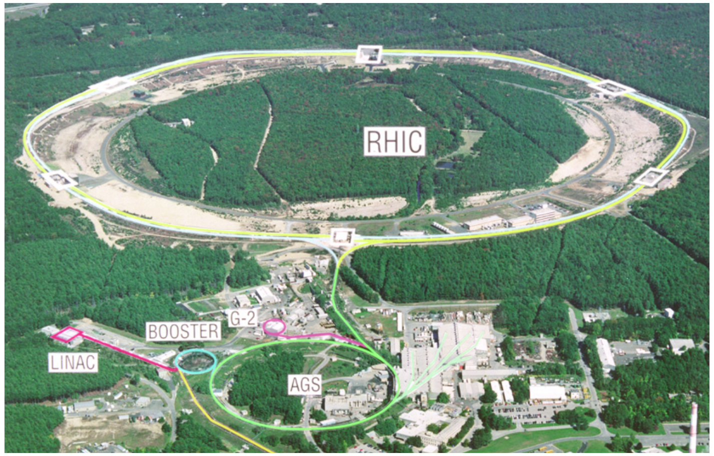
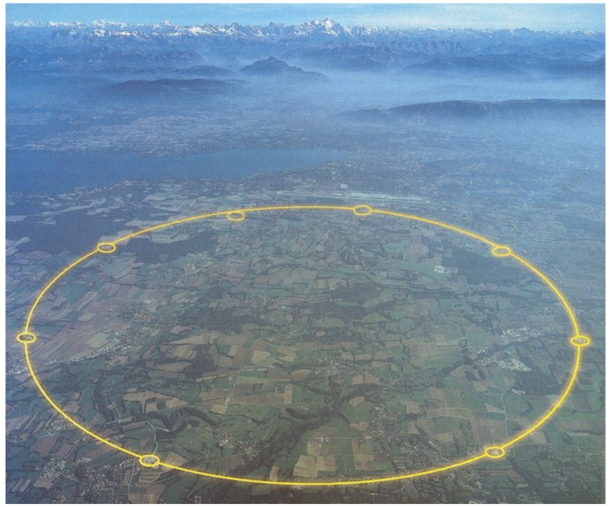
Heavy Ion Physics and EIC



Tatsuya Chujo
Univ. of Tsukuba

pre-DIS workshop
April 15, 2018, Kobe



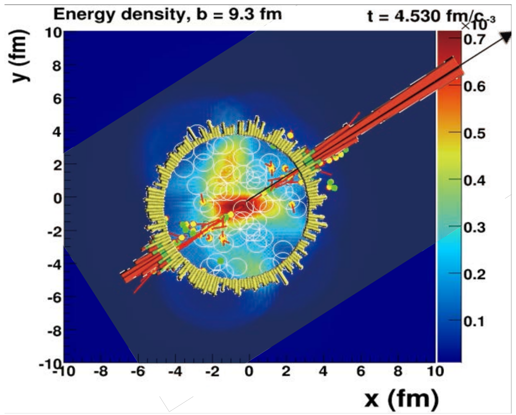
筑波大学
University of Tsukuba

1. Introduction:

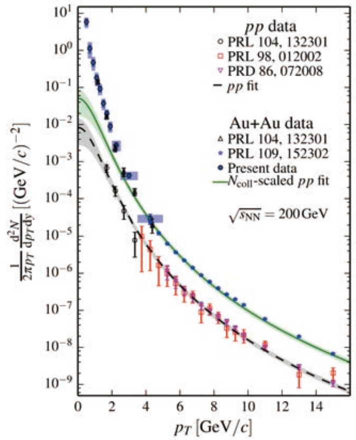
Heavy Ion Physics and small-x Physics

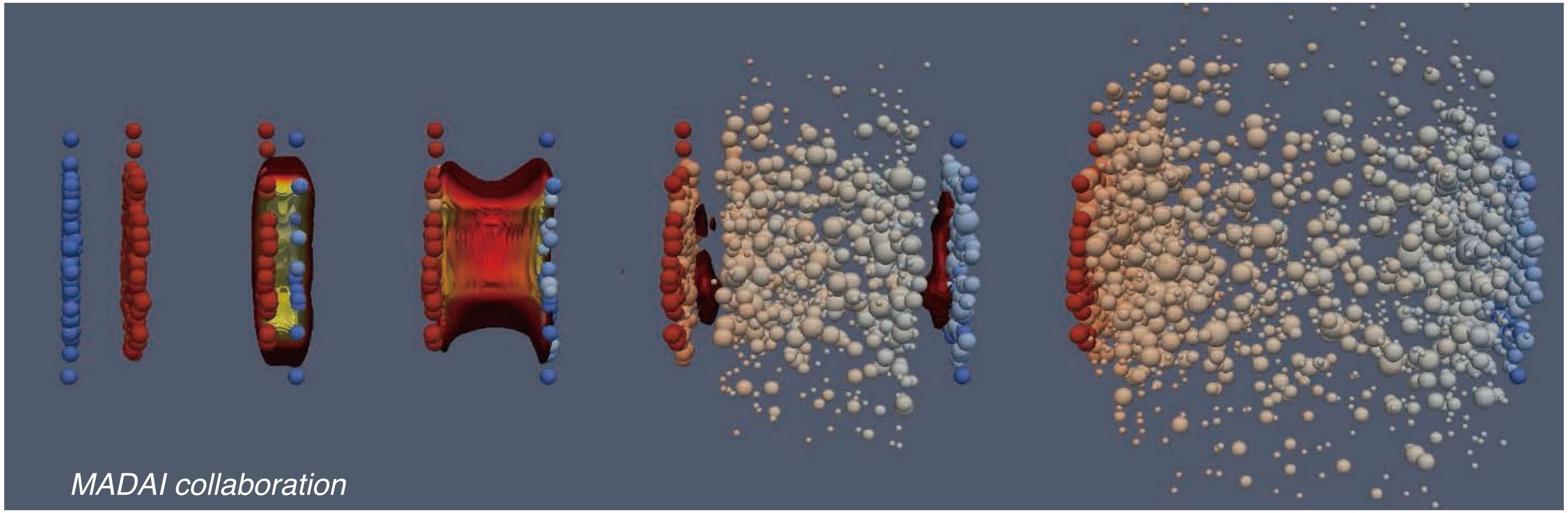
Heavy Ion Collisions at RHIC and LHC

1. jet quenching

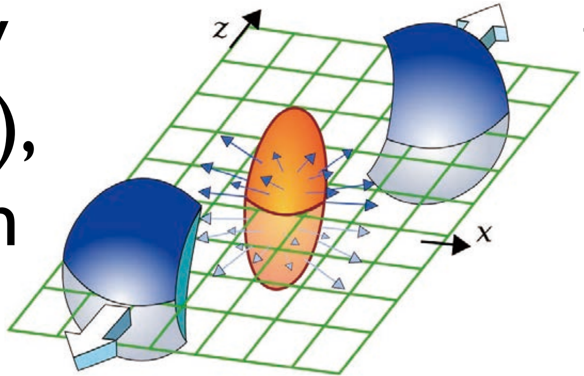


2. thermal photon emission

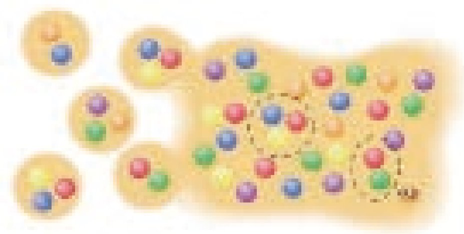




3. large elliptic flow
perfect fluid (sQGP),
early thermalization



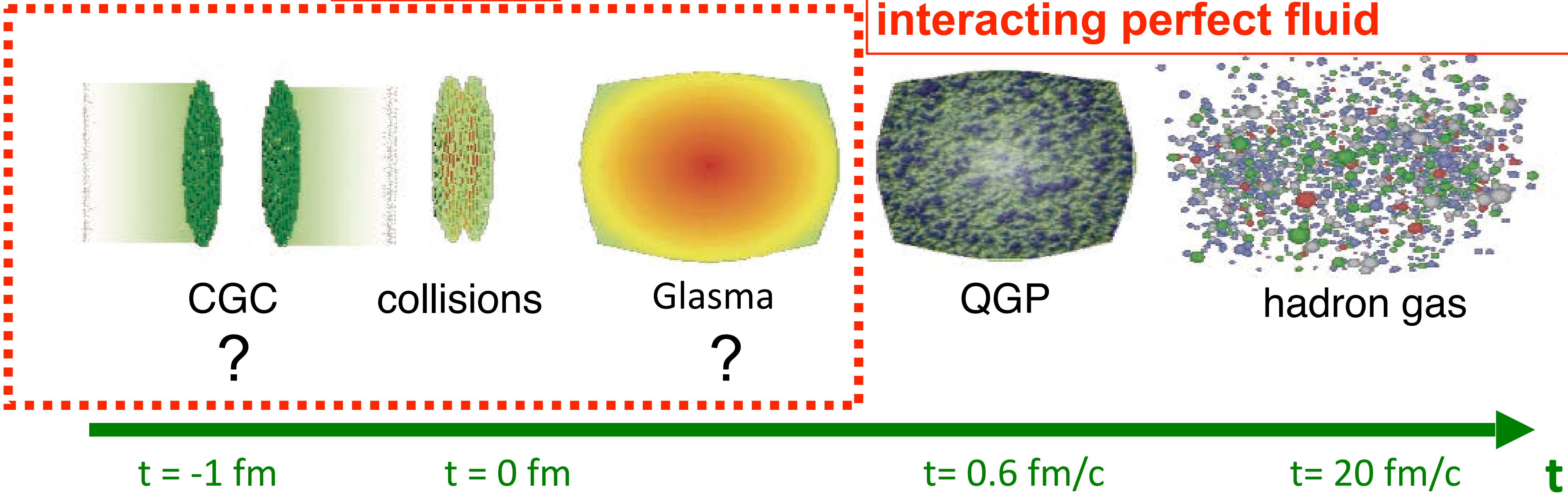
4. quark recombination



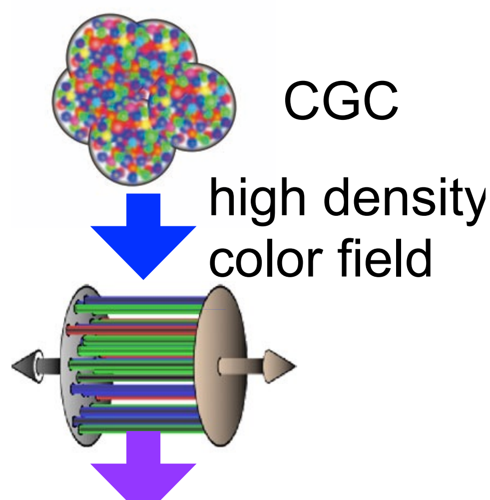
How QGP is thermalized so quickly ?

Unknown !

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



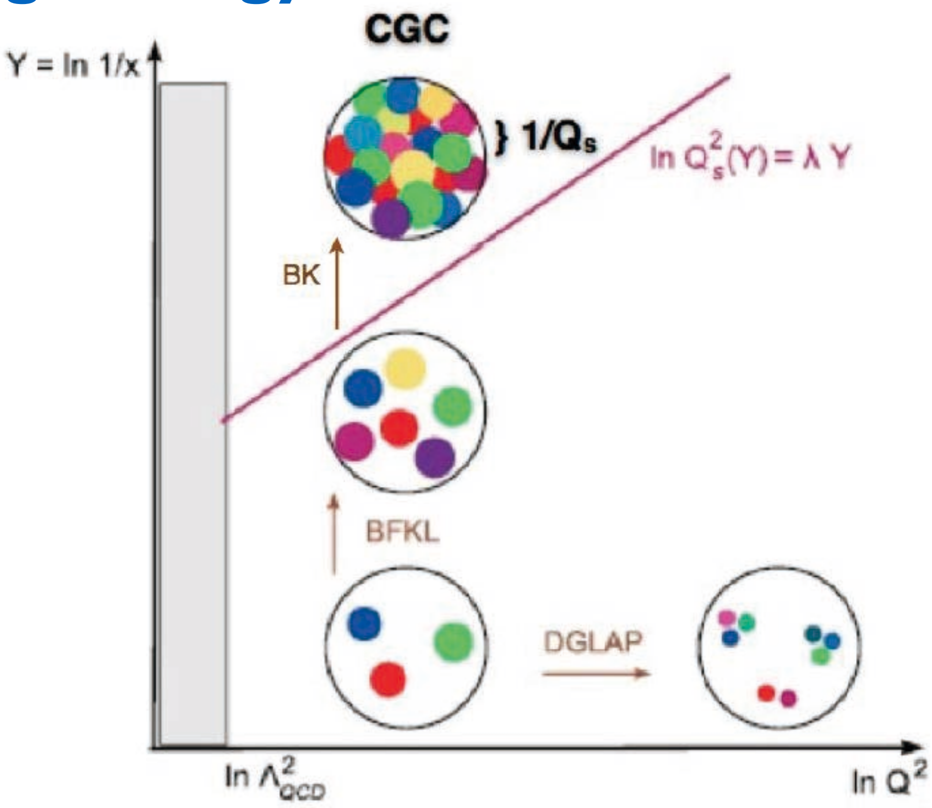
- **High energy nucleus = What is the initial condition?**
- **Why so rapidly thermalized (t=0.6 fm/c)?**
  - **Instability of strong color field？**
- **Find the clear evidence for CGC formation as an initial condition (or exclude it).**
- **Connections: initial condition, CGC, strong color fields, and creation of thermalized QGP**



QGP rapid thermalization?

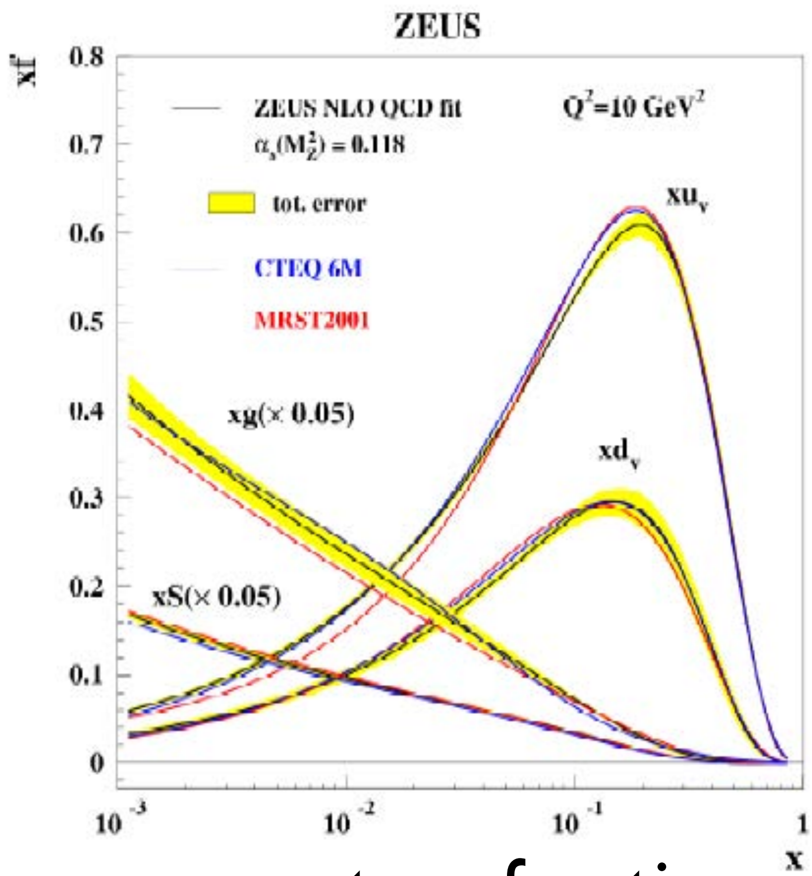
Saturation physics at small-x

high energy



hard process

distribution function

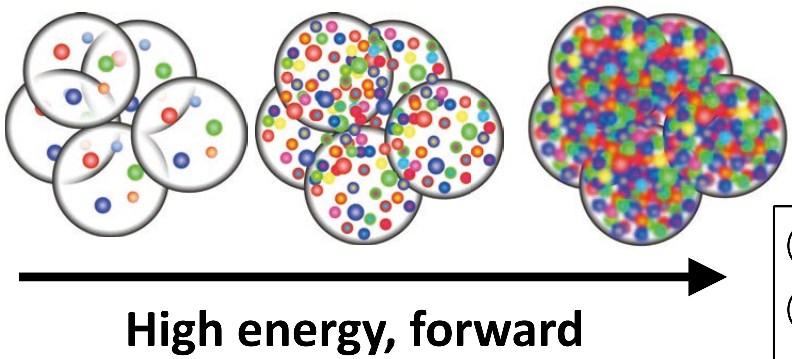


momentum fraction

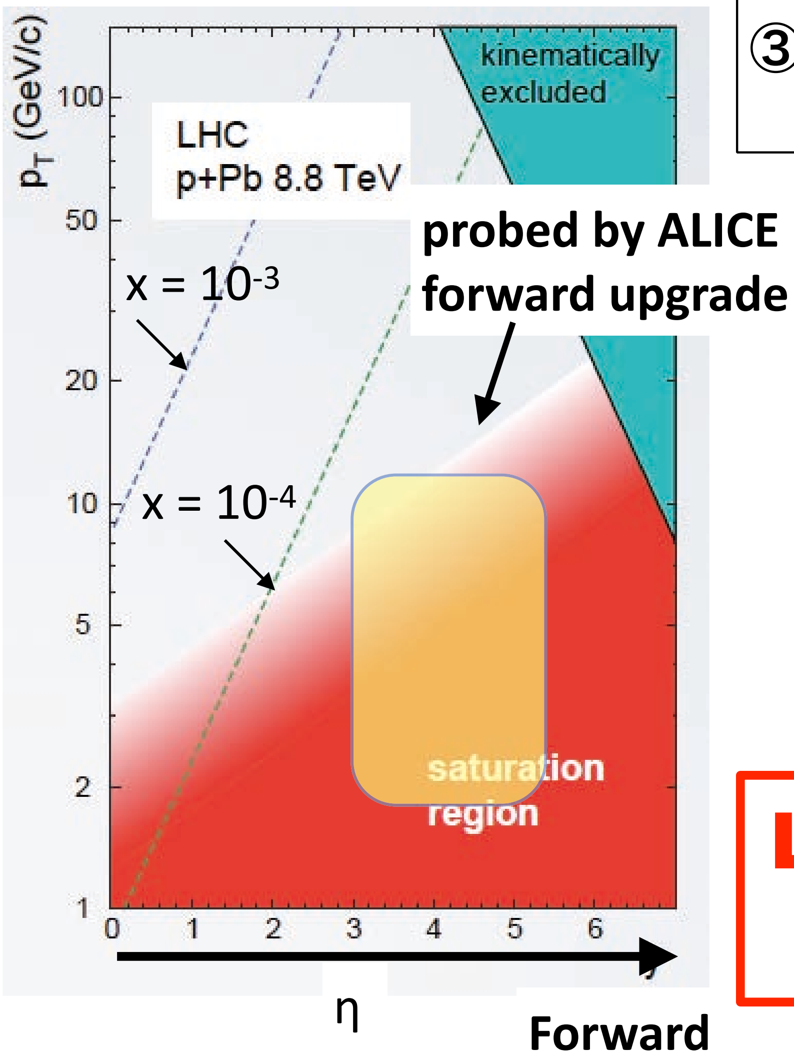
At small x and small Q^2, the parton density will become large by non-linear effects due to gluon fusion

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

Color Glass Condensate (CGC)



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)

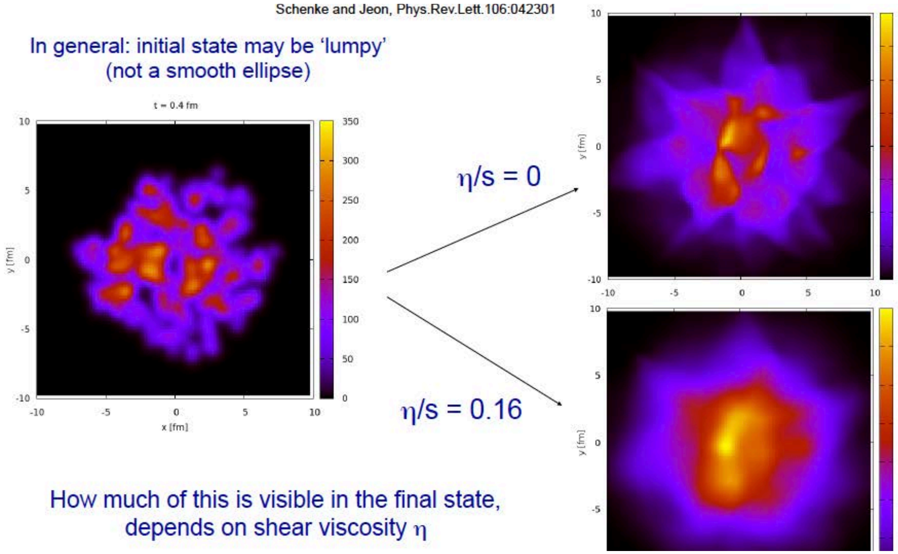
（3） p < A

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

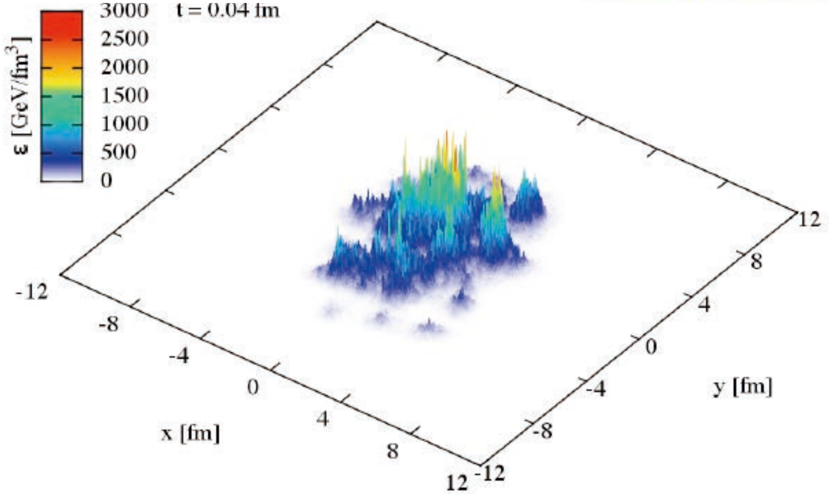
$$x_{\min} = \frac{2p_T}{\sqrt{s}} \exp(-\eta),$$

LHC forward provides an ideal experimental field for CGC

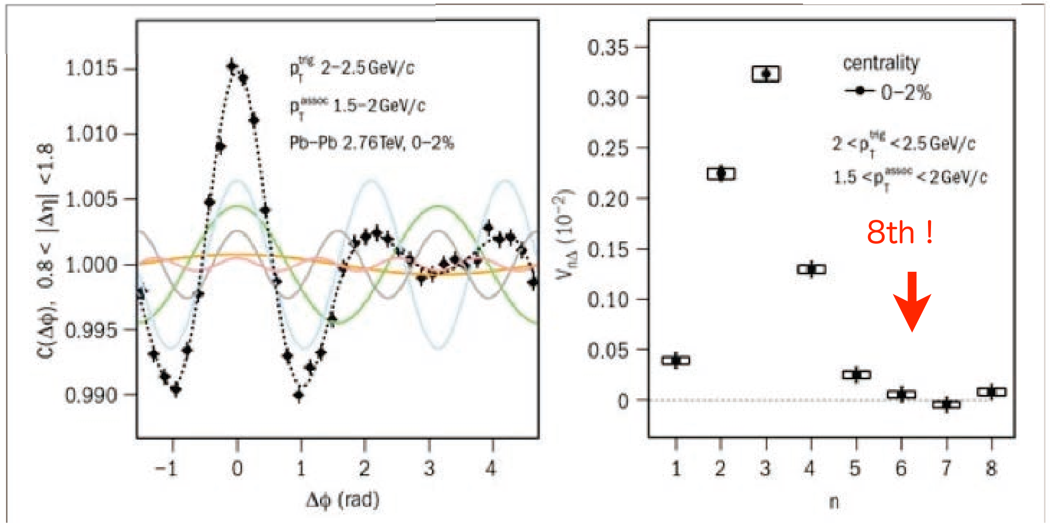
Initial condition of HIC and “hot” matter properties



Initial state **Final state** ALICE (2011)



l parameters



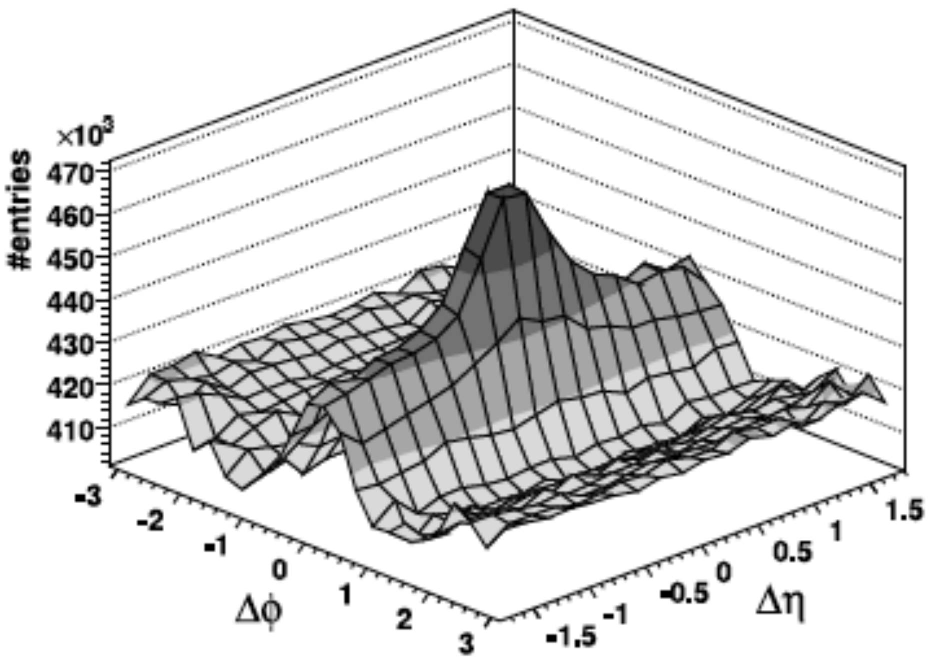
IP-Glasma: Color charges and gluon fields fluctuation

Understanding of initial condition:
→**key** to understand the QGP properties (e.g. η/s) and early thermalization.

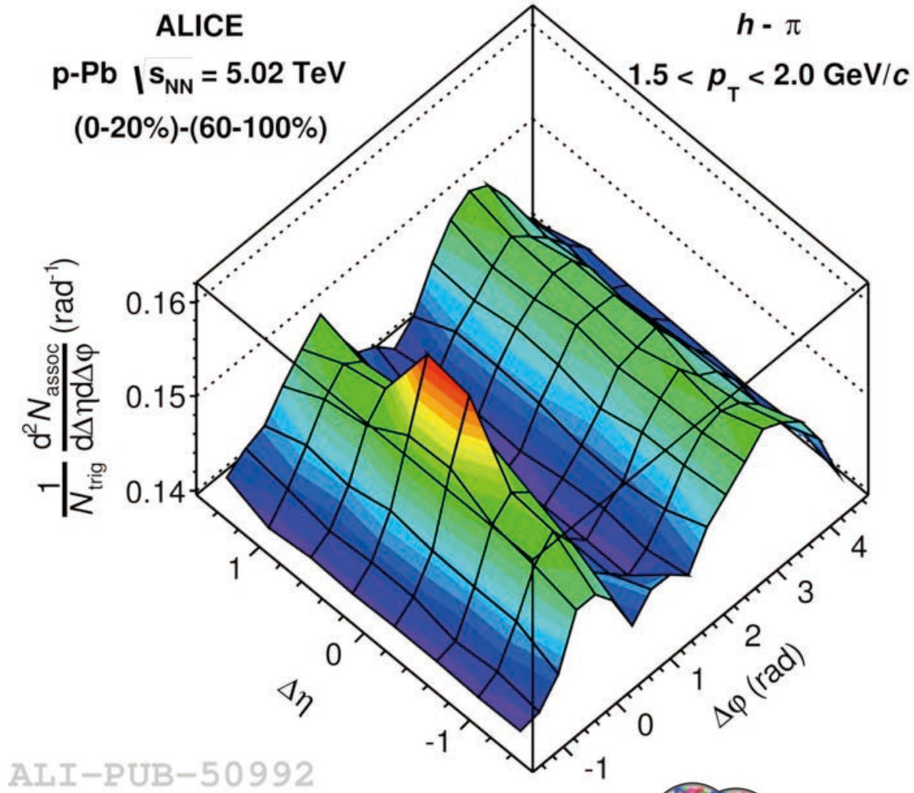
2. Current experimental data in p-A @ RHIC and LHC

Long range correlations "Ridge"

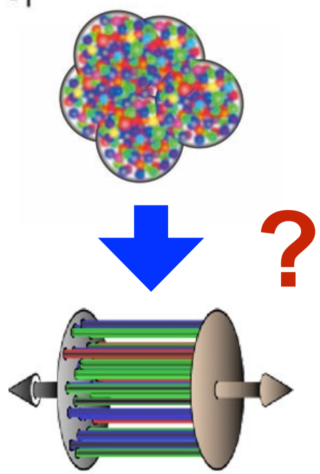
RHIC (STAR, Au+Au 200 GeV)



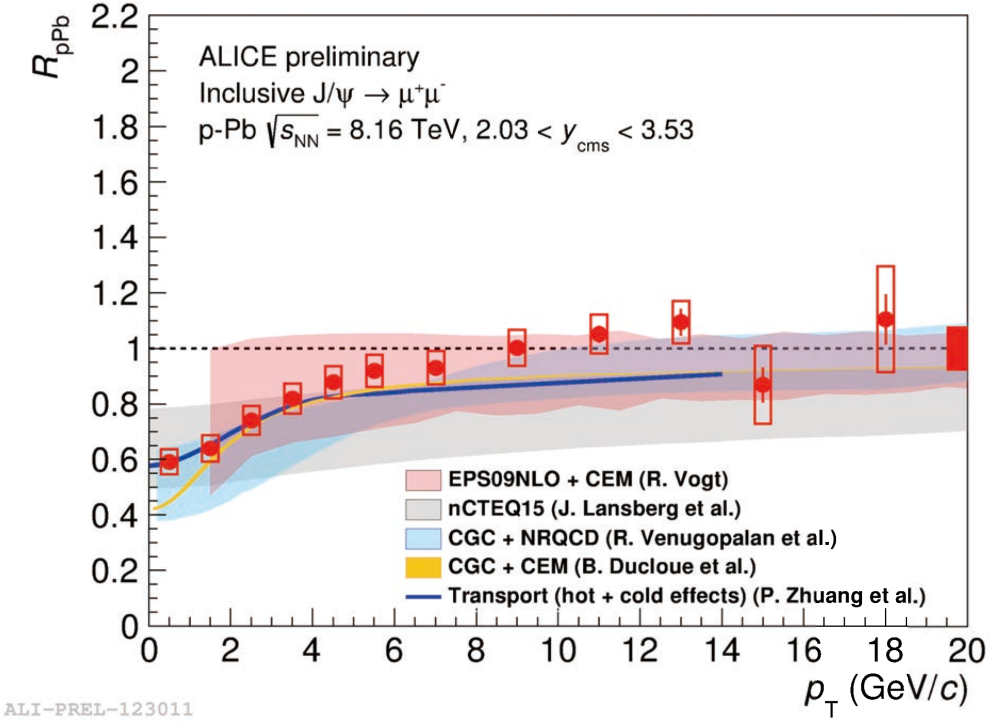
LHC (ALICE, pPb, 5.02 TeV)

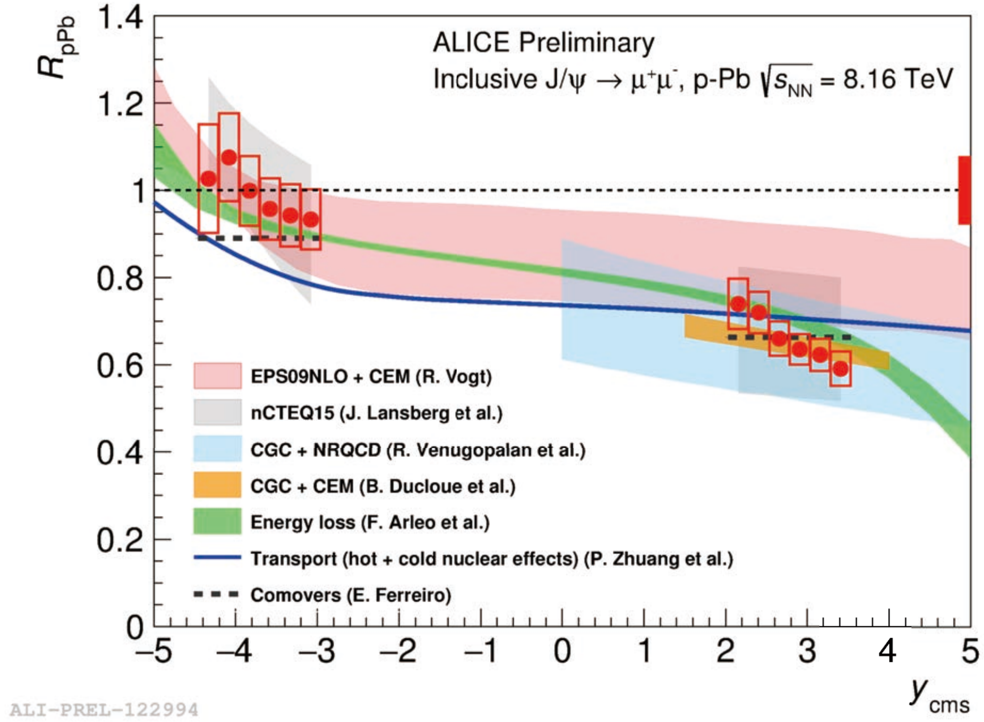


- Long range Δη correlations (ridge) at RHIC and LHC.
- Also observed **at high multiplicity event** in small system in pp, p-Pb.
- Origin is unknown.
- CGC (initial condition) or others?



J/ψ in pA

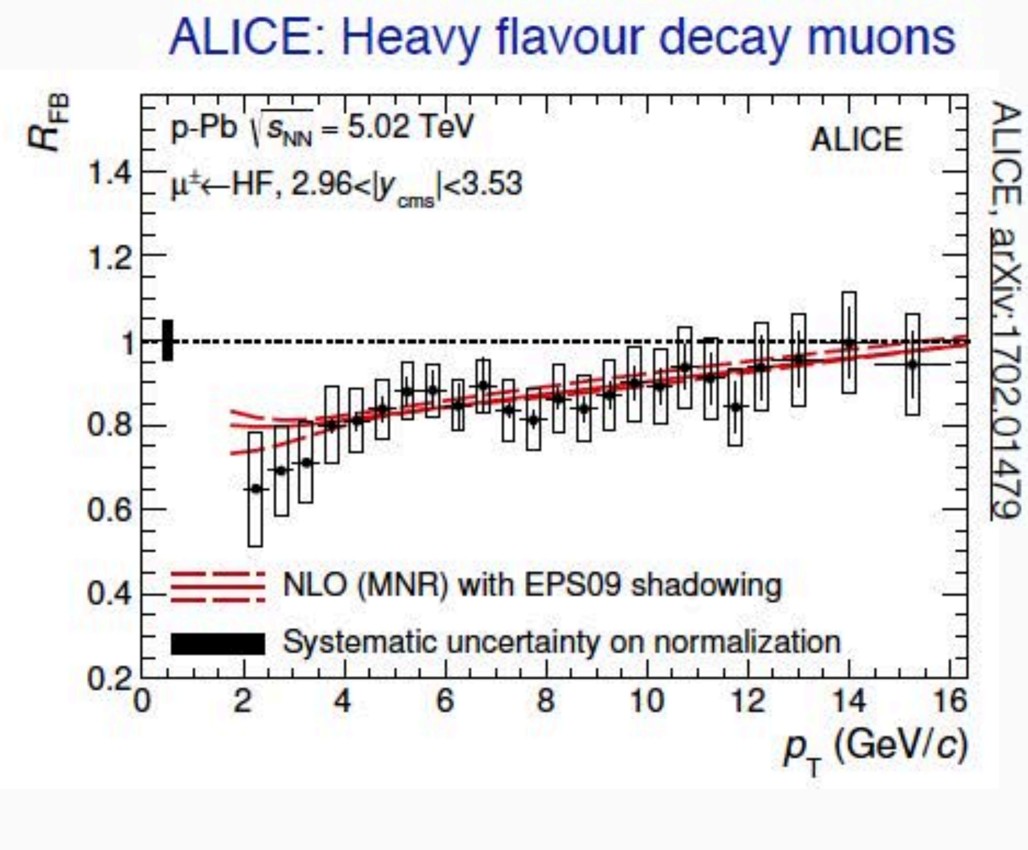


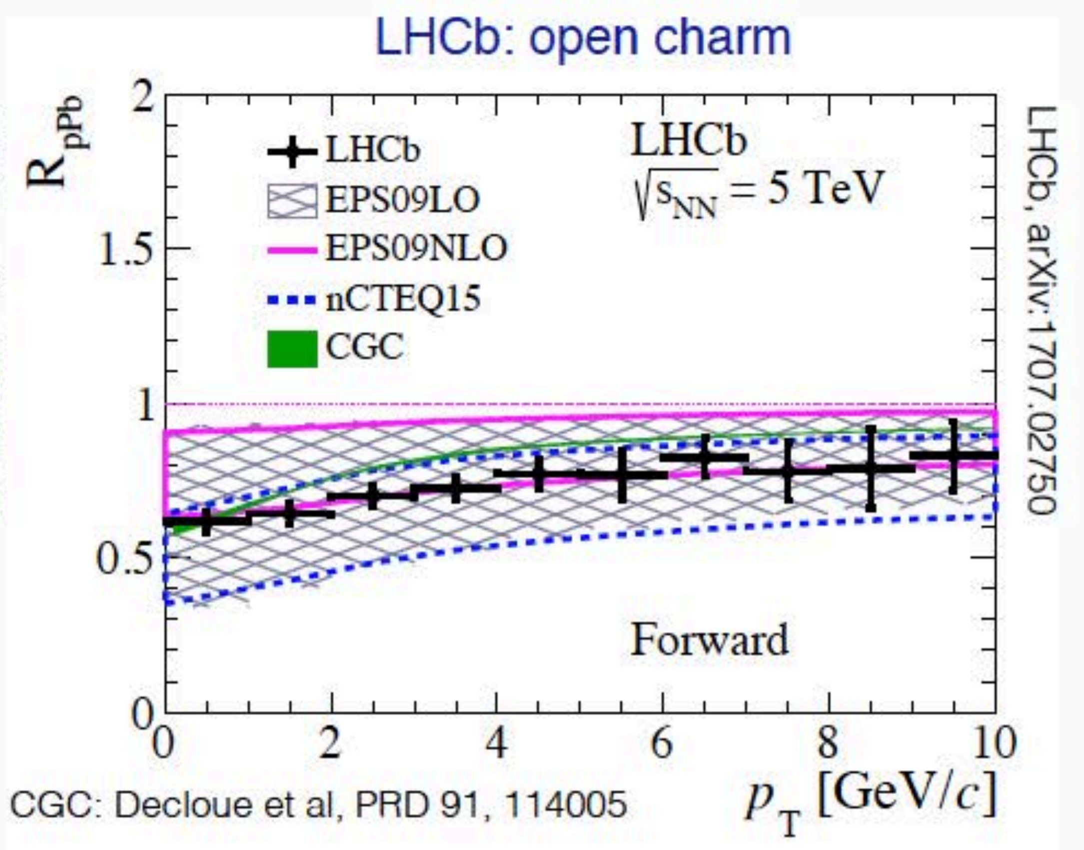


- **Hadron suppression on forward (proton-going) side at low p_T.**
- J/ψ yield: described by nPDFs nor by a CGC calculation
- Uncertainties on:
  - Production mechanism (x sensitivity etc.)
  - Other nuclear modifications (e.g. energy loss, thermalization in pA?)

Difficult to obtain conclusive data by hadrons only.

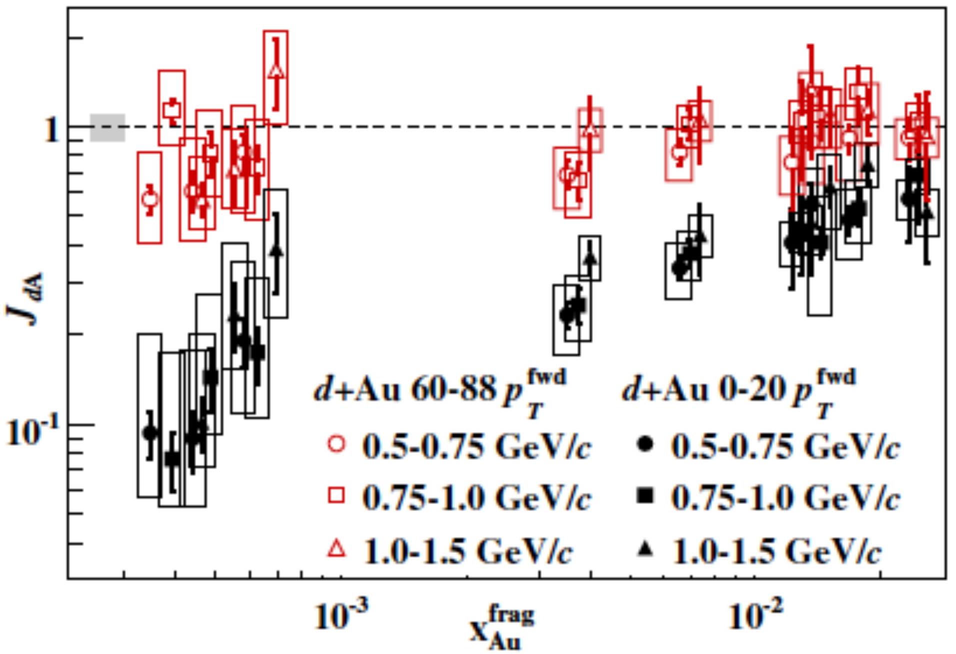
Open charm at forward rapidity





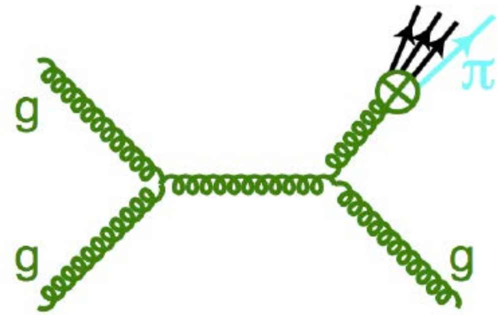
- Significant reduction of open charm yield at forward rapidity seen
- Compatible with nuclear PDFs (shadowing) and CGC calculations

π^0-π^0 correlation at RHIC



PRL 107, 172301 (2011), PHENIX

$$J_{AB} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\sigma_{AB}^{pair} / \sigma_{AB}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

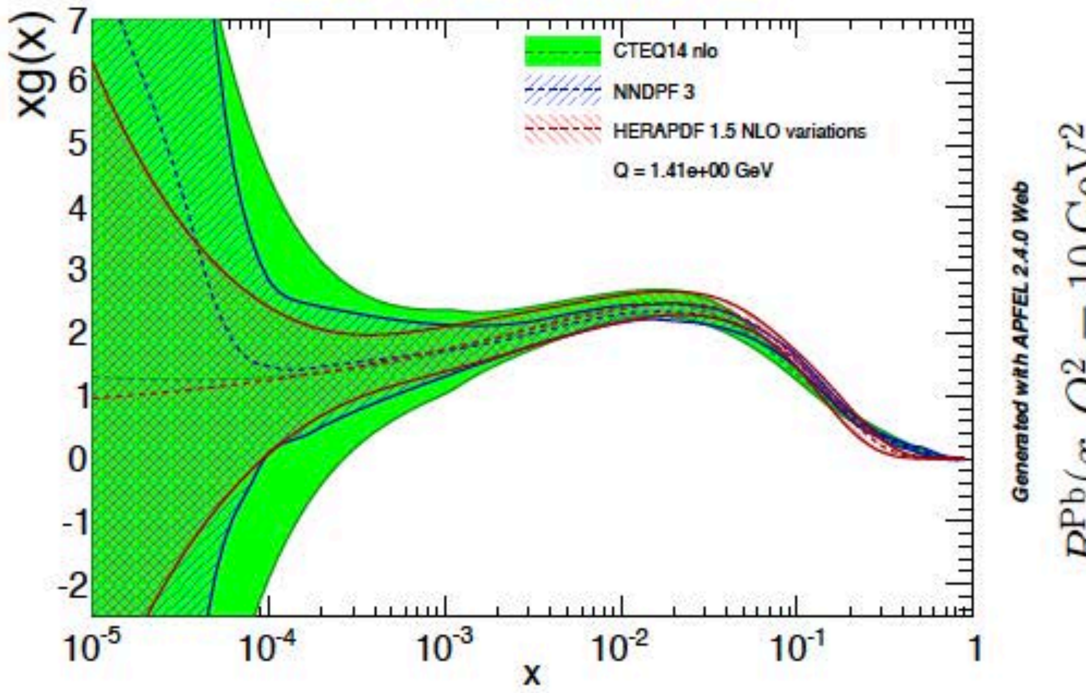


- π^0-π^0 correlations w/ p_T and rapidity cut on near and away side jets.
  → tight constraint on x_2 and Q^2 of hard process.
- J_{dA}: correlated pair yield suppression factor on away side.
  - x_2 like property: $$\boxed{x_{Au}^{frag} = (\langle p_{T3} \rangle e^{-\langle \eta_3 \rangle} + \langle p_{T4} \rangle e^{-\langle \eta_4 \rangle}) / \sqrt{s_{NN}}}$$
  - Strong suppression at low x, consistent with CGC expectation.
  - Little or no suppression for peripheral.

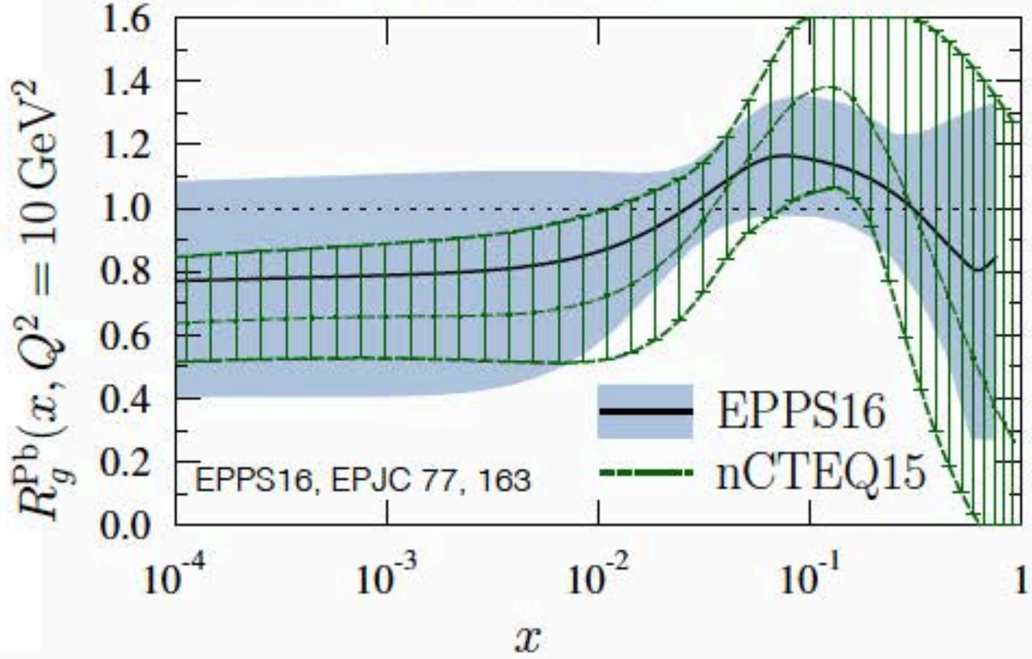
3. Clearer probes for gluon density in a hadron collider

Gluon Densities at small x

Gluon density in proton



Gluon density in Pb nucleus



Even in the proton, (very) limited information about gluons at $x < 10^{-4}$

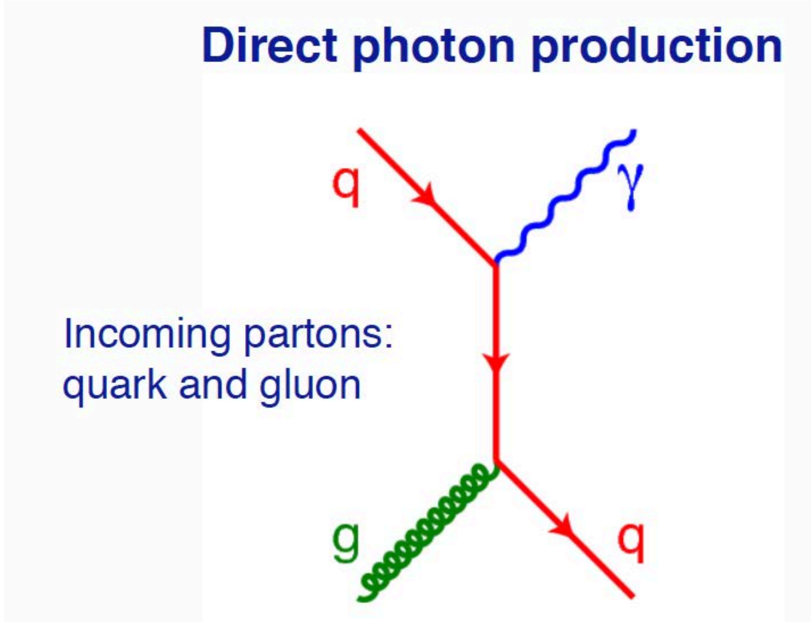
Ratio Pb/p has large uncertainties over broad x range

Photons vs. Charm

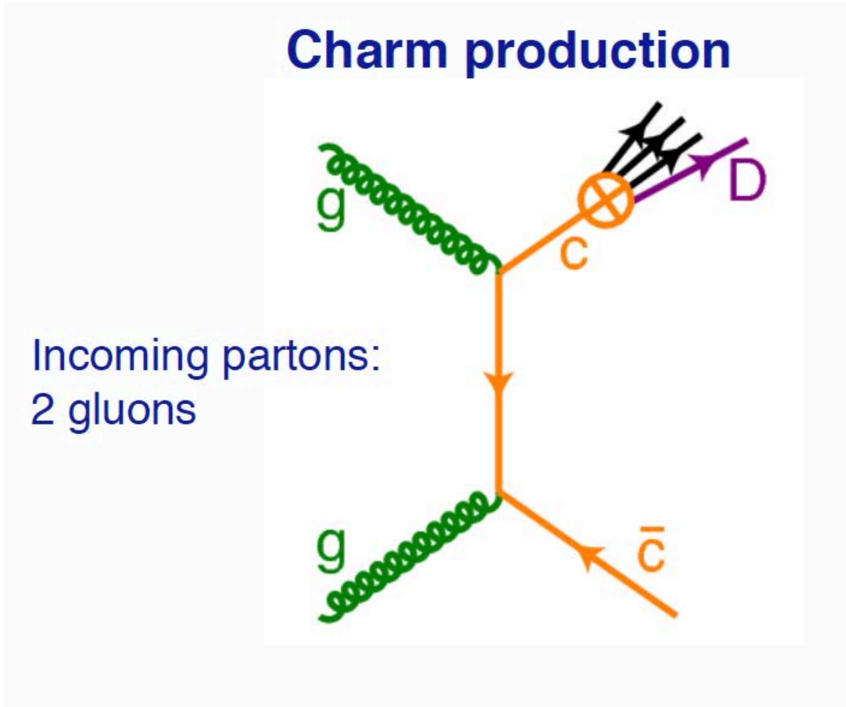
Direct photons can provide strong constraints on the gluon PDFs

- LO dominant process: quark-gluon Compton.
- Fragmentation photon can be suppressed by isolation cut.

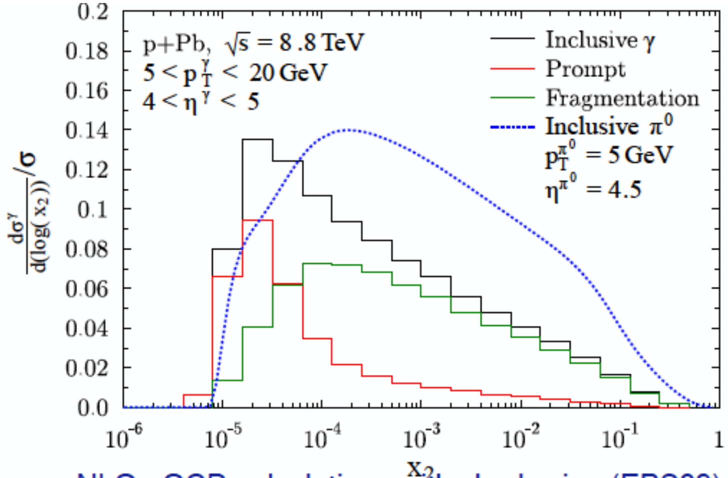
→Direct access to the gluon PDFs and saturation physics



Charm production
- also directly sensitive
- but fragmentation reduces kinematic constraint



Why photos?

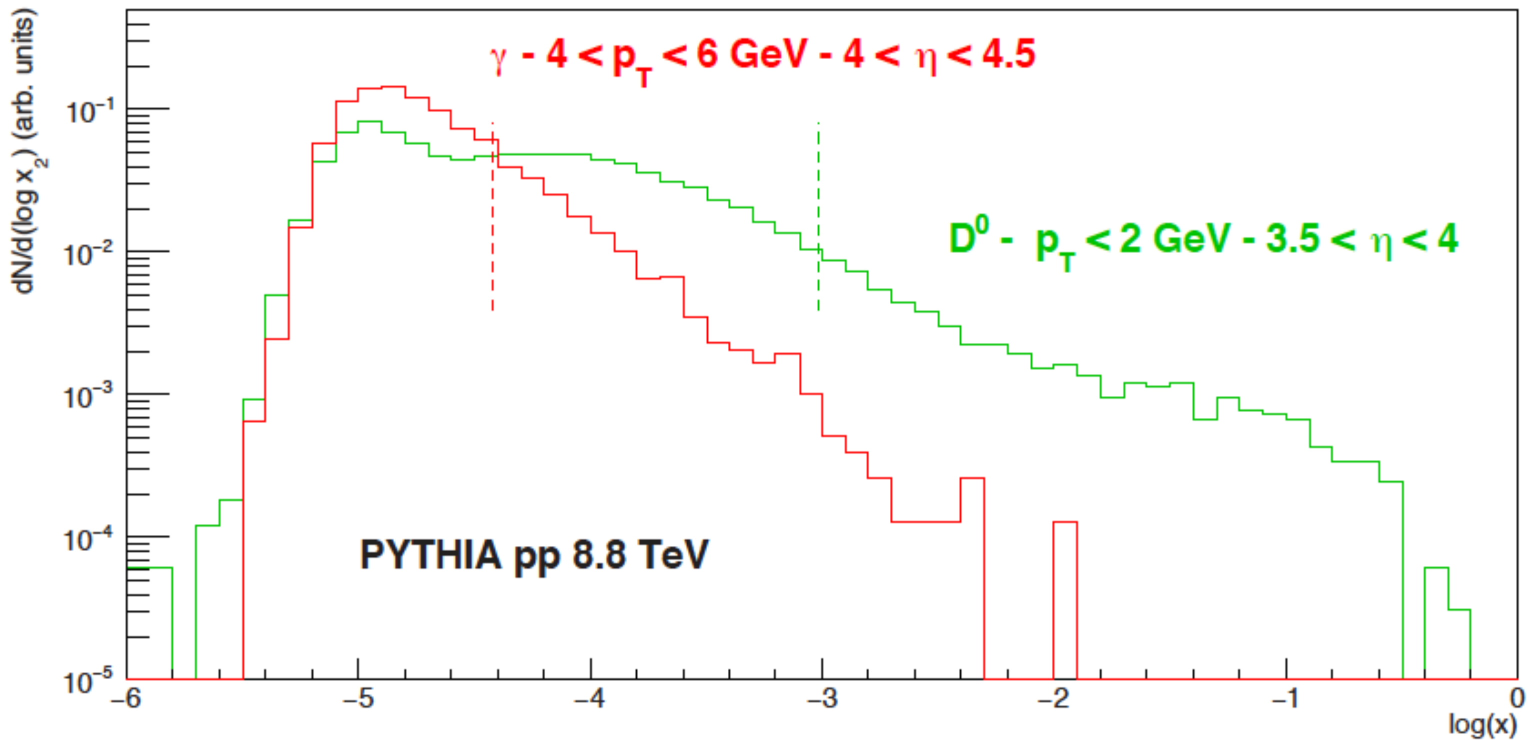


NLO pQCD calculations with shadowing (EPS09)
Helenius, Eskola, Paukkunen, arXiv:1406.1689

- **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 with expected luminosity.

- **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)?

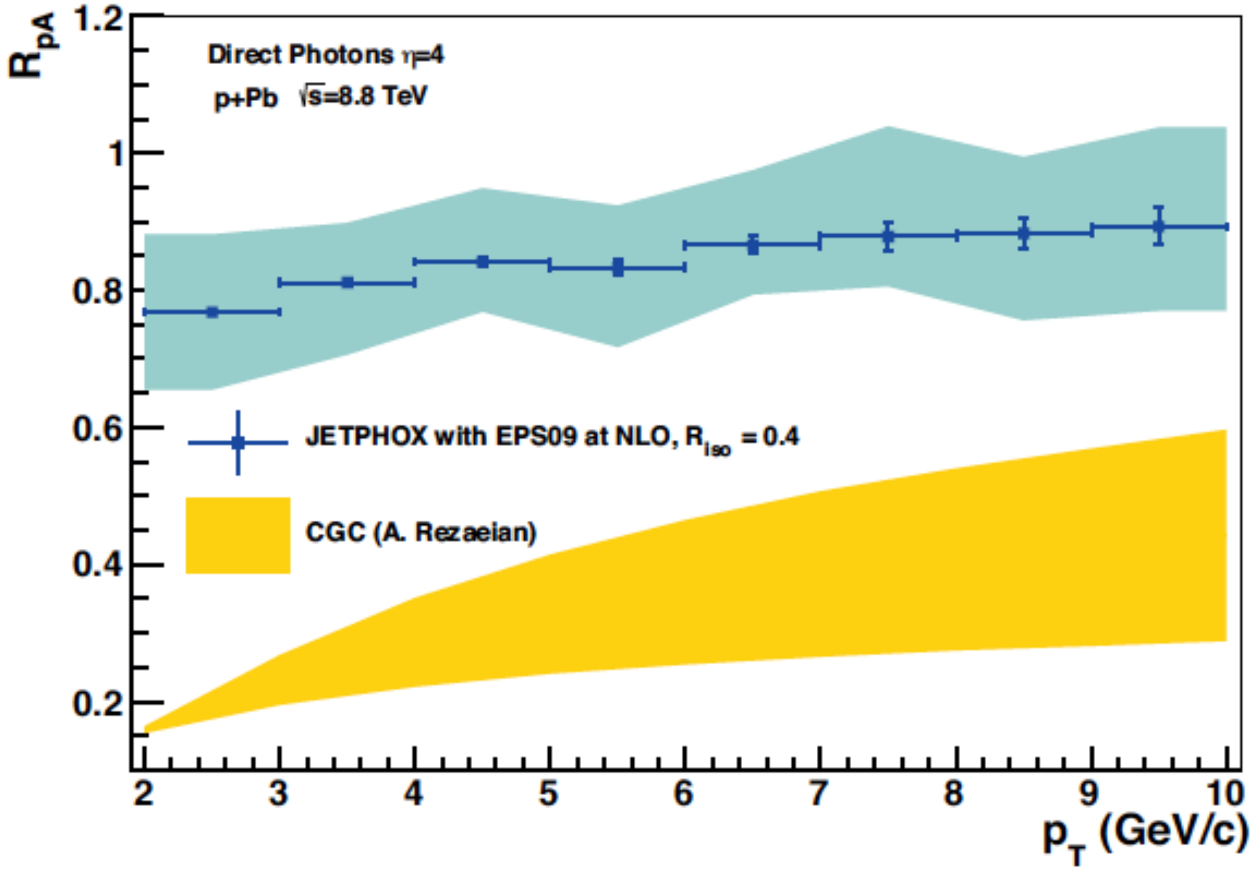
x-Sensitivity: photons vs D



x_2 distribution for forward production

- 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.

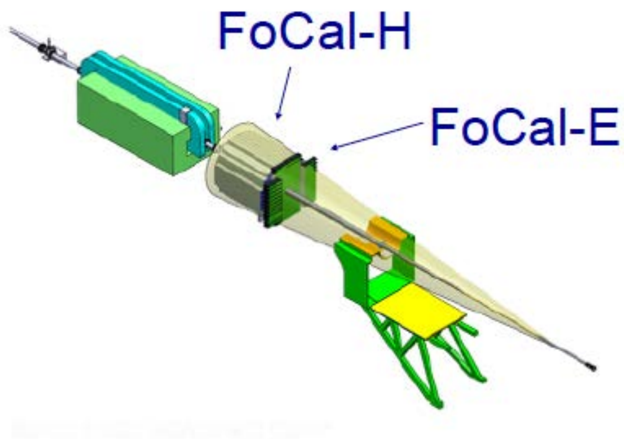
4. Physics program of Forward Calorimeter at LHC

ALICE FoCal Project

FoCal = Forward Calorimeter:

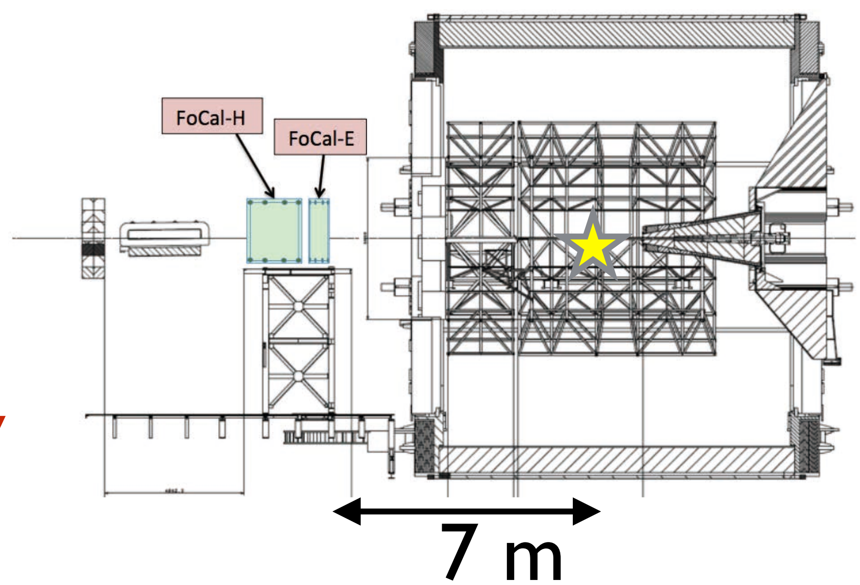
FoCal-E: EM Calorimeter
FoCal-H: Hadronic Calorimeter

★7 m away from the interaction point.
★ main challenge: separate γ/π^0 at high energy
★ Si-W calorimeter, effective granularity ≈ $1 mm^2$

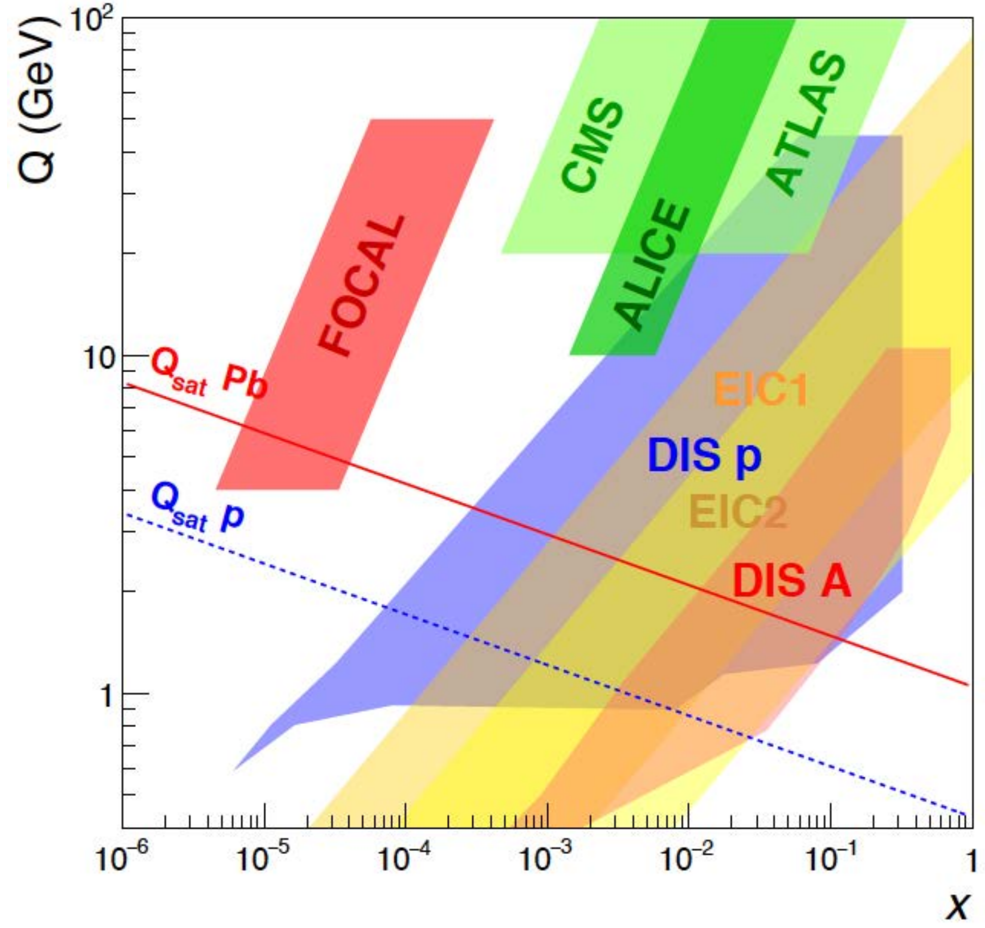


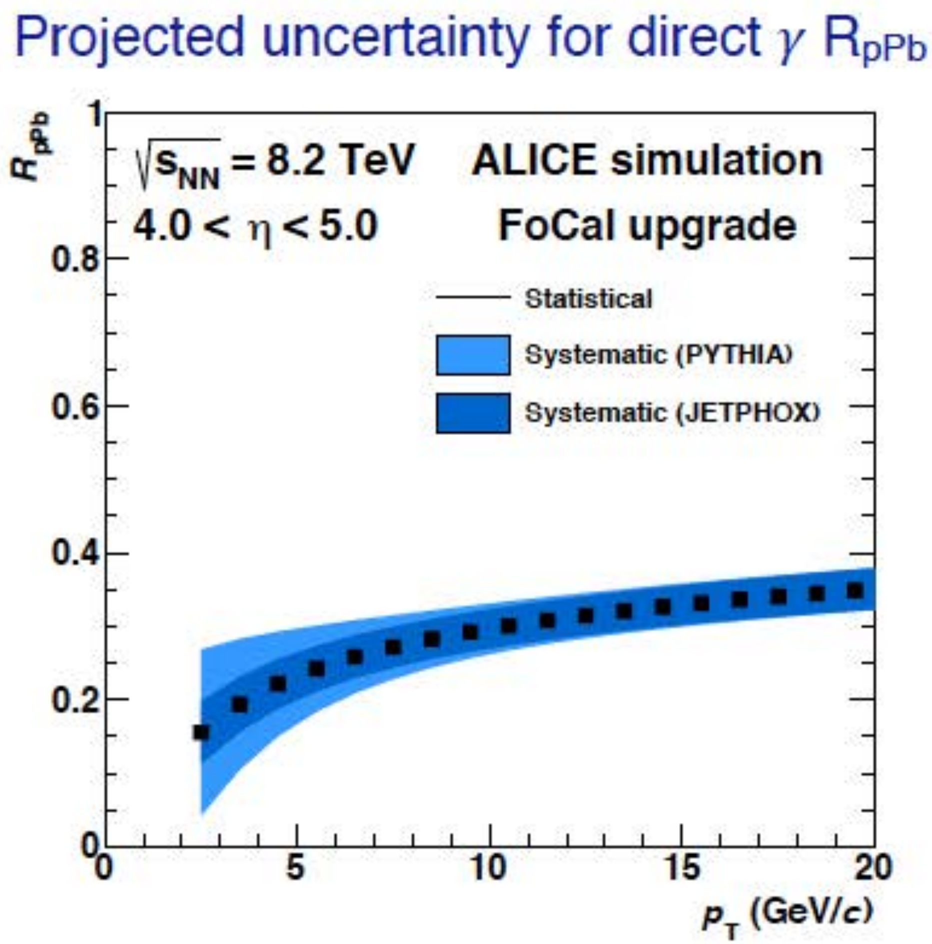
$3.2 < \eta < 5.3$

- **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 production, baseline**
  - (same as p-Pb)
- **Pb-Pb: medium density at forward y**
  - 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)



Kinematic reach by FoCal, and photons





Forward measurements at LHC access unique rage in x and Q²

FoCal: direct photons and hadrons (π⁰), jets

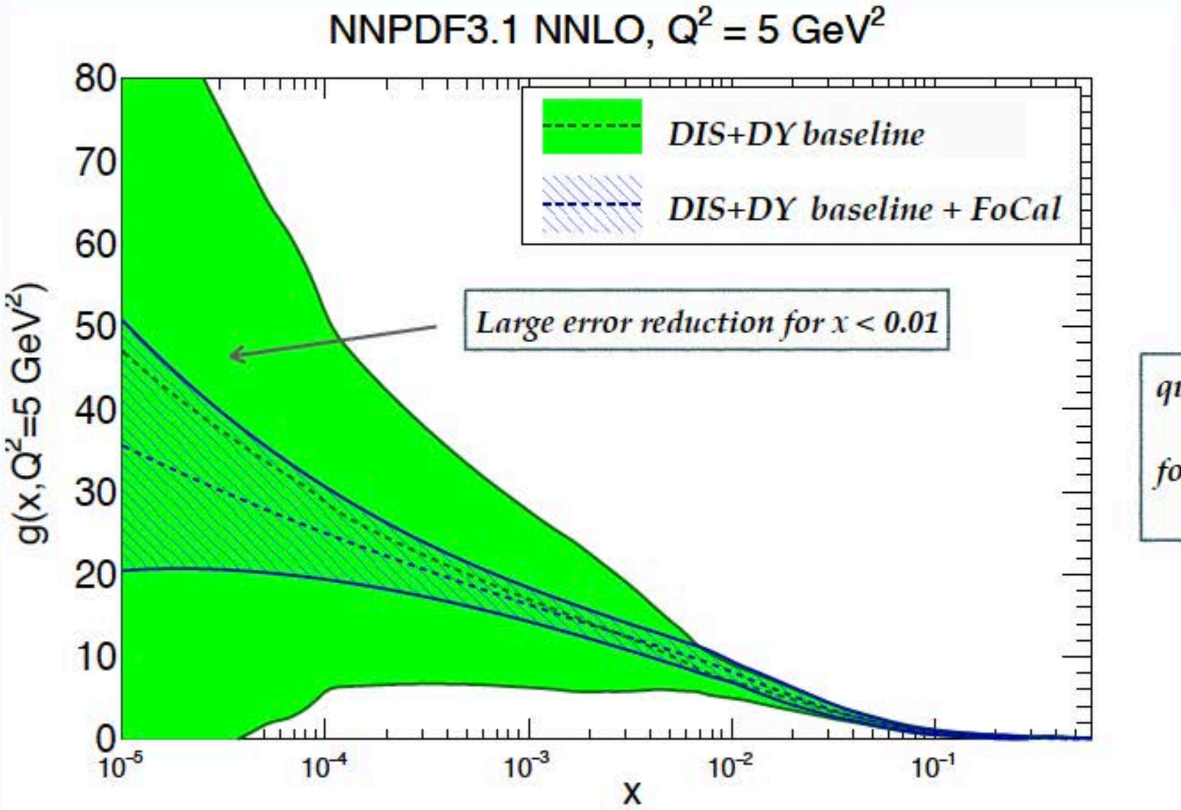
Others: hadronic probe only

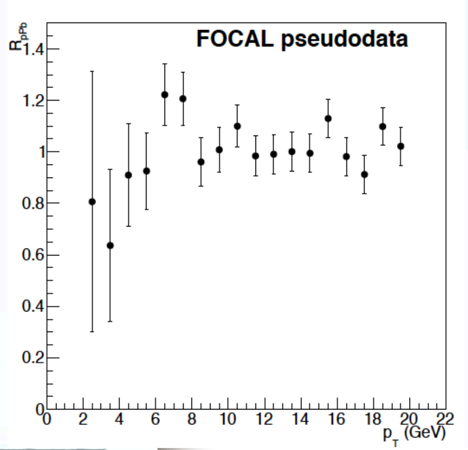
FoCal pseudo data, impact on gluon nPDF

Impact on a ``nuclear'' dataset

When added on top of a **nuclear-like dataset** (DIS and DY data only) the impact of the FoCal data becomes much more significant, since there is no "nuclear HERA"

Assuming that **collinear DGLAP factorisation** works, a determination of the **nuclear modifications of the gluon PDF at the 10% level down to x=10-4** would be possible





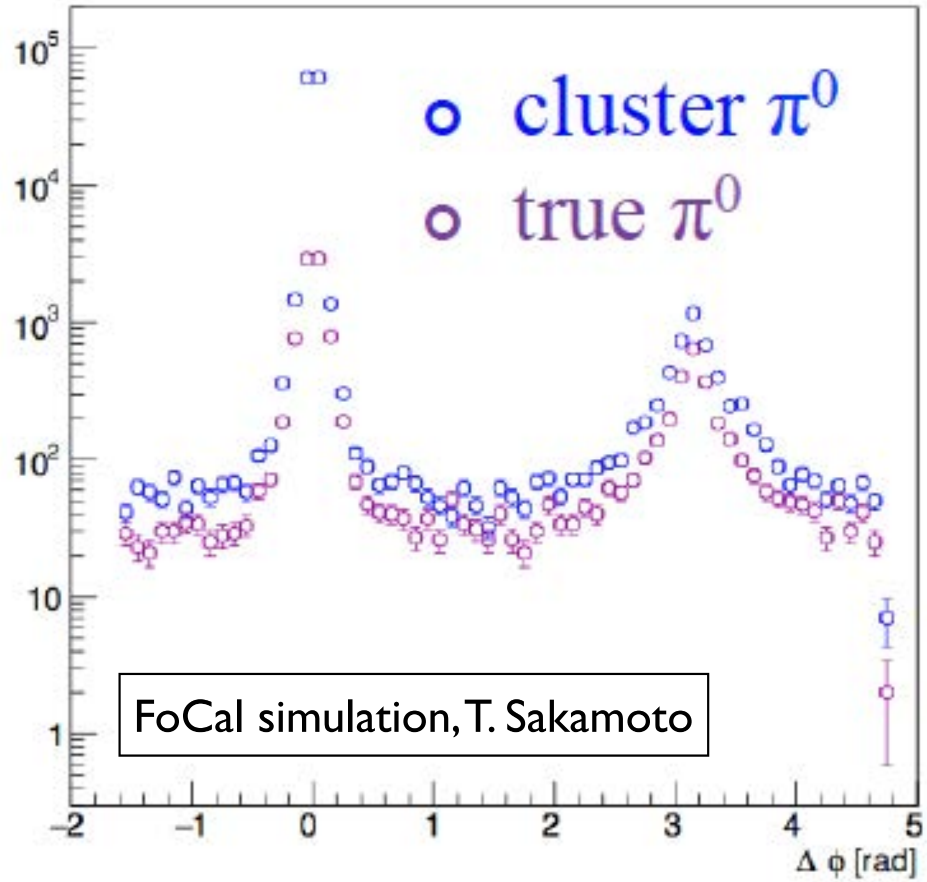
quantifies impact of FoCal for a nuclear PDF analysis!

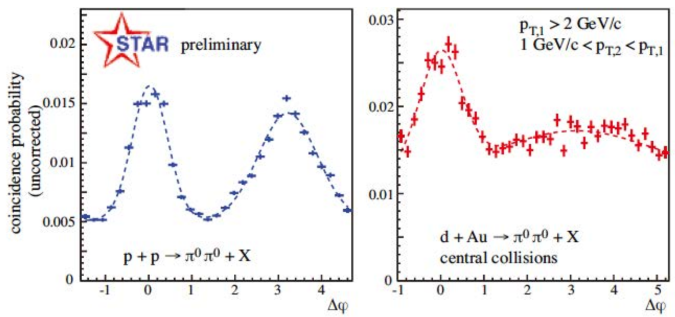
Juan Rojo 13 ALICE FoCal meeting, CERN, 27/3/2018

Workshop: Low-x gluon structure of nuclei and signals of saturation at LHC (CERN, Mar. 27, 2018)
https://indico.cern.ch/event/713518/

π^0-π^0 correlation and jet measurement by FoCal

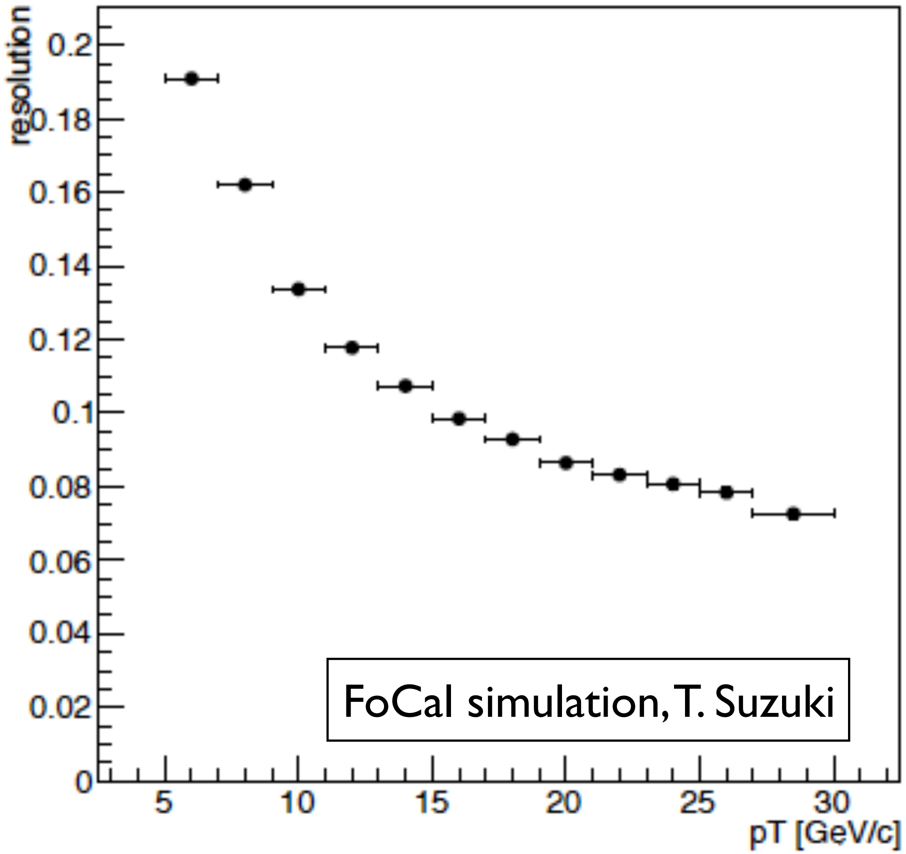
π^0-π^0 correlations

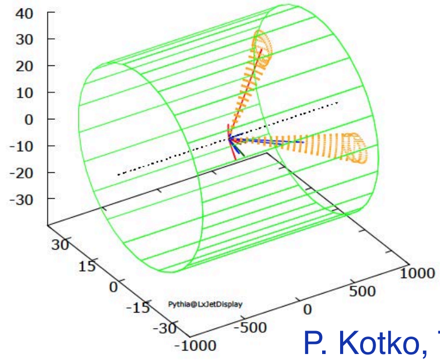




E. Braidot et al. (STAR collaboration),arXiv:1005.2378

Jet p_T resolution

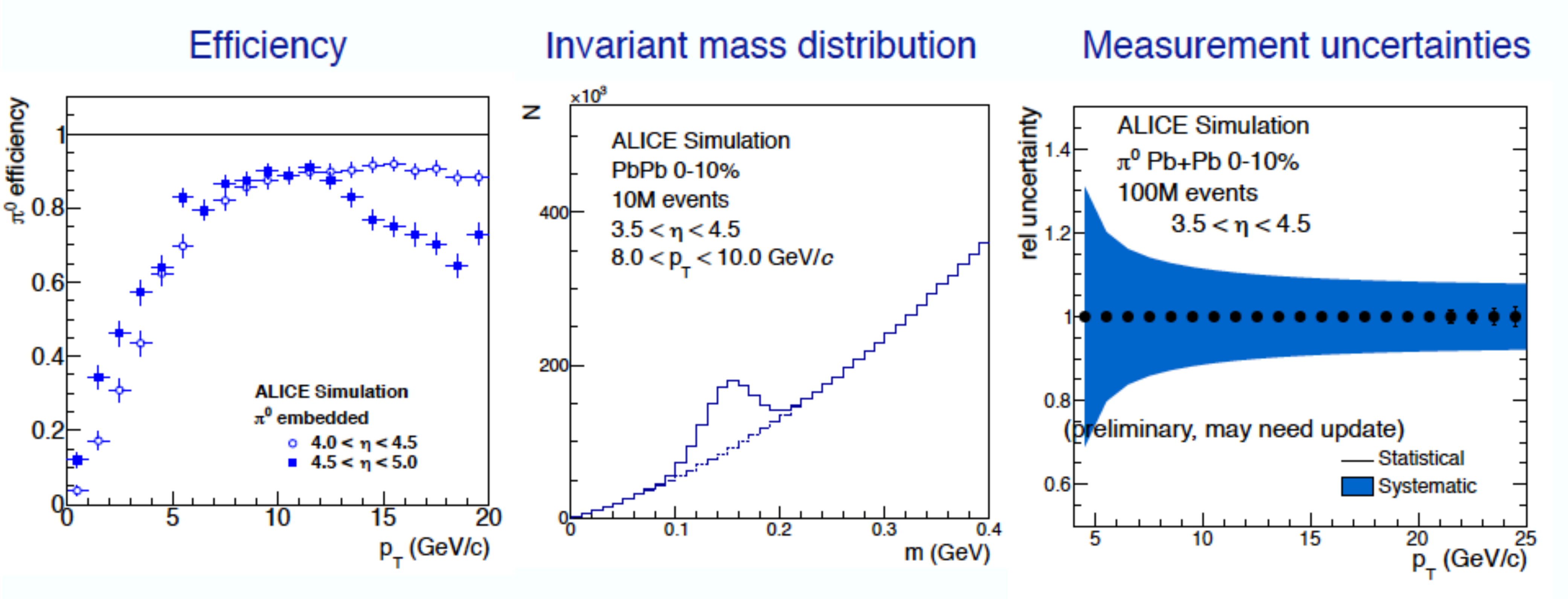




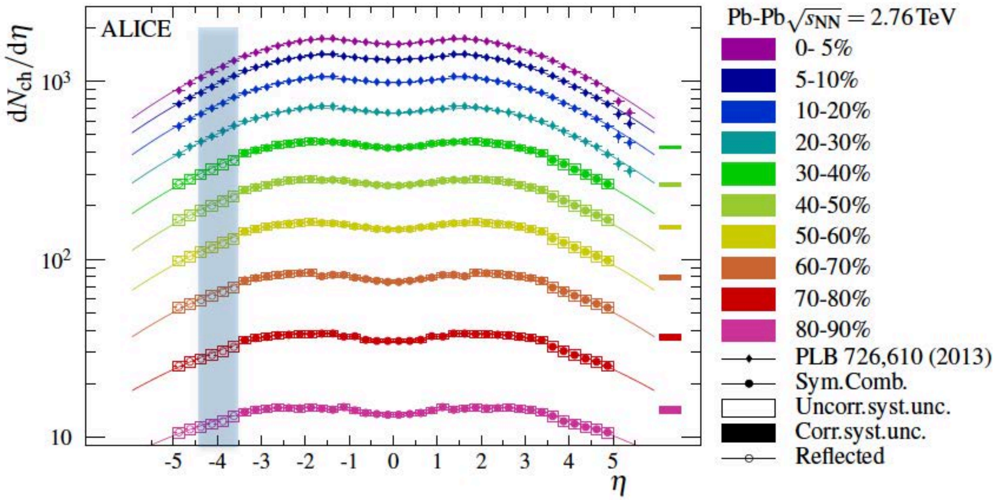
P. Kotko, Talk at RBRC workshop (2017)

Measuring π^0 in Pb-Pb events

Pb-Pb program:
Nuclear modification at forward rapidity and high p_T

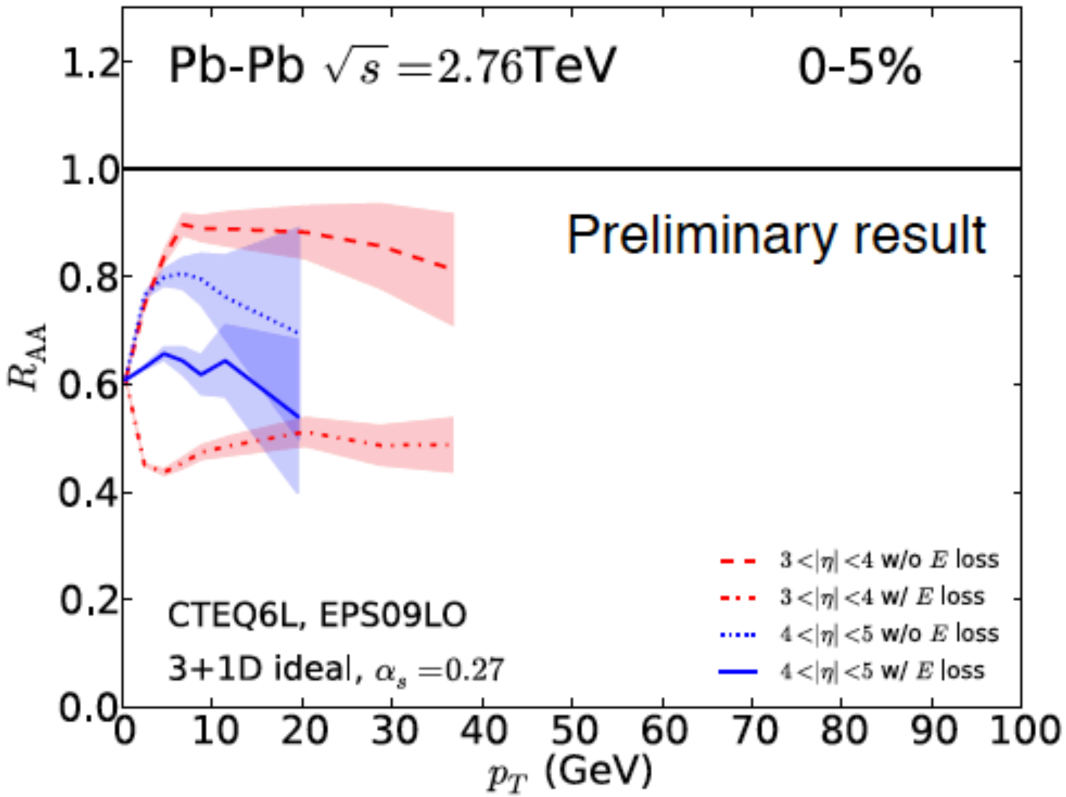


Longitudinal medium flow at forward rapidity



Density at η~4 is about
0.8 times mid-rapidity

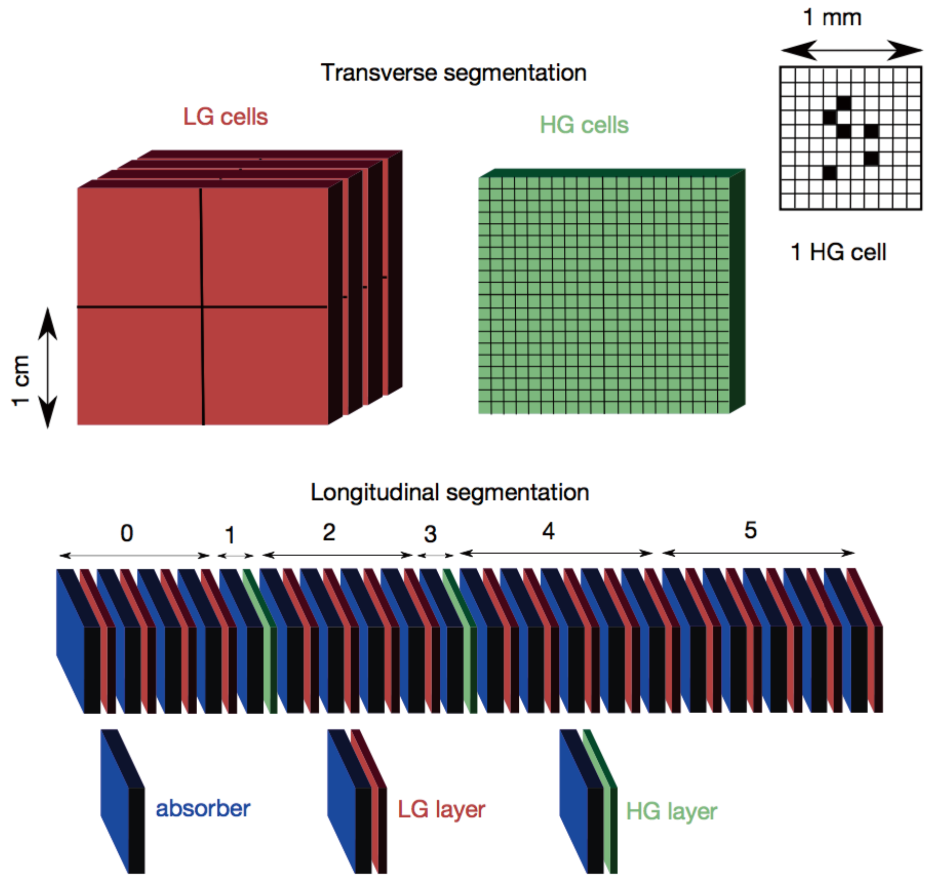
C Park, S Jeon etc al



First look in MUSIC
shows strong increase
of R_{AA} at forward rapidity

5. Forward Calorimeter Detector R&D

FoCal-E prototype design



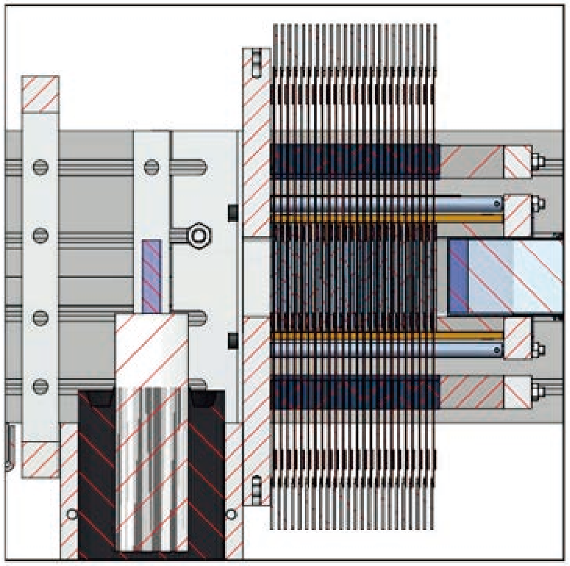
- **LG segments**
  - 4 (or 5) layers
  - Si-pad with analog readout
  - cell size 1 x 1 cm^2
  - longitudinally summed
- **HG segments**
  - single layer
  - CMOS-pixel (MAPS*)
  - pixel size ≈ 30 x 30 μm^2
  - digitally summed in 1mm^2 cells

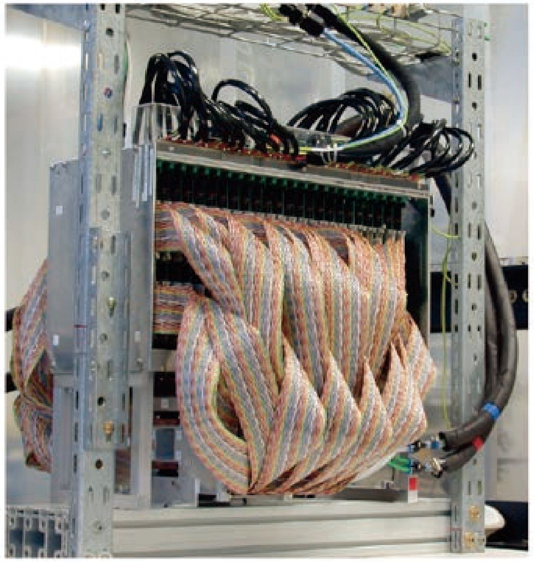
*MAPS = Monolithic Active Pixel Sensor

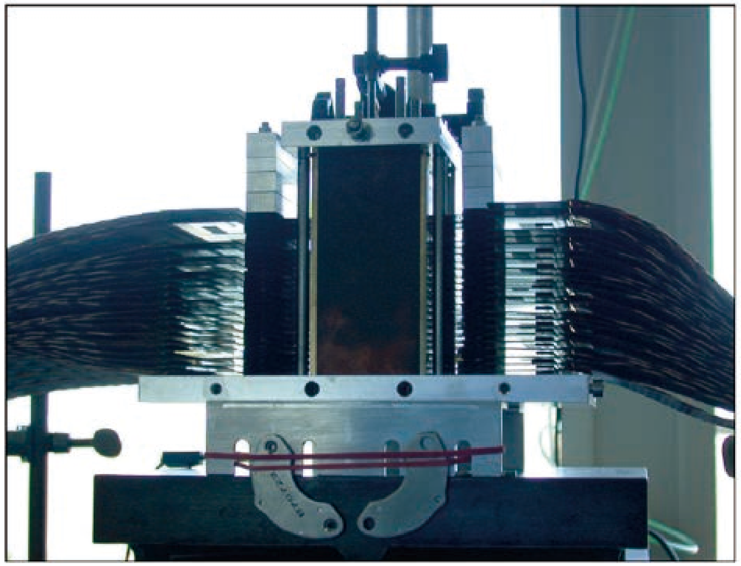
- **Si/W** sandwich calorimeter layer structure:
  - W absorbers (thickness $1X_0$)+ Si sensors
- Longitudinal segmentation:
  - 4 segments low granularity (LG)
  - 2 segments high granularity (HG)

* 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 (NL, NO)

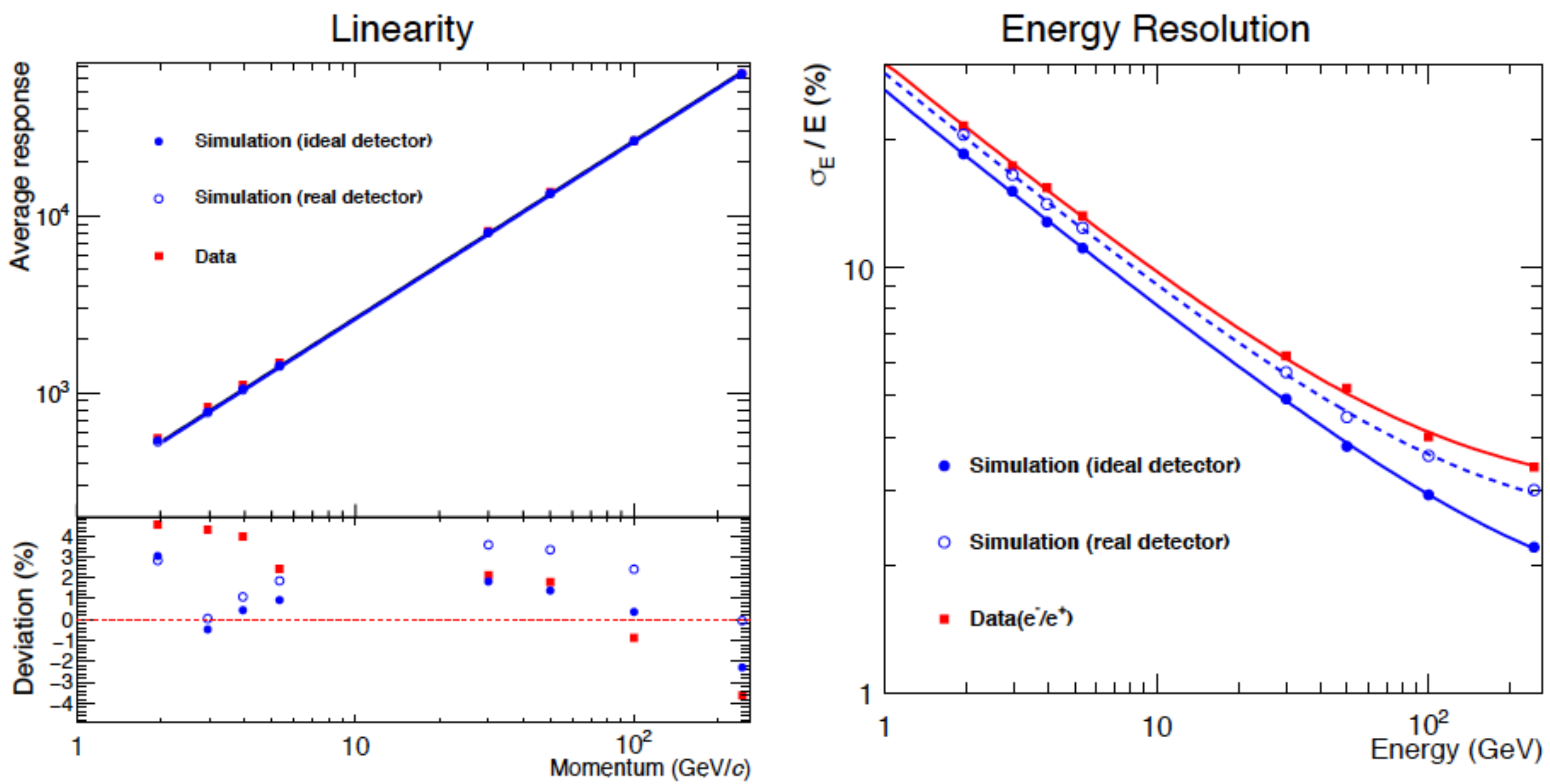






- 4x4 cm^2 cross section, 28 X_0 depth
- 24 layers: W absorber + 4 MAPS each
- MIMOSA PHASE 2 chip (IPHC Strasbourg)
  - 30 µm pixels
  - 640 µs integration time (needs upgrade – too slow for experiment)
- 39 M pixels total
- Test with beams at DESY, CERN PS, SPS

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.

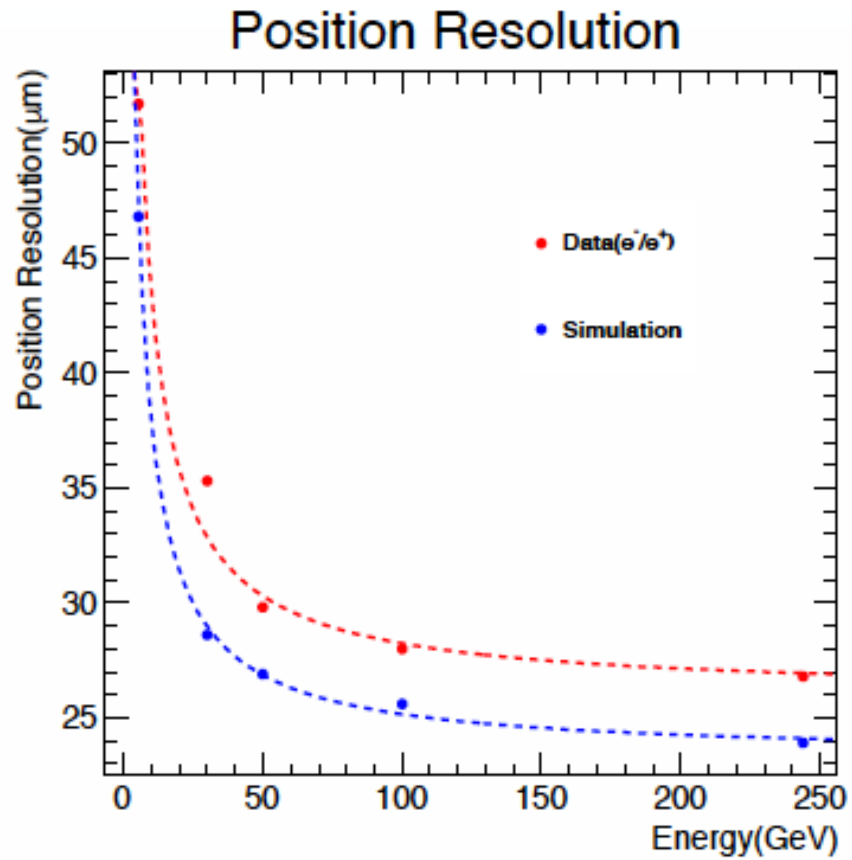
High Granularity (HG) Prototype, MAPS (2)

Position resolution:

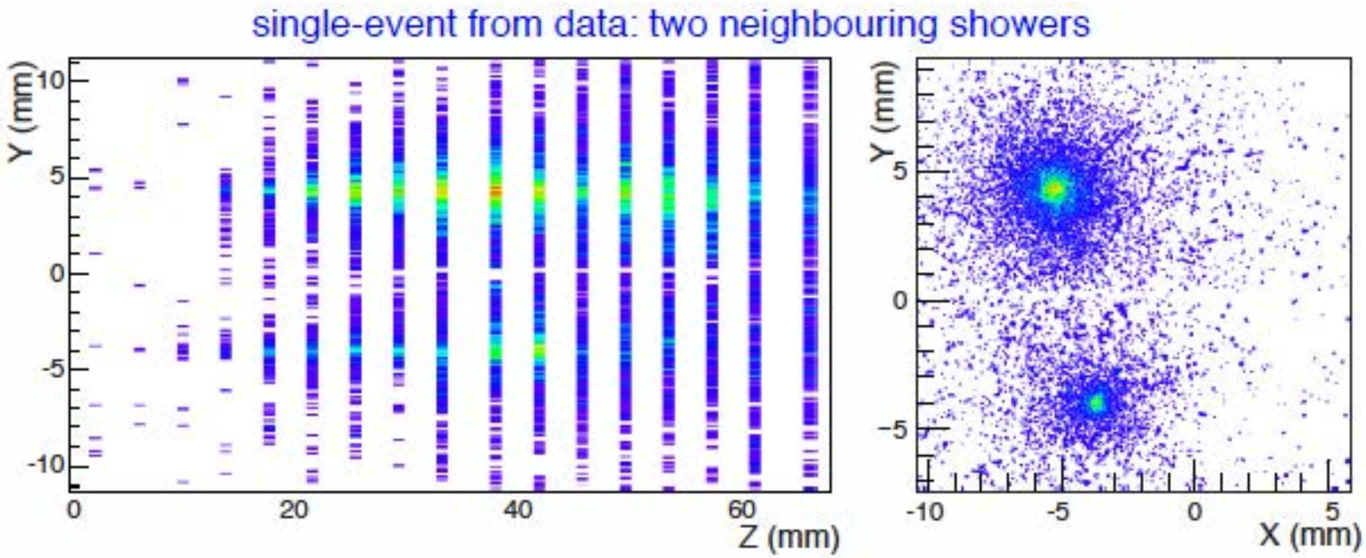
calculate difference of position from

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

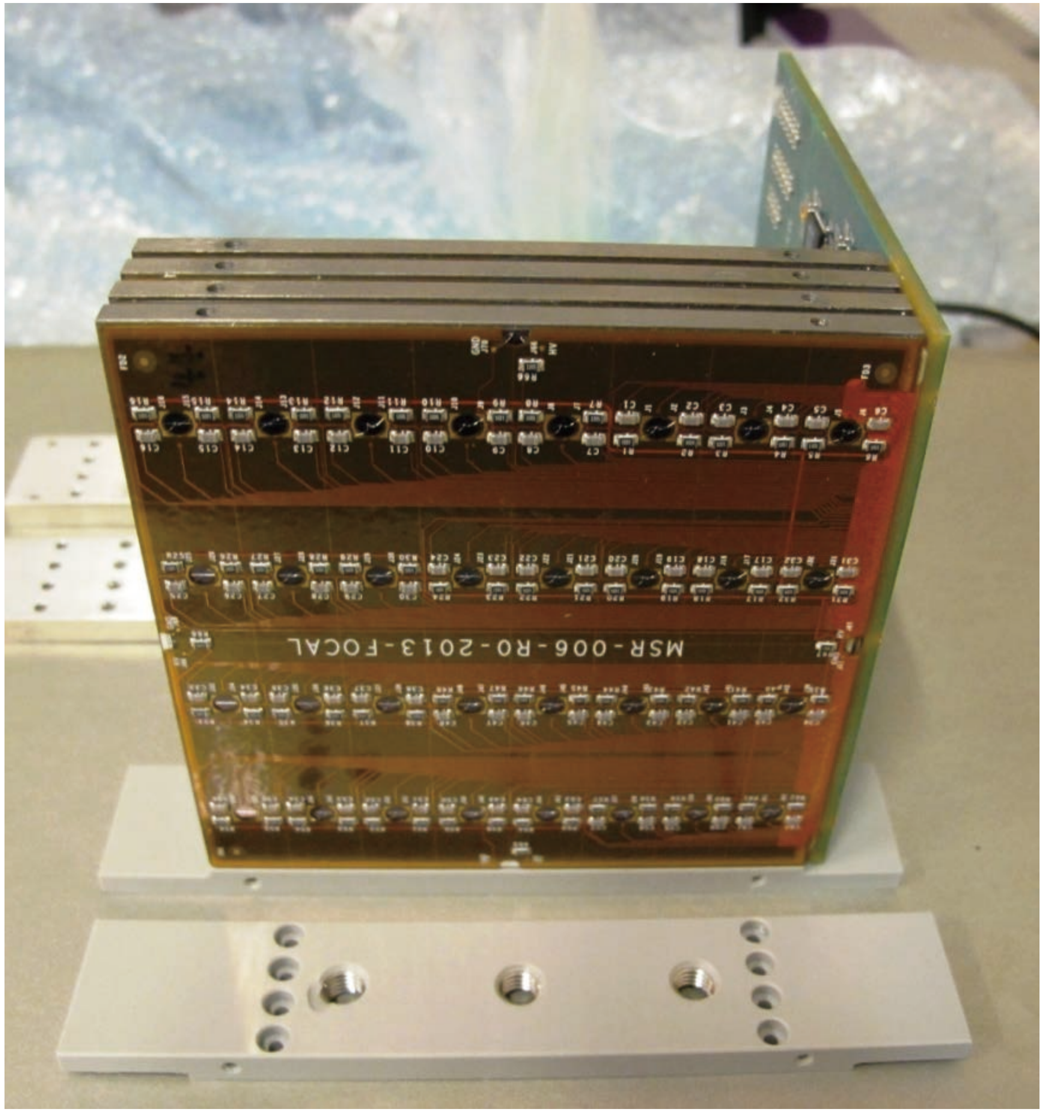
single shower position resolution obtained from width of residuals

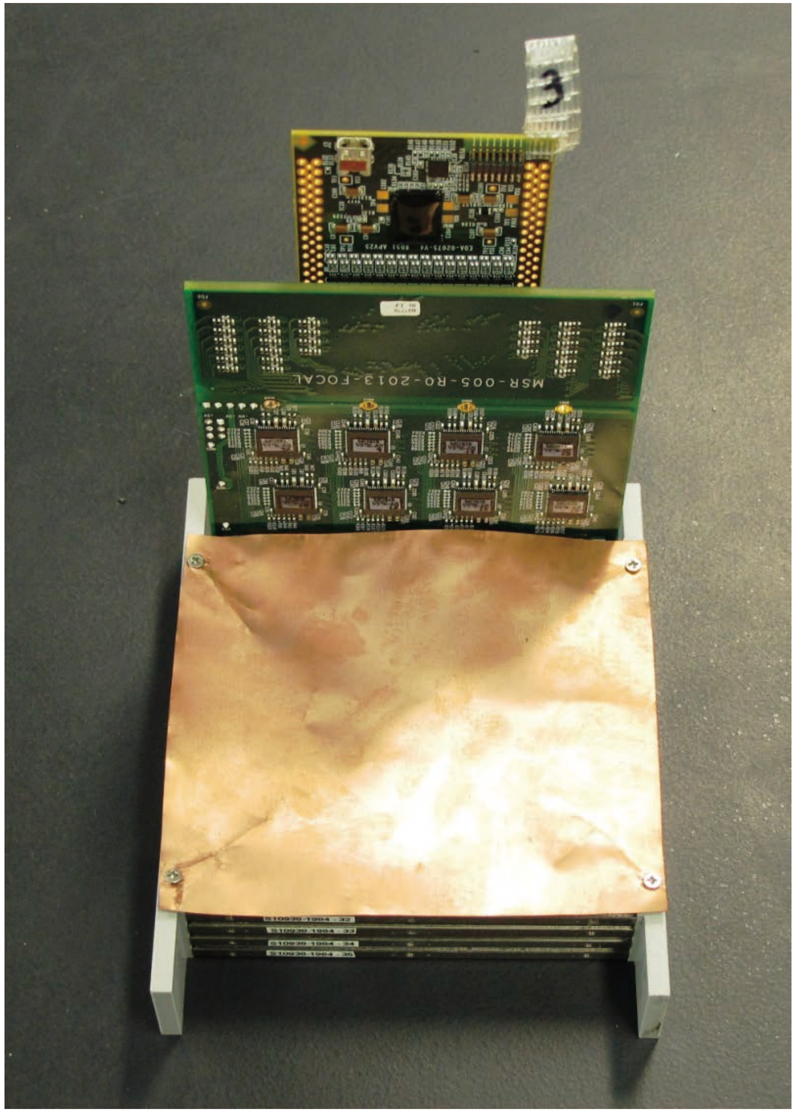


can provide excellent two-shower separation

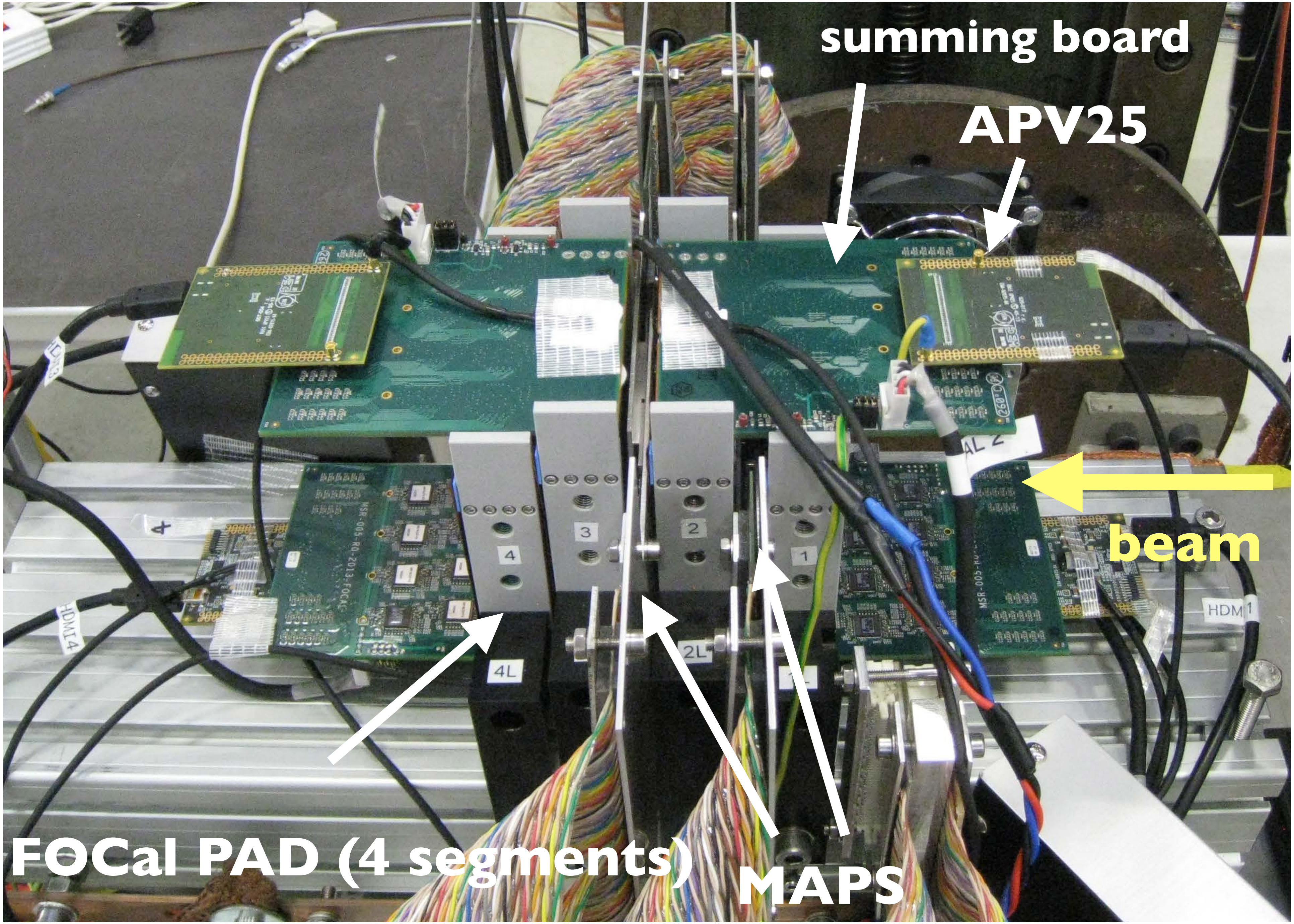


Low Granularity (LG) Prototype, PAD (JP, US)





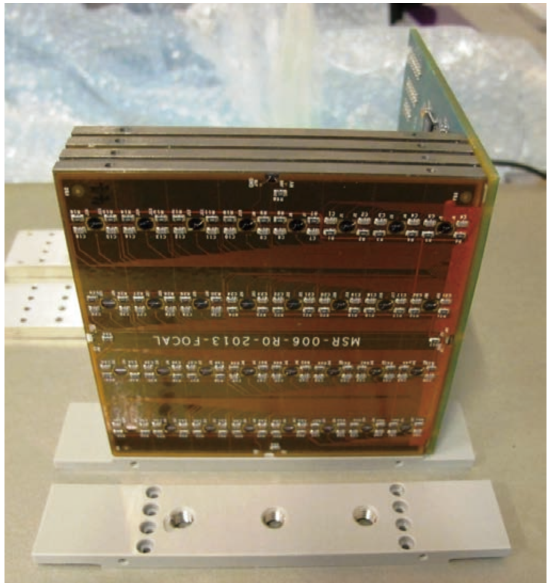
FoCal PAD proto type, 1 segment (ORNL, Tsukuba, CNS-Tokyo)

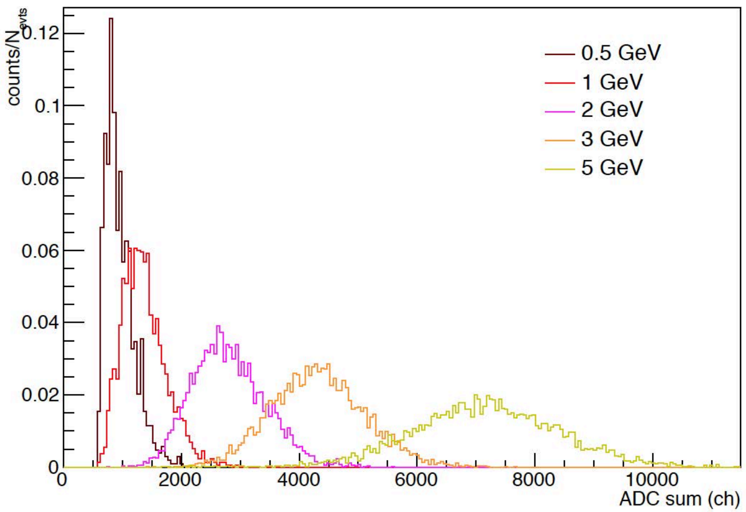


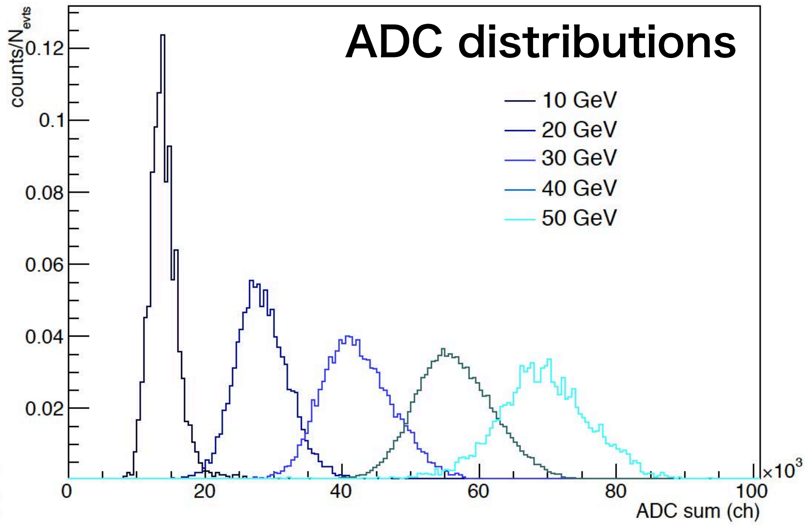
Test beam setup @ PS (same for SPS) in 2015

PAD perfomance at PS/SPS (2014, 2015, 2016)

D. Kawana, Y. Kawamura, T. Suzuki





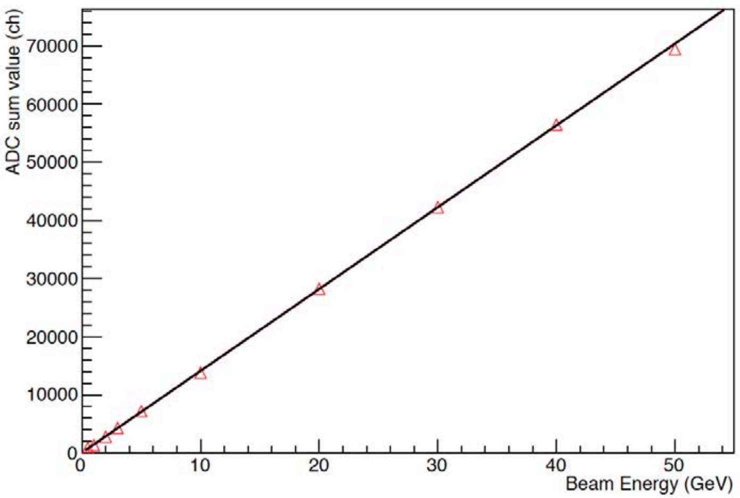


↑ **ORNL PAD prototypes**

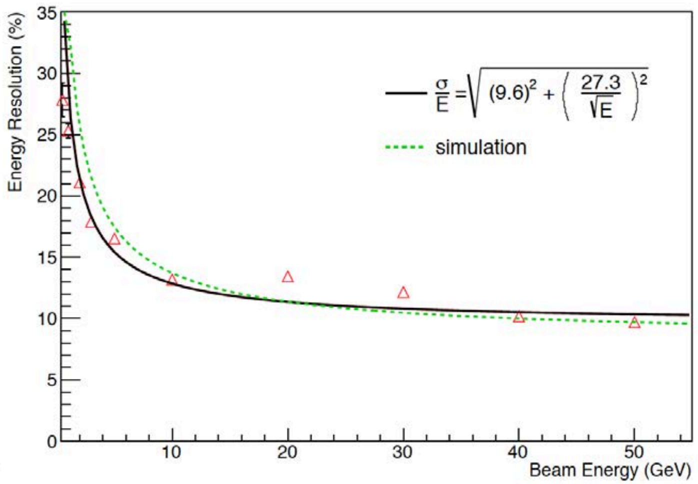
Tested by Tsukuba, Nara W. team, Utrecht, Indian team (2014-2016)

PAD (JP): APV+SRS is used for readout

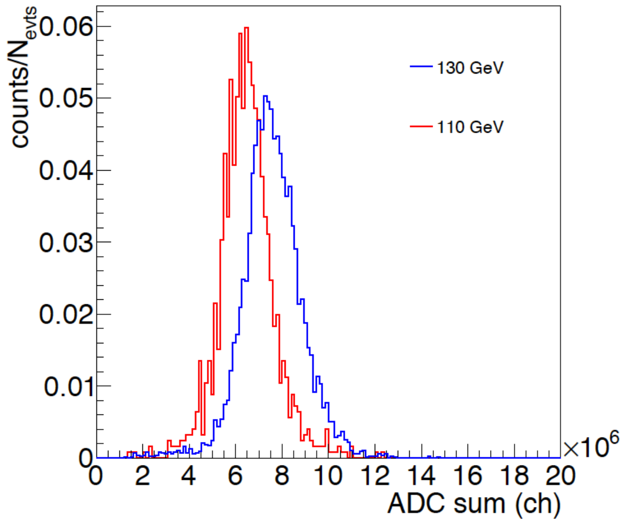
- **Prototype working as expected.**
- **NIM paper under preparation.**



Linearity

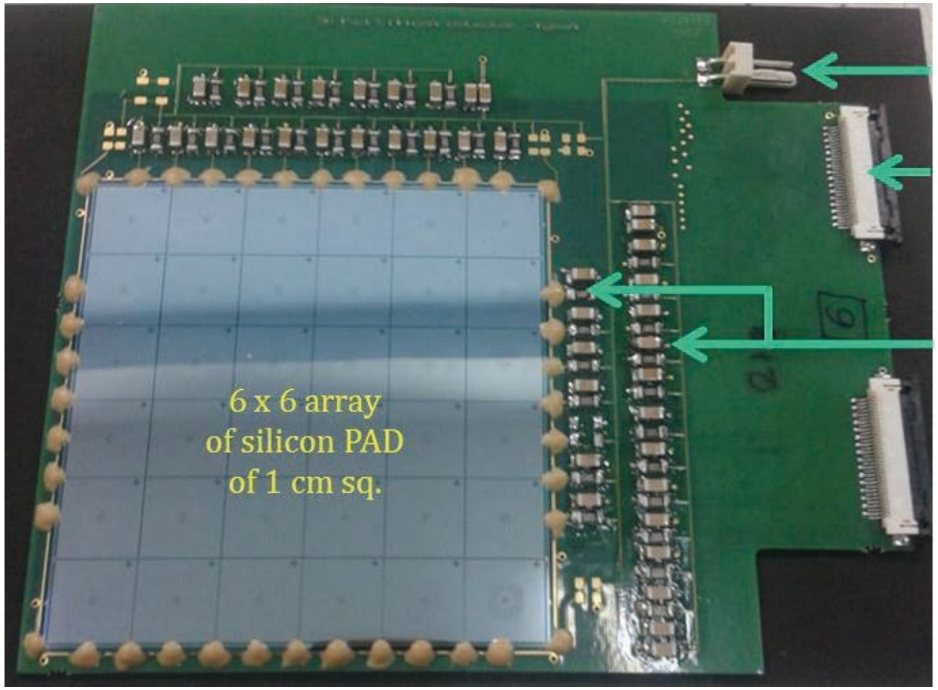


Energy resolution



ADC distributions

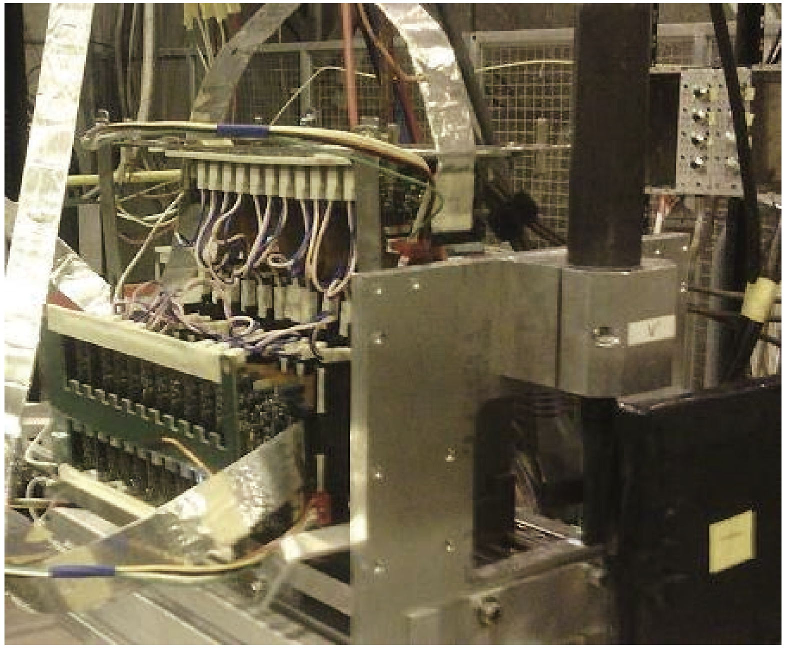
Low Granularity (LG) Prototype, PAD (India)

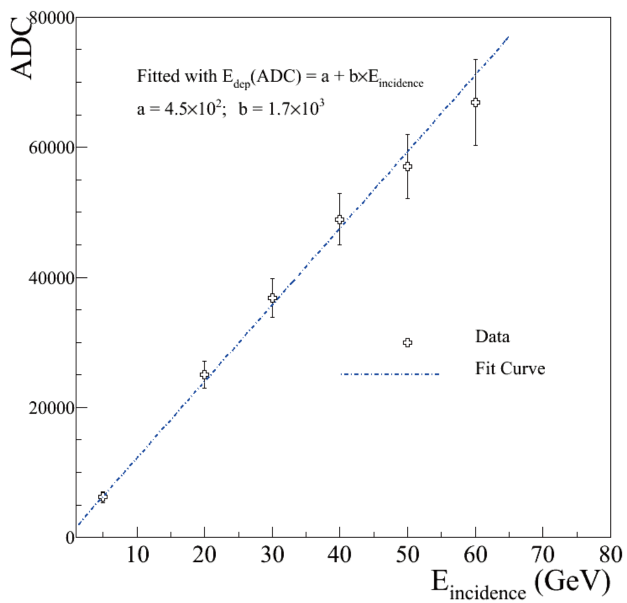


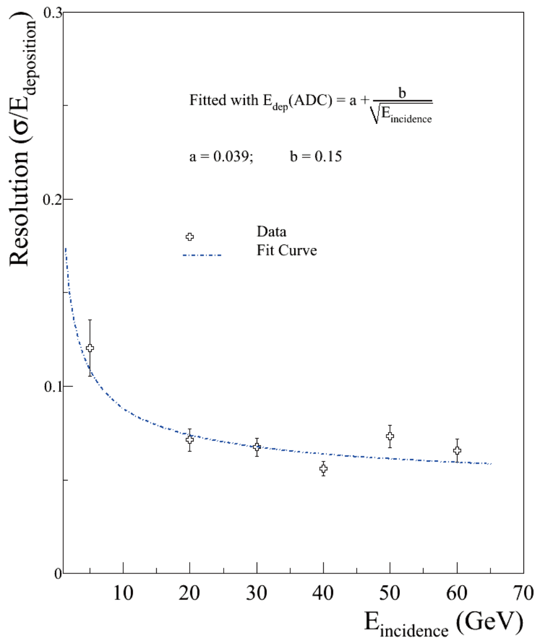
HV connector

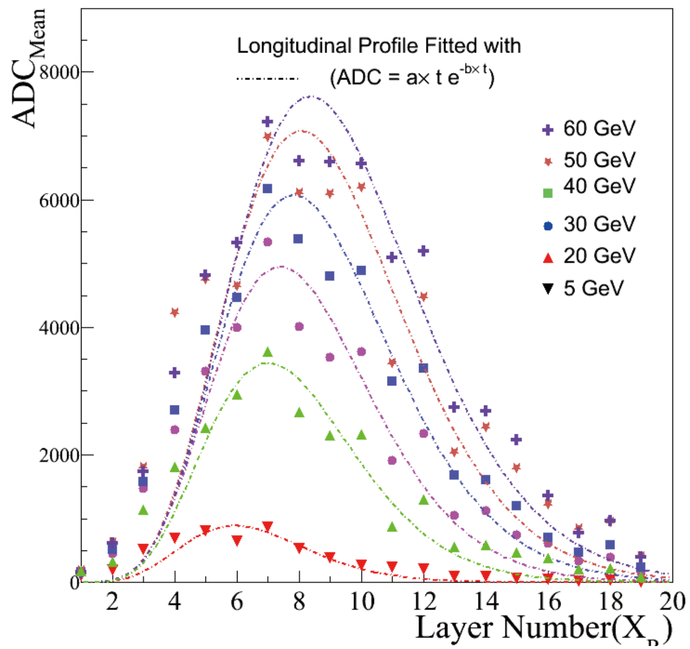
Connector for kapton cable to FEE boards

Bias resistors and capacitors





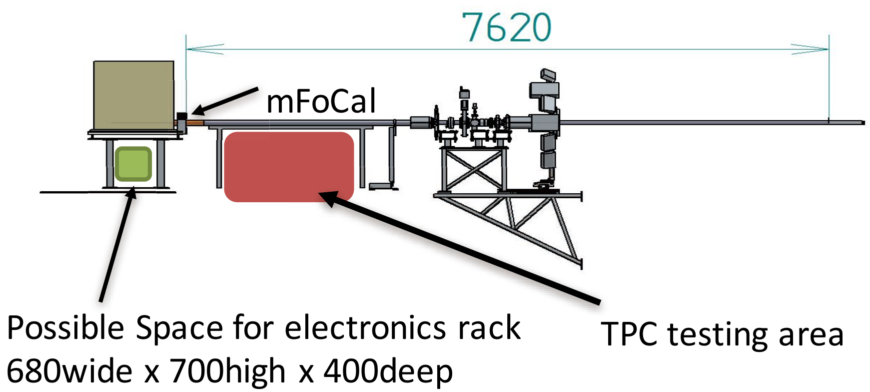


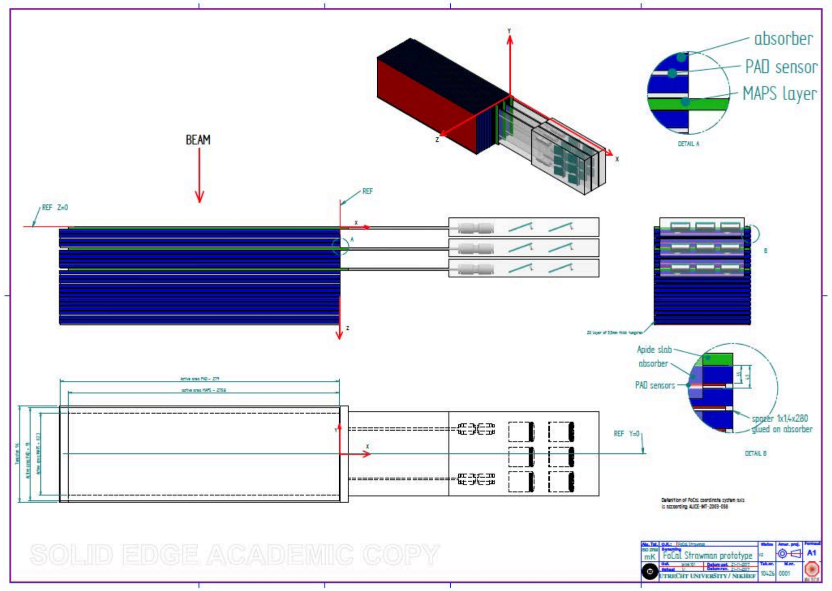


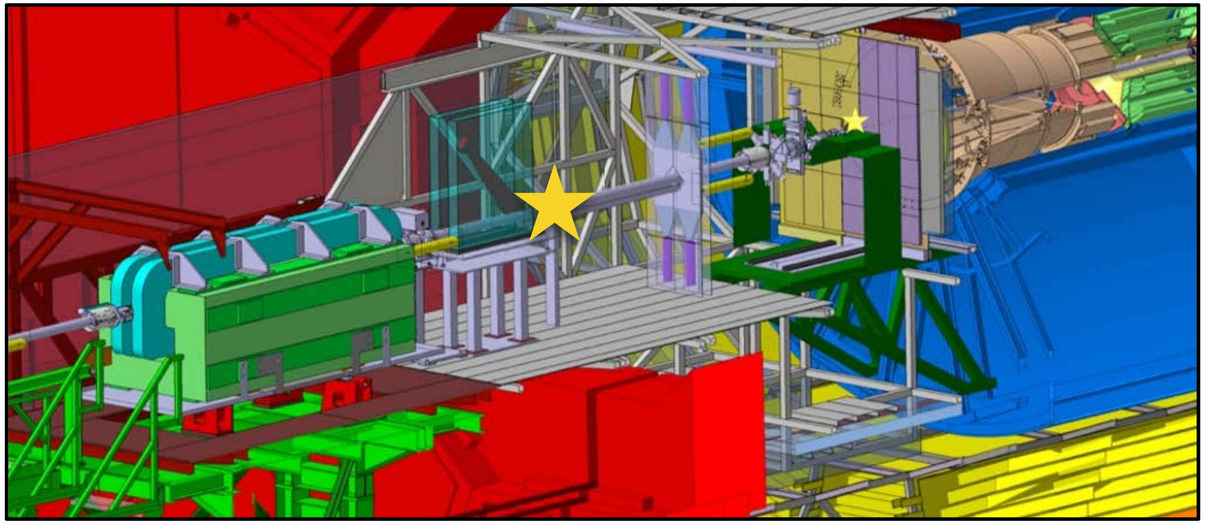
Good linearity and energy resolution for FoCal

Plan in 2018

- mini-FoCal production and test at PS/SPS, and under discussion to test in ALICE (7.6 m from IP)
- Three tower structure, EM-part.





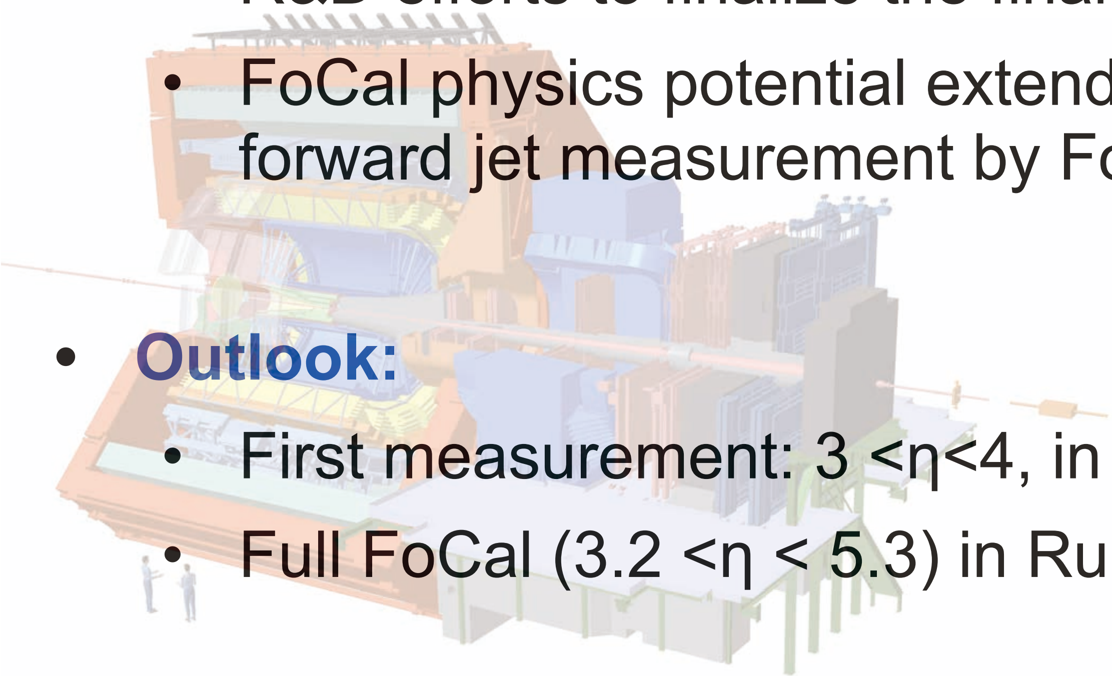


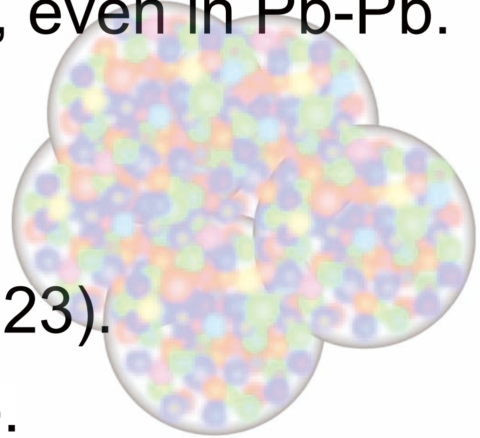
A. van den Brink

Summary

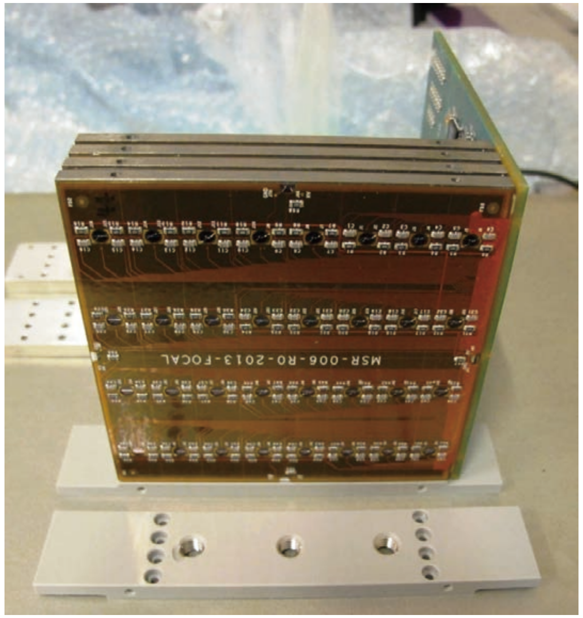
- **Rich physics and unexplored region @ forward rapidity at LHC**
  - CGC (or not), nature of CGC.
  - Strong connections to QGP thermalization mechanism, strong field, long range $\Delta\eta$ correlations (ridge).
  - Advantage of direct photon measurement at LHC forward region.
  - FoCal project is 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.

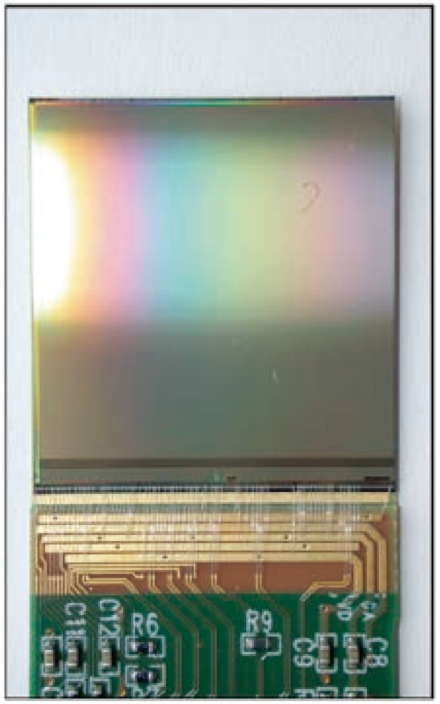
- **Outlook:**
  - First measurement: 3 <η<4, in Run-3 (2021-2023).
  - Full FoCal (3.2 <η < 5.3) in Run-4 (2026-2029).





Perspective to use a similar technology at EIC ?

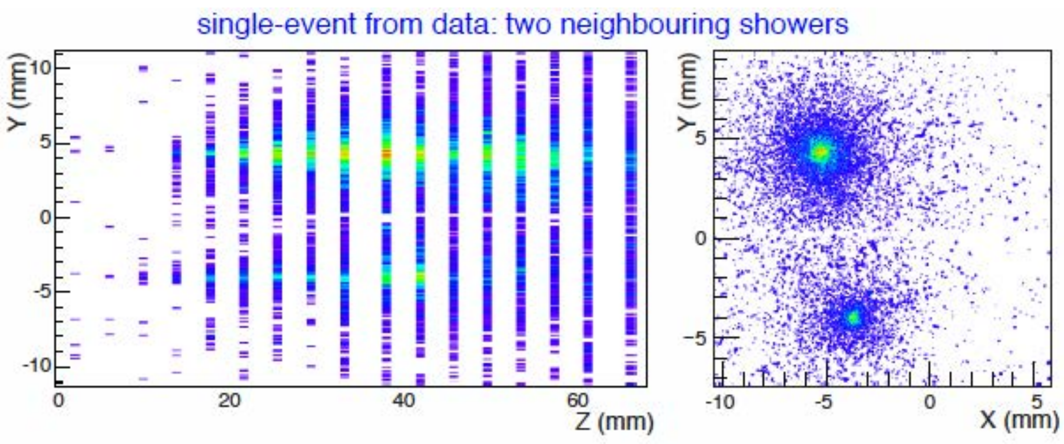




<u>Si-W with high position resolution EMCal:</u>

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

- Happy to discuss for possible collaboration with EIC!



Thank you !