Summary talk - theory

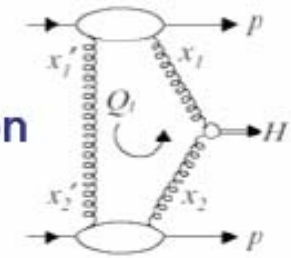
Krzysztof Golec-Biernat
INP, Cracow

Blois2007, Hamburg, 21-25 May 2007

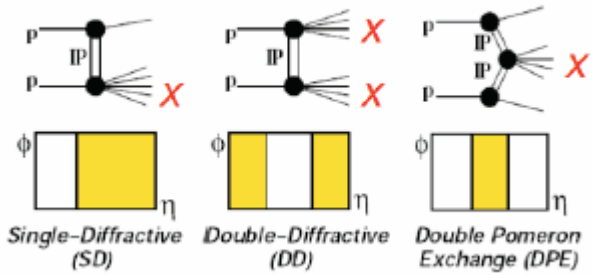
A. Hamilton

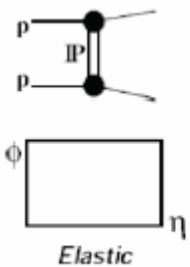
Forward physics at LHC

Exclusive Diffraction



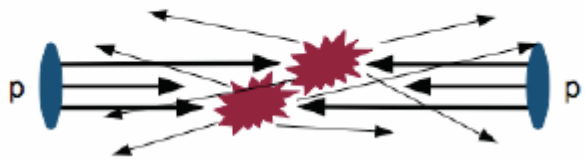
Inclusive Diffraction(soft and hard)





Elastic Scattering and Luminosity

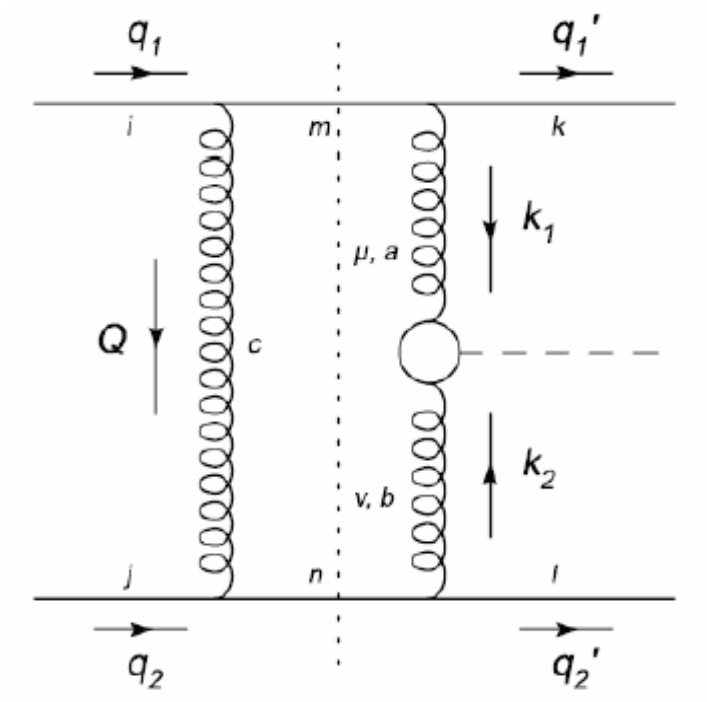
Multiple Interactions



Diffractive Higgs production

Diffractive Higgs production

J. Forshaw



the quark level amplitude

replace the quarks by protons

Sudakov suppression

get the single logarithms right

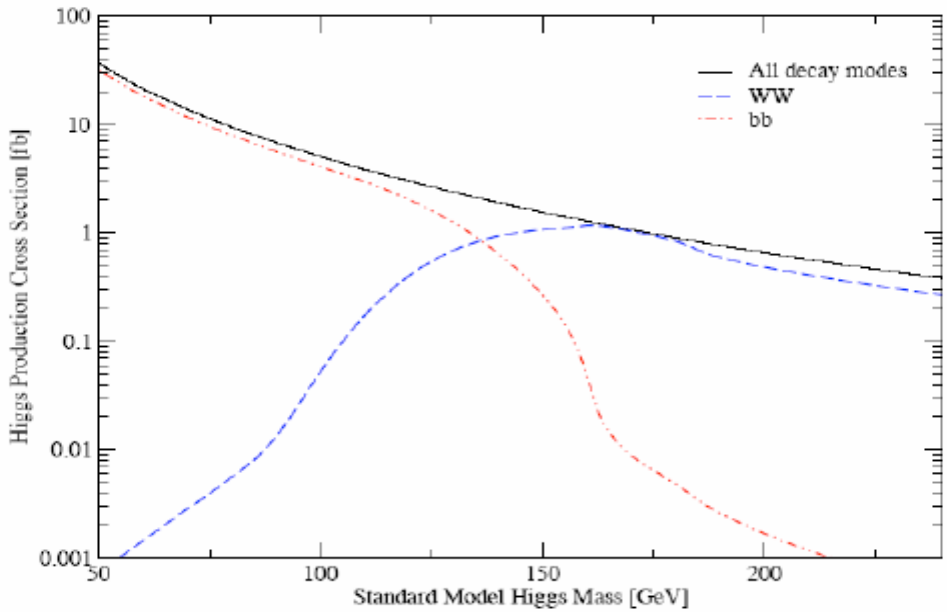
finally….gap survival

It's ok to use perturbation theory

$$\frac{d\sigma}{dy} \approx \frac{1}{256\pi b^2}\frac{\alpha_s G_F\sqrt{2}}{9}\left[\int \frac{d^2\mathbf{Q_T}}{\mathbf{Q_T}^4} f(x_1,Q_T)f(x_2,Q_T)\right]^2 \times (1.2)^4 \times \boxed{S^2}$$

SM Higgs

WW decay channel: require at least one W to decay leptonically (trigger). Rate is large enough….



Don't need many events to measure the mass and establish cleanly that Higgs is a scalar particle.

V. Khoze

Production by hard and soft *Pomeron-Pomeron* collisions

(KMR hep-ph/0702213)

Requirement: $M_{PP} = M_{missing}$ lies with mass interval $M_{bb} \pm \Delta M_{bb}$

Suppression: $\frac{1}{2}(\Delta M_{bb}/M_{PP})^2 * g^2{}_P(1-\Delta M_{bb}/M_{PP})$ (soft PP and qualitatively for hard PP)

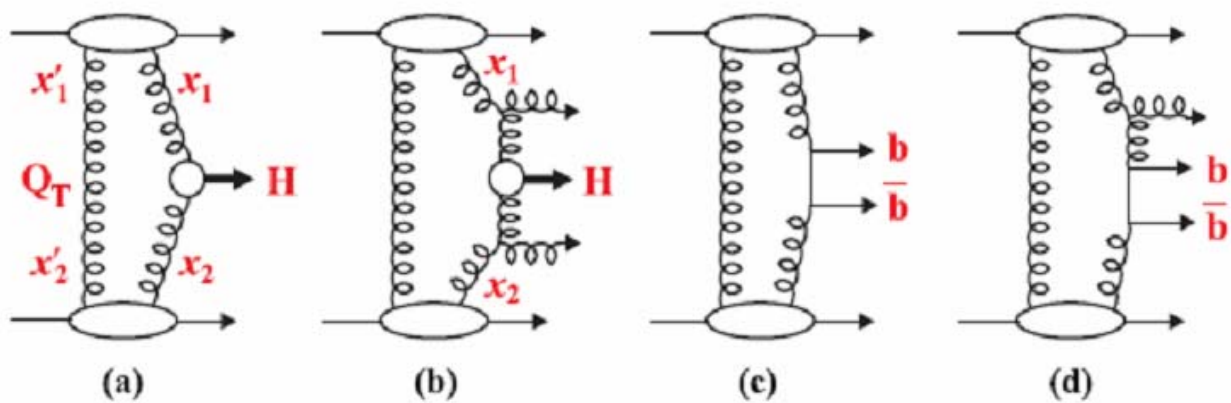


Figure 1: (a) Exclusive Higgs production by the fusion of two hard Pomerons; (b) Higgs production, via hard Pomerons, but accompanied by the emission of two undetected gluons; (c,d) background QCD $b\bar{b}$ production processes. For (b,c,d) we account for the full set of Feynman diagrams at this order and, moreover, for (b,d) allow for additional soft gluon emission.

For Higgs mass < 150 GeV there is a chance to observe main H -> bbar mode and measure its Yukawa coupling.

MSSM Higgs

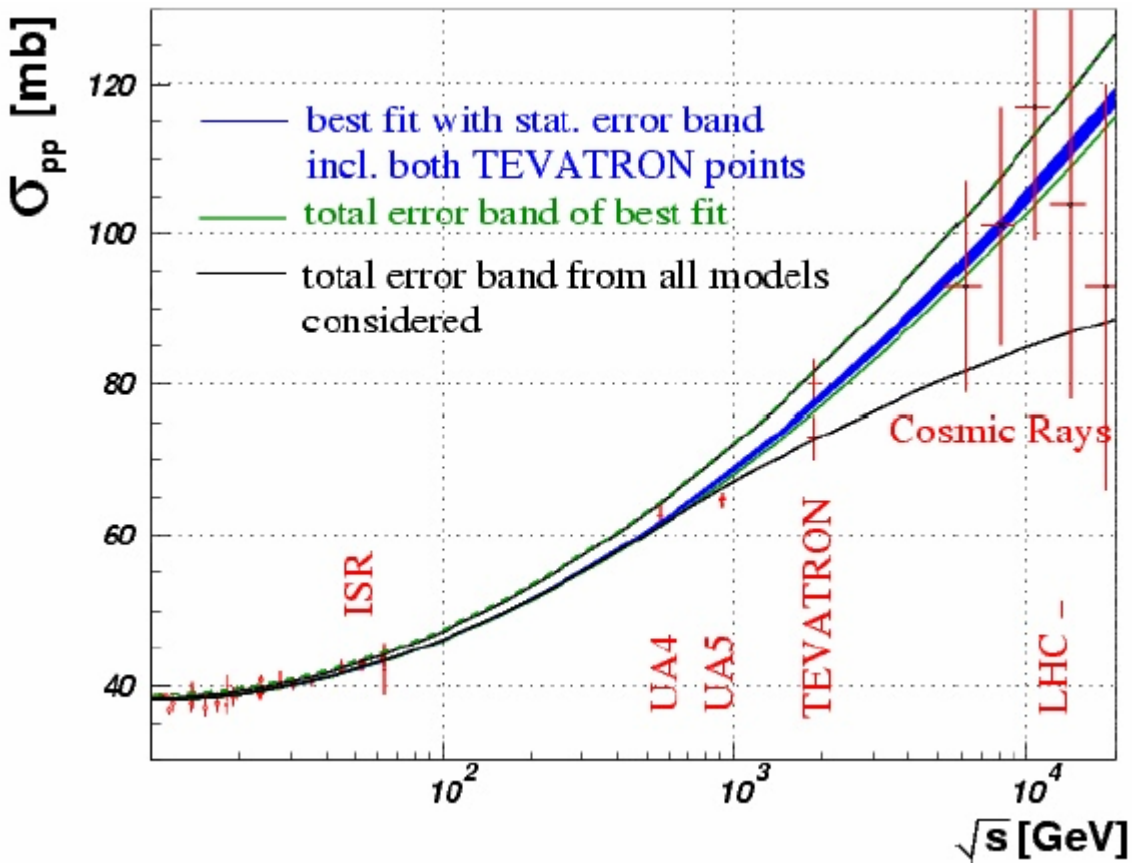
$b\bar{b}$ decay mode

- It is possible (due to 0^+ selection rule) & very desirable

  Especially in scenarios where coupling of Higgs to W/Z bosons is suppressed.
- Enhanced rates at large tan β
- Possibility to see both the h and H (A suppressed)

Total and elastic cross section

Total and elastic cross section



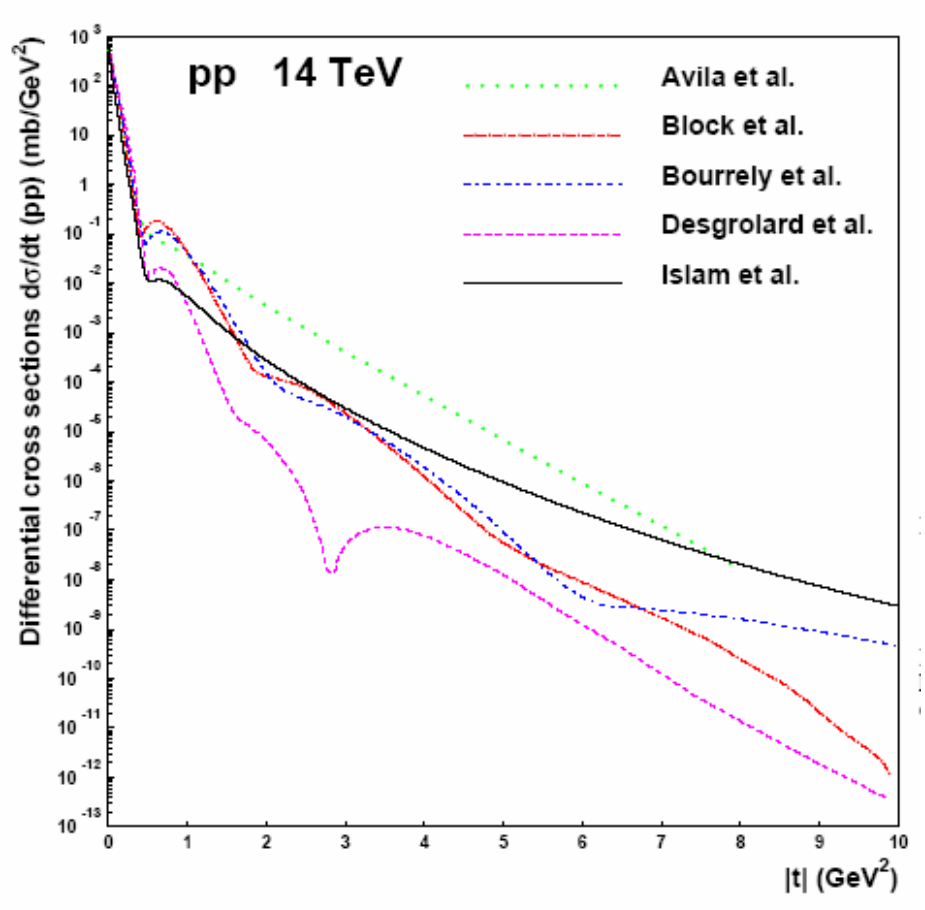
J-R. Cudell

O.V. Selyugin

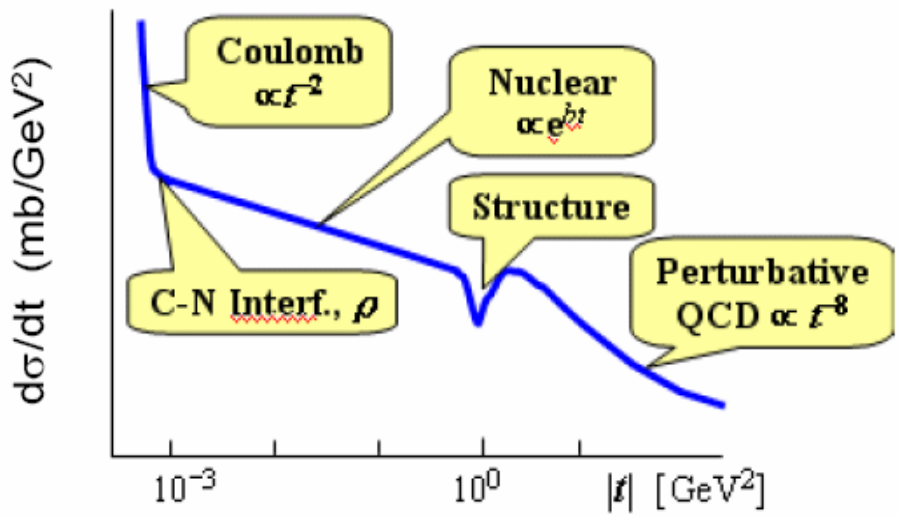
85 mb$< \sigma_{tot}^{pp}(14\ \mathrm{GeV}) <$150 mb

M. Islam

Elastic cross section



C. Sbarra

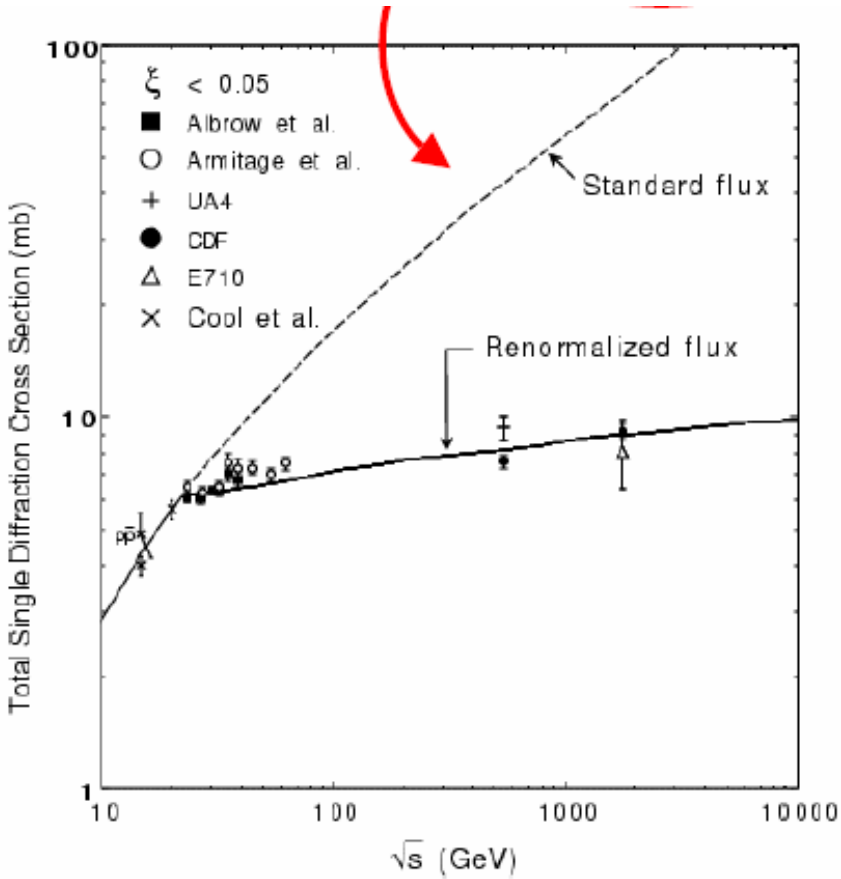


L, σ_{tot}, b, and ρ from FIT in CNI region (UA4)

Diffraction

D. Goulianos

Diffraction at Tevatron



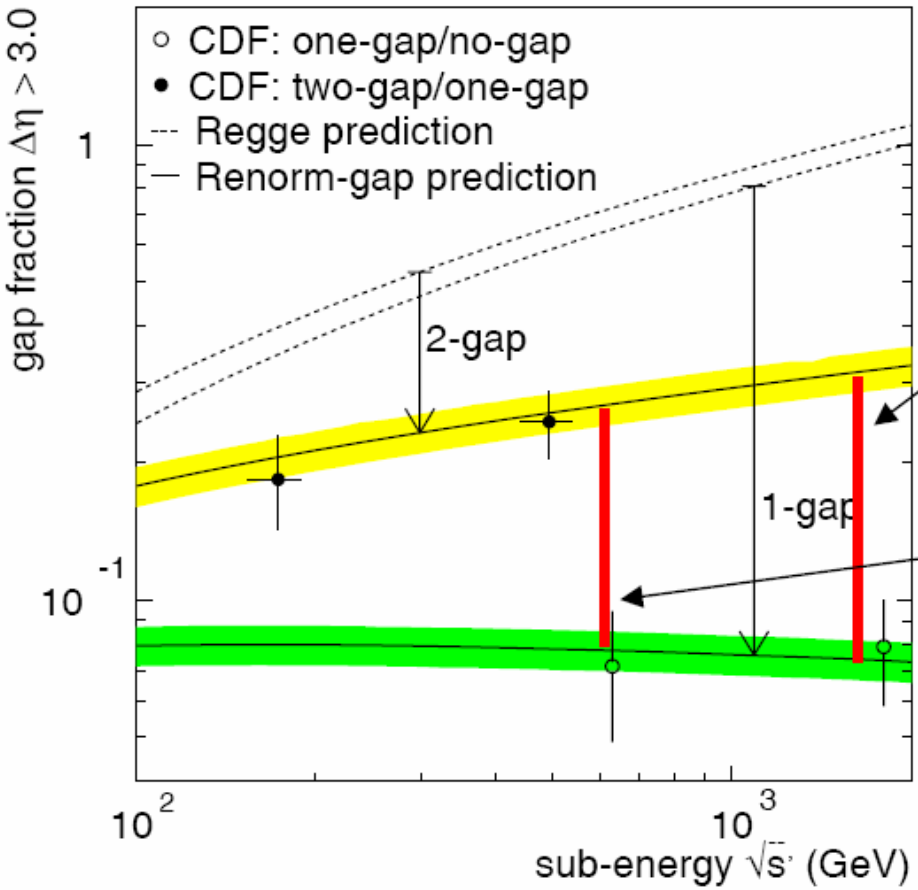
- **Unitarity problem:**
  Using factorization and std pomeron flux σ_{SD} exceeds σ_T at $\sqrt{s} \approx 2$ TeV.

- **Renormalization:**
  Normalize Pomeron flux to unity to eliminate overlapping gaps

KG, PLB 358 (1995) 379

$$\int_{\xi_{min}}^{0.1} \int_{t=-\infty}^{0} f_{IP/p}(t,\xi)\, d\xi\, dt = 1$$

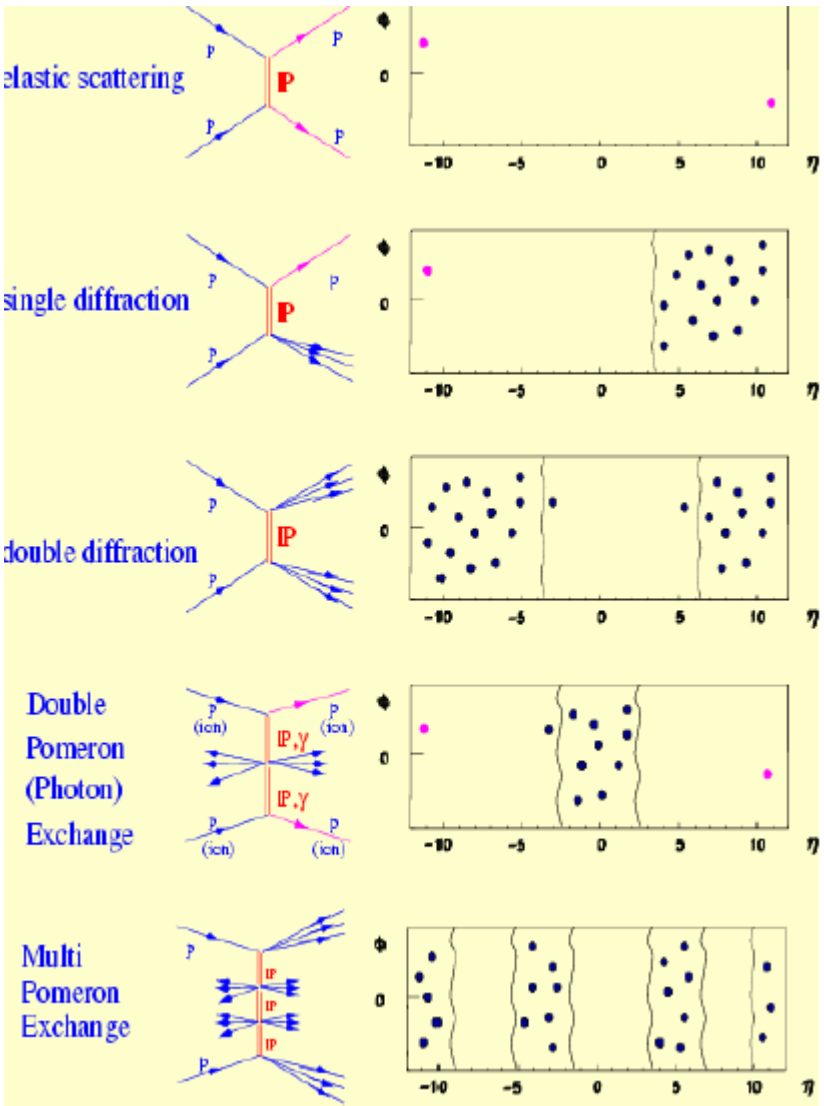
Gap Survival Probability



$$S^{1-gap/0-gap}_{2-gap/1-gap}(1800\ \mathrm{GeV}) \approx 0.23$$

$$S^{1-gap/0-gap}_{2-gap/1-gap}(630\ \mathrm{GeV}) \approx 0.29$$

Diffraction at LHC:



- Gap dynamics in pp presently not fully understood!

Build:

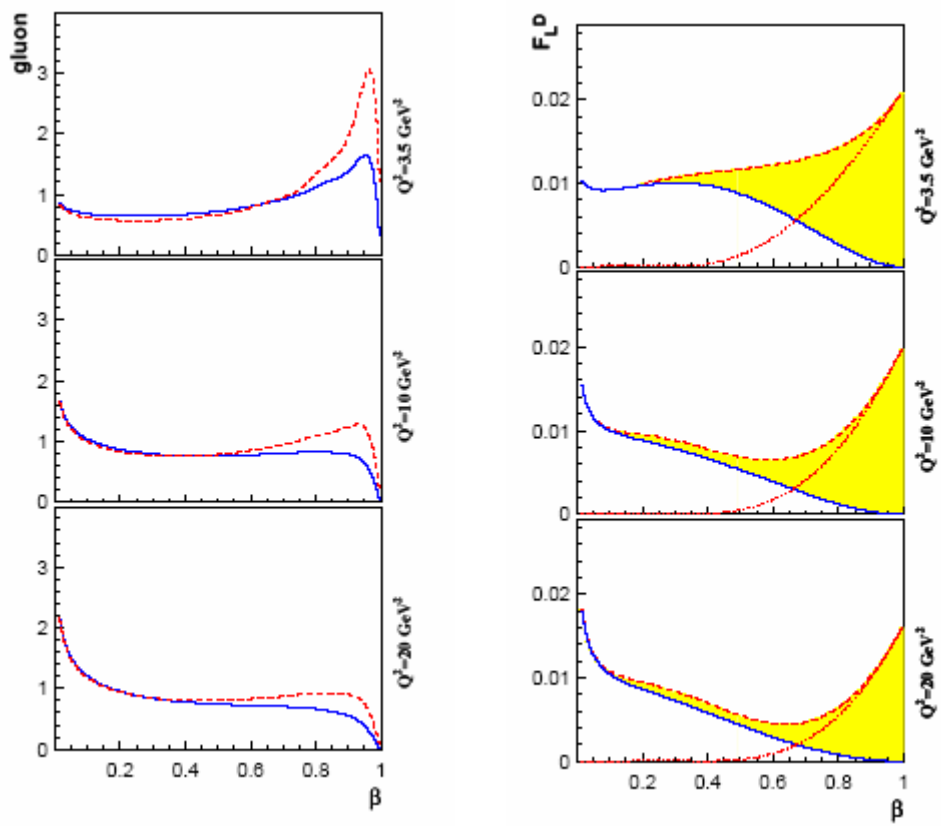
➢ QCD theory of diffraction

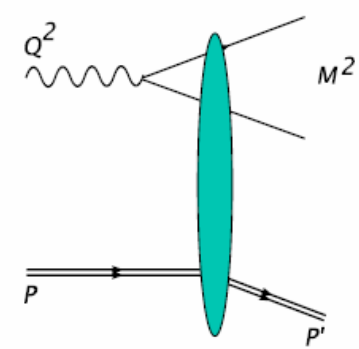
DIS diffraction

K. Golec-Biernat

Fits to diffractive data with higher twist

$$F^D_{2,L} = \underbrace{C^a_{L,D} \otimes f^D_a}_{leading\ twist} + F^{q\bar{q}}_L$$

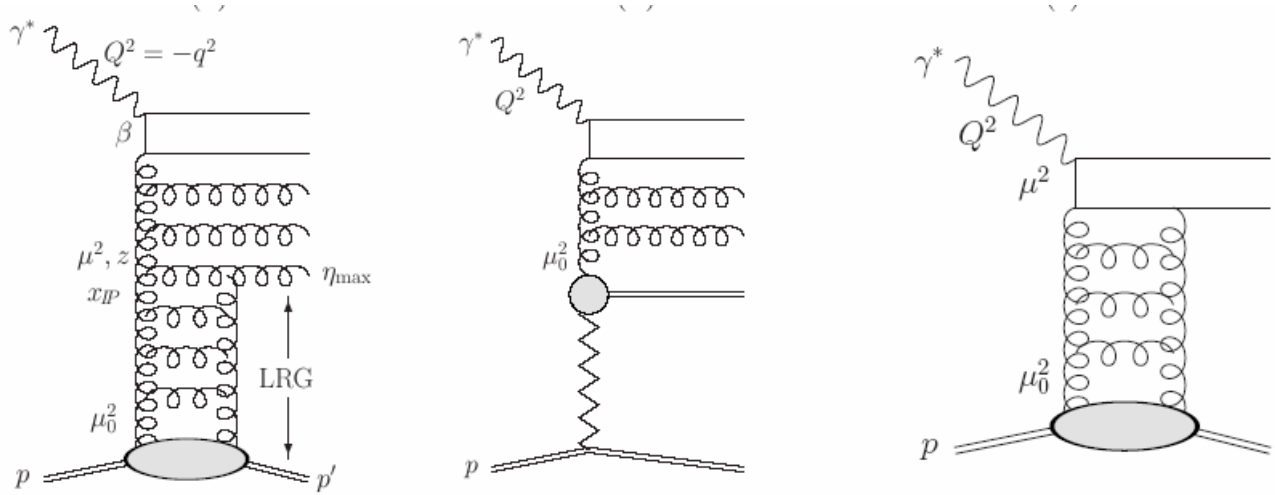




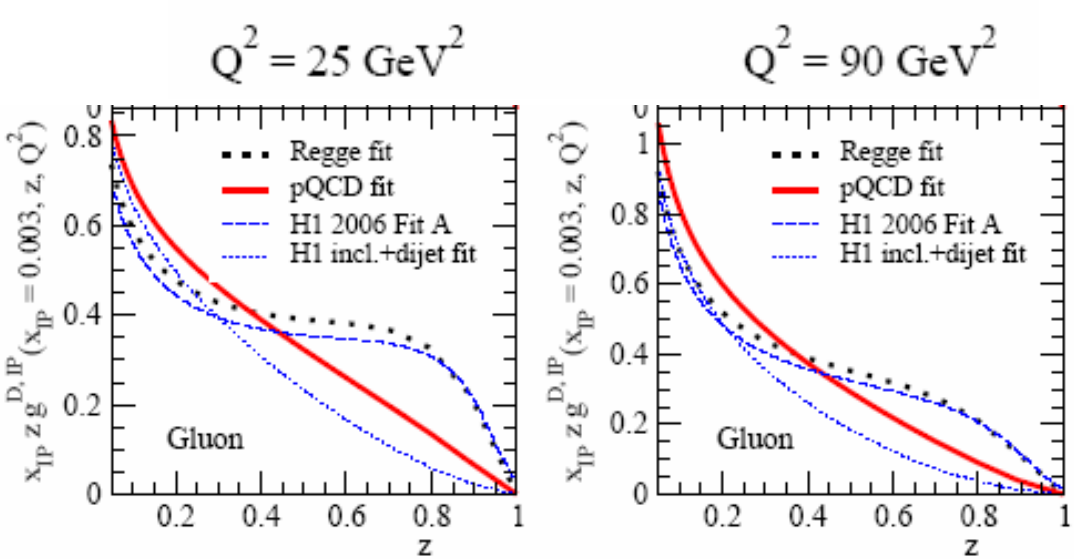
- gluon stronger peaked near $\beta \approx 1$ in the fit with higher twist
- longitudinal structure function strongly change due to higher twist

M. Ryskin

Resolved and direct pomeron



Nonhomogenious evolution equations



No enhancement of gluon at

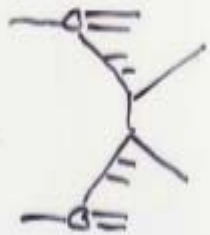
$$\beta \approx 1$$

Multiple interactions

Phenomenology side

Minijet cross section

Collinear factorization



1 subcollision = 2 jets

$$\frac{d\sigma^{subcoll}}{dp_\perp^2} \sim \int dx_1\, dx_2\, f(x_1, p_\perp^2)\, f(x_2, p_\perp^2)\, \underbrace{\frac{d\hat{\sigma}(\hat{s}=x_1 x_2 s, p_\perp^2)}{dp_\perp^2}}_{\sim \frac{1}{p_\perp^4}}$$

Cutoff needed: $p_{\perp min}$

Result: $\sigma_{subcoll} >> \sigma_{tot}$

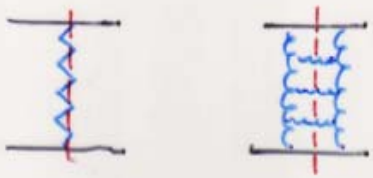
$\Rightarrow$ On average several subcoll./event

Theory side

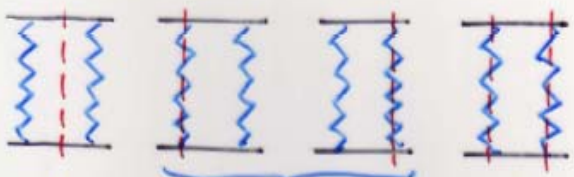
Multiple collisions and unitarity

AGK cutting rules

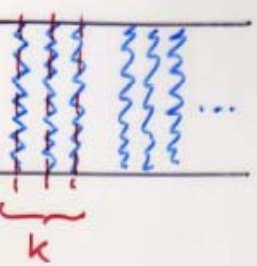
$\mathbb{P}$ = gluon ladder



Double $\mathbb{P}$ exch.



1 : −4 : 2



k cut $\mathbb{P}$. Arbitrary # uncut $\mathbb{P}$ =>

Poisson distrib.: $e^{-\bar{x}} \frac{\bar{x}^k}{k!}$ $(k \neq 0)$

Cf. Pythia

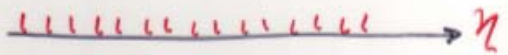
Problems

Relation $E_\perp - n_{ch}$ not as expected.

Rick Field's tunes fit both $E_\perp$ flow and particle flow, but pay a price.

1 cut $\mathbb{P}$:

2 cut $\mathbb{P}$:



Double particle density expected

CDF data : $E_\perp$ grows more than the multiplicity

Rick's tunes: Color rearrangement

What could be missing?

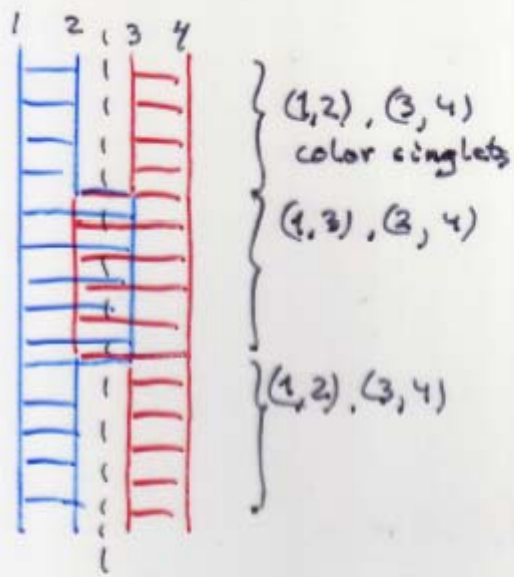
$\mathbb{P}$ interactions

Uncorrelated subcollisions $\Rightarrow$

Prob. (n subcollisions) = Poisson distrib.

Study fluctuations and correlations

J. Bartels

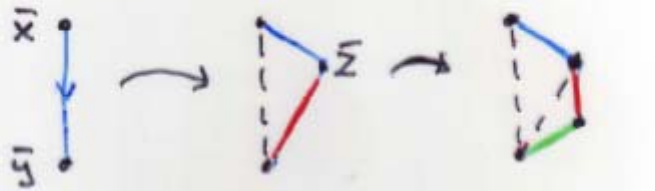


$2\mathbb{P} \to 2\mathbb{P}$ coupling

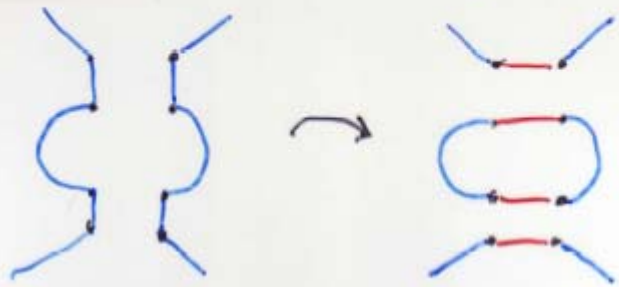
Bound state: $\mathbb{P}$ cut $\to$ pole (Bartels-Ryskin)

Dipole cascade models and $\mathbb{P}$ loops

Mueller: Color dipole cascade



Mult. coll. ⇒ Color loops ~ $\mathbb{P}$ loops



Aim: Bridge the gap between dipole cascades, AGK and trad. MC generators

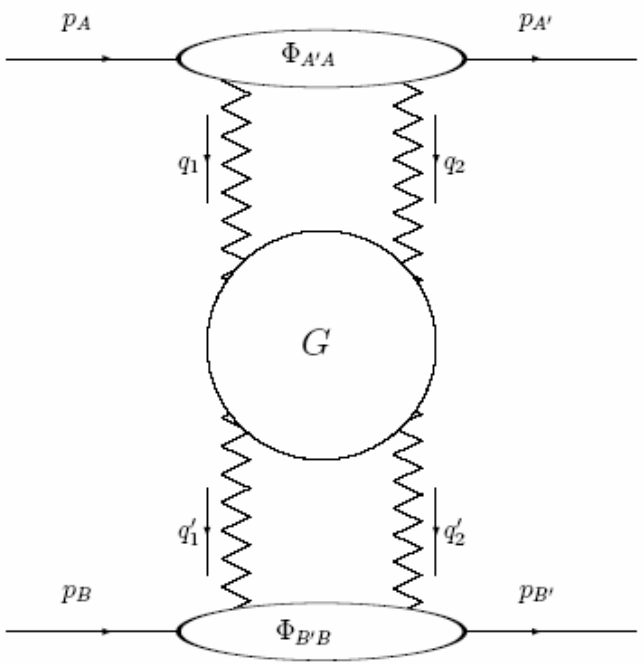
⇒ Event Generator fully compatible with unitarity and AGK.

See M. Salvadore talk on AGK in QCD

BFKL and beyond

V. Fadin

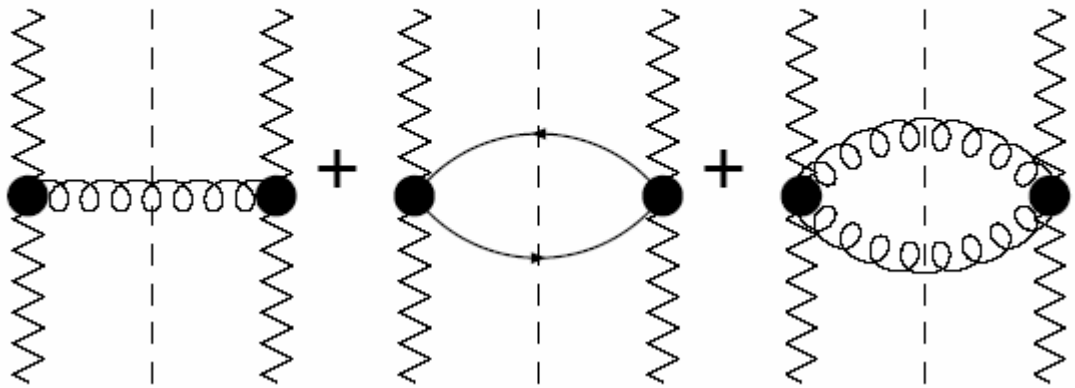
BFKL at NLLO



G – Green's function for two interacting Reggeized gluons,

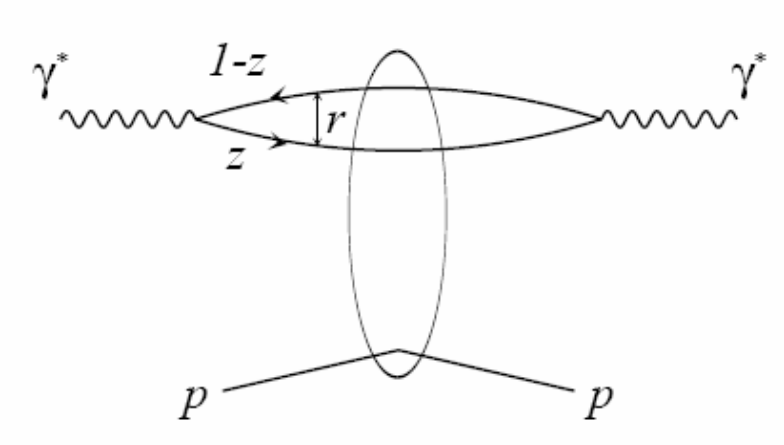
$$\widehat{\mathcal{G}} = e^{Y\widehat{\mathcal{K}}} \qquad \widehat{\mathcal{K}} = \widehat{\Omega} + \widehat{\mathcal{K}}_r$$

$$\widehat{\mathcal{K}}_r = \widehat{\mathcal{K}}_G + \widehat{\mathcal{K}}_{Q\overline{Q}} + \widehat{\mathcal{K}}_{GG}$$



Real part of BFKl kernel

Colour dipole picture



Dipole-proton interaction in terms of

$$\sigma_{dp}(r,x) = 2\int d^2b\, \mathcal{N}(\vec{r}_1,\vec{r}_2;Y)$$

$$\frac{\partial \mathcal{N}}{\partial Y} = \widehat{\mathcal{K}}_{dip}\mathcal{N}$$

The colour singlet BFKL kernel is more general than the dipole one

In the NLO the dipole form can be written as

$$\langle \vec{r}_1\vec{r}_2|\hat{\mathcal{K}}_d^{NLO}|\vec{r}_1{}'\vec{r}_2{}'\rangle = \frac{\alpha_s^2(\mu)N_c^2}{4\pi^3}\Bigg[\delta(\vec{r}_{11'})\delta(\vec{r}_{22'})\int d\vec{\rho}\, g^0(\vec{r}_1,\vec{r}_2;\vec{\rho})$$

$$+\delta(\vec{r}_{11'})g(\vec{r}_1,\vec{r}_2;\vec{r}_2{}') + \delta(\vec{r}_{22'})g(\vec{r}_2,\vec{r}_1;\vec{r}_1{}') + \frac{1}{\pi}g(\vec{r}_1,\vec{r}_2;\vec{r}_1{}',\vec{r}_2{}')\Bigg]$$

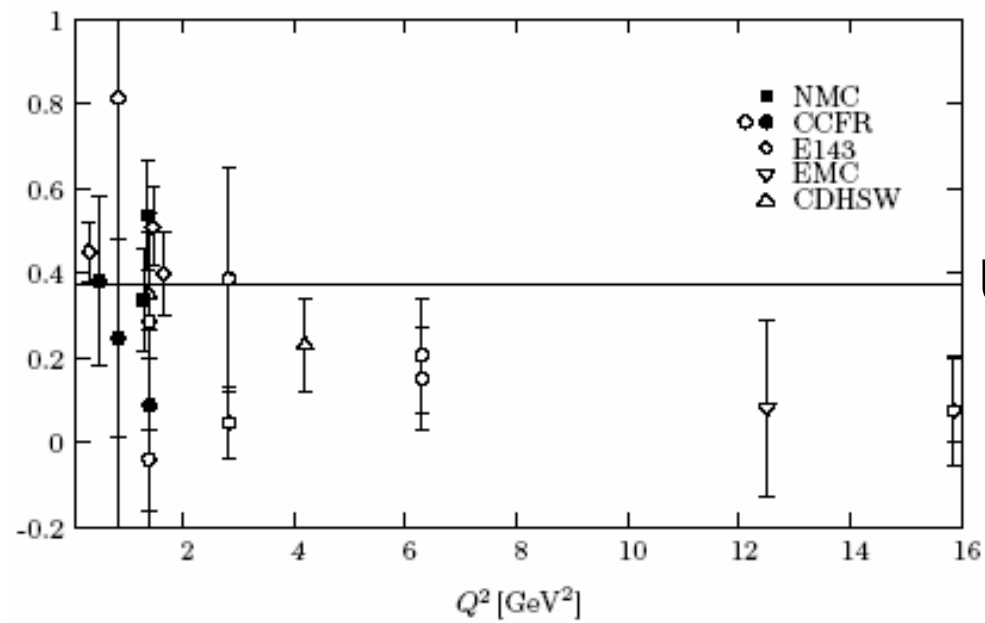
All g functions vanish for $\vec{r}_1 = \vec{r}_2$: dipole property

C. Ewerz

Test of LO dipole picture formula

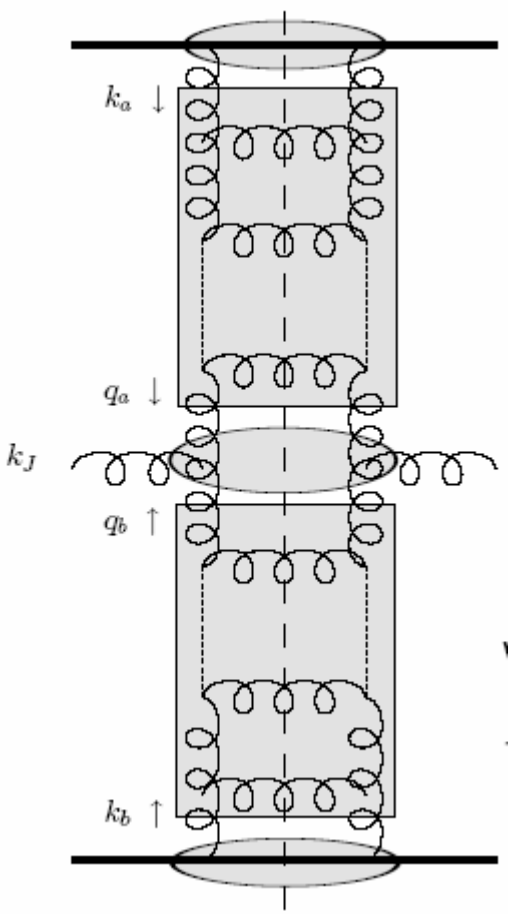
$$\sigma_{\gamma^*}(x, Q^2) = \int d^2r \int_0^1 dz |\Psi_{\gamma^*}(r, z, Q^2)|^2 \sigma_{dp}(r, x)$$

R



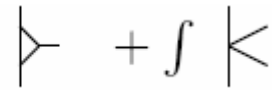
Upper bound

Jet production at LO BFKL



Changes at NLO BFKL

- real Kernel $\mathcal{K}_{\text{real}}$ contains at NLO two particle prod

$\mathcal{K}_{\text{real}} \sim$ 

  - both together form a jet
  - one forms the jet, other one unresolved

- energy scale s_0 is now a relevant parameter

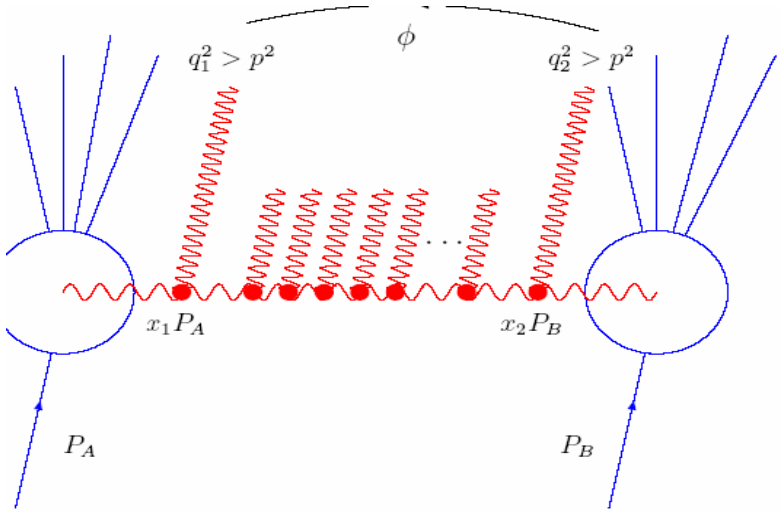
$$s_0 = |\mathbf{k}_a|\,|\mathbf{k}_{Jet}| \rightarrow s_0 = \mathbf{k}_{Jet}^2$$

asymmetric change effects complete evolution

  - modified proton impact factor
  - modified Kernel
  - modified vertex

A. Sabio Vera

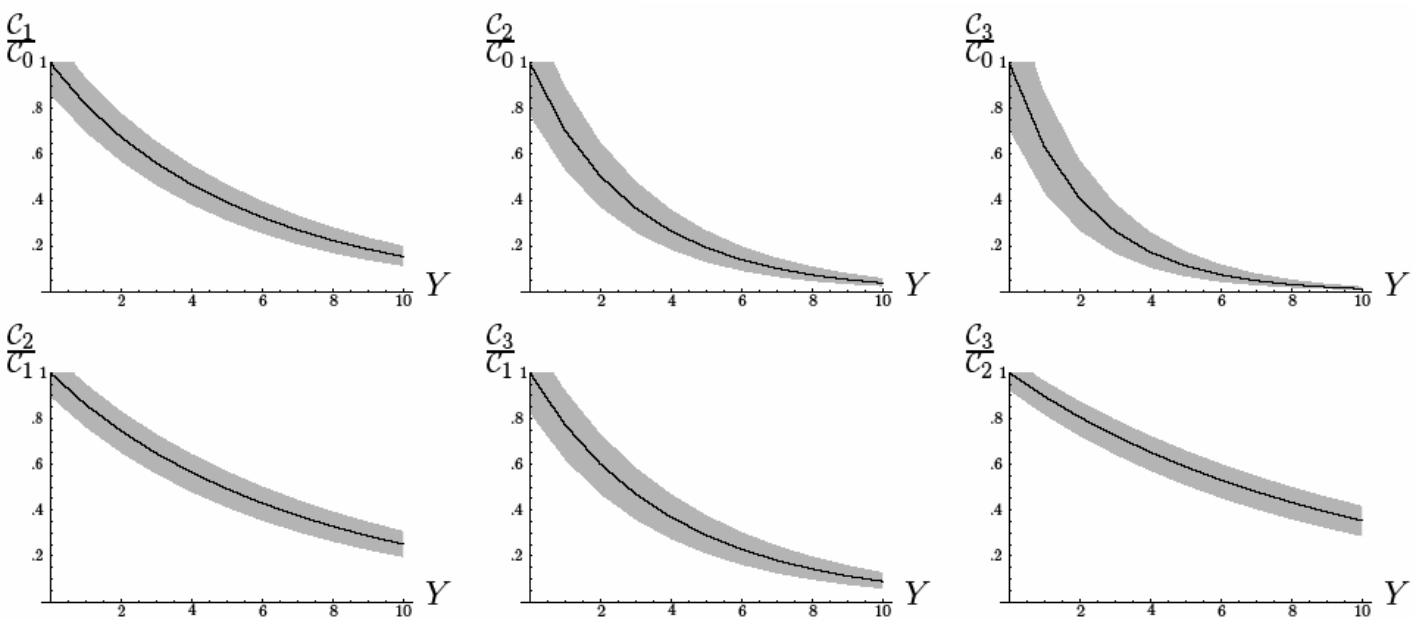
Angular decorrelations in Mueller–Navelet jets and DIS



$$\frac{1}{\hat{\sigma}}\frac{d\hat{\sigma}}{d\phi} = \frac{1}{2\pi}\sum_{n=-\infty}^{\infty} e^{in\phi}\frac{\mathcal{C}_n(\mathrm{Y})}{\mathcal{C}_0(\mathrm{Y})}$$

$\mathcal{C}_n$ obtained using a collinearly resummed BFKL kernel

for all angular components



Colorless multigluon states in the LLA

n reggeized gluon states

BKP Hamiltonian

$$H_n = -\frac{1}{N_c}\sum_{i<j} T_i^a T_j^a H_{ij}$$

4 Gluon Kernel

$$H_4 = \frac{1}{N_c}\left[A\left(H_{12}+H_{34}\right)+CAC\left(H_{13}+H_{24}\right)+SCACS\left(H_{14}+H_{23}\right)\right]$$

the leading eigenvalue is given by $E_0(N_c) = E_0(\infty)\left(1+\frac{2.465}{N_c^2}\right)$

large N_c approximation corresponds to an error of 27%.

BFKL equation and anomalous dimensions in $N = 4$ SUSY

Lev N. Lipatov
Petersburg Nuclear Physics Institute
Hamburg University

Content

8 Pomeron and graviton

BFKL Pomeron in a diffusion approximation

$$j = 2 - \Delta - D\nu^2$$

Anomalous dimension of twist-2 operators

$$\gamma = 1 + \frac{j-2}{2} + i\nu$$

Constraint from the conservation of $T_{\mu\nu}$

$$\gamma = (j-2)\left(\frac{1}{2} - \frac{1/\Delta}{1+\sqrt{1+(j-2)/\Delta}}\right)$$

AdS/CFT for the graviton Regge trajectry

$$j = 2 + \frac{\alpha'}{2}t\,,\ t = E^2/R^2\,,\ \alpha' = \frac{R^2}{2}\Delta$$

Gubser, Klebanov and Polyakov prediction

$$\gamma_{|z,j\to\infty} = -\sqrt{j-2}\,\Delta^{-1/2}_{|j\to\infty} = \sqrt{\pi j}\,z^{1/4}$$

Pomeron intercept at large α (K.,L.,O.,V.)

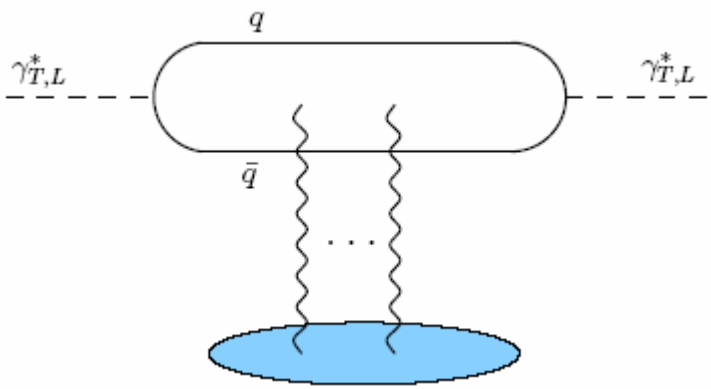
$$j = 2 - \Delta\,,\ \Delta = \frac{1}{\pi}z^{-1/2} \approx \frac{\sqrt{3}}{2\pi}z^{-1/2}\,,$$

$$\frac{\pi^2}{6}z = -\tilde{b} + \frac{1}{2}\tilde{b}^2\,,\ b = \gamma'(2) = -\frac{\pi^2}{6}z + \frac{\pi^4}{72}z^2 - \frac{\pi^6}{540}z^3$$

High Energy QCD

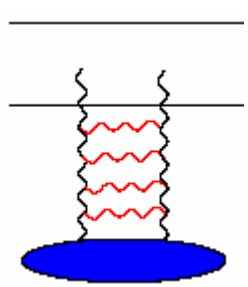
S. Munier, A. Shoshi

A proton (nucleus) probed with a dipole: $T(\boldsymbol{r}, x_{Bj}, \boldsymbol{b})$

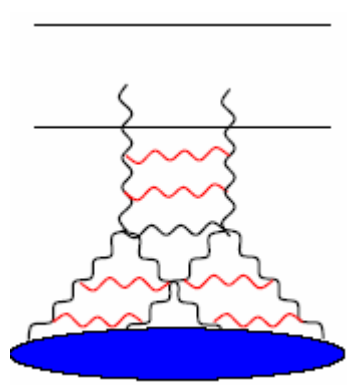


How does $T(\boldsymbol{r}, Y)$ change if $Y \to Y + dY$?

- BFKL equation:



- Kovchegov equation:



$\langle TT \rangle_Y \approx \langle T \rangle_Y \langle T \rangle_Y$

- B-JIMWLK equations:

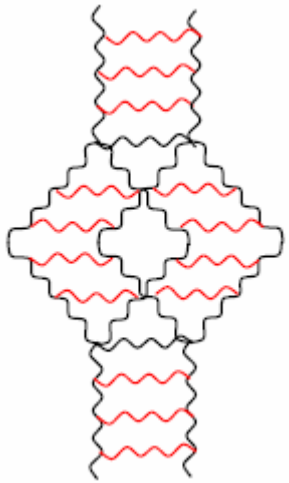
$\langle TT \rangle_Y \neq \langle T \rangle_Y \langle T \rangle_Y$

Fluctuations

Numerical result

$\langle T \rangle_Y^{\text{Kovchegov}} \approx \langle T \rangle_Y^{\text{B-JIMWLK}}$

- Pomeron loops missed!

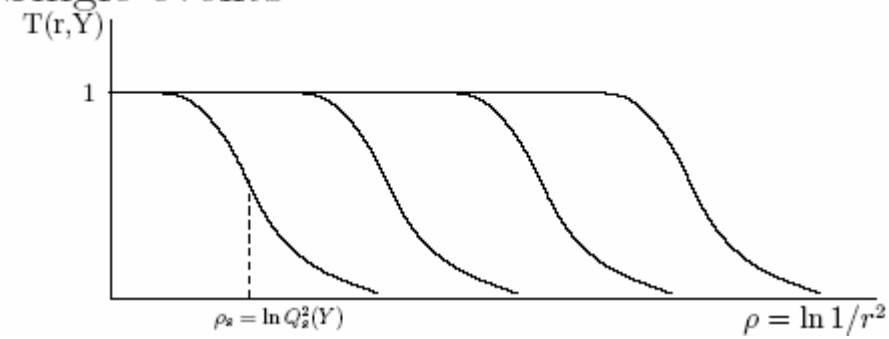


- Langevin-type version:

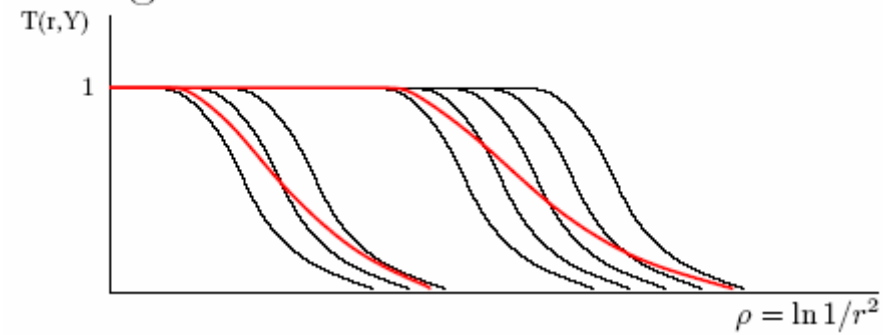
$$\frac{\partial}{\partial Y} T_Y \propto \alpha_s \left[T_Y - T_Y\, T_Y + \sqrt{\alpha_s^2\, T}\ \nu \right]$$

Gluon number fluctuations from event to event!

Single events



Average over events



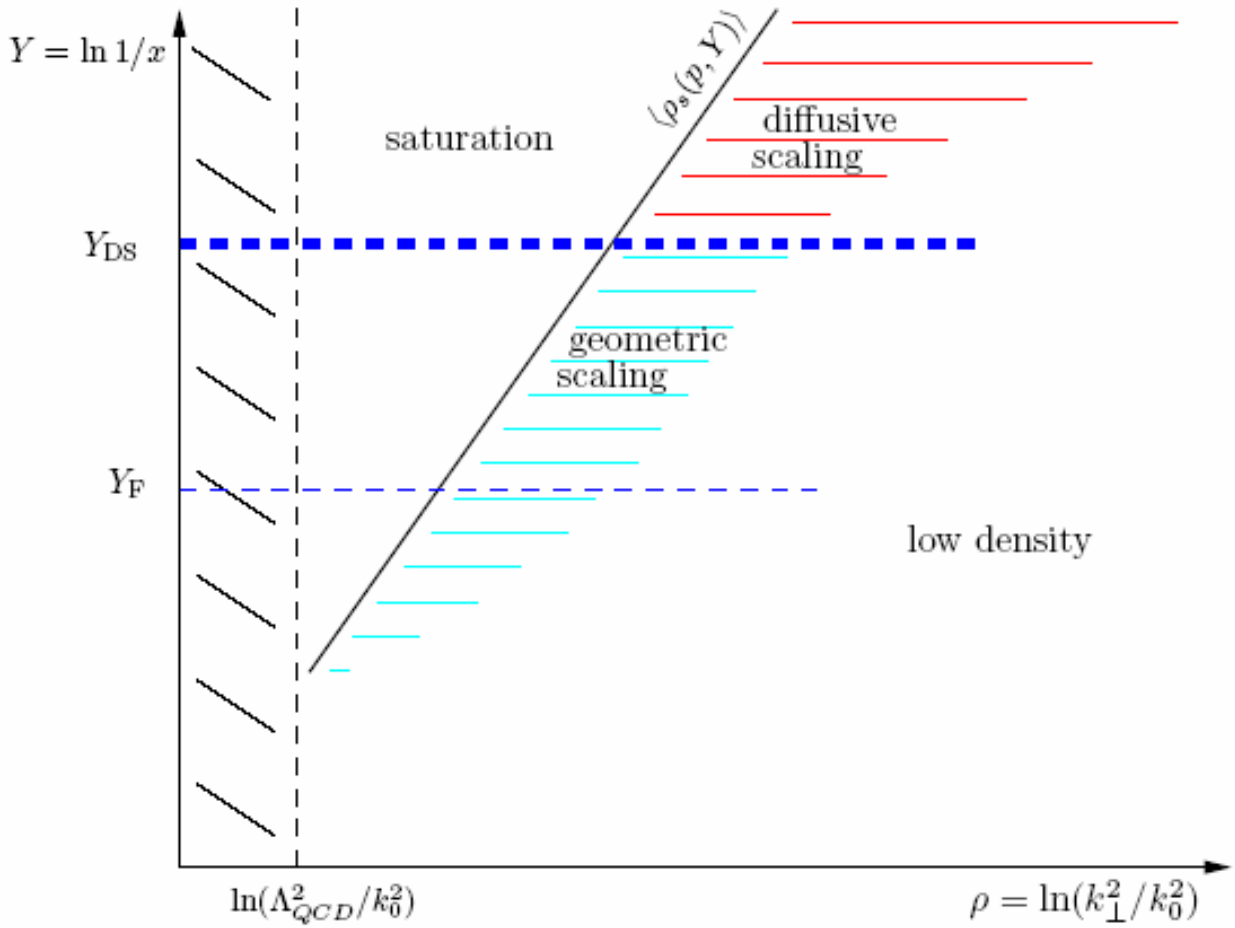
Geometric scaling

$$T(r,Y) = T(r^2\, Q_s^2(Y))$$

Diffusive scaling

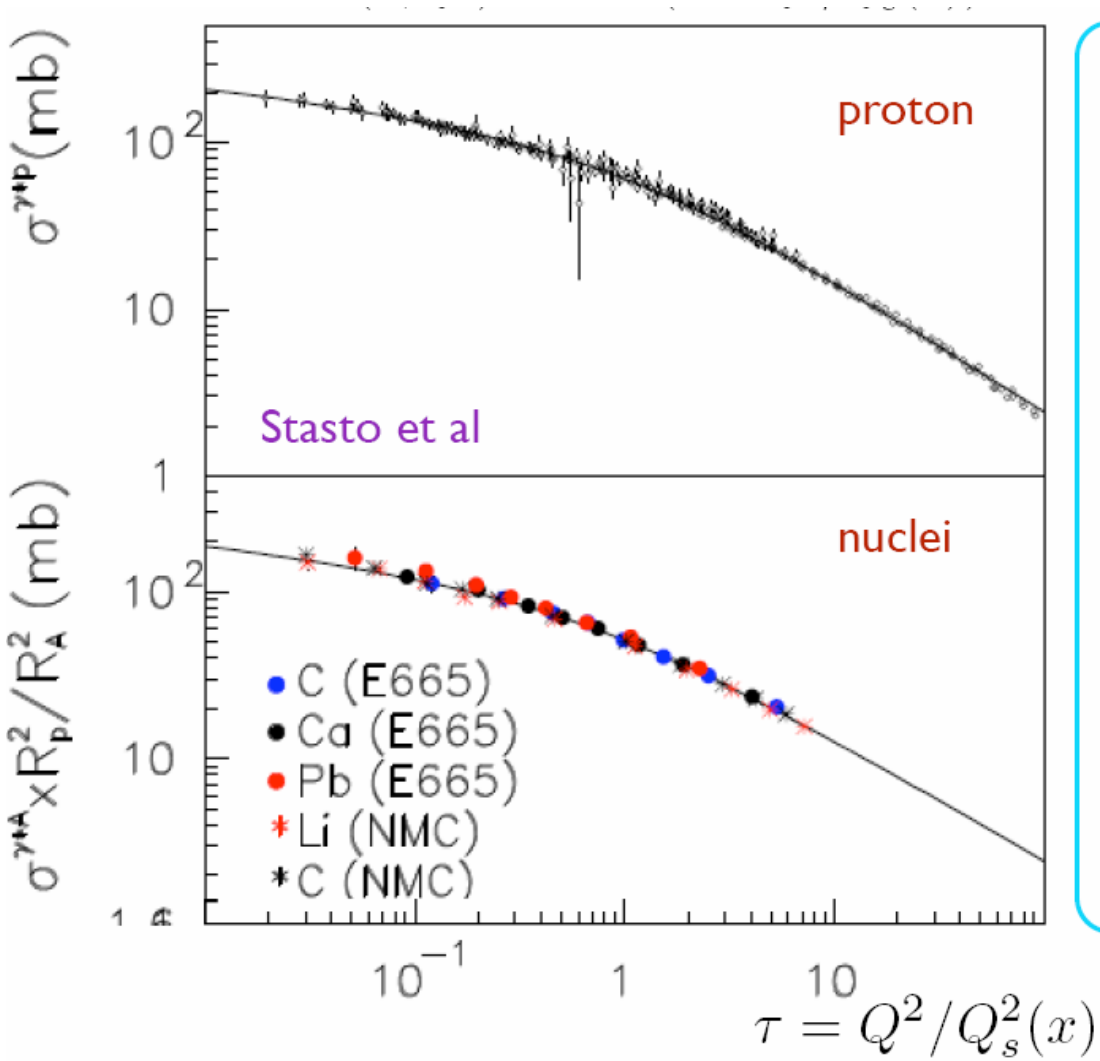
$$\langle T(r,Y) \rangle = T\left(\frac{\ln(\bar{Q}_s^2(Y)\ r^2)}{\sqrt{\alpha_s Y / \ln^3(1/\alpha_s^2)}} \right)$$

"Phase diagram"



J. Albacete

- *Geometric scaling* found in DIS small-x data both in nuclear and proton reactions
- (A good part of) RHIC phenomenology is based on this empirical information



- For proton:
Golec-Biernat Wustoff

$$Q_{sp}^2 = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

$$\lambda \approx 0.28$$

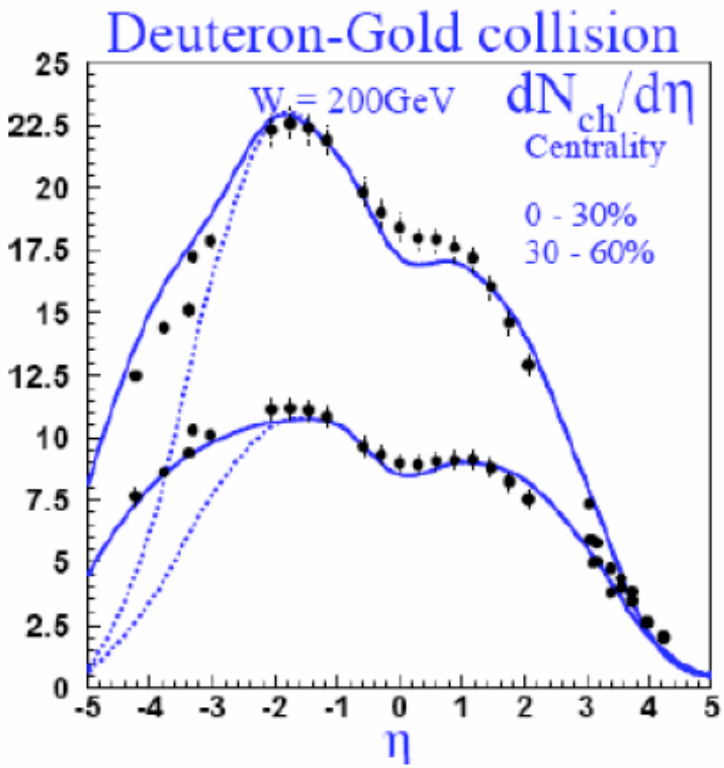
- For nuclei:
Armesto et al

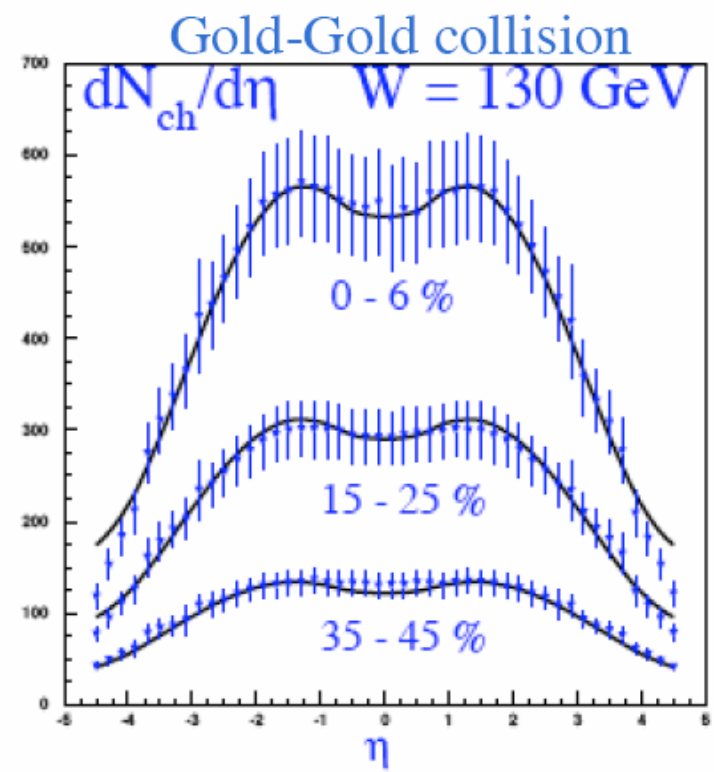
$$Q_{sA}^2 = Q_0^2 \, A^{1/3\delta} \left(\frac{x_0}{x}\right)^\lambda$$

$$\delta \approx 0.8$$

@ Saturation based models reproduce the collision energy, pseudorapidity and centrality dependence of multiplicity densities at RHIC

Kharzeev-Levin-Nardi

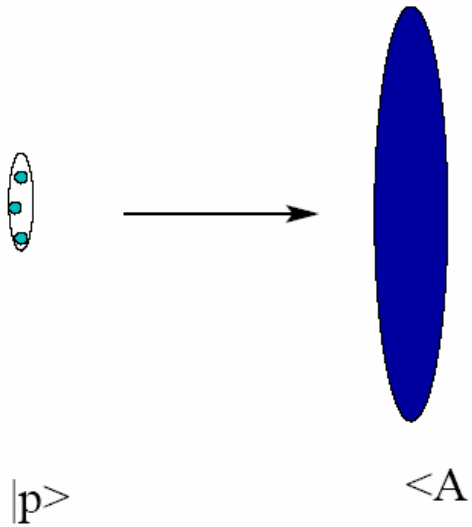




@ CGC provides good initial conditions for hydrodynamics evolution

WHERE ARE WE: PERTURBATIVE SATURATION

SMALL ON LARGE: **p-A scattering**.

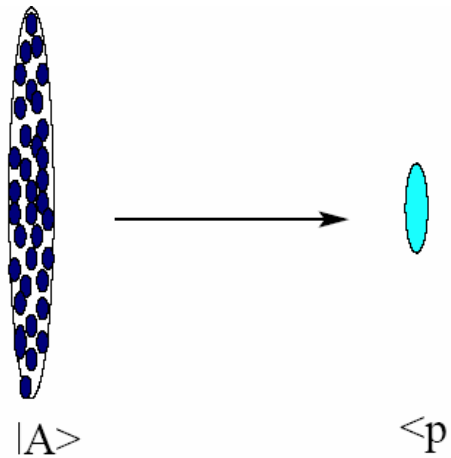


color charge grows exponentially according to BFKL

The scattering amplitude unitarizes due to multiple scattering effects

Balitsky Kovchegov

LARGE ON SMALL : **A - p scattering**



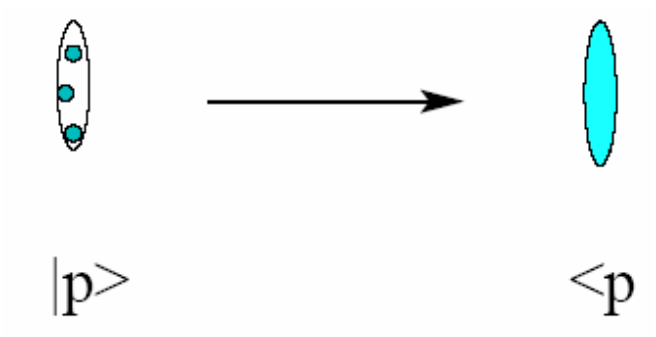
nonlinear evolution of the large dense object

JIMWLK equation

soft gluons

scatter only via two gluon exchange

SMALL ON SMALL : **p - p scattering**.

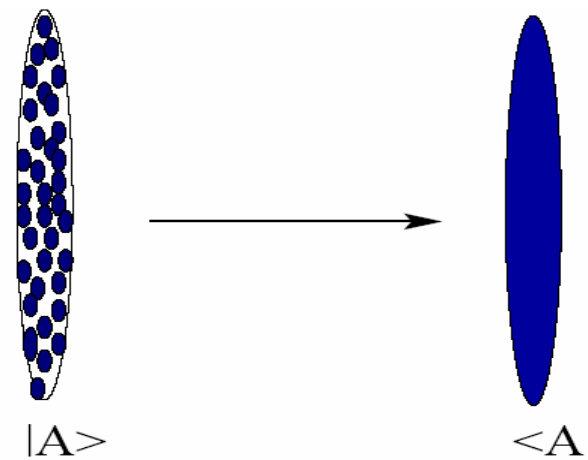


"STATISTICAL MODELS" APPROACH

Mueller, Munier,Iancu

Connection to QCD tenuous.

LARGE ON LARGE : **A - A scattering**.



emission is nonlinear and scattering is multiple

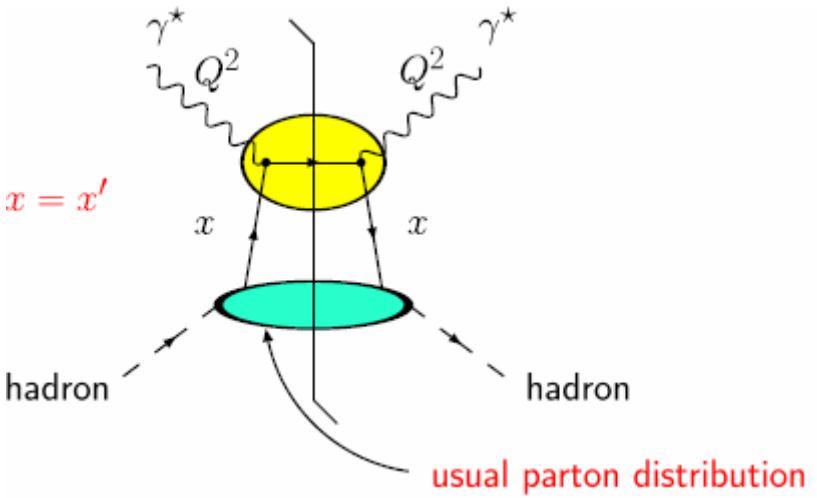
it's all saturated anyway, so $S = 0$.

"Pomeron loops" must be very important for the final state structure

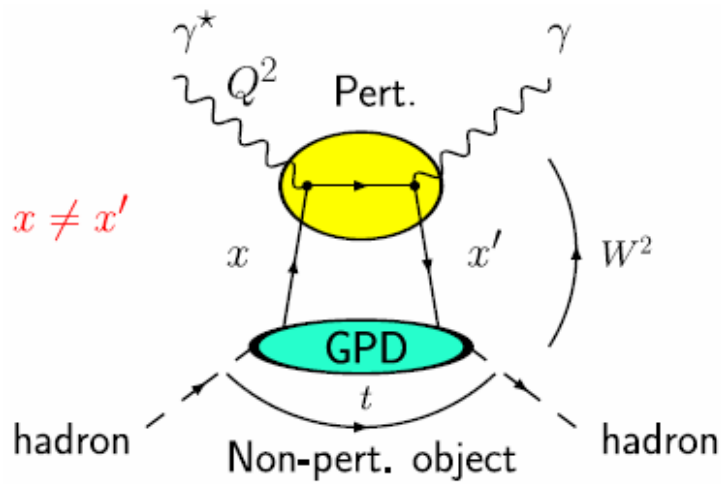
Exclusive reactions

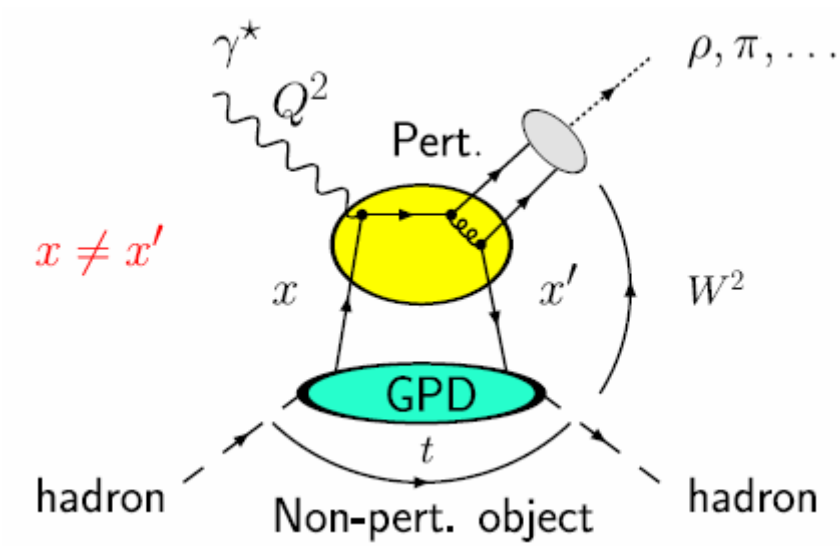
Exclusive processes in QCD

DIS: inclusive process

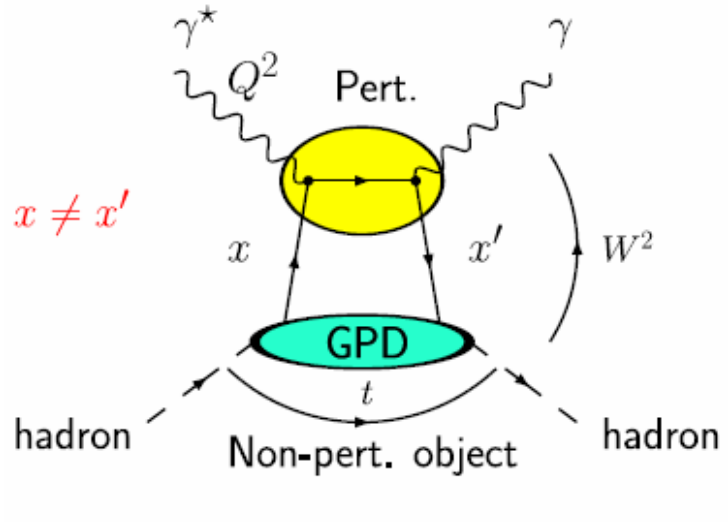


DVCS: exclusive process

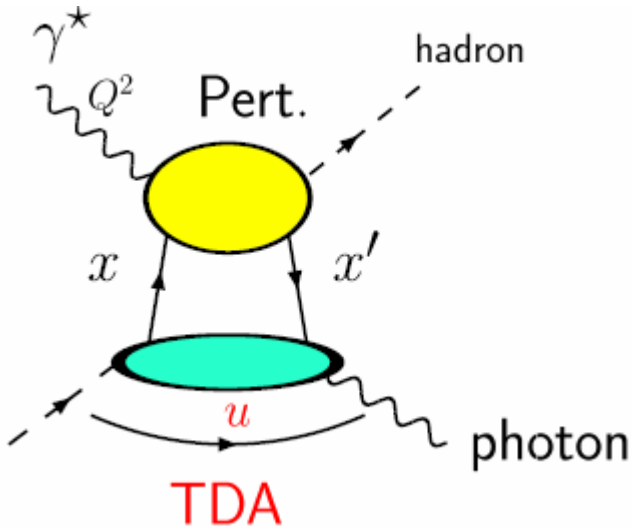




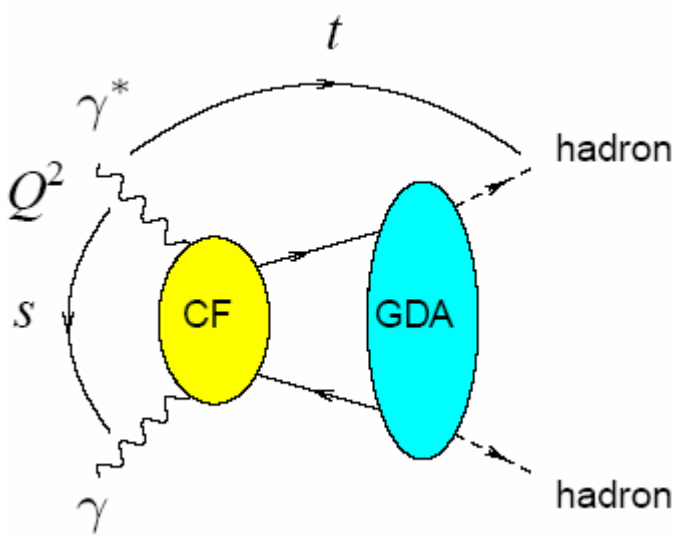
Meson production



$t \to u$



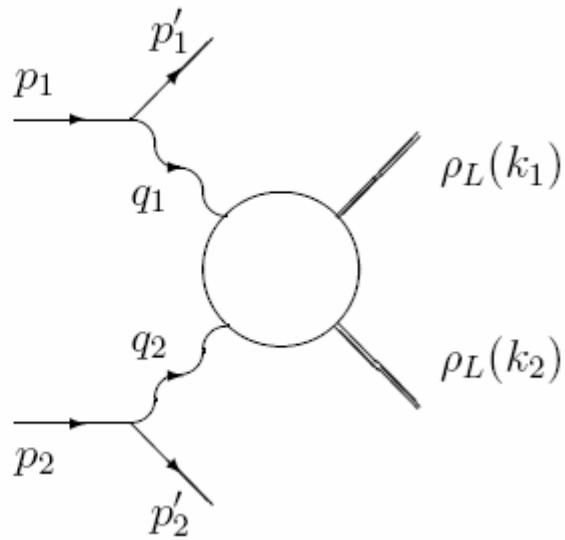
Crossed process: $s \ll -t$



S. Wallon

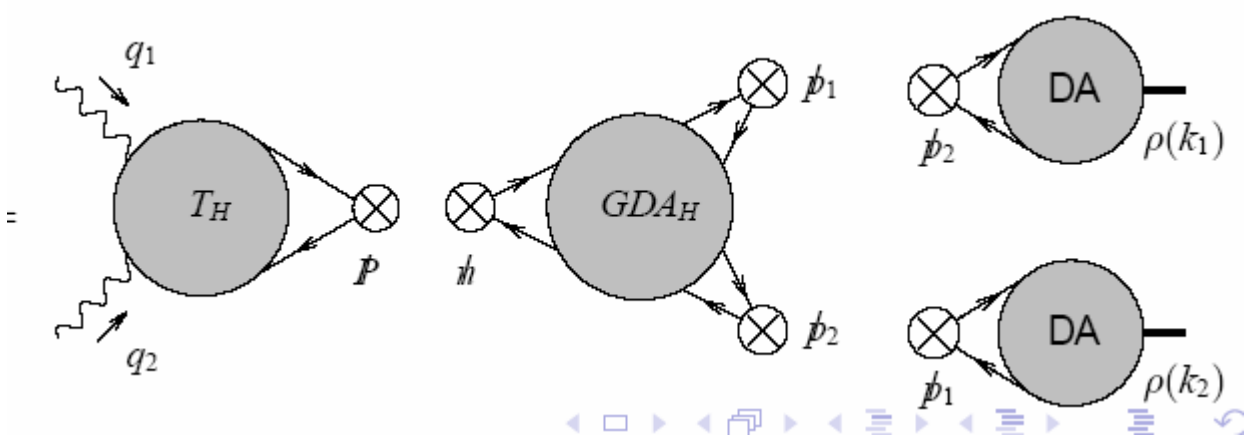
QCD factorization for $\gamma^*\gamma^* \to \rho_L^0 \rho_L^0$

$$e^+e^- \to e^+e^- \rho_L^0 \rho_L^0$$



Relevant for ILC

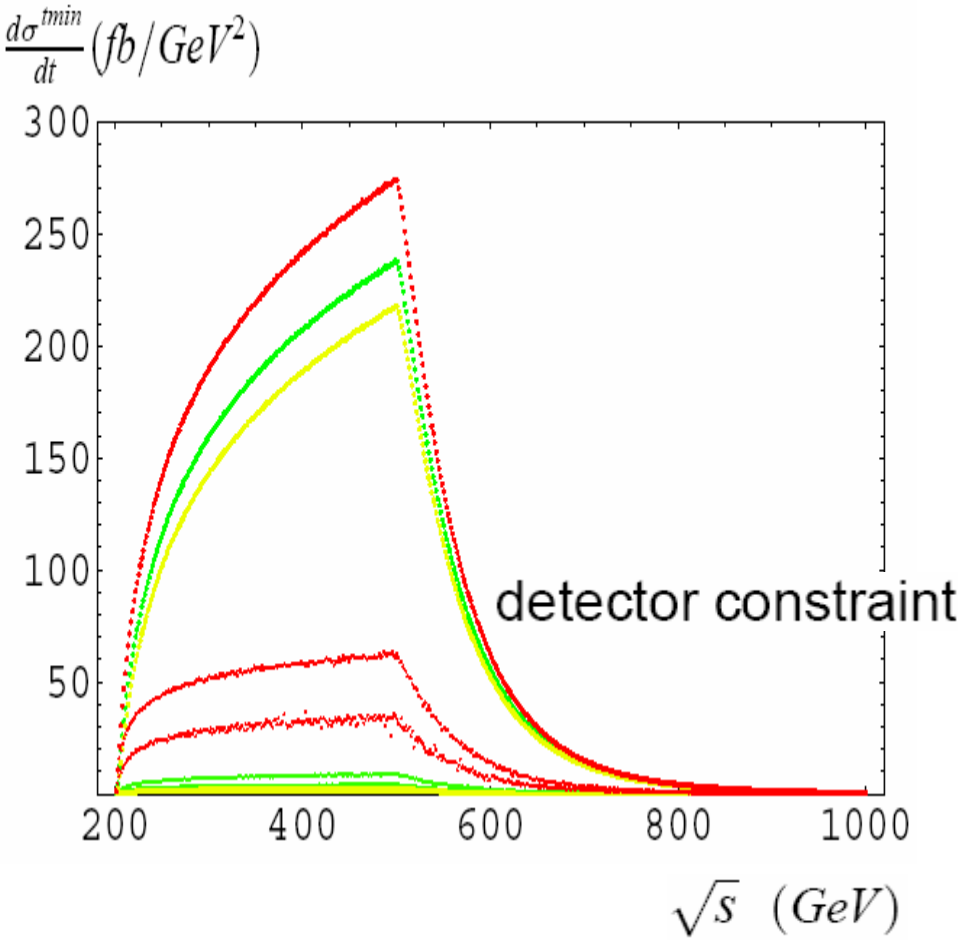
QCD factorizations

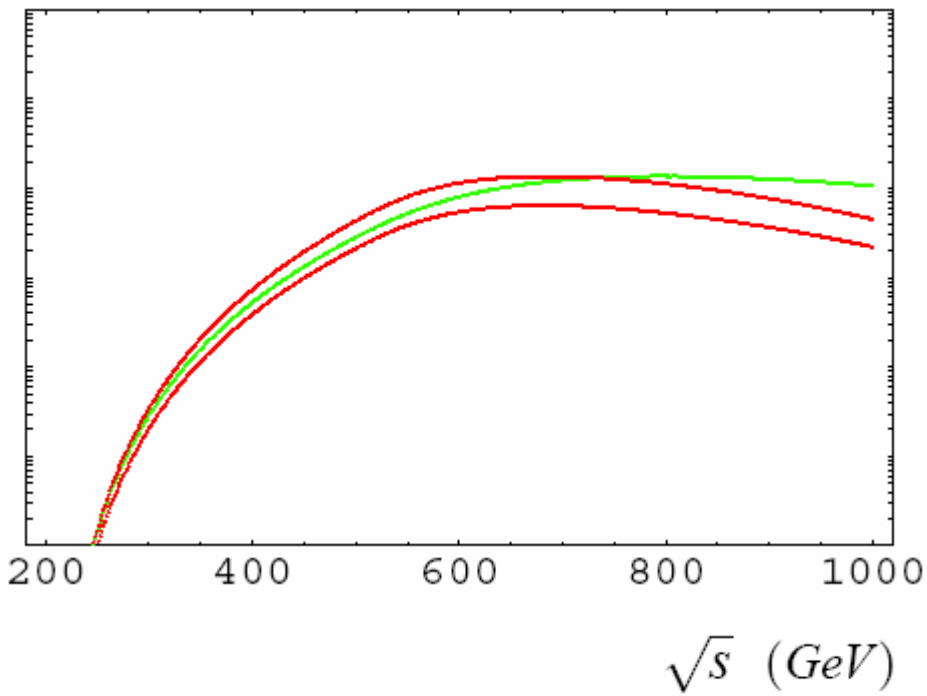


Born results

BFKL enhancement

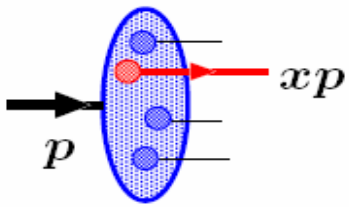
flattish curve to be compared with sharked curve at Born level

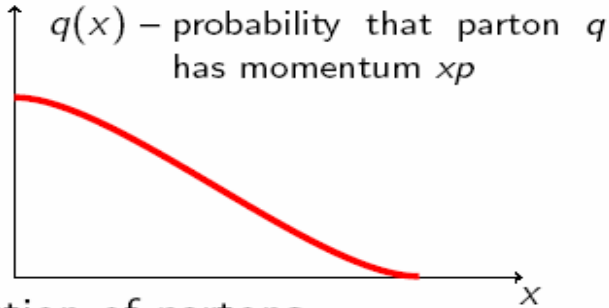




GPDs and DVCS

Parton distribution functions

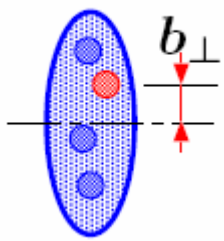


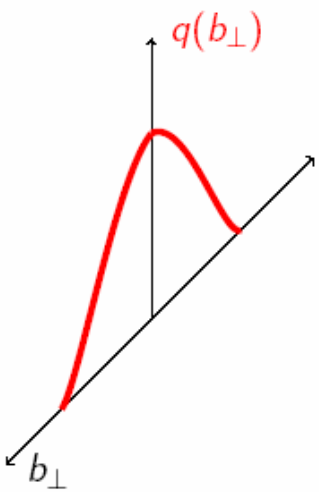


- no information on spatial distribution of partons

Electromagnetic form factors

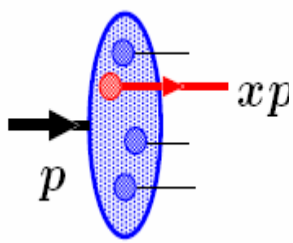
$$q(b_\perp) \sim \int \mathrm{d}b_\perp \, e^{iq_1 \cdot b_\perp} F_{1,2}(t = q_1^2)$$

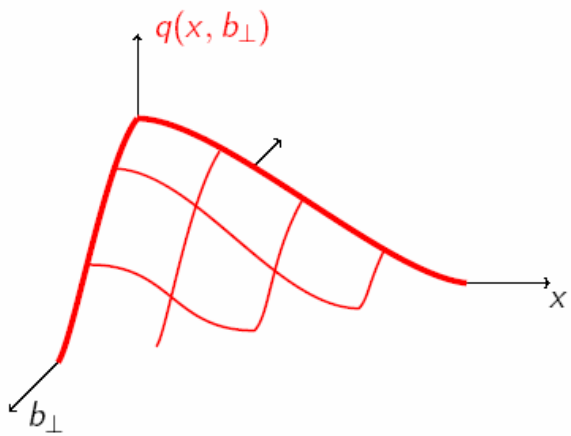




GPDs

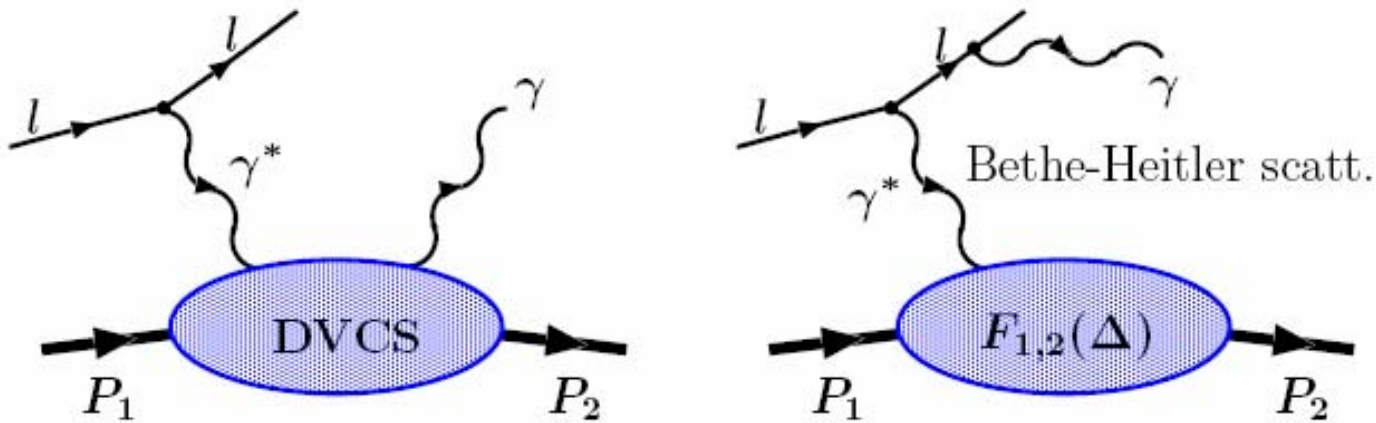
$$H^q(x, 0, t = \Delta^2) = \int \mathrm{d}b_\perp \, e^{i\Delta \cdot b_\perp} q(x, b_\perp)$$





Deeply virtual Compton scattering (I)

- Measured in leptoproduction of a real photon:



- There is a background process but it can be used to our advantage:

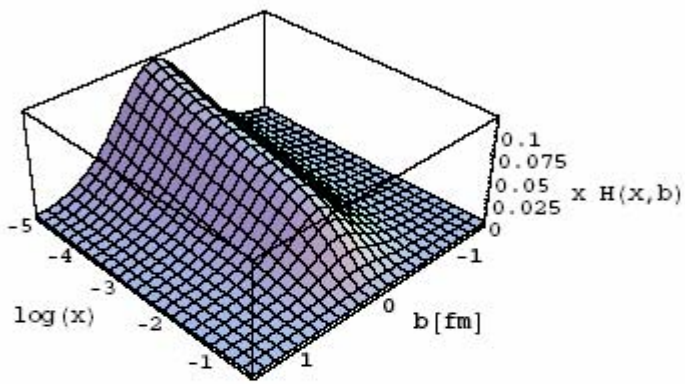
$$\sigma \propto |\mathcal{T}_{\rm DVCS}|^2 + |\mathcal{T}_{\rm BH}|^2 + \mathcal{T}^*_{\rm DVCS}\mathcal{T}_{\rm BH} + \mathcal{T}_{\rm DVCS}\mathcal{T}^*_{\rm BH}$$

- Using $\mathcal{T}_{\rm BH}$ as a referent "source" enables measurement of the phase of $\mathcal{T}_{\rm DVCS}$ → proton "holography" [Belitsky and Müller '02]

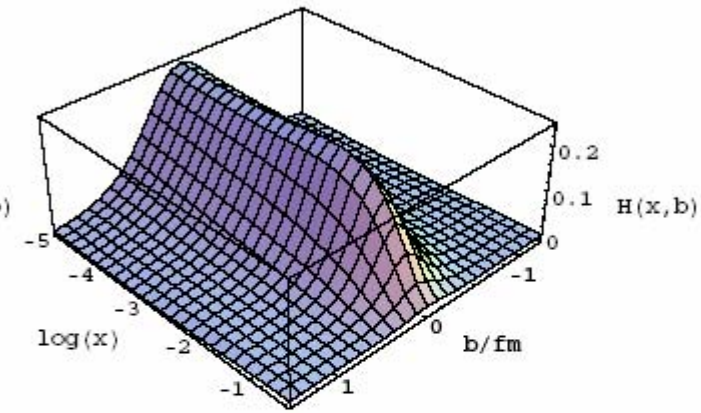
Fits to available DVCS and DIS data work well and give access to transversal distribution of partons.

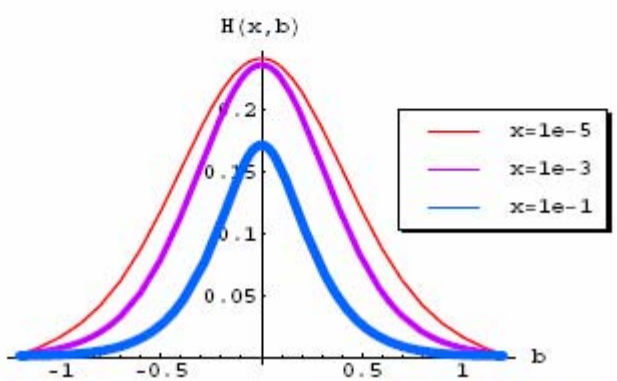
Three-dimensional image of a proton

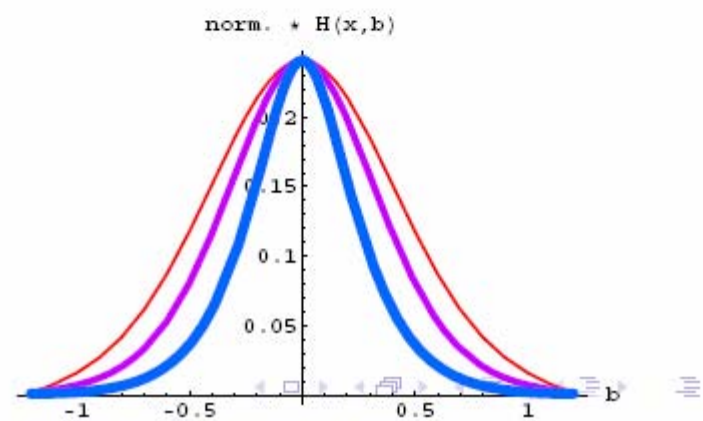
Quarks:



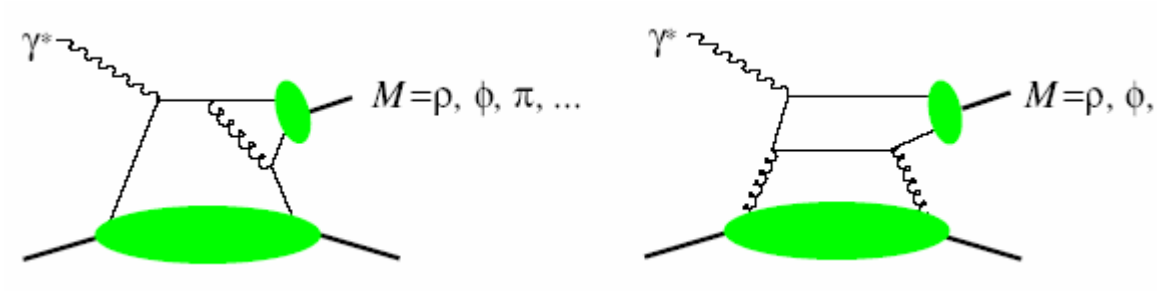
Gluons:



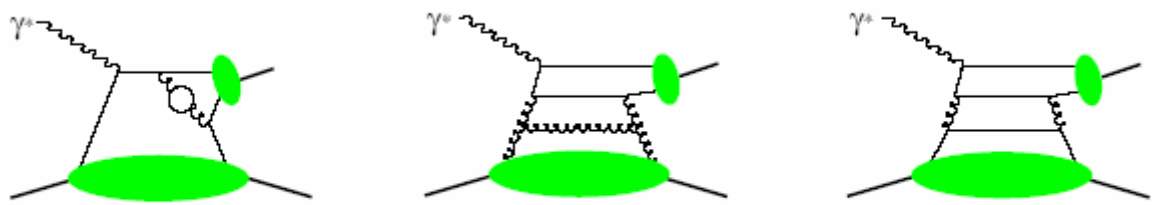




Exclusive vector meson electroproduction



NLO corrections



a) flavor singlet/nonsinglet b) gluons c) flavor singlet

small $x_B \lesssim 10^{-3}$: huge NLO corrections **BFKL type**

must resum high-energy logarithms for reliable expressions

- for DIS was done [Catani, Hautmann '94]

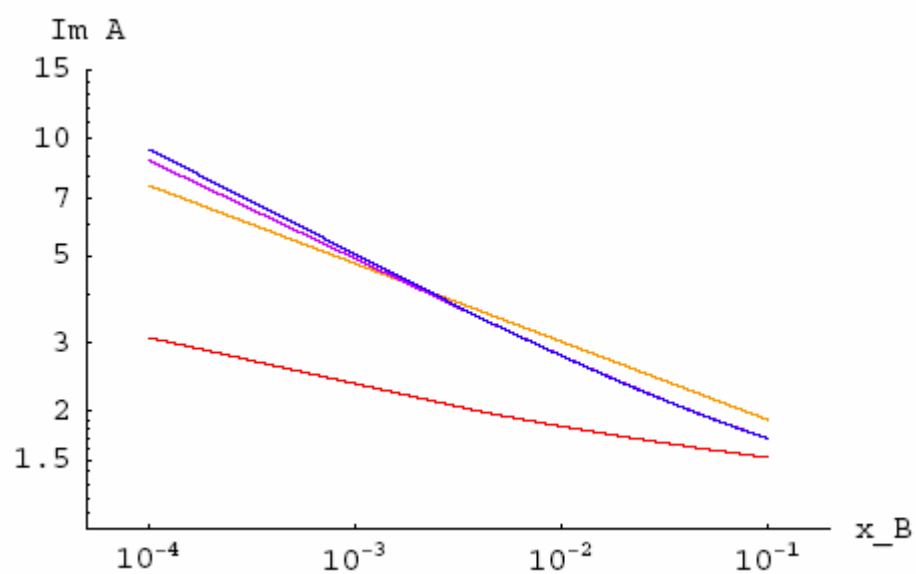
- may be generalized to exclusive/ nonforward processes

$$\mathcal{I}m A^g \sim H^g(\xi,\xi) + \int_{2\xi}^{1} \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1} \frac{x}{\xi}$$

Q^2=20 GeV^2, $\alpha_s = 0.16$

$\mu_F^2 = Q^2/2$

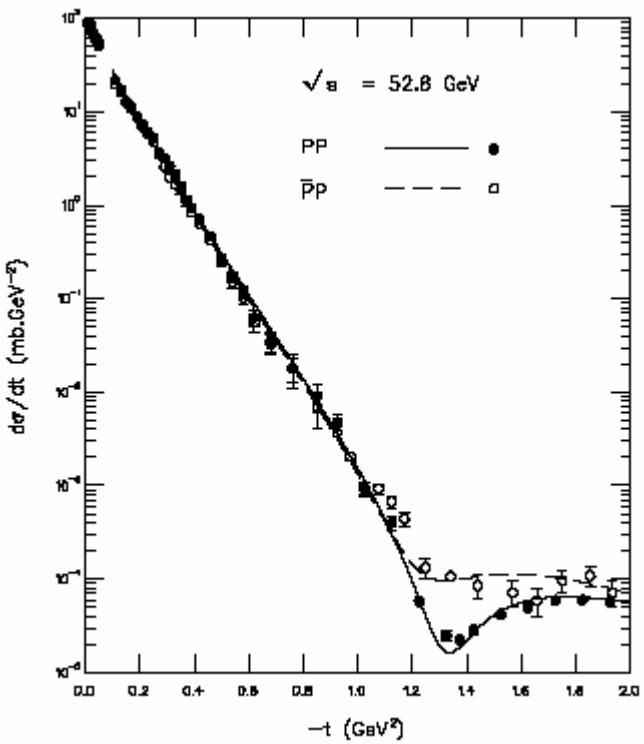
- LO
- $LO + 1st$ high en. term
- $LO + 2$ high en. terms
- $LO + 6$ high en. terms



Odderon

The odderon was introduced more than 30 years ago (Lukaszuk, Nicolescu, 1973; Joynson et al. 1975).

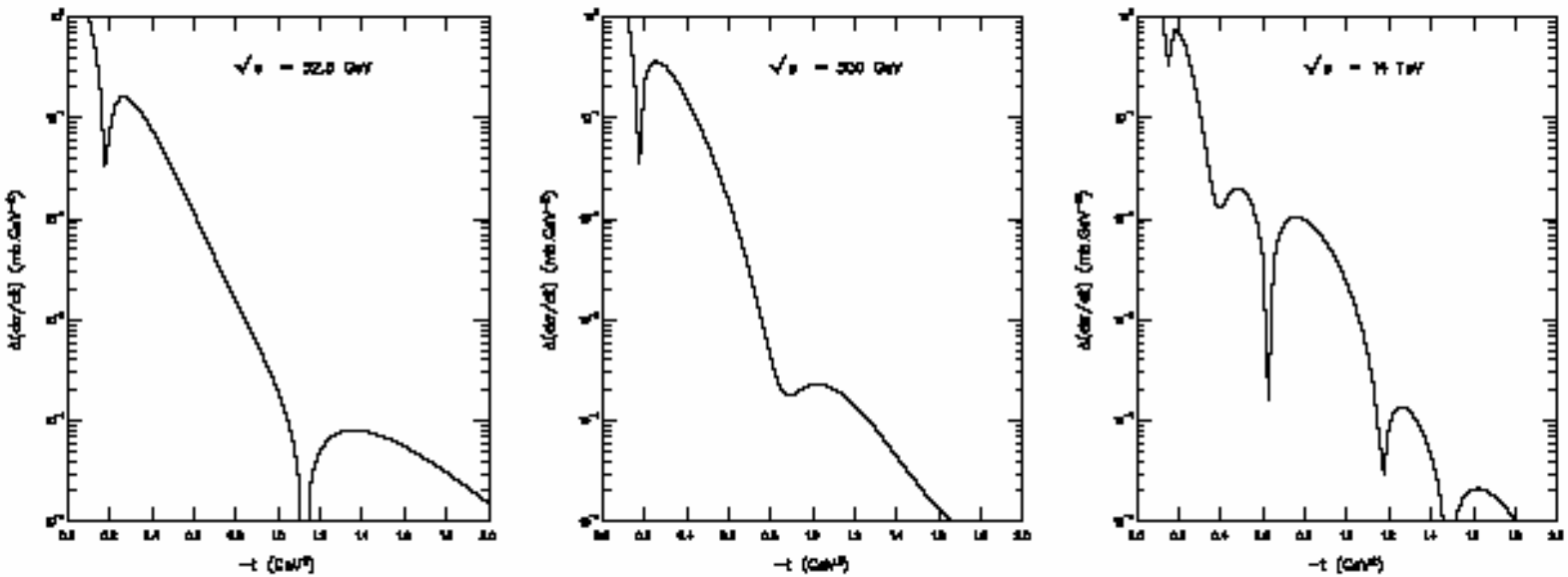
odderon: $C = P = -1$ exchange object in high energy scattering.



So far there is only weak experimental evidence for an odderon from pp / $p\bar{p}$ elastic scattering at $\sqrt{s} = 53$ GeV, $|t| \cong 1.3$ GeV^2.

Oscillations in the difference between the pp and $\bar{p}p$ differential cross-sections

$$\Delta\left(\frac{d\sigma}{dt}\right)(s,t) \equiv \left|\left(\frac{d\sigma}{dt}\right)^{\bar{p}p}(s,t) - \left(\frac{d\sigma}{dt}\right)^{pp}(s,t)\right|$$



ISR RHIC UA4/2 LHC

$\rho_{pp}(\sqrt{s} = 14\ \text{TeV},\ t = 0) = 0.103$

$$\sigma(\gamma p \to \pi^0 N^*) \begin{cases} \approx 300\ nb & \text{theory } * \\ < 49\ nb & \text{H1 exp.} \end{cases}$$

Chiral symmetry

$$\text{Ampl}(\gamma^* p \to \pi^0 p) \underset{PCAC}{\propto} \frac{1}{m_\pi^2} \text{Ampl}(\gamma^* p \to \partial^\mu A_\mu^3\ p)$$

$$\propto \frac{1}{m_\pi^2} m_\rho^2 \propto m_\pi^2$$

- In the chiral limit, $m_\pi^2 \to 0$, the amplitude for π^0 production via odderon exchange vanishes

suppression of odderon $\sigma(\gamma p \to \pi^0 N^*) \approx 6\ nb$ or less

large suppression for $\gamma\gamma \to \pi^0 \pi^0$

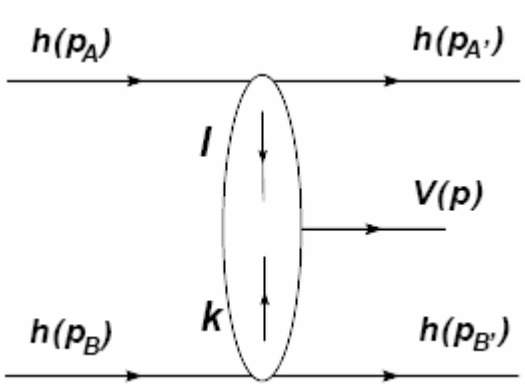
QCD and Odderon

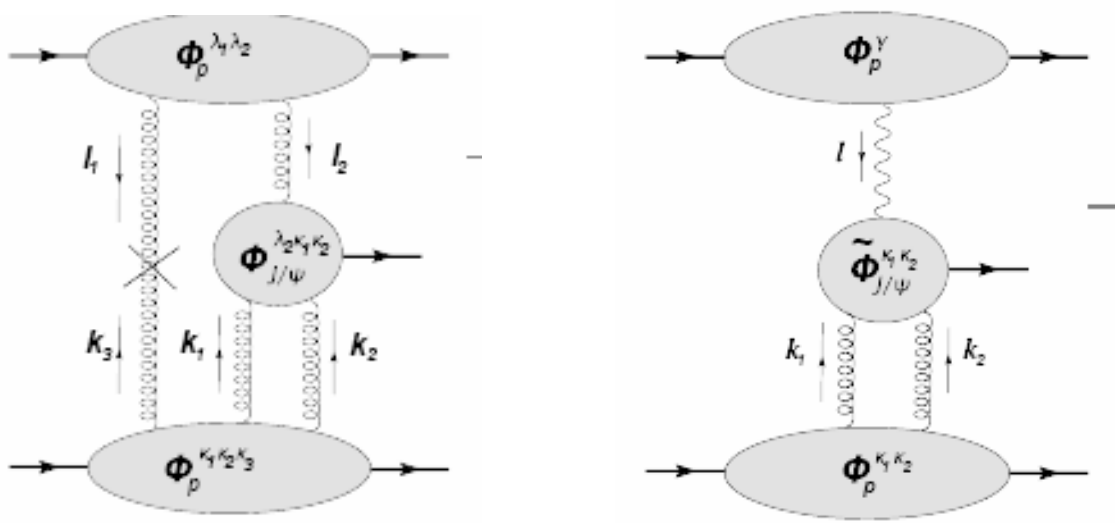
Pomeron: C=+1, two color singlet gluons

Odderon: C= -1, three color singlet gluons

Exclusive J/Ψ and Υ hadroproduction

L.Szymanowski

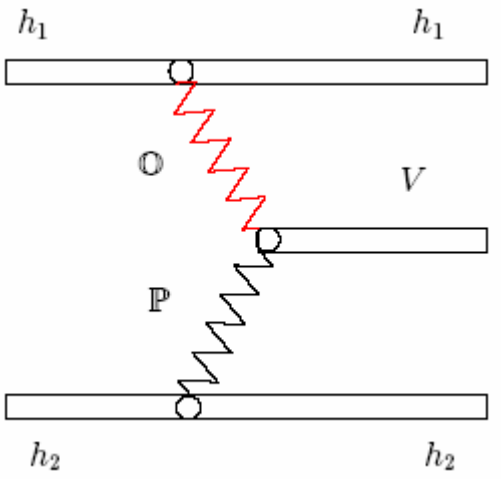


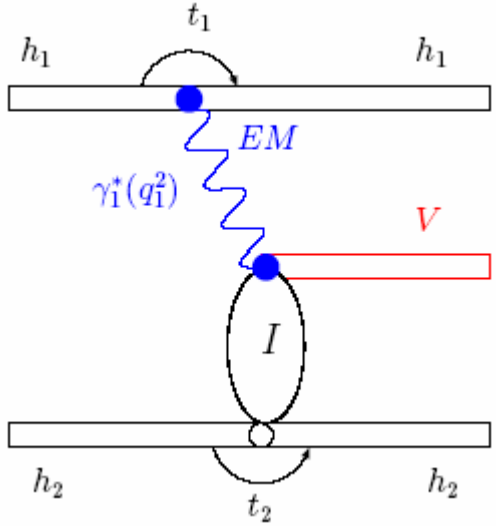


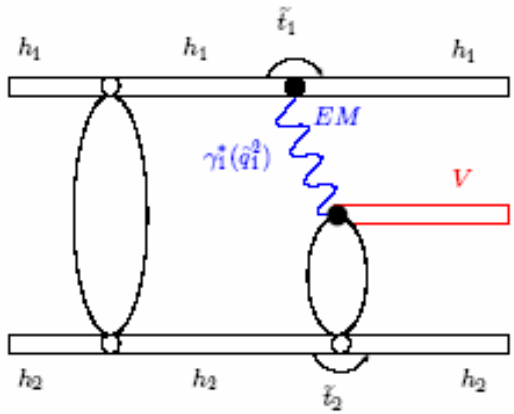
Tag scattered proton(s) to see odderon graph

A. Szczurek

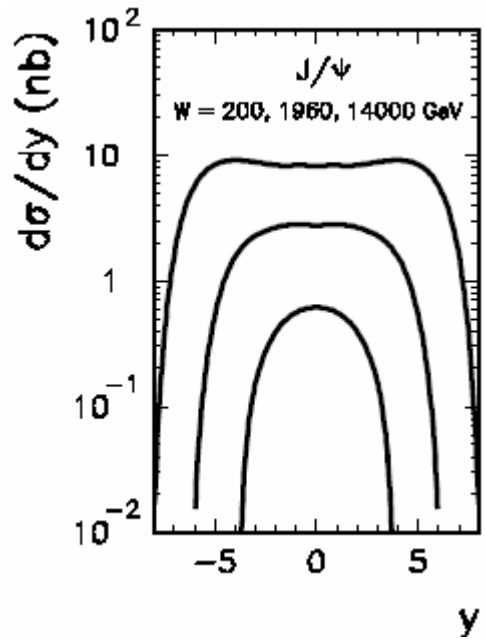
Search for odderon exchanges

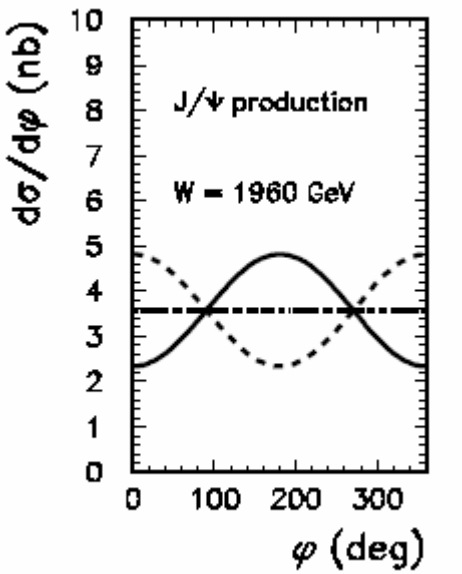


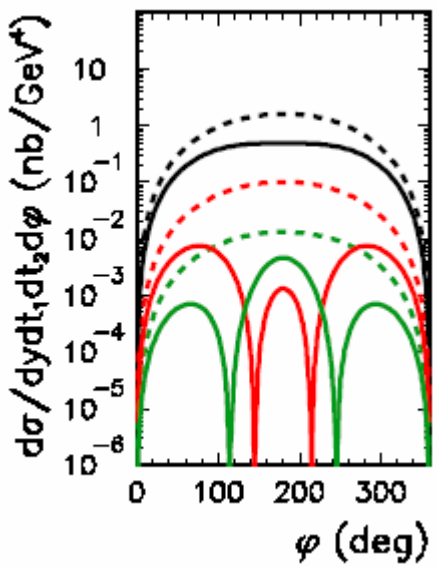




Absorption effects







I do appologize for not giving credit to all wonderful talks

I thank all the organizers for a marvelous time we had in Hamburg