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Prompt photon physics with the ALICE FoCal

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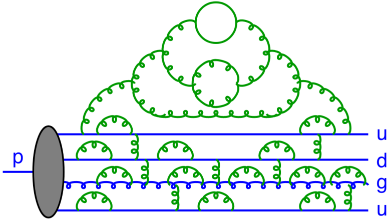
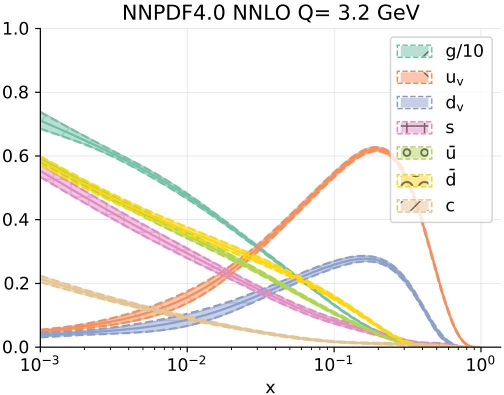
Forward QCD workshop, 24.05.2022

PDFs: What does it look like inside a proton?

- 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) → 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 → described by QCD evolution equations (DGLAP etc.)
- **low PDF uncertainties → low prediction uncertainties!**





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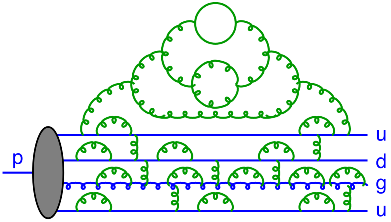
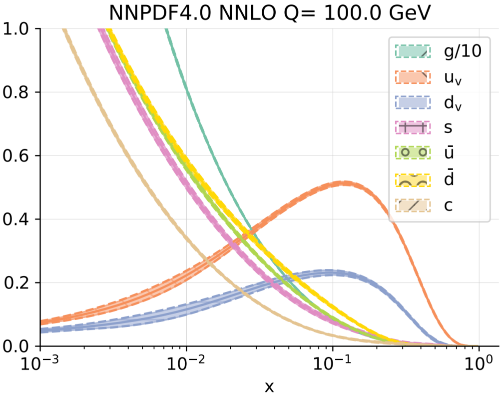
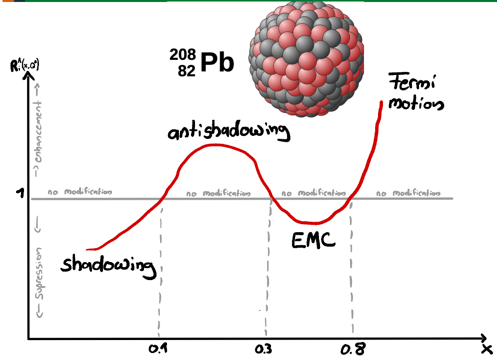
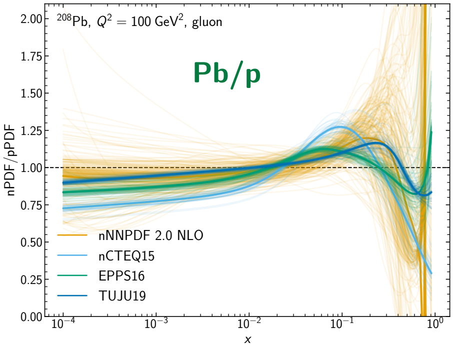



NNPDF4.0 NNLO Q= 100.0 GeV

The initial state: Nuclear modification

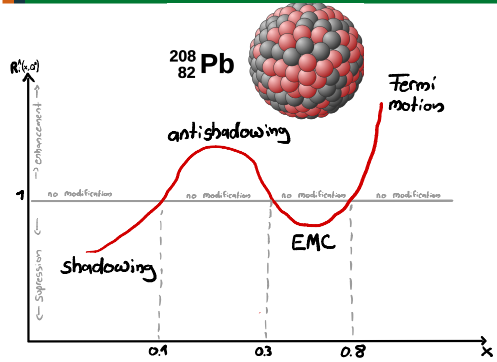




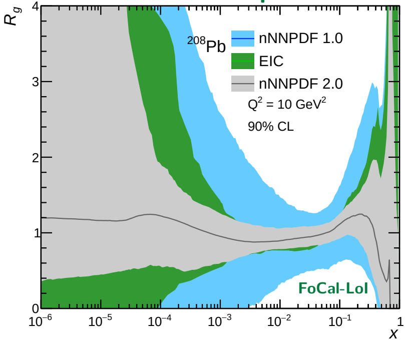
- the initial state of proton in nucleus (e.g. Pb) is modified with respect to the free proton case!
  - shadowing: outer nucleons "shield" inner nucleons
  - EMC effect: explanations vary, some change in scale involved (increase in quark confinement size, nucleon size, nuclear treatment without quarks ...)
  - 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!

The initial state: Nuclear modification



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)

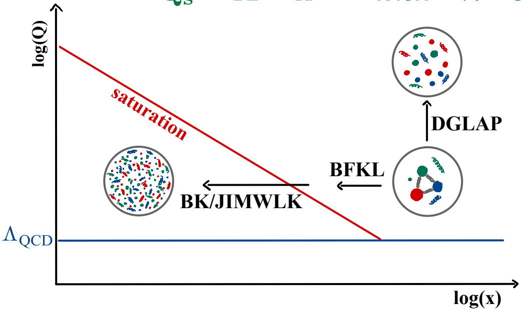
Quantifying nuclear effects in the initial state (IS)

- how strong is gluon shadowing at low-x?

Non-linear QCD evolution

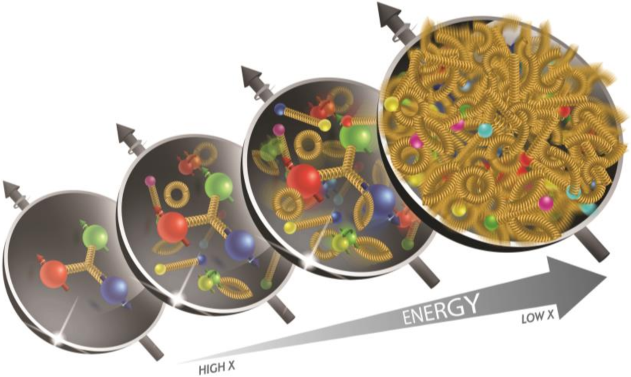
- interesting nonlinear physics at low-x and Q where gluon density is very high:
  - gluon splitting and gluon fusion start to balance each other, leading to gluon saturation
  - most prominent model to describe regime of gluon saturation is the Color Glass Condensate (CGC) model
- nuclear environment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

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



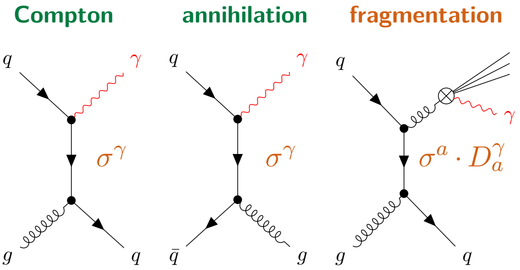
First conclusions

- we would like to know about gluons inside the proton
- very soft gluons (low-x) are especially interesting because ...
    - PDFs are not well constrained (large uncertainties)
    - shadowing of gluons expected
    - gluon saturation expected

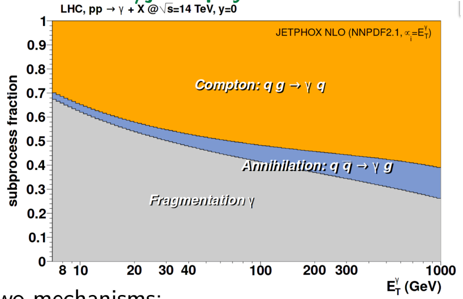


How can we access this regime?

Inclusive Prompt photon production



10.1016/j.nuclphysb.2012.03.003



- prompt photons produced in 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 particle complicated by fragmentation function $D_a^\gamma(z;\mu_f)$

Prompt photon cross section

$$\sigma(p_\gamma) = \sum_{a=q,\bar{q},g} \int_0^1 \frac{\mathrm{d}z}{z} \hat{\sigma}^a\left(\frac{p_\gamma}{z};\mu_r,\mu,\mu_f\right) \cdot D_a^\gamma(z;\mu_f) + \hat{\sigma}^\gamma(p_\gamma;\mu_r,\mu,\mu_f)$$

Isolation: Role for experiment and theory

Problem:

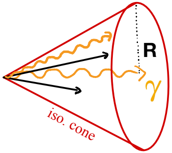
➊ **(theory+exp)** fragmentation prompt photons increase complexity of calculation & relation with initial state

➋ **(exp)** most photons produced are decay photons (low S/B ratio)

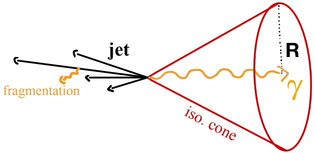
Solution: Isolation

- isolation := applying a restriction on activity in vicinity of photon
- fixed-cone isolation: study $\sum E_\mathrm{T}$ in radius R around photon and cut
- smooth-cone isolation (Frixione): reject more activity the closer one gets to photon

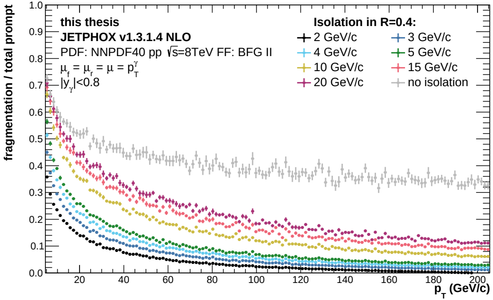
not isolated



isolated



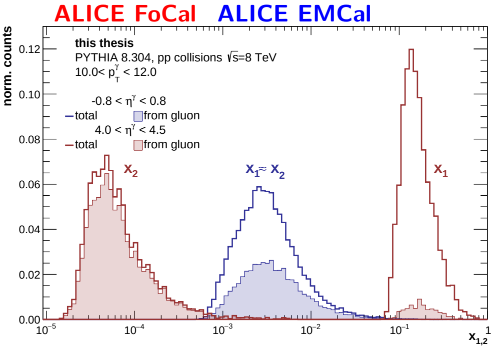
fixed-cone isolation



→ **suppresses fragmentation due to collinear fragmentation**

→ **suppresses decay photons (often come with other particles from hadronization)**

What are we probing with prompt photons?

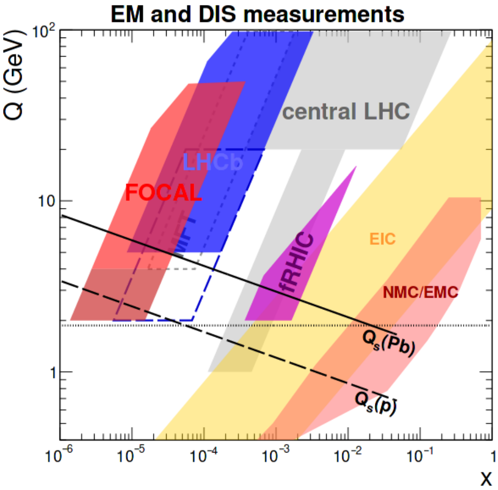


- direct access to gluon density (at LO)
- test for pQCD calculations
- prompt photons allow to probe a wide phasespace in x and Q:

Probed momentum fraction (LO)

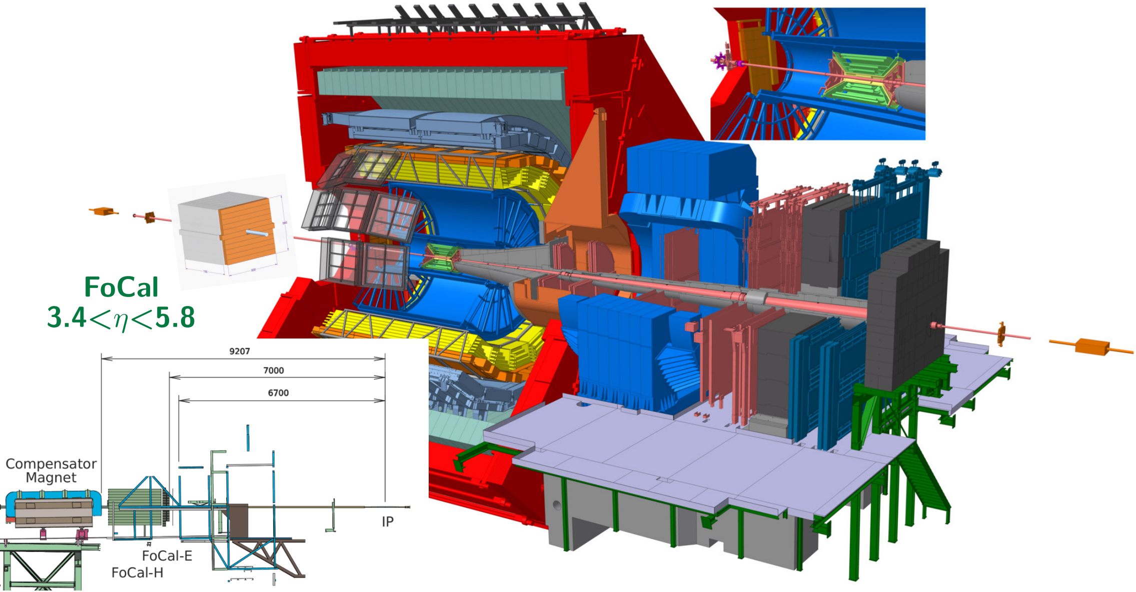
$$x \approx \frac{2p_{\mathrm{T}}}{\sqrt{s}} \exp(-y)$$

x: momentum fraction carried by parton in proton



the FoCal allows access to saturation regime by measuring at large rapidities!

The Forward Calorimeter (FoCal)

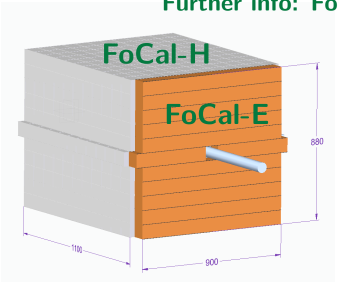


FoCal
$3.4 < \eta < 5.8$

The Forward Calorimeter (FoCal)

Operational in Run4 (2029)

Further info: FoCal-LoI



$3.4<\eta<5.8$

General:

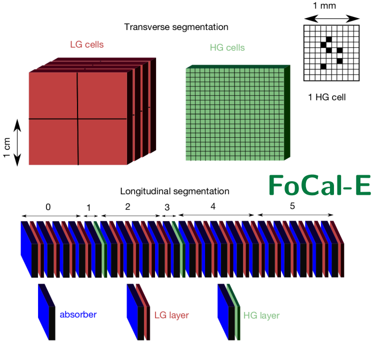
- very forward calorimeter consisting of two parts (FoCal-E and FoCal-H) located $\approx 7\,\mathrm{m}$ from IP
- main physics goal: explore non-linear QCD evolution

FoCal-E (electromagnetic):

- high-granularity Si-W sampling calorimeter combining two readout granularities ($1\times1\,\mathrm{cm}^2$ and $30\times30\,\mu\mathrm{m}^2$)
- ability to "track" longitudinal component of shower!
- used to measure photons and π^0

FoCal-H (hadronic):

- conventional metal-scintilator hadronic calorimeter behind FoCal-E
- design using scintillation fibres tested 2021 at SPS test beam
- used to measure photon isolation, jet energy etc.



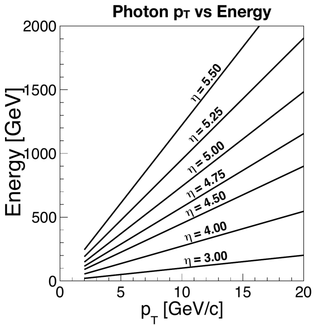
Prompt photons with FoCal

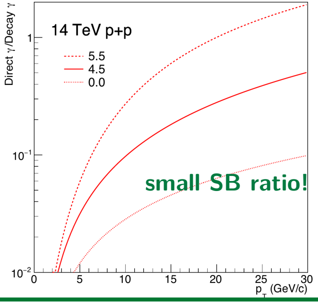
Challenges:

- small signal/background ratio → smallest at low-p_T – the most interesting part for us
- reliable identification of signal and background
- forward rapidity → showers with very high energies

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

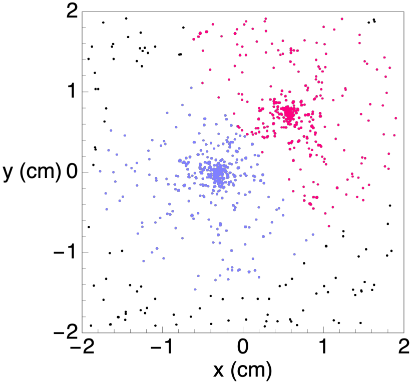


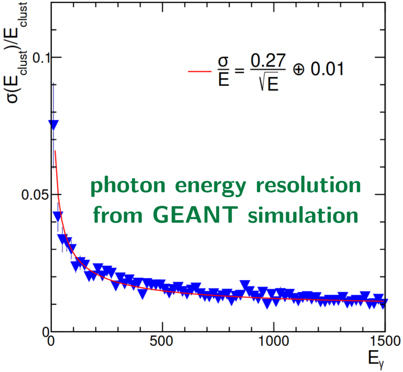


small SB ratio!

Measuring photons with the FoCal-E

- moderate requirements on energy resolution (constant $<5\,\%$ sufficient)
- Tungsten absorber offers low $X_0 \approx 3.5\,$mm for a compact shower (total depth $\approx 20X_0$)
- good shower separation is crucial to identify decay photon background (achieved by the $30 \times 30\,\mu$m^2 pixel layers)
- photon efficiency (signal): ≈ 1 for $E \gtrsim 75\,$GeV
- π^0 efficiency (background): over $90\,\%$ for $5 \leq p_\mathrm{T} \leq 15\,GeV/c$





photon energy resolution from GEANT simulation

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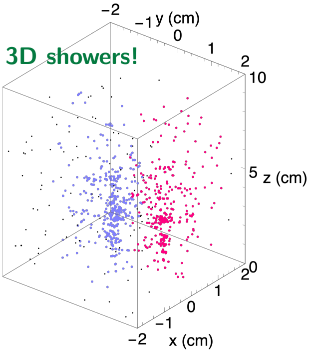
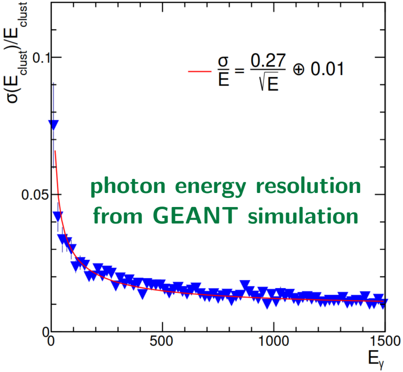
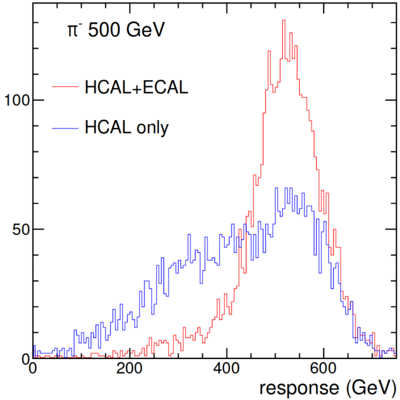
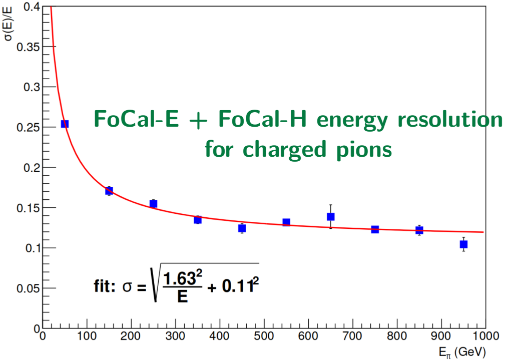




Measuring charged pions with FoCal-E and FoCal-H

- to measure isolation of a photon, detector should be capable of measuring charged particles
- main interest in high E hadrons → constant term in resolution dominates
- charged pions leave signal in FoCal-E and FoCal-H; response can be combined to single singnal





FoCal-E + FoCal-H energy resolution for charged pions

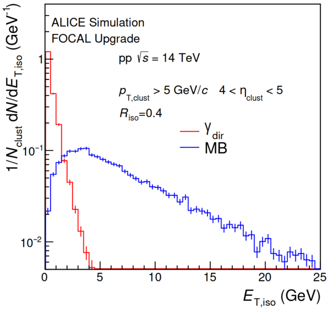
$$\text{fit: } \sigma = \sqrt{\frac{1.63^2}{E} + 0.11^2}$$

- studies show that already a standard metal-scintillator sampling calorimeter fulfils physics requirements

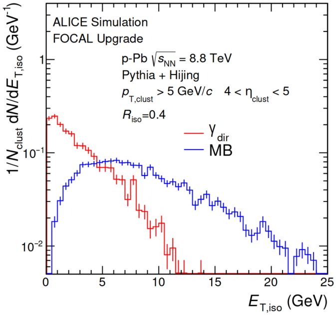
Isolating photons using FoCal-H and FoCal-E

- isolation in cone $R = 0.4$ tested using full MB Pythia simulations and Pythia Gamma–Jet (for p–Pb embedded in Hijing)
- isolation cut $p_{\mathrm{T}}^{\mathrm{iso.}} < 5\,\mathrm{GeV}/c$ rejects $\approx 80\,\%$-$90\,\%$ & selects $\approx 90\,\%$ signal in pp collisions
- using ECal **and** HCal for isolation improves S/B ratio

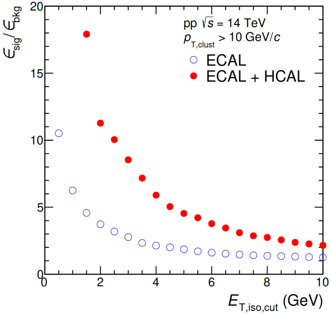
isolation in pp collisions



isolation in p–Pb collisions

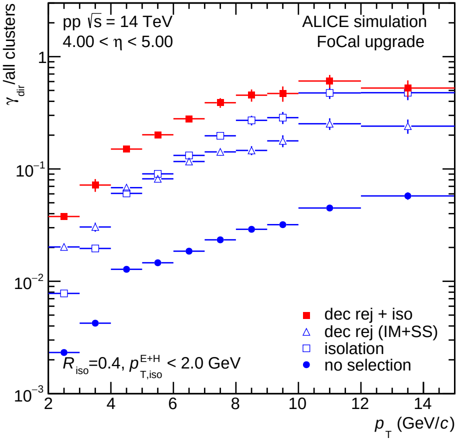


effect of isolation cut

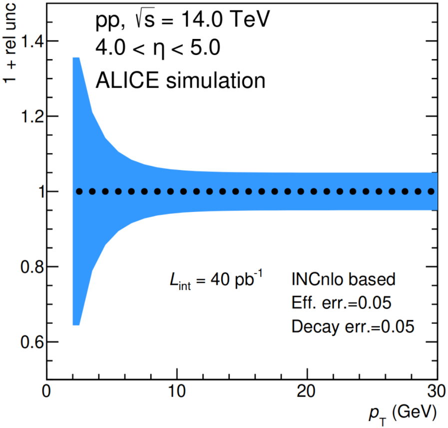


- in addition to isolation photon tagging helps to reject photons originating from decays

Putting it all together



- signal fraction increases significantly by factor 4–8 when applying isolation and decay photon rejection!



- uncertainties in pp (p–Pb) have been estimated to range from $5\,\%$ to $\approx 30\,\%$
- main sources: background subtraction (low p_T); energy resolution (high p_T)

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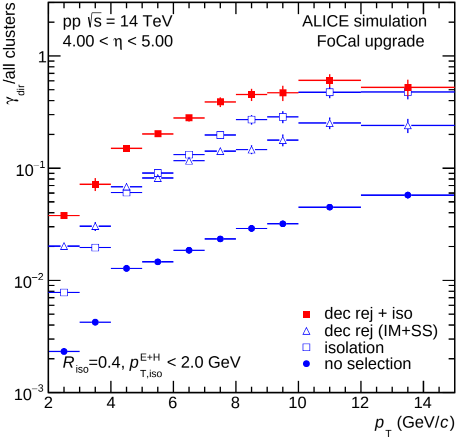

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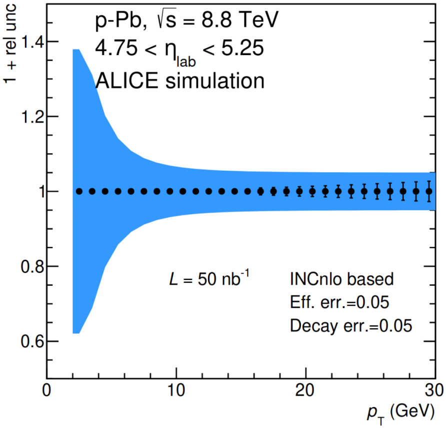

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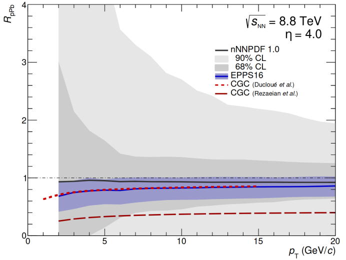
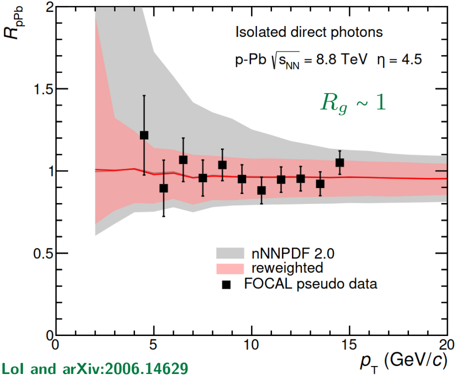
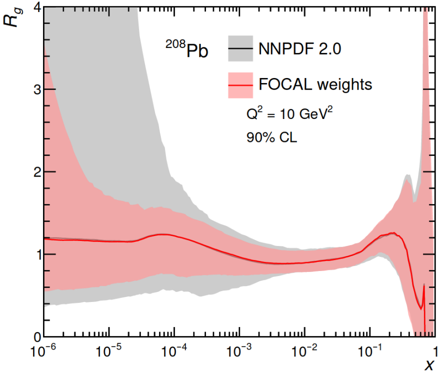
Impact of FoCal on nuclear PDFs

- pseudo-data projections using INCNLO allow to estimate physics impact
- sys. uncertainties estimated using phys. simulations (dominant low-p_T: purity)
- re-weighting of nNNPDF2.0 using pseudo-data illustrates potential to significantly reduce nPDF uncertainties at low-x





$R_g \sim 1$



taken from FoCal-LoI and arXiv:2006.14629

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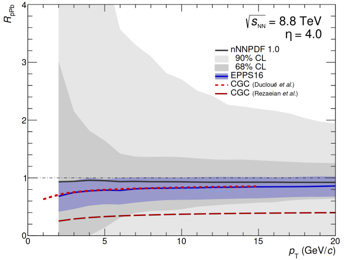
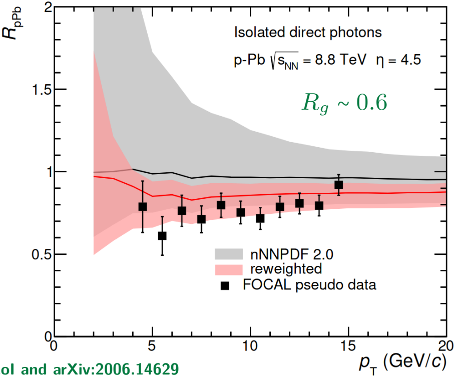
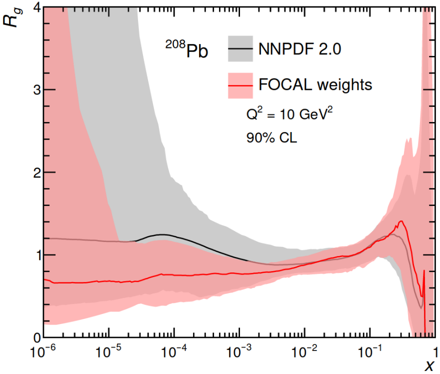




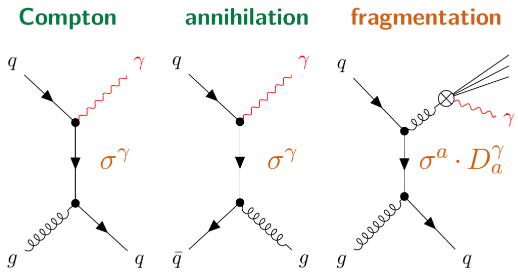


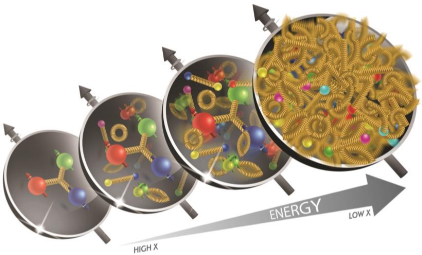
taken from FoCal-LoI and arXiv:2006.14629

Summary

- isolated photons are a valuable direct probe for the gluon PDF
  - improving uncertainties of PDFs and nPDFs
  - improving knowledge of nuclear effects in the initial state
  - interesting physics at low-x (gluon saturation, CGC)
- the FoCal (planned operation Run4) calorimeter allow to access very low $x \sim 10^{-5}$ by measuring at forward rapidities
- isolated photons are a key ingredients for the physics goal of exploring non-linear QCD evolution

Interested? Comments? Feel free to discuss with me over a coffee and check out the FoCal LoI!





Backup

Kinematic variables

Mandelstam invariant s

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

Coverage x:

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

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

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

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

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

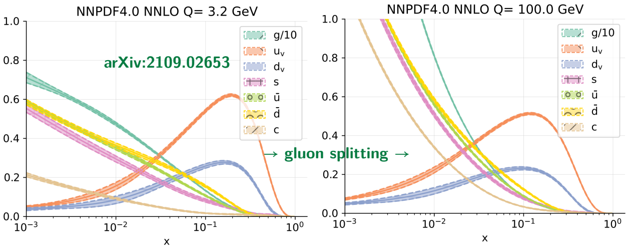
$$Q^2 = -q^2 \tag{7}$$

The initial state: Parton Distribution Functios (PDFs)

virtual photon $\lambda \propto 1/Q$

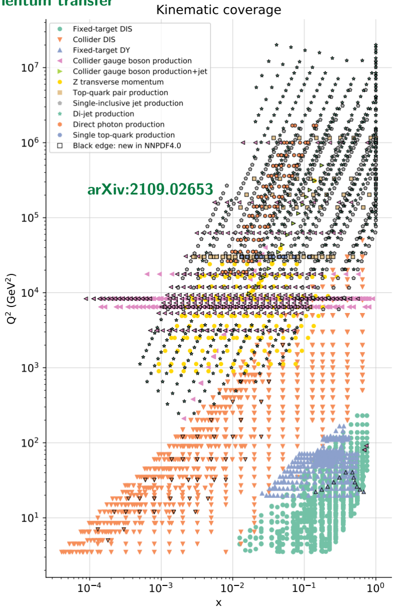
→ DGLAP →

x momentum fraction; Q momentum transfer



arXiv:2109.02653

→ gluon splitting →



arXiv:2109.02653

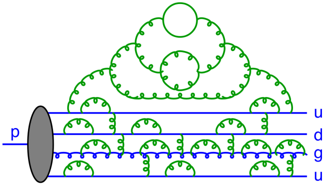
- can not be obtained a priori from calculations*
- PDFs obtained via fitting of vast amount of experimental data, each measurement constraining a different region in x and Q, as well as different parton flavours (a lot of DIS but also collider data from LHC)
- valence quarks peak at $\approx 0.3x$ and as expected $u_v \approx 2d_v$
- only $50\,\%$ is carried by quarks; the rest by gluons!
- PDFs evolve with scale Q → described by QCD evolution equations (DGLAP etc.)
- **low PDF uncertainties → low prediction uncertainties!**

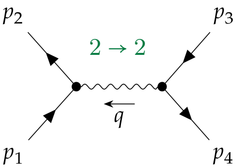
* but their evolution with scale can be calculated

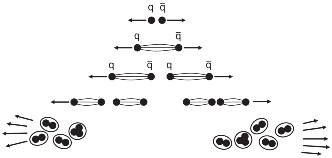
How does one describe hadronic collisions?

Things are complicated …

pQCD=perturbative QCD







The inital state (before coll.)

- initial state, i.e. state before collision, e.g. partons bound in proton
- complicated structure that also evolves with time (virt. gluons, sea quarks)
- out of reach for pQCD

Hard scattering

- process is happening on level of partons e.g. quark-quark→quark-quark
- for high enough momentum transfers $-q^2 = Q^2$ →can be treated in pQCD

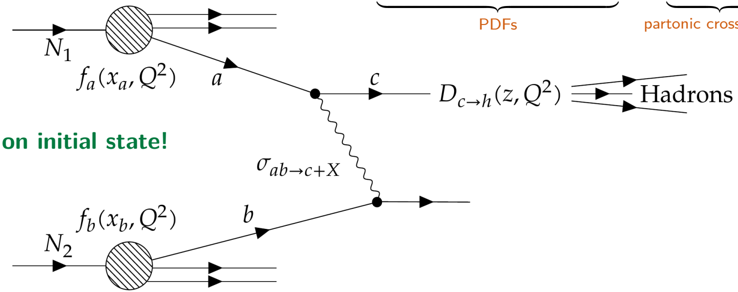
Final state (after coll.)

- outgoing quarks can not exist as free quarks (confinement)
- process of hadronisation through string breaking
- complicated final state of bound objects and a complicated way to get from quarks to hadrons → out of reach for pQCD

Fig.: M. Thomson - Modern Particle Physics and arXiv:1207.2389

Factorization: A recipe to describe hadronic collisions

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



Focus today on initial state!

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 → 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)

Sources of photons in hadronic collisions

photons do not interact strongly in final state → carry direct information of production source

Decay photons

- dominant source of photons produced in a collisions
- mainly originating from decays $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$
- can be used to reconstruct a variety of hadrons that allow to test pQCD, PDF and fragmentation
- interesting rare decays e.g. Higgs$\rightarrow \gamma\gamma$

Thermal photons

- in heavy-ion collisions (e.g. Pb–Pb) energy densities reached are high enough to form QGP
- interactions in partonic- and hadronic phase of QGP produce photons
- slope of spectrum related to effective QGP temperature

relevant at $p_{\mathrm{T}}^{\gamma} \lesssim 4\,\mathrm{GeV}/c$

Prompt photons

- photons created in the initial hard scattering
- at LO point-like coupling to partons going into the scattering process → prompt photons contain information about the initial state
- main production mechanism: $qg \rightarrow \gamma q$ (more on next slide)

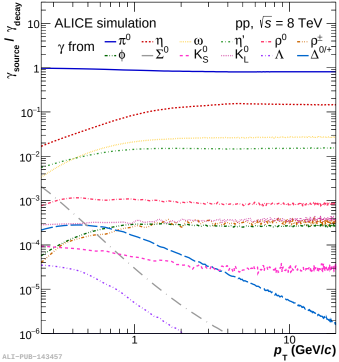
increasingly relevant at large p_{T}^{γ}

QGP= Quark-Gluon Plasma

Sources of photons in hadronic collisions

photons do not interact strongly in final state → carry direct information of production source

Decay photons



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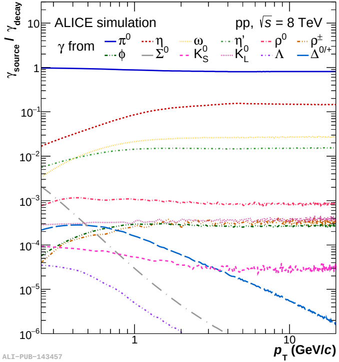
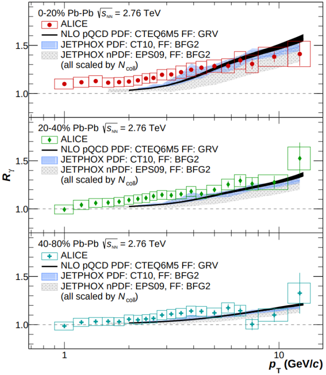


Thermal photons

$$R_\gamma = N^\gamma_{\text{incl.}} / N^\gamma_{\text{decay}}$$



10.1016/j.physletb.2016.01.020

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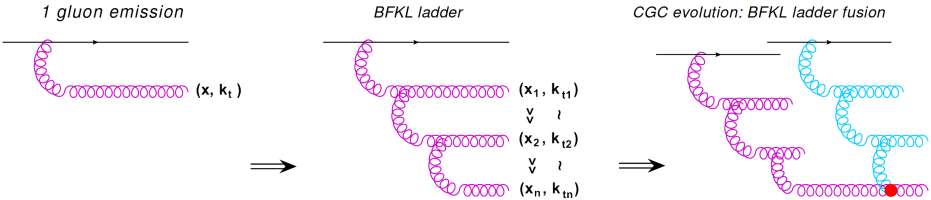
A closer look at saturation

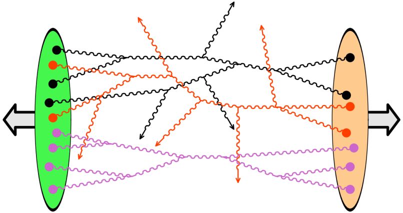


1 gluon emission

BFKL ladder

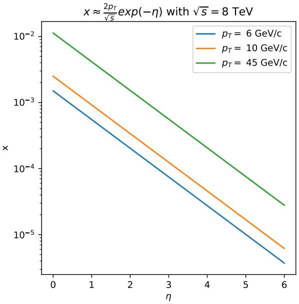
CGC evolution: BFKL ladder fusion

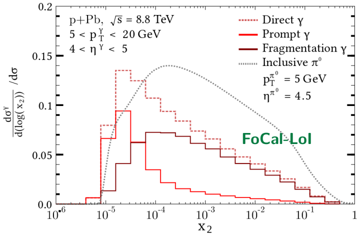
- probability P of Bremsstrahlung emmision of a gluon carrying x increases with $P \sim \alpha_s \ln(1/x)$
  → exponential rise of soft gluons at low-x described by BFKL/DGLAP evolution
- when gluon densities get very large, gluon recombination/fusion occurs, probability depends on gluon density
- initial-state of collision is dense gluon color fields described by CGC
- early stage of collision is initial condition for hydro transport models, and affects event bulk properties (multiplicity, flow, . . .)



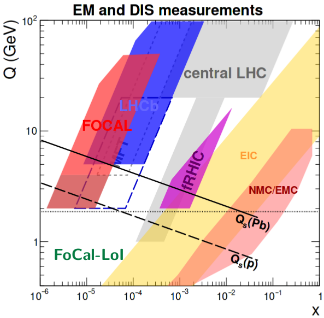
Kinematic coverage of isolated photons with FoCal

- measuring at very-forward rapidities $3.4<\eta<5.8$ allows to access low-x regime
- non-linear evolution becomes accessible below saturation scale Q_s





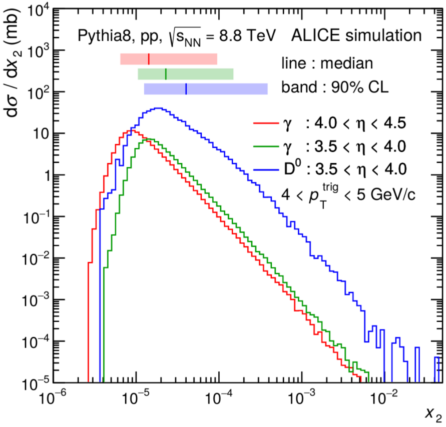
accessible gluon-x $\sim 10^{-5}$

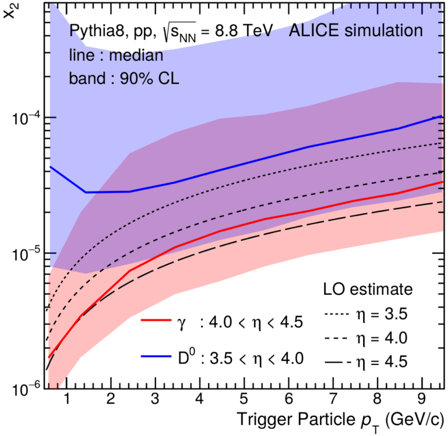


- going forward (large η) exponentially lowers x
- a more detailed look at gluon-x sensitivity using JETPHOX NLO + EPS09
- FoCal competitively placed in (x, Q) phasespace

Access to the gluon: Photons vs. D^0

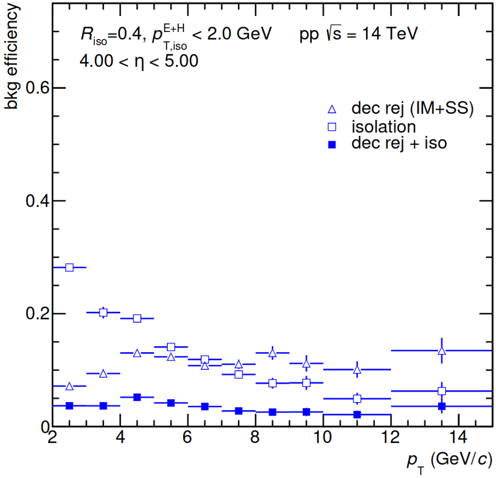
- direct prompt photons are relatively easy to caclulation + direct connection to gluons at LO
- fragmentation component highly supressed when using isolation
- no color-charge → no final-state energy loss

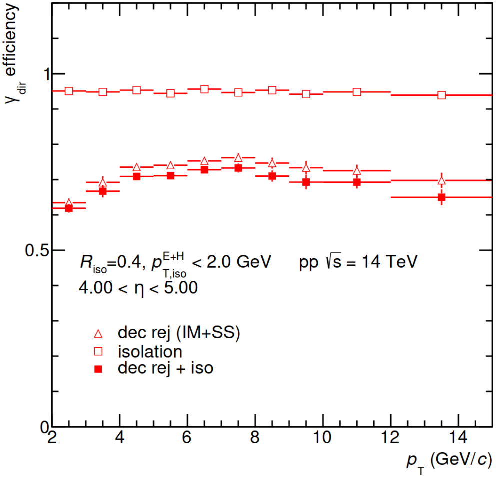




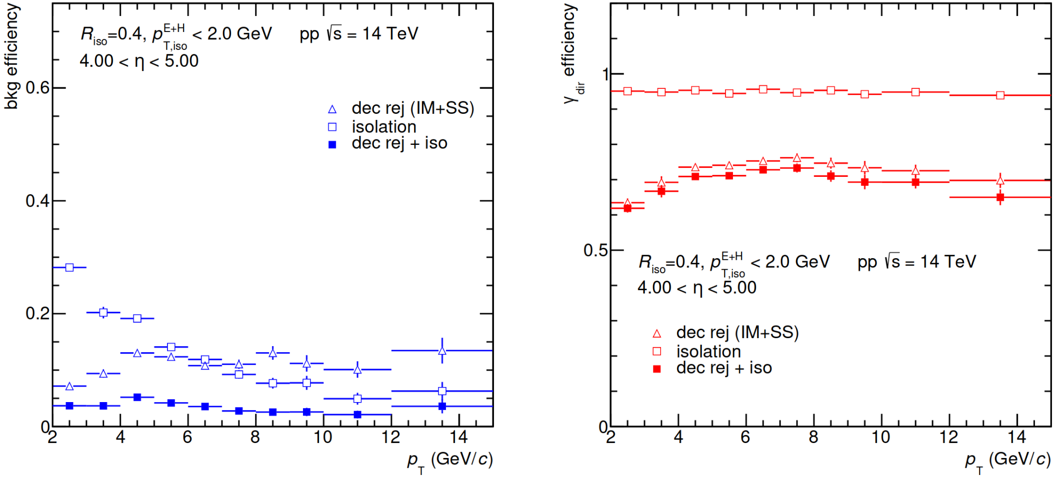
- direct photons probe lower x than D^0 (open charm); broadening from fragmentation

FoCal-E efficiencies in pp collisions

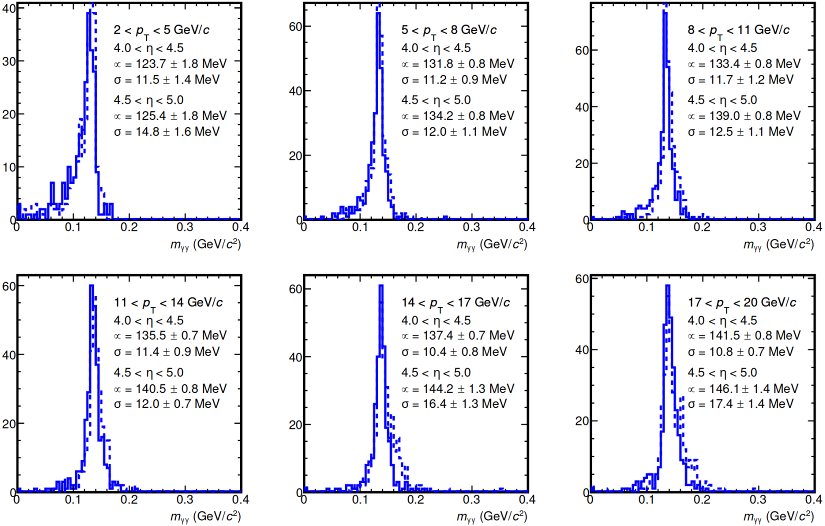




FoCal-E efficiencies in p–Pb collisions



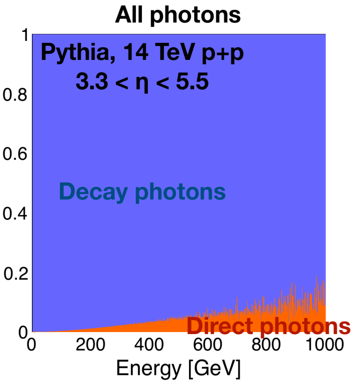
Measurement of π^0 with FoCal-E

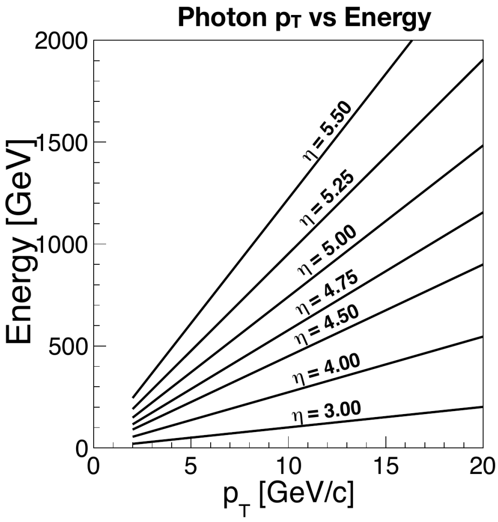


Measuring photons at forward rapidities

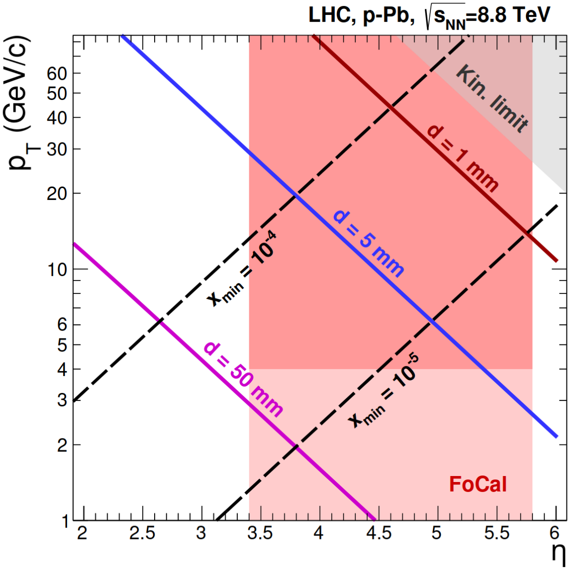
- large forward rapidities → large energies!
- measurements in $3.3 < \eta < 5.8$ for $p_{\mathrm{T}} \approx 4 - 20\,\mathrm{GeV}/c$ correspond to 40 to $2500\,\mathrm{GeV}$ (!)

→ detector needs to measure small signal over large energy ranges



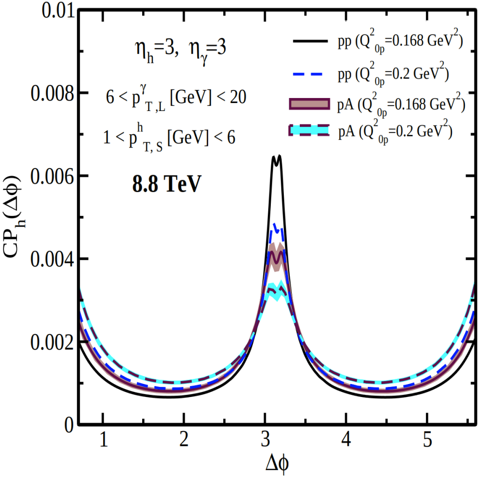


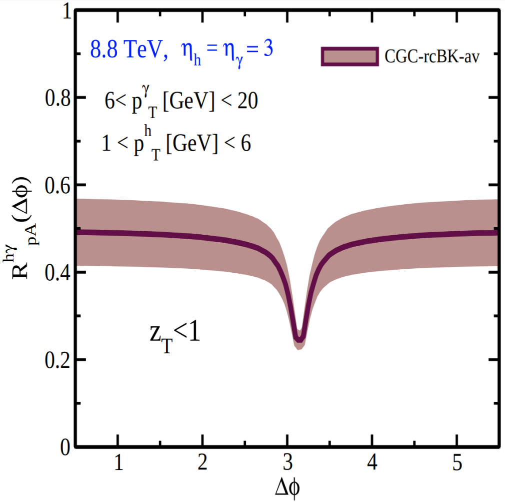
Effect of photon separation on phasespace



Correlation measurements

arXiv:1209.0478





- γ-hadron correlations promising measurement to investigate nonlinear QCD effects

Previous publications & Contact information:

- F.Jonas and C. Loizides: Centrality dependence of electroweak boson production in PbPb collisions at the CERN Large Hadron Collider (Phys. Rev. C 104, 0449052021 (2021))
- ALICE Collaboration: Production of ω mesons in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ The European Phys. Journal C 80, 1130 (2020)

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