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Probing the initial state of nuclear collisions using isolated prompt photons with ALICE

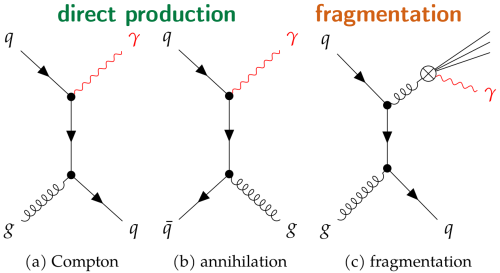
Florian Jonas for the ALICE collaboration

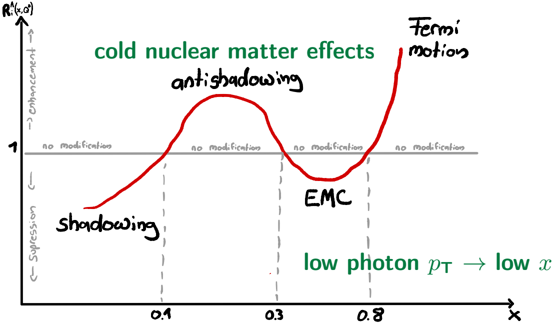
Hard Probes Conference 2023

- prompt photons are produced in the hard scattering via two mechanisms:
  1. **direct production** (Compton scattering, annihilation, ...) → direct access to incoming parton (e.g. gluon)
  2. **fragmentation** of outgoing parton → relationship to incoming parton complicated by frag. function
- photons don't interact strongly in final state

Key motivation of measurement:

- test pQCD description of prompt photon production at NLO
- provide experimental constraints for low-x gluon (nuclear) PDFs
- quantify cold nuclear matter effects (e.g. gluon shadowing)





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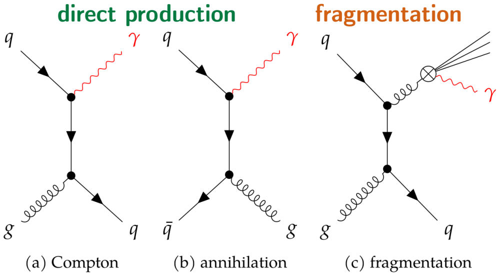


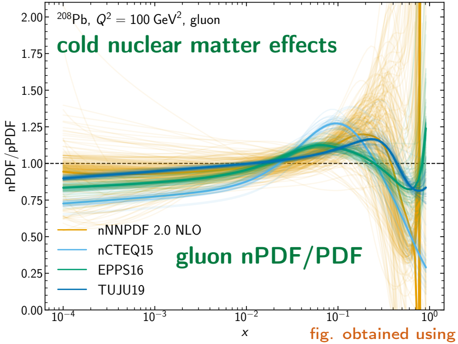
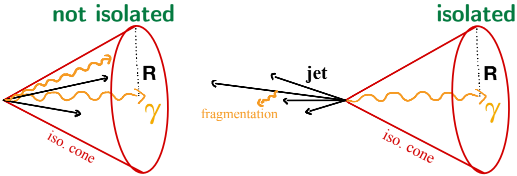


fig. obtained using LHAPDF6

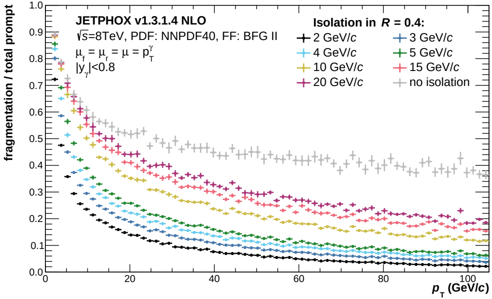
Isolation: Role for experiment and theory

Problem:

1. **(theory & exp)** fragmentation prompt photons increase complexity of calculation & relation with initial state
2. **(exp)** most photons produced are decay photons (low S/B ratio)



suppression of frag. contribution



for more information see also JHEP 05 (2002) 028

Solution: Isolation

- isolation = applying a restriction on activity in vicinity of photon
- fixed-cone isolation: study $p_T^{iso} = \sum p_T$ in radius $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$ around photon and cut
- smooth-cone isolation (Frixione): reject more activity the closer one gets to photon

→ **suppresses fragmentation due to collinear fragmentation**
→ **suppresses decay photons (often come with other particles from hadronization)**

EMCal= ElectroMagnetic Calorimeter, DCal = DijetCalorimeter, TPC = Time Projection Chamber, ITS = Inner Tracking System

In this talk:

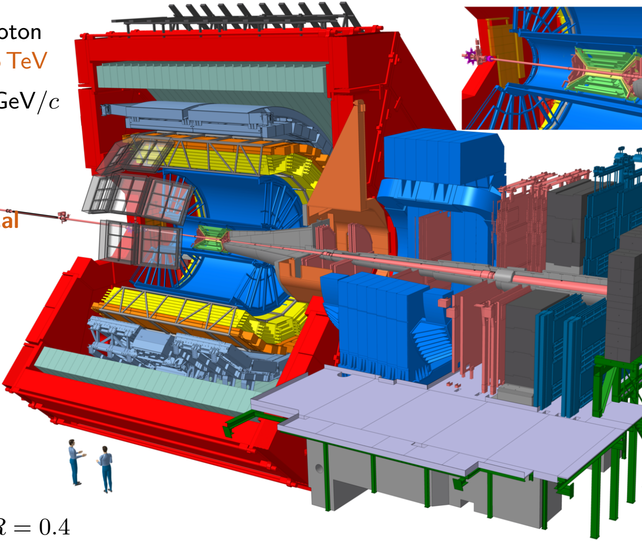
- **new preliminary results** on isolated prompt photon production in **p–Pb collisions at** $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV
- first isolated prompt photon R_{pA} for $p_{\mathrm{T}} < 20$ GeV/c

Measurement of photons:

- measurement of EM showers in **EMCal and DCal**
- **coverage:** $|\eta| < 0.68$ & $|\eta_{\mathrm{DCal}}| > 0.23$, $\Delta\varphi_{\mathrm{EMCal}} = 107°$, $\Delta\varphi_{\mathrm{DCal}} = 67°$
- photon identification using track matching and shower shape

Measurement of isolation:

- charged tracks measured in **ITS and TPC**
- **coverage:** $|\eta| < 0.9$ over full azimuth angle
- **isolation requirement:** $p_{\mathrm{T}}^{\mathrm{iso,\,ch}} < 1.5$ GeV/c in $R = 0.4$
- underlying event subtraction using perpendicular cones



ALICE figure 11219

Measuring isolated prompt photon production with ALICE

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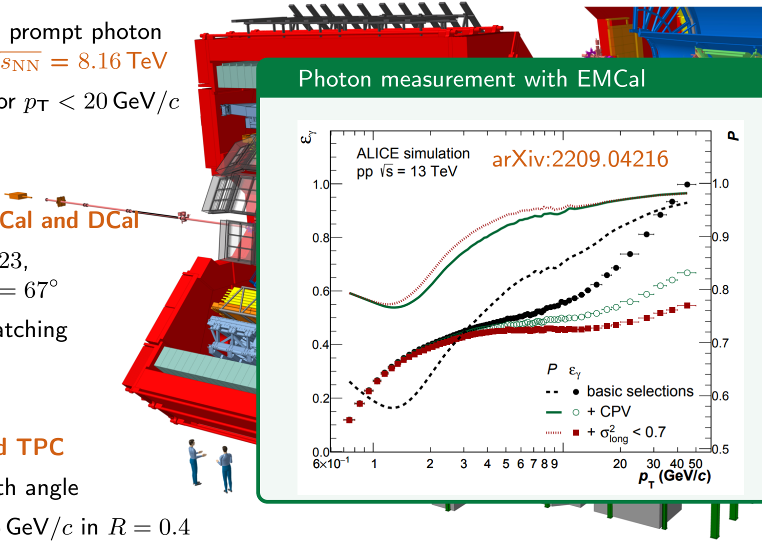
Photon measurement with EMCal



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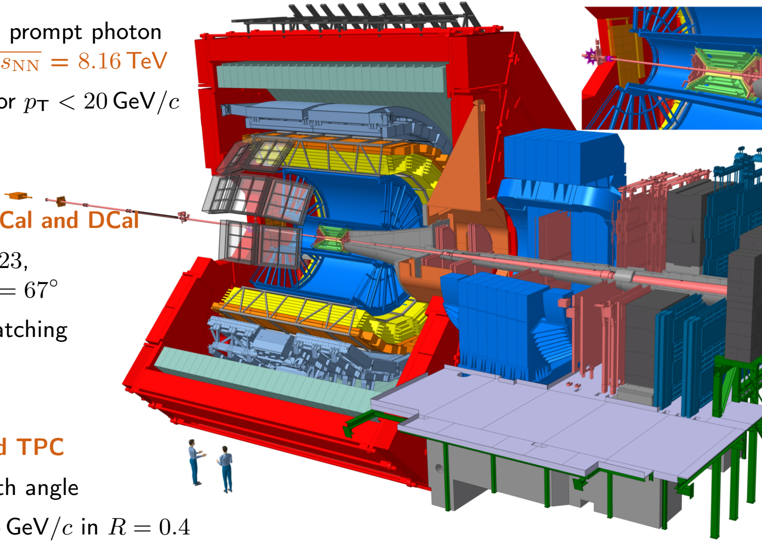

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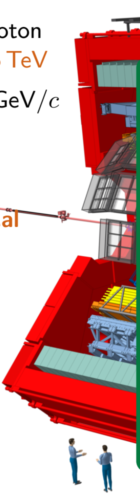
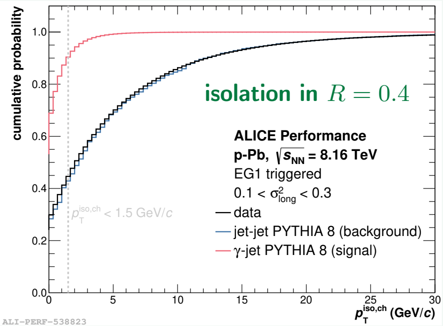


Impact of isolation

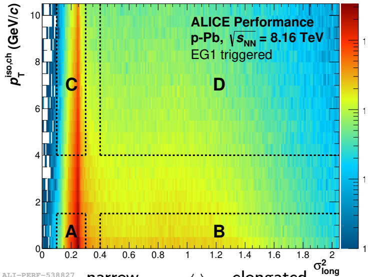


ALICE figure 11219

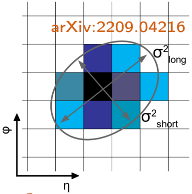
ABCD method (default)

- idea: σ^2_{long} - isolation plane of clusters divided into 4 regions $\rightarrow$ three background dominated regions are used to estimate background contribution in signal region
- data-driven approach; only requires PYTHIA for corrections of correlations between σ^2_{long} and iso. energy

$$P = \left(\frac{C/A}{D/B}\right)_{\text{data}} \times \left(\frac{A/C}{B/D}\right)_{\text{PYTHIA}}$$



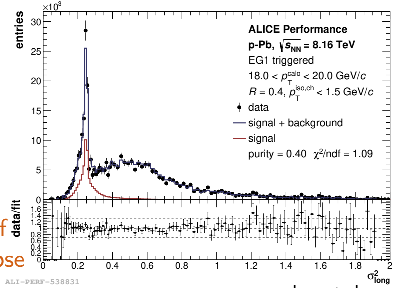
narrow ↔ elongated



σ^2_{long} = long axis of shower shape ellipse

Template fit (cross-check)

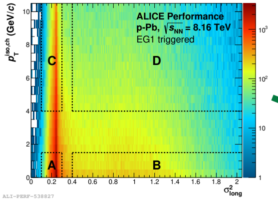
- a template fit to the σ^2_{long} distribution is used to obtain purity
  - data: iso. photons from data
  - signal: iso. prompt + frag photons from γ-jet PYTHIA processes
  - background: anti-isolated photons from data
- correlation weights for background temp. obtained from jet-jet PYTHIA processes



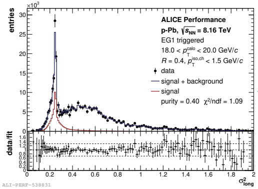
narrow ↔ elongated

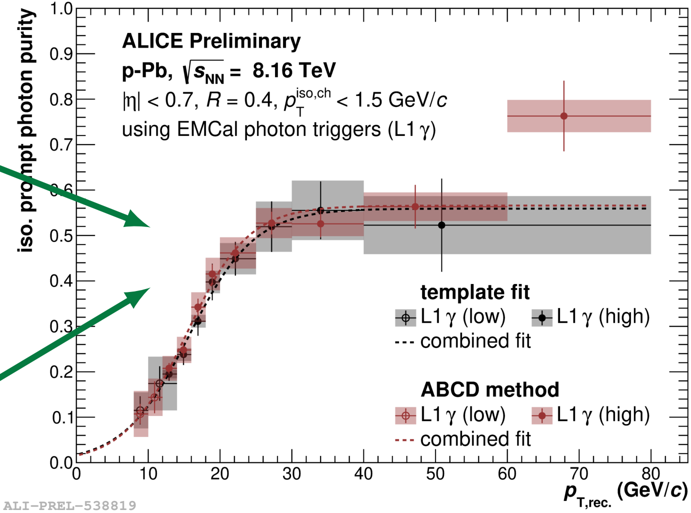
Purity determination

ABCD method



Template fit



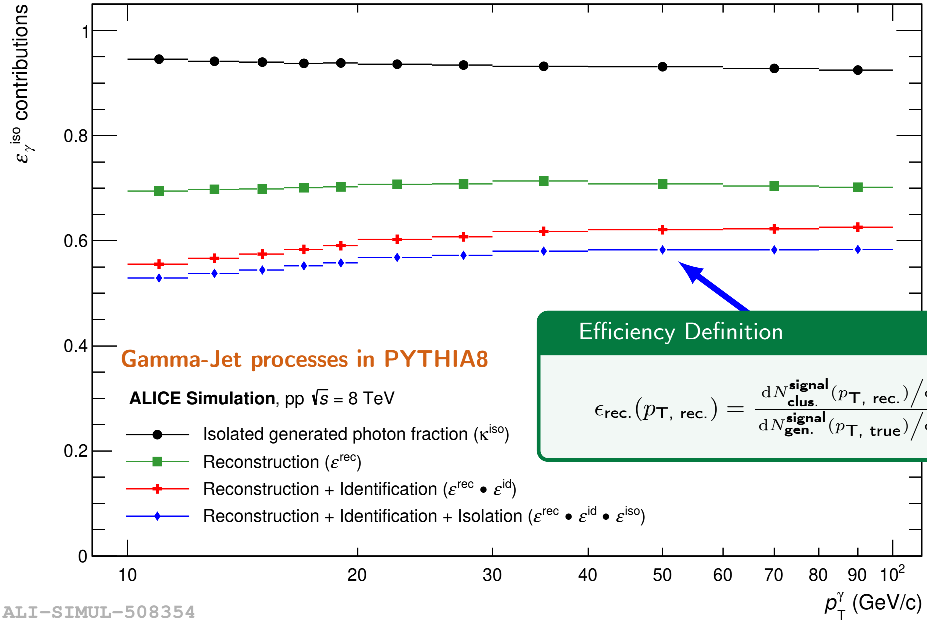


- both **data-driven purity** methods show good agreement with each other
- signal purity reaches up to $60\,\%$ for $p_T > 30\,\mathrm{GeV}/c$

$E_{trig}^{low} > 5.5$ GeV

$E_{trig}^{high} > 8.0$ GeV

Efficiency



Efficiency Definition

$$\epsilon_{\text{rec.}}(p_{\text{T, rec.}}) = \frac{\mathrm{d}N^{\text{signal}}_{\text{clus.}}(p_{\text{T, rec.}}) / \mathrm{d}p_{\text{T, rec.}}}{\mathrm{d}N^{\text{signal}}_{\text{gen.}}(p_{\text{T, true}}) / \mathrm{d}p_{\text{T, true}}}$$

Iso. photons in pp and p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with ALICE

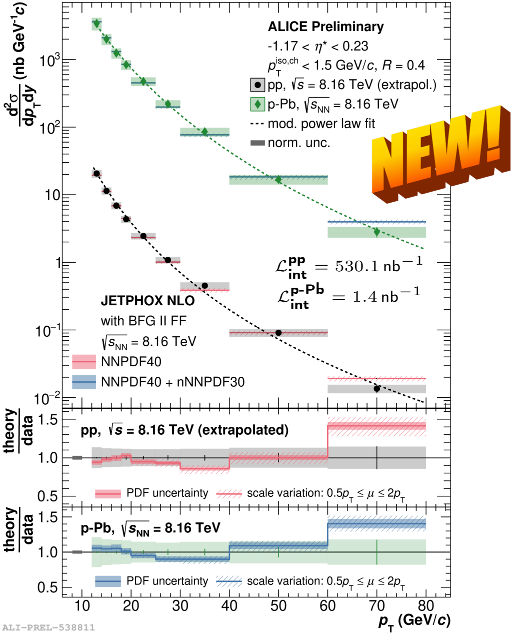
$$\frac{\mathrm{d}^2\sigma^\gamma}{\mathrm{d}p_\mathrm{T}^\gamma\,\mathrm{d}y} = \frac{1}{\mathcal{L}_\mathrm{int}} \cdot \frac{\mathrm{d}^2 N_\mathrm{n}^\mathrm{iso}}{\mathrm{d}p_\mathrm{T}^\gamma\,\mathrm{d}y} \cdot \frac{P}{\epsilon \cdot A}$$

Measurement:

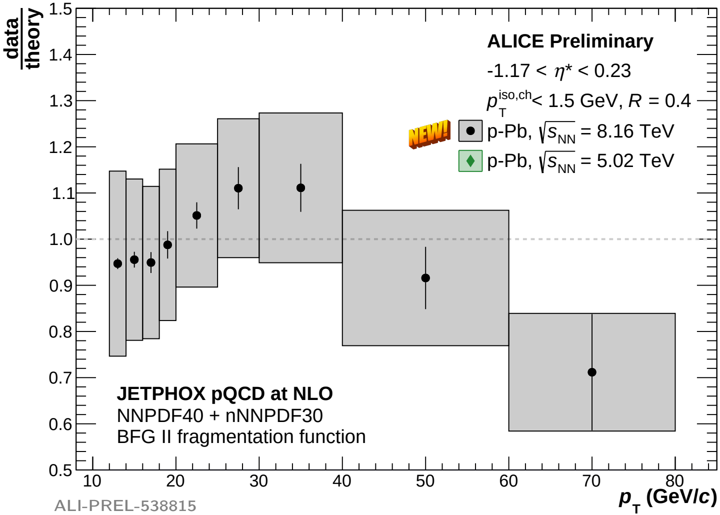
- ALICE measured the isolated prompt photon production cross section in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$, as well as corresponding pp reference cross section
- **isolation:** $p_\mathrm{T}^\mathrm{iso,ch} < 1.5\,\mathrm{GeV}/c$ in cone of $R = 0.4$
- **coverage:** $12 < p_\mathrm{T} < 80\,\mathrm{GeV}/c$ and $|\eta^\mathrm{lab}| < 0.7$
- systematic uncertainties less than $22\,\%$ for covered momentum range

Comparison to theory:

- production cross sections in both systems **consistent with NLO calculations** using recent (n)PDFs and FF



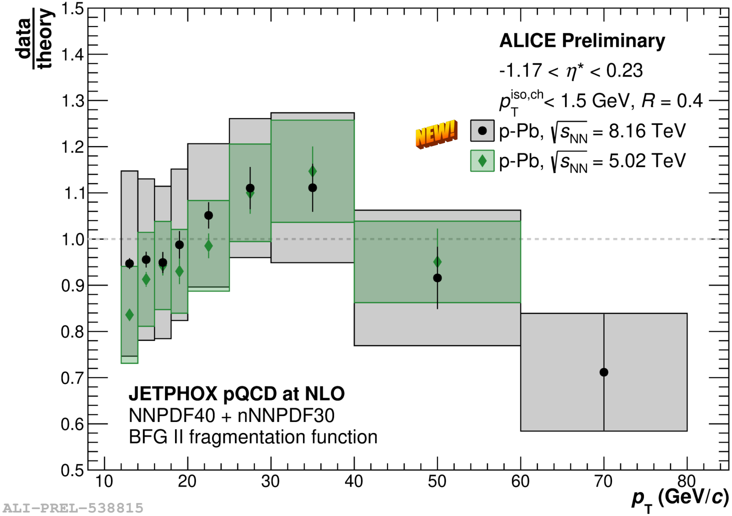
Comparison to p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



- agreement with pQCD at NLO consistent with preliminary ALICE results in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (ALI-PREL-22280)

(shown at Quark Matter 2022)

Comparison to p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



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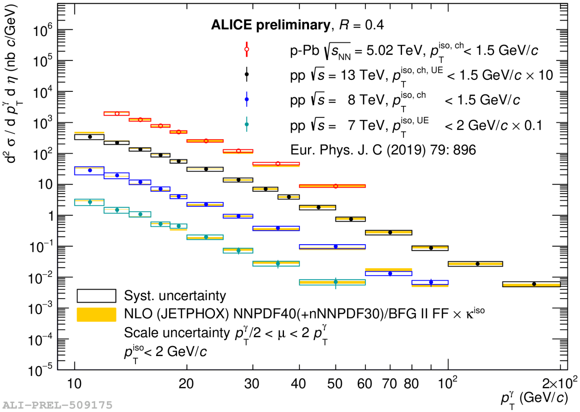
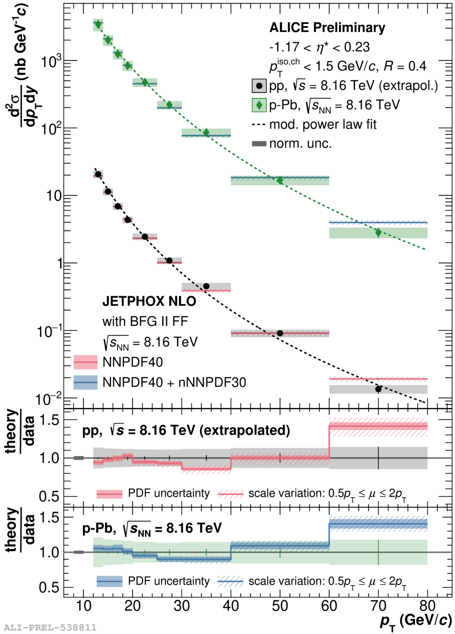
Overview of ALICE measurements





- ALICE has measured iso. prompt photon production in pp collisions at $\sqrt{s} = 7$, 8 and 13 TeV and in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and 8.16 TeV

stay tuned for our upcoming publications!

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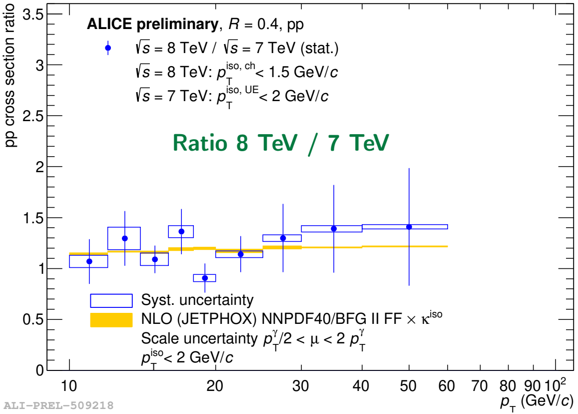

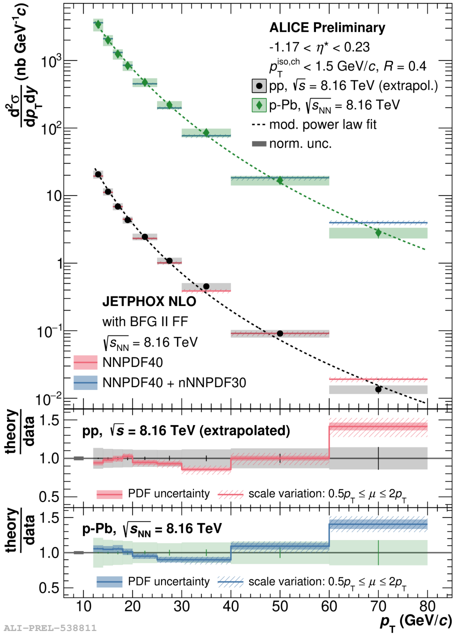

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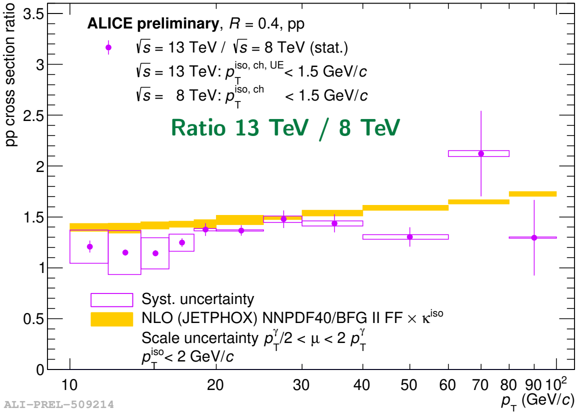

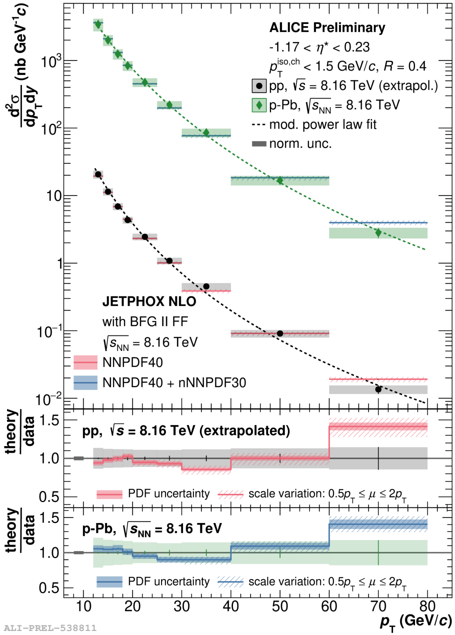

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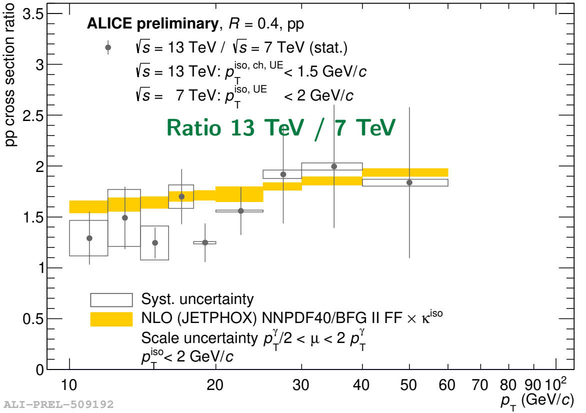

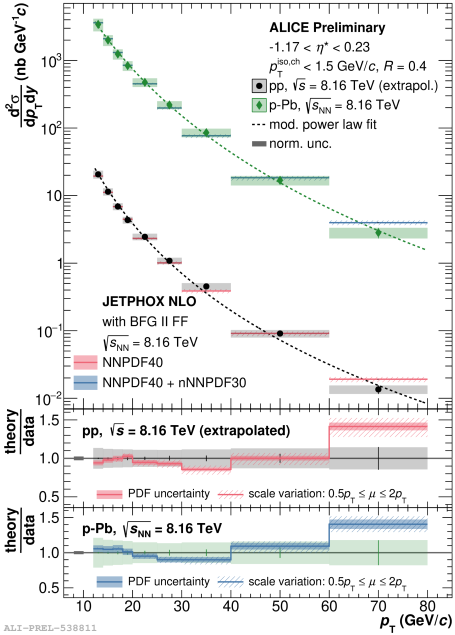

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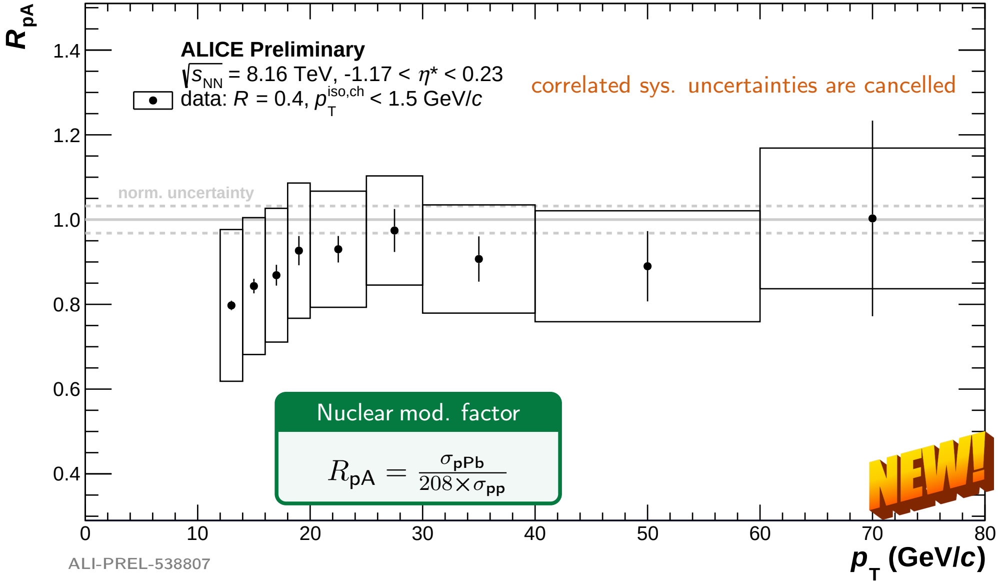
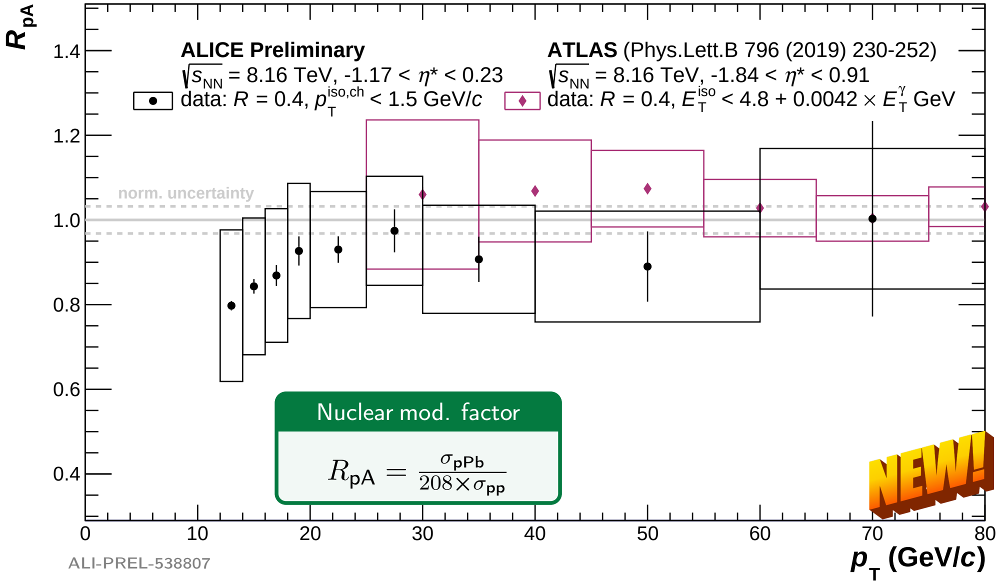
Nuclear modification factor of iso. prompt photon production



Nuclear mod. factor

$$R_{pA} = \frac{\sigma_{pPb}}{208 \times \sigma_{pp}}$$

→ hints of suppression at low-p_T; presence of CNM effects? → not (yet) significant within exp. unc.



Nuclear mod. factor

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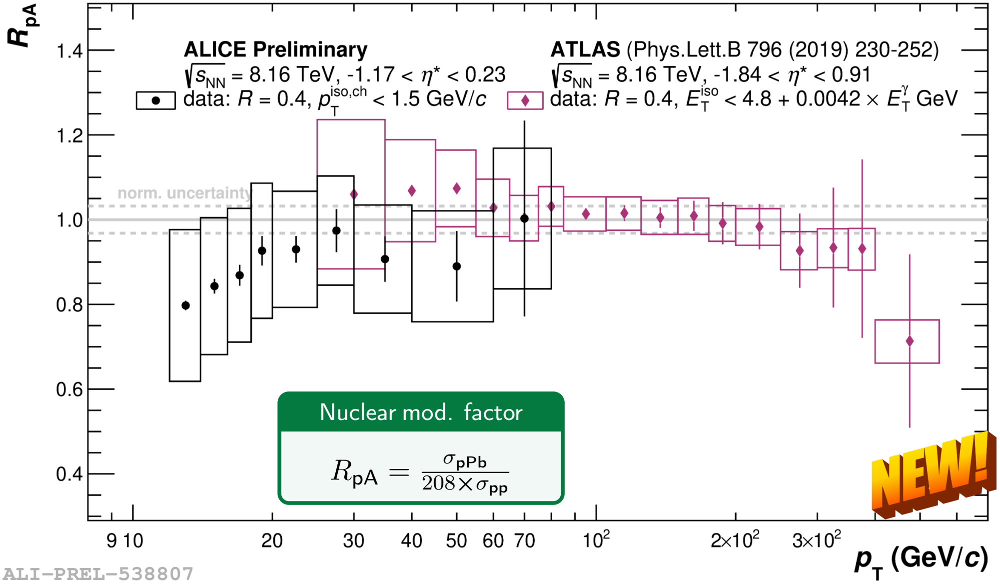
→ no suppression at high-p_T, in agreement with ATLAS measurement

Nuclear modification factor of iso. prompt photon production



Nuclear mod. factor

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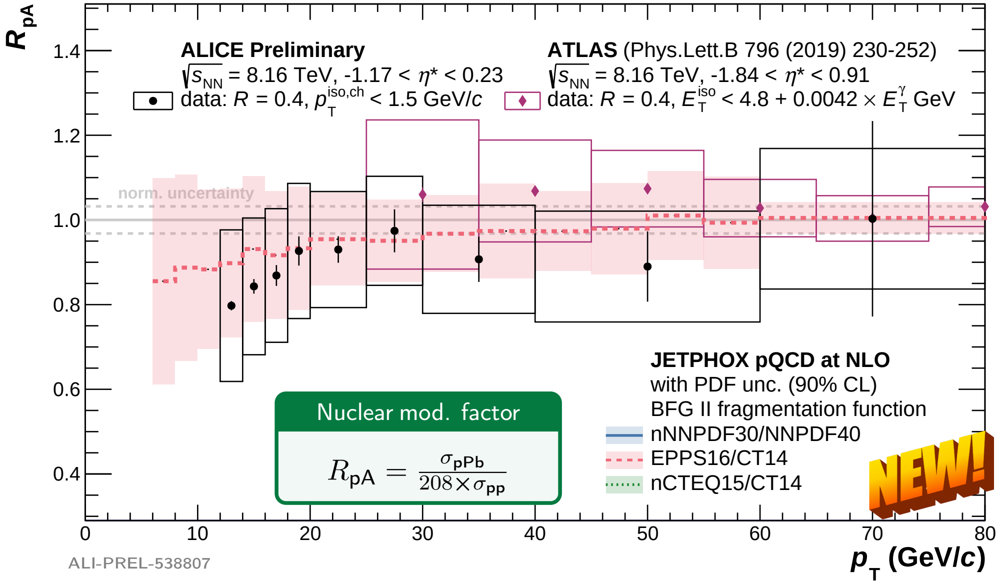
→ ALICE complements ATLAS measurement at low-p_T



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→ "suppression" of comparable size as predicted by **nPDFs including gluon shadowing**

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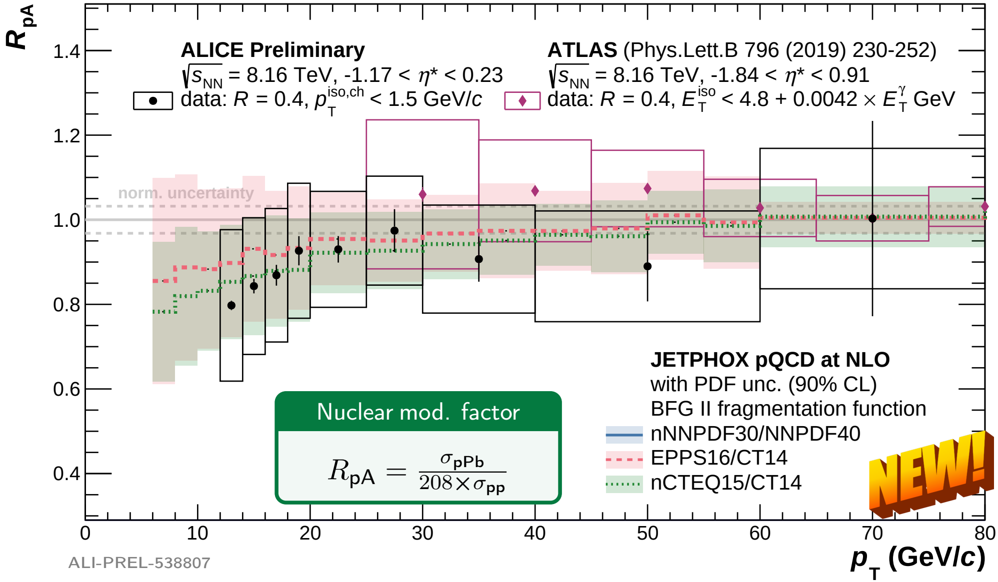

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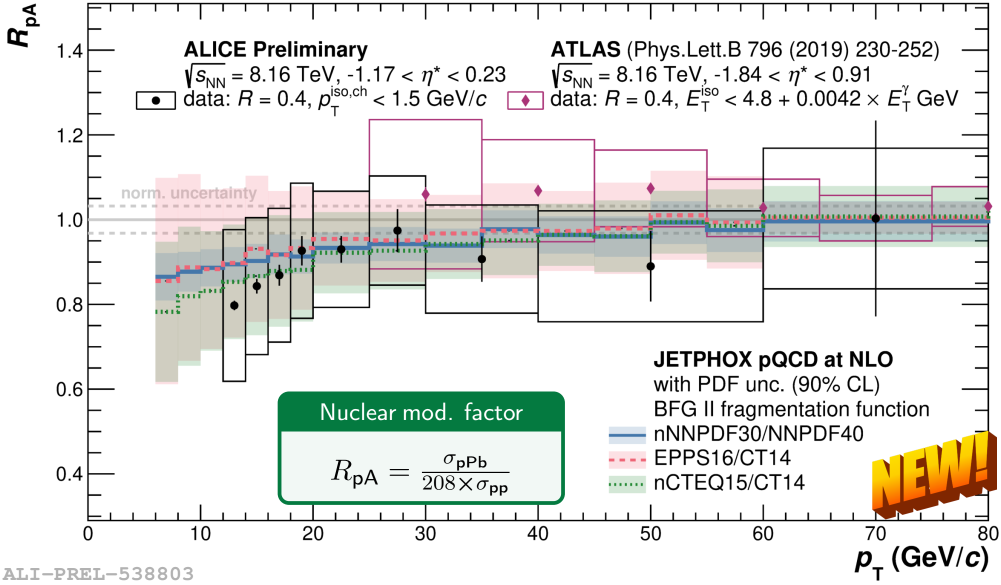

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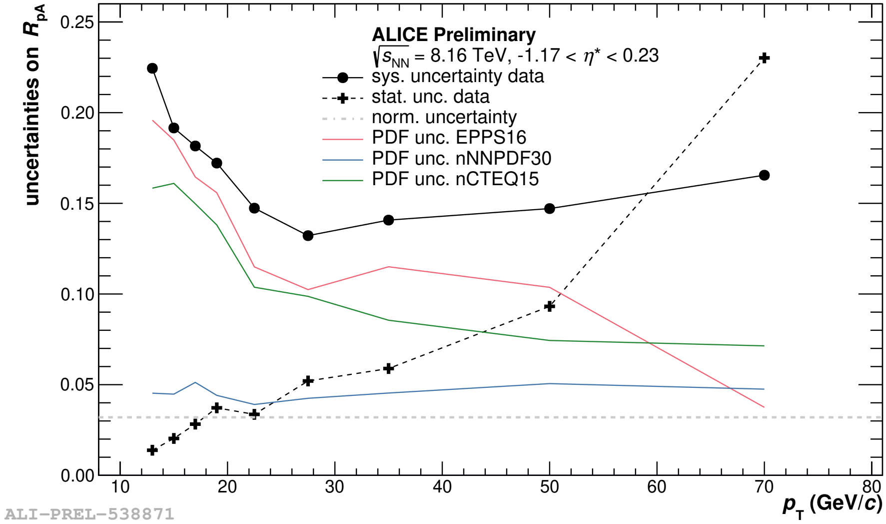
Overview of experimental and theoretical uncertainties



- experimental uncertainties are dominated by purity determination at low-p_T
- further reduction of uncertainties could further improve constraining power of measurement

Summary & Outlook

Summary:

- fully corrected isolated prompt photon production cross section in **p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV** measured by ALICE presented for the first time
- comparison of cross sections to **NLO calculations** using recent (n)PDFs and BFGII frag. function indicates **good agreement**
- **nuclear modification factor** R_{pA} measured for the **first time for** $p_{\mathrm{T}} < 20$ GeV$/c$:
  - compatible with ATLAS measurement at high-p_{T}
  - extends coverage to $p_{\mathrm{T}} = 12$ GeV$/c$
  - **hints of suppression** for $p_{\mathrm{T}} \lesssim 20$ GeV$/c$ compatible with nPDFs
  - suppression not (yet) significant within experimental uncertainties

Outlook:

- many ALICE publications are on the way for pp collisions at $\sqrt{s} = 8$ and 13 TeV as well as p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and 8.16 TeV
- ALICE is planning to install a **Forward Calorimeter (FoCal)** for LHC Run 4!
  - allows for iso. prompt photon measurements at $3.4 < \eta < 5.8$
  - exciting prospects to **explore gluon saturation** at low Bjorken-x!

→ link to FoCal LoI

→ Talk by Tatsuya Chujo TODAY at 15:20!

isolated prompt photons are an exciting probe to study gluons in the initial stage of nuclear collisions

Backup

Electromagnetic Calorimeter (EMCal) details

arXiv:2209.04216

Table 4: EMCal module physical parameters.

Parameter	Value
Tower Size (on front face)	$6.0 \times 6.0 \times 24.6$ cm^3
Tower Size (at η=0)	$\Delta\eta \times \Delta\varphi \simeq 0.0143 \times 0.0143$
Sampling Ratio	1.44 mm Pb / 1.76 mm Scint.
Layers	77
Scintillator	Polystyrene (BASF143E + 1.5%pTP + 0.04%POPOP)
Absorber	natural lead
Effective radiation length X_0	12.3 mm
Effective Molière radius R_M	3.20 cm
Effective Density	5.68 g/cm^3
Sampling Fraction	1/10.5
No. of radiation lengths	20.1

Table 5: EMCal FEE main characteristics.

Parameter	Value
High gain range	15.3 MeV to 15.6 GeV
Low gain range	248 MeV to 250 GeV
Time integration window	1.5 μs
ALTRO sampling rate	10 MHz
Light yield at APD	$\approx$ 4.4 photoelectrons/MeV
APD gain	$\approx$ 30
Shaping time	$\approx$ 235 ns

Analysis cuts

Cluster selection

- V1 clusterizer (S500A100)
- $0.1 \leq \sigma^2_{\text{long}} \leq 0.3$
- full cross talk emulation in MC
- timing: $-30\,\text{ns} \leq t_{\text{clus.}} \leq 35\,\text{ns}$
- track matching in η and φ p_{T}-dependent + E/P
- $E_{\text{clus.}} > 0.7$

Charged Isolation

- isolation using global hybrid tracks + generic track quality cuts
- cone radius: $R = 0.4$
- $p_{\text{T}}^{\text{iso.}} < 1.5\,\text{GeV}$
- Anti-isolation: $4\,\text{GeV} \leq p_{\text{T}}^{\text{iso.}} \leq 10\,\text{GeV}$

Kinematic variables

Mandelstam invariant s

$$\sqrt{s} = \sqrt{(p_1 + p_2)^2} = \sqrt{(p_3 + p_4)^2} \tag{1}$$

Coverage x:

$$\sqrt{s_{12}} = x_1 x_2 \sqrt{s} \tag{2}$$

$$x_1 = \frac{p_T}{\sqrt{s}}(\exp(\eta_3) + \exp(\eta_4)) \tag{3}$$

$$x_2 = \frac{p_T}{\sqrt{s}}(\exp(-\eta_3) + \exp(-\eta_4)) \tag{4}$$

$$x \approx \frac{2p_T}{\sqrt{s}} \exp(-\eta) \tag{5}$$

$$x = \frac{Q^2}{2p_2 \cdot q} \tag{6}$$

$$Q^2 = -q^2 \tag{7}$$

ABCD method

Yield of isolated photon candidates is:

$$N_n^{\text{iso}} = S_n^{\text{iso}} + B_n^{\text{iso}} \tag{8}$$

Contamination is:

$$C = B_n^{\text{iso}} / N_n^{\text{iso}} \tag{9}$$

Purity is:

$$P = 1 - C = 1 - B_n^{\text{iso}} / N_n^{\text{iso}} \tag{10}$$

Assumption 1: Proportions stay the same:

$$B_n^{\text{iso}} / B_n^{\overline{\text{iso}}} = B_w^{\text{iso}} / B_w^{\overline{\text{iso}}} \tag{11}$$

solve for B_n^{iso} and plug into purity

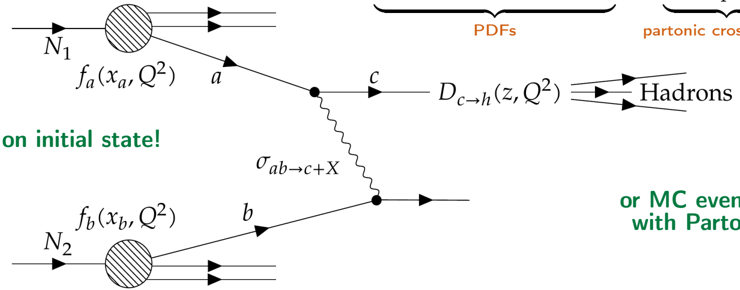
$$P = 1 - B_n^{\text{iso}} / N_n^{\text{iso}} = 1 - \frac{B_w^{\text{iso}} B_n^{\overline{\text{iso}}} / B_w^{\overline{\text{iso}}}}{N_n^{\text{iso}}} = 1 - \frac{B_n^{\overline{\text{iso}}} / N_n^{\text{iso}}}{B_w^{\overline{\text{iso}}} / B_w^{\text{iso}}} \tag{12}$$

Assumption that $B = N$ for background regions:

$$1 - \frac{N_n^{\overline{\text{iso}}} / N_n^{\text{iso}}}{N_w^{\overline{\text{iso}}} / N_w^{\text{iso}}} \tag{13}$$

Factorization: A recipe to describe hadron collisions

$$E\frac{d^3\sigma_{NN\rightarrow h}}{dp^3} = \sum_{a,b,c} \underbrace{f_a(x_a,\mu_f^2)\otimes f_b(x_b,\mu_f^2)}_{\text{PDFs}} \otimes \underbrace{\frac{d^3\sigma_{ab\rightarrow c+X}}{d\hat{p}^3}}_{\text{partonic cross section}} \otimes \underbrace{D_{c\rightarrow h}(z,\mu_f^2)}_{\text{fragmentation}}$$



Focus today on initial state!

or MC event generator with Parton Showers

Solution: the problem can be factorized into three components

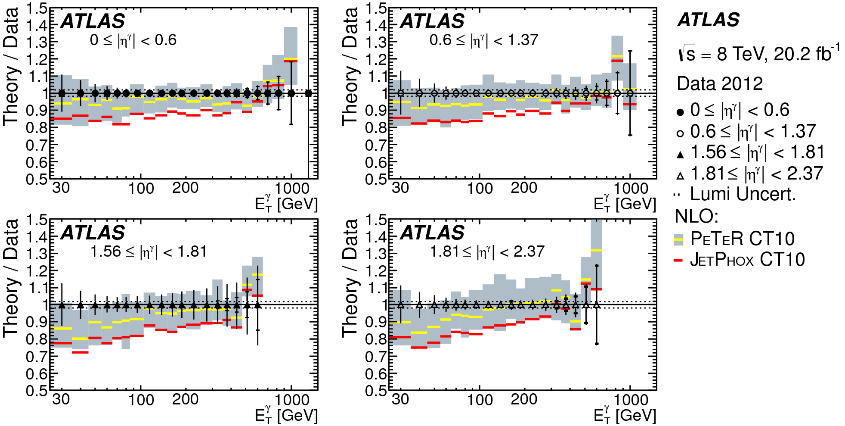
- factorization possible since fluctuations inside hadron happen on timecale much longer than initial scattering process (scattering "sees" snapshot of structure)

1. **Parton Distribution Function (PDF)** absorbs none-perturbative physics of initial state in parametrizations that give probability density to find a parton i, carrying momentum fraction x at scale Q $\rightarrow$ needs to be determined from experimental data
2. **partonic cross section:** describes scattering, can be treated in pQCD for large enough Q
3. **Fragmentation function:** relates outgoing quark c to hadron h (absorbs hadronization process)

ATLAS measurement in pp collisions at $\sqrt{s} = 8$ TeV

JHEP08(2016)005

next-to-next-to-next-to-leading-logarithmic (NNNLL) level



- measurement by ATLAS with significant increase of available statistics ($4.6\,\mathrm{fb}^{-1}$ vs. $20.2\,\mathrm{fb}^{-1}$)
- reduced experimental uncertainties reveal underestimation of JETPHOX NLO by up to $20\,\%$
- comparison to PeTeR (includes some higher order corrections*) shows good agreement

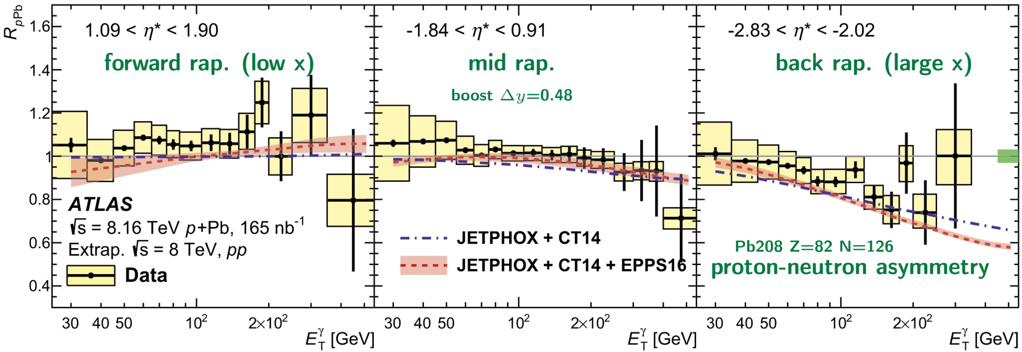
→ **higher order corrections needed to describe prompt photon production?**

ATLAS R_{pA} at $\sqrt{s} = 8.16$ TeV

j.physletb.2019.07.031

- most recent measurement in nuclear collisions by ATLAS in p–Pb collisions at $\sqrt{s} = 8.16$ TeV
- measurement performed for $E_T > 20$ GeV

$$R_{pA} = \frac{\sigma_{pPb}}{A_{Pb} \times \sigma_{pp}}$$

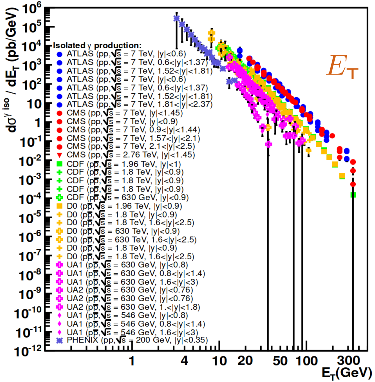


- study of nuclear modification factor R_{pA} to check for nuclear effects
- underestimation by NLO cancels → better constrains for PDFs
- measurement in agreement with CT14+EPPS16 over full covered phasespace
- data in agreement with unity at low E_T → no shadowing observed

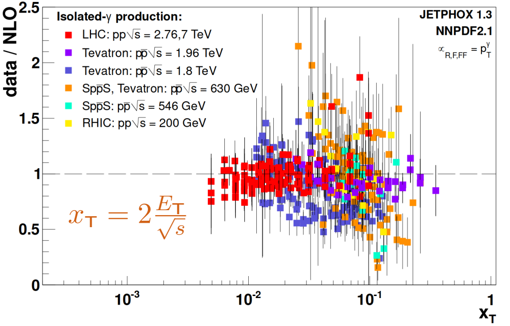
→ **no significant cold nuclear matter effects observed → lower E_T reach needed**

Tevatron, Sp$\bar{\text{p}}$S, RHIC and early LHC

- several studies in the last 20 years performed systematic comparisons of isolated prompt photon data with NLO calculation → d'Enterria et al (2012) for $\sqrt{s} \geq 200$ GeV



- isolated prompt photon cross section follows power-law dependence
- results collapse on a single curve in x_T when scaled with $\sqrt{s}^n$ ($n \approx 4.5$) → universal production mechanism



- good data-theory agreement with Jetphox pQCD NLO over whole x_T range

"[. . .] *we see no objection why isolated-photon data should not become integral part of future global QCD analyses.*"

10.1016/j.nuclphysb.2012.03.003

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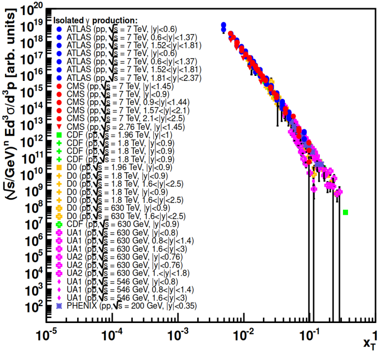

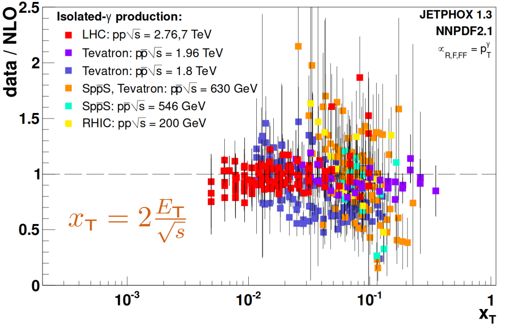

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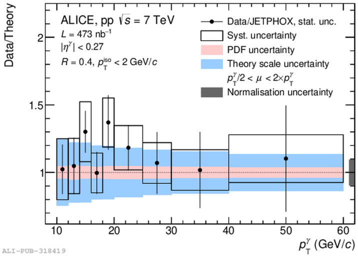
10.1016/j.nuclphysb.2012.03.003

Measurements in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

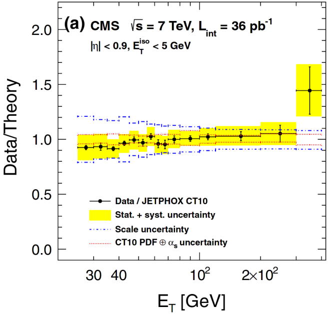
Eur. Phys. J. C (2019) 79:896

ALICE



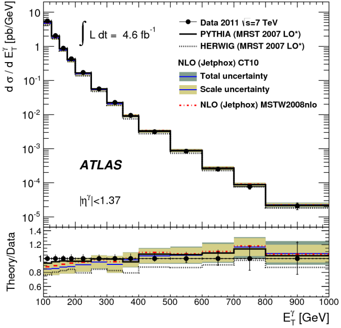
Phys. Rev. D 84, 052011

CMS



Phys. Rev. D 89, 052004

ATLAS

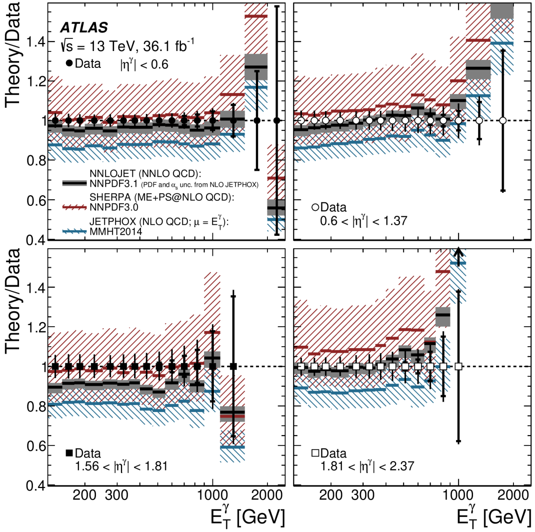


- measurements in early LHC data at $\sqrt{s} = 7\,\text{TeV}$ by ALICE, ATLAS and CMS up to $E_{\text{T}} = 1000\,\text{GeV}$
- ALICE experiment especially suitable for measurements at low E_{T}
- overall good agreement with Jetphox pQCD NLO over whole E_{T} range (for various PDFs)
- slight tendency of underestimation by NLO for lowest E_{T} visible for ATLAS measurement

ATLAS measurement in pp collisions at $\sqrt{s} = 13$ TeV

JHEP10(2019)203

- ATLAS measurement in largest pp dataset at $\sqrt{s} = 13$ TeV with experimental uncertainties from $3\,\%$–$17\,\%$
- underestimation by **JETPHOX NLO pQCD** of up to $20\,\%$ in line with findings at 8 TeV
- **fixed-order NNLO** calculations show good agreement with data
  - in addition: scale uncertainties reduced by a factor 2–20
- **SHERPA NLO + Parton Shower (PS)** similarly shows good agreement with data



→ **higher order corrections improve description of data + sigificantly reduce theoretical unc.**

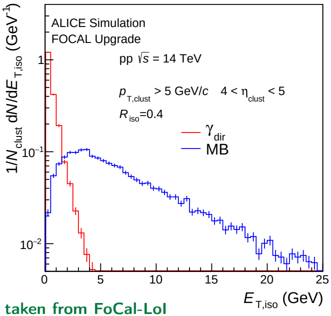
→ **using parton showers to obtain final-state observables improves description**

Outlook: Measuring isolated photons with the FoCal

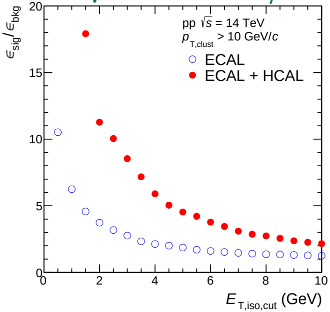
FoCal analysis strategy:

- perform measurement in pp at $\sqrt{s} = 14$ TeV and p–Pb at $\sqrt{s} = 8.8$ TeV to constrain PDFs and access gluon saturation
- measure photons using the FoCal-E
- obtain isolation in cone combining response in FoCal-E and FoCal-H
- further improve S/B by "decay photon tagging"
  - reject pairs of photons that give π^0 mass

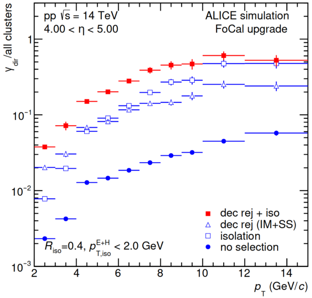
Isolation



impact of iso. on S/B

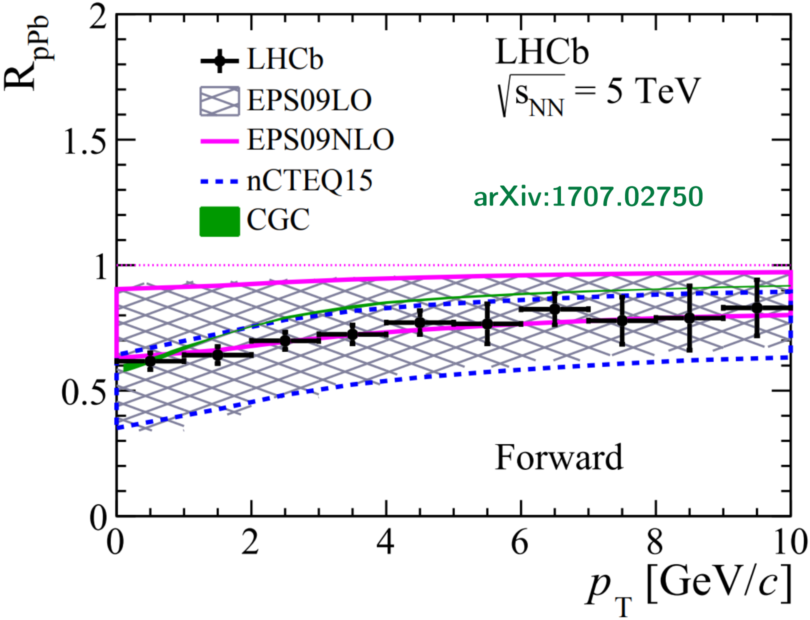


signal fraction

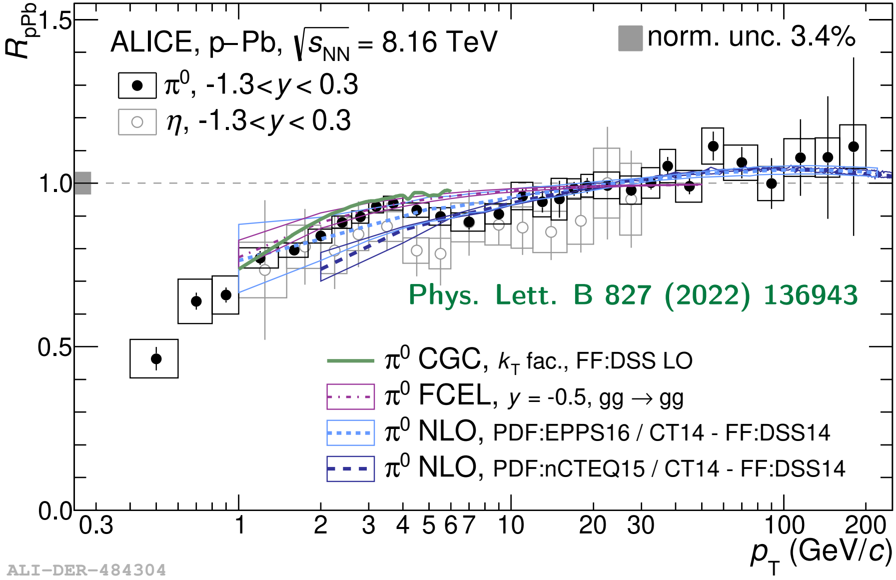


all figures taken from FoCal-LoI

Nuclear modification of prompt D^0 with LHCb



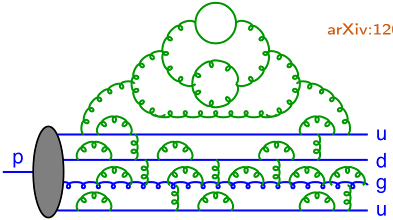
Nuclear modification of π^0 and η with ALICE



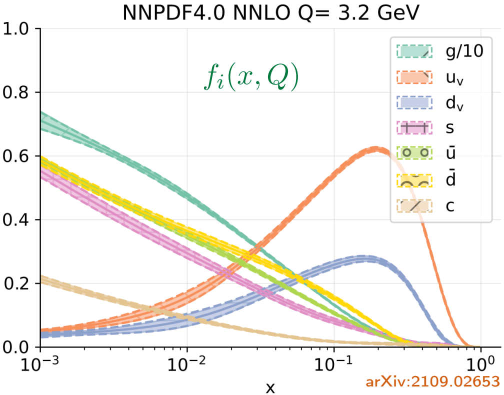
Parton Distribution Functions (PDFs)

x momentum fraction; Q momentum transfer

- protons are a complex structure of quarks bound to each other via gluons and a constant creation/annihilation of virtual quarks and gluon
- can not be described from first principles using perturbative QCD (pQCD) $\rightarrow$ use universal parametrizations determined by experimental data
- Parton Distribution Function (PDF) gives probability density to find parton i carrying fraction x of protons momentum at scale Q
- only $50\,\%$ is carried by quarks; the rest by gluons!
- PDFs evolve with scale Q $\rightarrow$ described by QCD evolution equations (DGLAP etc.)
- **low PDF uncertainties $\rightarrow$ low prediction uncertainties!**



arXiv:1207.2389



arXiv:2109.02653

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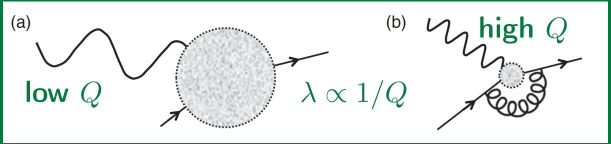

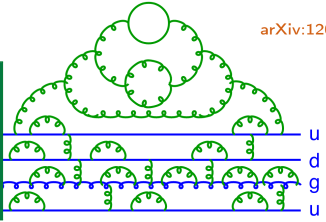

using perturbative QCD (pQCD) → use universal parametrizations determined by experimental data

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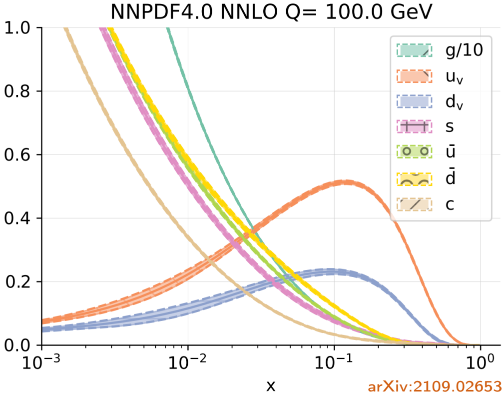

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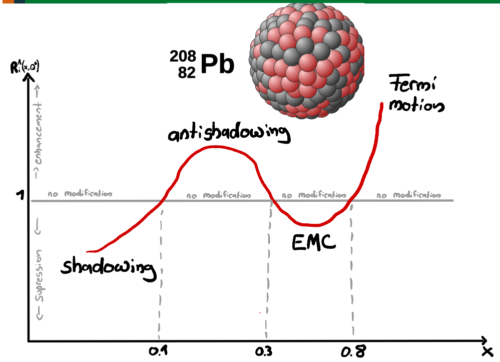
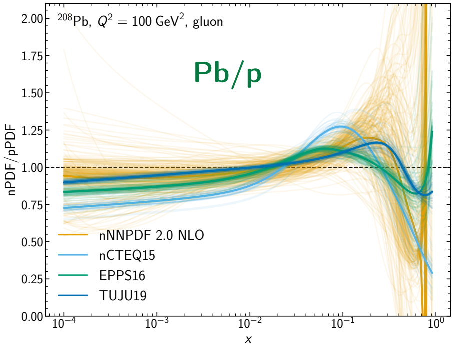
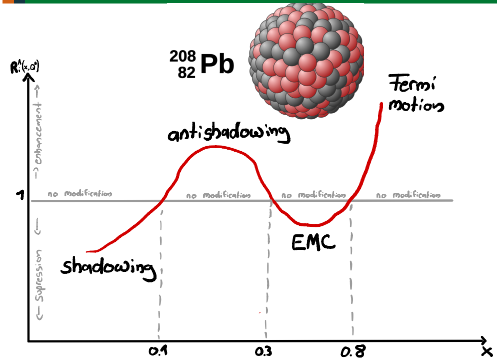


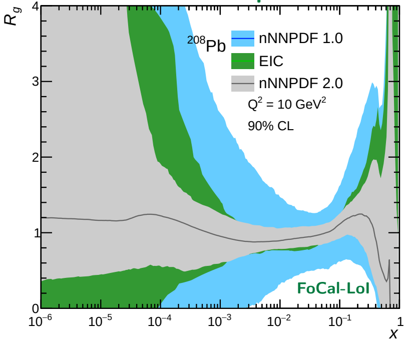


- the initial state of proton in nucleus (e.g. Pb) is modified with respect to the free proton case!
  - shadowing: outer nucleons "shield" inner nucleons
  - EMC effect: explanations vary, some change in scale involved (increase in quark confinement size, nucleon size, nuclear treatment without quarks . . .)
  - fermi motion: nucleons themselves move inside nucleus
- energy loss of incoming partons **before** hard scattering?
- better understanding of nuclear effects in the initial state is crucial for disentangling from final-state effects (e.g. QGP)

⇒still a lot to understand and learn!



uncertainties "blow up" for low-x



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The gluon PDF

Constraining PDFs and nPDFs → improve predictions

- gluon PDFs are one of the least constrained PDFs
- gluons drive significant fraction of scatterings at the LHC → precise knowledge improves predictions (prominent example gg→H) (and enter a variety of measurements)

Quantifying nuclear effects in the initial state (IS)

- how strong is gluon shadowing at low-x?

Non-linear QCD evolution

- interesting nonlinear physics at low-x and Q where gluon density is very high:
  - gluon splitting and gluon fusion start to balance each other, leading to gluon saturation
  - most prominent model to describe regime of gluon saturation is the Color Glass Condensate (CGC) model
- nuclear environment → higher saturation scale Q_s

$$\mathbf{Q_s \propto A^{1/3} x^{-\lambda}} \quad \text{with} \quad \lambda \approx 0.3$$