Confirming RHIC saturation signals at the LHC ? at the FCC?

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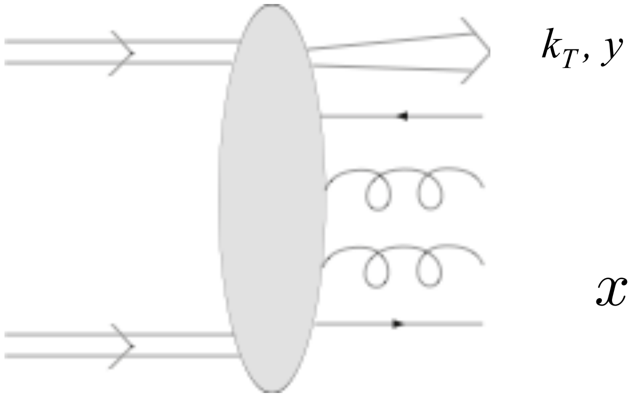
Saturation signal #1:

forward rapidity suppression
of the nuclear modification
factor in p+A vs p+p

Single inclusive hadron production

forward rapidities probe small values of *x*



transverse momentum k_T, rapidity $y > 0$

values of x probed in the process:

$$x_1 = M_T\ e^{y}/\sqrt{s} \qquad x_2 = M_T\ e^{-y}/\sqrt{s}$$

$$M_T^2 = (k_T/z)^2 + m_h^2$$

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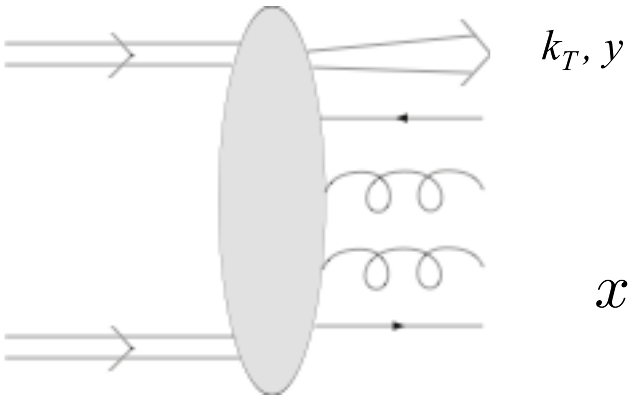

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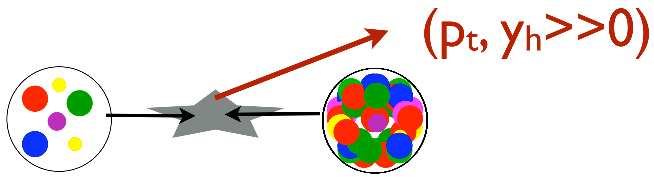

large-x parton from proj. (pdf)

small-x glue from target (CGC)

$$\frac{dN_h}{dy_h\, d^2p_t} = \frac{K}{(2\pi)^2} \sum_q \int_{x_F}^{1} \frac{dz}{z^2} \left[x_1 f_{q/p}(x_1, p_t^2)\, \tilde{N}_F\left(x_2, \frac{p_t}{z}\right) D_{h/q}(z, p_t^2) \right.$$

$$\left. + \, x_1 f_{g/p}(x_1, p_t^2)\, \tilde{N}_A\left(x_2, \frac{p_t}{z}\right) D_{h/g}(z, p_t^2) \right]$$

fragmentation

Nuclear modification factor

$R_{dA} = 1$ in the absence of nuclear effects, i.e. if the gluons in the nucleus interact incoherently as in A protons

$$R_{dA} = \frac{1}{N_{coll}} \frac{\dfrac{dN^{dA \to hX}}{d^2kdy}}{\dfrac{dN^{pp \to hX}}{d^2kdy}}$$

the suppressed production ($R_{dA} < 1$) was predicted in the Color Glass Condensate picture, along with the rapidity dependence

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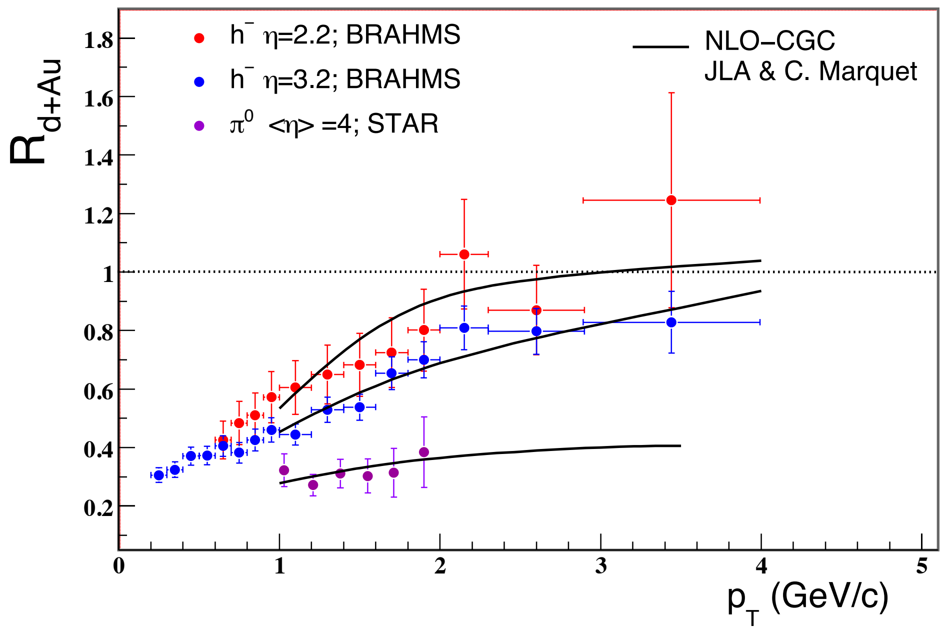


Albacete and CM (2010)

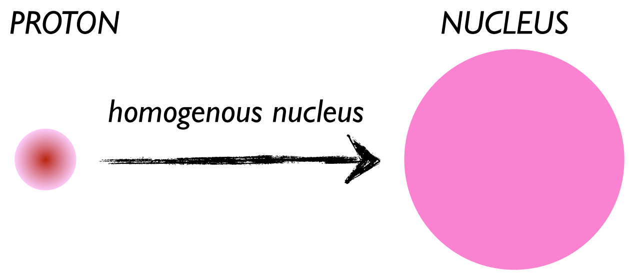
note: alternative explanations (large-x energy loss effects) have been proposed

Kopeliovich et al (2005), Frankfurt et al (2007)

Importance of nuclear geometry

- the impact parameter dependence of the gluon density and of Q_S

in the case of a proton, using an impact-parameter averaged saturation scale is enough most of the time, but in the case of a nucleus it is not



leads to R_{pA} strongly dependent on the chosen nuclear saturation scale value, p_t dependence too flat

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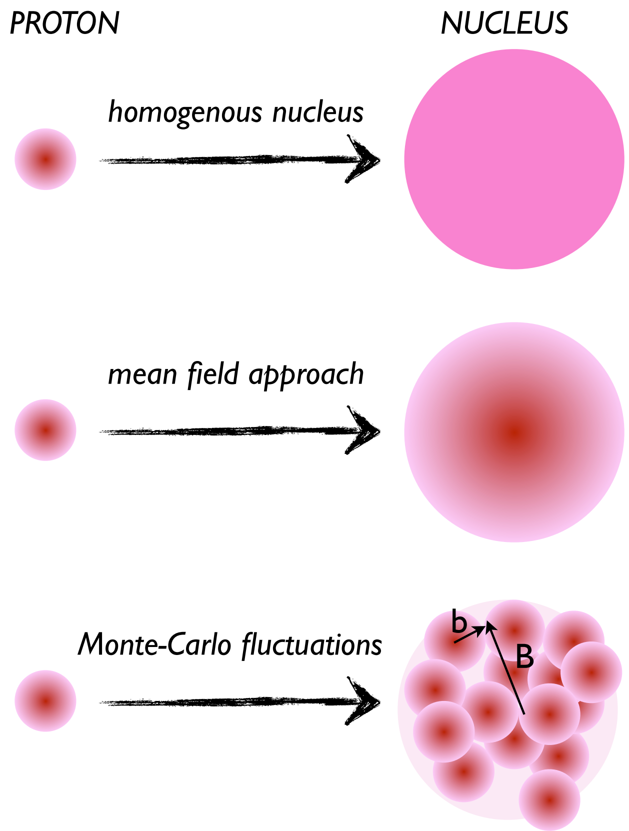


leads to R_{pA} strongly dependent on the chosen nuclear saturation scale value, p_t dependence too flat

p_t dependence of R_{pA} better, but still a large uncertainty due to modeling of the B profile

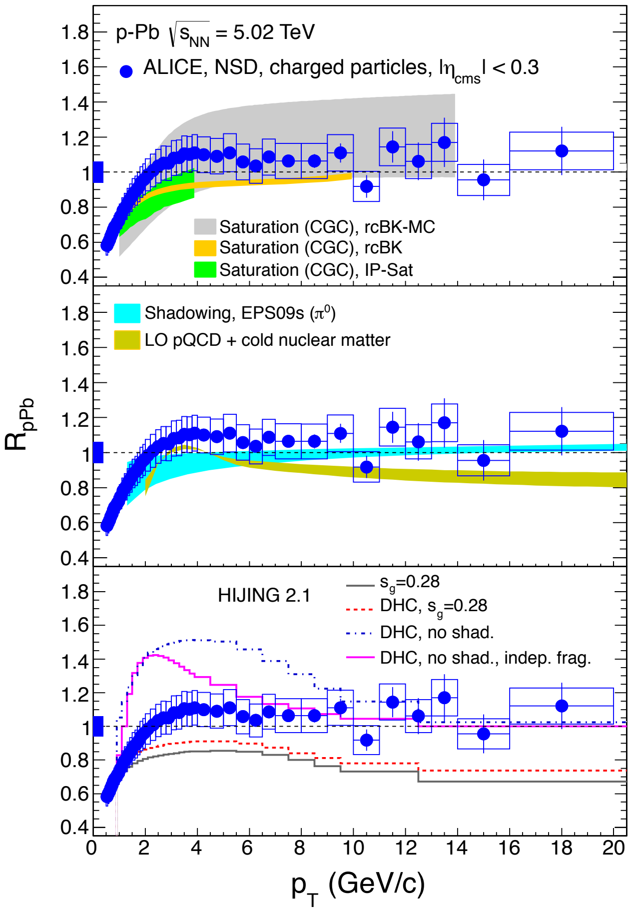
proper modeling of the nuclear geometry and of its fluctuations done in the rcBK and IP-Glasma MCs

Schenke, Tribedy and Venugopalan (2012)

Albacete, Dumitru, Fujii and Nara (2013)

p+Pb @ the LHC

- mid-rapidity data



good description but not much non-linear effects

p+Pb @ the LHC

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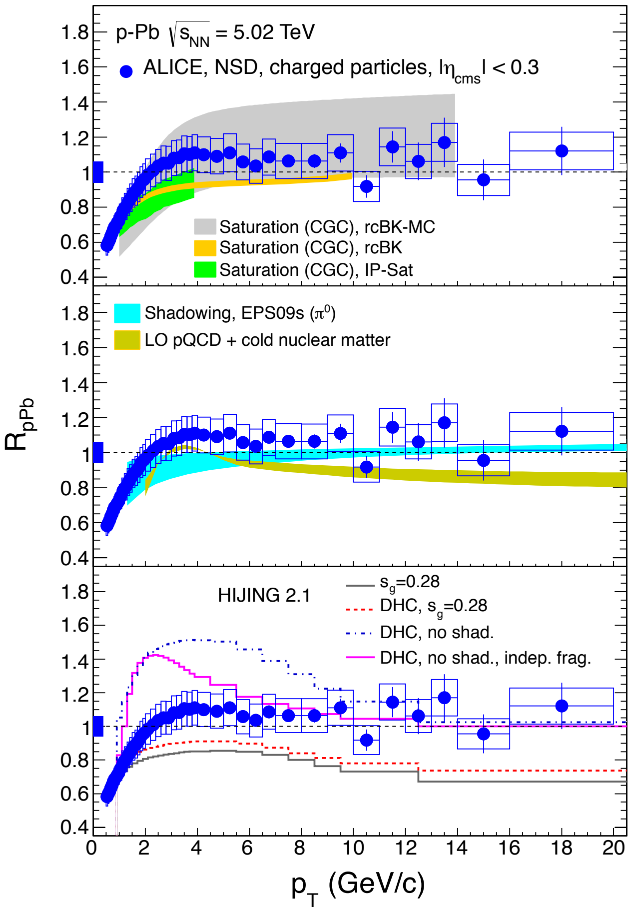

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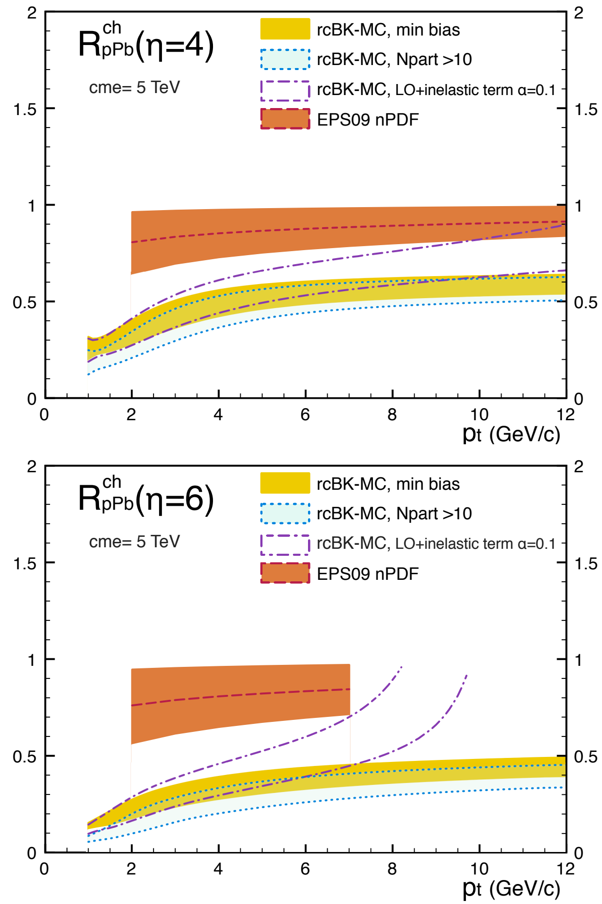
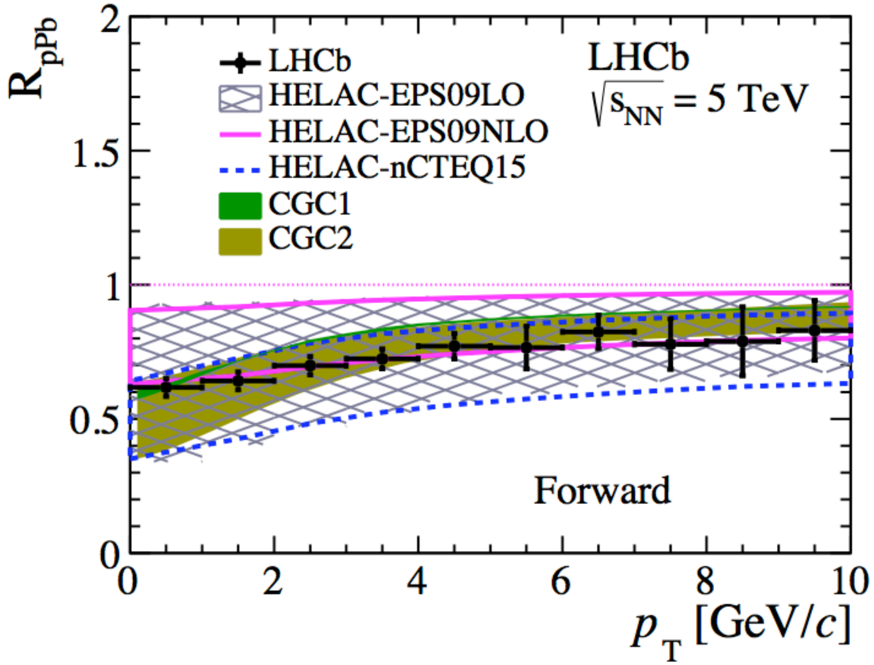
- predictions for forward rapidities



strong non-linear effects
but huge uncertainty above 6 GeV

Forward D mesons

- now we have forward-rapidity hadron data to compare to:



first forward R_{pA} measured at the LHC
(omitting quarkonia who are also sensitive
to other suppression mechanisms)

first saturation hint in LHC R_{pA}
study to be made for FCC

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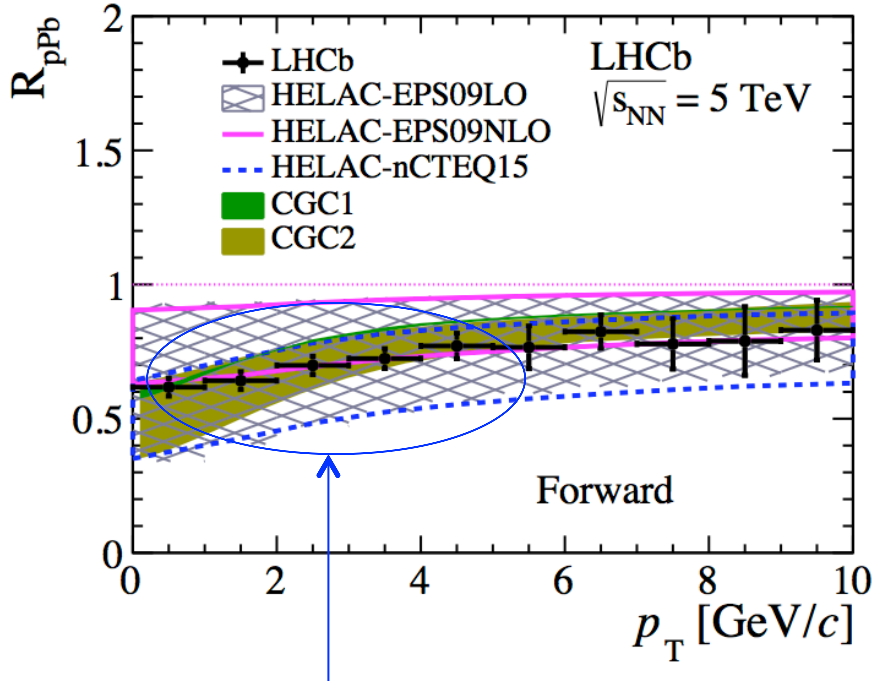

saturation effects here

first forward R_{pA} measured at the LHC
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collinear factorization calculations
are also consistent with the data,
but suffer from huge uncertainties
in the 1-6 GeV range

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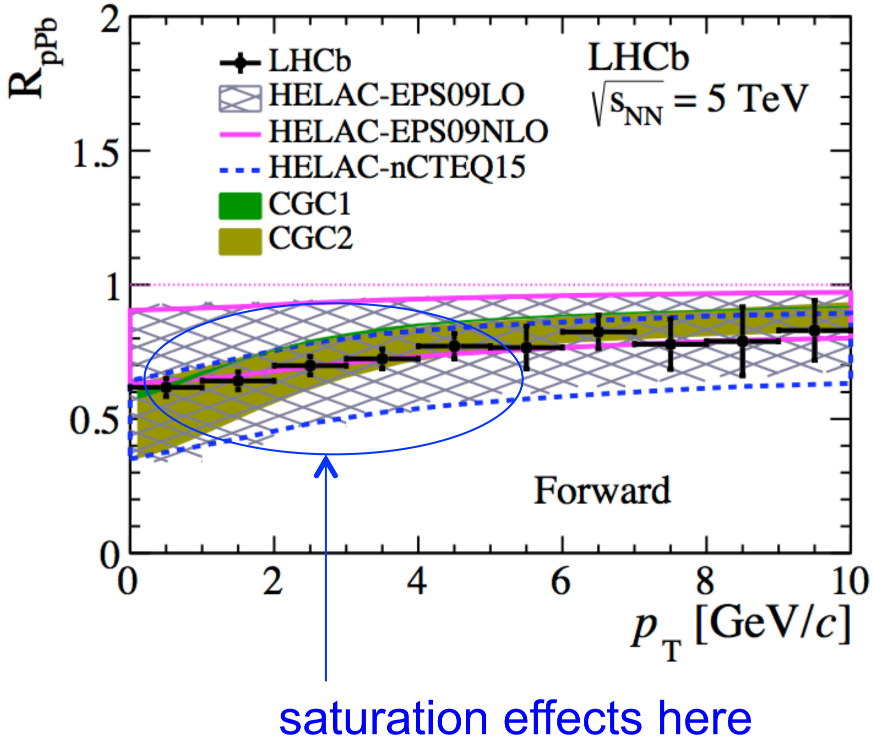

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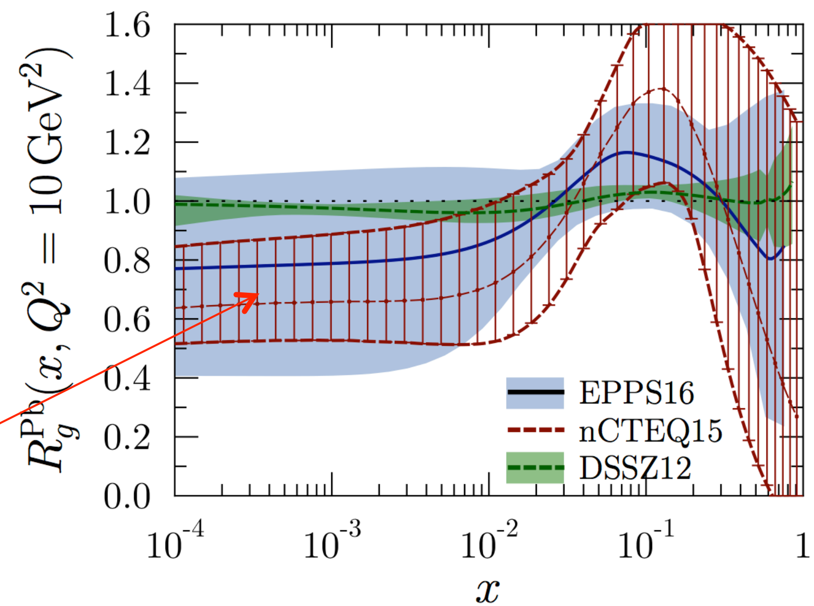
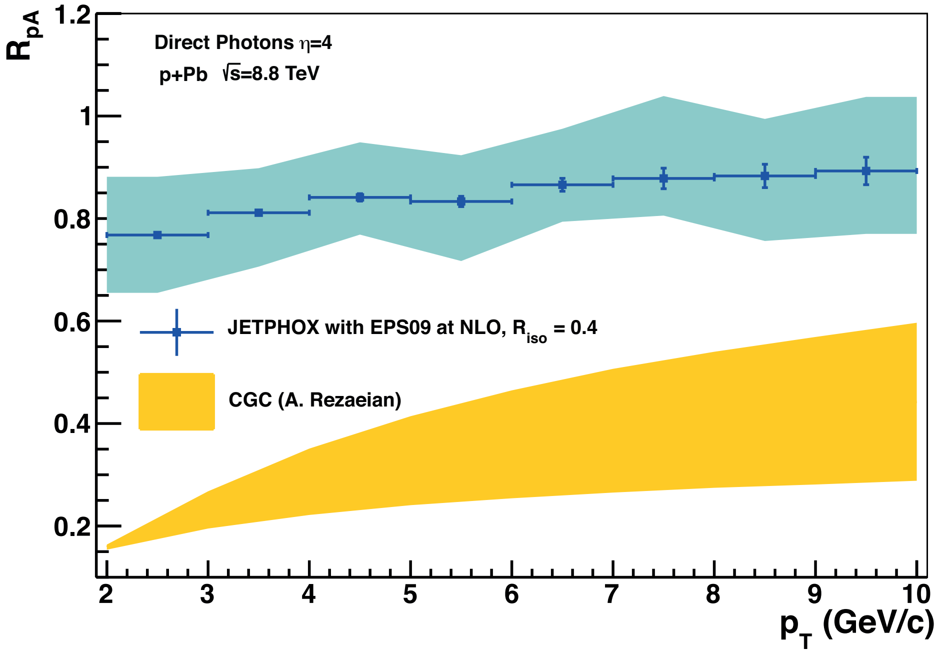


collinear factorization calculations are also consistent with the data, but suffer from huge uncertainties in the 1-6 GeV range

Best way to confirm R_{pA} suppression ?

- isolated photons at forward rapidities
  - no isospin effects in p+Pb vs p+p (contrary to d+Au vs p+p at RHIC)
  - smallest possible *x* reach: no mass, no fragmentation
  - no cold matter final-state effects (E-loss, …)

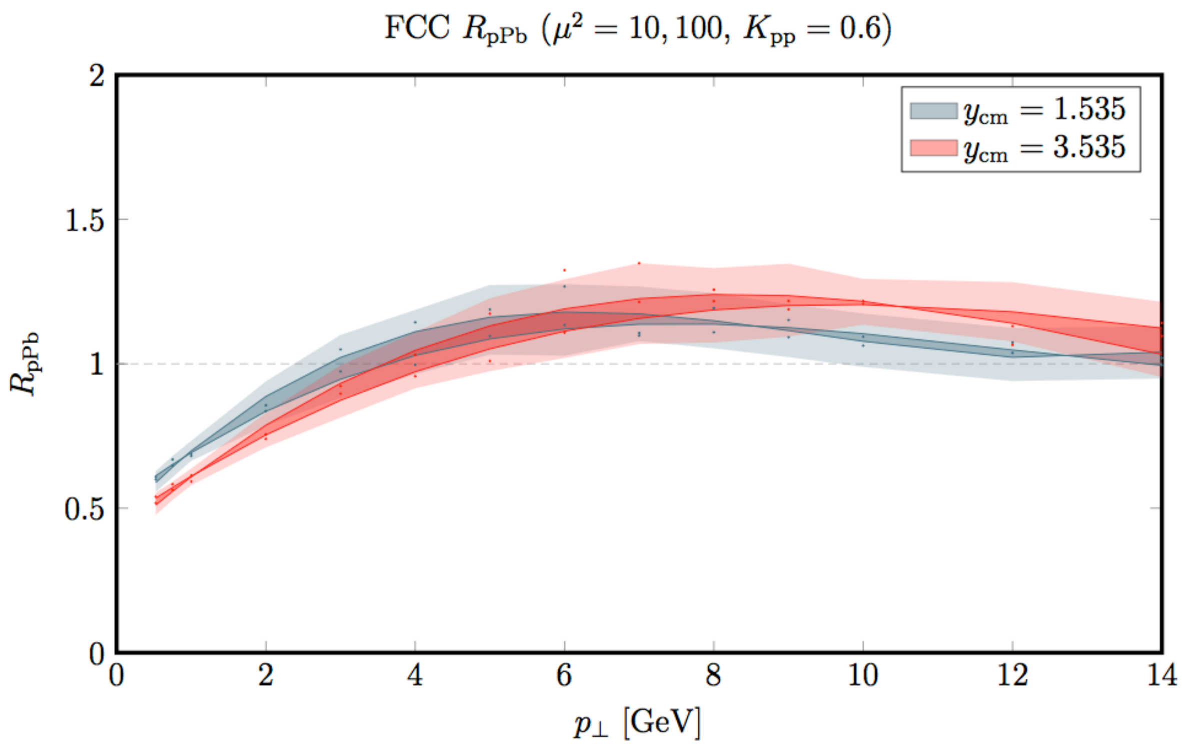


large EPS09 / CGC difference
In forward rapidity predictions

not sure nuclear geometry was
properly included to make that curve
(but I believe it is in the FCC study)

Now we have (almost) NLO

- p+Pb @ the FCC:



this is preliminary, but what if saturation effects impact R_{pA} only below 3 GeV, even at the FCC ?

Saturation signal #2:

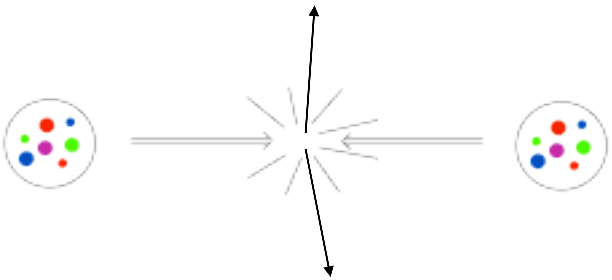
forward rapidity suppression
of di-hadron azimuthal
correlations in p+A vs p+p

Di-hadron final-state kinematics

final state : $k_1, y_1 \quad k_2, y_2$

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

scanning the wave functions:



$$x_p \sim x_A < 1$$

central rapidities probe moderate x

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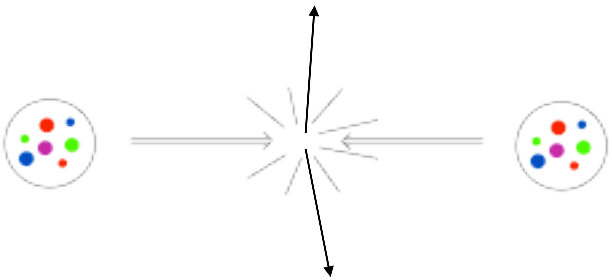
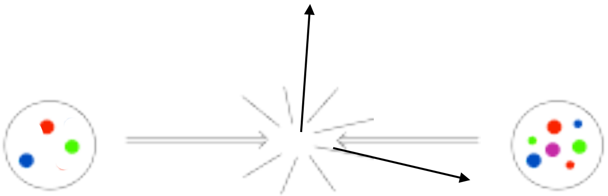


$$x_p \sim x_A < 1$$

central rapidities probe moderate x

x_p increases | x_A ~ unchanged



$$x_p \sim 1,\, x_A < 1$$

forward/central doesn't probe much smaller x

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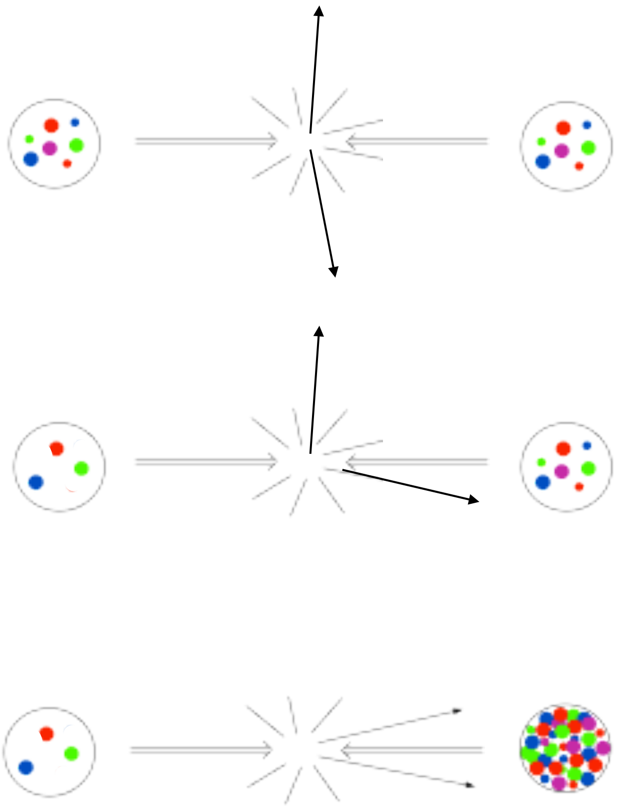

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central rapidities probe moderate x

x_p increases | x_A ~ unchanged

$$x_p \sim 1,\, x_A < 1$$

forward/central doesn't probe much smaller x

x_p ~ unchanged | x_A decreases

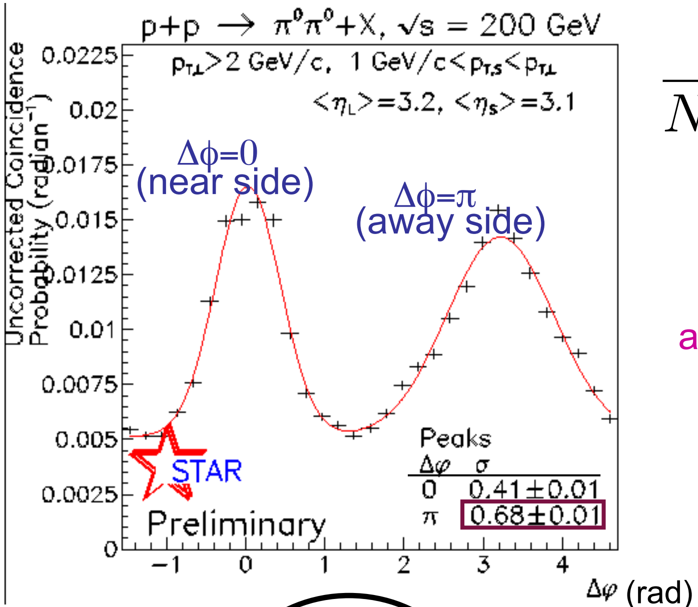
$$x_p \sim 1,\, x_A << 1$$

forward rapidities probe small x

Di-hadron angular correlations

comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → h_1 h_2 X

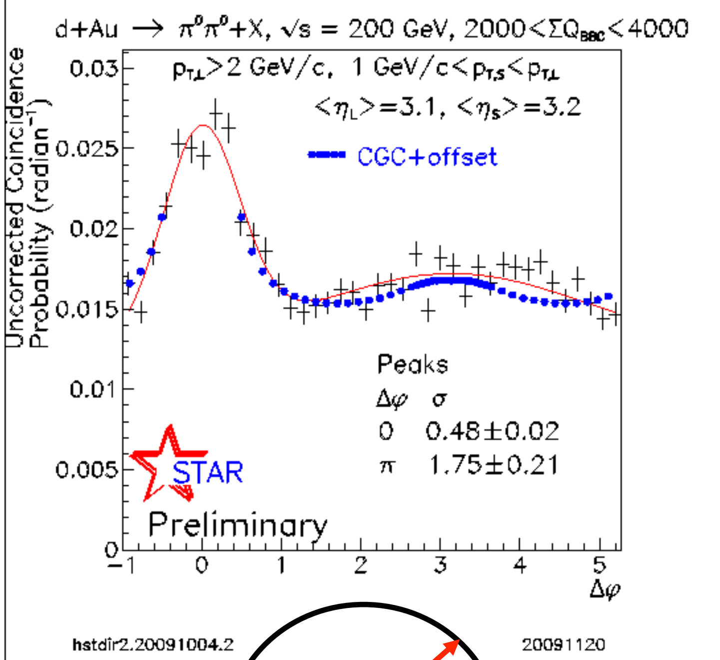
p+p collisions

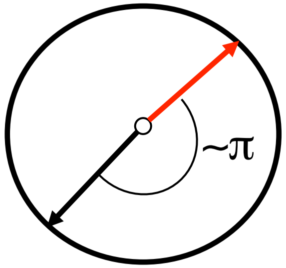


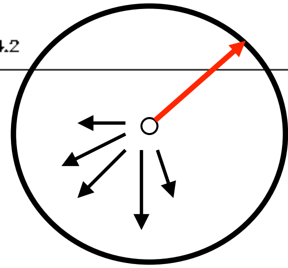
$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

Albacete and CM (2010)

central d+Au collisions







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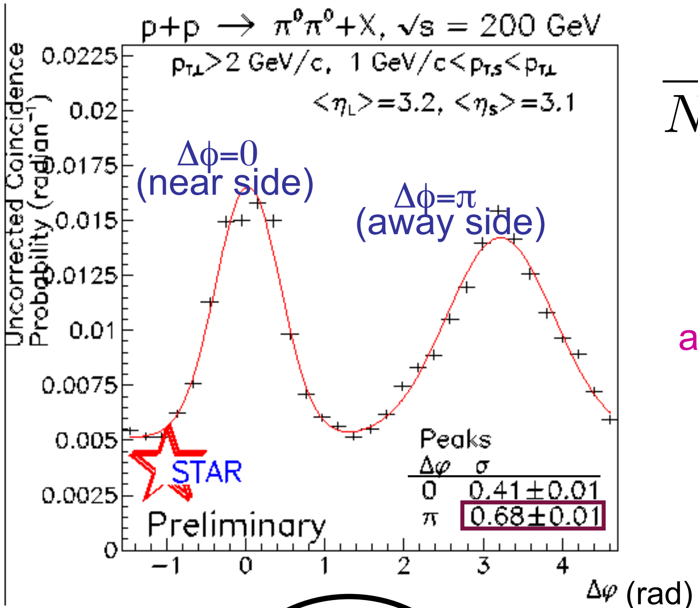

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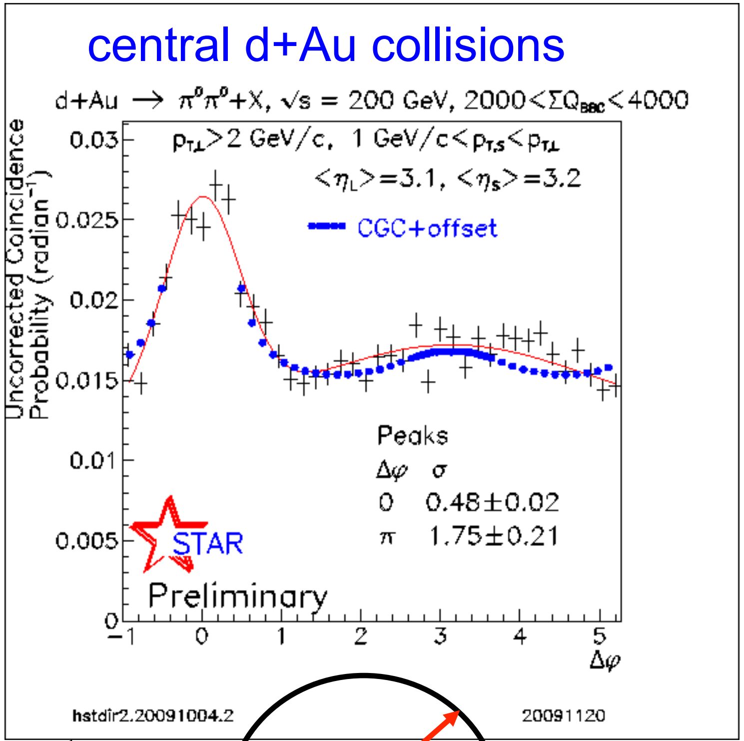
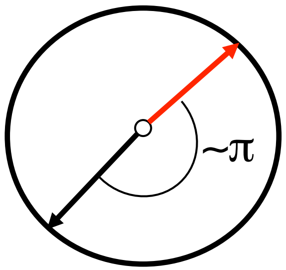
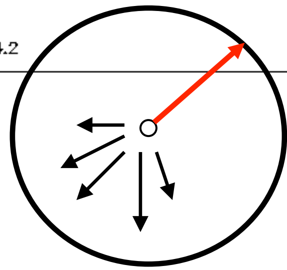




$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

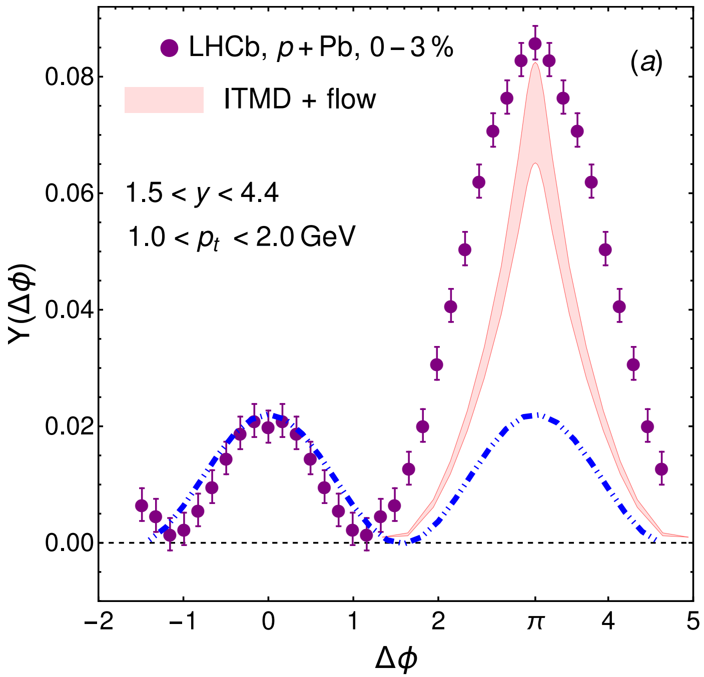


however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$),
the p+p and d+Au curves are almost identical

LHCb forward di-hadrons

- LHCb measured the di-hadron correlation function at forward rapidities

the delta phi distribution shows:
- a ridge contribution (could be flow, Glasma graphs or something else)
- the remainder of the away-side peak can be qualitatively described in the CGC



- need p+p baseline to be conclusive
- study to be made for FCC

Giacalone and CM, in progress

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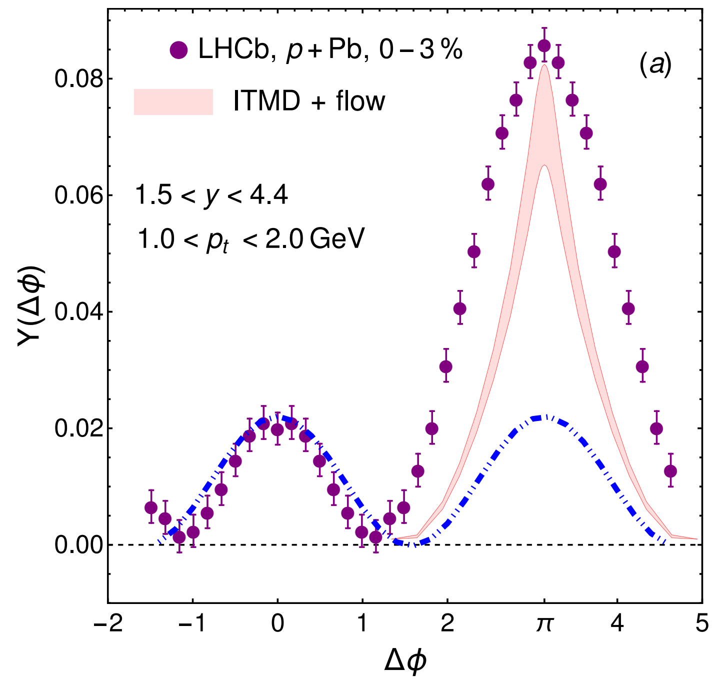

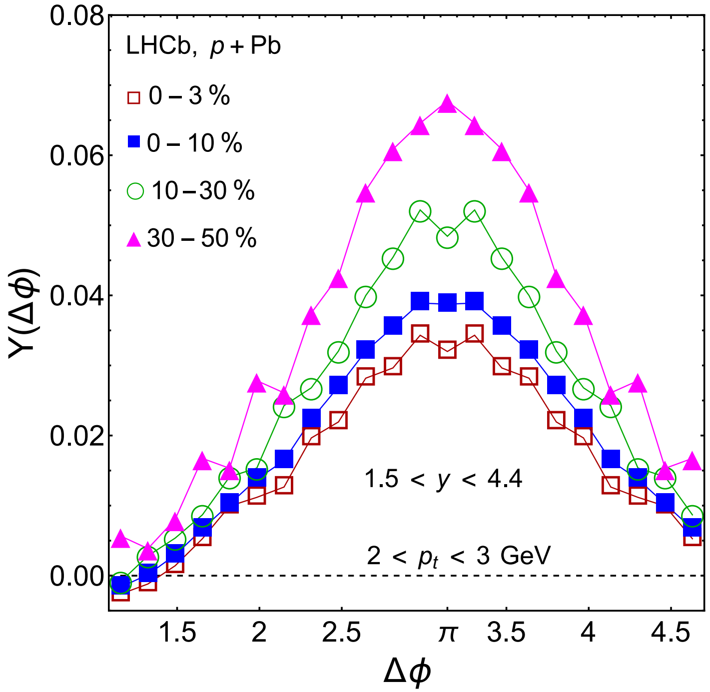

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Giacalone and CM, in progress

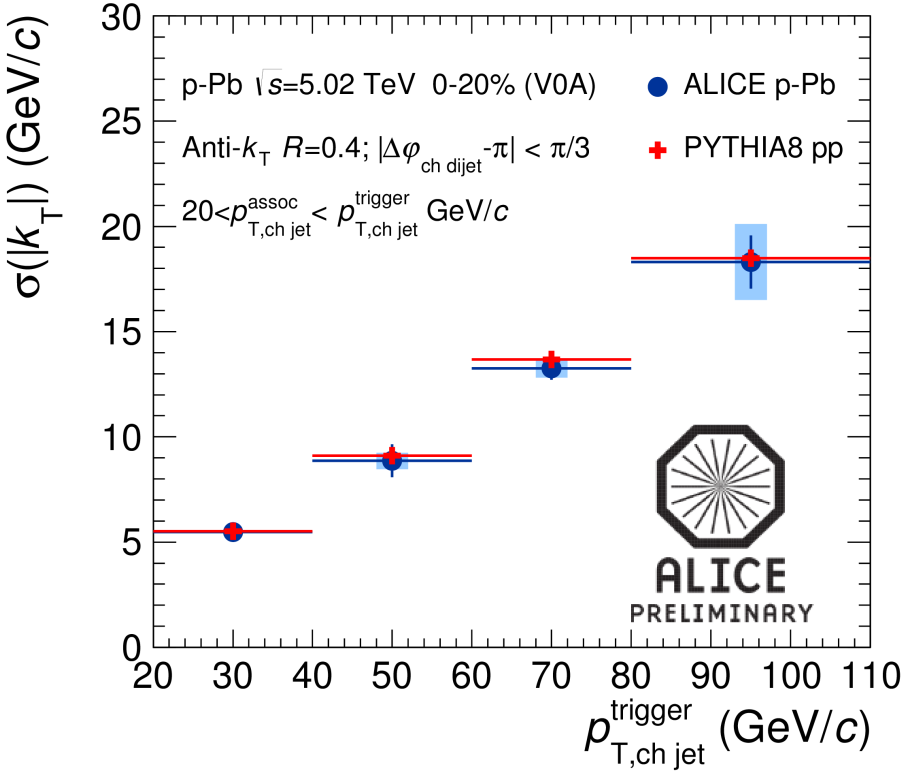
suppression of the away-side peak with increasing centrality seen in the data

What about forward di-jets?

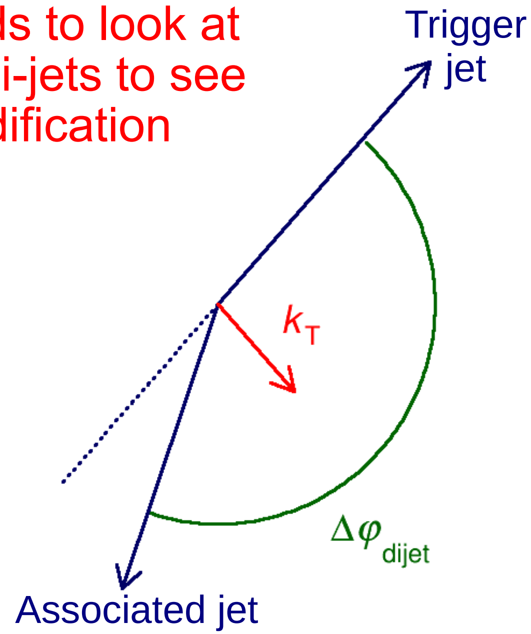
due to saturation effects, nuclear modifications of the transverse momentum imbalance are expected

the idea is to look at $k_T \sim Qs$, non-linear effects at small-x will be important, even though individually the jet p_t's are large

- no sign of such effects at mid-rapidity at the LHC



one needs to look at forward di-jets to see a modification

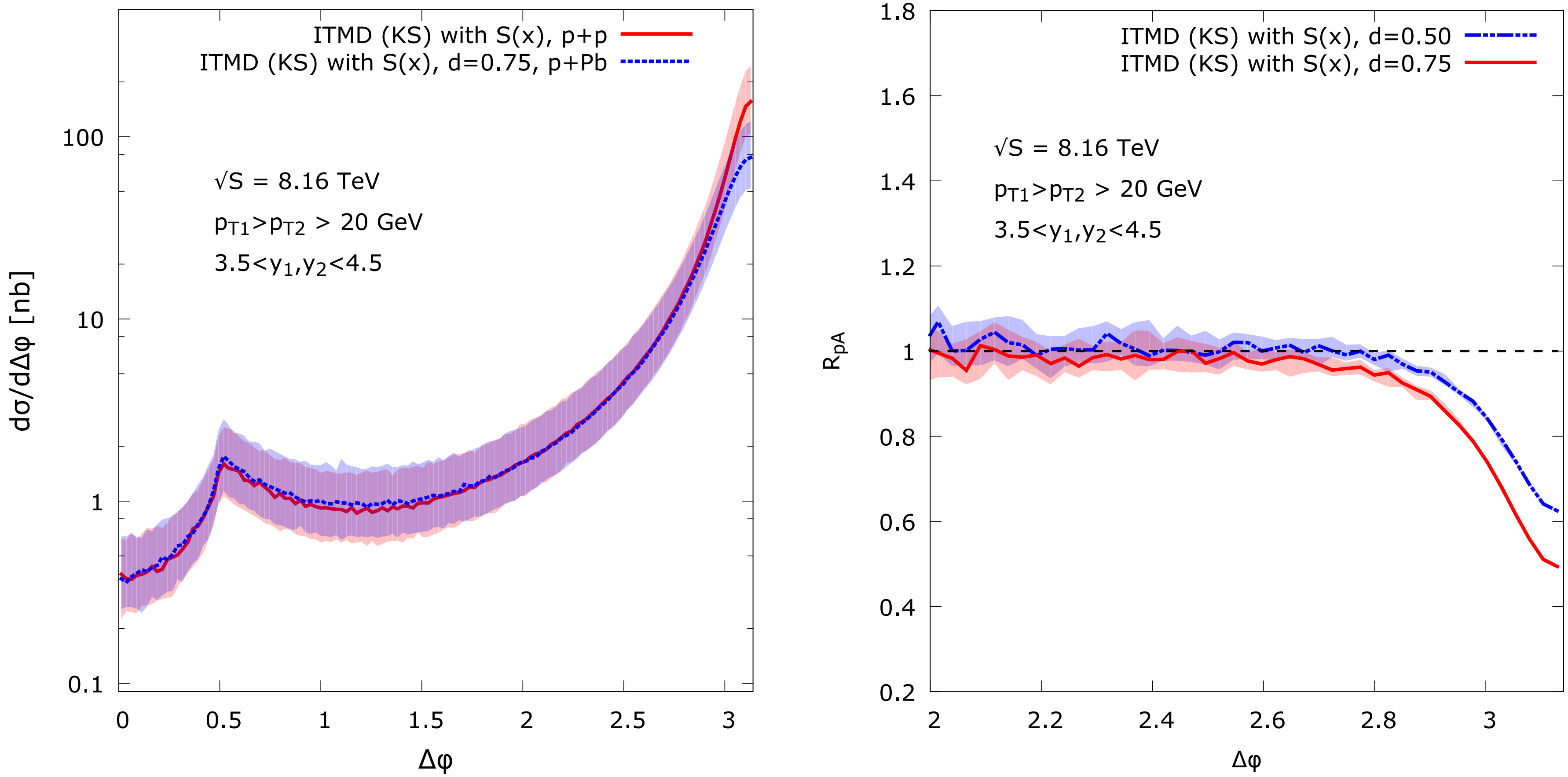


R_{pA} of forward-forward di-jets

- with a free parameter to vary the nuclear saturation scale

$$Q_{sA}^2 = d\ A^{1/3} Q_{sp}^2$$

van Hameren, Kotko, Kutak, CM, Petreska and Sapeta (2016)

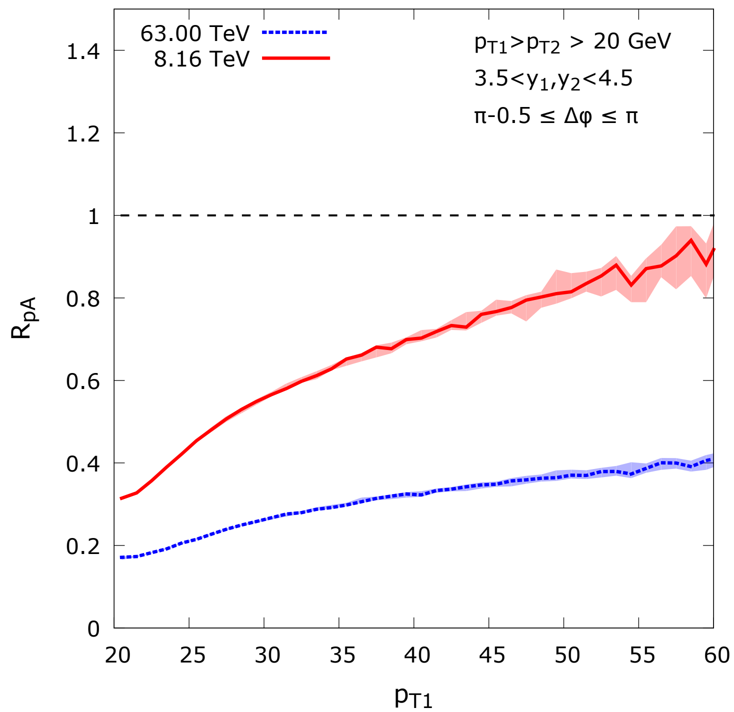


non-linear effects become sizeable near $\Delta\varphi = \pi$, as expected

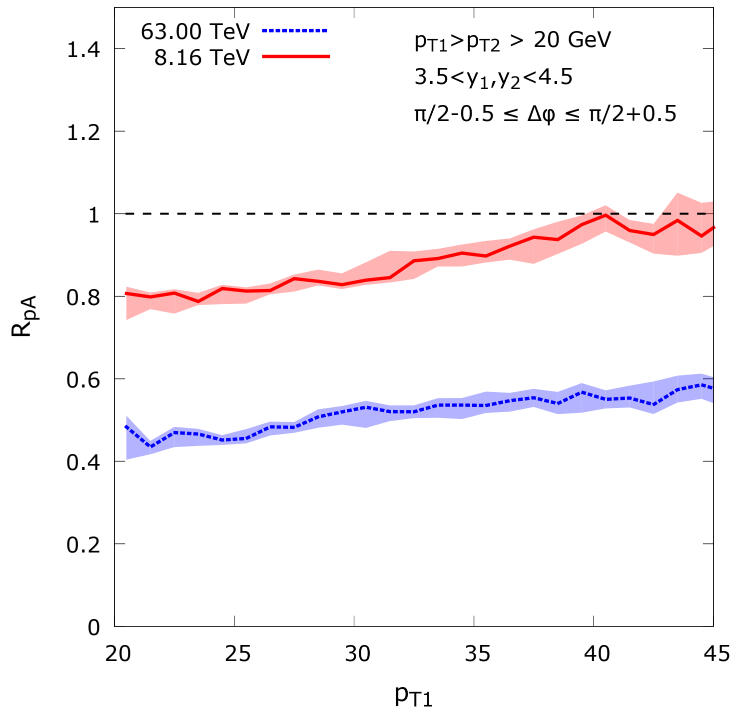
Forward di-jets at FCC

- at FCC energies, the suppression in p+Pb vs p+p is much bigger

near $\Delta\varphi = \pi$



near $\Delta\varphi = \pi/2$

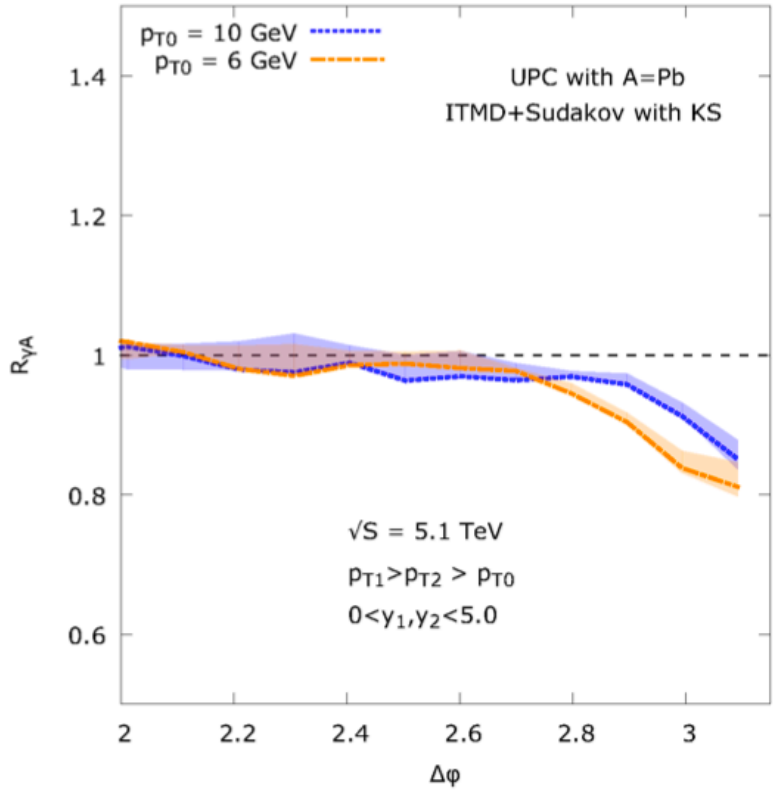


near $\Delta\varphi = \pi$, we expect small NLO corrections (as in collinear factorization)
but a resummation of Sudakov logarithms may be crucial (work in progress)

Di-jets in UPC γ+A collisions

- similar predictions have been made for di-jets in photon-nucleus collisions at the LHC

Kotko et al (2017)



again the suppression
is localized near $\Delta\varphi = \pi$

the Sudakov resummation
is modeled here

study to be made for FCC

Conclusions

- RHIC saturation signals starting to get confirmed at the LHC:

  - suppression of forward D mesons in p+Pb vs p+p seen by LHCb
  - suppression of back-to-back correlations of di-hadrons also seen

- The best way to confirm the R_{pA} suppression is forward photons (smallest x reach, no cold matter e-loss effects)

- But, if NLO calculations confirm that saturation effects impact R_{pA} only below 3 GeV, then this won't provide the best saturation signal, even at FCC

- Forward low-p_t di-hadrons are good, but the ridge (whatever the origin) mingles with the saturation signal, and it's magnitude at FCC energies is not known (to be studied)

- Back-to-back di-jets is the next thing to try (also at the LHC)