Probing the initial state of small collision systems measuring the production of neutral mesons with ALICE

Low-x 2021

September 26, 2021 to October 1, 2021

Jens Lühder
for the ALICE collaboration

Westfälische Wilhelms–Universität Münster
Institut für Kernphysik

All new results shown can be found in arXiv:2104:03116

Motivation

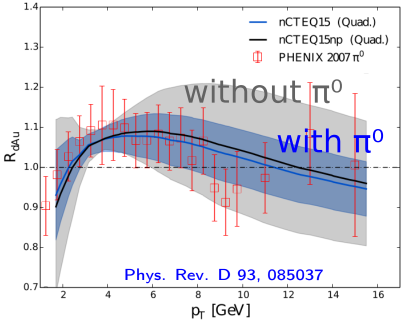
Nuclear modification factor

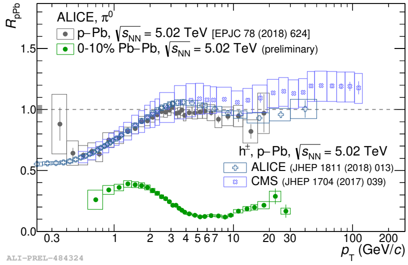
$$R_{\mathrm{pA}} = \frac{1}{A_{\mathrm{Pb}}} \frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \Big/ \frac{\mathrm{d}^2\sigma_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

- Probing inital and final state effects
  - Gluon saturation (CGC)
  - p_{T} broadening (Cronin effect)
  - Energy loss
- Constraints on nuclear PDFs
- Baseline measurements for Pb–Pb

Benefits of p–Pb $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

- Highest available collision energy leads to wider x reach than previous measurements at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
- Energy dependence of R_{pPb} can be studied





Photon Reconstruction

Photon Conversion Method (PCM)

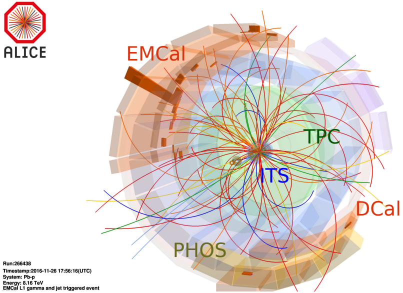
- Acceptance: $|\eta| < 0.9,\ 0^\circ < \varphi < 360^\circ$
- Photons have probability of $\approx 8.5\,\%$ to convert within inner detector material
- $e^{\pm}$ tracked by ITS and TPC and identified with TPC via dE/dx
- Lower p_{T} reach than for calorimeters

Electromagnetic Calorimeters (EMCal and DCal):

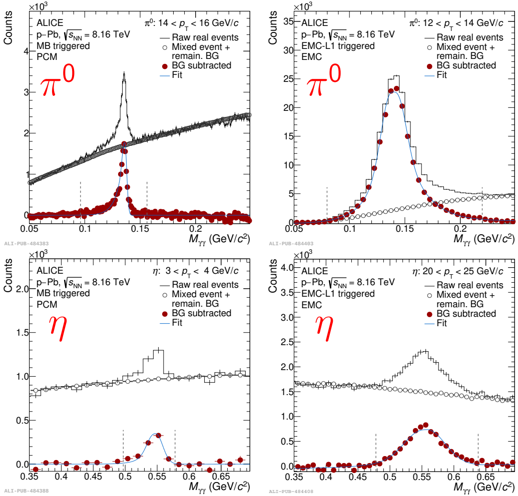
- Acceptance
  EMCal: $|\eta| < 0.7,\ 80^\circ < \varphi < 187^\circ$
  DCal: $0.22 < |\eta| < 0.7,\ 260^\circ < \varphi < 320^\circ$
  and $|\eta| < 0.7,\ 320^\circ < \varphi < 327^\circ$
- Shashlik Pb-scintillator calorimeter
- Designed for high-p_{T} photon and jet measurements

Photon Spectrometer (PHOS):

- Acceptance: $|\eta| < 0.13,\ 250^\circ < \varphi < 320^\circ$
- Homogeneous $PbWO_4$ calorimeter
- High momentum resolution compared to EMCal, but low momentum resolution compared to PCM



π^0 and/or η meson measurement with ALICE



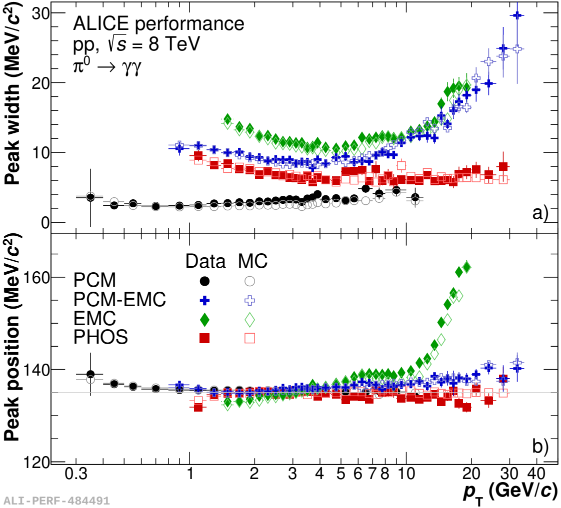
arXiv:2104:03116

- Neutral mesons are reconstructed by their two-photon invariant mass

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma1}E_{\gamma2}\left(1 - \cos(\Theta_{1,2})\right)}$$

- Event mixing used to estimate combinatorial background
- Additional linear function used to subtract residual background
- Signal parametrization by Gaussian with an exponential tail
- Raw yield obtained by bin counting within fixed mass window around peak after background subtraction

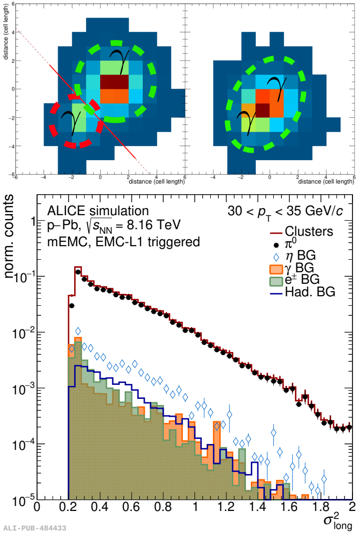
Signal properties of π^0 meson measurement with ALICE



arXiv:2104:03116

- Peak properties well described in MC
- PCM has high resolution (small peak width), but is limited in p_T reach
- π^0 EMCal extraction up to 20 GeV/c
- Peak position for EMCal increases at high p_T
  - Artifact of opening angle cut (needed due to merging clusters)
- PHOS has worse resolution than PCM but enables π^0 extraction up to 30 GeV/c

π^0 meson measurement with merged EMCal clusters with ALICE



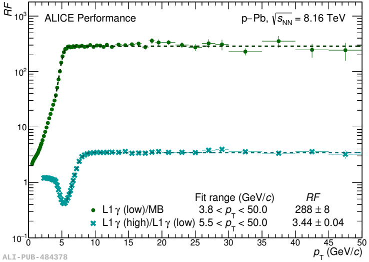
arXiv:2104:03116

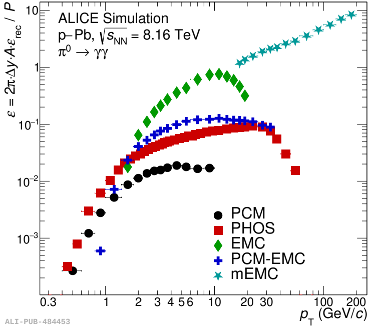
- Opening angle of photons coming from a meson is decreasing with increasing p_T
  - Two photons are reconstructed as a single cluster
  - Discriminate π^0 and γ through elongation of cluster
  - Reject photon clusters via cut on long axis of clusters ($\sigma^2_{long} < 0.2$)
- Merged EMCal (mEMC) analysis is purity based (purity > 80 %)
  - Purity corrections have to be applied
- First measurement with EMCal clusters above 50 GeV

Corrections

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

- $\mathcal{L}_{int}$: Integrated luminosity including trigger rejection factor (RF)
  - EMCal gamma trigger enhancements: $RF_{L1\ (low)} \approx 288$ and $RF_{L1\ (high)} \approx 990$
  - PHOS gamma trigger enhancements: $RF_{L0} \approx 1.66 \cdot 10^3$ and $RF_{L1} \approx 1.58 \cdot 10^4$
- P: Purity correction for mEMC
- $A\epsilon_{rec.}$: Acceptance and reconstruction efficiency
- $F_{\text{pile-up}}$: Out of bunch pileup correction for PCM
- $N^{\pi^0}_{sec.}$: Secondary π^0 from K^0_S, K^0_L, Λ from cocktail simulation





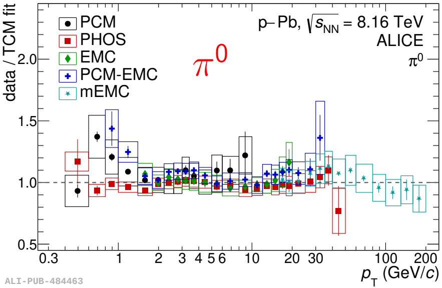
arXiv:2104:03116

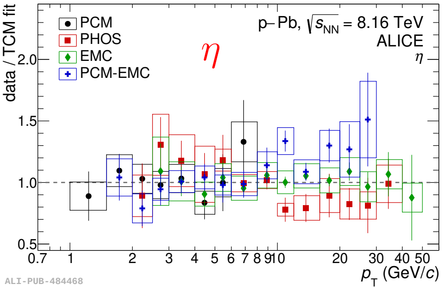
Comparison of different measurements

- Two-component model (TCM) fit:

$$E\frac{d^3\sigma}{dp^3} = A_e \exp(-E_{T,\,kin}/T_e) + A\left(1\frac{p_T^2}{T^2 n}\right)^{-n}$$

- Good agreement of all individual measurements above 2 GeV/c for π^0 and over full p_T range for η
- Slight tensions at low p_T for π^0 within 2σ of uncertainties
- Dominating systematic uncertainties:
  - Signal extraction, material uncertainties, shower overlap and π^0 energy resolution





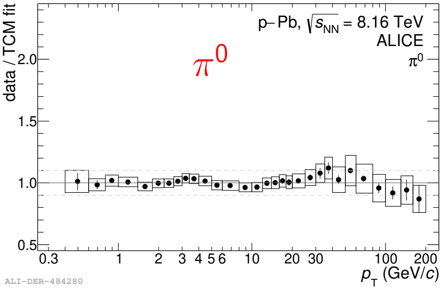
arXiv:2104:03116

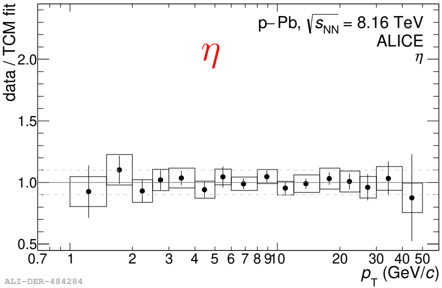
Combination of different measurements

- Two-component model (TCM) fit:

$$E\frac{d^3\sigma}{dp^3} = A_e \exp(-E_{T,\,kin}/T_e) + A\left(1\frac{p_T^2}{T^2 n}\right)^{-n}$$

- Good agreement of all individual measurements above 2 GeV/c for π^0 and over full p_T range for η
- Slight tensions at low p_T for π^0 within 2σ of uncertainties
- Dominating systematic uncertainties:
  - Signal extraction, material uncertainties, shower overlap and π^0 energy resolution
- Combination of spectra via best linear unbiased estimate (BLUE) method
  - Takes into account statistical and systematic uncertainties of respective methods and their correlations
- p_T reach π^0: $0.4 < p_T < 200$ GeV/c
- p_T reach η: $1.0 < p_T < 50$ GeV/c





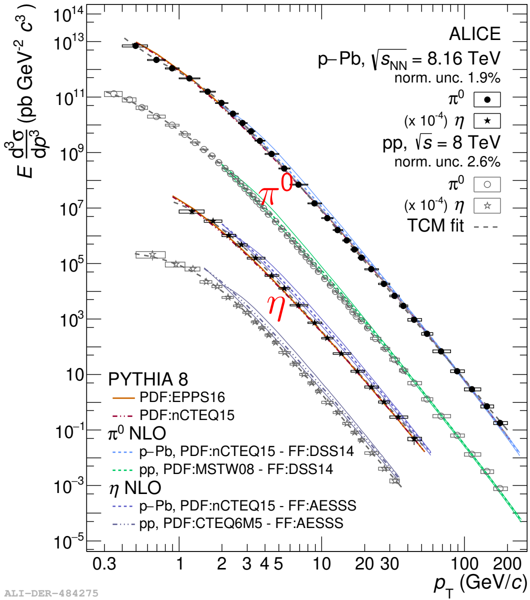
arXiv:2104:03116

Invariant cross section

Invariant cross sections in p–Pb $\sqrt{s_{NN}} = 8.16$ TeV

- Reference pp measurement was extended from 35 GeV/c to 200 GeV/c (mEMC measurement)
- π^0 measurement has highest p_T reach of all identified particles so far

Thanks to Werner Vogelsang for providing NLO calculations

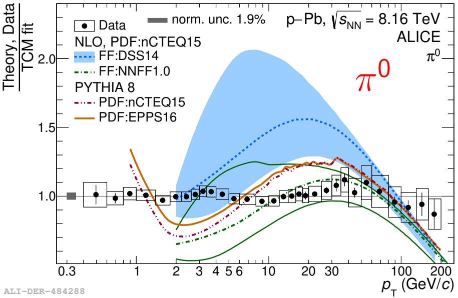


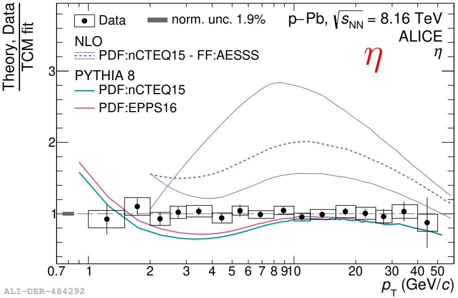
arXiv:2104:03116

Invariant cross section

Invariant cross sections in p–Pb $\sqrt{s_{\rm NN}} = 8.16$ TeV

- Reference pp measurement was extended from 35 GeV/c to 200 GeV/c (mEMC measurement)
- π^0 measurement has highest $p_{\rm T}$ reach of all identified particles so far
- NLO overestimates data
  - Fragmentation Functions (FF) need improvement
- PYTHIA 8 underestimates data for low $p_{\rm T}$ but is within uncertainties for η at high $p_{\rm T}$



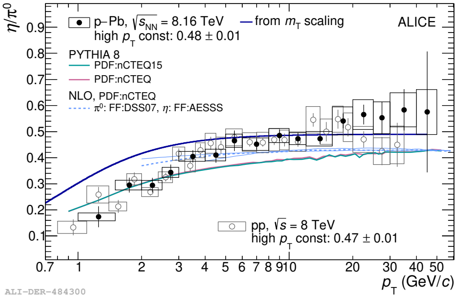


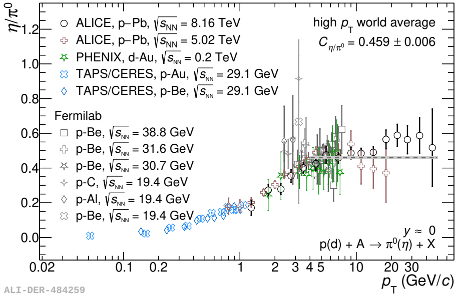
arXiv:2104:03116

η/π^0 ratio

- η/π^0 ratio measured up to 50 GeV/c
- Good agreement between pp $\sqrt{s} = 8$ TeV and p–Pb $\sqrt{s_{NN}} = 8.16$ TeV
- NLO Calculations agree within uncertainties between 3 and 8 GeV/c
- PYTHIA 8 tends to underestimate ratio by approximately 25% at high p_T, but agrees within uncertainties for low p_T

- Good agreement of η/π^0 ratio in p–Pb collisions with measurement in other pA collision systems
- World average high p_T constant fit value (0.459 ± 0.006) differs from measured value in p–Pb at $\sqrt{s_{NN}} = 8.16$ TeV (0.48 ± 0.01)



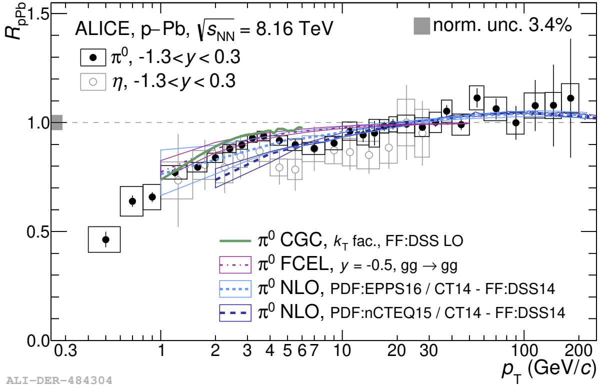


arXiv:2104:03116

Nuclear modification factor (R_{pA}) of π^0

$$R_{pA} = \frac{1}{A_{Pb}} \frac{d^2\sigma_{pPb}}{dp_T dy} \Big/ \frac{d^2\sigma_{pp}}{dp_T dy}$$

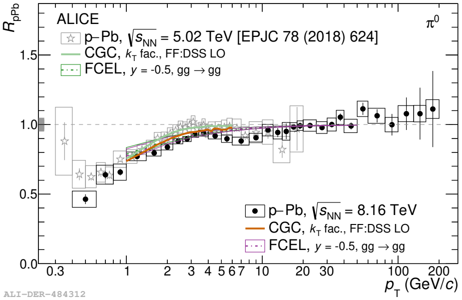
- pp $\sqrt{s} = 8$ TeV spectrum has to be scaled for center of mass energy (p–Pb $\sqrt{s_{NN}} = 8.16$ TeV) and rapidity, extracted from PYTHIA 8 simulation and NLO calculation
- Suppression at low p_T
- No suppression at high p_T
- R_{pA} for π^0 and η are in agreement
- R_{pA} in very good agreement with CGC, FCEL and NLO calculations

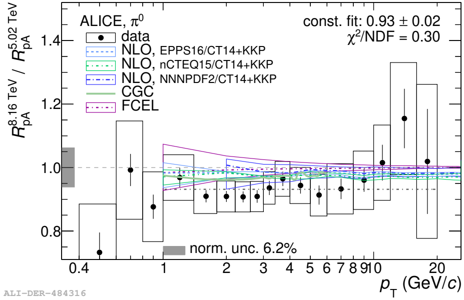


arXiv:2104:03116

$\sqrt{s_{NN}}$ - dependence of π^0 R_{pA}

- Increase of p_T range by an order of magnitude compared to previous π^0 R_{pA} measurements
- Suppression at low p_T is consistent with measurement at $\sqrt{s_{NN}} = 5.02$ TeV within uncertainties
  - Larger suppression than in $\sqrt{s_{NN}} = 5.02$ TeV
  - Constant fit of ratio gives value of 0.93 ± 0.02
  - Large normalization uncertainties of 6.2% due to interpolation of $\sqrt{s_{NN}} = 5.02$ TeV reference
- FCEL (energy loss) model and NLO calculations predict smaller difference, whereas CGC predicts $1\% - 5\%$ stronger suppression
  - Hint for onset of gluon saturation

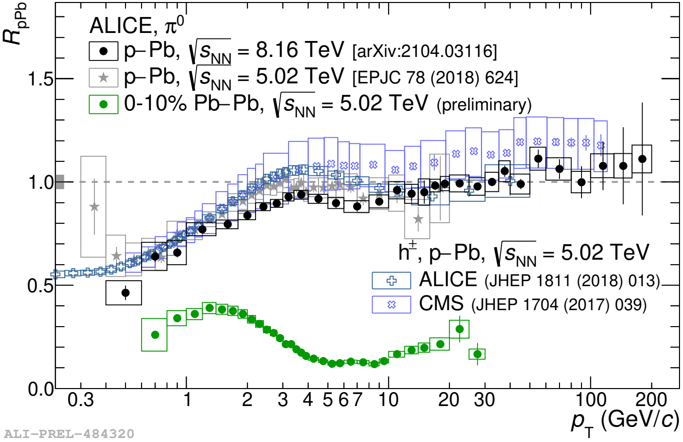




arXiv:2104:03116

R_{pA} - measurement comparisons

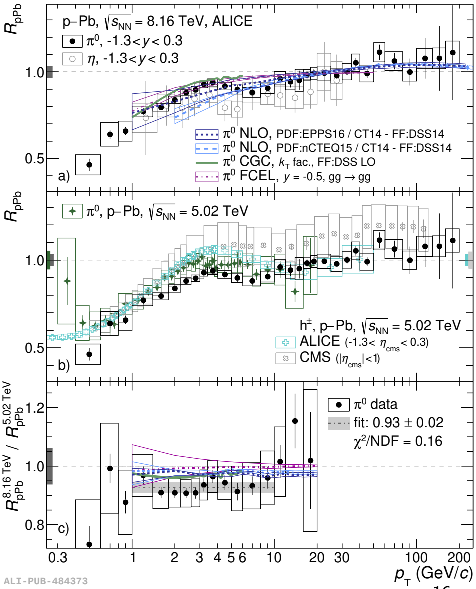
- p_T range exceeds all single charged particle measurements
- No modification at $p_T > 10\mathrm{GeV}/c$ can be stated
    - Negligible final state effects



arXiv:2104:03116

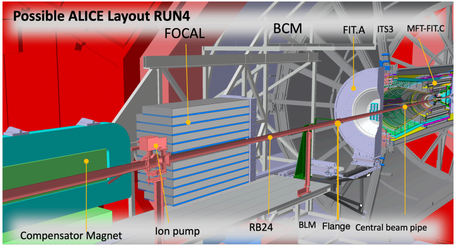
Summary

- Increase of p_T range of π^0 measurement by an order of magnitude
  - Driven by mEMC analysis
- η/π^0 ratio in agreement with other measurements
  - No system dependence observed
  - Strong constraints for $p_T > 20\,\mathrm{GeV}/c$ in p–A
- No modification for high p_T could be observed
- Provide constraints for nPDFs (arXiv:2105:09873)
- Hint for stronger low p_T suppression in R_{pA} in $\sqrt{s_{NN}} = 8.16\,\mathrm{TeV}$
  - Possible onset of saturation effects
  - Possible larger shadowing in nPDFs
- Read more in arXiv:2104:03116

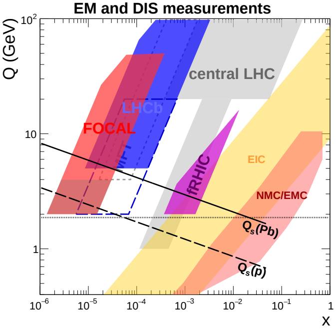


Outlook - The ALICE Forward Calorimeter

- Forward calorimeter, rapidity coverage: $3.4 < \eta < 5.8$
  - FoCal-E: High-granularity Si-W sampling sandwich calorimeter for photons and π^0
  - FoCal-H: Metal-scintillator sampling calorimeter for photon isolation and jets



Letter-of-Intent: CERN-LHCC-2020-009

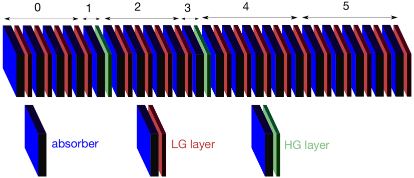


- Goal: Measure forward photon production to probe small-x gluons in the nucleus

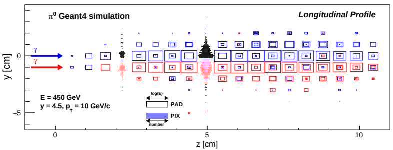
- Full physics program:
  - π^0 (neutral mesons) in pp, p-Pb, Pb-Pb
  - Isolated (direct) photons
  - Jets (and di-jets)
  - J/Ψ (Υ) in UPC

Outlook - FoCal-E conceptual design

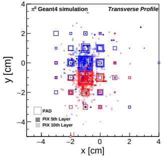
- Main challenge: Two photon separation from π^0 decay
  - Need granularity $\sim 1\,\text{mm}^2$
  - Implementation:
    - Pad layers with $1\text{x}1\,\text{cm}^2$
    - High-granularity readout with 2 pixel layers with $30\text{x}30\,\mu\text{m}^2$

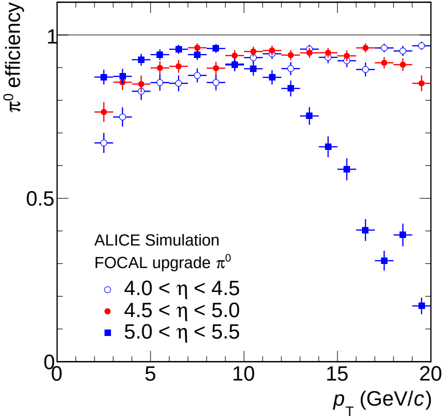


Longitudinal profile (2γ showers)



Trans. profile

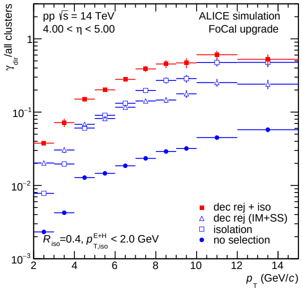




Letter-of-Intent: CERN-LHCC-2020-009

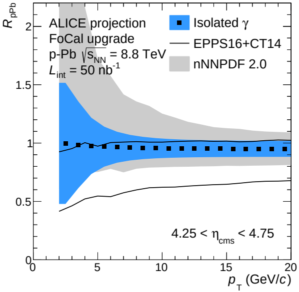
Outlook - Expected performance and impact on nPDF

Direct γ/all cluster ratio



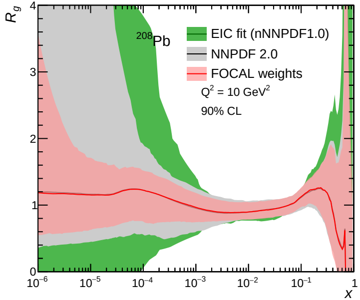
- Decay rejection cut and isolation cut suppressed the decay photon background

Projected uncertainty on R_{pA}



- Significant improvement (up to factor 2) on EPPS16, nNNDF 2.0 uncertainties

Reweighted nuclear PDFs



nNNPDF 2.0 from DIS + LHC
(minimal theoretical assumptions)

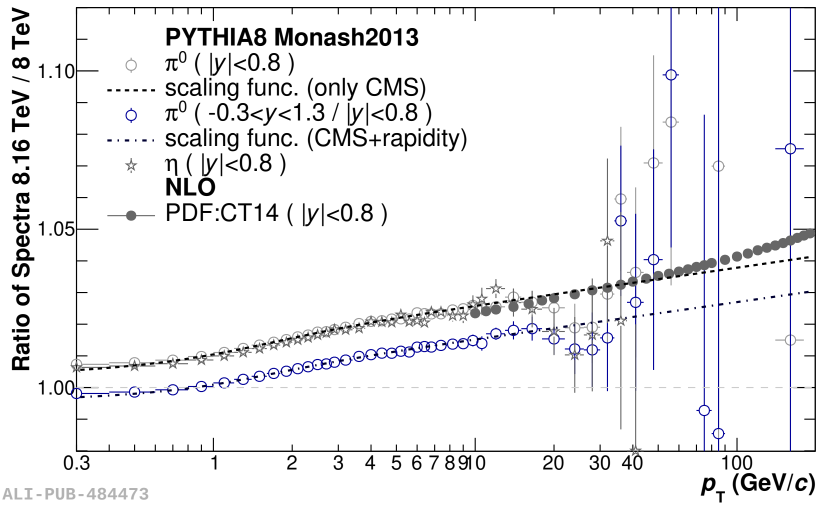
- No constraints for $x < 10^{-2}$ from DIS
- FOCAL adds constraints over a broad range: 10^{-5}-10^{-2} at small Q^2

Letter-of-Intent: CERN-LHCC-2020-009

The End

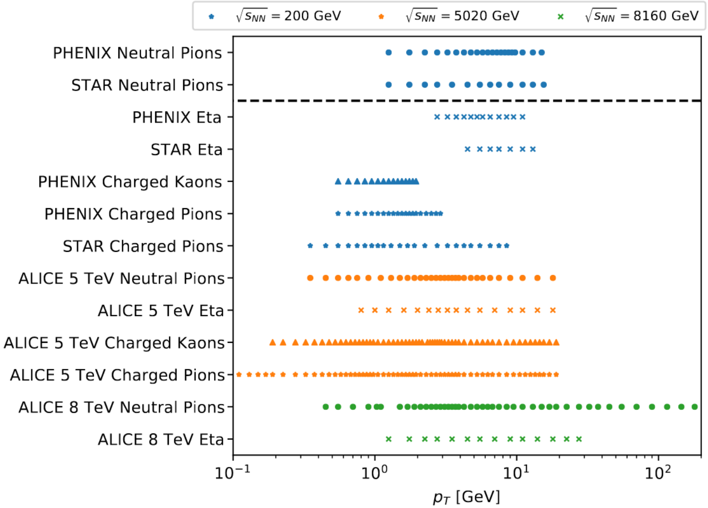
Thank you for your attention!

Backup



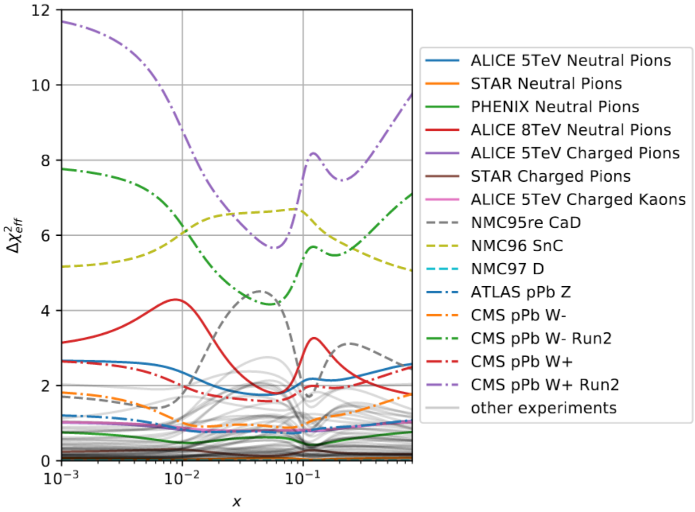
arXiv:2104:03116

Backup



arXiv:2105.09873

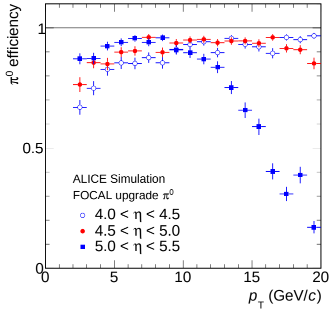
Backup



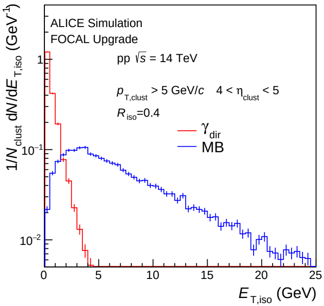
arXiv:2105.09873

Backup - Key ingredients for isolated photon measurement

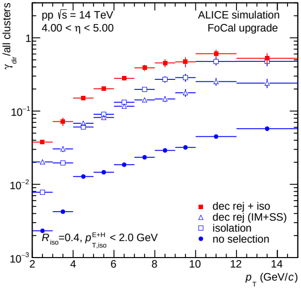
π^0 reconstruction efficiency



Isolation energy distribution



Direct γ/all cluster ratio



Main ingredients for direct photon identification

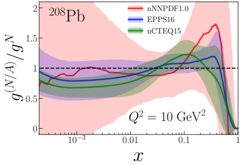
- π^0 reconstruction efficiency: measure background
- Rejection of decays by invariant mass reconstruction
- Isolation cut (EmCal + HCal)

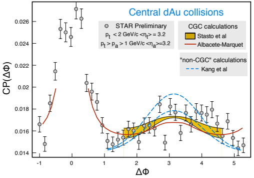
Improvement in signal fraction by factor $\sim$ 10 to $\sim$ 0.1-0.6

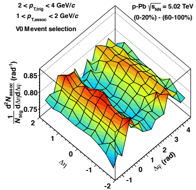
Letter-of-Intent: CERN-LHCC-2020-009

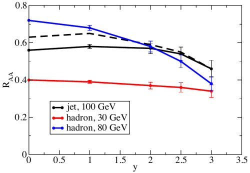
Backup - Physics programme

- Quantify nuclear modification of the gluon density at small-x
  - Isolated photons in pp and pPb collisions
- Explore non-linear QCD evolution
  - Azimuthal π^0-π^0 and isolated photon-π^0 (or jet) correlations in pp and pPb collisions
- Jet quenching at forward rapidity
  - Measure high p_T neutral pion production in PbPb
- Other measurements
  - Jets and dijets in pp/pPb and UPC
  - Quarkonia in UPC (and pp)
  - Photon and pion HBT
  - W,Z in pp/pPb?
  - Isolated photons in PbPb
  - Measurements at 14 TeV
    - Universality at small-x
    - Saturation in pp
    - High-x (>0.1) gluon constraints









Letter-of-Intent: CERN-LHCC-2020-009