Heavy Ion Collisions

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Spanish High Energy Physics School
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Probing Hot QCD Matter with hard probes

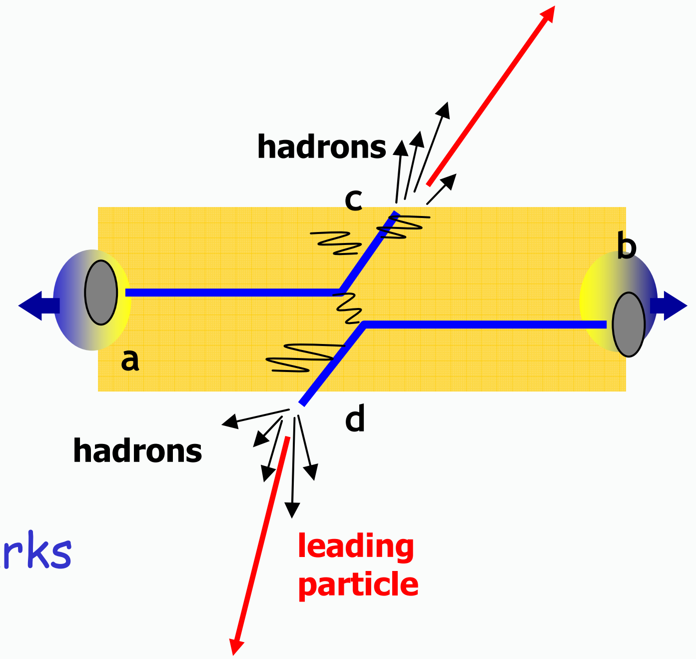
Hard Probes:

"highly penetrating observables (particles, radiation) used to explore properties of matter that cannot be viewed directly!"

$$p_T, m > 2\ \mathrm{GeV} >> \Lambda_{\mathrm{QCD}}$$

Hard probes

p+p:
- parton scattering → fragmentation → jet
- can be calculated in perturbative QCD
- collinear factorization



A+A:
- partons traversing medium lose energy
  gluon radiation, elastic collisions
- energy loss different for g, light/heavy quarks
  (color factor, dead cone effect)

X.-N. Wang, M. Gyulassy, Phys. Rev. Lett. ***68*** *(1992) 1480*

Goal: Use in-medium energy loss to measure medium properties

$$\frac{d\sigma_{pp}^{h}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) \frac{D_{h/c}^{0}}{\pi z_c}$$

Parton distribution function	Matrix element	Fragmentation function
measured in DIS initial state (saturation?)	pQCD	e^+e^- final state (energy loss?)

Medium modifications.

$$R_{AA}(\sqrt{s_{NN}}, p_T, y, m; b) = \frac{\text{"hot/dense QCD medium"}}{\text{"QCD vacuum"}} \propto \frac{\Phi_{AA}(\sqrt{s_{NN}}, p_T, y, m; b)}{\Phi_{pp}(\sqrt{s}, p_T, y, m)}$$

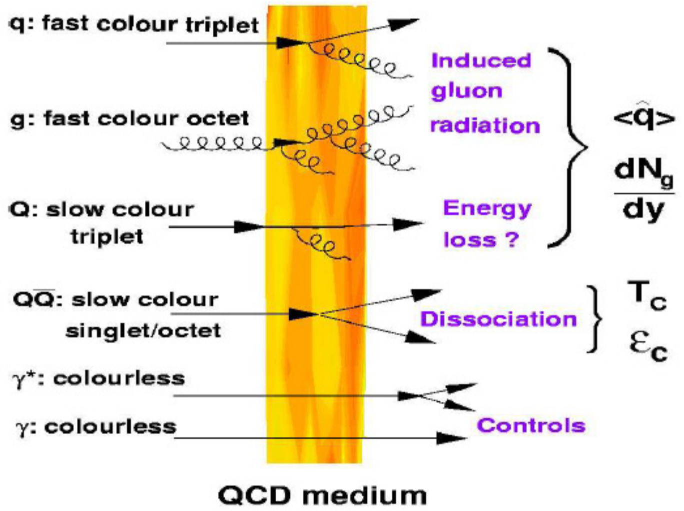


Figure 3. Examples of hard probes whose modifications in high-energy *AA* collisions provide direct information on properties of QCD matter such as the $\langle \hat{q} \rangle$ transport coefficient, the initial gluon rapidity density dN^g/dy, and the critical temperature and energy density.

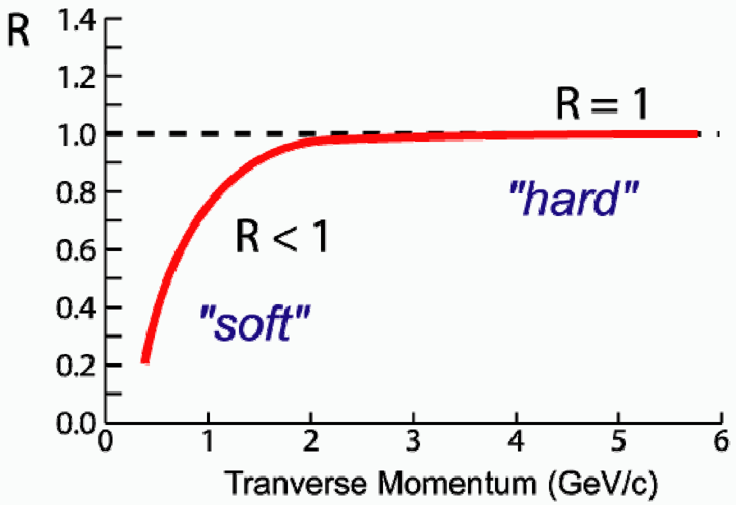
Any observed *enhancements* and/or *suppressions* in the $R_{AA}(s_{NN}, p_T, y, m; b)$ ratios can then be directly linked to the properties of strongly interacting matter.

Measurement in pp collisions is essential/ mandatory

Medium modifications: R_{AA}, R_{CP}

Nuclear modification factor:

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$



No "Effect":
- R < 1 at small momenta
- R = 1 at higher momenta where hard processes dominate

Suppression:
- R < 1

In case pp is not measured, R_{CP}:

$$R_{CP}(p_t) = \frac{1}{\langle N_{coll} \rangle} \times \frac{dN_{AA}/dp_t / \langle T_{AA} \rangle [central]}{dN_{AA}/dp_t / \langle T_{AA} \rangle [peripheral]}$$

Hard cross sections in pp at RHIC

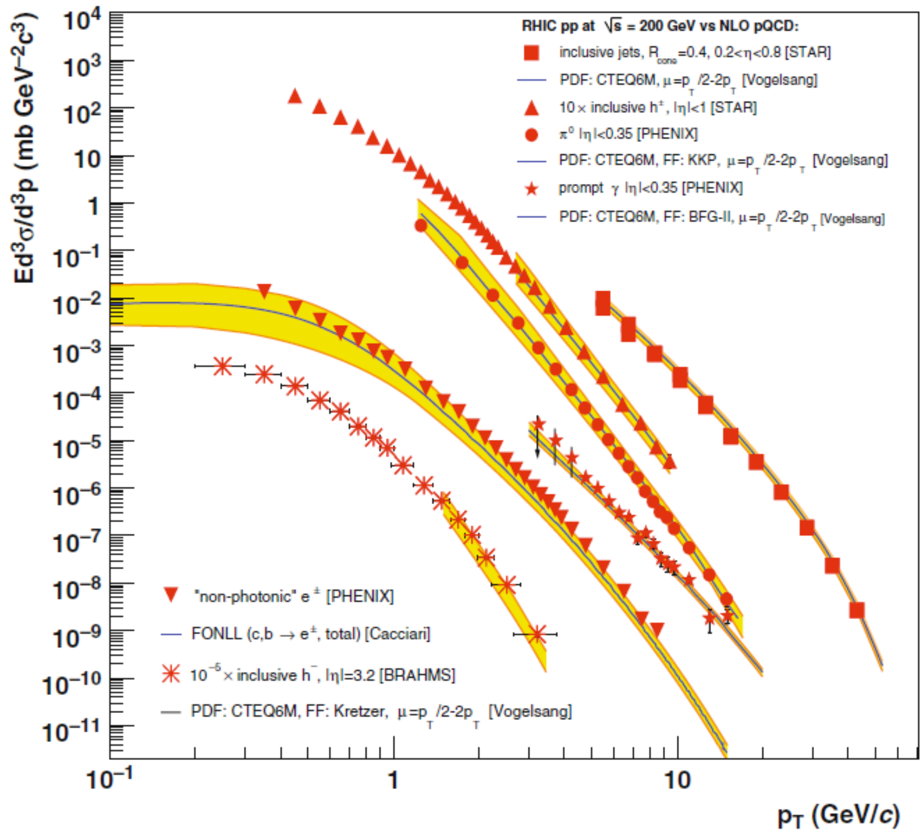


Fig. 13 Compilation of hard cross sections in pp at $\sqrt{s}$ = 200 GeV measured by STAR [125, 126], PHENIX [127–129], and BRAHMS [130] (10–30% syst. uncertainties not shown for clarity) compared to NLO [131–138] and NLL [139] pQCD predictions (*yellow bands*)

Discovery of jet quenching at RHIC

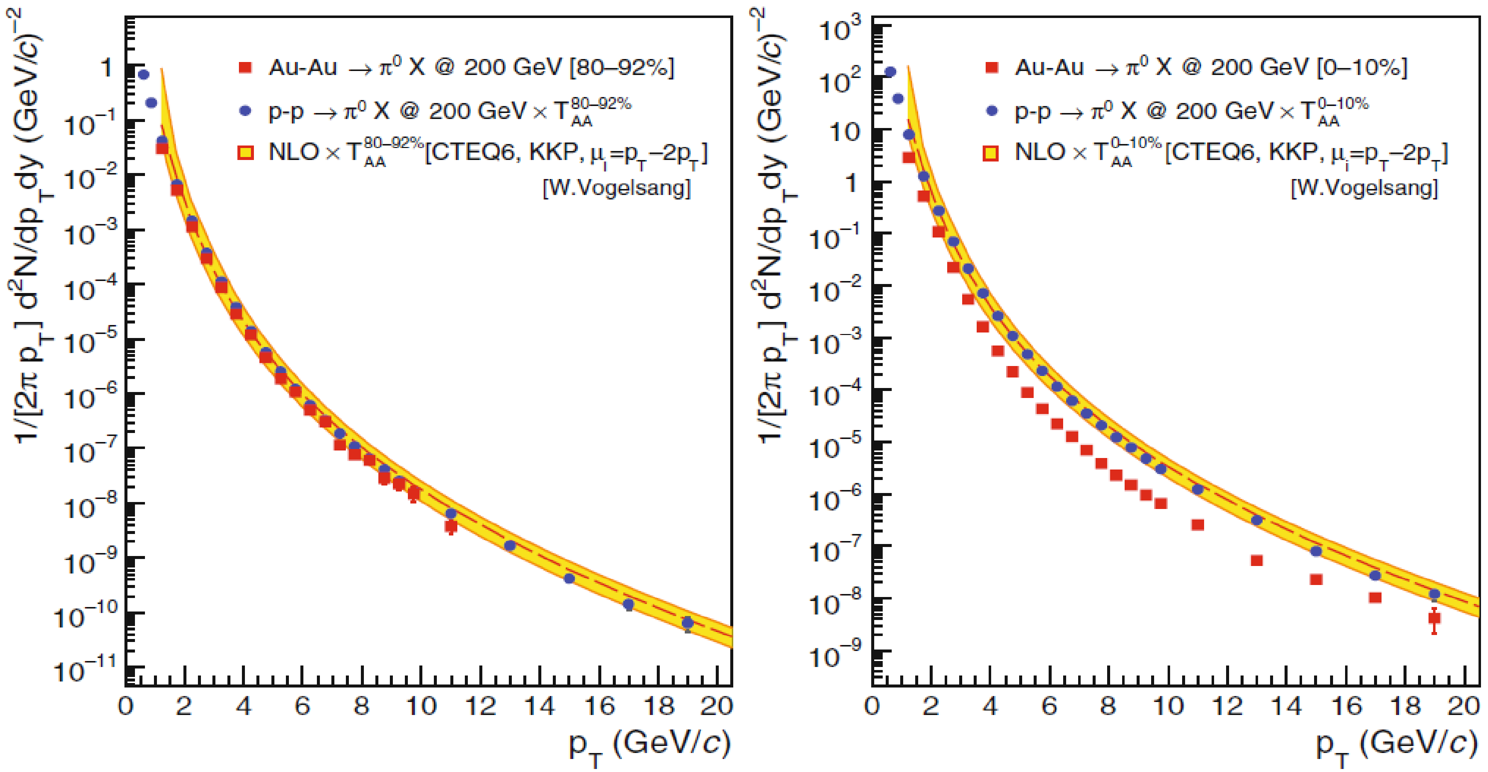
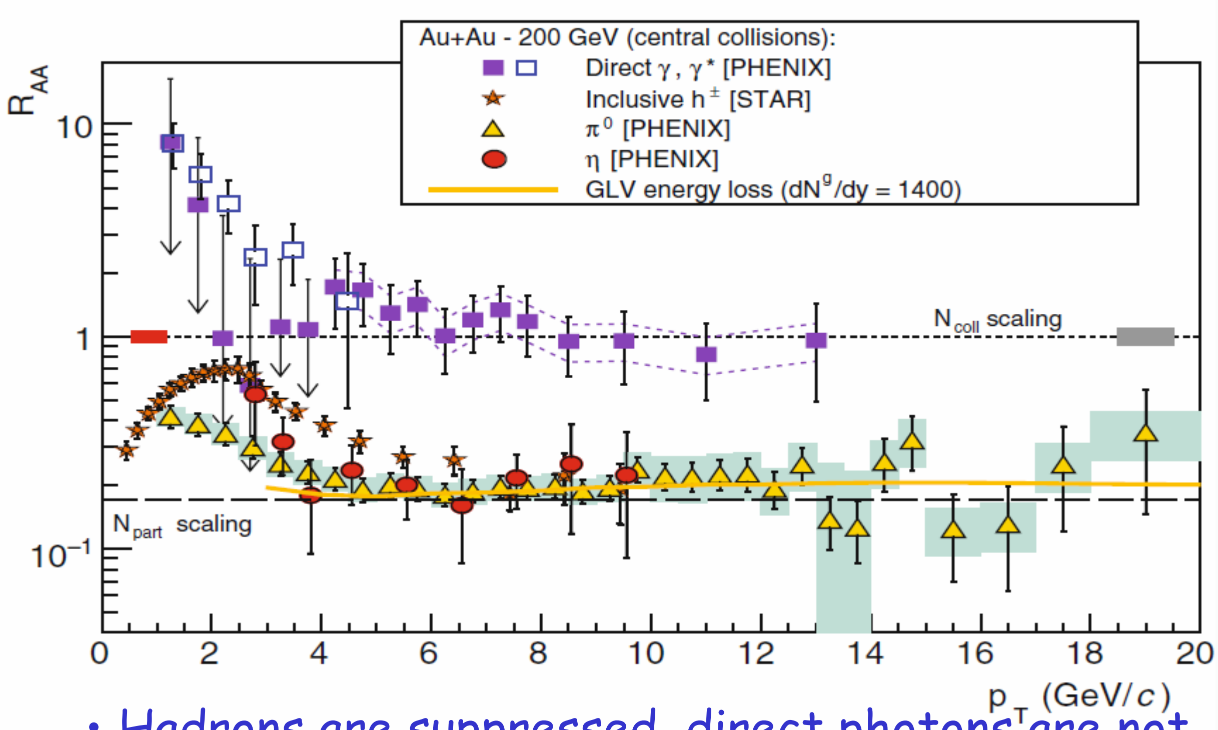


Fig. 15 Invariant π^0 yields measured by PHENIX in peripheral (*left*) and central (*right*) AuAu collisions (*squares*) [100] compared to the (T_{AA}-scaled) *pp* π^0 cross section (*circles*) [152] and to a NLO pQCD calculation (*curves* and *yellow band*) [131–133]

Large high-p_T hadron suppression
(R_{AA} <1) observed in central AuAu compared to *pp* or *d*Au reactions.

Discovery of jet quenching at RHIC



PHENIX: Phys.Rev.Lett.88:022301, 2002
PHENIX: Phys.Rev.Lett.91:072301, 2003
PHENIX: Phys.Rev.Lett.94:232301, 2005
STAR: Phys.Rev.Lett.89:202301,2002
STAR: Phys.Rev.Lett.90:082302,2003
STAR: Phys.Rev.Lett.91:172302,2003

R_{AA}^{γ} ~=1

$R_{AA}^{\pi^0,\eta}$ ~=0.2

- Hadrons are suppressed, direct photons are not
- The hadron spectra at RHIC from p+p, Au+Au and d+Au collisions establish existence of *parton energy loss* from strongly interacting, dense QCD matter in central Au-Au collisions

$$\varepsilon_{\text{loss}} \approx 1 - R_{AA}^{1/(n-2)}$$

$\langle \hat{q} \rangle$ = 4 – 13 GeV2 / fm

dN^g/dy~1400+-200

S. Bass et al. PRC79 (2009) 024901

https://wiki.bnl.gov/TECHQM/index.php/Main_page

Theory-Experiment Collaboration on Hot Quark Matter

Discovery of jet quenching at RHIC

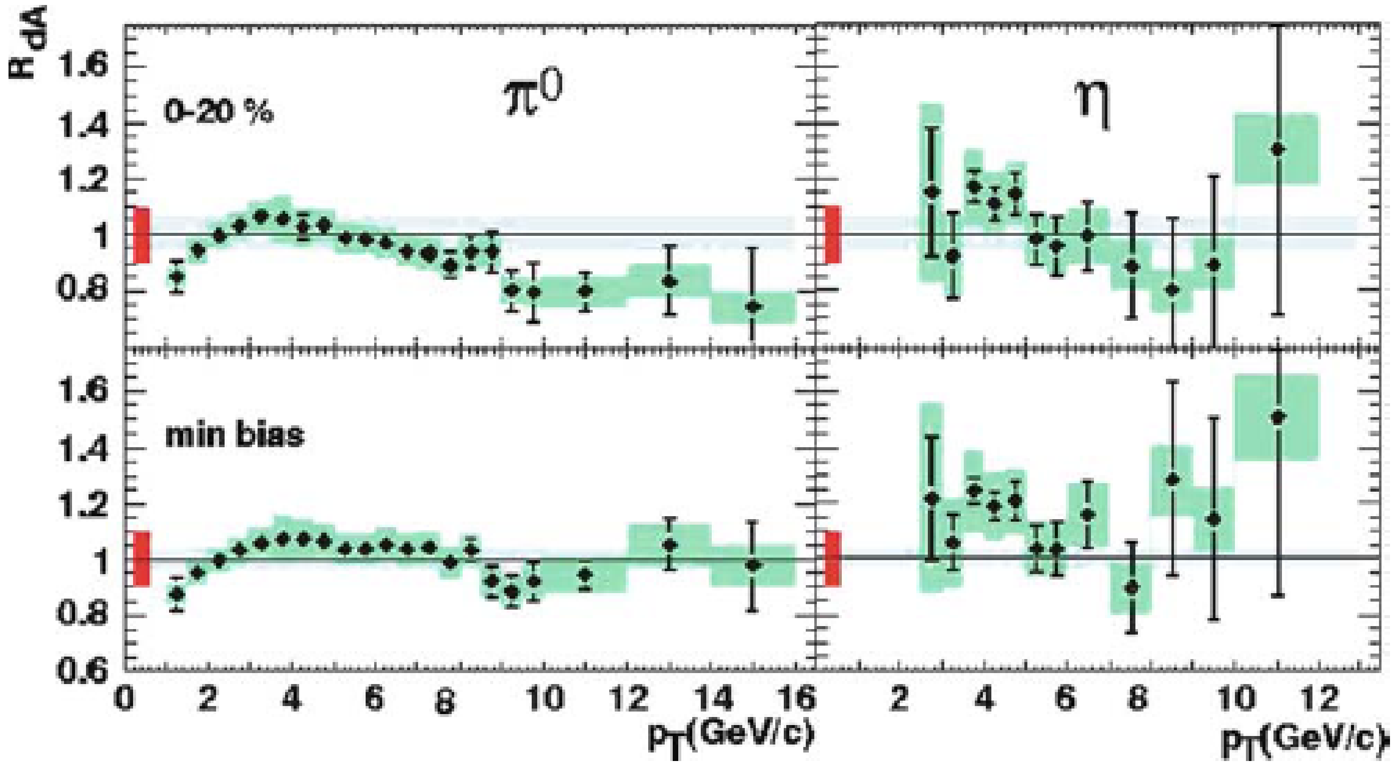


Fig. 14 Nuclear modification factors for high-p_T π^0 (*left*) and η (*right*) mesons at midrapidity in dAu collisions at $\sqrt{s_{NN}}$ = 200 GeV [143, 144] compared to pQCD calculations [145, 146] with EKS98 [147] nuclear PDFs

No suppression in dAu. Evidence for final state effect.

Energy dependence of the suppression

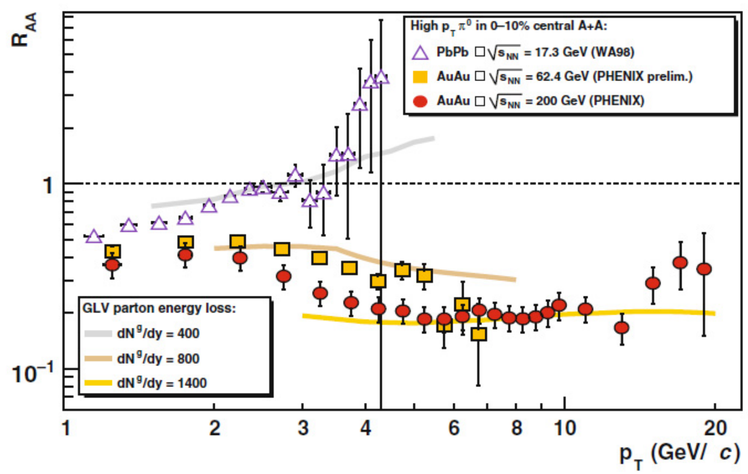


Fig. 18 Nuclear modification factor, $R_{AA}(p_T)$, for neutral pions in central PbPb at $\sqrt{s_{NN}}$ = 17.3 GeV [168, 169] and AuAu at $\sqrt{s_{NN}}$ = 62.4 GeV [170], 200 GeV [153]; compared to GLV energy loss calculations for initial gluon densities: dN^g/dy = 400, 800, 1400 [160, 161, 171], respectively. Experimental normalisation errors, $\mathcal{O}$(10–25%), not shown

Table 2 Initial gluon densities dN^g/dy [160, 161, 171], and transport coefficients $\langle \hat{q} \rangle$ [89] for the dense media produced in central AA collisions at SPS and RHIC energies obtained from parton energy loss calculations reproducing the observed high-p_T π^0 suppression at each $\sqrt{s_{NN}}$. The measured charged particle densities at midrapidity, $dN_{ch}^{exp}/d\eta$ [166, 167], are also quoted

	$\sqrt{s_{NN}}$ (GeV)	$\langle \hat{q} \rangle$ (GeV^2/fm)	dN^g/dy	$dN_{ch}^{exp}/d\eta$
SPS	17.3	3.5	400	312 ± 21
RHIC	62.4	7.	800	475 ± 33
RHIC	130.	∼11	∼1000	602 ± 28
RHIC	200.	13	1400	687 ± 37

Heavy quarks as medium probes: Energy Loss

q: colour triplet

u,d,s: m~0, C_R=4/3
(difficult to tag at LHC)

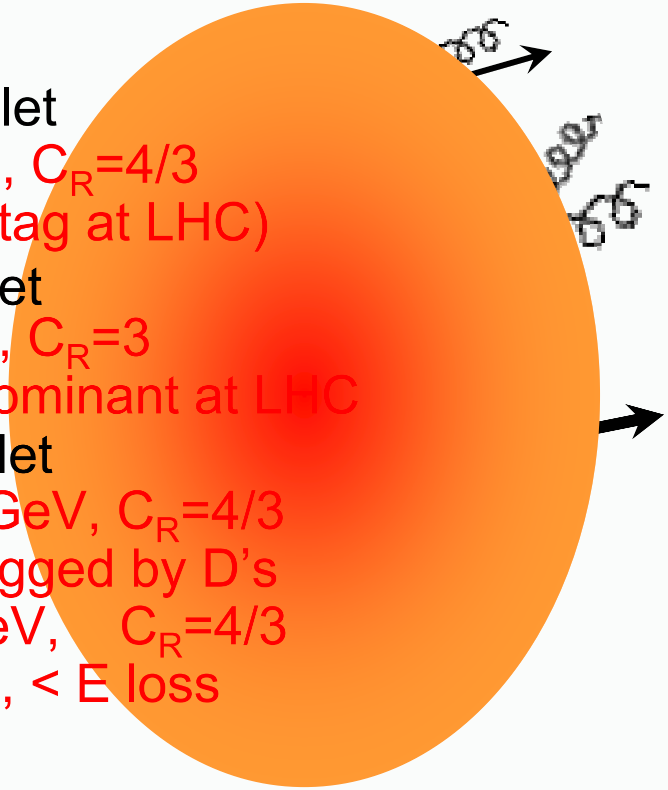
g: colour octet

g: m=0, C_R=3
> E loss, dominant at LHC

Q: colour triplet

c: m~1.5 GeV, C_R=4/3
small m, tagged by D's

b: m~5 GeV, C_R=4/3
large mass, < E loss



QCD medium

Parton Energy Loss by

- medium-induced gluon radiation
- collisions with medium gluons

$$\Delta E(\varepsilon_{QGP}; C_R, m, L)$$

pred: $\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$

→ $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$

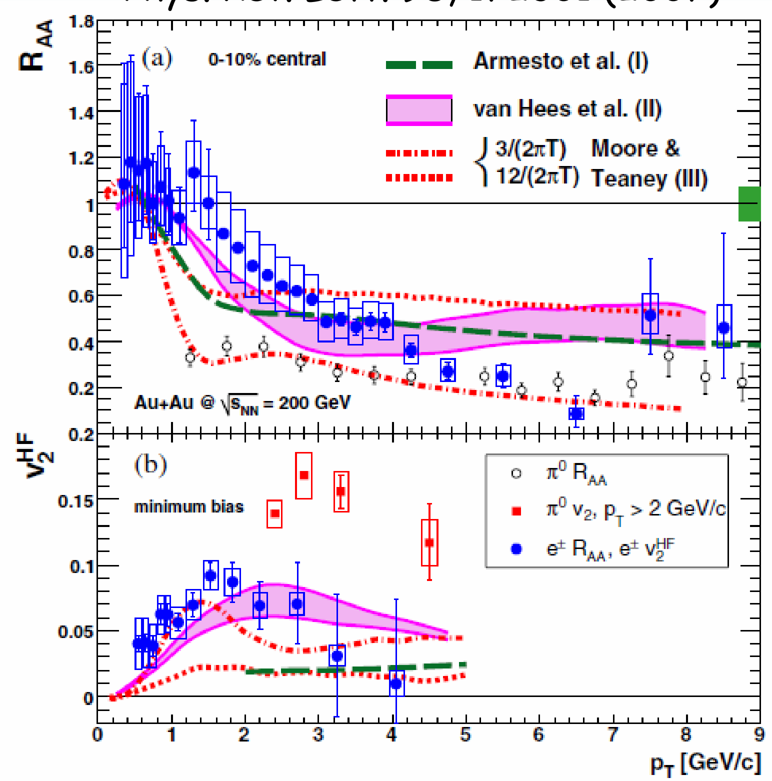
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.

Djordjevic, Gyulassy, Wicks, nucl-th/0512076

Heavy flavour electrons

The inclusive electron spectra consist of
(i) "nonphotonic" electrons from heavy-flavor decays,
(ii) "photonic"background from Dalitz decays and photon conversions
(mainly in the beam pipe), and (iii) nonphotonic background
from $K \rightarrow e\ \pi\nu$ and dielectron decays of vector mesons.

Phys. Rev. Lett. 98, 172301 (2007)



$\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (dead-cone effect)

But, strong suppresion of heavy flavour electrons observed from $2<p_t<5$ GeV/c

Models have difficulties to explain both R_{AA} and v_2

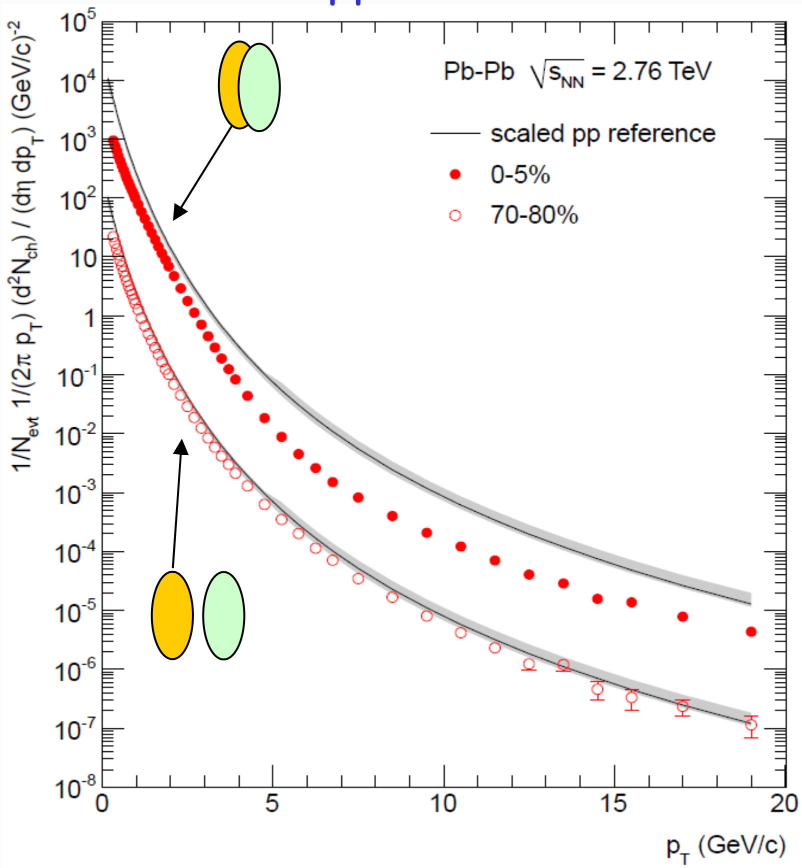
van Hees *et al.*: only elastic scattering mediated by resonance excitation of D and B-like states

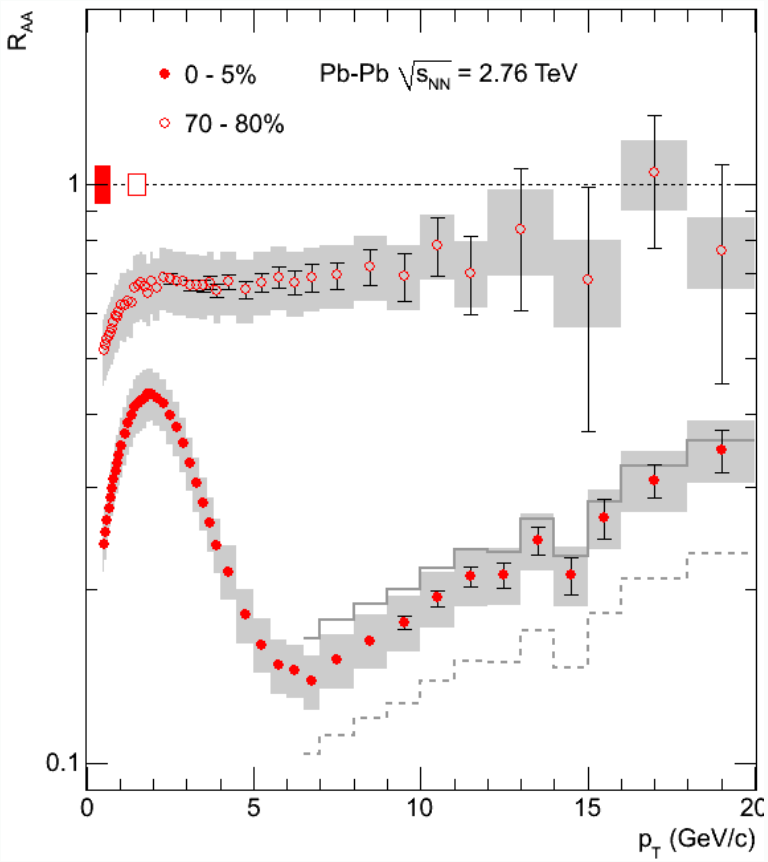
RAA@LHC: ALICE

Suppression of high p_t particles (~ leading jet fragments)

- Rising with p_t !
- Accuracy limited by pp reference
  - => need pp at 2.76 TeV !

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

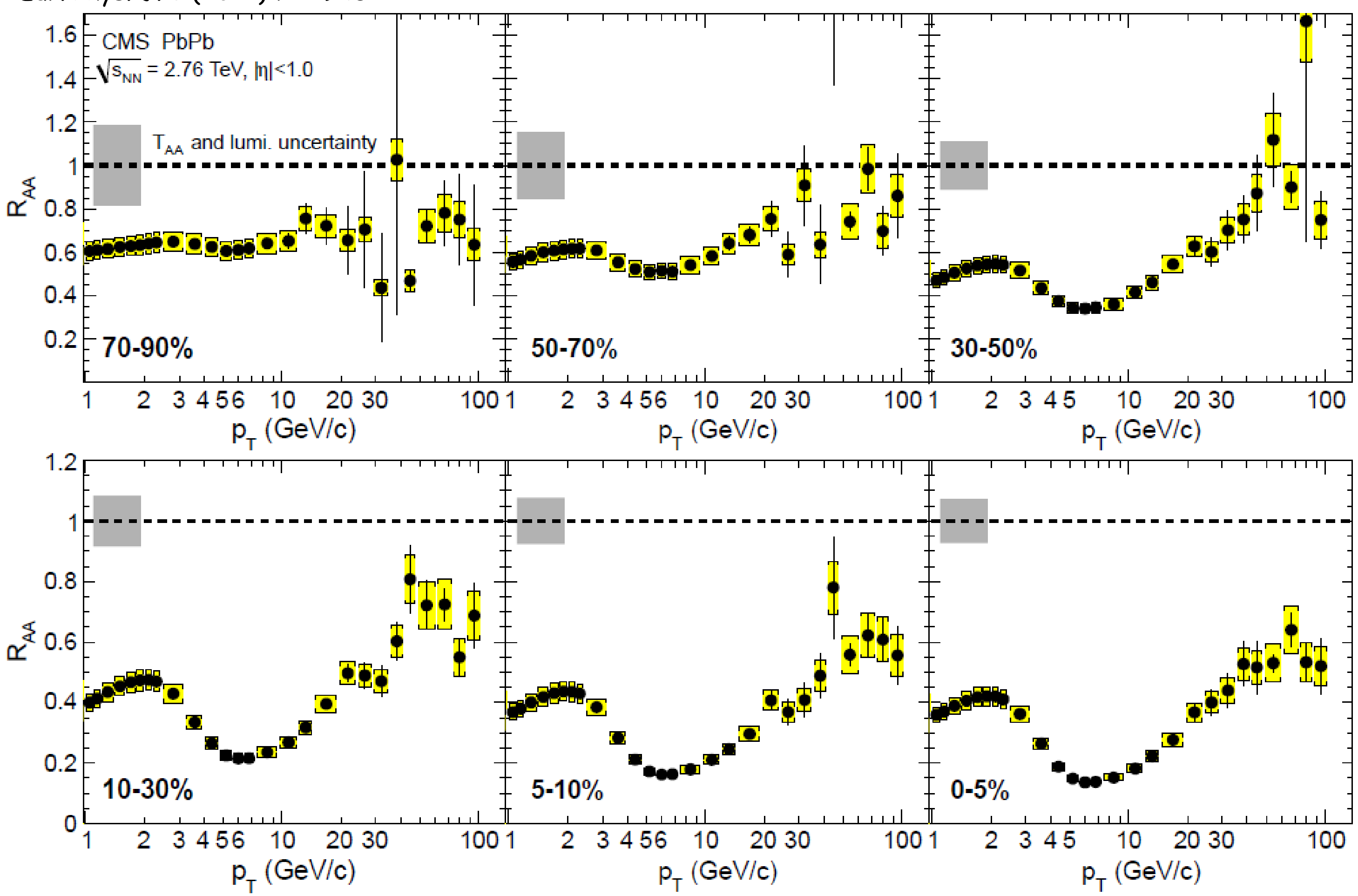




ALICE, Phys. Lett. B 696 (2011) 30

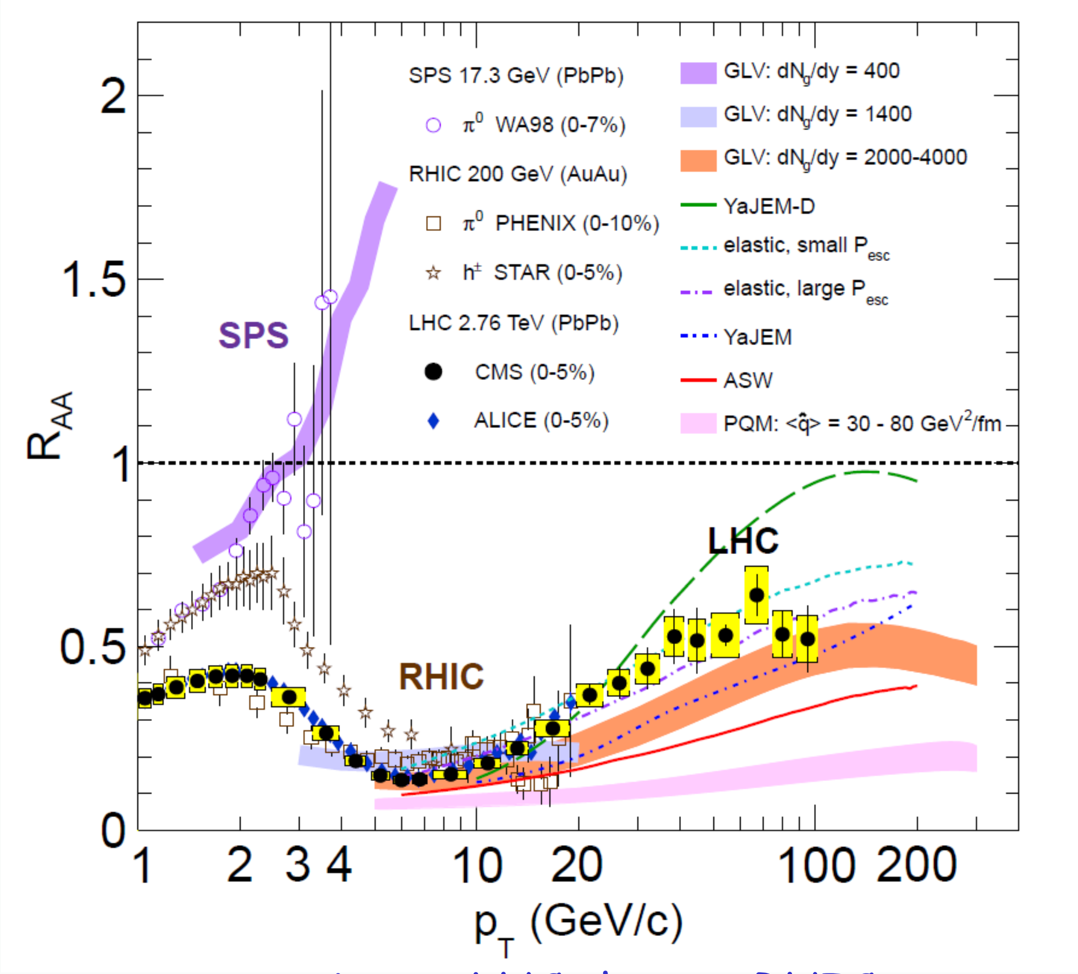
RAA@LHC: CMS

Eur. Phys. J. C (2012) 72:1945



In 0-5% centrality R_{AA} reaches a minimum value of about 0.13 at p_T = 6–7 GeV/c. At higher p_T, the value of R_{AA} rises and levels off above 40 GeV/c at ~0.5.

Measurements of R_{AA} in central HIC

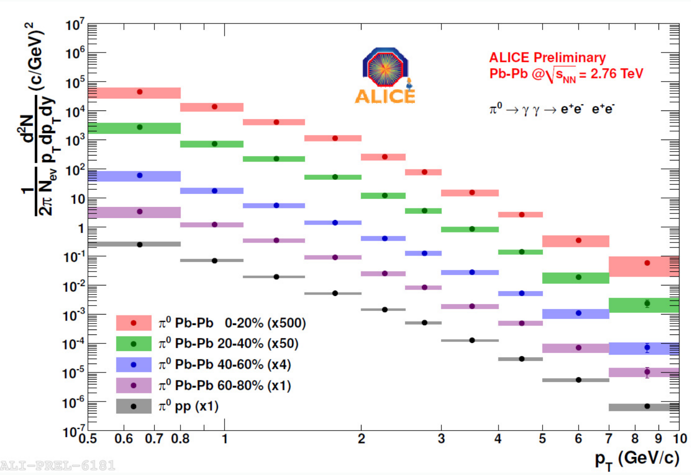


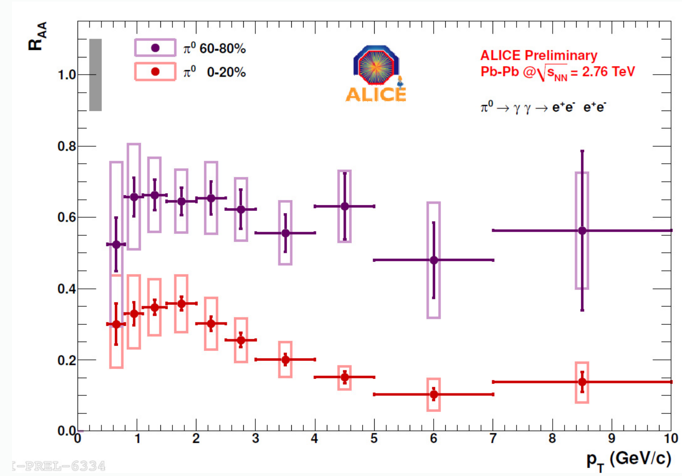
Eur. Phys. J. C (2012) 72:1945

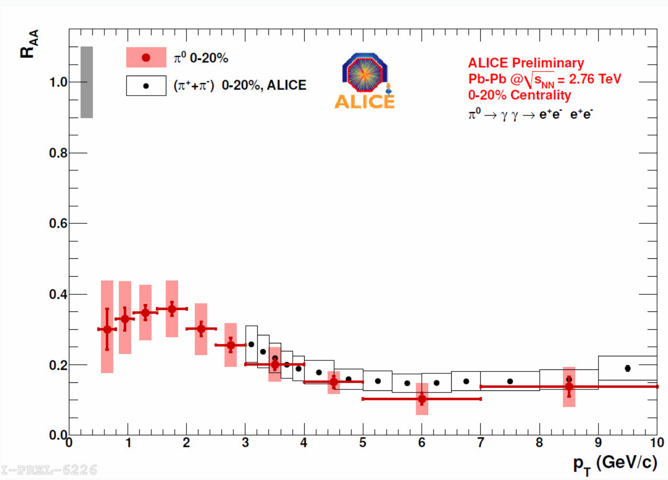
- Larger suppression at LHC than at RHIC.
- Most models predict the generally rising behavior of R_{AA}
- Measurement can be used to constrain the quenching parameters used in these models

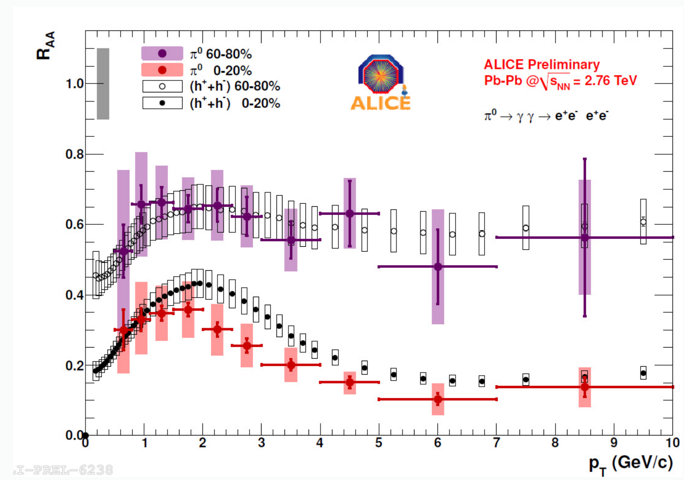
Identified particles: π^0 R_{AA}

J.Phys.G G38 (2011) 124117







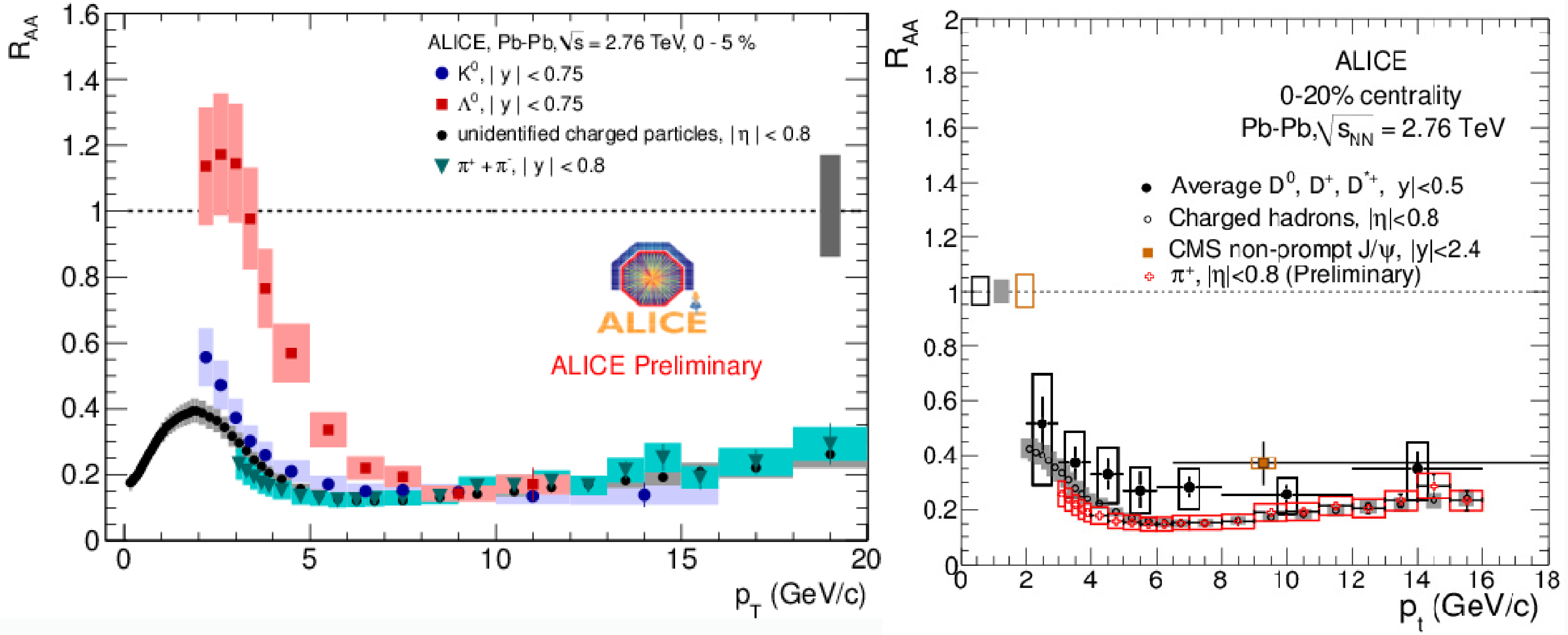


Agreement with charged pion R_{AA}

Different to charged particle R_{AA}

R_{AA} for light/heavy quark hadrons

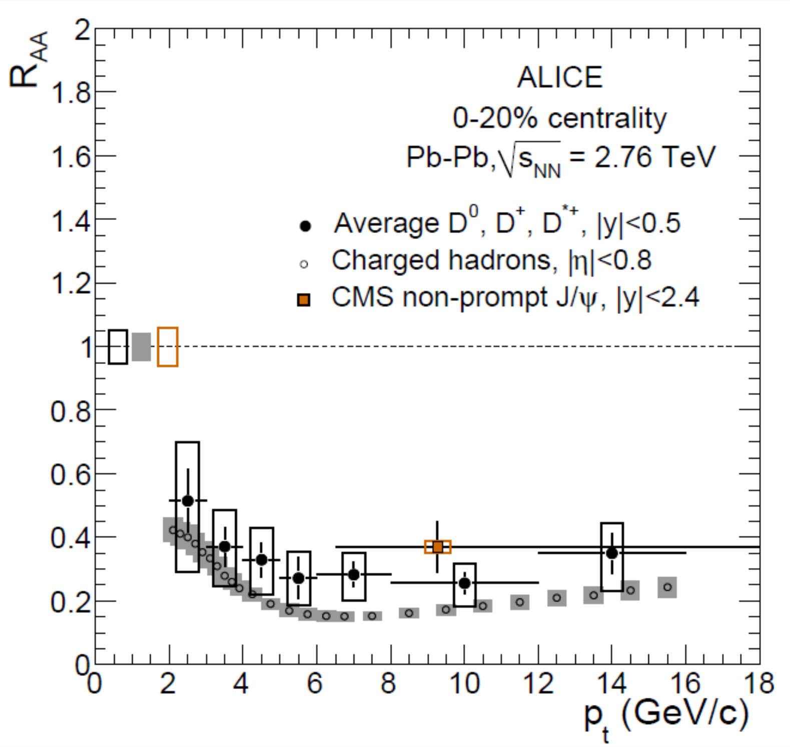
arXiv:1203.2160

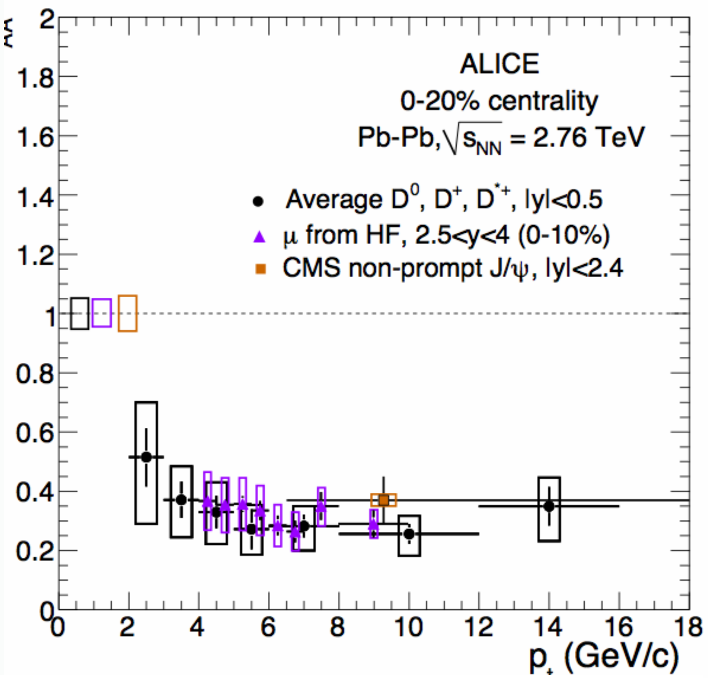


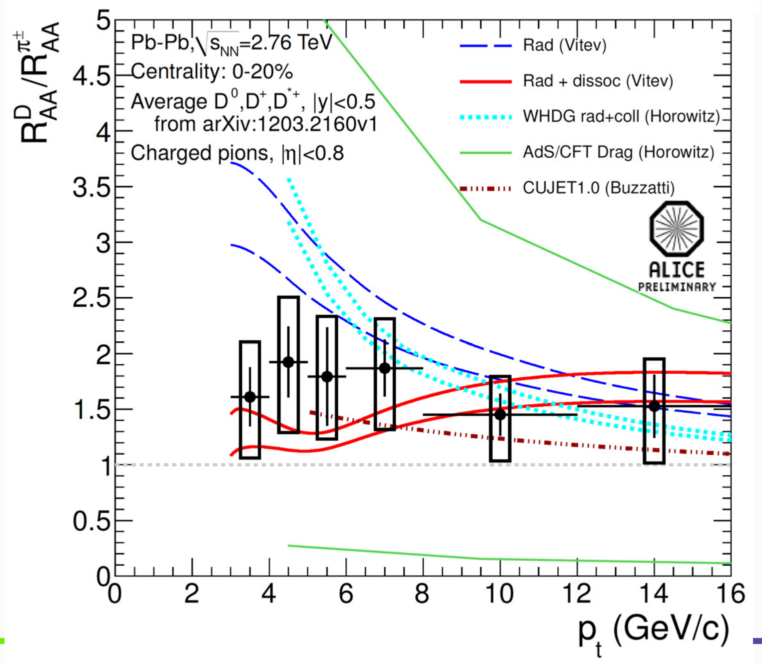
- Light quark hadrons with p_T > 8 GeV/c are equally suppressed
- This seem to indicate that medium interactions do not affect fragmentation for p_T > 8 GeV/c - fragmentation occurs into vacuum
- Light quark results also provide a baseline for understanding heavy quark energy loss

Heavy/light quark R_{AA}

arXiv:1203.2160

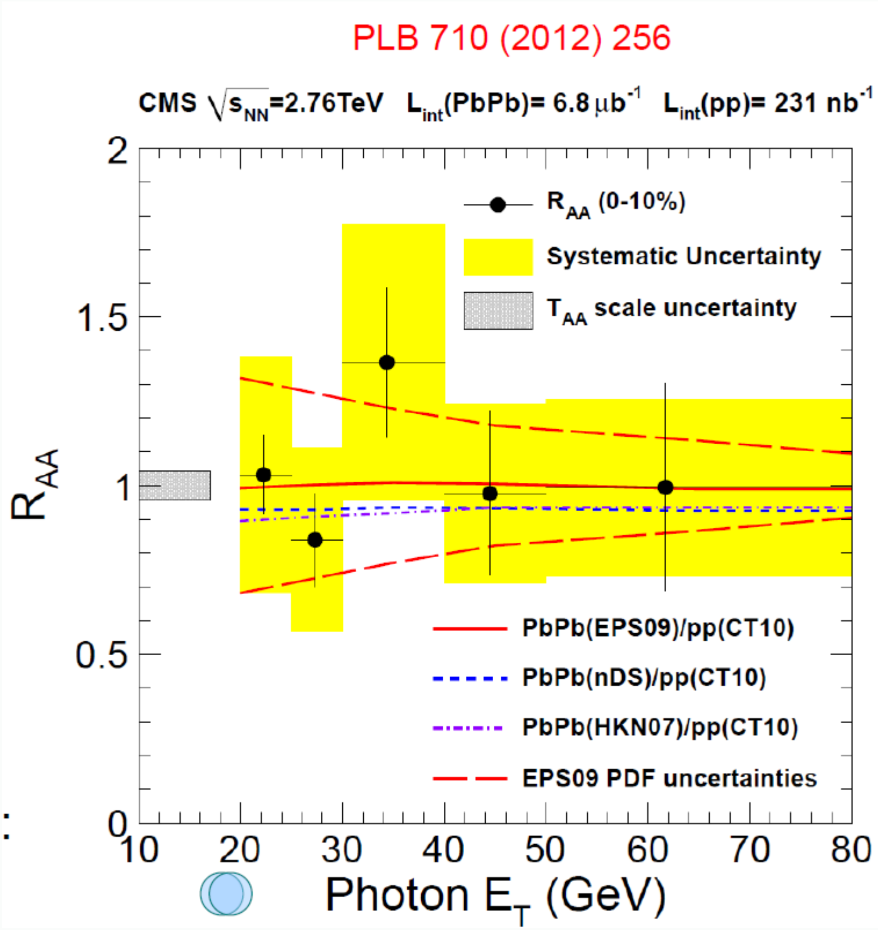


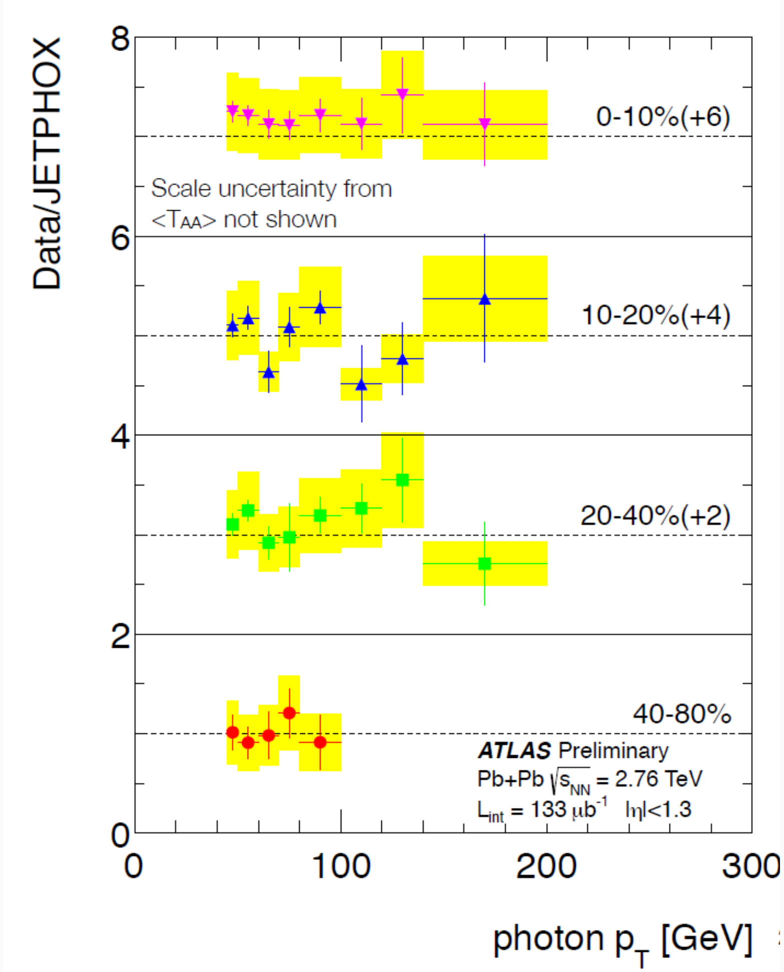




Evidence for $R^D_{AA}/R^{\pi}_{AA}>1$

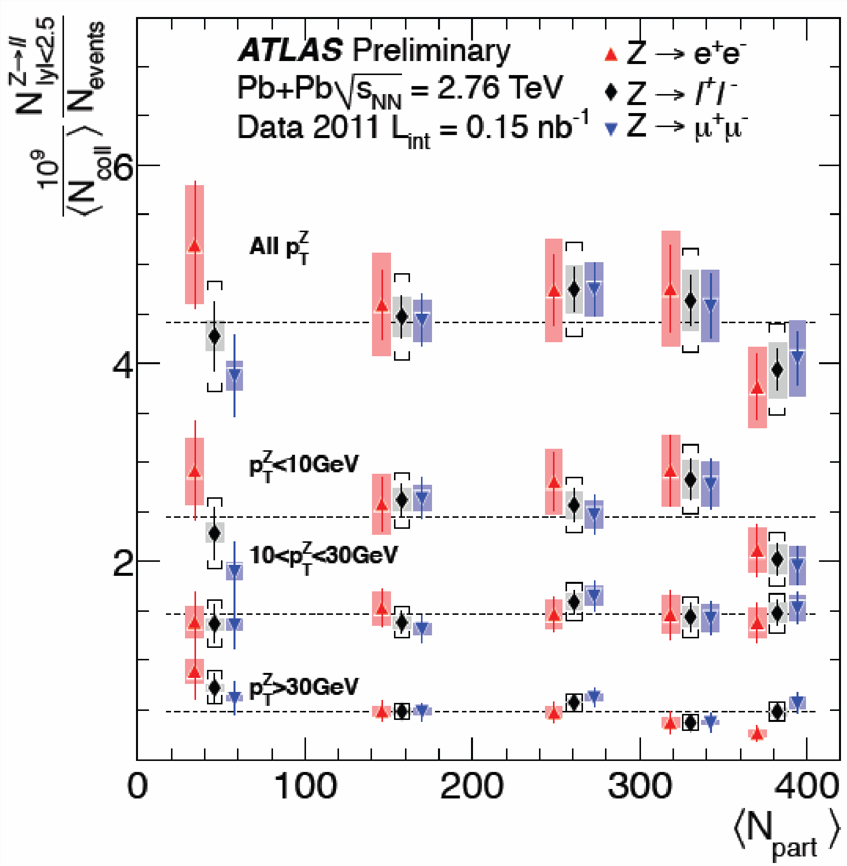
Isolated photon R_{AA}. CMS & ATLAS

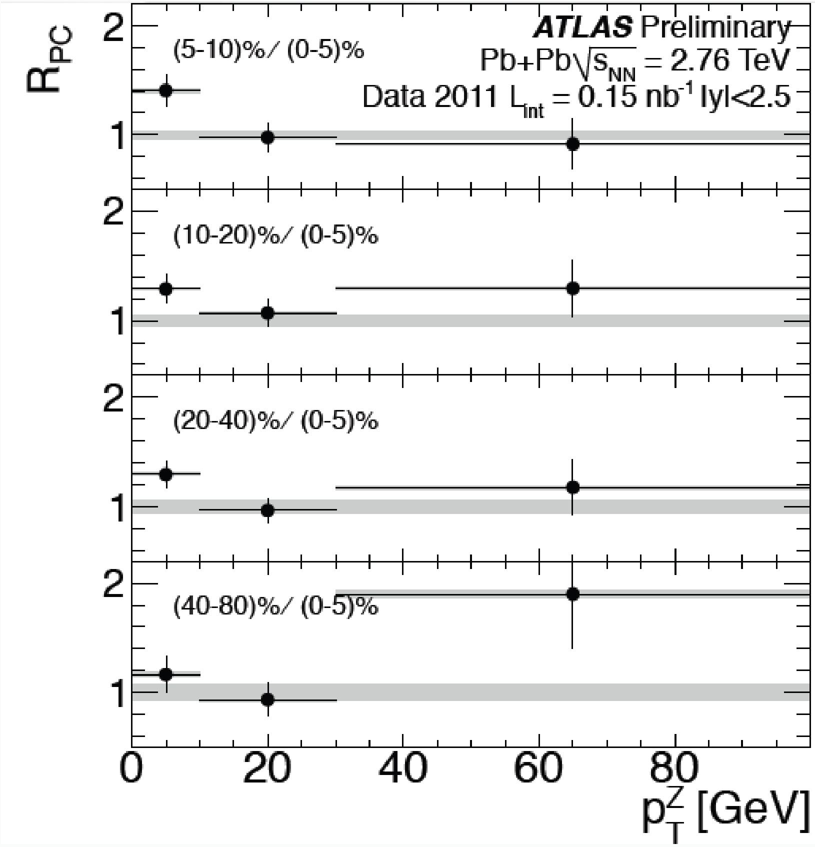




Colorless probes are unaffected

Z boson R_{PC} .ATLAS

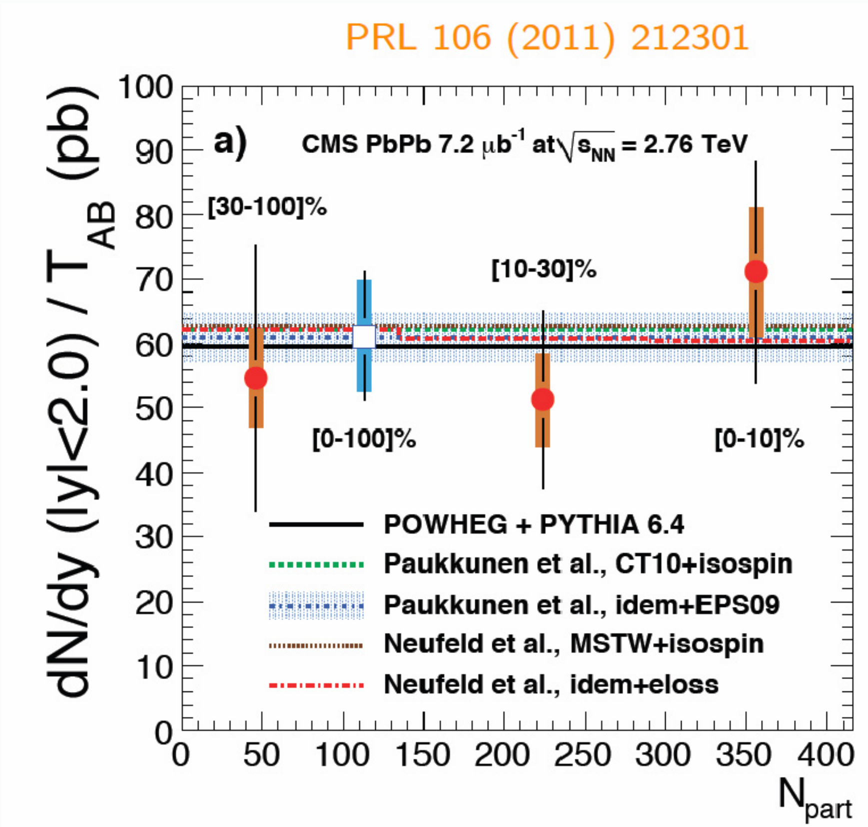


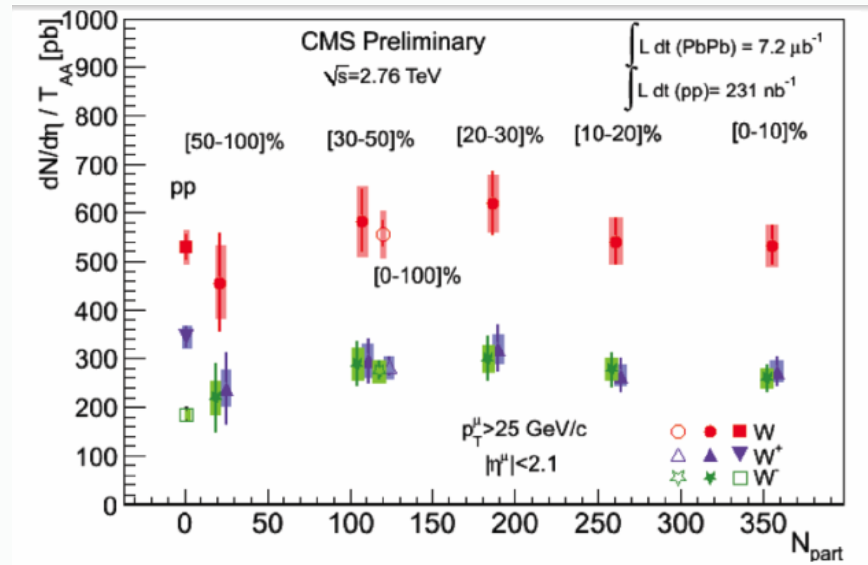


Comparing production in different centrality bins consistent with binary collision scaling

Colorless probes are unaffected

Z and W boson . CMS

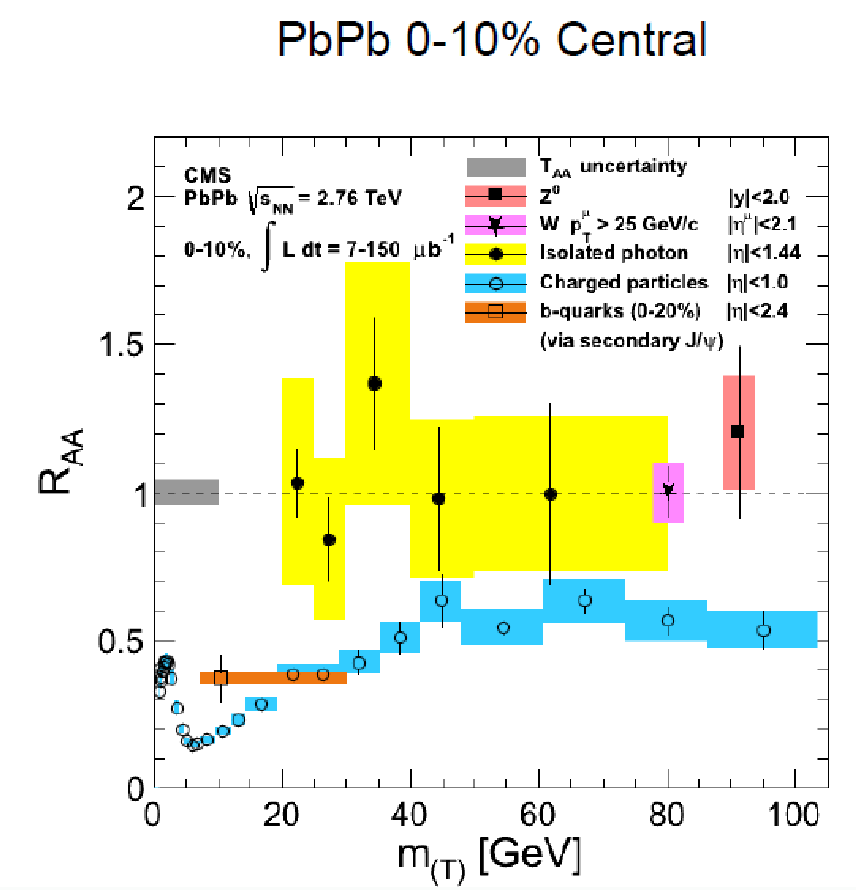




Once summed W+ and W-   consistent with pp

Colorless probes are unaffected

Compilation of R_{AA} by CMS

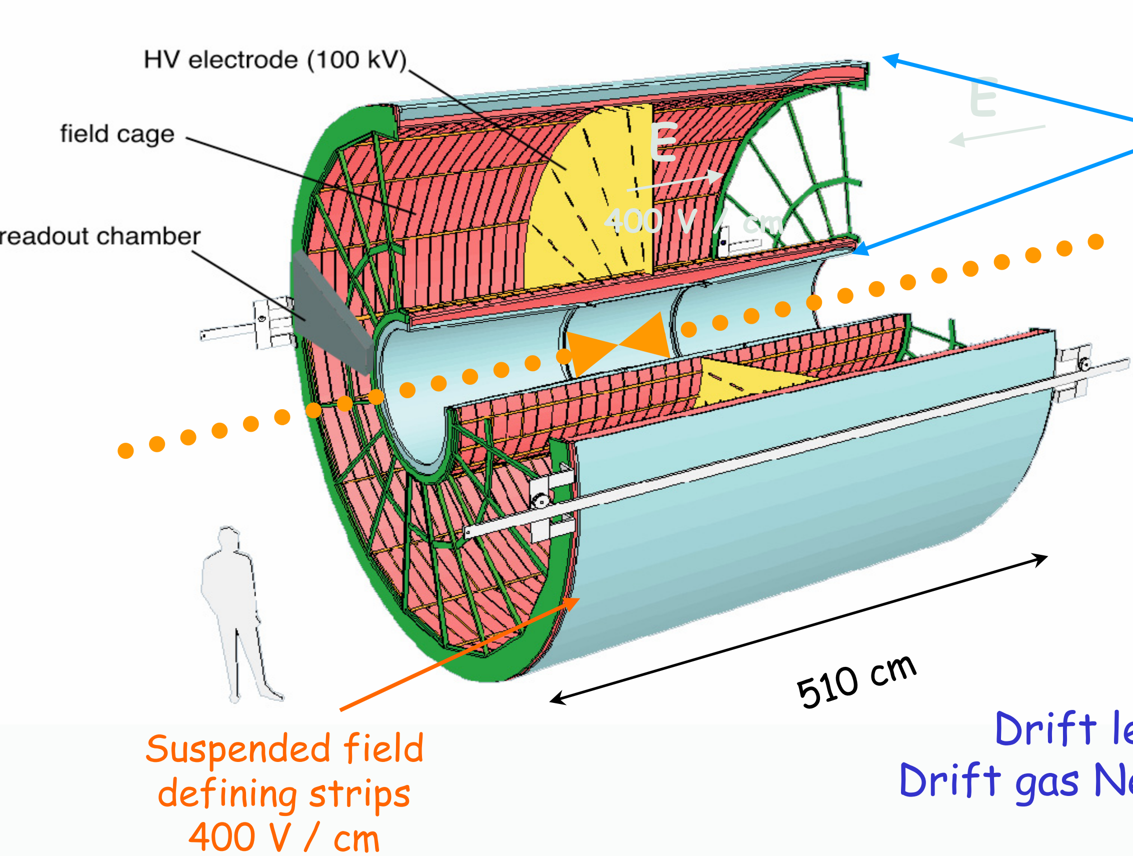


Data Table: https://twiki.cern.ch/twiki/bin/view/CMSPublic/HIN11002Data

- **backup**

The Time Projection Chamber

Main tracking detector (charged particles) of the ALICE Central Barrel



- very thin & lightweight FC ~3% X_0
- high track density & small space charge
  drift gas, chamber lay-out, field strips, ..

845 < r < 2466 mm
Drift length 2 x 2500 mm
Drift gas $Ne\text{-}CO_2\text{-}N_2$ (86/9/5)
Gas volume 95 m3
557568 readout pads

Functions, Functions, …

$$\frac{dN}{p_T dp_T} \propto \left(1+\frac{p_0}{p_T}\right)^{-n}$$ power law (high-p_T)

$$\frac{dN}{m_T dm_T} \propto m_T \; K_1\left(\frac{m_T}{T}\right) \xrightarrow{m_T>>T} \sqrt{m_T}\, e^{-m_T/T}$$ thermal emission (4π)

$$\frac{dN}{m_T dm_T} \propto m_T e^{-m_T/T}$$ thermal emission (y=0)

$$\frac{dN}{m_T dm_T} \propto \int_0^R r\, dr\, m_T\; I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$ thermal + flow

$$\frac{dN}{m_T dm_T} \propto e^{-m_T/T}$$ simple

$$\frac{dN}{m_T dm_T} \propto \frac{e^{-m_T/T}}{\mathrm{m_T}^{\lambda}}$$ Empirical parametrization from pp ($\mathrm{m_T}$-scaling)

but also from theoretical model (flux-tube + Schwinger)
(Gatoff, Wong, PRD 46, 997 (1992)

Note: "T" depends on function used
in papers often more than one fit function quoted …

Assumptions:

- Factorization between the hard part and the non perturbative PDF and fragmentation function Dq→H(zq,Q2)

- Universal fragmentation and PDFs (e.g PDF from ep, fragmentation fz. from ee, but used in pp data)

Medium modifications: R_{AA}, R_{CP}

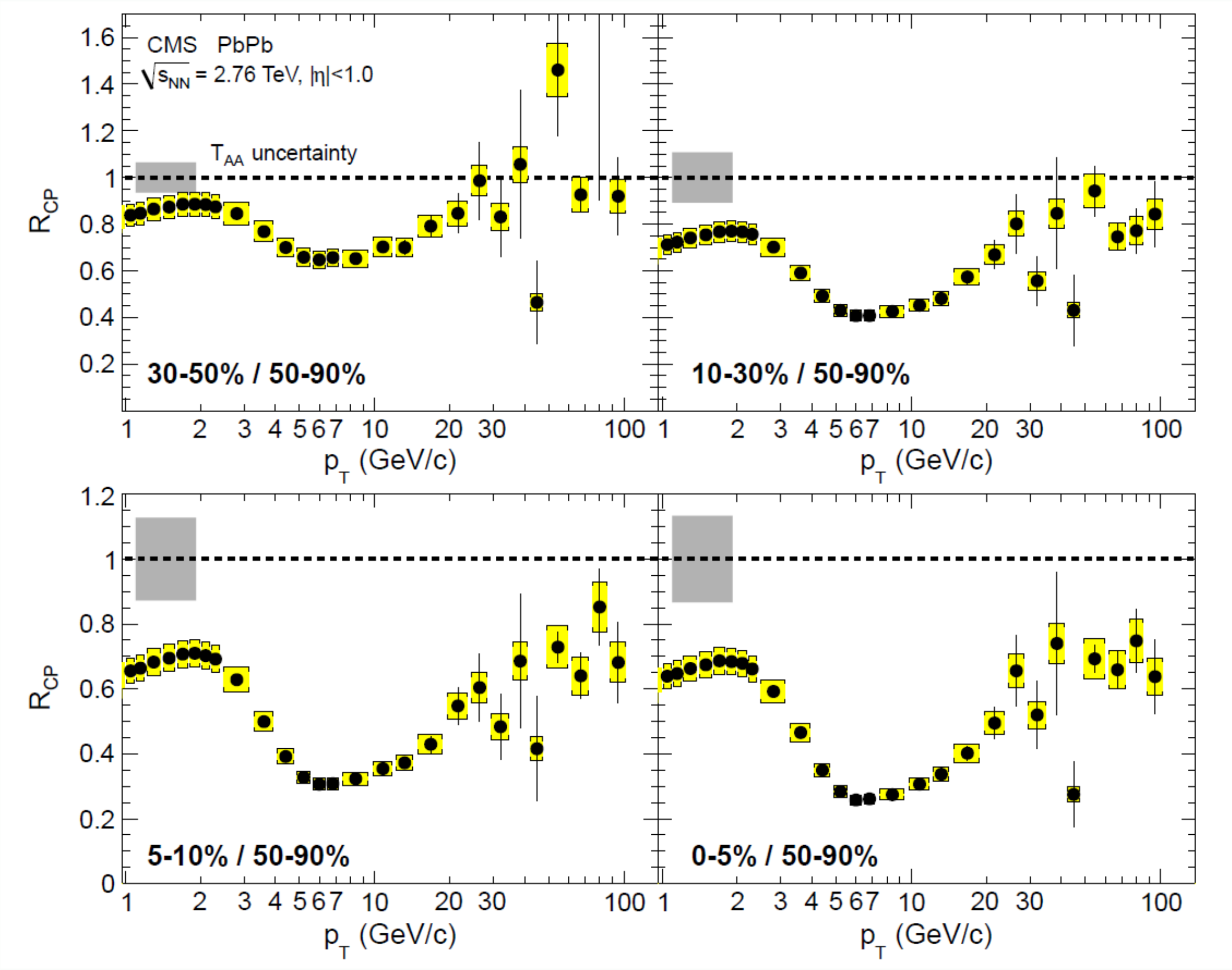
Nuclear modification factor for:

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \times \frac{\mathrm{d}N_{AA}/\mathrm{d}p_t}{\mathrm{d}N_{pp}/\mathrm{d}p_t}$$

- **π^0, η, direct γ (not coming from neutral meson decays)**
- **Charm. Heavy flavour electrons** (not photonic, or dielectron decays of mesons, or direct γ, or J/ψ and Y)

$$R_{CP}(p_t) = \frac{1}{\langle N_{coll} \rangle} \times \frac{\mathrm{d}N_{AA}/\mathrm{d}p_t / \langle T_{AA} \rangle [central]}{\mathrm{d}N_{AA}/\mathrm{d}p_t / \langle T_{AA} \rangle [peripheral]}$$

and status in ALICE...


CMS PbPb
$\sqrt{s_{NN}}$ = 2.76 TeV, |η|<1.0
T_{AA} uncertainty
30-50% / 50-90%
10-30% / 50-90%
5-10% / 50-90%
0-5% / 50-90%
R_{CP}
p_T (GeV/c)