Exclusive Reactions at High Momentum Transfer
Jefferson Lab, Newport News, VA
May 21-24, 2007

Imaging the Proton via Hard Exclusive Production in Diffractive pp Scattering

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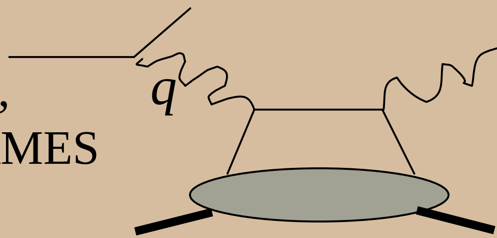
L.Frankfurt, Ch.E.H., M. Strikman, Ch.Weiss, *Phys.Rev.* **D75** 054009 (2007).
Ch.E.H., L.Frankfurt, M. Strikman, Ch.Weiss, DIS2006: hep-ph/0608312

Quark & Gluon Imaging

- Example of Deeply Virtual Compton Scattering (DVCS) $ep \rightarrow ep\gamma$

JLab, HERMES



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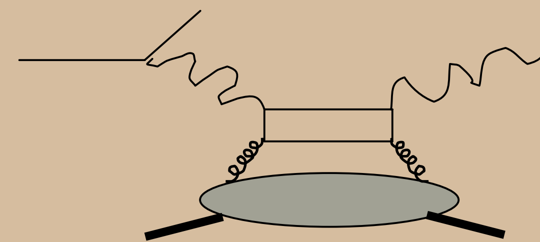


HERA, COMPASS EIC?

  - Large Virtuality $-q^2 = Q^2$: $\Rightarrow$ Factorization of perturbative sub-process.
  - Longitudinal momentum transfer:
    - $2\xi = 2x_{Bj}/(2-x_{Bj})$ = skewness = difference of initial and final momentum fractions
    - $\xi = 0$: Densities; $\xi > 0$: Wigner functions
  - $\Delta = (q-q')$, $\Delta^2 = t$ $\Delta_\perp{}^2 \approx t_{\min} - t$
  - $\Delta_\perp$ Fourier conjugate to *impact parameter,* **b.**
- *Parton Tomography:*
  - *Correlation of parton longitudinal momentum and transverse position*

Idea of pp Diffractive Production

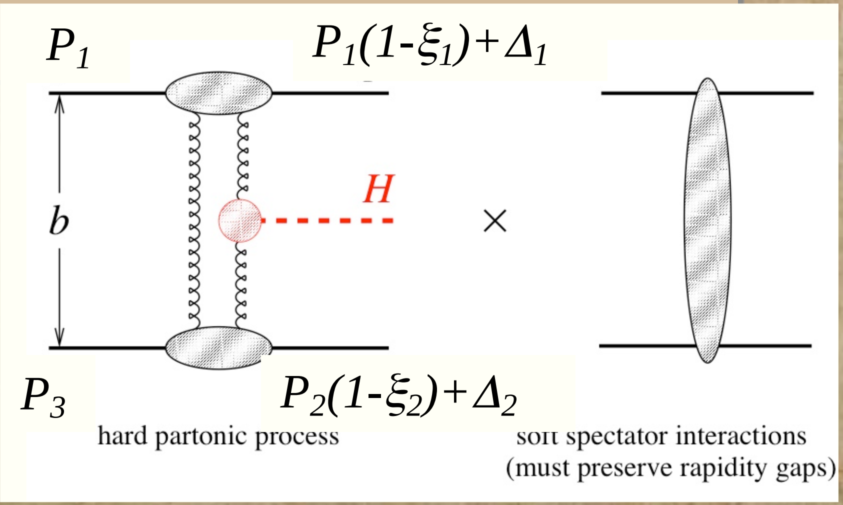
- $p_1 + p_2 \rightarrow p_3 + gap + H + gap + p_4$
  - *H = Higgs, di-jet, Upsilon, J/Ψ, di-hadron, di-lepton, di-photon…*
- $M_H^2 = \xi_1 \xi_2 s << s$: Phase space for rapidity gaps
- $M_H^2 >> \Lambda^2_{QCD}$: Perturbative mechanism
- $t_1 = (p_3 - p_1)^2 \approx -(\Delta_1)^2$ $\quad$ $t_2 = (p_4 - p_2)^2 = -(\Delta_1)^2$
- $\Delta_{1,2}$: Fourier Conjugate to impact parameters $\mathbf{b}_{1,2}$ of hard scattering process
  - pp impact parameter $\mathbf{b} = \mathbf{b}_2 - \mathbf{b}_1$

- Irreducible soft interactions:

•Convolute hard and soft contributions to $\Delta_{1,2}$

•Measure/compute soft interaction effects?

•Does hard scattering measure properties of ground state or of soft collisional excited state?

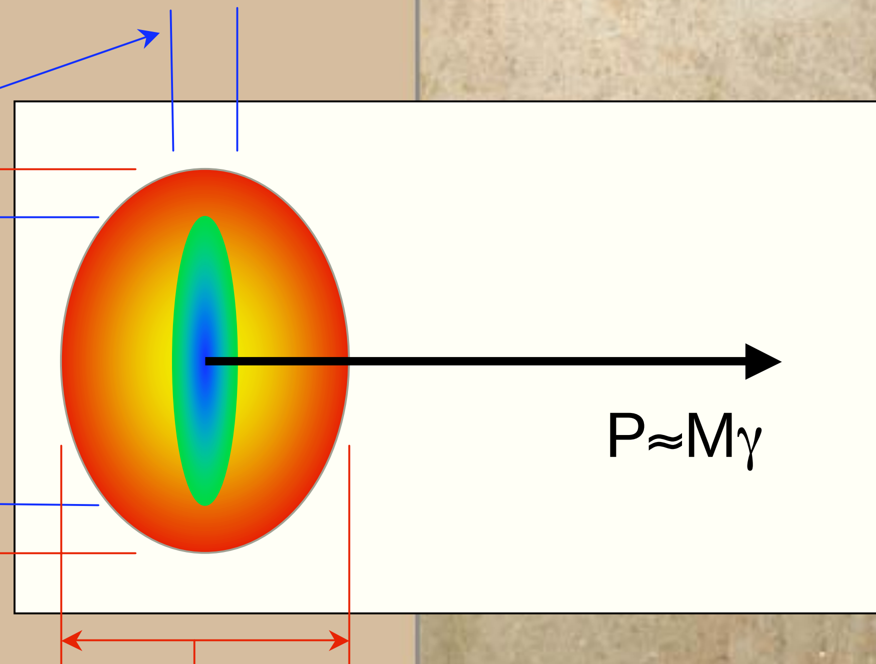


Gribov Picture of Fast Projectiles

hep-ph/0006158

- Large-x partons (x>0.01)
  - confined to a volume:

$$\langle R^2\rangle_\perp \otimes \left[\frac{\sqrt{\langle R^2\rangle}}{\gamma}\right]_{\parallel}$$



- Low-x partons ($x \geq 1/\gamma$).
  - Transverse diffusion
    - … $\sqrt{\langle R^2\rangle}\ln(x_0/x)$
  - Longitudinal spread …
    - Invariant longitudinal size.

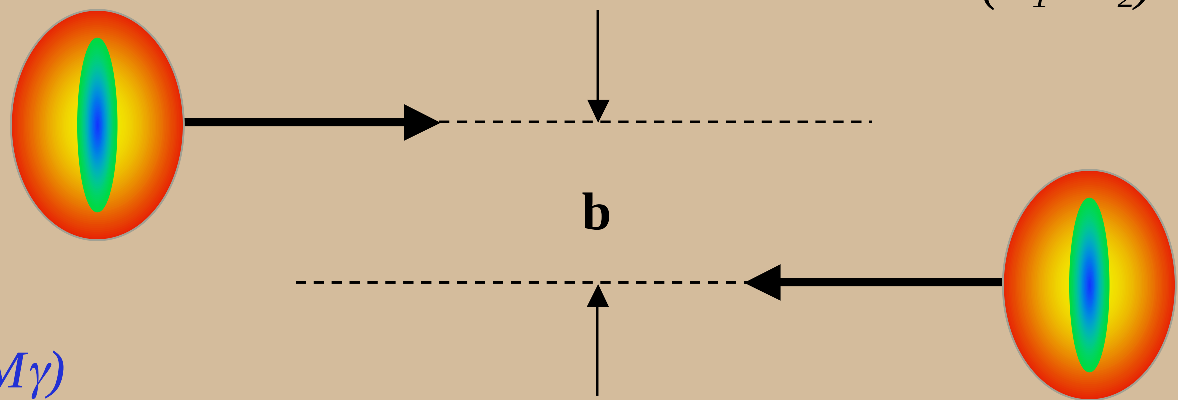
$$\frac{\langle x\rangle}{x}\frac{\sqrt{\langle R^2\rangle}}{\gamma} \approx \sqrt{\langle R^2\rangle}$$

Elastic Scattering & Black Disk Limit

Impact Parameter (**b**) Representation

$P_1^{\mu} = M\gamma\,(1,0,0,\beta)$

$s = (P_1 + P_2)^2 = 4M^2\gamma^2$



$\delta b \approx 1/(M\gamma)$

b is a good quantum #

$P_2^{\mu} = M\gamma\,(1,0,0,-\beta)$

Elastic Scattering Amplitude T_{El}, for ⊥-Momentum Transfer Δ:

Elastic scattering = diffraction pattern of **b**-dependent absorption $i\Gamma(\mathbf{b},s)$.

$$T_{El}(\boldsymbol{\Delta},s) = [is/(4\pi)] \int d^2\mathbf{b}\; e^{i\boldsymbol{\Delta}\cdot\mathbf{b}}\; \Gamma(\mathbf{b},s)$$

Center of Proton is Black: Black Disk Limit (BDL) = Pure Absorption

$\Gamma(\mathbf{0},s) = 1$ (s≥Tevatron) → Stabilizes numerical estimates

Elastic, Inelastic, and Total Scattering Cross Sections

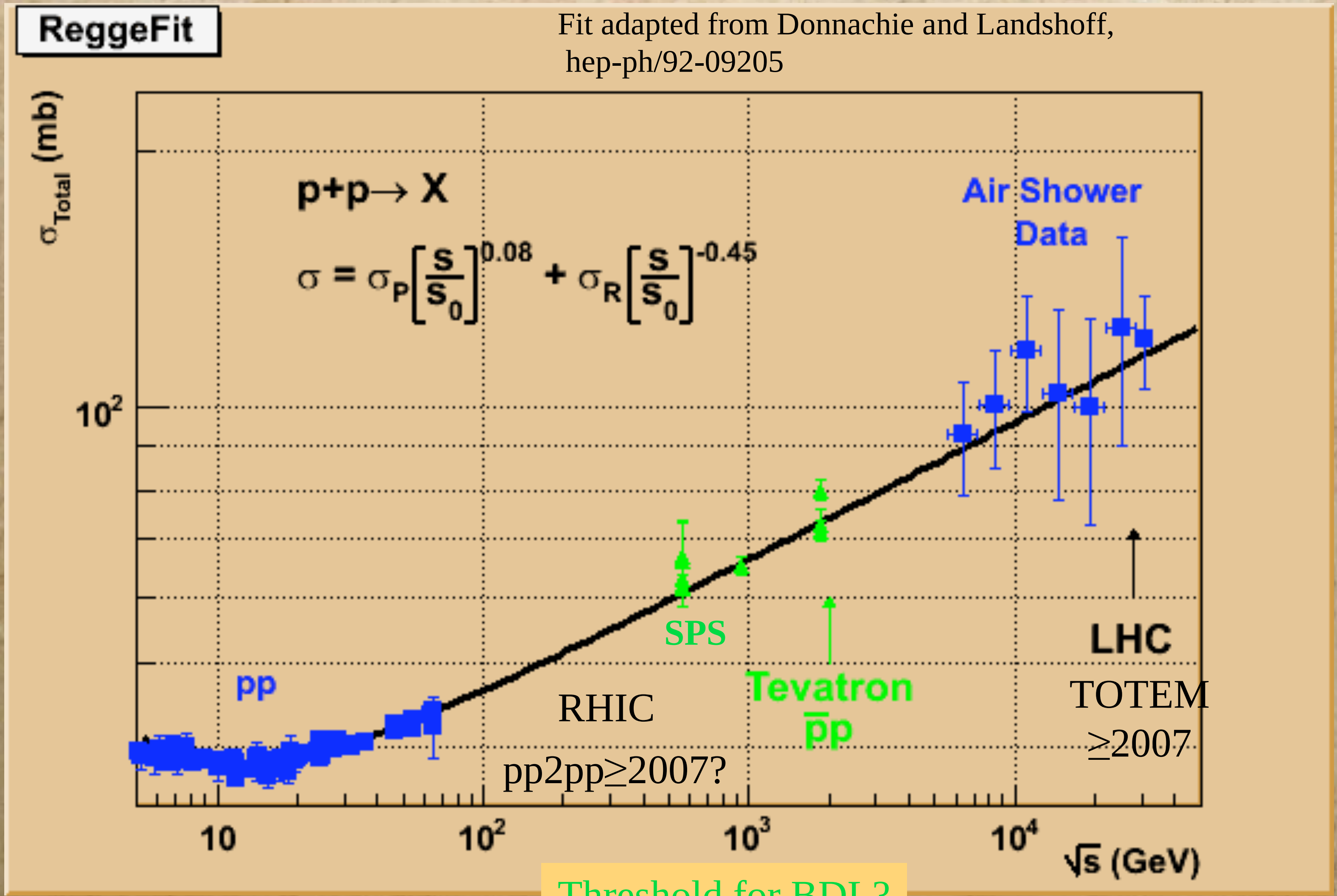
- Impact Parameter Representation:

$$d^2\sigma_{\mathrm{El}}(s) = \frac{d^2\Delta}{(2\pi)^2}\left|\int d^2\mathbf{b}e^{-ib\cdot\Delta}\Gamma(\mathbf{b};s)\right|^2$$

$$\left.\begin{array}{c}\sigma_{\mathrm{El}}(s)\\ \sigma_{\mathrm{Tot}}(s)\\ \sigma_{\mathrm{Inel}}(s)\end{array}\right\} = \int d^2\mathbf{b}\times\left\{\begin{array}{c}\left|\Gamma(\mathbf{b};s)\right|^2\\ 2\Re\left[\Gamma(\mathbf{b};s)\right]\\ \left[1-\left|1-\Gamma(\mathbf{b};s)\right|^2\right]\end{array}\right.$$

- $|1-\Gamma(\mathbf{b};s)|^2$ = Probability of no inelastic scattering at impact parameter **b**.
- Elastic S-matrix: $S_{El}(\Delta,s) = \int e^{i\Delta\cdot\mathbf{b}}d^2\mathbf{b}\left[1-\Gamma(\mathbf{b},s)\right]$

pp Total Cross Sections



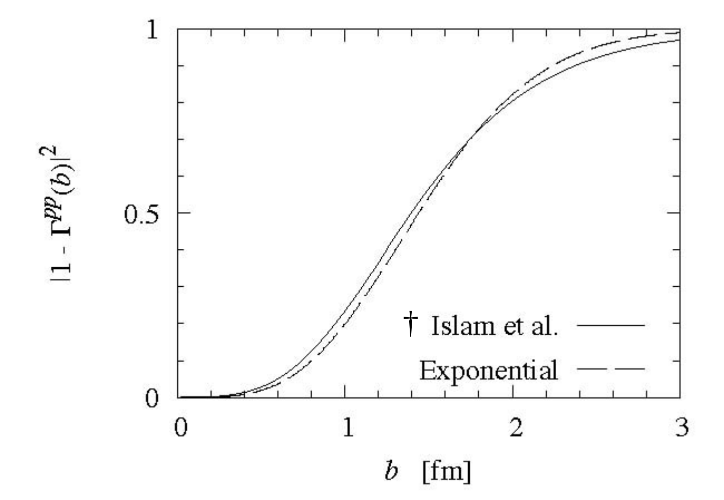
Threshold for BDL?

Behavior of σ_{Total} & $\Gamma(\mathbf{b};s)$

BDL:
$1-\Gamma(0,s) = 0$

Ultraperipheral:
$\Gamma(\infty,s)=0$

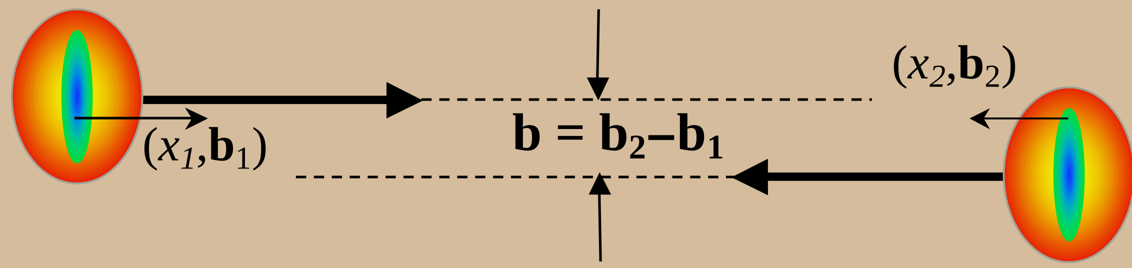
- Gaussian model:
  - $\Gamma(\mathbf{b},s) = exp[-\mathbf{b}^2/B(s)]$.
  - $\sigma_{Total} = 4\pi B(s)$
- Regge Fit
  - $\sigma_{Total} \rightarrow \sigma_0\, (s/s_0)^{0.08} + \ldots$
    - $B(s) = B_0(s/s_0)^{0.08}$.
    - $B = 21.8\ GeV^{-2}$ $\quad s = (14\ TeV)^2$: *LHC.*
- $\Gamma(\mathbf{b},s)$ is a slowly varying function of s at high energy.



† M. Islam, *et al*, PLA**18**, 743, 2003. Model of Kaidalov, Khoze, Martin, and Ryskin gives similar results

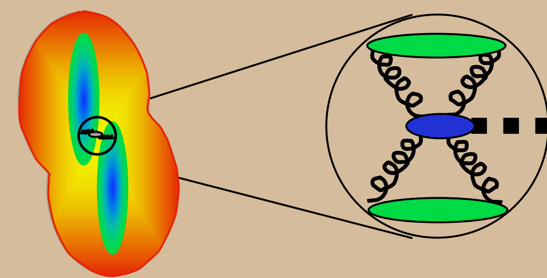
Diffractive High Mass Production

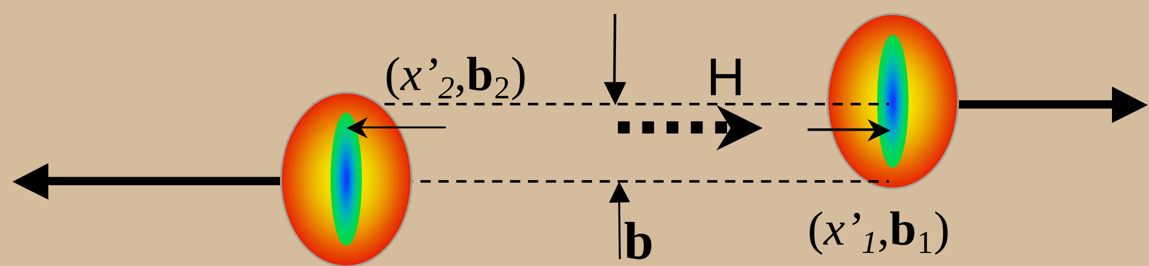
t << –R



Soft interactions for
–R ≤ t ≤ R

Hard interactions for
$|t| \leq R/\gamma$

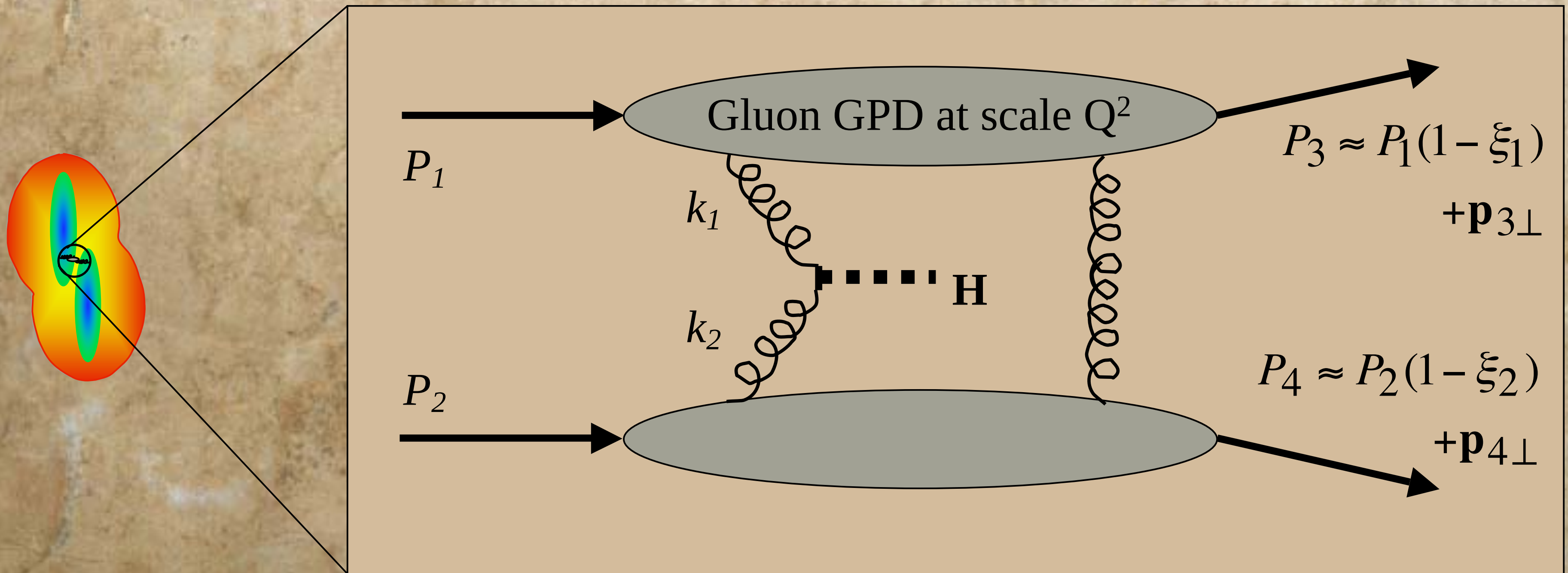




t > +R

Time scales of hard and soft interactions differ by factor γ.

Hard Scattering Kinematics, $s=(P_1+P_2)^2$



- $k_1 \approx x_1 P_1 + \mathbf{k}_{1\perp}$ $\quad\quad k_2 \approx x_2 P_2 + \mathbf{k}_{2\perp}$
- $k = (x_1 - \xi_1)P_1 + \mathbf{k}_\perp - (x_2 - \xi_2)P_2 \approx \mathbf{k}_\perp$
- Post Selection of Rapidity Gap ⇒ Suppression of gluon bremsstrahlung: Loop Virtuality: $k_1^2 \sim k_2^2 \sim k^2 \sim Q^2$.

Kinematic Hierarchy:

$$\Lambda^2_{QCD} << \langle Q^2 \rangle << M_H^2 << s$$

$$x_1 x_2 s \approx M_H^2$$

$$(x_i - \xi_i) << x_i \approx \xi_i << 1$$

Factorization of Hard & Soft Scattering

- $T_{\text{Diff}} = \langle p_3 p_4 | S_{\text{Soft}}(\infty,0) V_{\text{Hard}}(H) S_{\text{Soft}}(0,-\infty) | p_1 p_2 \rangle$
  - V_{Hard} :
    - Diagonal in impact parameter
    - Time scale = R/γ << R = Time scale of S_{Soft}
    - Does not mix Fock sub-spaces in diffractive production.
    - Conserves parton helicity
  - $[V_{\text{Hard}}, S_{\text{Soft}}] \approx 0$
    - $T_{\text{Diff}} = \langle P_3 P_4 | S_{\text{Soft}}(\infty,-\infty) | X \rangle \langle X | V_{\text{Hard}}(H) | P_1 P_2 \rangle$
    - Broken by transverse correlations of hard and soft partons
  - V_{Hard} and S_{Soft} populate orthogonal inelastic intermediate states. Excitation of low mass N* by S_{Soft} suppressed at LHC energies (Goulianos hep-ph/0510035).
- $T_{\text{Diff}} \rightarrow \langle P_3 P_4 | S_{\text{Elastic}}(\infty,-\infty) | p' p'' \rangle \langle p' p'' | V_{\text{Hard}}(H) | P_1 P_2 \rangle$

Scattering Amplitude in Impact Parameter Space

- GPD h_g in impact parameter space.

$$h(x,\xi,\rho) = \int \frac{d^2\Delta}{(2\pi)^2} e^{i\Delta\cdot\rho} H(x,\xi,t=-\Delta^2)$$

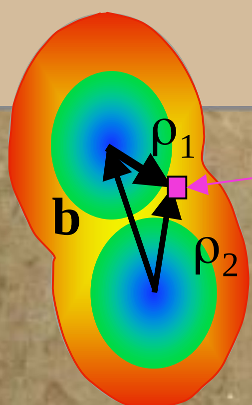
- Scattering amplitude

$$T_{Diff}(\xi_1,\mathbf{p}_3,\xi_2,\mathbf{p}_4) = \int d^2\rho_1 \int d^2\rho_2 e^{-i\left[\rho_1\cdot\mathbf{p}_3+\rho_2\cdot\mathbf{p}_4\right]}$$

$$\kappa(\xi_1,\xi_2) h(x_1,\xi_1,\rho_1,Q^2) h(x_2,\xi_2,\rho_2,Q^2)$$

$$\left[1-\Gamma(\rho_2-\rho_1,s)\right]$$

Soft Scattering



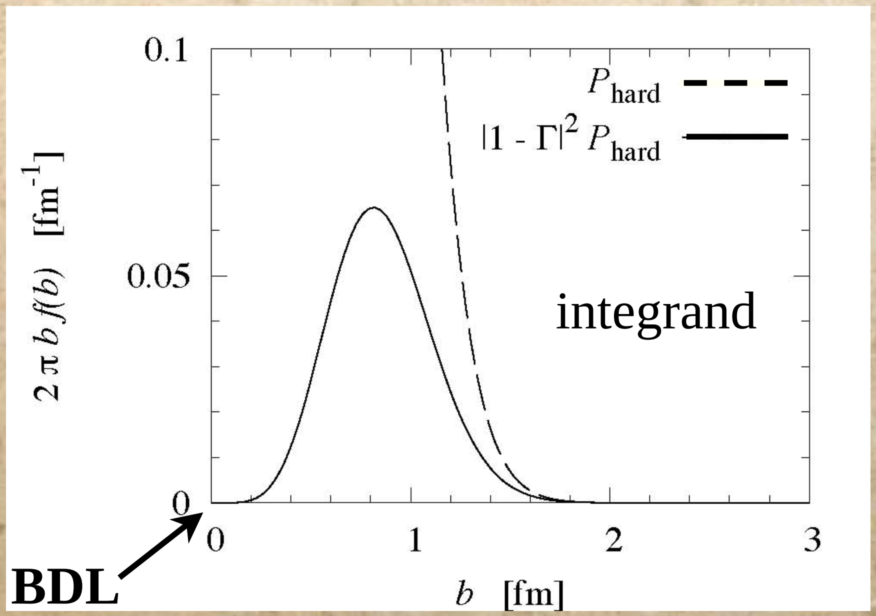
Hard Scattering

$\mathbf{b}=\rho_2-\rho_1$

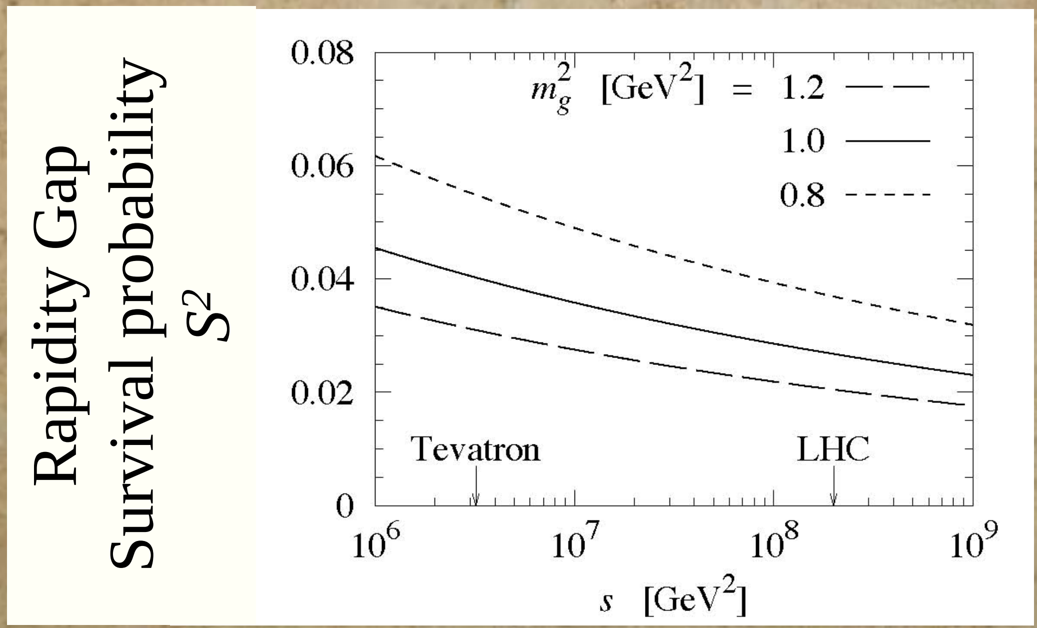
"Beam-pipe view":
One projectile coming towards us, one moving away.

S^2: Rapidity Gap Survival Probability for Hard Exclusive Production

- Surface Peaking:
  - Integrand = gluon density × [1-Γ]

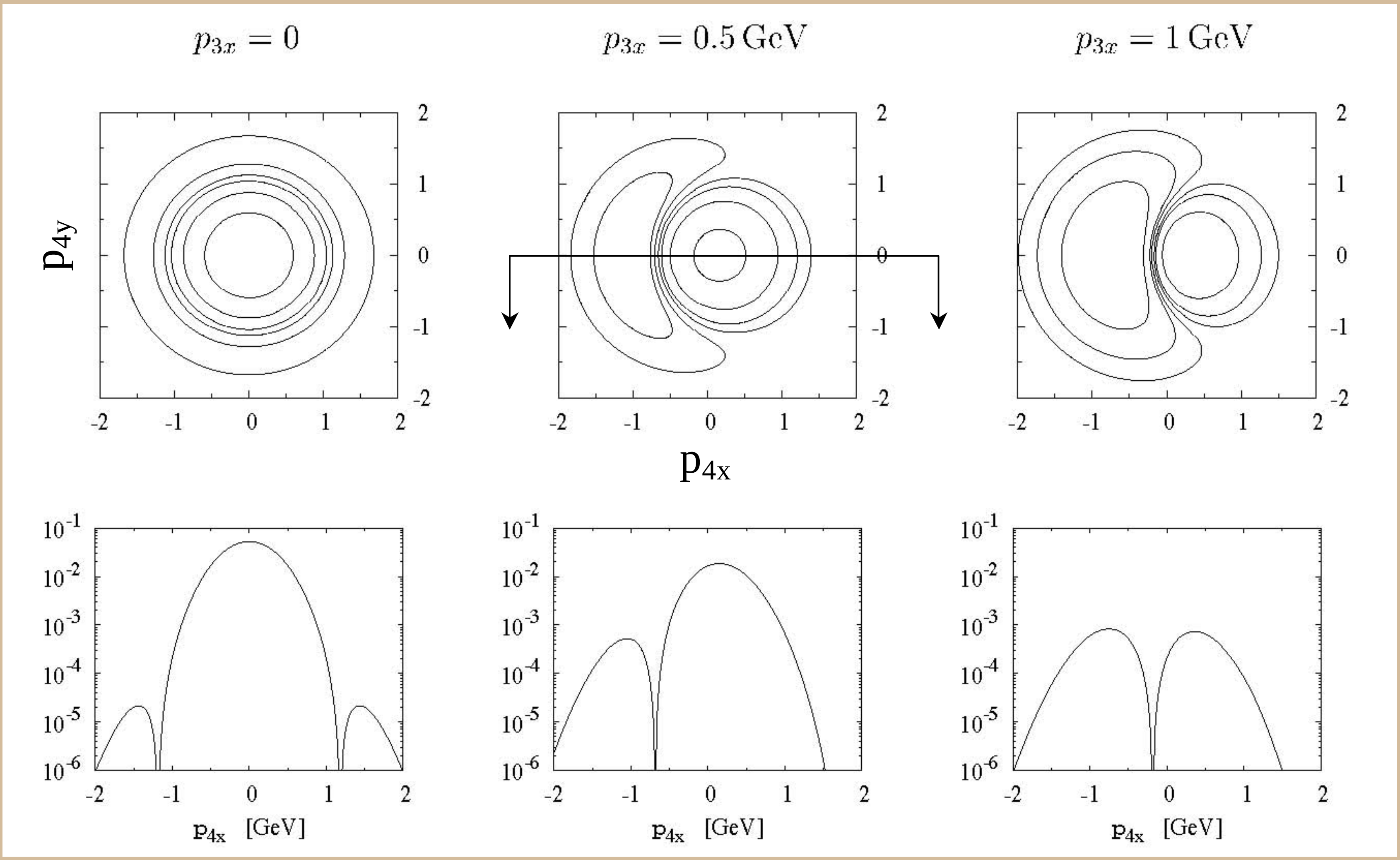


$$S^2 \equiv \frac{\sigma_{DD}(\text{Full})}{\sigma_{DD}(\text{no\_soft} : \Gamma = 0)}$$
$$= \int d^2\mathbf{b} P_{hard}(\mathbf{b}) |1 - \Gamma(\mathbf{b}, s)|^2$$



Diffractive images in transverse plane (p_{3y}=0)

Optical analog: { H(,Δ)= fourier transform of Diffraction Grating,
[1-Γ(ρ2–ρ1)] = single slit profile of each grating

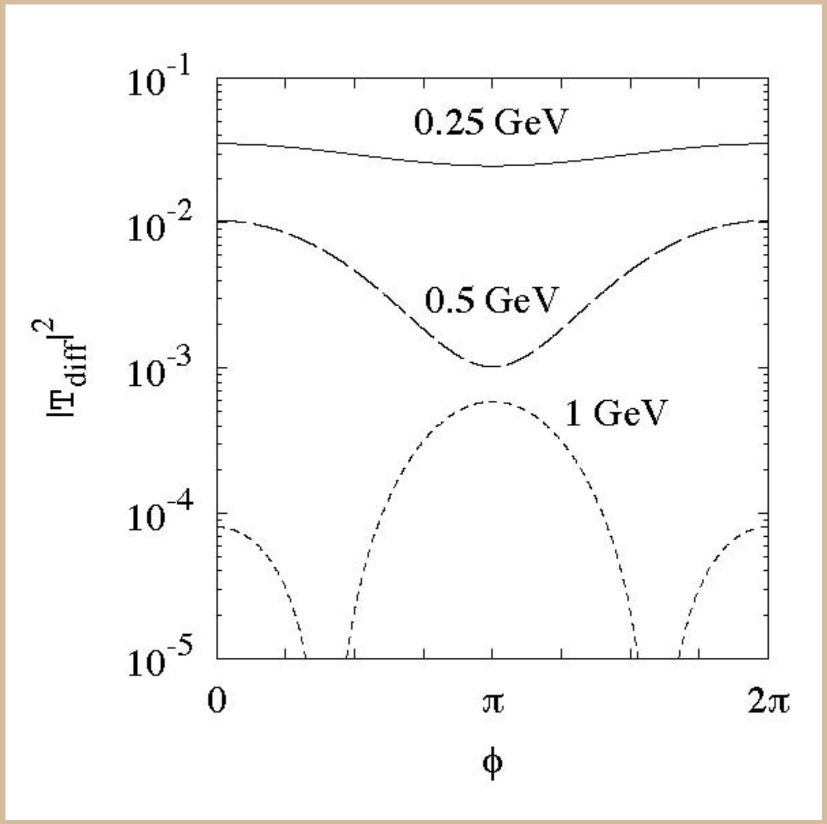


Azimuthal Distribution of $\mathbf{p}_4$ vs $\mathbf{p}_3$

- $\phi = \phi_4 - \phi_3$.
  - 0^+ production ($g^{\mu\nu}$) maximizes $\mathbf{p}_3 \cdot \mathbf{p}_4$
    - $\phi = \pi$: both projectiles recoil in same direction
  - 0^- production ($\varepsilon^{\mu\nu\rho\sigma}$) maximizes $E_1\, \mathbf{p}_2 \cdot (\mathbf{p}_3 \times \mathbf{p}_4)$
    - $\phi = \pi/2$: projectiles recoil at right angles.
- Sensitivity to parity of new particles

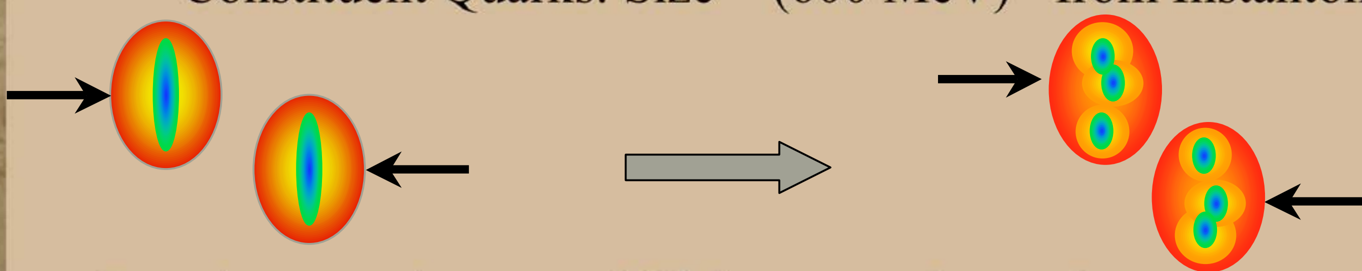
0^+ production:

140 GeV Higgs at 7 TeV



Correlations of soft and hard partons in transverse plane

- Hard Scattering of parton at impact parameter ρ_1 in projectile 1 on parton at impact parameter ρ_2 in projectile 2.
- Local density of soft partons in each projectile near $\rho_{1,2}$ is greater than average density in each projectile.
  - Partons are clustered in hadrons
- Sources of parton clustering:
  - Pion-cloud for $\xi < m_\pi/M \rightarrow 6\%$ reduction of S^2.
  - Constituent Quarks: Size = $(600\ \text{MeV})^{-1}$ from Instantons



- Previous estimate of S^2 is upper bound

Conceptual Conclusions:
Rapidity Gap Survival in Central Hard Diffraction

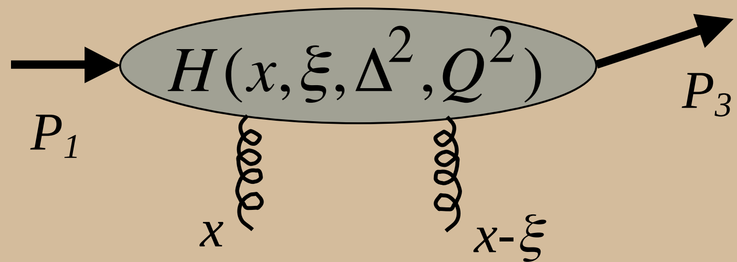
- Generalized Parton Distributions:
  - Unifying Concept for Hard Exclusive Reactions: *ep*, *pp*, …
- Impact Parameter representation gives physical picture
  - Quantum Numbers (parity) of new particles
  - [Approximate] factorization of hard & soft interactions
  - Transverse-spatial imaging of [quark &] gluon distributions
  - Model independent Parameterization of Soft Interactions
  - Black Disk Limit at b=0, s≥Tevatron highly constrains numerical estimates
  - P_T distributions (spatial distribution of gluons) Depend on Rapidity
- Correlations of Hard and Soft partons in impact parameter
  - Complicates separation of hard and soft scattering
  - Examples: Pion-cloud, constituent-quarks, instantons:
  - Diffraction may provide new tool for observation of correlations.
  - Bound on Rapidity Gap Survival: $S^2 \leq 0.03$.

Experimental Outlook

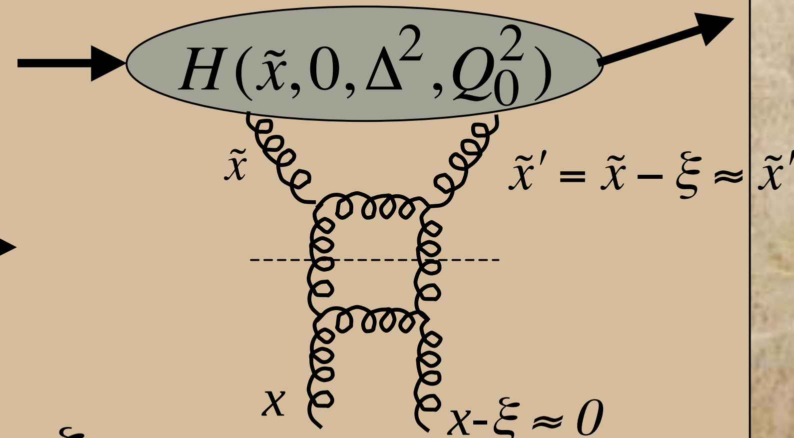
- RHIC: pp2pp @ STAR $\sqrt{s}$=200 GeV
  - Si tracker at ≈60 m   ≥ 2007
    - Elastic polarized pp scattering amplitude
    - Constrain onset of Black Disk Limit?
  - Si tracker at ≈20 m   ≥ 2008
    - Rapidity gap events with central production in STAR
  - $\sqrt{s}$=500 GeV ≤2010?
- LHC
  - TOTEM (CMS ≥ 2007): Si tracker at 200 m
    - Elastic Scattering, total cross section, Re/Im ratio at $t=0$.
    - Rapidity gap tagging for $0.01<\xi<0.1$
  - LHC420 (≥ 2008): Si tracker at 420 m
    - Rapidity gap tagging for $0.001 < \xi < 0.01$

Additional Transparencies

Evolution and Parton model



$Q^2 >> Q_0^2$



$$P_3 \approx P_1(1-\xi) + \Delta_\perp \qquad x - x' = \tilde{x} - \tilde{x}' = \xi$$

$$x - \xi << x, \xi << \tilde{x} \approx \tilde{x}' << 1$$

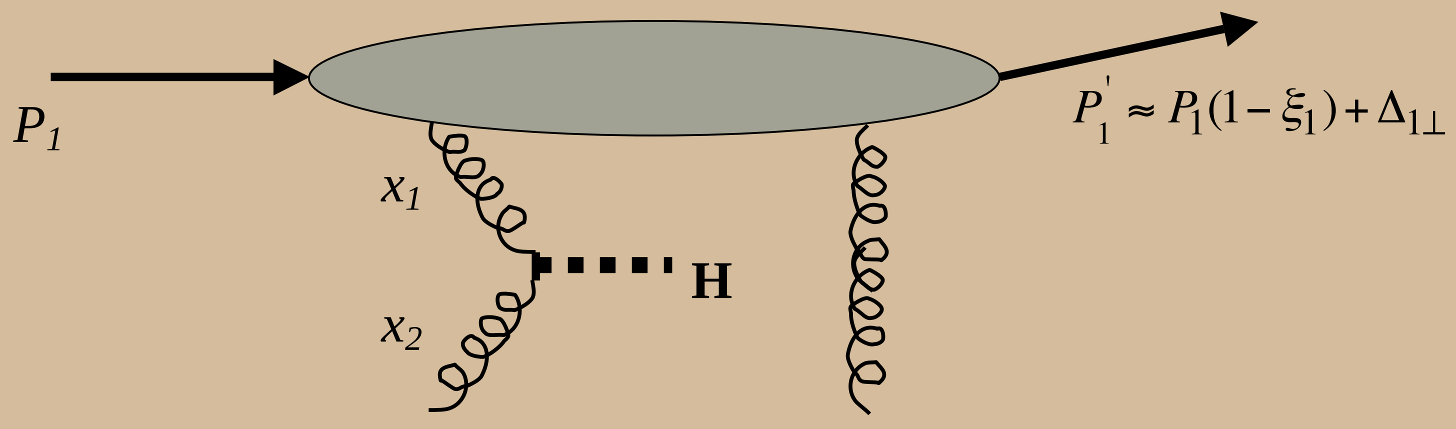
- *Example:* *p=7 TeV* M_H *= 100 GeV*

  $$x \approx 10^{-2} << \tilde{x} << 1$$

- *Virtuality* Q^2*:* evolution local in impact parameter space,

Hard Scattering Amplitude:

Un-integrated Generalized Parton distributions



- Perturbative kernel for *gluon(x_1)+gluon(x_2)* $\rightarrow H$
- Soft matrix elements of projectiles
  - *Gluon +Proton -> Gluon +Proton*
  - Compton amplitude for gluons of virtuality Q^2
    - $\Lambda_{QCD}^2 << \langle Q^2 \rangle << M_H^2$.
  - *Virtuality Q^2:* evolution is local in impact parameter space

Scattering Amplitude in Momentum Transfer Space

- pQCD kernel; Gluon GPDs of Projectiles

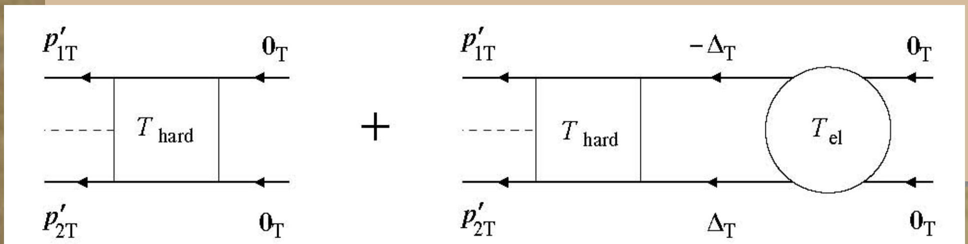
$$T_{Diff}(\xi_1,\mathbf{p}_3,\xi_2,\mathbf{p}_4)=\int\frac{d^2\Delta_\perp}{(2\pi)^2}\kappa(\xi_1,\xi_2)H_g(x_1,\xi_1,t_3,Q^2)H_g(x_2,\xi_2,t_4,Q^2)$$

$$\underbrace{\left[(2\pi)^2\delta^{(2)}(\Delta_\perp)+\frac{4\pi i}{s}T_{El}(s,t)\right]}_{S_{Soft}}dx_1dx_2$$

$$t=-\Delta^2$$

$$t_3=-(\mathbf{p}_3-\Delta)^2$$

$$t_4=-(\mathbf{p}_4+\Delta)^2$$



Gaussian Model

$$H_g(x,\xi,\Delta^2) = H_0(x,\xi)e^{-\Delta^2 B_g(\xi)}$$
$$T_{El} = \int d^2\mathbf{b}\, e^{-i\Delta\cdot\mathbf{b}}\Gamma(\mathbf{b},s)$$
$$\Gamma(\mathbf{b},s) = e^{-\mathbf{b}^2/B}$$

J/Ψ Photoproduction,
$B_g \approx 3.24\ GeV^{-2} << B \approx 22\ GeV^{-2}$
Transverse size $\sqrt{B_g}$ of 'hard' gluons is smaller than hadronic radius $\sqrt{B}$.
$GPD(x \approx 0.05,\ Q_0^2 \approx 3\ GeV^2)$
dominates determination of
$GPD(x=0.01,\ Q^2 \approx 20\ GeV^2)$
M_H =140 GeV @ LHC

$$T_{\mathbf{Diff}} = e^{-\left[B_g(\xi_1)\mathbf{p}_3^2 + B_g(\xi_2)\mathbf{p}_4^2\right]/2}\left\{1 - \frac{B}{B_{Tot}} e^{\left[B_g(\xi_1)\mathbf{p}_3 + B_g(\xi_2)\mathbf{p}_4\right]^2/[2B_{Tot}]}\right\}$$

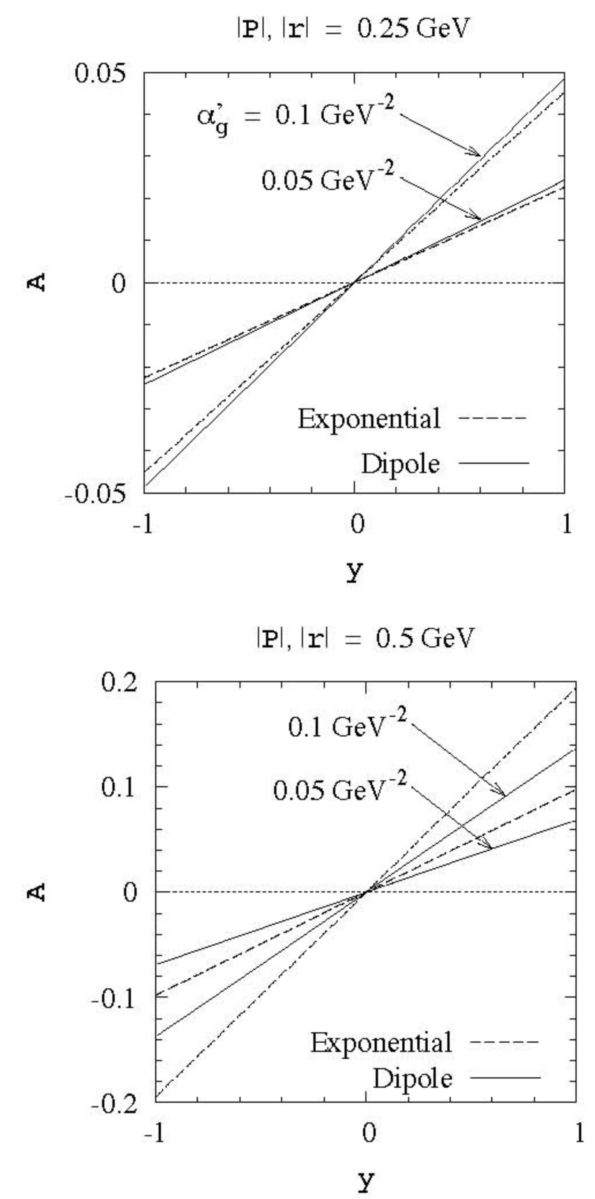
$$B_{Tot} = B_g(\xi_1) + B_g(\xi_2) + B$$

Rapidity Dependence

- Rapidity y of Higgs
  - $\xi_0 = [\xi_1\ \xi_2\ ]^{1/2} = M_H / \sqrt{s}$
  - $\xi_{1,2} = \xi_0\ e^{\pm y}$
  - $B_g(\xi_{1,2}) \approx B_g(\xi_0) + \alpha_g' \ln[\xi_{1,2} / \xi_0]$
  - $B_g(\xi_{1,2}) \approx B_g(\xi_0) \pm y\alpha_g'$
- Forward backward asymmetry depends only on α_g'

$$A = \frac{d\sigma(\xi_1,\xi_2) - d\sigma(\xi_2,\xi_1)}{d\sigma(\xi_1,\xi_2) + d\sigma(\xi_2,\xi_1)} \propto y\alpha_g'$$

$$\mathbf{r} = (\mathbf{p}_3 - \mathbf{p}_4)$$
$$\mathbf{P} = (\mathbf{p}_3 + \mathbf{p}_4)/2$$



Rapidity Gap Survival Probability: S^2

- S^2 not an observable, but a useful statistic
  - σ_{DD} = total Double Diffractive cross section.

$$\sigma_{DD}(\xi_1,\xi_2) \propto \int \frac{d^2\mathbf{p}_{3\perp}}{(2\pi)^2} \int \frac{d^2\mathbf{p}_{4\perp}}{(2\pi)^2} \left| T_{\text{Diff}}(\xi_1,\mathbf{p}_{3\perp}) \right|^2$$

$$\propto \int d^2\rho_1 \int d^2\rho_2\, h_g^2(\xi_1,\rho_1) h_g^2(\xi_2,\rho_2) \left| 1-\Gamma(\rho_2-\rho_1,s) \right|^2$$

$$S^2 \equiv \frac{\sigma_{DD}(\text{Full})}{\sigma_{DD}(\text{no\_soft}:\Gamma=0)} = \int d^2\mathbf{b} P_{hard}(\mathbf{b}) \left| 1-\Gamma(\mathbf{b},s) \right|^2$$

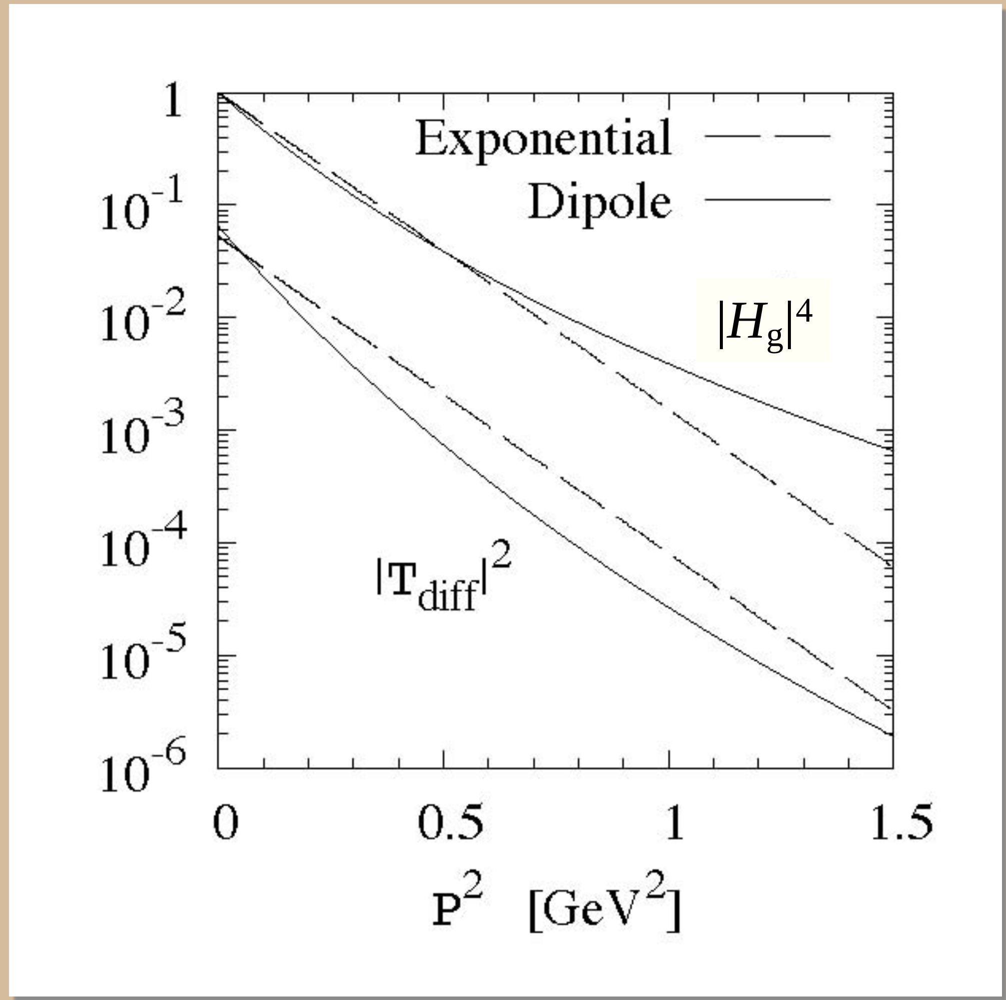
S^2 depends on hard sub-process

$$P_{hard}(\mathbf{b}) = \int d^2\rho_1 \int d^2\rho_2 \delta^{(2)}(\mathbf{b}+\rho_1-\rho_2) \left[\frac{h_g^2(\xi_1,\rho_1)}{\int d^2\rho' h_g^2(\xi_1,\rho')} \right] \left[\frac{h_g^2(\xi_2,\rho_2)}{\int d^2\rho'' h_g^2(\xi_1,\rho'')} \right]$$

Effect of Rapidity Gap Survival Probability

- $|T_{\rm diff}|^2$ = Full Diffractive calculation
- $|H_{\rm g}|^4 = |T_{\rm diff}|^2$ with $S_{\rm soft} = 1$ (Γ=0, No soft absorption)

$$\mathbf{r} = (\mathbf{p}_3 - \mathbf{p}_4)$$
$$\mathbf{P} = (\mathbf{p}_3 + \mathbf{p}_4)/2$$



Sensitivity to form of Gluon Distribution H_g

- Exponential and Dipole forms

$$H_g(x,\xi,-\Delta^2) = \begin{cases} e^{-\Delta^2 B_g(\xi)/2} \\ \dfrac{1}{\left[1+\Delta^2/m_g^2\right]^2} \end{cases}$$