An introduction to Diffraction

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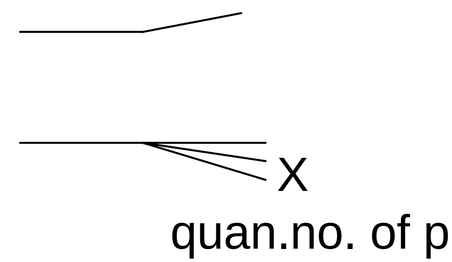
What is diffraction ?

Two alternative definitions:

1. Diffraction is elastic or quasi-elastic scattering caused, via s-channel unitarity, by the absorption of components of the wave functions of the incoming particles
   e.g. pp→pp,
   pp→pX (single proton dissociation, SD),
   pp→XX (both protons dissociate, DD)



2. A diffractive process is characterized by a large rapidity gap (LRG), which is caused by t-channel Pomeron exch. (or, to be more precise, by the exchange corresponding to the rightmost singularity in the complex angular momentum plane with vacuum quantum numbers).

Let us start with the

s-channel viewpoint

Unitarity gives us the optical theorem

S matrix and the Optical Theorem

$$\sum_n P(i \to n) = 1 = \sum_n |\langle n|S|i\rangle|^2 = \sum_n \langle i|S^\dagger|n\rangle\langle n|S|i\rangle = \langle i|S^\dagger S|i\rangle = 1$$

true for any $|i\rangle$, so $S^\dagger S = I.$ Introduce trans matrix T: $S = I + iT$

$$(I - iT^\dagger)(I + iT) = I$$

$$i(T^\dagger - T) = T^\dagger T$$

$$i\langle f|T^\dagger - T|i\rangle = \sum_n \langle f|T^\dagger|n\rangle\langle n|T|i\rangle$$

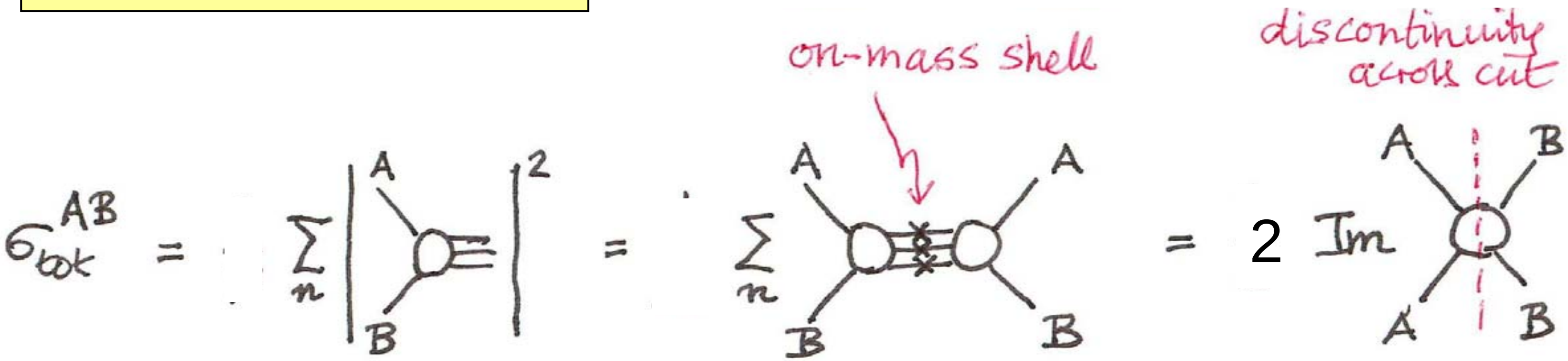
$$2\ \mathrm{Im} T(i \to f) = \sum_n \langle n|T^*|f\rangle\langle n|T|i\rangle$$

put $f = i$, forward elastic scatt. $\to$ Optical theorem

$$2\ \mathrm{Im} T_{\mathrm{el}}(t = 0) = \sum_n |T(i \to n)|^2 = \sigma_{\mathrm{tot}}$$

Optical Theorem

$$\sigma_{\text{tot}} = 2\,\text{Im}T_{\text{el}}(s,t=0)$$



1. The sum over all inelastic channels forms a “shadow”, which “generates” elastic scattering
   → diffraction → can generalise

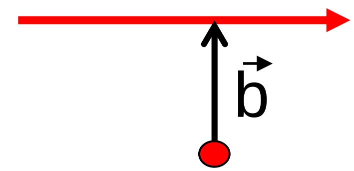
2. As s increases Im $T_{el}(s,0)$ is the sum over increasing number of positive terms. No such constraint exists for Re T_{el}. $T_{el}(0)$ is predominantly imag. at HE.

3. Away from forward dir^{n}, phases in $2\text{Im}T_{el} \sim T_{nf}^{*}\, T_{ni}$ vary. $T_{el}(s,t)$ rapidly decreases away from t=0.

Eikonal (Ω(s,b)) parametrization

$$2\,\mathrm{Im}T_{\mathrm{el}} = \sum_n |T(i\to n)|^2 = |T_{\mathrm{el}}|^2 + G_{\mathrm{inel}}$$

best to work in b space, since at high energies the value of b is frozen



$$2\,\mathrm{Im}T_{\mathrm{el}}(s,b) = |T_{\mathrm{el}}(s,b)|^2 + G_{\mathrm{inel}}(s,b)$$

$$\sigma_{\mathrm{tot}} = 2\int d^2b\ \mathrm{Im}T_{\mathrm{el}}(s,b) = 2\int d^2b\ (1-e^{-\Omega/2})$$

$$\sigma_{\mathrm{el}} = \int d^2b\ |T_{\mathrm{el}}(s,b)|^2 = \int d^2b\ (1-e^{-\Omega/2})^2$$

$$\sigma_{\mathrm{inel}} = \int d^2b\ [2\mathrm{Im}T_{\mathrm{el}}(s,b) - |T_{\mathrm{el}}(s,b)|^2] = \int d^2b\ (1-e^{-\Omega})$$

with $\mathrm{Re}\Omega \geq 0$. Amp ∼ imag. at HE so eikonal Ω is real

Note $e^{-\Omega(s,b)}$ is prob. no inelastic inter^n occurs at b

At HE the inelastic contribution, $G_{\rm inel}$, dominates; $\Omega(s,b) \gg 1$.
In this so-called "black disk" limit $\quad {\rm Im}T_{\rm el}(s,b) = 1$

Example: black disc of radius R

for $b < R$, $\Omega = \infty$ $(T_{el} = i)$

for $b > R$, $\Omega = 0$ $(T_{el} = 0)$

$$\sigma_{inel} = 2\pi \int_0^R (1 - e^{-\Omega})\, b\, db = \pi R^2$$

total absorption

$$\sigma_{el} = \pi R^2$$

shadow due to absorption leads to elastic scattering

$$\sigma_{tot} = 2\pi R^2$$

Since $\quad \dfrac{d\sigma_{\rm el}}{dt} = |{\rm Im}T_{\rm el}(s,t)|^2\ (1+\rho^2)$

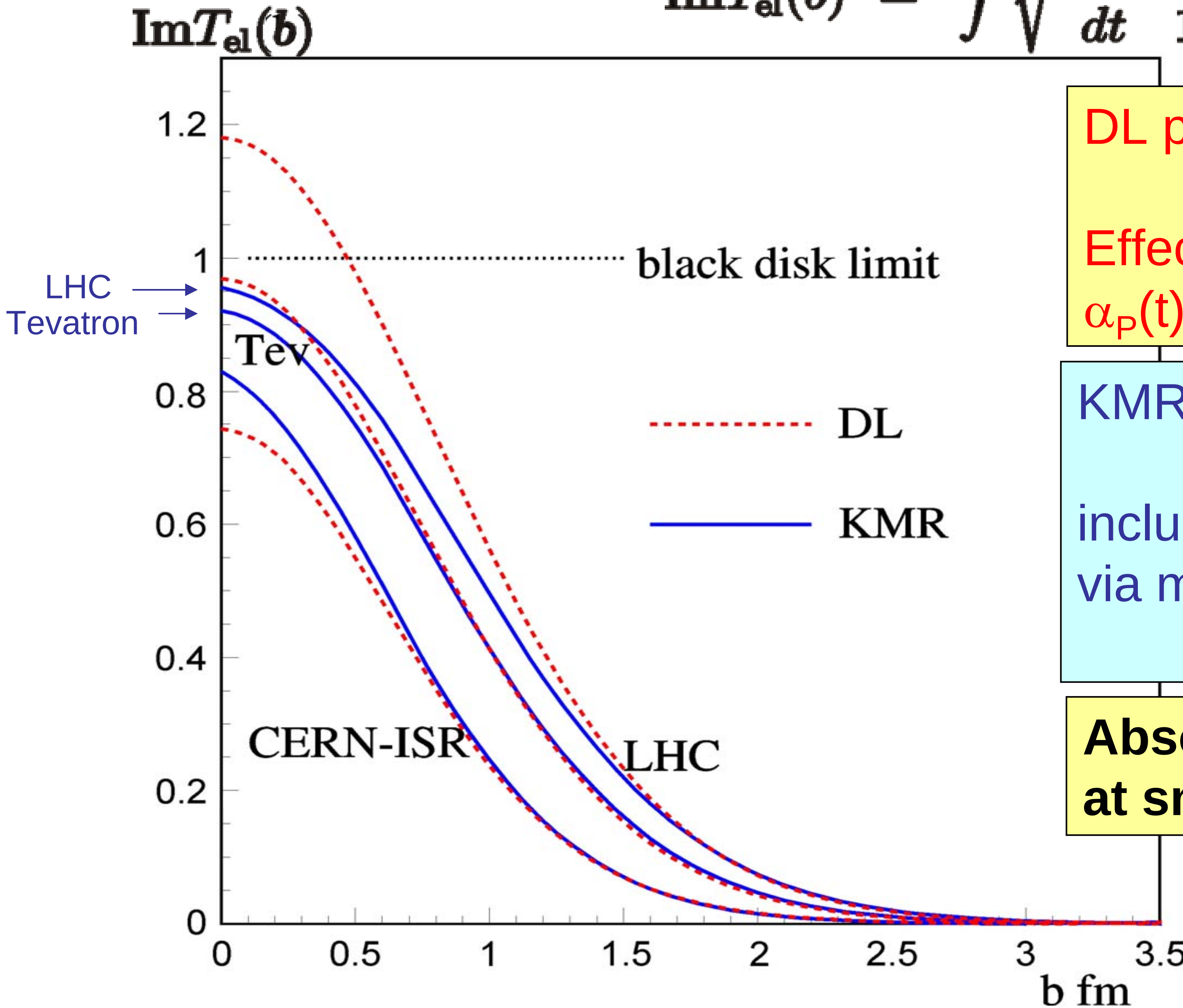
data directly determines ${\rm Im}T_{\rm el}(s,b)$

Fourier transform to b-space: $(-t = q_T^2)$

$\vec{b} \longleftrightarrow \vec{q}_T$

wide narrow

$$\mathrm{Im}T_{el}(b) = \int \sqrt{\frac{d\sigma_{el}}{dt}\,\frac{16\pi}{1+\rho^2}}\; J_0(q_T b)\,\frac{q_T\,dq_T}{4\pi}$$



DL parametrization:

Effective Pom. pole

$\alpha_P(t) = 1.08 + 0.25t$

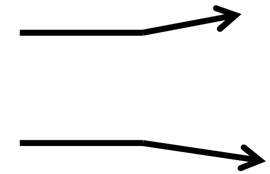
KMR eikonal param^n

includes absorption via multi-Pomeron effects

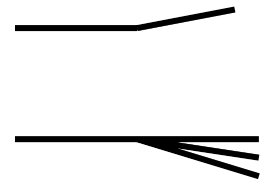
Absorption crucial at small b

t-ch view, see later

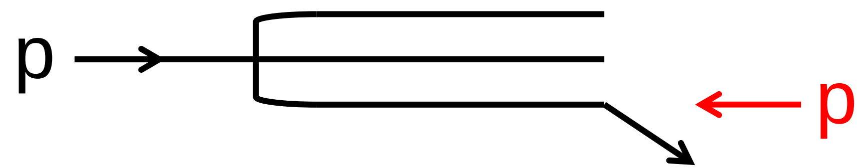
So far only discussed elastic diffraction



What about inelastic diffraction ?



Inelastic diffraction is a consequence of internal struct of p



At HE fluctuations of p are frozen.

A constituent of p can scatter and destroy coherence of fluctuations

→ inelastic, as well as, elastic diffraction (single diffractive dissociation)

Good-Walker formalism for low-mass diff^{ve} dissoc^{n}

We write $|p\rangle = \sum a_k |\phi_k\rangle$ where $|\phi_k\rangle$ diagonalise T

The $|\phi_k\rangle$ undergo "elastic-type" scatt $\langle \phi_j | T | \phi_k \rangle = 0 \quad (j \neq k)$

$|p\rangle \rightarrow$ diffractive eigenstates $|\phi_k\rangle \rightarrow$ multichannel eikonal

$$\text{Im}\, T = a F a^T \qquad \text{where} \quad \langle \phi_j | F | \phi_k \rangle = F_k \, \delta_{jk}$$

Elastic amp. $\langle p | \text{Im}\, T | p \rangle = \sum |a_k|^2 F_k = \langle F \rangle$

average of F over the initial prob. distrib. of diff. estates

$$\frac{d\sigma_{tot}}{d^2b} = 2\langle p|\mathrm{Im}T|p\rangle = 2\sum |a_k|^2 F_k = 2\langle F\rangle$$

$$\frac{d\sigma_{el}}{d^2b} = |\langle p|T|p\rangle|^2 = \left(\sum |a_k|^2 F_k\right)^2 = \langle F\rangle^2$$

$$\frac{d\sigma_{el+SD}}{d^2b} = \sum_k |\langle \phi_k|T|p\rangle|^2 = \sum_k |a_k|^2 F_k^2 = \langle F^2\rangle$$

Comments

1. $$\frac{d\sigma_{SD}}{d^2b} = \langle F^2\rangle - \langle F\rangle^2$$ statistical dispersion in absorp. prob. of diff. estates

2. If all compts. of incident proton absorbed equally then diffracted superposition = incident one. No inelastic diffraction e.g. Small b: $F_k \simeq 1$ (~black disc), so diffr prod ~ zero → diffraction mainly on periphery.

3. $0 \leq F_k \leq 1$, $F_k^2 \leq F_k$, $\langle F^2 \rangle \leq \langle F \rangle$

Pumplin bound: $$\frac{d\sigma_{SD}}{d^2b} \leq \frac{1}{2} \frac{d\sigma_{tot}}{d^2b} - \frac{d\sigma_{el}}{d^2b}$$

(can be violated, see later)

4. Easy to allow both protons to dissociate; expand both $|p\rangle$'s in diffractive eigenstates

5. High-mass dissociation not included yet.

Summary of the s-channel viewpoint

- s-channel unitarity plays a key role.
- Impact parameter representation best.
- Inelastic scattering generates elastic amp.
- Eikonal formalism preserves unitarity.
- Slow approach to black disc limit at small b.
- Multichannel eikonal necessary for proton dissociation.
- Diffraction mainly in the periphery (large b).
- Need t-channel approach for high-mass dissociation.

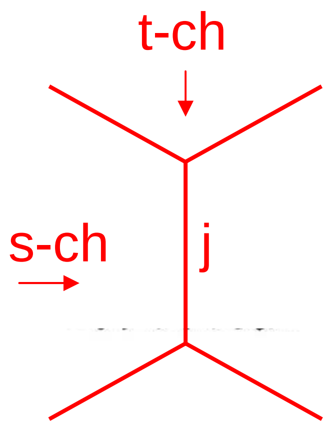
t-channel picture of Diffraction

First, v. brief overview of Regge Poles

see Martin Poghosyan's talk

partial wave expansion in t-ch: $T(s,t) \propto \sum_\ell (2\ell+1)\, a_\ell(t)\, P_\ell(\cos\theta_t)$

so exchange of particle of spin j in t-ch



$$T(s, t \sim M_j^2) \sim \frac{P_j(\cos\theta_t)}{M_j^2 - t} \rightarrow s^j \quad \text{as } s \to \infty$$

$$\cos\theta_t = 1 - \frac{s}{2k_t^2}$$

$$P_j(\cos\theta_t) \sim (\cos\theta_t)^j$$

whereas from unitarity

$$T(s, t=0) \lesssim c\, s \log^2 s$$

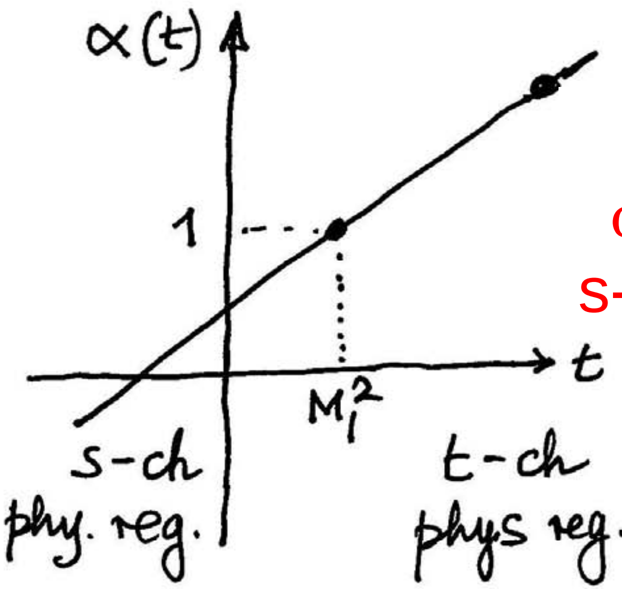
so s^j violates unitarity if $j > 1$.

So we need a way to sum partial-wave series

(Sommerfeld-Watson transform   see MP's talk)

Consider particles lying on a single linear Regge trajectory

$$\alpha(t) = \alpha_0 + \alpha' t$$



OK
$\alpha<1$ in
s-ch reg.

pole in ℓ^{th} (t-ch) partial wave

$$a_\ell(t) \simeq \frac{\beta(t)}{\ell - \alpha(t)} = \frac{\beta(t)/\alpha'}{M_\ell^2 - t}$$

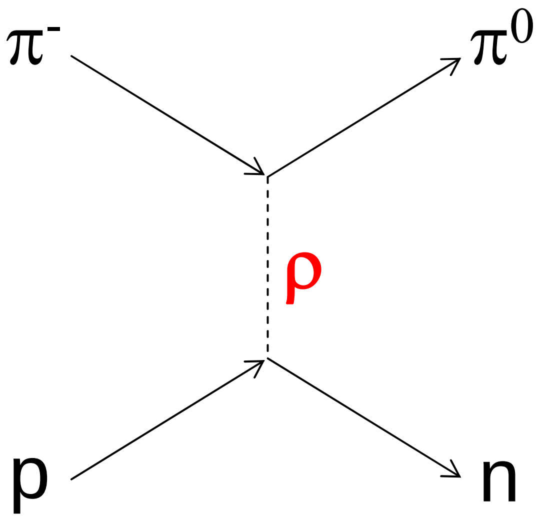
$$(\ell = \alpha_0 + \alpha' M_\ell^2)$$

$$T(s,t) = \sum_\ell (2\ell+1)\frac{\beta(t)}{\ell-\alpha(t)} P_\ell(\cos\theta_t) \underset{\substack{s\to\infty \\ \text{fixed } t}}{\sim} \sum_\ell \frac{\beta(t)\,(\cos\theta_t)^\ell}{\ell-\alpha(t)} \sim \beta(t)\,(\cos\theta_t)^{\alpha(t)}$$

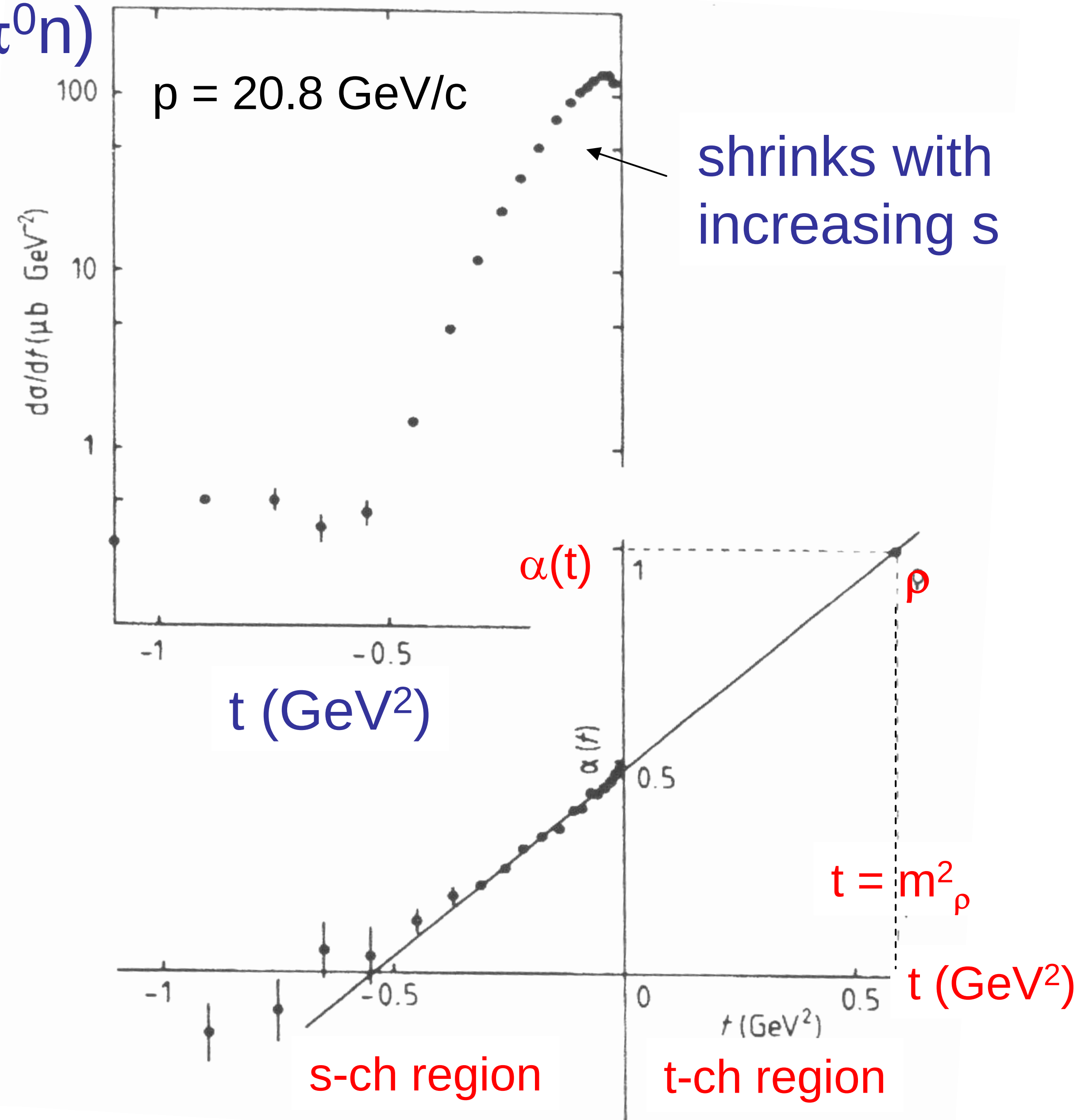
$$\sim \beta(t)\, s^{\alpha(t)}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}|T(s,t)|^2 \sim F(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2} \sim F(t)\left(\frac{s}{s_0}\right)^{2\alpha_0-2} \exp\left[2\alpha'\left(\log\frac{s}{s_0}\right)t\right]$$

so we have shrinkage of forward peak, exp(-Bt), as s increases e.g $d\sigma/dt\ (\pi^- p \to \pi^0 n)$



$\alpha_\rho(t) \sim 0.5 + 0.9\ t$



obtained from data with p = 20-200 GeV/c

HE behaviour dominated by leading (highest) Regge-exch. trajectory

σ_{tot}(hadron-hadron) → const. (actually slightly rising as s → infinity)

that is T(s, t=0) ~ s (actually $s^{1.08}$)

(In our discussion on Regge poles we use more usual normal^n of T such optical theorem reads $2\text{Im}\, T_{el}(s,t=0) = \text{flux}\, \sigma_{tot} = 2s\, \sigma_{tot}$)

Implies Regge-pole exchange with $\alpha(0) = 1$ (1.08 ?)

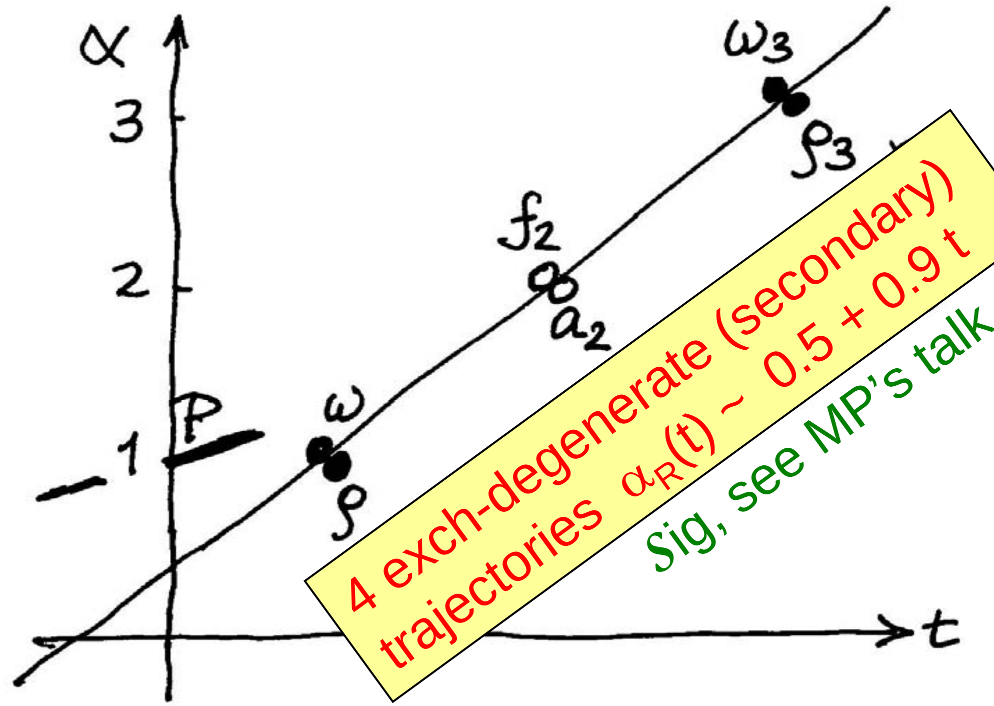
called the Pomeron

We shall see later that the Pomeron is represented by gluon exchange – we need two gluons to form colourless exchange. But, for the moment, let us consider the Pomeron as a simple (effective) Regge pole

Donnachie-Landshoff type simple Regge pole fit to

σ_{tot} and $d\sigma_{el}/dt$ for pp, $p\bar{p}$, πp, Kp,…

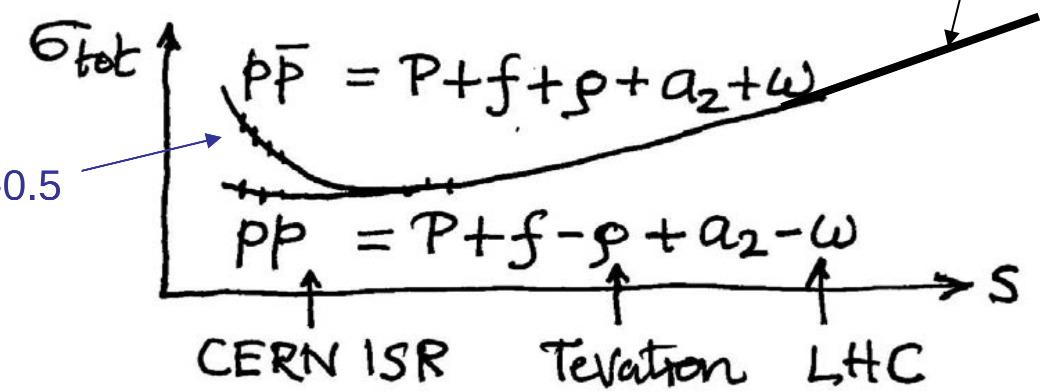
Good description up to Tevatron energies with



$\alpha_P^{eff}(t) \sim 1.08 + 0.25\,t$

$s^{\alpha(0)-1} \sim s^{0.08}$

$s^{-0.5}$



$\alpha_R(t) \sim 0.5 + 0.9\,t$

$\sigma_{tot} \sim s^{\alpha(t=0)}/s$

Impact parameter picture of Regge pole exchange

sig.factor $\mathcal{S}$
see MP's talk

$$T(s,b) = \int T_{Reg}(s,t)\, e^{-i\vec{b}\cdot\vec{q}_T}\, d^2q_T$$

with $T_{Reg}(s,t) = \beta(0)\,\eta\left(\frac{s}{s_0}\right)^{\alpha(0)-1} e^{Bt}$

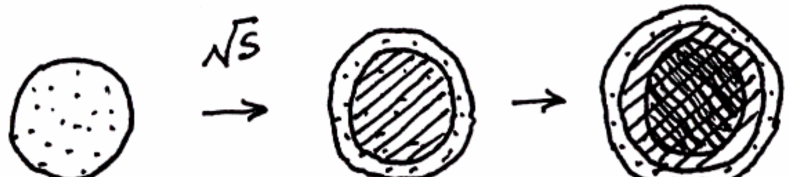
$$\left\{ \begin{array}{l} \eta = \dfrac{i}{\sin\frac{\pi\alpha}{2}},\ \mathcal{S}=1 \\ \quad = \dfrac{1}{\cos\frac{\pi\alpha}{2}},\ \mathcal{S}=-1 \end{array} \right.$$

where $B(s) = R_c^2 + \alpha'\left[\ln\left(\frac{s}{s_0}\right) - i\frac{\pi}{2}\right]$

R_c is t-dep. of Regge couplings $\beta_{AC}(t)\,\beta_{BD}(t)$

$$T(s,b) = \frac{\beta(0)\eta}{B}\left(\frac{s}{s_0}\right)^{\alpha(0)-1} \exp\left(-\frac{b^2}{4B}\right)$$

Naive 'eff' Pomeron pole: $\alpha(0)-1 \equiv \Delta \sim 0.08$, $\alpha' \sim 0.25\ \mathrm{GeV}^{-2}$



narrower q_T
wider b distrib^n

Im $T_{Pom}(s,b)$ exceeds black disc limit, at small b, before LHC energies

To correct for unitarity: eikonalize amplitude

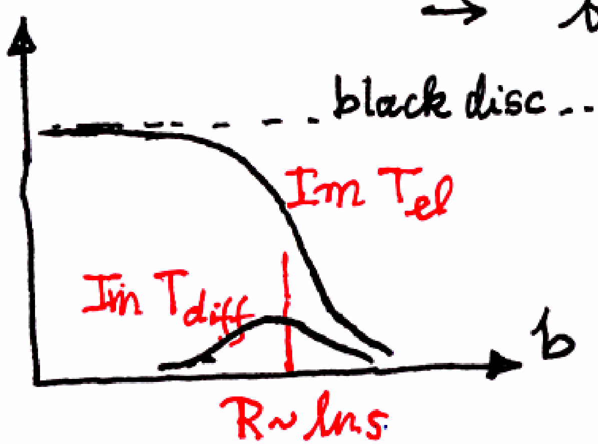
i.e. $\mathrm{Im}\, T_{el} = \left(1 - e^{-\Omega/2}\right)$

with $$\frac{\Omega}{2} = \frac{\beta\eta}{B}\left(\frac{s}{s_0}\right)^{\Delta} \exp\left(-\frac{b^2}{4B}\right)$$

$$\underset{HE}{\sim} \frac{\beta\eta}{B} \exp\left(\Delta \ln\left(\frac{s}{s_0}\right) - \frac{b^2}{4\alpha' \ln\left(\frac{s}{s_0}\right)}\right)$$

$$\gg 1 \quad \text{for } b^2 < R^2 = 4\alpha' \Delta \ln^2 \frac{s}{s_0}$$

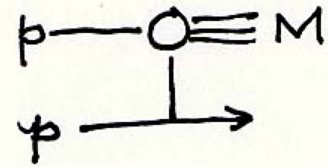
→ black disc for $b \lesssim R$



ere $B(s) = \cancel{R_c^2} + \alpha'\left[\ln\left(\frac{s}{s_0}\right) - i\cancel{\frac{\pi}{2}}\right]$

$$T(s,b) = \frac{\beta(0)\eta}{B}\left(\frac{s}{s_0}\right)^{\alpha(0)-1} \exp\left(-\frac{b^2}{4B}\right)$$

Recall low M diffraction



Let $|p\rangle, |N^*\rangle, \ldots \Rightarrow \sum a_{ik} |\phi_k\rangle$

$i = 1, \; 2, \ldots$

↑ diffractive eigenstates only undergo "elastic-type" scatt.

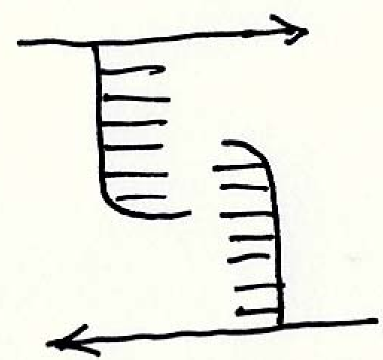
$i=1,2$ sufficient

two-channel eikonal

High M diffraction ?

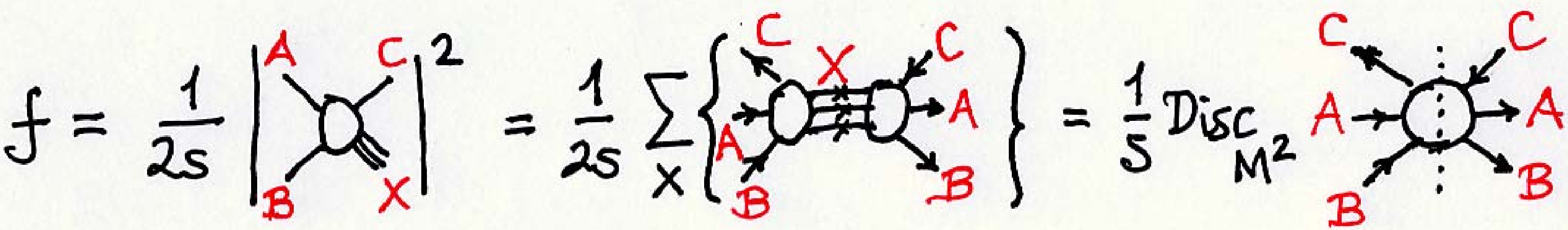
Enlarge no. of $|\phi_k\rangle$'s ?

Even if practical, have the problem of overlapping particle production for central rapidities



Mueller optical theorem

$$f = E_c \frac{d\sigma}{d^3p_c}(AB \to CX) = \frac{1}{s}\,\mathrm{Disc}_{M^2}\,T(AB\bar{C} \to AB\bar{C})$$

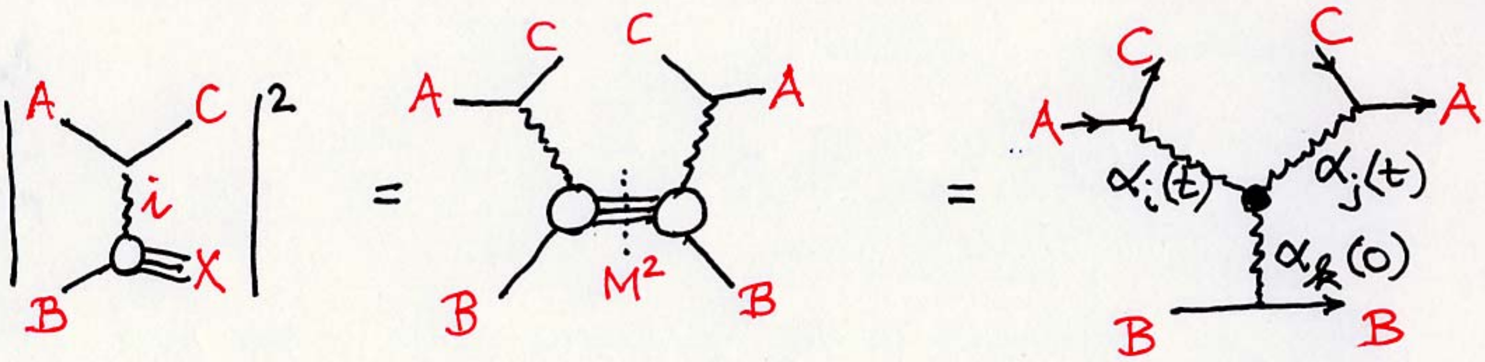


Proof is not trivial. C is an outgoing particle and we are not in the physical region of the elastic process. We need to make a delicate analytical continuation of a many variable 3-body amplitude.

Triple Regge region

$M^2 \to \infty, \quad \frac{s}{M^2} \to \infty$

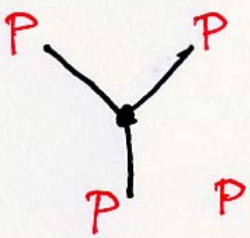
high mass diff^{ve} dissoc^{n}



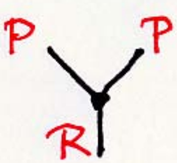
$$f = \frac{1}{s}\,\beta^{i}_{AC}(t)\,\beta^{j}_{AC}(t)\left(\frac{s}{M^2}\right)^{\alpha_j(t)+\alpha_i(t)} \mathrm{Disc}_{M^2}\left(\alpha_i B \to \alpha_j B\right)$$

$$= \frac{1}{s}\,\beta_{ijk}(t)\left(\frac{s}{M^2}\right)^{\alpha_j(t)+\alpha_i(t)} \left(M^2\right)^{\alpha_k(0)}$$

$$= \beta_{ijk}(t)\; s^{\alpha_j(t)+\alpha_i(t)-1} \left(M^2\right)^{\alpha_k(0)-\alpha_j(t)-\alpha_i(t)}$$

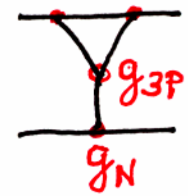


$$f(s, t=0, M^2) \sim \frac{s}{M^2} \qquad \text{if } \alpha_P(0) = 1$$

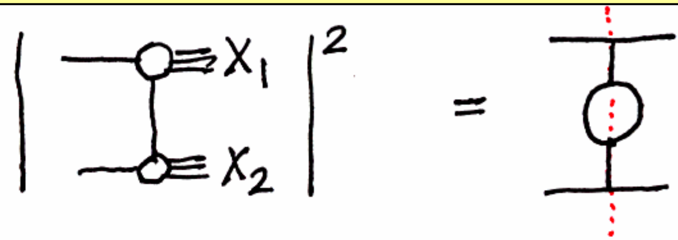


$$f(s, t=0, M^2) \sim s\left(M^2\right)^{-3/2} \qquad \text{if } \alpha_R(0) = 0.5$$

Single dissocation: $\frac{d\sigma^{SD}}{dM^2 dt} \sim \frac{1}{s} g_N^3 g_{3P} \left(\frac{s}{M^2}\right)^{2\alpha_P(t)-1} (M^2)^{\alpha_P(0)-1}$



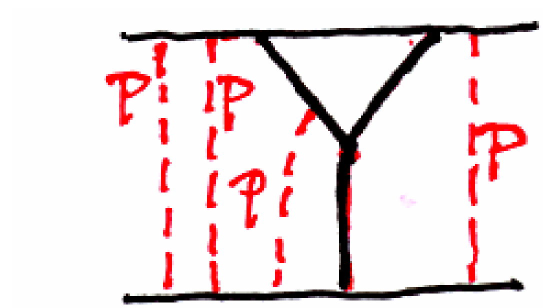
Double diffractive dissociation



$$\frac{d\sigma^{DD}}{dM_1^2 dM_2^2 dt} \sim \frac{1}{s} g_N^2 g_{3P}^2 \left(\frac{s}{M_1^2 M_2^2}\right)^{2\alpha_P(t)-1} (M_1^2)^{\alpha_P(0)-1} (M_2^2)^{\alpha_P(0)-1}$$

So far Pomeron regarded as an exchanged particle.
But Pomeron with “intercept” $\Delta = \alpha_P(0) - 1 > 0$ leads to a violation of unitarity as s→ infinity: $\sigma_{tot} \sim s^{\Delta}$, $\sigma_{SD,DD} \sim s^{2\Delta}$

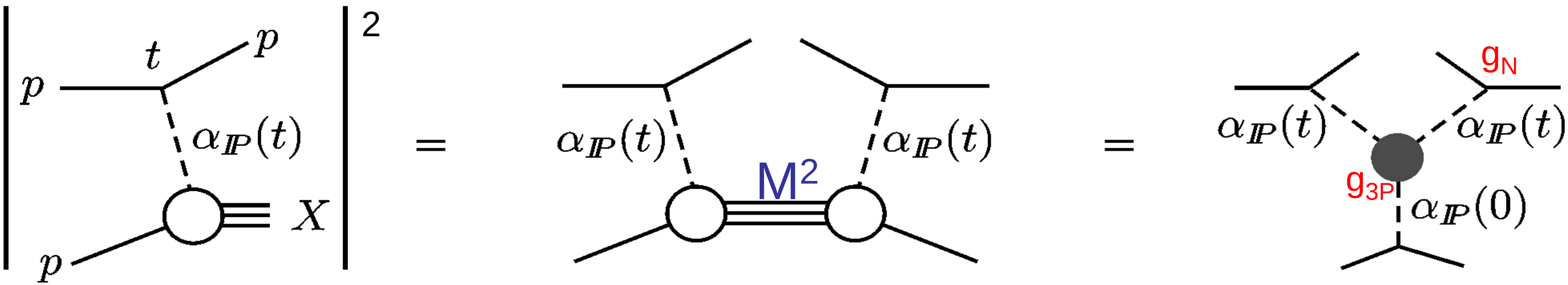
Multi-Pomeron exch^s suppress this growth and restore s-ch unitarity.
Called unitarity/screening/abs corr^{ns}



find $g_{3P} = \lambda\, g_N$ $\lambda \sim 0.2$

← why is λ sufficently large, that enh. multi-Pom diagrams important at HE ?

naïve argument without absorptive effects:



$M^2 d\sigma_{SD}/dM^2 \sim g_N^3\, g_{3P} \sim \lambda \sigma_{el}$

$\ln s/M_0^2$

$(\sigma_{el} \sim g_N^4)$

$$\sigma_{\rm SD} = \int \frac{M^2 d\sigma_{\rm SD}}{dM^2} \frac{dM^2}{M^2} \sim \lambda \ln(s/M_0^2)\, \sigma_{el}$$

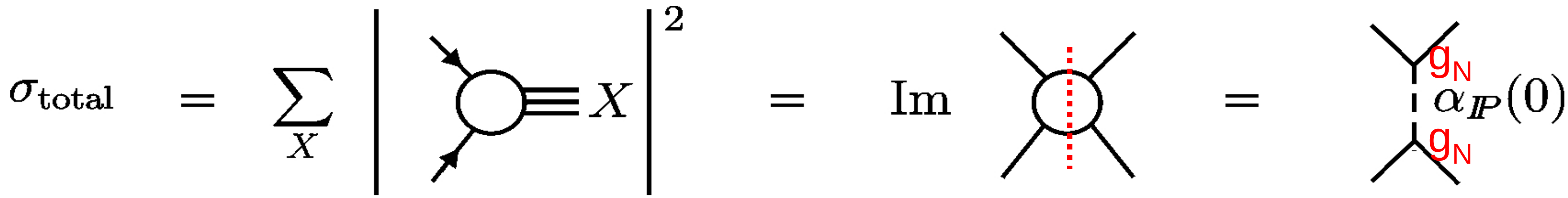
so at HE collider energies σ_{SD}(large M) $\sim \sigma_{el}$

SD is "enhanced" by larger phase space available at HE.

Summary

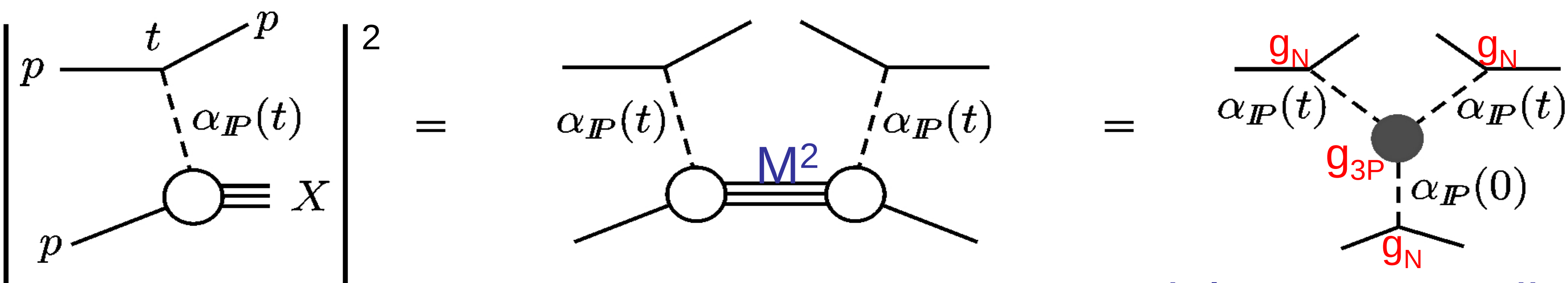
Optical theorems

at high energy
use Regge



$$g_N^{\,2}\left(\frac{s}{s_0}\right)^{\alpha_{I\!P}(0)-1}$$

High-mass diffractive dissociation

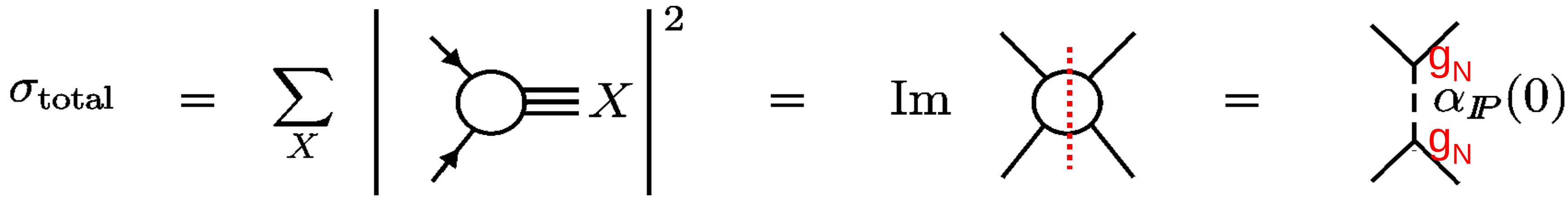


triple-Pomeron diag

$$g_N^{\,3}g_{3P}\left(\frac{M^2}{s_0}\right)^{\alpha_{I\!P}(0)-1}\left(\frac{s}{M^2}\right)^{2\alpha_{I\!P}(t)-2}$$

Optical theorems

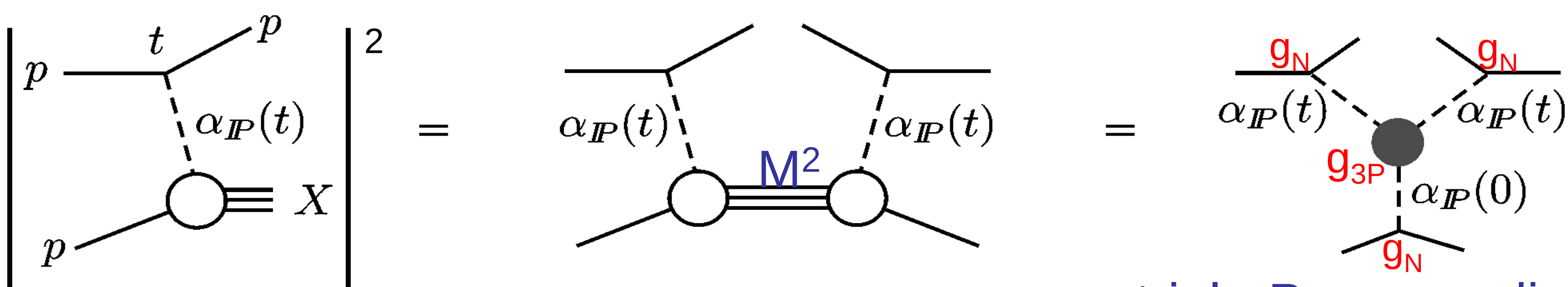
at high energy
use Regge



but screening/s-ch unitarity
important so σ_{total} suppressed

$$g_N^2 \left(\frac{s}{s_0}\right)^{\alpha_{I\!P}(0)-1}$$

High-mass diffractive dissociation



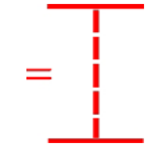
triple-Pomeron diag

$$g_N^3 g_{3P} \left(\frac{M^2}{s_0}\right)^{\alpha_{I\!P}(0)-1} \left(\frac{s}{M^2}\right)^{2\alpha_{I\!P}(t)-2}$$

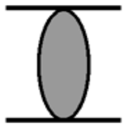
but screening even more important

Elastic amp. $T_{el}(s,b)$

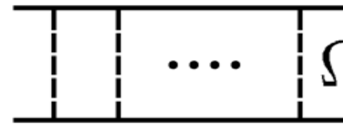
bare amp. $\Omega/2$ =



$$\mathrm{Im}\ T_{\rm el} =$$



$$= 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty}$$

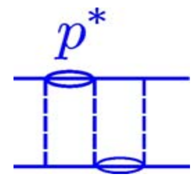


$\Omega/2$

(s-ch unitarity)

(-20%)

Low-mass diffractive dissociation

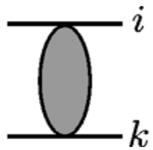


→multichannel eikonal

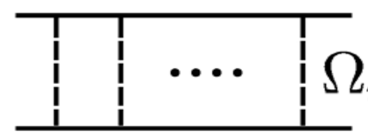
introduce diff^ve estates ϕ_i, ϕ_k (comb^ns of p,p*,..) which only undergo "elastic" scattering (Good-Walker)

(-40%)

$$\mathrm{Im}\ T_{ik} =$$



$$= 1 - e^{-\Omega_{ik}/2} = \sum$$

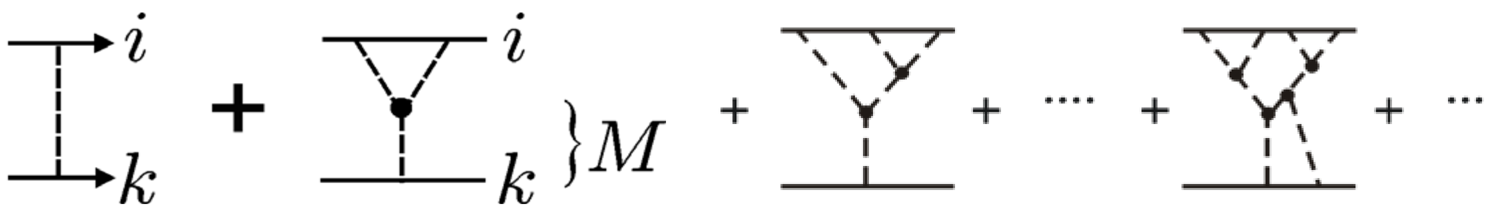


$\Omega_{ik}/2$

include high-mass diffractive dissociation

(SD -80%)

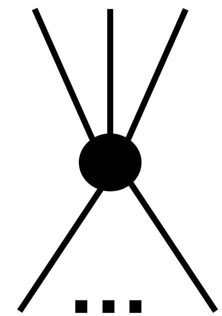
$$\Omega_{ik} =$$



Multi-Pomeron couplings

So far, considered only triple-Pomeron coupling → leads to σ_{tot} which decreases at asymptotic energies.

More reasonable to include
m → n Pomeron vertices

$g^m{}_n$ = 

Data favour

$$g^m{}_n = g_{3P}\,(\lambda g_N)^{m+n-2}$$

(this form satisfies AGK cutting rules).

see EPJ**C71**(2011)1617 for more discussion.

Summary of t-channel viewpoint

Regge formalism appropriate for HE (large s) and
forward scattering (t~0) --- for "soft" HE hadron inter^{ns}

Constant or increasing $\sigma_{tot}(s)$ with s → **Pomeron →**

→ (a) processes with large rapidity gaps
→ valuable exclusive HE data
(b) soft multiparticle production
→ vital to understand the underlying event
to rare New Physics processes at the LHC

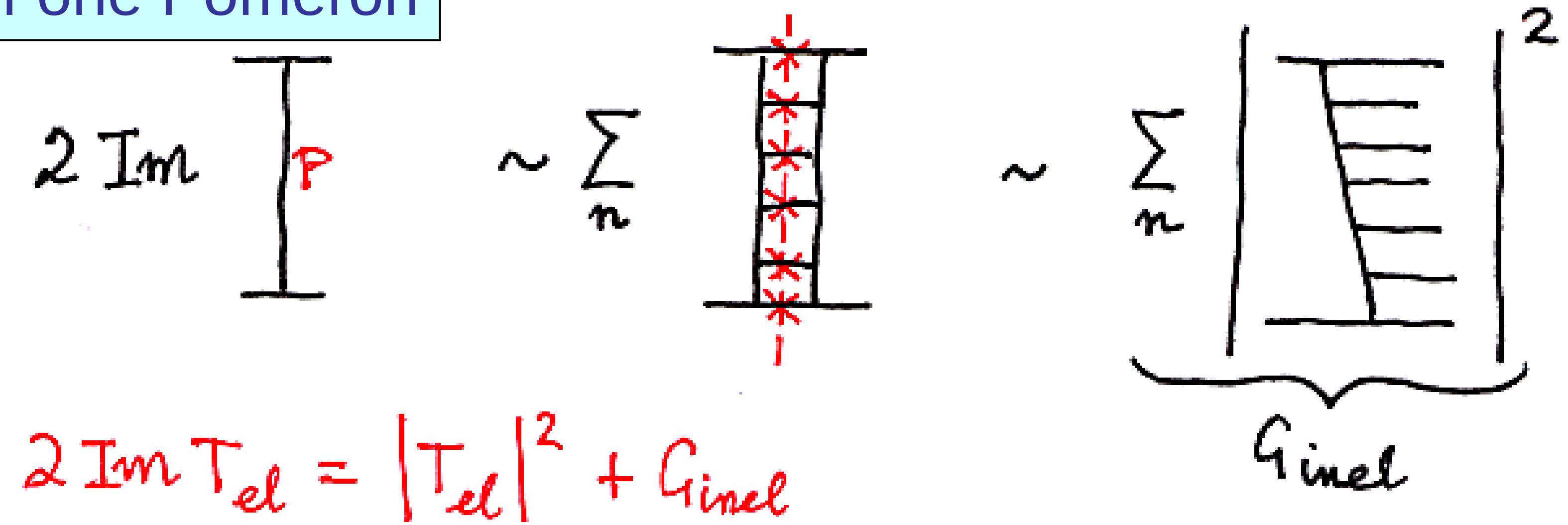
Triple Regge needed for high-mass dissociation

Importance of absorption (unitarity corrections)
→ multi-Pomeron exchanges

s-channel unitarity and Pomeron exchange

Unitarity relates the Im part of ladder diagrams (disc T = 2 Im T) to cross sections for multiparticle production

Exch. of one Pomeron

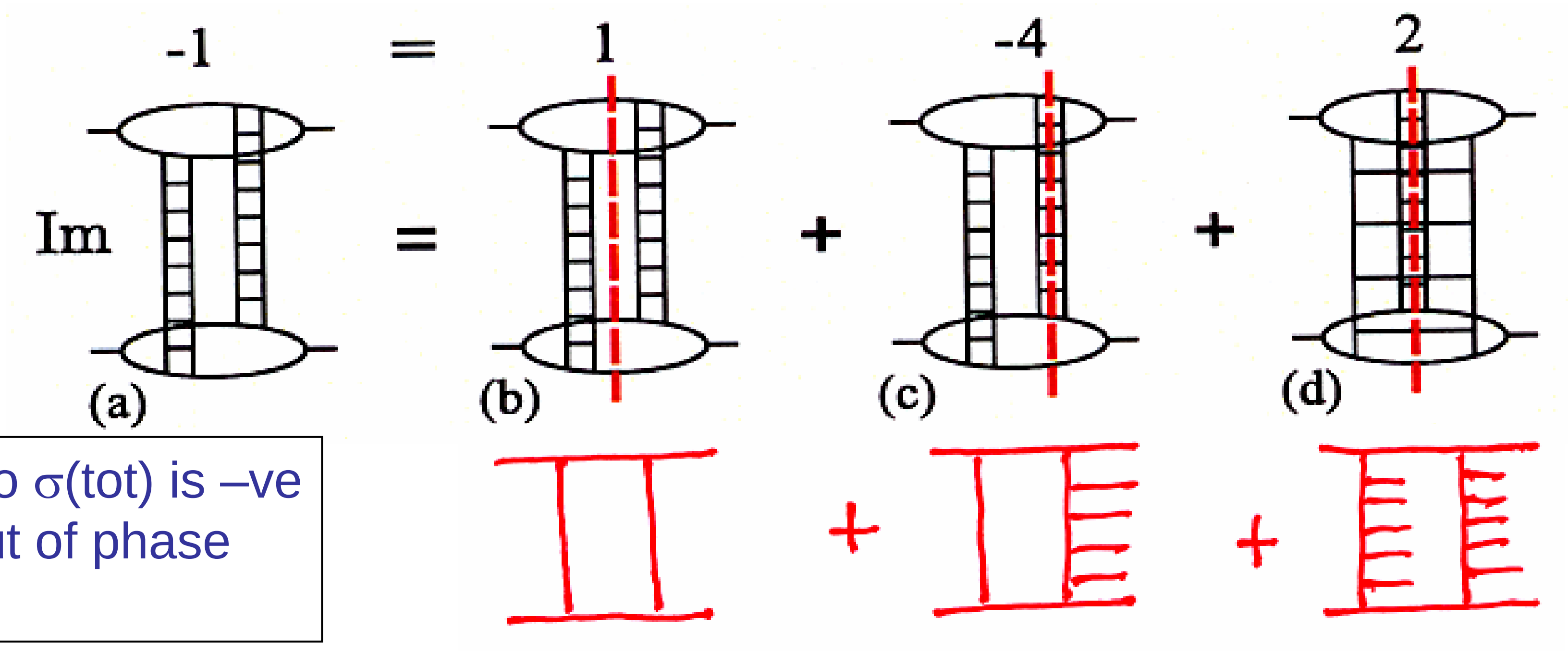


The coherence of ψ(beam) is destroyed by interaction of last exch. pt. with target. Leads, not only to inelastic high-multiplicity production, but also, via unitarity, to elastic scattering. Elastic scattering is due to the absorption of an initial coherent component, and originates from the remaining part of ψ(beam) which preserves its coherence

eikonal multi-Pom diagrams: $\text{Im } T = 1-e^{-\Omega/2} = \Omega/2 - \Omega^2/8 + \ldots$

Exch. of two Pomerons

now three types of "cut" diagrams



contrib^n to σ(tot) is –ve
PxP is out of phase
with P

$\sigma_0 = \sigma$(el), no multiplicity

σ_1, single P multiplicity
abs. corr. to one P amp

σ_2

-- Factors 1, - 4, 2 come from AGK cutting rules (see MP's talk)

-- **σ_0, σ_2** must be positive (real final states)

-- A multi-Pom diagram describes several different processes

Partonic model of the Pomeron ?

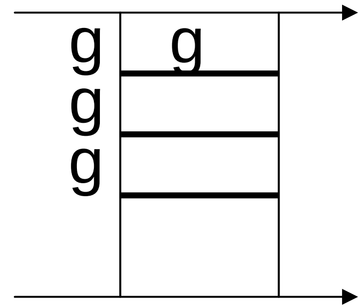
If we had a partonic model of the Pomeron perhaps we could merge “soft” and “hard” high energy pp interactions ?

Could lead to a reliable all-purpose Monte Carlo which describes all aspects on minimum bias data – total, differential elastic X-sections, diffraction, multi-particle production, jet production – in a unified framework ?

Very important to precisely describe the underlying event to the rare New Physics signals at the LHC

Ladder structure of the Pomeron after QCD

Shortly after the discovery of QCD it was proposed that (colourless) two-gluon exch. had properties of Pomeron exch:
vacuum quantum no's, singularity at j=1



--Later, using the BFKL formalism, in which the t-ch gluons (rather than hadrons) become Reggeized, it was found possible (for sufficiently large k_T) to describe HE (low x) interactions in pQCD.

--BFKL sum up the leading $(\alpha_s \log 1/x)^n$ contributions and build up the hard/pQCD/BFKL Pomeron.

--The Pomeron, is not a pole, but a branch cut in the complex angular momentum plane, plus more complicated cuts at HO

"Soft" and "Hard" Pomerons ?

A vacuum-exchange object drives soft HE interactions. Not a simple pole, but an enigmatic non-local object. Rising σ_{tot} means multi-Pom diags (with Regge cuts) are necessary to restore unitarity. σ_{tot}, $d\sigma_{el}/dt$ data, described, in a limited energy range, by eff. pole $\alpha_P^{eff} = 1.08 + 0.25t$

Sum of ladders of Reggeized gluons with, in LLx BFKL, a singularity which is a cut and not a pole. When HO are included the intercept of the BFKL/hard Pomeron is $\alpha_P^{bare}(0) \sim 1.3$

$\mathbf{\Delta = \alpha_P(0) - 1 \sim 0.3}$

$\alpha_P^{eff} \sim 1.08 + 0.25\ t$

up to Tevatron energies

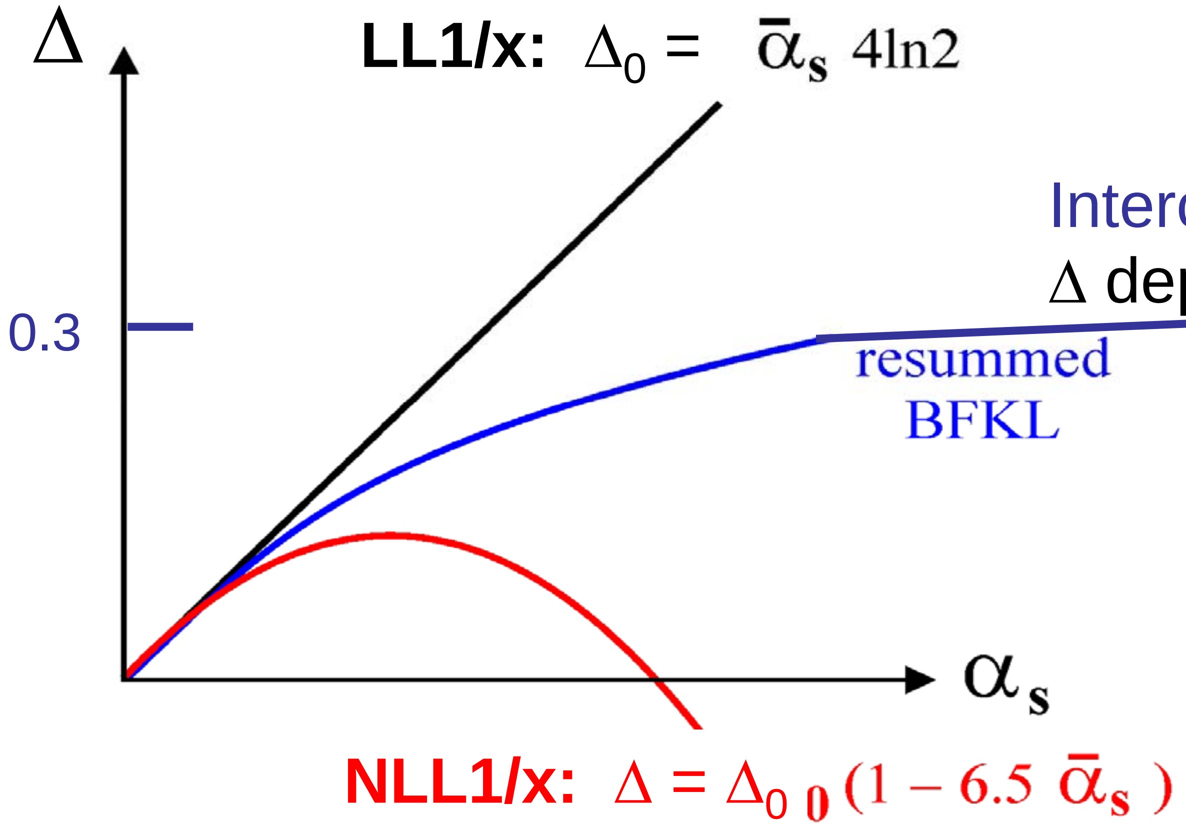
$(\sigma_{tot} \sim s^{\Delta})$

$\alpha_P^{bare} \sim 1.3 + 0\ t$

with absorptive (multi-Pomeron) effects

BFKL stabilized

$\Delta = \alpha_P(0) - 1$



Intercept $\Delta = \alpha_P(0) - 1 \sim 0.3$

Δ depends weakly on k_t for low k_t

DGLAP: $\alpha_s \ln Q^2$

BFKL: $\alpha_s \ln 1/x$

Small-size "BFKL" Pomeron is natural object to continue from "hard" to "soft" (low k_t) domain

“Soft” and “Hard” Pomerons ?

A vacuum-exchange object drives soft HE interactions. Not a simple pole, but an enigmatic non-local object. Rising σ_{tot} means multi-Pom diags (with Regge cuts) are necessary to restore unitarity. σ_{tot}, $d\sigma_{el}/dt$ data, described, in a limited energy range, by eff. pole $\alpha_P^{eff} = 1.08 + 0.25t$

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$\Delta = \alpha_P(0) - 1 \sim 0.3$

$\alpha_P^{eff} \sim 1.08 + 0.25\ t$

up to Tevatron energies

($\sigma_{tot} \sim s^{\Delta}$)

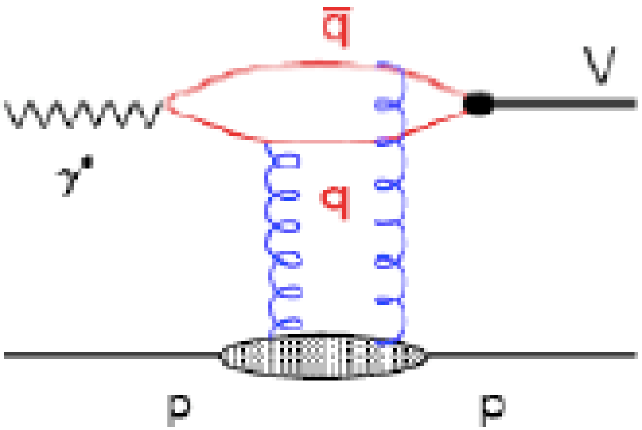
$\alpha_P^{bare} \sim 1.3 + 0\ t$

with absorptive (multi-Pomeron) effects

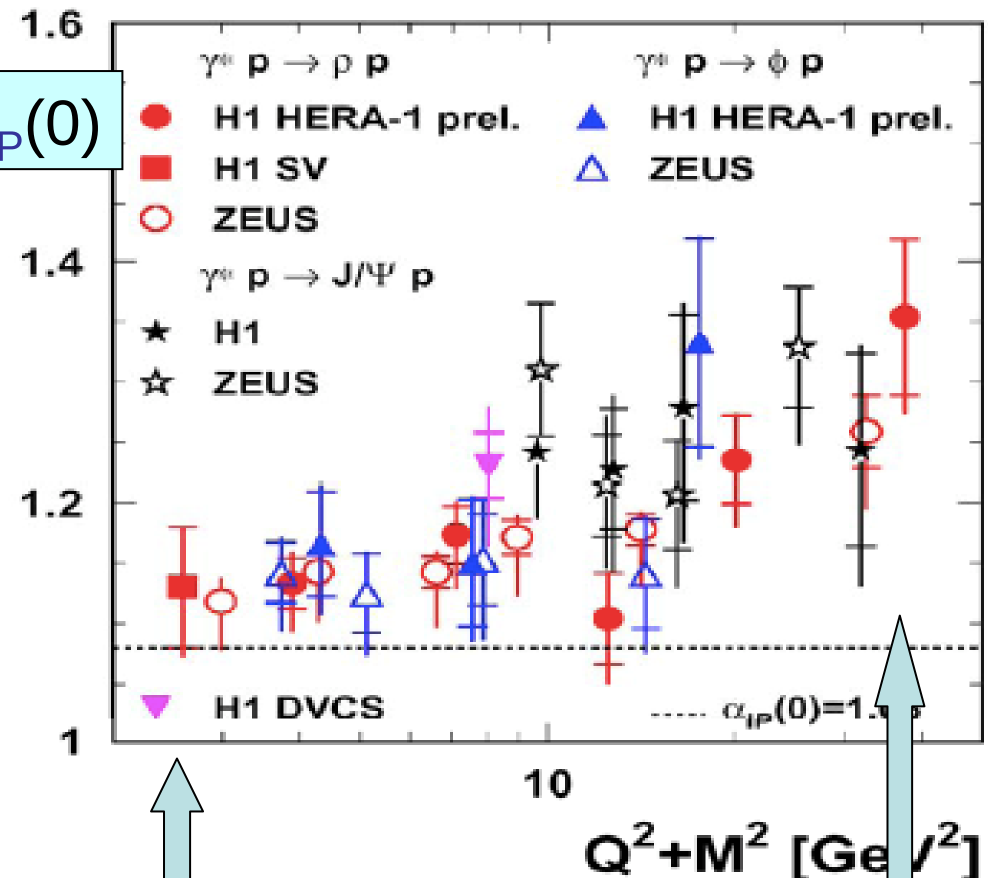
Vector meson prod^{n} at HERA
~ bare QCD Pom. at high Q^2
~ no absorption

hard energy dependences

Q^2



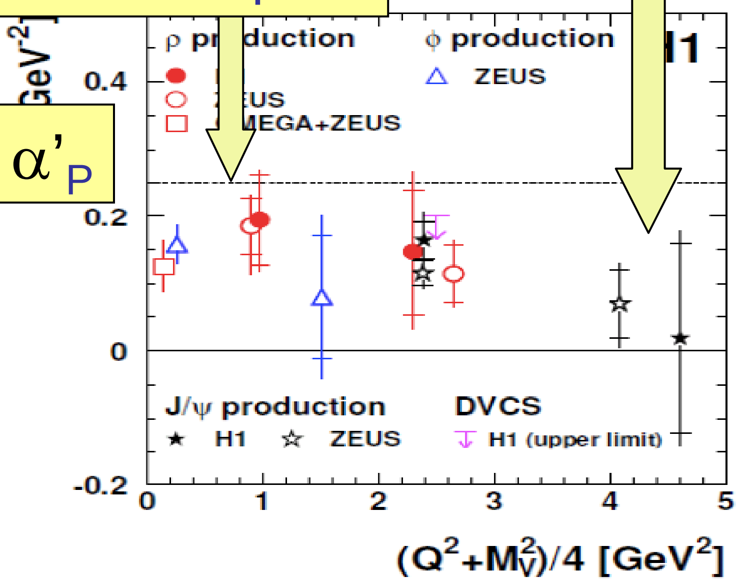
$\alpha_P(0)$



$\alpha'_P(0) \sim 0.25$
after absorption

$\alpha'^{bare}_P(0) \sim 0$

α'_P



$\alpha_P(0) \sim 1.1$
after absorption

$\alpha_P^{bare}(0) \sim 1.3$

Phenomeno$^{\text{logical}}$ hints that $R_{\text{bare Pom}} << R_{\text{proton}}$

small slope $\alpha'_{\text{bare}} \sim 0$

success of Additive QM

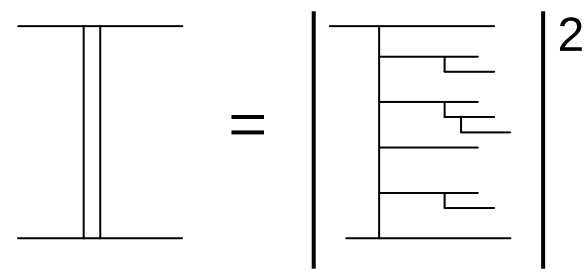
small size of triple-Pomeron vertex

small size of Bose-Einstein correlations at low N_{ch}

$$\alpha'_P \propto 1/\langle k_t^2 \rangle \propto R^2_{\text{Pom}}$$

$$r_{qq} \sim R_{\text{Pom}} \ll R_p$$

Pomeron is a parton cascade which develops in ln(1/x) space, and which is not strongly ordered in k_t.
However, above evidence indicates the cascade is compact in b space and so the parton k_t's are not too low. We may regard the cascade as a hot spot inside the two colliding protons



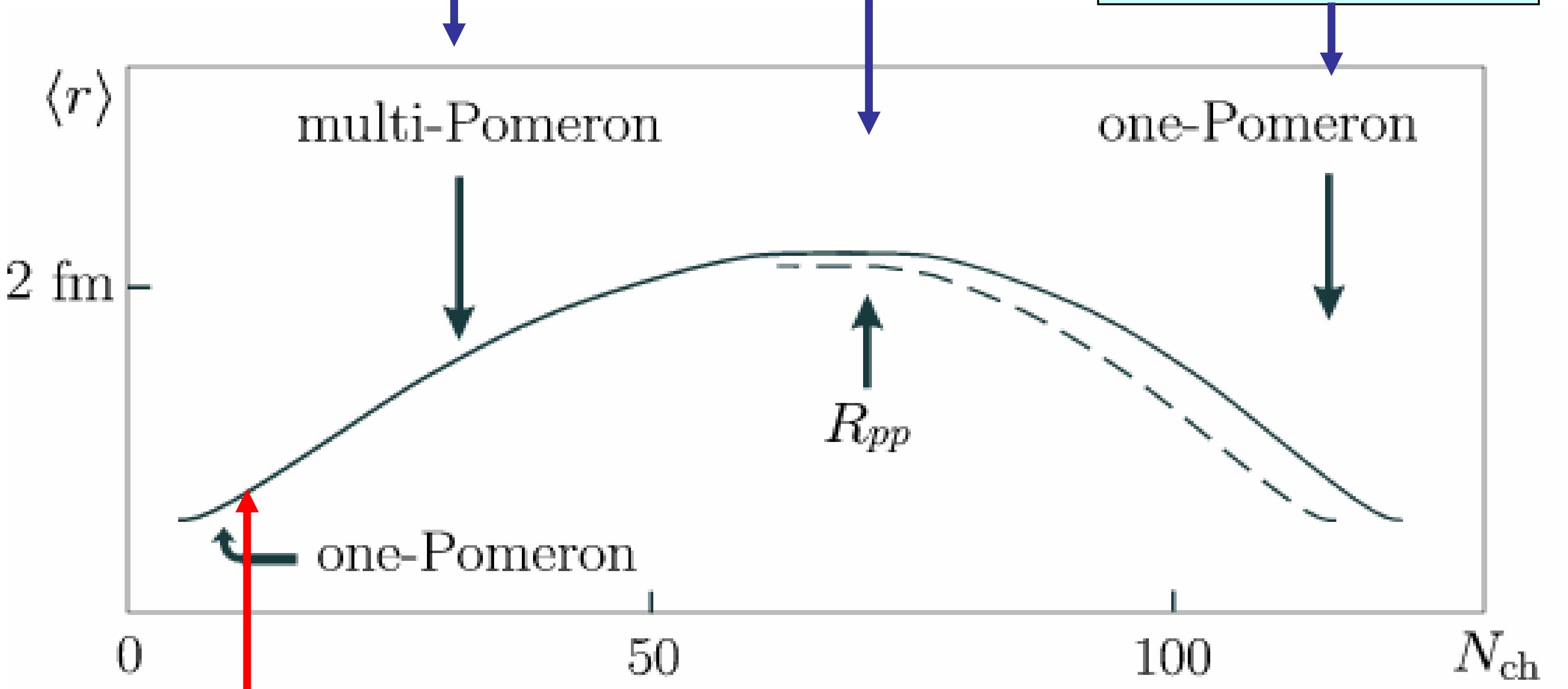
Probe of hot spots → Bose-Einstein correlations

identical pion correlations measure size of their emission region

dist. between Pomerons

saturates at $R_{pp} \sim B_{el}(s)^{1/2}$

large N_{ch} from high-E_T process from one ladder

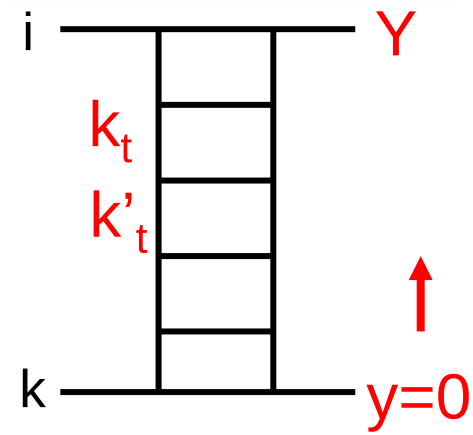


size indep. of s -- Pom. universal, but $r > R_{Pom}$ due to hadroniz^n

bkgd due to pions from resonances -- reduced for pions of larger k_t

Partonic structure of "bare" Pomeron

$\Omega = \Omega_{ik}(y, k_t, b)$



BFKL evol^{n} in rapidity generates ladder

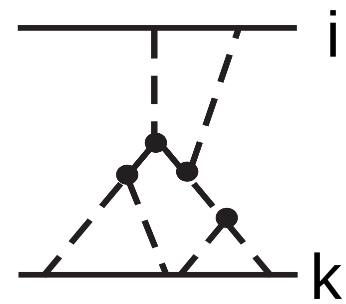
$$\frac{\partial \Omega(y,k_t)}{\partial y} = \bar{\alpha}_s \int d^2k'_t \; K(k_t,k'_t)\; \Omega(y,k'_t)$$

- At each step k_t and b of parton can be be changed – so, in principle, we have 3-variable integro-diff. eq. to solve

Khoze,Martin,Ryskin

- **Inclusion of k_t crucial to match soft and hard domains. Moreover, embodies less screening for larger k_t comp^{ts}.**
- KMR use a simplified form of the kernel K with the main features of BFKL – diffusion in log k_t^2, $\Delta = \alpha_P(0) - 1 \sim 0.3$
- b dependence during the evolution is prop' to the Pomeron slope α', which is v.small ($\alpha' < 0.05$ GeV^{-2}) -- so ignore. Only b dependence comes from the starting evol^{n} distrib^{n}
- Evolution gives → $\Omega = \Omega_{ik}(y, k_t, b)$

How are Multi-Pomeron contrib^{ns} included?



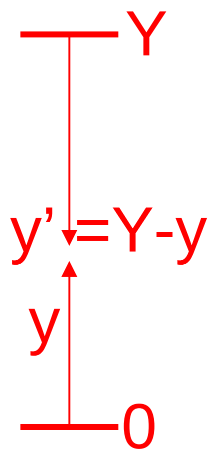
Now include rescatt of intermediate partons with the “beam” i and “target” k (KMR)

evolve up from y=0

$$\frac{\partial \Omega_k(y)}{\partial y} = \bar{\alpha}_s \int d^2k_t' \, \exp(-\lambda(\Omega_k(y) + \Omega_i(y'))/2) \, K(k_t, k_t') \, \Omega_k(y)$$

evolve down from y’=Y-y=0

$$\frac{\partial \Omega_i(y')}{\partial y'} = \bar{\alpha}_s \int d^2k_t' \, \exp(-\lambda(\Omega_i(y') + \Omega_k(y))/2) \, K(k_t, k_t') \, \Omega_i(y')$$



where $\lambda\Omega_{i,k}$ reflects the different opacity of protons felt by intermediate parton, rather the proton-proton opacity $\Omega_{i,k}$ $\lambda \sim 0.2$

solve iteratively for $\Omega_{ik}(y,k_t,b)$ **inclusion of k_t crucial**

Note: data prefer $\exp(-\lambda\Omega)$ → $[1 - \exp(-\lambda\Omega)] / \lambda\Omega$

Form is consistent with generalisation of AGK cutting rules

In principle, knowledge of $\Omega_{ik}(y,k_t,b)$ (and hadronization) allows the description of all soft, semi-hard pp high-energy data:

σ_{tot}, $d\sigma_{el}/dt$, $d\sigma_{SD}/dtdM^2$, DD, DPE…

LRG survival factors S^2 (to both eikonal, enhanced rescatt)

PDFs and diffractive PDFs at low x and low scales

Indeed, such a model can describe the main features of all the data, in a semi-quantitative way, with just a few physically motivated parameters. (KMR, EPJ C71)

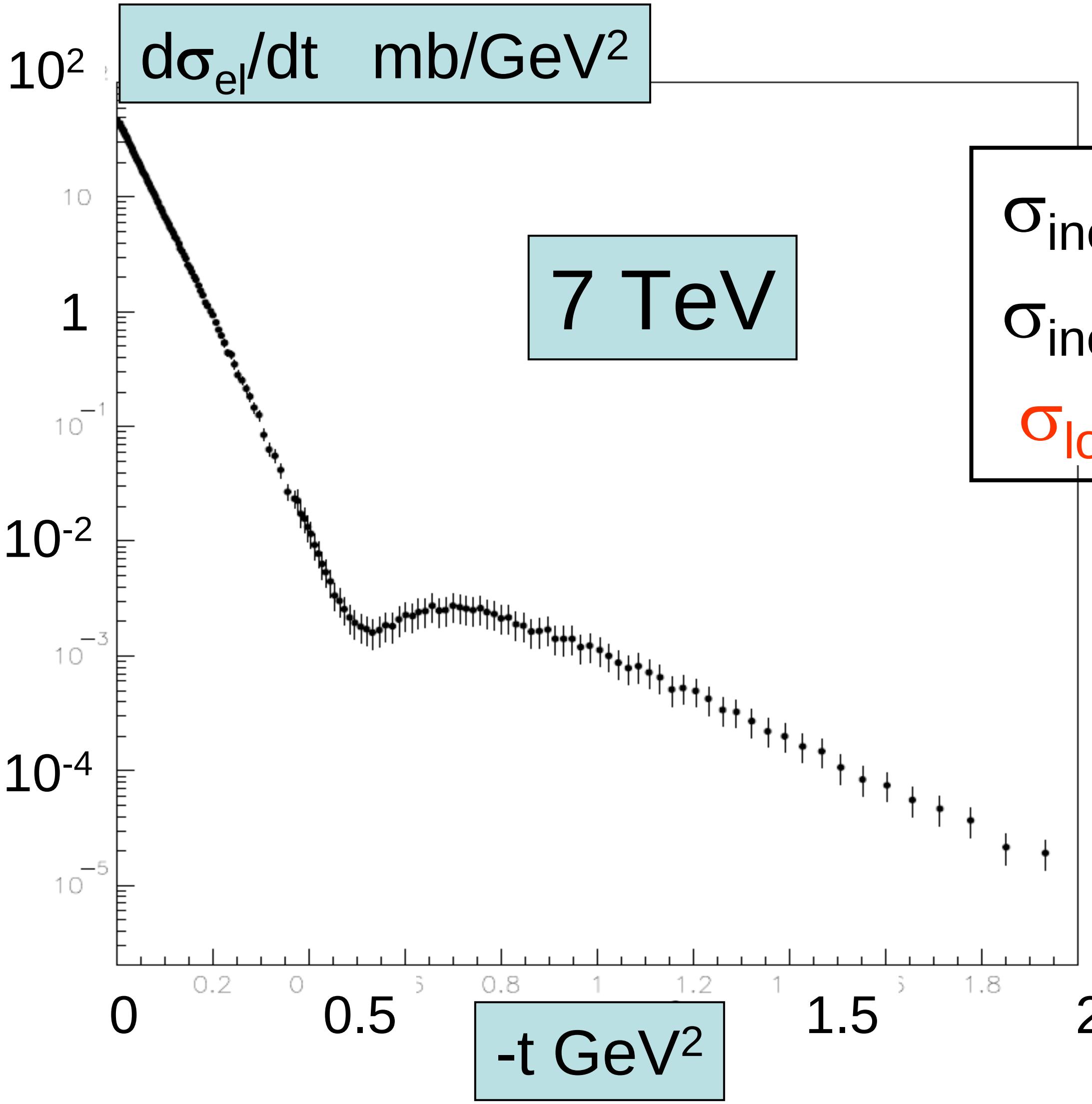
To describe less inclusive quantities we need a Monte Carlo including hadronization, see later.

Case Study: TOTEM data

see Mario Deile's talk

σ_{tot} = 98.6 +/- 2.2 mb

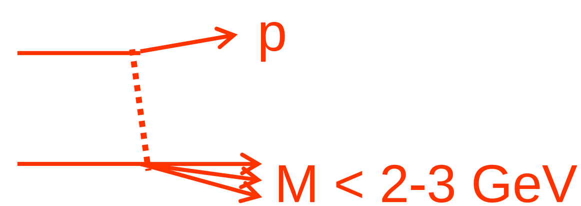
σ_{el} = 25.4 +/- 1.1 mb



σ_{inel} = 73.1 +/- 1.3 mb

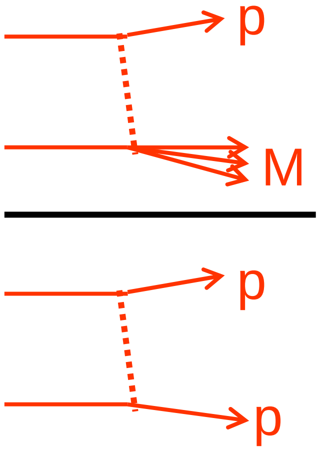
$\sigma_{inel(|\eta|<6.5)}$ = 70.5 +/- 2.9 mb

$\sigma_{low\ M\ dissn.}$ = 2.6 +/- 2.2 mb



What does it tell us about the Pomeron?

Only one other expt^al^ estimate of $\sigma_{\text{low M}}$



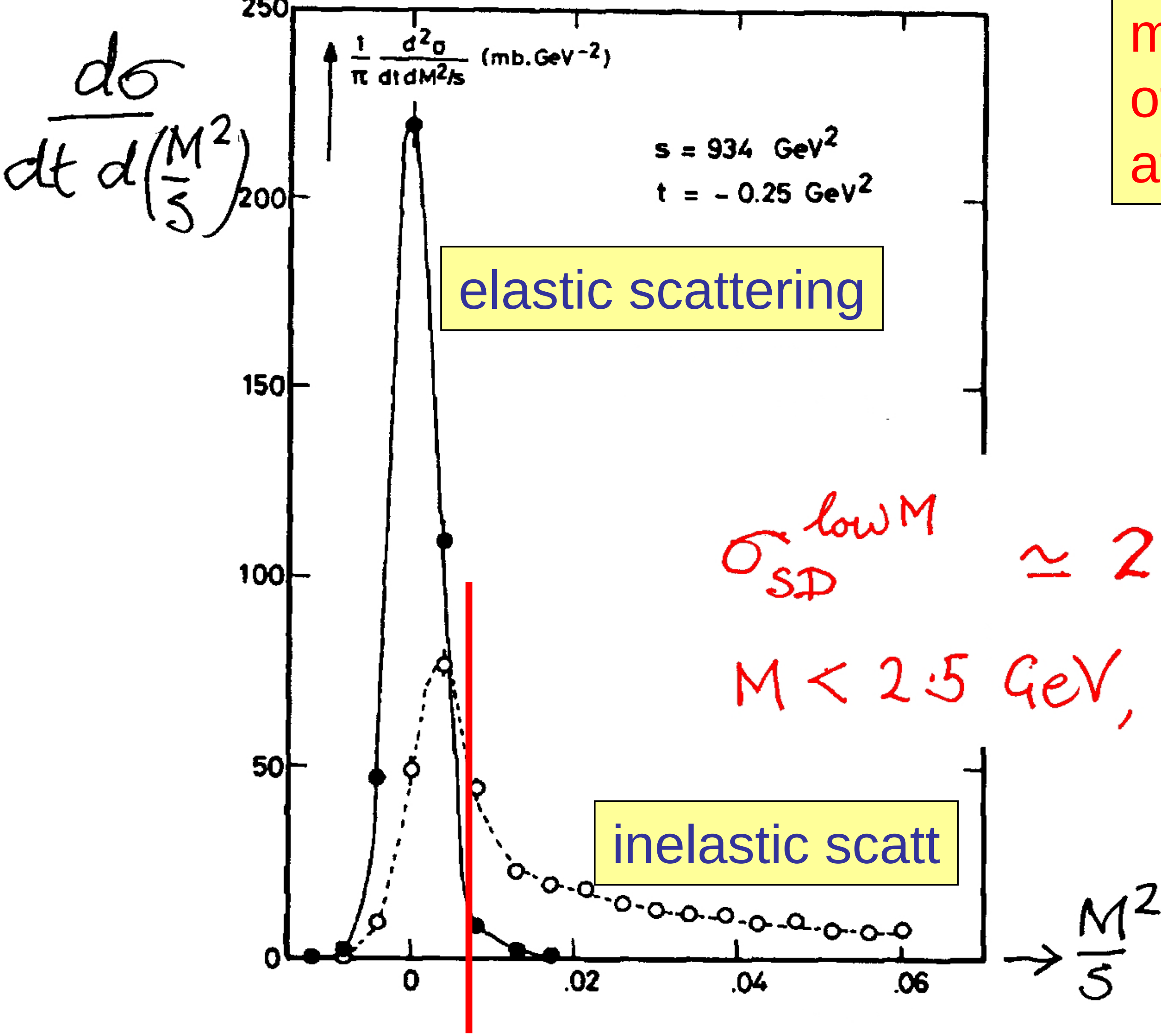
	CERN-ISR 31-62.5 GeV		TOTEM 7 TeV

$$\frac{\sigma_{\text{low M}}}{\sigma_{\text{elastic}}} = \frac{2\text{-}3\ \text{mb}}{7\ \text{mb}} \stackrel{?}{=} \frac{2.6\ \text{mb}}{25.4\ \text{mb}}$$

Unexpectedly small

Before TOTEM, models predicted $\sigma_{\text{low M}} \sim$ 6-10 mb

CERN-ISR measurements of single dissoc^n at low mass



$\sigma_{SD}^{\text{low}\,M} \simeq 2\text{ mb} - 3\text{ mb}$

$M < 2{\cdot}5$ GeV, $\sqrt{s} \simeq 31$ GeV

Can we describe all “soft” HE data

σ_{tot}, $d\sigma_{el}/dt$, $\sigma_{low\ M}$, (+ $\sigma_{high\ M}$)

from CERN-ISR → Tevatron → LHC

in terms of a single “effective” pomeron ?

Recall, low-mass dissociation is a consequence of the internal structure of proton. A constituent can scatter & destroy coherence of $|p\rangle$

Good-Walker: $|p\rangle = \Sigma\, a_i\, |\varphi_i\rangle$

where φ_i diagonalize T -- have only “elastic-type” scatt

Usually GW eigenstates assumed independent of t & s

KMR (1306.2149) parametrize form factor $F_i(t)$ for each $\varphi_{i=1,2}$

- Allows for $B_{el} \sim 10\ \text{GeV}^{-2}$ at CERN-ISR
  $B_{el} \sim 20\ \text{GeV}^{-2}$ at LHC (7 TeV)

  as well as diff^{ve} dip

→ smaller |t| at LHC, |p⟩ less distorted, so $\sigma_{\text{low M}}$ smaller

model 1

- Pomeron is a (BFKL) cut, not a pole

← low k_t ● high k_t → diffusion in log k_t

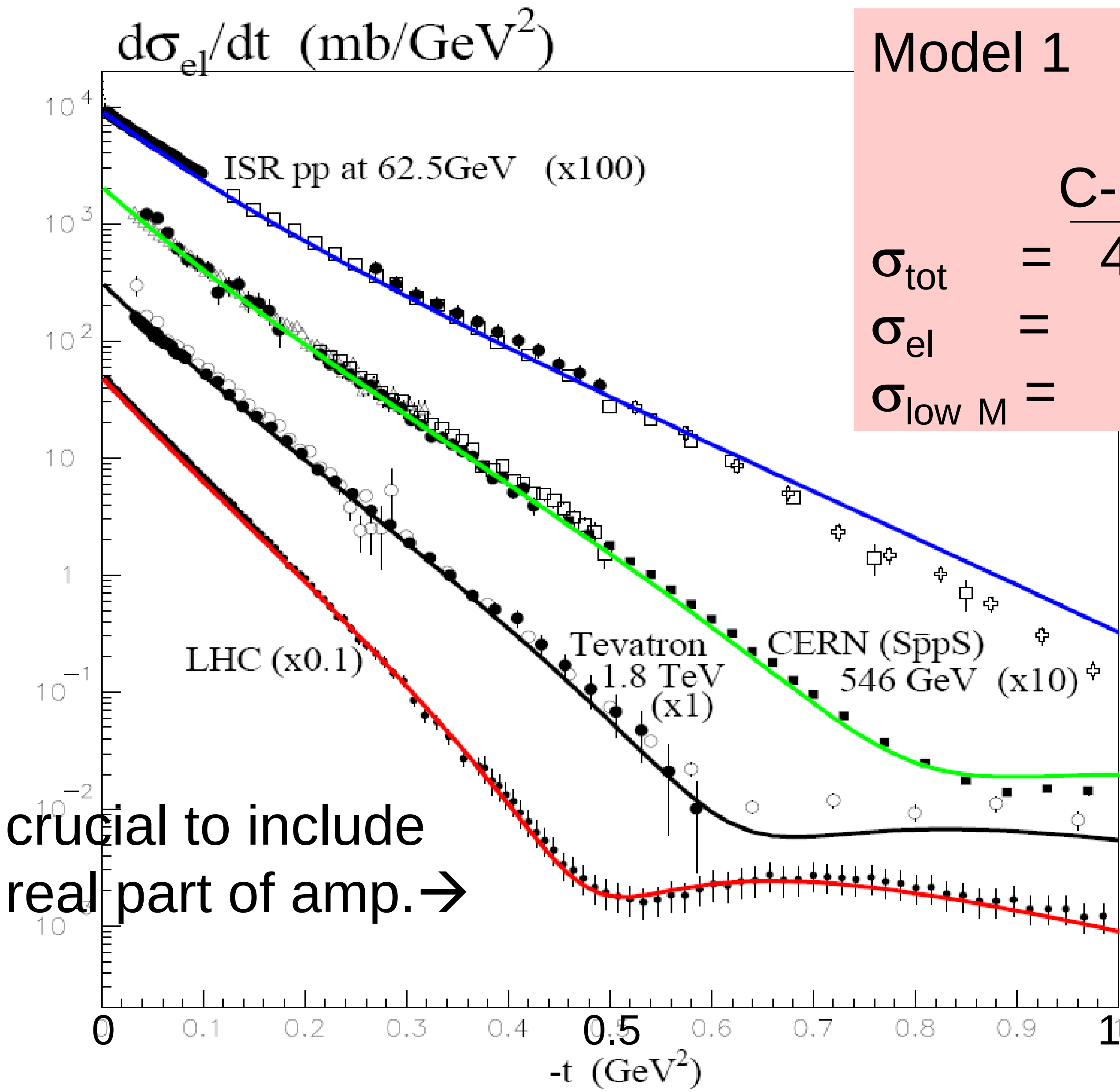
abs. corr^{ns} between intermediate parton-parton inter^{ns}

$\sigma_{abs} \sim 1/k_t^2$, suppress low k_t → mean k_t increases with s

$k_{min}^2 \sim s^{0.12}$

model 2

(enhanced multi-pom effects introduce dynamical infrared cutoff, see later)



crucial to include real part of amp.→

Model 1 (GW indep. of s)

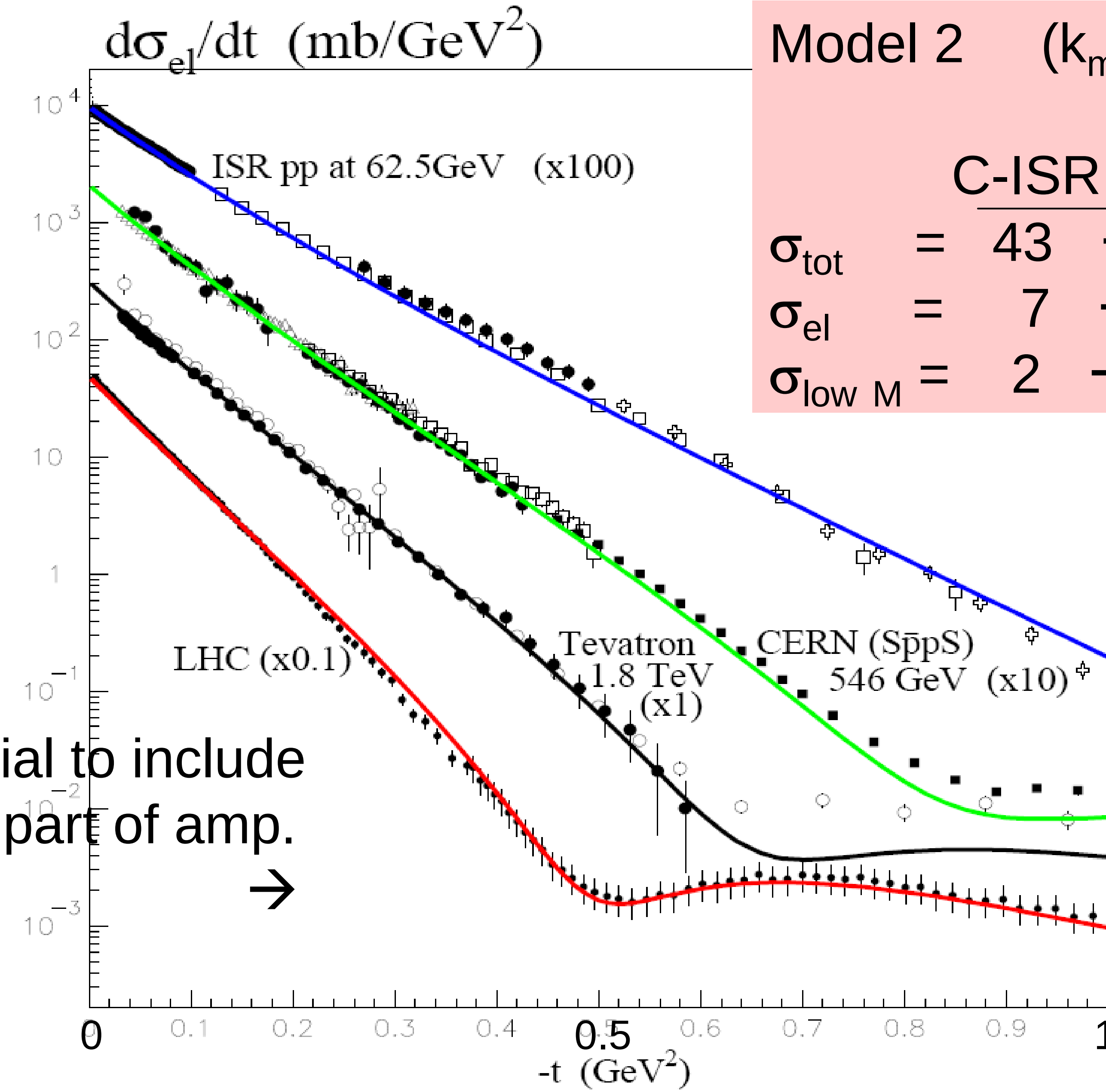
	C-ISR → LHC
σ_{tot} =	42 → 97 mb
σ_{el} =	7 → 23 mb
$\sigma_{low\ M}$ =	2 → 5 mb

better,
data 2.6 +/- 2.2

A description with
$\sigma_{low\ M}$ = 1 → 3 mb
is possible (secondary reggeon at ISR→1mb?)

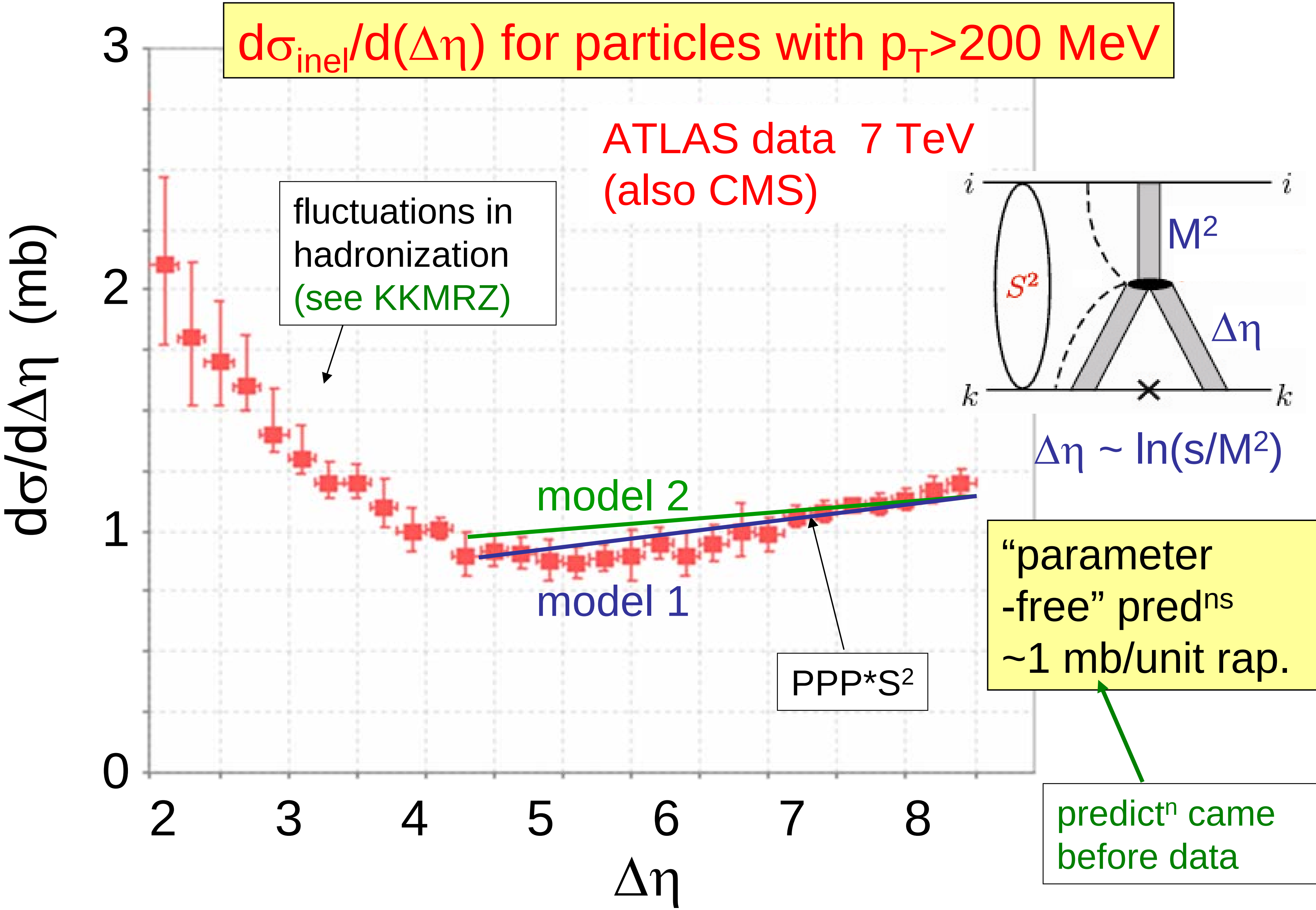
Model 2 ($k_{min} \sim s^{0.12}$)

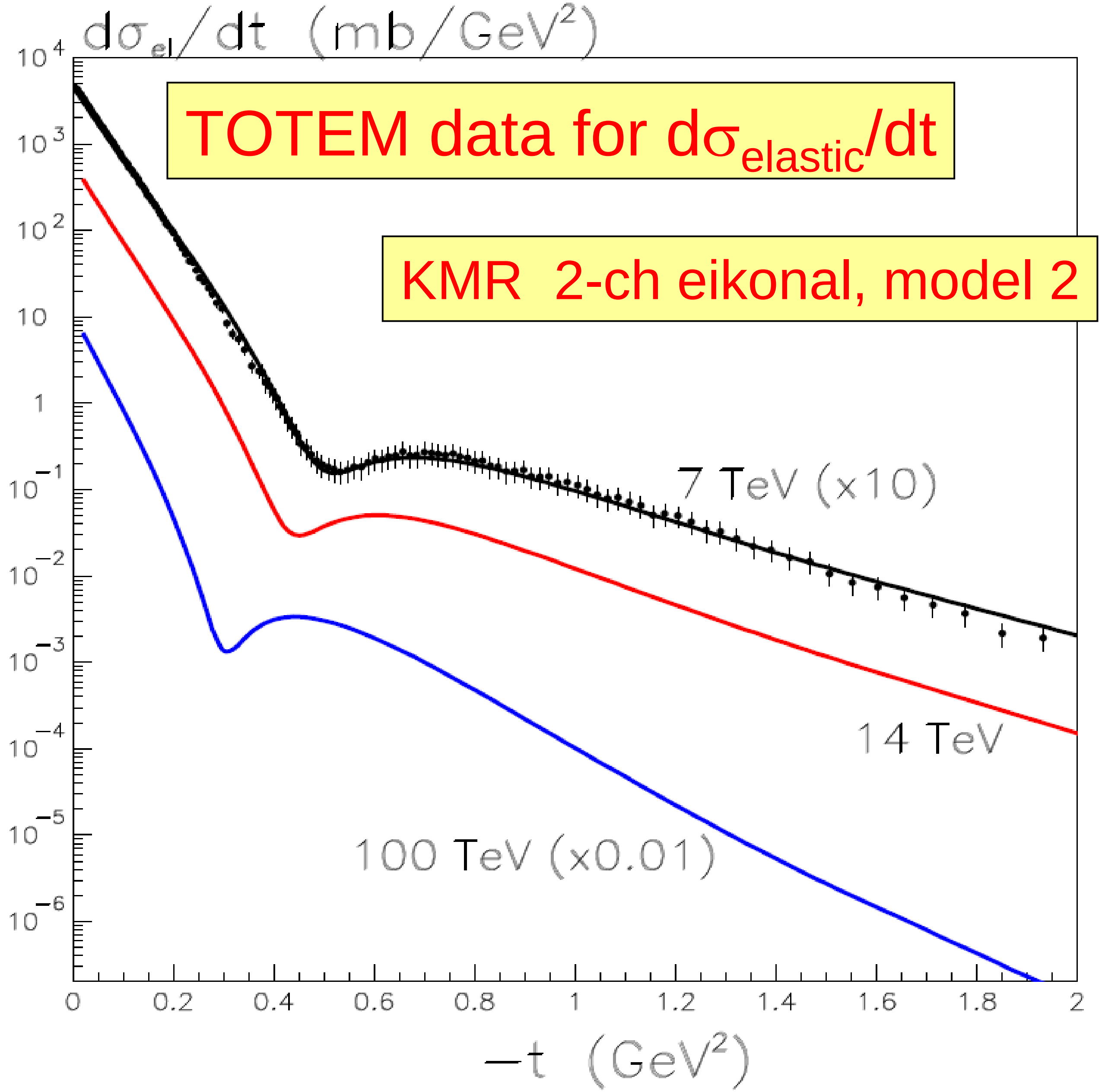
	C-ISR → LHC
σ_{tot} =	43 → 96.4 mb
σ_{el} =	7 → 24 mb
$\sigma_{low\ M}$ =	2 → 3.2 mb



crucial to include real part of amp. →

high-mass dissociation →


dσinel/d(Δη) for particles with pT>200 MeV
ATLAS data 7 TeV
(also CMS)
fluctuations in
hadronization
(see KKMRZ)
model 2
model 1
PPP*S2
i
i
M2
S2
Δη
k
k
Δη ~ ln(s/M2)
"parameter
-free" predns
~1 mb/unit rap.
predictn came
before data
dσ/dΔη (mb)
Δη
0
1
2
3
2
3
4
5
6
7
8


TOTEM data for $d\sigma_{elastic}/dt$
KMR 2-ch eikonal, model 2
$d\sigma_{el}/dt$ (mb/GeV^2)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
$-t$ (GeV^2)
7 TeV (x10)
14 TeV
100 TeV (x0.01)

Yes, it is possible to describe all “soft” HE data

σ_{tot}, $d\sigma_{el}/dt$, $\sigma_{low\ M}$, (+ $\sigma_{high\ M}$)

from CERN-ISR → Tevatron → LHC

in terms of a single “effective” pomeron

Energy dep. of σ_{el}, σ_{tot} controlled by intercept and slope of “effective” pomeron trajectory

Diffractive dip and $\sigma_{low\ M}$ controlled by properties of GW eigenstates

High-mass diss^n driven by multi-pomeron effects

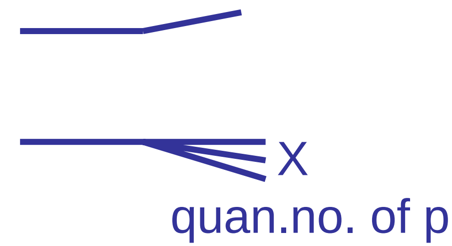
Two alternative definitions of diffraction

1. Diffraction is elastic or quasi-elastic scattering caused, via s-channel unitarity, by the absorption of components of the wave functions of the incoming particles

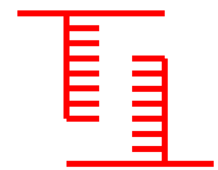
   e.g. pp→pp,

   pp→pX (single proton dissociation, SD),

   pp→XX (both protons dissociate, DD)

   (but problems with high M_X dissociation)

2. A diffractive process is characterized by a large rapidity gap (LRG), which is caused by t-channel Pomeron exch.

   (or, to be more precise, by the exchange corresponding to the rightmost singularity in the complex angular momentum plane with vacuum quantum numbers).

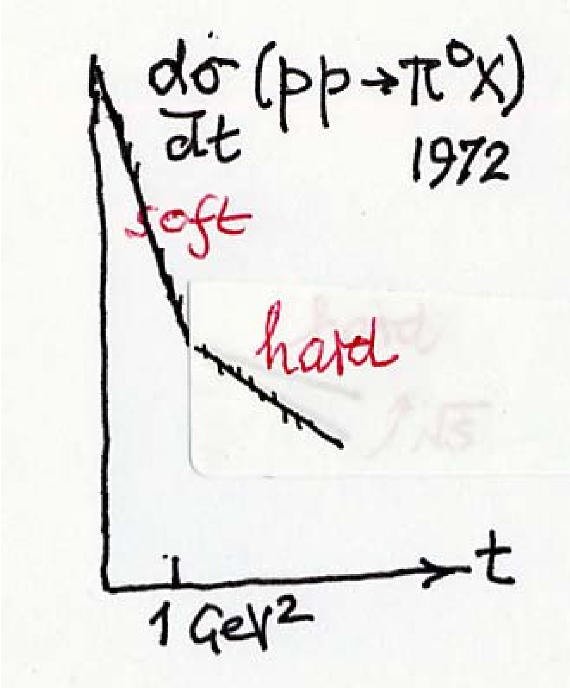
   (but plagued by background which produces rapidity gaps due to Reggeon exchange & fluctuations during hadronization process)

Soft and Hard HE interactions

Soft processes

have momentum transfer squared |t| less ~0.5 GeV^2, and have $d\sigma/dt \sim e^{-20t}$ at LHC, so v.few large |t| events.

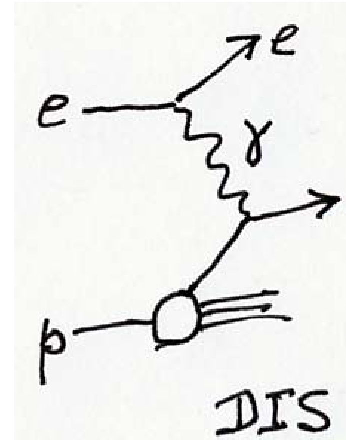
Such processes described by Regge Field Theory.
At high energies, Pomeron exch. dominates, and gives both LRGs & multi-pt events.



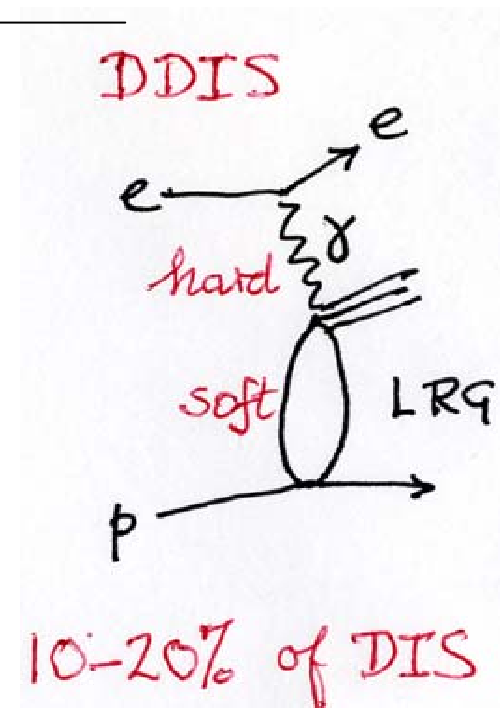
Hard processes

characterized by a large energy scale, |t| more ~ 2 GeV^2 – slower, power-like, fall-off with |t|, modulo logs.
Here perturbative QCD is appropriate

Hard processes continued



The required non-pert properties of the proton are determined from global analyses of data on DIS and related hard scatt. processes. In this way universal PDFs of the proton are obtained. Factorization theorems exist so PDFs can be taken from one hard process to another.



Hard diffractive processes exist. For example Diffractive DIS where there is a LRG between the p and the hadroniz^n products of the struck parton. From such data we obtain diffractive PDFs. These are not universal. To transport them we need to calculate the survival probability, S^2, of the LRG to soft rescattering, which is process dependent.

Survival prob., S^2, of rapidity gaps

Examples:

1. CDF and HERA diffractive dijet production

2. CDF diffractive dijet ratios

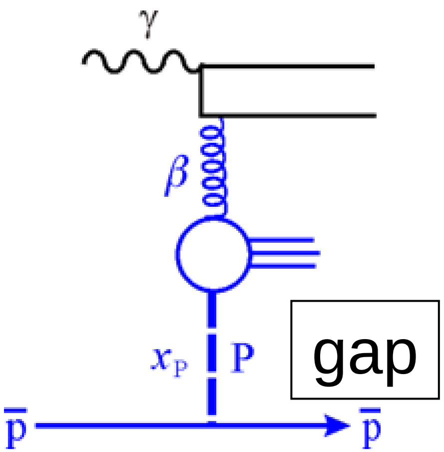
3. Exclusive J/ψ prod^n: $pp \to p+J/\psi+p$ Ronan McNulty
   (γ^* Pom $\to$) Joakim Nystrand

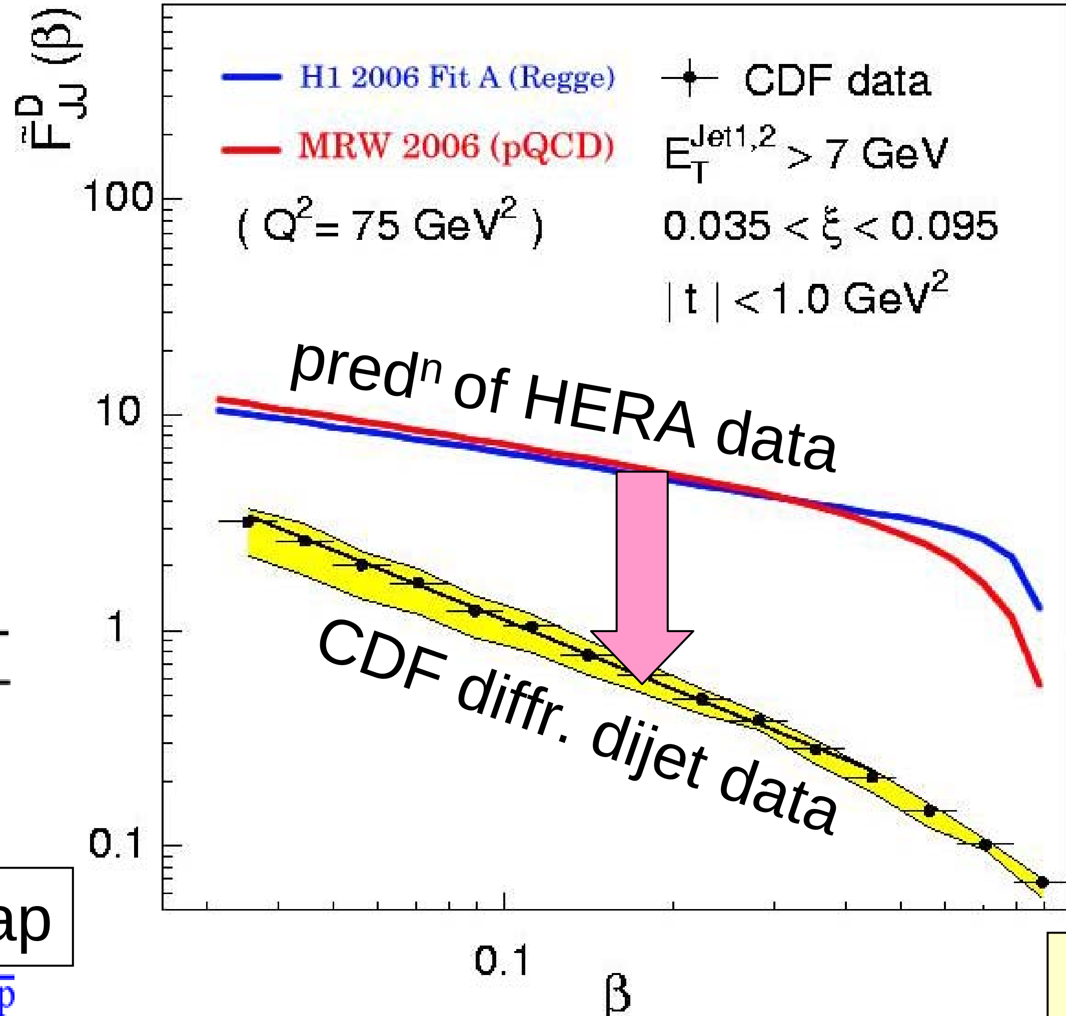
4. Central exclusive prod^n: $pp \to p+A+p$
   with A=Higgs, dijet, $\gamma\gamma$, χ_c.. Mike Albrow
   Antoni Szczurek

5. LHC check of S^2 using W+gap events

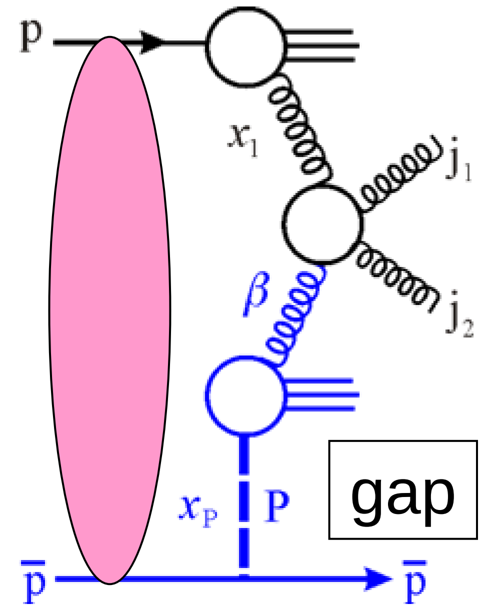
Example 1

Kaidalov
+KMR, 2001





soft
rescatt.



CDF diff^{ve} dijets

HERA→diff^{ve} PDFs

So, need to calculate survival probability, S^2, of the LRG to soft rescattering

Need $S^2 \sim 0.1$

Calculation of S^2

average over diff. estates i,k

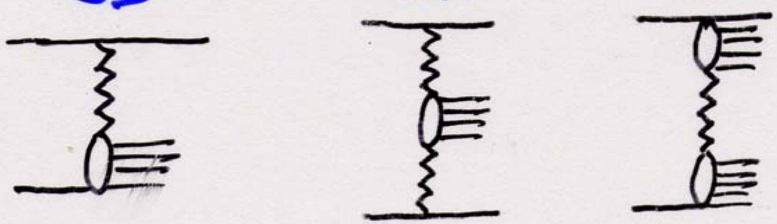
over b

prob. of proton to be in diffractive estate i

hard m.e. i k → H

$$\overline{S^2} = \frac{\sum_{i,k} \int d^2b\, |a_{pi}|^2\, |a_{p'k}|^2\, |\mathcal{M}_{ik}|^2\, \exp(-\Omega_{ik}(s,b))}{\sum_{i,k} \int d^2b\, |a_{pi}|^2\, |a_{p'k}|^2\, |\mathcal{M}_{ik}|^2}$$

survival factor w.r.t. soft i-k interaction.
Recall that $e^{-\Omega}$ is the prob. of no inelastic scatt. (which would otherwise fill the gap)

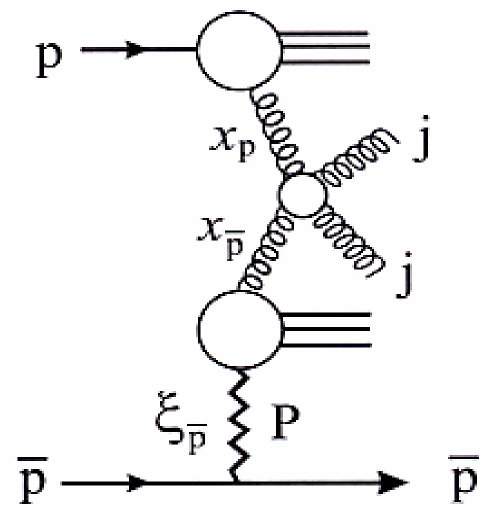


Values of S^2	SD	CD	DD
Tevatron	0.10	0.05	0.15
LHC	0.06	0.02	0.10

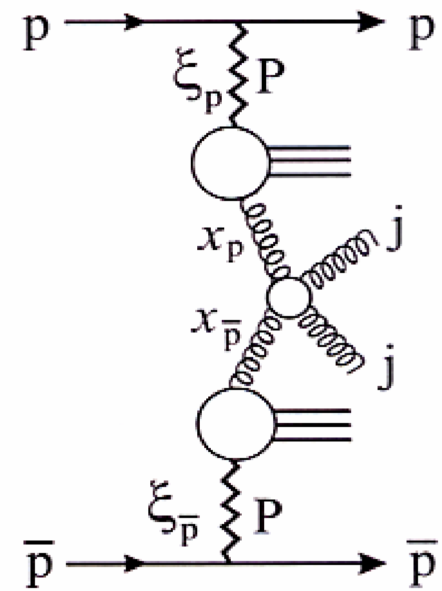
Example 2

A.B. Kaidalov et al. / Physics Letters B 559 (2003)

Dijet production at the Tevatron

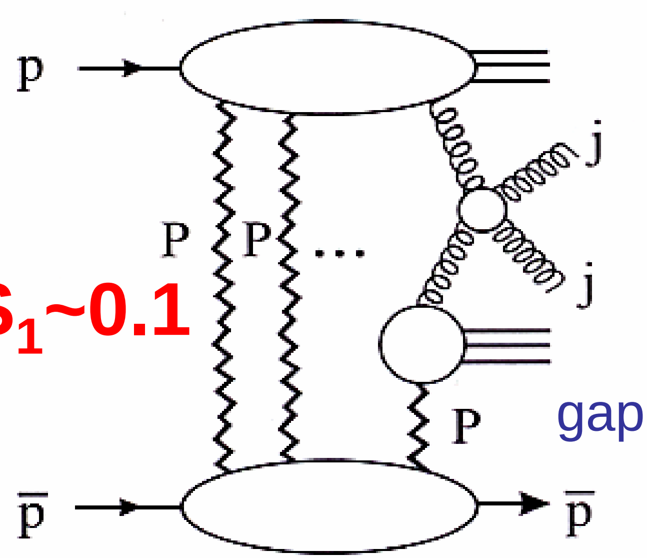


SD

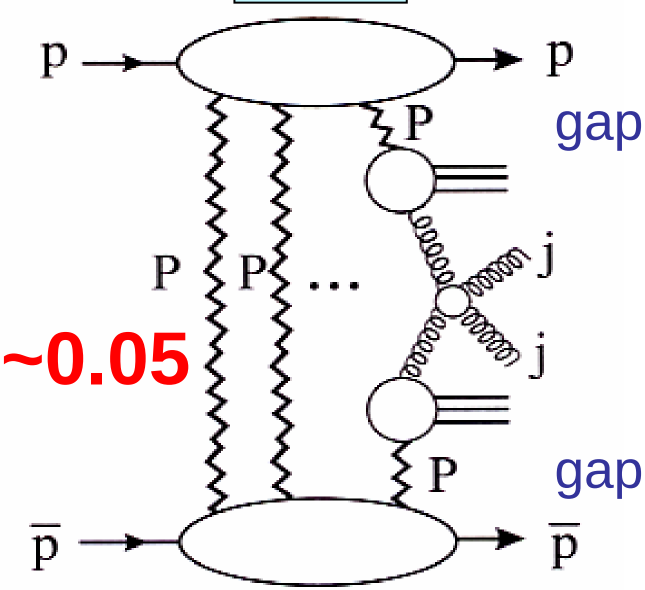


DPE

Survival prob. of gaps:

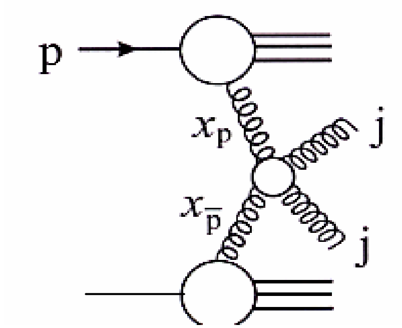


$S_1 \sim 0.1$

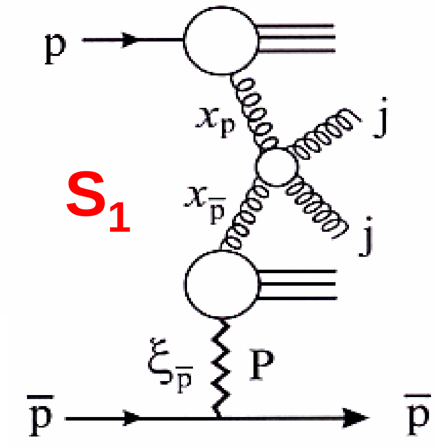


$S_2 \sim 0.05$

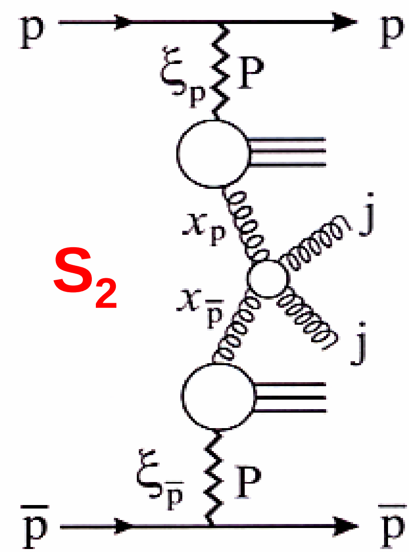
F_P is Pomeron "flux factor"
ξ is fraction of incoming mom. carried by Pom.
$x = \beta\xi$
f are the effective PDFs



ND



SD



DP

$$R^{SD}_{ND} \equiv \frac{\sigma^{SD}_{jj}}{\sigma^{ND}_{jj}} = \frac{F_P(\xi_{\bar p}) f_P(\beta)\beta}{f_{\bar p}(x_{\bar p}) x_{\bar p}} S_1$$

$$R^{DP}_{SD} \equiv \frac{\sigma^{DP}_{jj}}{\sigma^{SD}_{jj}} = \frac{F_P(\xi_p) f_P(\beta_1)\beta_1}{f_p(x_p) x_p} \frac{S_2}{S_1}$$

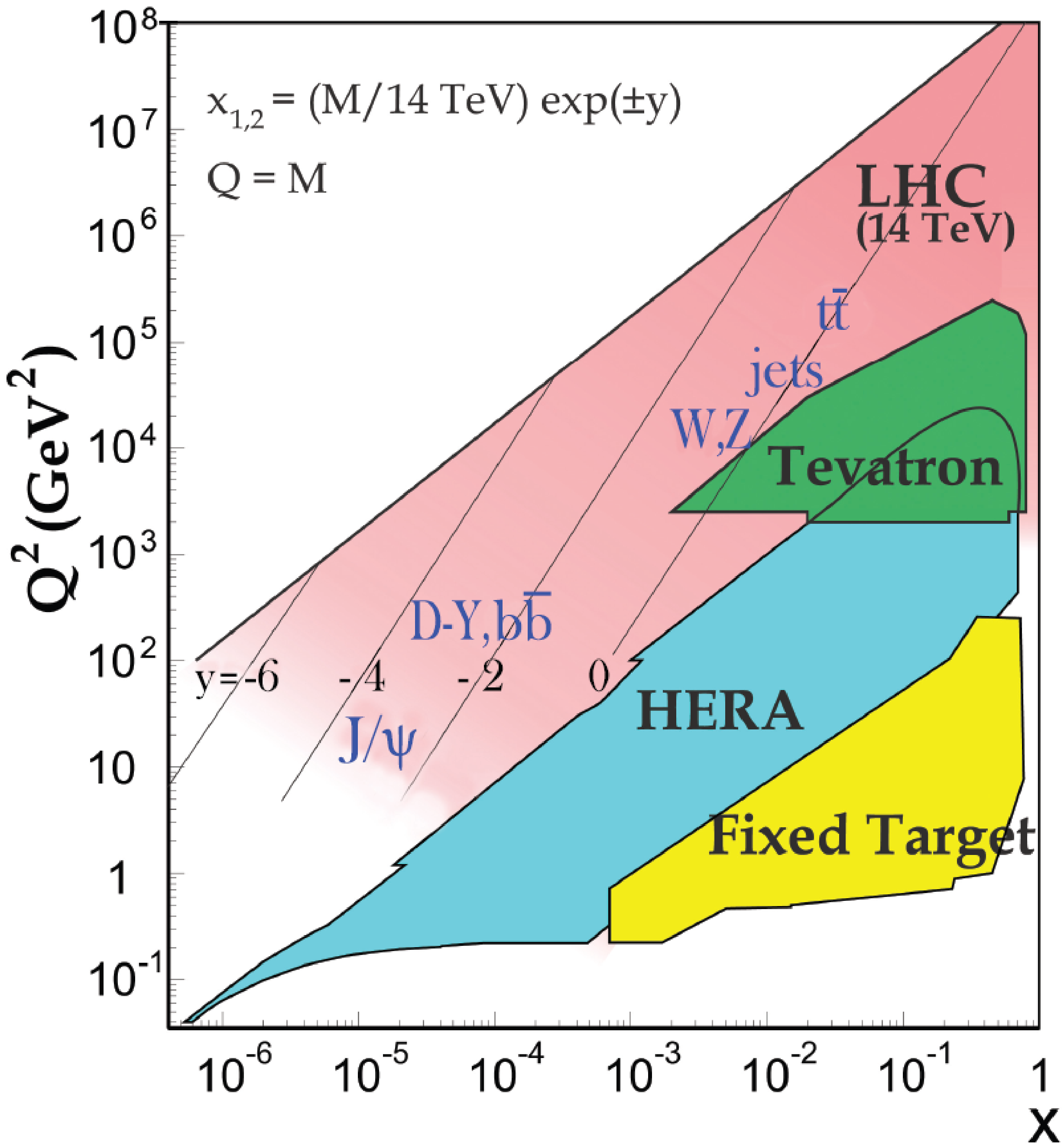
Need same kinematics.
Uncertainities cancel.
Could study $S(\beta)$

$$D = \frac{R^{SD}_{ND}}{R^{DP}_{SD}} = \frac{F_P(\xi_{\bar p}) f_P(\beta)\beta}{F_P(\xi_p) f_P(\beta_1)\beta_1} \frac{f_p(x_p) x_p}{f_{\bar p}(x_{\bar p}) x_{\bar p}} \frac{S_1^2}{S_2}$$

$= S_1^2/S_2$ (if $\beta=\beta_1$, same ξ)

$\sim 0.1^2/0.05 = 0.2$

CDF data D = 0.19 +/- 0.07



Example 3

Exclusive J/ψ at LHC,
pp → p+J/ψ+p,
probe gluon PDF down to x ~ 10^{-5}

see the talks by
Ronan McNulty
Joakim Nystrand

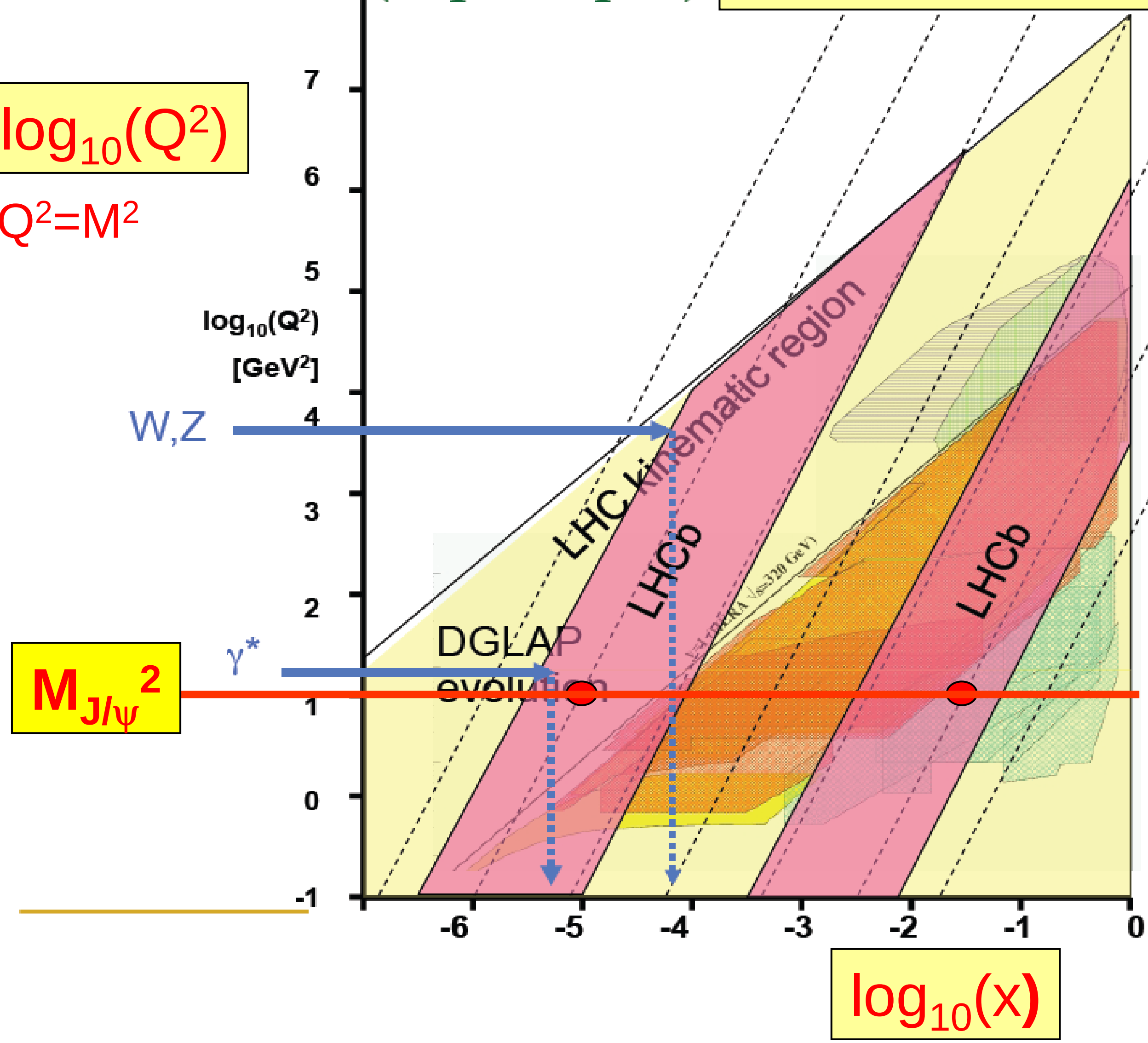
Also HERA data on
$\gamma^*p \rightarrow J/\psi+p$

Recent JMRT analysis arXiv:1307.7099

From Ronan McNulty (LHCb at 7 TeV)

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm Y)$$

Exclusive J/ψ is of great important for low-x gluon distribution (in principle!)



$M_{\mu+\mu-} = M_{J/\psi}$
$|Y|=4$
$x_1 \sim 2\times10^{-2}$
$x_2 \sim 10^{-5}$

LHCb:

Collision between one well understood parton and one unknown or large DGLAP evolved parton.

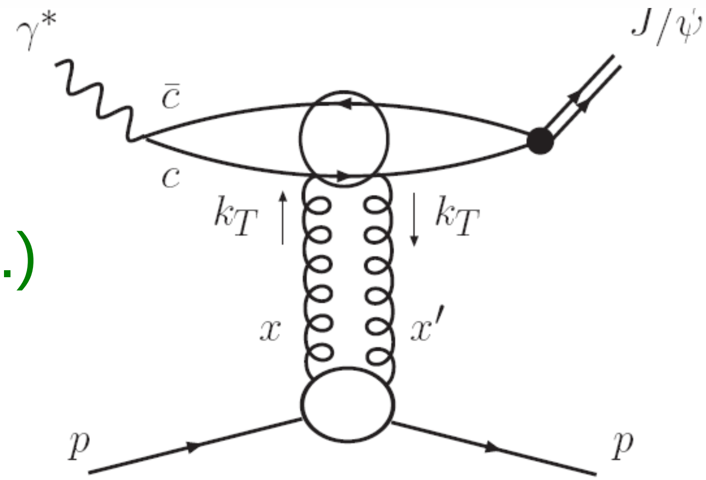
Potential to go to very low x, where PDFs essentially unknown

$p_T(\mu\mu)$ cut

LO formula for $\gamma^*p \rightarrow J/\psi + p$ (Ryskin 1993)

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4\,, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)$$



Allow for skewing ($x \neq x'$) (a la Shuvaev et al.)

Allow for real part

Mimic NLO by including k_T^2 integration in the last step of evolution (a la Kimber et al)

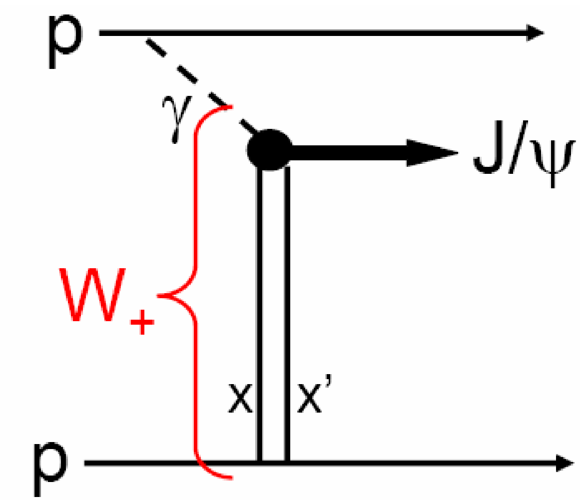
$$\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right] \longrightarrow \int_{Q_0^2}^{(W^2 - M_{J/\psi}^2)/4} \frac{dk_T^2\, \alpha_s(\mu^2)}{\bar{Q}^2(\bar{Q}^2 + k_T^2)} \frac{\partial\left[xg(x,k_T^2)\sqrt{T(k_T^2,\mu^2)}\right]}{\partial k_T^2}$$

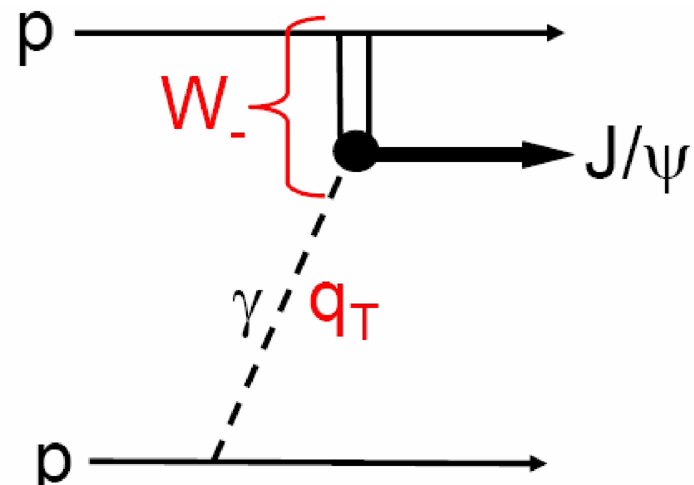
+ Q_0 contrib^n

pp → p + J/ψ + p at the LHC

$$W_{\pm}^2 = M_{J/\psi}\sqrt{s}\; e^{\pm|y|}$$

γp, pγ ambiguity





|y|=4

x ~ $M_{J/\psi}\exp(-|y|)\,/\sqrt{s}$ ~ 10^{-5}

x ~ $M_{J/\psi}\exp(|y|)\,/\sqrt{s}$ ~ 0.02

fit LHCb

show

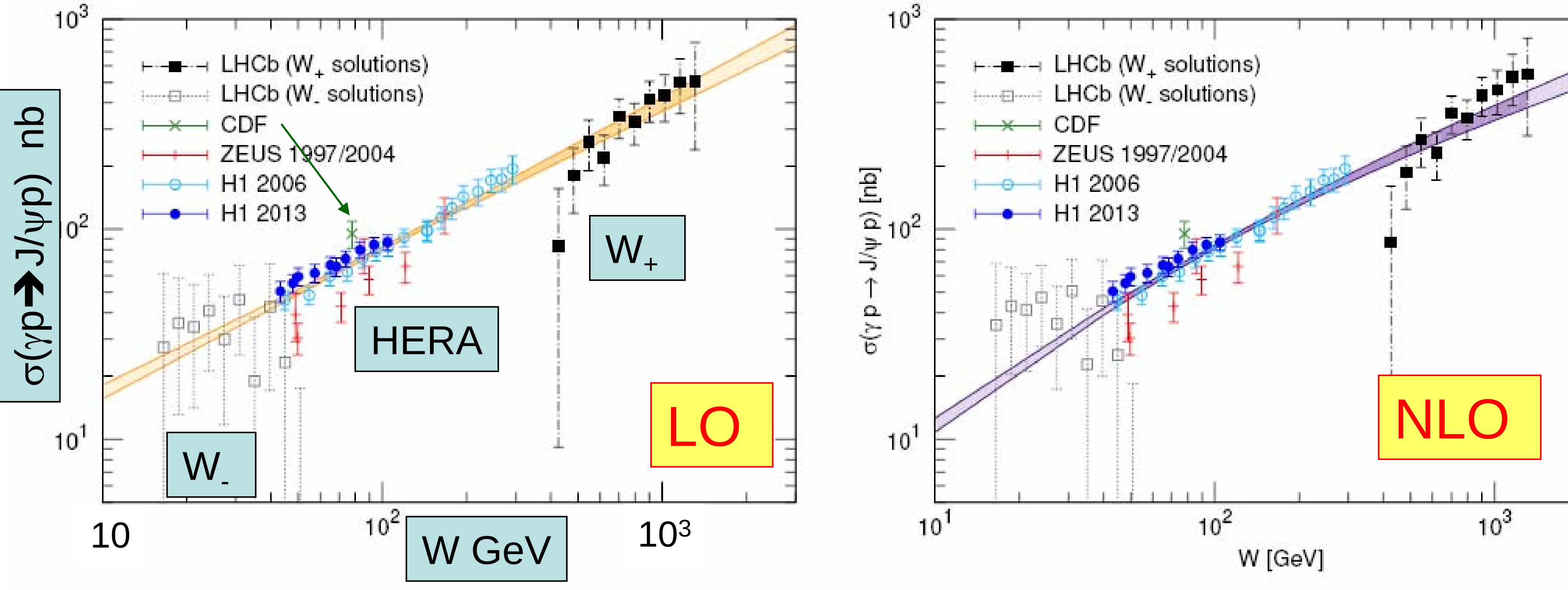
show

$$\frac{\mathrm{d}\sigma^{\mathrm{th}}(pp)}{\mathrm{d}y} = S^2(W_+)\left(k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\right)\sigma_+^{\mathrm{th}}(\gamma p) + S^2(W_-)\left(k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\right)\sigma_-^{\mathrm{th}}(\gamma p)$$

where (…) is photon flux for photon energy $k_{\pm}$

and S^2 are survival probabilities of LRG

Combined fit to HERA and LHC exclusive J/ψ data



survival factors for pp data at 7 TeV

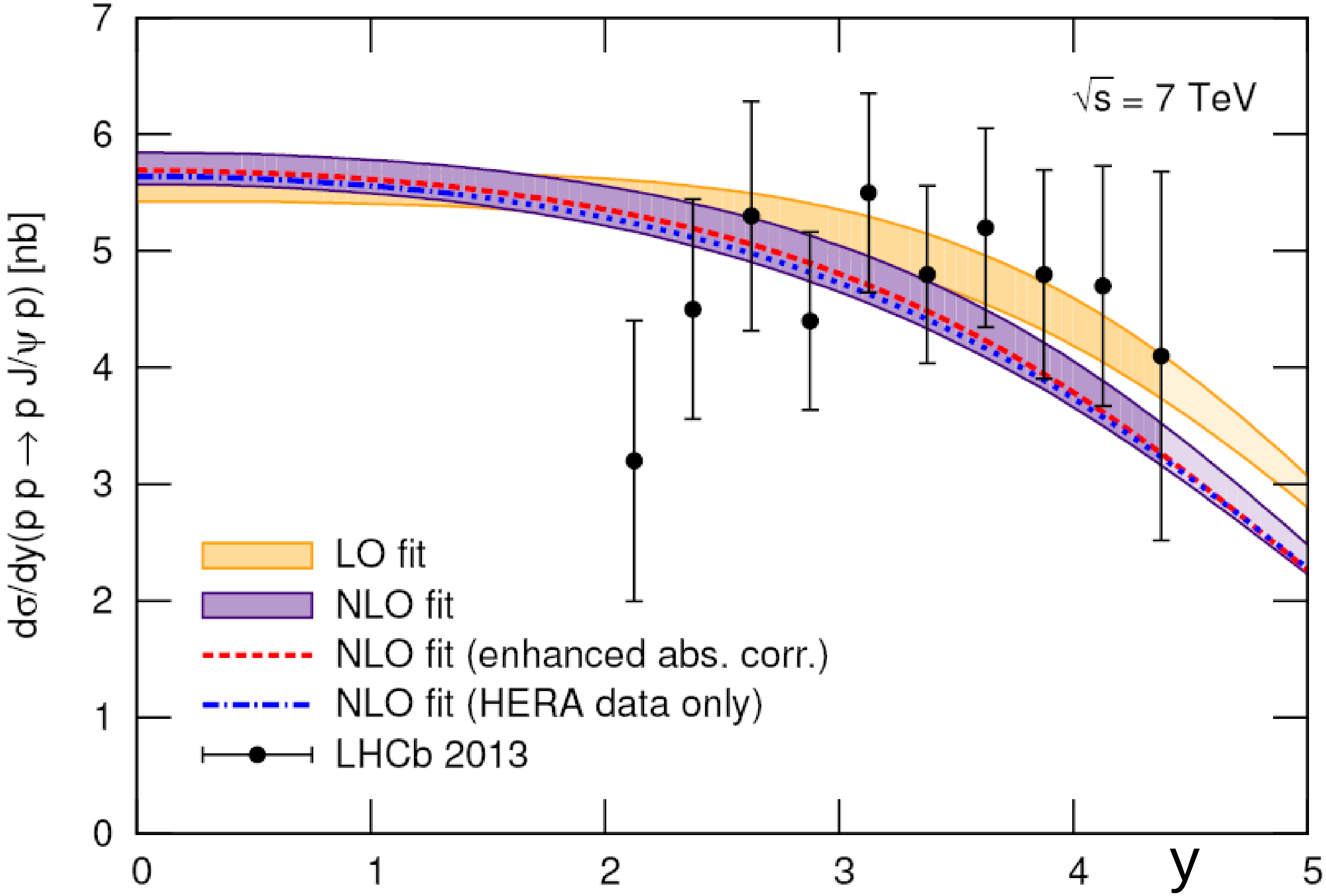
y=2 $S^2(W_+)=0.87$ $S^2(W_-)=0.93$

y=4 $S^2(W_+)=0.74$ $S^2(W_-)=0.95$

survival factor for HERA data $S^2\sim1$

JMRT
arXiv:1307.7099

Actual description of LHCb data in combined fit



need parameterization of gluon from x ~10^{-5} to 0.1 to cover data

$$xg(x,\mu^2) \;=\; N x^{-a} (\mu^2)^b \exp\left[\sqrt{16 N_c/\beta_0 \ln(1/x) \ln(G)}\right] \qquad \text{with} \quad G = \frac{\ln(\mu^2/\Lambda^2_{\rm QCD})}{\ln(Q_0^2/\Lambda^2_{\rm QCD})}$$

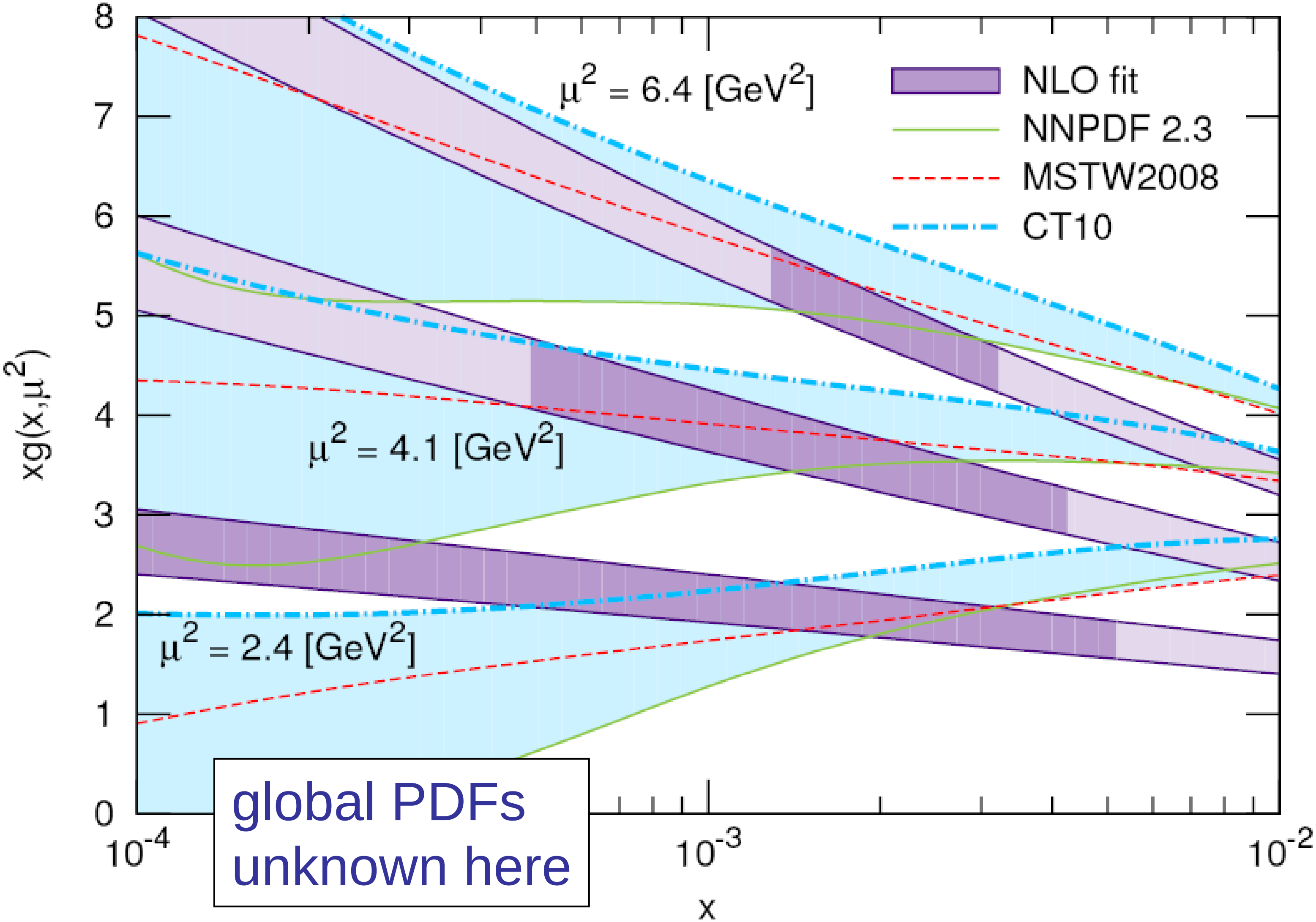
NLO

gluon PDF obtained from combined HERA+LHCb fit to $\gamma^* p \to J/\psi + p$ data

indicative plot:

pred[ns] for g (purple) only have expt[al] data errors!

compared to only central values of global PDFs (blue). Huge errors for $x \sim 10^{-4}$ or less



Promising future

Much more precise exclusive J/ψ data at 8, 14 TeV

Ronan McNulty

Expect exclusive Υ data : probe gluon at scale $\mu^2 \sim M_{\Upsilon}^2/4 \sim 23\ \text{GeV}^2$

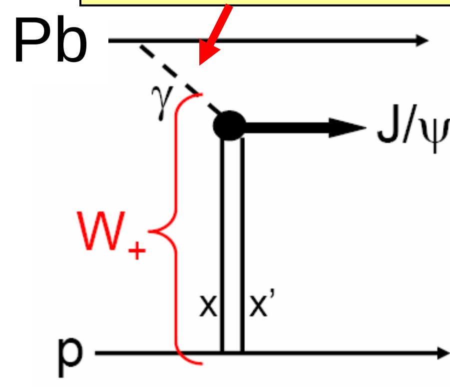
Heavy ions Joakim Nystrand

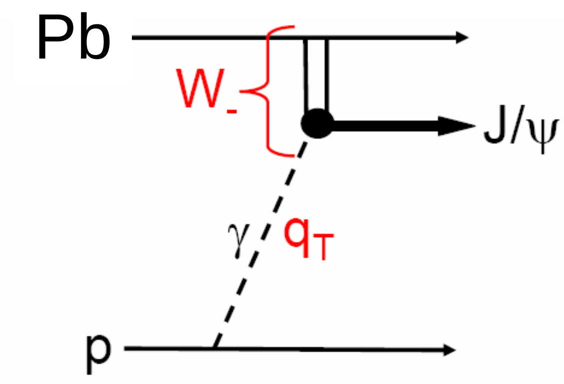
Pb - p

W_+ dominates
low x comp^t !

S^2 more difficult to calculate & is smaller

Z² enhancement





Pb - Pb

$b > 2R_A \sim 12$ fm, but $b < 1/\text{sqrt}(t_{min})$ with $t_{min} \sim (xm_p)^2/(1-x)$, so need v.small t_{min}, leading to small $W^2 = xs_{pp}$ (~HERA).

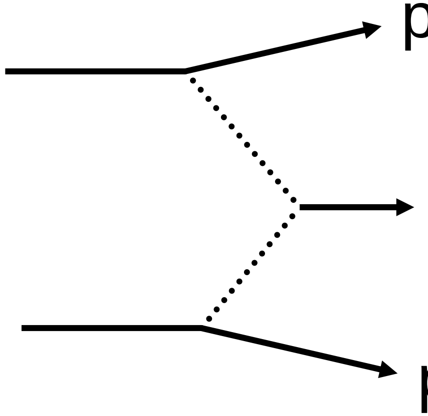
So cannot probe v.low x, rather probe nuclear effects on g PDF

Used incomplete NLO (but main kinematic effects included.
Need confirmation of full NLO (hep-ph/0401131)

Example 4

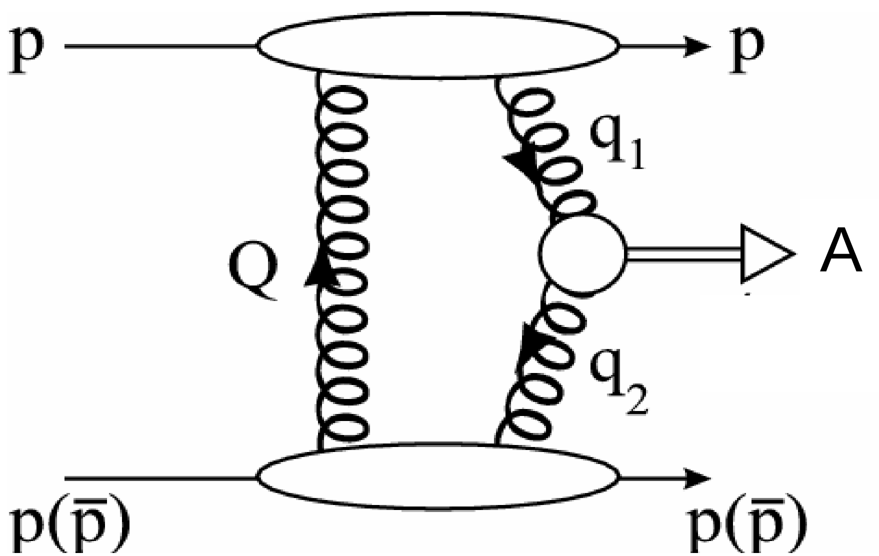
Central exclusive prod: pp → p+A+p

Mike Albow
Antoni Szczurek



A = Higgs, dijet, $\gamma\gamma$, χ_c,….

dominant diagram



$$\mathcal{M}(\bar{p}p \to \bar{p} + A + p) \;\sim\; S^2 \int \frac{d^2Q_t}{Q_t^4}\, f_g f_g$$

tho' pred^{ns} become more unreliable as M_A becomes smaller, and infrared region not so suppressed by Sudakov factor

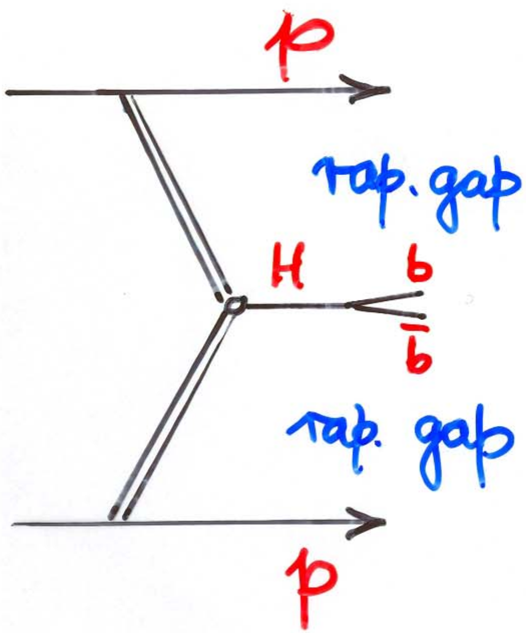
$$T = \exp\left(-\int_{Q_t^2}^{M_A^2} dk_t^2 \ldots\right)$$

Excuse some old notes

Double-diff^{ve} exclusive Higgs production at the LHC

Khoze, Martin, Ryskin

$pp \to p + H + p$



<u>advantages:</u>

- $M_H = \begin{cases} M(b\bar{b}) \\ M_{missing} \end{cases}$ if protons tagged
- LO $gg \to b\bar{b}$ background v. suppressed by $J_z = 0$ selection rule ($= 0$ for $m_b = 0$ and forward protons)
- unique LHC signal if $M_H \lesssim 130$ GeV ($S/B \sim 1$)
- for SUSY Higgs, S/B $\tan\beta$ enhanced

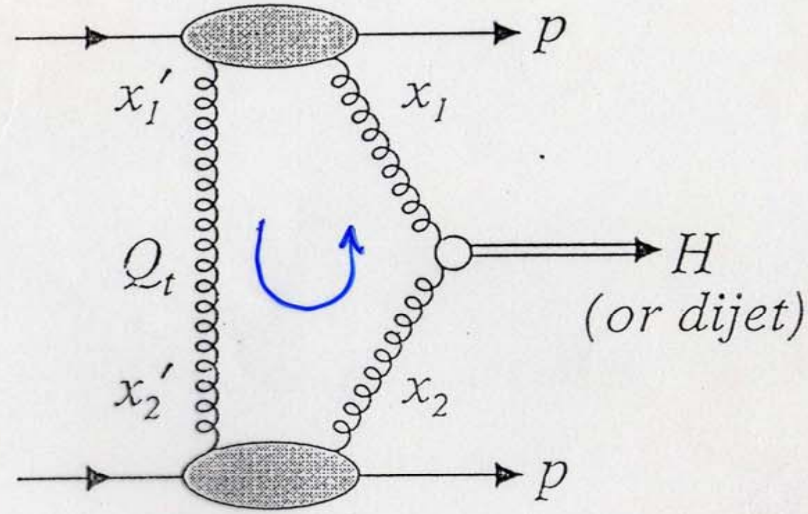
The price for rapidity gaps ? →

$pp \to p + H + p$

Survival prob. of rap. gaps

$$W = S^2 \, T^2$$

price for [no soft rescatt.] → S^2; [no g rad^n in $gg \to H$] → T^2



$$\Lambda^2_{QCD} \ll Q_t^2 \ll M_H^2 \quad \to \text{pQCD}$$

$$\left(x' \sim \frac{Q_t}{\sqrt{s}}\right) \ll \left(x \sim \frac{M_H}{\sqrt{s}}\right) \ll 1$$

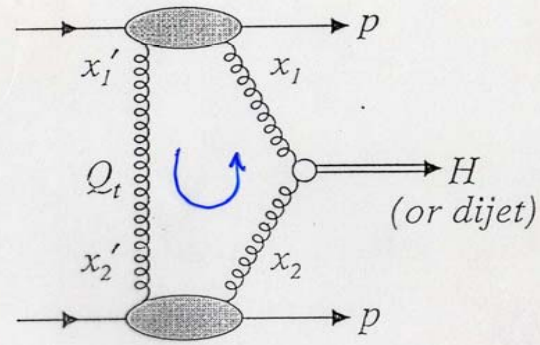
need uninteg. skewed gluons

$pp \to p + H + p$

Survival prob. of rap. gaps

$$W = S^2 \, T^2$$

price for: no soft rescatt. (S^2); no g rad^n in $gg \to H$ (T^2)



$$\Lambda^2_{QCD} \ll Q_t^2 \ll M_H^2 \quad \to \text{pQCD}$$

$$\left(x' \sim \frac{Q_t}{\sqrt{s}}\right) \ll \left(x \sim \frac{M_H}{\sqrt{s}}\right) \ll 1$$

need uninteg. skewed gluons

$$\mathcal{M} = \frac{A}{M_H^2} \int \vec{Q}_{1t} \cdot \vec{Q}_{2t} \, \frac{d^2 Q_t}{Q_t^6} \, f\left(x_1, x_1', Q_t^2, \frac{M_H^2}{4}\right) f\left(x_2, x_2', Q_t^2, \frac{M_H^2}{4}\right)$$

where $f(x, x', Q_t^2, \mu^2) \approx R \dfrac{\partial}{\partial \ln Q_t^2} \left[\sqrt{T(Q_t, \mu)} \, x g(x, Q_t^2) \right]$

R is calculable skewed effect (R=1.2 at LHC)

$$T(Q_t, \mu) = \exp\left(- \int_{Q_t^2}^{\mu^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s}{2\pi} \int_0^{1-k_t/\mu} dz \, z P_{gg} \ldots \right)$$

strongly suppresses Q_t infrared region

no emission when $(\lambda \sim 1/k_t) > (d \sim 1/Q_t)$

i.e. only emission with $k_t > Q_t$

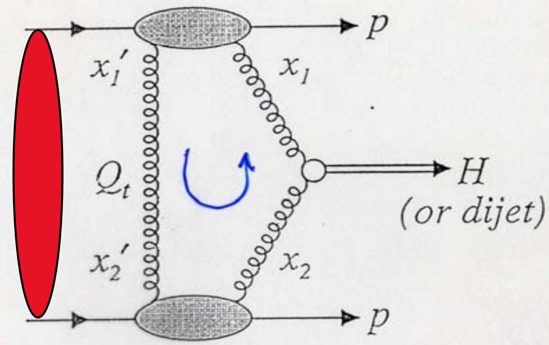
$pp \to p + H + p$

Survival prob. of rap. gaps

$$W = S^2 \, T^2$$

price for: no soft rescatt. (S^2) — no g rad^n in $gg \to H$ (T^2)

calculated using detailed 2-channel eikonal global analysis of soft pp data
$S^2 = 0.026$ at LHC
$S^2 = 0.05$ at Tevatron



$$\Lambda^2_{QCD} \ll Q_t^2 \ll M_H^2 \quad \to \text{pQCD}$$

$$\left(x' \sim \frac{Q_t}{\sqrt{s}}\right) \ll \left(x \sim \frac{M_H}{\sqrt{s}}\right) \ll 1$$

need uninteg. skewed gluons

$$\mathcal{M} = \frac{A}{M_H^2} \int \vec{Q}_{1t} \cdot \vec{Q}_{2t} \, \frac{d^2 Q_t}{Q_t^6} \, f\left(x_1, x_1', Q_t^2, \frac{M_H^2}{4}\right) f\left(x_2, x_2', Q_t^2, \frac{M_H^2}{4}\right)$$

where $f(x, x', Q_t^2, \mu^2) \simeq R \, \frac{\partial}{\partial \ln Q_t^2} \left[\sqrt{T(Q_t, \mu)} \, x g(x, Q_t^2) \right]$

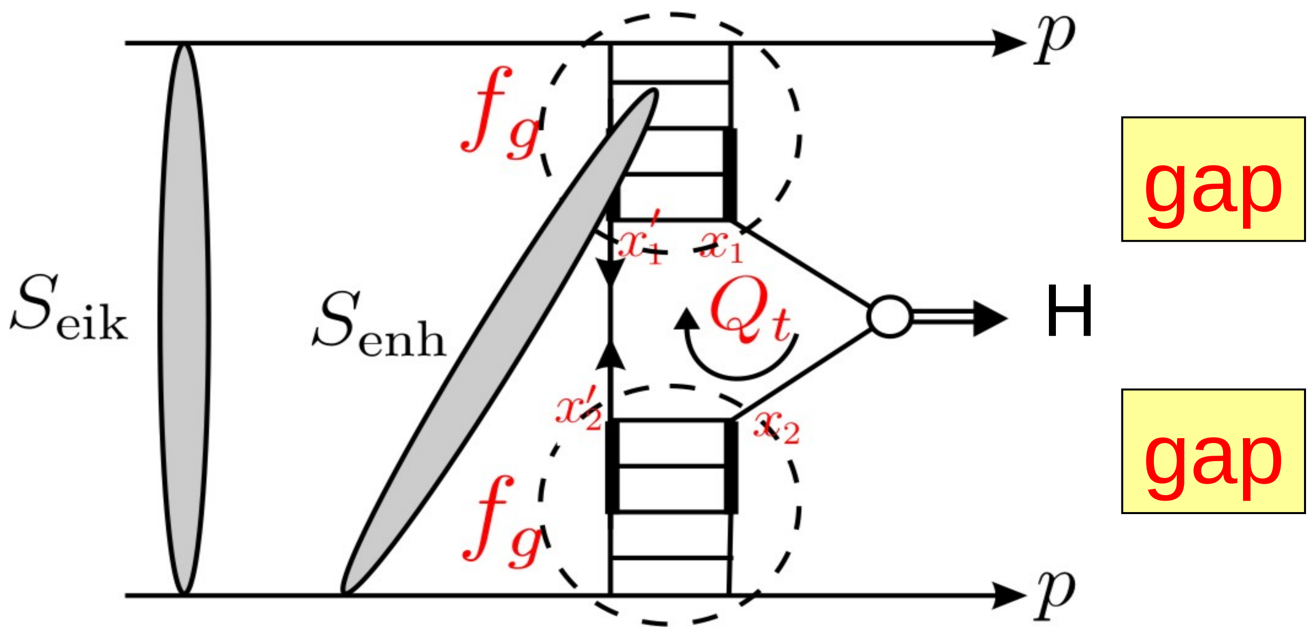
R is calculable skewed effect (R=1.2 at LHC)

$$T(Q_t, \mu) = \exp\left(- \int_{Q_t^2}^{\mu^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s}{2\pi} \int_0^{1-k_t/\mu} dz \, z P_{gg} \ldots \right)$$

strongly suppresses Q_t infrared region

M_H=120GeV $\rightarrow$ $\sigma(p+H+p) \simeq \begin{cases} 3 \text{ fb} & \text{at LHC} \\ 0.2 \text{ fb} & \text{at Tevatron} \end{cases}$

Also have to consider $S^2_{enhanced}$ for pp → p + H +p



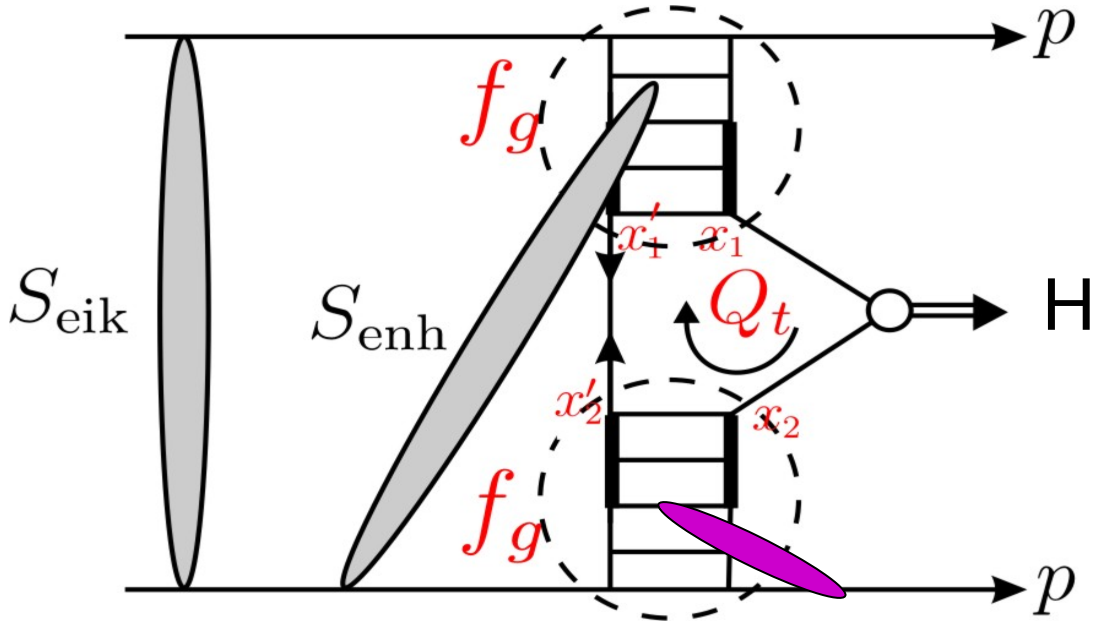
soft-hard factoriz^n

eikonal rescatt: between protons ← conserved

enhanced rescatt: involving intermediate partons ← broken

The new soft analysis, with Pomeron q_t structure, enables S^2_{enh} to be calculated (see KMR, 0812.2413)

Two subtlities



gap

gap

1. f_g's from HERA data already include rescatt. of intermediate partons with parent proton
2. Usually take p_t=0 and integrate with $\exp(-Bp_t^2)$. S^2/B^2 enters (where $1/B = \langle p_t^2\rangle$). But enh. abs. changes p_t^2 behaviour from exp., so quote $S^2\langle p_t^2\rangle^2$

   $\langle S^2_{tot}\rangle = \langle S^2_{eik} S^2_{enh}\rangle \sim 0.015$ (for B=4 GeV^{-2})

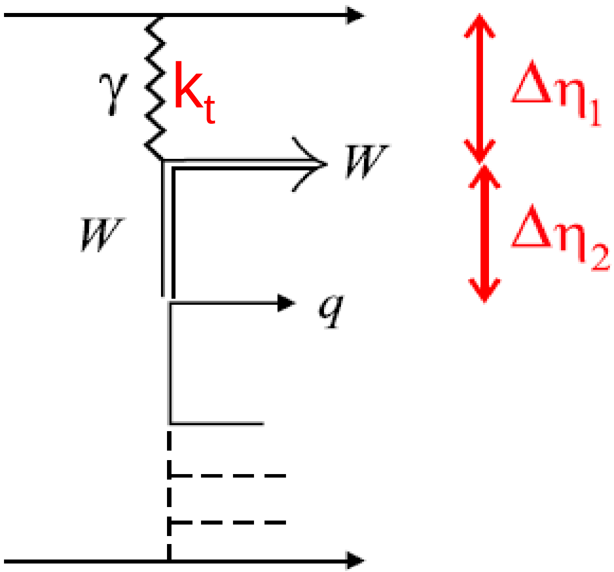
   $\langle S^2_{tot}\rangle\langle p_t^2\rangle^2 = 0.0010$ GeV^4 see 0812.2413

3. See KMR 1306.2149 for latest S^2(Higgs)

Example 5 — LHC check of S^2 using W+gap events

W+gaps

$$\int \frac{dk_t^2\; k_t^2}{(|t_{\min}| + k_t^2)^2} \quad \text{with} \quad |t_{\min}| \simeq \frac{m_N^2 \xi^2}{1-\xi}$$



Even without a proton tag

$x_p = 1 - \xi$ can be measured by

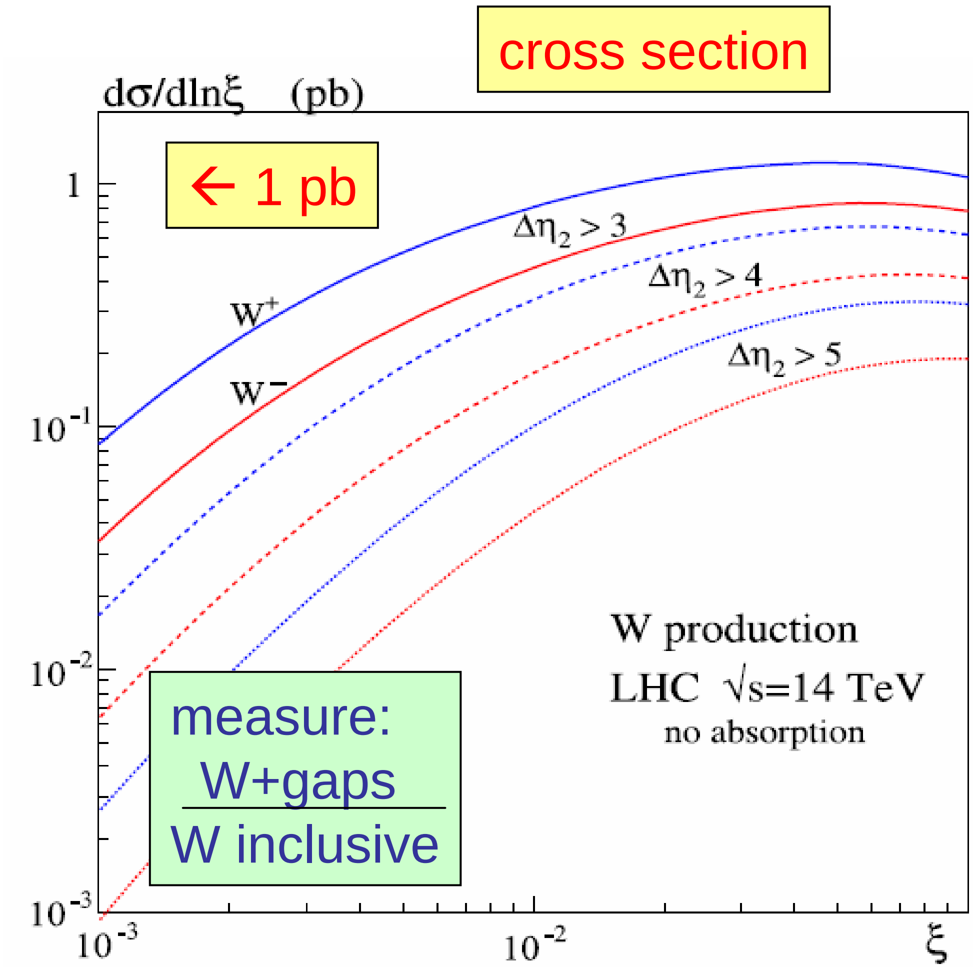
$$\xi = \sum \sqrt{m_i^2 + k_{ti}^2}\; e^{y_i} / \sqrt{s}$$

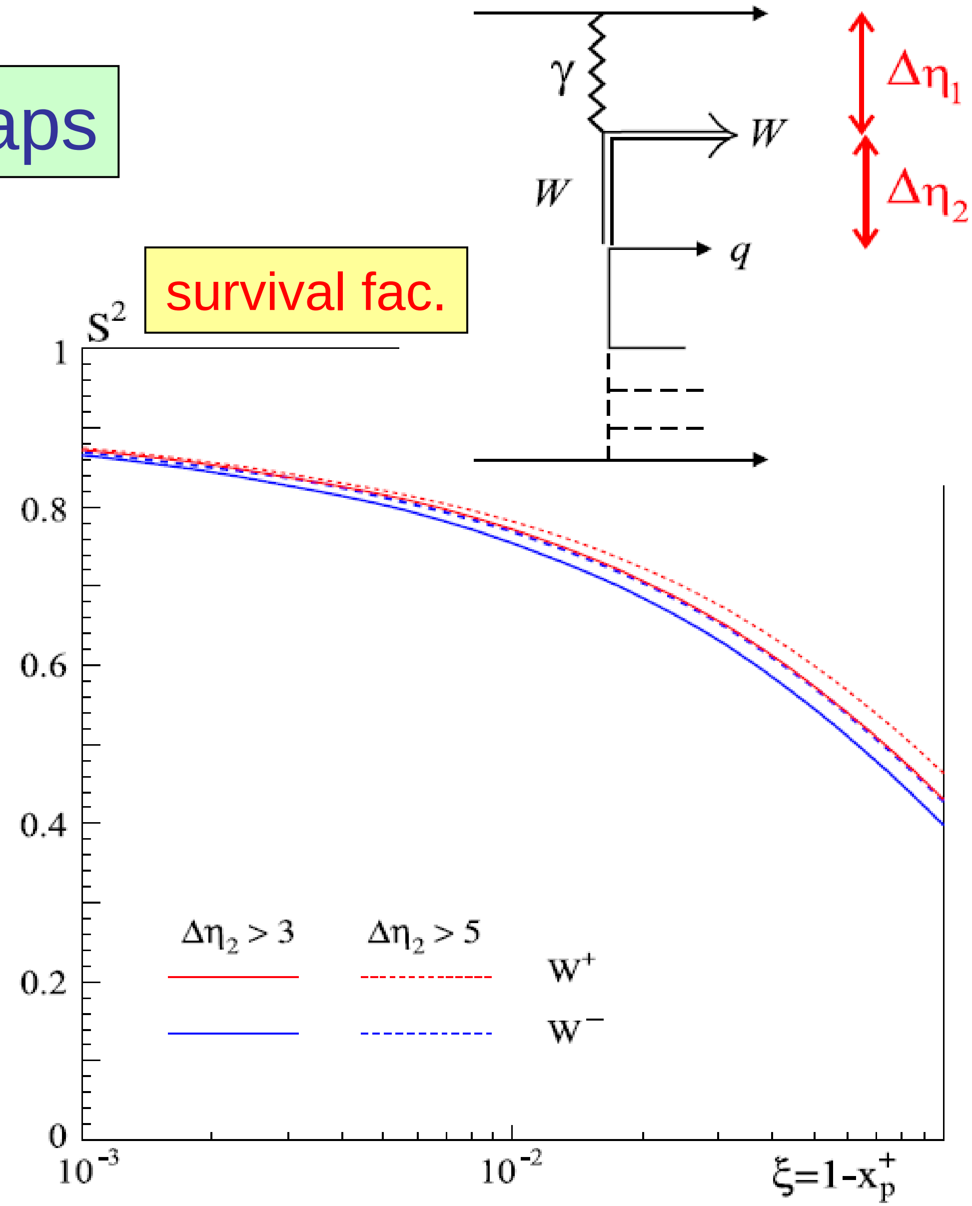
i=W decays+pts.in calor. ($\Delta\eta_2$ large)

successfully used by CDF

$$\eta_W = 2.3(-2.3) \;\Rightarrow\; \xi \sim 0.1(0.001)$$

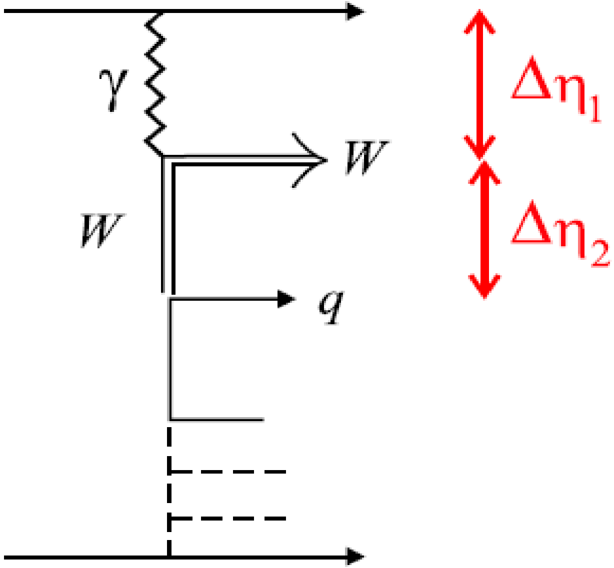
W+gaps





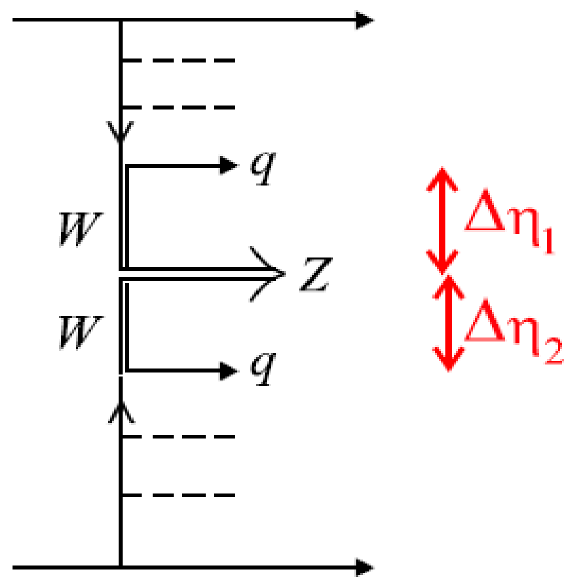
S^2 large, as large b_t (small opacity)

W+gaps has S^2 large, as large b_t for γ exch (small opacity)



Z+gaps has b_t more like excl. Higgs

σ~0.2pb for $\Delta\eta_i$>3 and E_T(b)>50GeV
but to avoid QCD bb backgd use Z→l^+l^-



Other examples in
EPJ**C55**(2008)363

use track counting veto

Recall, that besides LRGs, the Pomeron also describes "soft" multi-particle production.

Constant or increasing $\sigma_{tot}(s)$ with s → **Pomeron →**

→ { (a) processes with large rapidity gaps
→ valuable exclusive HE data
(b) soft multiparticle production
→ vital to understand the underlying event
to rare New Physics processes at the LHC

Further, recall that the "hard" Pomeron (based on BFKL), with abs. corr^{ns}, continues smoothly into "soft" Pomeron

“Soft” and “Hard” Pomerons ?

A vacuum-exchange object drives soft HE interactions. Not a simple pole, but an enigmatic non-local object. Rising σ_{tot} means multi-Pom diags (with Regge cuts) are necessary to restore unitarity. σ_{tot}, $d\sigma_{el}/dt$ data, described, in a limited energy range, by eff. pole $\alpha_P^{eff} = 1.08 + 0.25t$

Sum of ladders of Reggeized gluons with, in LLx BFKL, a singularity which is a cut and not a pole. When HO are included the intercept of the BFKL/hard Pomeron is $\alpha_P^{bare}(0) \sim 1.3$

$\mathbf{\Delta = \alpha_P(0) - 1 \sim 0.3}$

$\alpha_P^{eff} \sim 1.08 + 0.25\ t$

up to Tevatron energies

$(\sigma_{tot} \sim s^{\Delta})$

$\alpha_P^{bare} \sim 1.3 + 0\ t$

with absorptive (multi-Pomeron) effects

High-energy pp interactions

soft | **hard**

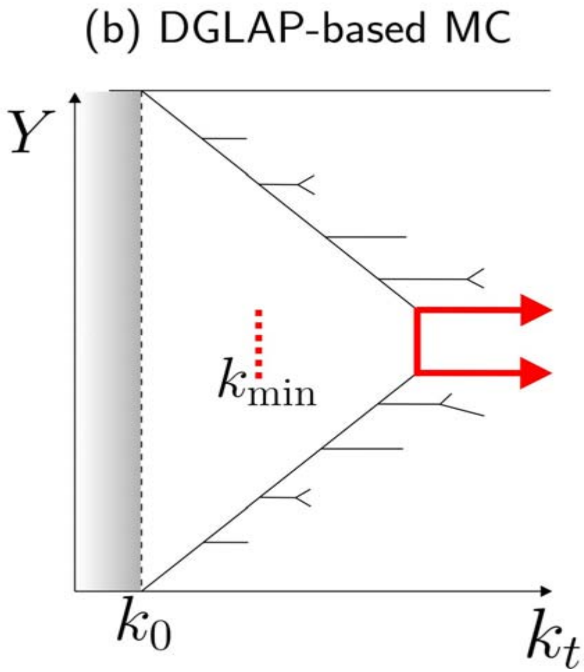
Reggeon Field Theory
with phenomenological
soft Pomeron

← pQCD
partonic approach

smooth transition using
QCD / “BFKL” / hard Pomeron

There exists only one Pomeron, which makes
a smooth transition from the hard to the soft regime

Could lead to a reliable **all-purpose Monte Carlo** which describes all aspects on minimum bias data – total, diff. elastic X-sections, diffraction, multi-particle production, jet production – in a unified framework ?



Existing all-purpose MCs describe inclusive spectra with hard parton-parton interaction in central region, with secondaries from backward evol^n.

Infrared cutoff k_{min}~3 GeV at LHC(7 TeV) compared to cutoff k_{min}~2.15 GeV at Tevatron.

Understood in pQCD: in relevant low x region, prob of rescatt. large, corresponding abs^{ve} corr^n, σ_{abs}~$1/k_t^2$, suppress low k_t.

Model → $d\sigma/dy \sim s^{0.2}$ like LHC data for 0.9 to 7 TeV

LHC

DGLAP ln k_t^2 evol^n interval << BFKL ln(1/x) evol^n interval

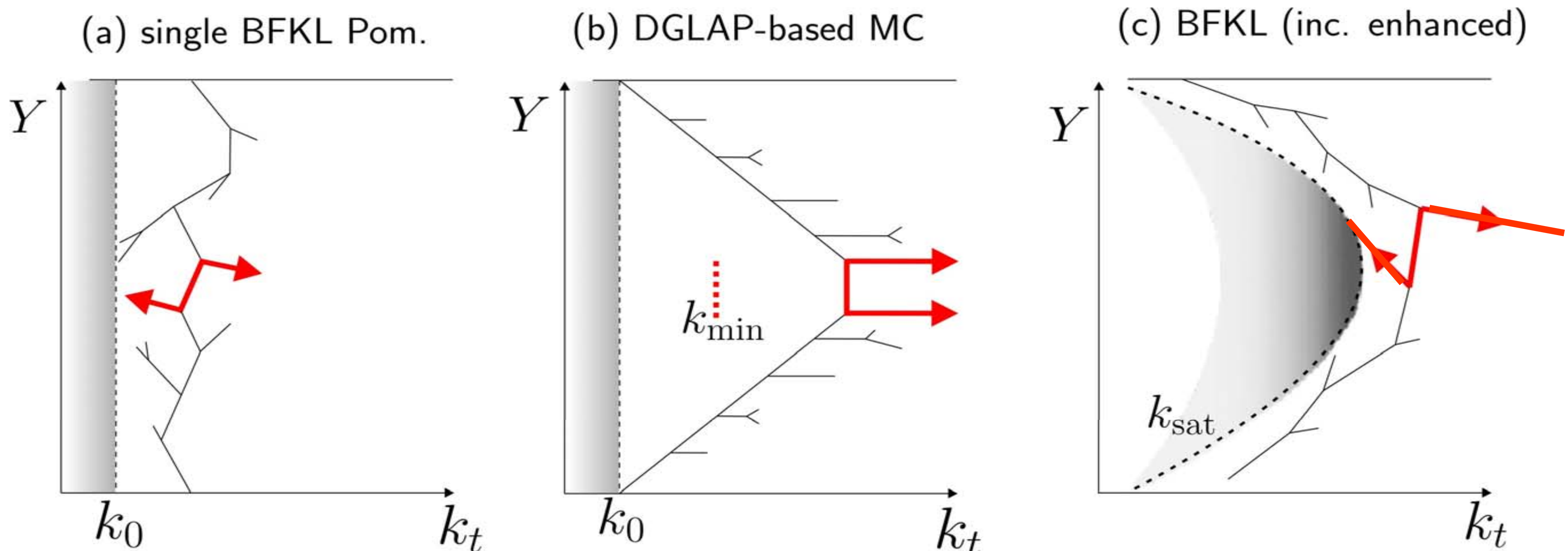
overestimates $<k_t>$

underestimates growth dN/dy

not strongly-ordered in k_t

$dN/dy = n_P \, (dN_{1\text{-}Pom}/dh)$

n_P=no. of Poms. grows



$d\sigma_{subp}/dk_t^2 \sim 1/k_t^4$

→tune cutoff to data

$k_{min} \sim s^a$, $a \sim 0.12$

Enh: $\sigma_{abs} \sim 1/k_t^2$

→dyn.cutoff k_{sat}

→besides SD, DD

Can conclude from the LHC data:

The $<p_T>$ of hadrons measured by ATLAS, CMS, ALICE is smaller than that expected from the **DGLAP-based** MC's (which have strong-ordering in k_T going from the protons to the central region) tuned to lower energy data.

After this tuning the MC's, find smaller $<p_T>$ and
larger particle density dN/dy at LHC.

This indicates the need for a **BFKL-based** MC (with multi-Pomeron absorptive corrections), where we have diffusion in log k_T and a growth of particle density as we go to large initial energy, that is smaller x.

Existing "all purpose" (DGLAP) Monte Carlos split eikonal

$$\Omega(s,b) = \Omega_{\text{soft}} + \Omega_{\text{hard(pQCD)}}$$

Seek MC that describes all aspects of minimum bias
-- total, differential elastic Xsections, diffraction, jet prod...—
in a unified framework; capable of modelling exclusive
final states.

SHERPA Monte Carlo based on KMR framework

"SHRiMPS" MC
= **S**oft-**H**ard **R**eactions **i**nvolving **M**ulti-**P**omeron **S**catt.

Krauss, Hoeth, Zapp et al

OUTLINE of SHRiMPS:

Solve coupled evol eqs. in y to generate $\Omega(y,b)$, specifying boundary conditions of GW eigenstates. Eigenstates give elastic, quasi-elastic scatt.

Select no. of ladders exchanged (according to Poisson distribution with parameter $\Omega_{ik}(b)$) to simulate inelastic state

Incoming protons dissolved into val. q, diquark and gluons

For each pair we check prob. to exchange next ladder

Gluon emissions from ladder according to Markov chain, ordered in y, with pseudo Sudakov form factor

t-ch propagators are reggeized gluon in either colour singlets or octets. Prob(singlet) = $P_1 = (1-\exp(-\delta\Omega/2))^2$

Each gluon emission leads to two new propagators---
allowed combinations P_1P_8, P_8P_1, P_8P_8-----singlet propagators give rise to rapidity gaps associated with elastic scatt.

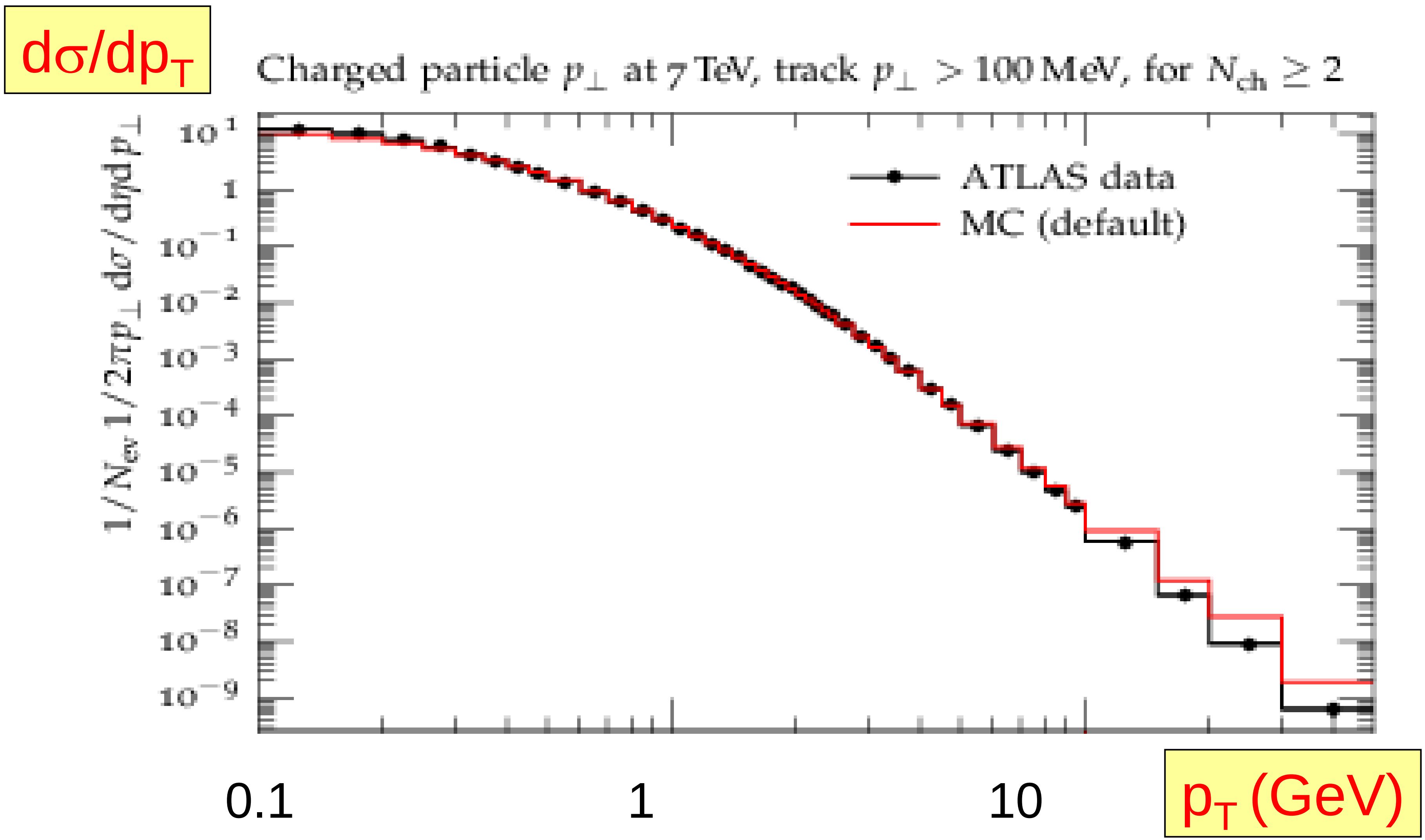
Also rescatt. can give inelastic interaction of secondaries, producing new ladders with Poisson prob. $\exp(-\delta\Omega)(\delta\Omega)^n/n!$

single gluon emission iterated until active interval is colour singlet or no further emissions are kinematically allowed in rapidity interval

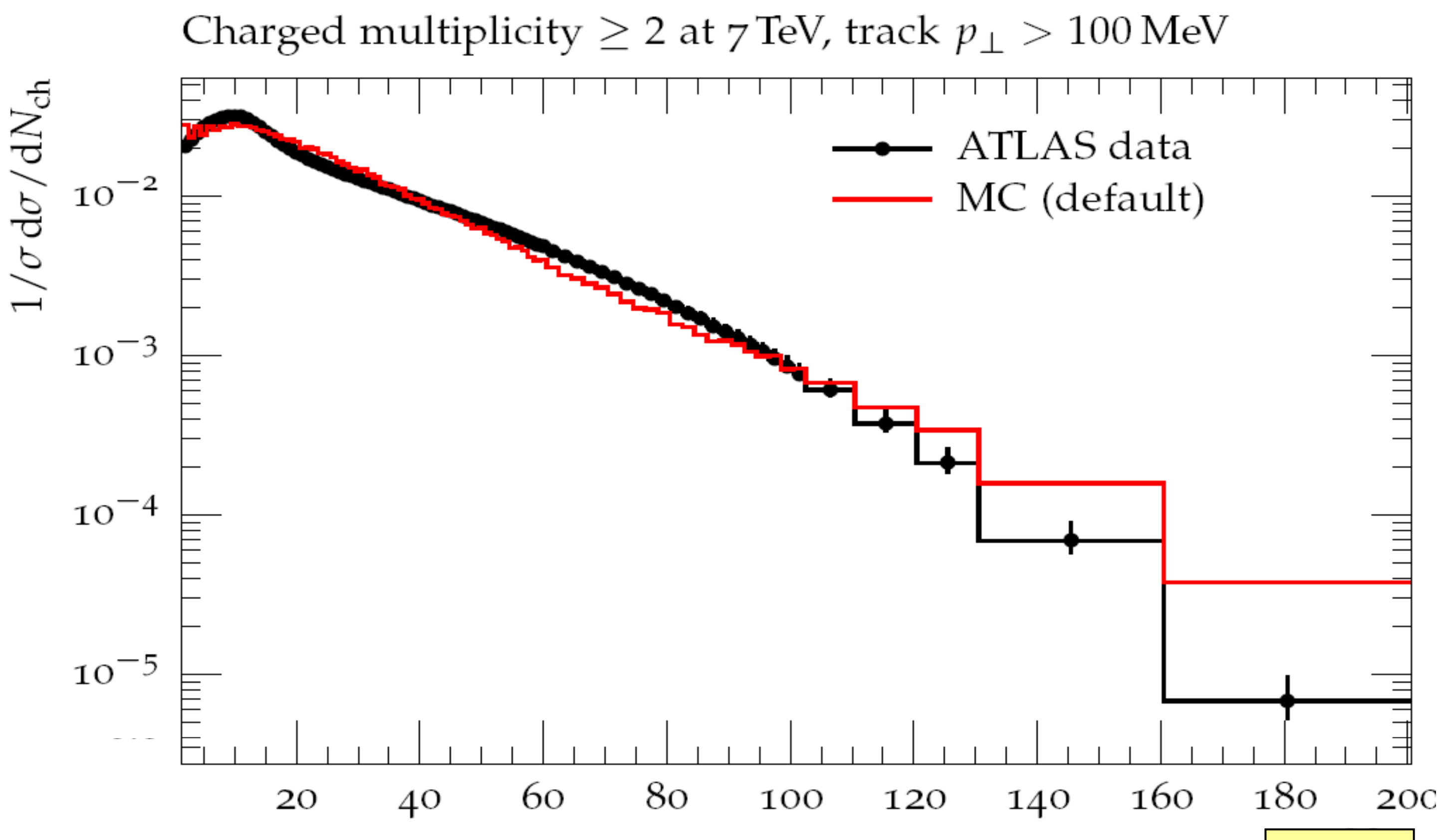
Finally usual hadronization, plus hadron decays, plus QED, to produce final scatter of observed particles.

A few typical plots from SHRiMPS Monte Carlo (in SHERPA)

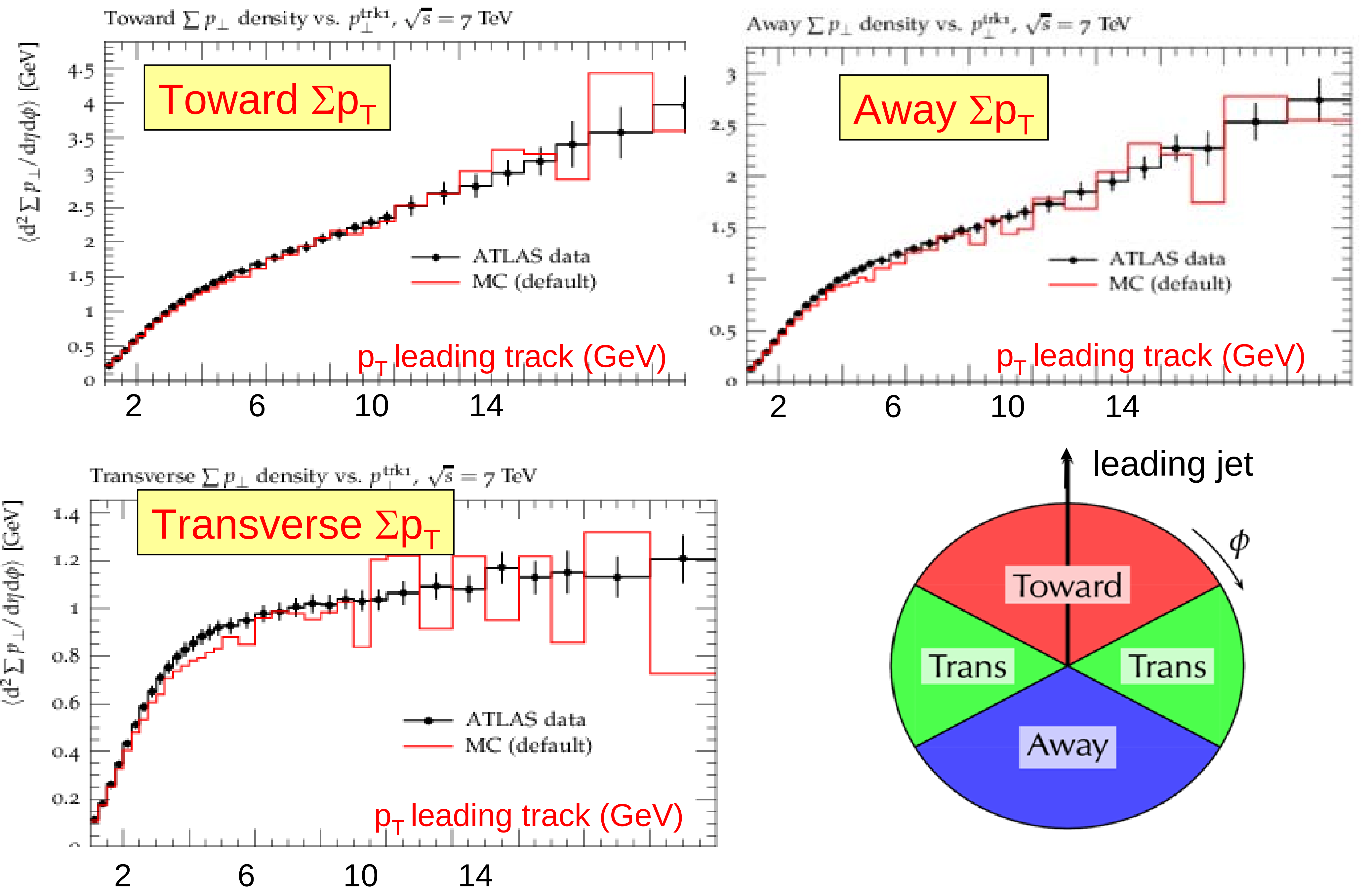
→


dσ/dp_T
Charged particle p⊥ at 7 TeV, track p⊥ > 100 MeV, for N_ch ≥ 2
1/N_ev 1/2πp⊥ dσ/dηdp⊥
ATLAS data
MC (default)
10^1
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
0.1
1
10
p_T (GeV)

$1/\sigma \; d\sigma/dN_{ch}$

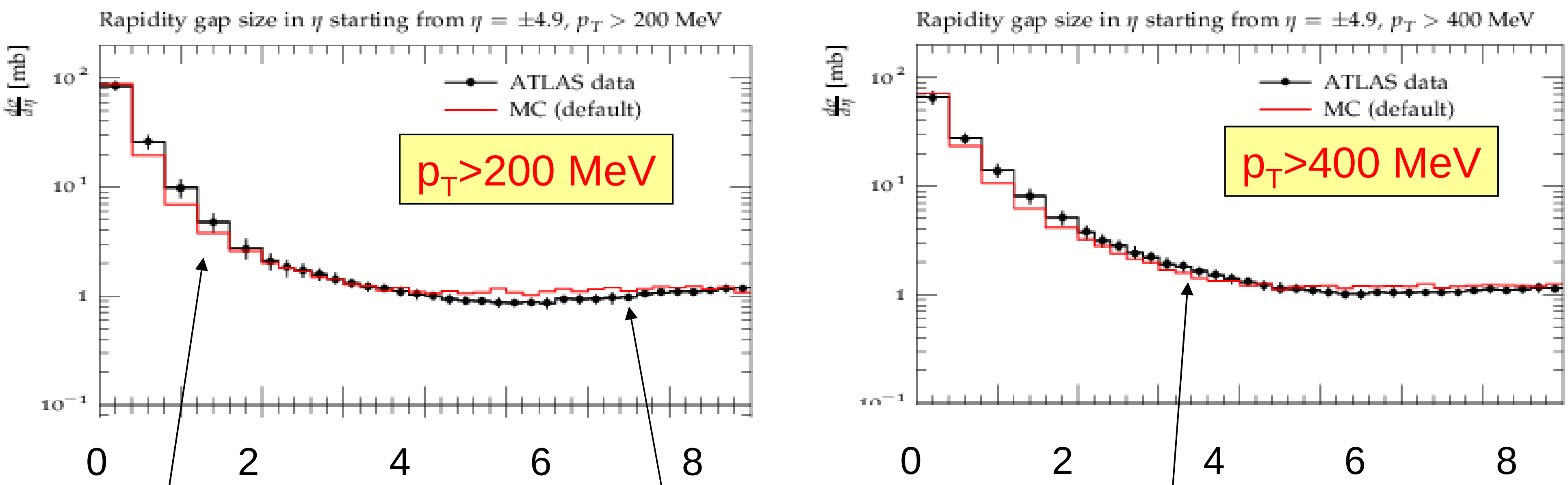


N_{ch}



Toward $\sum p_\perp$ density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
Toward Σp_T
$\langle d^2 \sum p_\perp / d\eta d\phi \rangle$ [GeV]
ATLAS data
MC (default)
p_T leading track (GeV)
Away $\sum p_\perp$ density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
Away Σp_T
ATLAS data
MC (default)
p_T leading track (GeV)
Transverse $\sum p_\perp$ density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
Transverse Σp_T
$\langle d^2 \sum p_\perp / d\eta d\phi \rangle$ [GeV]
ATLAS data
MC (default)
p_T leading track (GeV)
leading jet
ϕ
Toward
Trans
Trans
Away

$d\sigma/d(\Delta\eta)$



fluctuations in hadronization

PPP*S^2

$\Delta\eta$

fluctuations extend to larger $\Delta\eta$

Conclusion on “SHRiMPS” Monte Carlo

Seek MC that describes all aspects of minimum bias
-- total, differential elastic Xsections, diffraction, jet prod...—
in a unified framework; capable of modelling exclusive
final states.

Incorporate the KMR model in SHERPA MC framework

Krauss, Hoeth, Zapp + KMR

KMR model is based on bare QCD Pomeron, with
absorptive multi-Pomeron rescattering corrections →

“SHRiMPS” MC

= **S**oft-**H**ard **R**eactions **i**nvolving **M**ulti-**P**omeron **S**catt.

Special properties of "SHRiMPS" Monte Carlo

- Based on partonic model of Pomeron, which enables **BFKL-like** structure to be continued into soft domain, increasingly subject to absorptive corrections

- Stronger absorption of low k_T partons automatically gives effective infrared cutoff k_{min} which increases with collider energy
  (Existing general purpose **DGLAP-based** MCs have external parameter giving an energy dependent cutoff. "BFKL-like diffusion in $\ln k_T$ + absorption of low k_T" can be approximately mimicked by DGLAP)

- Consistently includes low-mass diffraction, via 2-channel eikonal.

Special properties of "SHRiMPS" MC continued

- Consistent inclusion of (absorptive) multi-Pomeron effects.

  A multi-Pomeron diagram simultaneously describes several different processes depending on which Pomeron ladders are cut
  (i) multiparticle production results from "cut" ladders
  (ii) processes with rapidity gaps (no cut ladders in gap)

- Offers the possibility of a reliable description of the underlying event to New Physics "hard" processes.

Some review-type references

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These lecture notes can be found on
http://www.ippp.dur.ac.uk/~martin/Heidel13.pdf