Energy and system dependence of nuclear modification factors of inclusive charged particles and identified light hadrons measured in p-Pb, Xe-Xe and Pb-Pb collisions with ALICE

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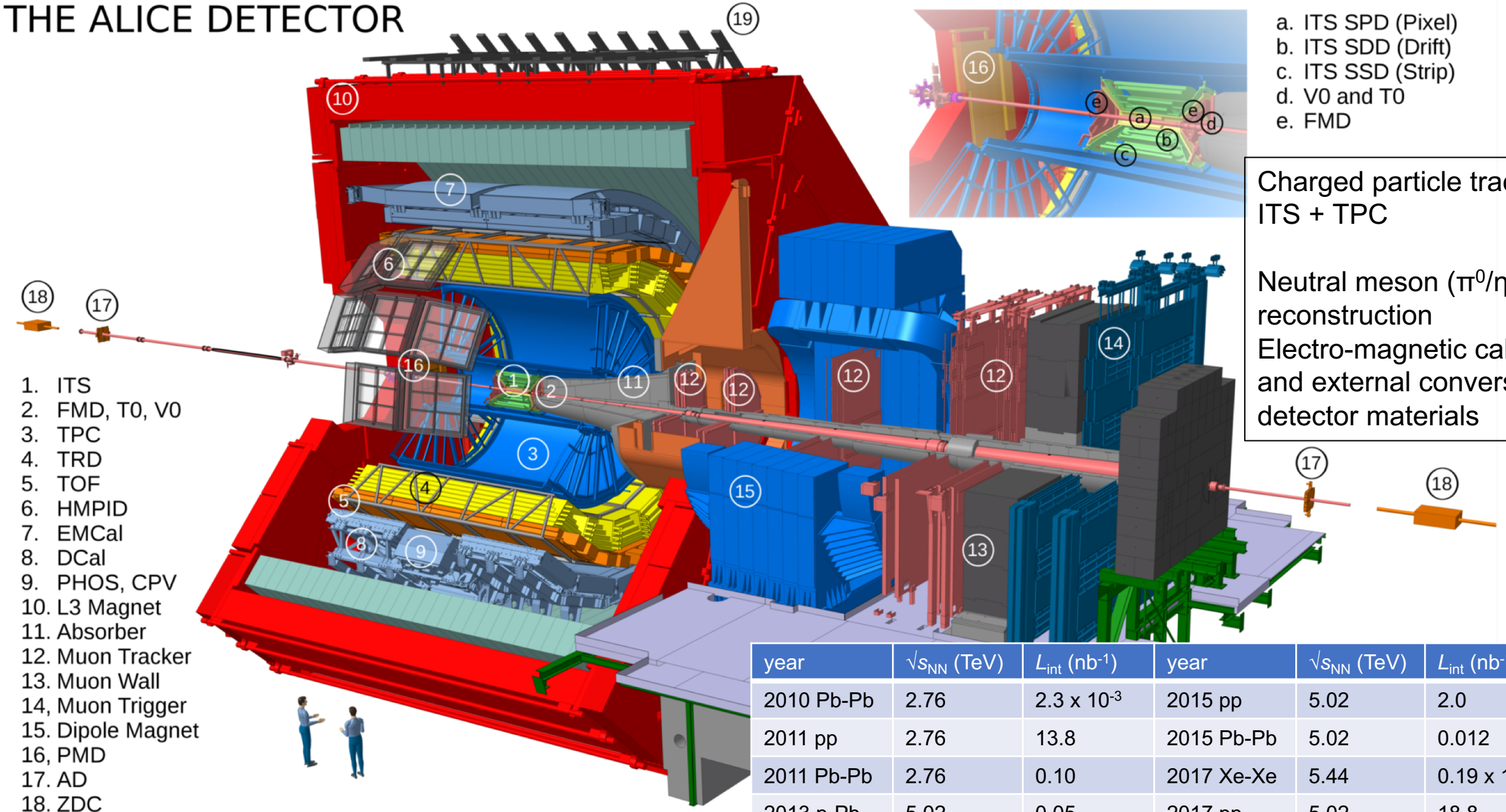
Motivation

- Partons originating from initial hard scatterings lose their energy in the hot and dense medium, which results in suppression of high p_T hadrons.
- Light flavor particles are powerful probes to measure the suppression in a wide p_T range with high precision.

- The suppression is up to a factor of 5 in central Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC.
- It reaches a factor of 7-8 in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV at LHC.

- Hadron measurements in pp are baseline for pA and AA collisions.
- Results in pA collisions allow to disentangle whether this suppression comes from initial or final state effect.
- Xe-Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV allow to study system size and geometry dependence of particle production.

THE ALICE DETECTOR



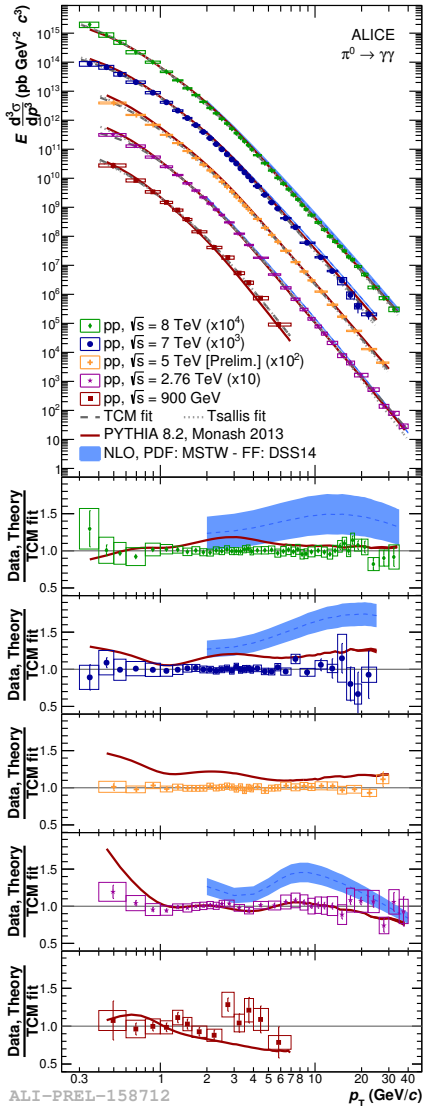
Charged particle tracking
ITS + TPC

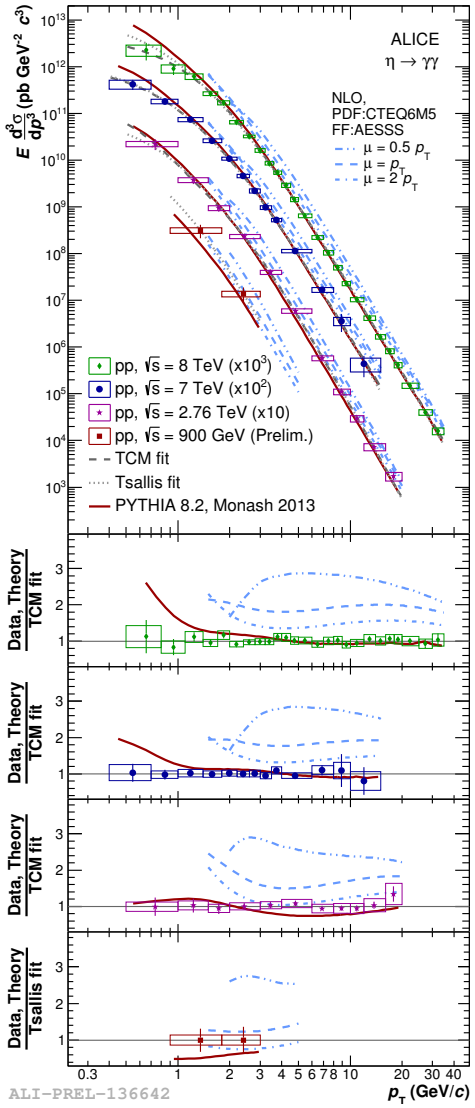
Neutral meson ($\pi^0/\eta\rightarrow\gamma\gamma$) reconstruction
Electro-magnetic calorimeters and external conversion in detector materials

year	$\sqrt{s_{NN}}$ (TeV)	L_{int} (nb^{-1})	year	$\sqrt{s_{NN}}$ (TeV)	L_{int} (nb^{-1})
2010 Pb-Pb	2.76	2.3×10^{-3}	2015 pp	5.02	2.0
2011 pp	2.76	13.8	2015 Pb-Pb	5.02	0.012
2011 Pb-Pb	2.76	0.10	2017 Xe-Xe	5.44	0.19×10^{-3}
2013 p-Pb	5.02	0.05	2017 pp	5.02	18.8
2013 pp	2.76	47.1			

(in this analysis)

Neutral meson spectra in pp at different energies



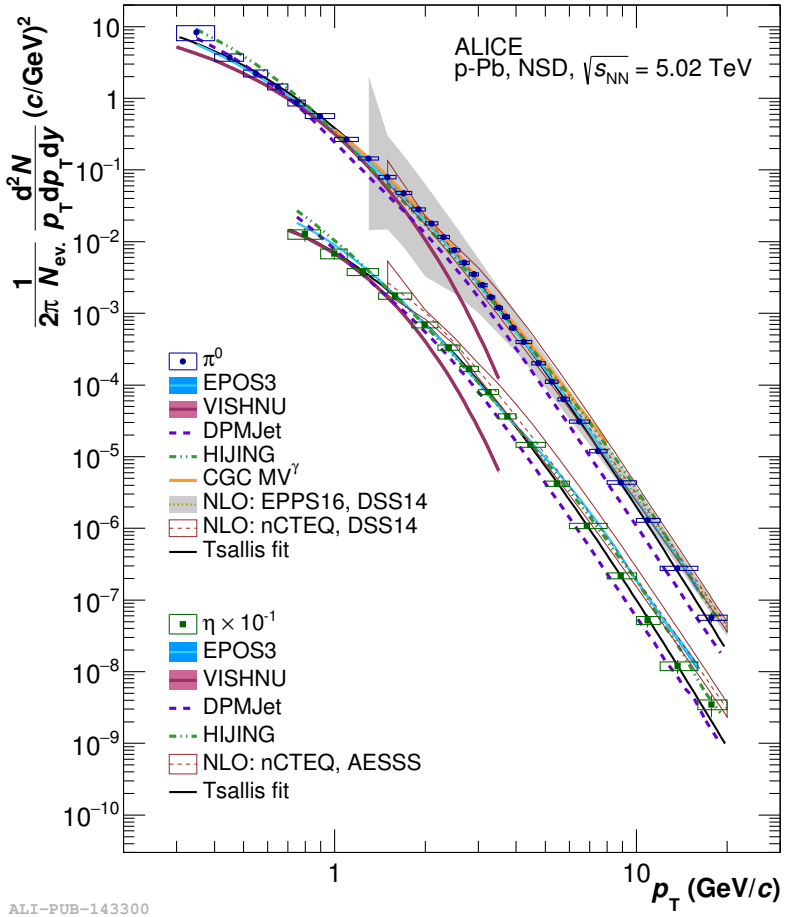


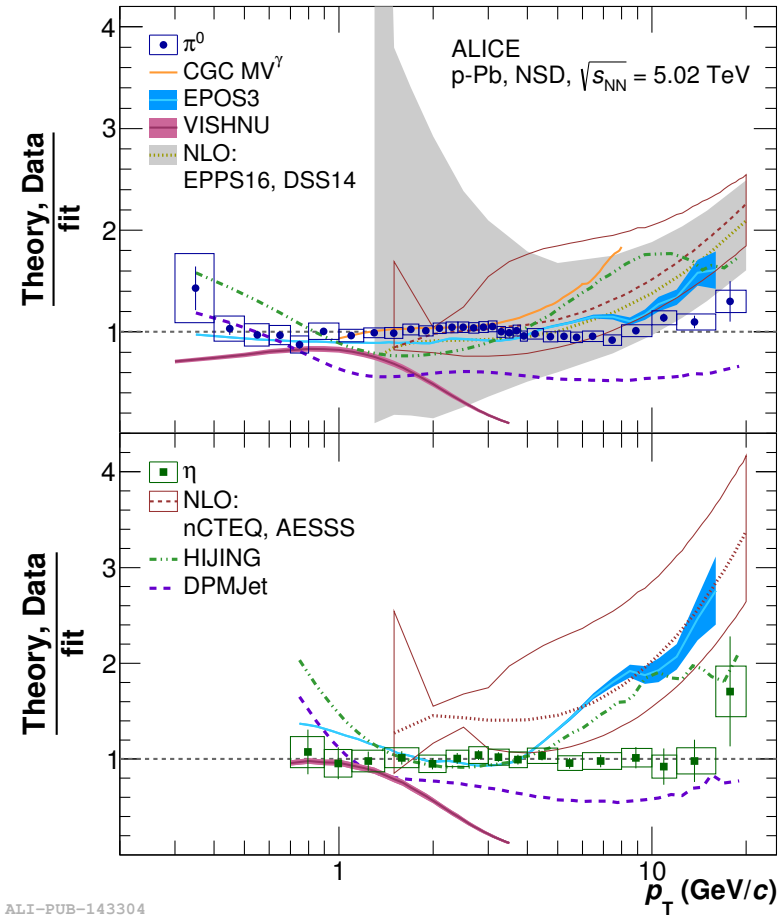
- Baseline measurements of π^0 and η meson in a wide p_T range at different energies.
- Power-law behavior at high p_T.
- PYTHIA 8.2 Monash 2013 shows agreement with data.
- NLO pQCD calculations overpredict π^0 and η cross sections.

8 TeV ALICE collaboration : Eur. Phys. J. C (2018) 78:263
2.76 TeV ALICE collaboration : Eur. Phys. J. C 77 (2017) 339
7 and 0.9 TeV ALICE collaboration : Phys. Lett. B 717 (2012) 162-172

Neutral meson spectra in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE collaboration : arXiv:1801.07051



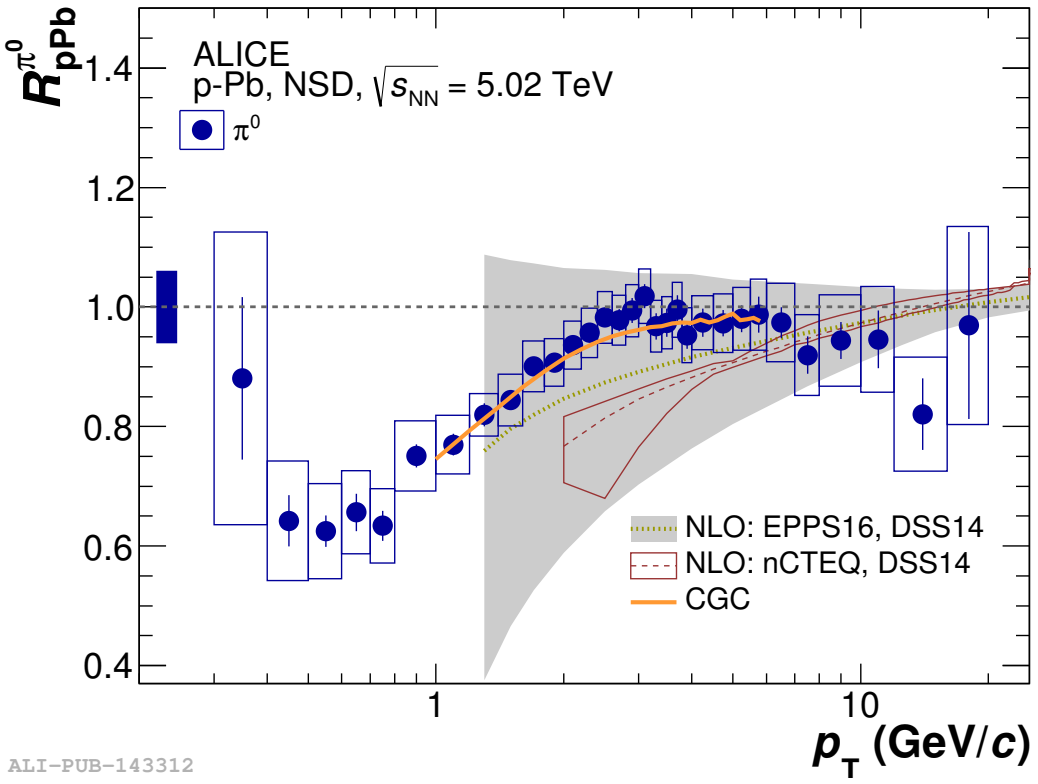


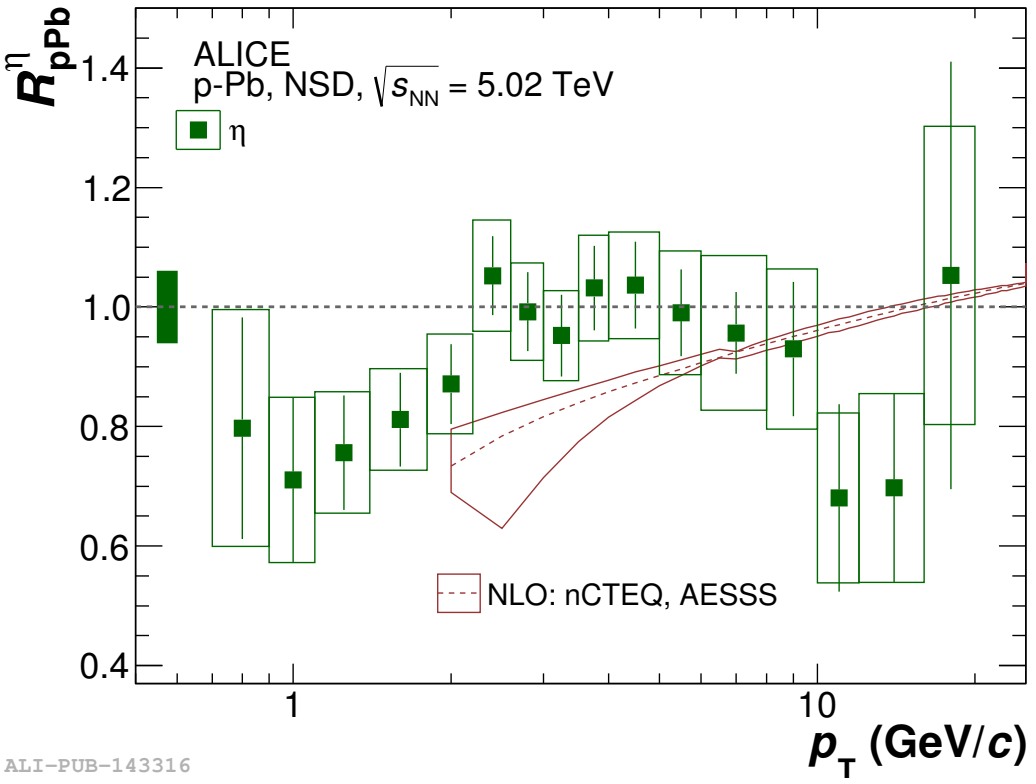
- π^0 : 0.3 < p_T < 20 GeV/c
- η : 0.7 < p_T < 20 GeV/c
- Key measurement to disentangle initial/final state effects.
- EPOS3 describes the data over the entire p_T range for π^0 and up to p_T = 4 GeV/c for η.
- Hydrodynamic model (VISHNU) agrees with the data at low p_T.
- NLO pQCD calculations describe the π^0 spectrum, but fail to describe the high p_T region for η.

EPOS3 : Phys. Rev. C 89, 064903 (2014), K.Werner et al.
VISHNU : Phys. Rev. C 95, 014906 (2017), C.Shen et al.
CGC : Phys. Rev. D 88, 114020 (2013), T.Lappi et al.

R_{pA} of neutral mesons and comparison with theoretical models

ALICE collaboration : arXiv:1801.07051





- The pp reference at $\sqrt{s}$ = 5.02 TeV is obtained by the interpolation of the measured spectra at $\sqrt{s}$ = 2.76/7/8 TeV.

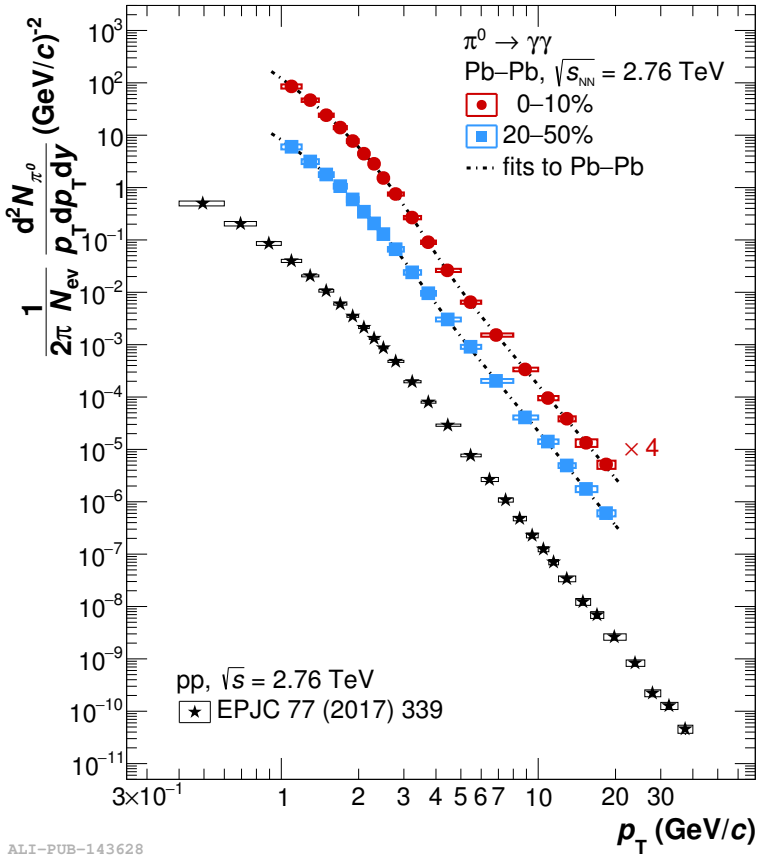
$$R_{pA}(p_T) = \frac{1}{\langle T_{pA} \rangle} \frac{dN_{pA}/dp_T}{d\sigma_{pp}/dp_T}$$

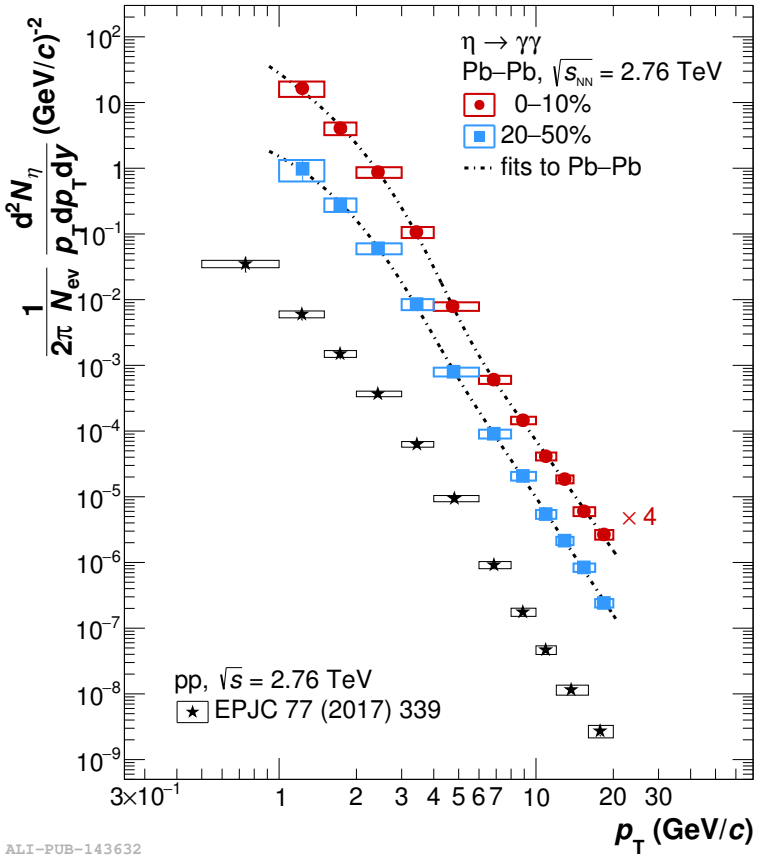
- R_{pPb} is consistent with unity at p_T > 2 GeV/c for π^0 and η mesons.
- Agreement with the measured R_{pPb} and CGC predictions within uncertainties.

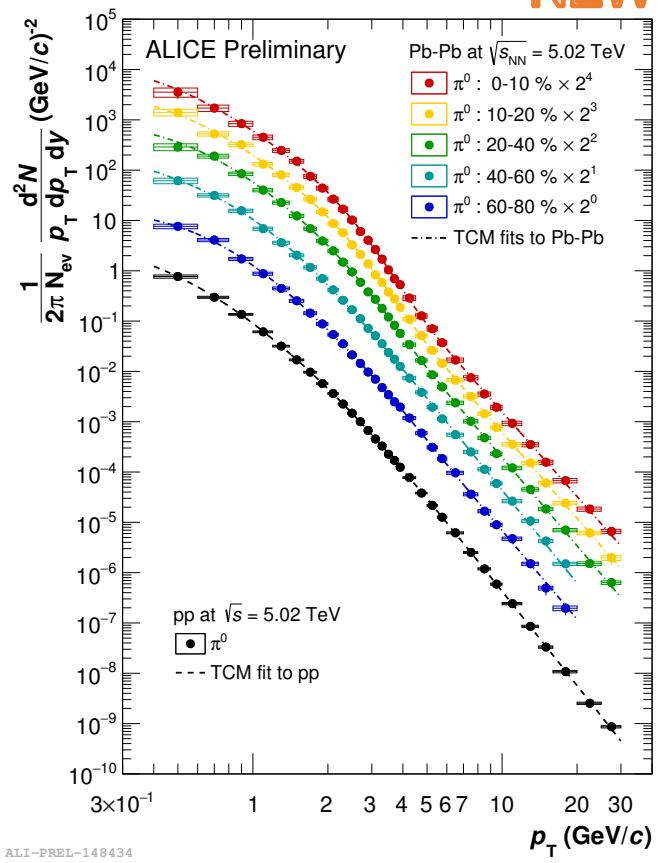
Neutral meson spectra in Pb-Pb at 2.76 and 5.02 TeV

ALICE collaboration : arXiv:1803.05490 (Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV in 2011)

NEW ALICE

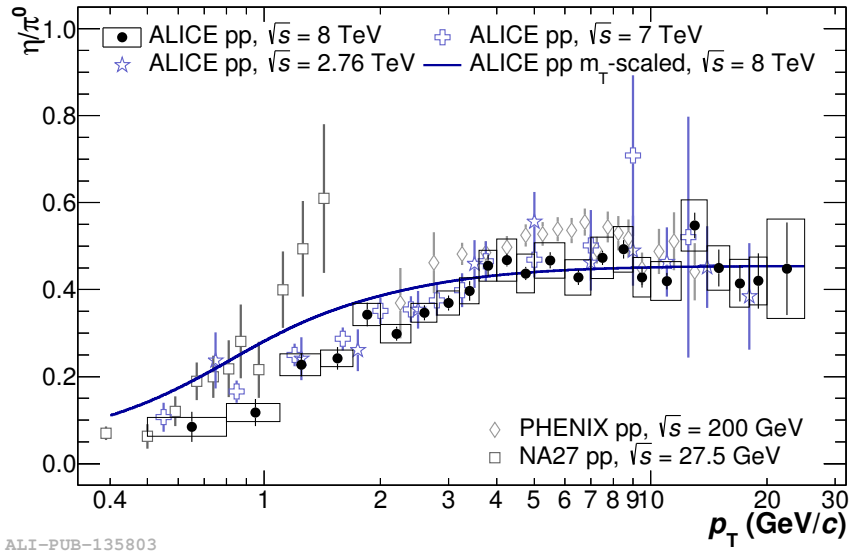


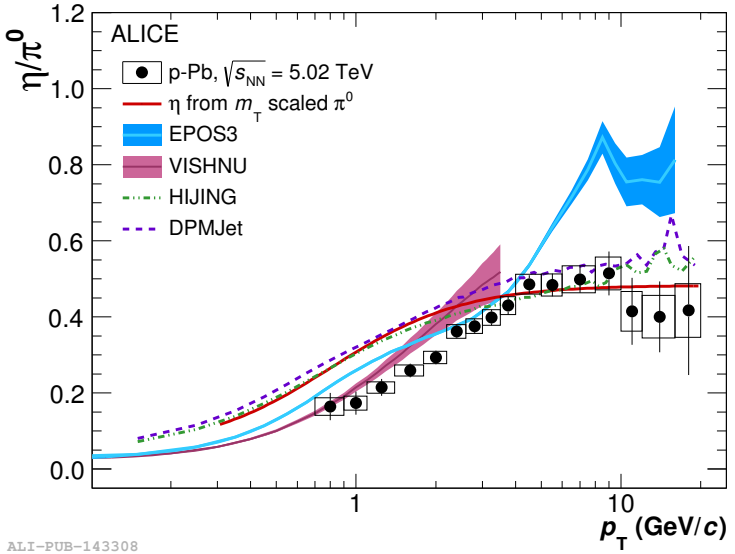


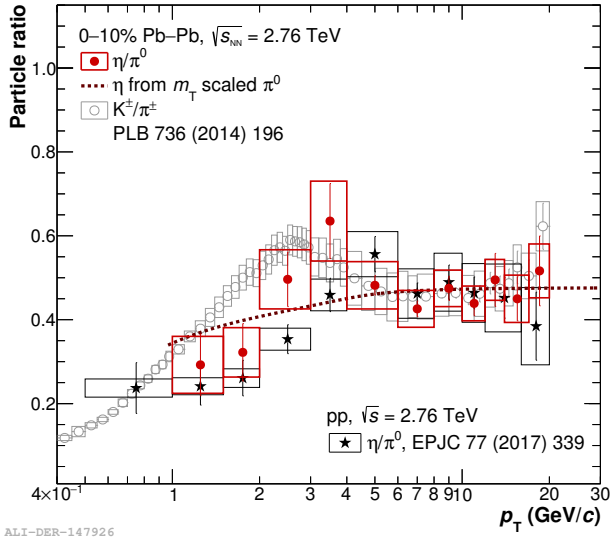


- π^0 and η : 1 < p_T < 20 GeV/c in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV with centrality triggers.
- π^0 : 0.4 < p_T < 30 GeV/c in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV.

η/π^0 ratio and m_T scaling at different energies and systems





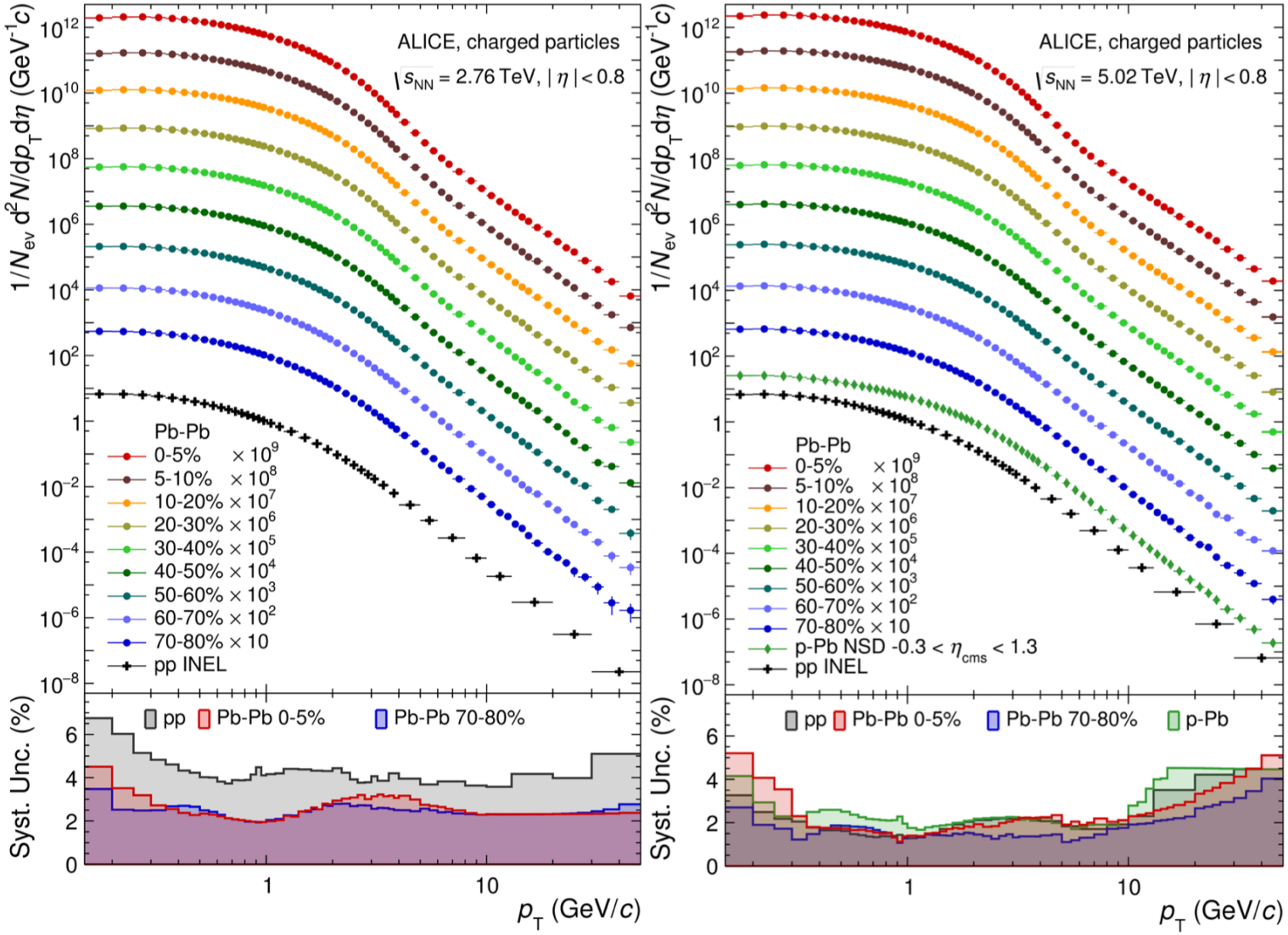


- In pp and p-Pb, a universal shape, independent of collision energy.
- In Pb-Pb, a hint of deviations from behavior in pp is observed at intermediate p_T.
- η/π^0 ratio reaches ~0.48 at high p_T.
- m_T scaling overestimates η/π^0 ratio at low p_T.

→m_T scaling violation at low p_T emphasizes importance of precise measurements of all neutral mesons which is needed for cocktail simulations used in several measurements. (direct photons, di-leptons e.t.c.)

Charged particles spectra in Pb-Pb at 2.76 and 5.02 TeV

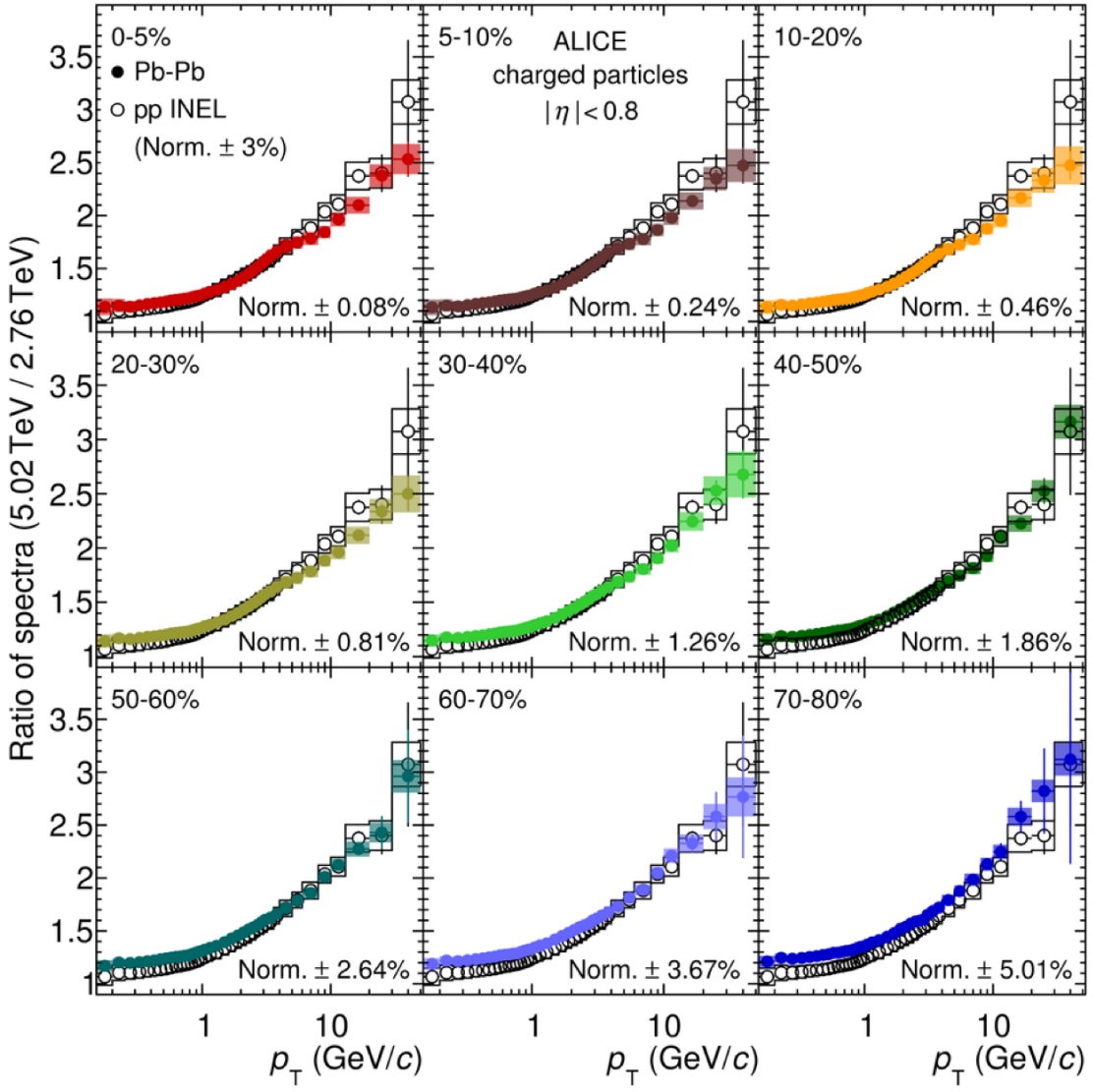
ALICE collaboration : arXiv:1802.09145



- $0.15 < p_T < 50$ GeV/c at mid-rapidity.
- Thanks to better understanding of tracking efficiency correction, systematic uncertainties are reduced.

Ratio of charged particles spectra 5.02/2.76 TeV

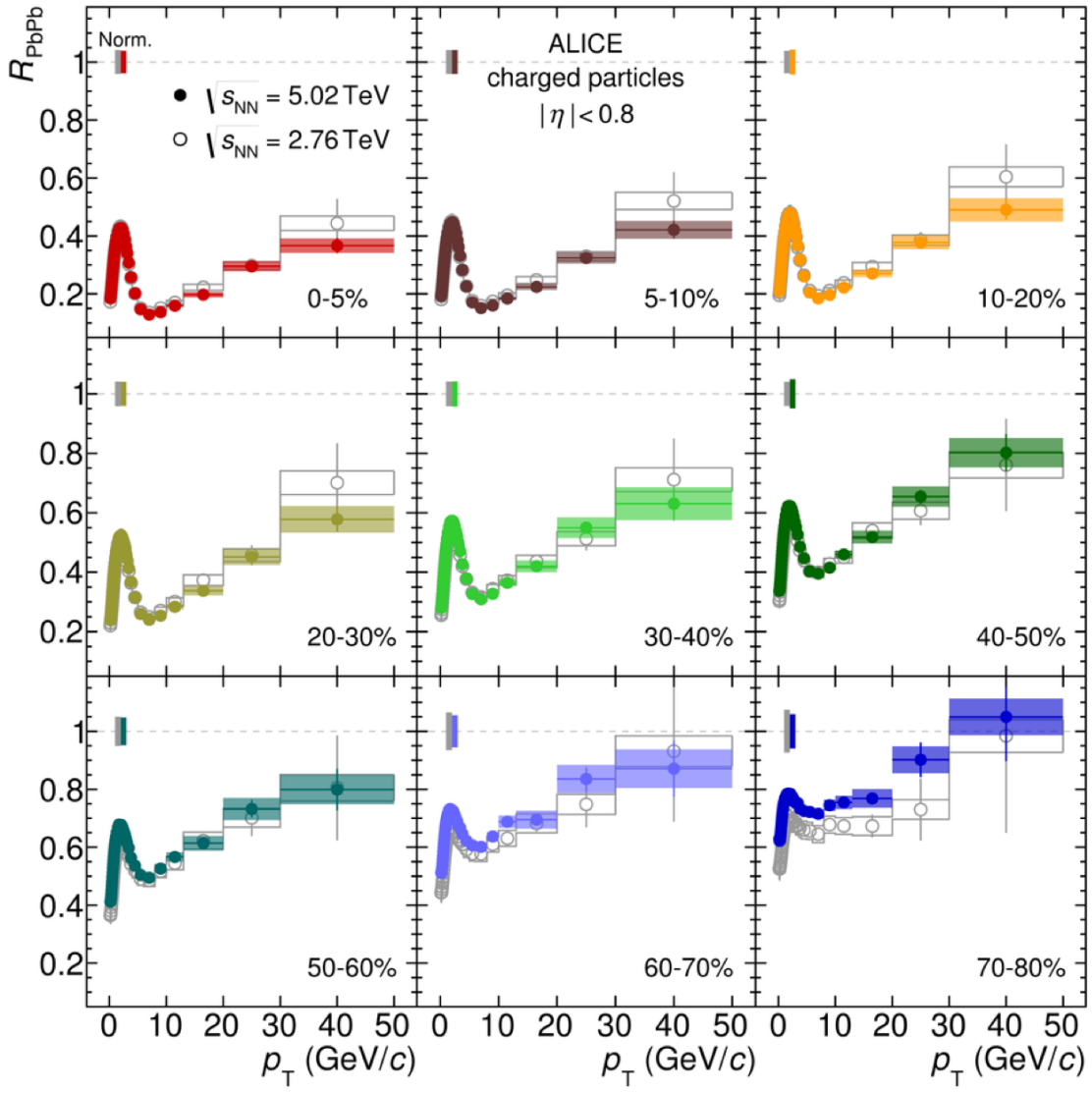
ALICE collaboration : arXiv:1802.09145



- p_T spectra at higher collision energy are significantly harder for both Pb-Pb and pp collisions.
- Similar energy dependence of the shape of the ratio in peripheral Pb-Pb and in pp collisions.
- Smaller ratio towards central Pb-Pb collisions.

R_{AA} of charged particles at 2.76 and 5.02 TeV

ALICE collaboration : arXiv:1802.09145



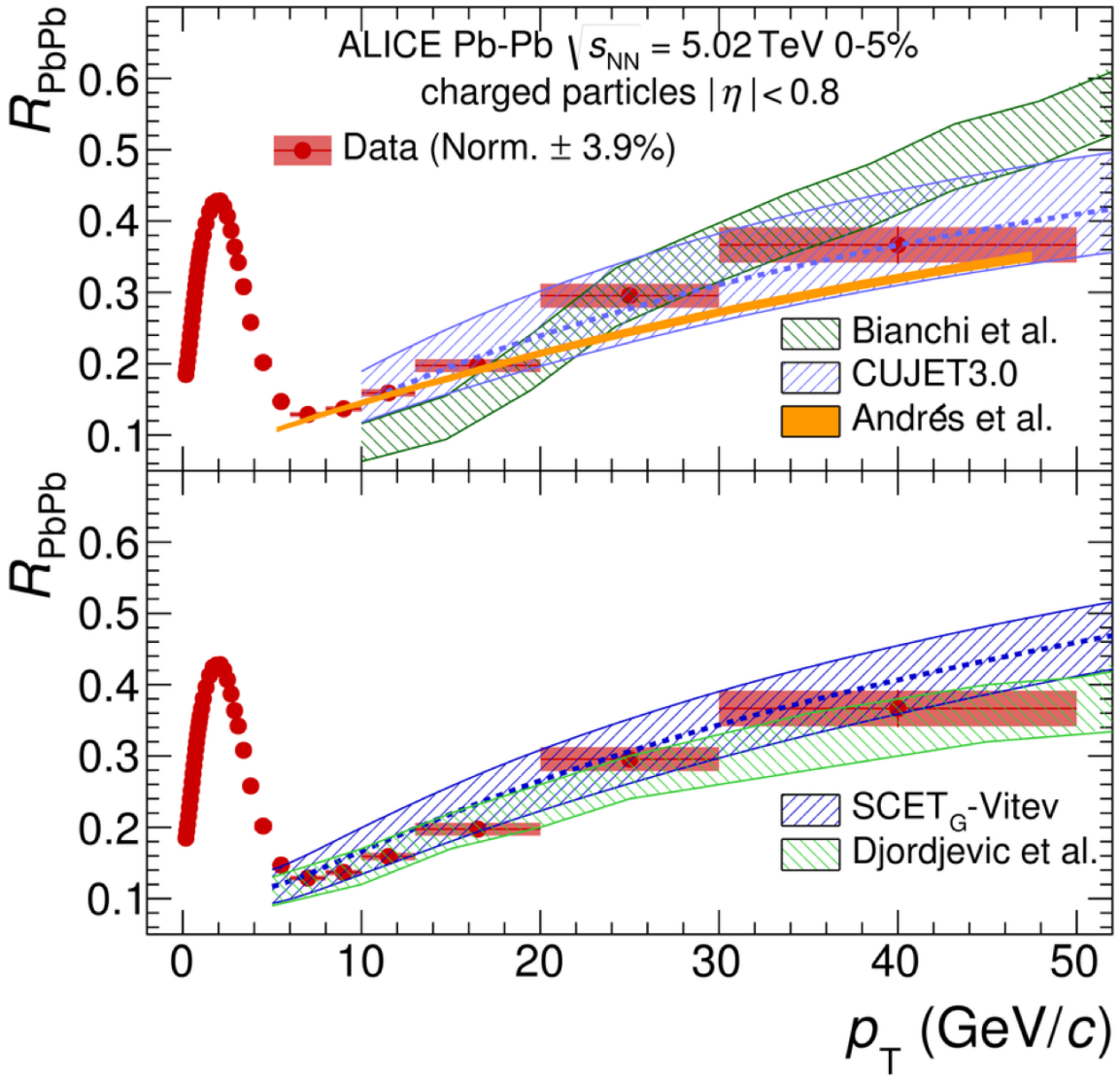
- Strong centrality dependence.
- Similar R_{AA} for the two collision energies, but harder p_T slope at higher collision energy.

→ Larger energy loss at higher collision energy.

- Strongest suppression by a factor of about 8 at p_T = 6-7 GeV/c in the most central collisions (0-5%).
- The suppression is about 30% for the intermediate p_T and reaches unity for the highest p_T bin in peripheral collisions (70-80%).

Comparison with theoretical models

ALICE collaboration : arXiv:1802.09145



- All models presented here describe the main features of the data.
- The models by Vitev et al., Djordjevic et al. and CUJET 3.0 give quantitatively good description of the data.

Djordjevic et al. : Phys. Rev. C 94, 044908 (2016)
SCET$_G$-Vitev : Phys. Rev. D 93, 074030 (2016)
Andrés et al. : Eur. Phys. J. C76 (2016) 475
Bianchi et al. : arXiv:1702.00481
CUJET 3.0 : Chin. Phys. Lett. 32 (2015) 092501, JHEP 02 (2016) 169

Comparison of π^0 R_{AA} at 2.76 and 5.02 TeV

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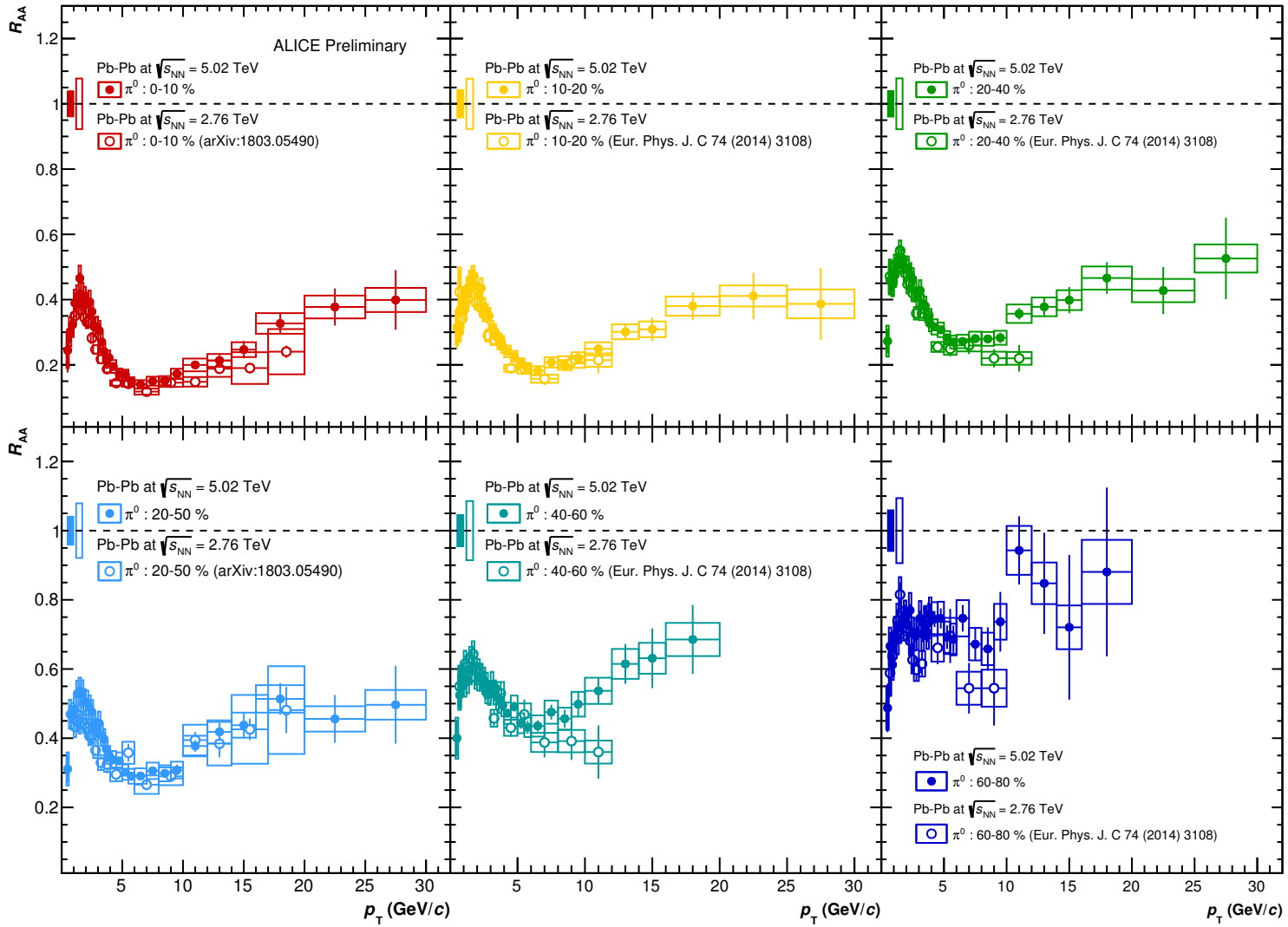

ALI-PREL-148488

- Well defined fragmentation function for an identified hadron, compared to inclusive charged particles.
- Strong centrality dependence.
- Similar R_{AA} for the two collision energies.

2010 data
ALICE collaboration :
Eur. Phys. J. C (2014) 74:3108

2011 data
ALICE collaboration :
arXiv:1803.05490

R_{AA} of π^0 with theoretical models

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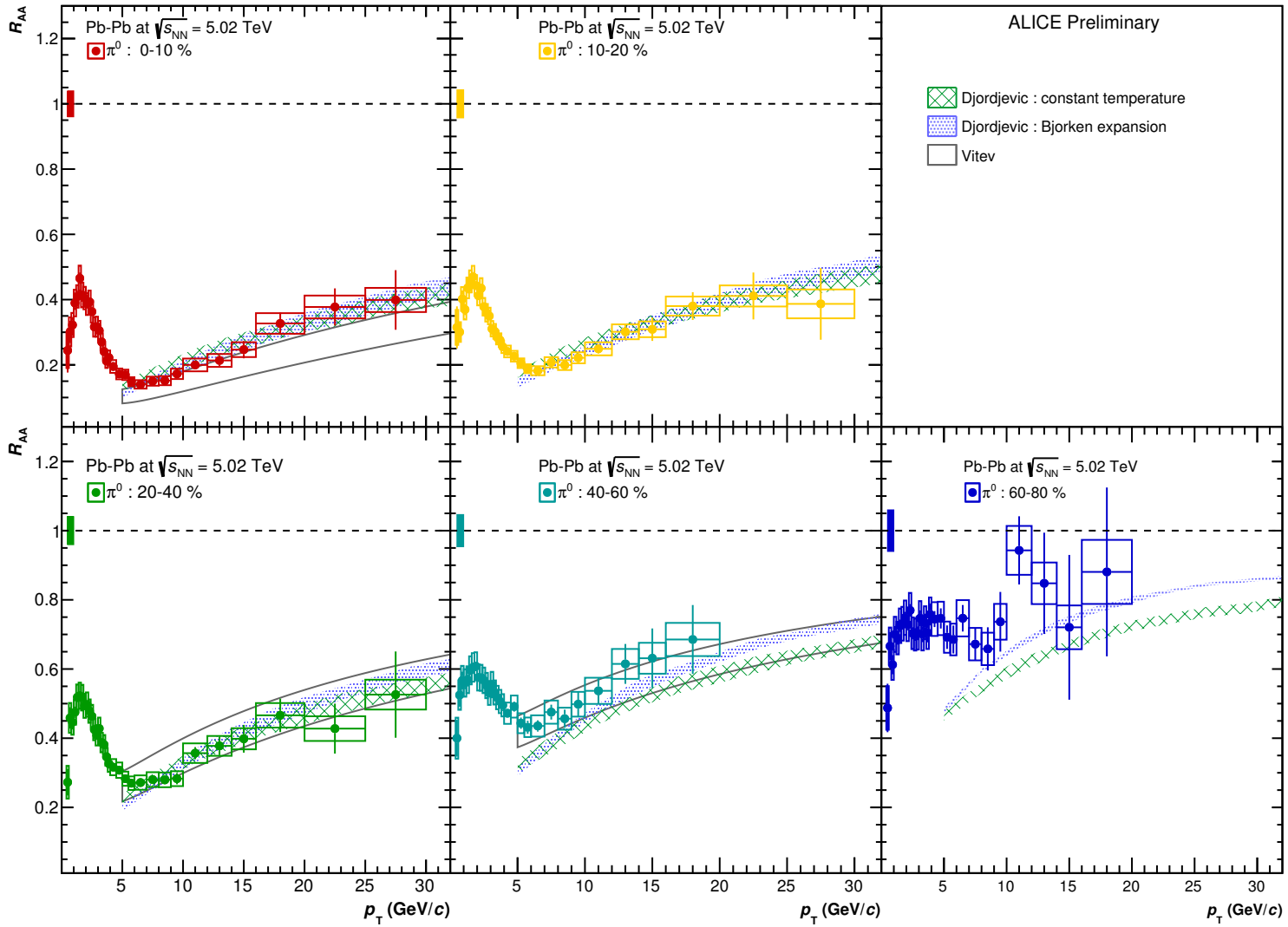


ALI-PREL-148492

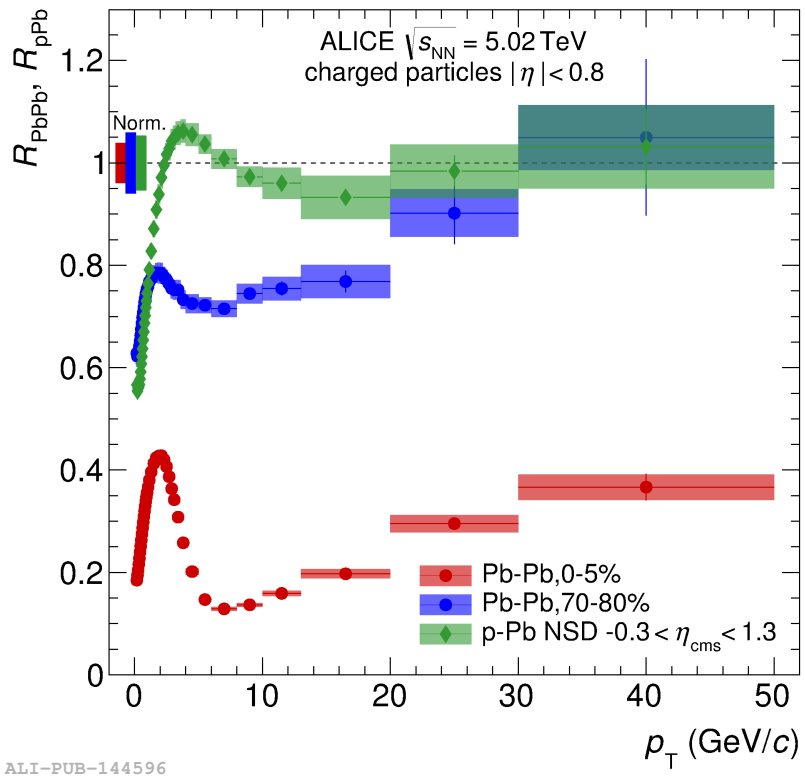
- The predictions by both Djordjevic et al. and Vitev et al. describe the data in all centrality classes.

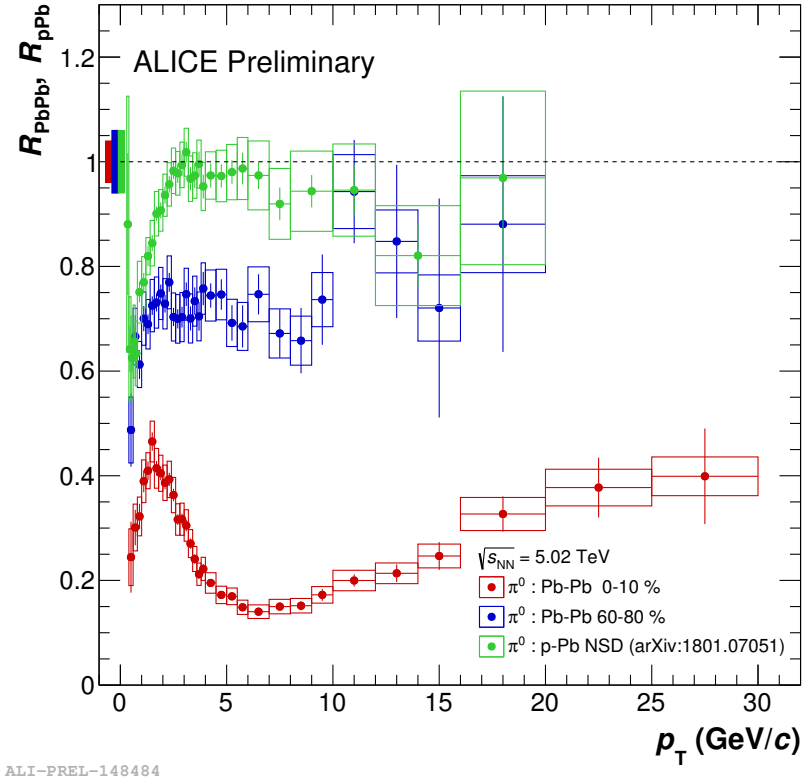
Djordjevic et al. :
Phys. Rev. C 94, 044908 (2016)
arXiv:1805.03494:
Energy loss in evolving finite-size QGP

Vitev et al.: Phys. Rev. D 93, 074030 (2016): Soft-Collinear effective theory for jet propagation in matter.

R_{AA} and R_{pA} of charged particles and π^0

ALICE collaboration : arXiv:1802.09145





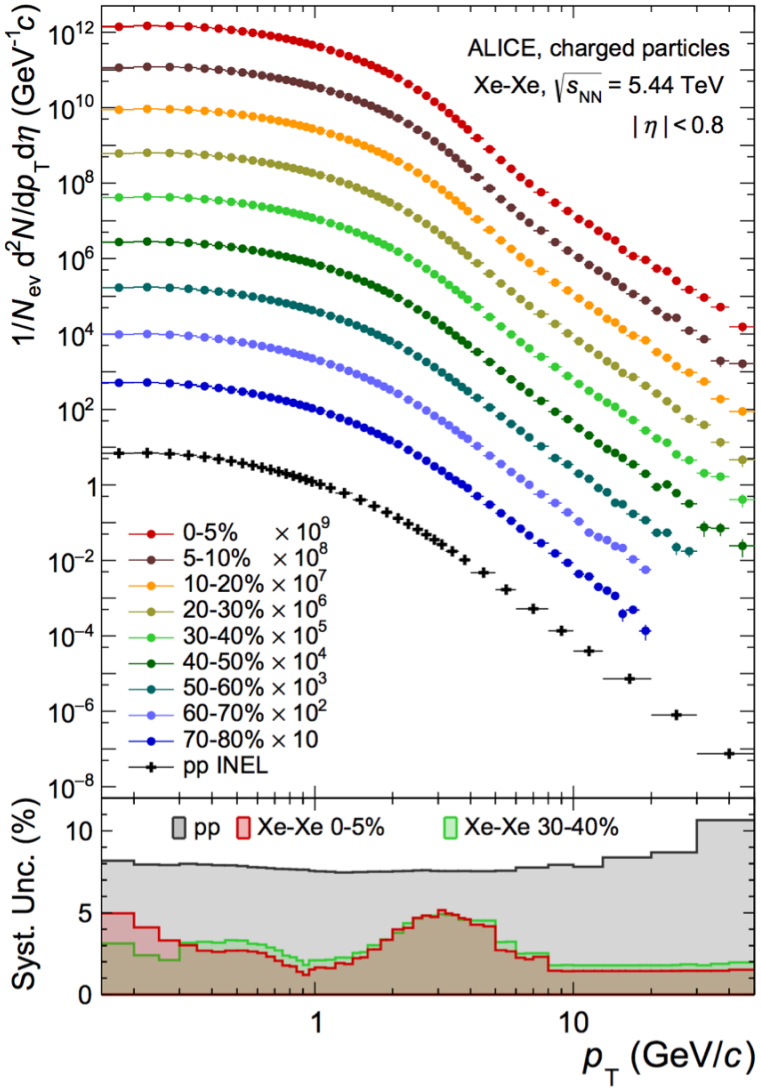
- R_{pPb} exhibits a maximum for $2 < p_T < 6$ GeV/c (Cronin peak).
- R_{pPb} is consistent with unity at high p_T.

→This demonstrates that the strong suppression observed in central Pb-Pb collisions is related to the formation of hot and dense QCD matter.

Charged particles spectra in ^{129}Xe-^{129}Xe at 5.44 TeV

NEW

arXiv:1805.04399



- The pp reference at $\sqrt{s}$ = 5.44 TeV is obtained by the interpolation of the measured spectra at $\sqrt{s}$ = 5.02 and 7 TeV.
- The systematic uncertainty of the pp reference spectrum is dominated by the interpolation uncertainty.
- Necessary for systematic study of system size and geometry dependence, complementary for centrality dependence in ^{208}Pb-^{208}Pb.

R_{AA} in Xe-Xe at 5.44 TeV

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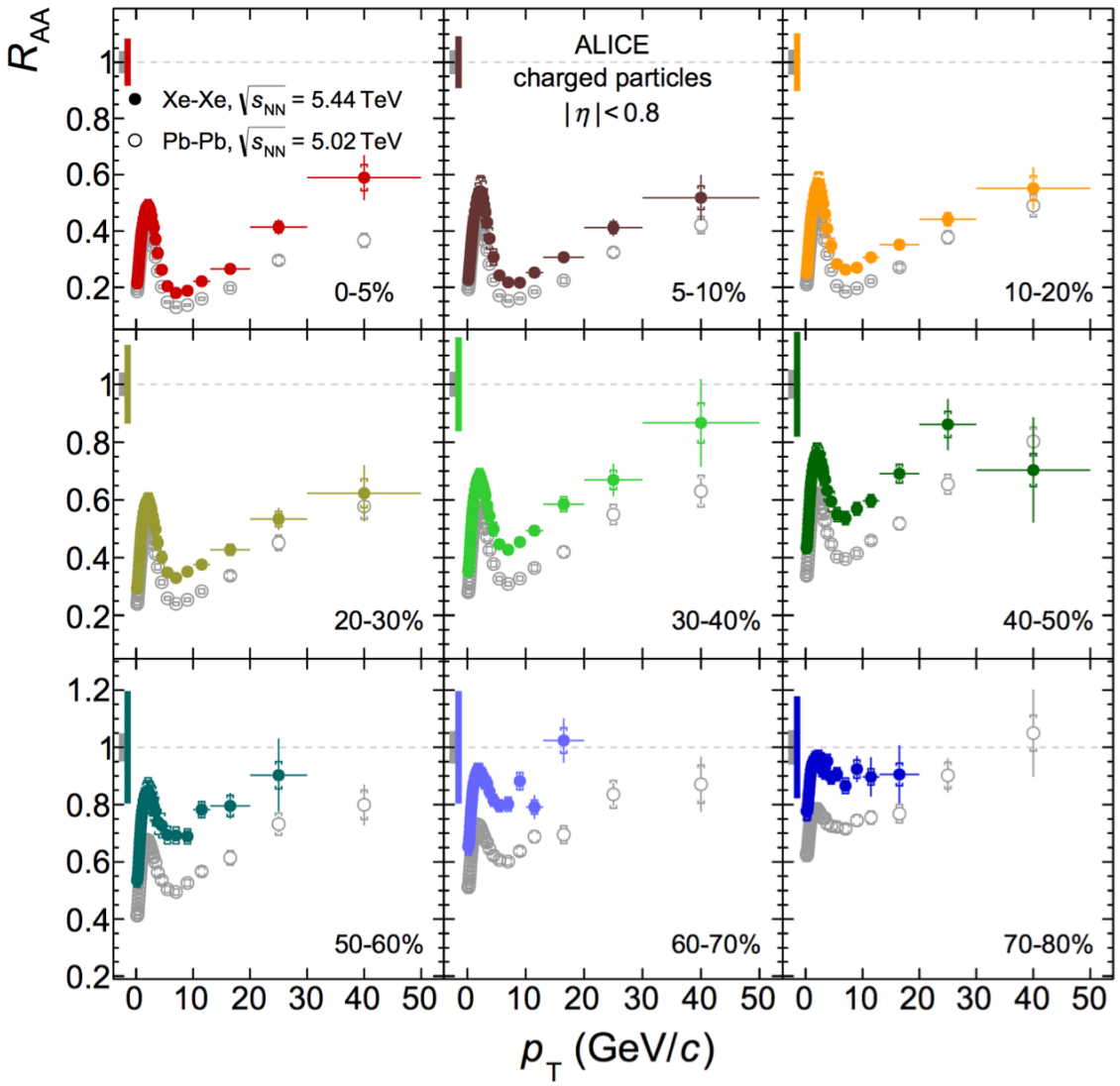

- Strong centrality dependence.
- A minimum around p_T = 6-7 GeV/c and an almost linear rise at higher p_T.
- The strongest suppression by a factor of about 6 at the minimum in the most central collisions (0-5%).
- R_{AA} = 0.6 at the highest p_T bin (30-50 GeV/c) in the most central collisions.

arXiv:1805.04399

ALICE

R_{AA} in Xe-Xe and Pb-Pb vs. p_T at similar $dN_{ch}/d\eta$

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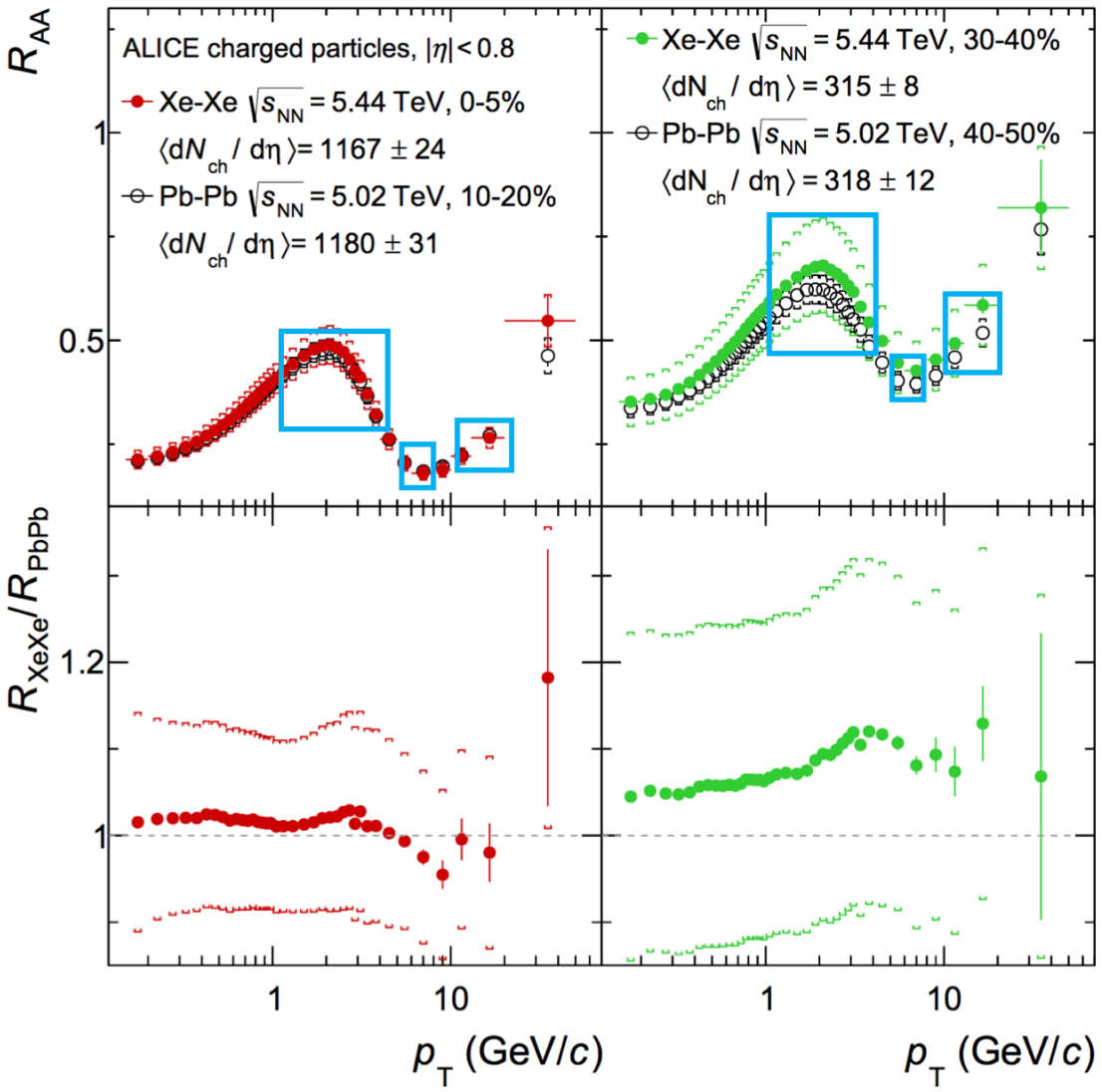
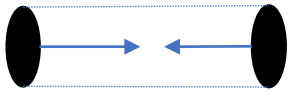
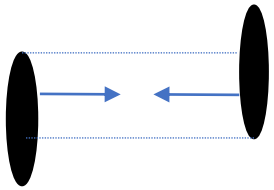


- Similar R_{AA} in the most central Xe-Xe collisions to that in 10-20% Pb-Pb collisions over the entire p_T range.
- Agreement of R_{AA} between 30-40% Xe-Xe and 40-50% Pb-Pb collisions within uncertainties.

central Xe-Xe collision



semi-central Pb-Pb collision



centrality	N_{part}
0-5% Xe-Xe	236 ± 2
10-20% Pb-Pb	263 ± 4
30-40% Xe-Xe	82.2 ± 3.9
40-50% Pb-Pb	86.3 ± 1.7

arXiv:1805.04399

R_{AA} in Xe-Xe and Pb-Pb vs. dN_{ch}/dη

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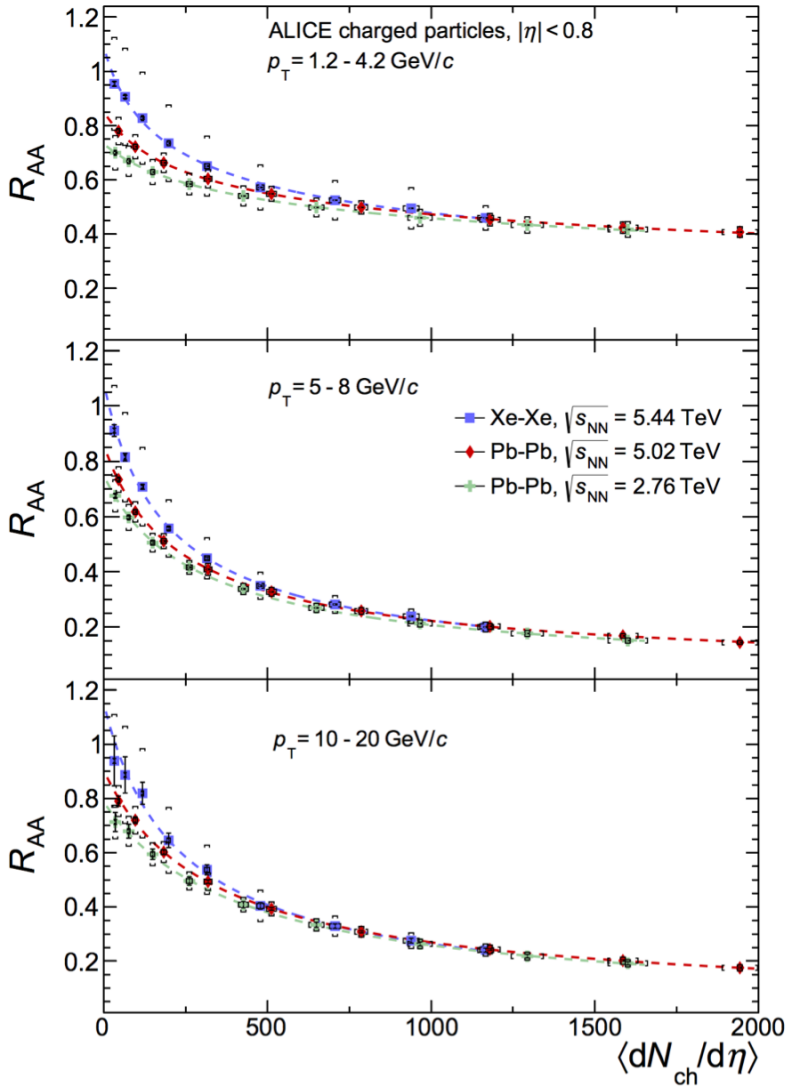


arXiv:1805.04399

ALICE

- A remarkable similarity in R_{AA} is observed between Xe-Xe collision at $\sqrt{s_{NN}}$ = 5.44 TeV and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 and 2.76 TeV for dN_{ch}/dη > 400.

$\langle \Delta E \rangle \propto \varepsilon \times L^2 \propto \langle dN_{ch}/d\eta \rangle / A_T \times L^2$

ΔE : radiative energy loss

ε : energy density

L : path length (related to the radius of the nucleus)

A_T : initial transverse area = $\pi \times r^2$ (r : radius of the colliding nuclei)

Phys. Rev. C 97, 034904
arXiv:0902.2011

→This result can provide insight on the path length dependence of medium induced parton energy loss.

Summary

- The spectra and nuclear modification factors of primary charged particles in p-Pb, Pb-Pb and Xe-Xe collisions and neutral mesons in p-Pb, Pb-Pb collisions at different collision energies were presented.

- The strong suppression in central Pb-Pb collisions is related to the formation of hot and dense QCD matter.

- The similar suppression level is found at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV.

- A similar R_{AA} for the same $\langle dN_{ch}/d\eta \rangle$ is found for Xe-Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 and 2.76 TeV for $dN_{ch}/d\eta > 400$.

backup

N_{part} in Pb-Pb at 5.02 TeV and Xe-Xe at 5.44 TeV

TABLE I. The $\langle dN_{\mathrm{ch}}/d\eta \rangle$ and $(2/\langle N_{\mathrm{part}} \rangle)\langle dN_{\mathrm{ch}}/d\eta \rangle$ values measured in $|\eta| < 0.5$ for 11 centrality classes. The values of $\langle N_{\mathrm{part}} \rangle$ obtained with the Glauber model are also given. The errors are total uncertainties, the statistical contribution being negligible.

Centrality	$\langle dN_{\mathrm{ch}}/d\eta \rangle$	$\langle N_{\mathrm{part}} \rangle$	$(2/\langle N_{\mathrm{part}} \rangle)\langle dN_{\mathrm{ch}}/d\eta \rangle$
0%–2.5%	2035 ± 52	398 ± 2	10.2 ± 0.3
2.5%–5.0%	1850 ± 55	372 ± 3	9.9 ± 0.3
5.0%–7.5%	1666 ± 48	346 ± 4	9.6 ± 0.3
7.5%–10%	1505 ± 44	320 ± 4	9.4 ± 0.3
10%–20%	1180 ± 31	263 ± 4	9.0 ± 0.3
20%–30%	786 ± 20	188 ± 3	8.4 ± 0.3
30%–40%	512 ± 15	131 ± 2	7.8 ± 0.3
40%–50%	318 ± 12	86.3 ± 1.7	7.4 ± 0.3
50%–60%	183 ± 8	53.6 ± 1.2	6.8 ± 0.3
60%–70%	96.3 ± 5.8	30.4 ± 0.8	6.3 ± 0.4
70%–80%	44.9 ± 3.4	15.6 ± 0.5	5.8 ± 0.5

ALICE collaboration : PRL 116, 222302 (2016)

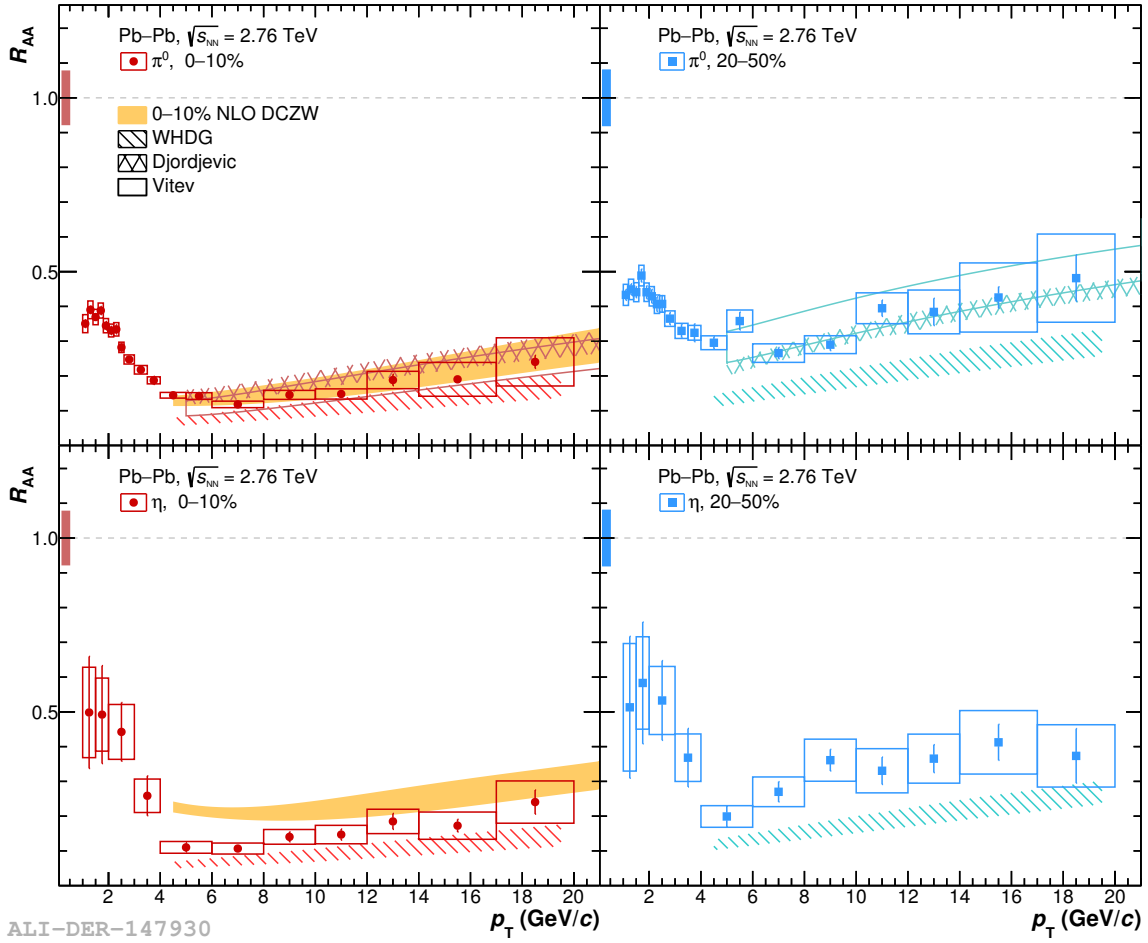
Centrality	$\langle N_{\mathrm{part}} \rangle$	$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	$\frac{2}{\langle N_{\mathrm{part}} \rangle}\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	$N_{\mathrm{ch}}^{\mathrm{tot}}$	$\frac{2}{\langle N_{\mathrm{part}} \rangle}N_{\mathrm{ch}}^{\mathrm{tot}}$
0–1%	246 ± 2	1302 ± 17	10.6 ± 0.2	14700 ± 300	120 ± 2.6
1–2%	241 ± 2	1223 ± 25	10.1 ± 0.2	13840 ± 250	115 ± 2.3
2–3%	236 ± 3	1166 ± 23	9.88 ± 0.23	13250 ± 280	112 ± 2.8
3–4%	231 ± 2	1113 ± 20	9.64 ± 0.19	12700 ± 290	110 ± 2.7
4–5%	225 ± 3	1069 ± 20	9.50 ± 0.22	12180 ± 260	108 ± 2.7
0–2.5%	242 ± 2	1238 ± 25	10.2 ± 0.2	14100 ± 320	115 ± 4.7
2.5–5.0%	229 ± 2	1096 ± 27	9.57 ± 0.25	12440 ± 280	109 ± 4.5
5.0–7.5%	214 ± 3	986 ± 25	9.21 ± 0.27	11230 ± 330	104 ± 5.4
7.5–10%	199 ± 2	891 ± 24	8.95 ± 0.26	10300 ± 300	103 ± 5.0
0–5%	236 ± 2	1167 ± 26	9.89 ± 0.24	13230 ± 280	112 ± 2.6
5–10%	207 ± 3	939 ± 24	9.07 ± 0.27	10820 ± 280	105 ± 3.1
10–20%	165 ± 3	706 ± 17	8.56 ± 0.26	8200 ± 310	99.4 ± 4.2
20–30%	118 ± 4	478 ± 11	8.10 ± 0.33	5670 ± 300	96.1 ± 6.0
30–40%	82.2 ± 3.9	315 ± 8	7.66 ± 0.41	3770 ± 270	91.7 ± 7.9
40–50%	54.6 ± 3.6	198 ± 5	7.25 ± 0.51	2460 ± 220	90.1 ± 10
50–60%	34.1 ± 3.0	118 ± 3	6.92 ± 0.63	1480 ± 170	86.8 ± 13
60–70%	19.7 ± 2.1	64.7 ± 2.0	6.57 ± 0.73	828 ± 44	84.1 ± 10
70–80%	10.5 ± 1.1	32.0 ± 1.3	6.10 ± 0.68	437 ± 16	83.2 ± 9.2
80–90%	5.13 ± 0.46	13.3 ± 0.9	5.19 ± 0.58	181 ± 7.0	70.6 ± 6.9

Table 1: The $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ and $N_{\mathrm{ch}}^{\mathrm{tot}}$ values for different centrality classes, defined by V0 multiplicity. The errors are total uncertainties, the statistical contribution being negligible. The values of $\langle N_{\mathrm{part}} \rangle$ obtained with the Glauber model are also reported. The errors are obtained by varying the parameters of the NBD-Glauber calculation.

ALICE_PUBLIC-2018-003

Comparison of R_{AA} of neutral mesons in Pb-Pb at 2.76 TeV with theory

ALICE collaboration : arXiv:1803.05490



NLO DCZW :
Phys. Lett. B750 (2015) 390-395
WHDG :
Int. J. Mod. Phys. E16 (2007) 2193-2199
Djordjevic :
Phys. Lett. B734 (2014) 286-289
Vitev et al.:
Phys. Rev. D 93, 074030 (2016)

- Djordevic et al. describes the π^0 suppression in both centrality classes within uncertainties.
- WHDG predicts larger suppression for both mesons in the centrality class 20-50%.

Summary of systematic uncertainties of neutral mesons in Pb-Pb at 2.76 TeV

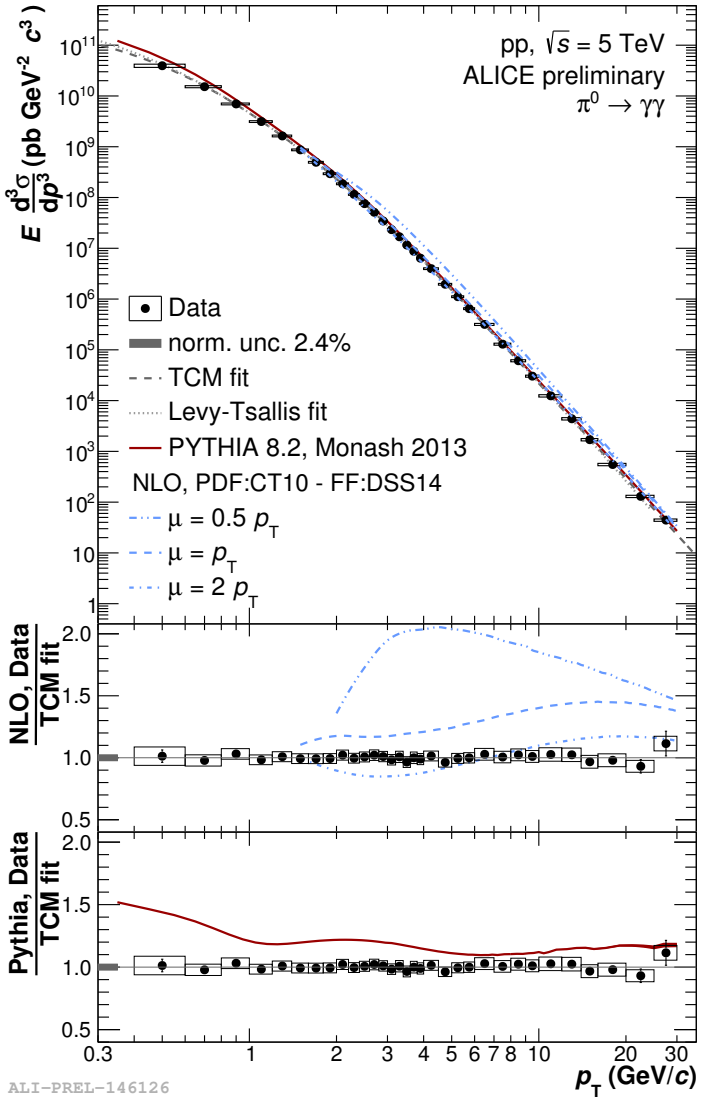
ALICE collaboration : arXiv:1803.05490

	PCM							
	0–10%				20–50%			
	π^0		η		π^0		η	
	1.1 GeV/c	5.5 GeV/c	2.5 GeV/c	5.0 GeV/c	1.1 GeV/c	5.5 GeV/c	2.5 GeV/c	5.0 GeV/c
Material budget	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Track reconstruction	2.3	2.6	6.0	6.2	1.4	2.3	7.0	9.0
Yield extraction	1.5	2.1	6.4	7.0	2.5	2.8	10.0	11.0
e^+/e^- identification	1.7	2.5	6.0	6.1	1.4	2.4	5.5	9.3
Photon reconstruction	3.7	2.1	13.7	13.6	2.1	2.2	8.0	8.6
	EMCal							
	0–10%				20–50%			
	π^0		η		π^0		η	
	7.0 GeV/c	18.5 GeV/c	7.0 GeV/c	18.5 GeV/c	7.0 GeV/c	18.5 GeV/c	7.0 GeV/c	18.5 GeV/c
Signal extraction	2.9	5.1	4.2	5.5	7.5	5.8	6.0	7.1
Photon identification	9.5	8.0	4.6	6.0	7.5	4.5	14.1	5.0
Energy response	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6
Material budget	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Hijing simulation	8.6	10.0	8.6	10.0	2.0	5.3	2.0	5.3
Monte Carlo input	2.0	3.0	<1	1.5	<1	<1	<1	<1
Higher mass decays	4.0	2.0	-	-	3.2	2.0	-	-

Table 2: Summary of the systematic uncertainties in percent for selected p_T regions for the PCM and EMCal analyses.

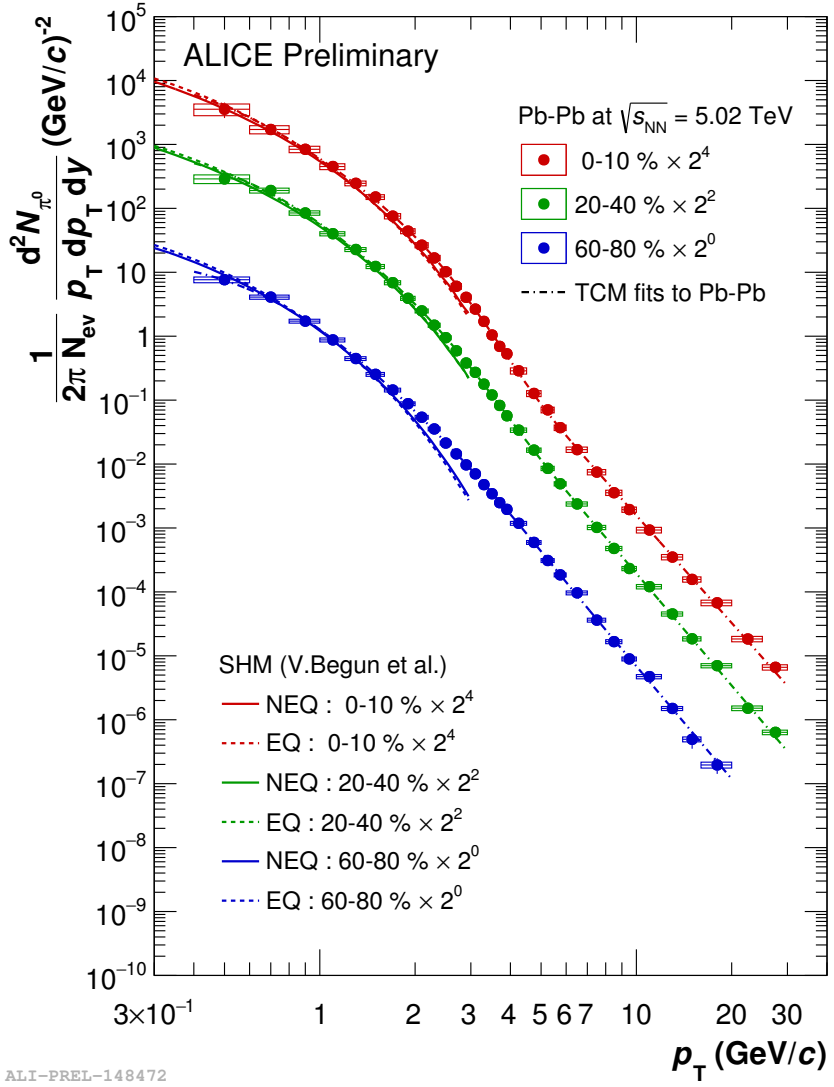
Neutral pion spectrum in pp at $\sqrt{s_{NN}}$ = 5.02 TeV

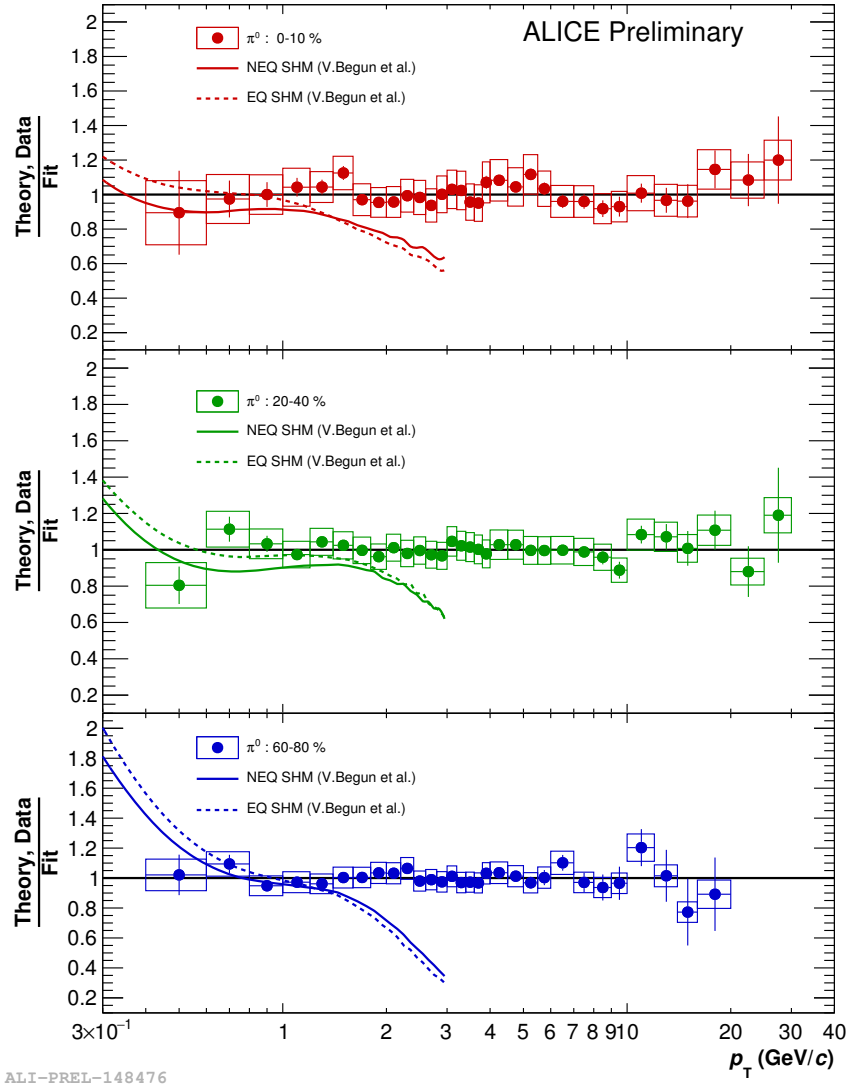
NEW



π^0 spectra in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

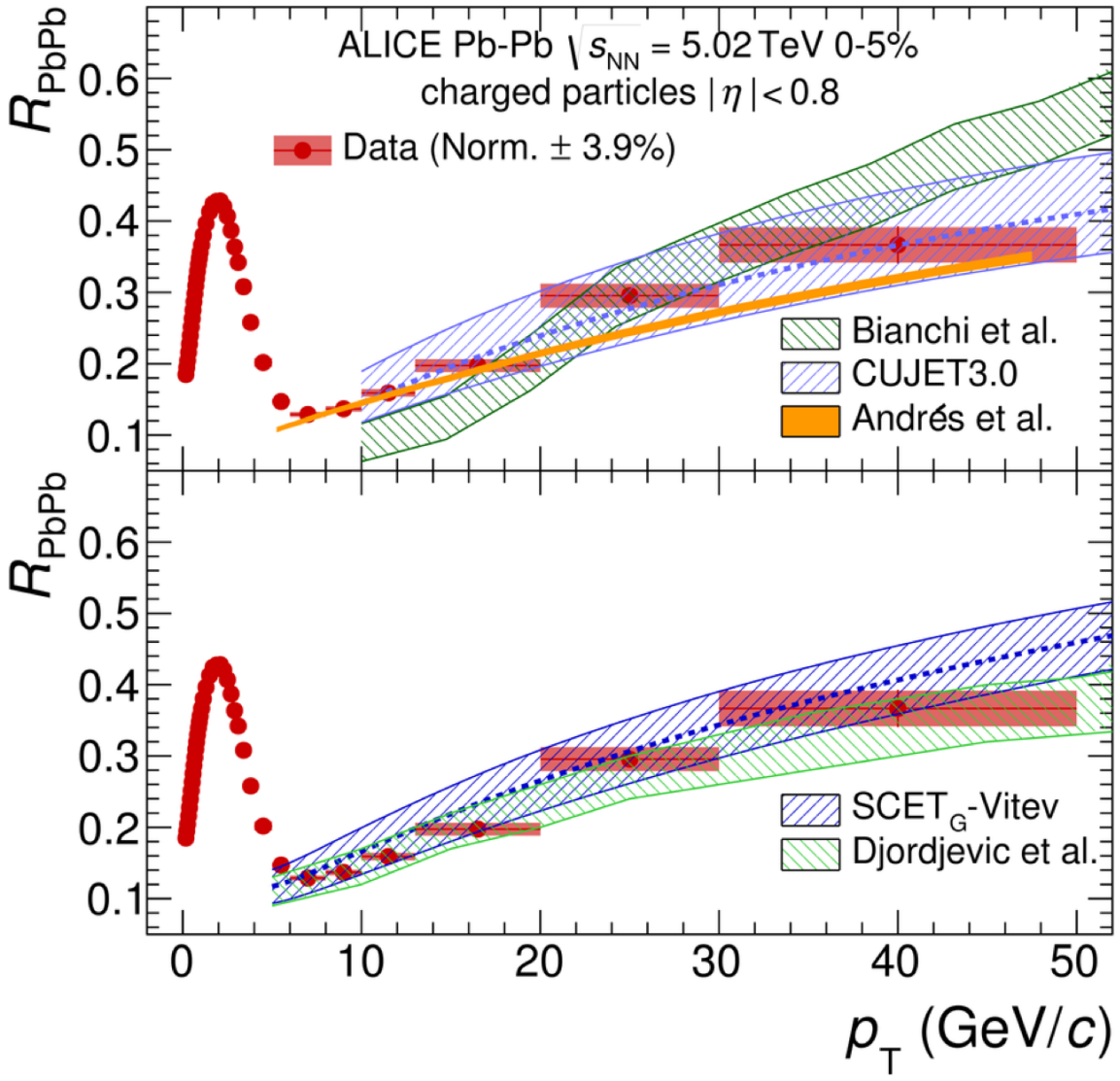
NEW





Comparison with theoretical models

ALICE collaboration : arXiv:1802.09145



- Andrés et al.

  -consists of fitting a K factor defined as $K \equiv \hat{q}/2\varepsilon^{3/4}$,based on the perturbative estimate, $\hat{q}_{ideal} \sim 2\varepsilon^{3/4}$. The local energy density ε is taken from a hydrodynamical model of the medium. K factor is the only free parameter in the fitting to nuclear modification factors.

  Andrés et al. : Eur. Phys. J. C76 (2016) 475
  Nucl. Phys. A715 (2003) 209–218

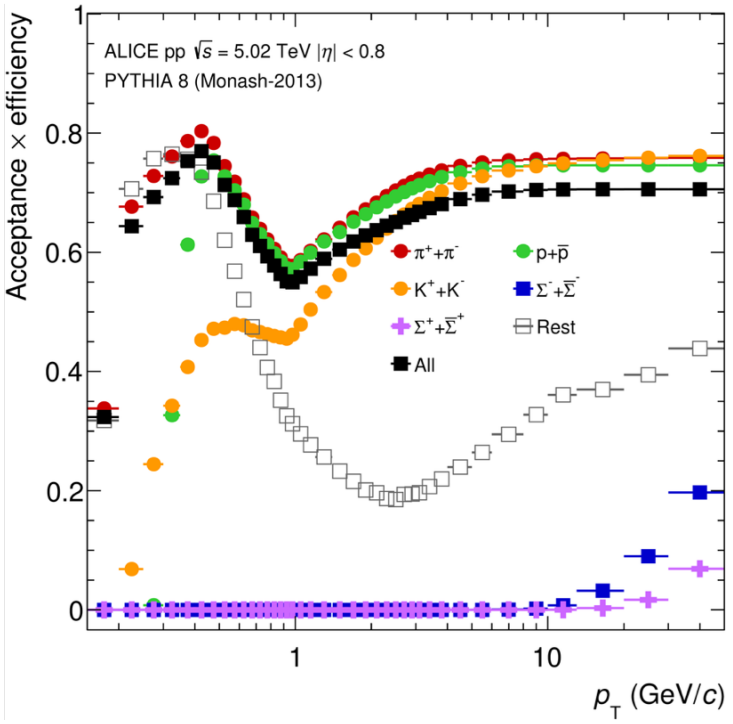
- Bianchi et al.

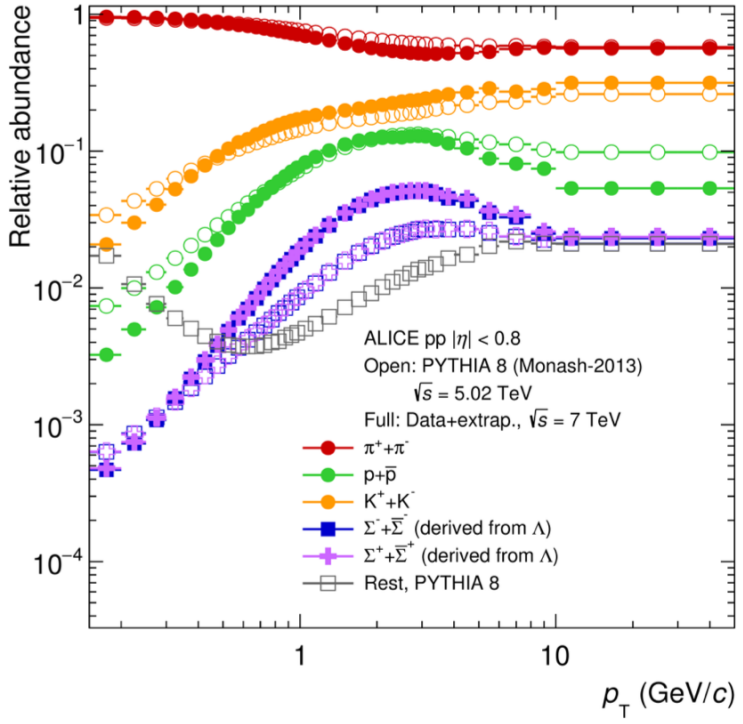
  -pQCD-based radiative energy loss in a hydrodynamically expanding medium. High p_T hadrons arise from fragmentation of hard partons, which lose their energy prior to hadronization via interactions with the medium.

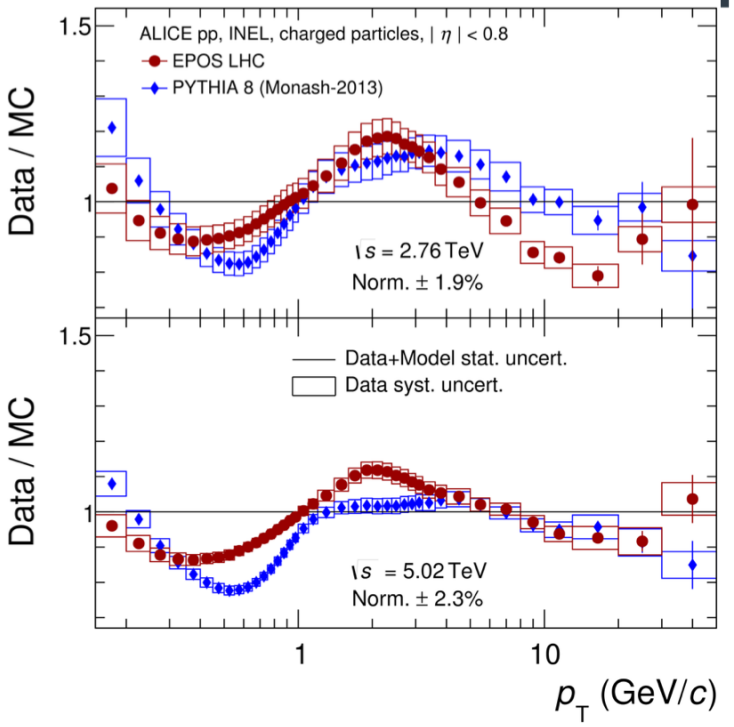
  Bianchi et al. : arXiv:1702.00481

Tracking efficiency of inclusive charged particles in pp

ALICE collaboration : arXiv:1802.09145

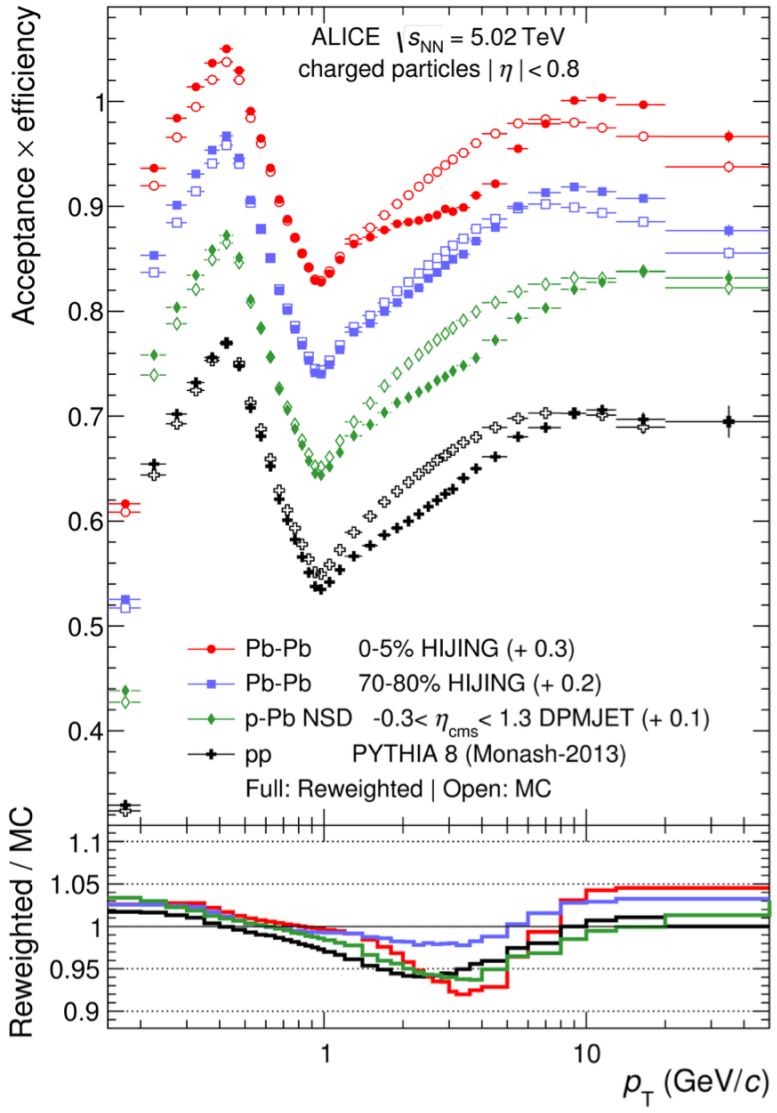


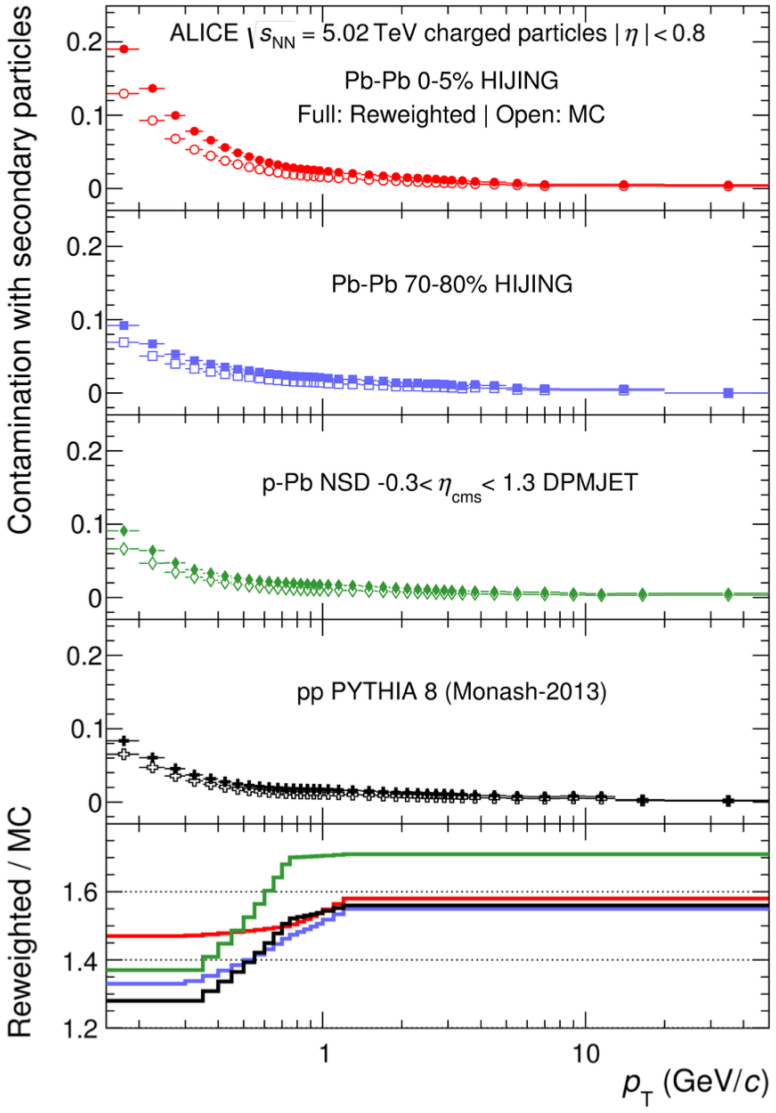




Tracking efficiency of inclusive charged particles in Pb-Pb

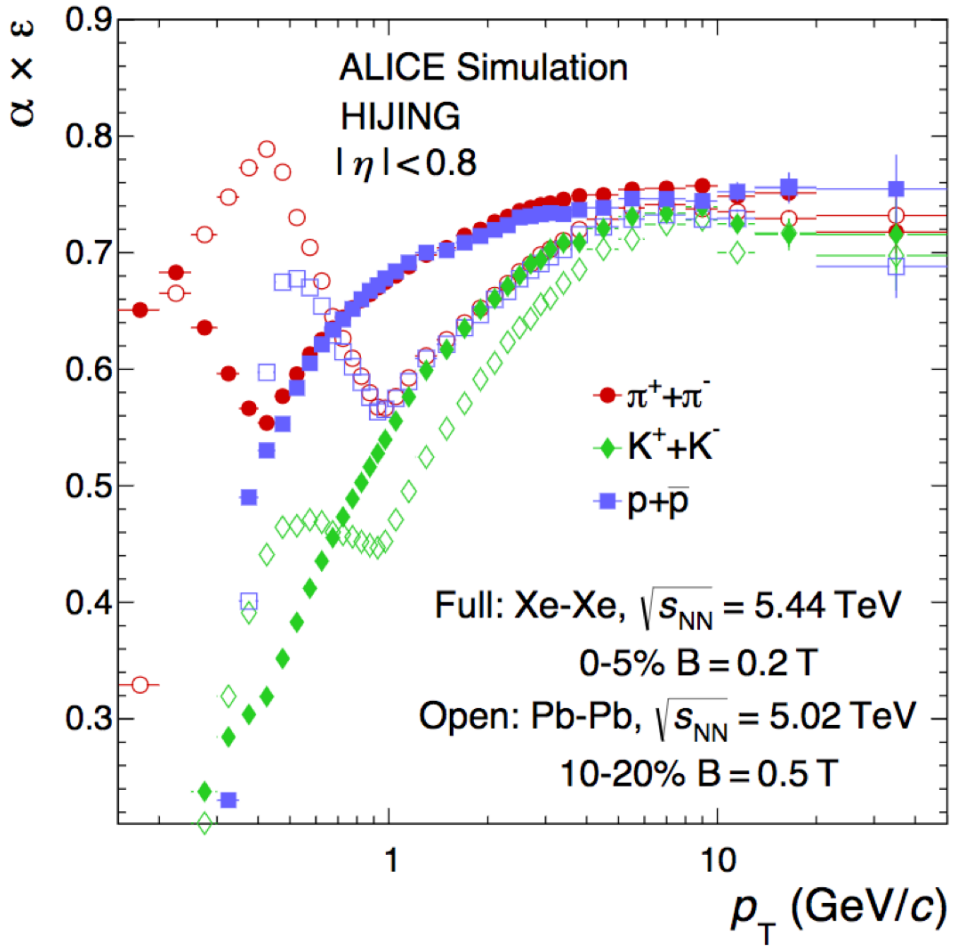
ALICE collaboration : arXiv:1802.09145



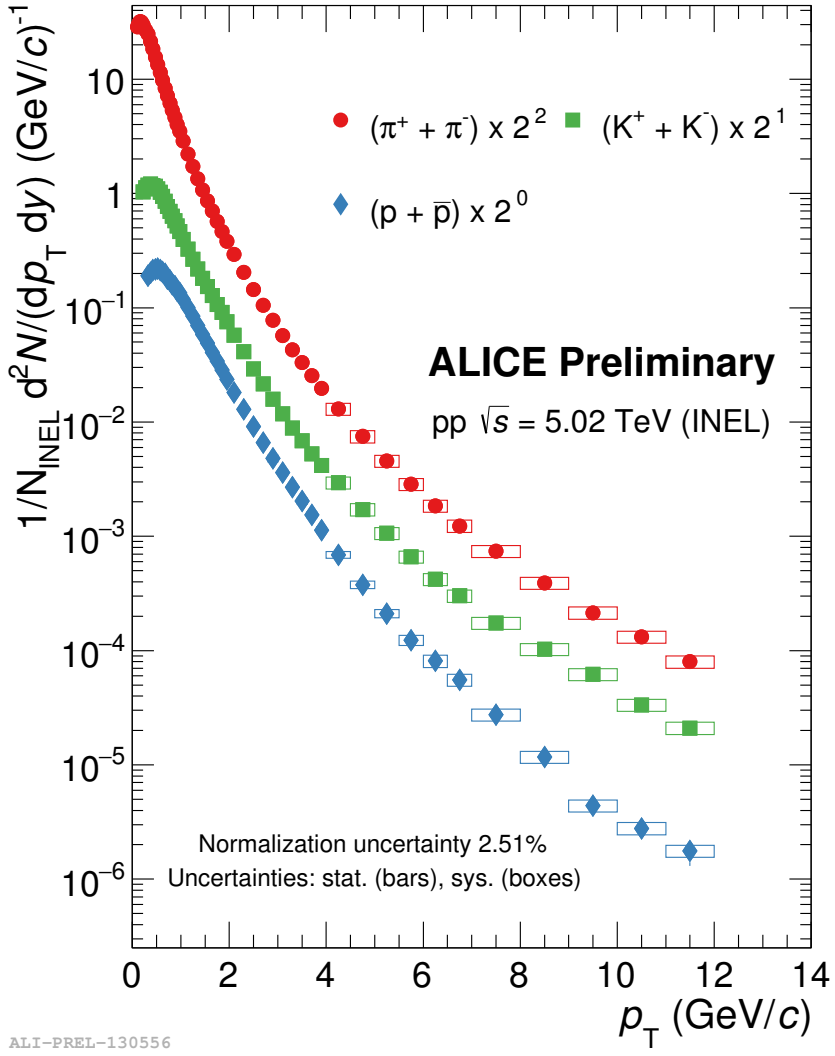


Tracking efficiency of inclusive charged particles in Xe-Xe

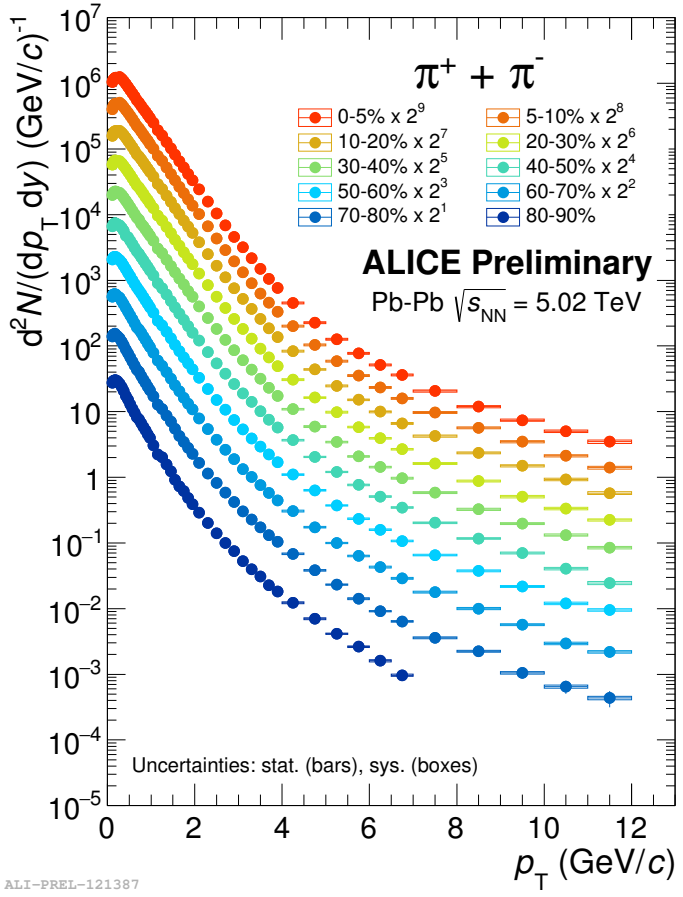
arXiv:1805.04399

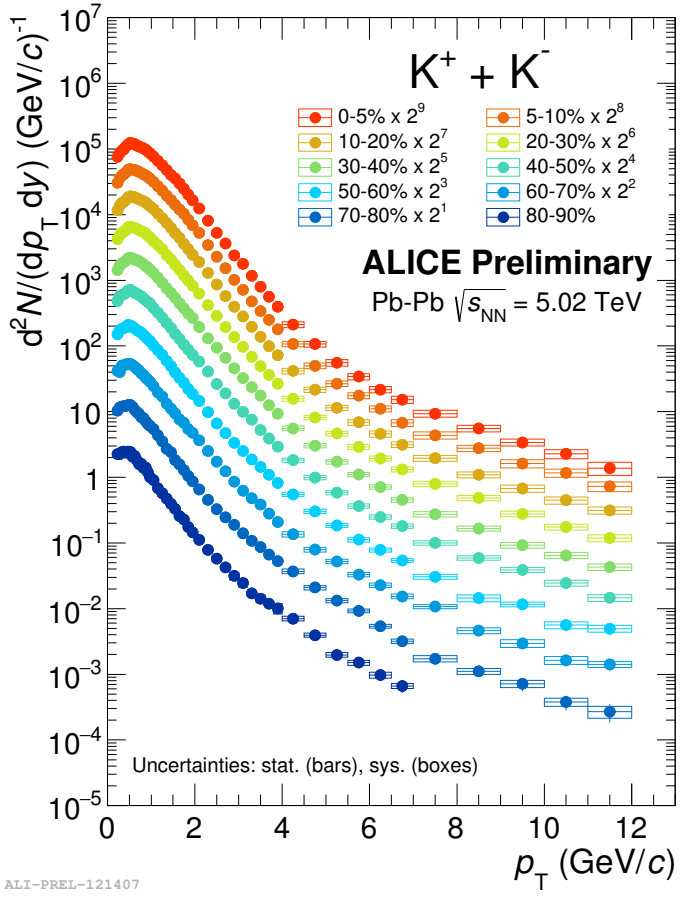


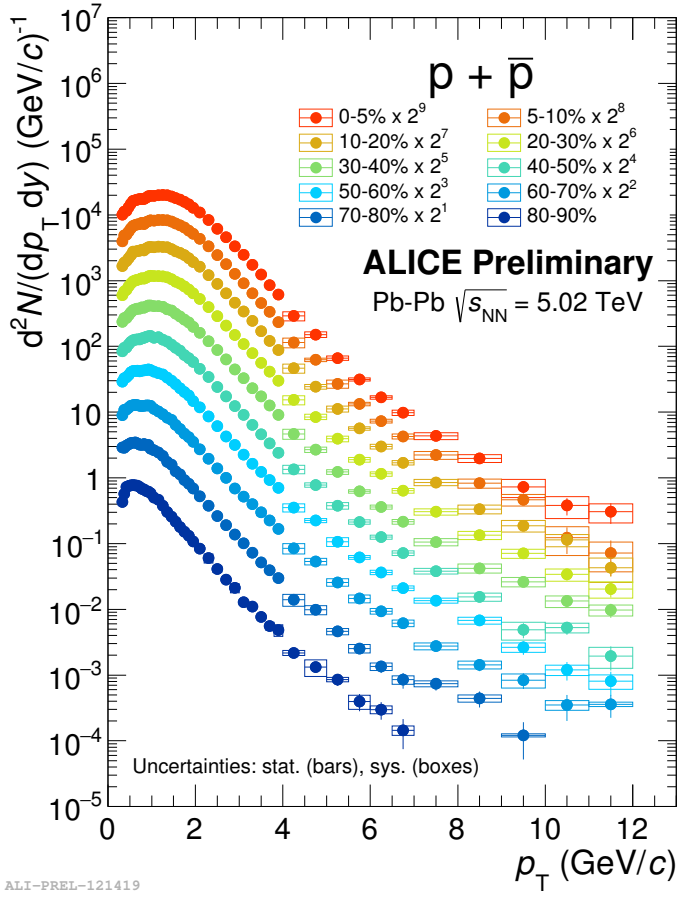
Identified charged particles spectra in pp at 5.02 TeV



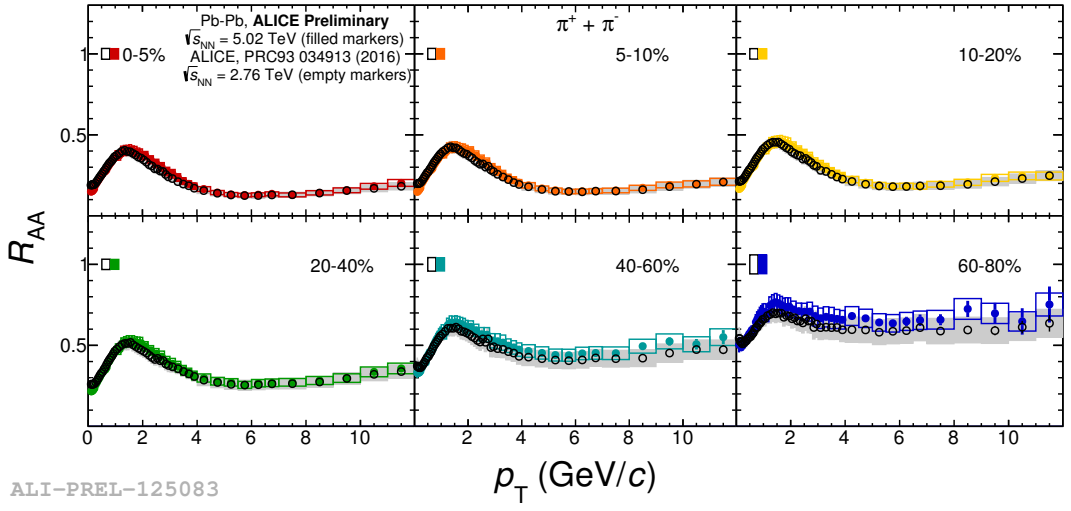
Identified charged particles spectra in Pb-Pb at 5.02 TeV







R_{AA} of identified charged particles at 2.76 and 5.02 TeV



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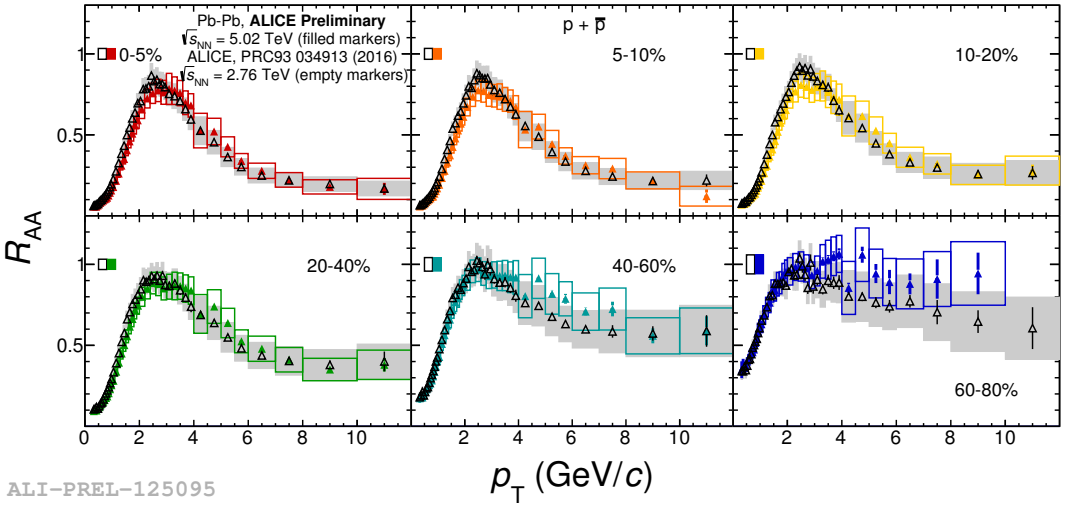

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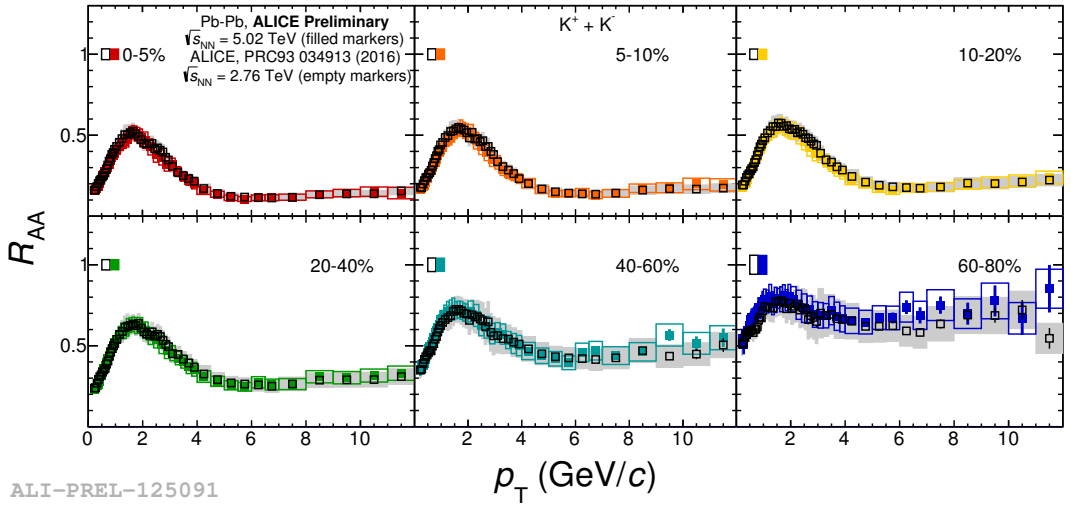

ALI-PREL-125091