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# **Neutral meson measurements in ALICE in pp collisions at $\sqrt{s} = 13$ TeV**

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Joshua König, Goethe-Universität Frankfurt  
for the ALICE collaboration

**International Conference on High Energy Physics**  
Bologna (Italy), July 6-13, 2022



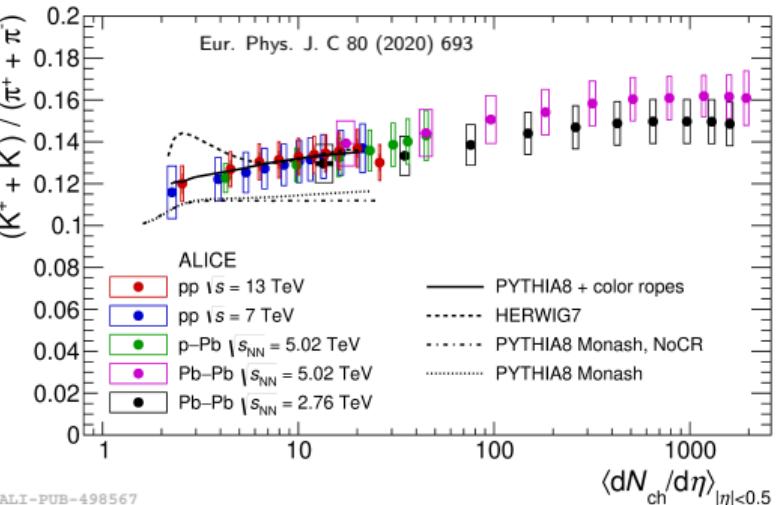
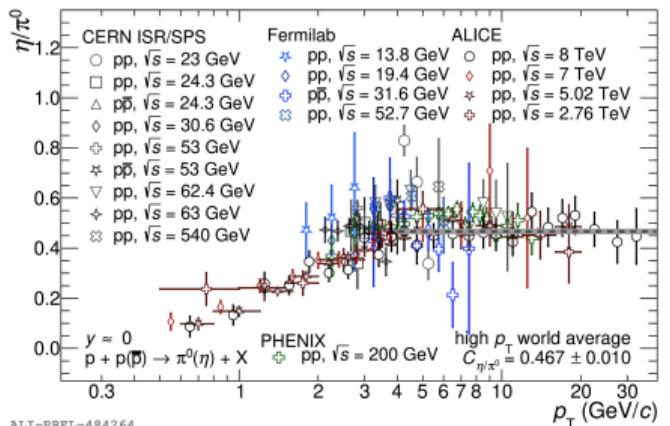
**FSP ALICE**  
Erforschung von  
Universum und Materie



# Motivation

## Neutral mesons in pp collisions

- Study particle production mechanisms
- Test scaling properties:  $x_T$ ,  $m_T$
- Input for theory calculations:  
Fragmentation functions (FF)  
Parton distribution functions (PDF)
- Essential input for direct photon analyses



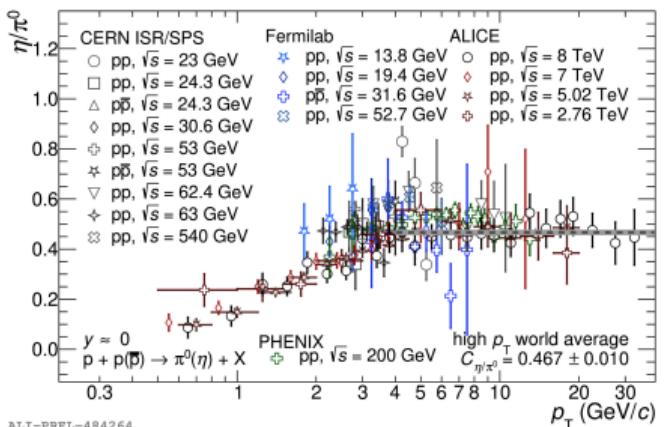
## Multiplicity dependence

- Collective effects observed in high-multiplicity pp collisions  
(Phys. Lett. B 765 (2017) 193)
- Modification of particle production with rising multiplicity
- Study universality of  $\eta/\pi^0$  ratio

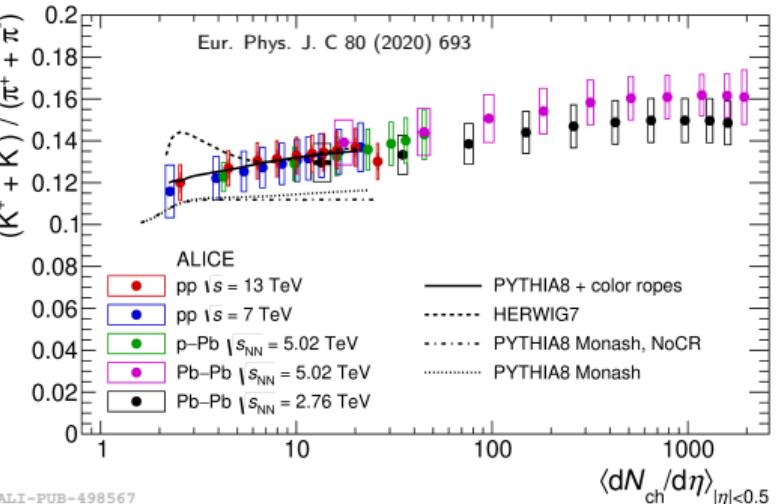
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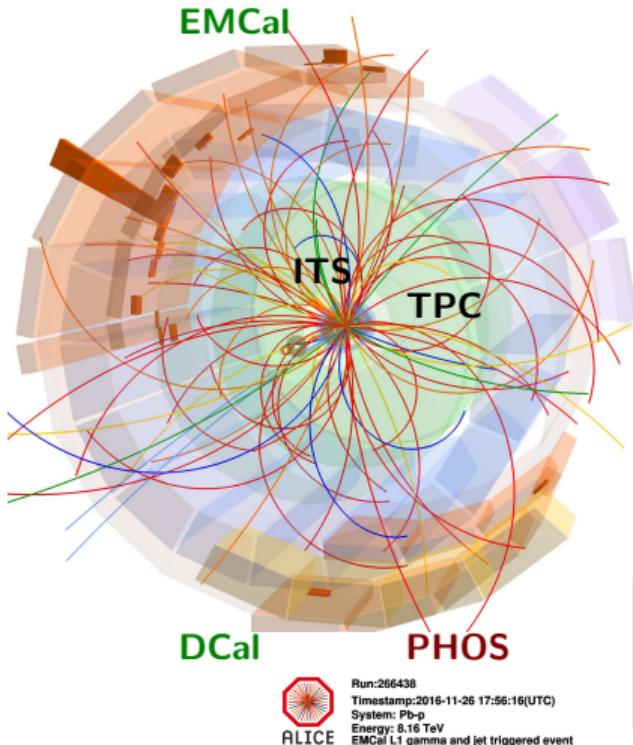
Talks on  
07.07.2022:  
D. Sekihata  
(5:00 pm)  
M. Sas  
(6:40 pm)



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→ Study universality of  $\eta/\pi^0$  ratio

# Photon measurement with ALICE in LHC Run 2



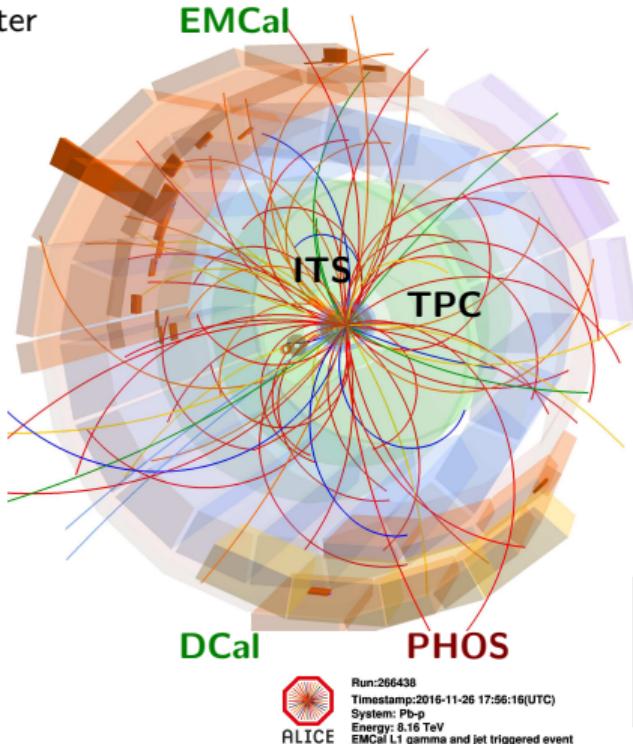
$\pi^0(\eta) \rightarrow \gamma\gamma$ , BR  $\approx 98.8\%$  (39.4%)  
 $\pi^0(\eta) \rightarrow \gamma e^+ e^-$ , BR  $\approx 1.2\%$  (0.7%)  
 $\omega \rightarrow \pi^0\pi^+\pi^-$ , BR  $\approx 89.3\%$

# Photon measurement with ALICE in LHC Run 2



## Electromagnetic calorimeter (EMC = EMCal + DCal)

- Lead-scintillator calorimeter
- Large acceptance



## Photon Spectrometer (PHOS)

- Lead-tungsten crystals
- Good energy resolution

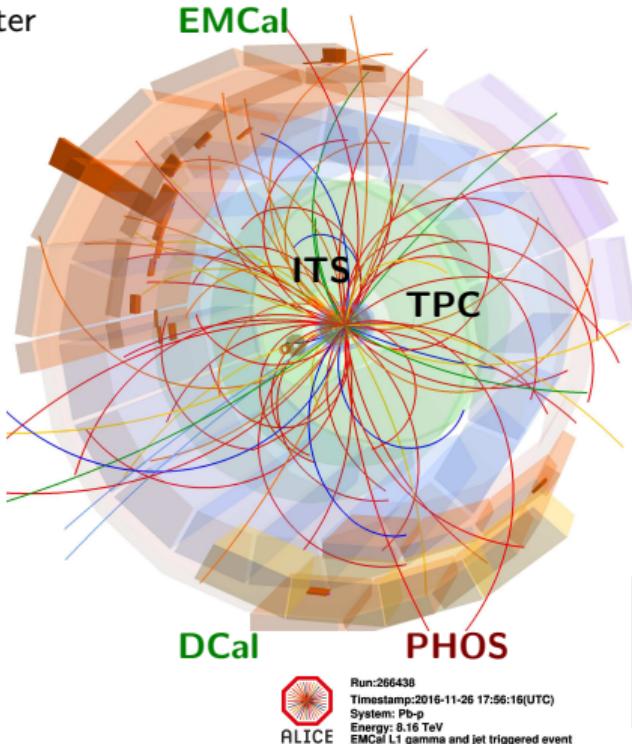
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## Photon Conversion Method (PCM)

- Utilizing  $\gamma$  conversion probability of  $\approx 8\%$
- Using  $e^\pm$  V0-tracks from ITS + TPC
- Excellent energy resolution at low  $p_T$

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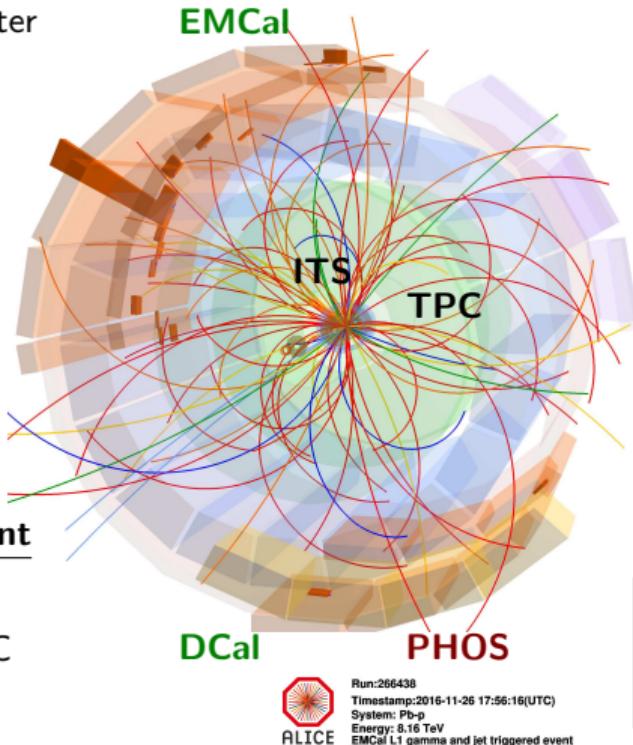
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# Photon measurement with ALICE in LHC Run 2



## Electromagnetic calorimeter (EMC = EMCal + DCal)

- Lead-scintillator calorimeter
- Large acceptance



## Charged particle measurement

- ITS+TPC
- PID via  $dE/dx$  from TPC

## Photon Conversion Method (PCM)

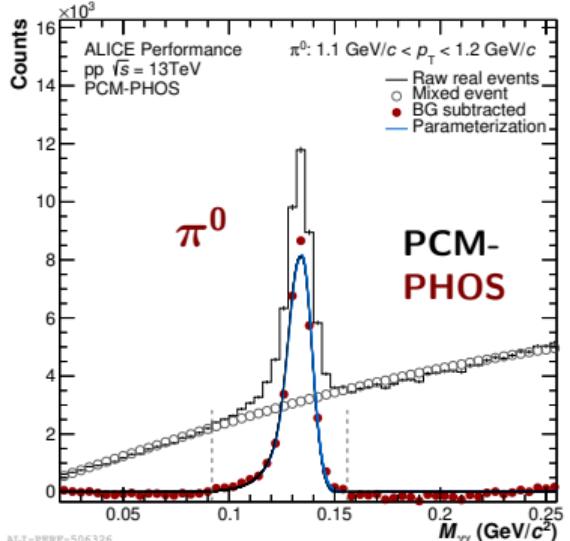
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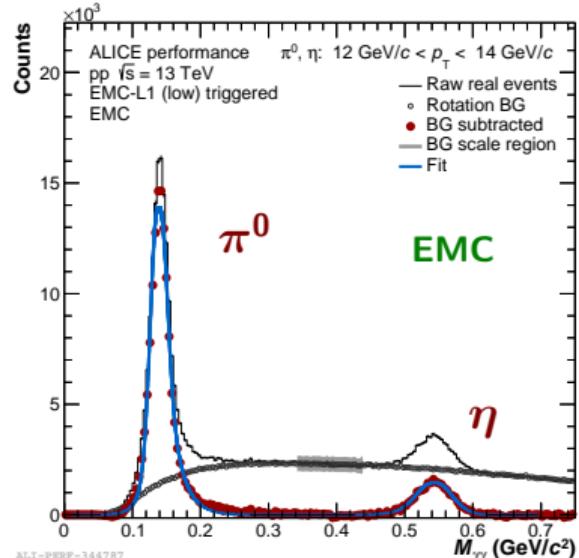
# Neutral meson measurement



## Invariant mass based

- Reconstructing signal by **pairwise photon combination**
- Background subtraction + integration around mass position → Raw yield

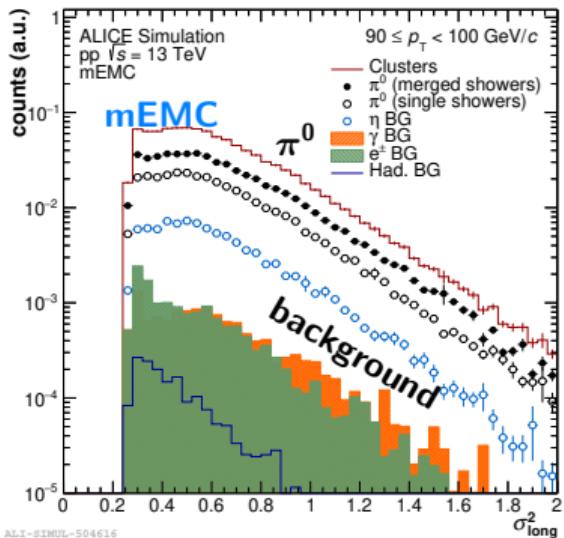
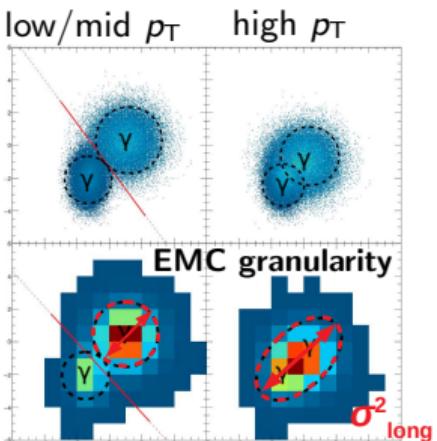
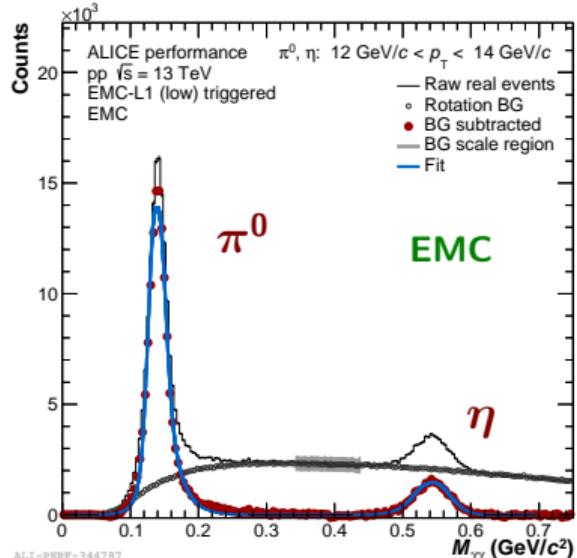
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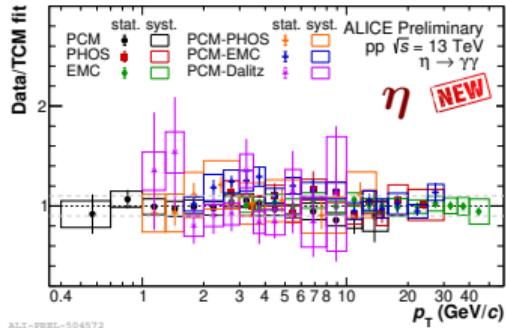
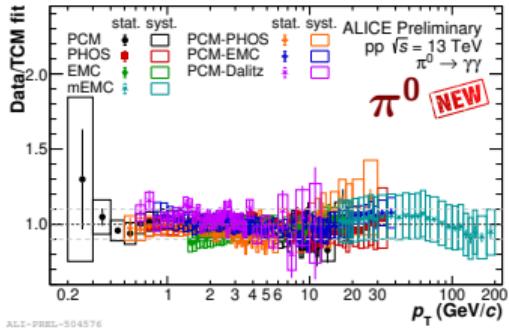
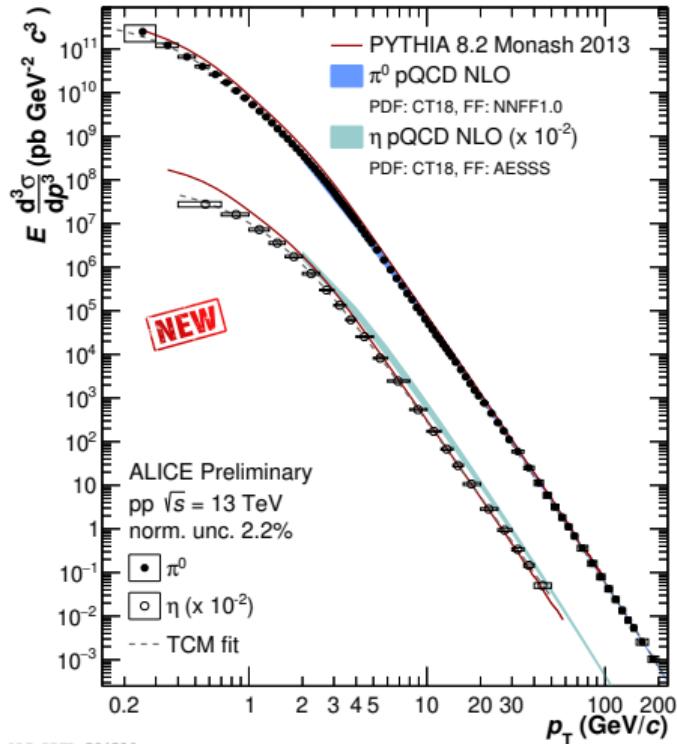
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## Purity based $\pi^0$ measurement (mEMC)

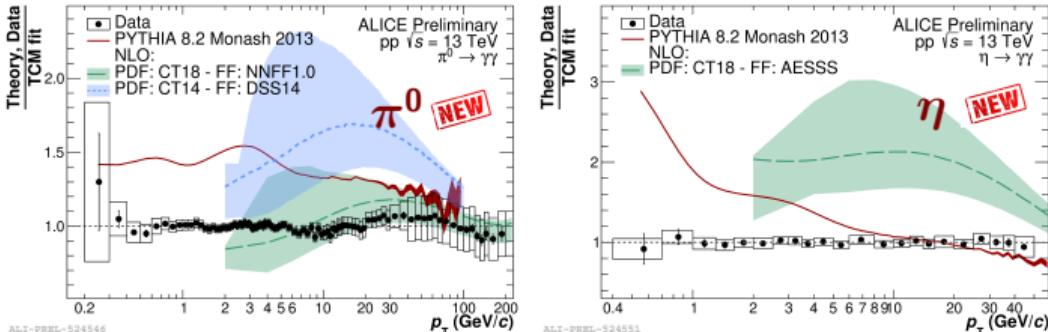
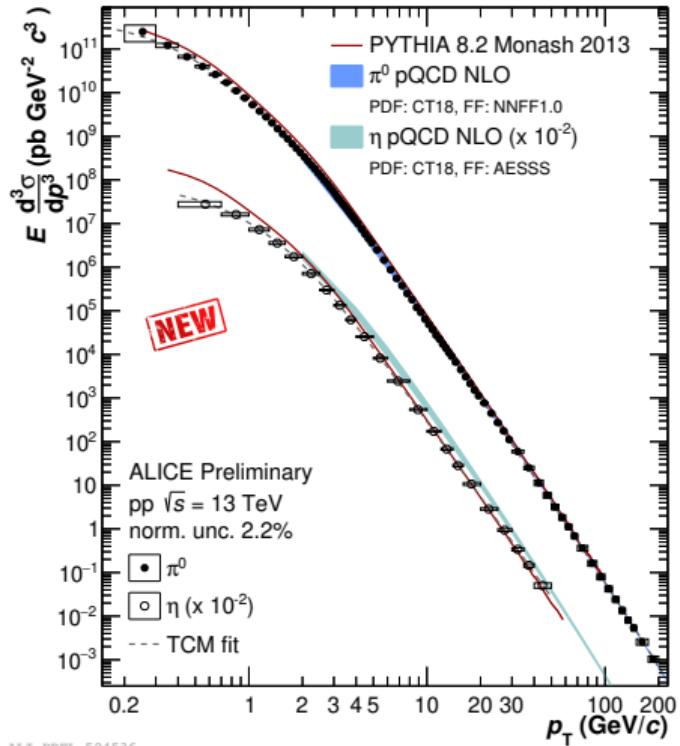
- Using EMCal clusters containing both  $\pi^0$  decay photons
  - Differentiate between merged  $\pi^0$  and single  $\gamma$  clusters via long axis of shower ellipse ( $\sigma_{\text{long}}^2$ )
  - **High  $\pi^0$  purity (> 70%)**

# $\pi^0$ and $\eta$ in pp at $\sqrt{s} = 13$ TeV



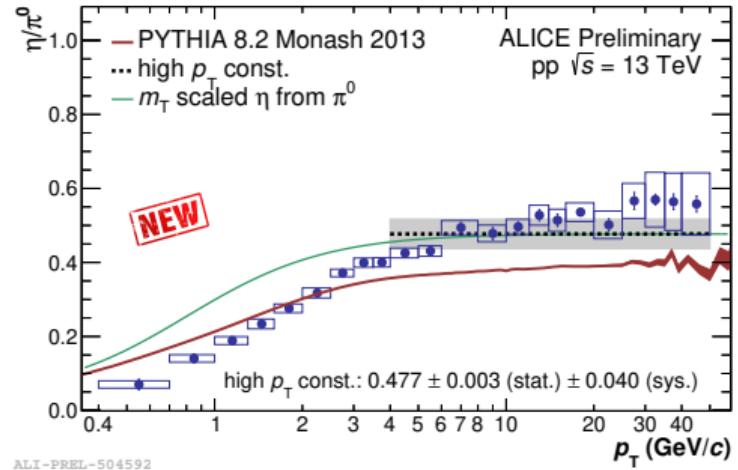
- Combination of 7 (6) reconstruction methods
- $B = 0.2$  T data used to extract  $\pi^0$  down to 0.2 GeV/c
- Inv. cross section in pp at  $\sqrt{s} = 13$  TeV
  - $\pi^0$ :  $0.2 \leq p_T < 200$  GeV/c
  - $\eta$ :  $0.4 \leq p_T < 50$  GeV/c

# $\pi^0$ and $\eta$ in pp at $\sqrt{s} = 13$ TeV



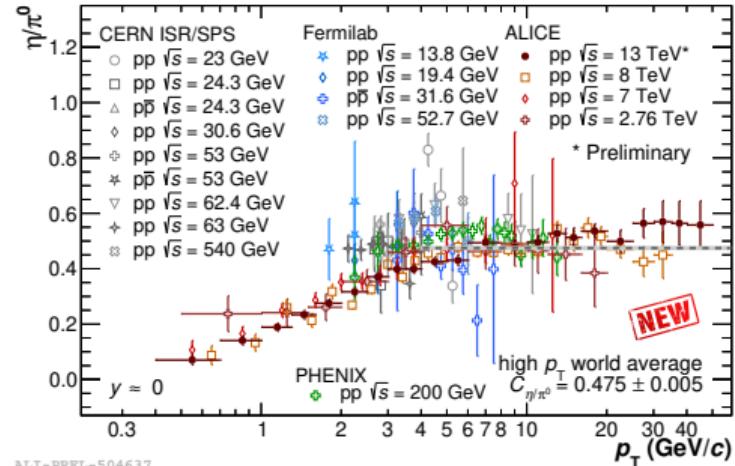
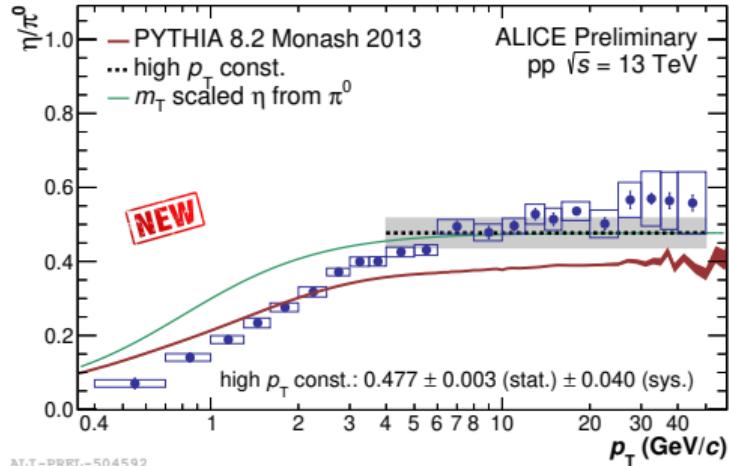
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  - $\pi^0$ :  $0.2 \leq p_T < 200$  GeV/c
  - $\eta$ :  $0.4 \leq p_T < 50$  GeV/c
- NLO with **updated FF** describes the  $\pi^0$  spectrum
- PYTHIA 8 overshoots and does not describe shape of spectra

# $\eta/\pi^0$ ratio



- Measurement reaches **up to 50 GeV/c**
- High  $p_T$ :  $\eta/\pi^0 = 0.477 \pm 0.04$
- PYTHIA predicts lower value at high  $p_T$
- $m_T$ -scaling not fulfilled below  $p_T \approx 4$  GeV/c  
(expected due to feed down)

# $\eta/\pi^0$ ratio

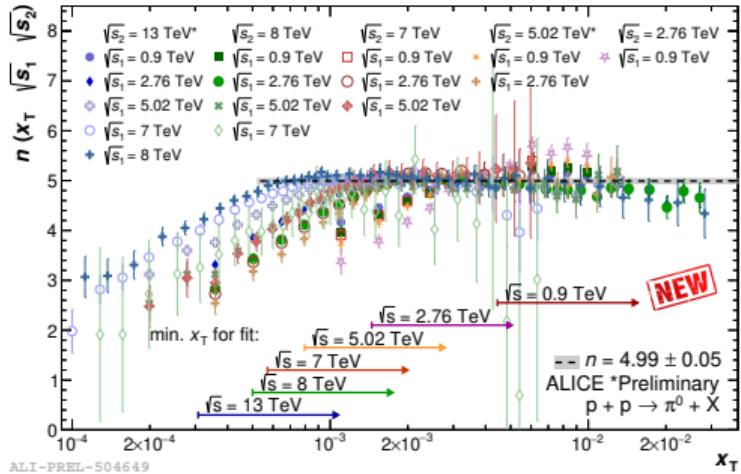


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## Comparison to other measurements

- **Universal behavior for all collision energies**
- World data at high  $p_T$ :  $\eta/\pi^0 = 0.475 \pm 0.005$

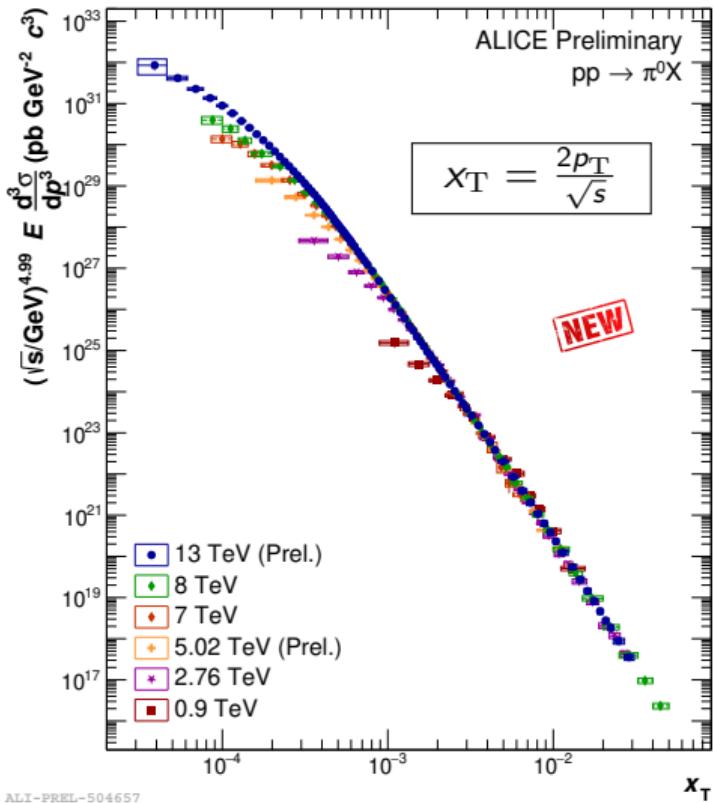
# Collision energy dependence: $\pi^0$ spectra



- $x_T$  scaling: Universal behavior for  $x_T$ -spectra scaled with  $\sqrt{s}^n$

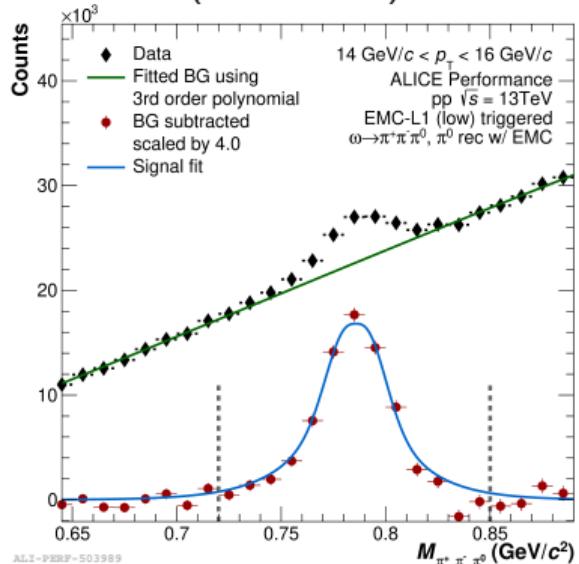
$$\rightarrow n = 4.99 \pm 0.05$$

- Measurement at  $\sqrt{s} = 13$  TeV has large overlap in  $x_T$  with previous ALICE results
- **Universal behavior for  $p_T > 3$  GeV/c observed**

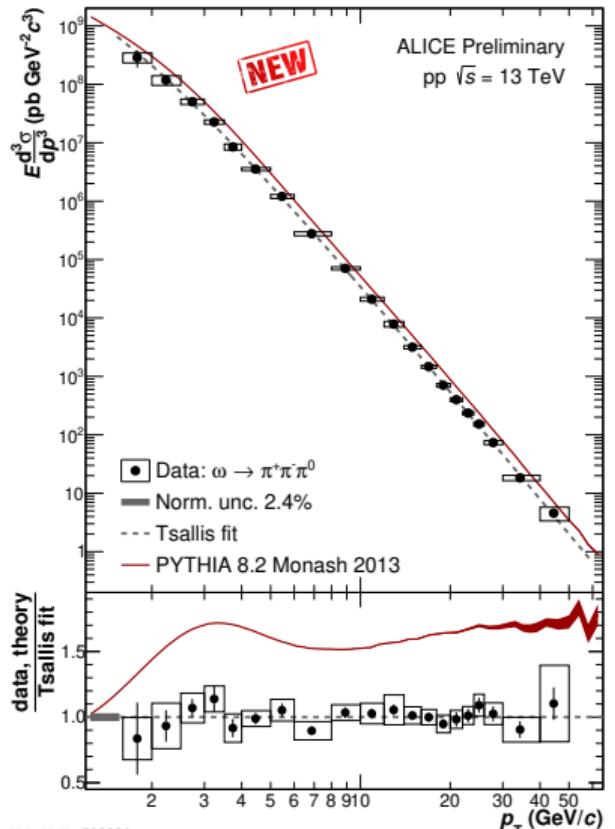


# $\omega$ meson in pp at $\sqrt{s} = 13$ TeV

$\omega \rightarrow \pi^0 + \pi^+ + \pi^-$   
 $(\text{BR} \approx 89\%)$

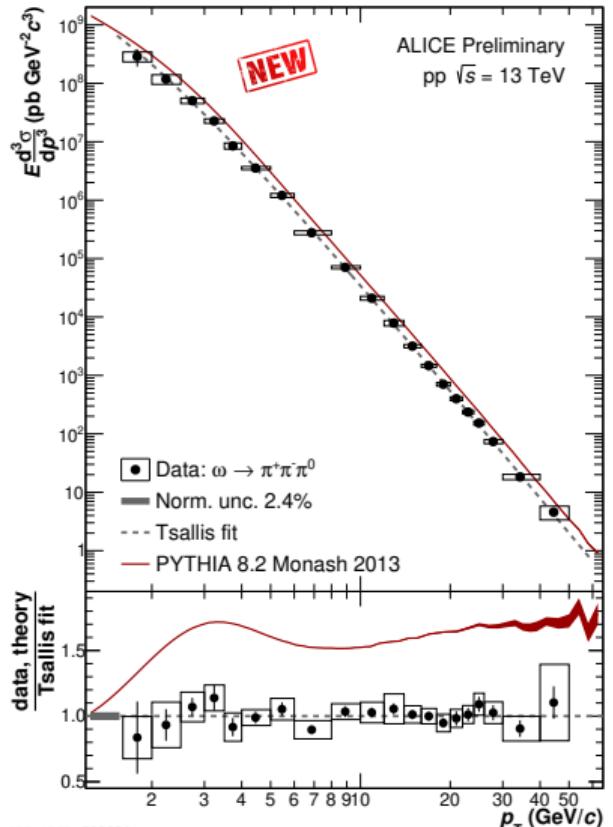


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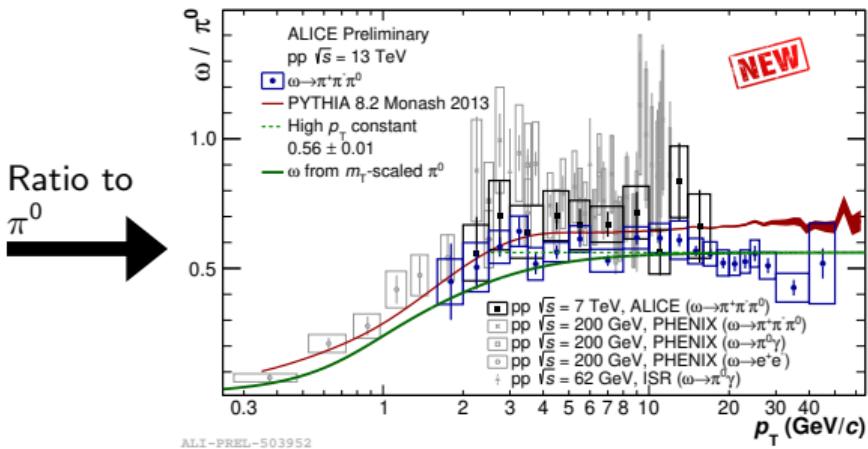


- $\omega$  invariant cross section in pp at  $\sqrt{s} = 13$  TeV
  - $1.5 \leq p_T < 50 \text{ GeV}/c$
- PYTHIA overshoots the data

# $\omega$ meson in pp at $\sqrt{s} = 13$ TeV

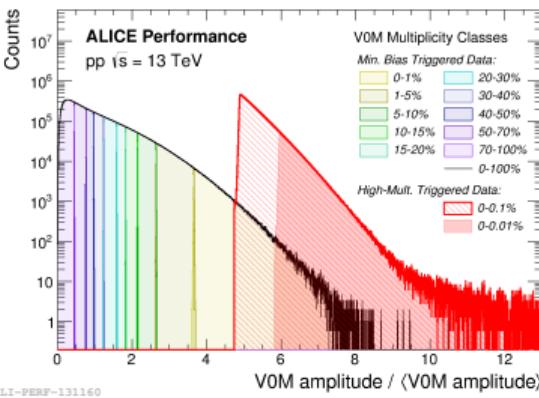
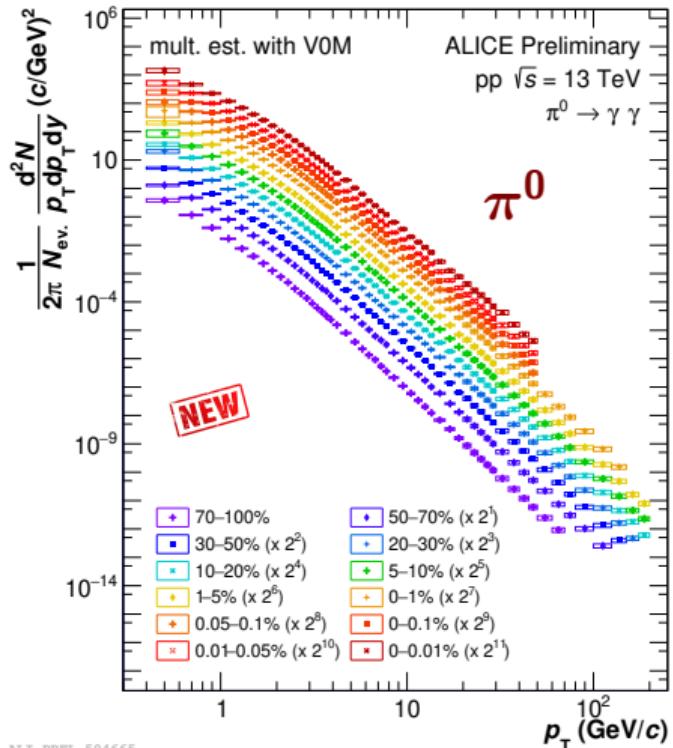


- $\omega$  invariant cross section in pp at  $\sqrt{s} = 13$  TeV
  - $1.5 \leq p_T < 50$  GeV/c
- PYTHIA overshoots the data
- $\omega/\pi^0$  -ratio
  - Unprecedented  $p_T$  reach and precision
  - Slight tension to results at lower  $\sqrt{s}$  and PYTHIA



ALI-PREL-503994

# Multiplicity dependence — $\pi^0$ spectra



V0M multiplicity estimator:

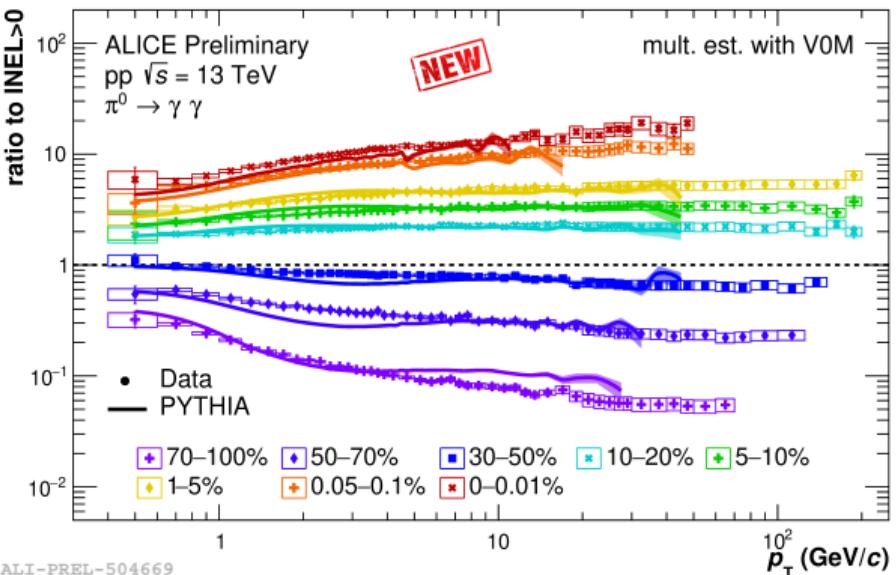
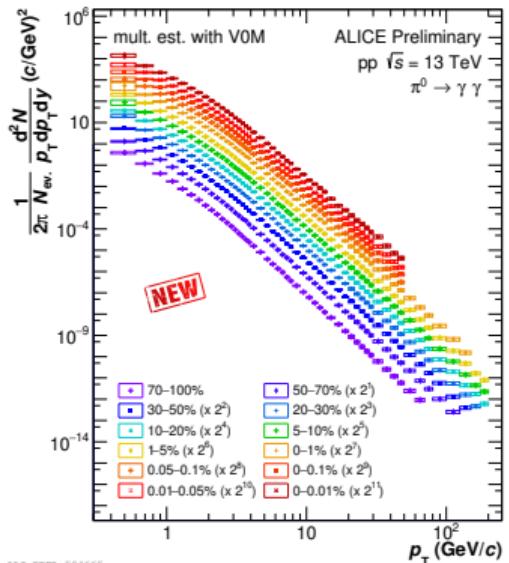
$2.7 < \eta < 5.1$

$-3.7 < \eta < -1.7$

- Forward multiplicity dependent spectra **extracted in 12 intervals**
  - Using V0M high multiplicity triggered data  $> 0.1\%$
  - $\pi^0$   $p_T$  spectra cover nearly 3 orders of magnitude depending on multiplicity
- Combination of all available reconstruction methods via BLUE<sup>(1)</sup> method

(1) Combination of spectra using BLUE method Nucl. Instrum. Meth. A 270 (1988) 110.

# Multiplicity dependence — $\pi^0$ spectra



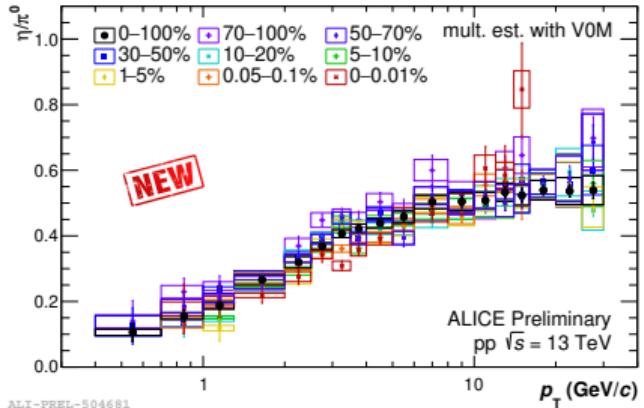
## Ratio to INEL>0

- Combination of methods directly on the ratios
- Large fraction of systematic uncert. cancel
- Hardening of  $p_T$  spectra with rising multiplicity**

## Comparison to PYTHIA

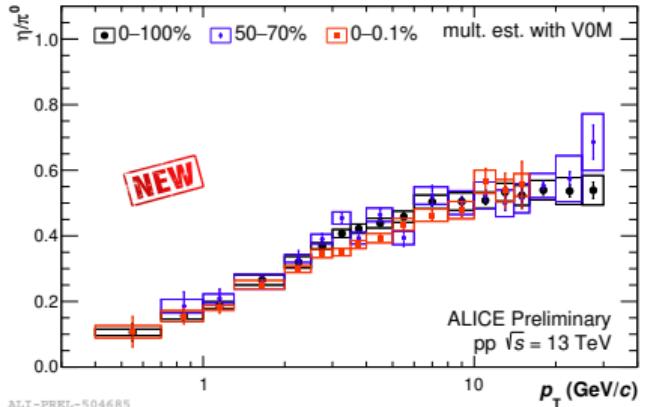
- General ordering and magnitude described by PYTHIA
- Slightly different  $p_T$  dependence

# Multiplicity dependence of $\eta/\pi^0$

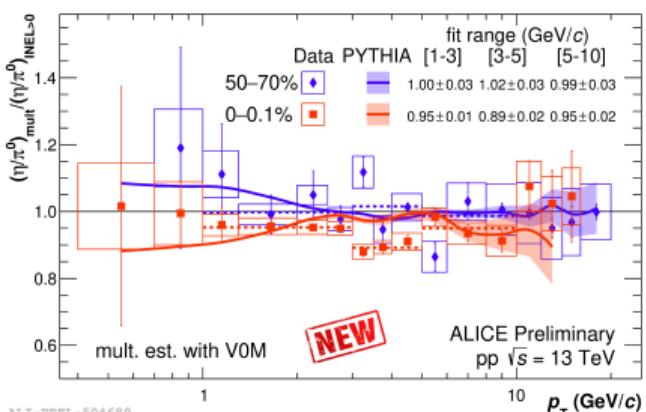


- $\eta/\pi^0$  extracted for all multiplicity intervals
- Hint at multiplicity ordering visible

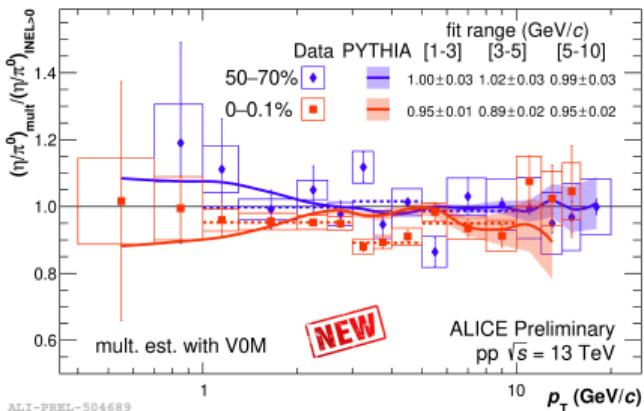
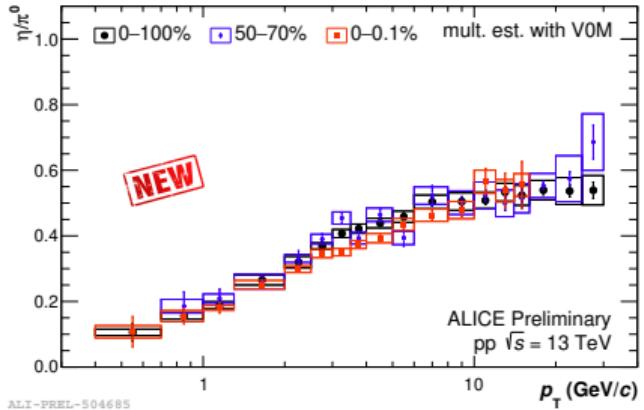
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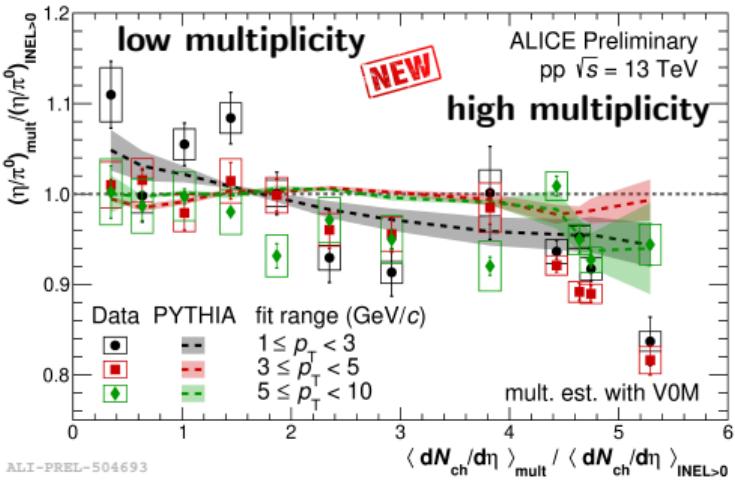
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# Multiplicity dependence of $\eta/\pi^0$



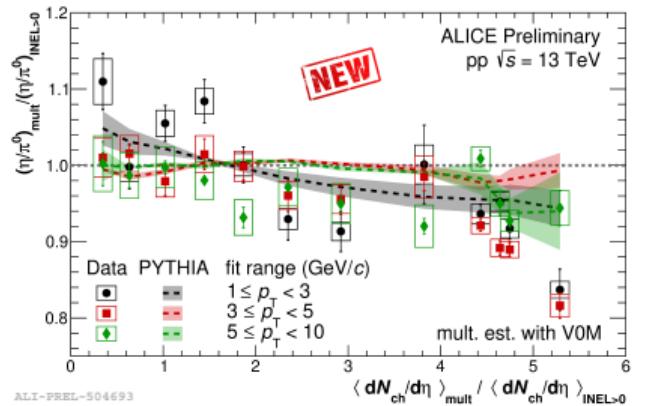
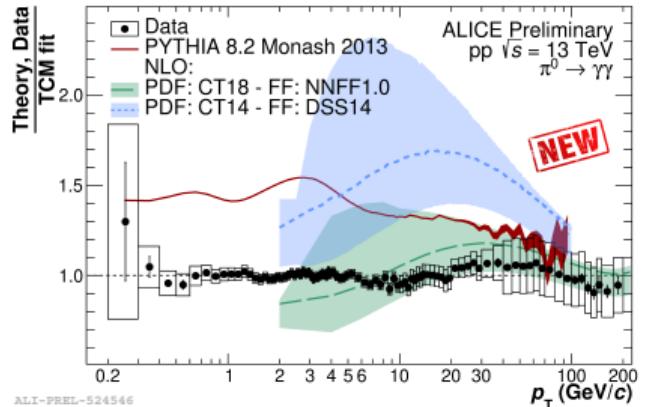
- $\eta/\pi^0$  extracted for all multiplicity intervals
- Hint at multiplicity ordering visible
- **Slight suppression observed** at higher multiplicities
- Larger fraction of mesons inside jets? (see back-up slide 21)
- PYTHIA predicts differences below  $p_T \approx 2$  GeV/c



# Summary

- $\pi^0$ ,  $\eta$  and  $\omega$  mesons in pp at  $\sqrt{s} = 13$  TeV
  - All available reconstruction techniques included
  - Large  $p_T$  reach for all mesons
  - $\eta/\pi^0$  in  $\sqrt{s} = 13$  TeV compatible with results from other collision energies
  - Unprecedented  $p_T$  reach for  $\omega/\pi^0$  ratio
- Multiplicity dependence
  - Clear ordering of  $\pi^0$  and  $\eta$   $p_T$  spectra
  - Slight suppression of  $\eta/\pi^0$  at very high multiplicities observed

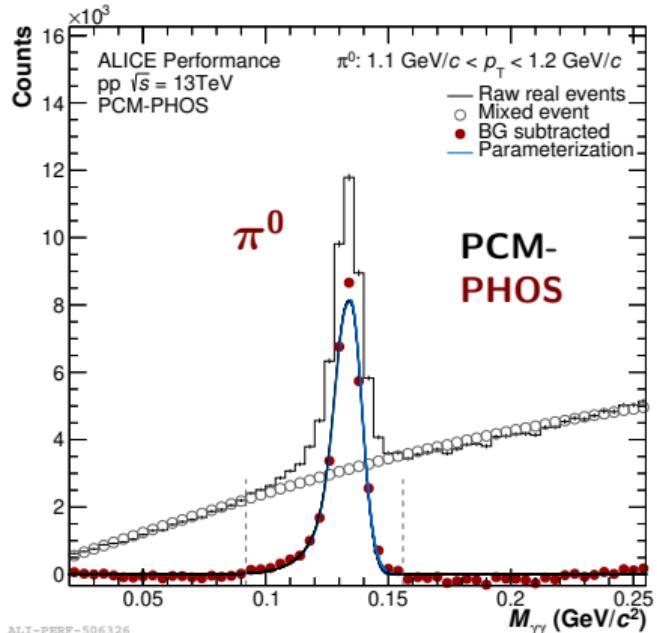
Publication coming soon



## BACKUP

# Neutral meson measurement

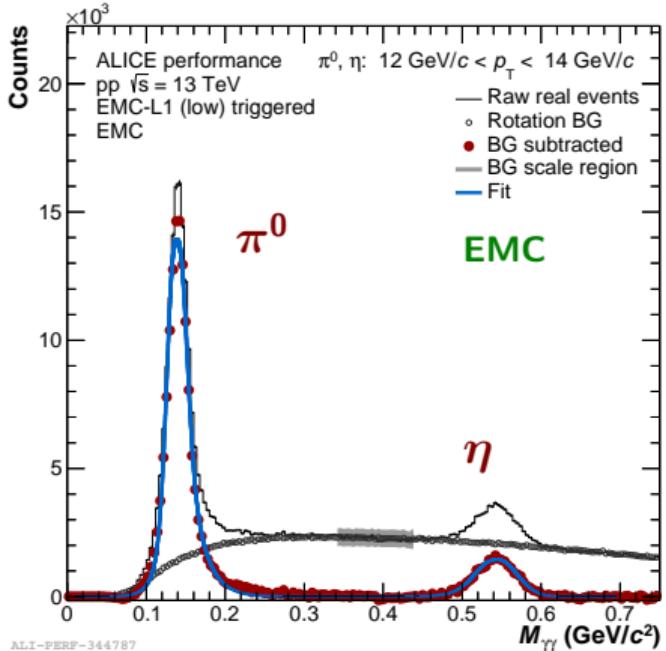
- Reconstructing signal by **pairwise photon combination**
- Photons can be reconstructed with the same method or via two different methods (hybrid methods)
- Background described by:
  - Mixed event + residual linear background
  - In-event rotation technique
- Signal parameterized with Gaussian + exponential tail
- Tail: (PCM: Bremsstrahlung, EMC: Late conversions)
- Integration in fixed window around estimated mass position



$$M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos(\Theta_{1,2}))}$$

# Neutral meson measurement

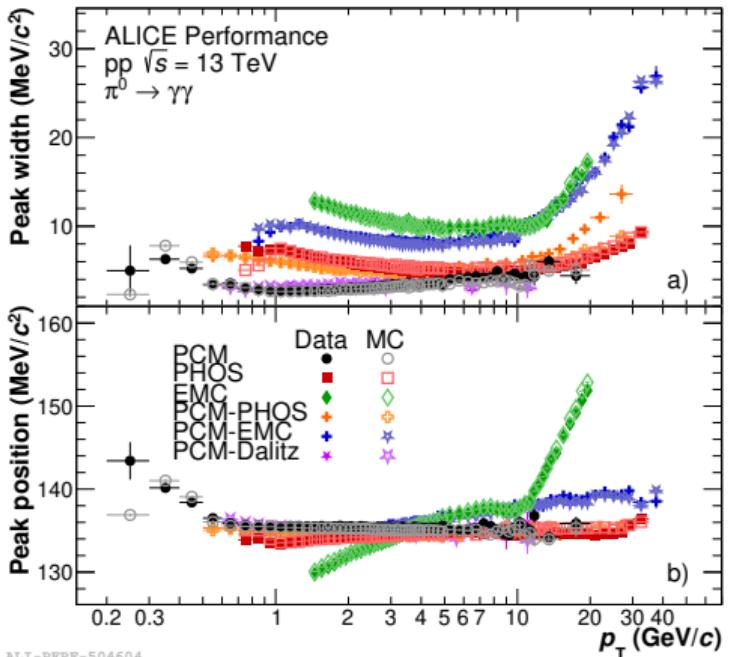
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- Integration in fixed window around estimated mass position
- **Good agreement between data and simulation**

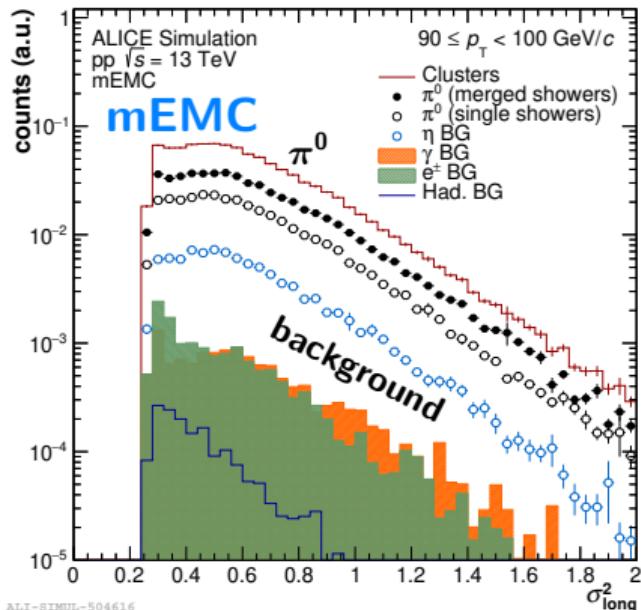
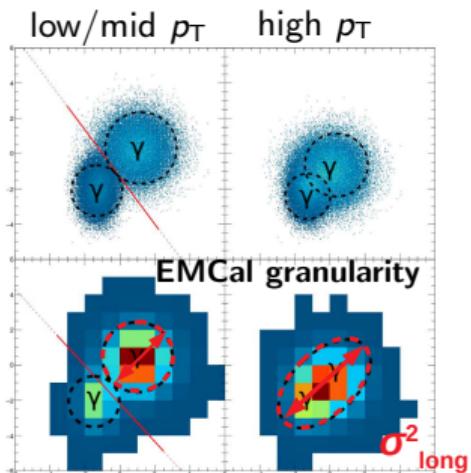


$$M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos(\Theta_{1,2}))}$$

# Neutral meson measurement at high $p_T$

## purity based measurement

- Utilizing EMCAL clusters containing both decay photons from  $\pi^0$  (merged  $\pi^0$  cluster)
- Differentiate between merged  $\pi^0$  and single  $\gamma$  clusters via long axis of shower ellipse ( $\sigma_{\text{long}}^2$ )
- **High  $\pi^0$  purity (> 70%)**



**Correct abundance of background components** in simulation

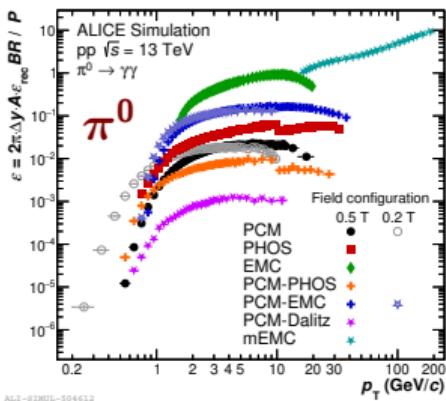
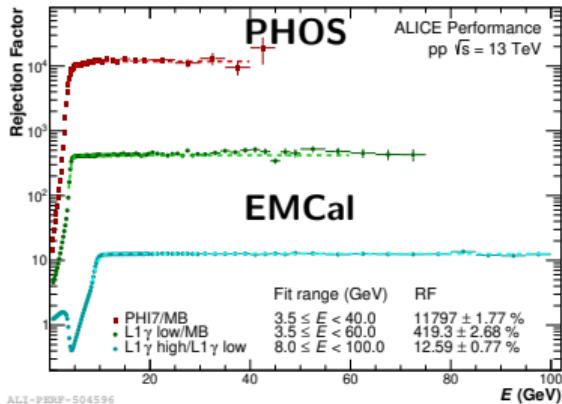
- η from  $\eta/\pi^0$  ratio at high  $p_T$
- Contribution from prompt photons from  $\gamma$ -Jet MC
- Electrons from weak decays ( $W^\pm, Z$ ) from Powheg

# Calculating the invariant cross section

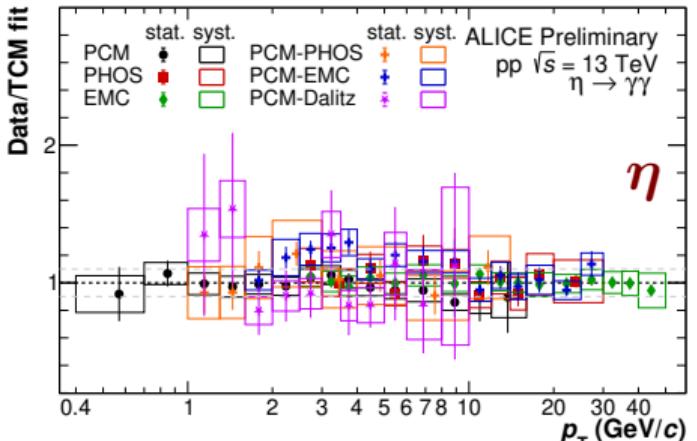
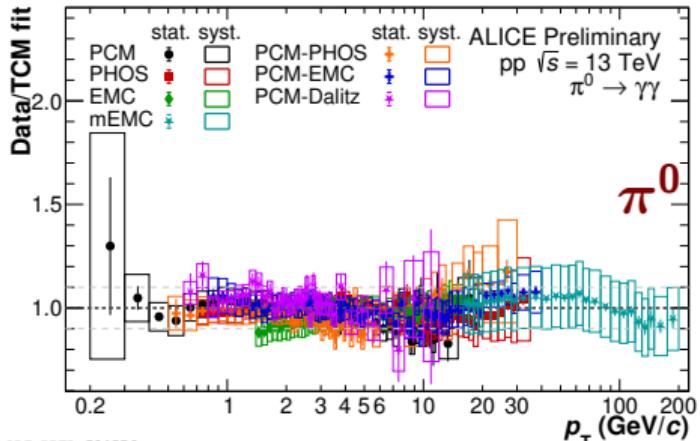
$$E \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi p_T} \frac{1}{\mathcal{L}_{\text{int}}} \frac{P}{A\varepsilon_{\text{rec}}} \frac{F_{\text{pile-up}} N^{\pi^0(\eta)} - N_{\text{sec.}}^{\pi^0}}{\Delta y \Delta p_T}$$

## Corrections:

- $\mathcal{L}_{\text{int}}$ :  $\frac{N_{\text{evt.}}}{\sigma_{\text{INT7}}} (\cdot RF)$ 
  - Calo triggers: **Trigger rejection factor (RF)** via ratio of cluster spectra
- $P$ :  $\pi^0$  purity (mEMC only) ( $> 70\%$ )
- $A\varepsilon_{\text{rec}}$ : Acceptance and reconstruction efficiency
  - Efficiency includes energy resolution correction
  - PCM efficiency includes conversion probability ( $\approx 8\%$ )
- $F_{\text{pile-up}}$ : Out of bunch pile up correction for PCM
- $N_{\text{sec.}}^{\pi^0}$ : Secondary  $\pi^0$  from  $K_s^0$ ,  $K_L^0$  and  $\Lambda$  from **data-driven cocktail simulation**



# Combination of different methods



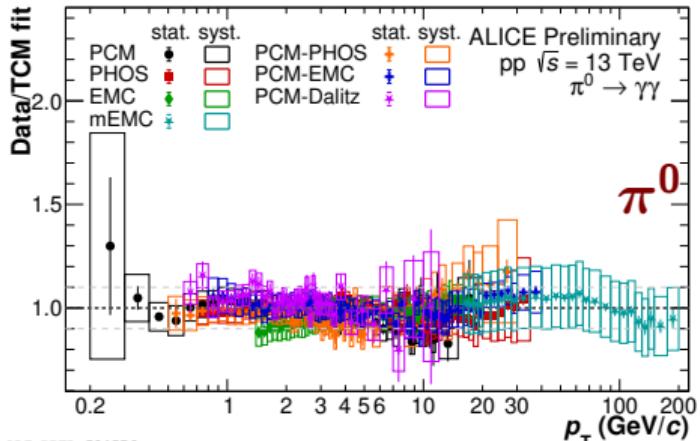
- Good agreement between all 7(6) methods

- Dominating systematic uncertainty:

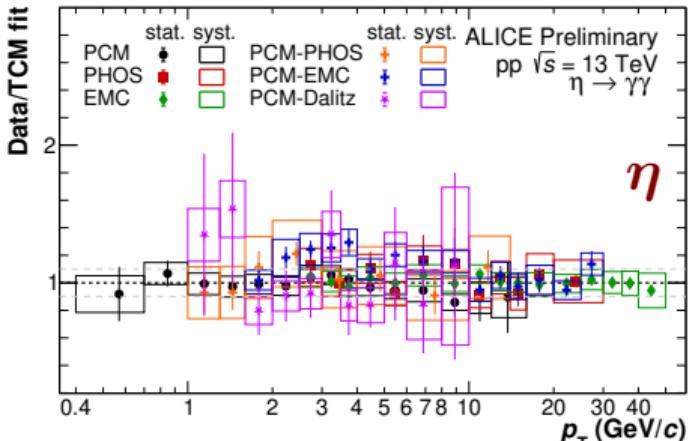
- Material unc.: 5% for PCM and 4.2% for EMC
- Shower overlap and  $\pi^0$  energy resolution:  
10-15% for mEMC
- Signal extraction

detector thickness correction

# Combination of different methods



ALI-PREL-504576



ALI-PREL-504572

- Good agreement between all 7(6) methods

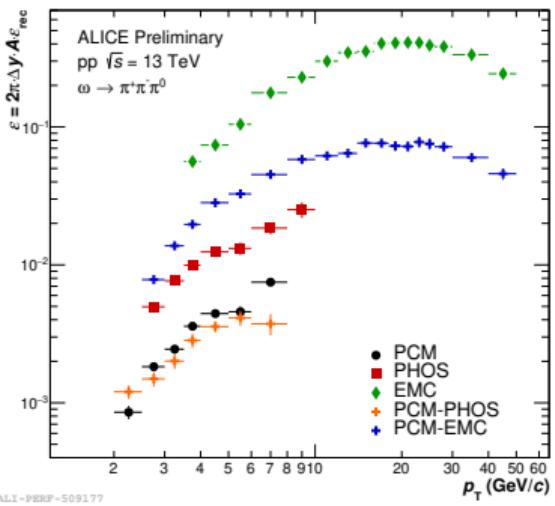
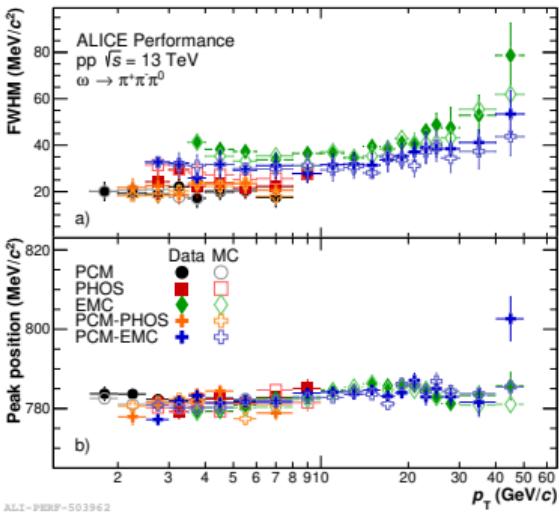
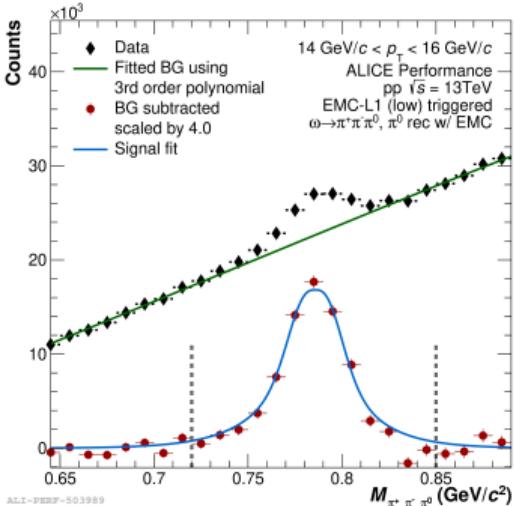
- Dominating systematic uncertainty:

- Material unc.: 5% for PCM and 4.2% for EMC
- Shower overlap and  $\pi^0$  energy resolution: 10-15% for mEMC
- Signal extraction

- Combination of spectra with BLUE method

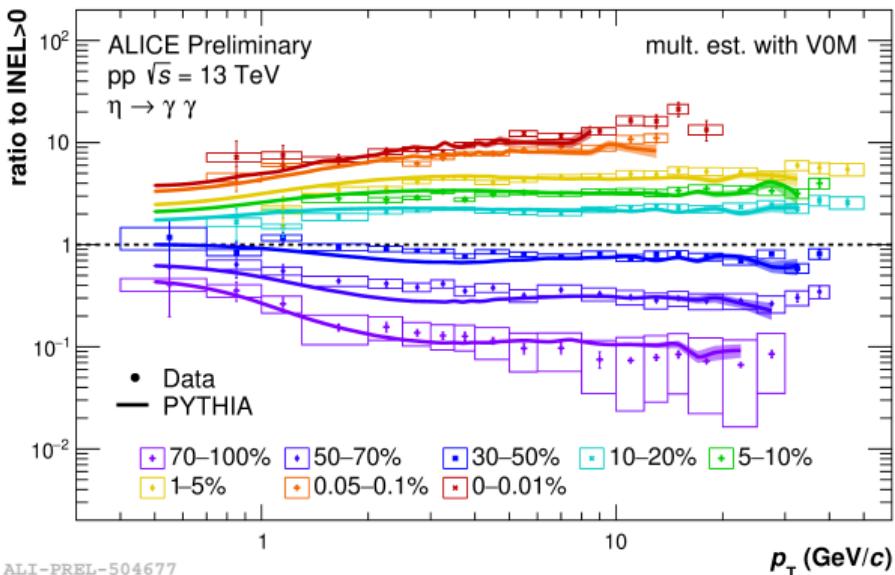
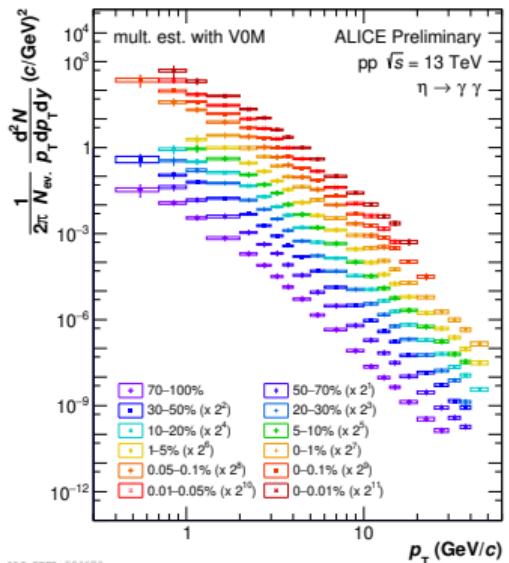
- Based on statistical and systematical uncertainties
- Taking correlations between methods into account

# $\omega$ meson signal extraction



- Using dominant decay channel into  $\pi^+ \pi^- \pi^0$  ( $\approx 89\%$ )
- Inv. mass based  $\pi^0$  measurement done with 5 different methods
- Charged pions measured in central tracking detectors
- Background described by parameterization

# Multiplicity dependence — $\eta$ spectra



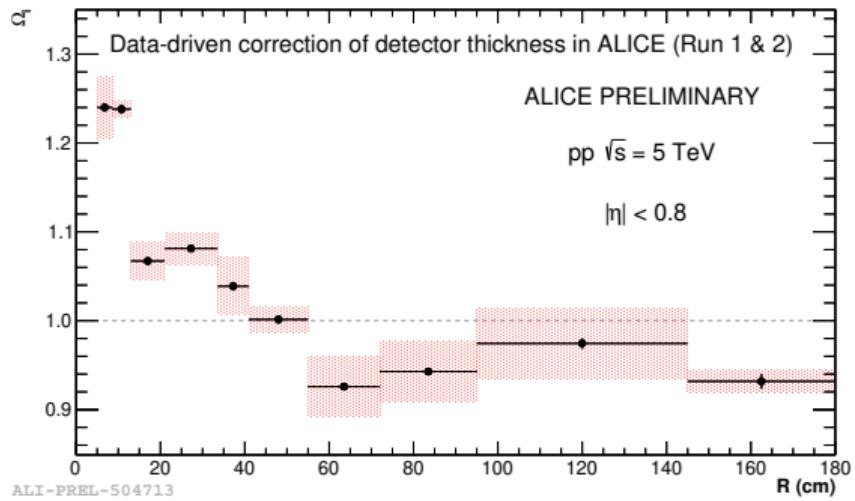
## Ratio to min. bias

- Combination of methods directly on the ratios
- Large fraction of systematic uncert. cancel
- Hardening of  $p_T$  spectra with rising multiplicity

## Comparison to PYTHIA

- General ordering and magnitude described by PYTHIA
- Slightly different  $p_T$  dependence

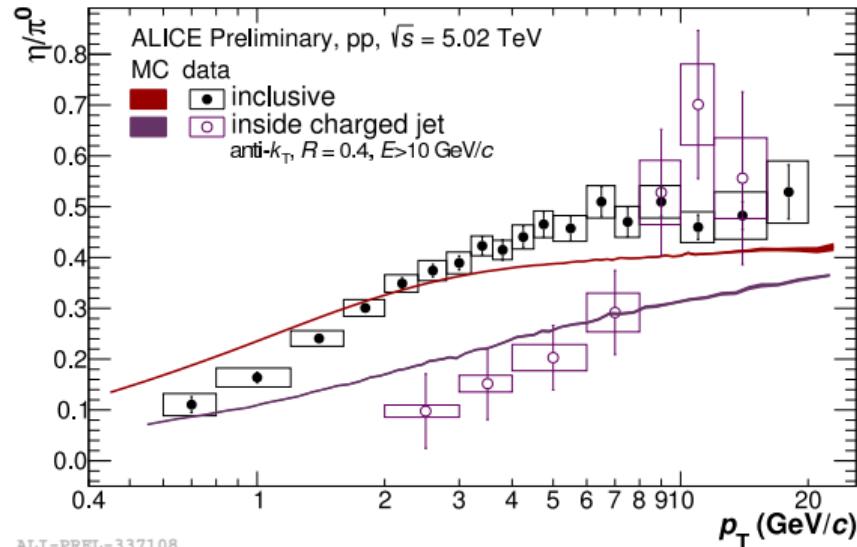
# Data driven reweighting of the detector thickness



- Description of detector thickness in simulation not perfect
  - Largest contribution of the sys. uncertainty for PCM so far (9% for mesons, 4.5% per photon)
- Data driven correction in several radial intervals
- Correction factor  $\Omega_i$  used for reweighting of photons in simulation
- **Reduces uncertainty to 5% per mesons and 2.5% per photon**

Publication coming soon

# $\pi^0$ and $\eta$ production inside jets



ALI-PREL-337108

- Meson production in pp collisions at  $\sqrt{s} = 5$  TeV
- Strong suppression of  $\eta/\pi^0$  inside jets
- Detailed studies in pp collisions at  $\sqrt{s} = 13$  TeV currently ongoing