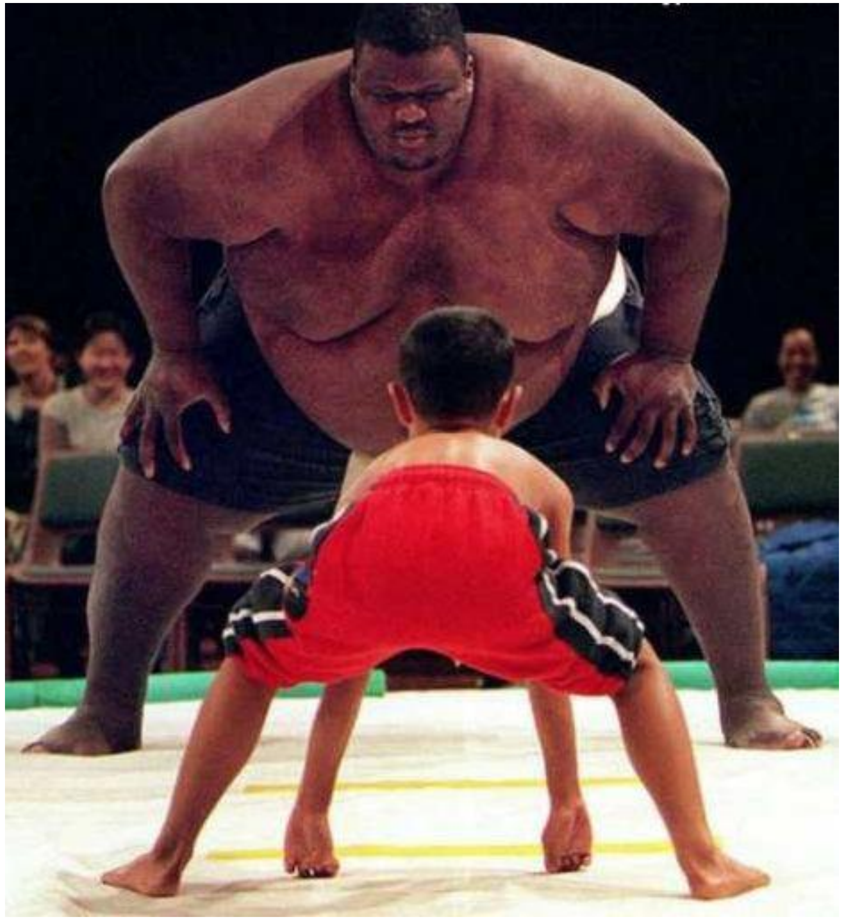
Event activity correlations in small systems



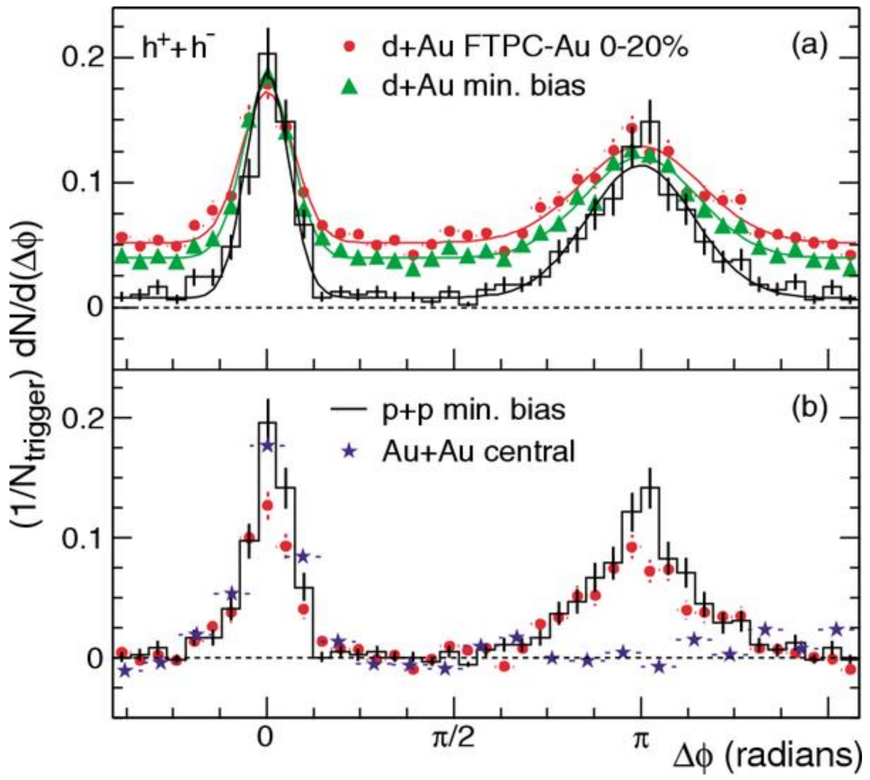
Gabor David
SBU, BNL
HEP Chile, January 10, 2023

"Small systems" → "small-on-large" or "very asymmetric" collisions, like p+Au, d+Au, ^{3}He+Au, p+Pb ("xA")

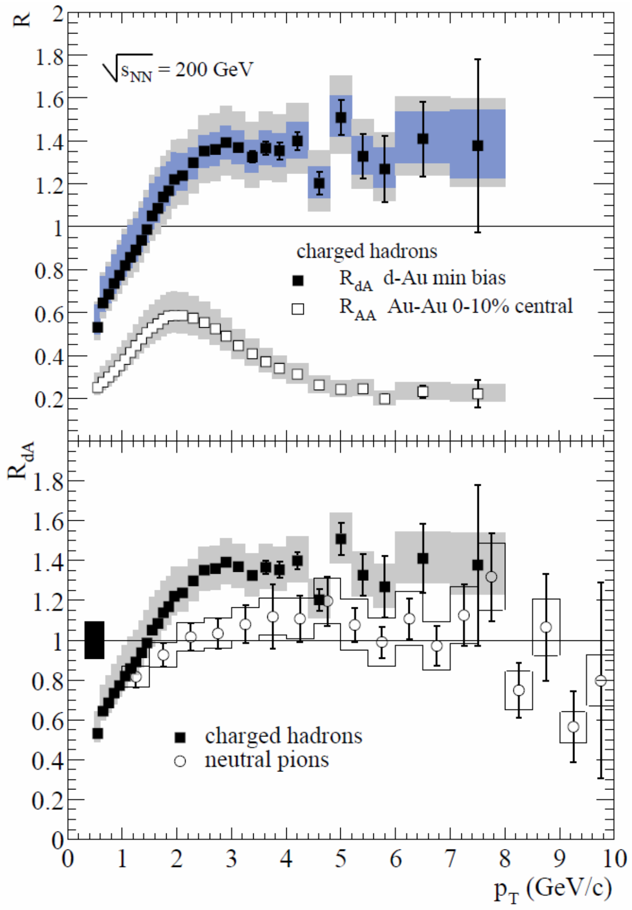
Is today's calibration tomorrow's discovery? ☺

Remember *RHIC 2003*, the first d+Au run, meant to be the *control experiment* to prove FS effects in Au+Au?
(**"Obviously no QGP in d+Au"** so any suppression in Au+Au must be final state effect)

STAR, PRL 91 (2003) 072304



PHENIX, PRL 91 (2003) 072303



STAR: back-to-back jets reappear in d+Au
PHENIX: large suppression in Au+Au,
no suppression in d+Au
→ ***final state effect (as of 2003)***

But then, some funny things happened

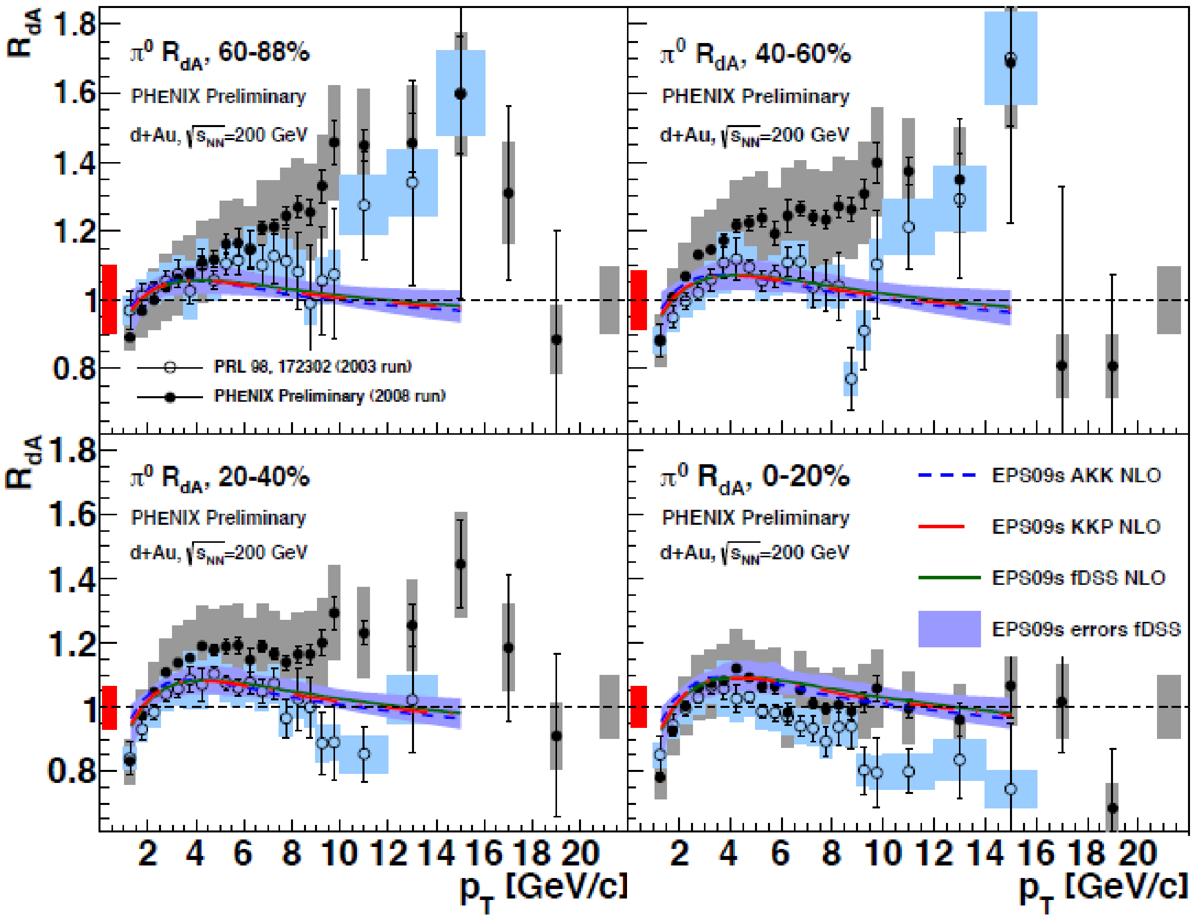
For instance this PHENIX preliminary at QM2012: enhancement in peripheral d+Au!

No reasonable, obvious explanation (Even if QGP were formed, what physics mechanism would enhance peripheral RdAu?)

Reminder:

$$R_{xA} = \frac{dN_{xA}/dp_T \times \sigma_{pp}^{\mathrm{inel}}}{\langle N_{\mathrm{coll}} \rangle \times d\sigma_{pp}/dp_T},$$

…and the plot thickened with time…

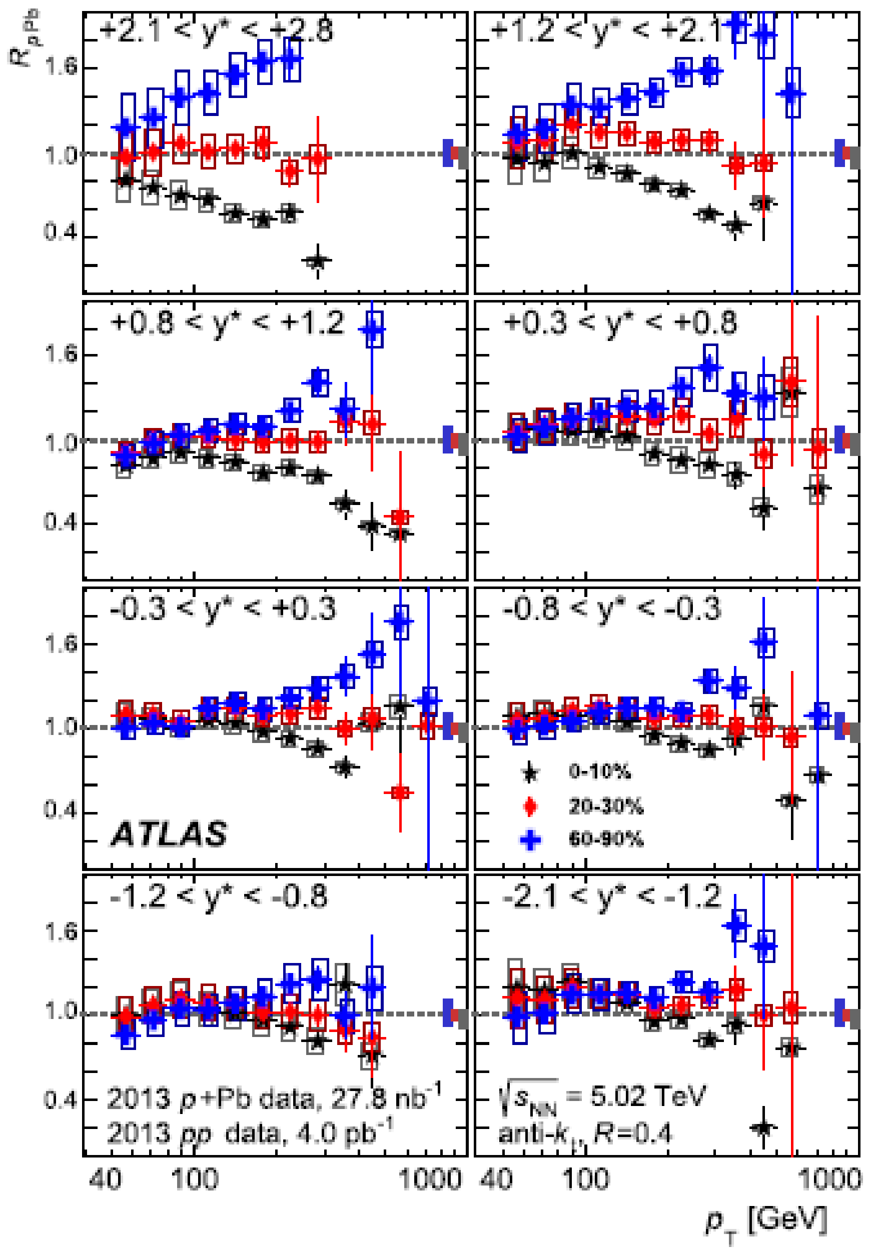


Rapidity dependence of jet R_{xA} – ATLAS, standard Glauber

PLB 748 (2015) 392-413

Centrality: E_T in FCAL,
Pb-going side (large gap)

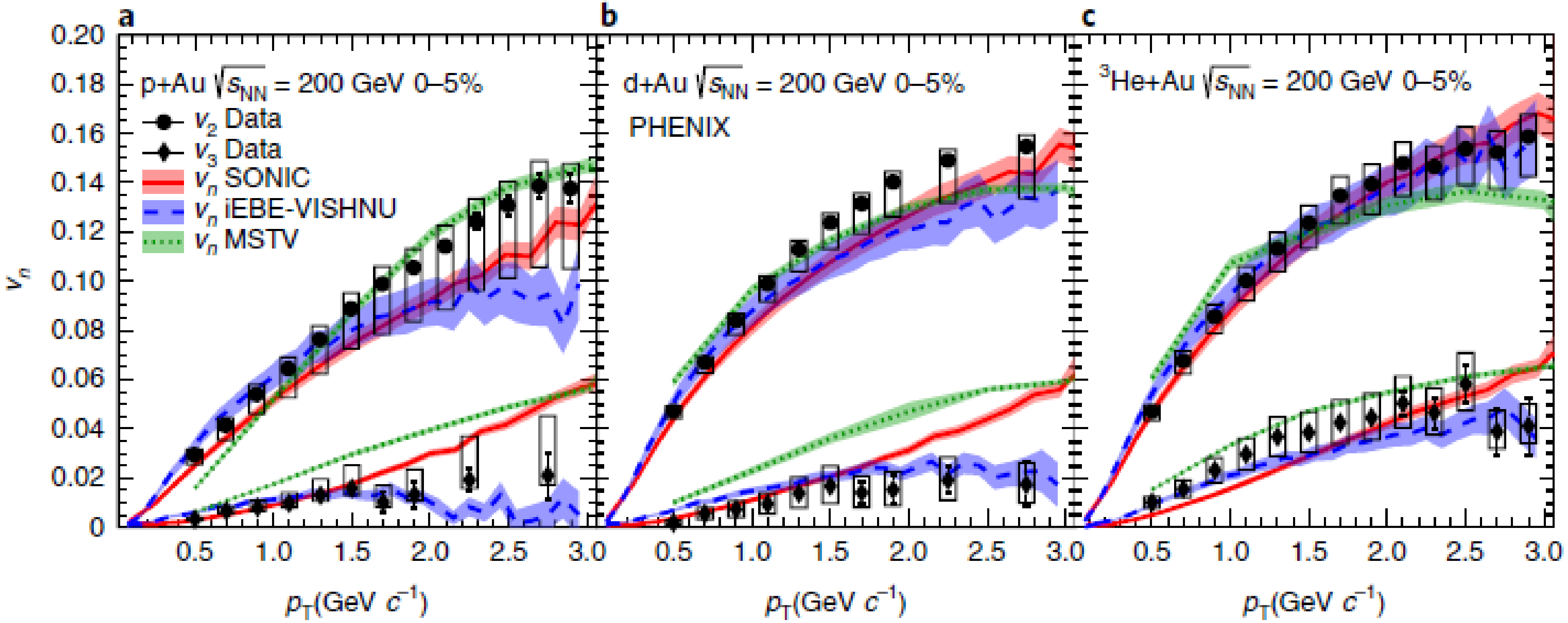
Mid-rapidity
Suppression in central
enhancement (!!!) in
peripheral!



p-going direction
(large projectile x)

Pb-going direction
(small projectile x)

PHENIX, v_2, v_3 in small systems – Nature Physics 15, (2019) 214-220



Indicating strong collectivity, “QGP droplets” in small systems

So – then there might be QGP in xA, after all?

In 2012 → a can of worms opened, still swirling

Neuralgic questions in xA (“small systems”)
- Is there collectivity is xA? (Apparently yes.)
- Is there flow (QGP-like medium, “droplets”?)
- Is there parton energy loss (“jet quenching”)

The presence of genuine (hydro) flow does not mean necessarily jet quenching (pathlengths!)

Nuclear modification factor inseparable of “collision centrality” → NOT a direct observable
→ calculated based on some kind of “event activity”

But: event activity is not the same thing as collision geometry – even if tightly correlated in A+A
Need to map purely theoretical ***b*** to experimental observables

Glauber → low energy (average) scattering, on-shell all the time
Gribov → high energy theory of soft interactions, frozen configuration

Mapping theoretical *b* to experimental observables – Glauber MC

N_{ch}
charged mult
(large η gap)

N_{part}
participating
(wounded) nucleons

N_{coll}
binary (NN)
collisions

Ann.Rev.Nucl.Part.Sci.57:205-243,2007

3.1 Methodology

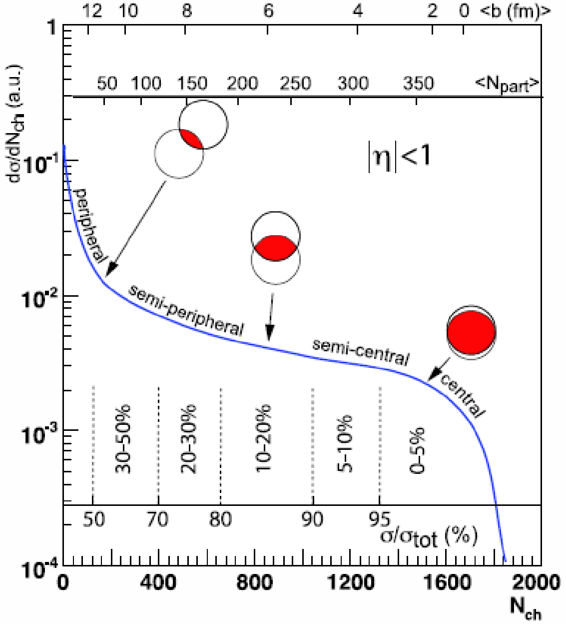
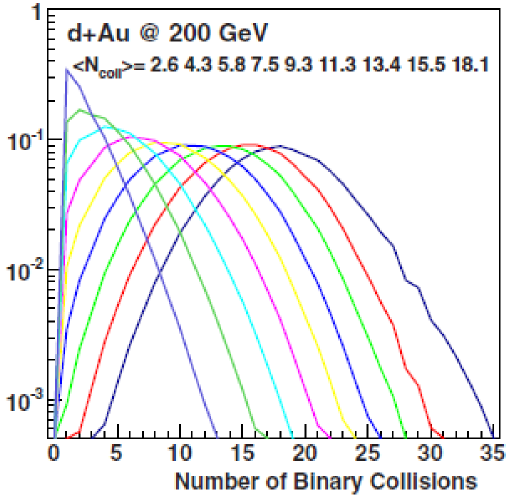
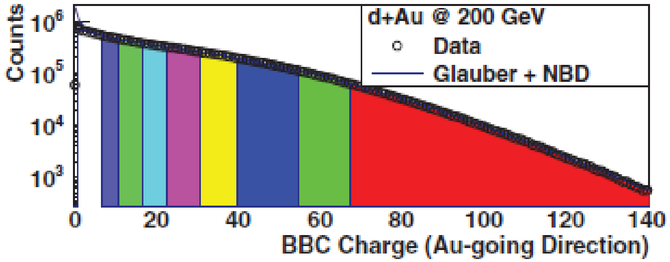
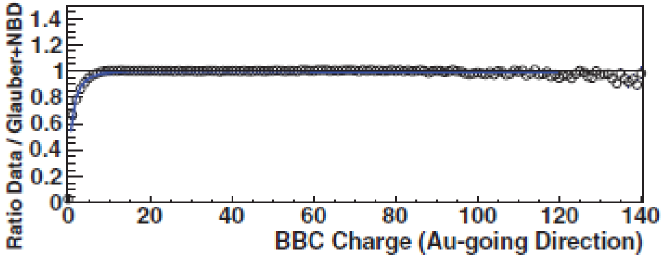


Figure 8: A cartoon example of the correlation of the final state observable N_{ch} with Glauber calculated quantities (b, N_{part}). The plotted distribution and various values are illustrative and not actual measurements (T. Ullrich, private communication).

PRC 90, 034902 (2014)





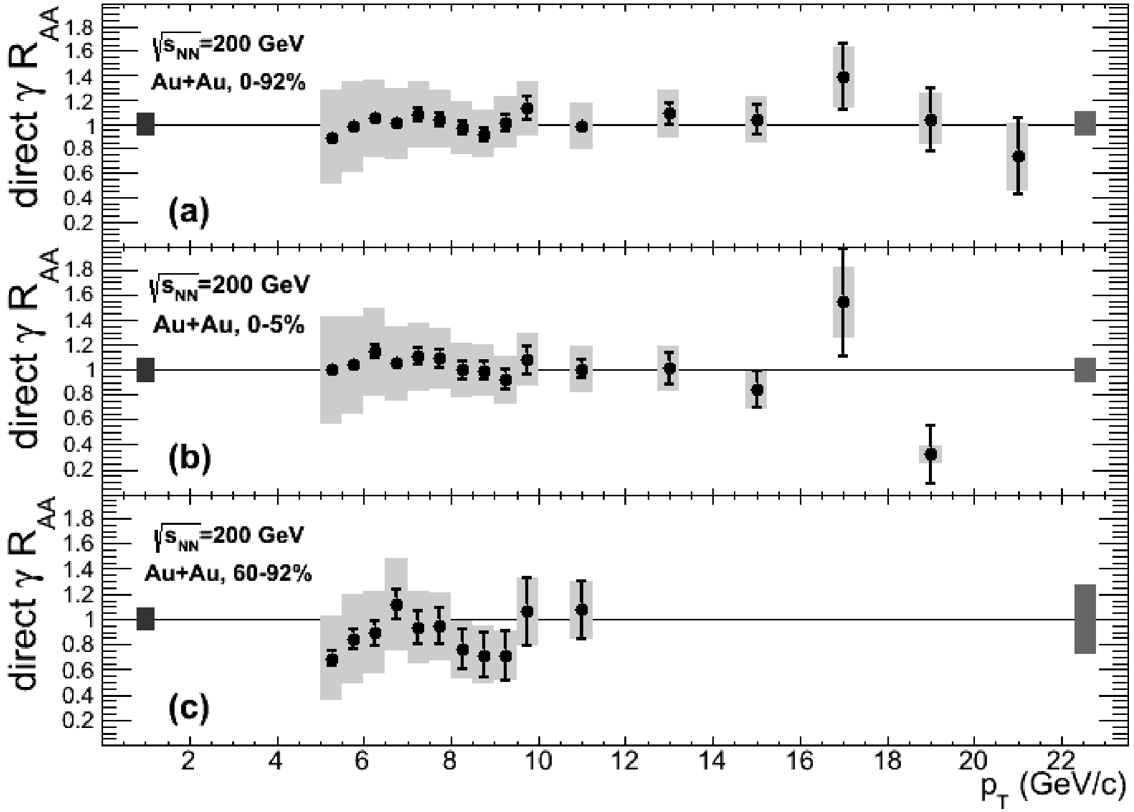


"In heavy ion collisions, we manipulate the fact that the majority of the initial state nucleon-nucleon collisions will be analogous to minimum bias p+p collisions…"

Glauber MC works in A+A – experimental proof

Hard e.m. probes immune to final state effects → R_{AA} should be unity (with some caveats, like isospin effect)

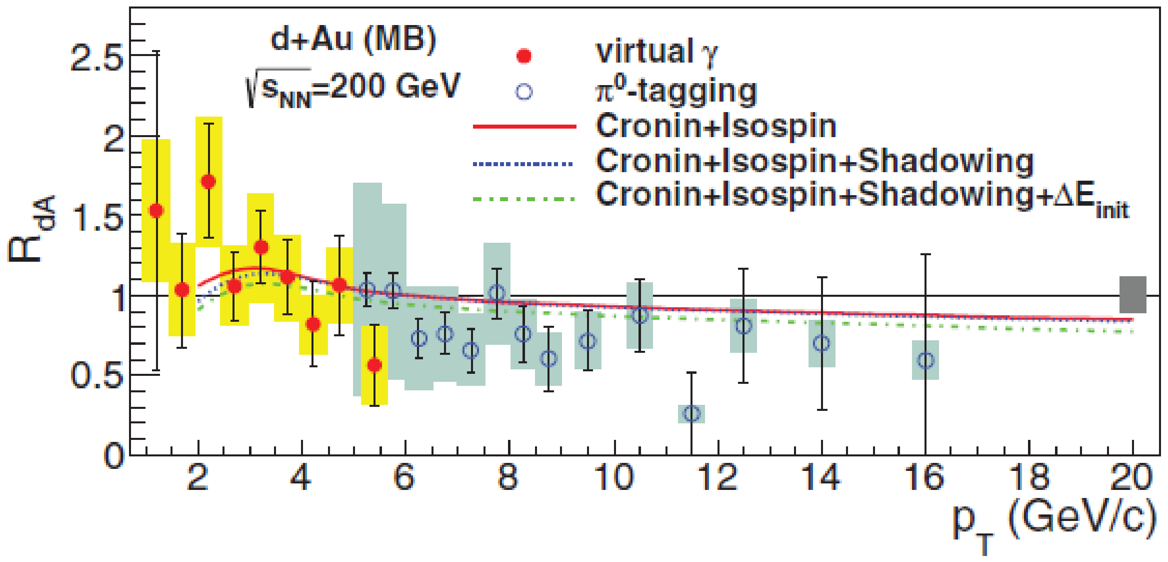
Au+Au



PHENIX, PRL 109, 152302 (2012)

d+Au

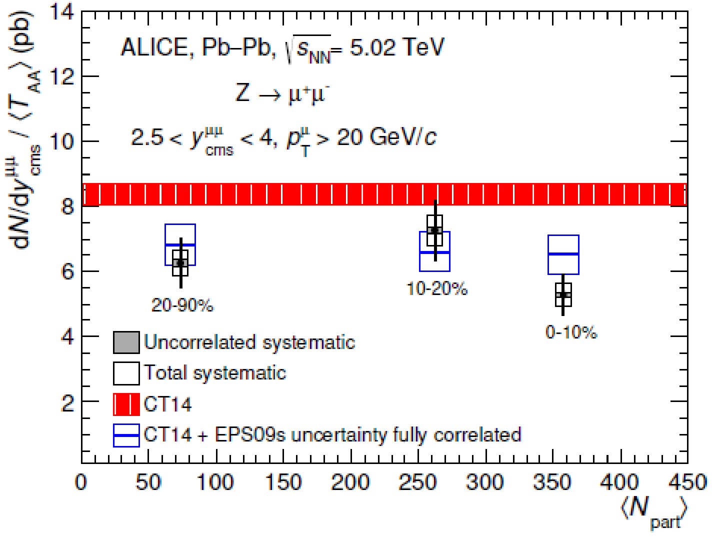
PHYSICAL REVIEW C 87, 054907 (2013)



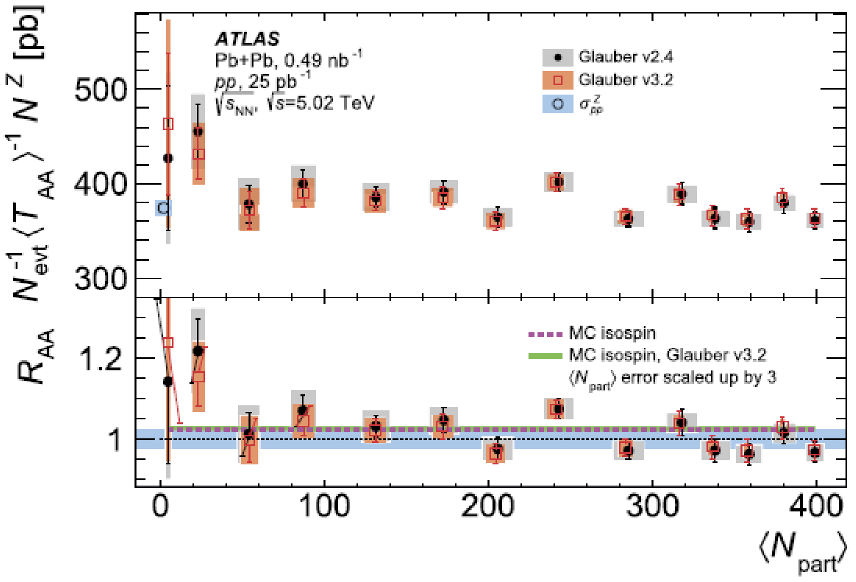
Large uncertainties, but hints of isospin effect

Z-bosons vs centrality in PbPb

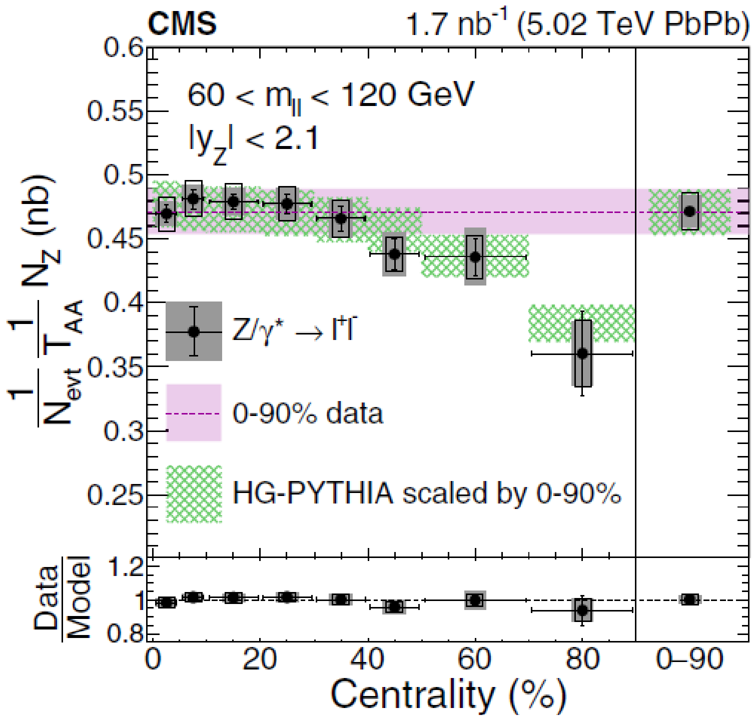
ALICE JHEP 09 (2020) 076



ATLAS PLB 802 (2020) 135262



CMS PRL 127, 102002 (2021)

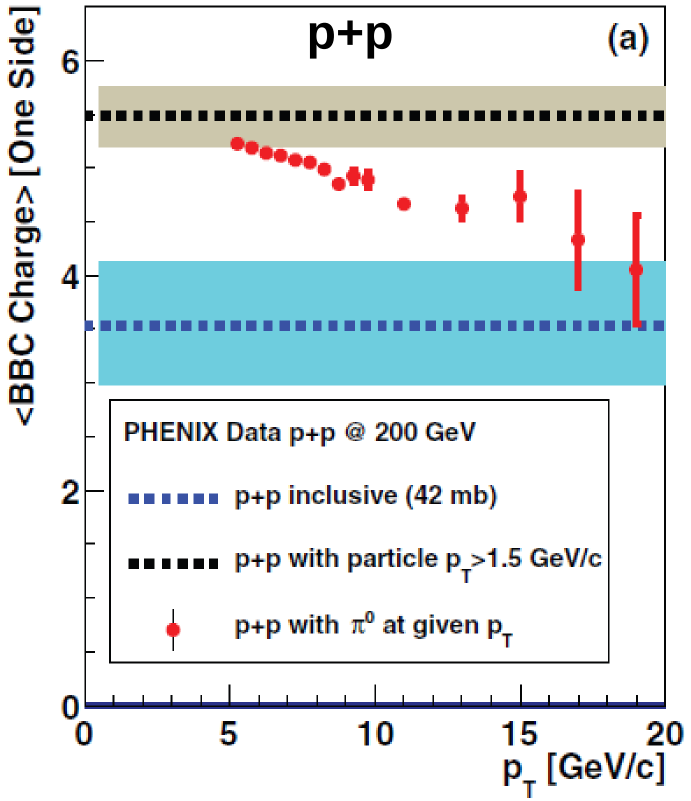


No centrality dependence, except for a few interesting points at CMS

Glauber MC works in A+A – does it work in x+A, too?

"In heavy ion collisions, we manipulate the fact that the majority of the initial state nucleon-nucleon collisions will be analogous to minimum bias p+p collisions…"

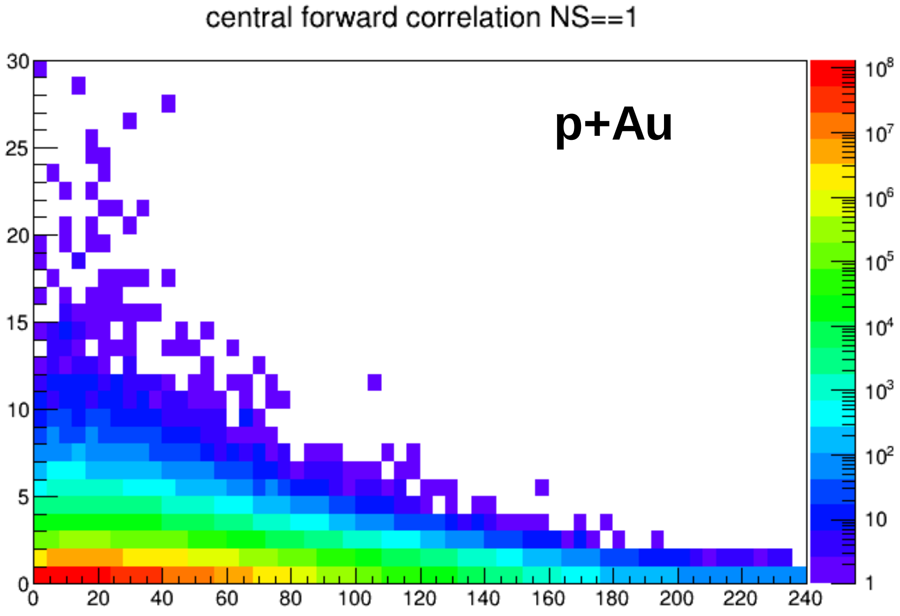
But what if you have a hard scattering? In A+A doesn't matter too much, multiple nucleons participate on both sides. But in x+A you have only one or few projectile nucleons, they alone have to do all the hard and soft production (with a large gap). Can they? (Asymptotically obviously not – energy conservation!)



PRC 90, 034902 (2014)

Highest p_T seen at $\eta = 0$

Anticorrelation!



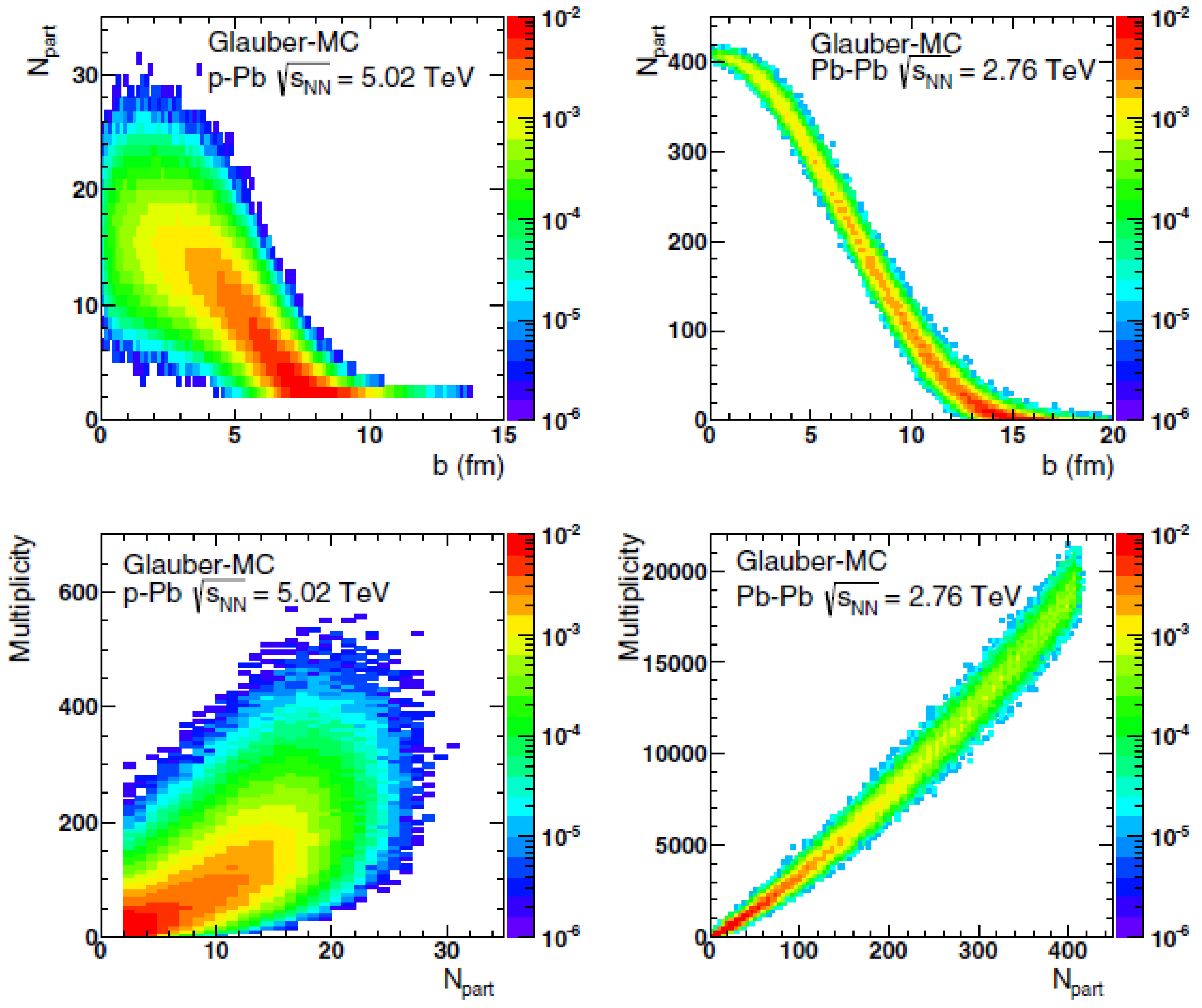
Charge seen at $-3.9 < \eta < -3.0$

Mapping $b \rightarrow N_{part} \rightarrow N_{ch}$

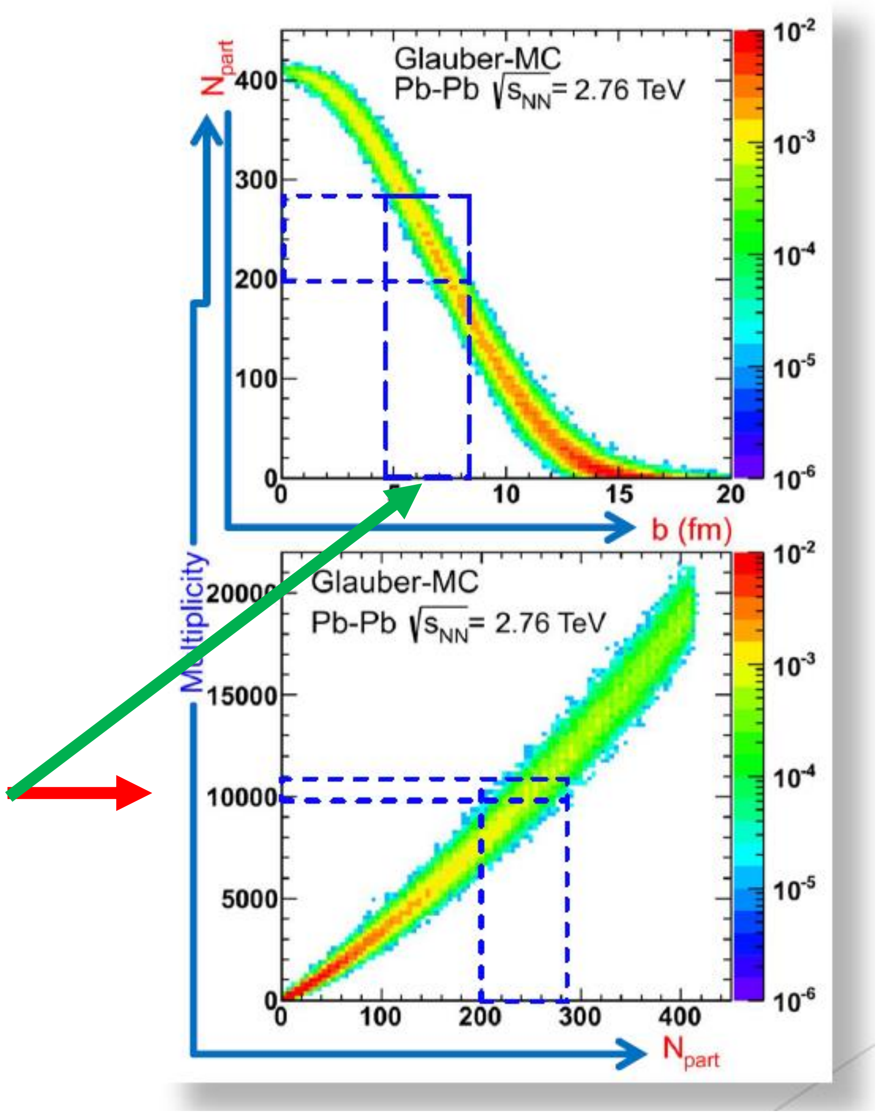
ALICE PRC 91 (2015) 064905

In essence, by selecting high (low) multiplicity one chooses not only large (small) average N_{part}, but also positive (negative) multiplicity fluctuations leading to deviations from the binary scaling of hard processes.

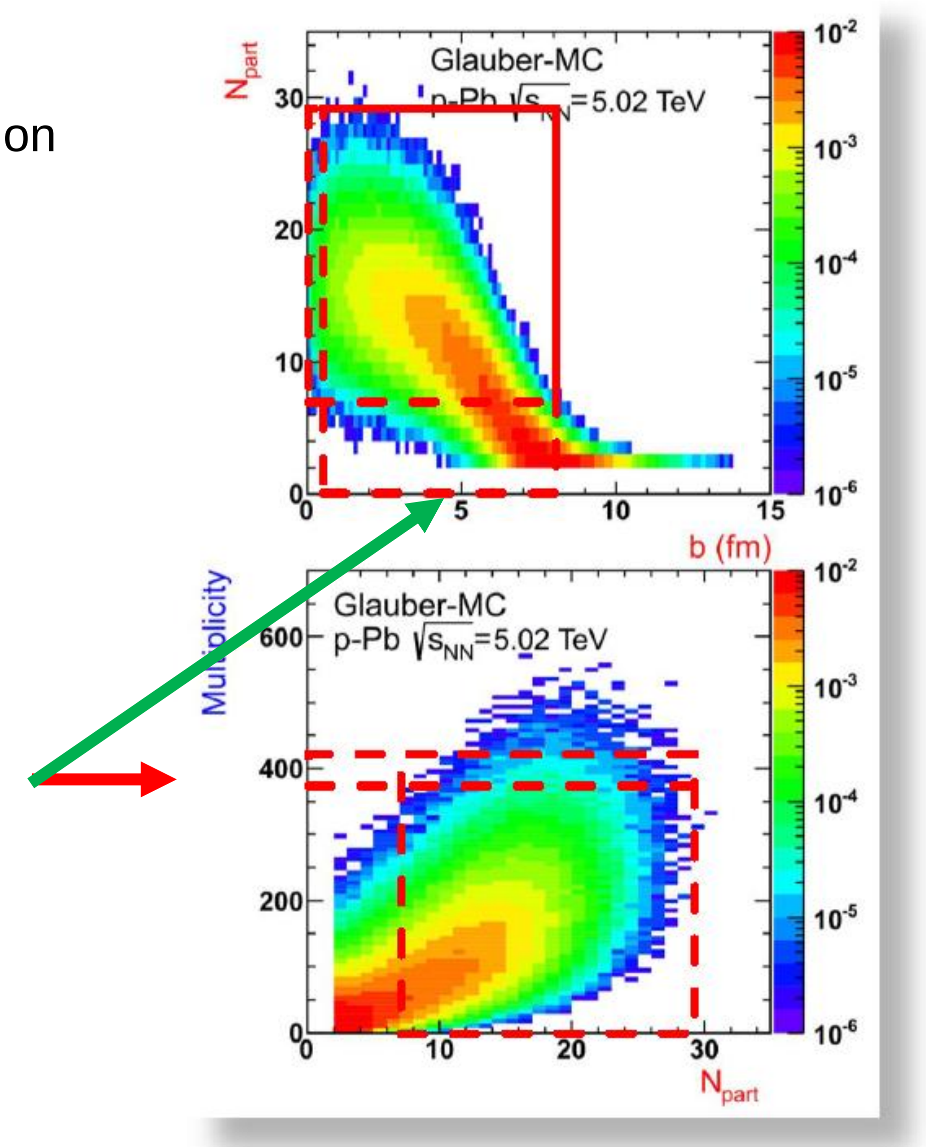
Remember, these are still MB (average) events; high p_T is rare



In other words…

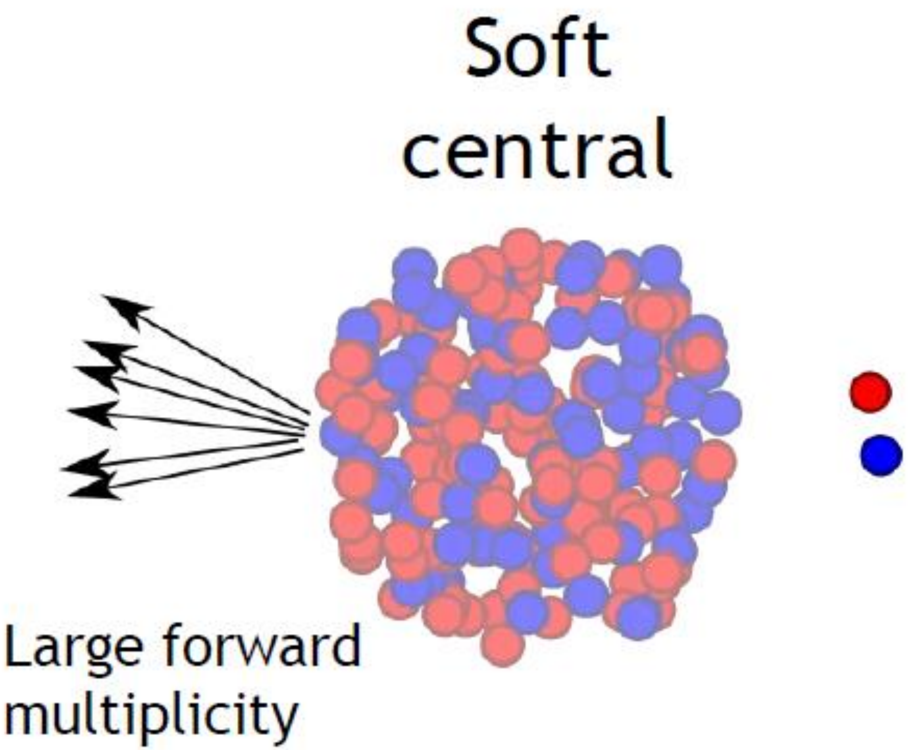


N_{ch}, N_{part}, ***b*** correlation
tight in PbPb,
very loose in pPb



Very large p_T at $\eta = 0$ – mis-binning of centrality?

This is essentially an energy conservation argument



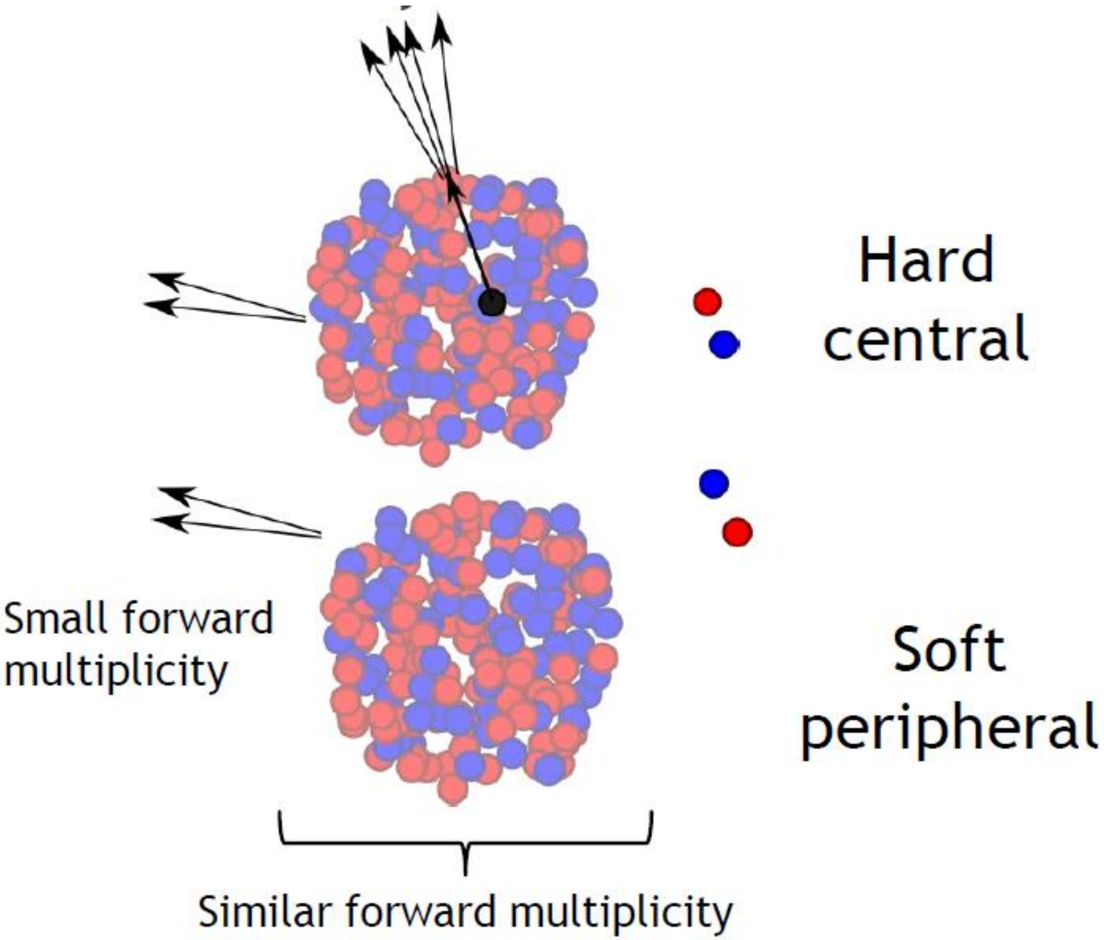
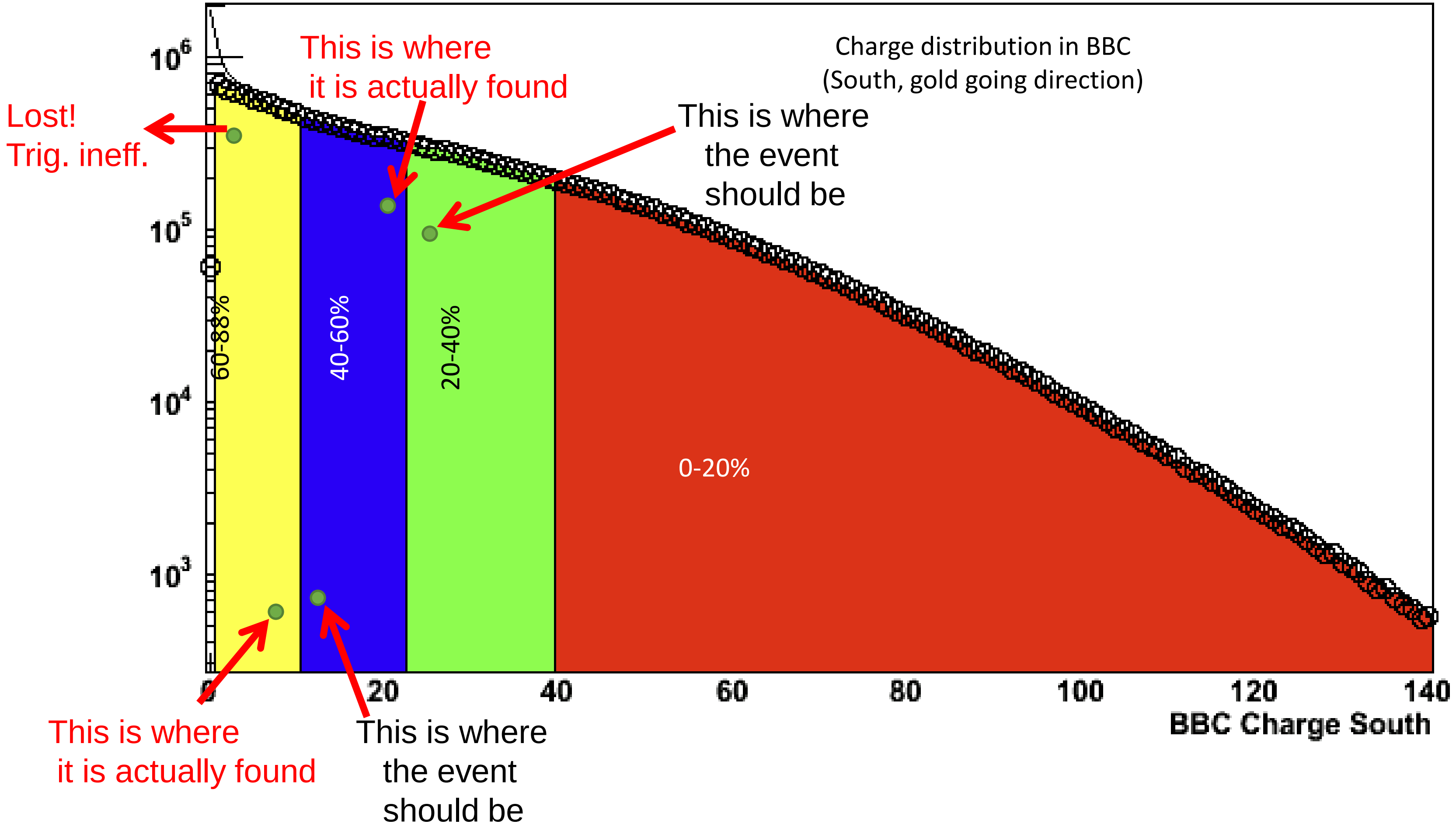


Illustration: shift between multiplicity classes



If (experimental) centrality is determined with fixed (forward) multiplicity thresholds, irrespective of what happened at η~0, events may end up in the wrong centrality class – and attributed an incorrect $\langle N_{coll} \rangle$

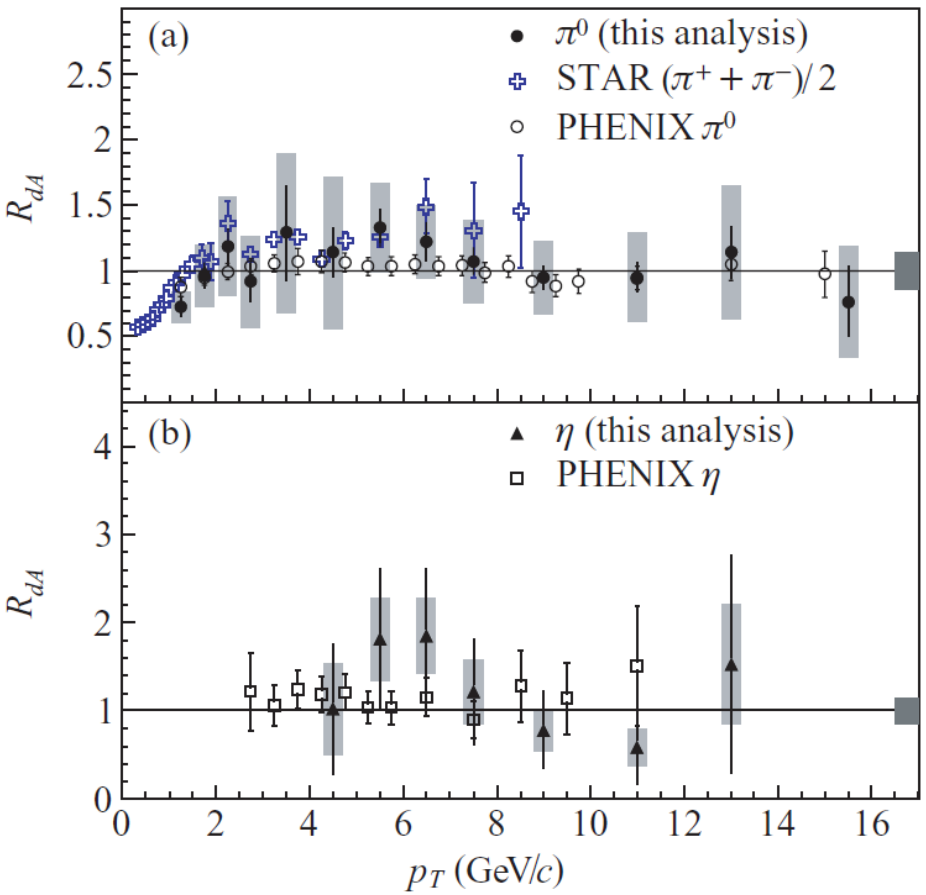
Mostly bin migration, since minimum bias R_{xA} – about unity

New datasets, energy and systems: 2008 RHIC → d+Au 200 GeV, 2012 LHC → pPb, 5.02 TeV
Using "traditional" centrality, same as for large systems
Consistent with unity within uncertainties

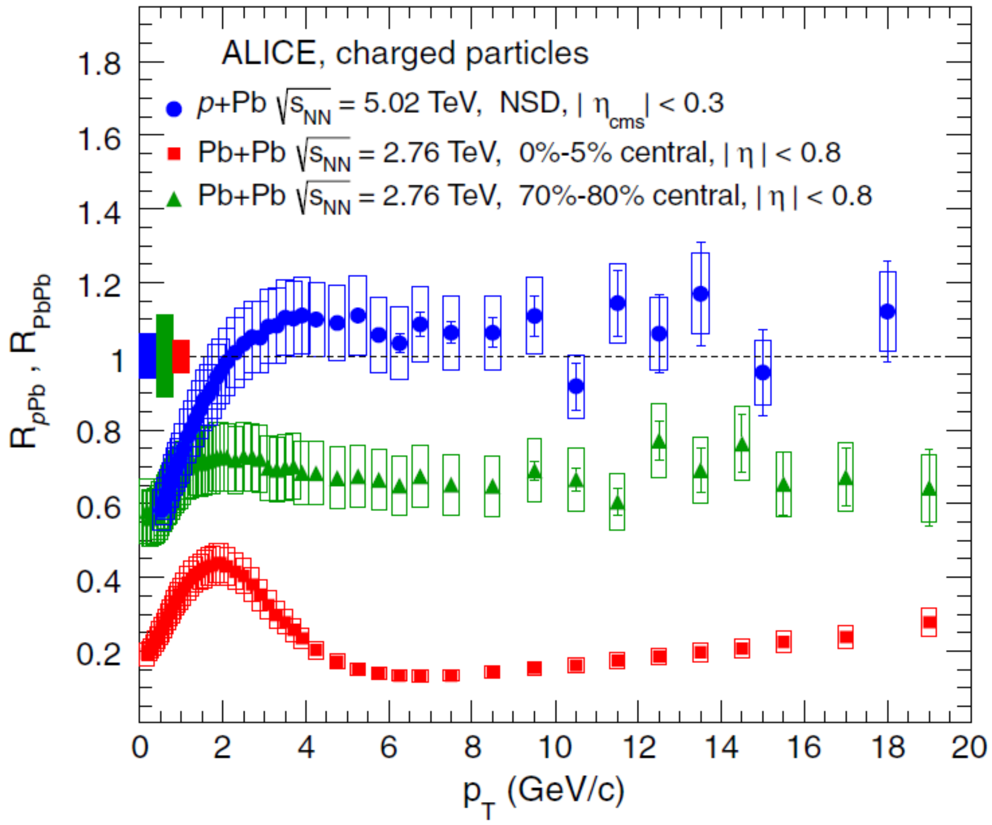
STAR, PHENIX

ALICE

PHYSICAL REVIEW C **81**, 064904 (2010)



PRL **110,** 082302 (2013) PHYSICAL REVI



Inelastic shadowing – *b*-dependent reduced N_{part}

Gribov → inelastic shadowing → color transparency → reduced cross-section

Kopeliovich, PRC 68, 044906 (2003)

PHYSICAL REVIEW C **68**, 044906 (2003)

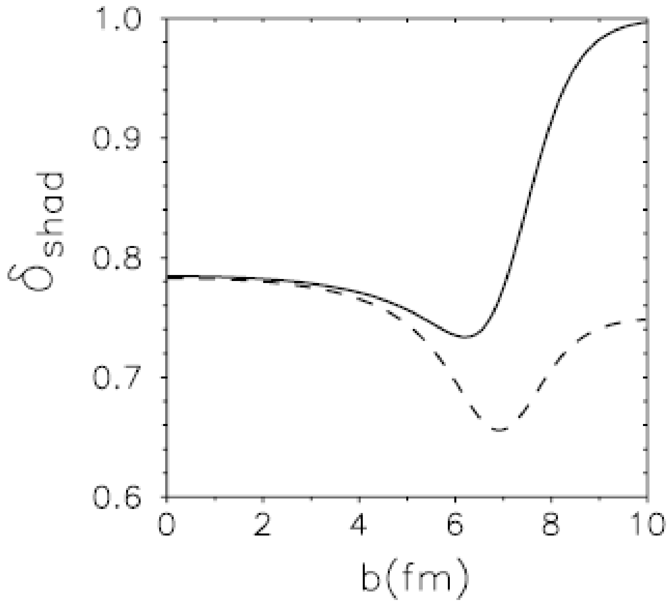


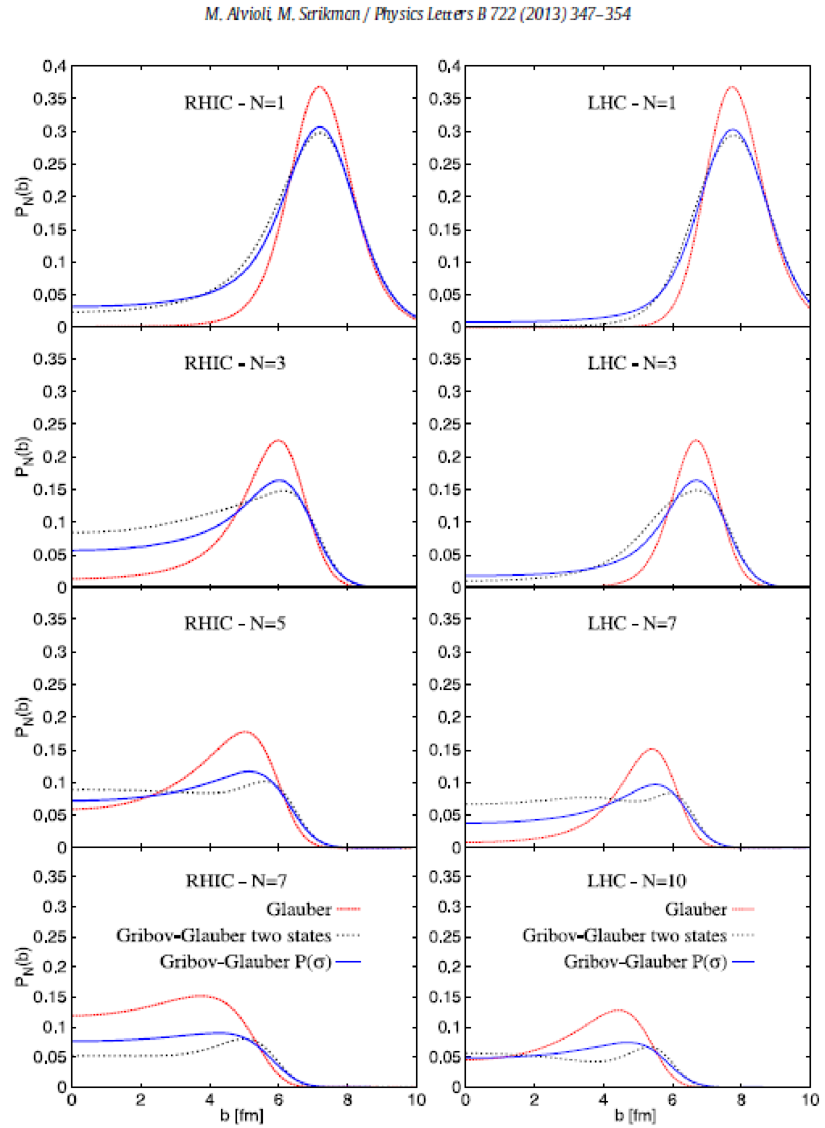
FIG. 9. Solid line is the correction factor, Eq. (81), for inelastic shadowing to the number of participants in *p*-Au collisions as a function of impact parameter. Dashed curve also includes a correction to σ_{in}^{NN} (see text).

Could be tested directly in p+Au or spectator neutron tagged d+Au

(An analysis not done yet.)

Color fluctuations

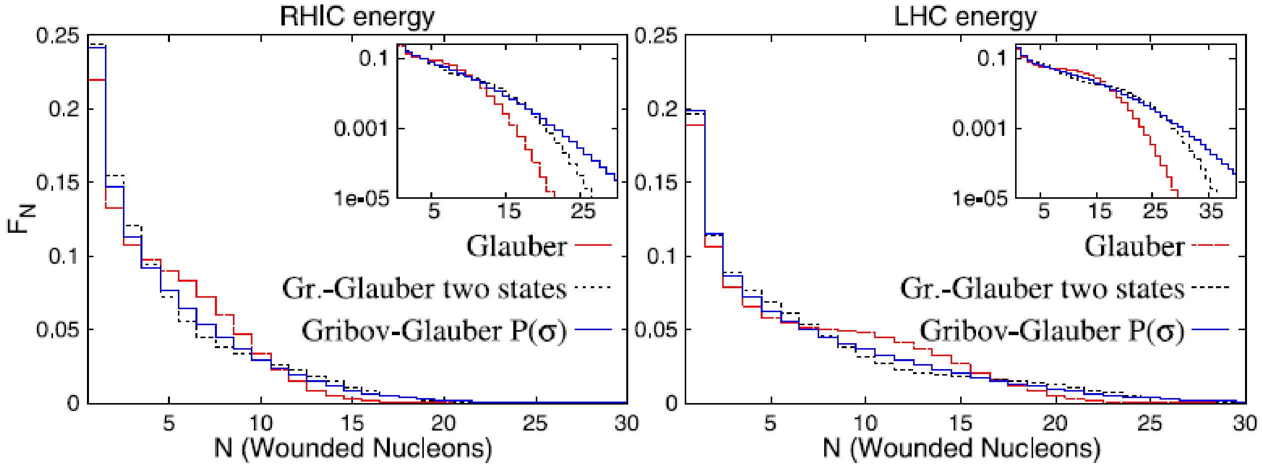
Alvioli, Strikman PLB 722 (2013) 347-354



pA collisions

Two-states model (two distinct σ)

Continuous σ model

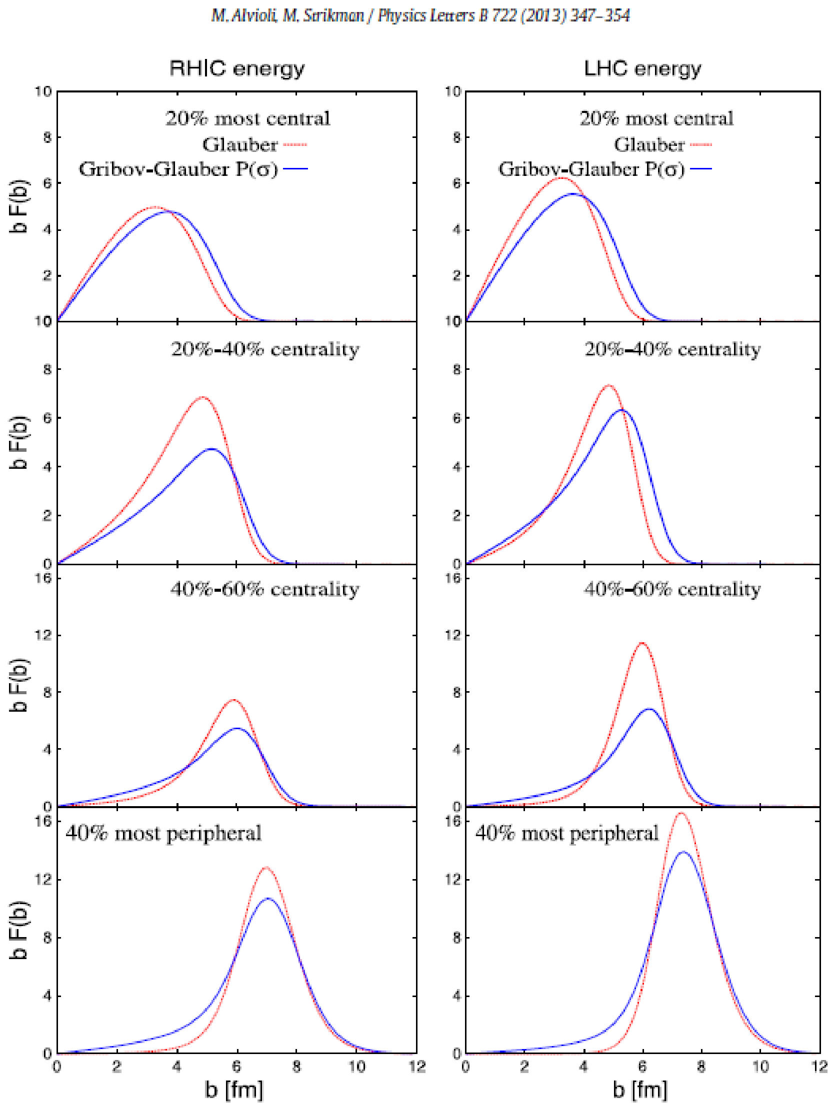


N_{part} fluctuations due to color fluctuations comparable to fluctuations due to position in the nucleus

Color fluctuations → cross section fluctuations

$$\int d\sigma_{tot}\left[\sigma_{tot}^2/(\sigma_{tot}^{hN})^2-1\right]P_h(\sigma_{tot})=\omega_\sigma\,,$$

Large x_p parton → smaller average proton size



Alvioli, Strikman PLB 722 (2013) 347-354

We have demonstrated that color fluctuations lead to a significant modification of the distribution over the number of nucleons involved in inelastic proton–nucleus collisions at collider energies. Study of the correlations between the soft central multiplicity and

the rate of hard parton–parton interactions in the pA collisions at the LHC would provide a new avenue for investigating the three-dimensional structure of proton. In particular such measurement will allow to test a conjecture that quark–gluon configurations in the proton containing large x_p partons have a significantly smaller than average size.

Another proton size fluctuation model vs data (PHENIX π^0)

PRC 94, 024915 (2016)

PRC 105, 064902 (2022)

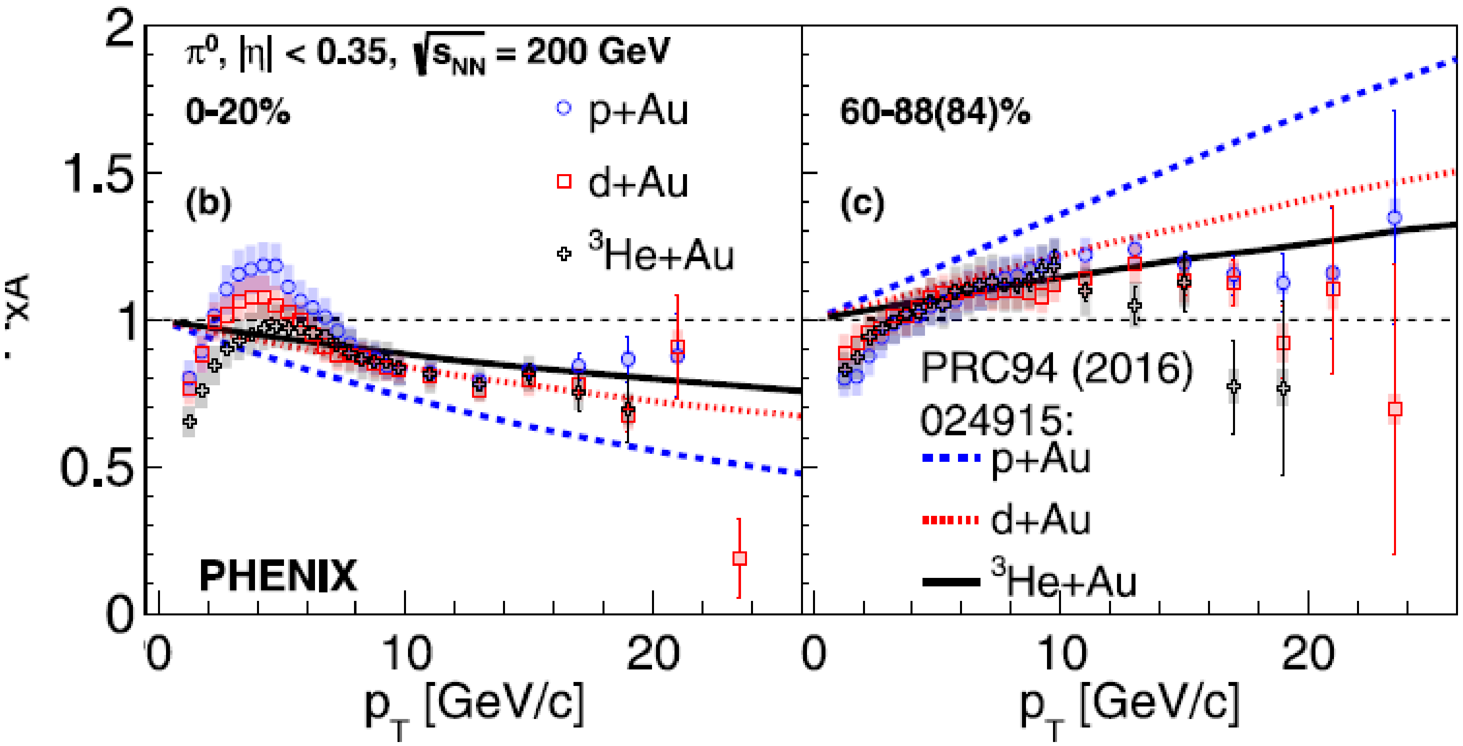
Shrinking nucleon:

$$R^{\mathrm{central}}_{p+\mathrm{Au}} < R^{\mathrm{central}}_{d+\mathrm{Au}} < R^{\mathrm{central}}_{^3\mathrm{He}+\mathrm{Au}}. \quad (12)$$

An inverted ordering would apply in the most peripheral collisions. On the other hand, if the modifications arise from an effect which grows with the amount of nuclear material in the collision (such as final state energy loss of hard-scattered partons in the nuclear medium), the opposite ordering may be expected:

Final state energy loss:

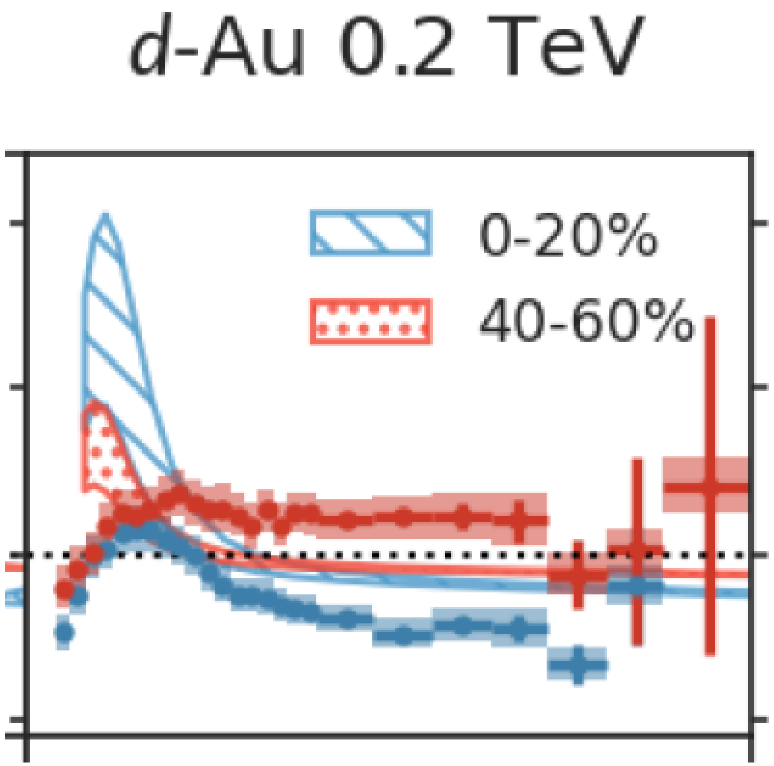
$$R^{\mathrm{central}}_{p+\mathrm{Au}} > R^{\mathrm{central}}_{d+\mathrm{Au}} > R^{\mathrm{central}}_{^3\mathrm{He}+\mathrm{Au}}. \quad (13)$$



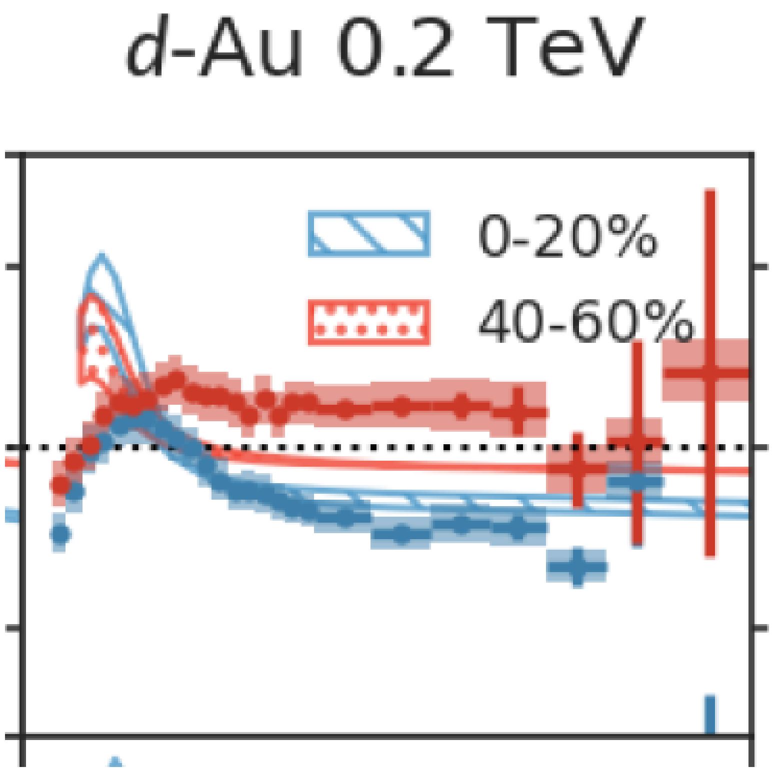
Even with the uncertainties the data disfavor the predicted ordering and the magnitude predicted for pA

And what if there is CNM and/or genuine suppression in R_{xA}?

Ke, Vitev arXiv:2204.00634



CNM only



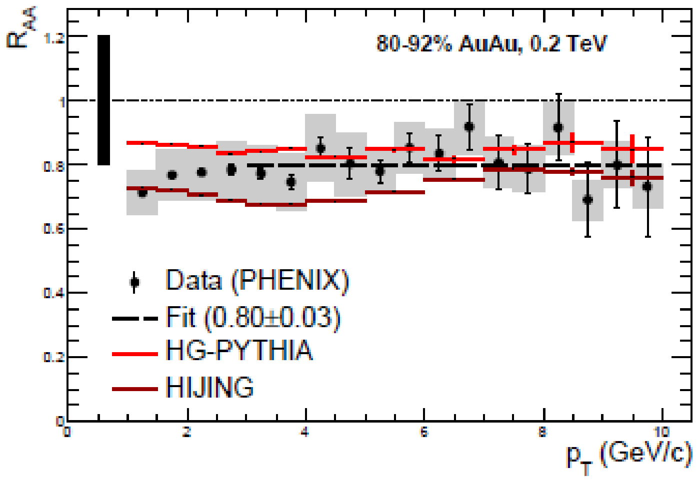
CNM and suppression in QGP

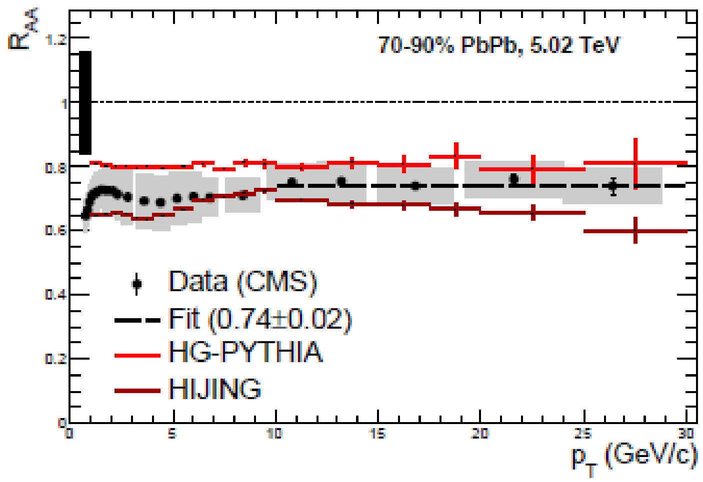
Describes only one particular case, not the evolution with centrality

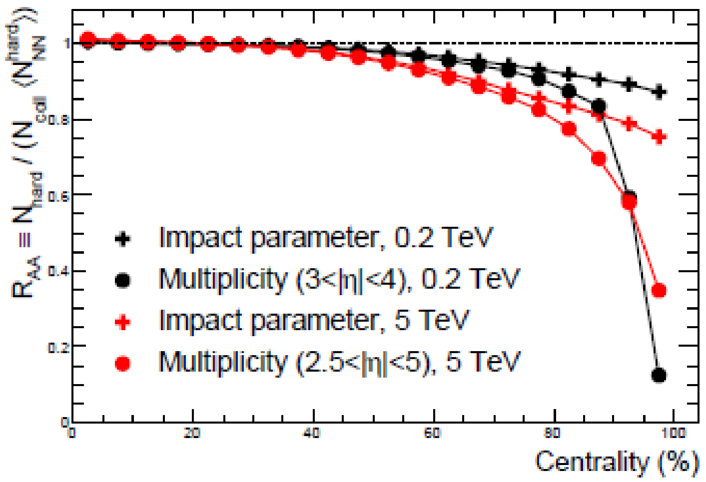
Similar ambiguities even in peripheral Au+Au and Pb+Pb

Loizides – Morsch 1705.08856, 2022 update

Just didn't want to buy into the concept that in peripheral Au+Au or Pb+Pb there is still significant suppression







HG-PYTHIA → HIJING initialization and PYTHIA evolution, including MPI

An attempt to model E_{loss} in p+Pb and peripheral Pb+Pb

ALEXANDER HUSS *et al.* PHYSICAL REVIEW C **103**, 054903 (2021)

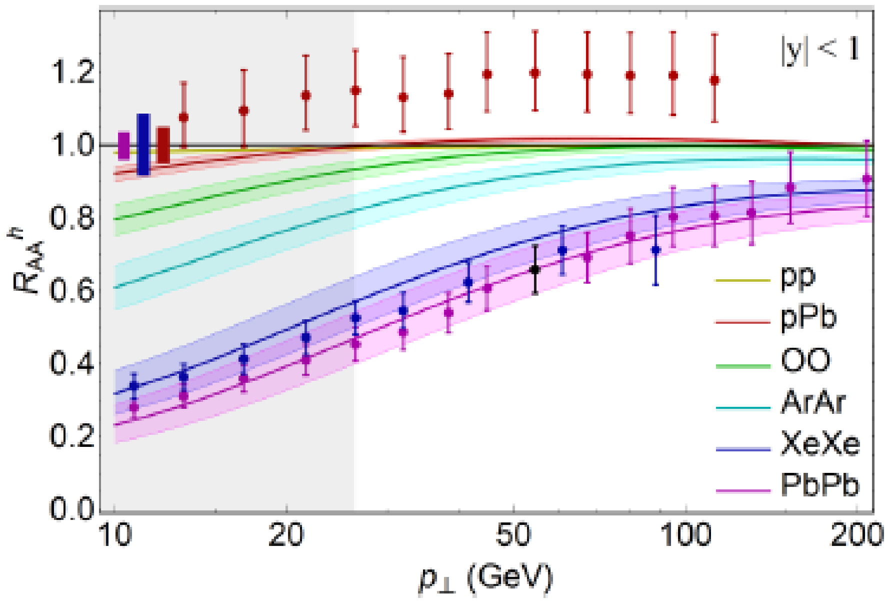


FIG. 6. The nuclear modification factor R_{AA}^{h} for different centrality averaged collision systems (curves follow the ordering of the legend). Normalization uncertainties in PbPb, XeXe, and *p*Pb data are shown as boxes [76,77].

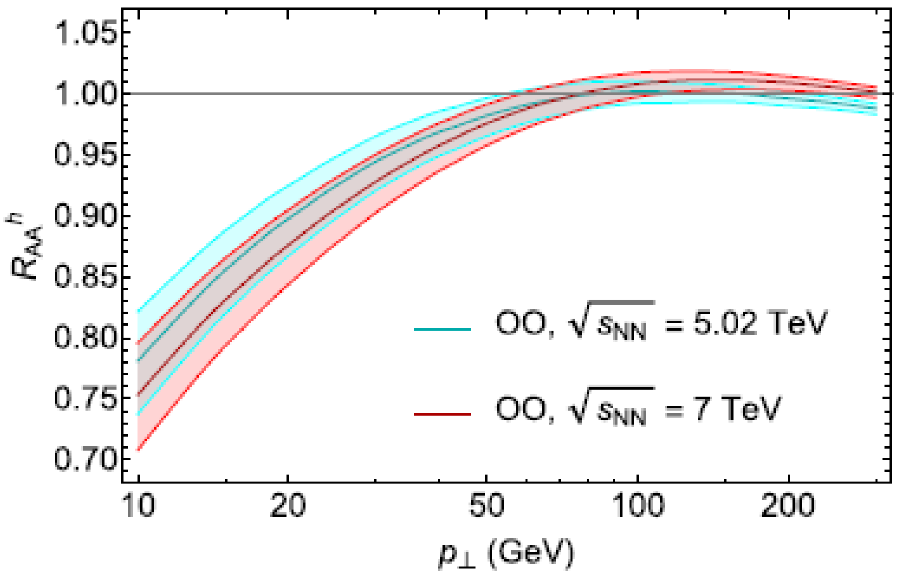
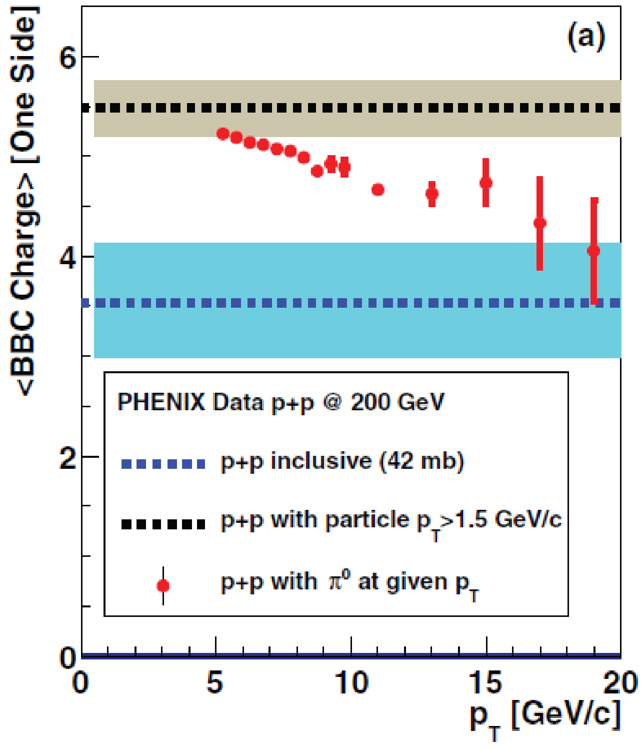


FIG. 7. Comparison of the minimum bias hadron nuclear modification factor in OO collisions at $\sqrt{s_{NN}} = 5.02$ TeV (upper band) and $\sqrt{s_{NN}} = 7$ TeV (lower band).

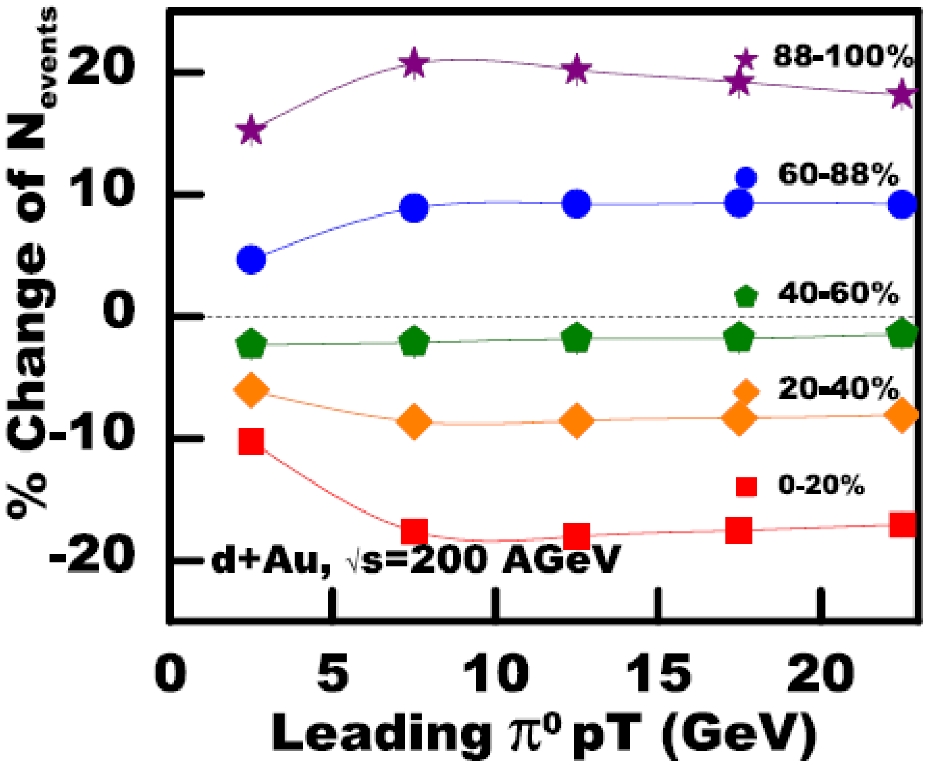
Color transparency or energy conservation in R_{xA}?

Kordell, Majumder PRC 97, 054907 (2018)

"…the puzzling enhancement in peripheral events … as well as the suppression seen in central events… are possibly due to ***mis***-binning of central and semicentral events, containing a jet, as peripheral events… due to suppression of soft particle production away from the jet, caused by the depletion of energy available in a nucleon of the deuteron in d-Au or proton in p-Pb after the production of a hard jet… "



PRC 90, 034902 (2014)



Centrality from bulk observables – but where?

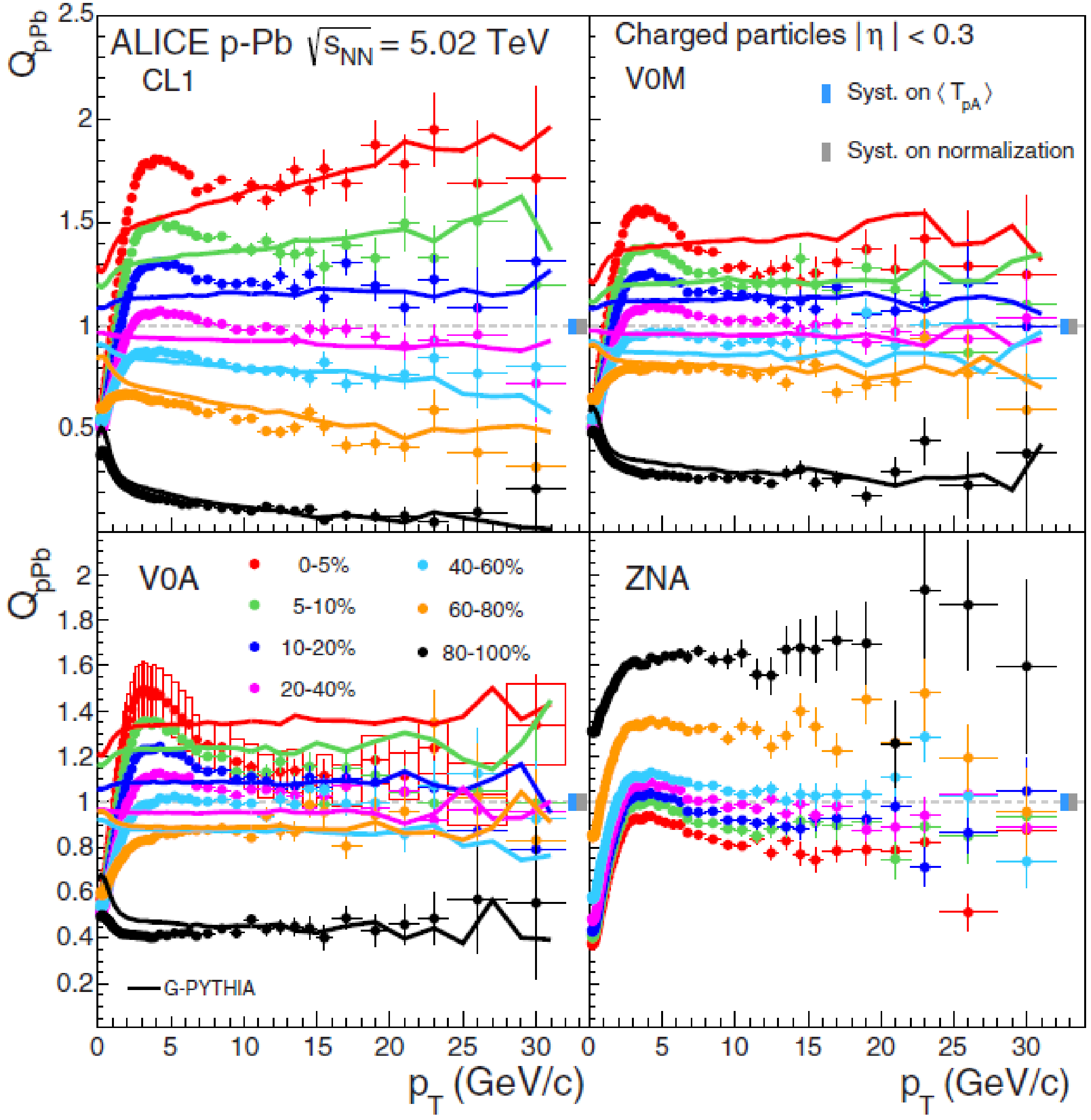
ALICE PRC 91 (2015) 064905

CL1 → |η| < 0.9
V0A → 2.8 < η < 5.1 (Pb-going side)
V0C → -3.7 < η < -1.7 (p-going side)
V0M → V0A + V0C
ZNA → ZDC on Pb-going side

Watch strong auto-correlation in CL1 central, jet veto bias in peripherals

Smaller fluctuations in V0A, mostly around unity, except vastly displaced peripheral due to multiplicity bias (?)

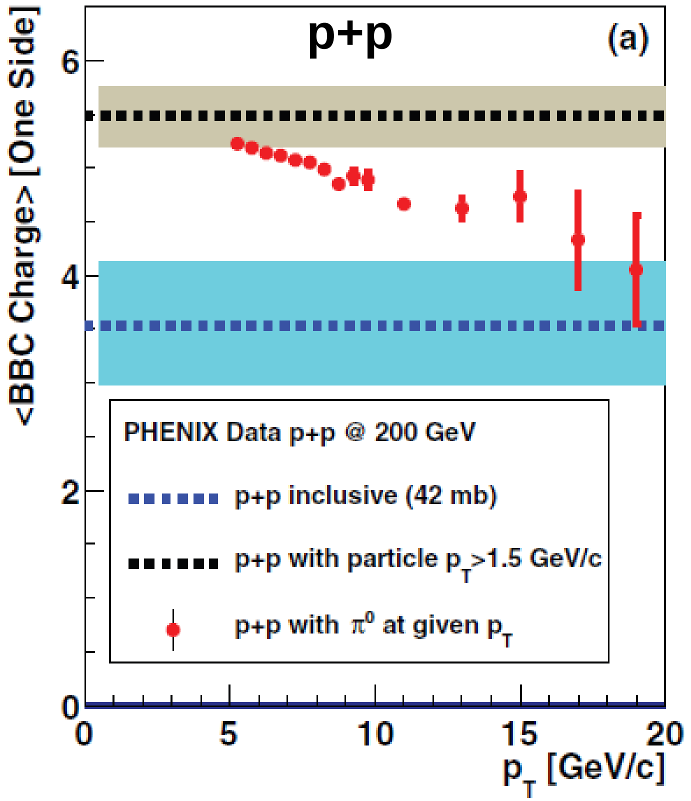
Reverse ordering for ZNA, as expected (as expected???)



Does bulk observable-based centrality fix N_{coll} once and for all?

"In heavy ion collisions, we manipulate the fact that the majority of the initial state nucleon-nucleon collisions will be analogous to minimum bias p+p collisions…"

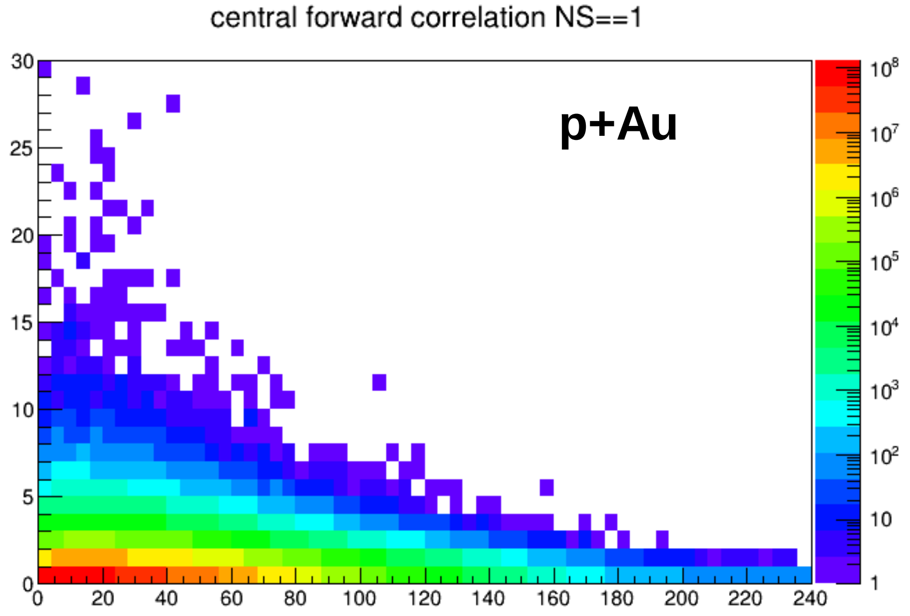
No, it is biased, and the bias changes as a function of the hardest scattering seen at mid-rapidity!



PRC 90, 034902 (2014)

Highest p_T seen at $\eta = 0$

Anticorrelation!



Charge seen at $-3.9 < \eta < -3.0$

A way out: actually measure N_{coll}

Is it possible? Yes, at least you can get close, and at the very least get rid of fake final state effects in R_{xA}.

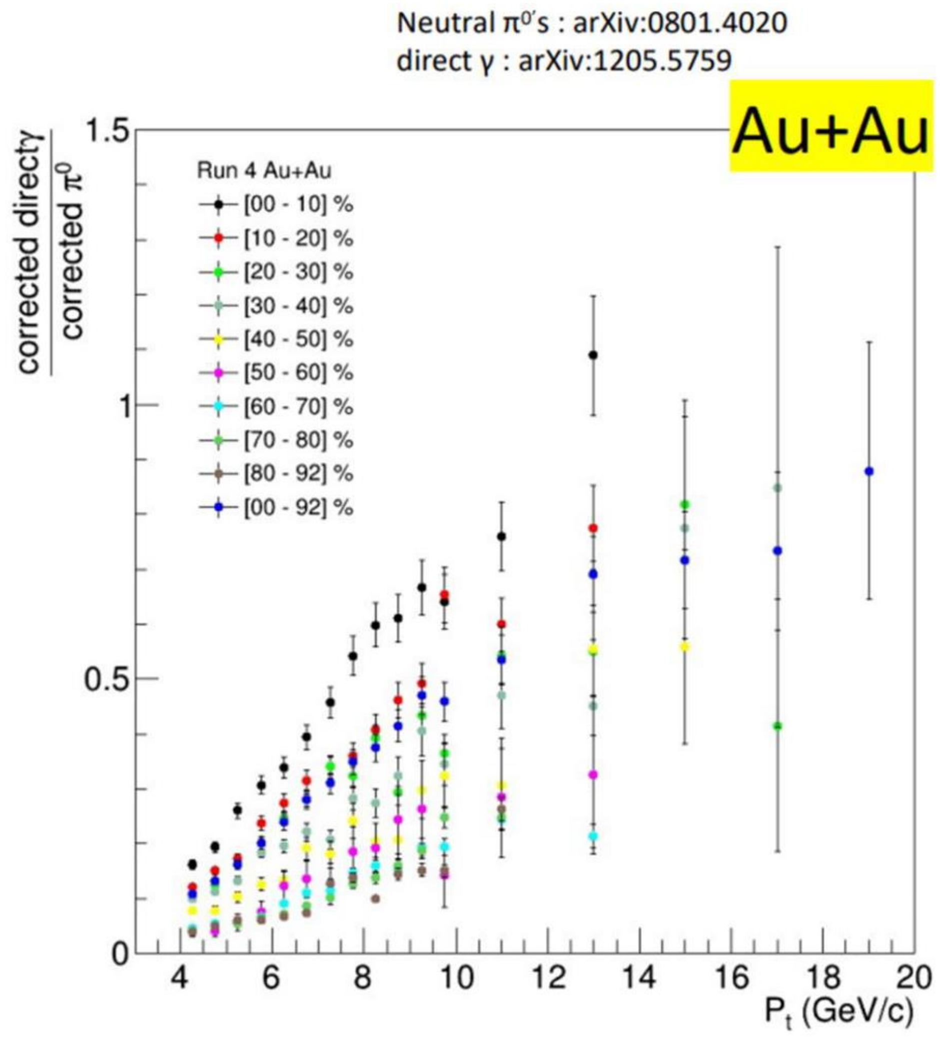
Remember, photons don't care about FS → mostly true, at high p_T most of them are from initial hard scattering and have 200+ *fm* mean free path in QGP (e.g. *Rept.Prog.Phys.* 83 (2020) 4, 046301)

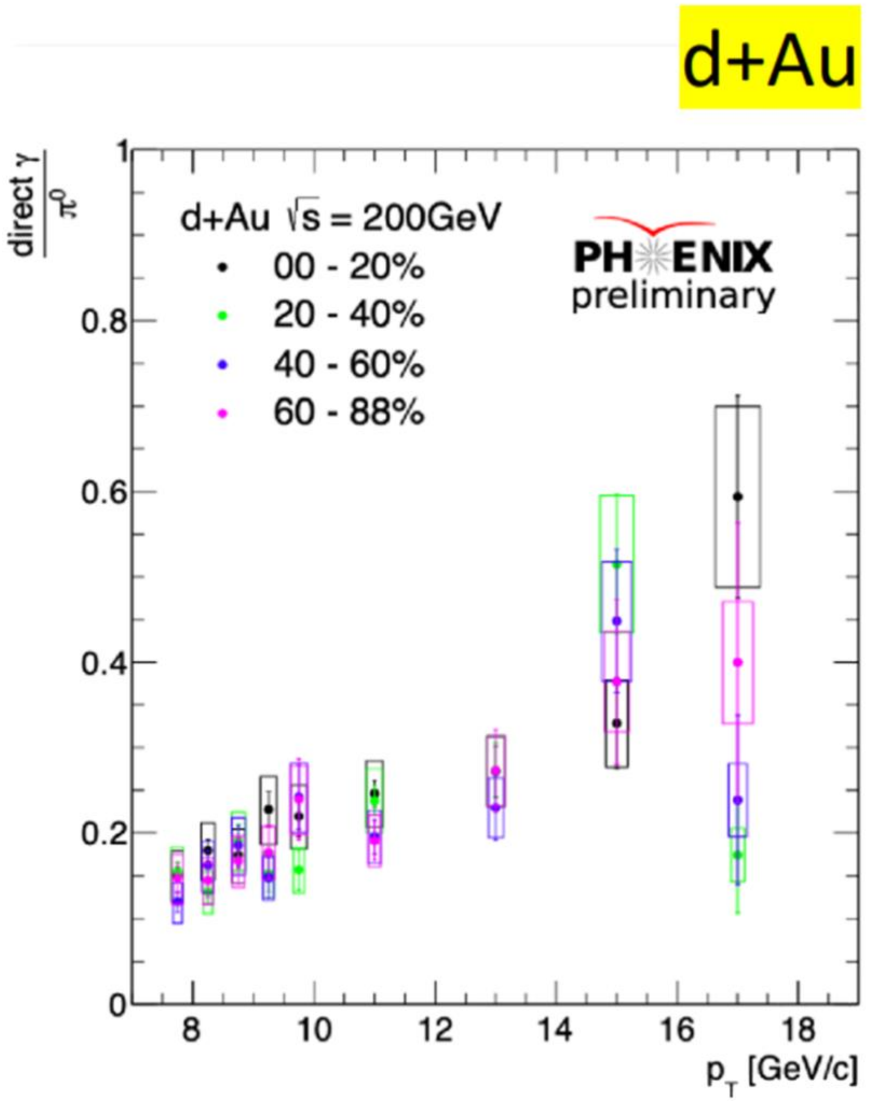
For an arbitrary "centrality" classification just take the ratio of the direct photon and hadron spectra
→ pure centrality bias (even if p_T-dependent) will affect both similarly
→ if the ratios change with centrality, there's a genuine final state effect on hadrons

Same idea, different realization: you can get N_{coll} experimentally from the $Y^g(AB,p_T)/Y^g(pp,p_T)$ direct photon yield ratios

$$N_{coll}^{EXP} = \frac{\left(\frac{d^2N_\gamma}{dp_T d\eta}\right)_{AB}}{\left(\frac{d^2N_\gamma}{dp_T d\eta}\right)_{pp}} = \frac{Y_{AB}^\gamma}{Y_{pp}^\gamma}$$

The direct γ/π^0 ratio in Au+Au and d+Au as a function of centrality





Clear separation between centralities in Au+Au, overlapping in d+Au

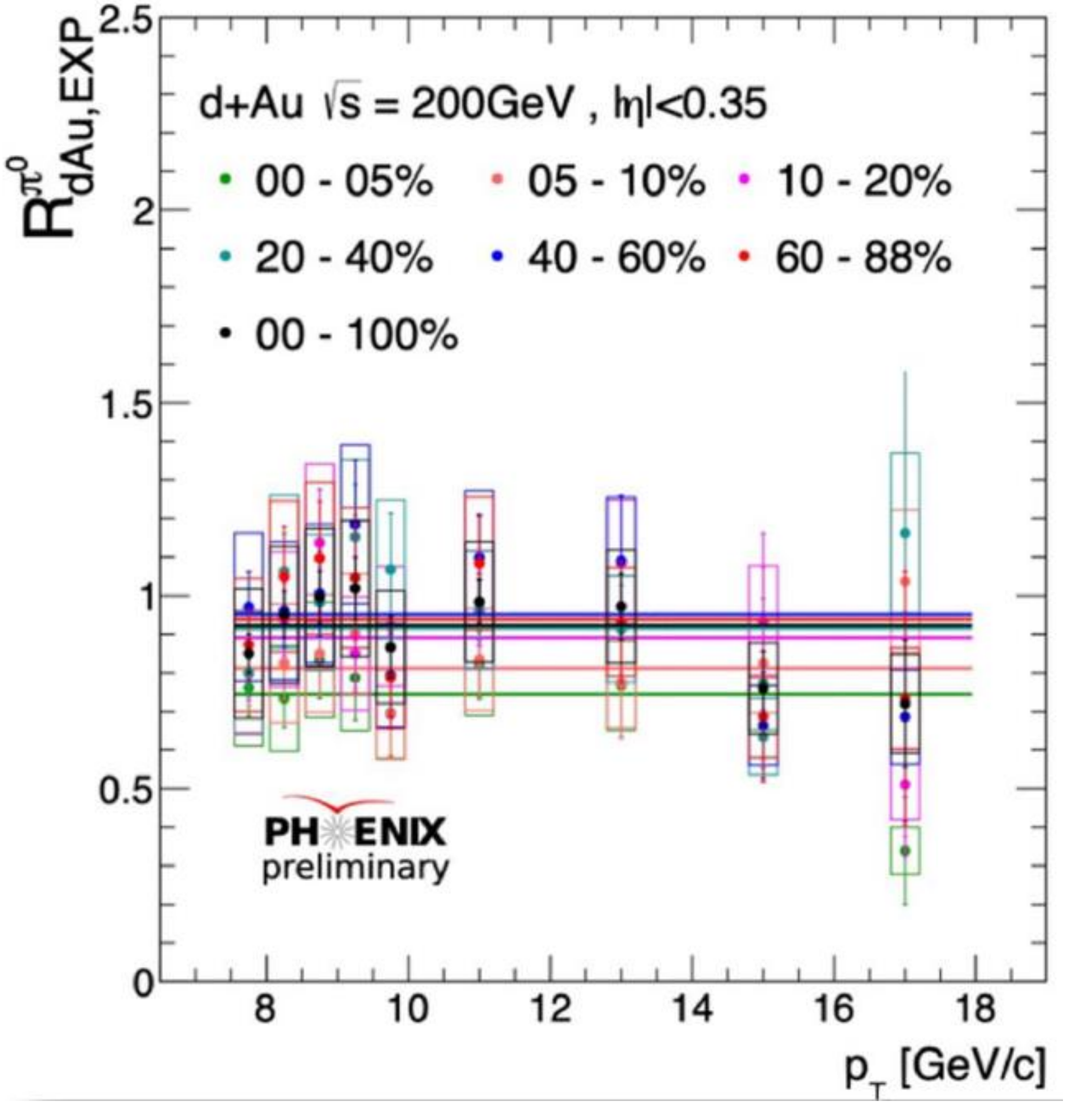
R_{dAu} with this experimental (photon-based) N_{coll}

Constant fits dominated by 8-10 GeV/c
(p$_T$-dependence not taken into account!)

No centrality dependence at 10-88% centrality

Some deviation for 0-5 and 5-10%, remains to be seen if it is
→ some second order bias
→ physics (small FS, IS, nPDF?)

High statistics p+Au and 3He+Au will help



Is this the wise's stone? No – but close ☺

It eliminates a large part of the centrality bias, which even increases with p_T

Caveats:

- photons have isospin-effect, hadrons do not
- photons sample lower x than the parent parton of the leading hadron
- photons come almost exclusively from quark-gluon Compton scattering
- CNM may affect them differently (theorists, any ideas)?

Summary

Starting with counter-intuitive R_{xA} results we found that the traditional Glauber MC fails at high p_T

The fundamental reason is energy conservation, no matter what language you chose to say this

The "excitation function" (system size and energy dependence) of the effect remains to be seen and should be very revealing

Once the above bias is eliminated, it is quite possible that finer, interesting effects will be found (IS or FS)

Maybe not the ultimate solution, but direct photons are currently the best estimate of the true, p_T-dependent N_{coll}

Better, more subtle ideas are welcome!

"Small systems", once upon a time a control experiment, are full of surprises and maybe new physics!

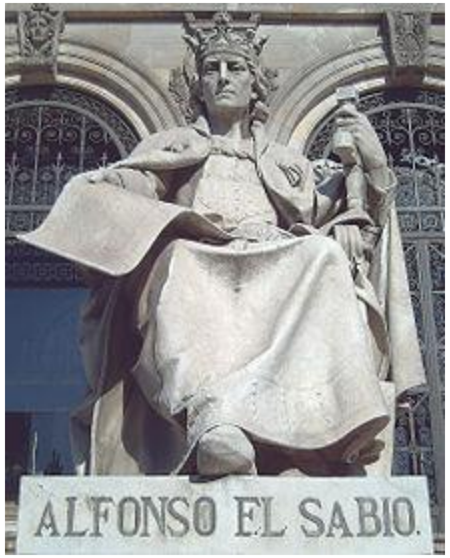
Thanks for your attention, but first a centuries old sigh…

Alfonso the Xth (“Alfonse the Wise”)

1221-1284
Monarch of Castilia
One of the best scientists of his age
(and big time supporter of science)

“Alfonsine tables” used even by
Copernicus, superseded only
by Kepler in 1627

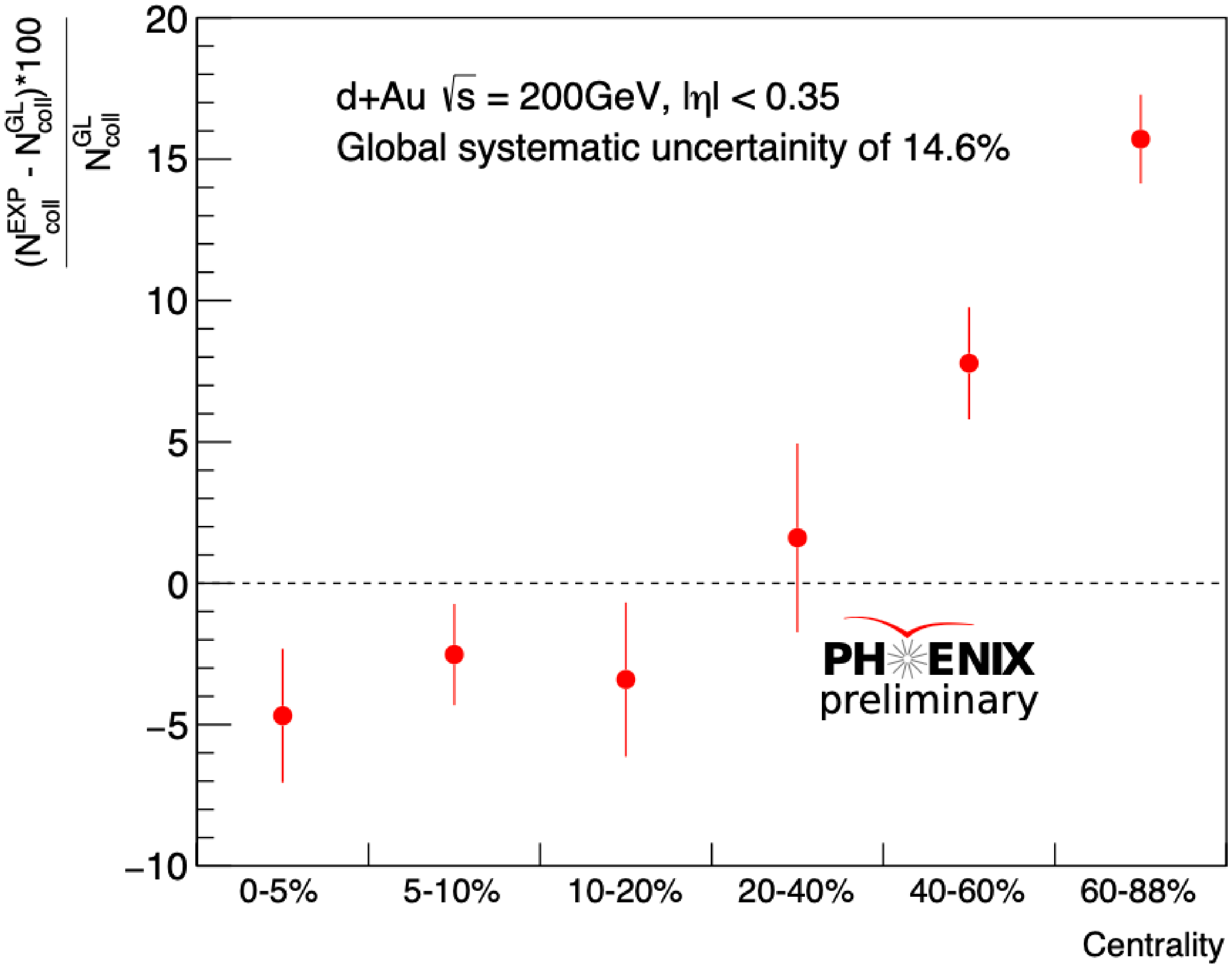
So he knew what he was talking about,
when sighed (and we all should agree…):



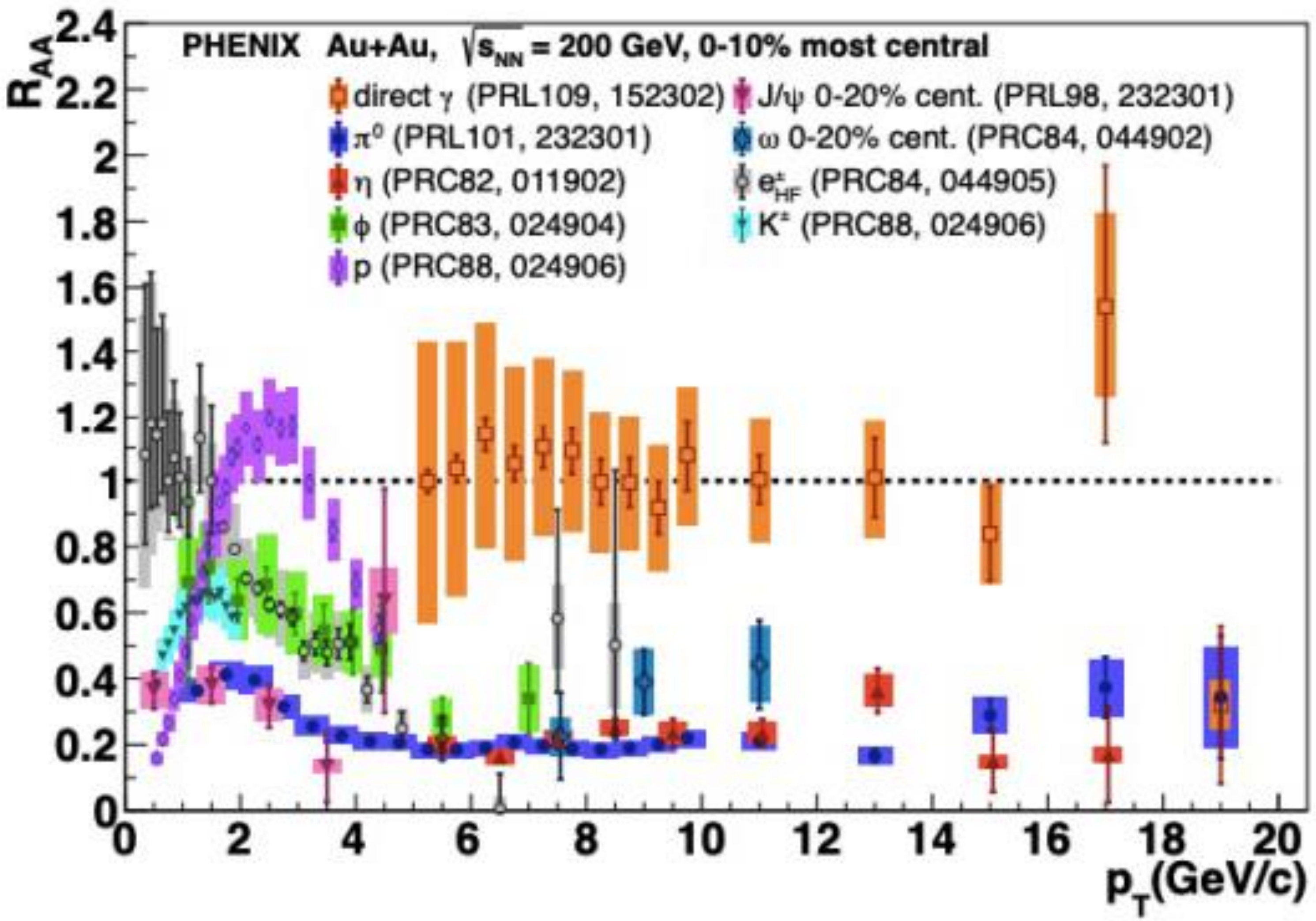
If the Lord Almighty had consulted me before embarking upon creation,
I should have recommended something simpler.

Backup

Glauber vs experimental N_{coll}



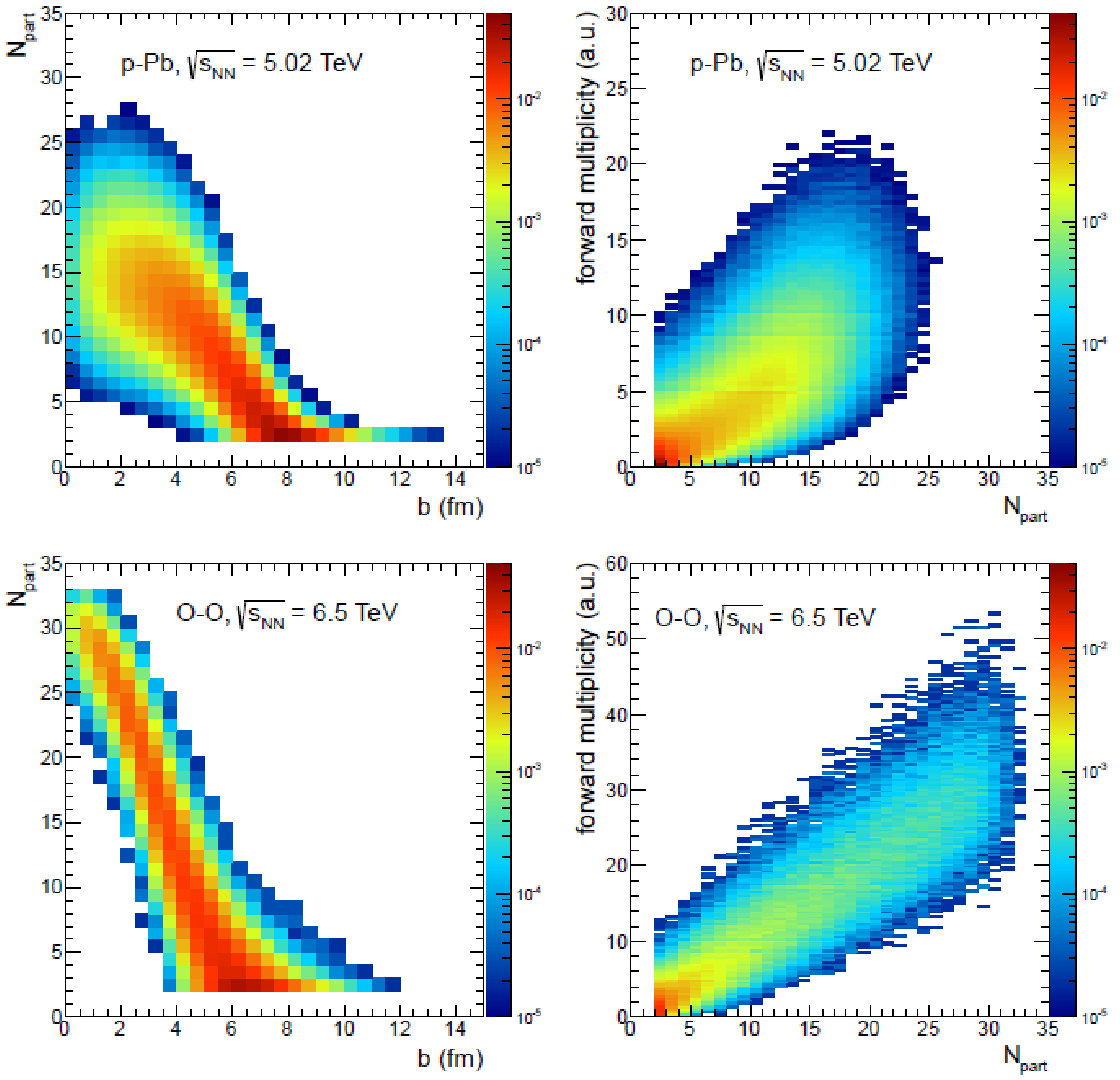
PHENIX T-shirt plot



CERN Perspectives of HE-LHC, WG 5

CERN-LPCC-2018-07
1812.06772

In essence, by selecting high (low) multiplicity one chooses not only large (small) average N_{part}, but also positive (negative) multiplicity fluctuations leading to deviations from the binary scaling of hard processes.



Event activity correlations in small systems

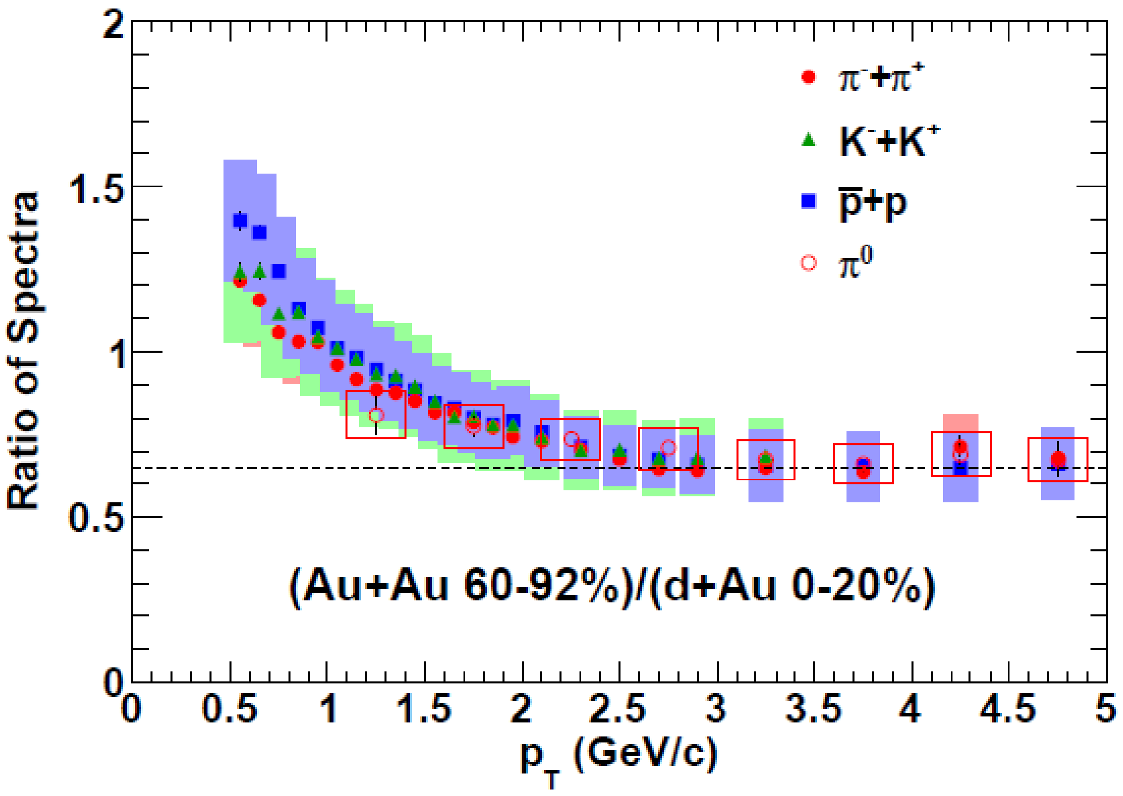
PHENIX, PRC 88, 024906 (2013)

N_{part}, N_{coll} are almost identical
If CNM depends on them, it would cancel in the ratio
E_{loss} in peripheral Au+Au?

No mass or quark content dependence

But: rapidity shift in d+Au (ratio up at low p_T)

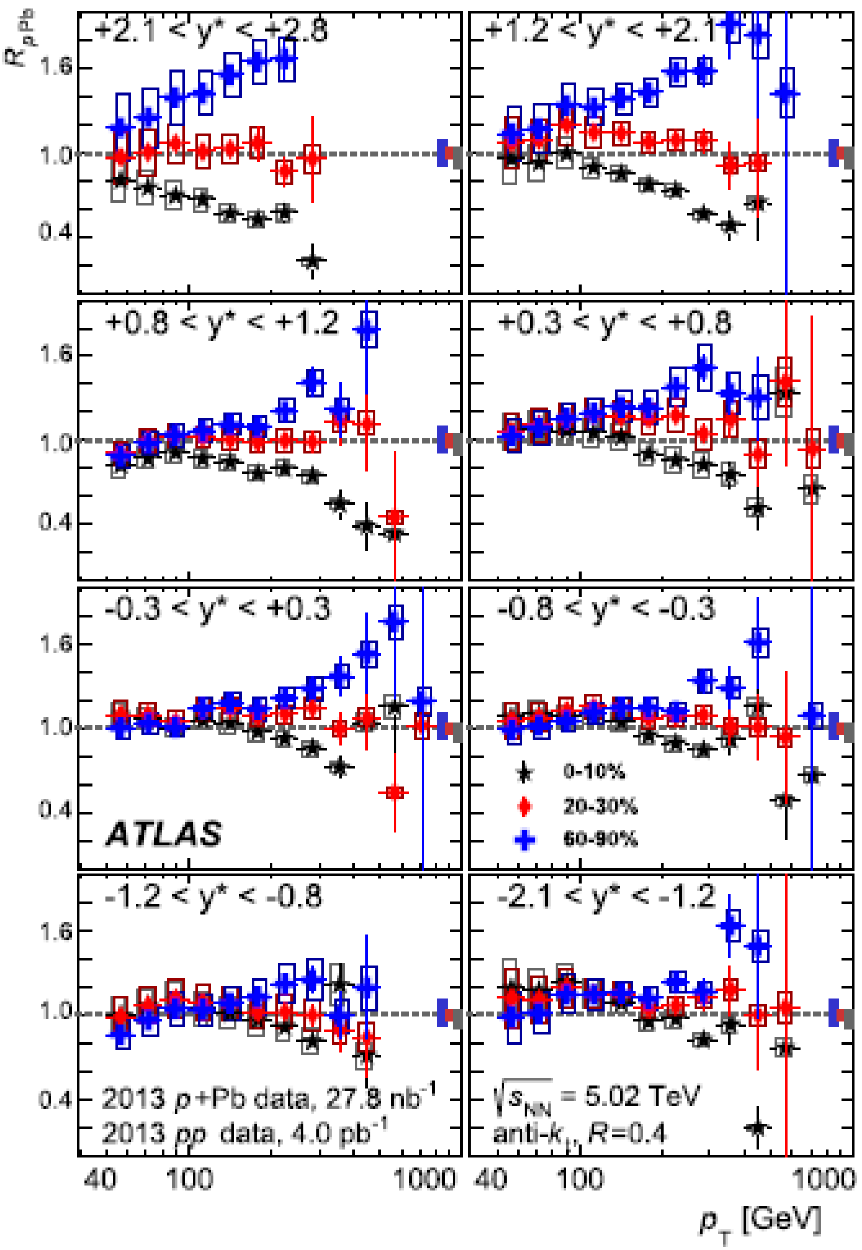
nPDF: both modified in Au+Au, only one in d+Au



Rapidity dependence of jet R_{xA} – ATLAS, standard Glauber

PLB 748 (2015) 392-413

Centrality: E_T in FCAL,
Pb-going side (large gap)



p-going direction
(large projectile x)

Pb-going direction
(small projectile x)

ALICE – jet quenching in p-Pb strongly constrained

PLB 783 (2018) 95-113

"… in p-Pb… out-of-cone energy transport … [15-50GeV jets]… is less than 0.4 GeV/c … over an order of magnitude smaller than a similar measurement for central Pb-Pb…

Based or event activity in ZNA and V0A, both consistent and at a large rapidity gap
No assumption about correlations of event activity and geometry

Charged jets recoiling from a high p_T hadron