Production of light neutral mesons in the ALICE experiment

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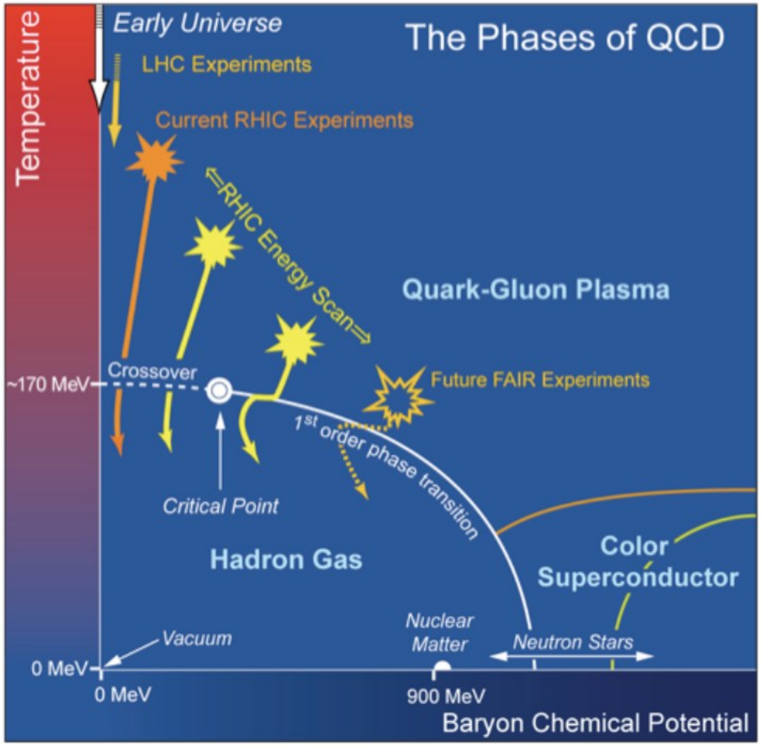
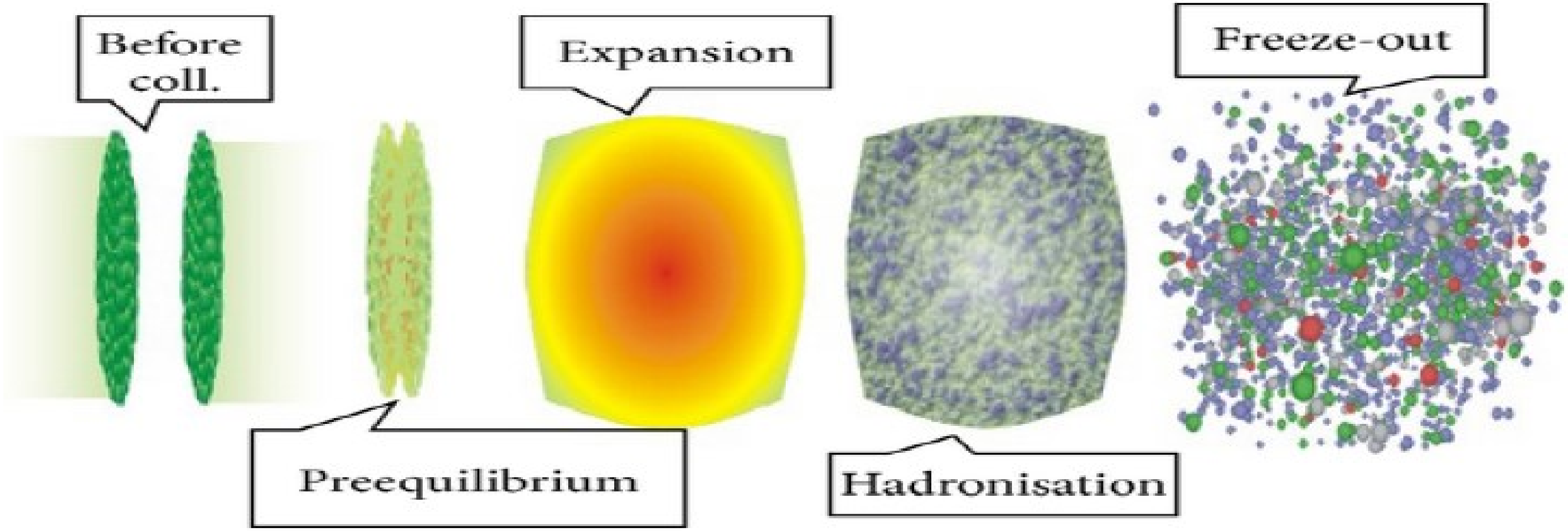
NZ23 Seminar

- Motivation
- ALICE subdetectors
- Reconstruction methods
- Neutral mesons in pp, p-Pb and Pb-Pb collisions
  - Production spectra, ratios, R_{AA}
- Summary++

Motivation

- Explore Quantum Chromodynamics (QCD) in unknown regimes → study QCD phase diagram
- Investigate properties of nuclear matter at high temperature ($T \geq 170$ MeV or 2×10^{12} K) and density
- Important input for the understanding of the chiral symmetry restoration and the deconfinement (transition from hadronic to quark matter)



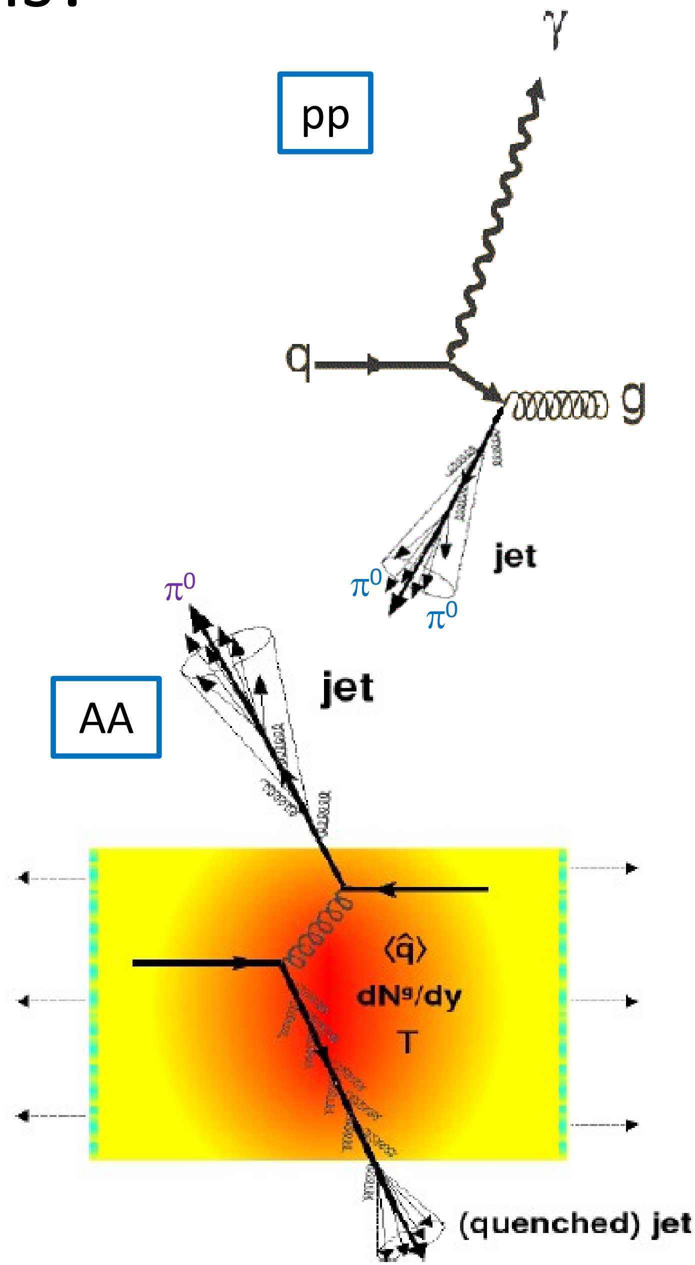


Why neutral mesons?

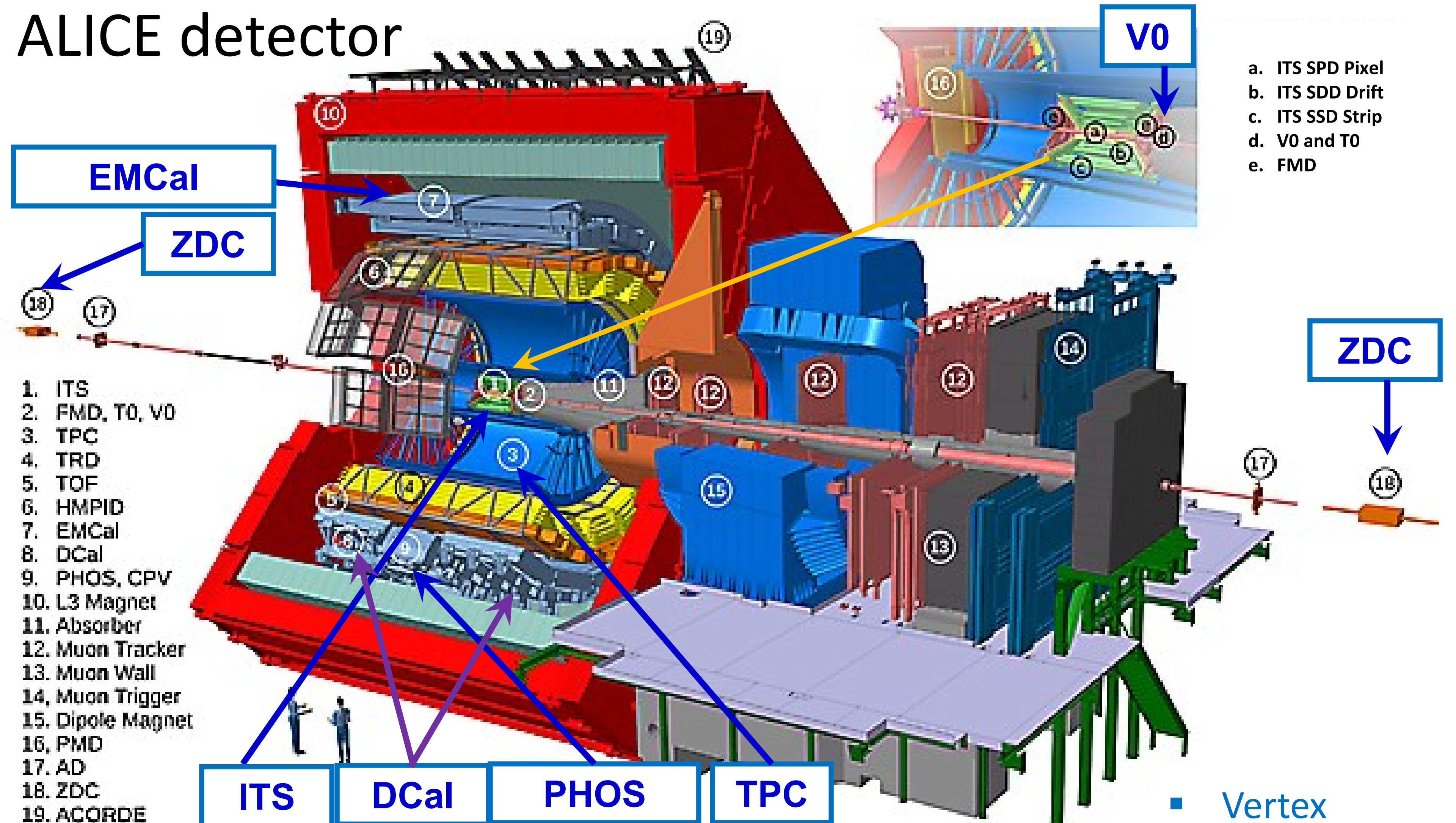
- Meson production in pp should be described by pQCD at large transverse momentum
  ⇒ How well do the current pQCD calculations describe the neutral meson production?
- Neutral meson spectra allow to put constraints on parameters of theoretical models in both perturbative (NLO, NNLO) and non-perturbative regime (parton distribution function, fragmentation function)
  ⇒ What about fragmentation and hadronization in modern Monte-Carlo generators?
- Hadrons carry information about medium
  - Studies of transport properties of quark-gluon matter
  - Initial gluon density

  ⇒ Do we understand hydrodynamic evolution of the matter produced in Pb-Pb or p-Pb collisions?

  ⇒ Is centrality evolution or strength of particle production reproduced?
- Test scaling laws
  ⇒ What about very low-p_T?
- Disentangle initial/final state effects

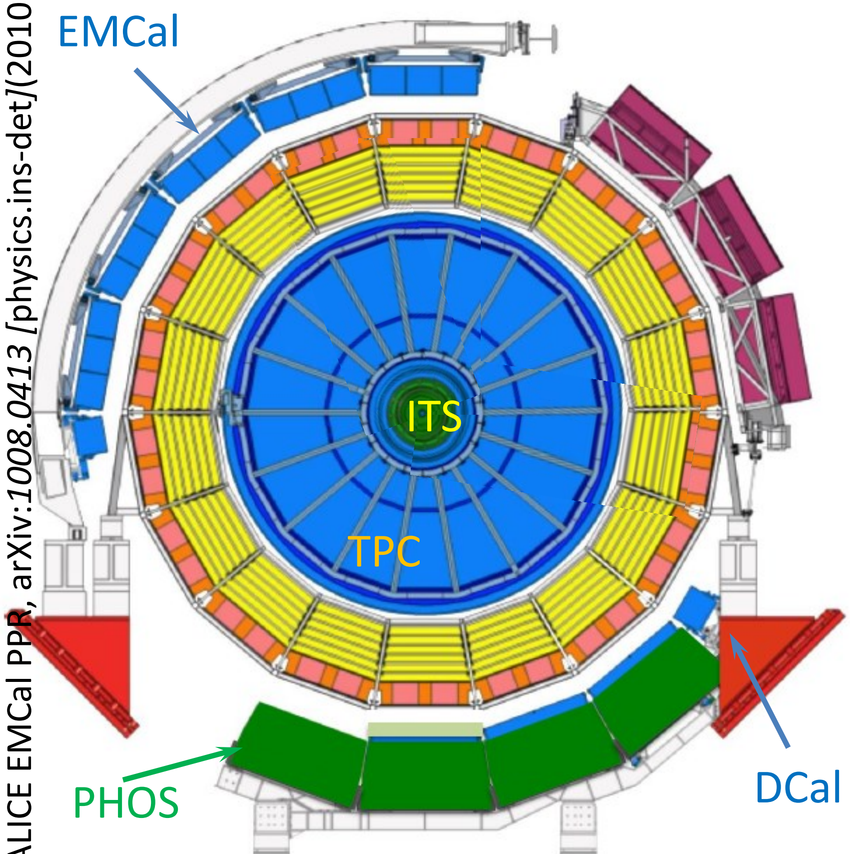


ALICE detector



- Vertex
  - Pixel
- V0 and ZDC
  - Centrality determination
  - Trigger
- Tracking ($e^{\pm}$, $h^{\pm}$)
  - PCM (γ, π^0, η)
  - TPC - gas drift detector
  - ITS - silicon detector
- EMCal + DCal (γ, π^0, η)
  - Pb-scintillator sampling calorimeter
  - Trigger
- PHOS (γ, π^0, η)
  - $PbWO_4$ crystal spectrometer
  - Trigger

Calorimeters



ALICE EMCal PPR, arXiv:*1008.0413* [physics.ins-det](2010).

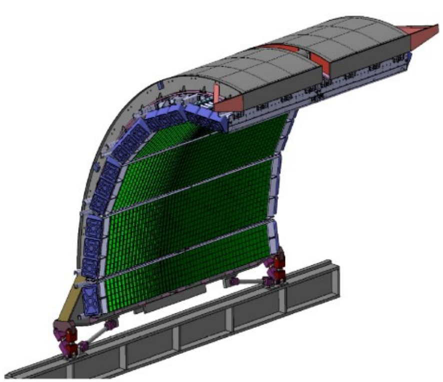
EMCal + DCal - electromagnetic calorimeter

- Lead (76 layers) scintillator (77 layers) shashlik
- Tower size: 6 cm × 6 cm × 24.6 cm
- 20 super-modules (10 + 4 × 1/3 + 6 × 2/3)
- Acceptance: 80° < φ < 187°, $|\eta|$ < 0.7 (EMCal)
- Acceptance: 260° < φ < 320°, 0.22<$|\eta|$<0.7 (DCal)
- Acceptance: 320° < φ < 327°, $|\eta|$<0.7 (DCal)
- 428 cm from the beam line
- ~ 20 radiation length
- Energy resolution:

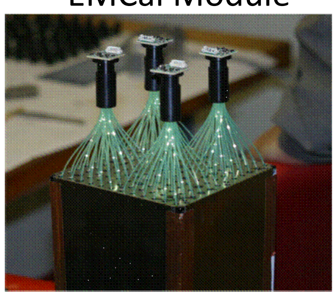
$$\sigma/E = (4.8 \pm 0.8)/E \oplus (11.3 \pm 0.5)/\sqrt{E} \oplus (1.7 \pm 0.3)\%.$$

PHOS – photon spectrometer

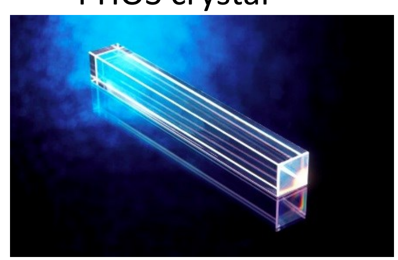
- Crystal of lead tungstate ($PbWO_4$)
- 3.5 × 64 × 56 crystals of size: 2.2 × 2.2 × 18 cm^3
- Acceptance: 250° < φ < 320°, $|\eta|$ < 0.12
- Energy resolution: $\sigma/E = 1.3/E \oplus 3.3/\sqrt{E} \oplus 1.12\%$
- Distance to IP: 4.6 m

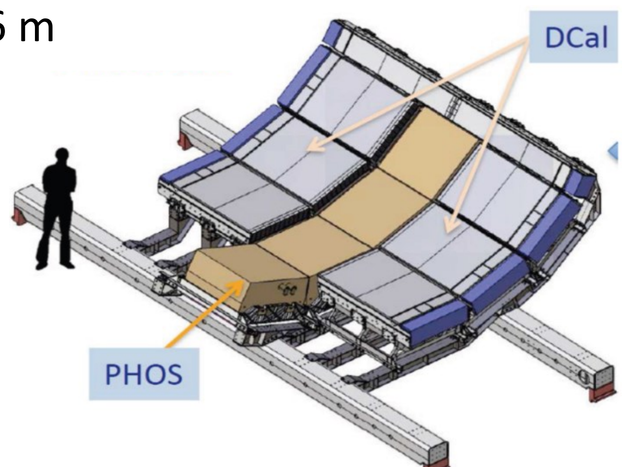


EMCal Module

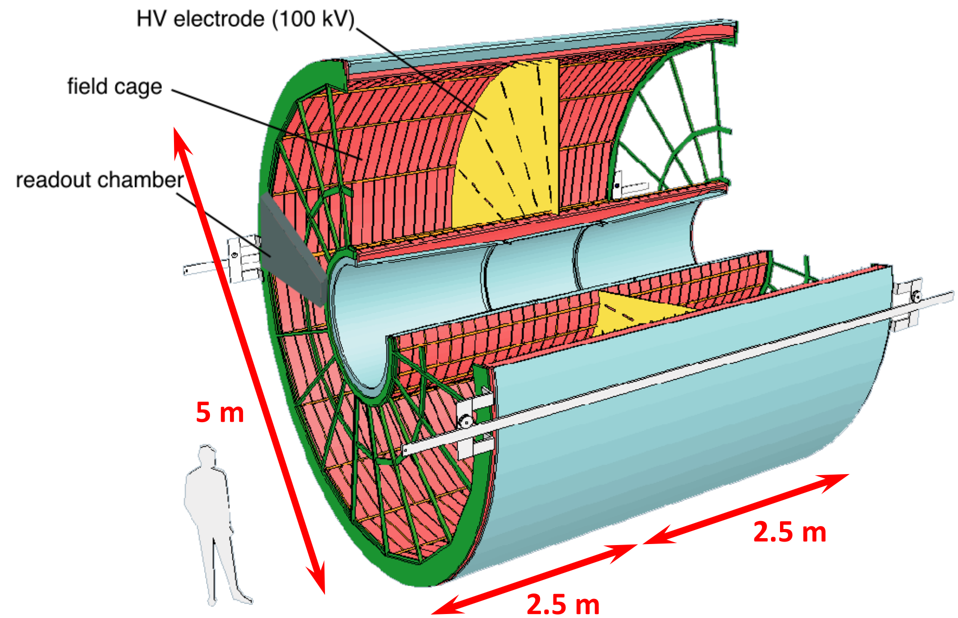


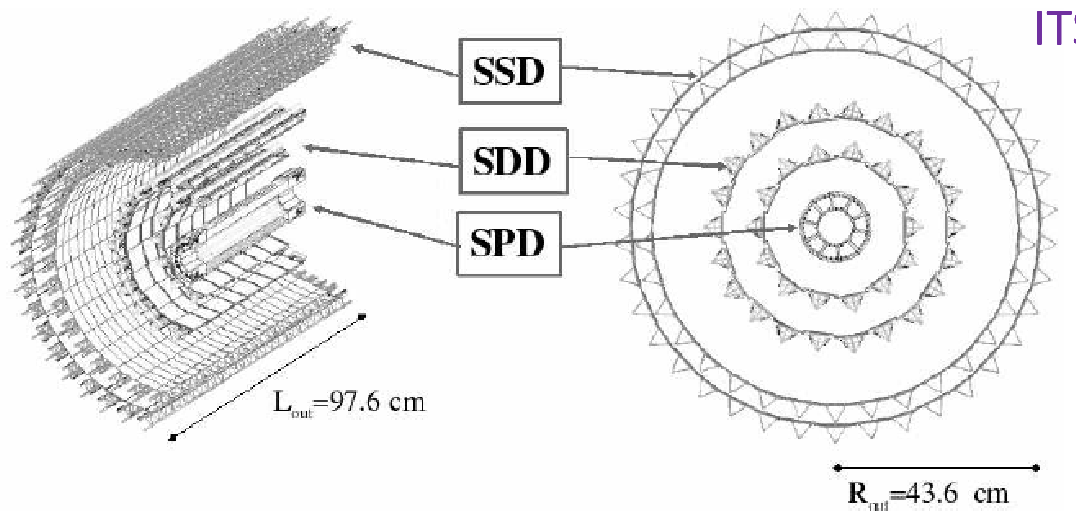
PHOS crystal





Tracking System = ITS + TPC





TPC – time projection chamber

- Diameter × Length : 5 m × 5 m
- Acceptance: $\Delta\varphi = 2\pi$, $|\eta|<0.9$
- Readout chambers: 72
- Pad readout (3 types): 557 568
- Drift field: 400 V/cm
- Maximum drift time: 92 μs
- Central electrode HV: 100 kV
- Gas:
  - Active volume: 90 m^3
  - Ne-CO_2-N_2: 85.7% - 9.5% - 4.8%

ITS – inner tracking system

- Layout
  - 2 layers of pixel detectors
  - 2 layers of drift detectors
  - 2 layers of strip detectors
- Acceptance: $\Delta\phi = 2\pi$, $|\eta|<0.9$

TS energy resolution: $\Delta E/E \approx 2\%$

Triggers and datasets

- MB (aka INT7):
  - coincidence of signal in both V0A and V0C
- EMCal trigger EMC7:
  - EMCal L0 trigger - 2x2 FastOR (4x4 cells) sliding window AND INT7
  - Threshold 2 GeV
- EMCEGA:
  - Higher thresholds: 5 and 9 GeV
- EMCal jet trigger EMCEJE:
  - 8x8 FastORs (16 x 16 cells)
  - Threshold 20 GeV
- PHI7:
  - 2x2 FastOR (4x4 cells) sliding window
  - Threshold 4 GeV

	$\sqrt{s}$ (TeV)	Data Set		Used triggers	# events
pp	5	Data	LHC15n pass 4	INT7	0.1 B
		Data	LHC15n pass 4	CF-EMC7	1.17 M
		PYTHIA8 (MC)	LHC17e2 + LHC18j3	INT7	0.09 B
		PYTHIA8 JJ (MC)	LHC16h3	Mimicking	145 M
pp	5	Data	LHC17p + LHC17q pass 1 FAST & CENT(woSDD)	INT7	0.83 B
		Data	LHC17p + LHC17q pass 1	kPHI7	1.2 M
		Data	LHC17p + LHC17q pass 1	CF-EG2	10.7 M
		PYTHIA8 (MC)	LHC17l3b + LHC18j2 FAST & CENT(woSDD)	INT7	0.72 B
		PYTHIA8 JJ (MC)	LHC18b8	Mimicking	28.7 M

	$\sqrt{s}$ (TeV)	Data Set		Used triggers	Number of events
Pb-Pb	5	Data	LHC15o	0-10%	7.36 M
				10-30%	14.7 M
				30-50%	14.8 M
				50-90%	29.5 M
Pb-Pb	5	Data	LHC18qr	0-10%	148.9 M
				10-30%	17.6 M
				30-50%	86.6 M
				50-90%	34.1 M

Used MC datasets: Pb-Pb

- 5 Anchored to 2015: LHC16h4, LHC18e1, LHC18e1(a,b,c)
- 7 anchored to 2018: LHC18l8(a4,b2,c2), LHC19h3, LHC19h2(a,b,c)

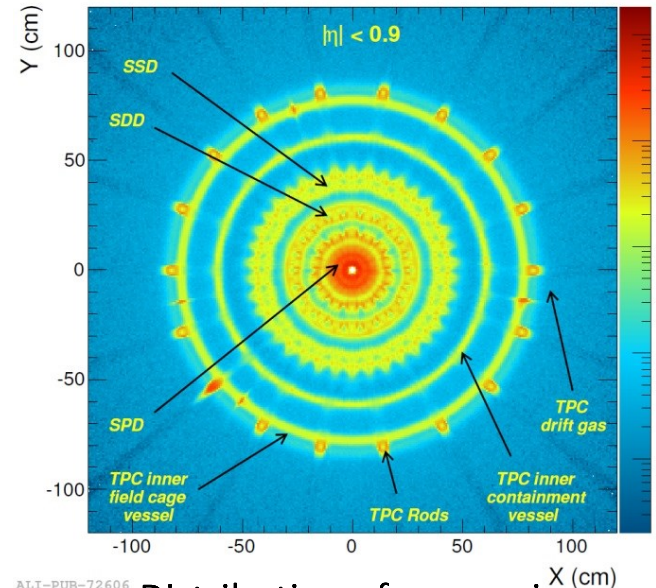
Method of photon extraction

- Energy deposit in calorimeter (EMCal, PHOS)
- External conversion electrons , $\gamma \rightarrow e^+ e^-$ (PCM)
  - Radiation length X/X0 = (11.4 ± 0.5) %
  - Small conversion probability (~ 8.5 %) is compensated by a wide acceptance
  - Material budget well known with relative precision of 4.5 %

Variable	Requirement
V0-finder	On-the-fly
Topology cut	no kinks
TPC refit	Required
p_T	> 50 MeV/c
Cut on $\frac{N_{\mathrm{clusterTPC}}}{N_{\mathrm{findableclusters}}}$	$> 60\%$
η cut for tacks and V^0	$\lvert\eta\rvert < 0.8$
Cut on R_{conv}	5 cm $< R_{\mathrm{conv}} <$ 180 cm
Cut on Z_{conv}	$\lvert Z_{\mathrm{conv}}\rvert <$ 240 cm

Table 2: Summary of track and V^0 selection cuts.

$$R_{\mathrm{conv}} > Z_{\mathrm{conv}} \cdot S(\eta_{\mathrm{cut}}) - Z_0$$
$$Z_0 = 7\ \mathrm{cm}$$



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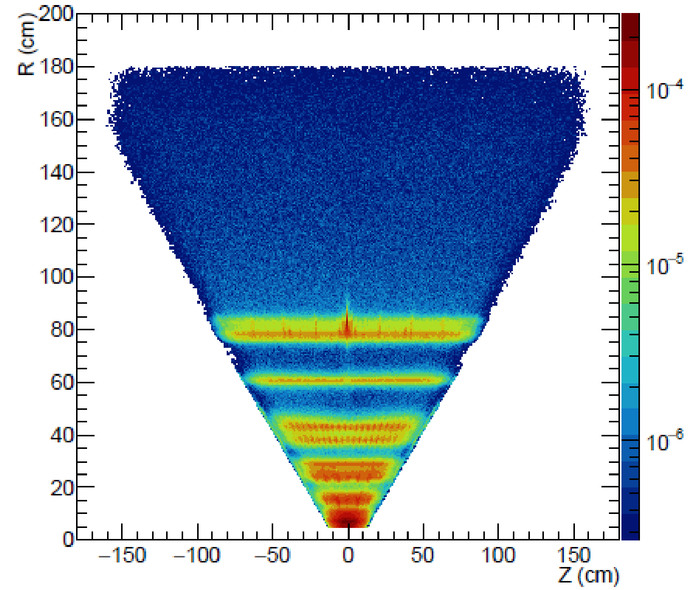
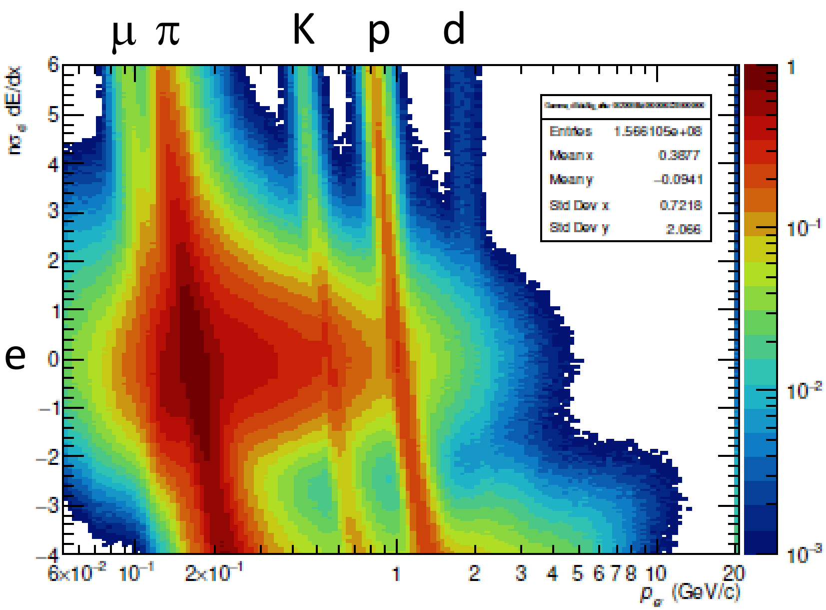
Distribution of conversions

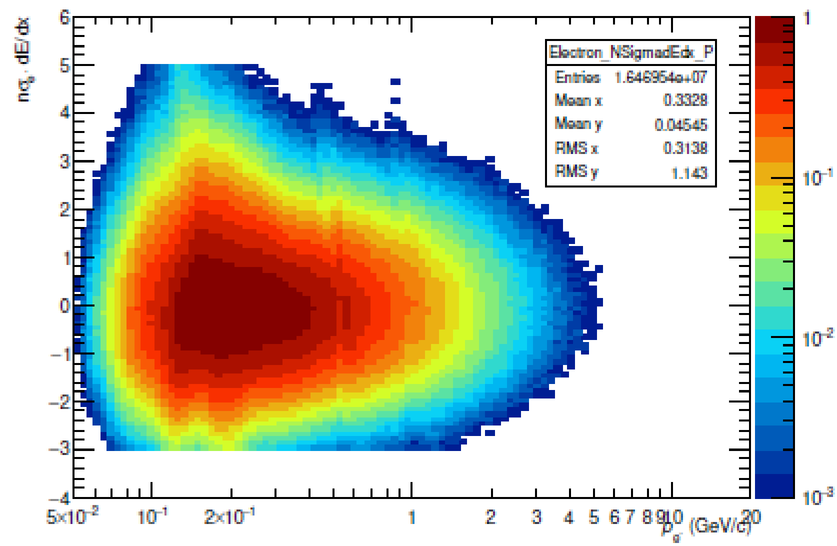


Electron ID cuts

Variable	Requirement
$n\sigma_e$ TPC dE/dx (accept)	$-3 < n\sigma_e < 3$
$n\sigma_\pi$ TPC dE/dx (reject)	$0.4 < p < 3.5\mathrm{GeV/c} : 1 < n\sigma_\pi$ $p > 3.5\mathrm{GeV/c}$: no cut



Before



After

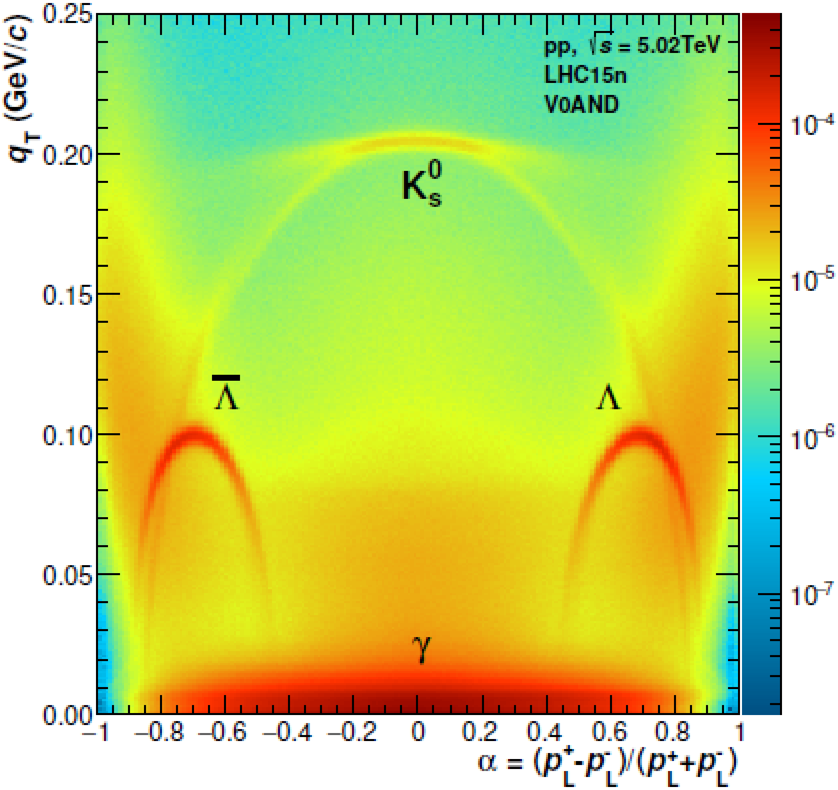
Armanteros-Podolanski γ selection

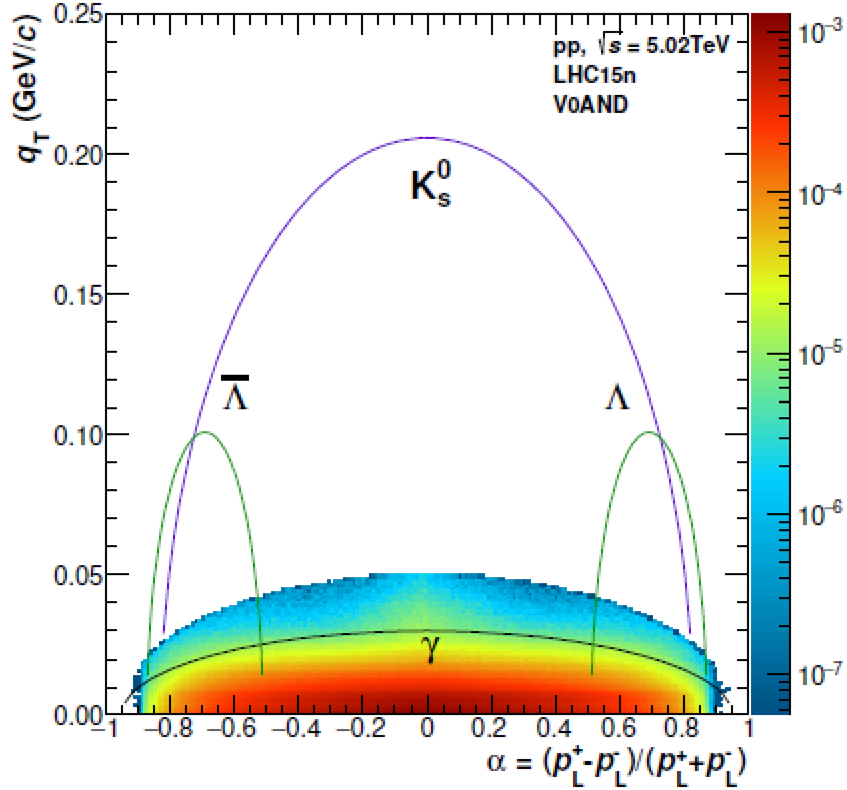
- Remove K^0_s, Λ, $\overline{\Lambda}$

$$q_T = \frac{|\vec{p_T^+} \times \vec{p_m}|}{|\vec{p_m}|} \qquad \alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

$$(\frac{\alpha}{\alpha_{max}})^2 + (\frac{q_T}{q_{T,max}})^2 > 1$$

$$\alpha_{max} = 0.95,\ q_{T,max} = 0.05\ \mathrm{GeV/c}$$





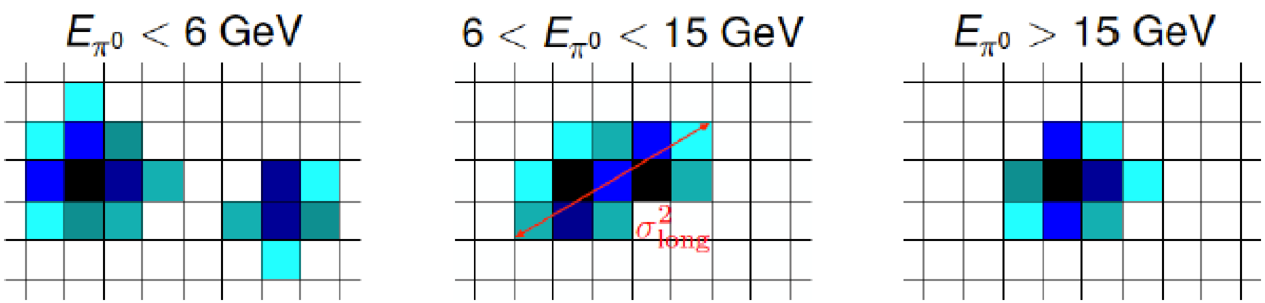
Methods of neutral meson extraction

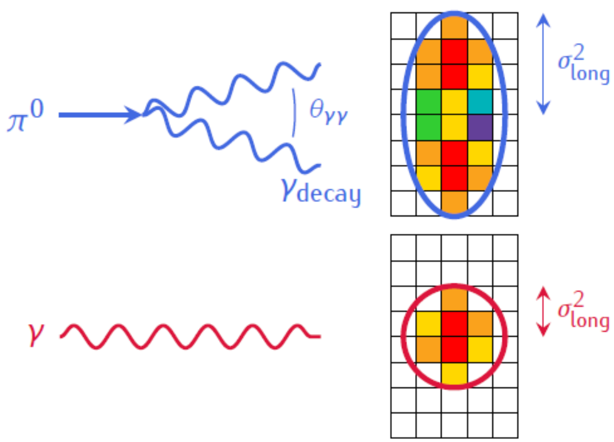
- Shower shape
  - High p_T π^0 decay pairs - showers overlap

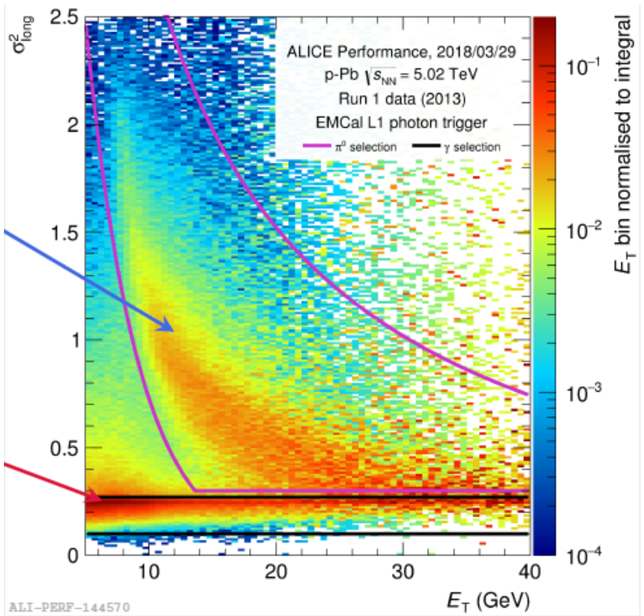
$$\sigma^2_{\text{long}} = 0.5\left(\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta} + \sqrt{(\sigma^2_{\varphi\varphi} - \sigma^2_{\eta\eta})^2 + 4\sigma^4_{\eta\varphi}}\right),$$

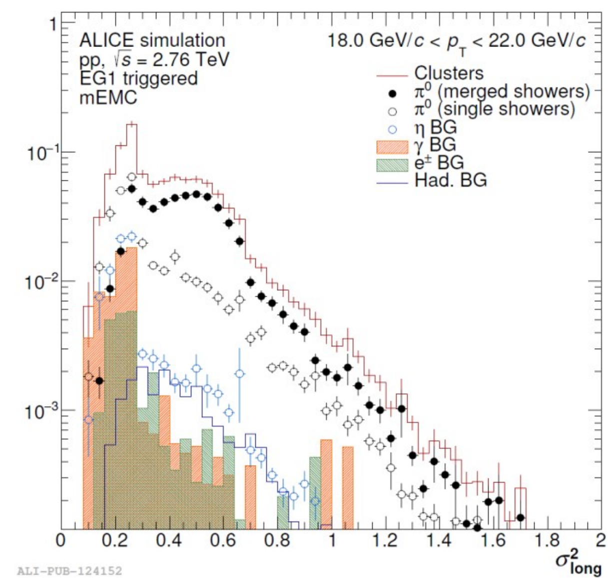
$$\sigma^2_{\alpha\beta} = \langle \alpha\beta \rangle - \langle \alpha \rangle \langle \beta \rangle,$$

$$\langle \alpha \rangle = \frac{\sum w_i \alpha_i}{\sum w_i},$$









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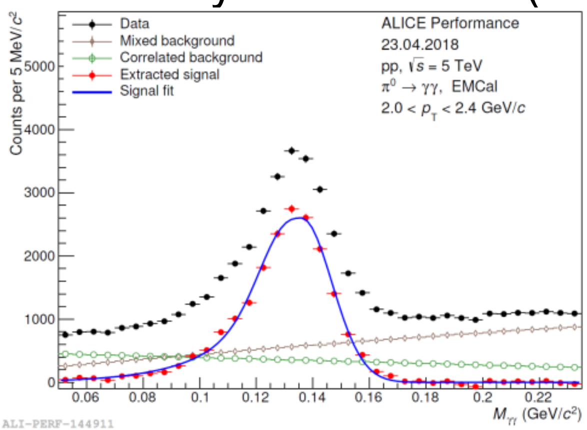
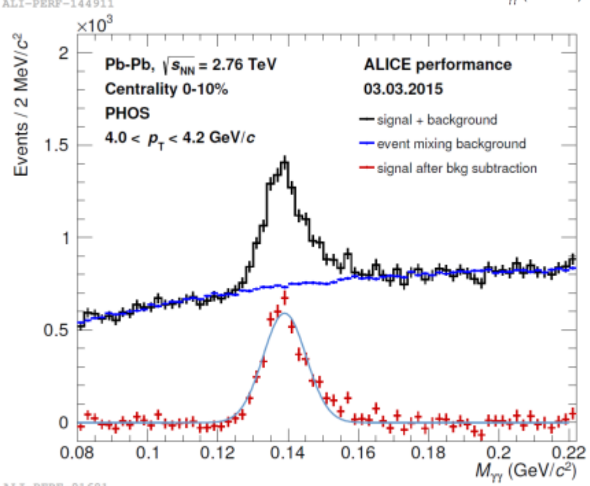
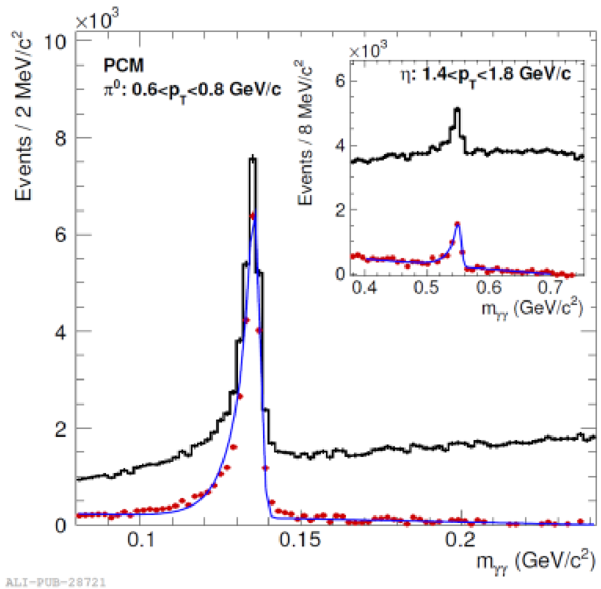
Methods of neutral meson reconstruction

- Invariant mass analysis: $M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$
  - $h \rightarrow \gamma + \gamma$ (PHOS, EMCal)
  - $h \rightarrow \gamma\,(\rightarrow e^+ e^-) + \gamma\,(\rightarrow e^+ e^-)$ (PCM)
  - Dalitz decays $h \rightarrow \gamma\,\gamma^* \rightarrow \gamma\,(\rightarrow e^+ e^-)\, e^+ e^-$
  - Hybrid methods (PHOS + PCM, EMCal +PCM)







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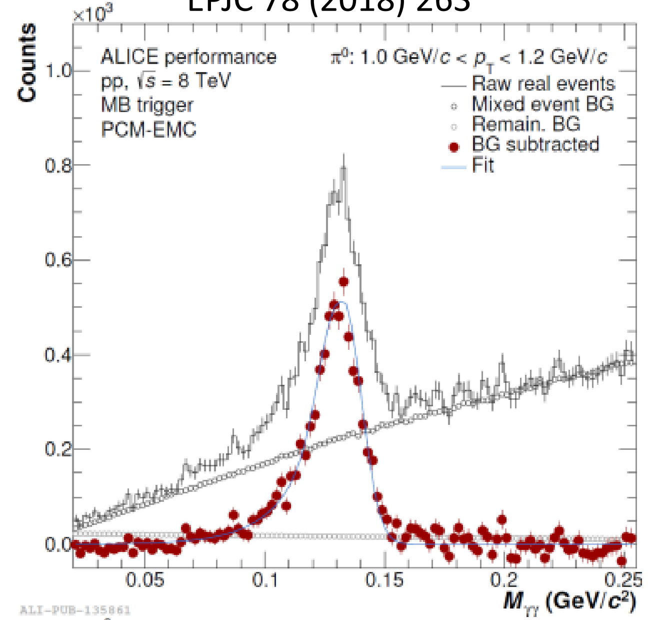

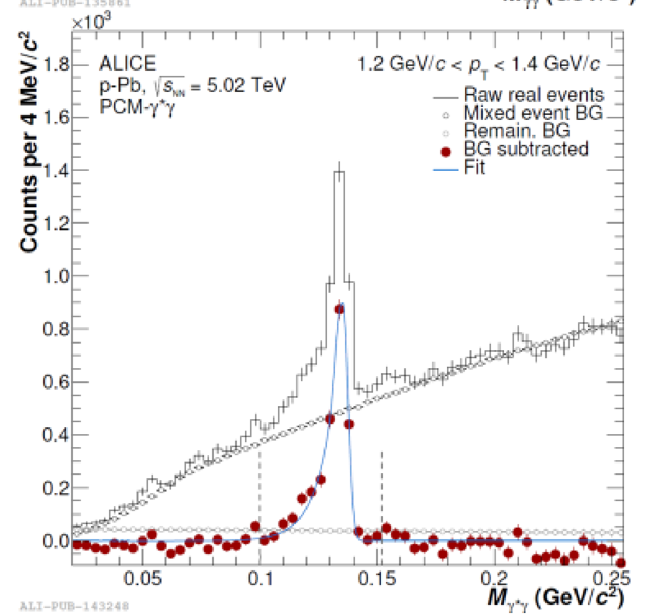

Neutral meson reconstruction flow

- Invariant mass $M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$
- Event mixing to estimate combinatorial background
- Extraction of signal (exponent + Gaussian) and background (polynomial) parameterization

$$y = A \cdot \left(G(M_{\gamma\gamma}) + \exp\left(\frac{M_{\gamma\gamma} - M_{\pi^0(\eta)}}{\lambda}\right)(1 - G(M_{\gamma\gamma}))\theta(M_{\pi^0,\eta} - M_{\gamma\gamma}) \right) + B + C \cdot M_{\gamma\gamma}$$

$$\text{with } G = \exp\left(-0.5\left(\frac{M_{\gamma\gamma} - M_{\pi^0,\eta}}{\sigma_{M_{\gamma\gamma}}}\right)^2\right)$$

- Corrections based on MC and data
  - In-bunch and out-of-bunch pile-up
  - Vertex reconstruction
  - Feed-down
  - Efficiency and acceptance
  - Trigger rejection factor
- Merging results from different methods
  - Finite p_{T} bin shift
- Cross-section:

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \frac{N_{\mathrm{rec}}}{p_{\mathrm{T}}^{*}\,\Delta p_{\mathrm{T}}\,\varepsilon\,\varepsilon_{\mathrm{trig}}}\frac{1}{L_{\mathrm{int}}}\frac{1}{\mathrm{BR}}$$

Neutral meson reconstruction flow

- Invariant mass $M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$
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Background

$$y = A \cdot \left(G(M_{\gamma\gamma}) + \exp\left(\frac{M_{\gamma\gamma} - M_{\pi^0(\eta)}}{\lambda}\right)(1 - G(M_{\gamma\gamma}))\theta(M_{\pi^0,\eta} - M_{\gamma\gamma}) \right) + B + C \cdot M_{\gamma\gamma}$$

Signal

$$\text{with } G = \exp\left(-0.5\left(\frac{M_{\gamma\gamma} - M_{\pi^0,\eta}}{\sigma_{M_{\gamma\gamma}}}\right)^2\right)$$

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Neutral meson reconstruction flow

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Signal

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- Corrections based on MC and data
  - In-bunch and out-of-bunch pile-up
  - Vertex reconstruction

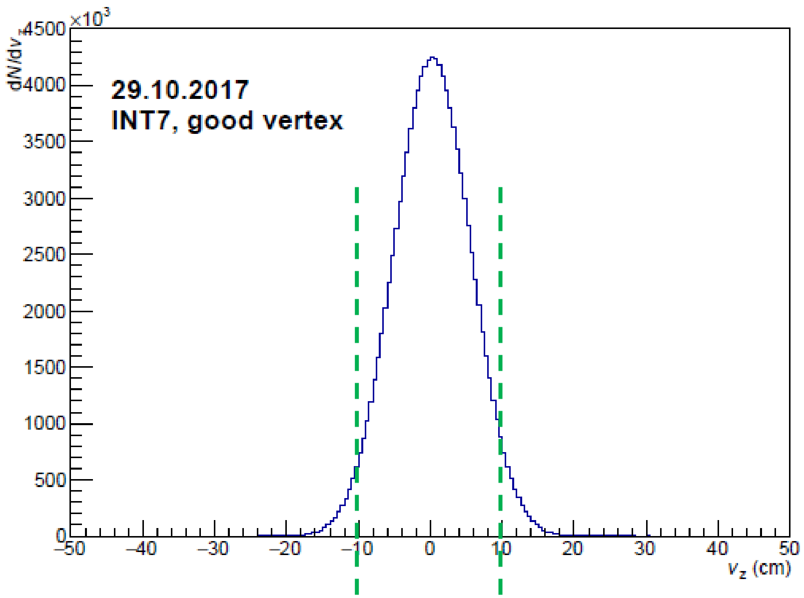
  → $L_{int} \times \sigma_{trig} = N_{ev}$
  - Feed-down → N_{rec} → N_{rec} - N_s
  - Efficiency and acceptance
  - Trigger rejection factor
- Merging results from different methods
  - Finite p_T bin shift
- Cross-section:

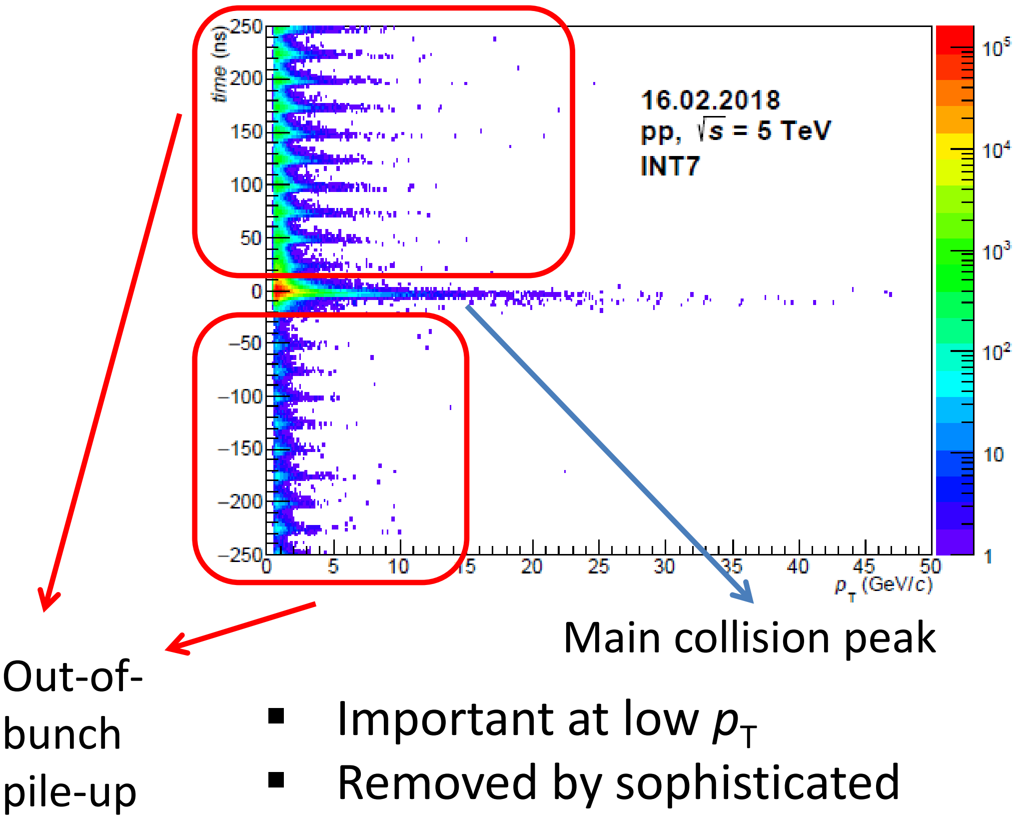
$$E\frac{d^3\sigma}{dp^3} = \frac{N_{rec}}{p_T^*\,\Delta p_T\,\varepsilon\,\varepsilon_{trig}}\,\frac{1}{L_{int}}\,\frac{1}{BR}$$

Vertex and pile-up

$$N_{\rm evt}^{\rm norm,trigger} = N_{\rm evt}^{\rm trigger} \frac{N_{{\rm vtx},|v_z|<10\ {\rm cm}}^{\rm trigger}}{N_{\rm vtx}^{\rm trigger}},$$

$$N_{\rm evt}^{\rm ana} \rightarrow N_{\rm evt}^{\rm norm,trigger}(1 - \mu/2)$$



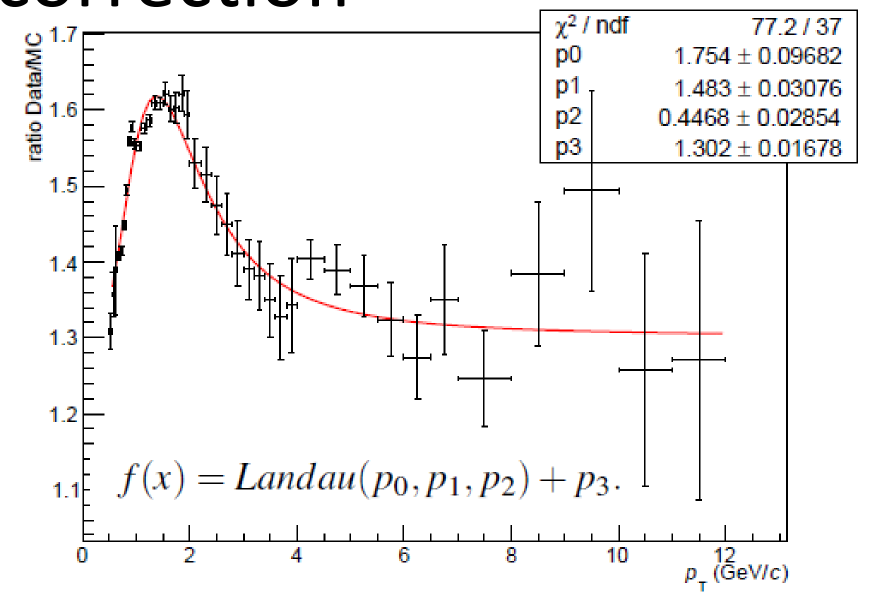


- Correction O(1%)

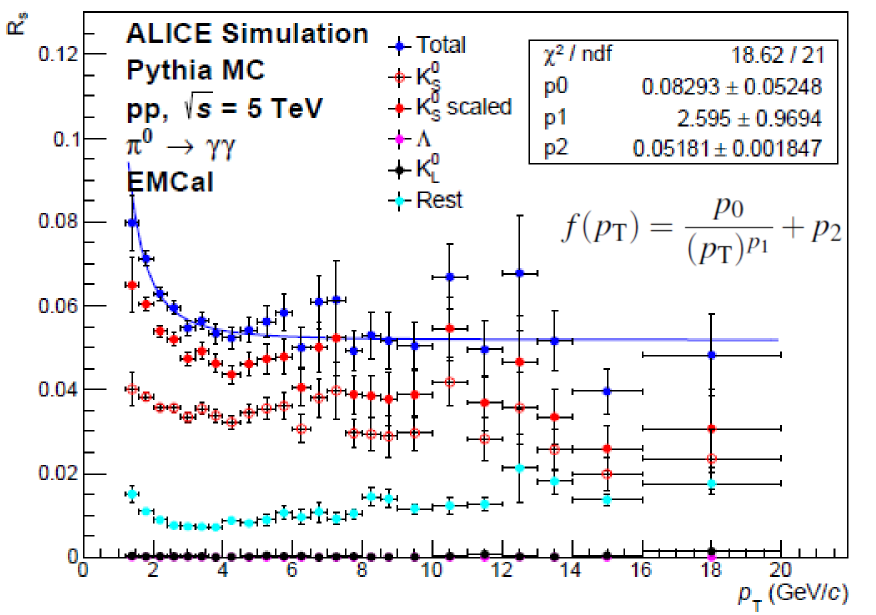
- Important at low p_T
- Removed by sophisticated Physics Selection + Past/Future protection + SPD

Feed-down correction

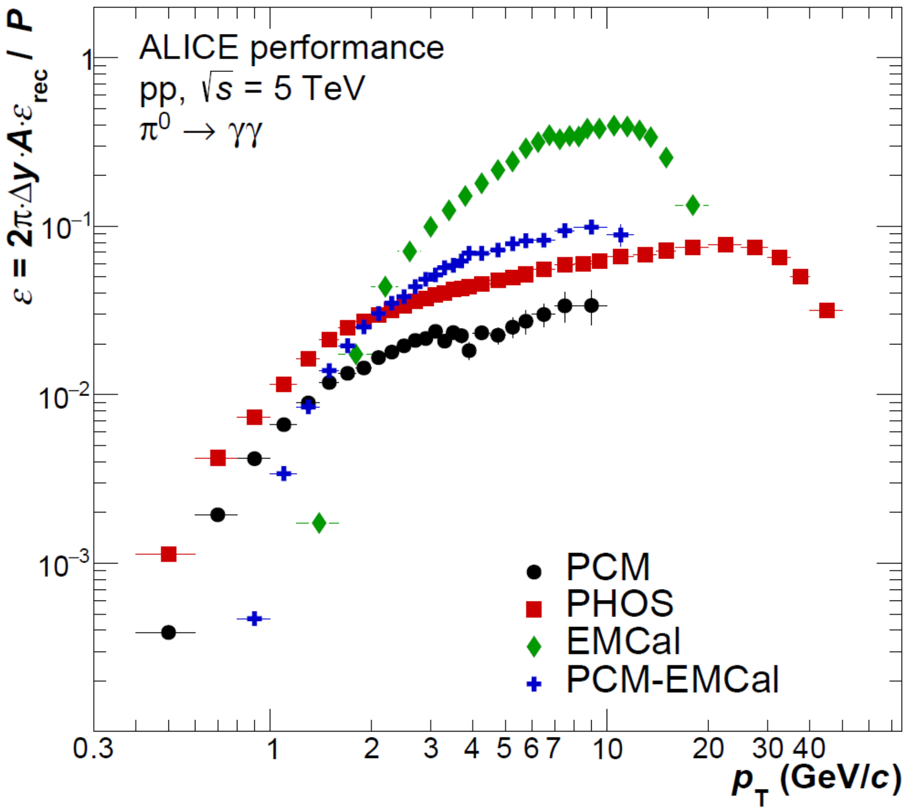
- Disagreement of K/π ratio in data and MC

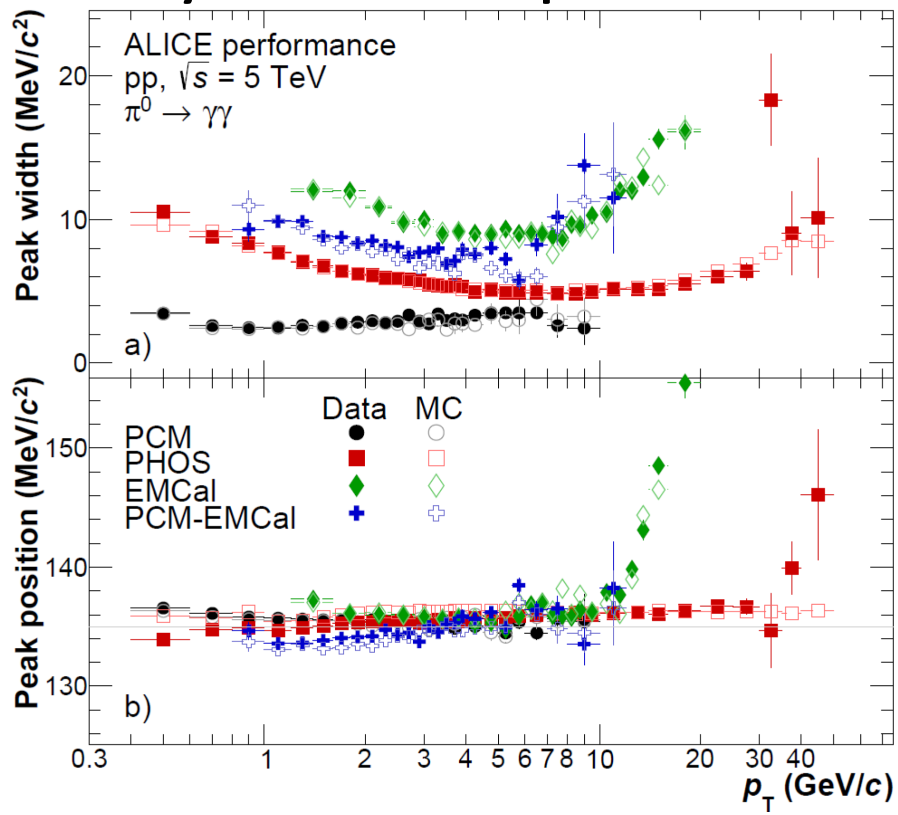


- Correction for π^0 coming from K^0_S and other strange particles – O(5%)
- Currently cocktail based



Effective efficiency = efficiency and acceptance





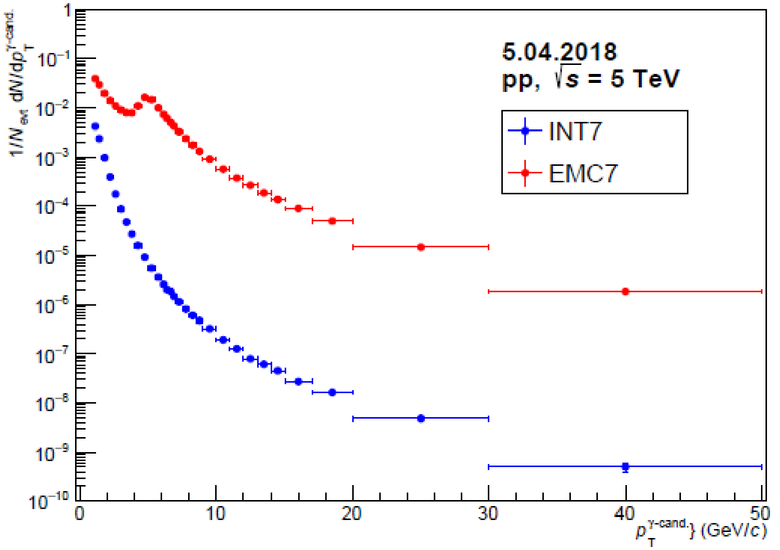
- Two ways of efficiency calculation:
  - Reconstructed as in data
  - Validated with MC true

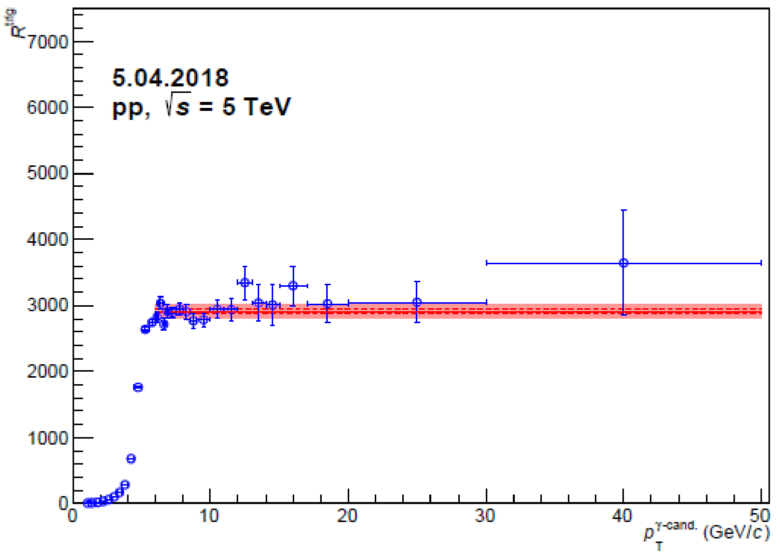
$\Rightarrow$ Good agreement between data and MC necessary

$\Rightarrow$ Good agreement between MC and MC true necessary

Trigger rejection factor

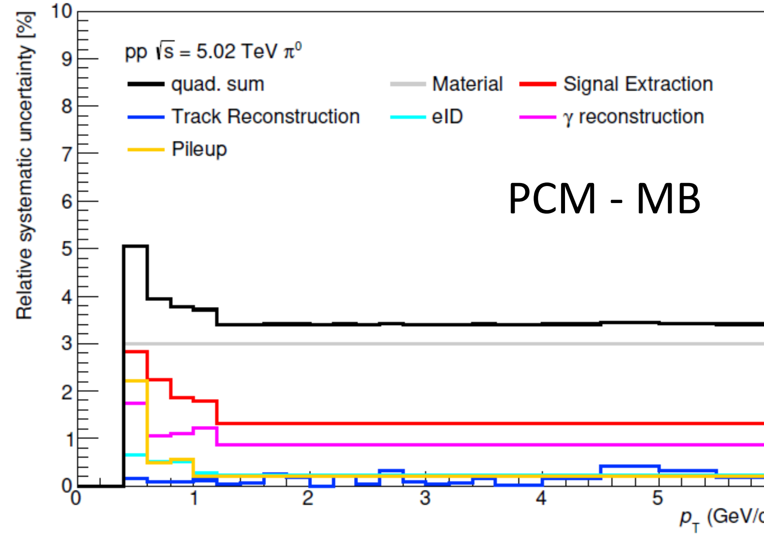
$$R^{\mathrm{trig}} = \frac{N_{\mathrm{evt}}^{\mathrm{INT7}}}{N_{\mathrm{evt}}^{\mathrm{EMC7}}} \frac{\mathrm{d}N^{\mathrm{EMC7}} / \mathrm{d}p_{\mathrm{T}}^{\gamma-cand}}{\mathrm{d}N^{\mathrm{INT7}} / \mathrm{d}p_{\mathrm{T}}^{\gamma-cand}}$$

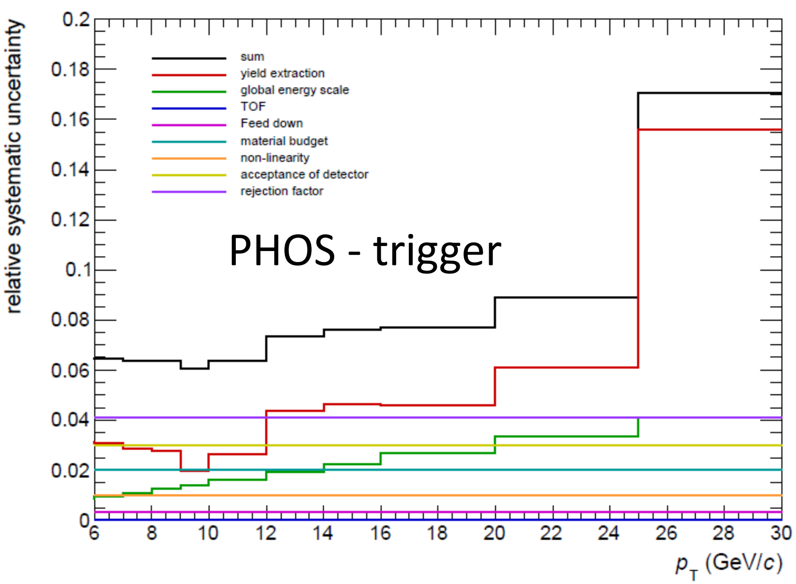


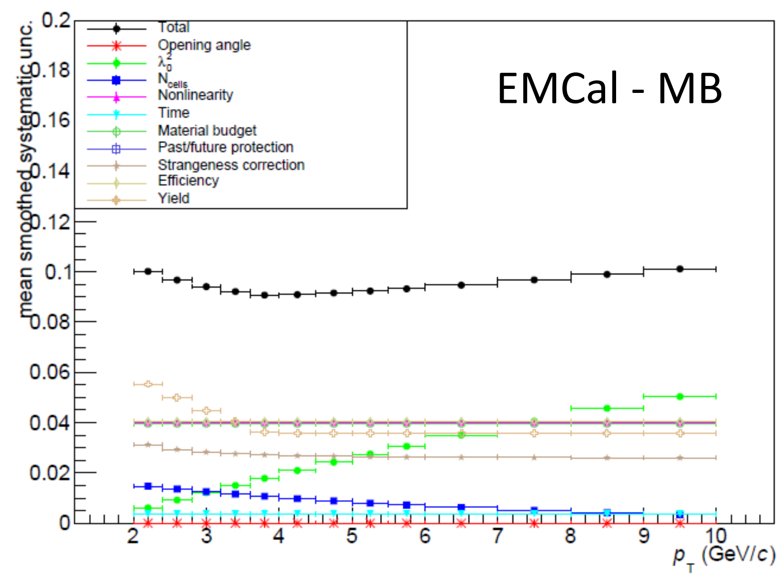


Systematics

- PCM
  - Material budget
  - Yield extraction
- Calorimeters
  - Yield extraction
  - Material budget in front of Calo
  - Energy scale (PHOS), nonlinearity (EMCal)





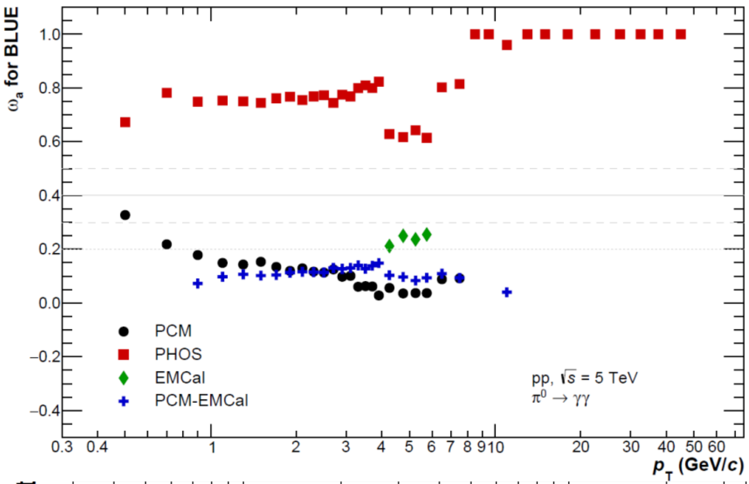


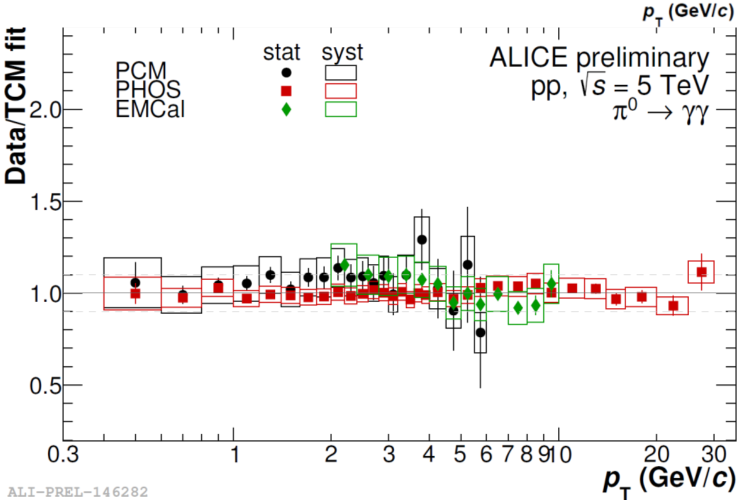
Results merging

- Triggers are merged at first by weighted average

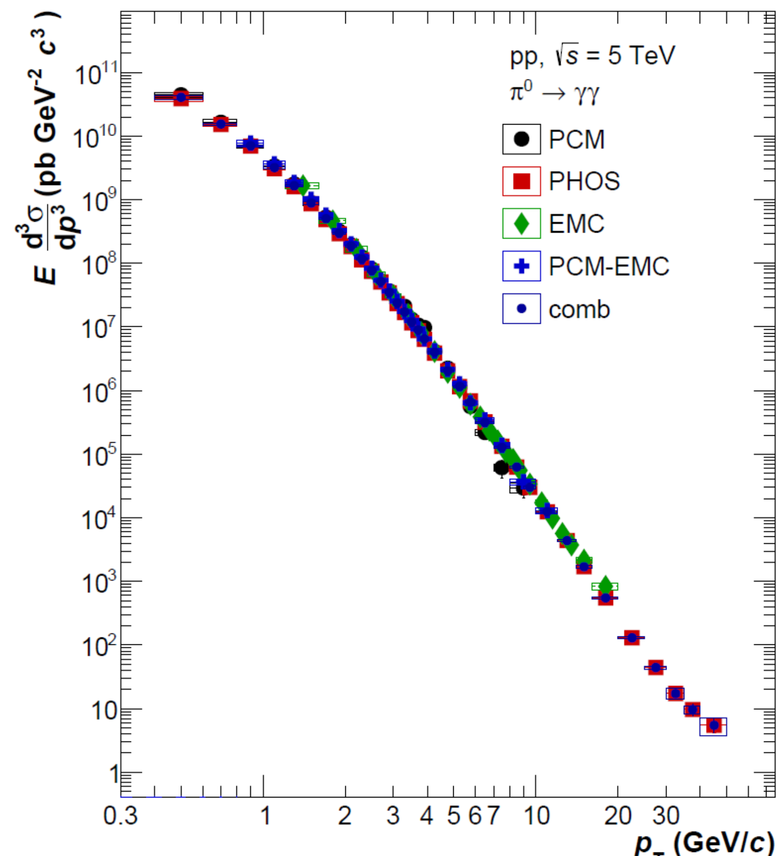
$$\hat{\mu} = \frac{1}{w}\sum_{i}^{n} w_i y_i \qquad w_i = \frac{1}{\sigma_i^2} \qquad w = \sum_i^n w_i$$

- Then systems are merged by BLUE algorithm, taking cross-correlations into

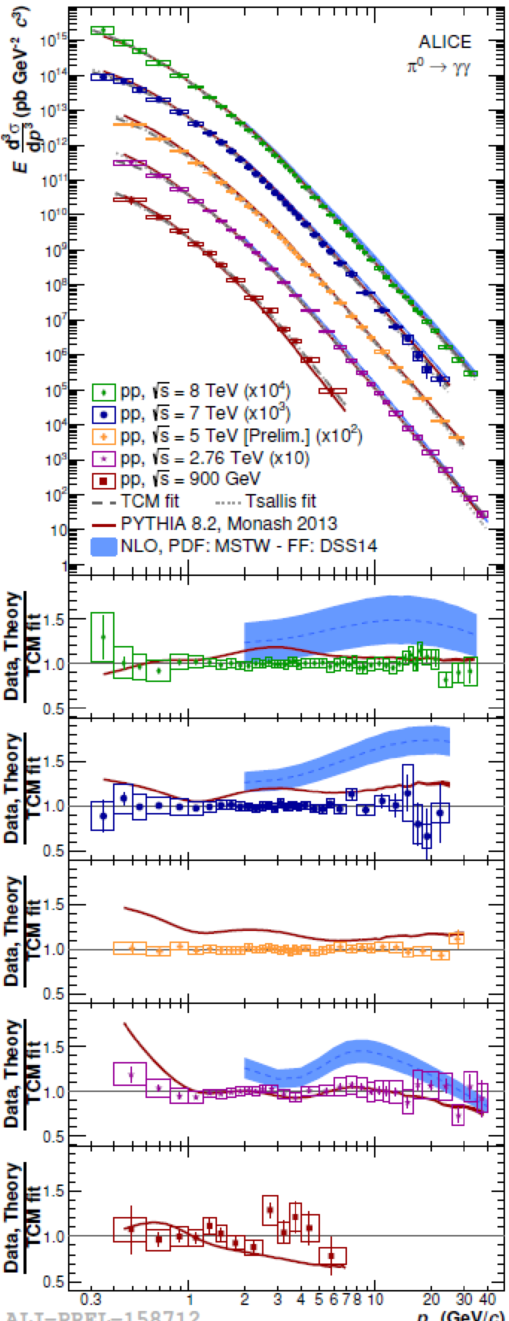


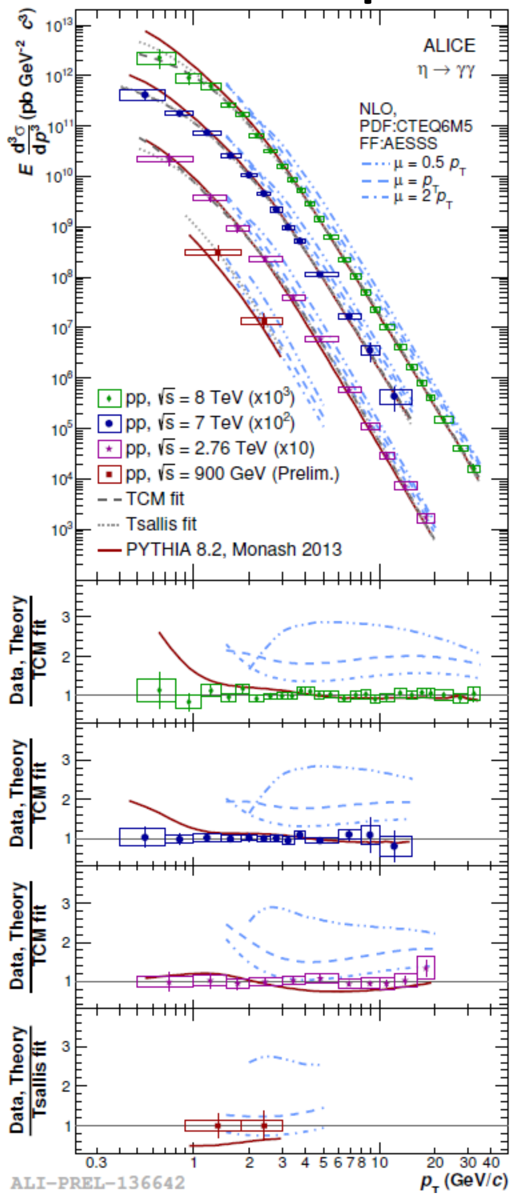


Good agreement between methods allowed for combined result



Neutral meson spectra in pp collisions



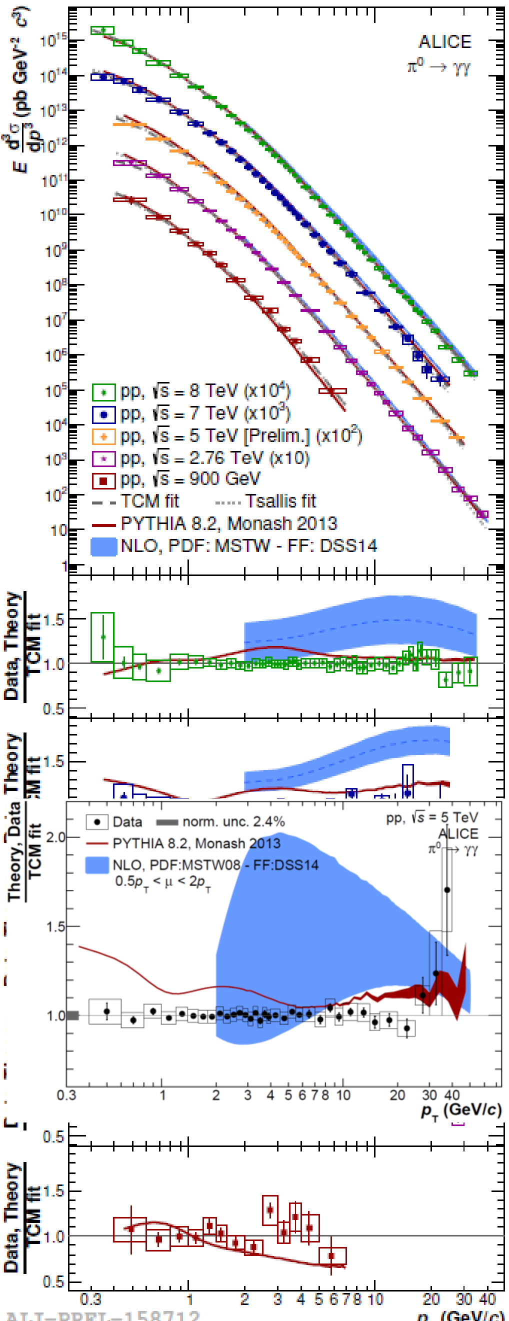


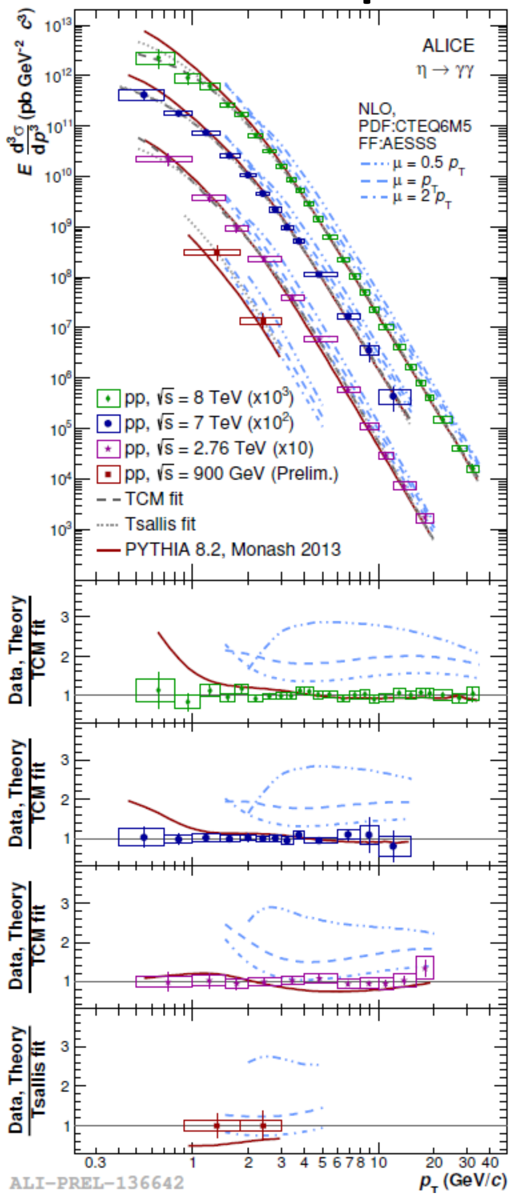
- Preliminary result for π^0 spectrum produced at $\sqrt{s}$ = 5 TeV
- π^0 and η mesons reconstructed in wide p_T range
- Power law dependence at high p_T
- PYTHIA 8.2 Monash 2013 MC describes data, but larger discrepancy at mid-p_T for higher energies
- NLO calculations overpredict data for both π^0 (20% - 60%) and η (50% - 100%)
  - Update on η FF desired (as done for pions and kaon)

0.9 , 7 TeV: PLB 717(2012) 162-172.
2.76 TeV: EPJC 74 (2014) 3108; EPJC 77 (2017) 339.
8 TeV: EPJC 78 (2018) 263

NLO: PRD 91 (2015) 1, 014035

Neutral meson spectra in pp collisions





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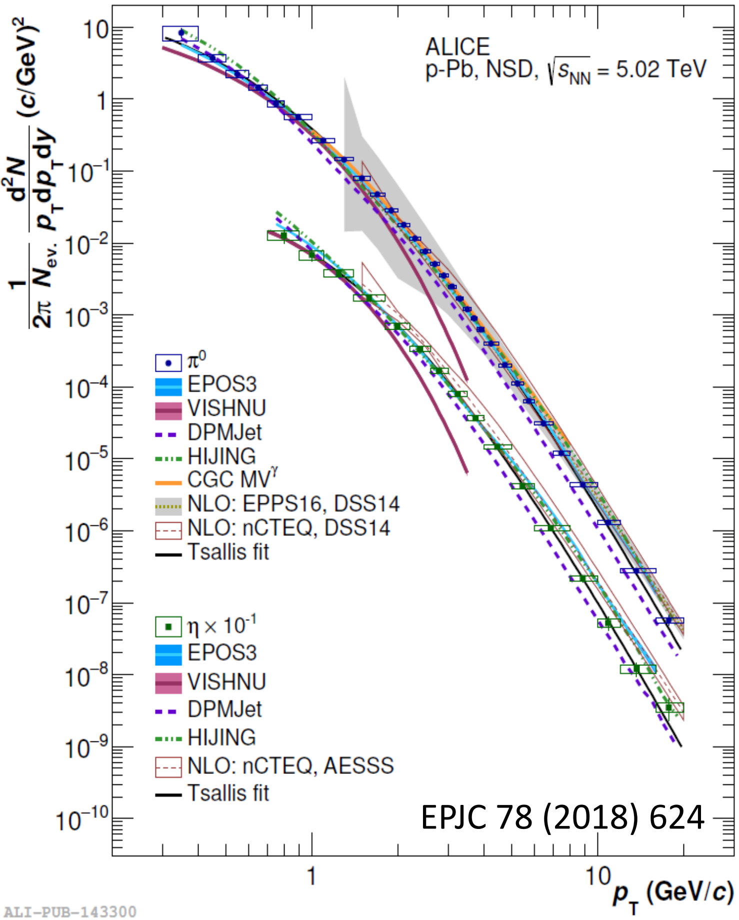
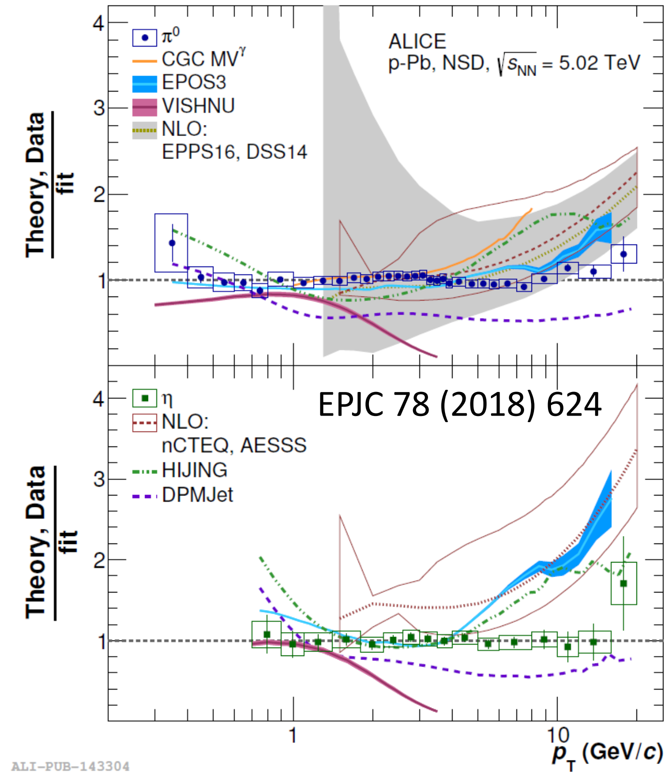
8 TeV: EPJC 78 (2018) 263

NLO: PRD 91 (2015) 1, 014035

Meson production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





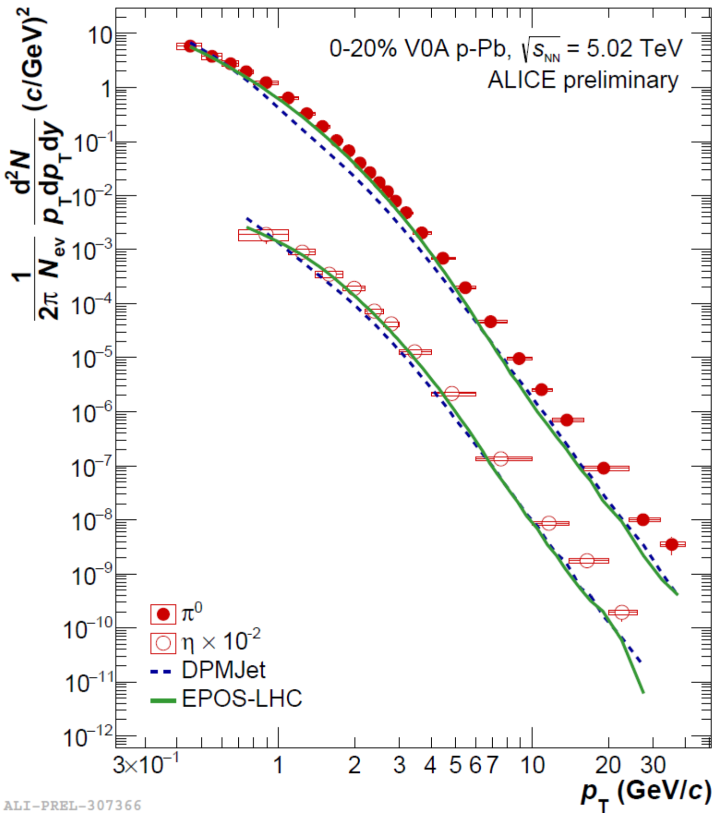
Wide p_T range:

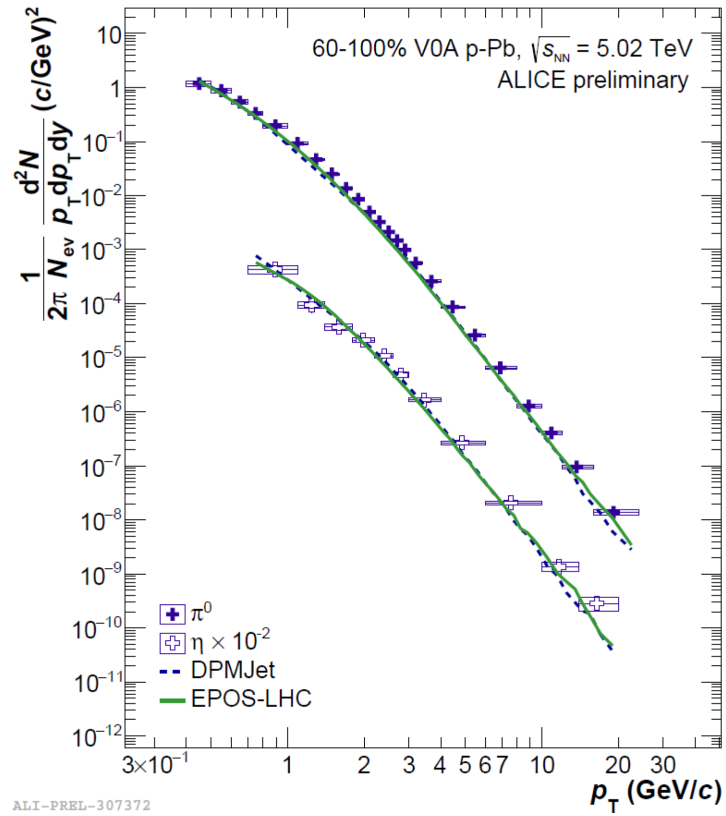
- $0.3 < p_T < 20$ GeV/c (π^0)
- $0.7 < p_T < 20$ GeV/c (η)

EPOS3: K.Werner et al., PRC89 (2014) 064903.
VISHNU: C.Shen at al., PRC95 (2017) 014906.
CGC: T.Lappi et al., PRD88 (2013) 114020.

- Data described by Tsallis function
- EPOS3 model describes π^0 spectrum (expected)
  - η spectrum reproduced for $p_T < 4$ GeV/c
- VISHNU (hydro) model describes low-p_T range (expected)
- Good description of π^0 spectrum by NLO pQCD calculations, but fails for η in high-p_T region

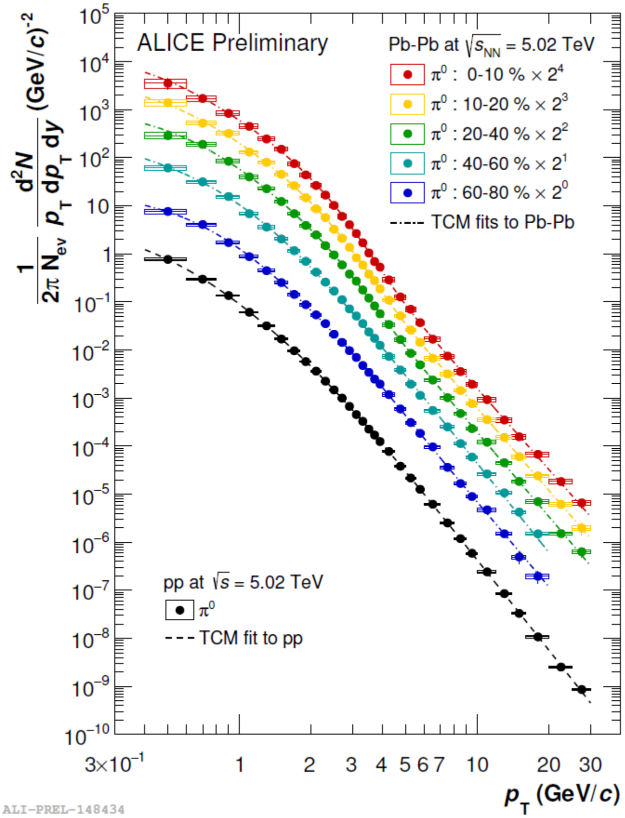
Meson production in centrality classes in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

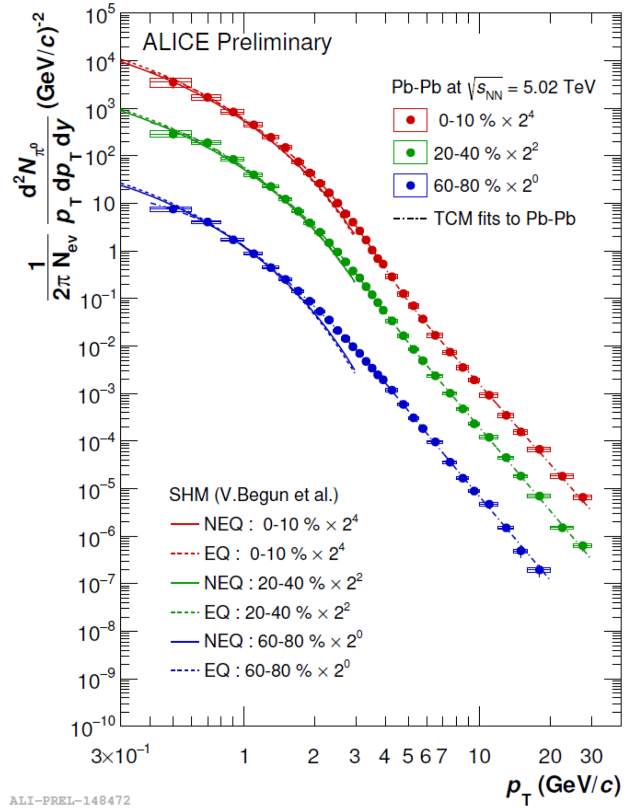


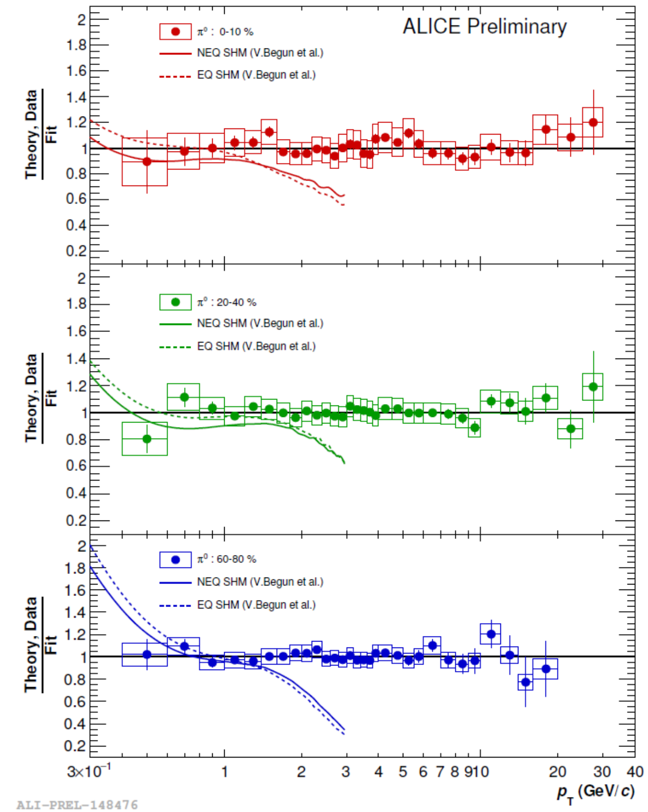


- Spectra of π^0 and η mesons measured in centrality classes
- Extended p_T range $\rightarrow$ up to 40 GeV/c by using PHOS trigger
- Both DPMJet and EPOS-LHC underpredict data at high p_T for every centrality class
- Low p_T data better described by EPOS-LHC than DPMJet

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







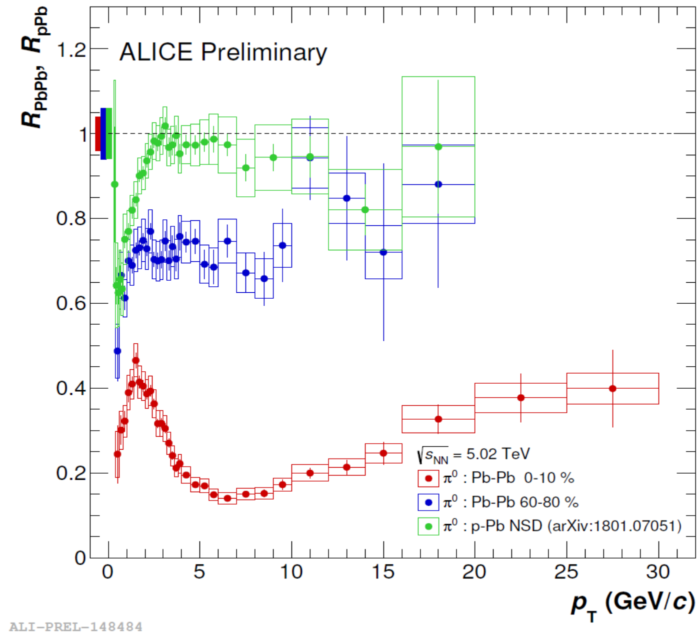
- Preliminary measurement of π^0 spectrum in several 5 centrality classes at $\sqrt{s_{NN}}$ = 5.02 TeV in the range $0.4 < p_T < 30$ GeV/c
- Good description of low-p_T region, failure or no description of high-p_T range

Nuclear modification factor

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

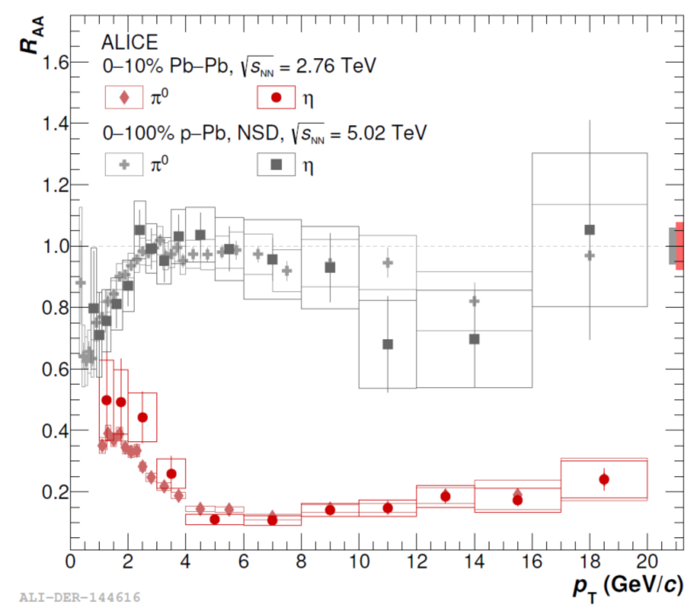
$N_{coll} = \sigma_{pp} <T_{AA}>$

- Illustrates 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

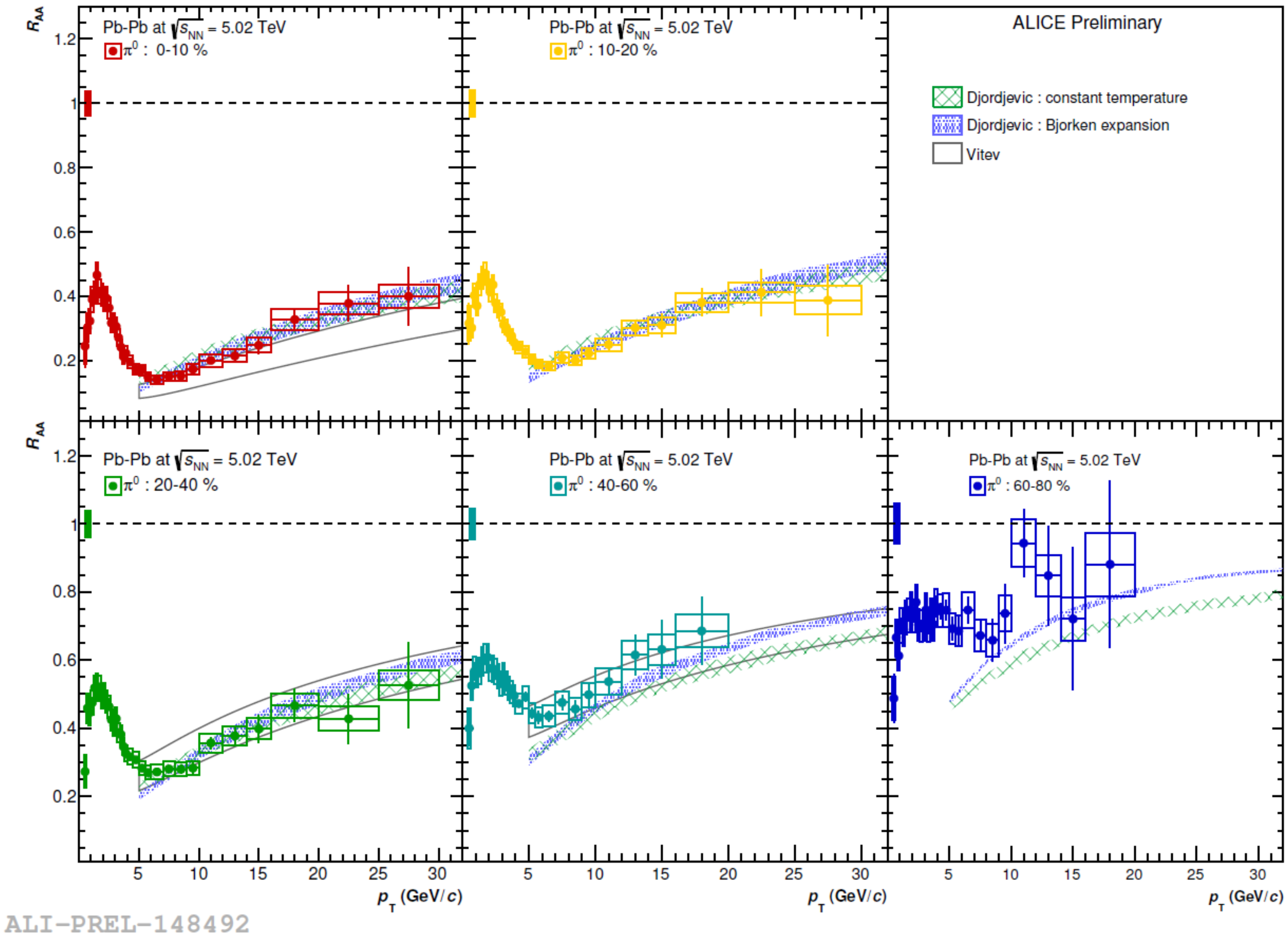


- Well defined fragmentation function in comparison to unidentified hadrons
- Very strong suppression in central Pb-Pb collisions above $p_T \approx 3$ GeV/c, p_T dependent, largest suppression $R_{AA} \sim 0.1$ at $p_T \approx 7$ GeV/c

  $\Rightarrow$ Formation of hot and dense QCD matter
- Centrality dependence
- Similar suppression for two Pb-Pb collision energies
- Consistent with unity above 2 GeV/c for p-Pb
- Agreement with results for charged hadrons



π^0 meson R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



Djordjevic:
PRC94 (2016) 044908
Energy loss in evolving finite-size QGP

Vitev:
PRD93 (2016) 074030
Soft-Collinear Effective Theory (SCET) for jet propagation in matter

- Relatively well described by models
- Centrality dependence reproduced
- Although worsening towards more peripheral collisions

m_T scaling (transverse mass)

$$m_T = \sqrt{m^2 + {p_T}^2}$$

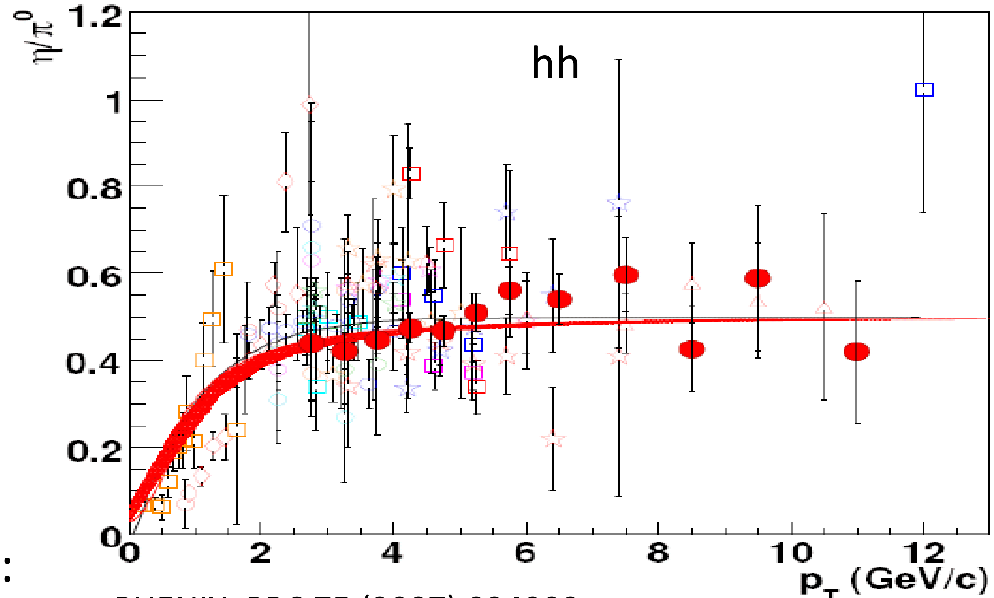
- Proposed empirical description of hadron production
  - Bourquin, Gaillard, NPB 114 (1976) 334.
- Differential cross-section as a function of the transverse mass:

$$E\frac{d^3\sigma}{dp^3} = C\,(m_T + a)^{-n}$$

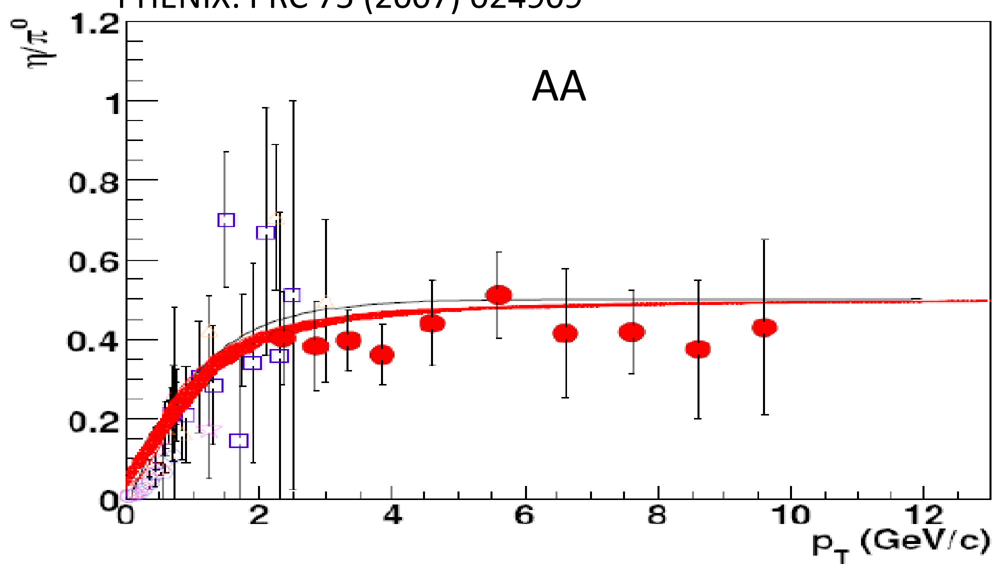
- Cross-section ratio of η and π^0 mesons:

$$R_{\eta/\pi^0}(p_T) = R_{\eta/\pi^0}\left(\frac{a + \sqrt{{m_\eta}^2 + {p_T}^2}}{a + \sqrt{{m_{\pi^0}}^2 + {p_T}^2}}\right)^n$$

- Let foreseen unknown production cross-section for not yet measured particles

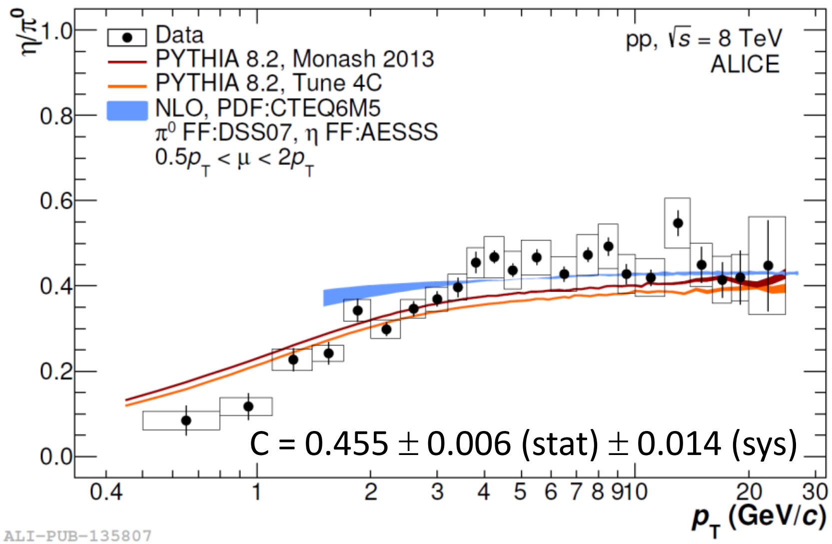


PHENIX: PRC 75 (2007) 024909

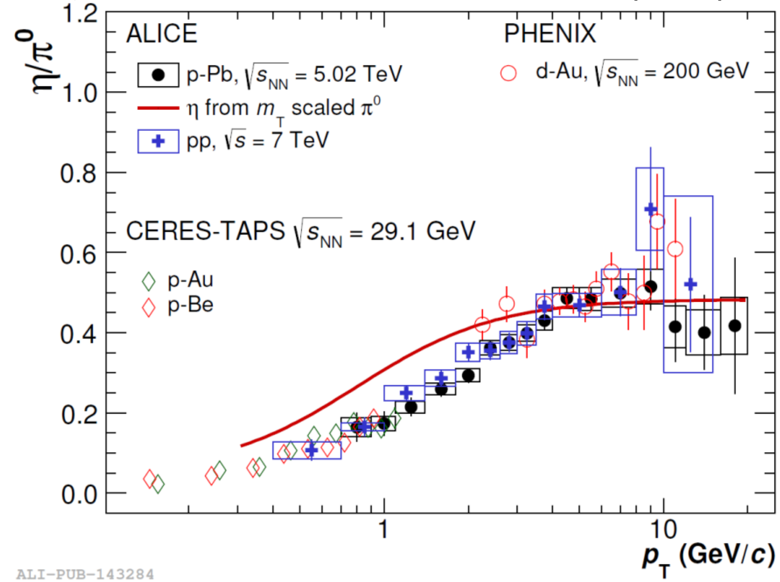


η/π^0 ratio and m_T scaling

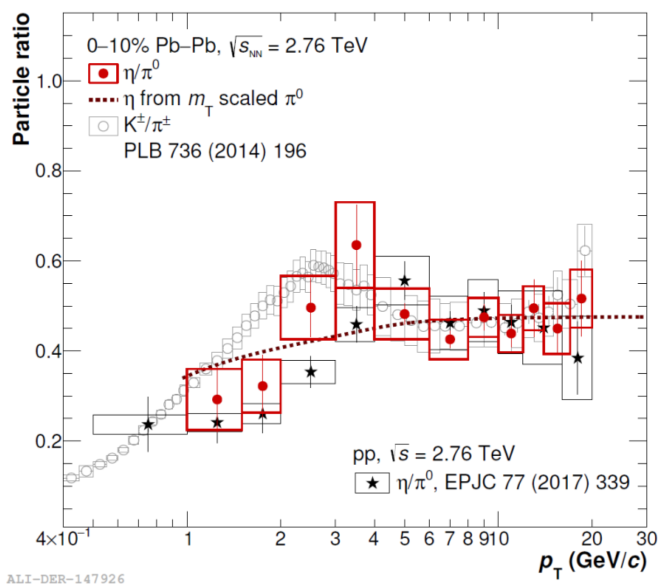
EPJC 78 (2018) 263



EPJC 78 (2018) 624



PRC 98 (2018) 044901



- Empirical law: $E\, d^3\sigma/dp^3 = C^m f(m_T)$
- Universal η/π^0 ratio among systems and energies
- Constant value (C) above $p_T = 3.5$ GeV/c
- Ratio reproduced by NLO calculations while not single spectra
- Observation of m_T scaling violation
  - Significance of 6.2σ below 3.5 GeV/c for pp at $\sqrt{s} = 8$ TeV
- Hint of flow at intermediate p_T in 0-10 % central in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

⇒ Importance of precise measurements

Summary

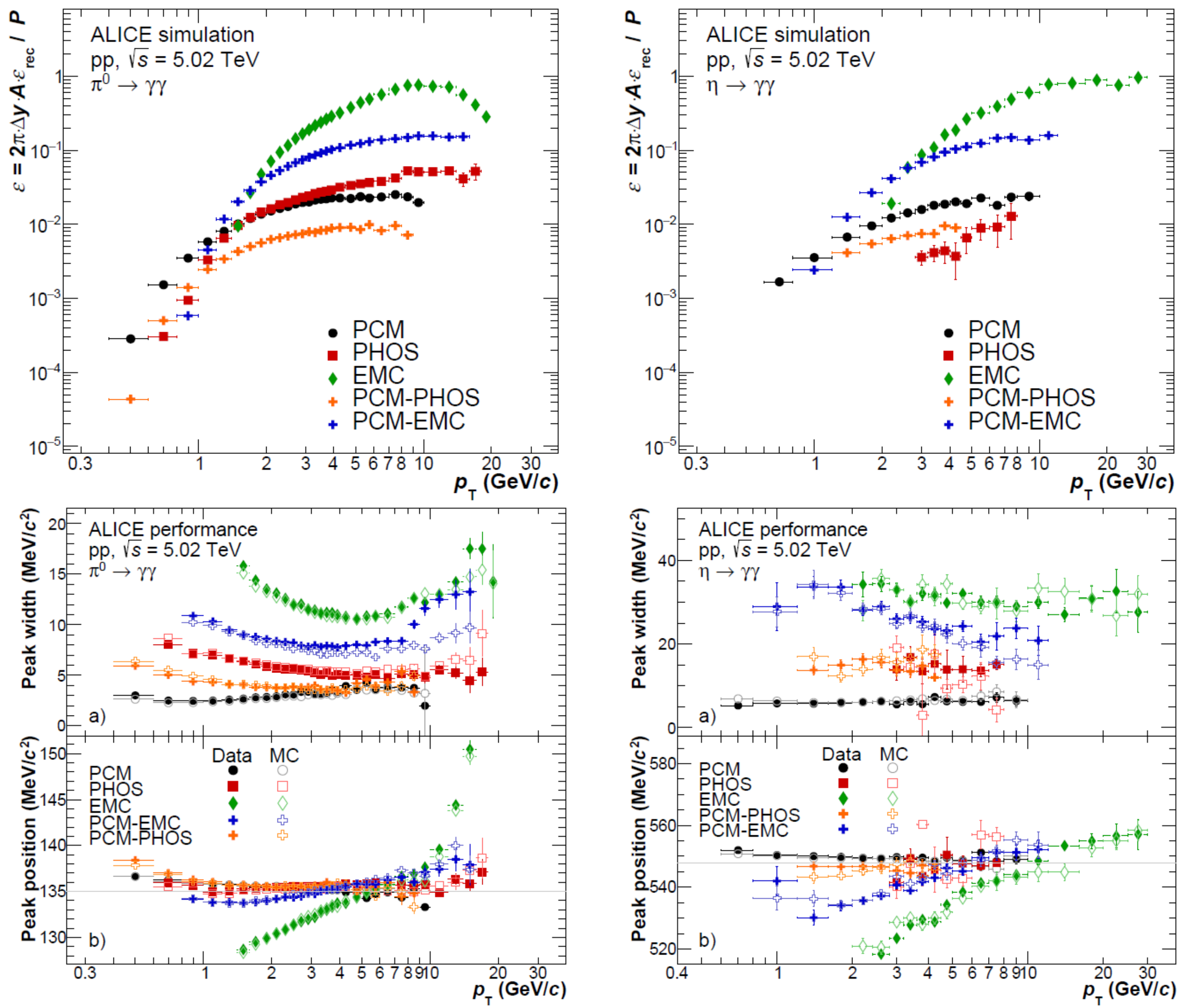
- ALICE can measure neutral mesons in wide p_T range
- Measurements allow testing perturbative QCD inspired models and parameterization of parton distribution and fragmentation functions
  - Higher yield predicted by NLO pQCD for π^0 (by 20-60%) and η (by 50-100%)
- Data relatively well described by variety of Monte Carlo generators, however there are some tensions
- Centrality, p_T dependence and suppression strength of neutral mesons in Pb-Pb reproduced by models

Verte →

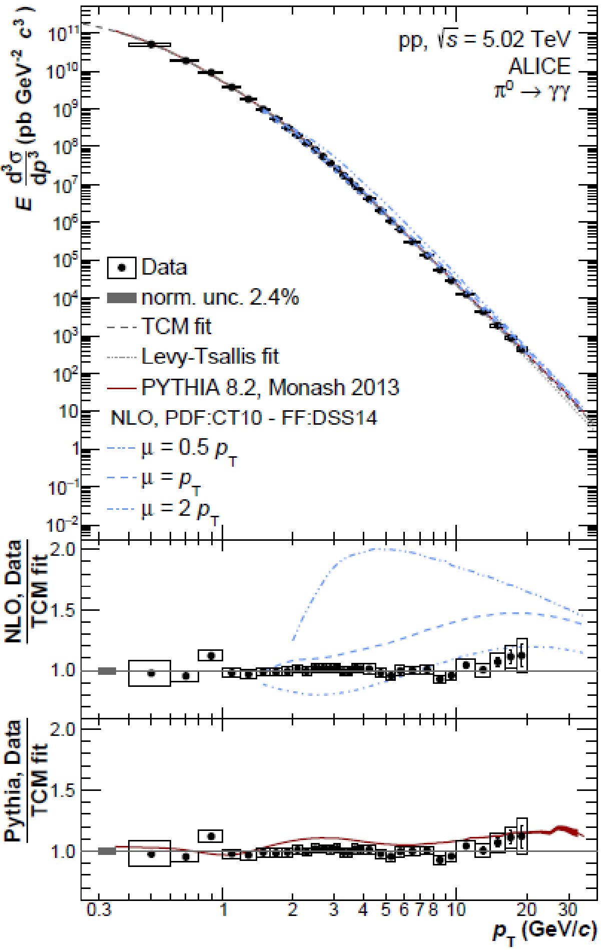
Ongoing activities

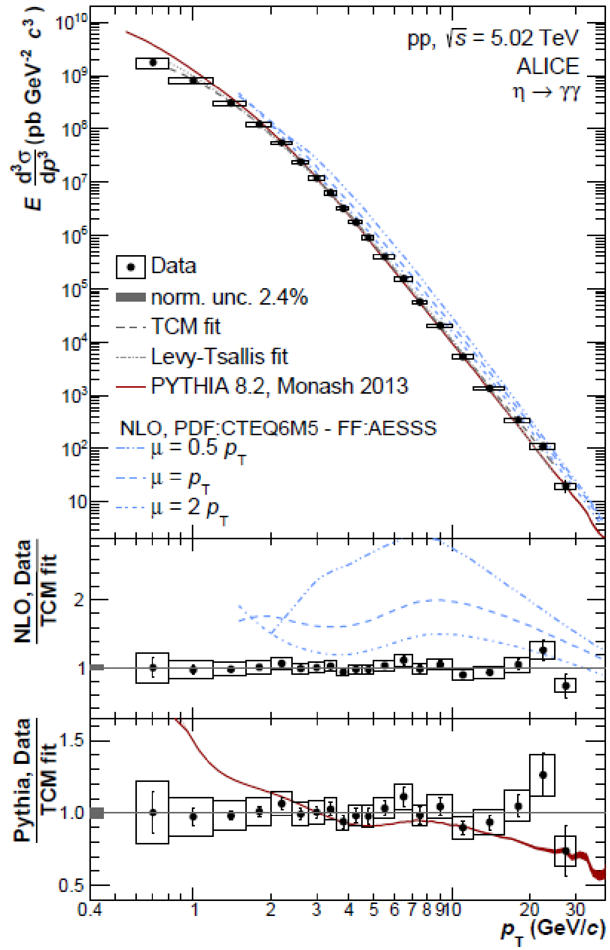
- Facing QM2019 new set of preliminaries is on its way:
  - Improved π^0 spectrum in pp and Pb-Pb collisions
  - New η spectrum in pp and Pb-Pb collisions
  - New η/π^0 ratio in pp and Pb-Pb collisions
  - Improved R_{AA} for π^0 in more centrality classes
  - New R_{AA} for η in centrality classes
- Paper is being written

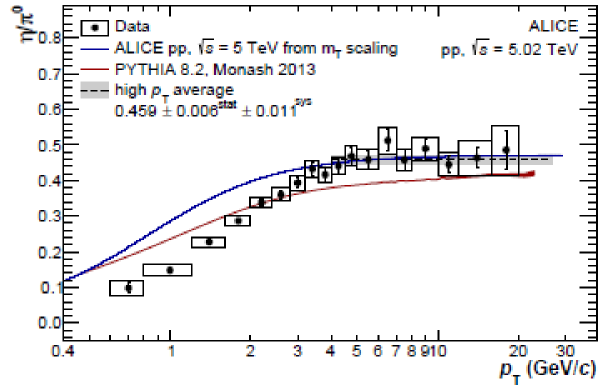
New measurements



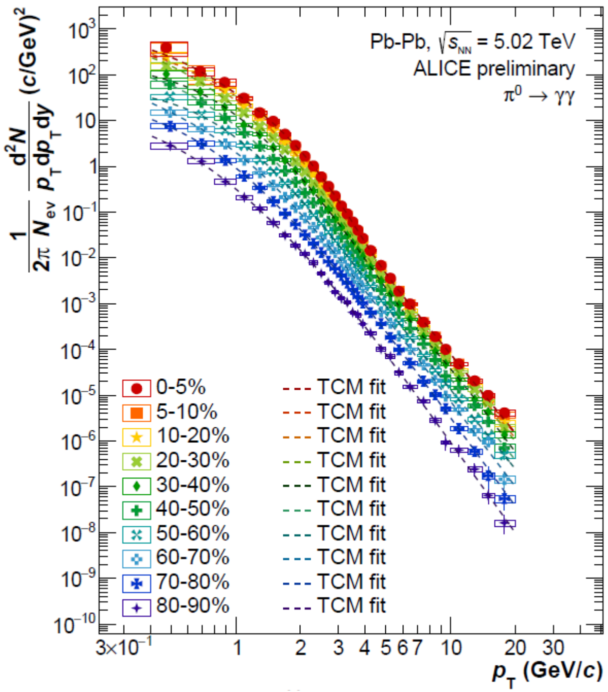
New results in pp

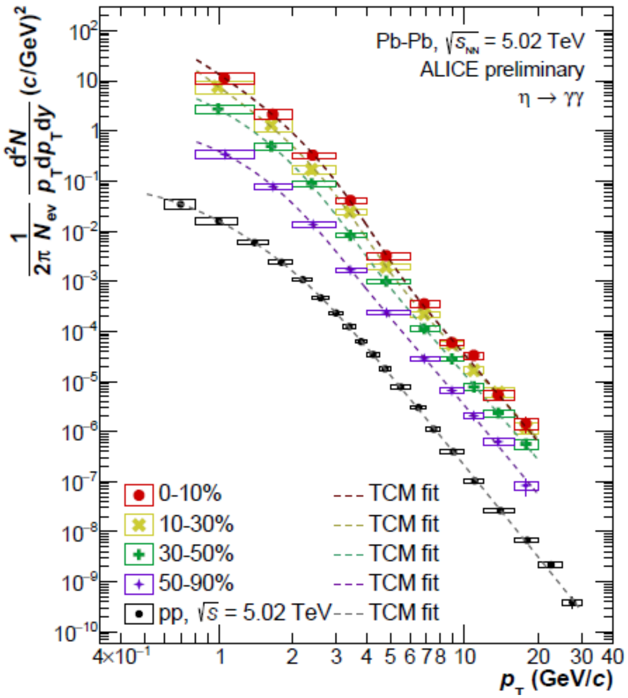


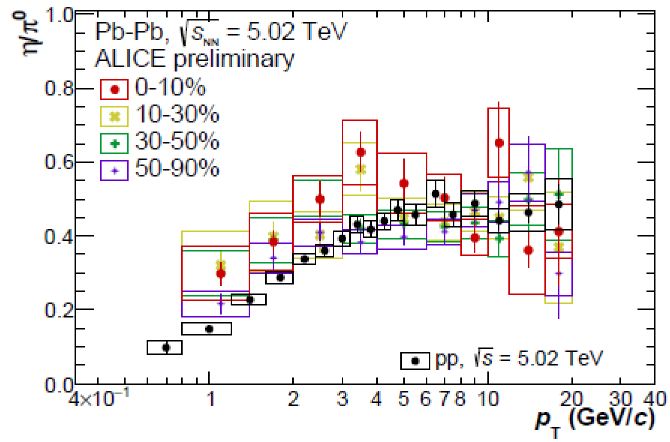


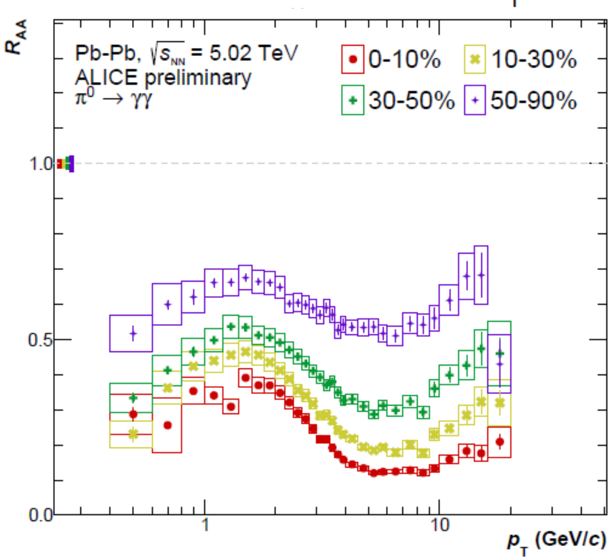


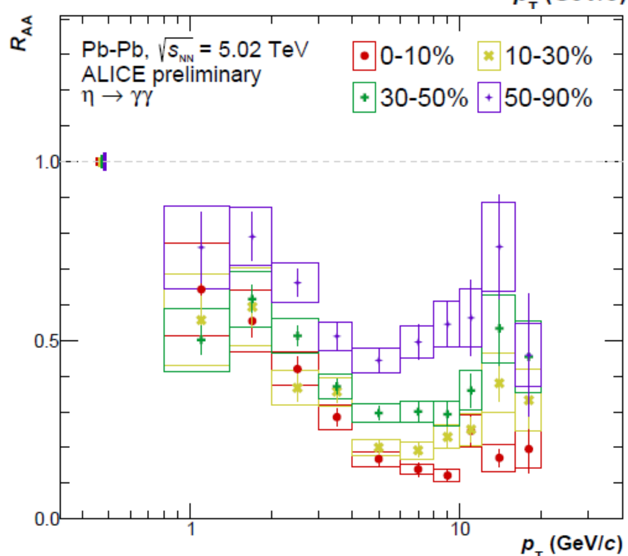
New results in Pb-Pb











Now is the end

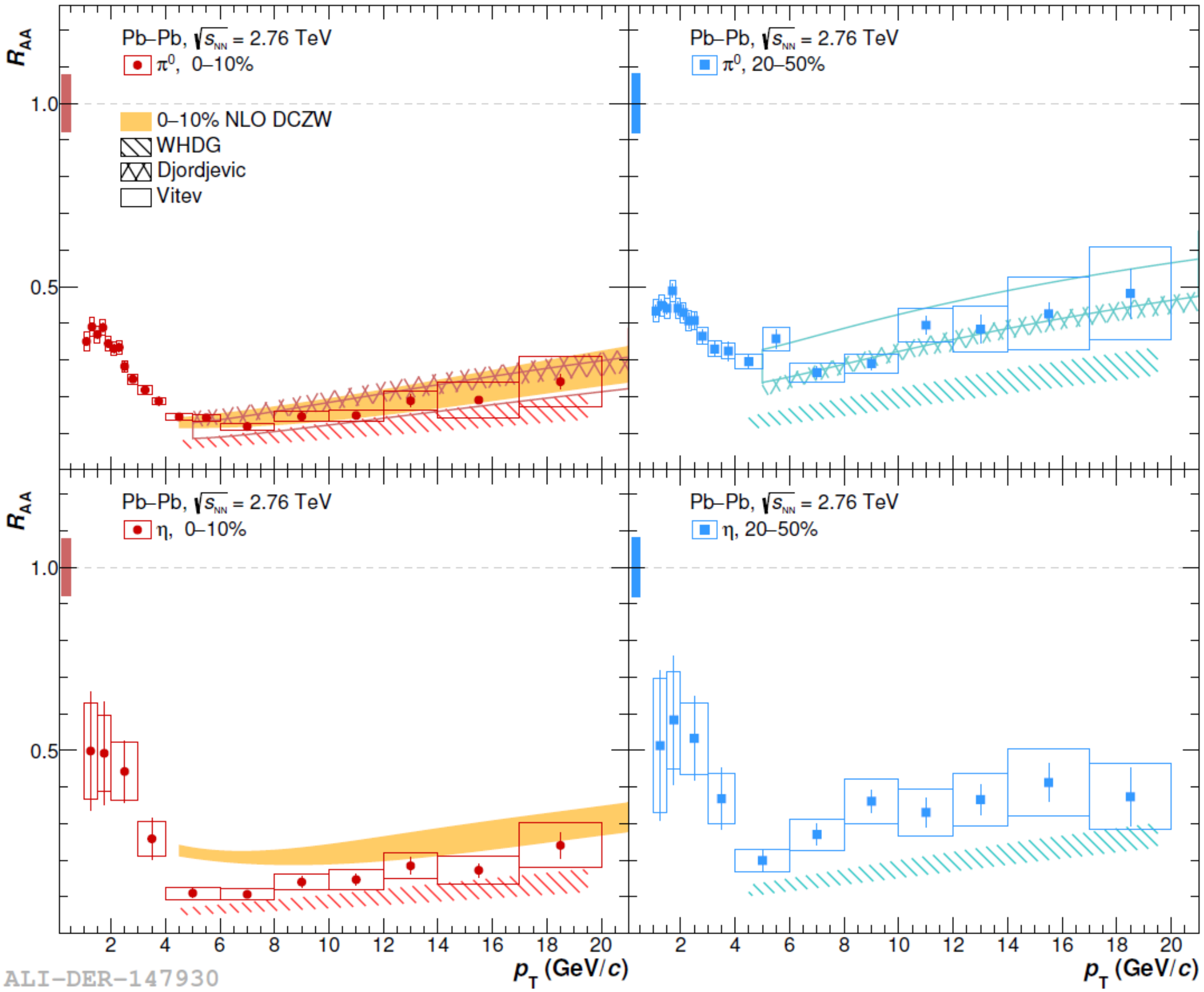
Thanks!

Backup

ALICE photon and neutral mesons papers

Neutral mesons	pp @ 0.9 , 7 TeV:	PLB 717(2012) 162-172.
Invariant mass	pp @ 2.76 TeV:	EPJC 74 (2014) 3108; EPJC 77 (2017) 339.
$M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$	pp @ 8 TeV:	EPJC 78 (2018) 263.
	p-Pb @ 5.02 TeV:	EPJC 78 (2018) 624.
	Pb-Pb @ 2.76 TeV:	EPJC 74 (2014) 3108; PRC 98 (2018)044901.
Direct photons	pp @ 2.76, 8 TeV:	PRC 99 (2019) 024912.
	Pb-Pb @ 2.76 TeV:	PLB 754 (2016) 23-248.
Isolated photons	pp @ 7 TeV:	arXiv:1906.01371.

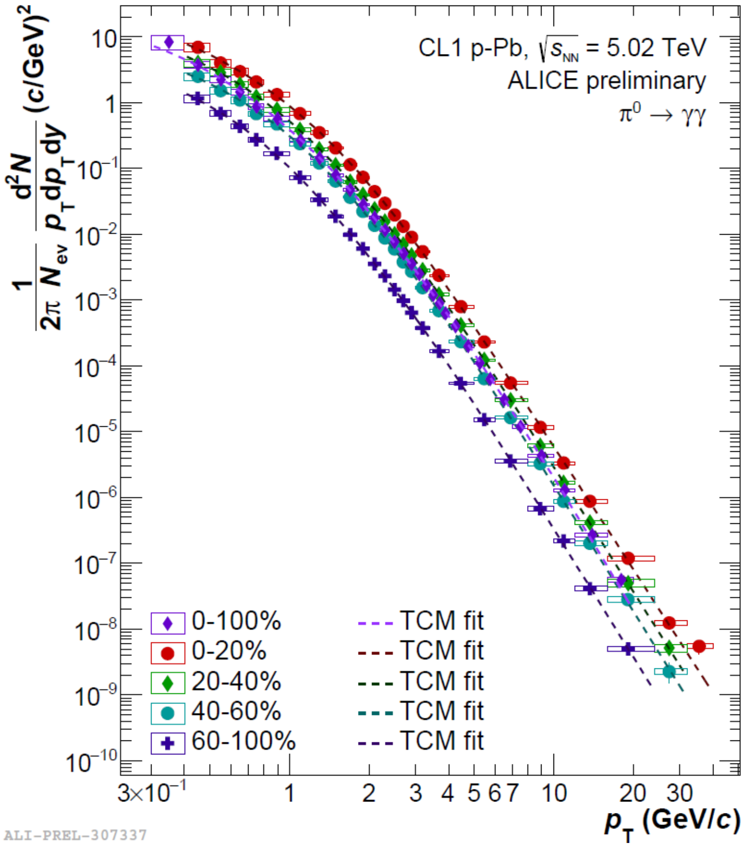
Neutral meson R_{AA} in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV

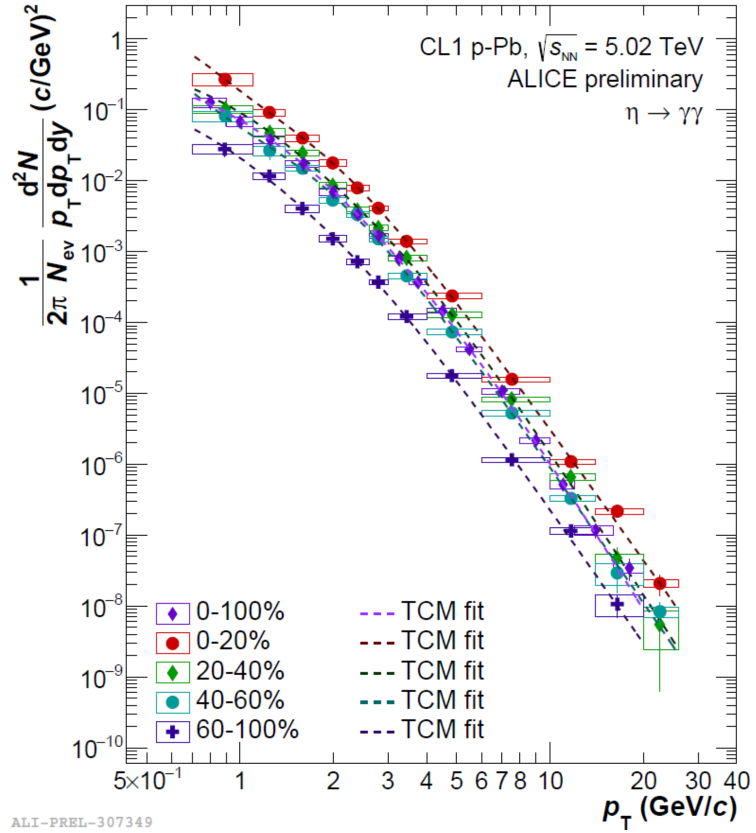


NLO DCZW :
Phys. Lett. B750 (2015) 390-395
WHDG :
Int. J. Mod. Phys. E16 (2007) 2193-2199
Djordjevic :
Phys. Lett. B734 (2014) 286-289
Vitev et al.:
Phys. Rev. D 93, 074030 (2016)

- NLO DCZ describes suppression in central Pb-Pb collsions for π^0 but overpredicts η
- Vitev and Djordjevic describe both centralities for π^0
- WHDG model predictions lie below measurements

Meson production in centrality classes in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

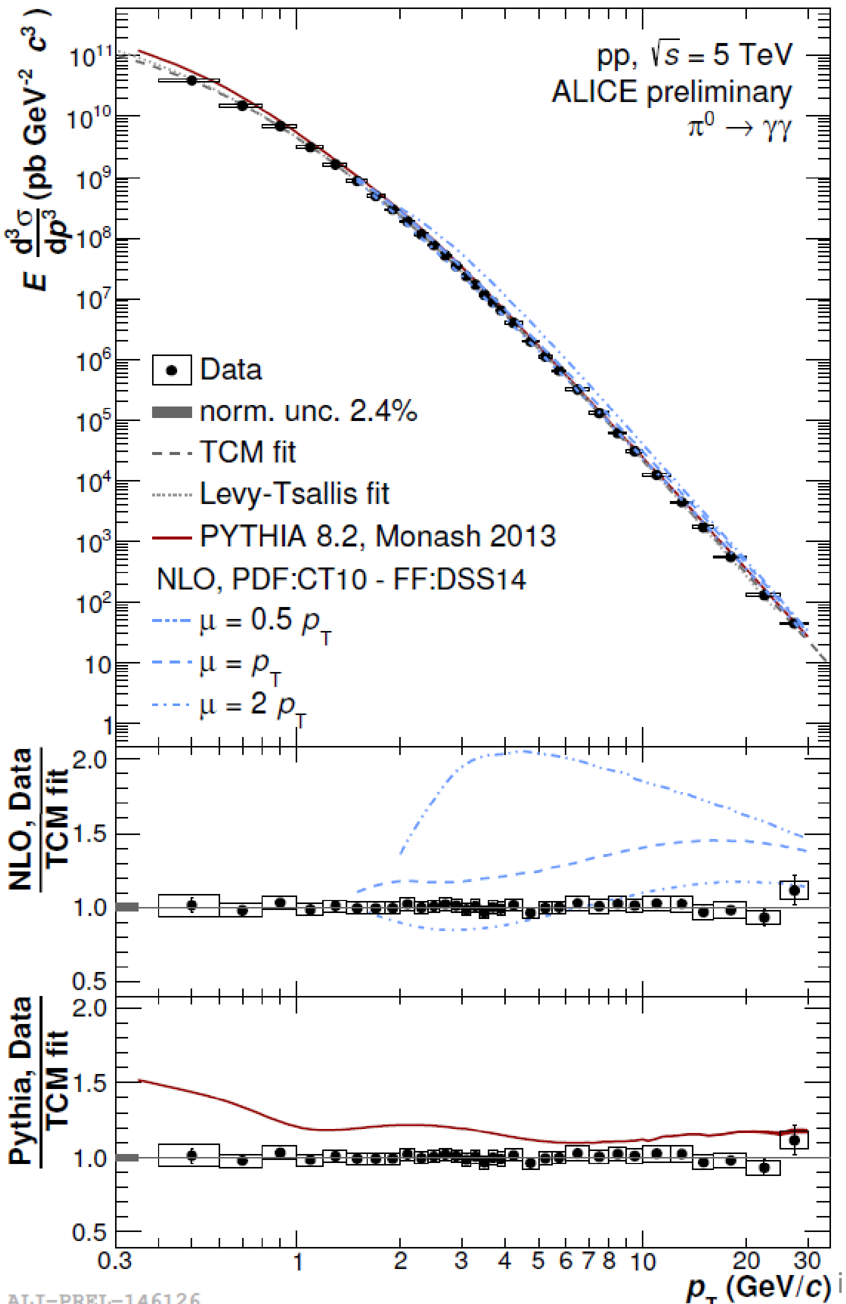




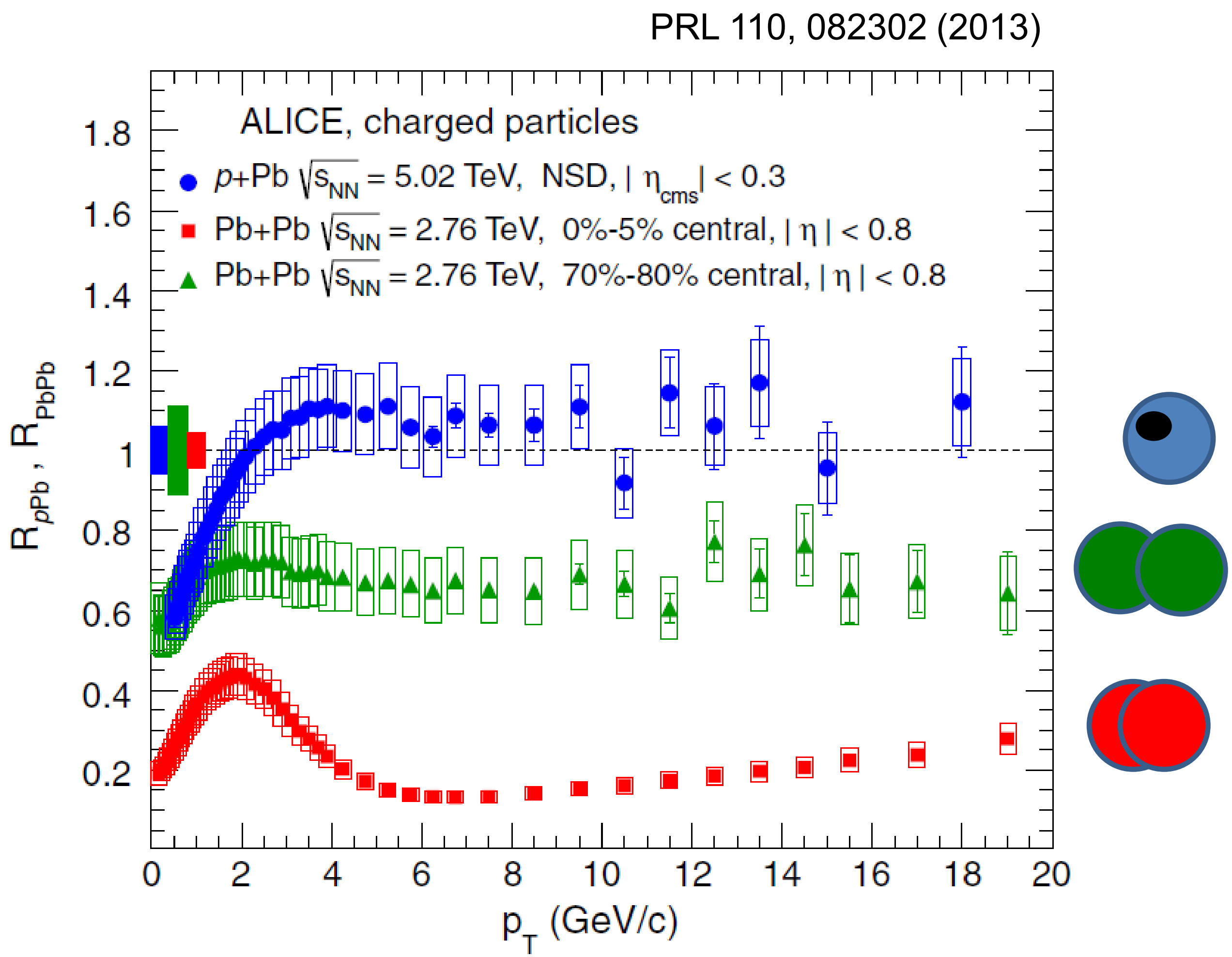
NSD p-Pb0-100%:
EPJ C78 (2018) 624

- Spectra of π^0 and η mesons measured in 4 centrality classes
- Extended p_T range $\to$ up to 40 GeV/c by using PHOS trigger

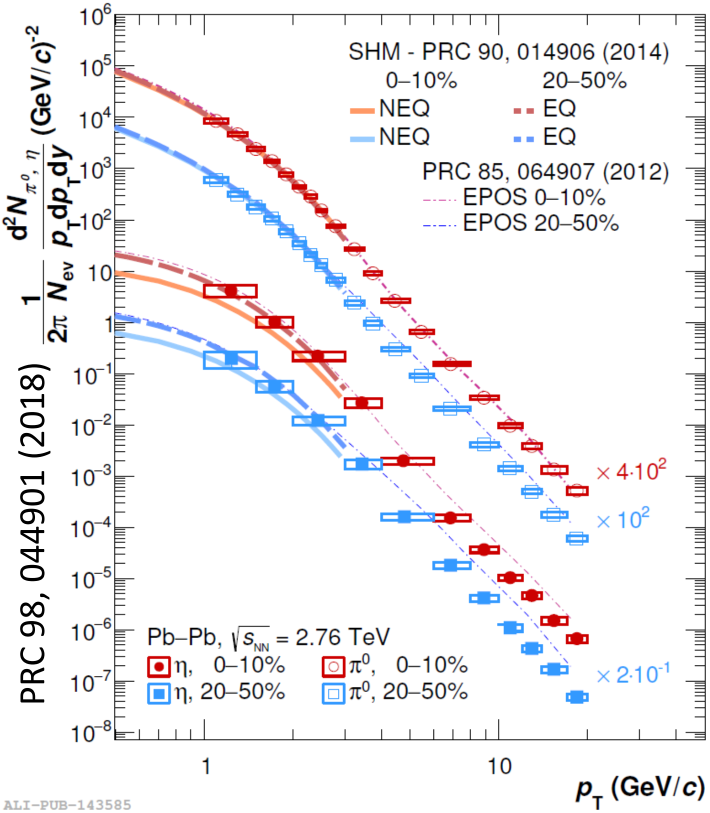
π^0 production spectrum in pp @ 5 TeV comparison

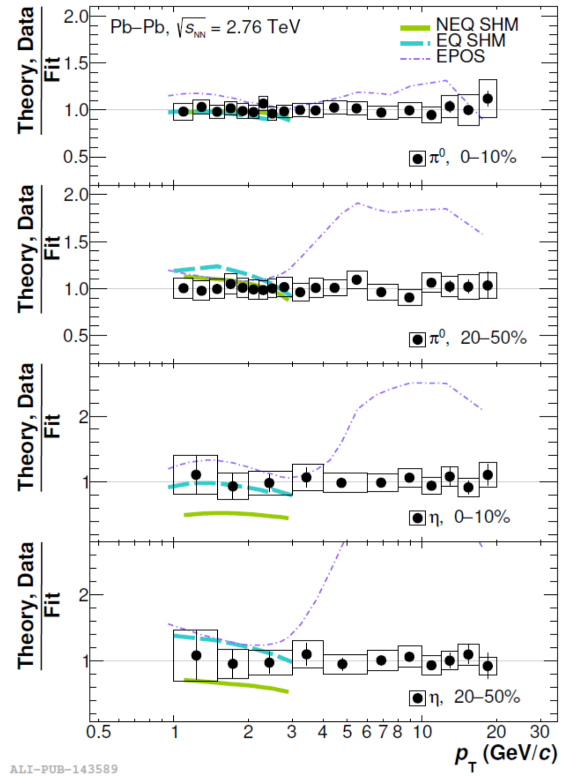


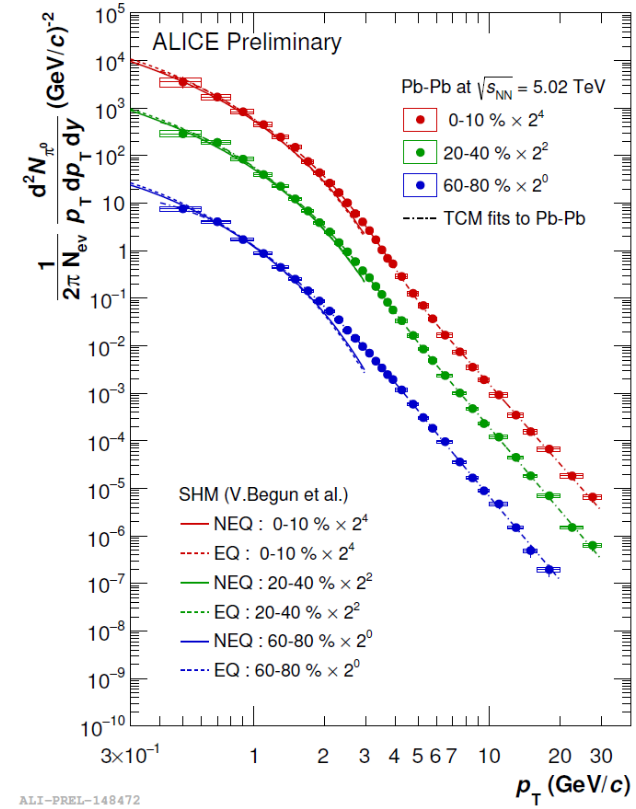
R_{AA} for p-Pb and Pb-Pb



Neutral meson spectra in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV





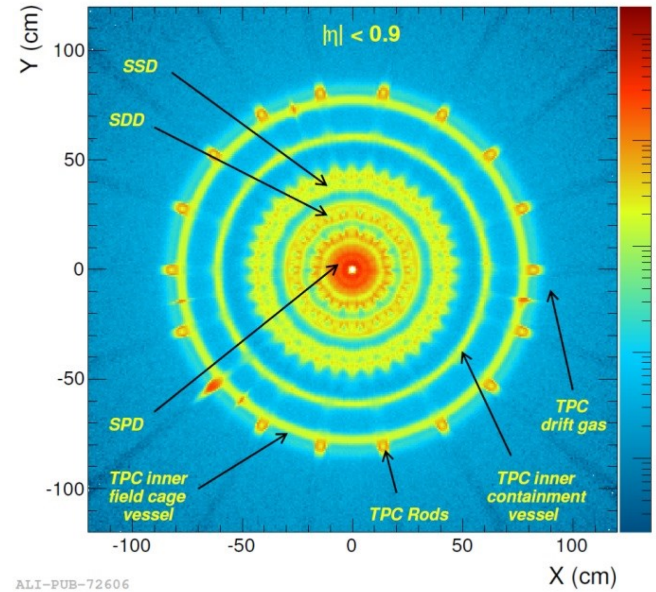


- Extended range up to p_T = 20 GeV/c for π^0 at $\sqrt{s_{NN}}$ = 2.76 TeV in comparison to PLB 717 (2012) 162-172
- First measurement of the η meson in Pb-Pb collisions at the LHC
- Preliminary measurement of π^0 spectrum in several centrality classes at $\sqrt{s_{NN}}$ = 5.02 TeV in the range 0.4 < p_T < 30 GeV/c
- Good description of low-p_T region, failure or no description of high-p_T range

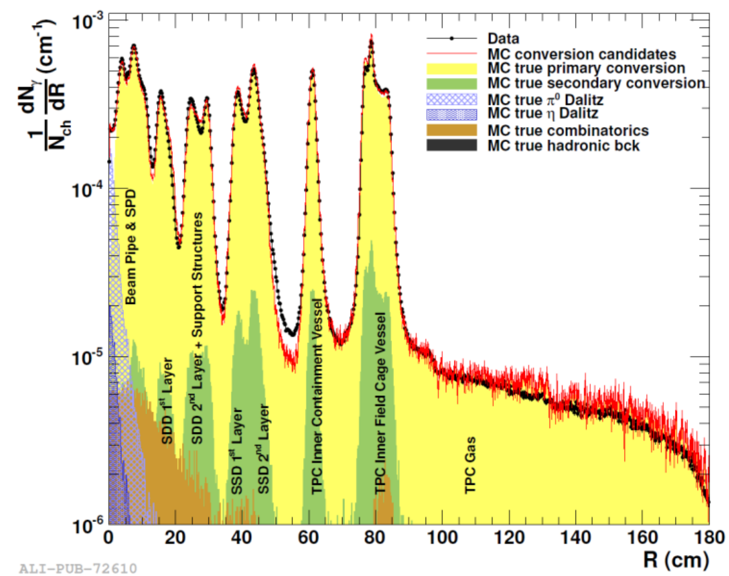
Method of photon and neutral meson extraction

- Photons
  - External conversion electrons , $\gamma \rightarrow e^+ e^-$ (PCM)
    - Small conversion probability (~ 8.5 %) is compensated by a wide acceptance
    - Material budget well known with relative precision of 4.5 %
    - Radiation length X/X0 = (11.4 $\pm$ 0.5) %
  - Energy deposit in calorimeter (EMCal, PHOS)
- Neutral mesons
  - Invariant mass analysis:
    - $h \rightarrow \gamma + \gamma$ (PHOS, EMCal)
    - $h \rightarrow \gamma (\rightarrow e^+ e^-) + \gamma (\rightarrow e^+ e^-)$ (PCM)
    - Dalitz decays $h \rightarrow \gamma \gamma^* \rightarrow \gamma (\rightarrow e^+ e^-) e^+ e^-$ (PCM)
    - Hybrid methods (PHOS + PCM, EMCal +PCM)
  - Shower shape
    - High p_T π^0 decay pairs - showers overlap

Distribution of conversions



Int. J. Mod. Phys. A **29**, 1430044 (2014)



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

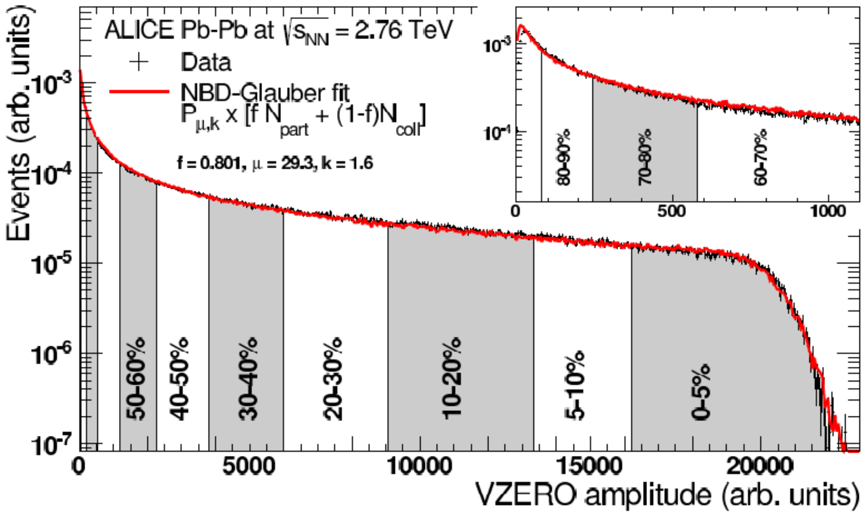
  $f \times N_{part} + (1 - f) \times N_{coll}$
- Number of particles produced by each source given by Negative Binomial Distribution (μ, κ)
- Glauber model fits to cross-section
  - 100% trigger efficiency
  - Background is negligible

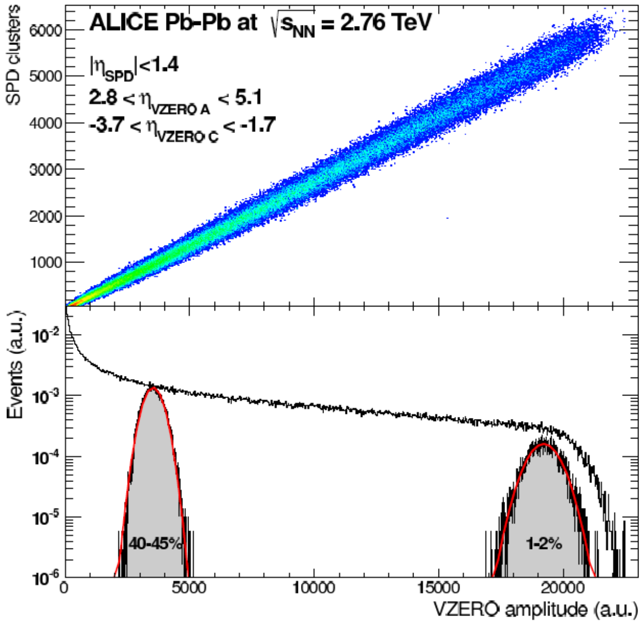
  → ~ 90% of total cross-section

  with σ_{INEL}^{NN} = 64 ± 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





Functions

- Tsallis

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

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

- Hagedorn

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

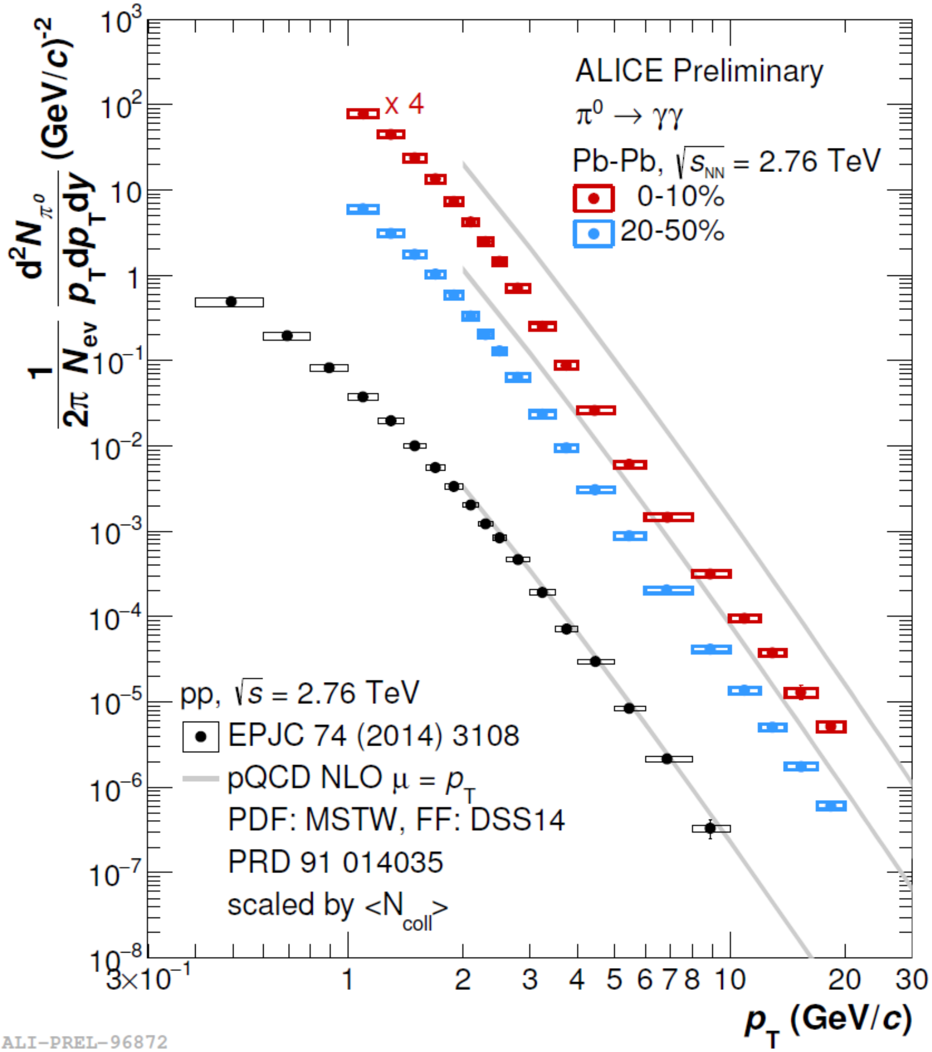
- Power law

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

- Two Component Model (TCM)

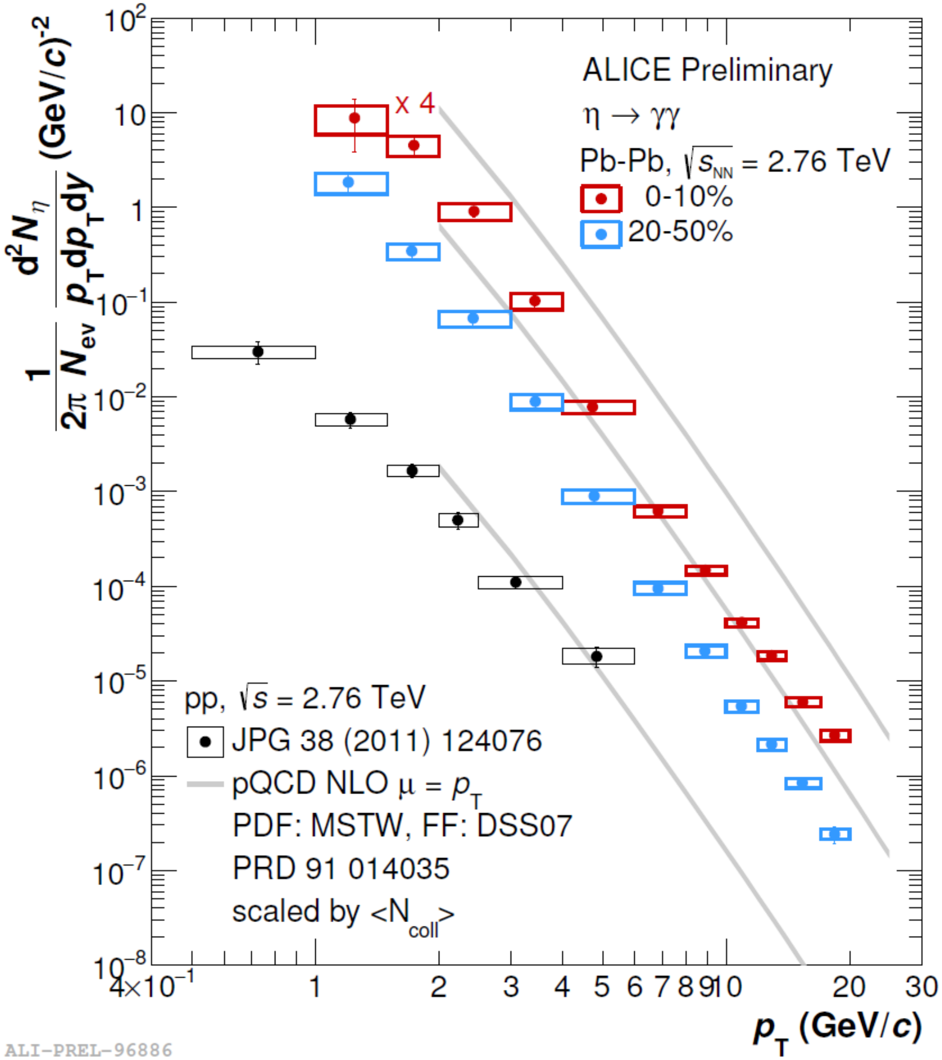
$$\frac{1}{2\pi N_{\mathrm{ev}}}\frac{\mathrm{d}^2N}{p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = A_{\mathrm{e}}\exp\left(-E_{\mathrm{T,kin}}/T_{\mathrm{e}}\right) + A\left(1+\frac{p_{\mathrm{T}}^2}{T^2n}\right)^{-n}$$

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



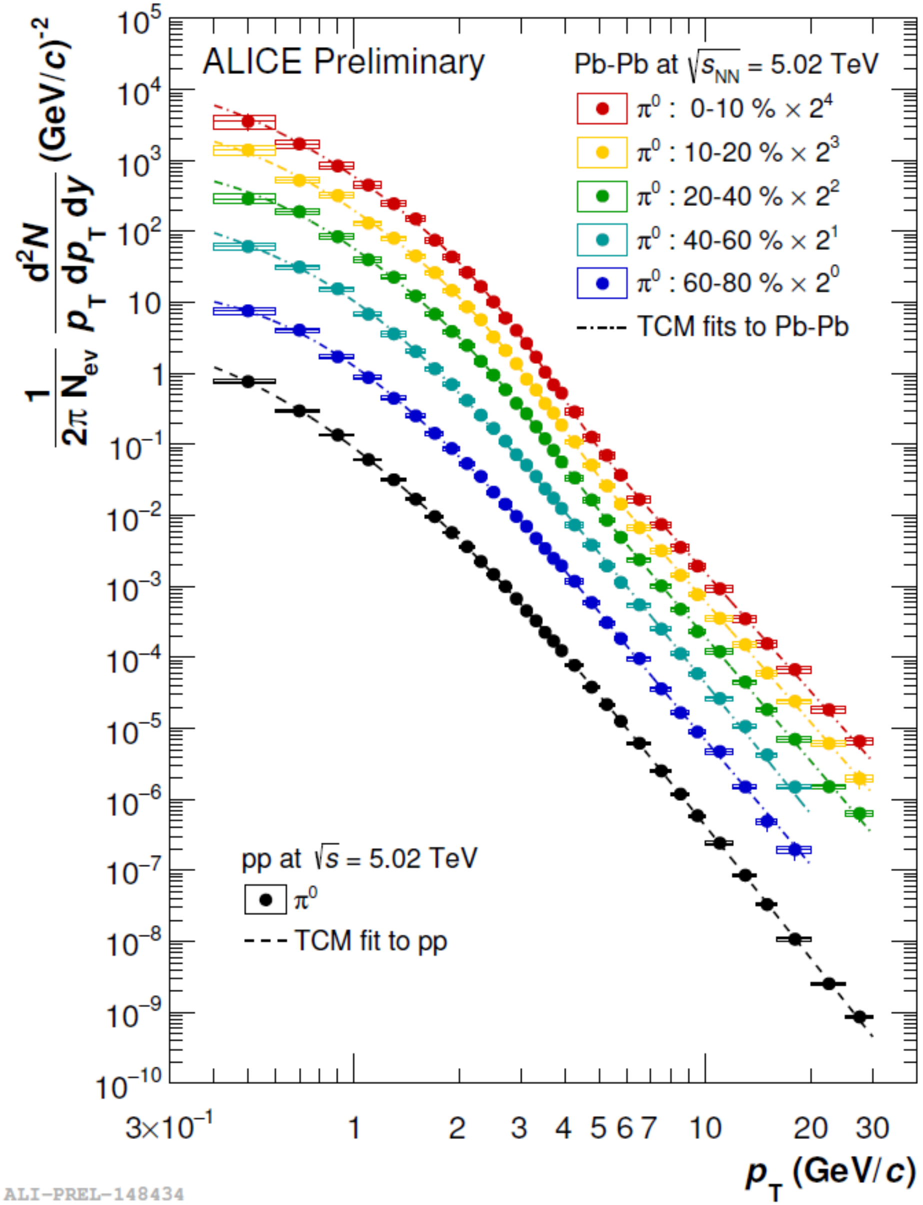
- 10 times more statistics in 2011 (L ~ 0.1 nb^{-1})
- Extended p_T range up to 20 GeV/c
- Two complementary analyses methods: EMCal and PCM
- Two centrality classes compared to pp
- Compared to NLO pQCD pp predictions scaled by N_{coll} (PRD 91 (2015) 1, 014035)

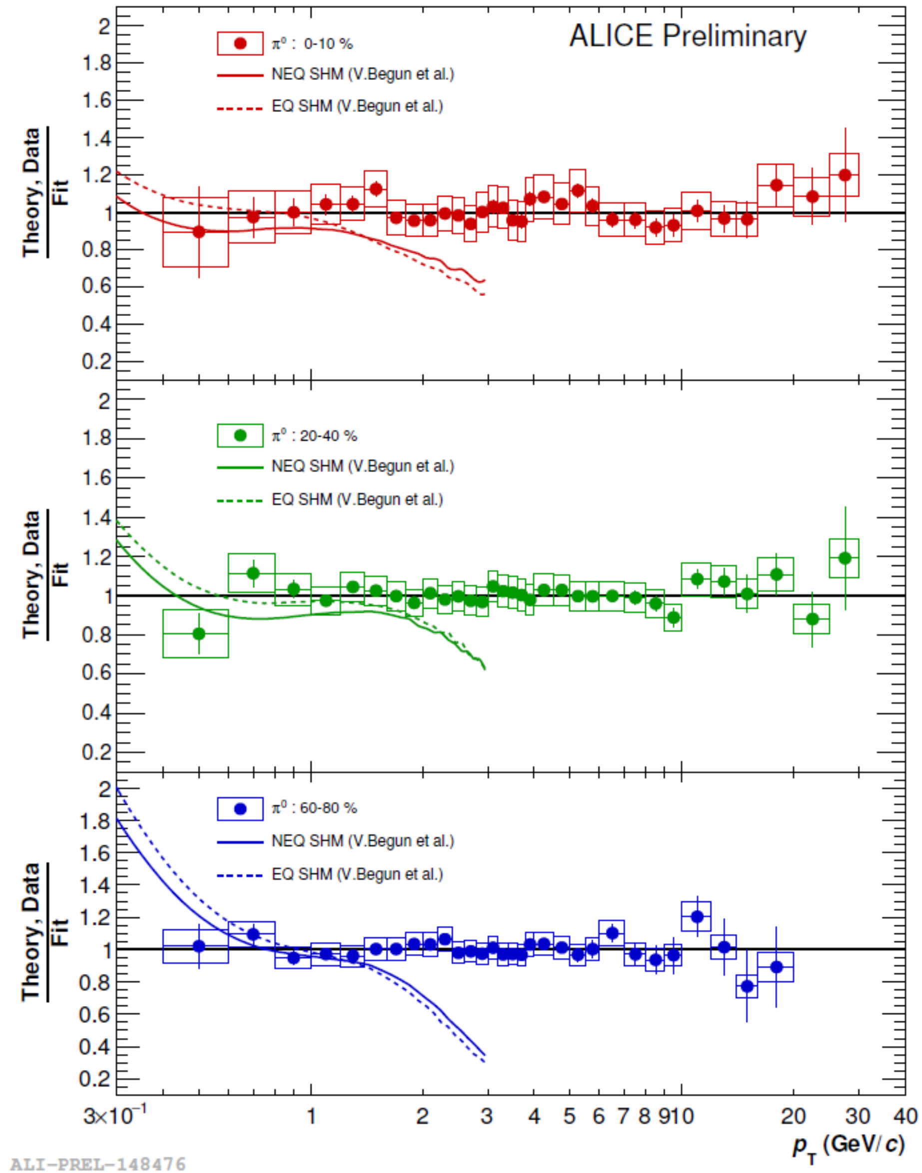
η spectra in Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV



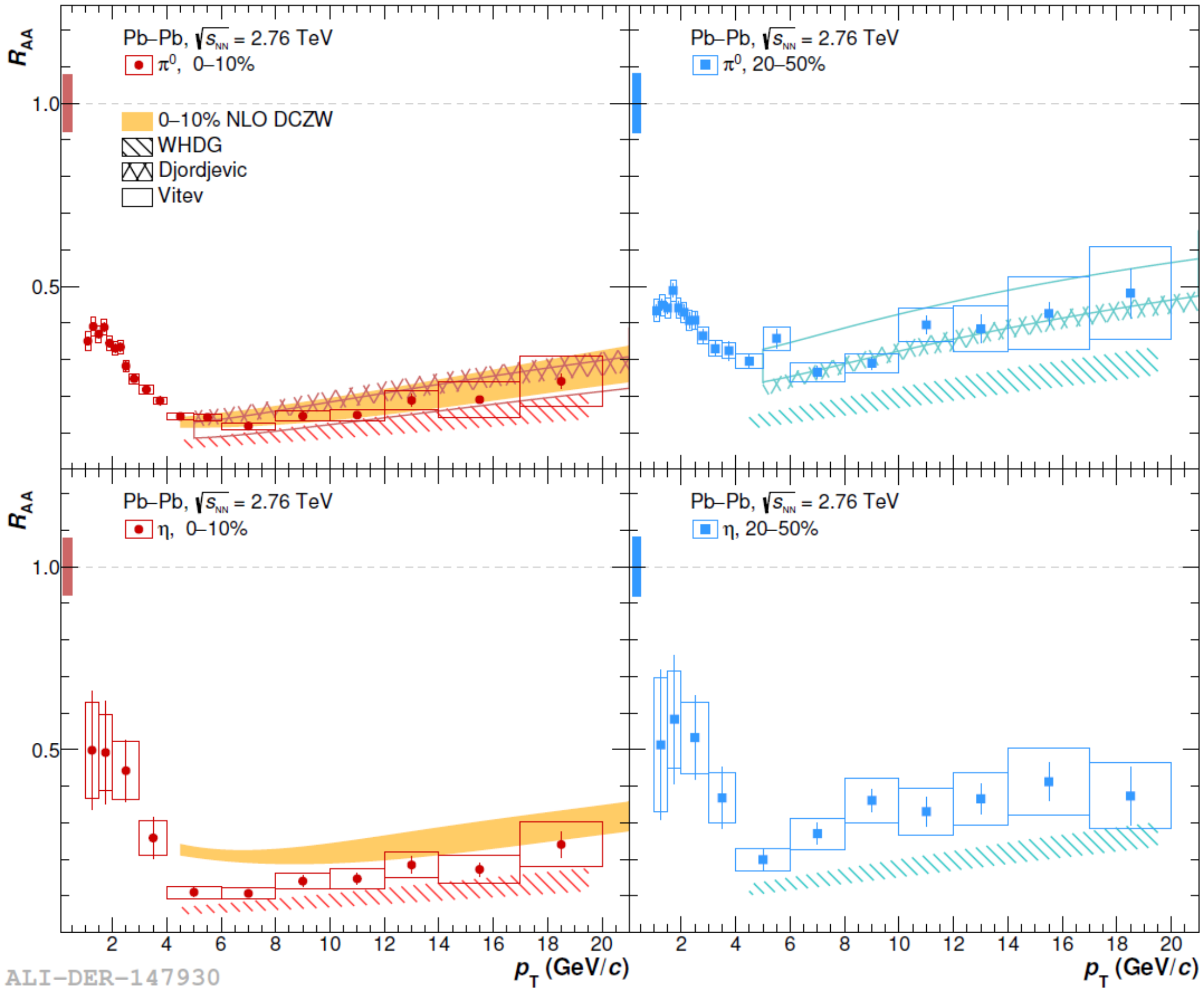
- First η measurement in Pb-Pb at the LHC
- Range: $1 < p_T < 20$ GeV/c
- Two complementary systems: EMCal and PCM
- Two centrality classes compared to pp
- Compared to η production of NLO pQCD pp predictions scaled by N_{coll} (PRD 91 (2015) 1, 014035)

π^0 spectra in Pb-Pb @ 5.02 TeV



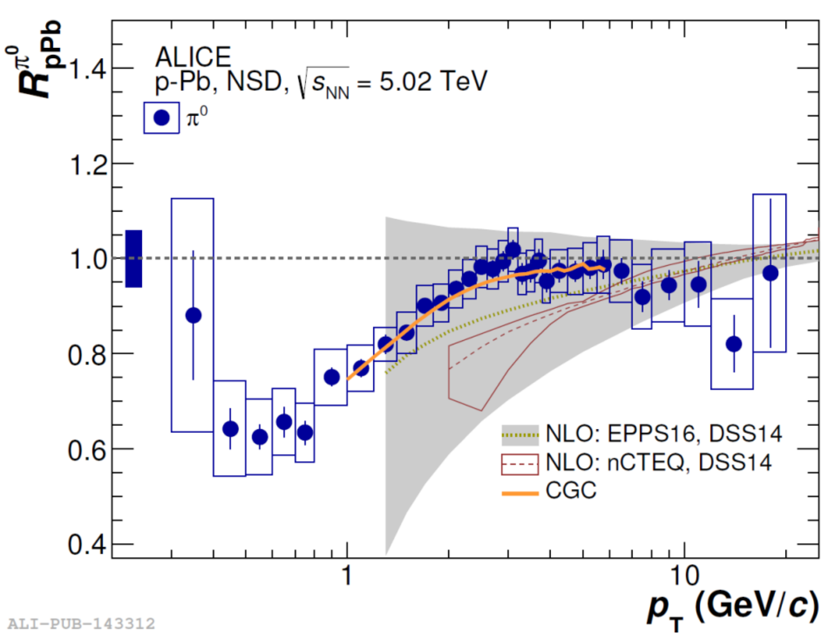


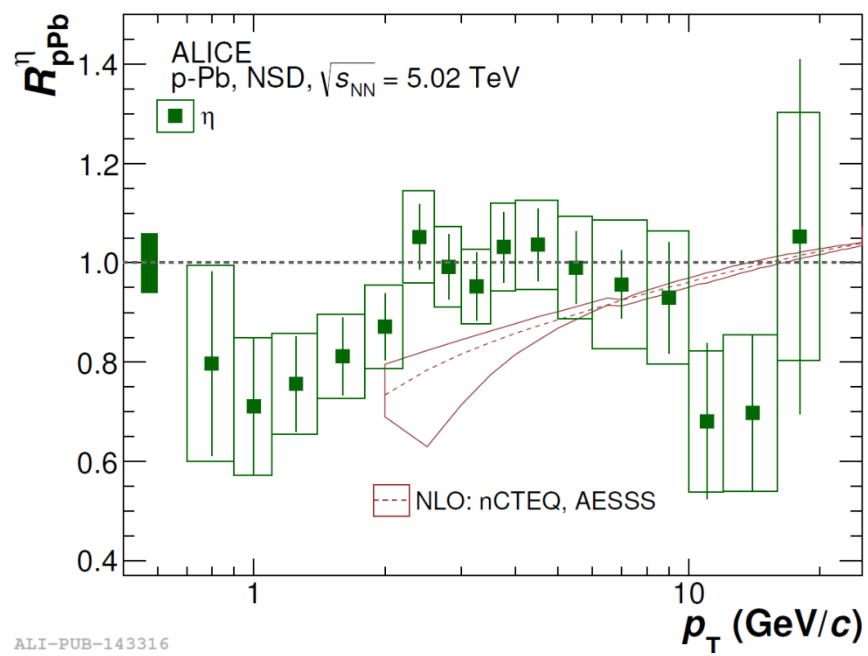
Meson R_{AA} in Pb-Pb @ 2.76 TeV



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)

Mesons R_{AA} in p-Pb @ 5.02 TeV





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