Nonperturbative QCD in pp scattering at the LHC

IX Simpósio Latino Americano de Física de Altas Energias
SILAFAE

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- Introduction: the transverse distance scale
- Total cross section, elastic scattering
- BFKL and recent developments
- multiple interactions
- saturation
- diffraction

Not covered: heavy ion collisions (AAS or pA)

Introduction

At the LHC we are looking for new physics (mostly)
at large momentum scales which allows to use 'hard QCD':

- parton densities,
- partonic subprocesses, $\Longrightarrow$ Gavin Salam's talk
- jets
- ...

But: there is another class of final states which

1) has large cross section:
   total cross section is about 100 mb
   For comparison:
   cross sections of hard processes are smaller: $\Longrightarrow$ this talk
   Typical jet cross section at the LHC: 10 - 100 μb
   Higgs cross section: $\mathcal{O}(pb)$
2) are fully or partly nonperturbative

Perturbative vs. nonperturbative QCD: relevant scale is the transverse distance

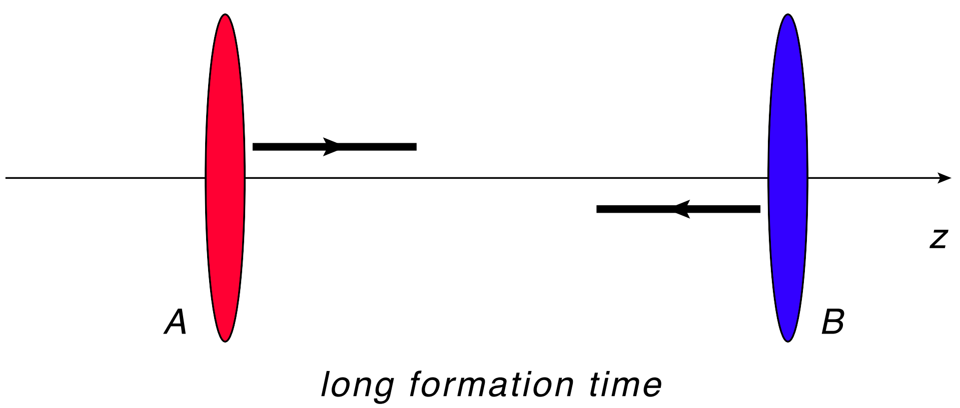
time, longitudinal direction

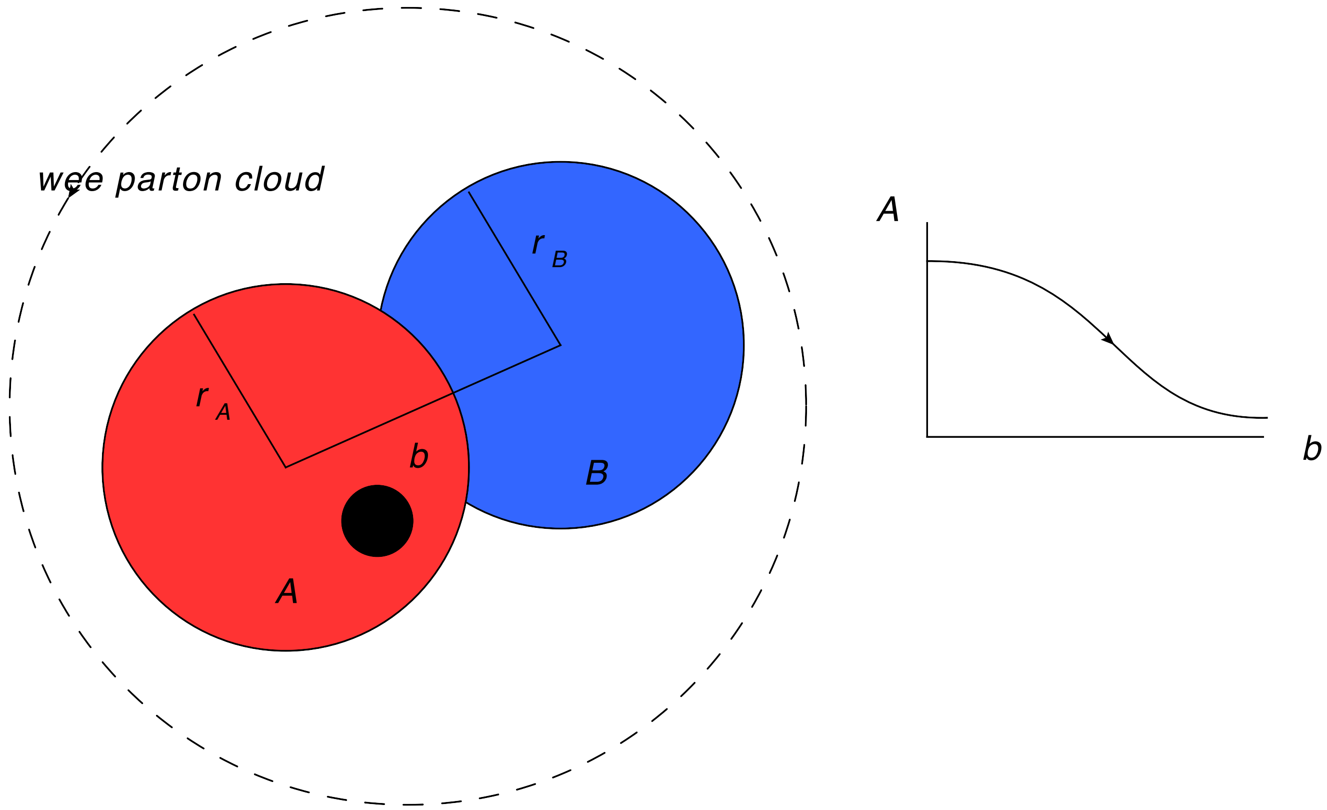
transverse plane

$$T(s,t) \sim is \int d^2b e^{i\vec{q}\cdot\vec{b}} A(s,\vec{b}), \quad t = -\vec{q}^{\,2}$$

$$\sigma_{tot} = \frac{1}{s} Im T(s,0) \sim \int d^2b A(s,\vec{b})$$

long extension along incoming direction



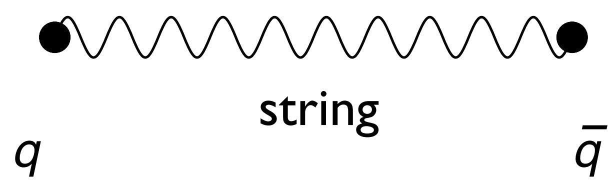


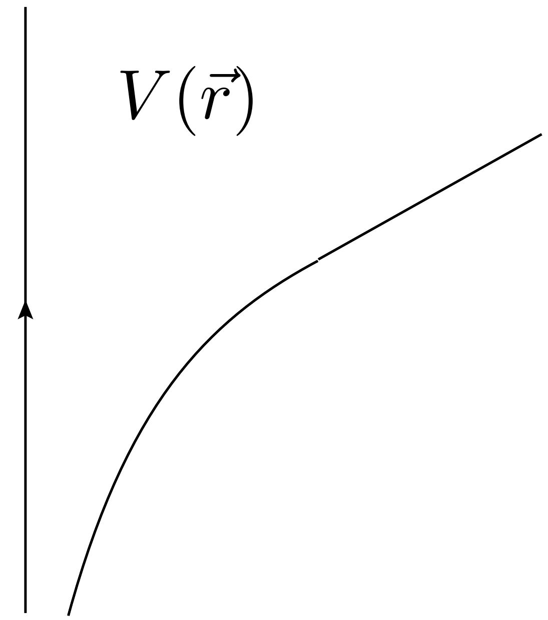
nonperturbative

$$R^2(s) = R_A^2 + R_B^2 + \alpha' \ln s$$

short distance - long distance:

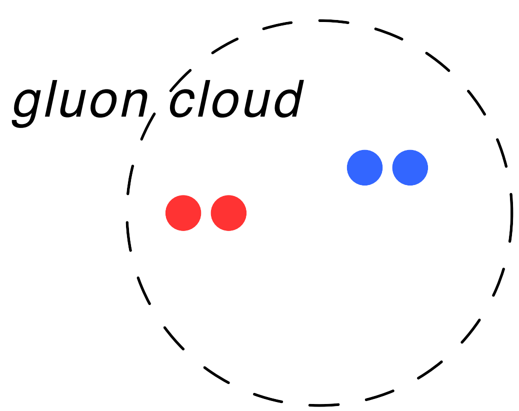
static potential:

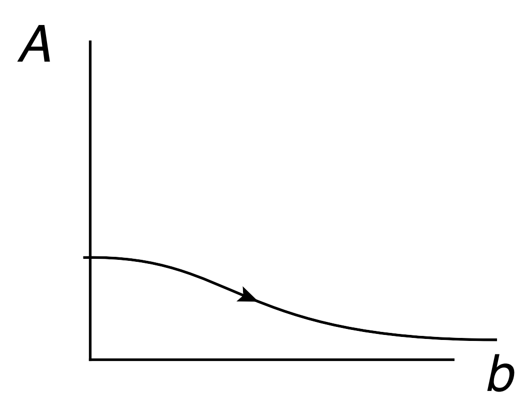


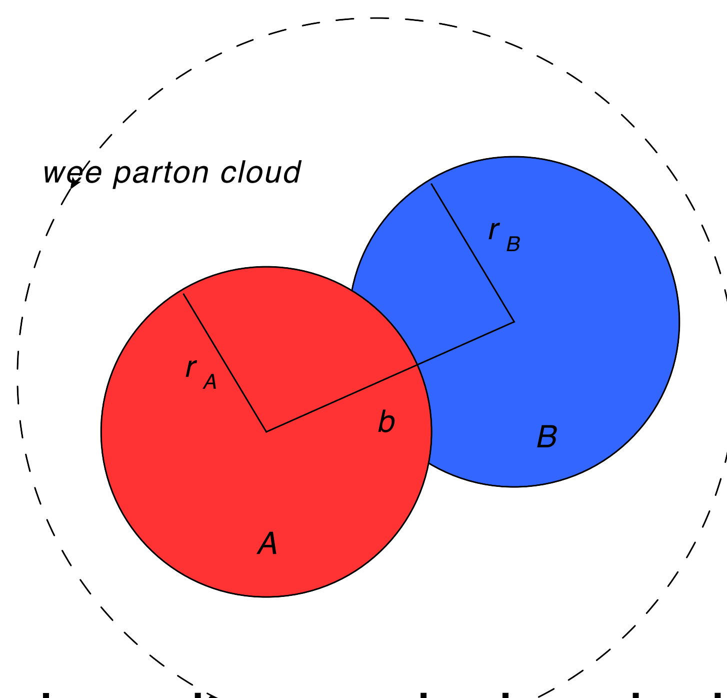


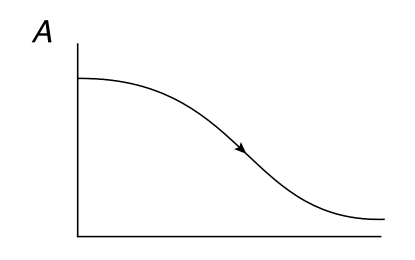
short distance:
coulomb potential

large distance:
linear potential, string tension









short distance: dipole-dipole: BFKL

long distance: hadron-hadron: Pomeron

no finite radius,
cloud grows with power of energy

hadron size $r_{A,B}$, Pomeron slope

- hard processes confined to small regions
- total cross section, elastic scattering probes all distances
- most processes lie in between; in particular:

  BFKL searches start in small regions, but are sensitive to large distances

  multiple interactions and saturation explore the interface

  hard diffraction is sensitive to small and large distances

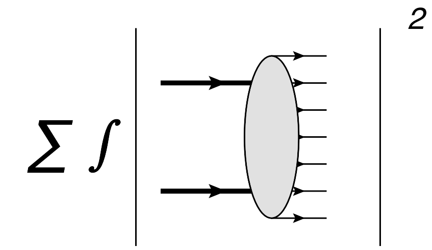
- each final state has its own way to exhibit large distance effects

  - Total cross section, elastic scattering
  - BFKL and recent developments
  - multiple interactions
  - saturation
  - diffraction

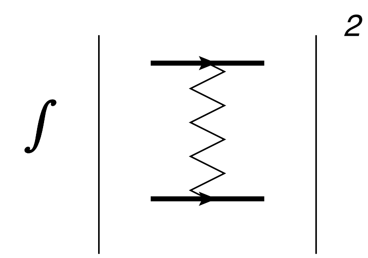
Total cross section, elastic scattering

Sizes of soft cross section:

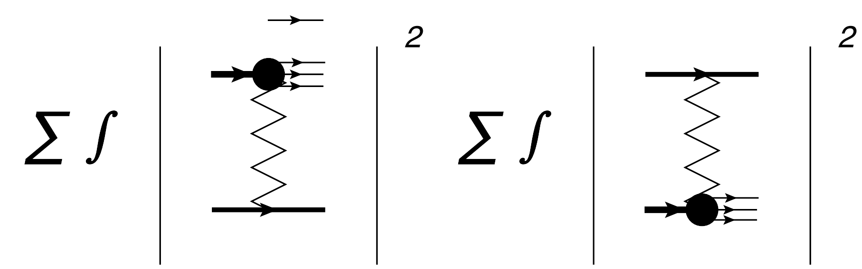
total cross section: 98 mb



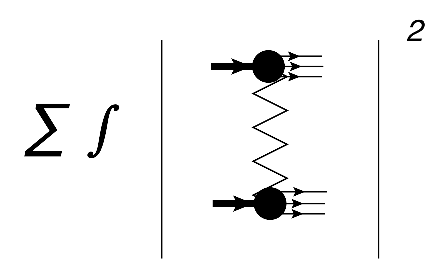
elastic cross section 24.8 mb



single diffractive cross section 14.16 mb



double diffractive cross section 8,8 mb



inelastic cross section 70 mb

Forward direction has large cross sections: theory wanted!

Totem results:

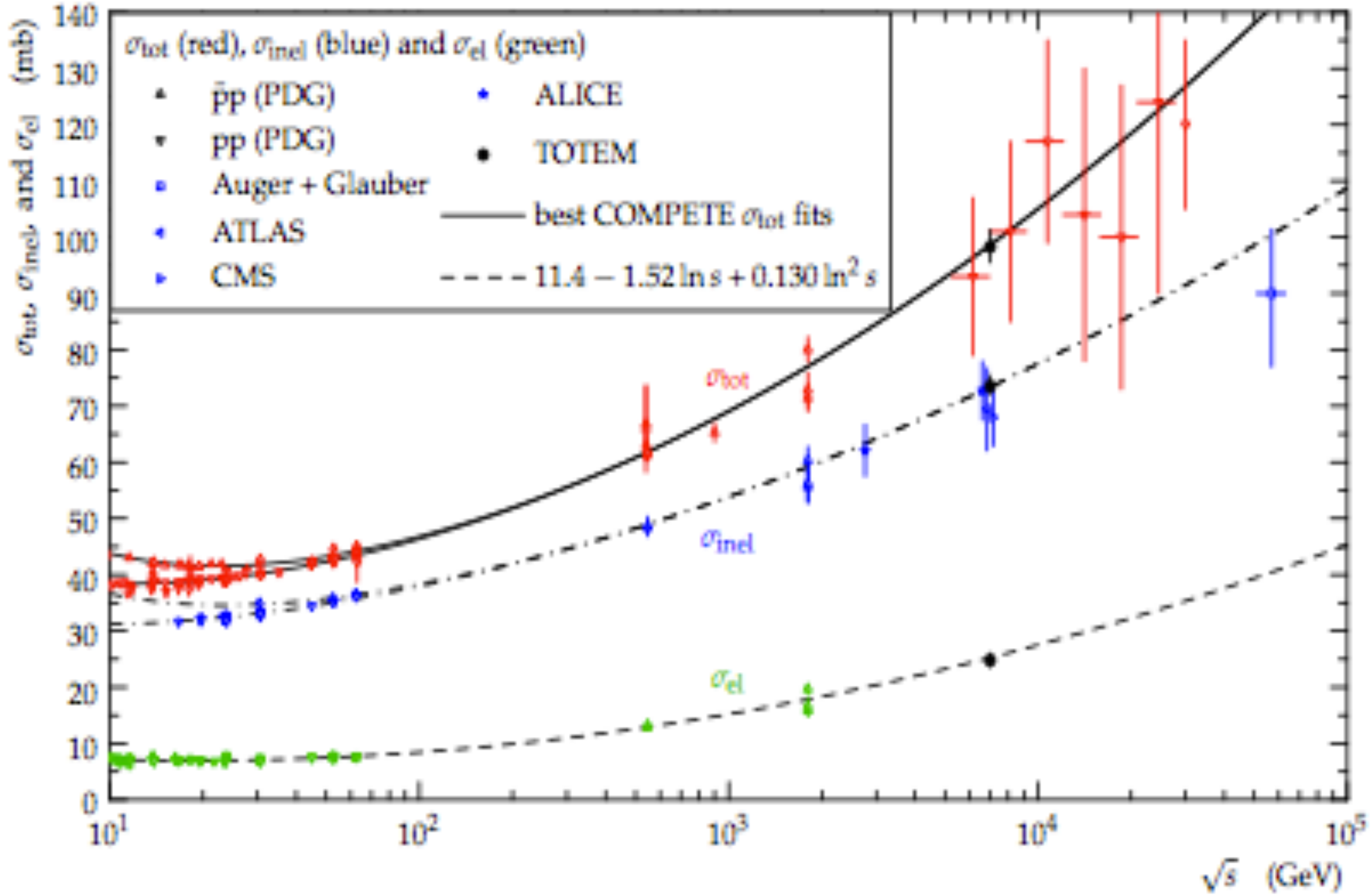


Fig. 2: The new TOTEM data demonstrate the continuation of the trends from earlier measurements, and indicate the high precision of the TOTEM experiment.[4]

Theory/models for total cross section: $Exp : \sigma_{tot} = 98.3mb$

Block, Halzen: Fit of formula (95.4)

$$\sigma_{tot} = 90.281\,(\ln \frac{\nu}{m})^2 - 1.44\,\ln \frac{\nu}{m} + 37.2 + 37.1\,(\frac{\nu}{m})^{-0.5}$$

Donnachie, Landshoff: Regge pole, soft plus hard (soft alone: $\sigma_{tot} \approx 91mb$)

$$\sigma_{tot} = c_1 s^{\alpha_{P,soft}(0)-1} + c_2 s^{\alpha_{P,hard}(0)-1} \qquad (98)$$

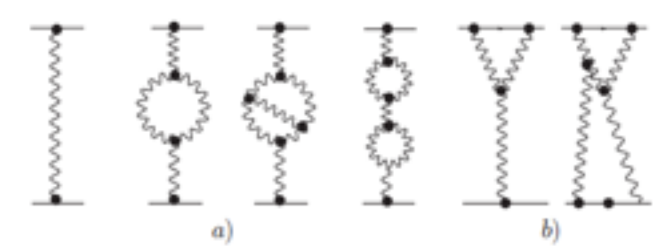
$$soft : \alpha_{P,soft}(t) = 1.093 + \alpha' + 0.25t \qquad hard : \alpha_{P,hard}(t) = 1.362 + \alpha' + 0.1t$$

Eikonal ansatz for elastic cross section

Tel Aviv (Gotsman, Levin, Maor) (98.6)
Durham (Martin, Khoze, Ryskin) (96.4)

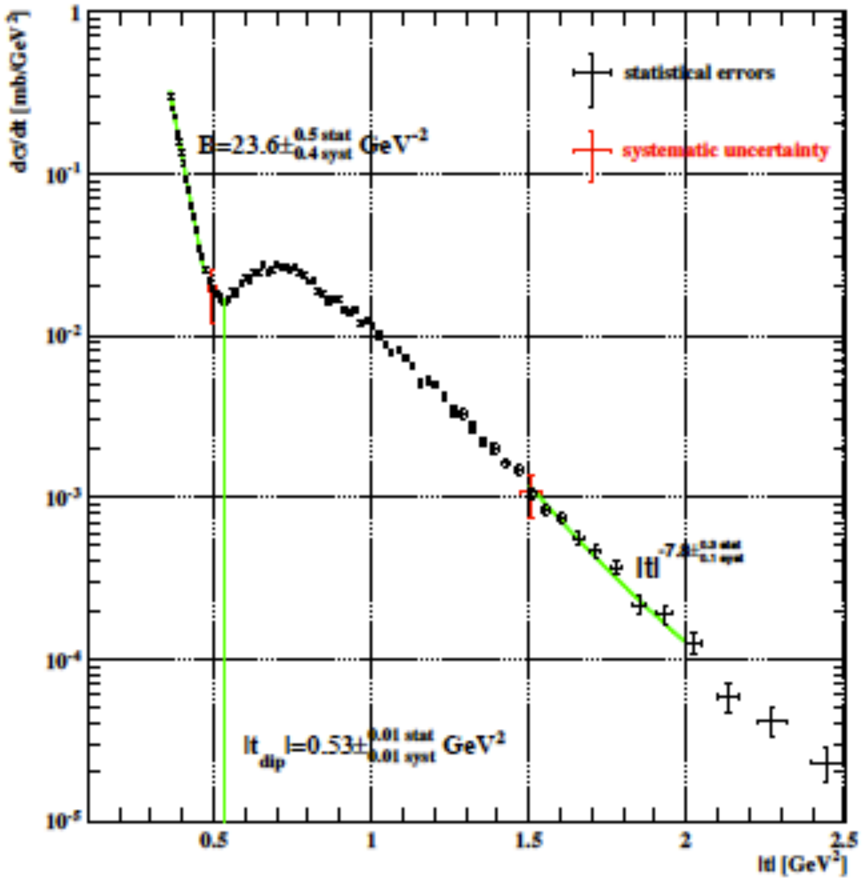
Pomeron graphs

Example of enhanced and semi-enhanced diagram

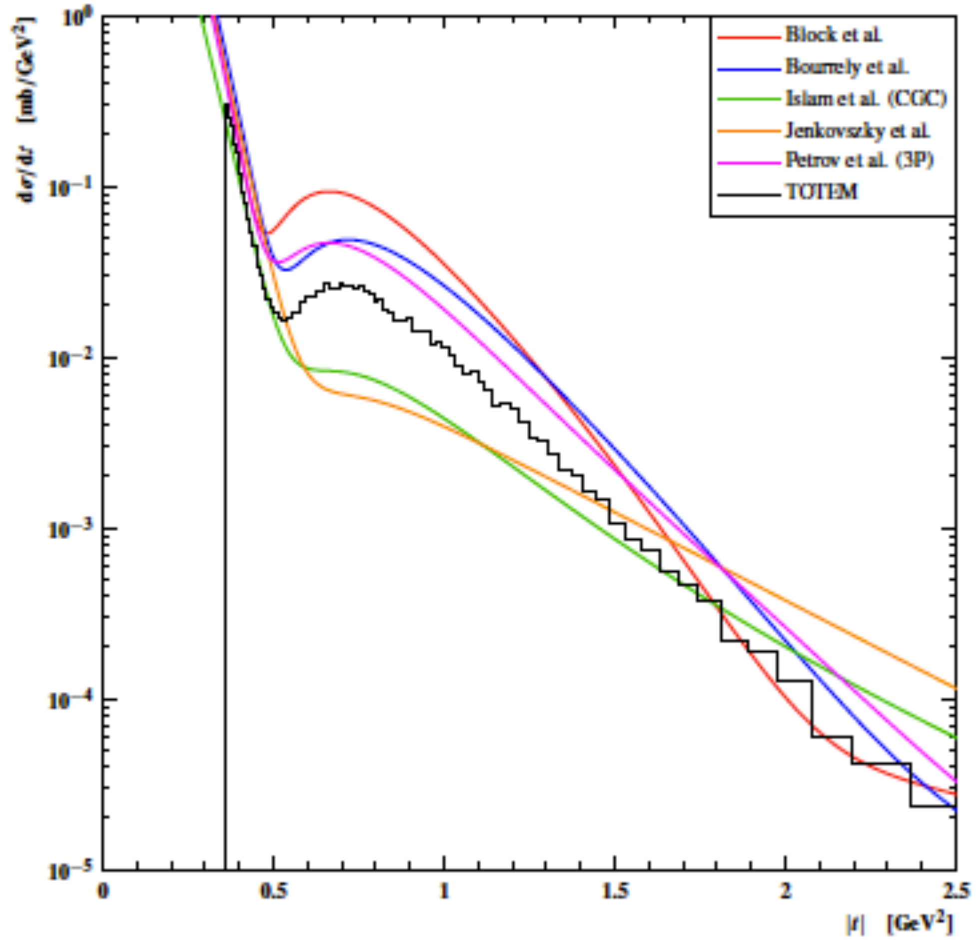


Different contributions to the Pomeron Green's function
a) examples of enhanced diagrams ;
(occur in the renormalisation of the Pomeron propagator)
b) examples of semi-enhanced diagrams
(occur in the renormalisation of the $I\!P$ -p vertex)
Multi-Pomeron interactions are crucial for the production of LARGE MASS DIFFRACTION

Elastic cross section: dip structure



(a) The first TOTEM data on differential cross-section of elastic p+p scattering at $\sqrt{s} = 7$ TeV, measured in the momentum transfer range of $0.36 \le |t| \le 2.5$ GeV^2.



(b) When compared to predictions of different models, the TOTEM elastic scattering $d\sigma/dt$ data show a strong discriminative power.[3]

Fig. 1: TOTEM elastic scattering $d\sigma/dt$ data measurements at $\sqrt{s} = 7$ TeV.

Comparison with $p\bar{p}$ (although at different energies): signal for the Odderon?

model-dependent analysis , before Totem
Jenkovsky et al

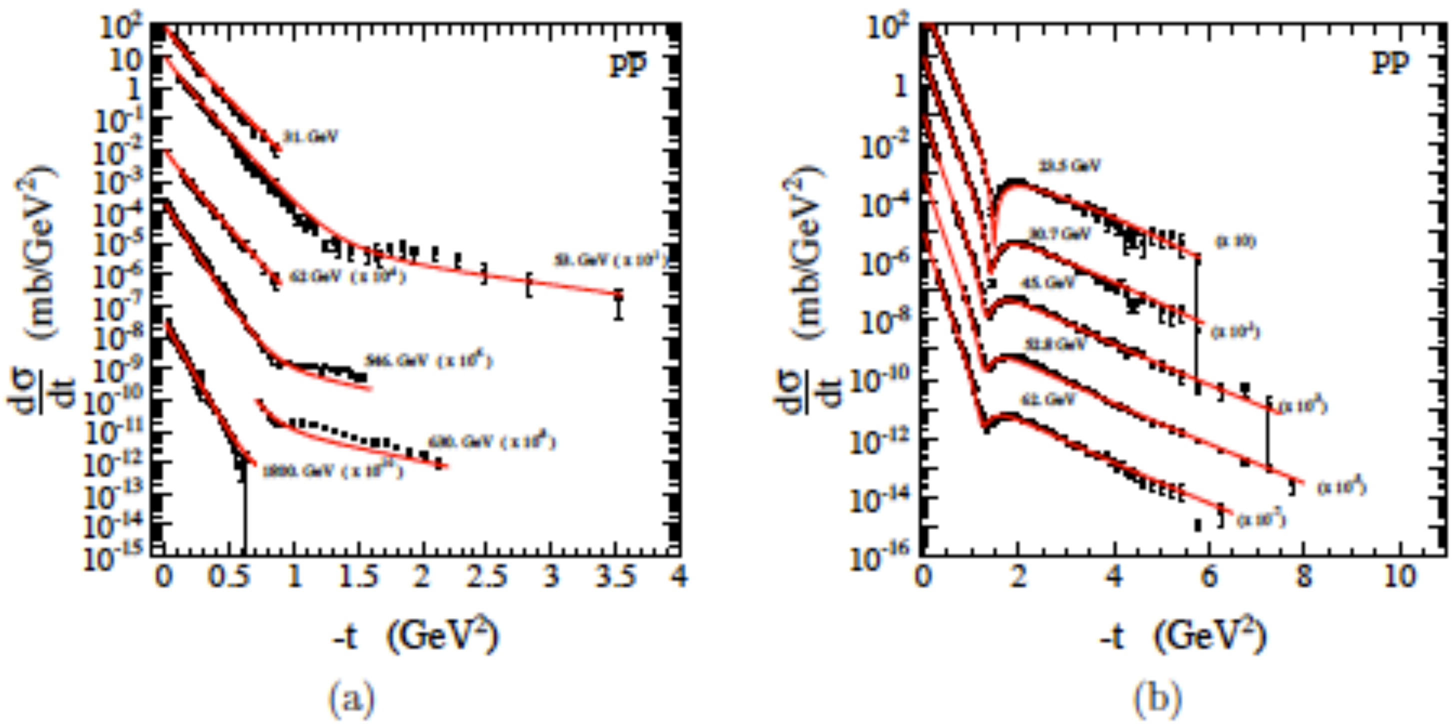


Figure 3: (a) $\bar{p}p$ differential cross sections calculated in model, Eqs. (2-8, TR.1), and fitted to the data, and fitted to the data in the range $-t = 0.1 - 8$ GeV^2. (b) pp differential cross sections calculated in the model and fitted to the data. The curves present calculations with the parameters shown in Table (3).

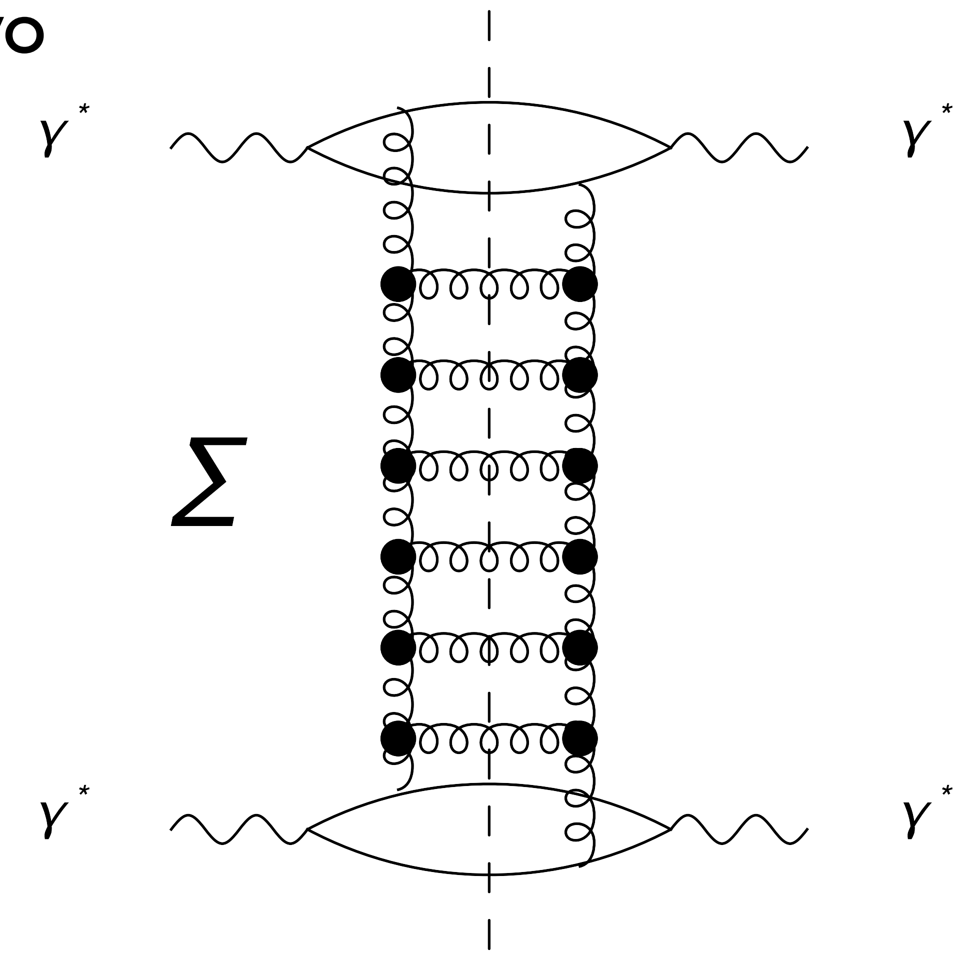
Simplest explanation: three gluon exchange (Donnachie, Landshoff: ISR data)
= beginning of Odderon (analogue of BFKL)

Small-size dipole scattering: BFKL

Balitsky,Fadin,Kuraev, Lipatov 1975/76

Elastic scattering of two small dipoles

$$Im\, T_{\gamma^*\gamma^*} = \sum$$

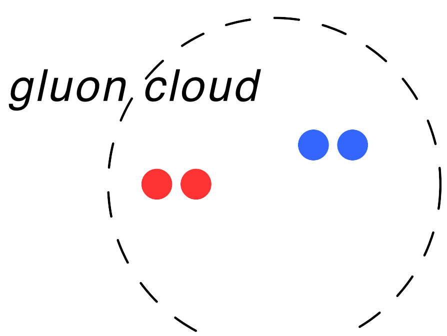


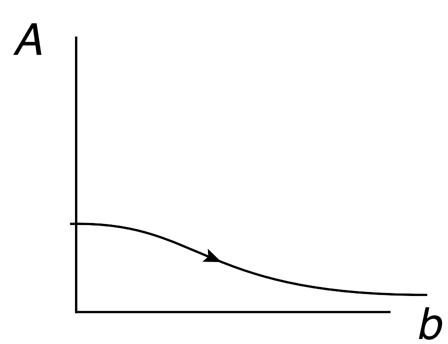
sum over gluon production

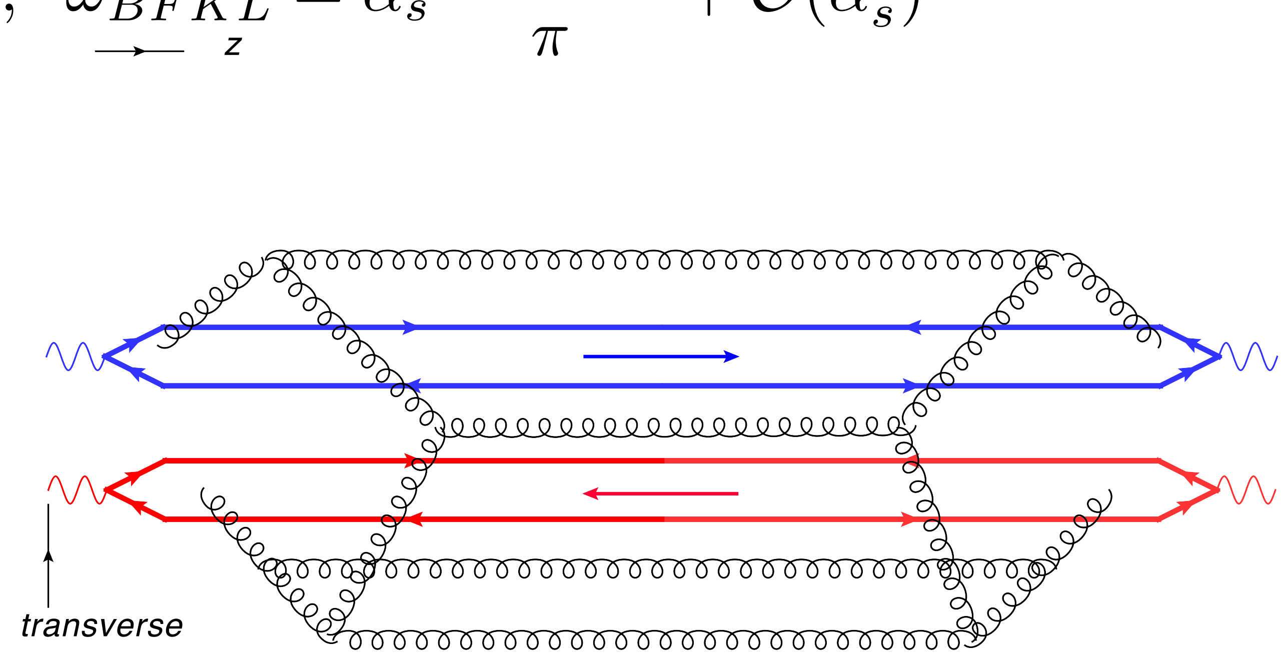
Important properties:

- growth with energy: $\sigma^{tot}_{\gamma^*\gamma^*} \sim s^{\omega_{BFKL}}, \quad \omega_{BFKL} = \alpha_s \frac{4N_c \ln 2}{\pi} + \mathcal{O}(\alpha_s^2)$

- strong growth in transverse direction







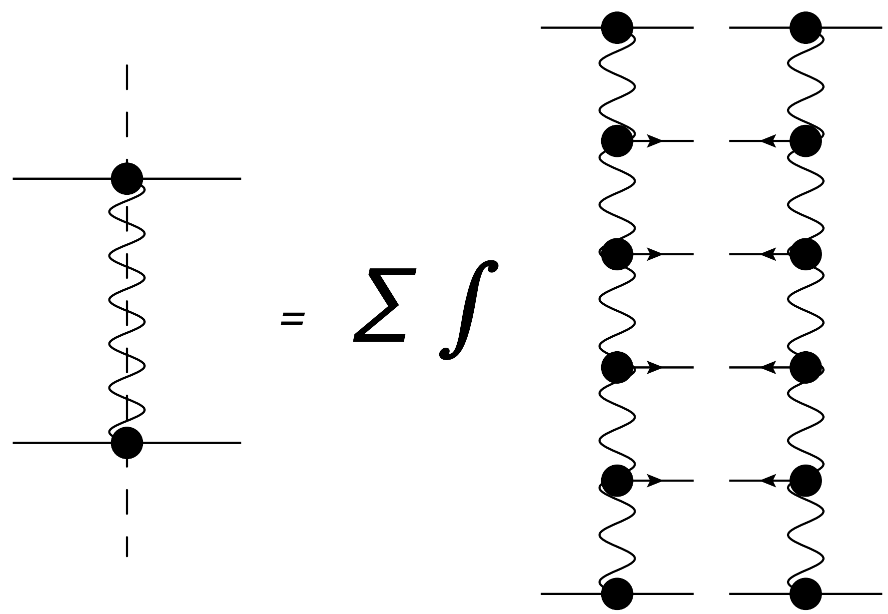
More remarkable properties of the BFKL Pomeron:

1) unitarity:

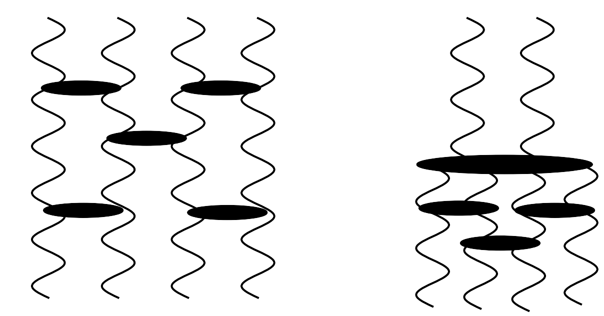
nonlinear equations

bootstrap equation

$$Im\, T_{2\to 2} = \sum_n \int d\Omega_n |T_{2\to n}|^2$$



2) Beginning of a 2+1 dim field theory, with reggeized gluons as d.o.f.



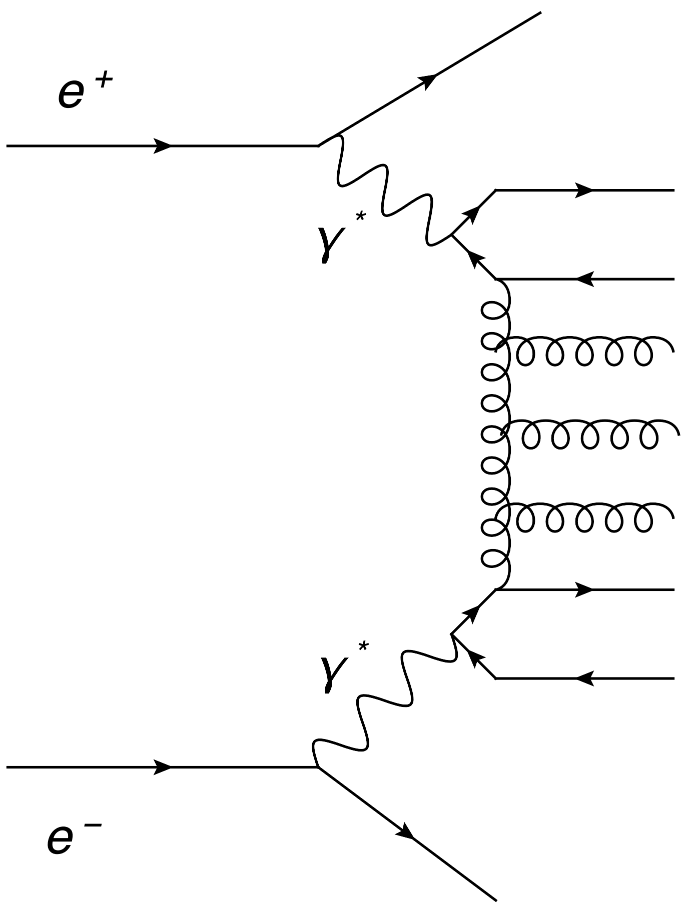
3) In LO: two-dimensional conformal invariance (Moebius invariance): connection with N=4 SYM (=most symmetric gauge theory), integrability, theory might be solvable

4) Electroweak theory, gravity: high energy behavior vs. renormalizibility

How to test this calculation:

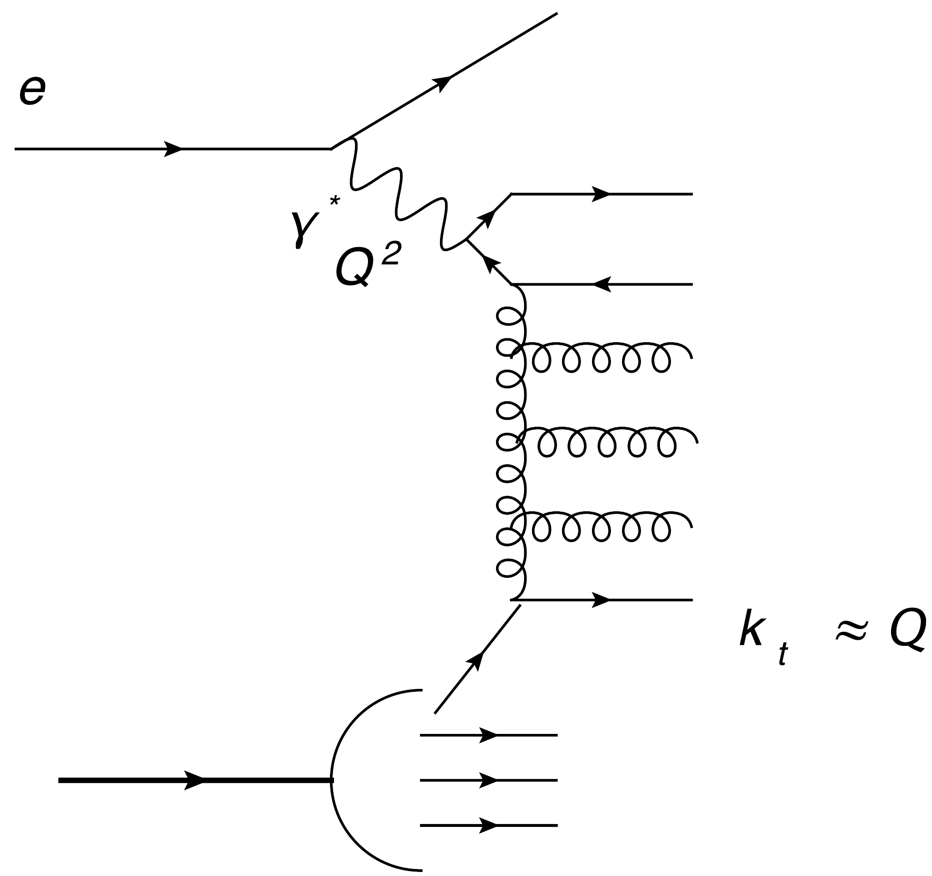
1) $\gamma^*\gamma^*$ collisions
in electron-positron scattering (LEP)

2) Mueller-Navelet jets
in pp-scattering (Tevatron, LHC)



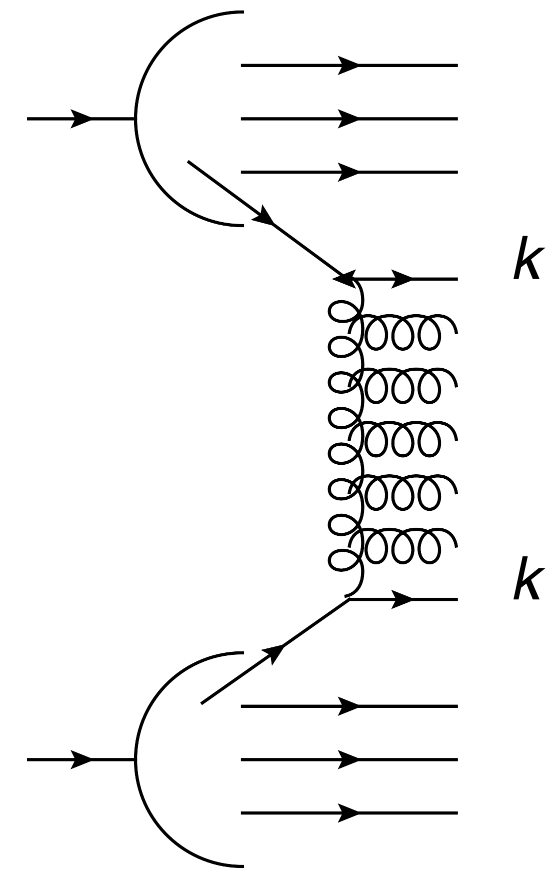
e^+e^-

ok, not fully convincing



HERA, forward jets

ok



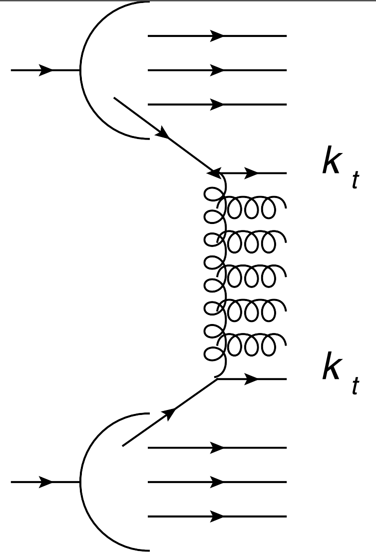
LHC, Mueller-Navelet

wait for data

Comments on BFKL-related activities for the LHC:

1) NLO available: BFKL, jet vertex, numerical analysis

Colferai et al.
Papa et al.



2) Angular decorrelation as BFKL signal

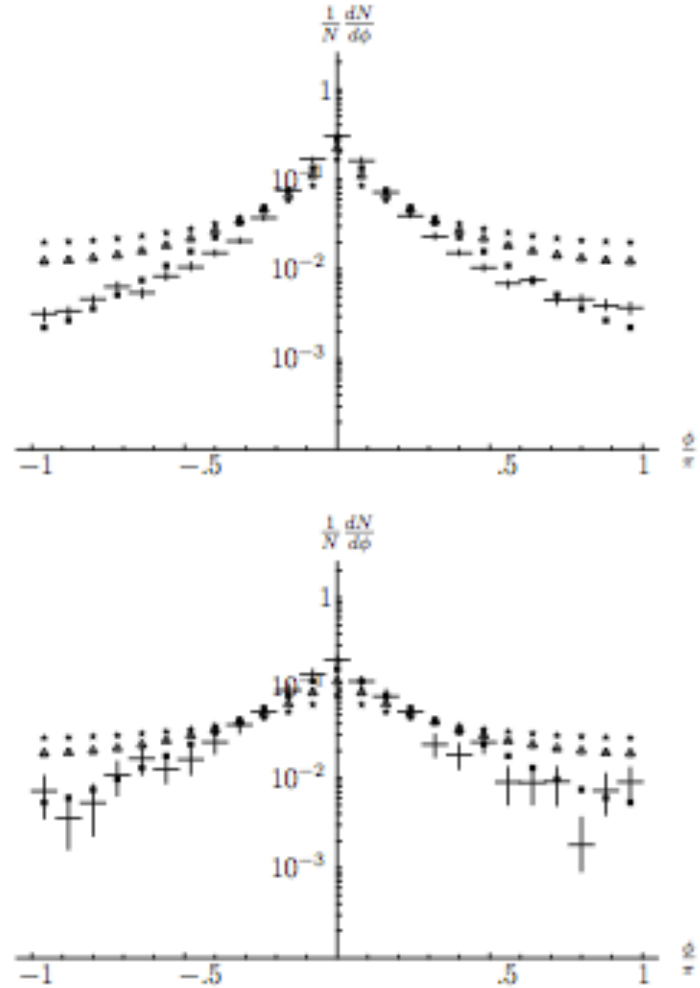
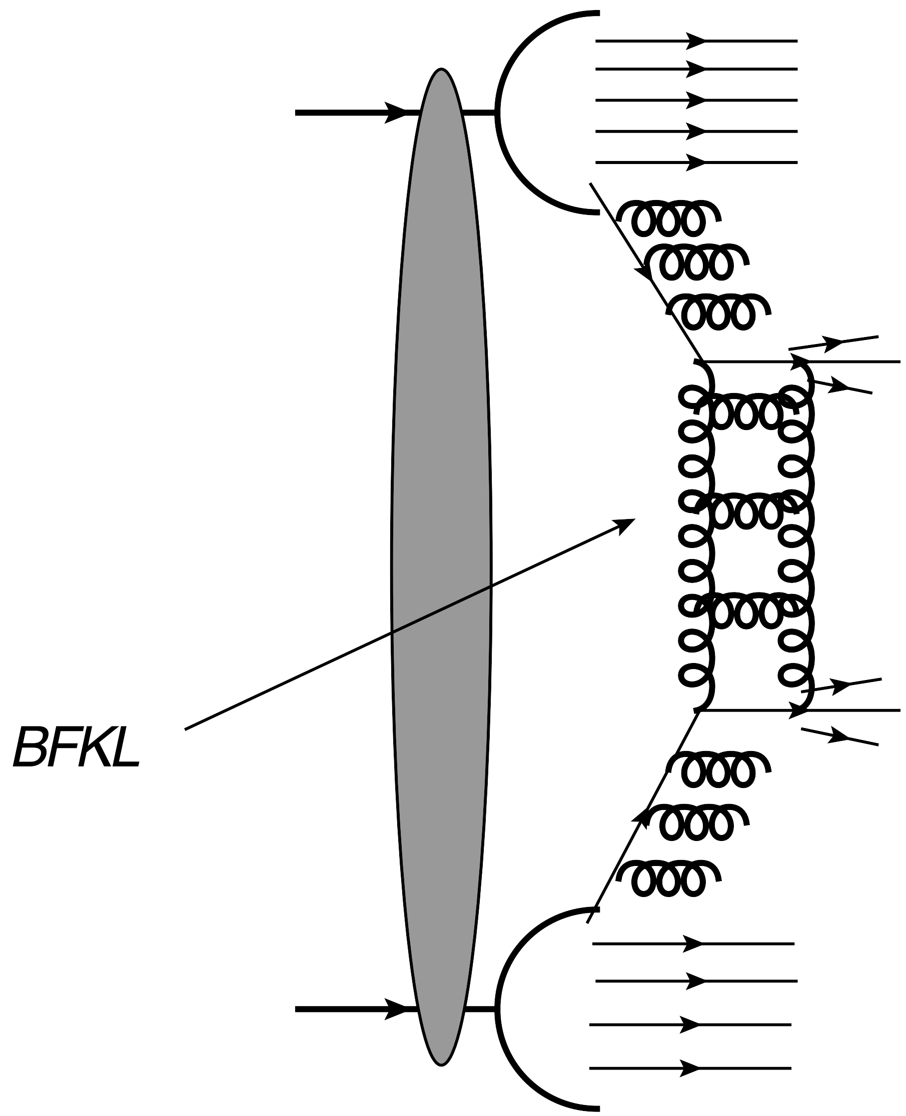


Fig. 2: $\frac{1}{N}\frac{dN}{d\phi}$ in a $p\bar{p}$ collider at $\sqrt{s}$=1.8 TeV using a LO (stars), NLO (squares) and resummed (triangles) BFKL kernel. Plots are shown for Y = 3 (top) and Y = 5 (bottom).

Sabio Vera, Schwennsen;
Colferai et al.
Papa et al:

3) BFKL energy dependence: use different machine energies

Jet-gap-jet (hard color singlet exchange)



Cox,Forshaw,Lonnblad;
Enberg,Ingelman, Motyka;
Royon

BFKL needs all conformal spins

$$\frac{d\sigma^{pp}}{dx_1 dx_2 dE_T^2} = S f(x_1, E_T) f(x_2, e_T) \frac{d\sigma^{qq\to JJ}(\eta, E_T)}{dE_T^2}$$

Survival factor S: (other chains, radiation?)
Modelled by Monte Carlo

New formulation of BFKL (HERA): discrete Regge poles

Kowalski, Ross, Lipatov

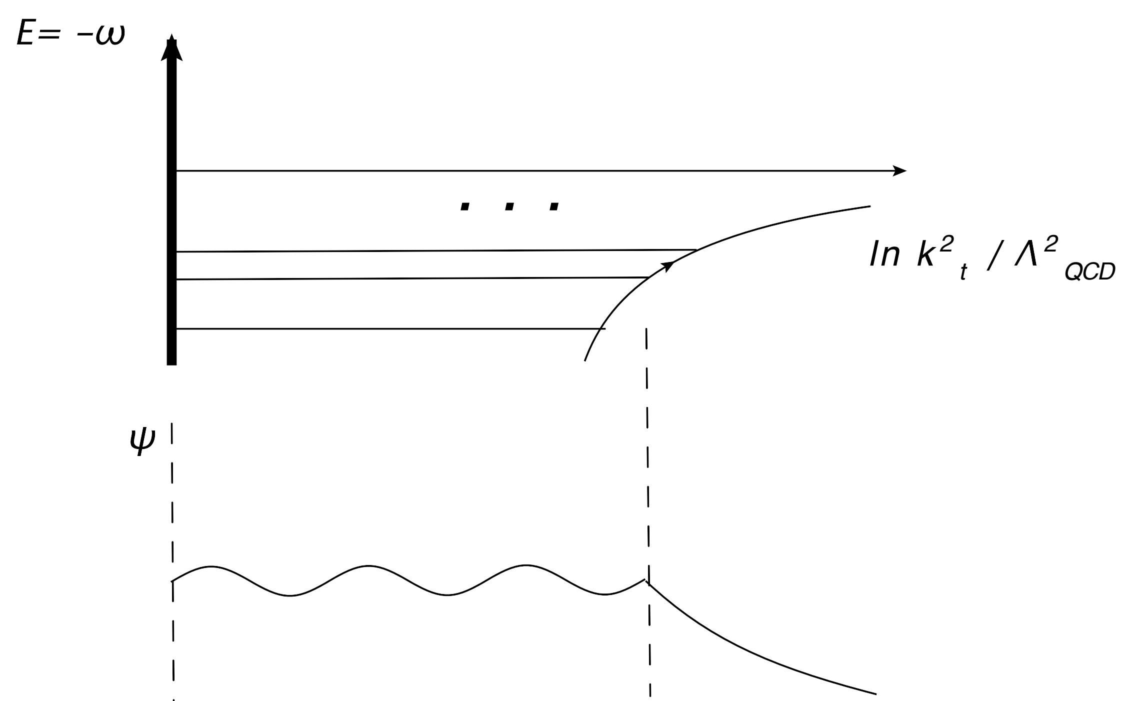
BFKL equation is often written as evolution equation

$$\frac{\partial}{\partial y}\psi(y,k) = \int d^2k' K_{BFKL}(k,k')\psi(y,k')$$

where kernel has continuous eigenvalue spectrum.

Instead: boundary conditions at infrared plus asymptotic freedom lead to discrete spectrum. Quasiclassical picture: Lipatov 1986

Eigenvalues and wave functions are sensitive to changes at turning points in UV region

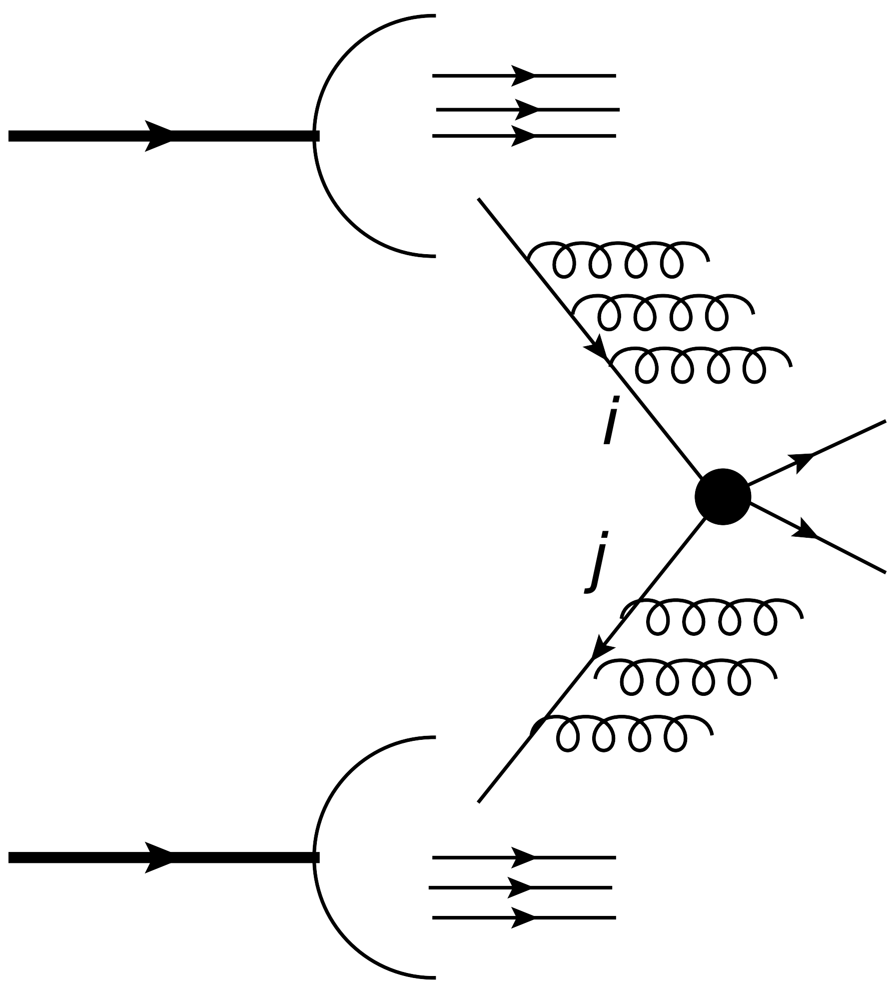


Fit to HERA data.
Signal of new physics?

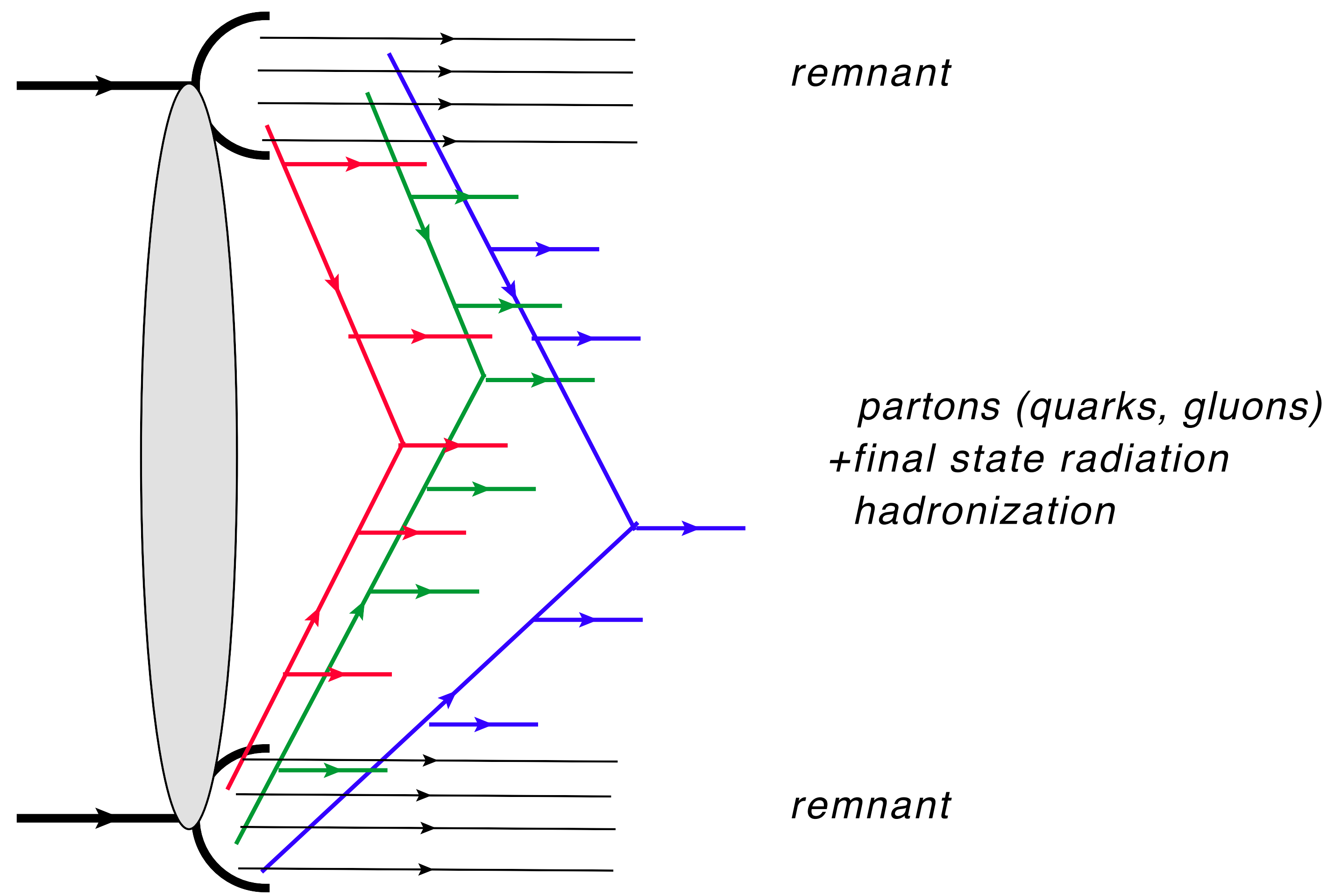
Multi-Parton Interactions (MPI)

Inclusive cross section vs.underlying event:

Inclusive cross section



event structure in pp collisions:
number of chains grows with energy



Mostly based uopn eikonal formula

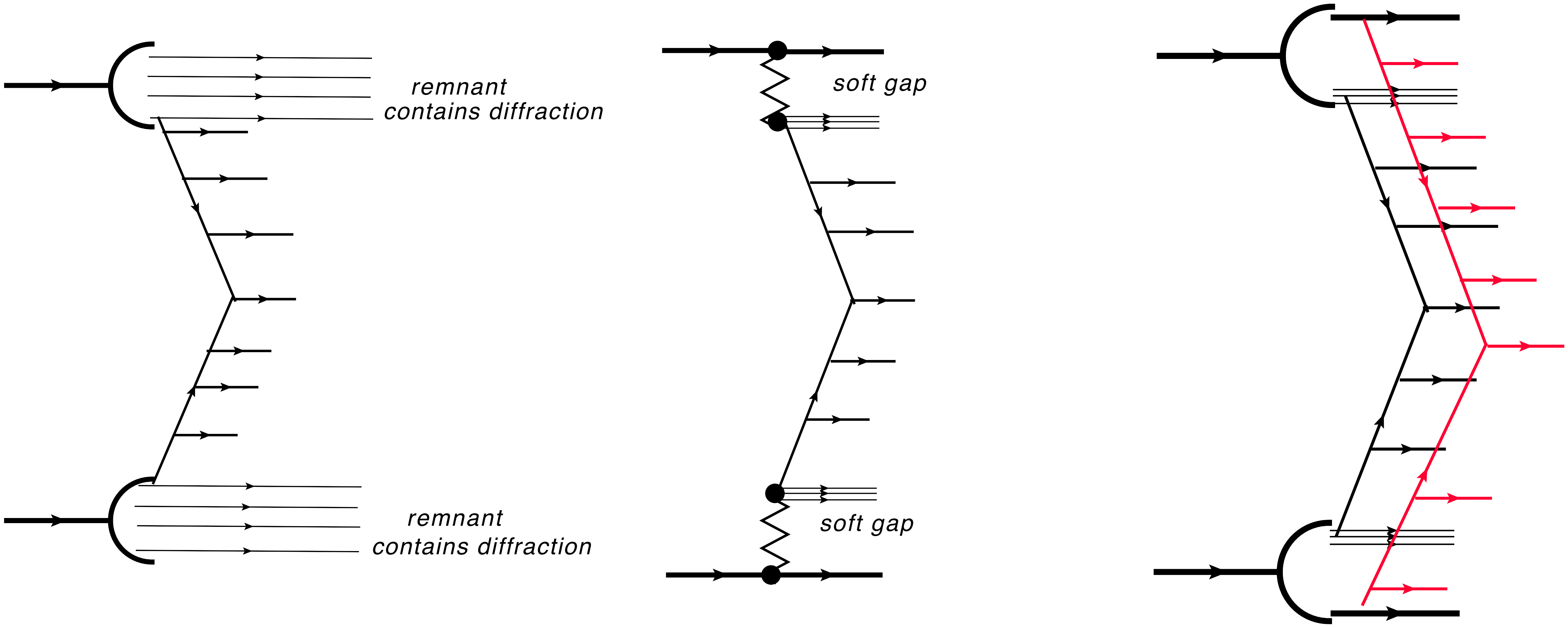
Pictures have slightly different meaning:

event $\longrightarrow$ cross section involves summation
Cancellations (collinear factorization, AGK)

Important consisteny check!

Important question: where is diffraction (rapidity gaps)?

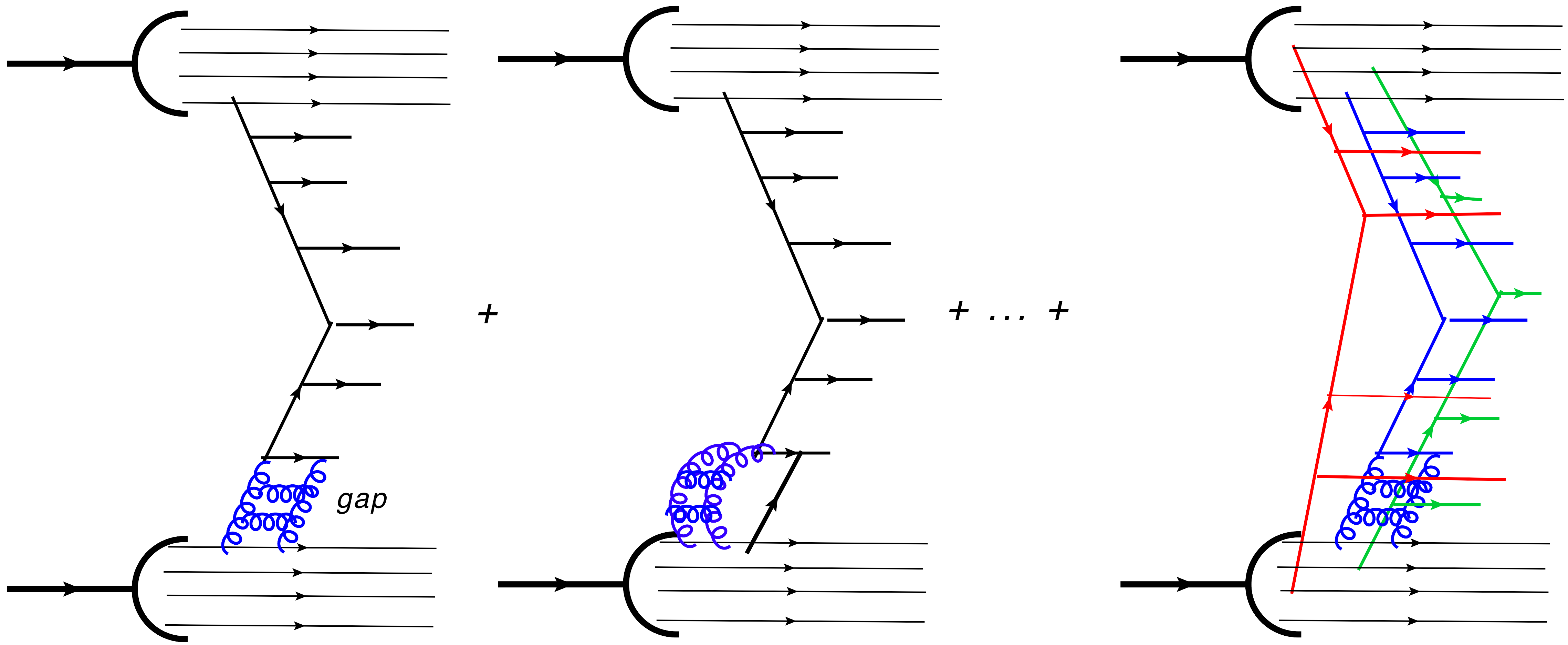
Soft diffraction:



BUT: second, third... chain may fill the gap, less diffraction

Sum over chains and all rescattering effects:
lowers the probability of rapidity gaps

(semi)hard diffraction:
add new contribution

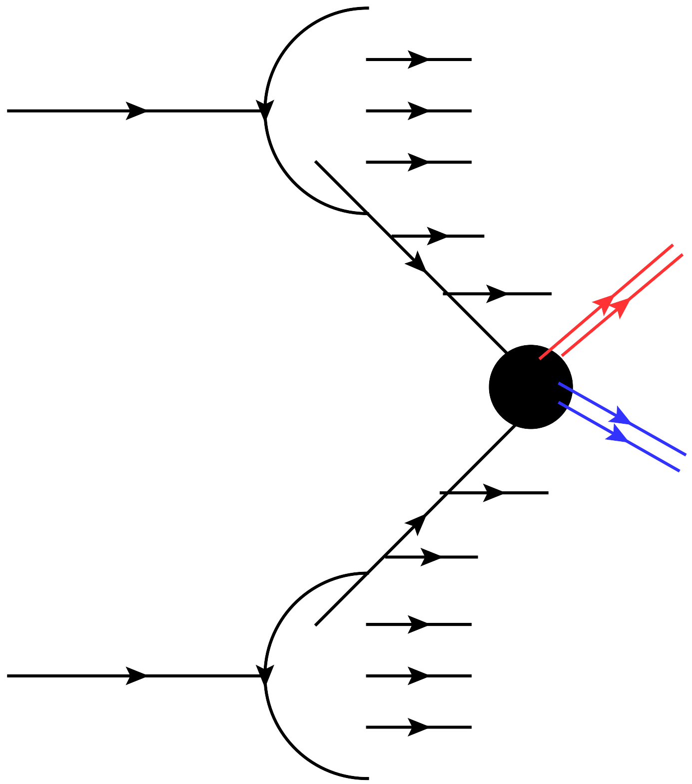


required by AGK

As in soft diffraction:
additional chains fill the gap.

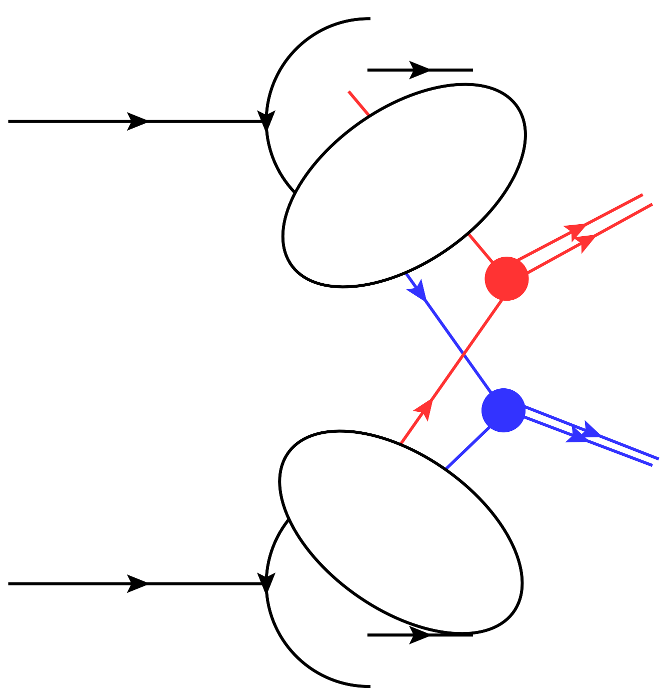
Leaves the eikonal approximation!

Double parton cross sections:



$$d\sigma = \sum_{i_1 i_2} \int dx_1 dx_2 f_{i_1}(x_1, \mu) d\hat{\sigma}_{i_1 i_2 \to 2\,jet}(x_1, x_2, \mu; p_1, Y_1, p_2, Y_2) f_{i_2}(x_2, \mu)$$

single parton (no rescattering)



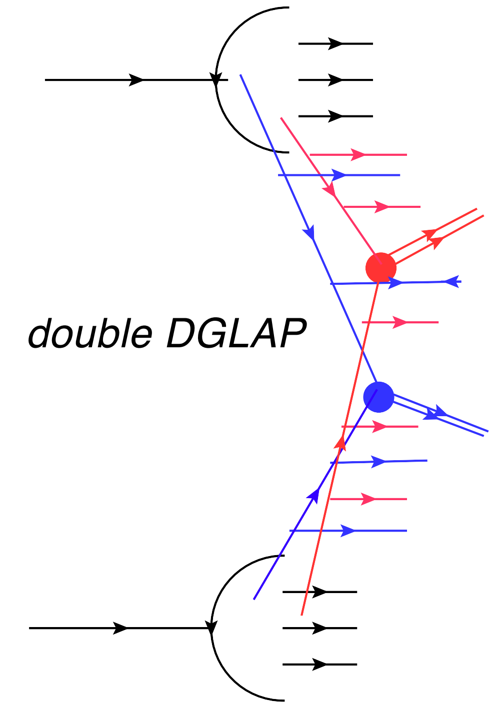
$$d\sigma^{DP} = \frac{m}{\sigma_{eff}} \sum_{i_1, j_1, i_2, j_2} \int dx_1 dy_1 dx_2 dy_2 H_{i_1 j_1}(x_1, y_1, \mu_a, \mu_b)$$

$$d\hat{\sigma}_{i_1 i_2 \to\, jet}(x_1, y_1, \mu_a; p_1, Y_1) d\hat{\sigma}_{j_1 j_2 \to jet}(y_2, y_2, \mu_b; p_2, Y_2) H_{i_2 j_2}(x_2, y_2, \mu_a, \mu_b)$$

correction: double parton (no rescattering)

AGK

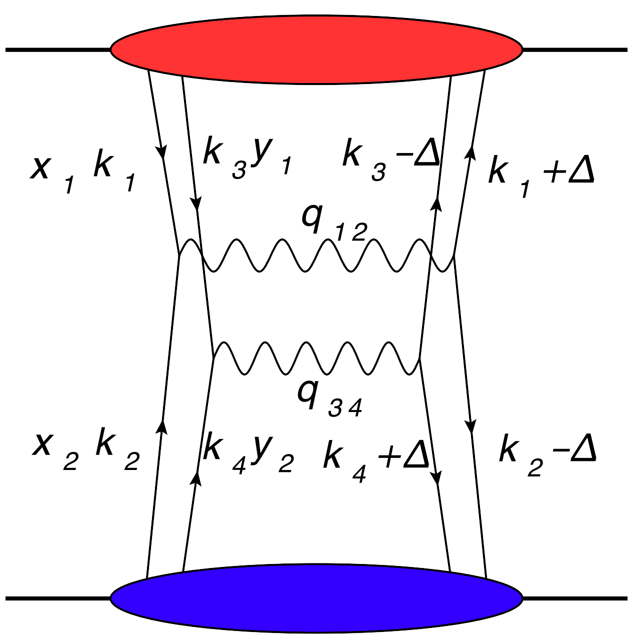
Cross sections have been calculated (e.g. double J/Psi)



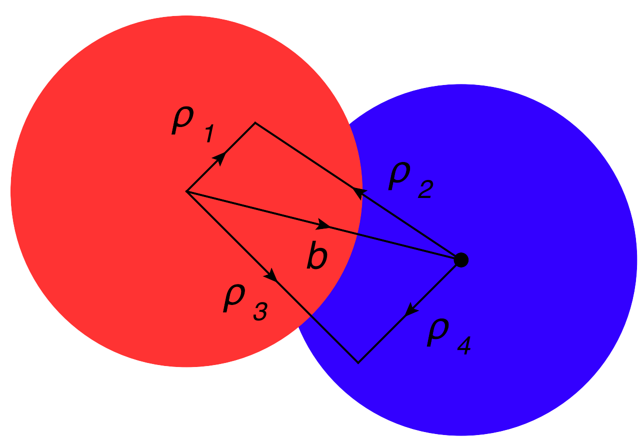
Theoretical questions being addressed:

Evolution of double parton densities:

- double DGLAP misses transverse dependence
- corrections: correlations, splitting



a

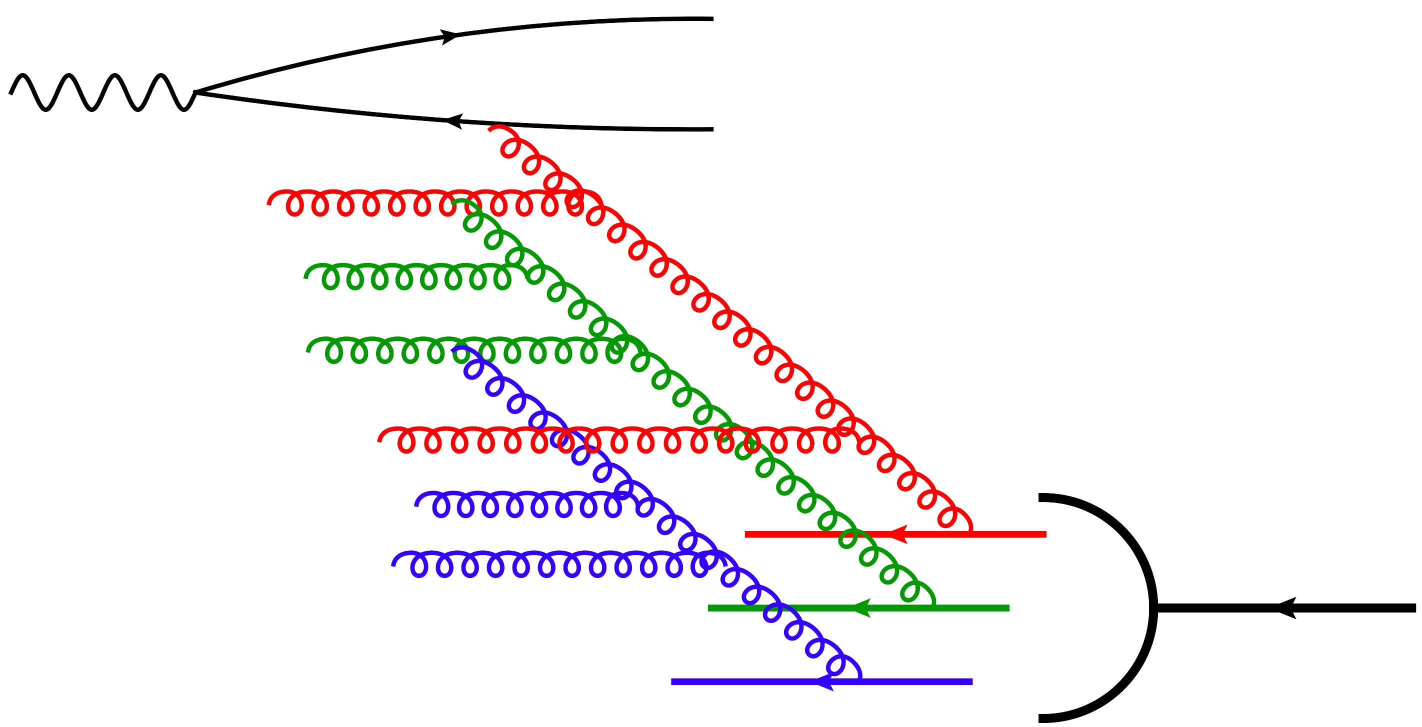


b

- Higher twist suppression: only after integration over jet momenta

Saturation

Saturation was first discussed in the context of small-x gluon densities at HERA, later on it started to play a major role in ion collisions (color glass condensate)



several chains recombinations

high gluon density saturation scale

nonlinear BK-equation

Saturation scale $Q_s^2 = Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$ $\quad Q_s \approx 1 GeV$ at $x = 10^{-5}$

Evidence in ep scattering :

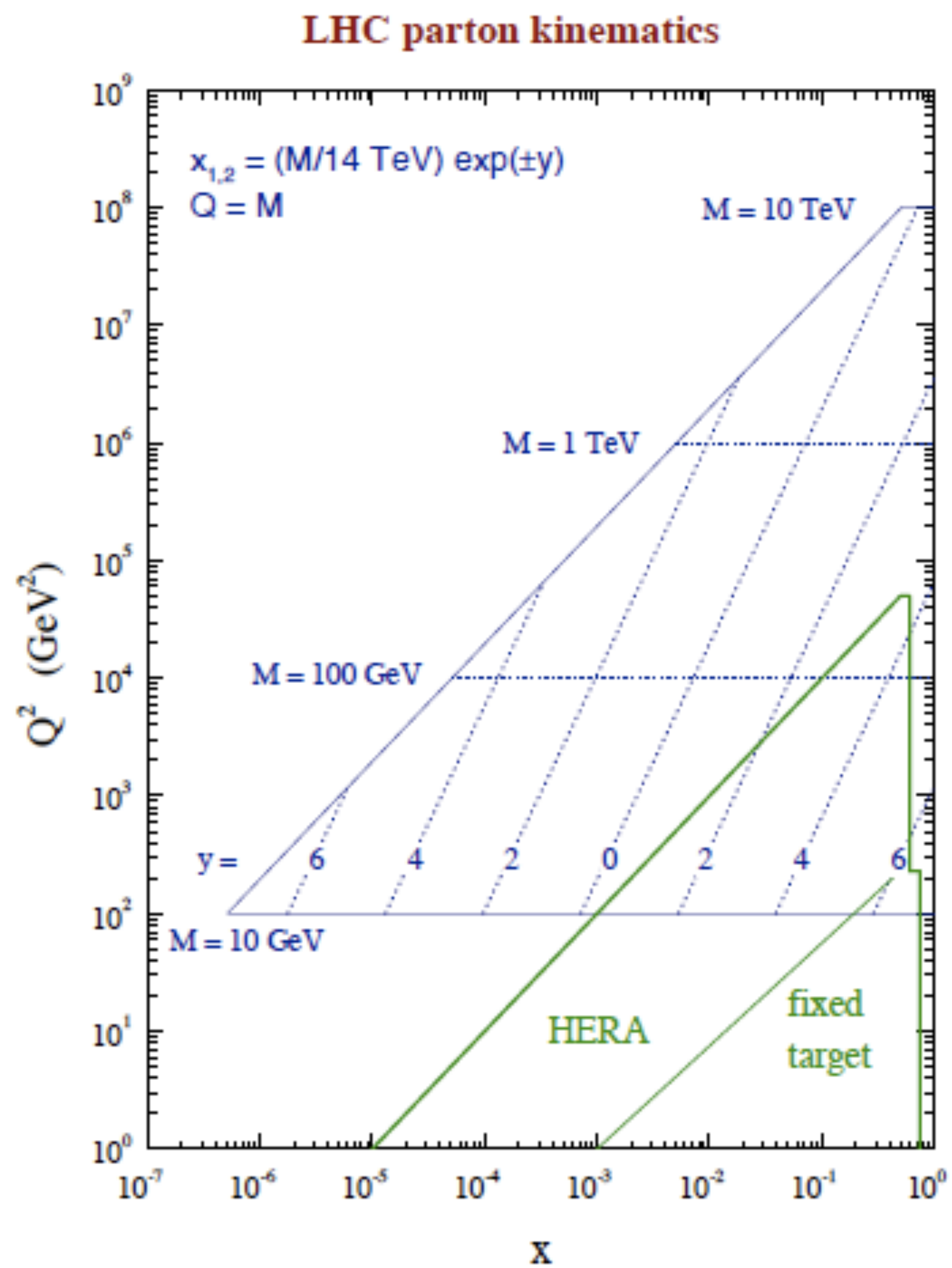
- geometric scaling
- successful models for F_2
- ratio of diffractive to total cross section

Saturation at the LHC (in pp):
larger kinematic region

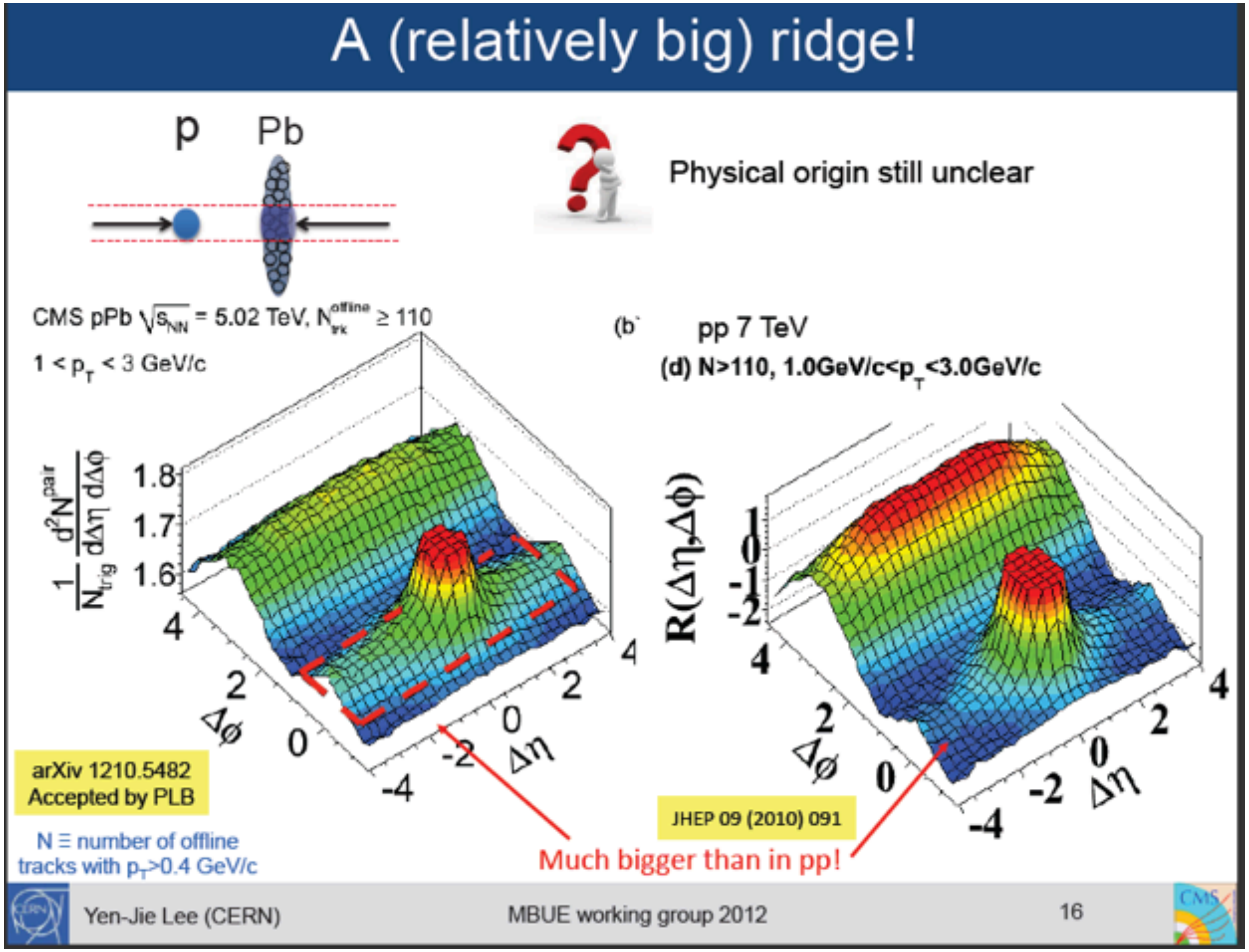
Potential signals:

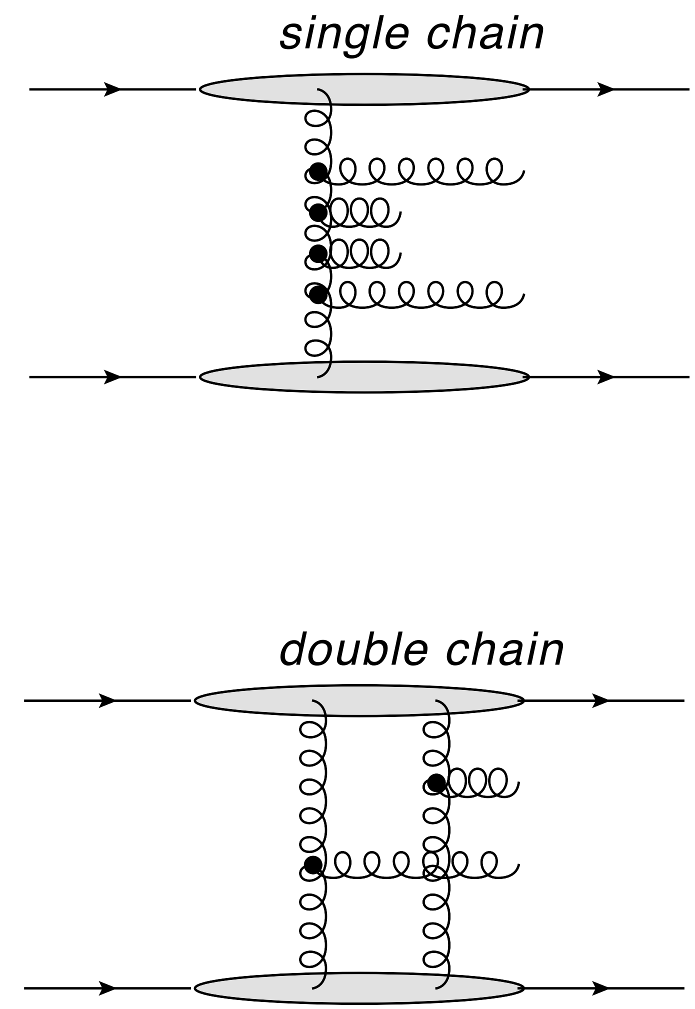
- <pt>, <n>?
- Ridge effect?
- Drell Yan in forward region

much more in AA and pA:
larger saturation scale



Ridge effect in pp and pA collisions:
two particle correlation, azimuthal correlations





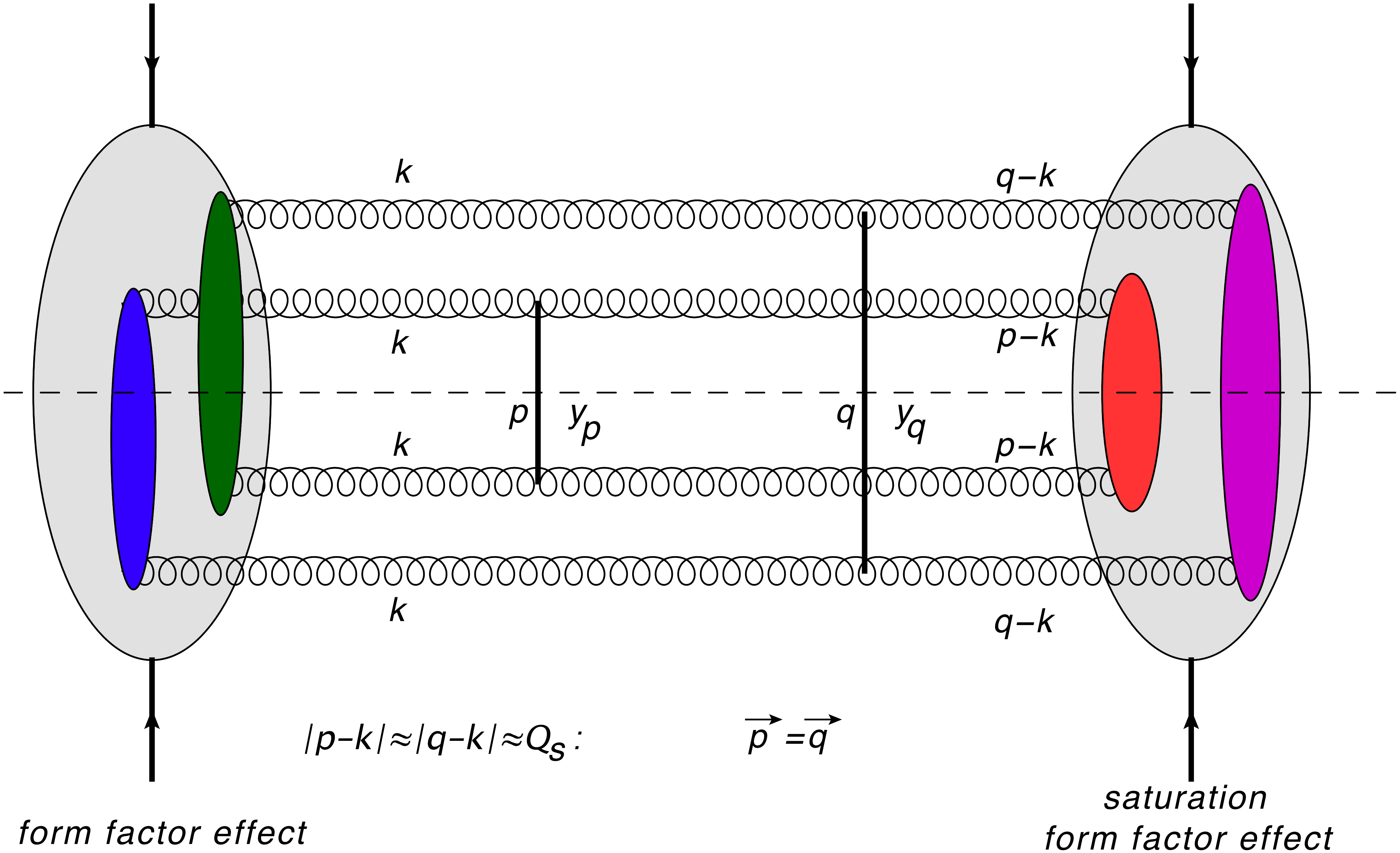
Saturation is a strong candidate:

- strong field: high density
- low p_T : saturation momentum

$$x = 10^{-5} \rightarrow Q_s \approx 1GeV$$

- angular correlation: need extra ingredient

Dusling, Venugopalan

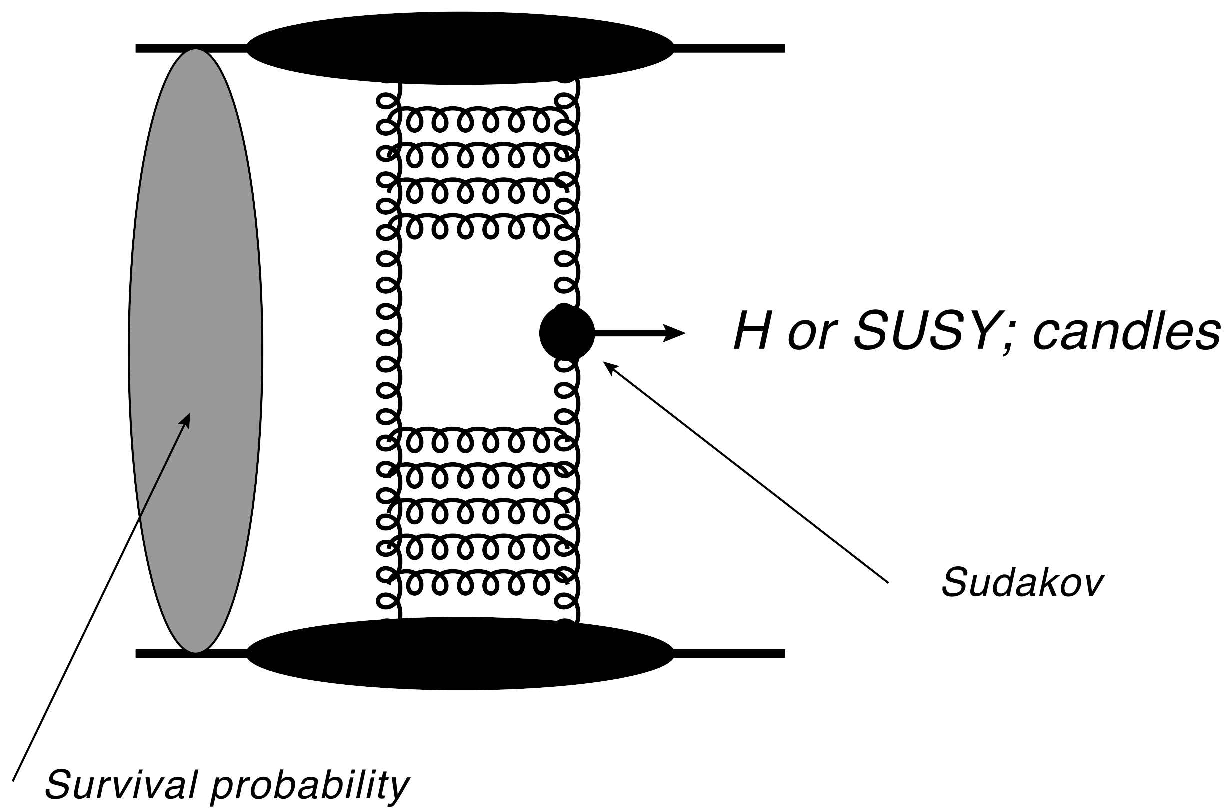


Difference between pp and pA
is in the details of saturation

Diffractive/rapidity gap processes

Central exclusive production (CEP): forward spectrometer

Topic of intense discussion (Bialas,Landshoff; ... ;Durham group)



Needed:
NLO calculation
of hard subprocess

$$\sigma(pp \to p + H + p) \sim \frac{\langle S^2 \rangle}{B^2} \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2$$

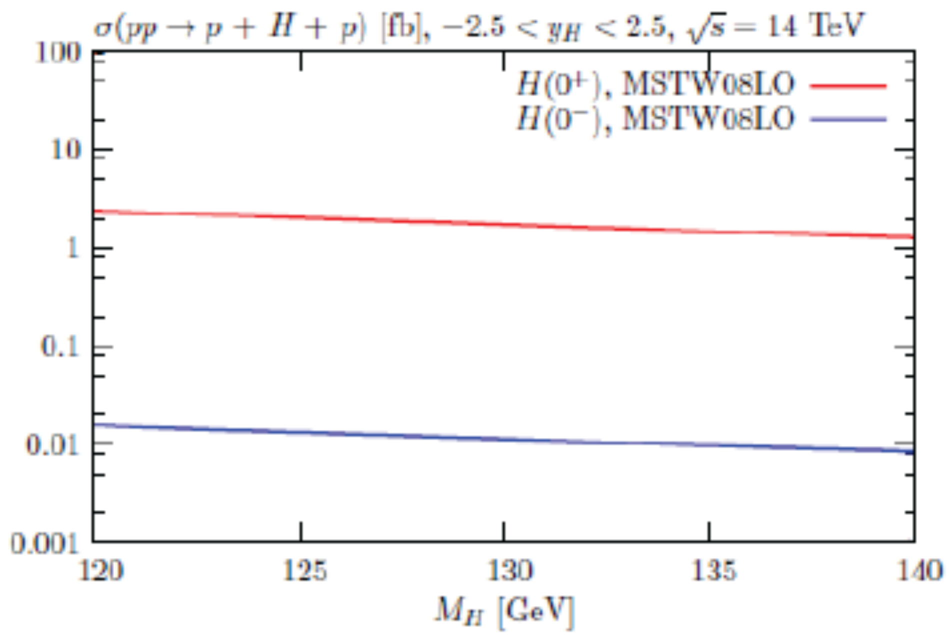
Experimental aspects: clean signal, precise mass determination
Theoretical ingredients: parton densities, Sudakov factor, suppression rules
survival probability

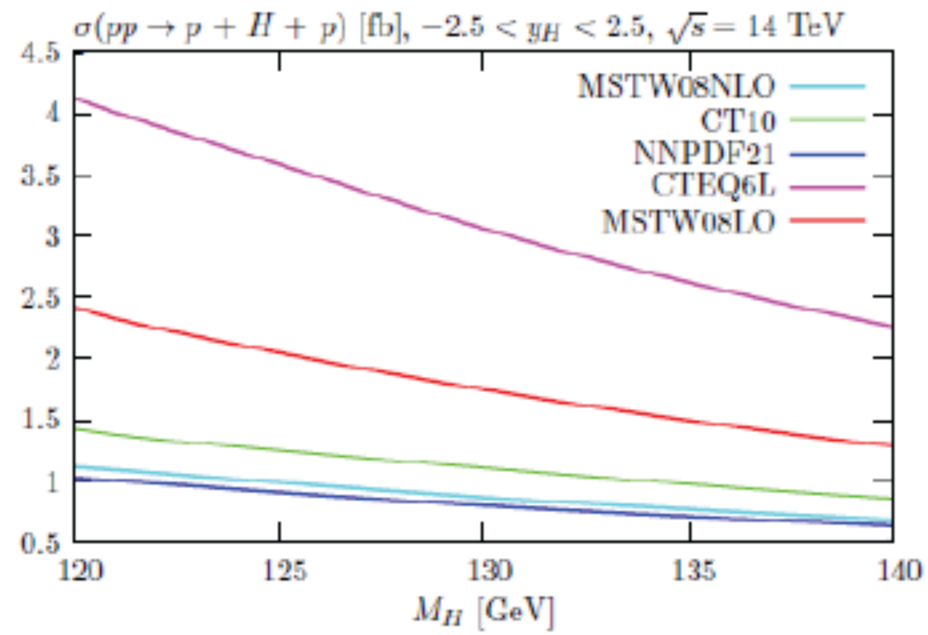
SuperCHIC

(ExHuME-05) .

Higgs Boson: cross section predictions (Halfway)

Khoze





$<S_{tot}^2>=0.02$

- Cross section $\sim$ fbs, i.e. roughly 4 orders of mag. lower than inclusive case (price paid for exclusivity).
- CEP of a CP–odd Higgs suppressed by $\sigma(0^-)/\sigma(0^+) \sim 1/100 \to$ with just a few signal events, the Higgs quantum numbers can be determined (does not rely on coupling to weak bosons).

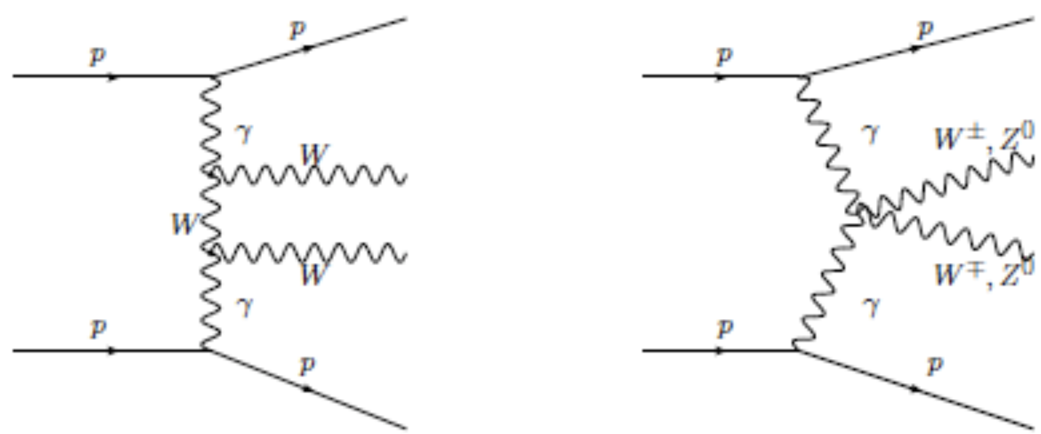
Recent developments:

- Diphoton seen at Tevatron
- double meson states, resonances
- χ_c production

} Learn about CEP dynamics

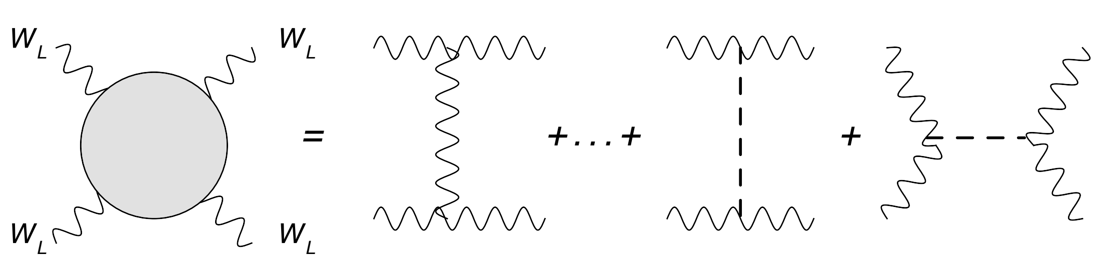
- Two photon physics:

$$W_{\gamma\gamma} \leq 1.8\,TeV$$



anomalous quartic coupling

Figure 1: Feynman diagrams for the signal (triple gauge couplings on the left, quartic on the right)



VV-scattering : unitarity problem

Conclusions

Fundamental problem in 'nonperturbative high energy QCD':
understand the transition and the large distance region

small ➡ large transverse distance region

Small: BFKL, DGLAP

Large: total, elastic cross section
(Pomeron)

most final states sensitive to both, e.g.

- multiple interactions
- saturation
- diffraction

their study provides the necessary theoretical help