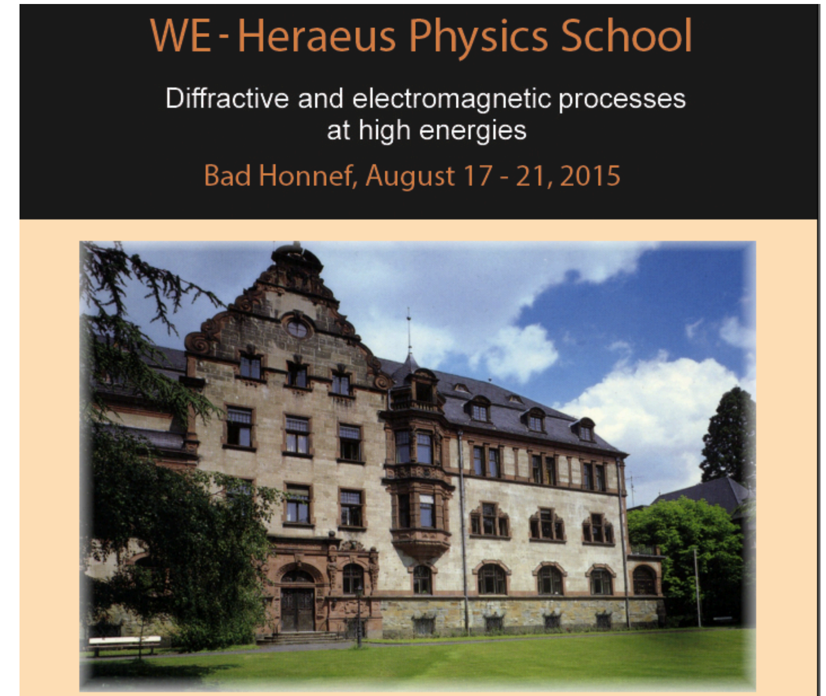
WE-Heraeus Physics School

Diffractive and electromagnetic processes
at high energies

Bad Honnef, August 17 - 21, 2015



Theory of Diffraction

➛ Jenkovszky's talk

Jochen Bartels, Hamburg Univérsity

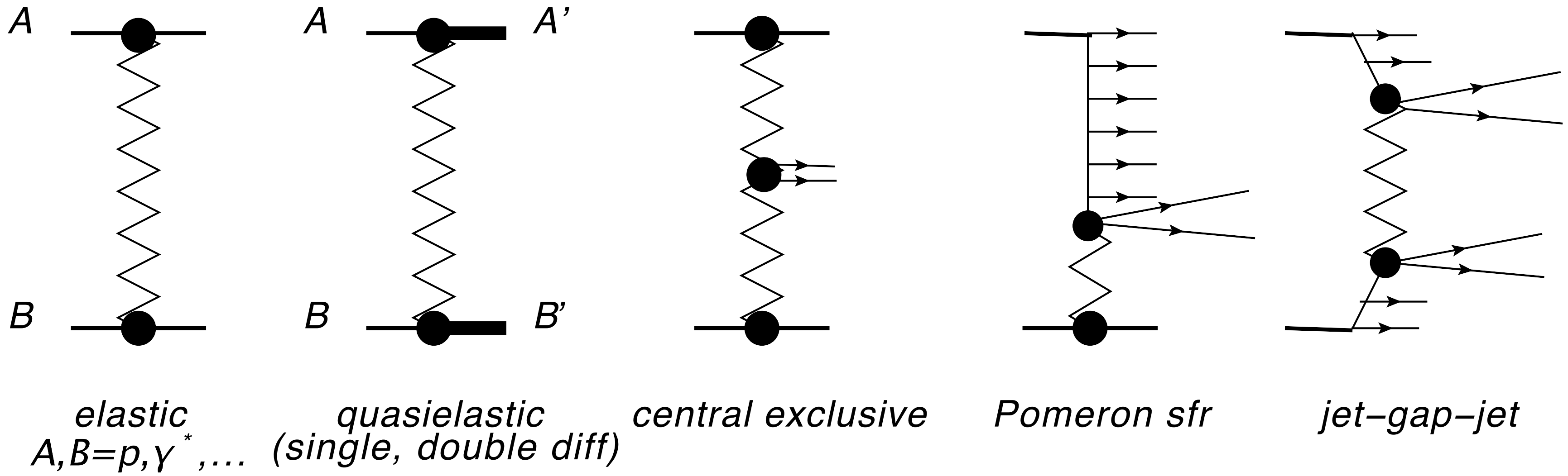
Part 1: Overview of basic concepts
- Regge theory (soft)
- BFKL (hard)
- multiparton interaction, survival factor

Part 2: a new theoretical attempt -
renormalization group analysis

Collaboration with C.Contreras and G.P.Vacca,
arXiv:1411.6670 and in preparation

Introduction

Examples of diffractive final states:



"Experimental definition": empty region, rapidity gap

Orava

"Theoretical definition": vacuum quantum number exchange, Pomeron

Only pieces of a theory. A useful guideline:
transverse momentum scale ↔ transverse distances ('hard', 'soft')

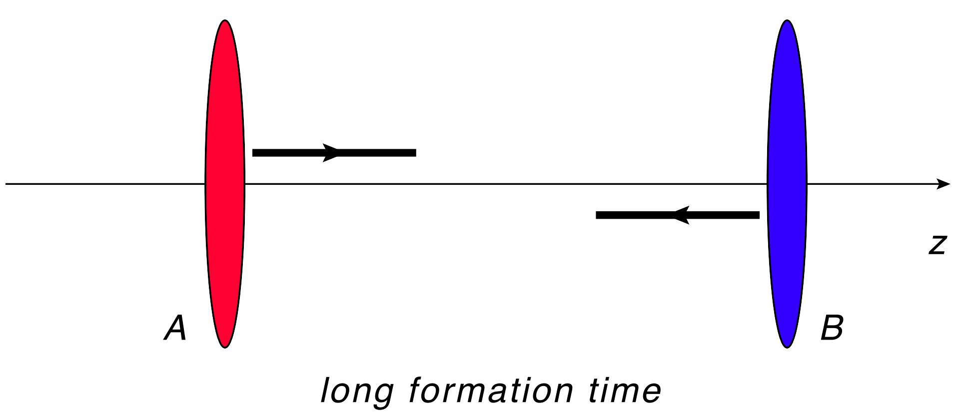
In the following:
1) Pomeron in a 'hard' environment
2) Pomeron in a 'soft' environment
3) Survival factor

In the final part: attempt to connect the two cases

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

time, longitudinal direction

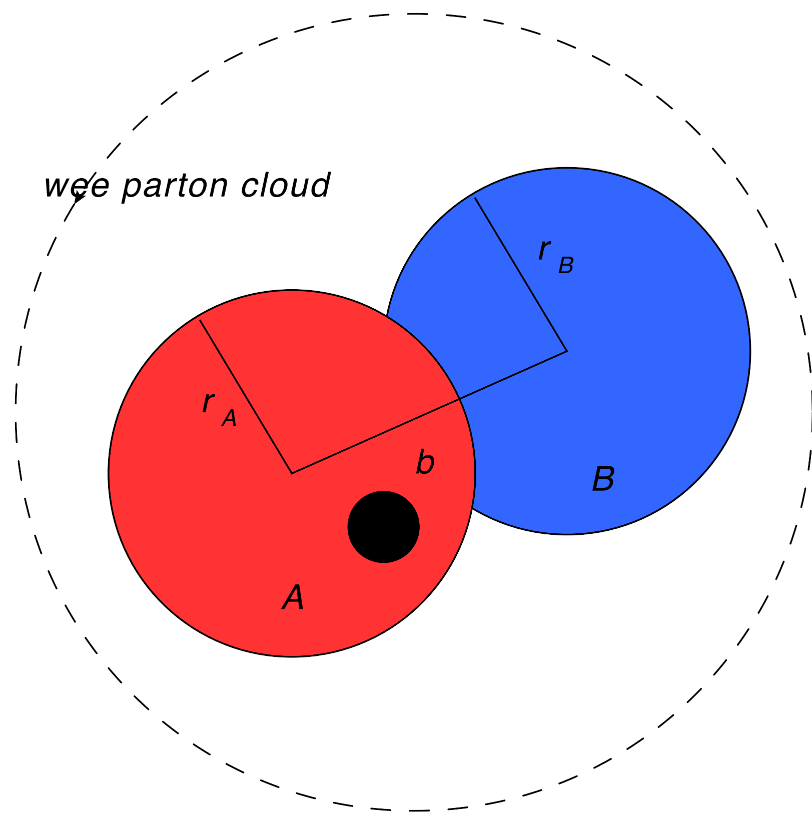
long extension along
incoming direction

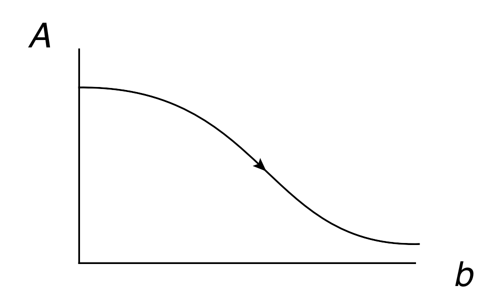


transverse plane

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

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



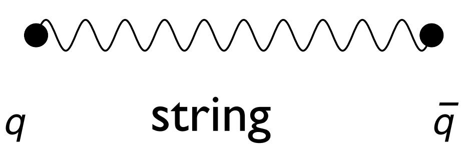


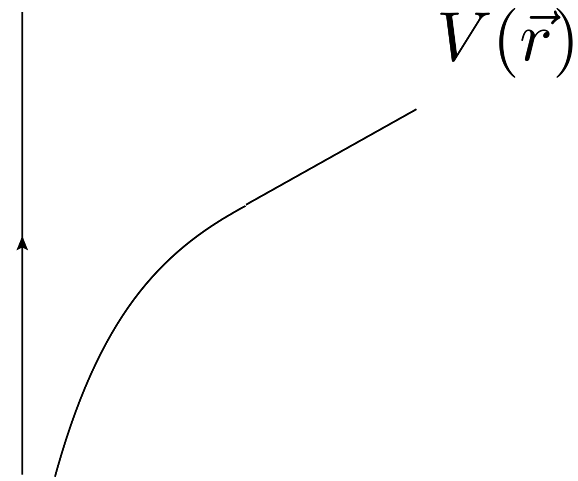
nonperturbative

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

short distance - long distance:

static potential:

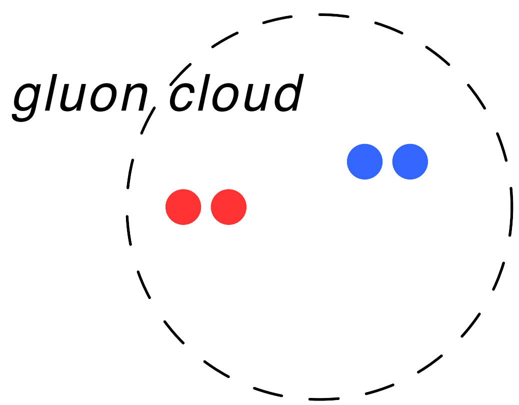


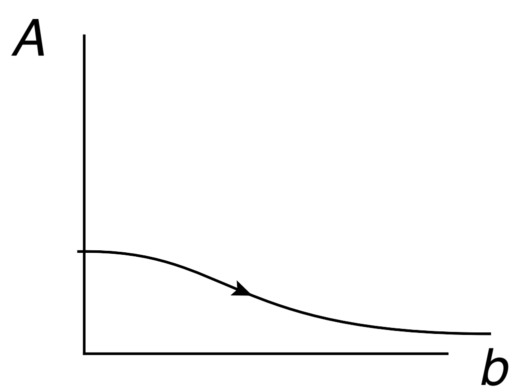


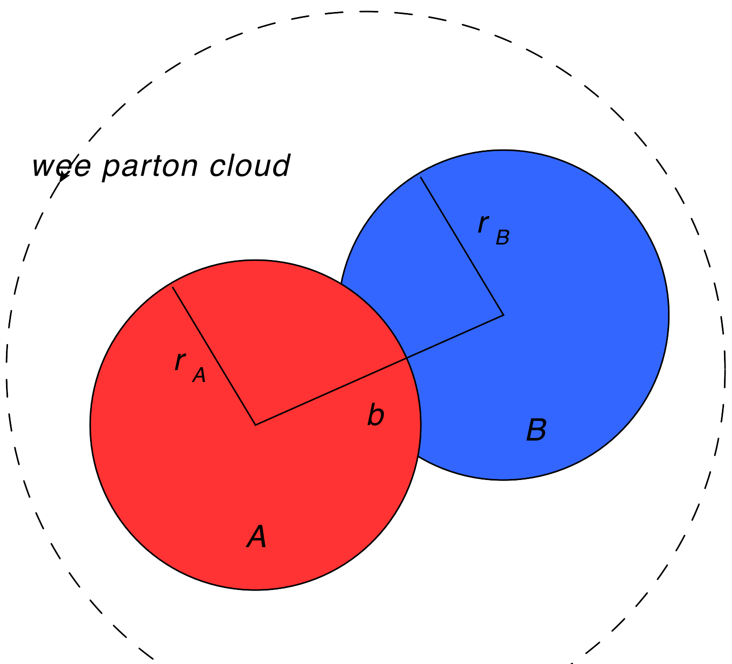
short distance:
coulomb potential

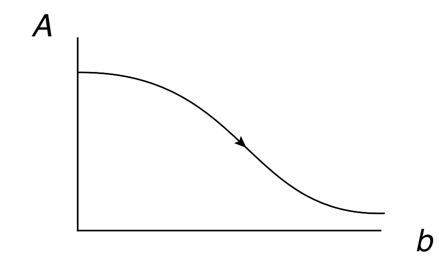
large distance:
linear potential, string tension

high energy scattering :
energy dependence of transverse picture









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

cloud grows logarithmically with energy

The situation at the LHC:

- hard processes provide environment for ‘hard’ Pomeron

- total cross section, elastic scattering probes small and large distances

- most processes lie in between; in particular:

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

In the following:
1) Pomeron in a ‘soft’ environment
2) Pomeron in a ‘hard’ environment
3) Survival factor

In the final part: attempt to connect the two cases

Pomeron in a 'Soft' environment: pp elastic scattering

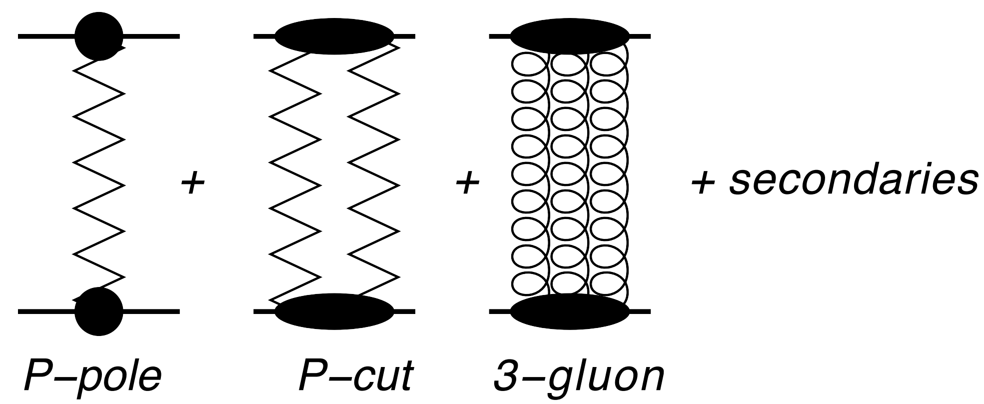
There exist different theoretical descriptions,
most of them based upon Regge theory (poles and cuts).
Only two examples:

1) Donnachie, Landshoff PL 2013

No hard Pomeron contribution.
Soft Pomeron parameters:

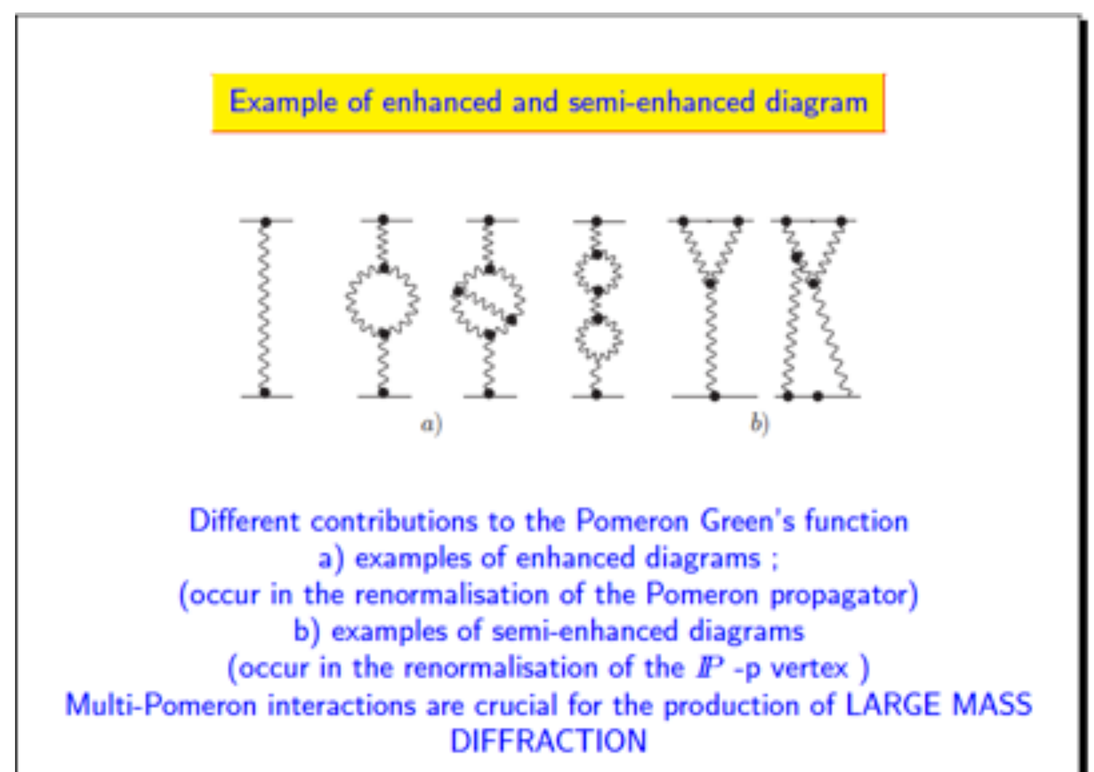
$$\alpha_p(0) - 1 = 0.110, \;\; \alpha'_p = 0.165\, GeV^{-2}$$

3-gluons: dips in $d\sigma_{el}/dt$ (odderon)



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

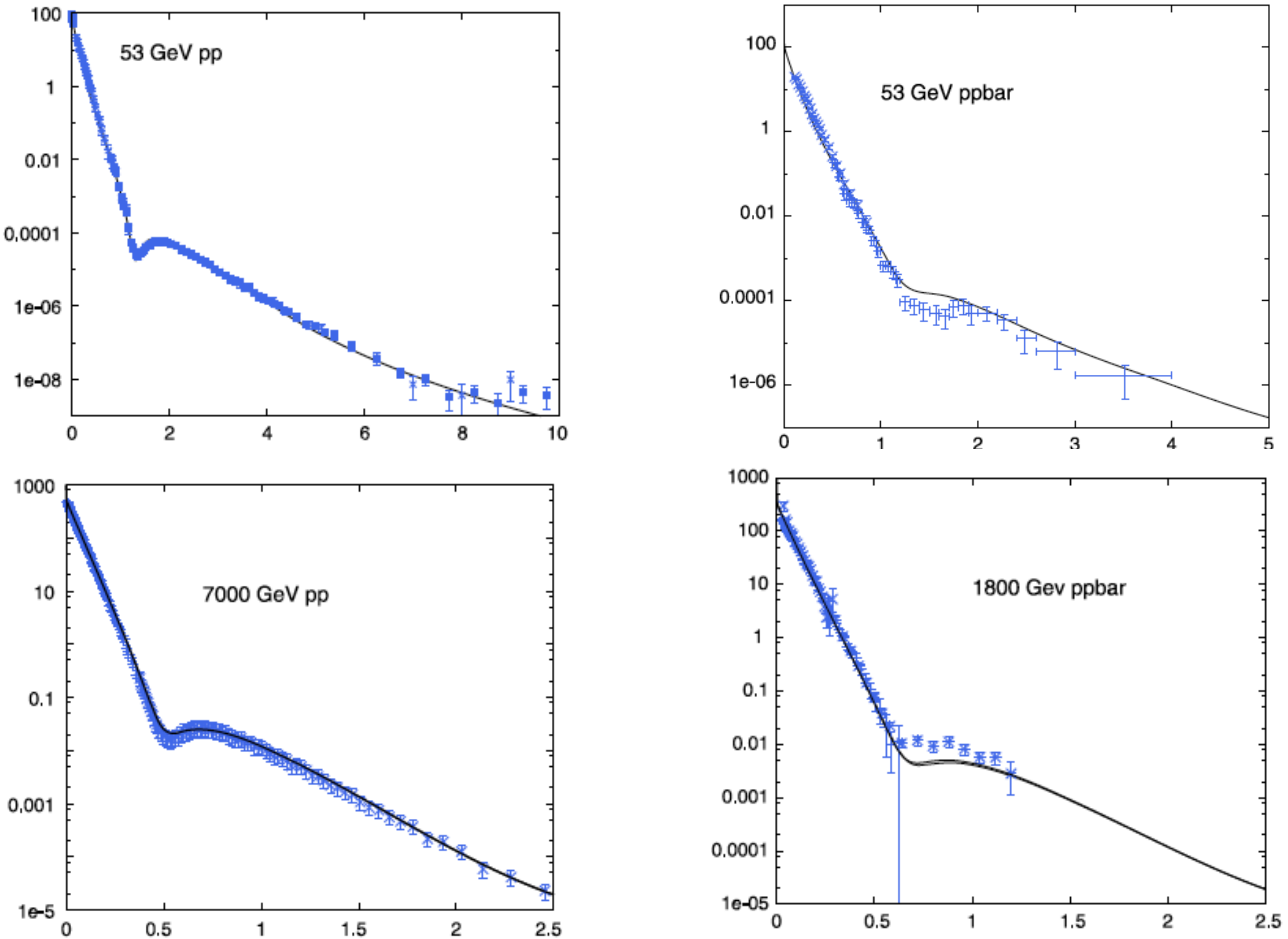
Regge cuts, reggeon field theory
Pomeron couplings: from fit to data:



Dips in $d\sigma_{el}/dt$:

from DL PL 2013

Jenkovszky's talk



Evidence for Odderon?

What is the ‘theory’ behind this:

Regge poles + Regge cuts with phenomenological parameters

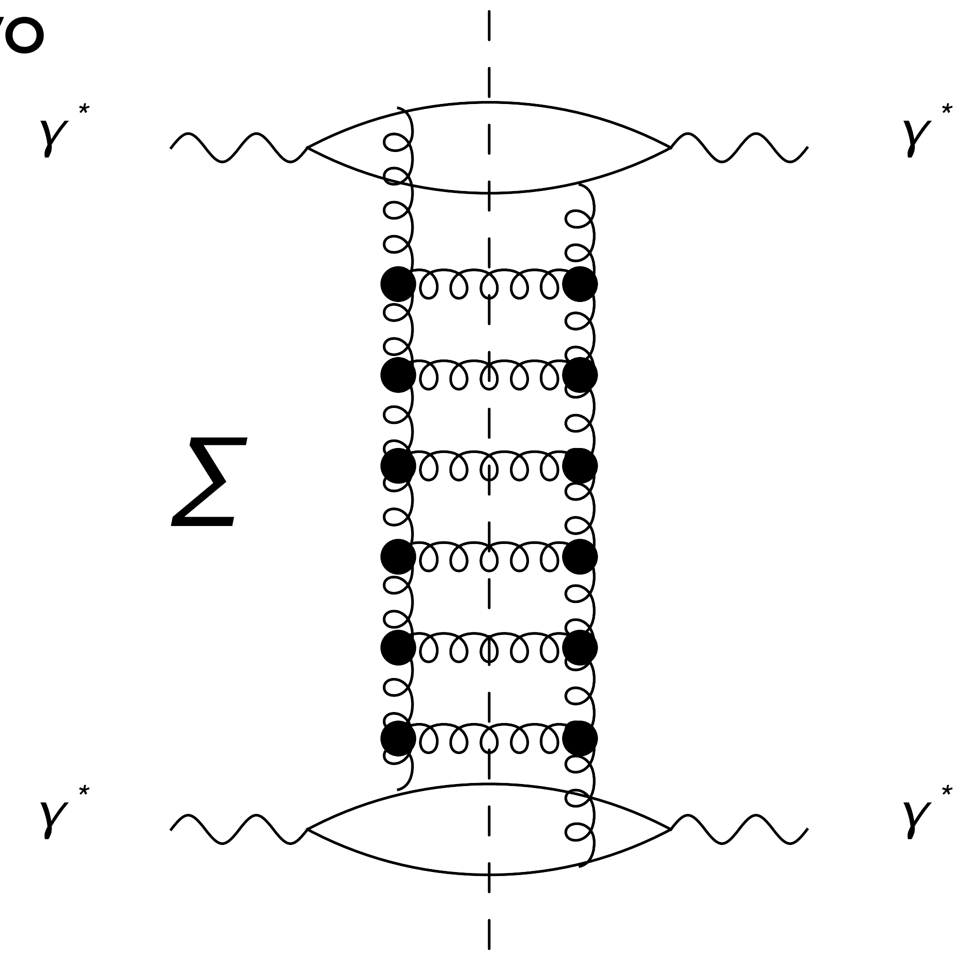
support for an ‘effective‘ field theory (field theory in 2+1 dimensions: Pomeron with intercept one is a massless particle!)

Pomeron in a 'hard' environment: BFKL

Balitsky,Fadin,Kuraev, Lipatov 1975/76

Elastic scattering of two small dipoles

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

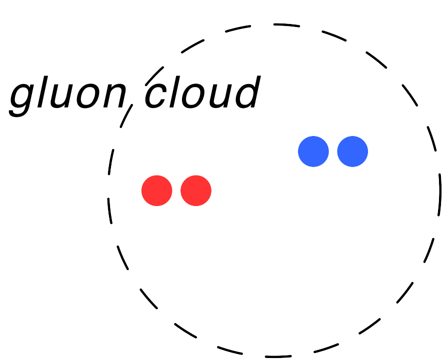


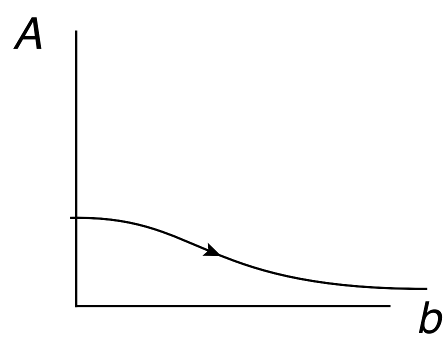
sum over gluon production

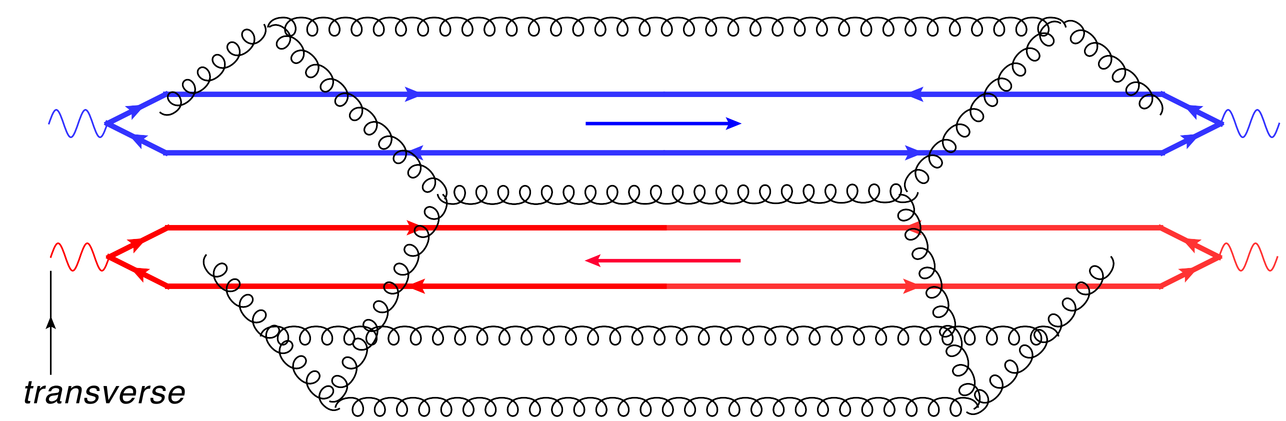
Important properties:

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

- strong growth in transverse direction



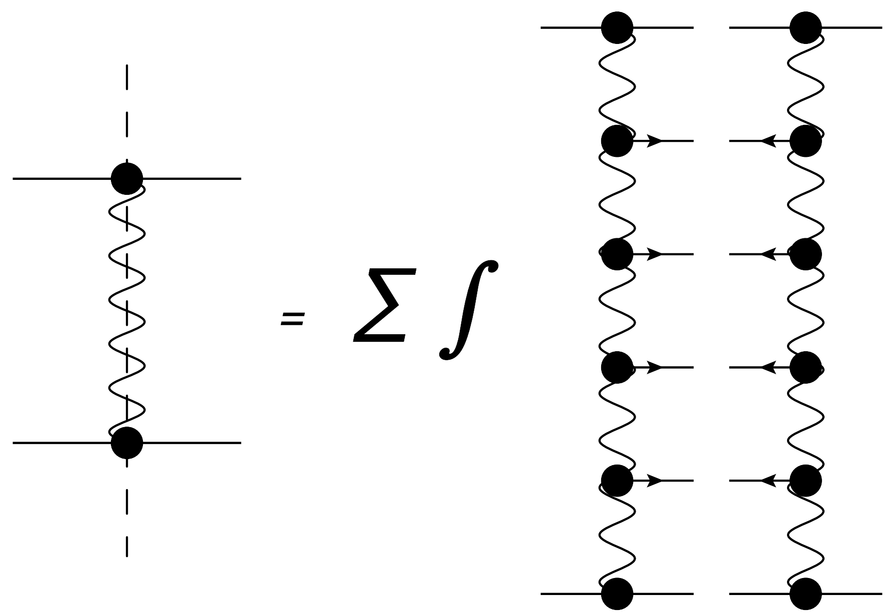




More remarkable properties of the BFKL Pomeron:

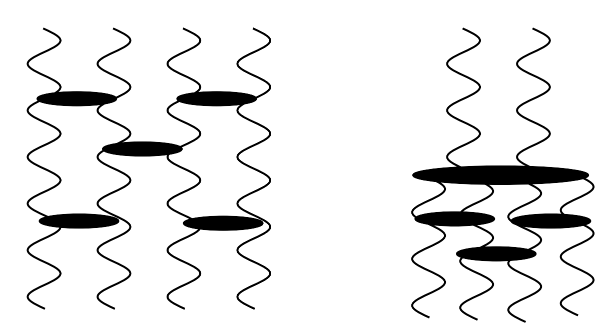
1) unitarity:
nonlinear equations
bootstrap equation

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



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

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



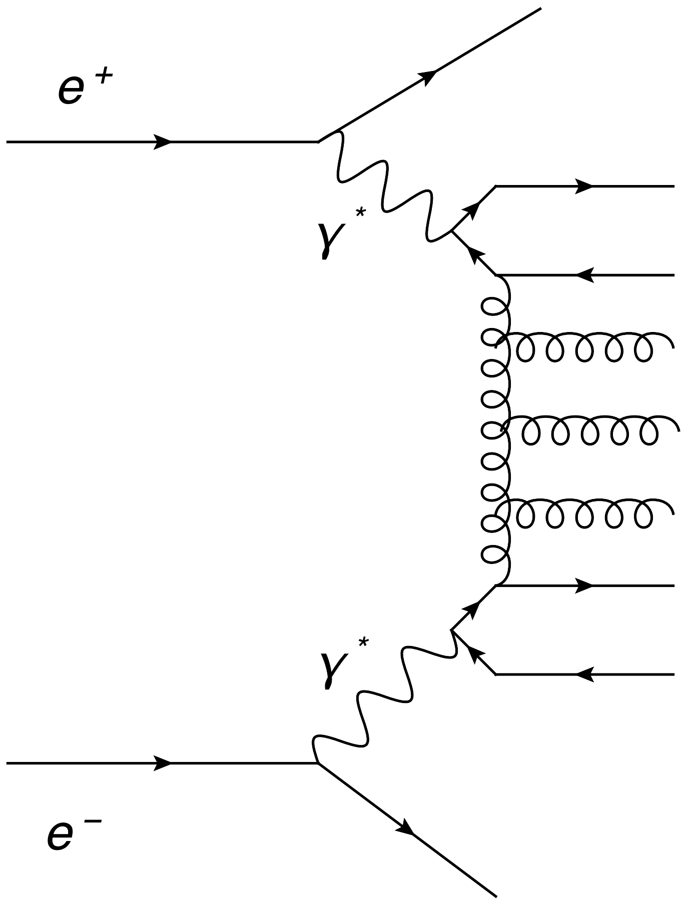
4) AdS/CFT, gravity;
electroweak Pomeron; unitarity problem

How to test this calculation:

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

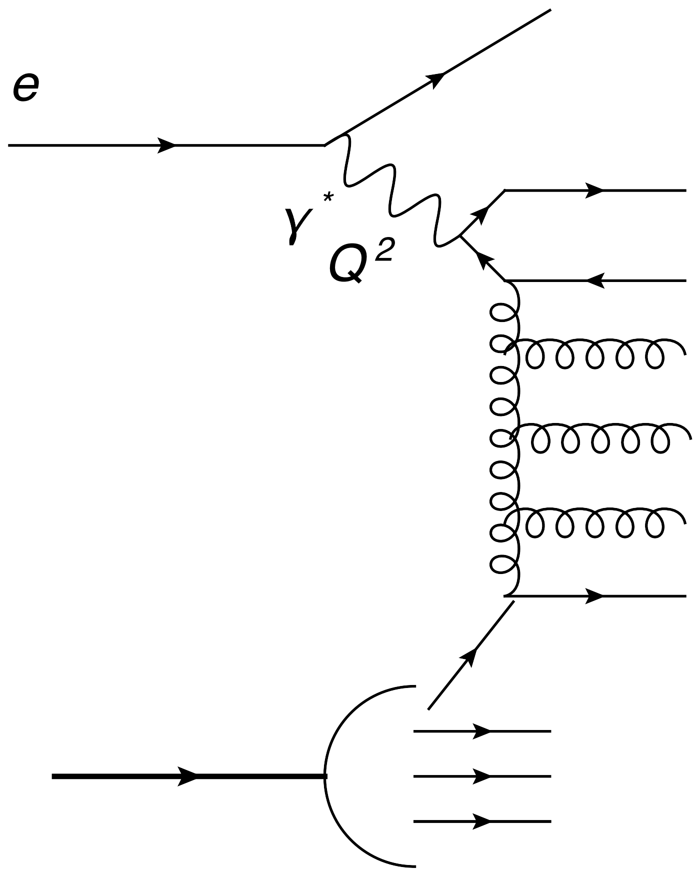
Mueller-Navelet jets
in pp-scattering (Tevatron, LHC)

Papa's talk



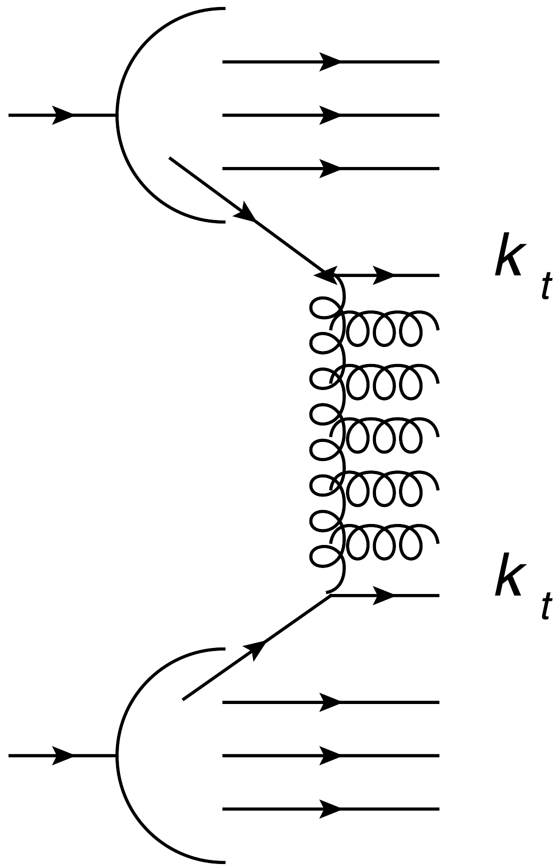
e^+e^-

ok, not fully convincing



HERA, forward jets

ok



LHC, Mueller-Navelet

successes,
but need more data

New formulation of BFKL (HERA): discrete Regge poles

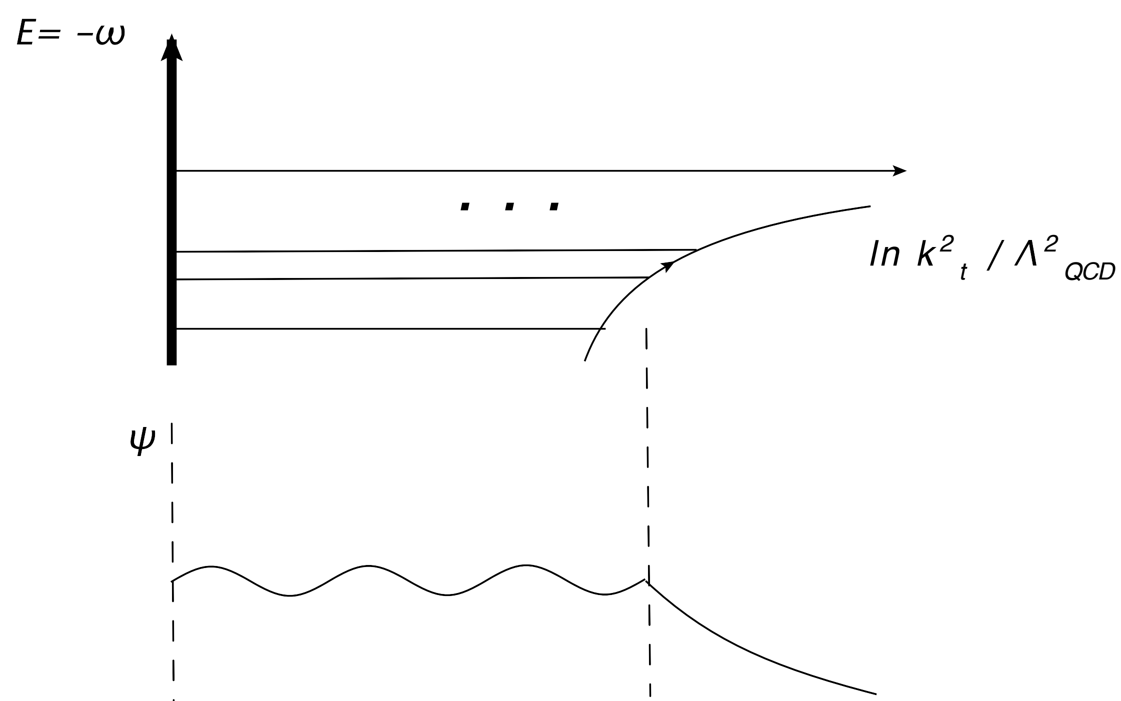
Kowalski, Ross, Lipatov

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

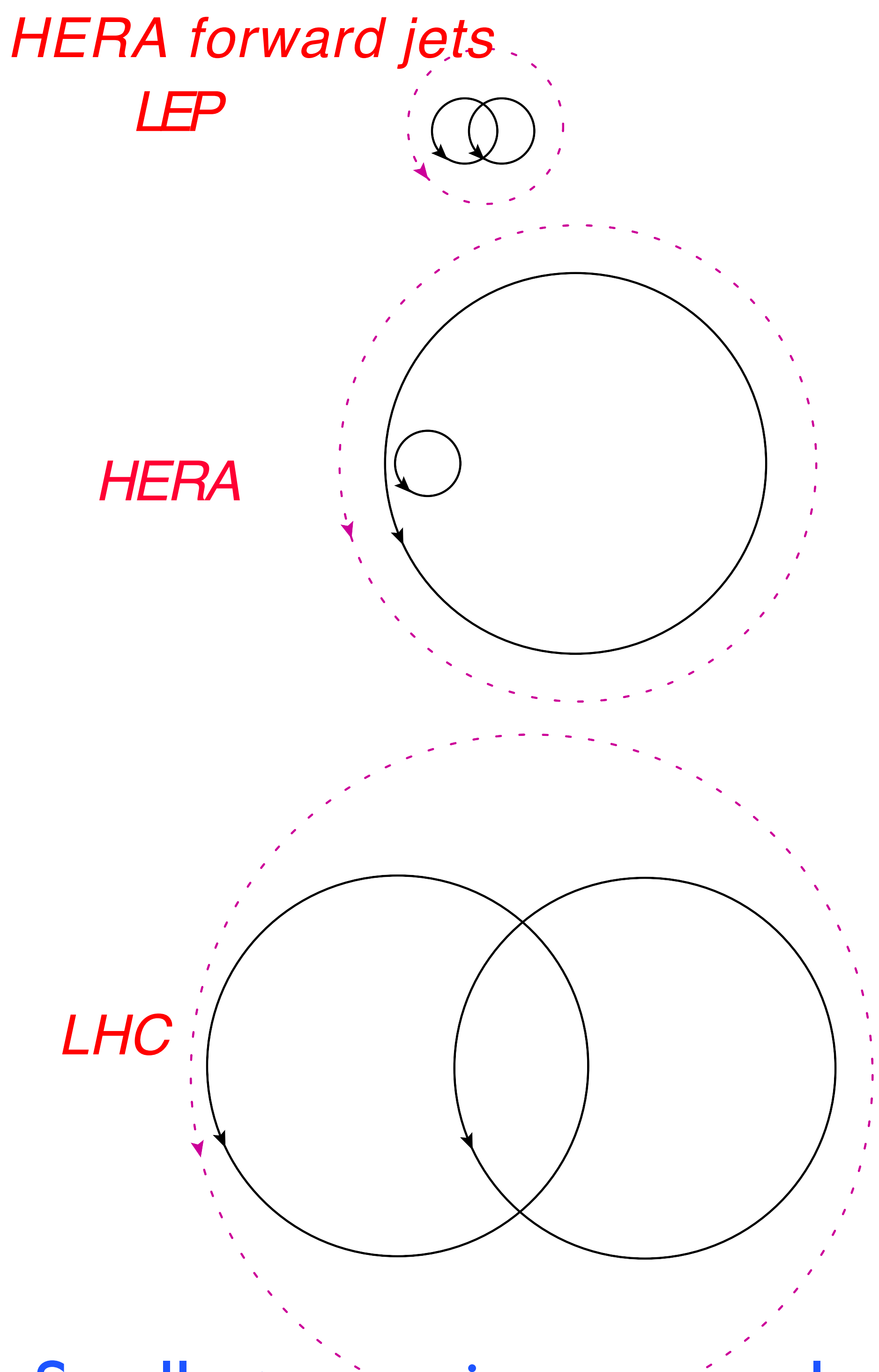
Fit to HERA data.
Signal of new physics?

Summary so far:

1) Regge structure seen both in soft and hard environement,

2) parameters are different: Pomeron intercept.

Some systematics:



$\gamma^* \gamma^* \quad \sigma_{tot} \approx s^{\omega_{BFKL}}$

$\gamma^* p \quad \sigma_{tot} \approx (W^2)^{\lambda}$

$p\, p \quad \sigma_{tot} \approx s^{0.08}$

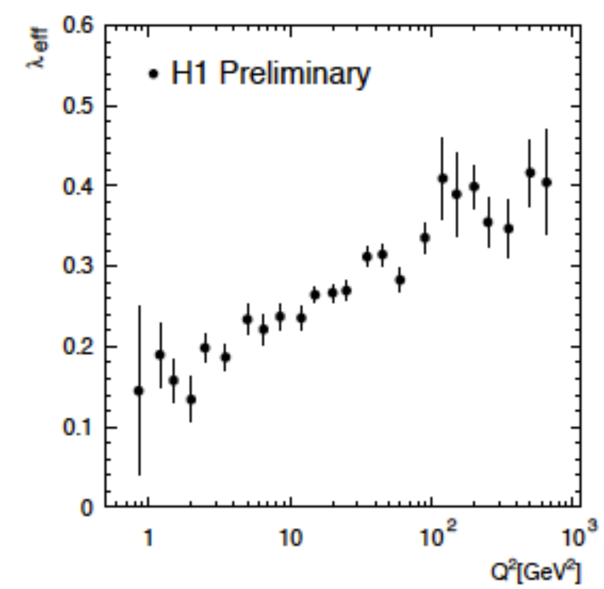


Figure 6: The slope $\lambda_{\rm eff}$ of F_2 as a function of Q^2 .

Even better:
diffractive vector production at HERA

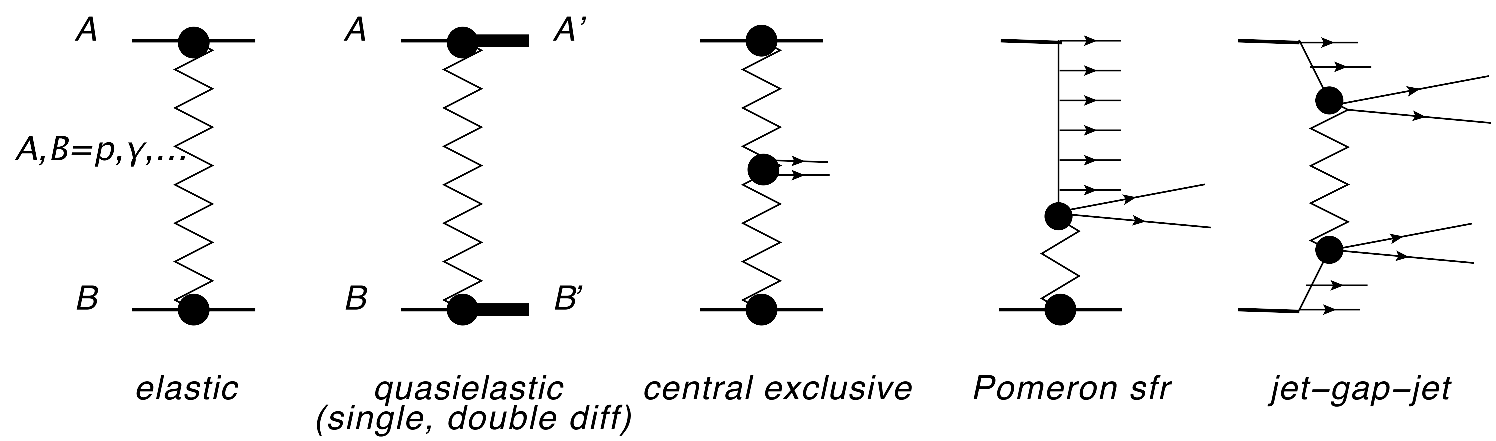
Levonian's talkt

Small: strong rise ---- large: slow rise

Other diffractive processes: survival probability, MPI

In inelastic
diffractive processes:

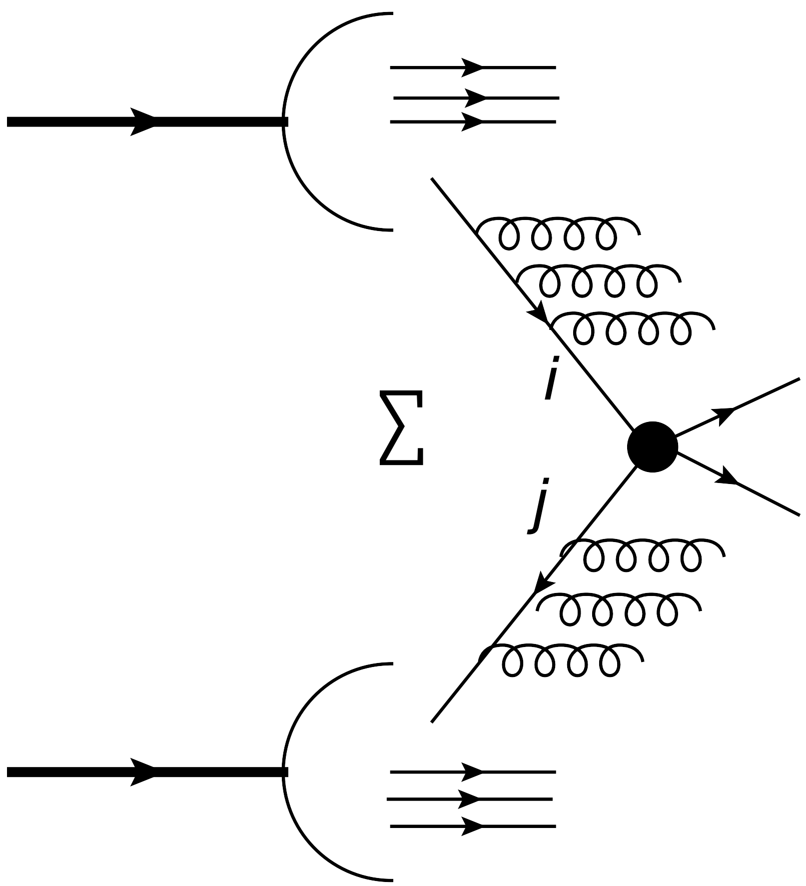
cannot simply insert
Pomeron (hard or soft):



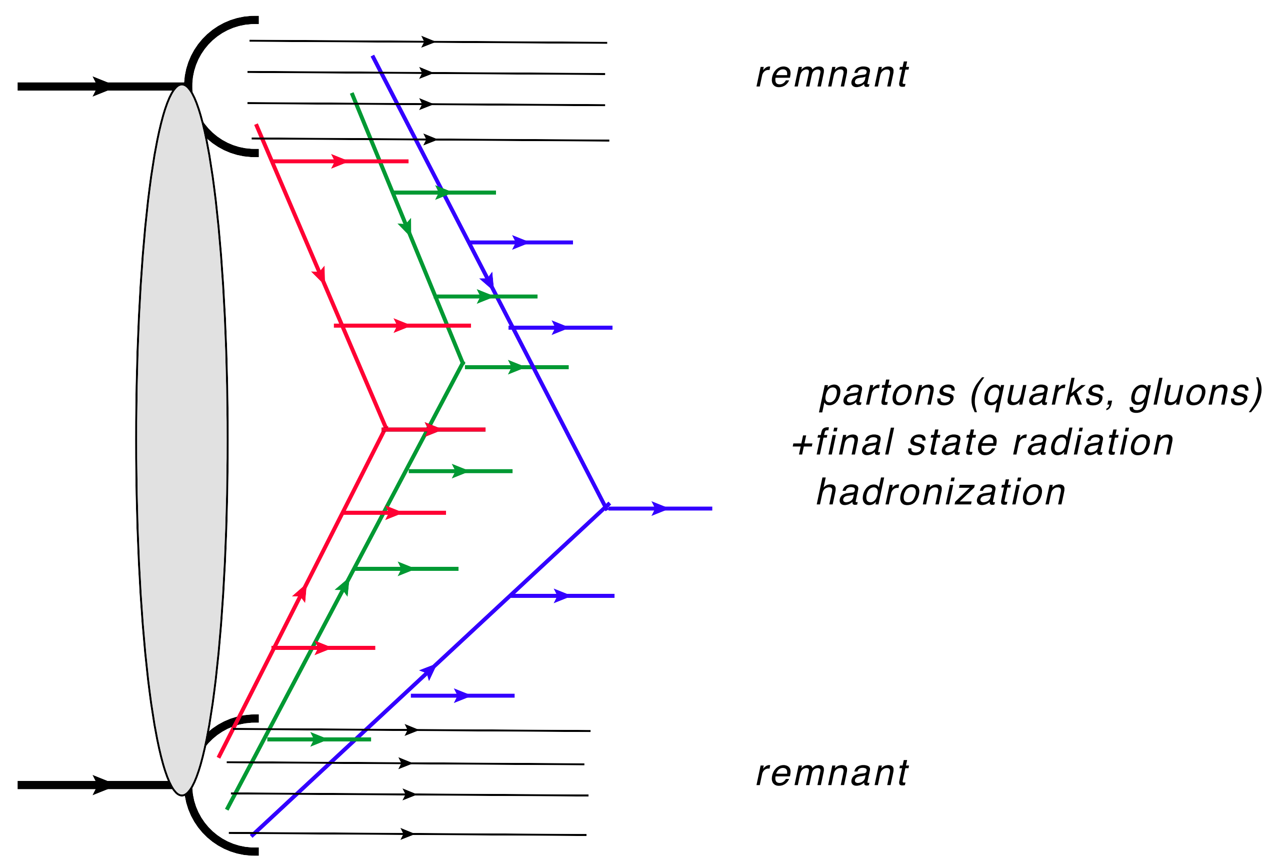
MPI, survival factor

Inclusive cross section vs.underlying event:

Inclusive cross section



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



Mostly based upon eikonal formula

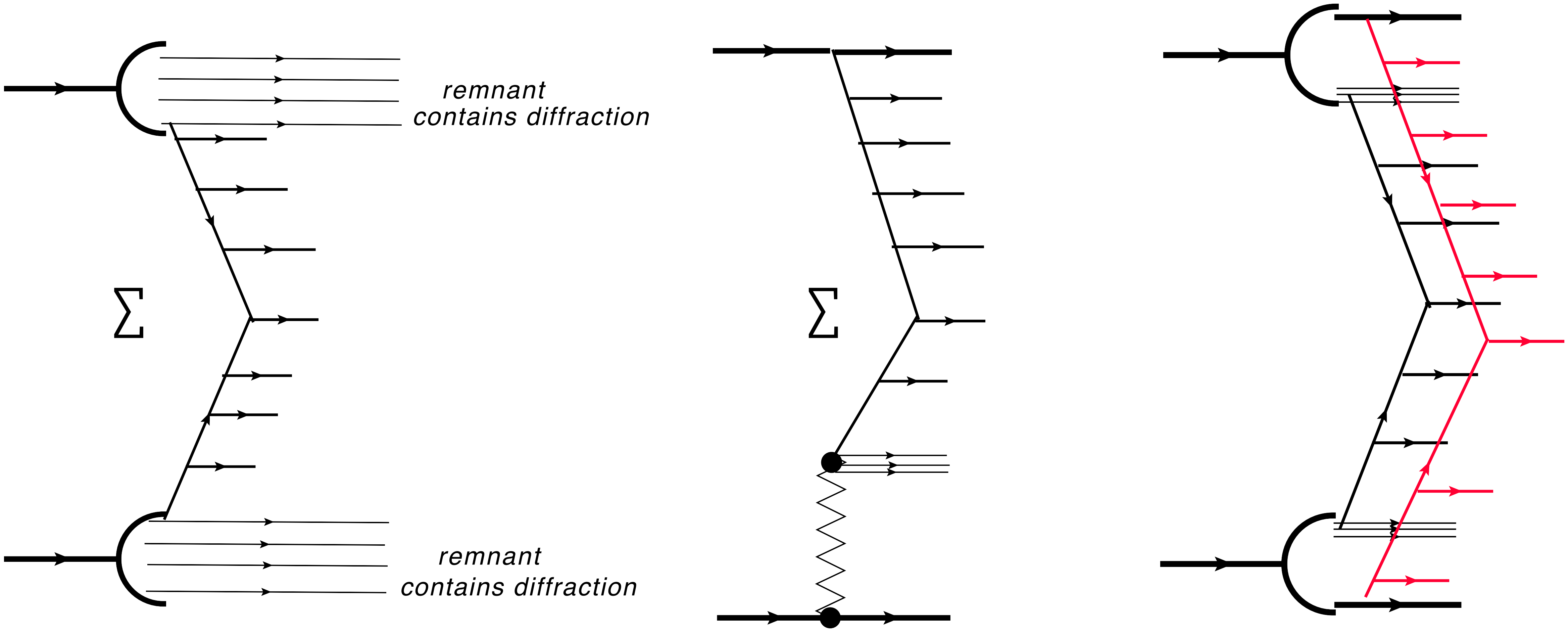
Pictures have slightly different meaning:

event ⟶ cross section involves summation

Cancellations (collinear factorization, AGK)

Important consisteny check!

Where is diffraction (rapidity gaps)?
DGLAP and diffraction:

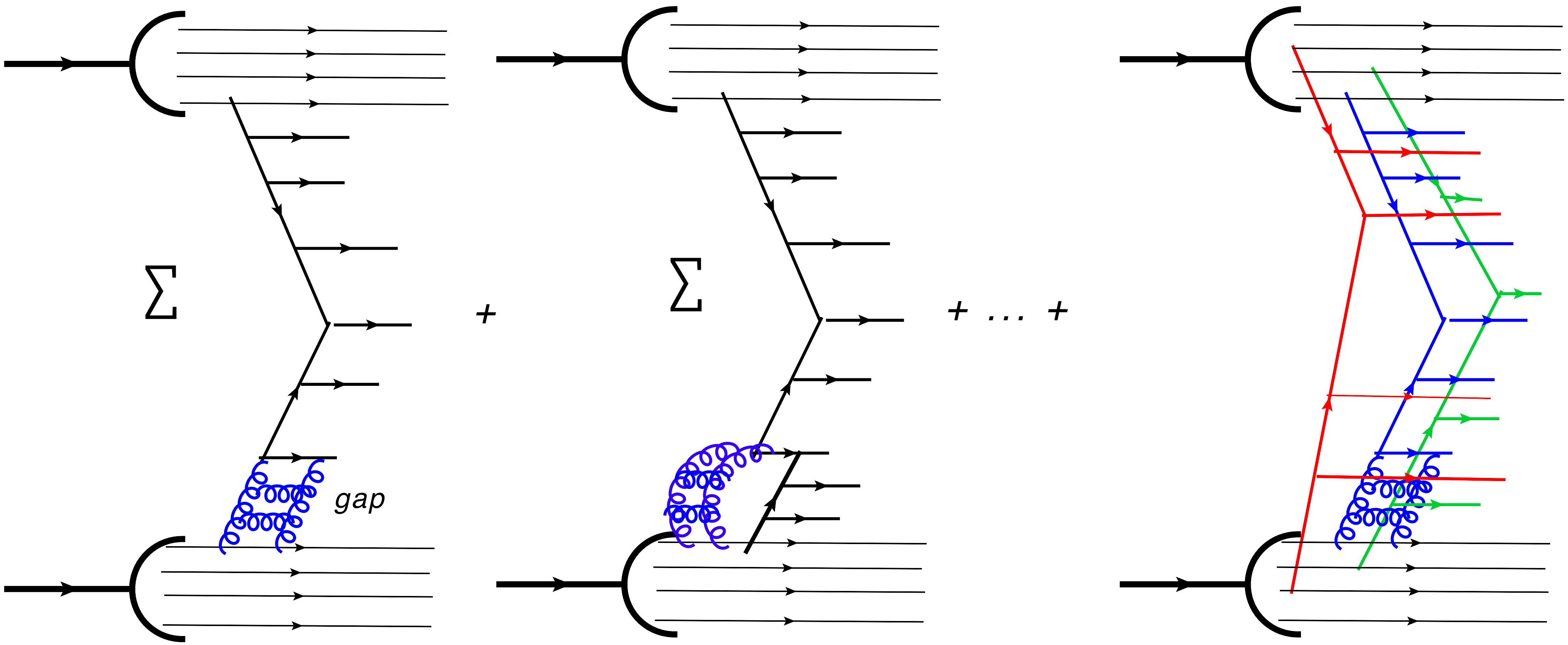


BUT: second, third... chain may fill the gap, less diffraction

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

'Survival probability' as phenomenological factor, no theory
Could be modelled by Monte Carlos with MPI and diffraction (Regge cuts)

In detail: in hard diffraction cannot simply add new contribution



required by AGK

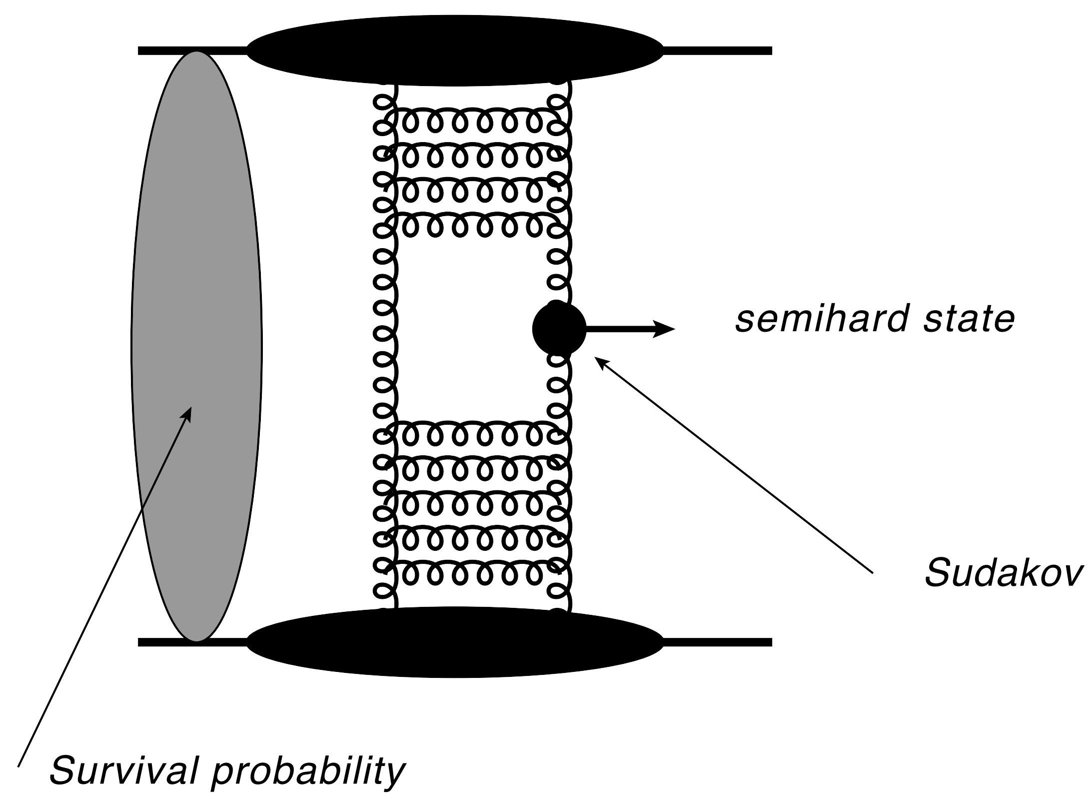
As in soft diffraction:
additional chains fill the gap.

Leaves the eikonal approximation!

First example: central exclusive production (CEP):

Topic of intense discussion

(Bialas,Landshoff; ... ;Durham group)



NLO calculation of hard subprocess?

Is eikonal enough?

JB, Motyka

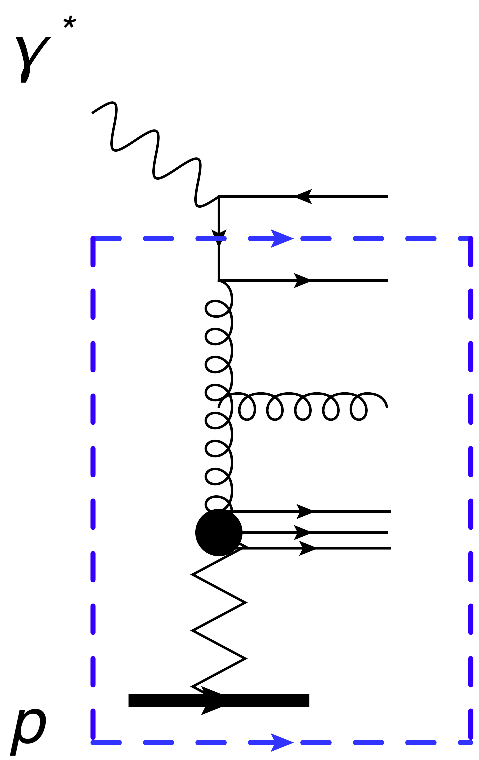
$$\sigma(pp \to p + X + p) \sim < S^2 > \otimes | \int \frac{dQ_t^2}{Q_t^4} f_g(x_1 x_1' Q_t^2, \mu^2) M_{hard} f_g(x_2 x_2' Q_t^2, \mu^2)|^2$$

Experimental aspects: clean signal, precise mass determination

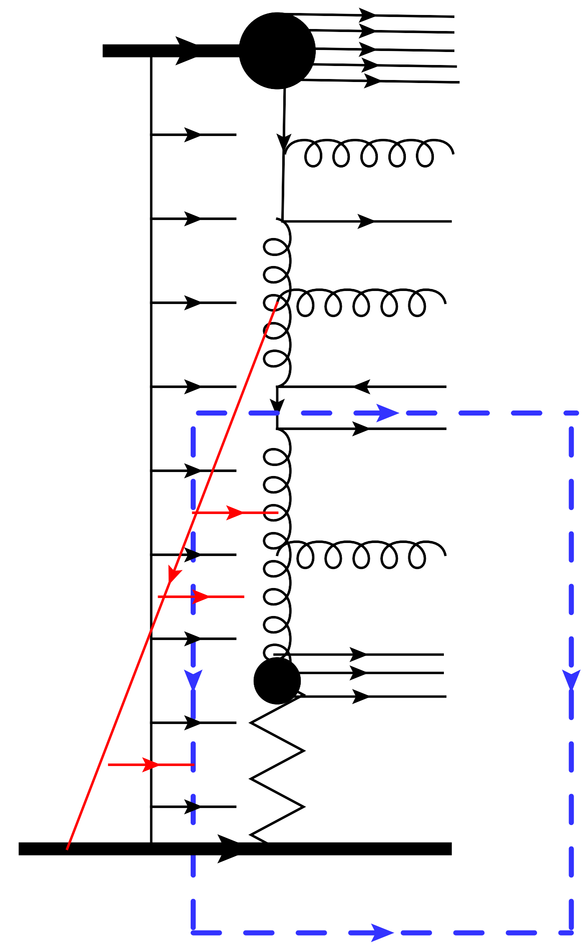
Theoretical ingredients: parton densities, Sudakov factor, suppression rules survival probability

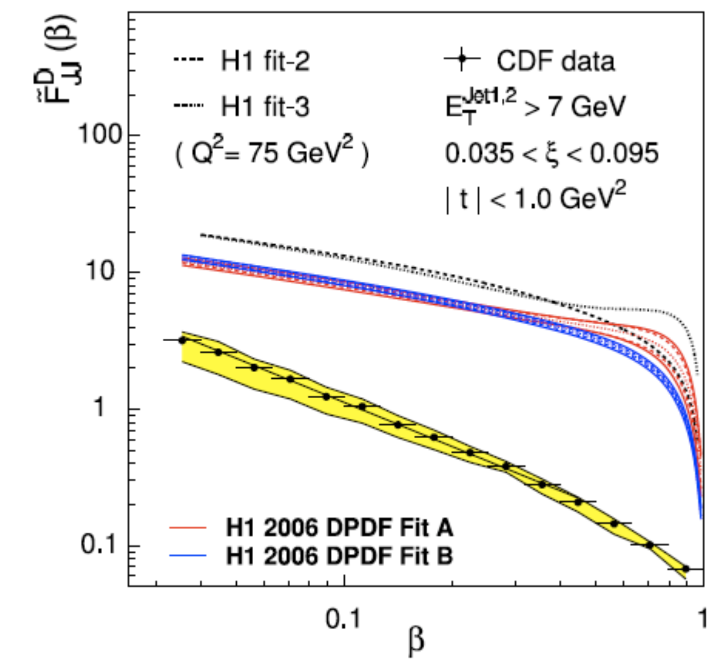
Diffractive parton densities, Pomeron SFR

HERA



LHC

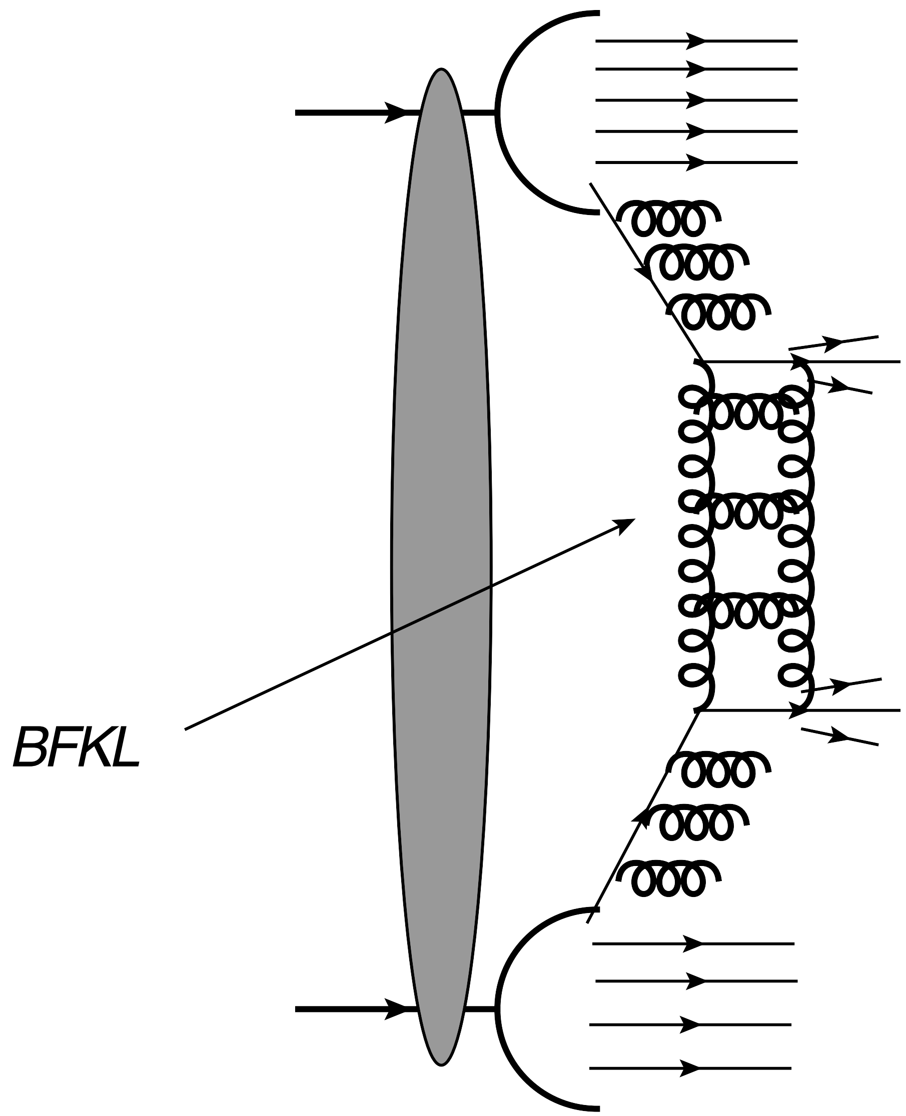




solid theoretical basis

'survival probability' S : simple factor,
related to MPI, no theory,
good place to measure S

Examples: Jet-gap-jet (hard color singlet exchange)



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

BFKL needs all conformal spins

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

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

Summary of this part:

building blocks (hard and soft Pomeron),
rules for inelastic diffractive states

In the remaining part:
address the question whether one can find bridge between soft and hard Pomeron

Collaboration with C.Contreras and G.P.Vacca,
arXiv:1411.6670 and in preparation

Can we connect hard and soft diffraction: a novel attempt

soft, long distances
(pp-scattering)

Regge pole with
$\alpha(0) = 1 + \epsilon,\ \epsilon \approx 0.1$

from data

hard, short distances
(virtual photons)

BFKL with intercept
$\omega_{BFKL},\ \omega_{BFKL} \approx 0.3$

computable

Reggeon field theory on both sides:
effective field theory in 2+1 dimensions
fields and parameters are different

$$S = \int d^2x d\tau \mathcal{L}(\psi, \psi^\dagger)$$

$$\mathcal{L} = \left(\tfrac{1}{2}\psi^\dagger \overleftrightarrow{\partial_y}\psi - \alpha' \psi^\dagger \nabla^2 \psi\right) + V(\psi, \psi^\dagger)$$

$$V(\psi, \psi^\dagger) = -\mu \psi^\dagger \psi + i\lambda \psi^\dagger (\psi^\dagger + \psi)\psi$$
$$+ g(\psi^\dagger \psi)^2 + g' \psi^\dagger ({\psi^\dagger}^2 + \psi^2)\psi + \cdots$$

interpolate between RFT at small distances (pQCD: BFKL)
and RFT at large distances: field theory with change of scale

Renormalization group equation:
flow from pQCD (short dist.) to nonperturbative (confinement, large dist.)
special hope: can follow the flow and compare with data.

The formalism: functional renormalization group

Reminder: Wilson approach

The standard Wilsonian action is defined by an iterative change in the UV-cutoff induced by a partial integration of quantum fluctuations:

$$\Lambda \to \Lambda' < \Lambda$$

$$\int [\mathrm{d}\varphi]^{\Lambda} e^{-S^{\Lambda}[\varphi]} = \int [\mathrm{d}\varphi]^{\Lambda'} e^{-S^{\Lambda'}[\varphi]} \qquad k < \Lambda$$

Alternatively: FRG-approach (Wetterich) IR-cutoff

(successful use in statistical mechanics and in gravity)

define a bare theory at scale Λ .

The integration of the modes in the interval $[k, \Lambda]$ defines a k-dependent average functional.

Letting k flowing down to 0 defines a flow for the functional which leads to full theory. k-dependent effective action:

regulator

$$e^{-\Gamma_k[\phi]} = \int [d\varphi] \mu_k e^{-S[\varphi] + \int_x (\varphi - \phi)_x \frac{\delta \Gamma_k[\phi]}{\delta \phi_x} - \Delta S_k[\varphi - \phi]}$$

Taking a derivative with respect the RG time t=log (k/k_0) one obtains

$$\partial_t \Gamma_k = \frac{1}{2} Tr\left[\left(\Gamma_k^{(2)} + \mathcal{R}_k\right)^{-1} \partial_t \mathcal{R}_k\right] - \frac{\dot{\mu}_k}{\mu_k}$$

$$\rightarrow \qquad \mathcal{R} = \text{regulator operator}$$

which is UV and IR finite
From this derive coupled differential equations for Green's and vertex functions.

Steps:
1) Start at the extreme long distance, high energy limit: $k \rightarrow 0$
can we define a theory? Existence of a fixed point?
2) Try to interpolate from BFKL to this long distance theory.

This talk: only first step
- existence of fixed point
- approach to this fixed point

Results:

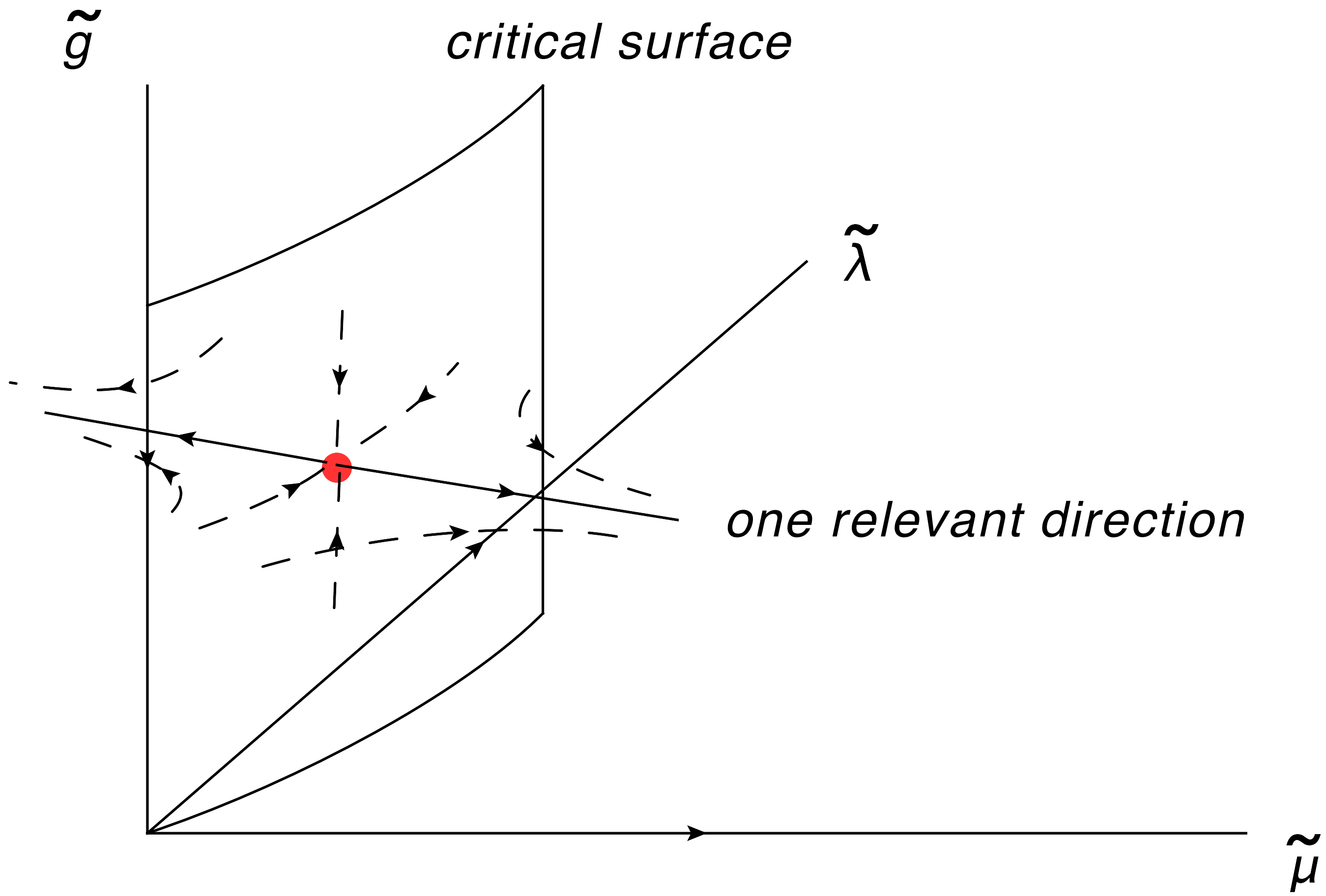
1) Existence of fixed point:
polynomial expansion around zero fields, use sequence of truncations (more and more couplings):
one robust fixpoint, good convergence

$truncation$	3	4	5	6	7	8	9	10	11	12
ν	0.53	0.59	0.59	0.78	0.76	0.72	0.72	0.74	0.74	0.73

Compare with Monte Carlo result for Directed Percolation (same universality class)

$$\nu = 0.73$$

Space of couplings:

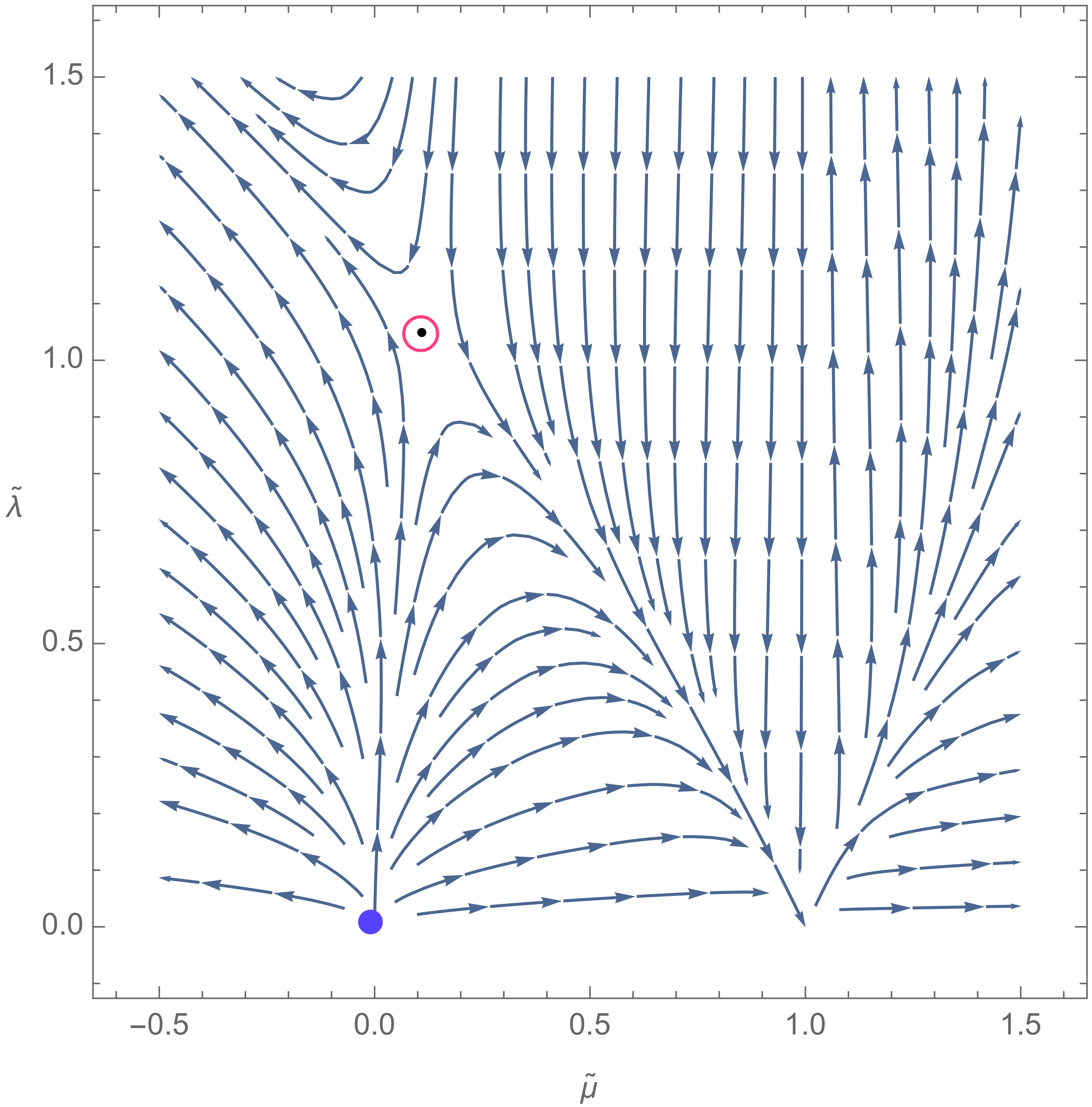


Remember:
small k means large transverse distances (soft Pomeron),
large k means hard physics (BFKL region)

either: repulsive UV fixed point with one relevant direction.
Start at some value, get dragged towards the relevant direction away from fixed point

or: attractive IR fixed point inside critical surface.
Start at value inside the critical surface and fall into the fixed point

projection on 2-dimensional plane:



arrows denote IR flow (cutoff to zero)

- Trivial fixed point: (IR unstable)
- Nontrivial fixed point with one relevant direction: same characteristics for all truncations: critical line (surface)

First glimpse at physics

Need to find out: on which trajectory is real physics?

Look at physical physical observable: Pomeron intercept $\mu = \alpha(0) - 1$:

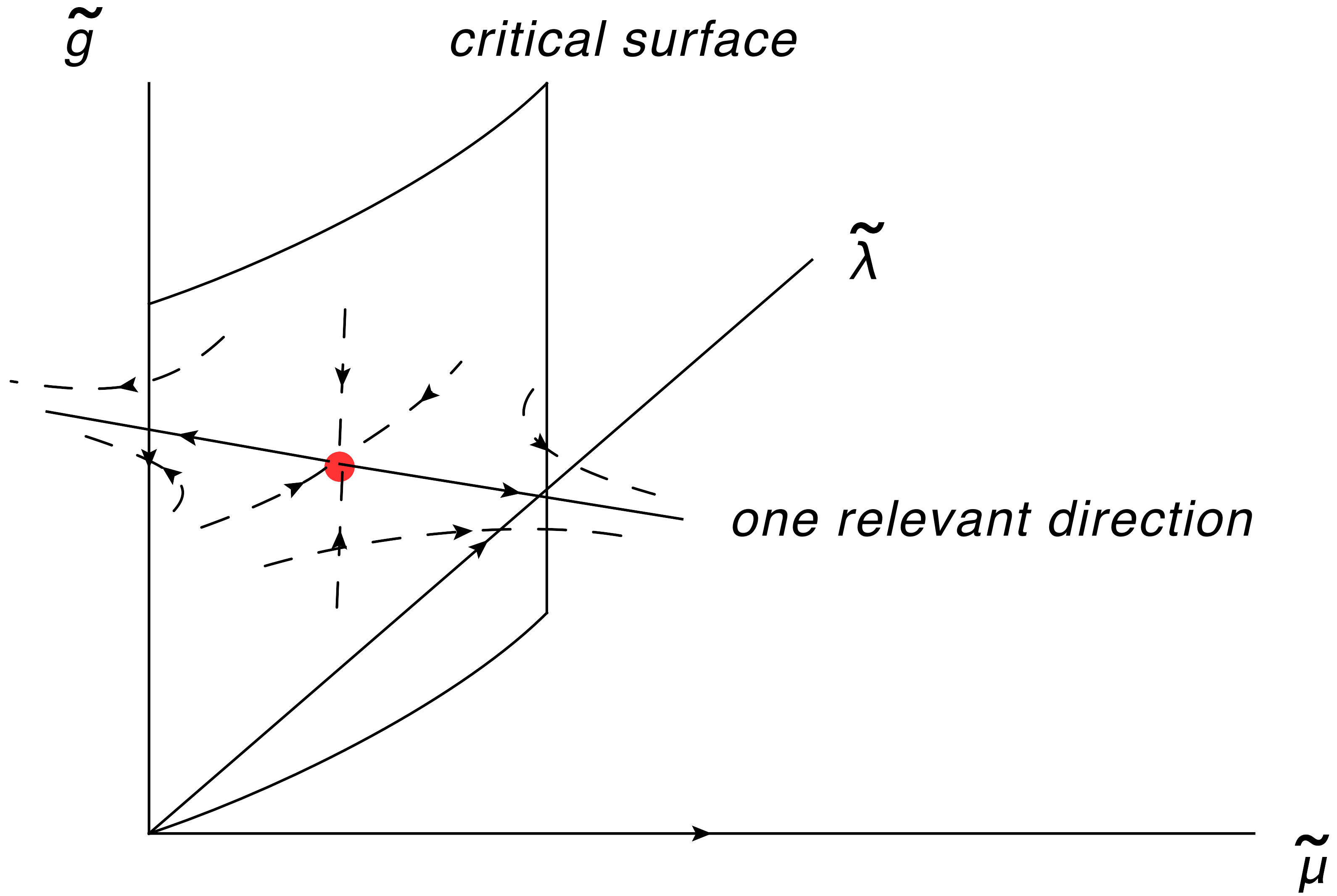
So far: fixed point analysis was done in terms of dimensionless variables: reggeon energy and momentum have different dimensions

$$S = \int d^2x\, d\tau \left(Z(\frac{1}{2}\psi^\dagger \overleftrightarrow{\partial_\tau} \psi - \alpha' \psi^\dagger \nabla^2 \psi) + V[\psi^\dagger, \psi] \right), \qquad [\psi] = [\psi^\dagger] = k^{D/2}, \qquad [\alpha'] = Ek^{-2}.$$

$$\tilde{\mu}_k = \frac{\mu_k}{Z_k \alpha'_k k^2}$$

$$\tilde{\lambda}_k = \frac{\lambda_k}{Z_k^{\frac{3}{2}} \alpha'_k k^2} k^{D/2}$$

Evolution of physical (=dimensionful) parameters $\tilde{\mu}_k, \tilde{\lambda}_k, \ldots$ looks quite different from dimensionless ones $\mu_k, \lambda_k, \ldots$



Physical parameters:

inside surface: $\mu = \alpha(0) - 1 \to 0, \;\lambda_{triplePomron} \to 0$

left to surface $\mu_\infty < 0$

right to surface $\mu_\infty > 0$

Very tentative interpretation:

infrared cutoff $k^2 \sim 1/\ln s$

At present energies: k still nonzero, $\alpha(0) > 1$

Could this be a candidate for the real world?

Conclusions

1) Overview of ‘pieces’ of theoretical description:

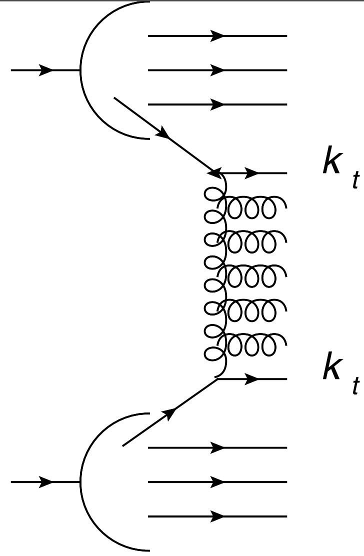
‘soft’ Pomeron
‘hard’ Pomeron
rescattering in inelastic diffraction

2) First steps in
finding a connection between hard and soft Pomeron

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

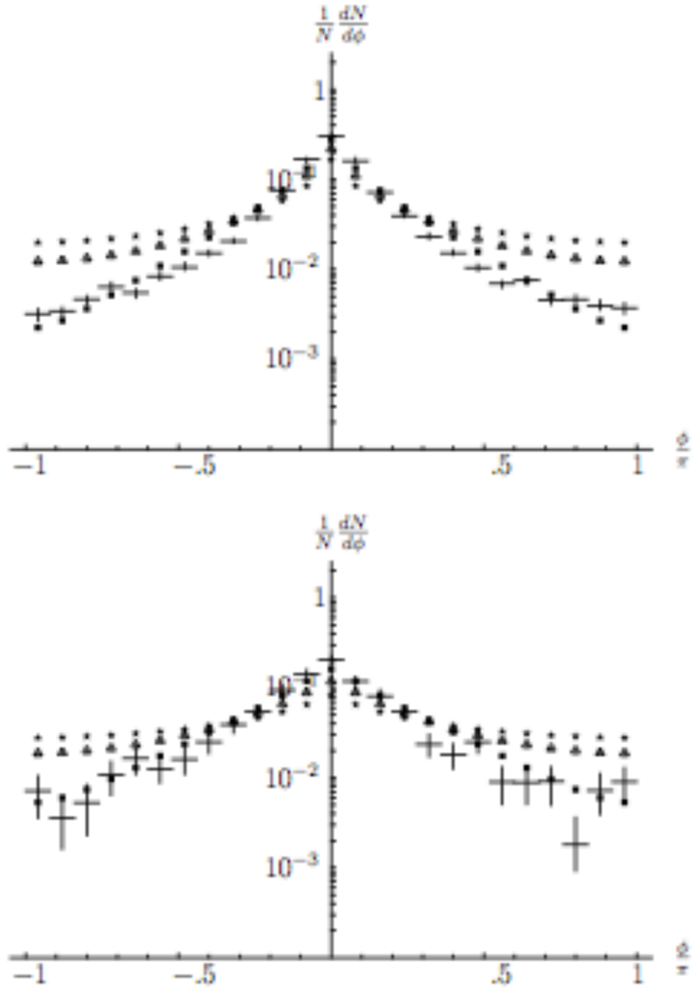
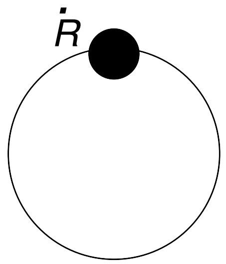


Fig. 2: $\frac{1}{N}\frac{dN}{d\phi}$ in a $p\bar{p}$ collider at $\sqrt{s}$=1.8 TeV using a LO (stars), NLO (squares) and resummed (triangles) BFKL kernel. Plots are shown for Y = 3 (top) and Y = 5 (bottom).

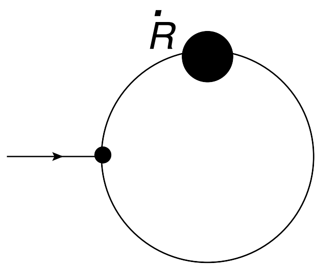
Sabio Vera, Schwennsen;
Colferai et al.
Papa et al:

3) BFKL energy dependence: use different machine energies

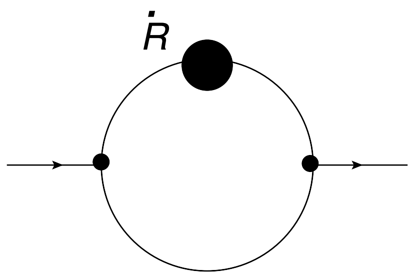
Vertex functions, Green's functions, physical observables:
take functional derivatives w.r.t. the fields:



$$\partial_t \Gamma_k = \frac{1}{2} G_{k;AB}\, \partial_t \mathcal{R}_{k;BA}$$



$$\partial_t \Gamma^{(1)}_{k;A_1} = -\frac{1}{2} G_{k;AB} \Gamma^{(3)}_{k;A_1 BC} G_{k;CD}\, \partial_t \mathcal{R}_{k;DA}$$



$$\begin{aligned}\partial_t \Gamma^{(2)}_{k;A_1 A_2} = \frac{1}{2} G_{k;AB} \Gamma^{(3)}_{k;A_1 BC} G_{k;CD} \Gamma^{(3)}_{k;A_2 DE} G_{k;EF}\, \partial_t \mathcal{R}_{k;FA} \\ + \frac{1}{2} G_{k;AB} \Gamma^{(3)}_{k;A_2 BC} G_{k;AB} \Gamma^{(3)}_{k;A_1 BC} G_{k;CD}\, \partial_t \mathcal{R}_{k;DA} \\ - \frac{1}{2} G_{k;AB} \Gamma^{(4)}_{k;A_1 A_2 BC} G_{k;CD}\, \partial_t \mathcal{R}_{k;DA}\end{aligned}$$

coupled partial differential equations

A bit more explicit:

$$\mu = \alpha(0) - 1$$

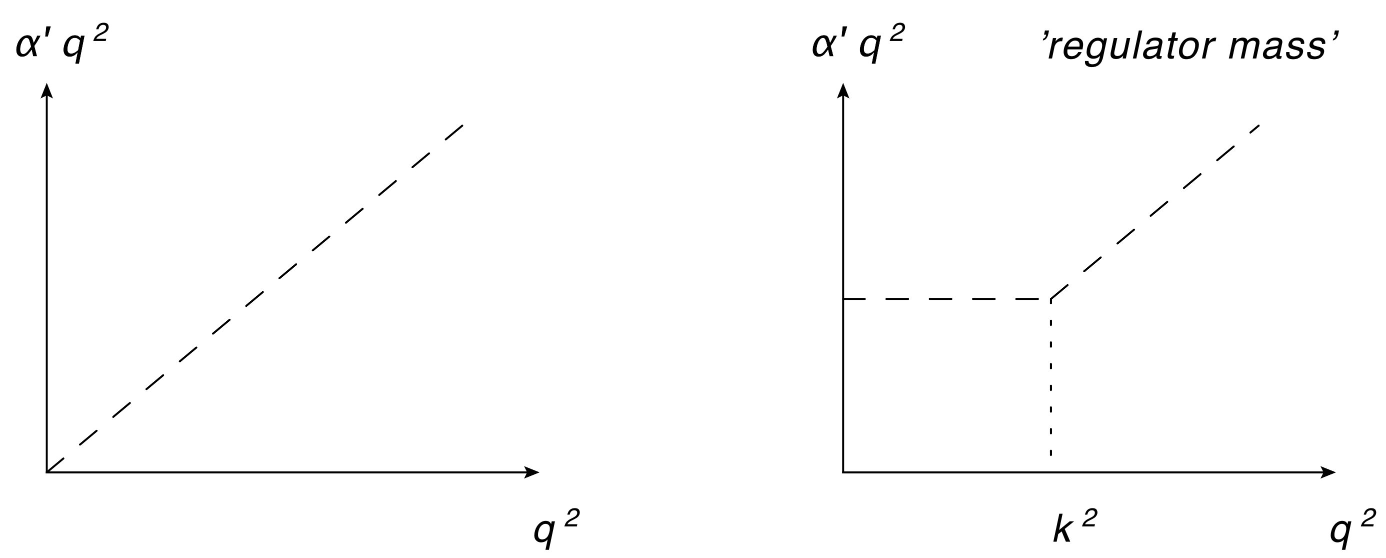
$$\Gamma[\psi^\dagger, \psi] = \int \mathrm{d}^2x \, \mathrm{d}\tau \left(Z(\frac{1}{2}\psi^\dagger \partial_\tau^{\leftrightarrow} \psi - \alpha' \psi^\dagger \nabla^2 \psi) + V[\psi^\dagger, \psi] \right),$$

$$V[\psi^\dagger, \psi] = -\mu\psi^\dagger\psi + i\lambda\psi^\dagger(\psi^\dagger + \psi)\psi + g(\psi^\dagger\psi)^2 + g'\psi^\dagger({\psi^\dagger}^2 + \psi^2)\psi$$
$$+ i\lambda_5 {\psi^\dagger}^2 \left(\psi^\dagger + \psi\right)\psi^2 + i\lambda_5' \psi^\dagger \left({\psi^\dagger}^3 + \psi^3\right)\psi + \ldots$$

After introducing a regulator: all parameters become k-dependent

$$\Gamma_k[\psi^\dagger, \psi] = \int d^2x \, d\tau \left(Z_k(\frac{1}{2}\psi^\dagger \partial_\tau^{\leftrightarrow} \psi - \alpha_k' \psi^\dagger \nabla^2 \psi) + \psi^\dagger R_k \psi + V_k[\psi, \psi^\dagger] \right)$$

There is freedom in choosing a regulator, for example:



First step:

Expand the potential in powers of fields, derive beta-functions for parameters of the potential (coupling constants):

$$\dot{\tilde{\mu}} = \tilde{\mu}(-2 + \zeta + \eta) + 2N_D A_D(\eta_k, \zeta_k)\frac{\tilde{\lambda}^2}{(1-\tilde{\mu})^2},$$

$$\dot{\tilde{\lambda}} = \tilde{\lambda}\left((-2 + \zeta + \frac{D}{2} + \frac{3\eta}{2}) + 2N_D A_D(\eta_k, \zeta_k)\left(\frac{4\tilde{\lambda}^2}{(1-\tilde{\mu})^3} + \frac{(\tilde{g} + 3\tilde{g}')}{(1-\tilde{\mu})^2}\right)\right),$$

$$\dot{\tilde{g}} = \tilde{g}(-2 + D + \zeta + 2\eta) + 2N_D A_D(\eta_k, \zeta_k)\left(\frac{27\tilde{\lambda}^4}{(1-\tilde{\mu})^4} + \frac{(16\tilde{g} + 24\tilde{g}')\tilde{\lambda}^2}{(1-\tilde{\mu})^3} + \frac{\left(\tilde{g}^2 + 9\tilde{g}'^2\right)}{(1-\tilde{\mu})^2}\right)$$

$$\dot{\tilde{g}}' = \tilde{g}'(-2 + D + \zeta + 2\eta) + 2N_D A_D(\eta_k, \zeta_k)\left(\frac{12\tilde{\lambda}^4}{(1-\tilde{\mu})^4} + \frac{(4\tilde{g} + 18\tilde{g}')\tilde{\lambda}^2}{(1-\tilde{\mu})^3} + \frac{3\tilde{g}\tilde{g}'}{(1-\tilde{\mu})^2}\right)$$

Fixed points: zeroes of the beta-functions

Results: 1) existence of fixed point

Local reggeon field theory:

$\mu = \alpha(0) - 1$

$$\mathcal{L} = (\tfrac{1}{2}\psi^\dagger \overleftrightarrow{\partial_y}\psi - \alpha'\psi^\dagger\nabla^2\psi) + V(\psi,\psi^\dagger)$$

$$V(\psi,\psi^\dagger) = -\mu\psi^\dagger\psi + i\lambda\psi^\dagger(\psi^\dagger + \psi)\psi$$
$$+ g(\psi^\dagger\psi)^2 + g'\psi^\dagger({\psi^\dagger}^2 + \psi^2)\psi + \cdots$$

some universal symmetry properties

Some history:

Gribov, Migdal; Abarbanel, Bronzan; Migdal, Polyakov, Ter-Martirosyan

In early seventies : first studies of RFT with triple couplings, expansion near D=4 (ϵ- expansion). IR-fixed point.

In 1980: J. Cardy and R. Sugar noticed that the RFT is in the same universality class of a Markov process known as Directed Percolation (DP). Critical exponents can then be accessed also with numerical montecarlo computations.

This attempt:
search in the full space of theories, no restriction to D=4