Small-x structure of nuclei and the Forward Calorimeter in ALICE

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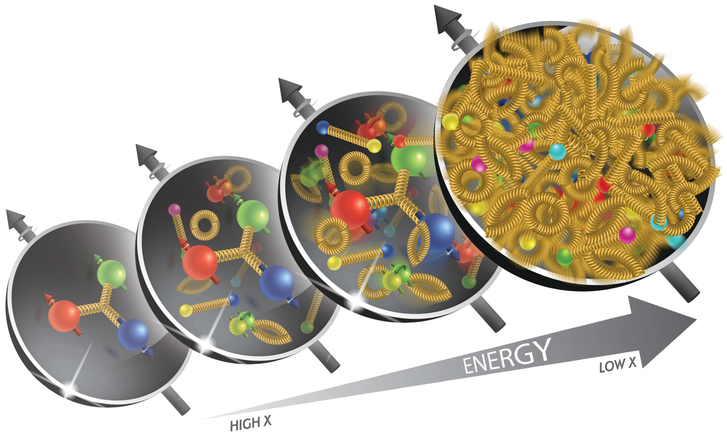
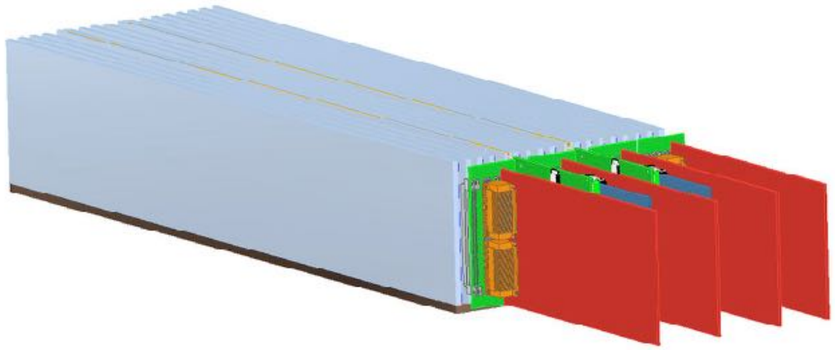
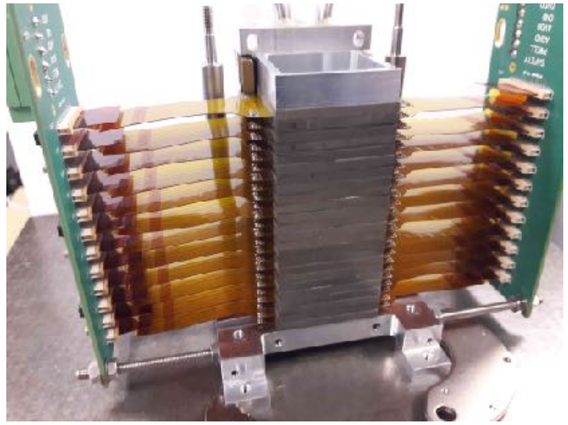
Colloqium Yonsei University

01.12.2021 (v1)



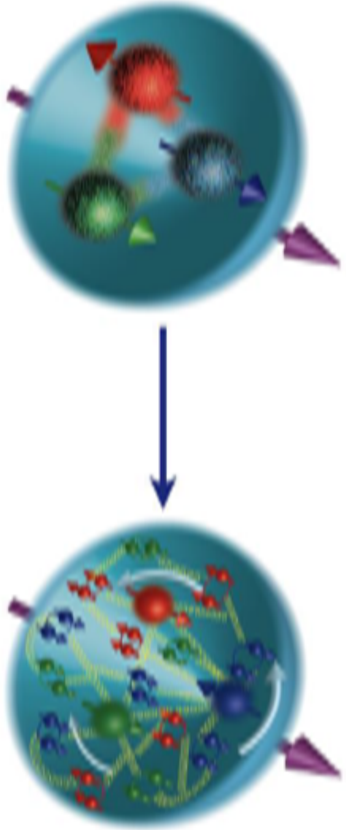




Proton structure: Parton density functions

- Protons and neutrons are *composite particles*, consisting of:
  - **quarks**: (*up, down, strange*…) carry mass, charge, flavor quantum numbers
  - **gluons**: mediate *interaction*; bind quarks together

e.g. proton = uud + gluons



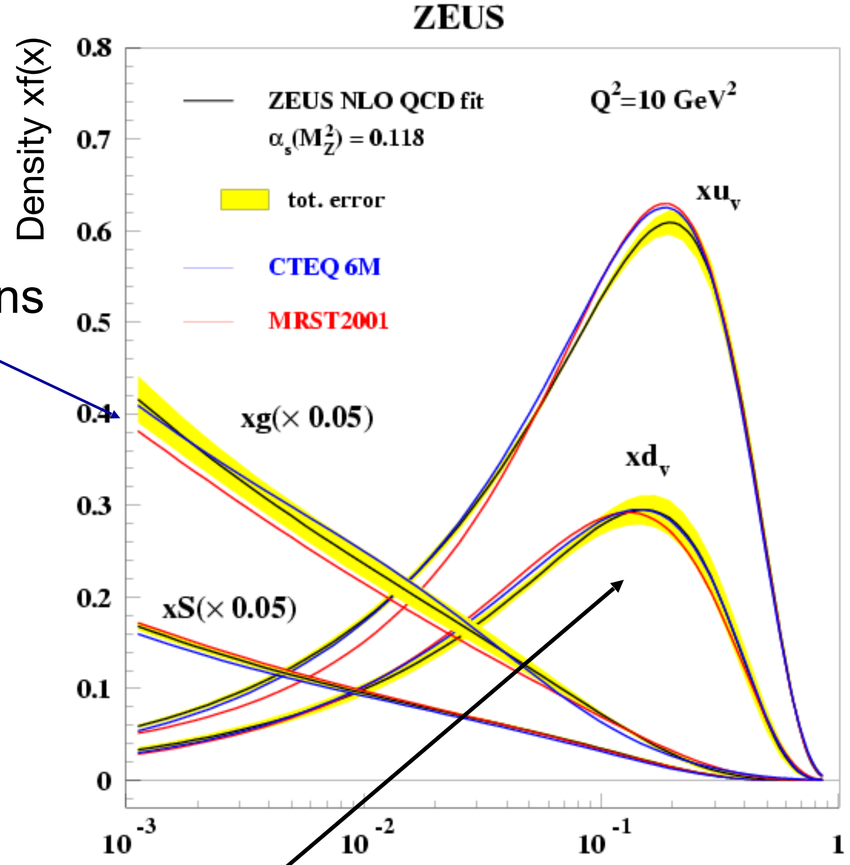
- Proton structure is specified by **Parton Distribution Functions**
  - *Density* of quarks, gluons, as a function of *momentum* fraction $x = p_{q,g}/p_p$ denoted as $g(x), u(x), \bar{u(x)} \ldots$
  - Density distributions depend on wave length (1/momentum) of probe: Q^2 or μ^2 denoted as $g(x, Q^2) \ldots$
  - Sum rules, e.g flavor sum (eg. $\int (u(x) - \bar{u}(x))\, dx = 2$) apply for each scale Q^2

Parton density functions govern differential cross sections,
i.e. probabilities for particle production as function of momentum

⇒ particle production in collisions *probes the nucleon/nucleus structure*

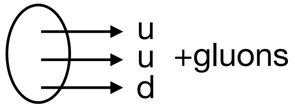
Proton structure: Parton density functions

Low Q^2; long wave length

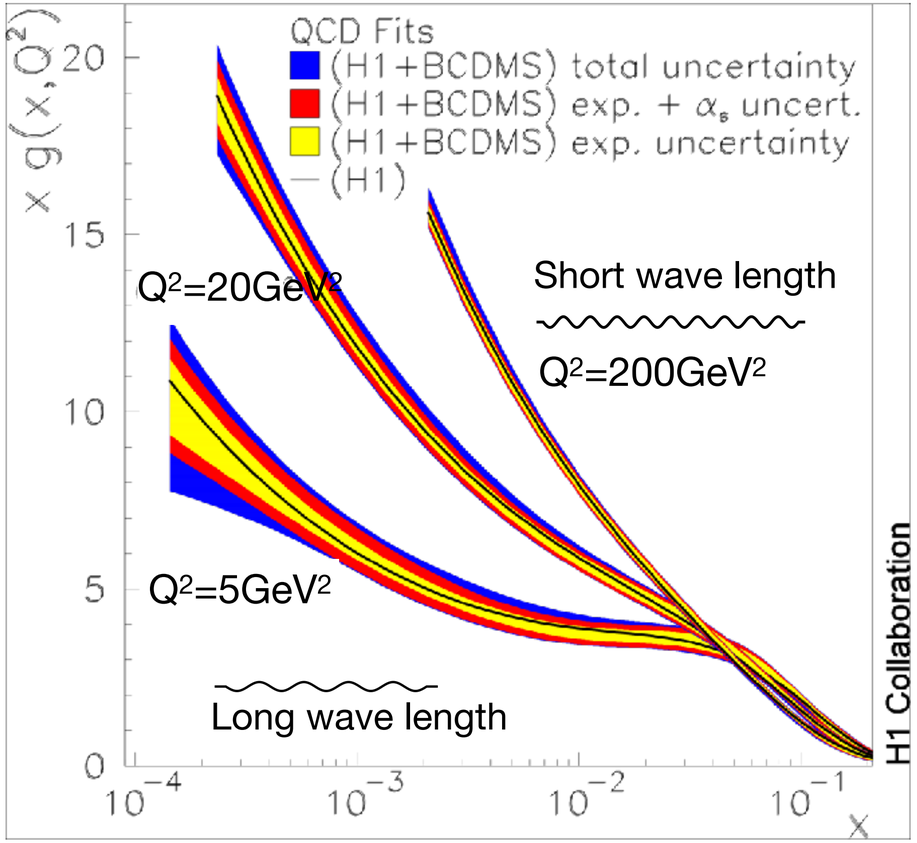


Soft gluons

Valence quarks (p = uud)
x ~ 1/3

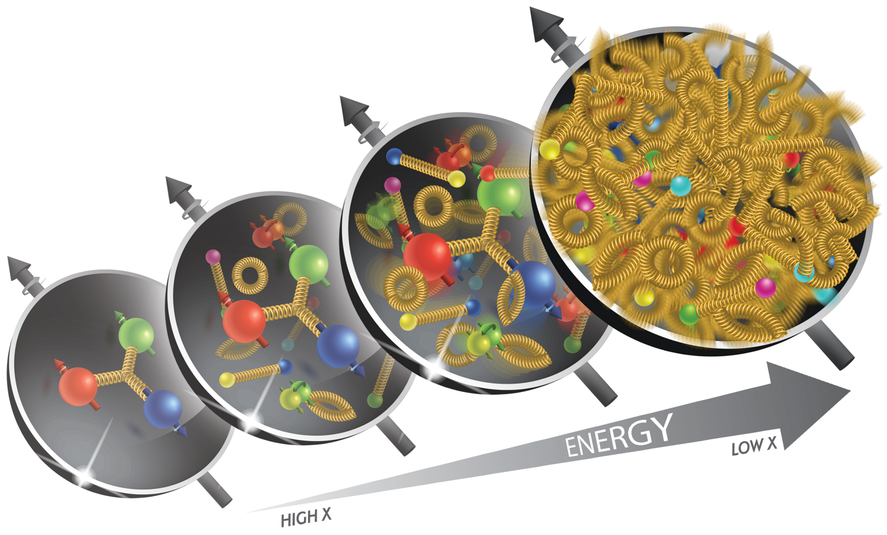


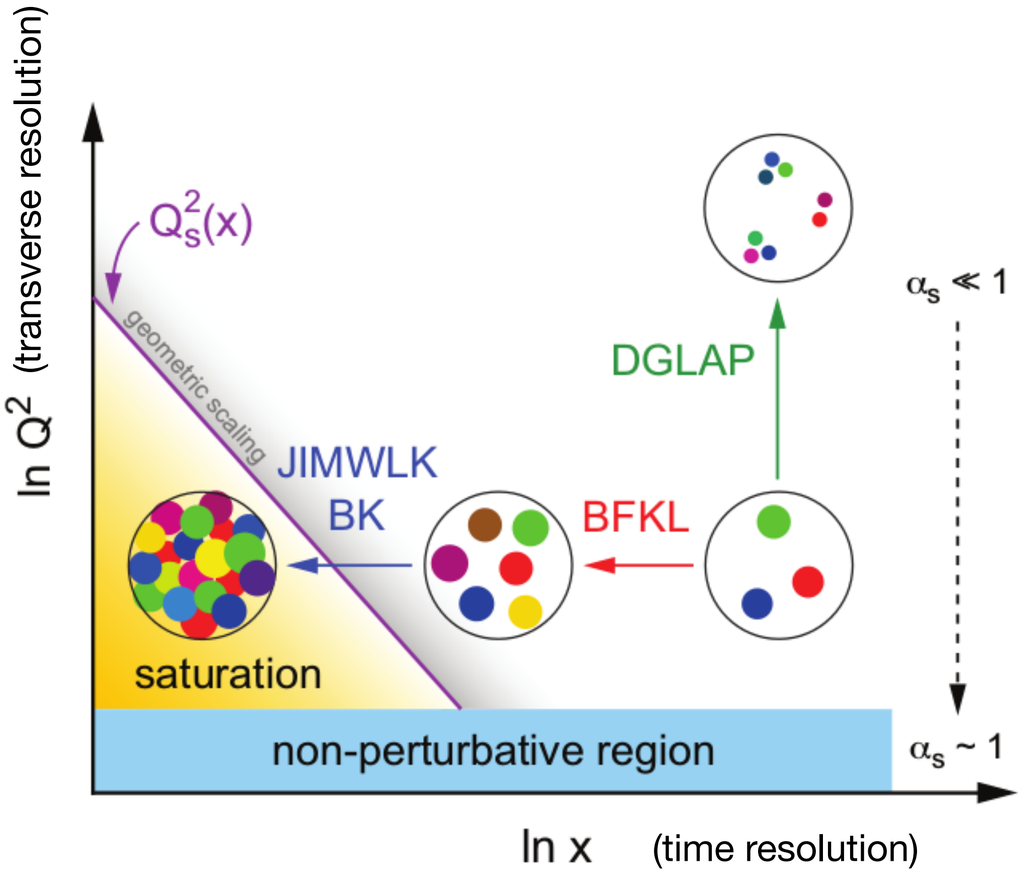
Q^2 evolution (gluons)



Gluon content of proton increases with Q^2

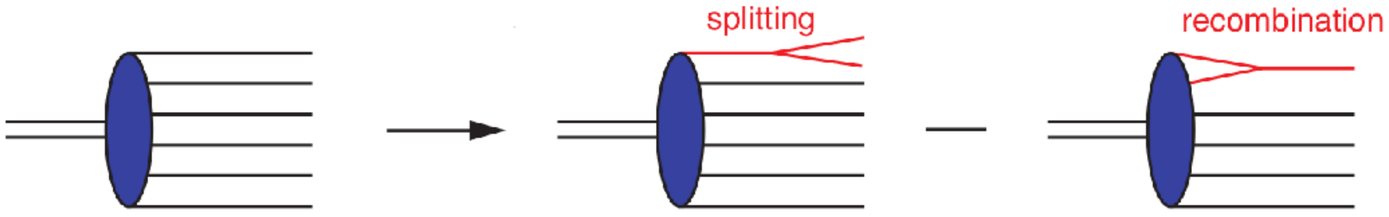
Evolution of the PDFs





Evolution of density functions with x and Q^2 governed by evolution equations:

- DGLAP: linear evolutions: splittings only
- BK/JMWLK: non-linear evolution: gluon fusion



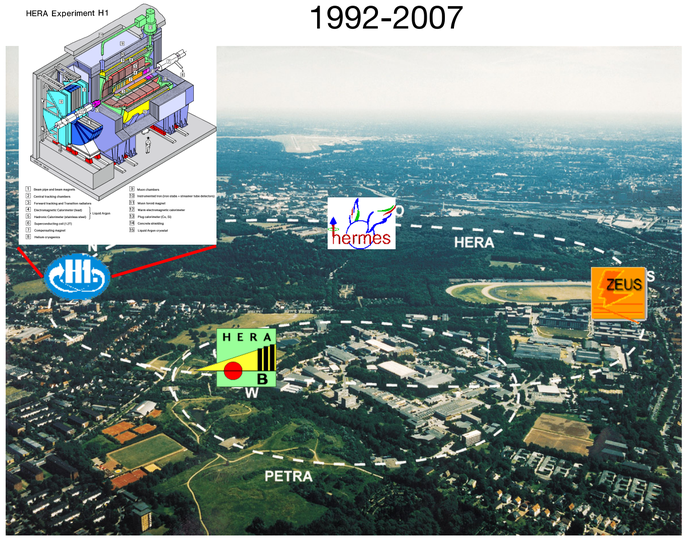
$$\frac{\partial}{\partial Y} N(x, k_T^2) = \alpha_s K_{BFKL} \otimes N(x, k_T^2) - \alpha_s [N(x, k_T^2)]^2$$

Saturation/non-linear evolution at:

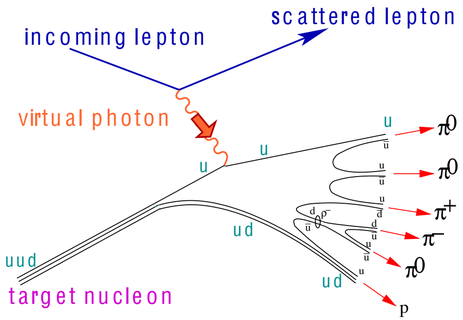
- small x: large gluon density
- small Q^2: large effective gluon size

Colliders for proton and nuclear structure

Hera at DESY, Hamburg
1992-2007



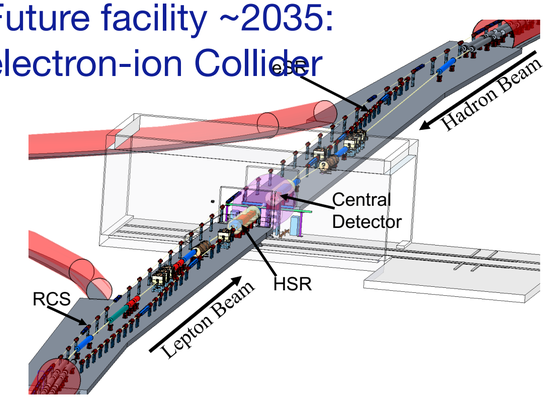
Deeply inelastic scattering
probe proton structure
with electron beams



RHIC, Brookhaven
2000-present

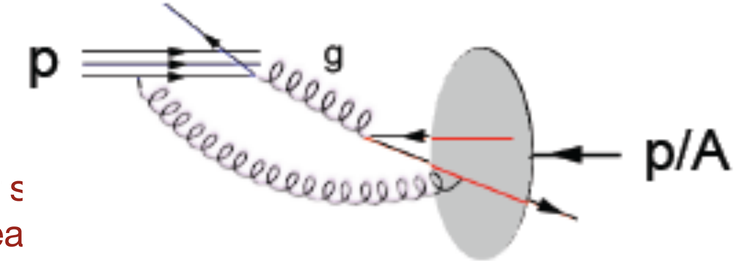
pp, p+Au, d+Au, Au+Au $\sqrt{s_{NN}}$= 200 GeV

Future facility ~2035:
electron-ion Collider



LHC, Geneva
2009-present

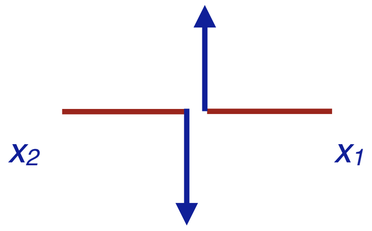
pp, p+Pb, Pb+Pb $\sqrt{s_{NN}}$= 2760-14000 GeV



p+A: probe nuclear s
with proton bea

Two-parton kinematics in pA collisions

Both outgoing partons at mid-rapidity

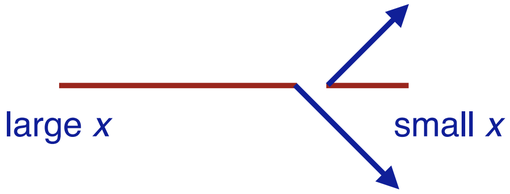


Both incoming partons at moderate x

$$\hat{s} = x_1 x_2 s \approx (2 p_{\mathrm{T}})^2$$

$$x_1 \approx x_2 \approx \frac{2 p_T}{\sqrt{s}}$$

Both outgoing partons at forward rapidity

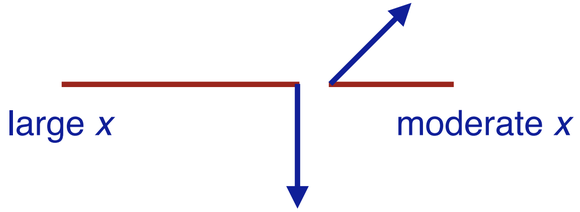


Boosted configuration:
One small-x, one large-x parton

$$\hat{s} = x_1 x_2 s \approx (2 p_{\mathrm{T}})^2$$

$$x_1 \approx \frac{p_T}{\sqrt{s}} e^{-y}$$

One parton forward, one closer to mid-rap



Large mass final state

$$Q^2 = \hat{s} > (2 p_{\mathrm{T}})^2$$

small probability

Note: 2 to 2 scattering is LO kinematics; NLO processes add additional freedom/smearing

RHIC forward particle suppression

Gluon density larger in nuclei:
compare nuclei to protons

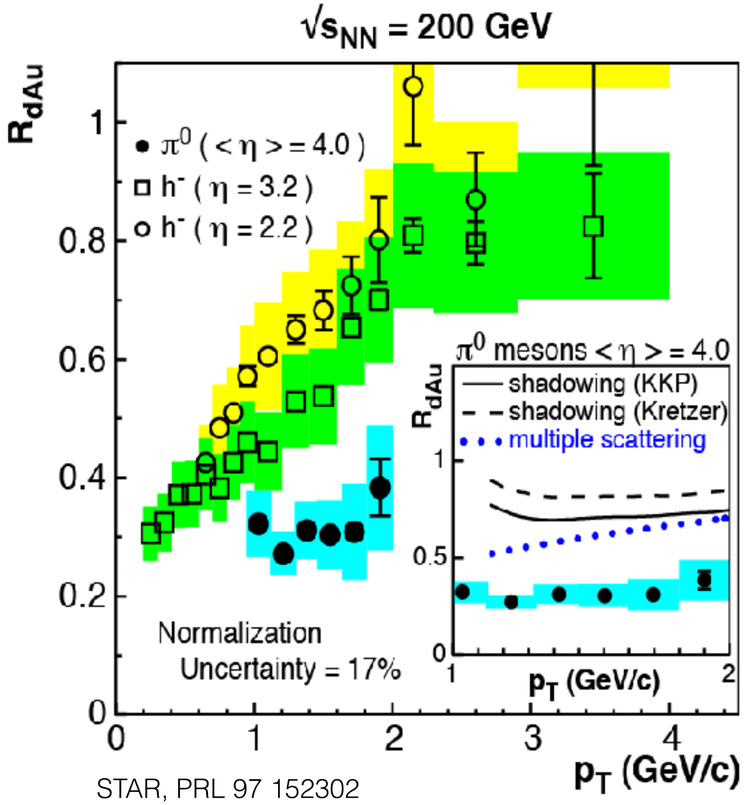
$$Q_s^2 \approx \frac{xG_A(x,Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda}$$

- Nuclear modification factor R_{dAu}

$$R_{dAu} = \frac{dN/dp_T|_{dAu}}{A\, d\sigma/dp_T|_{pp}}$$

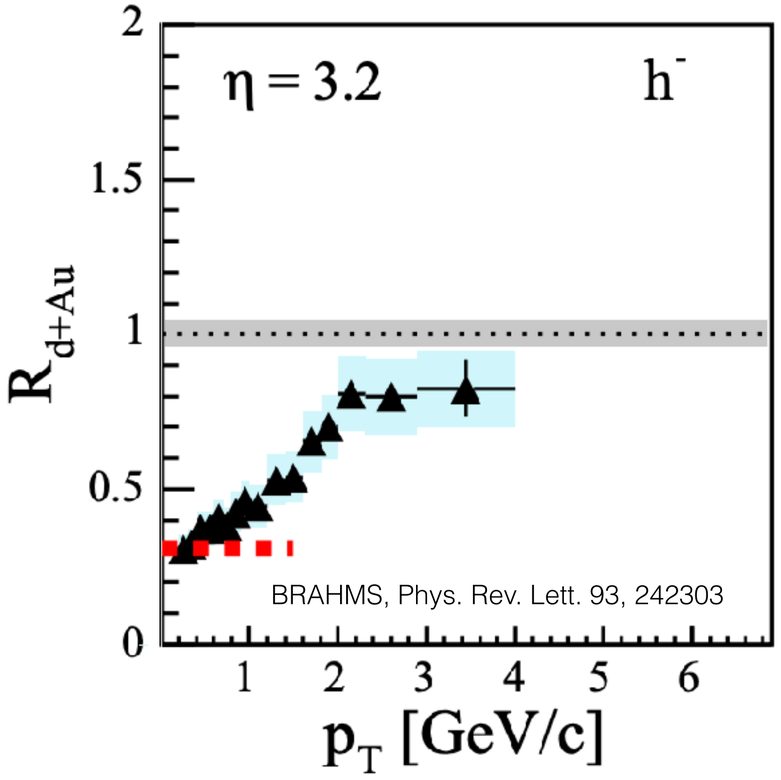
- Yield suppression $R_{dAu} < 1$ seen at RHIC

STAR: charged hadrons, π^0



STAR, PRL 97 152302

BRAHMS: charged hadrons

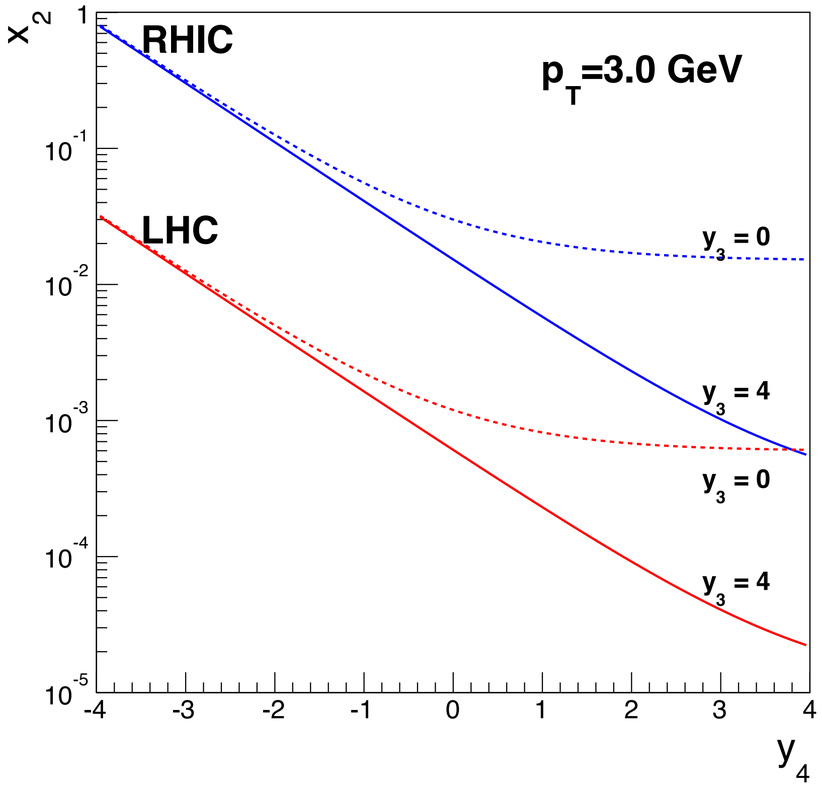


BRAHMS, Phys. Rev. Lett. 93, 242303

First hint of saturation
… at very low p_T; other effects might play a role
⇒ Can we confirm this at LHC?

Probes x ~ 10^{-3}

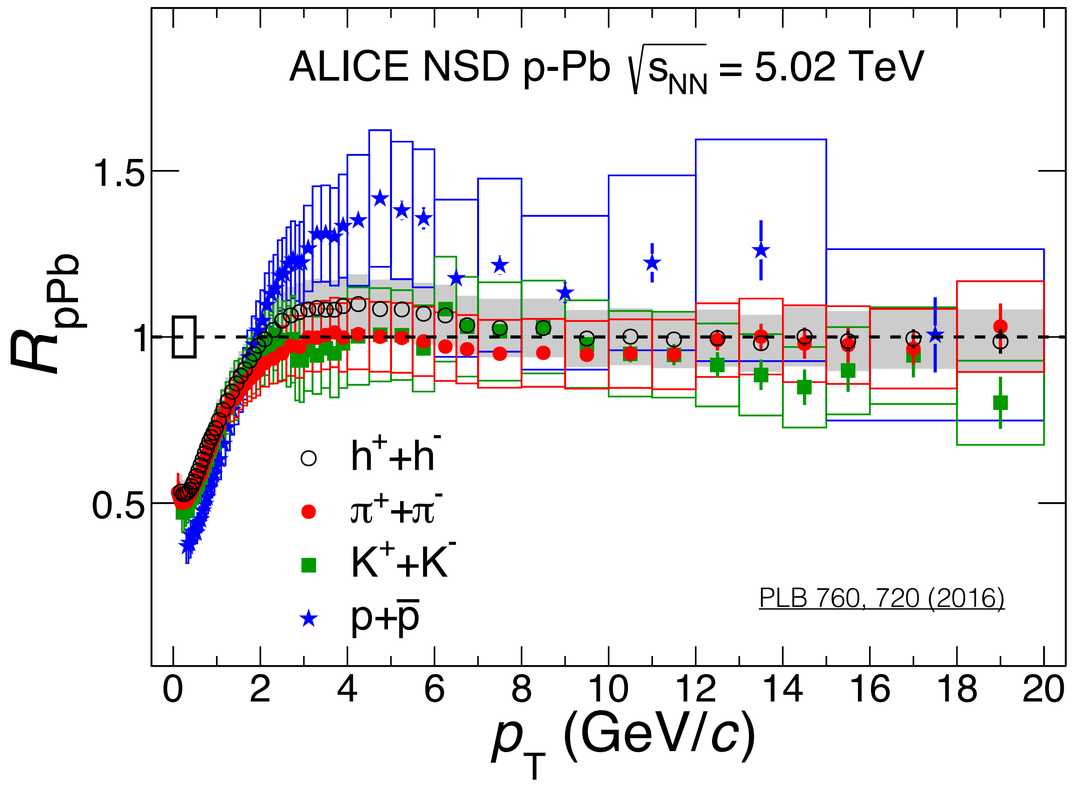
RHIC and LHC for x~10^{-3}



$$x_2 \approx \frac{p_T}{\sqrt{s}} \left(e^{-y_3} + e^{-y_4}\right)$$

Mid-rapidity at LHC ≈ forward rapidity at RHIC

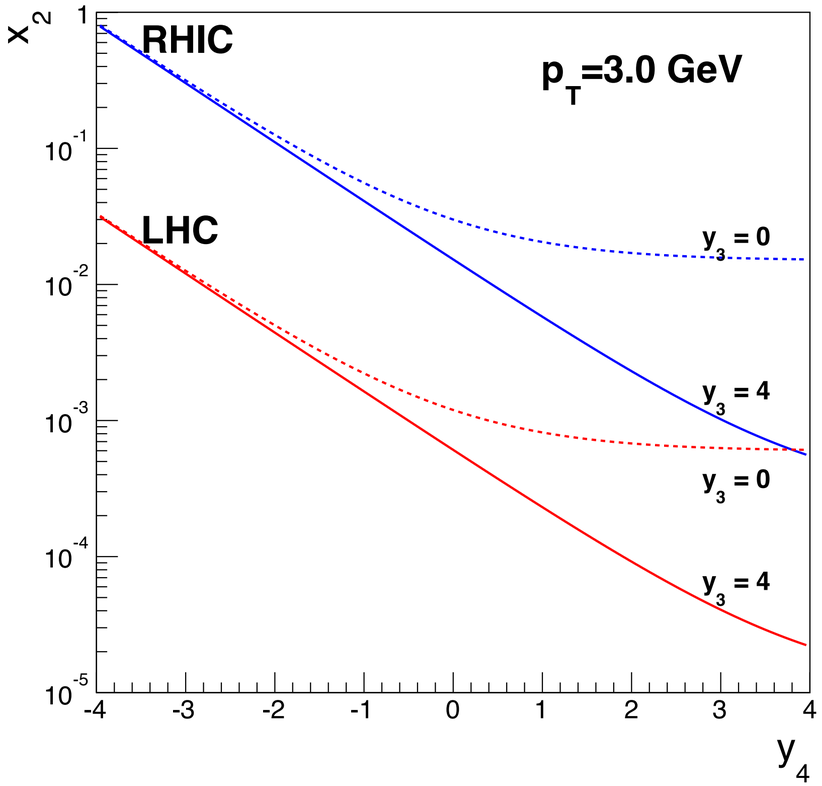
Light-flavour R_{pPb}



No sign of suppression at high p_T > 2 GeV

p_T < 2 GeV expect soft effects; N_{part} scaling

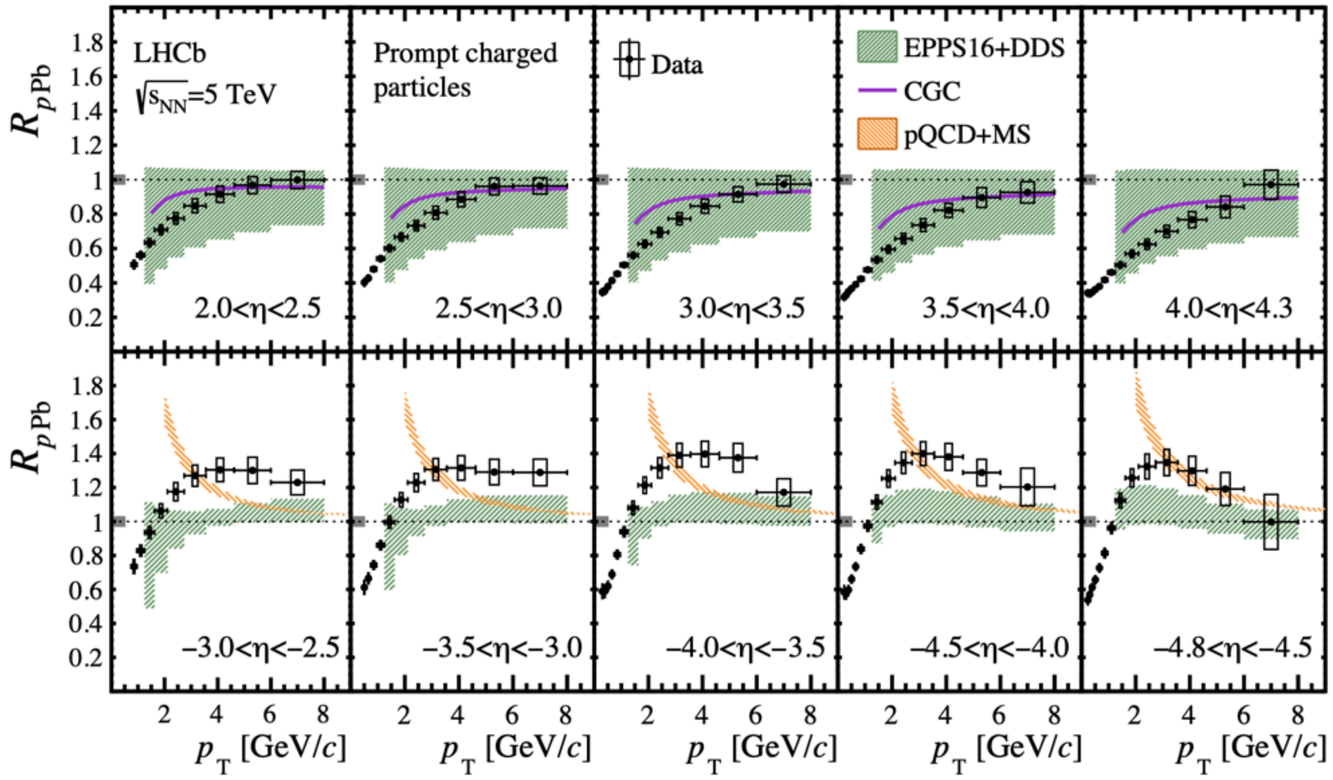
RHIC and LHC for x~10^{-4}



$$x_2 \approx \frac{p_T}{\sqrt{s}} \left(e^{-y_3} + e^{-y_4}\right)$$

Mid-rapidity at LHC ≈ forward rapidity at RHIC

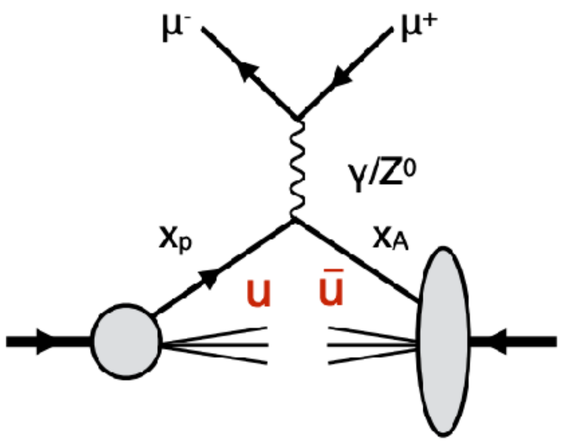
LHCB, arXiv:2108.13115



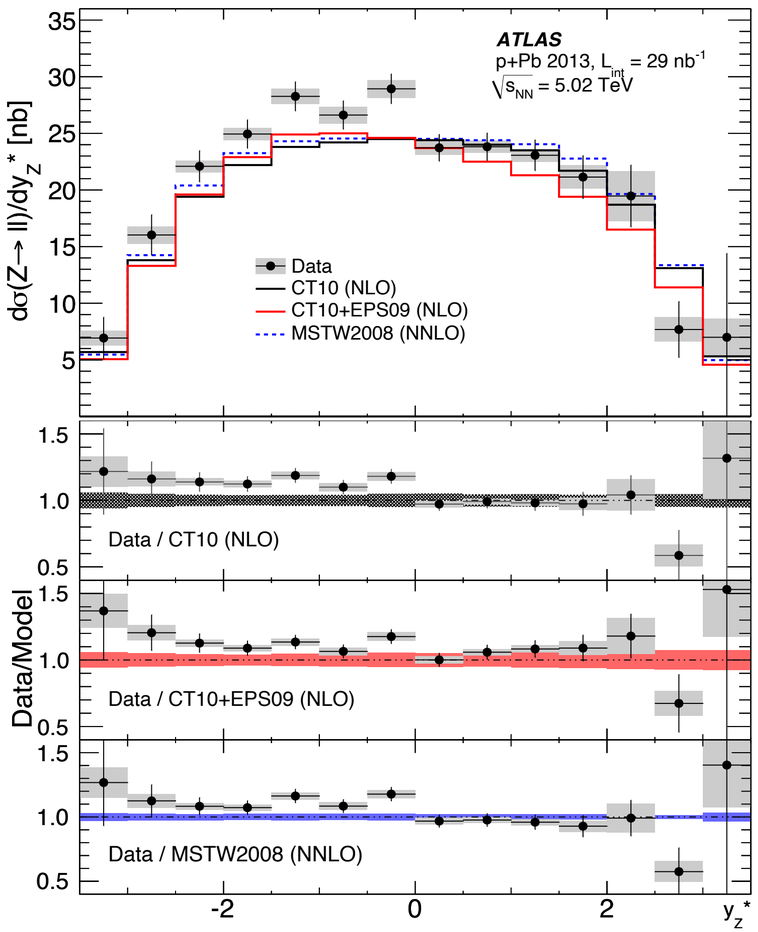
Sign of suppression at high p_T > 2 GeV in forward direction consistent with EPPS16 and CGC calculation

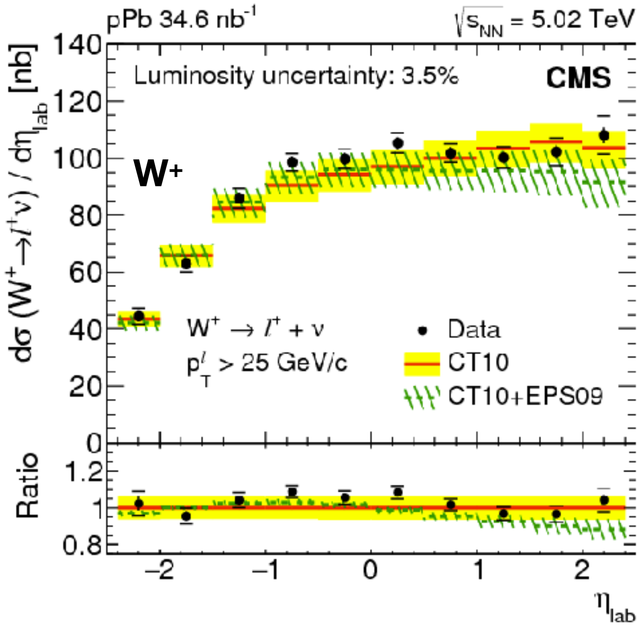
NB: Backward dependence not described by higher twist model that reproduces RHIC data in pAu

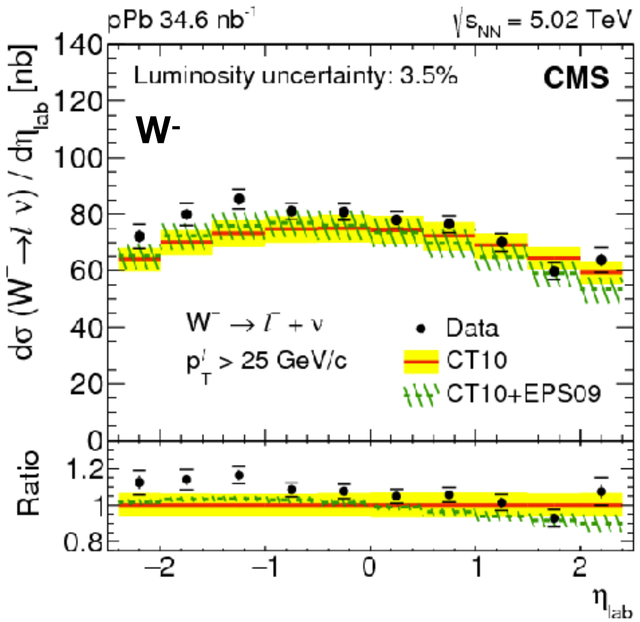
Electroweak probes: large Q^2



Electroweak boson production: Z, W probe quark structure of the nucleus at energy scale m_Z, $m_W \approx 90$ GeV

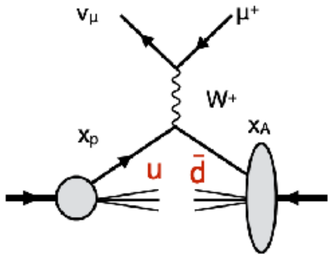






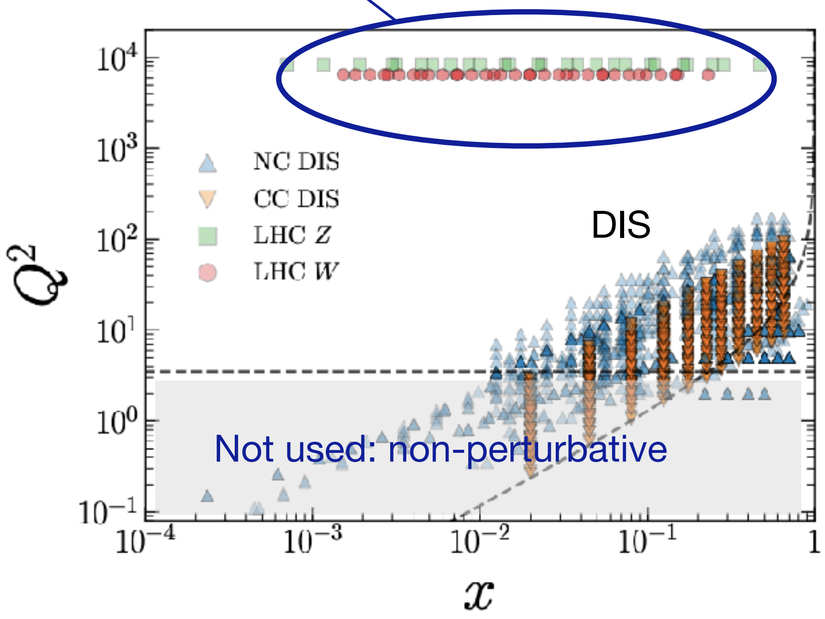
Measurements agree with expectations for pp (no nuclear modification) and nuclear PDFs

No/very small nuclear effect at large Q^2/small wave length



Putting it all together: Nuclear PDFs

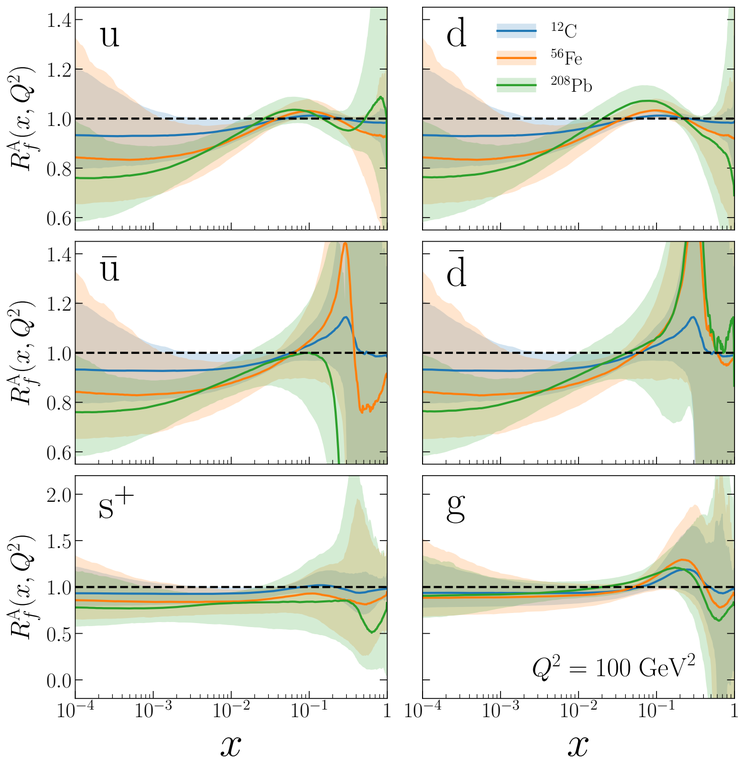
LHC electroweak data



NB: EPPS16 includes also hadron data at midrapidity from RHIC and LHC

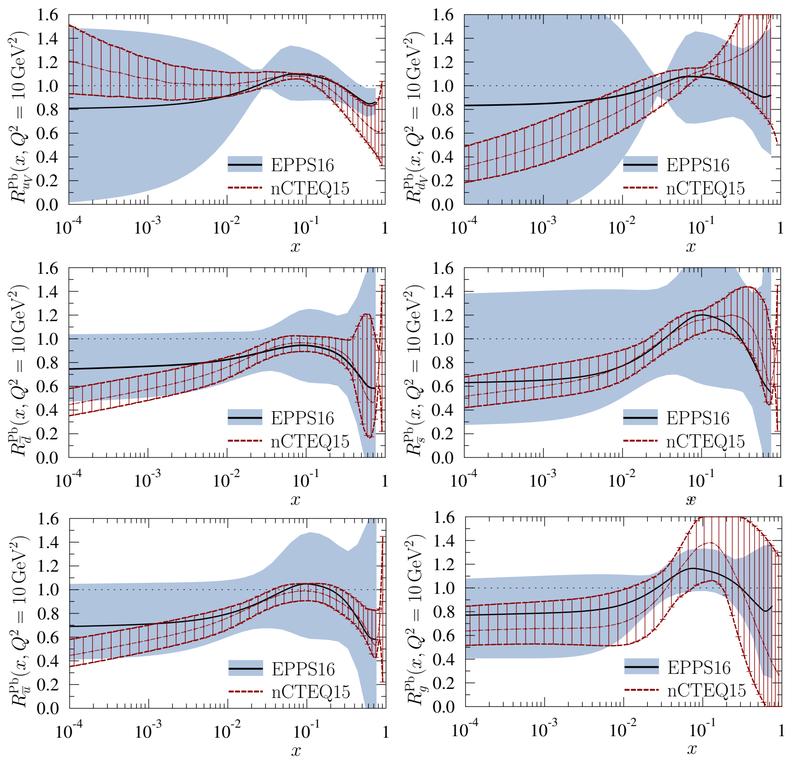
Nuclear modification factor for parton densities

nNNPDF2.0



R.A. Khalek, J.J. Ethier et al, arXiv:2006.14629

EPPS16 + nCTEQ15

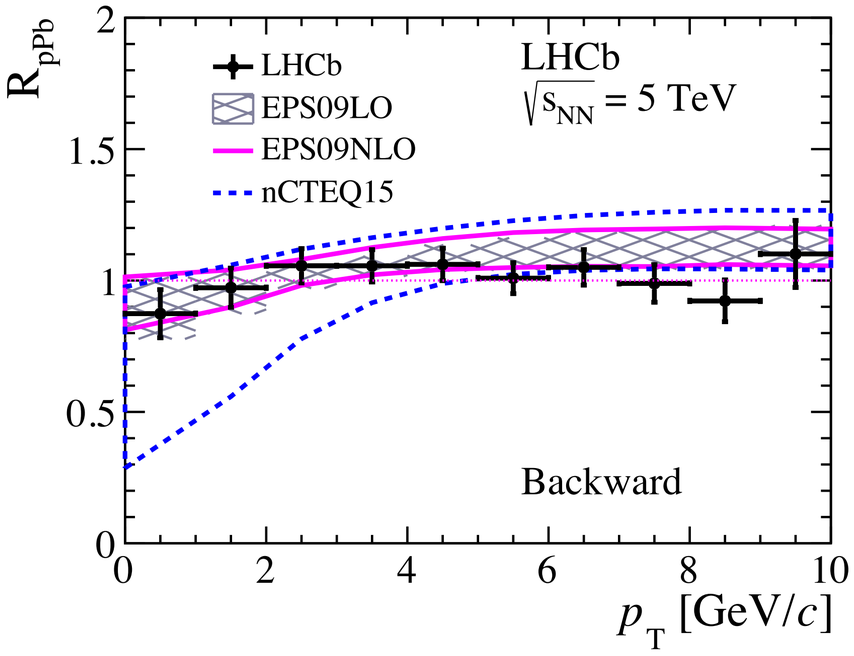


Eskola, Paakkinen, Puakkunen, Salgado, EPJC 77, 163

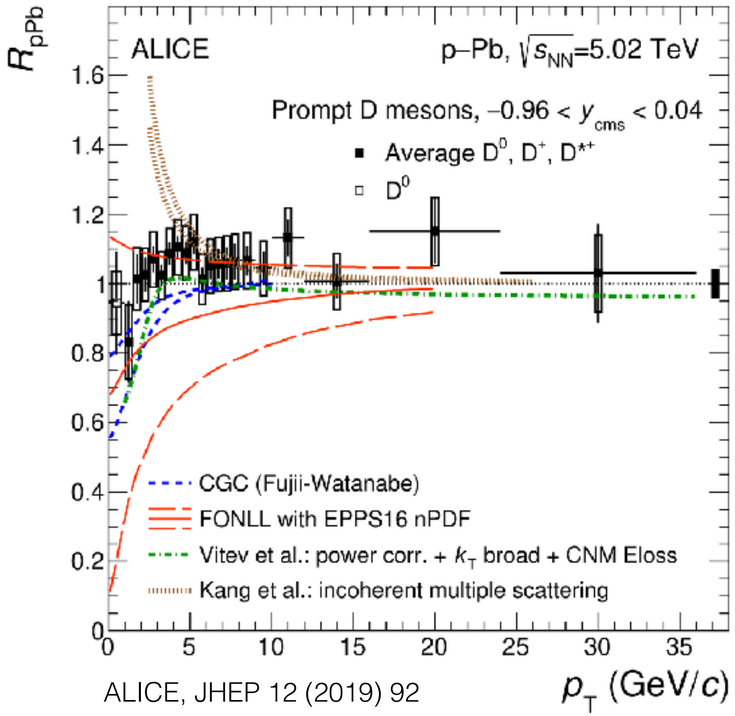
Nuclear PDF fits: combine experimental inputs to map the parton densities in nuclei

Open charm production at LHC

Backward rapidity: large x

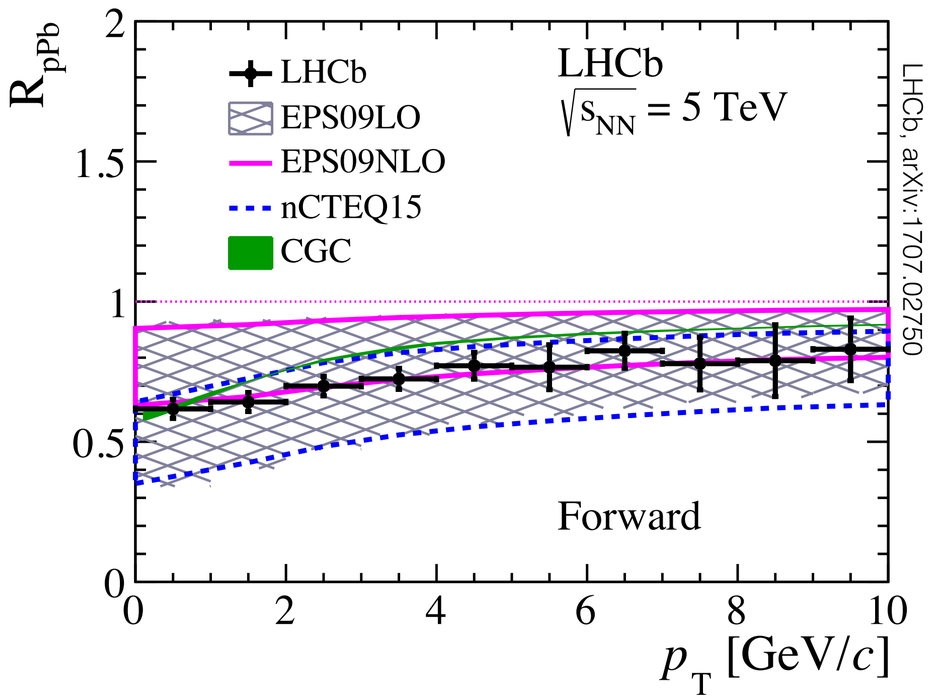


Mid-rapidity



ALICE, JHEP 12 (2019) 92

Forward rapidity: small x



LHCb, arXiv:1707.02750

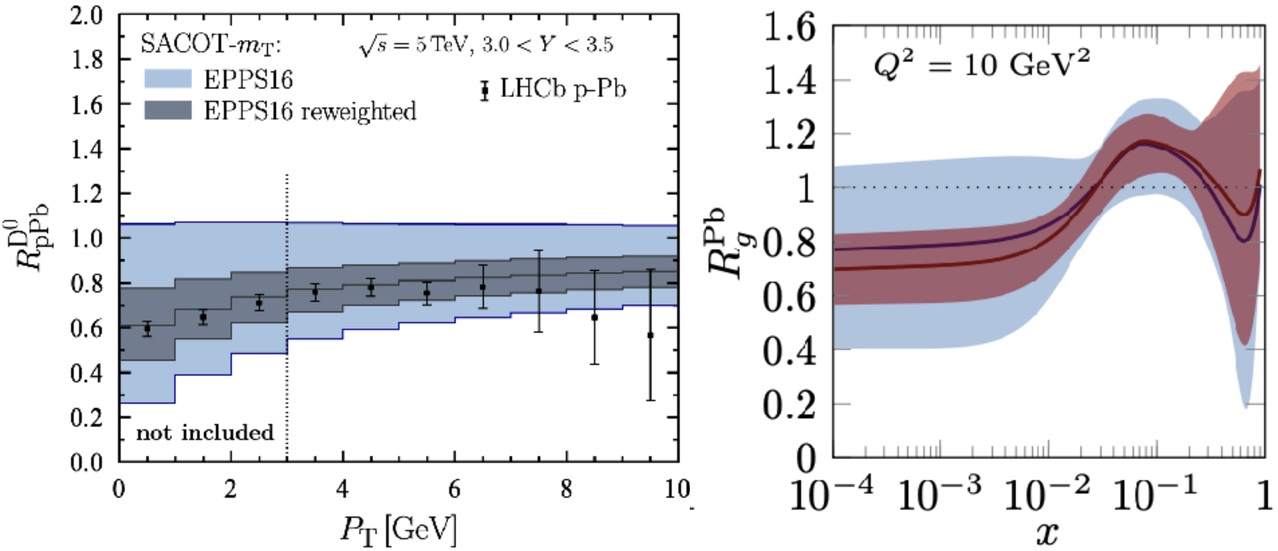
R_{pPb} ~ 1 at backward and mid-rapidity; below 1 at forward rapidity

Suppression at large rapidity compatible with gluon suppression
(in line with nuclear PDFs/shadowing and CGC calculations)

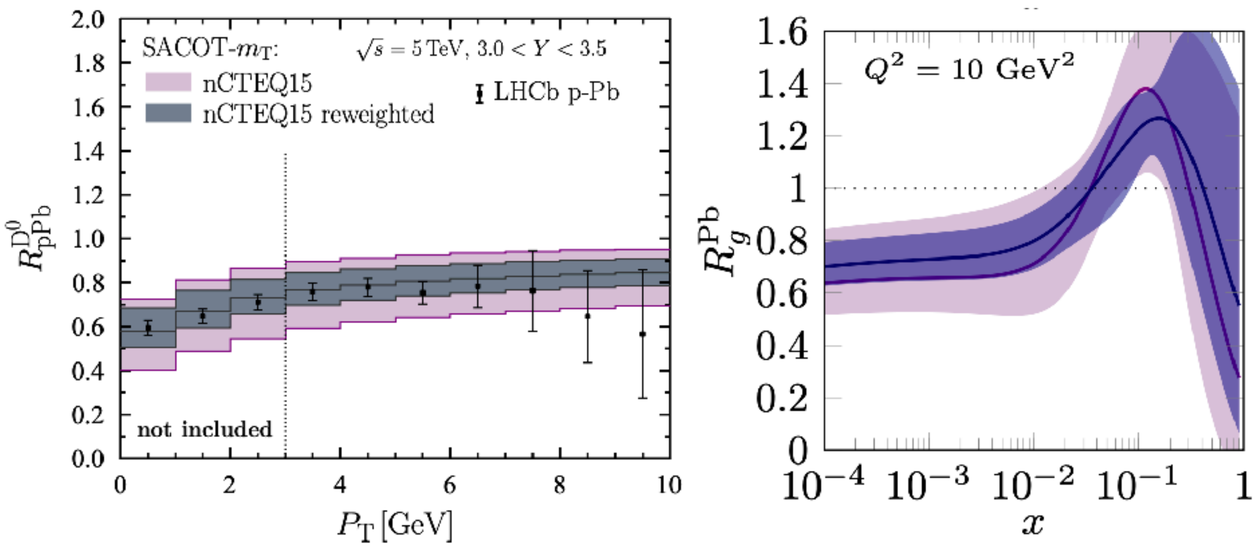
CGC: Decloue et al, PRD 91, 114005

PDF reweighting with charm data

EPPS16 reweighting



nCTEQ15 reweighting



Eskola, Helenius et al, JHEP 05 (2020) 037

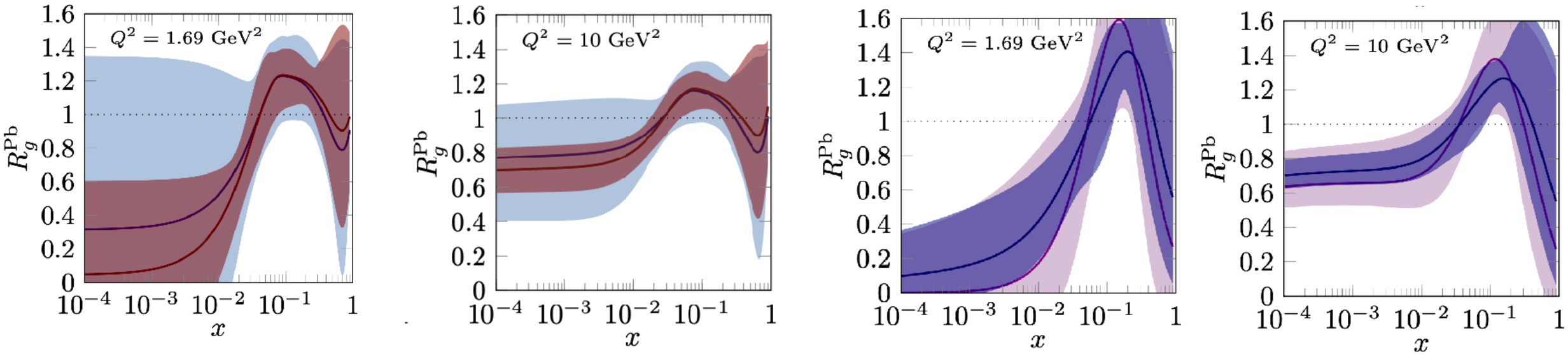
Forward charm data brings significant constraints; prefer shadowing with $R_g \sim 0.7$ at $x < 5\ 10^{-3}$ ($Q^2 = 10$ GeV)

Q2 dependence: Extrapolation to small Q

(large wave length)

EPPS16 reweighting

nCTEQ15 reweighting



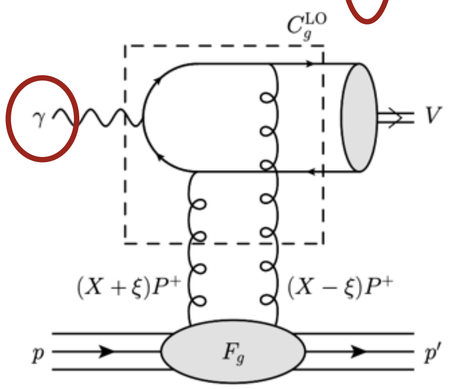
Charm reweighted PDFs show strong dependence on Q^2
due to DGLAP evolution

Can we test this experimentally? How low in Q^2 do we trust the formalism?

Ultra-peripheral collisions: a photon beam from Pb

Photon emitted by Pb nucleus

$$\gamma + Pb \rightarrow J/\psi + Pb$$

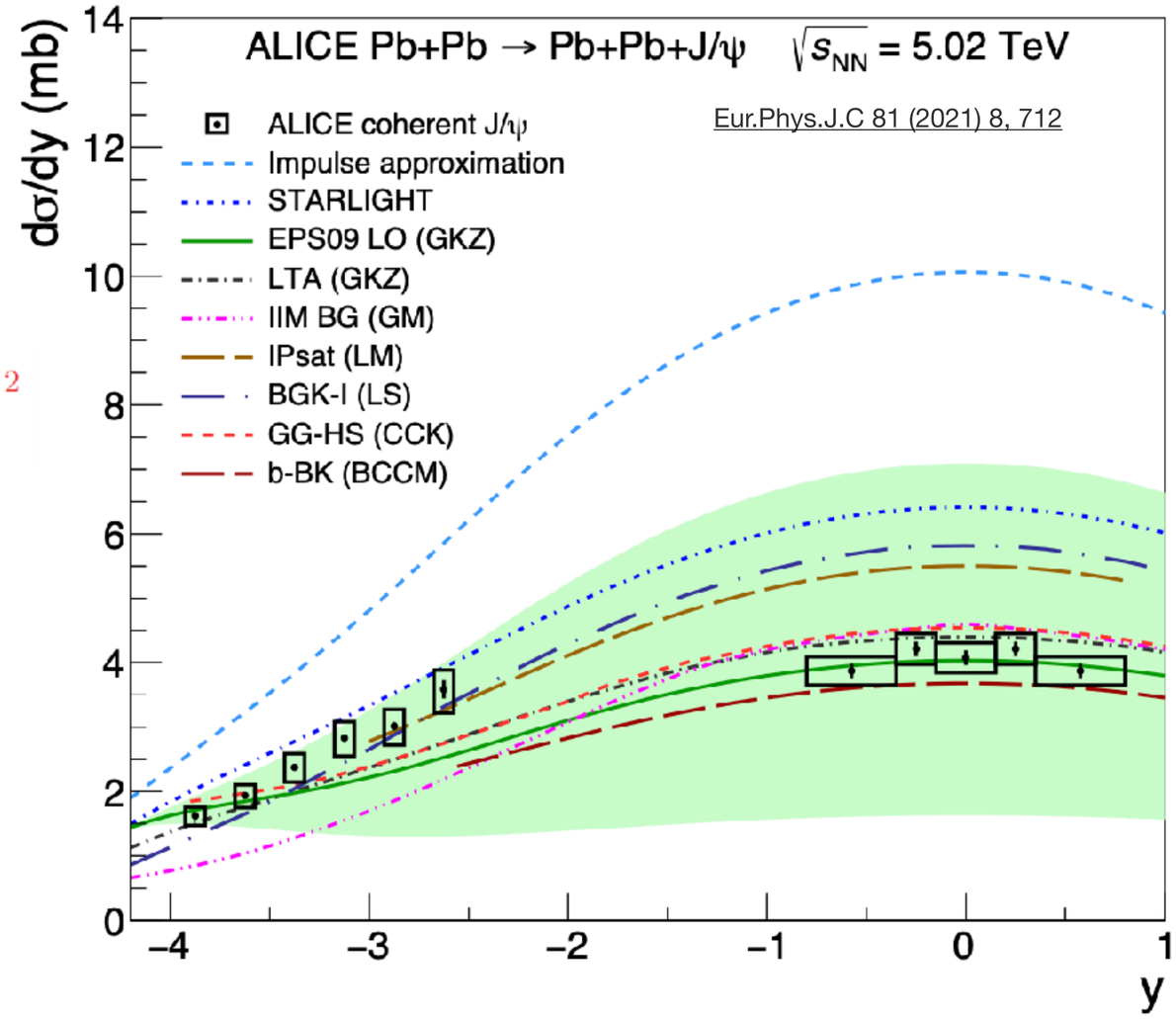


$$\left.\frac{d\sigma_{\gamma A \rightarrow J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s^2(Q^2)}{48 \alpha_{em} Q^8} \left[x g_A(x, Q^2)\right]^2$$

UPC Pb-Pb probes gluon density in nucleus

Measured cross section below free-nucleon 'impulse approximation'

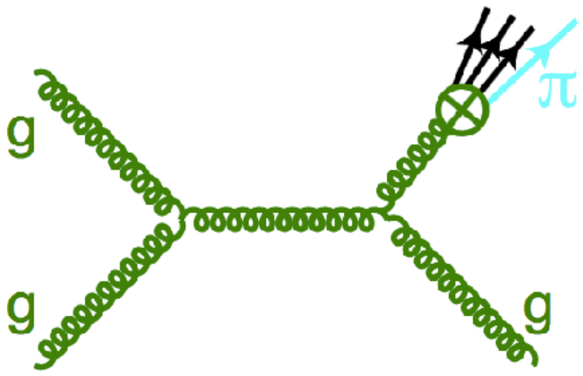
Indicates shadowing/saturation at small Q ≈ 1/2 $m_{J/\psi}$ = 1.5 GeV

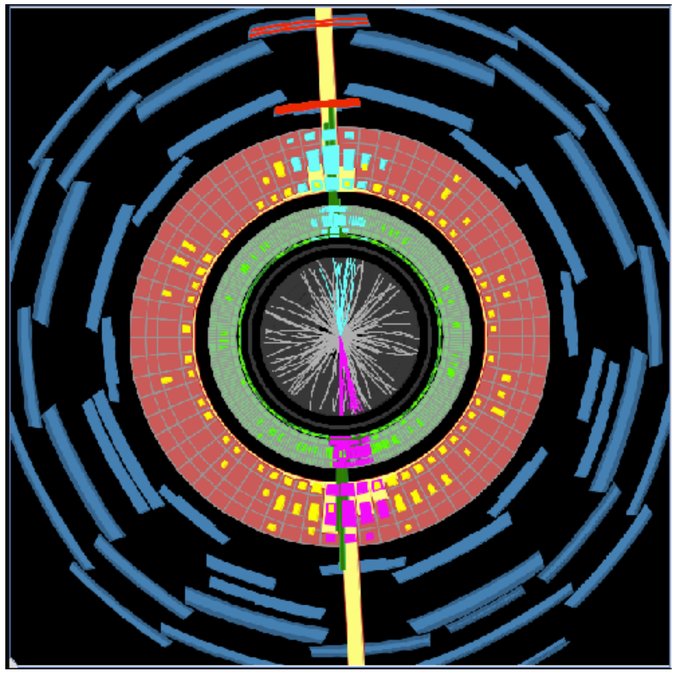


Two-particle correlations to probe non-linear evolution

QCD 2 → 2 scattering

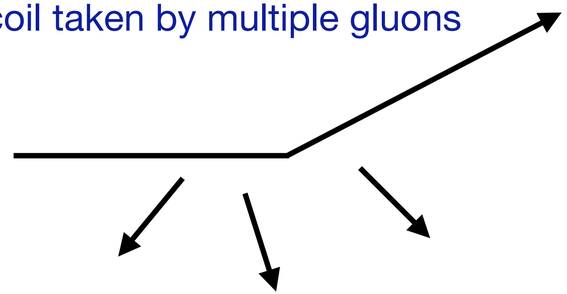
gluons from
incoming beams





Momentum balance in transverse plane
Produces a back-to-back jet

Color Glass Condensate:
recoil taken by multiple gluons



Soft gluon recoil

Recoil jet broadened/disappears

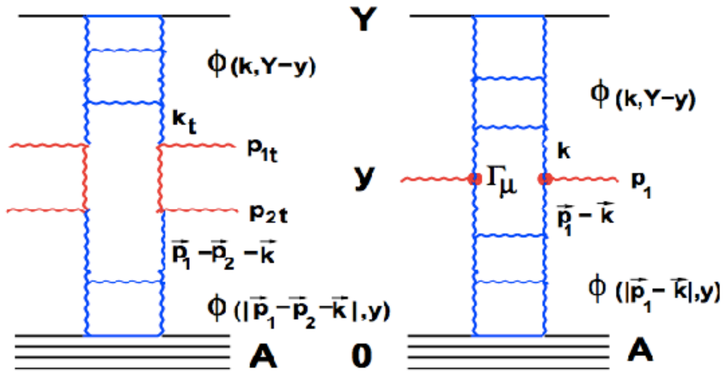


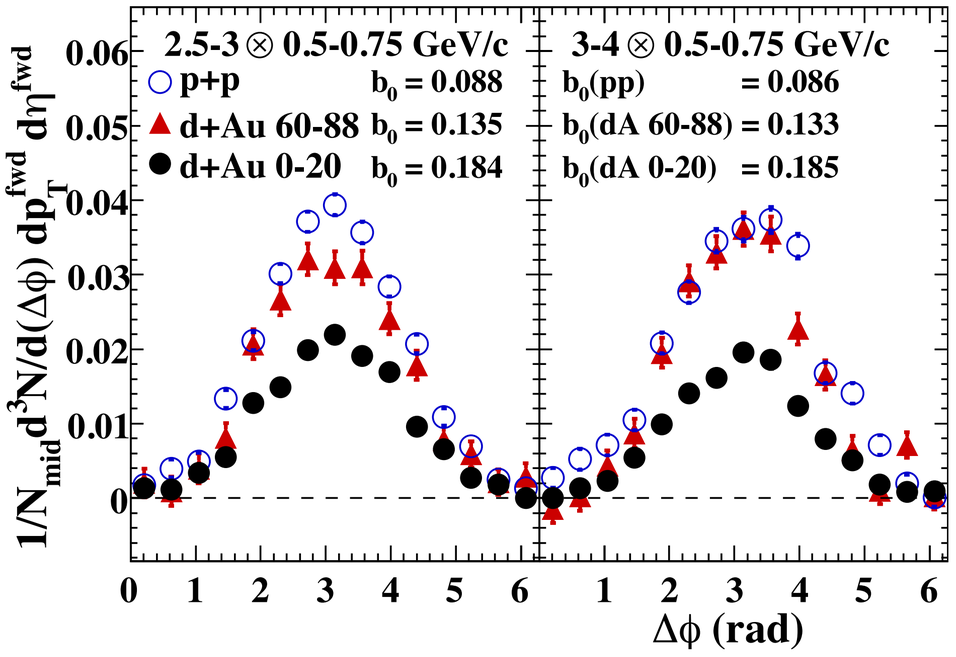
Fig. 3-a Fig. 3-b

Kharzeev et al, hep-ph/0403271

Directly probes multiple gluon interactions

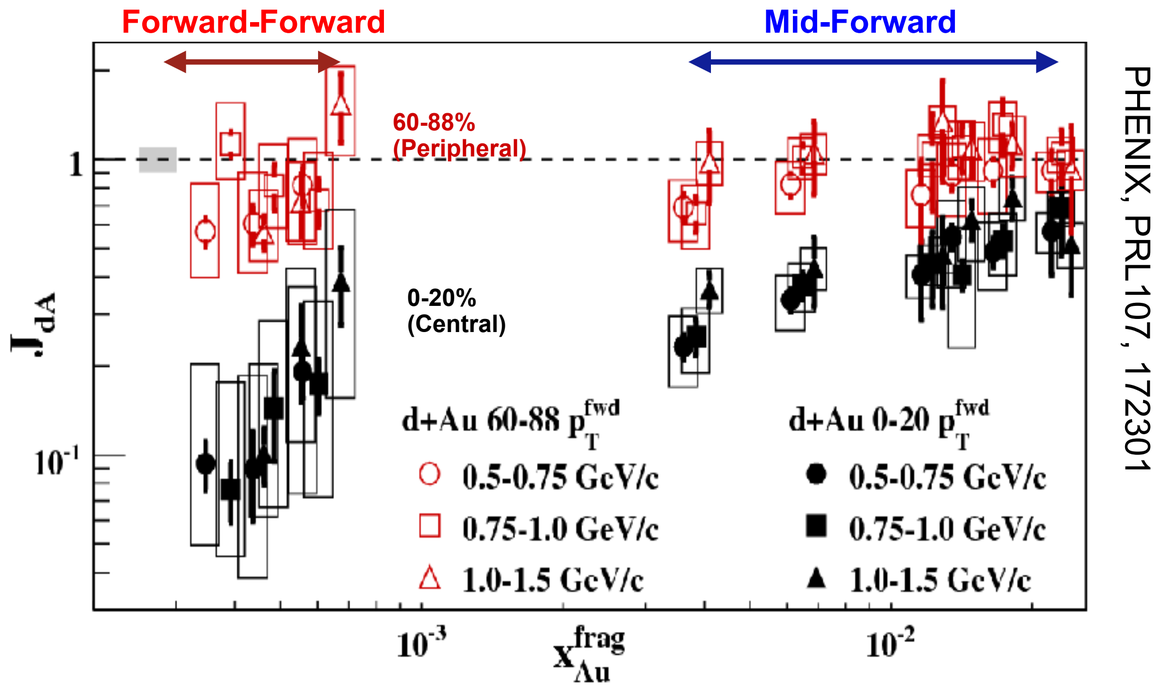
Two-particle correlations at RHIC: PHENIX

π^0-π^0 mid - forward



$|\eta| < 0.35$ and $3.0 < \eta < 3.8$

Recoil yield ratio



PHENIX, PRL107, 172301

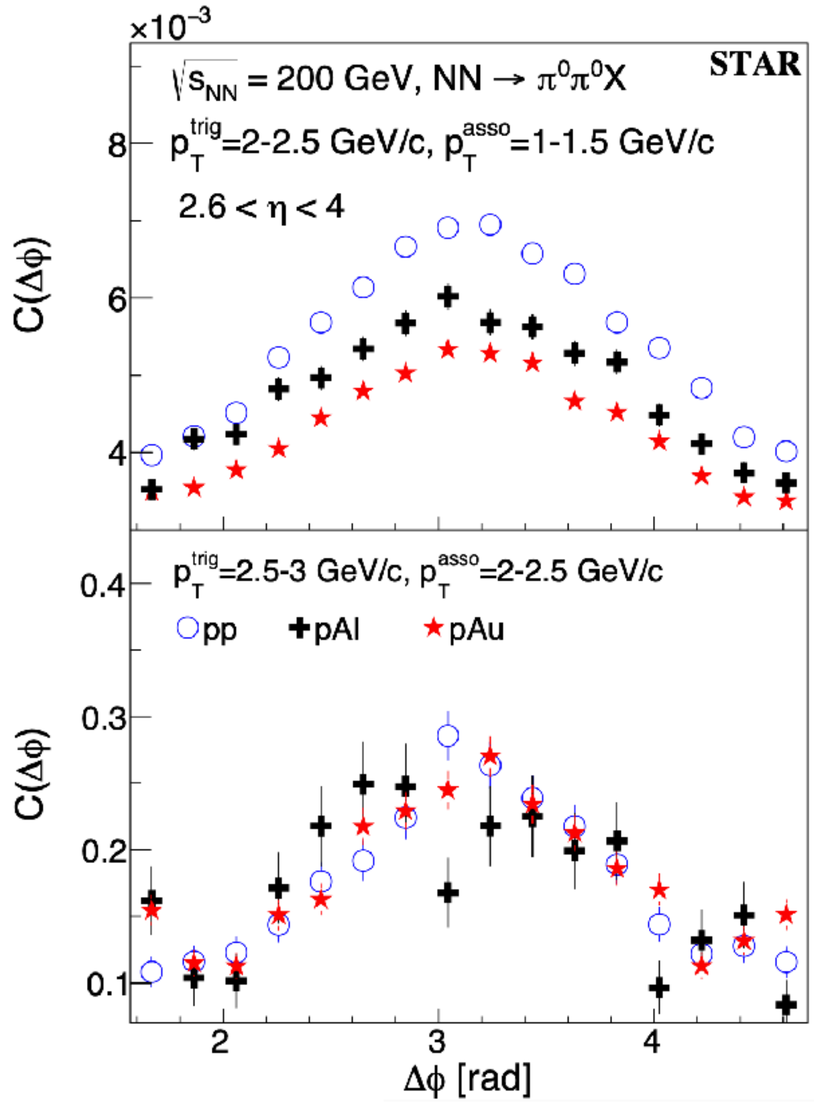
Scan 'x' with p_{T1} and forward, mid rapidity

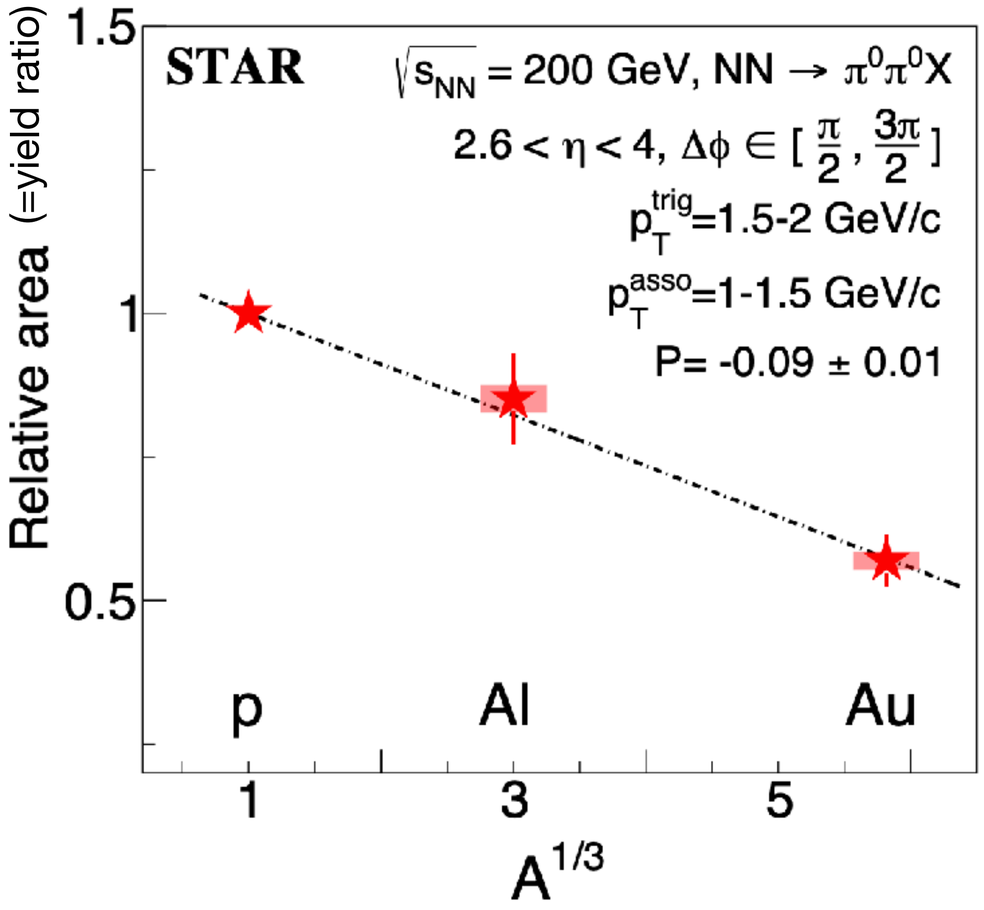
Decorrelation of away side yield; expected trend as a function of x

Large suppression at 'x' < 10^{-3} in central events, no significant broadening

Two-particle correlations at RHIC: STAR

STAR, arXiv: 2111.10396



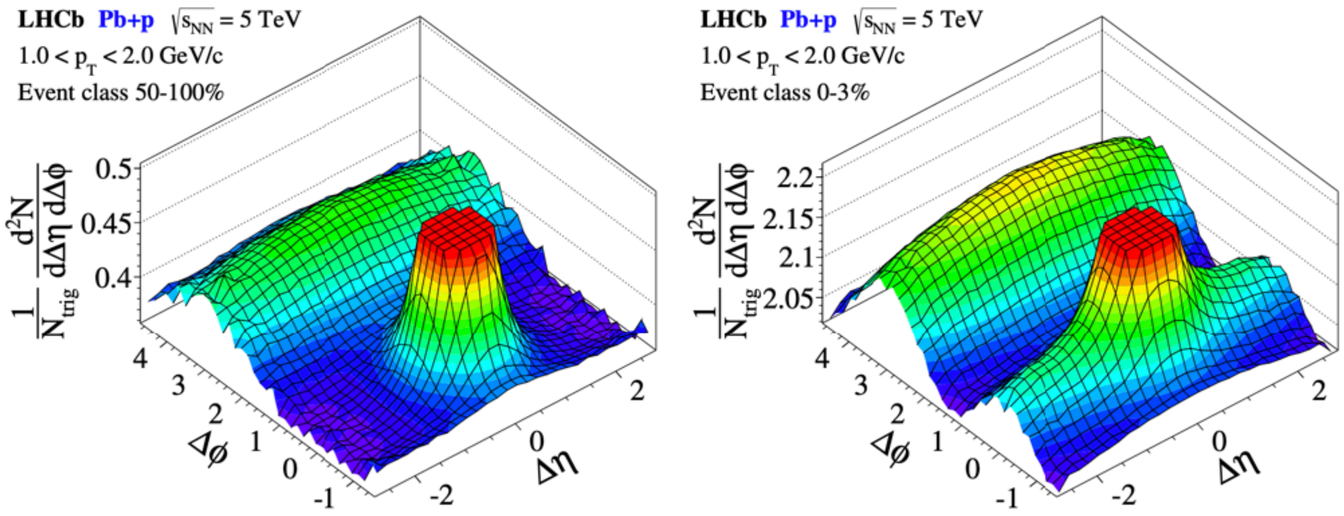


Suppression of conditional yield (roughly linear with $A^{1/3}$)

Similar as before, no obvious broadening found

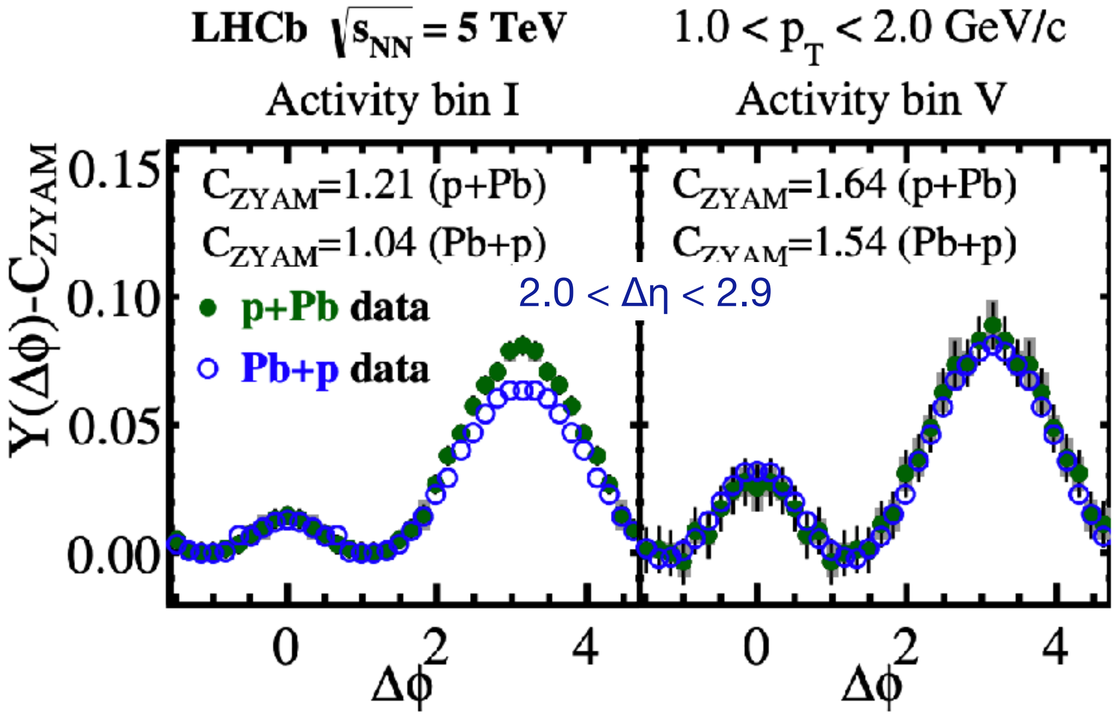
Two-particle correlations at LHC

LHCb, PLB762, 473



2.0 < η < 4.9

Multiplicity dependence of di-hadron correlations



Analysis geared towards flow-like effects:

Long range correlations

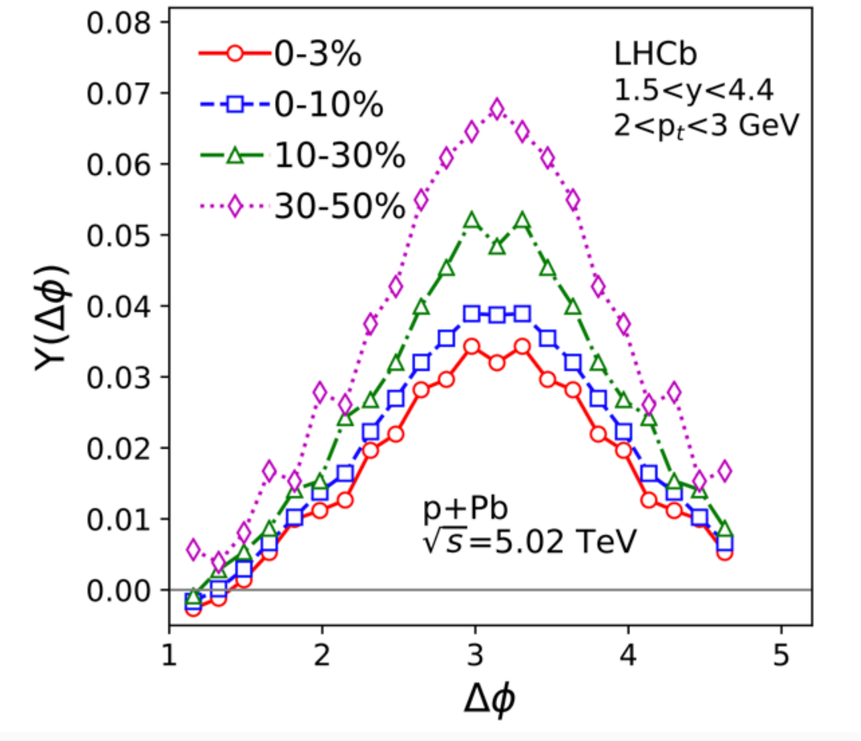
Try to separate jet-like and flow-like correlations?

Near side long range amplitude 20-40 per cent of away side!

Two-particle correlations at LHC

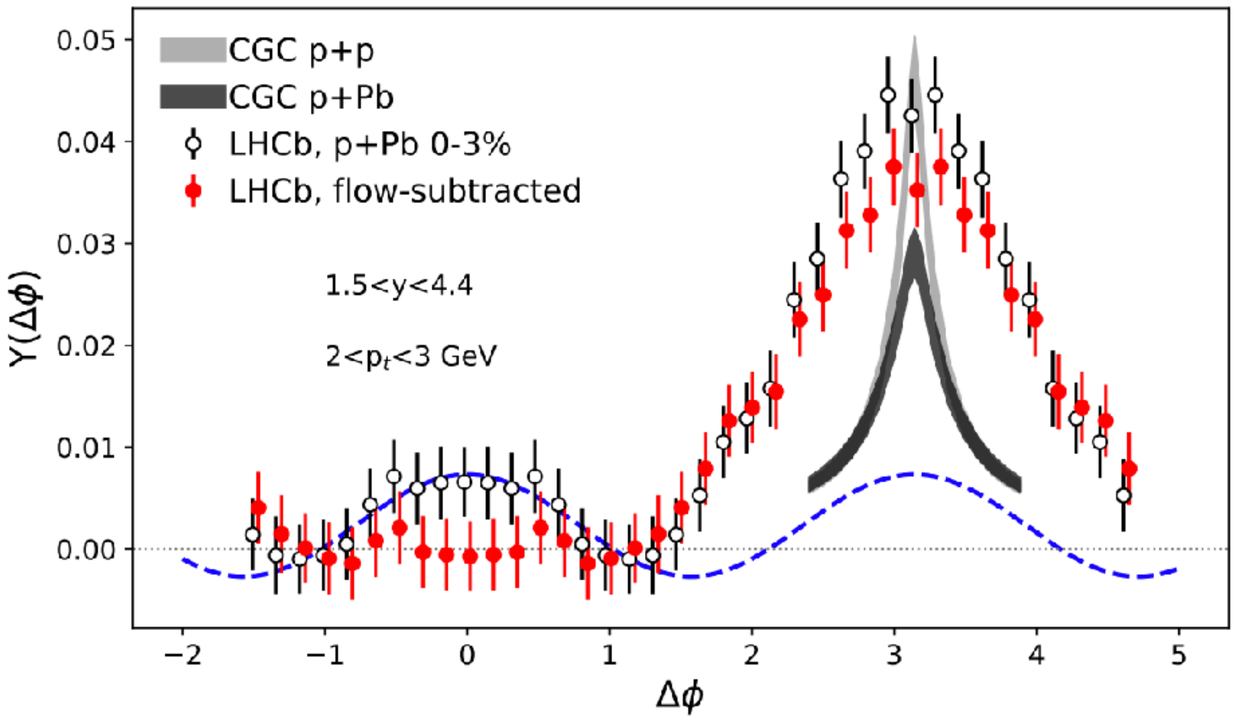
G Giacalone, C Marquet, NPA 982, 291 (QM2018)

Away-side peak after flow subtraction



Assumes pure v_2; near-away symmetry for long-range component

Comparison to CGC calculation

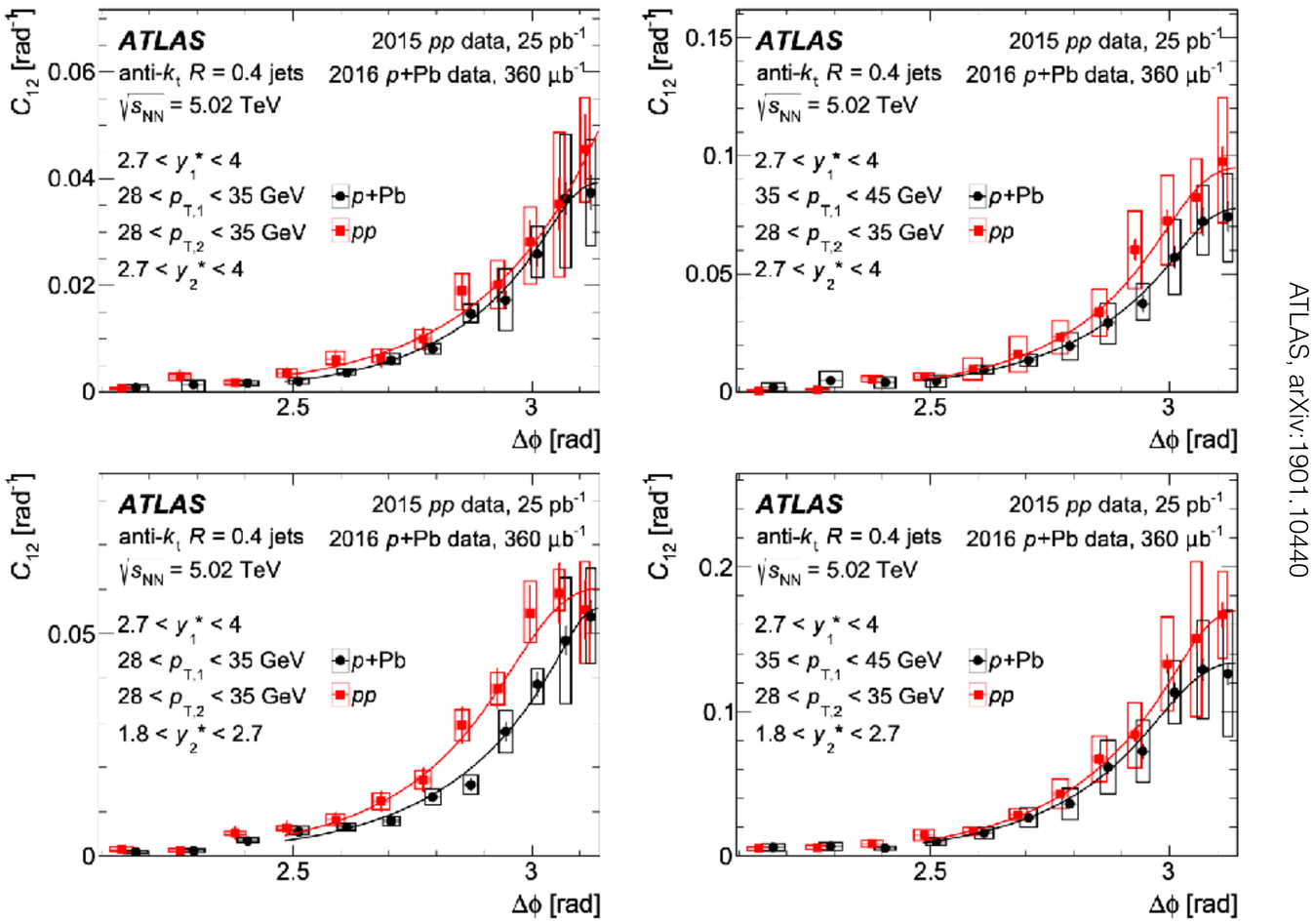


Theory calculations show narrow peak; add final state radiation/shower effects?

Yield suppression and mild broadening?

Di-jet correlations at LHC

Di-jets with p_T 28-45 GeV



ATLAS, arXiv:1901.10440

No strong effect seen in data so far…

Explore p_T dependence?

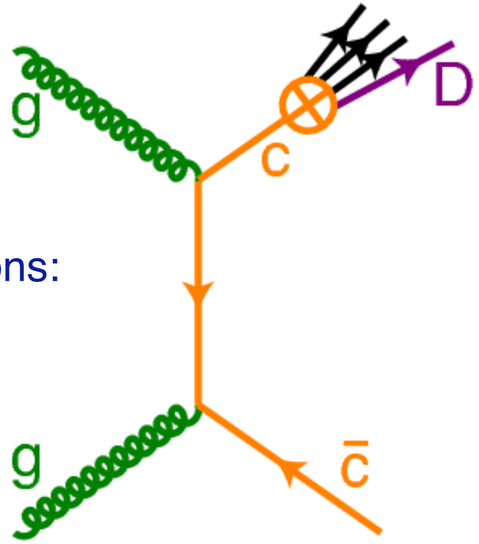
Summary so far

- Signs of **suppression of inclusive particle production in small-x regime**
  - RHIC: charged particle/light hadron suppression
  - LHC: Light hadron and *D* meson suppression at forward rapidity
- nPDF fits with forward *D* meson input: **smaller gluon density** in nuclei
- Two-particle correlations and UPC results also **indicate smaller gluon density** in nuclei
- However, some **open questions**:
  - RHIC and LHC see effects at different *x*
    - Multiple interactions near kinematic limits?
  - Broadening (two-particle correlations, or dijets) not seen so far
  - Hadronic observables also suspect to final state effects

New/cleaner measurements (photons; maybe UPC)
and/or confirmation by multiple experiments neededede!

Probing the gluon density in a hadron collider

Charm production

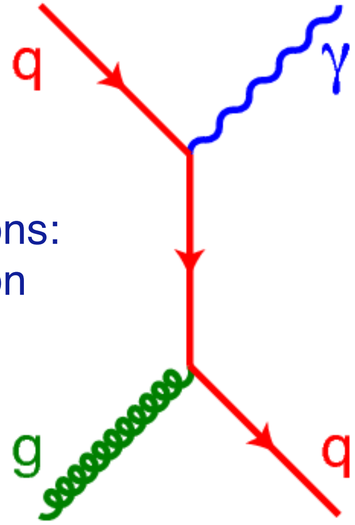


Incoming partons:
2 gluons

Heavy hadron:
also directly sensitive
but fragmentation reduces
kinematic constraint

More processes contribute, e.g. gluon splitting

Direct photon production



Incoming partons:
quark and gluon

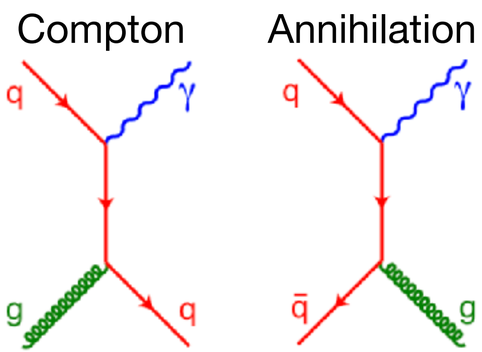
direct-γ, Compton (LO)

Photon momentum directly
related to incoming partons

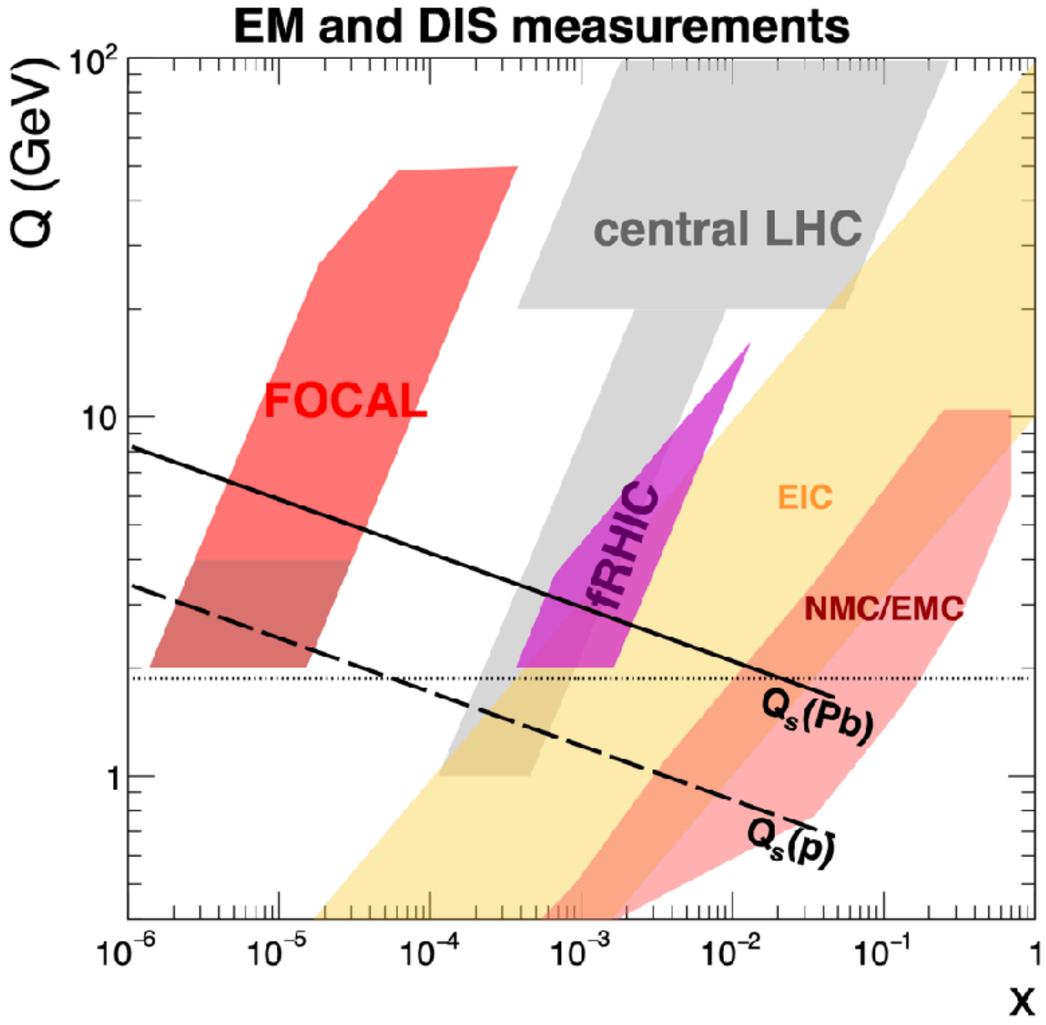
No final state interactions

More processes contribute, e.g. annilation

Forward isolated photons and the LHC small-x program



$$x \approx \frac{Q}{\sqrt{s}} \exp(-y)$$



- Measure forward isolated photons
  - At LO more than 70% from Compton with direct sensitivity to gluon density
  - Not affected by final state effects nor hadronization
  - Uniquely small-x coverage (similar to LHeC)

- Goal
  - Explore non-linear QCD evolution at small x
    - Constrain nuclear PDFs at small x
  - Logarithmic dep. of QCD evolution on Q and x, requires several measurements over largest possible range

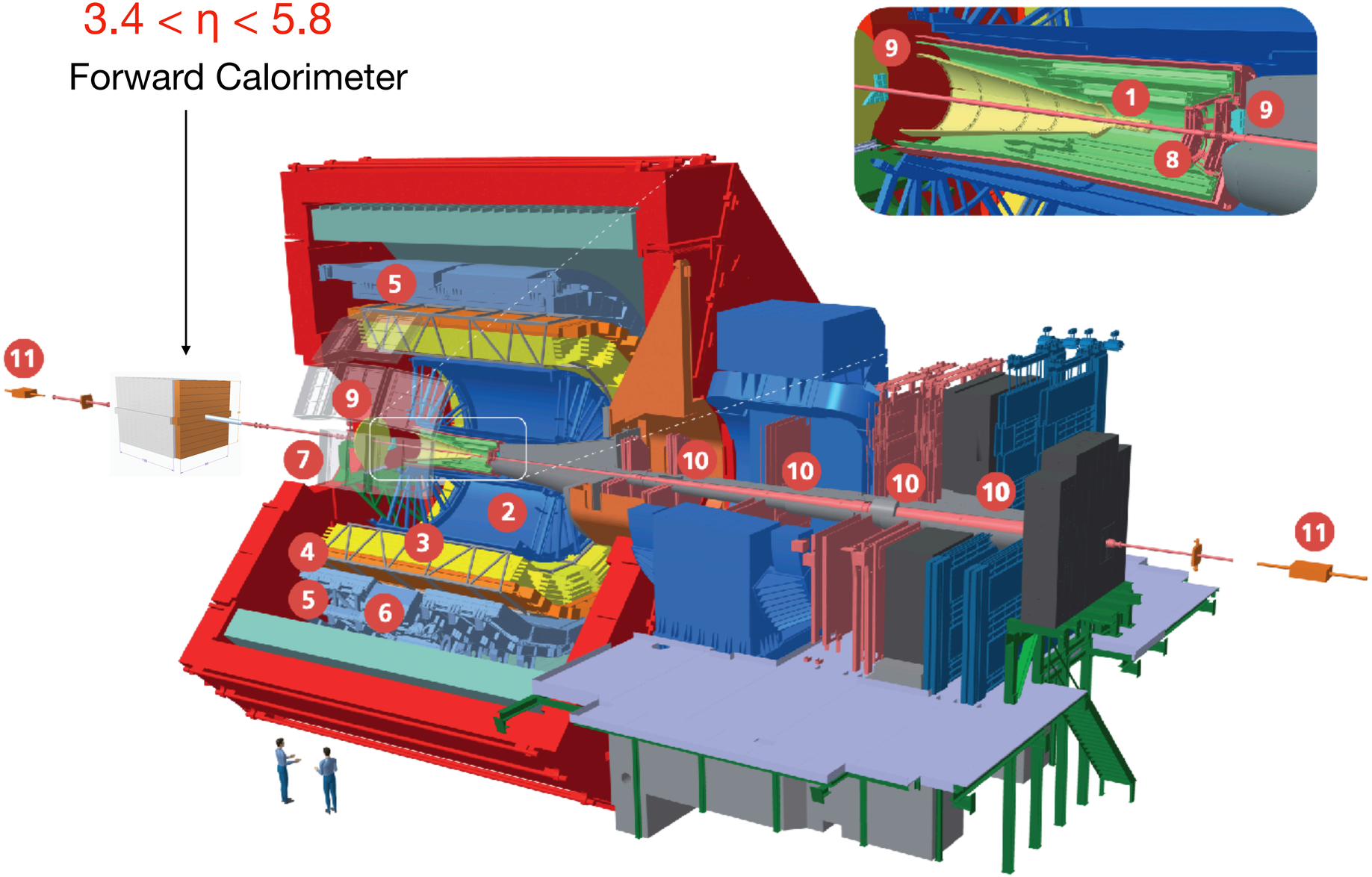
Strong small-x program at LHC

- Various experiments/measurements: isolated γ, DY, open charm (+UPC)
- Test factorization/universality
- Complementary to fRHIC + EIC

The ALICE FoCal project

$3.4 < \eta < 5.8$

Forward Calorimeter



1 **ITS** | Inner Tracking System

2 **TPC** | Time Projection Chamber

3 **TRD** | Transition Radiation Detector

4 **TOF** | Time Of Flight

5 **EMCal** | Electromagnetic Calorimeter

6 **PHOS / CPV** | Photon Spectrometer

7 **HMPID** | High Momentum Particle Identification Detector

8 **MFT**| Muon Forward Tracker

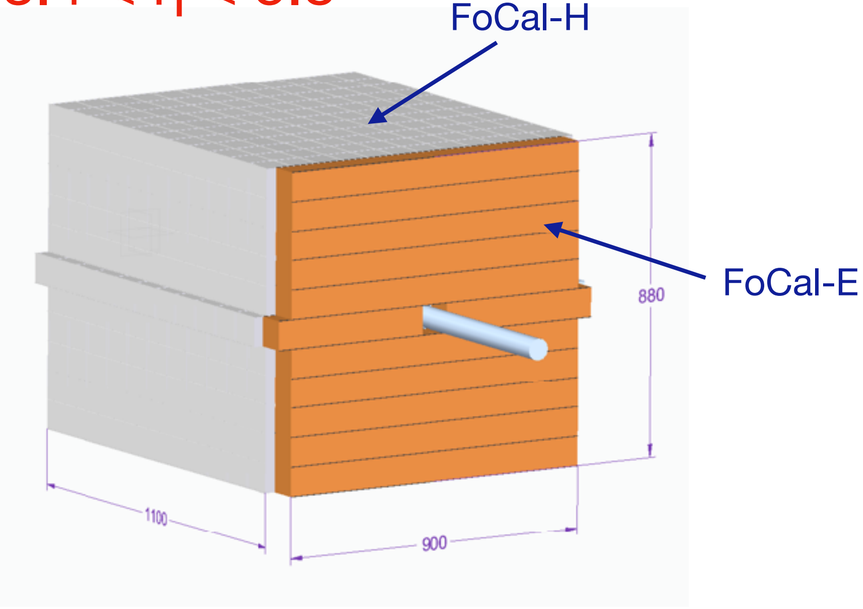
9 **FIT** | Fast Interaction Trigger

10 **Muon Spectrometer**

11 **ZDC** | Zero Degree Calorimeter

The FoCal concept

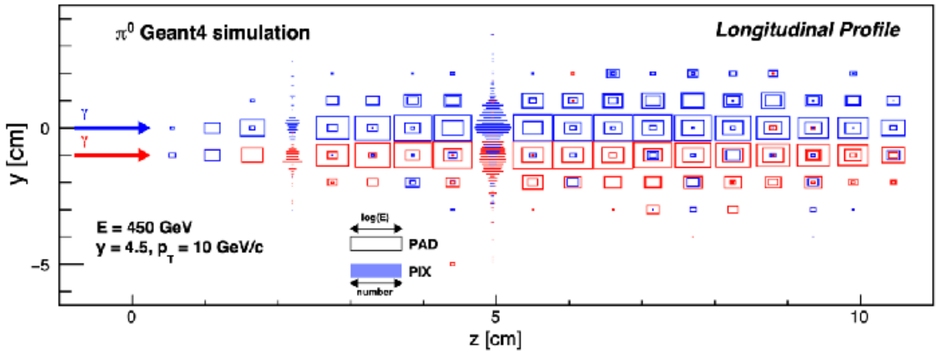
$3.4 < \eta < 5.8$



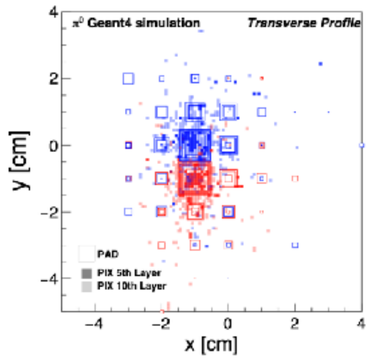
FoCal-E: high-granularity Si-W sampling sandwich calorimeter for photons and π^0

FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

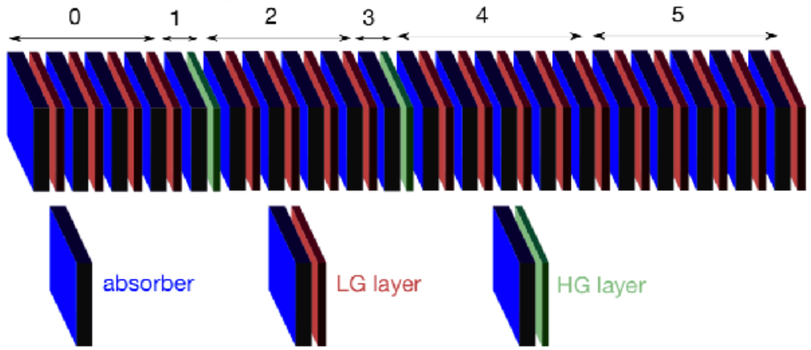
Longitudinal profile (2γ showers)



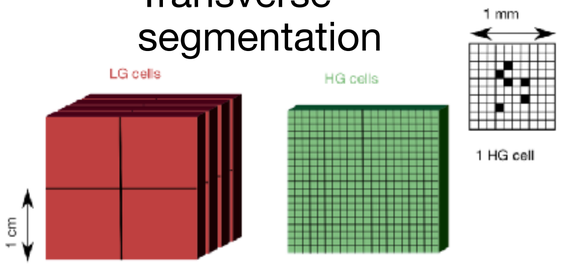
Trans. profile



Longitudinal segmentation



Transverse segmentation

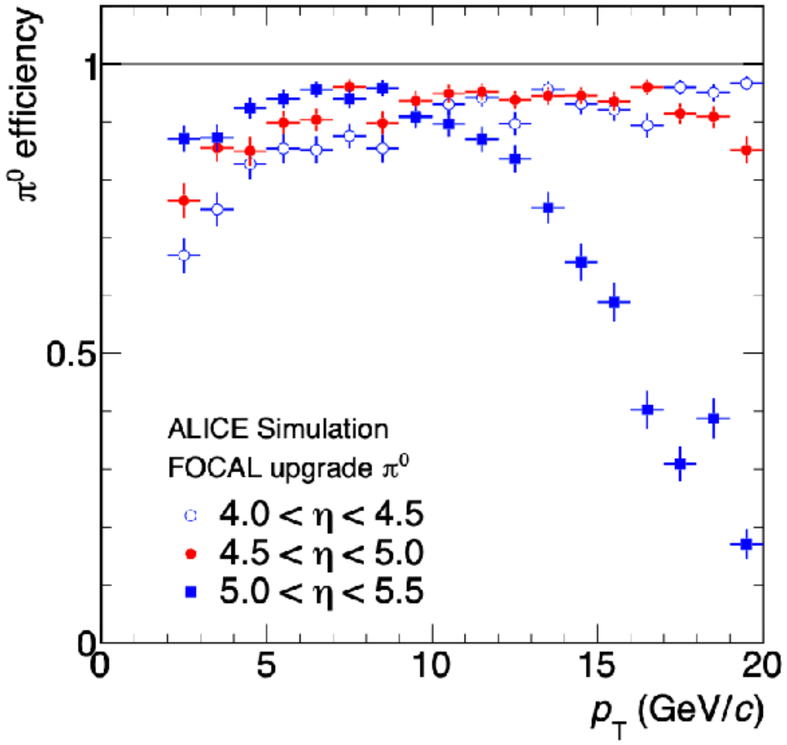


- Main challenge: Separate γ/π^0 at high energy
  - Two photon separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm
- Two readout granularities
  - PAD (LG) layers: granularity 1x1 cm^2, analog readout
  - PIXEL (HG) layers: 30x30 μm^2 digital readout (ALIPIDE)

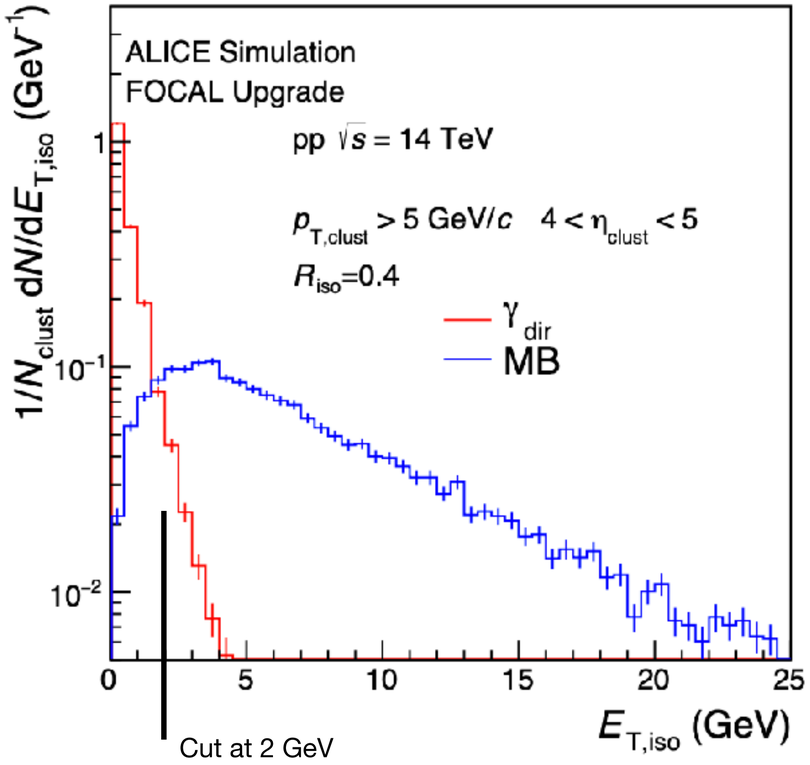
Letter-of-Intent, CERN-LHCC-2020-009

Key ingredients for isolated photon measurement

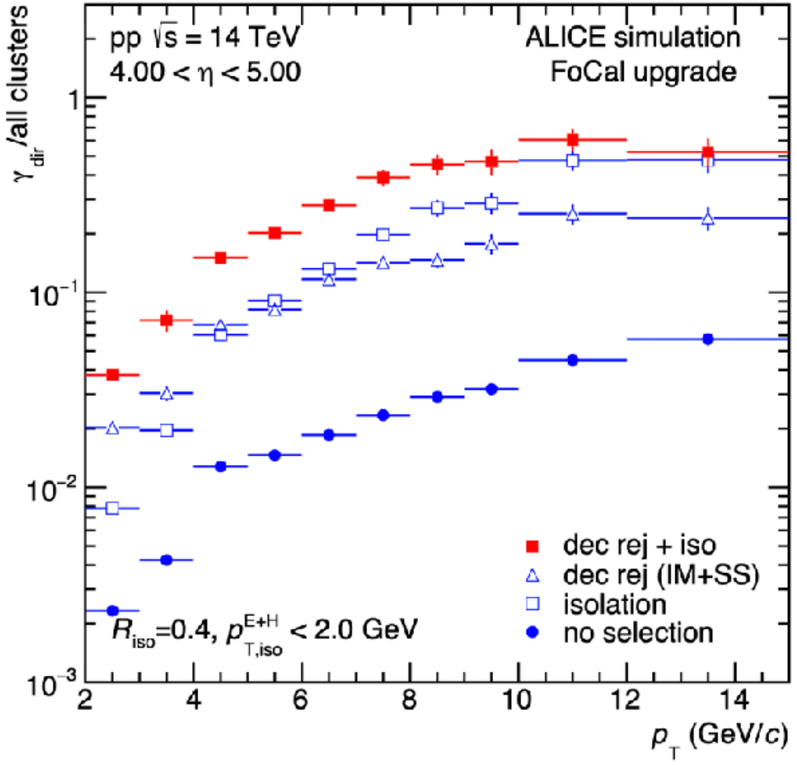
π^0 reconstruction efficiency



Isolation energy distribution



Direct γ/all cluster ratio



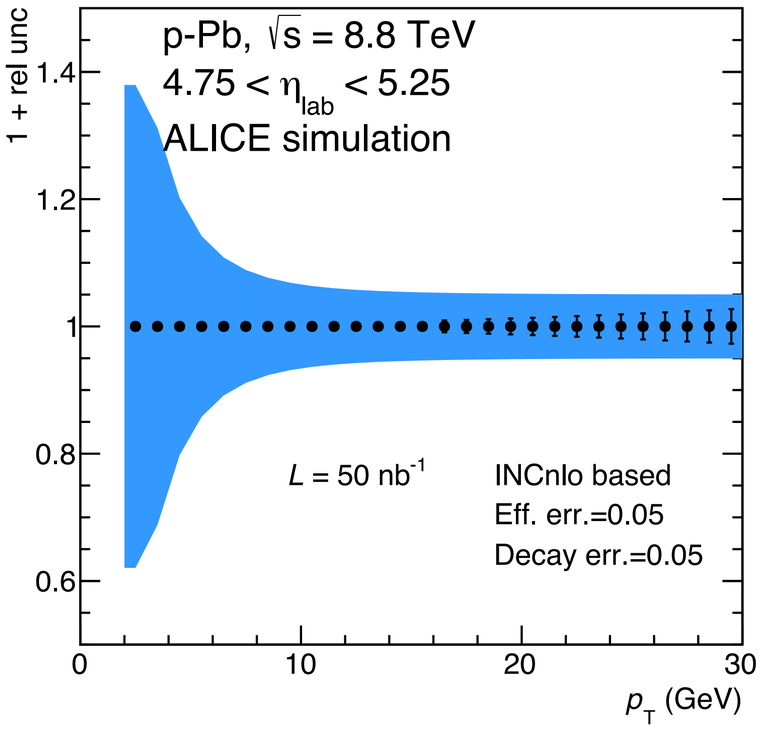
Main ingredients for direct photon identification

- π^0 reconstruction efficiency: measure background
- Isolation cut (EmCal + HCal)
- Rejection of decays by invariant mass reconstruction

Improvement in signal fraction by factor ~10 to ~0.1-0.6

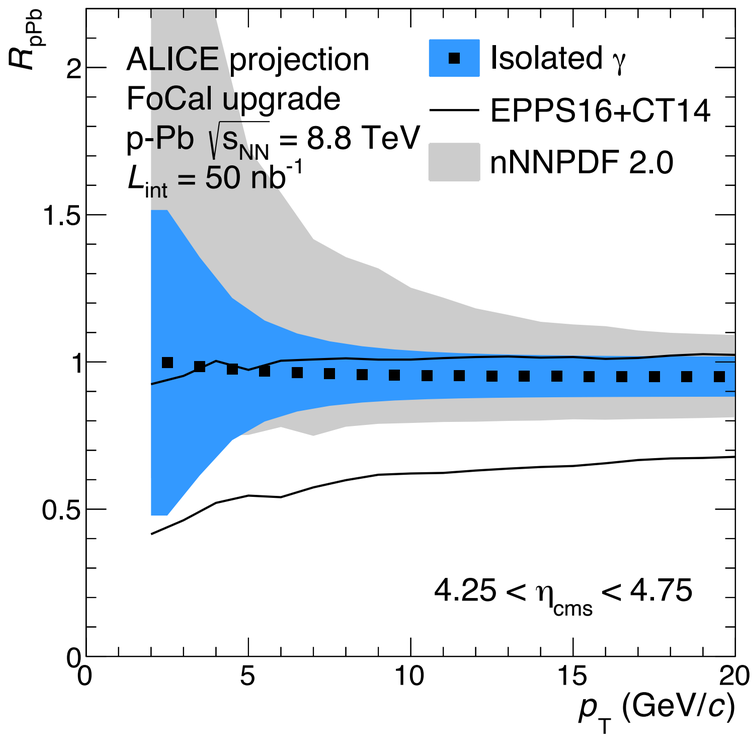
Expected performance and impact on nPDF

Relative uncertainties in pPb



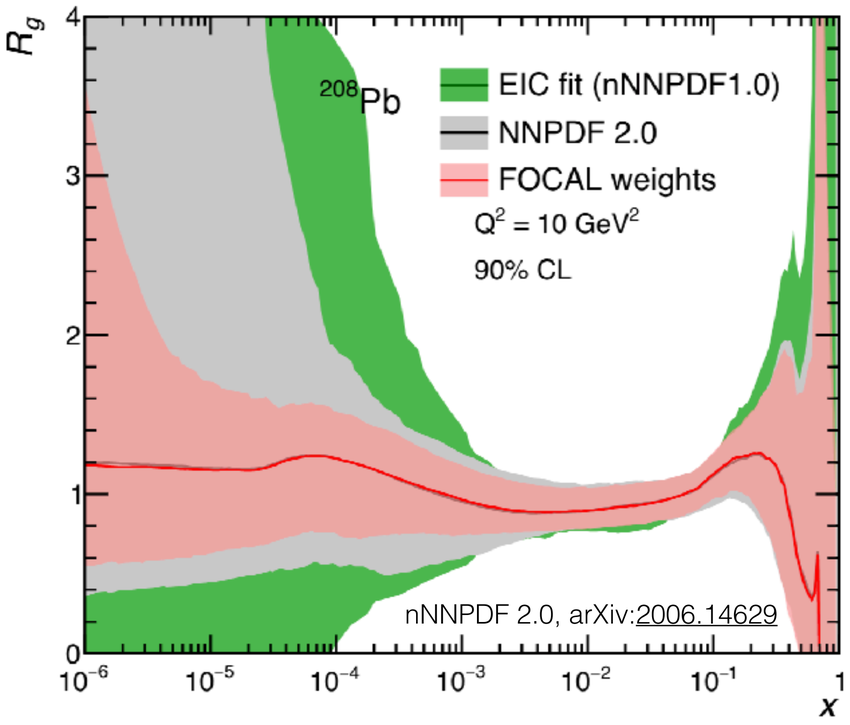
- Systematic uncertainty <10% at high p_T
- Below ~10 GeV, uncertainty rises due to remaining background

Nuclear modification factor



- Significant improvement (up to factor 2) on EPPS16, nNNDF 2.0 uncertainties
- Compare to e.g. open charm: test factorization/universality

Constraints on Rg

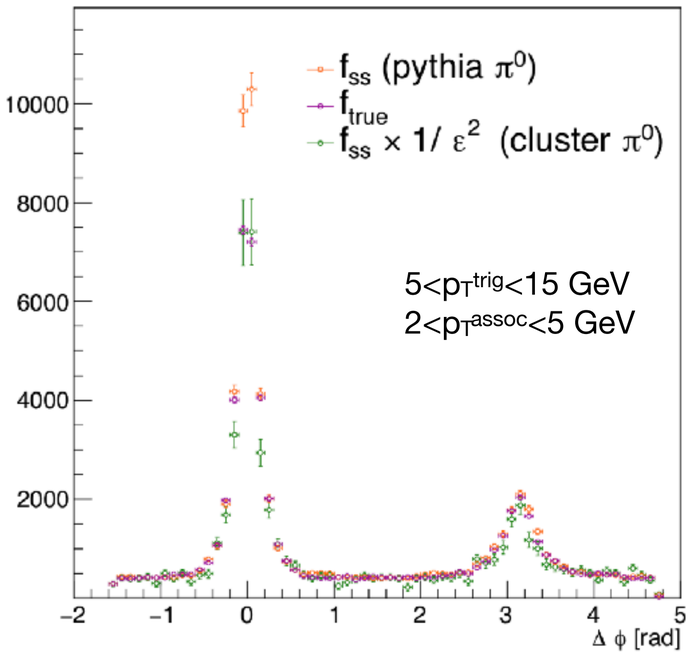


nNNPDF 2.0 from DIS + LHC

- No constraints for $x < 10^{-2}$ from DIS
- LHC: high-Q^2 constraints down to 10^{-4}
- FOCAL significant constraints over a broad range: ~10^{-5} - 10^{-2} at small Q^2
  - No additional constraints from EIC expected

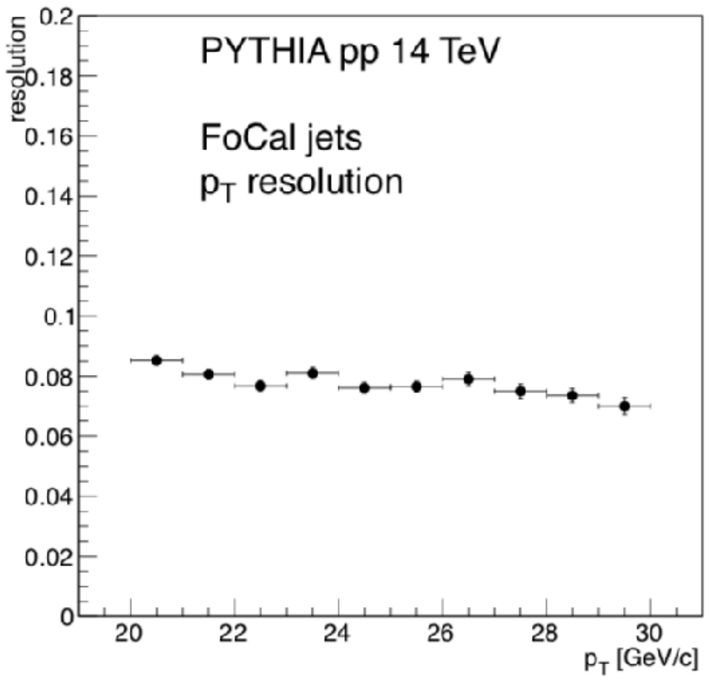
Focal physics program: other observables

π^0-π^0 correlations in pp



CGC decorrelation studies

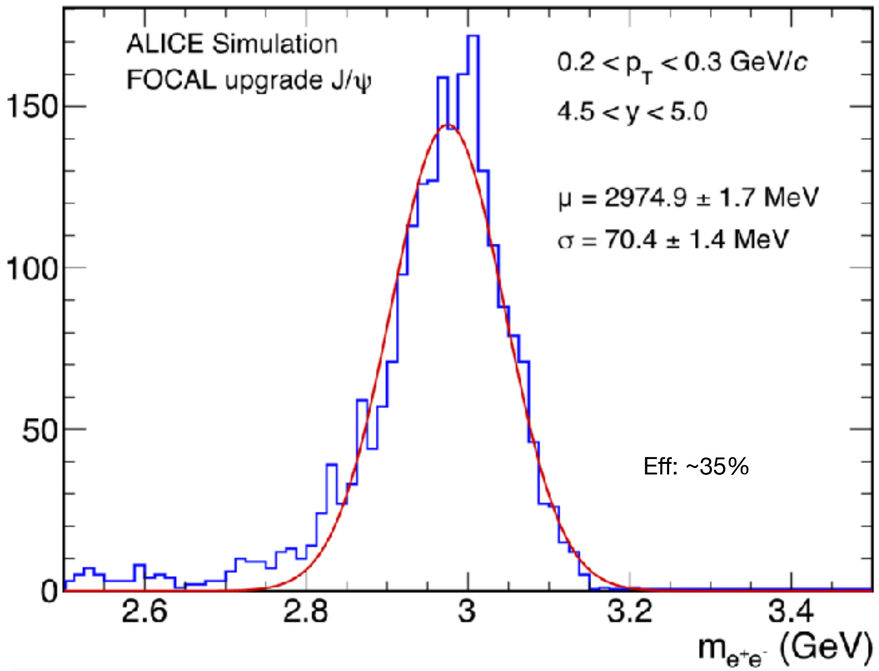
Jet resolution



Good performance of FoCal-E + H

jet, di-jets in pp, pPb, UPC

J/ψ reconstruction



Small-x with ultra-peripheral collisions

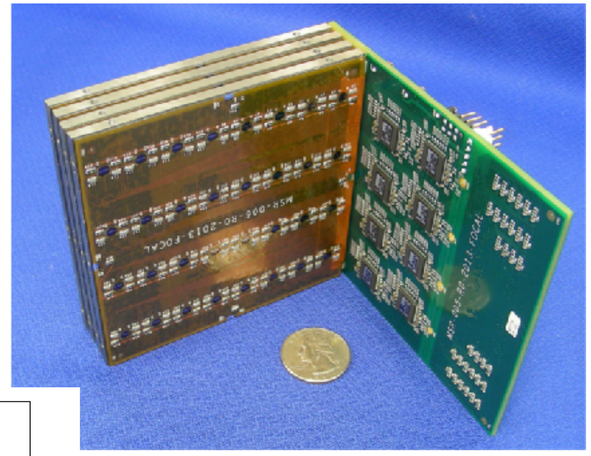
Large program beyond π^0 and γ in pp, p-Pb

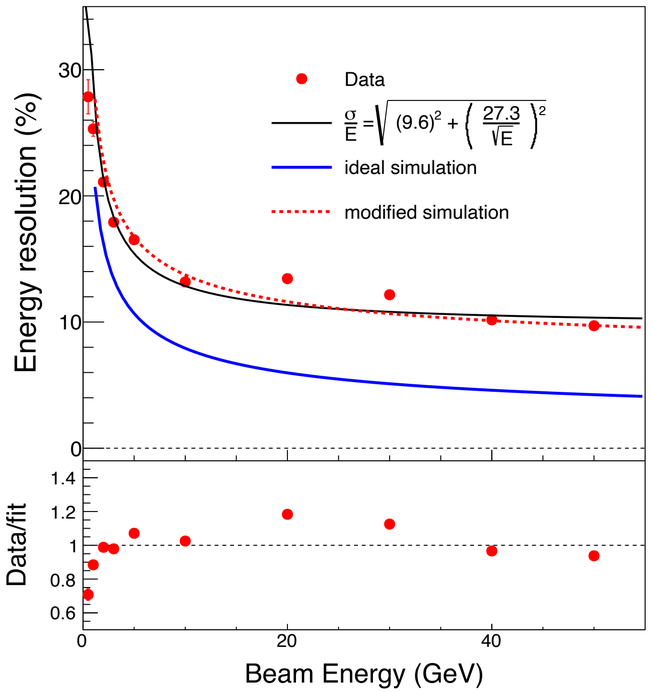
Early prototypes and tests: PAD layers

ORNL/Japan: initial concept

analog summing (ORNL)
APV25 hybrids
scalable readout system

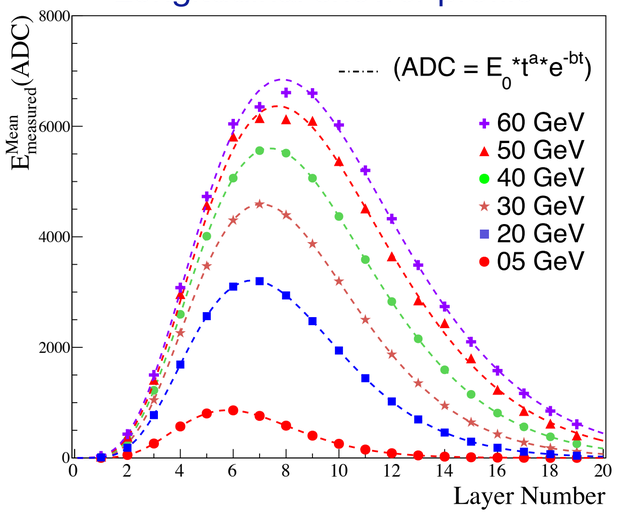
NIM A 988 (2021) 164796



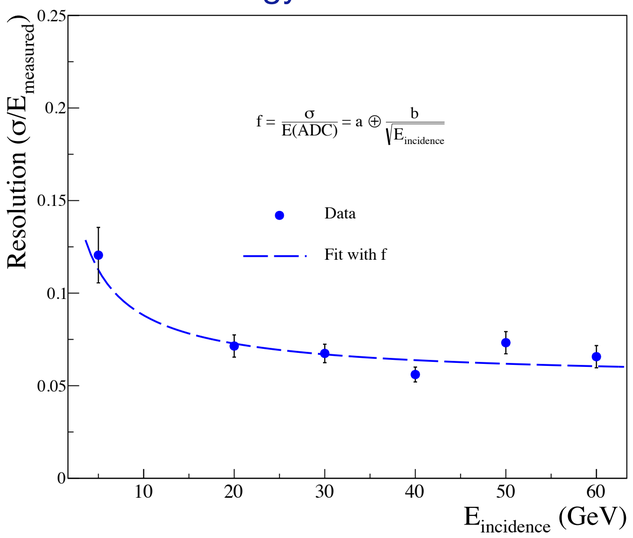


VECC/BARC prototypes: MANAS readout

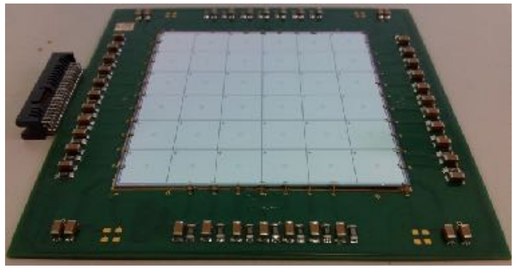
Longitudinal shower profile



Energy resolution



Several test beam campaigns,
with pixel and pad layers

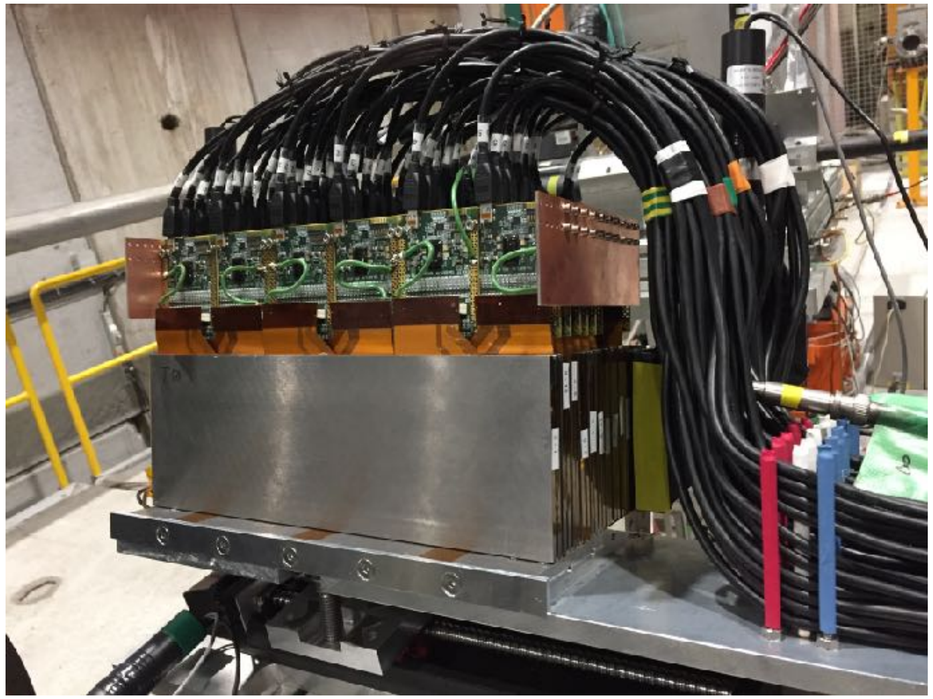


PS + SPS test beam
energy resolution:

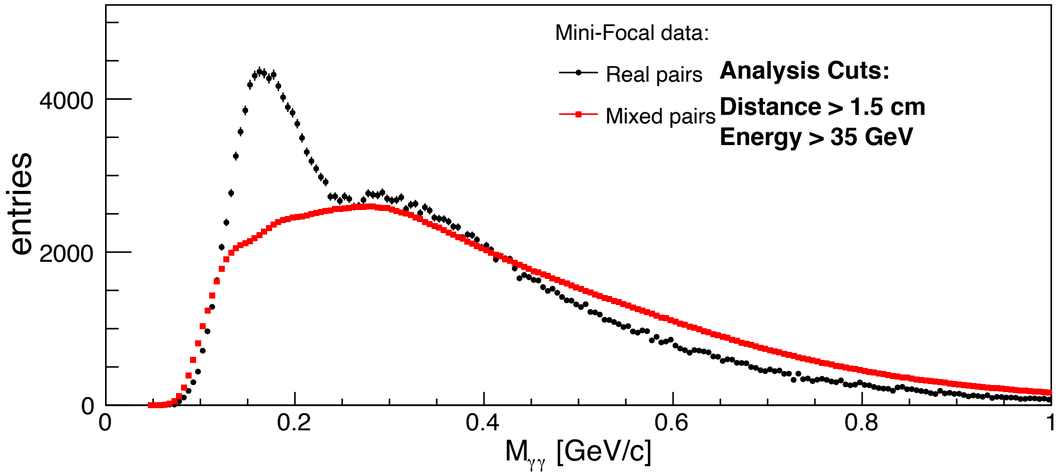
$$\frac{\sigma}{E} = \frac{15.36\,\%}{\sqrt{E}} \oplus 2\,\%$$

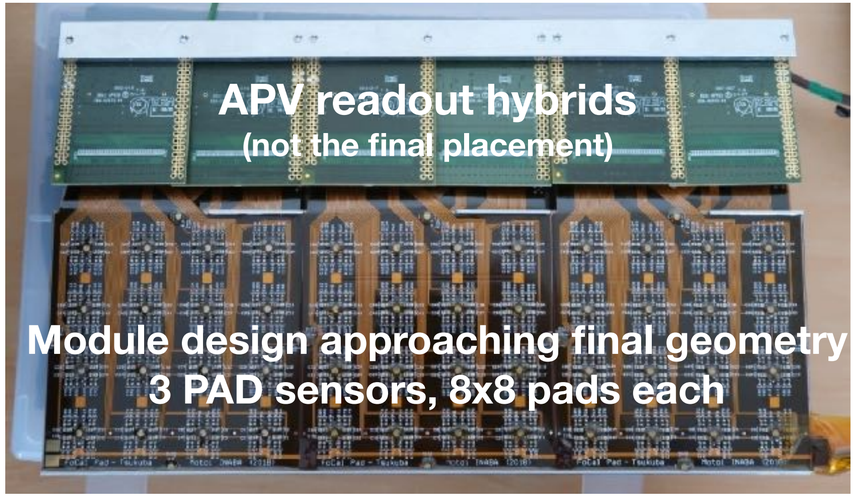
NIM A 764 (2014) 24
JINST 15 (2020) 03, P03015

Full module mini-FoCal at PS and SPS (2018)



Invariant mass: π^0 peak in 13 TeV pp collisions

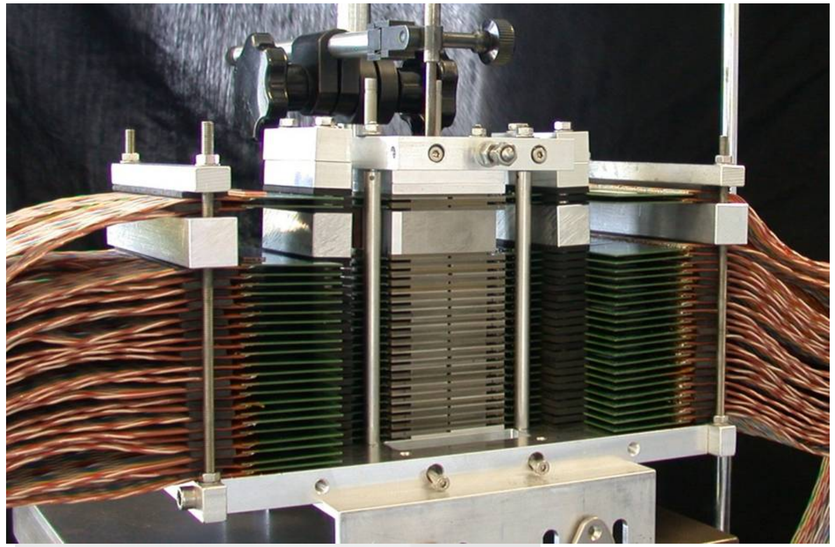


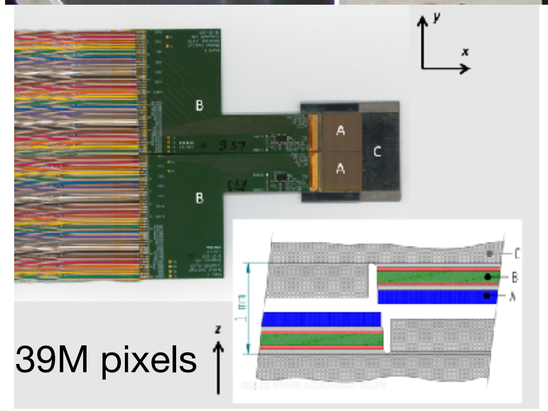


- 60 instrumented pad sensor wafers
- ~3600 channels
- APV25 hybrid + SRS readout
- built in Tsukuba
- beam tests at CERN (PS, SPS, ALICE)
- Encouraging results

Pixel prototypes: fully digital Si-W pixel calorimeter

EPICAL-1: MIMOSA pixel tower

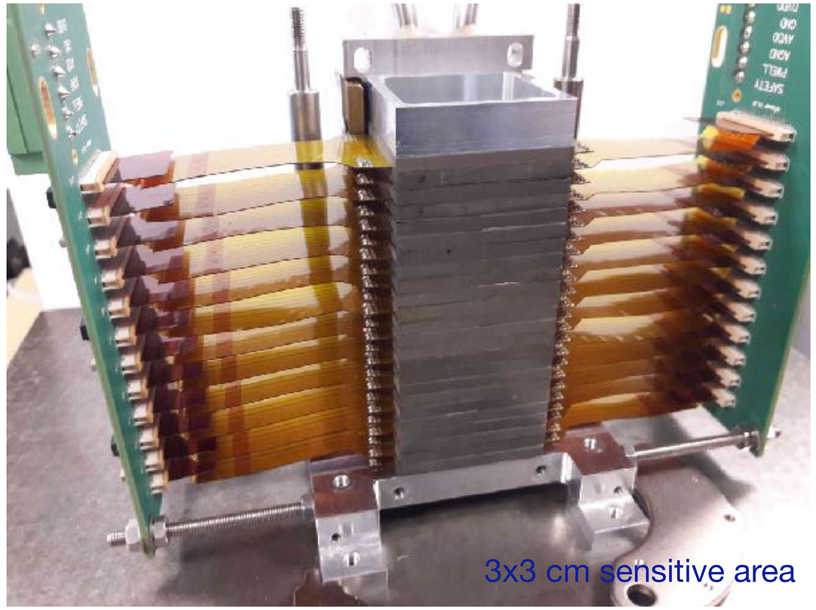




JINST 13 (2018) P01014

4x4 cm sensitive area

EPICAL-2: ALPIDE pixel tower



3x3 cm sensitive area

LCWS talks: T Rogoschinski, F Pliquett

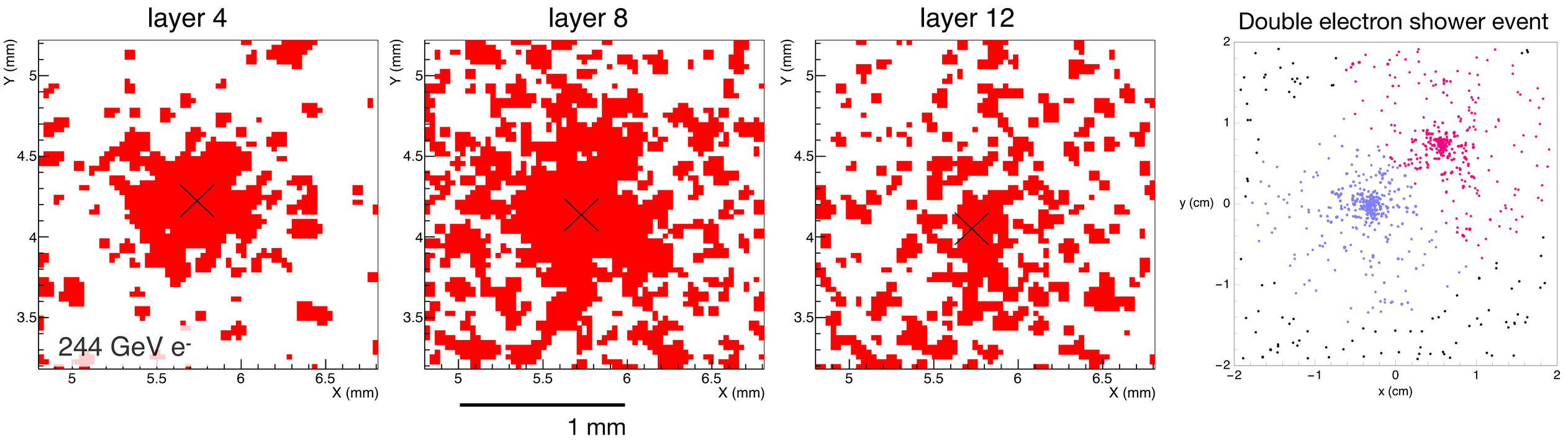
Extremely compact design: high pixel density and small Molière radius

Beam tests at DESY (e^-, 2-5.4 GeV), PS, SPS (mixed, 30-244 GeV)

Main activity in Norway (Bergen) and Netherlands (Utrecht/Nikhef)
R&D also in the context of medical application and CALICE

Detector seminar at CERN:
https://indico.cern.ch/event/856365/

Single Event Hit Distribution - FoCal Pixel Prototype

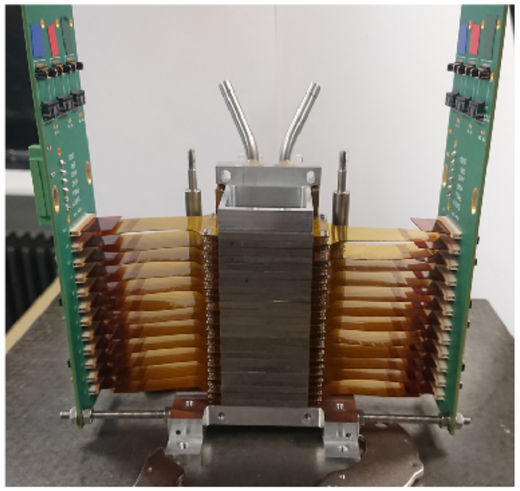


Pixel layers: very detailed view of shower

2-shower separation at mm scale

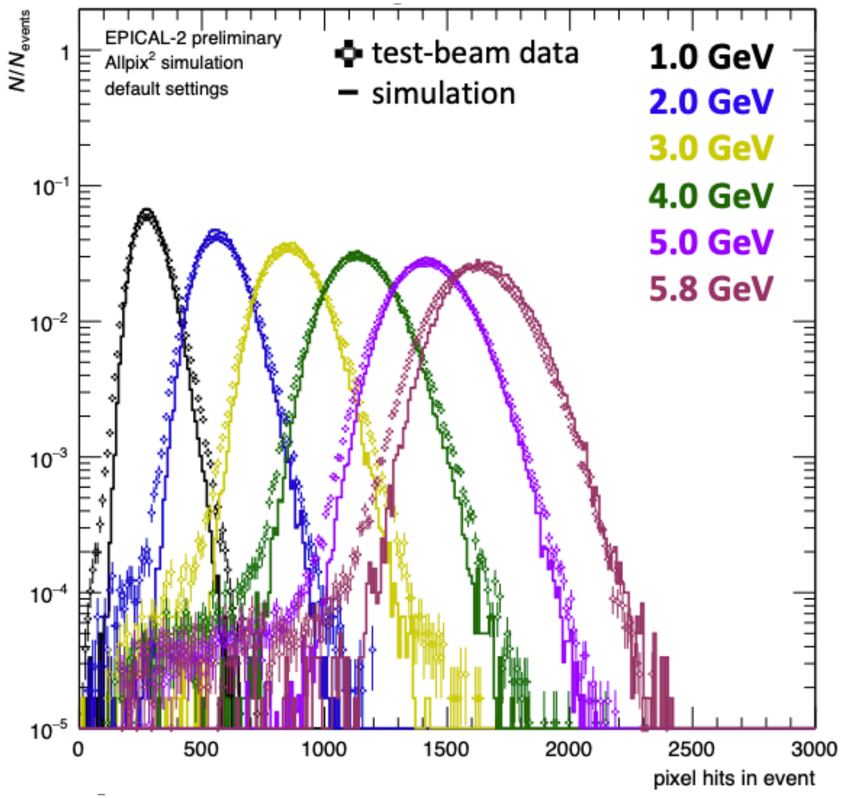
Use hit count as amplitude

EPICAL-2 test beam at DESY (2019/2020)



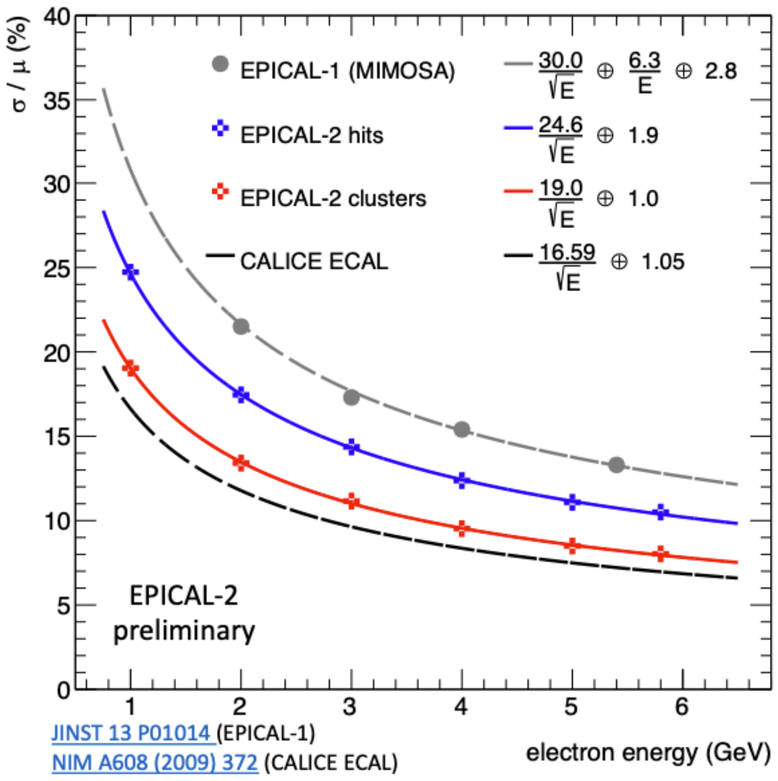
LCWS talks: T Rogoschinski, F Pliquett

Number of pixel hits



Detailed response simulations with AllPix²

Energy resolution

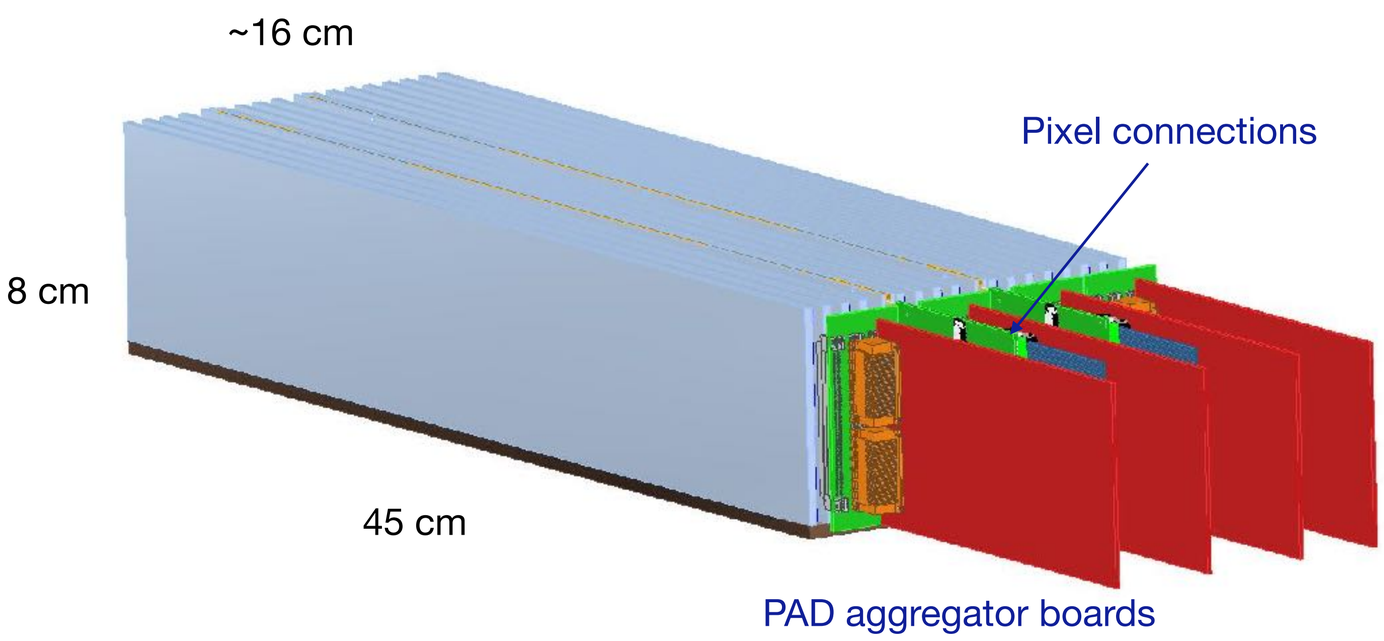


Cluster counting provides better energy resolution than hit counting

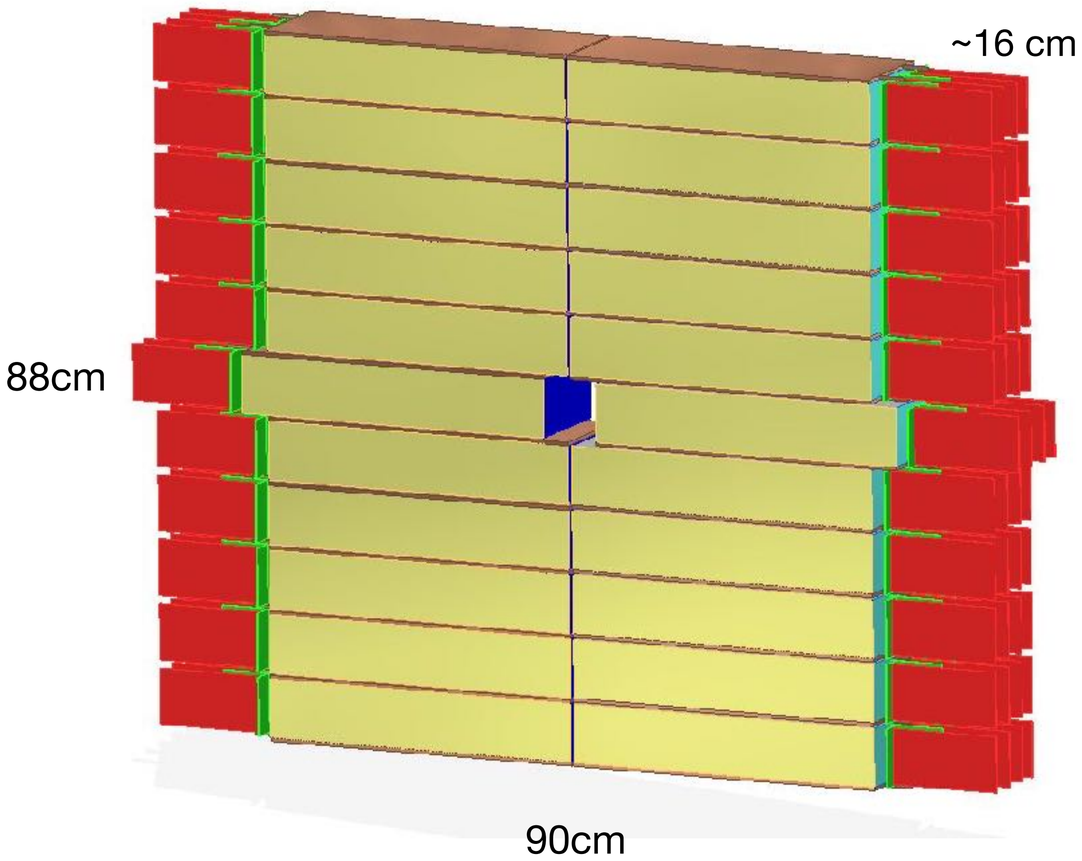
Digital pixel calorimetry: good energy resolution and excellent spatial resolution

Final detector: FoCal-E layout

Module: 18 pad layers + 2 pixels layers



FoCal-E: 22 modules



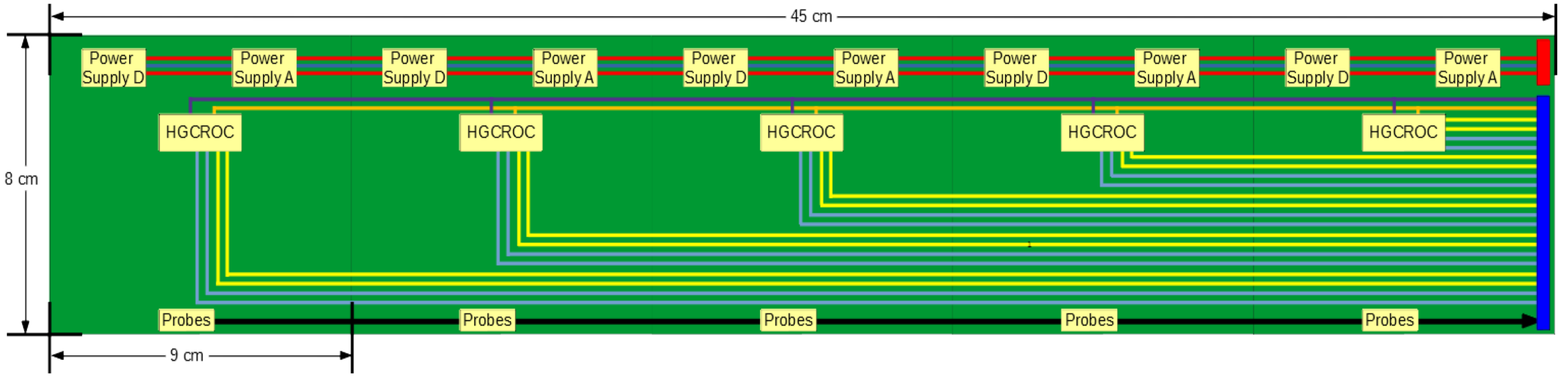
- PAD layers: aggregate groups of 4
- Pixel layers: individual readout

PAD module design

PCB carries 5 sensors (72 pads each), 5 HGCROC: ~45x8 cm

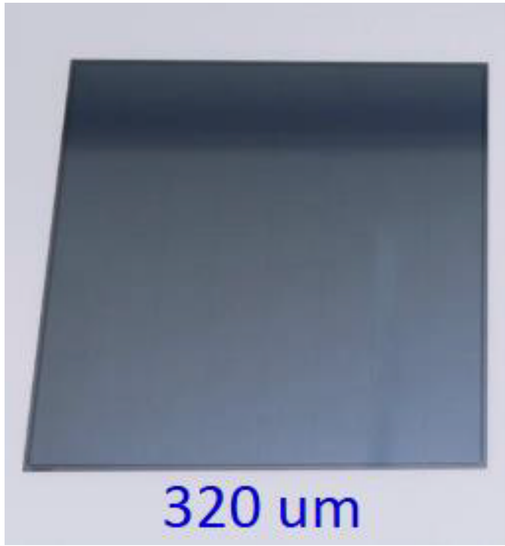
Read-out ASIC: HGCROC (CMS HGCAL)

- 72 channels per chip: ADC + TOT
- Dynamic range: MIP to 2 fC
- Internal buffer; data shipped on readout

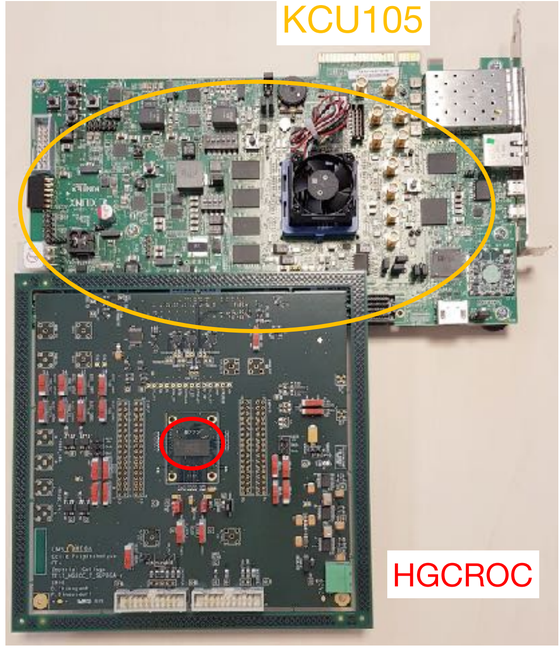


HGCROC tests and board design: LPSC, Grenoble

Si PAD

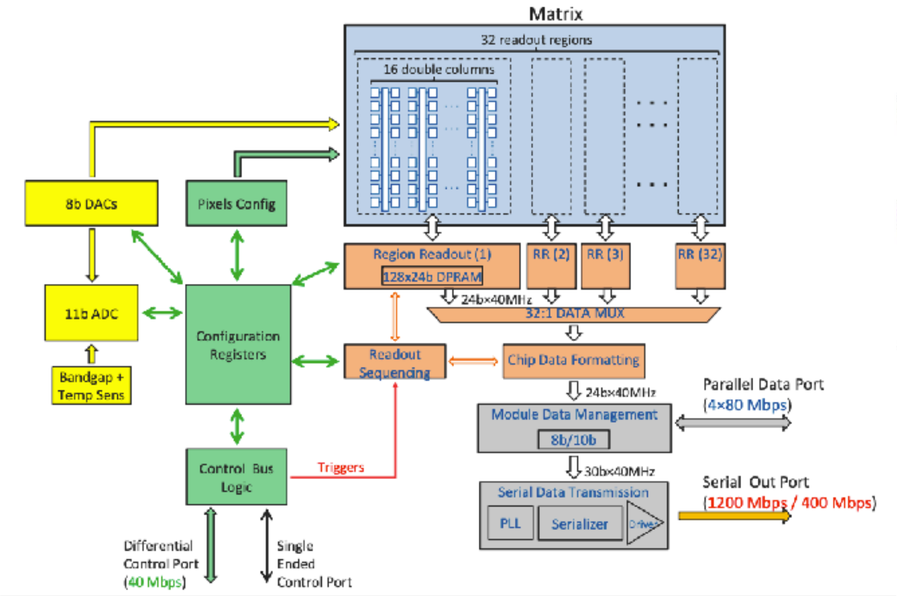


sub-module: PCB+Sensors+W plate

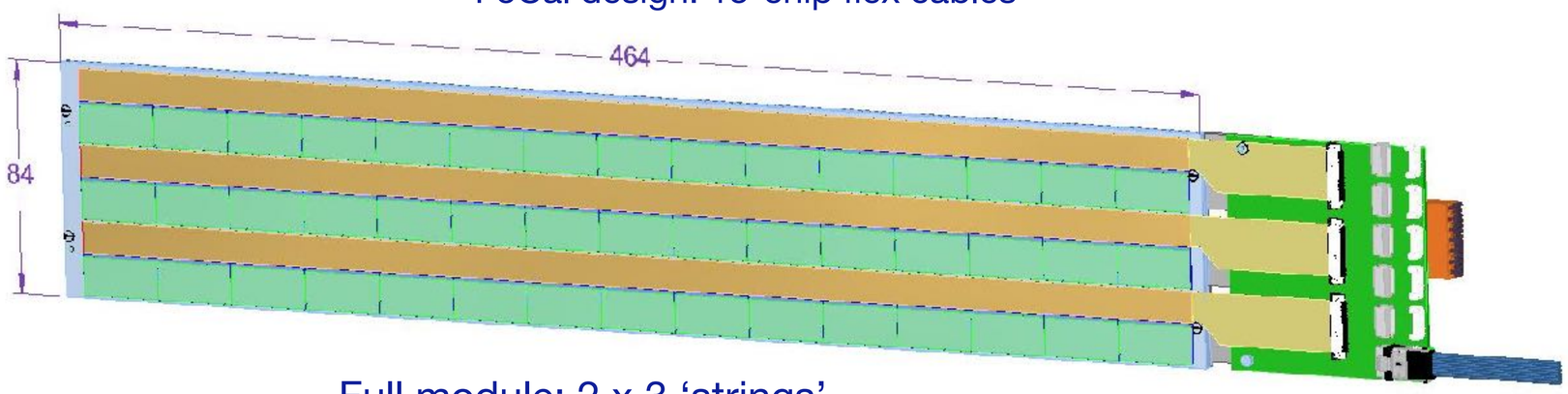


Experience with module assembly and design
at Tsukuba Univ., Tsukuba Tech

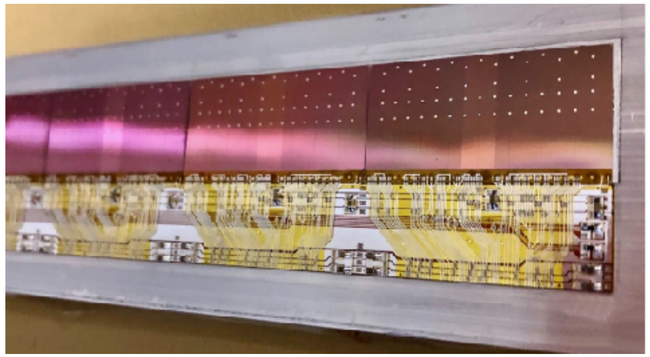
Pixel layer design



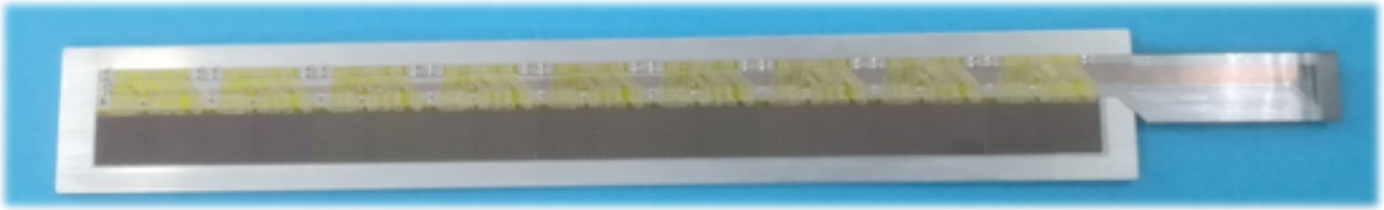
FoCal design: 15-chip flex cables



Full module: 2 x 3 ‘strings’

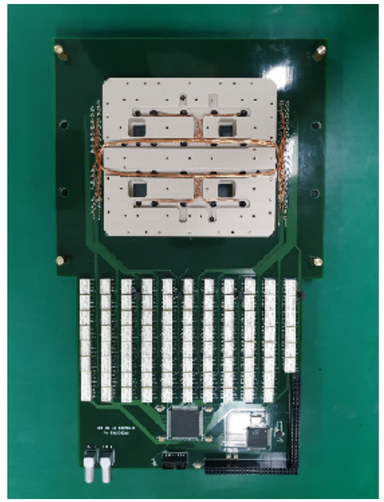


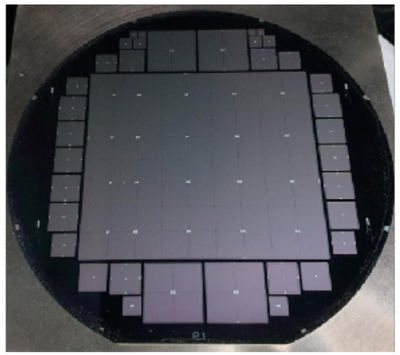
9 ALPIDE flex for pCT application)

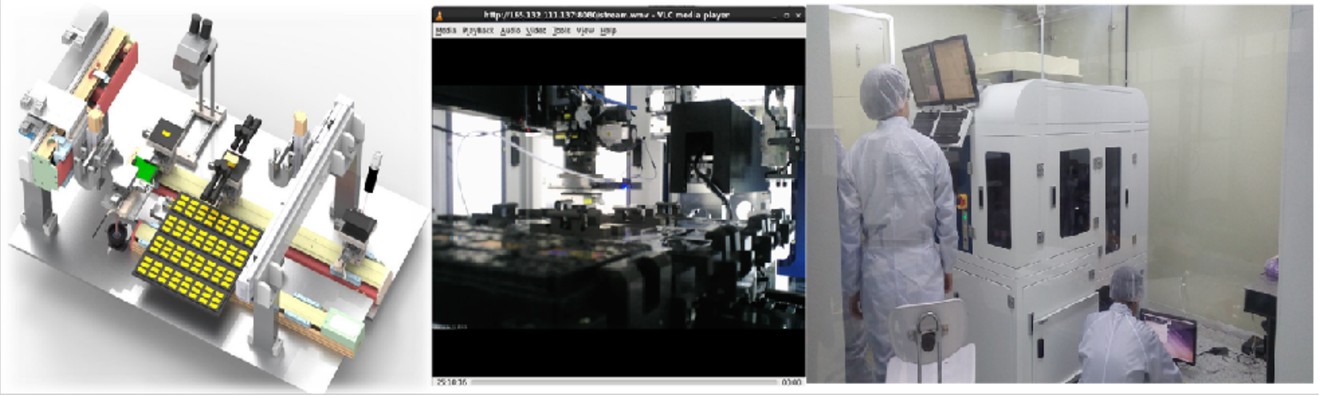


Sensor: ALPIDE pixel sensor
- Developed for ALICE ITS
- Continuous readout with priority encoder readout
- Shaping time ~ 5 μs
- Up to 960 Mb/s output per sensor

Validation and improvements of the sensors and readout chips





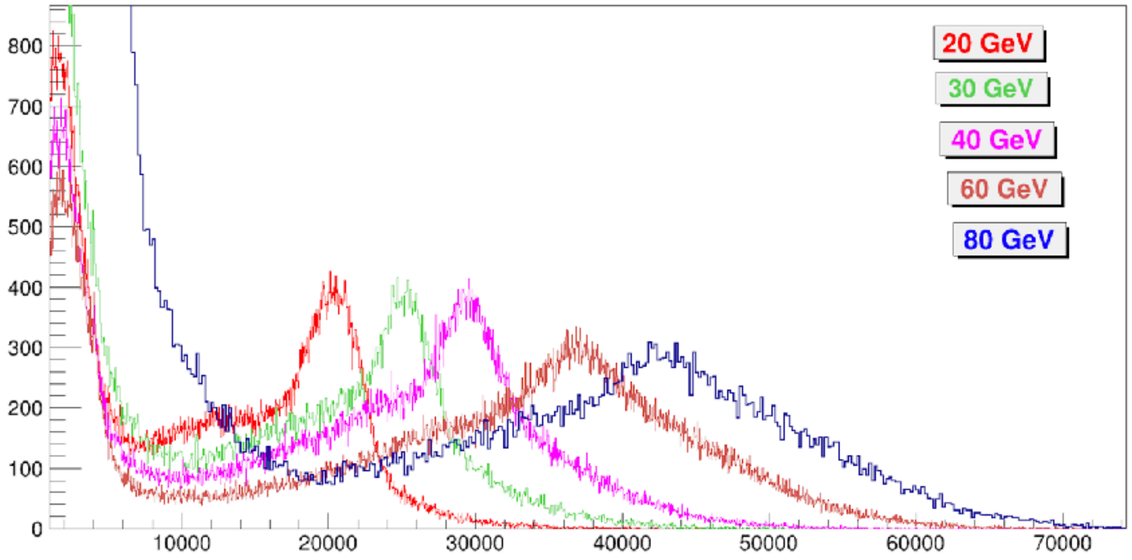


- R&D of Silicon sensor fabrication and test (p-pattern / n-type sensors)
- Explore possibility and funding
  - Test of HGCROC v2 readout chip with n-type sensors
  - Development and validate production of improved / fixed chip for n-type sensors

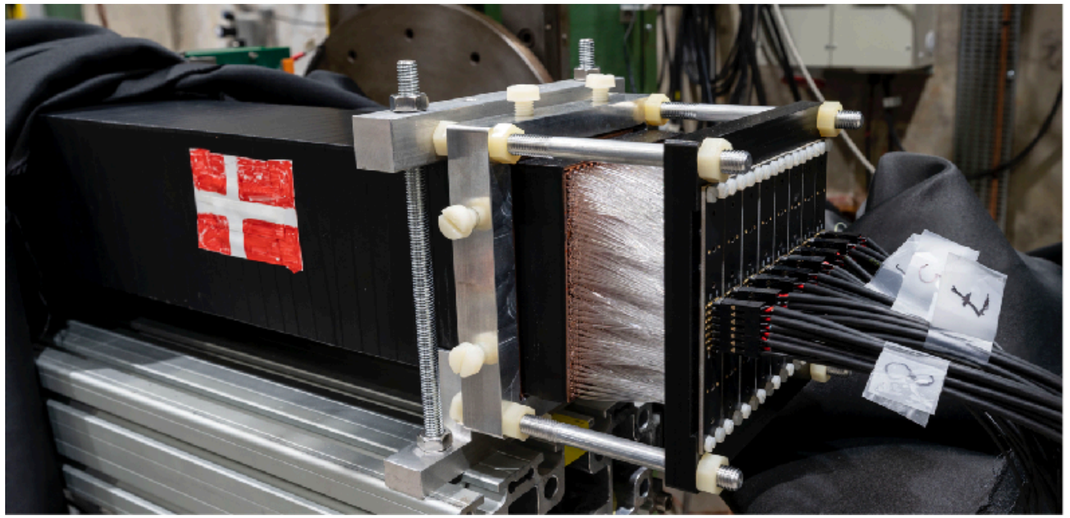
- Validate production of pixel sensors (ALPIDE) for the high granularity layers
- Explore possibility and funding for
  - ALPIDE-REBIN: reducing data load via rebinning the digital information into macro pixels (~factor 10 reduction)
  - ALPIDE++: Speeding up the readout

FoCal-H: Prototype and final design

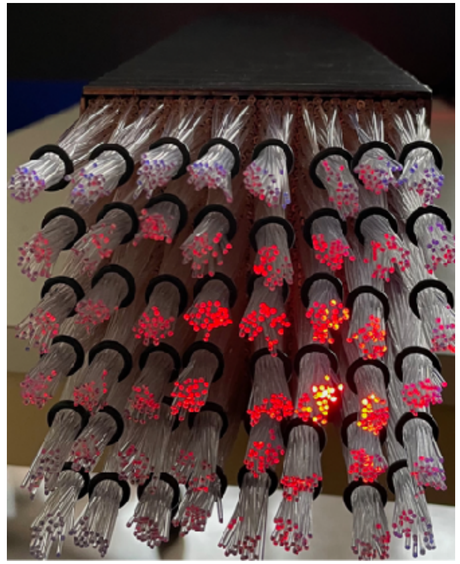
Raw charge distributions from fall 2021 SPS test beam



Copenhagen, Sofia uni.



10cm x 10cm x 55 cm



Exploring capillary-tubes based design for FoCal-H
filled with scintillating fibers + readout with HGCROC chip

- Size 90cm x 90 cm x 110 cm
- About 2000 channels

Attractive for production

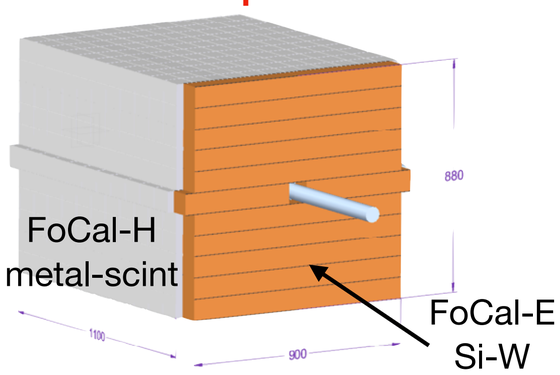
- Cu tubes are readily available
- Seamless tower stacking possible
- Synergies with EIC calorimetry and dual readout (IDEA, upgrades at EIC)

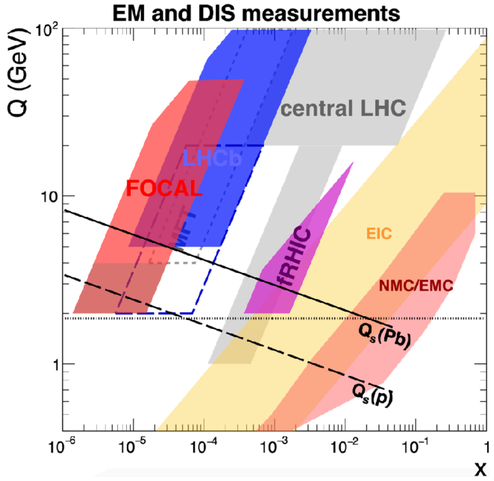
(Activity maybe also interesting for Korean institutes working on DR calorimetry)

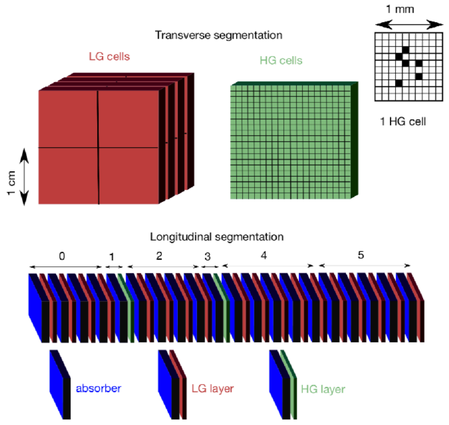
Summary

CERN-LHCC-2020-009

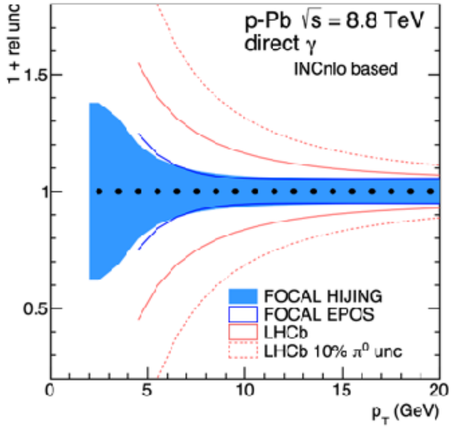
$3.4 < \eta < 5.8$

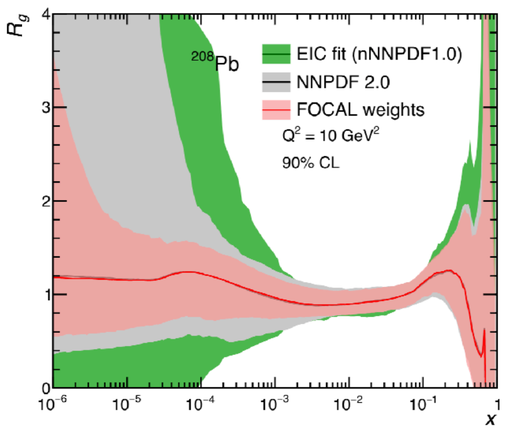


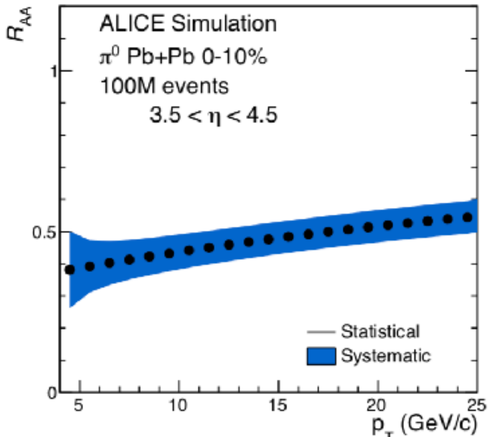




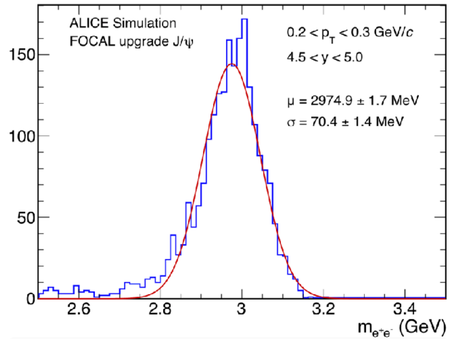
- Non-linear QCD evolution (saturation) is non-negotiable for QCD (similar to Higgs boson in SM)
  - One of the key topics at the EIC
- FoCaL very forward, highly-granular Si+W "shower tracking" ECal with HCal
  - Main physics goal to explore non-linear QCD evolution
    - Isolated photons, correlations, UPC
    - Excellent performance over large η down to low p_T with small uncertainties
    - Strong small-x program at LHC together with LHCb; smaller x-region than at fRHIC and EIC
- Exciting calorimeter concept and technology
  - Large experience with prototypes
  - Technology synergy (ALPIDE, HGCROC)
  - Feasibility (choice of technology, integration, adequate resources) established
- Challenging and interesting times ahead towards the TDR and production







+ UPC, correlations, jets



Extra

The FoCal physics program

1. Quantify nuclear modification of the gluon density at small-x
   - Isolated photons in pp and pPb collisions

2. Explore non-linear QCD evolution
   - Azimuthal π^0-π^0 and isolated photon-π^0 (or jet) correlations in pp and pPb collisions

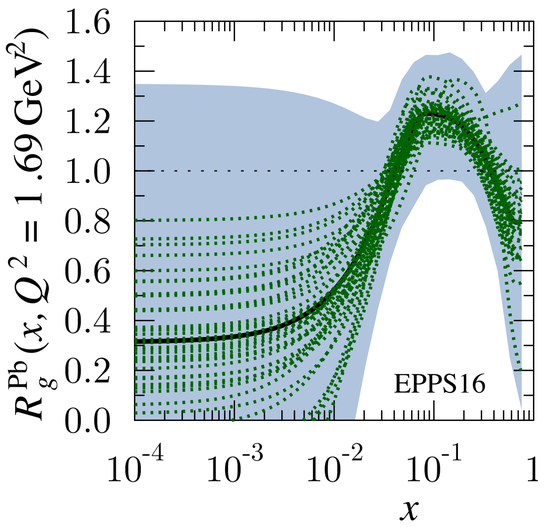
3. Investigate the origin of long range flow-like correlations
   - Azimuthal π^0-h correlations using FoCal and central ALICE (and muon arm) in pp and pPb collisions

4. Explore jet quenching at forward rapidity
   - Measure high p_T neutral pion production in PbPb

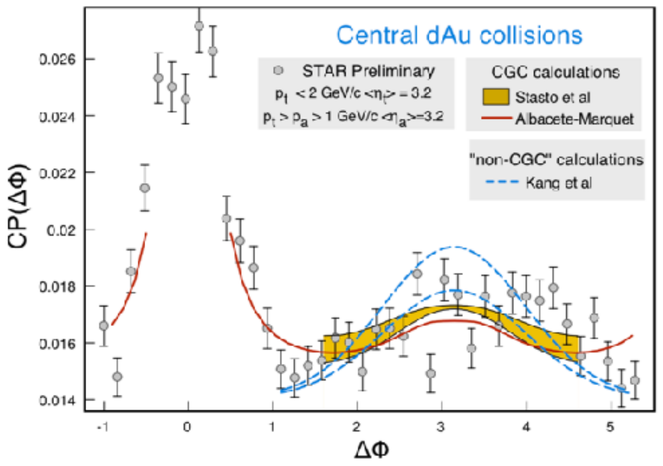
5. Other measurements
   - Jets and dijets in pp/pPb and UPC
   - Quarkonia in UPC (and pp*)
   - Photon and pion HBT (*)
   - W,Z in pp/pPb?
   - Isolated photons in PbPb (*)
   - Measurements at 14 TeV
     - Universality at small-x
     - Saturation in pp
     - High-x (>0.1) gluon constraints (*)

(*=feasibility not yet explored)

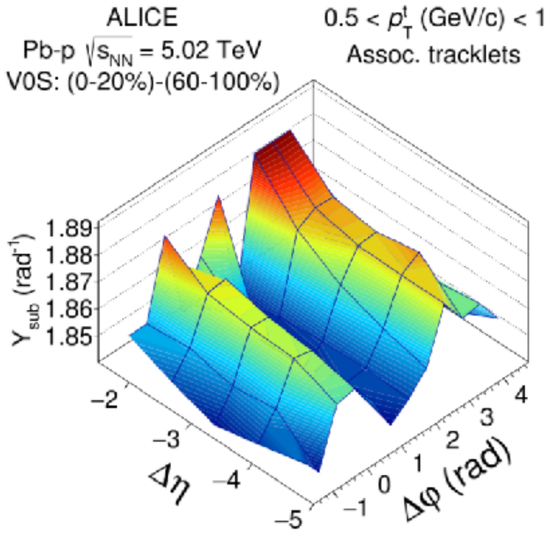
1. Nuclear PDFs



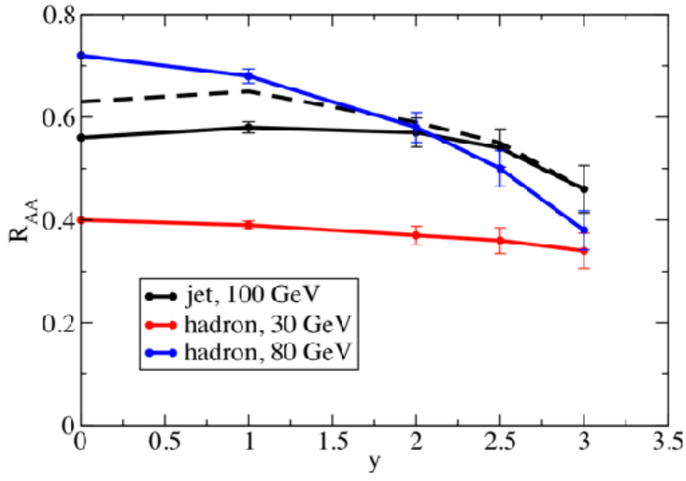
2. Non-linear evolution



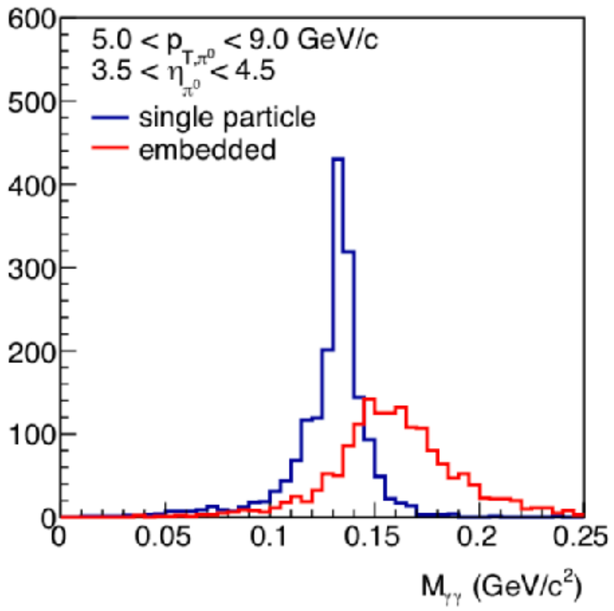
3. Long-range correlations

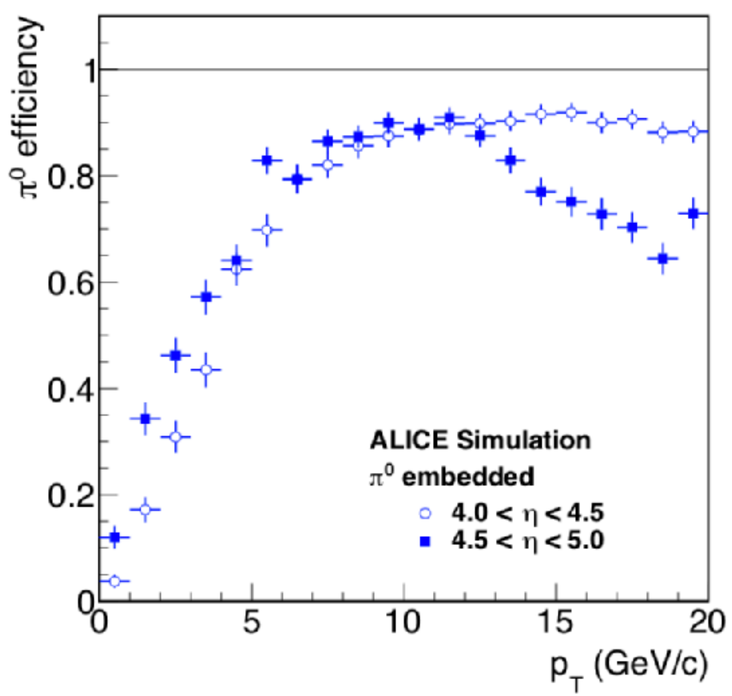


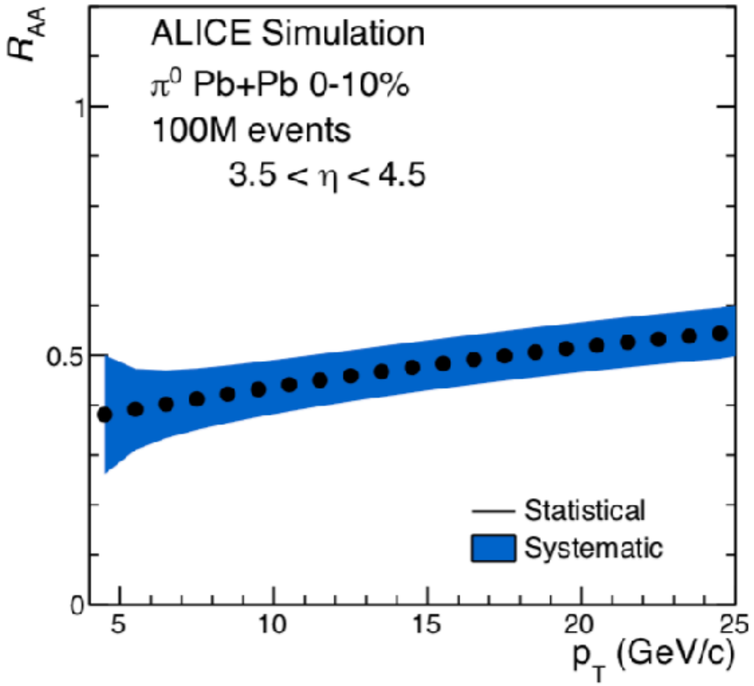
4. Jet quenching

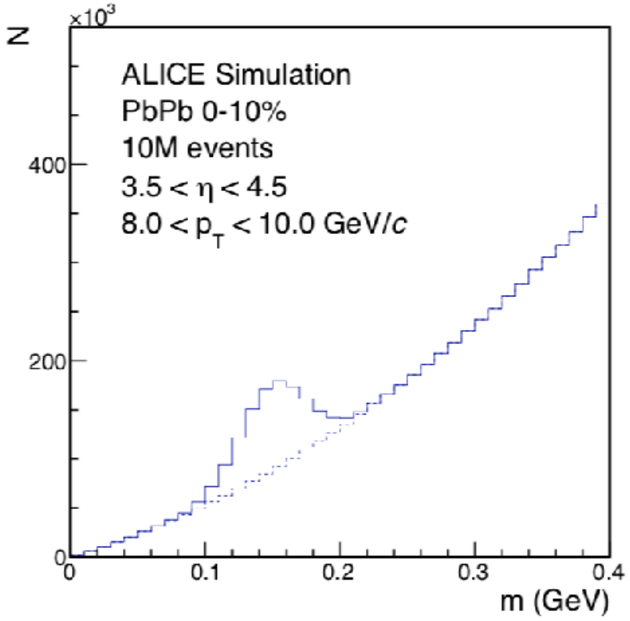


Performance in PbPb



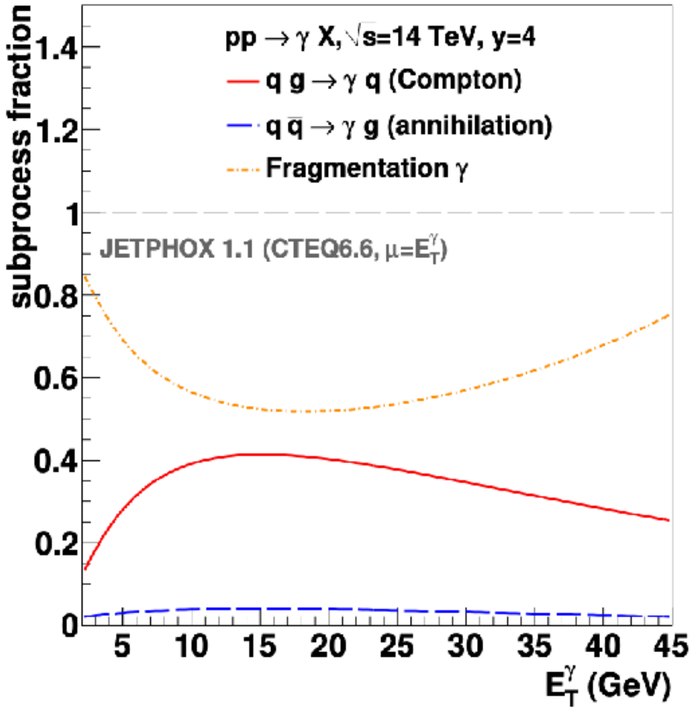


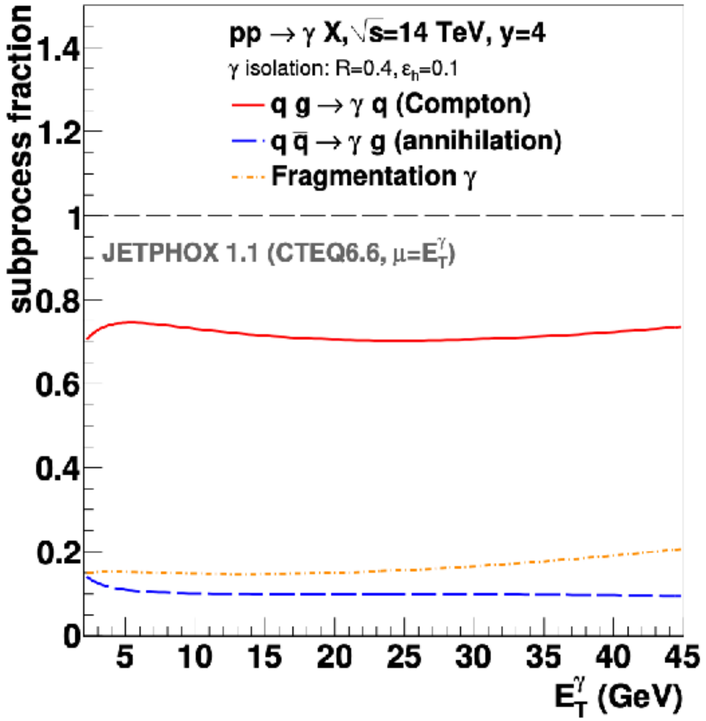


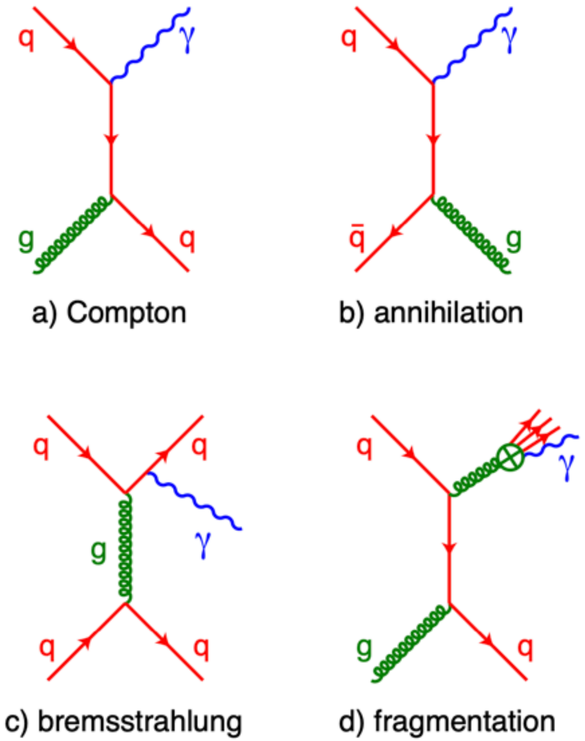


- Performance in PbPb affected by shower overlaps and combinatorial background
- Efficiency for high energy neutral pions nevertheless quite good
- Combinatorial background may prohibit very low p_T reconstruction, but above 5 GeV <u>expect a precise R_{AA} measurement</u>

Isolated photons

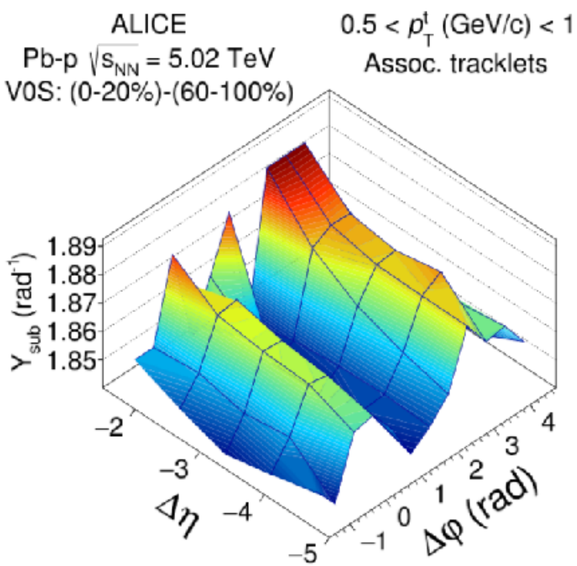


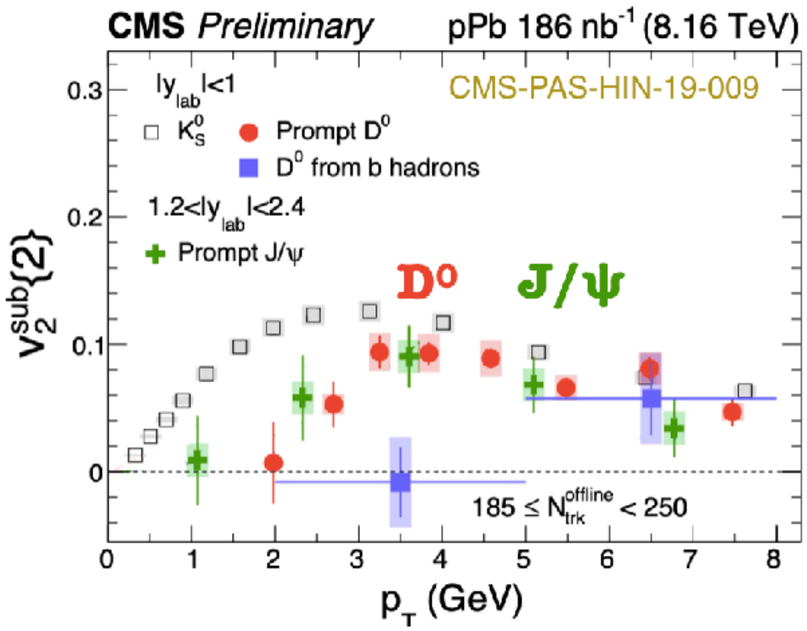


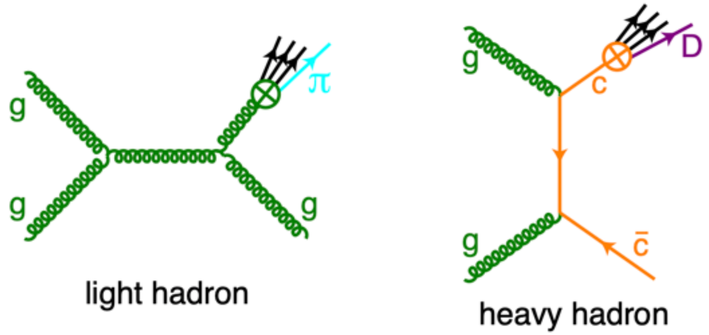


- Experimentally, measure isolated photons to suppress contribution from bremsstrahlung and fragmentation photons
  - In addition, rejects also decay photon background

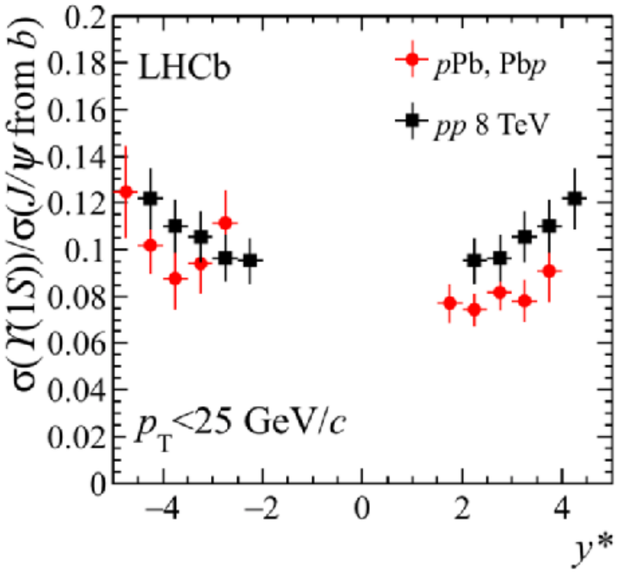
Light and heavy-flavor results

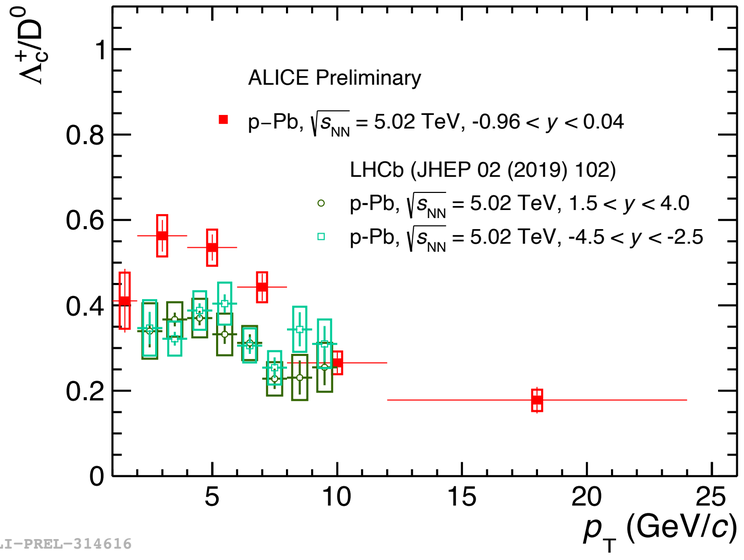






Sensitive to gluon PDF at NLO but also suspect to final state and hadronization effects

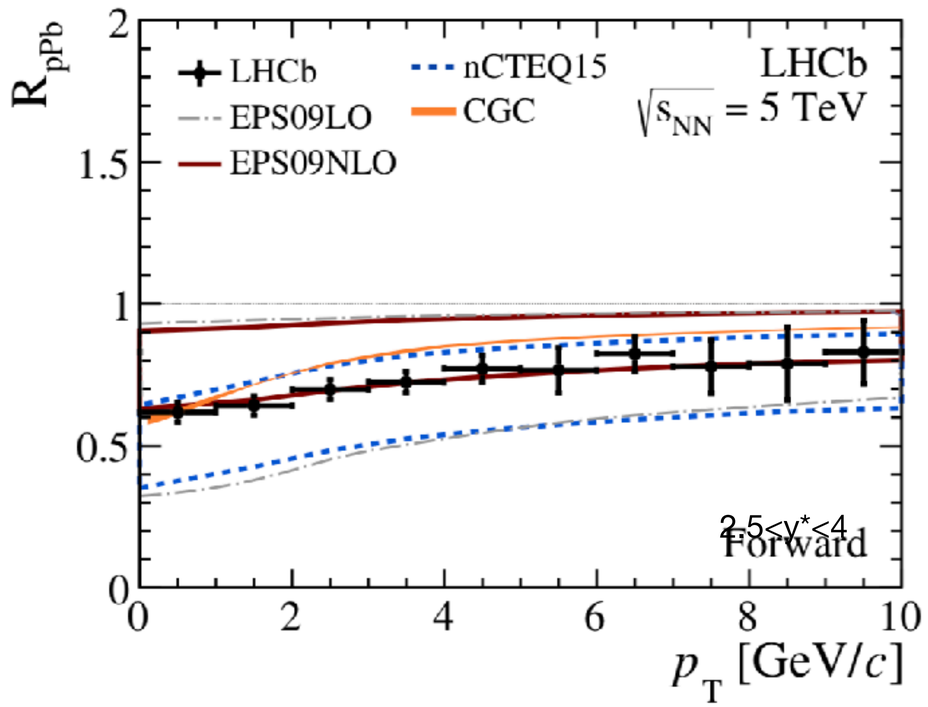




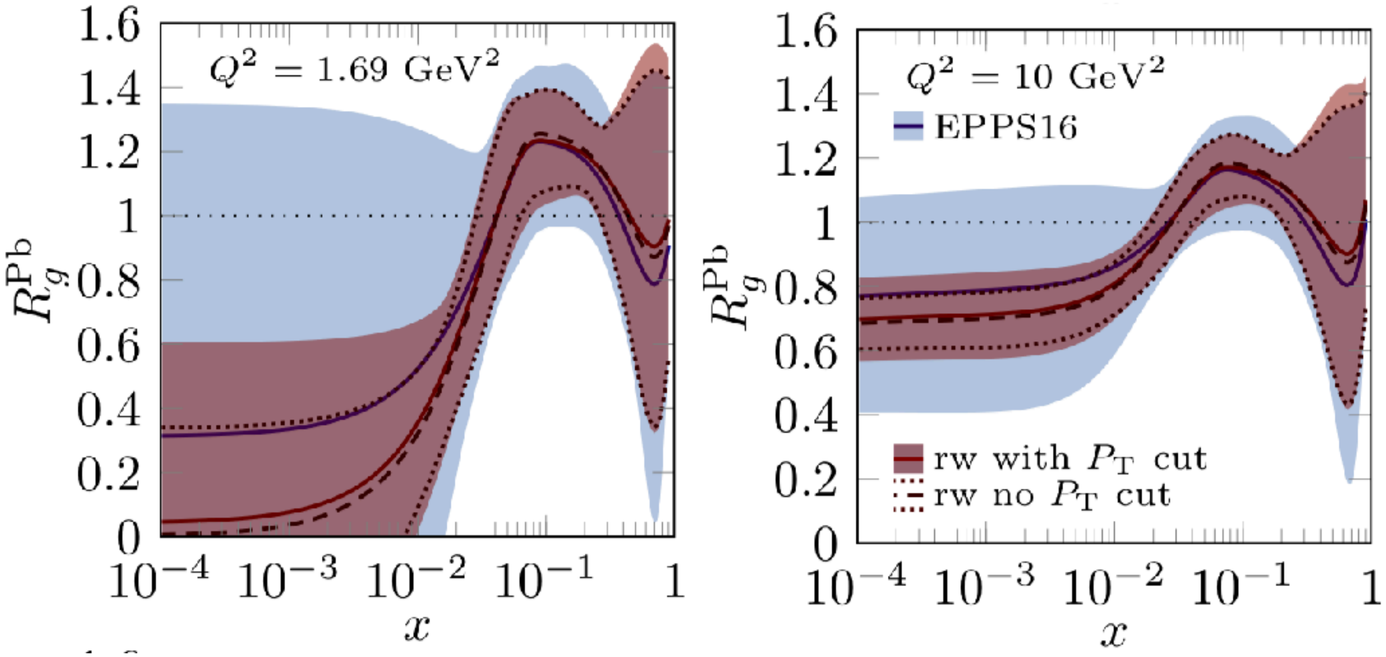
Measurements exhibit features that are difficult to disentangle between initial or final state effects

Forward open charm by LHCb

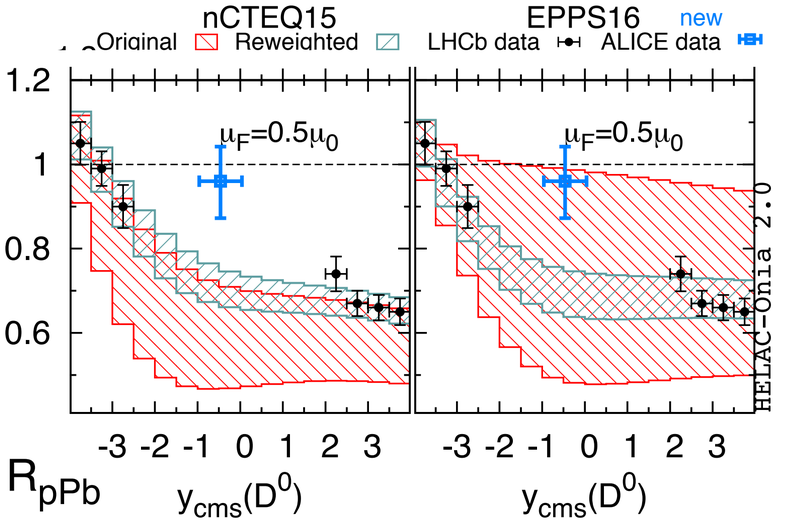
LHCb, arXiv:1707.02750



Eskola et al., arXiv:1906.02512

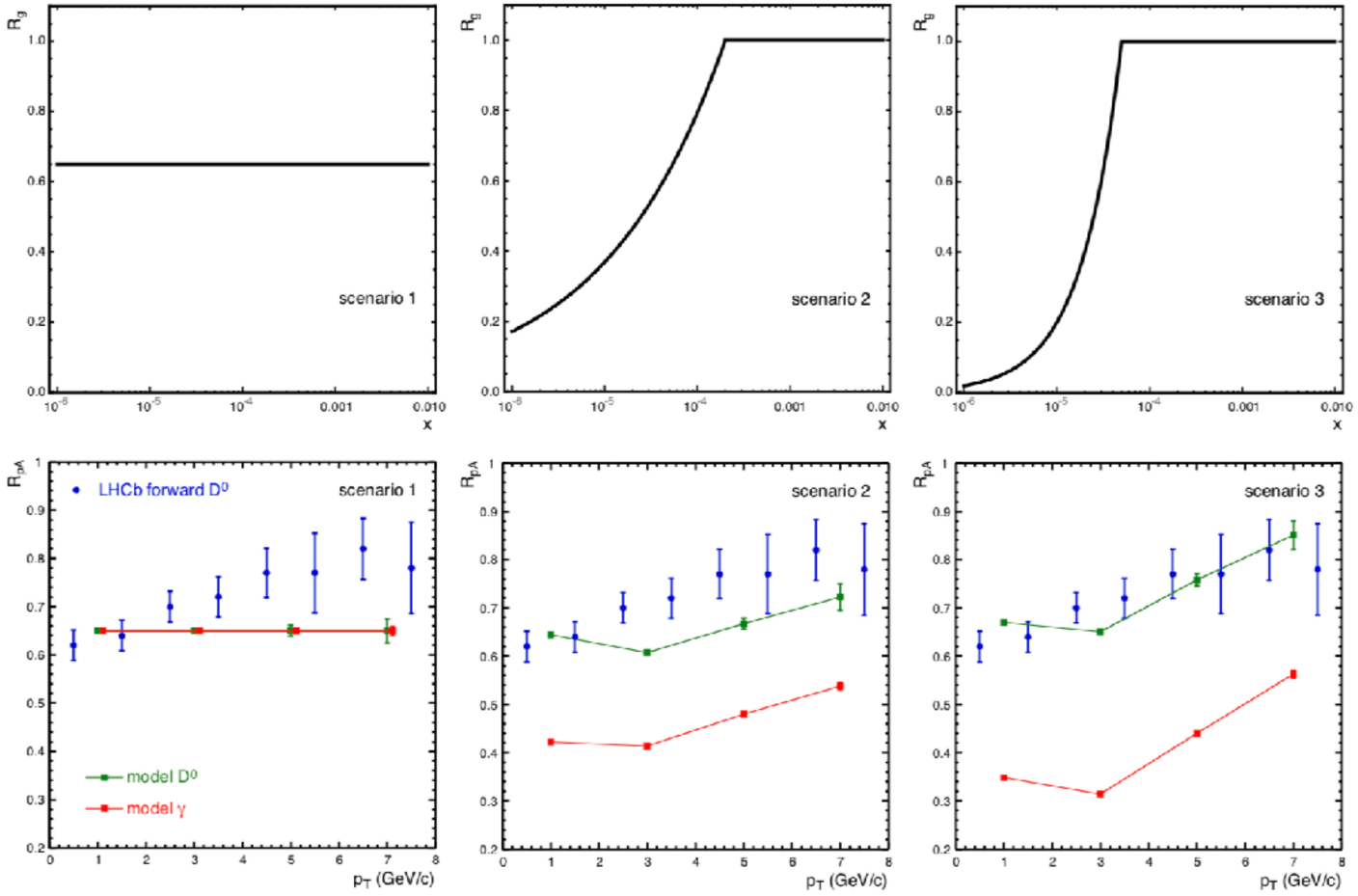


- Forward D^0 suppression observed by LHCb
- Consistent description with nuclear PDFs, with a large contribution from high x from fragmentation
  - Data constrain nPDF uncertainties by ~factor 2
  - Potential final state effects ignored
    - Small tension with ALICE mid-rap data
- Measurements with photons will verify factorization and universality



Kusina et al., PRL121 (2018) 052004 ALICE, arXiv:1906.03425

Charm vs photon sensitivity



Toy study: Photons are more sensitive to shape of Rg than charm

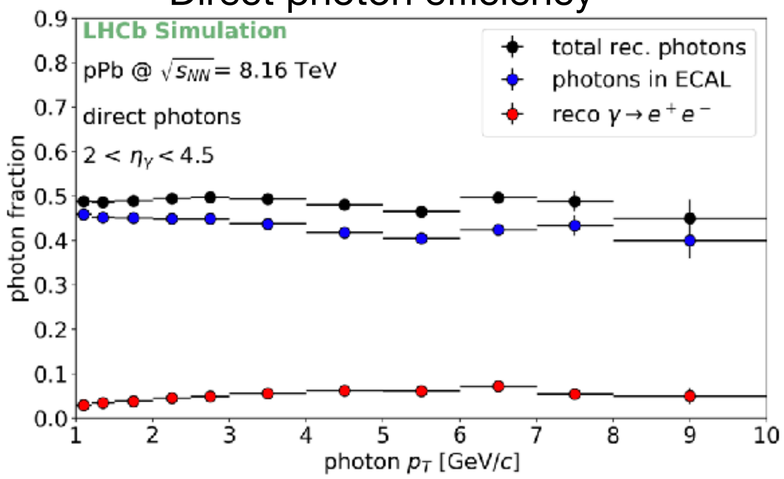
Isolated photons with LHCb

LHCb-FIGURE-2020-006

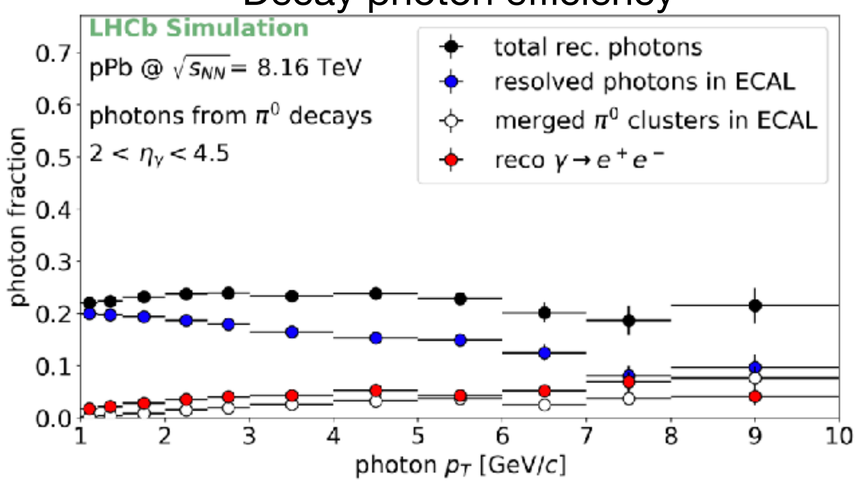
New analysis being pursued in LHCb (LANL group)

- Signal: (early) photon conversions
  - Clean identification
  - About ~0.25 X_0 with 6% uncertainty
  - Limited efficiency ~10% HLT trigger in Run 3
- Decay rejection by isolation
  - Accceptance limited to η<4 (isolation up to Ecal edge η=4.4)
- Final selection: cuts combined with BDT

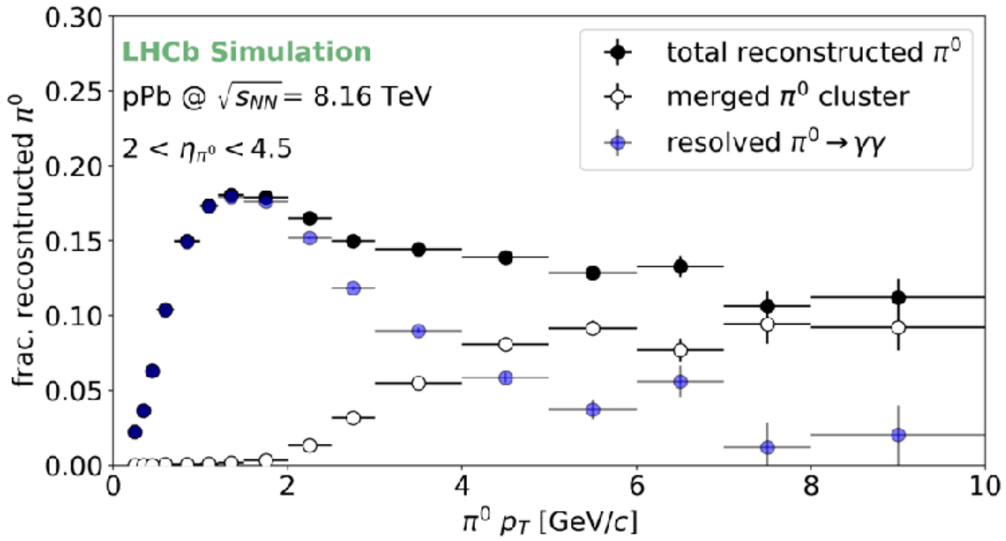
Direct photon efficiency



Decay photon efficiency



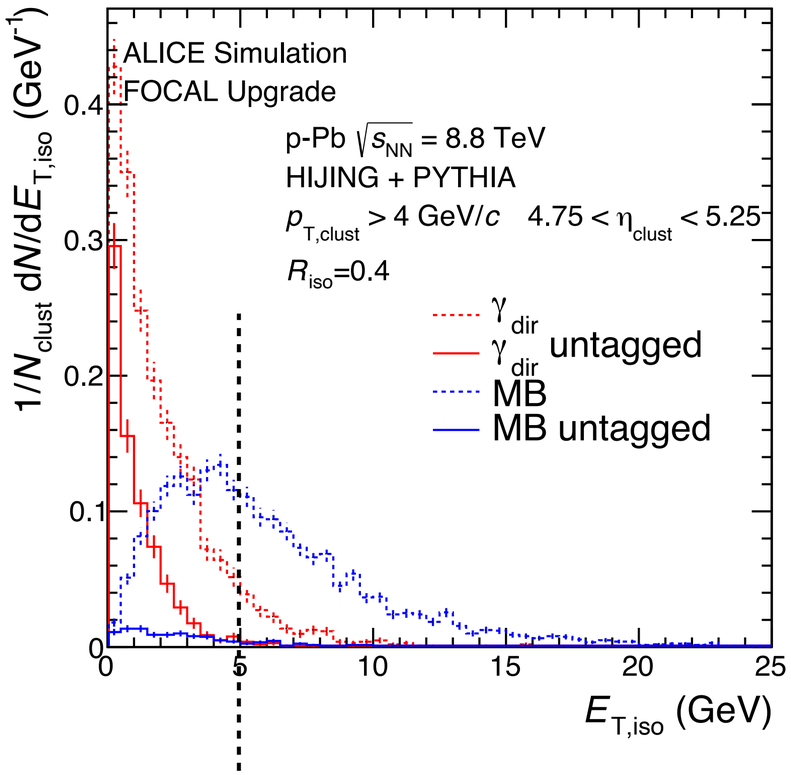
π^0 efficiency



- Photon efficiency between 25-45% (depending on activity)
- Reconstruction efficiency of π^0 only ~15% above 2 GeV
  - Compare with FoCal ~85%
- Direct tagging of decay photons very limited

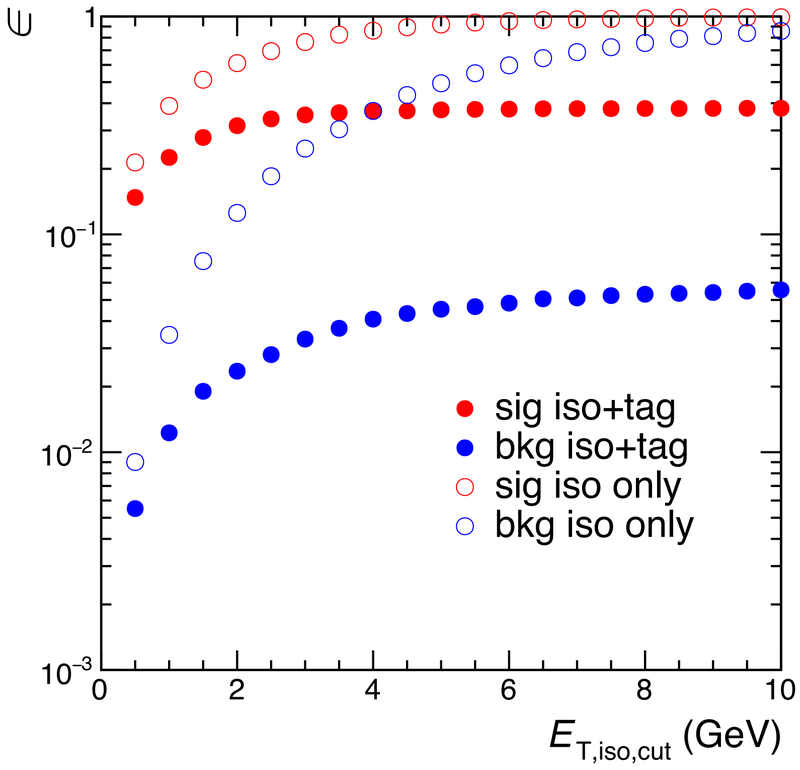
Focal performance (pPb)

(η_{lab} = 5)

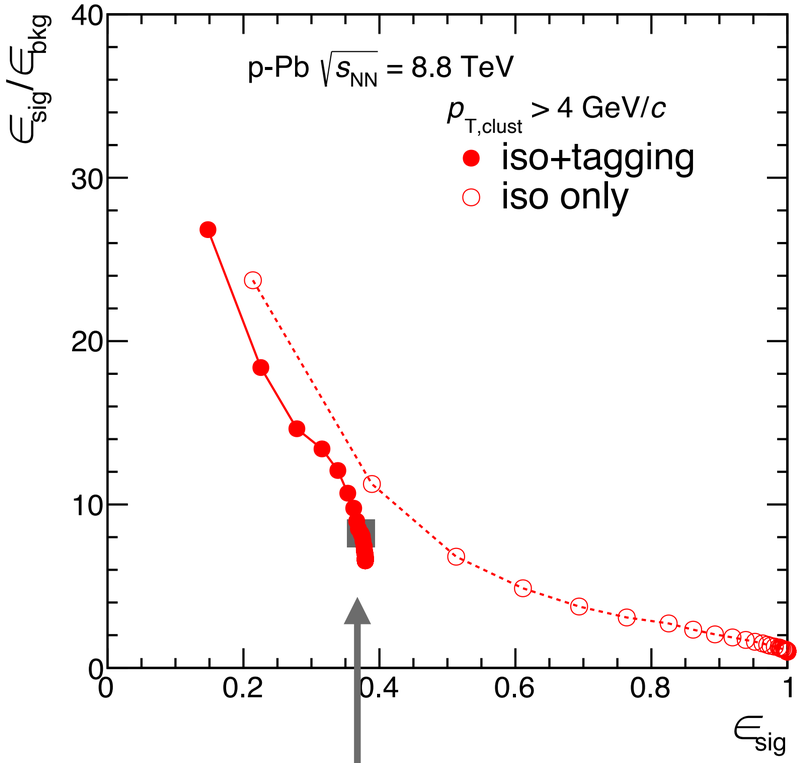


Default cut
$E_{T,iso}$ < 5 GeV

Efficiencies sig, bkg



Improvement (eff sig/eff bkg)

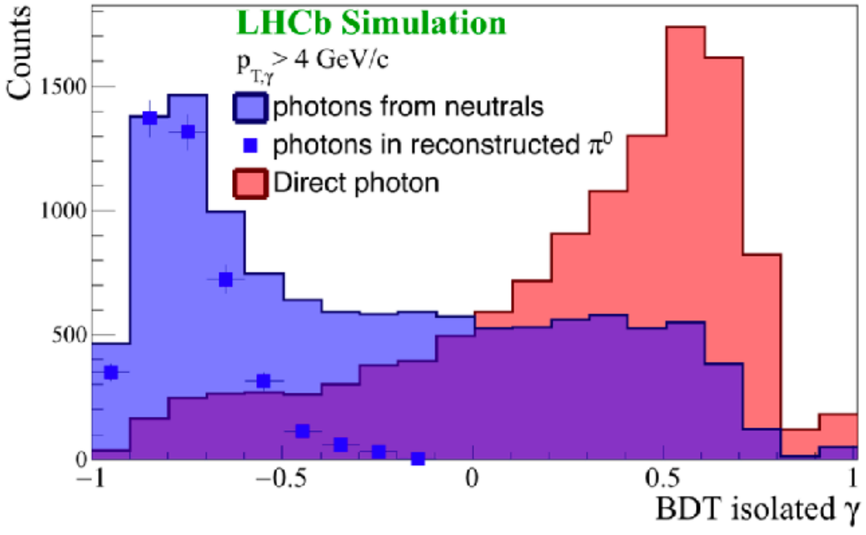


FoCal operating point in LOI

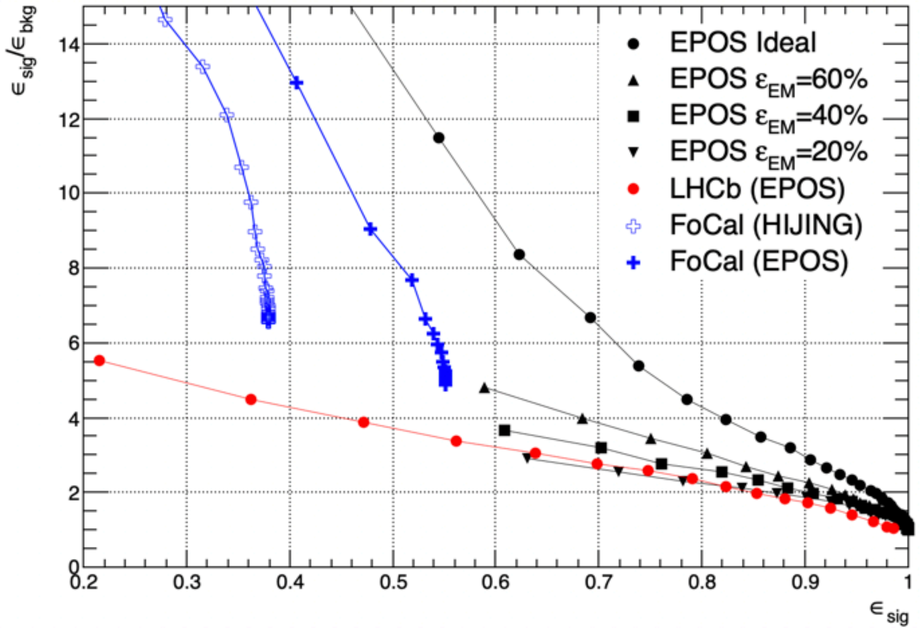
N.B.: "untagged" means "decay photon rejected"

Comparison with LHCb

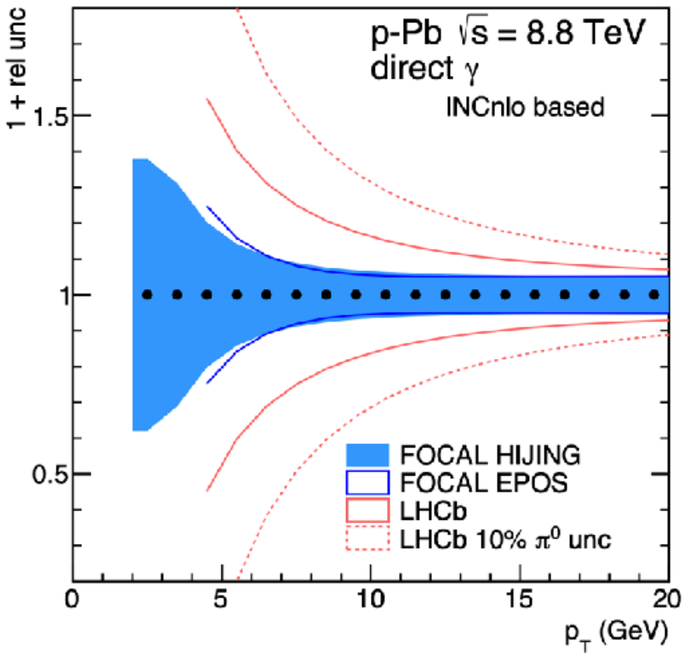
BDT response



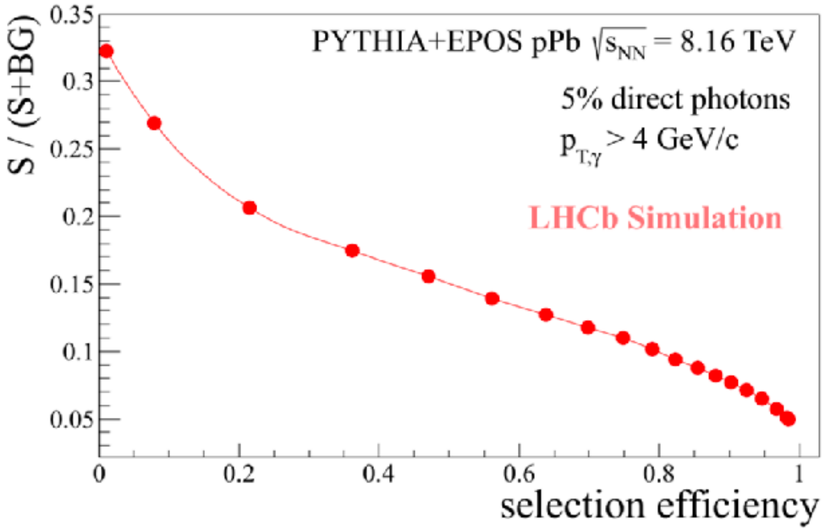
Improvement in S/B



Performance in pPb



Purity vs efficiency of BDT cut

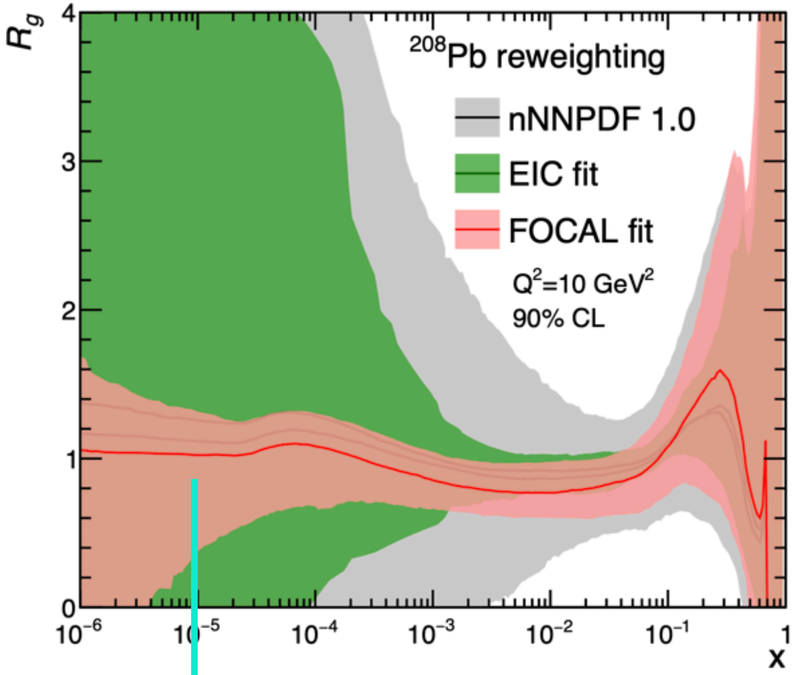


- LHCb analysis approach: identify signal by BDT based on a combination of variables, e.g. isolation energy
- Improvement in S/B significantly smaller than of FoCal
- Leads to factor 2 or larger systematic uncertainty compared to FoCal
  - Expected performance depends on uncertainty on remaining background

(WP at ε_{sig}=0.2 for LHCb, at ε_{sig}~0.4 for FoCal)

FoCal vs LHCb: sensitivity to nPDF

η=4.5 (FoCal)

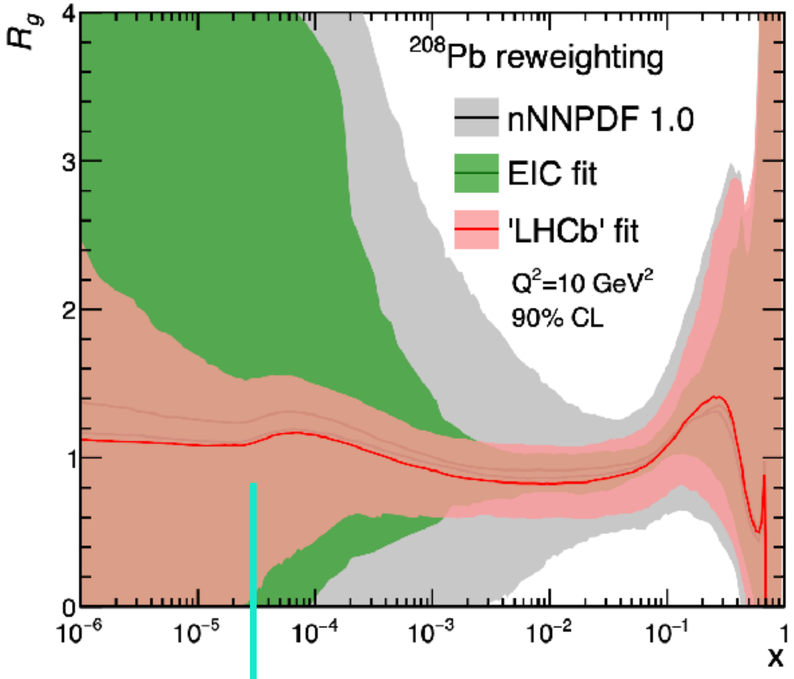


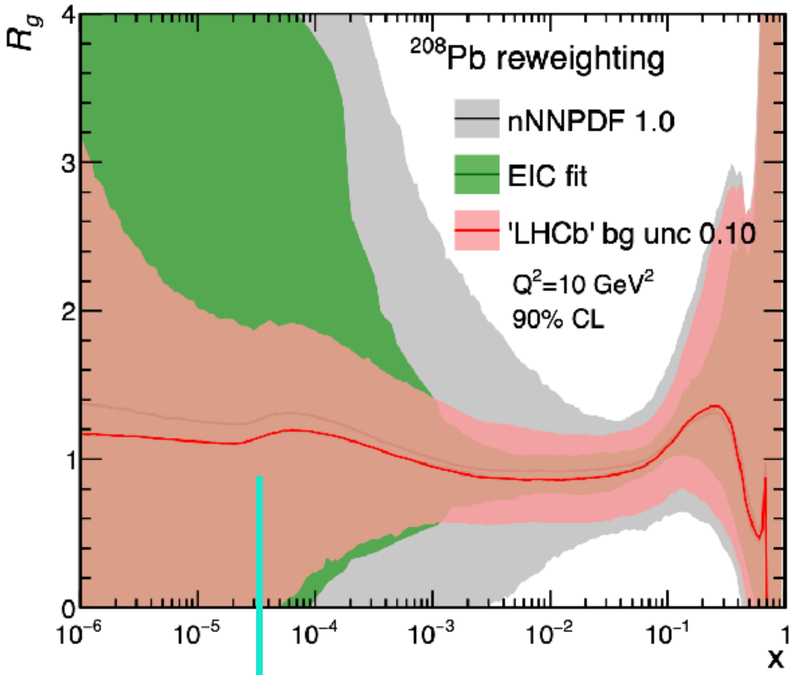
LO x reach

$$x \approx \frac{Q}{\sqrt{s}} \exp(-y)$$

FoCal uncertainties

η=3.5 (LHCb)

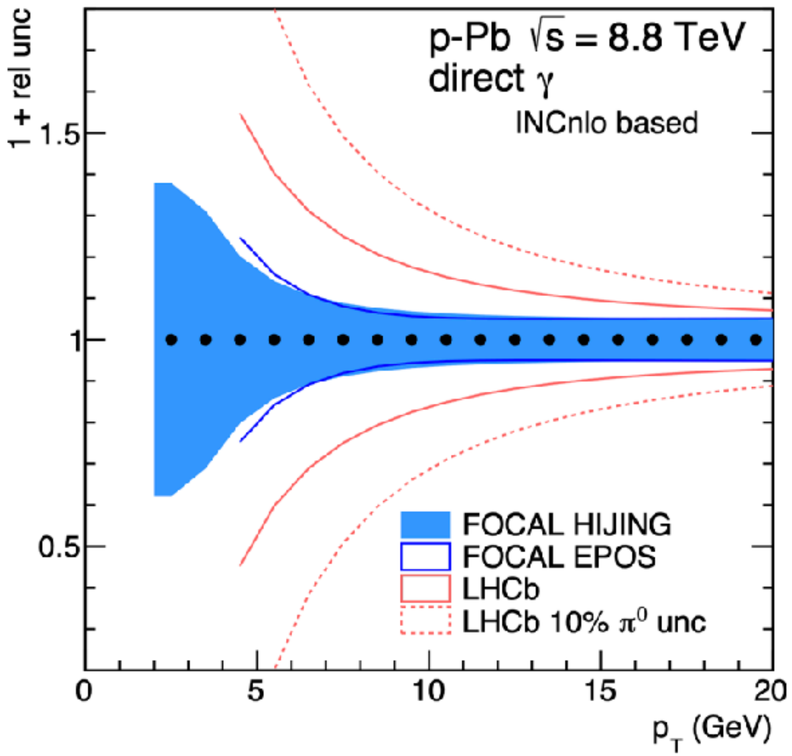


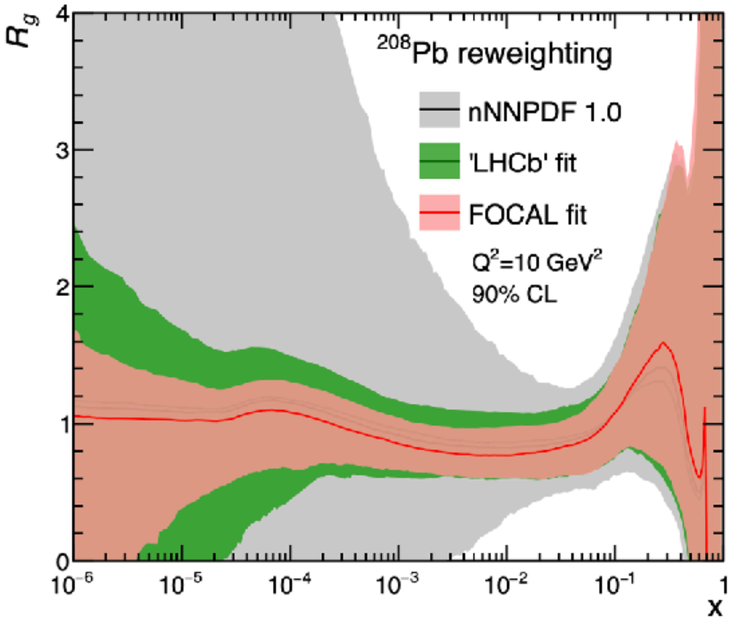


LHCb projected uncertainties
(5% vs 10% uncertainty on the background)

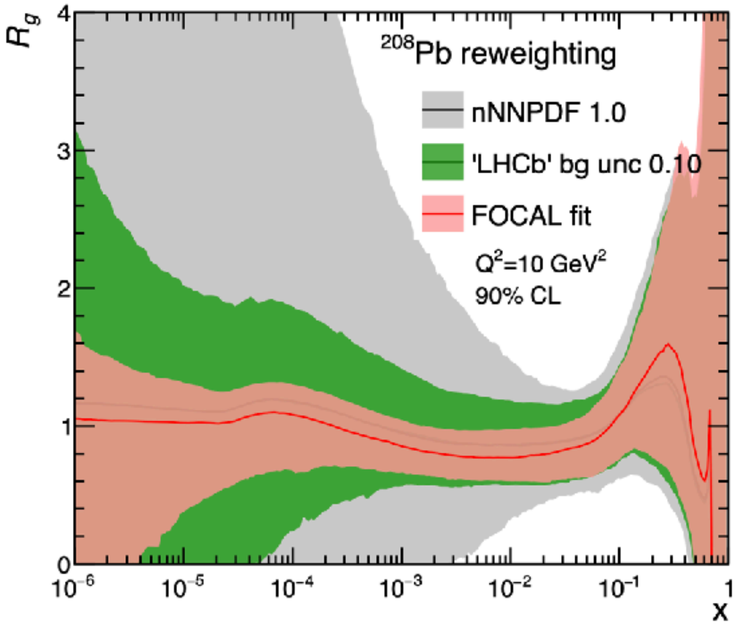
Significantly better performance on nuclear PDF expected by FoCal measurement
(in addition one unit higher reach in pseudorapidity, i.e. factor 3 smaller x reachable)

Comparison of isolated performance with LHCb projection





bgk unc=5%



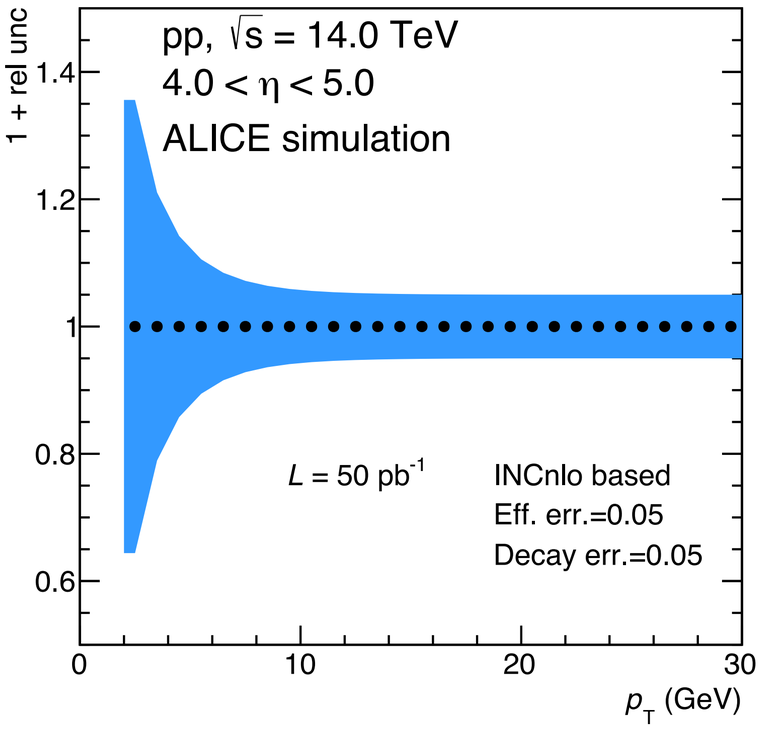
bgk unc=10%

FoCal performance (4<η<5) outperforms LHCb (3<η<4) by a factor of 2 or more in uncertainty (LHCb measures only about 25-40% of the photons from π^0)

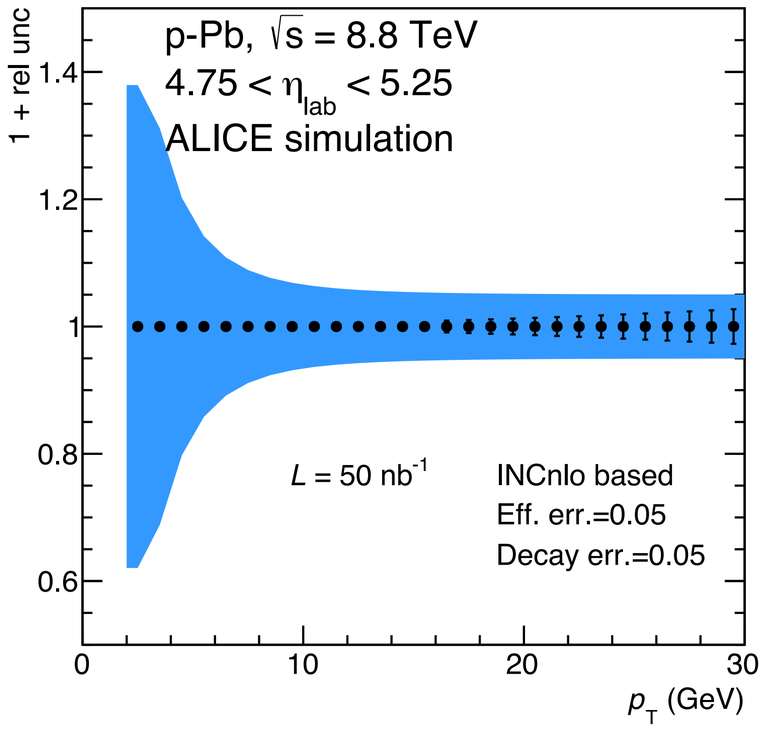
(WP at ε_{sig}=0.2 for LHCb, at ε_{sig}~0.4 for FoCal)

Direct photon uncertainties

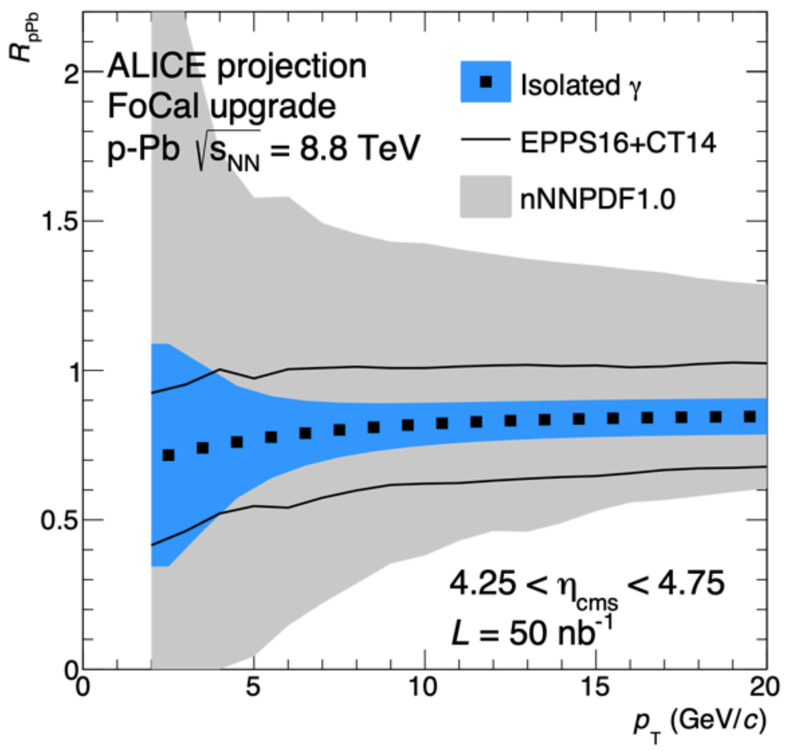
pp uncertainties



p-Pb uncertainties



R_{pPb} projection



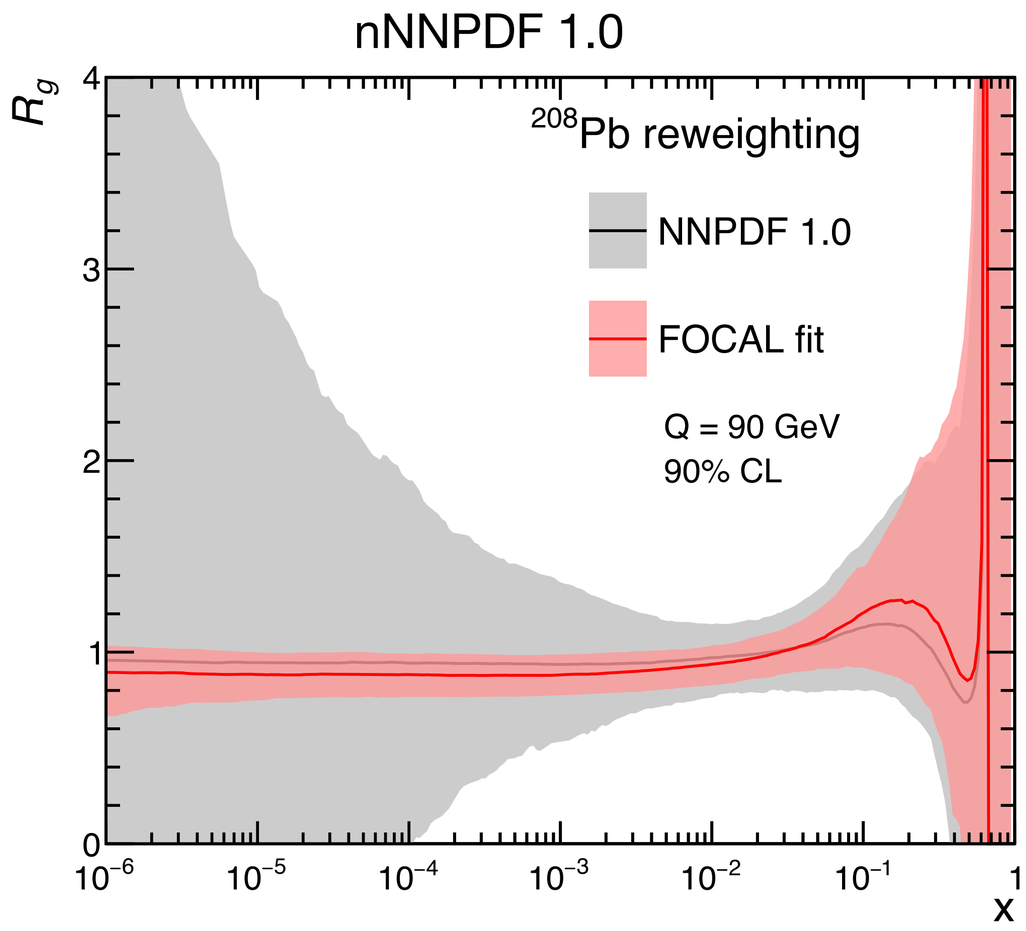
$\eta_{cms} = \eta_{lab} \sim 4.5$ for pp

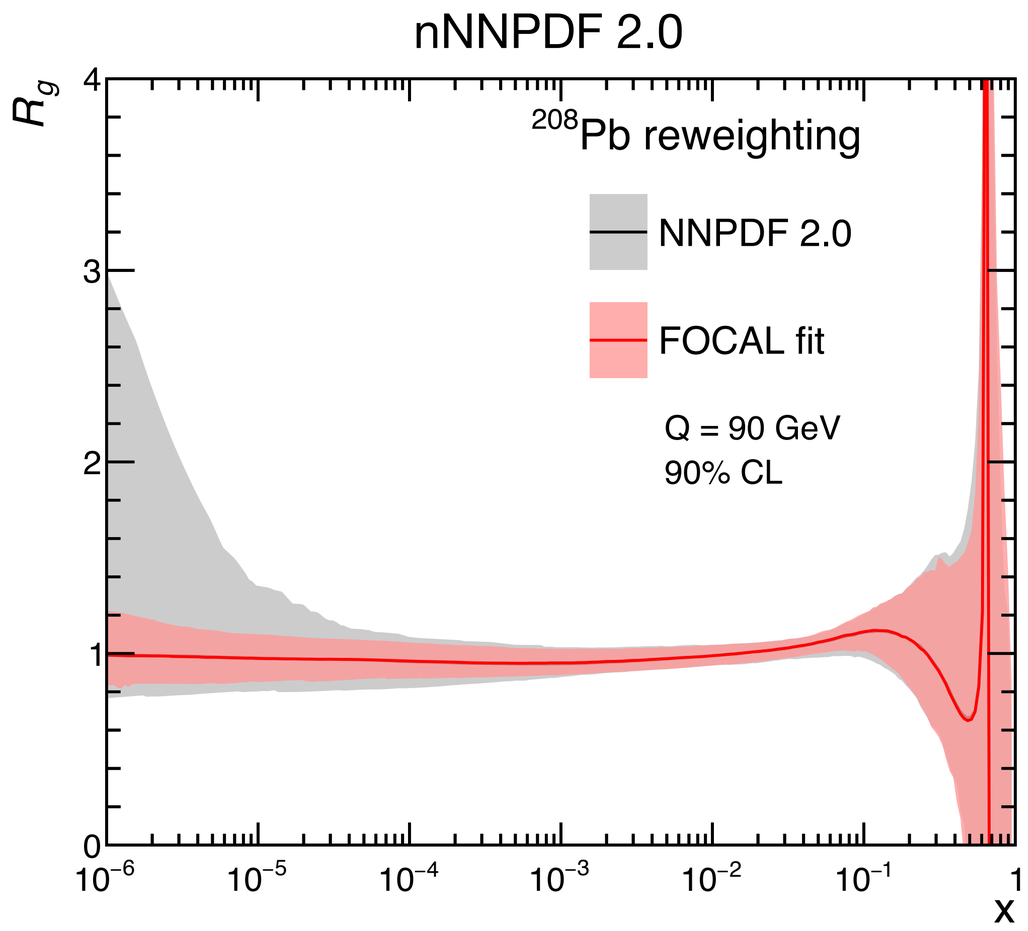
$\eta_{cms} \sim 4.5$: $\eta_{lab} \sim 5.0$ for p-Pb

nNNPDF 1.0 vs 2.0 at M_Z

arXiv:2006.14629

- Include (some) LHC W/Z data
- Include DIS charged current data: flavor separation
- Include 'positivity constraint' : F_L (long structure function) has to be positive



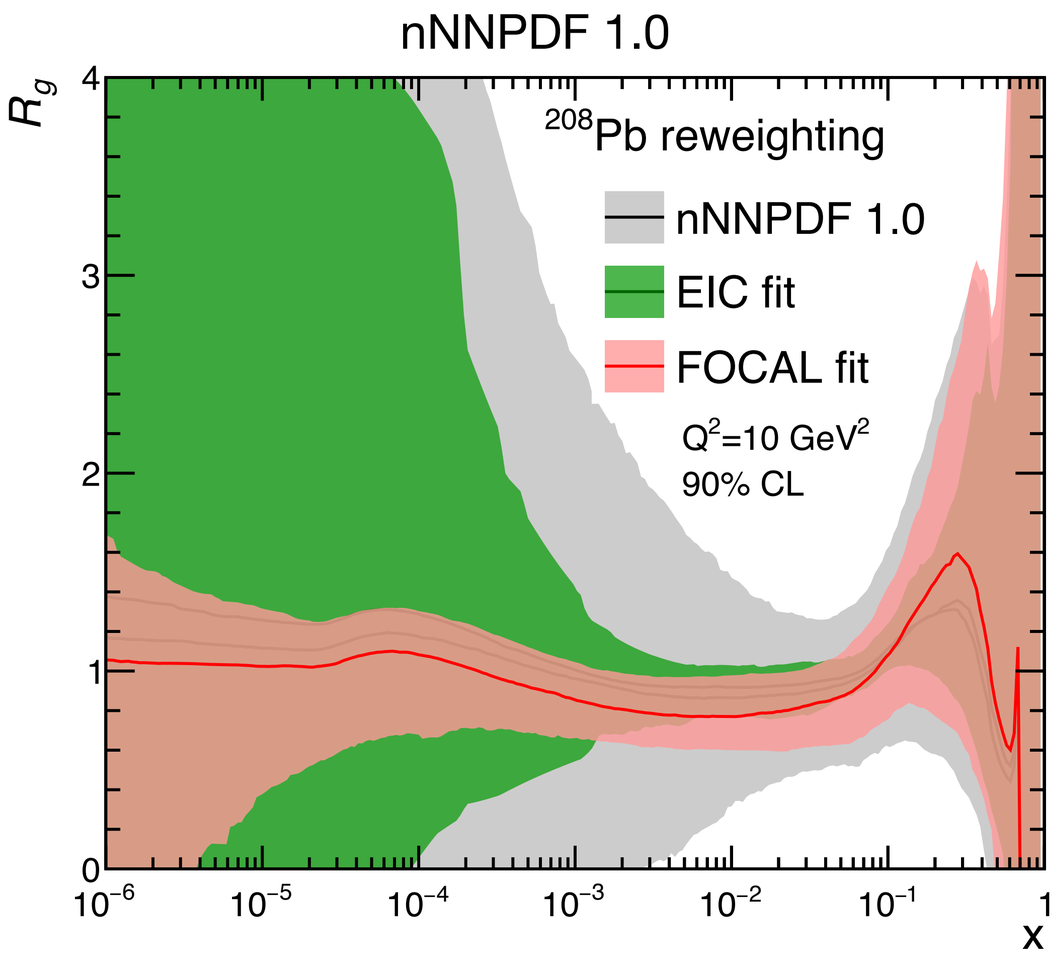


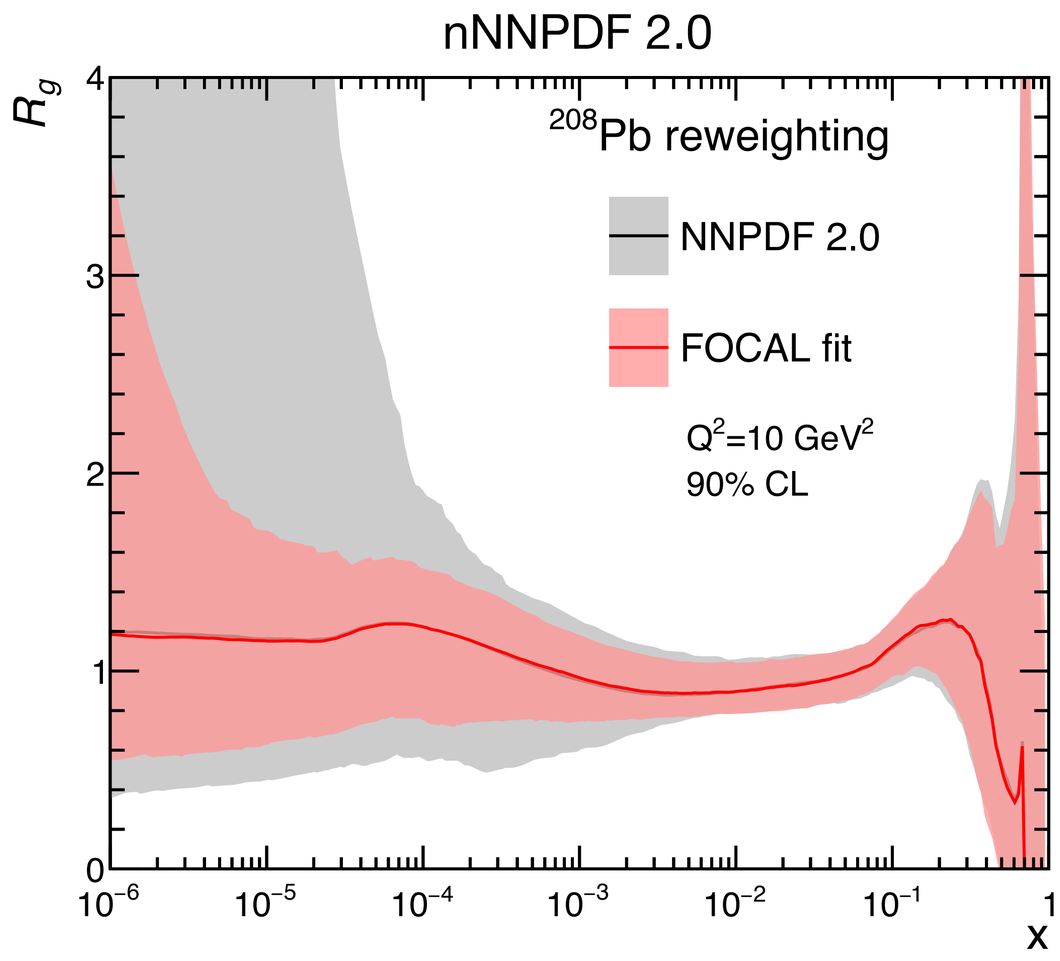
Clear impact of W/Z LHC data

NNPDF2.0

arXiv:2006.14629

- Include (some) LHC W/Z data
- Include DIS charged current data: flavor separation
- Include 'positivity constraint' : F_L (long structure function) has to be positive



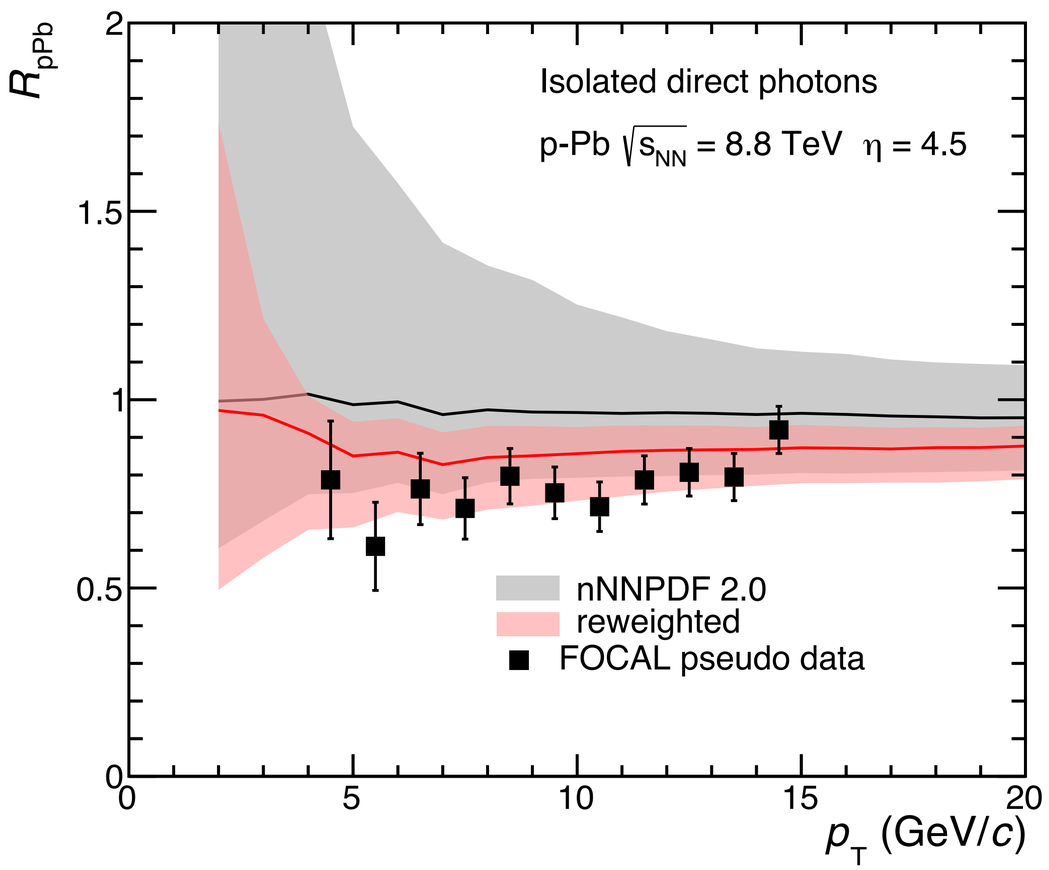


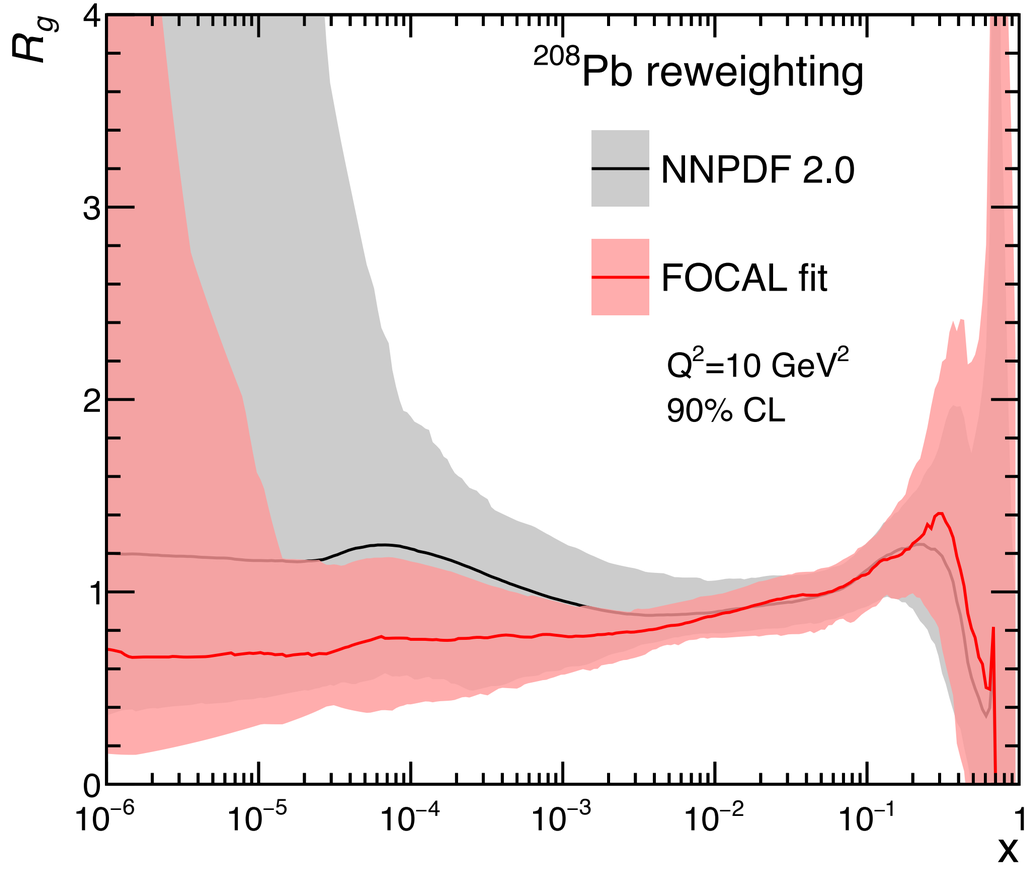
FOCAL places significant constraints in $10^{-5} < x < 10^{-3}$

Sensitivity to non-linear evolution: What if we see suppression?

arXiv:2006.14629

Use smaller central values for pseudo-data



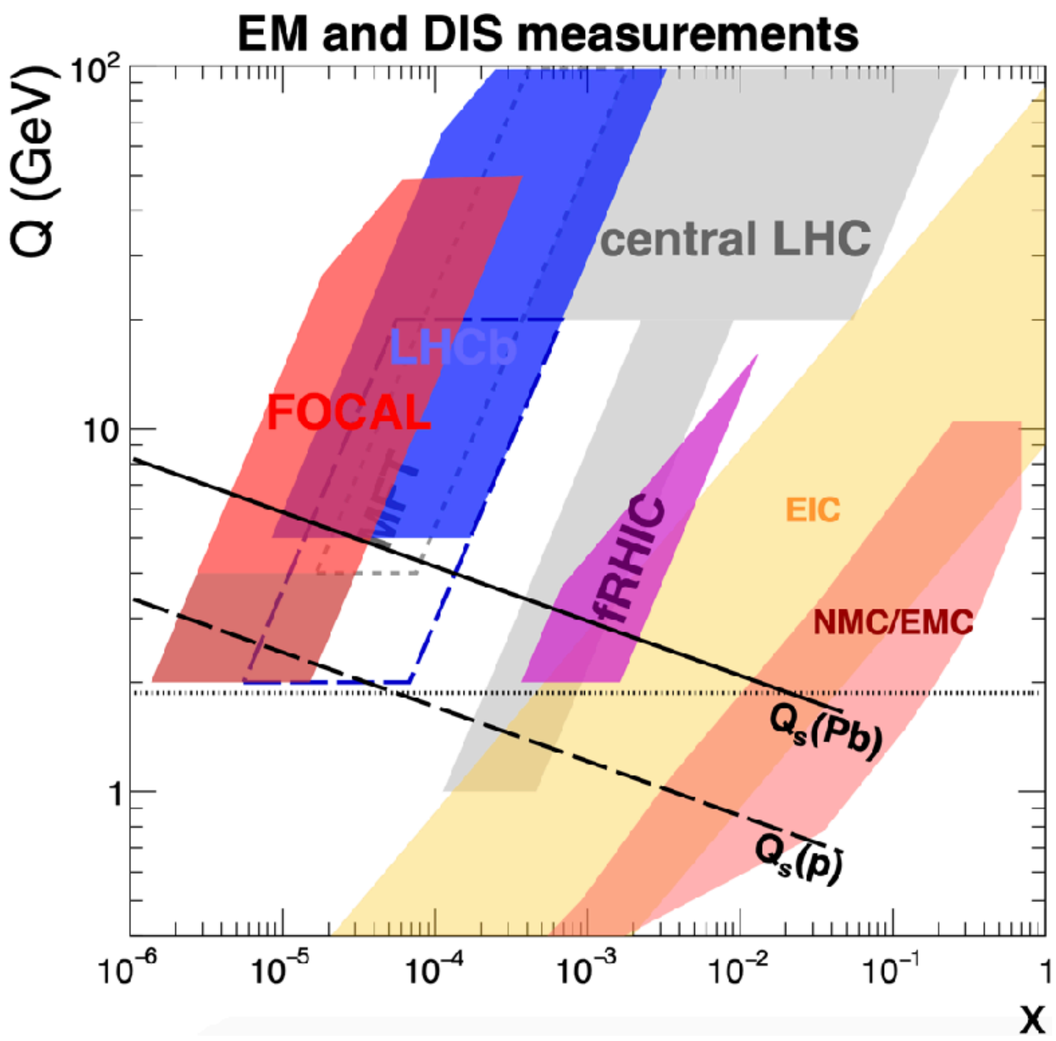


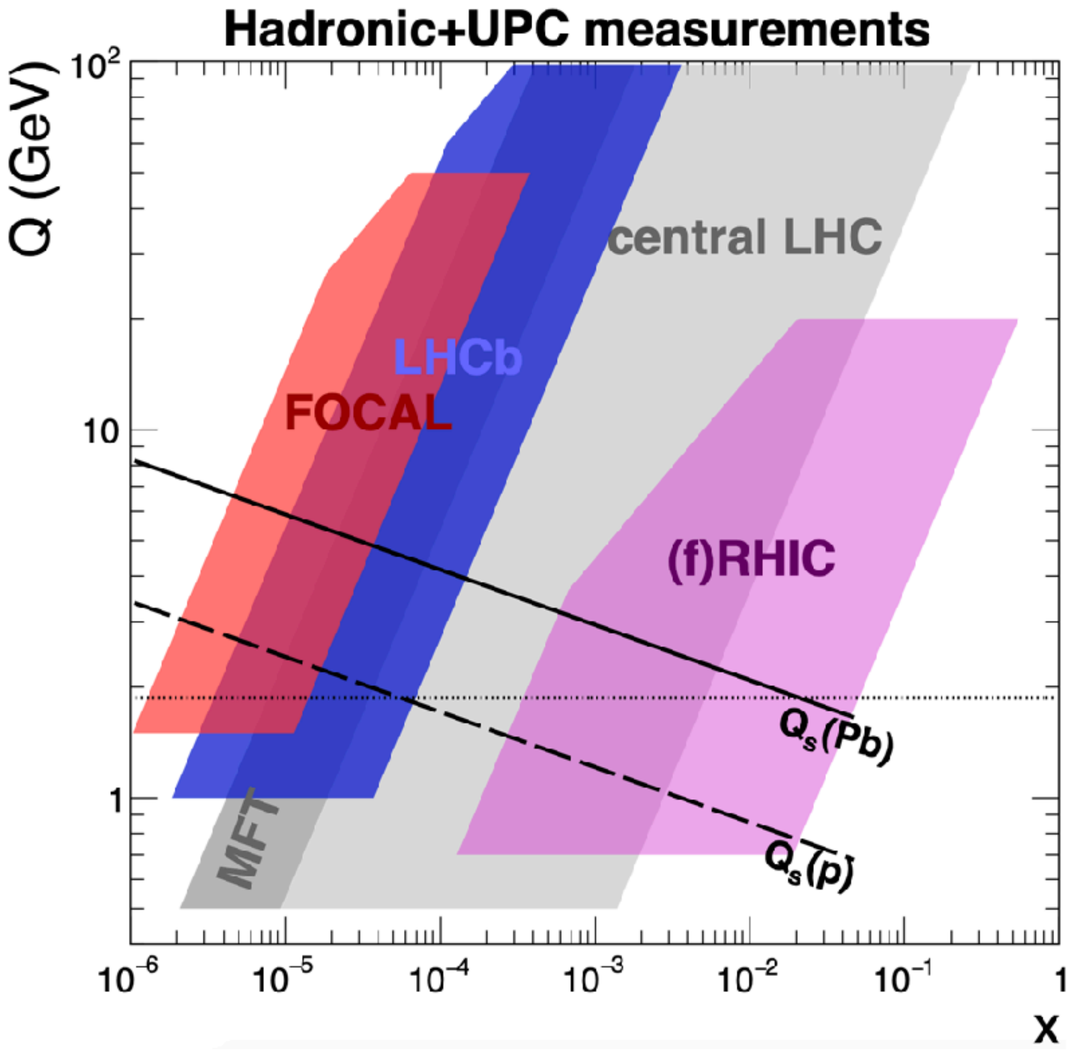
Clear tension between nNPDF2.0 and pseudo data:
Red band/line above the data points

Fit 'pulls down' both central value
and lower edge of band at small x
as expected

Conclusion: a suppression at LHC would result in a tension: sign of non-linear evolution?

Kinematic coverage

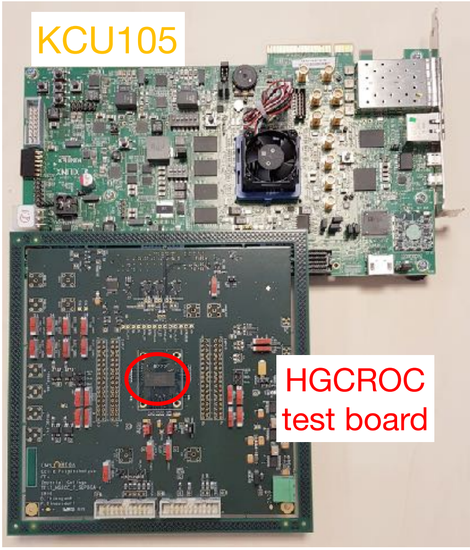




FoCal PAD readout: CMS HGCROC

Plan to use **CMS HGCROC** for final detector

- 72 channels + 6 calibration channels
  4 ch common mode + 2 MIP pads
- Large dynamic range via **ADC + Time-over-Threshold**
  - MIP to ~2 fC
- Readout samples all channels @ 40 MHz
  - Trigger summary sent for each bunch crossing
  - 512 bunch crossings stored on chip
  - Full data shipped out on request ('trigger')
    - 1 MHz max rate



Readout PCB prototype