Diffraction at the LHC

Khoze, Martin, Ryskin

1. Multi-component model of $\sigma_{\rm tot}, \ \frac{d\sigma_{\rm el}}{dt}, \ \frac{d\sigma_{\rm SD}}{dt dM^2}(pp \to pX)$...

2. Survival probability of rapidity gaps for exclusive processes
   pp → p+A+p at the LHC (A=Higgs,…)
   and at the Tevatron (A = γγ, dijet, χ_c)

3. Early LHC runs to check exclusive predictions

Krakow Epiphany Conference, Jan. '09, in memory of Jan Kwiecinski

Alan Martin, IPPP, Durham

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Parton distributions at small x

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EVIEW D VOLUME 43, NUMBER 5

Semihard QCD expectations for proton-(anti)proton scattering at CERN, Fermilab Tevatron, and the Superconducting Super Collider

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(Received 15 October 1990)

Model for "soft" high-energy interactions

needed to ---- understand asymptotics, intrinsic interest
---- describe "underlying" events at LHC
---- calc. rap.gap survival S^2 for exclusive prod^n

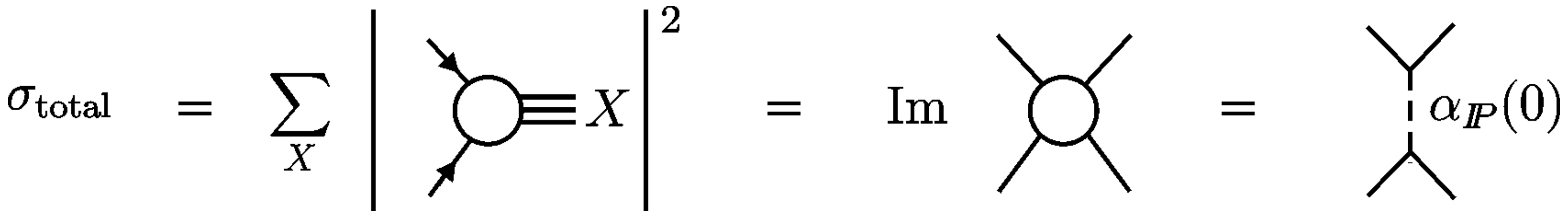
Model should:

1. be self-consistent theoretically --- satisfy unitarity
   → importance of absorptive corrections
   → importance of multi-Pomeron interactions
2. agree with available soft data CERN-ISR to Tevatron range $\sigma_{\rm tot}, \ \frac{d\sigma_{\rm el}}{dt}, \ \frac{d\sigma_{\rm SD}}{dt dM^2}(pp \to pX)$
3. include Pomeron comp^{ts} of different size---to study effects of soft-hard fact^n breaking

→ multi-component s- and t-channel model of "soft" processes

Optical theorems

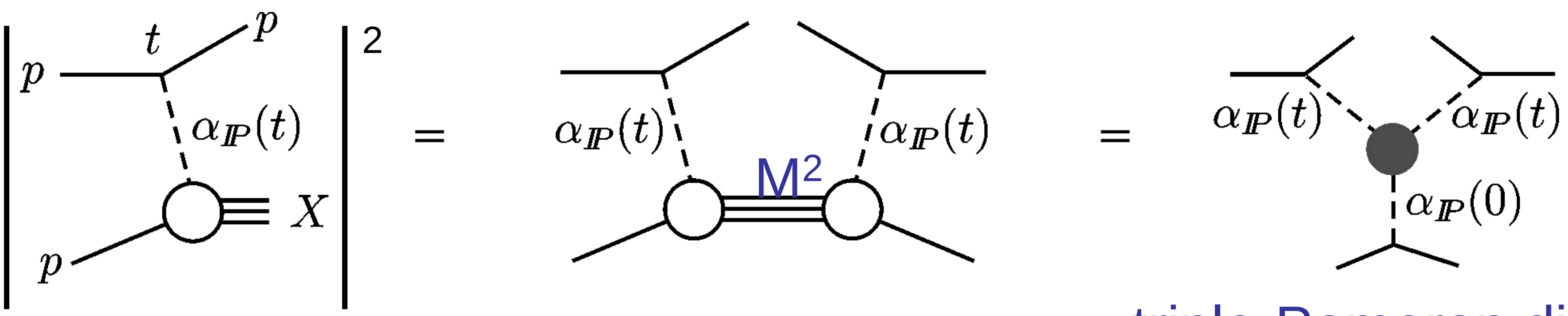
at high energy
use Regge



but screening 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

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

$$(g_{3P})_{\text{effective}} = S^2 (g_{3P})_{\text{bare}}$$ so $(g_{3P})_{\text{bare}}$ increased

diagonal in b

$$S S^\dagger = I \quad \text{with} \quad S = I + iT \quad \rightarrow \quad T - T^\dagger = i T^\dagger T$$

elastic unitarity →

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

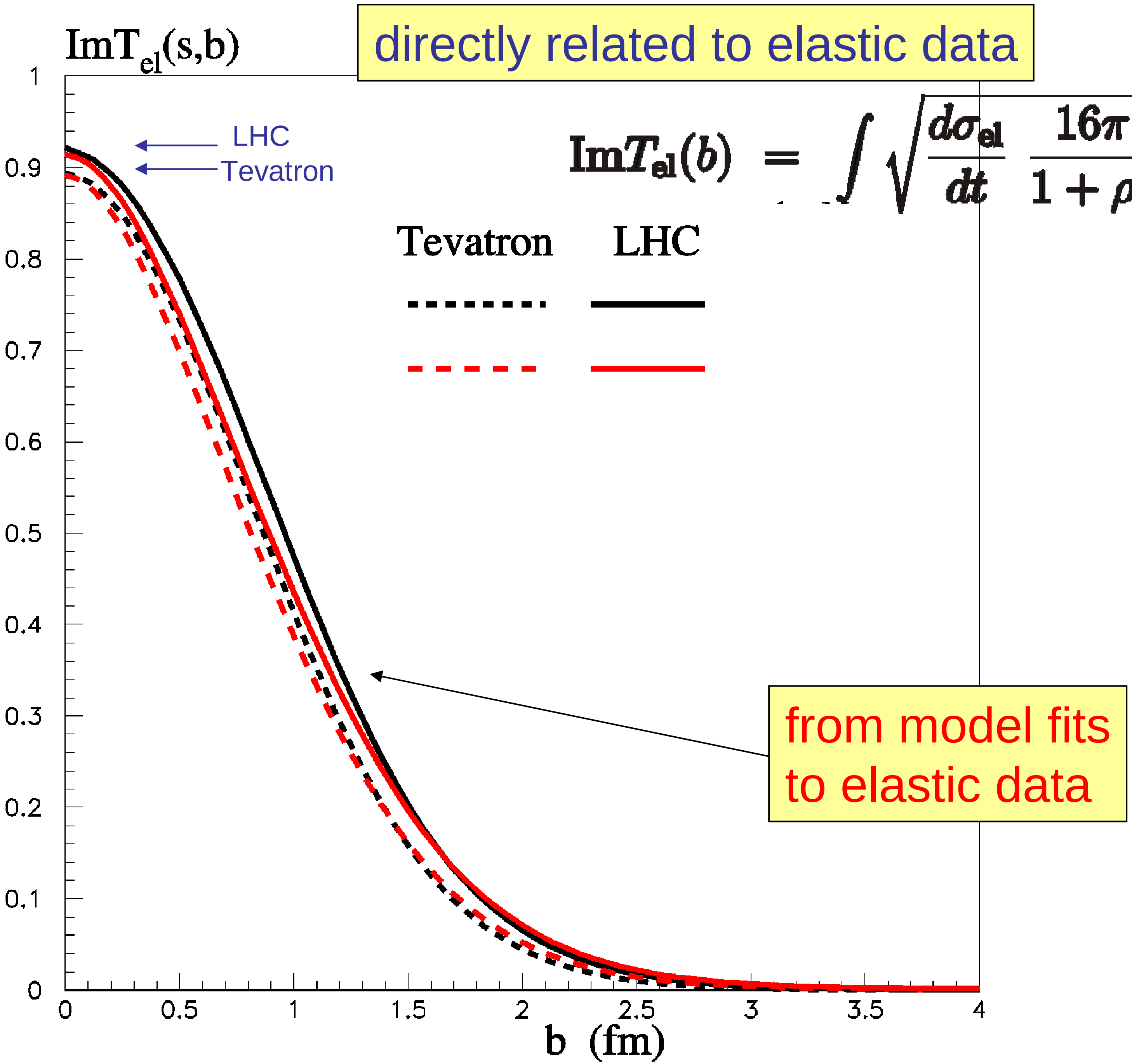
$$\begin{cases} \dfrac{d^2\sigma_{tot}}{d^2b} = 2\,\mathrm{Im}\,T_{el} = 2\left(1 - e^{-\Omega/2}\right) \\[2ex] \dfrac{d\sigma_{el}}{d^2b} = |T_{el}|^2 = \left(1 - e^{-\Omega/2}\right)^2 \\[2ex] \dfrac{d\sigma_{inel}}{d^2b} = 2\,\mathrm{Im}\,T_{el} - |T_{el}|^2 = 1 - e^{-\Omega} \end{cases}$$

Opacity / Eikonal $\Omega(s,b) \geq 0$

e.g. black disc

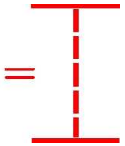
$$\left.\begin{array}{l} \\ \mathrm{Im}\,T_{el} = 1, \quad b < R \end{array}\right\} \quad \begin{array}{l} \sigma_{tot} = 2\pi R^2 \\ \sigma_{el} = \sigma_{inel} = \pi R^2 \end{array}$$

$e^{-\Omega}$ is the probability of no inelastic interaction

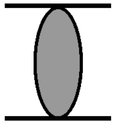
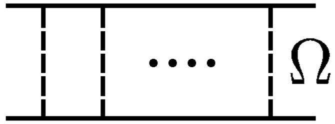


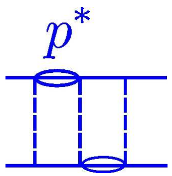
$$\mathrm{Im}T_{\rm el}(b) = \int \sqrt{\frac{d\sigma_{\rm el}}{dt}\,\frac{16\pi}{1+\rho^2}}\; J_0(qb)\,\frac{q\,dq}{2\pi}$$

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

bare amp. $\Omega =$ 

(-20%)

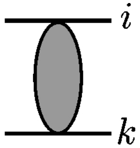
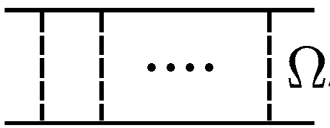
$T_{el} =$  $= 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty}$  Ω

Low-mass diffractive dissociation 

→multichannel eikonal

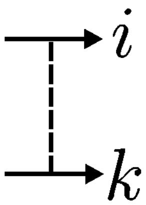
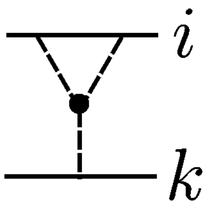
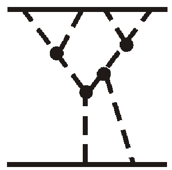
introduce diff^{ve} estates ϕ_i, ϕ_k (comb^{ns} of p,p*,..) which only undergo "elastic" scattering (Good-Walker)

(-40%)

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

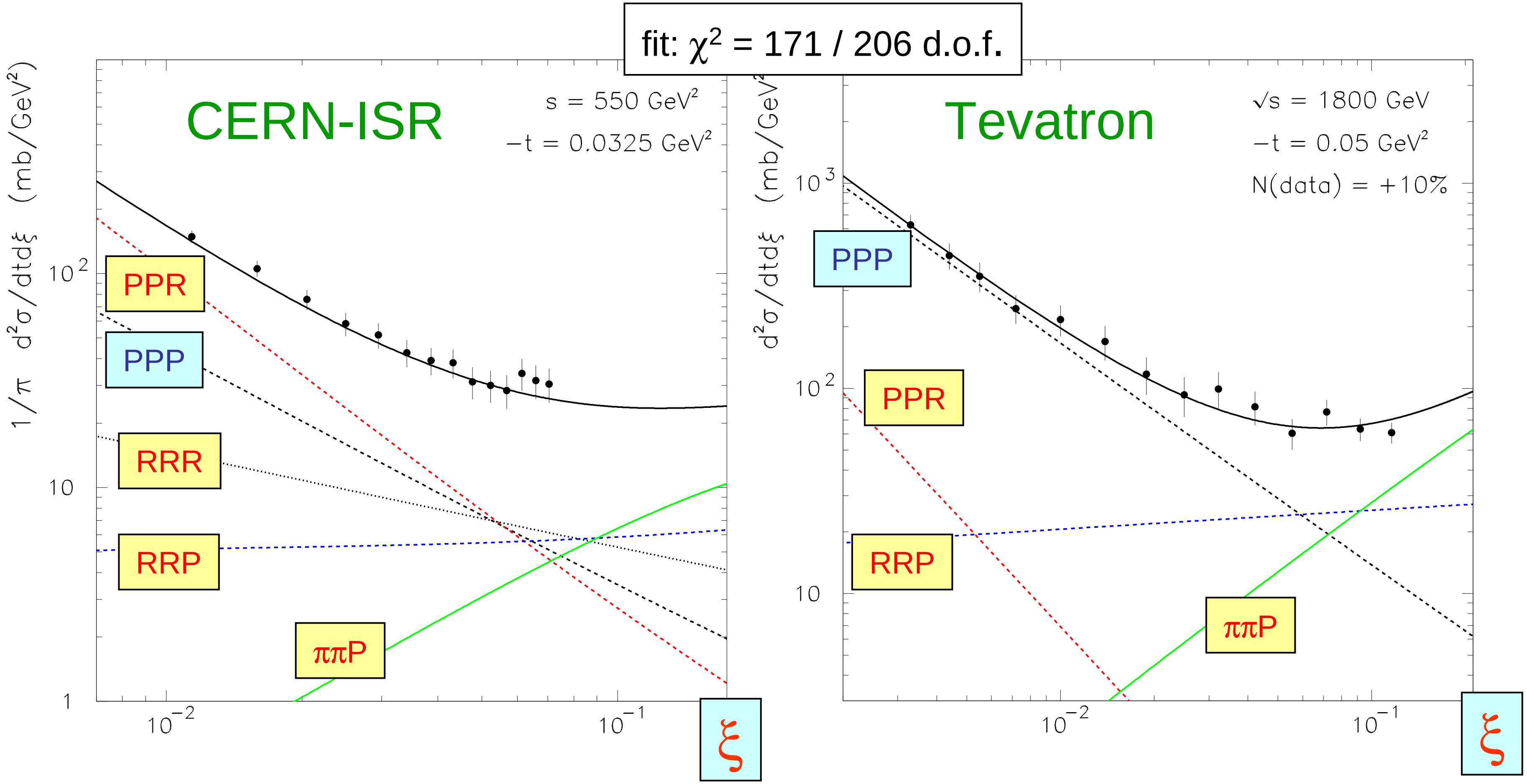
include high-mass diffractive dissociation

(SD -80%)

$\Omega_{ik} =$  **+**  $\}M$ +  + ... +  + ...

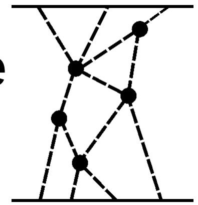
triple-Regge analysis of $d\sigma/dtd\xi$, including screening

(includes compilation of SD data by Goulianos and Montanha)

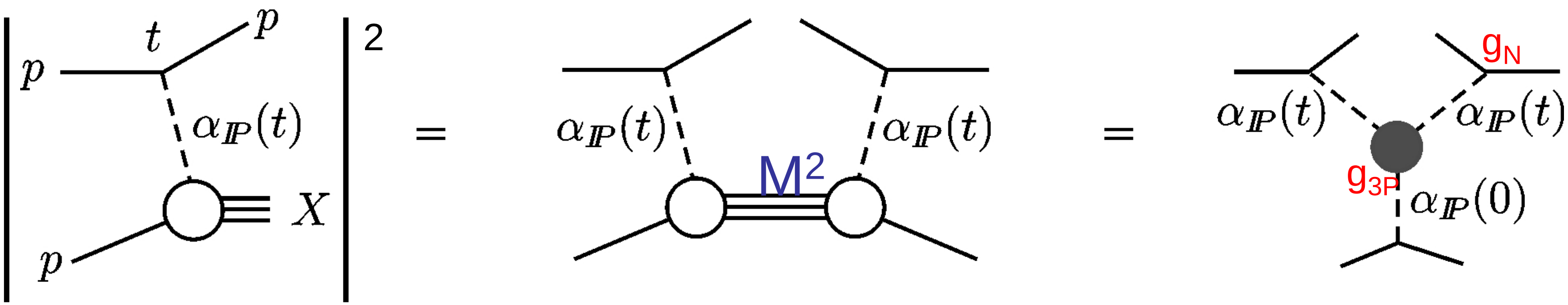


Luna+KMR; $g_{3P} = \lambda\, g_N \quad \lambda \sim 0.2$

g_{3P} large, need to include multi-Pomeron effects



$g_{3P} = \lambda\, g_N \qquad \lambda \sim 0.2$ ← large ?



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

ln s

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

so at collider energies $\sigma_{SD} \sim \sigma_{el}$

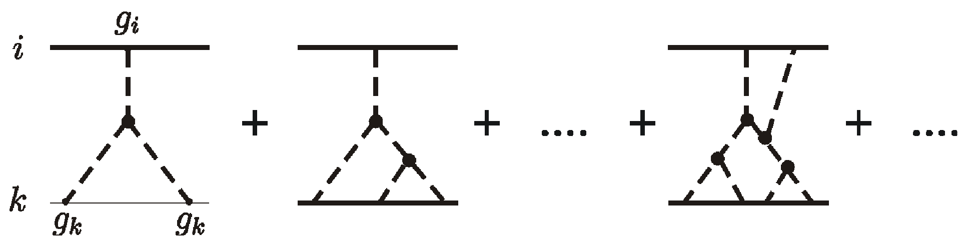
New analysis of soft data

KMR 2008

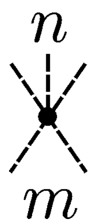
$$\sigma_{\rm tot}, \quad \frac{d\sigma_{\rm el}}{dt}, \quad \sigma_{\rm SD}(\text{low } M), \quad \frac{d\sigma_{\rm SD}}{dt\,dM^2}$$

model:

- 3-channel eikonal,
  ϕ_i with i=1,3



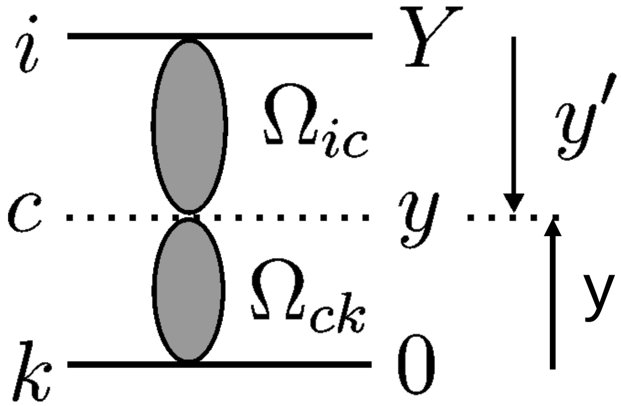
- include multi-Pomeron diagrams



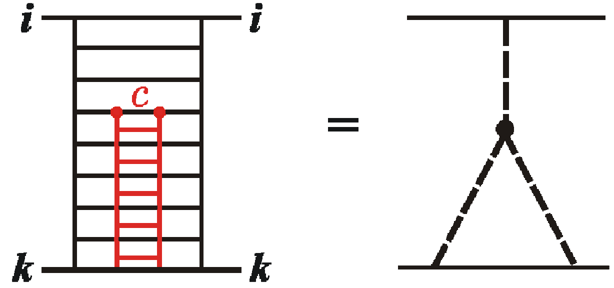
$$g_m^n = \lambda^{n+m-2} g_N$$

- attempt to mimic BFKL diffusion in log q_t by including three components to approximate q_t distribution –
  possibility of seeing "soft → hard" Pomeron transition

Include absorption – full set of multi-Pomeron diagrams



e.g.



evolve up from y=0

bare pole $\alpha_P = 1+\Delta+\alpha' t$ — absorptive effects

$$\begin{cases} \dfrac{d\Omega_{ck}(y)}{dy} = (\Delta + \alpha' \nabla_b^2)\Omega_{ck}(y)\; e^{-\lambda\Omega_{ck}(y)/2} e^{-\lambda\Omega_{ic}(y')/2} \\[2ex] \dfrac{d\Omega_{ic}(y')}{dy'} = (\Delta + \alpha' \nabla_b^2)\Omega_{ic}(y')\; e^{-\lambda\Omega_{ic}(y')/2} e^{-\lambda\Omega_{ck}(y)/2} \end{cases}$$

or evolve down from y'=Y-y=0

solve for $\Omega_{ik}(y,b)$ by iteration

Use four exchanges in the t channel

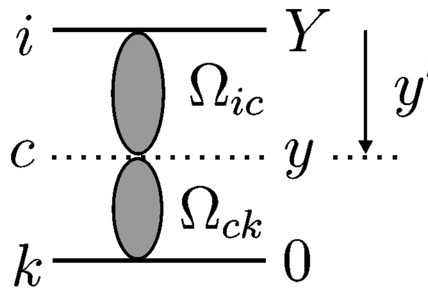
3 to mimic BFKL diffusion in ln q_t

sec. Reggeon

$$a = P_{large},\ P_{intermediate},\ P_{small},\ R$$

soft → pQCD

average q_{t1}~0.5, q_{t2}~1.5, q_{t3}~5 GeV



$V_{RP1} \sim g_{PPR}, g_{RRP}$

$V_{PiPj} \sim$ BFKL

evolve up from y=0 — bare pole — absorptive effects

$$\begin{cases} \dfrac{d\Omega^{a}_{ck}(y)}{dy} = (\Delta + \alpha' \nabla_b^2)\Omega^{a}_{ck}(y)\ e^{-\lambda\Omega_{ck}(y)/2} e^{-\lambda\Omega_{ic}(y')/2} + V_{aa'}\Omega^{a'}_{ic}(y) \\[2ex] \dfrac{d\Omega^{a}_{ic}(y')}{dy'} = (\Delta + \alpha' \nabla_b^2)\Omega^{a}_{ic}(y')\ e^{-\lambda\Omega_{ic}(y')/2} e^{-\lambda\Omega_{ck}(y)/2} + V_{aa'}\Omega^{a'}_{ck}(y') \end{cases}$$

evolve down from y'=Y-y=0

solve for $\Omega^{a}_{ik}(y,b)$ by iteration

Parameters

multi-Pomeron coupling λ from $\xi d\sigma_{SD}/d\xi dt$ data (ξ~0.01)

diffractive eigenstates from σ_{SD}(low M)=2mb at sqrt(s)=31 GeV,
-- equi-spread in R^2, and t dep. from $d\sigma_{el}/dt$

Results

All soft data well described

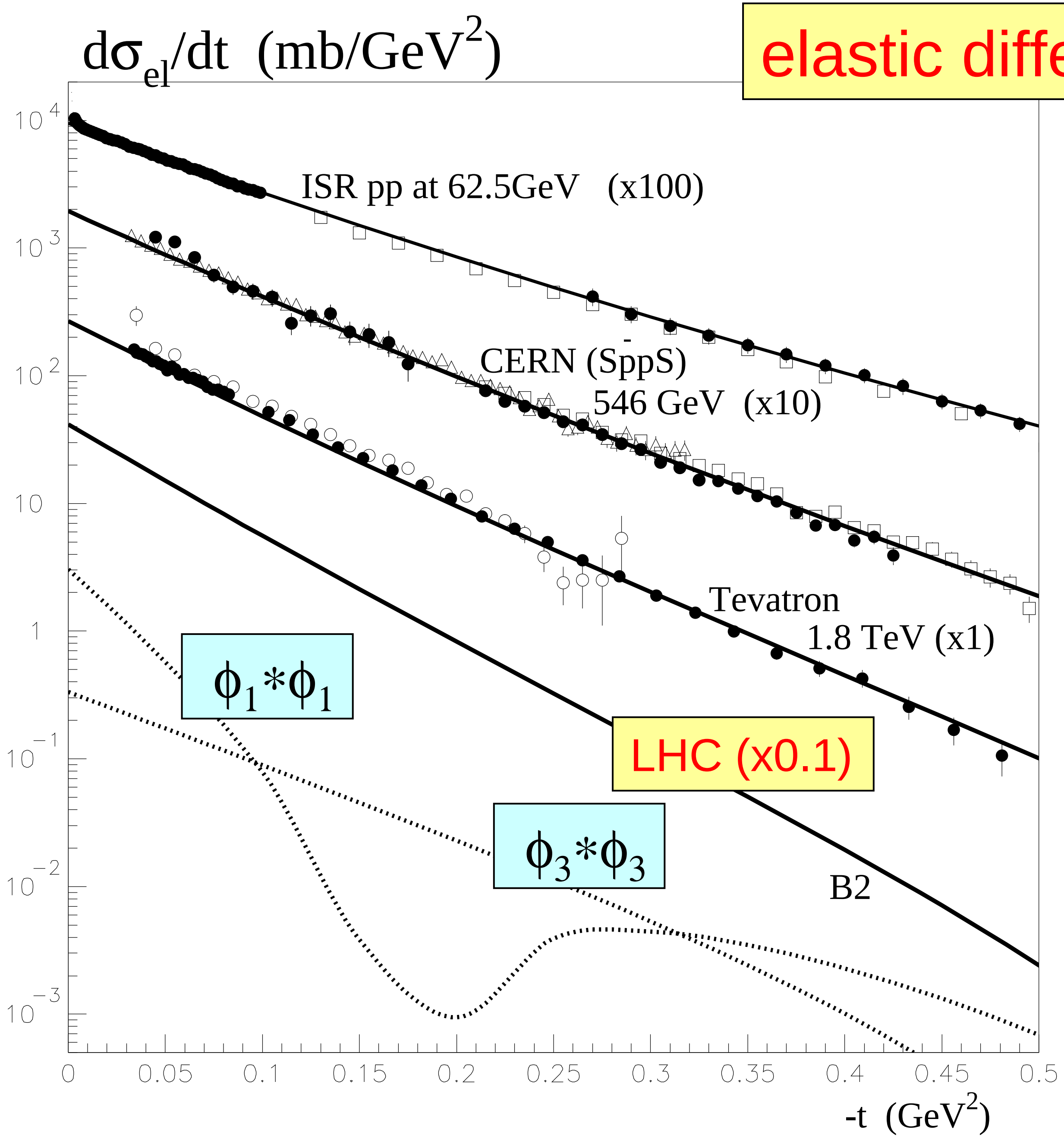
$g_{3P}=\lambda g_N$ with $\lambda=0.25$ (compared to $\lambda=0.2$ in Luna et al.)

$\Delta_{Pi} = 0.3$ (close to the BFKL NLL resummed value)
$\alpha'_{P1} = 0.05$ GeV^{-2}
These values of the bare Pomeron trajectory yield, after screening, the expected soft Pomeron behaviour ---
"soft-hard" matching (since P_1 heavily screened,….P_3~bare)

$\Delta_R = -0.4$ (as expected for secondary Reggeon)

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

elastic differential dσ/dt



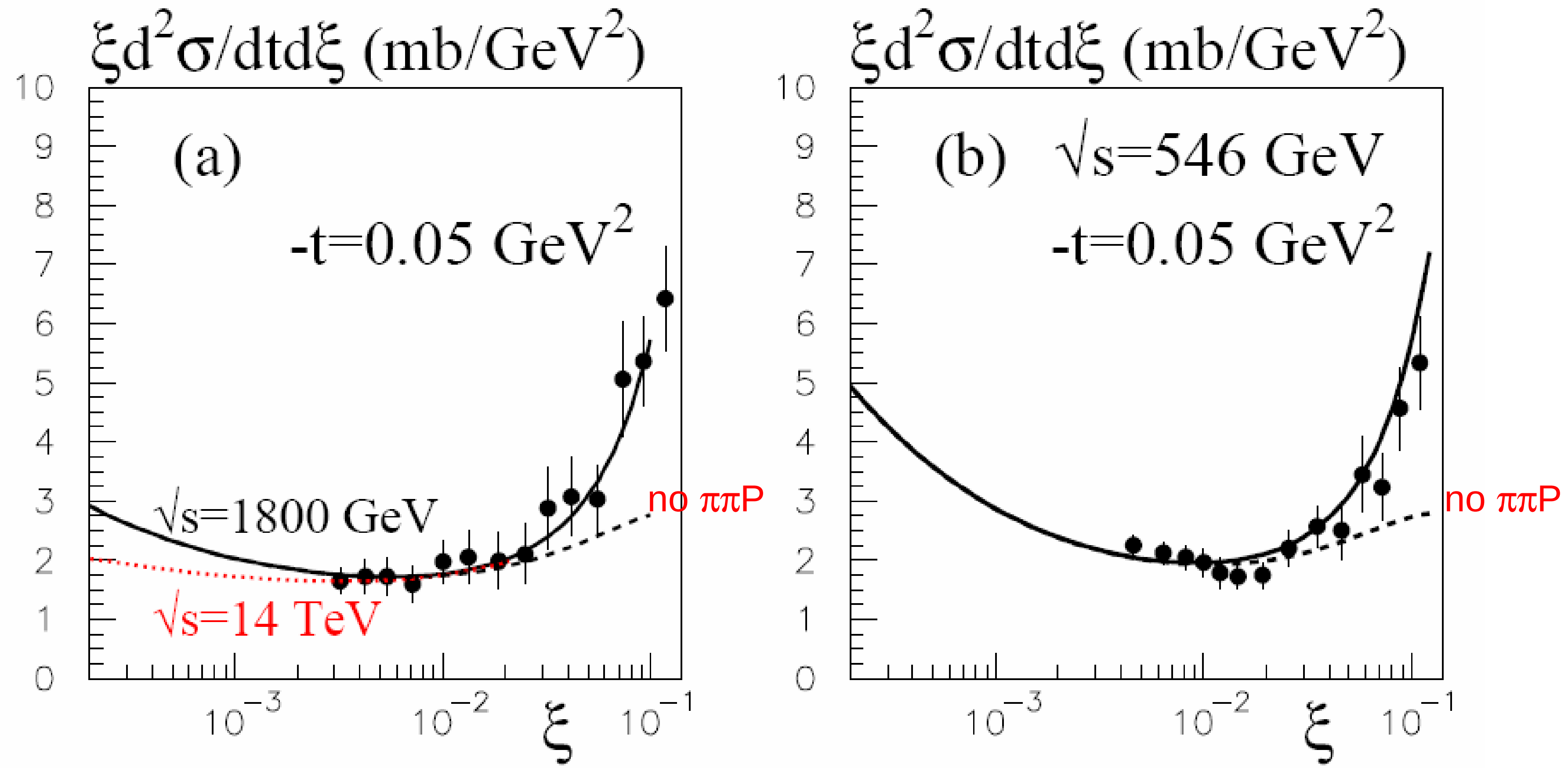
~ g, sea

ϕ_1: "large"

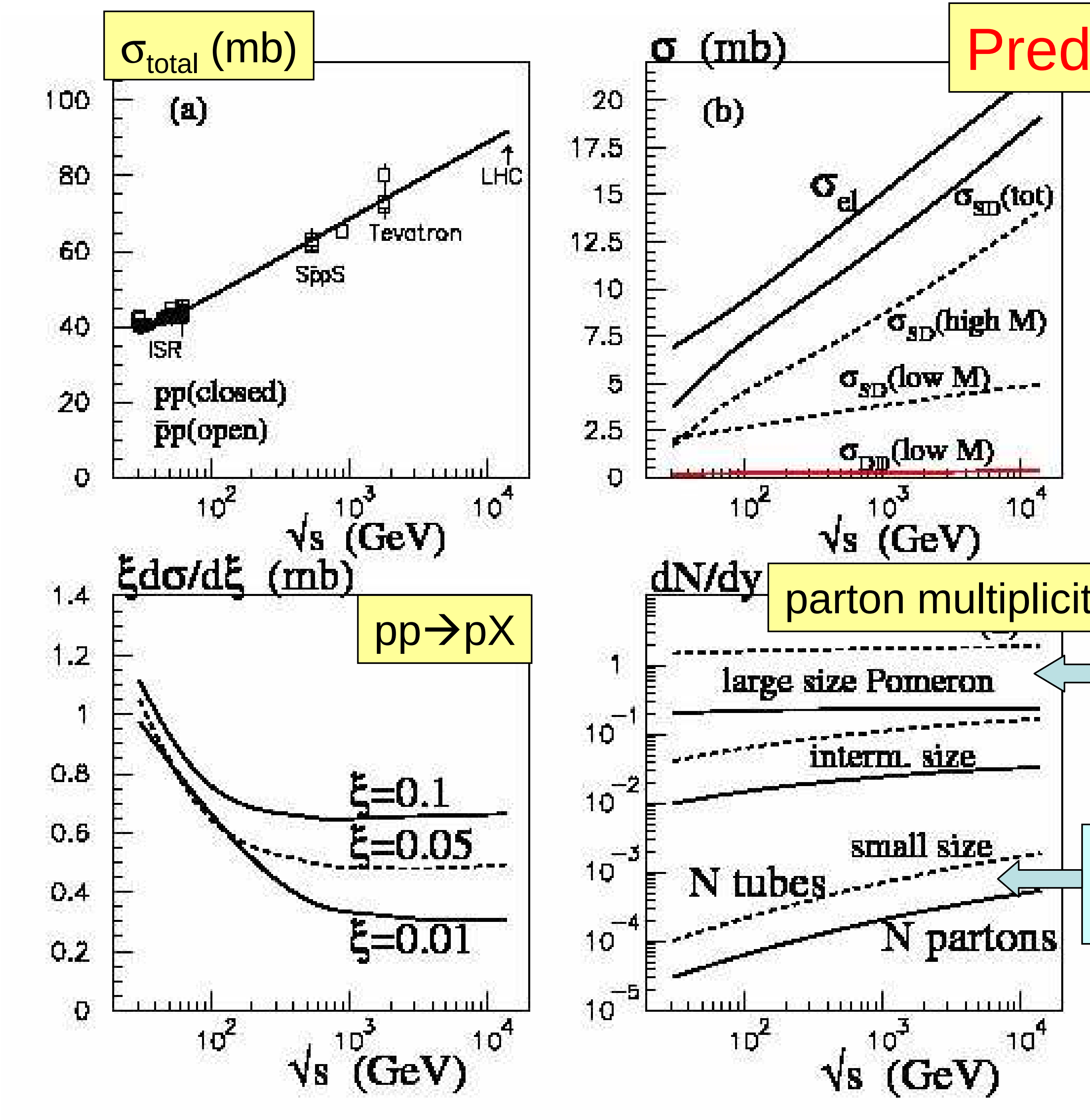
ϕ_3: "small"

more valence

Description of CDF dissociation data



Predictions for LHC



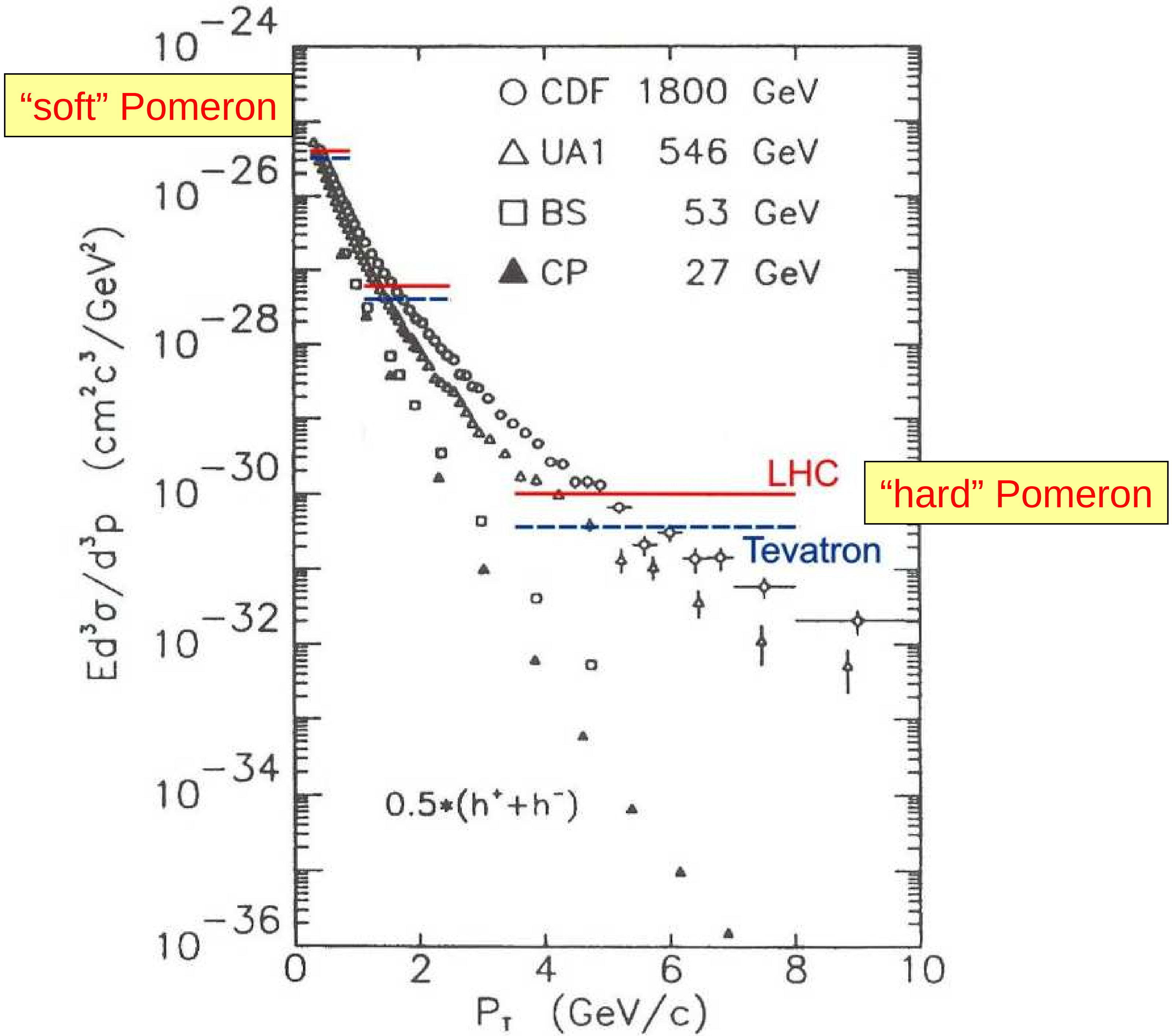
σ_{total} = 91.7 mb*
σ_{el} = 21.5 mb
σ_{SD} = 19.0 mb

*see also
Sapeta, Golec-Biernat;
Gotsman et al.

All Pom. compts have Δ_{bare}=0.3

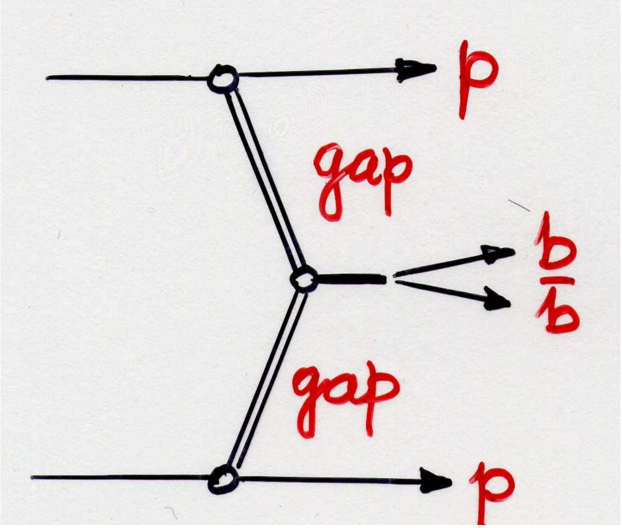
"soft", screened, little growth, partons saturated

"hard" ~ no screening much growth, $s^{0.3}$



"soft" Pomeron
"hard" Pomeron
LHC
Tevatron
○ CDF 1800 GeV
△ UA1 546 GeV
□ BS 53 GeV
▲ CP 27 GeV
0.5*(h⁺+h⁻)
$Ed^3\sigma/d^3p$ (cm^2c^3/GeV^2)
P_T (GeV/c)

Advantages of pp → p + ($H \rightarrow b\bar{b}$) + p
for Higgs studies at the LHC



-- accurate determination of M_H using tagged protons, $M_H = M_{missing}$

-- $M_H = M_{decay}$ must match $M_H = M_{missing}$

-- bb_{bar} QCD background suppressed by $J_z=0$ selection rule

-- can determine J^{PC}. Selection rule favours 0^{++} production

-- S/B ~ O(1) for SM 120 GeV Higgs (…but σ ~ few fb)

-- σ x 10 for some SUSY Higgs scenarios

e.g. $M_A > 140$ GeV: then $h \rightarrow h_{SM}$
H, A decouple from gauge bosons
H, A → bb_{bar}, ττ enhanced by tan β

Kaidalov+KMR
Heinemeyer,Khoze et al
Cox,Loebinger,Pilkington

bb background to pp → p + (H→bb) + p signal:

- -- irreducible QCD $gg^{PP} \rightarrow bb$ events
- -- gluons mimicing b jets
- -- $J_z=2$ contribution

New result:

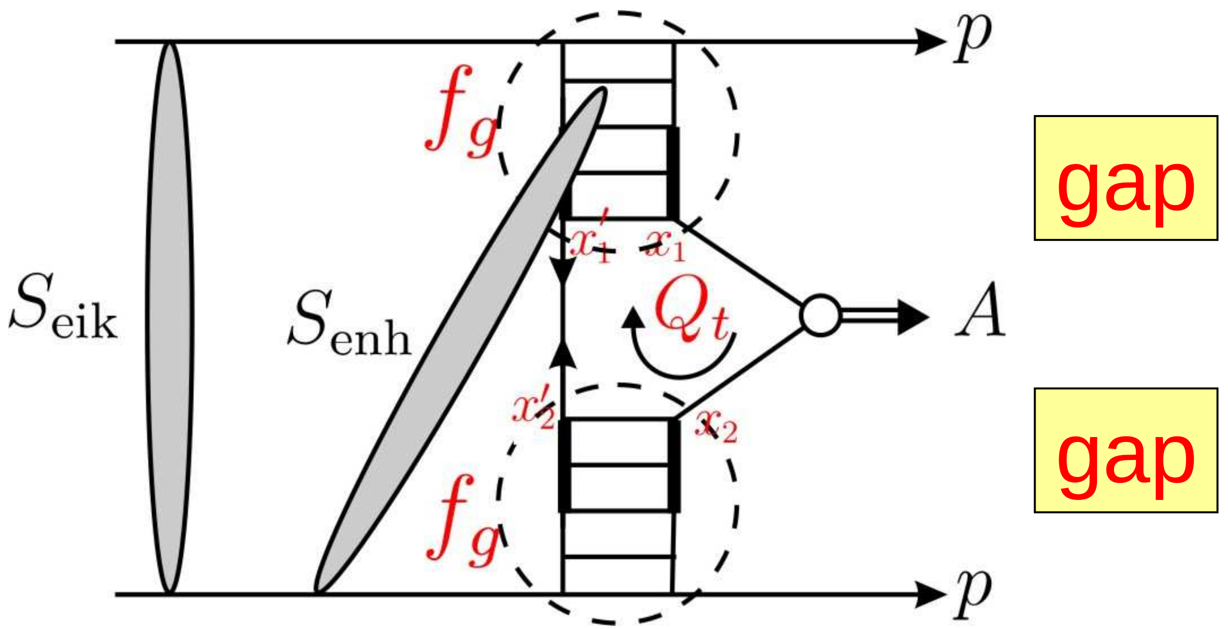
NLO calculation of $gg^{PP} \rightarrow bb$ reduces irreducible background by factor of 2 or more

Shuvaev+KMR

(also recent experimental improvements
in reducing the chance that gluons mimic b jets)

Price to pay for an exclusive process…

Survival probability of rapidity gaps for
pp → p+A+p ??



$$\sigma \sim S^2 \left| \int f_g \, \mathcal{M}(gg \to A) \, f_g \, \frac{dQ^2}{Q^2} \right|^2$$

Start with S_{eik} →

Calculation of S^2_{eik} for pp → p + H +p

prob. of proton to be in diffractive estate i

over b

hard m.e. i k → H

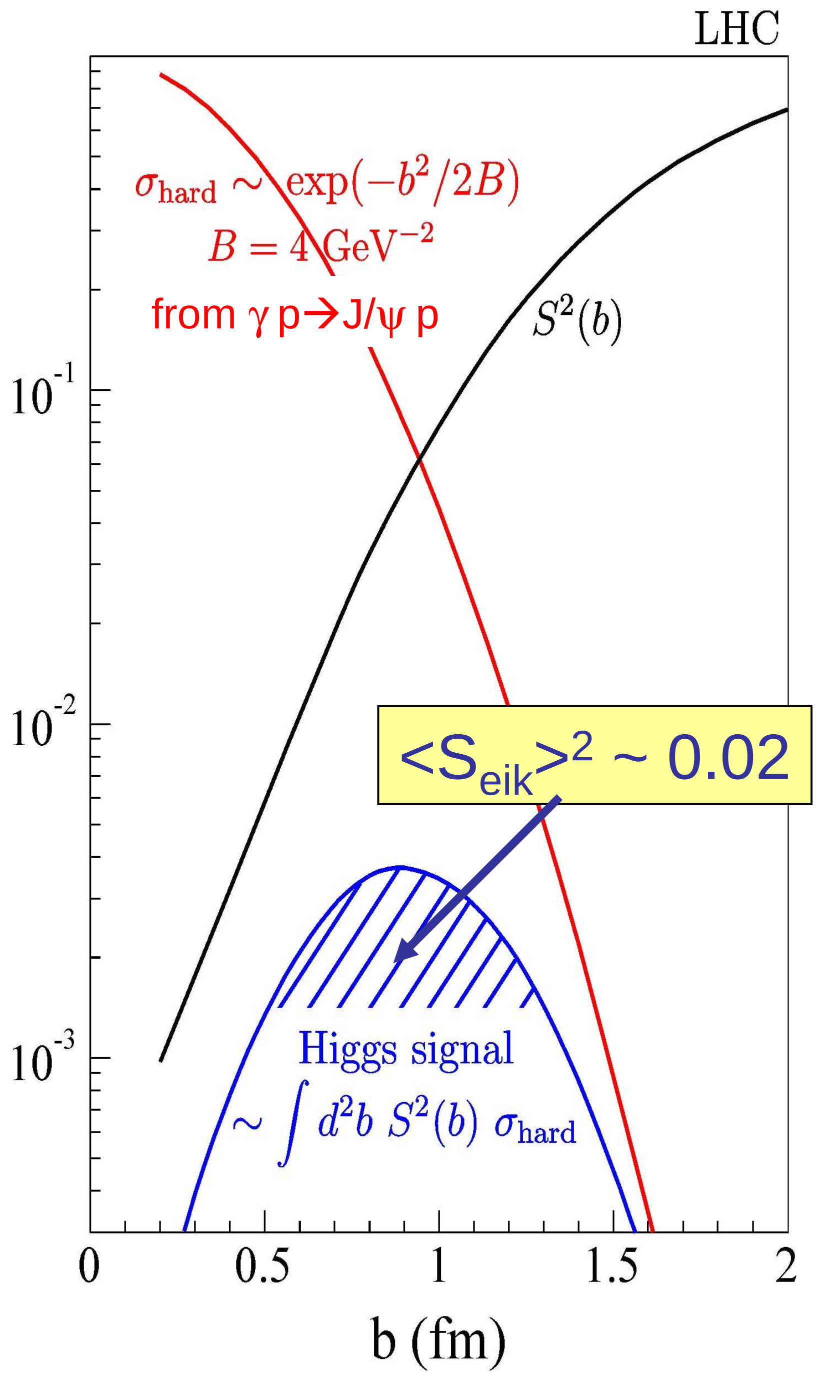
survival factor w.r.t. soft i-k interaction

average over diff. estates i,k

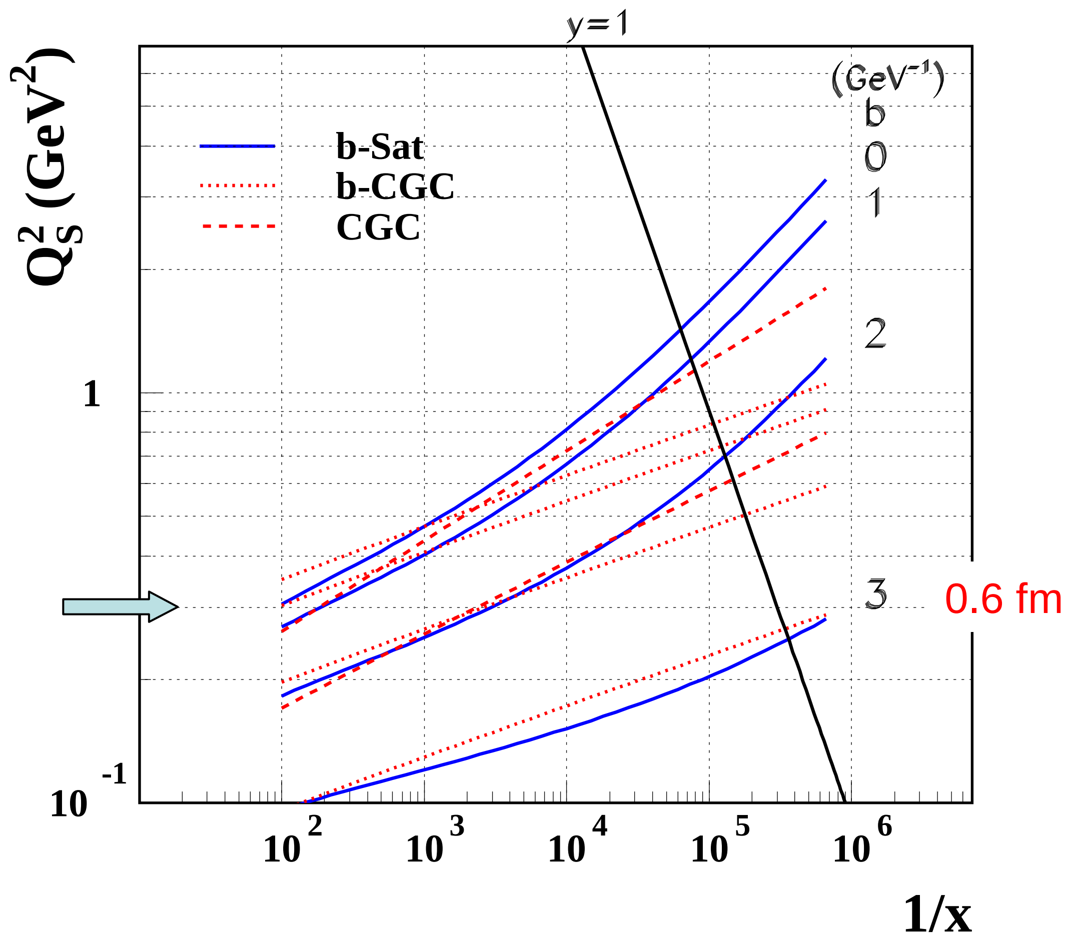
$$\overline{S^2} = \frac{\sum_{i,k} \int d^2b\, |a_{pi}|^2\ |a_{p'k}|^2\ |\mathcal{M}_{ik}|^2\ \exp(-\Omega_{ik}(s,b))}{\sum_{i,k} \int d^2b\, |a_{pi}|^2\ |a_{p'k}|^2\ |\mathcal{M}_{ik}|^2}$$

$\overline{S^2}_{eik} \sim 0.02$ for 120 GeV Higgs at the LHC

consensus



$<S_{enh}>^2 = ??$

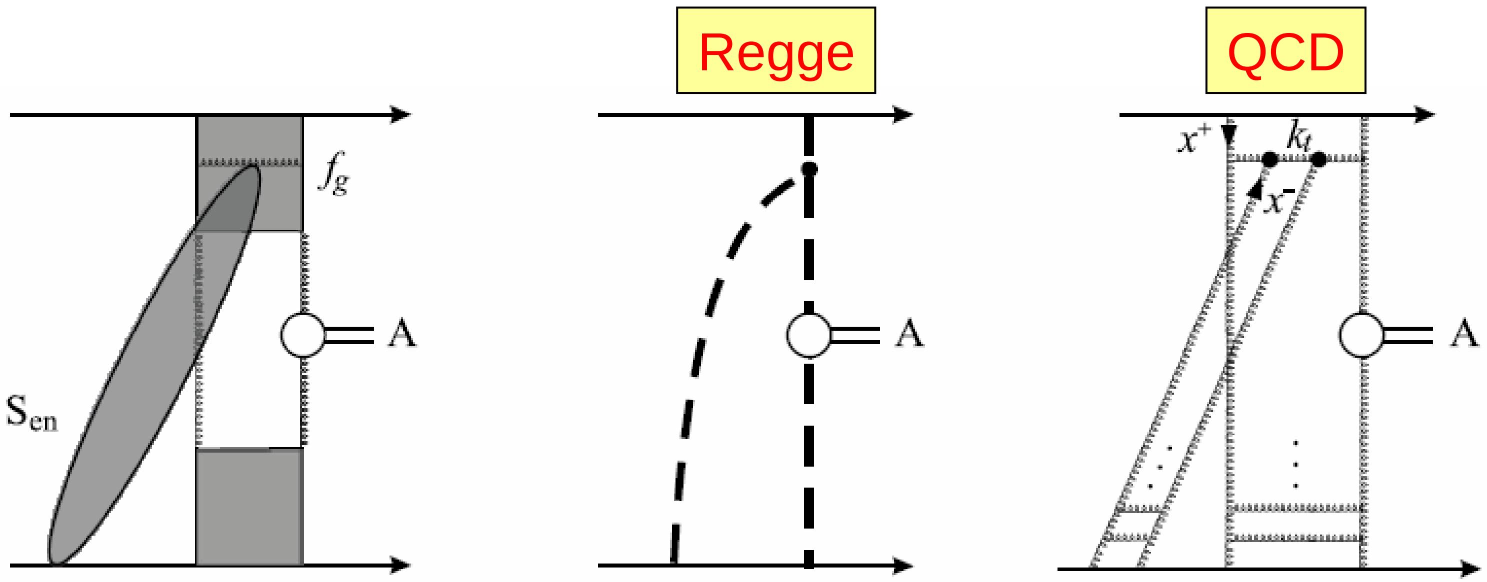


Watt, Kowalski

“Enhanced” absorptive effects

(breaks soft-hard factorization)

rescattering on an intermediate parton:



BBKM → large effect?

KMR → HO diagrams → sum → small effect

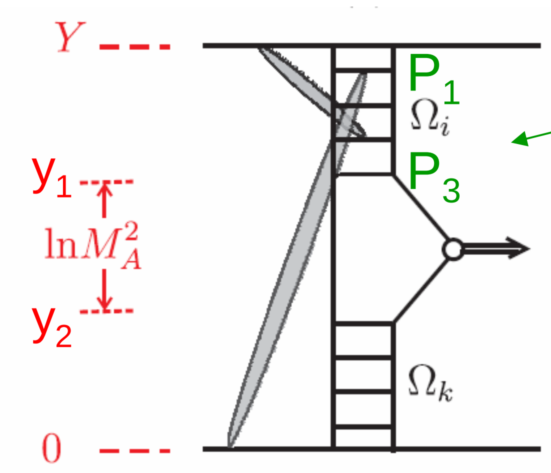
The new soft analysis, with Pomeron q_t structure, enables S^2_{enh} to be calculated model has 4 t-ch. exchanges

3 to mimic BFKL diffusion in ln q_t

a = P_{large}, $P_{intermediate}$, P_{small}, R

soft ⟶ pQCD

average q_{t1}~0.5, q_{t2}~1.5, q_{t3}~5 GeV



enh. abs. changes P_3 distrib^n

V_{RP1} ~ g_{PPR}, g_{RRP}

V_{PiPj} ~ BFKL

evolve up to y_2

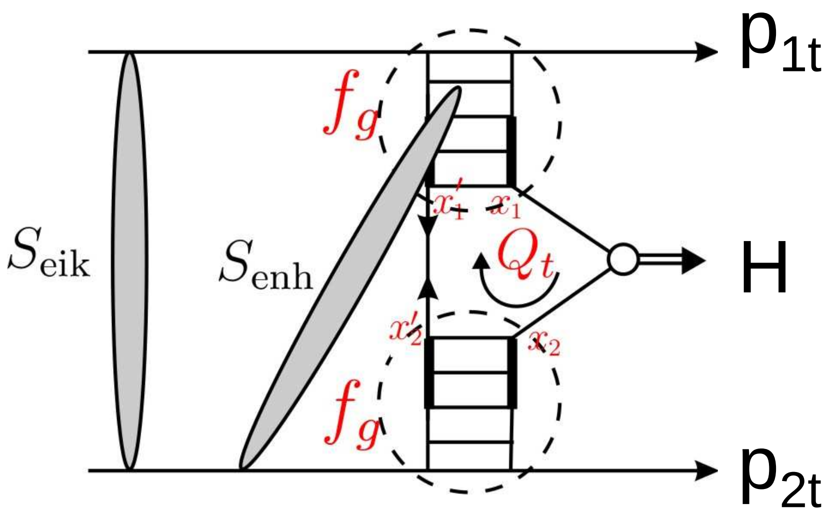
bare pole — absorptive effects

$$\begin{cases} \dfrac{d\Omega^{a}_{ck}(y)}{dy} = (\Delta + \alpha'\nabla^2_b)\Omega^{a}_{ck}(y)\; e^{-\lambda\Omega_{ck}(y)/2} e^{-\lambda\Omega_{ic}(y')/2} + V_{aa'}\Omega^{a'}_{ic}(y) \\[2ex] \dfrac{d\Omega^{a}_{ic}(y')}{dy'} = (\Delta + \alpha'\nabla^2_b)\Omega^{a}_{ic}(y')\; e^{-\lambda\Omega_{ic}(y')/2} e^{-\lambda\Omega_{ck}(y)/2} + V_{aa'}\Omega^{a'}_{ck}(y') \end{cases}$$

evolve down to y_1

~ solve with and without abs. effects

Survival prob. for pp → p+H+p



$\langle S^2_{eik}\rangle \sim 0.02$ consensus
$\langle S^2_{enh}\rangle \sim 0.01 – 1$ controversy

KMR 2008 →
$\langle S^2\rangle_{tot} = \langle S^2_{eik} S^2_{enh}\rangle \sim 0.015$ ($B=4$ GeV^{-2})

However enh. abs. changes p_t behaviour from exp form, so

$$\langle S^2\rangle_{tot}\langle p^2_t\rangle^2 = \begin{cases} 0.0015 & \text{LHC} \\ 0.0030 & \text{Tevatron} \end{cases} \text{KMR 2000 (no } S_{enh}\text{)}$$

$$\phantom{\langle S^2\rangle_{tot}\langle p^2_t\rangle^2 =} \begin{cases} 0.0010 & \text{LHC} \\ 0.0025 & \text{Tevatron} \end{cases} \text{KMR 2008 (with } S_{enh}\text{)}$$

CDF exclusive measurements ($\gamma\gamma$, dijet, χ) indicate that the above may be conservative lower limits

Experimental checks of calculation of $\sigma(pp \rightarrow p + A + p)$

KMR cross section predictions are consistent with the recent observed rates of three exclusive processes at the Tevatron:

CDF

$pp_{bar} \rightarrow p + \gamma\gamma + p_{bar}$

$pp_{bar} \rightarrow p + \text{dijet} + p_{bar}$

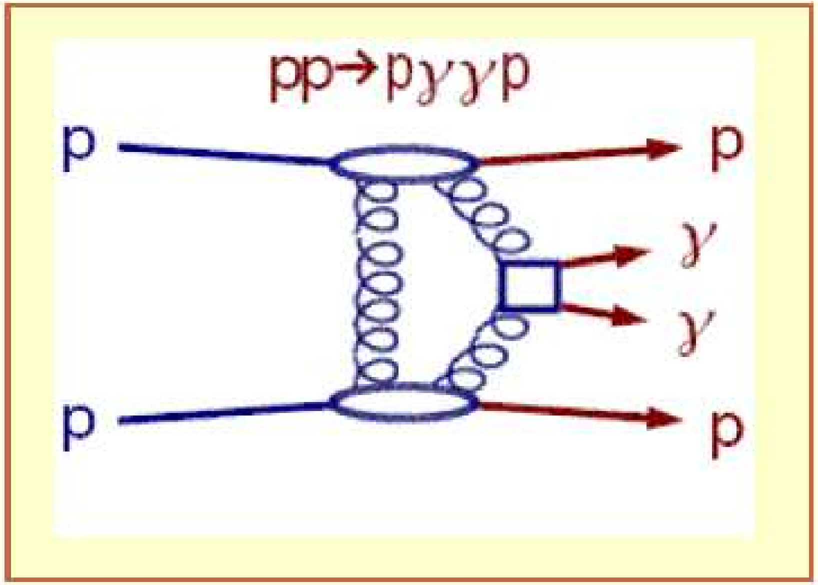
$pp_{bar} \rightarrow p + \chi_c + p_{bar}$ (68 $\chi_c^0 \rightarrow J/\psi + \gamma$ events)

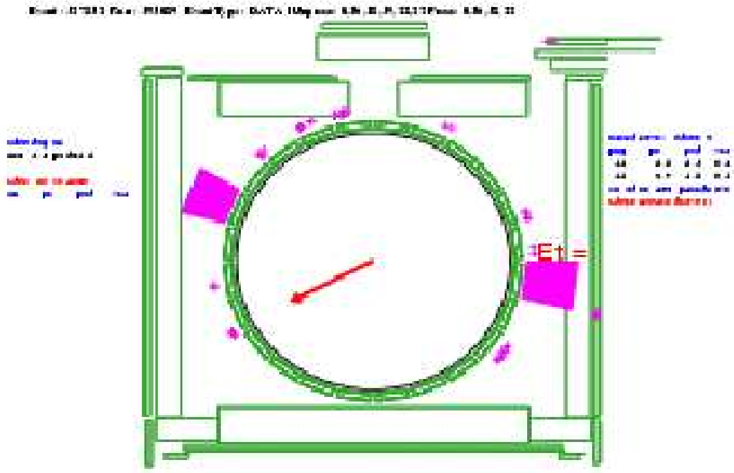
For the lighter χ_c system the enhanced suppression is 0.35
→ which takes KMRS prediction from above to below CDF rate

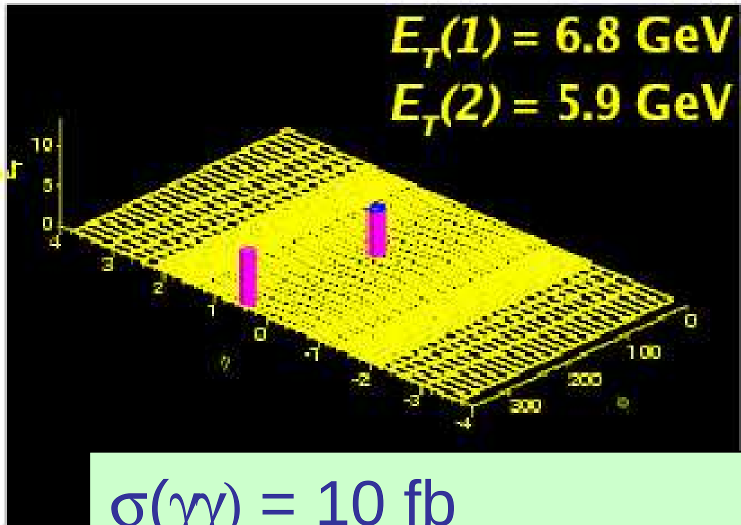
Early LHC runs can give detailed checks of all of the ingredients of the calculation of $\sigma(pp \rightarrow p + A + p)$, even without proton taggers

Exclusive γγ Candidates

CDF







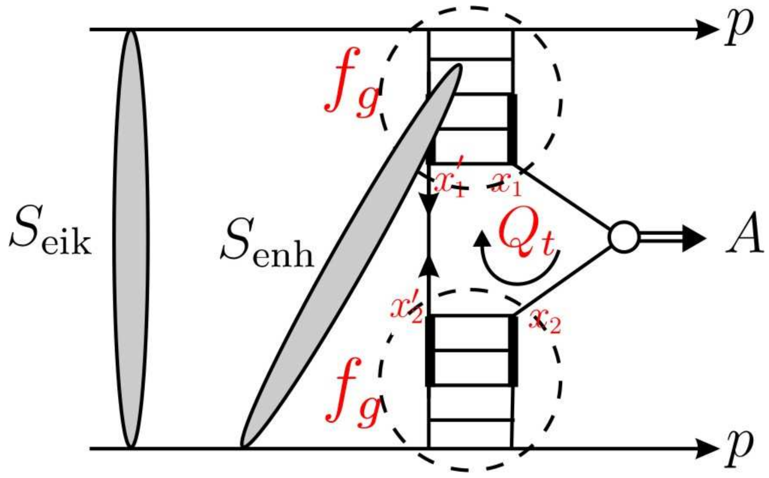
3 events observed
(one due to $\pi^0 \to \gamma\gamma$)

$\sigma(\text{excl } \gamma\gamma)_{\text{measured}} \sim 0.09$pb

$\sigma(\text{excl } \gamma\gamma)_{\text{predicted}} \sim 0.04$pb

$\sigma(\gamma\gamma) = 10$ fb
for $E_T^{\gamma} > 14$ GeV at LHC

Early LHC checks of theoretical formalism for pp → p + A + p ?



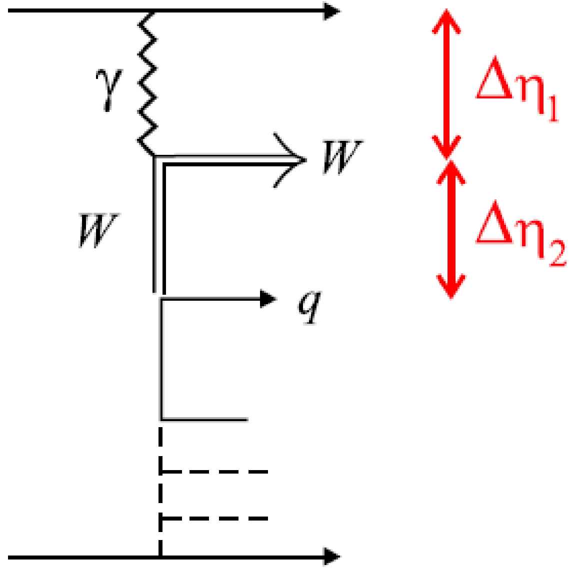
$$\sigma \sim S^2 \left| \int \frac{dQ_t^2}{Q_t^4} f_g f_g \right|^2$$

Possible checks of:

(i) survival factor S^2:	W+gaps, Z+gaps
(ii) generalised gluon f_g :	$\gamma p \to \Upsilon p$
(iii) Sudakov factor T :	3 central jets
(iv) soft-hard factorisation (broken by enhanced absorptive effects)	$\frac{\#(\text{A+gap})\ \text{evts}}{\#(\text{inclusive A})\ \text{evts}}$ with A = W, dijet, Υ…

W+gaps

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



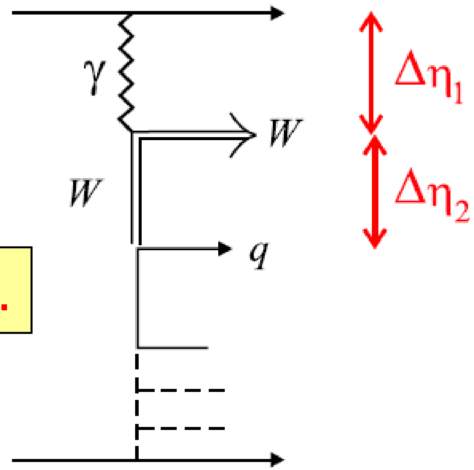
Even without a proton tag
$x_p = 1 - \xi$ can be measured by

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

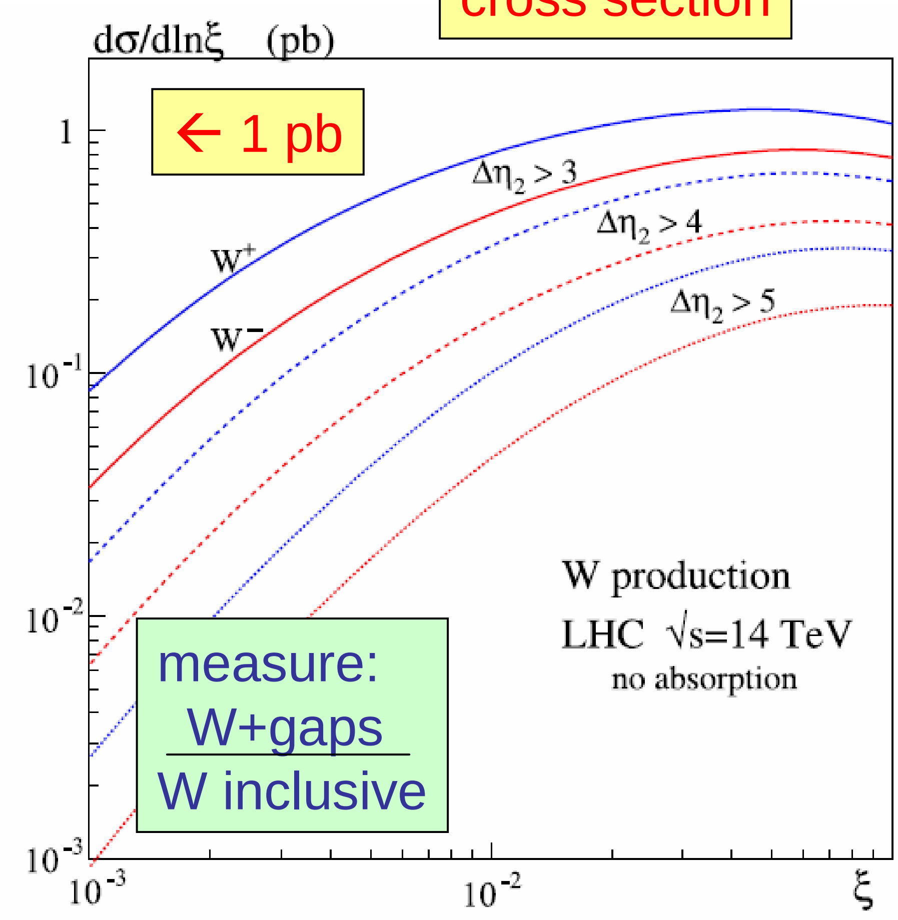
successfully used by CDF

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

W+gaps

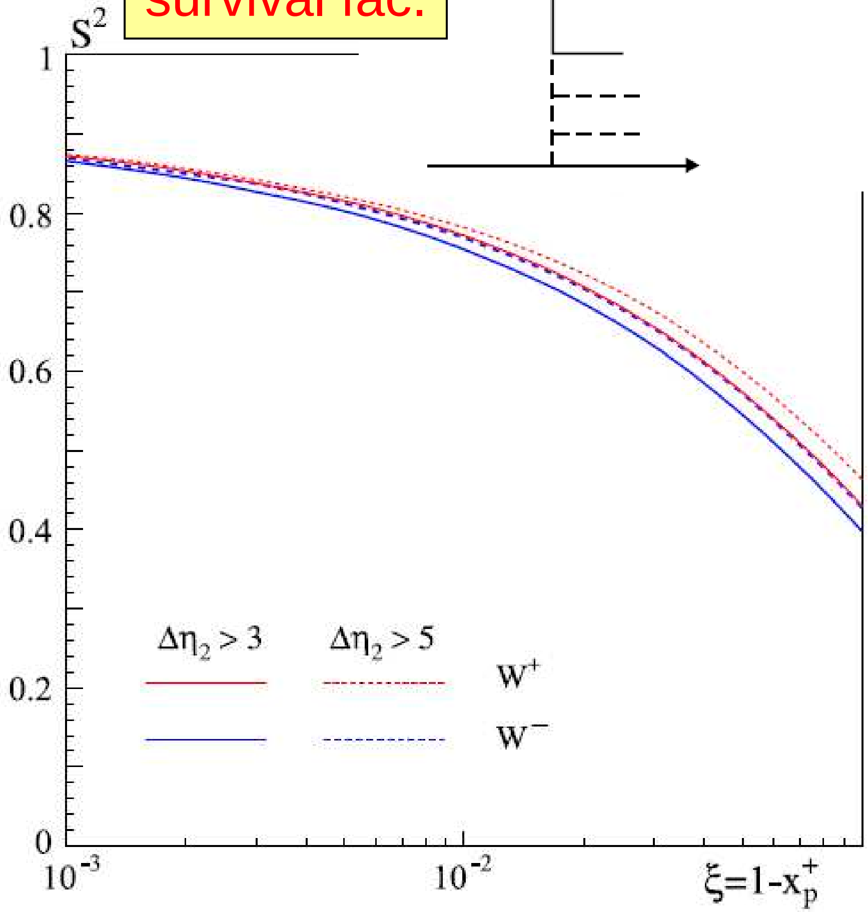


cross section



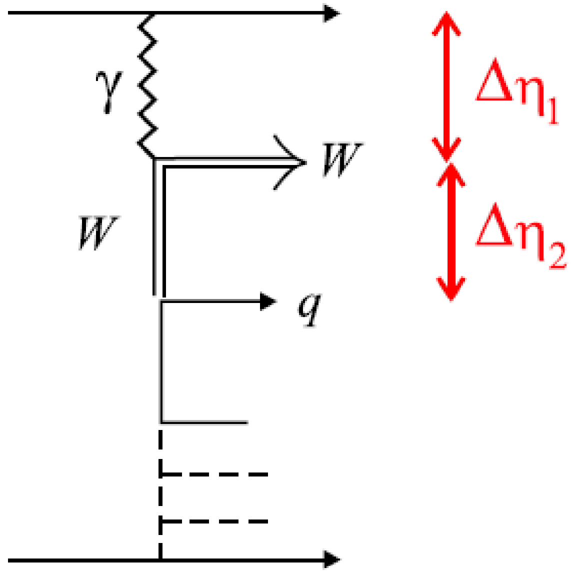
measure:
$\frac{\text{W+gaps}}{\text{W inclusive}}$

survival fac.



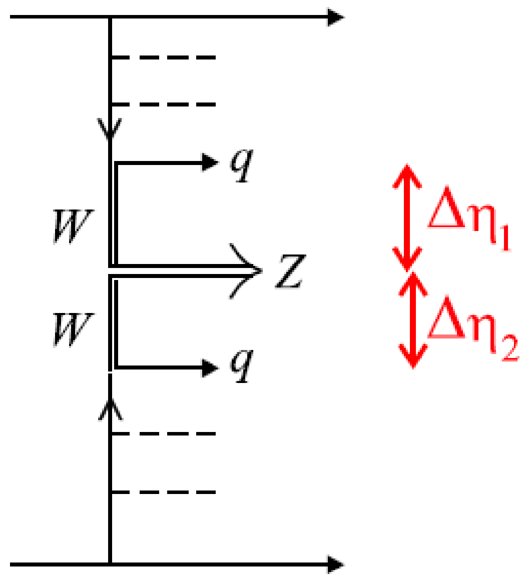
S^2 large, as large b_t (small opacity)

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



Z+gaps has b_t more like excl. Higgs

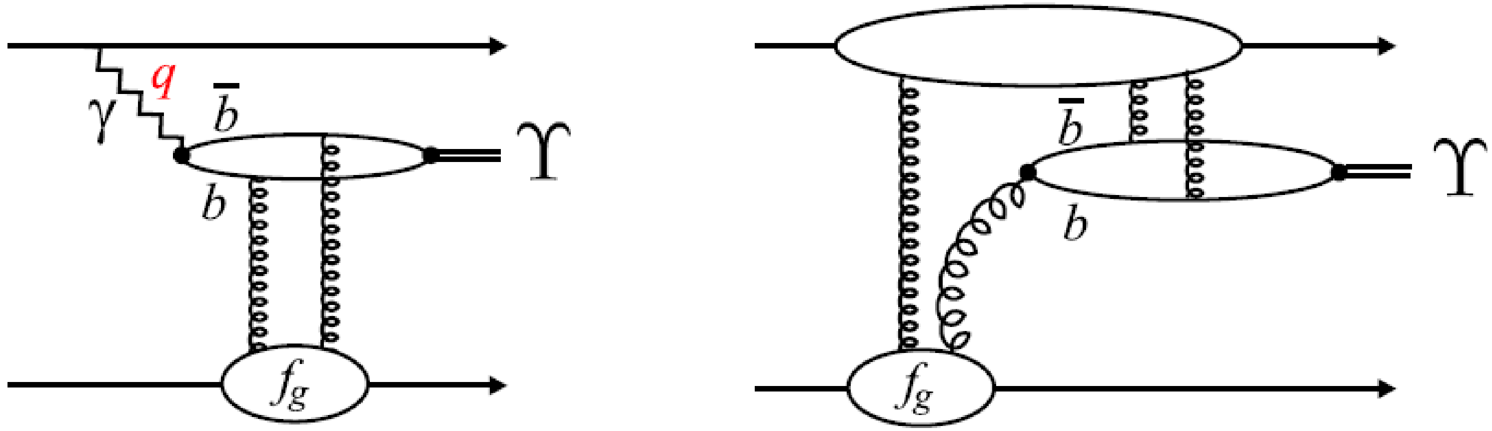
σ~0.2pb for $\Delta\eta_i$>3 and E_T(b)>50GeV
but to avoid QCD bb backgd use Z→l^+l^-



use track counting veto

Exclusive Υ production as probe of f_g

(a) γ exch (b) odderon exch



$$\left.\frac{d\sigma^{(a)}}{dy}\right|_{y=0} \simeq 50 \text{ pb}$$

x 0.025 (br for Υ→μμ)

Bzdak, Motyka,Szymanowski,Cudell

comparable ?

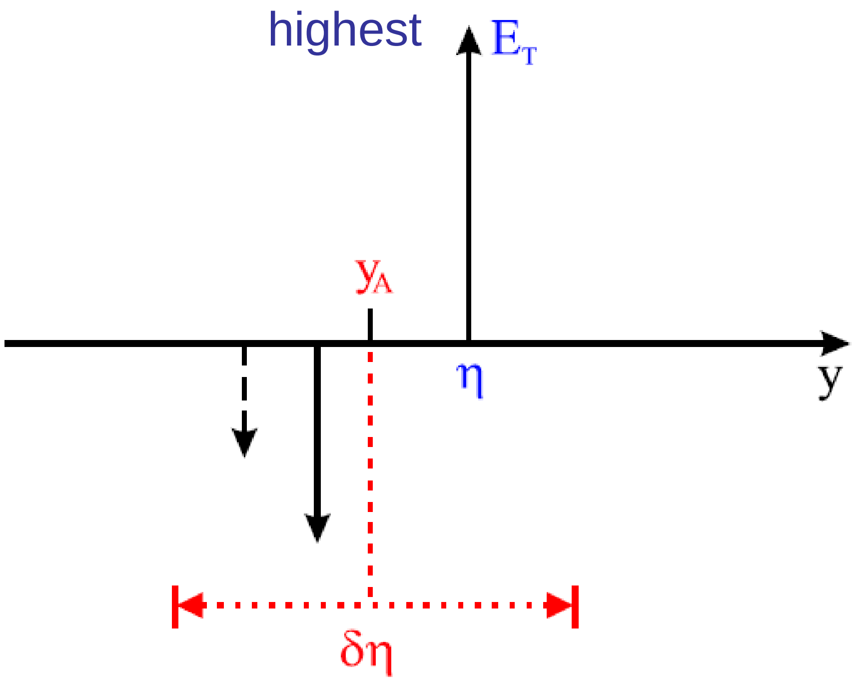
can separate by p_t if a tag of upper proton is done

If $|y_\Upsilon|<2.5$, then sample $f_g(x_1,x_2)$ with x_i in $(10^{-4}, 10^{-2})$

3-jet events as probe of Sudakov factor T

T is prob. not to emit additional gluons in gaps: pp → p + A + p
T=exp(-n), where n is the mean # gluons emitted in gap

3 central jets →allow check of additional gluon emission
System A must be colourless – so optimum choice is emission of third jet in high E_T dijet production

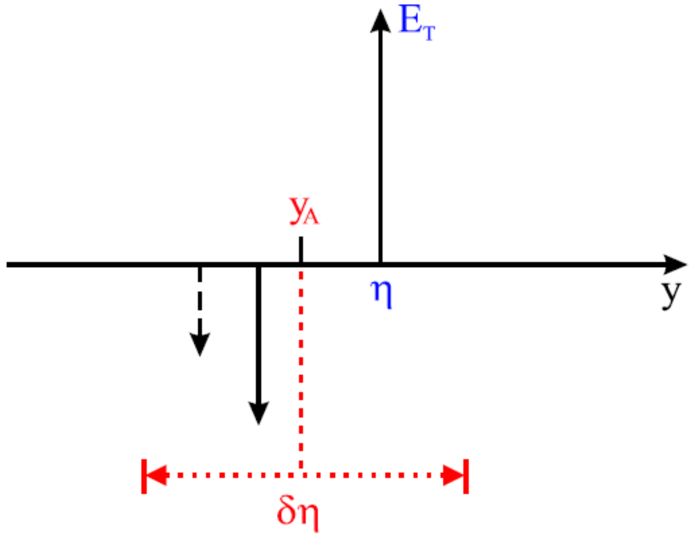


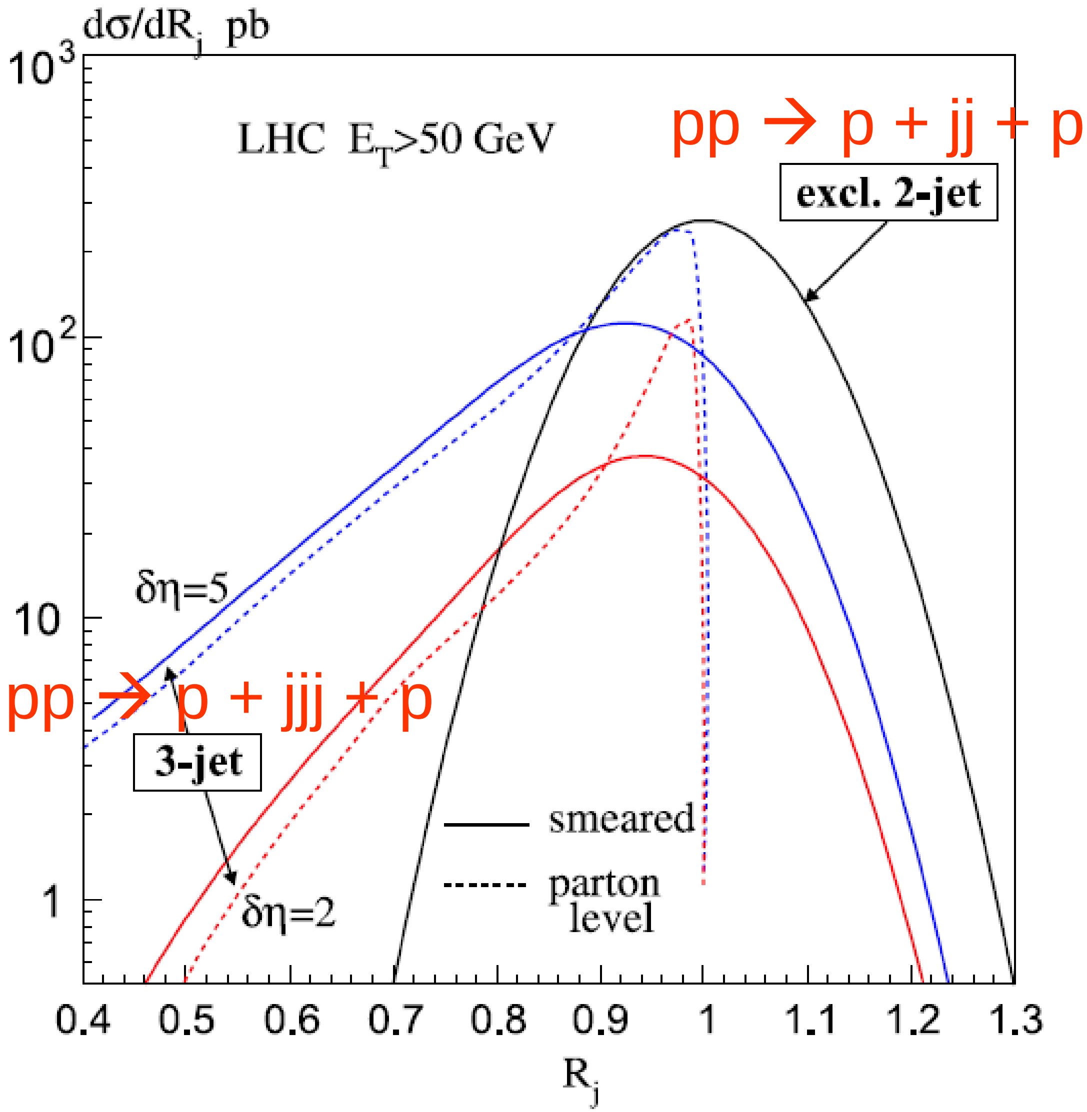
$$R_j = 2E_T\,(\cosh\eta^*)/M_A$$

$$M_A = \sqrt{s\,\xi^+\xi^-}$$

$$\eta^* = \eta - y_A$$

only highest E_T jet used – stable to hadronization, final parton radiation…





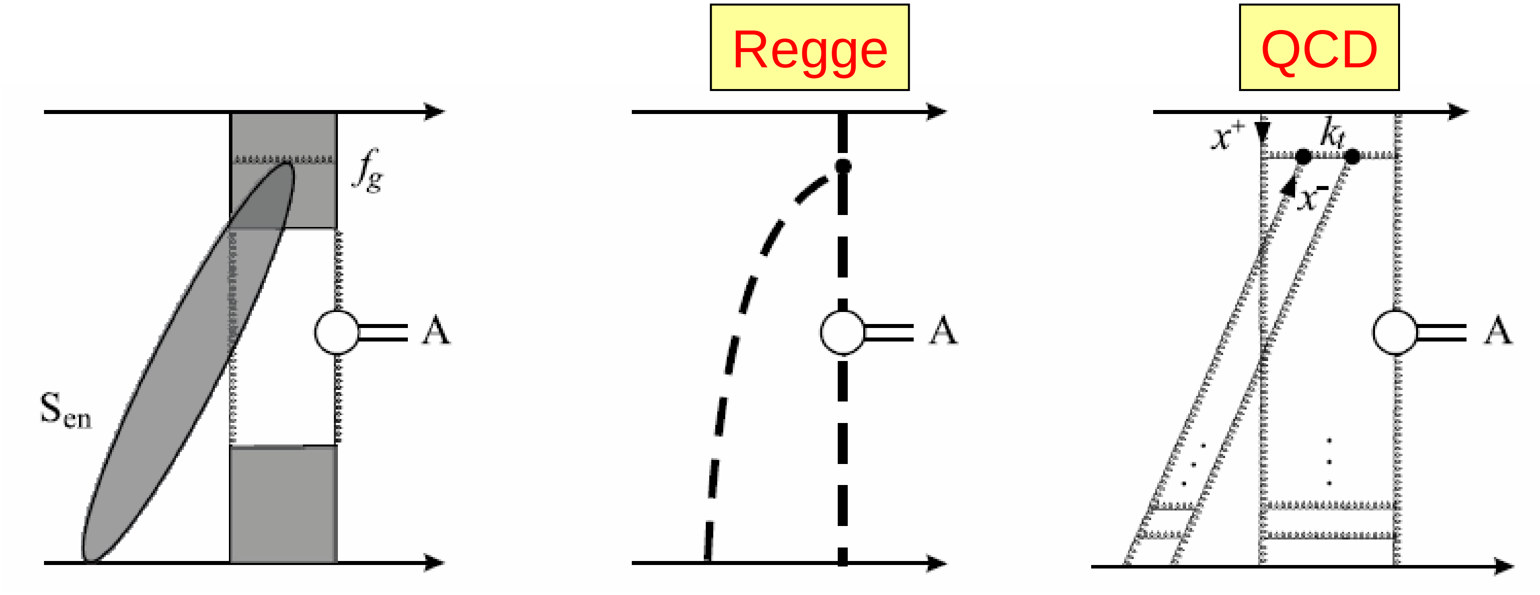
study both δη and E_T dependence of central 3-jet production

(negligible DPE background)

“Enhanced” absorptive effects

(break soft-hard factorization)

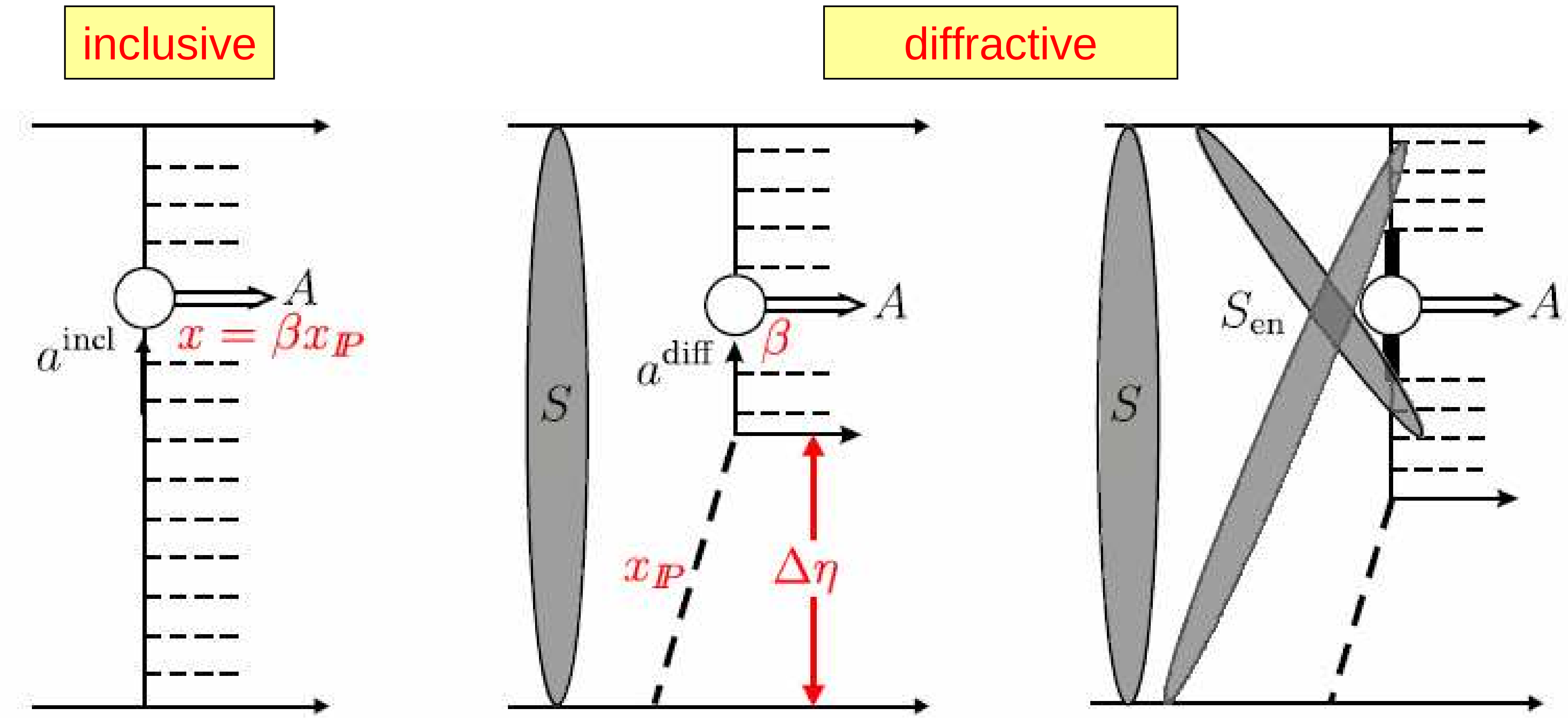
rescattering on an intermediate parton:



BBKM → large

KMR → HO diagrams → sum → small

can LHC probe this effect ?

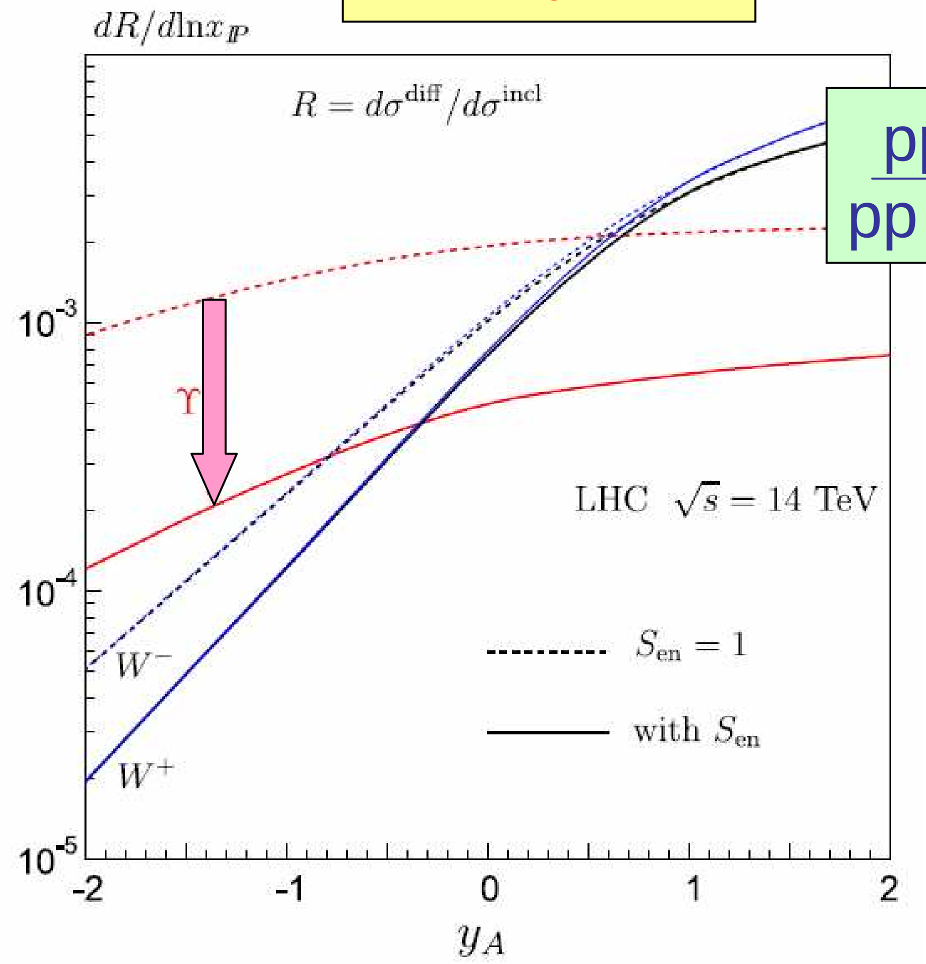


A = W or dijet or Υ ….

$$R = \frac{\text{no. of } (A + \text{gap}) \text{ events}}{\text{no. of (inclusive } A) \text{ events}} = \frac{a^{\text{diff}}(x_{I\!P}, \beta, \mu^2)}{a^{\text{incl}}(x = \beta x_{I\!P}, \mu^2)} \langle S^2 S^2_{\text{en}} \rangle_{\text{over } b_t}$$

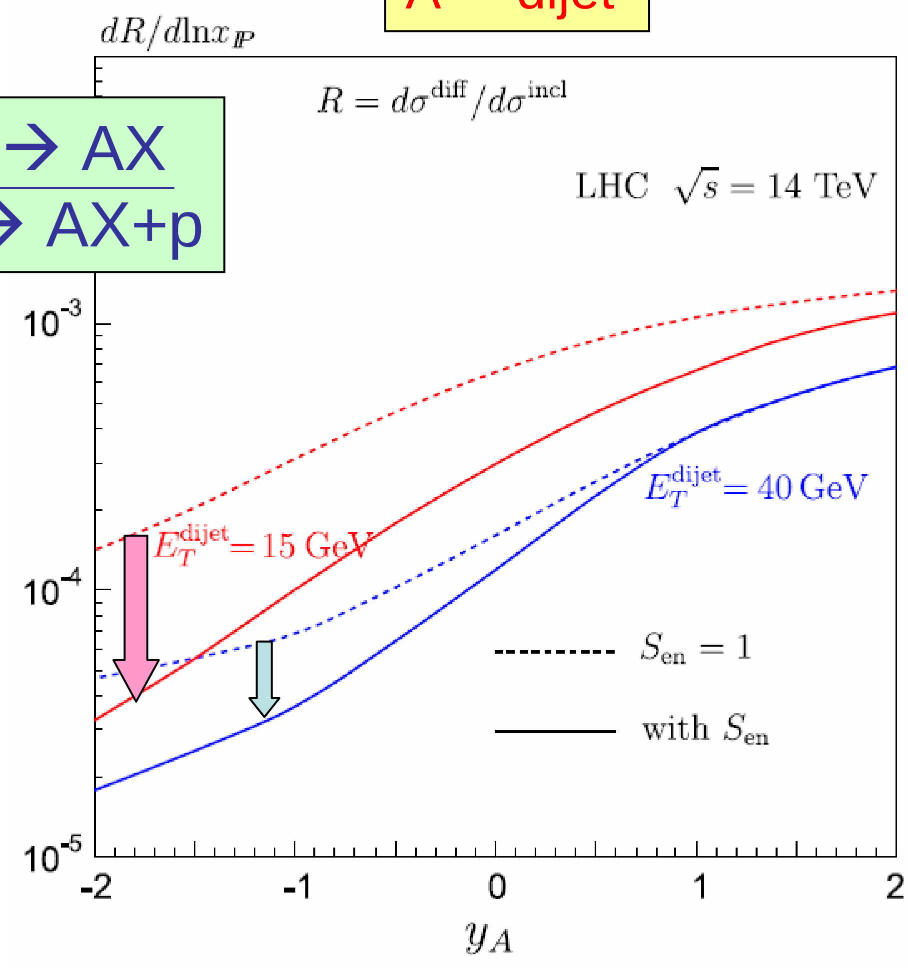
known from HERA

A = W or Υ ….



A = dijet

$$\frac{pp \rightarrow AX}{pp \rightarrow AX+p}$$



rough estimates of enhanced absorption $S^2_{\rm en}$

Conclusions – soft processes at the LHC

-- screening/unitarity/absorptive corrections are vital

-- Triple-Regge analysis with screening → g_{3P} increased by ~3

→ importance of multi-Pomeron diagrams

-- Latest analysis of all available "soft" data:

multi-ch eikonal + multi-Regge + compts of Pom. to mimic BFKL

(showed some LHC predictions ….. σ_{total} ~ 90 mb)

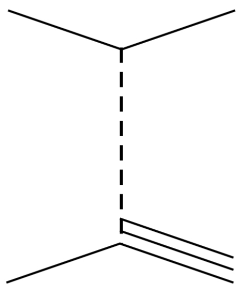
soft-hard Pomeron transition emerges

"soft" compt. --- heavily screened --- little growth with s

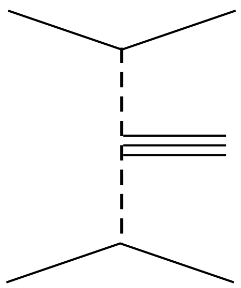
"intermediate" compt. --- some screening

"hard" compt. --- little screening --- large growth (~pQCD)

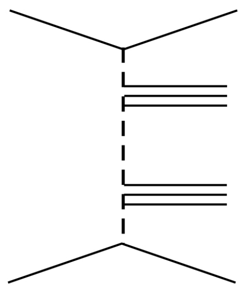
-- LHC can explore multigap events → probe multi-Pomeron structure



SD



DPE



LHC is a powerful probe of models of soft processes

Conclusions – exclusive processes at the LHC

soft analysis allows rapidity gap survival factors to be calculated for any hard diffractive process

Exclusive central diffractive production, pp→p+H+p, at LHC has great advantages, S/B~O(1), but σ ~ few fb for SM Higgs.
However, some SUSY-Higgs have signal enhanced by 10 or more.
Very exciting possibility, if proton taggers installed at 420 m

Formalism consistent with CDF data for pp(bar) → p + A + p(bar) with A = dijet and A = $\gamma\gamma$ and A = χ_c
More checks with higher M_A valuable.

Processes which can probe all features of the formalism used to calculate σ(pp→p+A+p), may be observed in the early LHC runs, even without proton taggers