Parton energy loss in small systems?
- and -
The FOCAL proposal and small-x physics at the LHC

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Part I:
Parton energy loss in small systems?

- Motivation
- What did we learn from pA about particle production at x<<0.1
- Applying concepts in pA to peripheral AA
- What's next

Summary of typical HI observables (LHC)

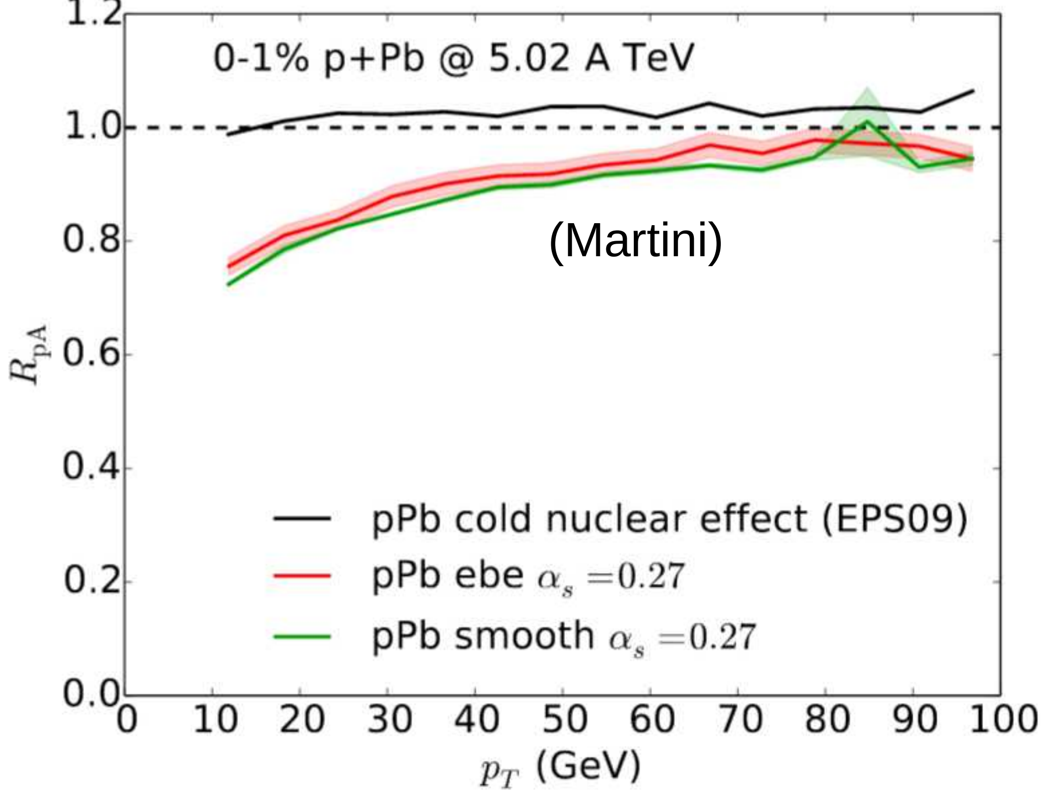
Observable or effect	PbPb	pPb (at high mult.)	pp (at high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[37–42]
Intermed. p_T ("recombination")	yes	yes	yes	[41–47]
Particle ratios Statistical model	GC level $\gamma_s^{GC} = 1$, 10–30%	GC level except Ω $\gamma_s^{GC} \approx 1$, 20–40%	GC level except Ω $\gamma_s^{C} < 1$, 20–40% [2]	[48–51] [52]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$ [3]	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[53–59]
Azimuthal anisotropy (v_n) (from two part. correlations)	$v_1 - v_7$	$v_1 - v_5$	v_2, v_3	[25–27] [60–67]
Characteristic mass dependence	v_2, v_3 [4]	v_2, v_3	v_2	[67–73]
Directed flow (from spectators)	yes	no	no	[74]
Higher order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$" [5]	[28, 29, 67] [75–83]
Weak η dependence	yes	yes	not measured	[83–90]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[91]
Event-by-event v_n distributions	$n = 2 - 4$	not measured	not measured	[92]
Event plane and v_n correlations	yes	not measured	not measured	[93–95]
Direct photons at low p_T	yes	not measured	not measured [6]	[96]
Jet quenching	yes	not observed [7]	not measured [8]	[97–105]
Heavy flavor anisotropy	yes	hint [9]	not measured	[106–109]
Quarkonia	$J/\psi \uparrow$, $\Upsilon \downarrow$	suppressed	not measured [8]	[110–116]

- Observations qualitatively similar across systems for similar mult
- Postulate sQGP even in high mult pA/pp collisions?
- But, no direct evidence for parton energy loss, even not in pA

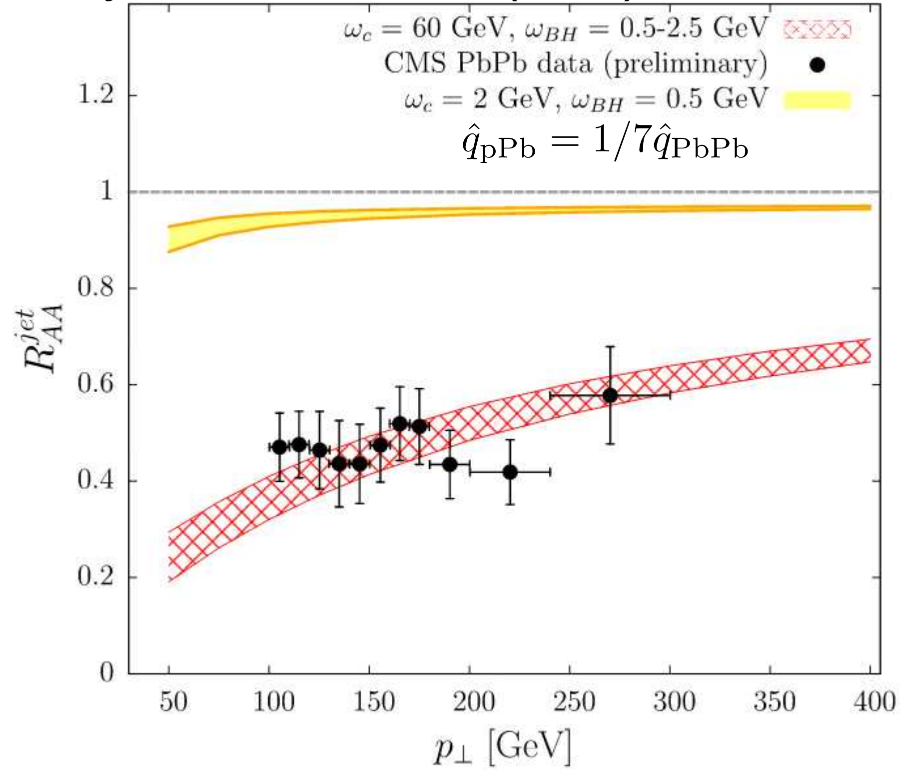
QM15, CL., arXiv:1602.09138
(see also update in arXiv:1812.06772)

Predictions from models

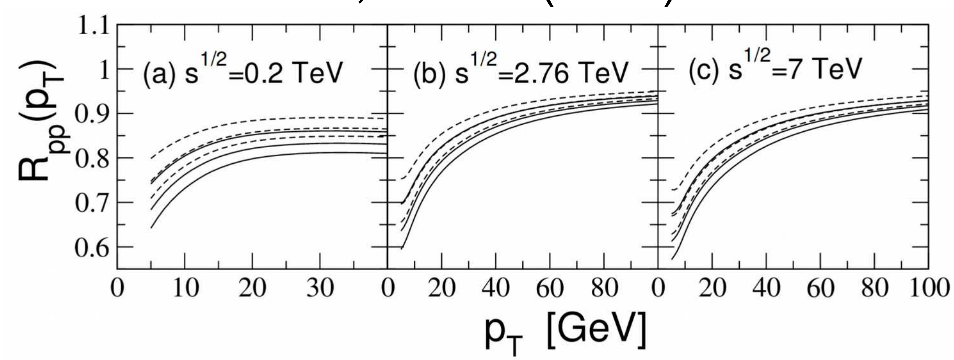
C.Shen et al., NPA956 (2016) 741



K. Tywoniuk, NPA 926 (2014) 85



B.Zakharov, JPG41 (2014) 075008

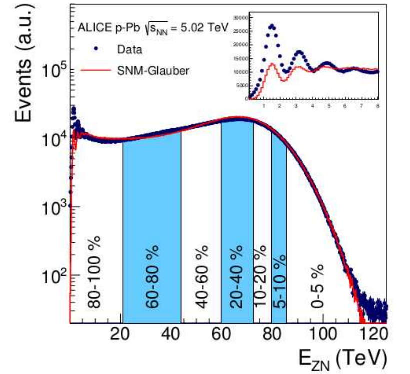


Calculations expect sizable (10-20%) suppression for “central” pPb and pp

No modification (at low p_T, ie. $x \ll 0.1$)

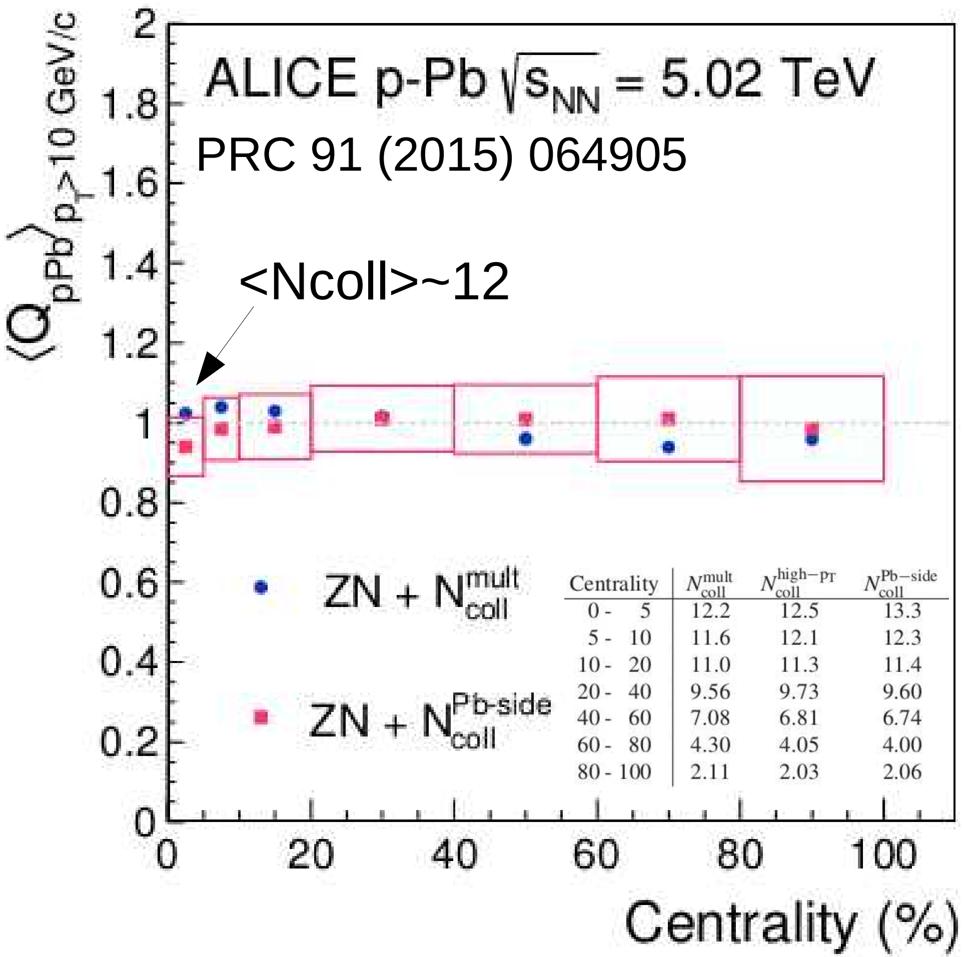
ALICE, PRC 91 (2015) 064905

ZN on Pb-side

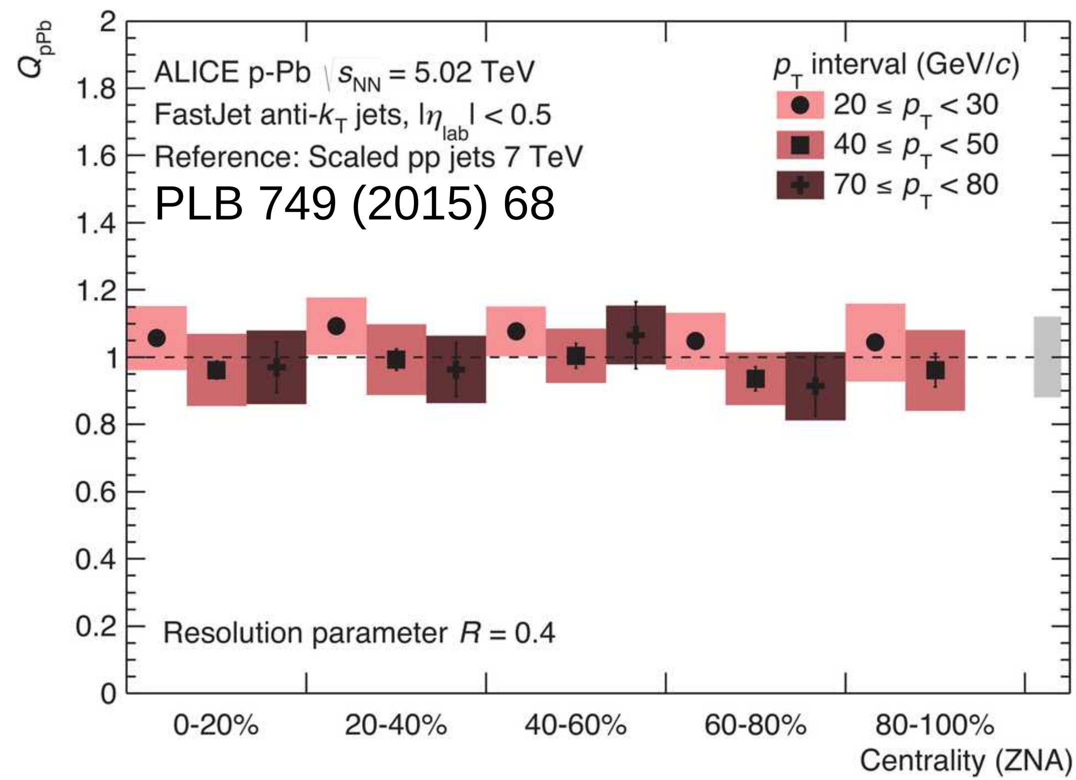


$$Q_{\mathrm{pPb}}^{\mathrm{ZN}} = \frac{1}{N_{\mathrm{coll}}} \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}}$$

(with selection on neutron ZDC on the Pb-side and Ncoll from multiplicity assuming the wounded nucleon model)



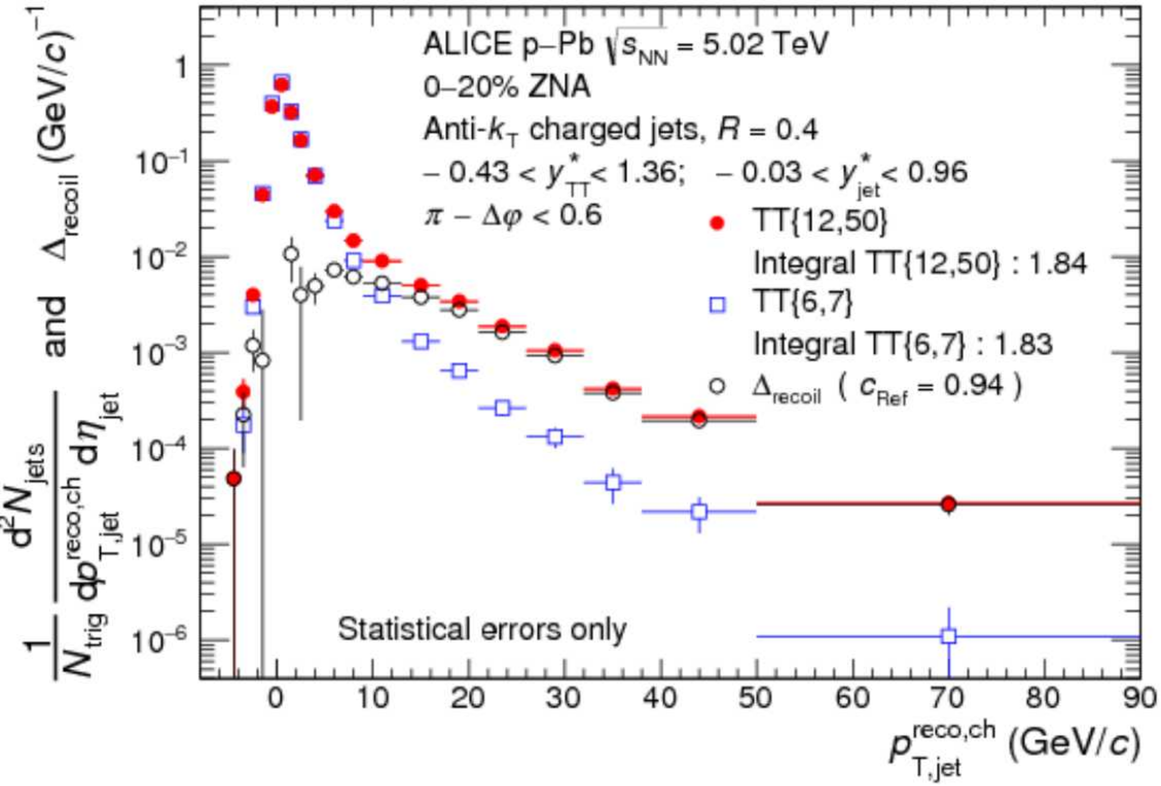
Centrality	N_{coll}^{mult}	$N_{coll}^{high-p_T}$	$N_{coll}^{Pb-side}$
0 - 5	12.2	12.5	13.3
5 - 10	11.6	12.1	12.3
10 - 20	11.0	11.3	11.4
20 - 40	9.56	9.73	9.60
40 - 60	7.08	6.81	6.74
60 - 80	4.30	4.05	4.00
80 - 100	2.11	2.03	2.06

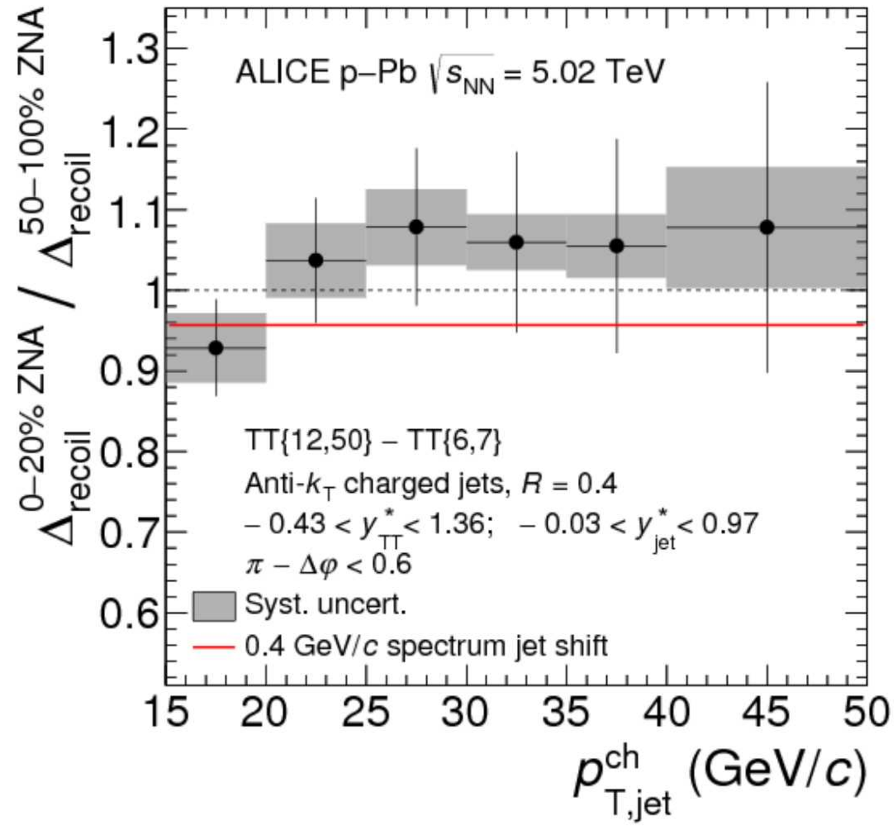


No suppression observed

Hadron-jet coincidence measurement

ALICE, PLB 783 (2018) 95





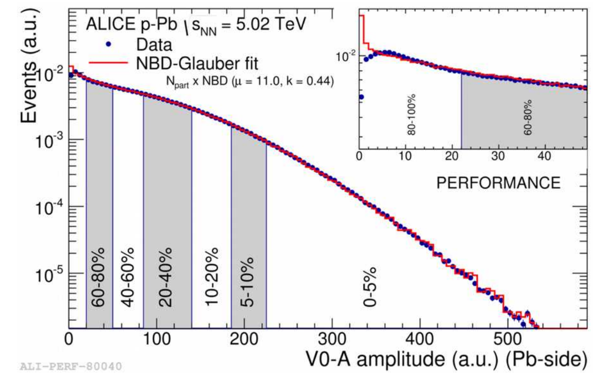
$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{d p_{T,jet}^{ch} d\eta}\Bigg|_{p_{T,trig} \in TT\{12,50\}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{d p_{T,jet}^{ch} d\eta}\Bigg|_{p_{T,trig} \in TT\{6,7\}}$$

No suppression (precision expected to improve with large 2015 pPb data!)

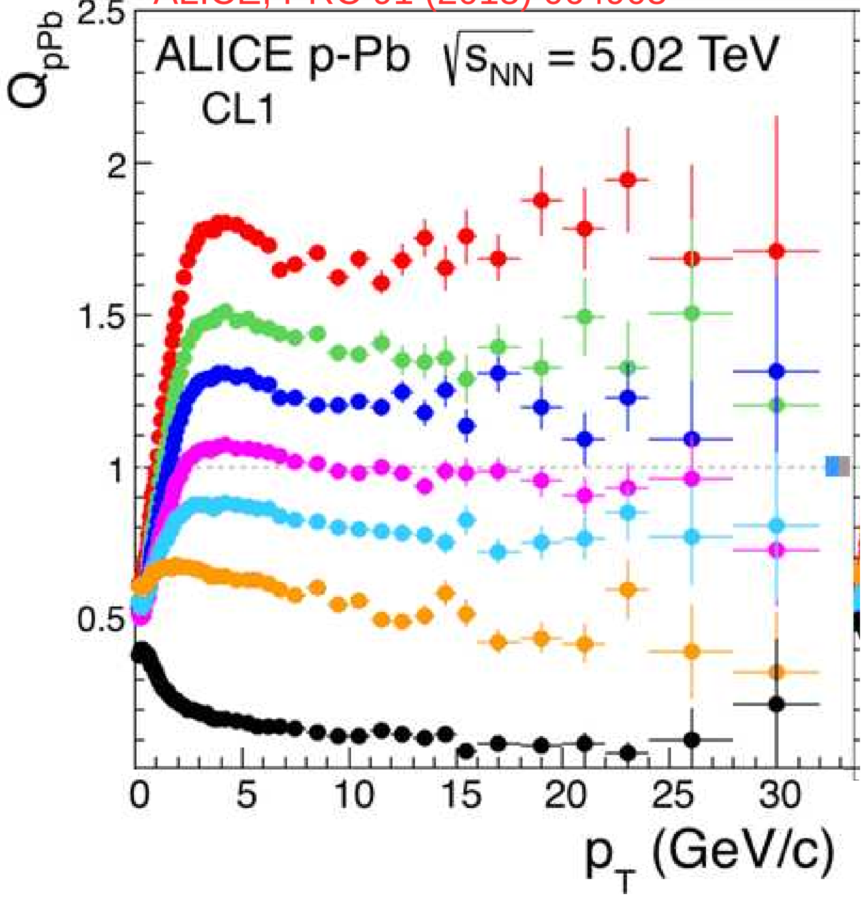
Multiplicity based selection

$$Q_{\mathrm{pPb}} = \frac{1}{N_{\mathrm{coll}}^{\mathrm{fit}}} \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}}$$

(with selection on multiplicity and Ncoll from Glauber fit)



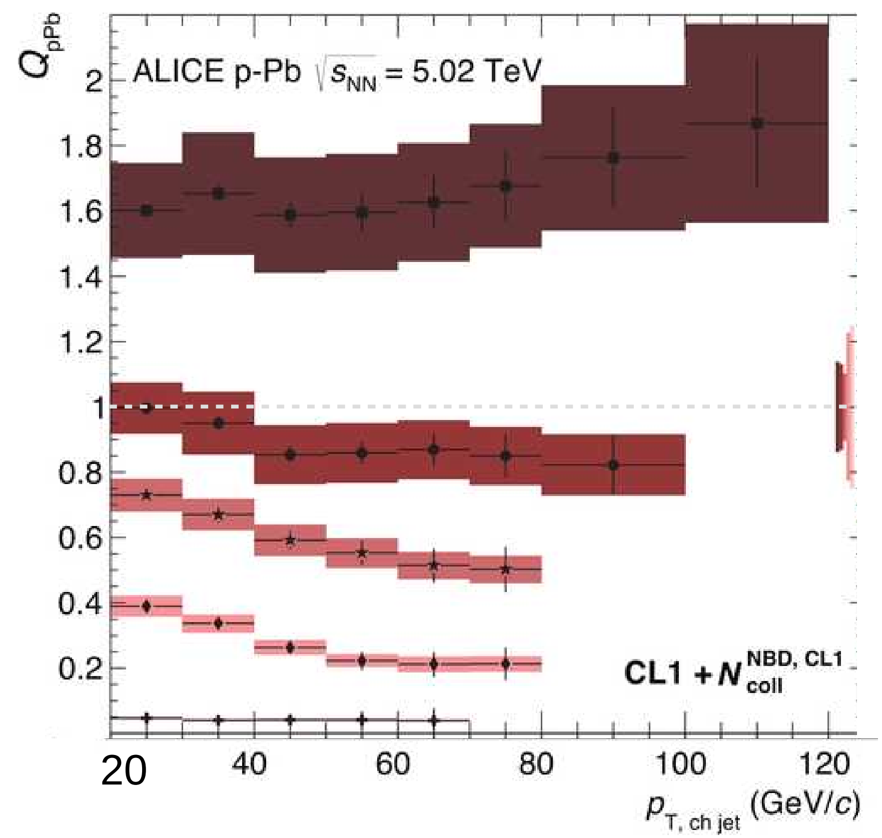
ALICE, PRC 91 (2015) 064905



Largest Mult bin

Lowest mult bin

ALICE-PUBLIC-2016-001



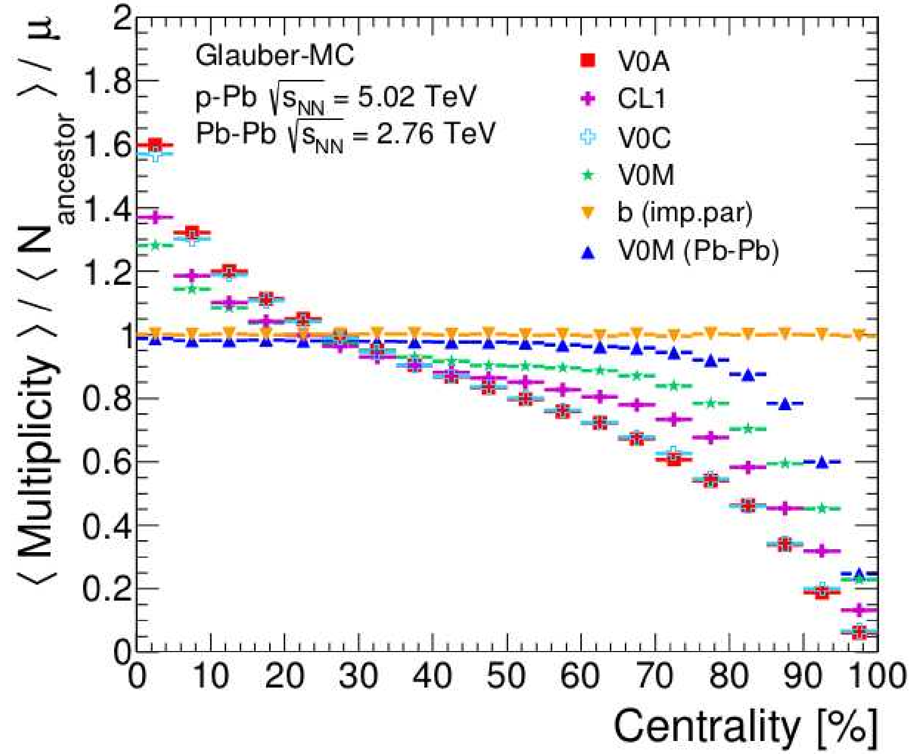
Huge effect

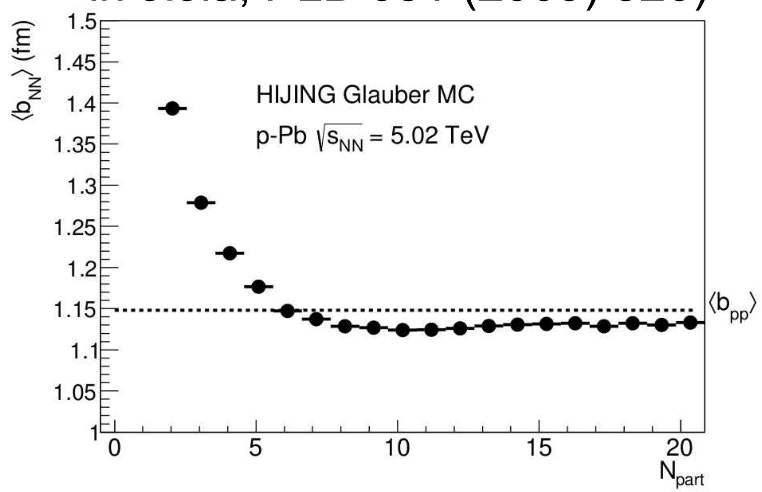
(but QpPb not necessarily one in absence of nuclear modification!)

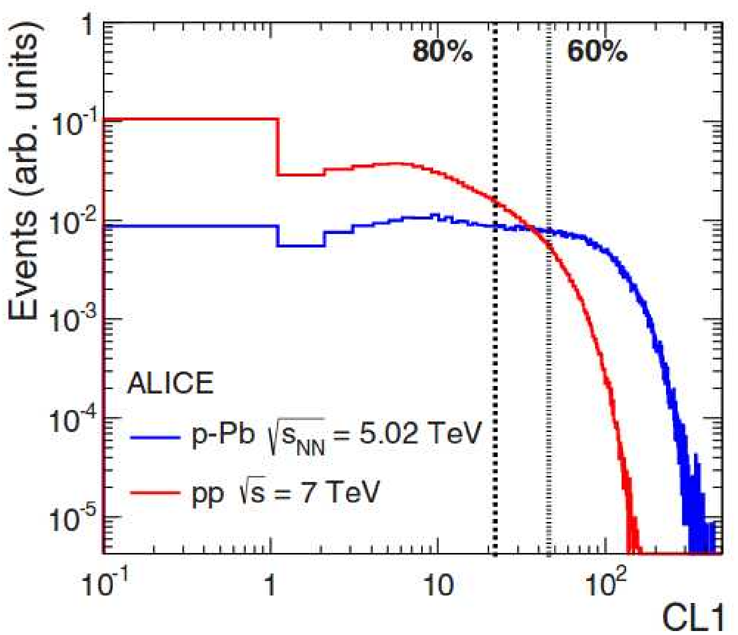
Multiplicity based selection (2)

ALICE, PRC 91 (2015) 064905

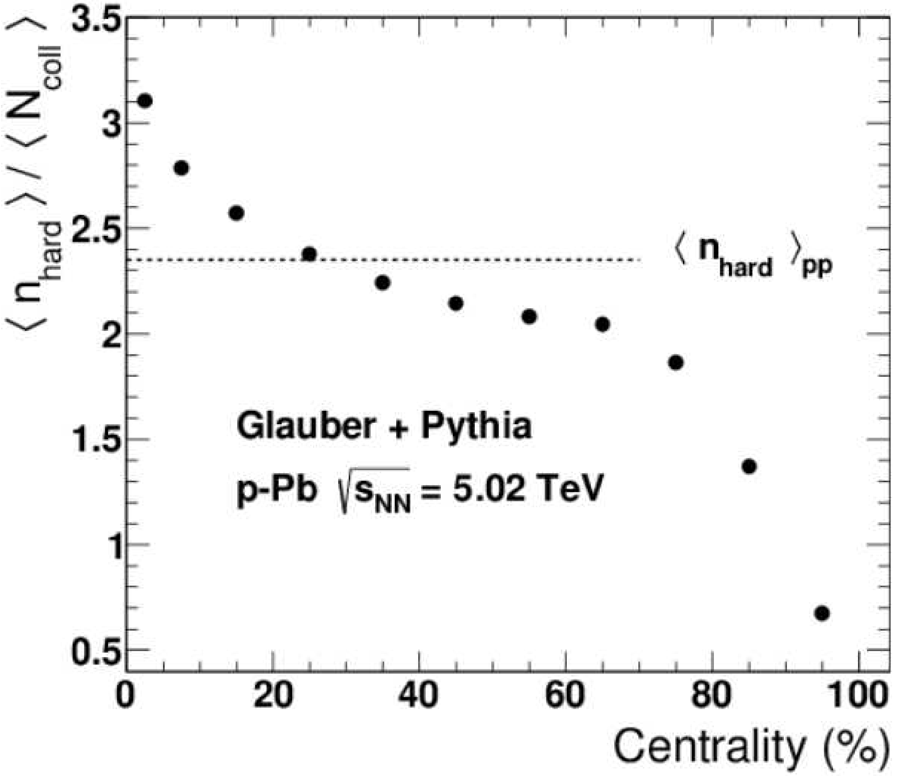
- Several biases are relevant
  - Multiplicity bias
    - Bias on the sources contributing to particle production
  - Jet veto bias
    - Auto-correlation between high p_T particle and soft multiplicity
  - Geometrical bias
    - Average NN impact parameter increases for peripheral collisions (explicitly discussed in J.Jia, PLB 681 (2009) 320)



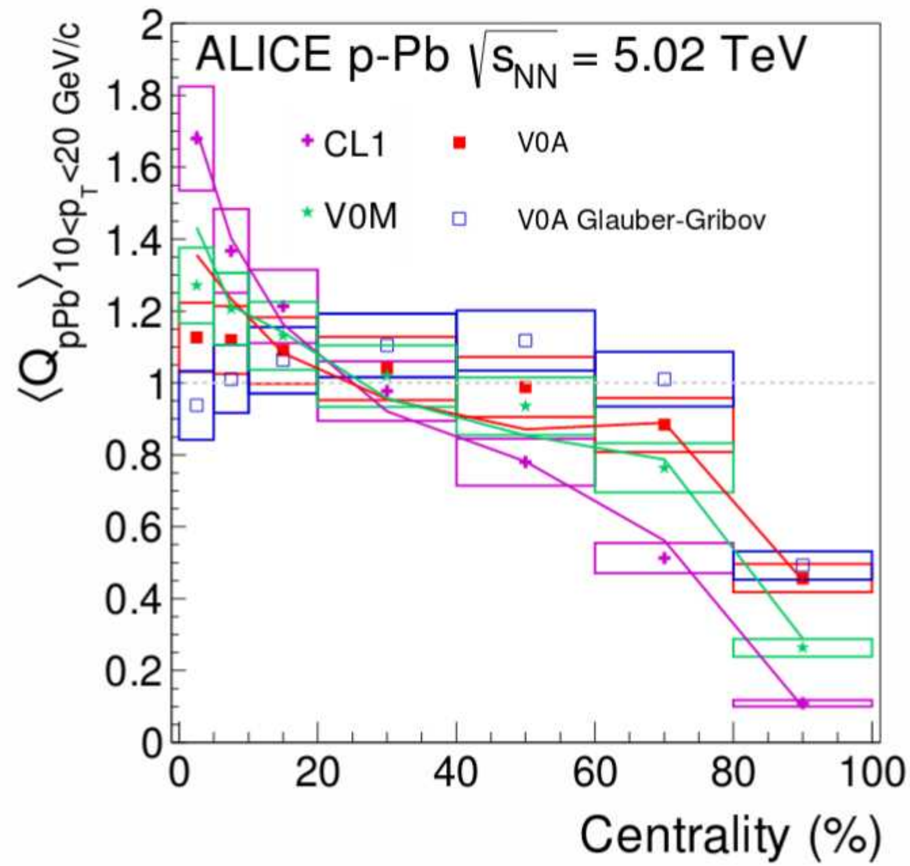




Demonstration using Glauber+Pythia



ALICE, PRC 91 (2015) 064905



G-PYTHIA:

1. For a given Glauber event, simulate Ncoll many PYTHIA pp events
2. Order events according to resulting total multiplicity (in given phase space)

Suggests, at high p_T

$$\langle Q_{\mathrm{pPb}} \rangle \propto \frac{N_{\mathrm{hard}}}{\mathrm{N_{coll}}\,\langle \mathrm{N}^{\mathrm{pp}}_{\mathrm{hard}} \rangle}$$

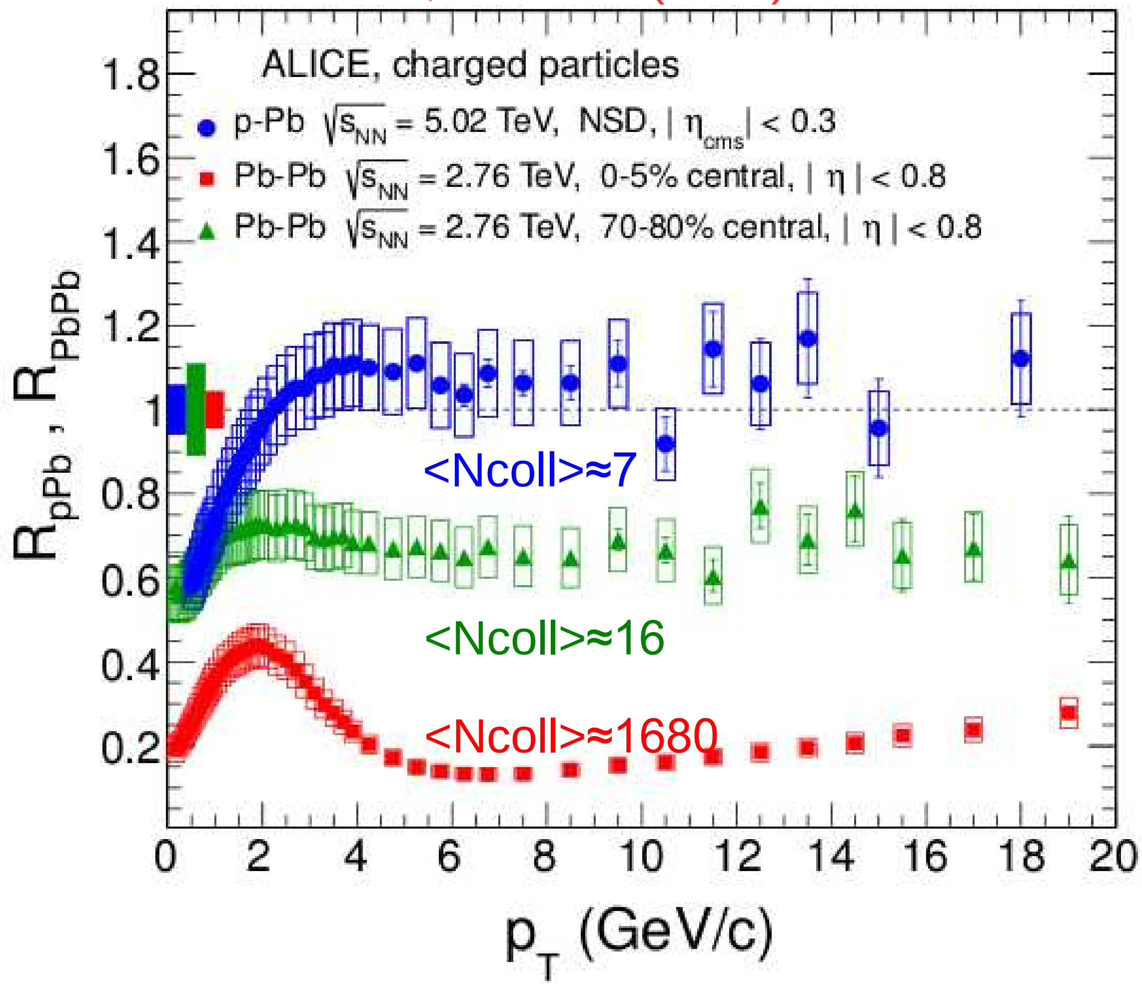
What about peripheral AA?

dN/dη≈17 (minbias pPb)

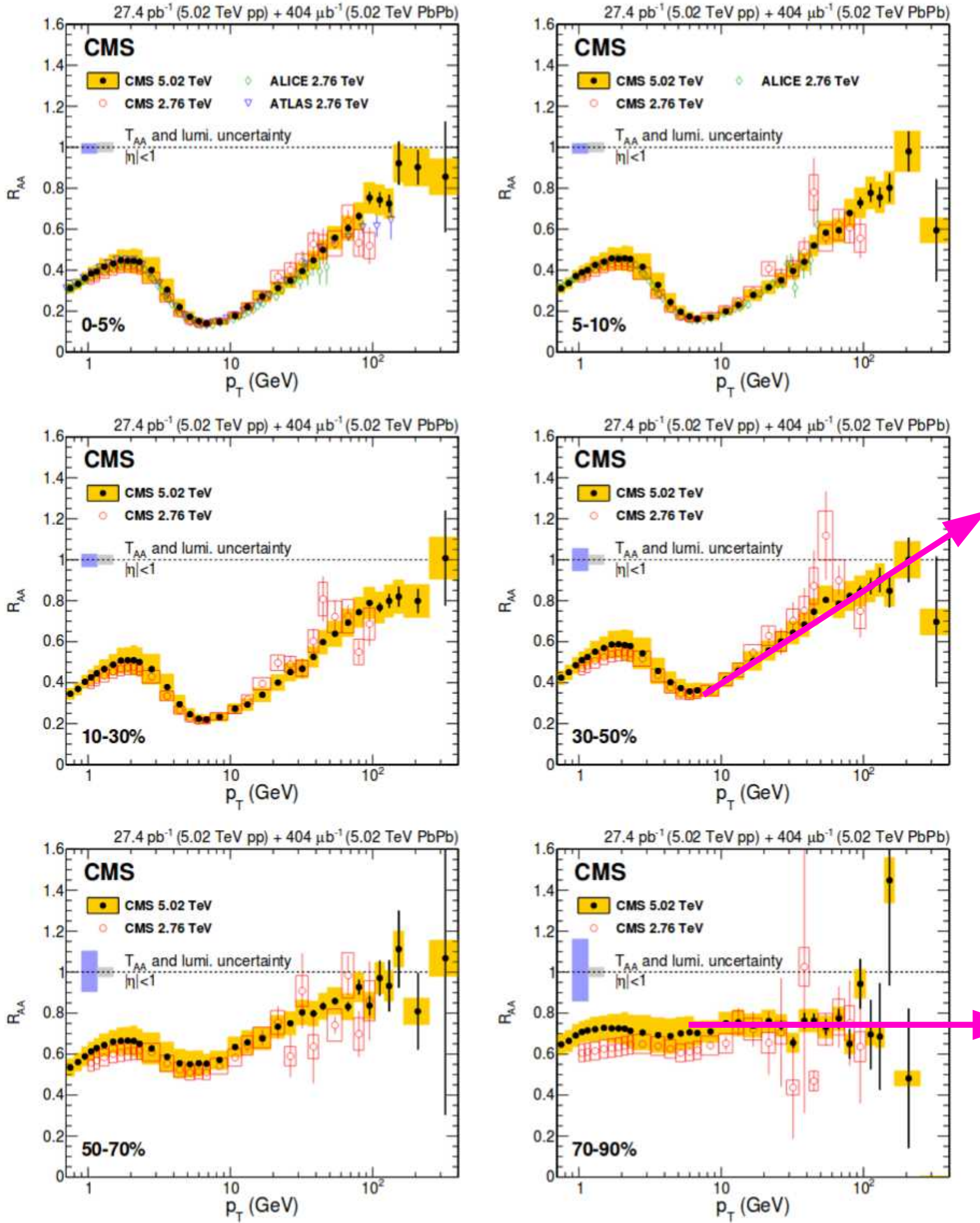
dN/dη≈35 (70-80% PbPb)

(corresponds to ~0-5% pPb)

ALICE, PRL 110 (2013) 082302



Expect gradual change as a function of multiplicity,
so can peripheral PbPb and high-mult pPb be reconciled?



Rising and approaching R~1!

Is it a multiplicity bias?

Seemingly constant at around R~0.8

Model comparison

Hijing:

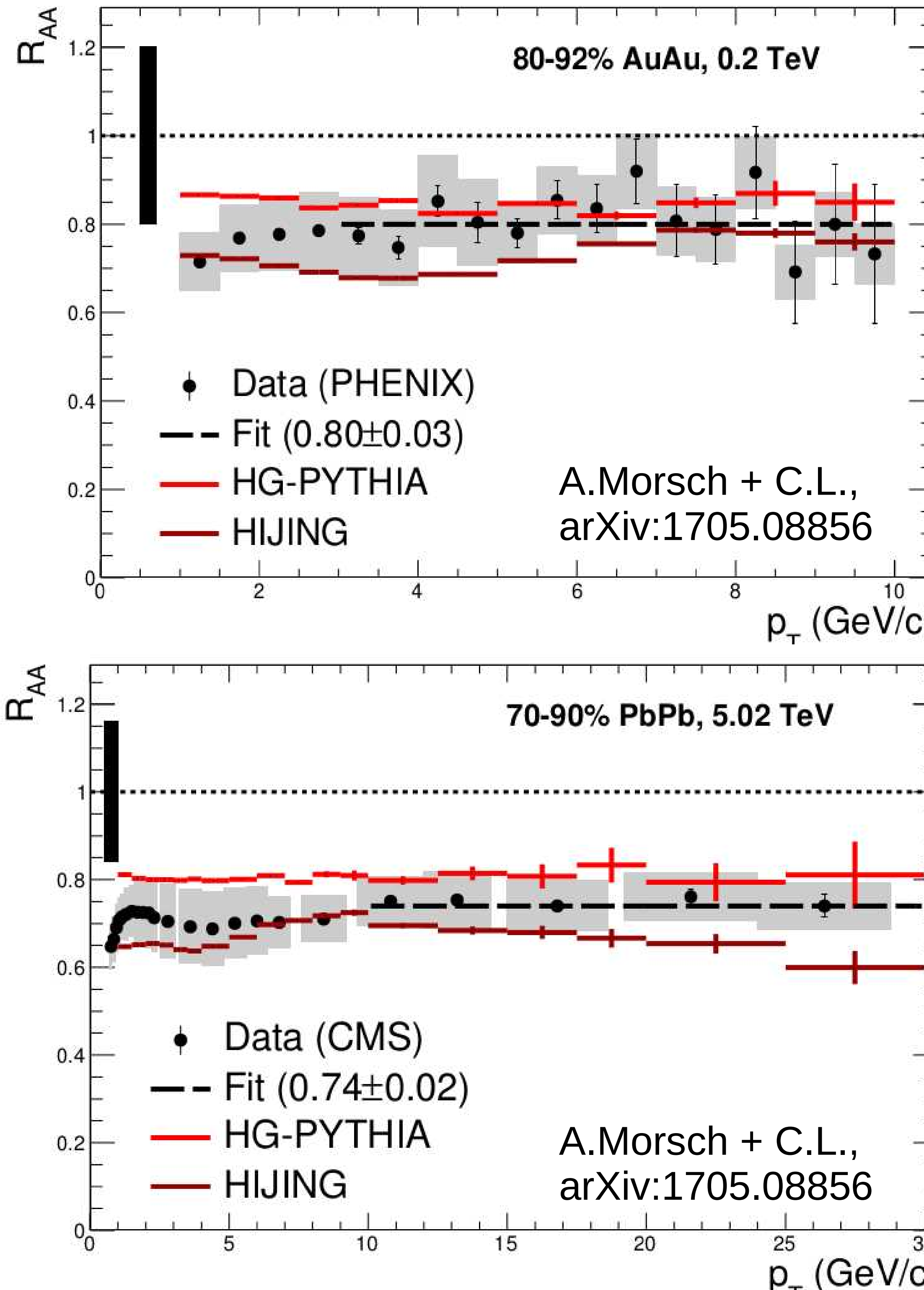
- No quenching, no shadowing, but ad-hoc momentum conservation and multiple scattering
- Does not give $R_{AA} \rightarrow 1$ at high p_T for central collisions

HG-Pythia:

- Use as HIJING nhard distribution (with Eikonal ansatz) as input to superimpose PYTHIA (Perugia 2011) events
- Does not reproduce multiplicity

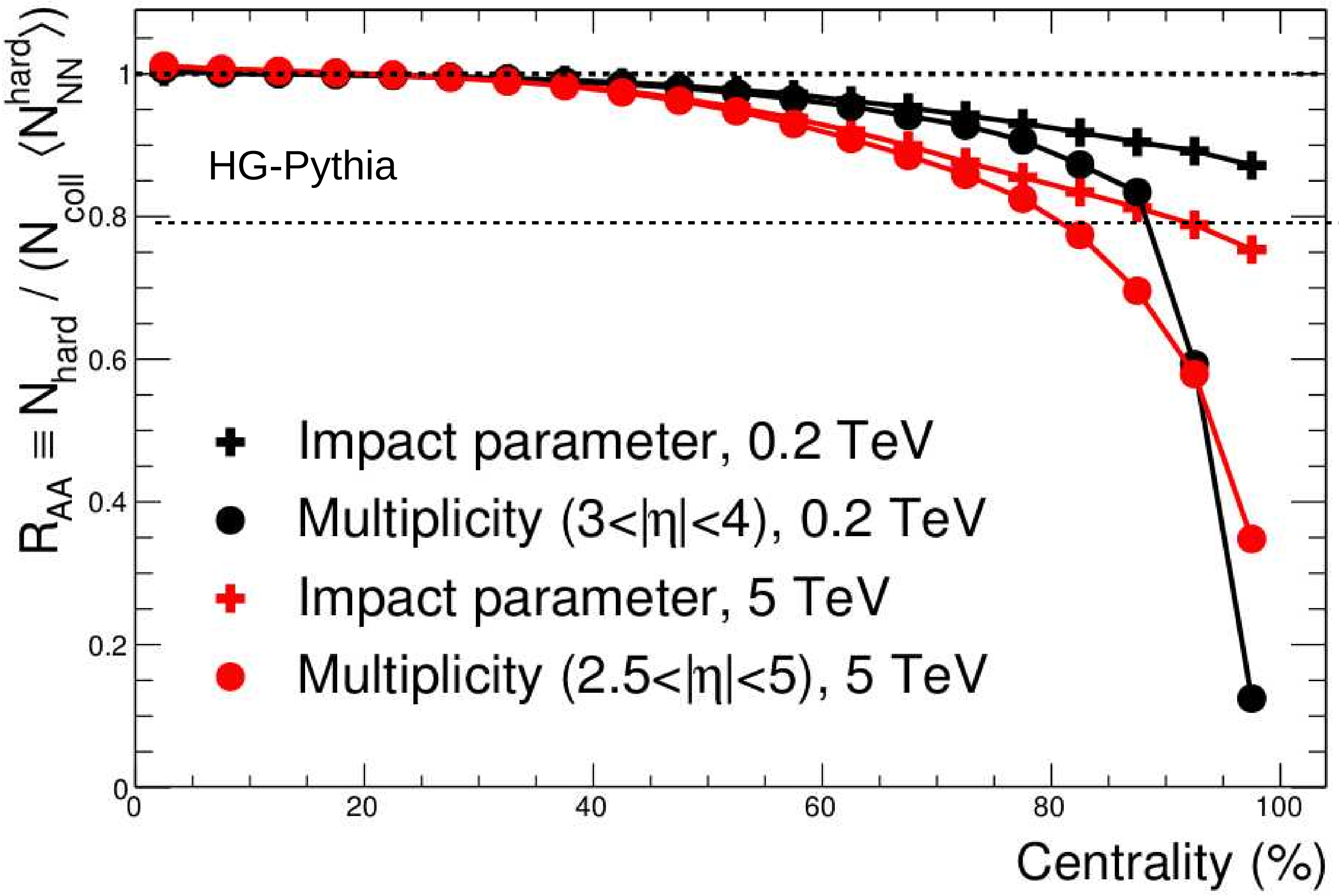
Results obtained using event ordering (slicing) for forward multiplicity as was done for the data

Multiplicity bias can cause the apparent suppression!



Multiplicity and geometry bias effect

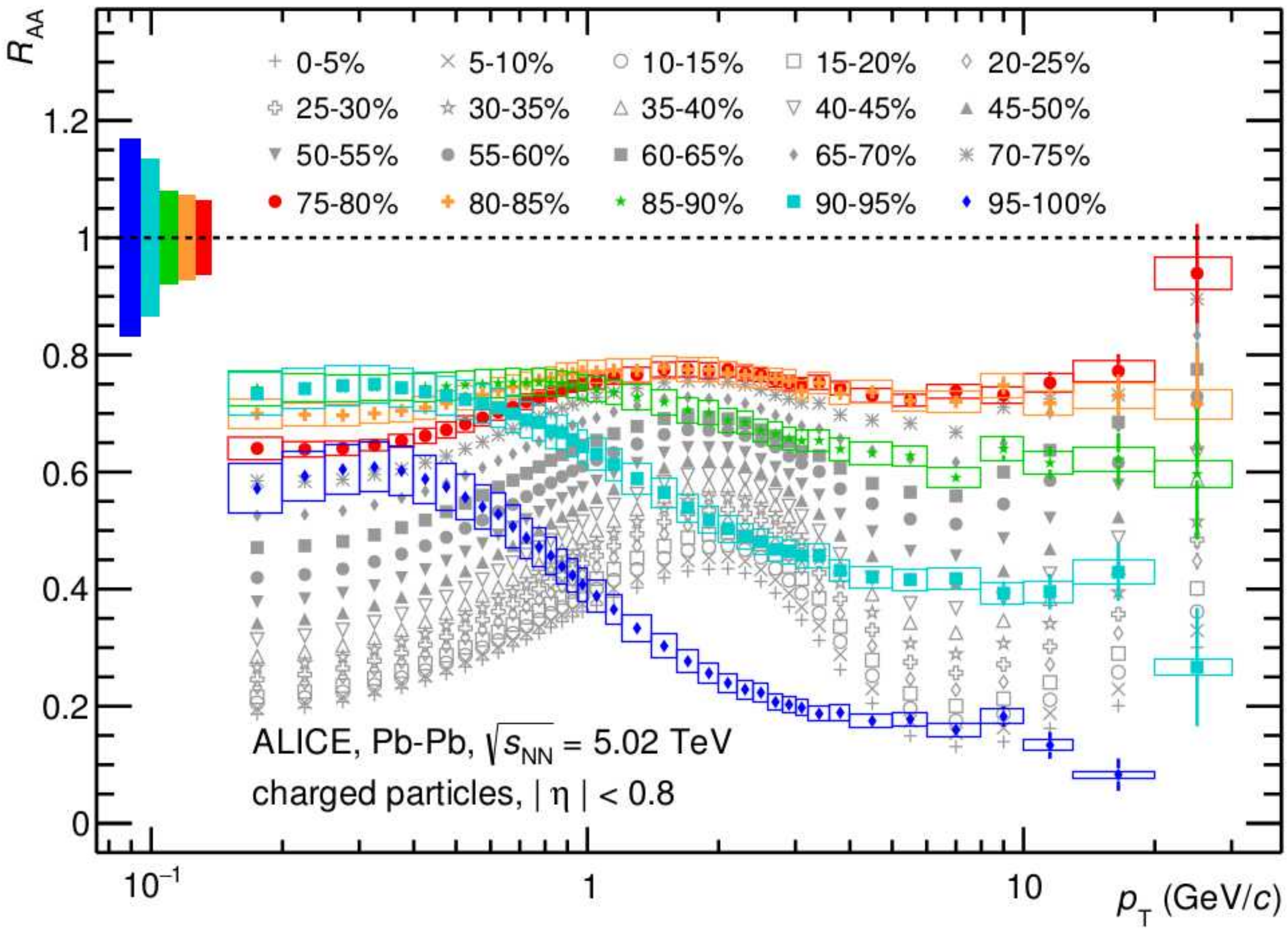
A.Morsch + C.L.,
arXiv:1705.08856

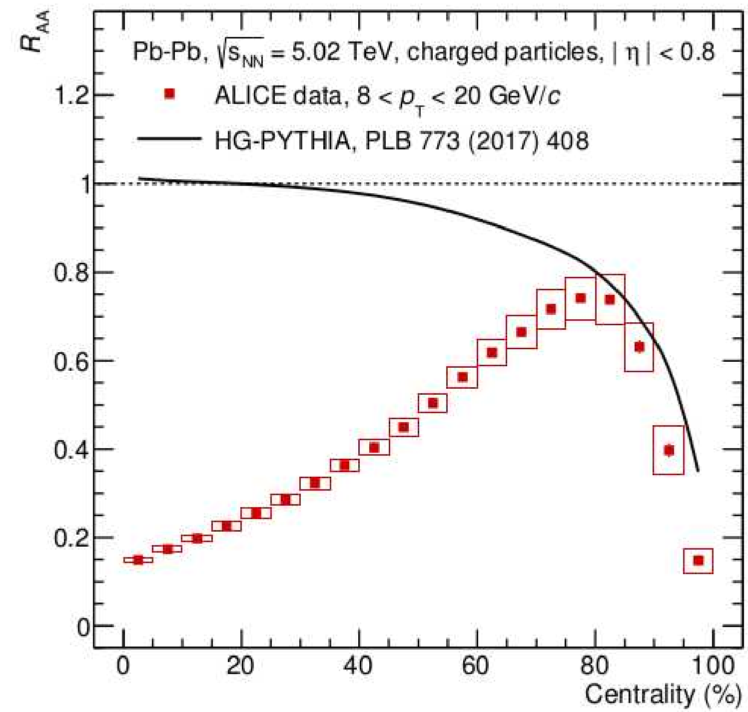


Peripheral collisions strongly affected by multiplicity bias

R_{AA} with focus on peripheral collisions

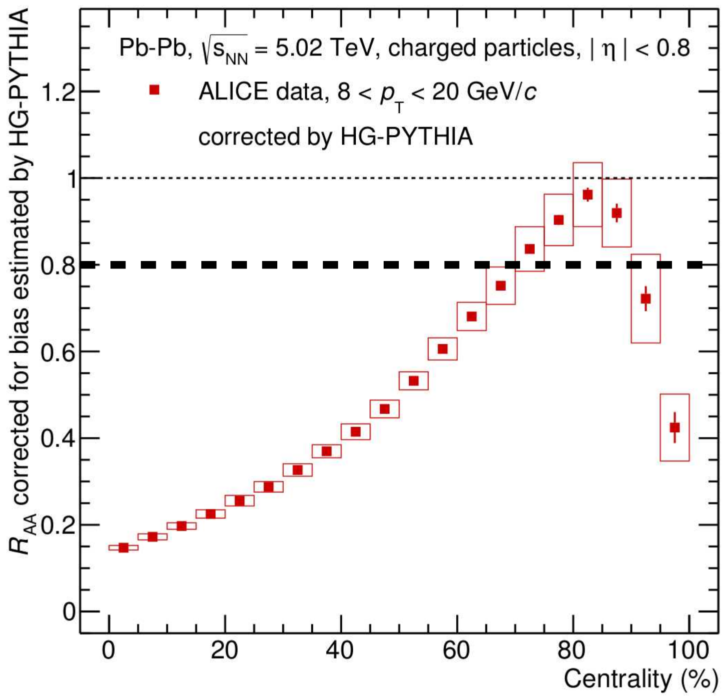
ALICE, arXiv:1805.05212



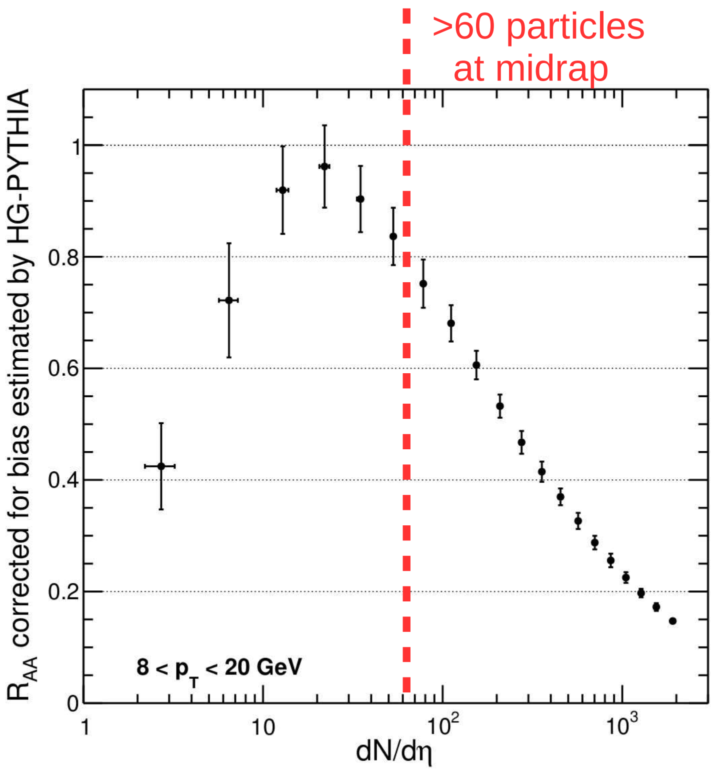


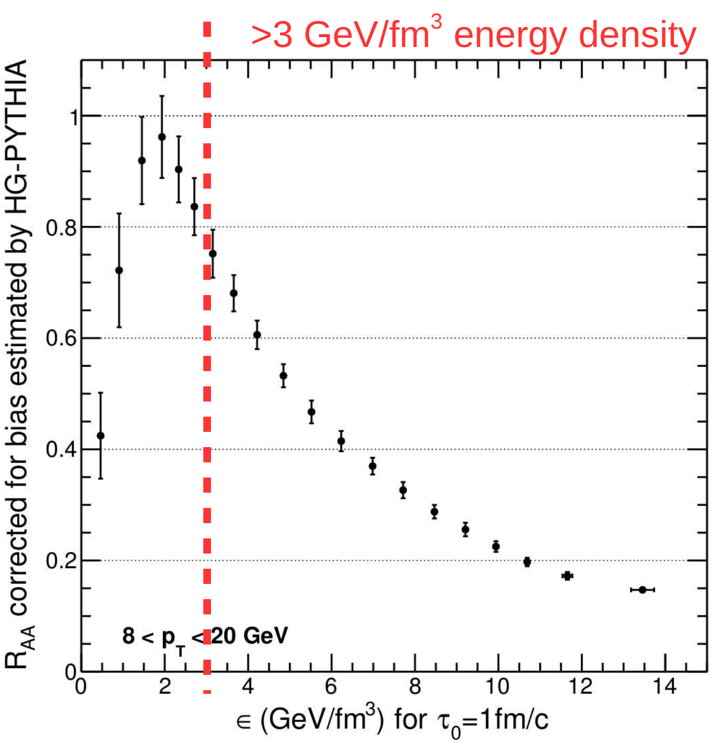
- Rigorous attempt to measure R_{AA} in 5% centrality bins
  - Most peripheral bin quite challenging (diffraction, EM interactions)
  - Consistent treatment: Ncoll(b) → Ncoll(V0M); relevant > 75% peripheral
- Observed spectra in peripheral bins exhibit similar bias as seen in pPb
- Integrated high p_T R_{AA} consistent with expectation from HG-PYTHIA

R_{AA} "corrected" by bias



65-70% centrality
~20% suppression

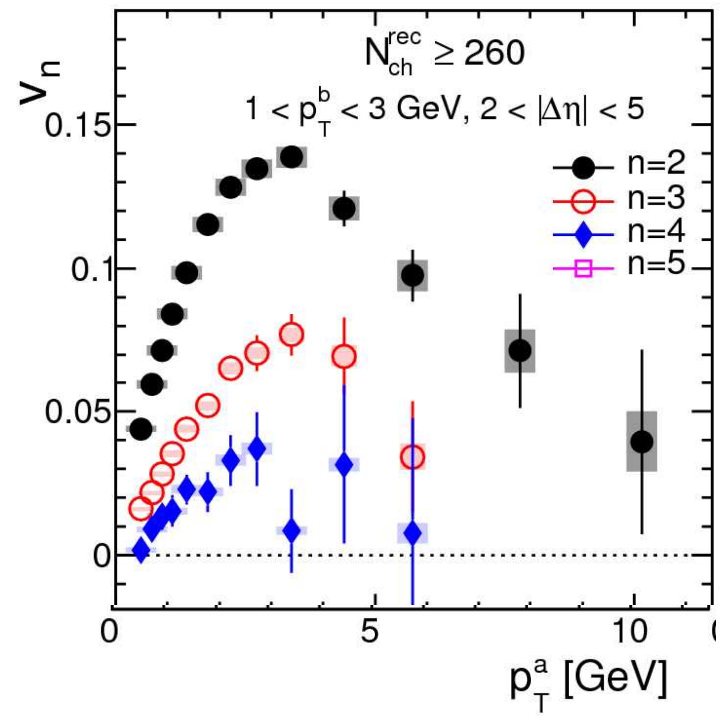


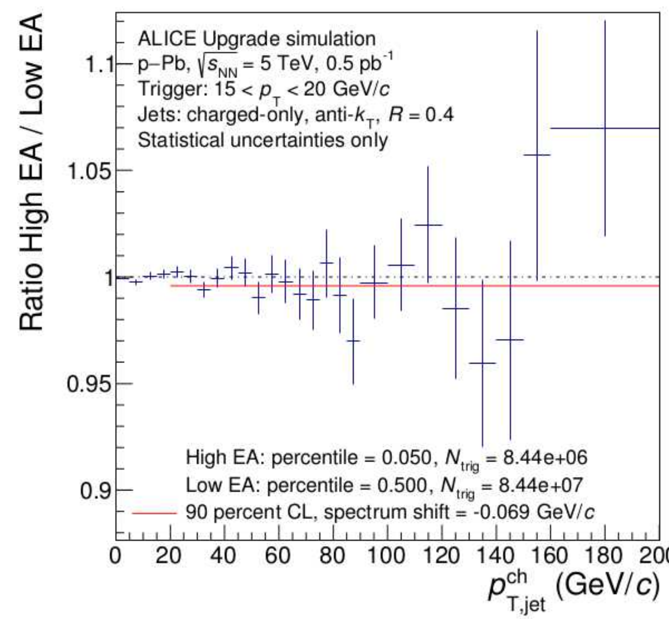


- PbPb collision exhibit 20% suppression at 65-70% centrality
  - Higher than 0-5% pPb mult interval usually explored by ALICE
  - Corresponds roughly to Ntrack ~200 region of ATLAS/CMS (~0.5‰)
- For spectra measurements in pPb would need to compare to particle production model

Model independent measurements

- Particle production (and geometry model) independent measurements
  - Measure vN in pPb (and peripheral PbPb) with high precision to high pT
    - Would be good to get predictions at ~10-20 GeV from parton energy loss
  - Semi-inclusive measurements
    - TAB cancels
  - Candle (cross section) measurements in pA and peripheral AA
    - Statistics limited (needs photon or Z as candle)

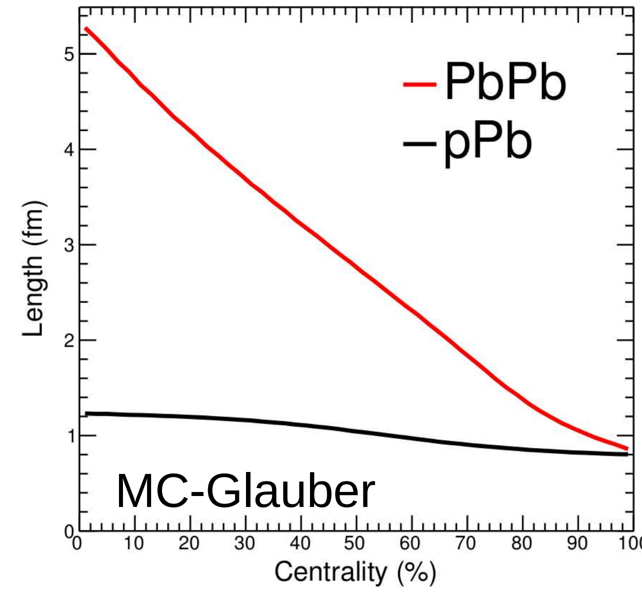




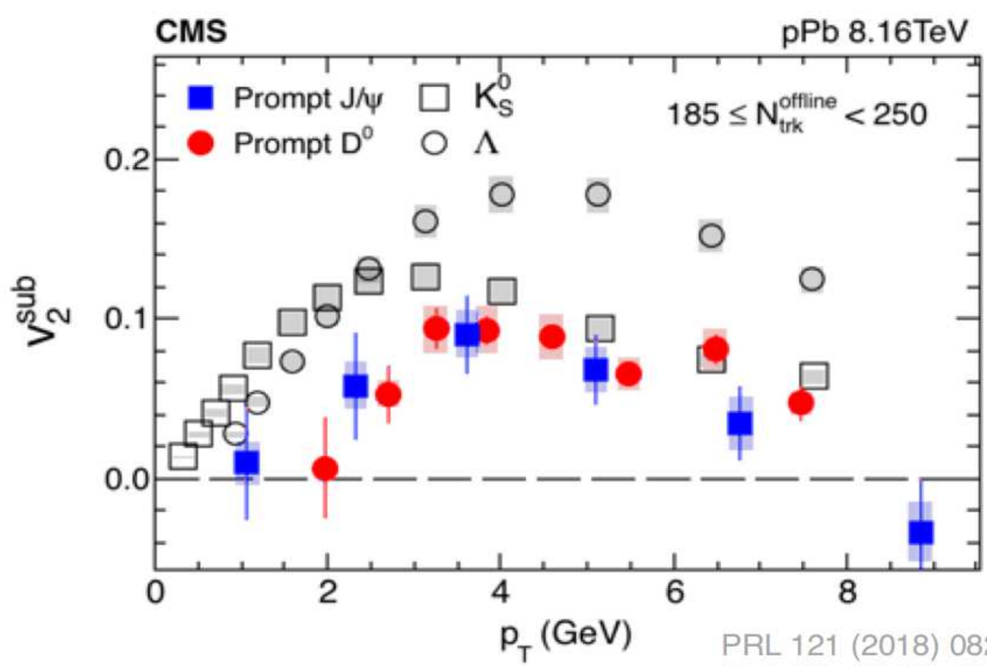
For run3/4 projections see arXiv:1812.06772

What if no parton energy loss?

- Small system, hard probe does not “probe the medium”?
  - Path lengths in MC Glauber for pPb <50% than in 65-70% PbPb



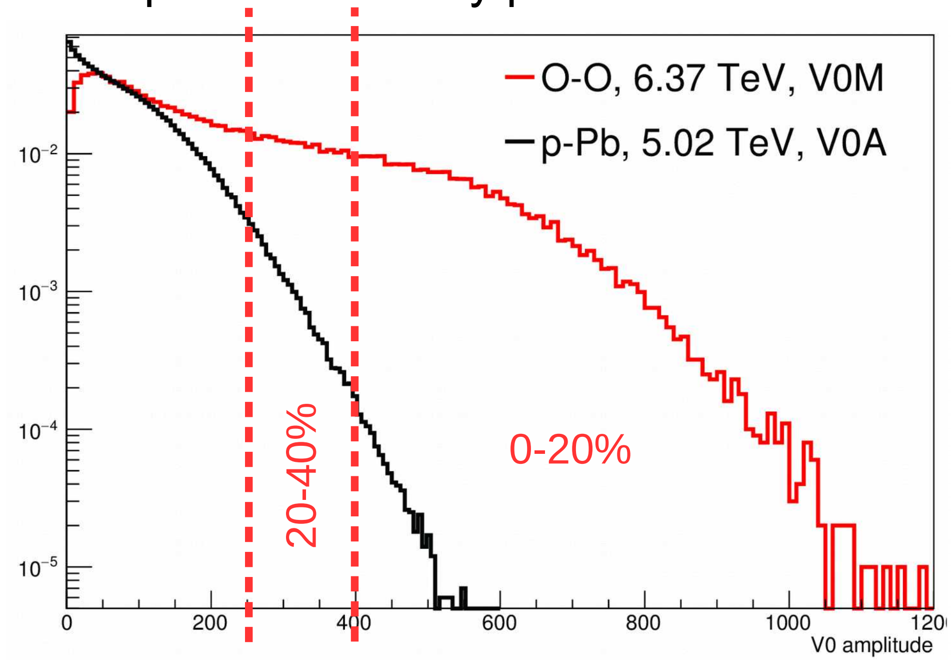
- How does the heavy flavor v_2 fit this picture?
  - In PbPb the idea is that HQ are dragged with the matter
  - In pPb there is quite large HQ anisotropy, so despite small system enough time to drag the HQ?
    - But still no parton energy loss? Puzzle



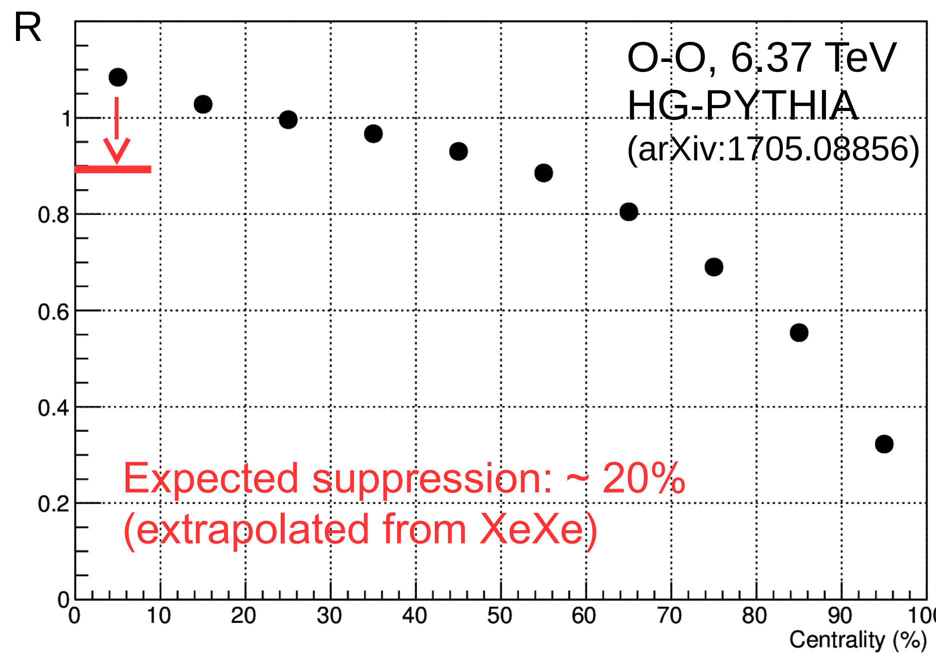
PRL 121 (2018) 082301
PLB 791 (2019) 172

Small nuclei to study onset of jet quenching

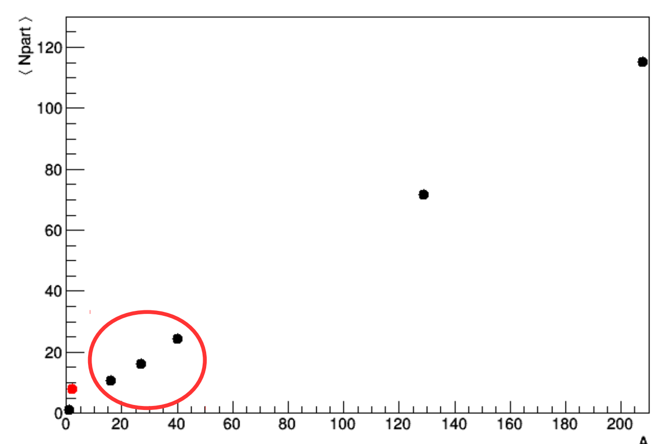
Expected centrality plateau



Expected centrality bias on R_{AA}



- Centrality shoulder allowing selection of geometry (Ncoll and ε_2)
  - Clear advantage over asymmetric system (pA, or others)
- System just large enough to exhibit jet quenching
  - Measure also minbias OO, Ncoll~13
- System scan (OO,AlAl,ArAr)
  - Only OO feasible at LHC, but maybe scan at RHIC?
  - For LHC, integrated luminosity ~500/µb enough for low pT charm and photons



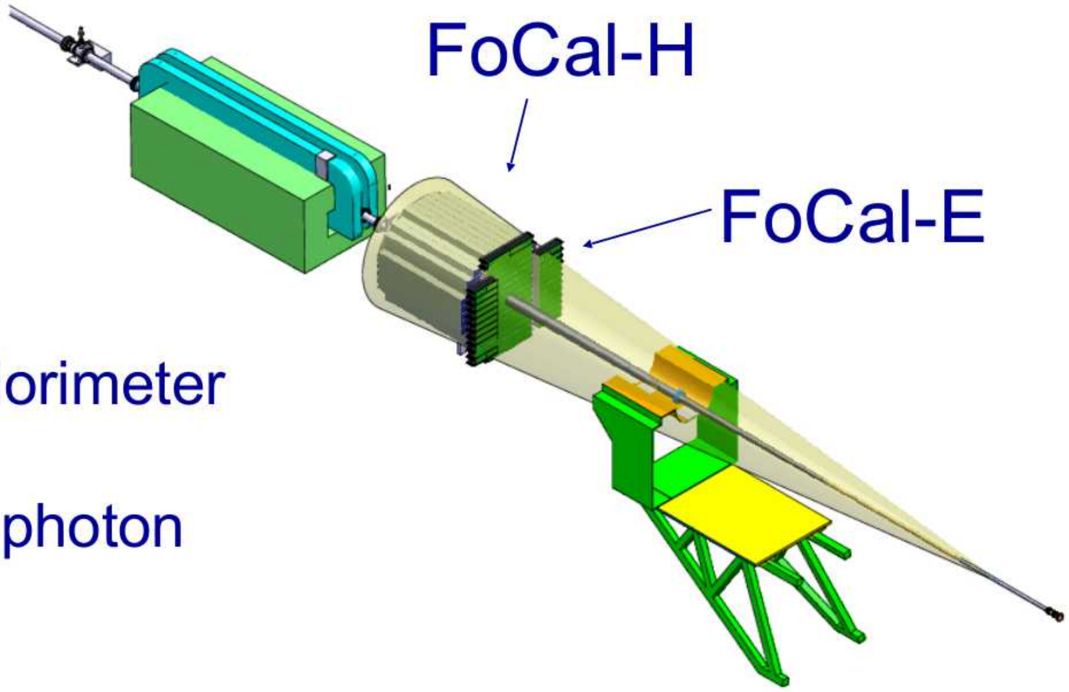
Part II:

The FOCAL proposal and small-x physics at the LHC

The FOCAL proposal

(under discussion within ALICE and DOE)

Acceptance ~3<η<~6



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

FoCal-H: hadronic calorimeter for photon isolation and jets

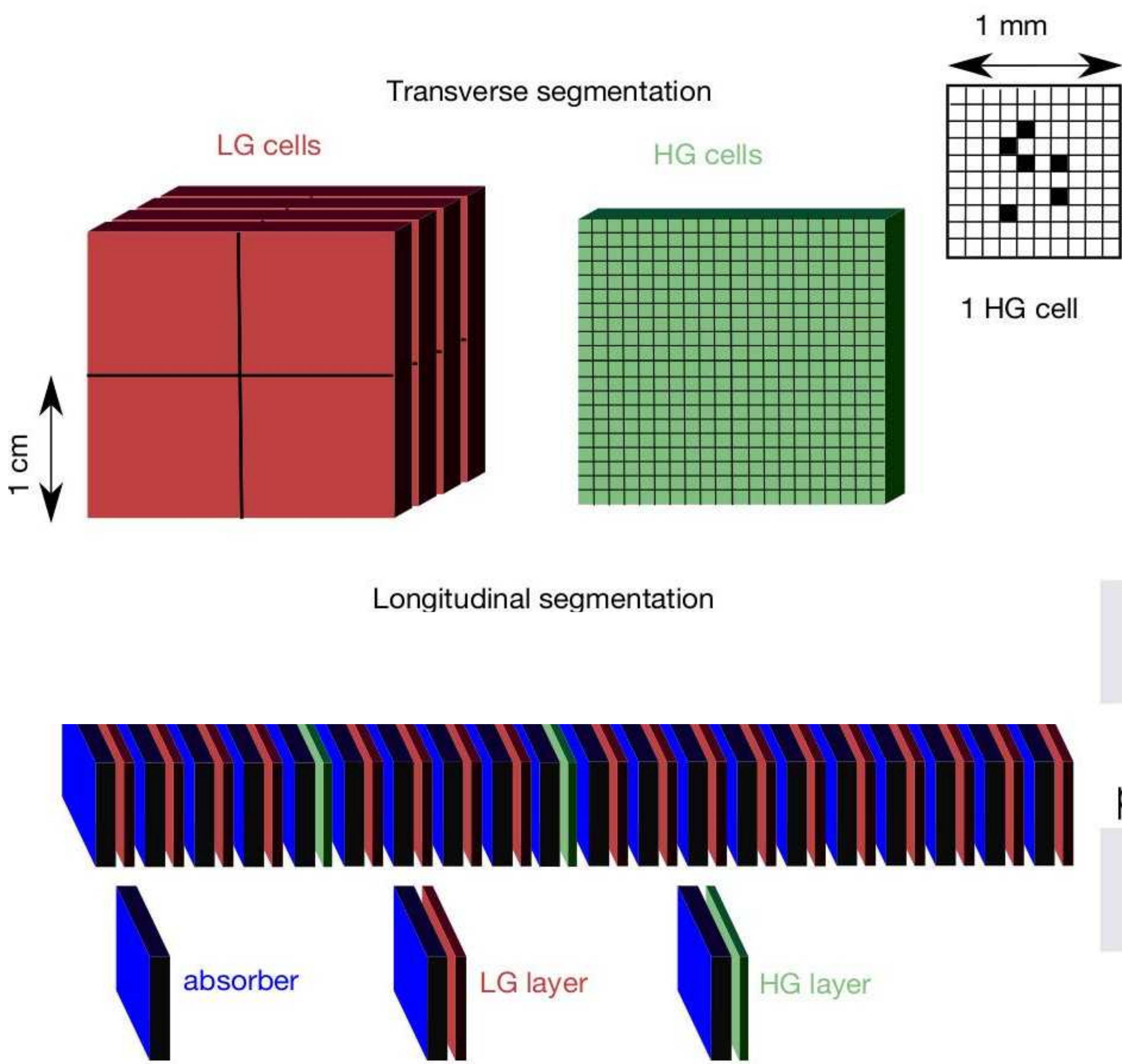
Observables:

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

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

Main challenge: Two-photon separation from neutral pion decays (~2mm at 10 GeV, y=4.5)

Design of FoCal-E



studied in performance simulations:

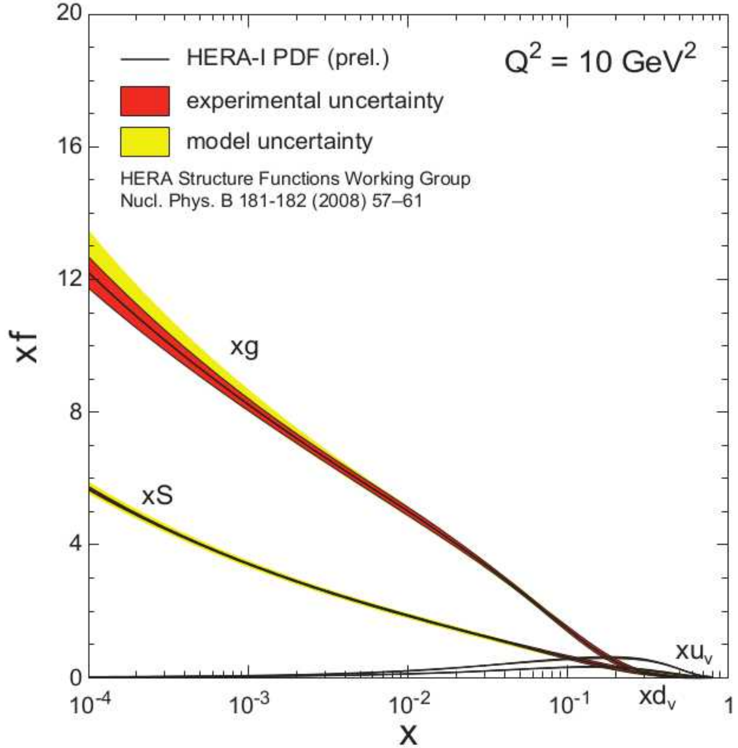
20 layers: W (3.5mm ≈ 1 X_0) + Si-sensors (2 types)
low granularity (LG), Si-pads
high granularity (HG), pixels
(e.g. CMOS-MAPS)

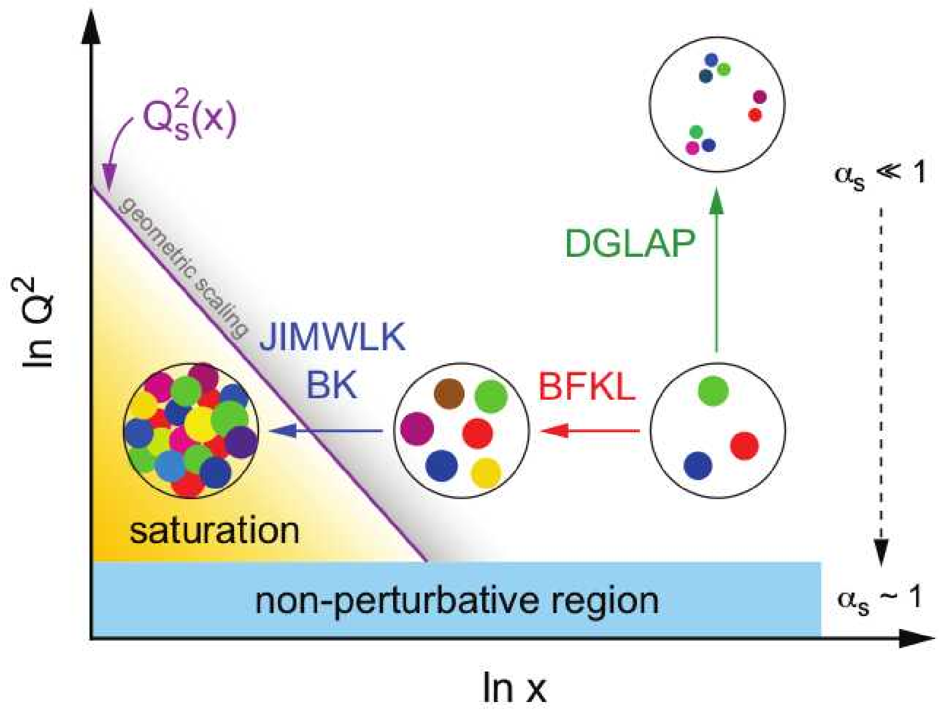
	LG	HG
pixel/pad size	≈ 1 cm^2	≈ 30x30 μm^2
total # pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9
readout channels	≈ 5 x 10^4	≈ 2 x 10^6

assuming ≈ 1m^2 detector surface

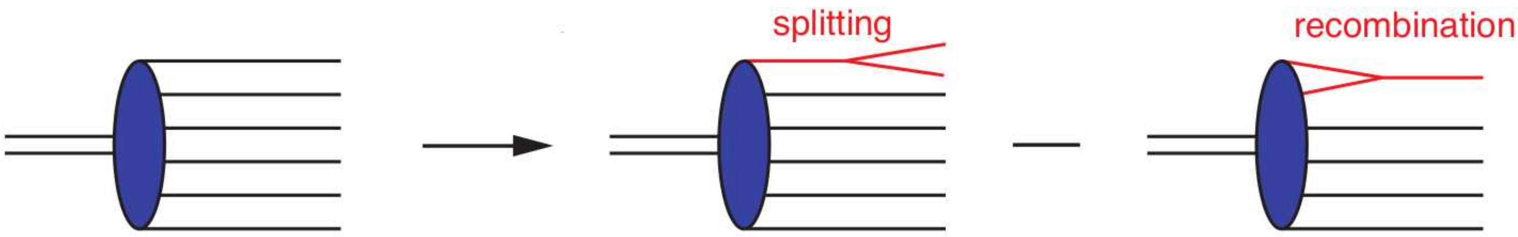
- Main design questions:
  - What should be the distance between layers → affects Moliere radius
  - Sizes of pads and pixels (and layer locations) → determines 2 photon shower discrimination

Physics motiviation: Gluon PDFs at low x

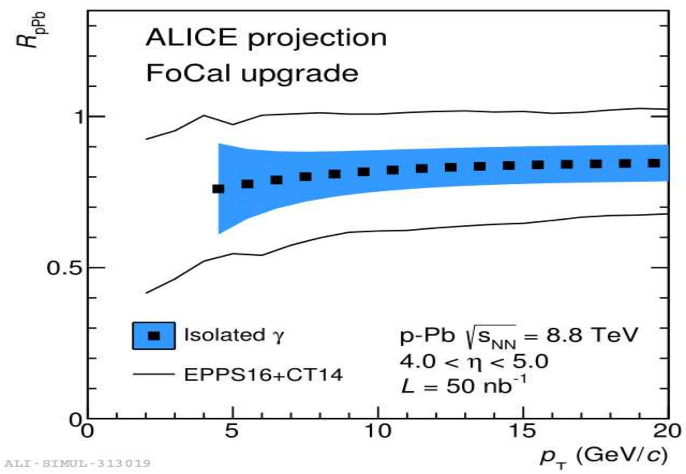


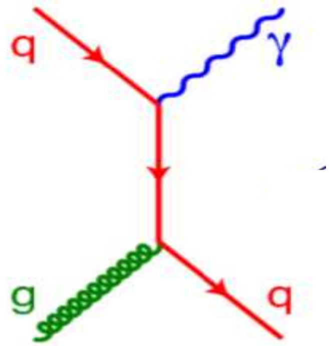


- Gluons dominate PDFs at small-x (<0.1)
  - Rapid rise in gluons naturally described by linear pQCD evolution
  - The rise can not be forever due to limits on cross section (unitarity)
  - Non-linear pQCD evolution equations tame this growth, leading to saturation of gluons, characterized by the saturation scale, $Q^2_s(x)$

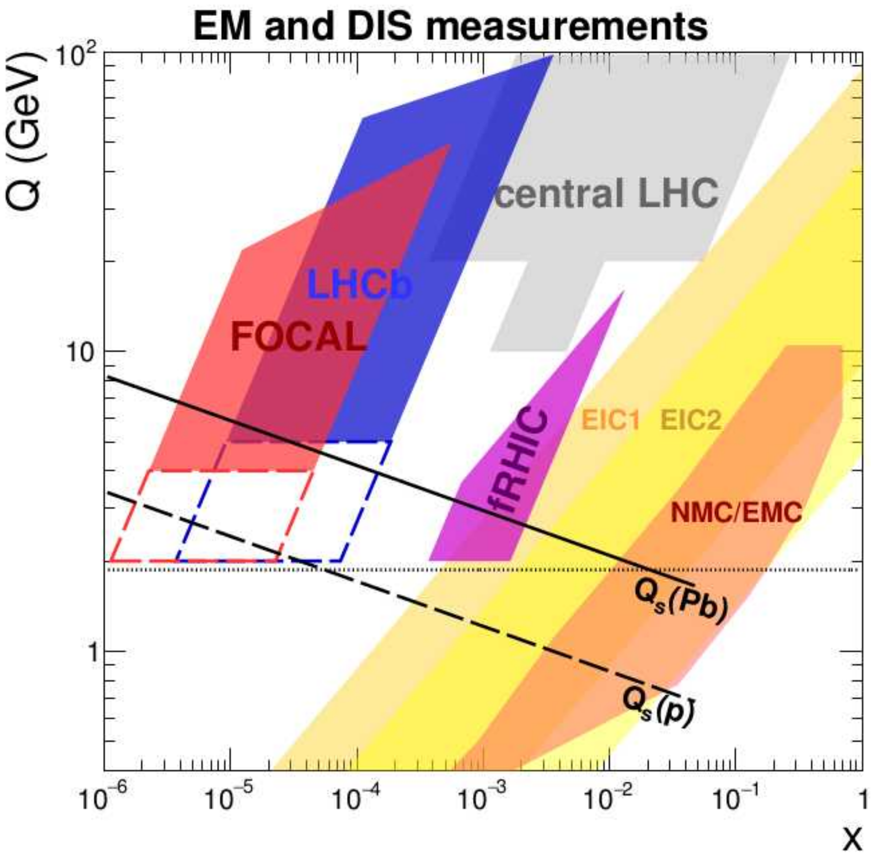


Physics motiviation: Gluon PDFs at low x





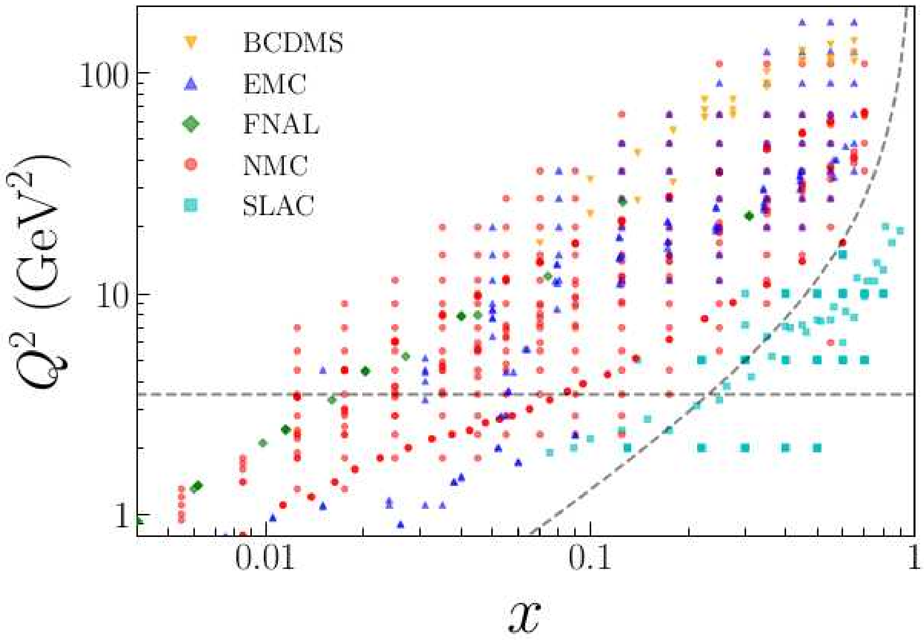
Direct-γ (LO)

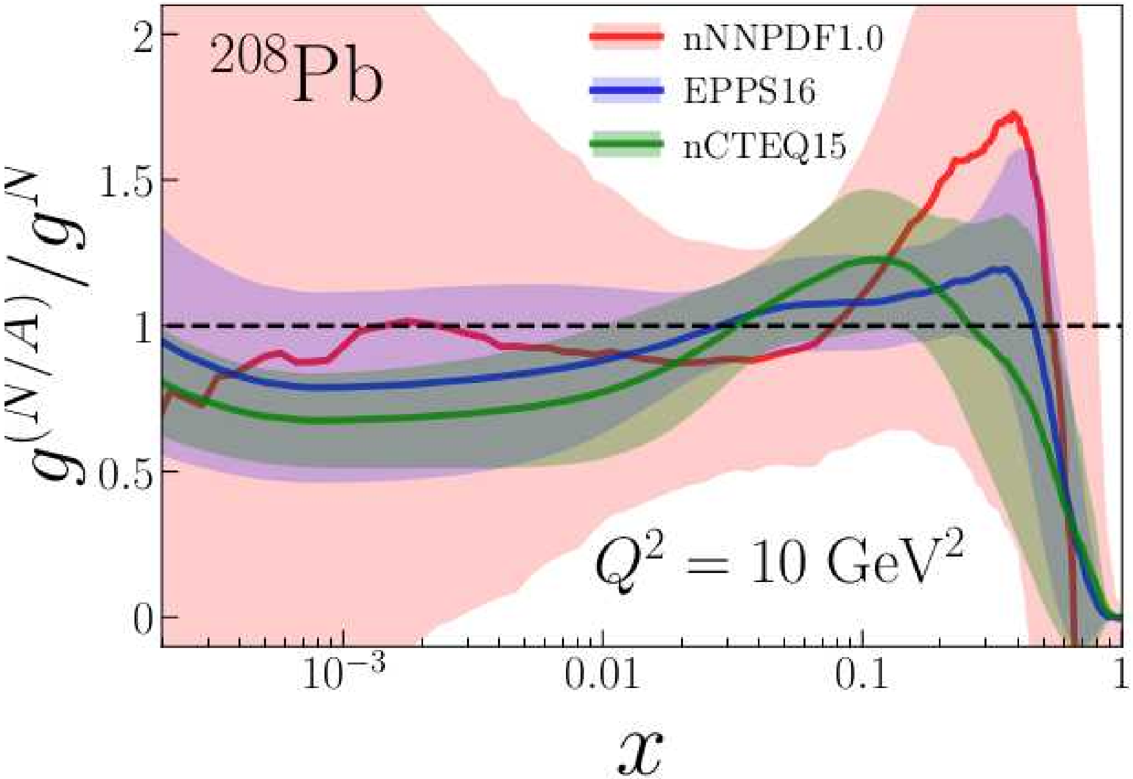


- Measure direct photons forward
  - At LO direct sensitivity to gluons
  - No final state effects or hadronization
  - Uniquely low-x coverage
- Access gluon saturation region to
  1) Prove or refute gluon saturation
  2) Explore non-linear QCD evolution at small-x
  3) Constrain nuclear PDFs at very small x

Current knowledge of nuclear PDFs

nNNPDF1.0,Khalek et al. arXiv:1904.00018

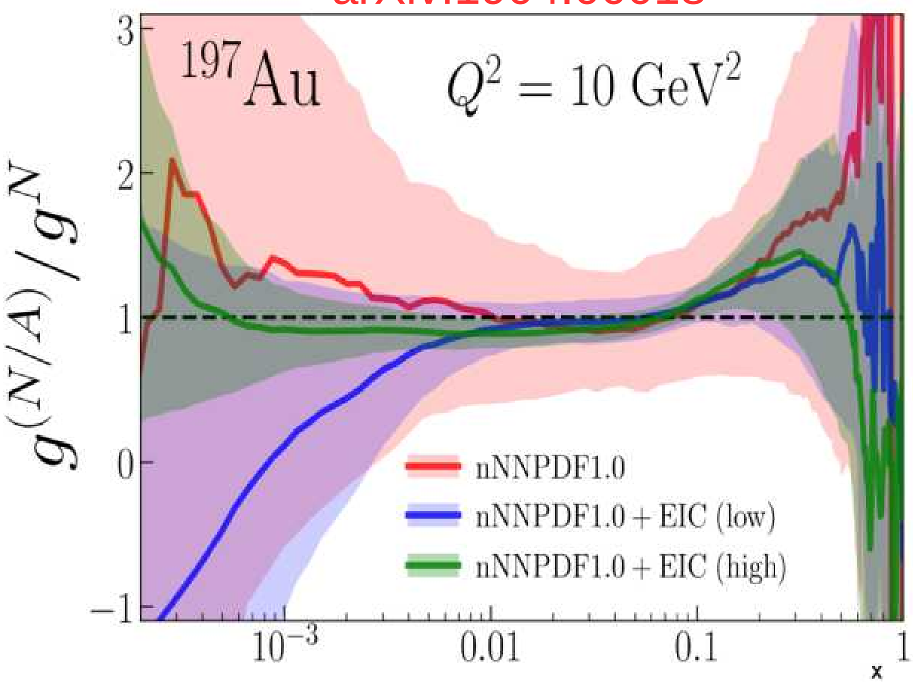




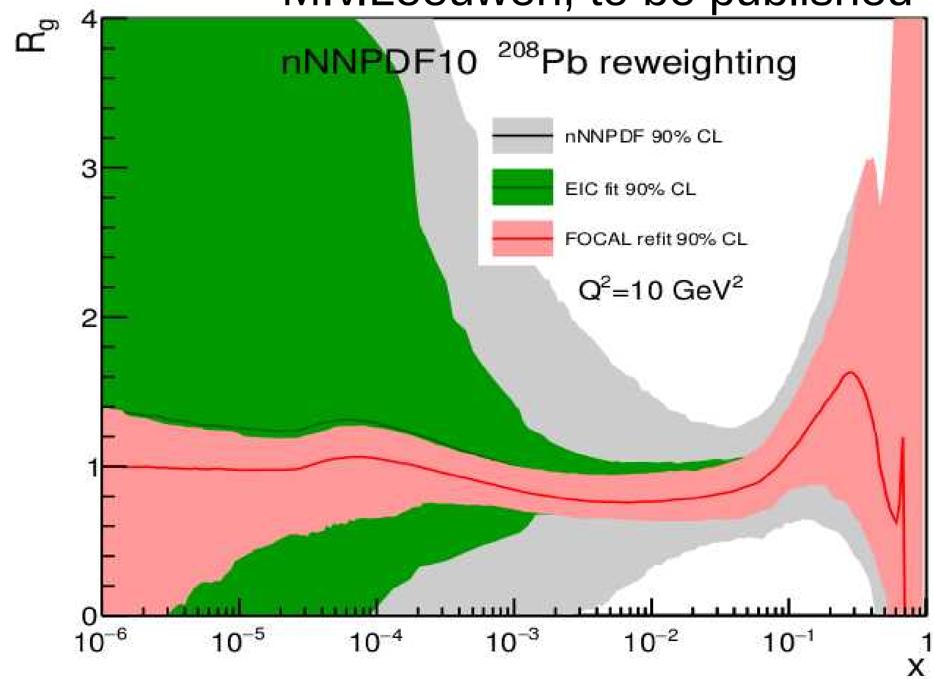
- Input to DIS from nucleus-lepton scattering
  - Additionally, EPPS16 and nCTEQ15 include W,Z,dijets and light hadron data from RHIC
- Limited datasets lead to large uncertainty at small x (and Q)
  - Smaller (but model dependent) uncertainty of EPPS16 since they assume the PDF to be constant at small x

Improvement with EIC and FOCAL

arXiv:1904.00018

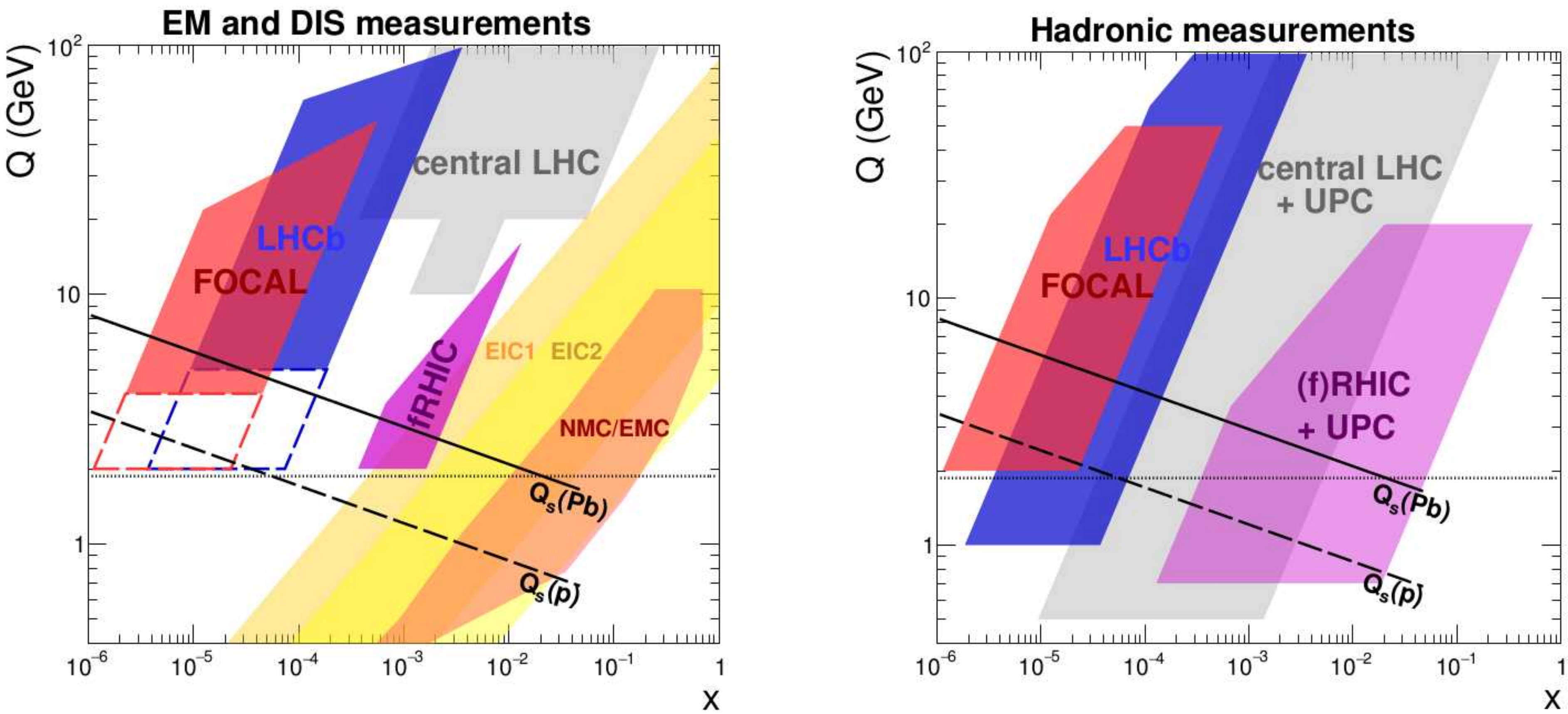


M.v.Leeuwen, to be published



- Including EIC and FOCAL pseudodata demonstrate the ability to significant constrain nPDFs and reduce the uncertainty
  - For EIC in the region up to x~0.005 as expected
    - At EIC, in addition one will be able to study dependence vs A
  - For FOCAL the lower region up to few 10^{-5} will be constrained

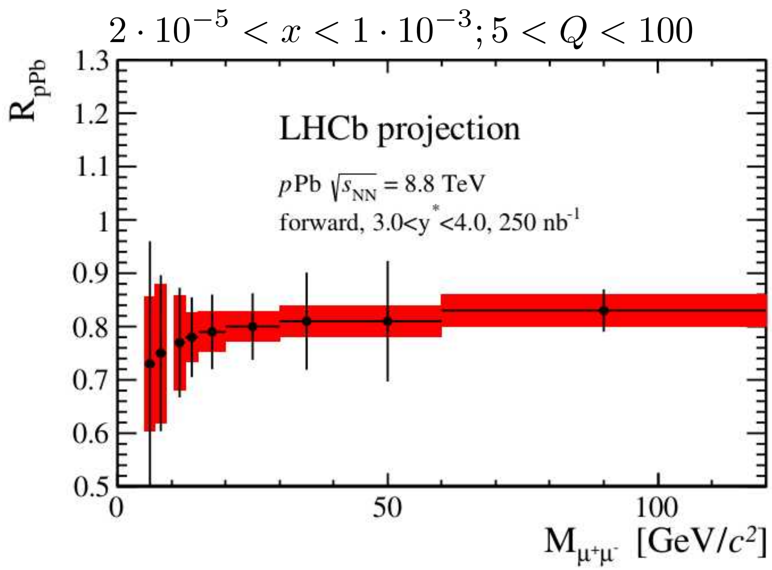
Coverage for small-x measurements

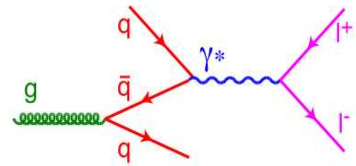


- Logarithmic dependence of QCD evolution on x and Q
- Requires many measurements over largest possible range to find change from linear evolution
  - Forward LHC: FOCAL and MFT/ALICE (photons,pi0,DY), LHCb(photons,DY,charm,hadrons)
  - Forward RHIC (photons,DY, see arXiv:1602.03922)
  - UPC (J/psi, dijets, see arXiv:1812.06772)
  - EIC

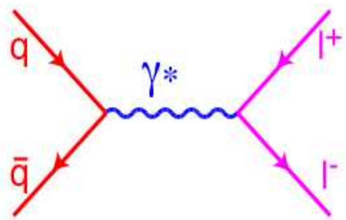
LHCb run-3/4 projections

LHCb-CONF-2018-005

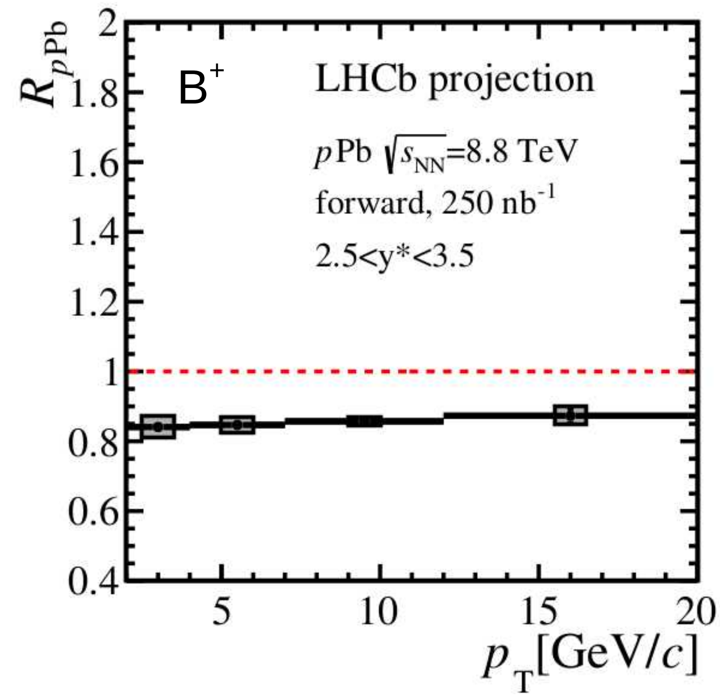




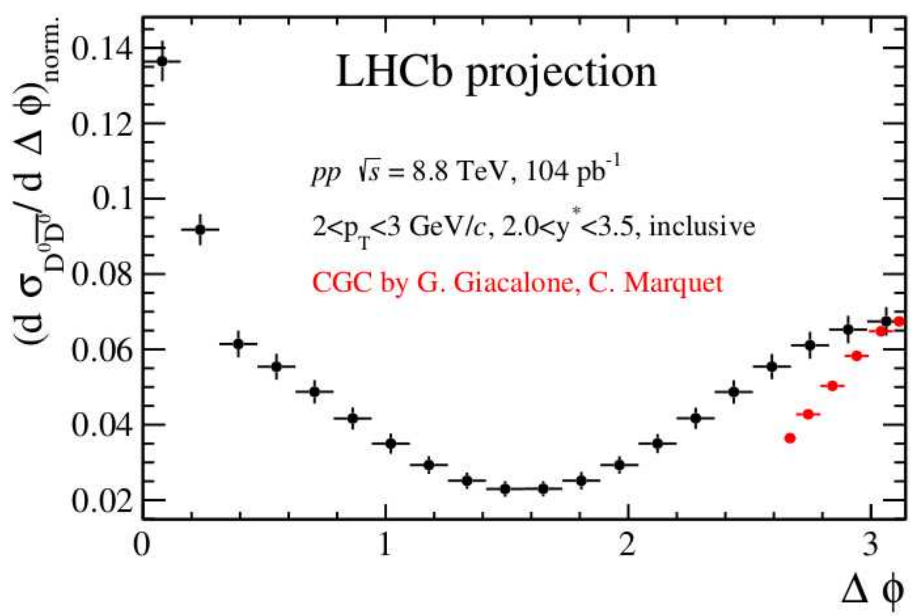
DY, virtual Compton (NLO)



DY (LO)



- DY forward (and backward)
  - Sensitive to gluons only at NLO
- In addition to D^0 production, measure D^0D^0 correlations
- Precision measurements of B^+
  - Advantage higher scale for calculation (but also higher x)



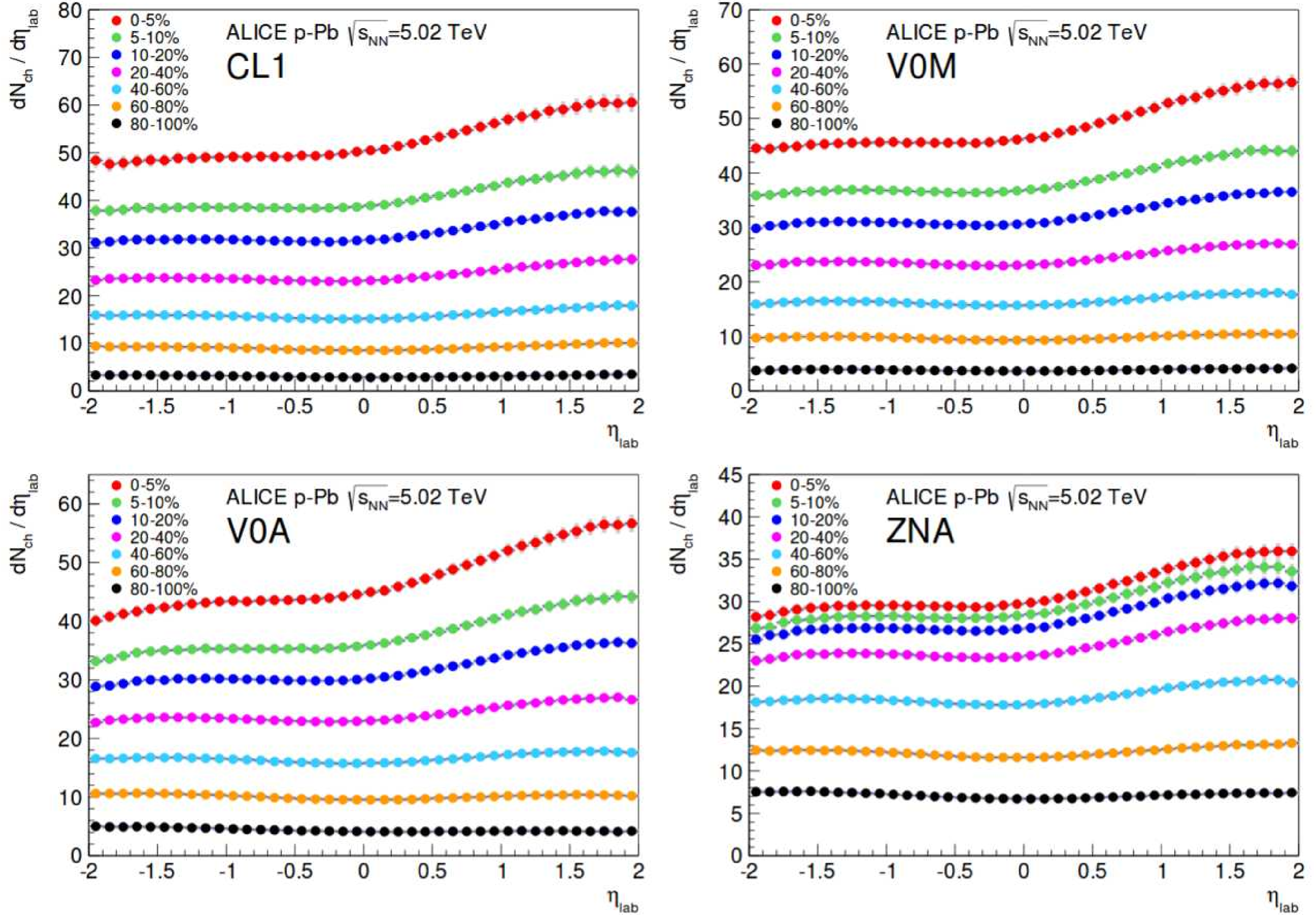
Summary

- Part I: Parton energy loss in small systems?
  - Similar fluctuations in particle production in pPb and peripheral PbPb qualitatively consistent with simple Glauber-based MPI model
  - Indicates little energy loss in both for >5% pPb and >70% PbPb
  - Self-normalized measurements in high multiplicity pPb (<5‰) but lifetime/system size may be too small to exhibit parton energy loss
    - How does observed HQ v2 fit in the picture?
  - Small nuclei exhibit centrality plateau, which is more efficient to study onset of parton energy loss
- Part II: The FOCAL proposal and small-x physics at the LHC
  - Proposal to build a forward calorimeter (FOCAL) covering $\sim 3 < \eta < \sim 6$ designed for isolated photon measurements
  - Together with LHCb, fRHIC and UPC at RHIC/LHC constitute a strong small-x program, well before the advent of the EIC
  - EIC will allow for controlled measurements in small-x region

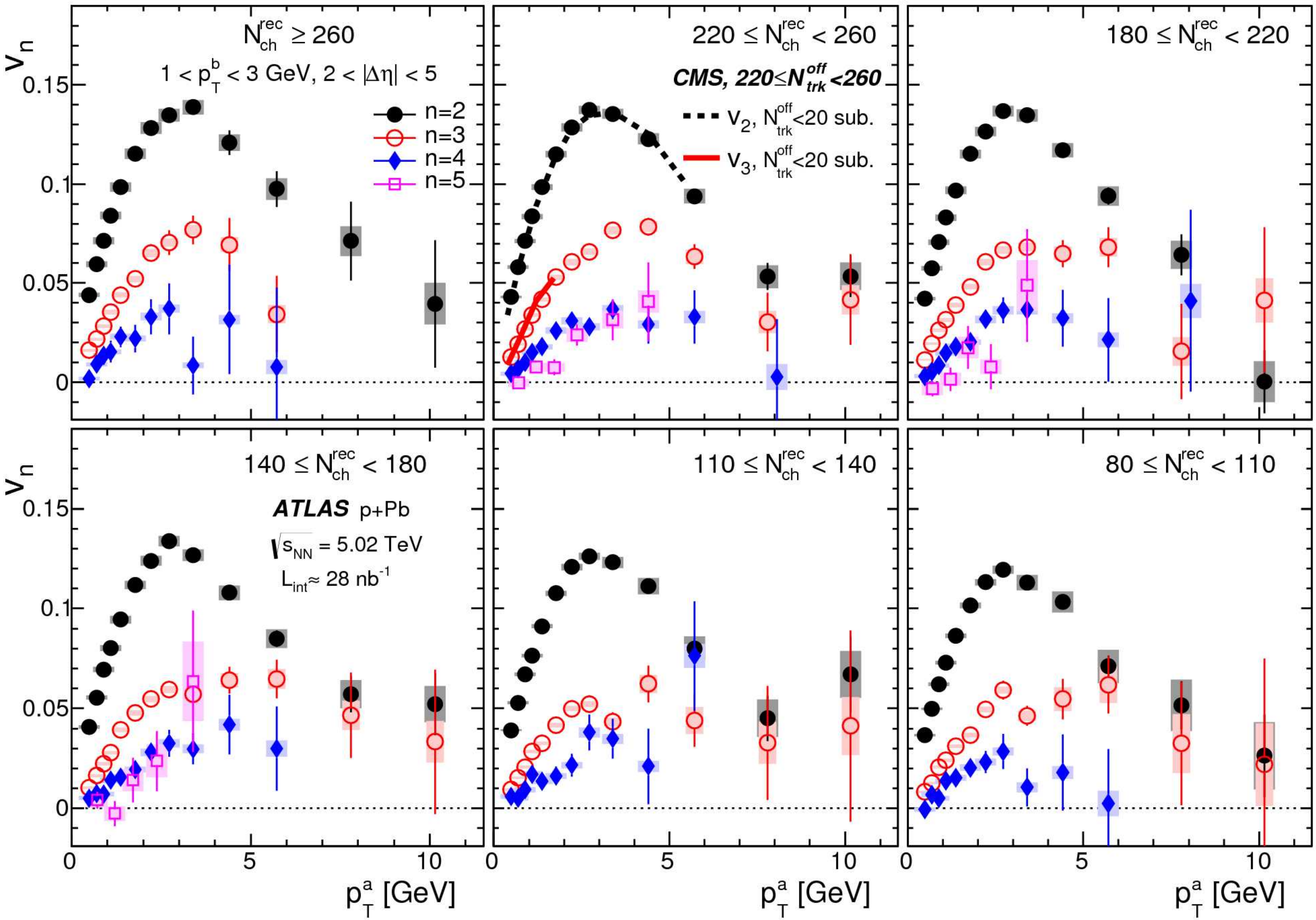
Extra

Midrapidity density for different estimators

ALICE, PRC 91 (2015) 064905



ATLAS, PRC 90 (2014) 044906



Multiple parton interactions (MPI)

- Naive factorization

$$\langle n_{2\to 2}\rangle = \frac{\sigma_{2\to 2}}{\sigma_{\rm tot}}$$

>1 at pert. scale

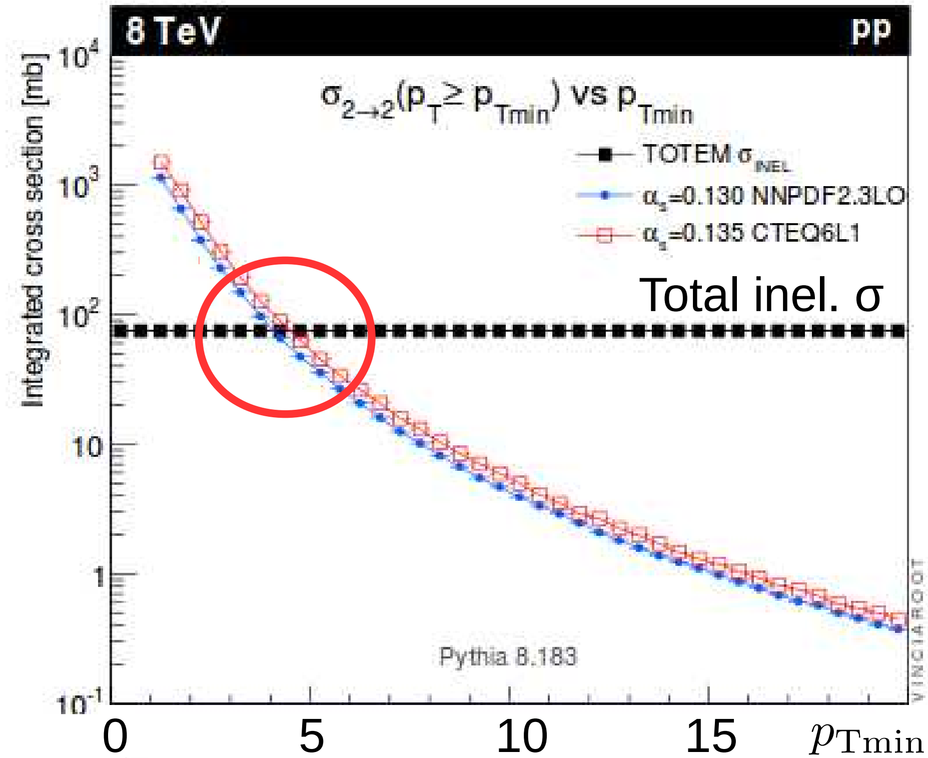
$$P_n = \frac{\langle n_{2\to 2}\rangle^n}{n!} exp\left(-\langle n_{2\to 2}\rangle\right)$$

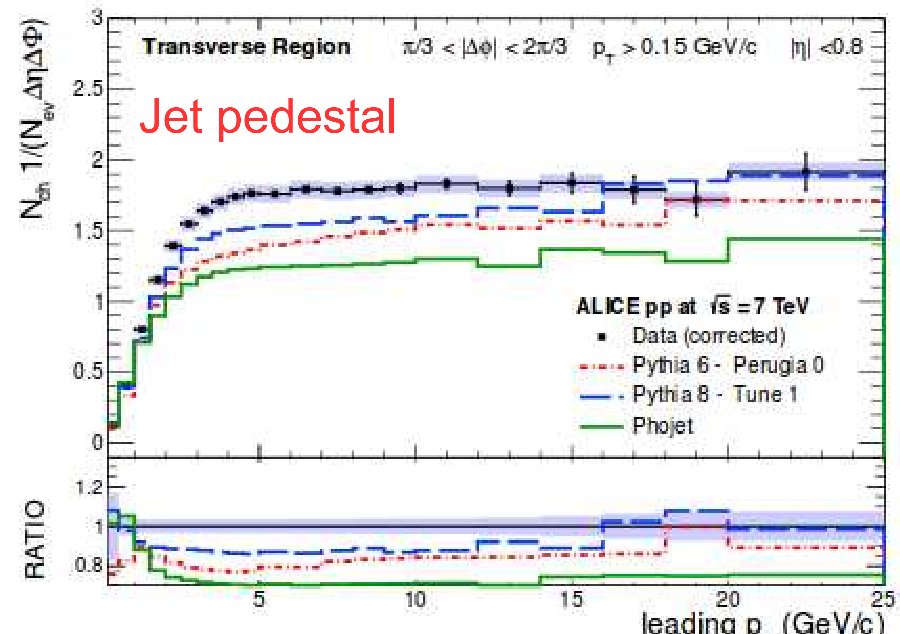
- Realistic models (eg. PYTHIA)
  - Color screening to regularize hard cross section at low p_T
  - Cut-off at high n because of energy conservation
  - Coherence between scatters
  - Impact parameter dependence

$$n_{\rm hard}(b) = \sigma_{\rm hard} T_{\rm p}(b)$$

    - Leads to a correlation between hard and soft particles as in AA

Skands, arXiv:1207.2389





Guidance from HIJING

PRD44 (1991) 3501

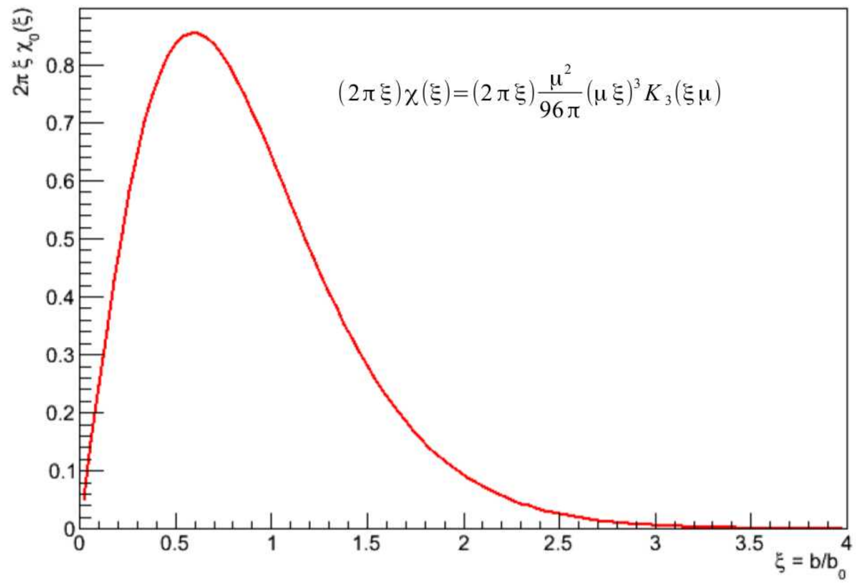
Inelasticic NN collision at b_{NN} given as

$$\sigma_{\mathrm{inel}} \propto 1 - e^{(\sigma_{\mathrm{soft}}+\sigma_{\mathrm{hard}})T_{\mathrm{N}}(b_{\mathrm{NN}})}$$

with nuclear overlap (Eikonal function)

$$T_{\mathrm{N}} \propto (\xi\mu)^3 K_3(\xi\mu) \ \text{ with } \xi = b_{\mathrm{NN}}/b_0$$

Eikonal function



Number of hard (mpi) collisions given by

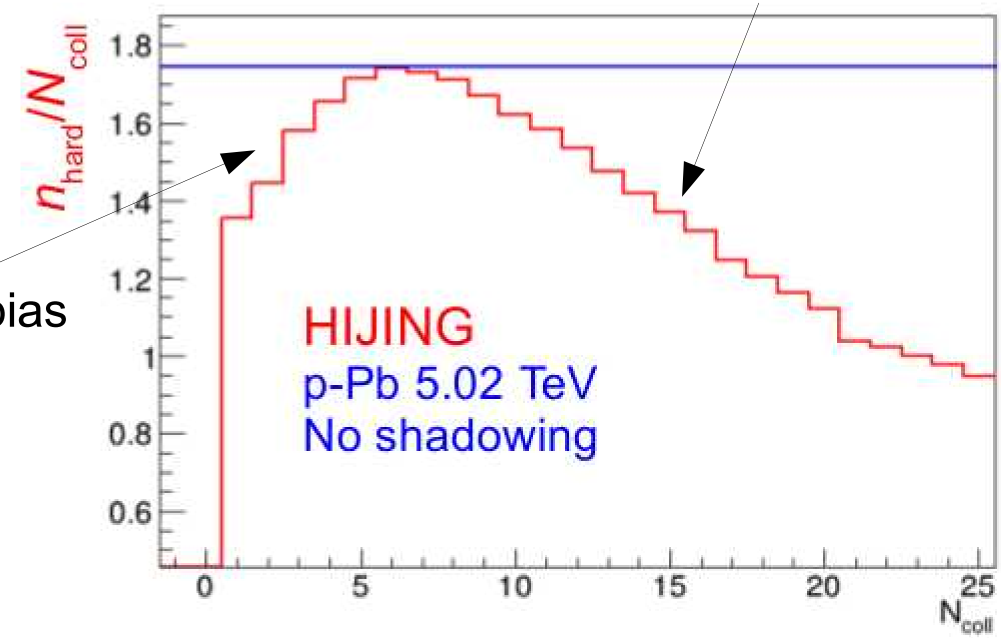
$$P(n_{\mathrm{hard}}) = \frac{\langle n_{\mathrm{hard}}\rangle^{n_{\mathrm{hard}}}}{n_{\mathrm{hard}}!} e^{-\langle n_{\mathrm{hard}}\rangle}$$

with

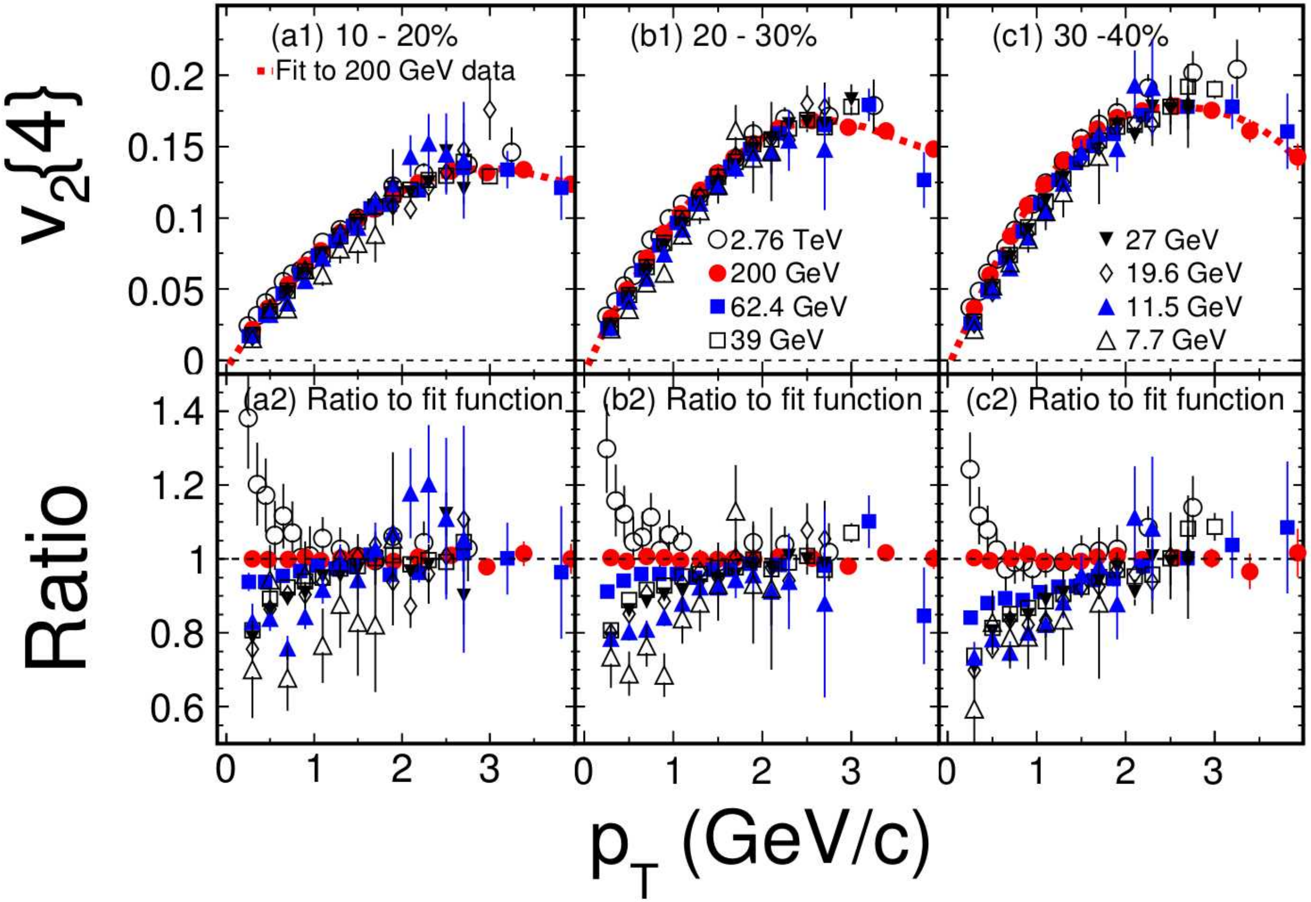
$$\langle n_{\mathrm{hard}}\rangle = \sigma_{\mathrm{hard}} T_{\mathrm{N}}$$

Energy-momentum conservation

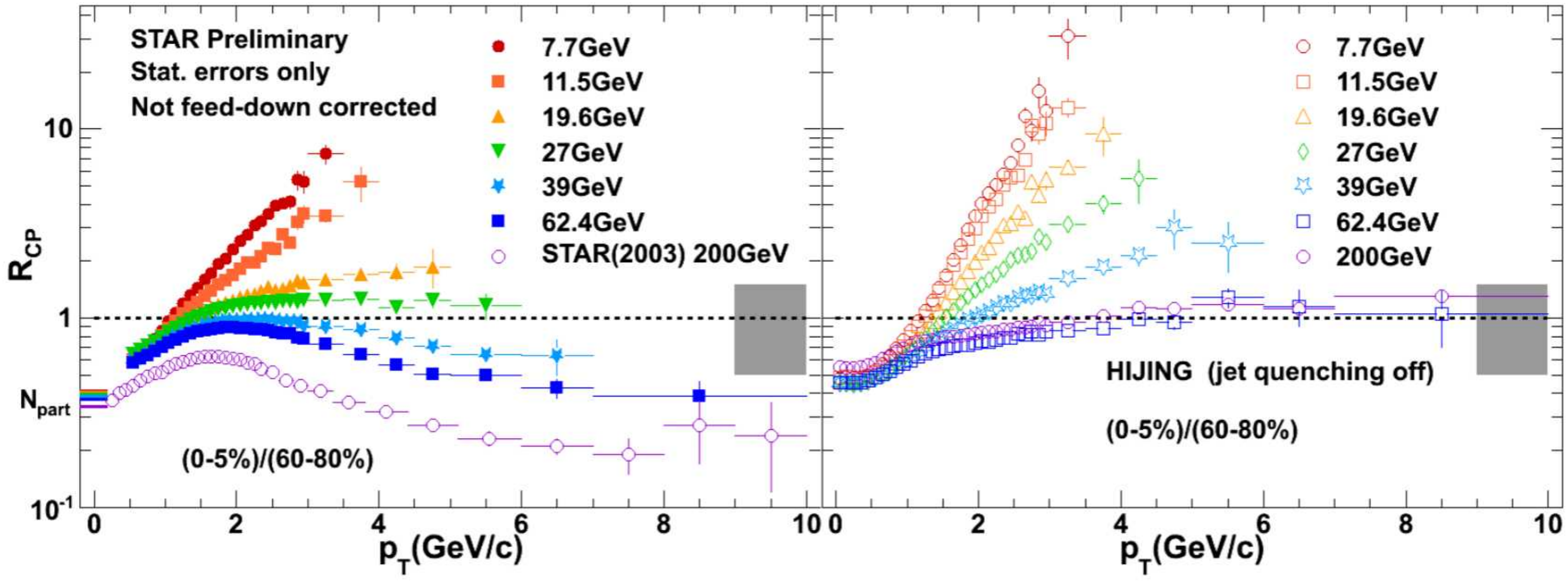
Geometry bias



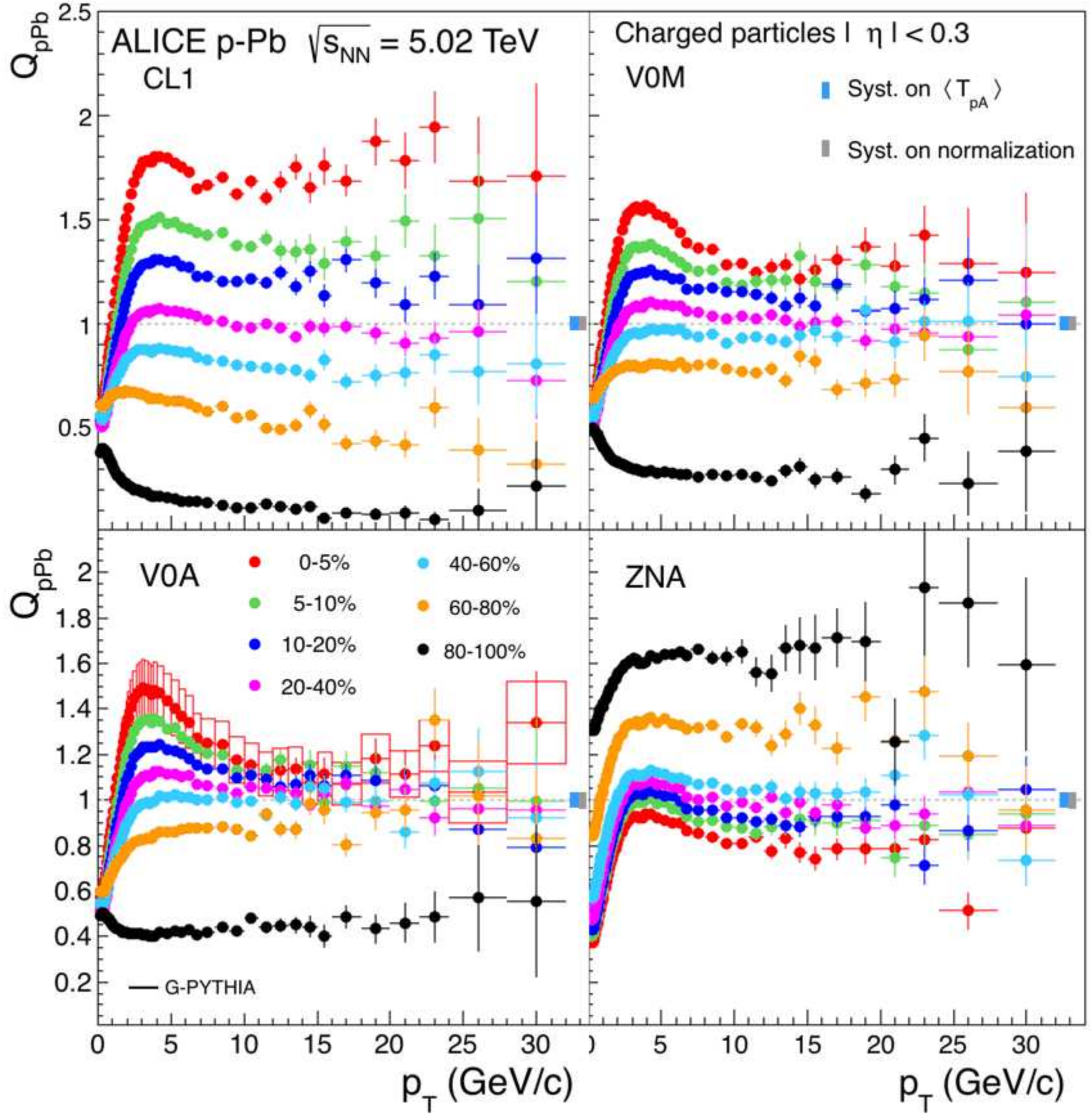
Energy scan



(a1) 10 - 20%
Fit to 200 GeV data
(b1) 20 - 30%
(c1) 30 -40%
2.76 TeV
200 GeV
62.4 GeV
39 GeV
27 GeV
19.6 GeV
11.5 GeV
7.7 GeV
(a2) Ratio to fit function
(b2) Ratio to fit function
(c2) Ratio to fit function
$v_2\{4\}$
Ratio
p_T (GeV/c)

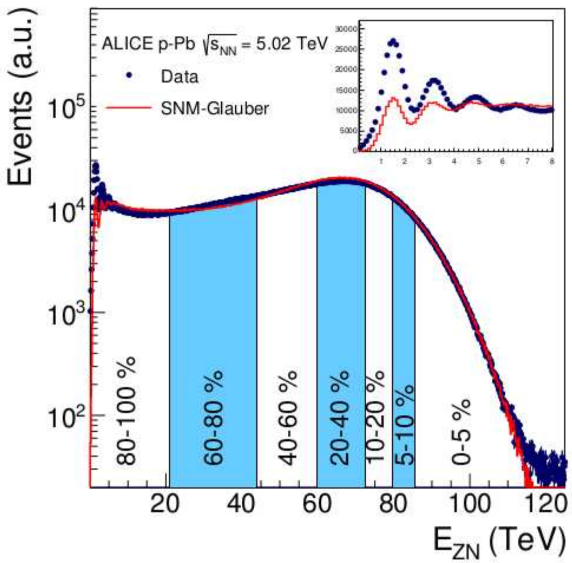


STAR Preliminary
Stat. errors only
Not feed-down corrected
7.7GeV
11.5GeV
19.6GeV
27GeV
39GeV
62.4GeV
STAR(2003) 200GeV
(0-5%)/(60-80%)
R_{CP}
N_{part}
p_T(GeV/c)
7.7GeV
11.5GeV
19.6GeV
27GeV
39GeV
62.4GeV
200GeV
HIJING (jet quenching off)
(0-5%)/(60-80%)
p_T(GeV/c)



ALICE, PRC 91 (2015) 064905

Centrality from HYBRID method



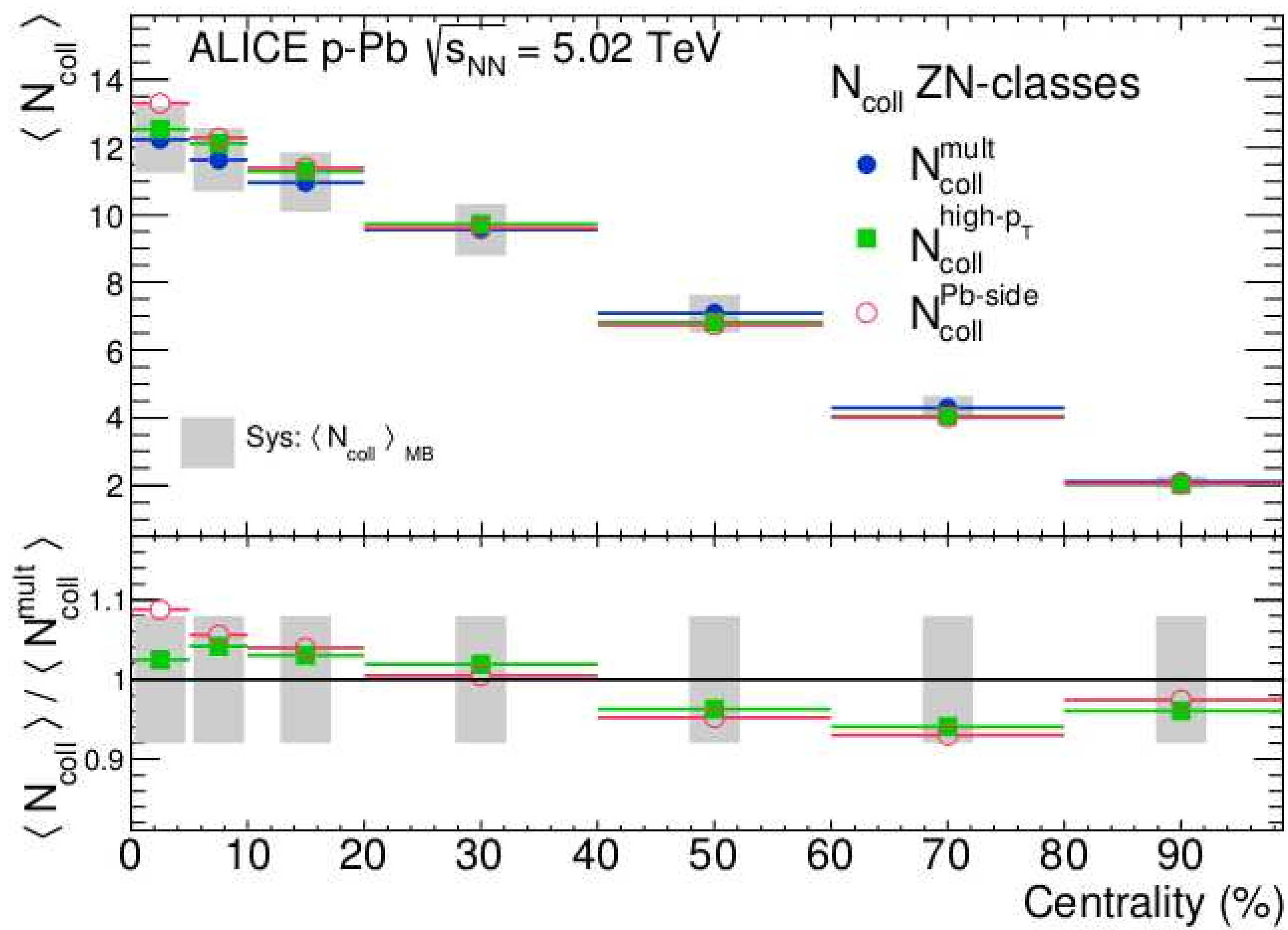
$$\langle N_{\rm coll}\rangle_i^{\rm mult} = \langle N_{\rm part}\rangle_{\rm MB} \left.\frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{\rm MB}}\right|_{-1<\eta<0} - 1$$

$$\langle N_{\rm coll}\rangle_i^{\rm high\,p_T} = \langle N_{\rm coll}\rangle_{\rm MB} \frac{\langle Y_{10<p_T<20}\rangle_i}{\langle Y_{10<p_T<20}\rangle_{\rm MB}}$$

$$\langle N_{\rm coll}\rangle_i^{\rm Pb\,side} = \langle N_{\rm coll}\rangle_{\rm MB} \frac{\langle S_{\rm V0Ar1}\rangle_i}{\langle S_{\rm V0Ar1}\rangle_{\rm MB}}$$

1) Assume ZN is bias free + define centrality classes
2) Construct similar model as for the Glauber fits

Resulting values within at most 10%



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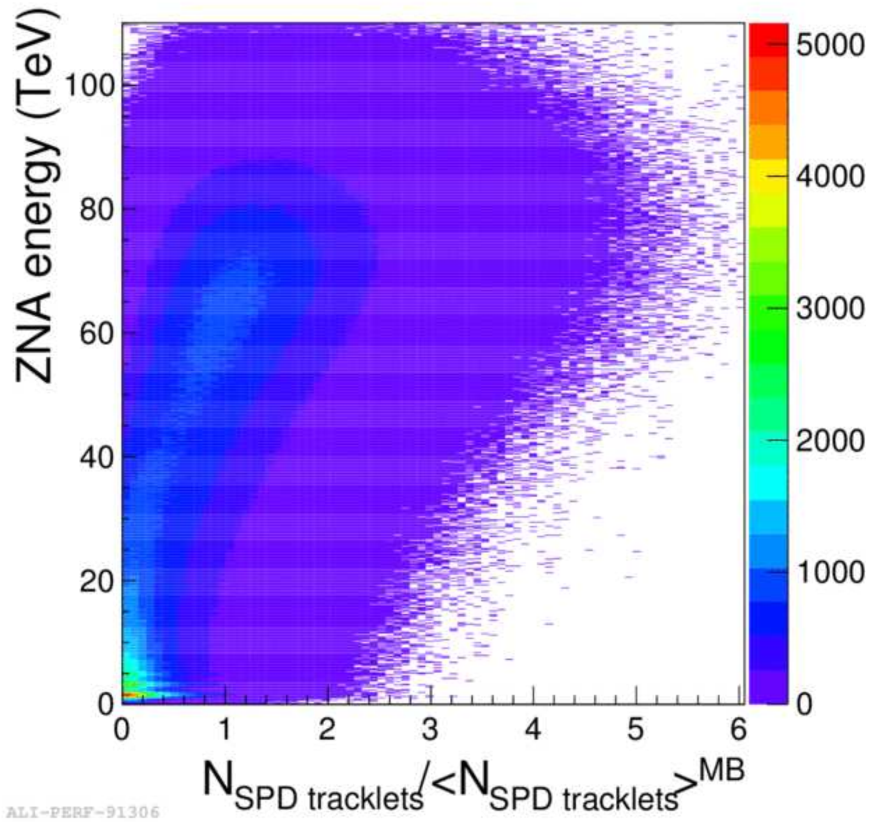
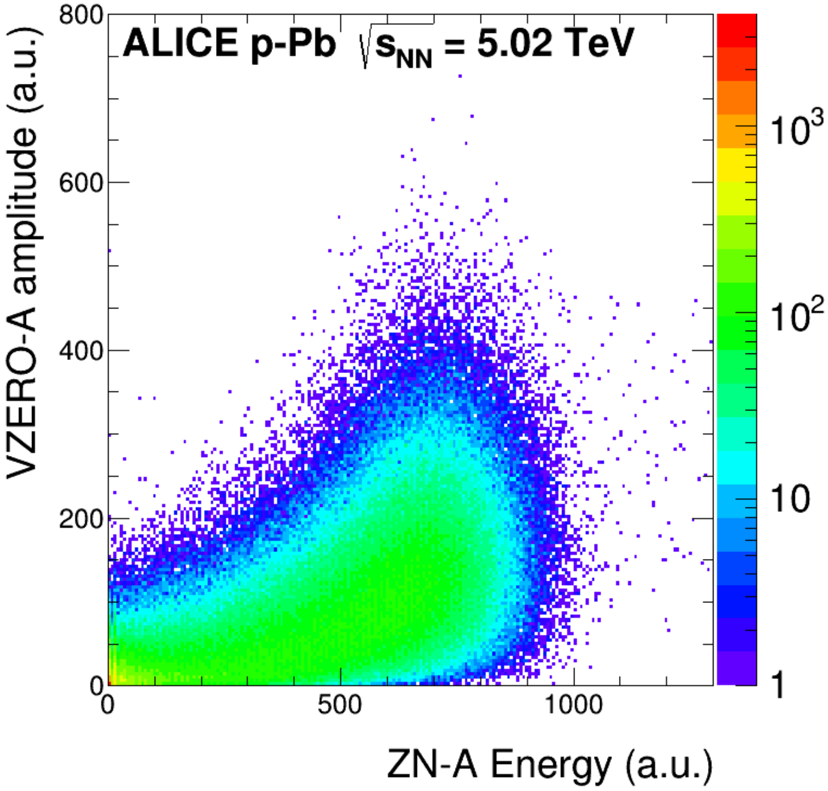
Correlation between ZNA and multiplicity

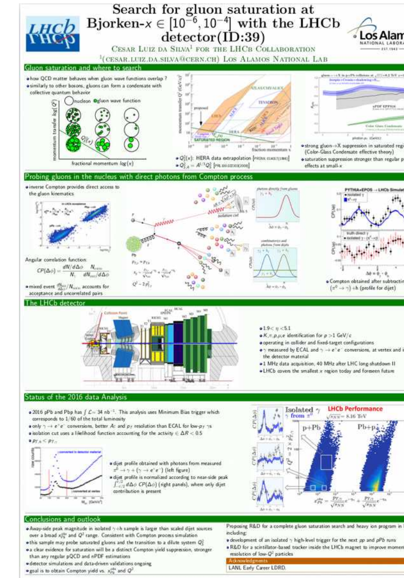


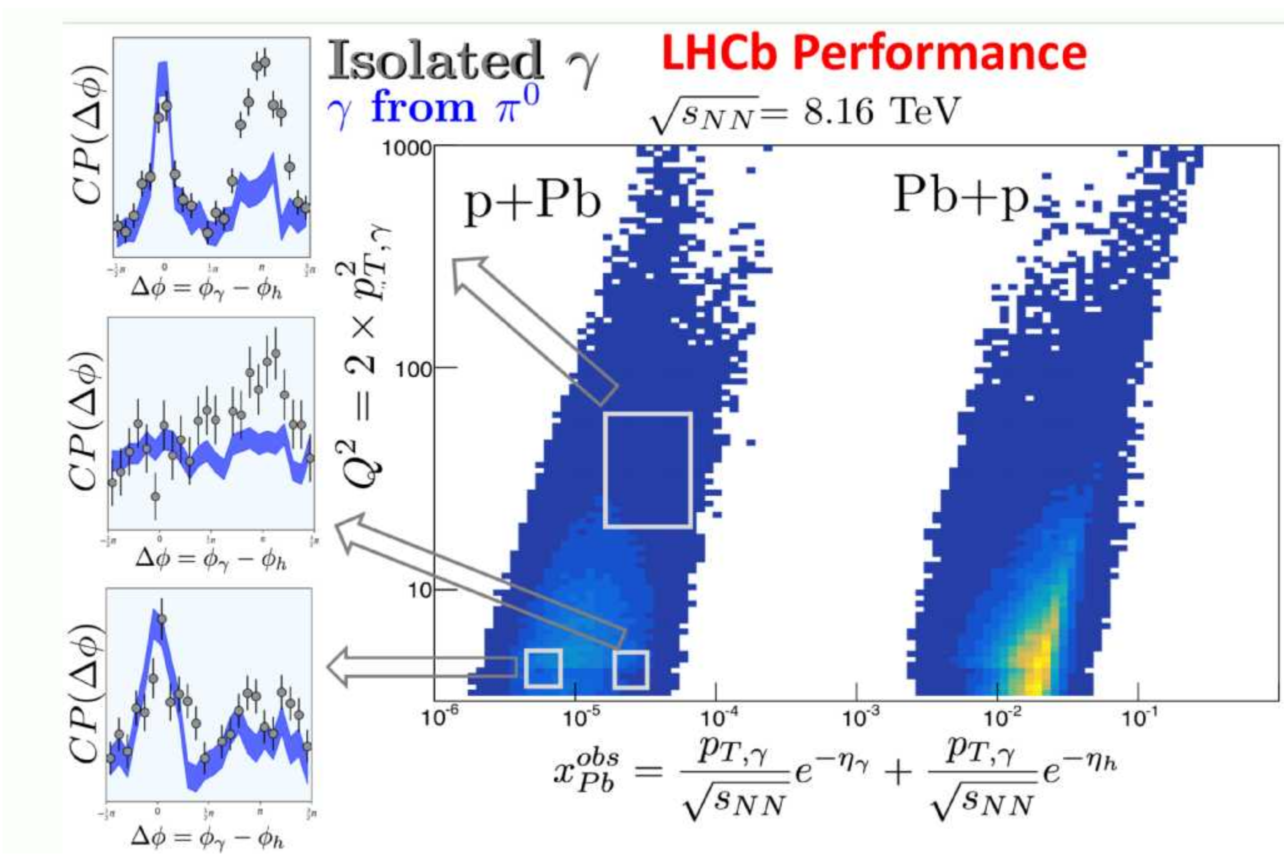


LHCb: Gamma-hadron correlations

https://cds.cern.ch/record/2319876?ln=en

Early Career Award (NSF/DOE)
→ Analysis (isolated conversions)
→ Develop dedicated high level trigger
→ R&D for small tracking stations
inside the LHCb magnet



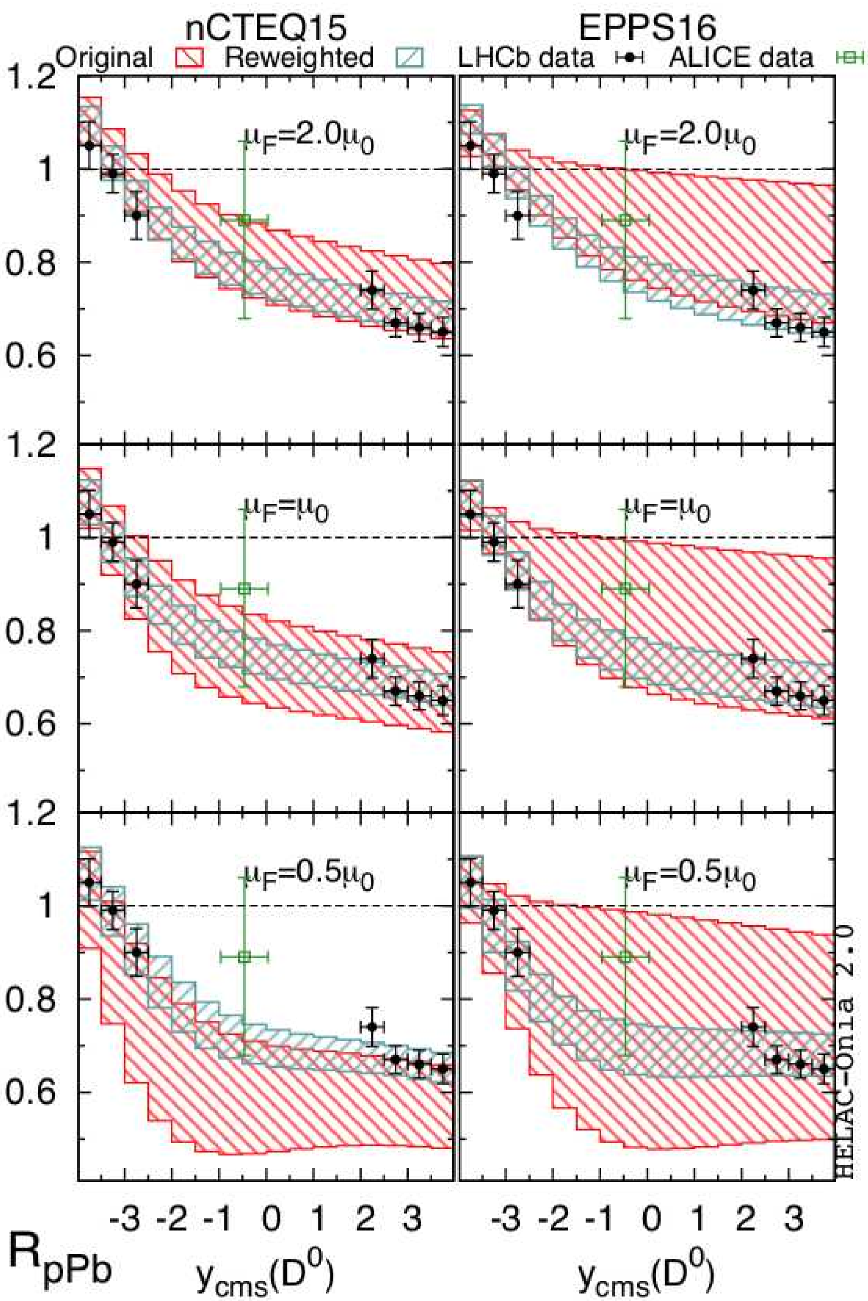


Promising approach for gamma-hadron correlations

LHCb run-1 open charm

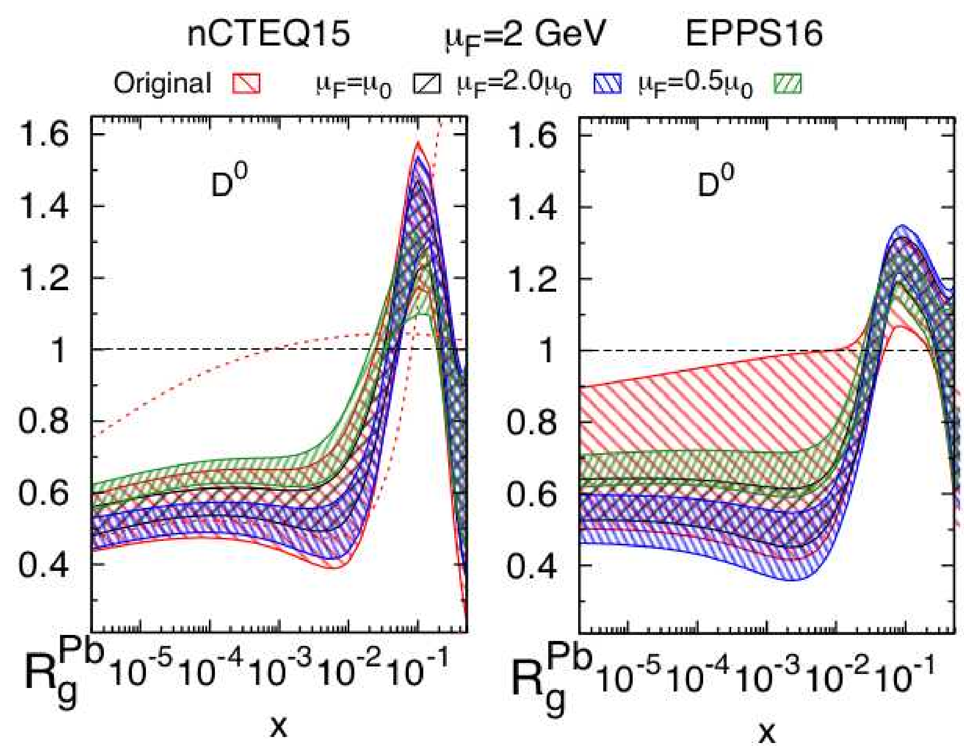
PDF fits using charm arXiv:1712.07024

Caveat: "Final-state" effects observed in pPb



- open charm used in re-weighting
  - significant reduction of uncertainties
  - significant suppression – on the low side of current PDFs
  - significant pQCD uncertainties (scale, fragmentation)

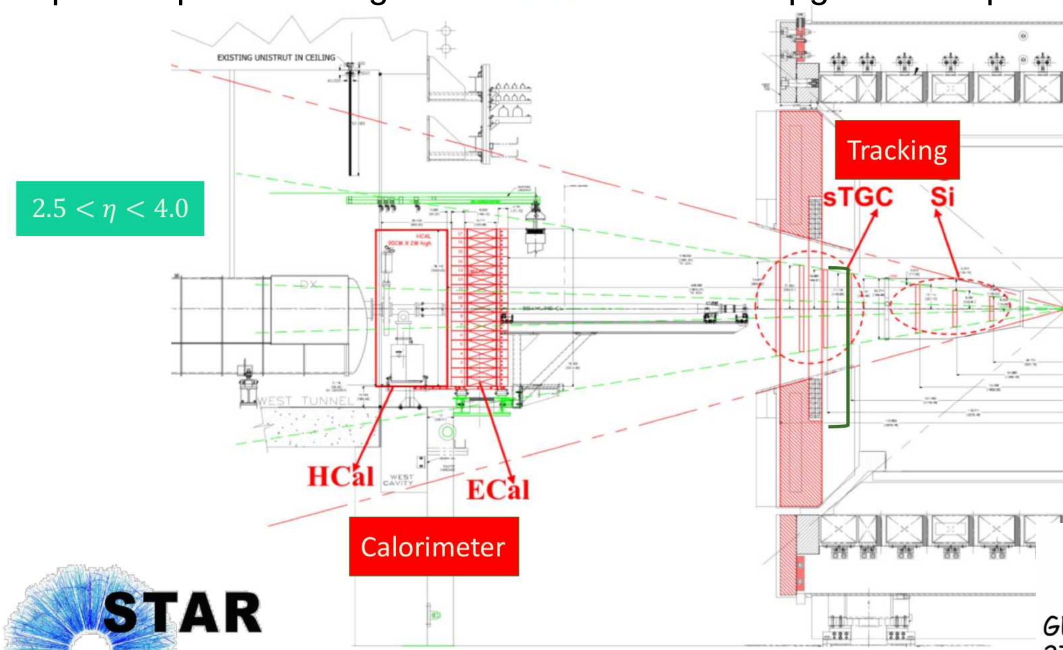
Fit predicts suppression at mid-rapidity; not observed



RHIC Cold QCD plan

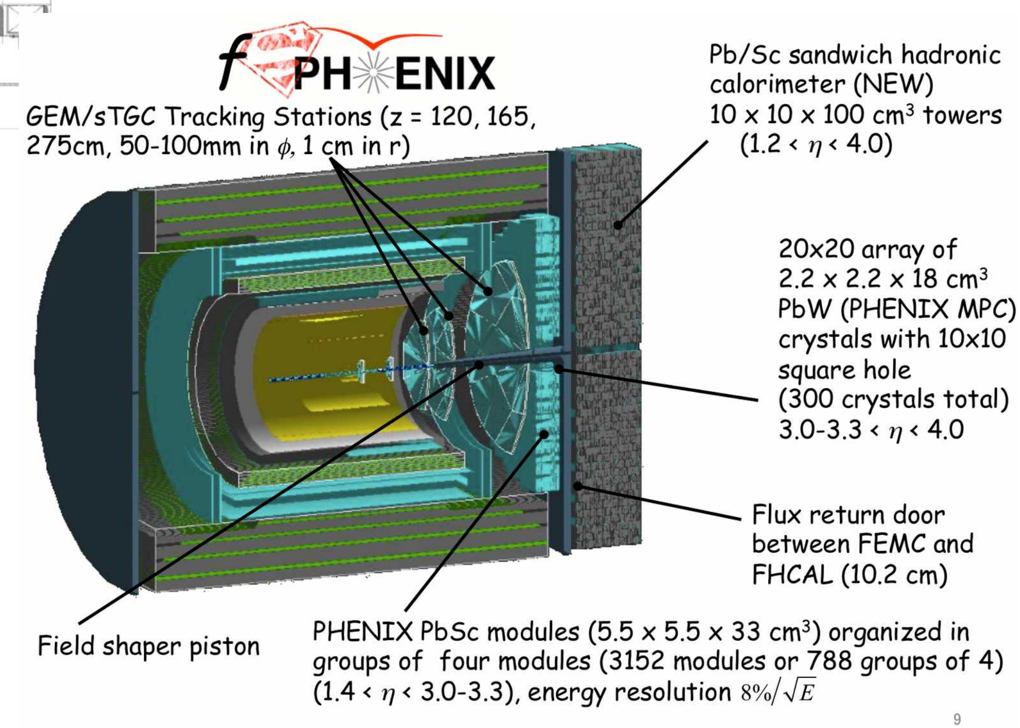
arXiv:1602.03922

https://drupal.star.bnl.gov/STAR/files/ForwardUpgrade.v20.pdf



Significant forward upgrade costs at RHIC (about 6M$ each)

Physics: forward DY and direct photons



https://www.sphenix.bnl.gov/web/system/files/sPH-cQCD-2017-001_draft_2017_06_02.pdf