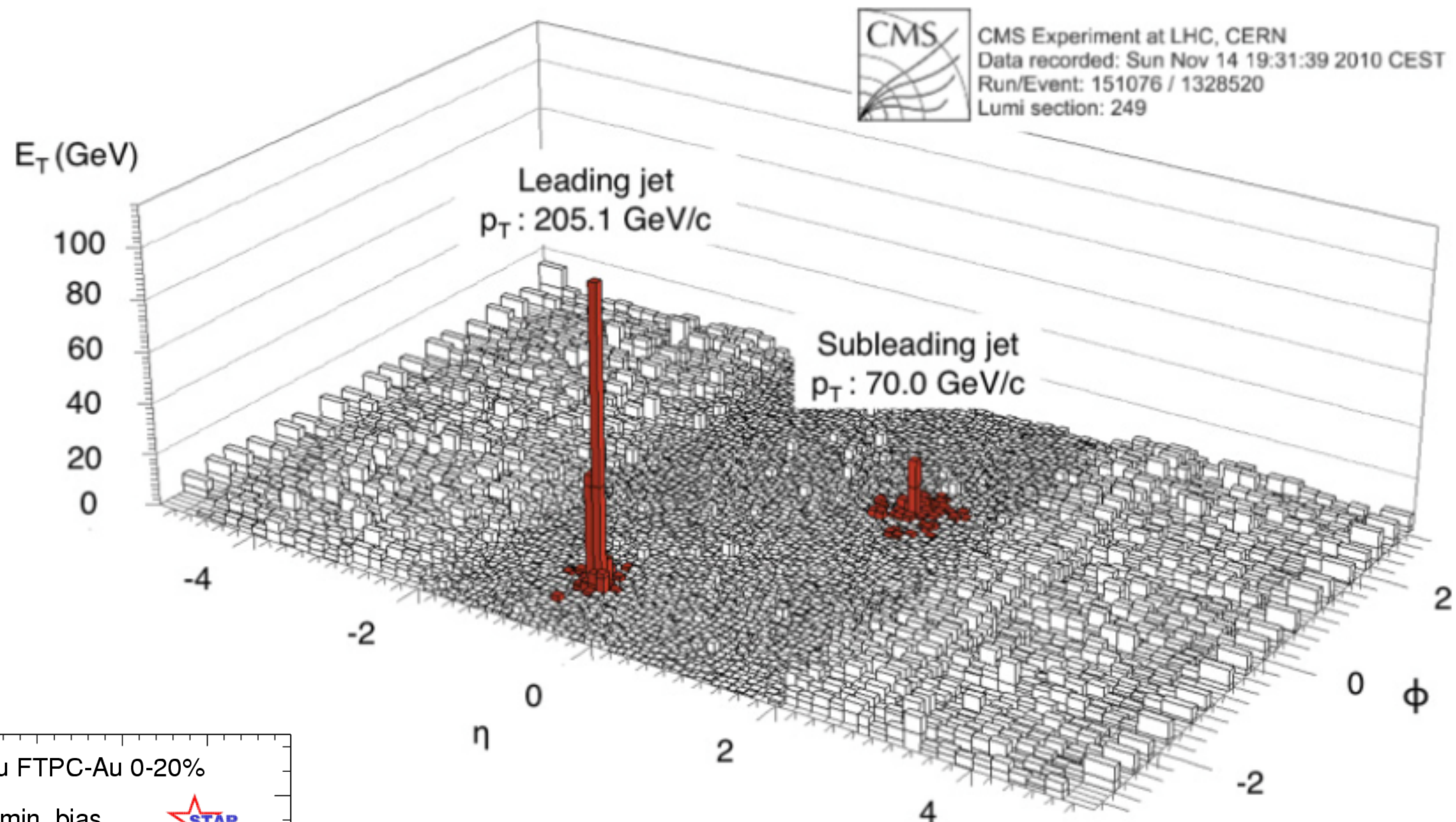


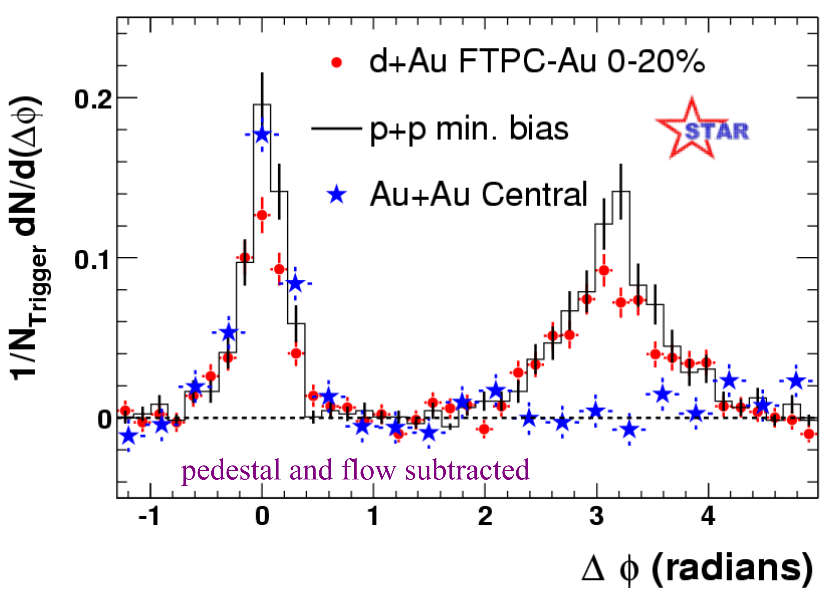
CMS, Eur. Phys. J. C 72 (2012) 1945
ALICE, Phys. Lett. B 696 (2011) 30-39, Phys.Lett. B720 (2013) 52-62

- Larger suppression at $\sqrt{s_{NN}}$ = 2.76 TeV than at $\sqrt{s_{NN}}$ = 200 GeV
- Characteristic p_T dependence reproduced by models (fragmentation, relative energy loss)
- **Evidence for parton energy loss and large medium density at the LHC**

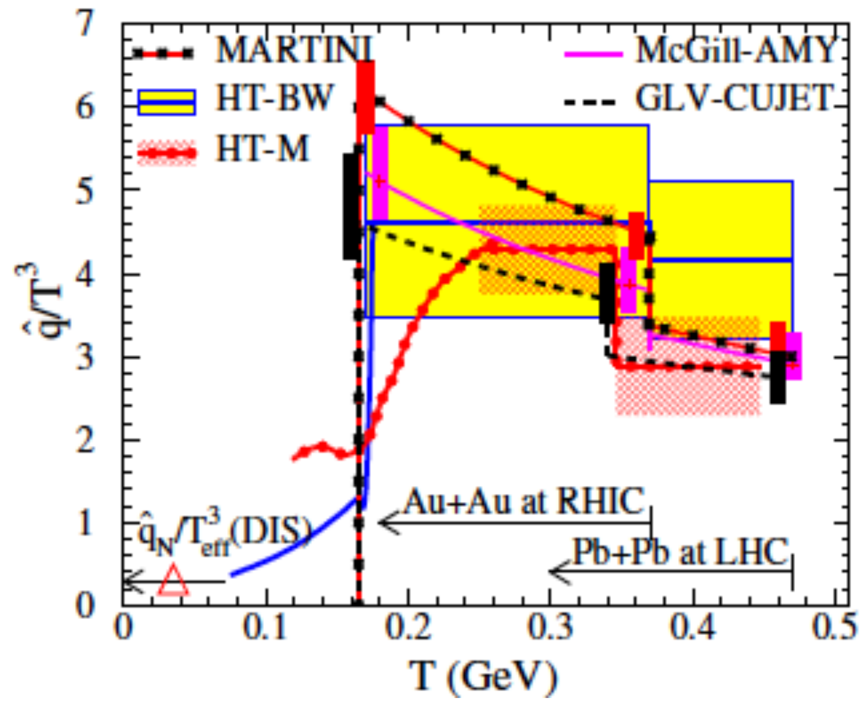
Suppression of back-to-back jets



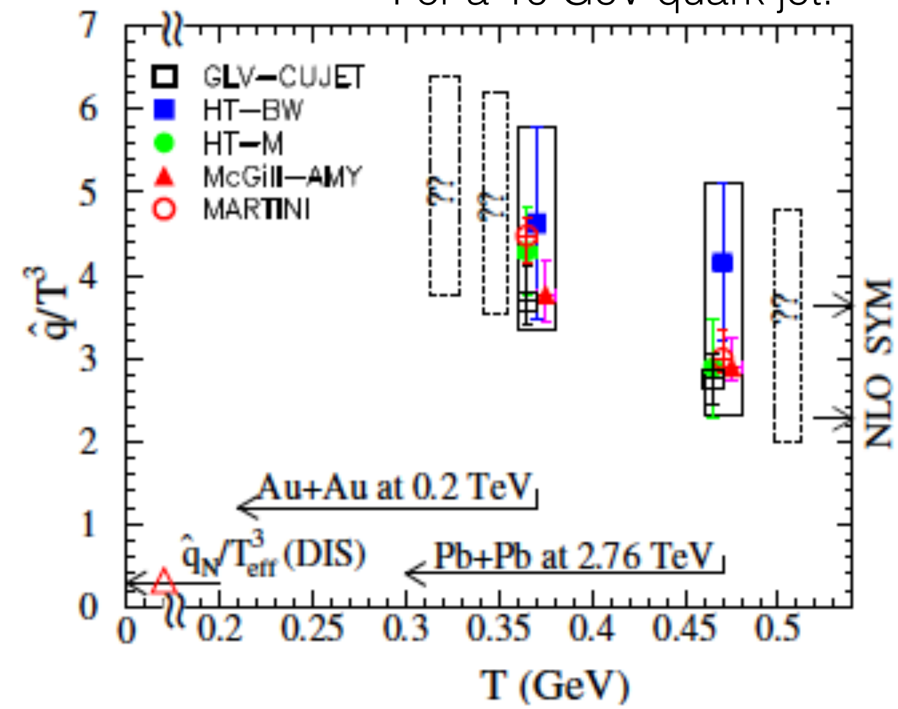




Constraining transport properties



For a 10 GeV quark jet:



JET, Phys. Rev. C **90**, 014909 (2014)

- Five different models considered (CUJET, MARTINI, McGill-AMY, HT-M, HT-BW)
- RHIC and LHC data on single hadron suppression constrain energy loss models
- For the highest temperatures (most central collisions)

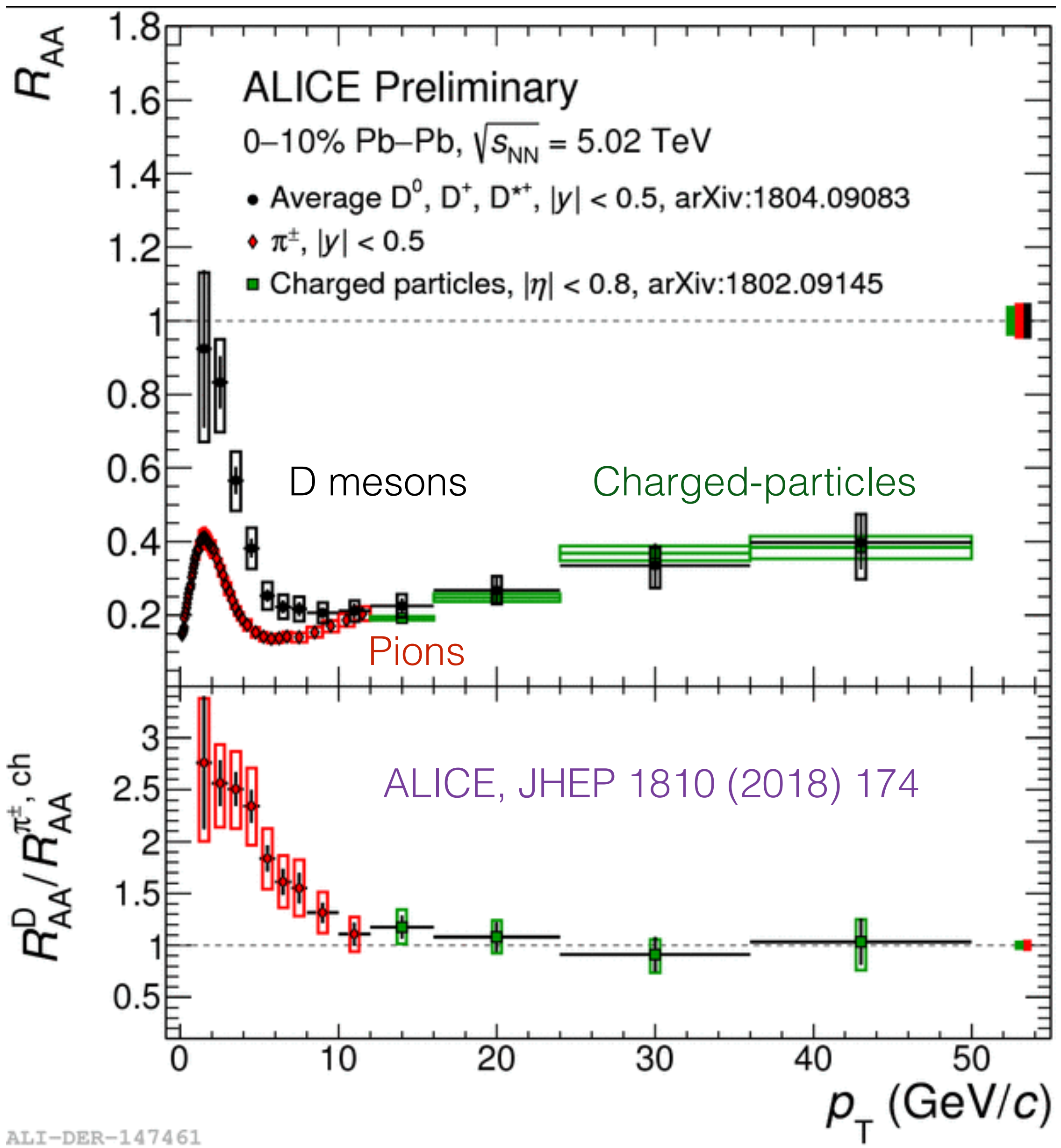
For a 10 GeV quark jet:

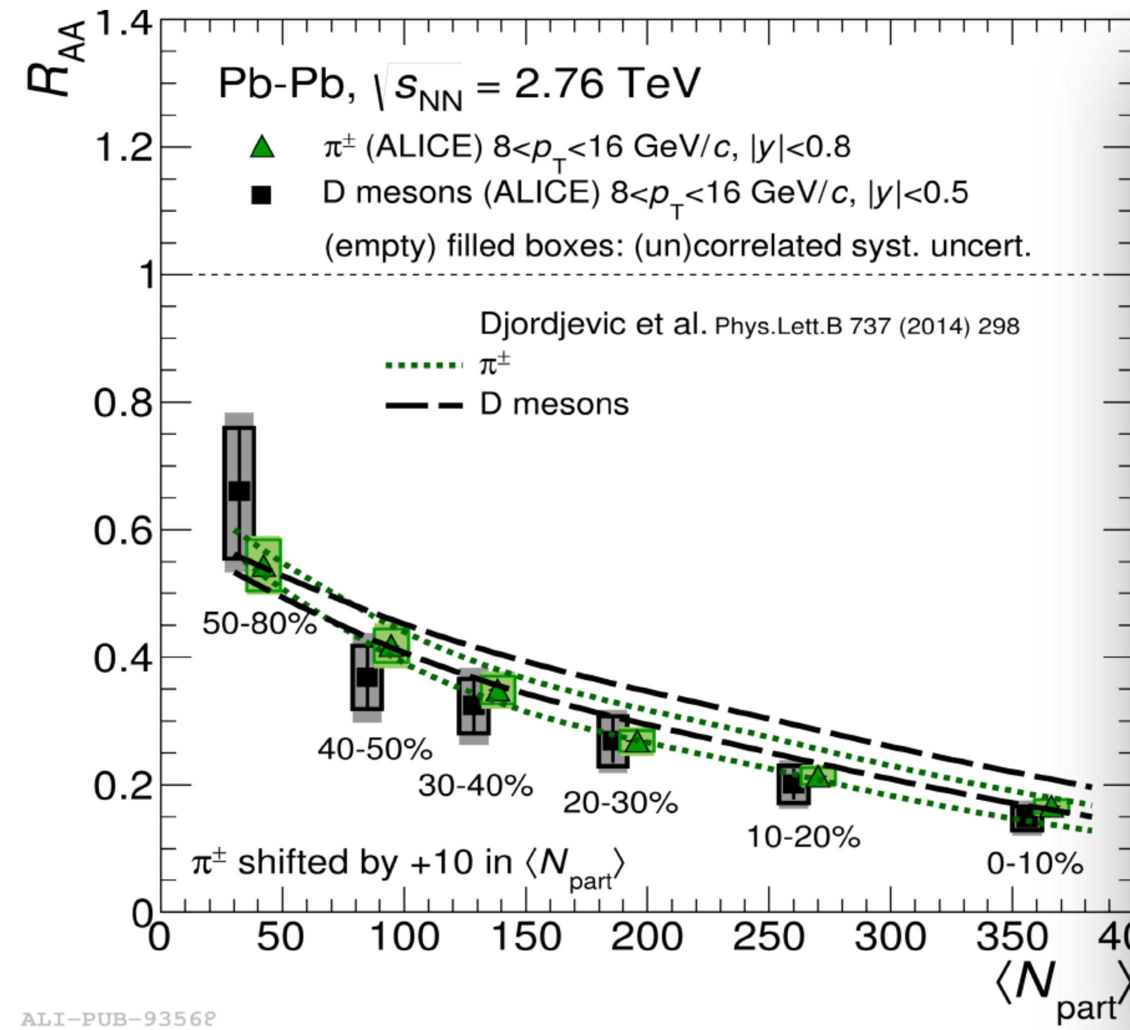
$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{at} \ \begin{matrix} T{=}370\ \mathrm{MeV}, \\ T{=}470\ \mathrm{MeV}, \end{matrix}$$

- Consistent results with LO pQCD and NLO AdS/CFT SYM results
- **Full MonteCarlo (hydro, quenching…) and a systematic comparison with all observables is required**

Colour dependence of parton energy loss



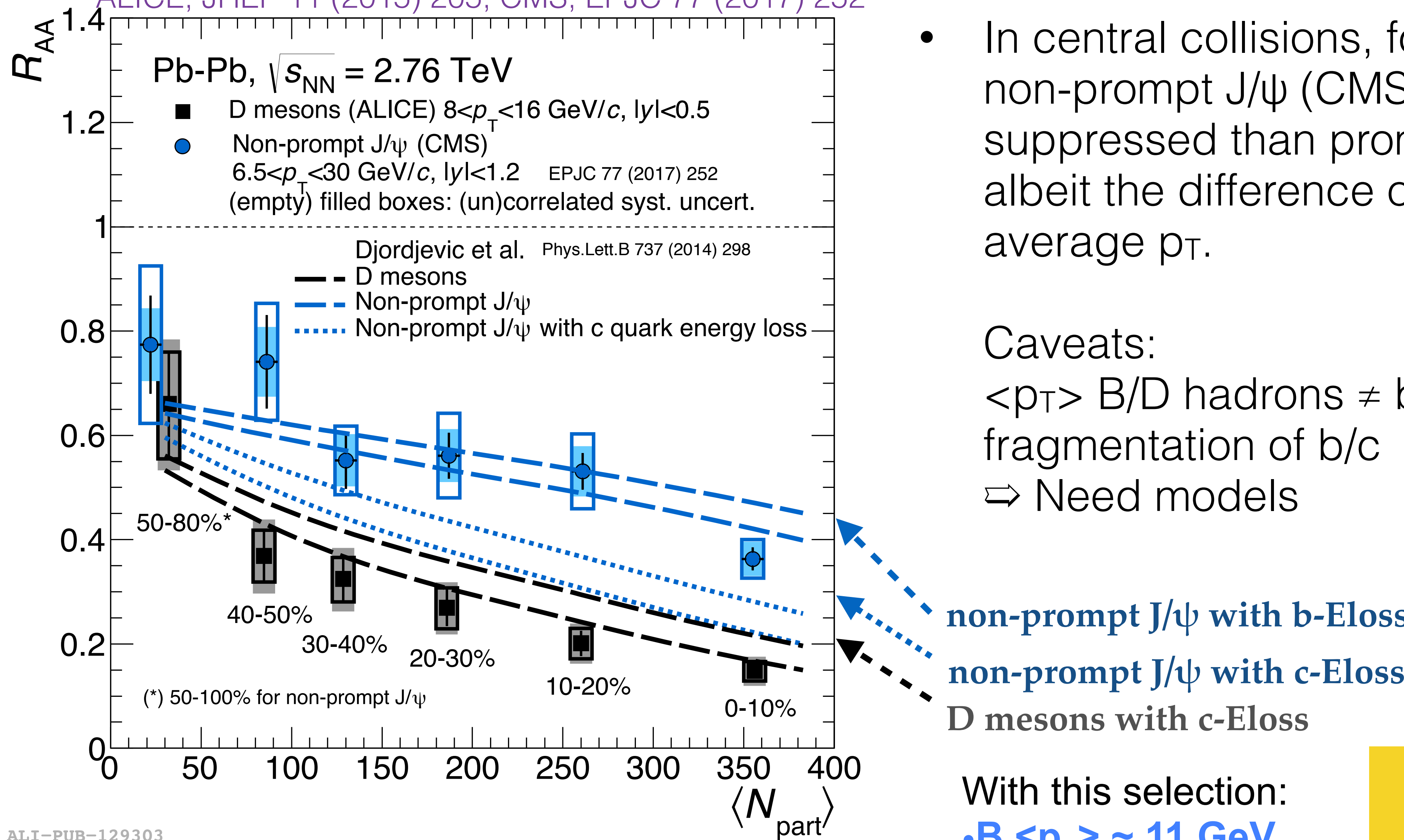


Energy loss colour charge dependence,
$\Delta E_{c,b} < \Delta E_{u,d,s} < \Delta E_g$?

- Strong suppression of high-p_T D-meson (increasing with centrality)
- Very similar D-meson and charged-particle R_{AA} from p_T~8 to 100 GeV/c
  - Similar rise above 10 GeV/c
- **Consistent with colour charge dependence of parton energy loss**

Mass dependence of parton energy loss

ALICE, JHEP 11 (2015) 205; CMS, EPJC 77 (2017) 252



- In central collisions, for p_T>6 GeV, non-prompt J/ψ (CMS) are less suppressed than prompt D mesons, albeit the difference on the b/c average p_T.

Caveats:
<p_T> B/D hadrons ≠ b/c quarks
fragmentation of b/c
⇨ Need models

With this selection:
- **B <p_T> ~ 11 GeV**
- **D <p_T> ~ 10 GeV**

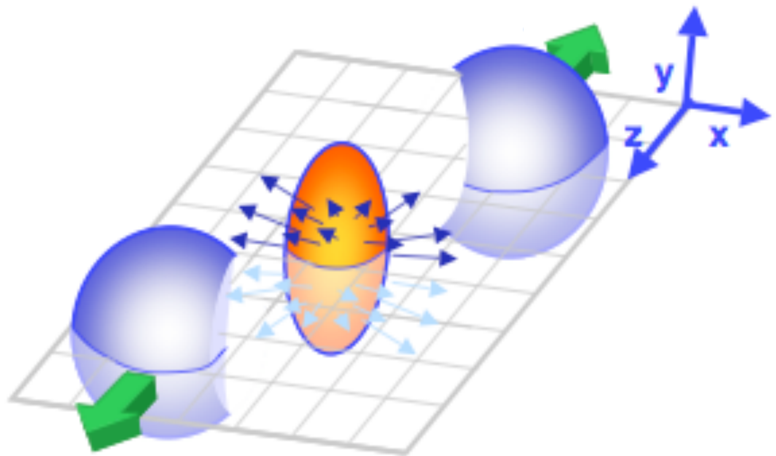
Energy loss mass dependence, $\Delta E_b < \Delta E_c$?

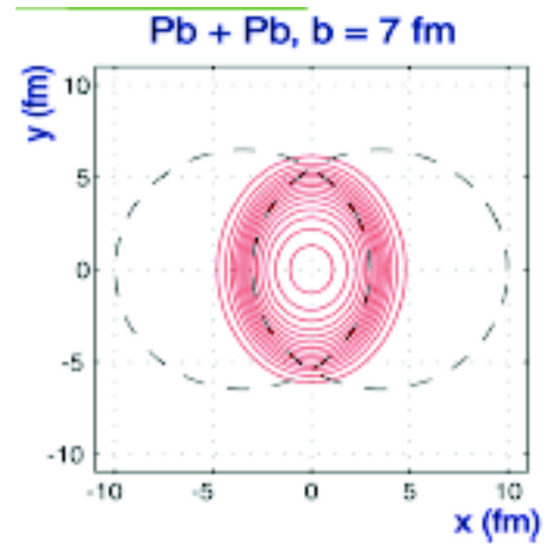
[Djordjevic: private comm (ALICE)]

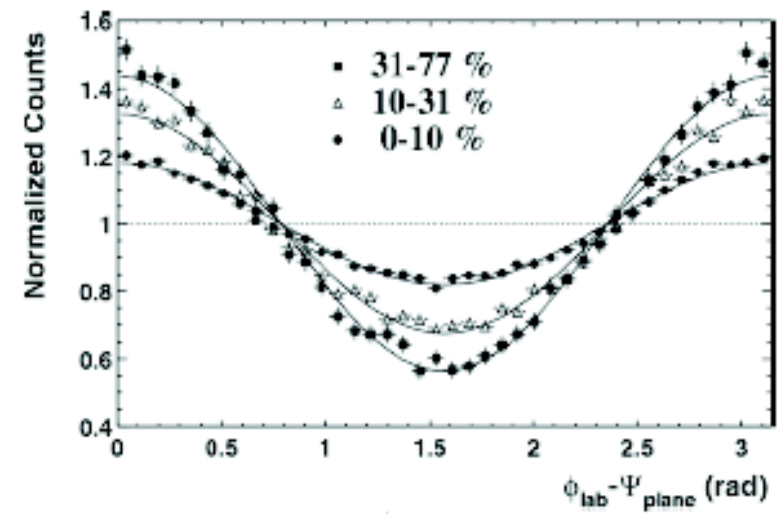
[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
[Vitev: R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C80 (2009) 054902; Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B 713 (2012) 224]

- **Consistent with the expectations of mass dependent parton energy loss**

Azimuthal anisotropy







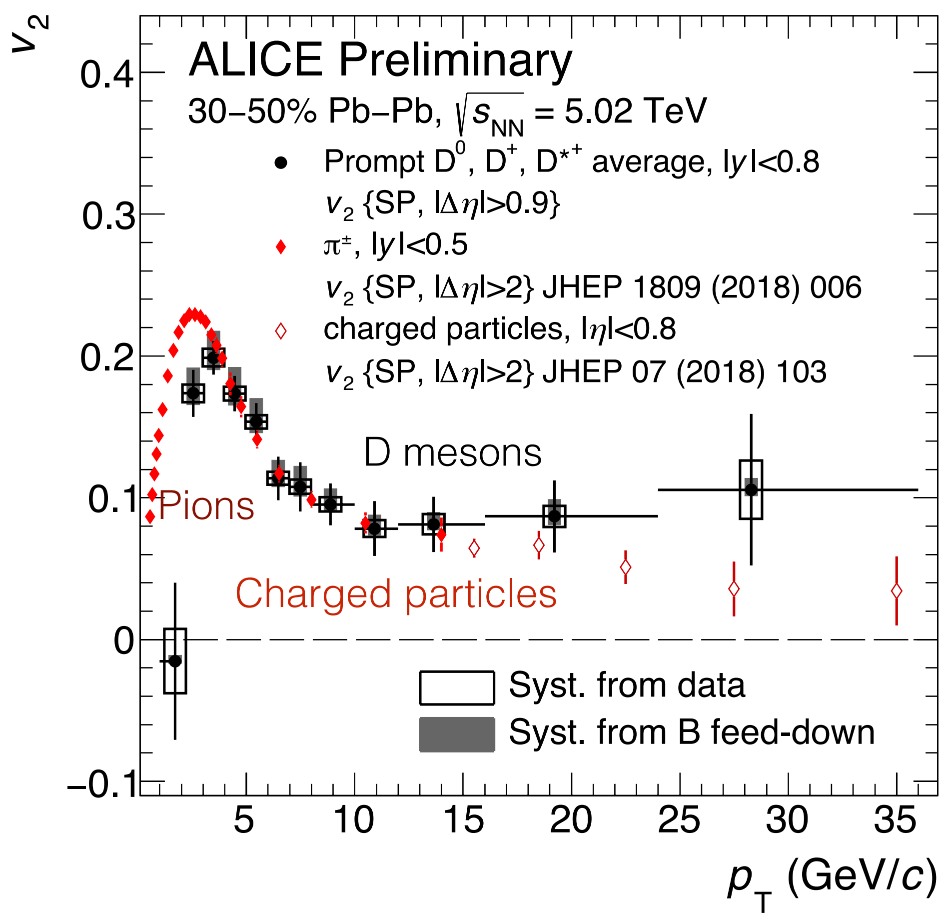
Almond-shape spatial anisotropy in coordinate space → Interactions / Rescattering → Anisotropy in momentum space

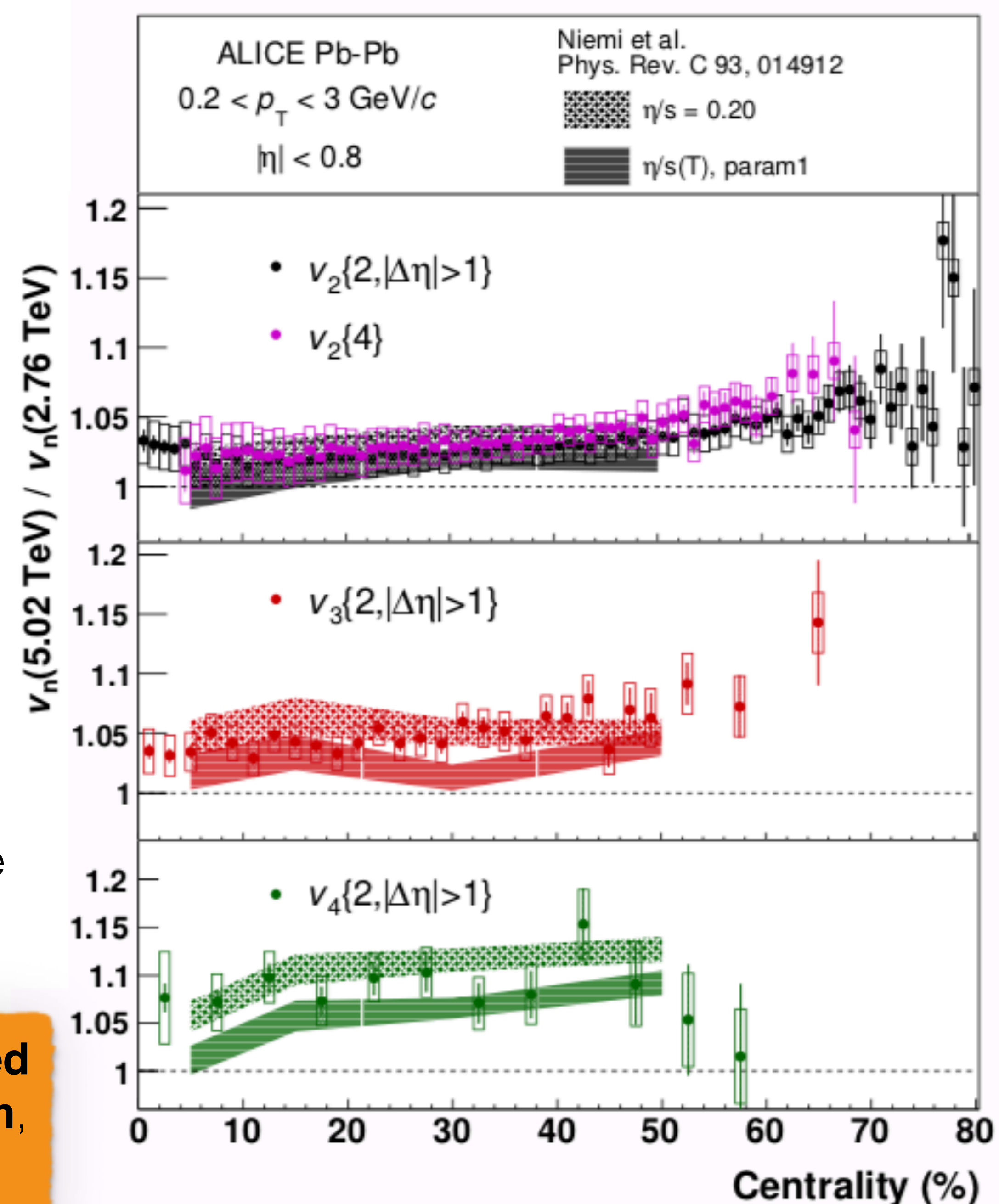
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\left(\phi - \Phi_{RP}\right)\right)\right)$$

Elliptic flow ≡ v_2 ≡ 2nd Fourier component

- Boosted momentum emission wrt. reaction plane
- Gases explode into vacuum uniformly in all directions.
- Liquids flow violently along the short axis and gently along the long axis.
- **We can observe the medium and understand if it is more liquid-like (non-zero v_2) or gas-like.**

Azimuthal anisotropy at the LHC

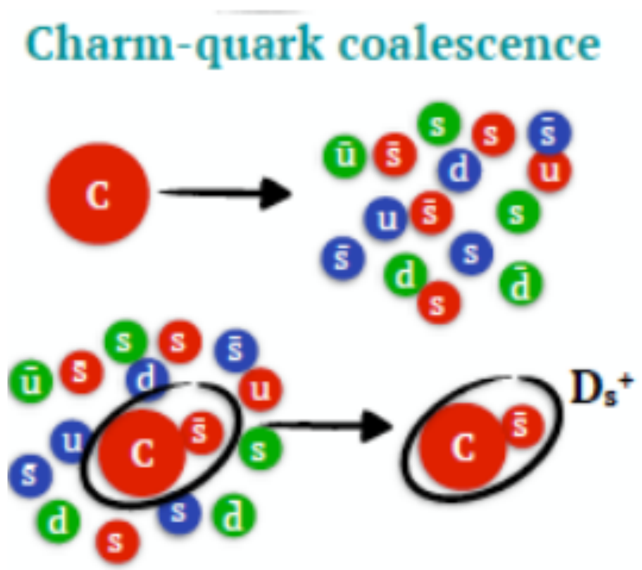


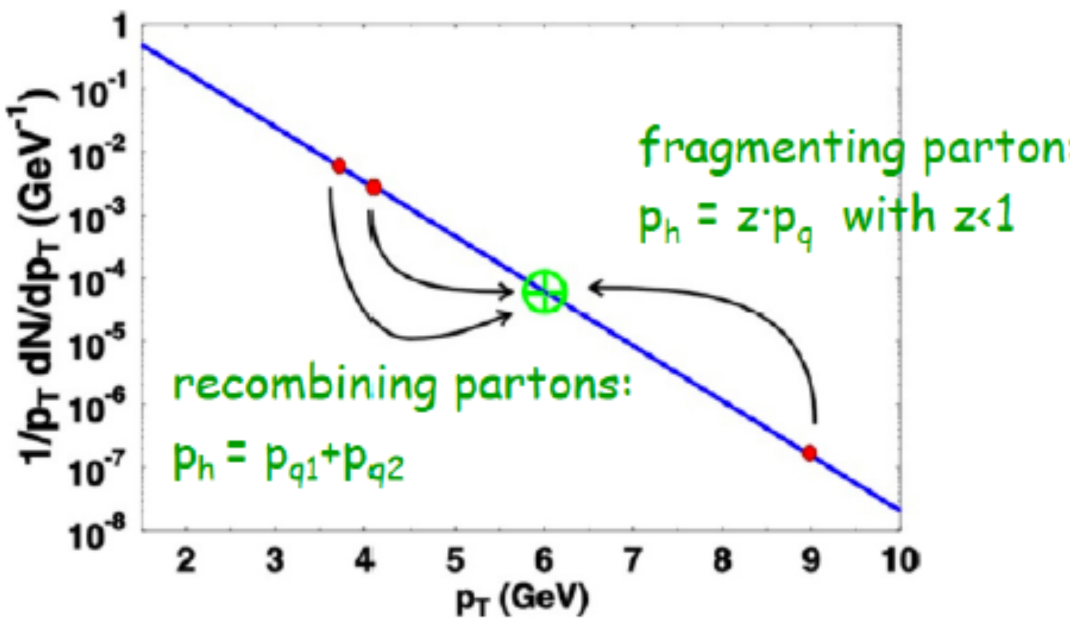


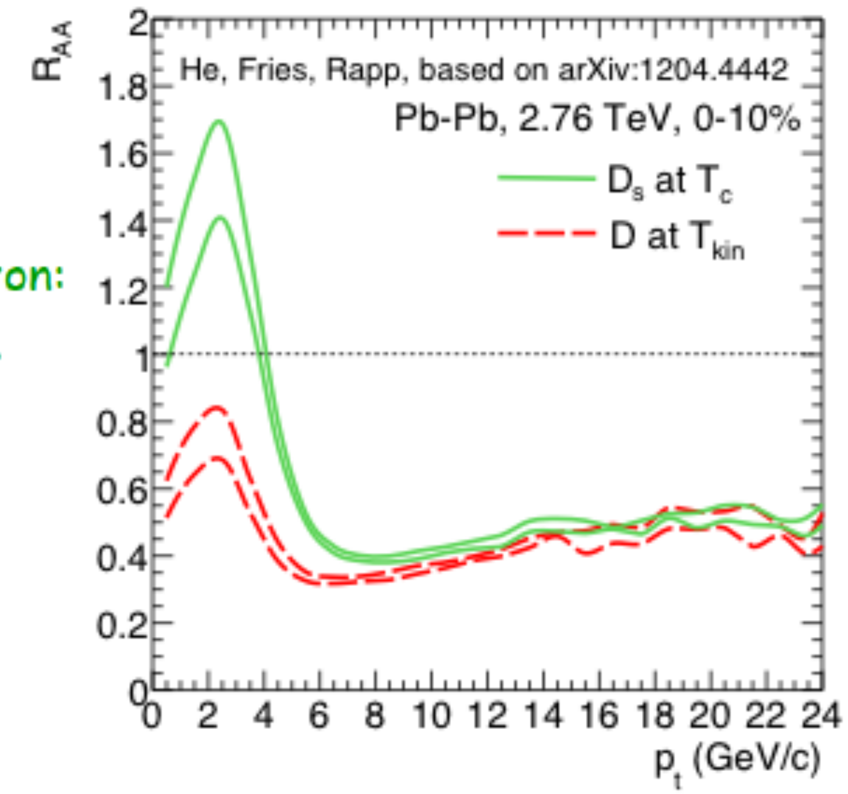
- Charged particle v_n have the potential to constrain initial-state fluctuations, transport parameters and path-length dependence of parton energy loss at high p_T.
- The **significant magnitude of anisotropic flow is interpreted as evidence of the formation of a strongly-coupled system**, which can effectively be described as a fluid with very **low shear viscosity to entropy-density ratio (η/s)**
- **Positive D-meson v_2 in mid-central Pb-Pb collisions indicates participation of charm quark in the collective motion**

ALICE
Charged pions JHEP 1809 (2018) 006
Charged particles JHEP 07 (2018) 103

Hadronisation via coalescence

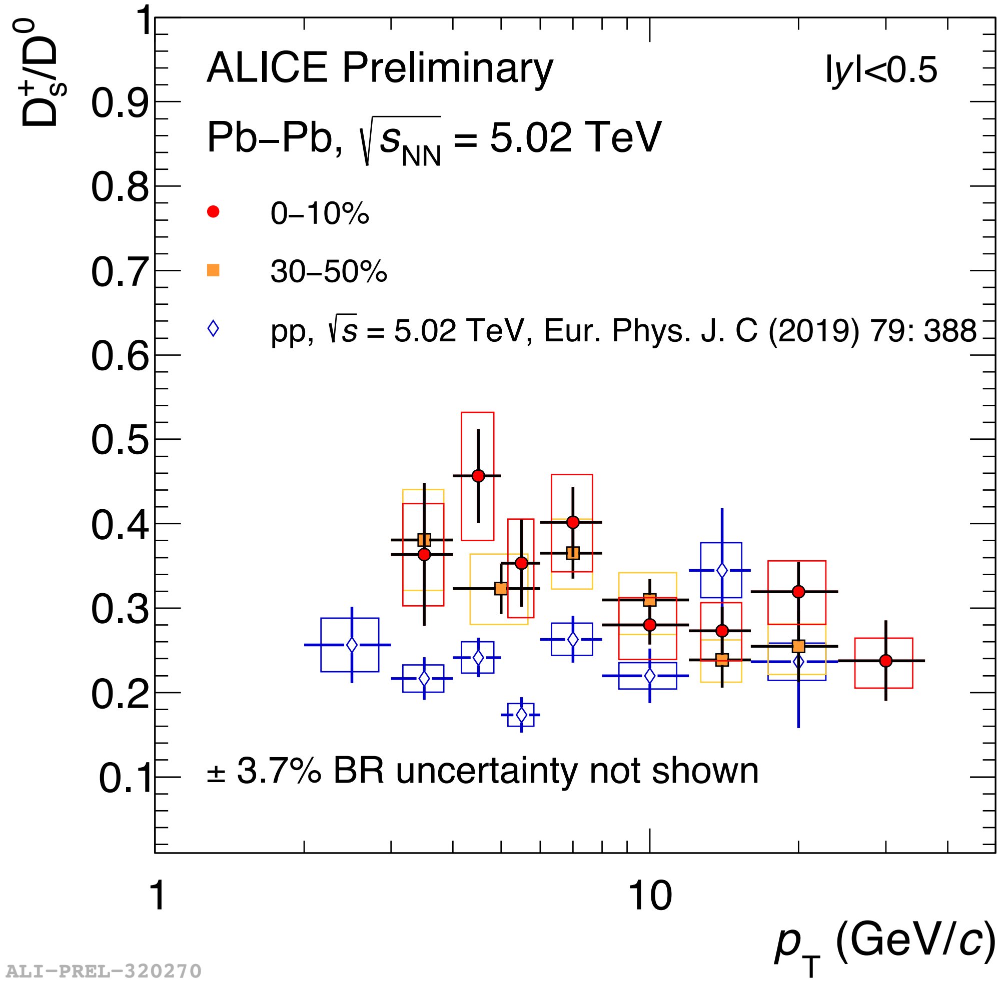


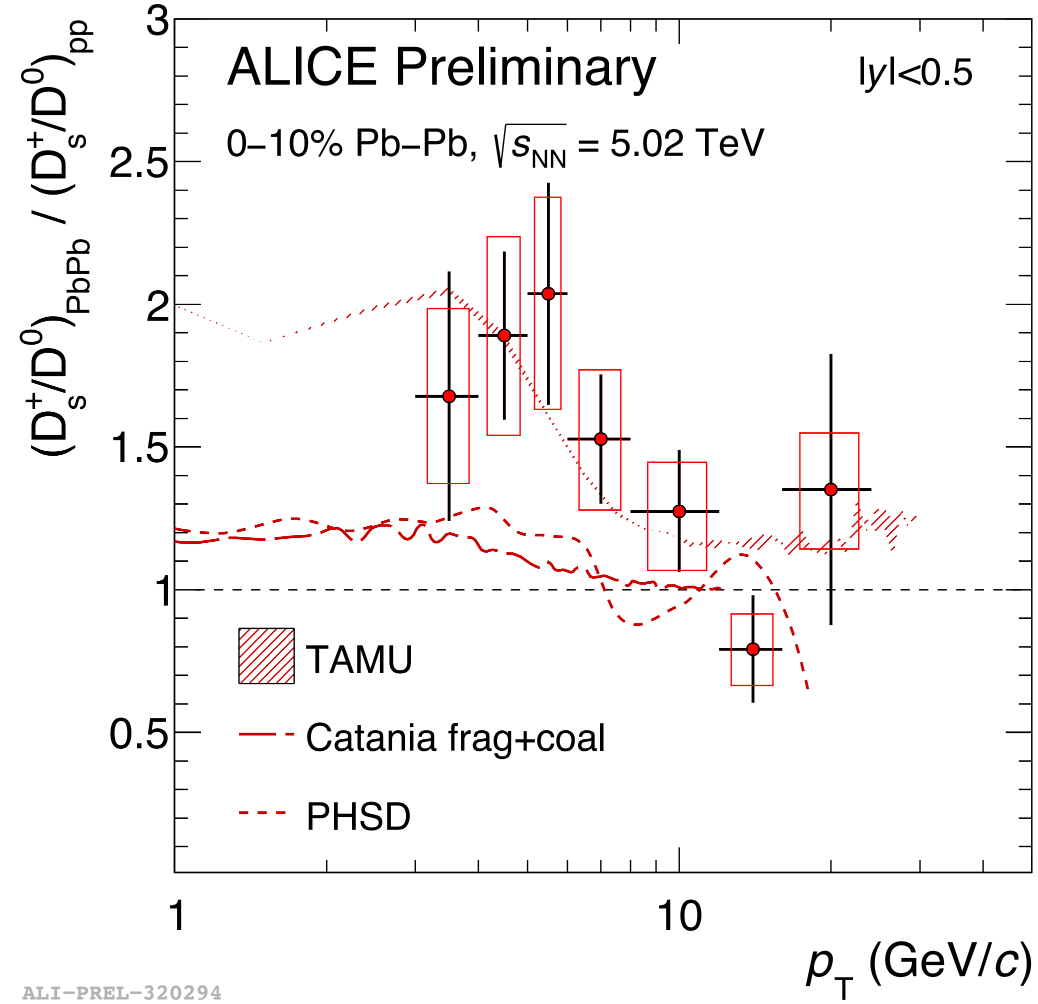




- Influence of hadronisation via coalescence:
  - modify the momentum distribution of heavy-flavour hadrons (radial flow ‘bump’)
  - enhance the elliptic flow (light-parton contribution)
  - modify the hadrochemistry: D_s, Λ_c enhancement

Strange / non-strange charmed hadrons



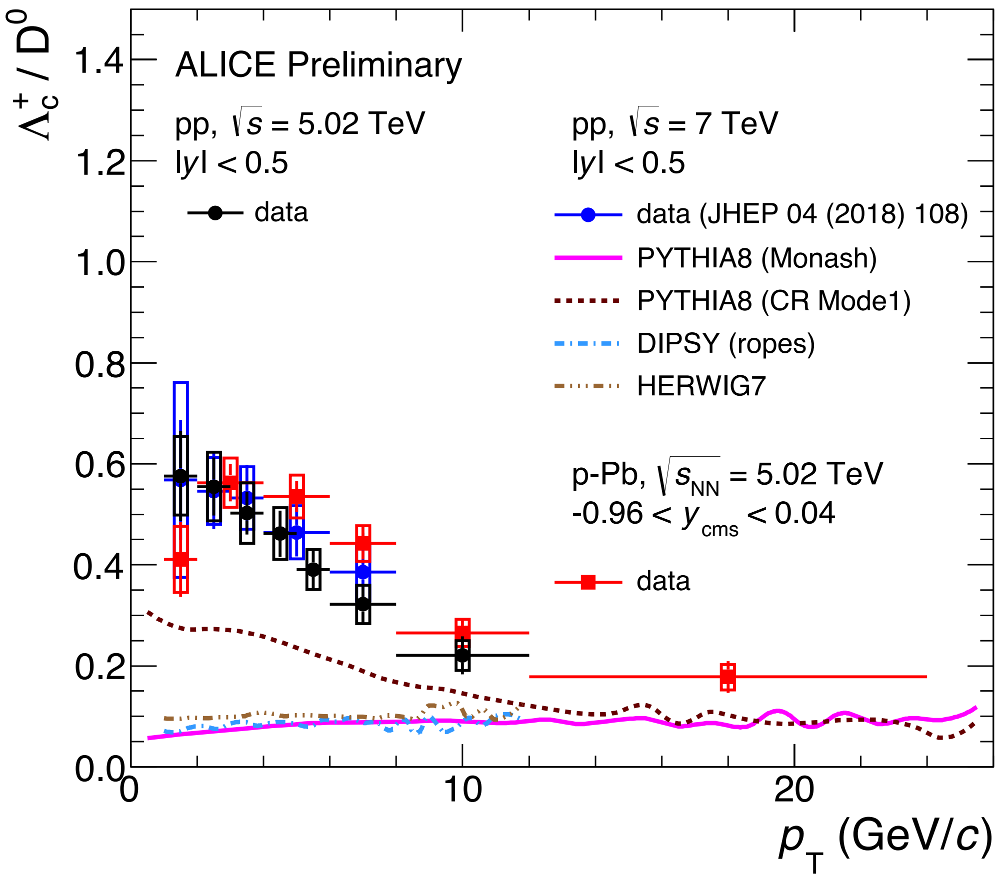


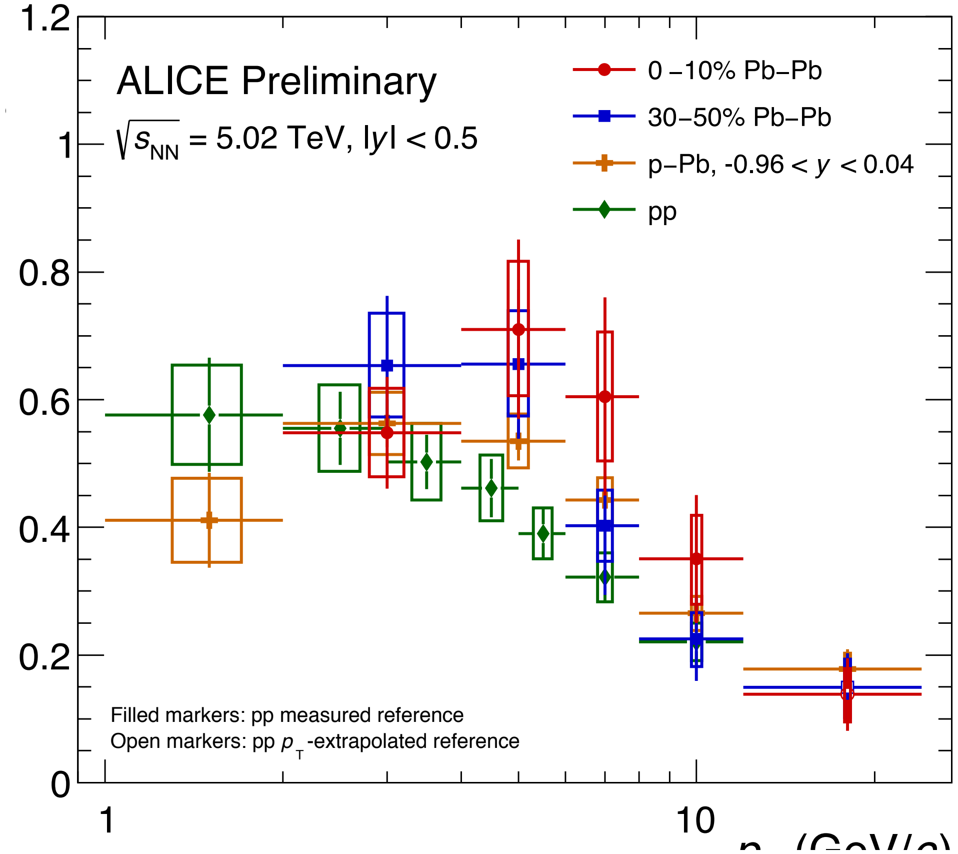
- A hint of a higher D_s^+ (c,s-bar) / D^0 (c,u-bar) ratio in Pb-Pb (0-10% and 30-50%) than in pp collisions up to p_T = 6 GeV/c.

- **Similar p_T trend as predicted by theoretical models of charm-quark transport in a hydrodynamically expanding medium**

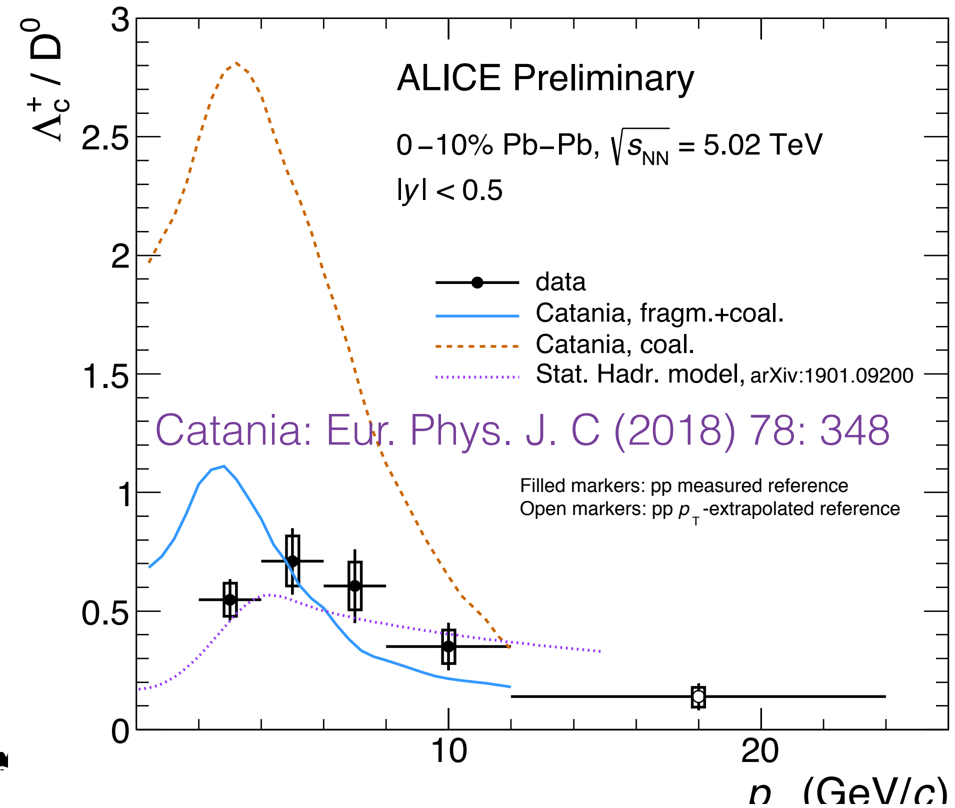
TAMU: Phys. Lett. B 735, 445 (2014)
Catania: Eur. Phys. J. C (2018) 78: 348
PHSD: Phys. Rev. C 93, 034906 (2016)

Baryon-to-meson ratio

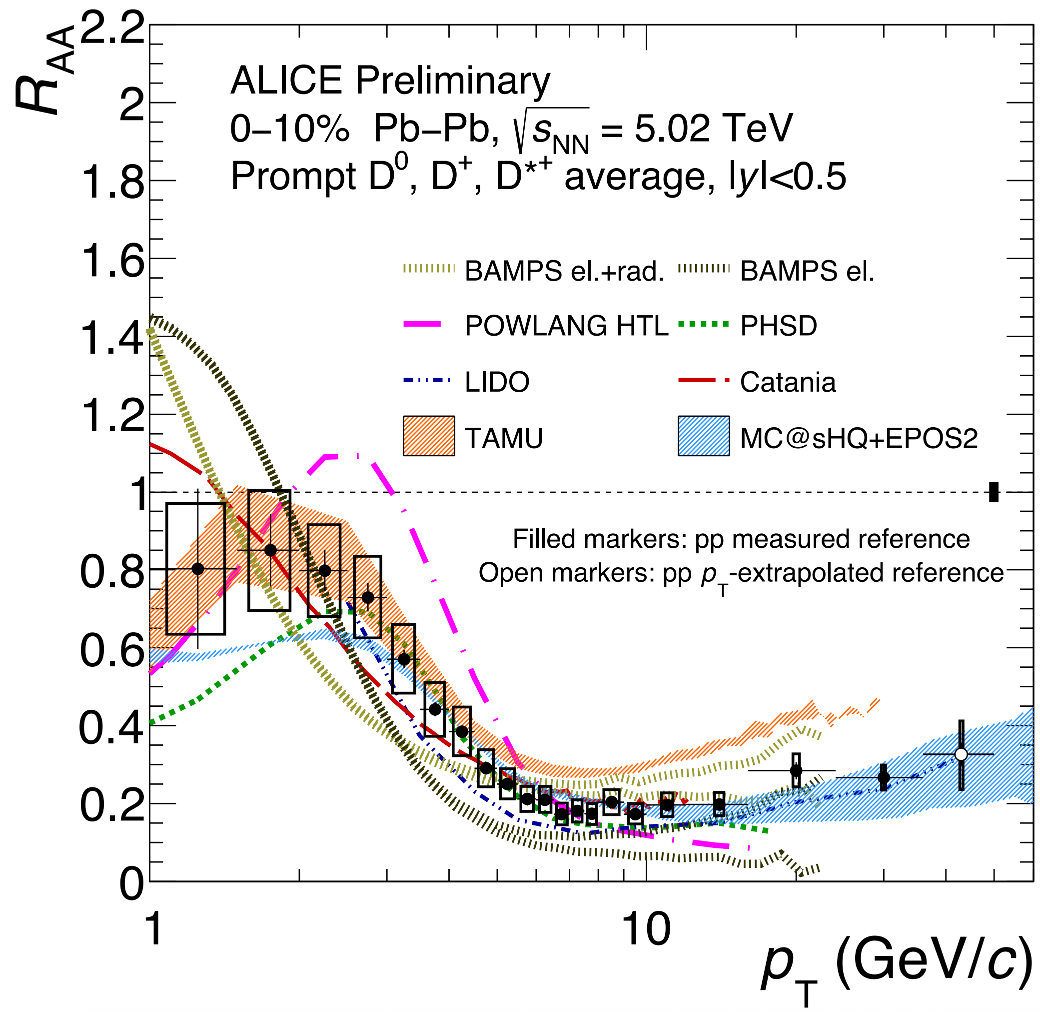




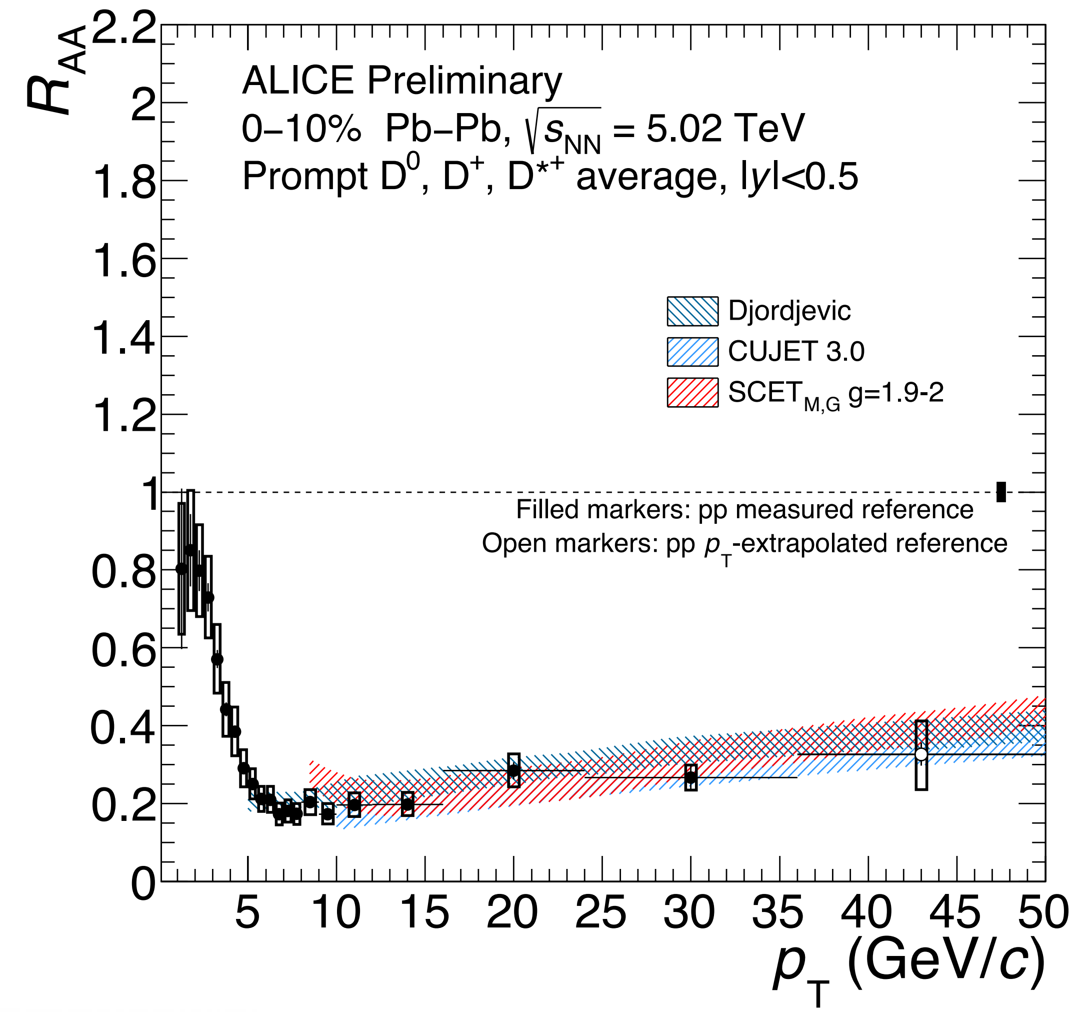
- Λ_c^+ (u,d,c) / D^0 (c,u-bar) ratio in pp better described by models including colour reconnection, but generally underestimated
- Measurements in pp and p-Pb in good agreement
- **Hint of increase of baryon-to-meson ratio in central Pb-Pb collisions at intermediate p_T (similar trend to the light-flavour sector)**



Charm meson vs. models



transport based models



p-QCD based models

- **High p_T** region dominated by **radiative energy loss**
  transport coefficient is the relevant parameter
  pQCD-based models provide a fair description

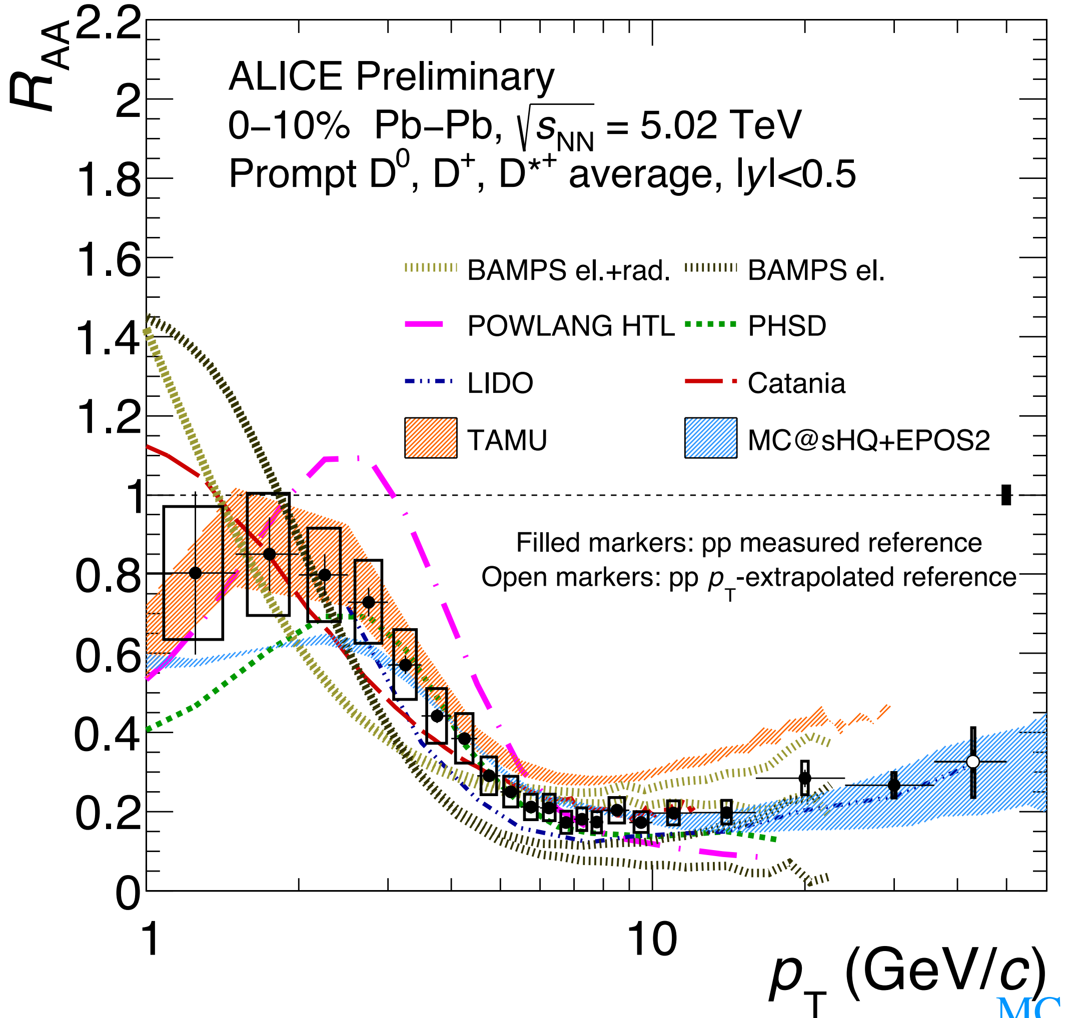
$$\hat{q} = \langle k_T^2 \rangle / \lambda = \langle k_T^2 \rangle \rho \, \sigma$$

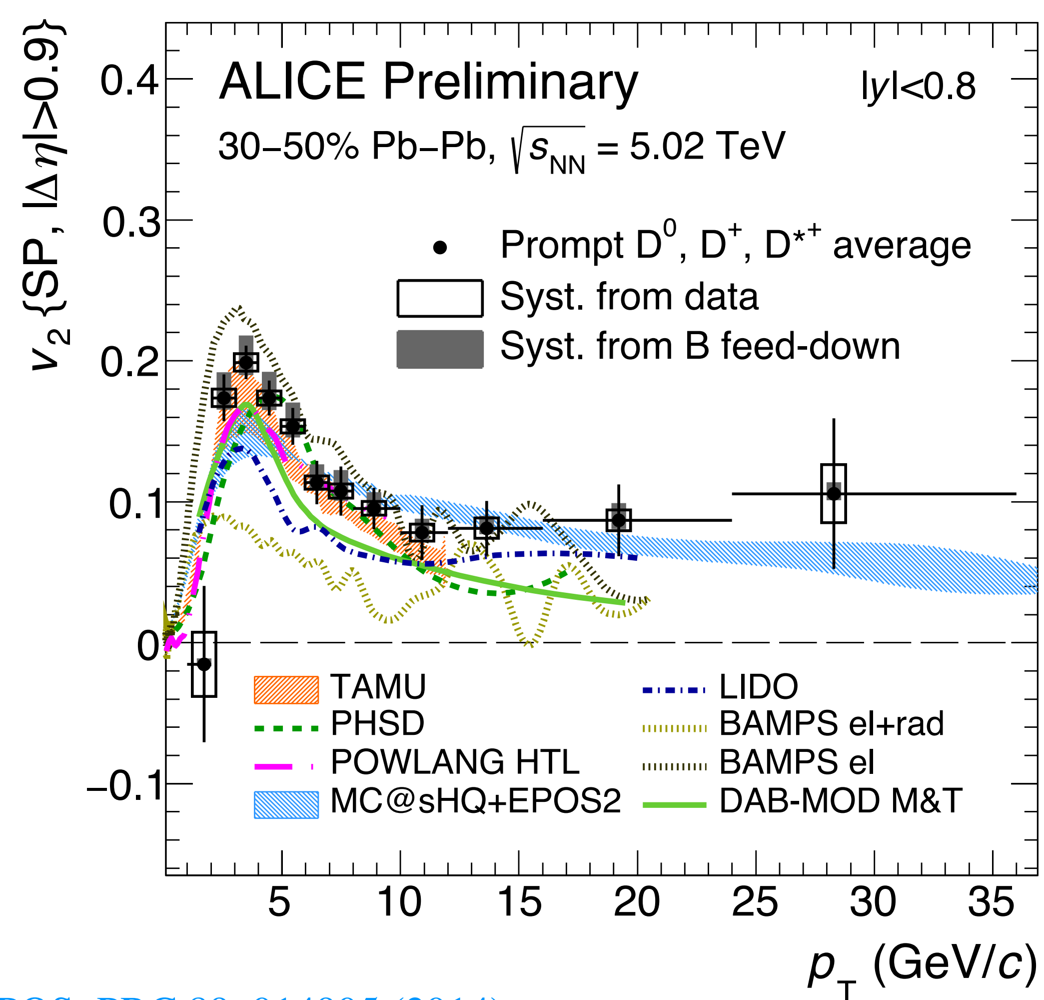
ρ medium density, σ cross section

- **Low p_T** region dominated by **'collisional' energy loss** (~Brownian motion)
  relevant parameter is the spatial diffusion coefficient D_s
  role of elastic scatterings, medium evolution and coalescence
  transport based models describe data

Injecting a particle at x=0 and t=0, the mean squared position at time t is: $\left\langle x^2(t) \right\rangle = 6 D_s t$

Charm meson vs. models





TAMU: PLB 735, 445-450 (2014)
PHSD: PRC 92, 014910 (2015)
POWLANG: EPJC 75, 121 (2015)

MC@sHQ+EPOS: PRC 89, 014905 (2014)
LIDO: PRC 98, 064901 (2018)
BAMPS: JPG 42, 115106 (2015)
Catania: EPJC 78, 348 (2018)

Djordevic: PRC 92, 024918 (2015)
CUJET3.0: JHEP 02 (2016) 169
SCET: JHEP 03 (2017) 146

- Models able to reproduce v_2 favour diffusion coefficient $2\pi TD_s(T)$ in the range 1.5-7 at T_c with a corresponding thermalisation time τ_{charm}=3-14 fm/c.
- **Powerful constraints by considering complementary observables (R_{AA} and v_2 of non-strange D and D_s^+) over wide p_T ranges and in different centrality classes.**
- Efforts ongoing from theorists and experimentalists to infer medium properties.

Summary

- Hard (large Q^2) probes: **"tomographic" probes** of the hottest and densest phase of the collision.
- W/Z production are sensitive to the flavour composition of (n)PDFs.
  - In Pb-Pb collisions: **average integrated yield per nucleon collision well described considering nPDFs** (not with only PDFs).
  - More precise data required to constrain the nPDF (in particular at large y and the impact parameter dependence).
- Charged particle production:
  - Evidence for **parton energy loss and large medium density at the LHC.**
  - Evidence of the formation of a **strongly-coupled system**, which can effectively be described as a fluid with very **low shear viscosity to entropy-density ratio (η/s).**
- Heavy flavours:
  - Both **'collisional' and radiative energy loss** play a role.
  - Measurements consistent with a dependence of the radiative energy loss with the **parton colour and mass**.
  - Low p_T charm quarks participate to the **collective motion** of the system.
  - **Coalescence** also seems to play a role at the hadronisation stage in the heavy flavour sector.

- **Powerful constraints by considering complementary observables** (R_{AA}, v_2,… of different particle species) over wide p_T ranges and in different centrality classes.
- **Many interesting results from run-II data, awaiting for the larger luminosity run-III.**

Disclaimer

- Only a (biased) selection of results has been shown… and focused on measurements in Pb-Pb collisions.
- But there're many interesting results in pp and p-Pb data as well.
  In particular, recent measurements in **small systems show intriguing features**, that in Pb-Pb collisions are interpreted as a signature of the QGP.

S. Porteboeuf plenary talk
Wednesday

Thanks for your attention!!