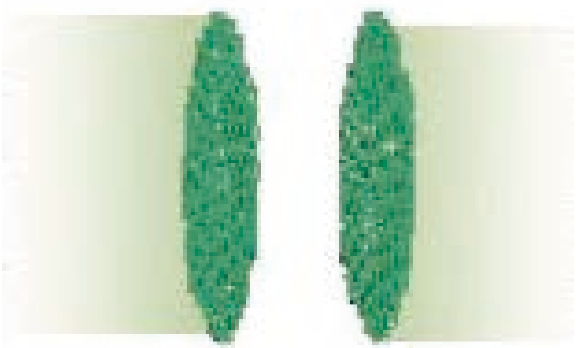
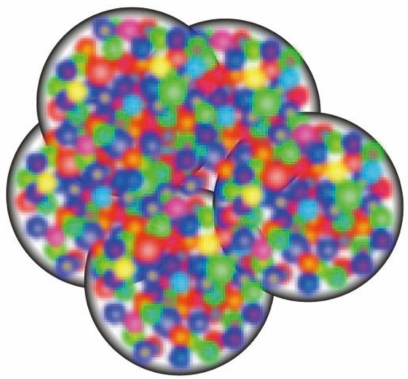
Physics potential of a forward upgrade in ALICE: *direct photons and CGC, initial conditions*



Tatsuya Chujo

Univ. of Tsukuba



Jun. 27, 2017

RBRC workshop

Synergies of pp and pA Collisions with an Electron-Ion Collider

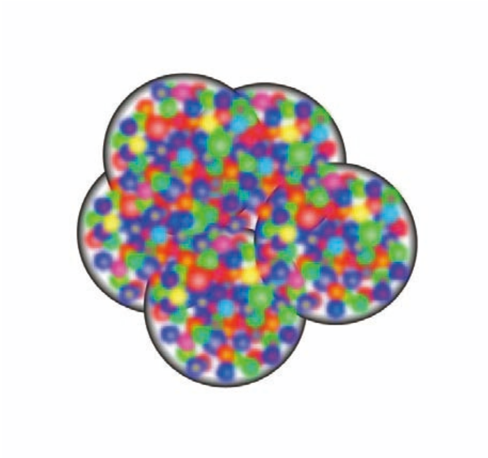
June 26-28, 2017, BNL

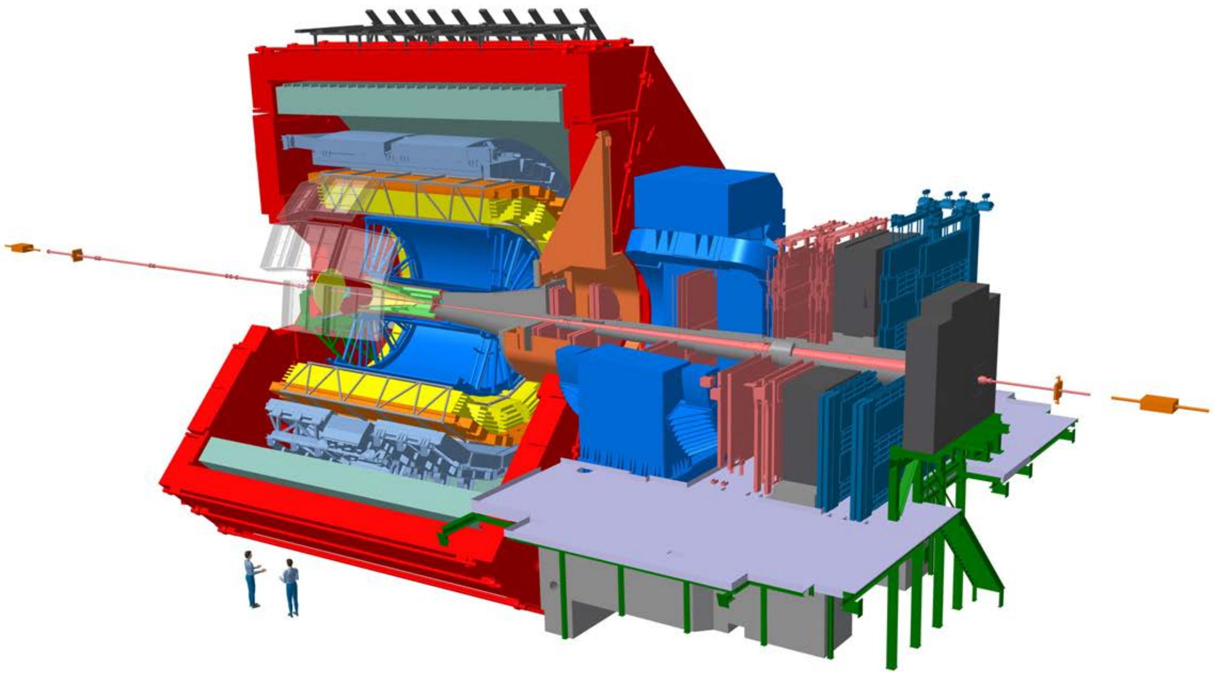
筑波大学

University of Tsukuba

Outline

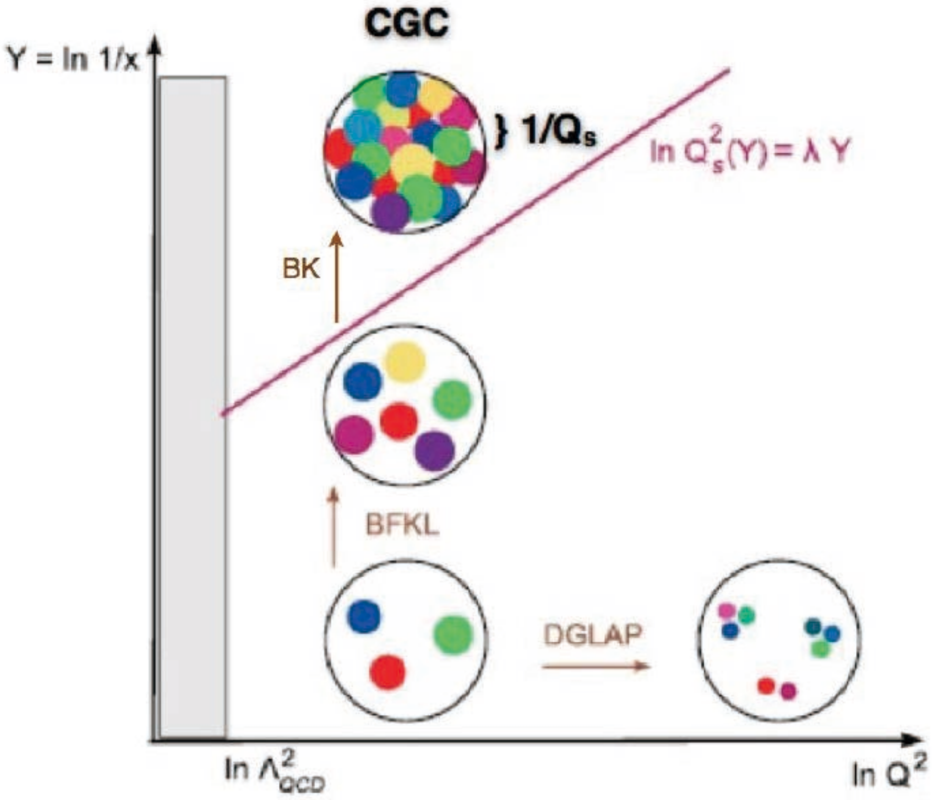
1. **Introduction:**
   - Saturation physics at small-x
   - Approach to thermalization mechanism in AA
2. **Forward experimental results at LHC**
3. **Forward Calorimeter Project (FoCal) in ALICE**
4. **Current status**
5. **Summary**





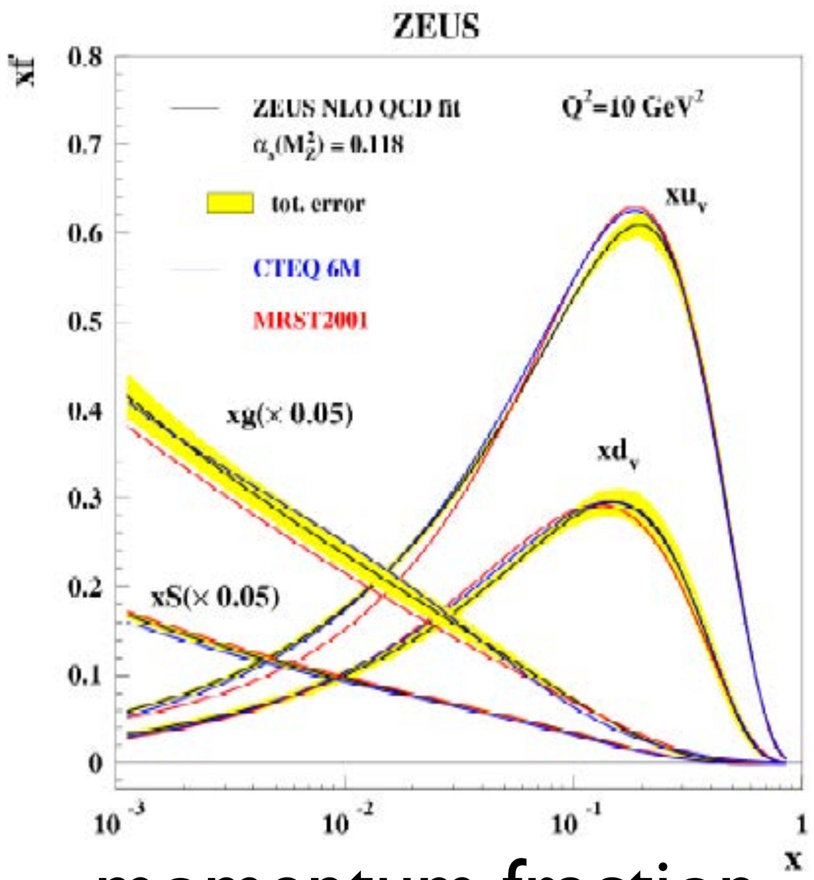
Saturation physics at small-x

high energy



hard process

distribution function



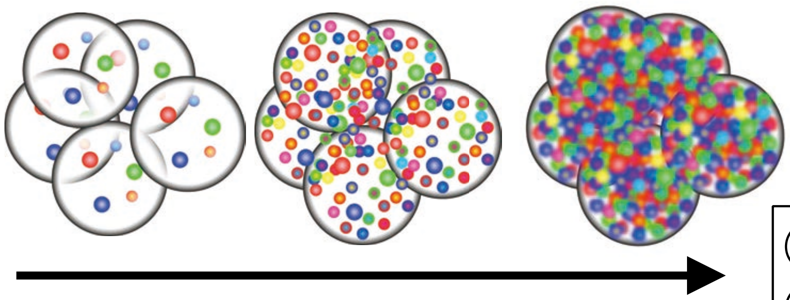
momentum fraction

At small x and small Q^2, the parton density will become large by non-linear effects due to gluon fusion

➡Gluon density saturate (competing between gluon isolated splitting and gluon fusion):
Gluon Saturation, Color Glass Condensate (CGC)

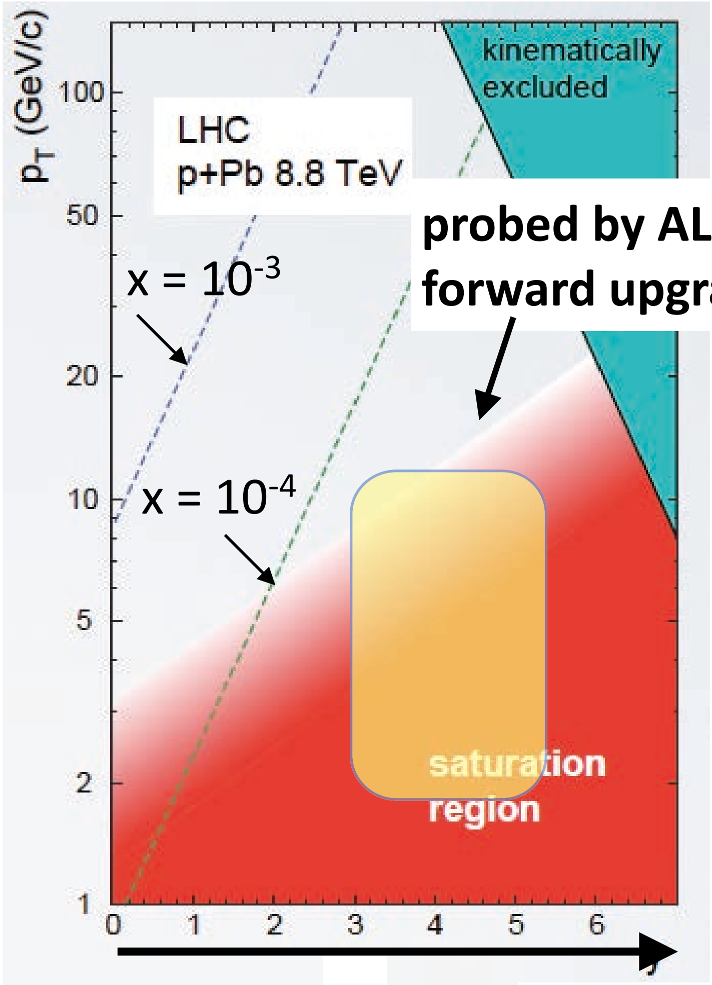
Color Glass Condensate (CGC)

3 quarks CGC



High energy, forward

① Saturated gluon state by the quantum fluctuation
② Universal picture at high energy nucleus and nucleon
③ No clear experimental evidence for the creation of CGC yet



To find/ test CGC by experiment…

（1） more forward

（2） Higher energy (LHC)

（3） p < A

（4） cleanness of probes: (e.g.) h < $\gamma_{dir.}$

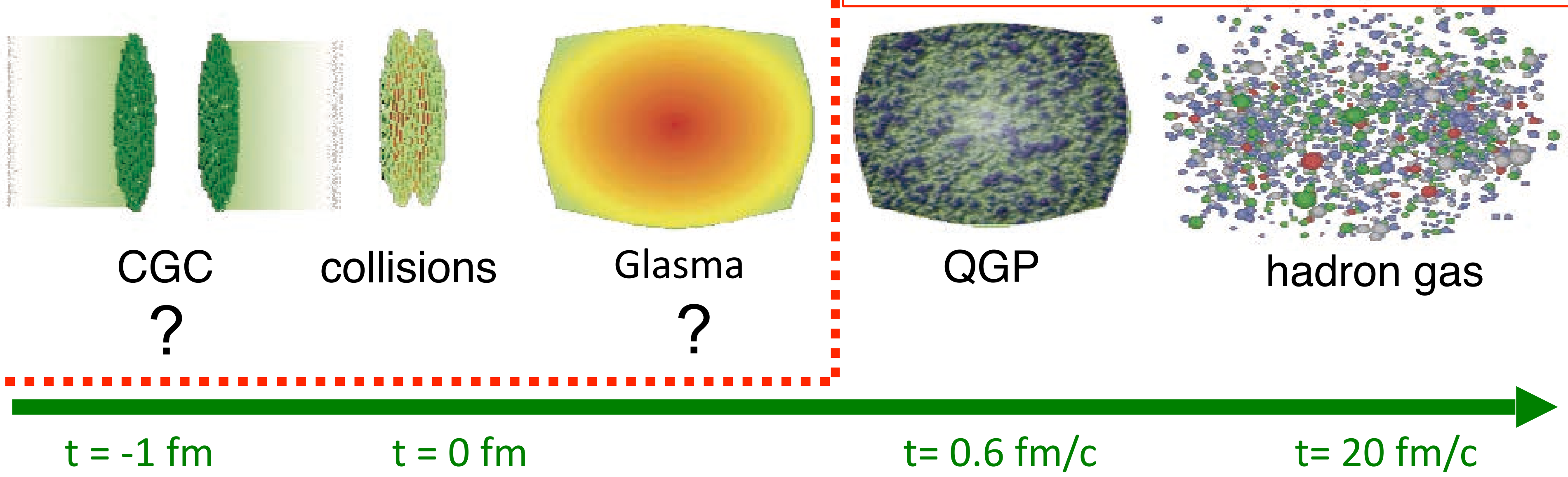
$$x_{\min} = \frac{2p_T}{\sqrt{s}} \exp(-\eta),$$

LHC forward provides an ideal experimental field for CGC

QGP thermalization mechanism

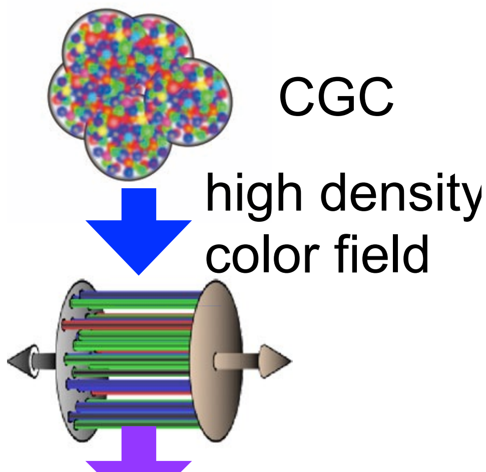
Unknown !

QGP (well studied):
rapid thermalization, strongly interacting perfect fluid



- **High energy nucleus ＝ What is the initial condition?**
- **Why so rapidly thermalized (t=0.6 fm/c)?**
  - **Instability of strong color field？**

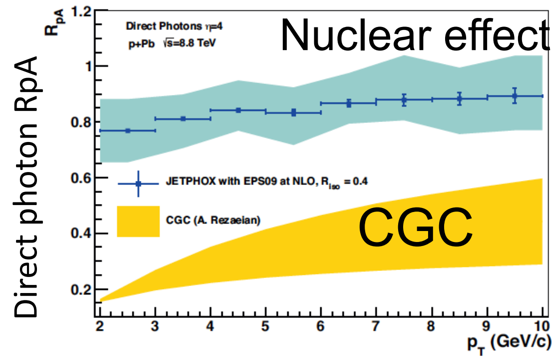
  → need to determine the initial condition clearly.
- **Find the clear evidence for CGC formation as an initial condition (or exclude it).**



QGP rapid thermalization?

High density gluon matter ↔Hot Quark Matter

A. Rezaeian, PLB 718, 1058



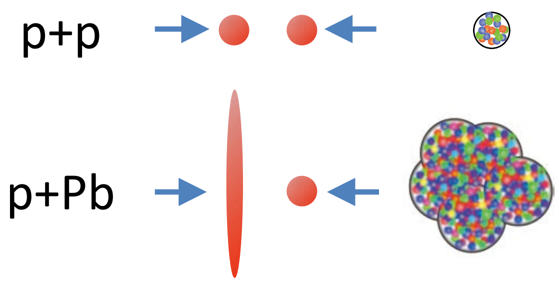
① Evidence for CGC

- direct photon ＝ most clean signal for CGC
- Forward direct photon: R_{pA} → CGC or not.

② Nature of CGC

- Direct photon R_{pA}: system, multiplicity, y & p_T dep.

  → characterize CGC size, structure, onset.

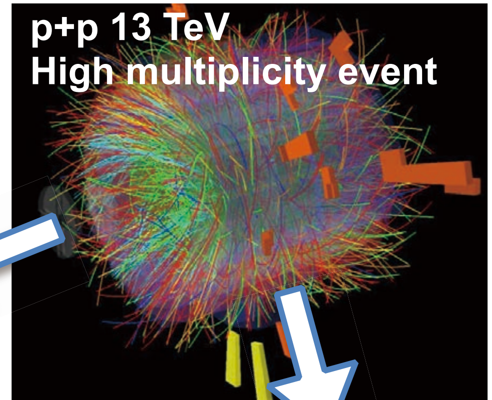


③CGC and QGP thermalization mechanism

- Size of CGC (direct photon) and QGP temperature,

  expansion velocity, fluctuation.
- Forward photon /hadron vs. mid. photon / hadron

  👉 correlation between CGC size and
  QGP thermalization (e-by-e)
  → Mechanism of rapid thermalization



ALICE Forward
photon ＝CGC state

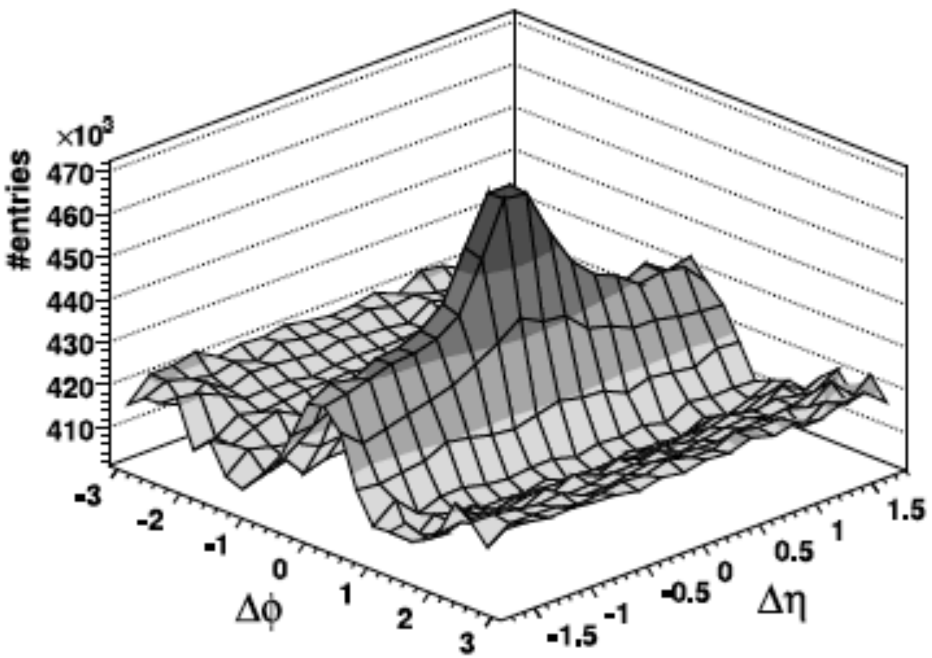
ALICE mid (DCal, PHOS, TPC)
photon ＝temperature
hadron＝expansion velocity

④ Connection to other research fields

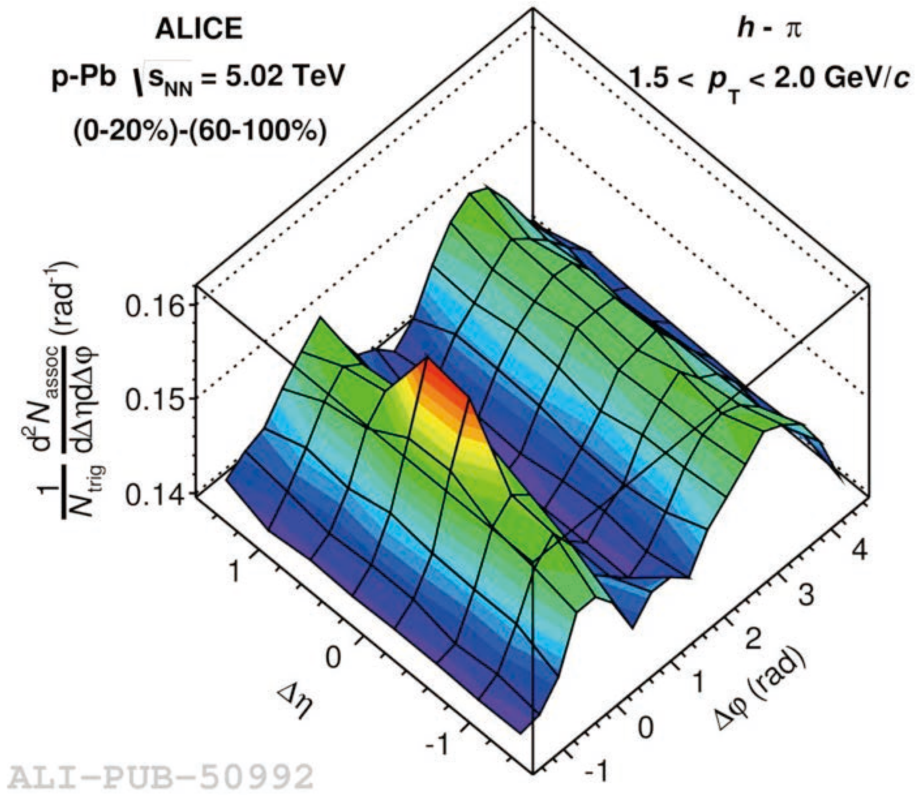
- 「strong field」：QCD color (gluon) field vs. QED field (Neutron star)
- 「forward」 ：High energy cosmic rays

Long range correlations in AA and pA (“Ridge”)

RHIC (STAR, Au+Au 200 GeV)



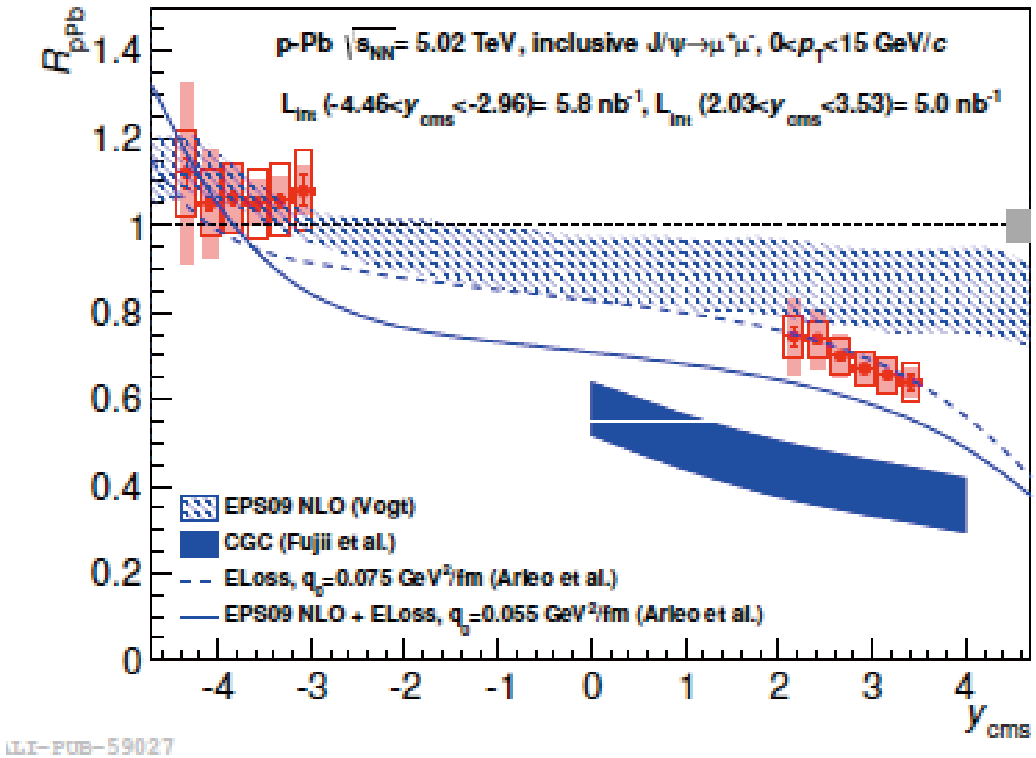
LHC (ALICE, pPb, 5.02 TeV)



- long range Δη correlations (ridge) at RHIC and LHC.
- Also observed at high multiplicity event in small system (pp, p-Pb)
- Origin is still unknown.
- CGC (initial condition) or others?

LHC Result (1): J/ψ in pA

J/ψ → μ⁺ + μ⁻



ALICE, 10.1007/JHEP02(2014)073, arXiv:1308.6726

- **Hadron suppression on forward (proton-going) side at low p_T.**
- J/ψ yield: not described by nPDFs nor by a CGC calculation
- Uncertainties on:
  - Production mechanism (x sensitivity etc.)
  - Other nuclear modifications (e.g. energy loss, thermalization in pA?)

Difficult to obtain conclusive data by hadrons only.

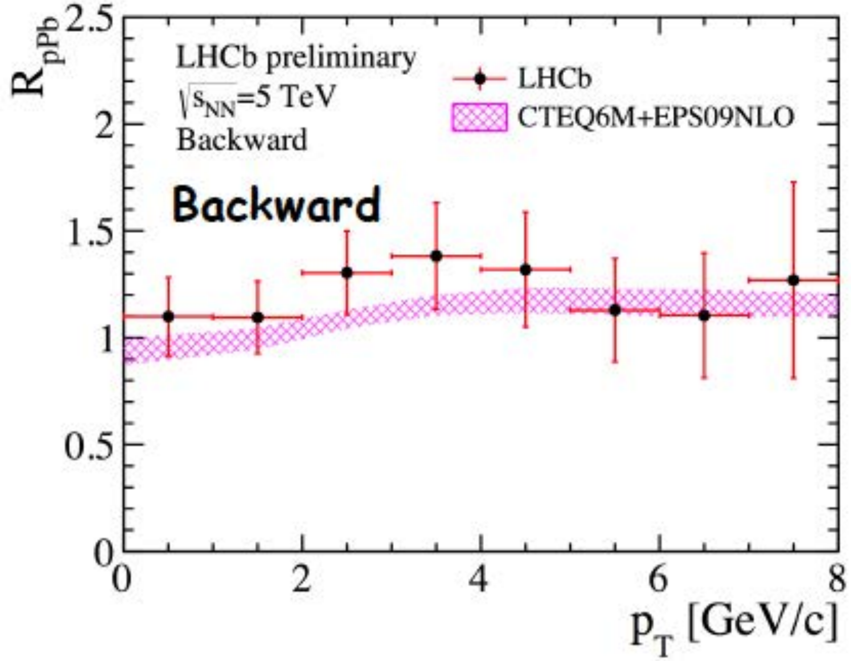
LHC Result (2): R_{pPb} for D^0

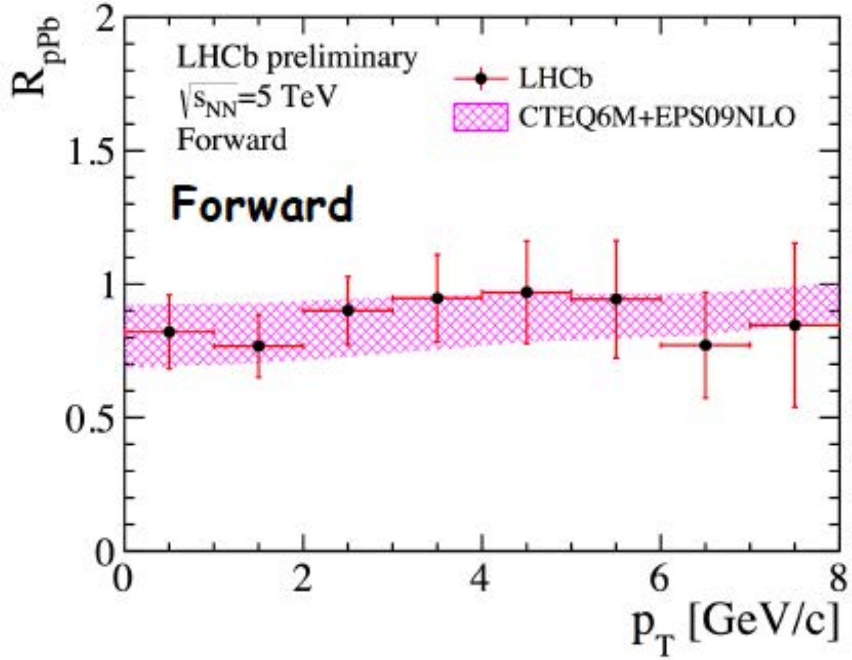
Prompt D^0 nuclear modification factor

LHCb-CONF-2016-003

New

- Calculated as: $R_{\mathrm{pPb}}(y, p_T) = \frac{1}{A} \times \frac{\sigma_{\mathrm{pPb}}(y^*, p_T, \sqrt{s_{NN}})}{\sigma_{\mathrm{pp}}(y^*, p_T, \sqrt{s_{NN}})}$, A=208
- D^0 cross-section in pp collision at $\sqrt{s} = 5$ TeV extrapolated using LHCb measurements at 7 and 13 TeV Nucl. Phys. B87 (2013), arXiv:1510.01707
  - ➢ pp data at $\sqrt{s} = 5$ TeV are being analyzed, will be updated soon



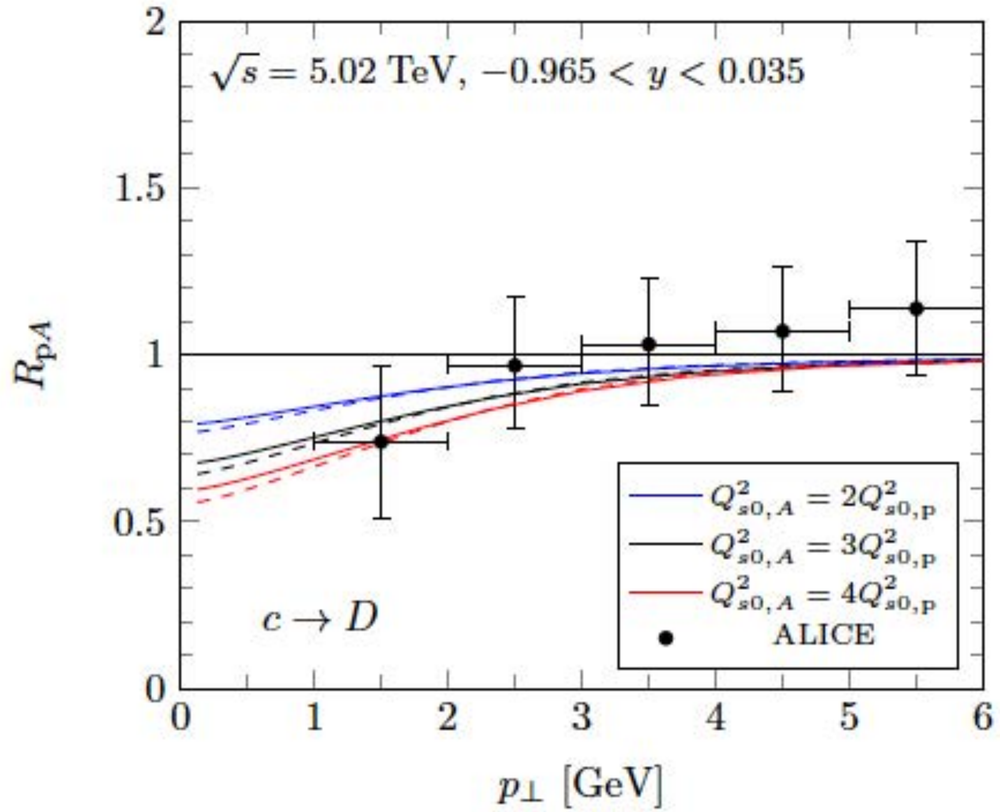


MNR with CTEQ6M+EPS09NLO: Nucl. Phys. B373 (1992) 295, JHEP 10 (2003) 046, JHEP 04 (2009) 065

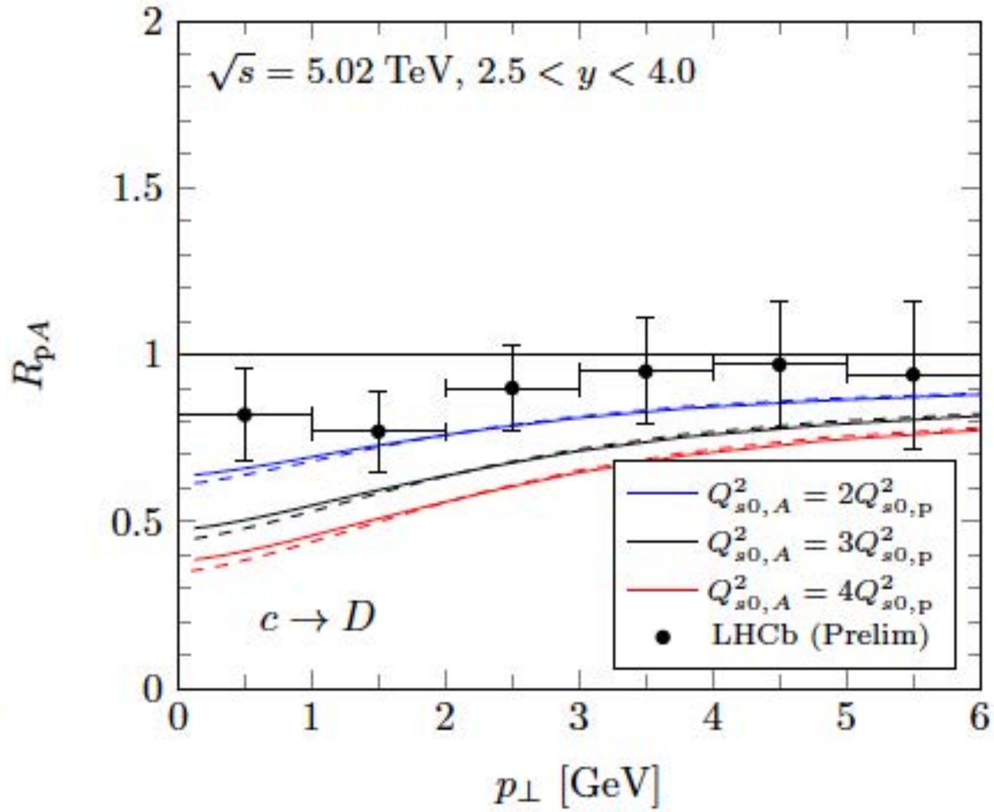
Comparison with CGC (D meson)

arXiv:1706.06728v1, Fujii and Watanabe

Mid-rapidly



Forward rapidity



At forward rapidity and low p_T, a CGC model predicts rather stronger suppression than data (LHCb)

Isolated photons vs. hadrons

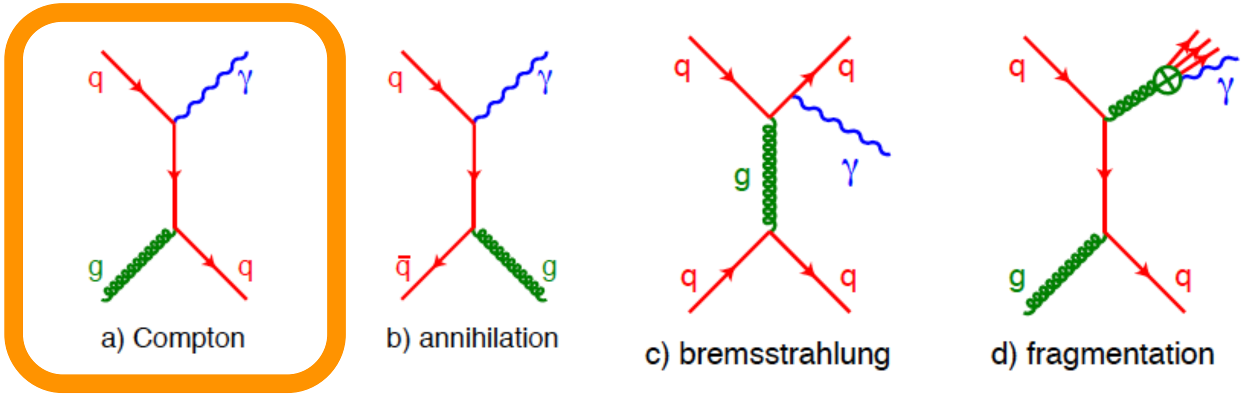
Isolated direct photons can provide strong constraints on the gluon PDFs

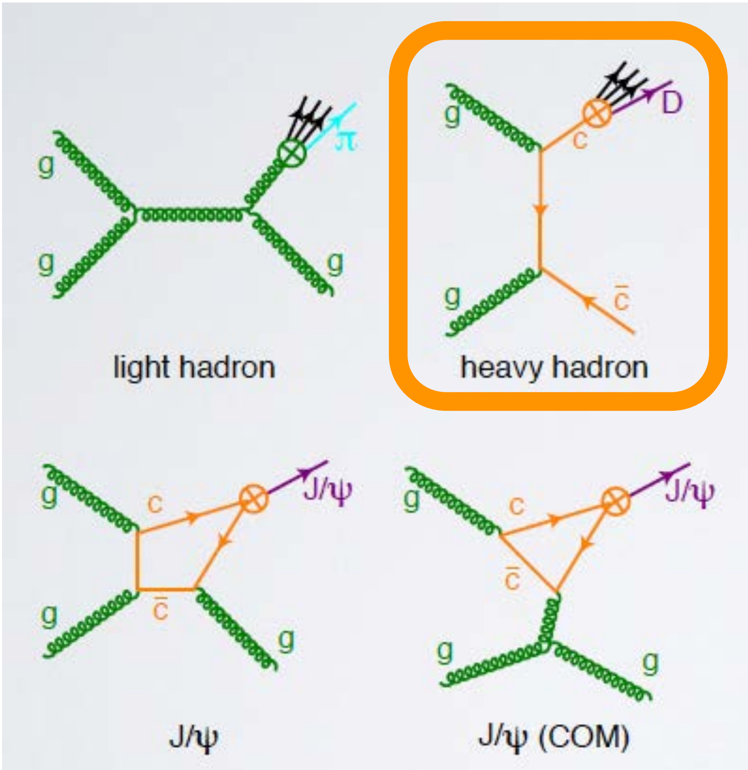
- LO dominant process: quark-gluon Compton.
- Quark-anti-quark annihilation contributing mostly at large x.
- NLO: At LHC, the majority of prompt photons are produced in the fragmentation process
- Fragmentation photon can be largely suppressed by the isolation cut.

→quark-gluon Compton process dominant, more direct access to the gluon PDFs and saturation physics

photons

R. Ichou and D. d'Enterria, Phys. Rev. D 82, 014015 (2010)



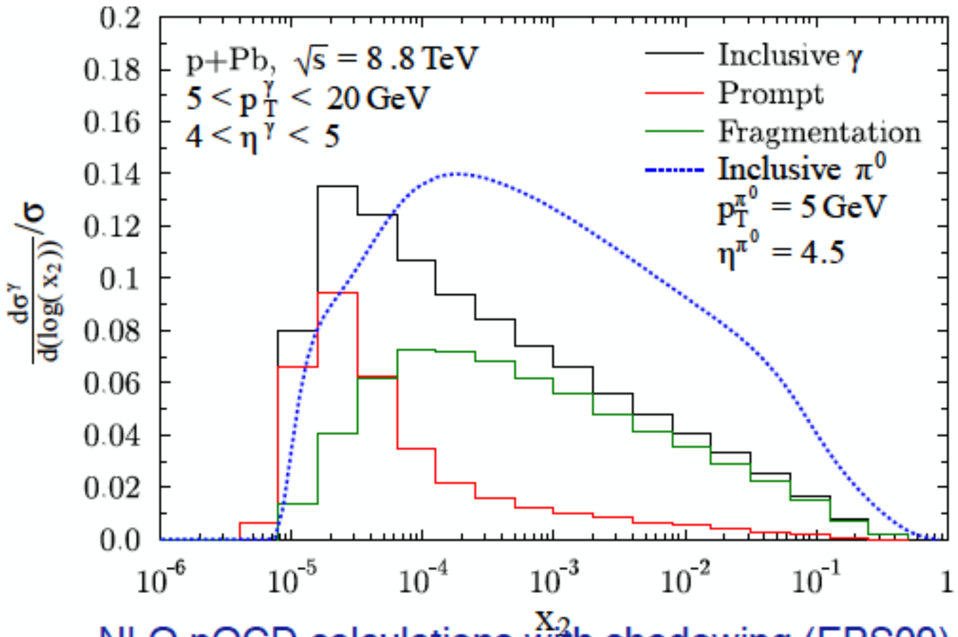


hadrons

by T. Peitzmann

Why photos?

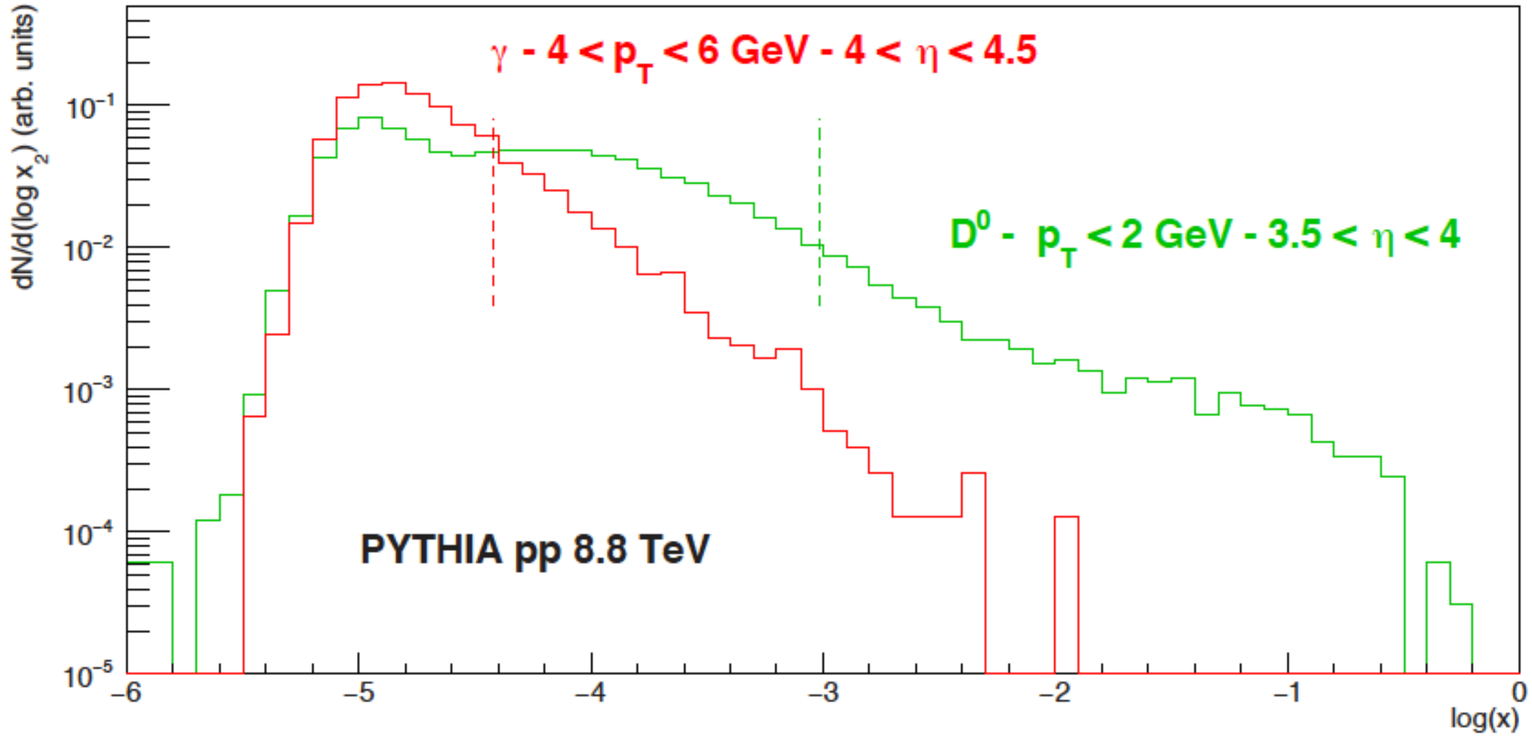
- **Cleaner observables: EM probes (direct photons, DY)**
  - no final state interaction
  - well-understood process
  - well-defined kinematics
- Direct photons: large cross section
- DY at forward p-A: likely not possible



NLO pQCD calculations with shadowing (EPS09)
Helenius, Eskola, Paukkunen, arXiv:1406.1689

- Hadronic observables:
  - final state modification in p-A.
  - production process uncertainties.
  - uncertainty of kinematic relation to Bjorken-x (e.g. fragmentation).
  - Best hadronic observables: open charm (e.g. D)
    - direct sensitivity to gluons
    - final state interaction?
    - x sensitivity (next slide)?

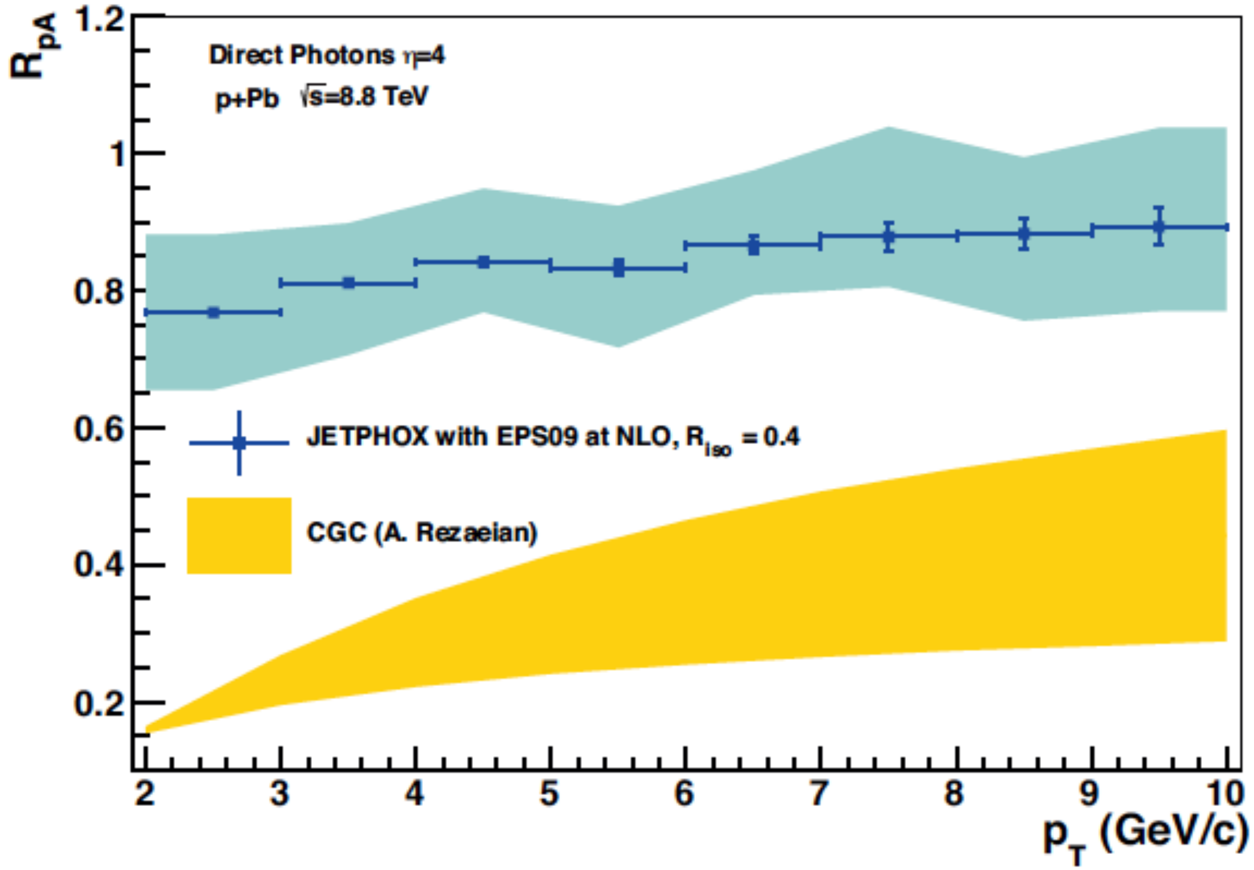
x-Sensitivity: photons vs D



<u>x_2 distribution for forward production</u>

- LO production from PYTHIA
- **D^0** (LHCb) vs. **prompt γ** (FoCal)
- prompt γ:
  - apparent peak at x ~ 10^{-5}
  - significantly larger mean value
- **Significant advantage of proposed direct photo measurement compared to charm in LHCb.**

A signal of CGC: R_{pA} for direct photons



A. Rezaeian, PLB 718, 1058

Two scenarios for forward γ production in p+A at LHC:

- Normal nuclear effects linear evolution, shadowing
- Saturation/CGC running coupling BK evolution

$$R_{pA} \equiv \frac{d^3N/dp_T^3(pA)}{\langle N_{coll}\rangle \cdot d^3N/dp_T^3(pp)},$$

- Strong suppression in direct γ R_{pA}.
- Signals expected at forward η, low-intermediate p_T.

ALICE FoCal Project

FoCal = Forward Calorimeter:

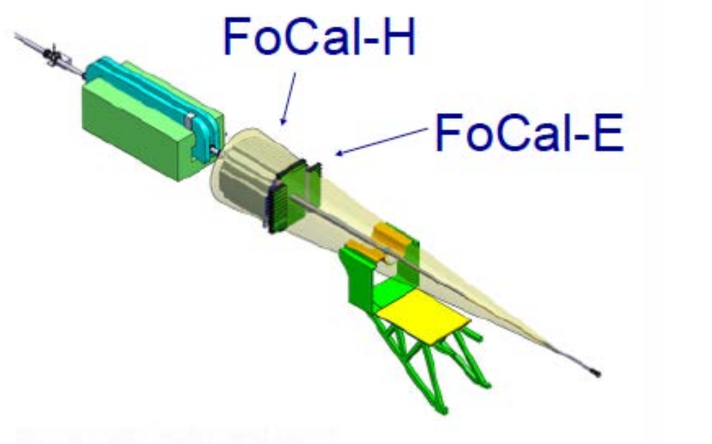
FoCal-E: EM Calorimeter

FoCal-H: Hadronic Calorimeter

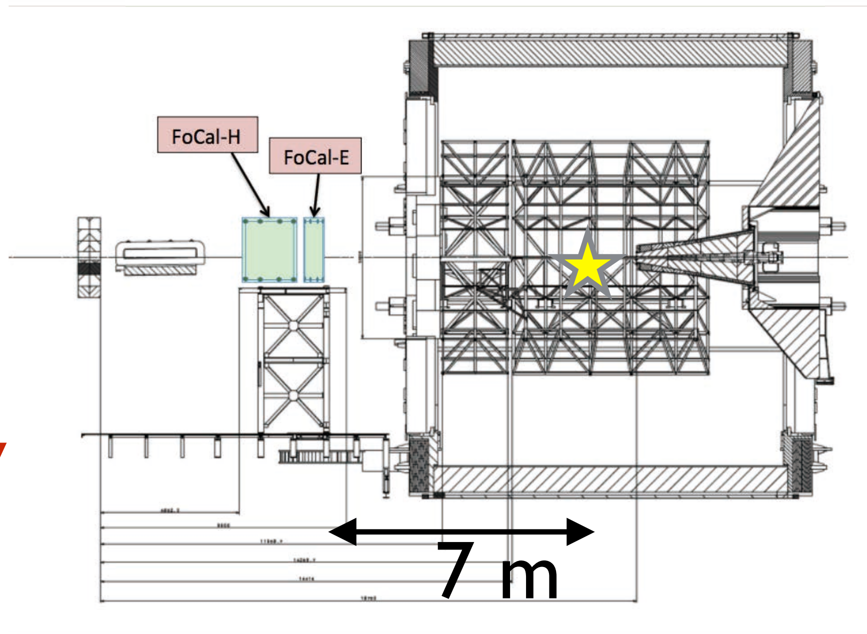
★ 7 m away from the interaction point.

★ main challenge: separate γ/π^0 at high energy

★ Si-W calorimeter, effective granularity ≈ $1mm^2$



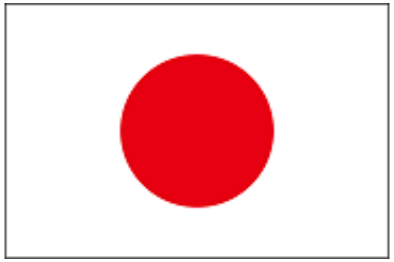
$3.2 < \eta < 5.3$



- **p-Pb: looking for CGC effects at small-x**
  - Direct photons,
  - π^0
  - di-hadron correlations (π^0-π^0)
  - jets, quarkonia
- **p-p: forward particle production, baseline**
  - (same as p-Pb)
- **Pb-Pb: medium density at forward rapidity**
  - π^0 at $3.2 < \eta < 4.5$
    - longitudinal evolution of medium
    - provide jet quenching at forward rap., same region for J/ψ (muon arm)

FoCal project (Institutes)

Utrecht, Nikhef



Tsukuba, Tsukuba Tech,
Hiroshima, Nara, CNS, Nagasaki

BARC, Bose, IITB, Indore,
Jammu, VECC

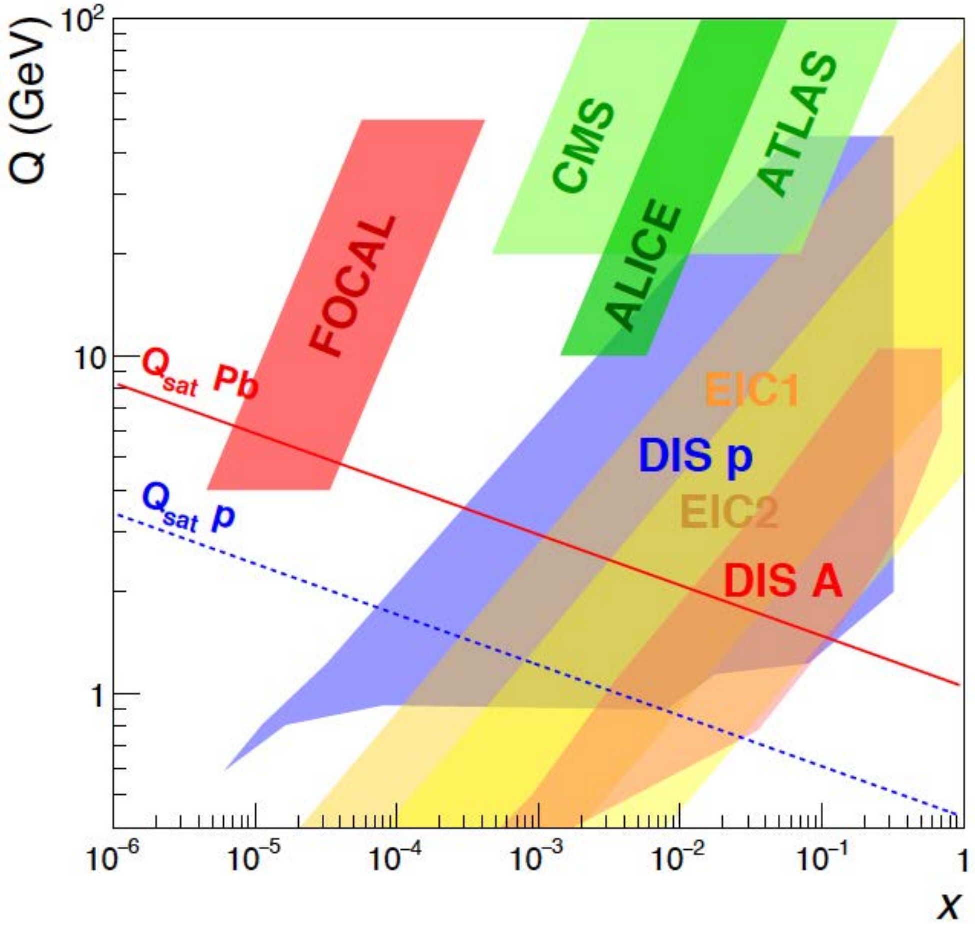
ORNL, Tennessee,
Wayne State

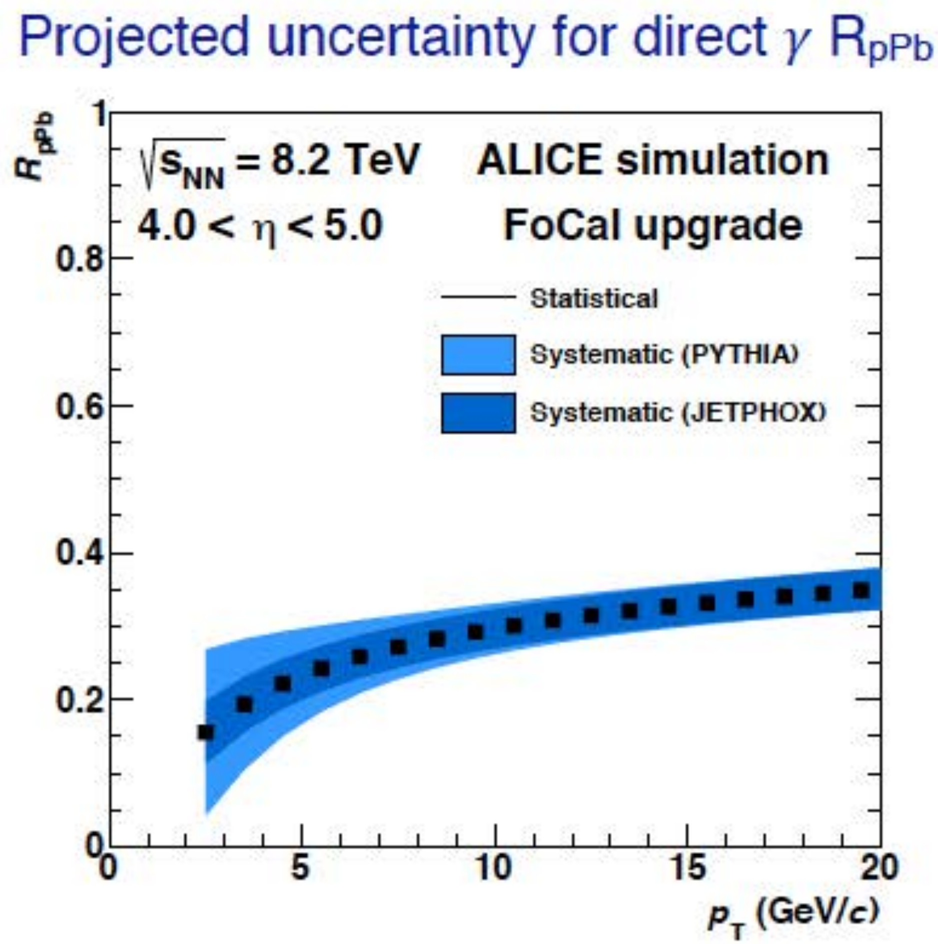
Short Name	Full Name	Representative
Amsterdam	Nikhef, Amsterdam, Netherlands	M. van Leeuwen
BARC	Bhaba Atomic Research Centre, Mumbai, India	V.B. Chandratre
Bergen	University of Bergen, Bergen , Norway	D. Roehrich
Bose	Bose Institute, Kolkata, India	S. Das
Detroit	Wayne State University, Detroit, USA	J. Putschke
Hiroshima	Hiroshima University, Hiroshima, Japan	T. Sugitate
IITB	Indian Institute of Technology Bombay, Mumbai, India	R. Varma
Indore	Indian Institute of Technology Bombay, Indore, India	R. Sahoo
Jammu	Jammu University, Jammu, India	A. Bhasin
Jyväskylä	University of Jyväskylä, Jyväskylä , Finland	J. Rak
Knoxville	University of Tennessee, Knoxville, USA	K. Read
Nagasaki	Nagasaki Inst. of Applied Science, Nagasaki, Japan	K. Oyama
Nara[§]	Nara Women's University, Nara, Japan	M. Shimomura
Oak Ridge	Oak Ridge National Laboratory (ORNL),Oak Ridge, USA	T. Cormier
Prague	Czech Technical University of Prague, Prague, Czech Republic	V. Petracek
Sao Paulo	Universidade de Sao Paulo (USP), Sao Paulo, Brazil	M. Munhoz
Tokyo	Center of Nuclear Study (CNS), Tokyo, Japan	T. Gunji
Tsukuba	University of Tsukuba	T. Chujo
Tsukuba Tech	Tsukuba University of Technology	M. Inaba
Utrecht	Utrecht University, Utrecht, Netherlands	T. Peitzmann
VECC	Variable Energy Cyclotron Centre, Kolkata, India	T. Nayak

ALICE

* Note: the list of institutes expressed interests in FoCal project

Kinematic reach by FoCal



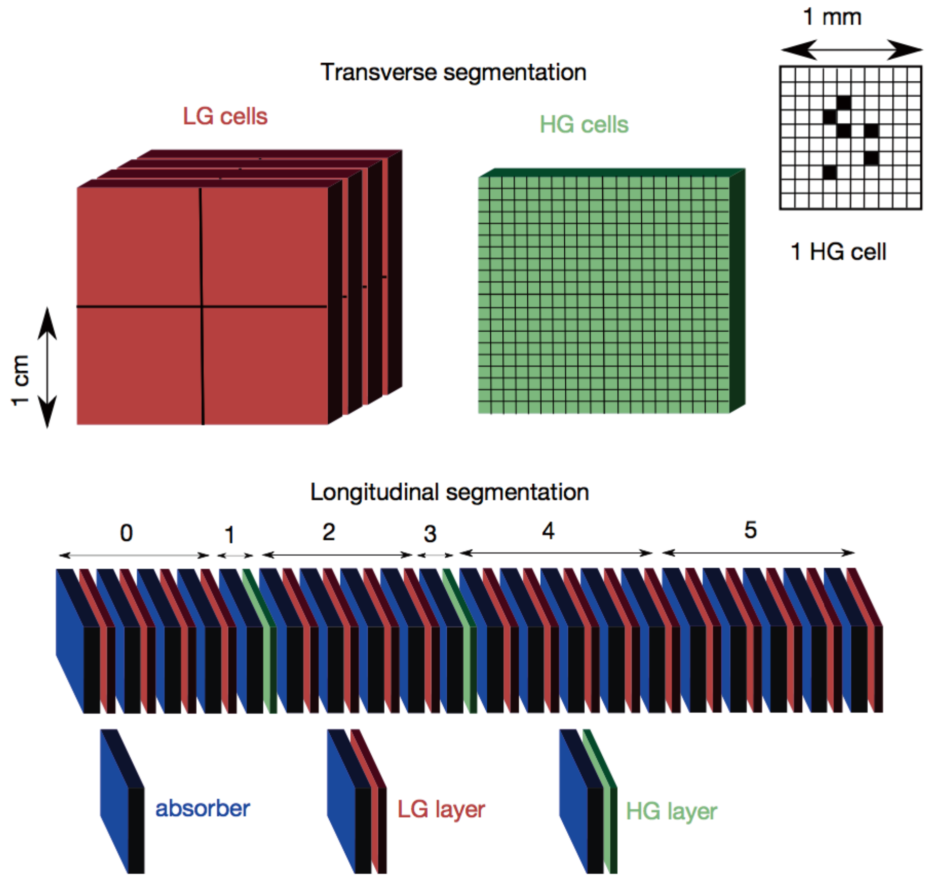


Forward measurements at LHC access unique rage in x and Q^2

FoCal: direct photons and hadrons (π^0), jets

Others: hadronic probe only

FoCal-E prototype design



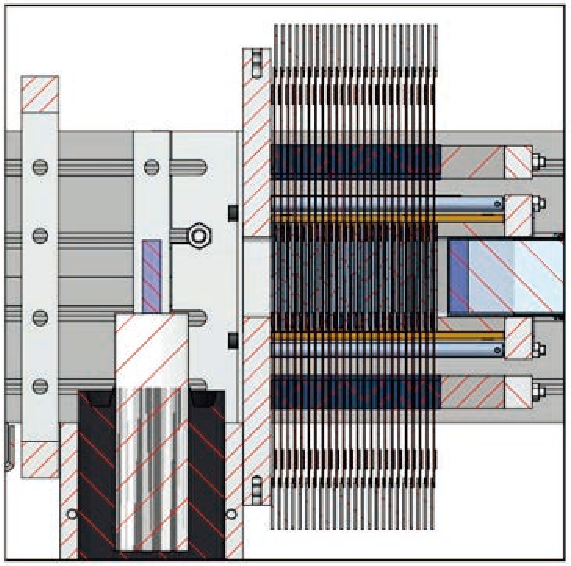
- **LG segments**
  - 4 (or 5) layers
  - Si-pad with analog readout
  - cell size 1 x 1 cm^2
  - longitudinally summed
- **HG segments**
  - single layer
  - CMOS-pixel (MAPS*)
  - pixel size ≈ 30 x 30 μm^2
  - digitally summed in 1mm^2 cells

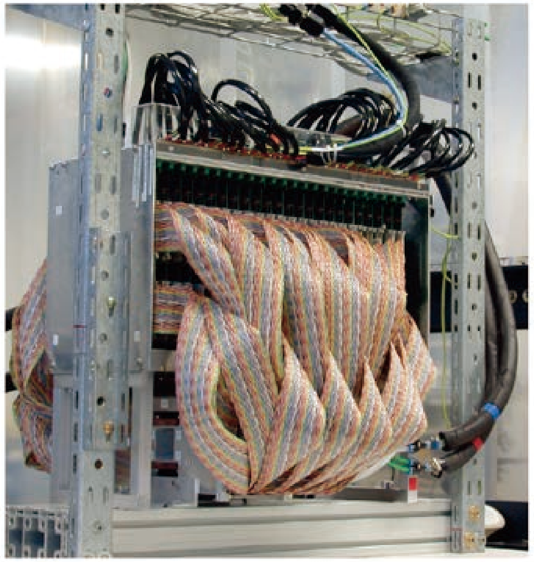
*MAPS = Monolithic Active Pixel Sensor

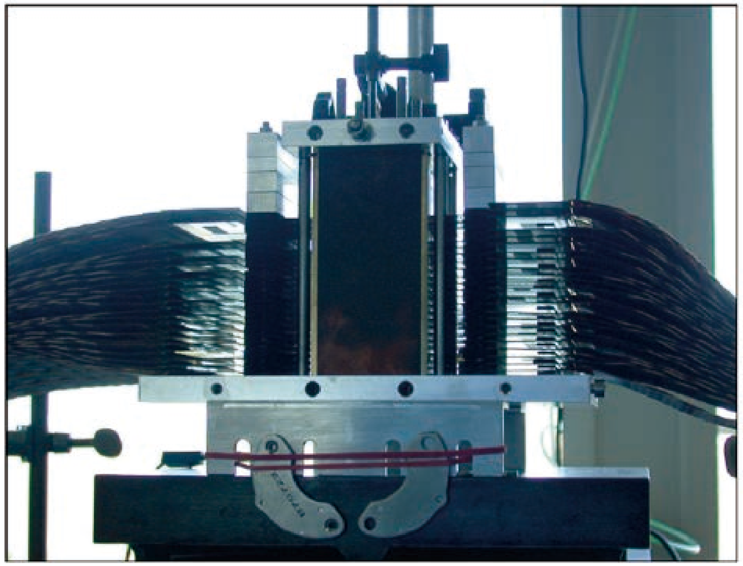
- **Si/W** sandwich calorimeter layer structure:
  - W absorbers (thickness $1X_0$)+ Si sensors
- Longitudinal segmentation:
  - 4 segments low granularity (LG)
  - 2 segments high granularity (HG)

* note: two-photon separation from π0 decay (pT = 10 GeV/c, y = 4.5, α = 0.5) is d = 2 mm.

High Granularity (HG) Prototype, MAPS

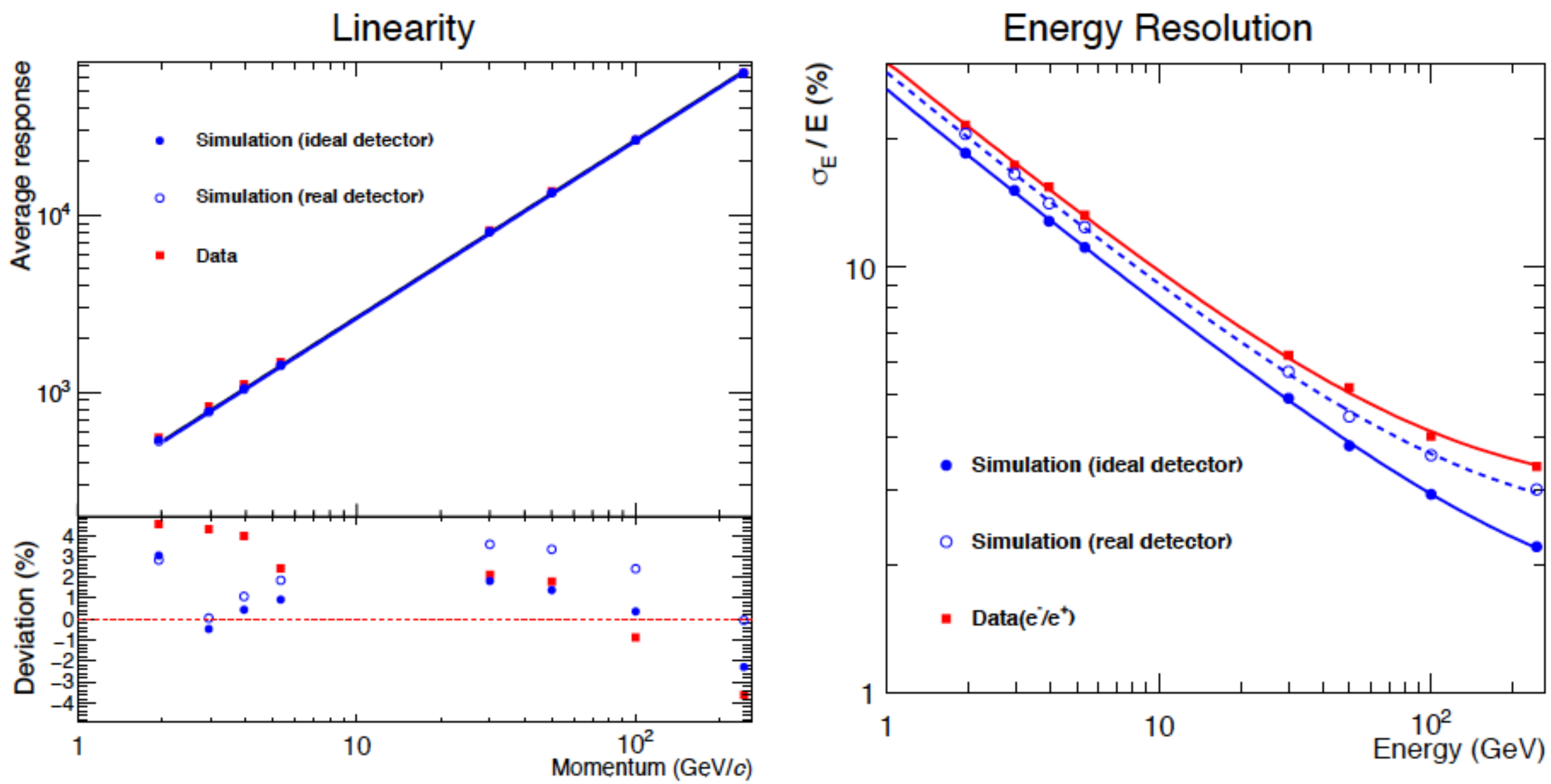






- 4x4 cm^2 cross section, 28 X_0 depth
- 24 layers: W absorber + 4 MAPS each
- MIMOSA PHASE 2 chip (IPHC Strasbourg)
  - 30 µm pixels
  - 640 µs integration time
    (needs upgrade – too slow for experiment)
- 39 M pixels total
- Test with beams at DESY, CERN PS, SPS

High Granularity (HG) Prototype, MAPS (1)



Good linearity and energy resolution (MAPS)

- different calibration for low/high energy, possibly still improve calibration.
- proof of principal of digital calorimetry works.

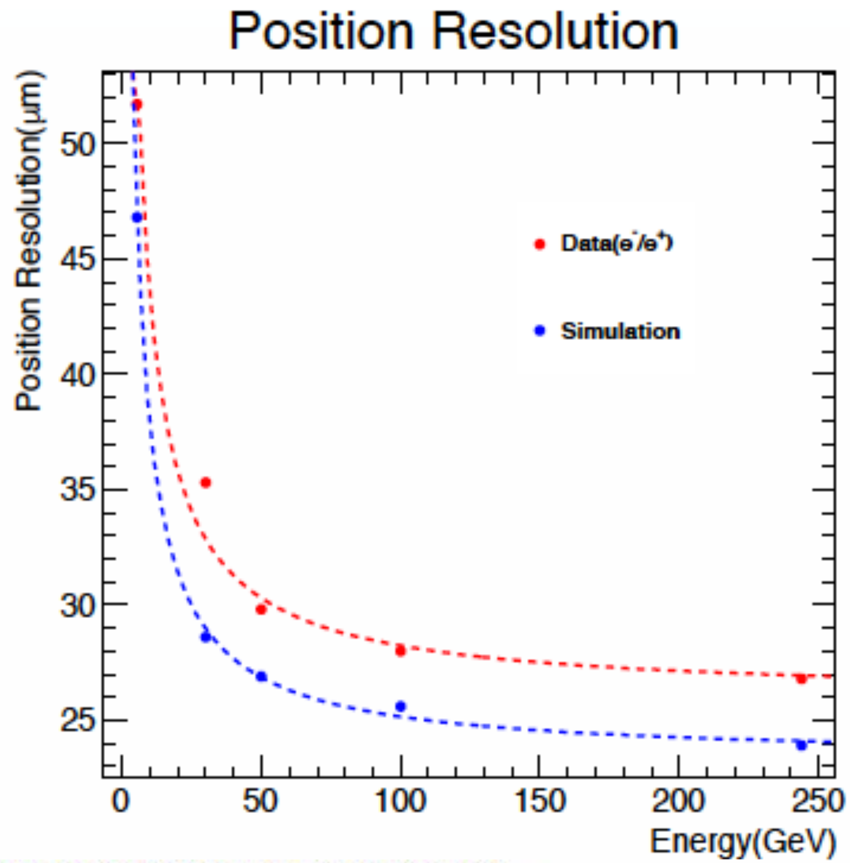
High Granularity (HG) Prototype, MAPS (2)

Position resolution:

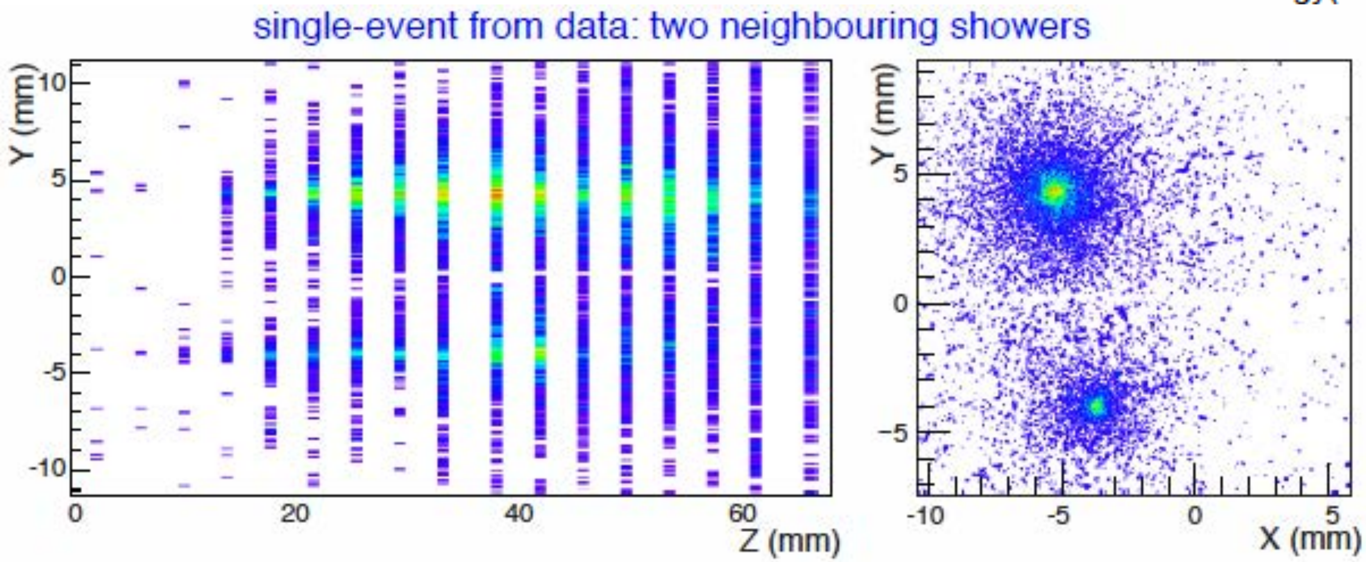
calculate difference of position from

- cluster in layer 0 and
- center of gravity of shower in layers 1 - 23

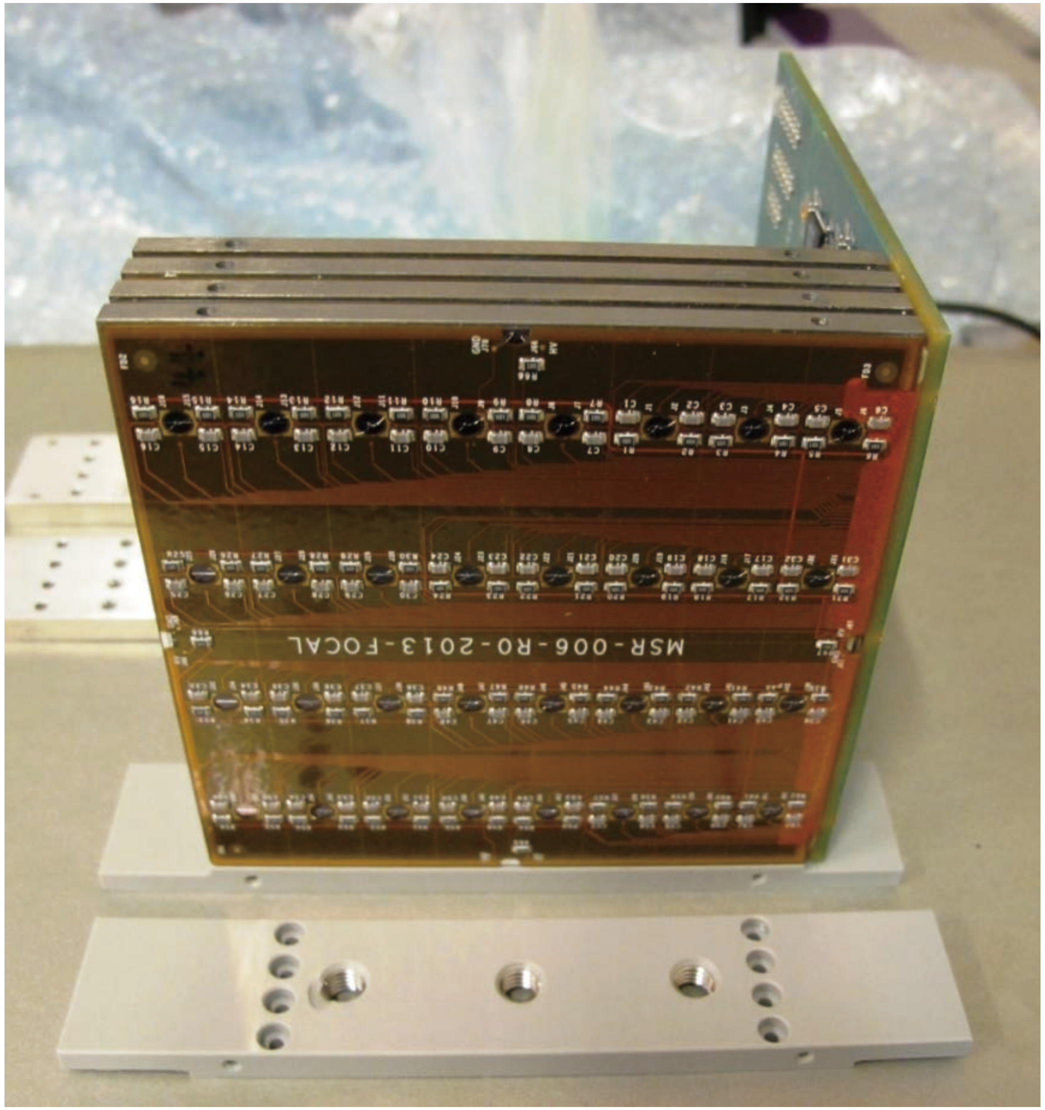
single shower position resolution obtained from width of residuals

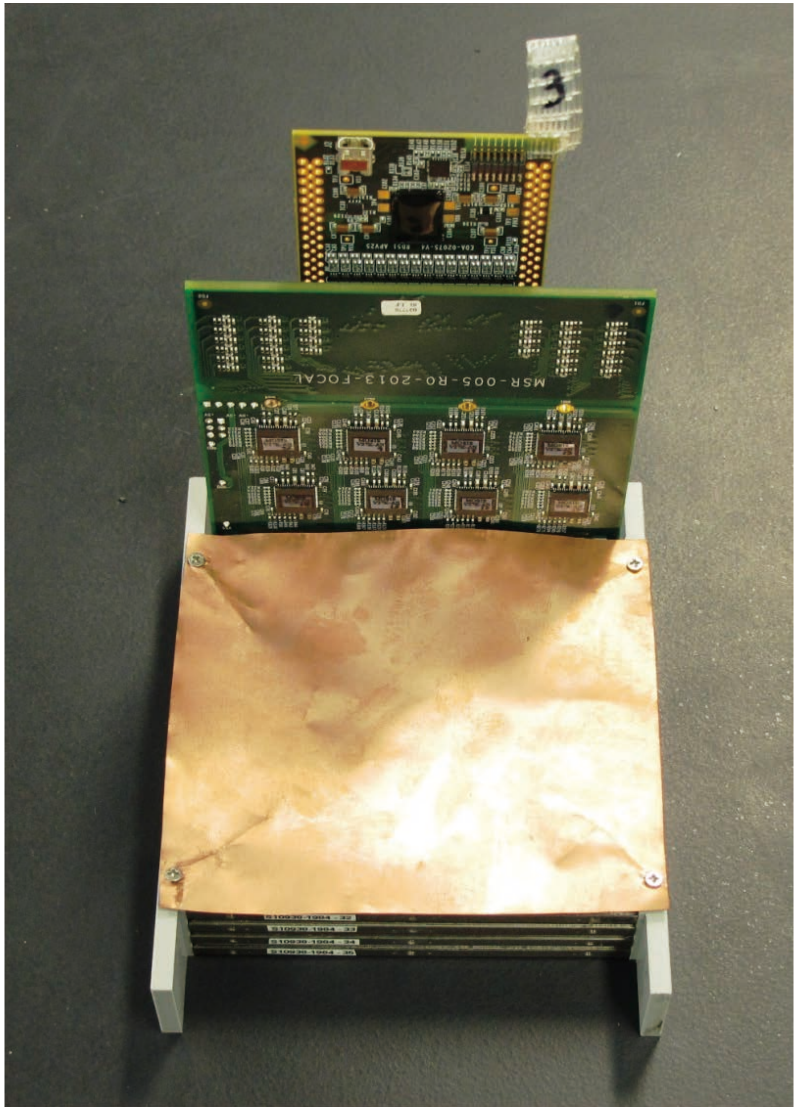


can provide excellent two-shower separation

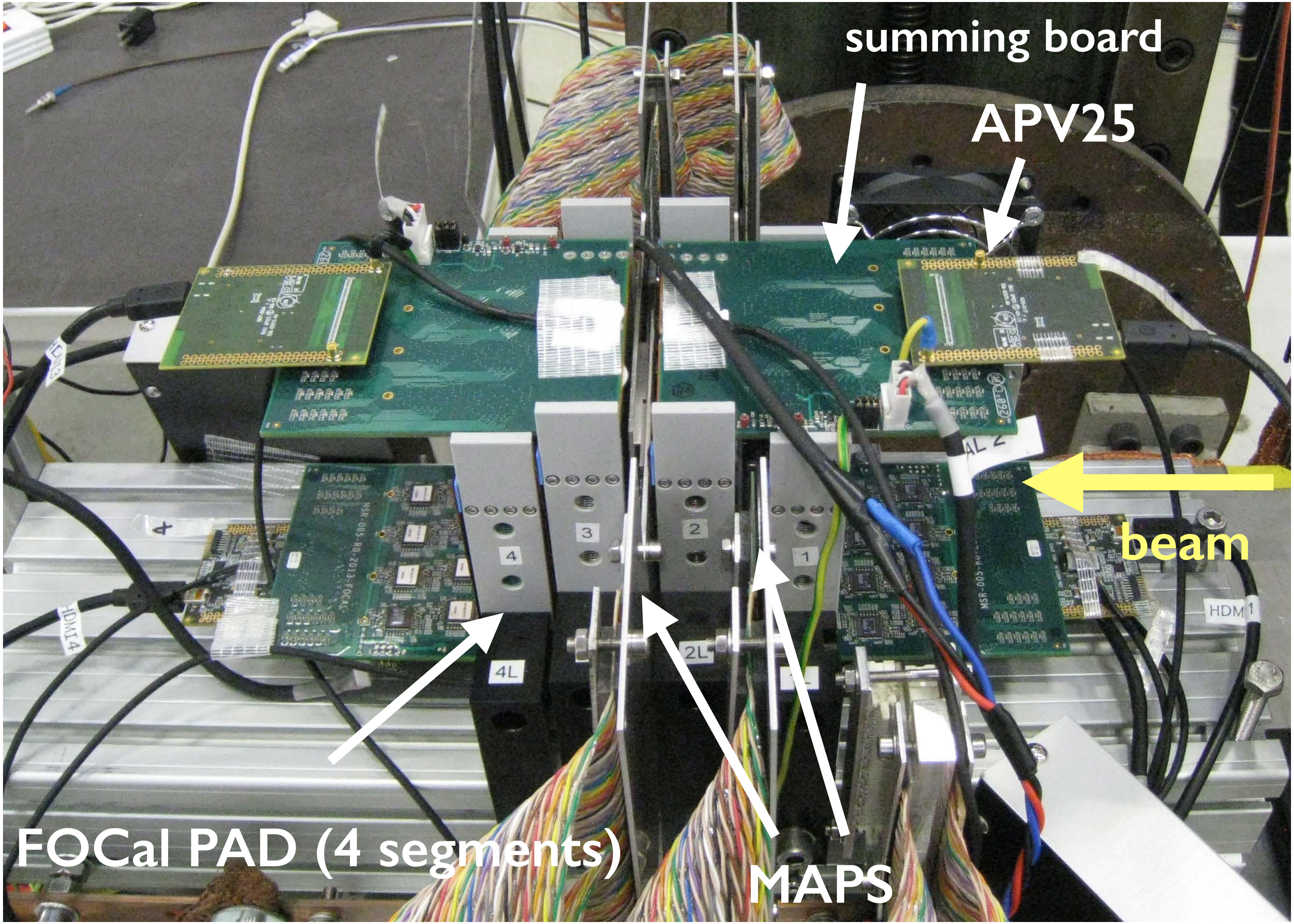


Low Granularity (LG) Prototype, PAD (JP, US)





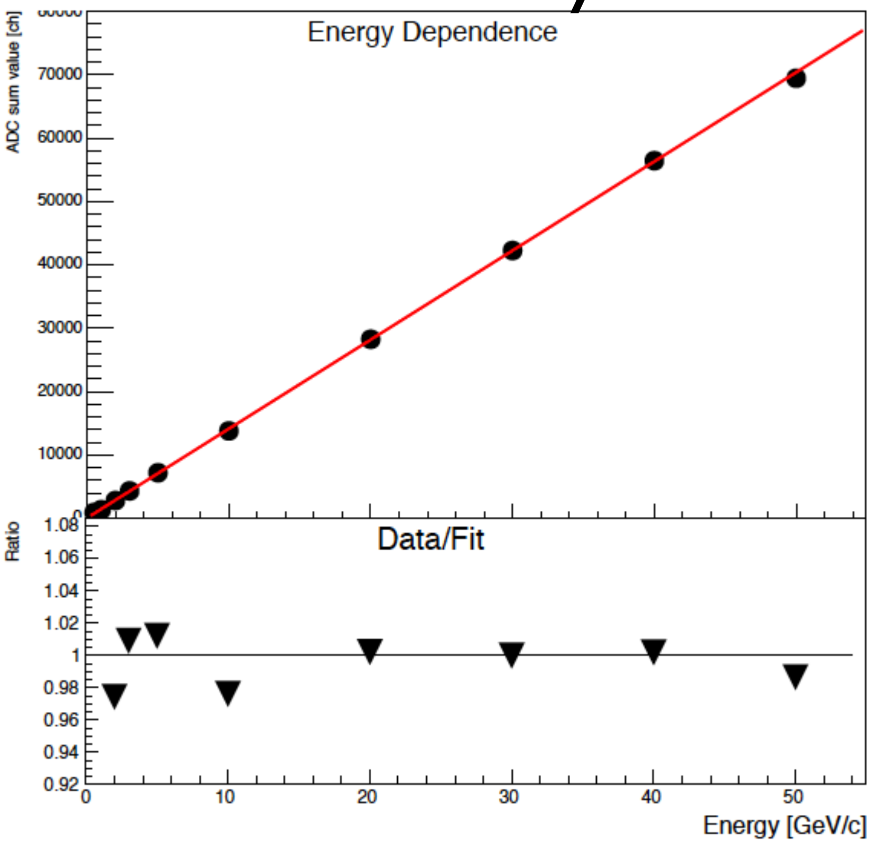
FoCal PAD proto type, 1 segment (ORNL, Tsukuba, CNS-Tokyo)



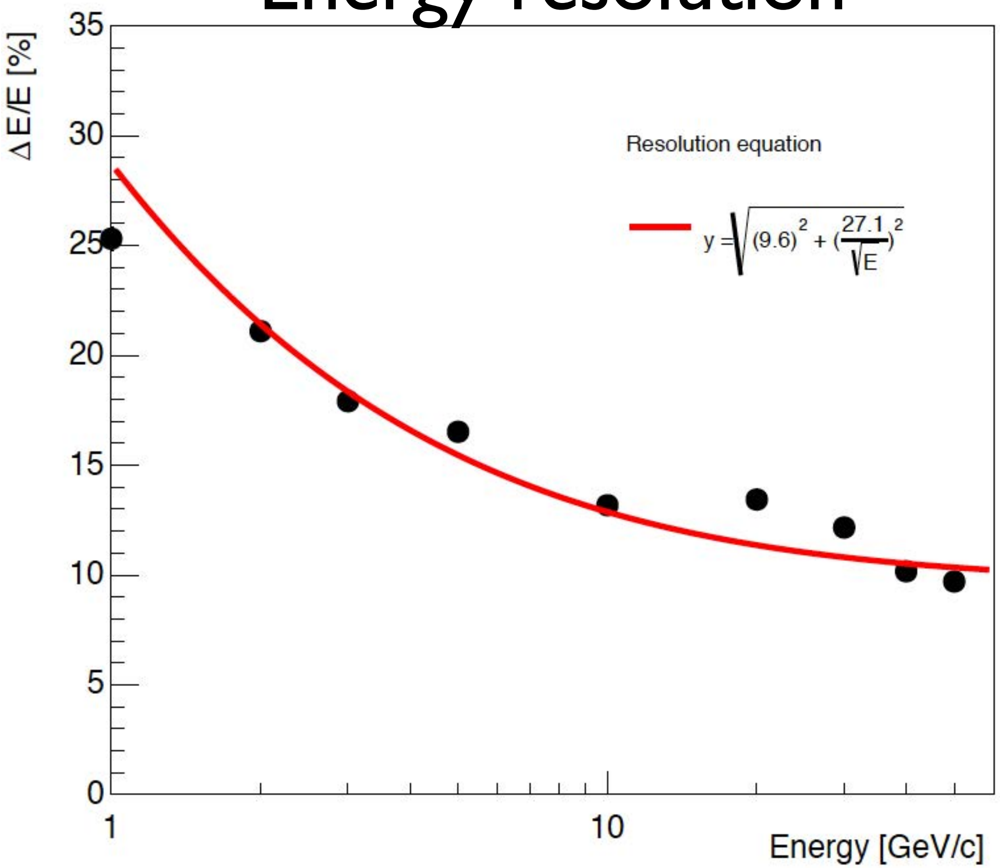
Test beam setup @ PS (same for SPS) in 2015

Low Granularity (LG) Prototype, PAD (JP, US)

Linearity

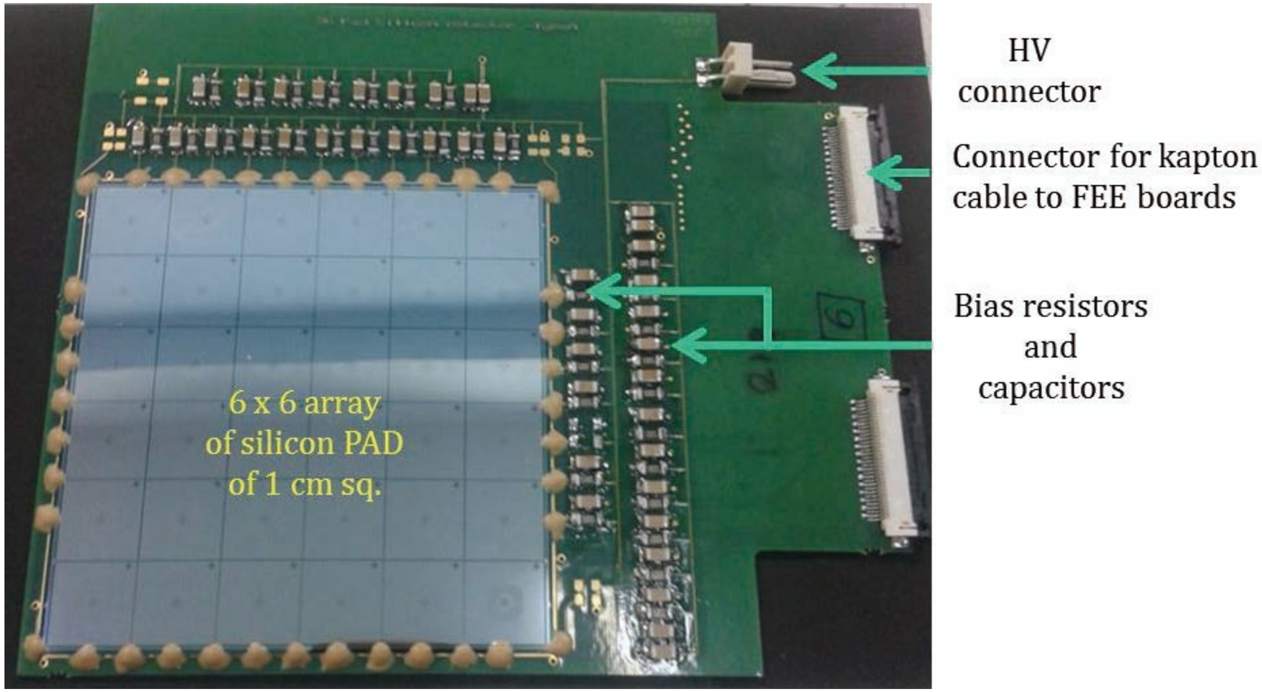


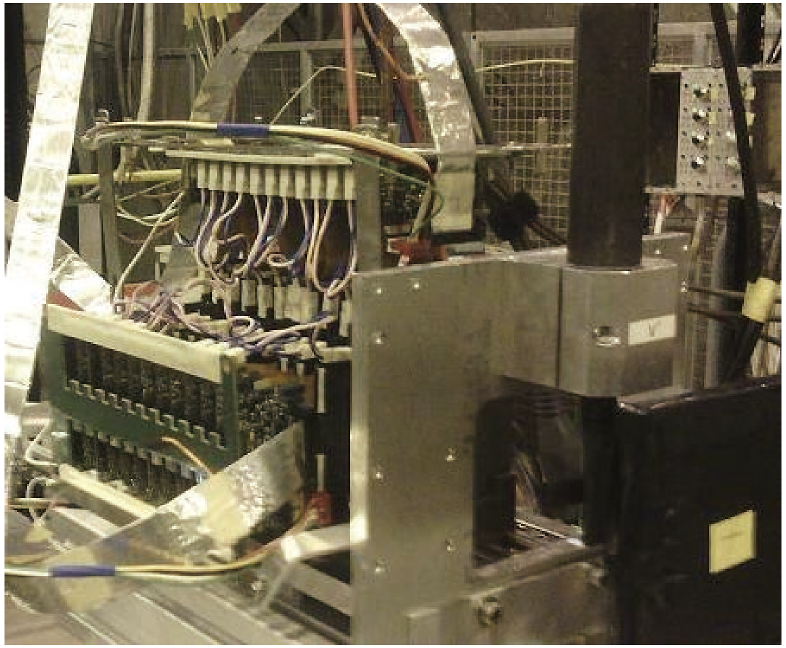
Energy resolution

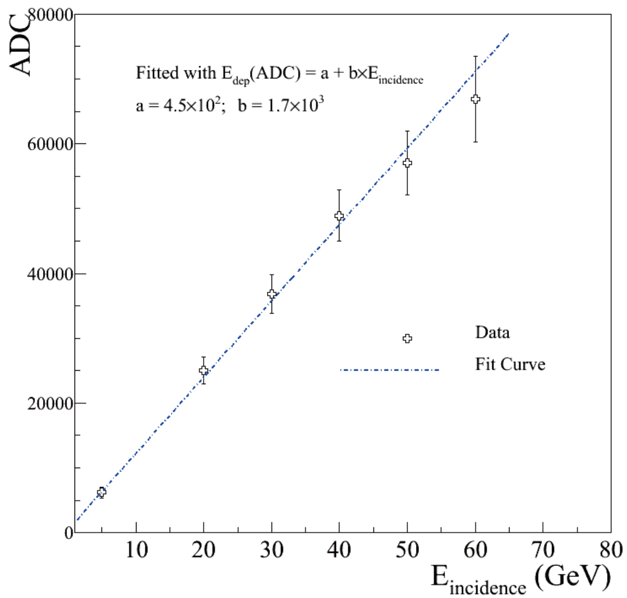


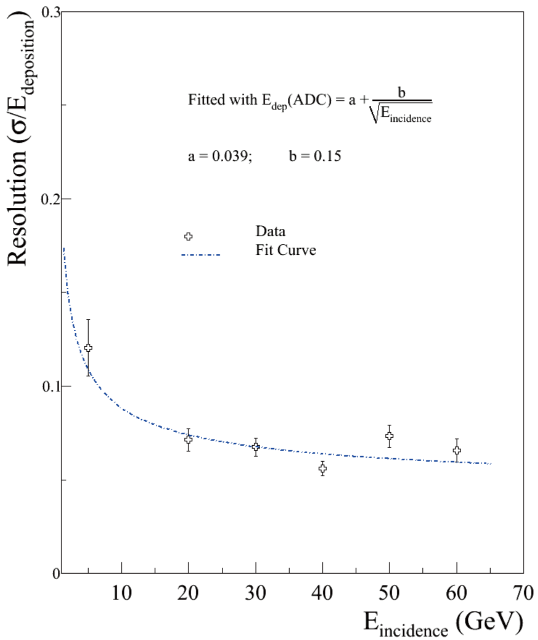
- **Good linearity within ~3% from PS to SPS energies.**
- **Good energy resolution, probability improved by further calibration.**

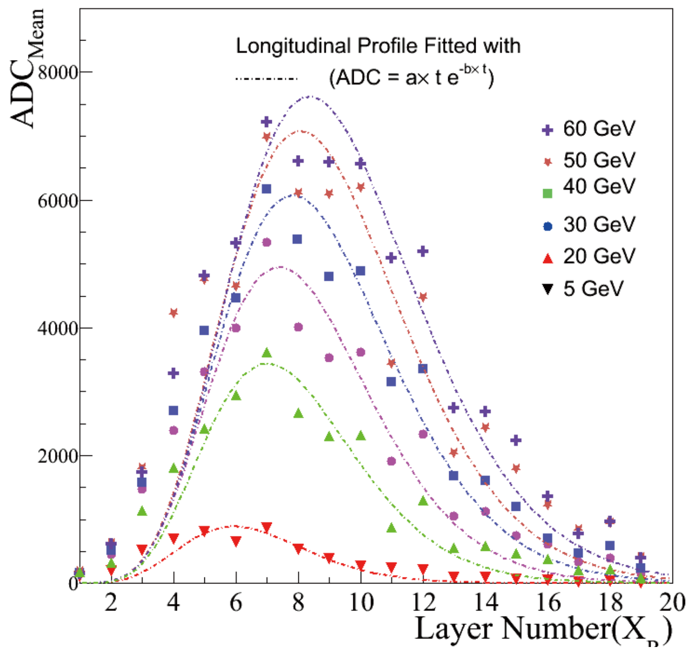
Low Granularity (LG) Prototype, PAD (India)











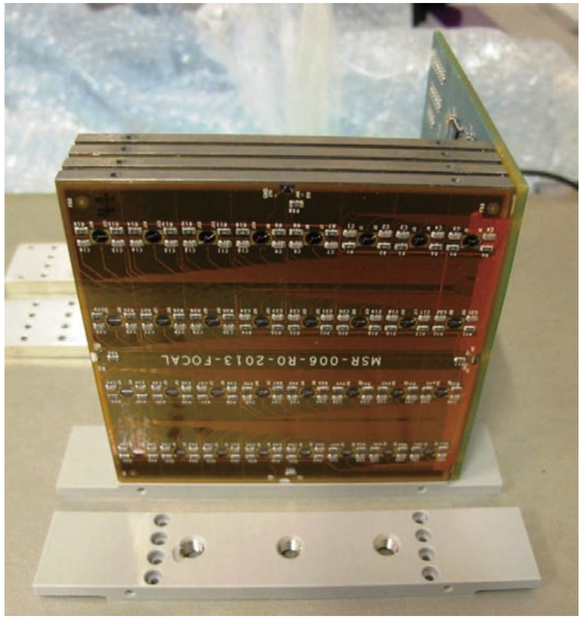
Good linearity and energy resolution for FoCal

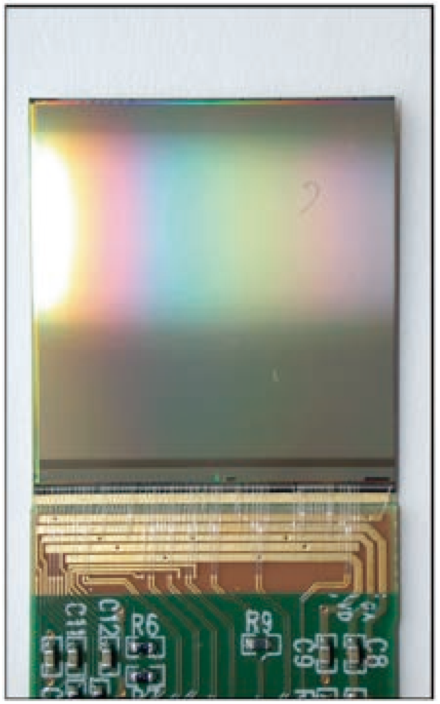
Summary

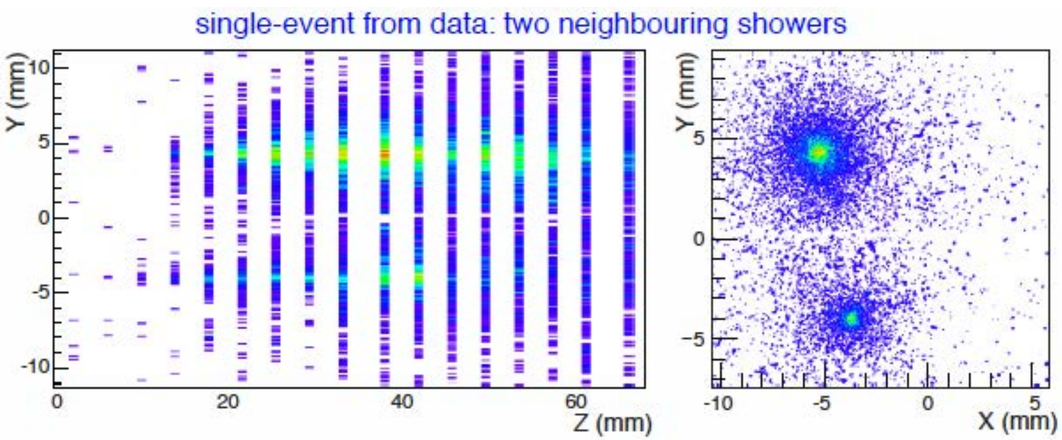
- **Rich physics and unexplored region @ forward rapidity at LHC**
  - CGC (or not), nature of CGC.
  - Strong connections to QGP thermalization mechanism, strong field, long range $\Delta\eta$ correlations (ridge).
  - Advantage of direct photon measurement at LHC forward region.
  - FoCal project is proposed in ALICE internally.
  - R&D efforts to finalize the final design are on-going.
  - FoCal physics potential extends to: forward π^0-π^0 correlations, forward jet measurement by FoCal in pp, p-Pb, even in Pb-Pb.

- **Outlook:**
  - First measurement: $3 < \eta < 4$, in Run-3 (2021-2023).
  - Full FoCal ($3.2 < \eta < 5.3$) in Run-4 (2026-2029).

Perspective to use a similar technology at EIC ?







Si-W with high position resolution EMCal:

- new technology
- could be useful for precise angler resolution at forward region in EIC

- If you are interested in, we are always welcome you, and discuss the spec you need for EIC!

Thank you!