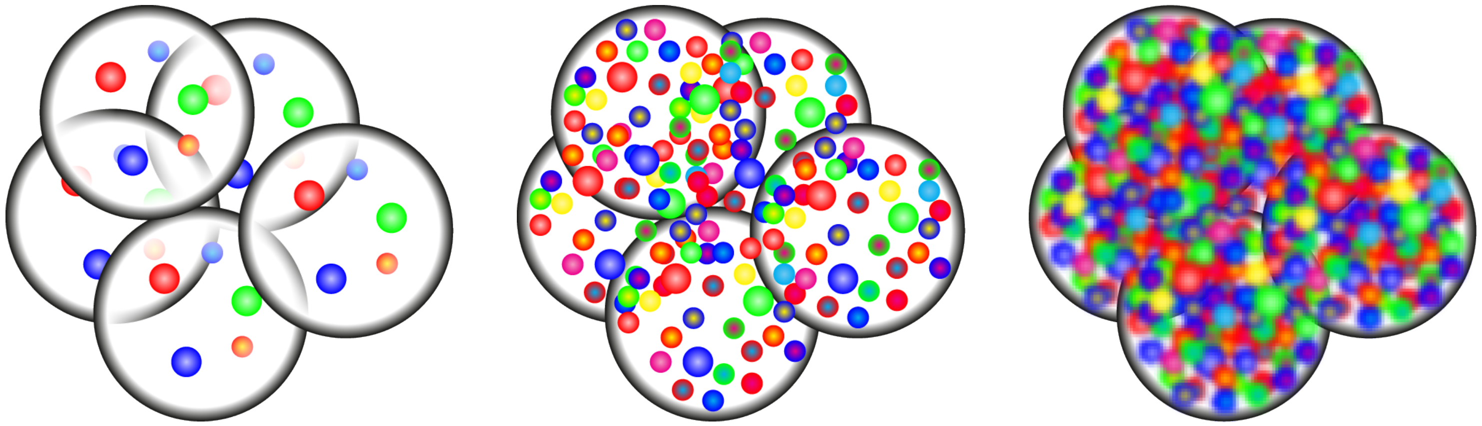
Probing small-x gluons with the ALICE Forward Calorimeter (FoCal) upgrade

Norbert Novitzky on behalf of the ALICE Collaboration
(University of Tsukuba, TCoHU)



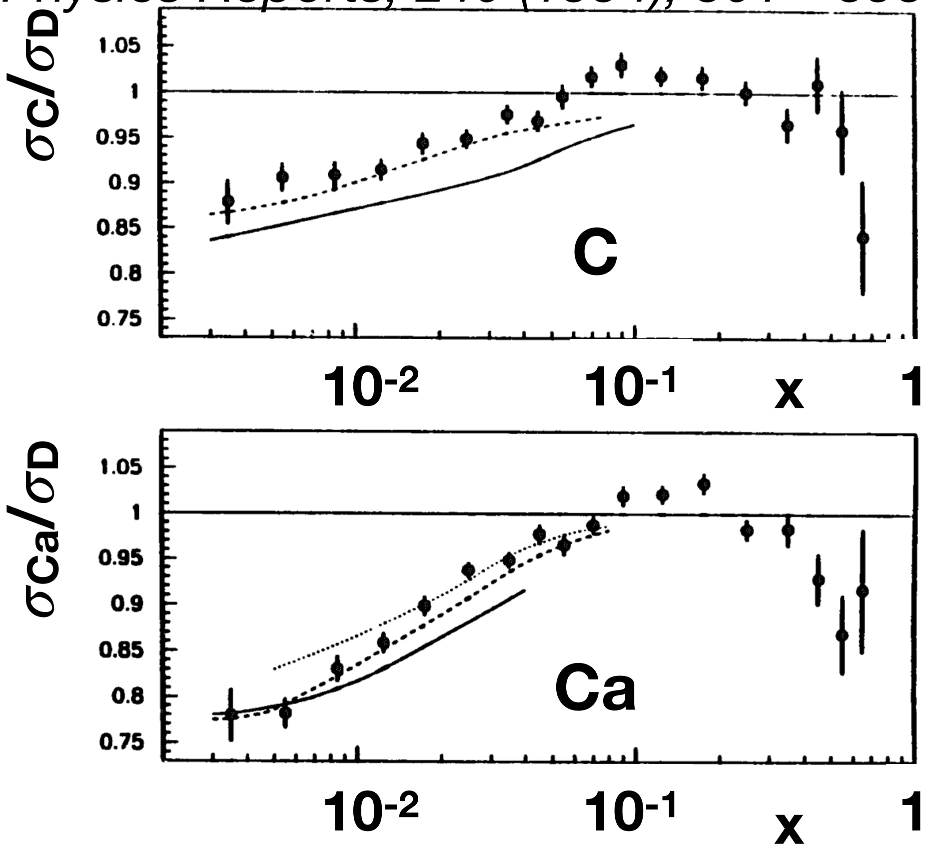
Initial Stages 2021, Weizmann Institute (online), 10-15 January

Tomonaga Center for the History of the Universe

筑波大学 University of Tsukuba

Nuclear Parton Distribution Function

Physics Reports, 240 (1994), 301—393

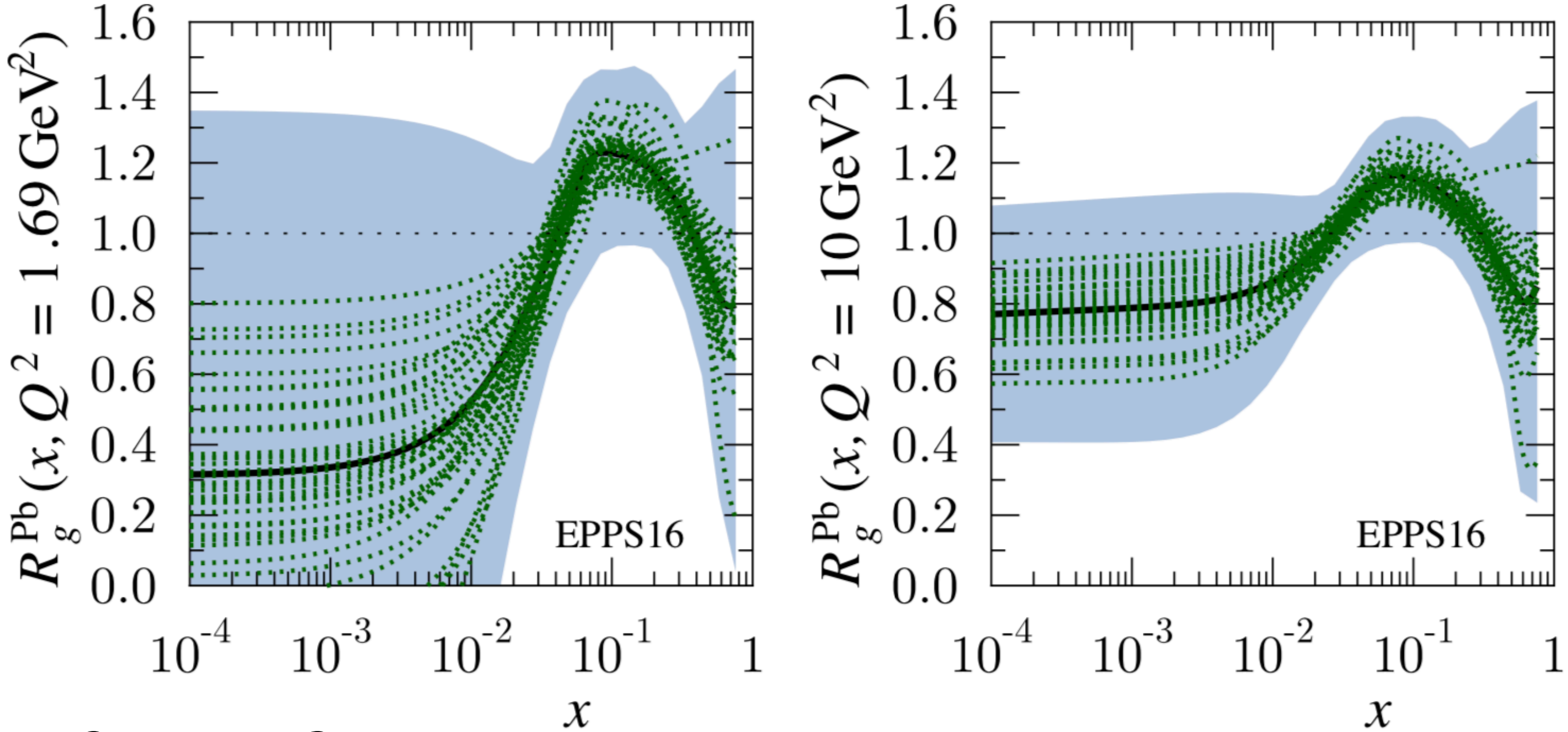


It was found that in nuclei, the parton distribution function is modified

First measurements of the nuclear parton distribution function from DIS measurements, e.g. European Muon Collaboration (EMC).

Nuclear parton distribution functions:

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{f_i^p(x, Q^2)}$$



EPPS16, EPJC 77, 163

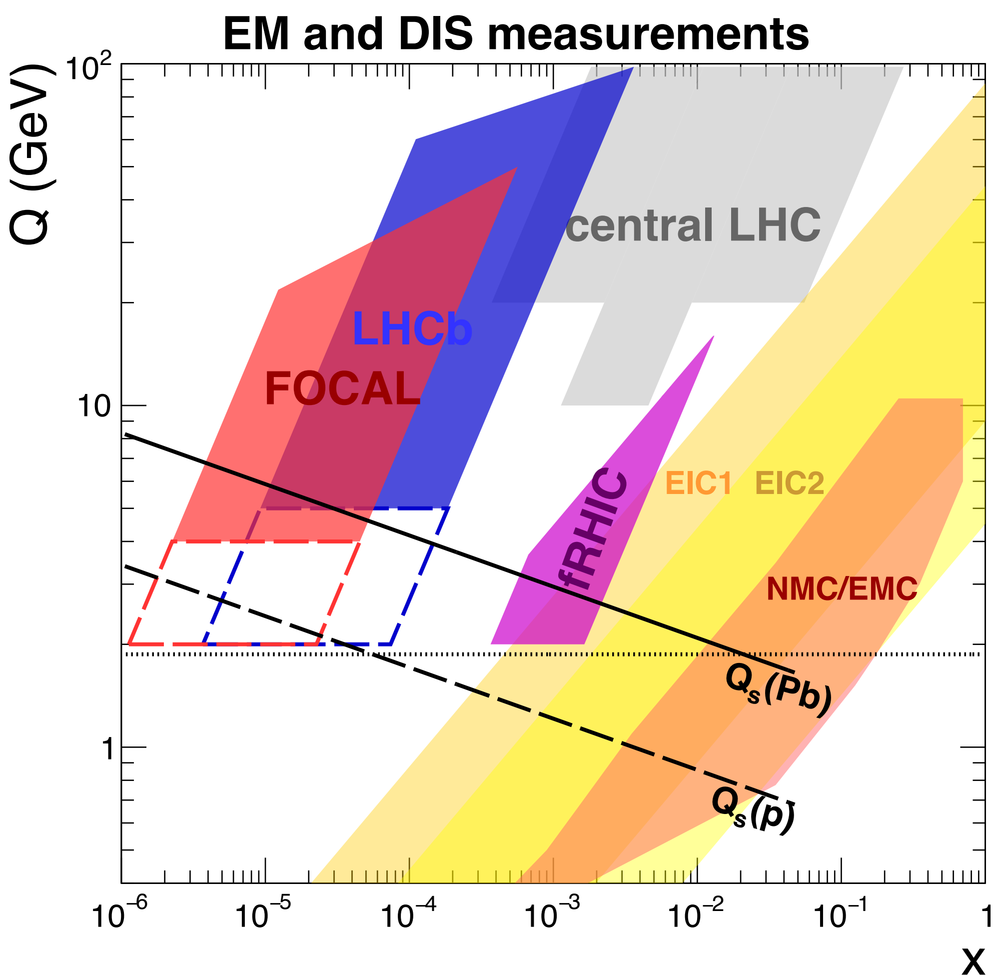
Large uncertainties on the gluon nPDFs:

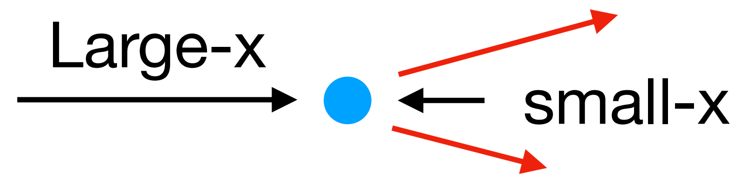
- Parametrized nuclear modification

Small-x region dependency:

- Very little is known from experimental results

Accessing nPDF at small-x





In the LO processes (at parton level)

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp\left(\pm \frac{y_3 + y_4}{2}\right)$$

In order to access the small-x region, we need to measure at very forward rapidities

Very limited data are available in this region so far.

The ALICE FoCal and LHCb allow us to probe this region of the phase space.

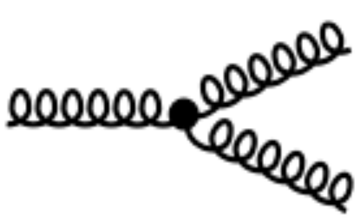
- LHCb: $2.5 < \eta < 5.0$
- FoCal: **$3.4 < \eta < 5.8$**
  - Main goal to measure direct photons and π^0 in *pp* and *p*-Pb collisions
  - Ongoing R&D work on the detector design
  - LoI endorsed by LHCC for Run 4, see: https://cds.cern.ch/record/2719928

Prediction of gluon-saturation

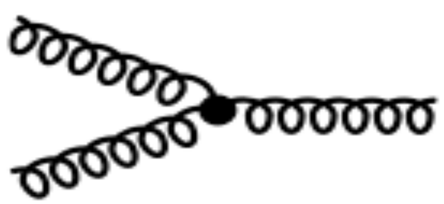
The BFKL equation (as well as DGLAP evolution) are linear equations and only include parton splitting

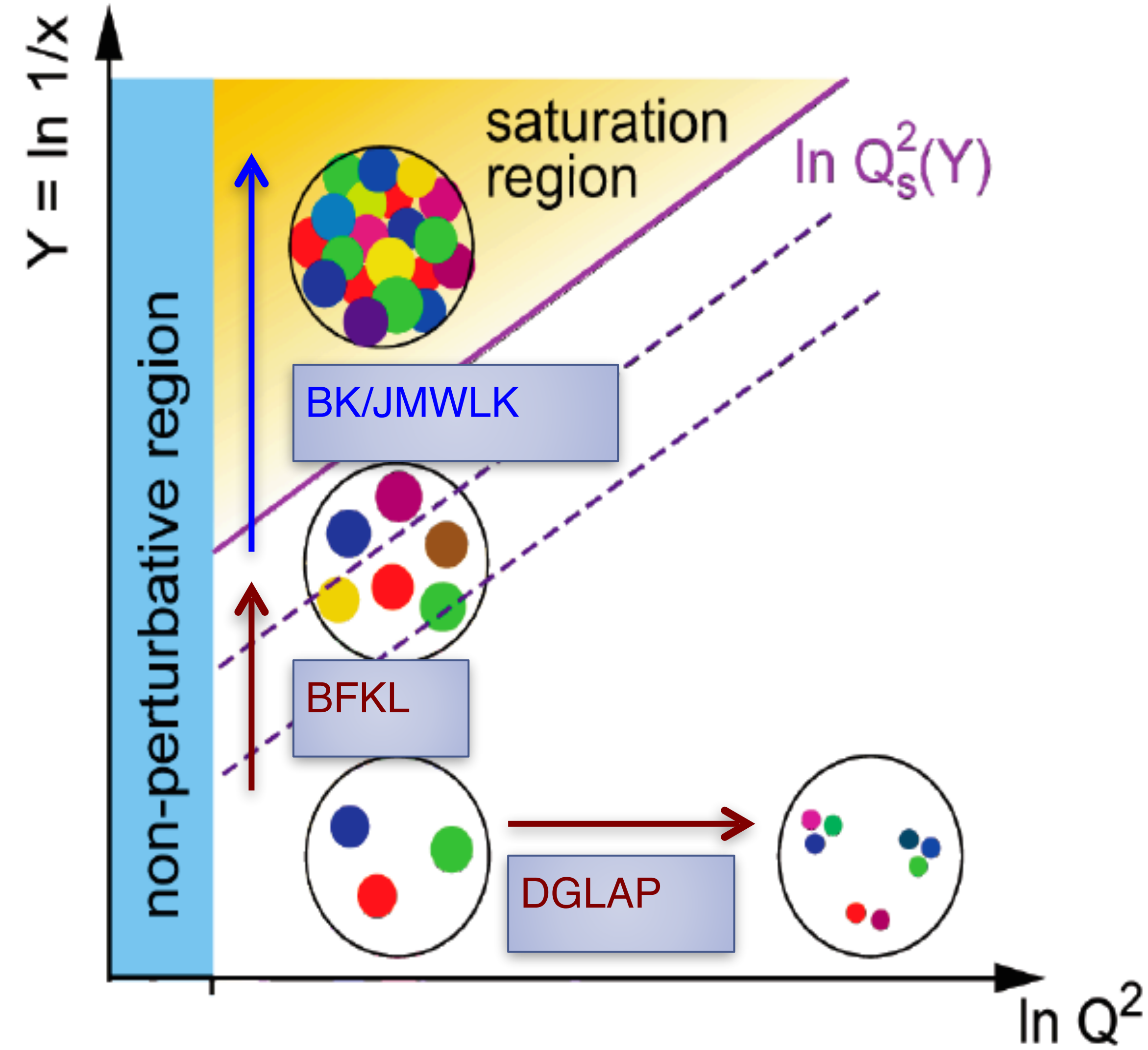
At high enough gluon densities the gluon would also recombine described by BK/JMWLK equations

Linear QCD
BFKL: gluon emission



Nonlinear QCD
BK/JMWLK gluon recombination





When these two processes are in *equilibrium*, the number of gluons is constant

$$Q_s^2 \approx \frac{xG_A(x, Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda}$$

The effective theory to describe this saturated gluon field: Color Glass Condensate (CGC)

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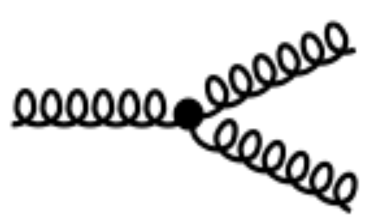
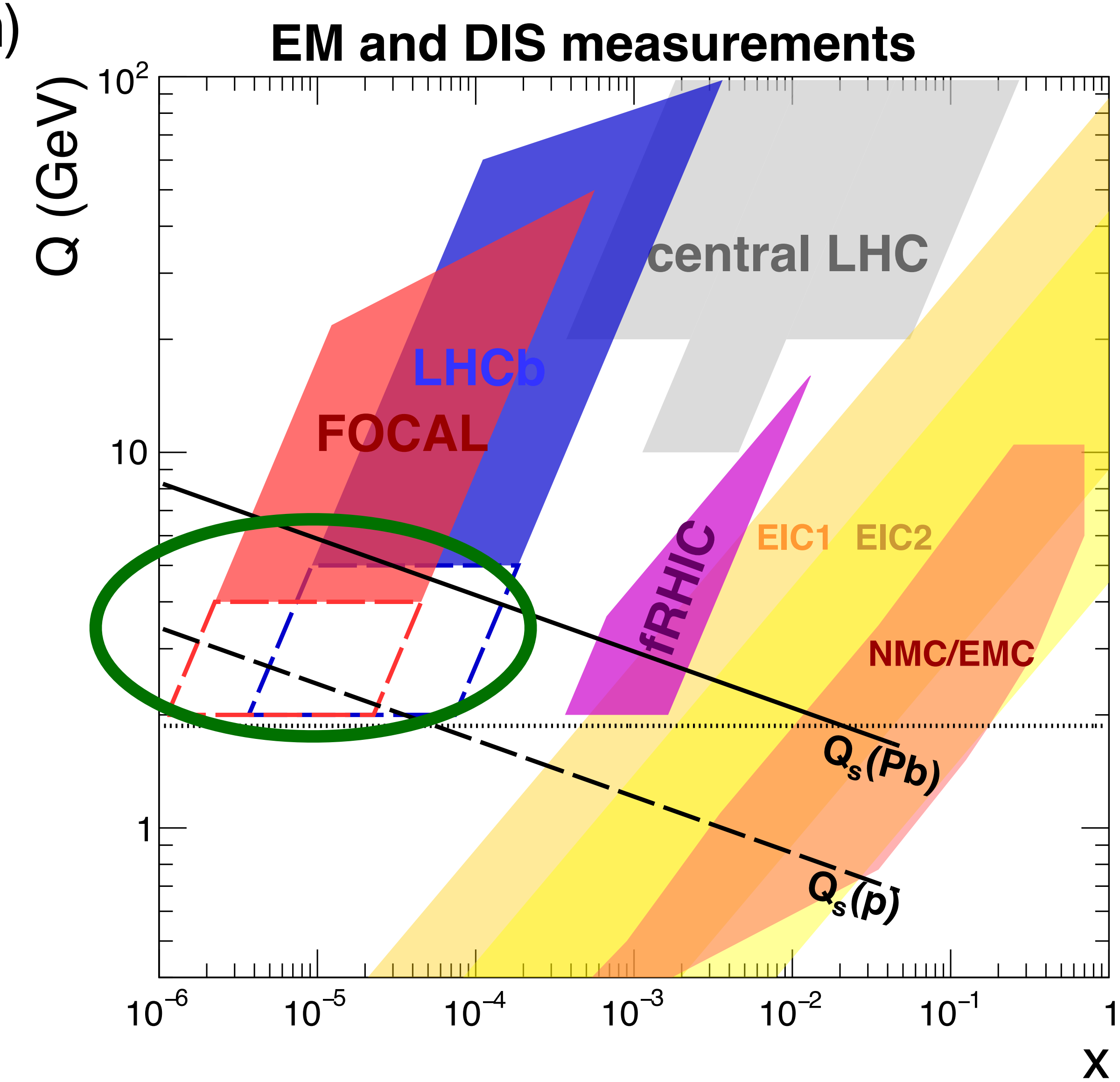


Nonlinear QCD
BK/JMWLK gluon recombination

EM and DIS measurements



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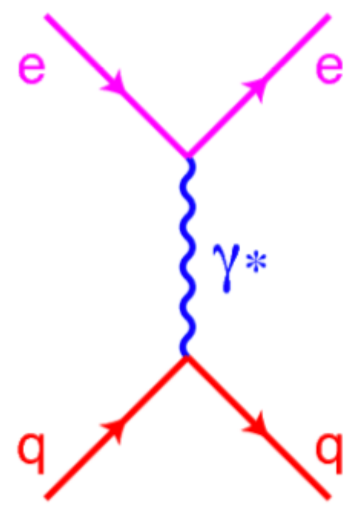
How to probe gluon density

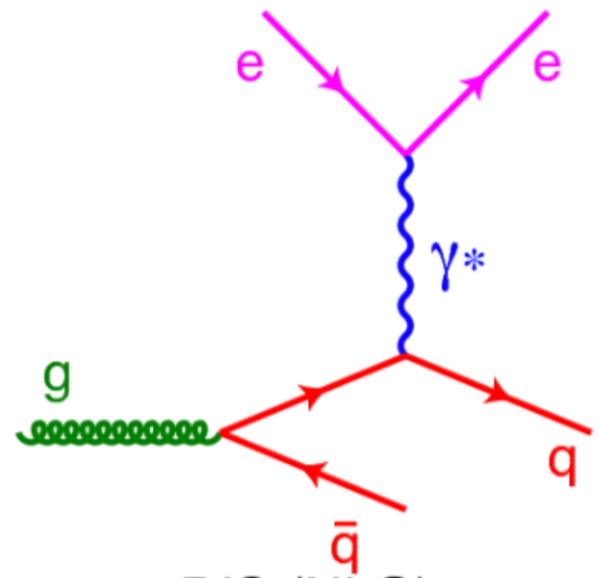
Probing the PDF in the nucleon:

- Classical method to measure the PDF is through the DIS collisions
- It is **not** sensitive to the gluon PDF in the LO

Gluons from NLO/evolution and/or F_L



DIS (LO)



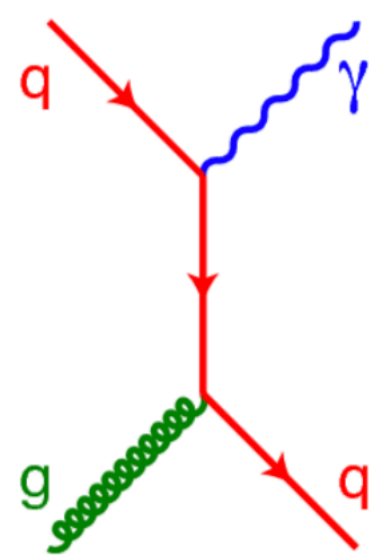
DIS (NLO)

Photon production in hadronic collision:

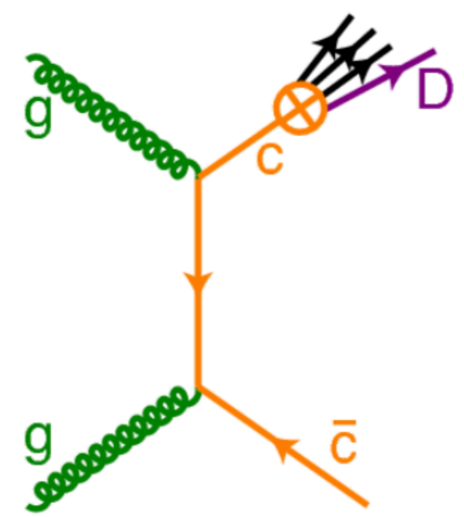
- Sensitive to the gluon PDF in the LO via the QCD Compton scattering

Heavy quark production is dominated by gluon fusion:

- convoluted with the fragmentation function

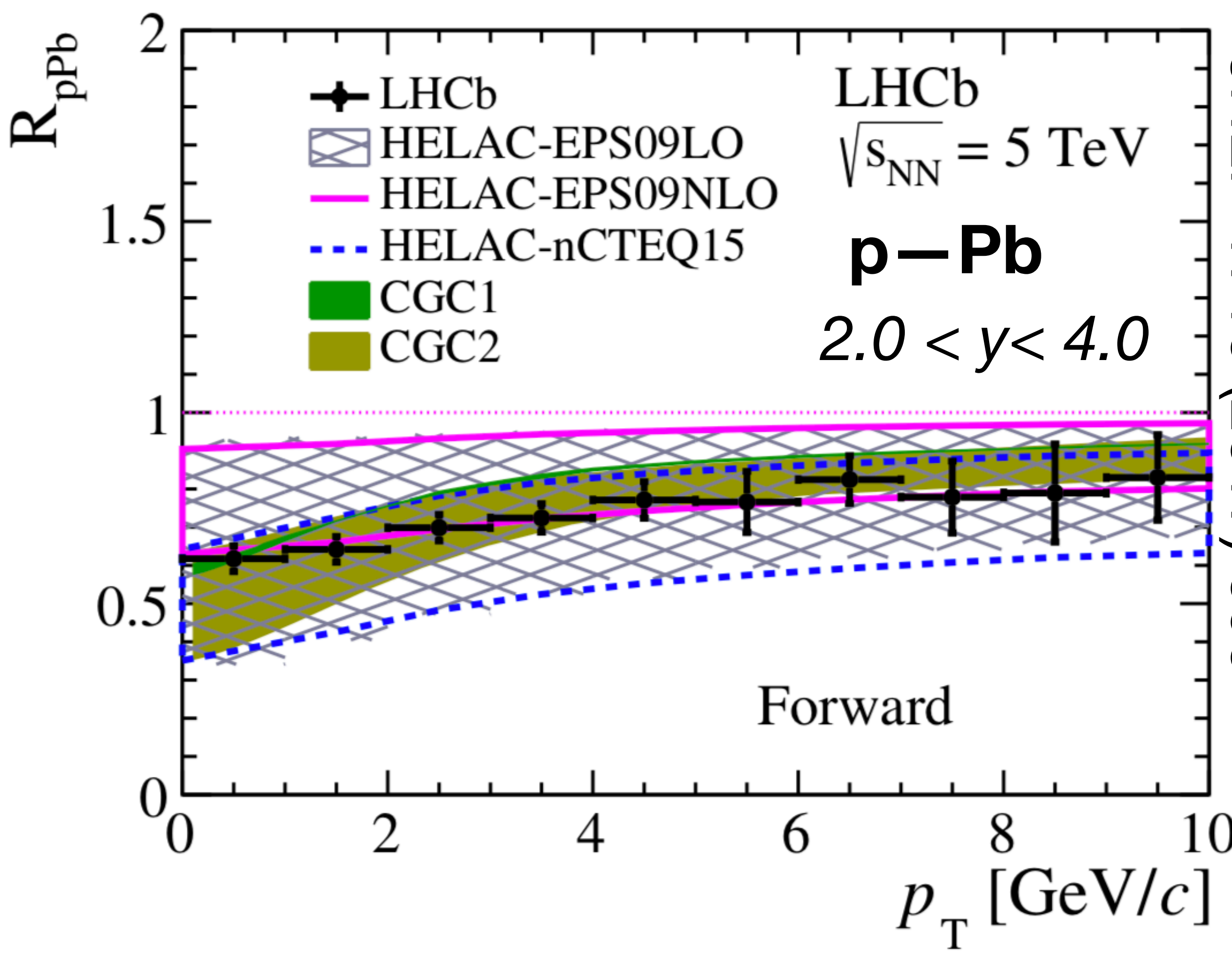


direct-γ, Compton (LO)



Heavy hadron:
tag hard scattering,
but includes fragmentation

Open heavy flavor measurement from LHCb



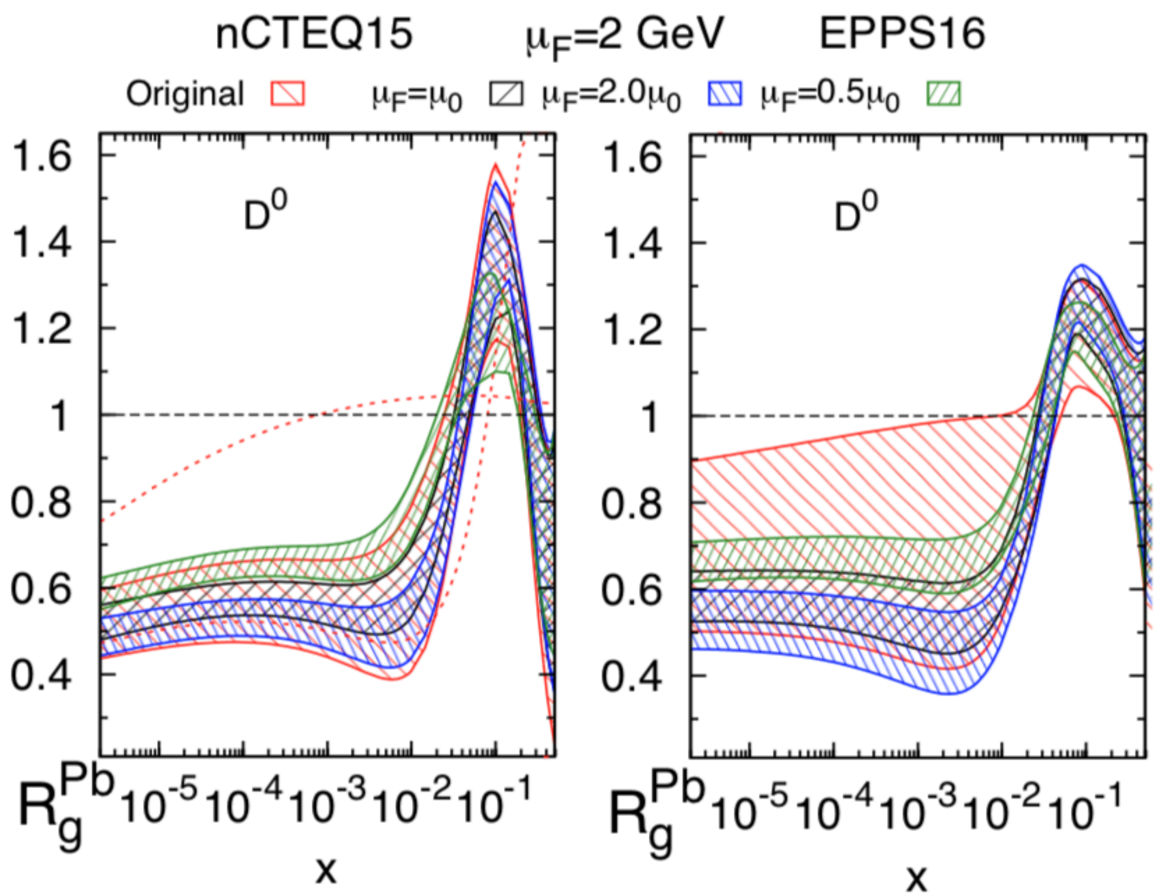
JHEP 1710 (2017) 090

Open charm used in re-weighting:

- Significant suppression in the very forward region

- relies on shape of parametrization: very little x-dependence at low-x

arXiv:2012.11562, JHEP 05 (2020)037



The data provide better constraints on the current gluon nPDF's:

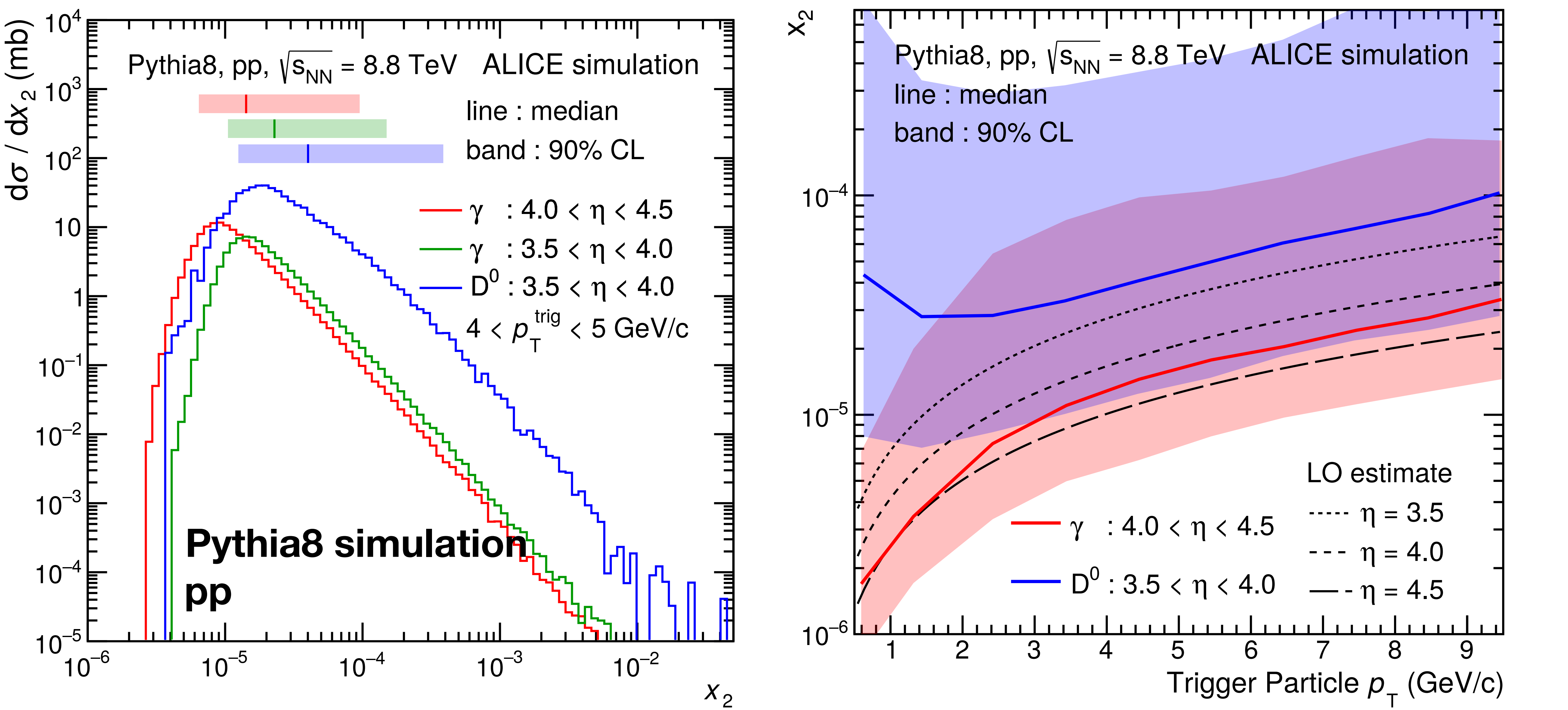
- Includes uncertainties from the fragmentation
- Possible final state effects are under discussion (D,J/ψ and HF electrons were observed to have azimuthal modulation in high multiplicity p-Pb)

Direct photons as probes

Direct photons are sensitive for the gluon PDF

In Run 4 we aim to measure in pp and p—Pb at 8.8 TeV

https://cds.cern.ch/record/2719928

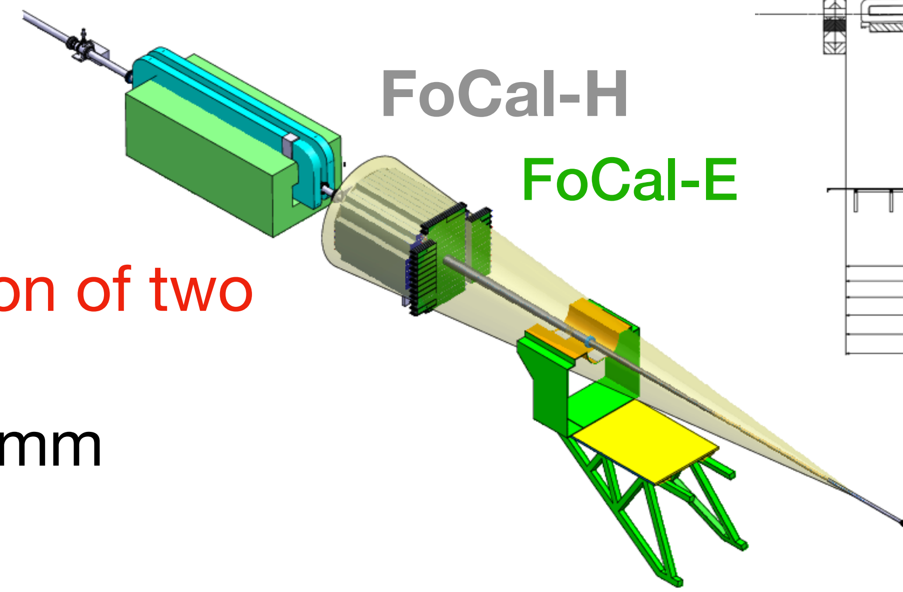


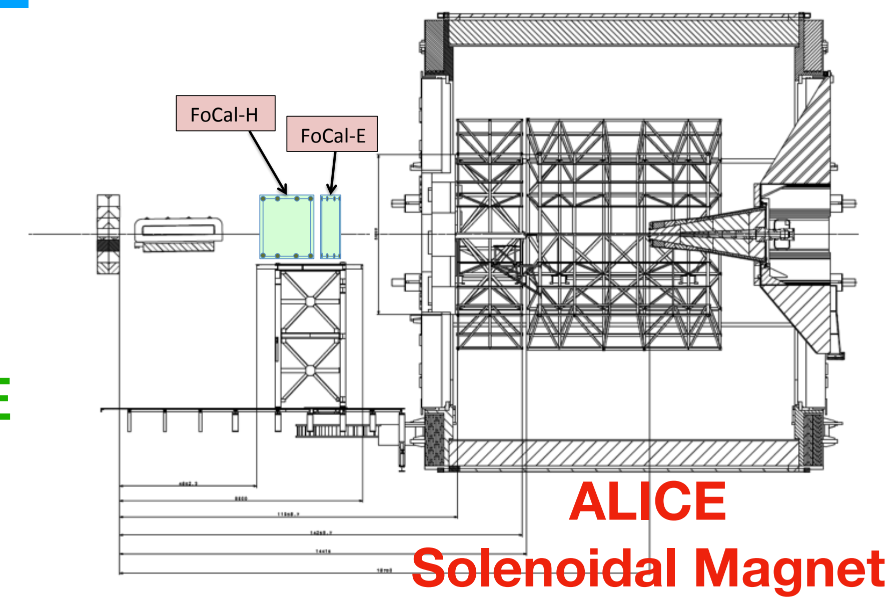
Comparison of the direct photon and D^0 as a probe for the nuclear PDF:

- No fragmentation is involved in the direct photon production
- Photons have no final-state interaction through the strong force

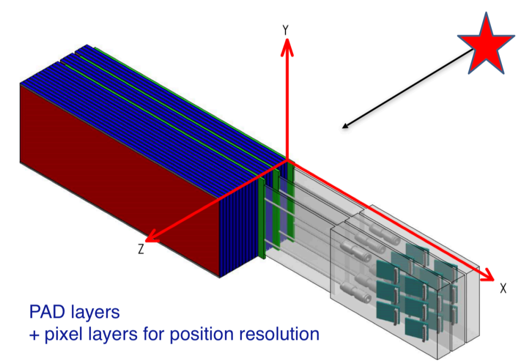
The ALICE - FoCal Proposal

FoCal Proposal:
- 7 m from the interaction point
  - covering **$3.4 < \eta < 5.8$**
- FoCal-E - electromagnetic part:
  - **direct-γ and π^0** measurement
  - Main challenge is the separation of two clusters at high energy
  - Shower separation down to 1 mm
  - Good energy resolution 2-5%
- FoCal-H - hadronic calorimeter:
  - Isolation cut
  - Jet measurement

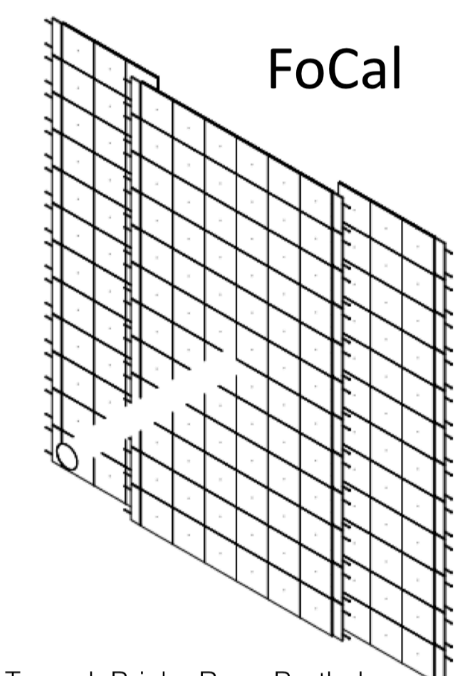




Installation possibility during LS3 (2024-2026) to be used in LHC Run 4.
Basic building block of the FoCal-E prototype already constructed and tested in 2018 in PS and SPS testbeams:
- Final design prototype scheduled to be tested in 2021

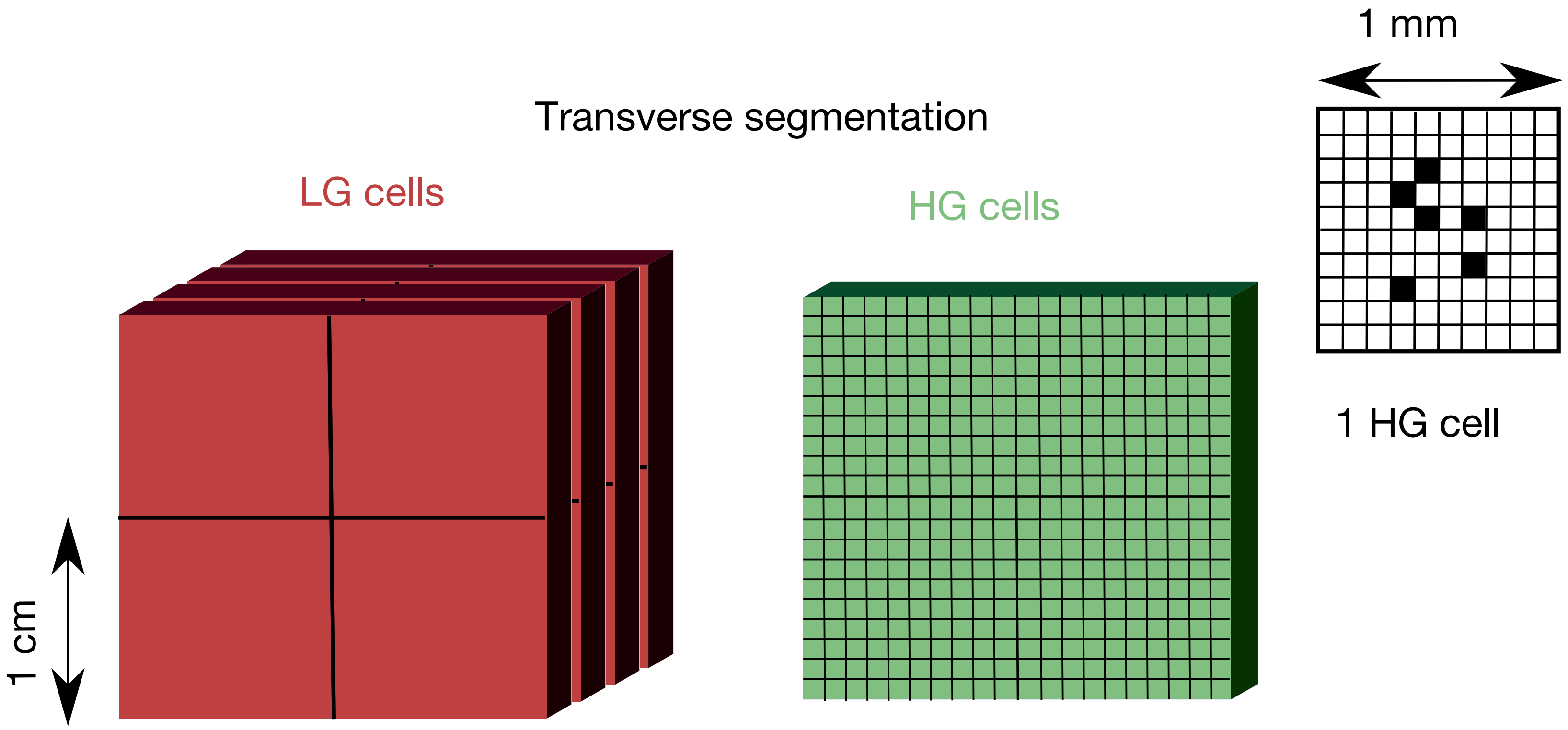


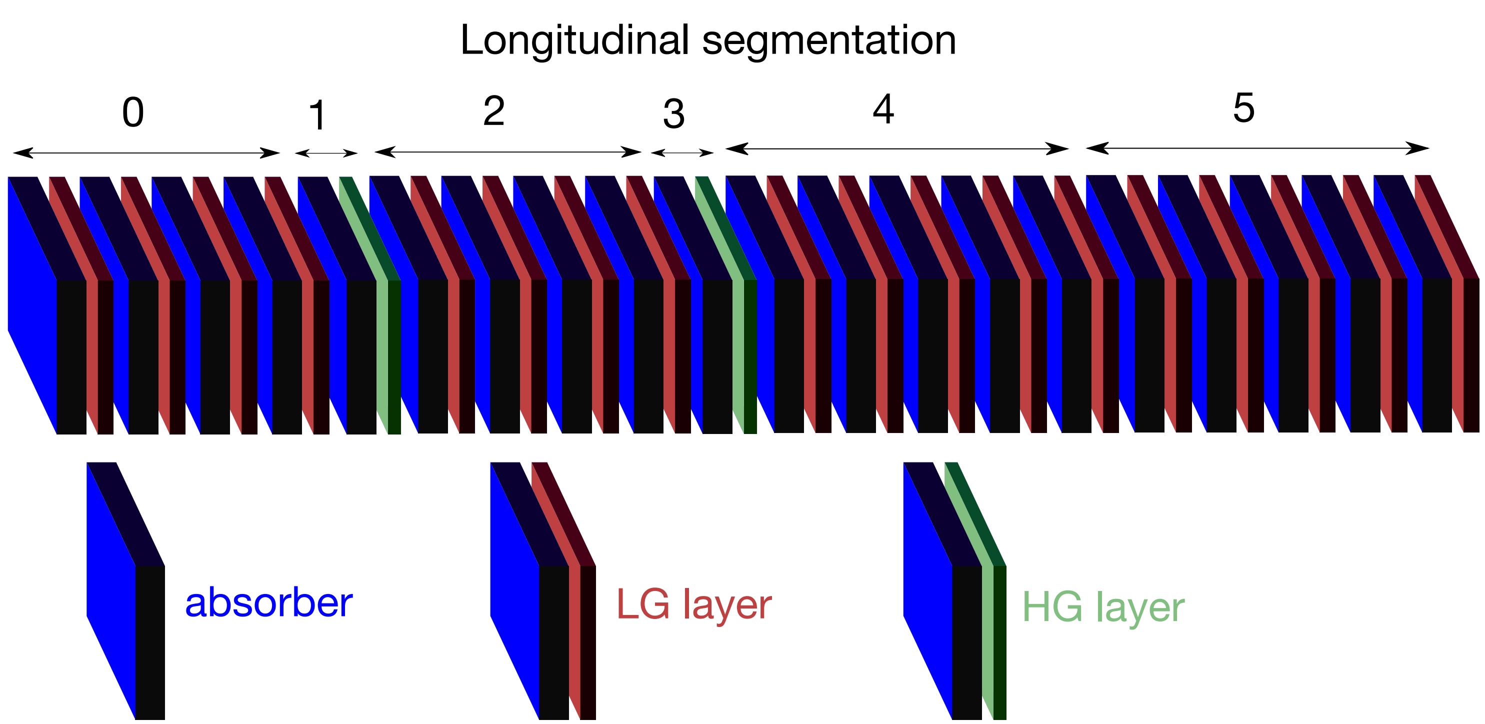
FoCal-E



Ton v.d. Brink, Rene Barthel

FoCal-E basic design





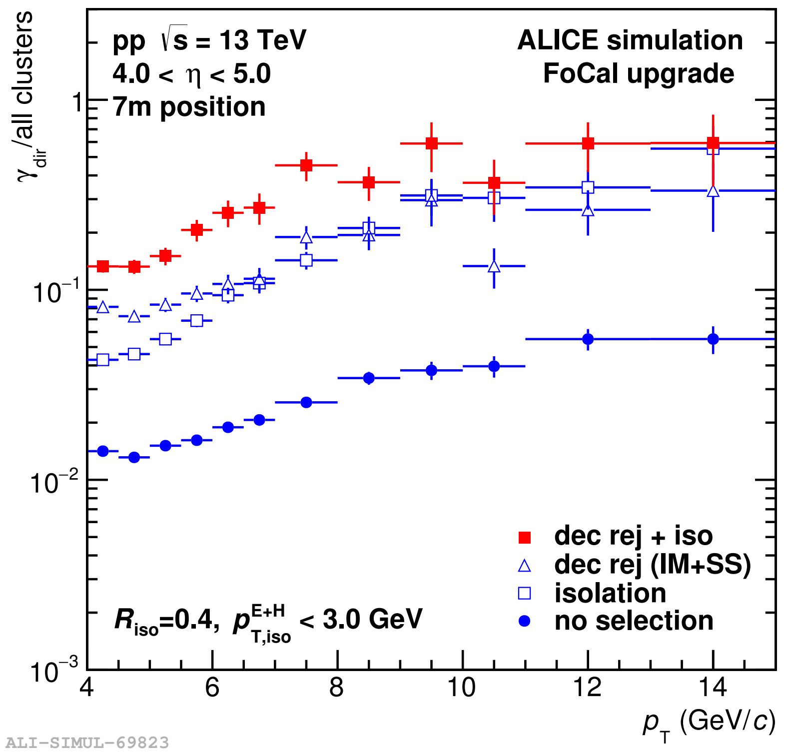
The design of the detector:

- 20 layers: W (**3.5 mm ≈ 1 X_0**) + Si-sensors (2 types):
  - **low granularity (LG), Si-pads**
  - **high granularity (HG), pixels (e.g. CMOS-MAPS)**
- Moliere radius ~ 1-2 cm

	LG	HG
pixel/pad size	≈ 1 cm^2	≈ 30x30 μm^2
total # of pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9

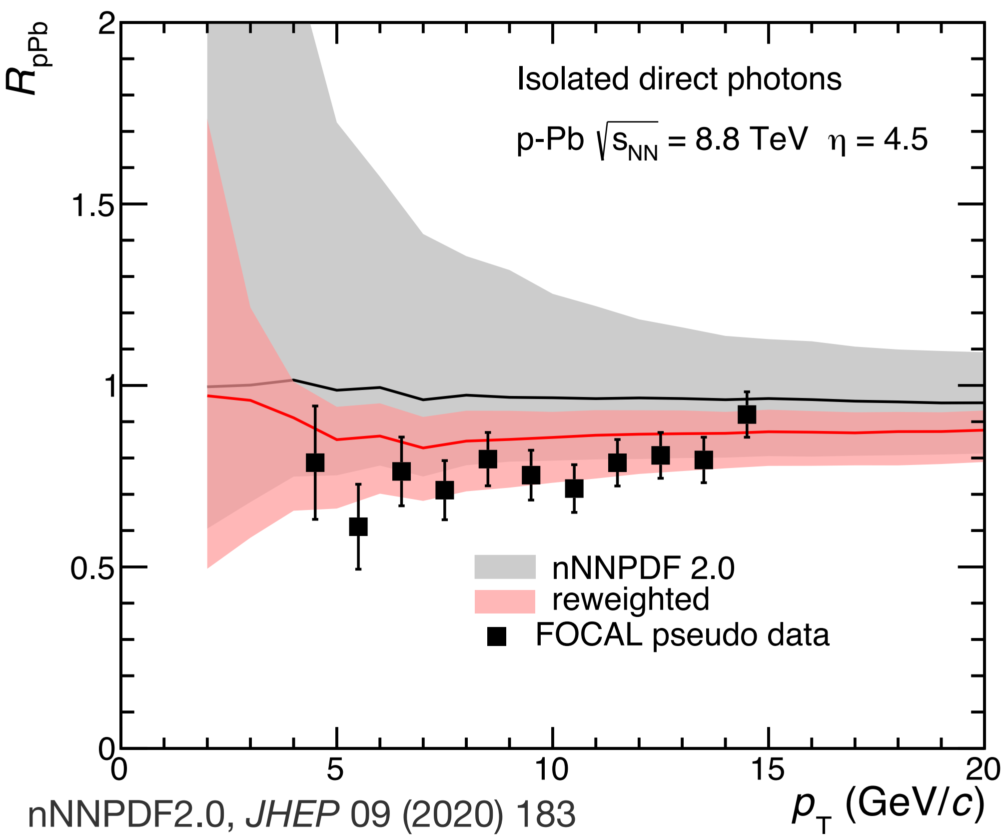
The surface area of the detector will be about 1 m^2

Performance studies

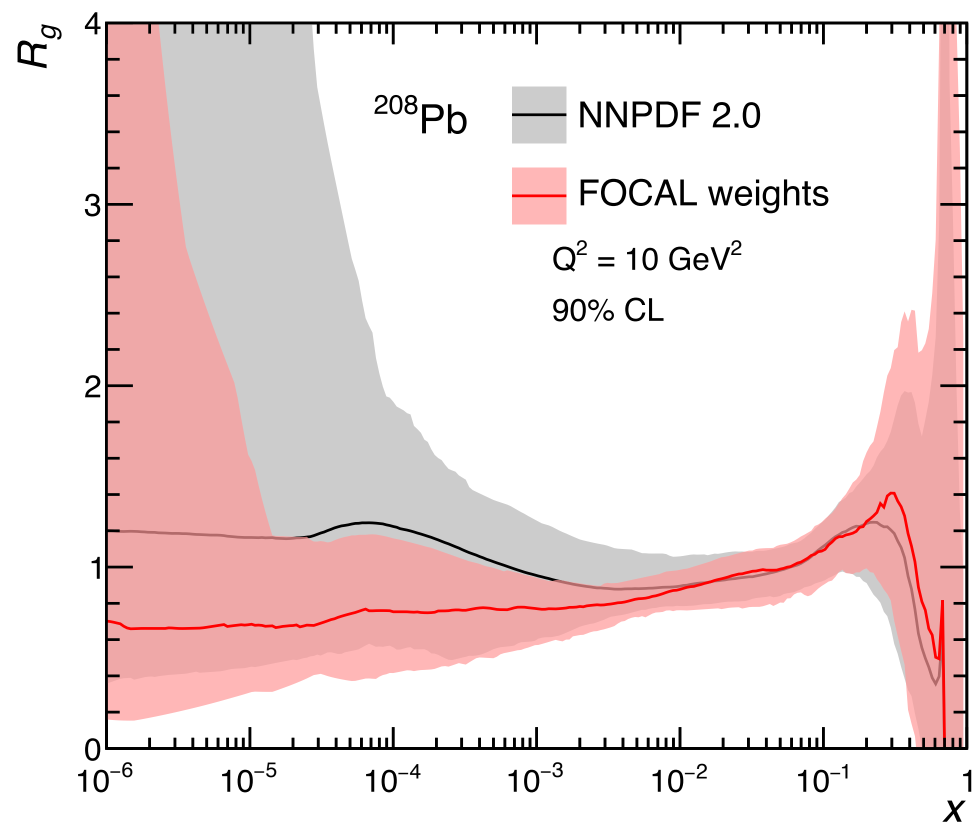


The detector is a novel design for calorimeters and enables us to achieve a better purity of direct photon measurements:

- Combined rejection (invariant mass and shower shape analysis, plus the isolation method)
- Combined Signal/Background improvement: factor 10 (largely p_T independent)
- Direct photon/all > 0.1 for p_T > 4 GeV/c



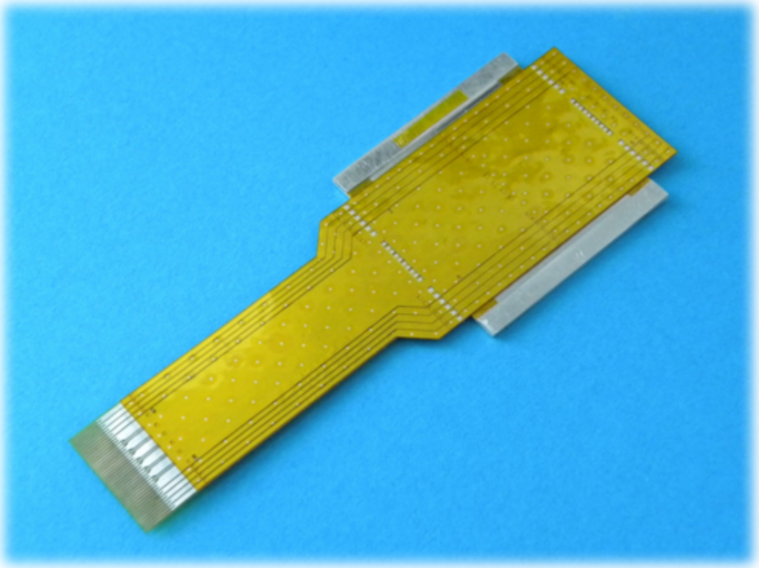
nNNPDF2.0, *JHEP* 09 (2020) 183

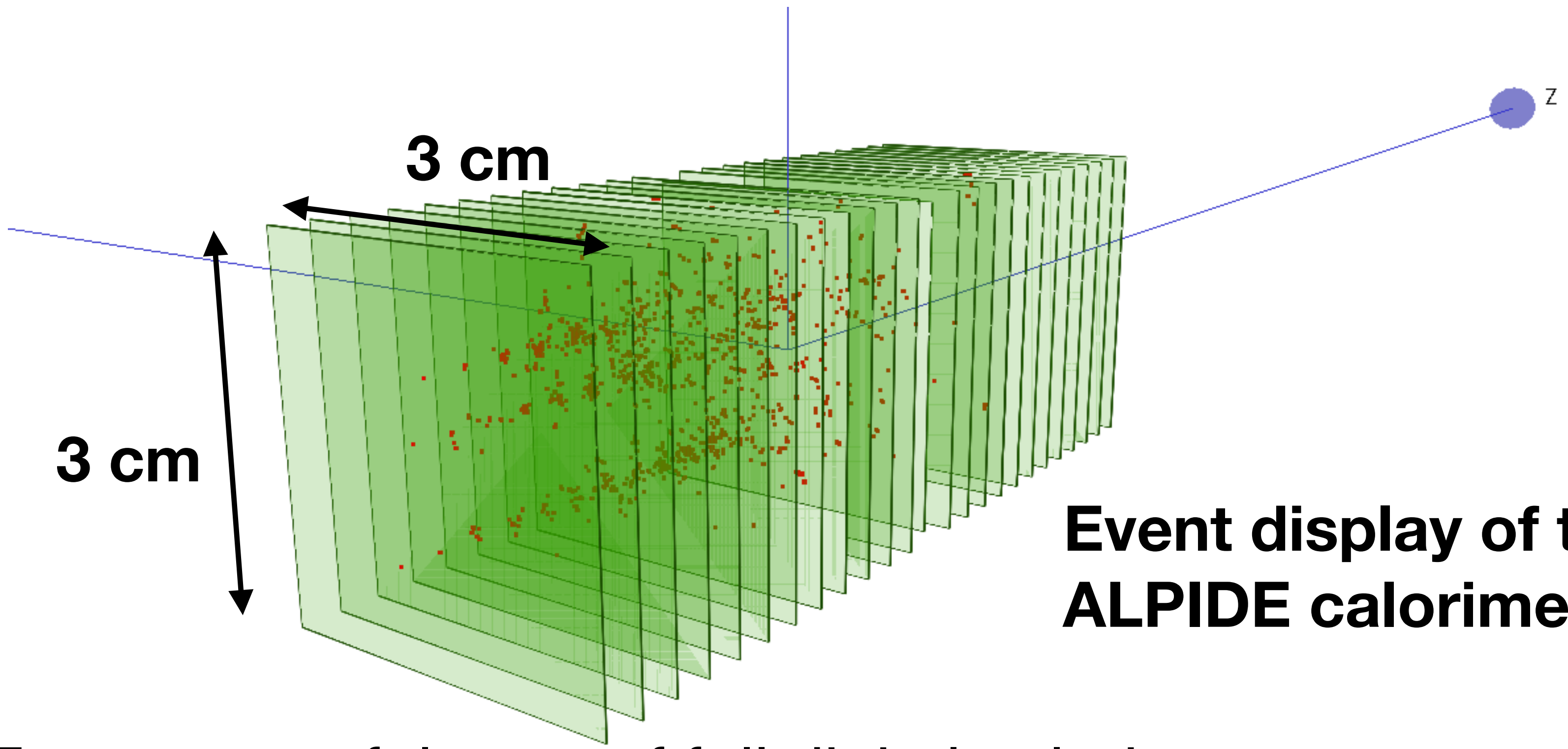


Projected uncertainties of the measurement and its impact on the PDF

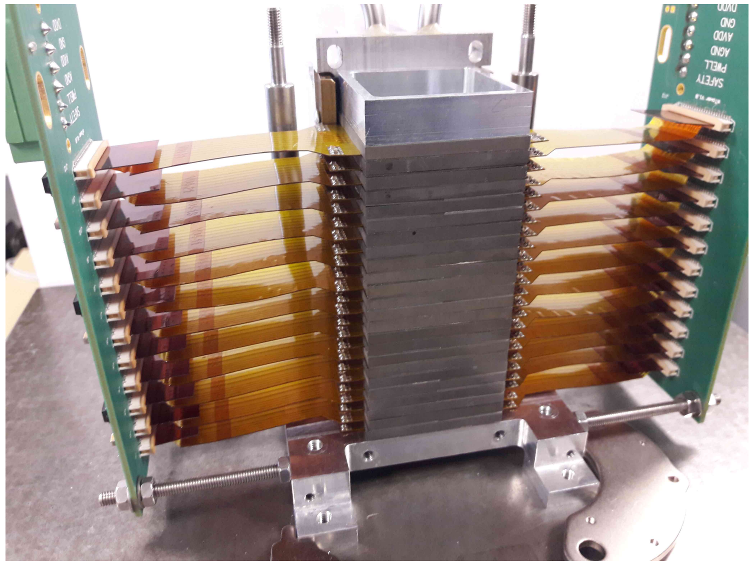
Significant improvement on the nPDF uncertainties down to x ~ 10^{-5}

Prototype MAPS detector





Event display of the ALPIDE calorimeter



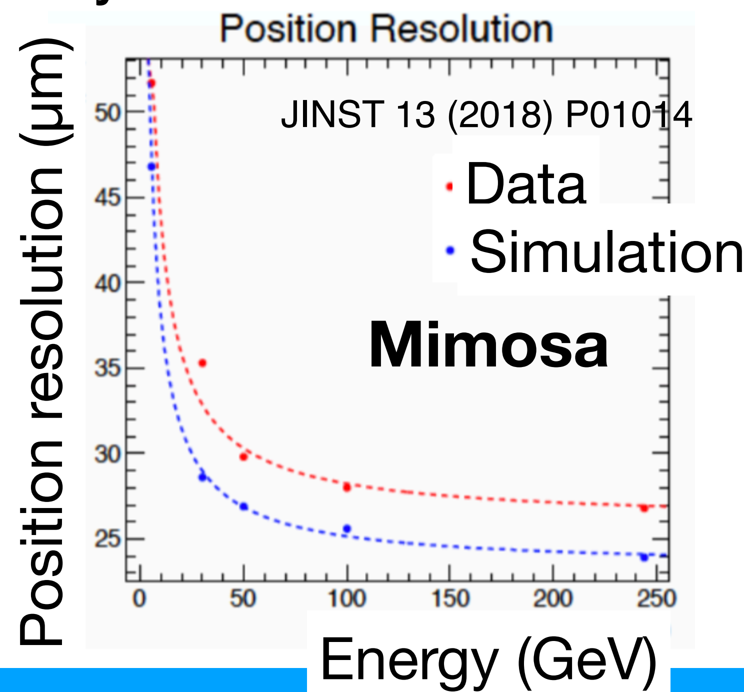
Two successful tests of full digital calorimeter:

- Mimosa sensor: published JINST 13 (2018) P01014
- ALPIDE sensor: DESY test in January 2020

Two shower separation is possible to very small distances:

Early stage of shower development is more collimated

With full digital calorimetry we can achieve ~30 μm position resolution of the single shower, in FoCal we require < 1 mm.

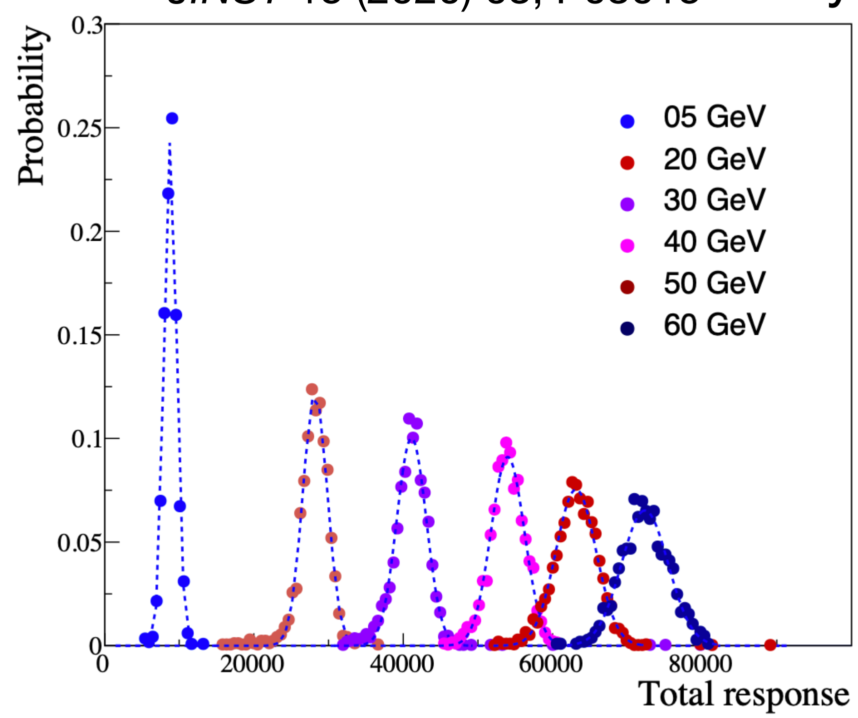


PAD layer prototypes

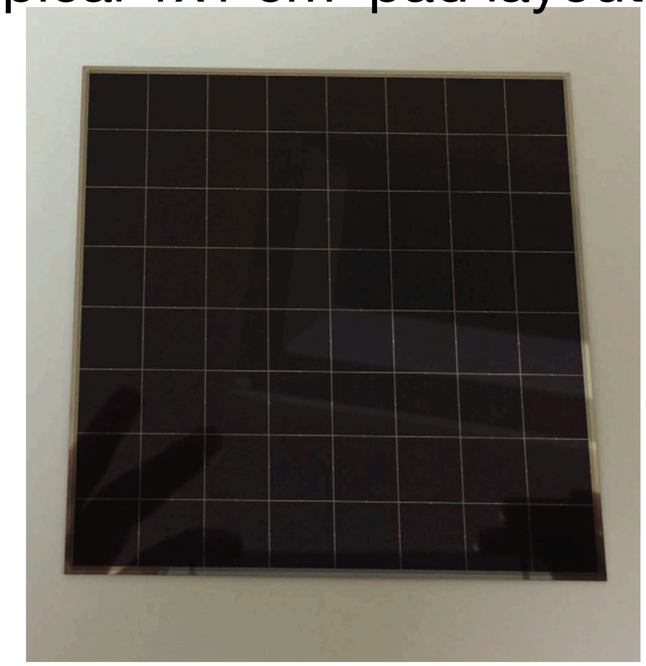
Few iterations of the PAD layer constructed

- India, 6x6 array, *JINST* 15 (2020) 03, P03015
- ORNL, Tsukuba: *NIM A 988 (2021) 164796*
- MiniFocal prototype
  - APV50 readout ASIC boards

JINST 15 (2020) 03, P03015

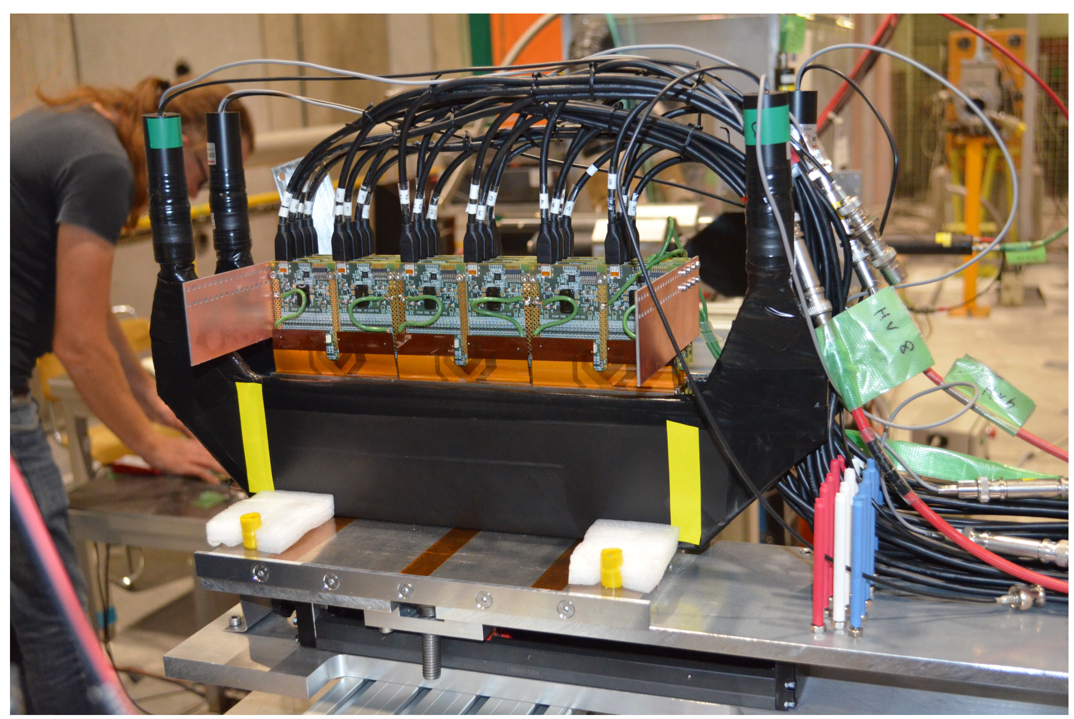


Typical 1x1 cm^2 pad layout

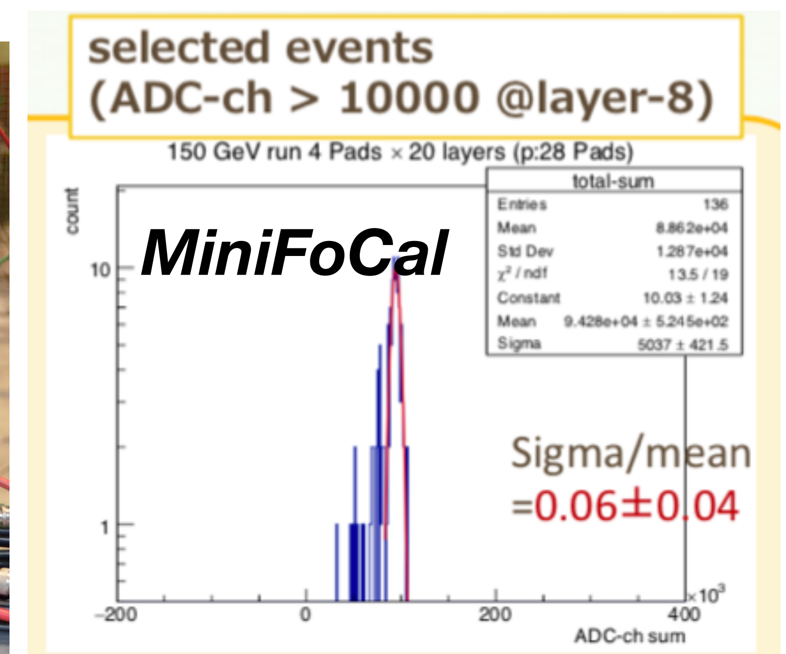


Testbeam measurements

- PS in 2018 July: 1-9 GeV electron and hadron beam
- SPS 2018 August: 50-250 GeV electron and hadron beam

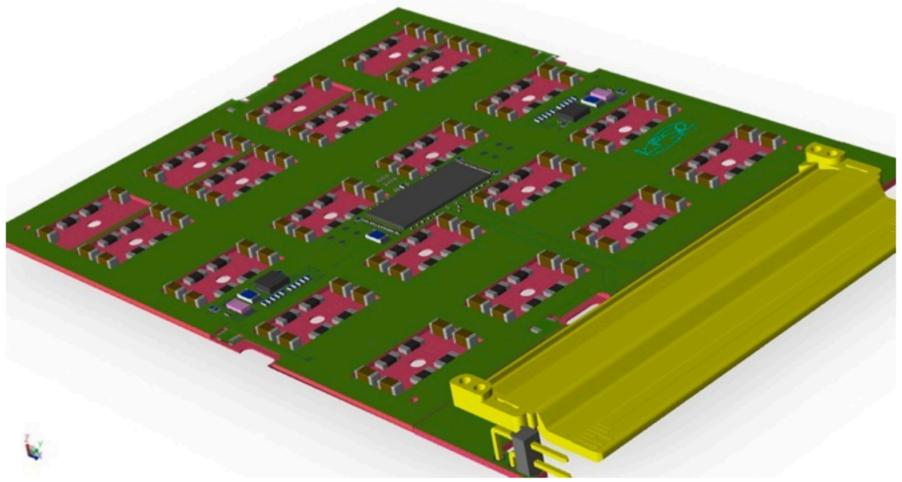


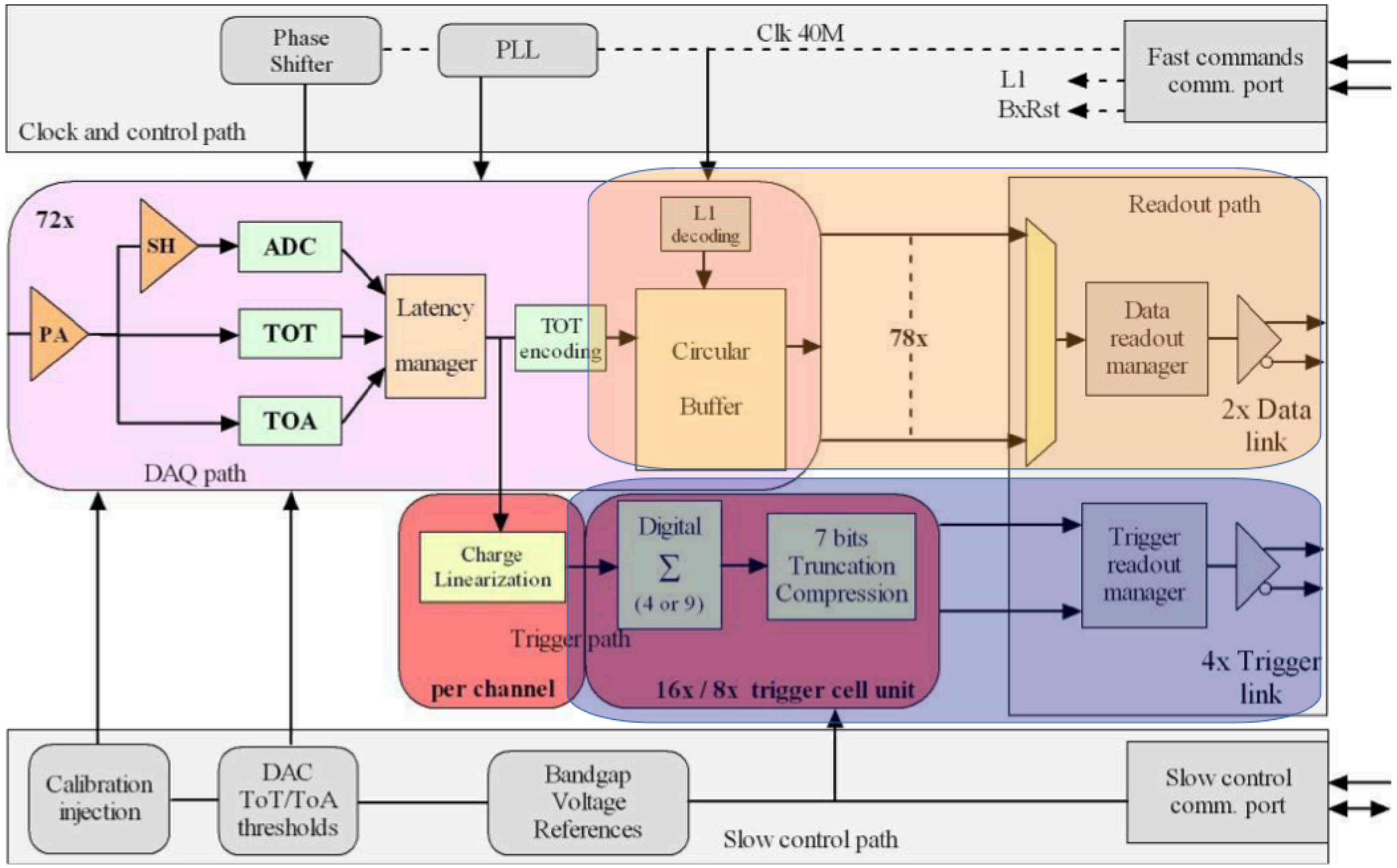
MiniFoCal setup



Initial analysis shows the resolution of the detector to be around 6% (work in progress)

HGCROC readout chip





HGCROC_v2 block diagram

Requirements on the electronics:

- From MIPs - used for calibration monitoring
- To 1 TeV shower maxima

FoCal-E front end:

- Low noise and large dynamic range 0.2 fC to 10 pC
- Linearity better than 1% on the full range
- Fast shaping time (peak time < 20 ns)
- High speed readout links (1.28 Gb/s)
- Low power budget < 20 mW
- High radiation resistance

HGCROC (Developed by CMS Collaboration)**:**

- 76 data channels (72 ch, 2 common noise, 2 calibration)
- ADC for low charge - 10b
- TOT for high charge - 12b

Summary

Forward physics at LHC provides an opportunity to study the low-x region:

- New constraints on the **gluon (n)PDF**
- Investigate the onset of possible of gluon saturation (**CGC)**
- Direct photons provide a more direct access to the low-x region (10^{-5})
  - No fragmentation function
  - No final-state effects

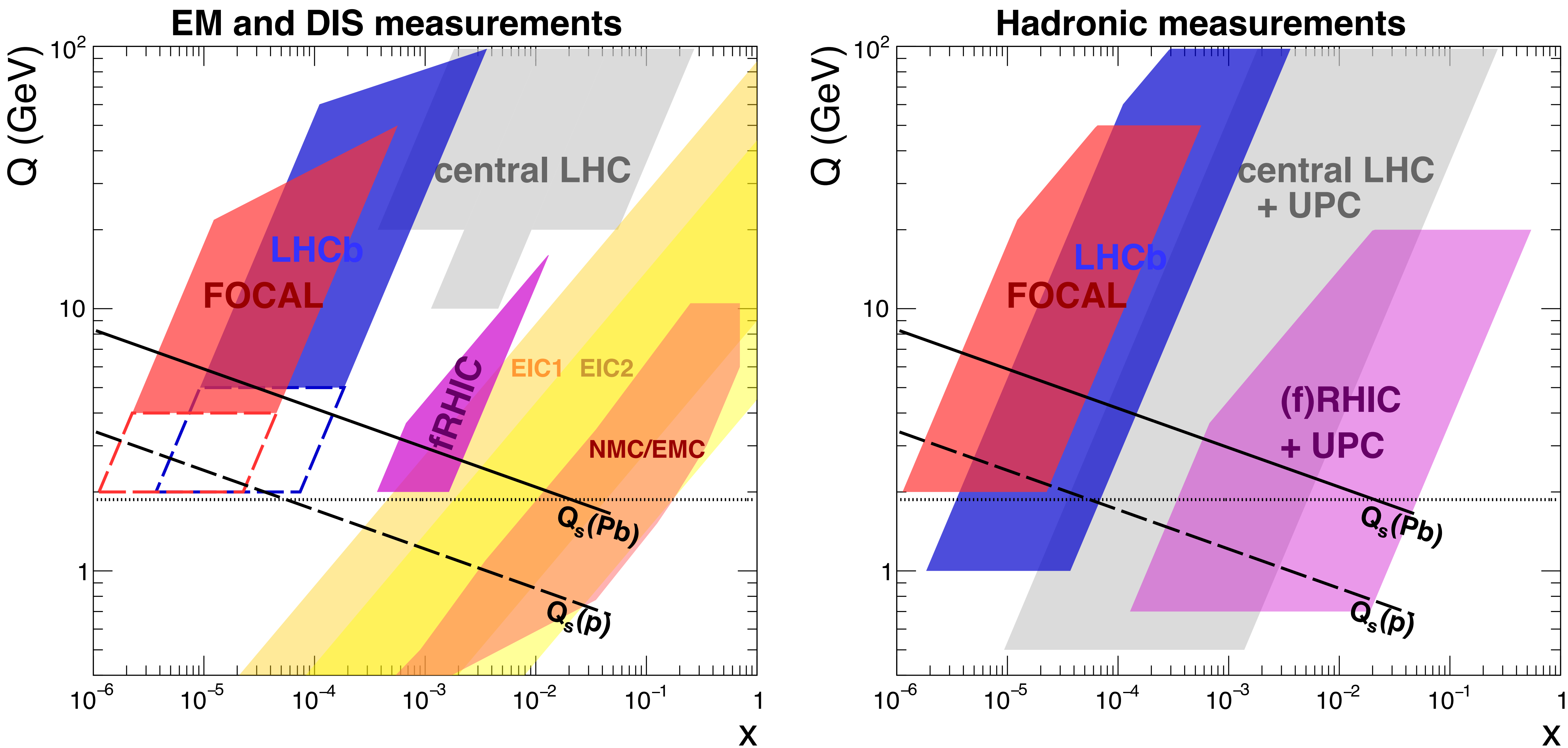
The ALICE FoCal proposal:

- Very forward detector to measure direct photon production at LHC:
  - Exclusive region up to 5.8 in pseudorapidity
- Proposed unique technology in design
  - Provide very good position resolution ~ 1 mm
  - Provide very good energy resolution ~ 2-5%
- Signal to background ratio > 0.1

- **LHCC endorsed the project for Run 4 (incl. 8.8 TeV p—Pb)**
- **Final prototype construction in 2021**
- **Technical Design Report (TDR) 2021-2022**

Backup

Coverage of the measurements



Coverage of the electromagnetic and hadronic probes by the current and planned measurements in LHC and other colliders.

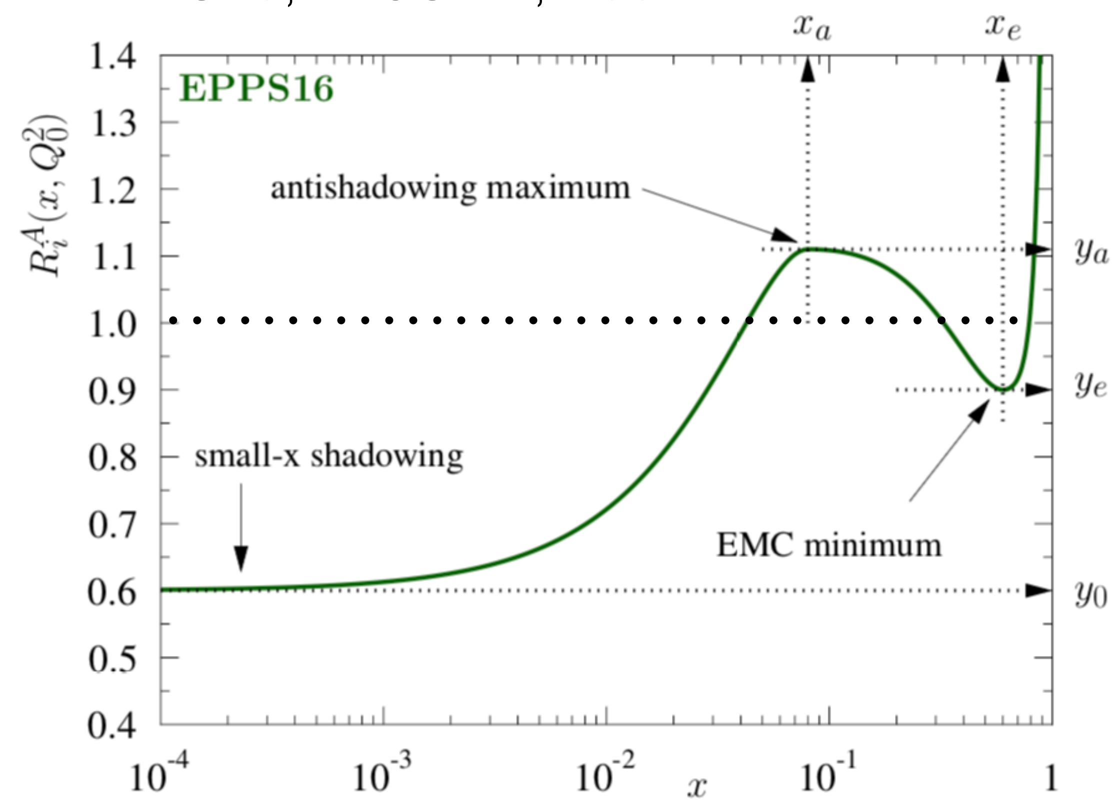
Nuclear Parton Distribution function

Defined as the ratio of the nuclear effect on the existing PDF's

Nuclear modification on the parton distribution function is usually parametrized as

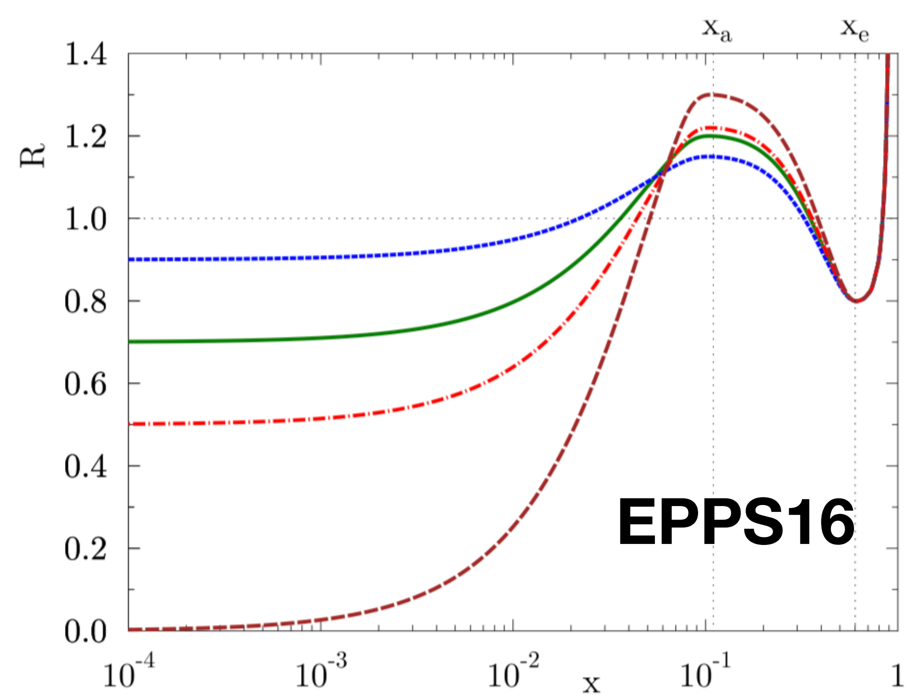
$$R_i^A(x,Q^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

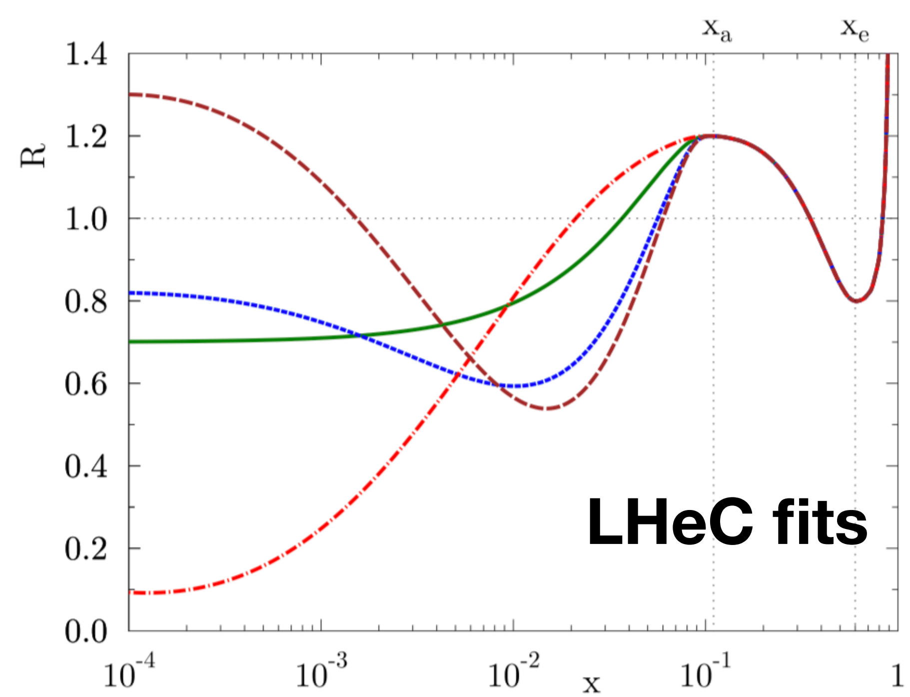
EPPS16, EPJC 77, 163



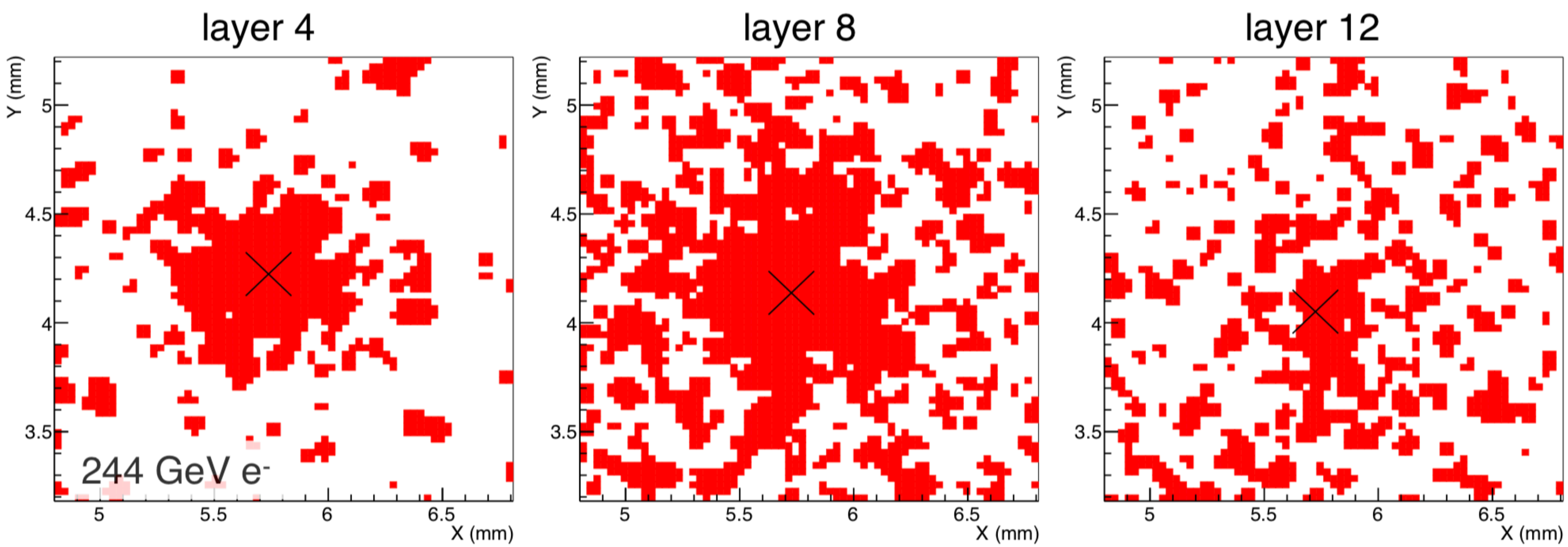
The shape of the nPDF's are constrained by the available world data - important to understand the initial state of heavy ion collisions

The small-x region is not very well constrained by data. The "plateau" of the data. The "plateau" of the shadowing region is the result of chosen parametrization. LHeC fits allow more flexibility on the shape.

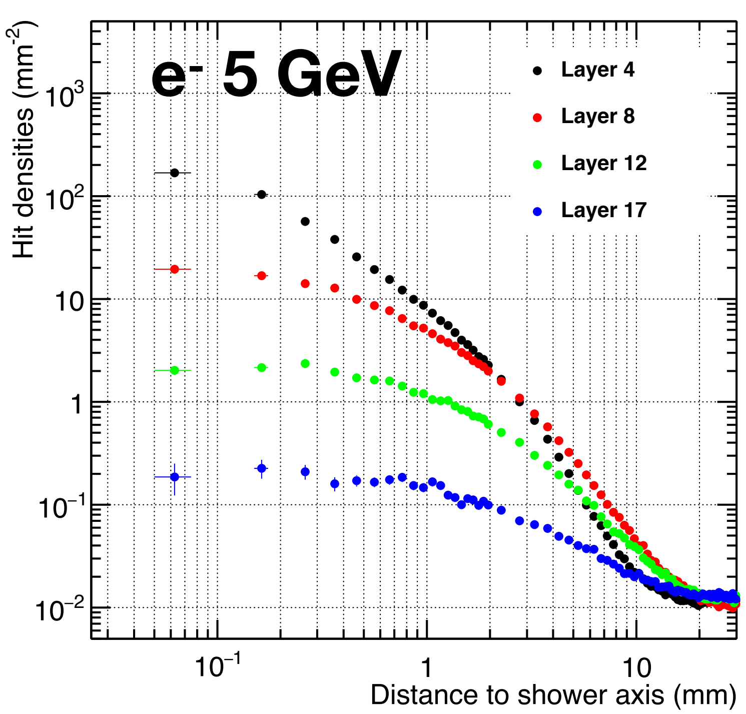


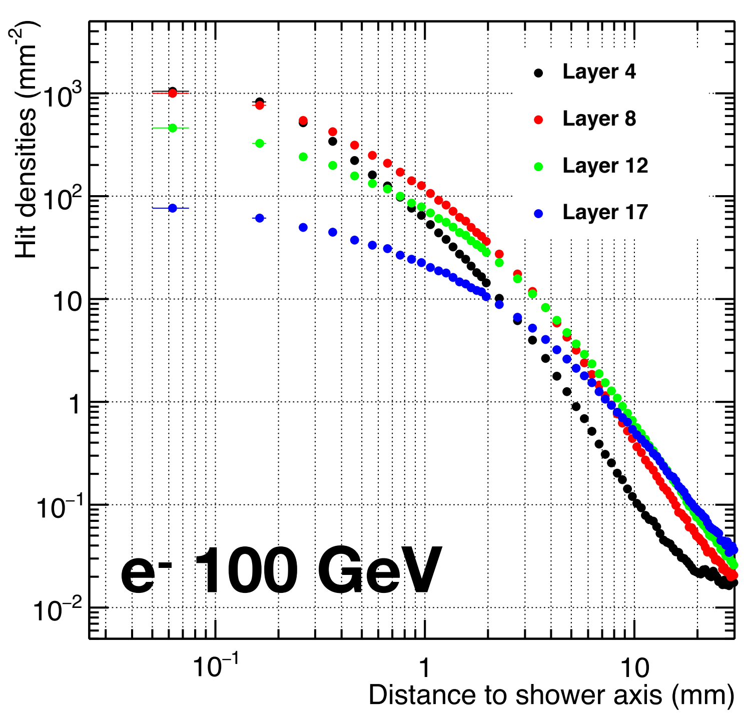


First prototype results



Example of an event: Very high density pixels provide precise profile of the electromagnetic showers





Have to use the number of hits to reconstruct the shower profile:

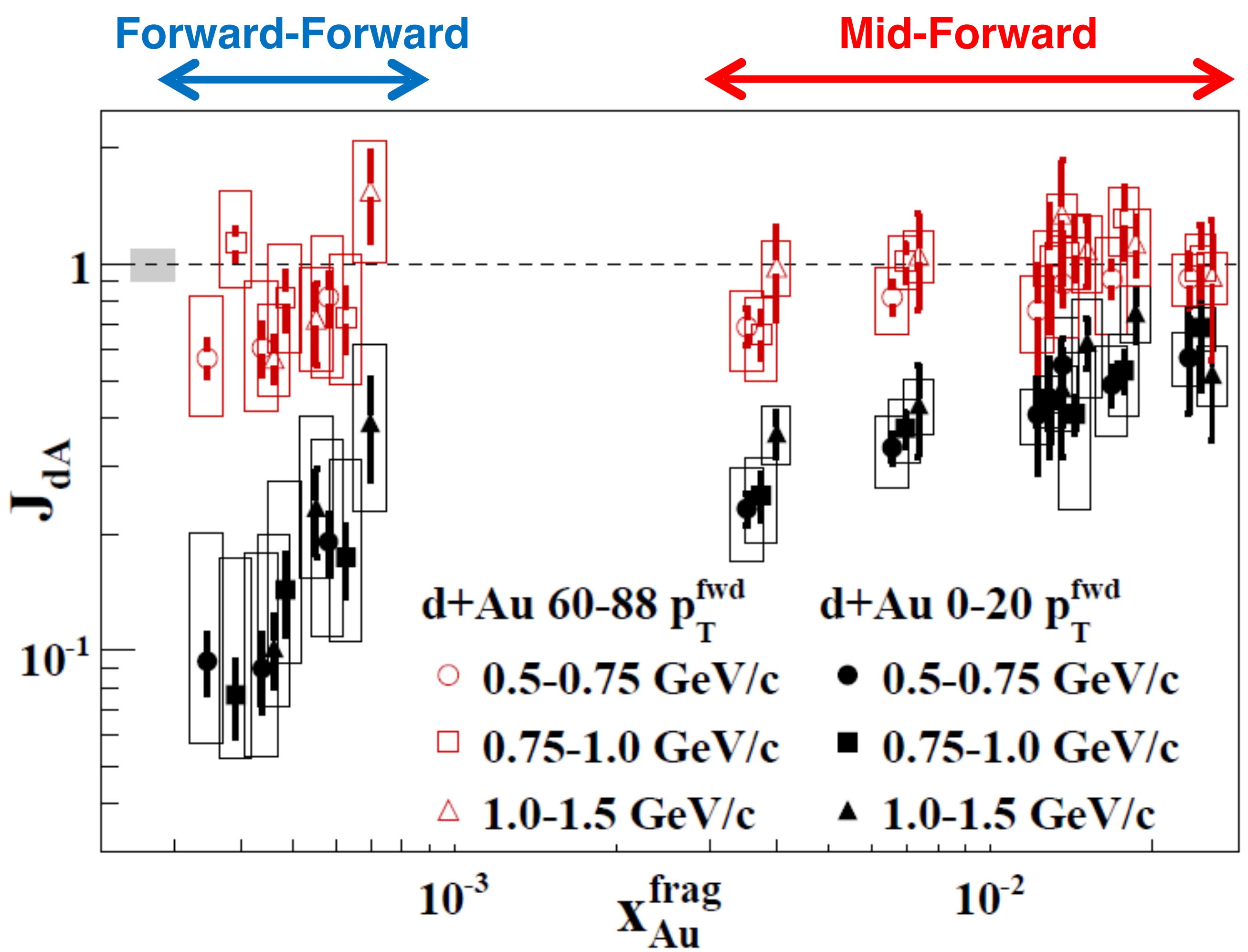
Average hit densities as a function of radius

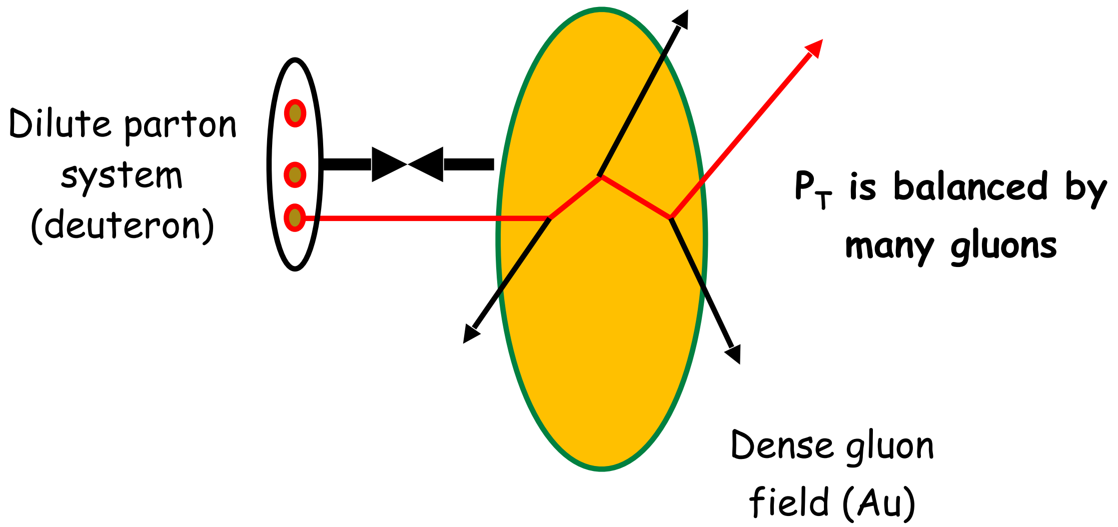
- Low energy: earlier shower maximum
- High energy: shower broadens up with depth

Results from RHIC at 200 GeV

The measurements of π-π correlations from RHIC in d+Au collisions at 200 GeV

PRL **107**, 172301





The results suggest a **large suppression** in the very forward region in the high multiplicity d+Au collisions

The suppression maybe cause as initial effect or final state effect.

Direct photon production is **unaffected** by the final state interactions - provide an ideal probe to test the observed suppression.