Gluon saturation with forward photons at LHC: prospects for a high-granularity calorimeter upgrade for ALICE

Marco van Leeuwen,
Nikhef and Utrecht University

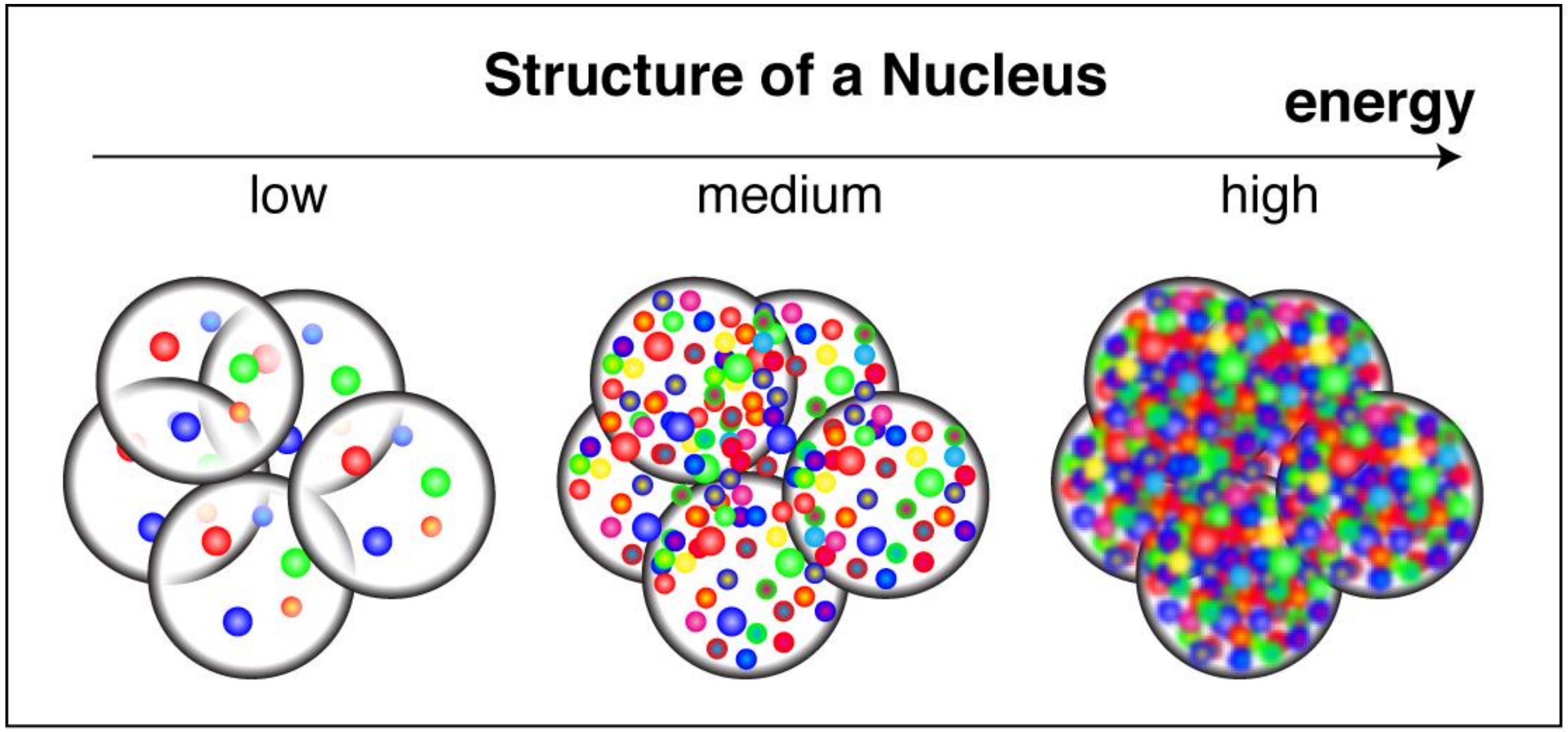
For the ALICE-FOCAL collaboration

Physics Utrecht

ΕΜΜΕΦ

NIKHEF

Saturation/Color Glass Condensate



Low x: large gluon density
Low Q^2: large effective size of gluons

} Strong fields, large occupation numbers

Large theoretical interest:

- Fundamentally new regime of QCD
- Theoretically calculable:
  Classical color fields; JIMWLK, etc

Experimental/phenomenological question:
Where/when is CGC dynamics relevant/dominant?

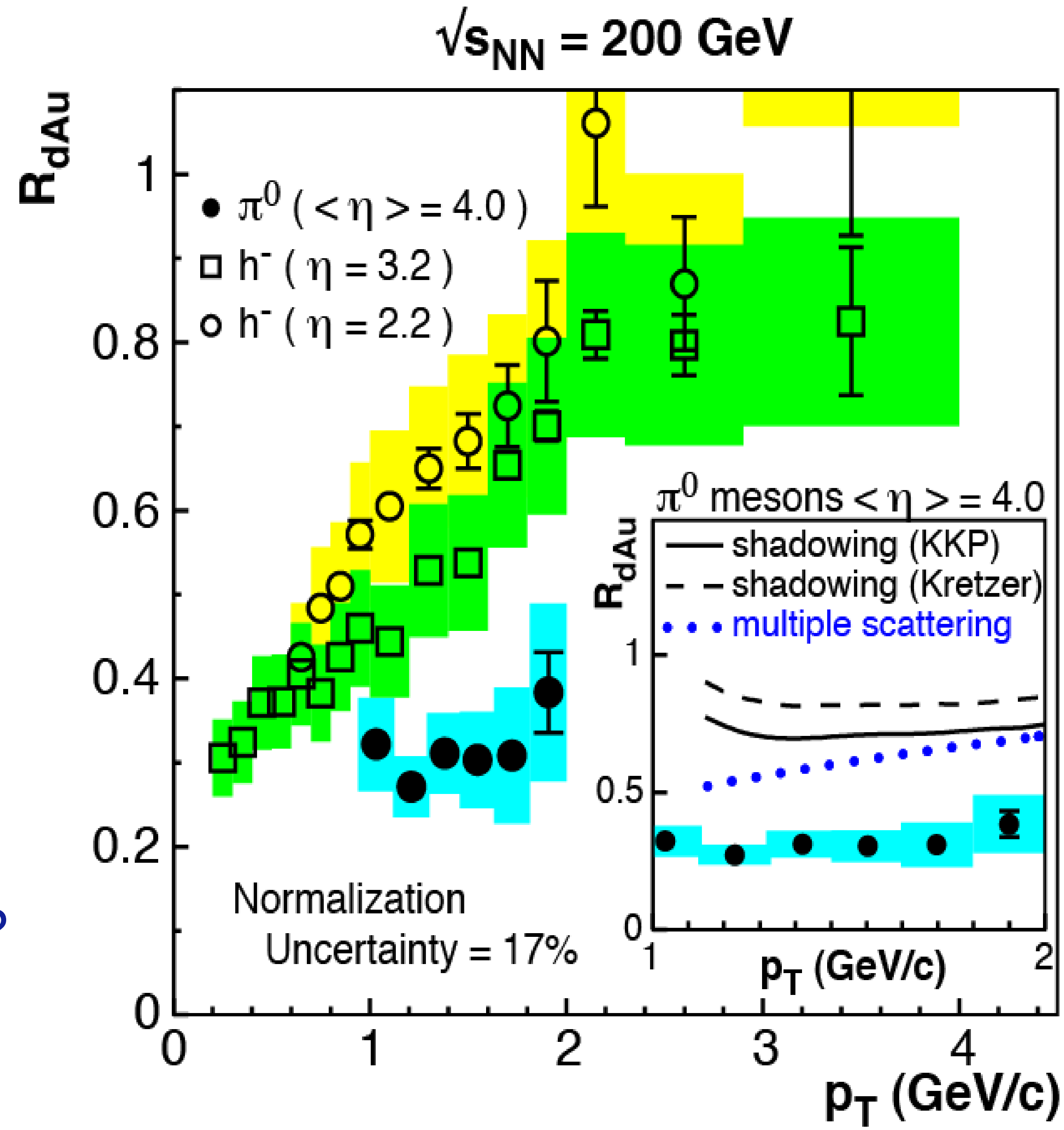
Non-linear evolution ™Reduced gluon density ™Suppression of yield
1 + many instead of 2 → 2 ™Suppression of recoil jet (mono-jets?)

Forward physics at RHIC

- Nuclear modification factor

$$R_{dAu} = \frac{1/N_{ev} \cdot d^2N/dp_T dy(d+Au)}{\langle N_{coll} \rangle \cdot 1/N_{ev} \cdot d^2N/dp_T dy(p+p)}$$

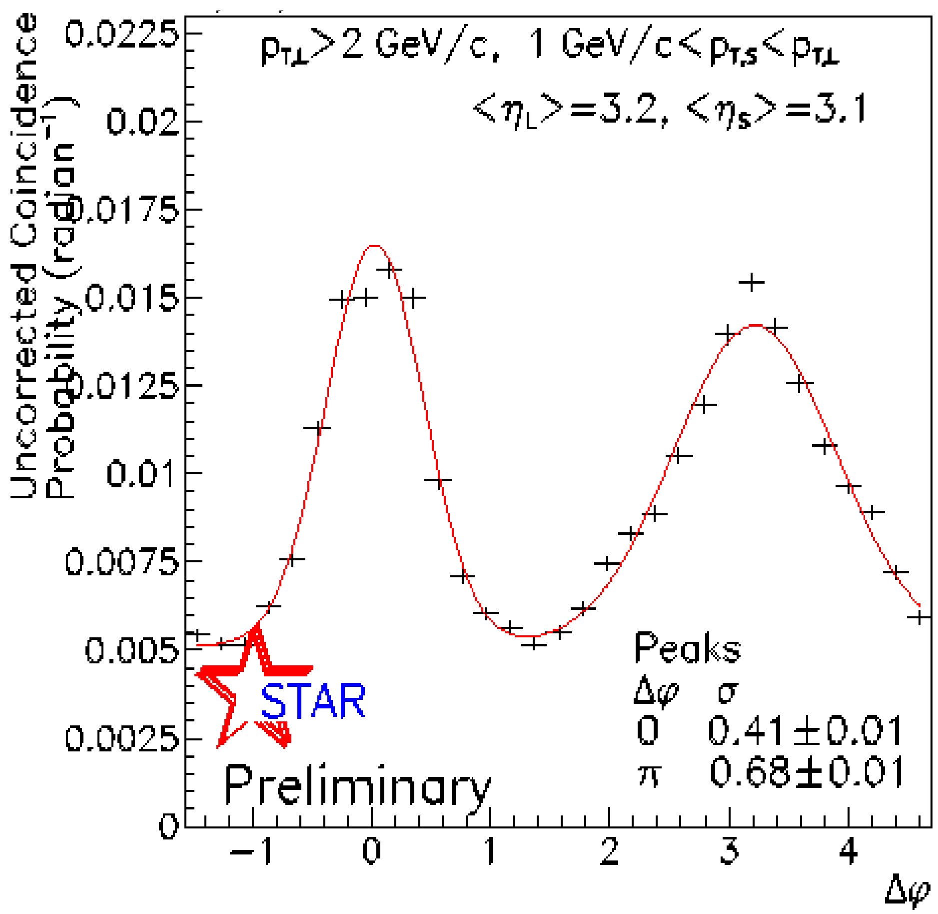
- Shadowing (nPDF) gives smaller suppression
- Qualitatively consistent with saturation
  - Still low p_T; other soft mechanisms?



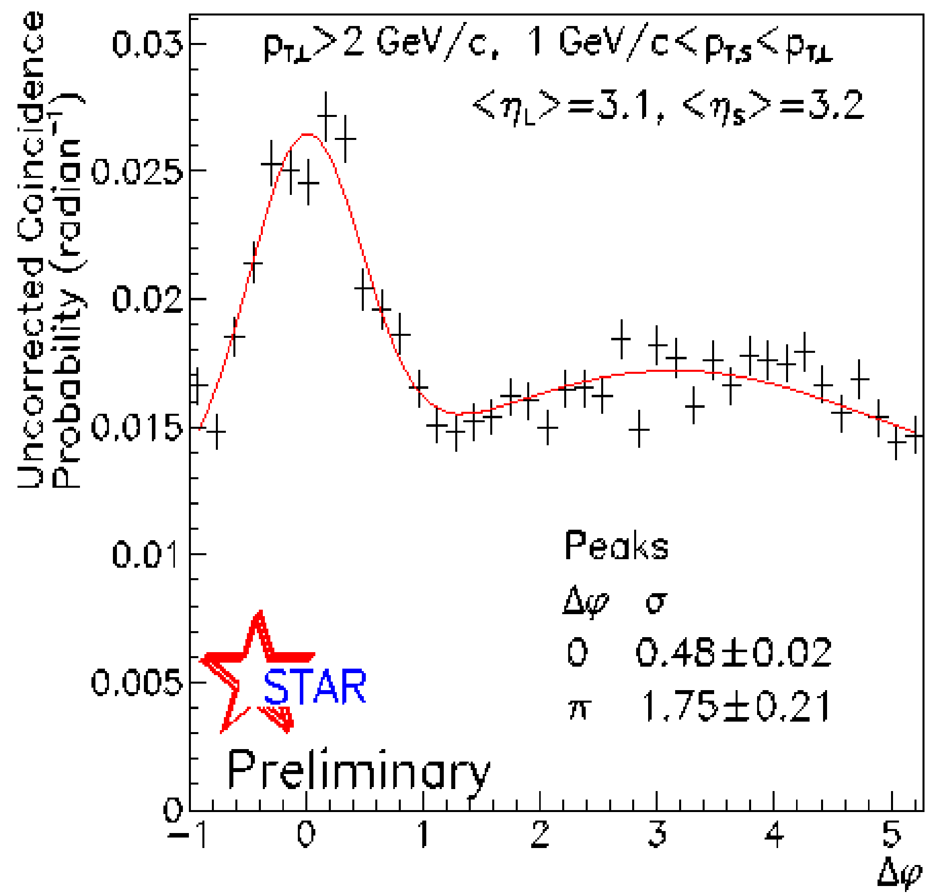
STAR, PRL97, 152302

Forward di-hadrons at RHIC

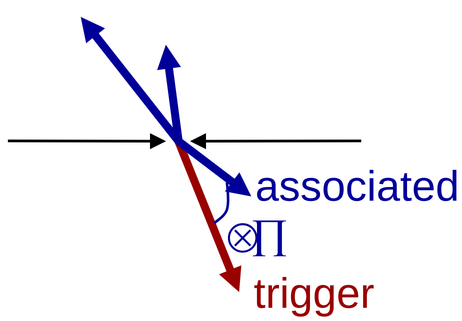
Minimum Bias d+Au collisions



Central d+Au collisions



STAR, Braidot, Ogawa et al.



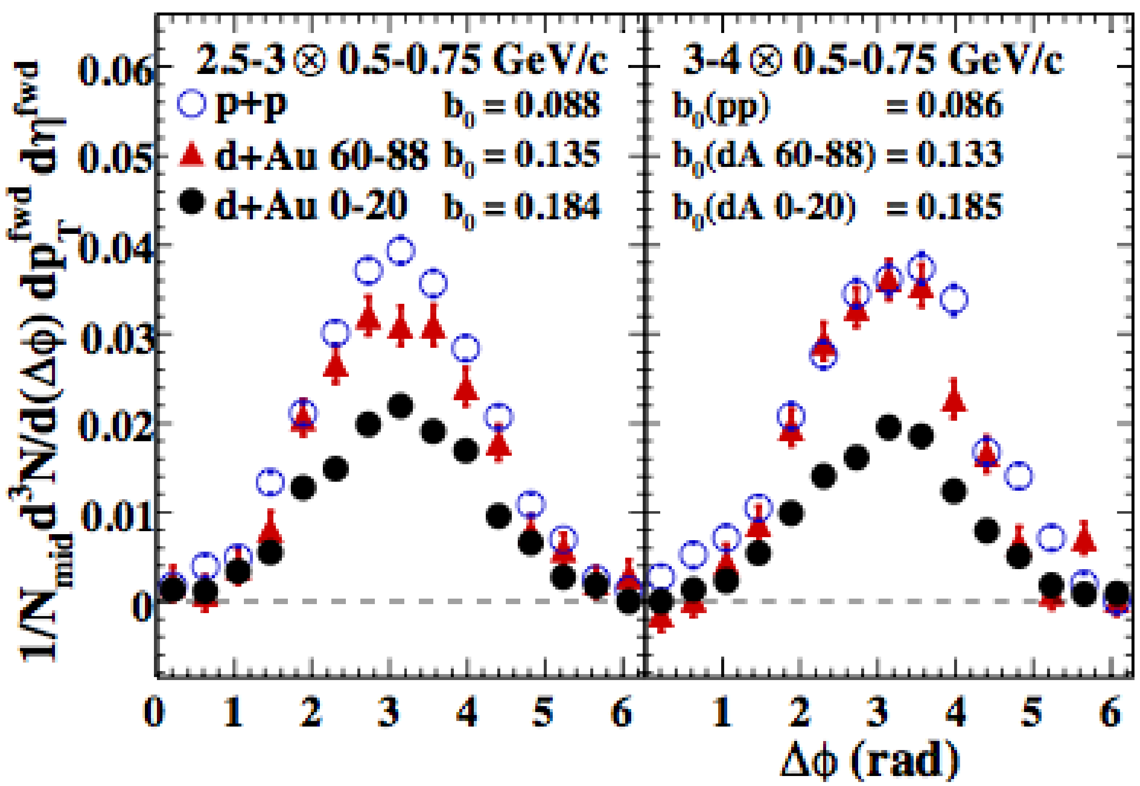
De-correlation of recoil yield

- –Consistent with CGC: coherent gluon field
- –What about multiple parton interactions?

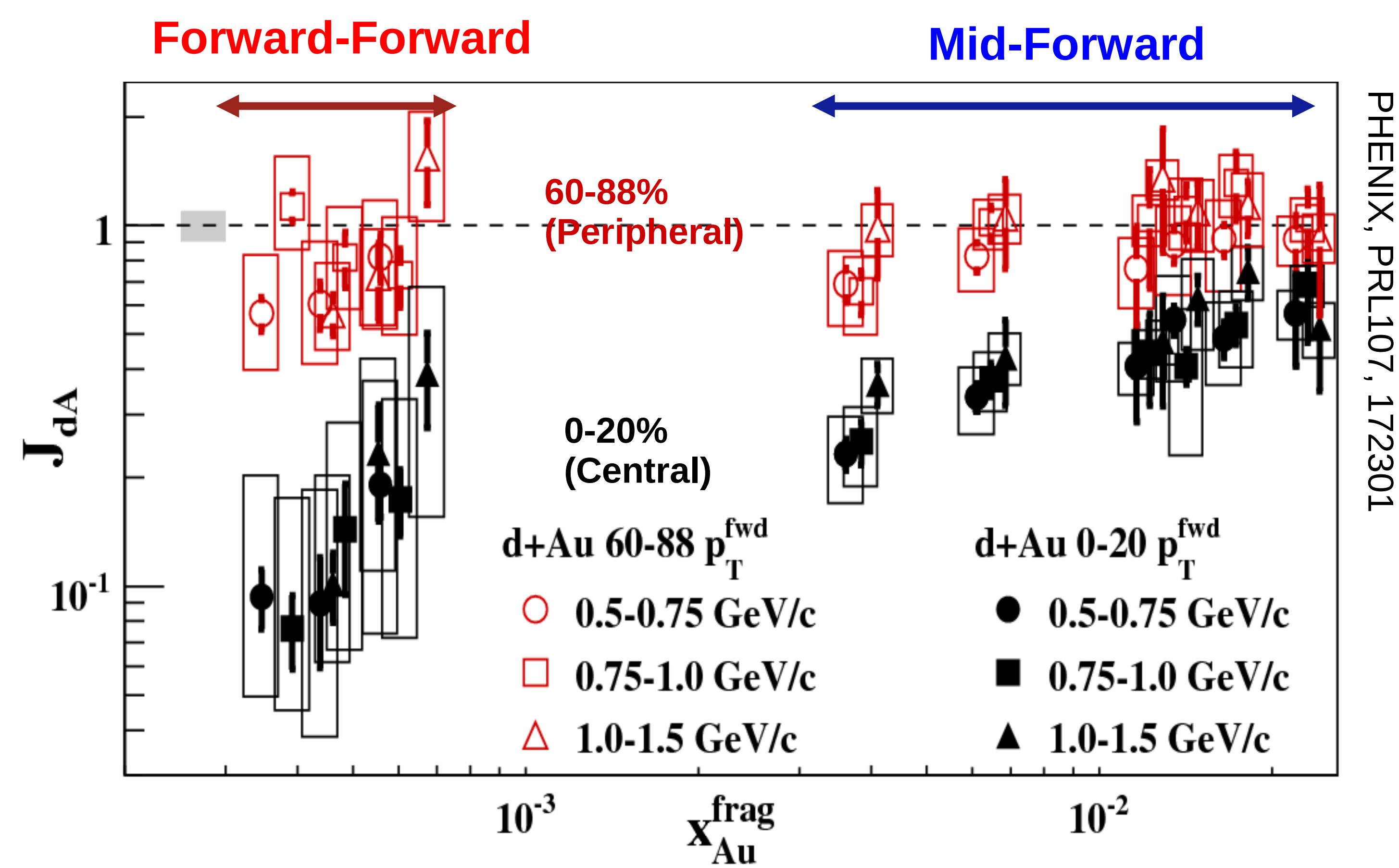
IMO: Much more compelling than inclusive suppression; could be 'smoking gun'

Di-hadron correlations at RHIC II

π^0-π^0 mid - forward



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

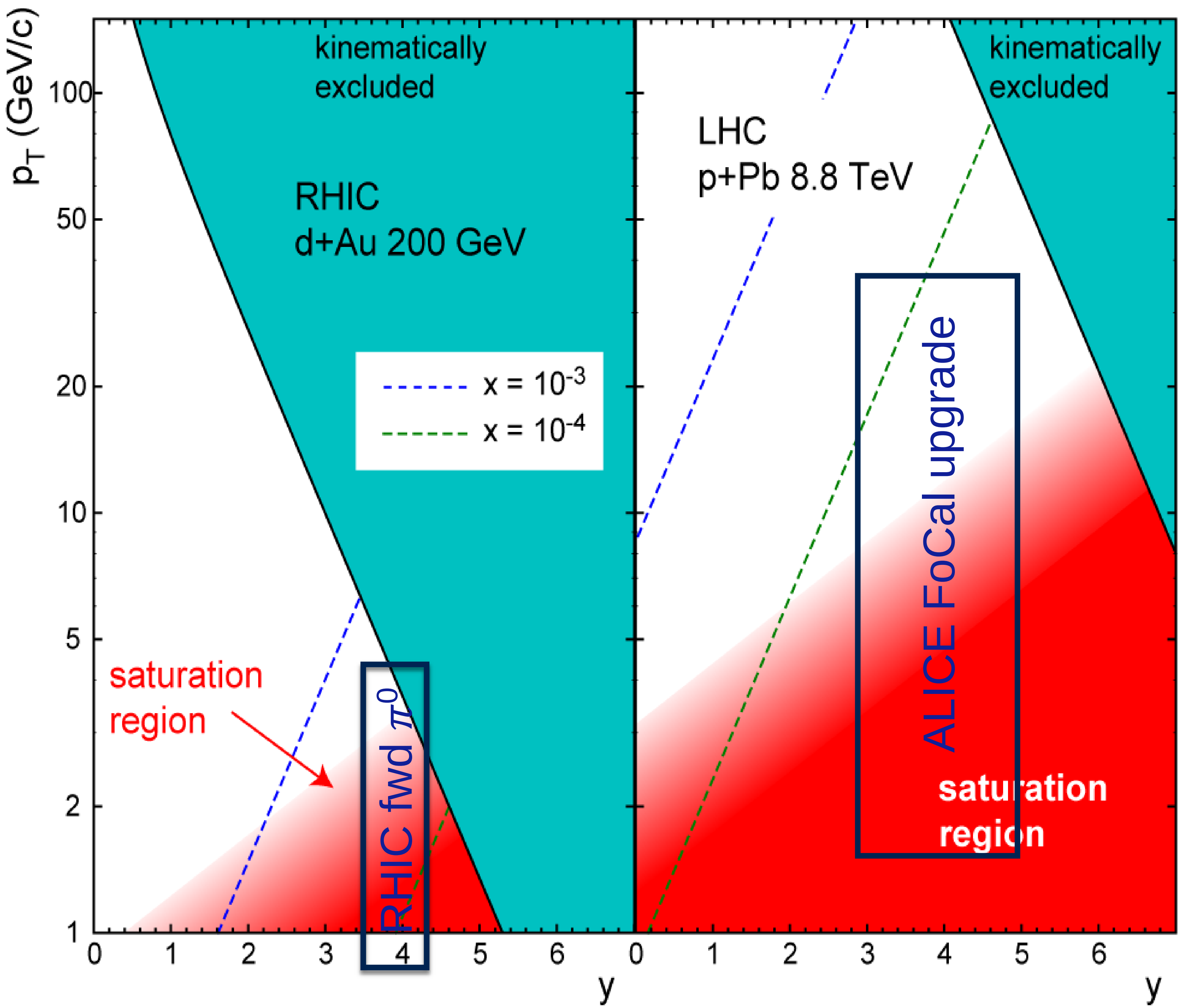


Scan '*x*' with p_{T1} and forward, mid rapidity

More systematic study shows similar effects, trends as a function of *x*

Large suppression at '*x*' < 10^{-3} in central events

LHC vs RHIC

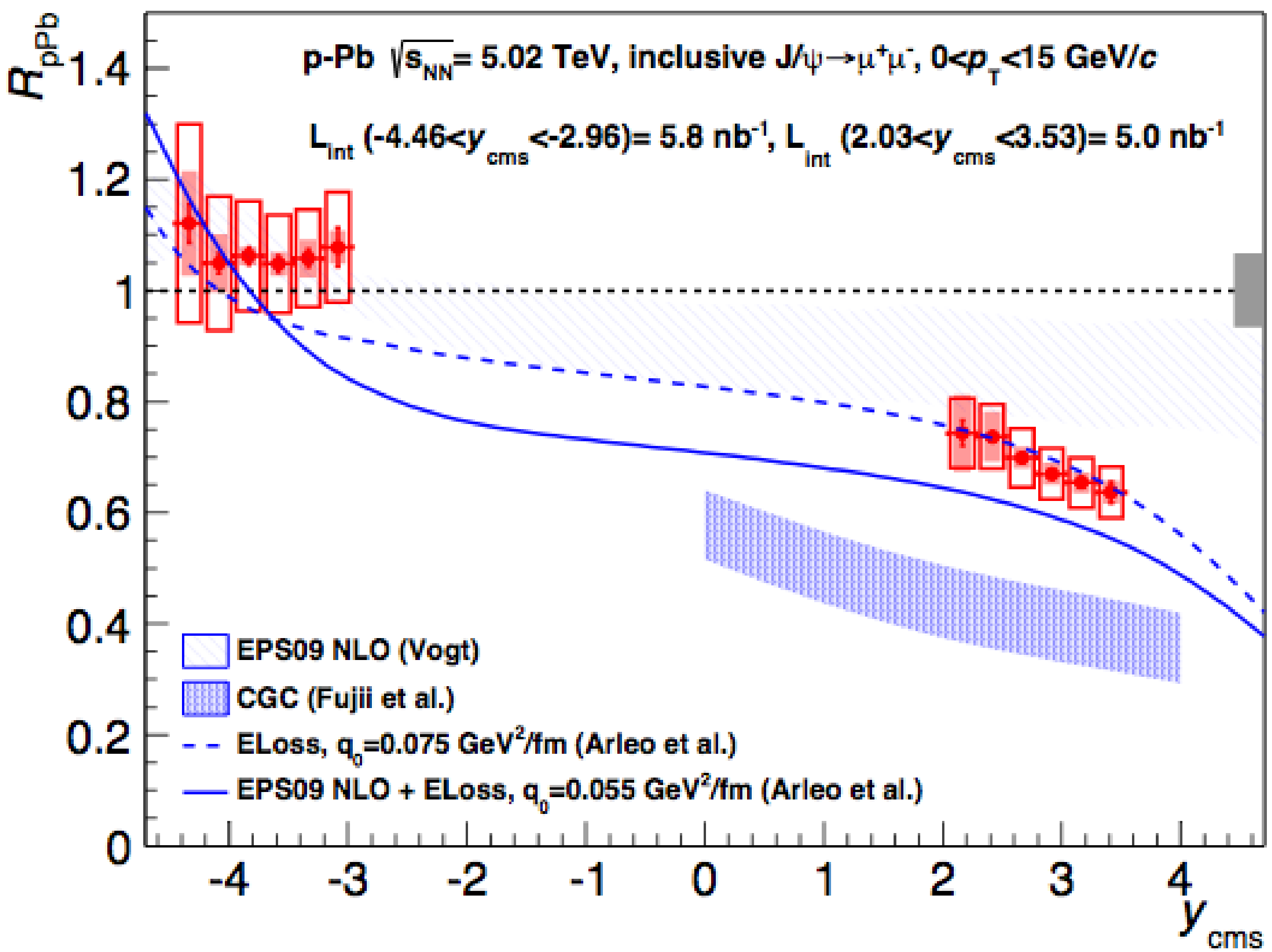


RHIC forward:
kinematic limit at $p_T \sim 5$ GeV

LHC: $x \sim 10^{-4} – 10^{-5}$ accessible,
with $p_T \sim Q \sim 3$-4 GeV

Recent results at forward rapidity

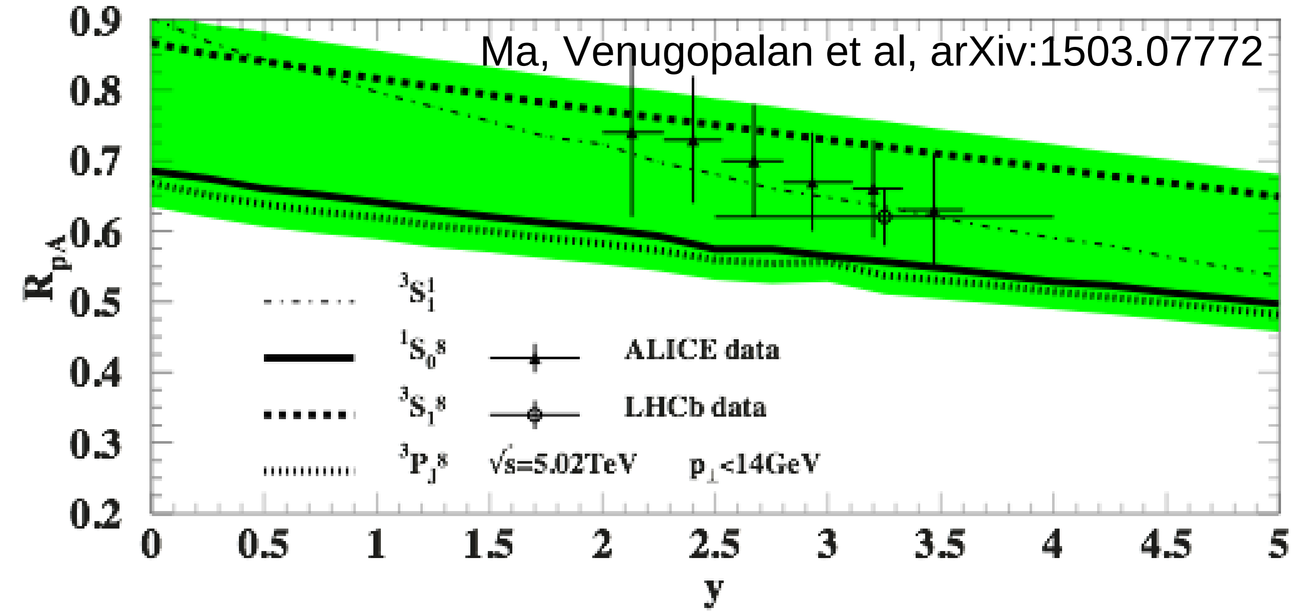
ALICE J/Ψ measurement



ALICE, JHEP 02, 073

Compatible with nPDFs + E-loss, but not CGC?

New CGC calculation

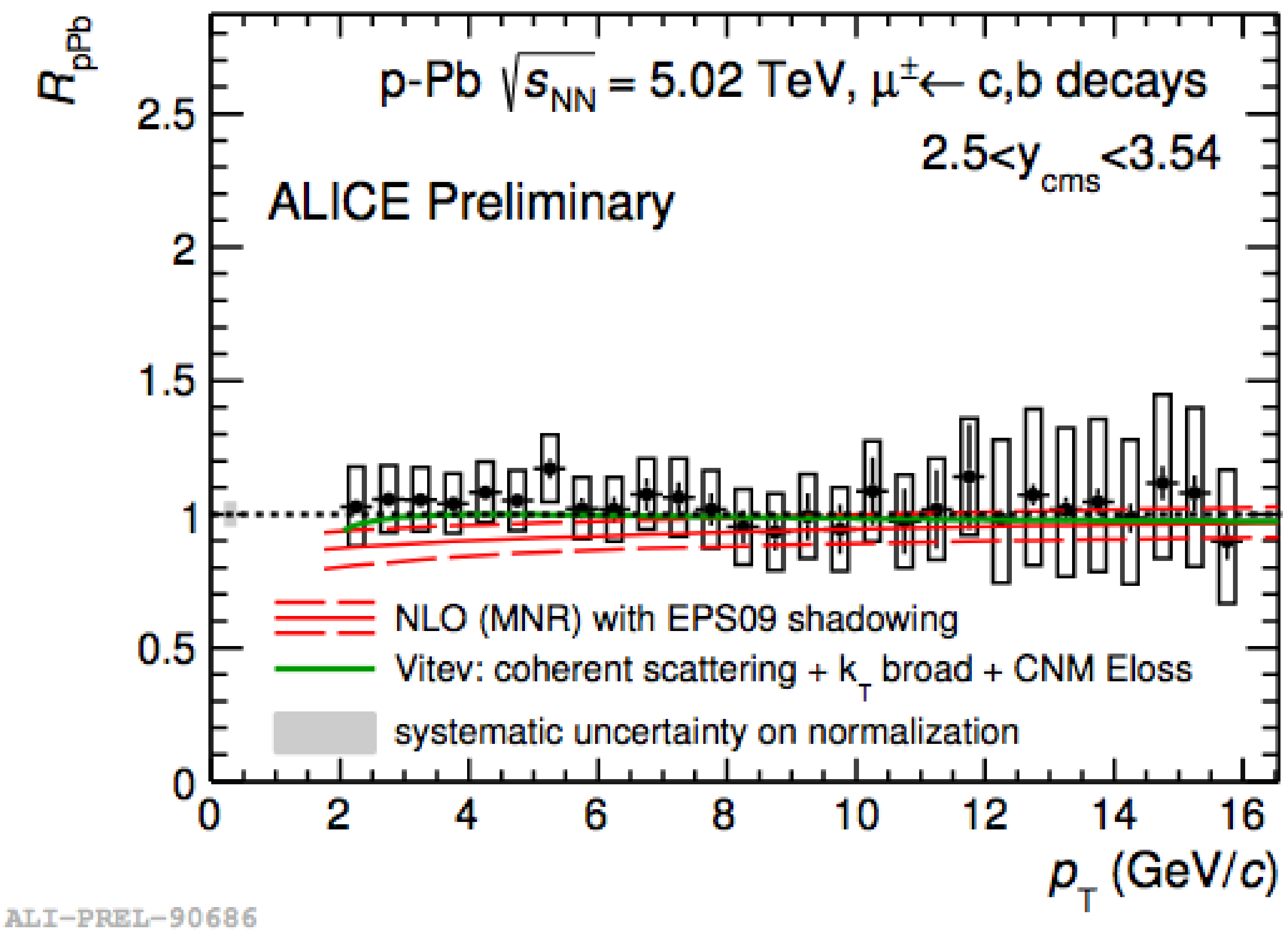


More recent CGC calculation compatible with observed J/Ψ

Not yet conclusive; J/Ψ has sizable hadronisation/CNM uncertainties

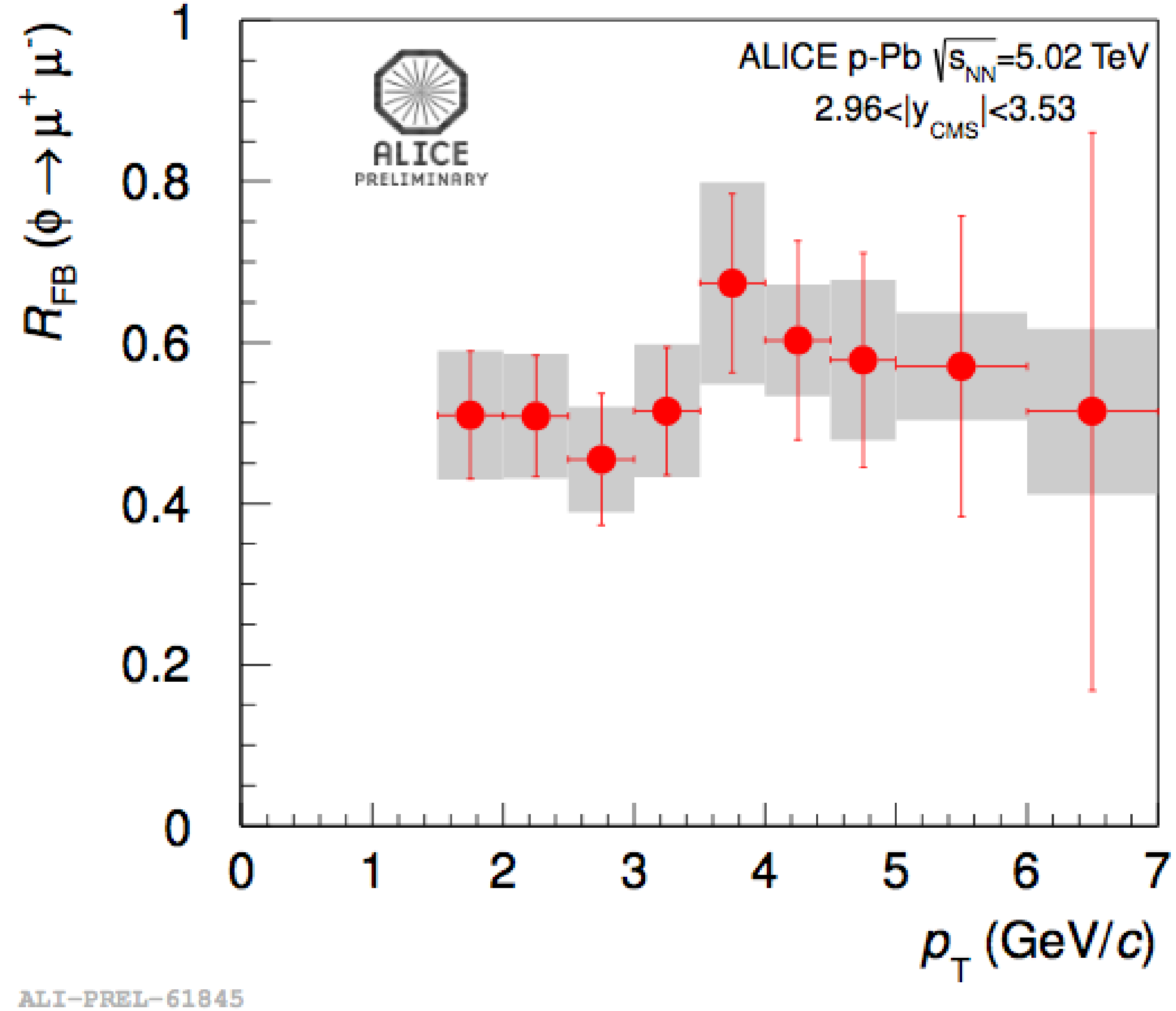
Other recent forward results

Muons from HF



R_{pPb} ~ 1, compatible with nPDF

φ meson

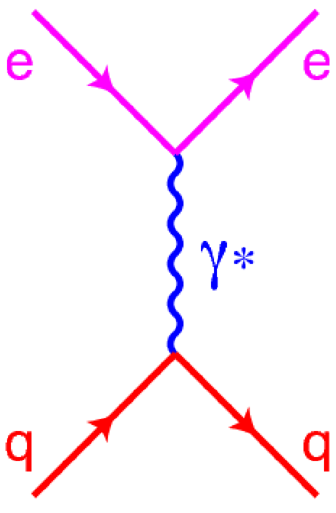


R_{FB} != 1
No clear physics interpretation?

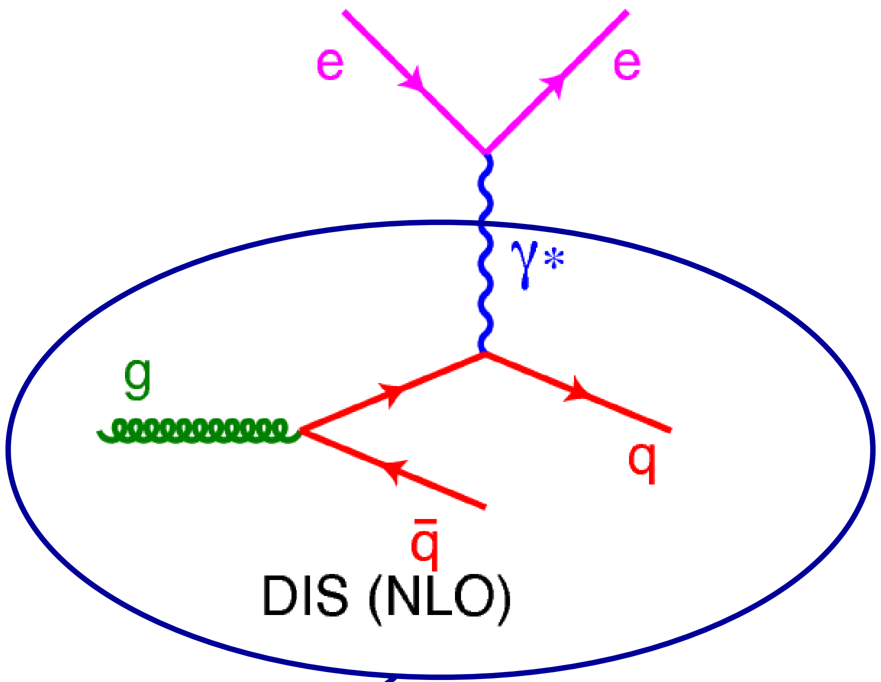
How to probe the gluon density

Deep-Inelastic Scattering (DIS)
Classical PDF method
Not sensitive to gluons at LO

Gluons from NLO/evolution
and/or F_L

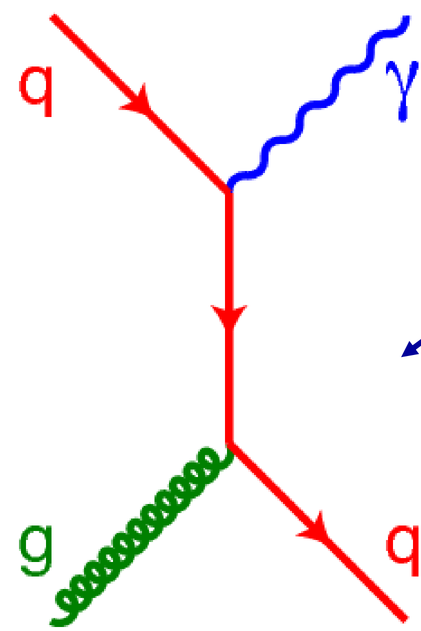


DIS (LO)



DIS (NLO)

Photon production
in hadronic collisions:
Sensitive to **gluons at LO**

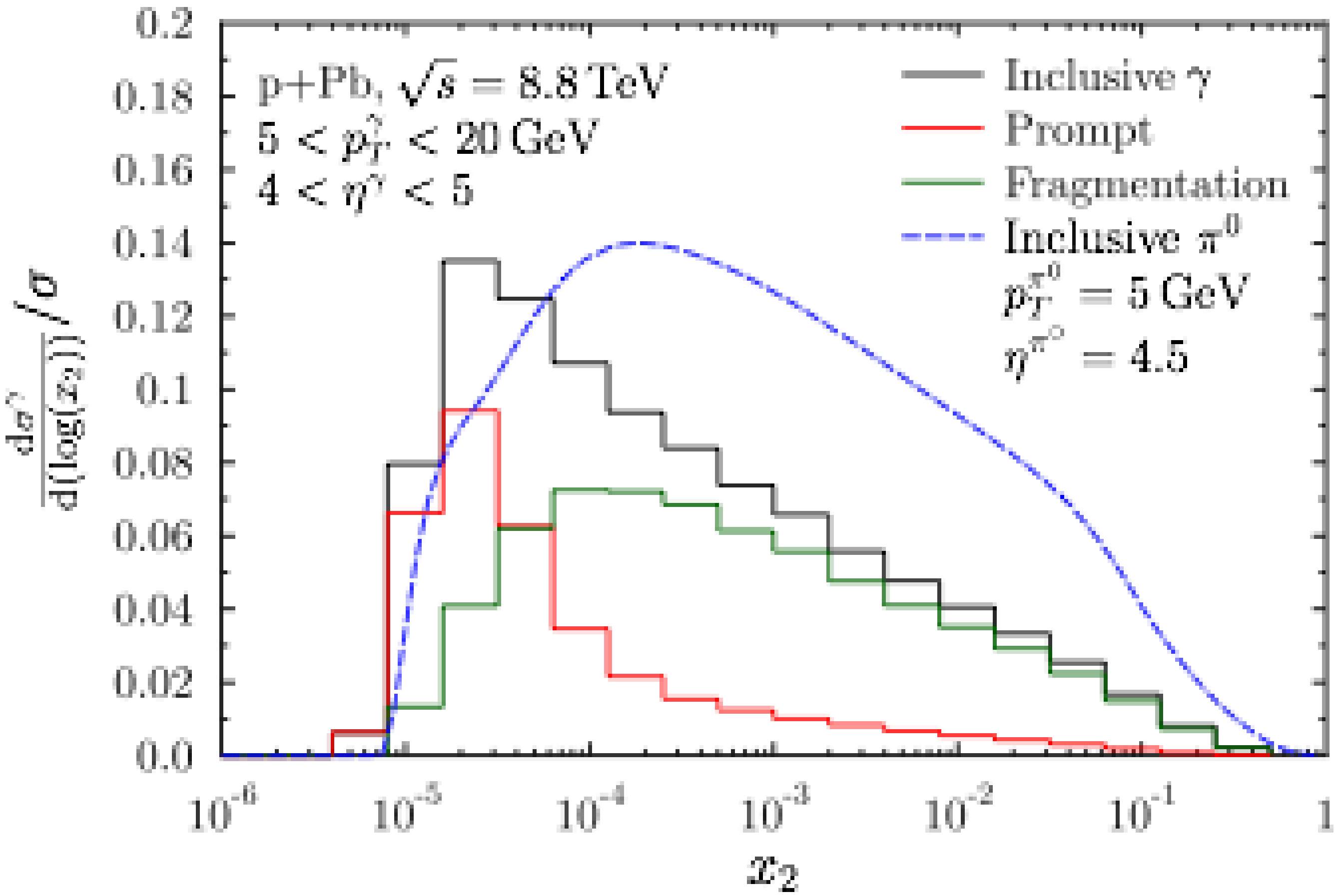


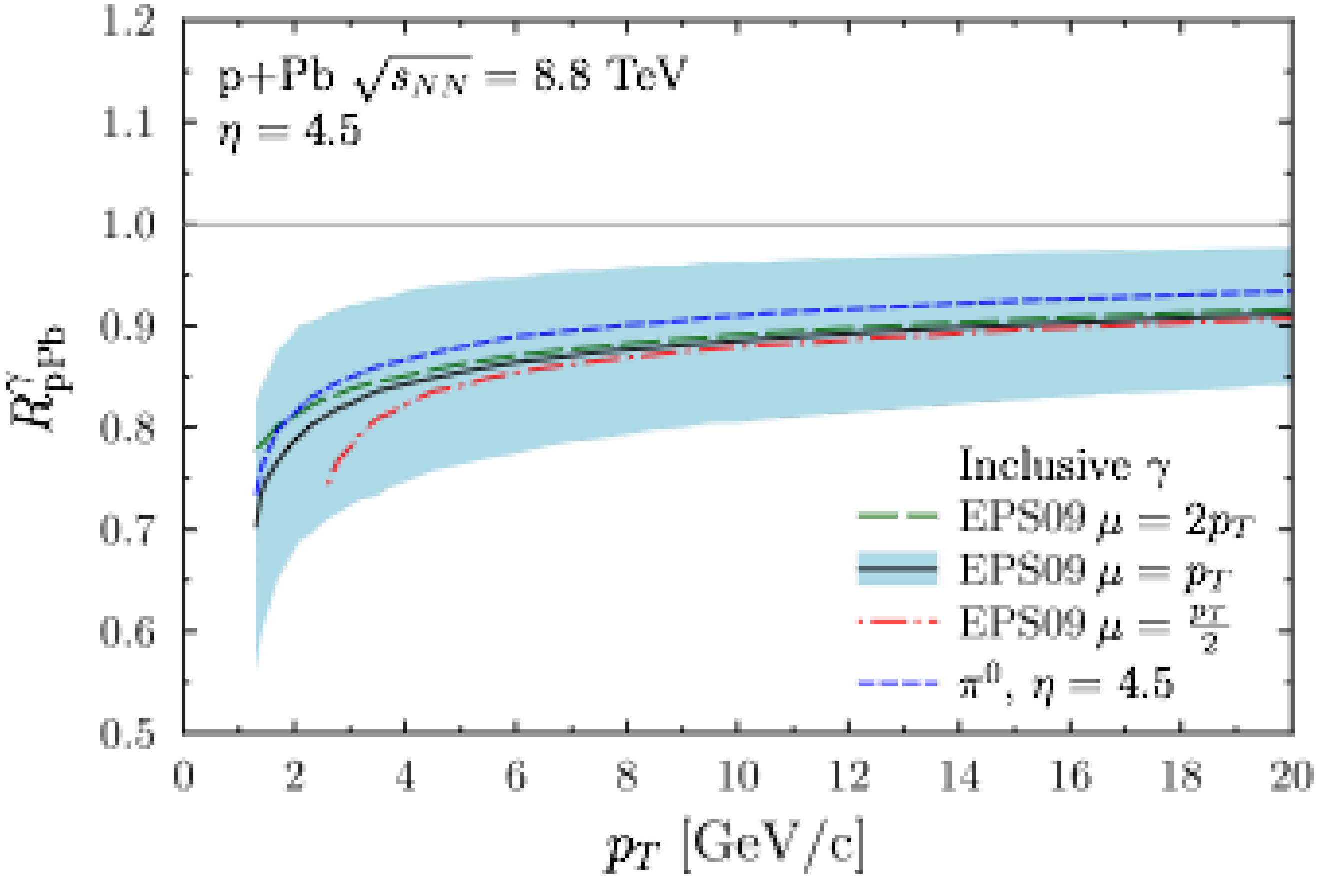
direct-γ, Compton (LO)

Directly related to DIS:
real instead of virtual photon

NLO studies of *x* sensitivity

Helenius et al, arXiv:1406.1689





γ reach factor ~10 lower *x*
(can be improved with isolation cuts)

R_{pPb} ~ 0.85 expected from gluon shadowing nPDFs

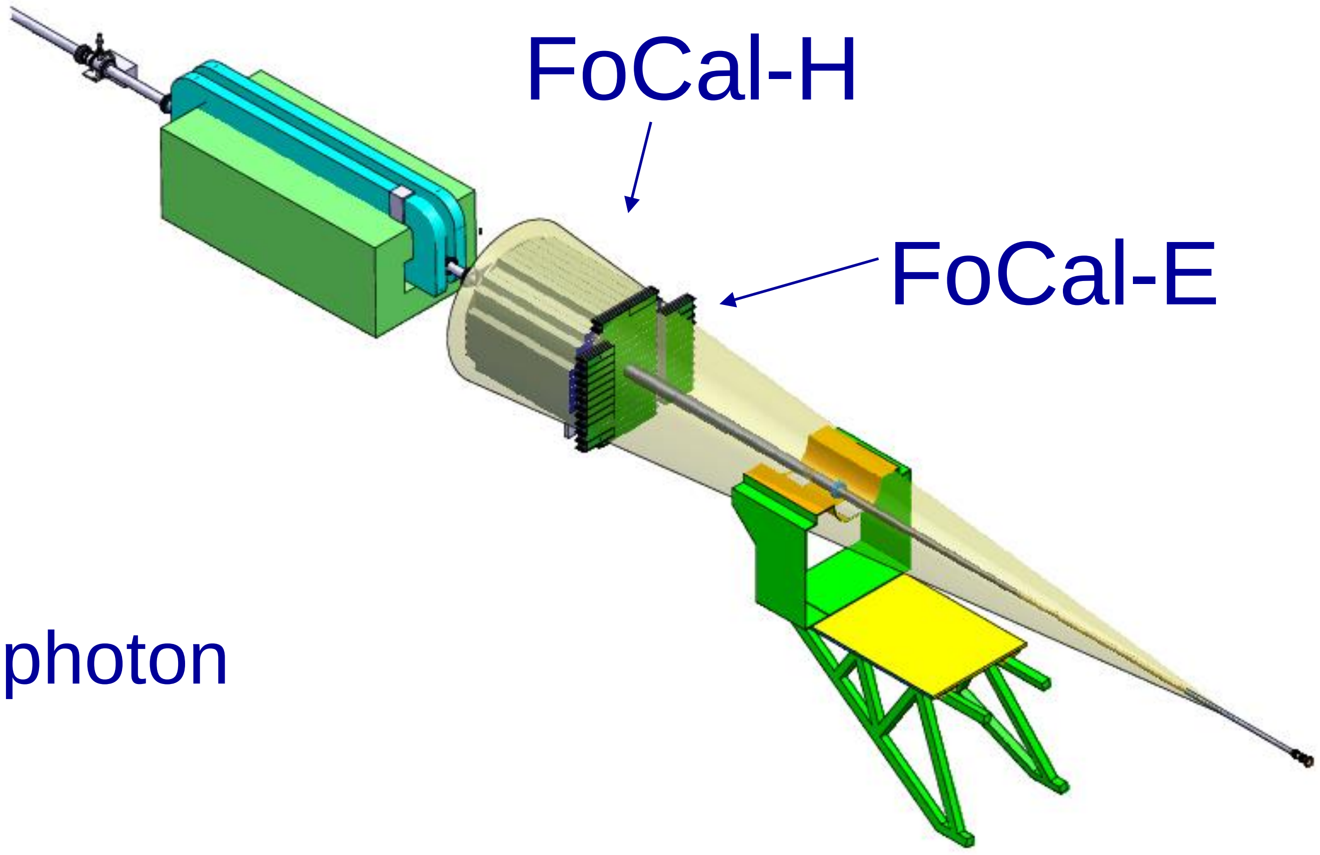
Still: sizeable tail to *x*-distribution: mean *x* not most probably *x*
how does this affect PDF constraining power?

Could use theory guidance/help on this:
How well does photon production constrain the gluon density at low *x*

The FOCAL proposal

Under discussion within ALICE

$3.2 < \eta < 5.3$



FoCal-E: high-granularity Si-W calorimeter for photons and π^0
FoCal-H: hadronic calorimeter for photon isolation and jets

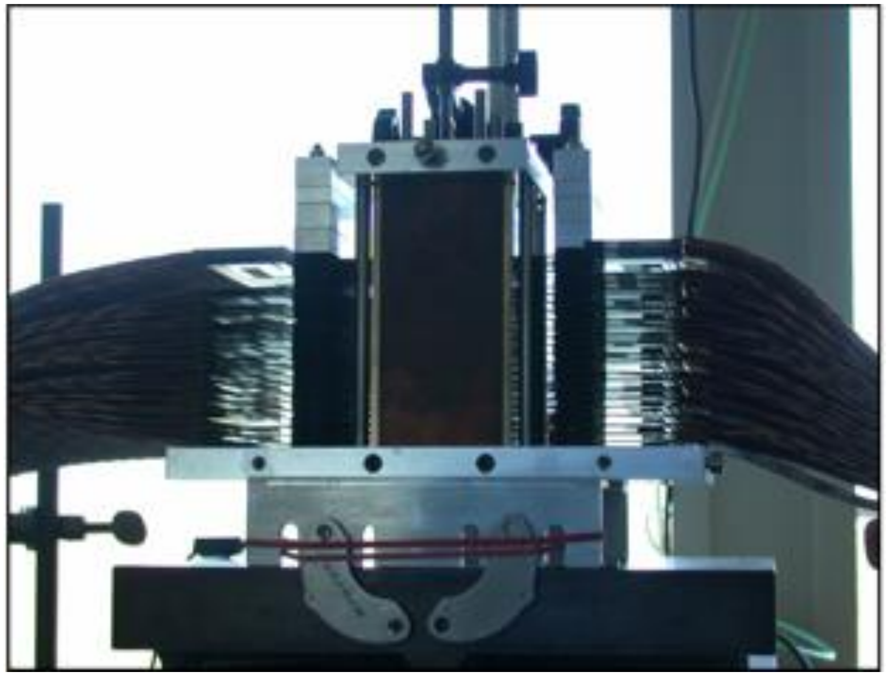
Observables:

- π^0
- Direct (isolated) photons
- J/ψ
- Jets

Advantage in ALICE:
forward region not instrumented;
'unobstructed' view of interaction point

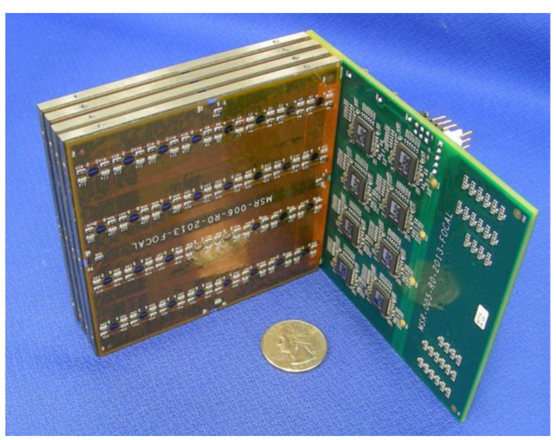
FoCal R&D: Si-W pixel and pad readout

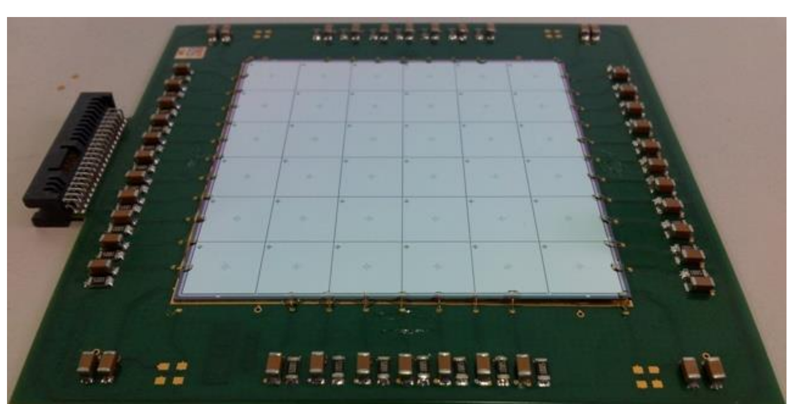
20 layer pixel detector

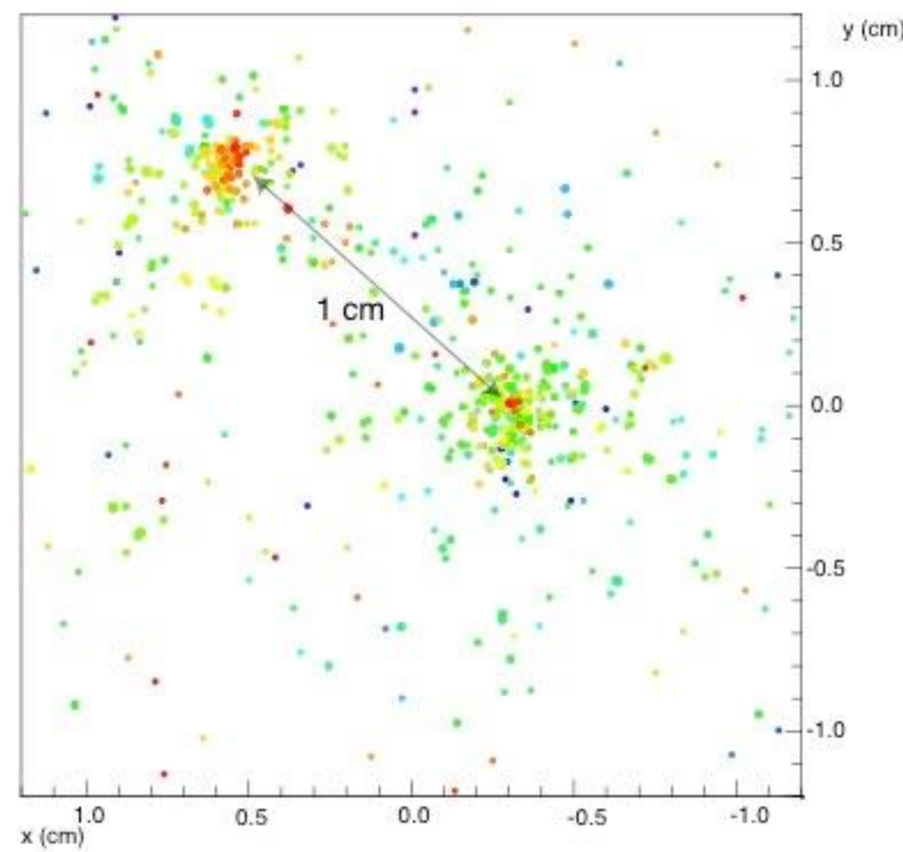


- Several groups involved:
  - Full prototype with pixel detectors CMOS (MIMOSA) 39Mpixels, 30μm pitch
  - Full prototype with pad readout
- Performed systematic tests:
  - Test beam data from 2 to 250 GeV (DESY, PS, SPS)
  - Cosmic muons

Pad layer integration

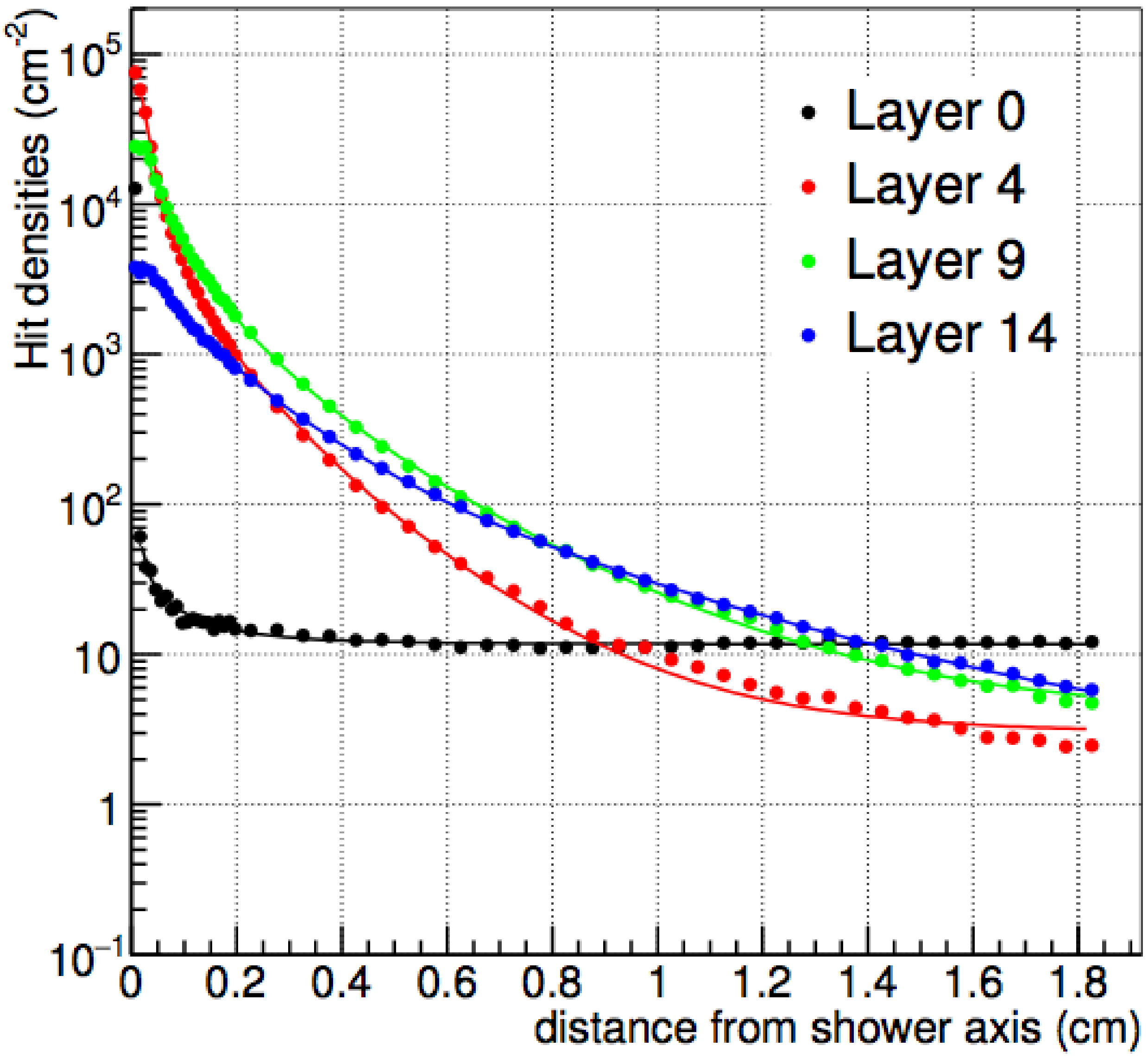




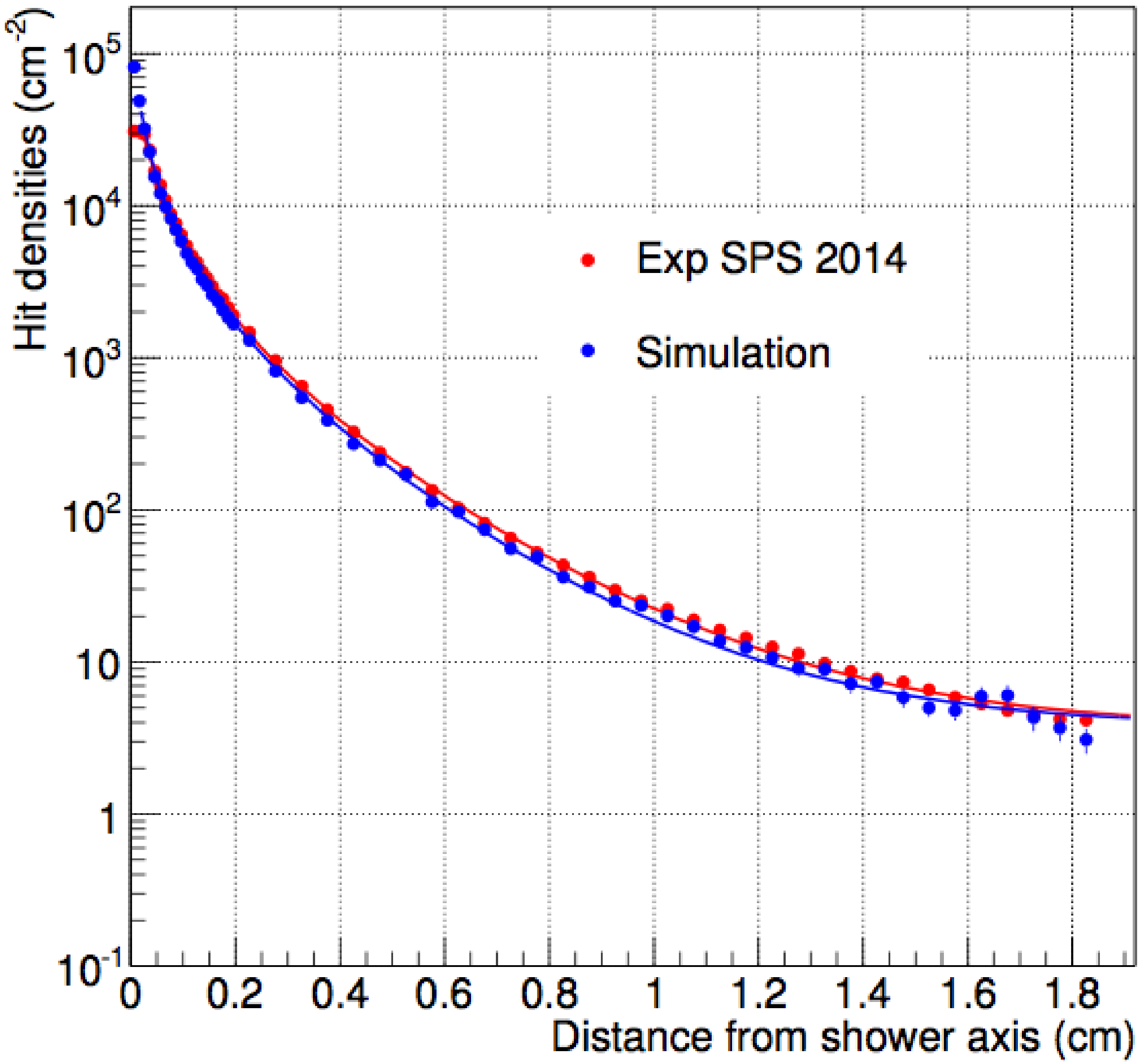


Testbed results: Lateral shower profiles

50 GeV electrons



Comparison to Geant4 simulations



Extremely good spatial resolution
$R_M \sim 1$ cm

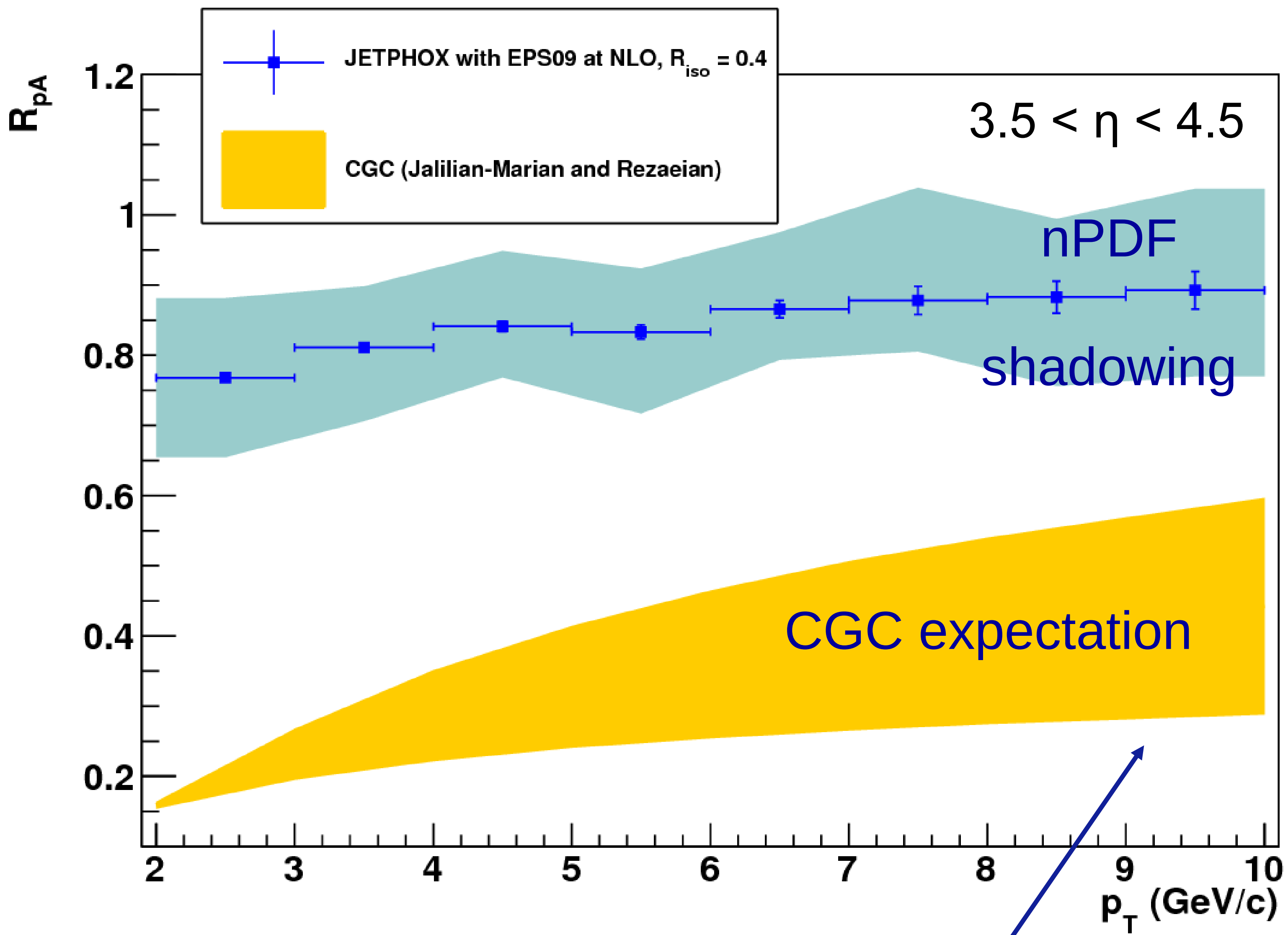
Good agreement with simulations
GEANT4 + charge diffusion

Two-photon separation at mm scale possible

Photons nPDF and CGC

Main physics motivation

Measure direct © R_{pA} to confirm or refute CGC effects



CGC: Jalilian-Marian, Rezaeian, PRD86, 034016

Direct © is the flagship case
FoCal can measure
□ □^{0} spectra
□ □^{0}-□^{0} correlations
□ ©-□^{0} correlations
which provide additional constraints

Should there be a return to $R_{pPb} = 1$ for $p_T >> Q_{sat}$?

Performance study: π^0 detection efficiency

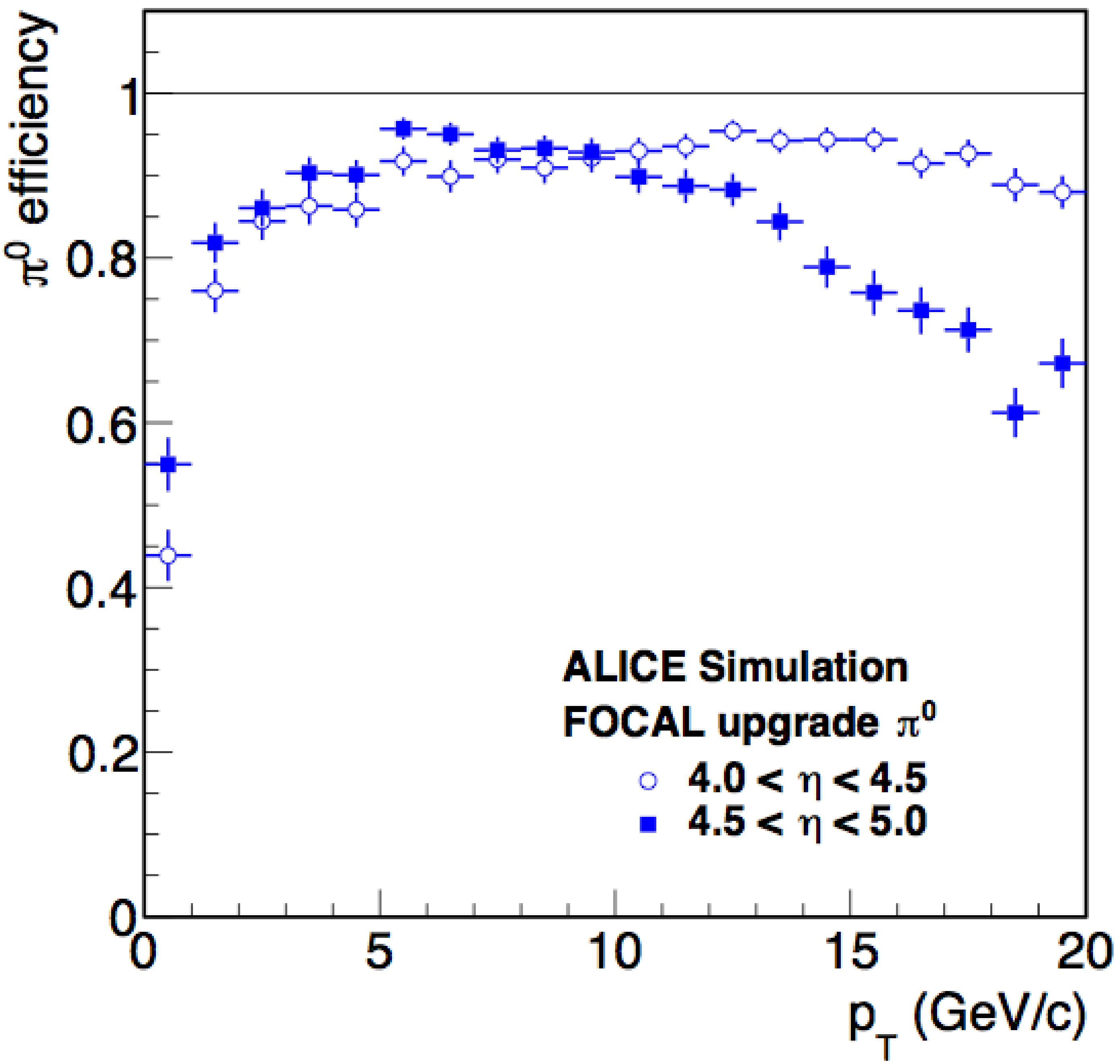
Use π^0 reconstruction
to reject decay photons

Very good efficiency > 90%

p_T ~ 2-18 GeV at η = 4.0-4.5

NB: η = 5, p_T = 12 GeV ⇒ E = 900 GeV

Single π^0 with GEANT



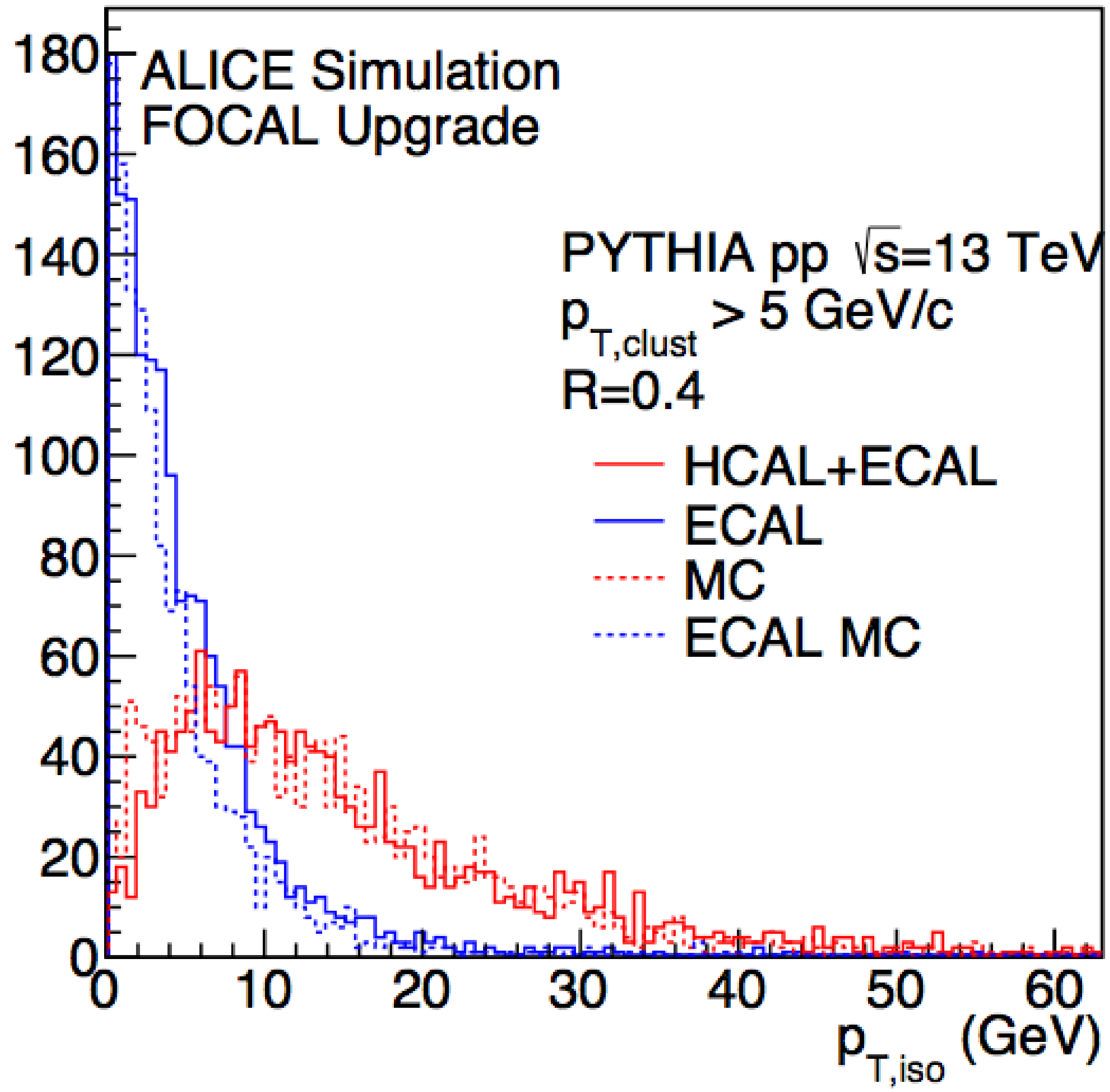
Covers the intended range for CGC measurements: low-intermediate Q^2

γ isolation: HCAL contribution

γ isolation is an important handle for γ identification

HCAL helps with isolation:
HCAL+ECAL energy peaks at 6 GeV instead of 0 GeV

Isolation energy distribution



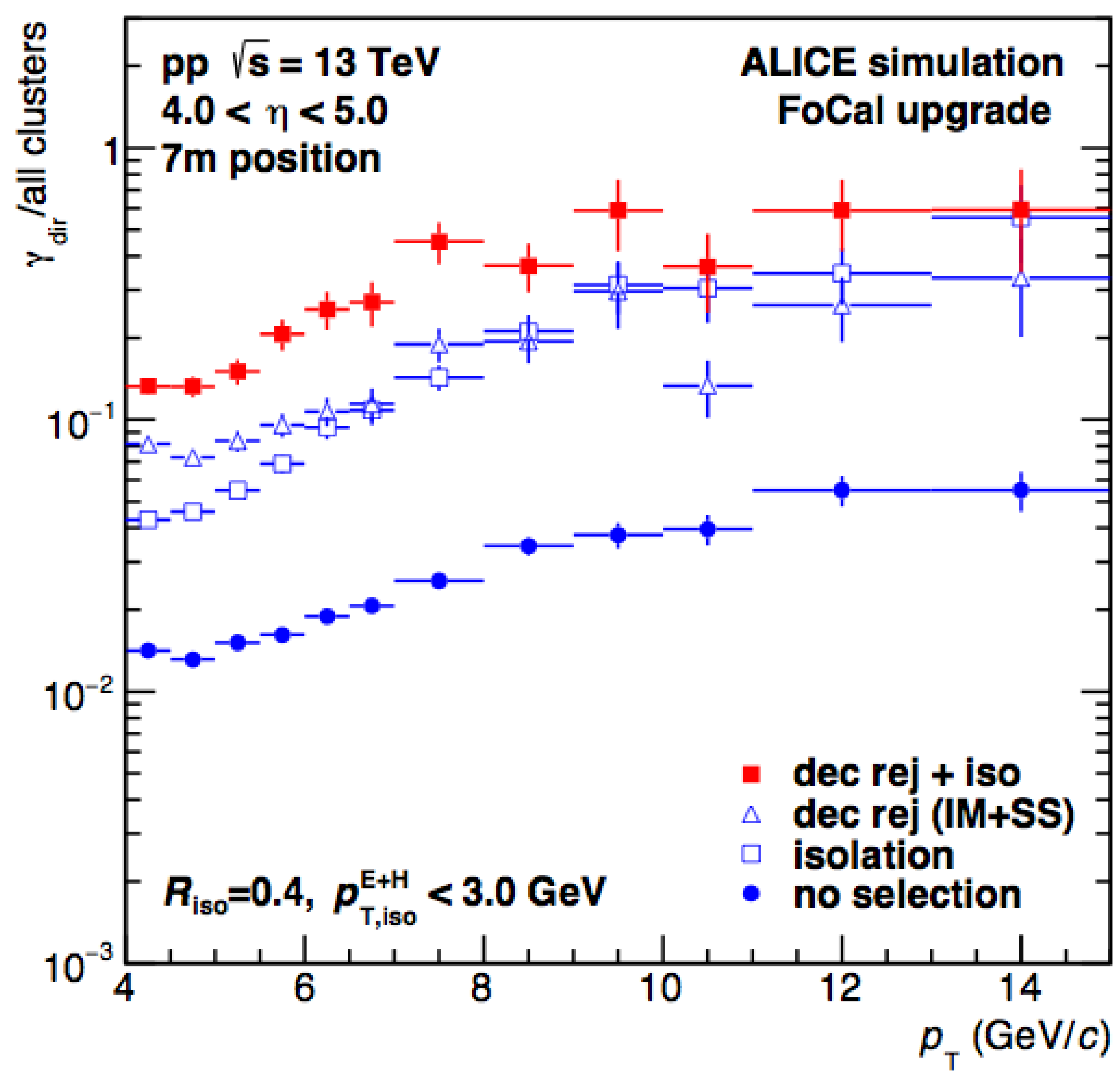
Full Pythia + GEANT
MC: particle level (dashed curves)

Direct/decay separation

Two main handles for direct gamma identification:

- Reject decays by invariant mass reconstruction
- Isolation cuts (EMCal + HCal)

Direct γ/all cluster ratio

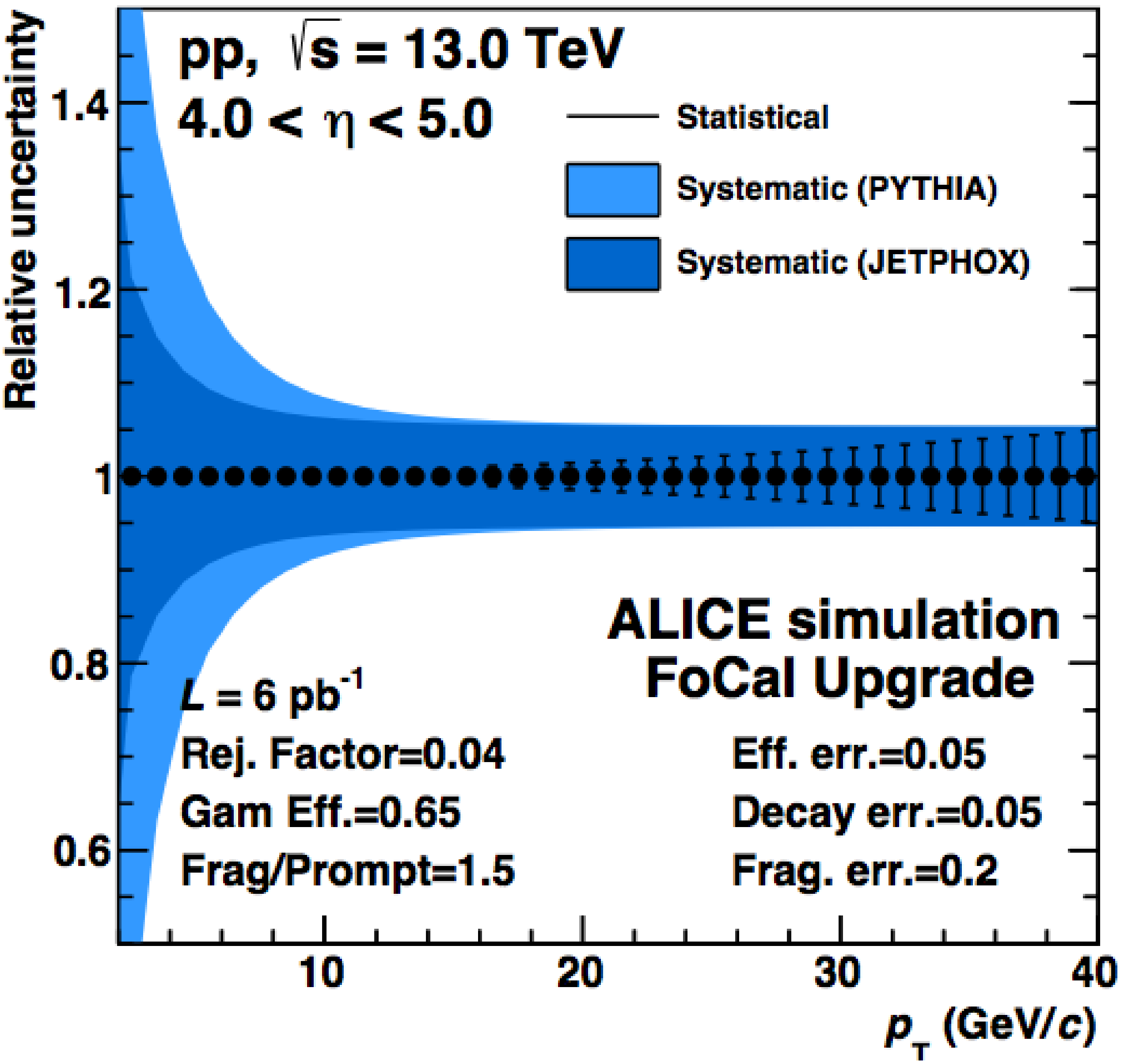


Improve signal fraction by factor ~10, from 0.01-0.06 to 0.1-0.6

Projected direct photon uncertainties

- Large signal fraction at $p_T > 10$ GeV
  - Uncertainties 5-7%
- Low p_T: decay photons important
  - Uncertainties depend on physical direct/decay fraction

Direct γ



Similar uncertainties expected for R_{pPb}: sensitive to CGC R_{pPb} ~ 0.4

FoCal physics program

- p+Pb physics program: gluon density (+ridge)
  - R_{pPb} of direct γ
  - R_{pPb} of π^0
  - Di-hadron measurements
    - Forward-forward: better constraints for low x
    - Mid-forward: ridge/flow-like effects
- PbPb medium effects
  - R_{PbPb} of π^0 at forward rapidity
    - Complementary to forward HF coverage; measure density, light flavour E-loss to calibrate models
  - Mid-forward correlations — ridge effects, flow

Plus a number of more challenging ideas: J/Ψ, jets, direct γ in PbPb

Summary/conclusion

- LHC forward physics provides unique opportunities for low-*x* physics in the short to medium term
  - First results on J/Ψ, φ, HF decay muons available from ALICE — no strong suppression seen in minimum bias events
  - R_{pPb} for hadrons could be explored now by LHCb, (CMS, ATLAS)
- Direct photons promise to be a very clean probe
  - No fragmentation: access to lower *x*
  - No final state effects
- ALICE is considering a forward calorimeter upgrade focused on
  - π^0 at forward rapidity (including correlations)
  - γ at forward rapidity

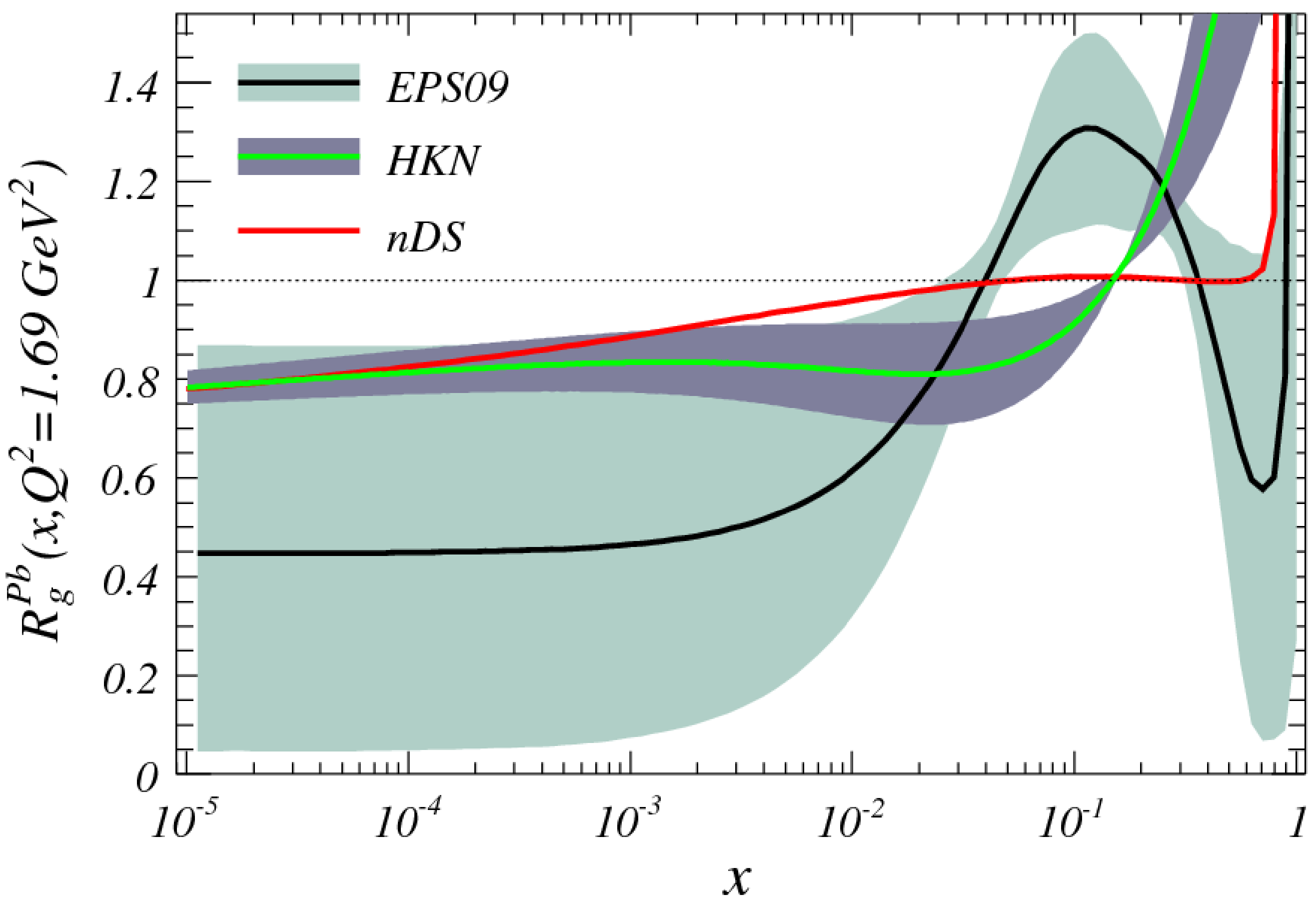
Input/discussion welcome:

- Theory: explore sensitivity of direct photon production to low-*x* gluons
- Experiment: new collaborators welcome!

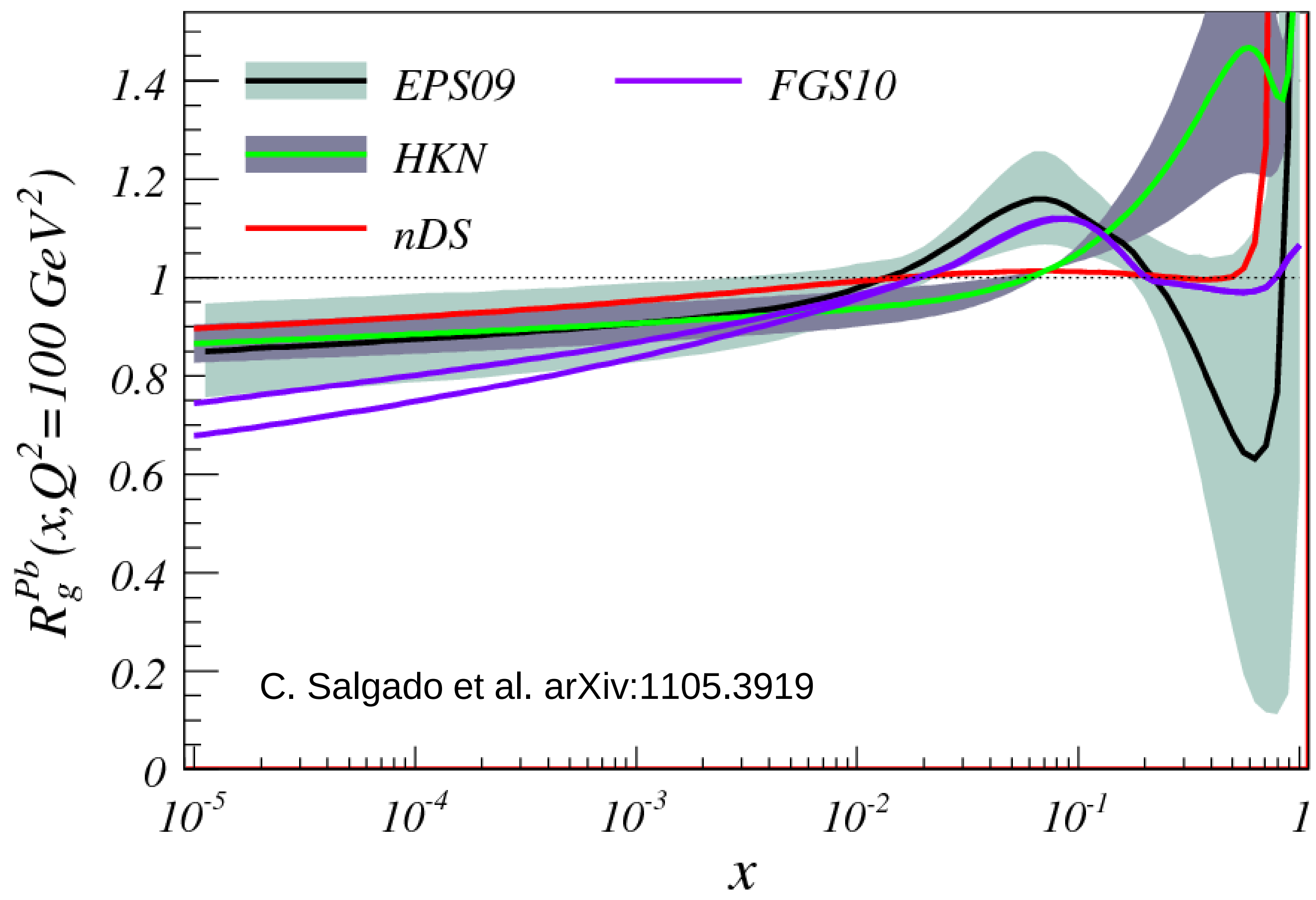
Extra slides

More ‘known physics’: nuclear PDFs

$Q^2 = 1.69\ GeV^2$



$Q^2 = 100\ GeV^2$



Nuclear modifications of PDF measured in DIS

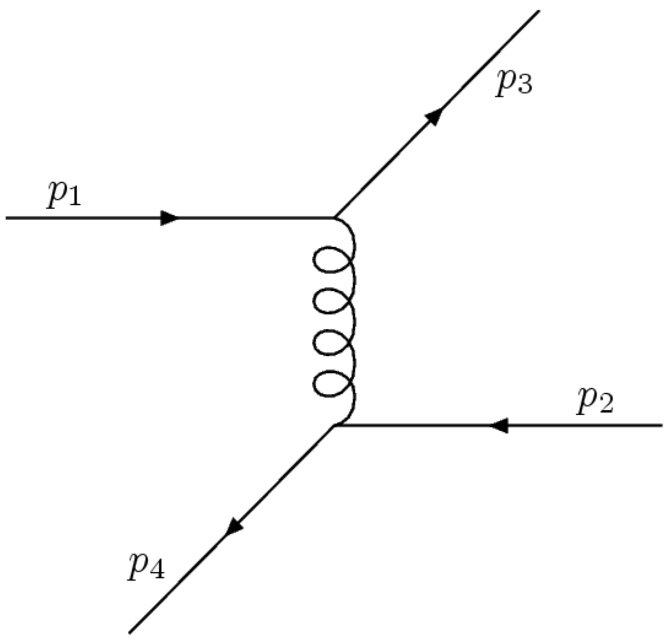
Gluon shadowing potentially large at $x < 10^{-3}$

Effect largest at low Q^2

Related to saturation/CGC or an independent phenomenon?

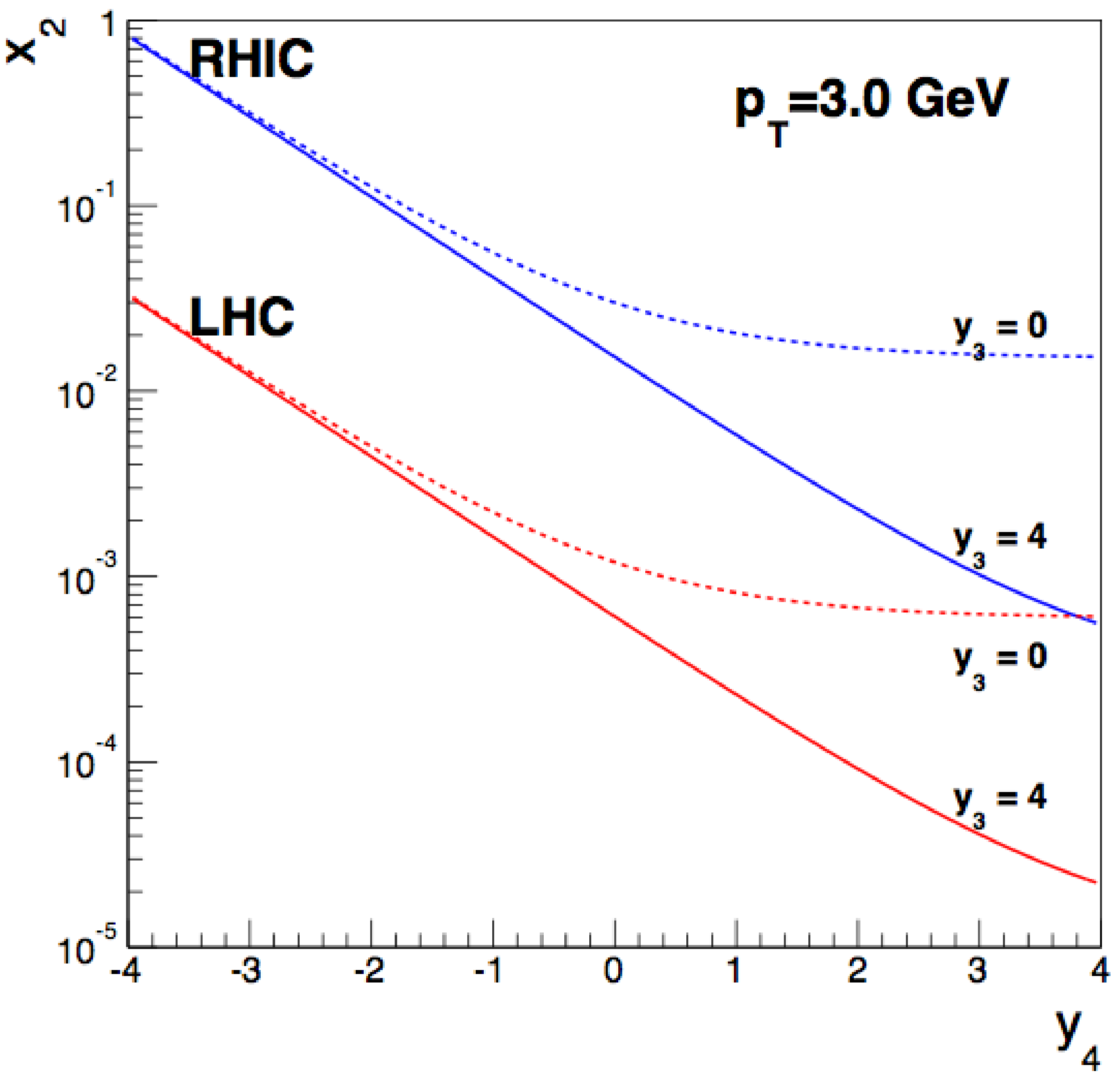
Reminder: how to get x and Q^2 in hadronic collisions

LO 2→2 kinematics:



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

$Q \sim p_T$



Forward rapidity is small x

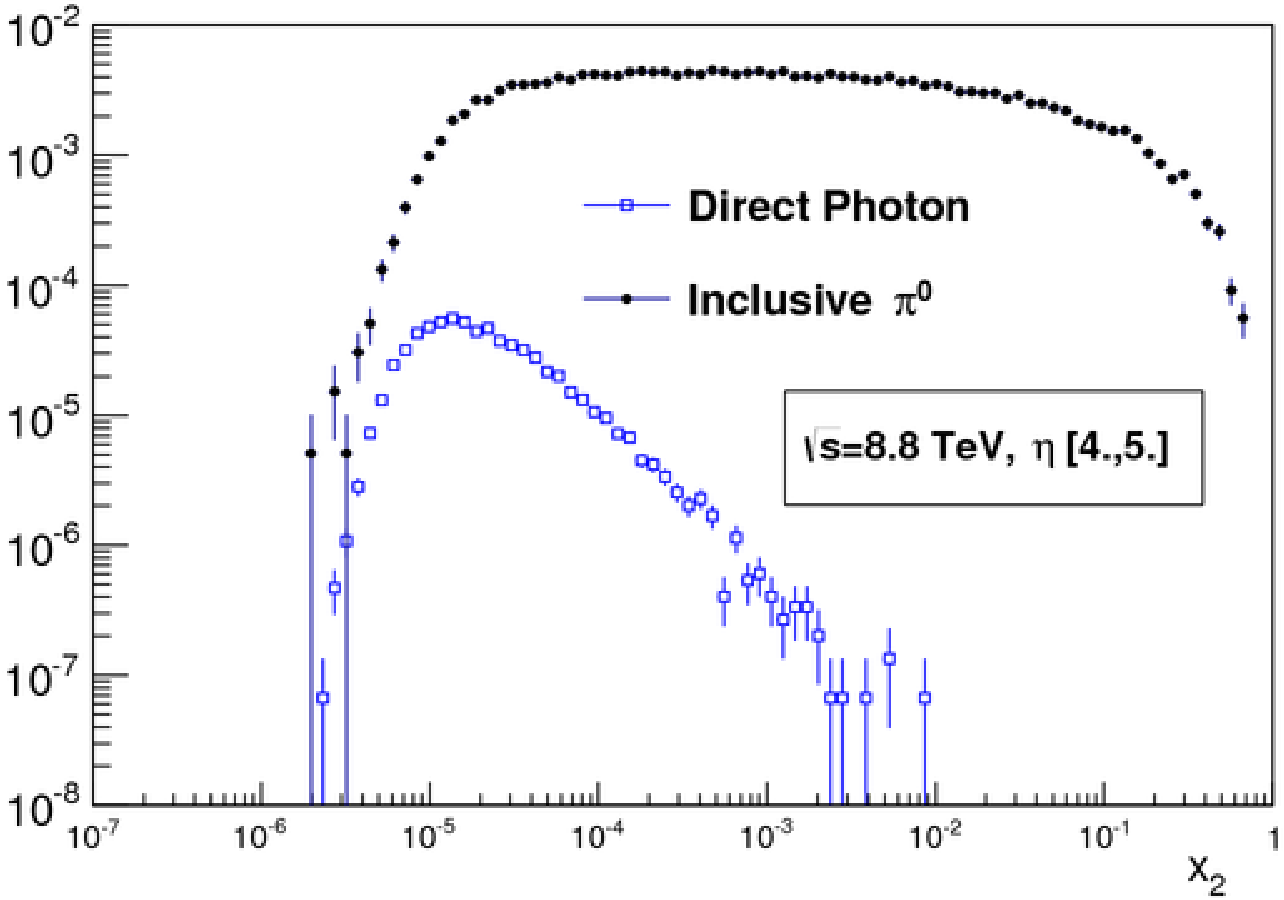
LHC probes lower x than RHIC

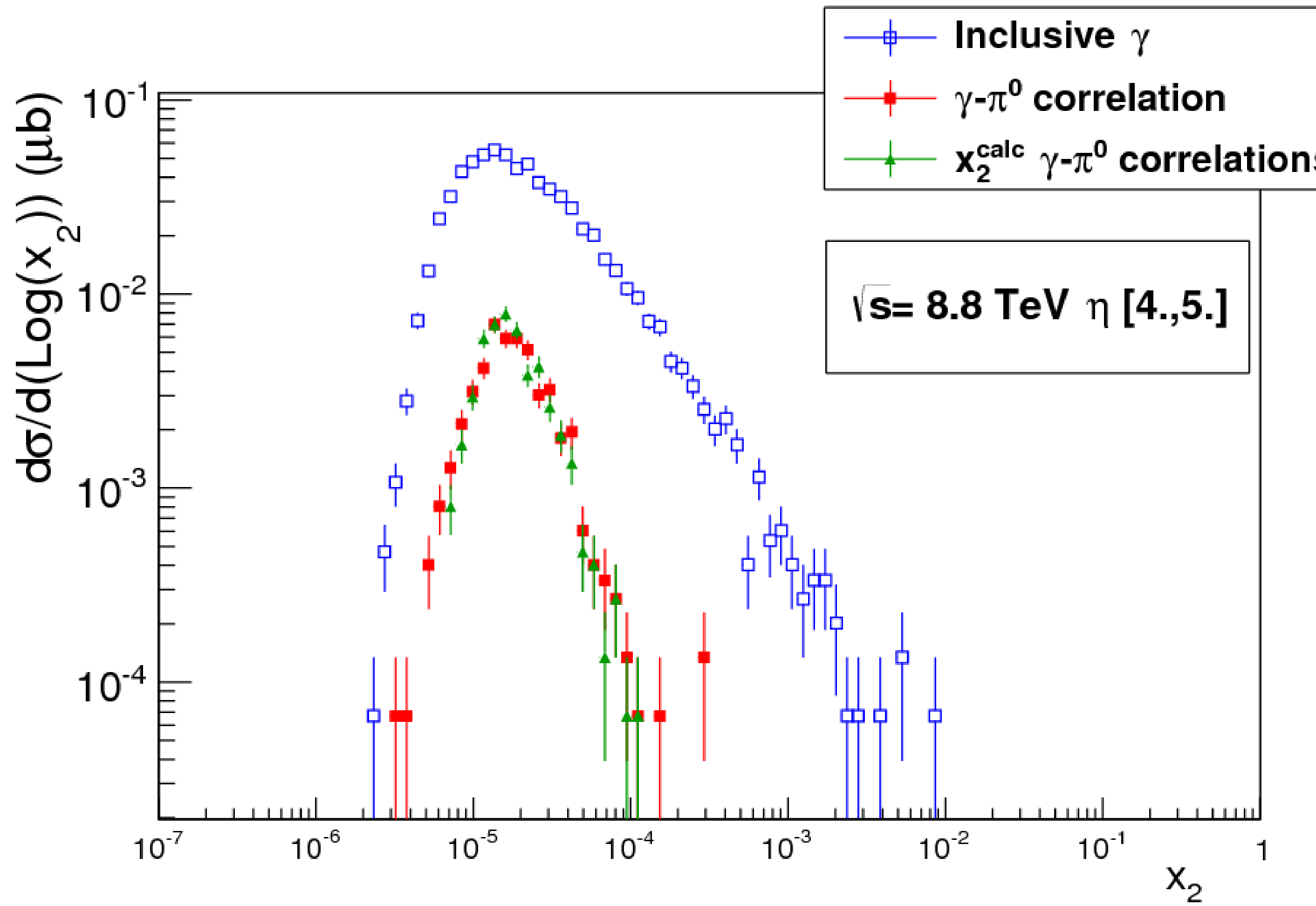
Mid-rapidity at LHC ≈ forward rap at RHIC

(Need both final state partons to reduce spread in x)

x sensitivity pion vs gamma

PYTHIA simulations





Forward © much more selective than □^{0}

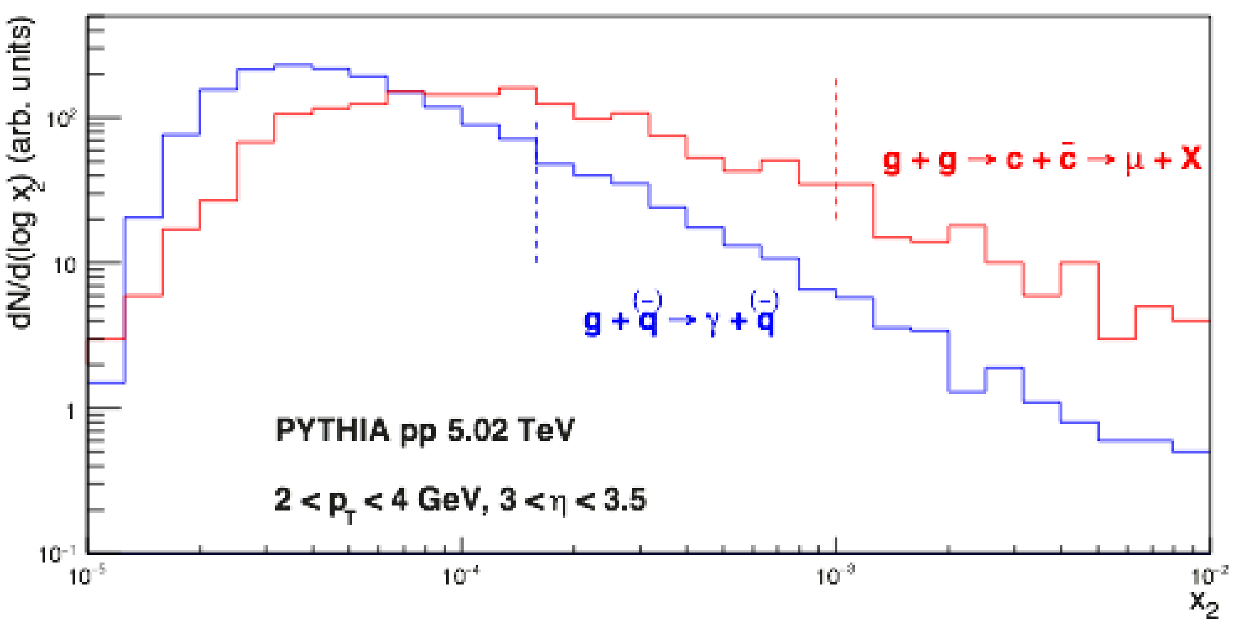
©-□^{0} correlations provide additional constraints

Pythia = LO + radiation

NLO effects under study – expect small effect for *isolated* photons

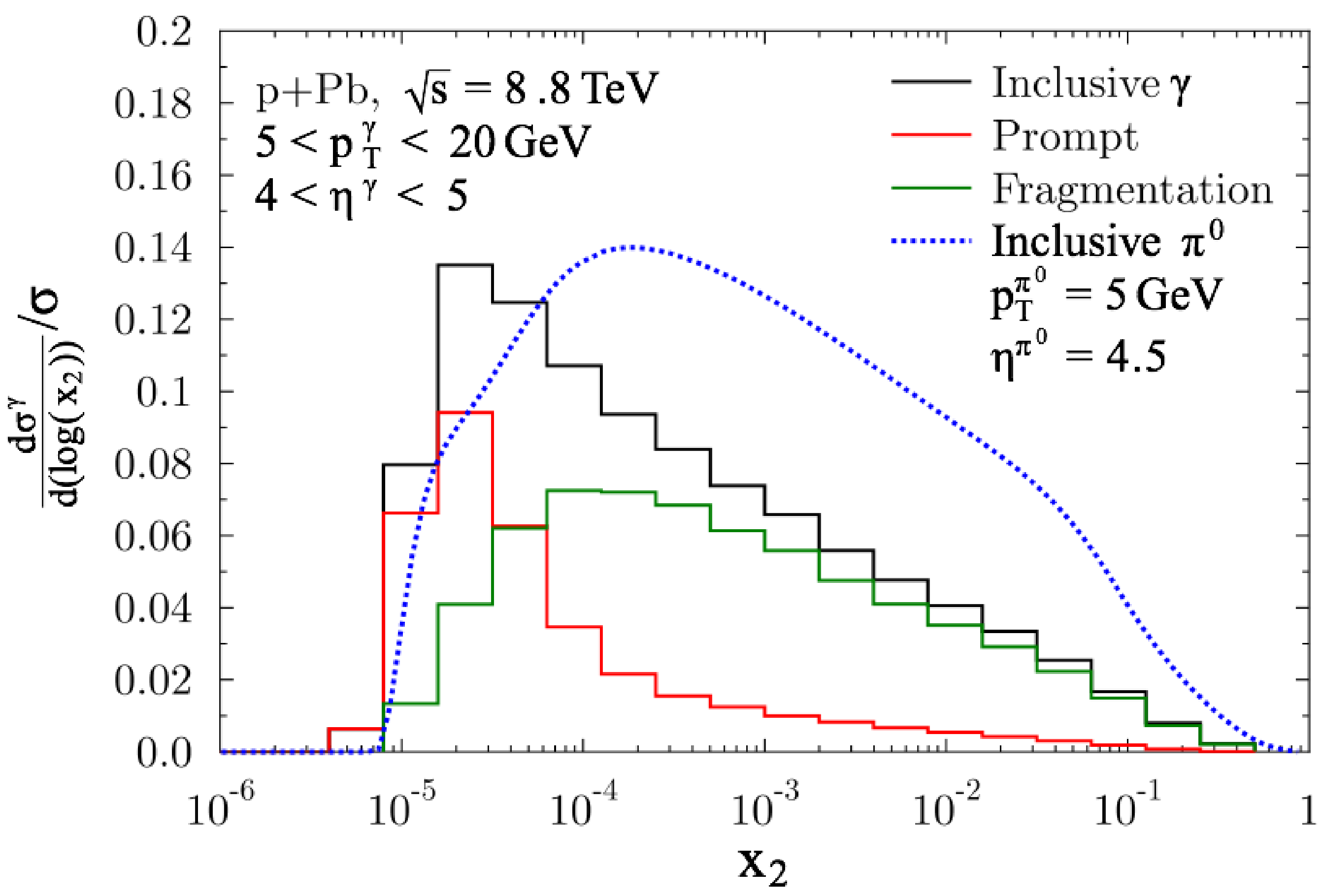
x-ranges

HF muons vs γ



HF sensitive to larger x 10^{-4} - 10^{-3}

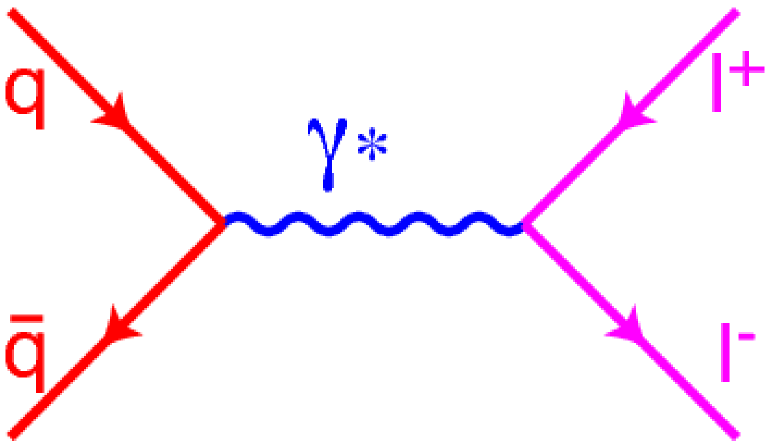
Direct γ, NLO contributions



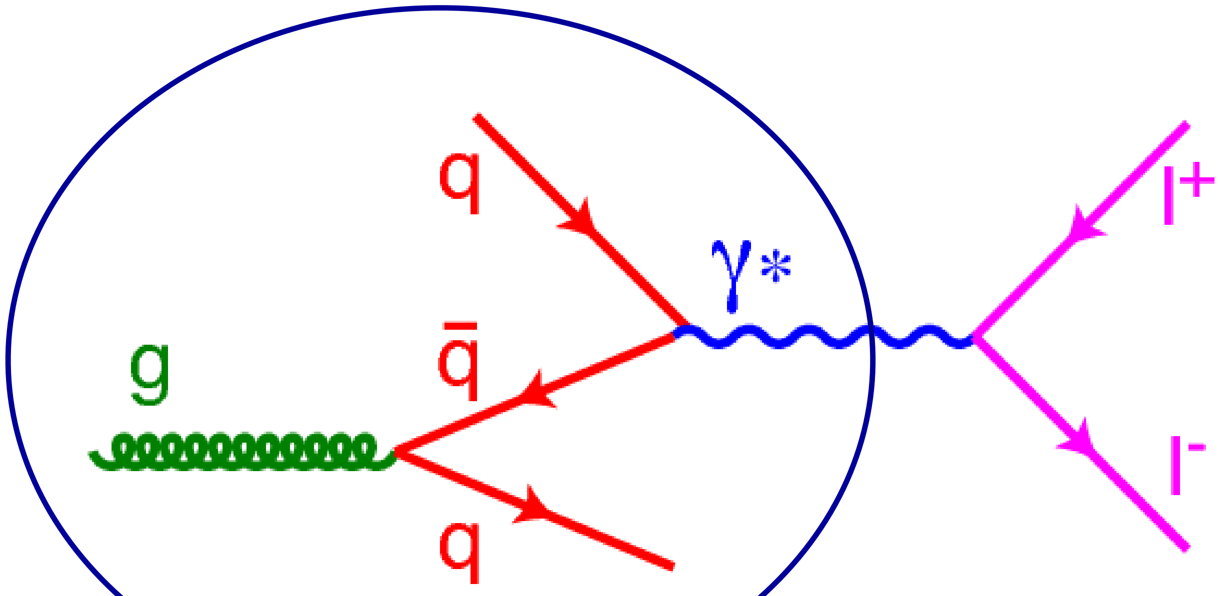
Isolation reduces higher-x contributions

Direct/isolation γ give clean access to lowest $x \sim 10^{-5}$ - 10^{-4}

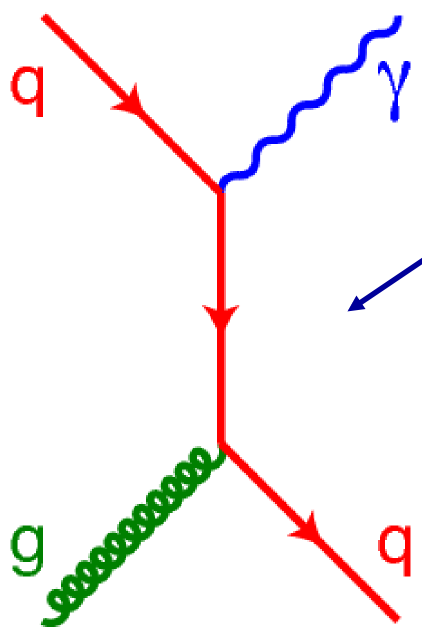
Virtual photon production: Drell-Yan



DY (LO)



DY, virtual Compton (NLO)

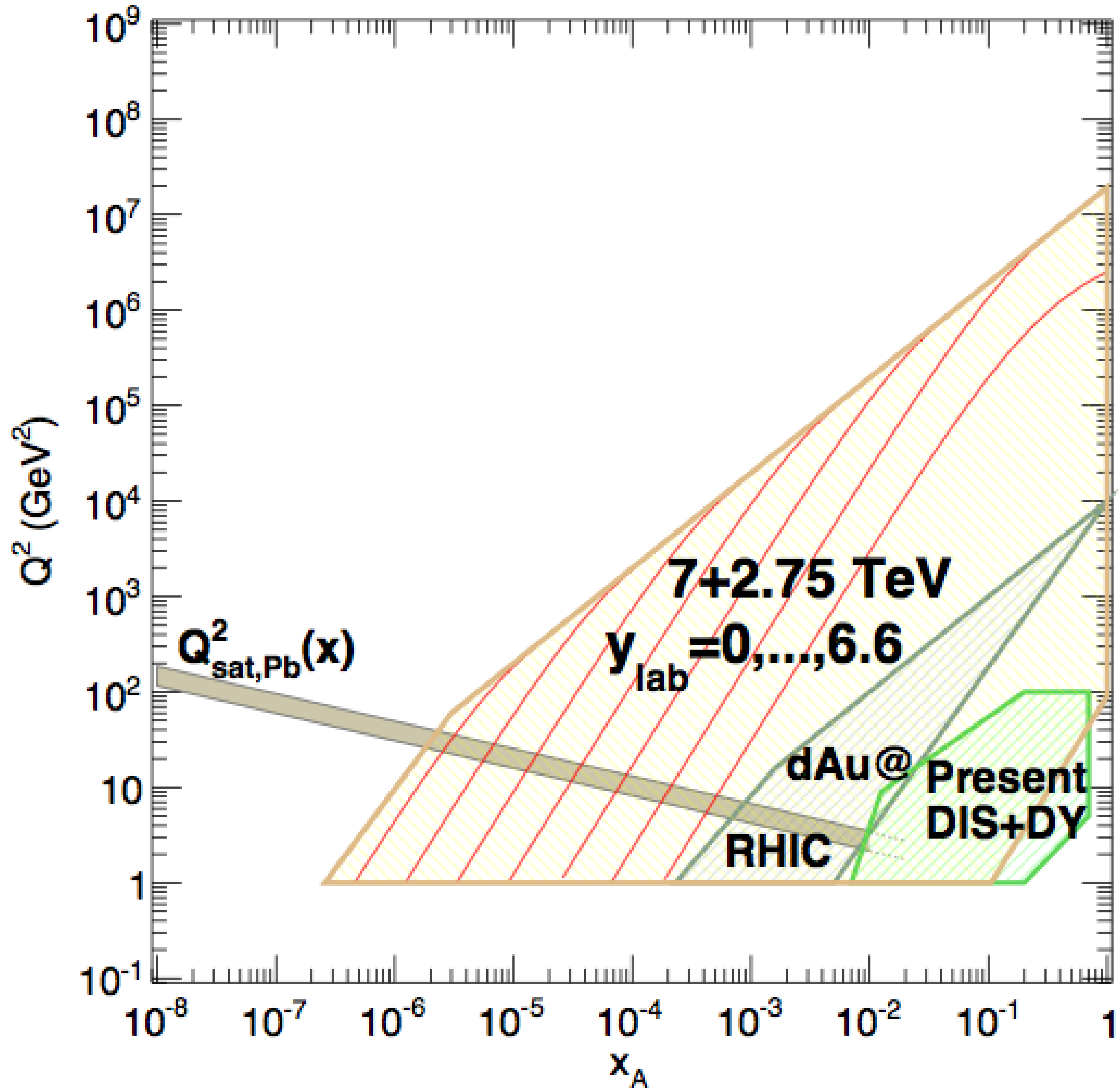


direct-γ, Compton (LO)

Drell-Yan only sensitive
to gluons at NLO

DY: small cross section,
not practical at LHC p+Pb

x, Q^2 coverage at LHC



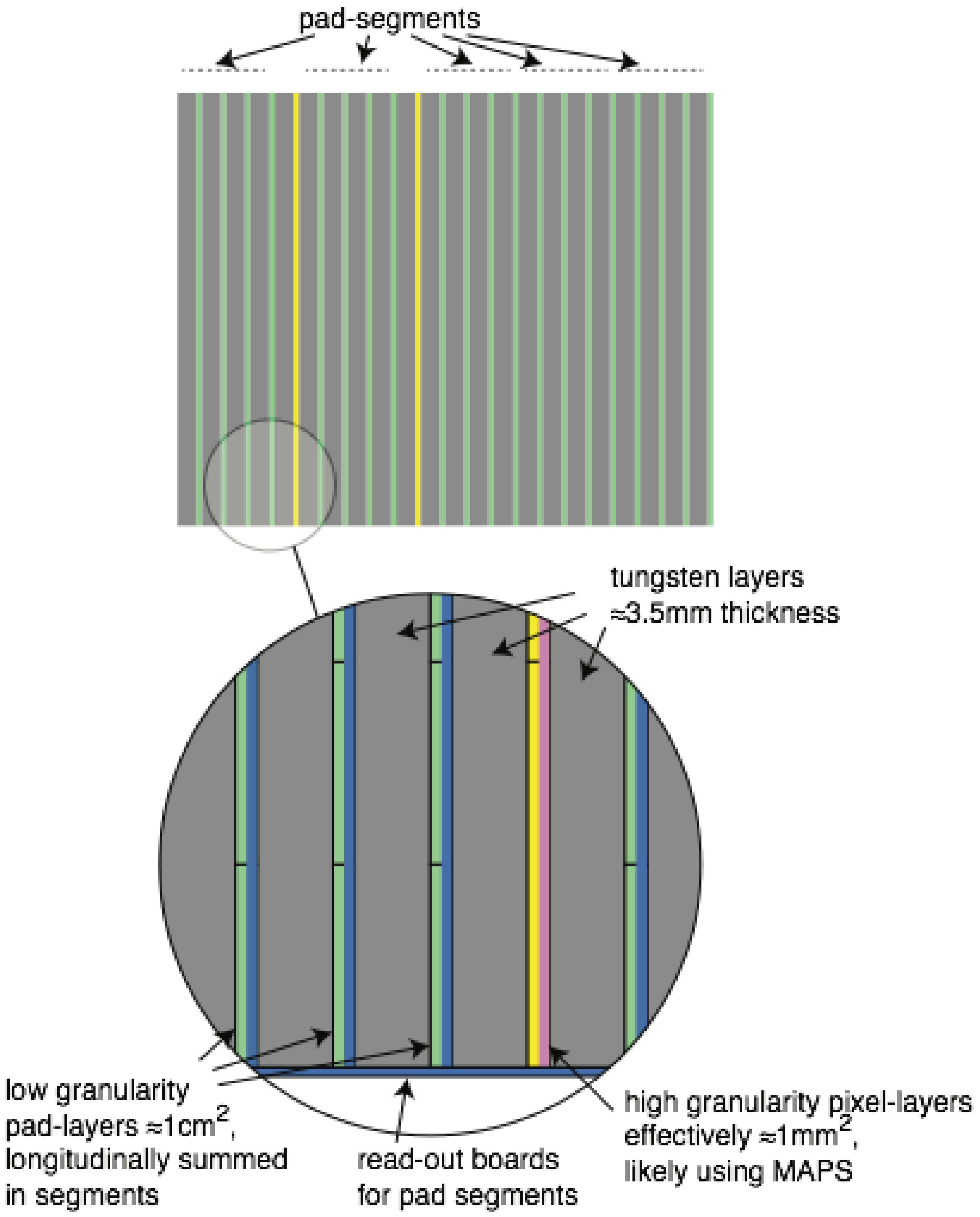
FoCal detector plan

ECAL: Si-W

Simulation uses current design
- 20 layers, 1 X_0 each
- Mostly pad layers 1x1 cm
- 2 pixel layers after 5 and 10 X_0

Pixel layers for 2-shower separation
Pixel size in simulations: 50 um

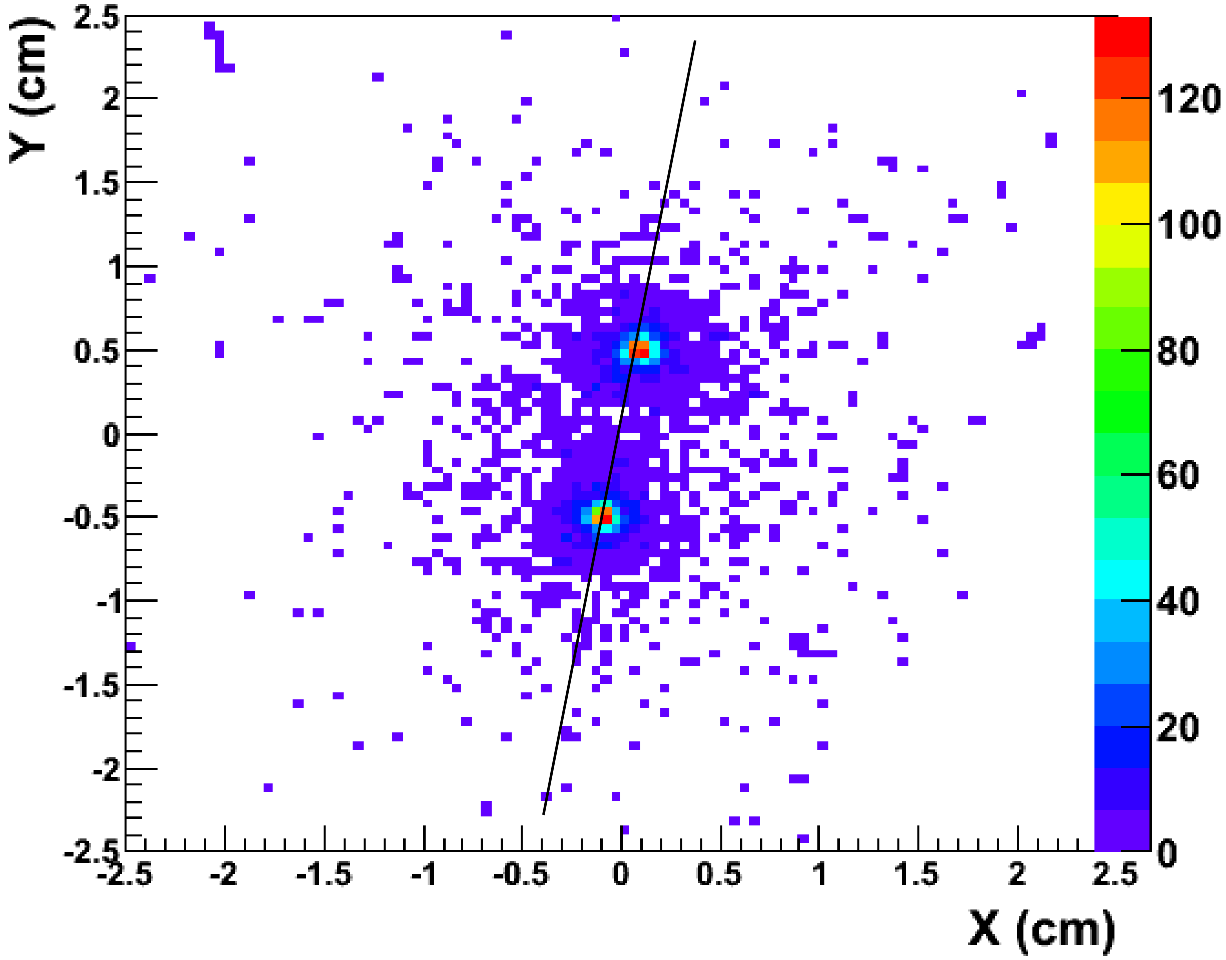
HCAL: Cu+Scintillator
~ 70 cm deep



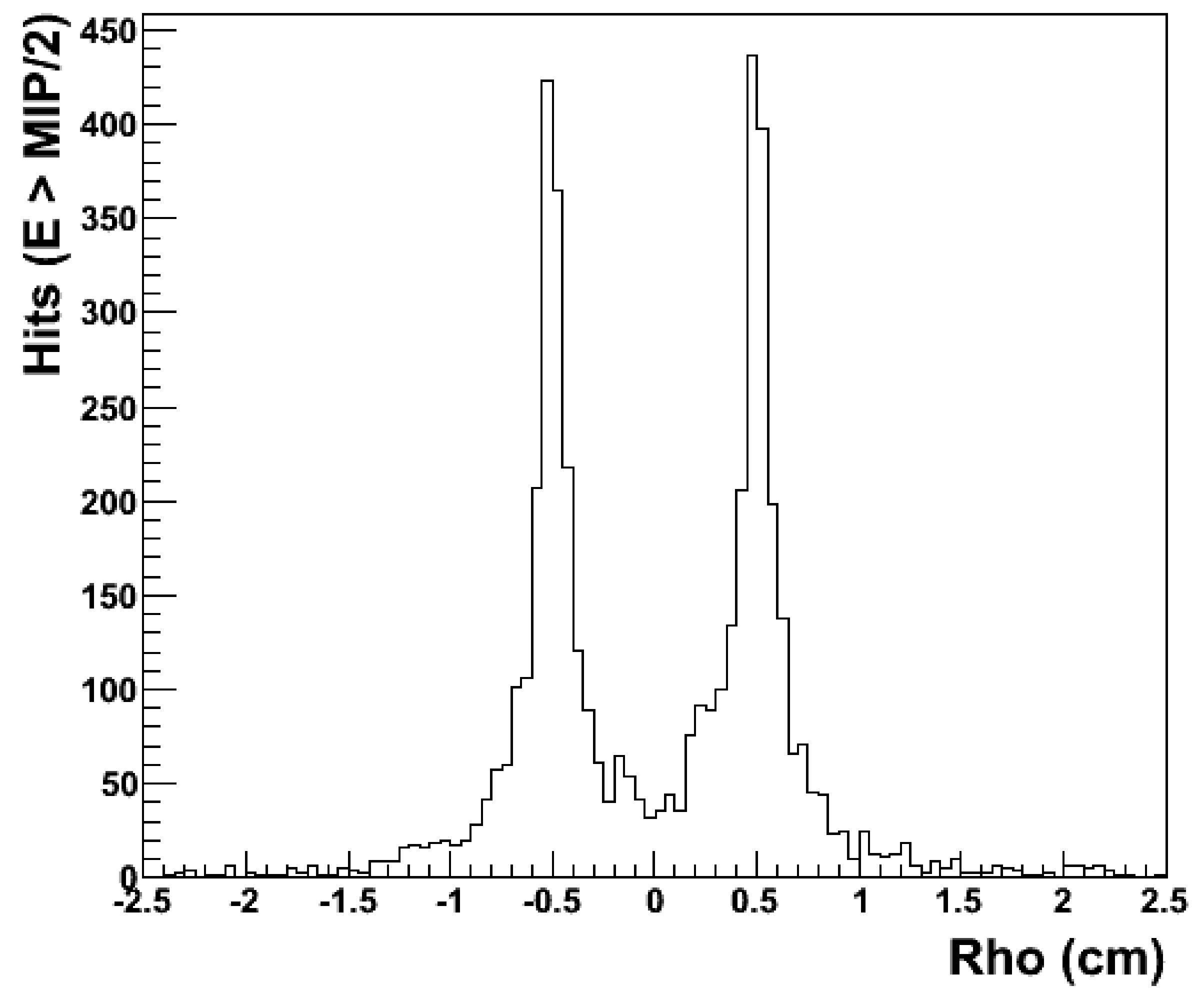
Two-photon separation

Simulated □^{0} decay

Granularity: ~500 ⌠m



Projection on separation axis

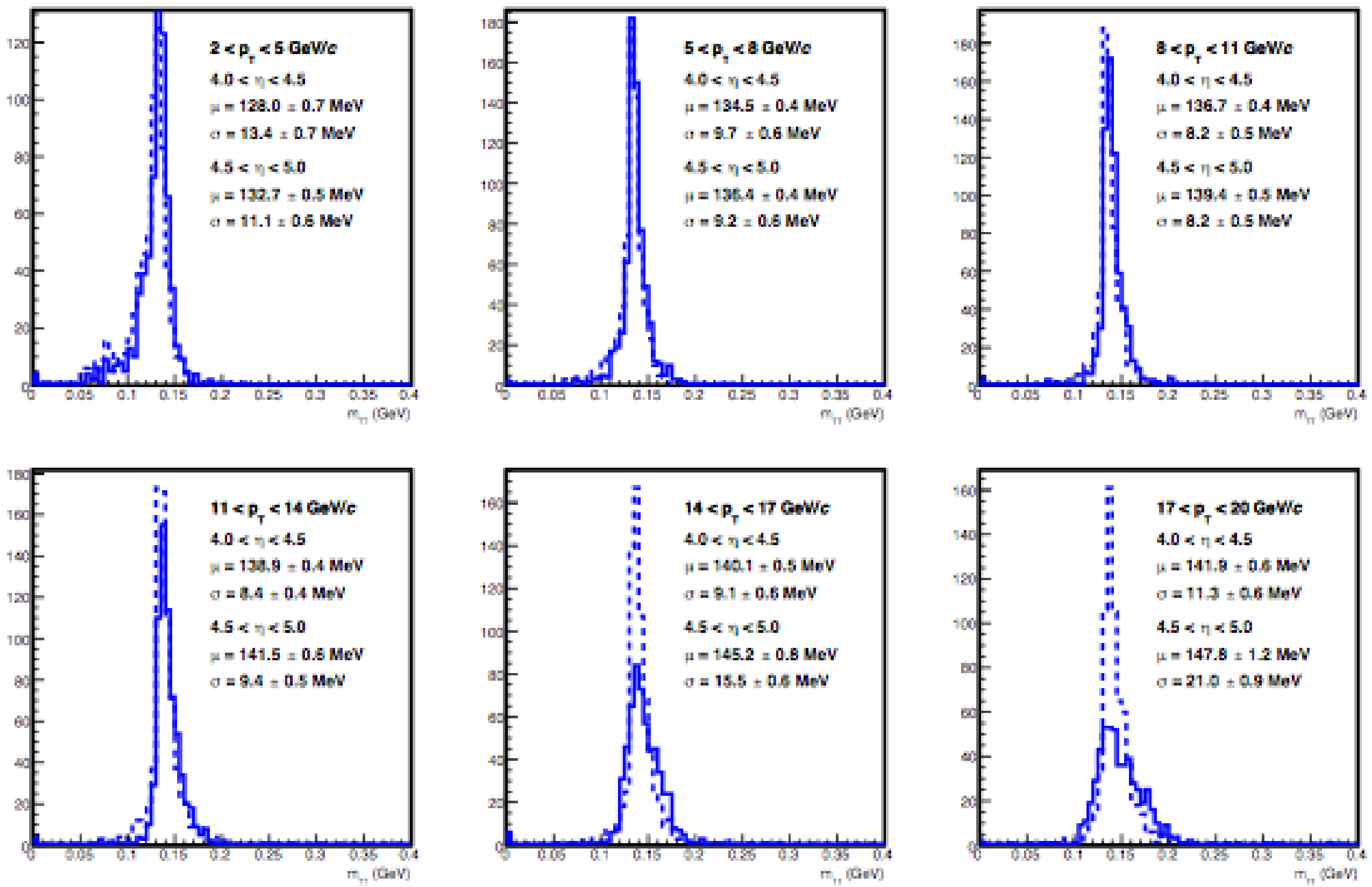


Position resolution of ~ 1 mm achievable (2-© separation few mm)

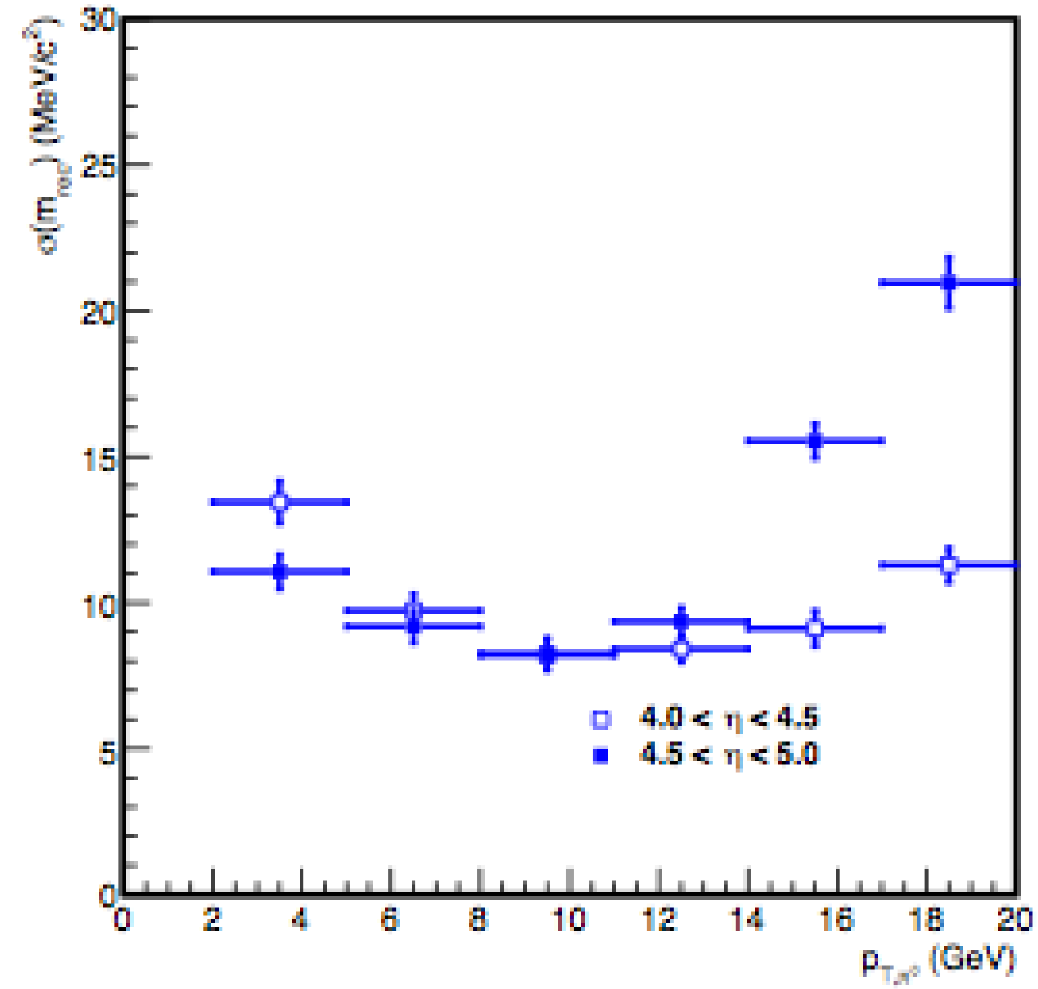
Energy resolution under study

Unexplored regime for calorimeters: verify in testbeam

π^0 mass peaks, resolution



π^0 peak width



High-granularity layers give excellent two-photon separation over large momentum range

Peak width ~ 10 MeV over large range in p_T