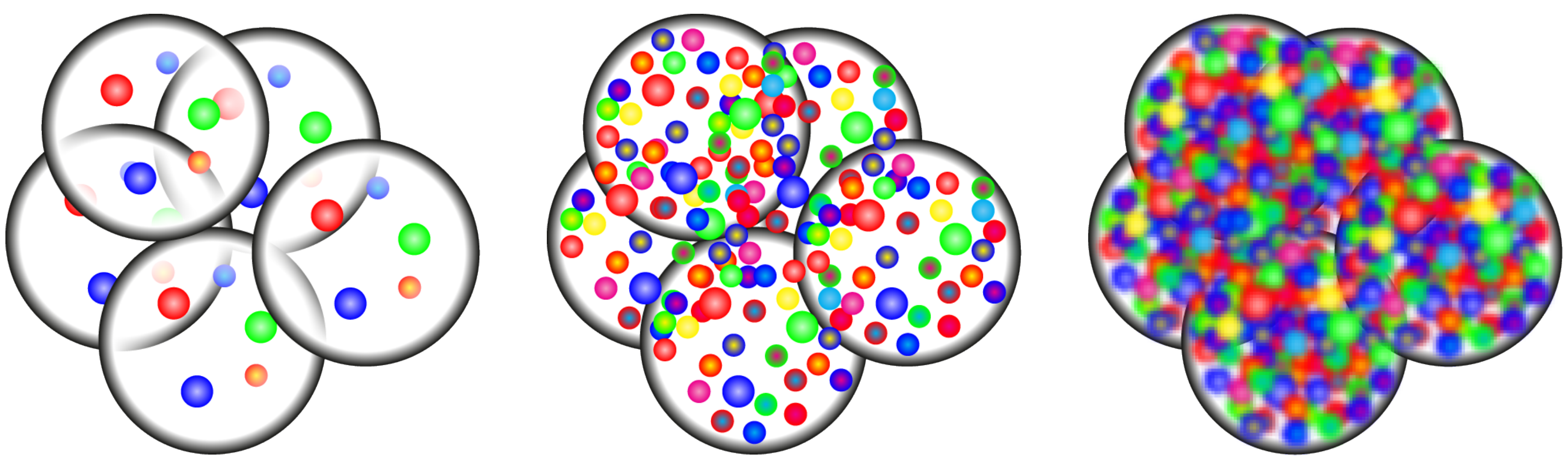
ALICE

Forward Calorimeter (FoCal) upgrade in ALICE

(*Physics and detector*)

Norbert Novitzky

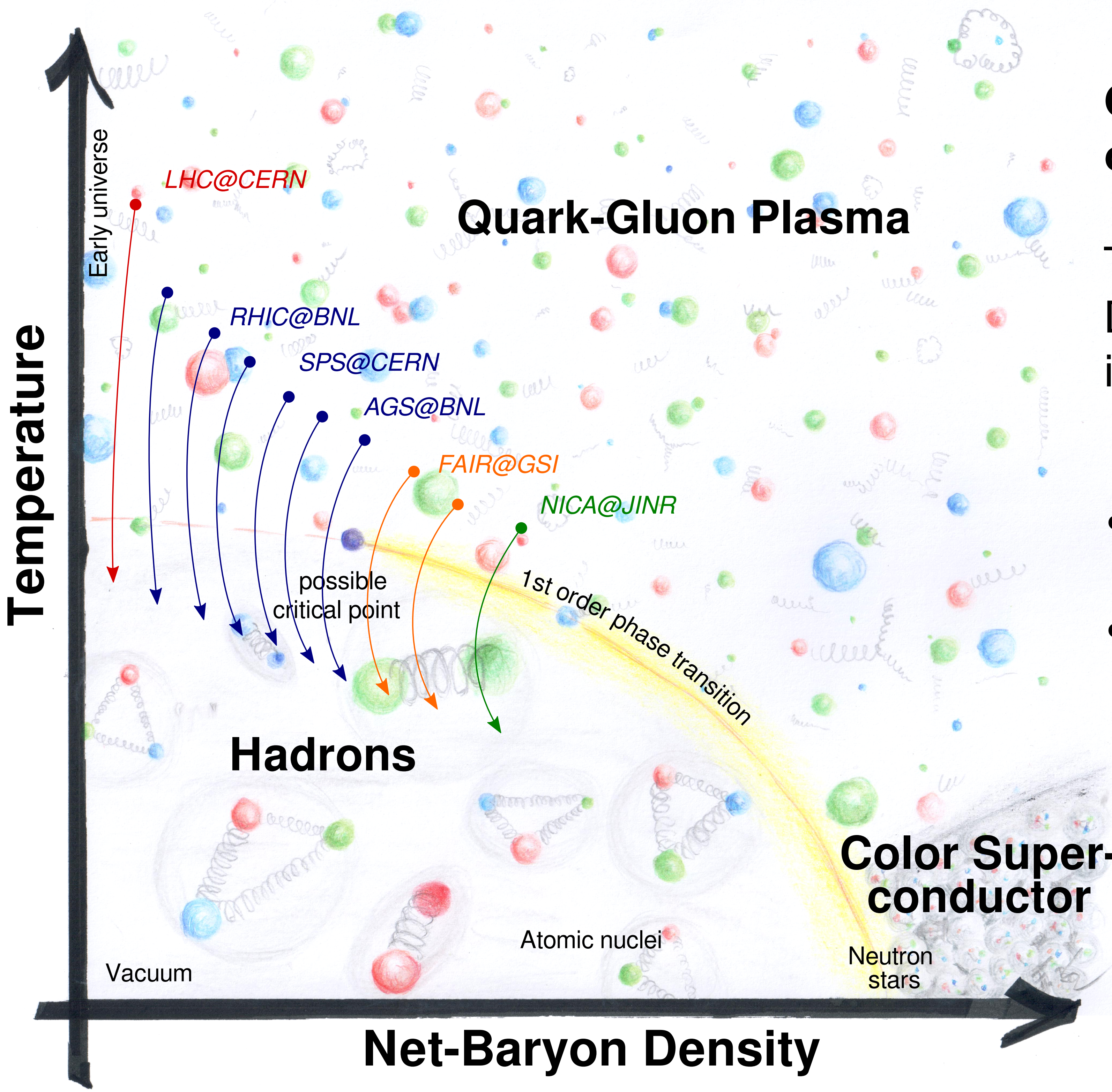
(University of Tsukuba, TCoHU)



筑波大学

University of Tsukuba

Heavy Ion physics

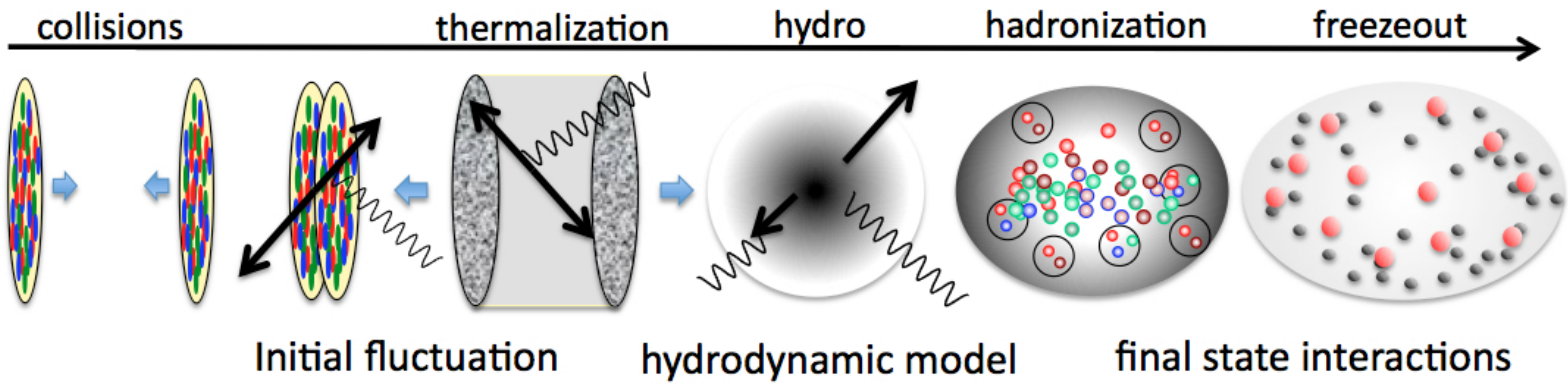


QCD phase diagram is characterized as:

Temperature (T) vs Net Baryon Density (μ_B) governed by QCD interactions

- **Quark-Gluon Plasma (QGP) is created in the early universe**
- **We can recreate this matter in the laboratory:**
  - First discovery in RHIC collisions
  - Observed as almost ideal fluid with $\eta/s \approx 0.08$

Heavy ion collisions



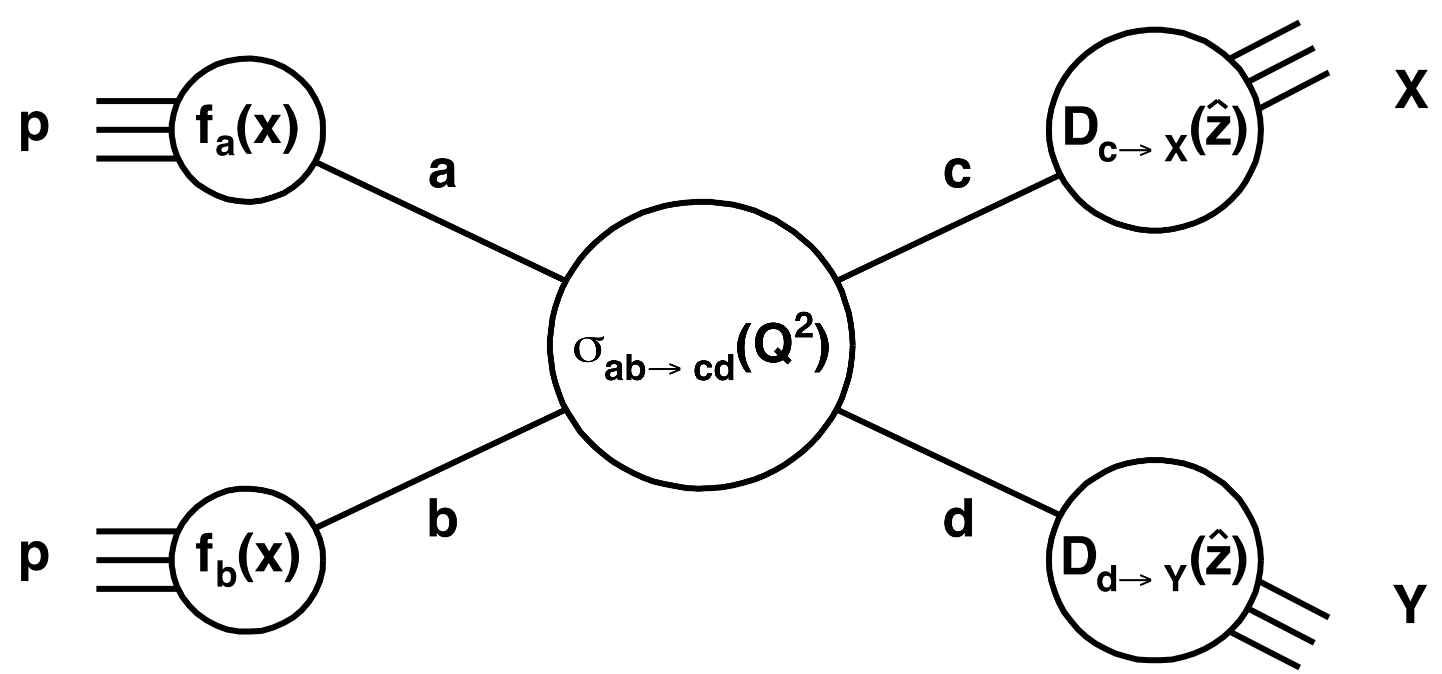
A strongly interacting matter (called Quark Gluon Plasma) is created in heavy ion collisions. We observe few strong evidences:

- Parton energy loss
- Hydrodynamical behavior
- Thermal radiation
- etc.

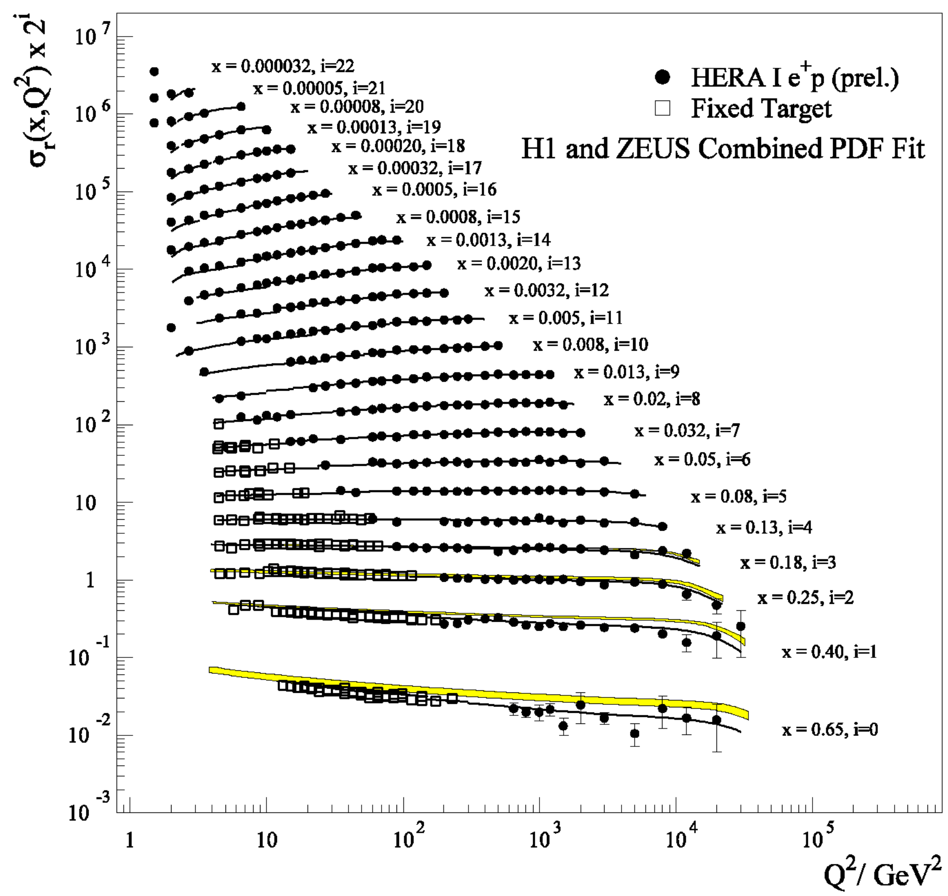
We use the hydrodynamical tools to describe the created medium, its dynamical behavior. However, the pre-equilibrium phase (or before the thermalization) is not very well understood.

Perturbative QCD

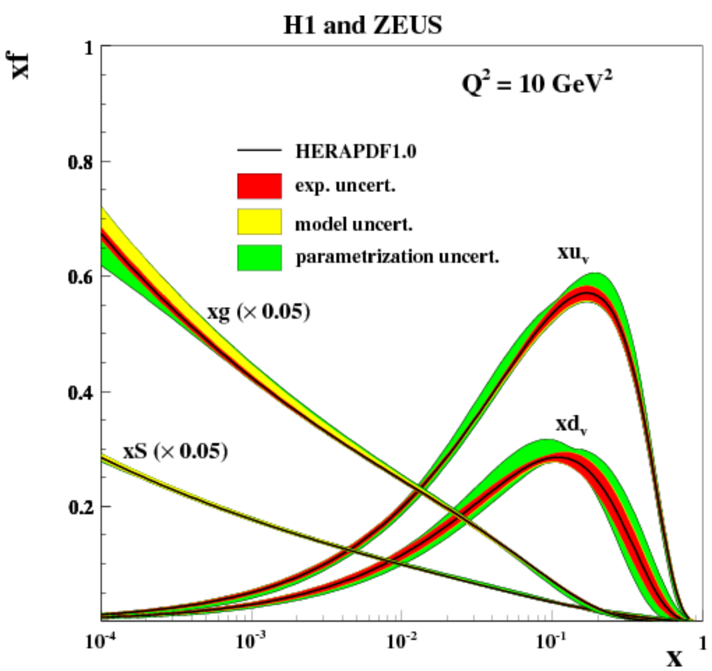
Hard Scattering process



Nucl.Phys.Proc.Suppl. 191, 5 (2009)



JHEP 1001 (2010) 109



Cross section calculated from the pQCD factorization:

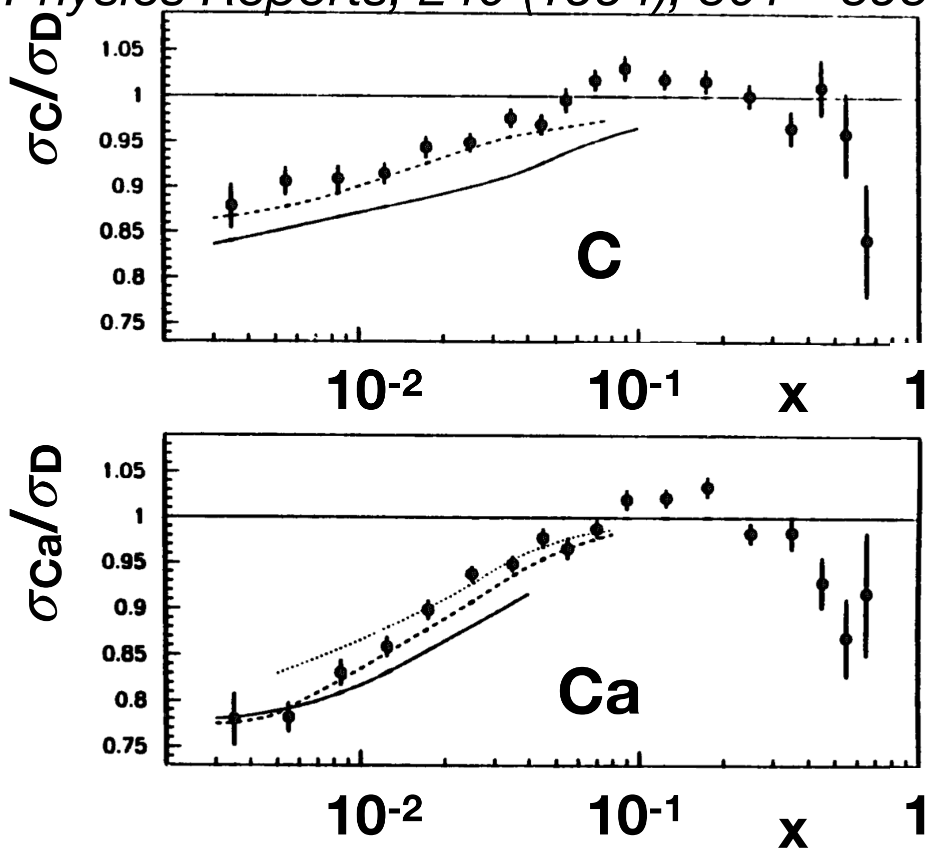
$$d\sigma = \int dx_1\, dx_2\, dz\, f_a(x_1, Q^2) f_b(x_2, Q^2) D_c^h(\hat{z}) \otimes d\sigma_{ab}^{cd}(Q^2)$$

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

- *There is also a theoretical effort to calculate them*

Nuclear Parton Distribution Function

Physics Reports, 240 (1994), 301—393

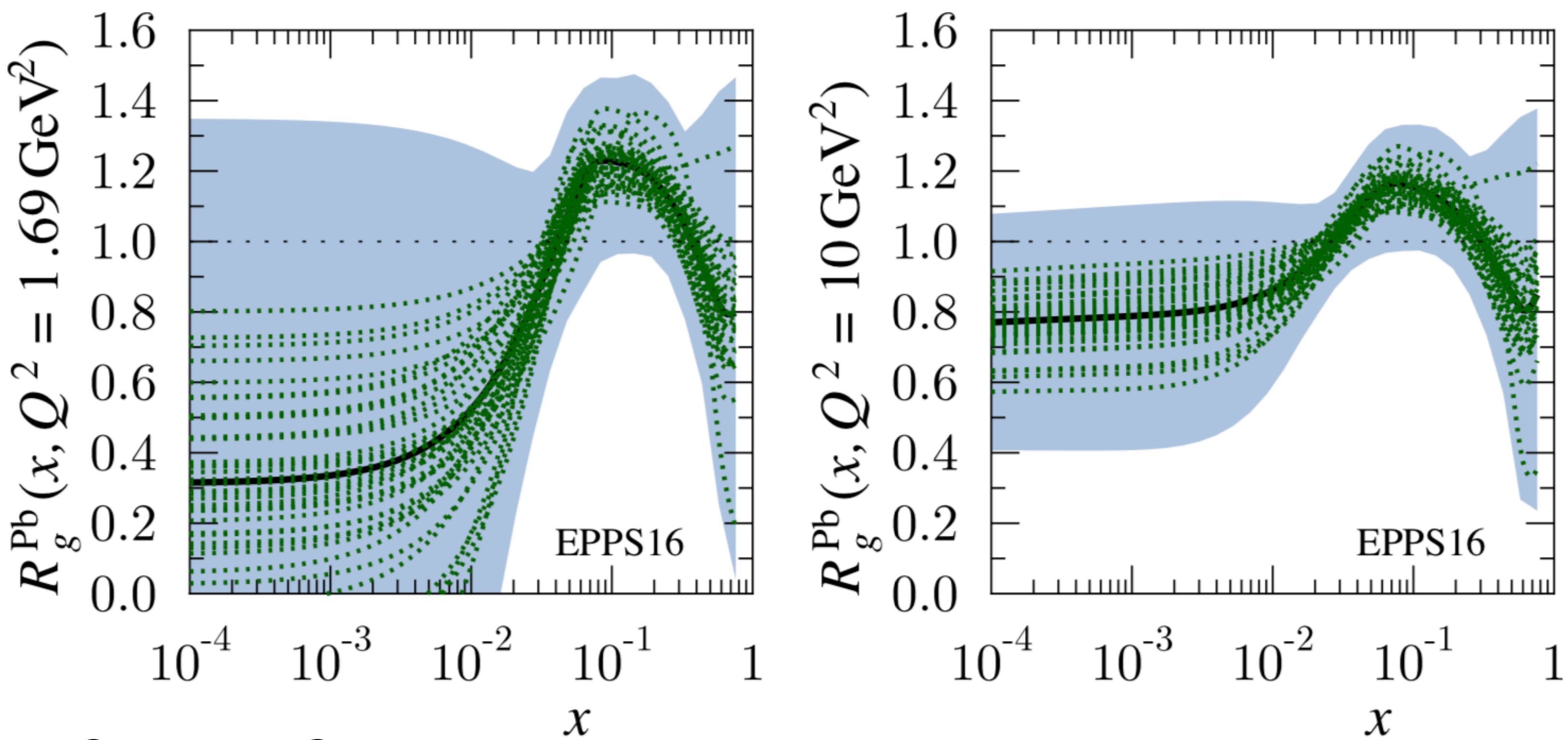


It was found that in nuclei, the parton distribution function is modified

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

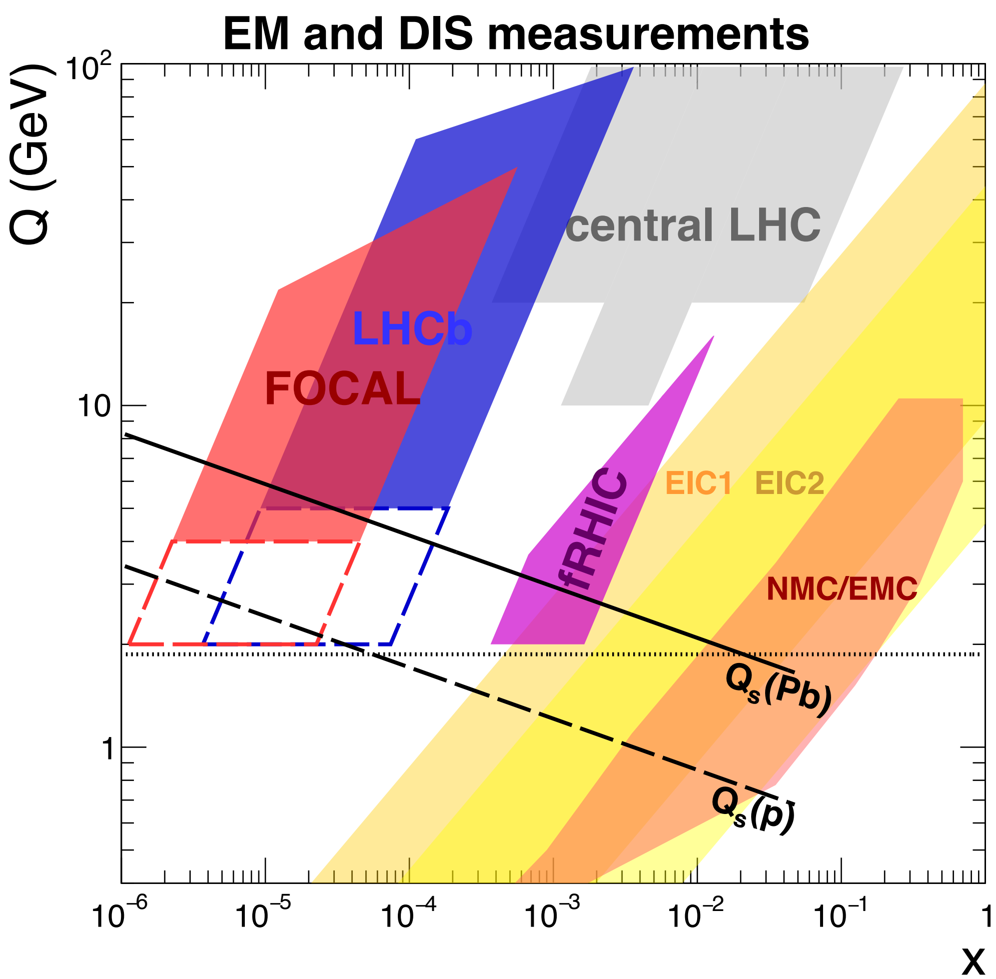
Large uncertainties on the gluon nPDFs:

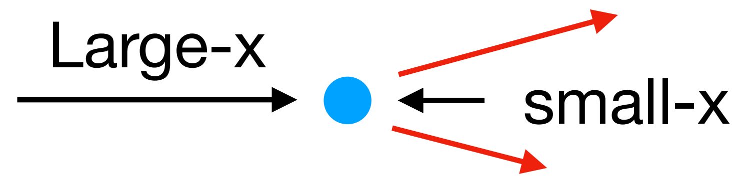
- Parametrized nuclear modification

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.

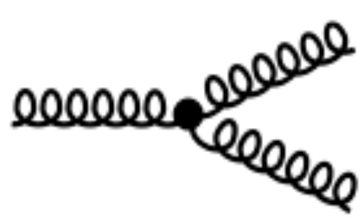
- LHCb: $2.5 < \eta < 5.0$
- FoCal: **$3.4 < \eta < 5.8$**
  - Main goal to measure direct photons and π^0 in *pp* and *p*-Pb collisions
  - Ongoing R&D work on the detector design
  - LoI endorsed by LHCC for Run 4,
    see: https://cds.cern.ch/record/2719928

Prediction of gluon-saturation

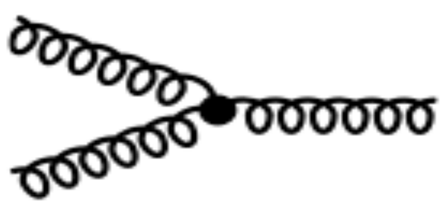
The BFKL equation (as well as DGLAP evolution) are linear equations and only include parton splitting

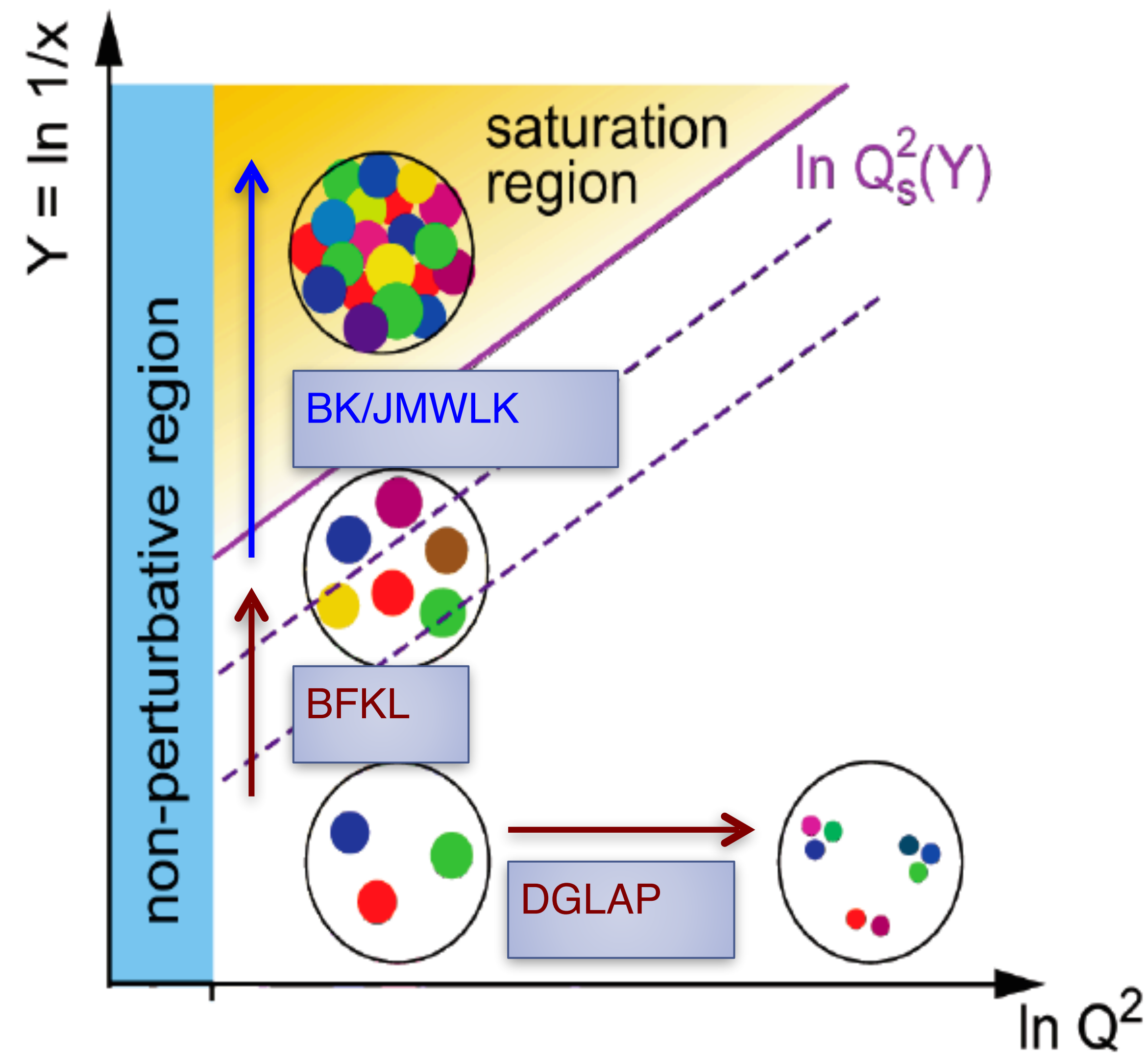
At high enough gluon densities the gluon would also recombine described by BK/JMWLK equations

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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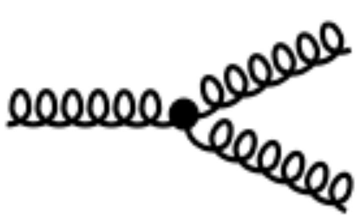
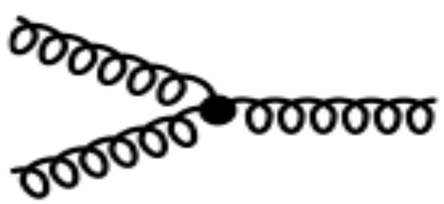
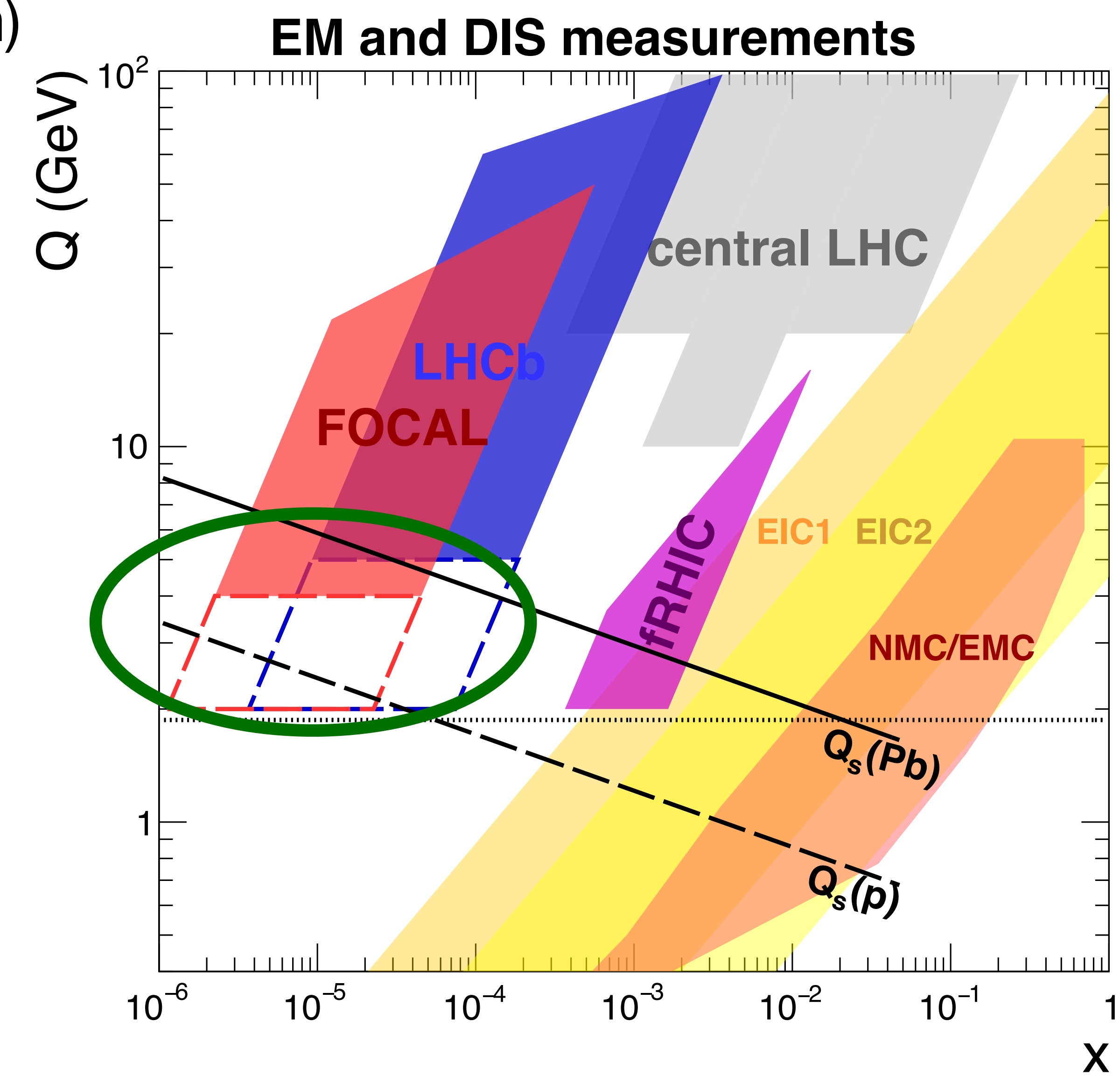


Nonlinear QCD
BK/JMWLK gluon recombination





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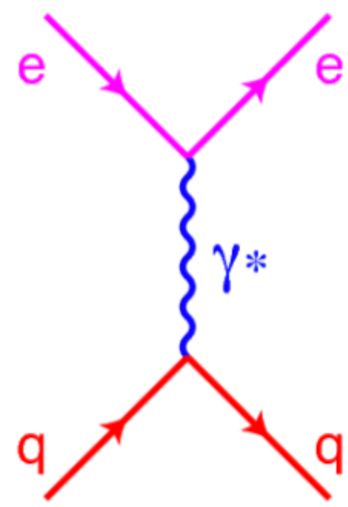
How to probe gluon density

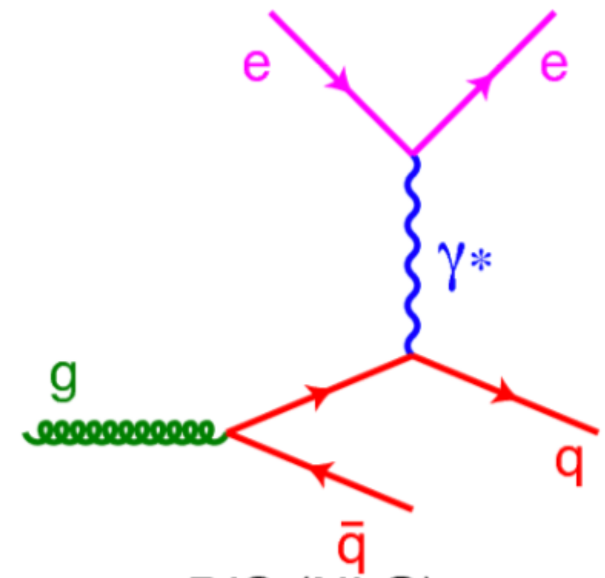
Probing the PDF in the nucleon:

- 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



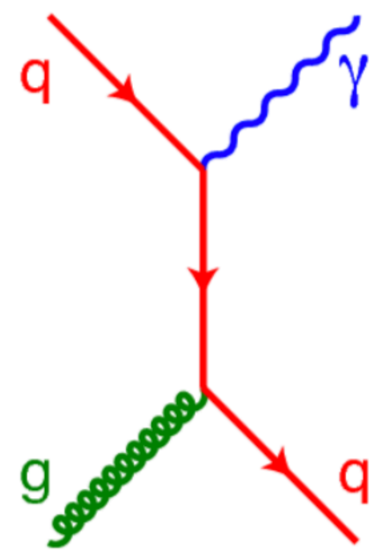
DIS (LO)



DIS (NLO)

Photon production in hadronic collision:

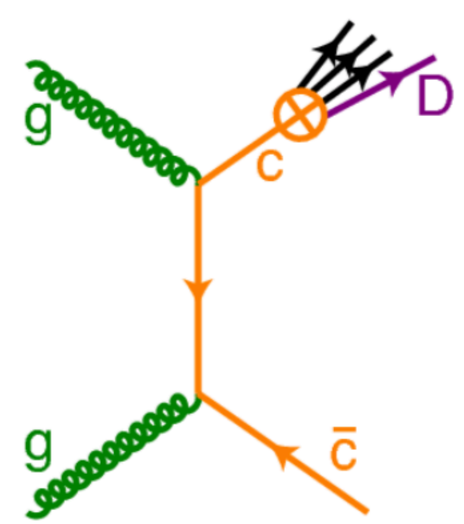
- Sensitive to the gluon PDF in the LO via the QCD Compton scattering



direct-γ, Compton (LO)

Heavy quark production is dominated by gluon fusion:

- convoluted with the fragmentation function



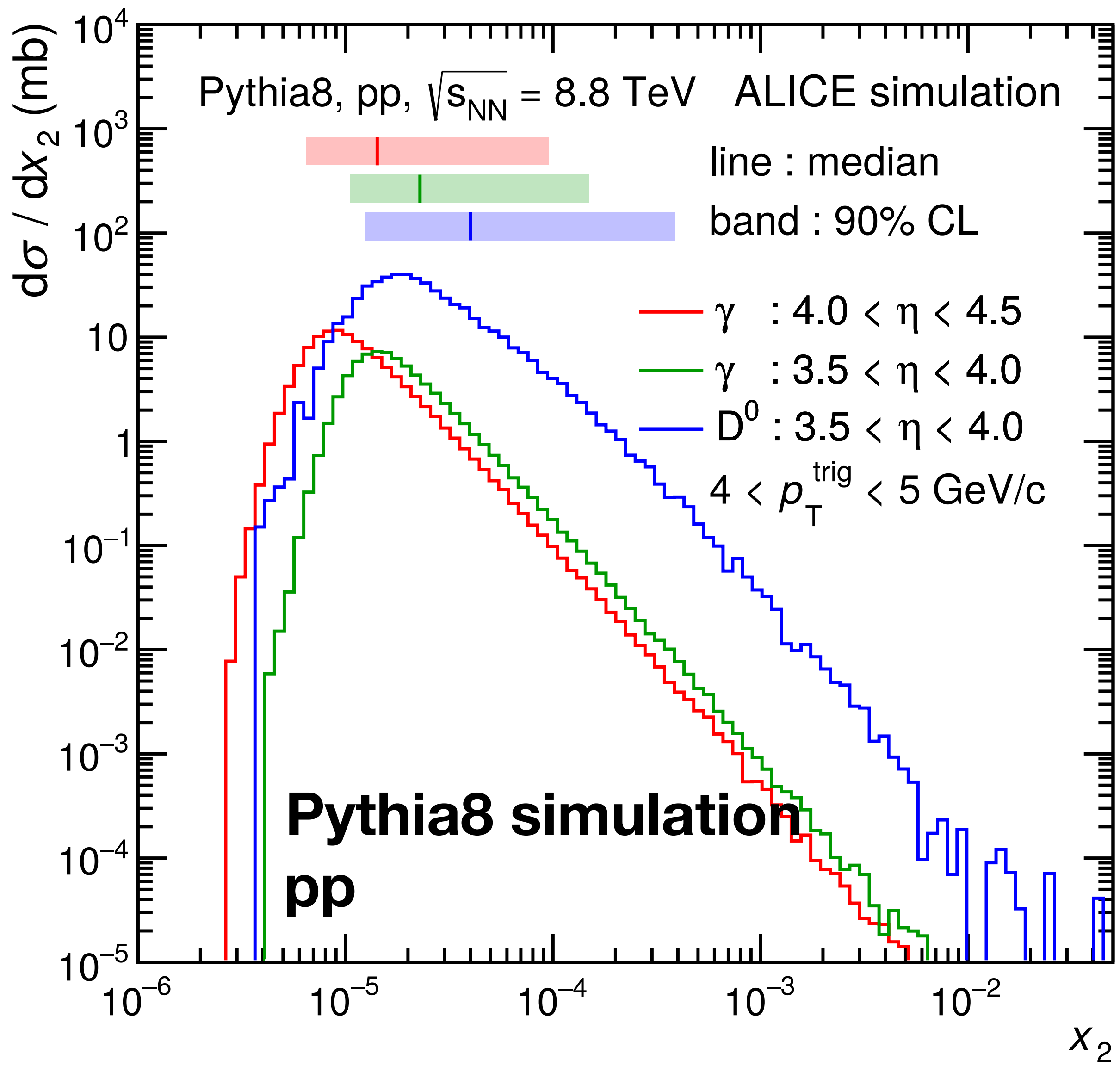
Heavy hadron:
tag hard scattering,
but includes fragmentation

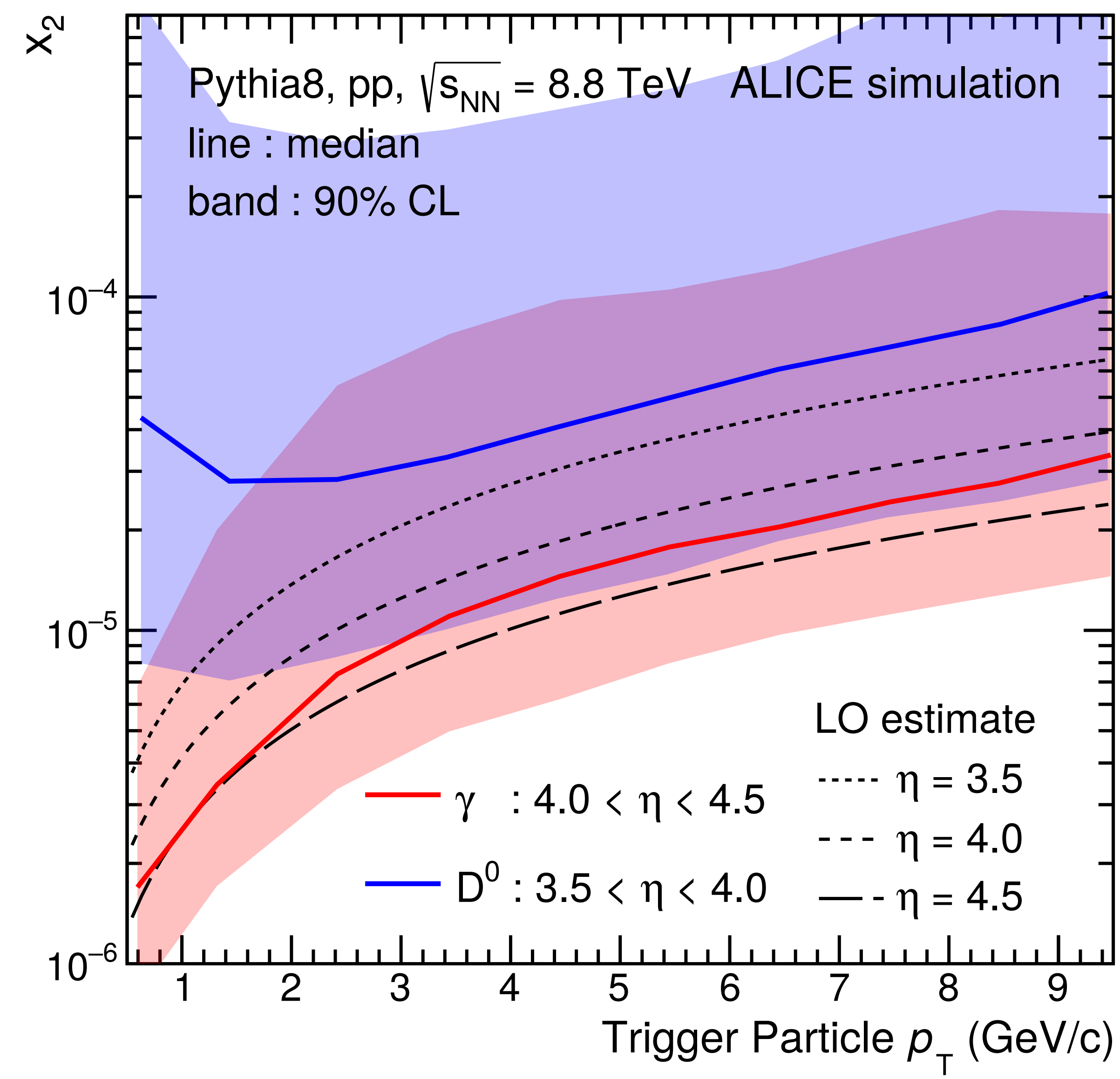
Direct photons as probes

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



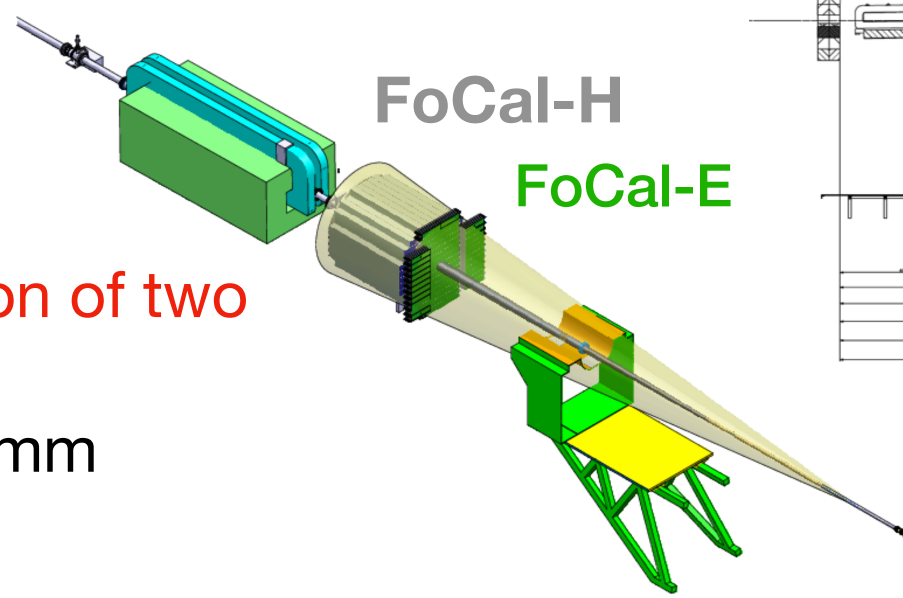


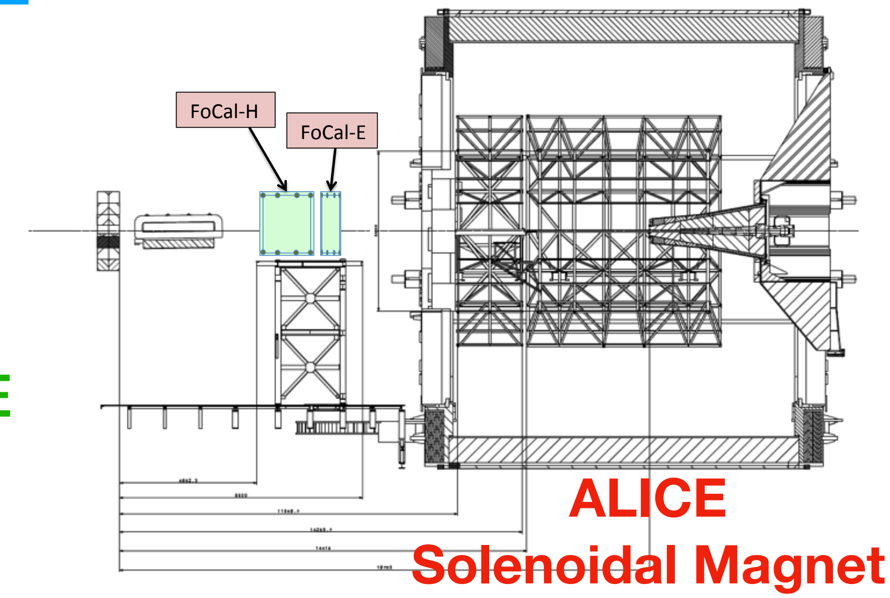
Comparison of the direct photon and D^0 as a probe for the nuclear PDF:

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

The ALICE - FoCal Proposal

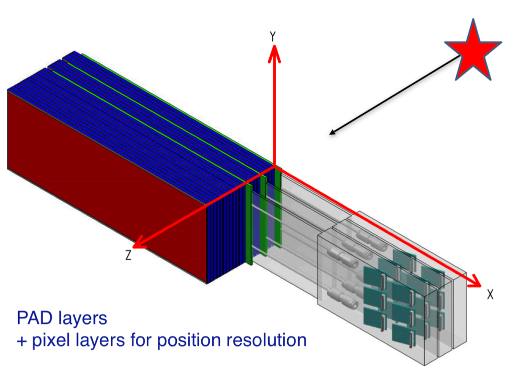
FoCal Proposal:
- 7 m from the interaction point
  - covering **$3.4 < \eta < 5.8$**
- FoCal-E - electromagnetic part:
  - **direct-γ and π^0** measurement
  - Main challenge is the separation of two clusters at high energy
  - Shower separation down to 1 mm
  - Good energy resolution 2-5%
- FoCal-H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



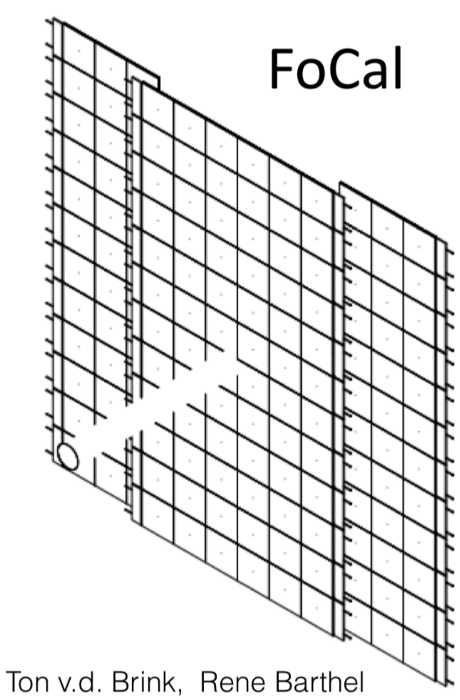


Installation possibility during LS3 (2024-2026) to be used in LHC Run 4.

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

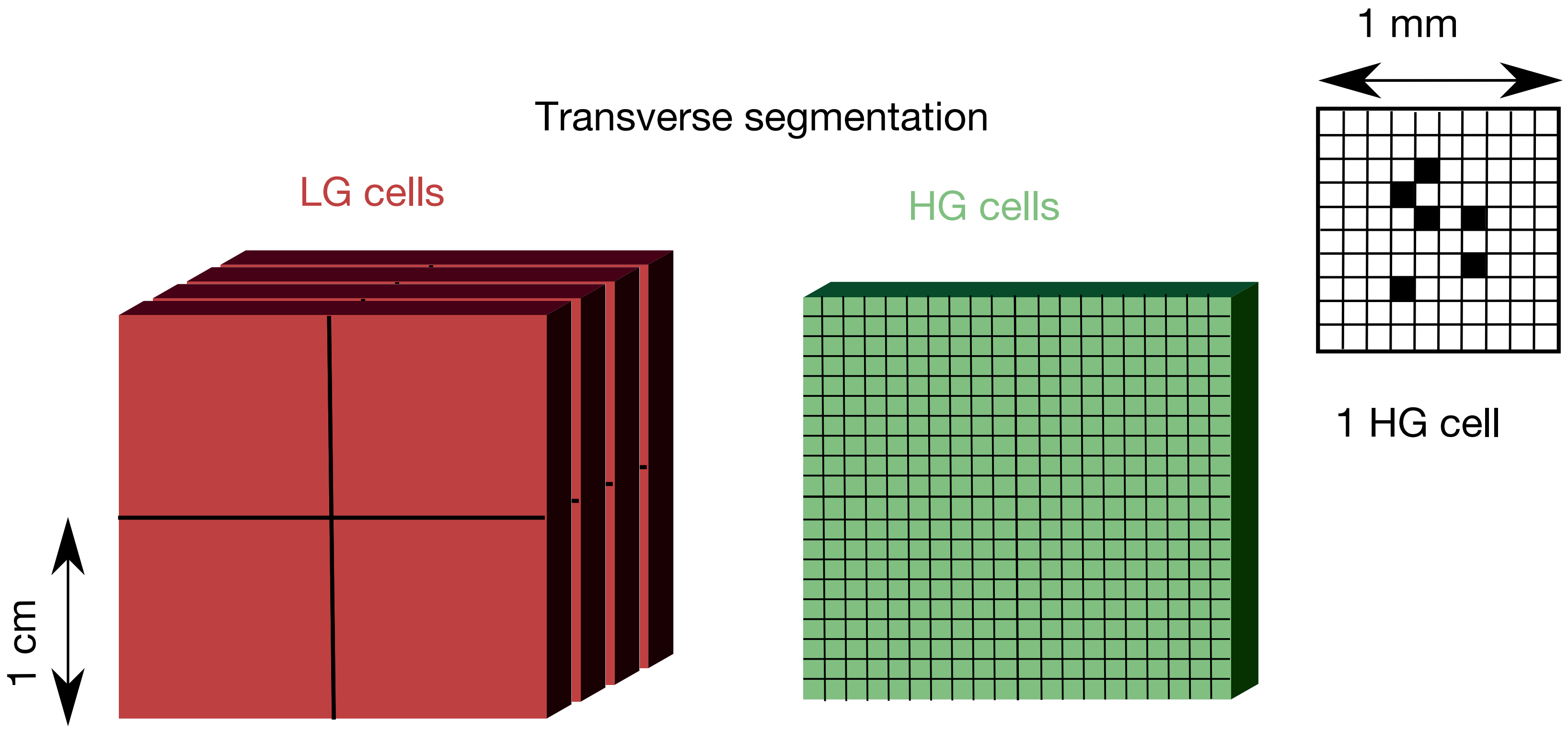


FoCal-E



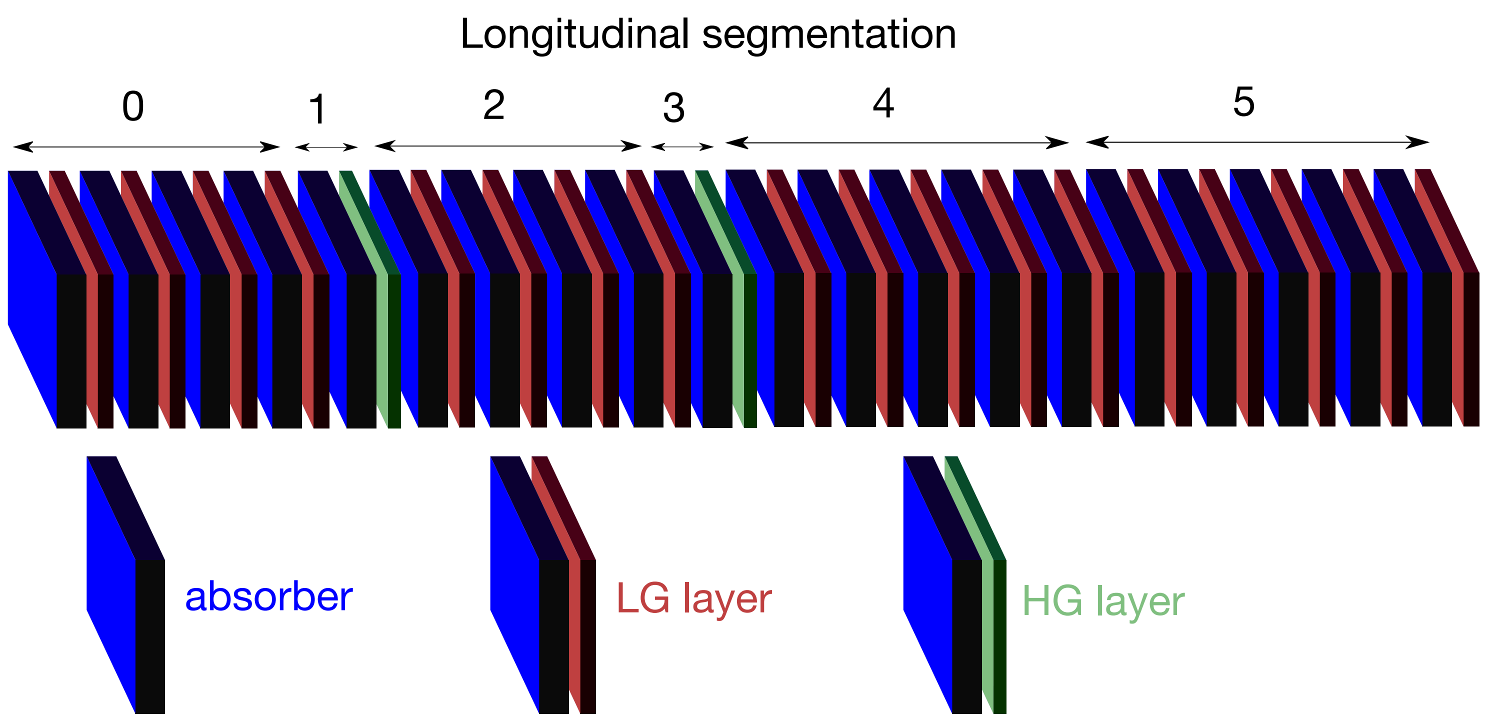
Ton v.d. Brink, Rene Barthel

FoCal-E basic design



The design of the detector:

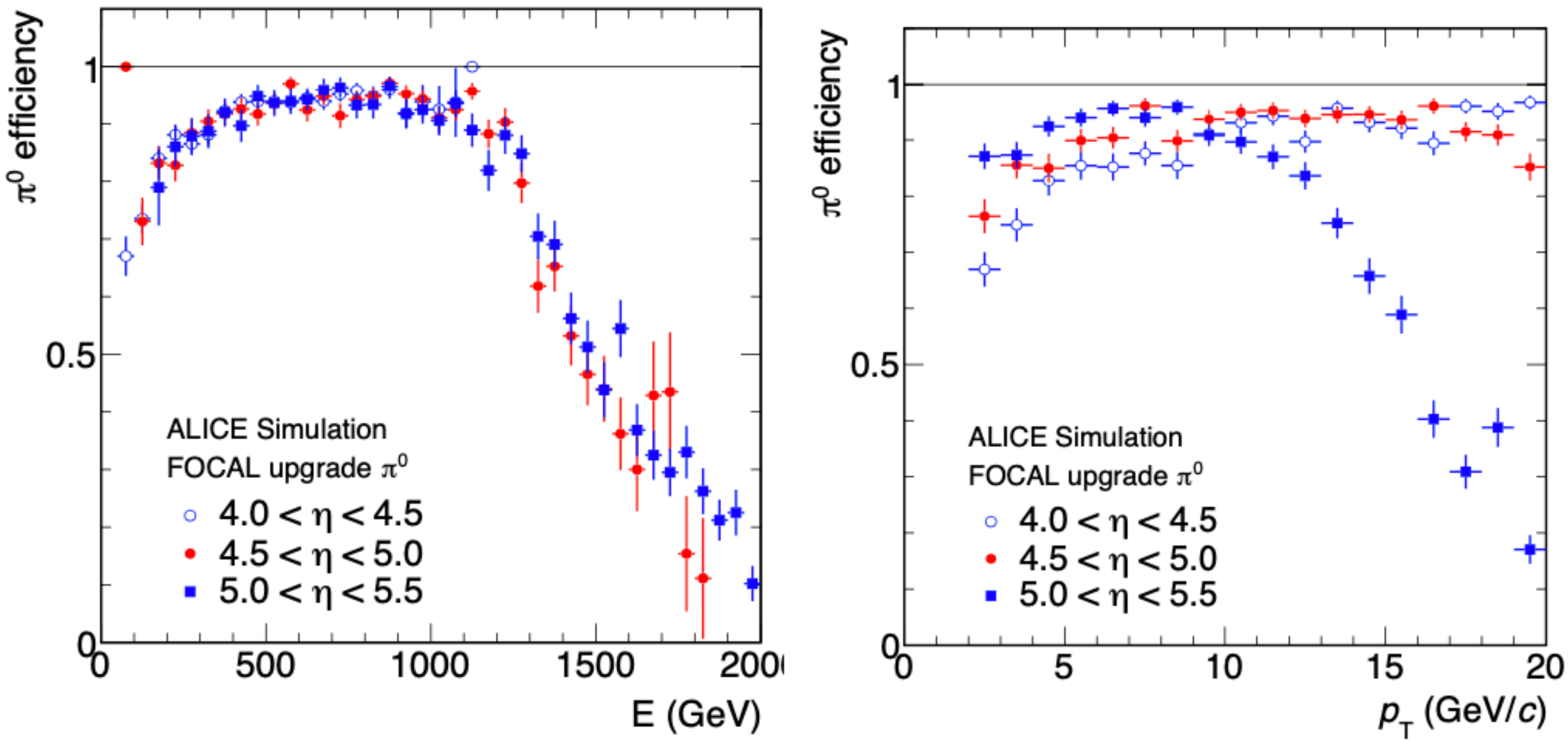
- 20 layers: W (**3.5 mm ≈ 1 X_0**) + Si-sensors (2 types):
  - **low granularity (LG), Si-pads**
  - **high granularity (HG), pixels (e.g. CMOS-MAPS)**
- Moliere radius ~ 1-2 cm



	LG	HG
pixel/pad size	≈ 1 cm²	≈ 30x30 μm²
total # of pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9

The surface area of the detector will be about 1 m²

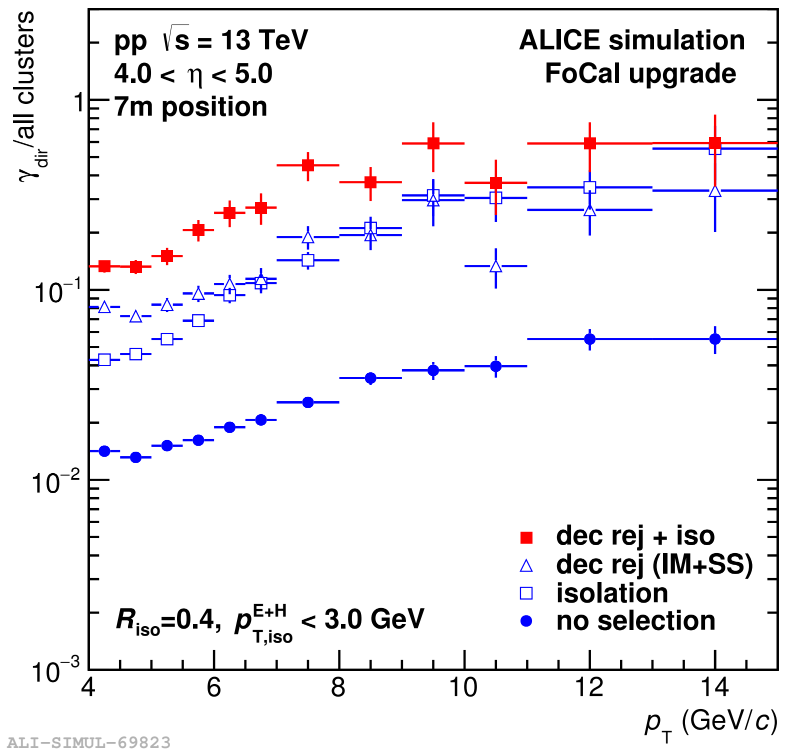
Single π^0 efficiency



Most of the photons come from the decay of mesons:

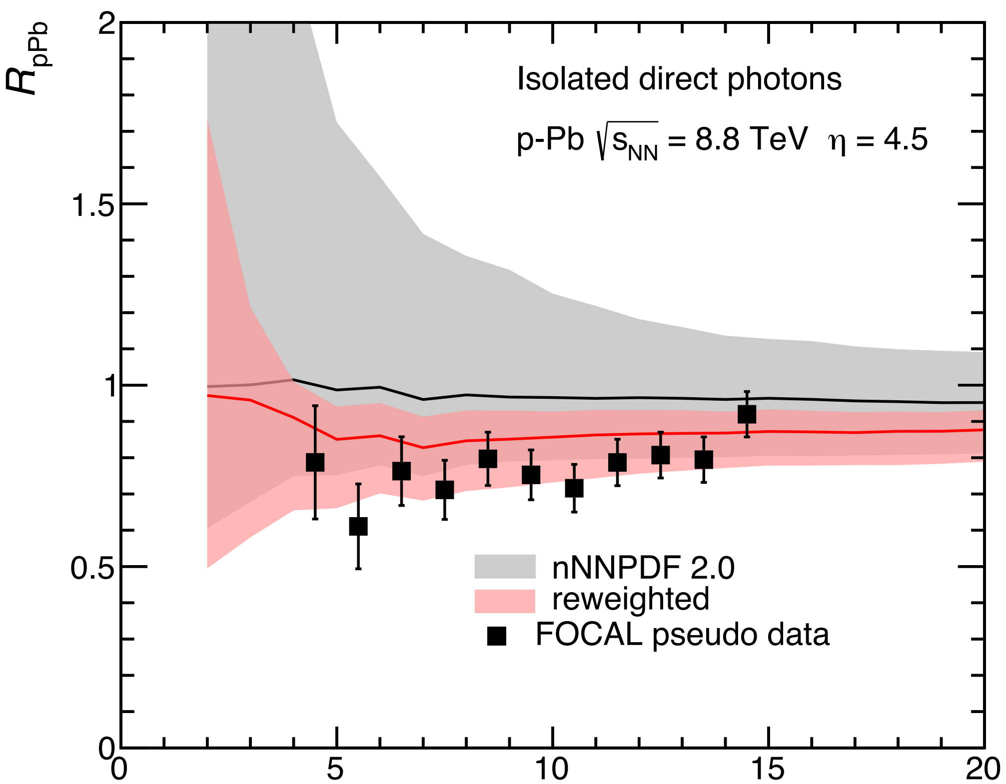
- decay photons from neutral pions are far the dominant source of the decay photons
- The efficiency of the pion reconstruction is above 90% in p_T ~ 4-20 GeV/c, lower in the most forward direction:
  - Efficiency start to drop over 1.2 TeV showers

Performance studies

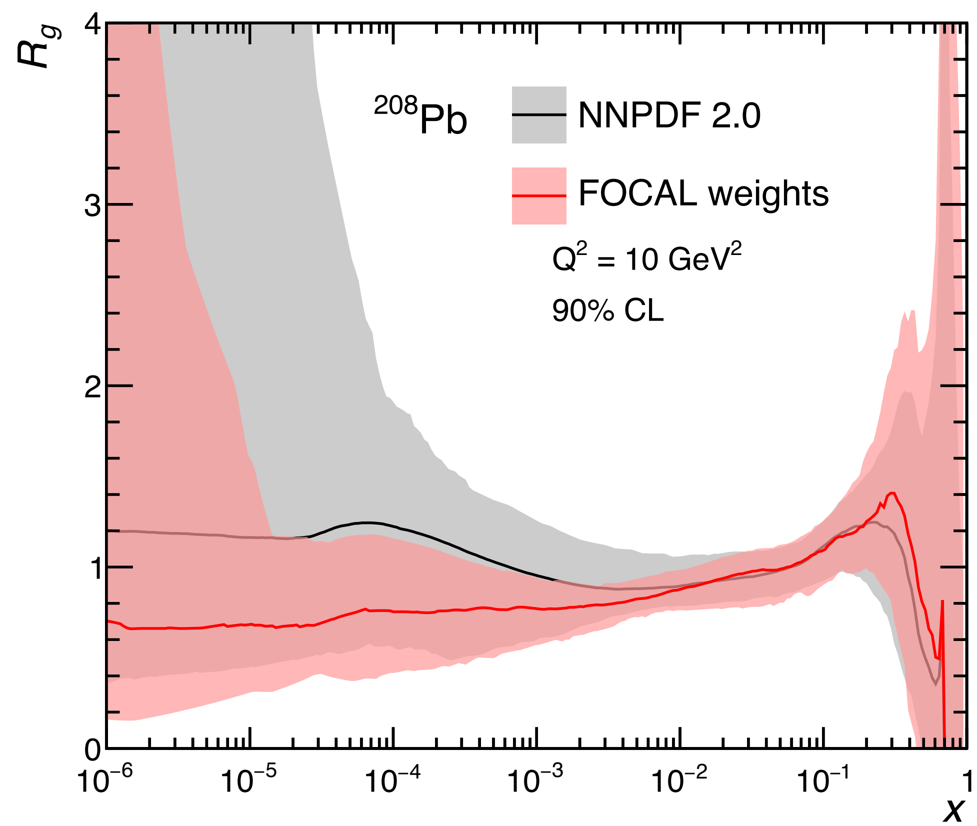


The detector is a novel design for calorimeters and enables us to achieve a better purity of direct photon measurements:

- 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



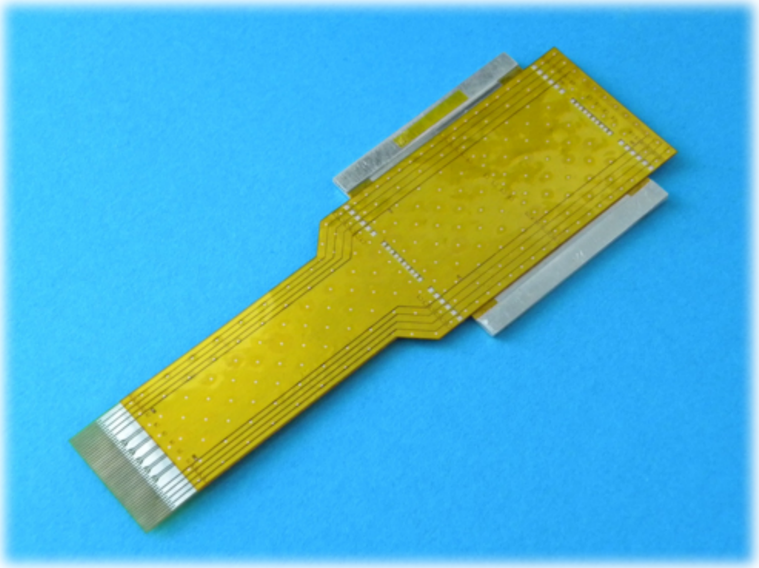
nNNPDF2.0, *JHEP* 09 (2020) 183

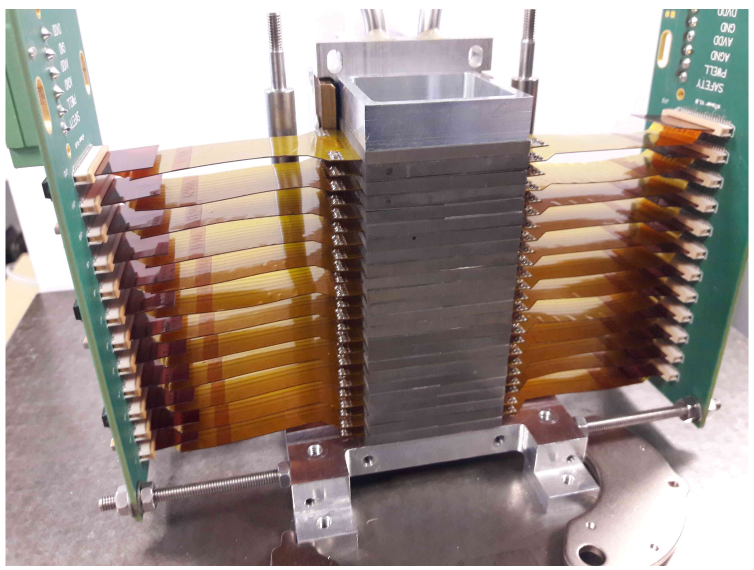


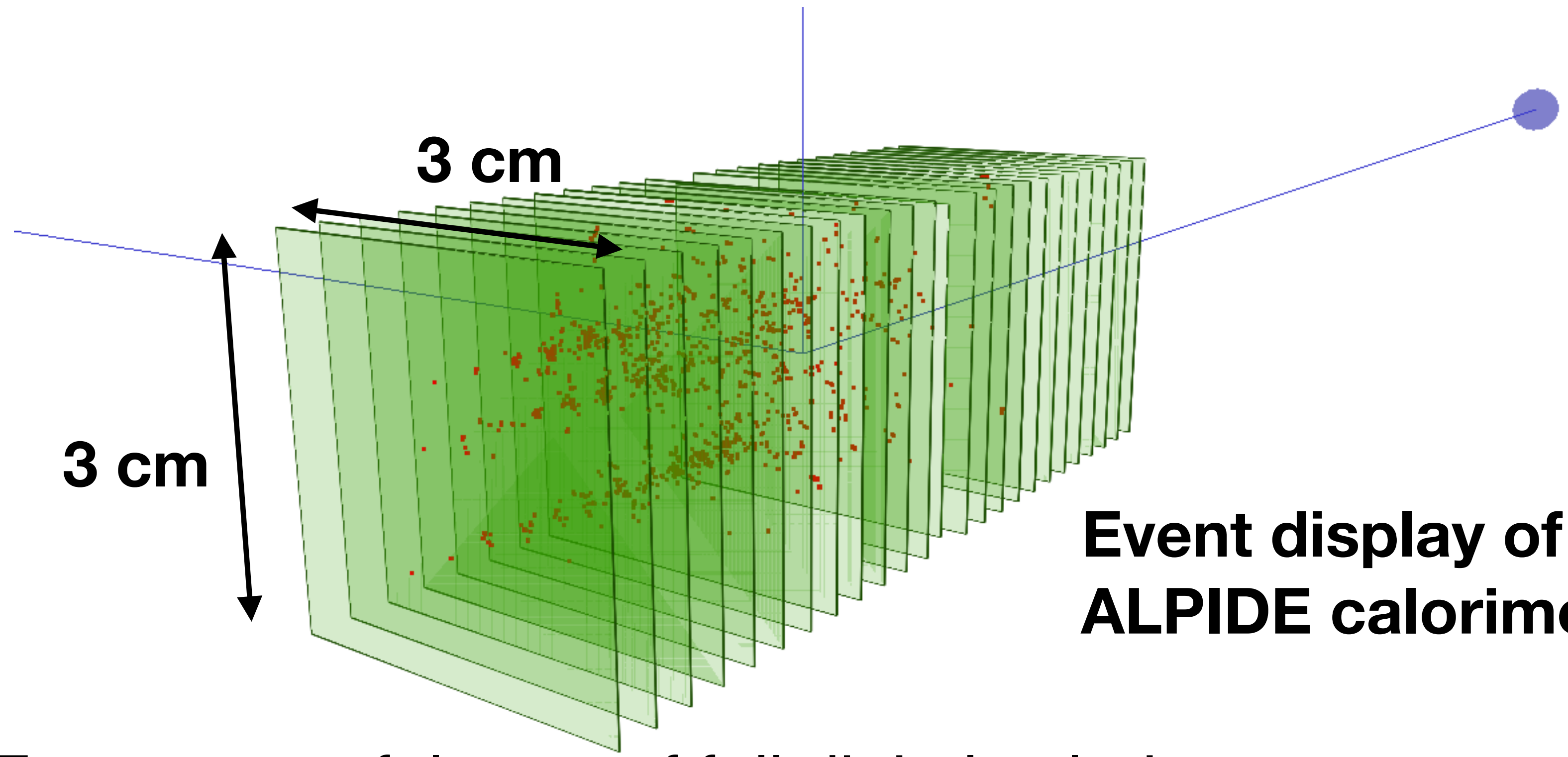
Projected uncertainties of the measurement and its impact on the PDF

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

Prototype MAPS detector







Event display of the ALPIDE calorimeter

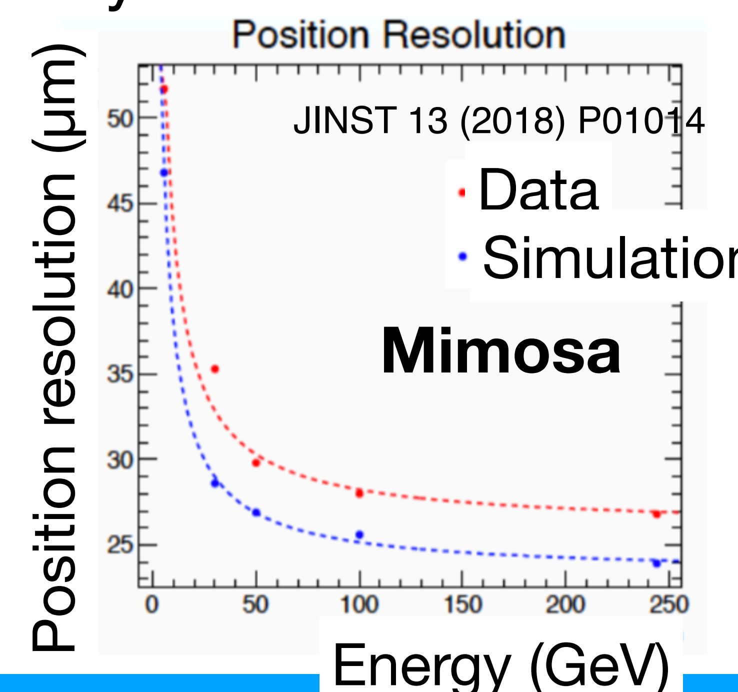
Two successful tests of full digital calorimeter:

- 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.

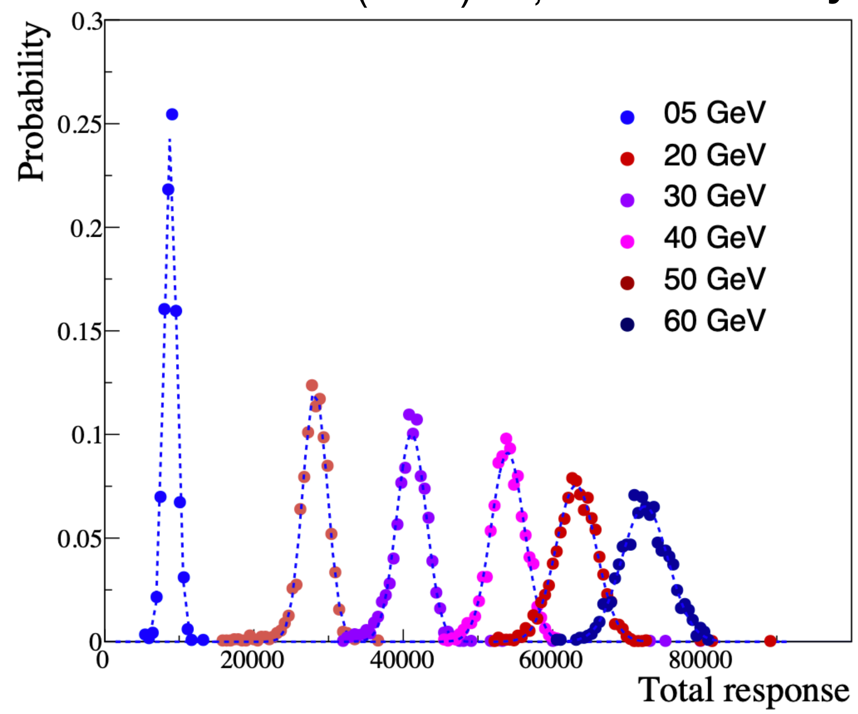


PAD layer prototypes

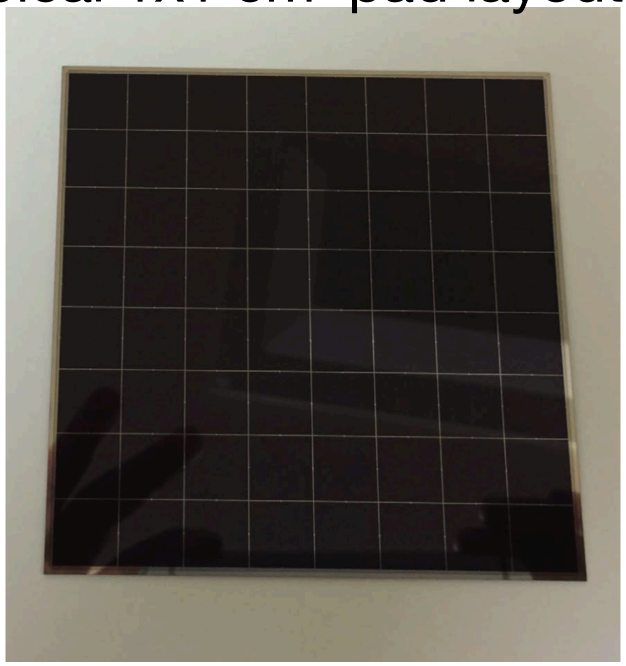
Few iterations of the PAD layer constructed

- 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

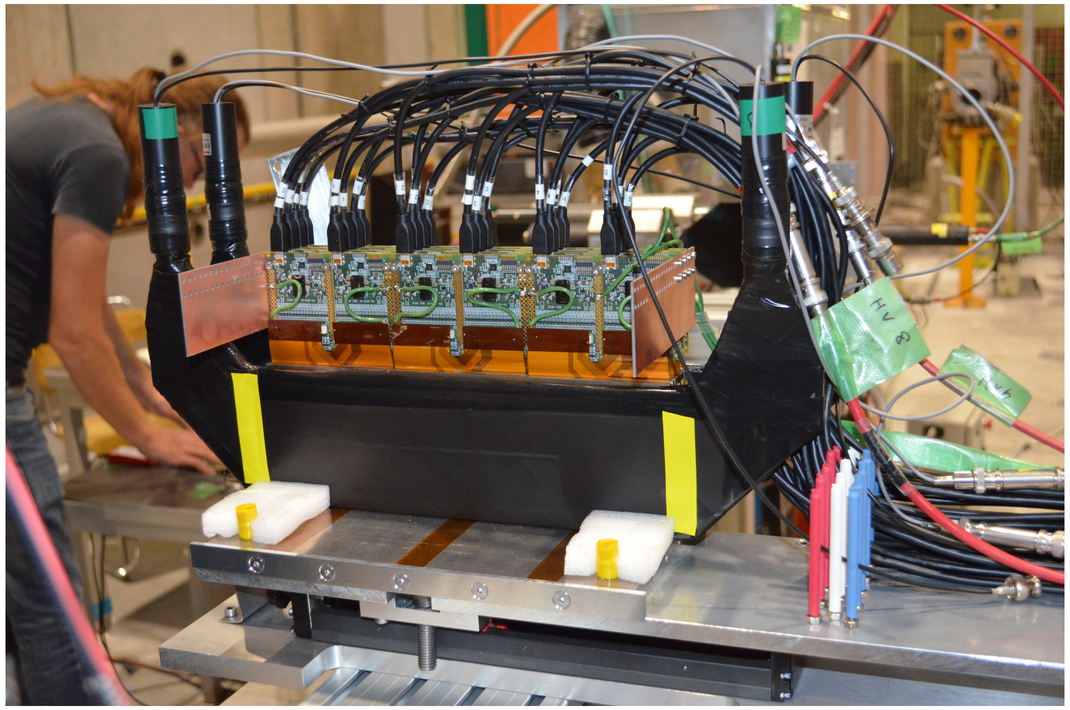


Typical 1x1 cm^2 pad layout

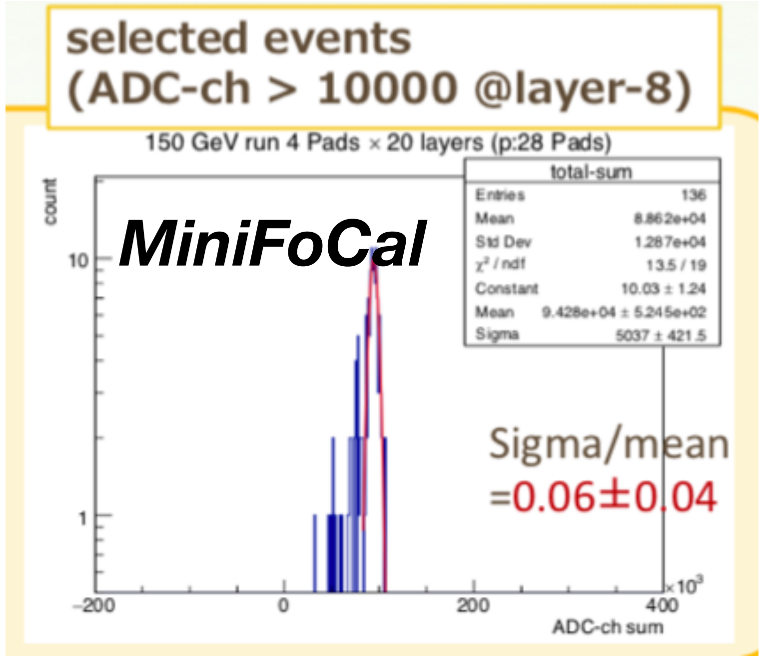


Testbeam measurements

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

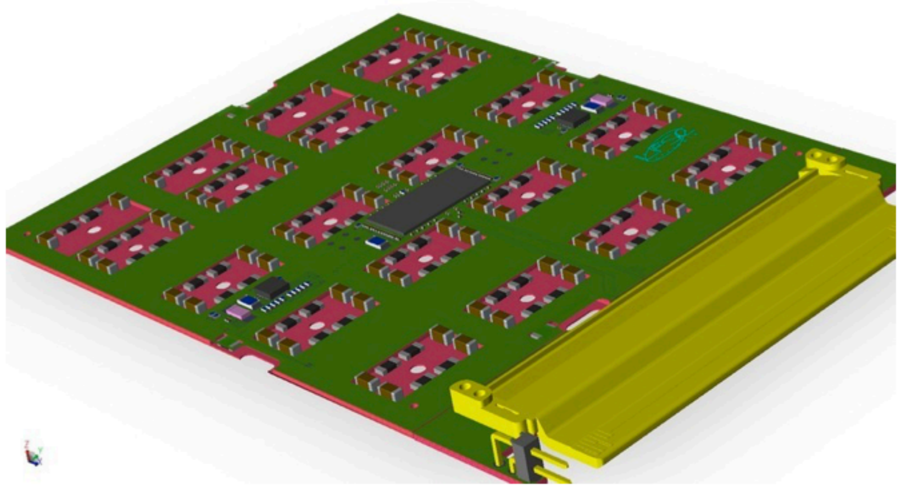


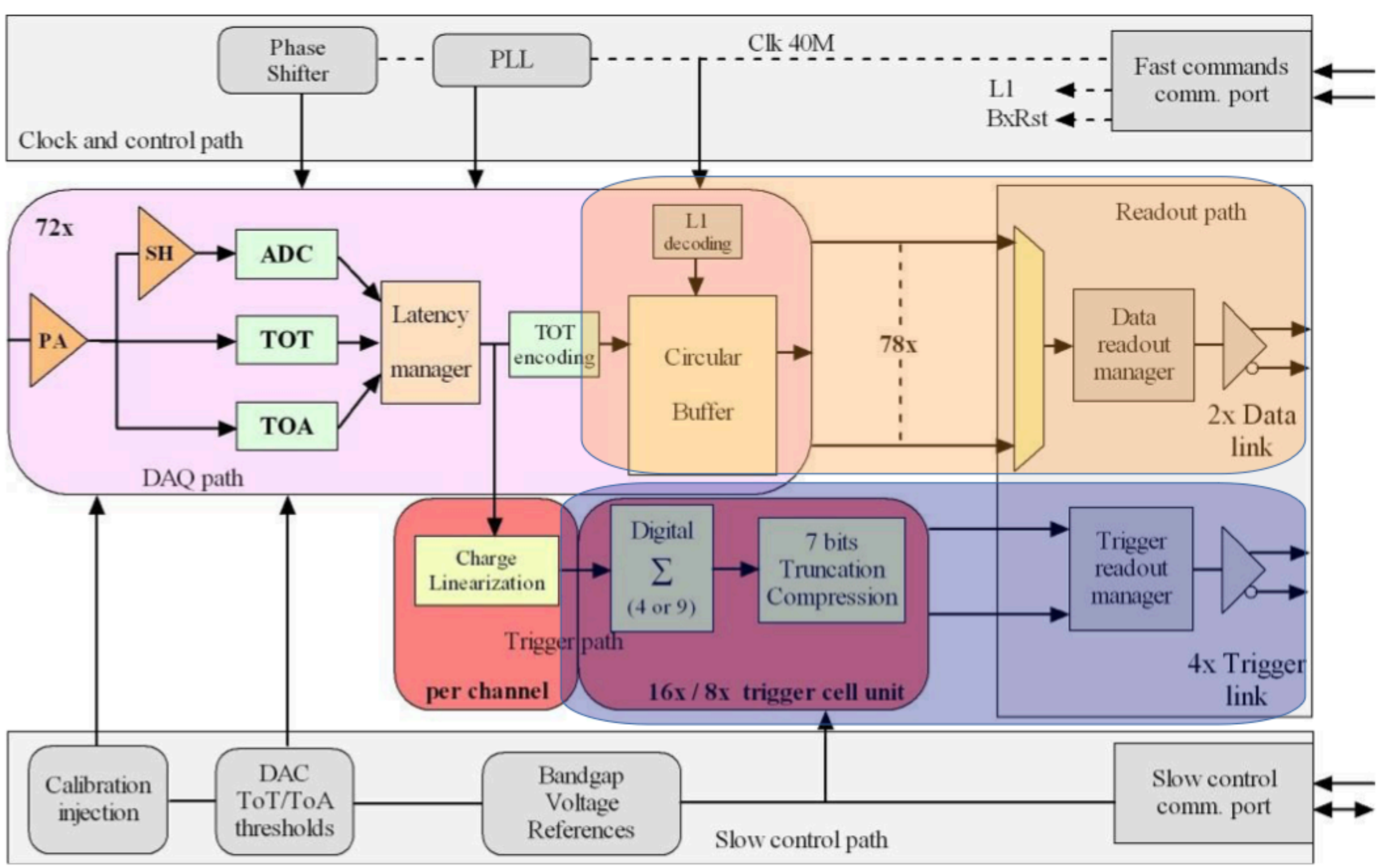
MiniFoCal setup



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:

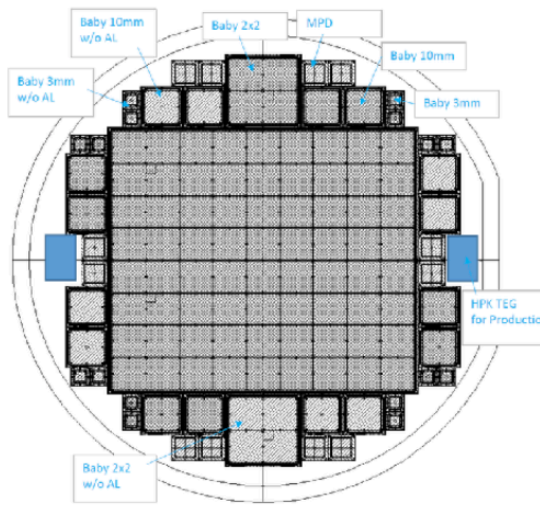
- Low noise and large dynamic range 0.2 fC to 10 pC
- Linearity better than 1% on the full range
- Fast shaping time (peak time < 20 ns)
- High speed readout links (1.28 Gb/s)
- Low power budget < 20 mW
- High radiation resistance

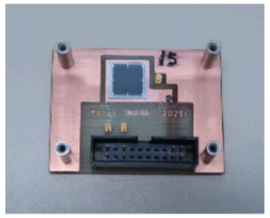
HGCROC (Developed by CMS Collaboration)**:**

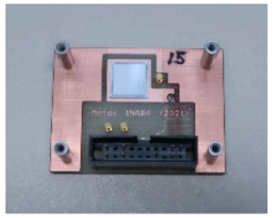
- 76 data channels (72 ch, 2 common noise, 2 calibration)
- ADC for low charge - 10b
- TOT for high charge - 12b

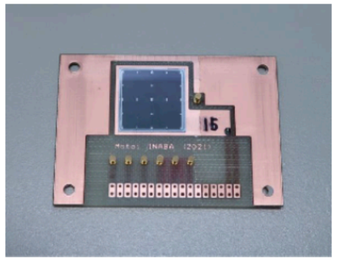
First Tests done in ELPH

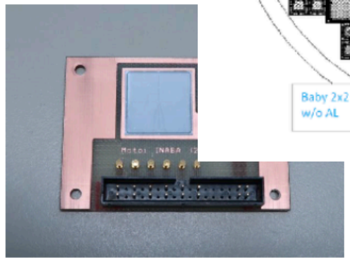
Hamamatsu S16211-0813
- p-sub
- 320 μm
- 1 cm^2 PADs, 9x8 in sensor

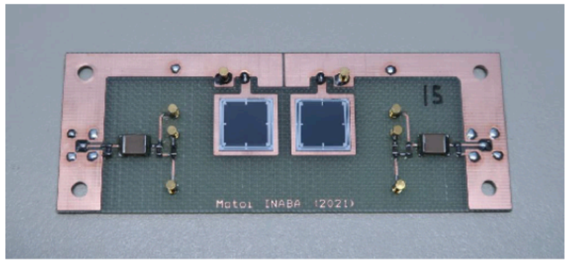


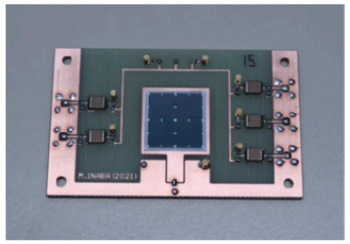

1x1 test cell (DC)

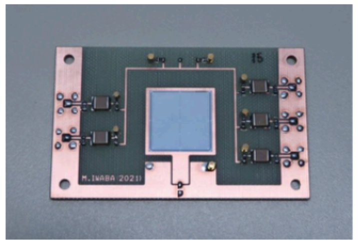

1x1 test cell w/ Al (DC)


2x2 test cell (DC)

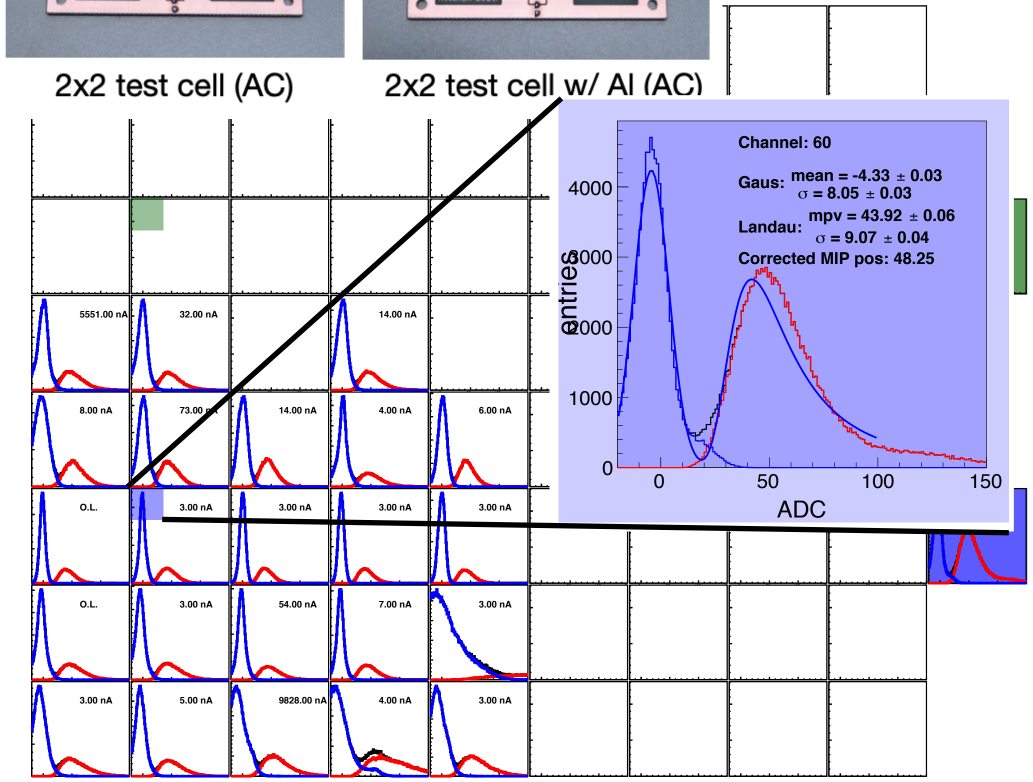

2x2 test cell w/ Al (DC)


1x1 test cells (AC)


2x2 test cell (AC)


2x2 test cell w/ Al (AC)

ELPH testbeam:
- First time to test p-sub sensors for FoCal
- 600 MeV/c positron beam was used
- Feb 16-19, 2021 @ Tohoku University
- Readout with APV chip:
- Next test with HGCROC is scheduled in July



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

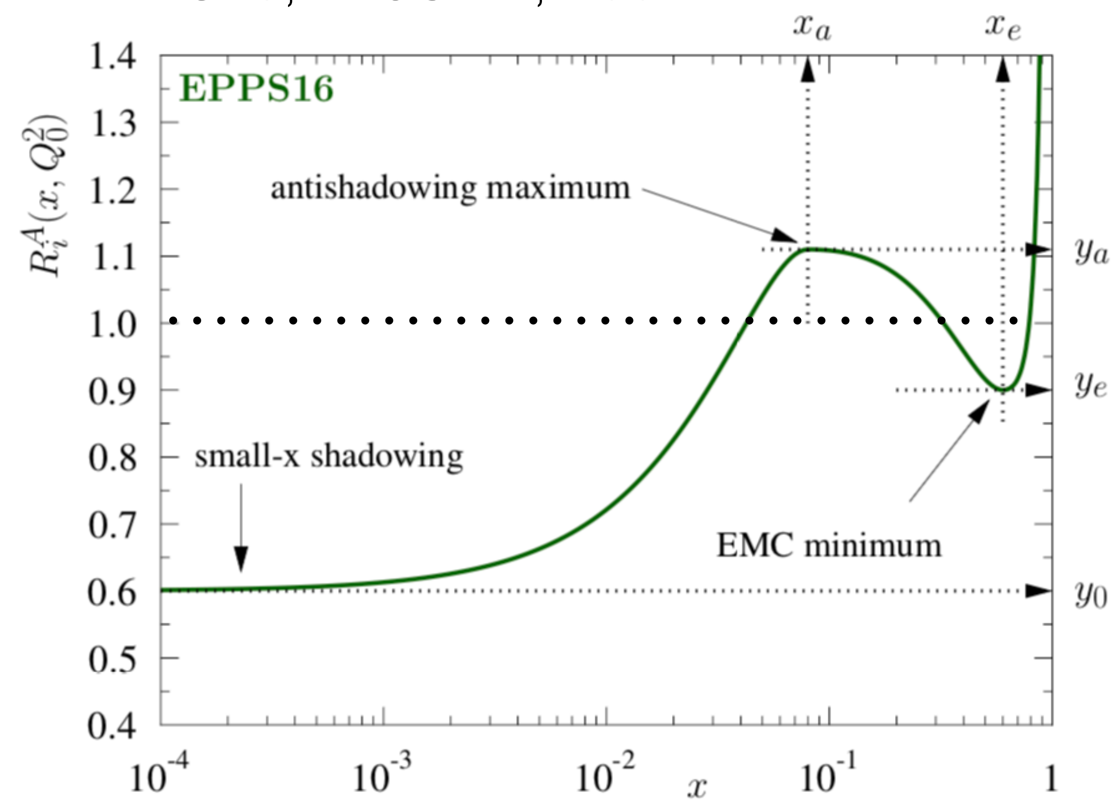
- **LHCC endorsed the project for Run 4 (incl. 8.8 TeV p—Pb)**
- **Final prototype construction in 2021**
- **Technical Design Report (TDR) 2021-2022**

Backup

Nuclear Parton Distribution function

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

EPPS16, EPJC 77, 163

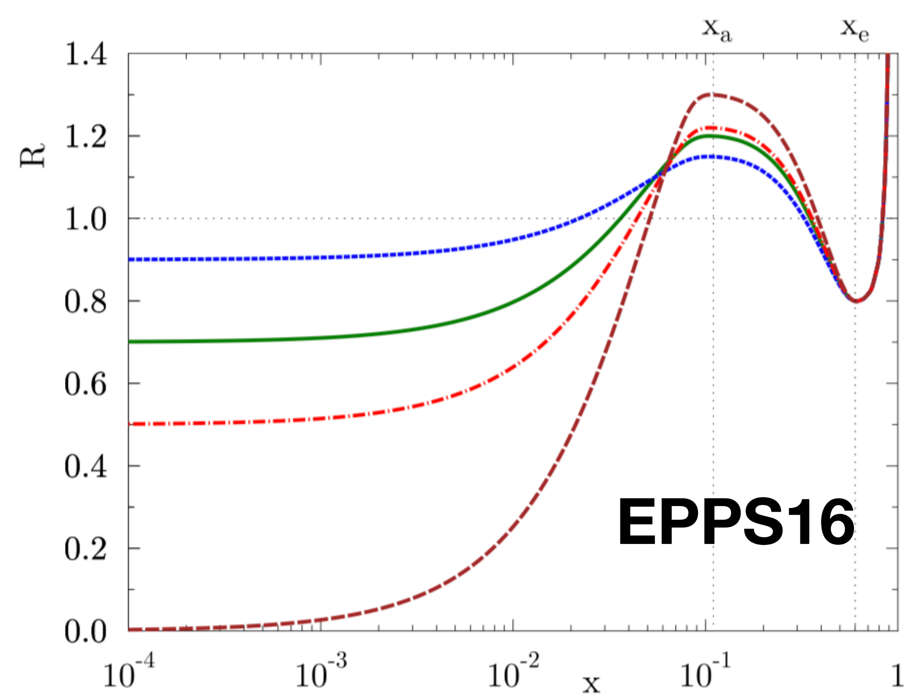


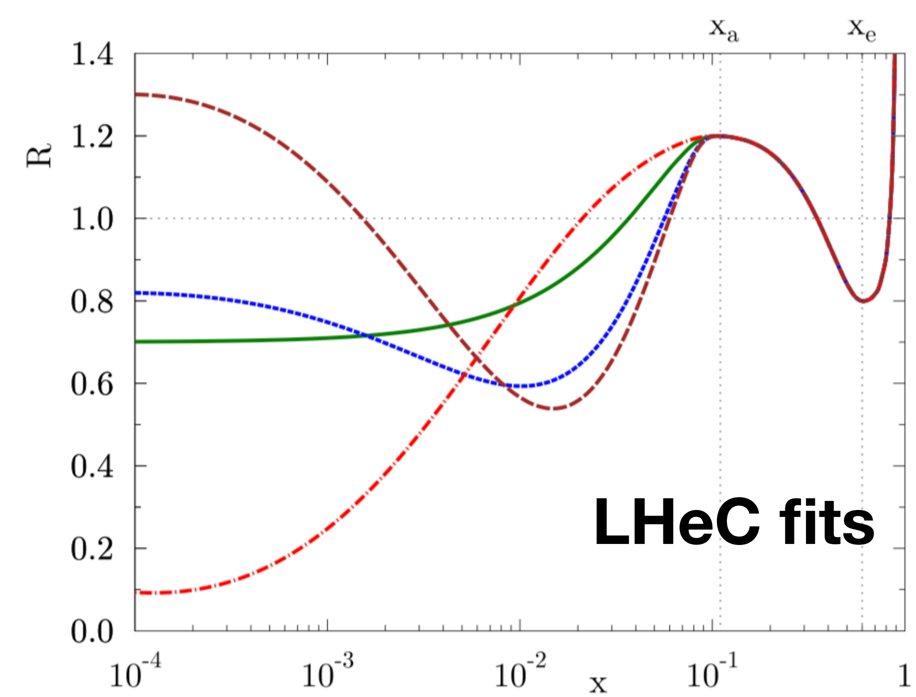
Nuclear modification on the parton distribution function is usually parametrized as

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

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

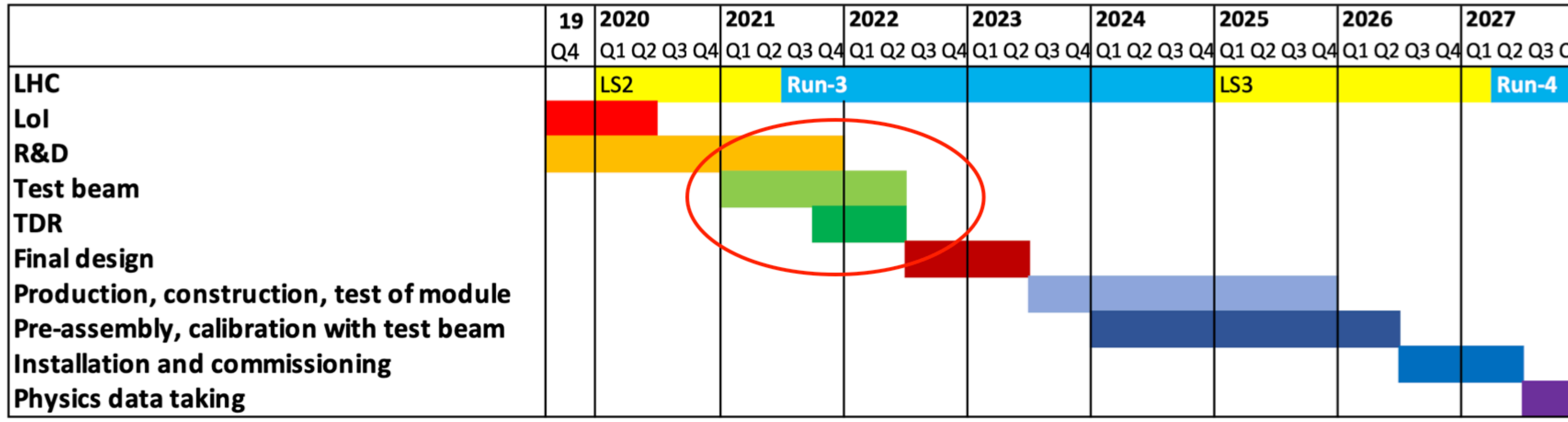
The small-x region is not very well constrained by data. The "plateau" of the shadowing region is the result of chosen parametrization. LHeC fits allow more flexibility on the shape.

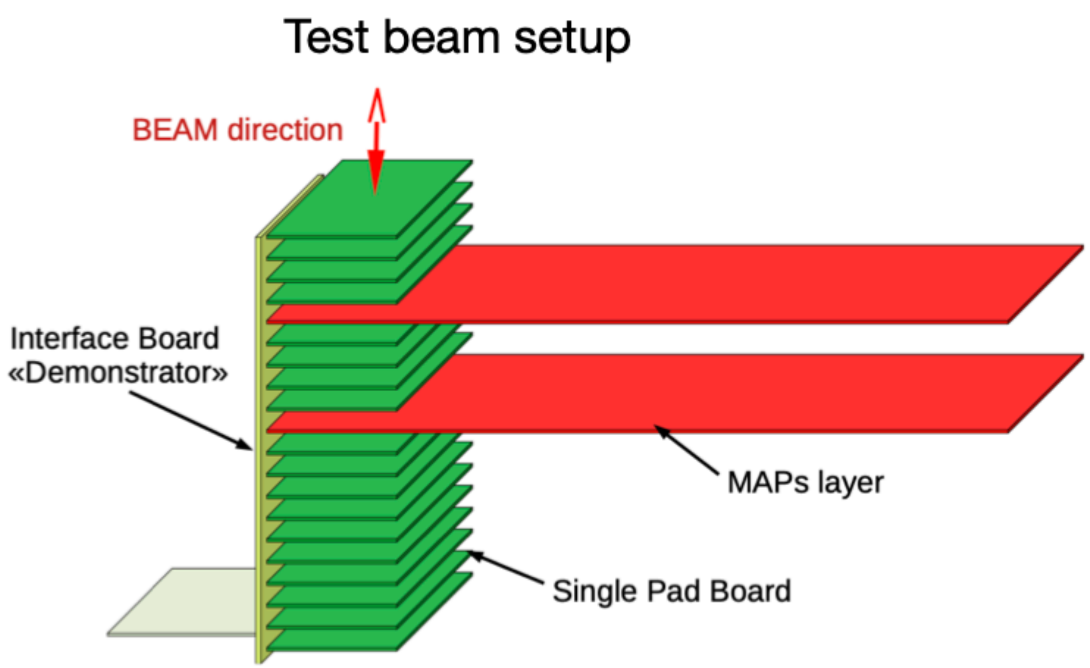




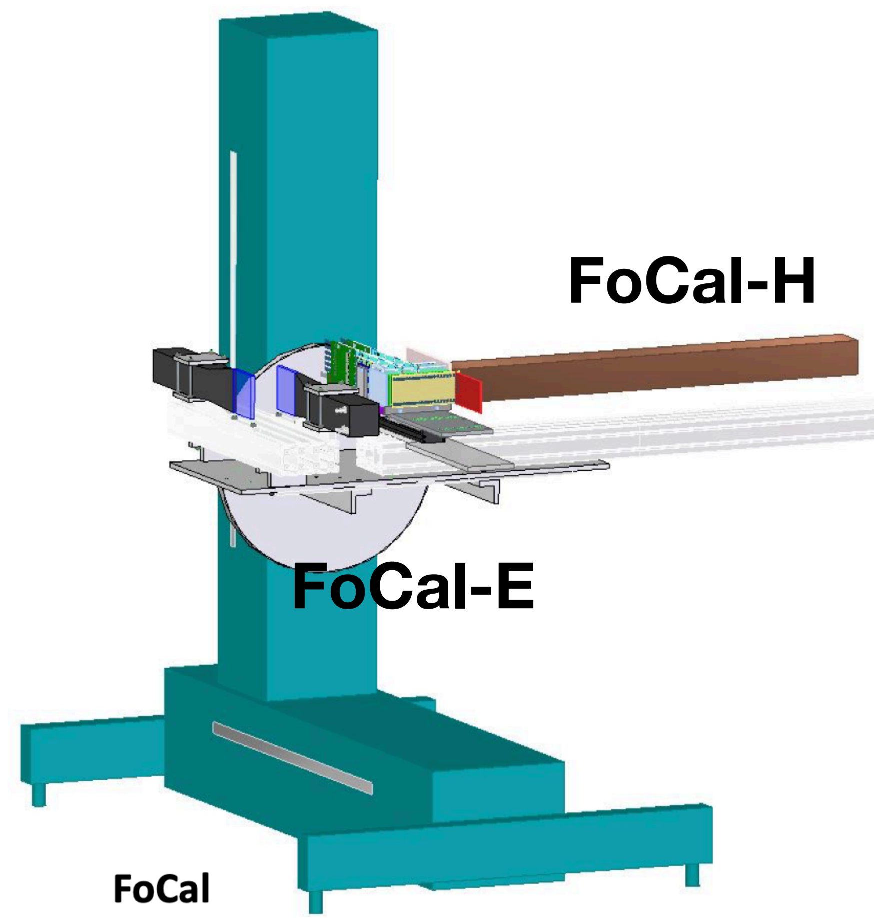
Test Beam for Final Prototype

Testbeam preparation and the finalization of the Technical Design Report (TDR) is the highest priority this year



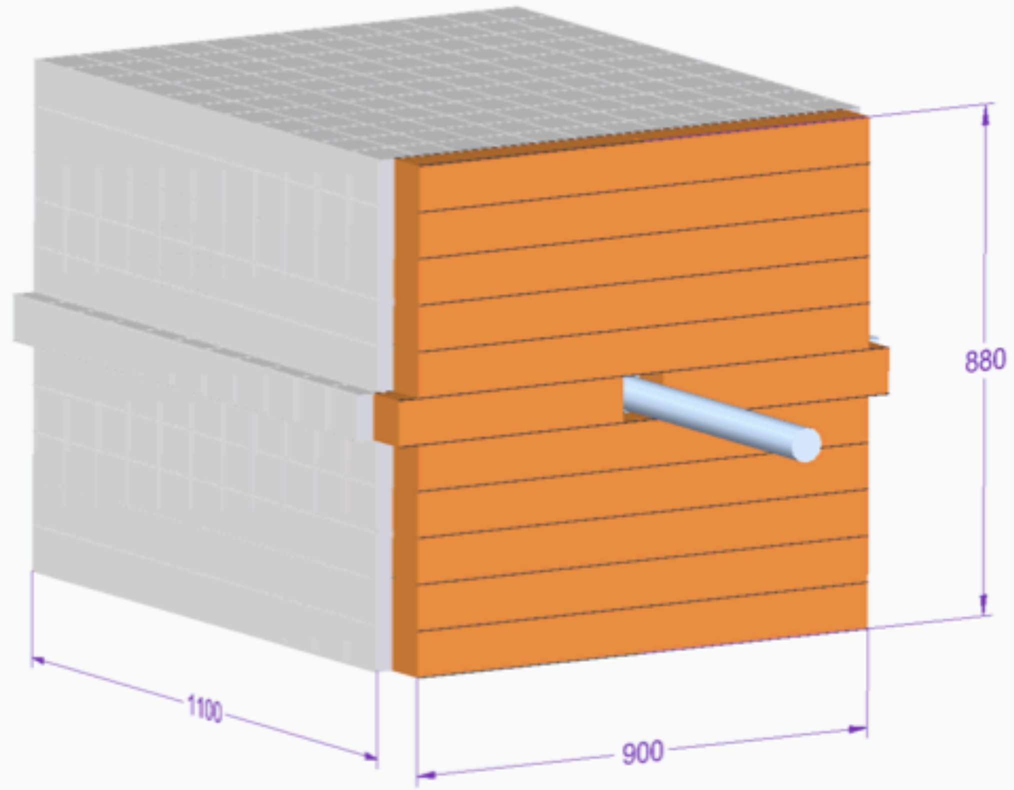


Test beam setup

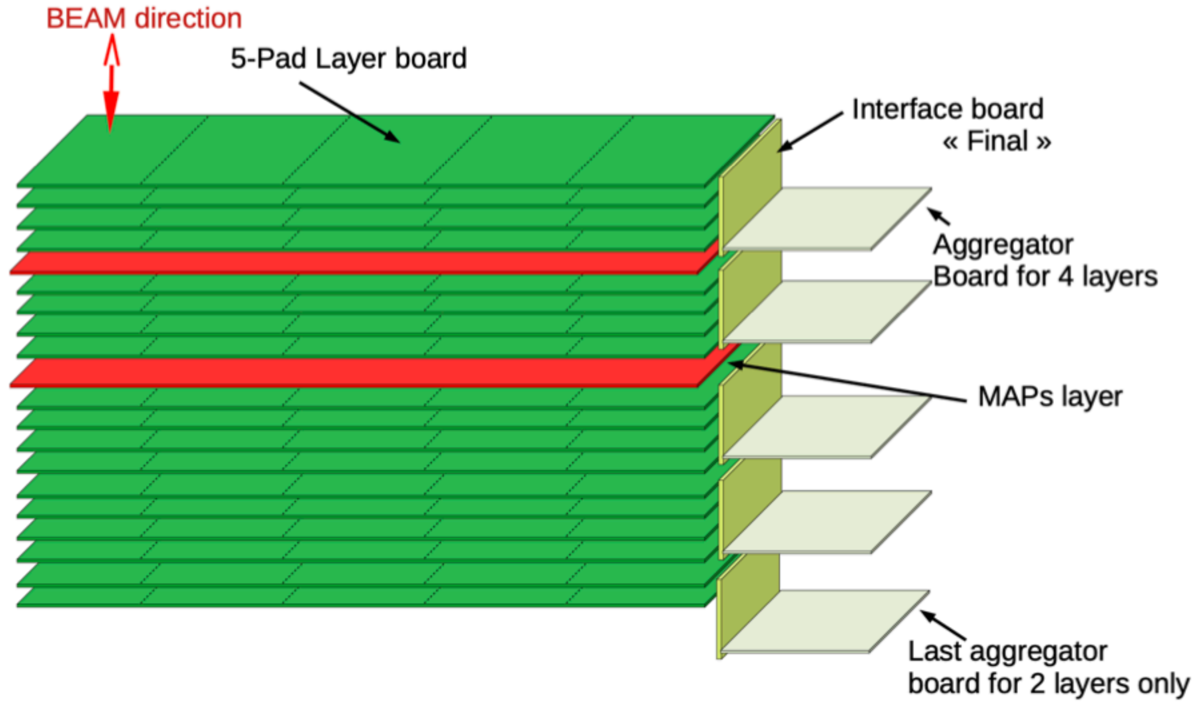


Final Detector Design

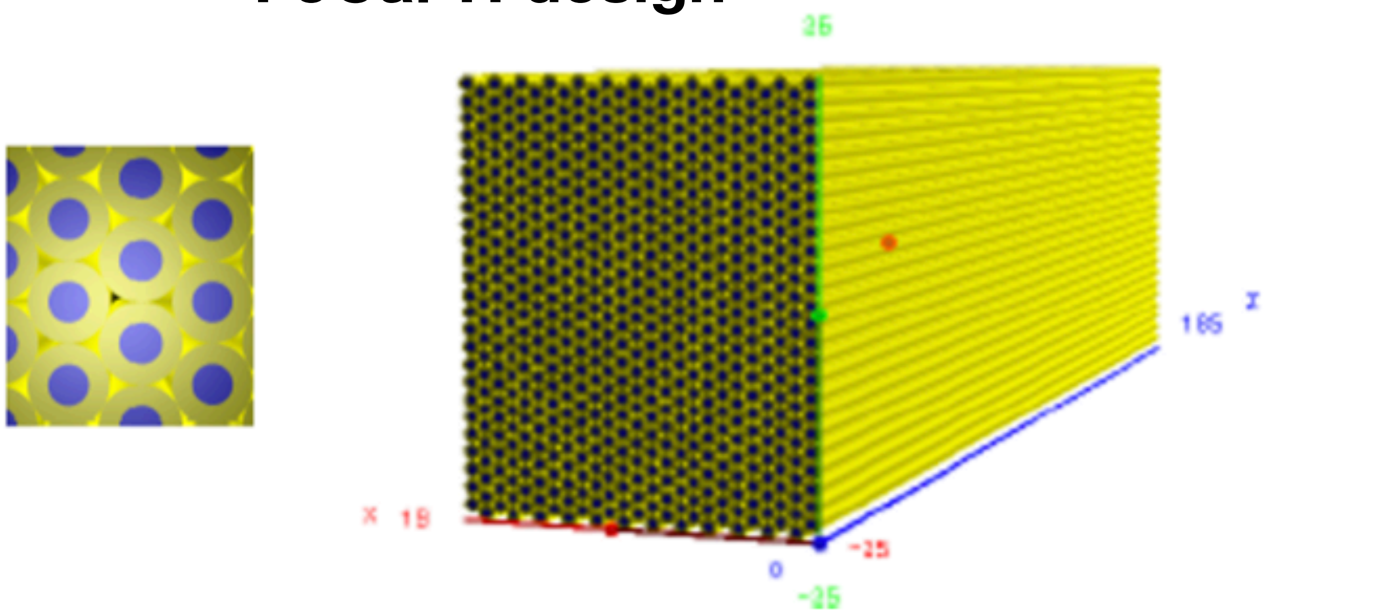
Schematic view of FoCal



FoCal-E design



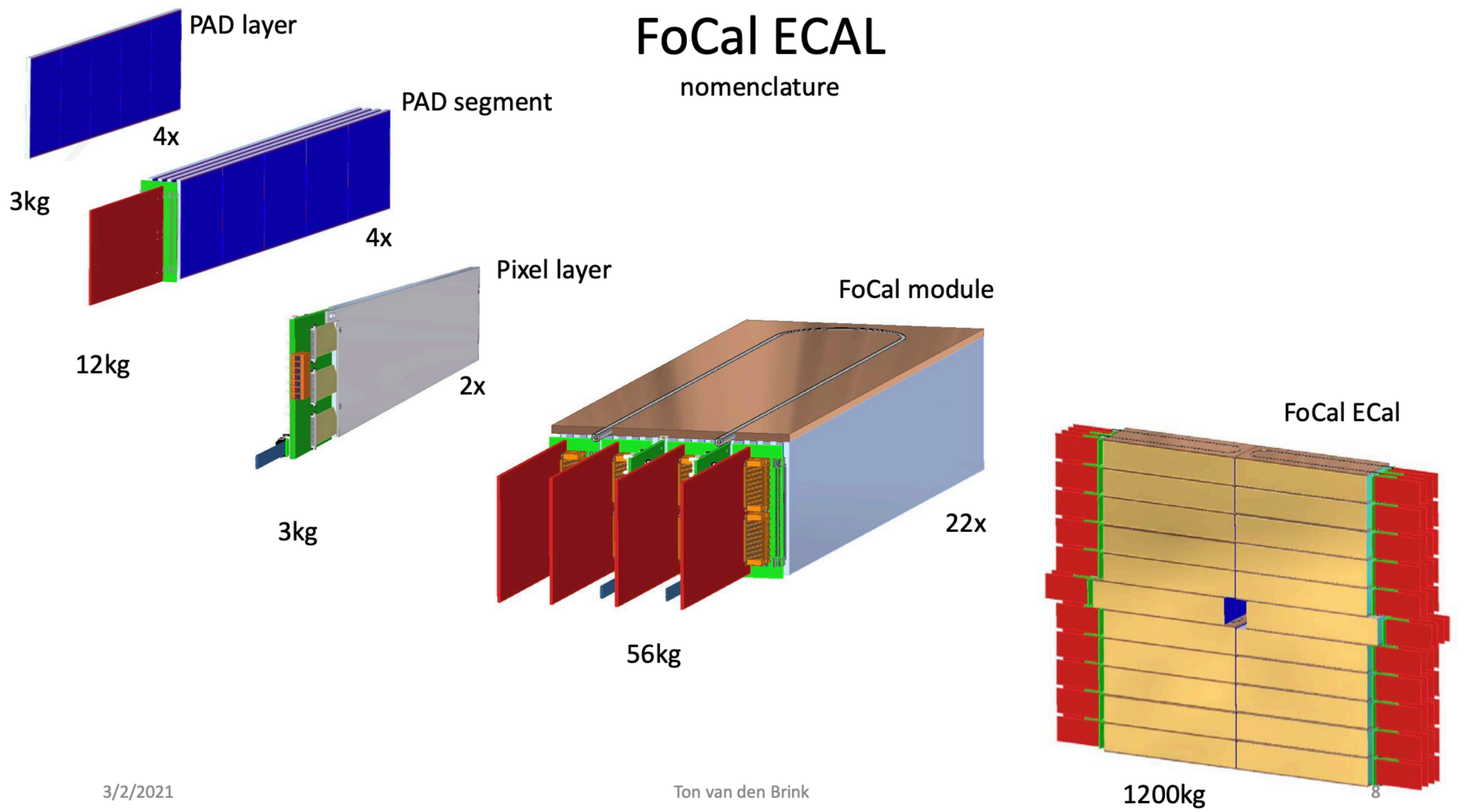
FoCal-H design



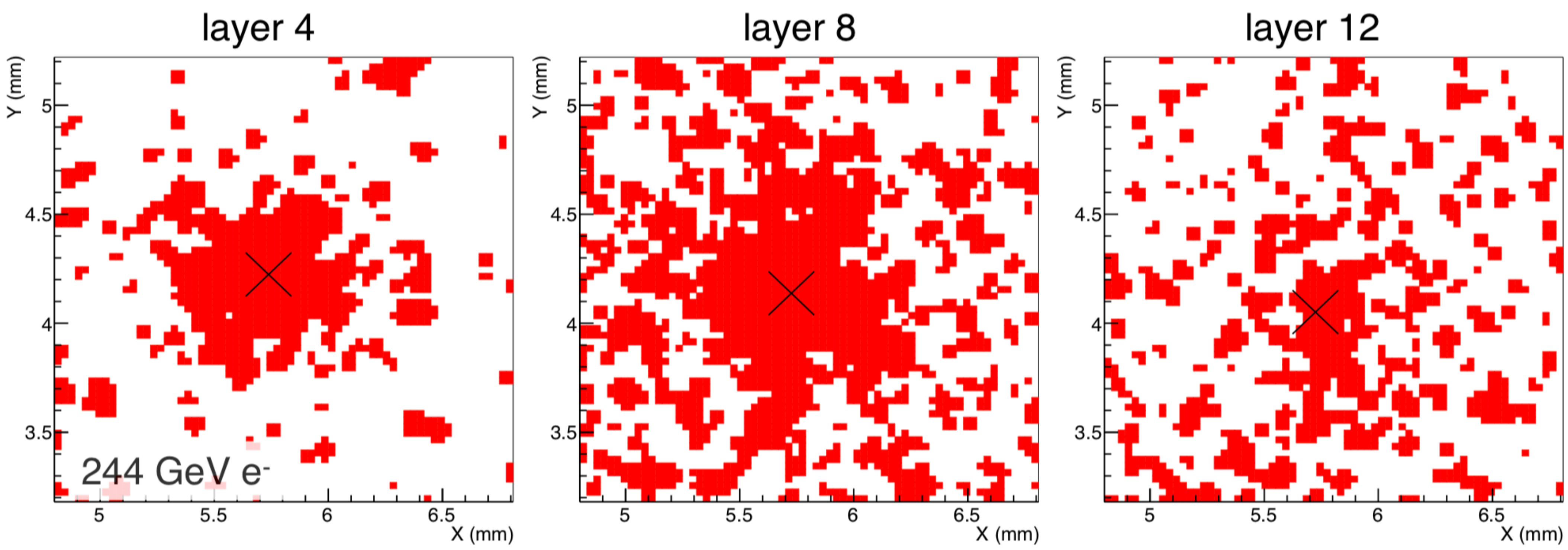
Final design of the FoCal detector:

- FoCal-E:
  - 18 layers of Si PAD
  - 2 layers of Si PIX
- FoCal-H:
  - Capilary tubes with scintillators and SiPMT readout
    - Similar proposal from IDEA collaboration (for FCC)

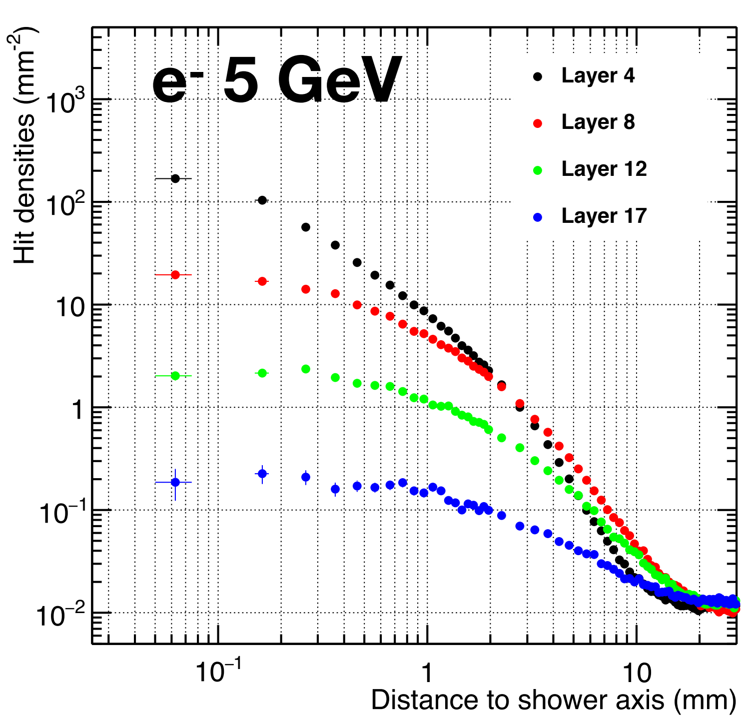
FoCal-E

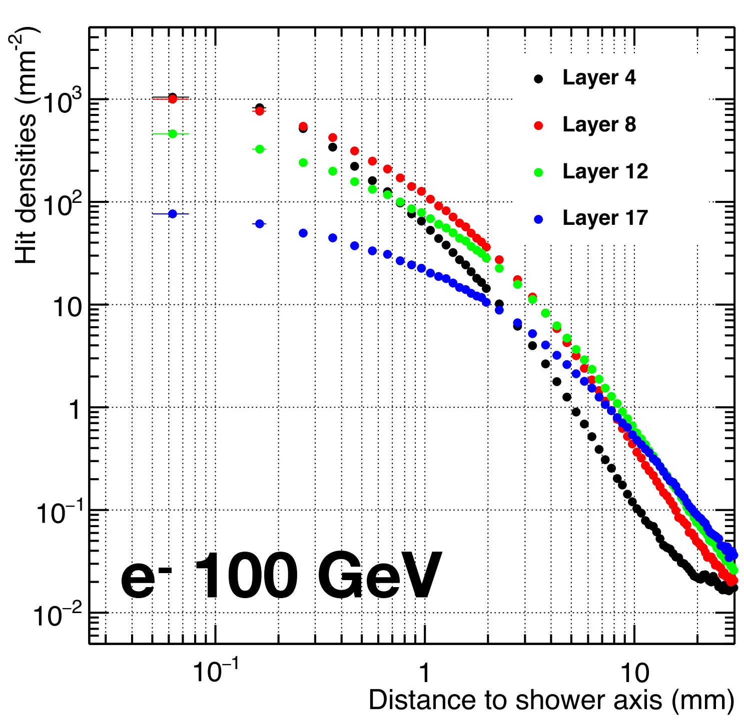

FoCal ECAL
nomenclature
PAD layer
4x
3kg
PAD segment
4x
12kg
Pixel layer
2x
3kg
FoCal module
22x
56kg
FoCal ECal
1200kg
3/2/2021
Ton van den Brink
8

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:

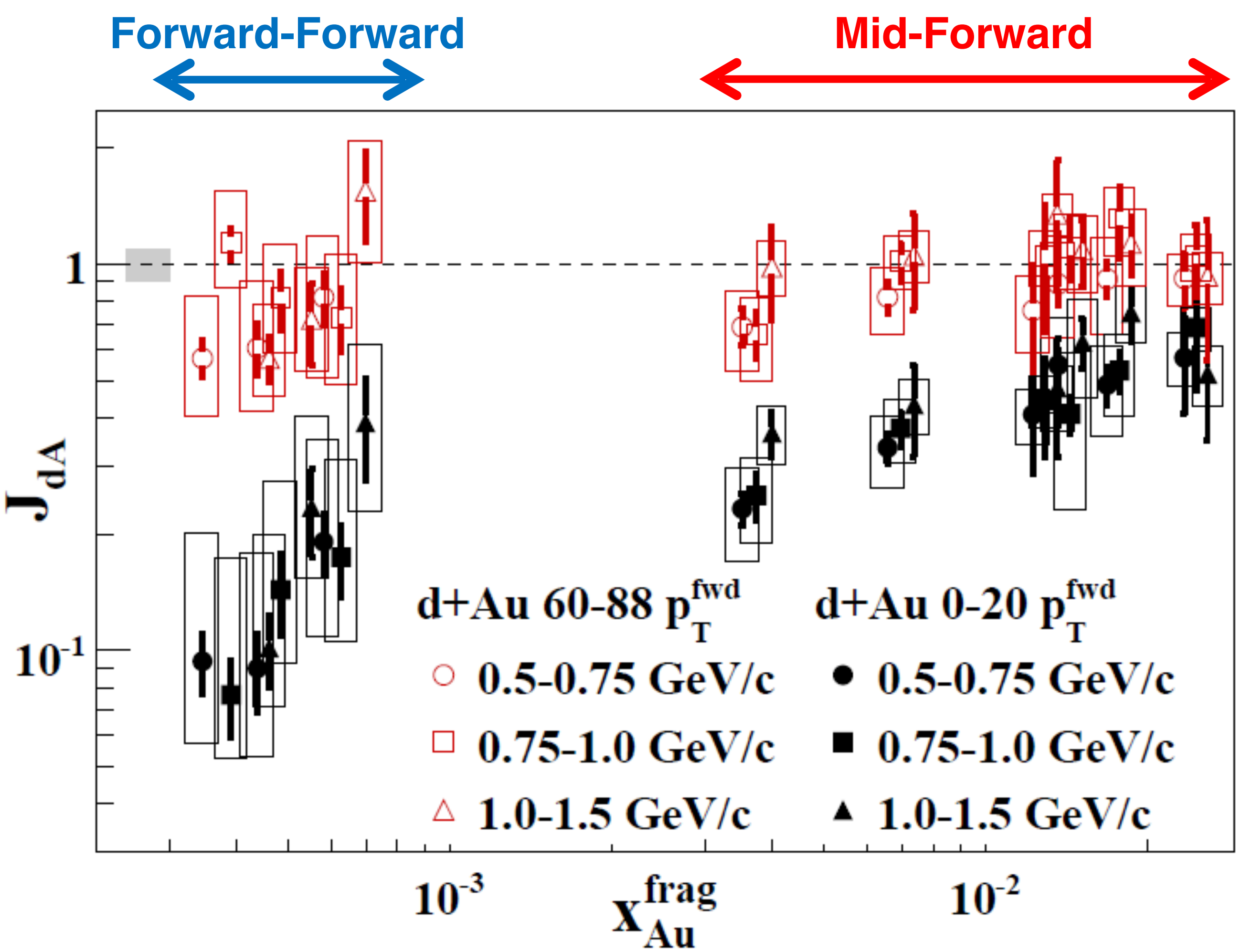
Average hit densities as a function of radius

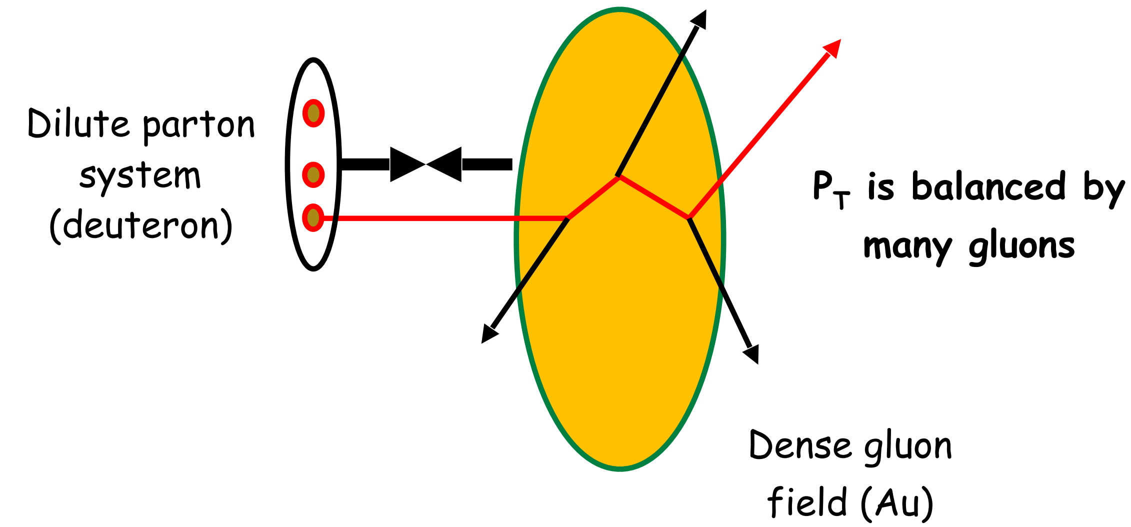
- Low energy: earlier shower maximum
- High energy: shower broadens up with depth

Results from RHIC at 200 GeV

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

PRL **107**, 172301



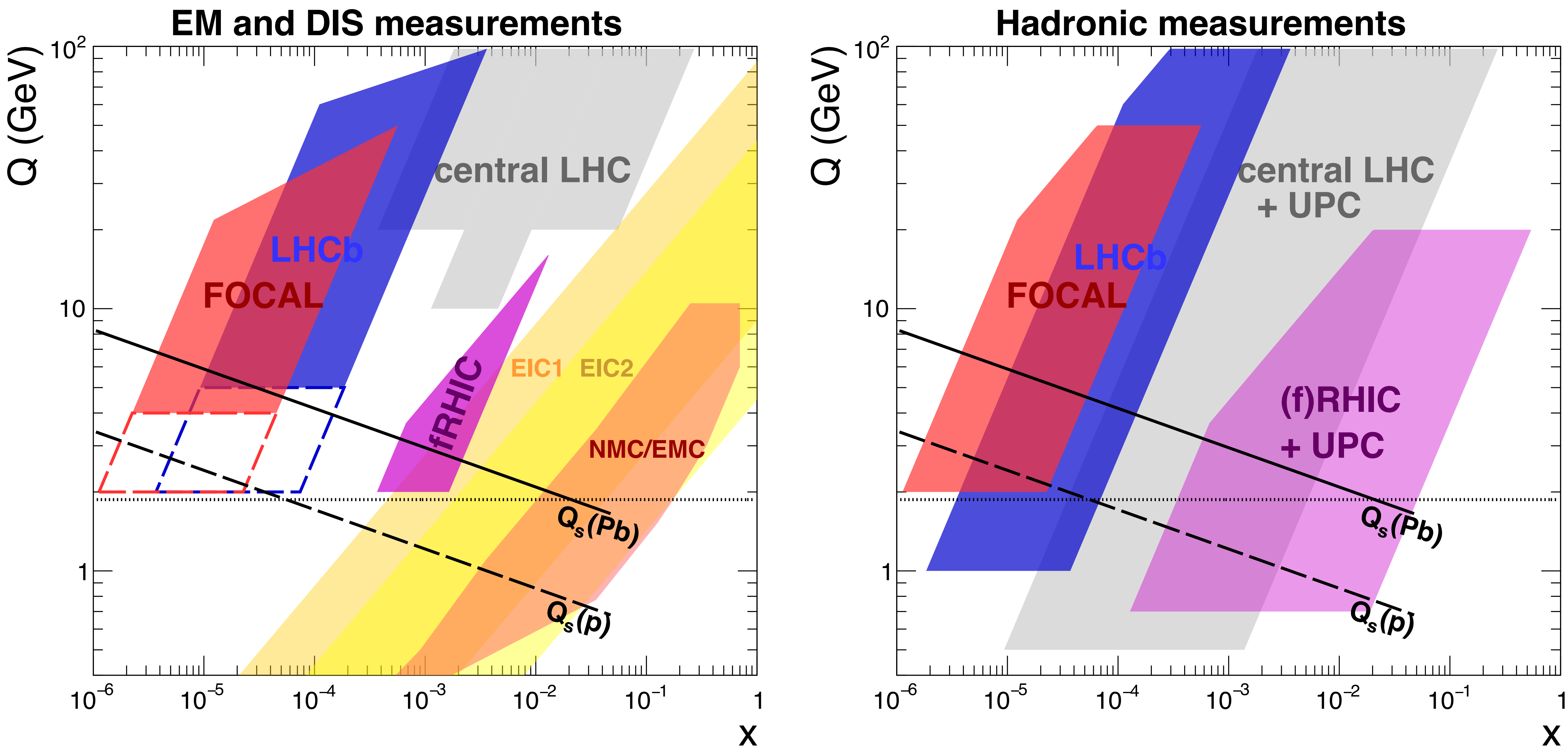


The results suggest a **large suppression** in the very forward region in the high multiplicity d+Au collisions

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.

Coverage of the measurements

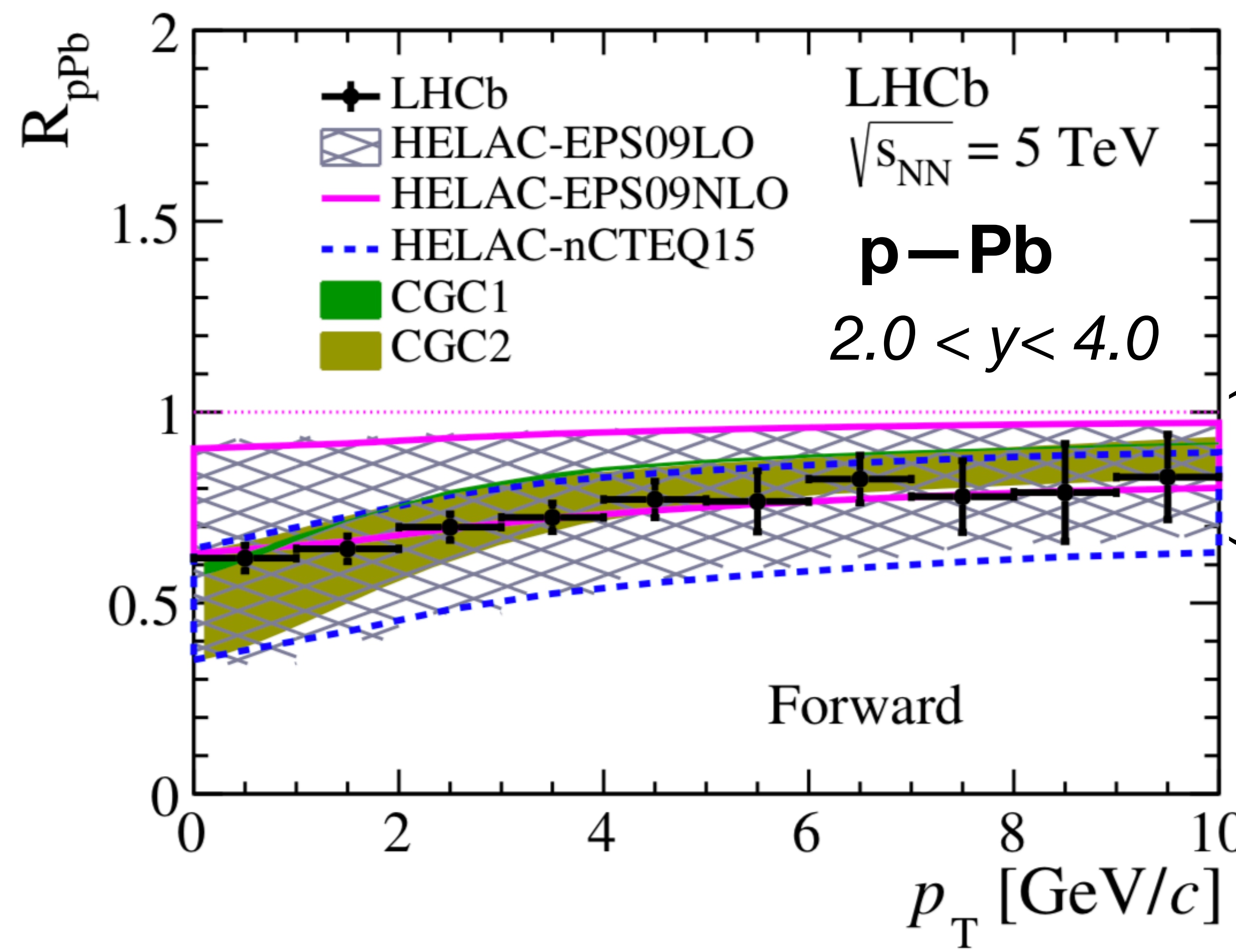


Coverage of the electromagnetic and hadronic probes by the current and planned measurements in LHC and other colliders.

Open heavy flavor measurement from LHCb

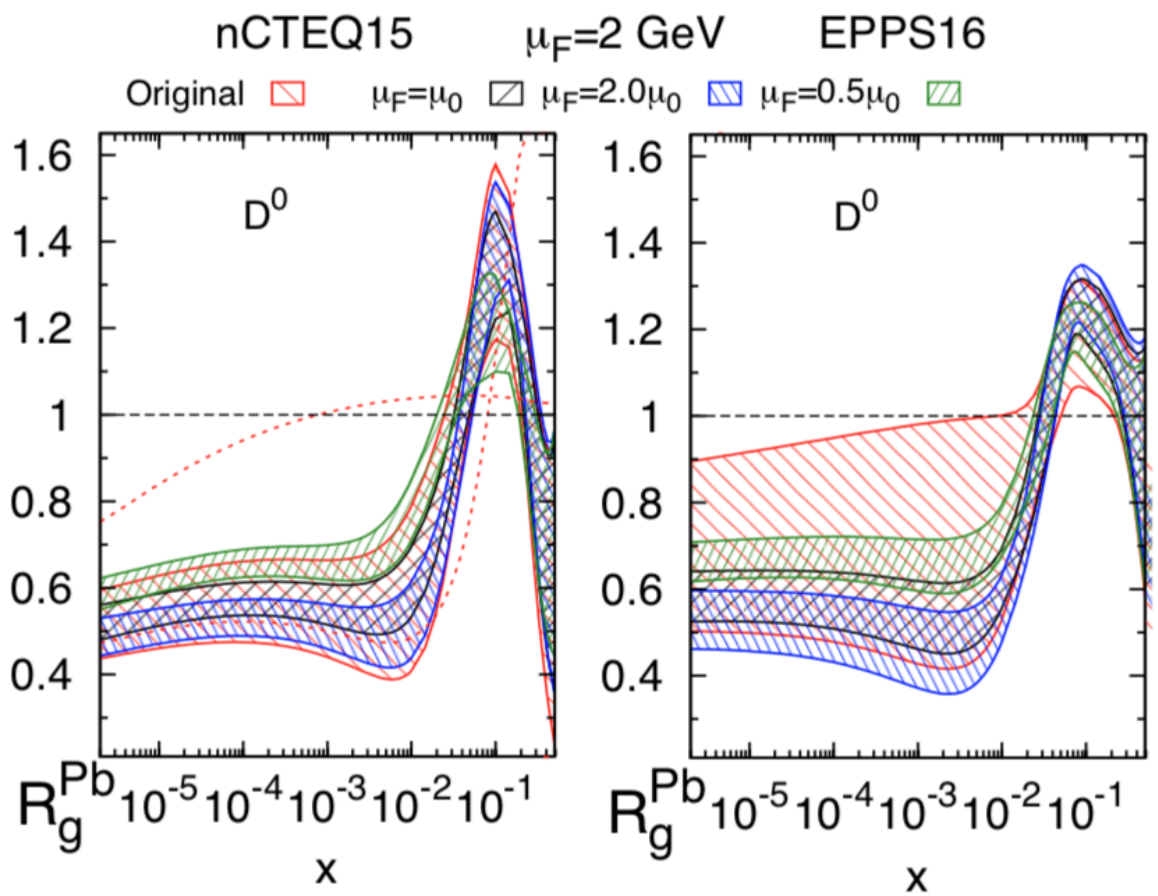
Open charm used in re-weighting:

- Significant suppression in the very forward region
- relies on shape of parametrization: very little *x*-dependence at low-*x*



JHEP 1710 (2017) 090

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)