Gamma and neutral mesons with ALICE

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on behalf of the ALICE collaboration

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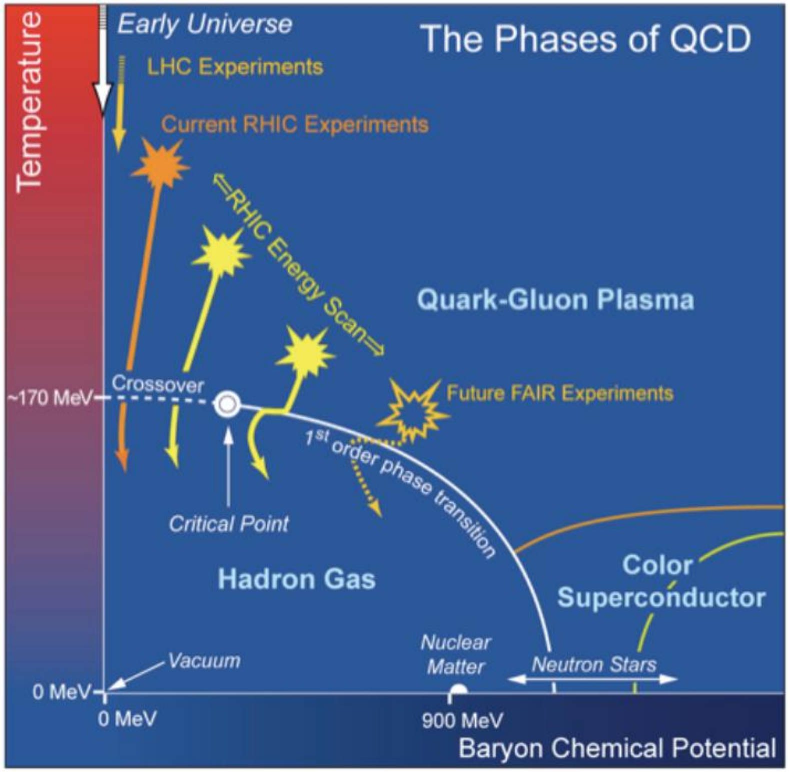
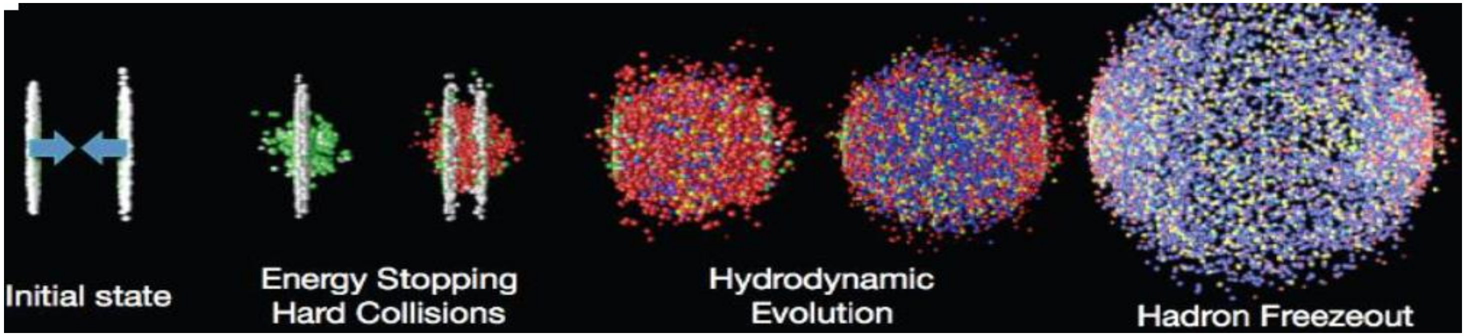
Outline

- Motivation
- ALICE detector
- Results
  - π^0 mesons in pp and Pb-Pb
  - η mesons in Pb-Pb
  - π^0 – hadron correlations
  - Direct photons
- First look into calorimeters results
- Summary

Motivation

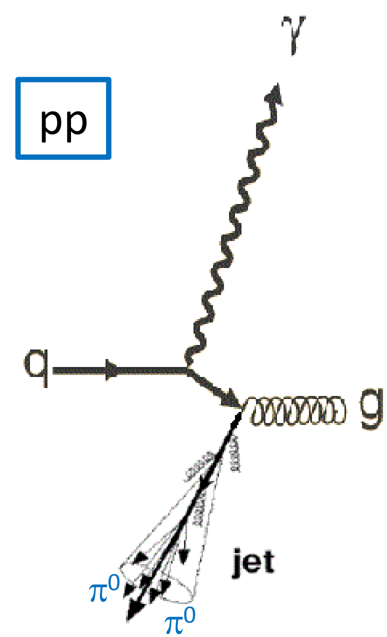
- Investigate properties of nuclear matter at high temperature ($T \geq 170$ MeV) and density
- Important input for the understanding of the confinement and the chiral symmetry restoration (transition from quark to hadronic matter)
- Explore QCD in unknown regimes $\rightarrow$ study QCD phase diagram
- QGP produced < 10^{-6} s after Big Bang
- We should search for QGP phase and measure its properties
- LHC gives us the great opportunity via heavy ion collisions ("little Big Bangs")

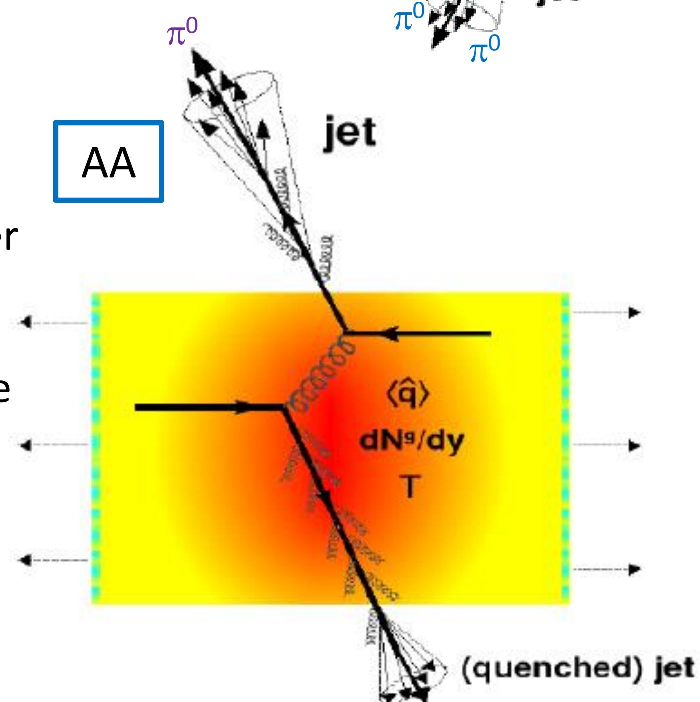




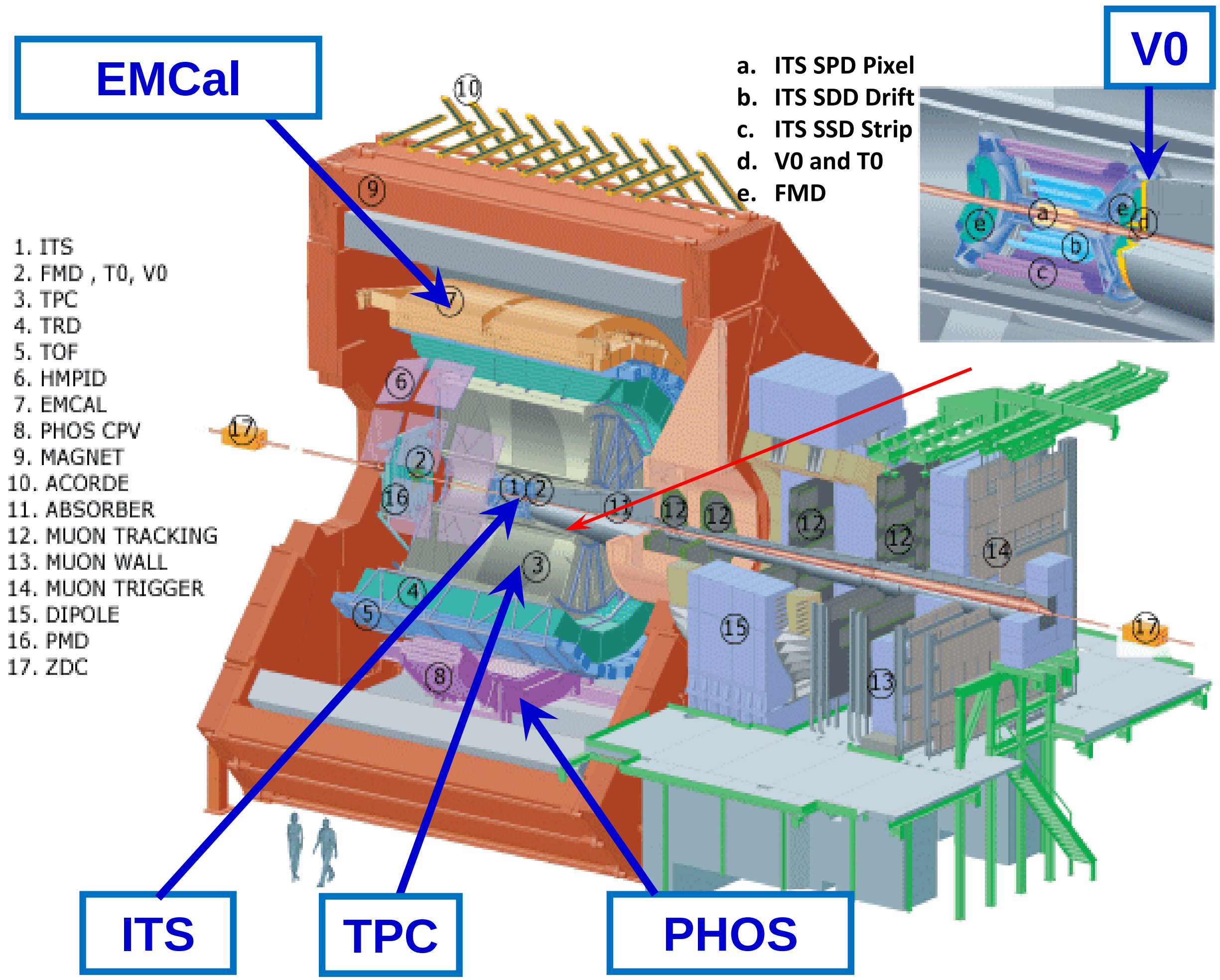
Why photons and mesons?

- Both, photon and meson production are described by pQCD in pp collisions
- Inclusive meson production spectrum is necessary for direct photons search
- pp and p-Pb provide reference data to compare with AA
- Temperature estimation via measurement of p_T distribution of direct photons
- Jet suppression via medium induced modification of π^0 meson distribution
- Neutral hadrons carry information about medium
  - Studies of transport properties of quark-gluon matter
  - Initial gluon density
  - $\Rightarrow$ constraint of parameters of theoretical models in both perturbative (NLO, NNLO) and non-perturbative regime (structure function, fragmentation function)
- π^0 – hadron correlation are important step in direct photon – hadron correlation
- Studies of jet modification by presence of hot and dense matter





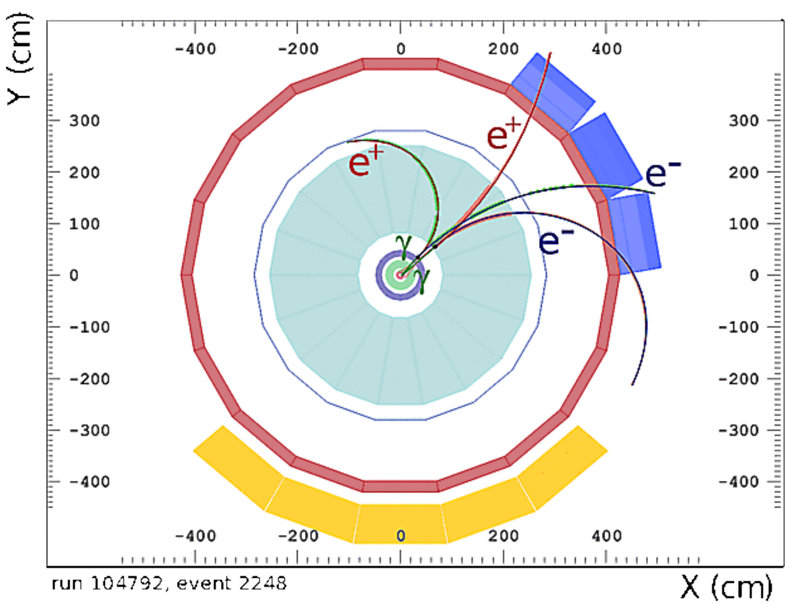
ALICE detector



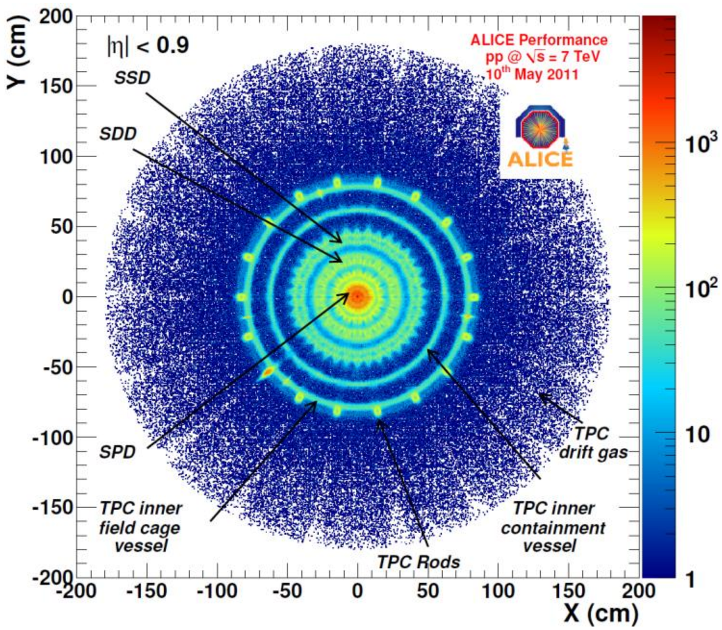
- Tracking
  - $|\eta| < 0.9$, $0 < \varphi < 2\pi$
  - TPC - gas drift detector
  - ITS - silicon detector
- EMCal
  - Pb-scintillator sampling calorimeter
  - $|\eta| < 0.7$, $80^o < \varphi < 180^o$
- PHOS
  - $PbWO_4$ crystal spectrometer
  - $|\eta| < 0.13$, $260^o < \varphi < 320^o$
- V0
  - Centrality determination

Method of neutral meson extraction

- Ways of neutral meson measurement via invariant mass analysis in ALICE
  - $\rightarrow$ photon pairs or external conversion electrons
  - $h \rightarrow \gamma + \gamma$ (PHOS, EMCal)
  - $h \rightarrow \gamma\ (\rightarrow e^+ e^-) + \gamma\ (\rightarrow e^+ e^-)$ (PCM)
    - Small conversion probability (~ 8.5 %) is compensated by a wide acceptance.



Reconstructed π^0 candidate through conversions

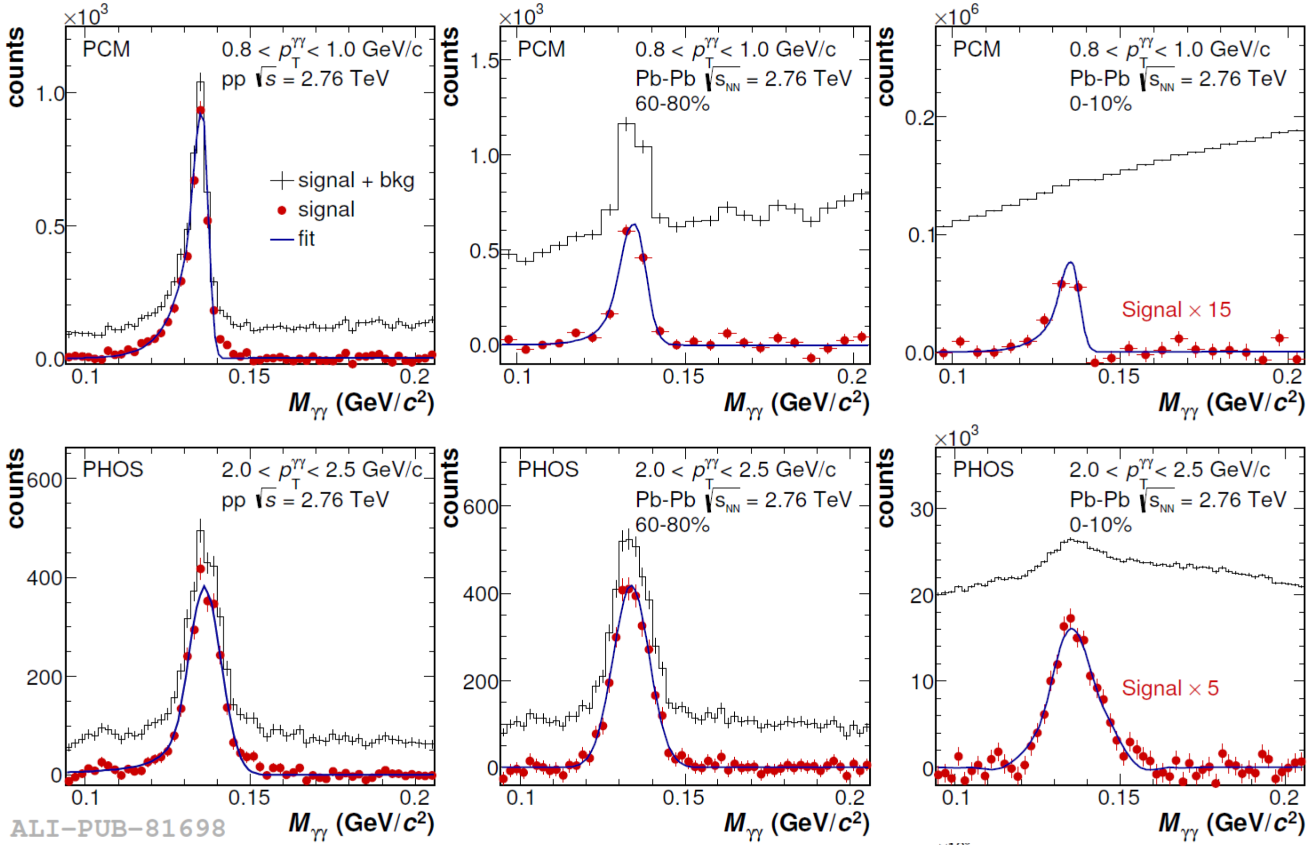


Distribution of conversions

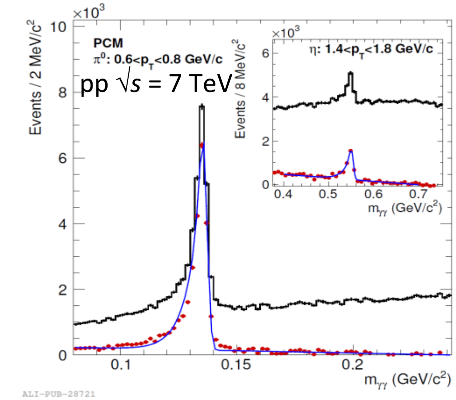
Material budget well known with relative precision of 4.5 %

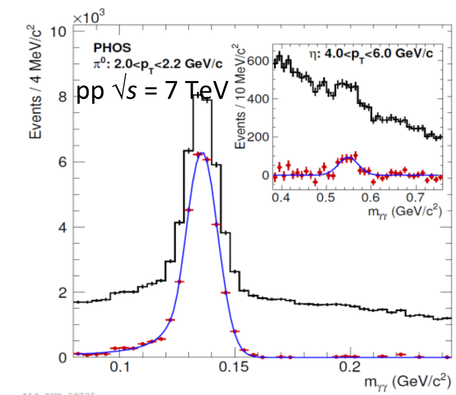
Invariant mass

EPJ C (2014) 74:3108



PLB 717 (2012) 162-172

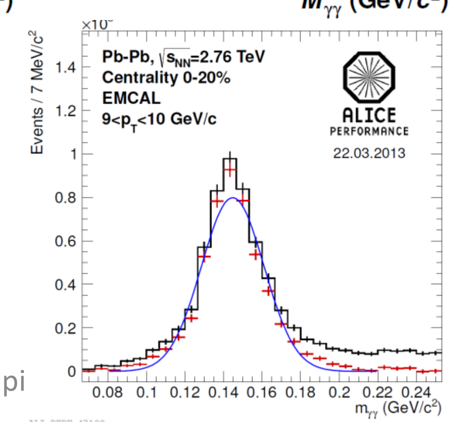


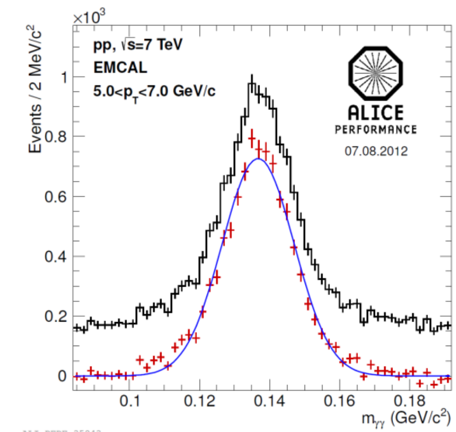


π^0 is reconstructed

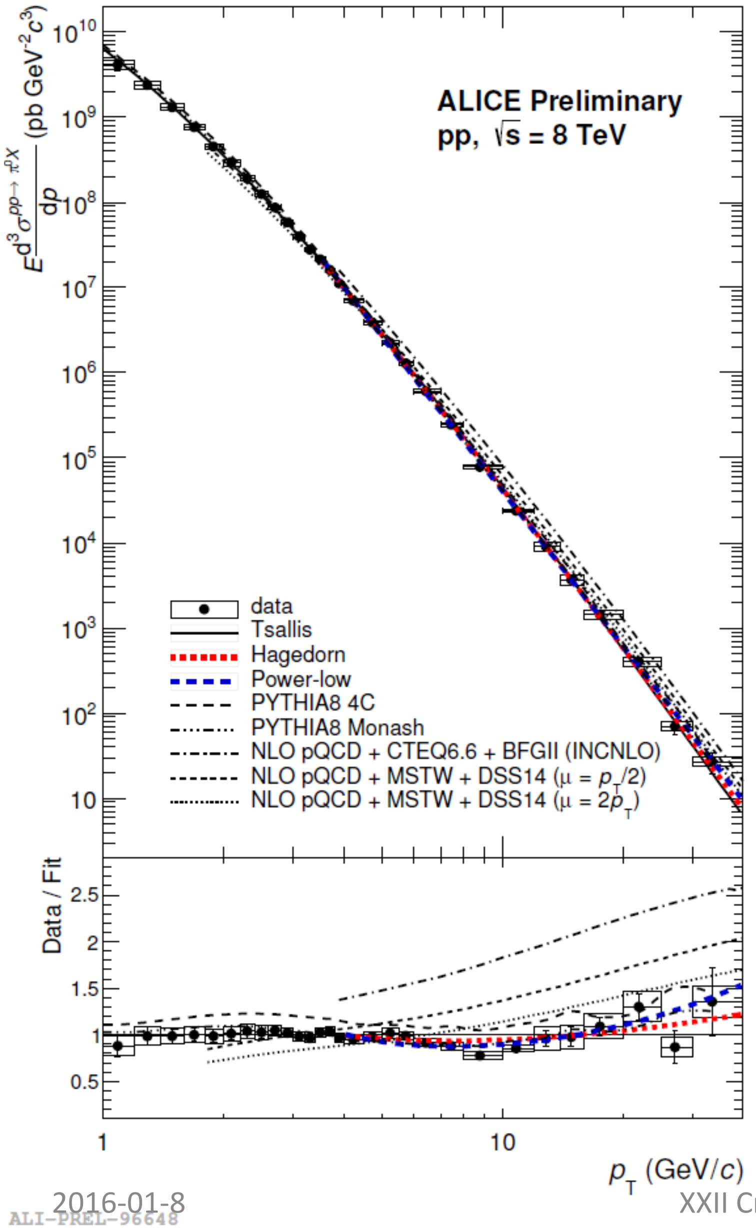
- For different collision energies
- In different systems (pp and Pb-Pb)
- Via different methods (detectors)
- In wide p_T range

Good agreement between methods



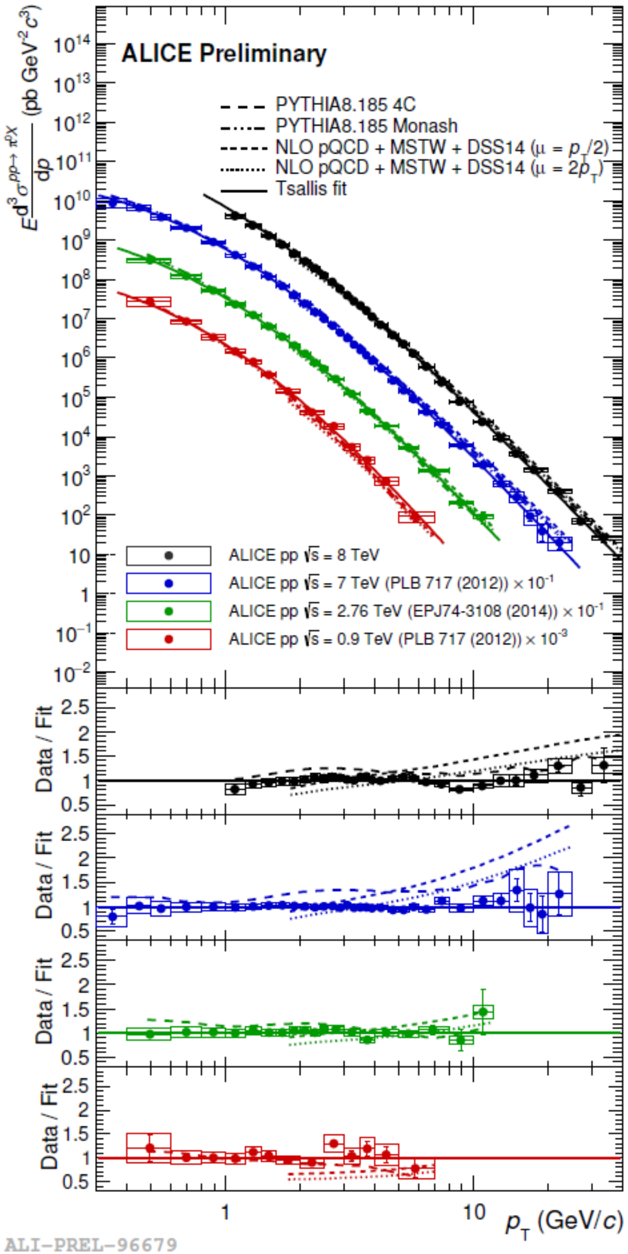


New results of π^0 production in pp at $\sqrt{s}$ = 8 TeV



- Measurement with PHOS.
- Wide p_T range: $1 < p_T < 40$ GeV/c.
- Data described by many functions: Tsallis, Hagedorn, power law.
- NLO pQCD MSTW+DSS14 describes data better than CTEQ6.6+BFGII.
- Increasing discrepancy as function of p_T.

π^0 spectra in pp



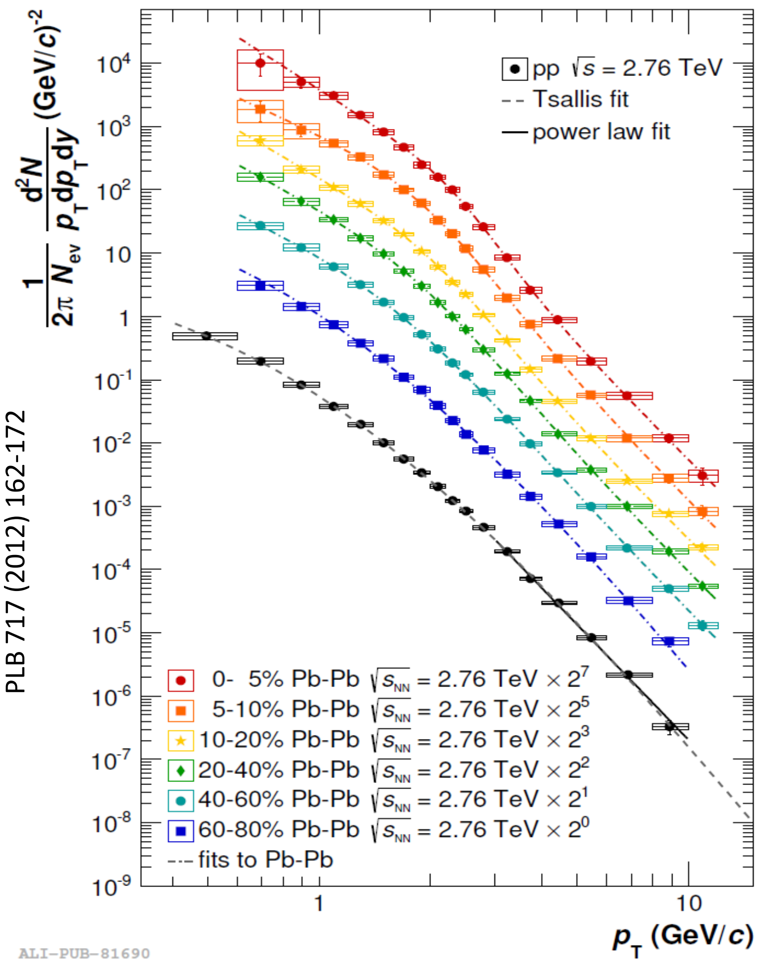
- Agreement between data and NLO pQCD (PRD 91 (2015) 1, 014035) at $\sqrt{s}$ = 0.9 and 2.76 TeV.
  - Parton Distribution Functions: MSTW
  - Fragmentation Functions: DSS14
- For higher energies NLO pQCD overpredicts data at higher p_T (still)
- Power law dependence at high p_T

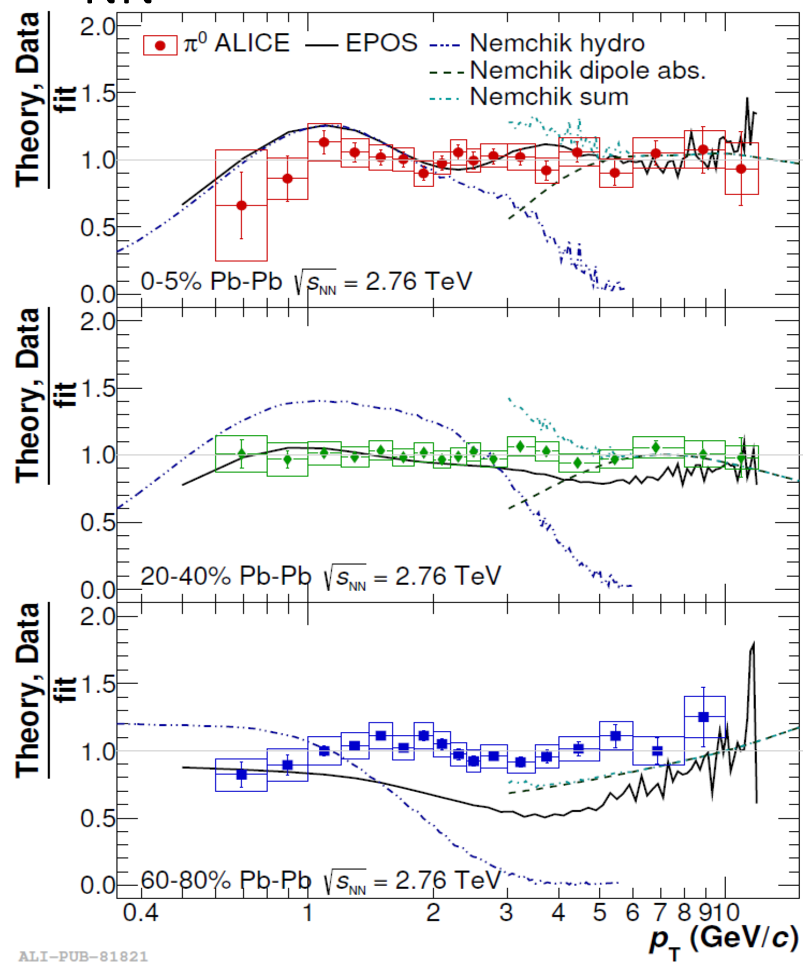
$\sqrt{s}$ (TeV)	n
0.9	7 ± 2
2.76	6.0 ± 0.5
7.0	6.04 ± 0.14
8.0	5.94 ± 0.15

For $\sqrt{s}$ = 0.2 TeV: $n = 8.22 \pm 0.1$

π^0 spectra in Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV

PLB 717 (2012) 162-172





- 6 centrality classes in Pb-Pb collisions
- Best agreement for most central collisions

EPOS: PRC 85, 064907 (2012):

Low p_T: Hydrodynamic flow,

High p_T: Energy loss of string segments.

Nemchik: PRC 86, 054904 (2012):

Low p_T: Hydrodynamic description

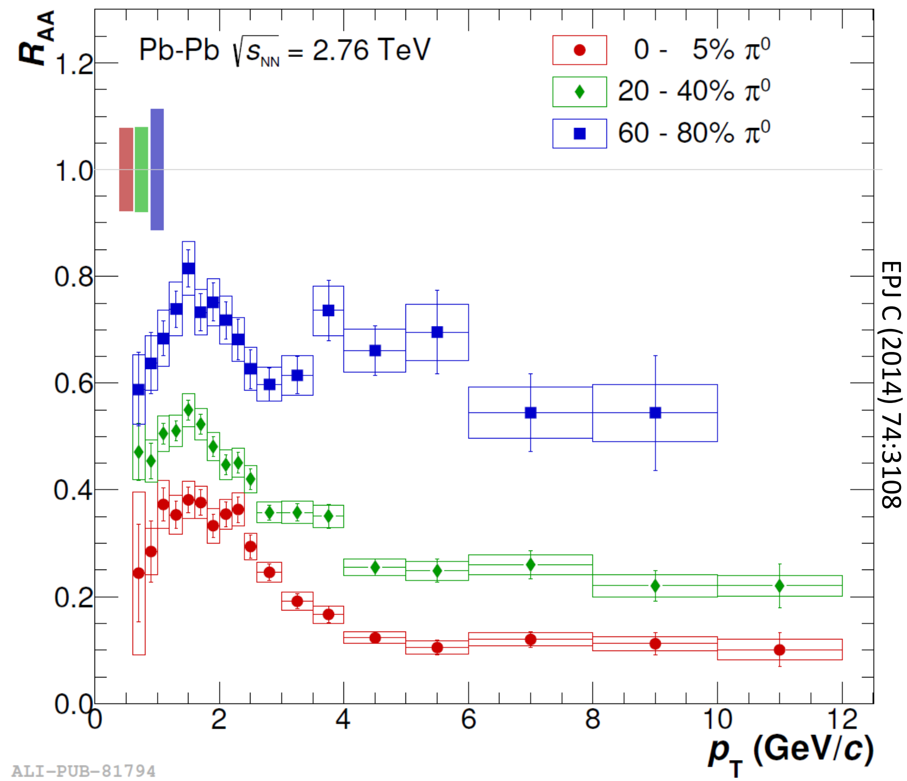
High p_T: Color dipole absorption.

Nuclear modification factor

$$R_{AA}(p_T) = \frac{d^2N/dp_T dy|_{AA}}{\langle T_{AA}\rangle \times d^2\sigma/dp_T dy|_{pp}}$$

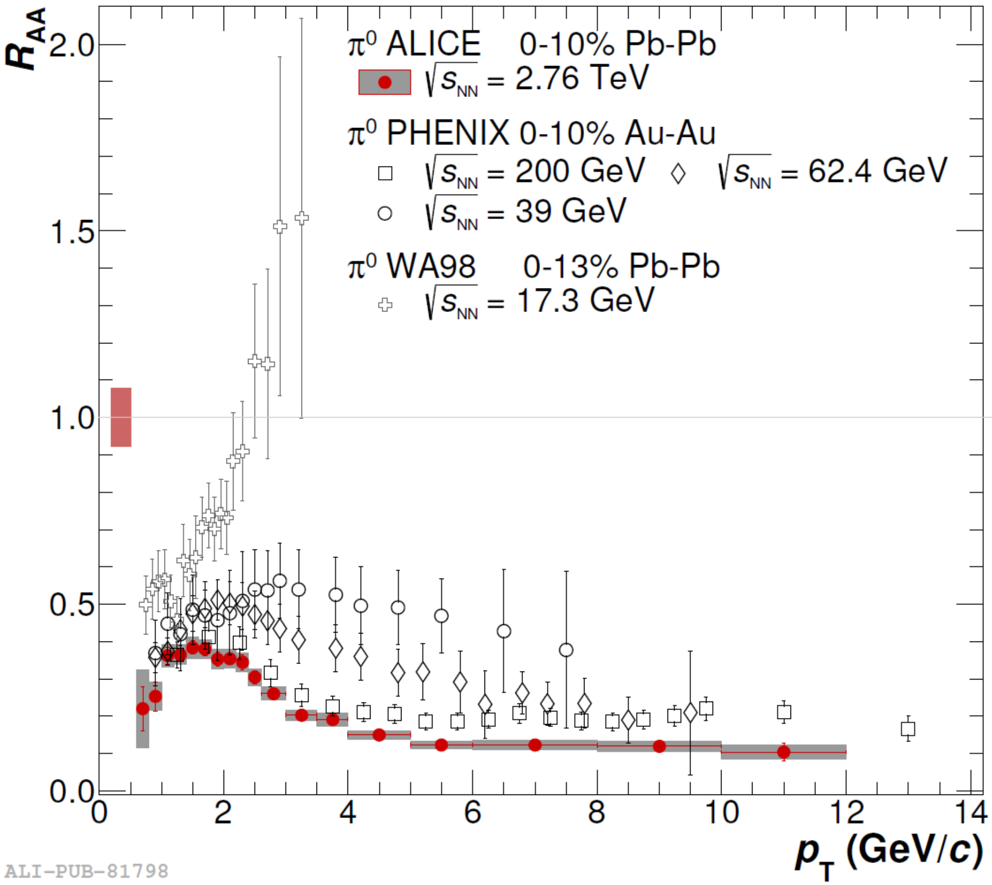
$N_{coll} = \sigma_{pp} \langle T_{AA} \rangle$

- Judges medium effect
- Contains both initial and final state effect
  - Initial state: i.e. Cronin, nuclear shadowing
  - Final state: collisional and radiative energy loss
- $R_{AA} = 1 \rightarrow$ no modification



- Very strong suppression (R_{AA} ~ 0.1) in central Pb-Pb collisions above $p_T \approx 3$ GeV/c
- Agreement with results for charged hadrons

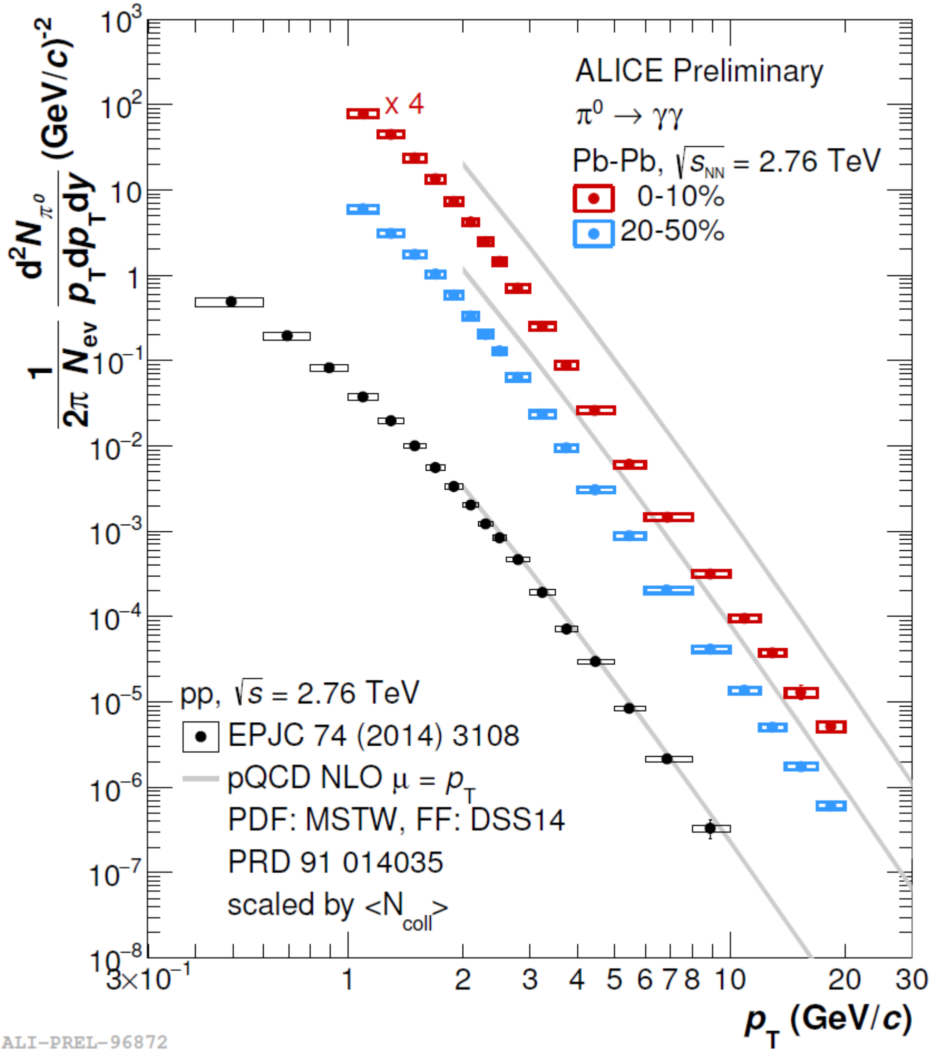
$\sqrt{s_{NN}}$ dependence of the π^0 R_{AA}



- Similar shape of π^0 R_{AA} for $\sqrt{s_{NN}}$ = 2.76 TeV and $\sqrt{s_{NN}}$ = 200 GeV
- The higher center of mass energy the larger suppression
- Onset of suppression between $\sqrt{s_{NN}}$ = 17.3 GeV and $\sqrt{s_{NN}}$ = 39 GeV

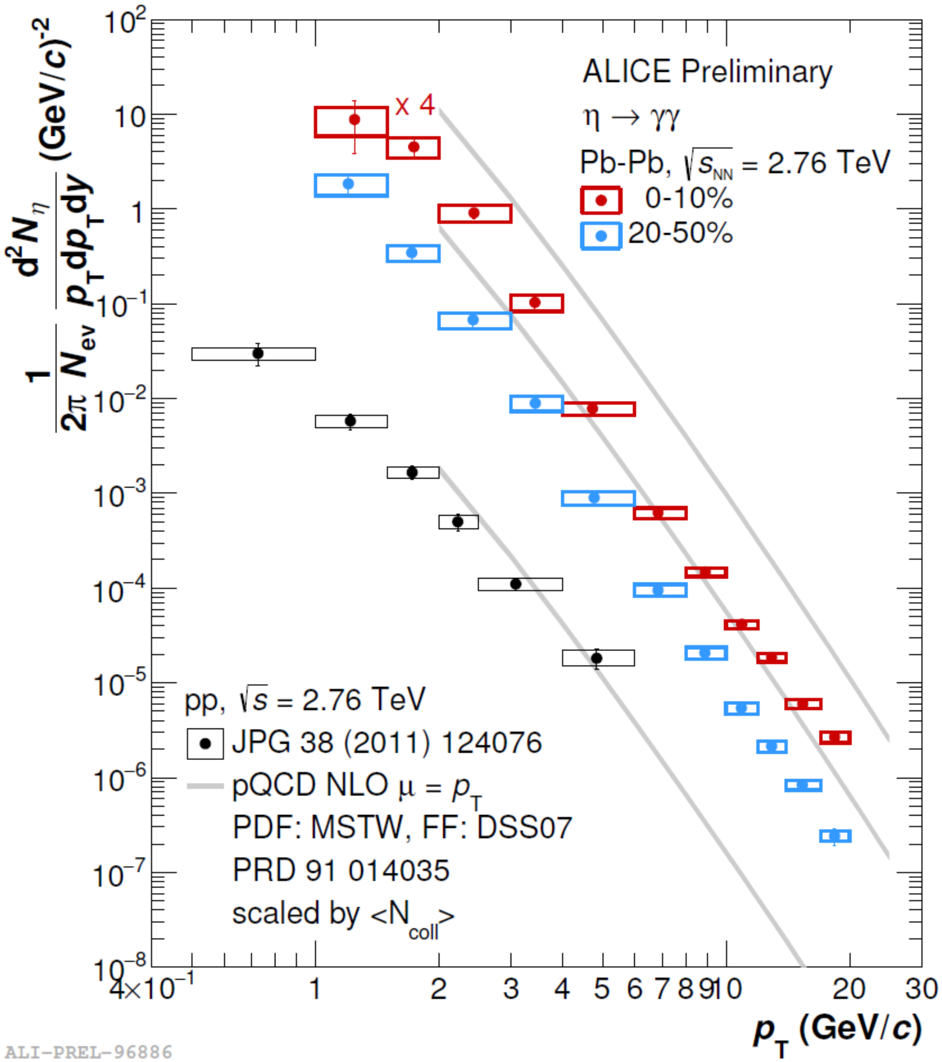
ALICE: EPJC 74 (2014) 10, 3108
PHENIX: PRL 109 (2012) 152301
PHENIX: PRL 101 (2008) 232301
WA98: PRL 100 (2008) 242301

π^0 spectra in Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV, new result



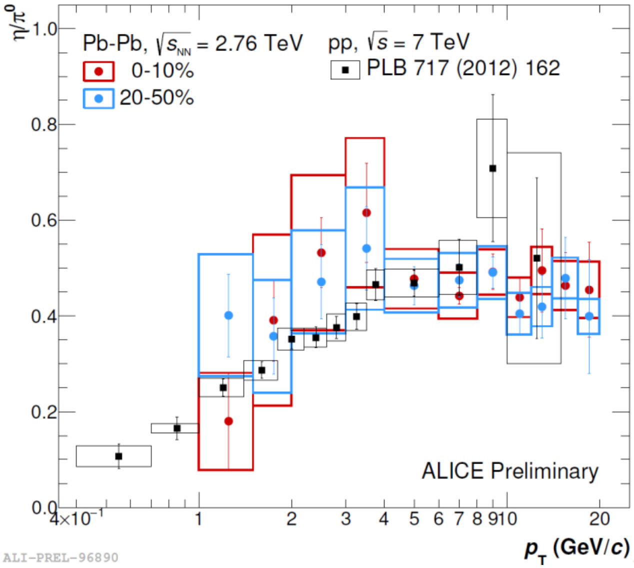
- 10 times more statistics in 2011 (L ~ 0.1 nb^{-1})
- Extended p_T range up to 20 GeV/c
- Two complementary analyses methods: EMCal and PCM
- Two centrality classes compared to pp
- Compared to NLO pQCD pp predictions scaled by N_{coll} (PRD 91 (2015) 1, 014035)

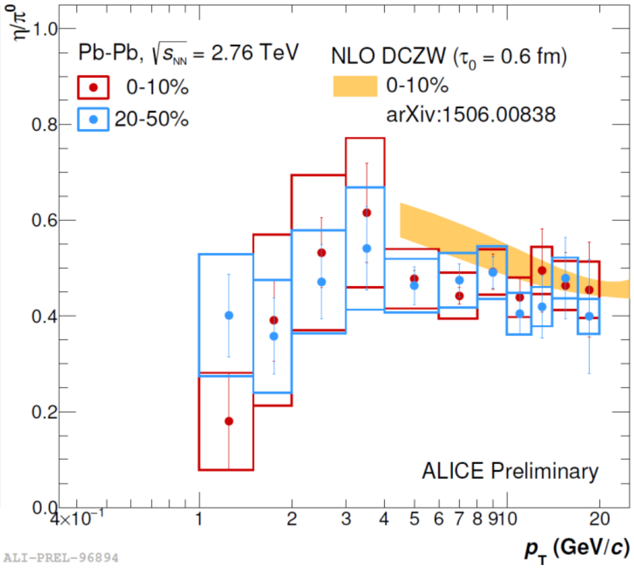
η spectra in Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV

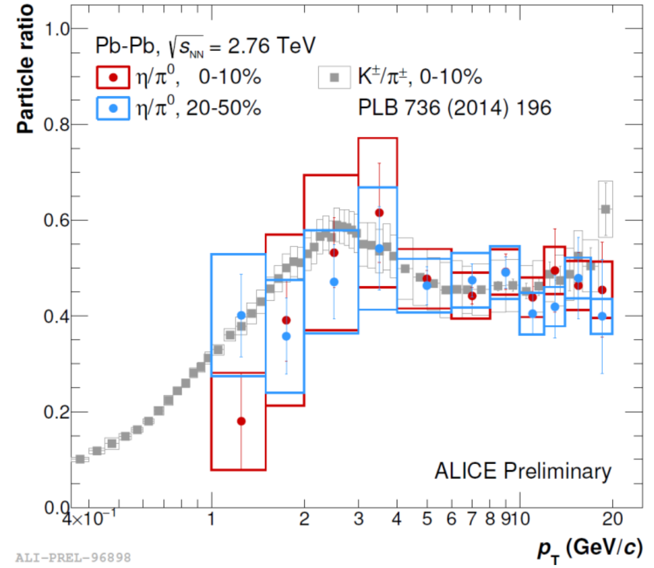


- First η measurement in Pb-Pb at the LHC
- Range: $1 < p_T < 20$ GeV/c
- Two complementary systems: EMCal and PCM
- Two centrality classes compared to pp
- Compared to η production of NLO pQCD pp predictions scaled by N_{coll} (PRD 91 (2015) 1, 014035)

η/π^0 ratio in Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV





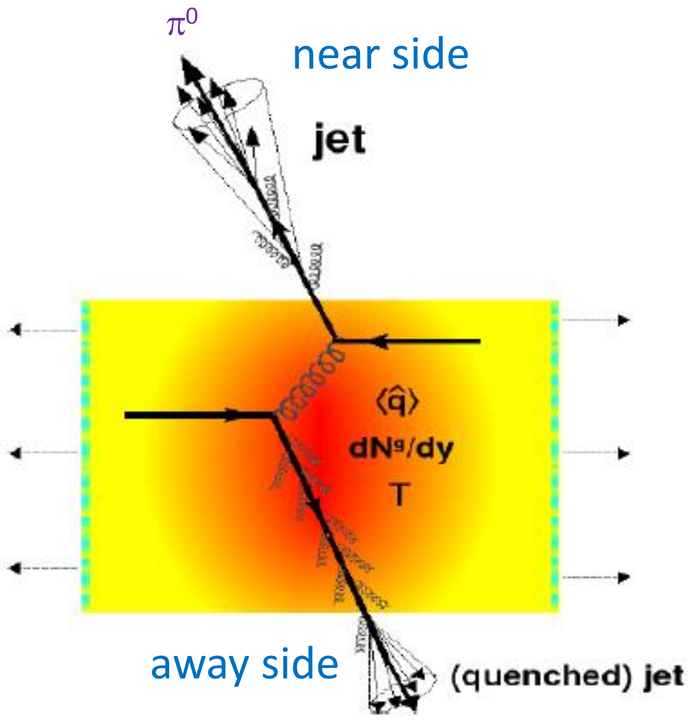


- Constant value of ratio above p_T = 4 GeV/c.
- Comparison of η/π^0 ratio for two centrality classes in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV to pp result at $\sqrt{s}$ = 7 TeV $\Rightarrow$ no significant differences.

- Theory jet quenching predictions by Wei Dai et al. (arXiv:1506.00838) compared to data.
- Good description of ratio within uncertainties.

- Comparison of η/π^0 ratio for two centrality classes to $K^\pm/\pi^\pm$ ratio measured by ALICE (PLB 736 (2014) 186).
- Consistency of trend and magnitude.

π^0-hadron correlations

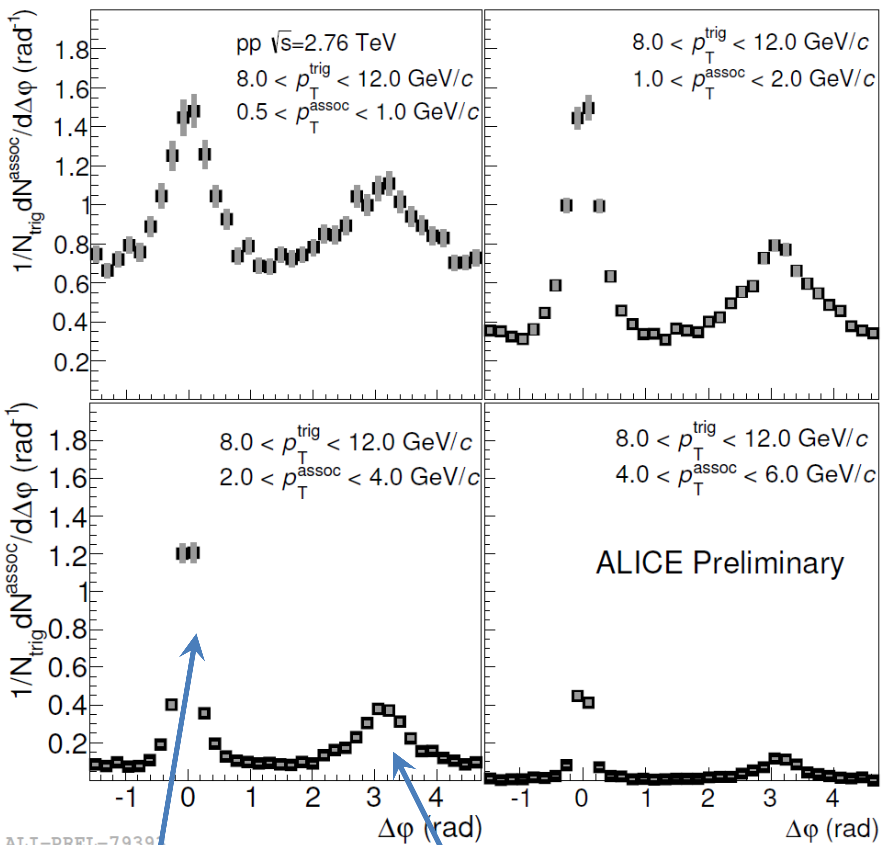


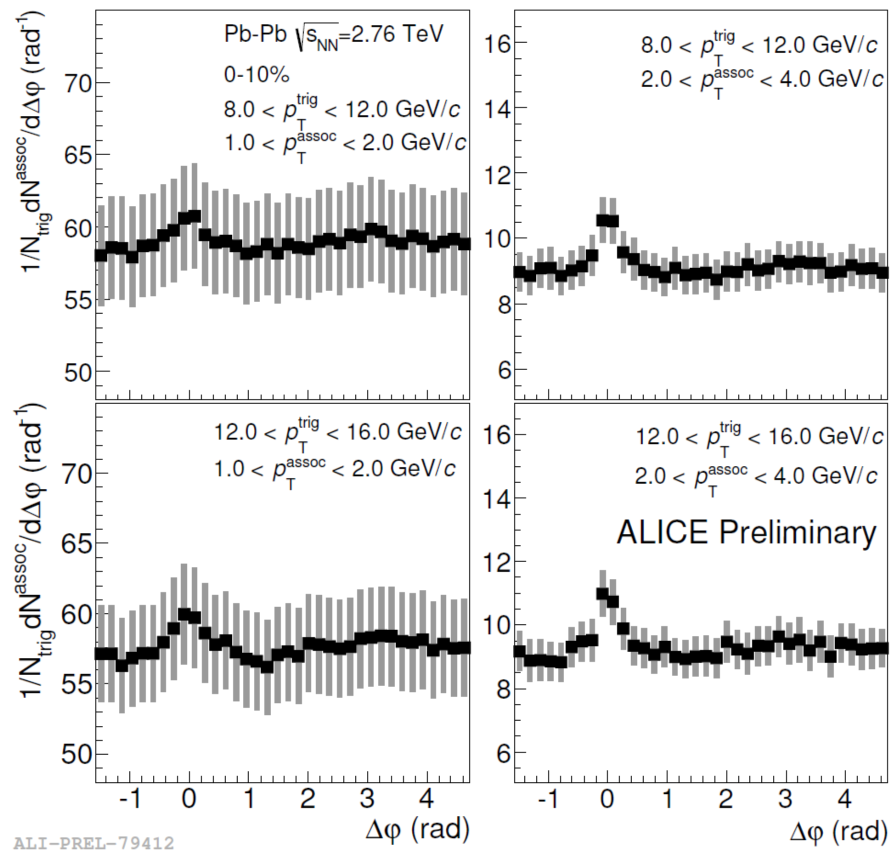
- Trigger particle:
  - high-p_T π^0 identified in EMCal
  - near side
- Associated particle:
  - charged hadron
  - away side
  - coming from parton traversing through matter which emerges attenuated
- Correlation in azimuthal angle:
  - $\Delta\varphi = \varphi^{trig} - \varphi^{assoc}$
- Medium induced per-trigger yield modification factor:

$$I_{AA}(p_T^{\pi^0}, p_T^{h^\pm}) = \frac{Y^{AA}(p_T^{\pi^0}, p_T^{h^\pm})}{Y^{pp}(p_T^{\pi^0}, p_T^{h^\pm})}$$

  - Near side: information on the fragmenting jet leaving medium
  - Away side: additionally reflects the probability that the recoiling parton survives the passage through the medium

π^0-$h^\pm$ azimuthal correlations in pp and Pb-Pb @ $\sqrt{s_{(NN)}}$ = 2.76 TeV

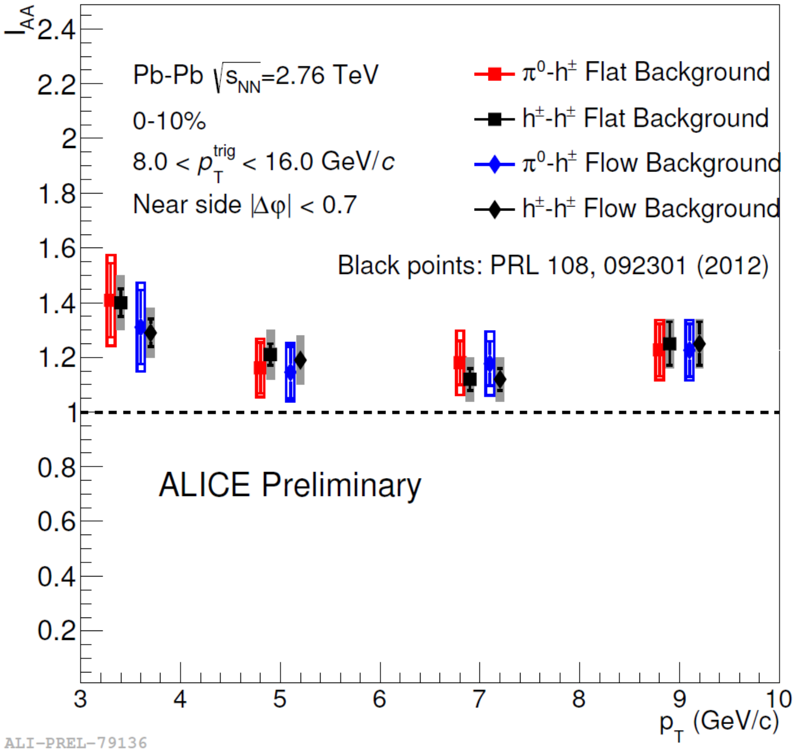


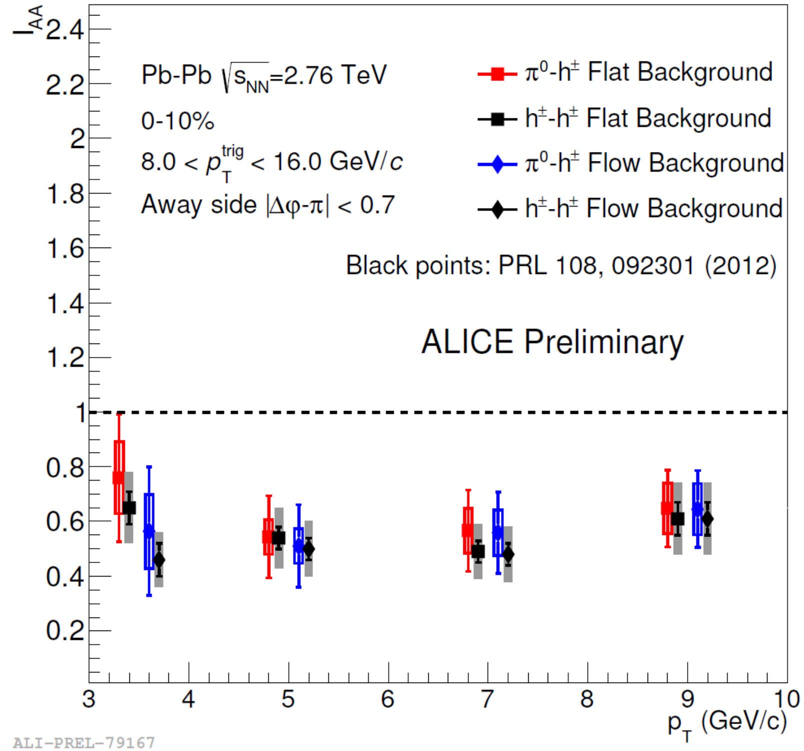


near side away side

- Both near and away peak well visible in pp

Per-trigger yield modification factor





- Good agreement between pi0-hadron and di-hadron correlations
- Near side – enhancement ($I_{AA} \approx 1.2$), probably due to:
  - Change of fragmentation function
  - Quark/gluon jet ratio modification
  - Bias on the parton p_T spectrum (due to energy loss)
- Away side – suppression ($I_{AA} \approx 0.6$), evidence of energy loss in medium

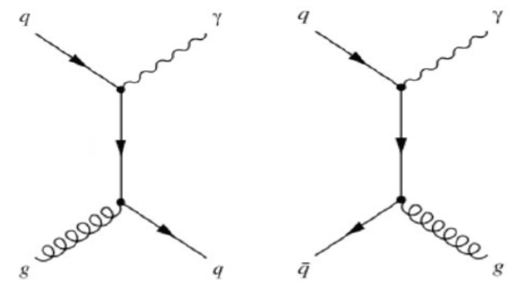
Method of direct photon measurement

- Direct photons = Inclusive photons – Decay photons

$$\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{1}{R}) \cdot \gamma_{inc}$$

$$R = \frac{\gamma_{inc}}{\gamma_{decay}}$$

- Decay photons
  - Come from photonic decays of particles like π^0, η or ω
  - Main background for direct photons
- Prompt photons
  - Produced in hard scattering of quarks and gluons
  - Contribute the most to hard part of direct photon spectrum (other contributions can come from fragmentation photons)
- Thermal photons
  - Come from volume of fireball
  - Dominant source for soft part of direct photon spectrum in Pb-Pb (other contributions: e.g. jet-medium photons or ISR)



➢ Double ratio

MC

$$R_\gamma = \frac{\gamma_{inc}}{\pi^0_{param}} / \frac{\gamma_{decay}}{\pi^0_{cocktail}} \approx R$$

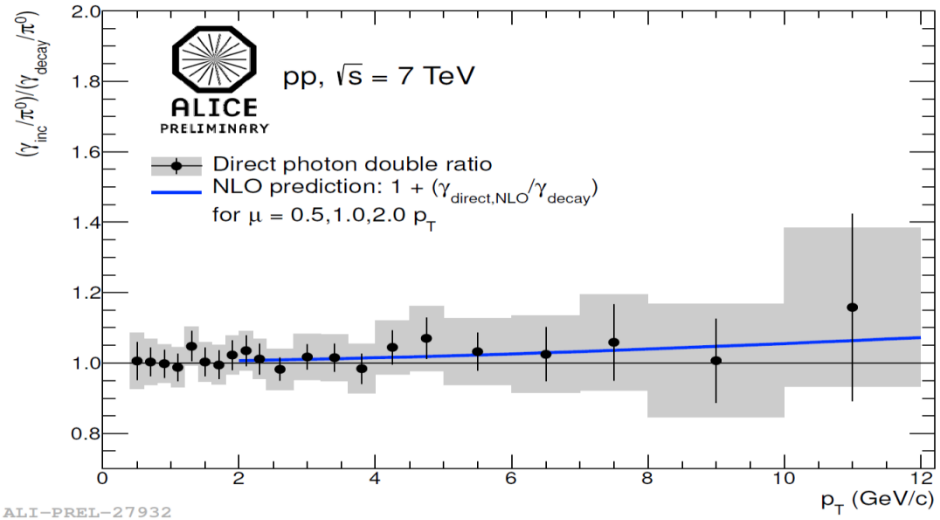
Data

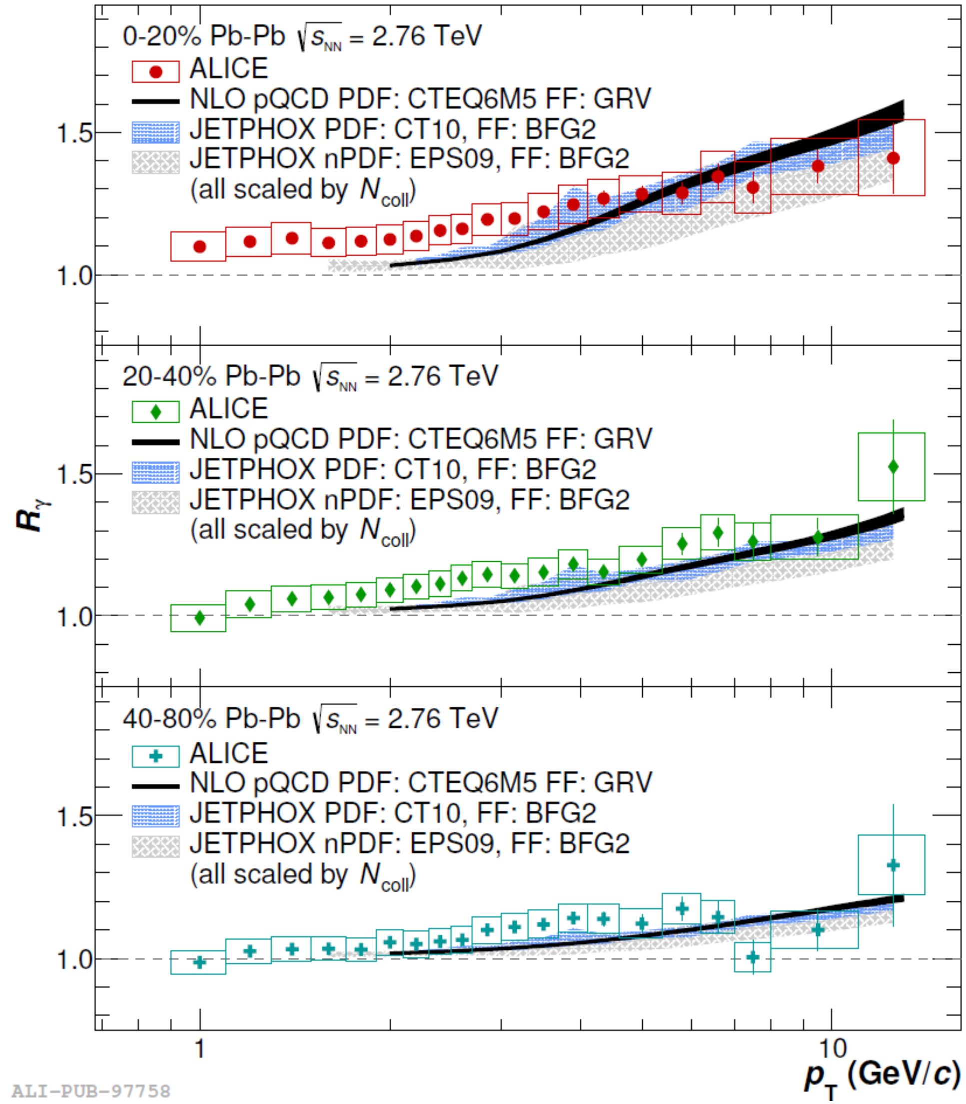
γ_{inc} – measured photon p_T spectrum
π^0_{param} – fit to measured π^0 meson p_T spectrum
γ_{decay} – evaluated by MC
$\pi^0_{cocktail}$ – evaluated by MC

$R_\gamma > 1$ indicates presence of direct photons

Direct photon double ratio

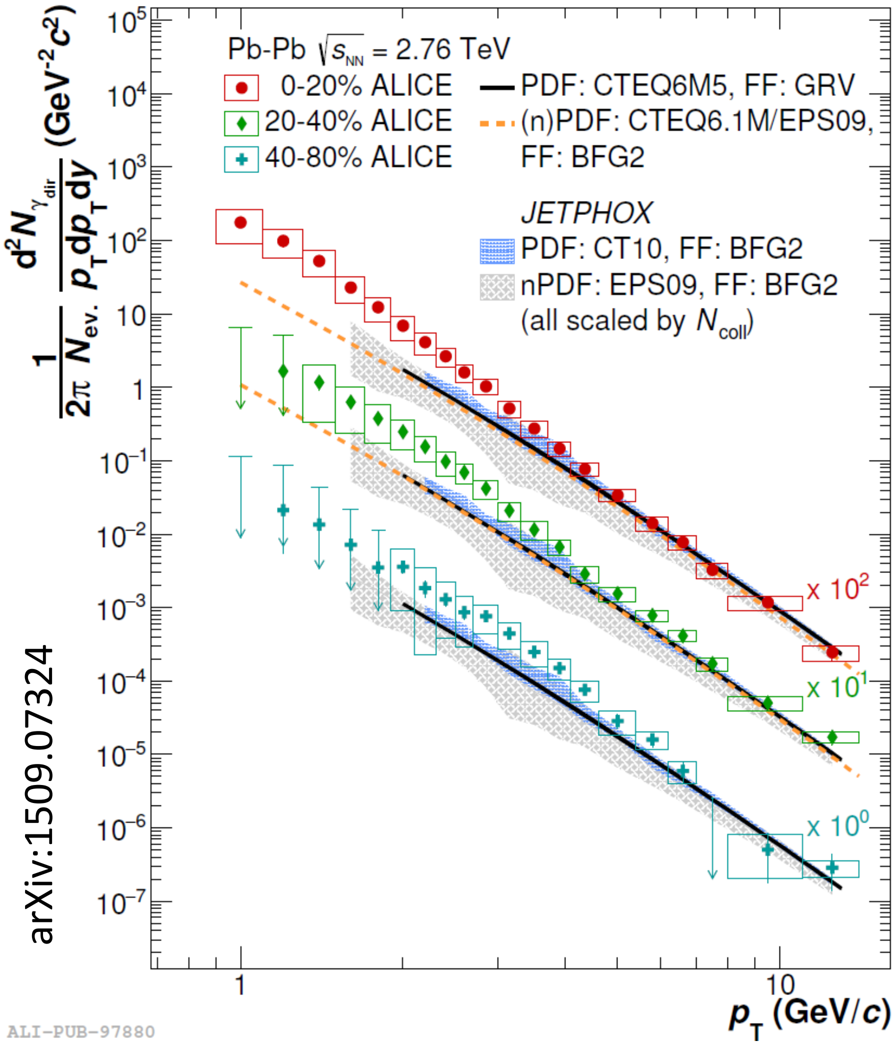
arXiv:1509.07324

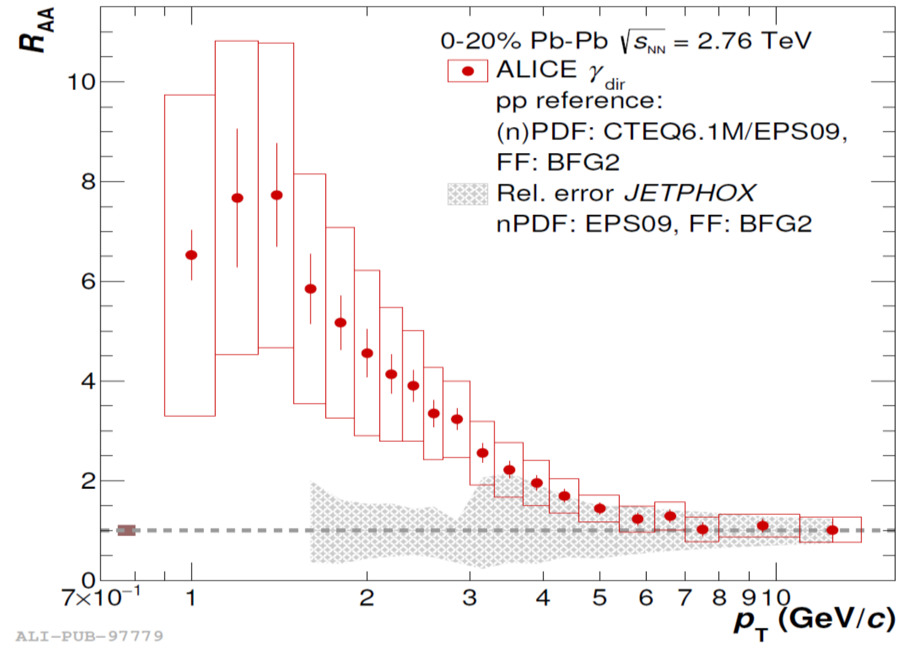




- Agreement with NLO pQCD predictions in pp collisions @ 7 TeV
- Excess of photons in Pb-Pb for all centrality classes in high p_T region compatible with pQCD predictions
- Excess of photons compared to NLO pQCD observed for $p_T \leq 4$ GeV/c in central Pb-Pb collisions
- Significance of 2.6 σ for $0.9 < p_T < 2.1$ GeV/c

Direct photon spectra and R_{AA}



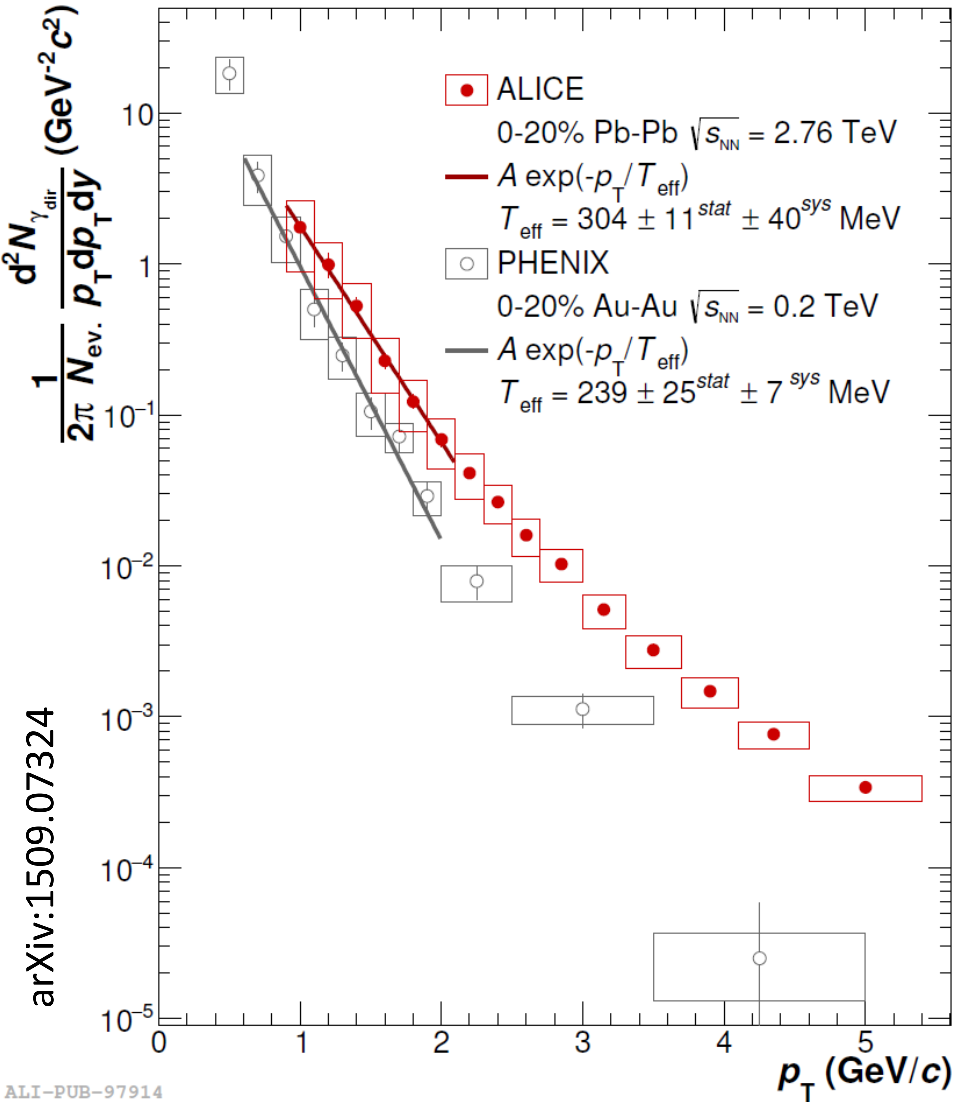


arXiv:1509.07324

- Three centrality classes
- Range: $0.9 < p_T < 14$ GeV/c
- Compared with N_{coll} scaled pQCD and JETPHOX calculations

  $\Rightarrow$ Good agreement with data for $p_T > 5$ GeV/c
- Excess for central and semi-central collisions at low p_T
- $R_{AA} > 6$ for central Pb-Pb in low p_T region

Direct photon spectrum compared to PHENIX

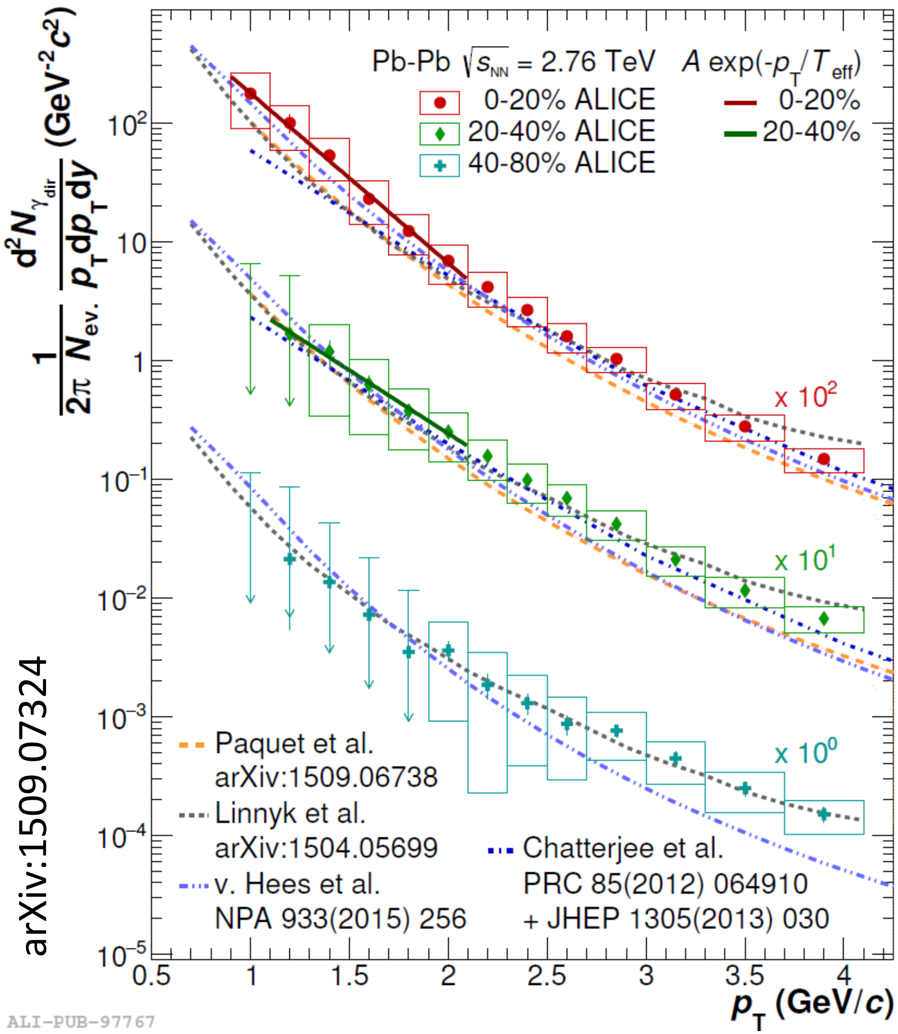


- For 0-20% Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
- Exponential fit $A \cdot \exp(-p_T/T_{eff})$ for p_T < 2.2 GeV/c

$\Rightarrow$ inv. slope $T_{eff} = 304 \pm 11^{stat} \pm 40^{sys}$ MeV

- effective temperature ~ 300 MeV $\rightarrow$ largest ever man-made
- Be careful with interpretation!
- PHENIX: $T_{eff} = 239 \pm 25^{stat} \pm 7^{sys}$ MeV for 0-20% Au-Au at $\sqrt{s_{NN}}$ = 200 GeV (PRL 104 (2010) 132301, PRC 91, 6 (2015) 064904)

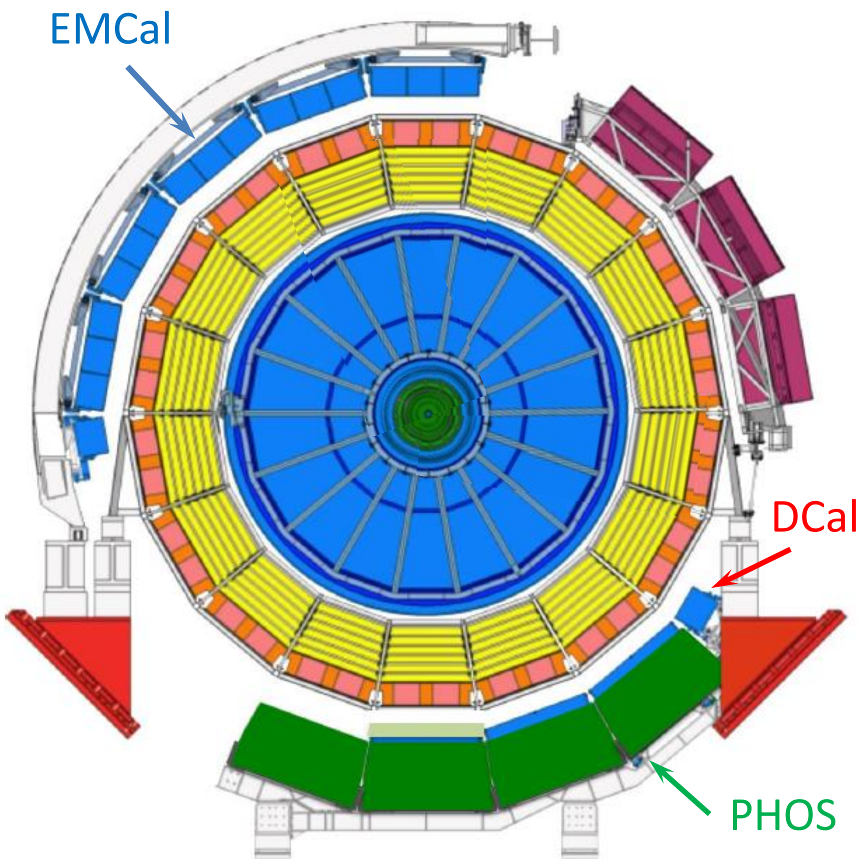
Direct photon spectrum compared to theory



arXiv:1509.07324

- Various models available
- All models assume QGP formation and include pQCD photons at high p_T
- Different level of agreement
- Treatment of space-time evolution
  - Paquet et al.: 2+1 viscous hydro with IP-GLASMA initial conditions, τ_0 = 0.14 fm/c, $\langle T_{init}^{0\text{-}20\%} \rangle$ = 385 MeV,
  - Linnyk et al.: off-shell transport, microscopic description of evelution,
  - v. Hees et al.: ideal hydro with initial flow, τ_0 = 0.2 fm/c, $T_{init}^{0\text{-}20\%}$ = 682 MeV,
  - Chatterjee et al.: 2+1 hydro, fluctuating initial conditions, τ_0 = 0.14 fm/c, $T_{init}^{0\text{-}20\%}$ = 740 MeV.

ALICE detector – Run II



EMCal:

- 12 SM (10 + 2 × 1/3)
- $|\eta| < 0.7$
- $80° < \varphi < 187°$ ($\Delta\varphi = 107°$)

PHOS:

- 3.5 SM
- $|\eta| < 0.12$
- $250° < \varphi < 320°$ ($\Delta\varphi = 70°$)

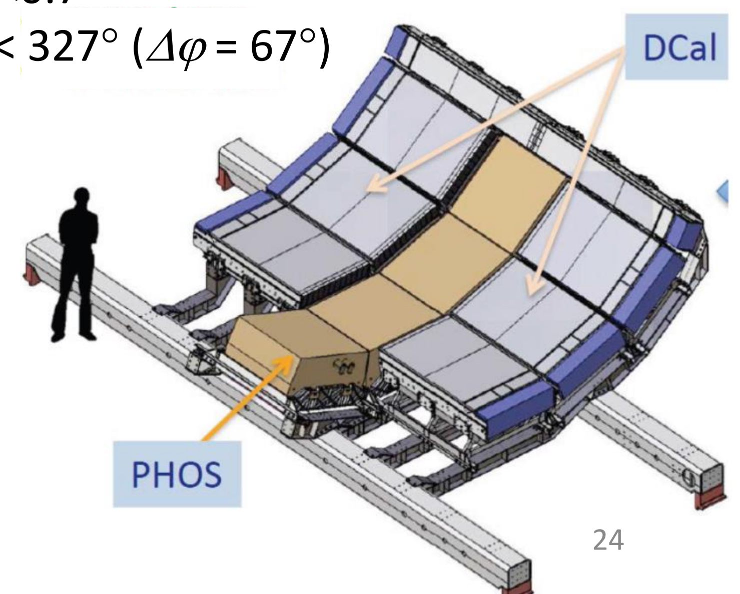
DCal:

- 6 × 2/3 SM + 2 × 1/3 SM
- $0.22 < |\eta| < 0.7$
- $260° < \varphi < 327°$ ($\Delta\varphi = 67°$)

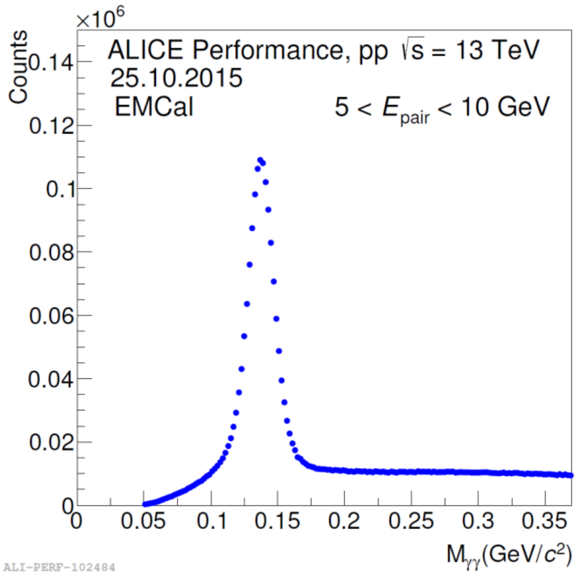
Super Module:

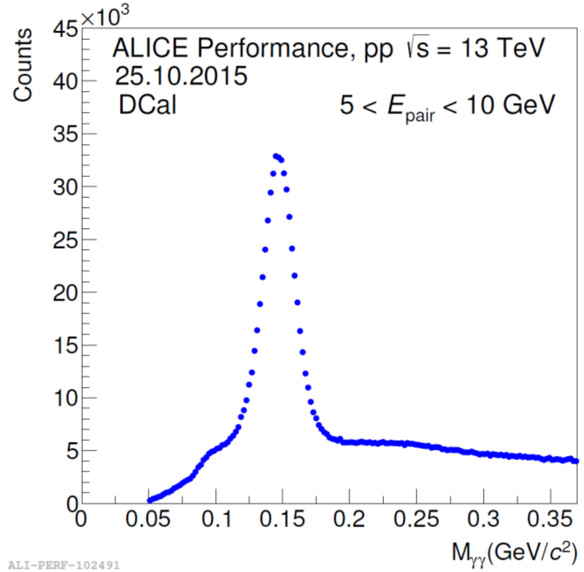
- $\Delta\varphi = 20°$
- $\Delta\eta = 0.7$ (EMCal)
- $\Delta\eta = 0.12$ (PHOS)

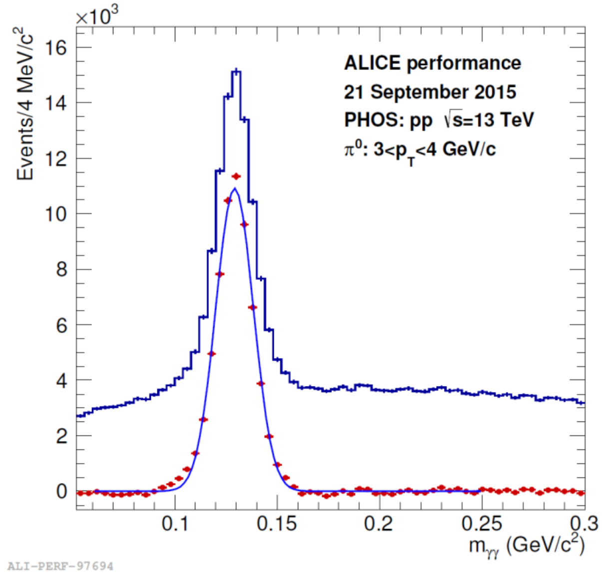
- Run II – 2015 - 2018
- pp @ 5 TeV, 13 TeV, HI @ 5 TeV
- Calorimeters acceptance gain ~1.6 of Run I

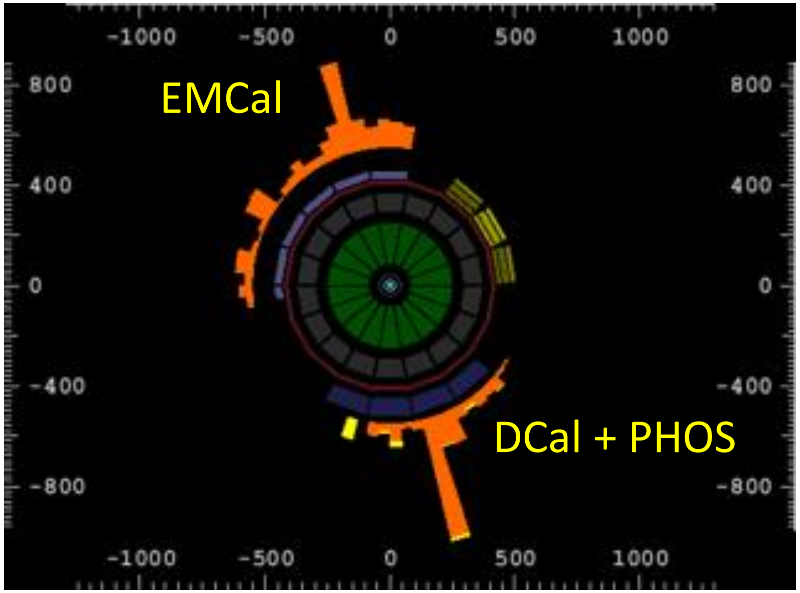


Colorimeters performance









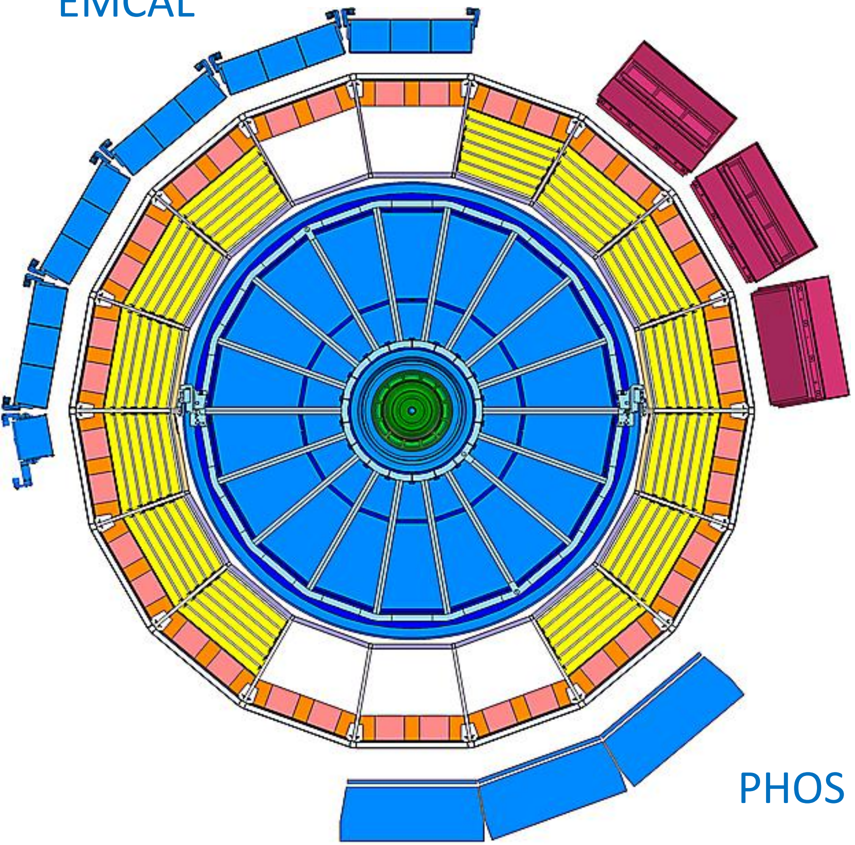
- Improvement of calibration on progress
- Calorimeters were fully operational in Run II Pb-Pb data taking period ($L_{int}^{CALO} \approx 126\ \mu b^{-1}$)
- Very promising periods of data taking

Summary

- ALICE can measure neutral mesons in wide p_{T} range
- Measurements allowed us to test perturbative QCD inspired models and parametrization of parton distribution and fragmentation functions
- Very strong π^0 suppression in Pb-Pb: $R_{\mathrm{AA}}^{\pi 0} \sim 0.1$
- First measurement of η meson in Pb-Pb collisions was shown
- Medium effects were observed in π^0-hadron correlations
- Excess in the double ratio $R_\gamma > 1$ for central Pb-Pb collisions was found to be not compatible with pQCD below 4 GeV/c
- Various models with QGP formation show different levels of agreement
- Effective temperature from direct photon spectrum is ~ 300 MeV
- Analysis of Run II data ongoing $\rightarrow$ new and interesting results are expected

Backup

ALICE detector - 2012



EMCAL:
- 12 SM* (10 + 2 × 1/3)
- $|\eta| < 0.7$
- $80° < \phi < 187°$ ($\Delta\phi = 107°$)

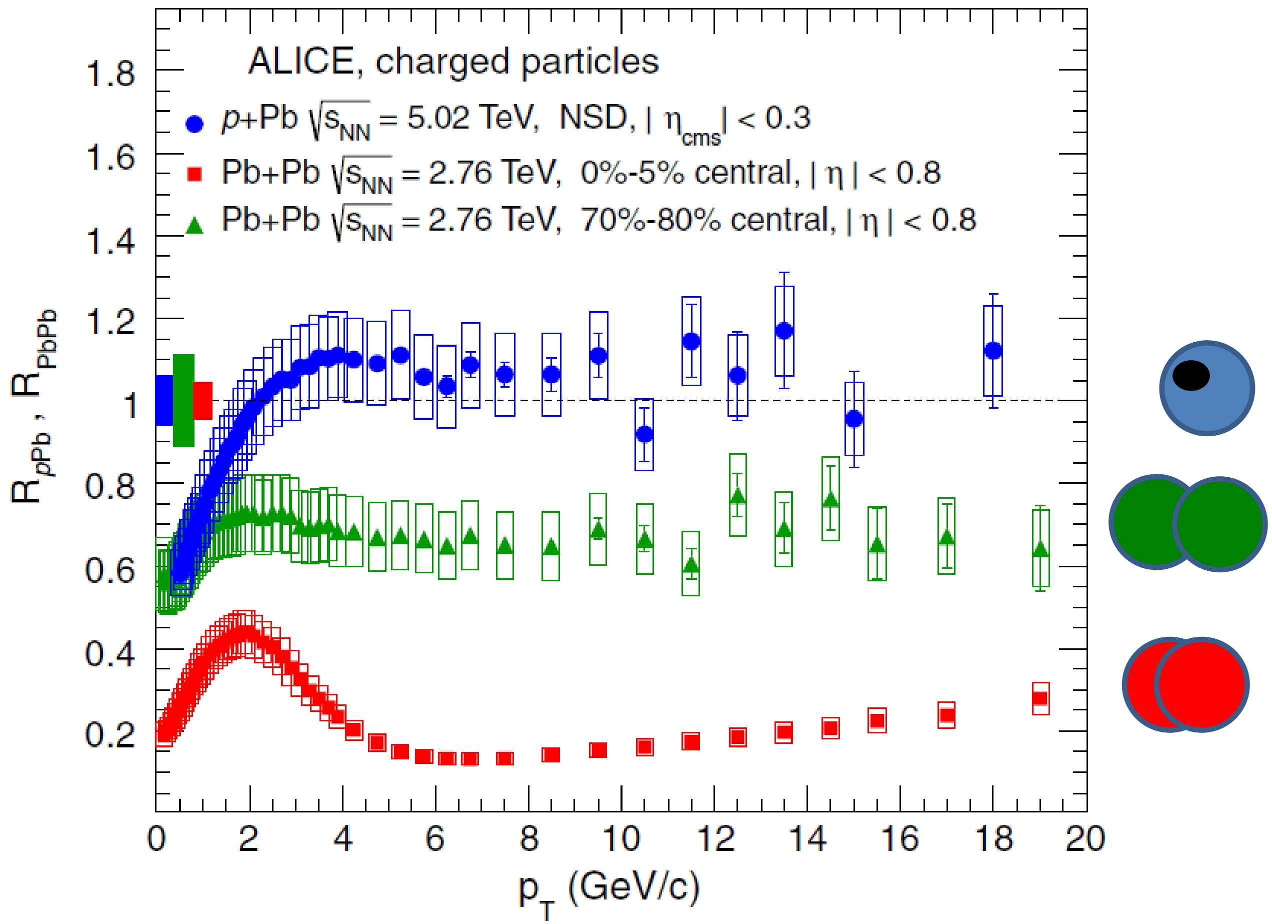
PHOS:
- 3 SM
- $|\eta| < 0.12$
- $260° < \phi < 320°$ ($\Delta\phi = 60°$)

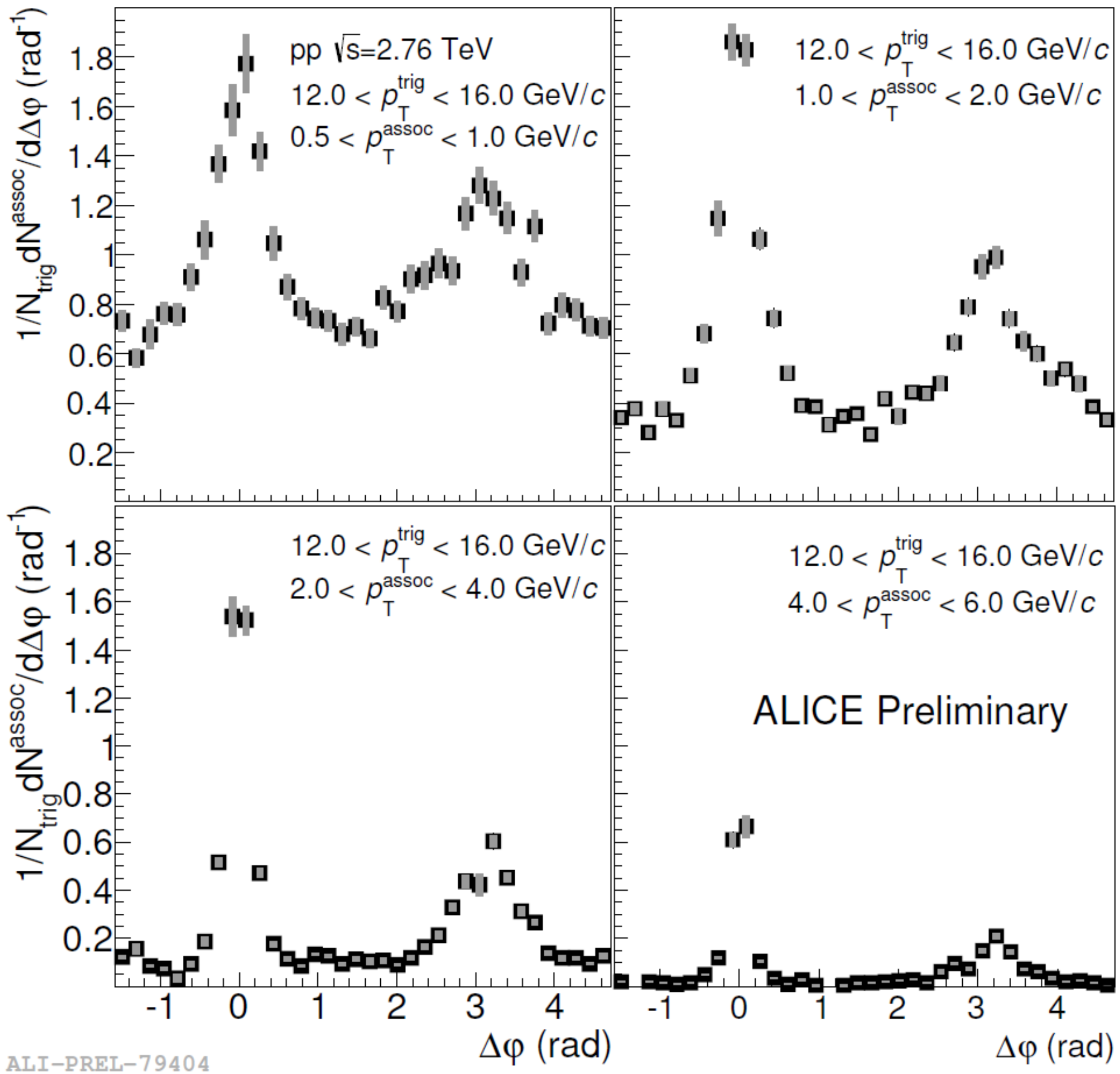
*10 SM are in readout

- Run I – 2012
- pp @ 8 TeV, p-Pb @ 5.02

R_{AA} for p-Pb and Pb-Pb

PRL 110, 082302 (2013)

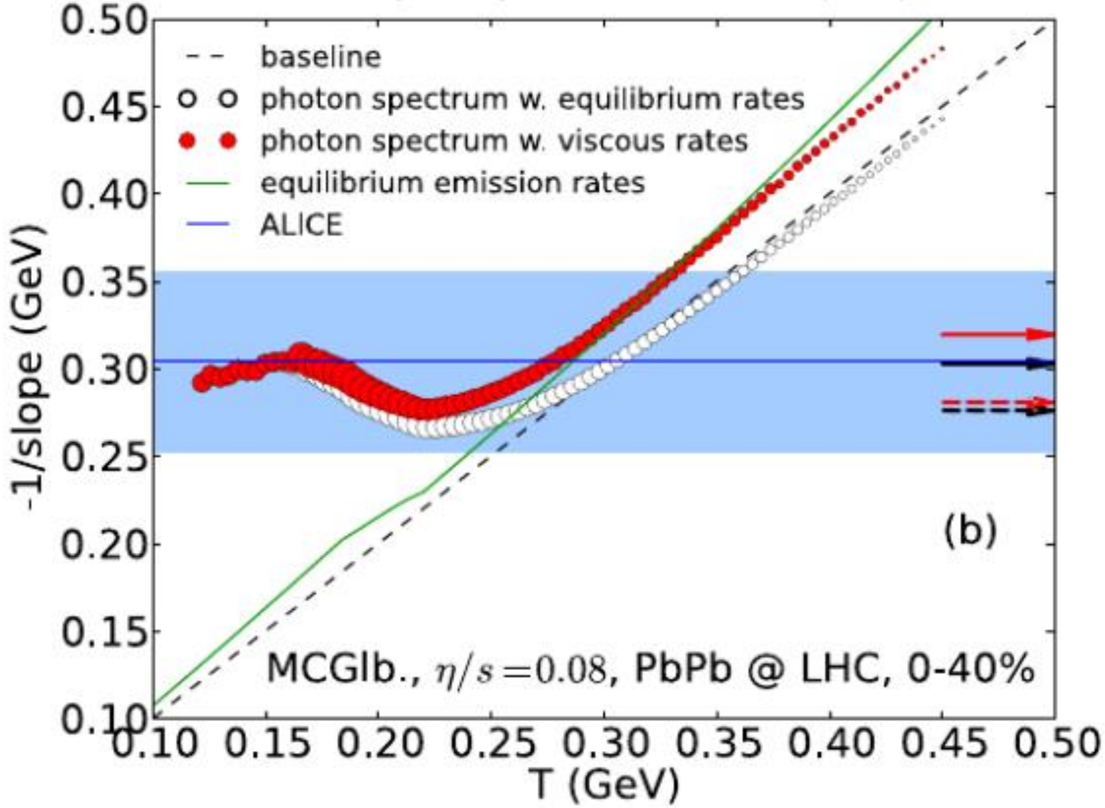



pp $\sqrt{s}$=2.76 TeV
$12.0 < p_T^{trig} < 16.0$ GeV/c
$0.5 < p_T^{assoc} < 1.0$ GeV/c
$12.0 < p_T^{trig} < 16.0$ GeV/c
$1.0 < p_T^{assoc} < 2.0$ GeV/c
$12.0 < p_T^{trig} < 16.0$ GeV/c
$2.0 < p_T^{assoc} < 4.0$ GeV/c
$12.0 < p_T^{trig} < 16.0$ GeV/c
$4.0 < p_T^{assoc} < 6.0$ GeV/c
ALICE Preliminary
$1/N_{trig} dN^{assoc}/d\Delta\varphi$ (rad^{-1})
$\Delta\varphi$ (rad)
ALI-PREL-79404

Doppler-shifted effective temperature:

$$T_{\mathrm{eff}} = T \cdot \sqrt{\frac{1+\beta}{1-\beta}}$$

C. Shen, U. Heinz, J.-F. Paquet, C. Gale, PRC 89 (2014) 4, 044910



Centrality estimation in Pb-Pb

Phys. Rev. C 88, 044909 (2013)

- Centrality observables
  - Charge particle multiplicity in VZERO
  - Forward energy in ZDC
  - SPD for systematics
- Number of particle sources

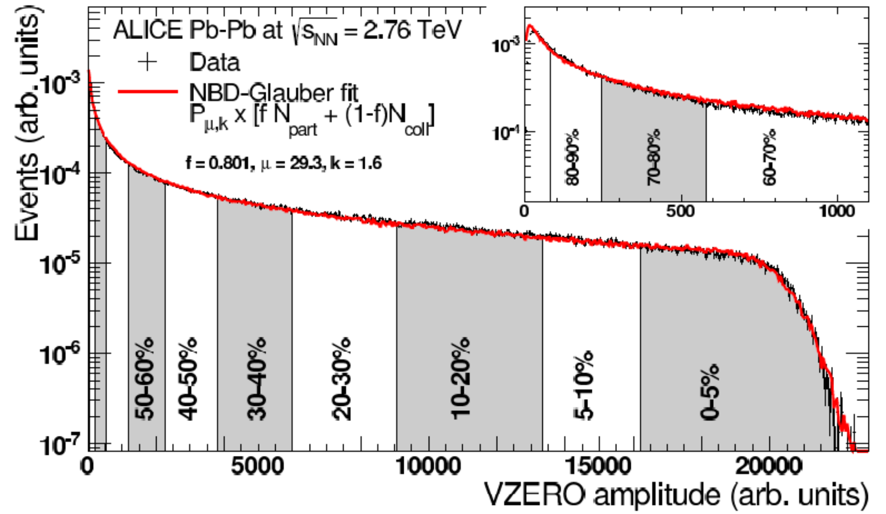
  $f \times N_{part} + (1 - f) \times N_{coll}$
- Number of particles produced by each source given by Negative Binomial Distribution (μ, κ)
- Glauber model fits to cross-section
  - 100% trigger efficiency
  - Background is negligible

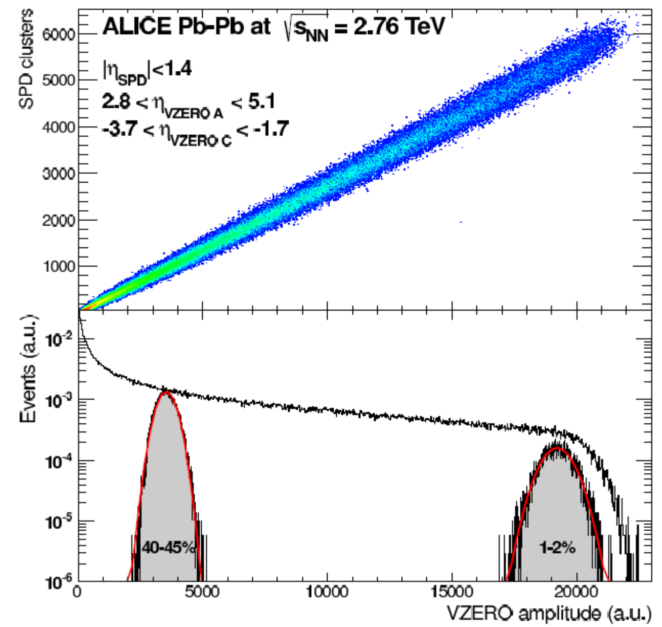
  $\rightarrow$ ~ 90% of total cross-section

  with $\sigma_{INEL}^{NN} = 64 \pm 5$ mb

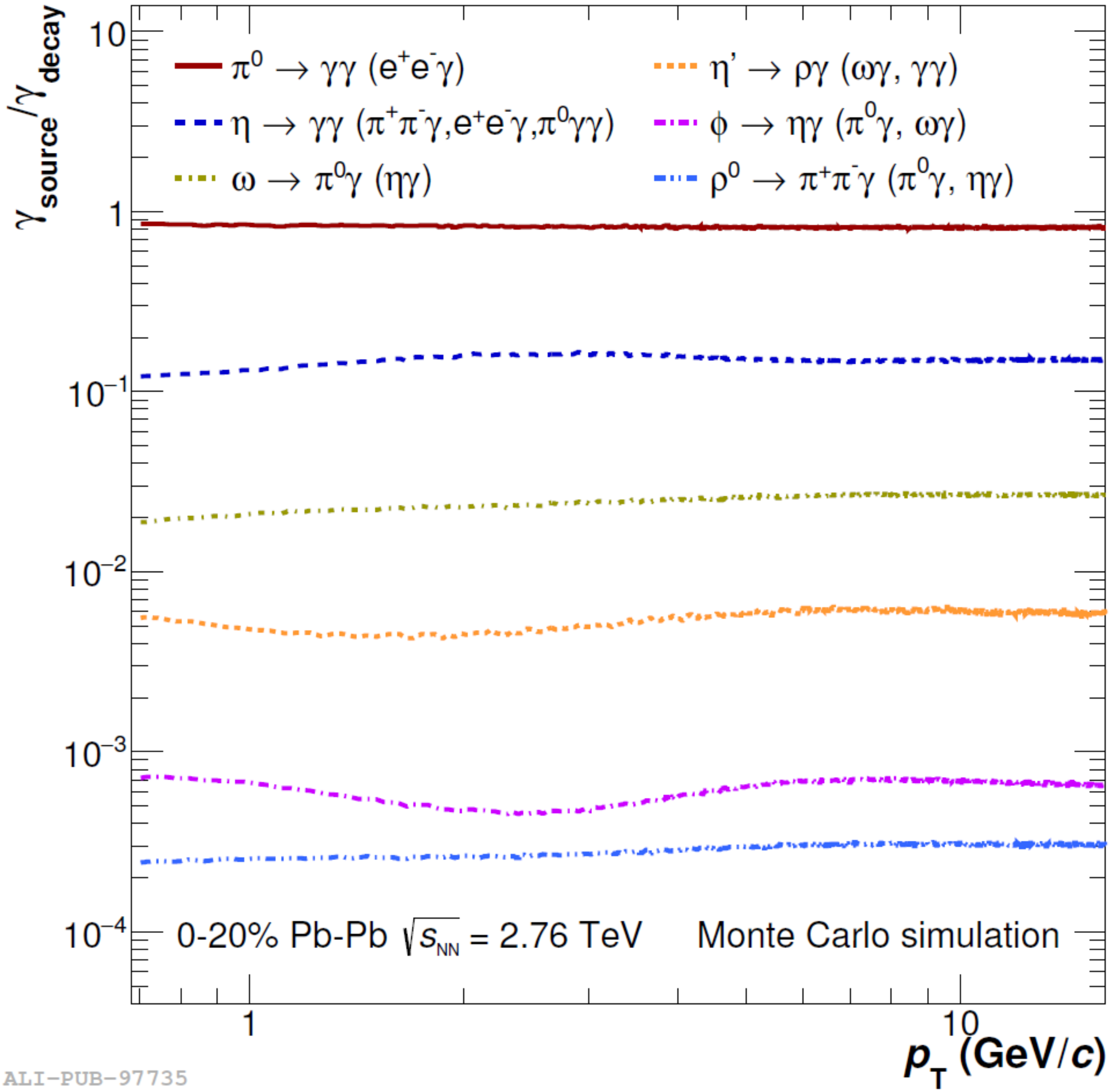
  <1% agreement (0-70%) N_{part} with Glauber fit

  3.5 % for peripheral (>70%)
- Define centrality classes corresponding to fractions of the inelastic Pb-Pb cross-section





Decay photon sources



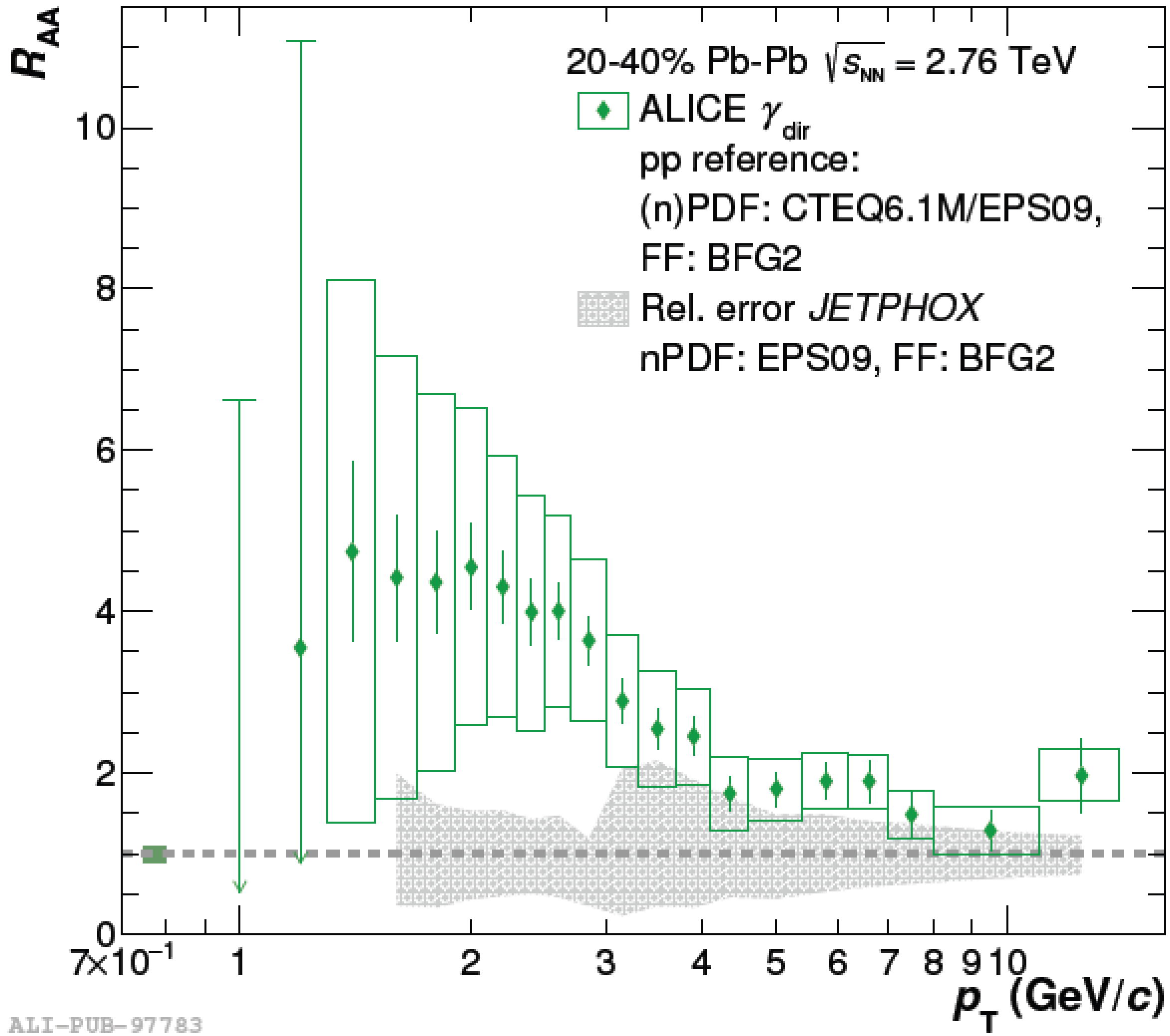
π^0: ≈ 86-88%

η: ≈ 10-12%

ω: ≈ 2-3%

others: very small

Direct photon R_{AA} in Pb-Pb for centrality 20-40 %



Functions

- Tsallis

$$f(p_T) = \frac{1}{2\pi}\frac{dN}{dy}\frac{(n-1)(n-2)}{nT(nT+m(n-2))}(1+\frac{\sqrt{p_T^2+m^2}-m}{nT})^{-n}$$

$$E\frac{d^3\sigma^{pp\to\pi^0X}}{dp^3} = \frac{\sigma_{pp}^{INEL}}{2\pi}A\frac{(n-1)(n-2)}{nC[nC+m(n-2)]}(1+\frac{m_T-m}{nC})^{-n}$$

- Hagedorn

$$E\frac{d^3\sigma^{pp\to\pi^0X}}{dp^3} = (\frac{p_0}{p_0-p_T})^n$$

- Power law

$$E\frac{d^3\sigma^{pp\to\pi^0X}}{dp^3} = c(\frac{1}{p_T})^n$$