Multiplicity dependent and inside-jet measurement of light neutral mesons in pp collisions with ALICE

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Goethe-Universität Frankfurt

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HGS-HIRe *for FAIR*
Helmholtz Graduate School for Hadron and Ion Research

FSP ALICE
Erforschung von Universum und Materie

ALICE

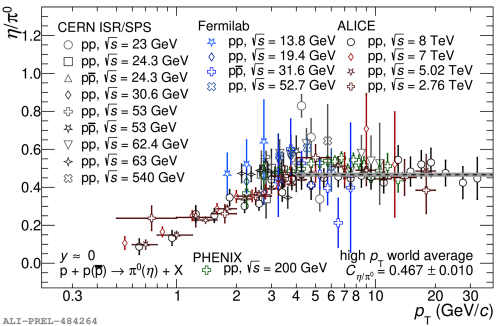
Motivation

$$E\frac{d^3\sigma^H}{d\vec{p}} = \sum_{a,b,c} \mathbf{PDF}_a \otimes \mathbf{PDF}_b \otimes d\sigma_{ab\to cX} \otimes \mathbf{FF}_c^H(z_c, Q)$$

Particle production at LHC energies

- **Initial state**:
  - Invariant cross section of identified particles
- **Fragmentation (parton → hadrons)**
  - Particle ratios (η/π^0, ω/π^0, ...)

  → Universality of fragmentation function (FF)?
- **Collectivity in small systems**



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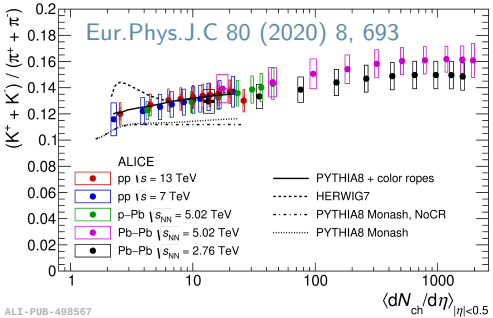

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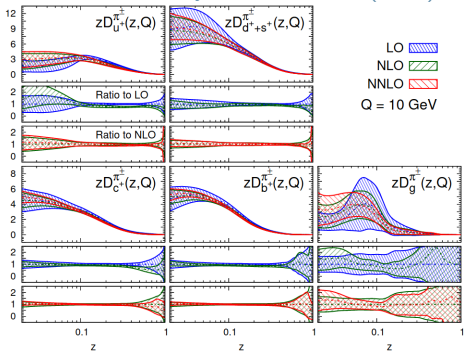
NNPDF: Eur. Phys. J. C 77, 516 (2017)



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Neutral meson measurement with ALICE

- Measurable over large p_{T} range

→ **Precise probe to study particle production** mechanisms (PDF, FF)

- Crucial input for direct photon and dielectron cocktail

Talk on Tuesday, 3:20pm: J. Jung

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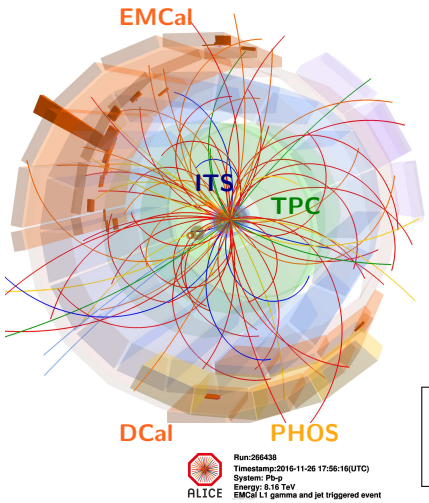
In this talk:

- **Inclusive neutral meson cross sections**
- **Multiplicity dependence**
- **In-jet meson production**

ALICE detector setup in LHC Run 2



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

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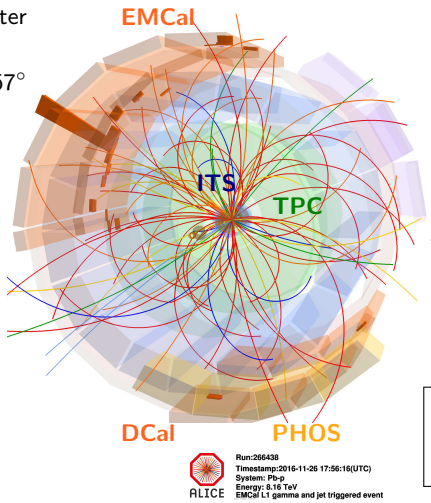
Electromagnetic calorimeter (EMC = EMCal + DCal)

- Lead-scintillator calorimeter
- Large acceptance
  $|\eta| < 0.7, \Delta\phi \approx 107° + 67°$

→ Photon and neutral jet measurement



Photon Spectrometer (PHOS)

- $PbWO_4$ crystals

→ γ measurement

- Fine granularity: π^0 decay γ shower separation up to $p_T = 50$ GeV/c

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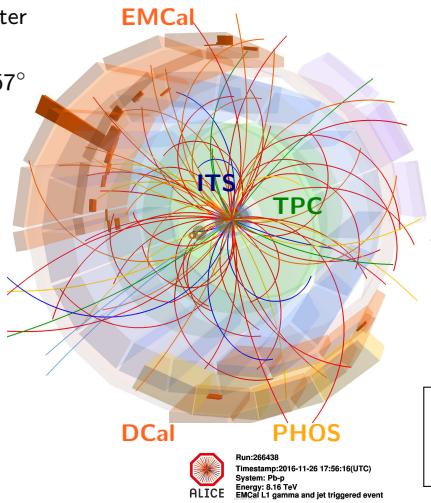

Photon Conversion Method (PCM)

- Utilizing γ conversion probability of $\approx 8\%$

→ Reconstruct γ via $e^{\pm}$ V0-tracks from ITS + TPC

- Excellent energy resolution at low p_T: $\sigma(E_\gamma)/E_\gamma \approx 1.5\%$

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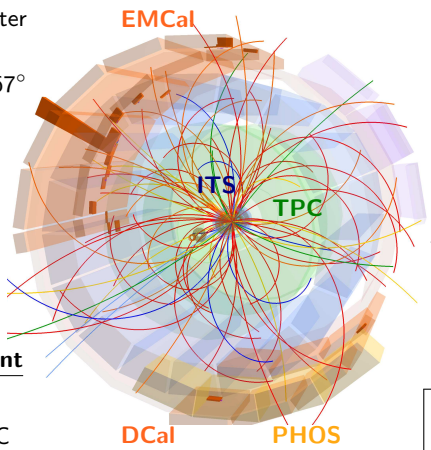

Charged particle measurement

- ITS+TPC
- PID via dE/dx from TPC
- Rec. tracks for charged jet measurement

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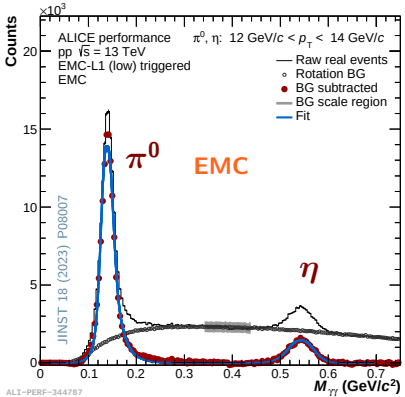
Raw signal extraction — Inv. mass based



- Reconstructing signal by **combining measured decay particles**
- Background subtraction + integration around mass position
  → Raw yield

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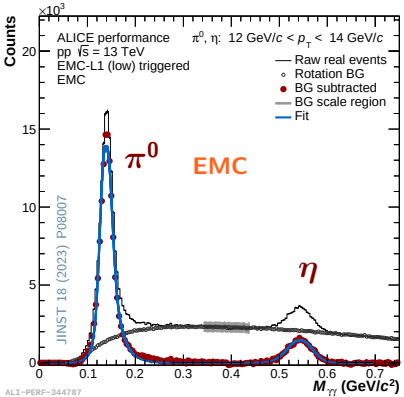

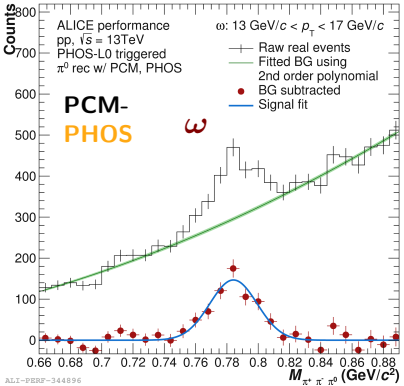

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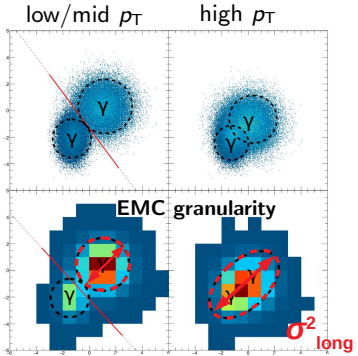
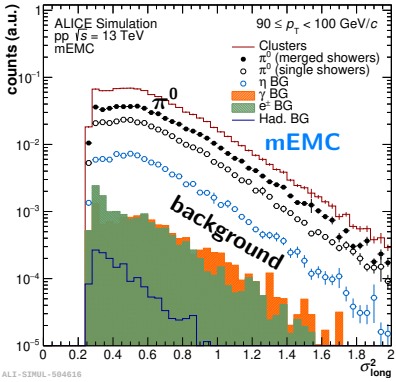
Raw signal extraction — Purity-based



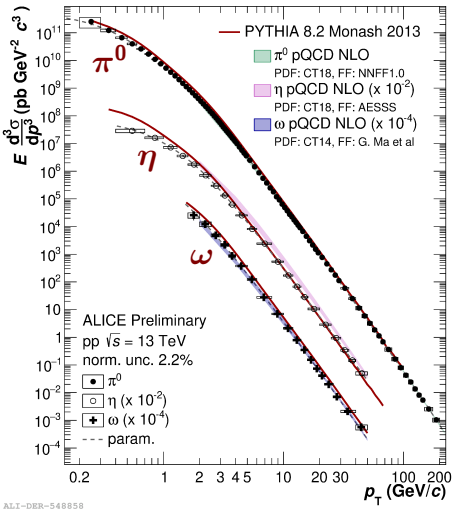


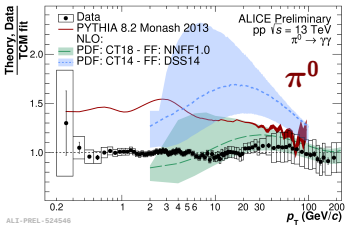
- Using EMCal clusters containing both π^0 decay photons

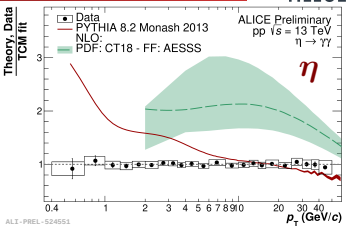
→ Differentiate between merged π^0 and single γ clusters via long axis of shower ellipse (σ^2_{long})

→ **High π^0 purity ($> 70\%$)**

π^0, η and ω in pp at $\sqrt{s} = 13$ TeV





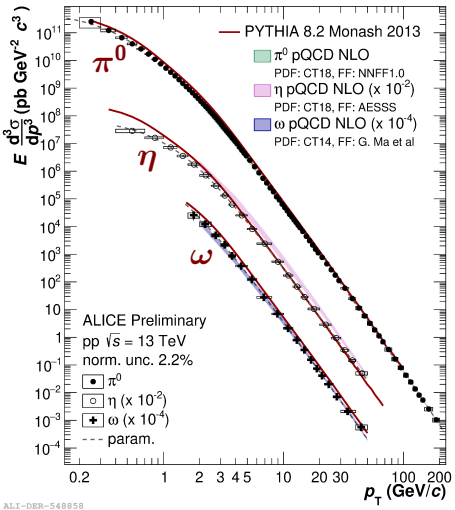


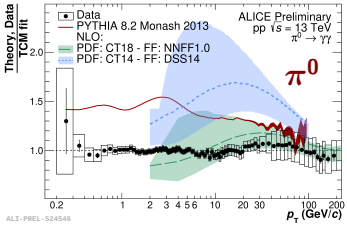
- Combination of various reconstruction methods
- $B = 0.2$ T data used to extract π^0 down to $p_{\mathrm{T}} = 0.2$ GeV/c
- Inv. cross section in pp at $\sqrt{s} = 13$ TeV
  - π^0: $\mathbf{0.2 < p_{\mathrm{T}} < 200}$ **GeV/c**
  - η: $\mathbf{0.4 < p_{\mathrm{T}} < 50}$ **GeV/c**
  - ω: $\mathbf{1.5 < p_{\mathrm{T}} < 50}$ **GeV/c**

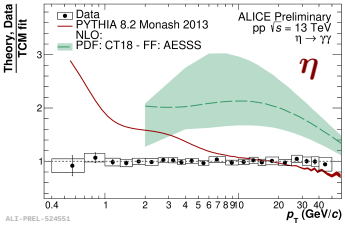
Combination of spectra using BLUE method Nucl. Instrum. Meth. A 270 (1988) 110.

NLO calculations from W. Vogelsang

π^0, η and ω in pp at $\sqrt{s} = 13$ TeV







- Combination of various reconstruction methods
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  - **η: $0.4 < p_T < 50$ GeV/c**
  - **ω: $1.5 < p_T < 50$ GeV/c**
- NLO with **NNFF1.0 FF describes π^0 spectrum**
- PYTHIA 8 overestimates and does not describe spectral shape

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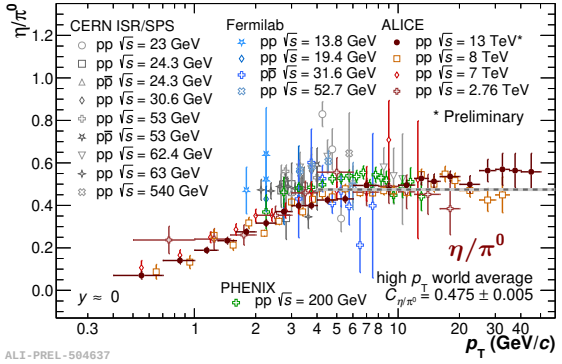
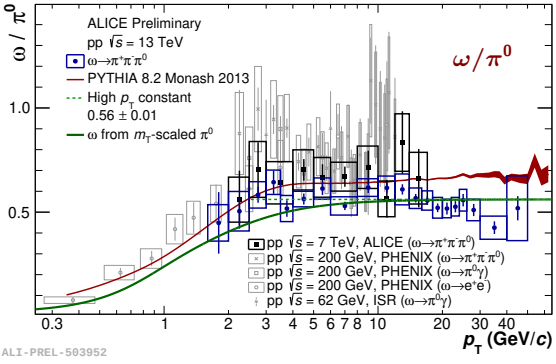
NLO calculations from W. Vogelsang

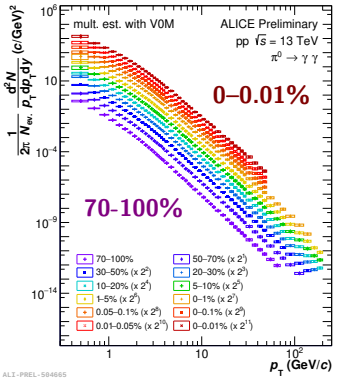
Particle ratios



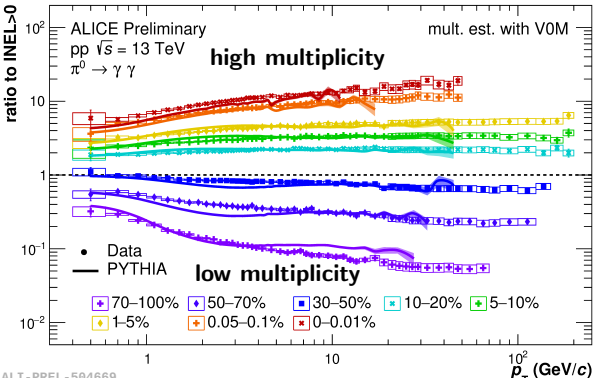


- Measurements in pp at $\sqrt{s} = 13$ TeV reach **up to $p_T = 50$ GeV/c**
- η/π^0: **No significant dependence on collision energy**
- ω/π^0: High p_T constant in pp at $\sqrt{s} = 13$ TeV lower than previous measurements at lower collision energies

Multiplicity dependence — π^0 spectra



Ratio to inclusive



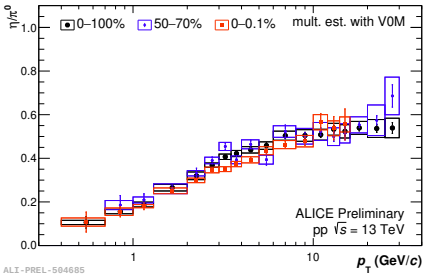
- Highest multiplicities (0–0.01%): $\approx 5.3 \times \langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle_{\mathrm{incl.}}$
- π^0 spectra from $p_T = 0.4$ up to 50–200 GeV/c
- Ratio of π^0 spectra in mult. intervals to inclusive

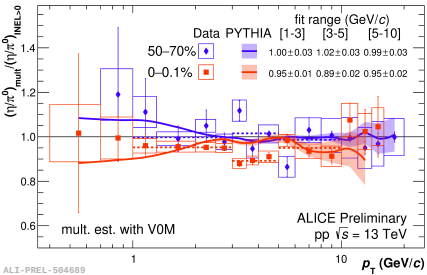
→ **Hardening of p_T spectra with rising multiplicity**

Comparison to PYTHIA

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

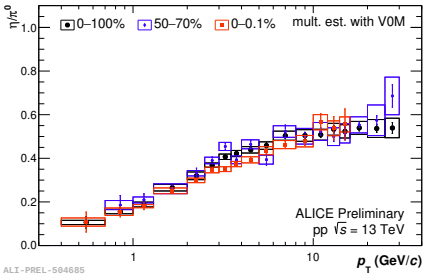
Multiplicity dependence of η/π^0

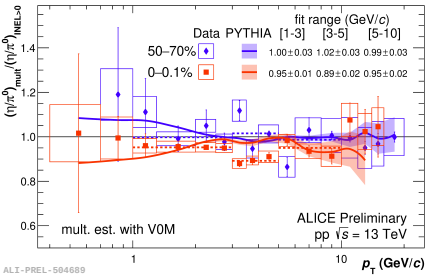




- η/π^0 extracted for all multiplicity intervals
- Hint at multiplicity ordering visible

Multiplicity dependence of η/π^0





- η/π^0 extracted for all multiplicity intervals
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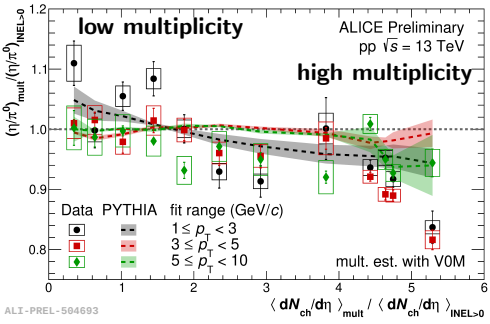
- **Slight suppression at low p_T** at high multiplicities



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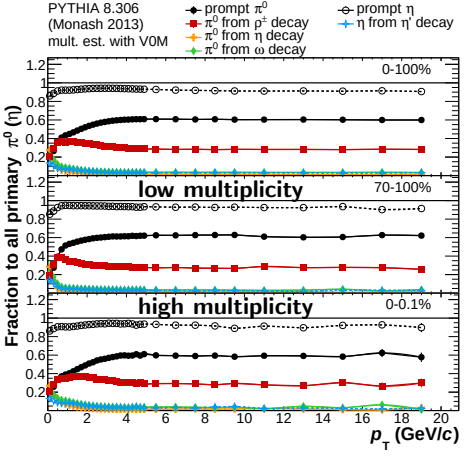

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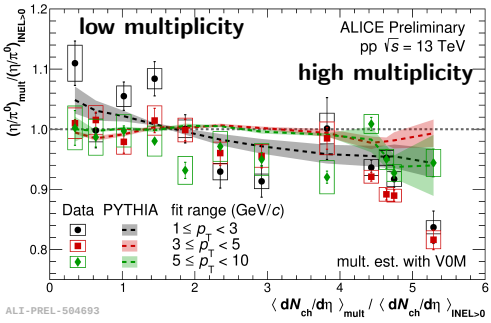
- Hint at multiplicity ordering visible
- **Slight suppression at low p_T** at high multiplicities

→ Larger fraction of π^0 feed-down from heavier particles (η, ω, $\rho^\pm$)

→ Described qualitatively by PYTHIA



Neutral mesons inside jets

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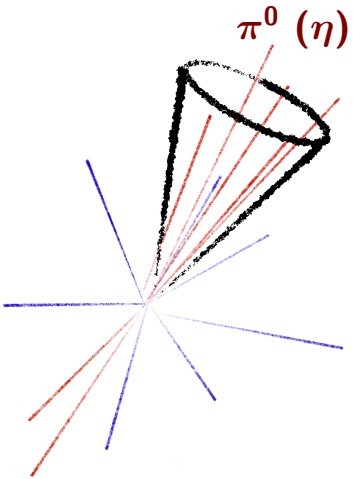
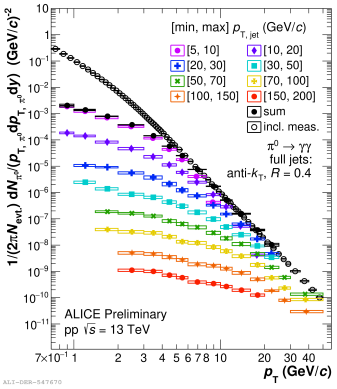


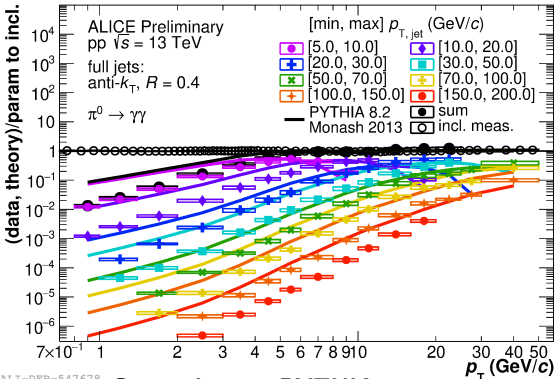
Observables

- **Full jet** momentum $\rightarrow Q$
- Correlation of meson inside jet cone with jet momentum $\rightarrow z = \frac{\vec{p}_{\pi^0} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2}$

π^0 mesons inside jets



Ratio to incl. param.



- Reconstruction of mesons inside jet cone ($R = 0.4$)
- Decomposition of π^0 spectra into single $p_{T,\,jet}$ bins

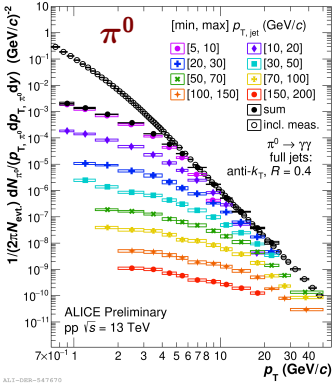
→ **Clear ordering and hardening of meson p_T-spectra with rising $p_{T,\,jet}$**

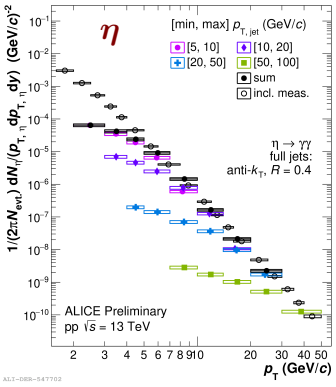
Comparison to PYTHIA

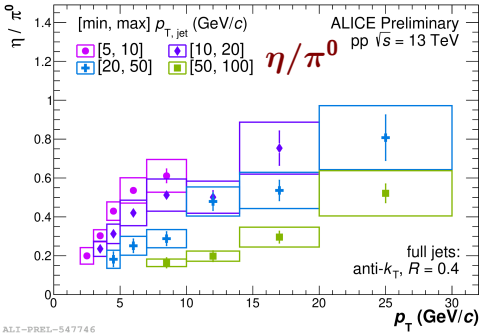
- General ordering and magnitude described
- Contribution to inclusive spectrum peaks at lower p_T

→ **Hint for softer fragmentation in PYTHIA**

π^0 and η mesons inside jets







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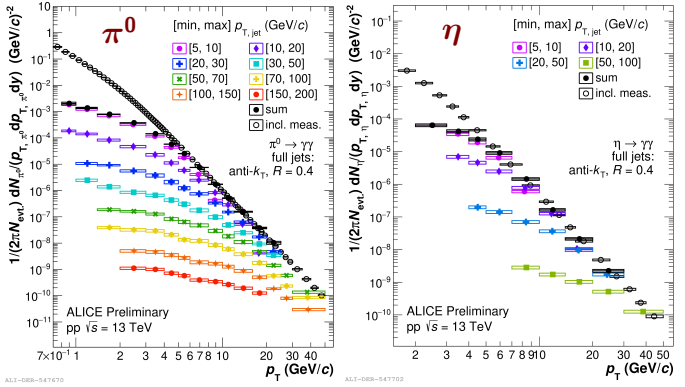
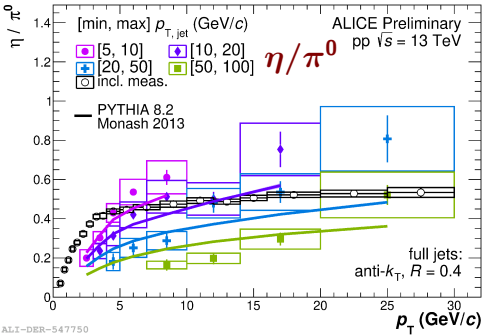
η/π^0 ratio

- Clear dependence on $p_{T,\,jet}$: **No universality**

→ Large fraction of **feed down from heavier particles** ($\rho^{\pm}$, ω and η) to π^0 spectrum

π^0 and η mesons inside jets





- Reconstruction of mesons inside jet cone (R = 0.4)
- Decomposition of π^0 spectra into single $p_{T,\,jet}$ bins

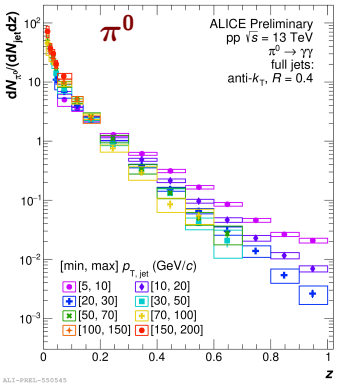
→ **Clear ordering and hardening of meson p_T-spectra with rising $p_{T,\,jet}$**

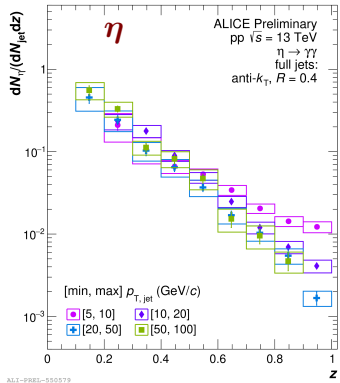
η/π^0 ratio

- Clear dependence on $p_{T,\,jet}$: **No universality**

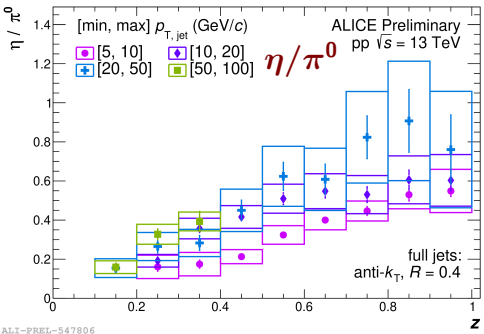
→ Large fraction of **feed down from heavier particles** ($\rho^{\pm}$, ω and η) to π^0 spectrum

π^0 and η mesons inside jets — Fragmentation



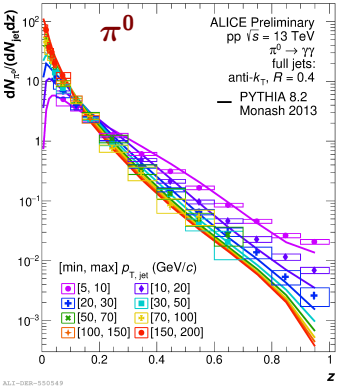


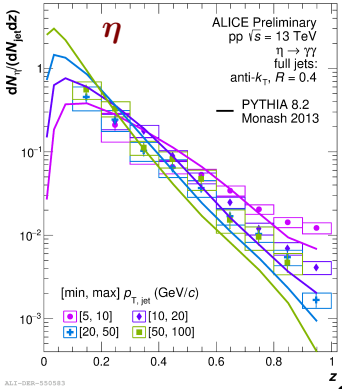
$$z = \frac{\vec{p}_{\pi^0} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2}$$



- **First measurement of π^0 and η fragmentation functions at LHC energies**
- For $p_{T,\,jet} > 20$ GeV/c:
  Only small dependence on $p_{T,\,jet}$
- **η/π^0 ratio similar for $p_{T,\,jet} > 10$ GeV/c** as function of z

π^0 and η mesons inside jets — Fragmentation





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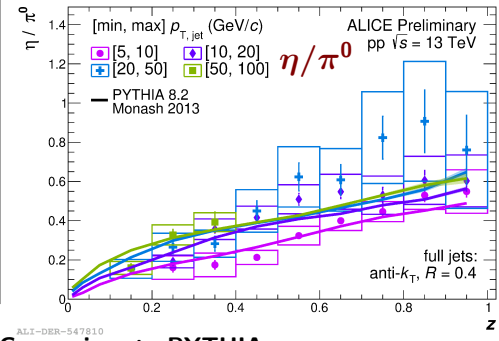


- **First measurement of π^0 and η fragmentation functions at LHC energies**
- For $p_{T,jet} > 20$ GeV/c:
  Only small dependence on $p_{T,jet}$
- **η/π^0 ratio similar for $p_{T,jet} > 10$ GeV/c** as function of z

Comparison to PYTHIA

- General ordering and magnitude described, shape slightly different

→ Softer fragmentation predicted by PYTHIA

- $p_{T,jet}$ dependence of η/π^0 described

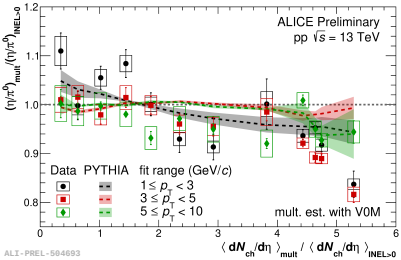
Summary

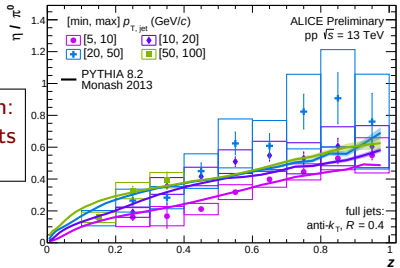
- π^0, η and ω mesons in pp at $\sqrt{s} = 13$ TeV
  - p_T spectra measured over wide p_T range with small uncertainties
  - Hint at energy dependence of ω/π^0
  - **Publications in preparation**
- Multiplicity dependence of π^0 and η production
  - Precise spectra up to high multiplicities (0–0.01%)
  - **Slight multiplicity dependence of η/π^0**

  → Driven by feed-down into π^0
  - **Publication in preparation**
- π^0 and η production inside jets
  - **Clear dependence of η/π^0 on $p_{T,\,jet}$ as function of $p_{T,\,\eta/\pi^0}$**

  → Driven by feed-down into π^0
  - **First measurement of fragmentation functions**

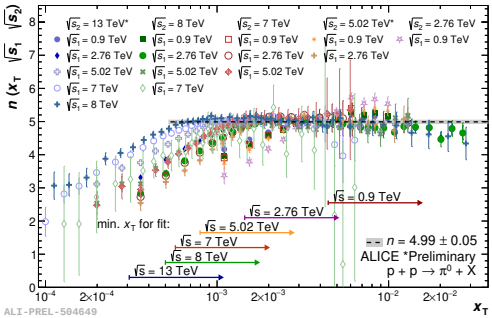
Talk on Wed, 9:50am:
strange baryons in jets
G. van Weelden





BACKUP

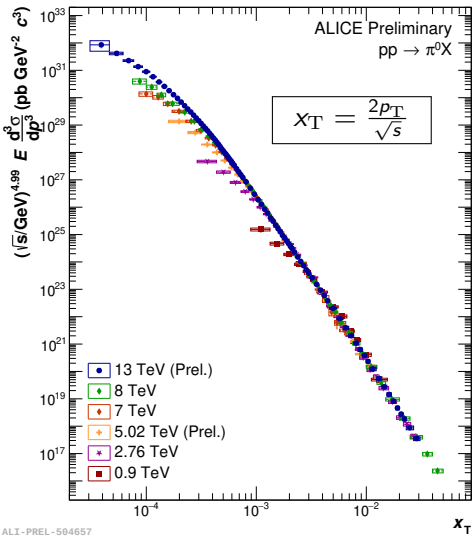
Collision energy dependence: π^0 spectra



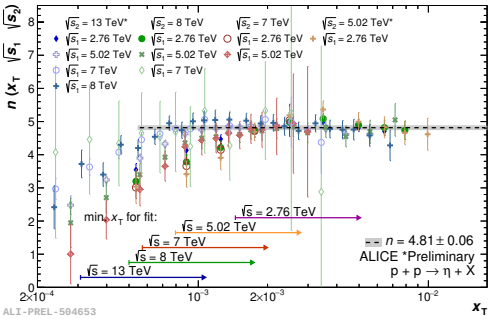
- x_T scaling: Universal behavior for x_T-spectra **scaled with $\sqrt{s}^n$**

→ n = 4.99 ± 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**



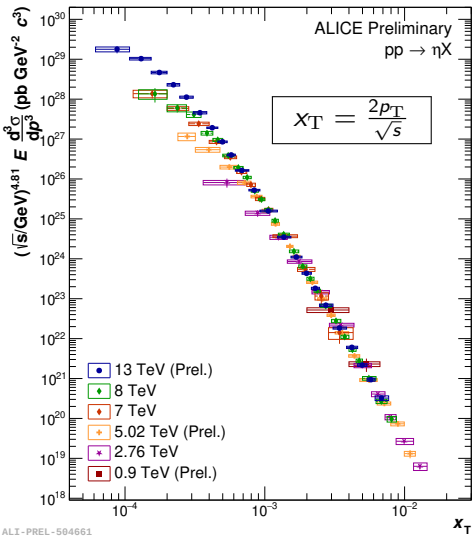
Collision energy dependence: η spectra



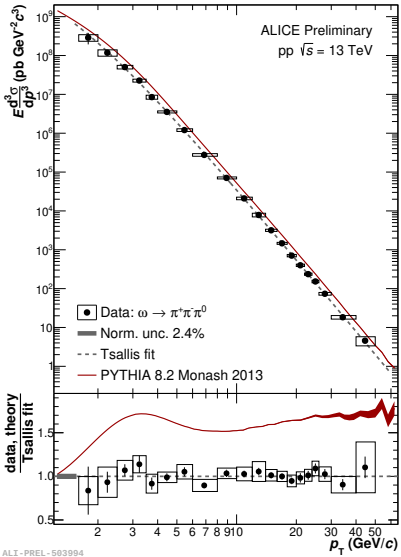
- x_T scaling: Universal behavior for x_T-spectra **scaled with $\sqrt{s}^n$**

→ n = 4.81 ± 0.06

- 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**

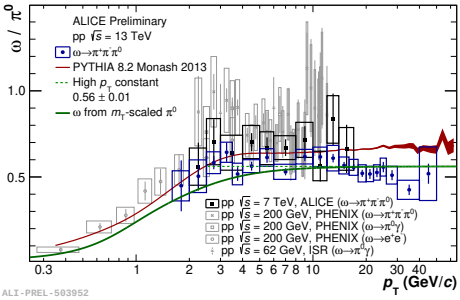


ω meson in pp at $\sqrt{s} = 13$ TeV

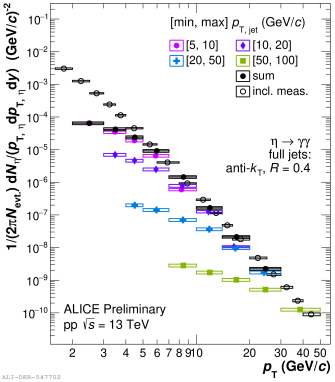


- ω invariant cross section in pp at $\sqrt{s} = 13$ TeV
  - **$1.5 < p_T < 50$ GeV/c**
- PYTHIA overshoots the data
- ω/π^0 -ratio
  - Unprecedented p_T reach and precision
  - Slight tension to results at lower $\sqrt{s}$ and PYTHIA

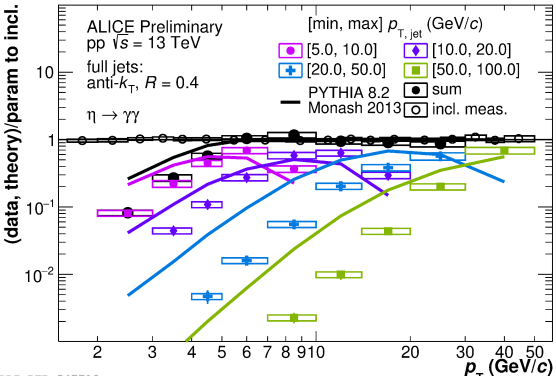
Ratio to π^0



η mesons inside jets



Ratio to param. to incl.



- Reconstruction of mesons inside jet cone (R = 0.4)
- Decomposition of η spectra into single $p_{T,\,jet}$ bins

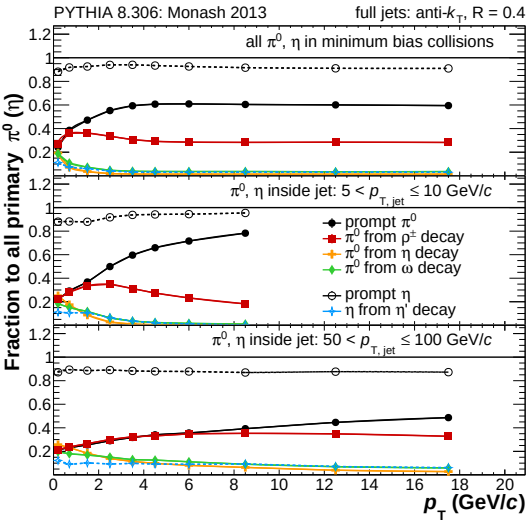
→ **Clear ordering and hardening with rising $p_{T,\,jet}$**

Comparison to PYTHIA

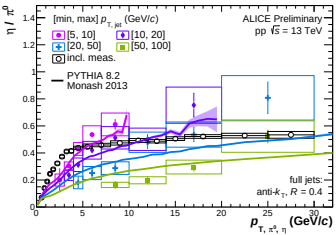
- General ordering and magnitude described
- Contribution to inclusive spectrum peaks at lower p_T

→ **Hints at softer fragmentation in PYTHIA**

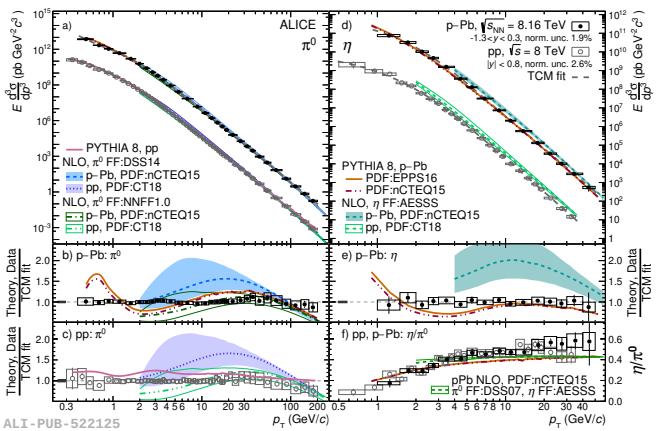
Influence of feed-down to meson spectra on η/π^0

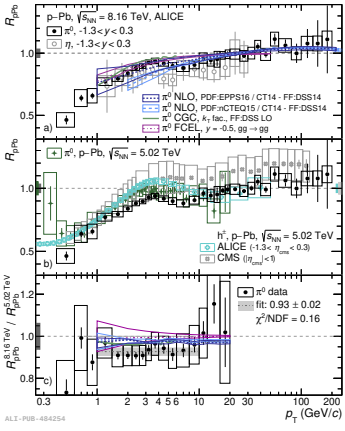


- Decays of heavy mesons into π^0 and η (feed-down) leads to increase of p_T spectra
- Contribution from feed-down:
  - Larger for π^0 spectra than for η
  - Suppressed for $p_{T,\,meson} \approx p_{T,\,jet}$
- Leading decays into π^0:
  $\rho^\pm \rightarrow \pi^\pm\pi^0$
  $\eta \rightarrow \pi^+\pi^-\pi^0$ or $\eta \rightarrow 3\pi^0$
  $\omega \rightarrow \pi^+\pi^-\pi^0$ or $\omega \rightarrow \pi^0\gamma$
- Leading decays into η:
  $\eta' \rightarrow \pi^+\pi^-\eta$



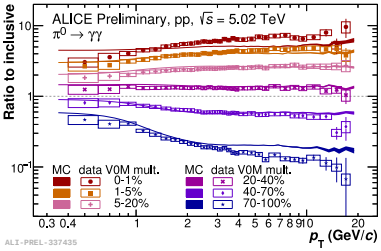
π^0 and η meson R_{pPb} at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

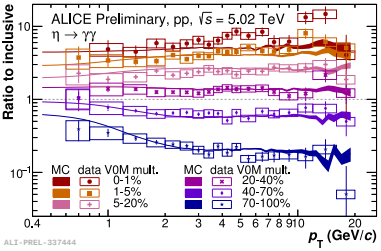


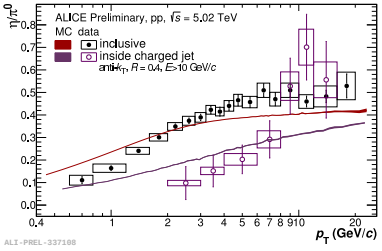


- **Published: Phys. Lett. B 827 (2022)** (arXiv: 2104.03116)
- Nuclear modification factor of π^0 (η) mesons up to $p_{\mathrm{T}} = 200$ (30) GeV/c

π^0 and η mesons in pp collisions at $\sqrt{s} = 5.02$ TeV





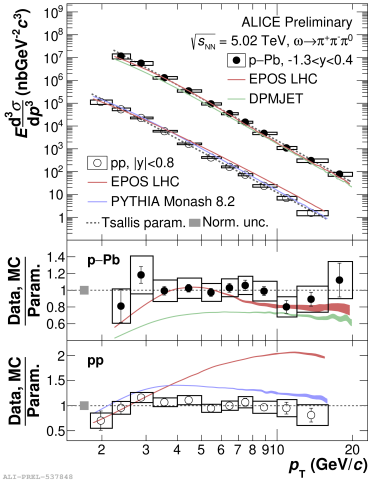


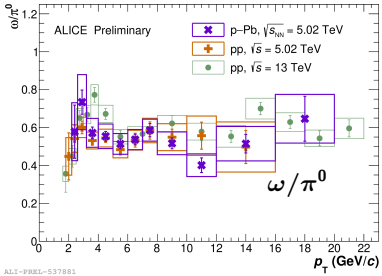
- Neutral meson production as function of multiplicity
- η/π^0 inside charged jets as function of meson p_T

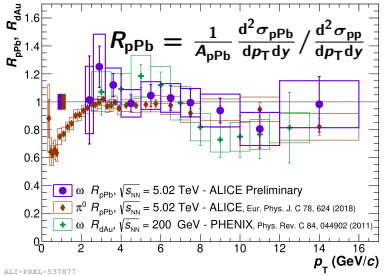
→ $p_{T,\,jet} > 10$ GeV/c

→ Strong suppression of η/π^0 observed

ω mesons in pp and p–Pb in $\sqrt{s_{NN}} = 5.02$ TeV







- **First measurement of ω meson in p–Pb collisions at LHC**
- ω/π^0 ratio consistent across collision systems
- **Extraction of ω R_{pPb}**:
  - Coherent analysis in pp and p–Pb collision reducing systematic uncertainties
  - **No nuclear modification** observed in measured p_T range
  - Consistent with previous ω and π^0 measurements