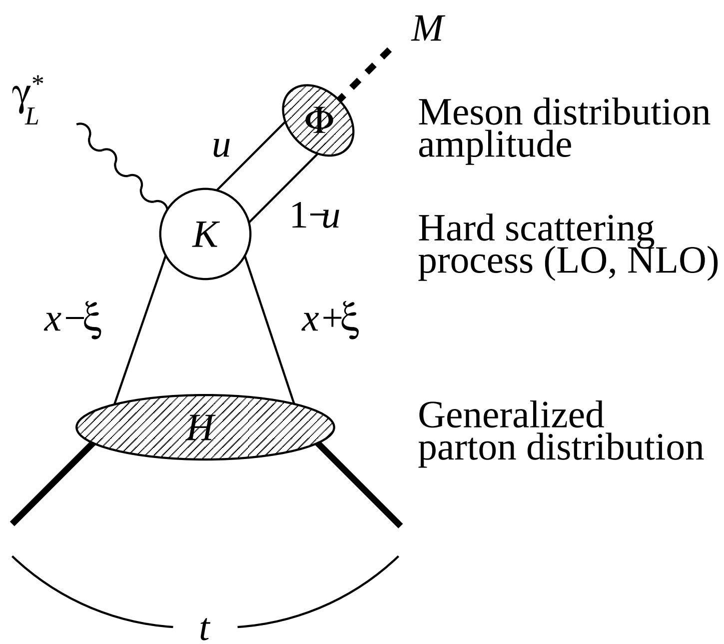
3D parton structure of the nucleon: ep, pp and pA

Ch. Weiss (Jefferson Lab), eA–pA Workshop, May 6, 2005

Exclusive processes in ep scattering at large Q^2	$\longleftrightarrow$	"Generalized parton distributions" $q(x, \rho)$ — longitud. momentum / transverse coordinate	$\longleftrightarrow$	Hard processes in high–energy pp collisions (dijets, Higgs production)
JLAB at 12 GeV HERMES, COMPASS HERA, EIC				LHC Tevatron RHIC

- Hard exclusive processes in ep
- What we know from HERA
- How eA can help: Nucleus as "detector" $\leftarrow$
- Applications to pp/pA

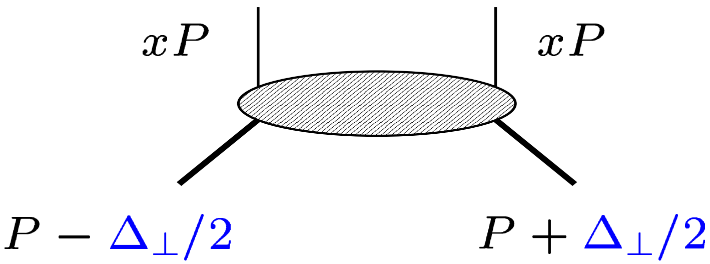
- Hard exclusive processes in ep: QCD Factorization
  [Brodsky et al. 94; Collins, Frankfurt, Strikman 96; Radyushkin 96]



$$
\begin{aligned}
\text{Amp} \quad &= \quad \int du\, \Phi^M(u) \\
&\times \quad \int dx\, K(x, u, \xi; Q^2) \\
&\times \quad H(x, \xi; t)
\end{aligned}
$$

- General consequences of factorization
  - σ_L(meson production) $\propto\ Q^{-6}$, $\quad \sigma$(DVCS) $\propto\ Q^{-4}$
  - Universality (process–independence) of GPD's

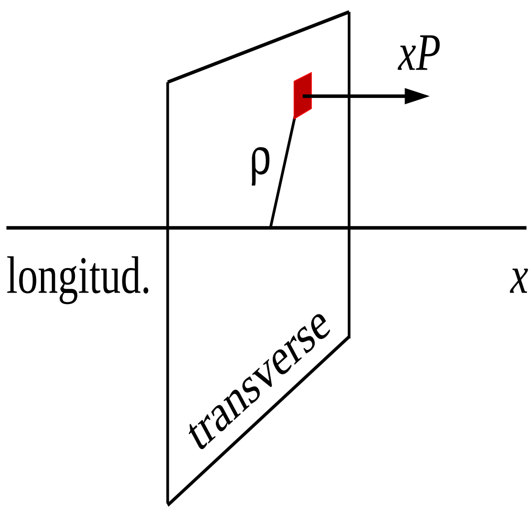
- Transverse spatial distribution of partons [Burkardt 02]



$$H(x, t) \quad = \quad \int d^2\rho \;\, e^{-i\vec{\Delta}_\perp \cdot \vec{\rho}} \;\, q(x, \rho)$$

form factor of quarks with longitudinal momentum xP

transverse spatial distribution



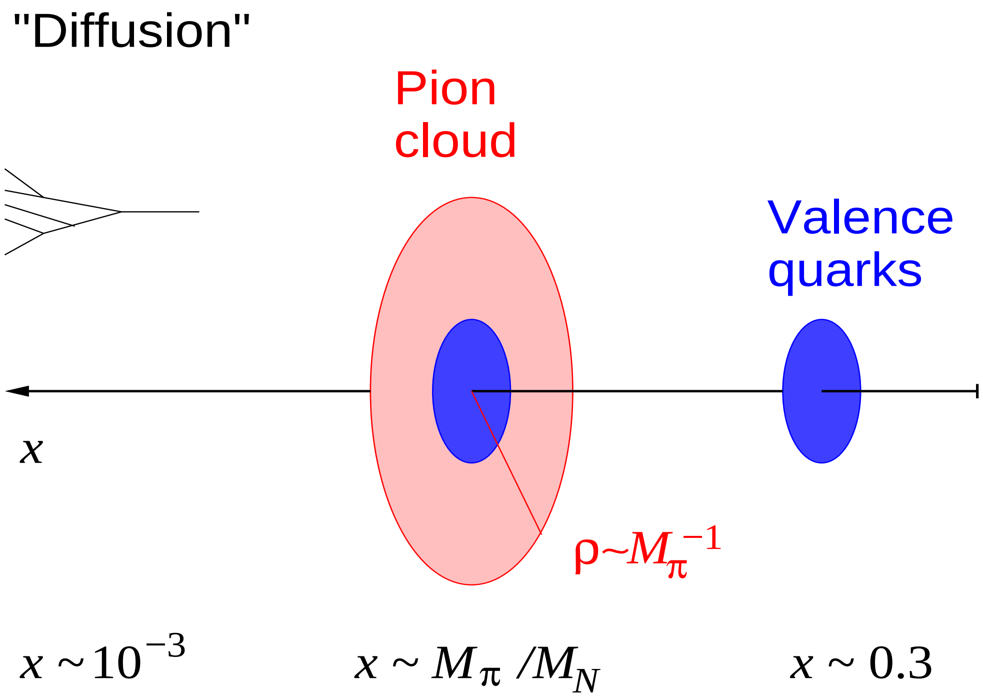
$$\int d^2\rho \, q(x, \rho) \;=\; q(x)$$

total quark density

$$\langle \rho^2 \rangle_x \;=\; 4 \, \frac{\partial}{\partial t} \; \frac{H(x, t)}{H(x, t = 0)}$$

transv. size of nucleon, x–dependent!

- Transverse spatial distribution: Dynamics

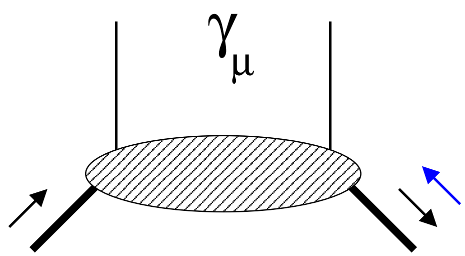


"Onion–like"
structure of nucleon

→ Transverse size $\langle \rho^2 \rangle_x$ grows with decreasing x

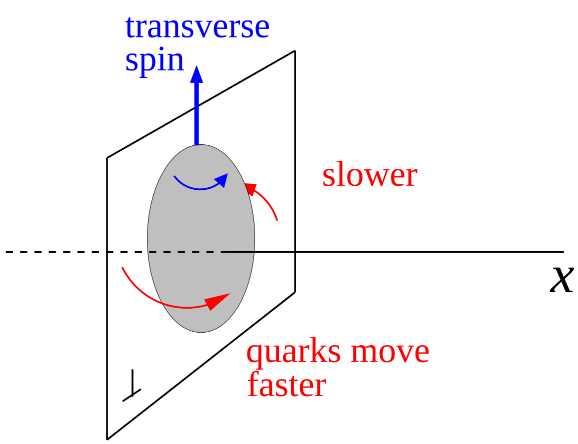
- Quark distributions: Polarization

Quarks unpolarized:



$=$ H, Dirac — E Pauli

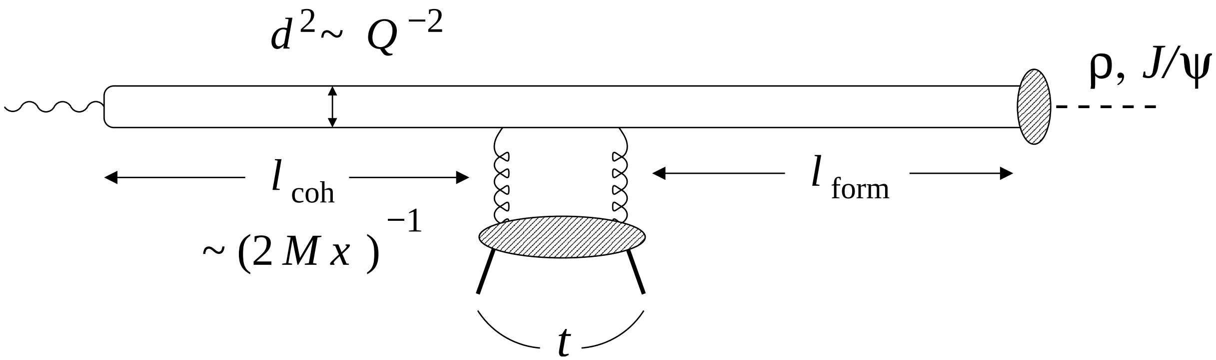
polarized: $\gamma_\mu \gamma_5$ — $\tilde{H}$, axial — $\tilde{E}$ pseudoscalar



$E(x)$: Distortion of longitudinal motion of quarks due to transverse spin [Burkardt 03]

. . . can be extracted from spin asymmetries in $eN \to eN\gamma$

- Hard exclusive processes at small x: Target rest frame
  [Brodsky, Frankfurt, Gunion, Strikman 94]

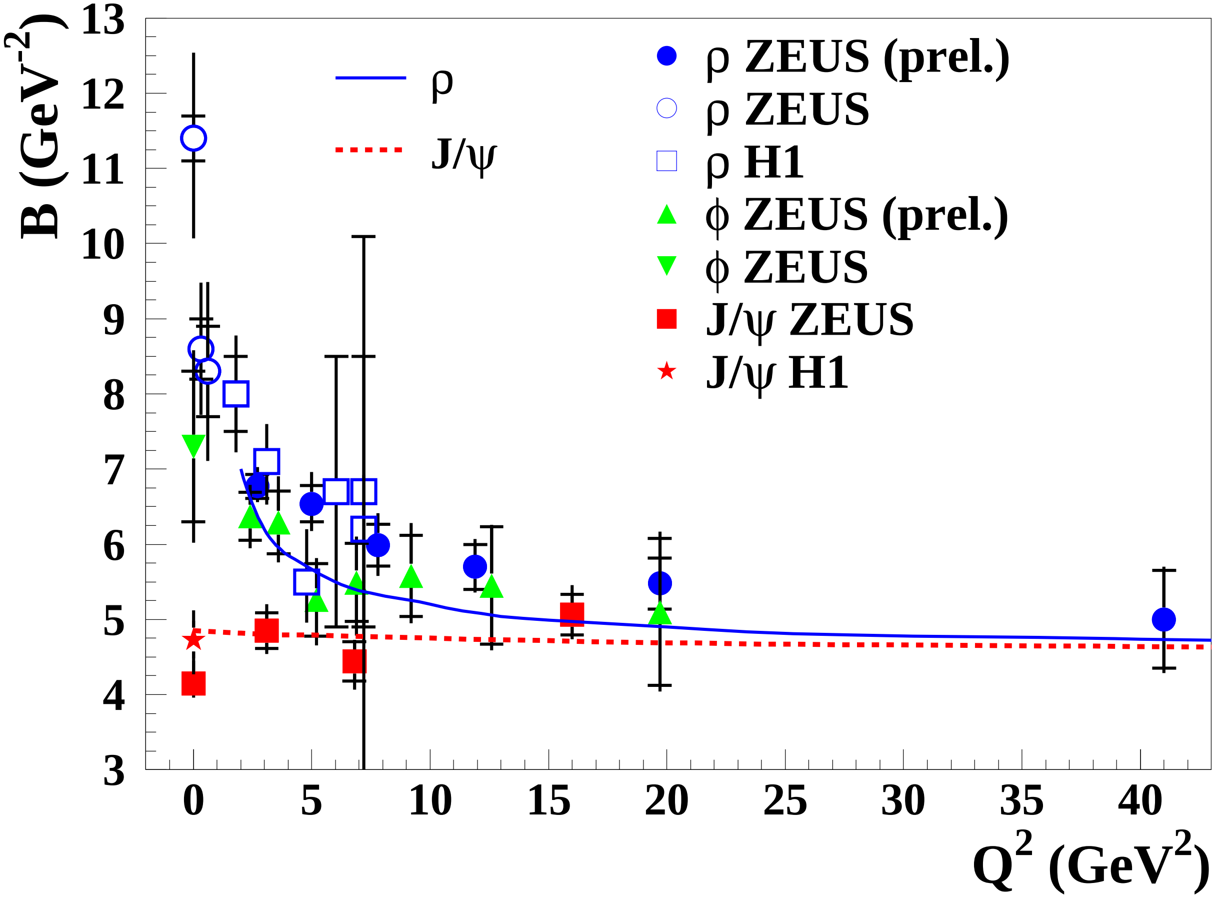


leading $\log Q^2$ approximation

$$A^{\text{dip–}p} \;=\; \text{(color factor)} \times d^2\, \alpha_s\, x\, G(x,t) \qquad (\text{scale} \;=\; \text{const} \times d^{-2})$$

  - Amplitude vanishes for $d \to 0$ ("Color transparency")
  - Increases rapidly at small x
  - Meson produced in small–size configuration ("squeezed")

- Universality of t–slopes: Test of reaction mechanism



$$\frac{d\sigma}{dt} \propto e^{Bt}$$

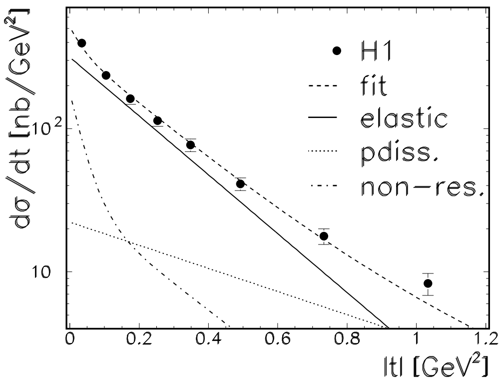
[Courtesy of A. Levy]

Also confirmed by HERA:

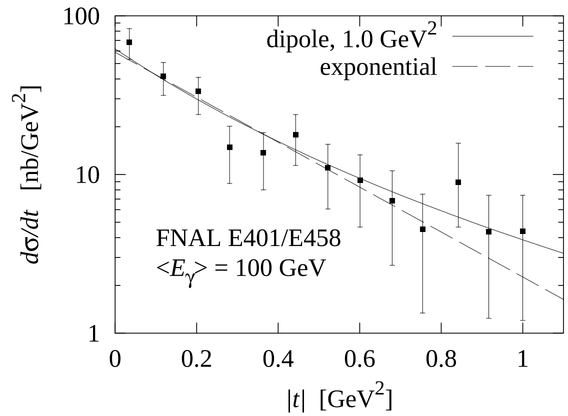
– Growth of cross section with energy

– Flavor symmetry

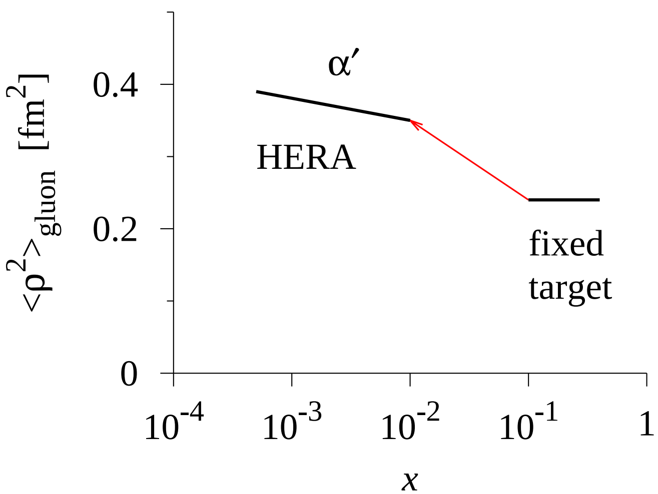
- Transverse gluonic size of nucleon: $d\sigma/dt \propto [xG(x,t)]^2$



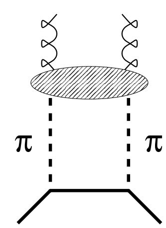
HERA H1 (00)



Fermilab E458 fixed–target (82)



Increase due to
pion cloud contributions

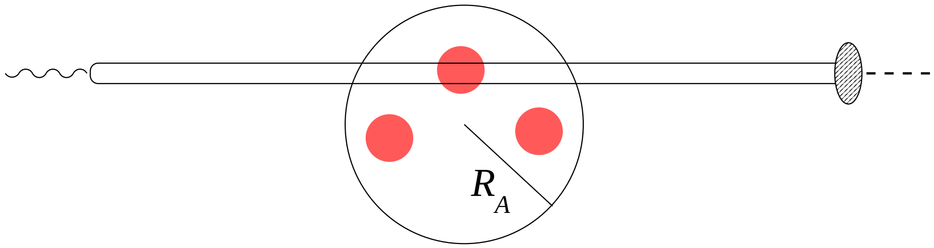


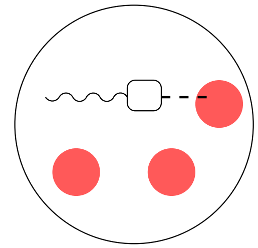
$x < M_\pi / M_N$

$\rho \sim 1/M_\pi$

$\rightarrow$ Phenomenological parametrization of transverse spatial gluon distribution $g(x, \rho)$
[Frankfurt Strikman, CW 03/04]

- Hard exclusive processes in eA





$l_{\rm coh},\ l_{\rm form}\ \gg\ R_A$

Color transparency ($d \ll 1\,{\rm fm}$)

$\sigma\ \propto\ A$

$l_{\rm coh},\ l_{\rm form}\ \ll\ R_A$

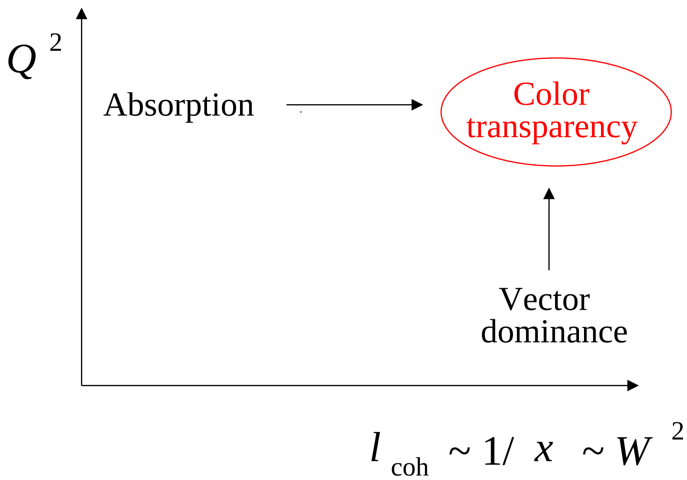
Absorption $\quad \sigma_{\pi N}\ \rho_{\rm nuc}\ R_A \sim 1$

$\sigma\ \propto\ A^{2/3}$

Coherent: $\quad d\sigma/dt(t=0) \propto A^2$

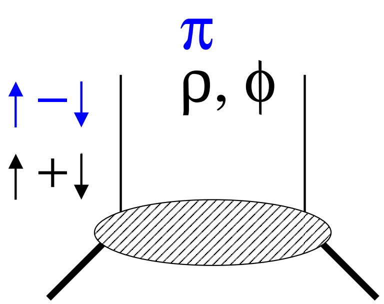
$$|t|\ \propto\ R_A^{-2}\ \propto\ A^{-2/3}$$

Nucleus as "filter" for small–size configurations!



Use leverage in x, Q^2 provided by collider!

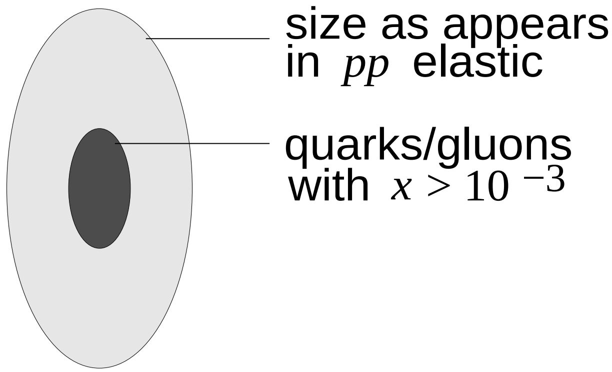
- Spin–flip vs. non-flip



Very different propabilities for leaving nucleus intact

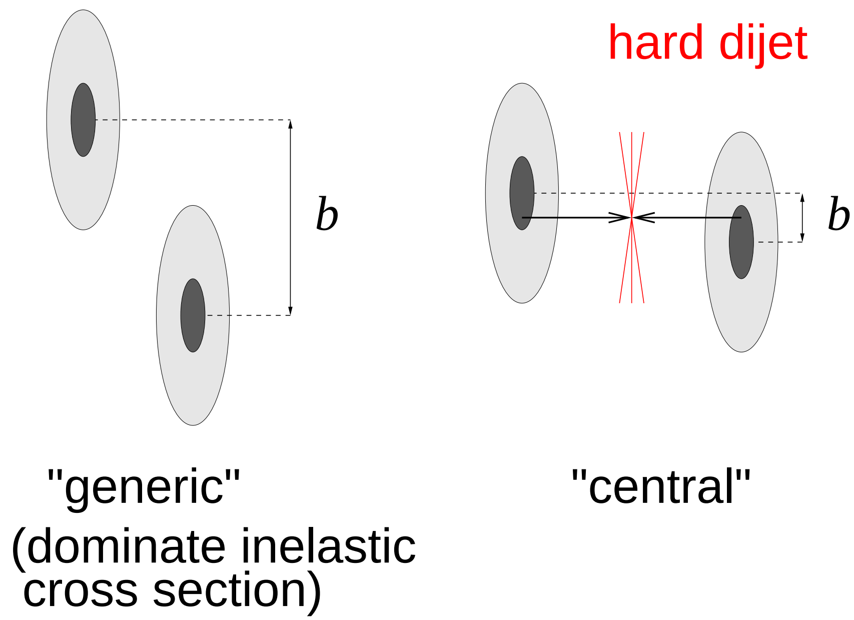
Nucleus as "filter" for quantum numbers of exclusive process!

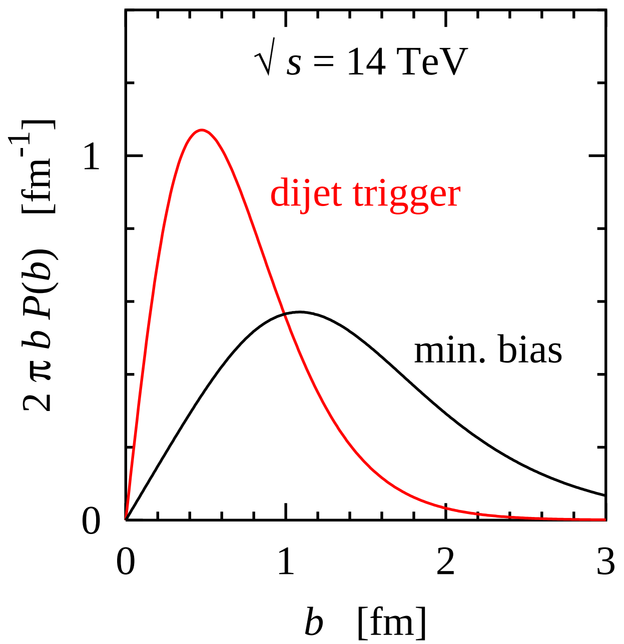
- Hard processes as centrality trigger [Frankfurt, Strikman, CW 03]



$\langle \rho^2 \rangle_{q,g} \ll R_{\rm el}^2$ at high energies

→ Classification of inelastic pp events





$\langle b^2 \rangle$ $[\mathrm{fm}^2]$ average impact parameter

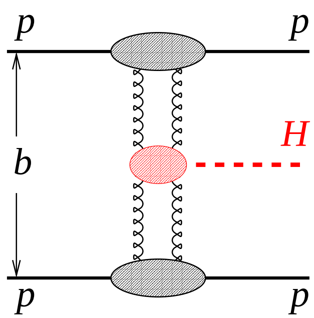
	W/TeV	dijet	double dijet	min. bias
LHC	14	0.67	0.26	2.7
Tevatron	1.8	0.63	0.24	1.8
RHIC	0.5	0.59	0.23	1.43

– “Objective” criterion for central events

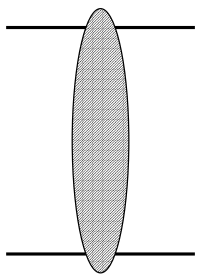
– Application: Studies of black–body limit in central pp collisions

– Higgs production at LHC: Central events

- Diffractive Higgs production [Frankfurt, Strikman, CW 04/05]



$\times$



hard partonic process

$P_{\mathrm{hard}}(b)$

$$\equiv \Big[\int d^2\rho_1\, d^2\rho_2 \times \delta(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) \times g(x_1, \rho_1)\, g(x_2, \rho_2) \Big]^2$$

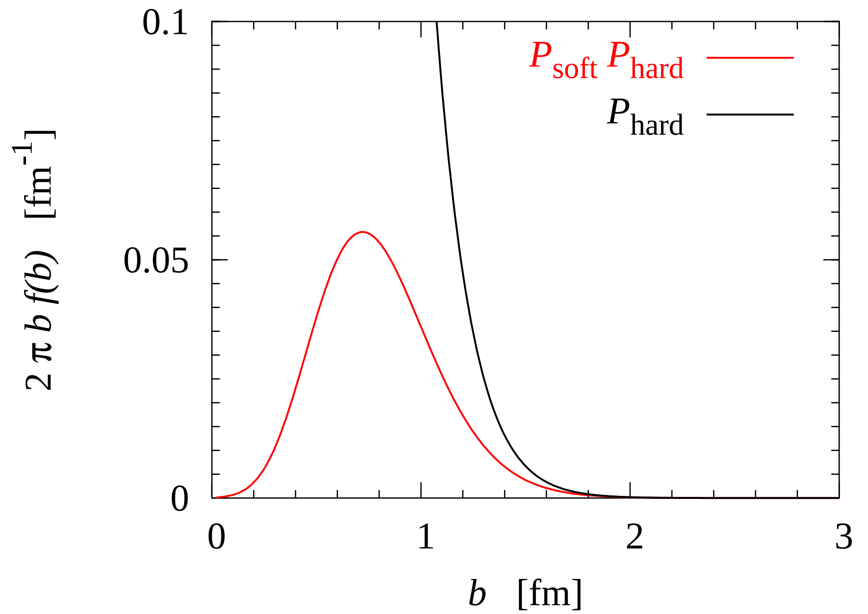
Overlap of gluon dist'ns

soft interactions (must preserve rapidity gaps!)

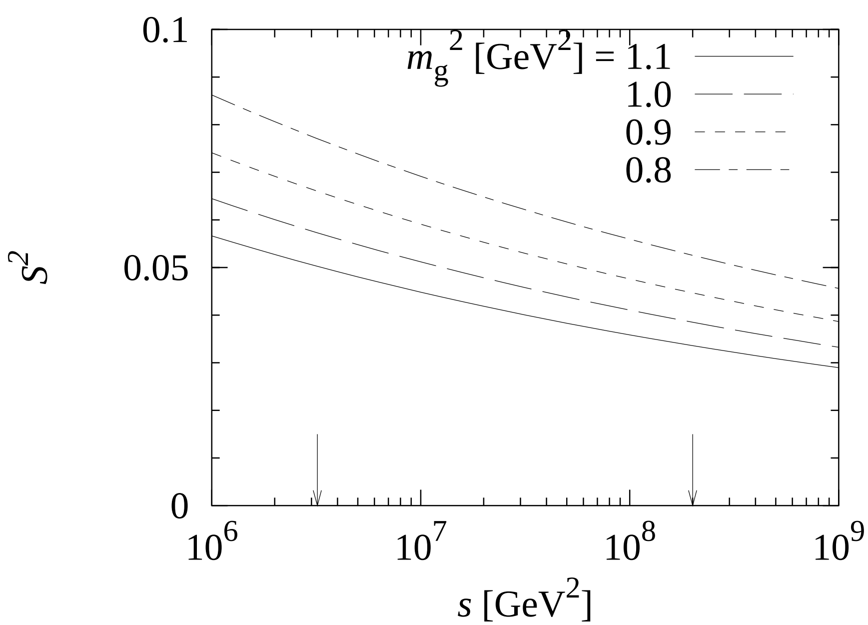
$P_{\mathrm{soft}}(b)$

$$\equiv |1 - \Gamma(b)|^2$$

"No inelastic interactions"

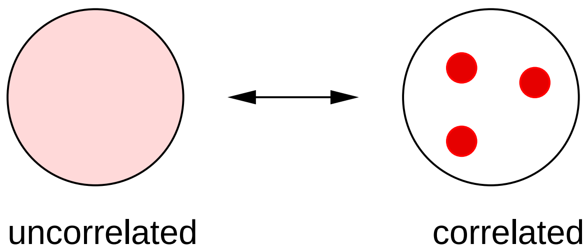


- Soft interactions suppress small impact parameters ("no chance to survive")
- Dominated by intermediate values $b \sim 0.7\,\mathrm{fm}$

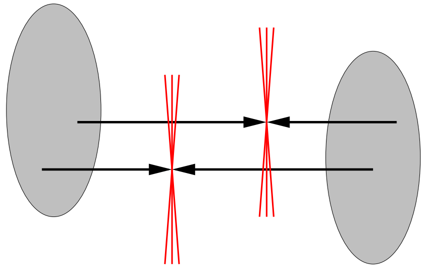


- Gap survival probability $S^2 = \int d^2b\ P_{\mathrm{hard}}(b)\ P_{\mathrm{soft}}(b)$
- Decreases slowly with s
- Estimates agrees well with double pomeron model [Khoze et al. 00]

- Correlations in transverse position of partons
  [Frankfurt, Strikman, CW 04]



. . . Can be probed in double dijet production!



CDF (Fermilab) data compatible with "constituent quarks" of size $\rho \sim 0.3\,\text{fm}$

cf. Instanton liquid picture of QCD vacuum [Diakonov, Petrov 84]

  – Effects of longitudinal and transverse correlations can be separated by comapring $pp \leftrightarrow pA$ (vary "thickness" of target)

Summary

- High–luminosity, tunable, polarized ep collider would provide unique opportunity to map the "3D parton structure" of the nucleon

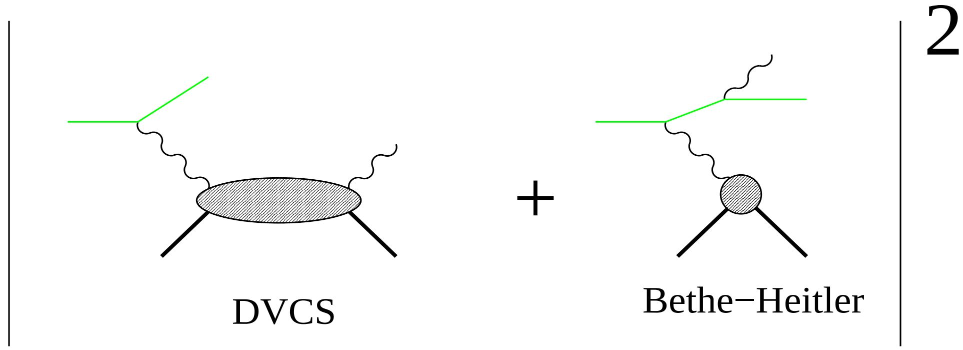
- eA measurements allow for independent tests of the reaction mechanism ("color transparency")

- Information about transverse spatial distribution of partons crucial for understanding dynamics of high–energy pp/pA collisions
  - Centrality trigger
  - Diffraction
  - Multiparton correlations

. . . Great potential in "cooperation" $ep/eA \leftrightarrow pp/pA$

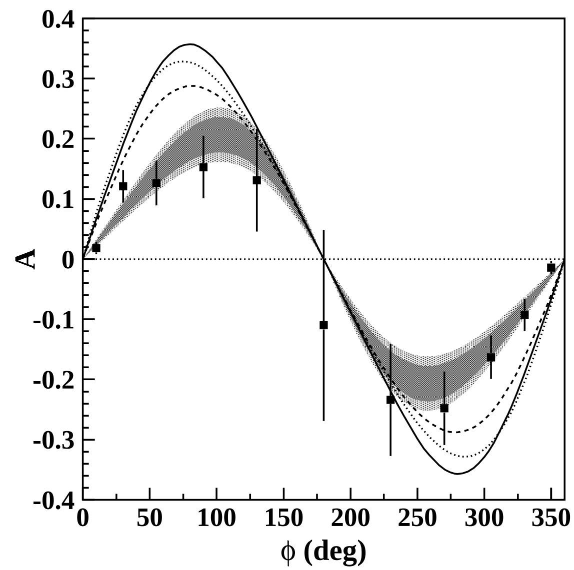
- Spin asymmetries in $ep \to ep\gamma$

$$\sigma(eN \to eN\gamma) \quad =$$



Spin asymmetries
$\to$ Interference term
$\quad \propto$ Im(DVCS)

Beam spin	H
Target spin L	$\tilde{H}$
Target spin T	E



Beam spin asym [CLAS 01]