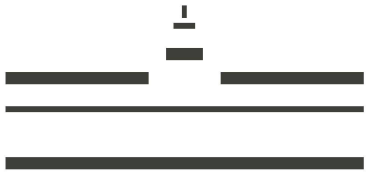

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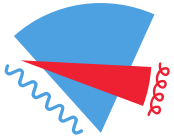

Graduiertenkolleg 2149
Research Training Group


# Measurement of Neutral Mesons and Direct Photons with ALICE at the LHC

Daniel Mühlheim
on behalf of the ALICE Collaboration

Westfälische Wilhelms-Universität Münster

PANIC, Beijing
September 03rd, 2017

# Content

- Physics motivation (→ Why neutral mesons and direct photons?)
- ALICE @ the LHC
- Photon reconstruction (PCM, EMCal, PHOS)
- Published neutral meson measurements by ALICE up to now
  - pp (QCD vacuum)
  - p-Pb (cold nuclear effects)
  - Pb-Pb (QGP creation → QCD medium effects)
- Direct photon measurements by ALICE
  - Pb-Pb (hot QCD medium → thermal photons)
- Summary & outlook

# Physics motivation

- List of observables:
  - Direct Photons: $\gamma$
    - Photon yields, $R_{AA}$, $R_{pPb}$
    - $R_\gamma = \frac{\gamma^{\mathrm{incl}}}{\gamma^{\mathrm{decay}}}$

✔ Photons escape the QCD medium basically unaffected, produced at every stage of the collision → very interesting probe

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    - Particle ratios
    - Integrated yields / mean $p_T$

    ✔ Important input for direct photons, dielectrons, HF electrons → dominant background

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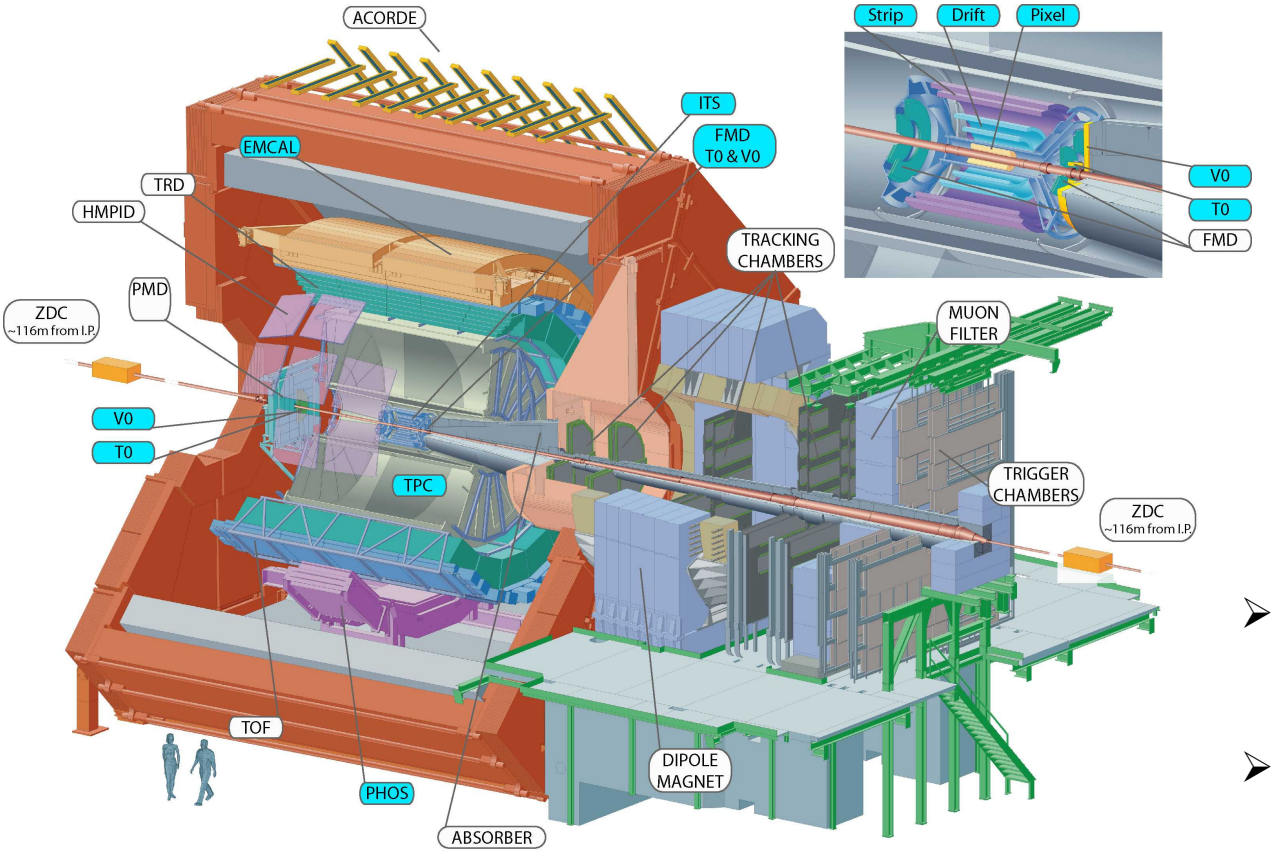
- pp / p-Pb / Pb-Pb measurements
  - Each system is unique, need all of them to develop full, consistent picture
  - Disentangle initial/final state effects in nuclear modification of spectra in Pb-Pb collisions
- Different collision energies
  - Test pQCD NLO / generator (PYTHIA,...) predictions
  - Test scaling laws/predictions → evolution of spectra with $\sqrt{s}$

# ALICE @ the LHC







- ITS/TPC - precise tracking + PID
- EMCal/PHOS – electromagnetic calorimeters
  - Triggering capabilities
    → extend high momentum reach

- Relevant detectors for reported analyses located at central barrel
- V0/T0 detectors: MB trigger and luminometers

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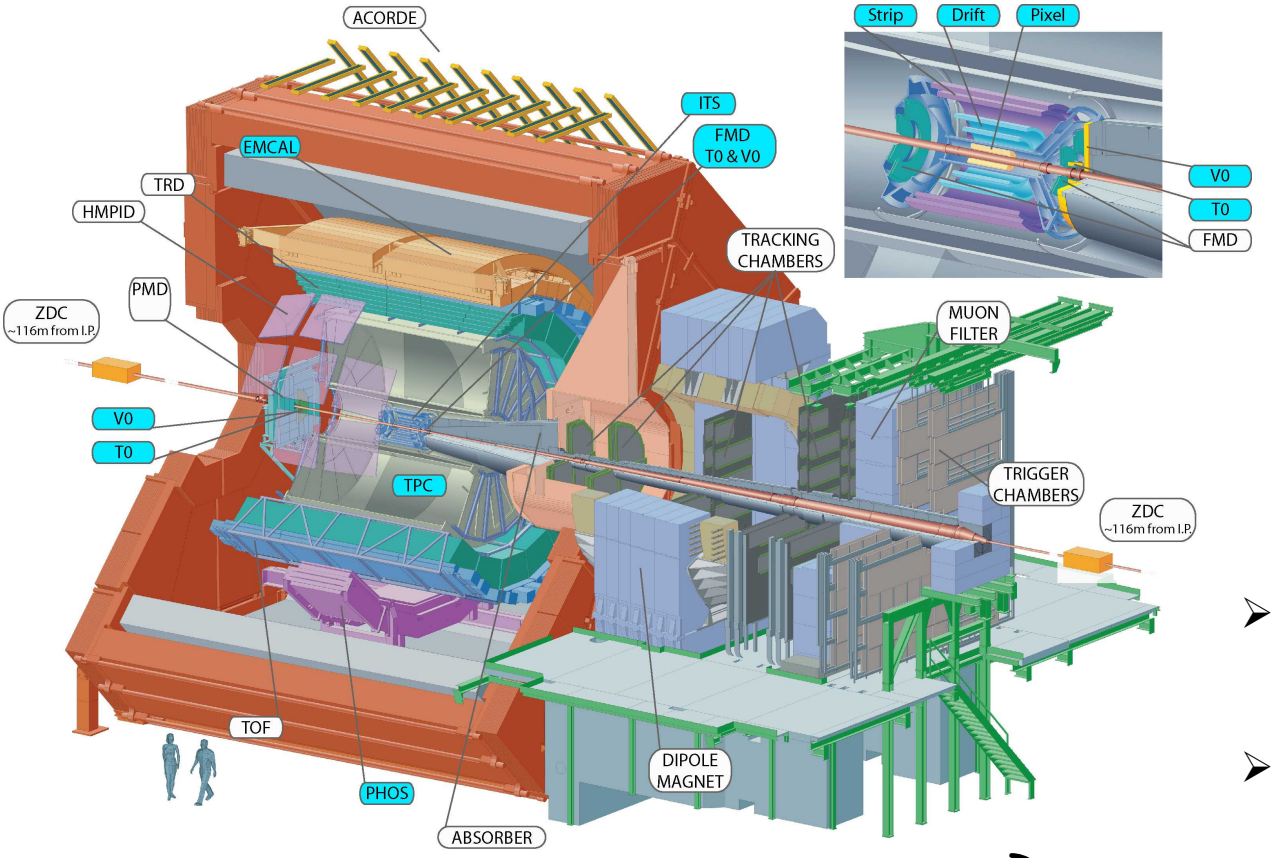





| LHC Run 1 | | |
|---|---|---|
| pp | p-Pb | Pb-Pb |
| 0.9 TeV | - | - |
| 2.76 TeV | - | 2.76 TeV |
| - | 5.02 TeV | - |
| 7 TeV | - | - |
| 8 TeV | - | - |

- Relevant detectors for reported analyses located at central barrel
- V0/T0 detectors: MB trigger and luminometers

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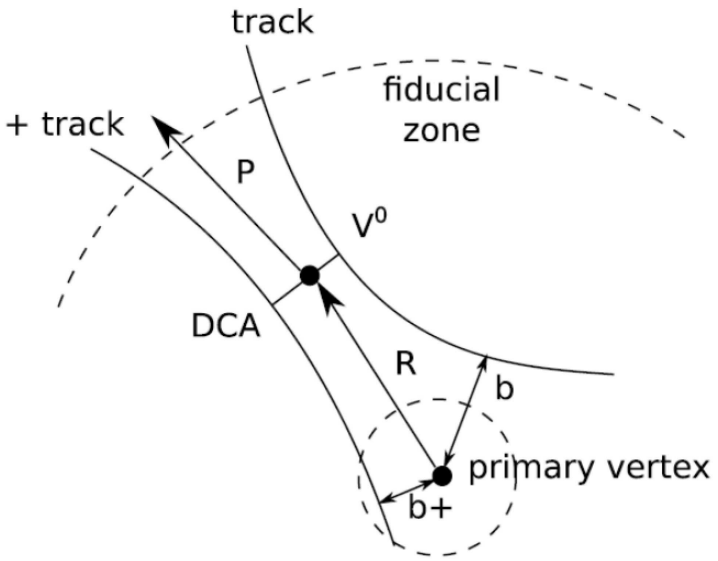
Photon reconstruction via three independent methods

# Photon reconstruction in ALICE using...

## (1) ... Photon Conversion Method (PCM)

- Pair charged particles with large impact parameter, if DCA small → $V^0$ candidate
- Background mainly combinatorial, use discriminators in analysis to primarily select photon candidates from $V^0$ sample on...



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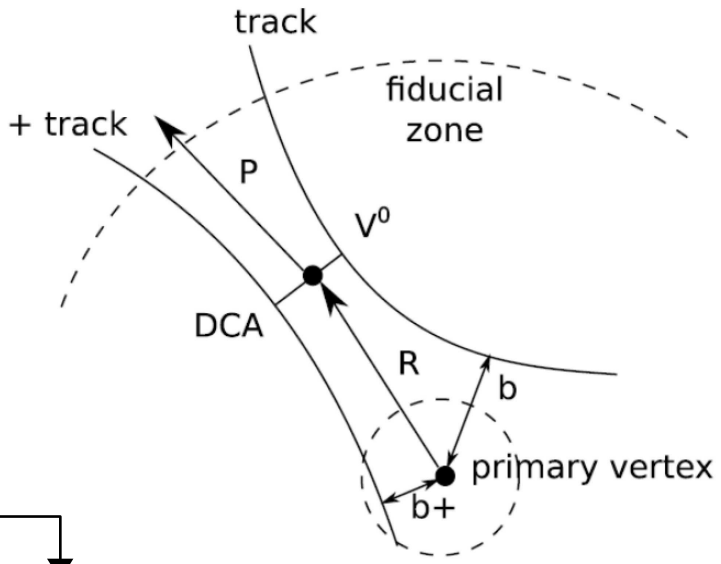
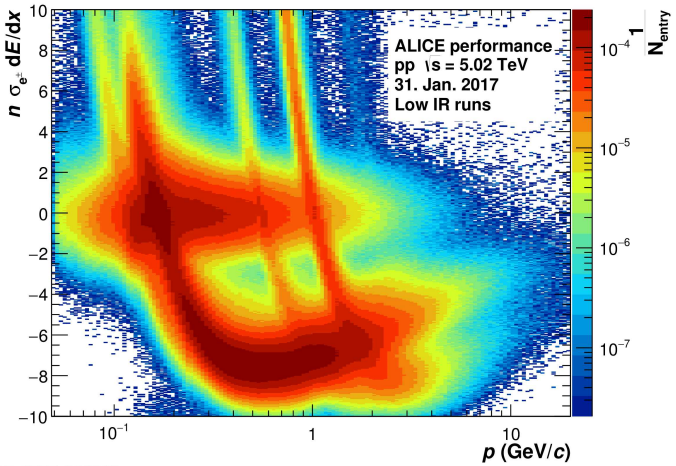
  - Track level




ALI-PERF-115747

# Photon reconstruction in ALICE using...

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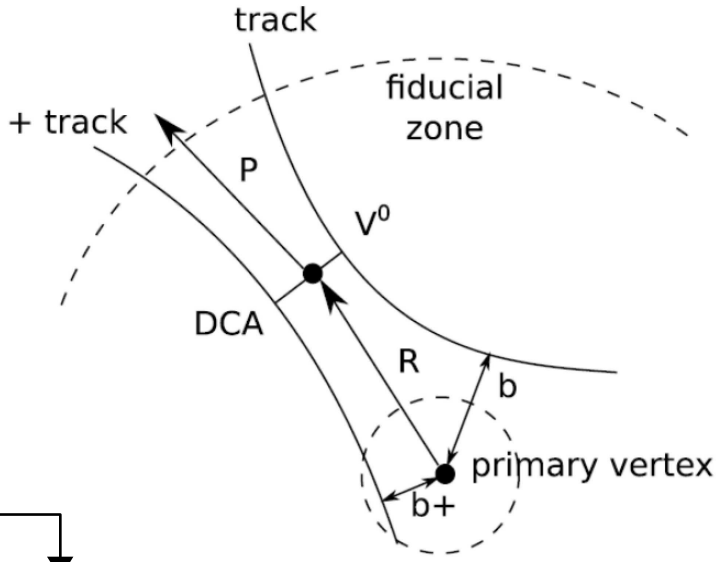
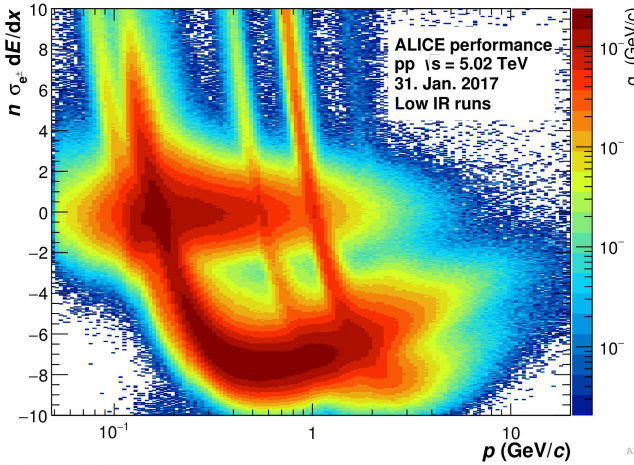
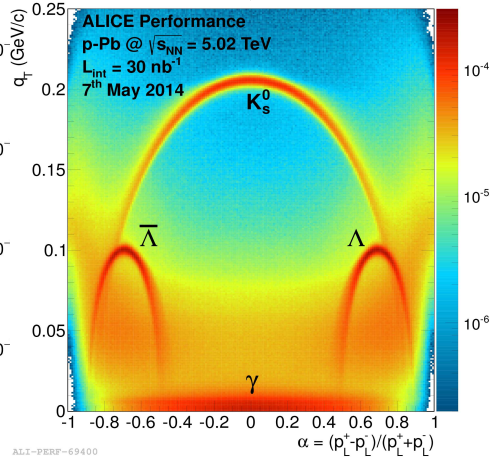
- Background mainly combinatorial, use discriminators in analysis to primarily select photon candidates from $V^0$ sample on...
  - General criteria
  - Track level
  - Photon topology
  - ➔ High purities in pp (>99%)
  - ➔ Most central Pb-Pb (>91%)
- $|\eta| < 0.9, 0 < \varphi < 2\pi$
- Excellent resolution, but $P_{conv}$~8.5%



# Photon reconstruction in ALICE using...

(2) ... Electromagnetic Calorimeter (EMCal)

- $|\eta| < 0.67, \Delta\varphi = 100°$
- Shashlik calorimeter (lead/scintillator)
- Cell dimensions: $\Delta\eta \times \Delta\varphi = 0.0143 \times 0.0143$

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(3) ... Photon Spectrometer (PHOS)

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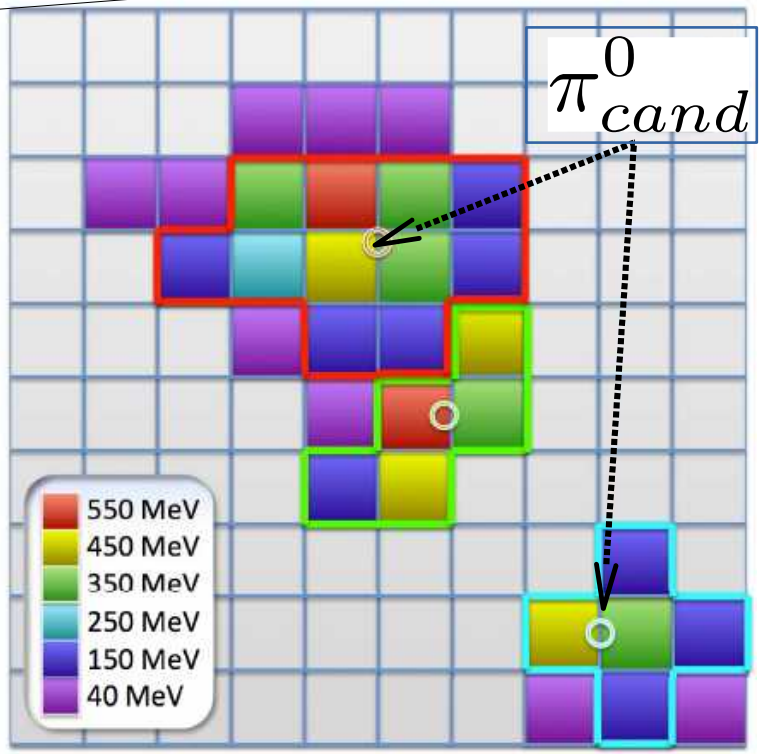



- Cells with deposited energy are grouped in clusters → photon candidates
- Trigger capabilities → select events with energy deposited above a threshold

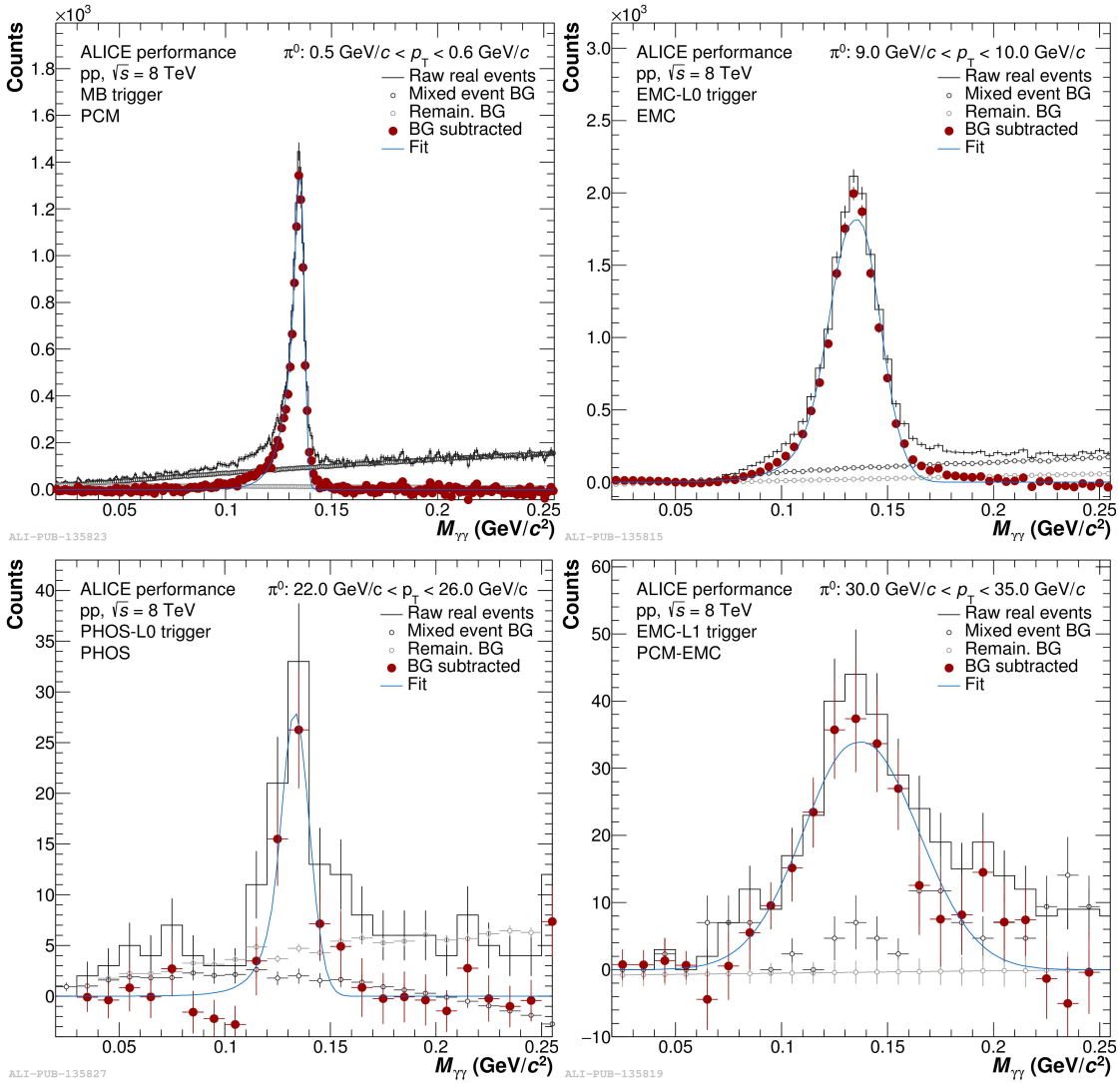
# Meson reconstruction

pp@8TeV – neutral pion

- Invariant mass of two photon candidates:

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma_1\gamma_2})}$$

- Event mixing for uncorrelated background (use different event pools – mult., z-bin,...)
- Fit with exponential + Gaussian + pol1
  → mass position, width
  → bin counting for raw yields
- Pairing two photons from PCM / PHOS / EMCal during reconstruction



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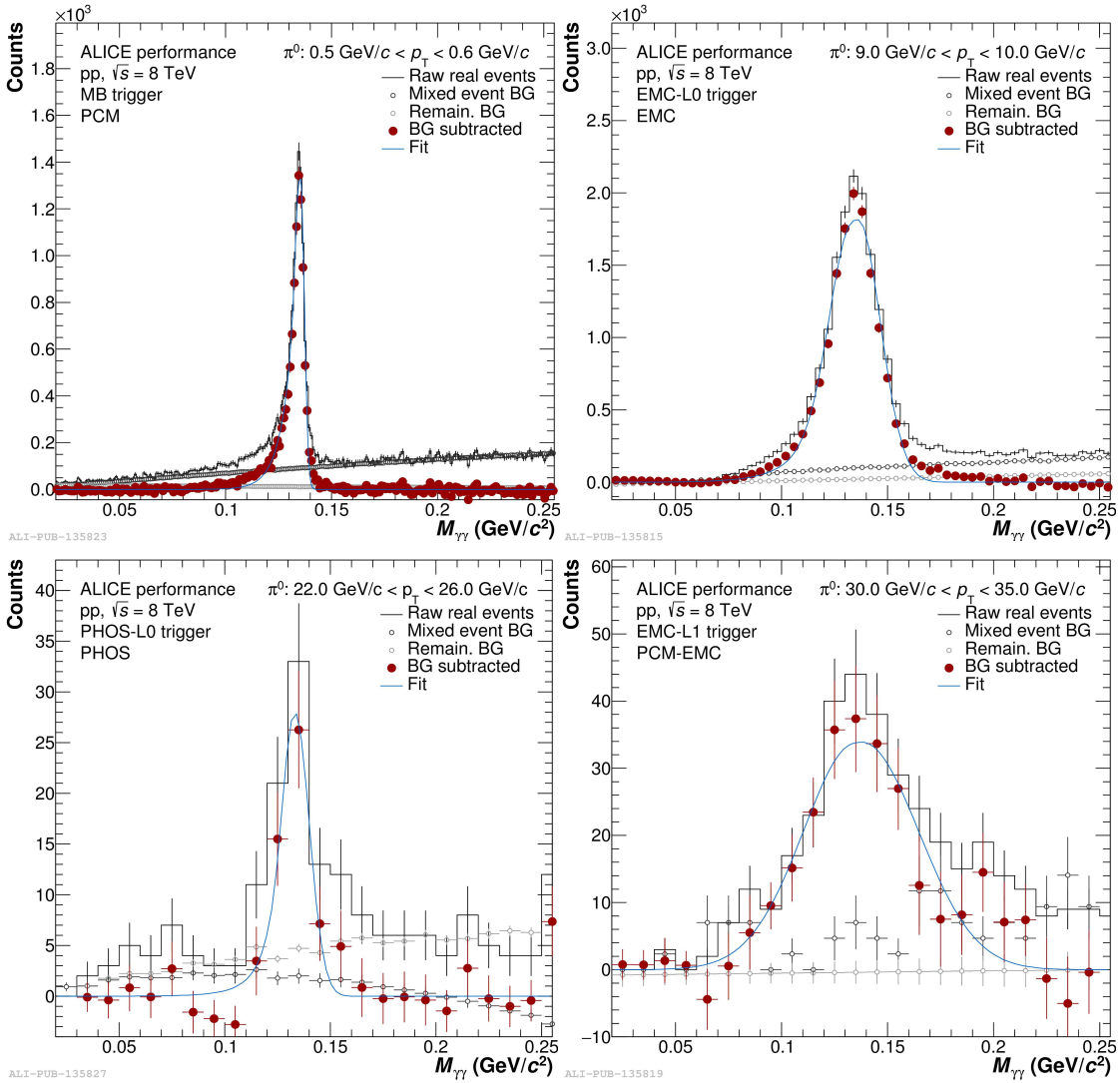
- Additionally: "hybrid" methods
  → PCM + calorimeter
  → combine advantages from both methods
  → important cross-check



# Meson reconstruction

pp@8TeV – eta meson

- Invariant mass of two photon candidates:

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- Event mixing for uncorrelated background (use different event pools – mult., z-bin,...)
- Fit with exponential + Gaussian + pol1
  → mass position, width
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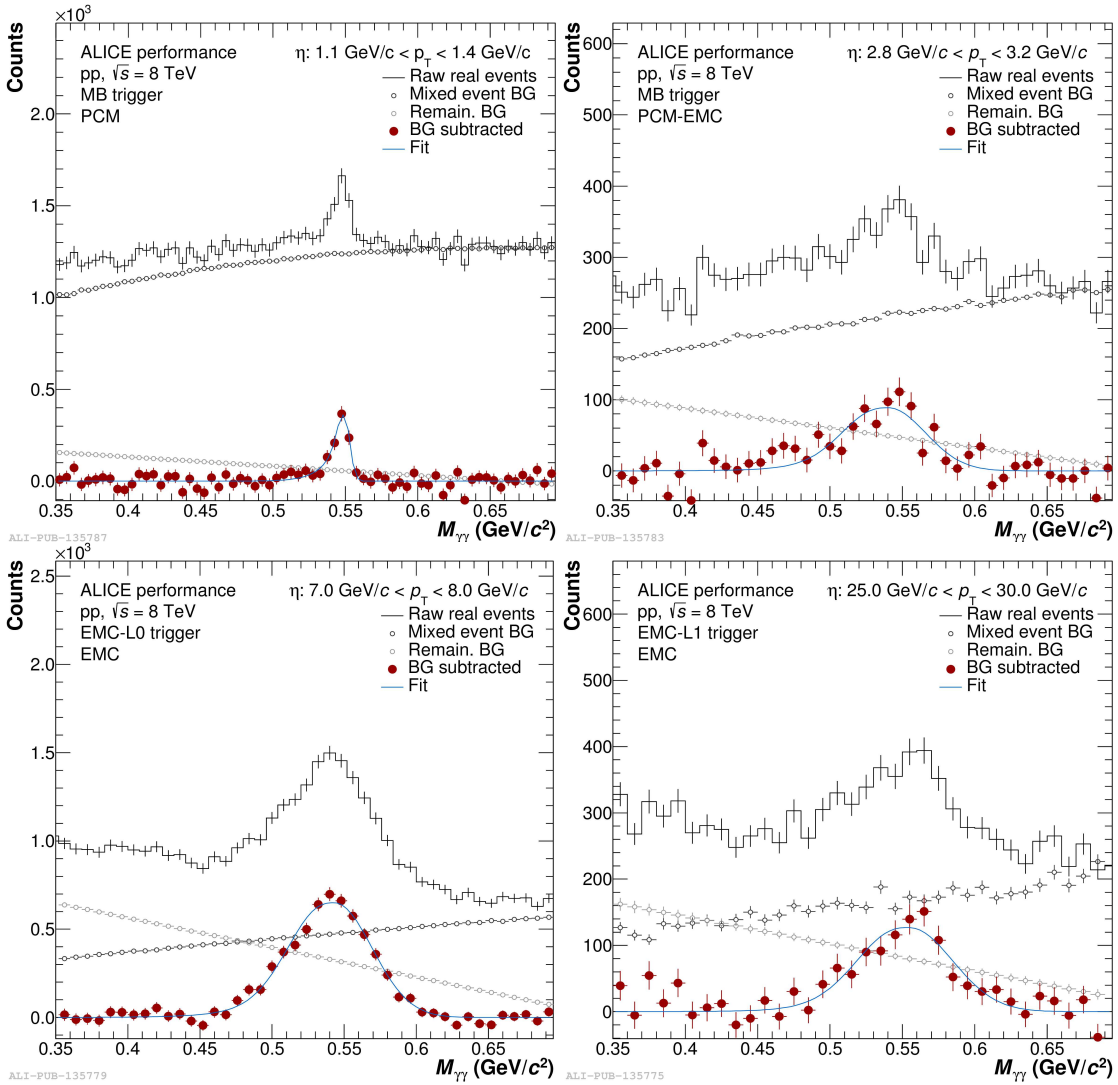
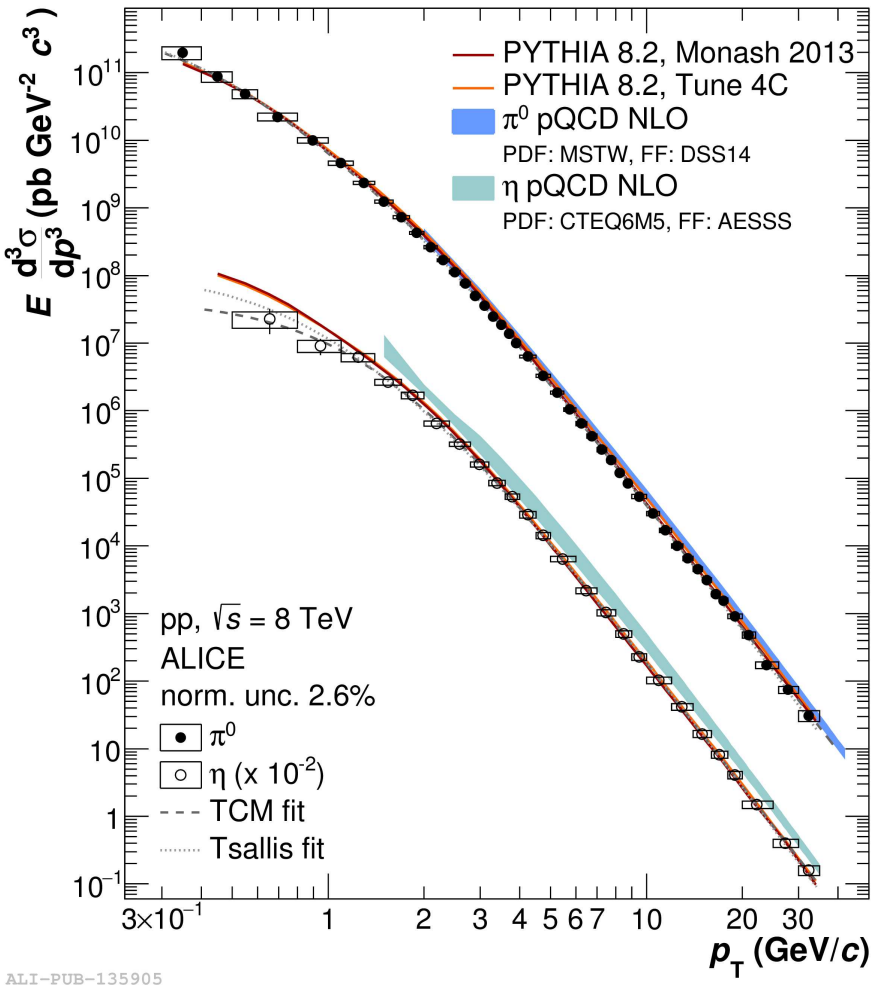


# Results – neutral mesons pp@8TeV

newly on arXiv: 1708.08745, submitted to EPJC




- High momentum reach for $\pi^0$ and $\eta$
  - Combining 4 methods with 4 different triggers
    - ➔ PCM, EMCal, PCM-EMCal, PHOS ($\pi^0$)
    - ➔ MB + Calorimeter triggers:
      → EMCal (~2, ~8 GeV) and PHOS (~4 GeV)

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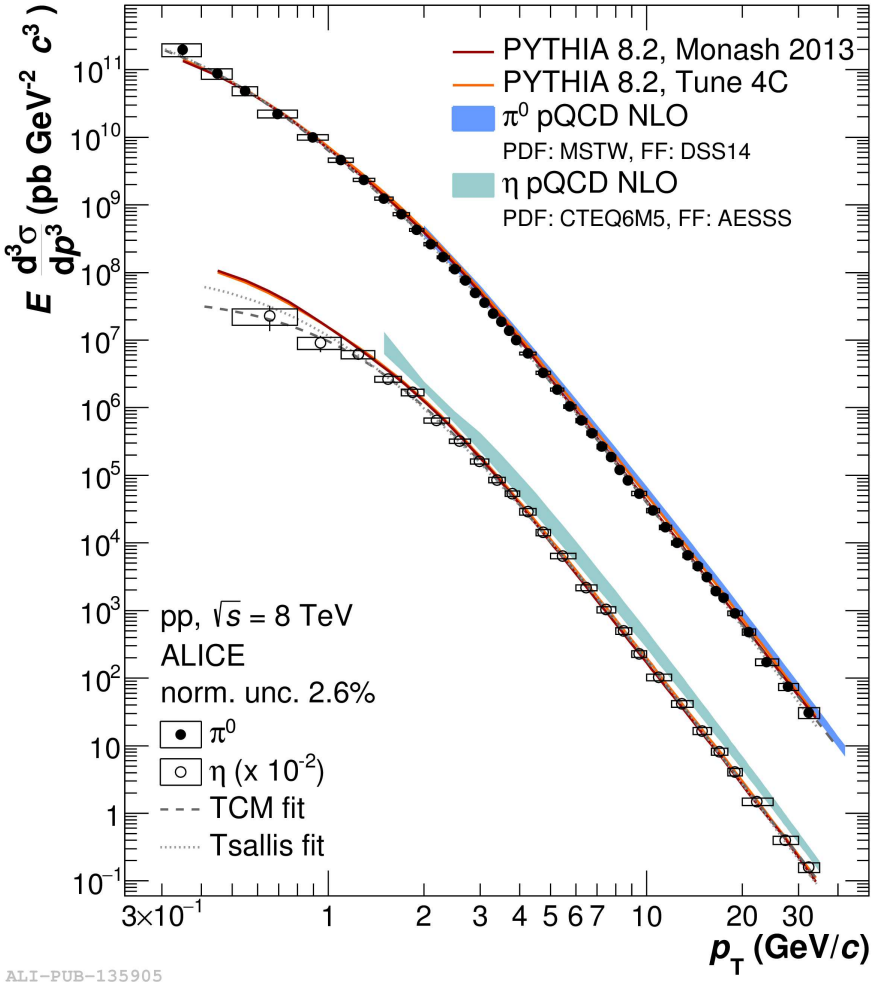


ALI-PUB-135905

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    - ➔ PCM, EMCal, PCM-EMCal, PHOS ($\pi^0$)
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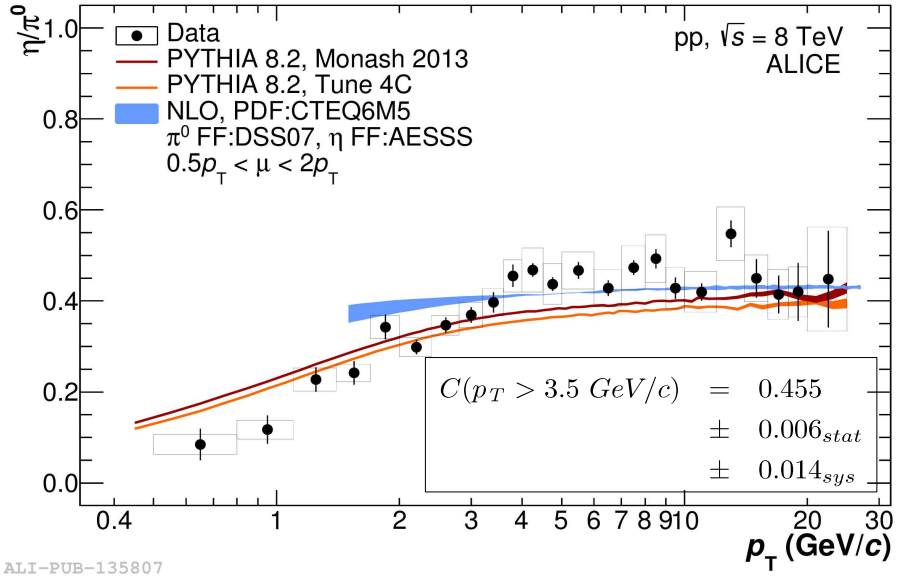
- Precise reference data for LHC Run 2 p-Pb @ 8TeV; total uncertainties (at ~3 GeV/c):
  → ~ 5% for $\pi^0$ → ~10% for $\eta$ and $\eta/\pi^0$




ALI-PUB-135807

# Results – neutral mesons pp@8TeV

newly on arXiv: 1708.08745, submitted to EPJC

- Data fitted with TCM (Tsallis), comparisons to:
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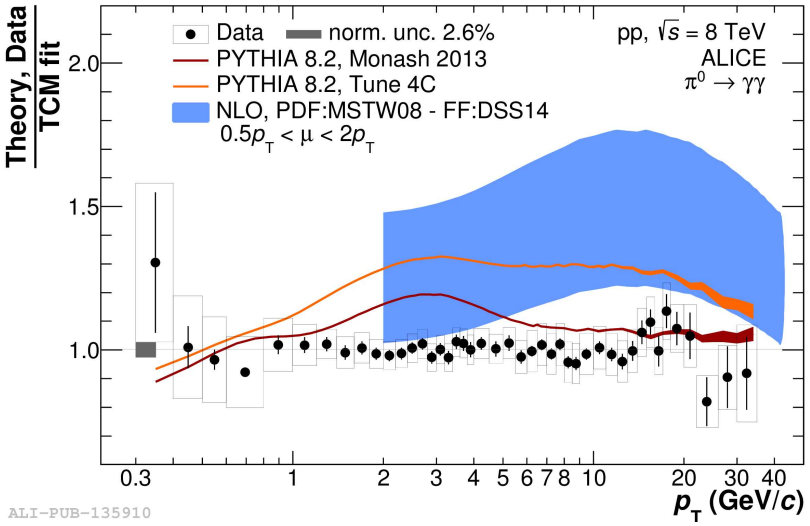
  - pQCD NLO calculations (FF:DSS14 / AESSS)



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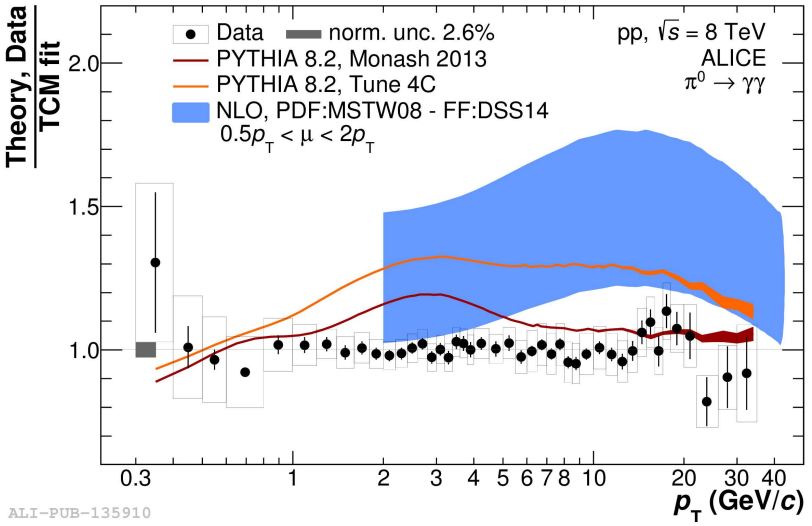


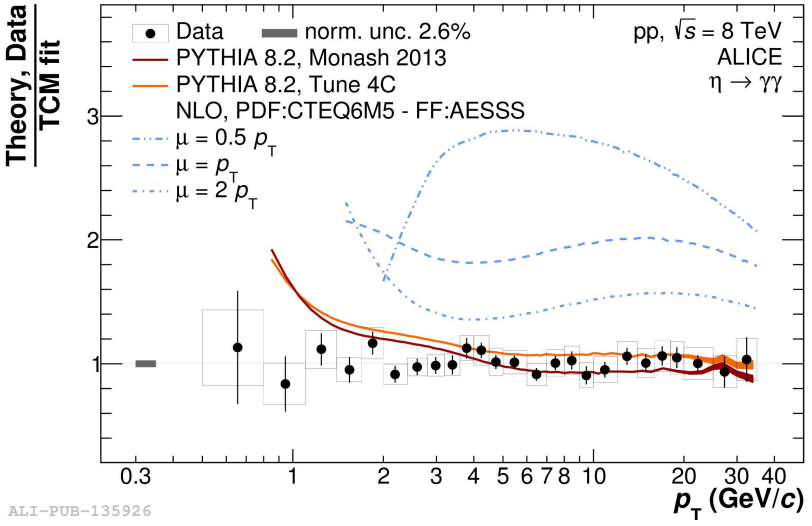

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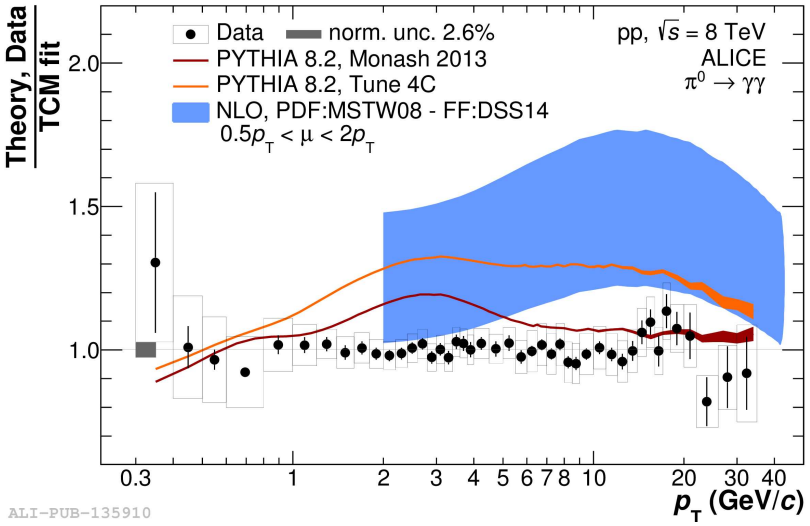
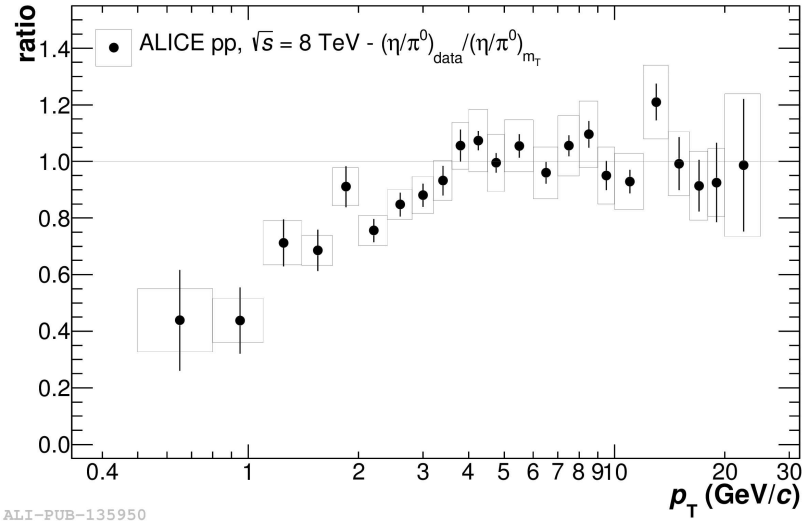
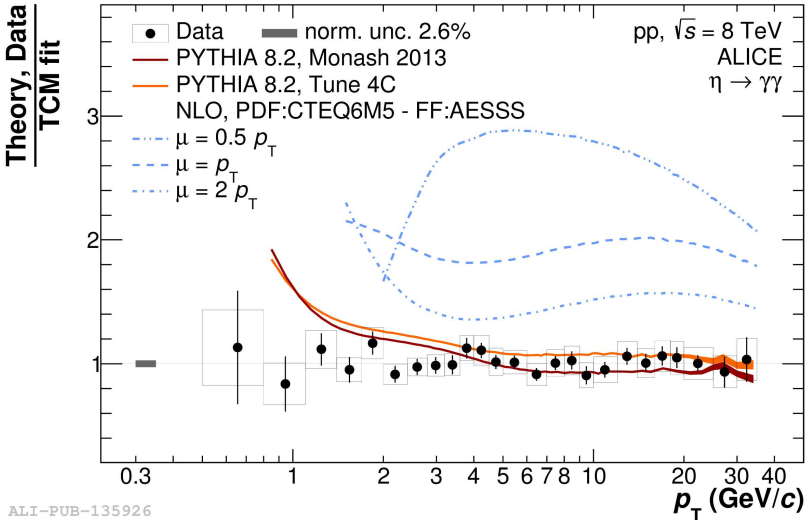
- Observation of $m_T$ scaling violation...
  - ... with significance of 6.2σ below 3.5 GeV/c



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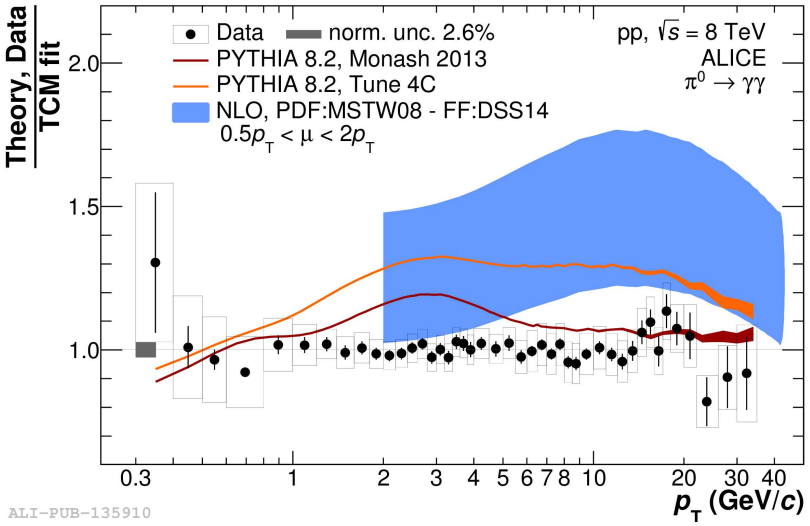
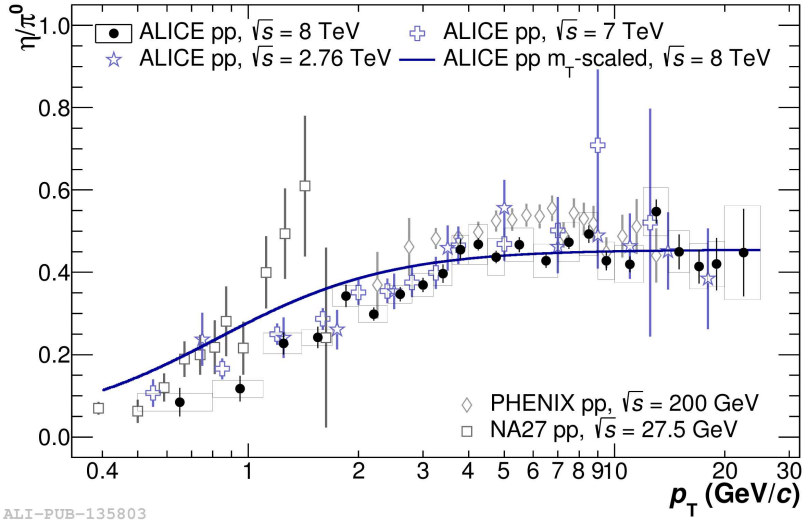
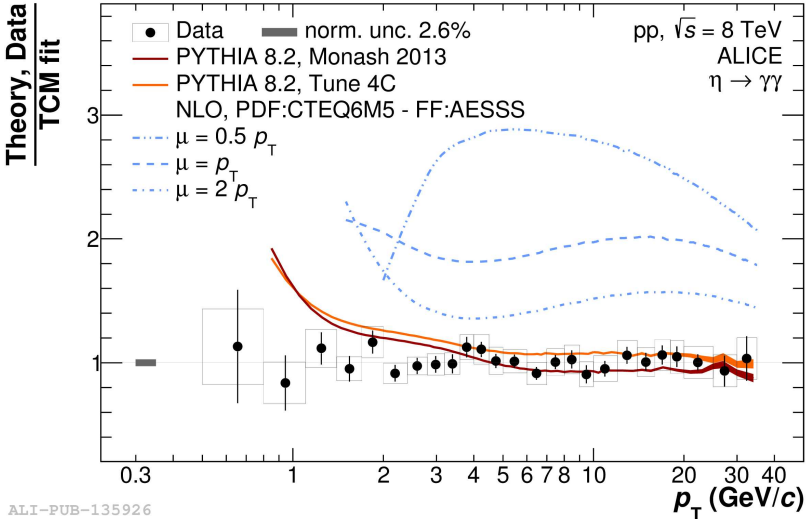
- Observation of $m_T$ scaling violation...
  - ... with significance of 6.2σ below 3.5 GeV/c
- Universality of $\eta/\pi^0$ ratio
  - NA27, PHENIX, ALICE within uncertainties

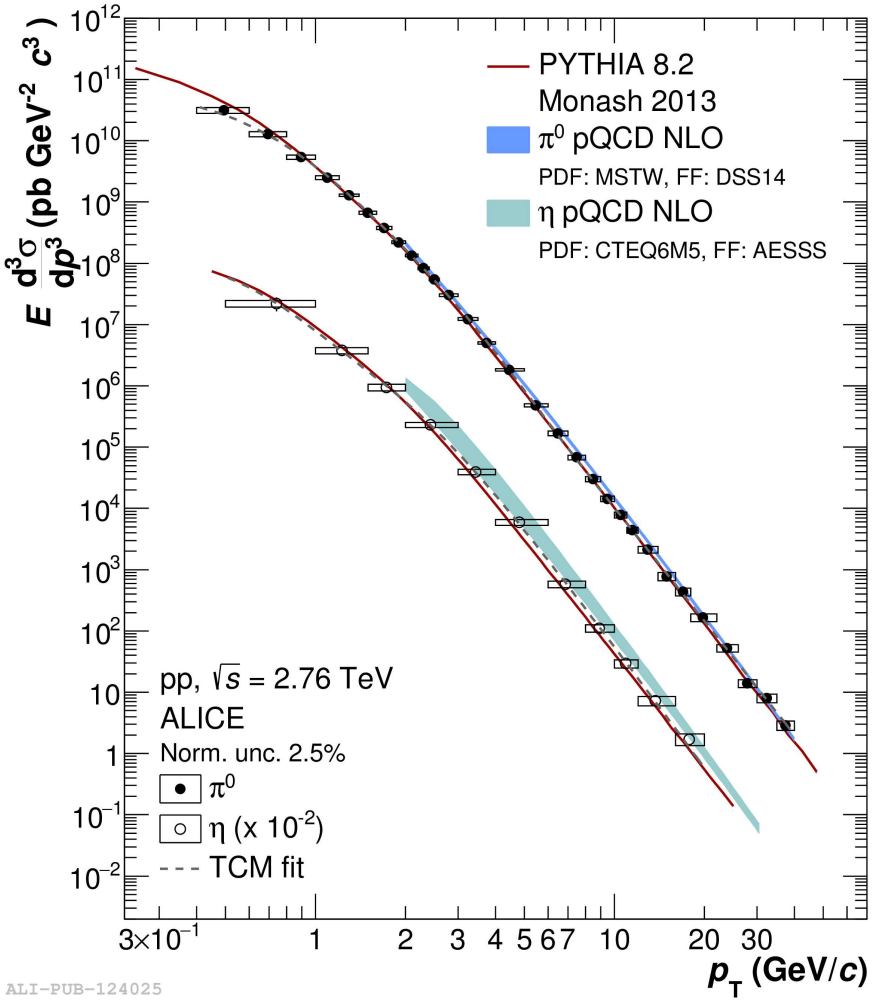


# Results – neutral mesons pp@2.76TeV

EPJC77 (2017) no.5, 339

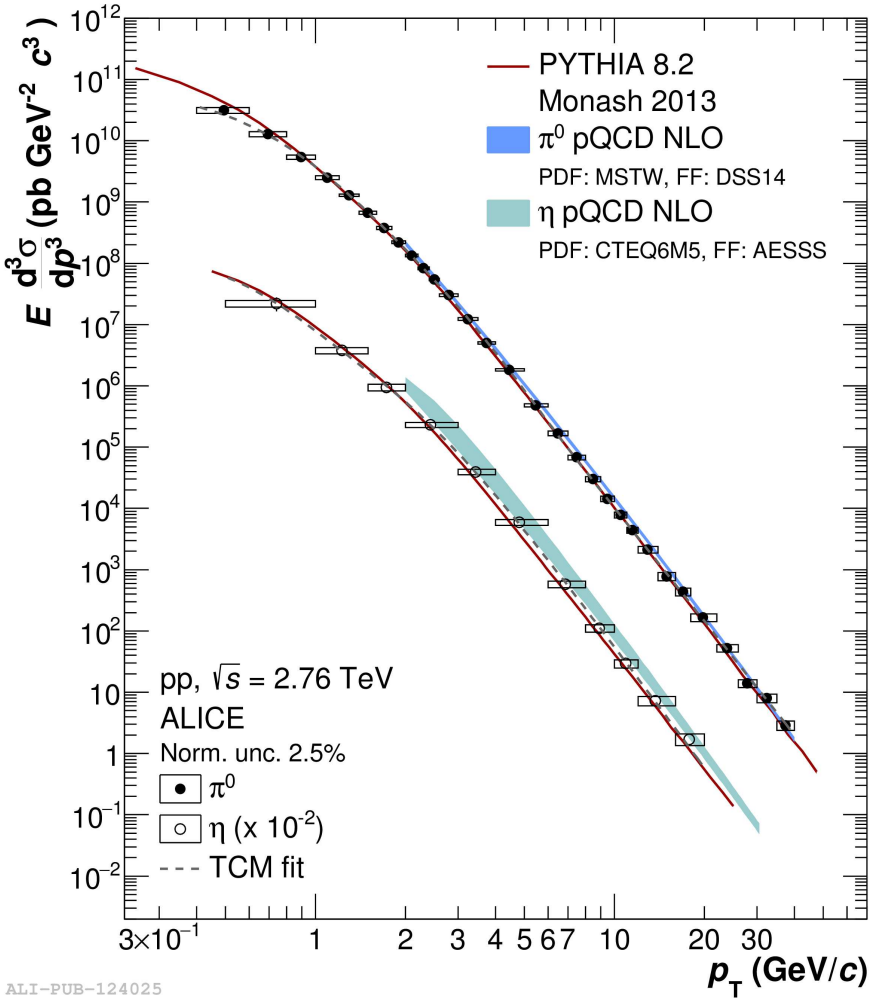



- High momentum reach for $\pi^0$ and $\eta$
  - Combining 5 methods with 8 different triggers (MB + calorimeter)
- Including new EMCal single cluster analysis (both $\pi^0$ decay photons in one cluster) for high momentum reach (16-40 GeV/c in this analysis)

ALI-PUB-124025

# Results – neutral mesons pp@2.76TeV

EPJC77 (2017) no.5, 339

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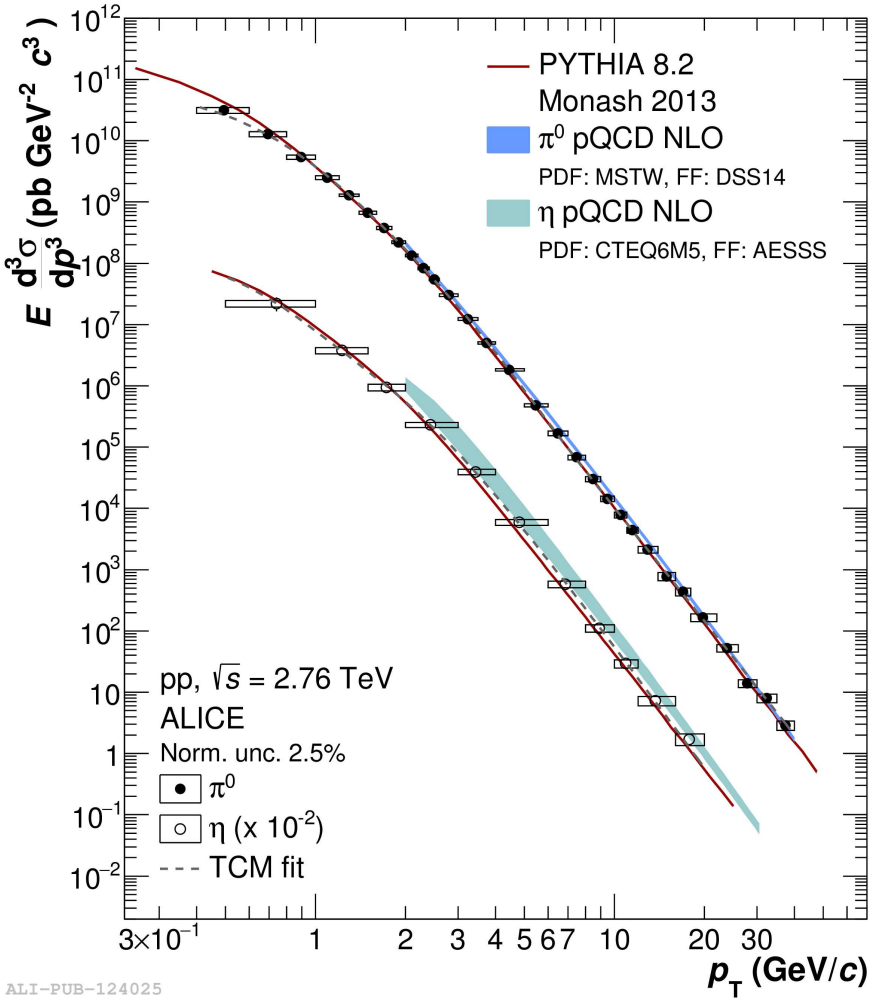
- Including new EMCal single cluster analysis (both $\pi^0$ decay photons in one cluster) for high momentum reach (16-40 GeV/c in this analysis)
- Improved reference data for Pb-Pb @ 2.76TeV; total uncertainties (at ~3 GeV/c):
  → ~ 5% for $\pi^0$ → ~15% for $\eta$ and $\eta/\pi^0$

ALI-PUB-124025

# Results – neutral mesons pp@2.76TeV

EPJC77 (2017) no.5, 339




ALI-PUB-124025

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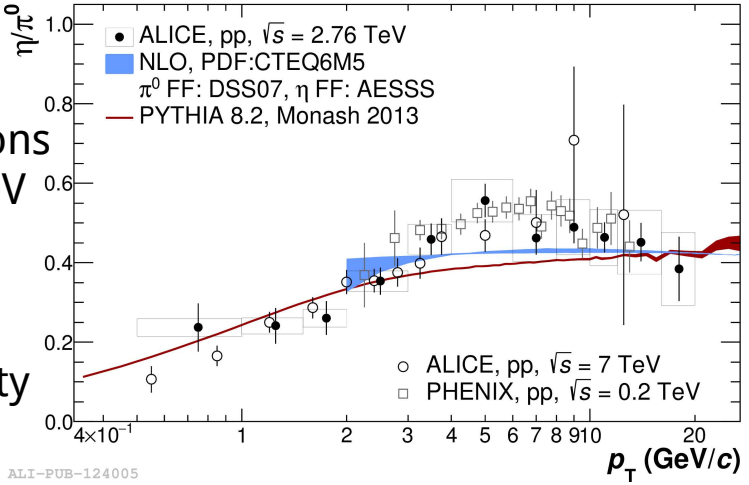
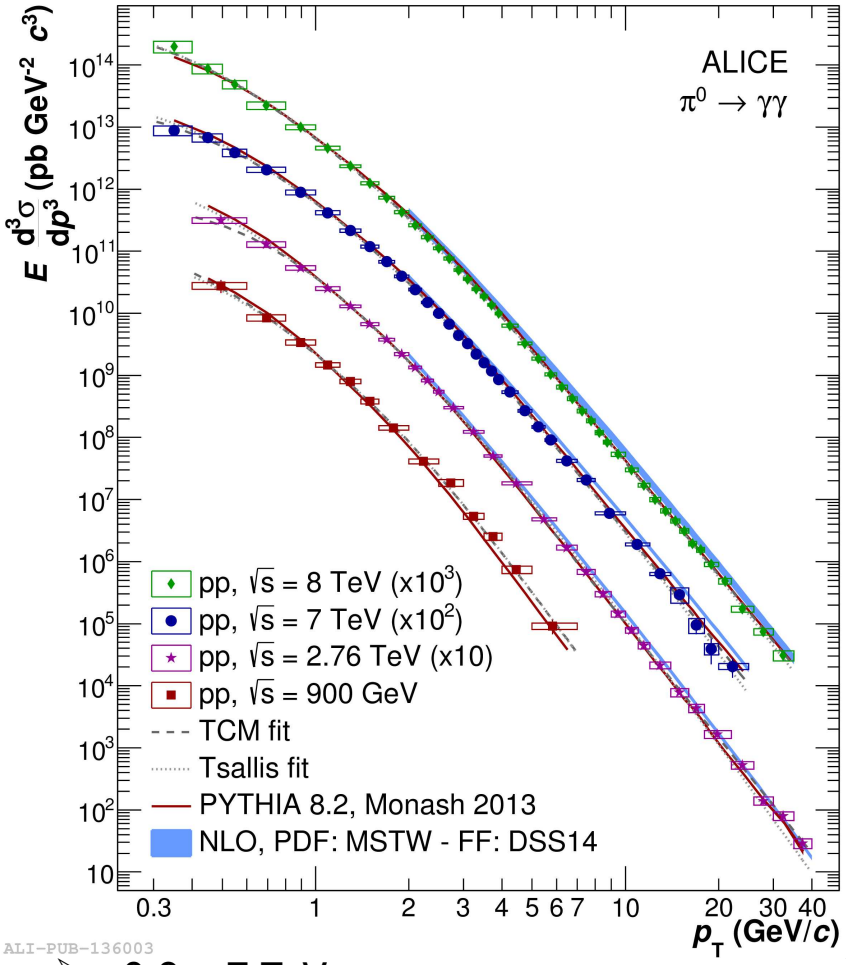
  → ~ 5% for $\pi^0$ → ~15% for $\eta$ and $\eta/\pi^0$
- Fits and comparisons as for 8 TeV paper available
- Universality of $\eta/\pi^0$

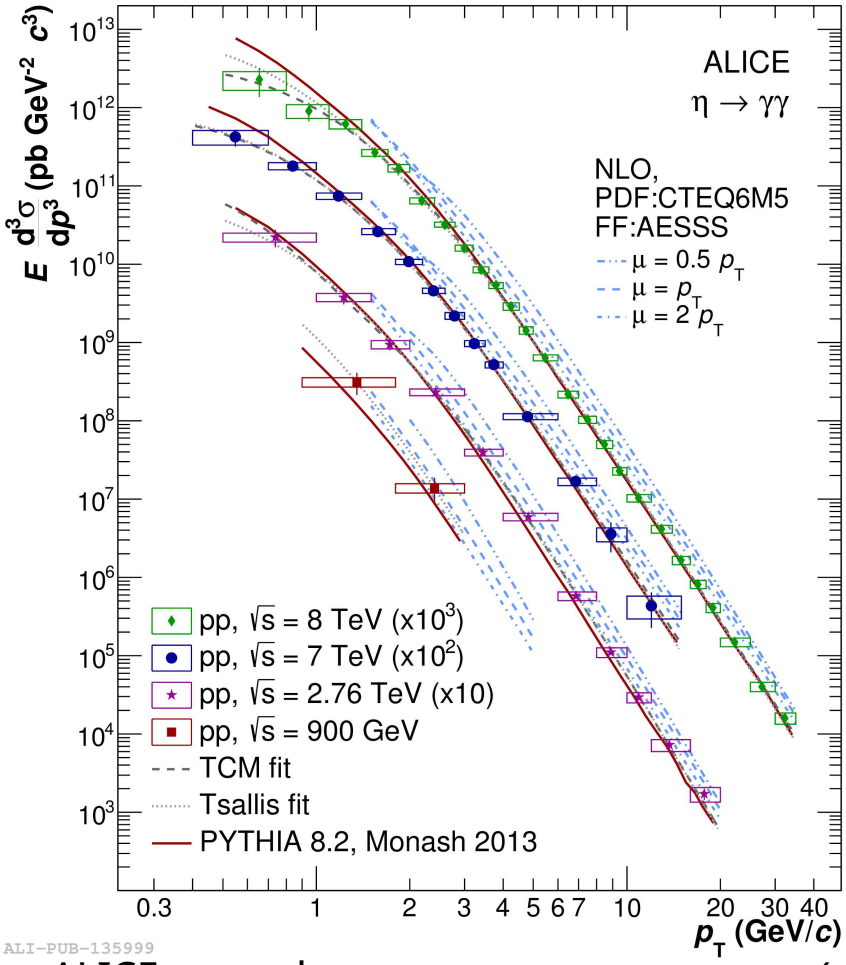



ALI-PUB-124005

$$C^{\eta/\pi^0}_{>3.5\mathrm{GeV}/c} = 0.474 \pm 0.015(\mathrm{stat}) \pm 0.024(\mathrm{sys})$$

# Results – LHC run1 pp analyses



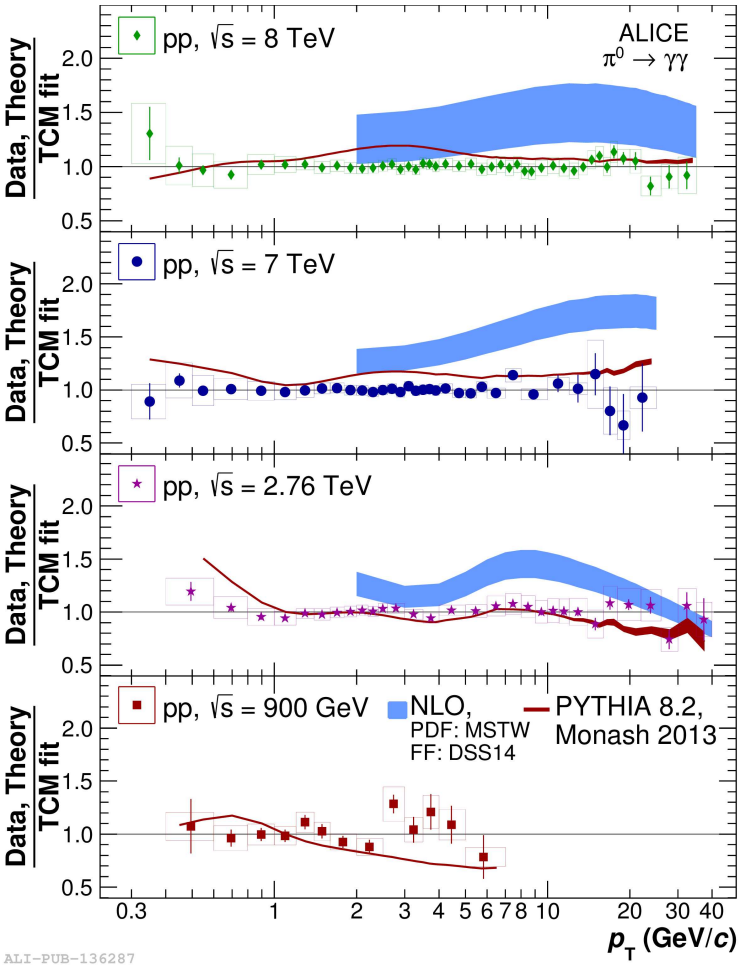



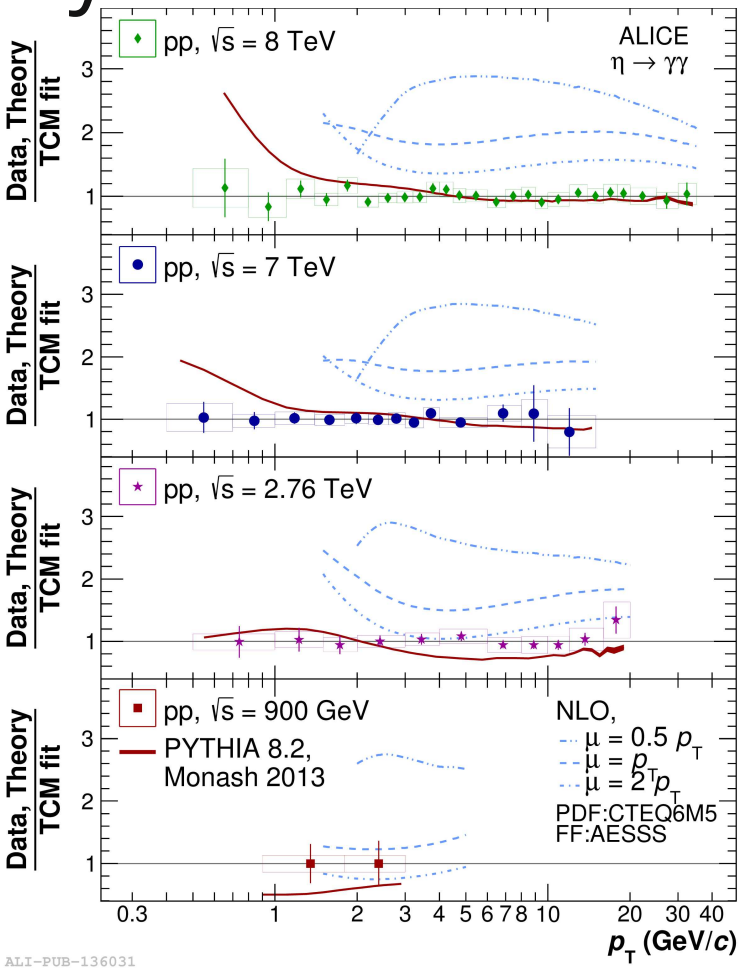

- 0.9 + 7 TeV measurement:

PLB717 (2012) 162-172

- ALICE neutral meson pp measurements (run 1)
  - Comparison with PYTHIA8.2 Monash2013 and recent pQCD NLO calculations

# Results – LHC run1 pp analyses

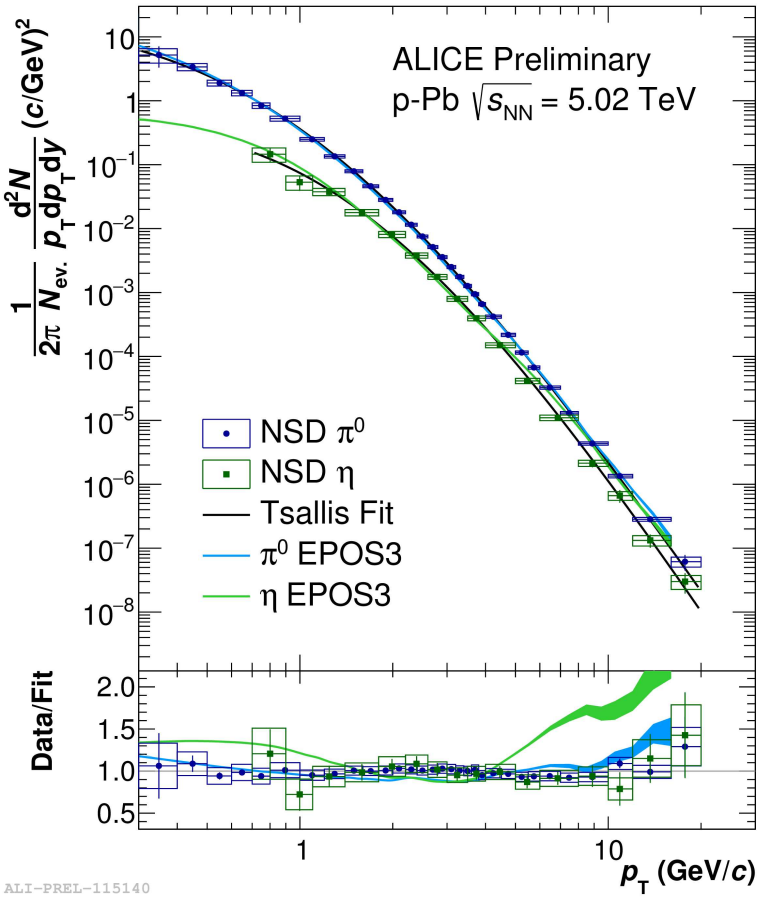



- DSS14 - D. de Florian et al.
  - "Parton-to-Pion Fragmentation Reloaded" [PRD91 (2015) no. 1, 014035]
- With all new data from Run1 energies → update of η fragmentation functions desired

# Results – neutral mesons p-Pb@5.02TeV

Preliminary - paper in preparation




- Disentangle cold nuclear effects
- Combining 6 methods → PCM-Dalitz

- Clear deviation of EPOS3 above 4 GeV/c → treatment needs to be revisited

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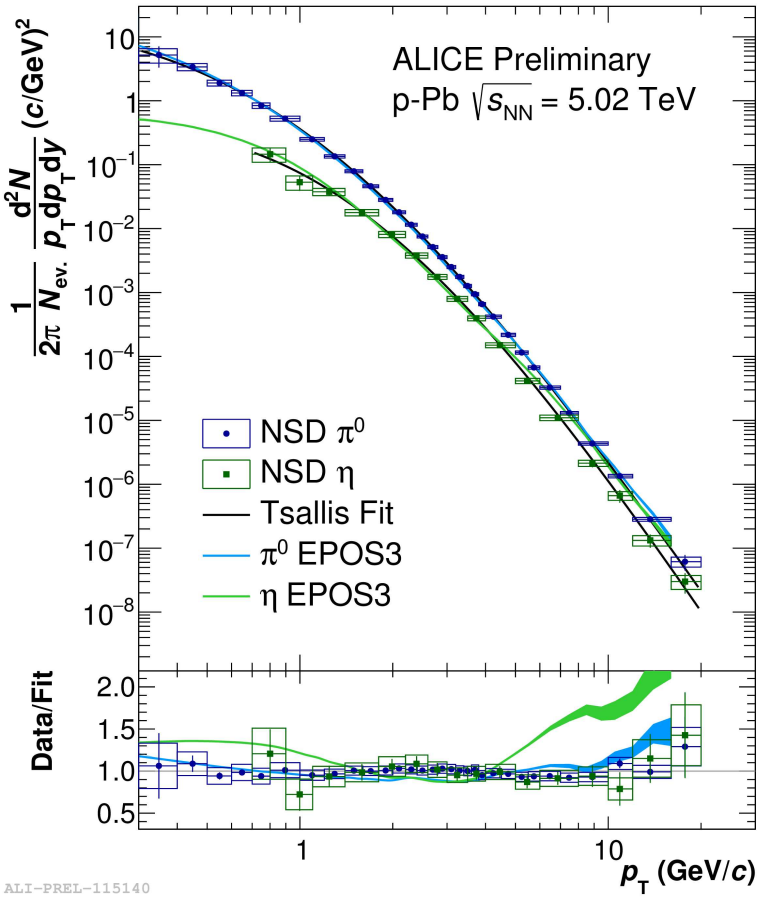


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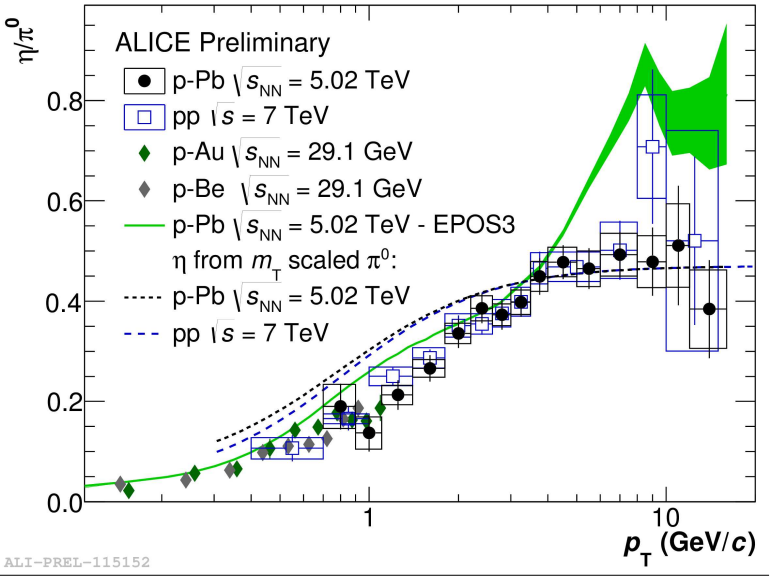


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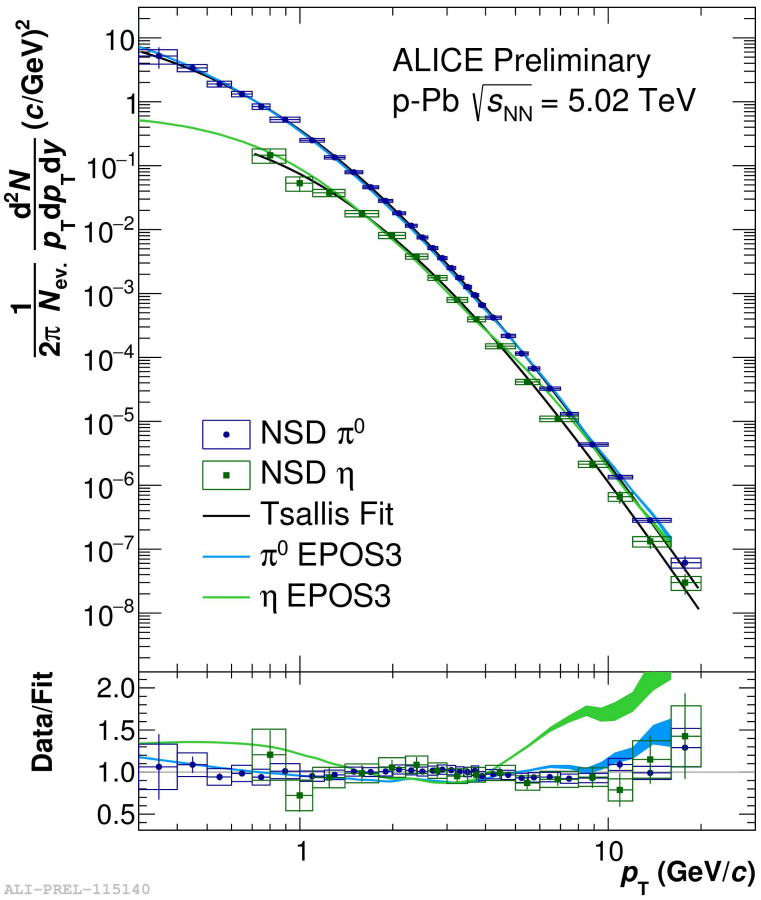


ALI-PREL-115140

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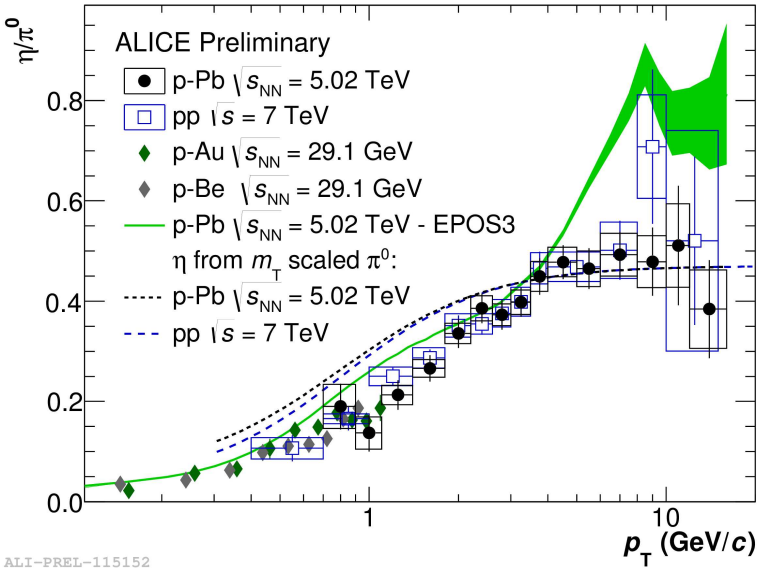
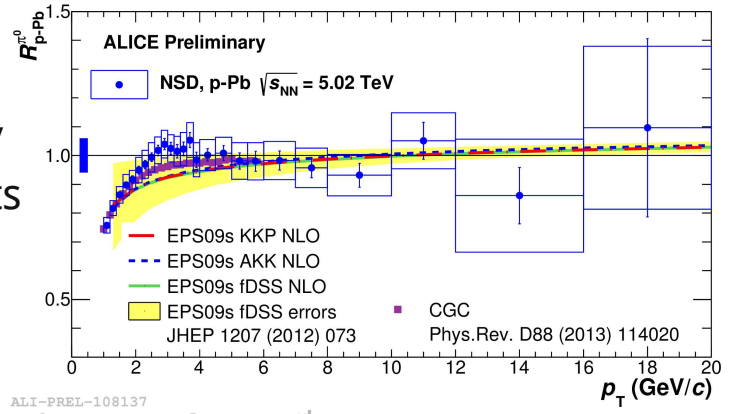



ALI-PREL-115152

- $R_{p\text{-}Pb}$ consistent with theory predictions within (large) uncertainties: ~1 for ≥2GeV/c
- p-Pb helps to disentangle between initial / final state effects in quenching
- Improve nPDFs

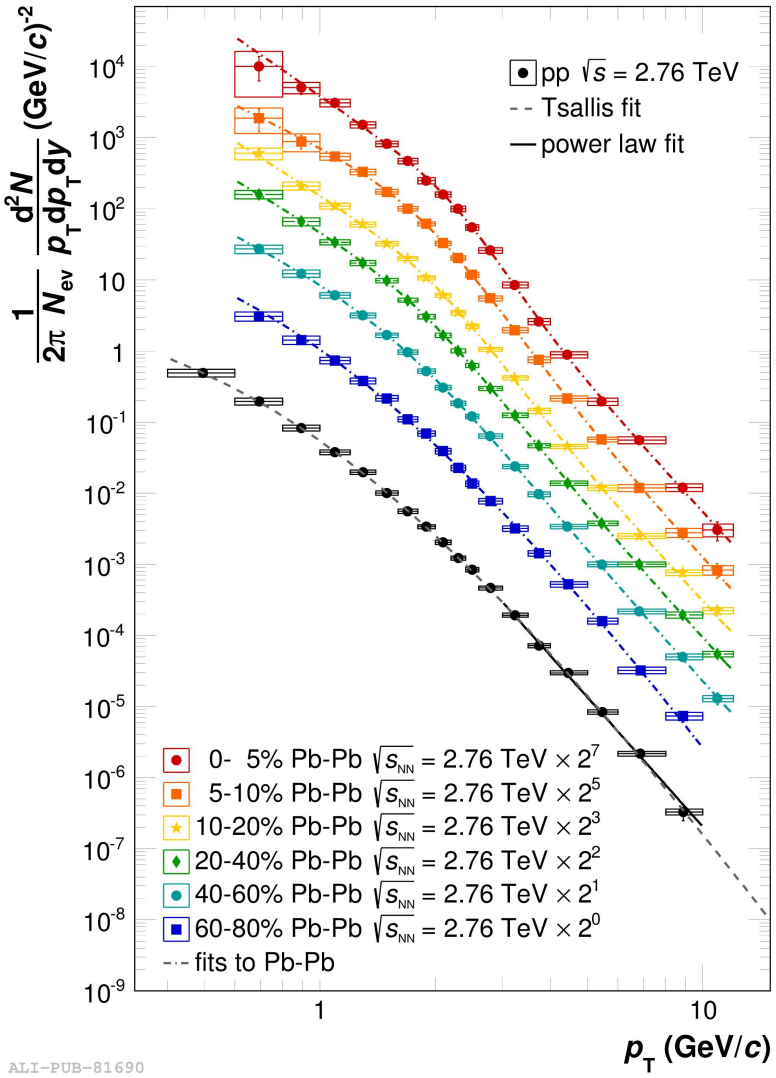



ALI-PREL-108137

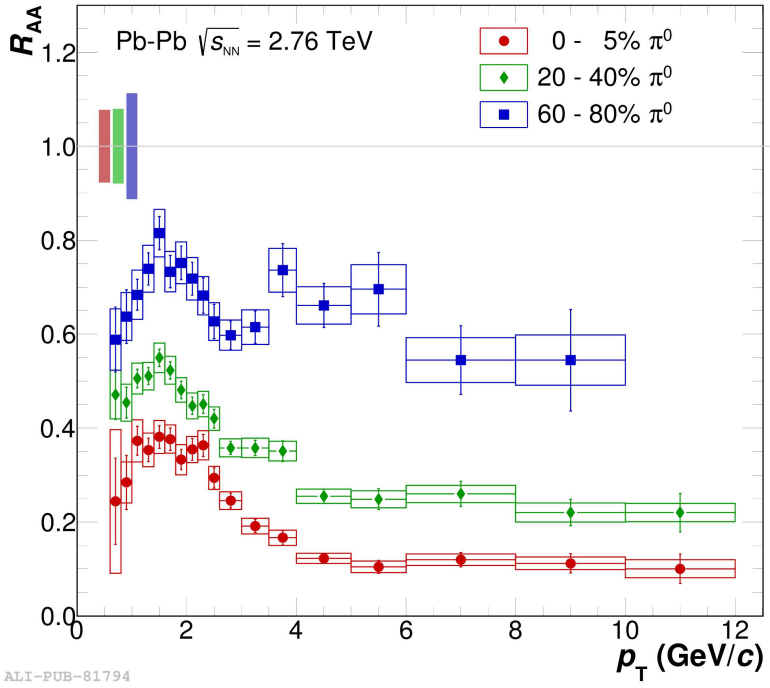
# Results – neutral mesons Pb-Pb@2.76TeV

EPJC74 (2014) no.10, 3108

- $\pi^0$ measurement very important input for direct photons
  - Stat. + sys. unc. dominate $R_\gamma$
- Suppression of neutral mesons in more central events




ALI-PUB-81690




ALI-PUB-81794

# Direct photon analyses

...via double ratio:

$$R_\gamma = \frac{\gamma^{\mathrm{incl}}}{\gamma^{\mathrm{decay}}} = \frac{\gamma^{\mathrm{incl}}}{\pi^0} \Big/ \frac{\gamma^{\mathrm{decay}}}{\pi^0_{param}}$$

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- Triggering capabilities of EMCal

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- Material related uncertainties cancel, but EMCal uncertainties enter
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- Needed for all measurements: "decay photon cocktail"
  - All relevant decay photon sources included, however $\pi^0$ and $\eta$ dominate source of decay photons
  - Important to measure neutral meson spectra with highest precision possible
  - If particle not measured, use $m_T$ scaling,

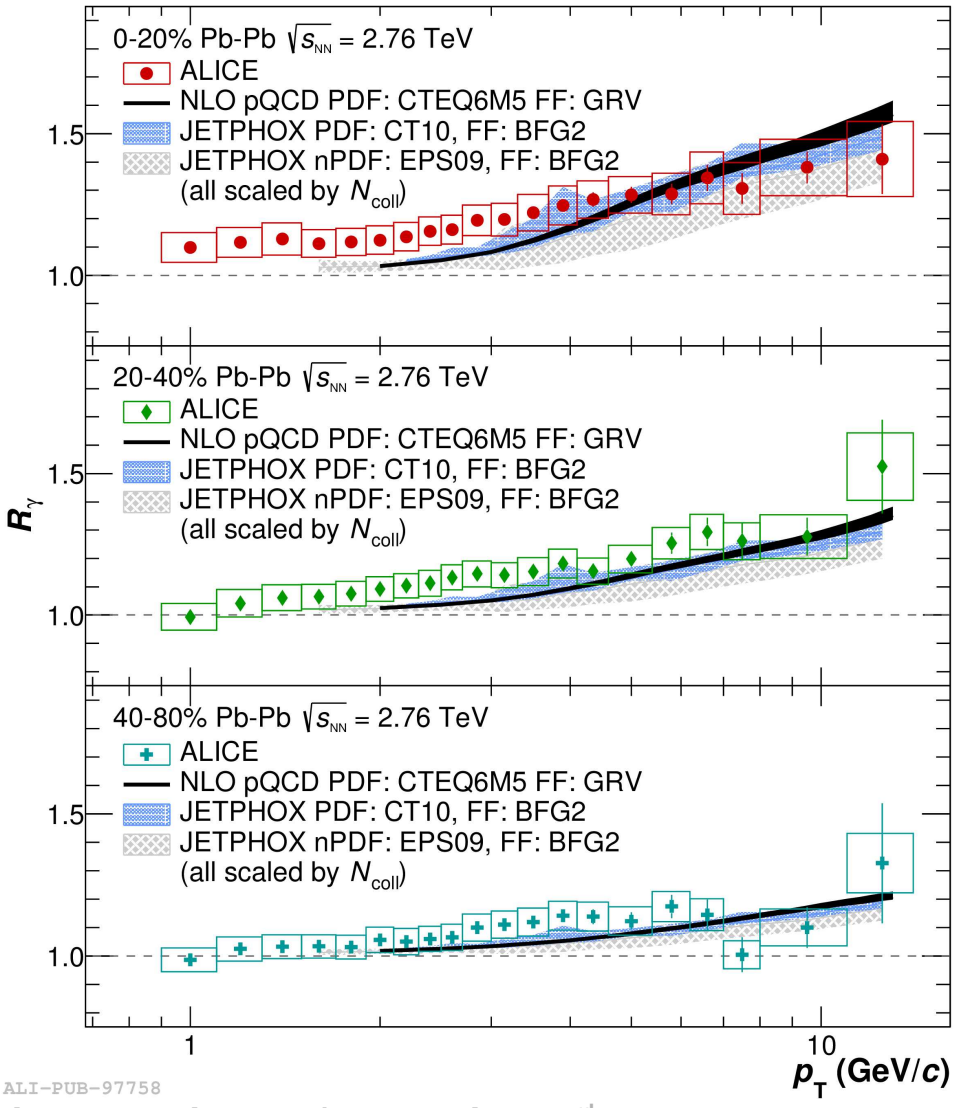
$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = C^{\mathrm{m}} f(m_T)$$

special caution needed as we know the limitations!

# Direct photon analyses

PLB754 (2016) 235-248

- At low momenta (<3 GeV/c)
  - **40-80%**: no significant access at any $p_T$
  - **20-40%**: excess of 1.5σ
  - **0-20%**: excess of 2.6σ




ALI-PUB-97758

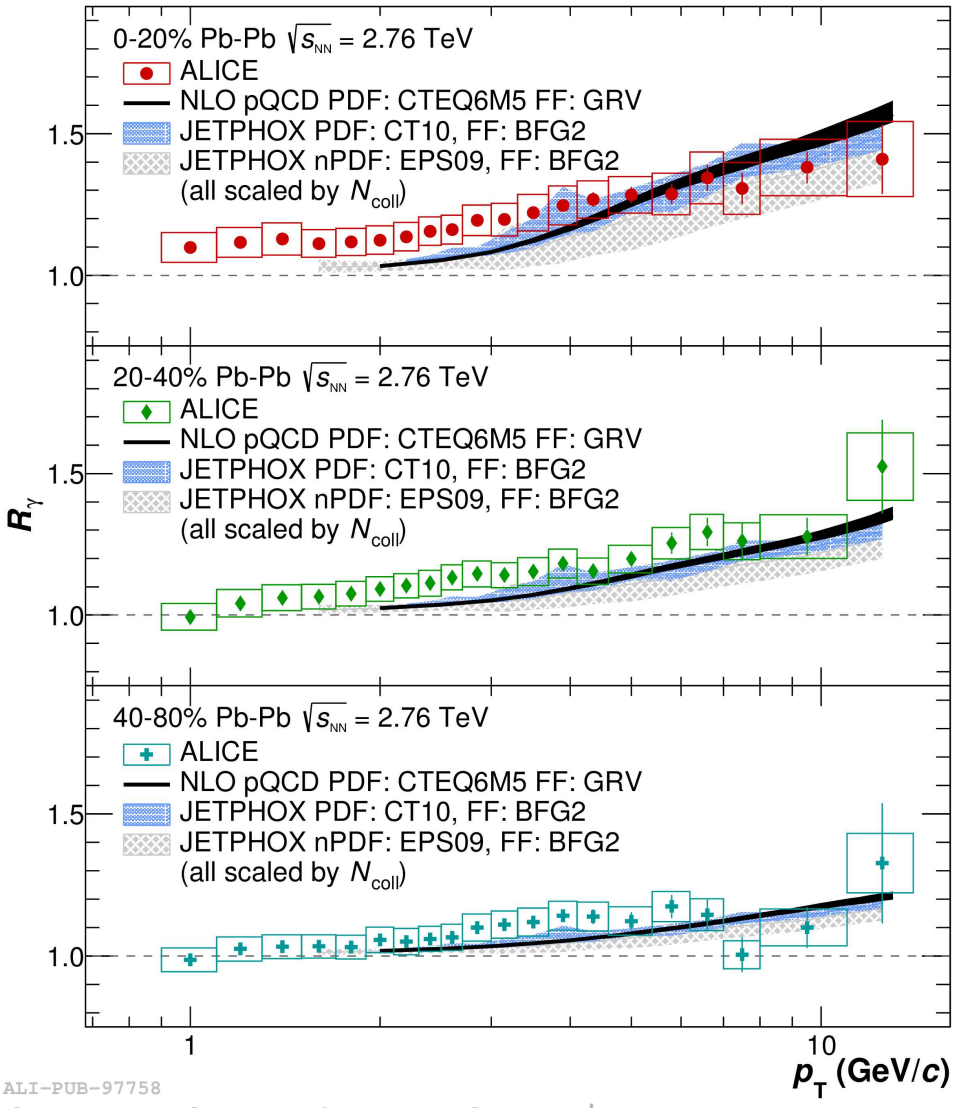
# Direct photon analyses

PLB754 (2016) 235-248

- At low momenta (<3 GeV/c)
  - **40-80%**: no significant access at any $p_T$
  - **20-40%**: excess of 1.5σ
  - **0-20%**: excess of 2.6σ
- Limiting factor is systematics
  - $\pi^0$ uncertainty
  - Energy scale for PHOS
  - Material budget for PCM

→ $\pi^0$-tagging may help to improve

- For higher momenta, all centralities consistent with direct photon predictions




ALI-PUB-97758

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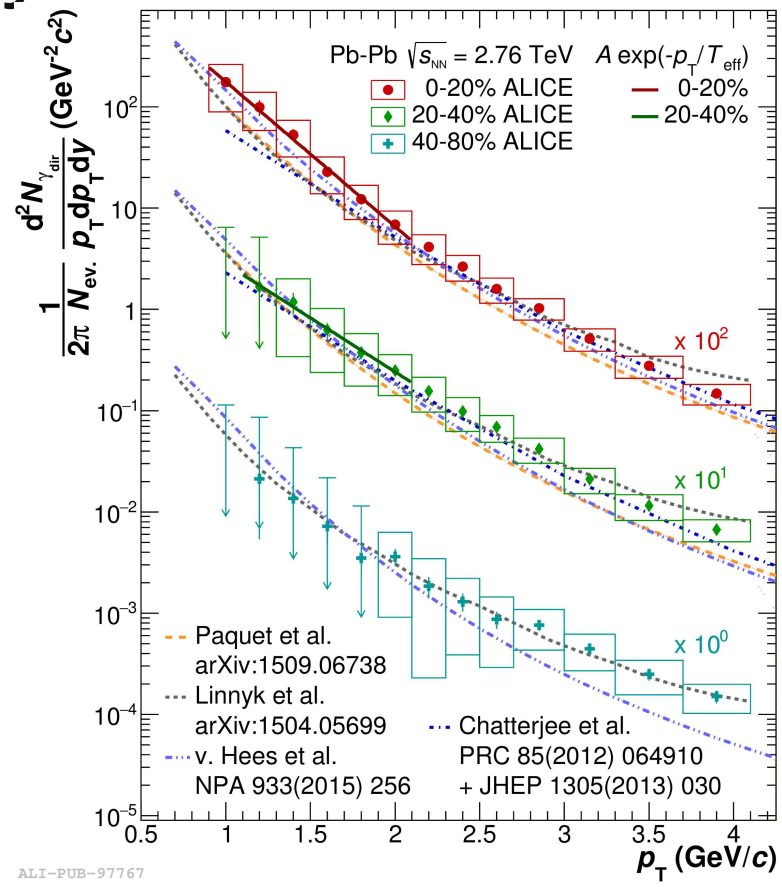
PLB754 (2016) 235-248




- need pp measurements to separate sources

- Theory calculations agree with data within unc.
- Inverse slope of $T_{eff}$≈300 MeV for 0.9 - 2.1 GeV/c for 0-20% → points to early creation - “thermal” photons

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PLB754 (2016) 235-248

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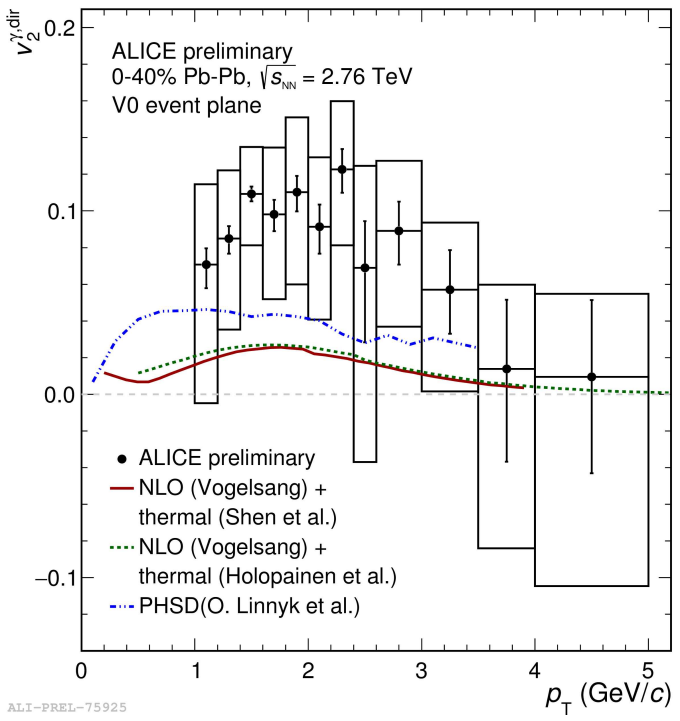


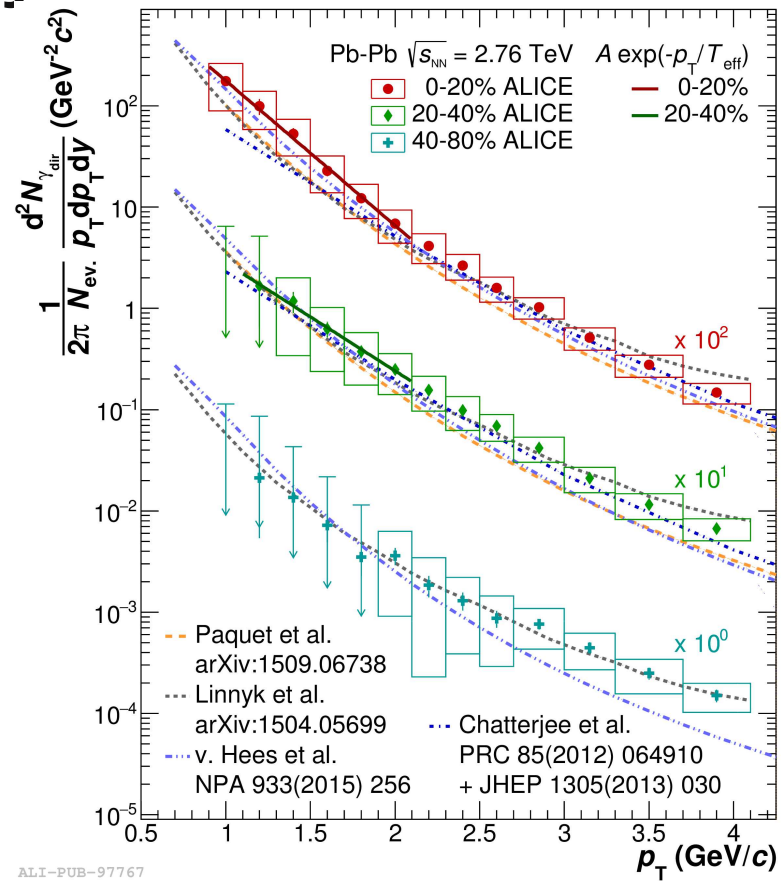


- need pp measurements to separate sources

- **"Photon puzzle"**
  - Hadron like $v_2$
    → points to late production
- What is the solution?

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- Inverse slope of $T_{eff}$≈300 MeV for 0.9 - 2.1 GeV/c for 0-20% → points to early creation - "thermal" photons

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  - Rather good agreement with Pythia8 (Monash2013)
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- ALICE took lots of promising data in LHC Run2; new systems:
  - pp collisions @ 5 TeV, 13 TeV
  - p-Pb collisions @ (5 TeV,) 8 TeV
  - Pb-Pb collisions @ 5 TeV

} Including calorimeter triggers to extend $p_T$ reach of neutral meson and photon measurements significantly