Jet quenching measurements with leading hadrons

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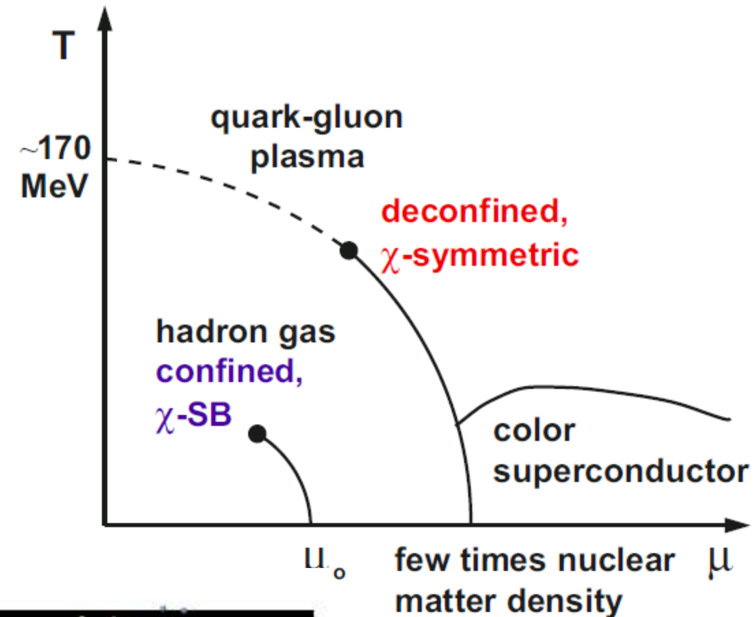
SEIT 1386

QCD thermodynamics – pressure and passion
Symposium in honor of Peter Braun-Munzinger
Schloss Waldthausen, August 24-26, 2016

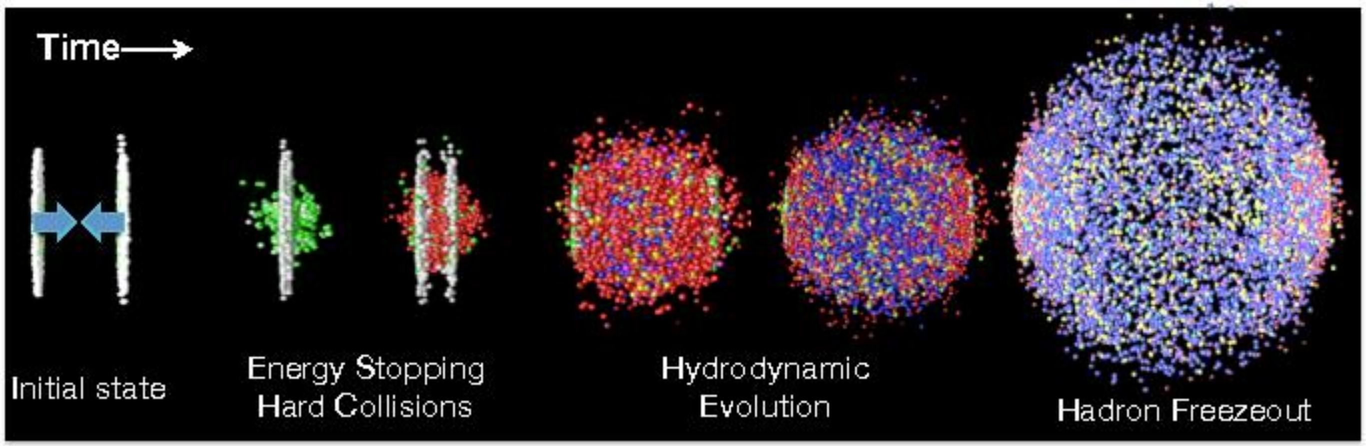
ALICE

Introduction

- use heavy-ion collisions to create the quark-gluon plasma and study its properties
- probes have to be created in the collision
- high p_T parton are produced in hard scattering at early times $t \sim 1/Q$
- QGP formation: $t \sim 1$ fm
- hadronization: $t \sim 10$ fm



The CBM Physics Book, Lect.Notes Phys. 814, 1 (2011)



Tapan K. Nayak, arXiv:1201.4264

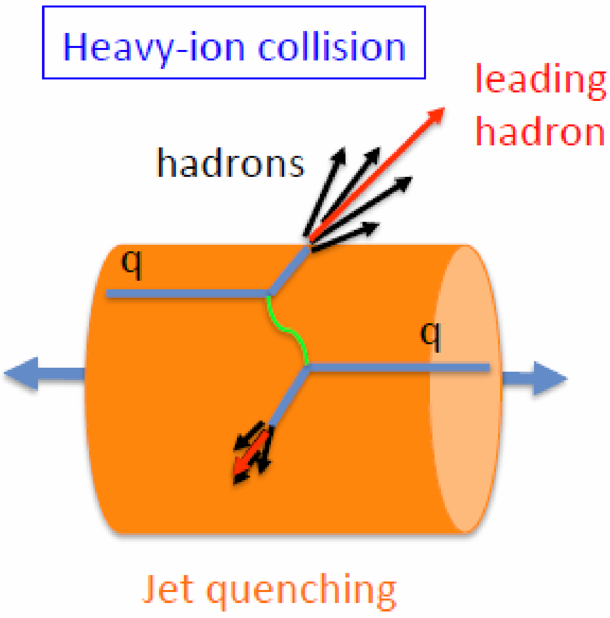
Jet quenching

- **High p_T partons travel through the medium**

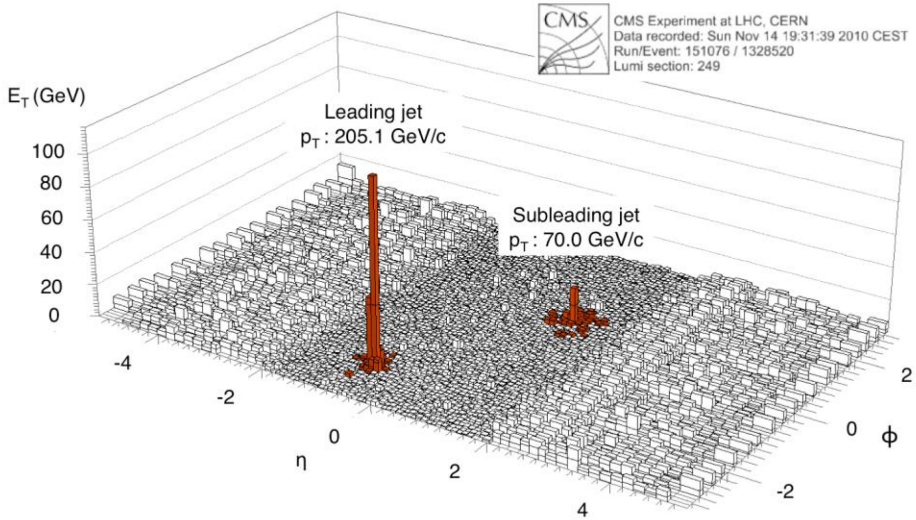
  -> parton energy loss (Bjorken 1982)

Experimental access to parton energy loss

- **single (leading) particle and reconstructed jets**

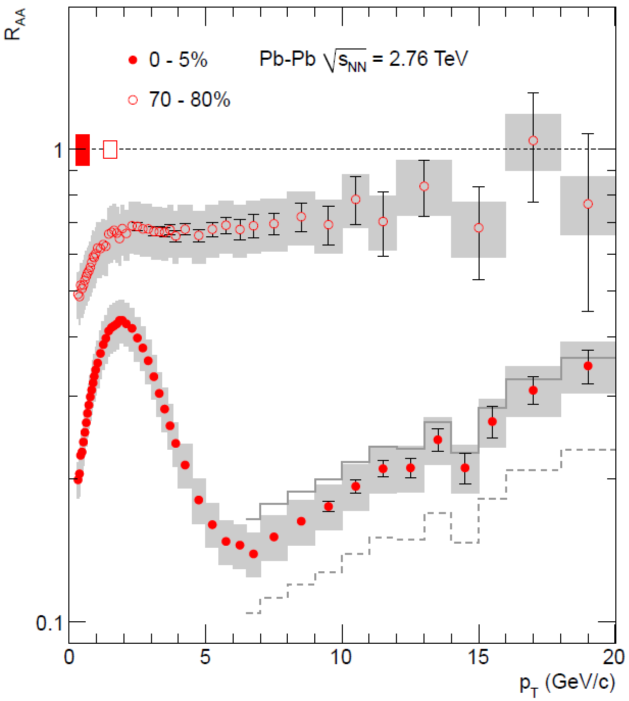


- **suppression of inclusive hadron and jet production**
- **di-hadron correlation**
- **di-jet asymmetry**
- **hadron-photon or jet-photon correlation**
- **modification of jet structure**
- **path length dependence**

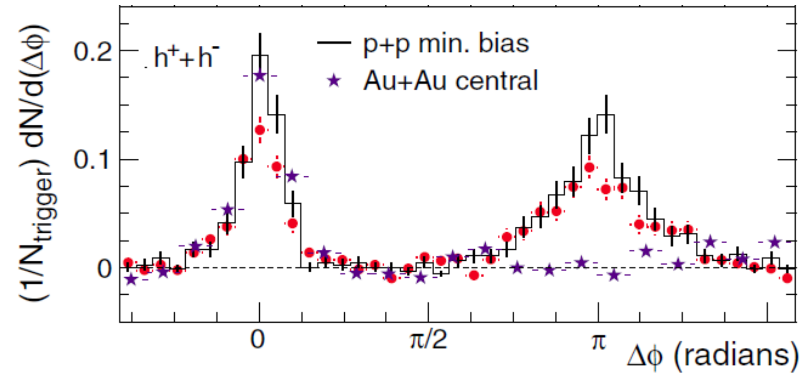


CMS Collaboration, Phys.Rev. C84 (2011) 024906

Observables for jet quenching



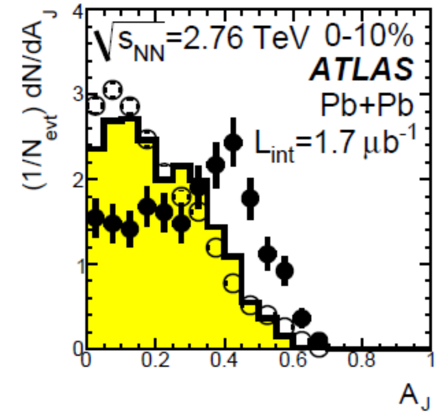
ALICE Collaboration, Phys.Lett. B696 (2011) 30-39

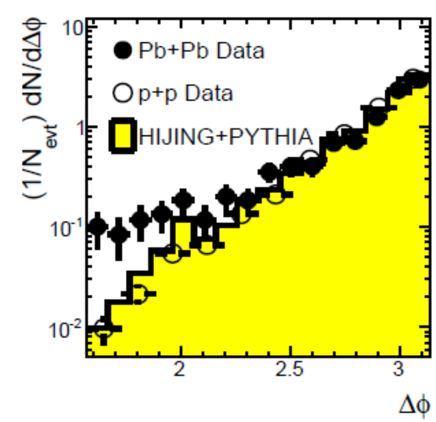


STAR Collaboration, Phys. Rev. Lett. 91, 072304

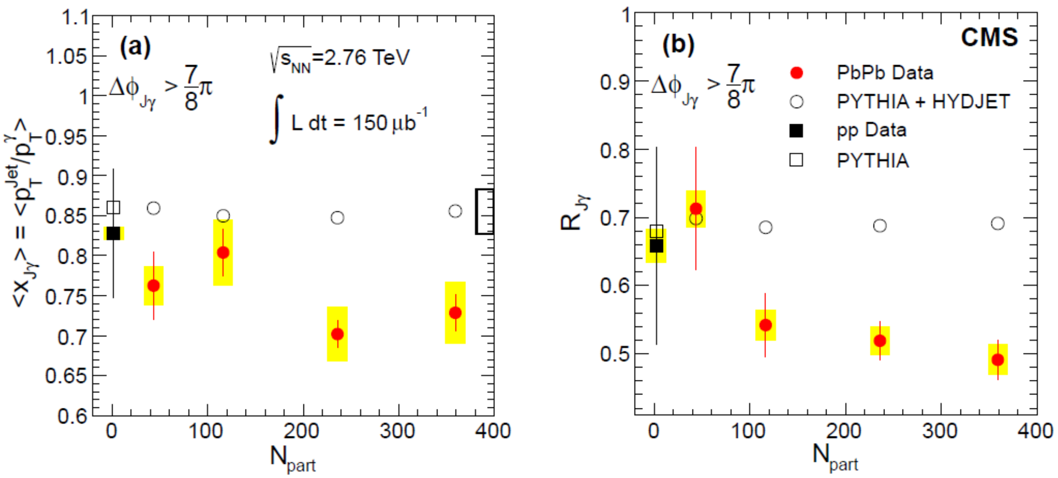
conclusions from comparison to pp or pA collisions

=> reference needed





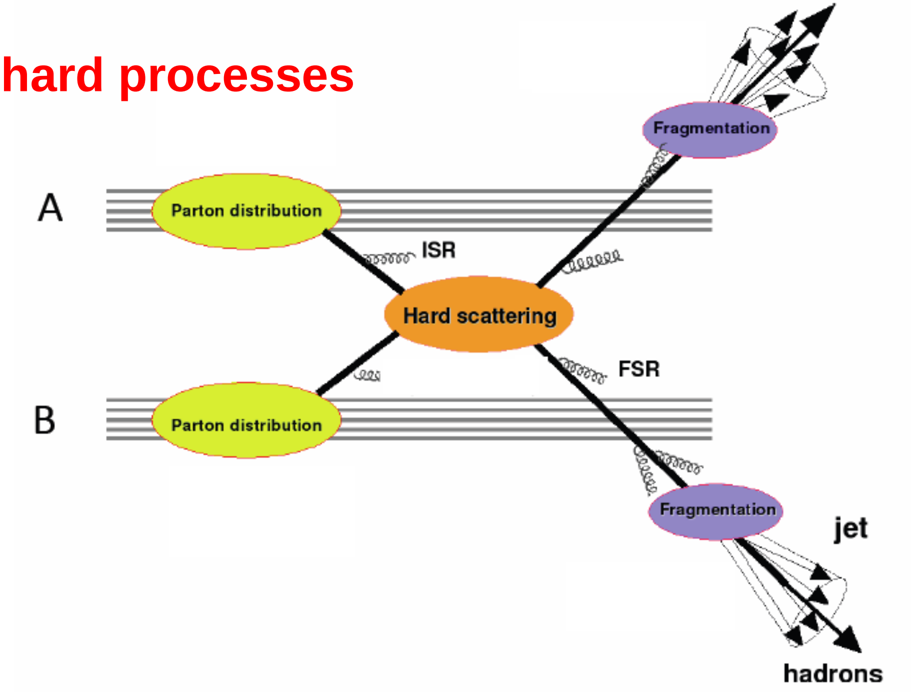
ATLAS Collaboration, Phys.Rev.Lett. 105 (2010) 252303



CMS Collaboration, Phys. Lett. B 718 (2013) 773

High p_T hadrons in pp collisions

QCD factorization of hard processes



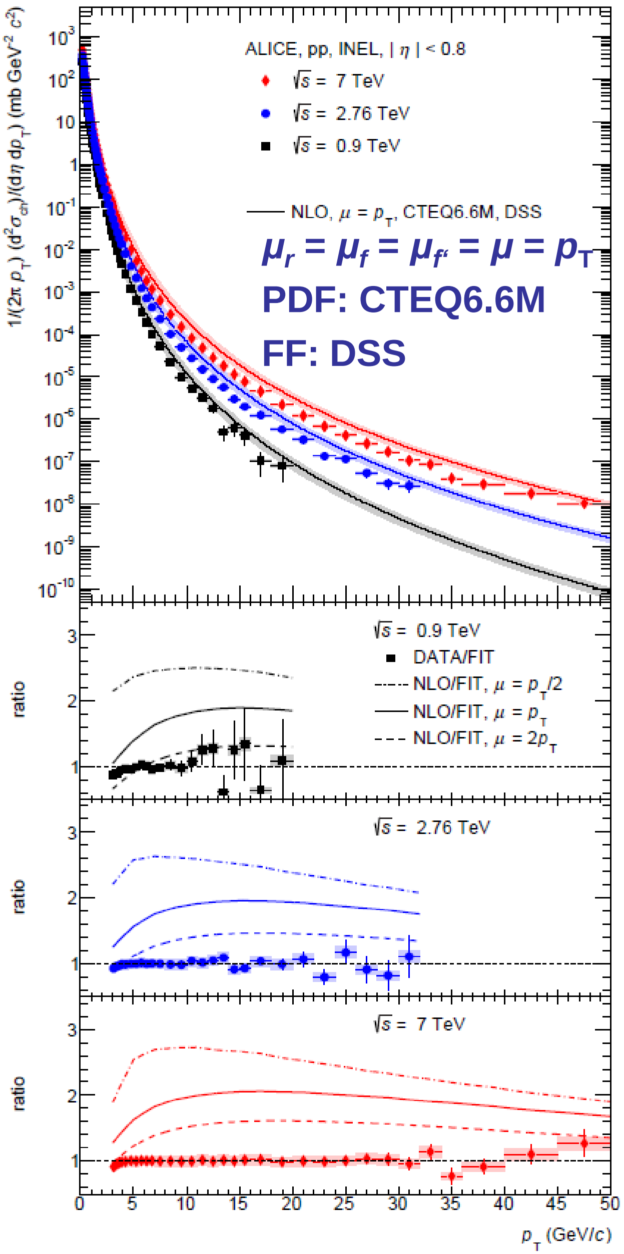
$$E\frac{d^3\sigma_{pp\to hX}}{dp^3} = \sum_{abc}\int dx_a dx_b \frac{dz}{z} f_a(x_a,\mu_f^2)\otimes f_b(x_b,\mu_f^2)$$ **initial state (PDF)**

$$\otimes\, |\vec{k}|\frac{d\hat{\sigma}_{a+b\to c+X}}{dk^3}(k=p/z,\mu_r^2)$$ **partonic cross section (pQCD)**

$$\otimes\, D_c^h(z,\mu_{f'}^2)$$ **fragmentation function (hadronization)**

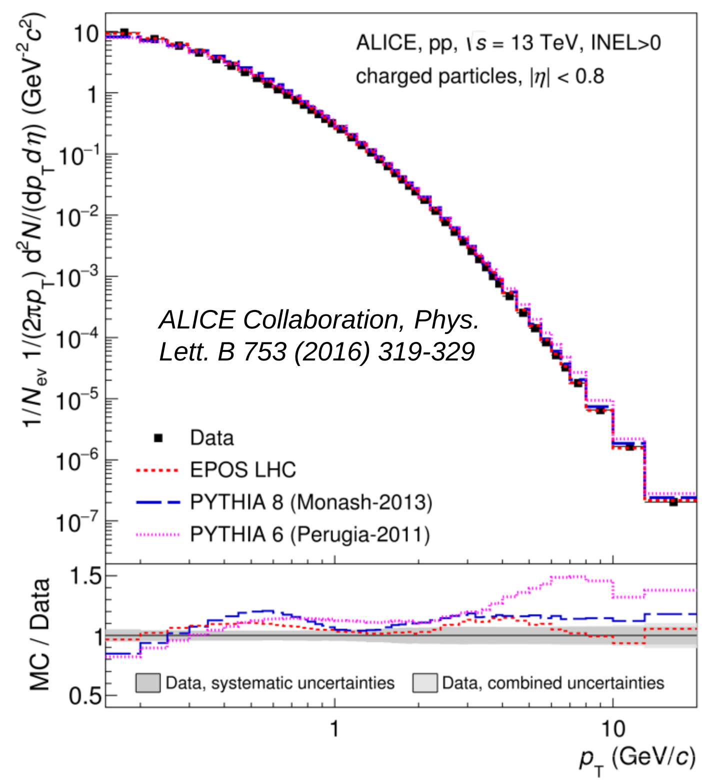
+ models for soft interactions

Charged particle production in pp collisions



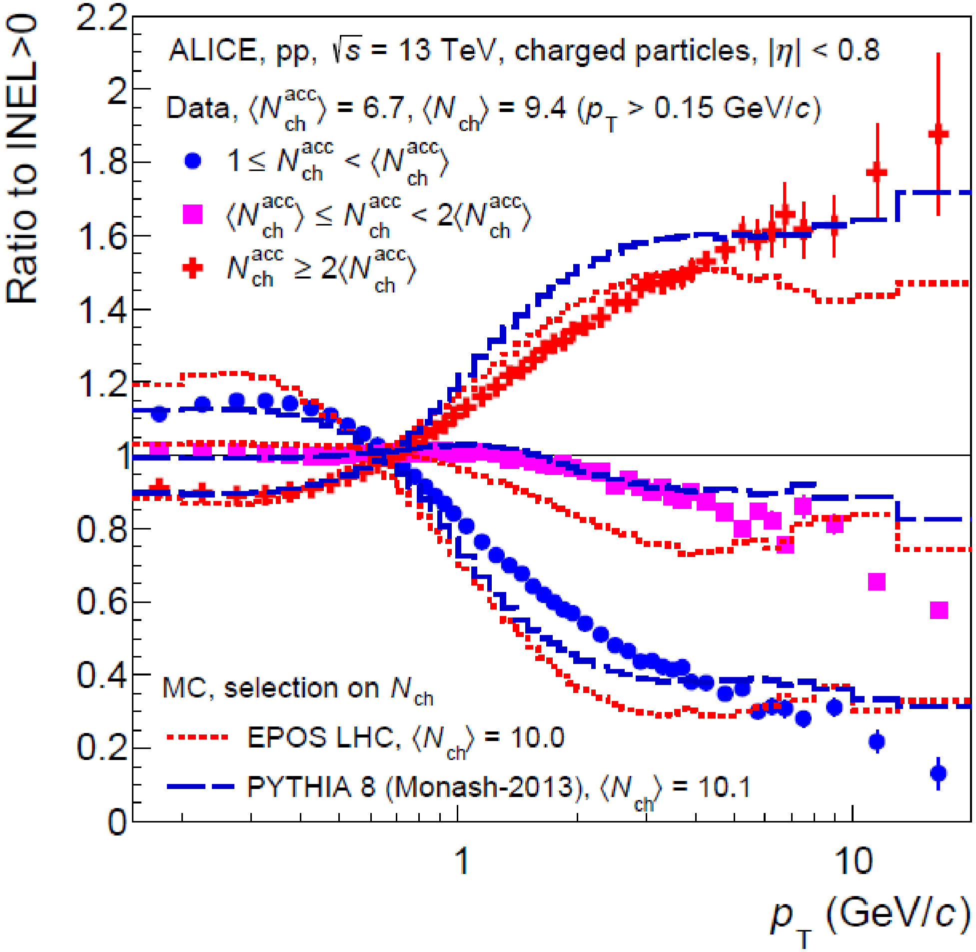
ALICE Collaboration, Eur.Phys.J.C (2013) 73:2662
NLO: Sassot, Zurita, Stratmann, Phys.Rev D 82, 074011 (2010)

- **NLO calculation overpredicts the cross section while jet spectra are well described** **(e.g. ALICE, Phys. Lett. B 722(2013) 262-272)** **=> FF too hard at LHC energy**
- **EPOS LHC and PYTHIA8 give good description of 13 TeV pp data**



Multiplicity dependence in pp

ALICE Collaboration, Phys. Lett. B 753 (2016) 319-329



- **low multiplicity events are softer because of „jet veto“**
- **larger multiplicity events in pp have a harder spectrum (jet enhanced)**
- **reproduced by MC generators**

High p_T hadrons in AA collisions

- **parton in dynamically evolving QGP**
  -> theory challenge, many parameters

$$E\frac{d^3\sigma_{AA\to hX}}{dp^3} = \sum_{abc'c}\int dx_a dx_b \frac{dz}{z}\frac{dz'}{z'} f_a^A(x_a,\mu_f^2)\otimes f_b^A(x_b,\mu_f^2)$$

initial state (PDF)

$$\otimes\, |\vec{k}|\frac{d\hat{\sigma}_{a+b\to c+X}}{dk^3}(k=p/z,\mu_r^2)$$

partonic cross section (pQCD)

$$\otimes\, P_{c\to c'}(\mu^2)$$

parton energy loss in the medium

$$\otimes\, D_{c'}^h(z,\mu_{f'}^2)$$

fragmentation function (hadronization)

input needed for:

- **initial production of high p_T partons (NLO pQCD)**
- **interaction with the medium**
  (weak coupling: pQCD, strong coupling: AdS/CFT)
- **time evolution of the medium (hydrodynamic models)**
  matched to describe soft observables (flow, multiplicity density)
- **hadronization/fragmentation (DGLAP)**

Nuclear modification factor

- In absence of medium interactions and PDF modifications factorization implies scaling of hard processes in pA or AA with the number of binary nucleon-nucleon collisions N_{coll}

$$R_{AA} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

- deviations quantified by the nuclear modification factors

$$R_{pPb}(p_T) = \frac{d^2N^{pPb}/d\eta dp_T}{\langle N_{coll}\rangle \cdot d^2N^{pp}/d\eta dp_T}$$

initial and final state
cold nuclear matter effects

$$R_{AA}(p_T) = \frac{d^2N^{Pb-Pb}/d\eta dp_T}{\langle N_{coll}\rangle \cdot d^2N^{pp}/d\eta dp_T}$$

+ parton energy loss

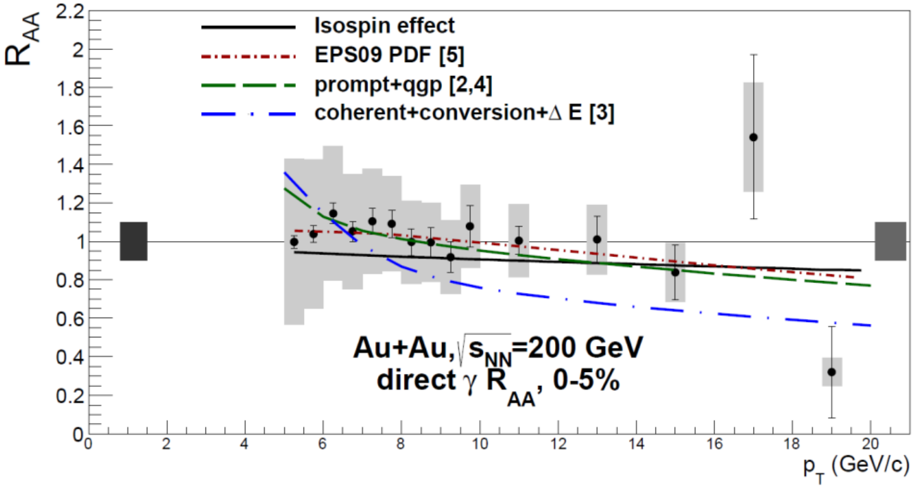
from MC Glauber model:

p-Pb:	$\langle N_{coll}\rangle = 6.9$	$\langle N_{part}\rangle = 7.9$	(MinBias 5.02 TeV)
peripheral Pb-Pb:	$\langle N_{coll}\rangle = 15.6$	$\langle N_{part}\rangle = 15.8$	(70-80%, 2.76 TeV)
central Pb-Pb:	$\langle N_{coll}\rangle = 1985$	$\langle N_{part}\rangle = 383$	(0-5%, 2.76 TeV)

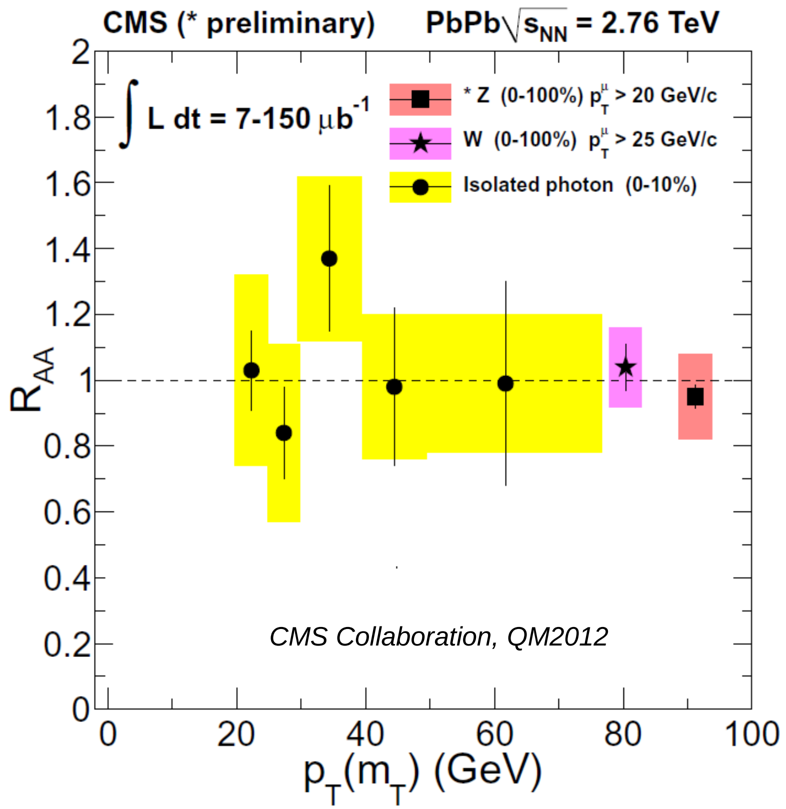
- soft particle production is observed to scale with the number of participating nucleons $N_{part} \sim N_{Coll}^{2/3}$

R_{AA} of electroweak probes

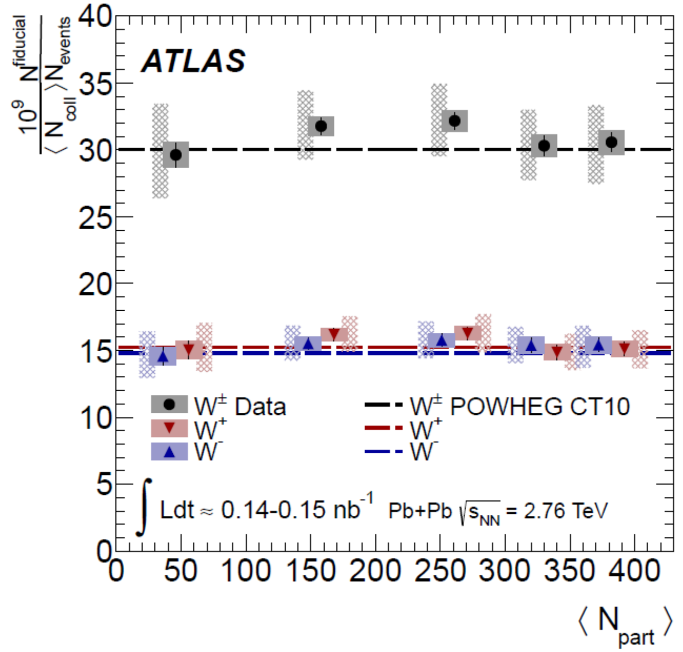
- **hard photons and weak bosons exhibit binary collision scaling**
- **only small deviations from unity expected**



PHENIX Collaboration, Phys.Rev.Lett. 109 (2012) 152302



CMS Collaboration, QM2012



ATLAS Collaboration, Eur. Phys. J. C (2015) 75:23

Nuclear PDF

parton distribution in nuclei differs from protons

nuclear modification factor for the PDF:

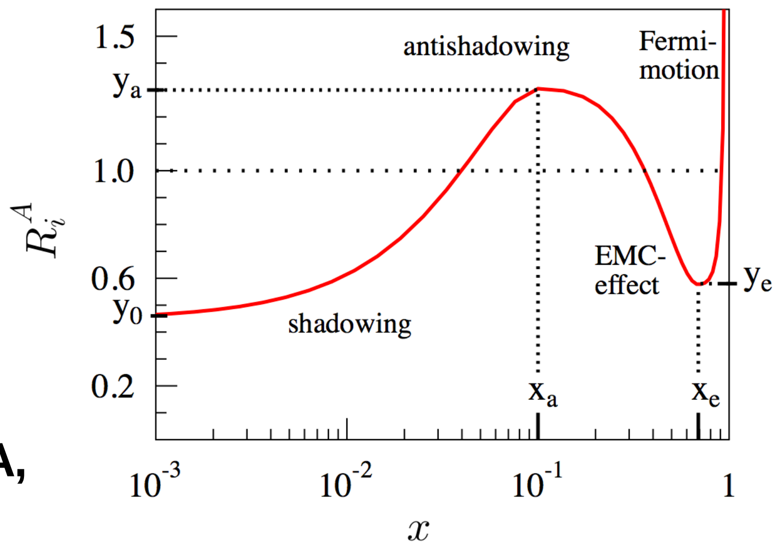
$$R_i^{Pb}\left(x,Q^2\right) \equiv f_i^{Pb}\left(x,Q^2\right) / f_i^{p}\left(x,Q^2\right)$$

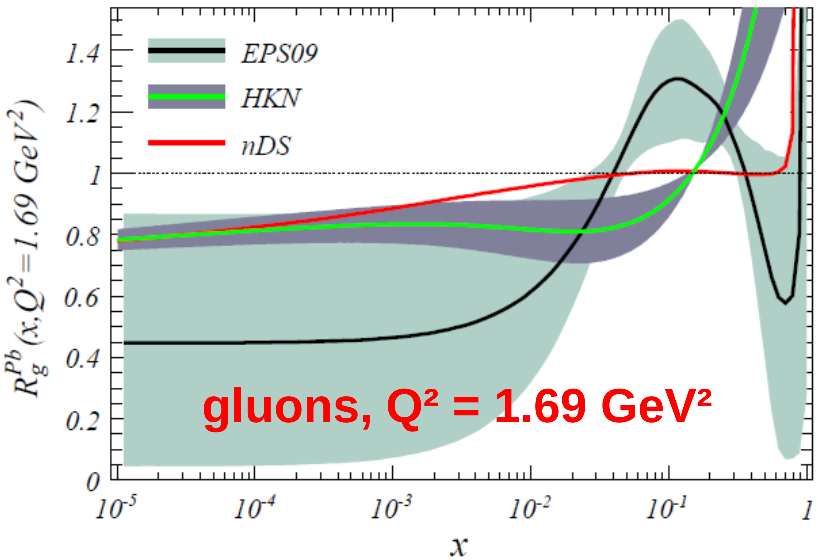
$x \sim p_T/\sqrt{s}\, e^{-y}$

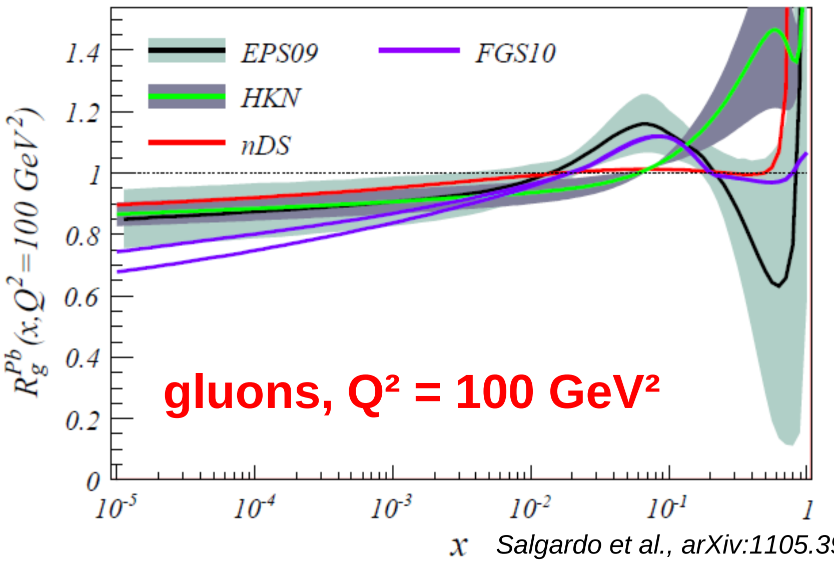
at LHC: $x \sim 10^{-5}...10^{-1}$

nuclear PDFs are not very well known from eA, but accessible also via pA collisions

Eskola et al., JHEP 0904:065, 2009



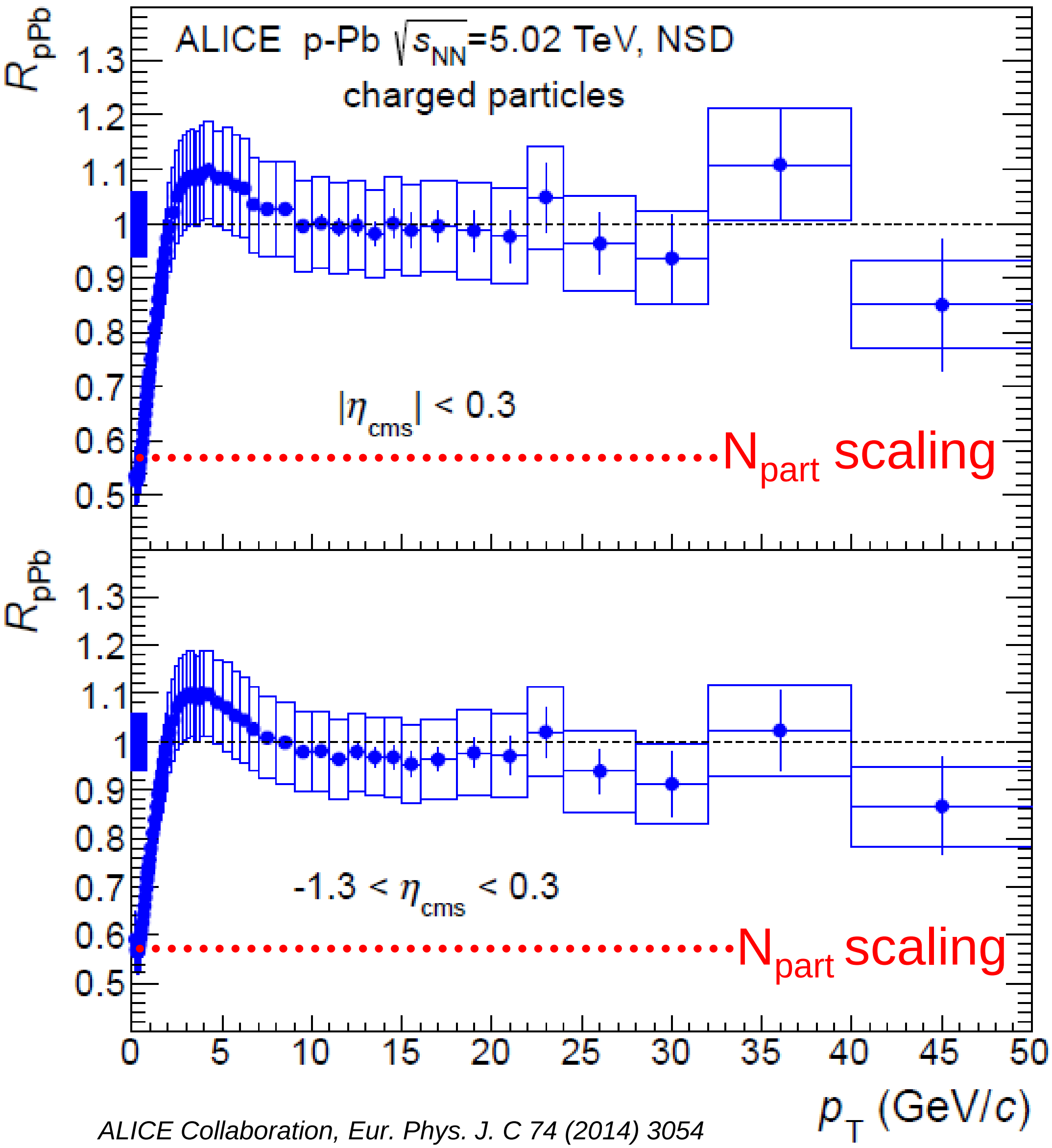




Salgardo et al., arXiv:1105.3919

R_{pPb} of charged particles

- **N_{coll} scaling at high p_T**
- **N_{part} scaling at low p_T**
- **small Cronin-like enhancement at intermediate p_T**



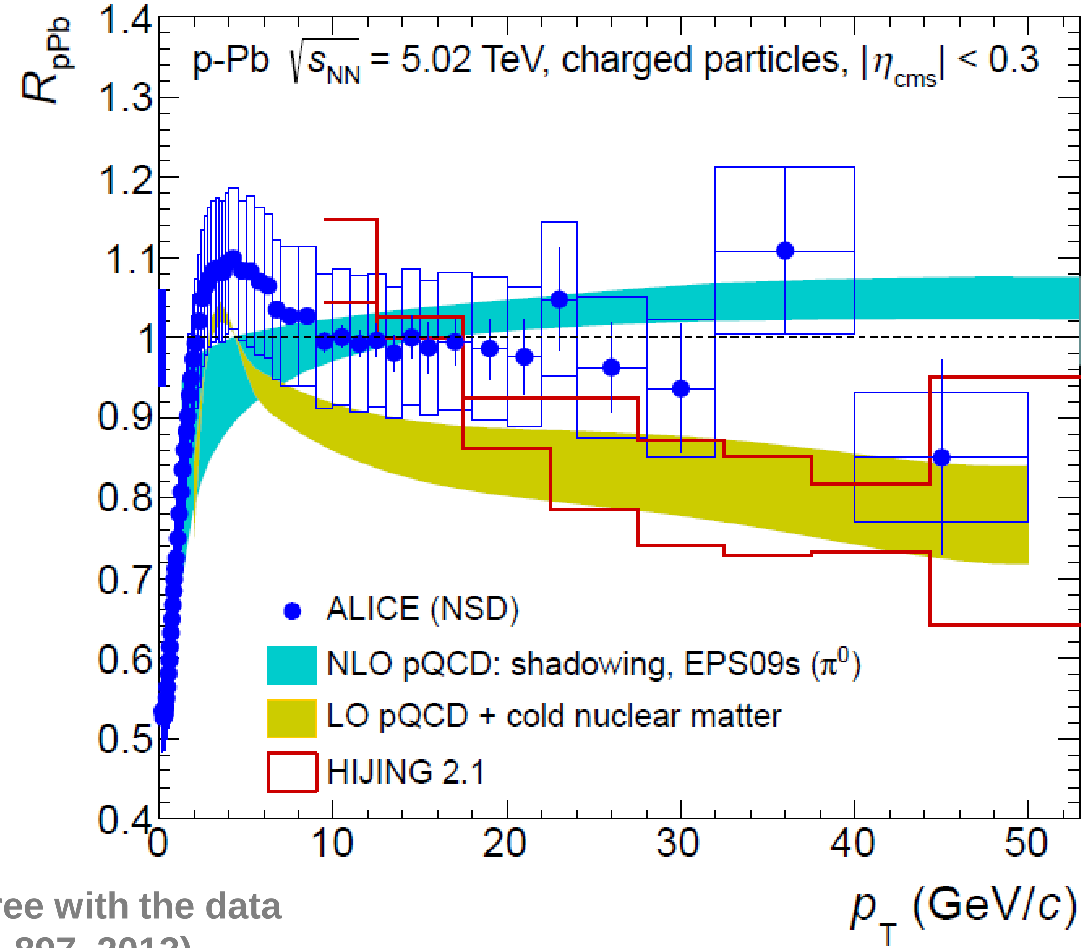
ALICE Collaboration, Eur. Phys. J. C 74 (2014) 3054

R_{pPb} compared to model calculations

- **NLO with EPS09s nPDF: agrees for p_T > ~6 GeV/*c***
- **LO with cold nuclear matter effects: not supported by data**
- **HIJING 2.1: stronger decrease of R_{pPb} with p_T not seen in data**
- **none of the models reproduces the Cronin enhancement**

NLO+EPS09s: Helenius et al., JHEP 1207 (2012) 073
LO+CNM: Kang et al., Phys.Lett. B718 (2012) 482-487
HIJING: Xu et al., Phys.Rev. C86 (2012) 051901

ALICE Collaboration, Eur. Phys. J. C 74 (2014) 3054



not included in the Figure:

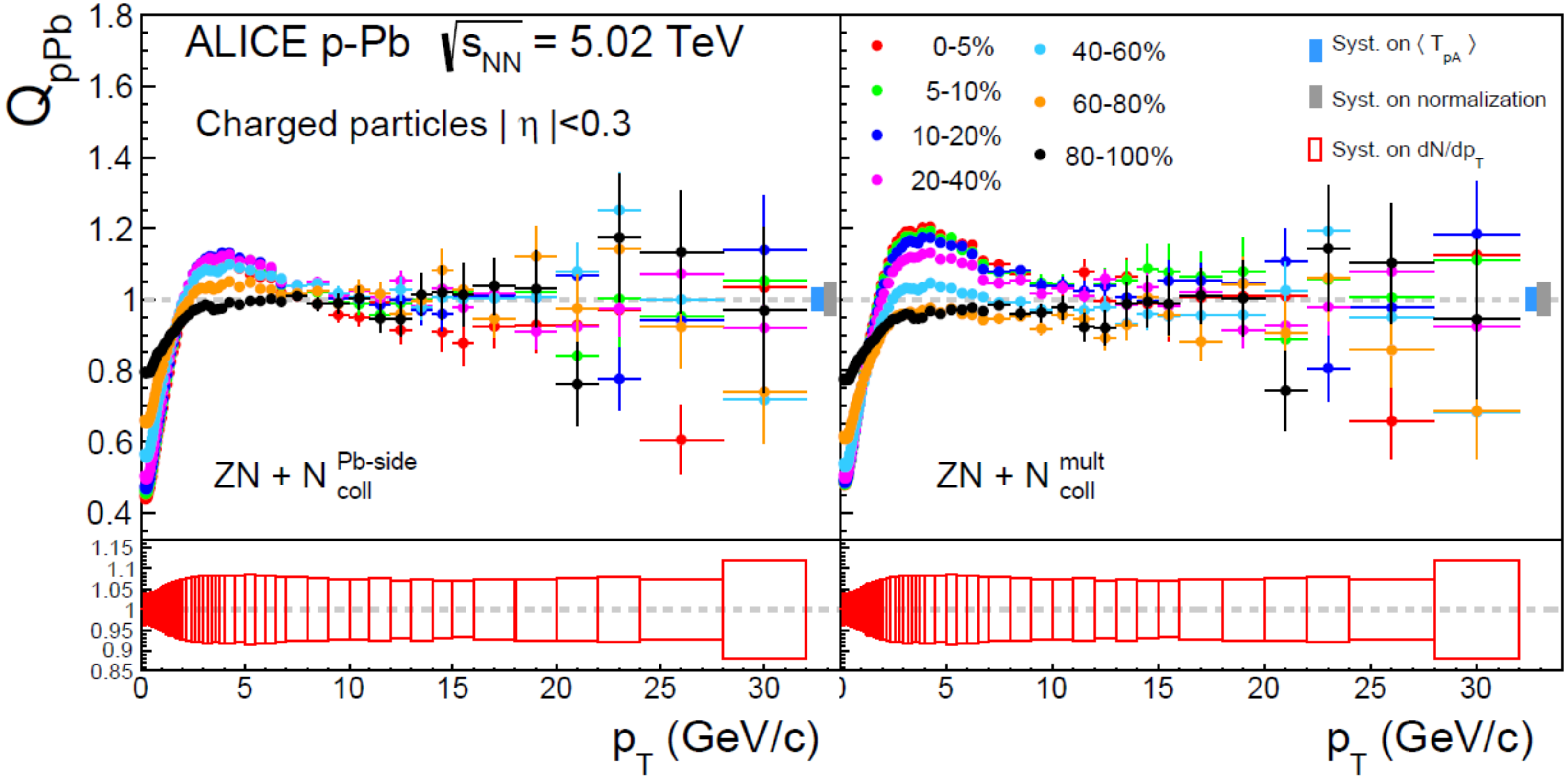
- **CGC predictions are for low p_T and agree with the data (rcBK-MC, Albacete et al. Nucl. Phys. A 897, 2013)**
- **EPOS3 with hydro describes R_{pPb} and the spectra (within ~20%) (K. Werner et al., arXiv:1312.1233)**
- **PHSD transport model does not describe the spectra for p_T > 2 GeV/*c* (V. P. Konchakovski et al., arXiv:1401.4409)**

Multiplicity dependence in p-Pb

- **event selection from forward (ZDC) neutrons**
- **N_{Coll} from central rapidity region**

$$Q_{\mathrm{pPb}}(p_{\mathrm{T}};\mathrm{cent}) = \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\langle N^{\mathrm{Glauber}}_{\mathrm{coll}}\rangle \mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

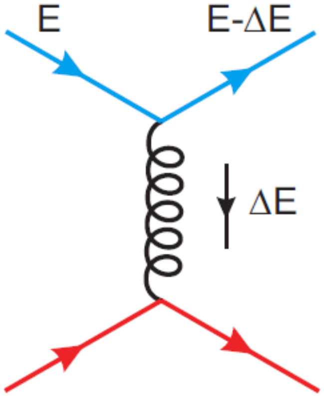
ALICE Collaboration, Phys. Rev. C 91, 064905 (2015)

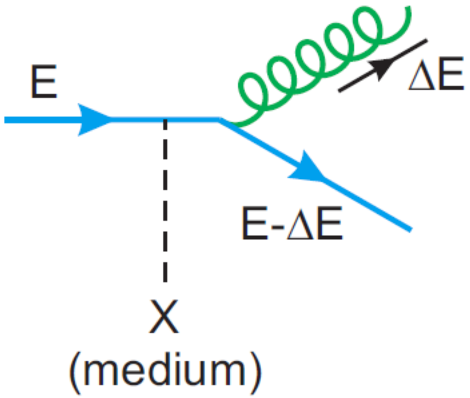


- **no centrality dependence at large p_T**

Parton energy loss

- collisional energy loss and radiative energy loss





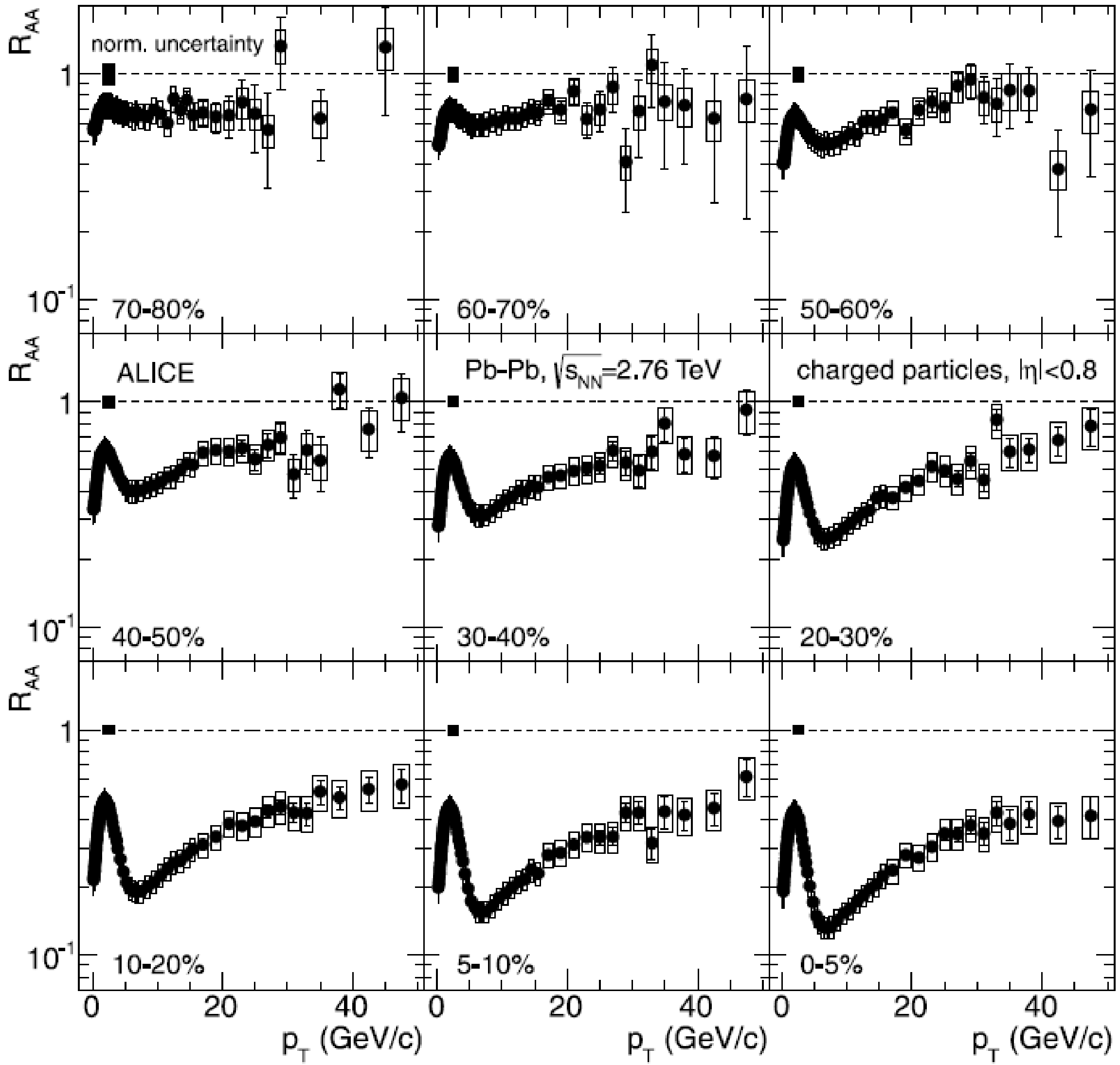
- at high energies radiative energy loss dominates
- coherent multiple emission of gluons (LPM effect)

$$\Delta E_{\mathrm{BH}} \approx \alpha_s C_R \hat{q} L^2 \ln \frac{\mathrm{E}}{\mathrm{m}_{\mathrm{D}}^2 \mathrm{L}} \qquad \Delta E_{\mathrm{LPM}} \approx \alpha_s C_R \hat{q} L^2$$

medium properties encoded in the parameter $\hat{q}$, which is the average squared transverse momentum transfer per unit path length

$$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda} = \frac{m_D^2}{\lambda} = m_D^2 \rho \sigma$$

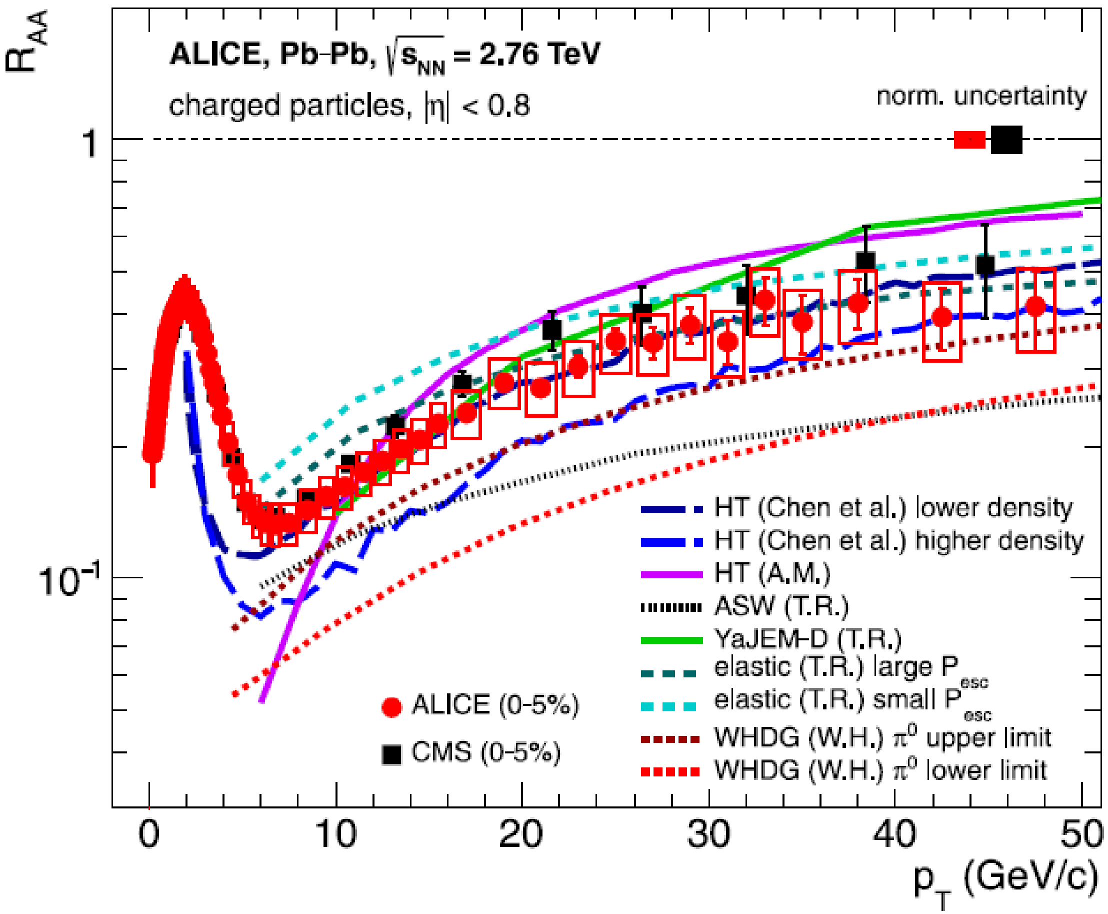
Centrality dependence of R_{AA}



- strongest suppression in central collisions
- R_{AA} decreases with centrality
- minimum of R_{AA} at p_T = 6-7 GeV/c for all centralities
- minimum ~0.12 for central collisions
- strongest centrality dependence around the minimum

ALICE Collaboration, Phys. Lett. B 720 (2013) 52–62

R_{AA}: comparison to models

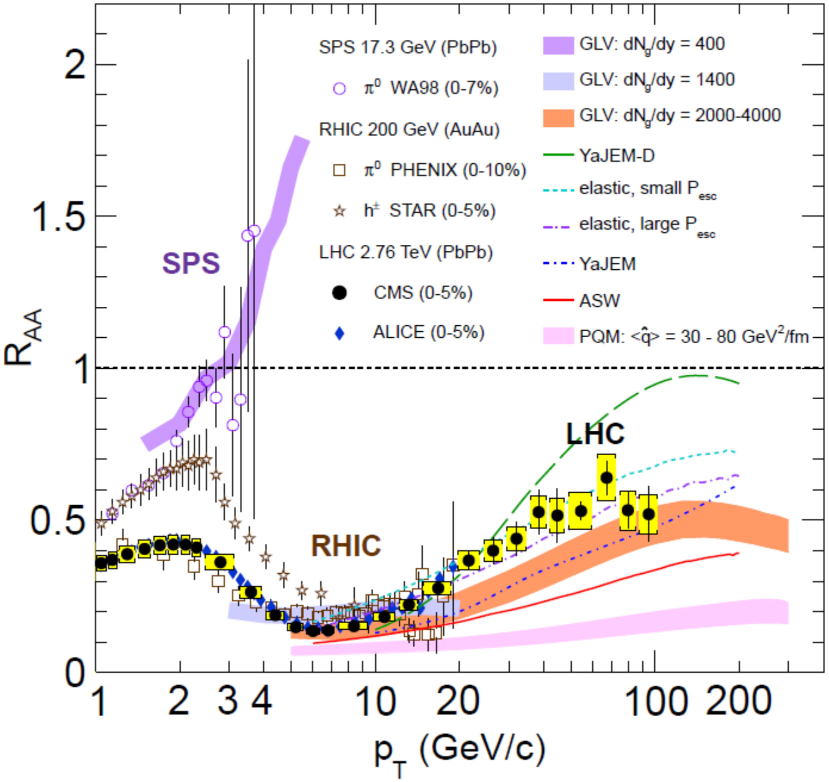


- rise of R_{AA} with p_T predicted by all models (decreased relative energy loss)
- magnitude depends on the energy loss mechanisms and medium modeling
- shown calculations precede the measurement for p_T > 20 GeV/c

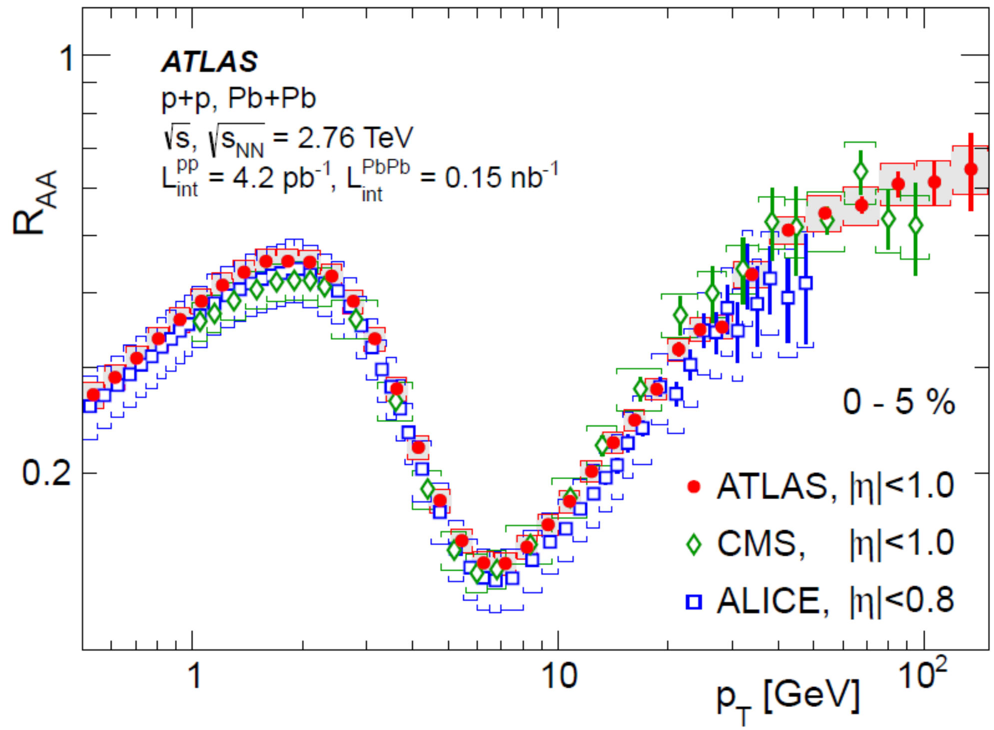
ALICE data: Phys. Lett. B 720 (2013) 52–62
CMS data: Eur. Phys. J. C 72 (2012) 1945
W.A. Horowitz, M. Gyulassy, Nucl. Phys. A 872 (2011) 265
C.A. Salgado, U.A. Wiedemann, Phys. Rev. D 68 (2003) 014008
X.-F. Chen, T. Hirano, E. Wang, X.-N. Wang, H. Zang, Phys. Rev. C 84 (2011) 034902
A. Majumder, B. Muller, Phys. Rev. Lett. 105 (2010) 252002
T. Renk, H. Holopainen, R. Paatelainen, K.J. Eskola, Phys. Rev. C 84 (2011) 014906
T. Renk, Phys. Rev. C 83 (2011) 024908

R_{AA} from CMS and ATLAS

CMS Collaboration, Eur. Phys. J. C (2012) 72:1945



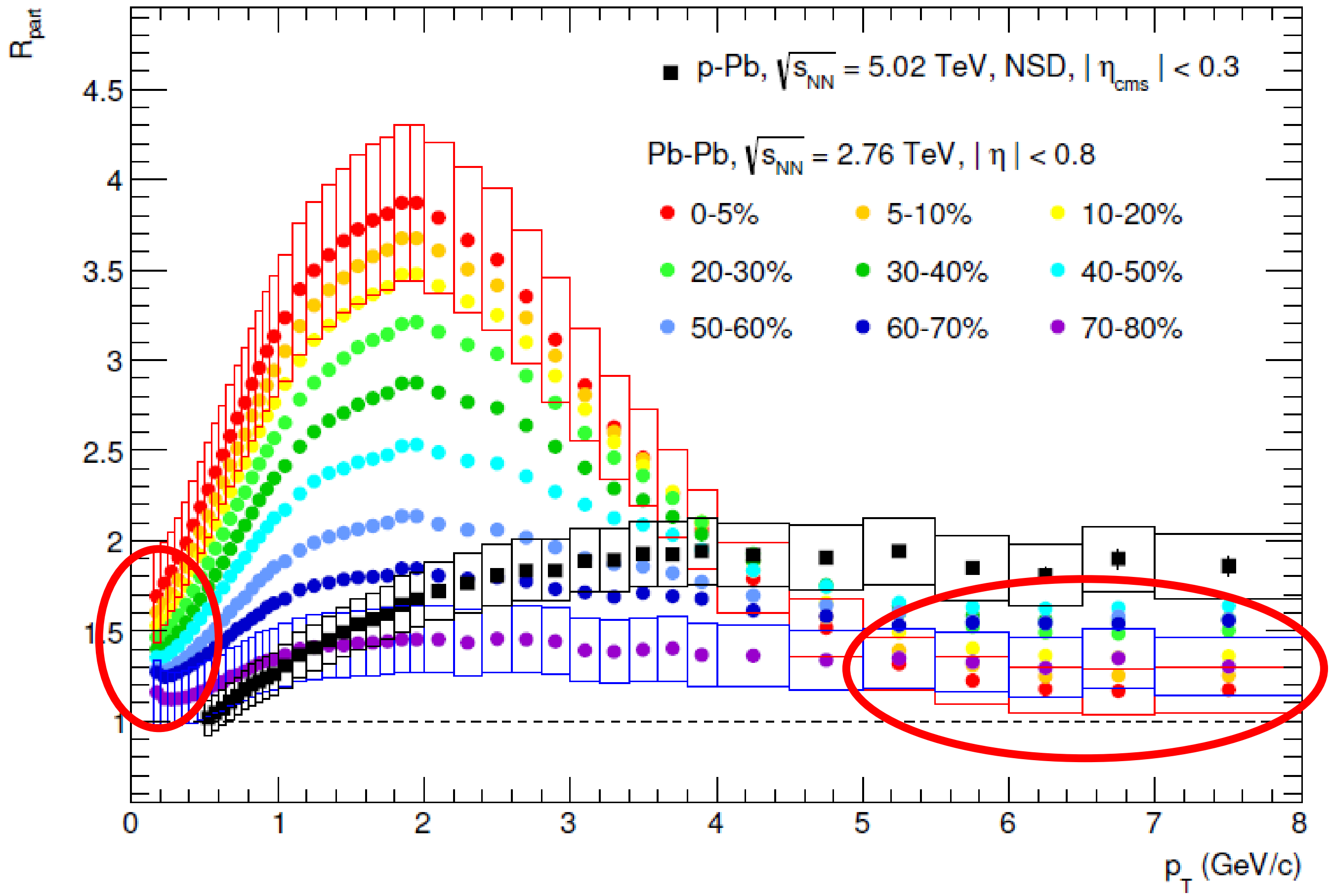
ATLAS Collaboration, JHEP09(2015)050



- CMS and ATLAS cover larger p_T
- all LHC experiments in agreement

Scaling by number of participants

$$R_{\text{part}}(p_T) = \frac{2 \cdot d^2 N_{\text{ch}}^{\text{Pb-Pb}} / d\eta dp_T}{\langle N_{\text{part}} \rangle \cdot d^2 N_{\text{ch}}^{\text{pp}} / d\eta dp_T}$$



- **approximate scaling with number of participants at low p_T and intermediate p_T (minimum of R_{AA}) observed**

Extraction of jet transport coefficient

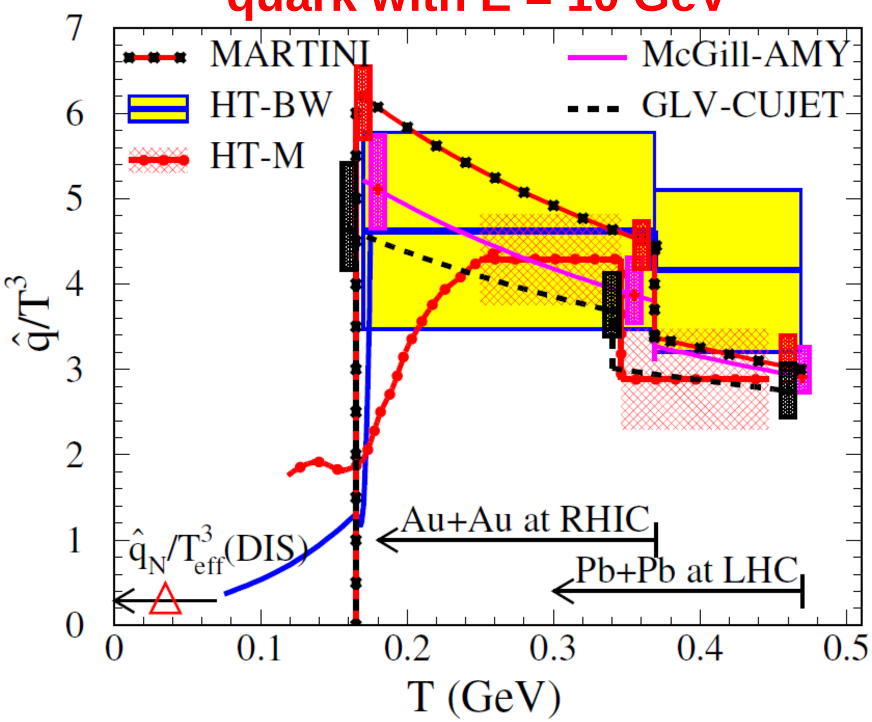
JET Collaboration using combined CMS and ALICE LHC data

5 different models with different approaches:

- **higher twist (HT-BW, HT-M)**
- **hard thermal loop (MARTINI, McGill-AMY)**
- **opacity expansion (GLV-CUJET)**

- **no fluctuations of initial condition**
- **same 2+1D and 3+1D hydro for all models**

quark with E = 10 GeV



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

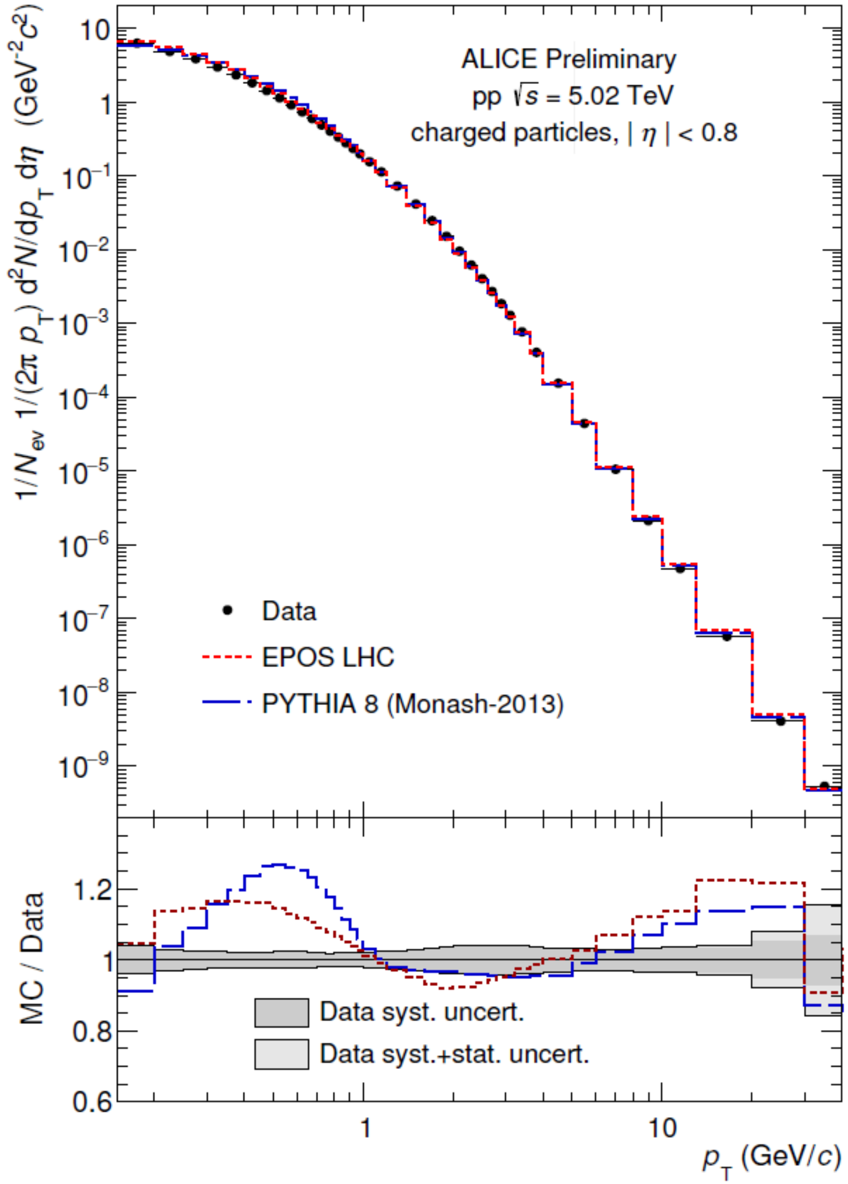
$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC.} \end{cases}$$

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

(at t_0 = 0.6 fm)

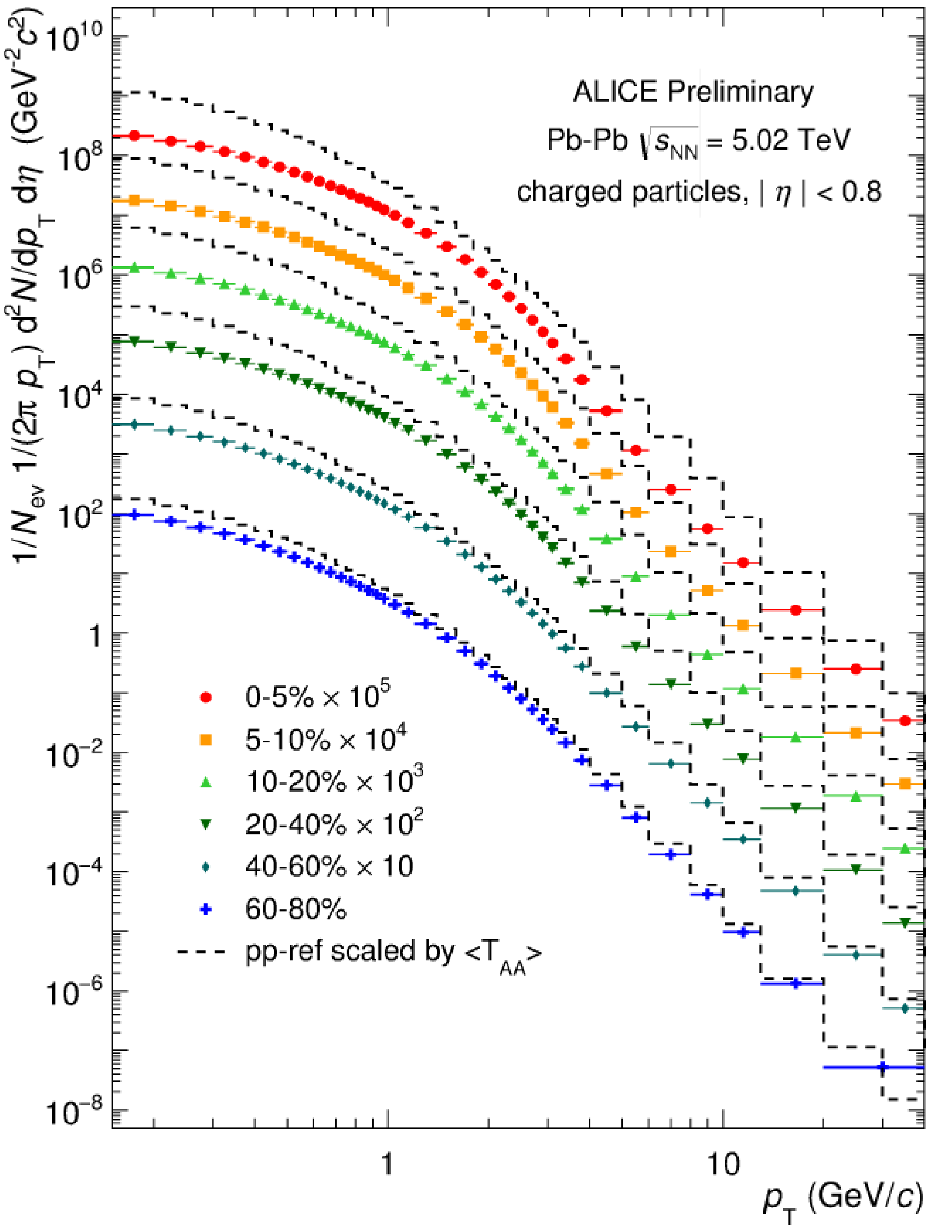
cold nuclear matter: $\hat{q}$ = 0.02 GeV²/fm

Results from run II: spectra in pp



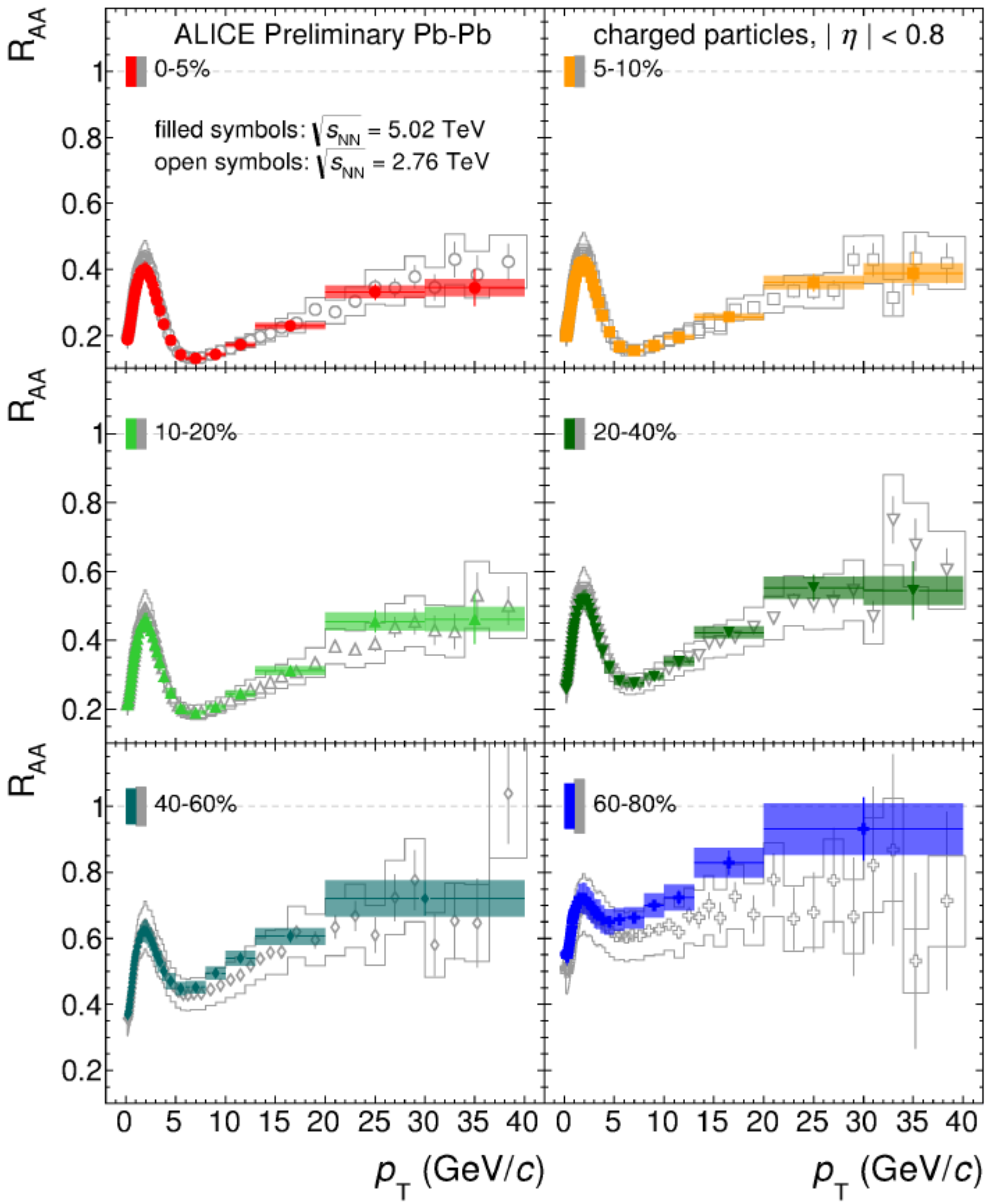
- **$25 \cdot 10^6$ events (25% of all recorded data)**
- **deviations from MC generators up to 20% (similar to pp data at other energies)**

Results from run II: spectra in Pb-Pb



- **$3.3 \cdot 10^6$ event (3% of all recorded data)**

Results from run II: R_{AA}



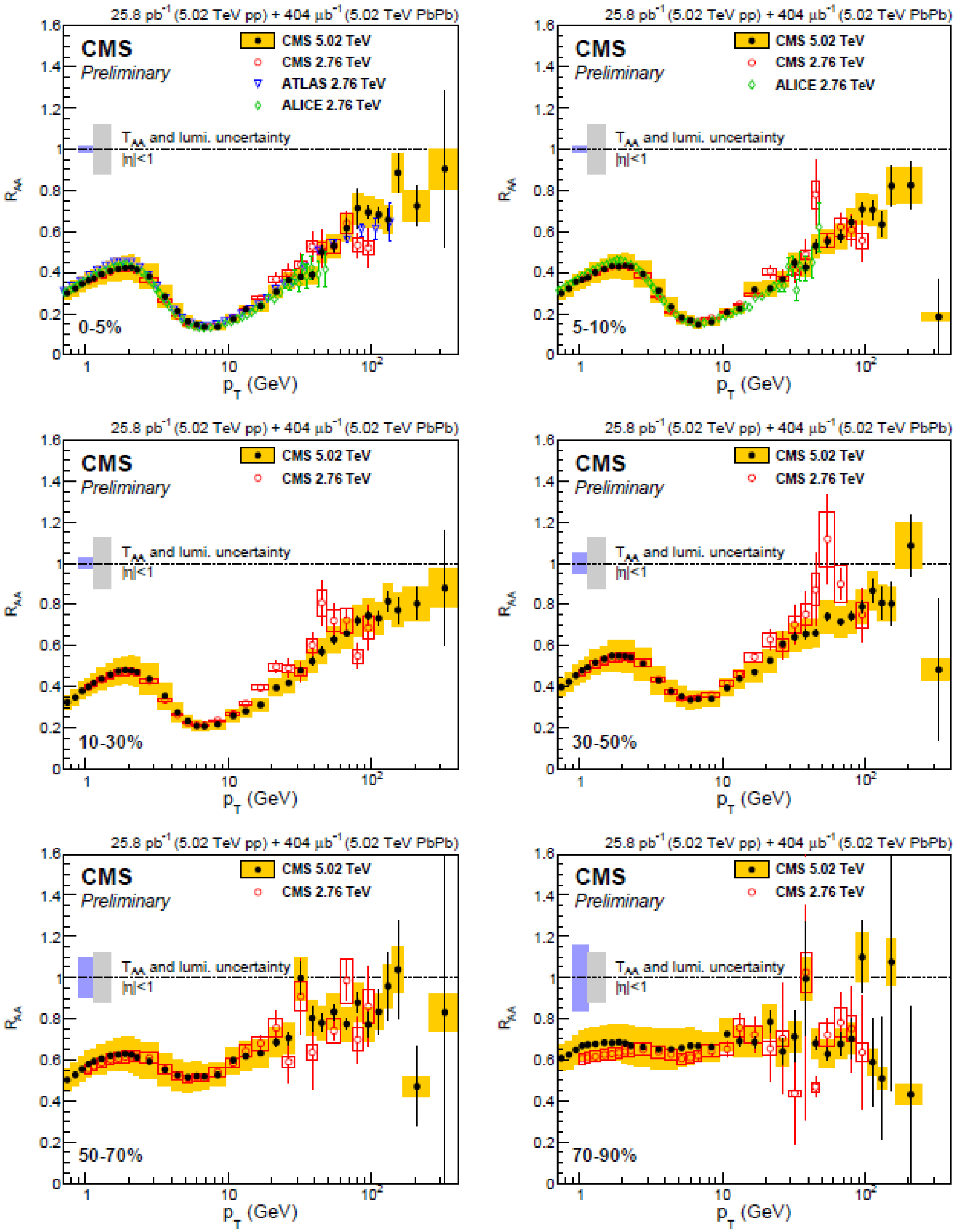
- R_{AA} very similar in 5.02 TeV and 2.76 TeV
- the spectra are different (harder at 5.02 TeV)

=> p_T shift increased

=> energy loss also increased

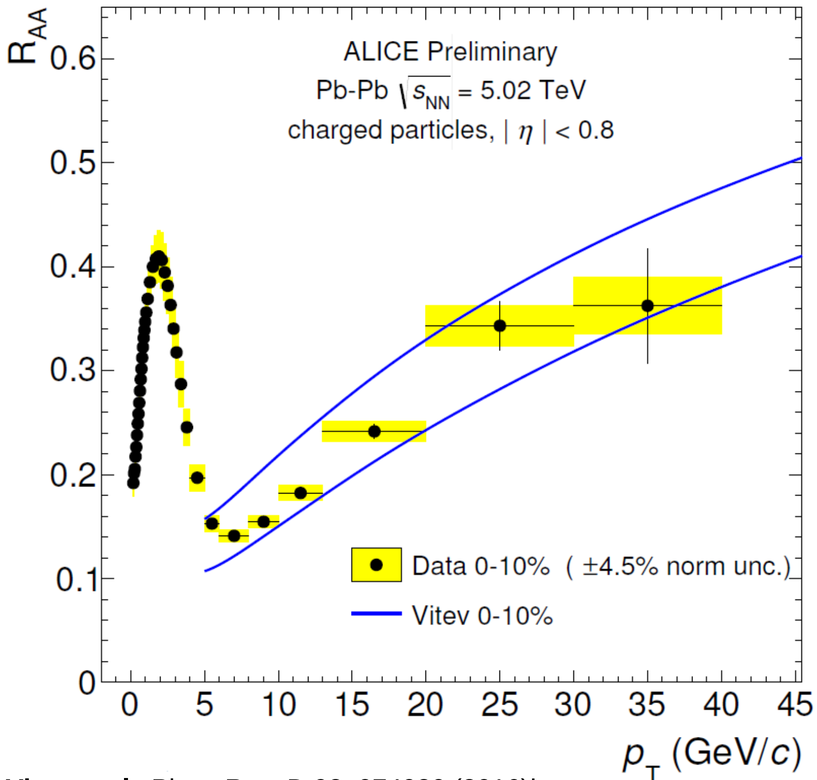
possibly larger, hotter, denser medium

CMS R_{AA} at 5.02 TeV

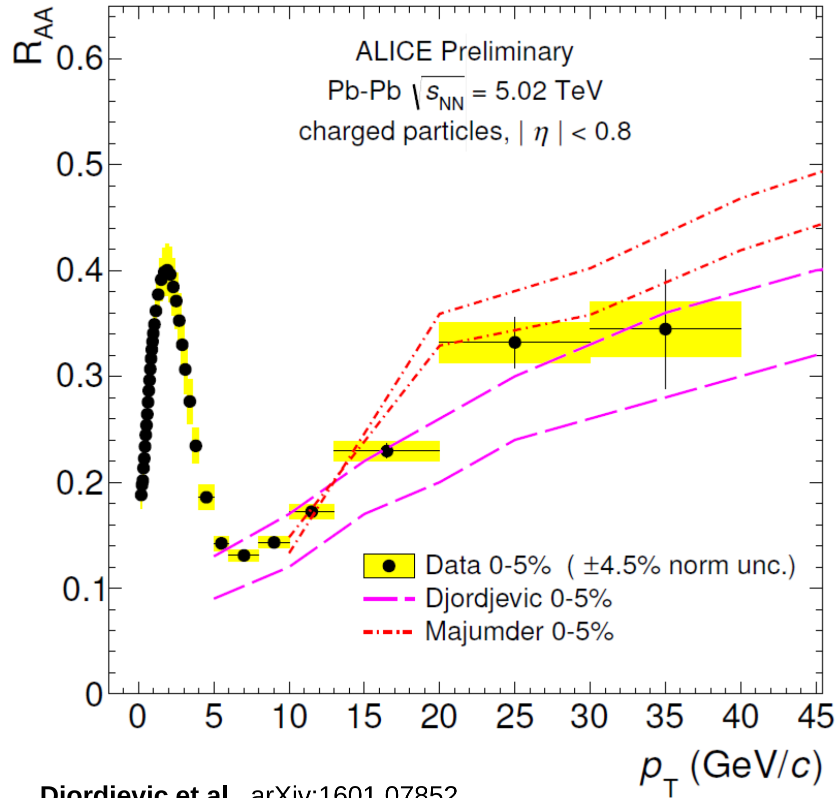


CMS Collaboration, CMS PAS HIN-15-015

Model Comparison



Vitev et al., Phys. Rev. D 93, 074030 (2016)|



Djordjevic et al., arXiv:1601.07852
Majumder et al., Phys.Rev.Lett. 109 (2012) 202301

Vitev

- opacity expansion
- radiative energy loss
- no LPM effect

Djordjevic

- opacity expansion
- radiative + elastic energy loss
- dynamic finite size medium

Majumder

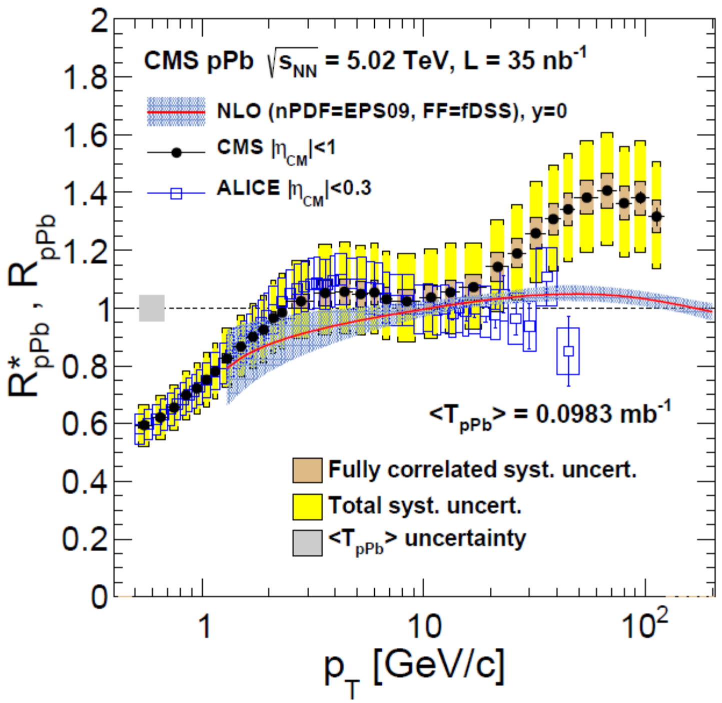
- higher twist
- radiative energy loss
- coherent multiple gluon
- in-medium splitting function

Outlook

ALICE has reduced systematic uncertainty of the measurement by factor 2

Further conclusions on energy loss models and medium properties requires

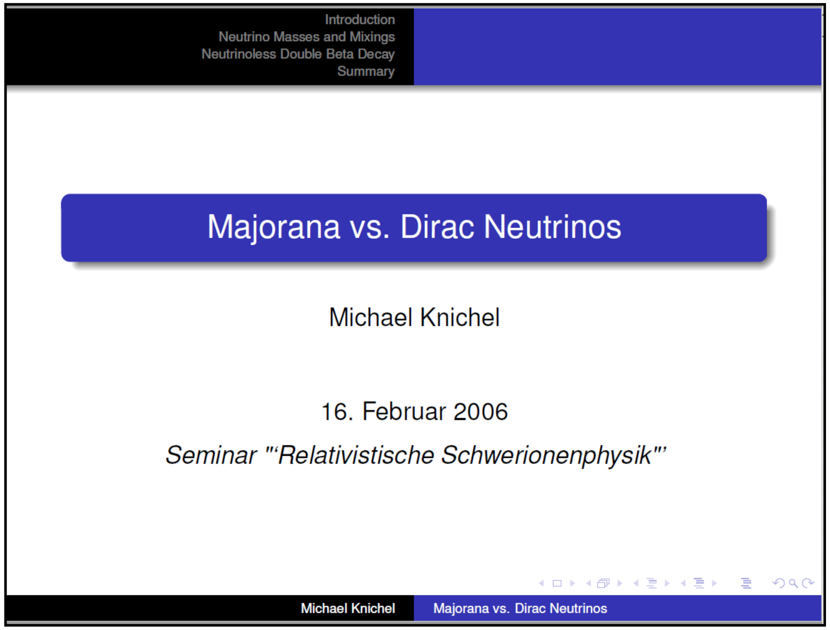
- **higher precision (data and models) for leading hadrons**
- **combination with other observables (jets, hadron-hadron correlation I_{AA}, flow at high p_T)**



CMS Collaboration, Eur.Phys.J. C75 (2015) no.5, 237

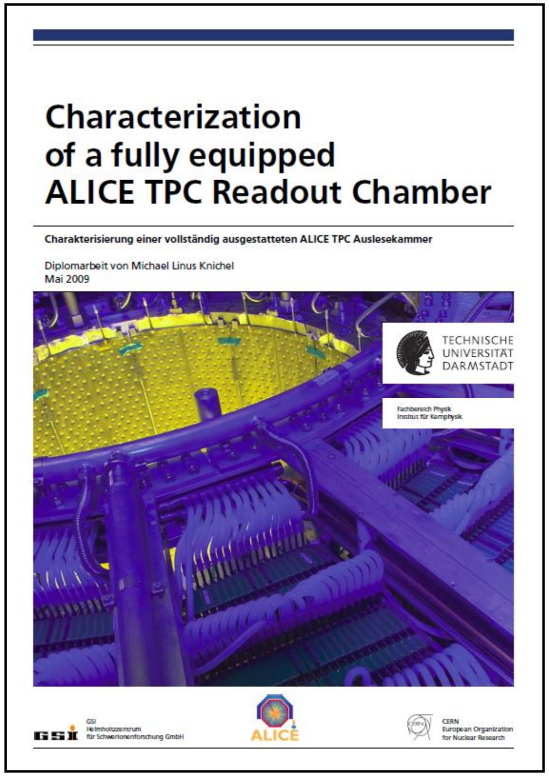
- **p-Pb results from CMS and ALICE used (different) interpolated pp references**
- **with the measurement at 5.02 TeV updated results with reduced systematic uncertainty expected**
- **ALICE has still more data at 5.02 TeV (pp and Pb-Pb) to analyze**

Happy Birthday!



2006

2009

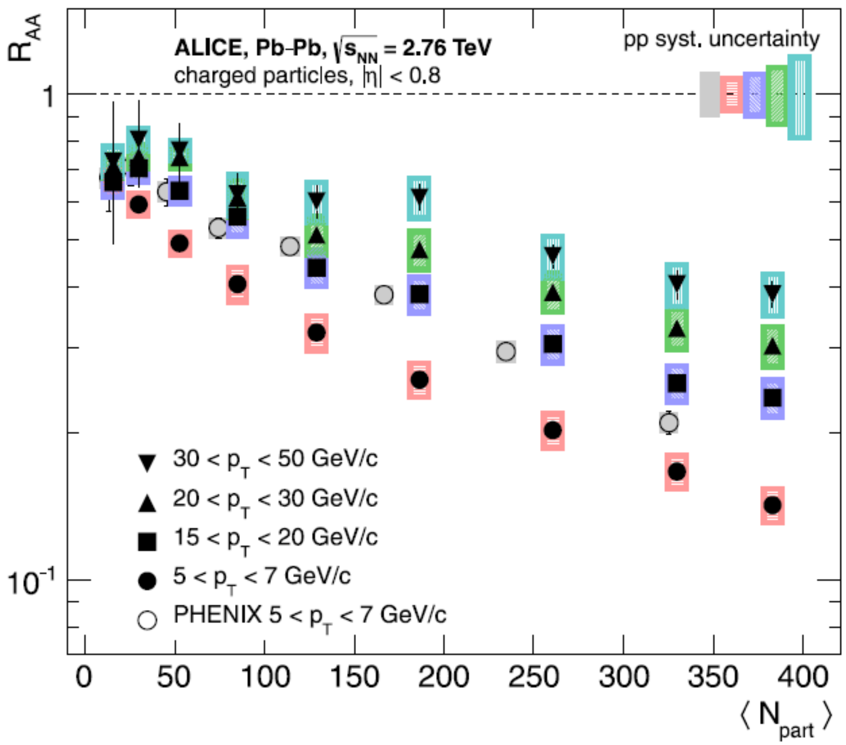


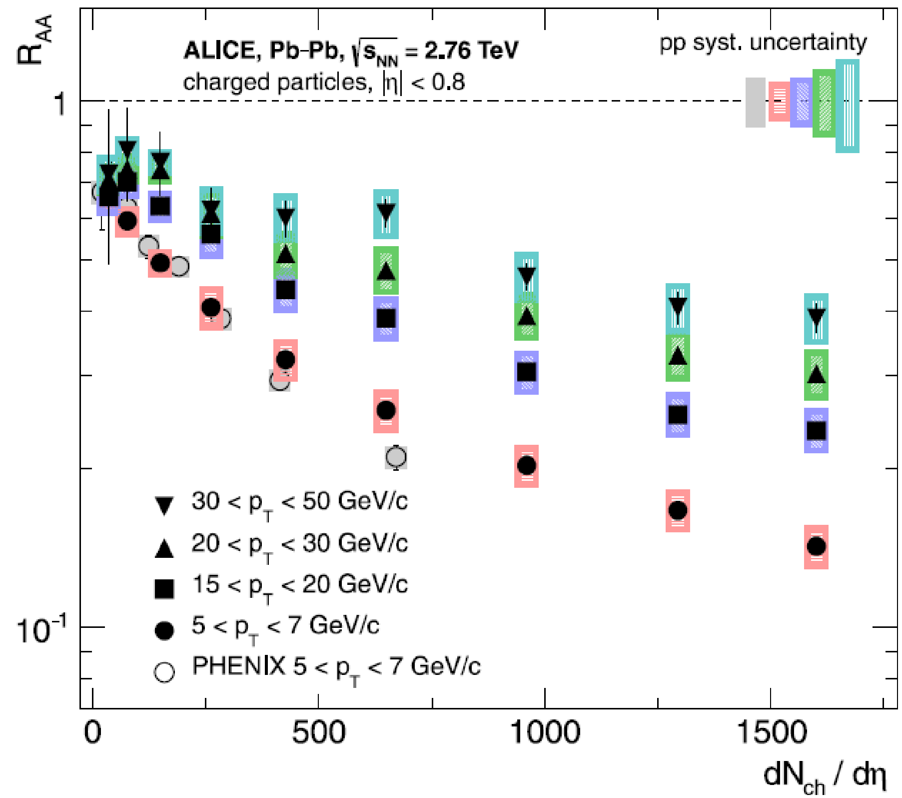
2014

2015

System size dependence of R_{AA}

- $\langle N_{part} \rangle$ corresponds to sytem size
- $dN_{ch}/d\eta$ correpsonds to energy density
- R_{AA} similiar $dN_{ch}/d\eta$ dependence at RHIC and LHC





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