Lessons from LHC elastic & diffractive data

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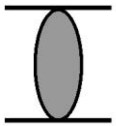
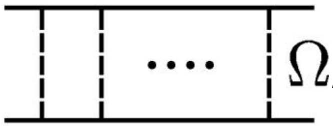
In the light of LHC data, we discuss the global description of all high-energy elastic and diffractive data, using a one-pomeron pole model, but including multi-pomeron interactions.

The LHC data indicate the need of a $k_T(s)$ behaviour, where k_T is the parton transverse momentum along the partonic ladder structure of the pomeron.

Diffraction 2014, Primosten, Croatia, Sept.10-16

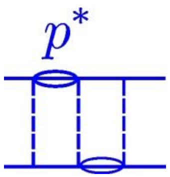
Elastic amp. $T_{el}(s,b)$

bare pomeron amp. $\Omega/2$ = 

$\text{Im } T_{\rm el} =$  $= 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty}$  $\Omega/2$

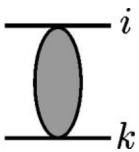
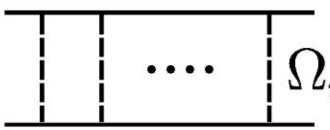
(s-ch unitarity)

Low-mass diffractive dissociation

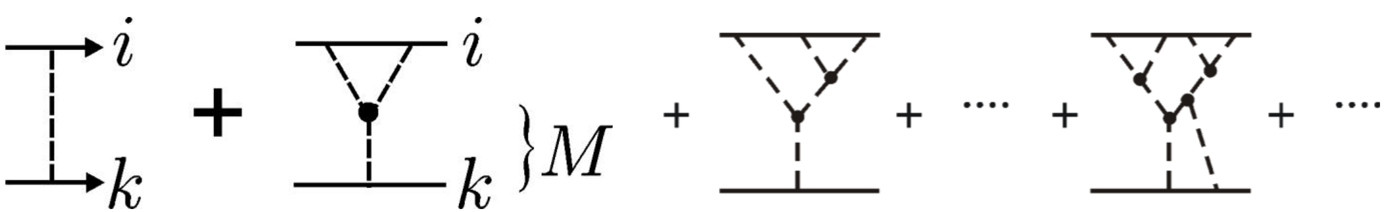


→multichannel eikonal

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

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

include high-mass diffractive dissociation

$\Omega_{ik} =$ 

KMR model for the global description of high energy diffractive data

soft

Reggeon Field Theory
with phenomenological
soft pomeron

hard

pQCD
partonic approach

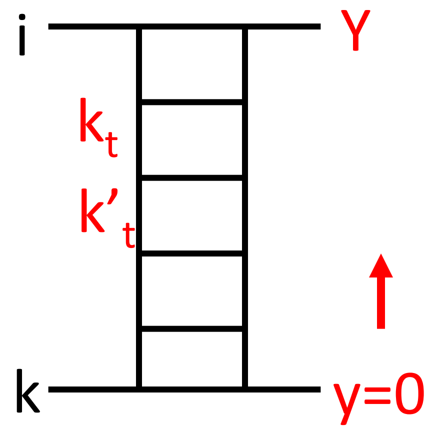
smooth transition using
QCD / "BFKL" / hard pomeron

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

KMR model is a partonic approach which includes the k_t dependence of the pomeron in the log(1/x) evolution/cascade, as well as eikonal and enhanced multi-pomeron absorptive effects

Partonic structure of "bare" Pomeron

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

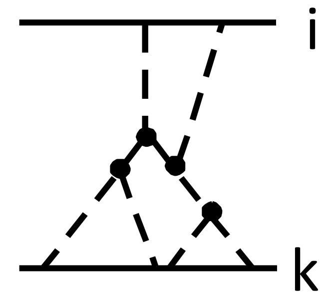


BFKL evol^n in rapidity generates ladder

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

- 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
- **Inclusion of k_t crucial to match soft and hard domains. Moreover, embodies less screening for larger k_t comp^{ts}.**
- We 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 $\longrightarrow$ $\boxed{\Omega = \Omega_{ik}(y, k_t, b)}$

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



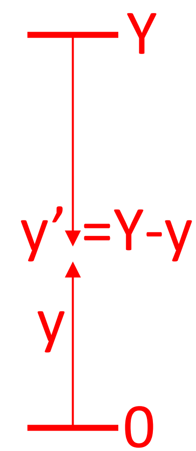
Now include rescatt of intermediate partons with the “beam” i and “target” k (KMR)

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 $\Omega_{i,k}$ λ~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

Surprises from LHC diffractive data

	σ(tot) (mb)	$B_{el}(0)$ (GeV^{-2})	σ^{SD}(low M) (mb)
KMR (before LHC) predict at 7 TeV	88	18.5	6
Expt. at 7 TeV			
TOTEM	98.6 $\pm$2.2	19.9 $\pm$0.3	2.6 $\pm$2.2
ATLAS (ALFA)	95.35 $\pm$1.3	19.73 $\pm$0.24	

also σ^{SD}(high M) , σ^{DD} predicted larger than TOTEM data

something is missing in the KMR model

Quote from Gotsman, Levin, Maor (August 2014)

The strong interaction at high energies is one of the most difficult and unrewarding problems of HEP.

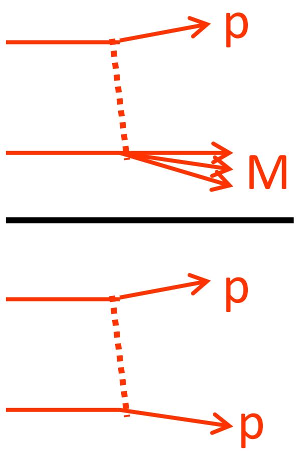
……

The LHC data showed that models [8-13] based on pomeron calculus failed to provide significant predictions and were not able to describe the data at high energy.

[8] A. Donnachie and P.V. Landshoff, Nucl. Phys. B231, (1984) 189; Phys. Lett. B296, (1992) 227; Zeit. Phys.
C61, (1994) 139.
[9] E. Gotsman, E. Levin and U. Maor, Eur. Phys. J. C 71, 1553 (2011) [arXiv:1010.5323 [hep-ph]].
[10] E. Gotsman, E. Levin, U. Maor and J. S. Miller, Eur. Phys. J. C 57, 689 (2008) [arXiv:0805.2799 [hep-ph]].
[11] A. B. Kaidalov and M. G. Poghosyan, arXiv:0909.5156 [hep-ph].
[12] A. D. Martin, M. G. Ryskin and V. A. Khoze, arXiv:1110.1973 [hep-ph].
[13] S. Ostapchenko, Phys.Rev. D 81, 11402 (2010).

Very few measurements of σ^{SD}(low M)

	CERN-ISR	**UA4**	**TOTEM**
	62.5 GeV	546 GeV	7 TeV
		M<4 GeV	M<3.4 GeV



$$\frac{\sigma_{\text{low M}}}{\sigma_{\text{elastic}}} = \frac{2\text{-}3}{7} = \frac{3}{12} \overset{?}{=} \frac{2.6\ \text{mb}}{25.4\ \text{mb}}$$

Unexpectedly small

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

Conventional Reggeon Field Theory assumes all k_T's are limited, and that trajectories and couplings do not depend on energy, $\sqrt{s}$.

LHC data indicates problems --- recall the observed growth of the $\langle k_T \rangle$ of secondaries with energy.

(ϕ_i are diff^{ve} estates of proton)

Missing physics

pomeron–ϕ_i couplings, γ_i, are driven by $\langle r_{i,\text{parton}} \rangle$ in ϕ_i states

However, γ_i's controlled by transverse size of pomeron ($\propto 1/k_{pom}$) when it becomes smaller than $\langle r_{i,\text{parton}} \rangle \propto 1/k_i$

$$\boxed{\gamma_i \propto 1/(k_{pom}^2 + k_i^2) \qquad \text{where} \quad k_{pom}^2 = k_0^2\, s^{0.28}}$$

As $s \to \infty$ all γ_i become equal, $\gamma_i \propto 1/k_{pom}^2$ (all $\gamma_i \to 1$)
so dispersion decreases, $\sigma^{SD} \propto (\langle \gamma_i^2 \rangle - \langle \gamma_i \rangle^2) \to 0$
so dissociation is suppressed as collider energy increases

We call this the $k_T(s)$ effect

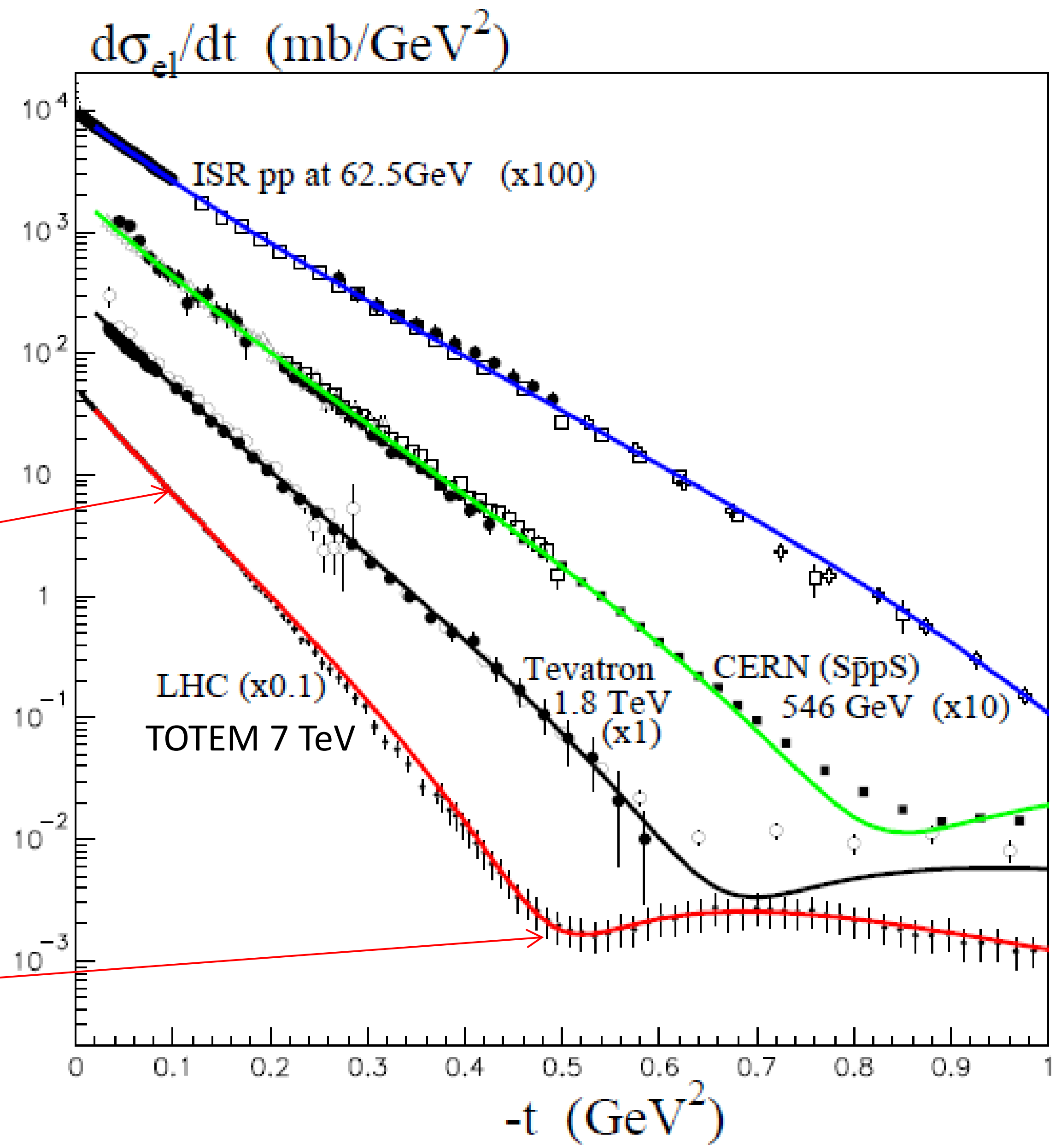
Decrease of γ_i dispersion means screening brings 2-ch eikonal closer to 1-ch eik. and absorption smaller. As a result it speeds up the growth of σ(tot) in the energy interval

		Tevatron	$\rightarrow$	LHC (7 TeV)	$\rightarrow$	100 TeV	TOTEM (7 TeV)
σ(tot)	mb	77	$\rightarrow$	98.7	$\rightarrow$	166	98.6 ± 2.2
$B_{el}(0)$	GeV^{-2}	16.8	$\rightarrow$	19.7	$\rightarrow$	29.4	19.9 ± 0.3
σ^{SD}(low M)	mb	3.4	$\rightarrow$	3.6	$\rightarrow$	2.7	2.6 ± 2.2

The $k_T(s)$ effect brings model into agreement with the TOTEM data; also describes high-mass σ^{SD}, σ^{DD} data

The acceleration of the growth of σ(tot) with s only takes place in the interval where the $\gamma_i(s) \rightarrow 1$

Global fit with two-channel eikonal – needed for σ^{SD}(low M)



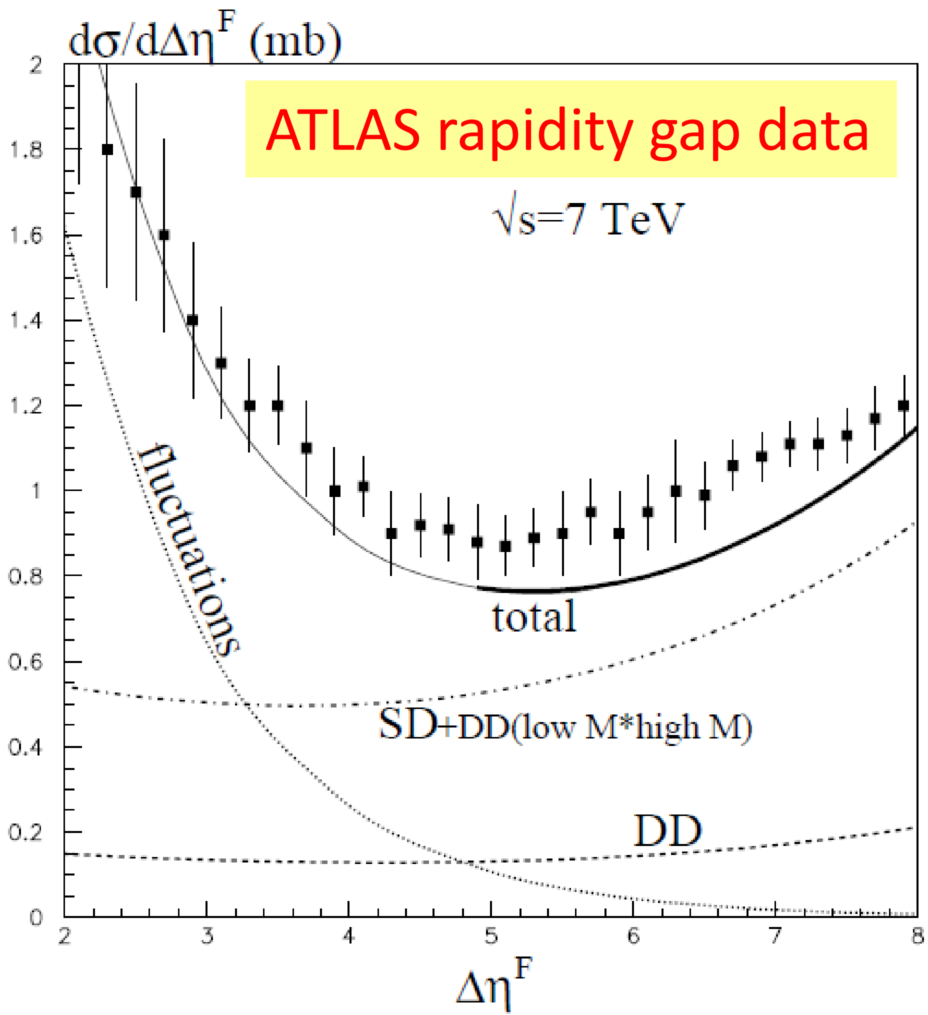
find form factors $F_i(t) \sim \exp(-b_i \sqrt{t})$ (coincidence—like Orear et al.)

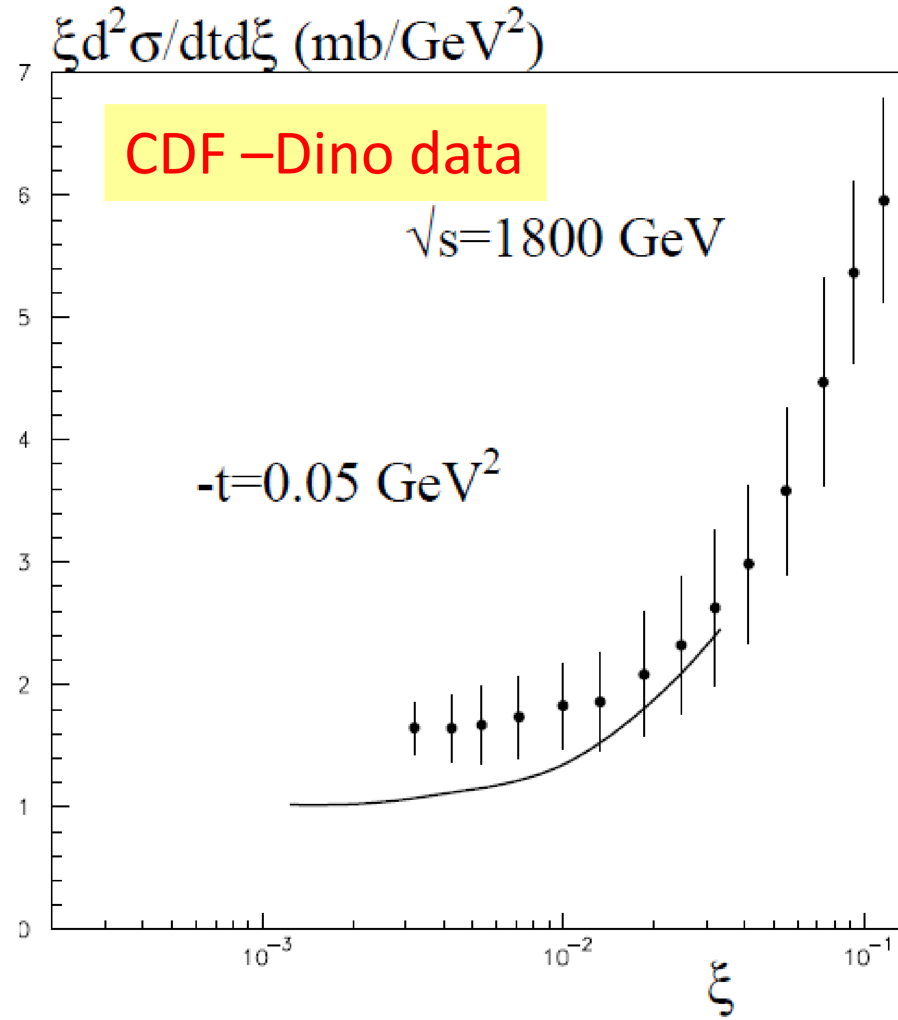
Real part important, calculate from dispersion relation

Tension between high-mass σ^{SD} data

Global fit exposes some tension between TOTEM and CDF (as well as ATLAS, CMS) single-diffractive data ---- see also Ostapchenko.

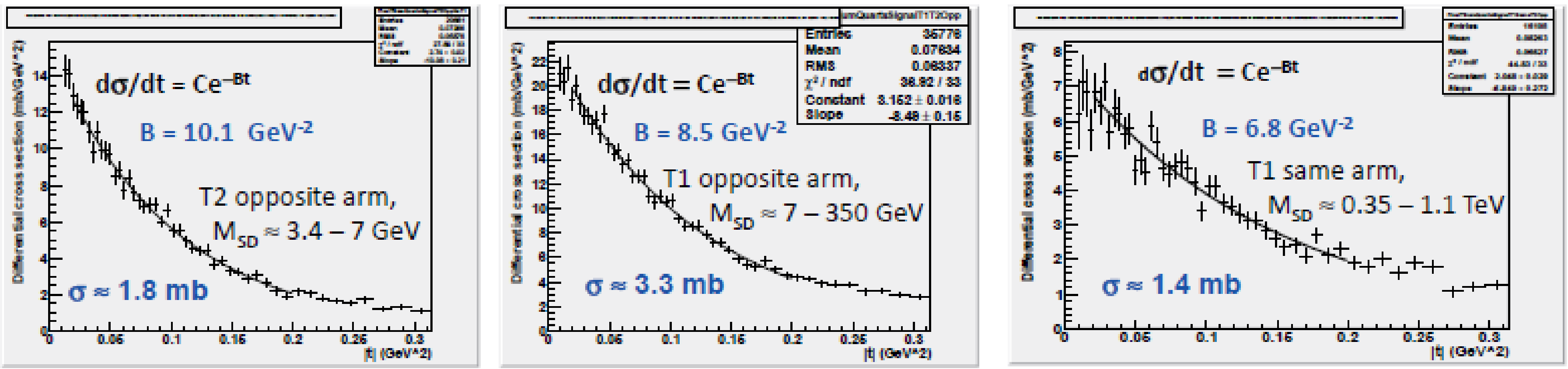
Description is a bit above TOTEM σ^{SD} data
and a bit below CDF, ATLAS, CMS data





Global KMR description below these SD data, yet above TOTEM σ^{SD}

Preliminary TOTEM results on single diffraction in three Mass bins



Uncertainty estimated on slope parameter B ~ 15 % and on cross sections ~20%

σ^{SD}(high M) mb

Mass interval (GeV)	(3.4, 8)	(8, 350)	(350, 1100)
Prelim. TOTEM data	1.8	3.3	1.4
CMS data		4.3	
Present model	2.3	4.0	1.4

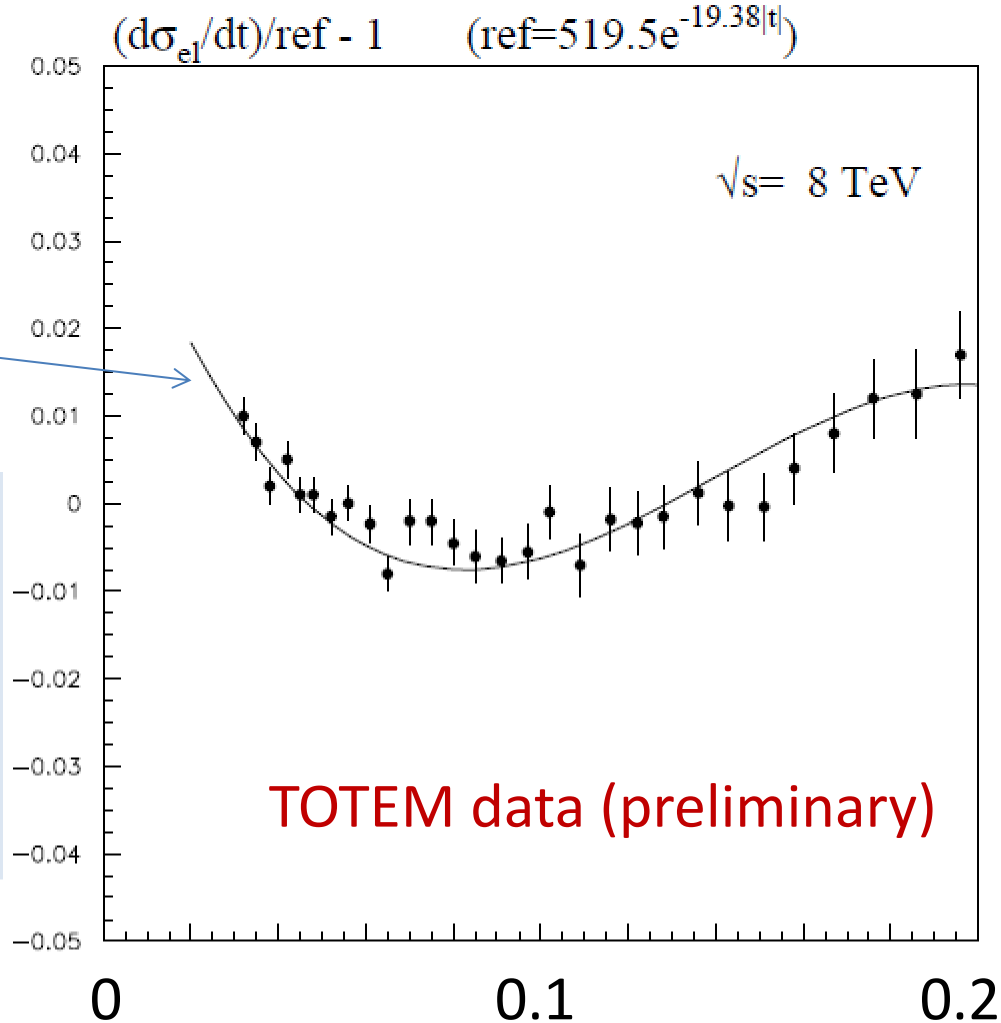
CMS integrated over 12 < M < 394 GeV, just a bit smaller than 8 < M < 350 GeV of TOTEM, in terms of log M.

Again above TOTEM below CMS

t dependence of elastic slope shown by TOTEM as deviation from pure exponential $d\sigma(el)/dt \sim \exp(19.38\, t)$

KMR model preliminary

decrease due
(i) pion-loop in pom.traj.
(ii) pomeron-proton ff



increase due absorptive corrections

$|t|$ GeV^2

KMR model values post-LHC

TOTEM $\Delta\eta$ bins

$\sqrt{s}$ (TeV)	$\sigma_{\rm tot}$ (mb)	$\sigma_{\rm el}$ (mb)	$B_{\rm el}(0)$ (GeV^{-2})	$\sigma_{\rm SD}^{{\rm low}\,M}$ (mb)	$\sigma_{\rm DD}^{{\rm low}\,M}$ (mb)	$\sigma_{\rm SD}^{\Delta\eta_1}$ (mb)	$\sigma_{\rm SD}^{\Delta\eta_2}$ (mb)	$\sigma_{\rm SD}^{\Delta\eta_3}$ (mb)	$\sigma_{\rm DD}^{\Delta\eta}$ (μb)
1.8	77.0	17.4	16.8	3.4	0.2				
7.0	98.7	24.9	19.7	3.6	0.2	2.3	4.0	1.4	145
8.0	101.3	25.8	20.1	3.6	0.2	2.2	3.95	1.4	139
13.0	111.1	29.5	21.4	3.5	0.2	2.1	3.8	1.3	118
14.0	112.7	30.1	21.6	3.5	0.2	2.1	3.8	1.3	115
100.0	166.3	51.5	29.4	2.7	0.1				

TOTEM

7	98.6 (2.2)	25.4	19.9 (0.3)	2.6 (2.2)		1.8	3.3	1.4	116 (25)

--- up to 20% ---

Main Conclusion

The LHC elastic and diffractive data expose deficiencies of the KMR model predictions based on global fits of pre-LHC data:

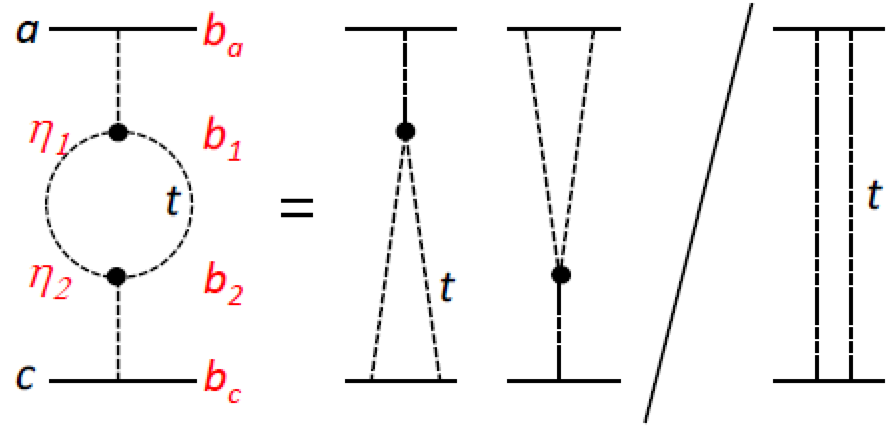
--- σ(tot) is larger than expected
--- $B_{el}(0)$ is larger than expected
--- TOTEM diffractive rates are smaller than predicted

These discrepancies may **all** be removed by noting that the "pomeron – proton (diffractive estate)" couplings should tend to a common limit as $s \to \infty$, when the decreasing pomeron size starts to control the couplings --- **the $k_T(s)$ effect**.

Possible exp^{tal} check: measure the p_T of B or D mesons as a function of s, and see the growth of p_T coming from the larger p_T of the incoming gluons in $gg \to QQ(\mathrm{bar})$

BACK UP SLIDES

Double Dissociation



$B^2_{\rm SD}/B_{\rm el}B_{\rm DD}$

$S^2_{\rm DD} \simeq 0.16$

$$\frac{\sigma_{\rm DD}\;\sigma_{\rm el}}{(\sigma_{\rm SD})^2} \simeq \frac{1.36}{6.8}\;\frac{0.16}{(0.08)^2} \simeq 5.0$$

old KMR

suppression of $d\sigma/dt|_{t=0}$

$S^2_{\rm SD} \simeq 0.08$

TOTEM data

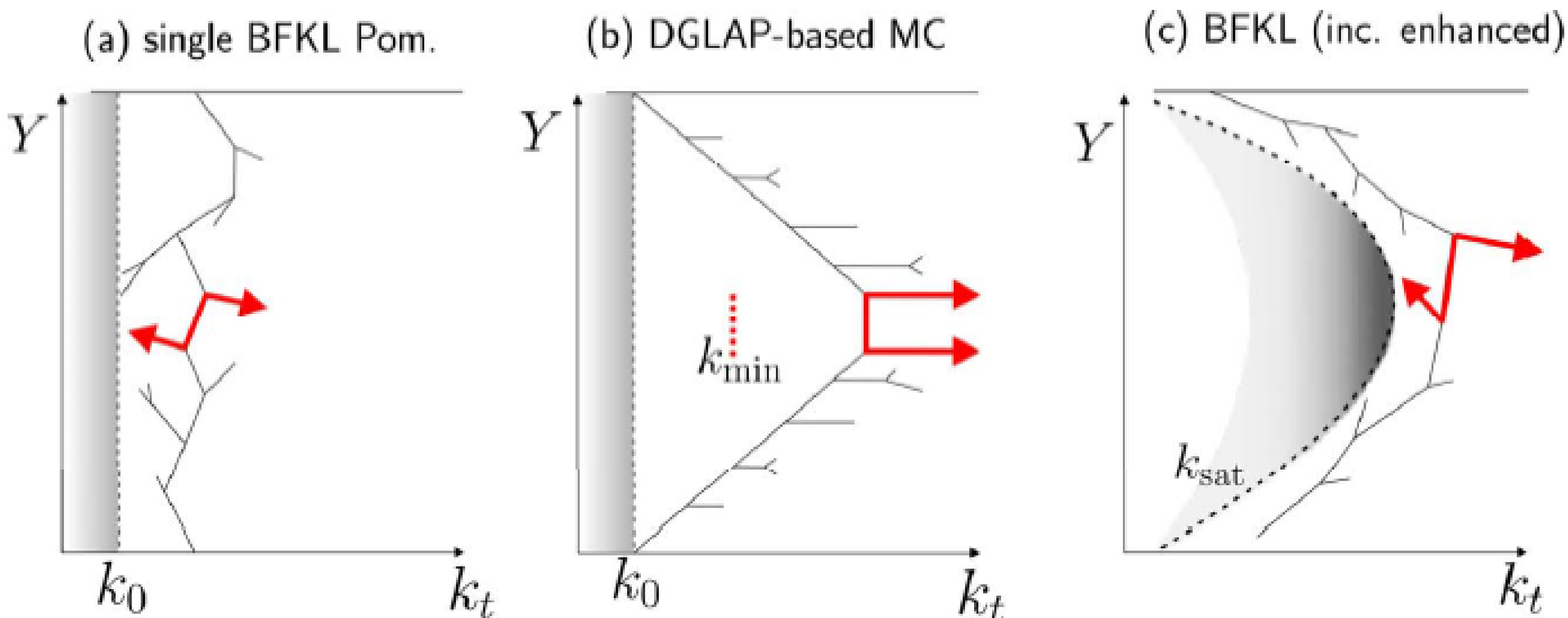
$$\frac{\sigma_{\rm DD}\;\sigma_{\rm el}}{(\sigma_{\rm SD})^2} \simeq \frac{0.116 \times 25}{(0.9)^2} \simeq 3.6$$

Discrepancy renconciled by $k_T(s)$ effect

LHC

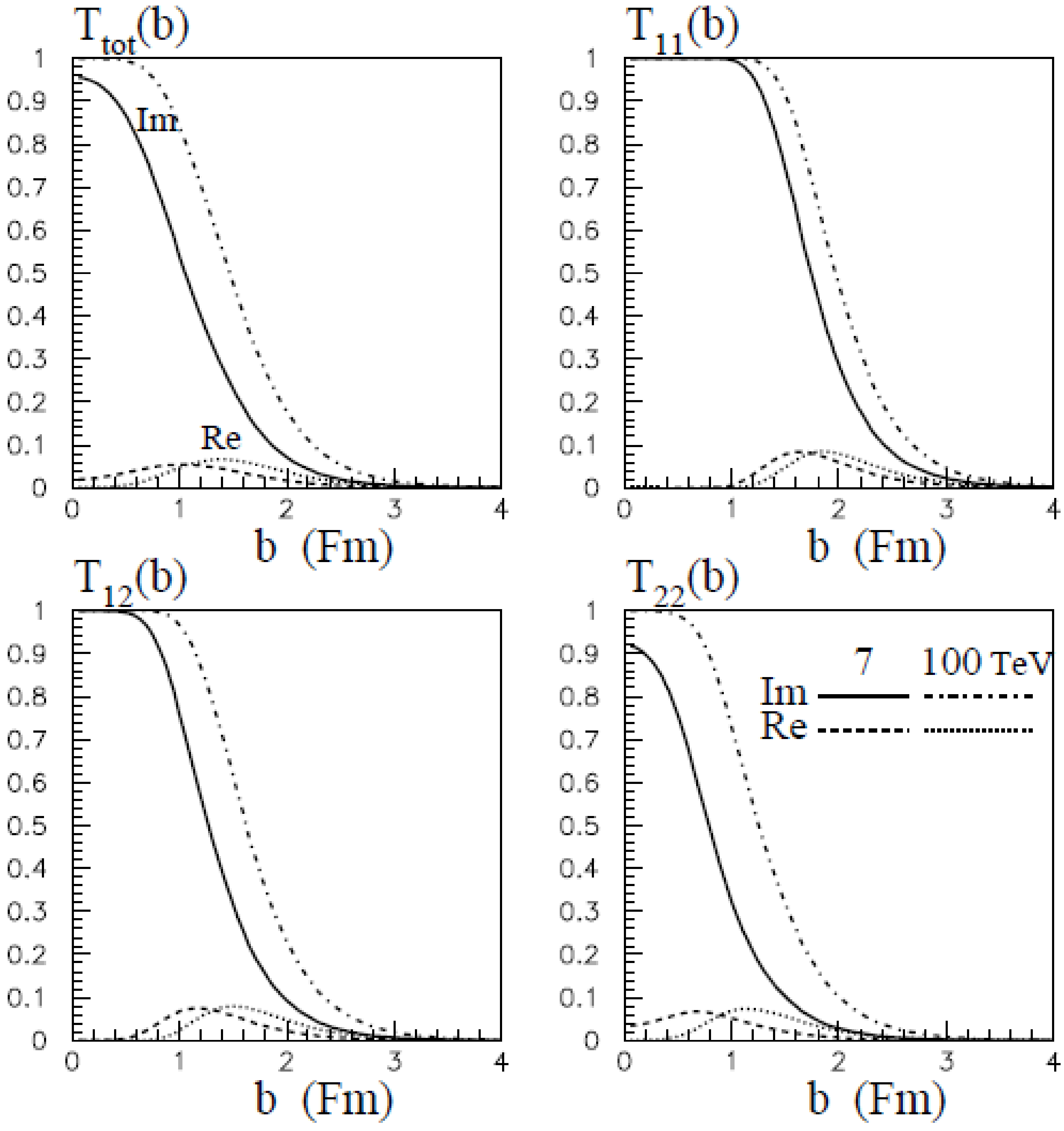
DGLAP ln k_t^2 evol^n interval << BFKL ln(1/x) evol^n interval

overestimates $\langle k_t \rangle$	not strongly-ordered in k_t
underestimates growth $dN/d\eta$	$dN/d\eta = n_P\,(dN_{1\text{-Pom}}/d\eta)$
	n_P=no. of Poms. grows

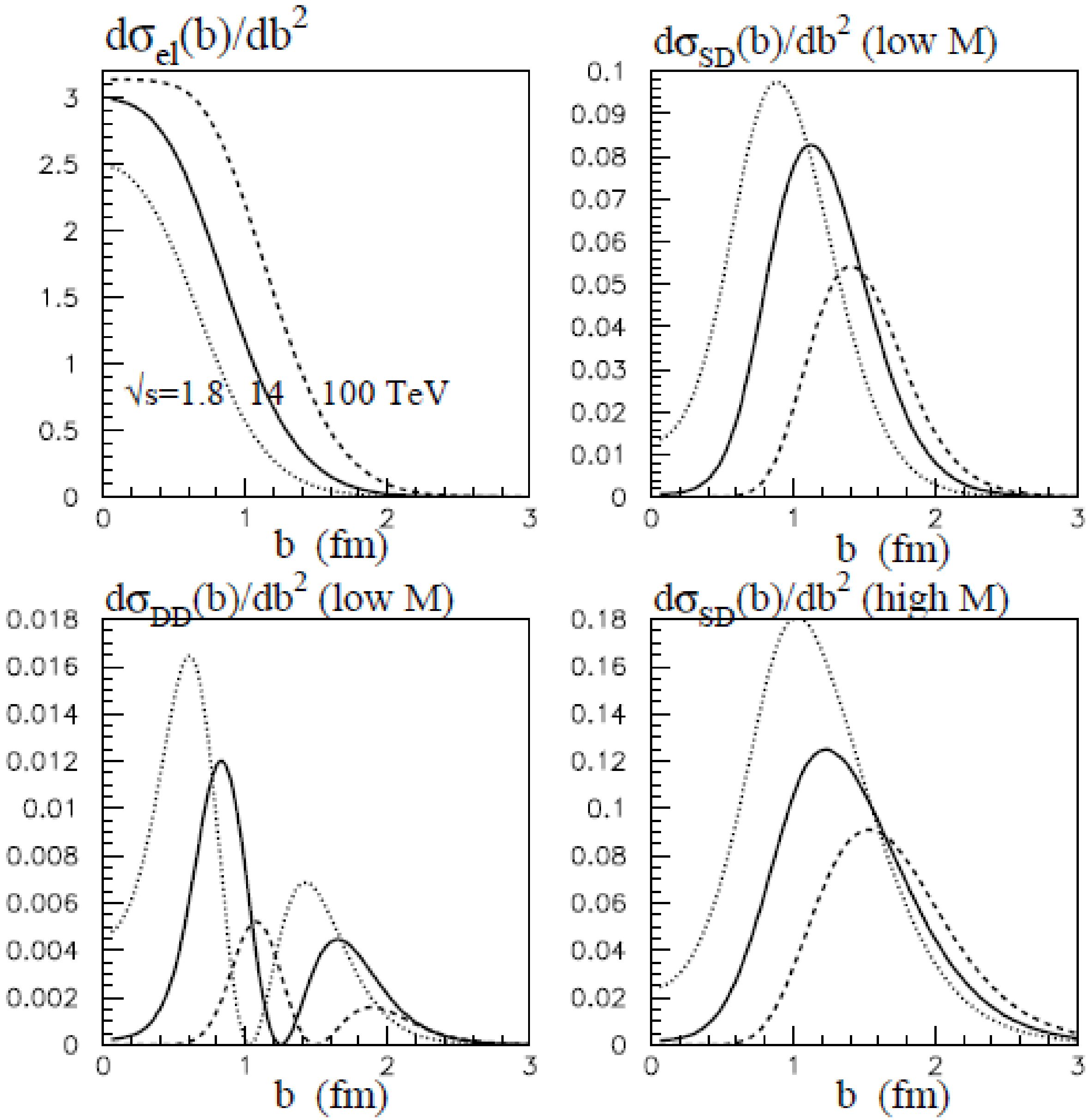


$d\sigma_{subp}/dk_t^2 \sim 1/k_t^4$
→tune cutoff to data
$k_{min} \sim s^a$, a=0.12

Enh: $\sigma_{abs} \sim 1/k_t^2$
→dyn.cutoff k_{sat}
→besides SD, DD



T_tot(b)
Im
Re
b (Fm)
T_11(b)
b (Fm)
T_12(b)
b (Fm)
T_22(b)
7
100 TeV
Im
Re
b (Fm)



the same central rapidity interval as that selected by TOTEM, which corresponds to $M_{\rm diss} = (8, 350)$ GeV at $\sqrt{s} = 7$ TeV. $\sigma_{\rm SD}$ is calculated for the dissociation of *one* proton.

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

Can this be the basis of a unified partonic model for
both soft and hard interactions ??

“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 $\alpha_P^{bare}(0) \sim 1.3 – 1.4$

$\boldsymbol{\Delta = \alpha_P(0) - 1 \sim 0.35}$

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

up to Tevatron energies

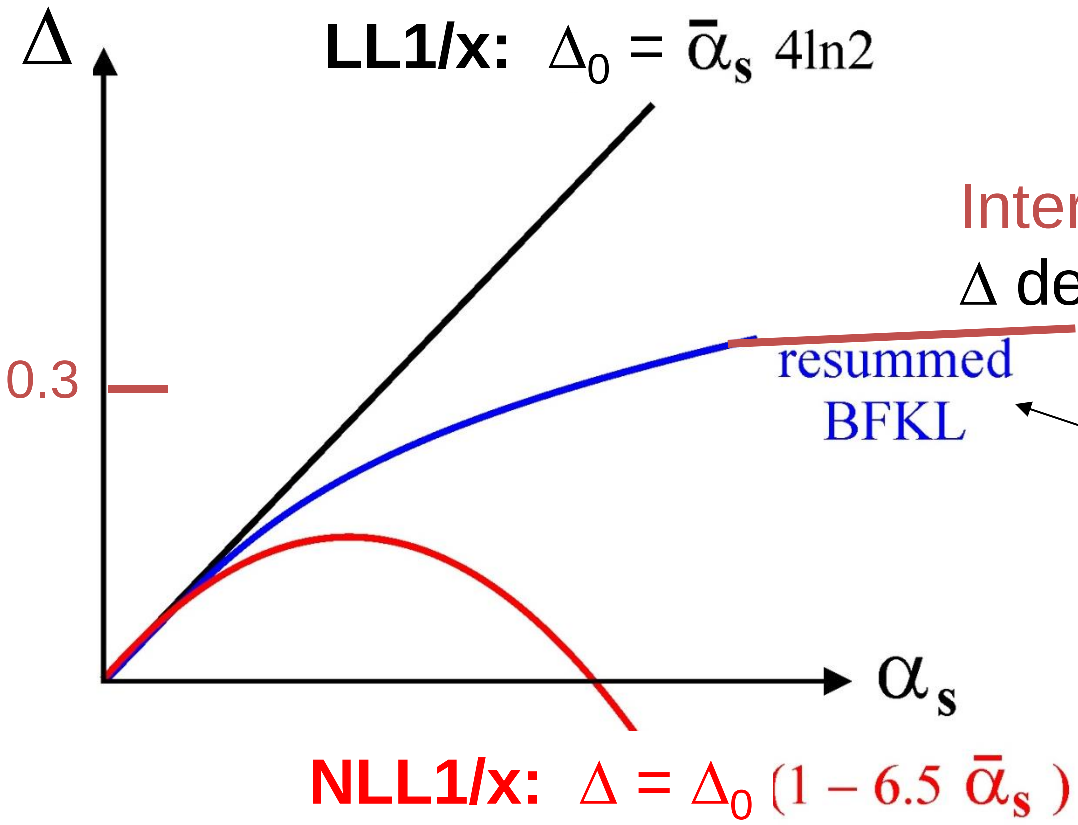
$(\sigma_{tot} \sim s^{\Delta})$

$\alpha_P^{bare} \sim 1.35 + 0\ t$

with absorptive (multi-Pomeron) effects

BFKL stabilized

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



Intercept $\Delta = \alpha_P(0) - 1 \sim 0.35$

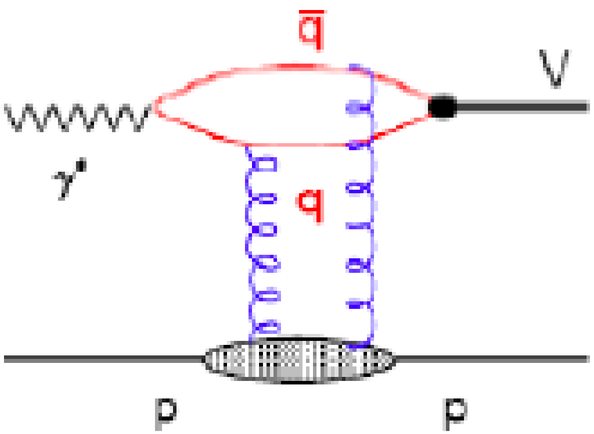
Δ depends weakly on k_t
for low k_t

see, for example, Salam, Zakopane school 1999

Small-size “BFKL” Pomeron is natural object to continue from “hard” to “soft” domain

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

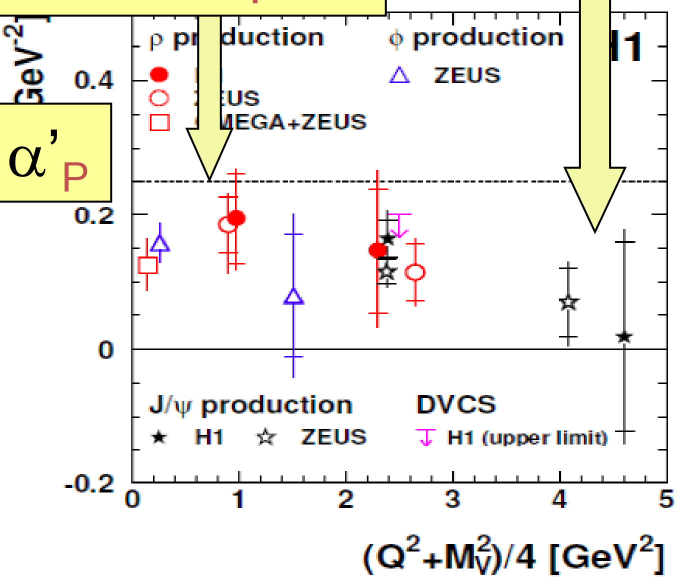
Q^2



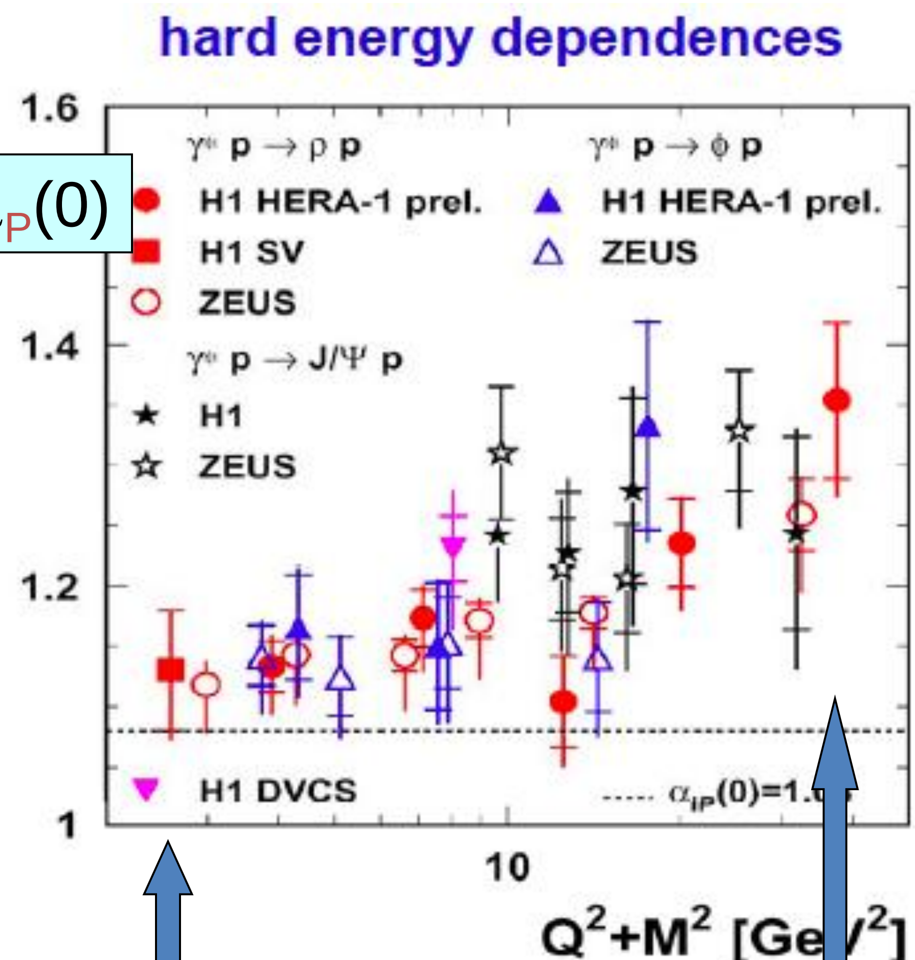
$\alpha'_P(0)$ ~ 0.25
after absorption

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

α'_P



$\alpha_P(0)$

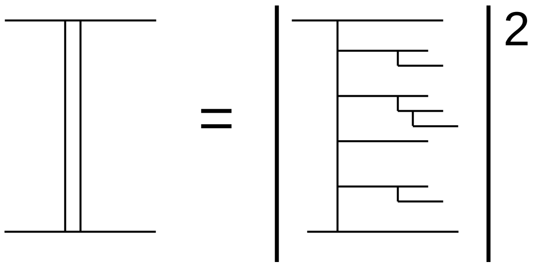


$\alpha_P(0)$ ~ 1.1
after absorption

$\alpha^{bare}_P(0)$ ~1.35

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

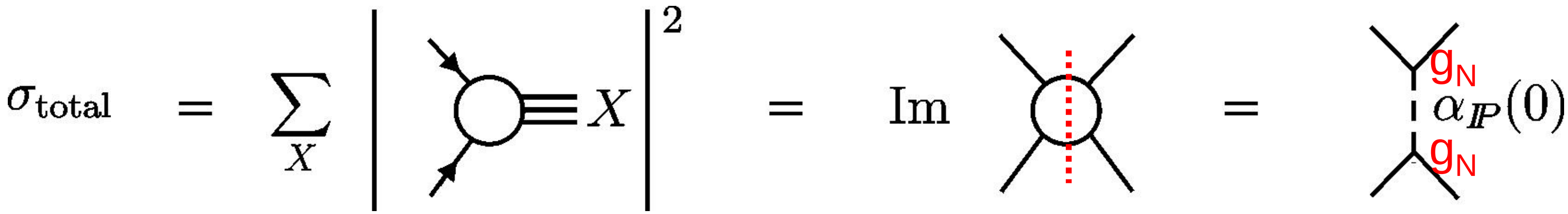
small slope $\alpha'_{\text{bare}} \sim 0$
success of Additive QM
small size of triple-Pomeron vertex
small size of BEC at low N_{ch}



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

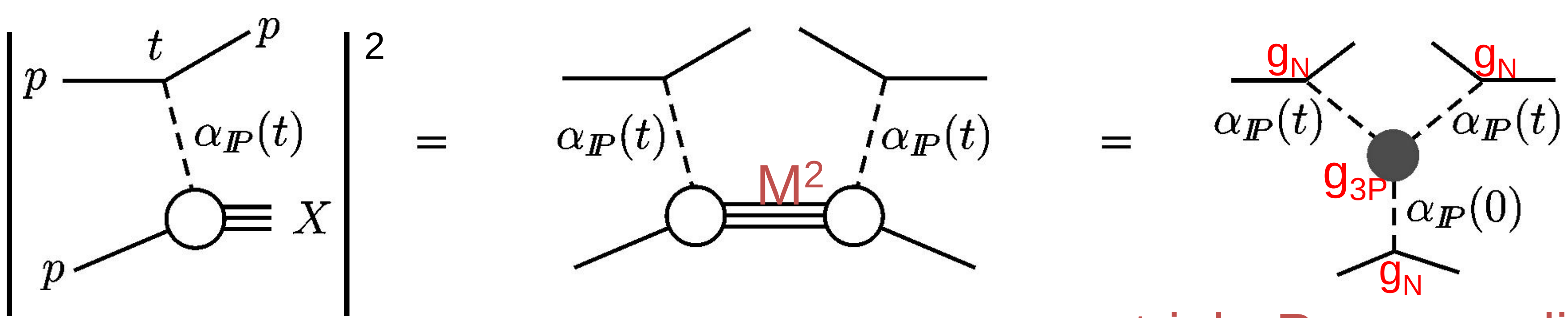
Optical theorems

at high energy
use Regge



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

High-mass diffractive dissociation

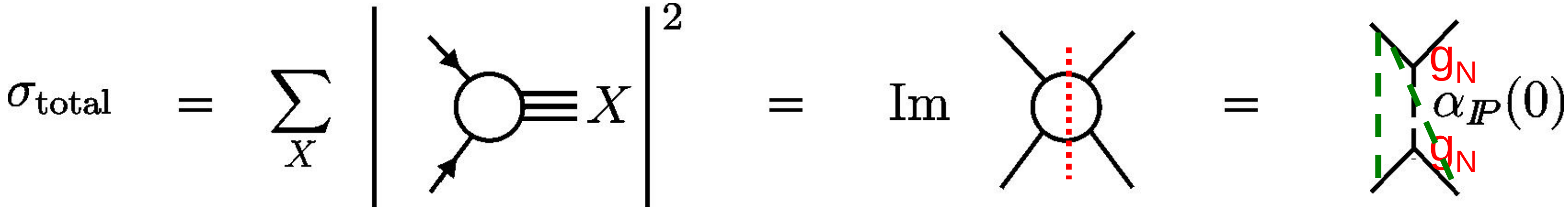


triple-Pomeron diag

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

Optical theorems

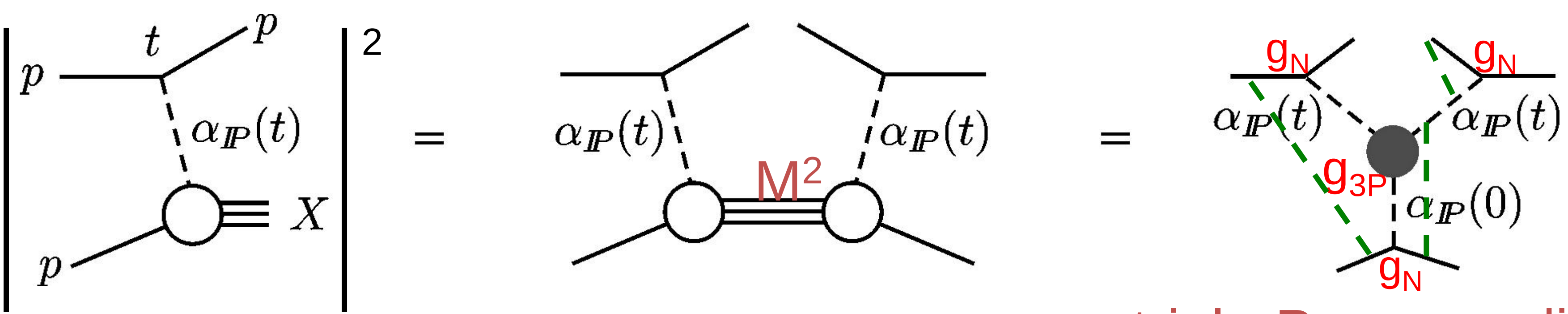
at high energy
use Regge



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

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

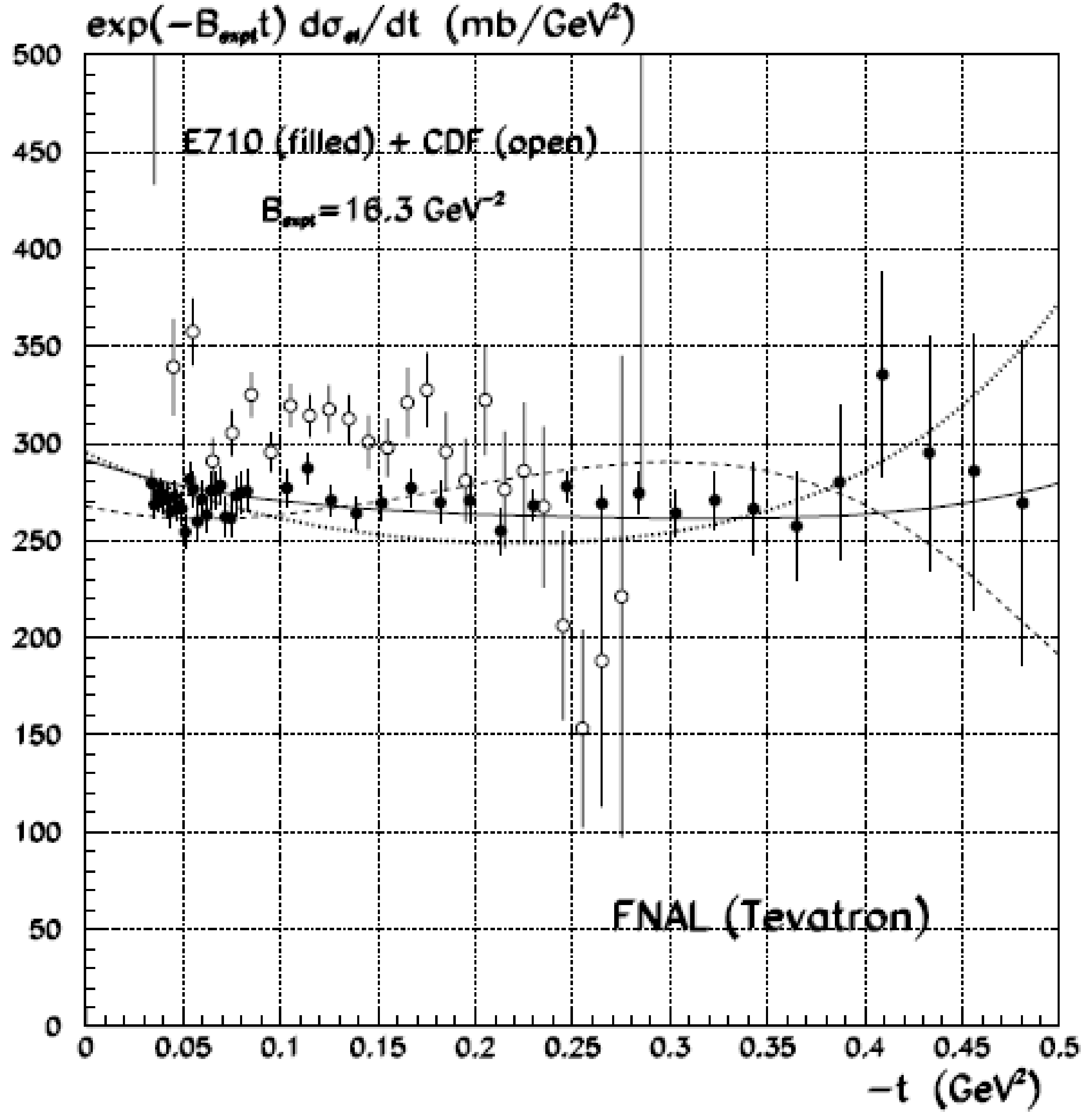
High-mass diffractive dissociation

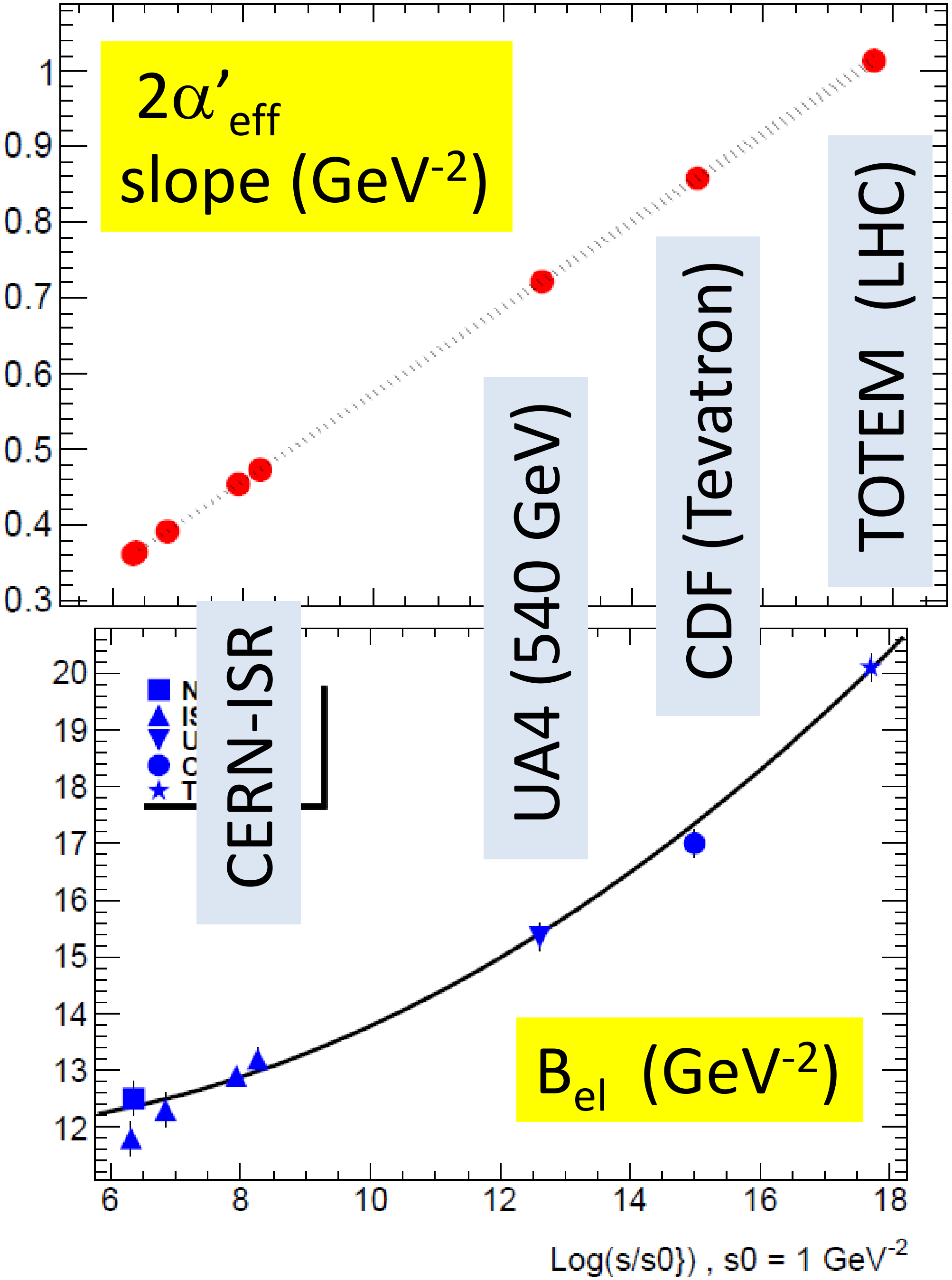


triple-Pomeron diag

but screening important

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


exp(−B_expt t) dσ_el/dt (mb/GeV²)
E710 (filled) + CDF (open)
B_expt=16.3 GeV⁻²
FNAL (Tevatron)
−t (GeV²)
0
50
100
150
200
250
300
350
400
450
500
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5



Schegelsky, Ryskin
1112.3243

$$B_{el} = B_0 + 2\alpha_P^{'eff} \ln(s/s_0)$$

$$B_{el} = B_0 + b_2 \ln^2(s/s_0)$$