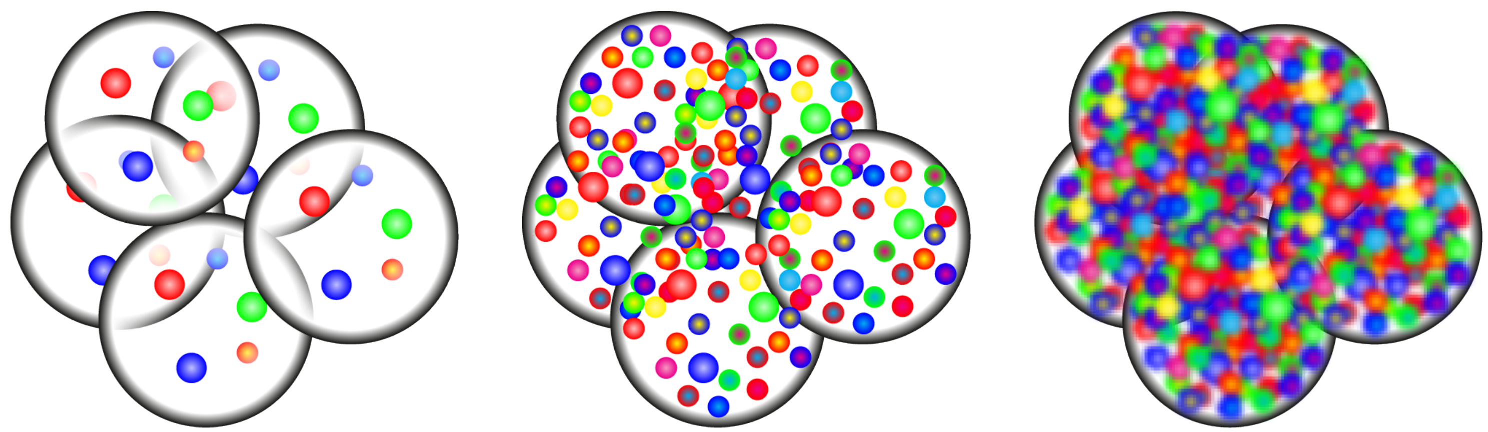
ALICE Forward Calorimeter (FoCal)

Detector design and physics reach

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



Joint CFNS & RBRC workshop

Tomonaga Center for the History of the Universe

筑波大学 University of Tsukuba

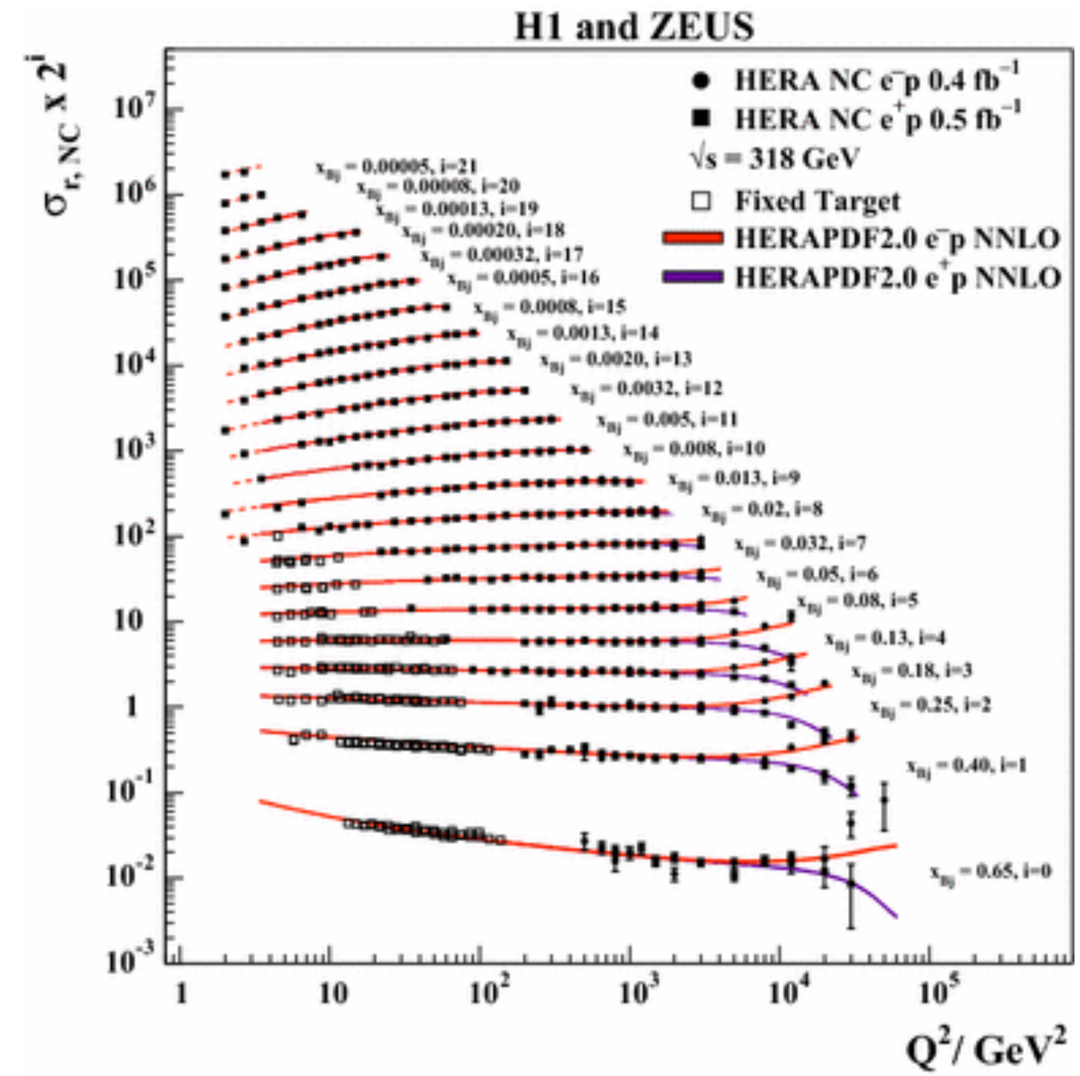
Parton Distribution Functions

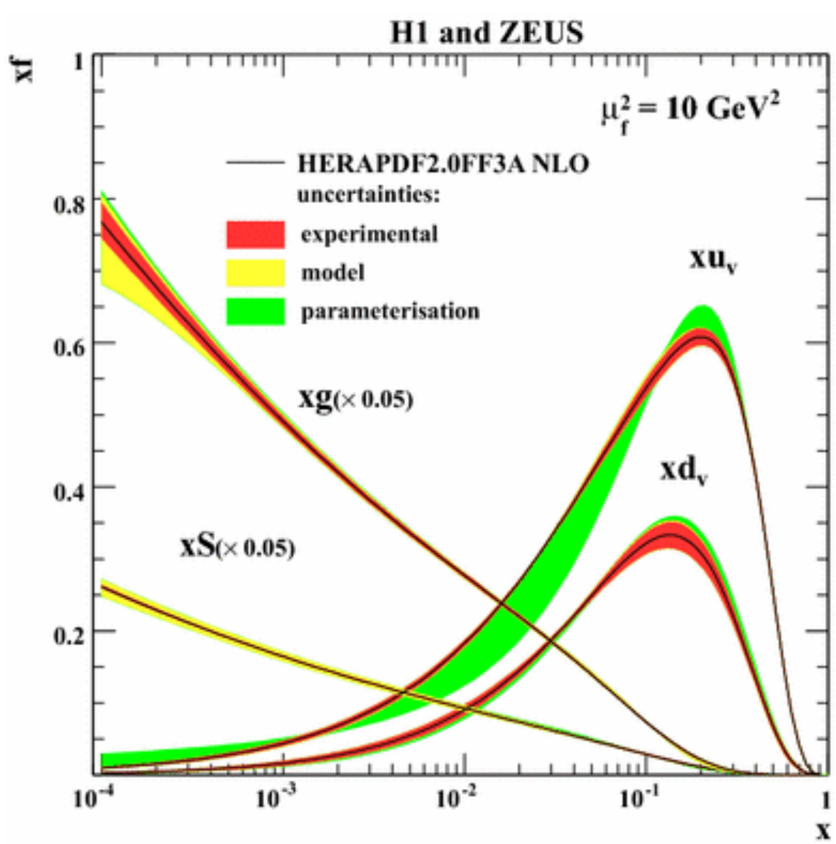
Eur. Phys. J. C (2015) 75: 580

Cross section calculated from the pQCD factorization:

$$d\sigma = \int dx_1\, dx_2\, dz\, f_a(x_1, Q^2) f_b(x_2, Q^2) D_c^h(\hat{z}) \otimes d\sigma_{ab}^{cd}(Q^2)$$

The parton distribution functions (PDF) and fragmentation function (FF) are obtained from the measured data.



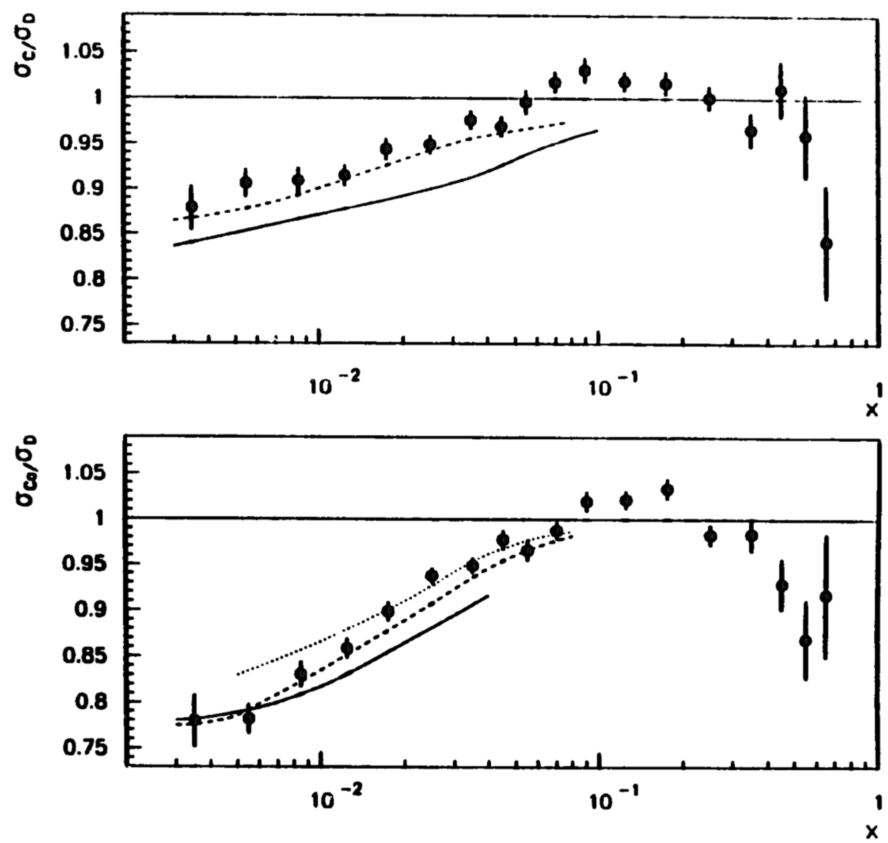


Measurements of of e⁻p collisions:

- Data follows the calculated DGLAP evolution
- Provide data for the the parton distribution functions

ALICE

Nuclear Parton Distribution Function



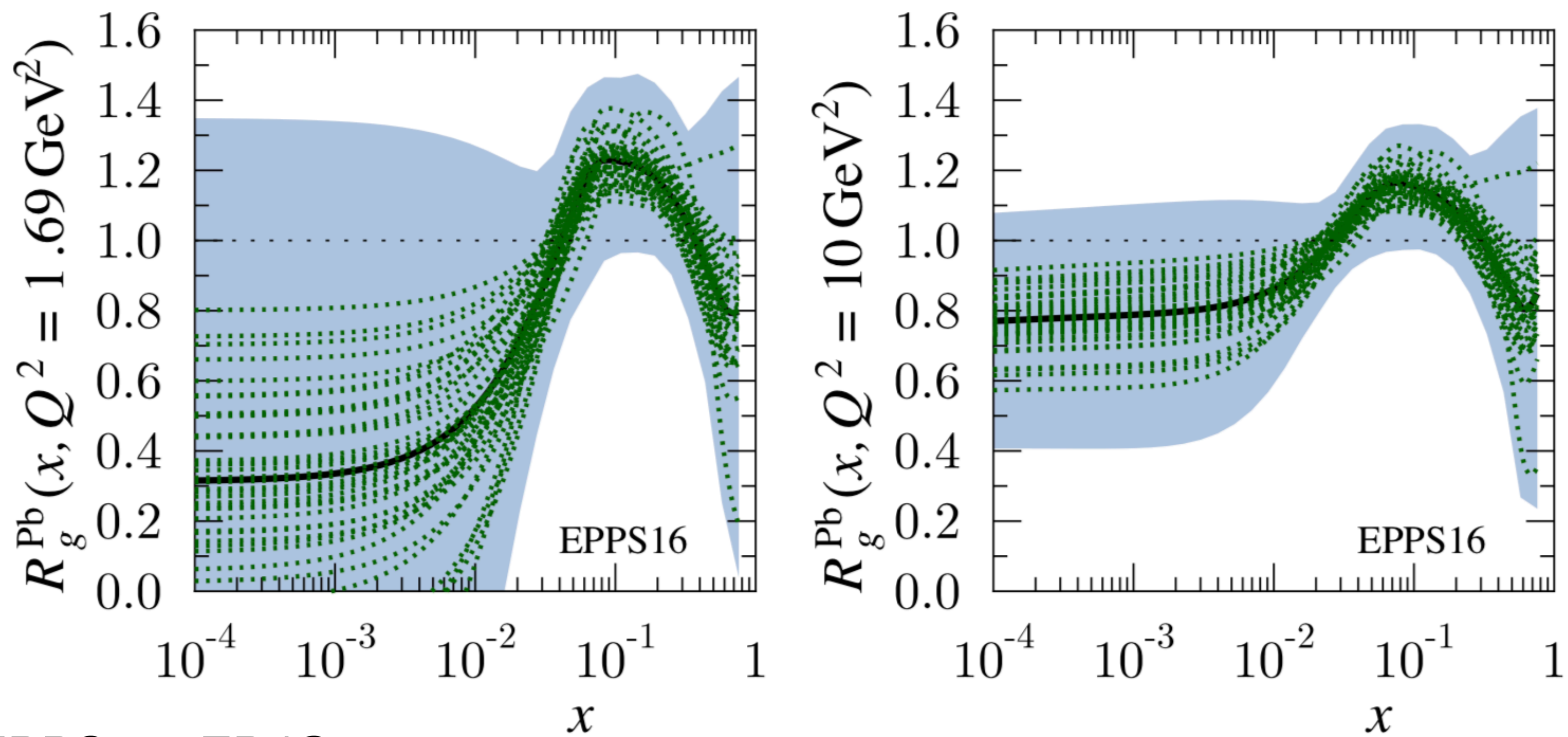
Physics Reports, 240 (1994), 301—393

It was found that in nuclear interaction, 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

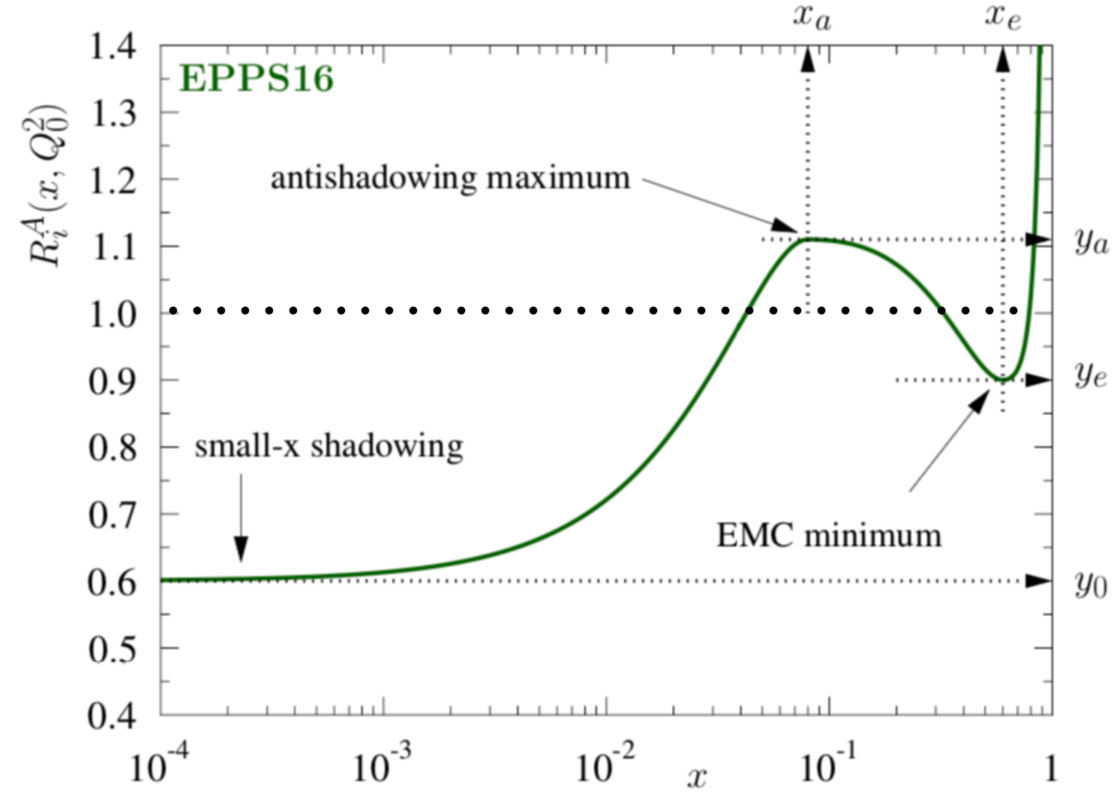
Nuclear Parton Distribution function

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

Nuclear modification on the parton distribution function is usually parametrized as

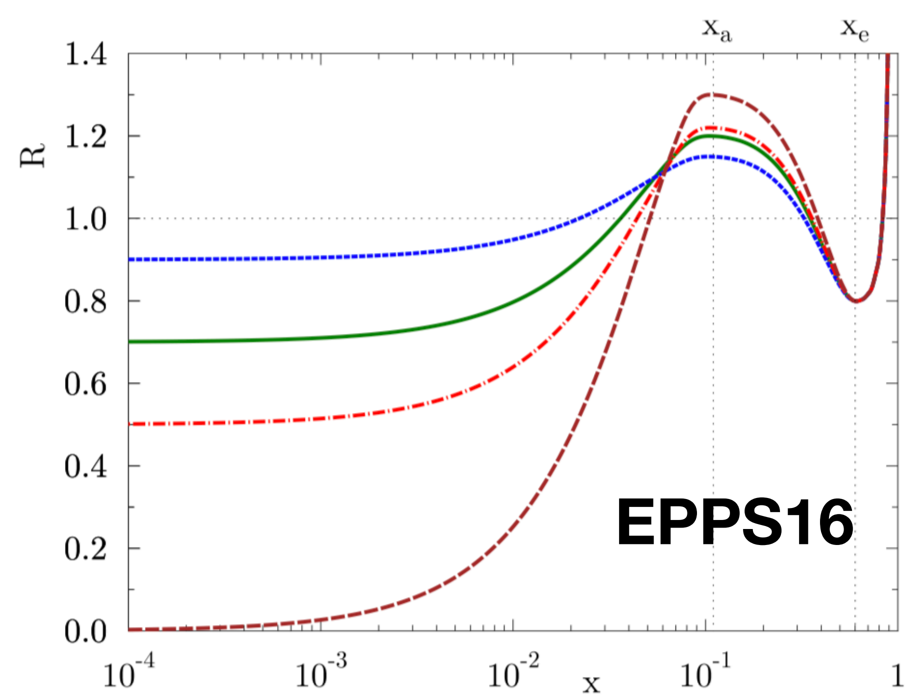
$$R_i^A(x,Q^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

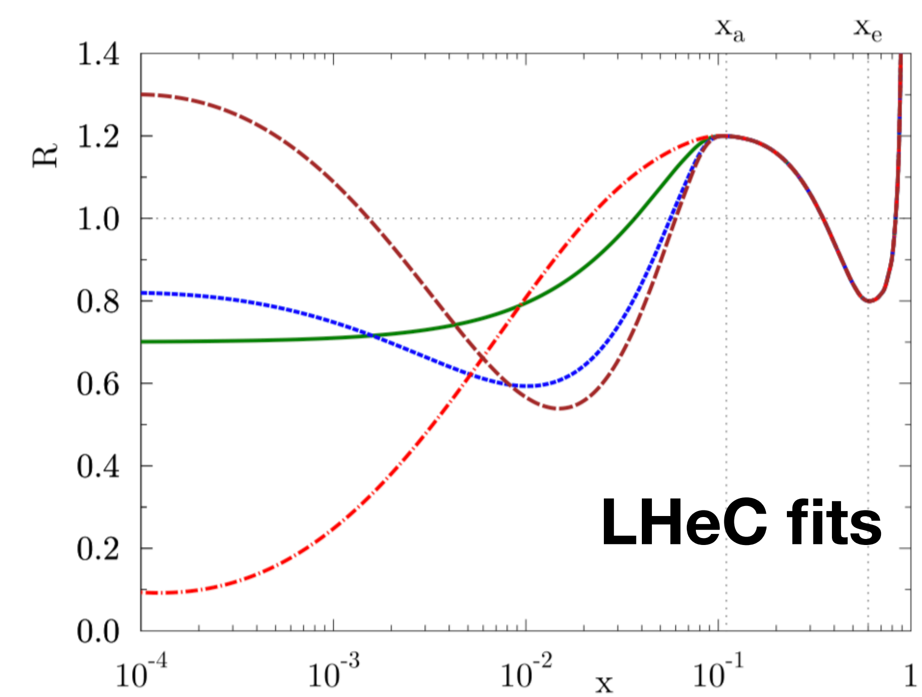
EPPS16, EPJC 77, 163



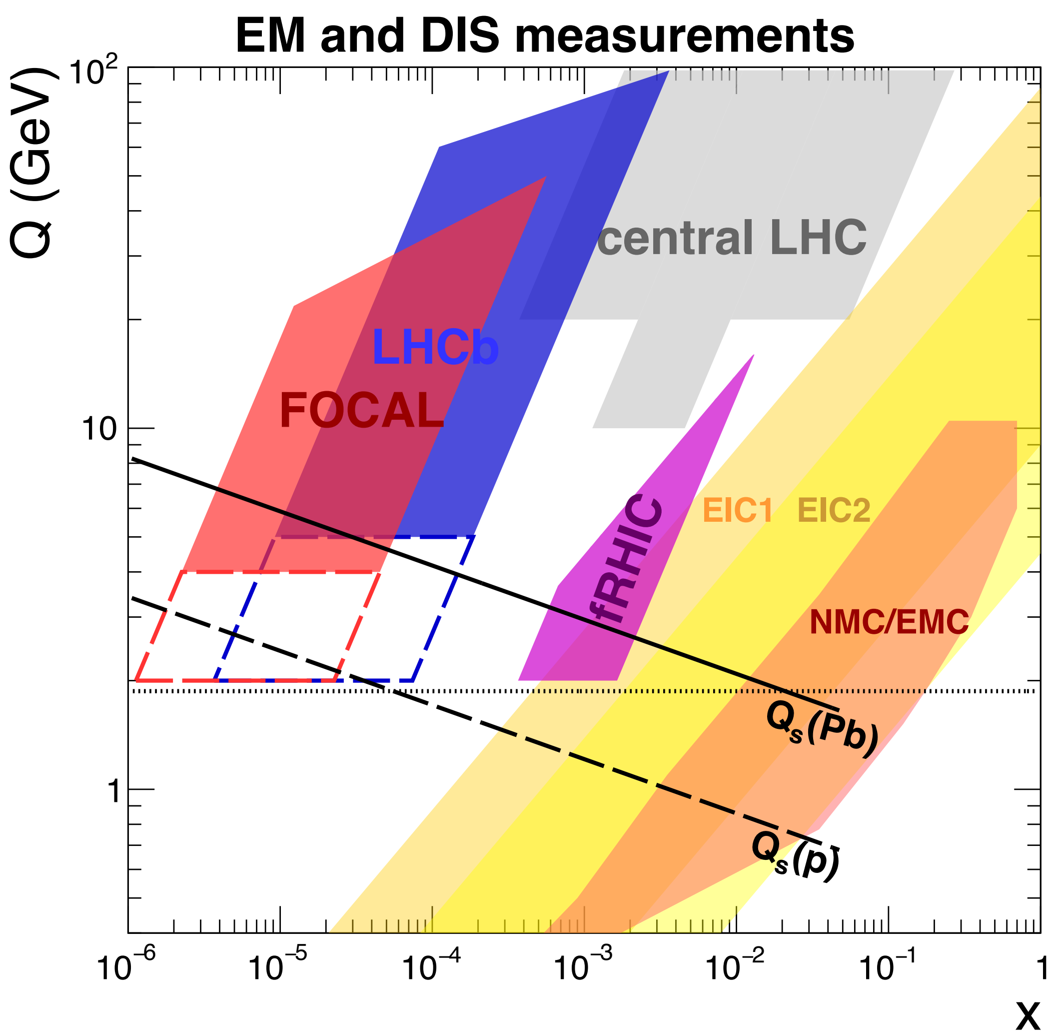
The shape of the nPDF’s are constrained by the available world data - important to understand the initial state of heavy ion collisions

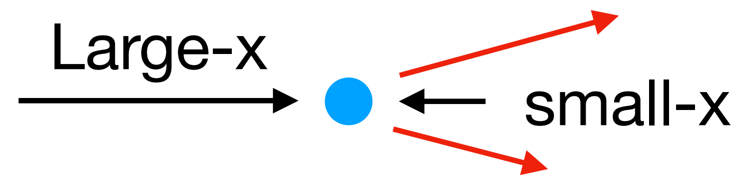
The small-x region is not very well constrained by data. The “plateau” of the data. The “plateau” of the shadowing region is the result of chosen parametrization. LHeC fits allow more flexibility on the shape.





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 FoCal and LHCb would be accessing this region of the phase space.

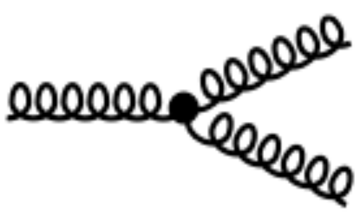
- LHCb: $2.5 < \eta < 5.0$
- FoCal: $3.3 < \eta < 5.8$
  - Main goal to measure direct photons and π^0 in *pp* and *p*-Pb collisions
  - Ongoing R&D work on the detector design
  - Under discussion in the ALICE collaboration

Prediction of gluon-saturation

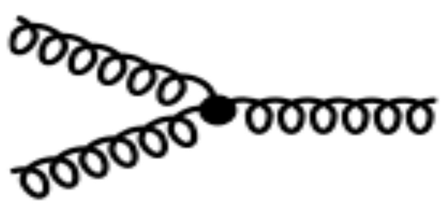
The BFKL equation (as well as DGLAP evolution) are linear equations and only include parton splitting

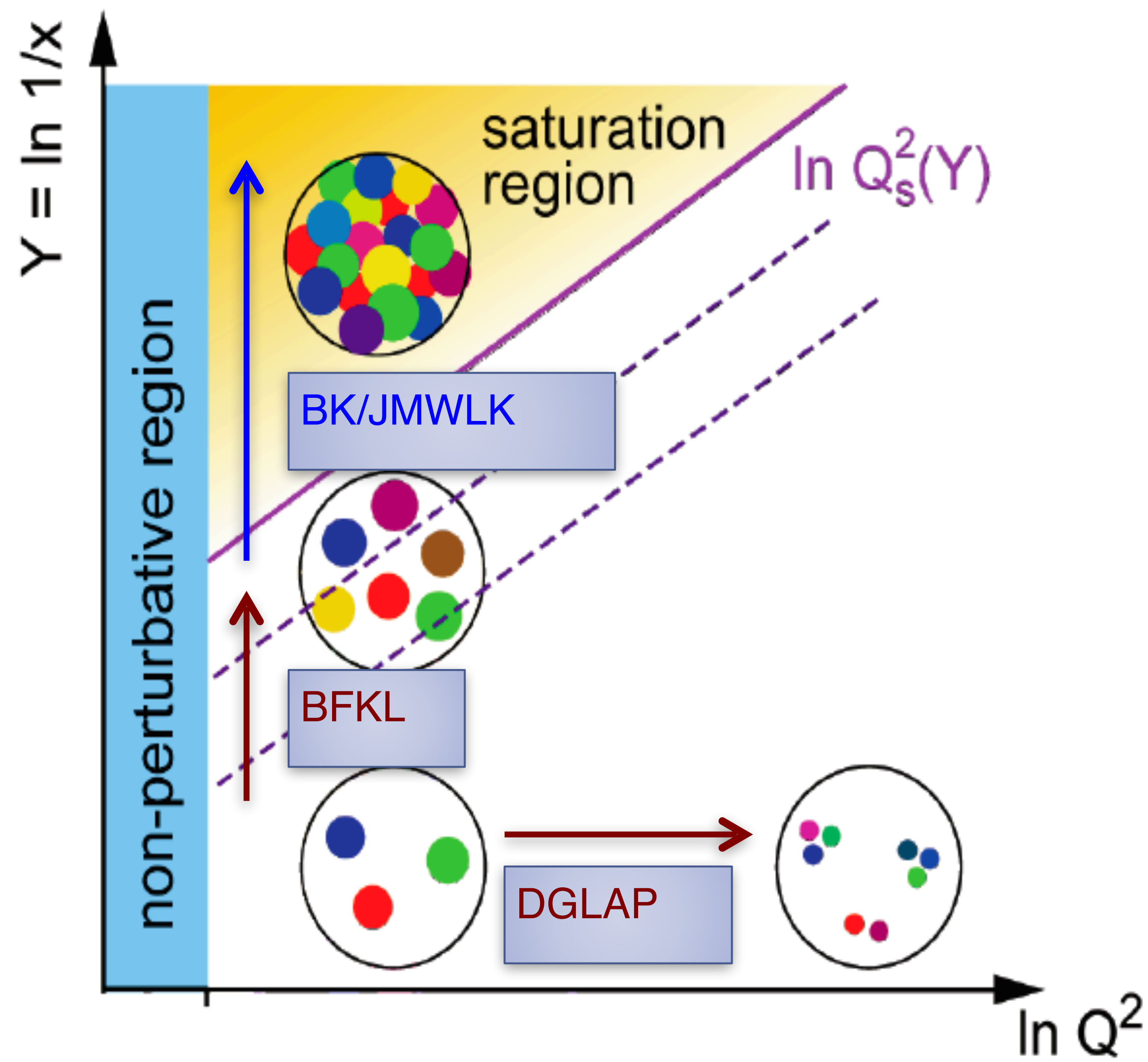
At high enough gluon densities the gluon would also recombine described by BK/JMWLK equations

Linear QCD
BFKL: gluon emission



Nonlinear QCD
BK/JMWLK gluon recombination





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

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

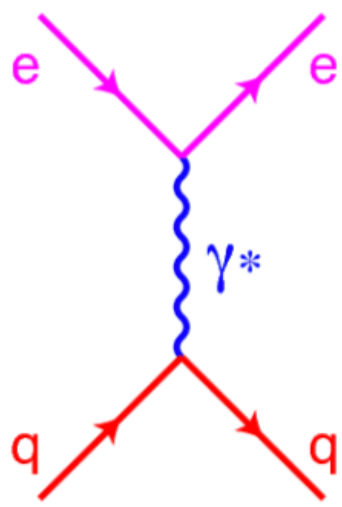
The effective theory to describe this saturated gluon field: Color Glass Condensate (CGC)

How to probe gluon density

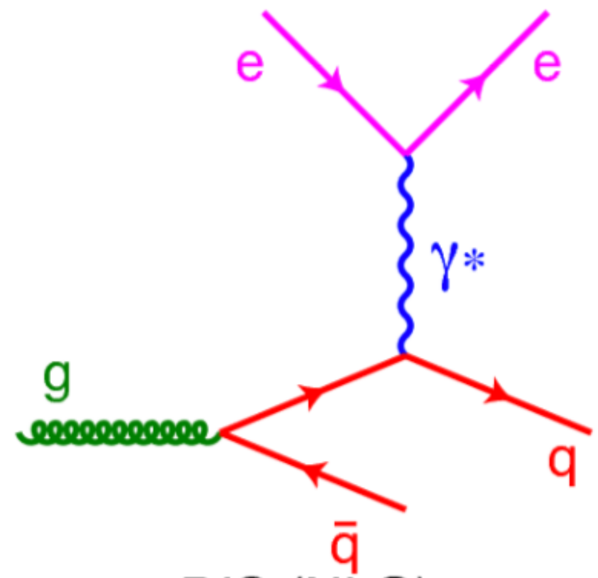
Probing the PDF in the nucleon:

- 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)



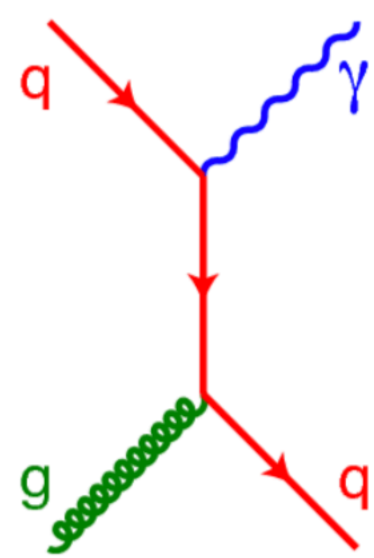
DIS (NLO)

Photon production in hadronic collision:

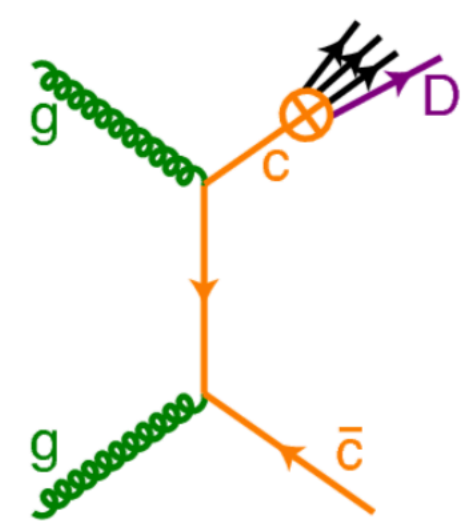
- Sensitive to the gluon PDF in the LO via the QCD Compton scattering

Heavy quark production is dominated by gluon fusion:

- It is convoluted with the fragmentation function



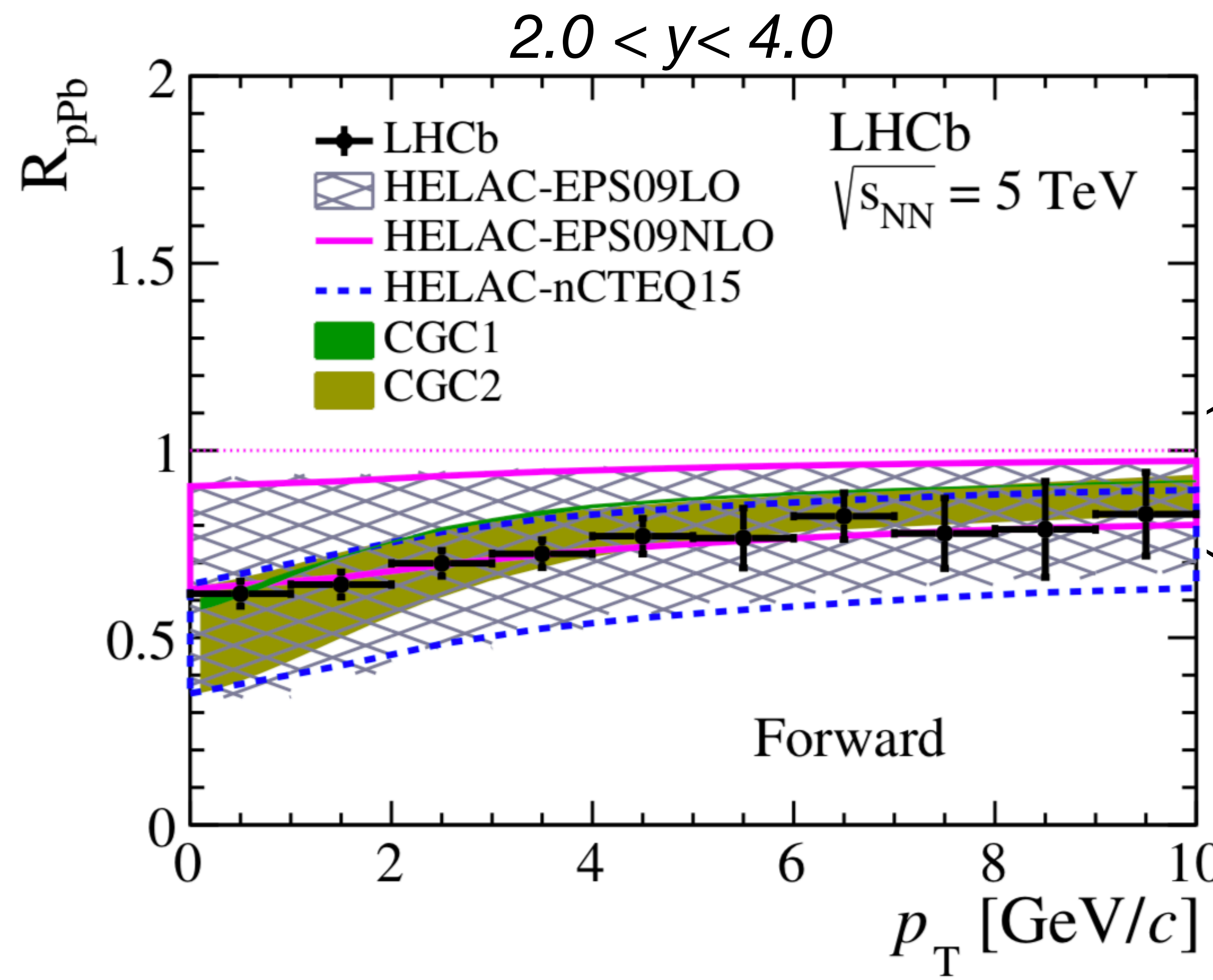
direct-γ, Compton (LO)



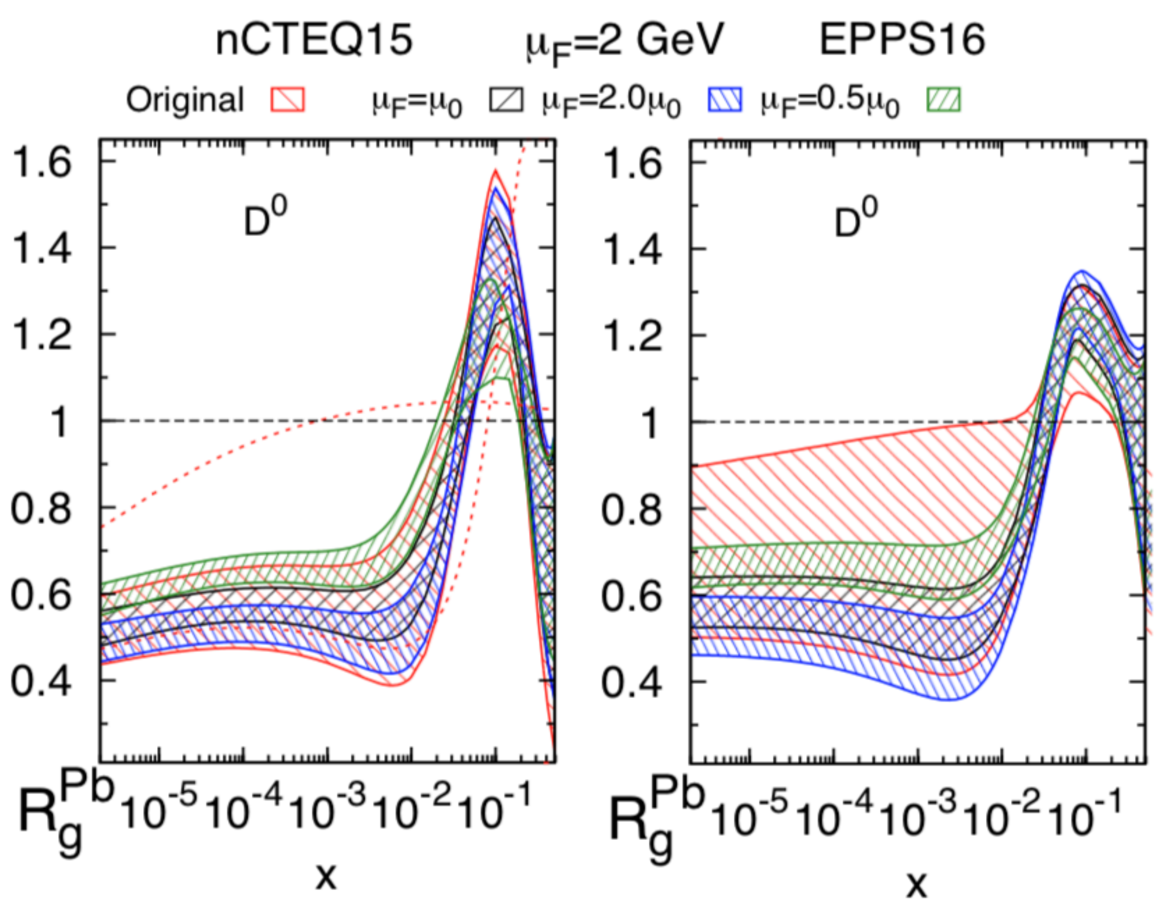
Heavy hadron:
tag hard scattering,
but includes fragmentation

Open heavy flavor measurement from LHCb

Open Charm used in re-weighting:
- Significant reduction of uncertainties
- Significant suppression in the very forward region
- Significant pQCD uncertainties (scale, fragmentation)
- relies on shape of parametrization: very little x-dependence at low-x



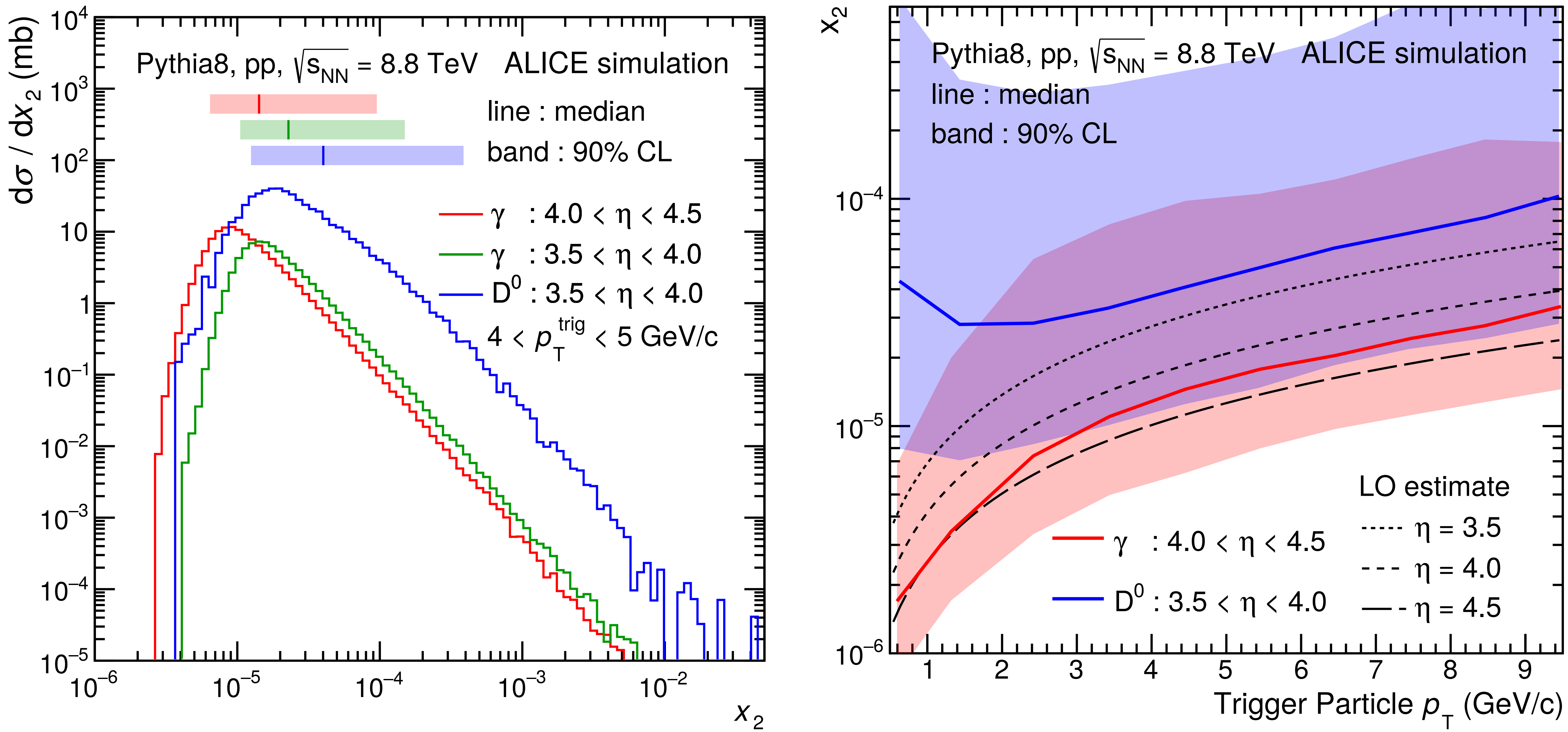
JHEP 1710 (2017) 090



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



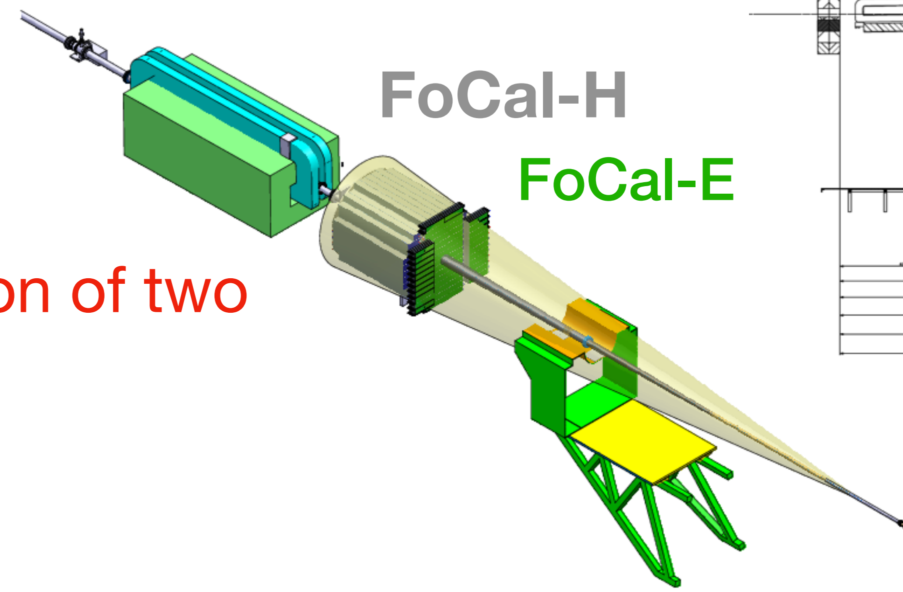
Comparison of the direct photon and D^0 as a probe for the nuclear PDF:

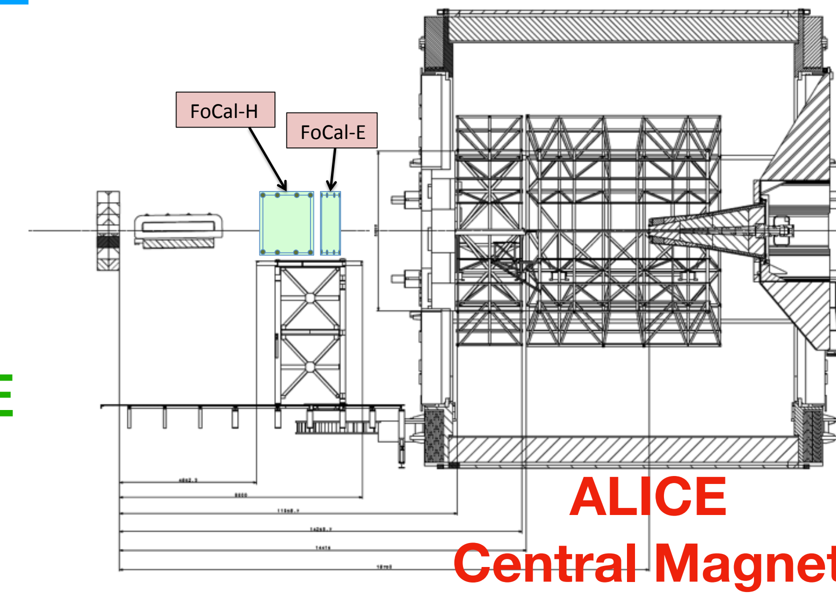
- Estimated at Run-4 *p*-Pb collision energy at 8.8 TeV
- No fragmentation is involved in the direct photon production
- Photons have no final-state interaction with the strong force

The ALICE - FoCal Proposal

FoCal Proposal:

- 7 m from the interaction point
  - covering $3.3 < \eta < 5.8$
- FoCal-E - electromagnetic part:
  - **direct-γ and π^0** measurement
  - Main challenge is the separation of two clusters at high energy
  - From MIPs to 1 TeV showers
- FoCal-H - hadronic calorimeter:
  - Jet measurement
  - Isolation cut

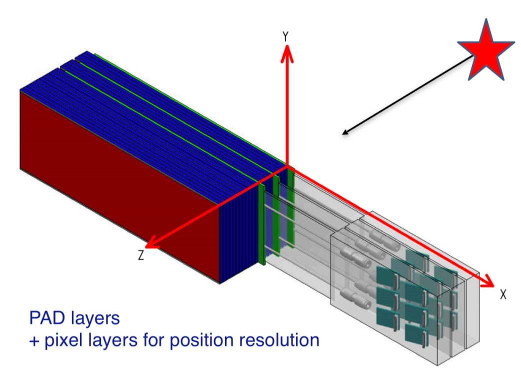




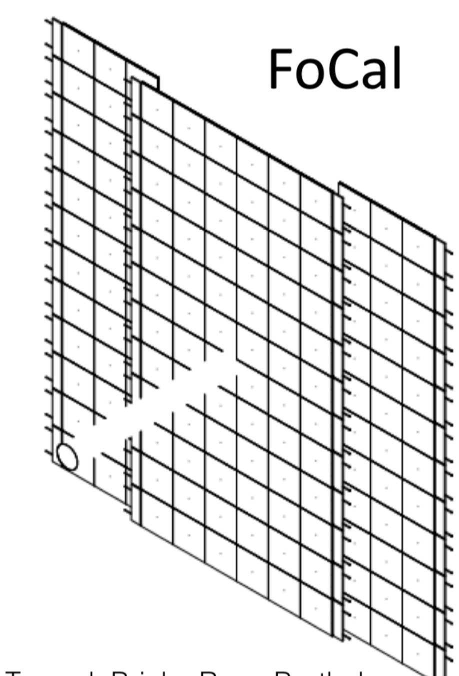
Installation possibility during LS3 (2024-2026) to be used in LHC Run-4.

Basic building block of the FoCal-E prototype already constructed and tested in 2018 in PS and SPS testbeams:

- R&D is still ongoing

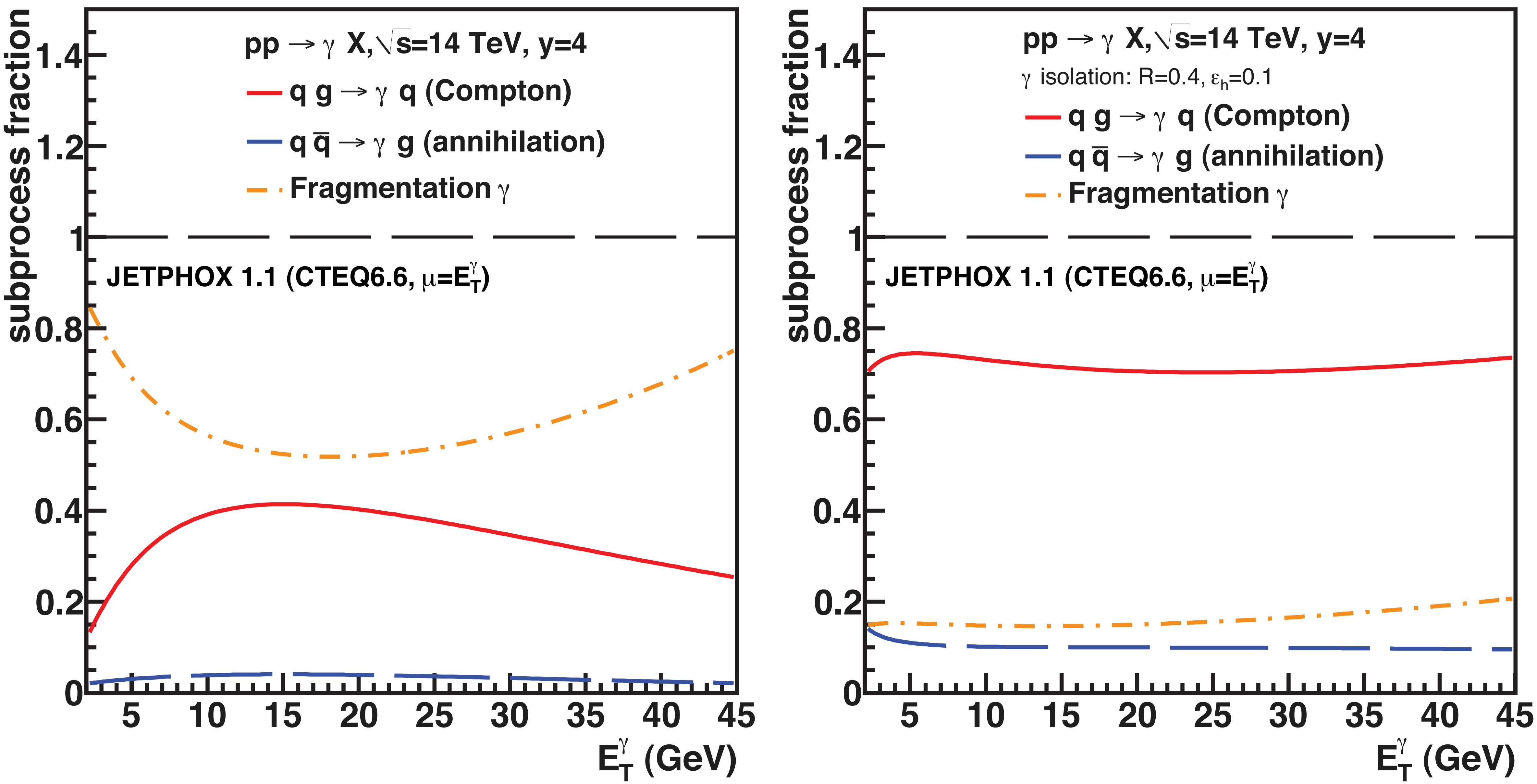


FoCal-E



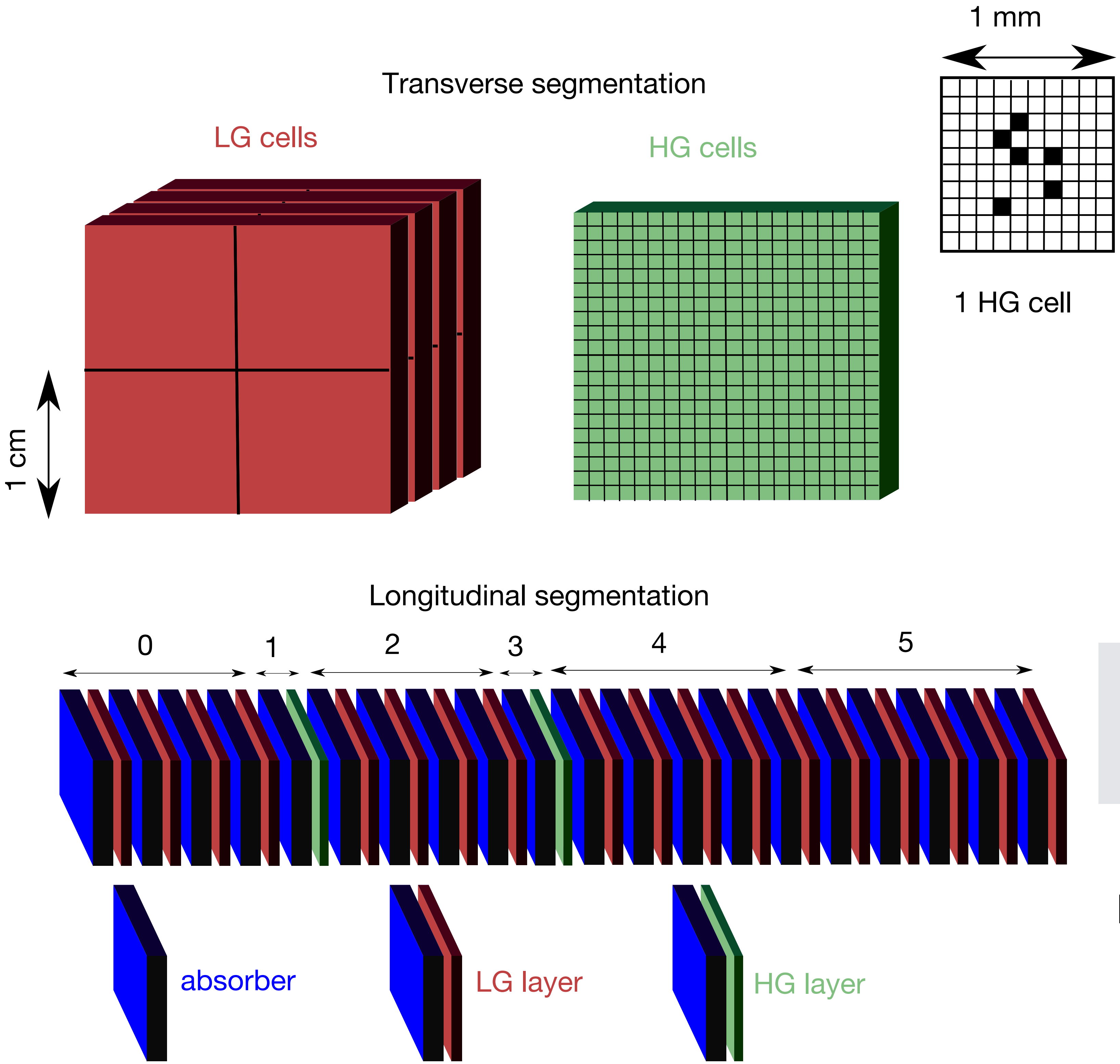
Ton v.d. Brink, Rene Barthel

The importance of FoCal-H



The isolation effect using the hadron calorimeter is important to enhance the prompt photons from the QCD Compton scattering

FoCal-E basic design



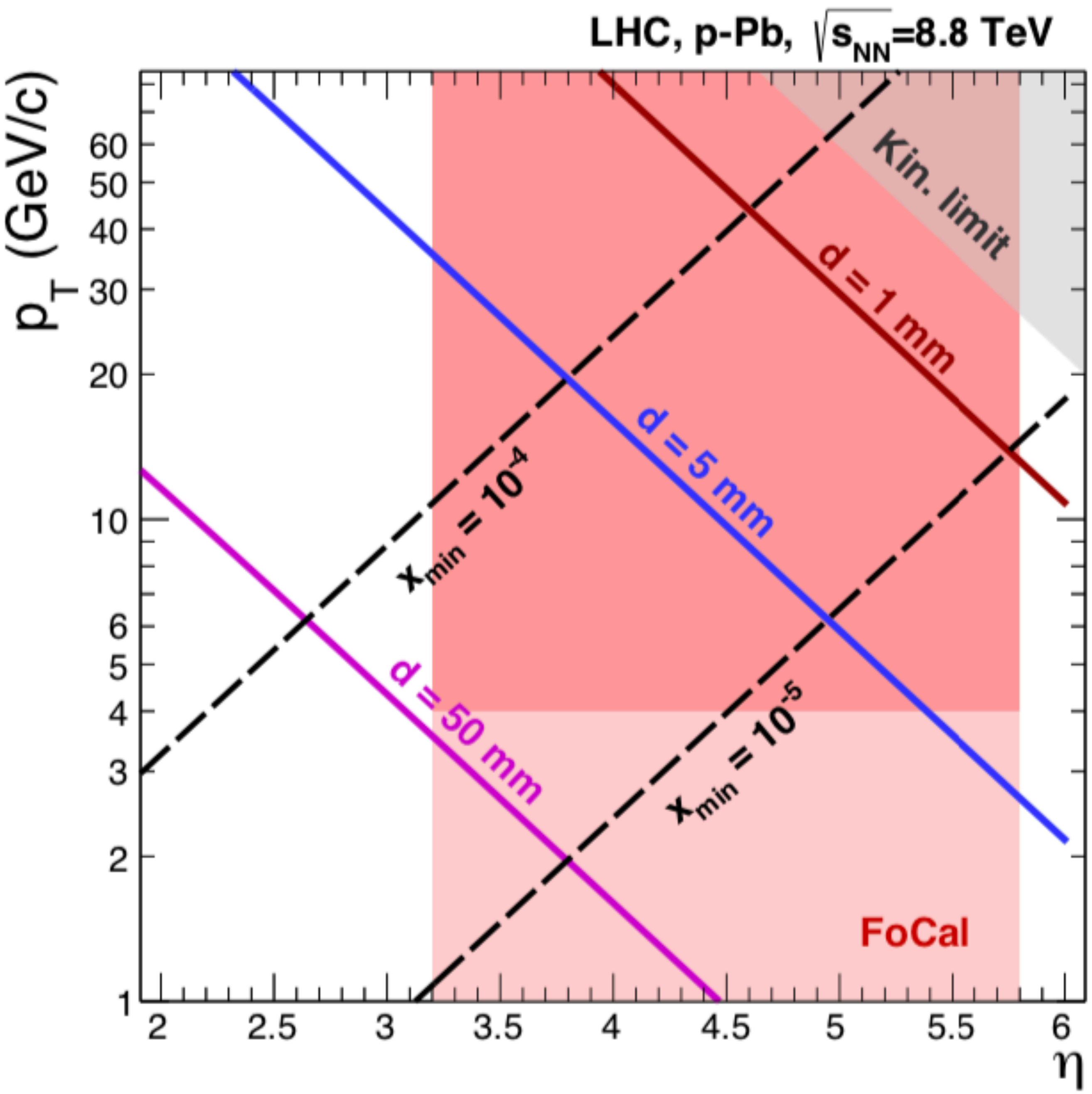
The design of the detector:

- 20 layers: W (**3.5mm ≈ 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

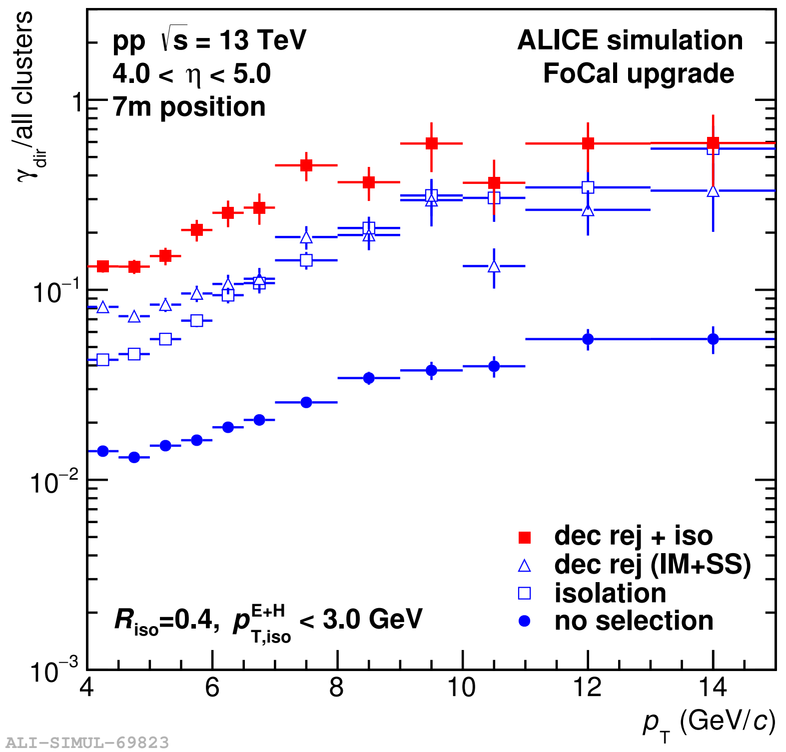
Accessible phase space



Kinematical reach of the FoCal detector:

- Kinematical limit for 8.8 TeV p-Pb is shown as the gray area
- Nominal acceptance at 7 m location is $3.2 < \eta < 5.8$
- Aim to reach the down to very small x 10^{-5}
- p_T reach of is depending on the S/B ratio:
  - Conservative p_T = 4 GeV/c
  - Decreasing to 1-2 GeV/c would extend the small-x reach also
- The min distance of the two photon separation:
  - 1 mm with the HG layers (macropixels)

Performance studies

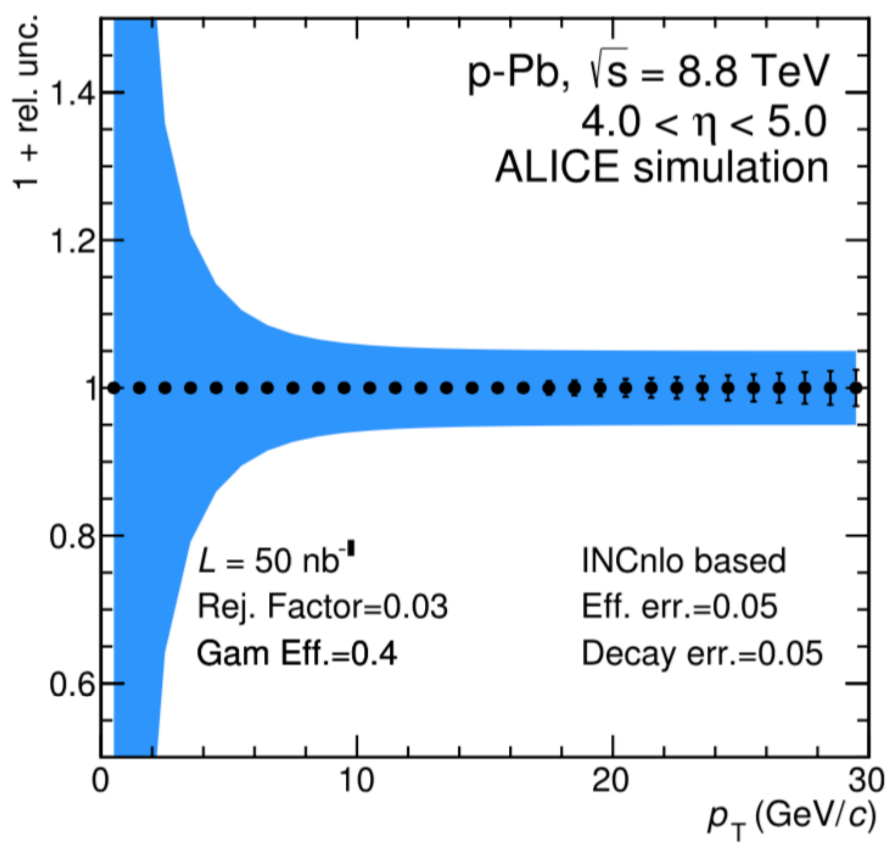


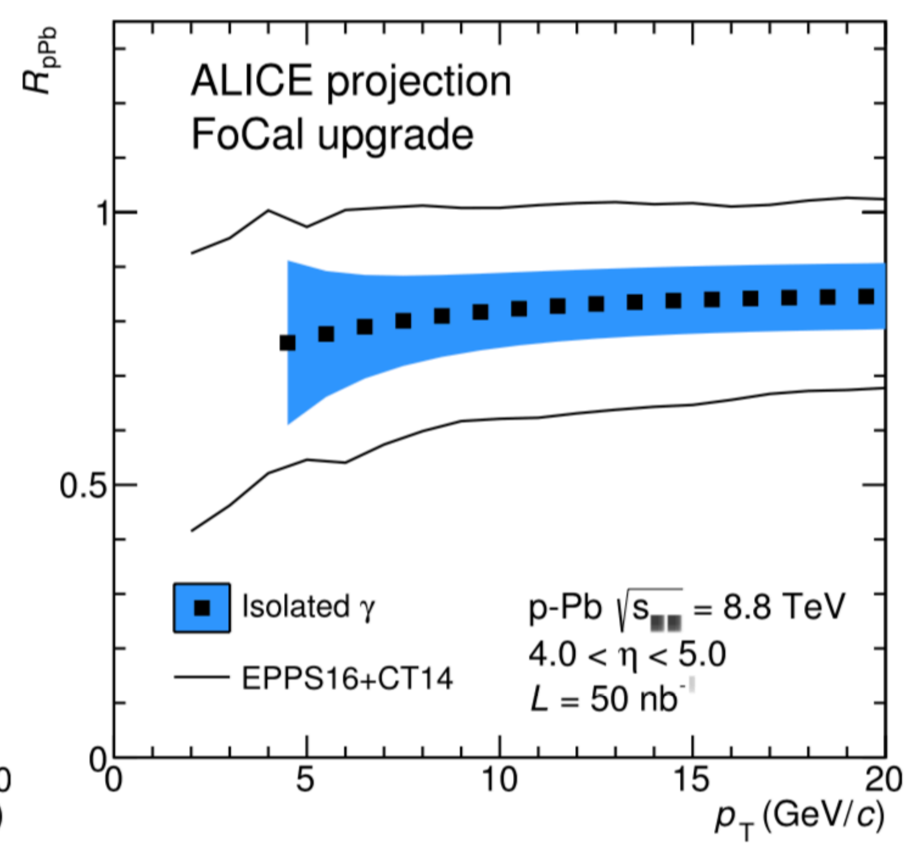
The detector is a novel design for calorimeters and enable us to achieve a better purity of direct photon measurements:

- Combined rejection (invariant mass and shower shape analysis, plus the isolation method)
- Combined suppression factor of the background relative to the signal is about factor of 10 (largely p_T independent)
- Direct photon/all > 0.1 for p_T > 4 GeV/c

The expected uncertainties of the measurements:

- For p_T > 4 GeV/c is about 20% uncertainty
- For p_T > 10 GeV/c the uncertainty is about 10%





Impact on the nPDF

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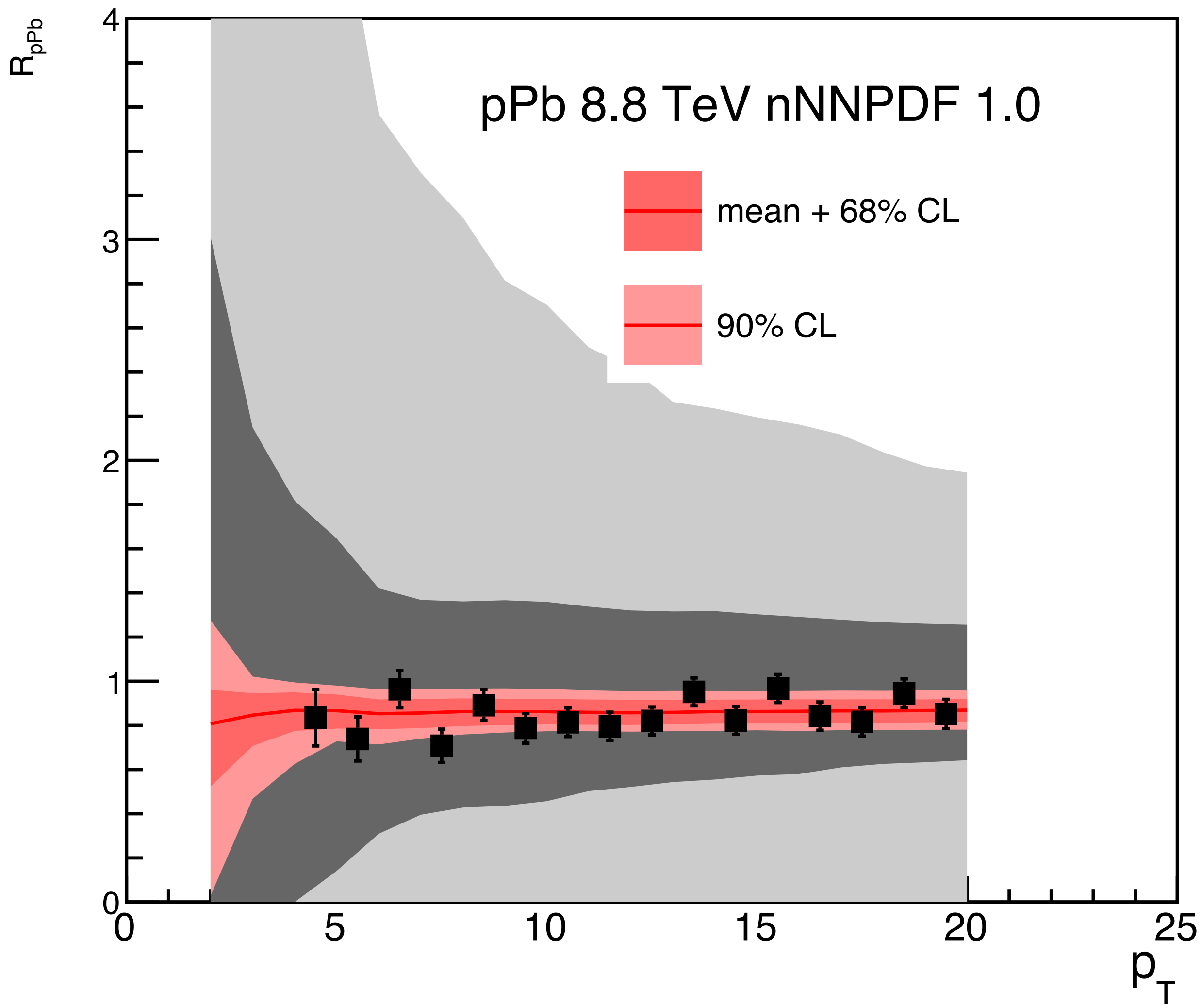
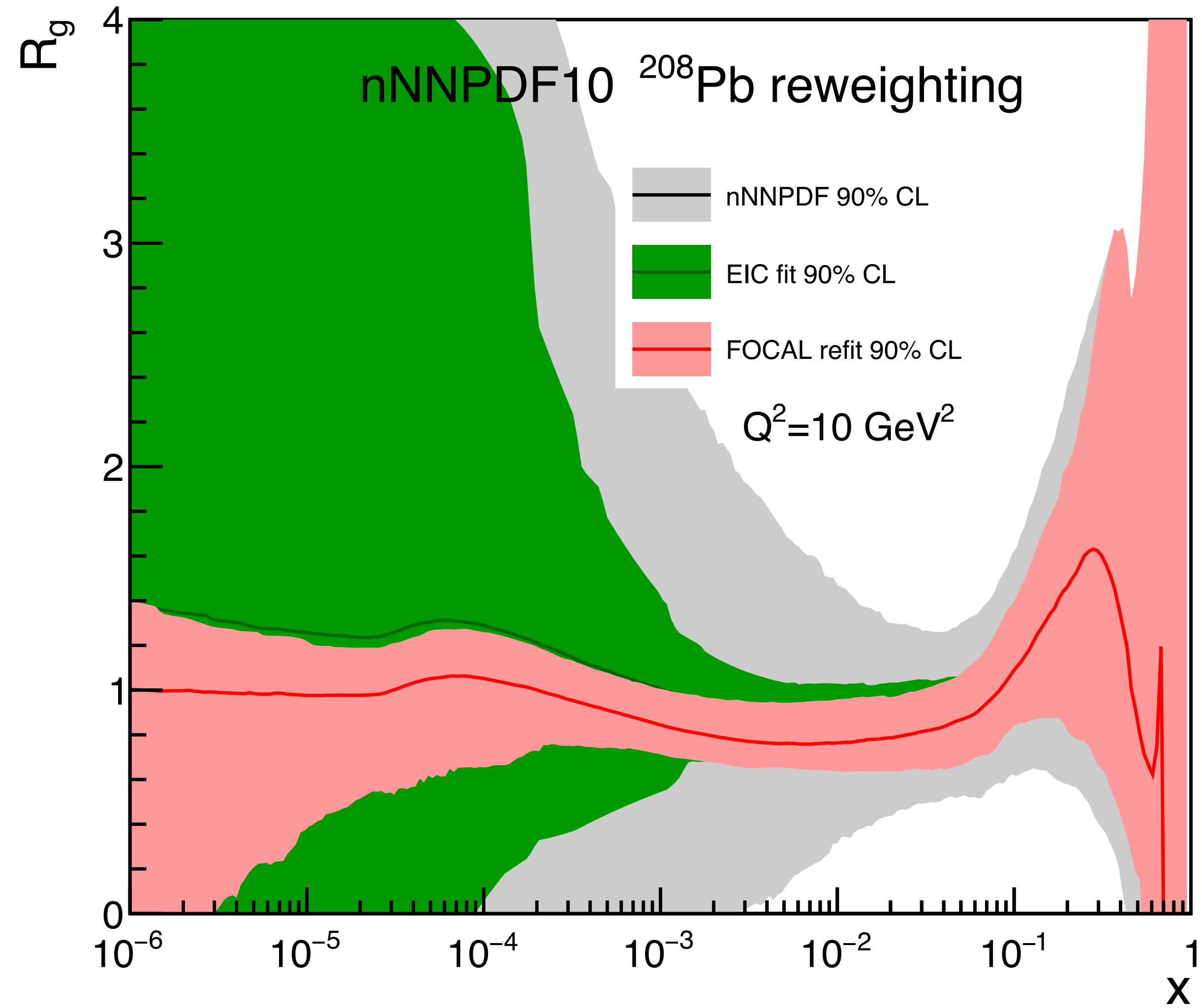


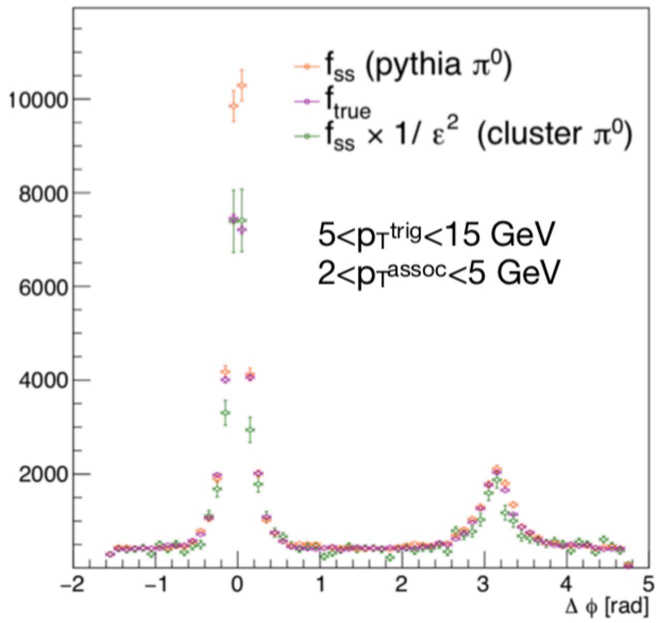


Projected uncertainties of the measurement and its impact on the PDF:

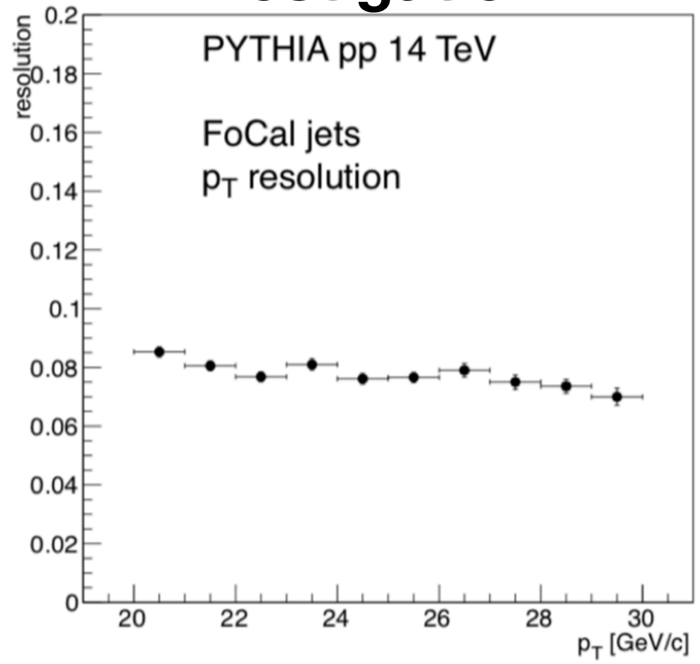
- Current nuclear NNPDF function include large uncertainties (larger than CTEQ15 and EPPS16)
- The current projections of the FoCal data would greatly constraint the gluon nPDF, even with the currently planned EIC detector in USA

Other measurements

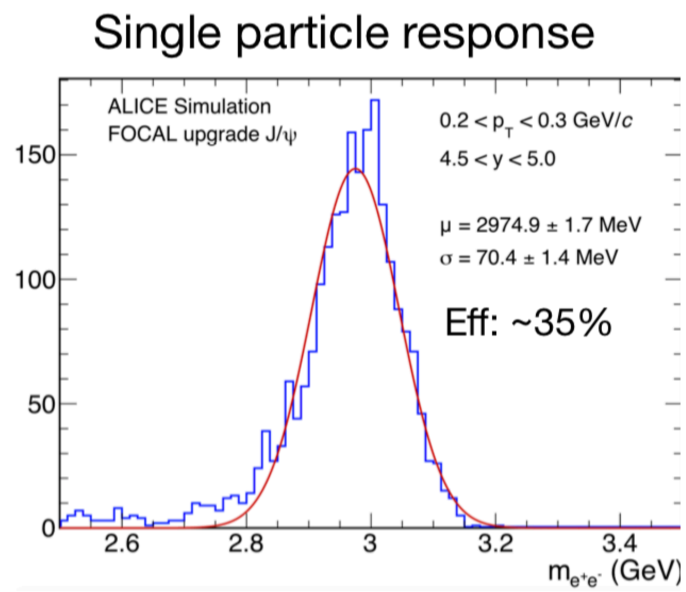
Correlations, jet measurement, J/ψ in UPC events, W/Z and other measurements under investigation



π^0-π^0 correlations in pp
(for decorrelation studies)

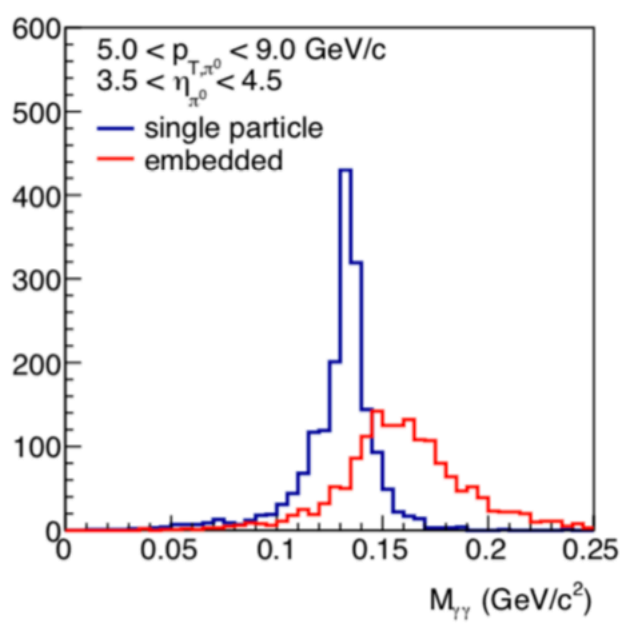


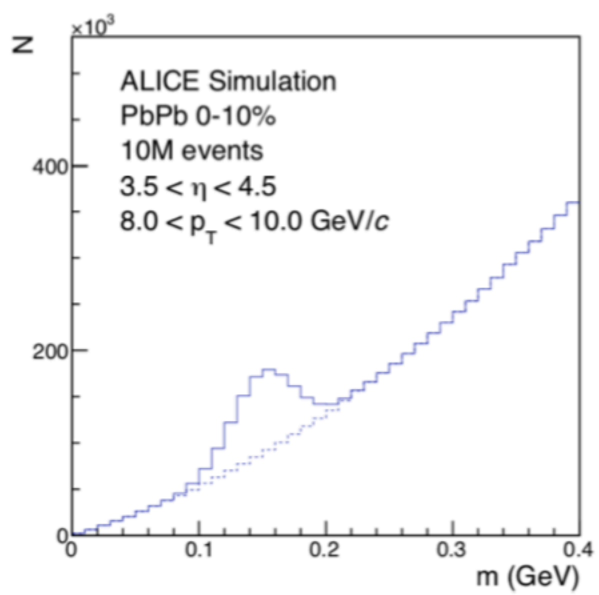
Jet resolution
(jet/dijets in pp/pPb/UPC)

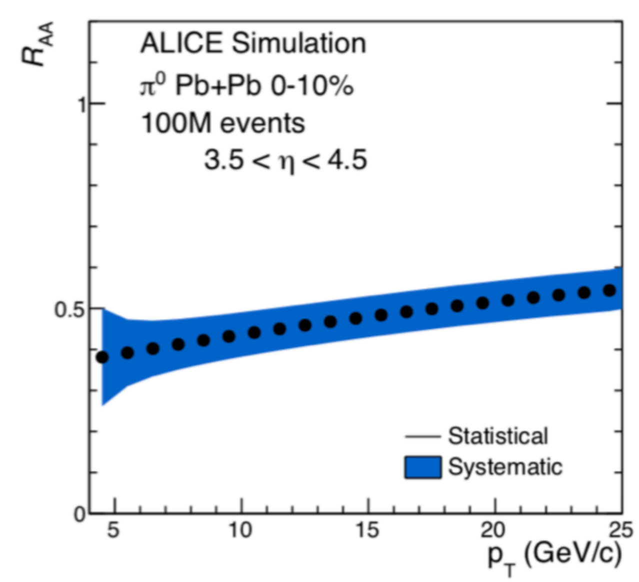


J/ψ reconstruction
(for UPC measurements)

Measurements in PbPb events are also under investigation





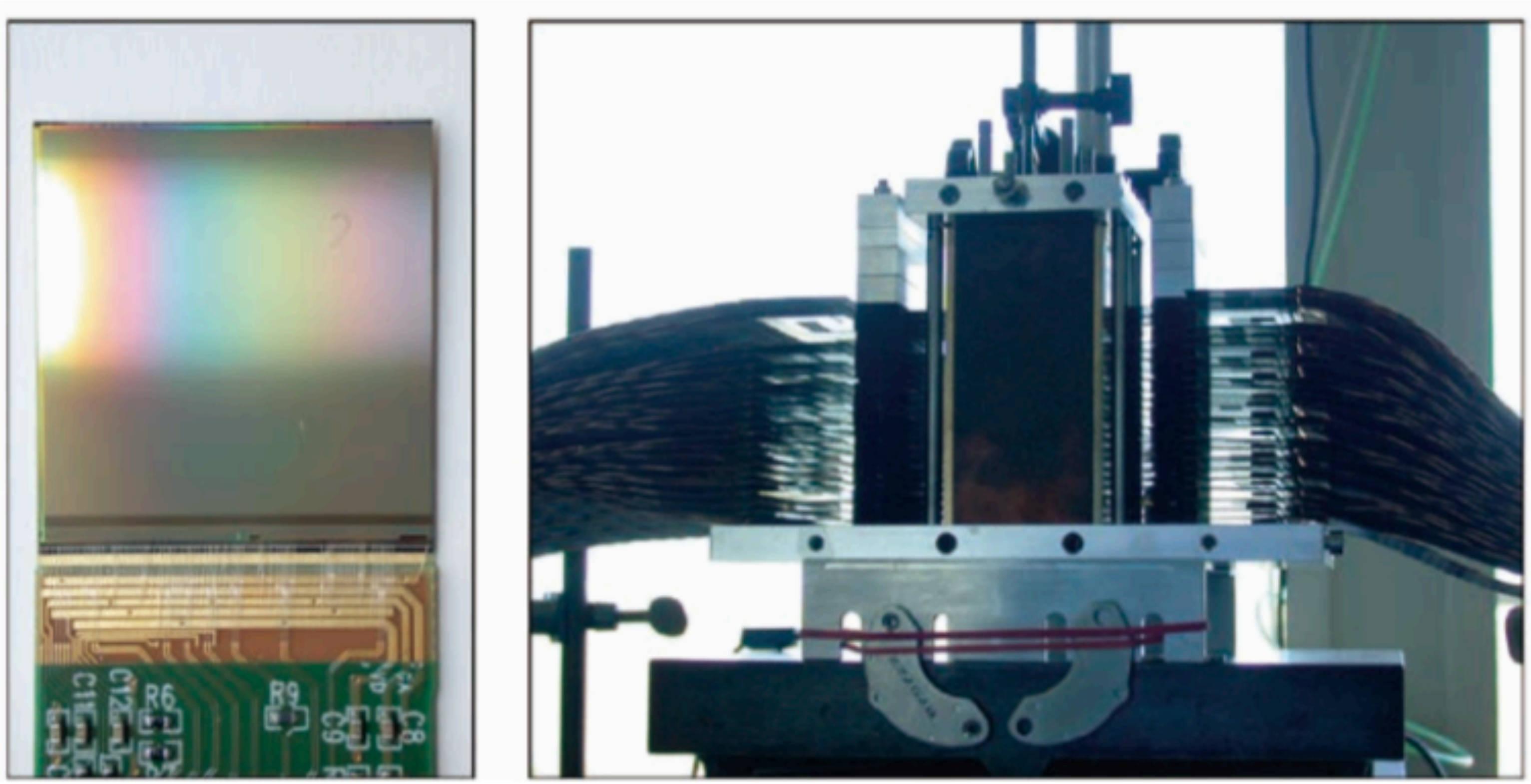


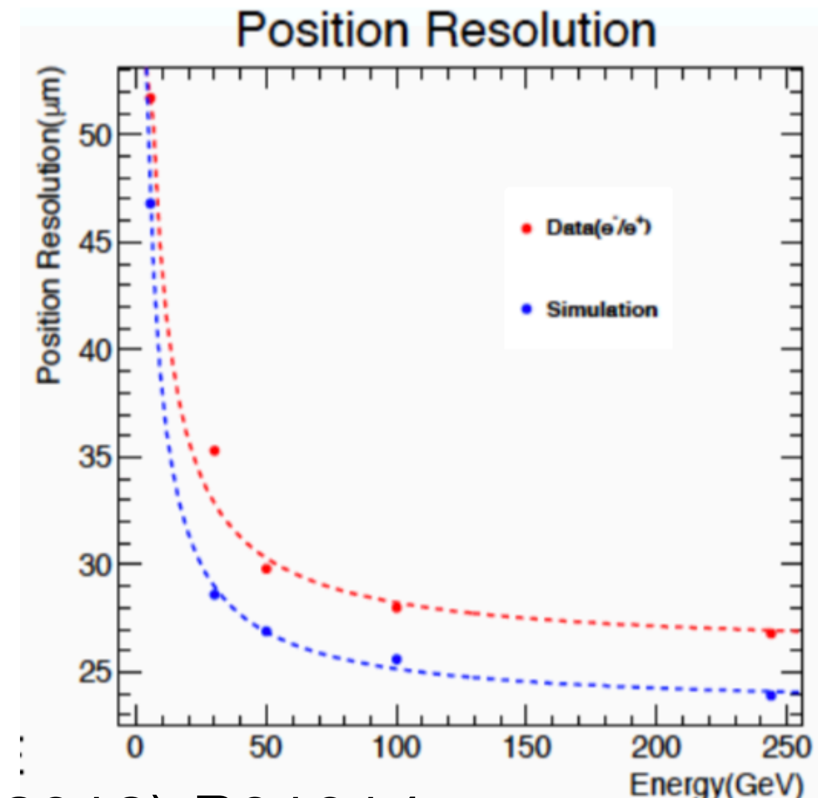
Forward neutral pion measurement is possible in investigation of the forward jet suppression

ALICE FoCal physics program

- **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**
- **Investigate the origin of long range flow-like correlations:**
  - **Azimuthal π^0-h correlations using FoCal and central ALICE (muon arm?) in pp and pPb collisions**
- **Explore jet quenching at forward rapidity:**
  - **Measure high-p_T neutral pion production in PbPb**

Prototype MAPS detector



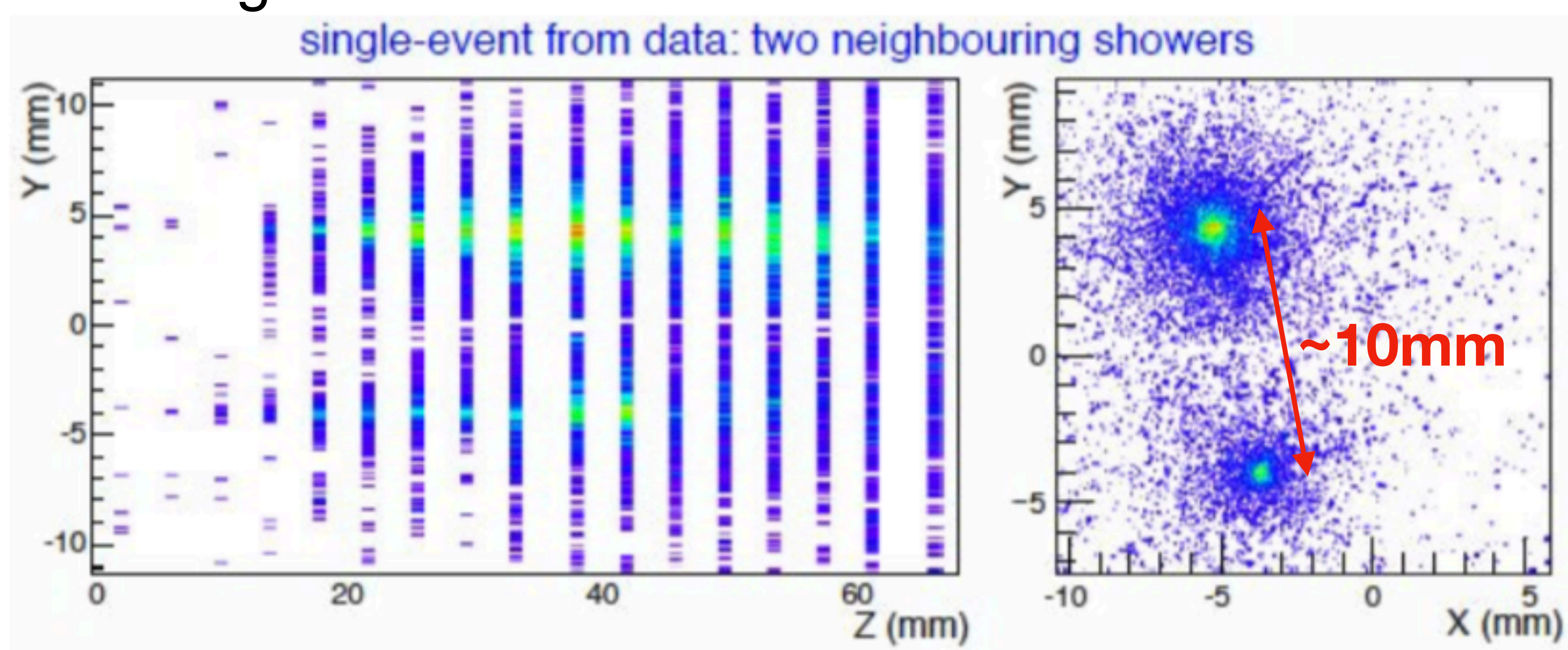


Successful test of first digital pixel calorimeter - JINST 13 (2018) P01014

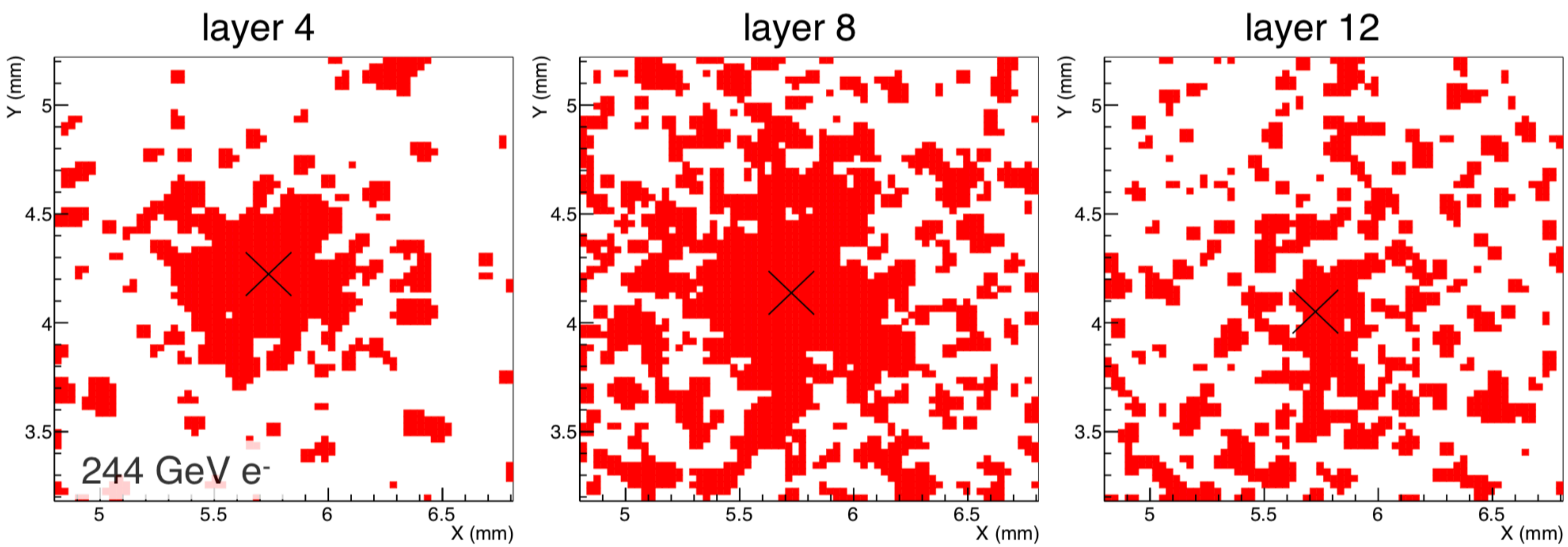
Now using MIMOSA sensor, next moving to ALPIDE

The detector provides very precise two-shower separation throughout the layers

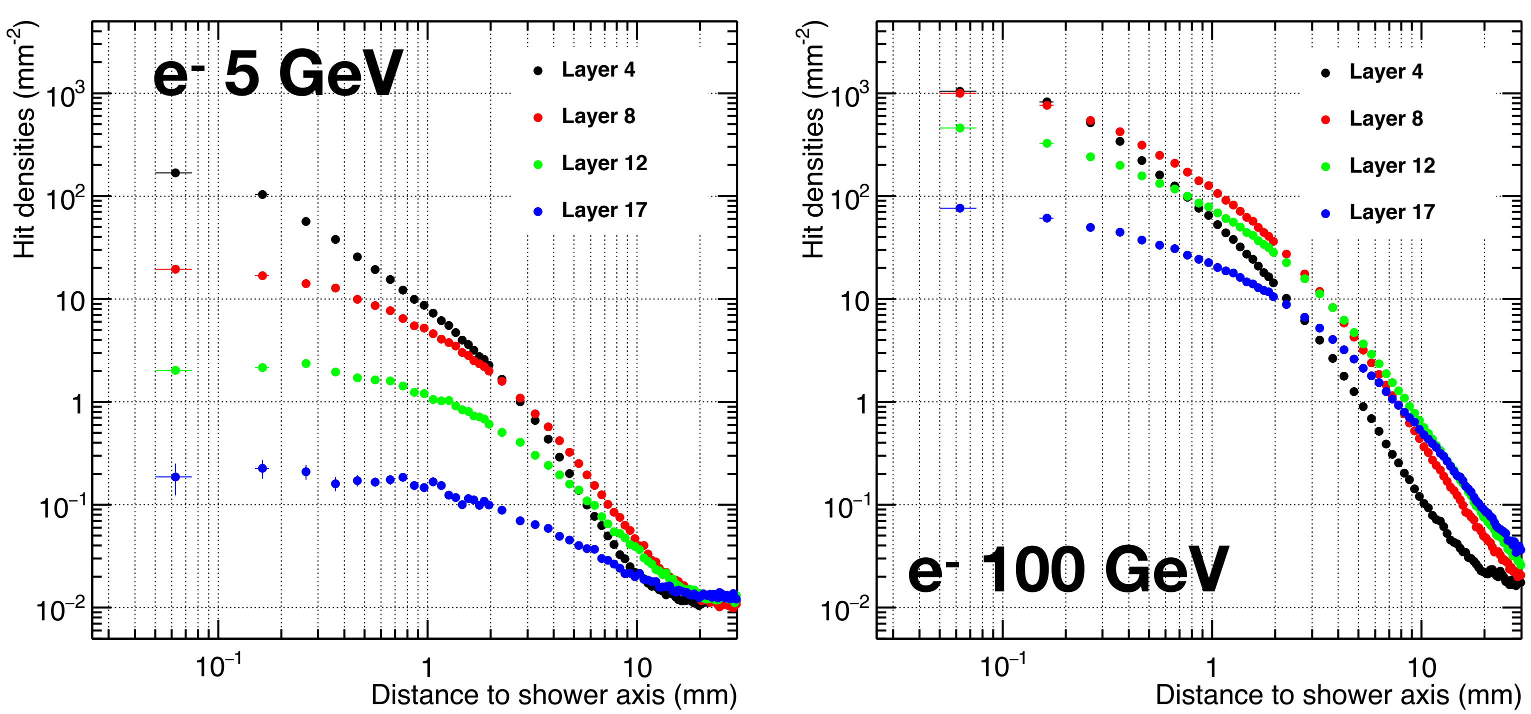
- The core of the shower is much smaller than the Moliere radius



First prototype results



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

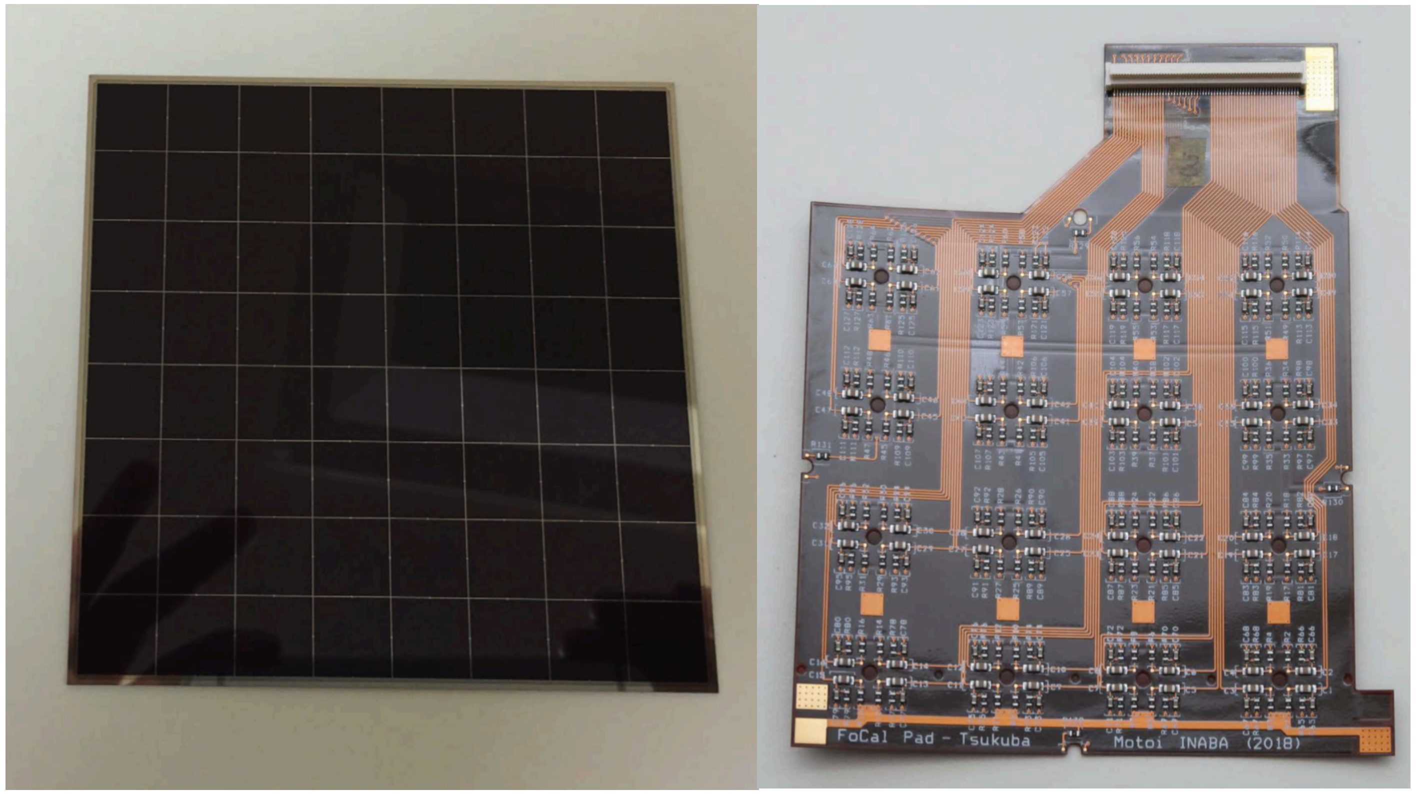


Have to use the number of hits to reconstruct the shower profile:

Average hit densities as a function of radius

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

MiniFoCal Prototype

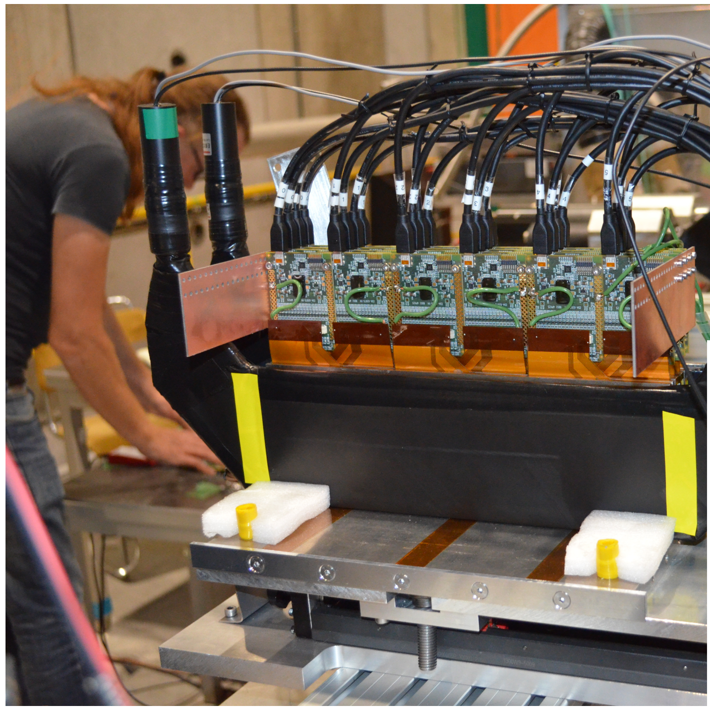


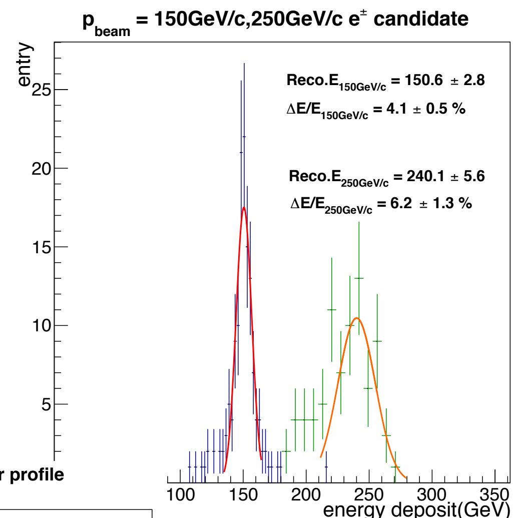
The PAD layer constructed at Tsukuba University:

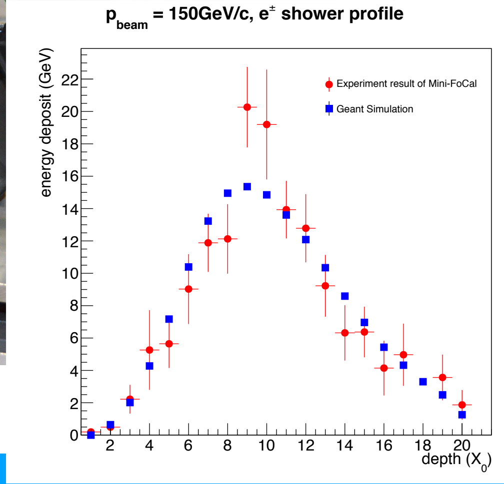
- 8x8 PAD of 1x1 cm^2 320 µm thick Si layer
- Flexible PCB to lead the signal out of the layers:
  - reduces the thickness of the layers

Testbeam measurements

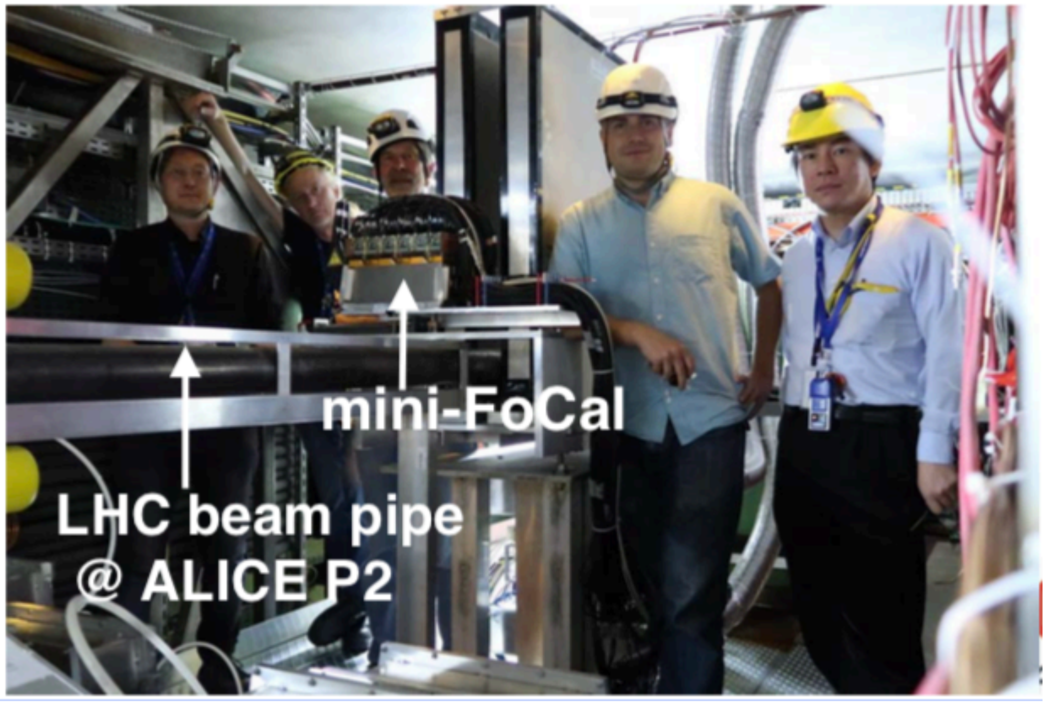
- 20 X_0 layers with 3 Si pads
- PS in 2018 July: 1-9 GeV electron and hadron beam
- SPS 2018 August: 50-250 GeV electron and hadron beam





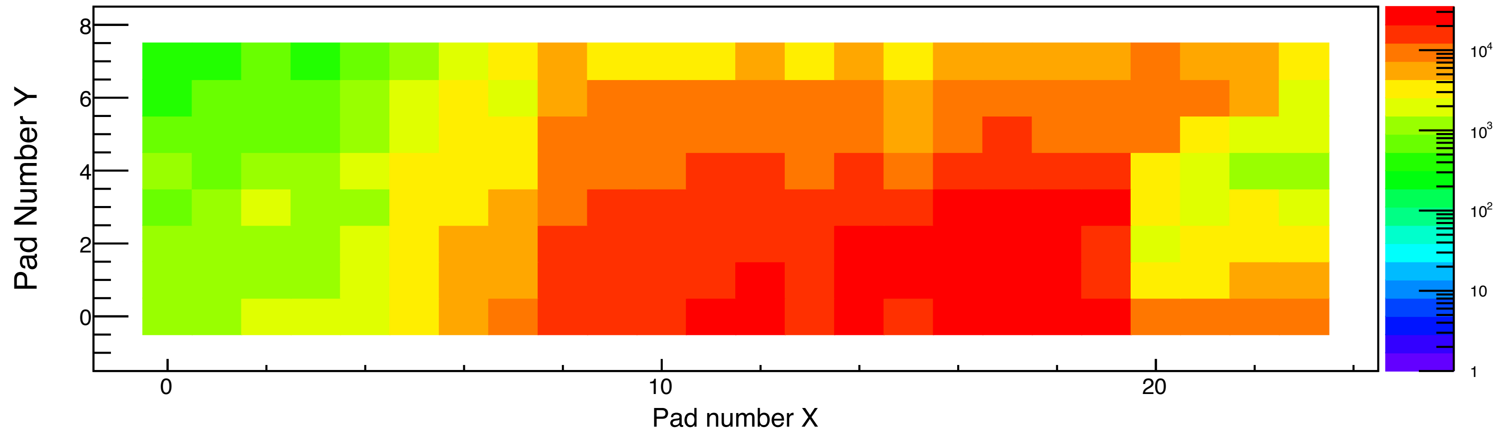


ALICE Engineering Run

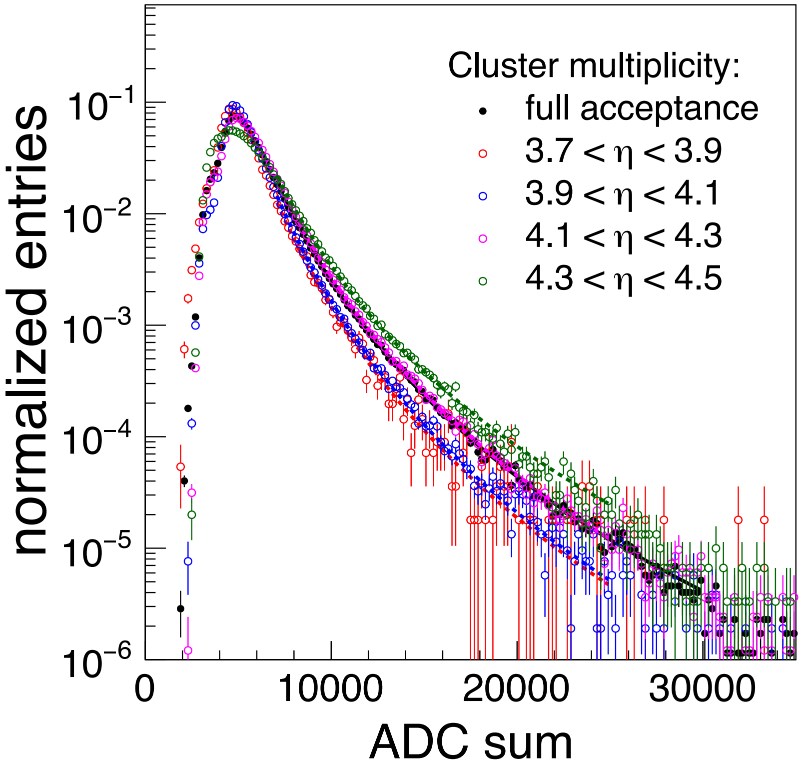


MiniFoCal in ALICE

Hitmap of clusters



The hitmap reflects some of the material (beam pipe valve, PMD detector, etc).



ALICE installation for engineering run:

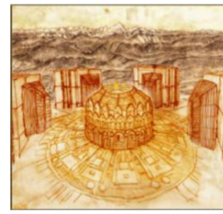
- We installed the miniFoCal prototype near the nominal location in ALICE
- The ADC sum ~ cluster energy
- Purpose to test the background
- Reconstruct π^0's (if possible)

Future electronics

CMS HGCROC:

- Chip developed for the forward calorimeter upgrade in CMS
- Has very similar requirements what is needed for FoCal
- Developed from the CALICE SKIROC

Slides from Phillipe Bloch (CERN)



Front-End Readout: requirements

TDR section 3.1.1

low noise (2500 e-) and **large dynamic range**, from 0.2fC to 10pC

linearity better than 1% over the full range

ability to provide **timing information** with a precision better than 100ps for pulses above ~12 fC (corresponding to about 3MIPs in the 300 um silicon)

fast shaping time (peaking-time <20ns) to minimize the out-of-time pileup

compensation of the leakage current which will develop in the silicon devices after irradiation (DC coupled sensors) up to 10uA

compatibility with negative and positive inputs sensors, to be able to read both p-on-n and n-on p

on detector digitization and **data processing for zero suppression, for linearization and summing of the trigger data**

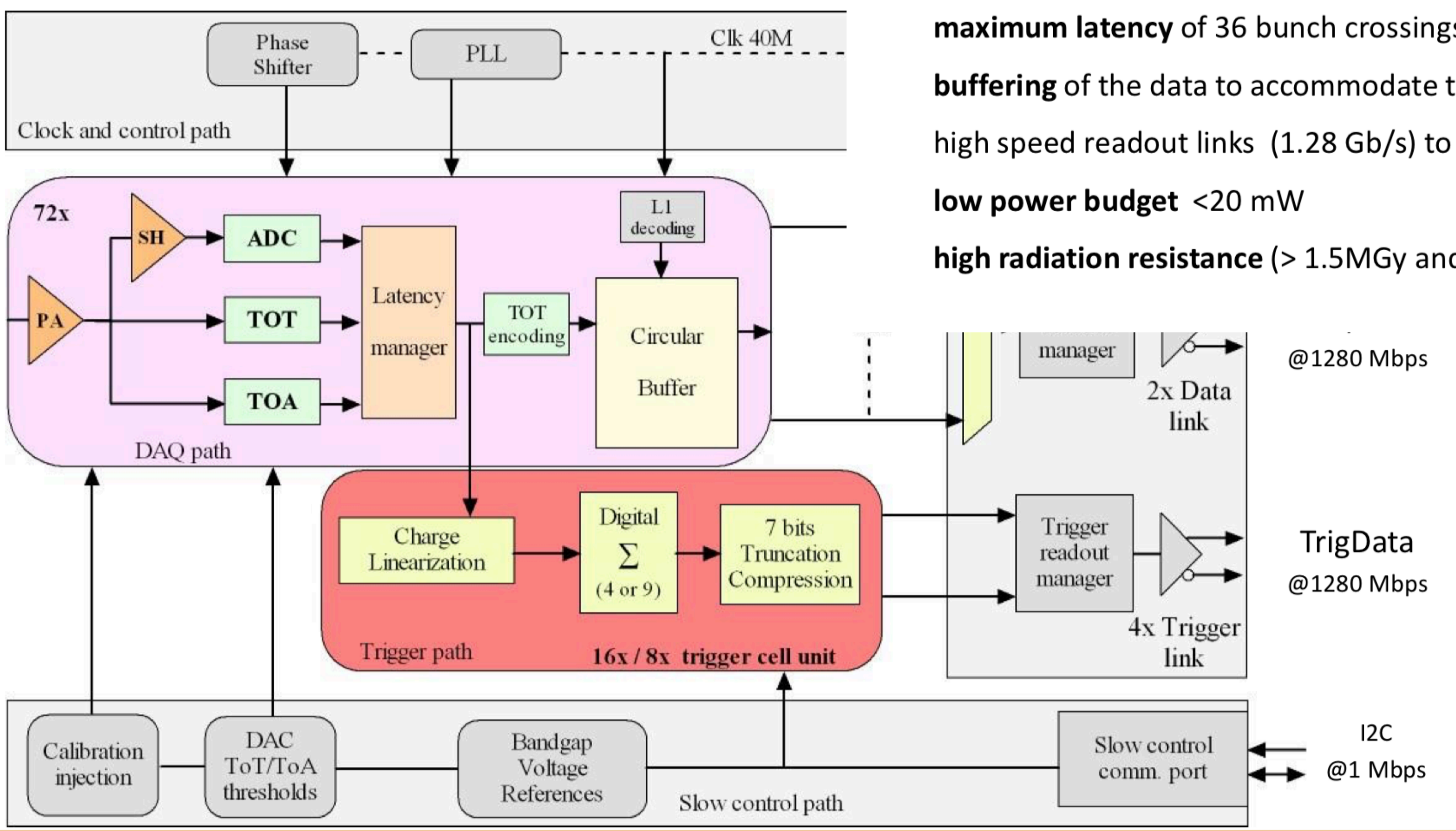
maximum latency of 36 bunch crossings for the trigger primitives at the output of the detector

buffering of the data to accommodate the 12.5 us latency of the L1 trigger;

high speed readout links (1.28 Gb/s) to interface with the 10Gb/s low power GBT serialiser

low power budget <20 mW

high radiation resistance (> 1.5MGy and 10^{16}neq) and SEU compliance



Close collaboration with CALICE and CMS groups

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 FoCal proposal:

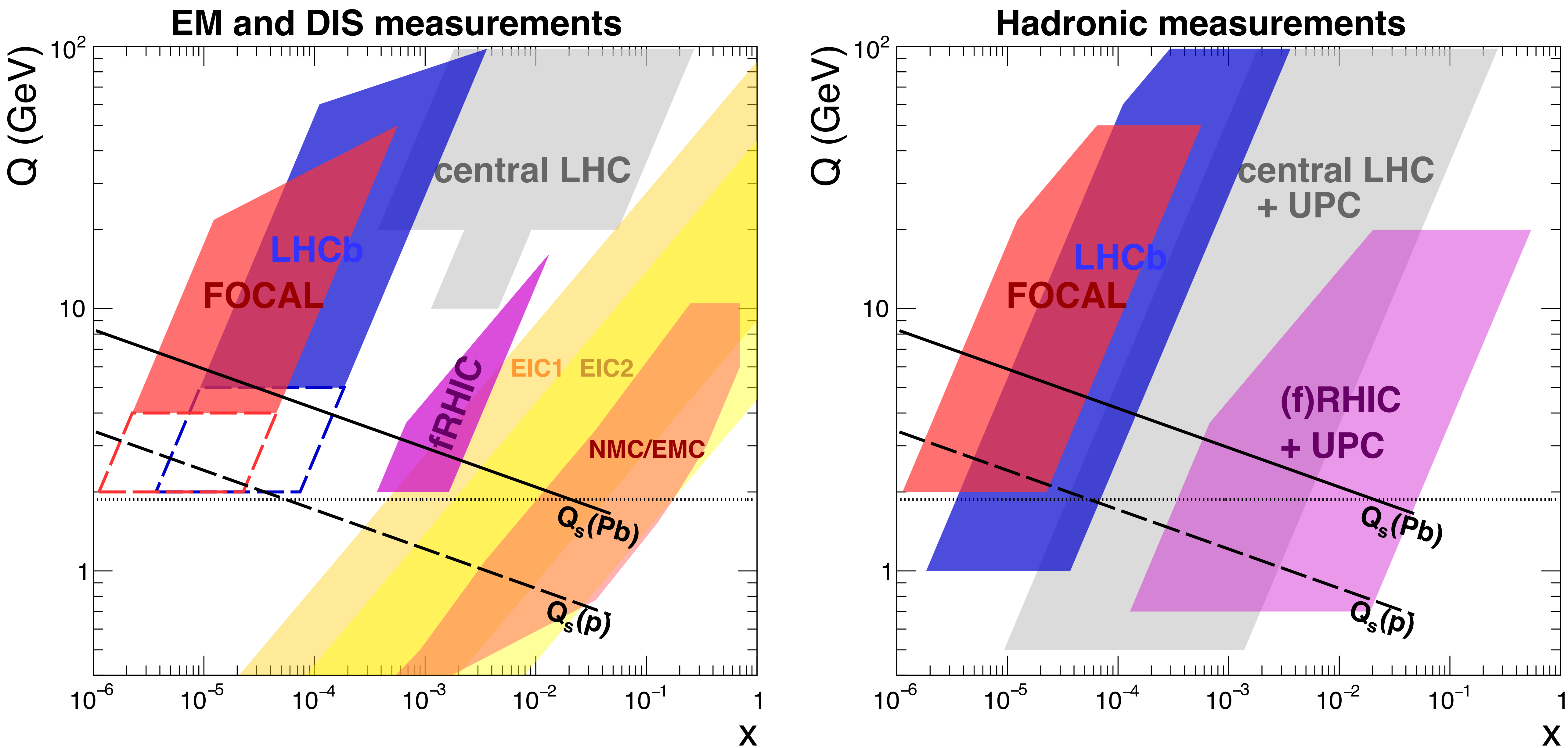
- Proposed unique technology in design
    - Provide very good energy resolution ~ 1%
    - Provide very good position resolution ~ 1 mm
- Signal to background ratio > 0.1

The ALICE FoCal proposal is under discussion in the collaboration.

Final detector should be installed and operational for Run-4 of the LHC (2026-2029)

Backup

Coverage of the measurements

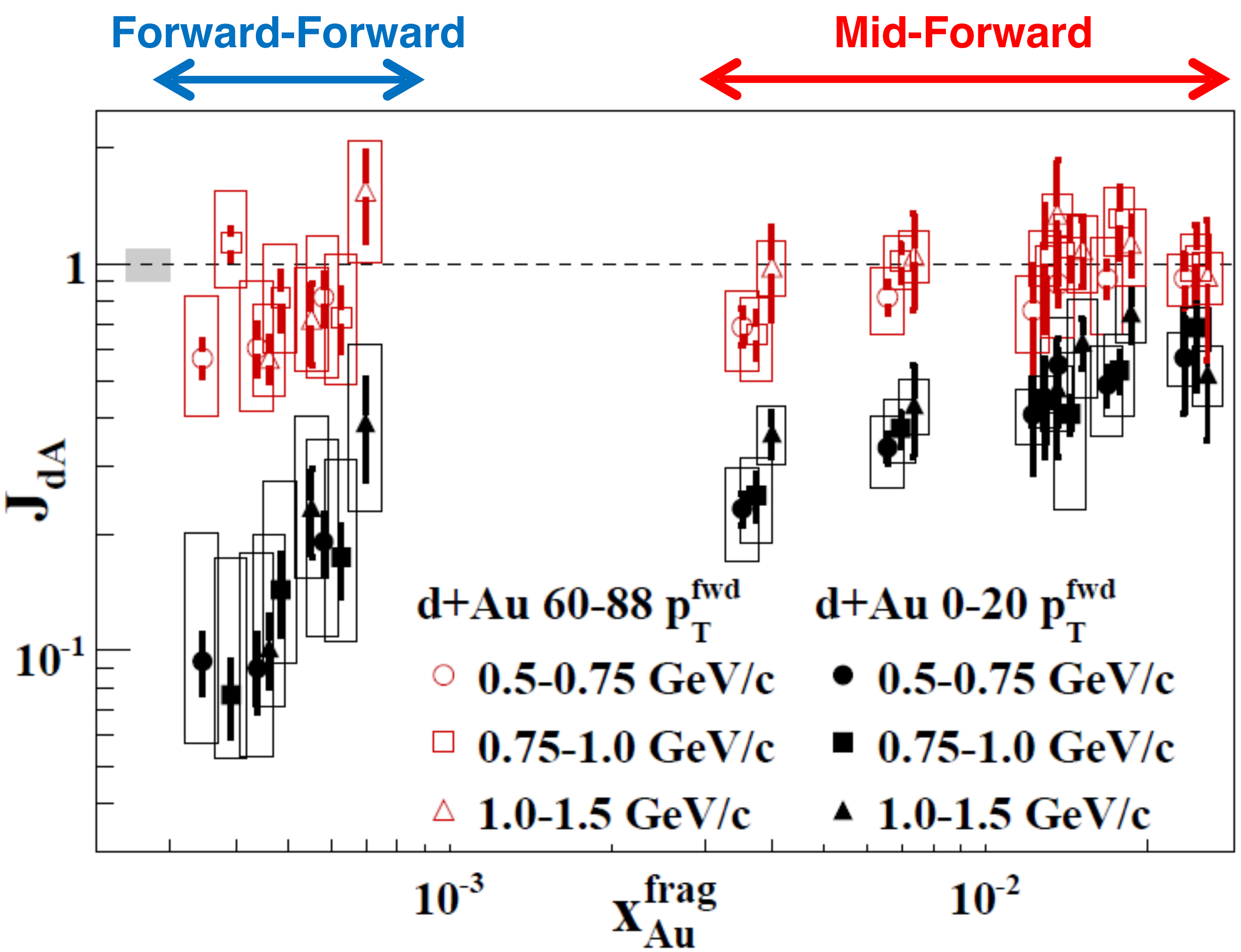


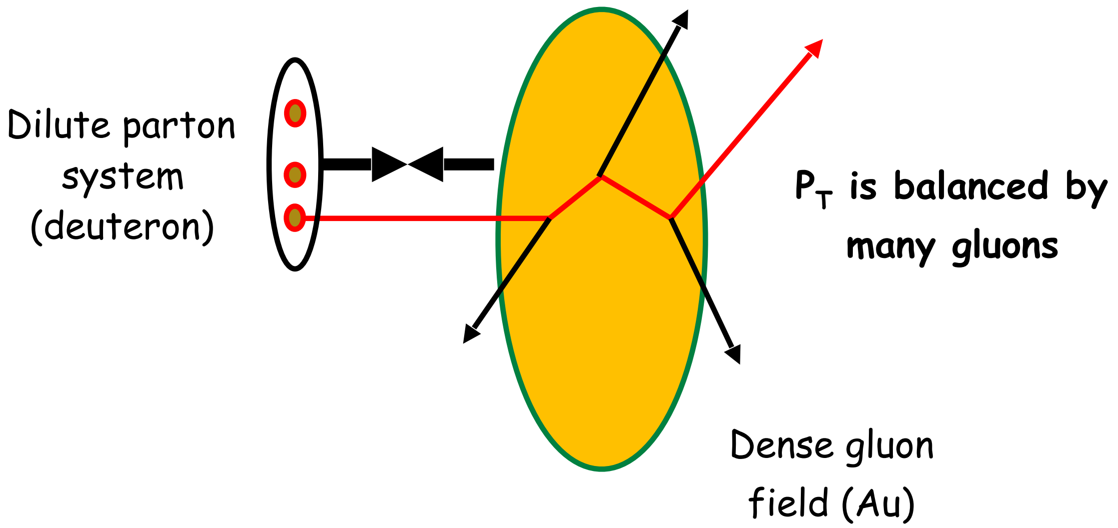
Coverage of the electromagnetic and hadronic probes by the current and planned measurements in LHC and other colliders.

Results from RHIC at 200 GeV

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

PRL **107**, 172301



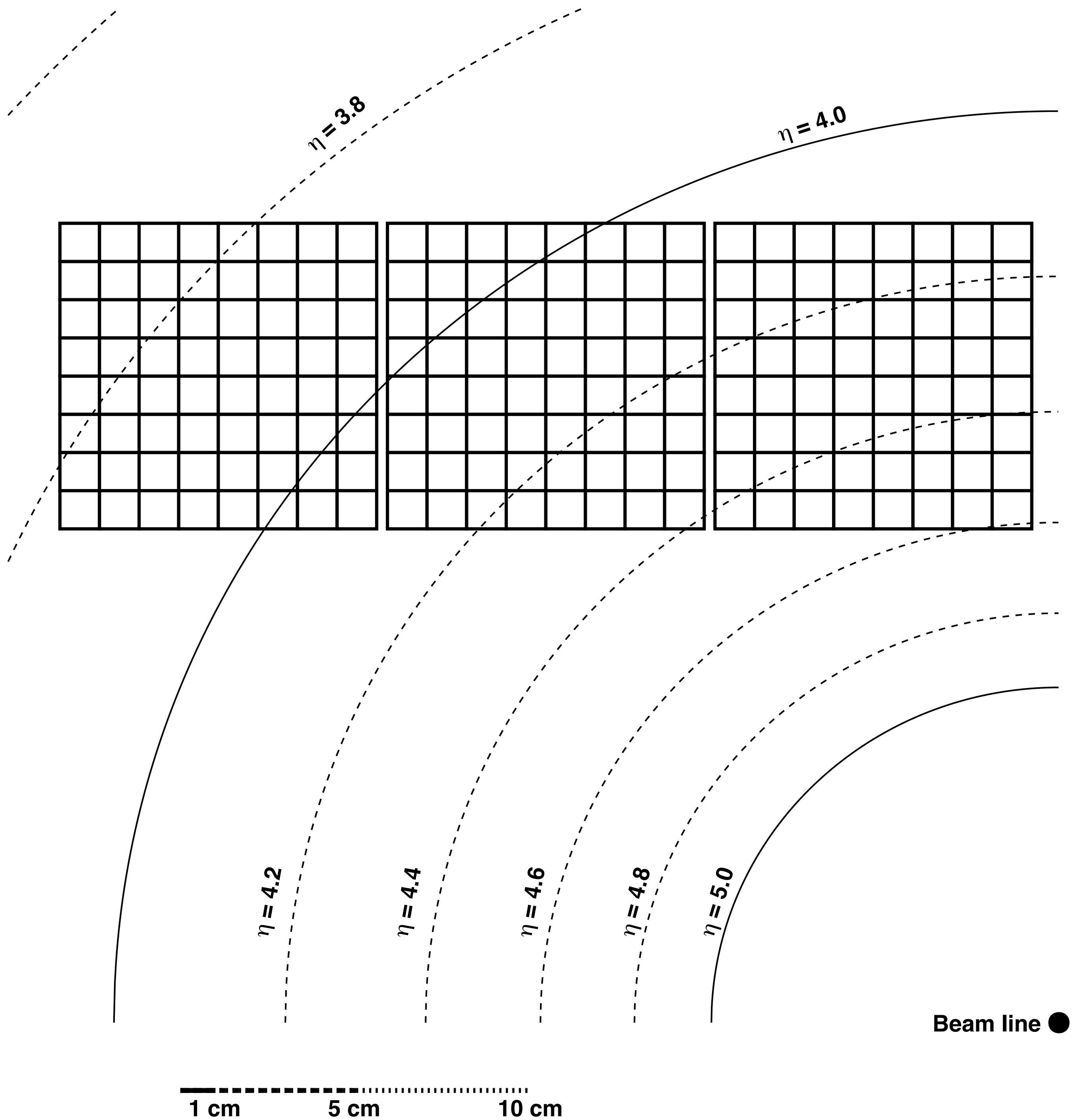


The results suggest a **large suppression** in the very forward region in the high multiplicity d+Au collisions

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.

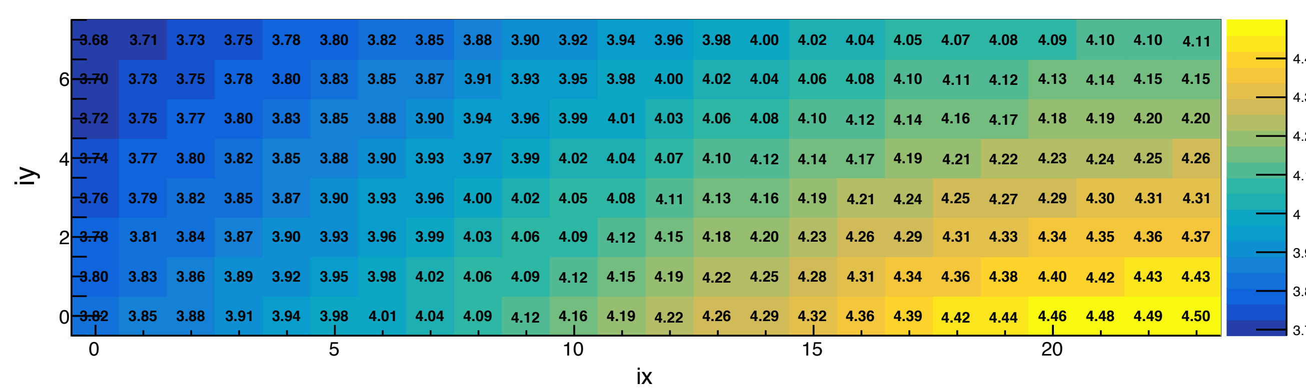
Geometry overview in ALICE



The miniFoCal rapidity distribution in ALICE:

- The acceptance is from η = [3.7,4.5]
- Calculated with the x,y,z positions from Ton and Rene

Pseudorapidity for the center of the PADs



MiniFocal in ALICE