

# "Soft" high-energy pp interactions

Vast majority of LHC interactions occur in "soft" domain  $|t| < 0.5 \text{ GeV}^2$   $(d\sigma/dt \sim e^{-20t})$ 

Moreover, about 40% of  $\sigma_{tot}$  comes from diffractive processes, like elastic scatt., SD, DD. Need to soft processes to understand the structure of  $\sigma_{tot}$  and the nature of the underlying events which accompany the sought-after rare hard subprocesses.

(Note the LHC detectors do not have  $4\pi$  geometry and do not cover the whole rapidity interval. So minimumbias events account for only part of total  $\sigma_{inelastic}$ .)

# "Soft" high-energy pp interactions

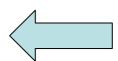
- HE soft interns are driven by the Pomeron. Pomeron??
- Historically, the "Regge" Pomeron was introduced to account for asymptotically constant pp, πp... X-sections
- "QCD" Pomeron ~ parton cascade ~ small transverse size
- It is natural object to extend into soft domain
- importance of eikonal & enhanced multi-Pomeron contribns
- A partonic model for soft interactions
   Khoze, Martin, Ryskin
- The possibility of a MC which unifies soft and hard interns
   Krauss et al

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  $\sigma_{tot}$  means multi-Pom diags (with Regge cuts) are necessary to restore unitarity.  $\sigma_{tot}$ ,  $d\sigma_{el}/dt$  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  $\alpha_P^{\text{bare}}(0) \sim 1.3 - 1.4$   $\Delta = \alpha_P(0) - 1 \sim 0.35$ 

 $\alpha_{\text{P}}^{\text{eff}}$  ~ 1.08 + 0.25 t up to Tevatron energies

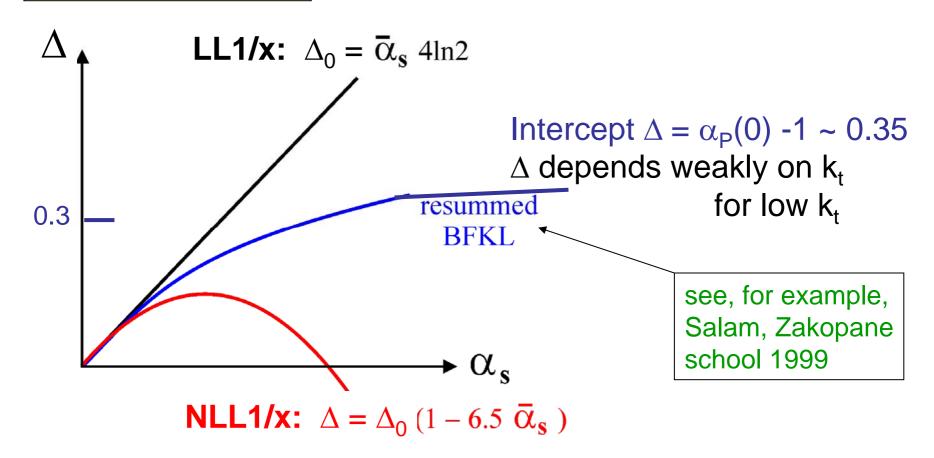
$$(\sigma_{\text{tot}} \sim S^{\Delta})$$

$$\alpha_{P}^{\text{bare}} \sim 1.35 + 0 \text{ t}$$

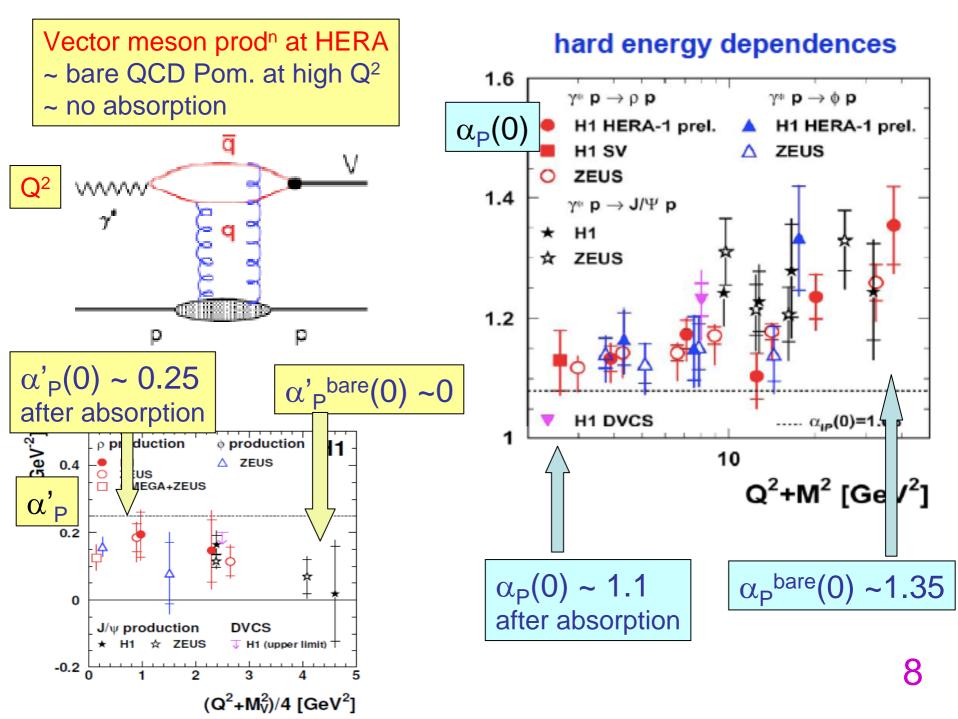
with absorptive (multi-Pomeron) effects

# BFKL stabilized

$$\Delta = \alpha_{P}(0) - 1$$



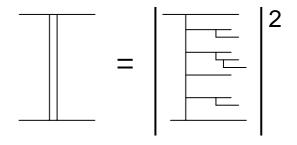
Small-size "BFKL" Pomeron is natural object to continue from "hard" to "soft" domain



# Phenomenological hints that $R_{bare\ Pom} << R_{proton}$

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

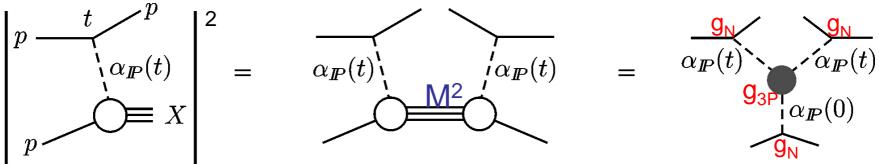


the cascade is compact in b space and so the parton  $k_t$ 's are not too low. We may regard the cascade as a hot spot inside the two colliding protons

# Optical theorems

$$\sigma_{\text{total}} = \sum_{X} \left| \sum_{\alpha_{IP}} (0) \right| = \lim_{\alpha_{IP}} \left( \frac{s}{s_0} \right)^{\alpha_{IP}(0) - 1}$$

# 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

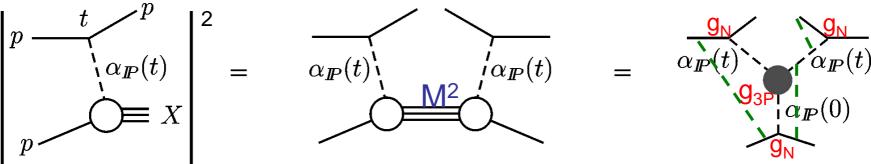
# at high energy use Regge

$$\sigma_{\text{total}} = \sum_{X} \left| \begin{array}{c} \sum_{X} \sum_{X} \left| \begin{array}{c} \sum_{X} \sum_{X} \left| \sum_{X} \sum_{X} \sum_{X} \left| \sum_{X} \sum_{X} \sum_{X} \left| \sum_{X} \sum_{X} \sum_{X} \sum_{X} \sum_{X} \left| \sum_{X} \sum_{$$

but screening/s-ch unitarity important so  $\sigma_{\text{total}}$  suppressed

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

# High-mass diffractive dissociation



triple-Pomeron diag

but screening important

$$\mathsf{g_N}^3 \mathsf{g_{3P}} \left( rac{M^2}{s_0} 
ight)^{lpha_{I\!\!P(0)}-1} \left( rac{s}{M^2} 
ight)^{2lpha_{I\!\!P}(t)-2}$$

$$\Omega = \sum_{n} \left| \begin{array}{c} k_{t} \\ \hline \end{array} \right|^{2} = \sum_{n} \left| \begin{array}{c} \\ \\ \end{array} \right|$$

 $s^{\Delta} \sim s^{0.3}$ 

growth of cascades with s → multi-Pomeron effects/absorption

#### Elastic & low-mass dissoc<sup>n</sup>

$$\square$$
 ....  $\Omega$ 

σ<sub>tot</sub>~ s<sup>0.08</sup> up toTevatron energies

Im  $T_{\rm el} = \boxed{ } = 1 - e^{-\Omega/2} = \sum_{\rm (s-ch\ unitarity)}$ 

include high-mass diffractive dissoc<sup>n</sup>

enhanced

$$\Omega_{ik} = \prod_{k}^{i} + \prod_{k}^{i} M + \prod_{k}^{i} \dots + \prod_{k}^{i} M$$

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

bare amp. 
$$\Omega/2 =$$

$$\operatorname{Im} \ T_{\mathrm{el}} = \overline{ } = 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty} \overline{ } \qquad \overline{ } \cdots \overline{ } \Omega/2$$
 (s-ch unitarity)

#### Low-mass diffractive dissociation



→ multichannel eikonal

introduce diff<sup>ve</sup> estates  $\phi_i$ ,  $\phi_k$  (comb<sup>ns</sup> of p,p\*,..) which only undergo "elastic" scattering (Good-Walker)

Im 
$$T_{ik} = \int_{k}^{i} = 1 - e^{-\Omega_{ik}/2} = \sum_{i=1}^{k} \frac{(-40\%)}{\Omega_{ik}/2}$$

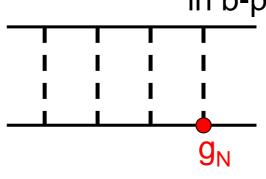
# include high-mass diffractive dissociation

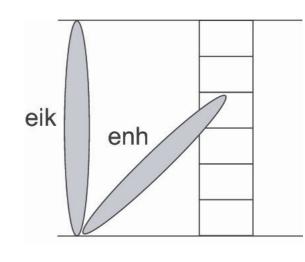
(SD -80%)

$$\Omega_{ik} = \prod_{k=1}^{i} + \prod_{k=1}^{i} M + \prod_{k=$$

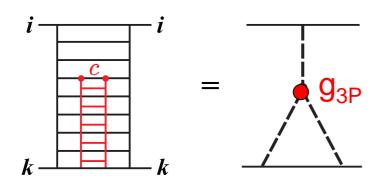
#### Multi-Pomeron contributions

eikonal: Pomerons well separated in b-plane





enhanced: interactions with partons in an individual cascade

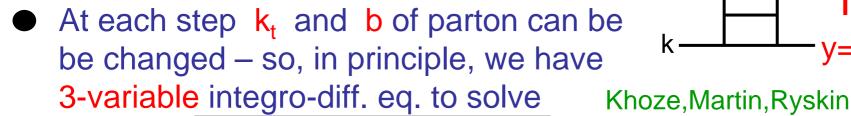


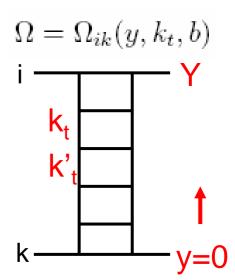
despite  $g_{3P}=\lambda~g_N$ , with  $\lambda\sim0.2$  enhanced by phase space, which grows with s means  $\sigma_{SD}\sim\sigma_{el}$  at LHC

#### Partonic structure of "bare" Pomeron

BFKL evol<sup>n</sup> in rapidity generates ladder

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





- Inclusion of k<sub>t</sub> crucial to match soft and hard domains.
  Moreover, embodies less screening for larger k<sub>t</sub> comp<sup>ts</sup>.
- We use a simplified form of the kernel K with the main features of BFKL diffusion in log  $k_t^2$ ,  $\Delta = \alpha_P(0) 1 \sim 0.35$
- b dependence during the evolution is prop' to the Pomeron slope α', which is v.small (α'<0.05 GeV<sup>-2</sup>) -- so ignore.
   Only b dependence comes from the starting evol<sup>n</sup> distrib<sup>n</sup>
- Evolution gives

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

#### How are Multi-Pomeron contribns included?

i k

Now include rescatt of intermediate partons with the "beam" i and "target" k

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

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

y 0

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  $\exp(-\lambda\Omega)$   $\rightarrow$   $[1 - \exp(-\lambda\Omega)] / \lambda\Omega$ Form is consistent with generalisation of AGK cutting rules 15 In principle, knowledge of  $\Omega_{ik}(y,k_t,b)$  (and hadronization) allows the description of all soft, semi-hard pp high-energy data:

 $\sigma_{tot}$ ,  $d\sigma_{el}$ /dt,  $d\sigma_{SD}$ /dtdM<sup>2</sup>, DD, DPE... LRG survival factors S<sup>2</sup> (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. Present status of above unified description of soft and semihard processes. (KMR model evolving -- 2000, 2007, 2009, 2011,.....)

Basis is BFKL-like evolution in rapidity, including multi-Pomeron absorptive effects. Pom. = gluon ladder (or, rather, g cascade)

#### Main parameters:

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\Delta = \alpha_P(0)-1, bare Pom. intercept (expect \Delta \sim 0.3-0.4) (s-dep.)
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slope  $\alpha'_P = 0$  (in 2011 analysis)

d controls BFKL diffusion in log k<sub>t</sub>

λ strength of triple (and multi) Pom. couplings (triple-Regge data)

γ specifies diff<sup>ve</sup> estates (determined by low M diff<sup>ve</sup> dissoc<sup>n</sup>)

N absolute value of initial gluon density

#### Some results of KMR model (EPJ C71, 2011):

- 1.  $\sigma_{tot}$  ~ 88 mb,  $\sigma_{el}$  ~ 22 mb, at 7 TeV  $\sigma_{SD}$ (low M) ~ 6 mb,  $\sigma_{SD}$ (high M) ~ 13 mb
- 2. Survival prob. of rapidity gaps in pp  $\rightarrow$  p+H+p S<sup>2</sup> = 0.010 0.016 for 120 GeV SM Higgs at 14 TeV
- 3. Growth of rapidity plateau with energy  $0.9 \rightarrow 7 \text{ TeV}$  do/dy ~  $s^{0.2}$  like the LHC data for 0.9 to 7 TeV

Lessons from LHC data → start with rapidity plateau

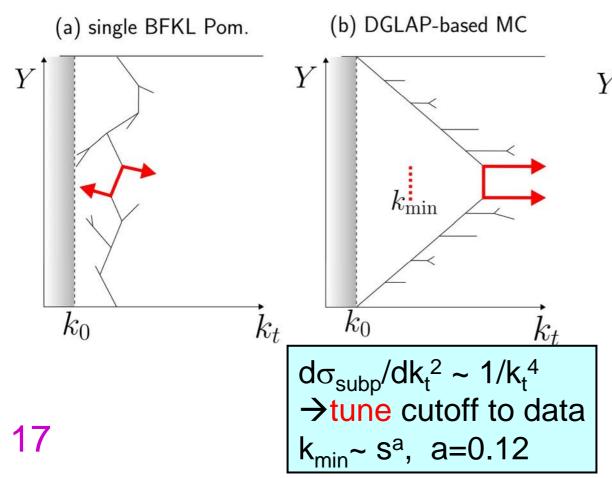
# rap. plateau

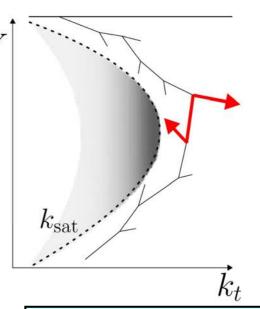
Lesson 1



DGLAP In  $k_t^2$  evol<sup>n</sup> interval << overestimates < $k_t$ > underestimates growth dN/d $\eta$ 

BFKL ln(1/x) evol<sup>n</sup> interval not strongly-ordered in  $k_t$   $dN/d\eta = n_P (dN_{1-Pom}/d\eta)$   $n_P$ =no. of Poms. grows





(c) BFKL (inc. enhanced)

Enh:  $\sigma_{abs} \sim 1/k_t^2$   $\rightarrow$ dyn.cutoff  $k_{sat}$  $\rightarrow$ besides SD, DD so the rise of the central plateau,  $d\sigma/dy \sim s^{0.2}$ , comes naturally out of the KMR model

# Implications:

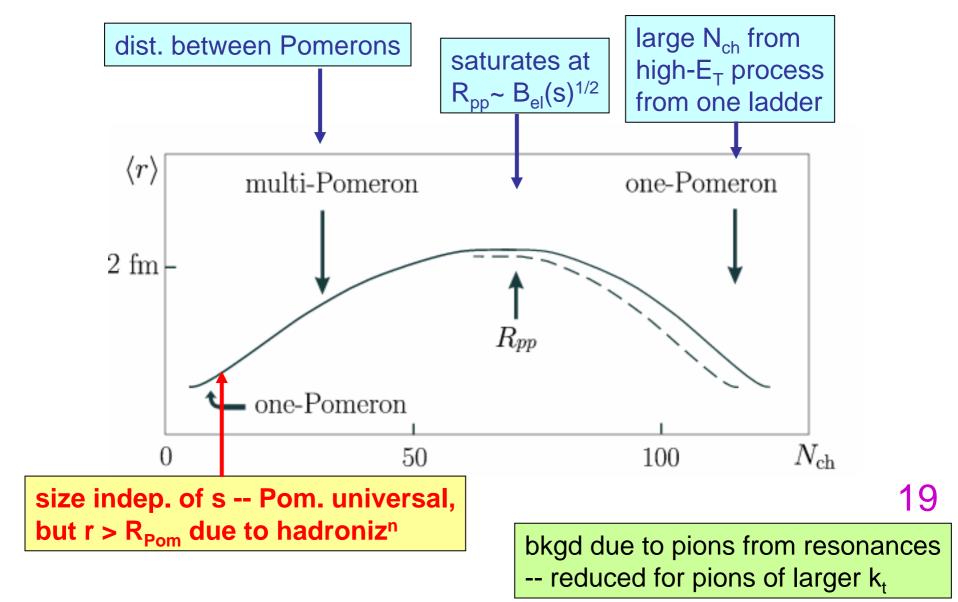
KMR framework can provide basis for MC describing soft and hard processes in a unified way, with only a few physically-motivated parameters (Krauss et al.)

Enhanced absorp. effects, with dynamical  $k_t$  cutoff,  $k_{sat}$ , in cascade, mean minijets are the main source of secondaries (correlations)

Several tests of framework, for example → BEC

#### Probe of Pom. hot spots → Bose-Einstein correlations

identical pion correlations measure size of their emission region



#### Further lessons from LHC data

Qualitative discussion --take observed cross sections at face value
(no attention paid to important exptal uncertainties)

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Lesson 2
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#### $\sigma_{inel}$ of CMS, ATLAS, ALICE v TOTEM

$$\begin{split} \sigma_{\text{inel}}(\text{ATLAS}) &= 60.3 \text{ mb} \quad \text{for M>15.7 GeV } \ (\xi=\text{M}^2/\text{s>5.10}^{-6}) \\ \text{extrapolate to cover all } \eta\colon \quad \sigma_{\text{inel}}(\text{ATLAS}) &= 69.4 \text{ mb} \\ \text{Similarly} \quad \sigma_{\text{inel}}(\text{CMS}) &= 68.0 \text{ mb} \\ \text{but TOTEM} \quad \sigma_{\text{inel}} &= \sigma_{\text{tot}} - \sigma_{\text{el}} &= 98.3 - 24.8 = 73.5 \text{ mb} \end{split}$$

even more than 7 mb predicted by KMR model

m

ATLAS measure

 $d\sigma/dlogM^2 \sim 1mb/unit y$ (7 < M < 700 GeV)

15.7

missing 5 mb is deficiency in low M extrapol<sup>n</sup>

 $\sigma_{\text{inel}}(\text{low M}) \sim 10 \text{ mb}$ 

 $\sigma_{\text{inel}}(\text{high M}) \sim 64 \text{ mb}$ 

3.6 mb

60.3 mb

ATLAS extrapolated ~ 9 mb?

observed

M(GeV)

Lesson 3 ot

 $\sigma_{tot}(TOTEM)$ 

LHC TOTEM:  $\sigma_{tot} = 98.3 \text{ mb}, \quad \sigma_{inel} = 73.5 \text{ mb}$  7 TeV KMR model: 88 mb 66 mb

Tevatron: differ 10%  $\sigma_{tot}(E710) = 72.8 \text{ mb}, \quad \sigma_{tot}(CDF) = 80.03 \text{ mb}$ 

KMR preferred this value

#### Implications for KMR:

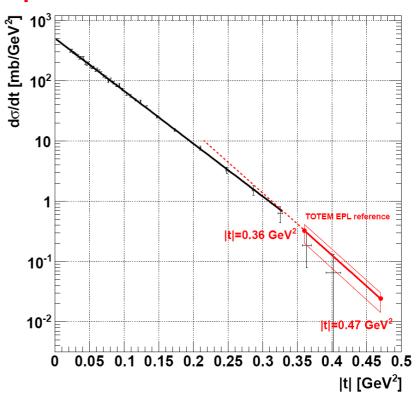
- 1. should now tune to a higher  $\sigma_{tot}$
- 2. should take  $\sigma_{SD}(low M) = 3 mb (max. allowed by CERN-ISR data) and not 2 mb$

# Lesson 4

# slope of elastic peak

$$\begin{aligned} \mathsf{B}_{\mathsf{el}}(\mathsf{TOTEM}) &= 20 \; \mathsf{GeV^{-2}} \\ \mathsf{B}_{\mathsf{el}}(\mathsf{KMR}) &= 18.5 \; \mathsf{GeV^{-2}} \\ \mathsf{assuming} \; \alpha'_{\mathsf{P}} &= 0 \end{aligned}$$

implications: KMR should re-instate parameter  $\alpha'_P$ <0.1 GeV<sup>-2</sup>



# Lesson 5

TOTEM find 
$$\sigma_{el}/\sigma_{tot} \sim 1/4$$

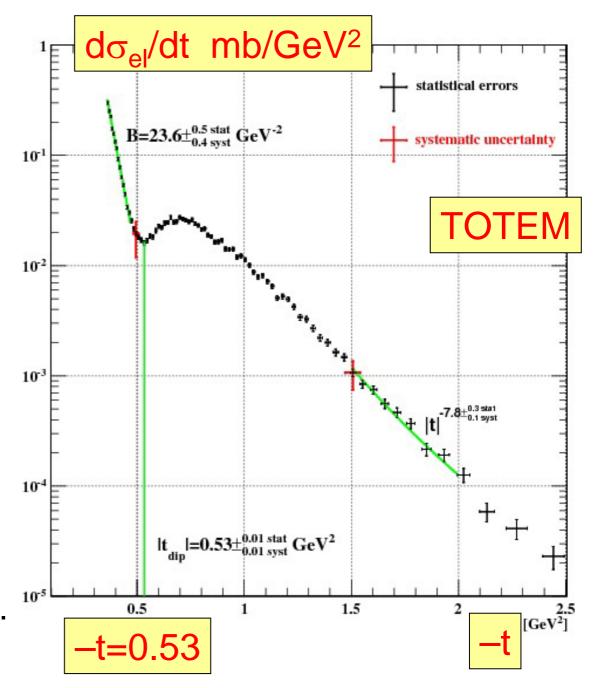
→ elastic amp. saturated at b=0

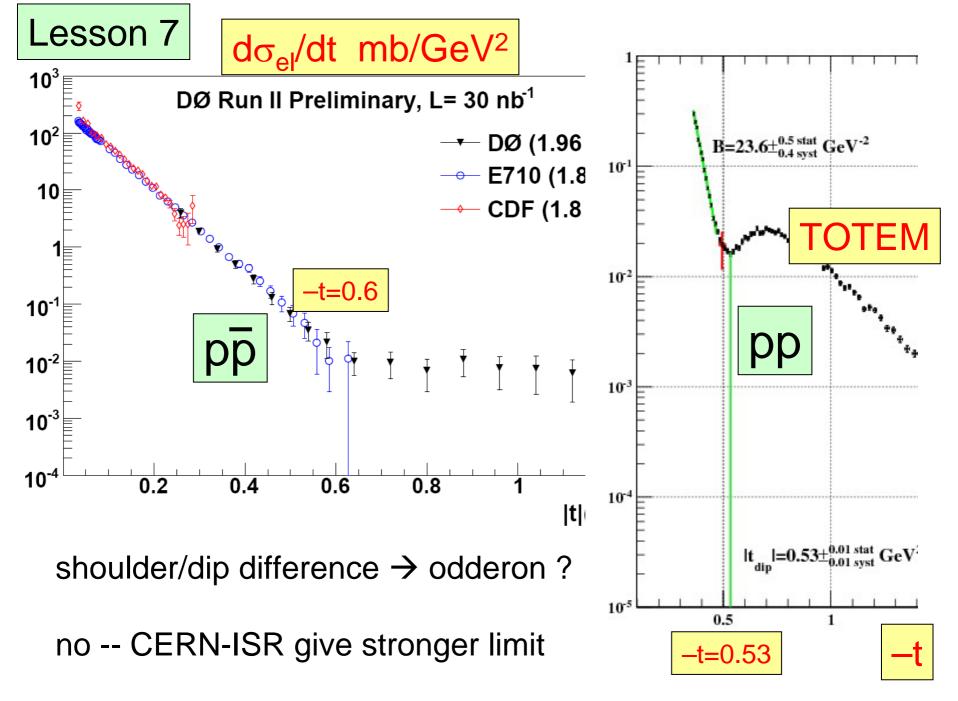
# Lesson 6

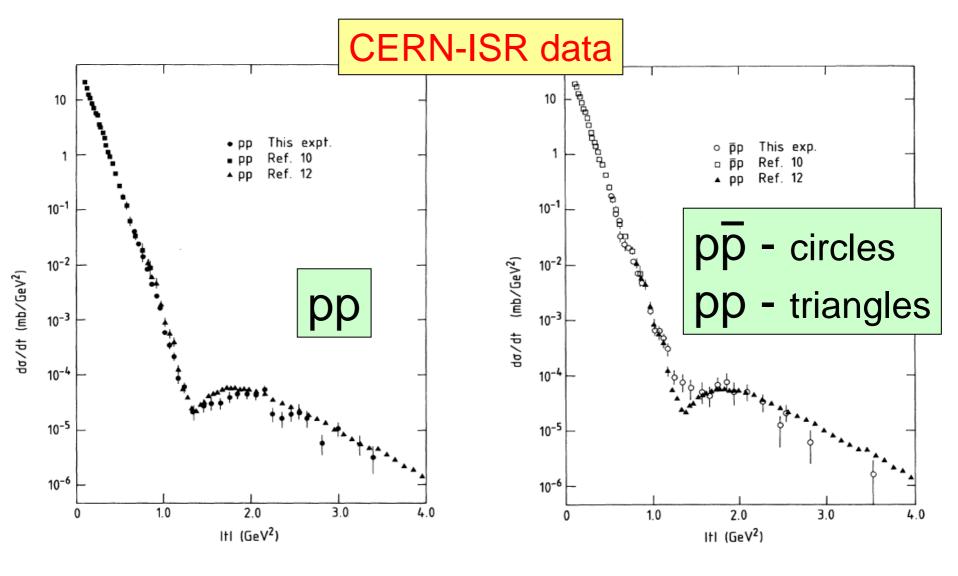
KMR model not applicable beyond forward peak.

Designed to describe soft and semi-hard inclusive processes, not rare exclusive large |t| processes.

It could describe dip but would require a many channel eikonal.







No visible odderon effects

#### Conclusions

Soft and semihard high-energy pp interactions described by small-size QCD Pomeron (~parton cascade)

#### Multi-Pomeron contributions essential

- (i) eikonal: needed to satisfy s-ch unitarity
- (ii) enhanced: provides dynamical  $k_t$  cutoff,  $k_{sat}$ , in cascade, as well as describing high-mass SD, DD. As a result minijets,  $p_T > k_{sat}$ , are main source of secondaries

Model, with few (physically motivated) parameters, tuned to describe soft high-energy pp data can

- (i) predict rapidity gap survival probabilities
- (ii) predict PDFs and diffractive PDFs at lowish scales
- (iii) form basis of MC for soft & hard interns (Krauss et al.)

