Opportunities for novel forward physics at the EIC and parallel studies in pp, pA collisions.

Mark Strikman, PSU

Workshop: Forward physics and instrumentation from colliders to cosmic rays, October 17 2018

Outline

- **Directions for fragmentation studies in $\vec{e}\vec{p}$ collisions at the EIC**

  x-dependent fragmentation
  spin effects

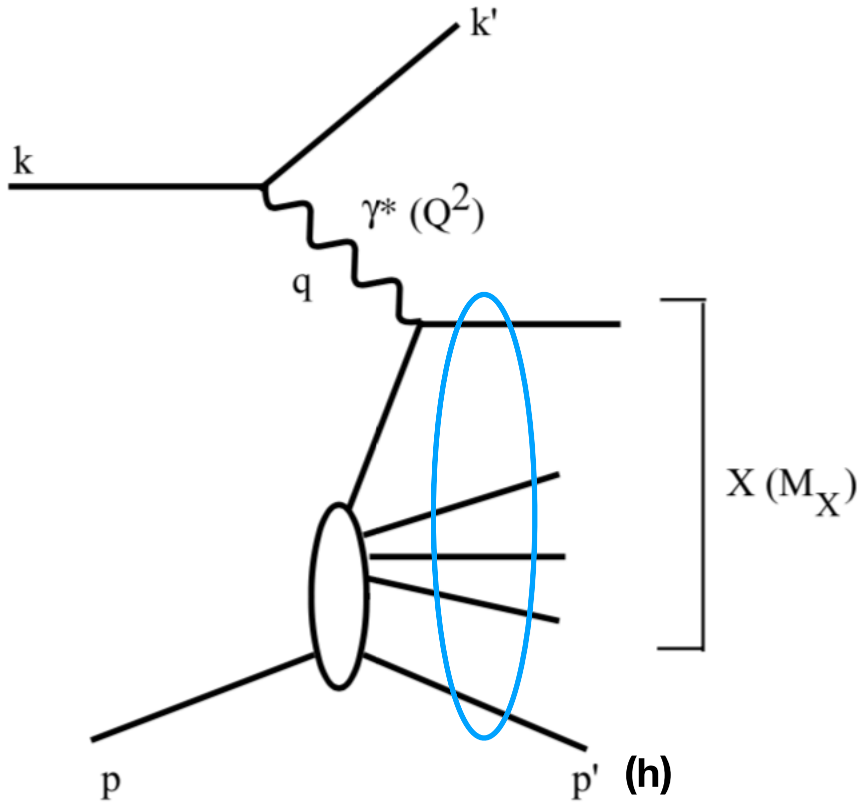
- **Central pA collisions - gross violations of the Feynman scaling**

  window to nonlinear effects

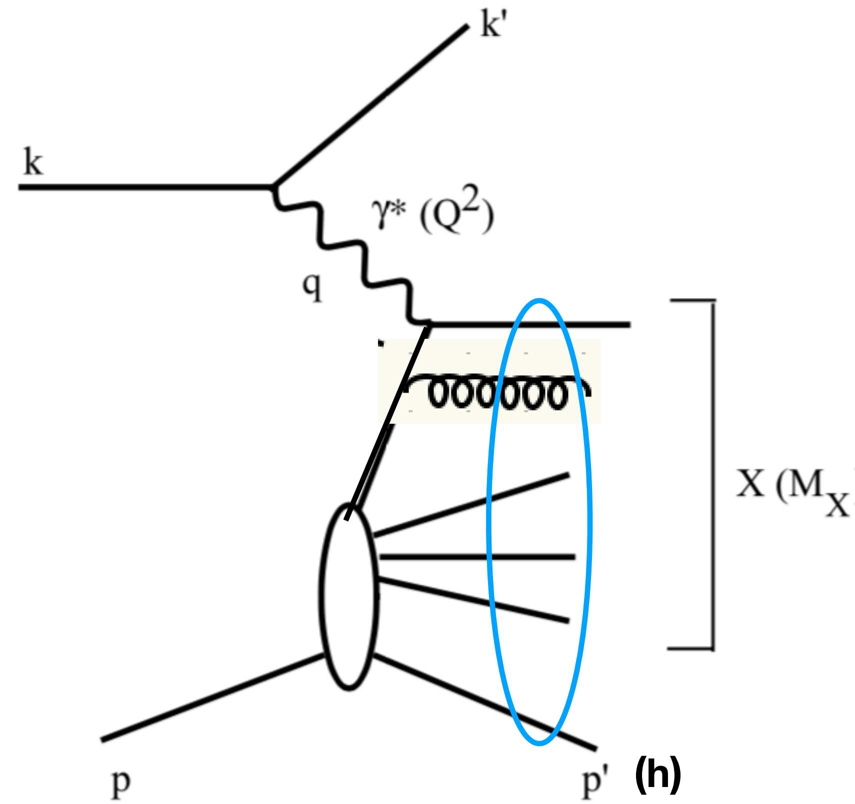
- **Centrality triggers in pp scattering**

Collins factorization theorem: consider hard processes like

$$\gamma^* + T \to X + T(T'), \quad \gamma^* + T \to \; jet_1 \; + \; jet_2 + X + T(T')$$

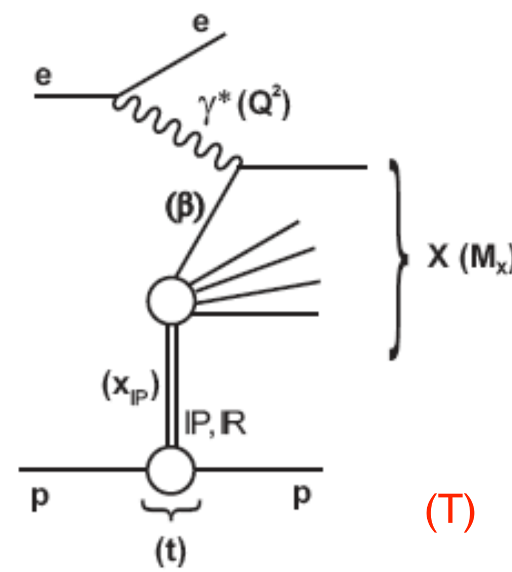


$$Q_0^2 \rightarrow Q^2$$



Interaction of partons which would form h h with the rest of partons: — does not change since overall interaction does not resolve qg which are located at transverse distance << 1/Q₀ one can define fracture (Trentadue &Veneziano) parton distributions

$\beta \equiv x/x_{I\!P} = Q^2/(Q^2 + M_X^2)$



$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$

(T) $x_{T_f} = 1 - x_{I\!P}$

$$F_2(x, Q^2) = x \sum_{j=q,\bar{q},g} \int_x^1 \frac{dy}{y} C_j\left(\frac{x}{y}, Q^2\right) f_j(y, Q^2)$$

$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = \beta \sum_{j=q,\bar{q},g} \int_\beta^1 \frac{dy}{y} C_j\left(\frac{\beta}{y}, Q^2\right) f_j^{D(4)}(y, Q^2, x_{\mathbb{P}}, t)$$

Theorem:

For fixed $x_{I\!P},\ t$ universal fracture pdf + the evolution is the same as for normal pdf's

Comment: $x_{I\!P}$ *is traditional notation - notions of Pomeron is not necessary in general factorization analysis*

Soft ladder mechanism - expect soft factorization

☛ $$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t) = f_j^D(\beta, Q^2) \cdot \phi(x_{I\!P})$$

☛ $$\phi(x_{I\!P}) \propto 1/x_{I\!P}^{\alpha_{I\!P}-1}$$

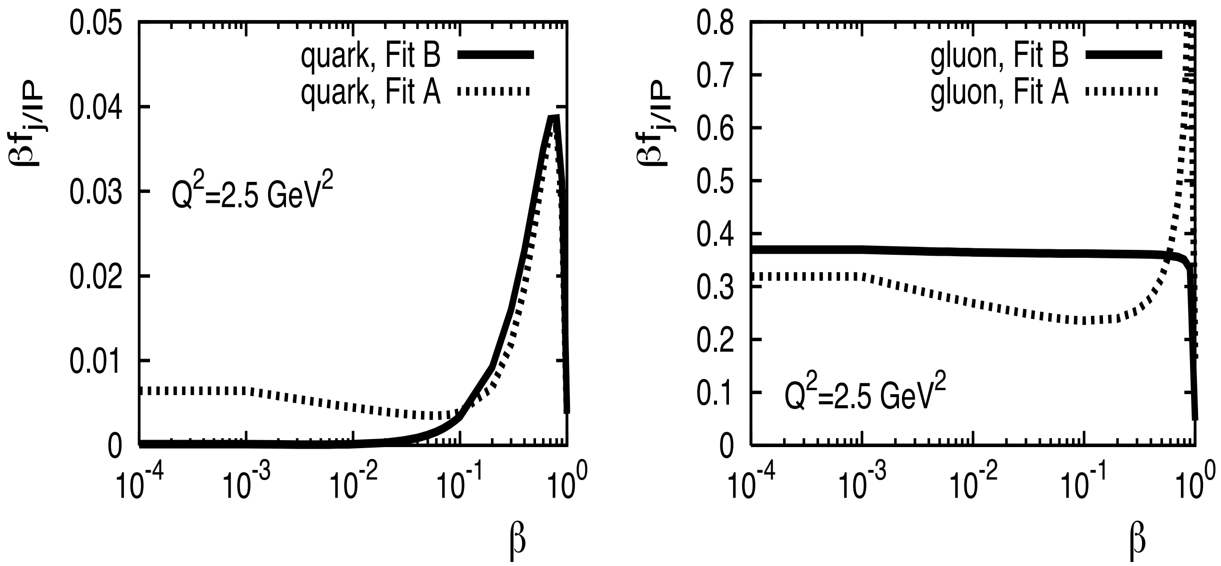
*Theorem is violated in dipole models of γ*N diffraction in several ways*

Summary - Diffractive phenomena - inclusive diffraction and measurement of diffractive pdf's

HERA: Good consistency between H1 and ZEUS three sets of measurements

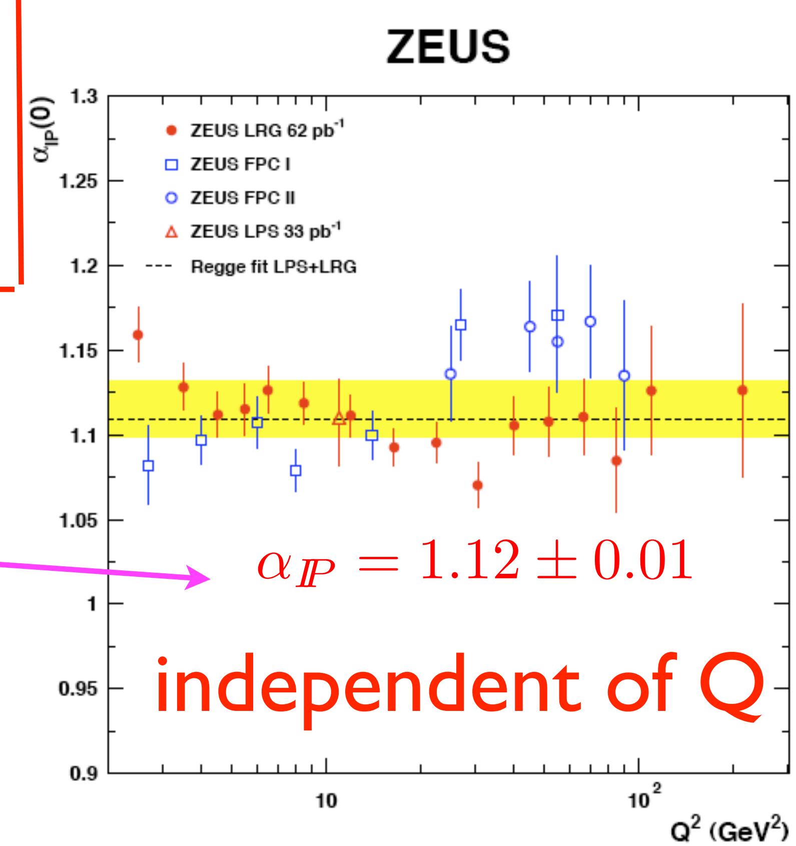
- ☞ *Measurements of $F_2^{D(4)}$*
- ☞ *Measurements of dijet production*
- ☞ *Diffractive charm production*

DGLAP describes totality of the data well several crosschecks - Collins factorization theorem valid for discussed Q^2,x range



gluon dPDF >> quark dPDF

The quark and gluon diffractive PDFs at Q^2 =2.5 GeV^2 as a function of β



$\alpha_{I\!P} = 1.12 \pm 0.01$

independent of Q

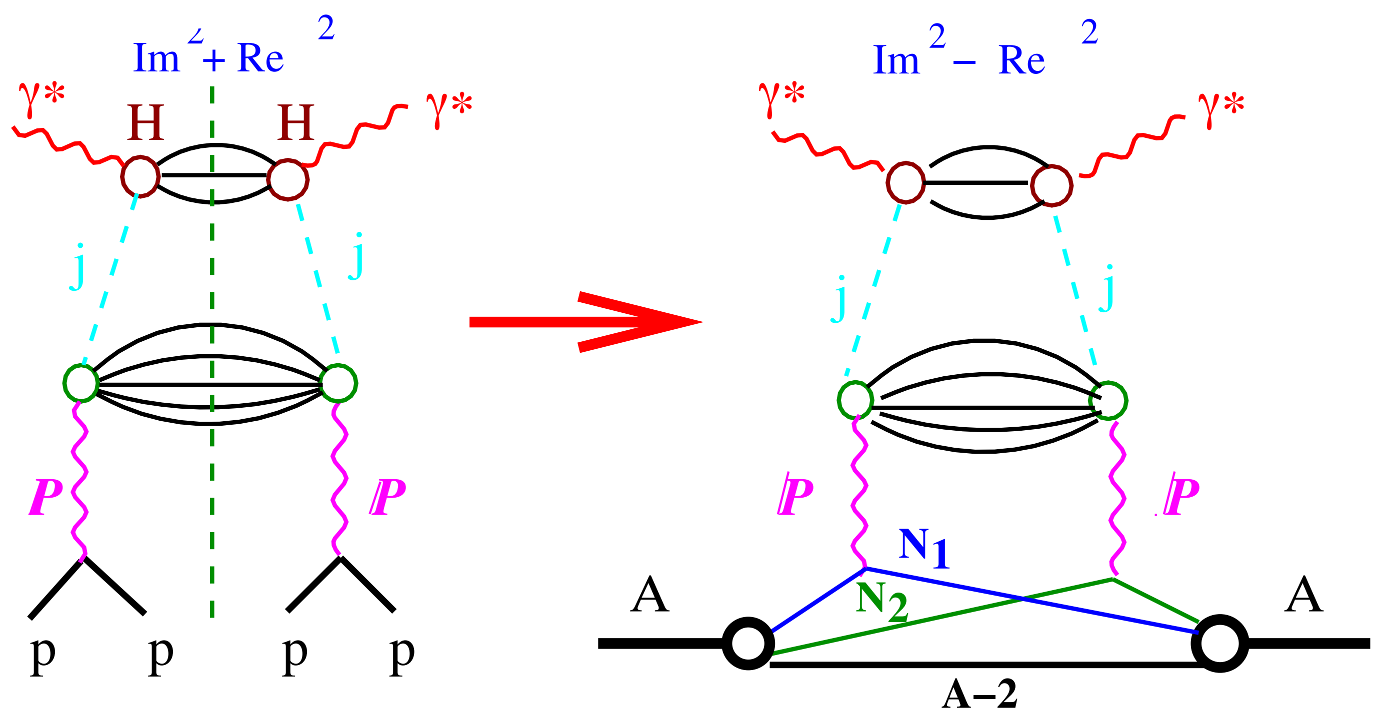
Current fits to soft hadron - hadron interactions find $\alpha_{IP}(0)$=1.09 - 1.10

☛Diffraction at HERA is mostly due to the interaction of hadron size components of γ* not small dipoles. Confirms QCD aligned jet logic for $x > 10^{-4}$

Theoretical expectations for shadowing in the LT limit

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98)
(instead of calculating F_{2A} only)
Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densities :

$$f_j^D\left(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t\right)$$



Hard diffraction off parton "j"

Leading twist contribution to the nuclear shadowing for structure function $f_j(x,Q^2)$

Theorem: in the low thickness limit (or for x>0.005)

$$f_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2+2\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$

$$\cdot f^D_{j/N}\left(\beta, Q^2, x_{I\!P}, t\right)\Big|_{k_t^2=0} \rho_A(b,z_1)\ \rho_A(b,z_2) \mathrm{Re}\left[(1-i\eta)^2 \exp(i x_{I\!P} m_N (z_1 - z_2))\right],$$

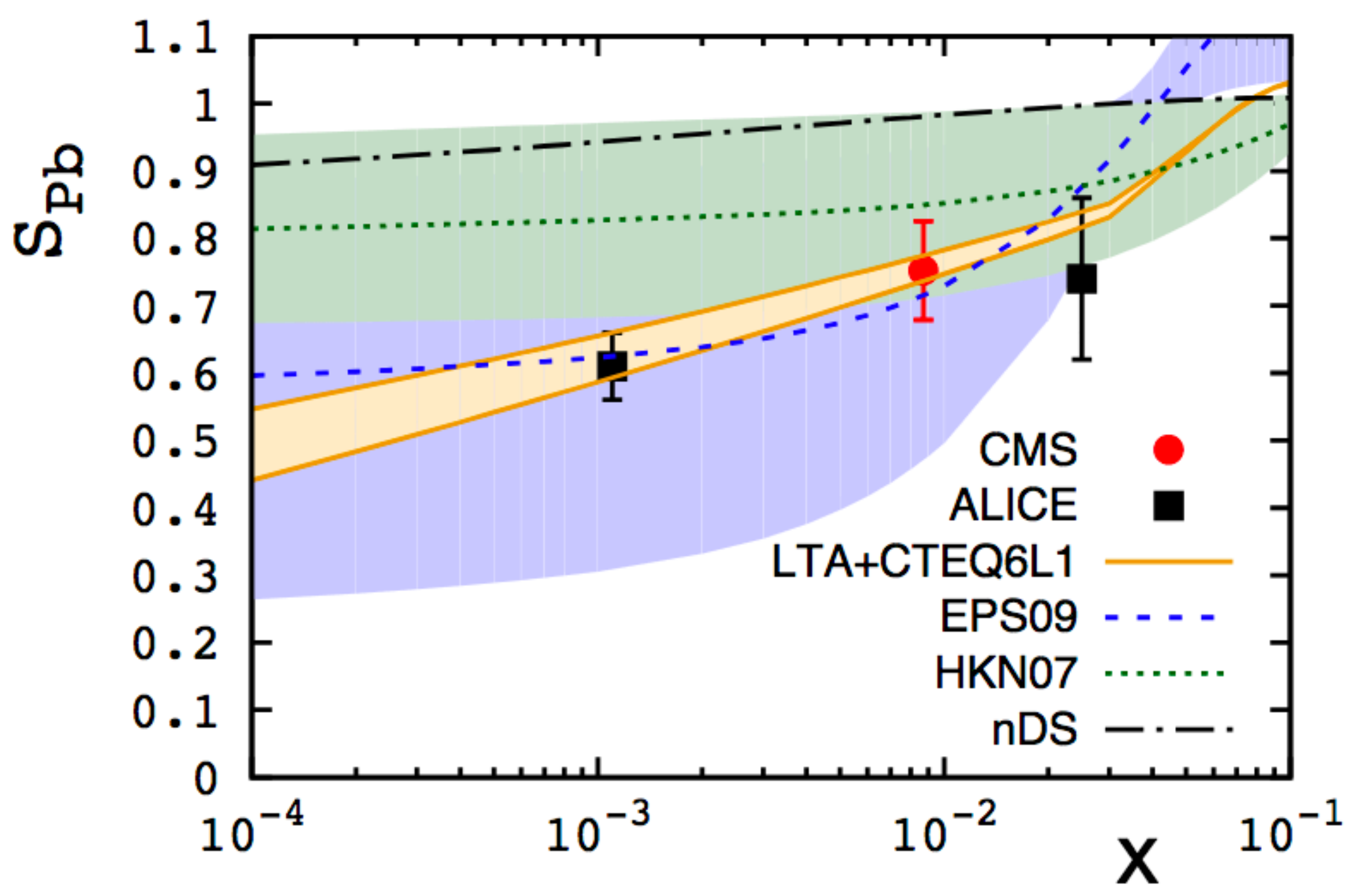
where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2)$ are nucleus(nucleon) pdf's,

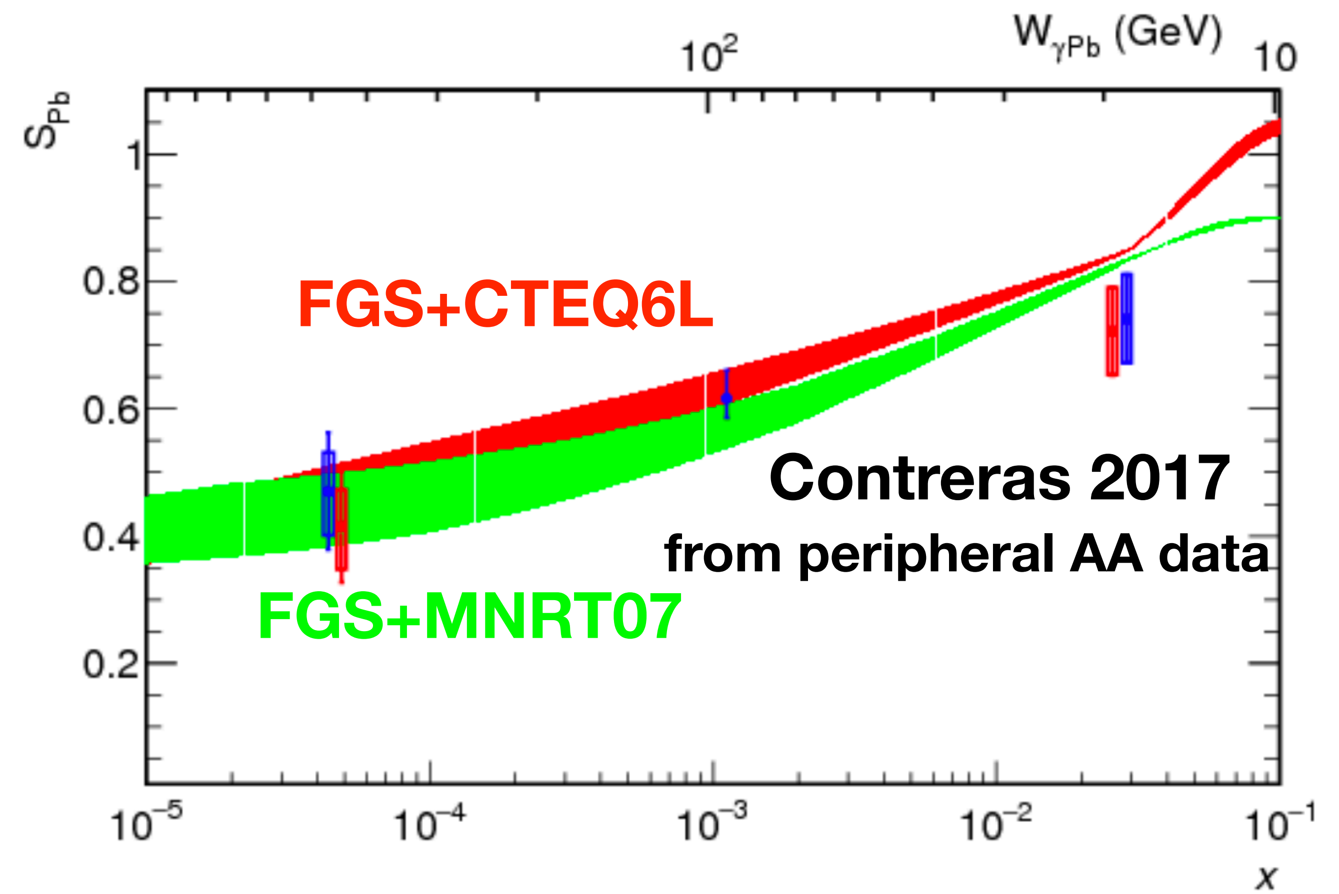
$\eta = ReA^{diff}/ImA^{diff} \approx 0.174,\ \rho_A(r)$ nuclear matter density.

$x_0(quarks) \sim 0.1,\ x_0(gluons) \sim 0.03$

Strong suppression of coherent J/ψ production observed by ALICE confirms our prediction of significant gluon shadowing on the $Q^2 \sim 3$ GeV^2 . Dipole models predict very small shadowing (S_{Pb}> 0.9).

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)}\right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$





Large gluon shadowing consistent with the leading twist theory prediction of FGS2012

***EIC - high precision measurement of diffractive cross sections, separation of LT and HT effects —> separation of LT and HT shadowing for the lightest nuclei* (for F_{2D} Gribov formula for the scattering off the deuteron has no free parameters and it is expected to be valid for all Q.)**

The cleanest way (and only realistic one if polarized D beams would be developed) to measure nuclear shadowing due to interaction with two nucleons is via tensor polarization asymmetry of eD cross section

Fracture pdfs are practically not explored except fragmentation in ep scattering in

$$p \to n, p \to p$$

Need high statistics as fj are functions of (x,β,Q^2,t) not not only β,Q^2,t like for quark fragmentation. Currently effectively integrals over x and $\beta << 1$.

Convenient quantity $x_L=p_h/p_p$ — light cone fraction of proton carried by h

$\boxed{z=x_L/(1-x) <1}$ **Maximal $x_L=(1-x)$**

Soft factorization: weak dependence on x for $z << 1$ and not very large Q^2

Strong dependence of leading (large z) baryon production on x:

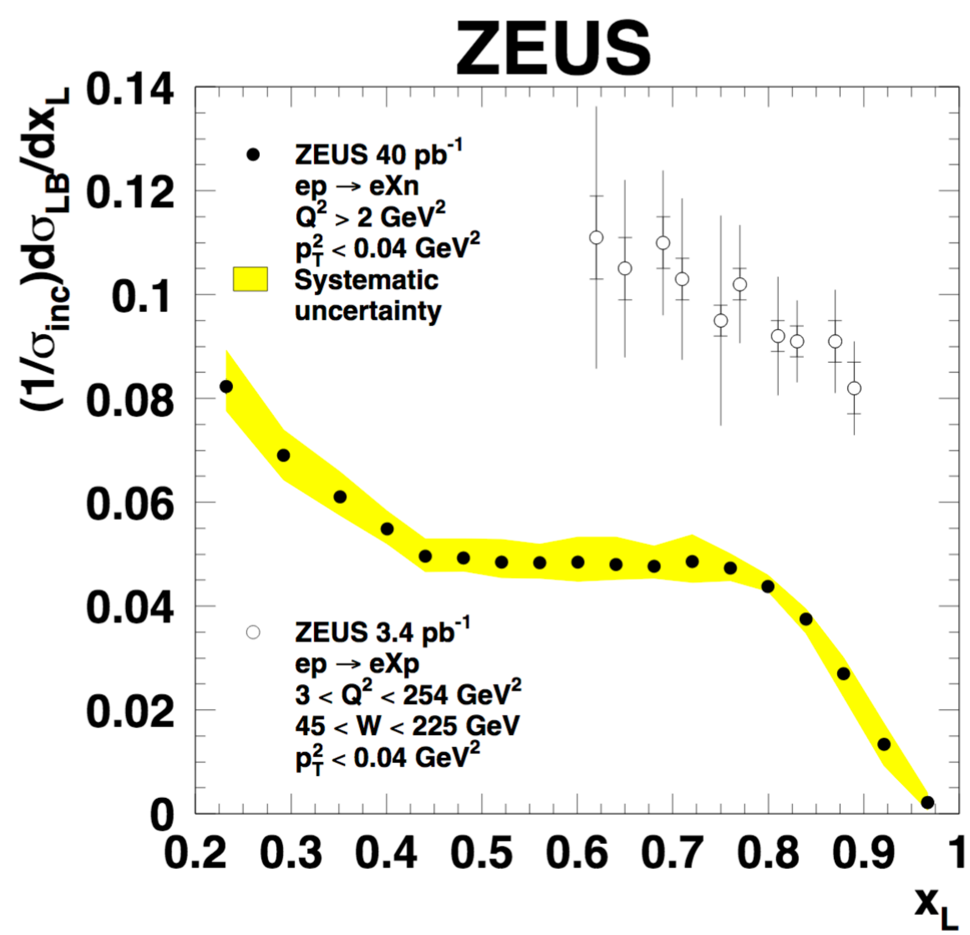
$$f_j(x,z) \propto (1-z)^{n(x)}$$

$n(x<0.01)=-1$	diffraction
$n(x\sim 0.1)=0$	onset of sea quarks
$n(x\sim 0.2)=1$	valence quarks
$n(x\sim 0.5)=2?$	fragmentation of two quarks with large relative momenta

Remark. There were numerous attempts to extract from reaction

$ep \to en + X$ pion pdfs

this contribution requires approaching the pion pole which is practically impossible. Soft factorization leads to contributions to nucleon yield from all fragmentation processes. Simple example - data report the ratio of p and n yields of 2, while in the pion model it is equal to 1/2.



A sample of interesting channels

By using polarized ep scattering and detecting pions in the current fragmentation region we can do a flavor & helicity separation. Qualitatively new information about working of confinement and about baryon structure.

Removal of u (d) quark with helicity = +/i helicity proton can compare

fragmentation of uu and ud with helicities 0 or 1.

- **is ud→ p = ud→ n**
- **how Δ isobar production / spin alignment depends on helicity of diquark**

  longitudinal polarization of hyperons
- **z-dependence of the meson production**
- **expect abundant production of baryon production for large x including rare/exotic baryons like 20-multiplet due to large angular momenta of spectator quarks (Feynman problem).**
- **meson production at large z: $(1-z)^n$, n -2 — 4?**
- **correlations of fragmentation and central multiplicity (easier at HERA)**

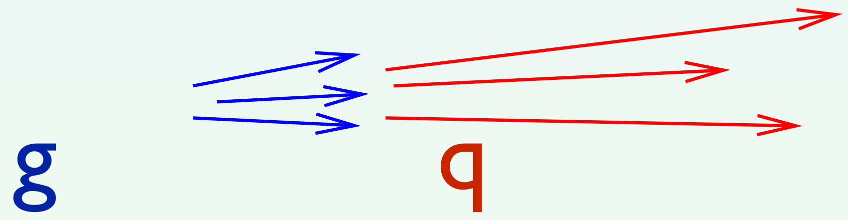
Summary: from discussed studies we would get a precision knowledge of how a proton wave packet evolves when a parton with given x and flavor, helicity is removed from it.

Removal of color octet vs removal a triplet for large z, and x >0.1 -

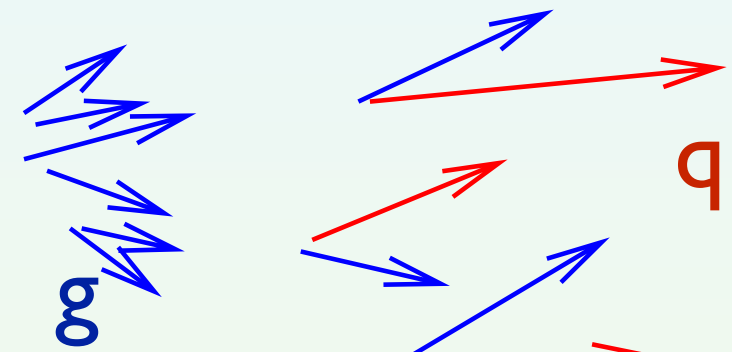
green pastures

Reference point for fragmentation in pp scattering with a hard (e.g.) dijet trigger. Screening, Multiparton interactions.

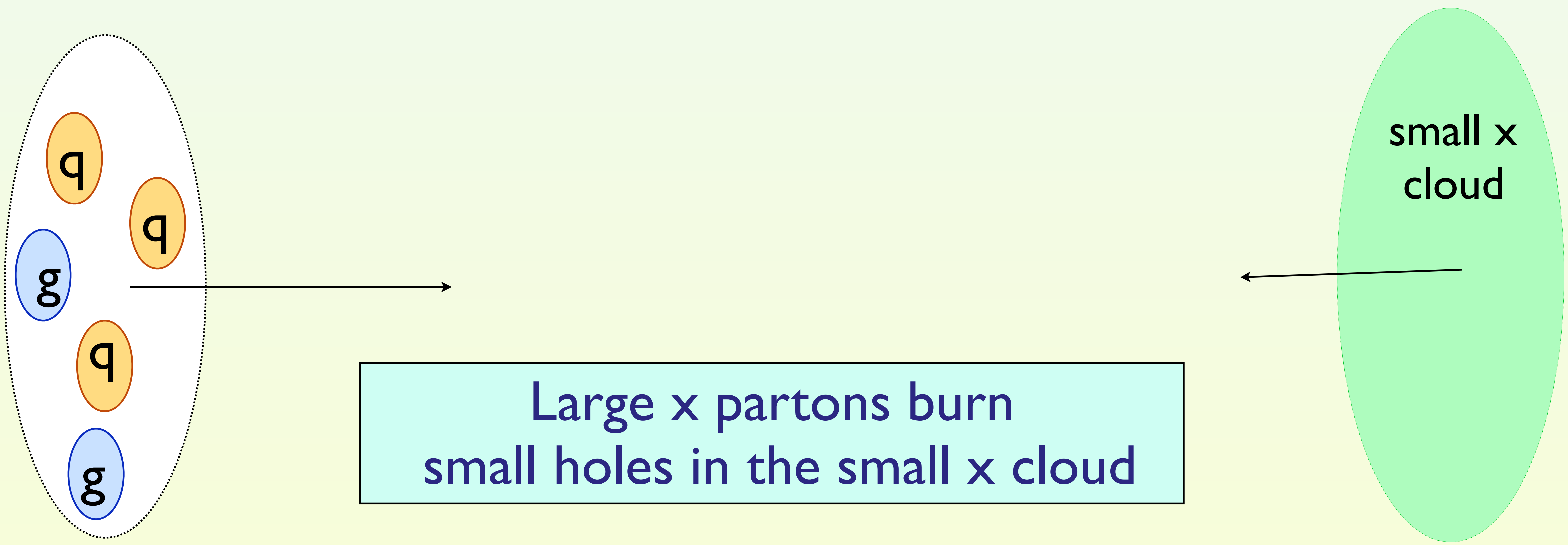
Leading hadron production in the central AA/pA(pp) collisions



fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions



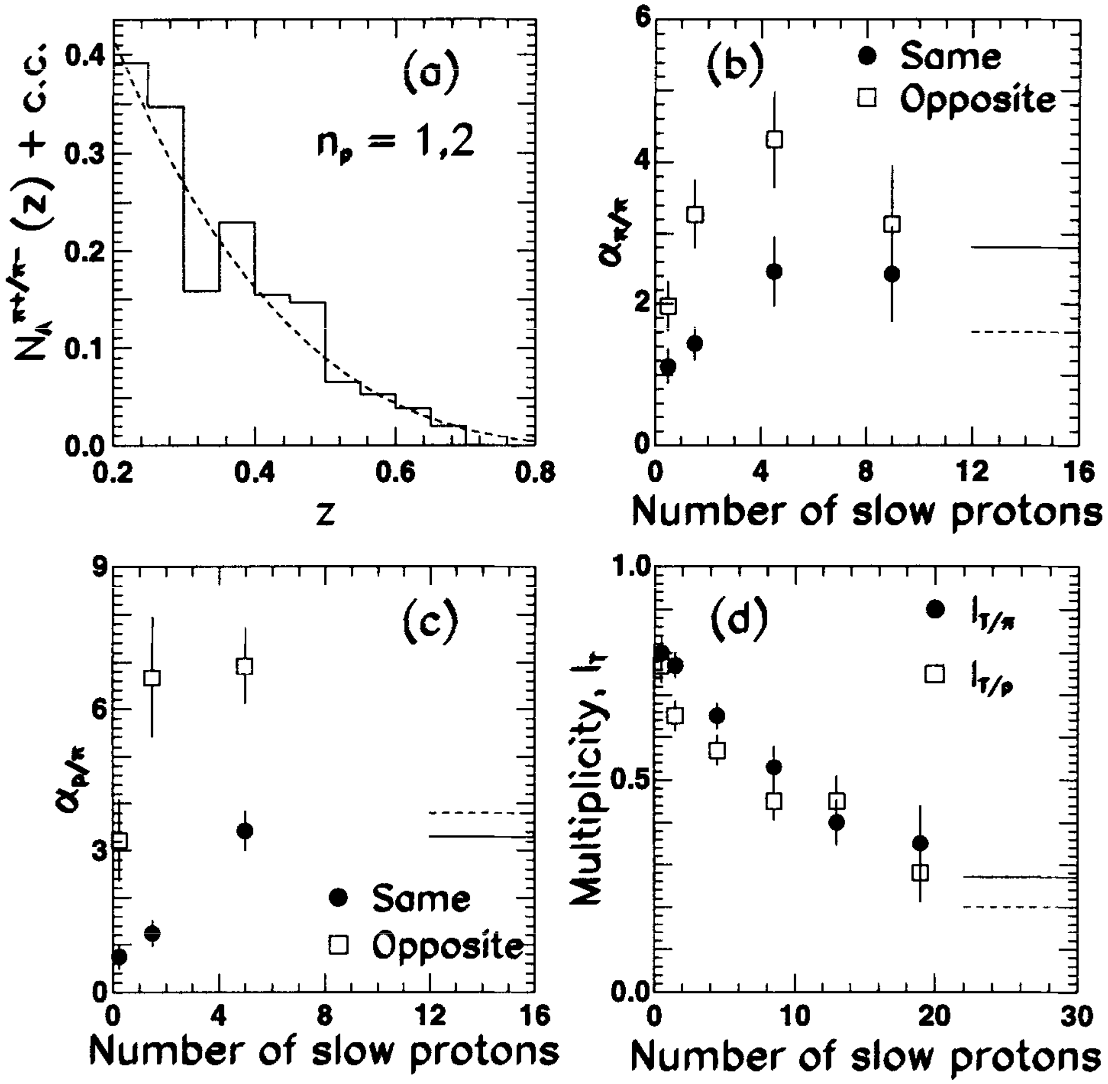
The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons. This model neglects additional suppression due to finite fractional energy losses in Black disk regime (BDR) - similar expectations in saturation regime.

$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\to h+X} = \sum_{a=q,g}\int dx\, x f_a^{(p)}(x,Q^2_{\rm eff}) D_{h/a}(z/x,Q^2_{\rm eff})$$

The limiting curve of leading particles from hadron-nucleus collisions at infinite A

A. Berera[a,1], M. Strikman[a], W.S. Toothacker[b], W.D. Walker[c], J.J. Whitmore[a]

Physics Letters B 403 (1997) 1–7



$$\frac{dN}{dz} \propto (1-z)^{\alpha}$$

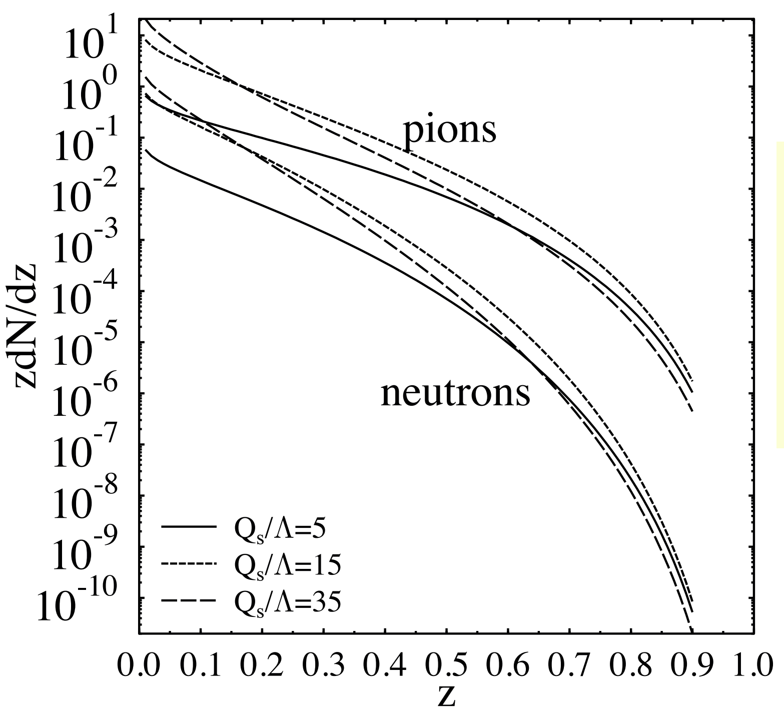
Fig. 2. Experimental results for h–A collisions at 100 GeV/c: (a) Differential multiplicity for $\pi^- A \rightarrow \pi^+$ combined with $\pi^+ A \rightarrow \pi^-$ for events with $n_p = 1,2$ (n_p is the number of slow protons). The dashed curve is a fit to the form $(1-z)^\alpha$; (b) Leading exponent α for $\pi A \rightarrow \pi$, solid circles (open boxes) when the produced π has the same (opposite) charge to that of the beam projectile; the horizontal lines on the right are the theoretical limits from QGSM fragmentation functions to the same (dashed) and opposite (solid) charge leading particle; (c) Leading exponent α for $\pi A \rightarrow p(\bar{p})$, the horizontal lines on the right are the theoretical results from EMC fragmentation functions to like (dashed) and opposite (solid) charge leading particle; (d) The integrated multiplicity of hadrons with $z_m > 0.2$ for $\pi^\pm$ (solid circles) and proton (open boxes) beam projectiles as a function of n_p. The horizontal lines on the right of the figure are the theoretical asymptotic limits for π (dashed) and proton (solid) projectiles.

Caveat - energy is pretty low. Effect could be due to energy conservation

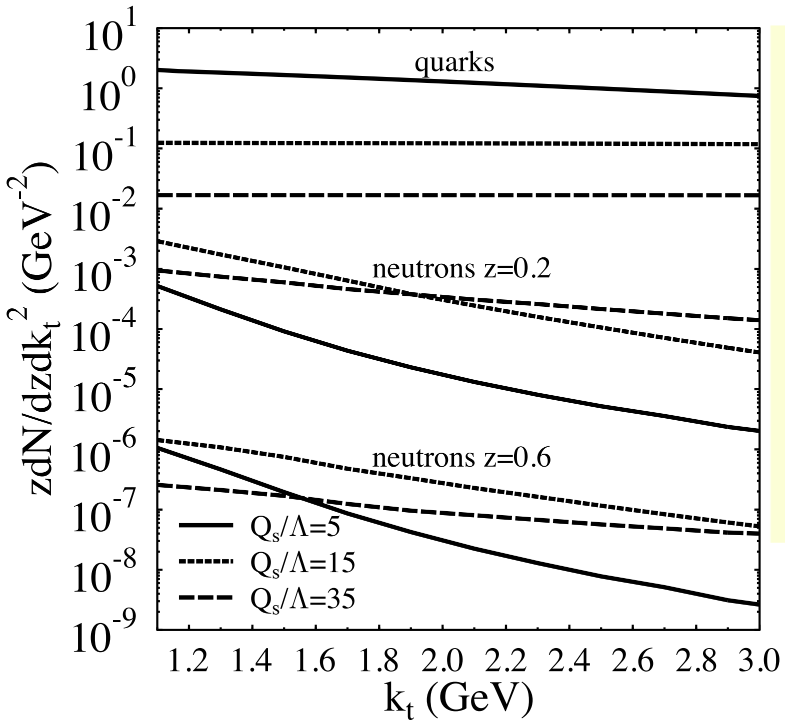
Simple model of p_t broadening - eikonal rescattering model with saturation (Boer, Dumitru 2003)

$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}) .$$

Quark gets a transverse momentum of the order Q_s but does not loose significant energy. Use of the convolution formula for fixed transverse momentum of the produced hadron using $C(k_t)$ - Dumitru, Gerland, MS -PRL03



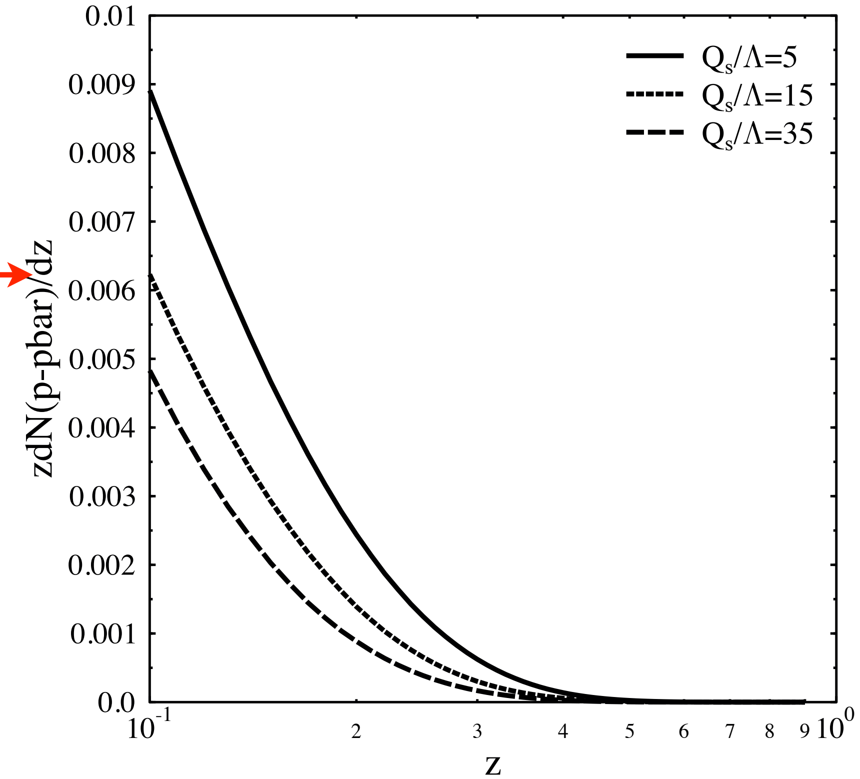
Steep fall with z, strong E_{inc} dependence



Weak p_t dependence, becomes weaker with increase if E_{inc}

Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate (CGC) model for central pA collisions. Spectra for central pp - the same trends.

Very few forward baryons!!!



Longitudinal distribution of net protons

Warning: Parton carrying a fraction y of the quark momentum, carries $y\,p_t$ part of the quark's transverse momentum.

Condition for independent fragmentation $y\,p_t > 1/r_N \sim .3 - 0.5$ GeV/c

For LHC independent fragmentation is probably safe for

$$z > \frac{0.5GeV}{Q_s} \times 0.2 \sim 0.05, \text{corresponds to}\, y_{max} - y \leq 3$$

Assumed $Q_s(x=10^{-6}) \sim 2$ GeV

Experimental situation is not clear - no data in the very forward region with centrality selection. Best hope - neutrons from ZDC

Expectation for pA:

With increase of centrality drop of energy/spectra at

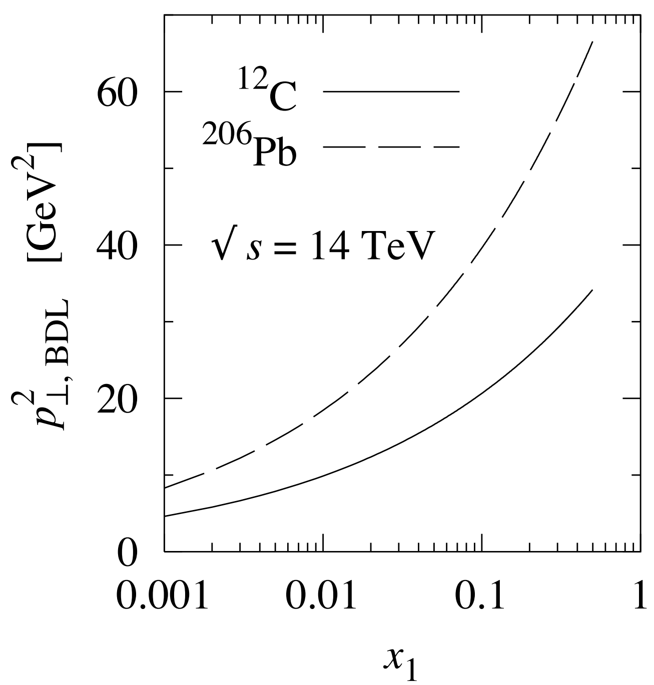
$$y_{max} - y \leq 3$$

increase of s: a stronger drop of energy deposition at fixed y_{max} -y and wider y_{max} -y range where the drop takes place

For 3< y_{max} -y < 5(?) increase of energy deposition with centrality

Implications for Quark-gluon densities in the nuclear fragmentation region in heavy ion collisions at LHC

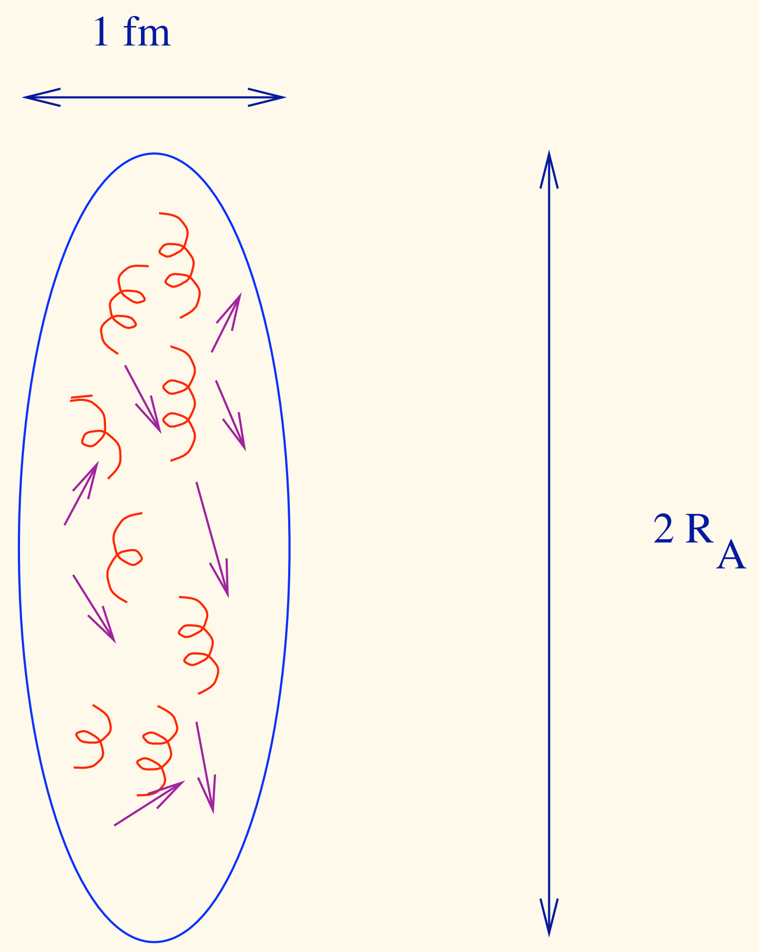
Frankfurt and Strikman: **Phys.Rev.Lett.91:022301,2003, MS 2005**



p_T (gluon)> 4 GeV/c for x> 0.1

p_T (quark)> 2.5 GeV/c for x> 0.1

Average p^2_T (gluon) for b=0 - for quarks p^2_T is a factor of 2 smaller



Quarks and gluons have predominantly transverse momenta with the third component of momentum more likely to be in opposite directions for quarks and gluons

Sketch of imploded quark-gluon system in its rest frame

Note that most of the energy of the colliding nuclei is stored in these two (forward and backward) disks !!!

Formed state has parton density $\geq 70\, partons/fm^3$

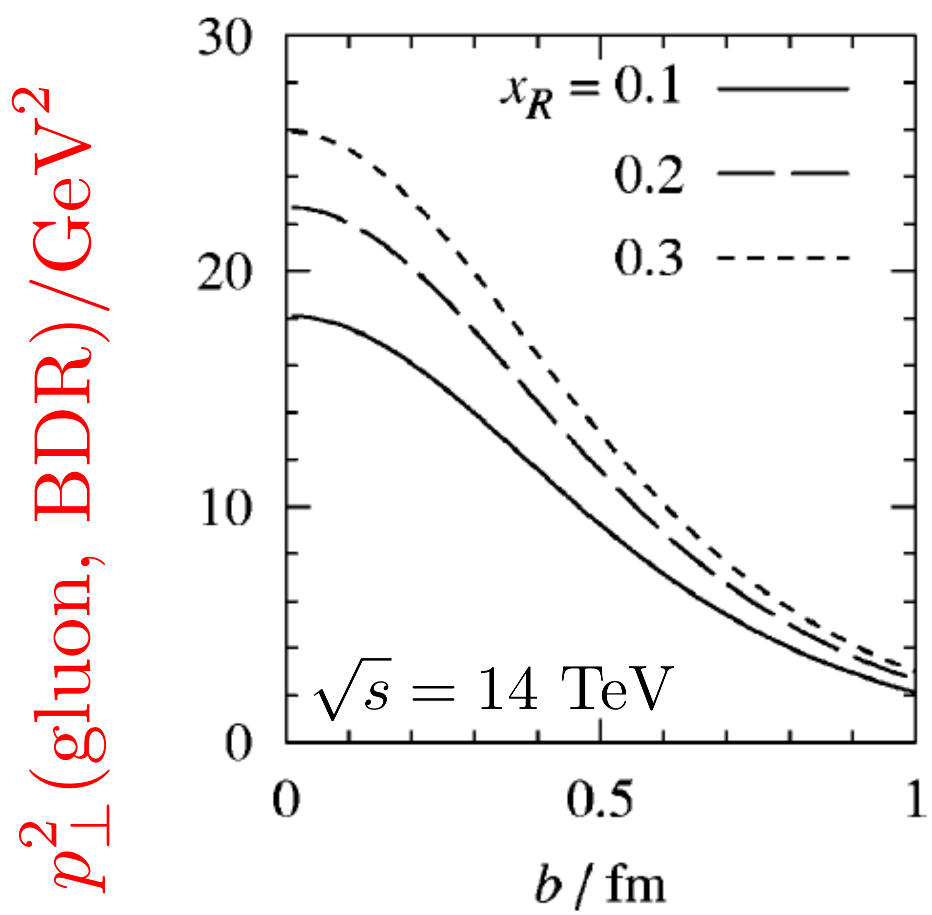
From central pA to central pp and GZK scale p-Air collisions

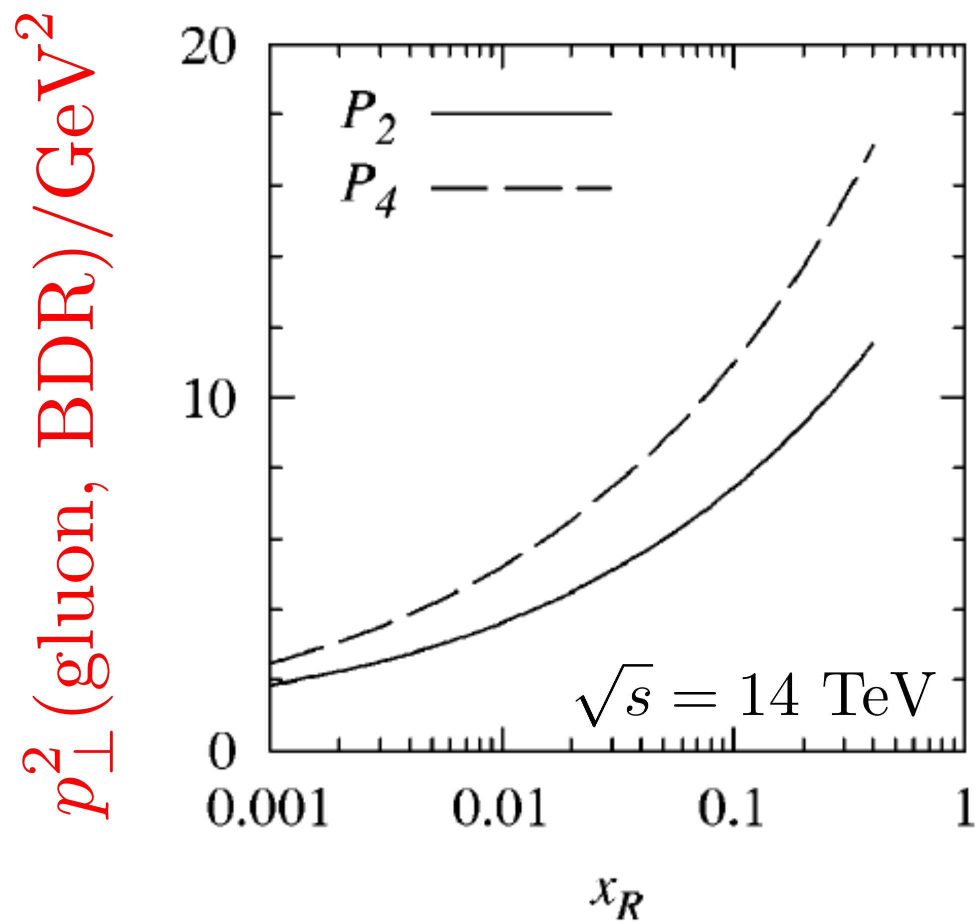
Trigger for super central pp collisions

At LHC largest nonlinear effects are for

events with centrality trigger - dijets (P_2); four jets via double parton interactions (P_4)

leading particles





Large flow of energy to central rapidities

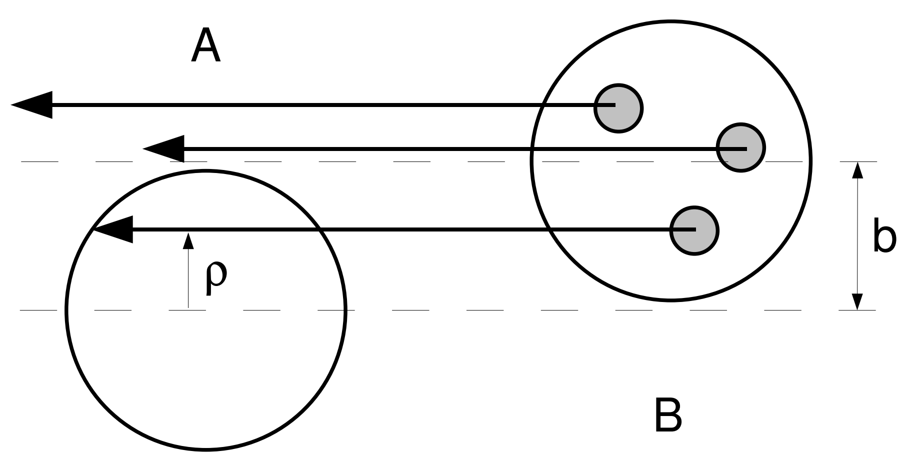
☞ **Better Centrality triggers for pp collisions**

using forward production information in addition to central jet production.

motivation: for small b in pp gluon densities are similar to AA

MC code was developed by H.Drescher and MS - focus on forward particles; PRL 08

Code generates configurations of three valence quarks, traces them through the gluon field of the second nucleon,



Transverse momenta are generated using the simplest version of color glass condensate model (no fractional energy losses) - similar to the one I described before for pA:

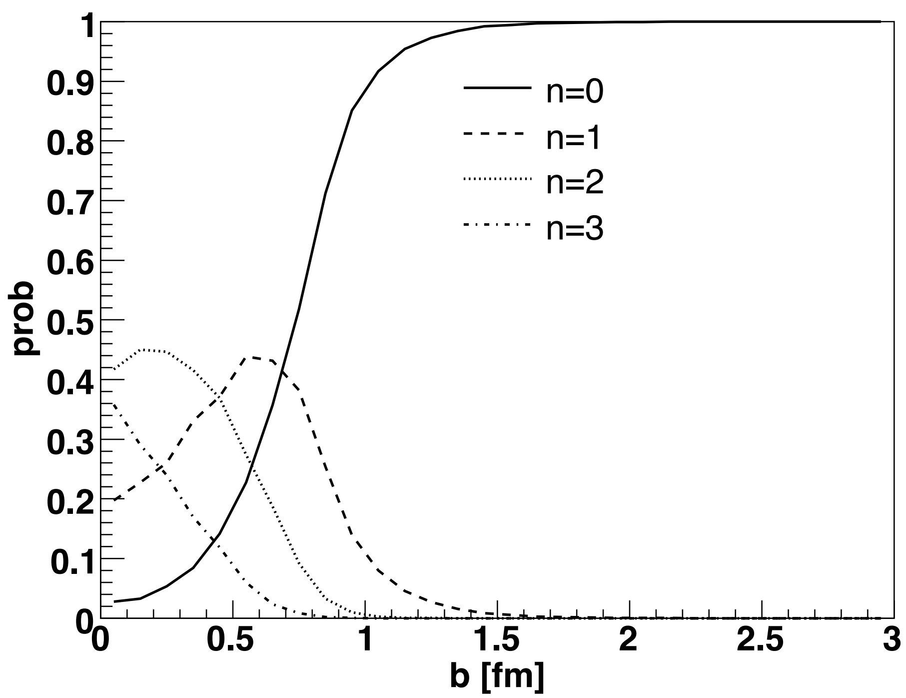
$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp\left(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}\right)$$

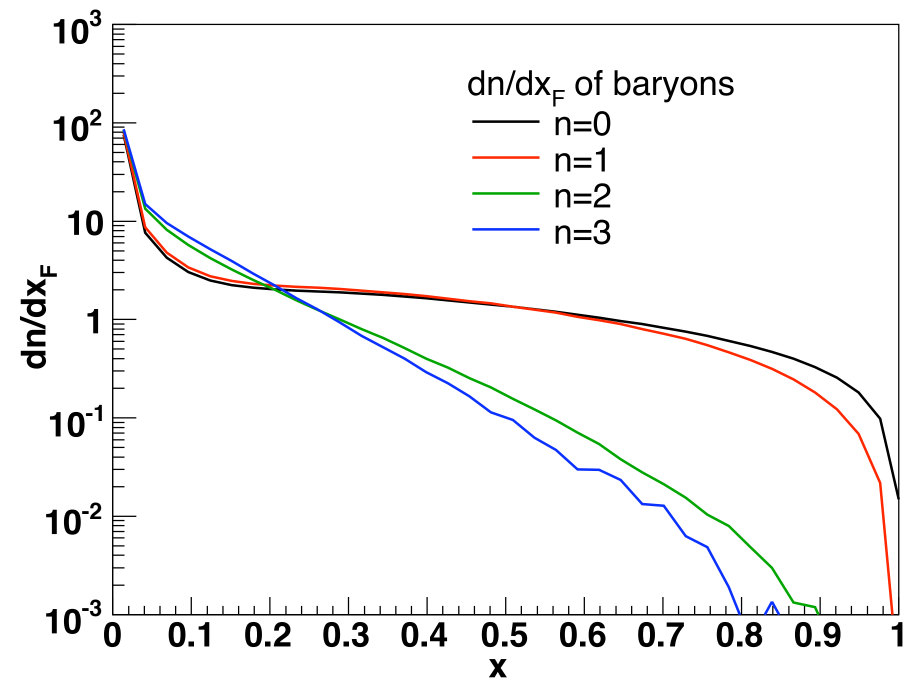
$$Q^2 = Q_s^2(x_A, |\vec{b} + \vec{\rho_i}|) \quad \text{with} \quad x_A = Q^2/(s x_B)$$

$$Q_s^2(x_A, \rho) = Q_{s,0}^2 \, (x_0/x_A)^{\lambda} \, F_g(x_A, \rho; Q_s^2)/F_g(x_0, 0; Q_{s,0}^2)$$

If generated transverse momentum large enough - independent fragmentation. Otherwise string junction.

Impact parameter dependence of interaction probabilities and forward spectra

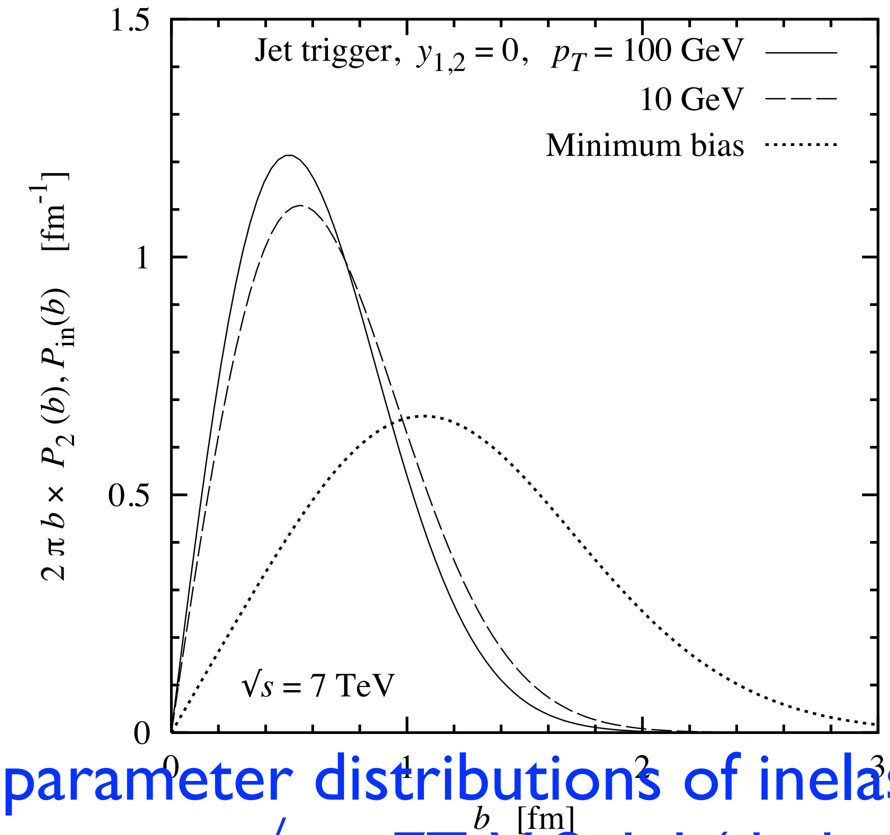




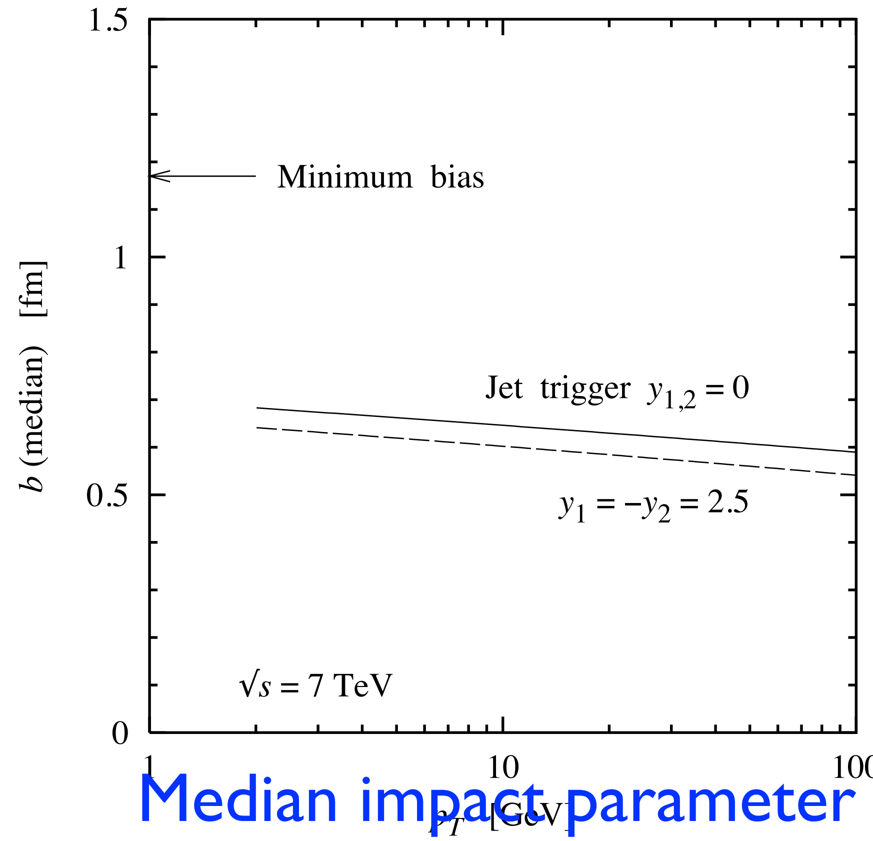
Relative probabilities for the different classes of events with n quarks struck at a given impact

strong suppression of large x for n=2,3

large b dominate in neutron production, <b> much larger than in events with dijet trigger



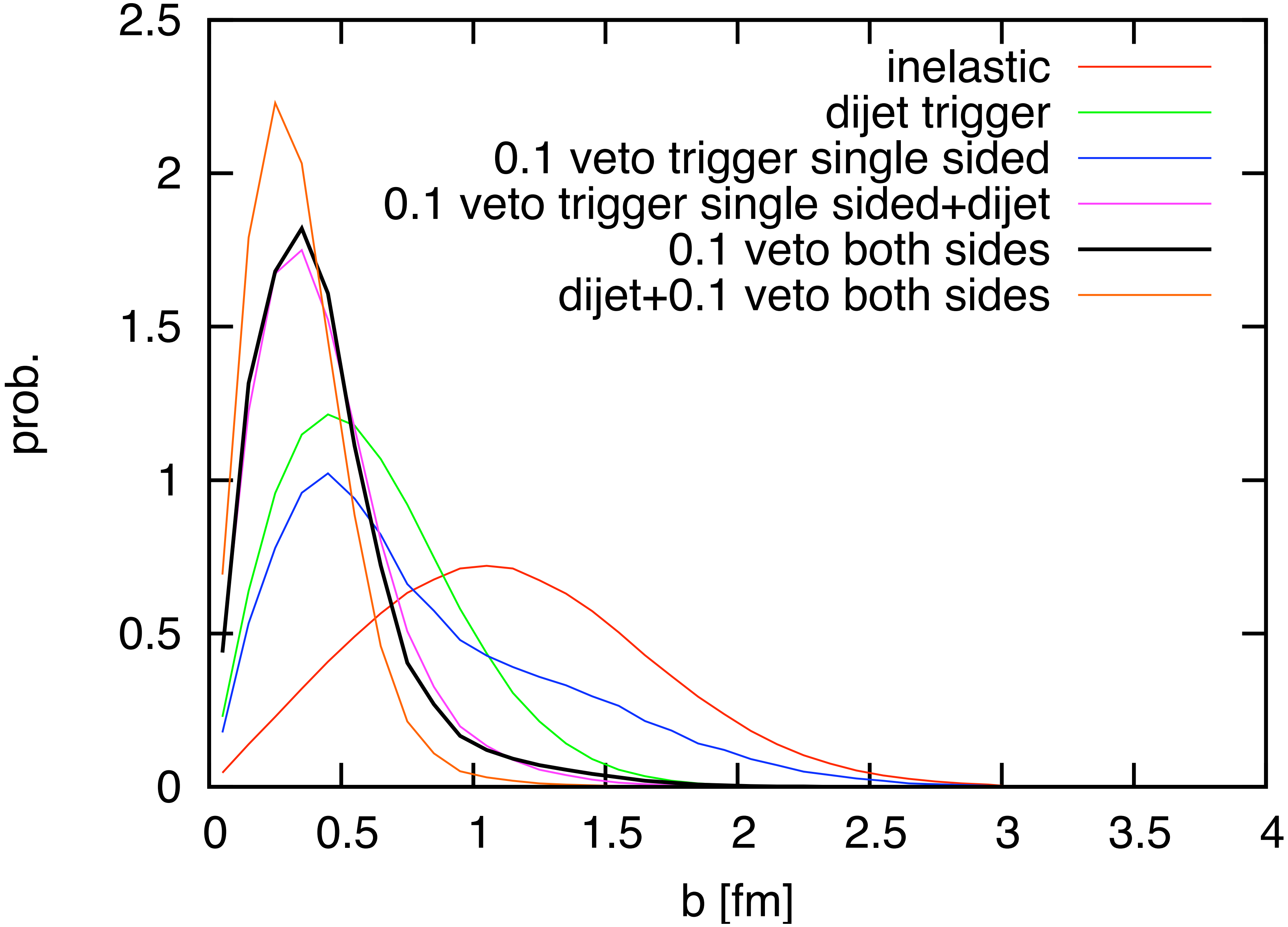
Impact parameter distributions of inelastic pp collisions at $\sqrt{s}$ = 7TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2} = 0$, c, for p_T = 100 (10) GeV . Dotted line: Distribution of minimum–bias inelastic events (which includes diffraction).



Median impact parameter b(median) of events with a dijet trigger, as a function of the transverse momentum p_T , cf. left plot. Solid line: Dijet at zero rapidity $y_{1,2} = 0$. Dashed line: Dijet with rapidities $y_{1,2} = \pm 2.5$. The arrow indicates the median b for minimum–bias inelastic events.

Frankfurt, MS, Weiss 2003 & 2010

Look for suppression of leading neutron & pion production in events with dijet trigger at central rapidities. Slow decrease of suppression with decrease of x_p for the parton in the fragmenting proton due to increase of the transverse size of the parton distribution with decrease of x.



0.1 veto single sided = no baryons with x>0.1

0.1 veto single sided ≈ 0.1 veto both sides no neutrons with x>0.1

One can trigger on $\langle b \rangle = 0.4$ fm - collisions with gluon field at $\langle \rho \rangle \sim 0.6$ fm where gluon density 2- 3 times smaller than in AA at LHC but at higher energy where $G_p(x)$ is higher by a factor of two. Encounted densities >> larger densities at RHIC. However dispersion in strength of interaction is much larger than in AA and central pA.

Connection to cosmic ray interactions at GZK energies

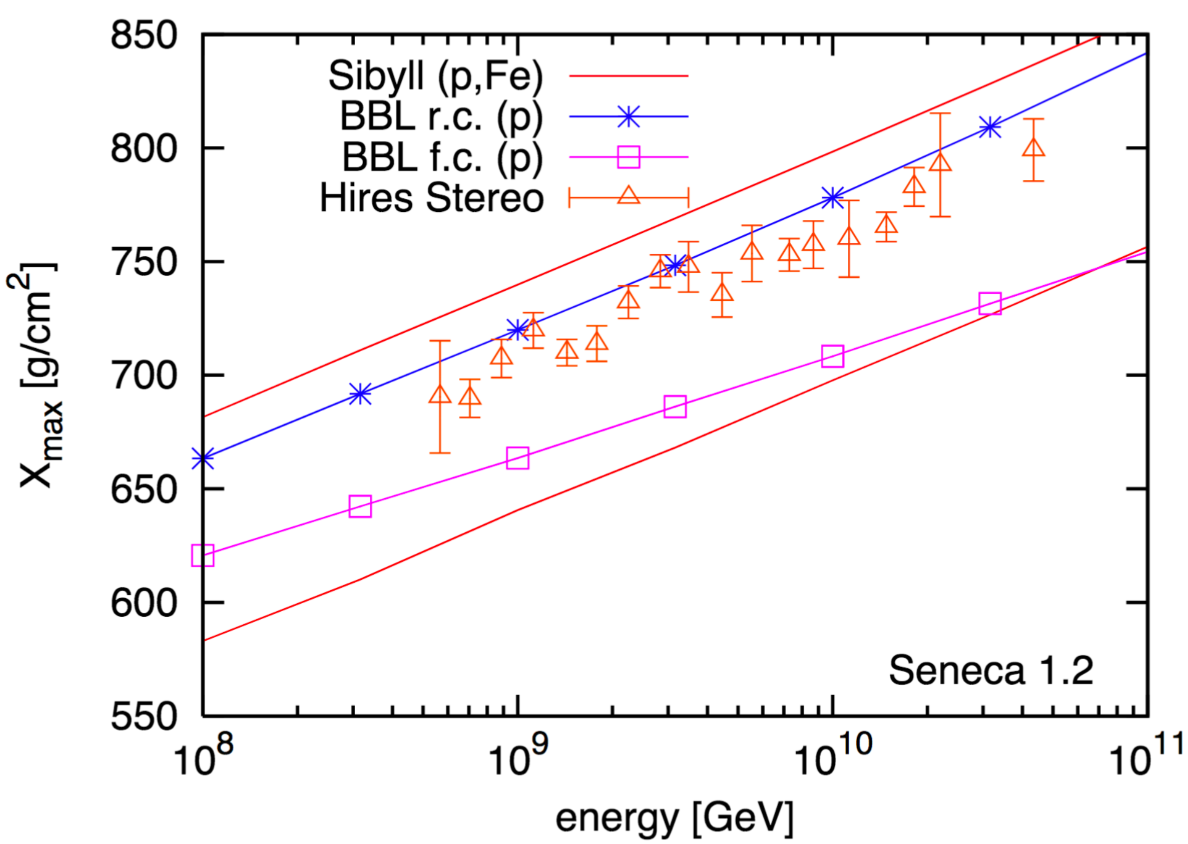
GZK energies are much higher than LHC - sensitive to interaction of the leading partons with gluons at much smaller x: $x_{min} \propto 1/s$

where gluon densities are a factor of ~ 5 larger than at the LHC

similar to central pPb collisions at the LHC

Another reason for studying experimentally very forward production in pPb with nuclear centrality trigger. If suppression grows with incident energy it would lead to slowing down of the increase of X_{max} with incident energy.

Dumitru, Dreschel, MS 2005



Additional effects - so far neglected - larger by 9/4 value of k_t^2 which gluons get in the propagation through nuclei

➡ independent fragmentation of gluons down to smaller x

$\Downarrow$

suppression of production of forward particles is underestimated

➡ Suppression for processes dominated by gluons (like charm production) should be larger for forward rapidities than for processes dominated by quarks.

CONCLUSIONS

Fragmentation in DIS, photon - nucleon collisions has a great potential for revealing baryon structure and confinement provided detectors have sufficient acceptance,

Parallel studies of fragmentation in DIS and in pp highly desirable - would provide clues on the role of the small x dynamics at the smallest x one can reach at a given energy.

Critical to check experimentally whether production of leading pions and nucleons in collisions at central impact parameters (centrality trigger) should be strongly suppressed and have a steeper fall off with x_L and broader distribution in k_t. Effect should be stronger in pA than in pp due to a better definition of centrality and larger value of k_t(BDR)

HERA data mining & Getting data from ultraperipheral $\gamma p, \gamma A$ collisions at the LHC