The FoCal project

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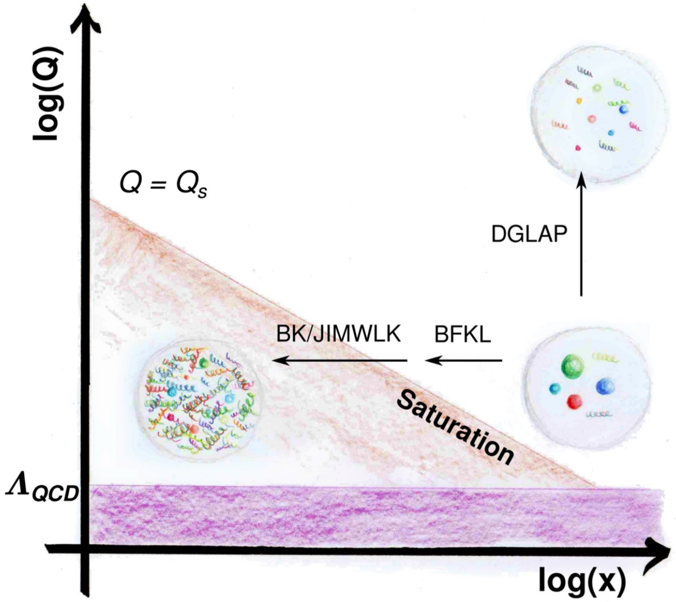
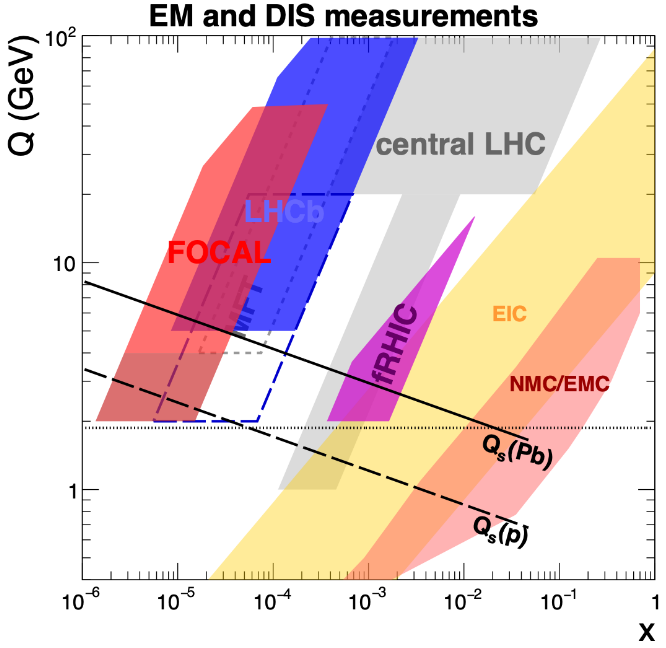
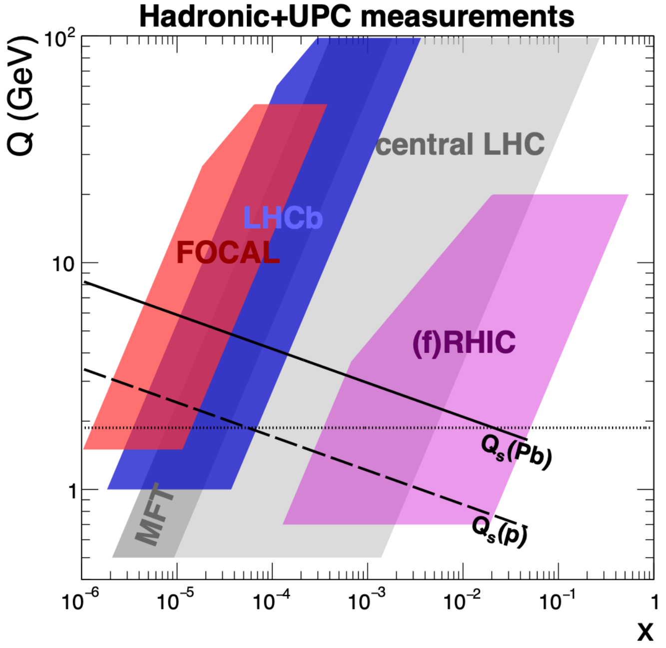
LHC Forward Physics meeting
24-25 Oct 2022, CERN

Pursue towards low-x – kinematics of FoCal







Two main motivations:

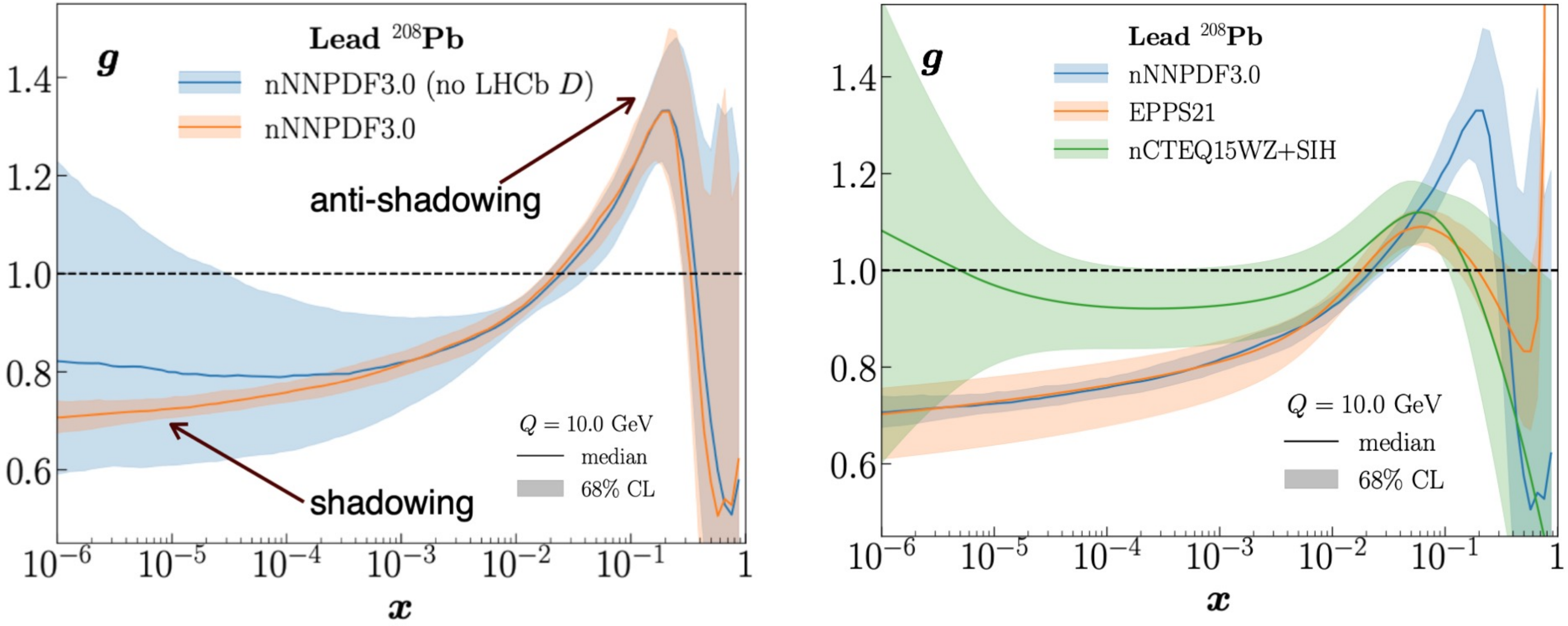
- Study nucleons and nuclei at unprecedently low Bjorken x
- Probe gluon saturated matter with a wide set of experimental observables

Saturation is not "on-off" phenomenon → To observe onset, need:

- many observables and large phase-space coverage in (x,Q^2)
- "calibrate" models in regions where they would be expected to agree
- search observables and regions in phase space where differences

Latest nuclear parton distribution functions, nPDF's

nNNPDF3.0, [EPJ.C82 (2022) 6, 507] ; EPPS21, [EPJ.C82 (2022) 5, 413]



New data included to global analysis:

- nNNPDF3.0: isolated photons (ATLAS), dijets (CMS), w/w-o D-mesons (LHCb)
- EPPS21: dijets (CMS) and D-mesons (LHCb)

→ D-meson data gives significant constraints to small-x

FoCal will go further forward that any other LHC experiments

Overview of FoCal physics program

1. **Nuclear modification of the gluon density at small-*x***
   - isolated photons in pp and pPb collisions

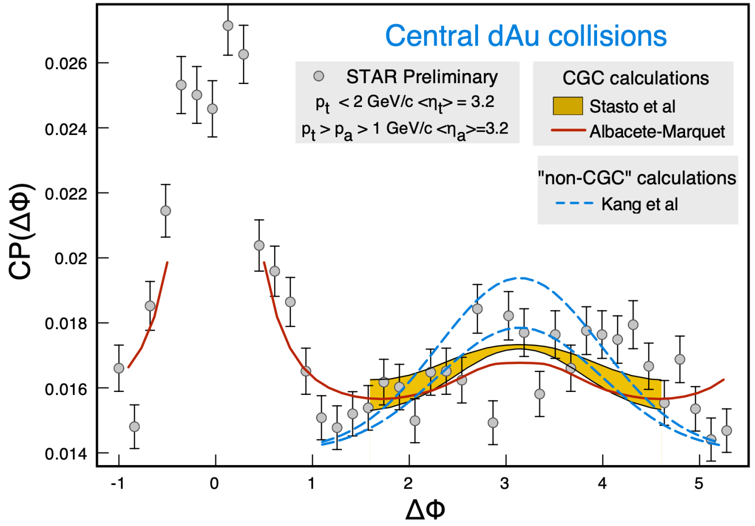
2. **Non-linear QCD evolution**
   - measurements of forward azimuthal correlations;
     $(\pi^0, \gamma^{isol}, \text{jet})_{trigg}$ x $(\pi^0, \text{jet})_{assoc}$
   - Quarkonia in UPC

3. **Long-range flow-like correlations**
   - azimuthal correlations using FoCal and central ALICE or muon arm

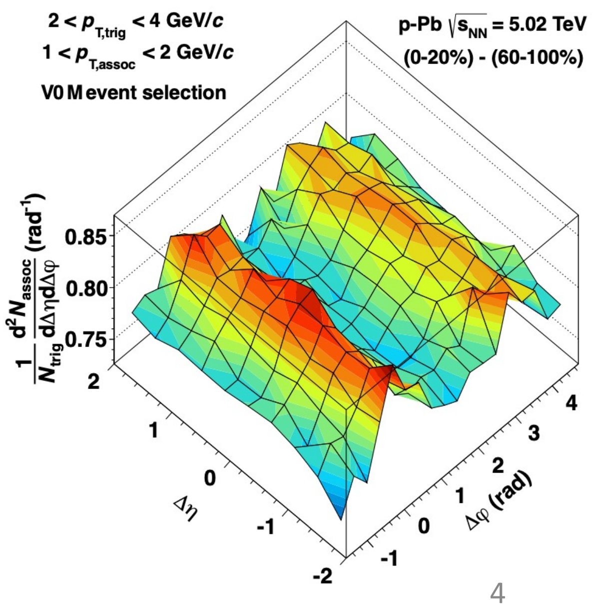
4. **Jet quenching at forward rapidities**
   - high-p_T neutral pion in PbPb

5. **More measurements being studied for the TDR**
   - Photon and pion HBT
   - Weak bosons in pp/pPb
   - direct/isolated photons in PbPb

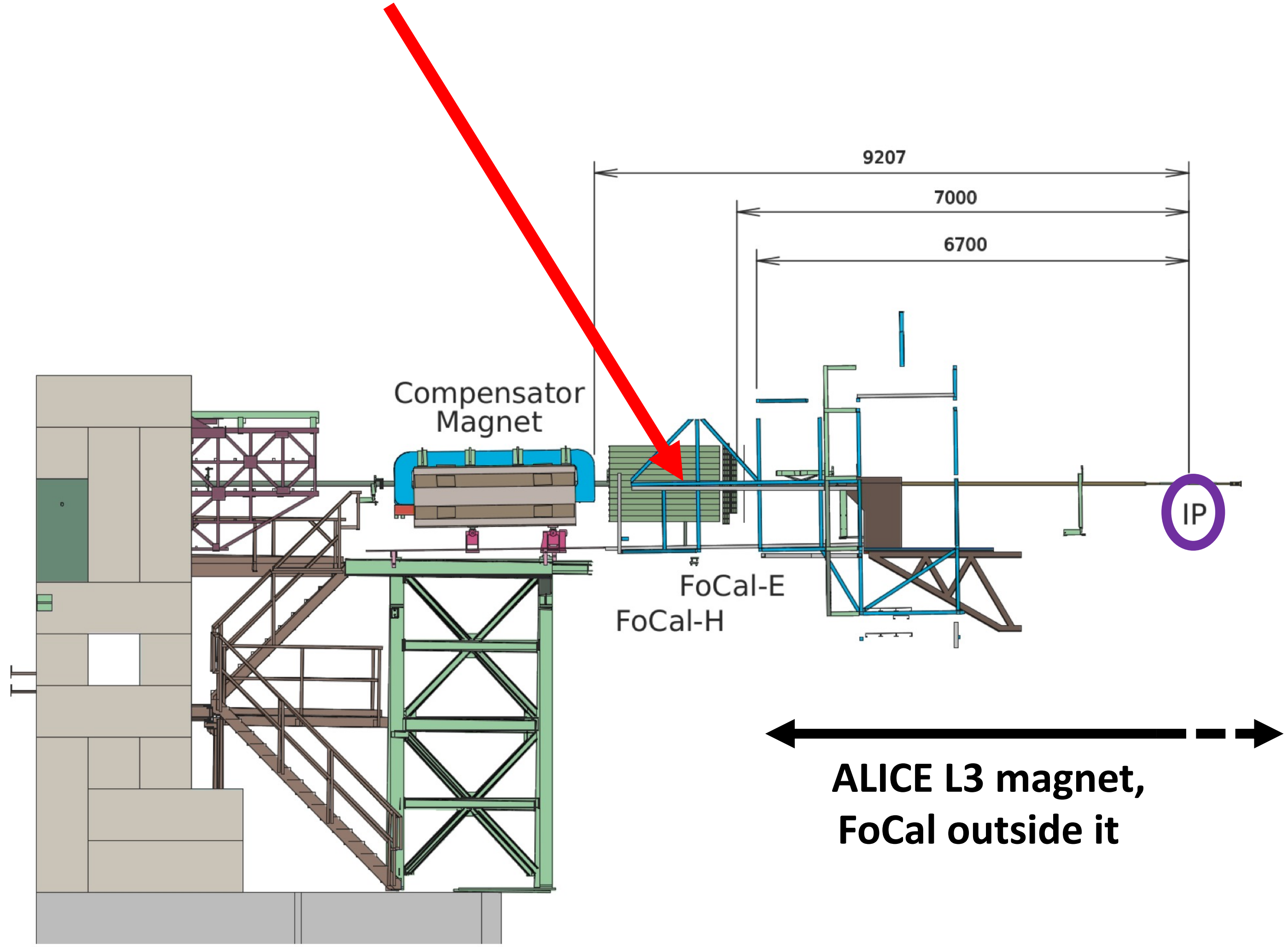
2. non-linear QCD



3. long-range correlations



Forward Calorimeter (FoCal) in ALICE



FoCal Letter of Intent (LoI)

Constraints for design:

- distance to interaction point 7 m, limited by the compensator magnet
- available longitudinal space ~130 cm
- physics program requires both EM and hadronic calorimeters:

Electromagnetic calorimeter FoCal – E

- Compact, length ~20 cm

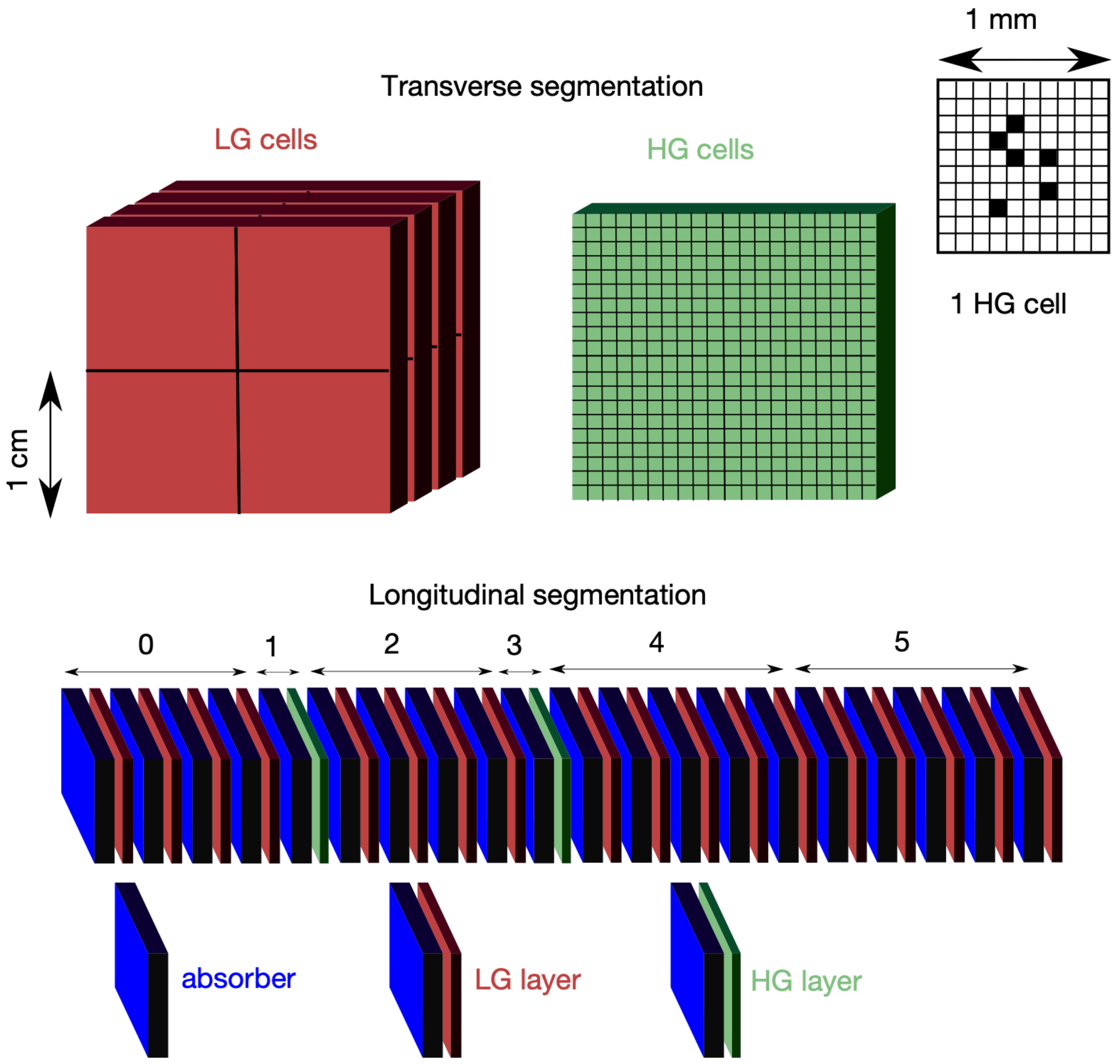
Hadronic calorimeter FoCal – H

- Length ~110 cm

Geometric acceptance

$$3.4 < \eta < 5.8$$

Electromagnetic Si+W sampling calorimeter, FoCal – E



Design targets:

- Small Molière radius → tungsten
- Shower separation → high-granularity
- Reduce costs and amount of data
  → low granularity

20 x 3.5 mm thick tungsten layers, each ~1 X_0

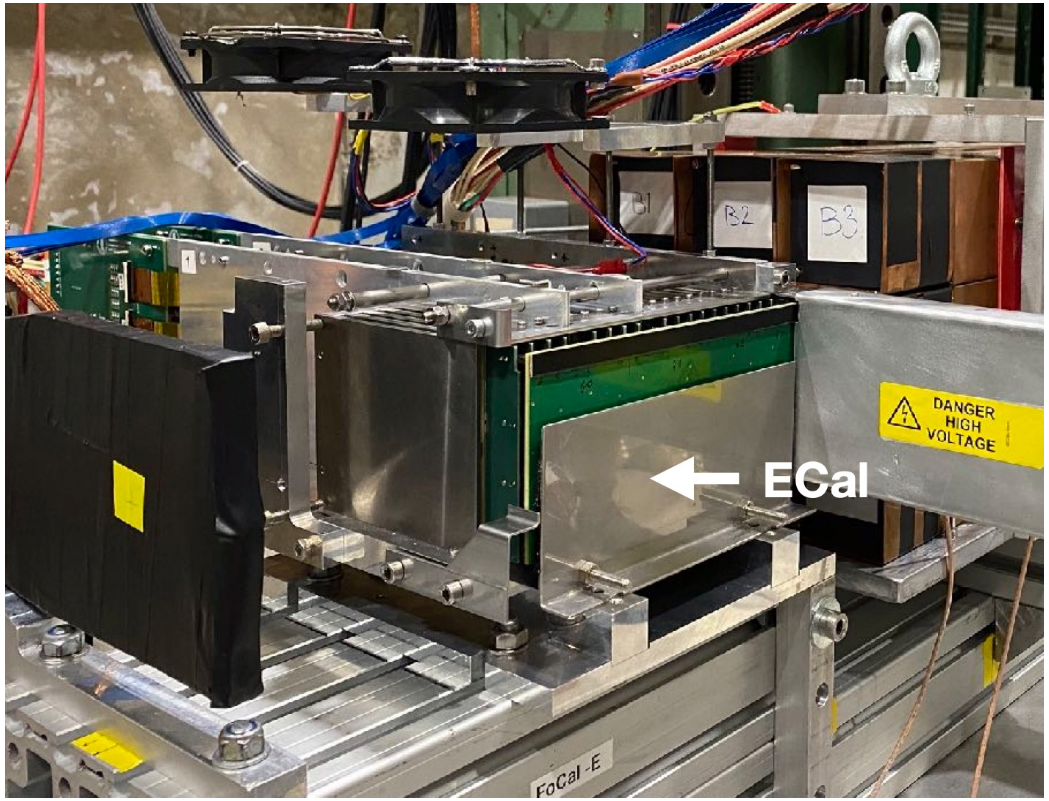
2 x high-granularity layers:

- CMOS pixels, size 30 x 30 μm
- Two-shower separation, position resolution

18 x low granularity layers

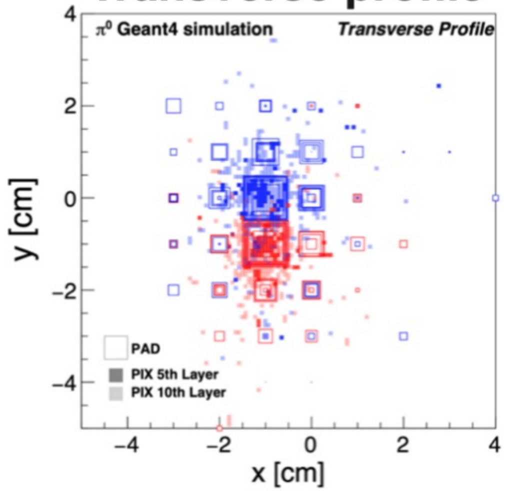
- PAD sensors, size 1 x 1 cm
- Energy measurement, timing

FoCal – E : shower separation with high-granularity layers

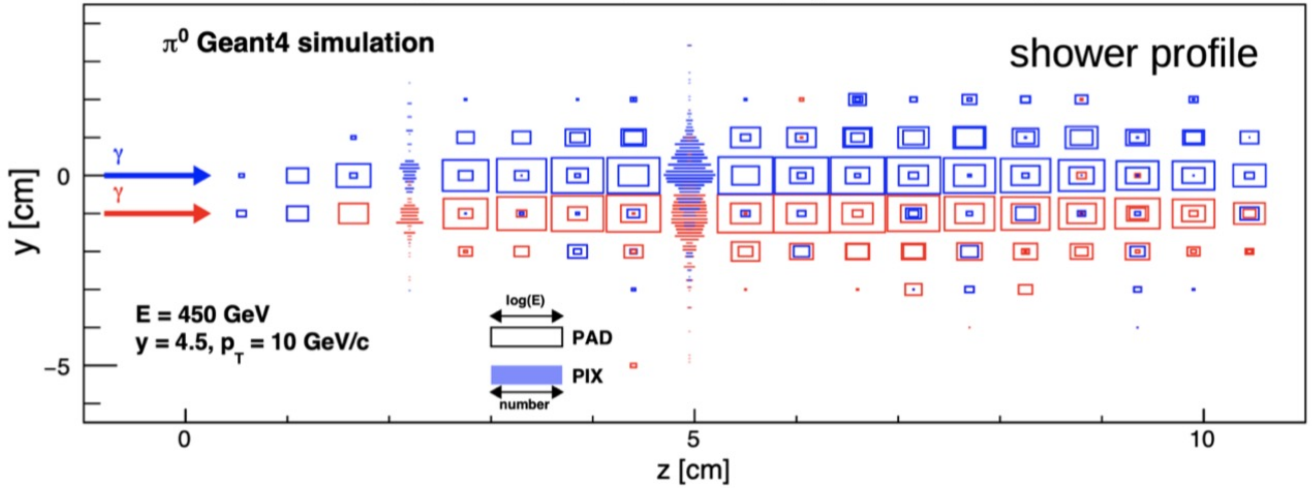


FoCal-E prototype, SPS test beam Sep 2022

Transverse profile



Longitudinal profile (2γ showers)



In-coming decay photon $\Delta_{\gamma\gamma} = 1$ cm

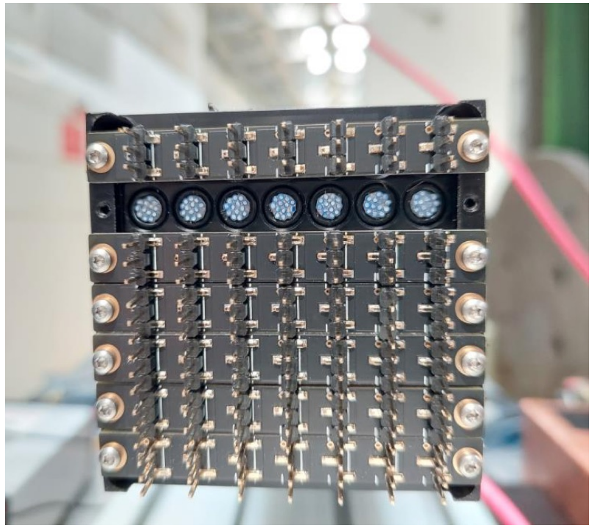
Hadronic spaghetti calorimeter, FoCal – H

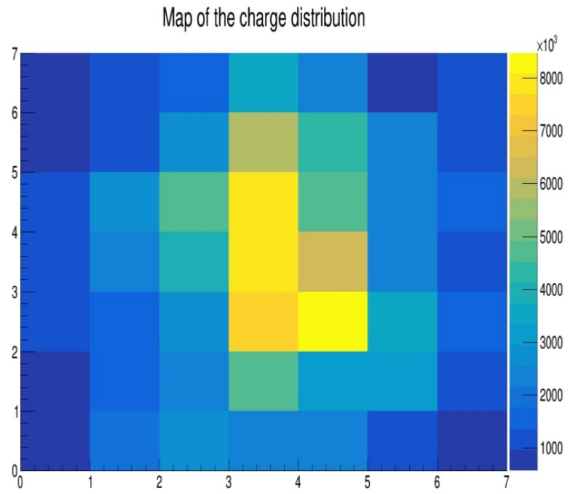
FoCal – H prototype, SPS test beam Sep 2022
9 x (19.5 x 19.5 x 110 cm^3)

Copper capillary tubes, length 110 cm $\sim 7\ \lambda_0$
(Length limited by space before compensator magnet)

1 mm scintillating fibres inside 2.5 mm Cu tubes

Bundle fibres and readout with SiPM





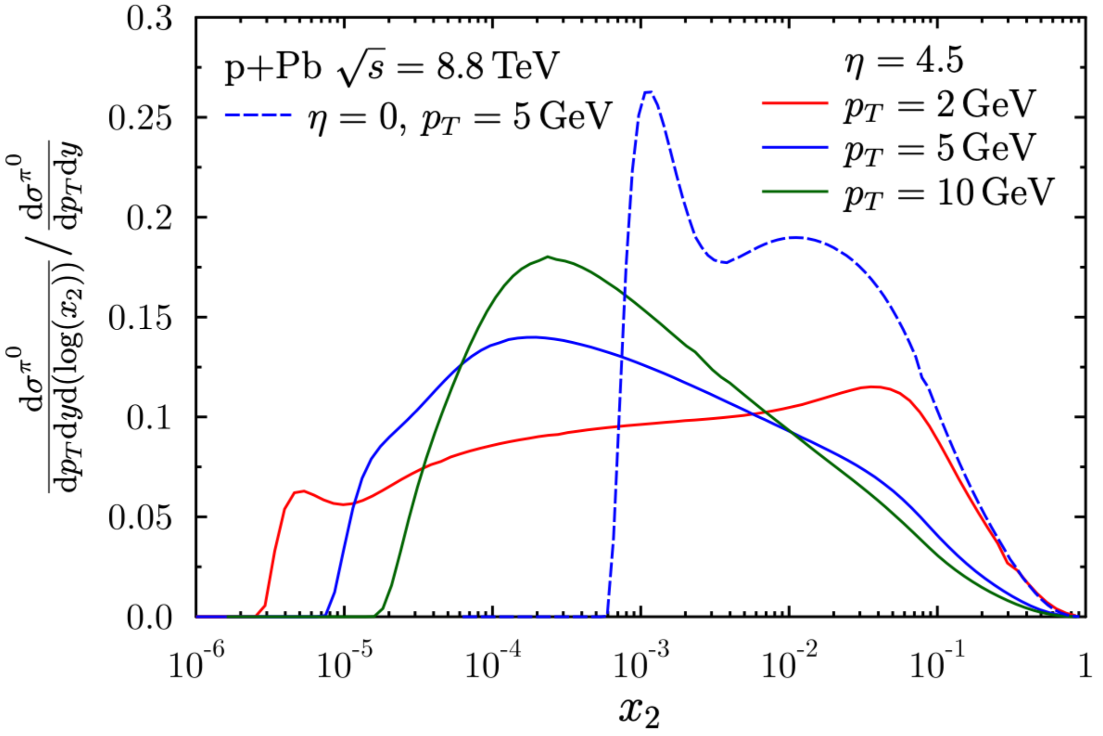
Smaller prototype, PS test beam Jun 2021

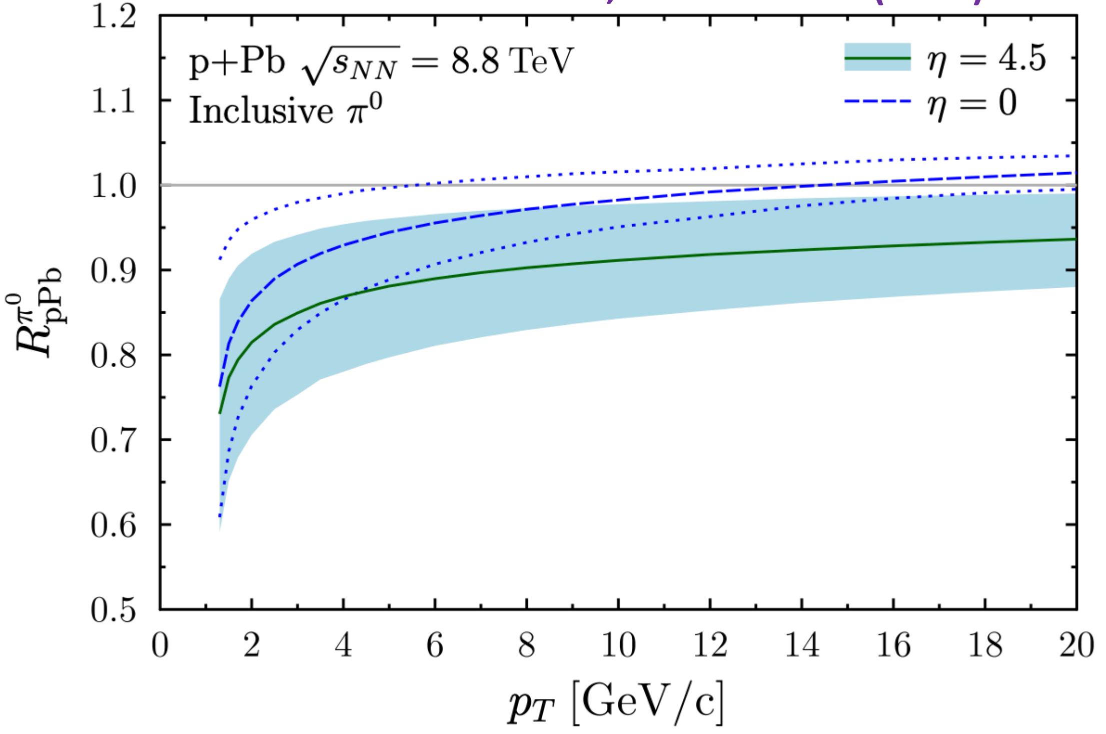
Some case studies for FoCal performance in proposed measurements

Case 1 : neutral pions in FoCal

Inclusive neutral pion R_{pPb} – nPDF's + pQCD

Helenius, et al. JHEP 09 (2014) 138

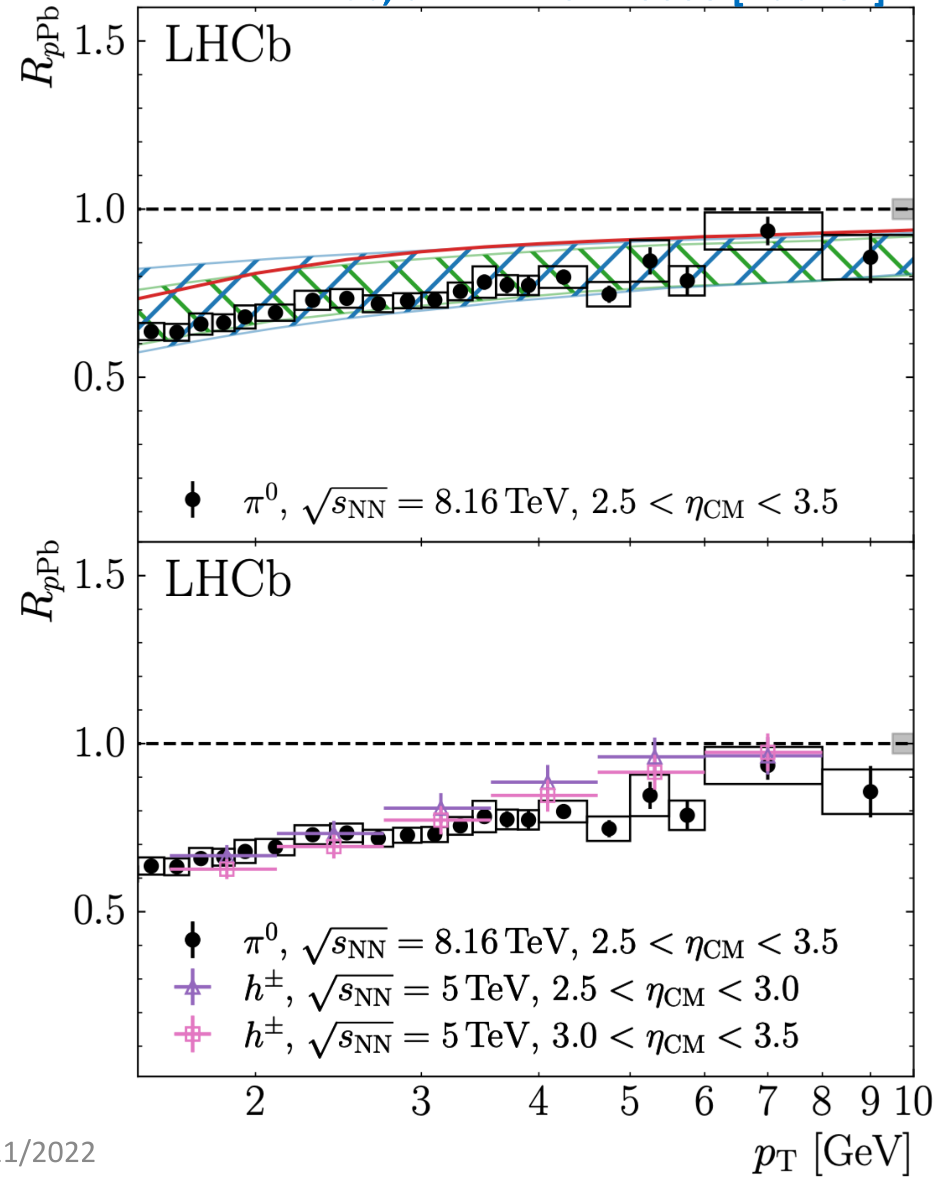


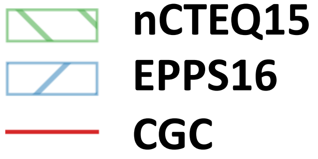


- Compared to mid-rapidity (dotted), forward π^0's probe smaller x
- Stronger shadowing in forward as compared to mid-rapidity
- However, the *x* -distributions for pions are wide

Inclusive neutral pion R_{pPb} – LHCb measurement

LHCb, arXiv: 2204.10608 [nucl-ex]





Theory references:
JHEP 09 (2014) 138
Phys. Rev. D88 (2013) 114020

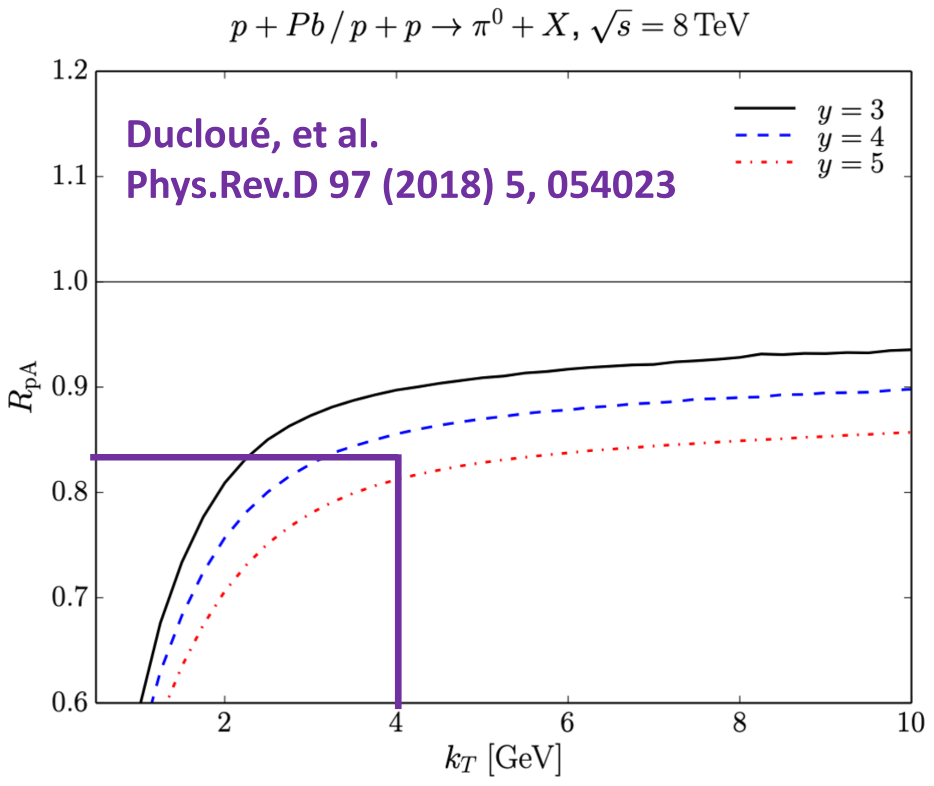
New LHCb measurement for forward π^0,

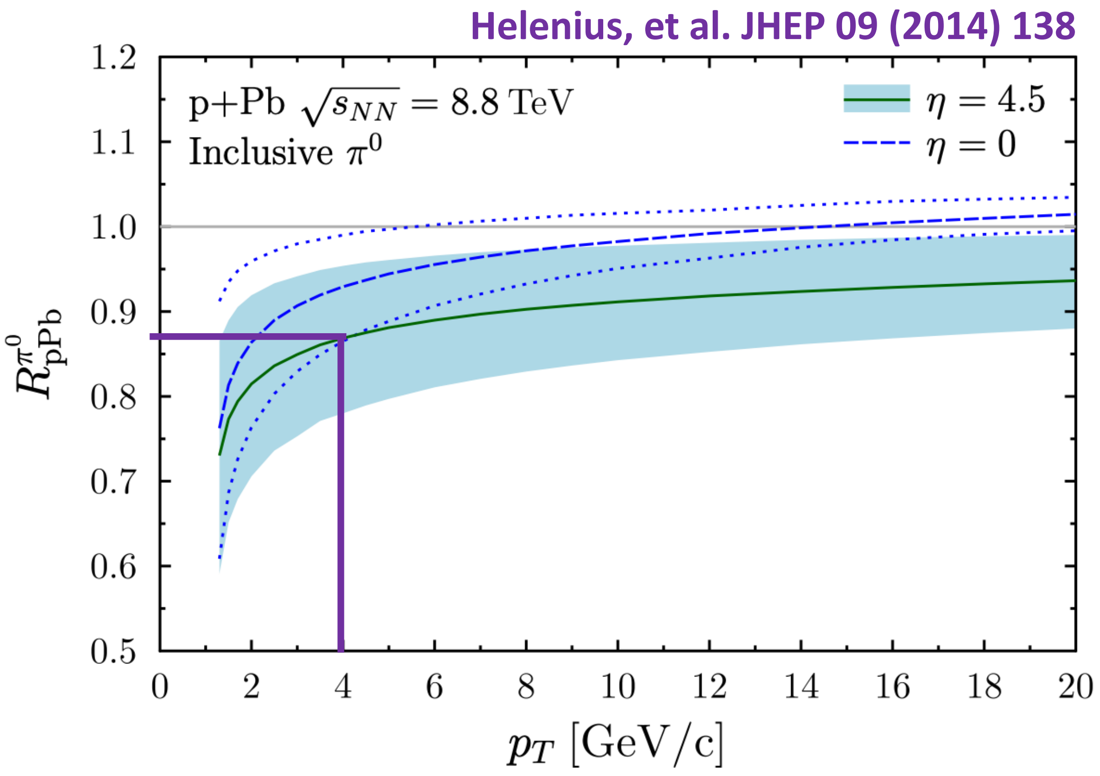
Neutral pions compatible with charged hadrons

Suppression clear, lower limits in theory

FoCal goes still more forward!
+ independent measurement

Inclusive neutral pion R_{pPb} – saturation vs nPDF's + pQCD





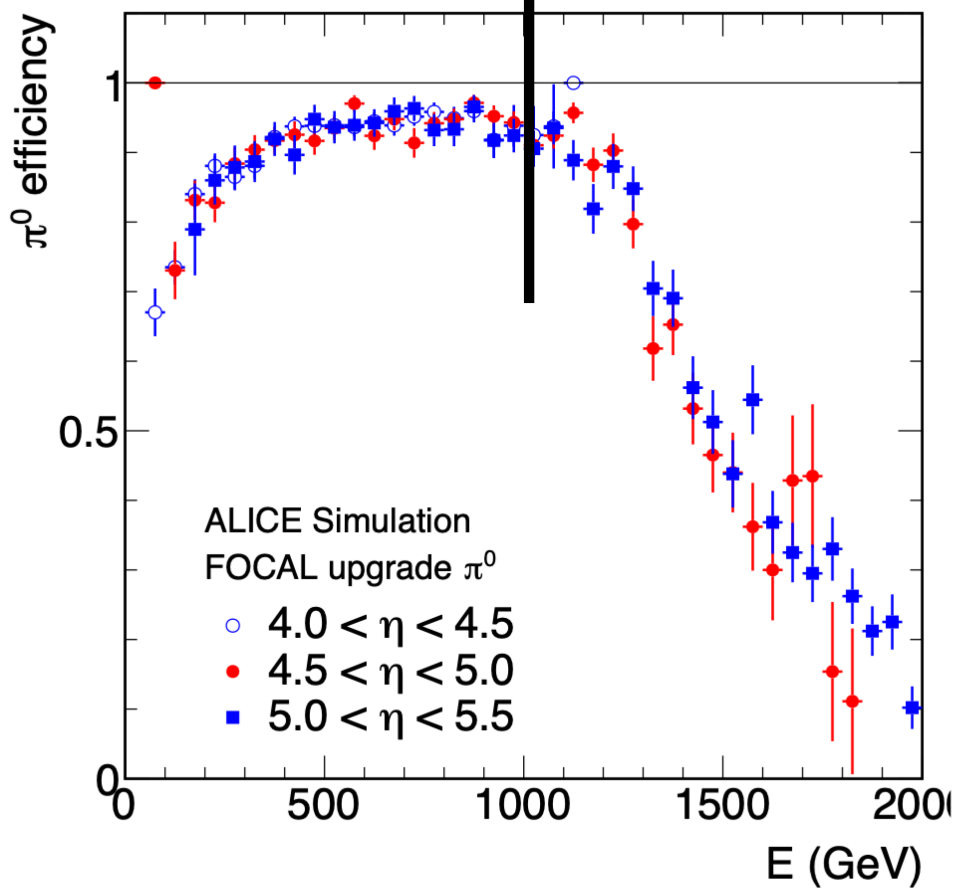
- Both calculations expect suppression of yield, around 10-20%
- Difference within model uncertainties (?). Is p_T dependence different?
- Gives a baseline: models agree with inclusive

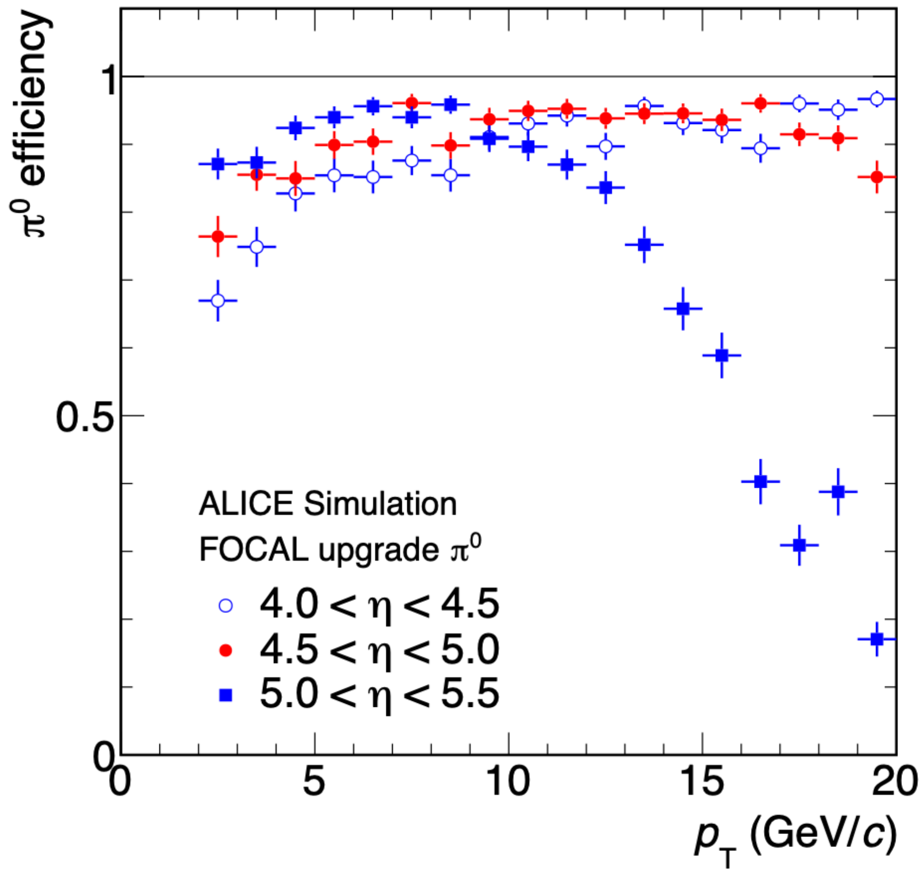
  → as much as possible, fix freedom in models and search differences with other observables

FoCal – E performance : neutral pions

LoI, LHCC-I-036 (2020)

After $E \sim 1$ TeV, the two-photon separation starts to limit



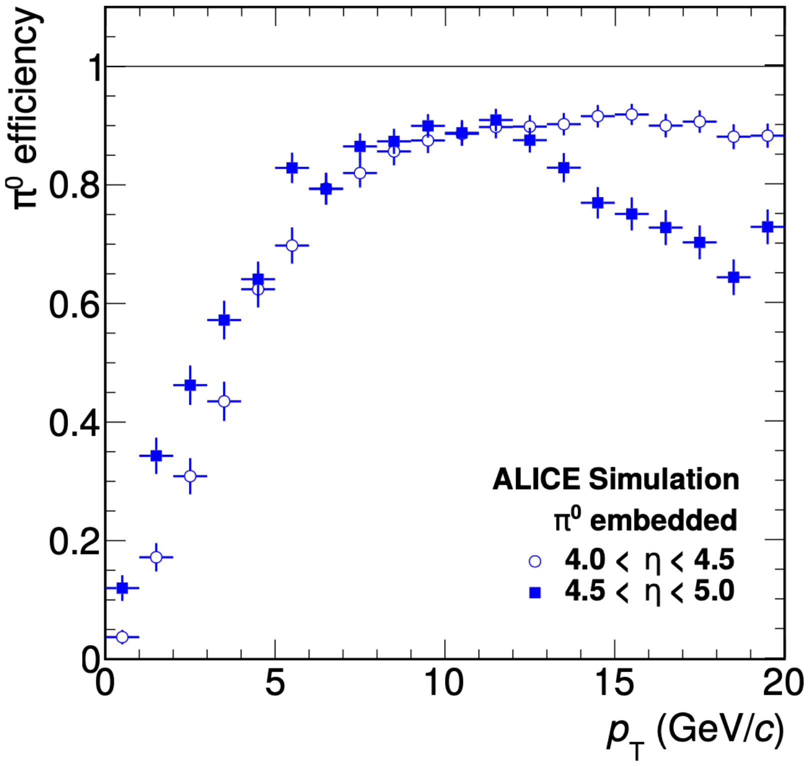


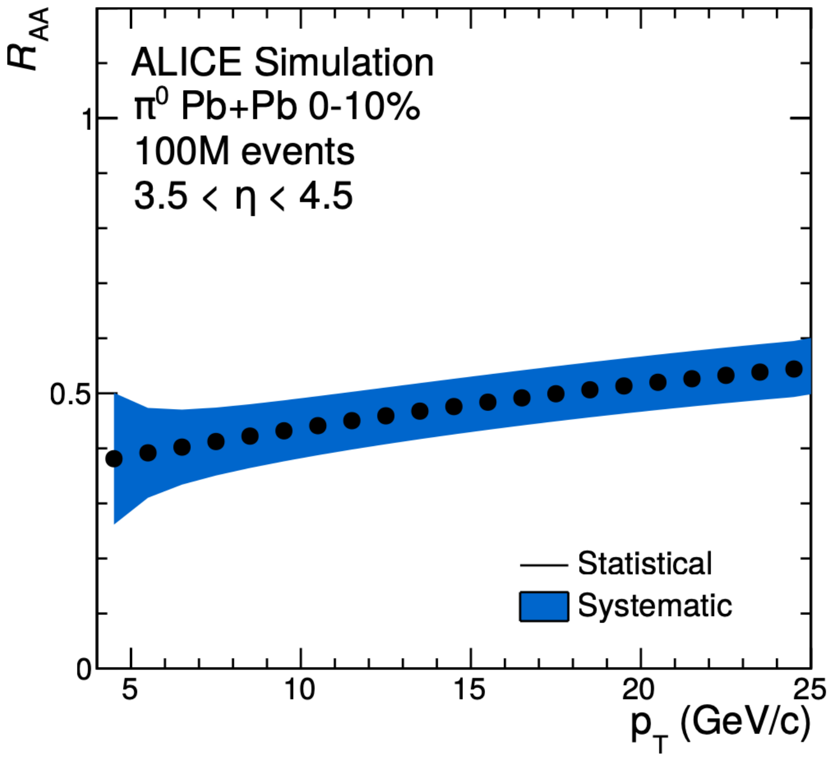
Reach in E_π same in all rapidities, energy dictates 2-γ opening angle

Reach in p_T depends on the rapidity range

$$p_T = \frac{E_\pi}{\cosh \eta}$$

FoCal – E performance : π^0's in Pb+Pb

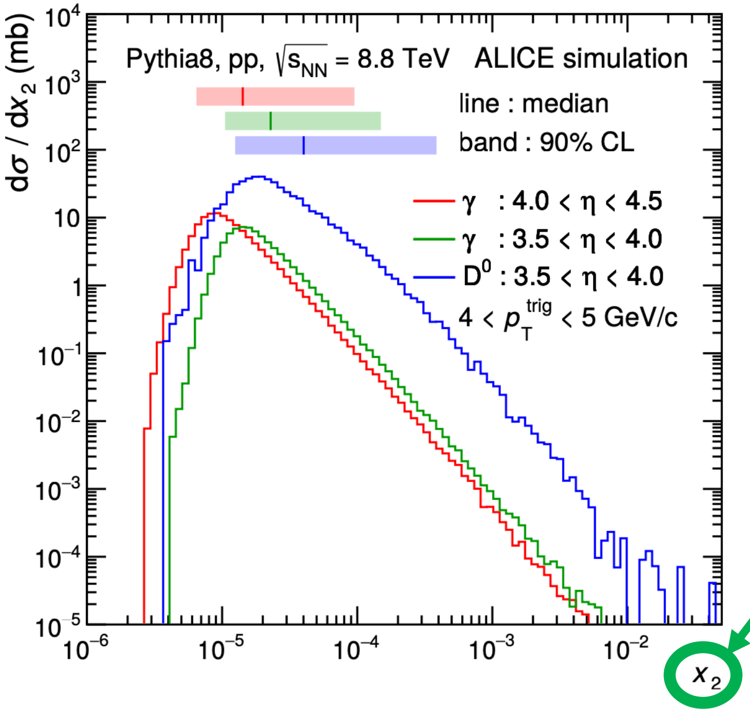


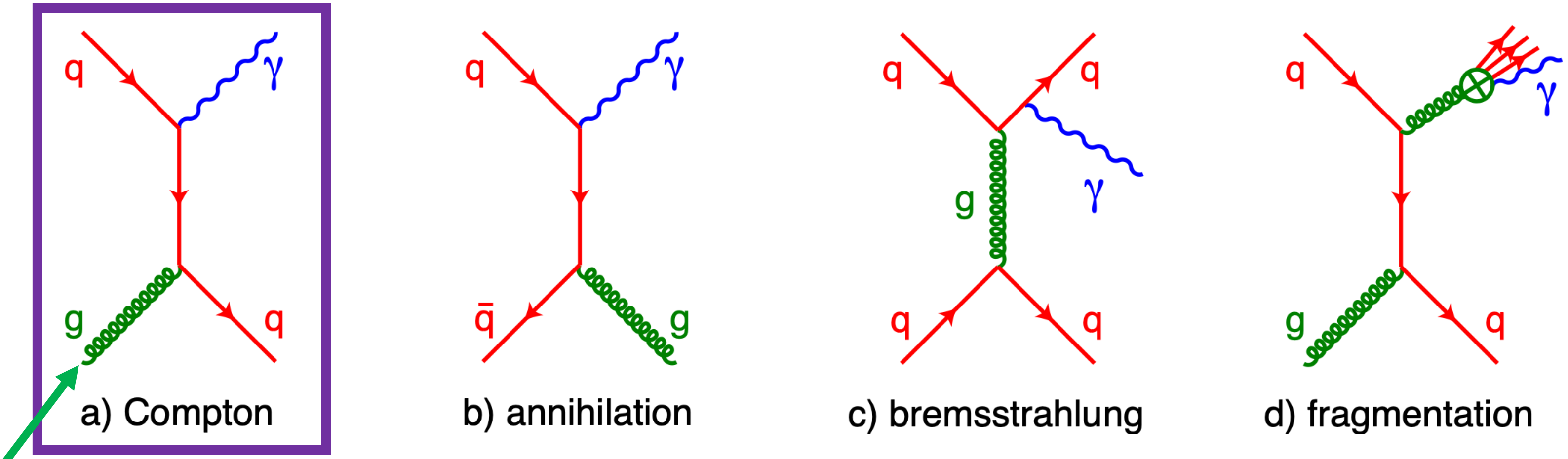


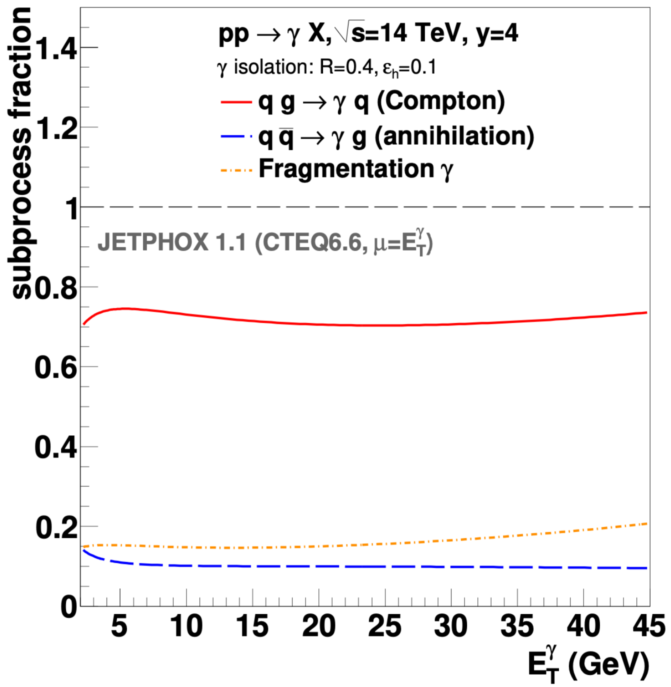
- Neutral pion efficiency is slightly lower in PbPb compared to pp/pPb
- We expect good neutral pion measurement in all collision systems

Case 2 : isolated photons in FoCal

Direct photons at forward rapidity:



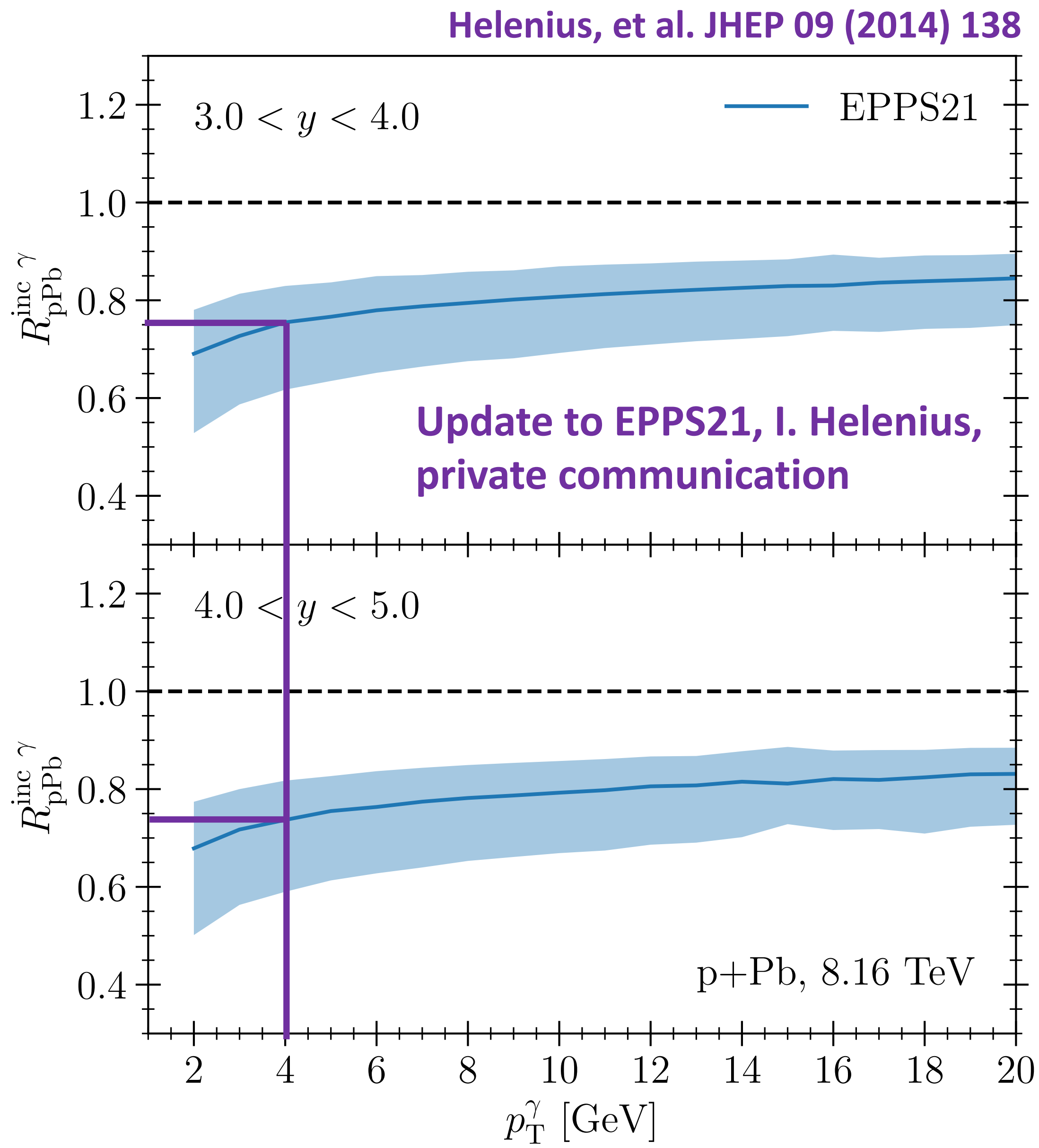


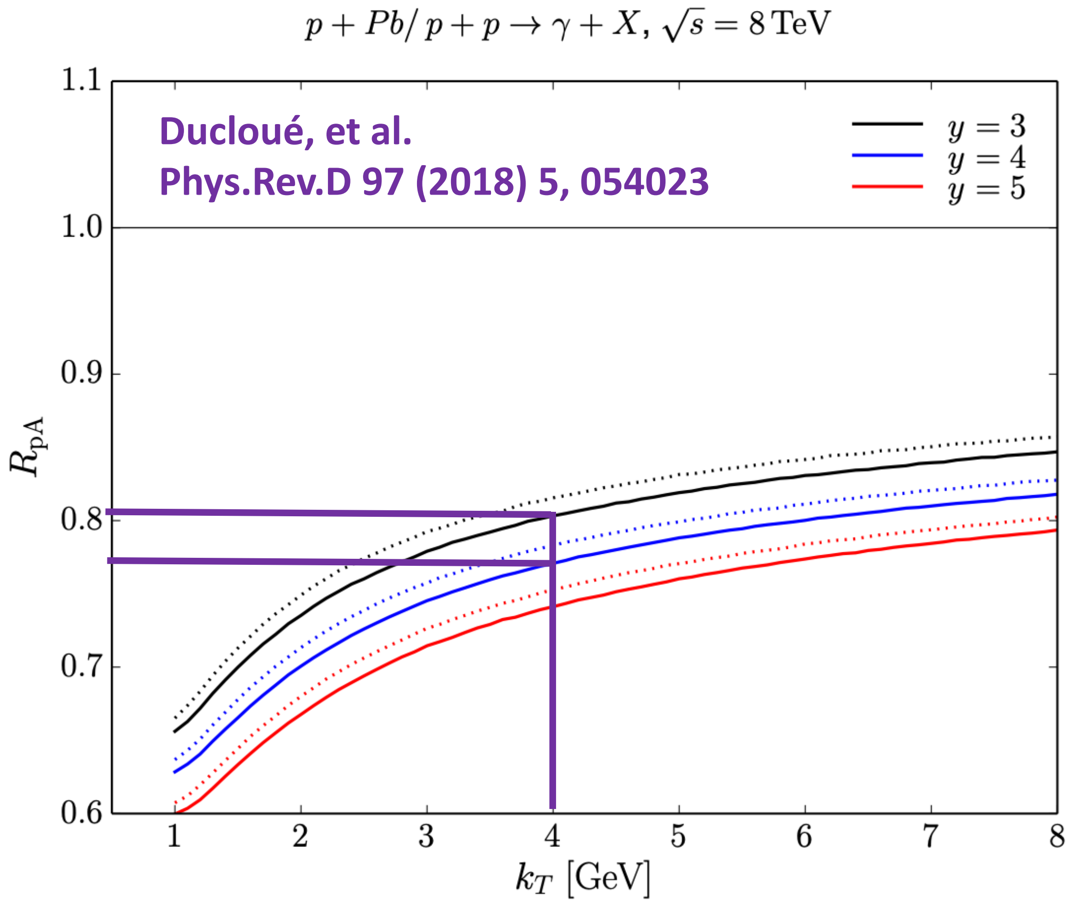


At forward rapidity

- QCD Compton channel dominates,
- Compared to π^0's, x_2 –distributions are narrower, and
- average $\langle x_2 \rangle$ smaller

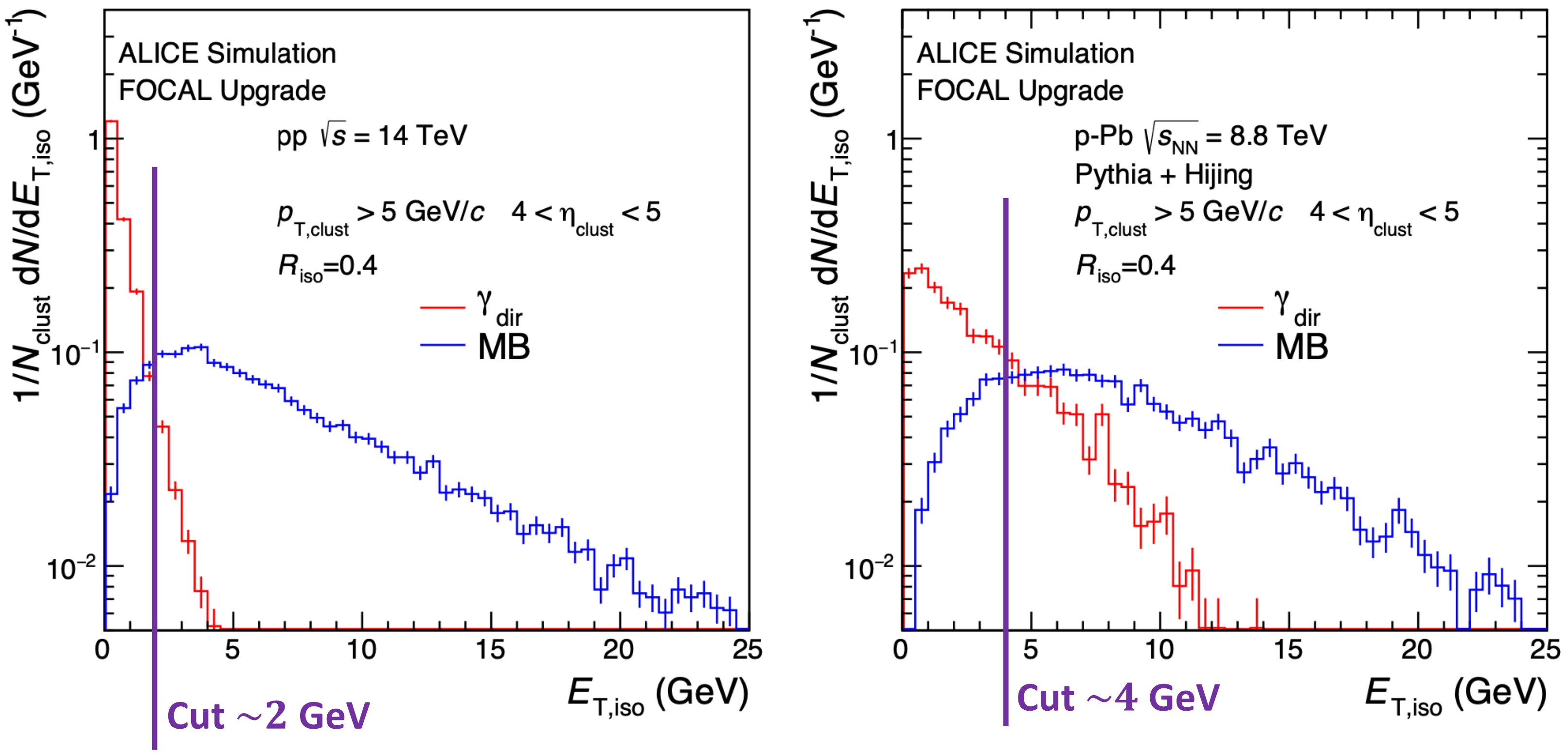
Direct photon R_{pPb} - compare nPDF's + pQCD and saturation





- Rapidity and p_T dependence in saturation model stronger. Significant?

FoCal – E performance : isolated photons



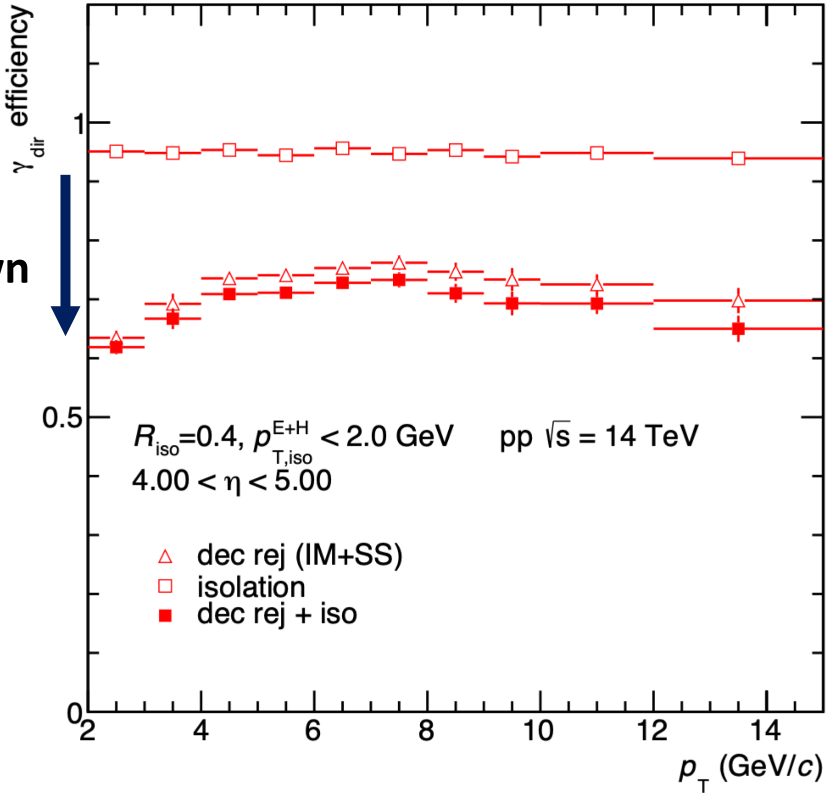
One cannot measure prompt photons experimentally

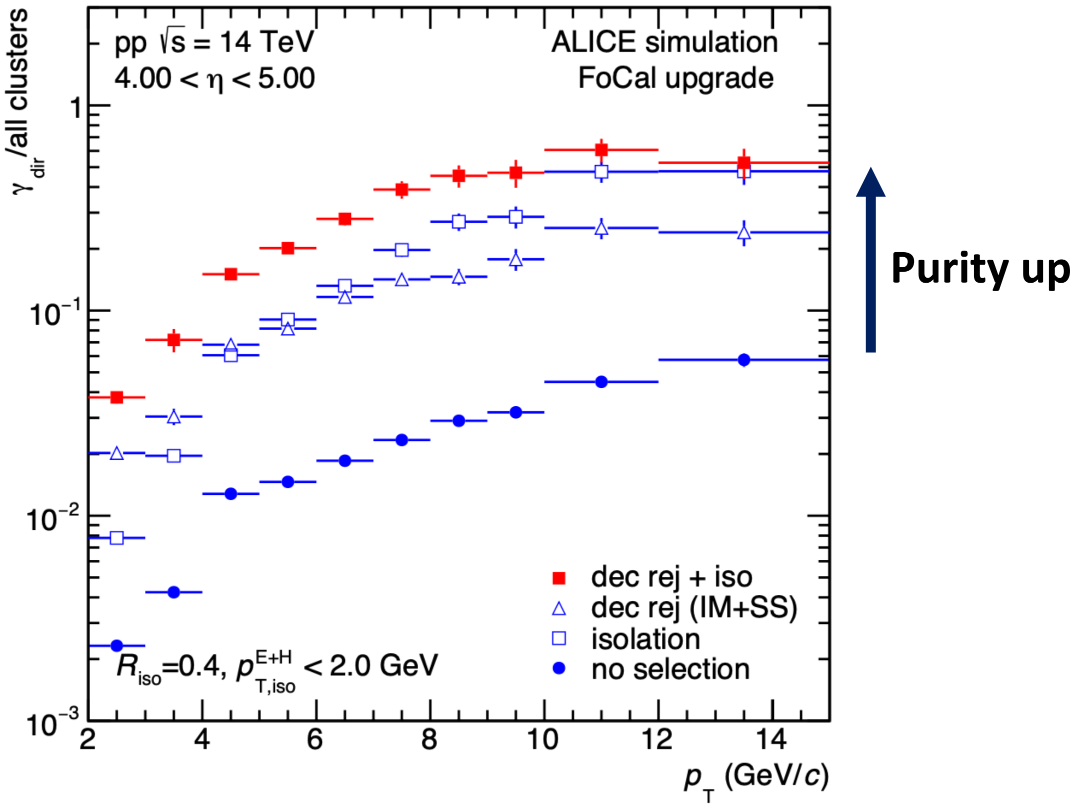
→ experimental observable: isolated photons

Require an upper limit of activity, energy in the isolation cone R = 0.4 around ECal cluster.

→ enrich the prompt photons over all photons

FoCal – E performance : isolated photons





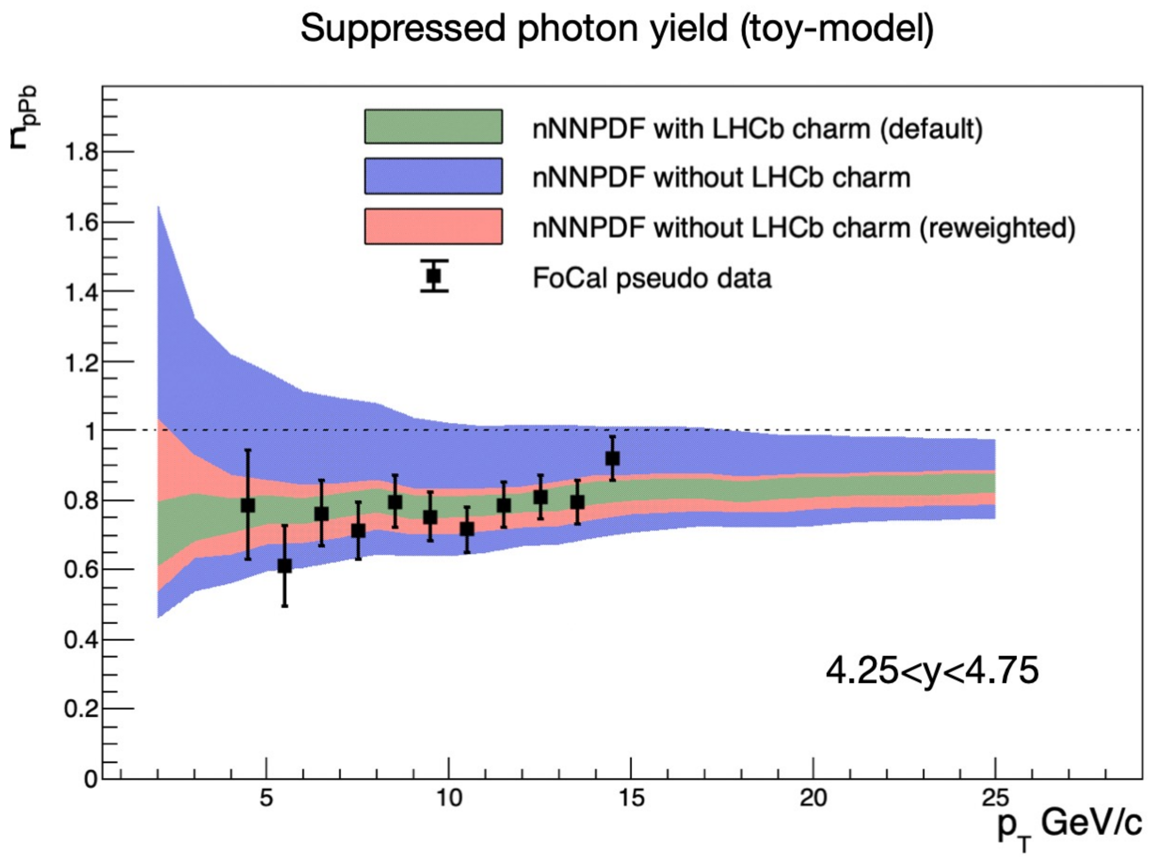
On top of the isolation cut, invariant mass (IM) and shower shape (SS) cuts

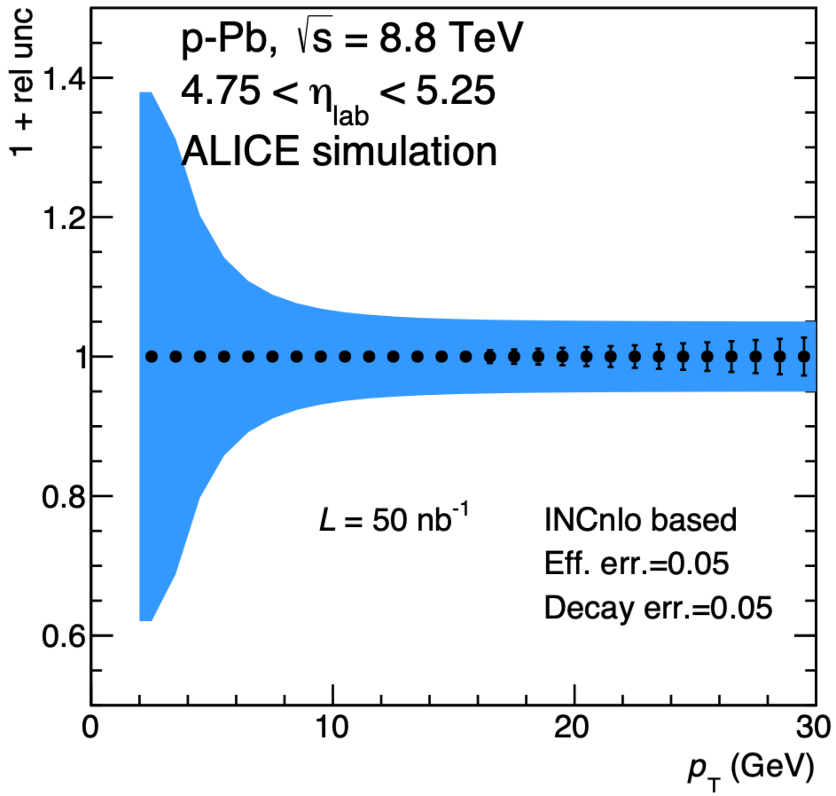
→ reject particularly decay photons

Purity increases (right) with a price of loosing efficiency (left)

These cuts to be optimised

Isolated photons with FoCal – impact to nPDF's





With the FoCal data

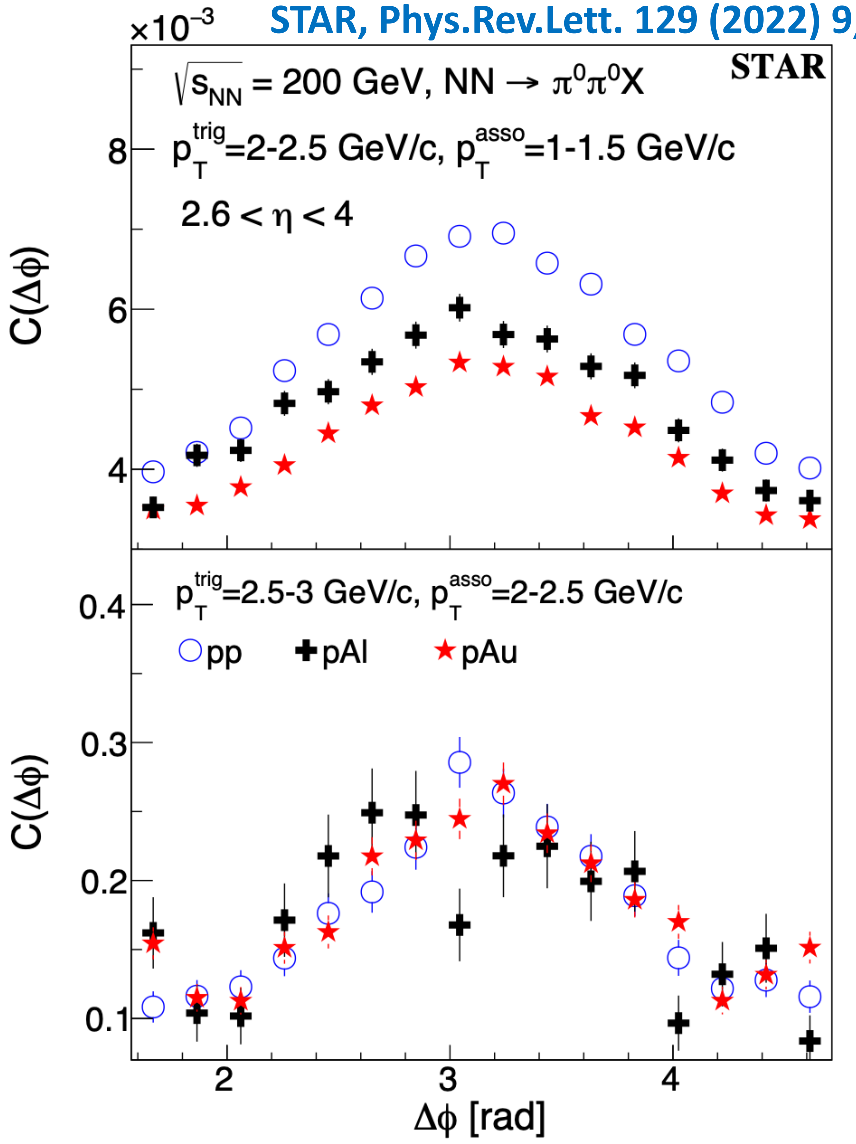
- Validation of factorization/universality; no fragmentation in the final state
- Improve constraints and improve fit qualities

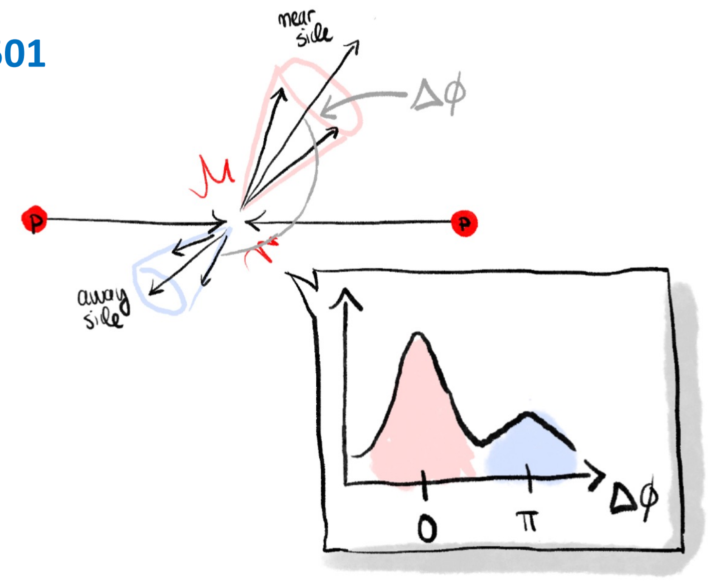
  → important in search of subtle differences

Case 3 : Forward azimuthal correlations

Azimuthal π^0-π^0 correlations by STAR @ $\sqrt{s} = 200$ GeV

STAR, Phys.Rev.Lett. 129 (2022) 9, 092501

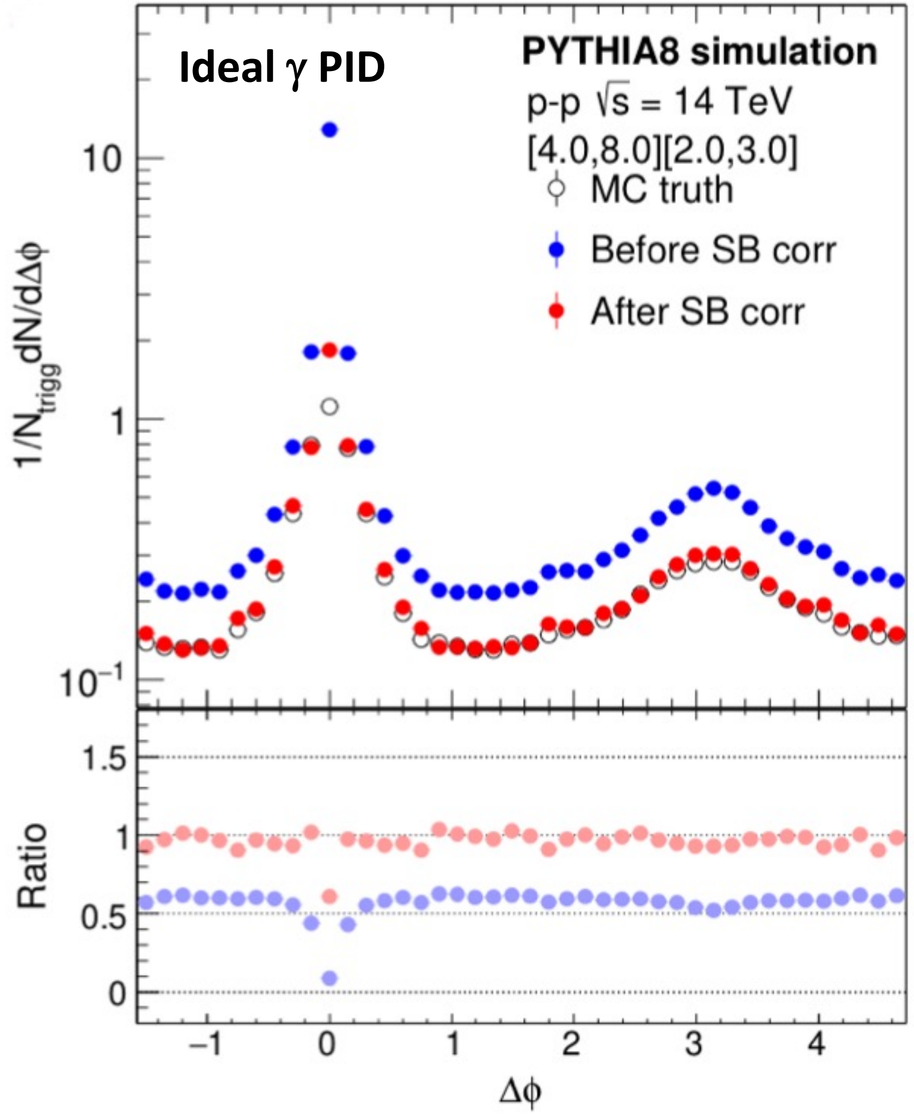




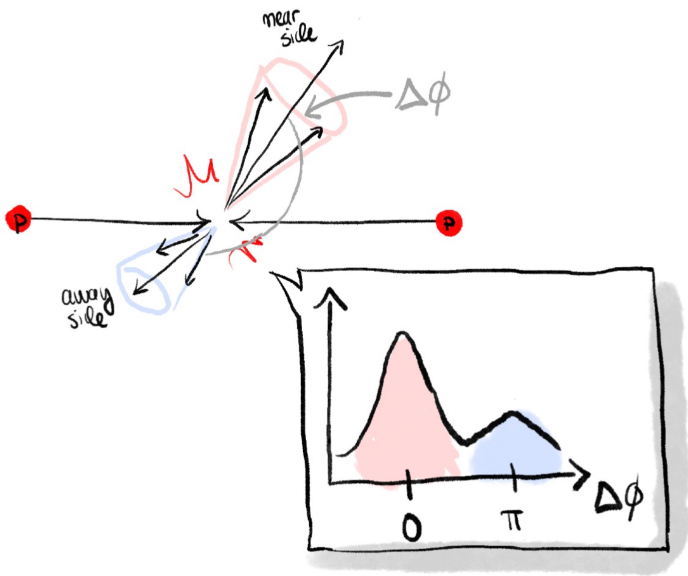
STAR measures forward π^0-π^0 in pp, p-Al and p-Au

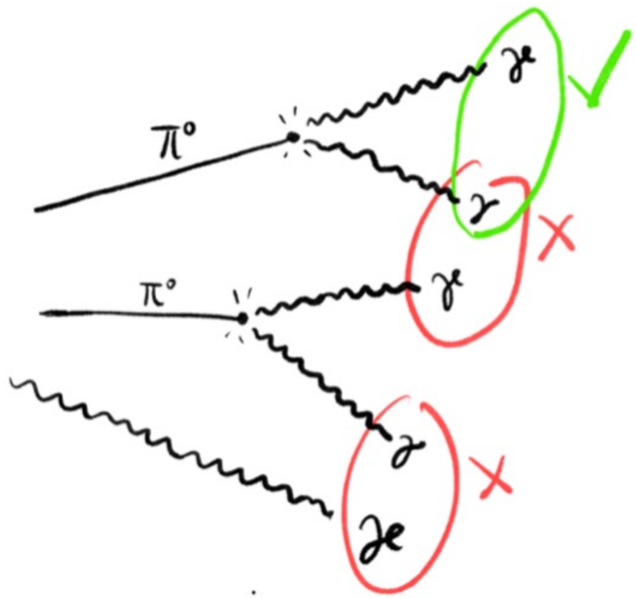
- Clear suppression of back-to-back yields with increasing mass number at low $p_{T,trigg}$ and $p_{T,assoc}$
- Correlation width does not depend on nucleus

PYTHIA8 simulation : forward π^0-π^0 correlations @ 14 TeV



H. Rytkönen, on-going PhD





Experimentally, ECal measures clusters, mainly γ's and e's

→ reconstruct neutral pion *candidates* with $m_{\gamma\gamma} \approx m_\pi$;
some real, some combinatorial fake π^0's

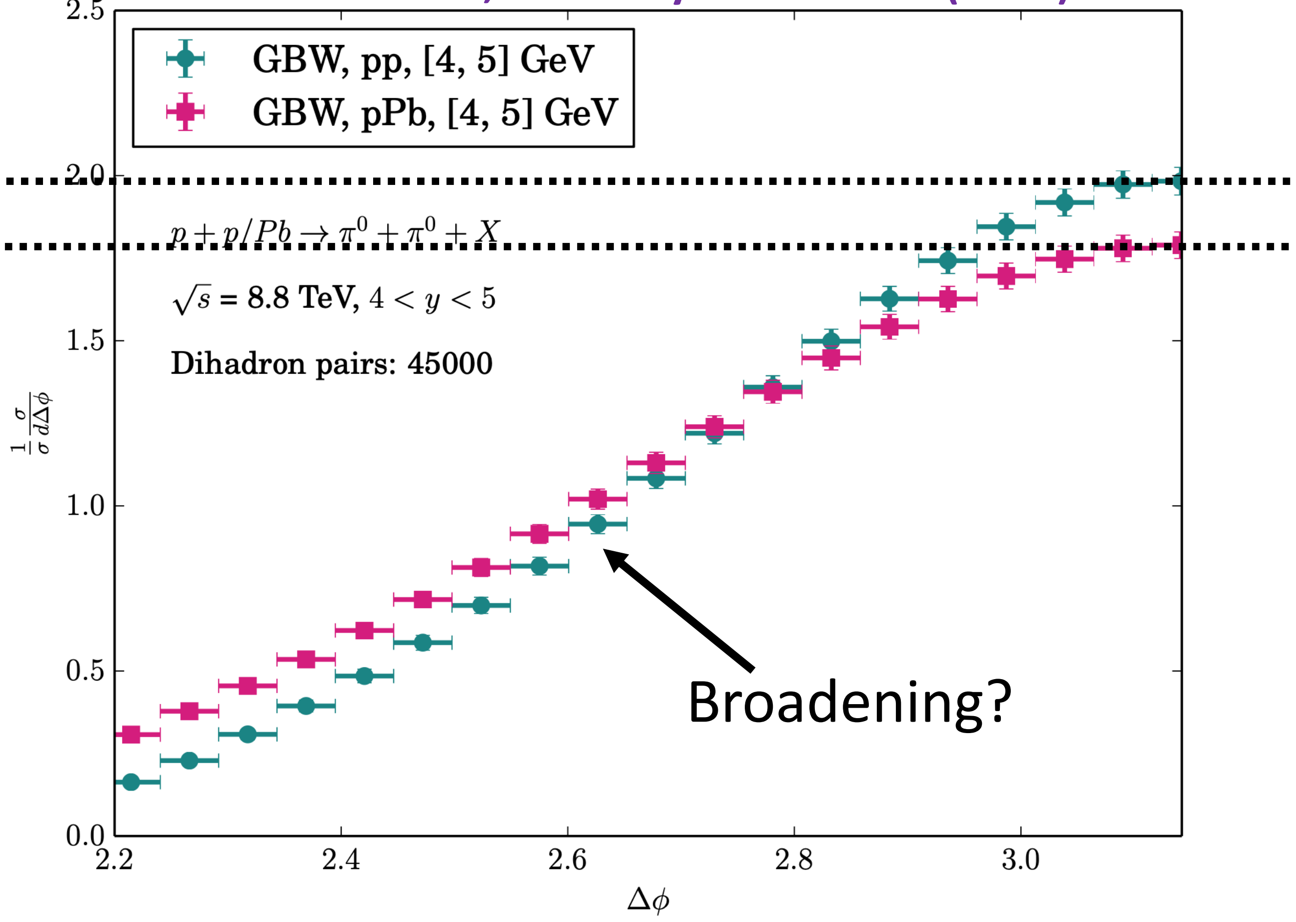
→ untrivial and significant correlated background

→ subtract using side-band method

Currently studying how low p_T's we can reach

Forward π^0-π^0 correlations – saturation model

Stasto, et al. Phys. Lett. B784 (2018) 301

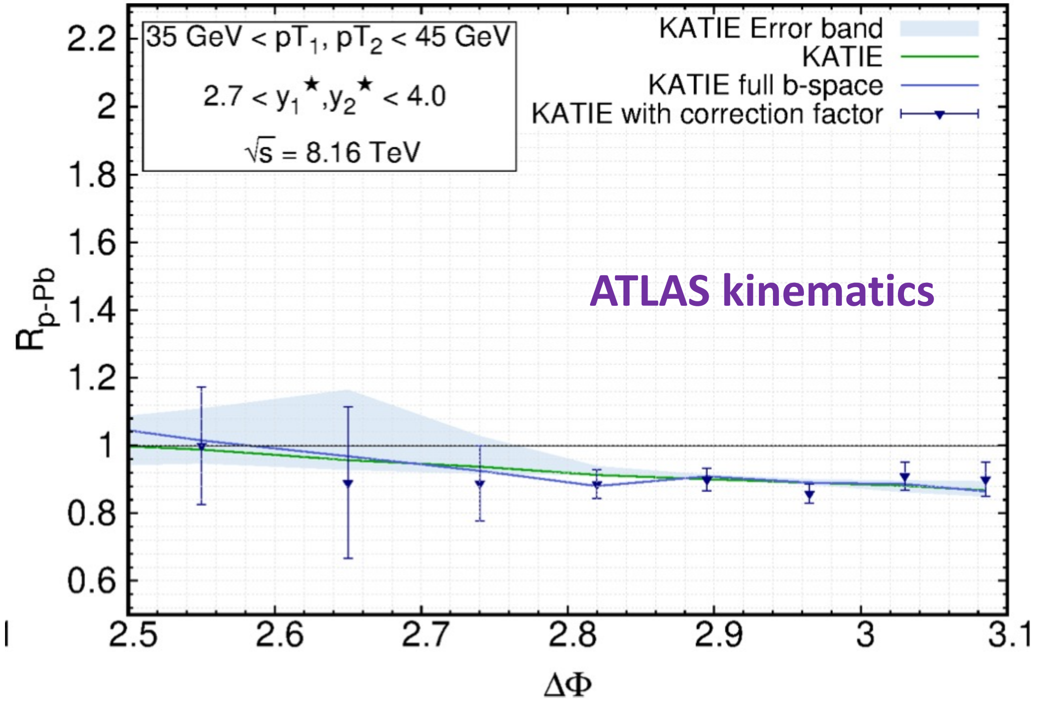


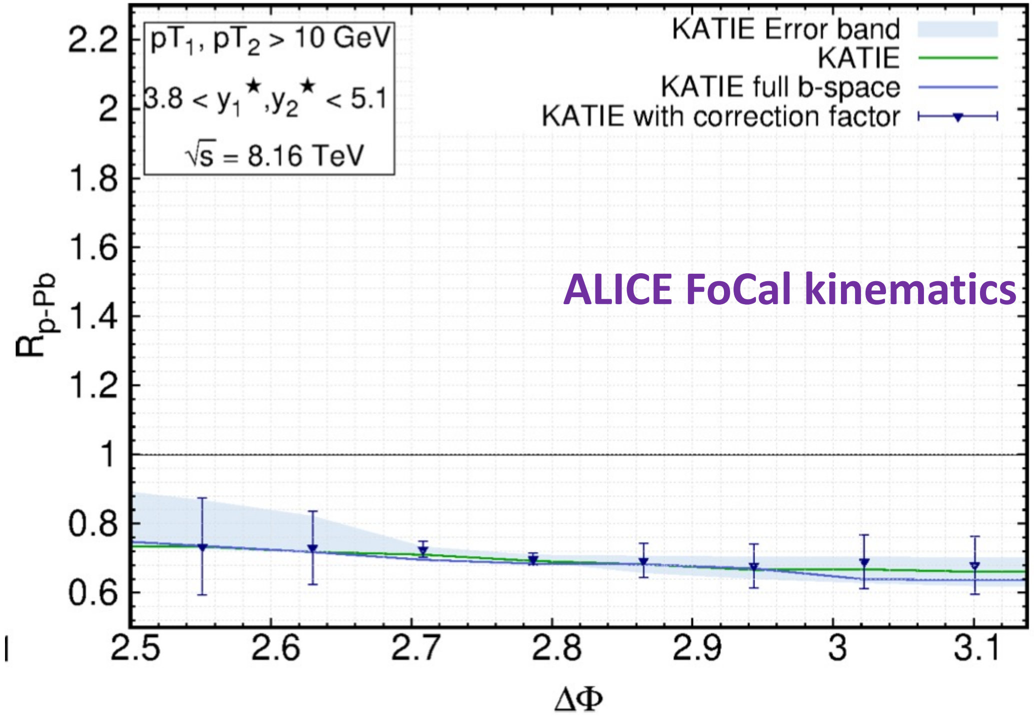
Suppression in R_{pPb}~10%

Detailed studies for FoCal performance on-going

Forward dijet correlations – saturation model

Abdullah Al-Mashad, et al. arXiv: 2210.06613 [hep-ph]





Dijet azimuthal correlations – different experimental challenges:

- ATLAS kinematics, suppression $< 10\%$
- ALICE kinematics, suppression may reach ~20-50%

⇔ very important to push down jet analysis down to $p_{T,jet} > 10$ GeV

Strength in ALICE : study low-p_T jets

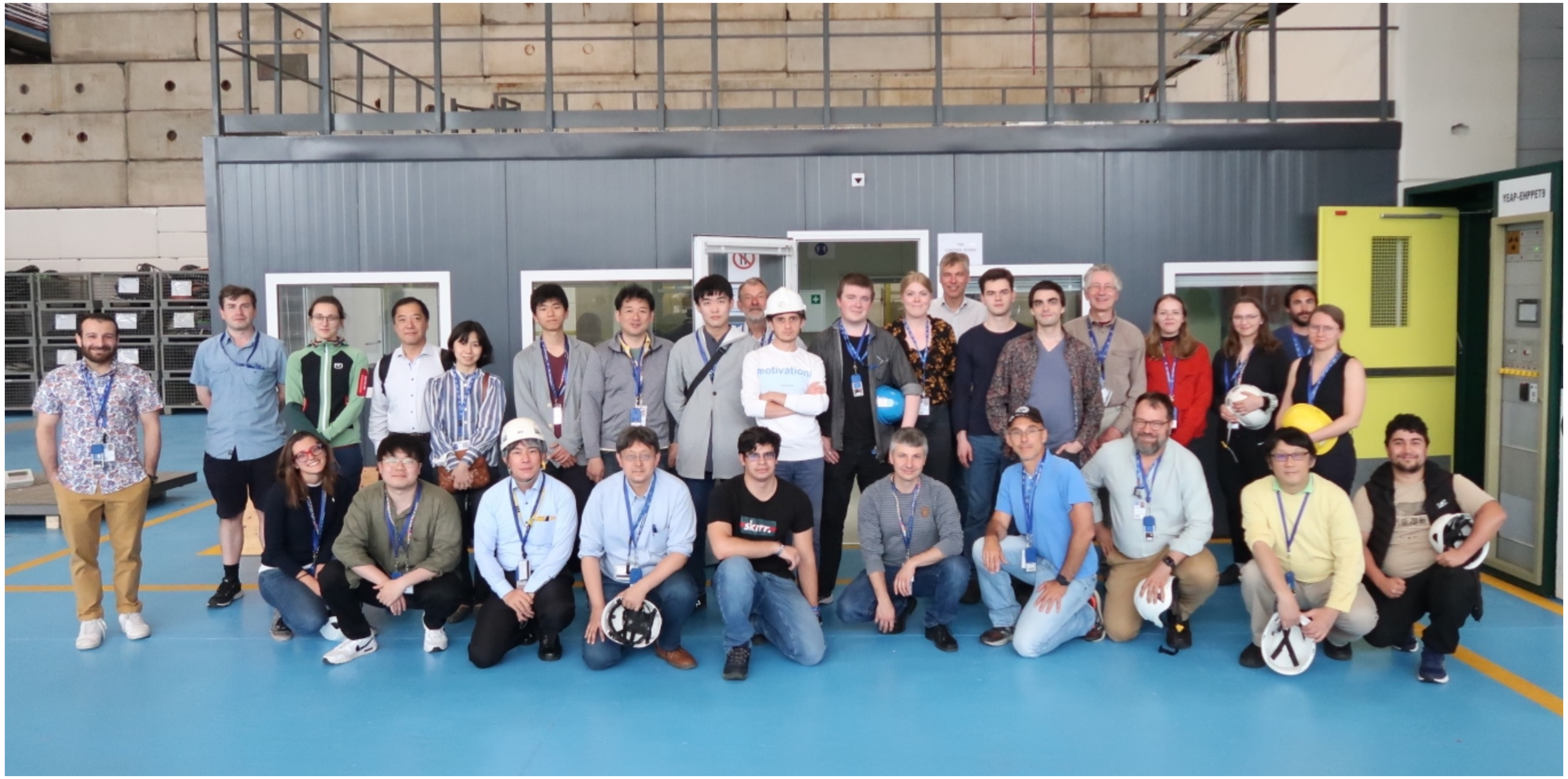
On-going FoCal simulation on physics analysis performance

On-going FoCal performance studies, not yet advanced enough to show:

- Jets and dijets in FoCal,
- Quarkonia and weak bosons,
- direct photon and neutral pion triggered correlations, and
- Long-range correlations

Targetting the TDR

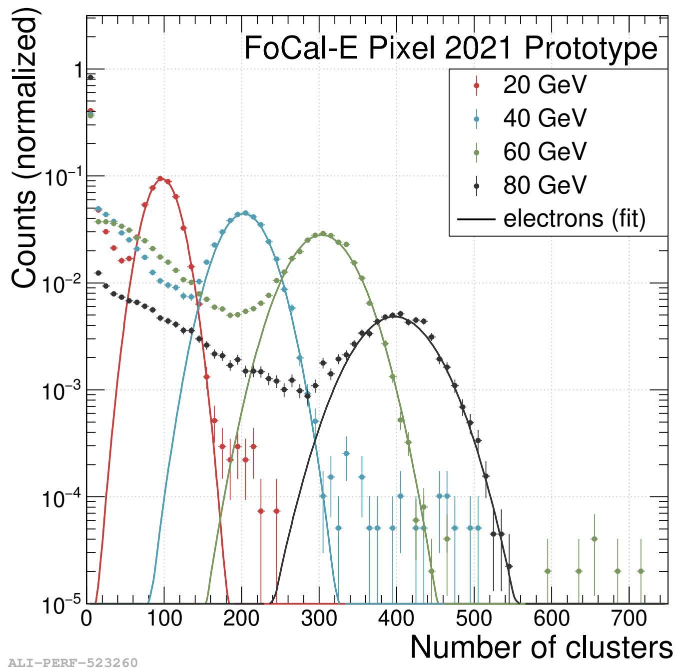
Huge effort in FoCal test beam campaigns

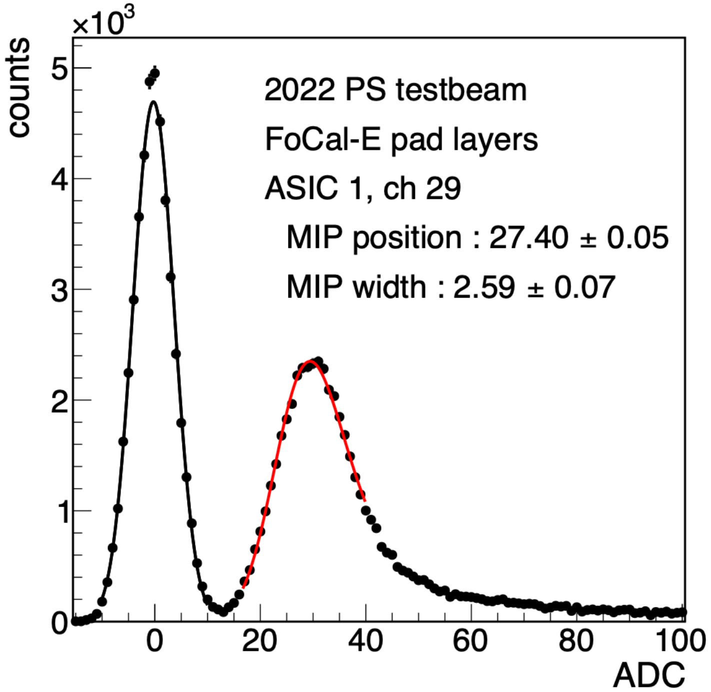


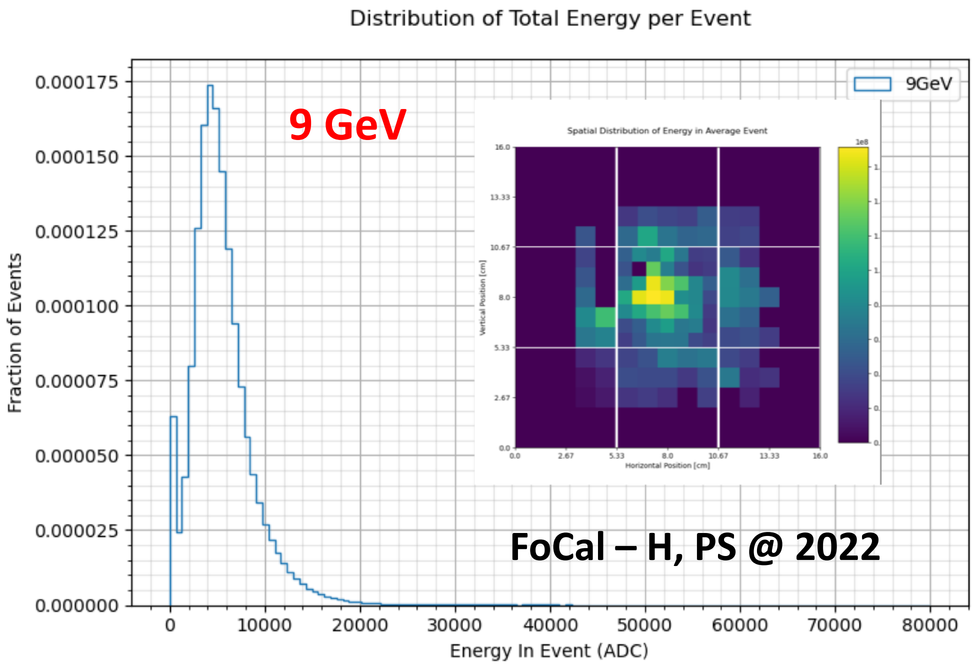
FoCal test beam @ PS, 6-21th June 2022

SPS @ Sep 2021
PS @ Jun 2022
SPS @ Sep 2022
PS @ Sep 2022
SPS @ Nov 2022

FoCal – E and FoCal – H prototypes tested

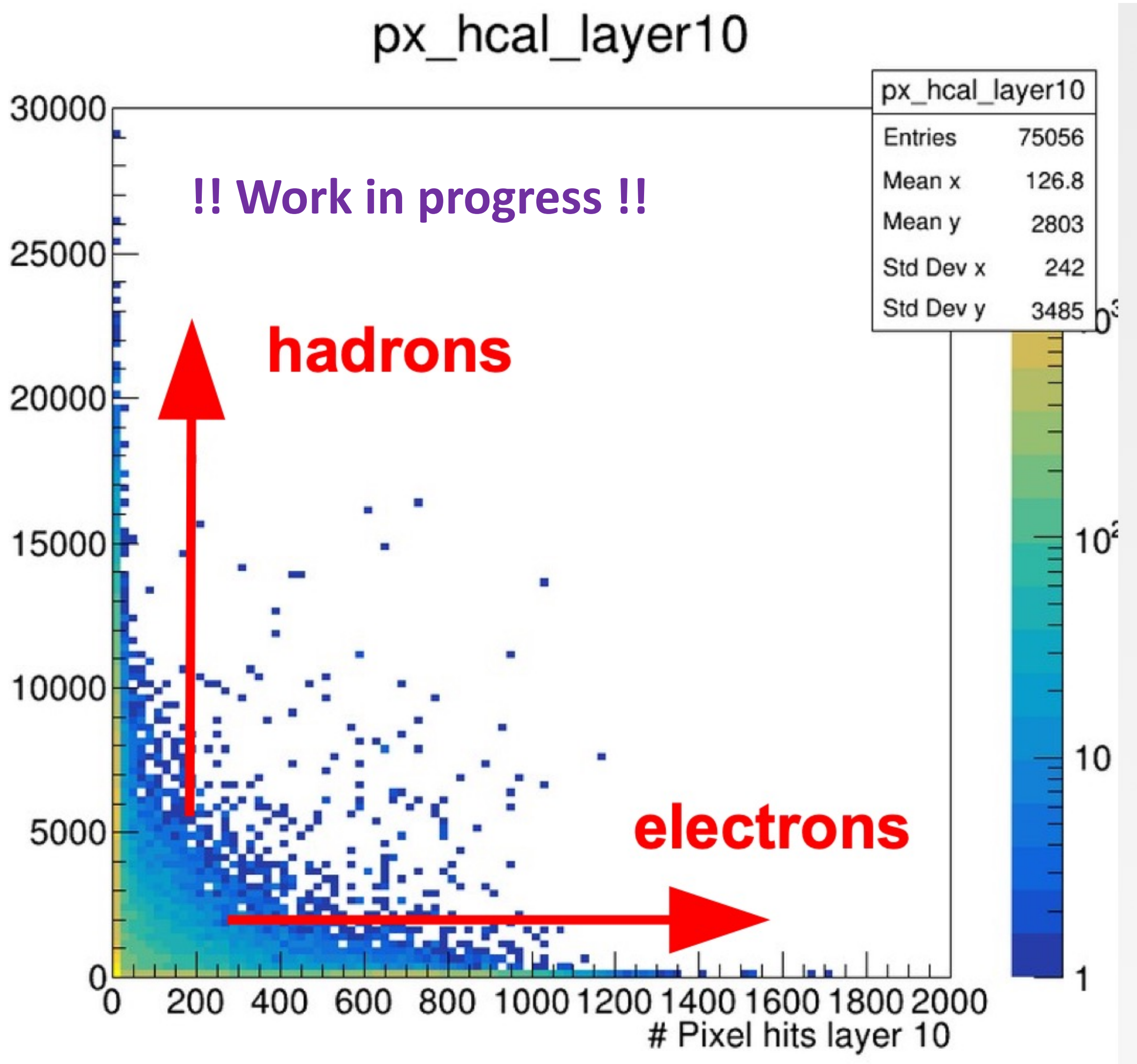


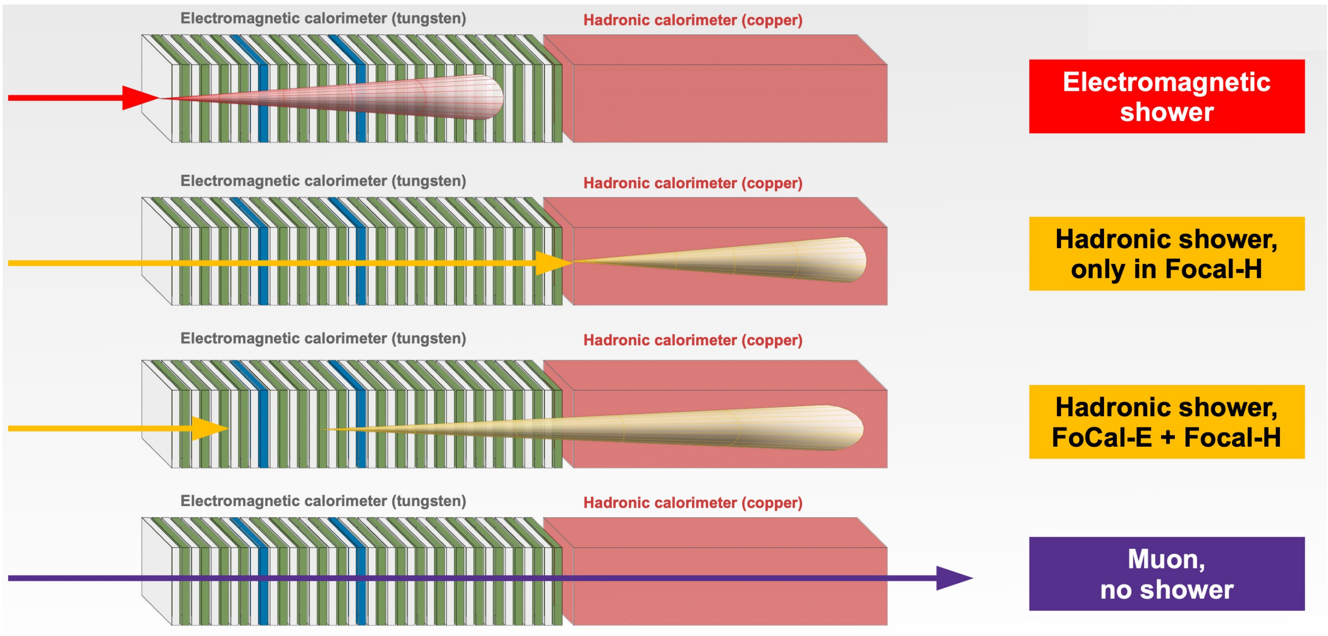




Building the FoCal-H prototype by Copenhagen students

FoCal – E and FoCal – H prototypes working together @ Sep 2022





FoCal E and H prototypes working together

x –axis : number of fired pixels in FoCal-E

y –axis : scintillation light seen by FoCal-H

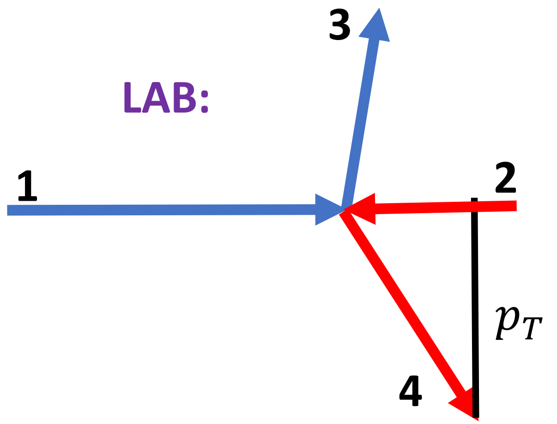
Electrons typically do not reach FoCal-H, hadrons leave smaller signal in FoCal-E

Summary:

- FoCal has a unique and extensive forward physics program at high energies:
  - nPDF's
  - non-linear QCD evolution
  - long-range correlations
  - parton energy loss at forward rapidity
- Performance on inclusive observables (still) most advanced,
  but performance in physics analysis on-going
- Intensive test beam campaign on-going

Backup:

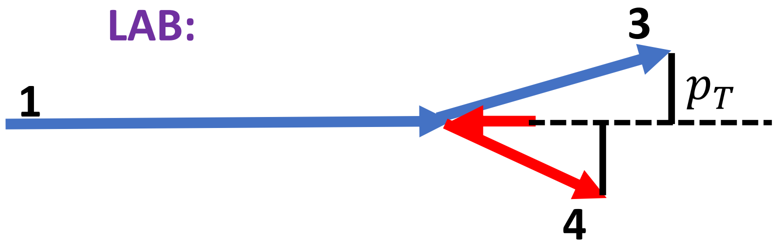
Reaching low-x : kinematics of hard 2-to-2 partonic process



Conservation of energy and longitudinal momentum:

$$x_1 = \frac{p_T}{\sqrt{s}}(e^{\eta_3} + e^{\eta_4})$$
$$x_2 = \frac{p_T}{\sqrt{s}}(e^{-\eta_3} + e^{-\eta_4})$$

Rule of a thumb: when $\eta_3 \approx \eta_4 \equiv \eta \gg 1$, "large" and "small" x

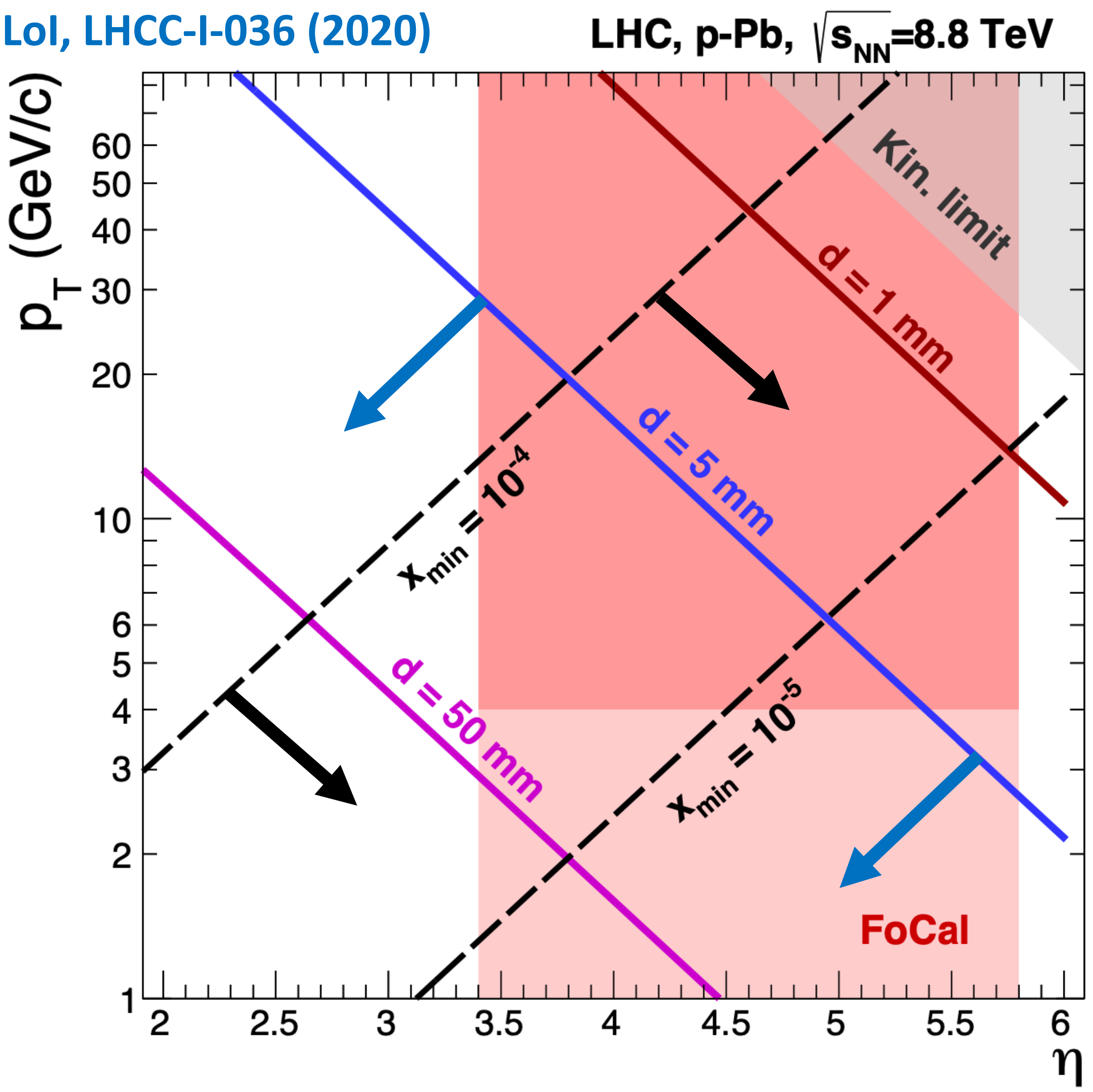


$$x_1 \approx \frac{2p_T}{\sqrt{s}} e^{+\eta} \gg 0$$
$$x_2 \approx \frac{2p_T}{\sqrt{s}} e^{-\eta} \ll 1$$

<u>Target</u>: high collision energy, low-p_T and large rapidity.

Need an excellent two-photon separation in FoCal – E

LoI, LHCC-I-036 (2020)



Experimentally, π^0's detected via 2-γ decay

$$\pi^0 \rightarrow \gamma + \gamma$$

Asymptotically, two-photon opening angle

$$\theta \sim \frac{2}{\gamma}\text{, where gamma factor } \gamma = \frac{E_\pi}{m_\pi} \sim \frac{p_T}{2m_\pi} e^{\eta}$$

=> cluster distance $d \sim \theta \times$(7 meters)

Illustration: given minimum cluster distance d_{min}

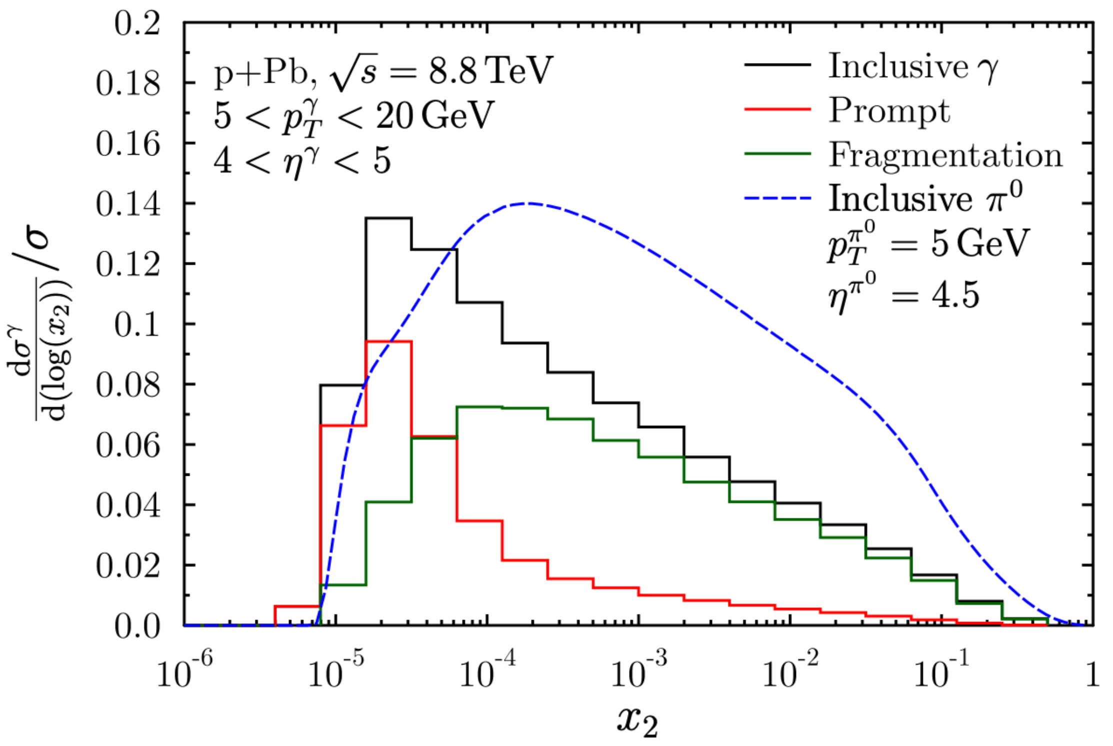
$$p_{T,max} \sim \frac{4 \times (7\text{ m})}{d_{min}} m_\pi e^{-\eta}$$

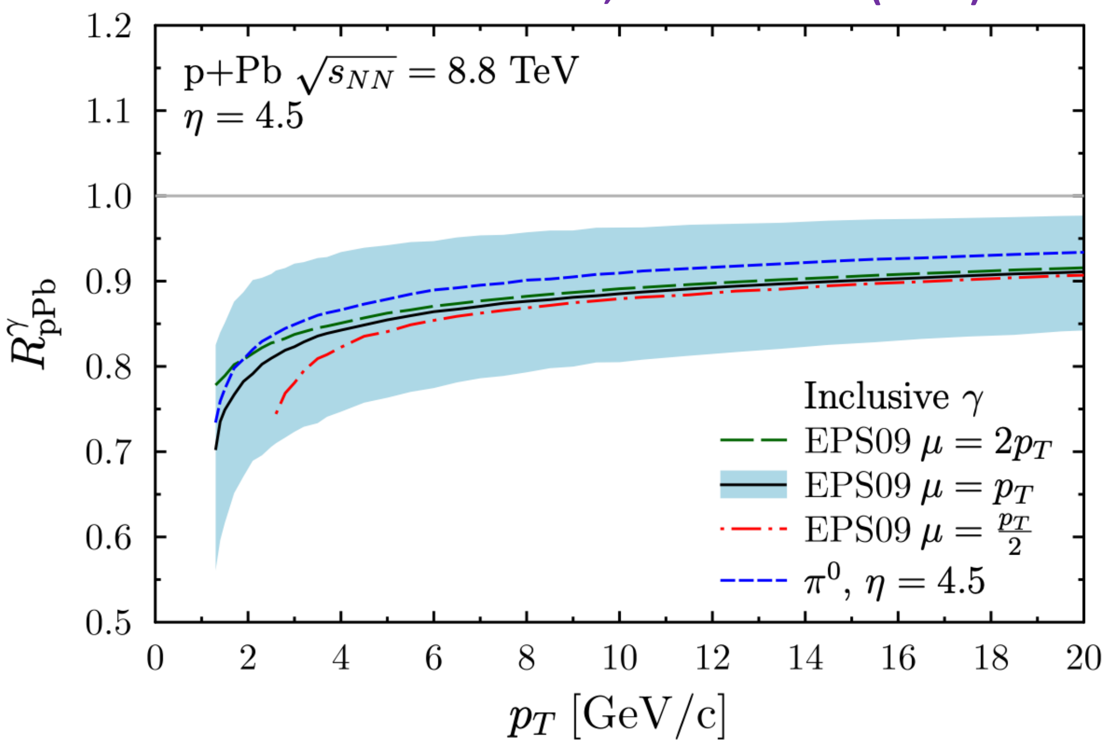
or desired typical x –scale to be probed

$$p_{T,max} \sim \frac{x_{min}\sqrt{s}}{2} e^{+\eta}$$

Direct photon R_{pPb} – nPDF's + pQCD

Helenius, et al. JHEP 09 (2014) 138



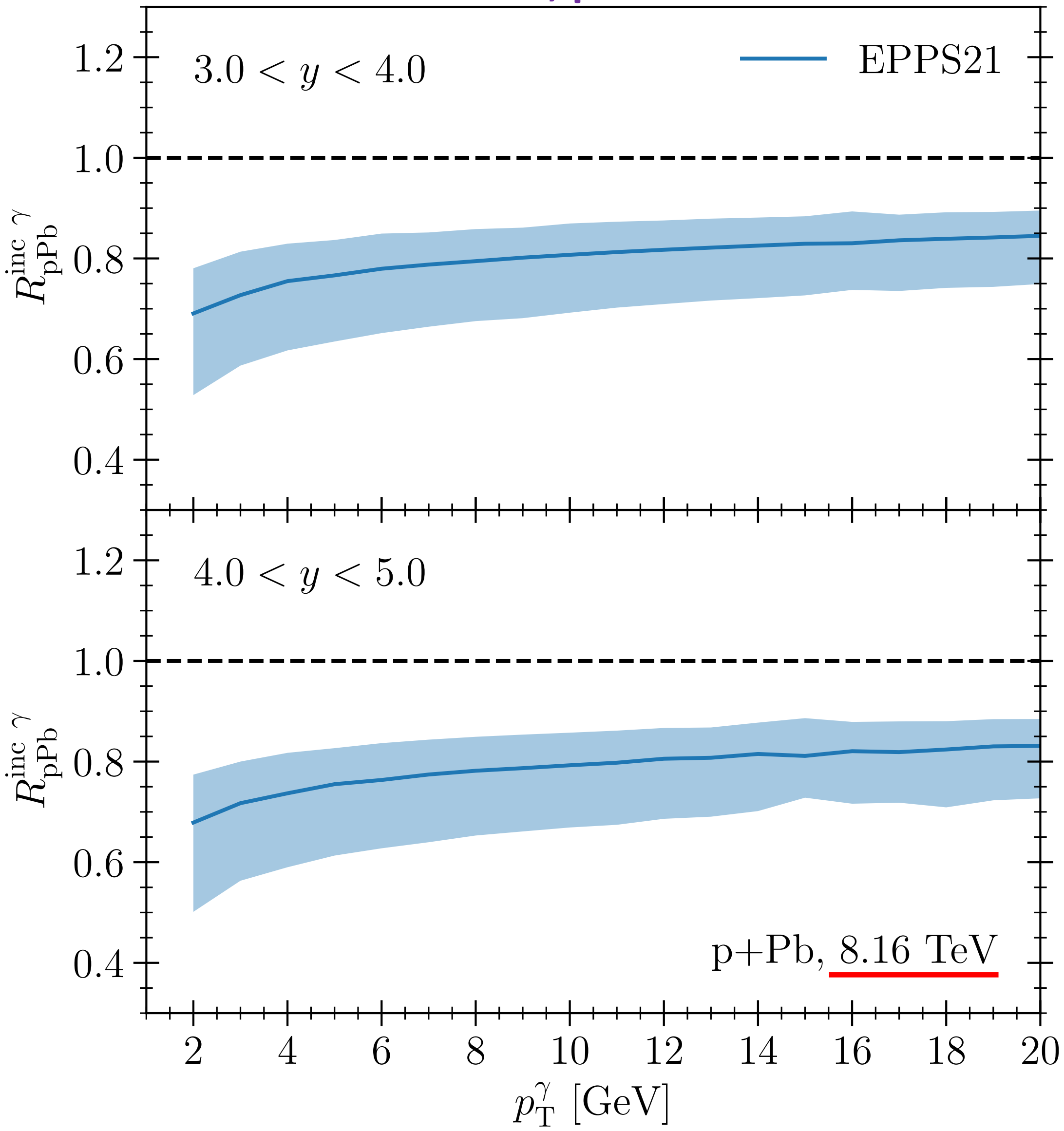


Note: here "inclusive γ" = inclusive direct = prompt + fragmentation

Prompt photons have, on the average, smaller average <x_2> compared to fragmentation photons

Direct photon R_{pPb} with nPDF's + pQCD – update to EPPS21:

I. Helenius, private communication



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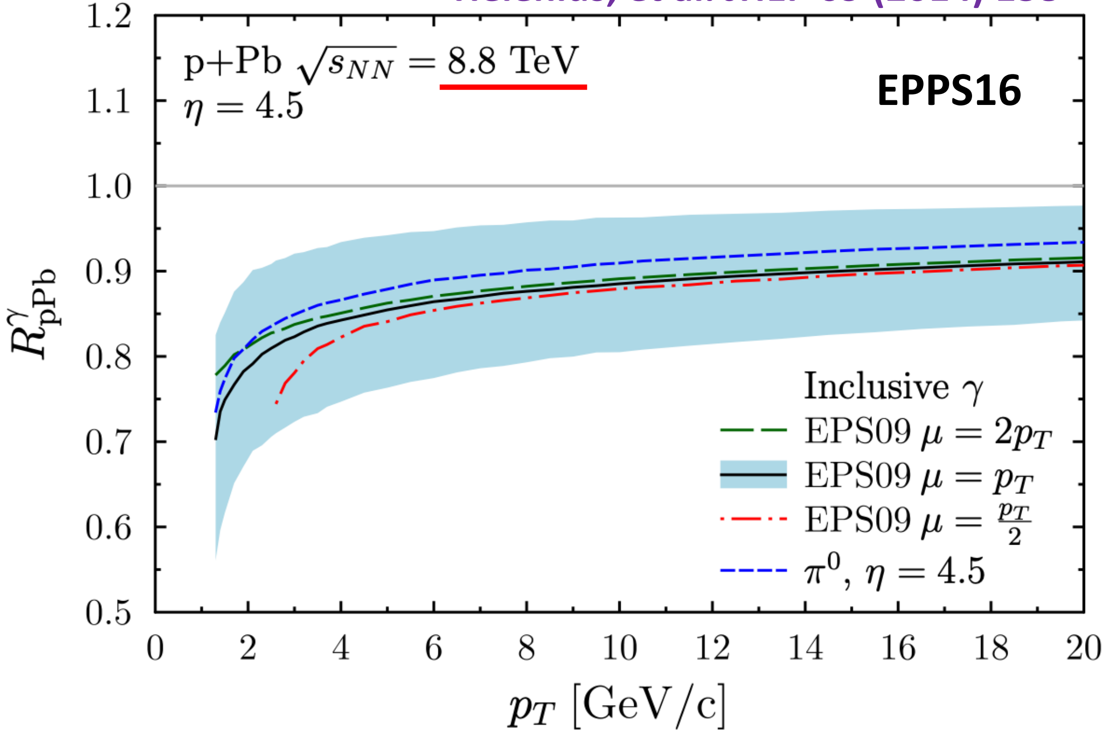

Here: "inclusive γ" = prompt + fragmentation, i.e. decay photons not included

(At tree level: prompt = Compton + annihilation)

Level of suppression similar to π^0's