Forward Physics at the LHC

1. Exclusive/diffractive Higgs signal: pp → p + H + p

2. Properties of "soft" interactions
   (forward/diffractive physics at the LHC)

3. Return to the exclusive processes
   (at the Tevatron and the LHC)

SM discoveries with early LHC data
UCL, March 30th - April 1st 2009

Alan Martin, IPPP, Durham

Advantages of pp → p + H + p with H → bb_{bar}

- If outgoing protons are tagged far from IP then $\sigma(M)$ = 1 GeV (mass also from H decay products)
- Unique chance to study H→bb_{bar}:
  QCD bb_{bar} bkgd suppressed by J_z=0 selection rule
  S/B~1 for SM Higgs M < 140 GeV
- Very clean environment, even with pile-up---10 ps timing
- SUSY Higgs: parameter regions with larger signal S/B~10,
  even regions where conv. signal is challenging and
  diffractive signal enhanced----h, H both observable
- Azimuth angular distribution of tagged p's→ spin-parity 0^{++}

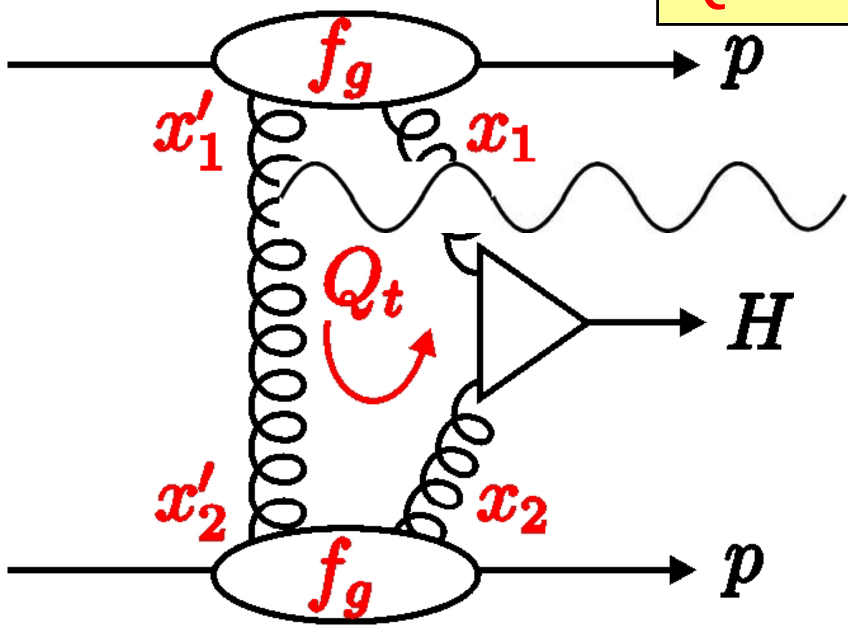
→ FP420 → ATLAS + CMS

Is the cross section large enough ?

How do we calculate $\sigma(pp \rightarrow p + H + p)$?

What price do we pay for an exclusive process with large rapidity gaps ?

QCD mechanism for pp → p+H+p



no emission when $(\lambda \sim 1/k_t) > (d \sim 1/Q_t)$
i.e. only emission with $k_t > Q_t$

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

$$\mathcal{M} \sim A(gg \to H) \int \frac{d^2 Q_t}{Q_t^4}\, f_g(x_1, x_1', Q_t^2, \mu^2)\; f_g(x_2, x_2', Q_t^2, \mu^2)$$

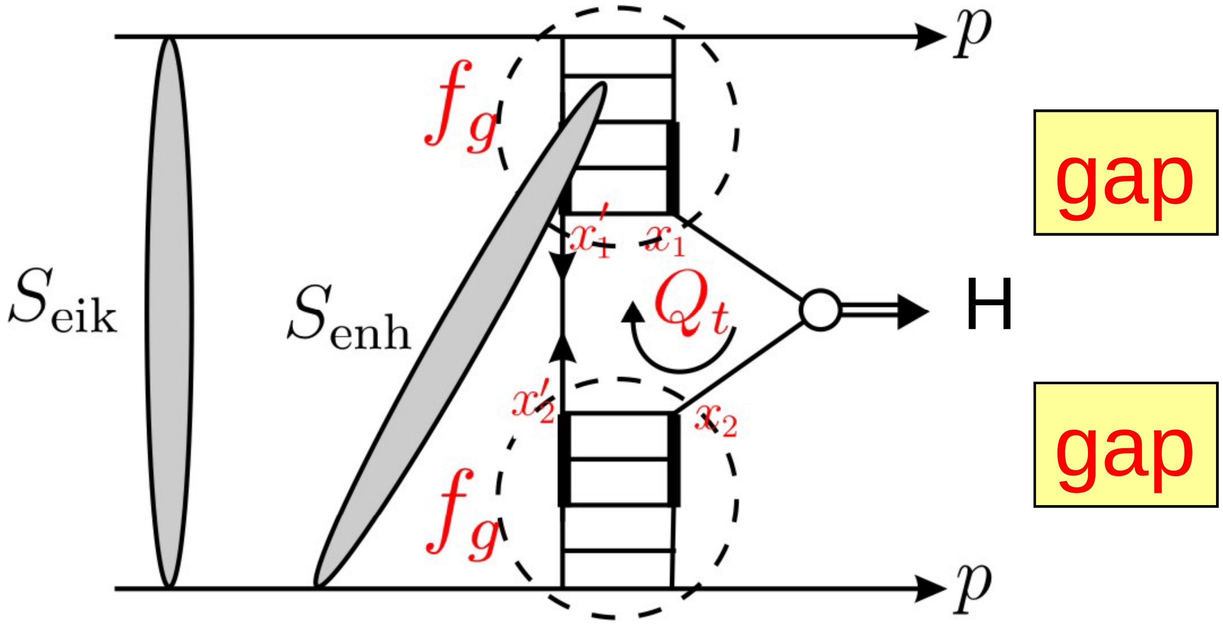
$\sim M_H^2$

unintegrated skewed gluons f_g given in terms of $g(x,Q_t^2)$ and Sudakov factor $T = \exp\left(-\int_{Q_t^2}^{\mu^2} dk_t^2 \ldots\right)$ which expon^ally suppresses infrared region

can use pQCD

σ > 100 fb !! but….

…but "soft" scatt. can easily destroy the gaps



soft-hard factoriz^n

eikonal rescatt: between protons ← conserved

enhanced rescatt: involving intermediate partons ← broken

→ soft physics at high energies

(Dark age?)

Model for “soft” high-energy interactions

needed to ---- understand asymptotics, intrinsic interest

---- describe “underlying” events for LHC jet algor^{ms}

---- calc. rap.gap survival S^2 for exclusive prod^n

Model should:

1. be self-consistent theoretically --- satisfy unitarity

→ importance of absorptive corrections

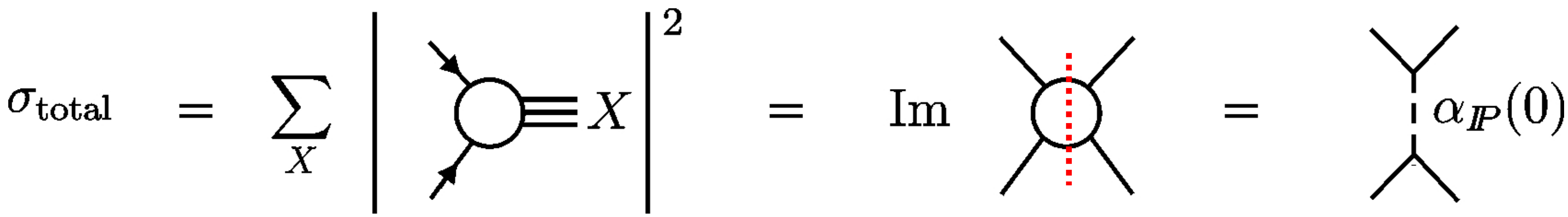
→ importance of multi-Pomeron interactions

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

Optical theorems

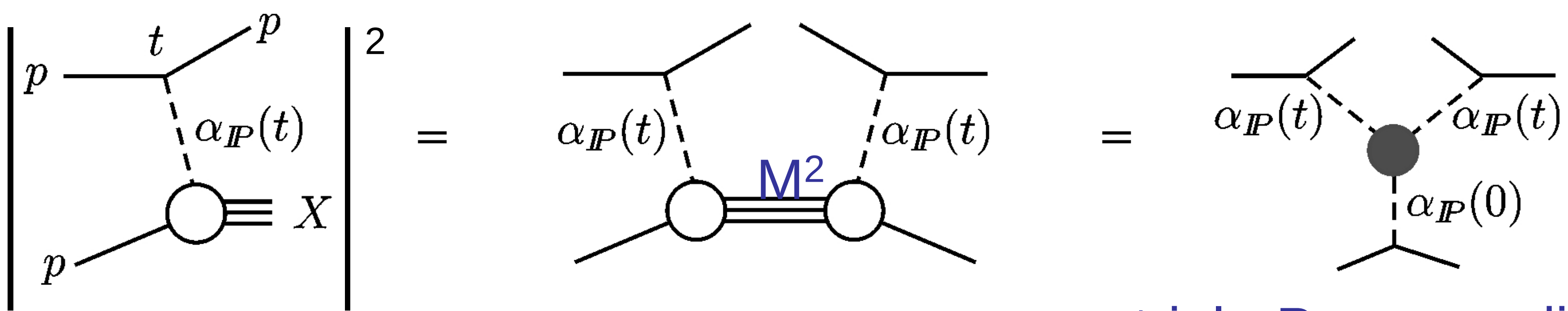
at high energy
use Regge



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

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

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

Must include unitarity

diagonal in b ~ ℓ/p

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

elastic unitarity →

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

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

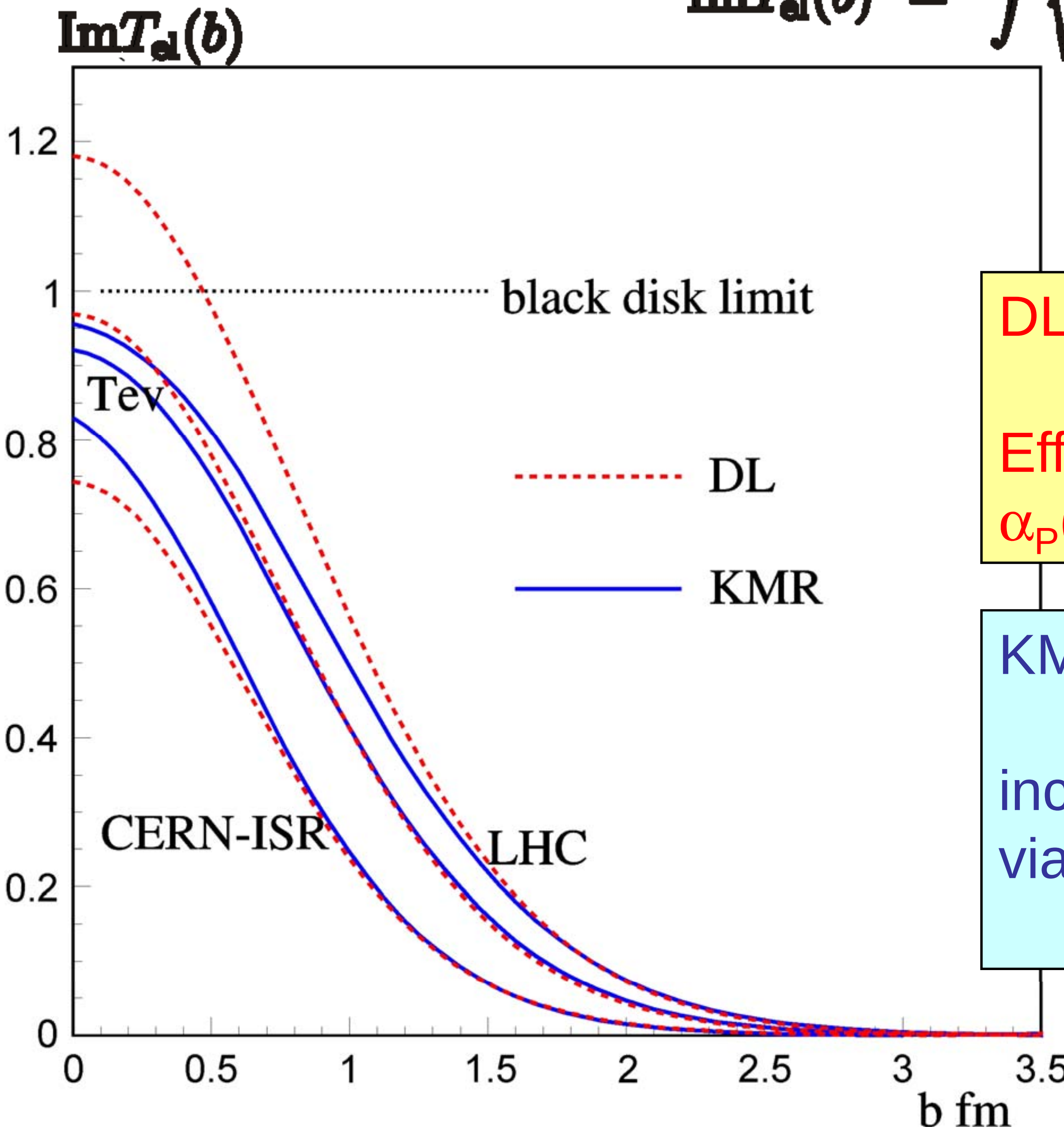
Opacity / Eikonal $\Omega(s,b) \geq 0$

e.g. black disc
$\mathrm{Im}\,T_{el} = 1, \quad b < R$

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

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

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



DL parametrization:

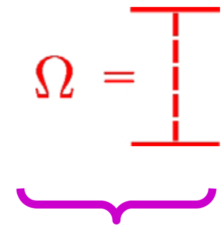
Effective Pomeron pole
$\alpha_P(t) = 1.08+0.25t$

KMR parametrization

includes absorption
via multi-Pomeron
effects

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

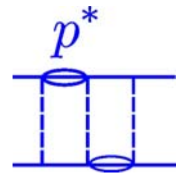
bare amp. $\Omega =$



(-20%)

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

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)

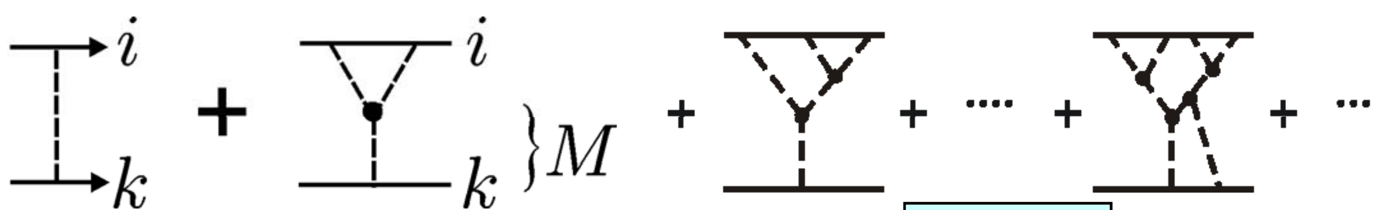
(-40%)

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

include high-mass diffractive dissociation

(SD -80%)

$\Omega_{ik} =$

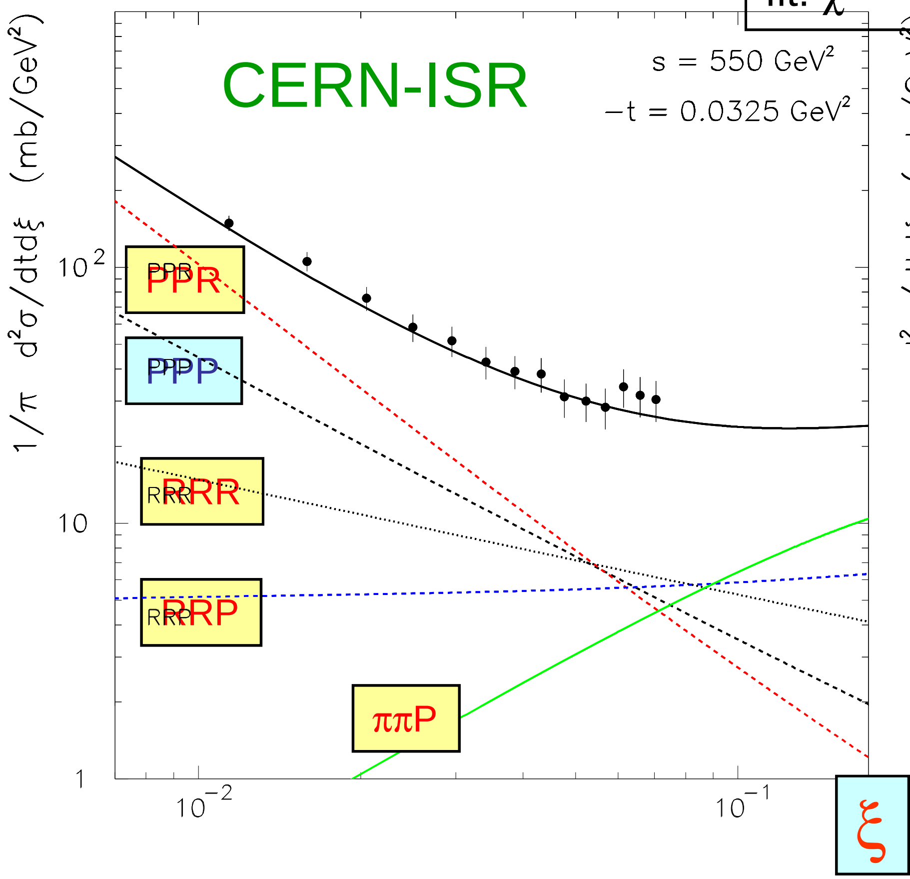


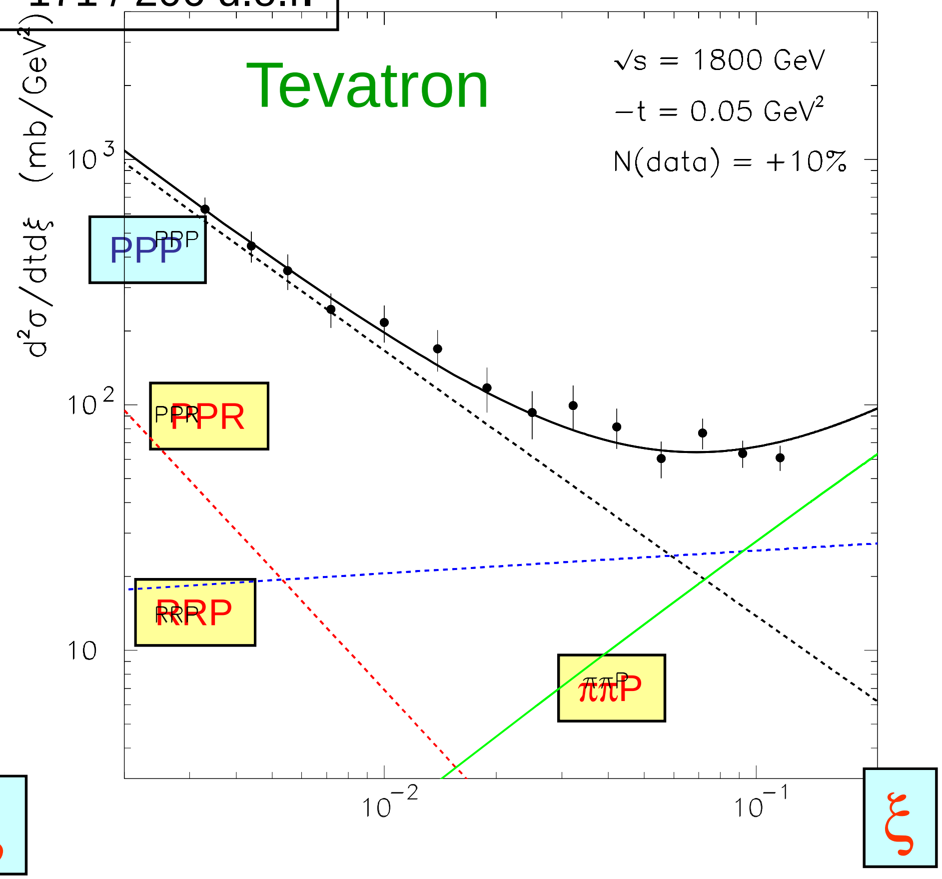
g_{3P} ?

triple-Regge analysis of dσ/dtdξ, including screening

(includes compilation of SD data by Goulianos and Montanha)

fit: χ^2 = 171 / 206 d.o.f.

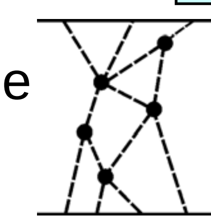




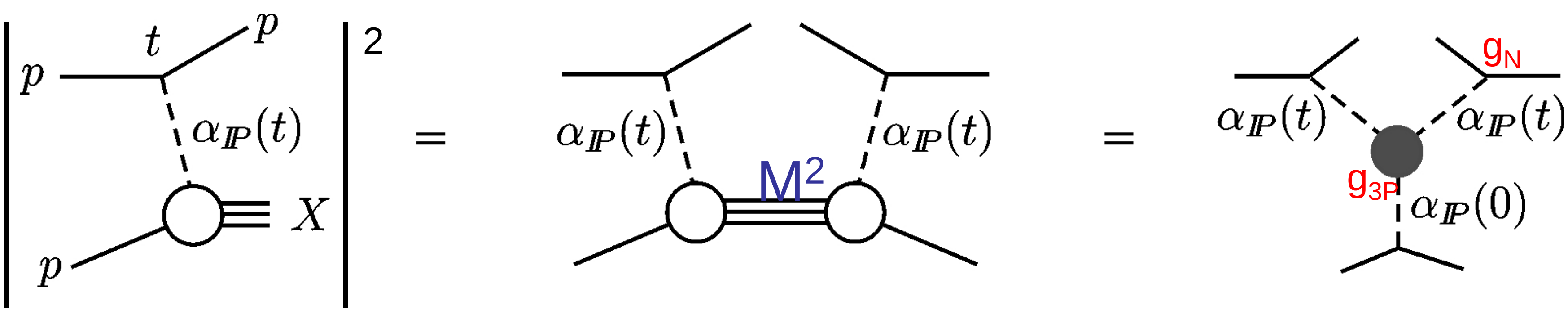
LKMR

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

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



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



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

ln s

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

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

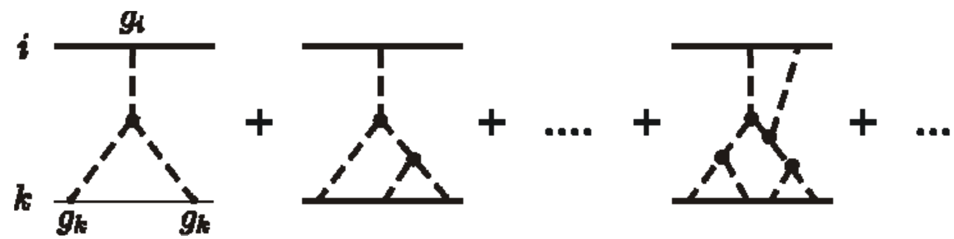
Multi-compt. s- and t-ch analysis of soft data

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

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

- 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

Use four exchanges in the t channel

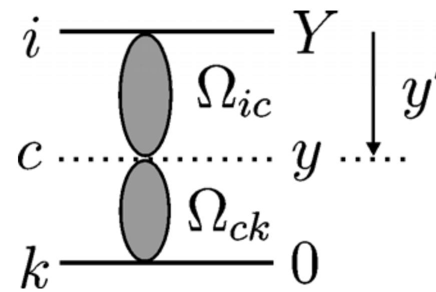
3 to mimic BFKL diffusion in ln q_t

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

$$\frac{d\Omega^a_{ck}(y)}{dy} = (\Delta + \alpha'\nabla^2_b)\Omega^a_{ck}(y)\; e^{-\lambda\Omega_{ck}(y)/2} e^{-\lambda\Omega_{ic}(y')/2} + V_{aa'}\Omega^{a'}_{ic}(y)$$

$$\frac{d\Omega^a_{ic}(y')}{dy'} = (\Delta + \alpha'\nabla^2_b)\Omega^a_{ic}(y')\; e^{-\lambda\Omega_{ic}(y')/2} e^{-\lambda\Omega_{ck}(y)/2} + V_{aa'}\Omega^{a'}_{ck}(y')$$

evolve down from y'=Y-y=0

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

(arXiv:0812.2407)

Parameters

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

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

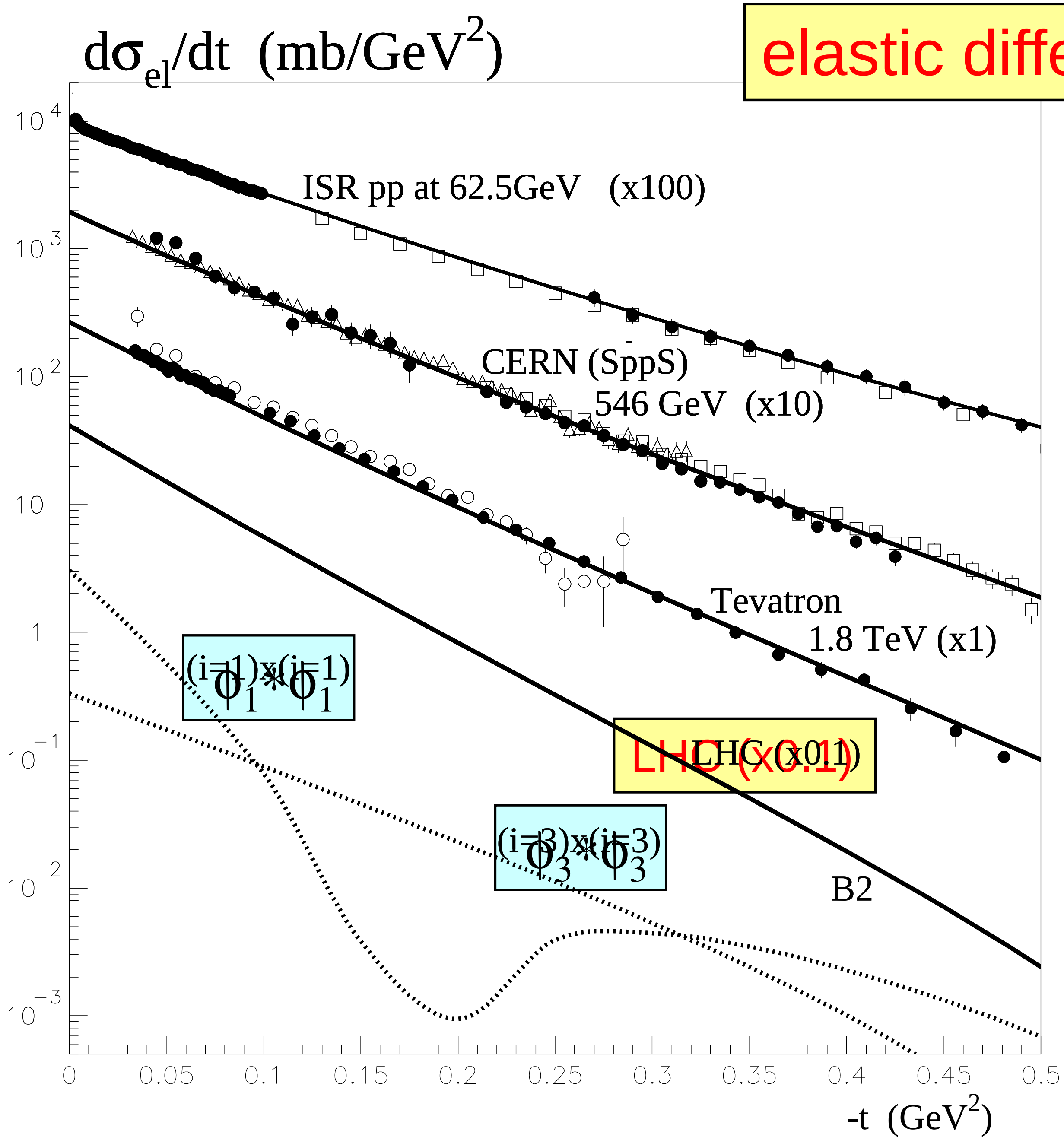
$g_{3P}=\lambda g_N$ with $\lambda=0.25$

$\Delta_{Pi} = 0.3$ (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 $d\sigma/dt$



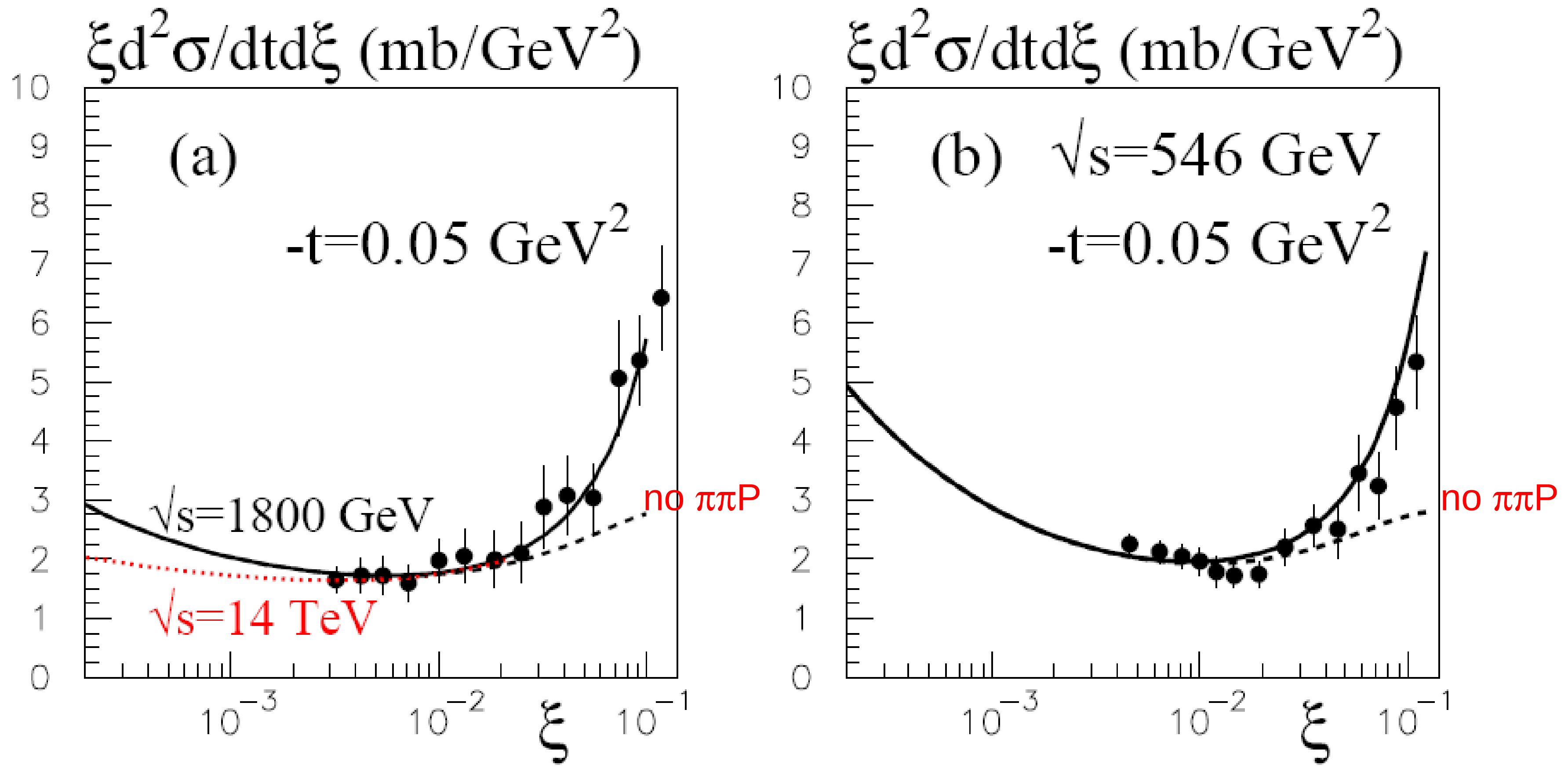
~ g, sea

ϕ_1: "large"

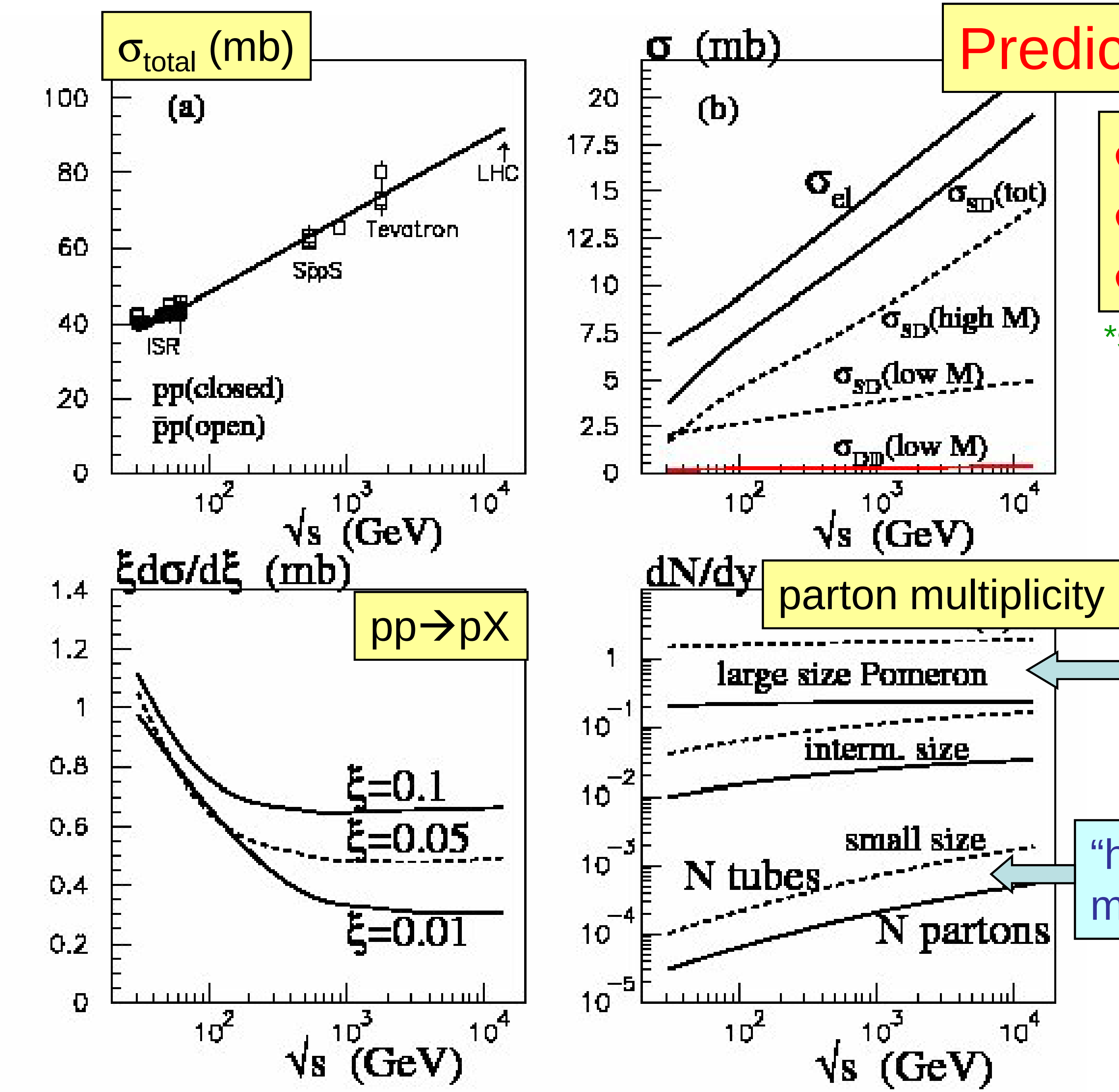
ϕ_3: "small"

more valence

Description of CDF dissociation data



Predictions for LHC



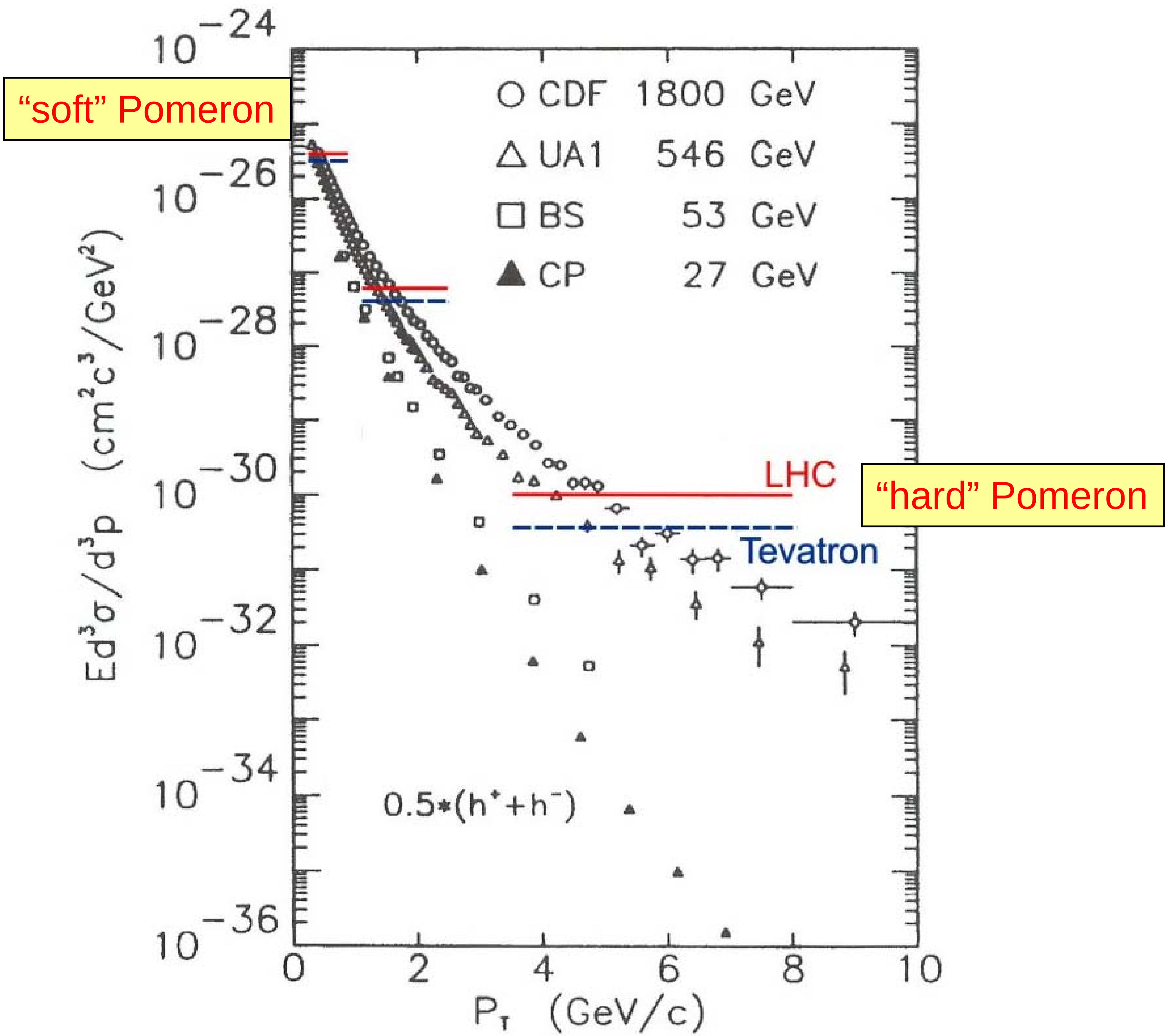
σ_{total} = 91.7 mb*
σ_{el} = 21.5 mb
σ_{SD} = 19.0 mb

*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, $s^{0.3}$



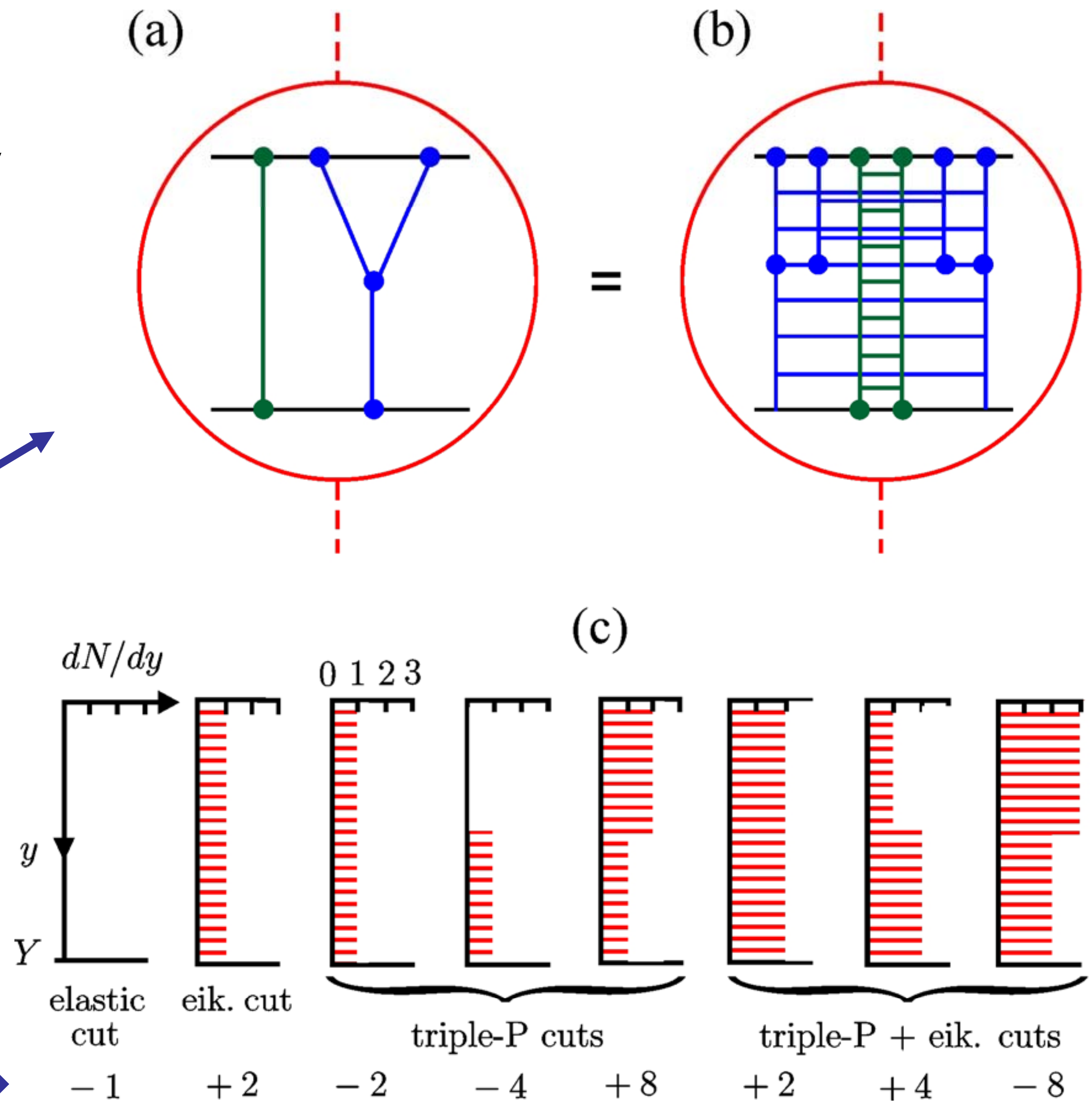
"soft" Pomeron
"hard" Pomeron
CDF 1800 GeV
UA1 546 GeV
BS 53 GeV
CP 27 GeV
LHC
Tevatron
0.5*(h⁺+h⁻)
Ed³σ/d³p (cm²c³/GeV²)
P_T (GeV/c)

Multi-Pomeron effects at the LHC

Each multi-Pomeron diag. simultaneously describes several different processes

Example

8 different "cuts"
AGK cutting rules →



Long-range correlations at the LHC

cutting n eikonal Pomerons → multiplicity n times that cutting one Pomeron

→ long range correlation even for large rapidity differences $|y_a - y_b| \sim Y$

$$R_2 = \frac{\sigma_{\rm inel} d^2\sigma/dy_a dy_b}{(d\sigma/dy_a)(d\sigma/dy_b)} - 1 = \frac{d^2N/dy_a dy_b}{(dN/dy_a)(dN/dy_b)} - 1$$

→ $R_2 > 0$

without multi-Pomeron exch. $R_2 > 0$ only when two particles are close, e.g. from resonance decays (short-range correlation)

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

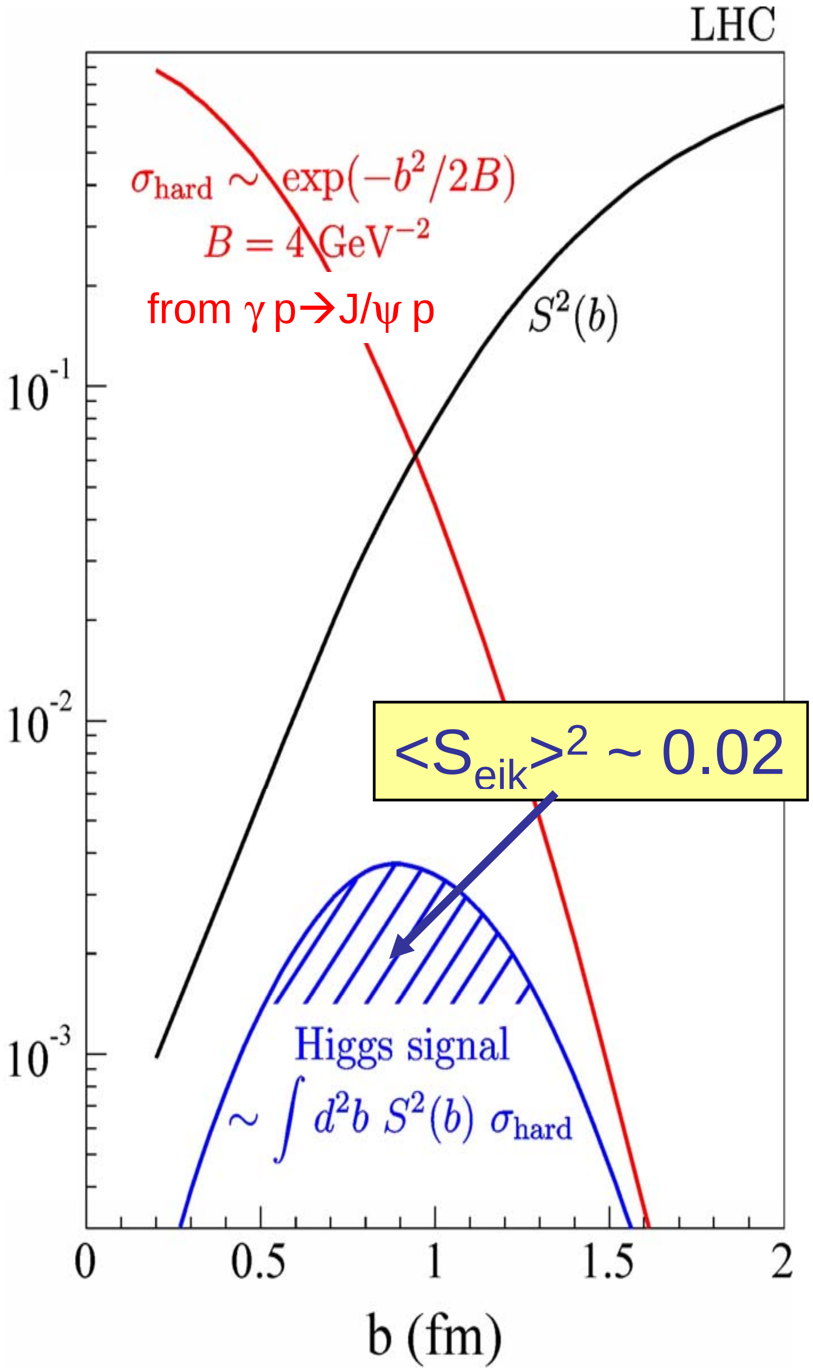
average over diff. estates i,k

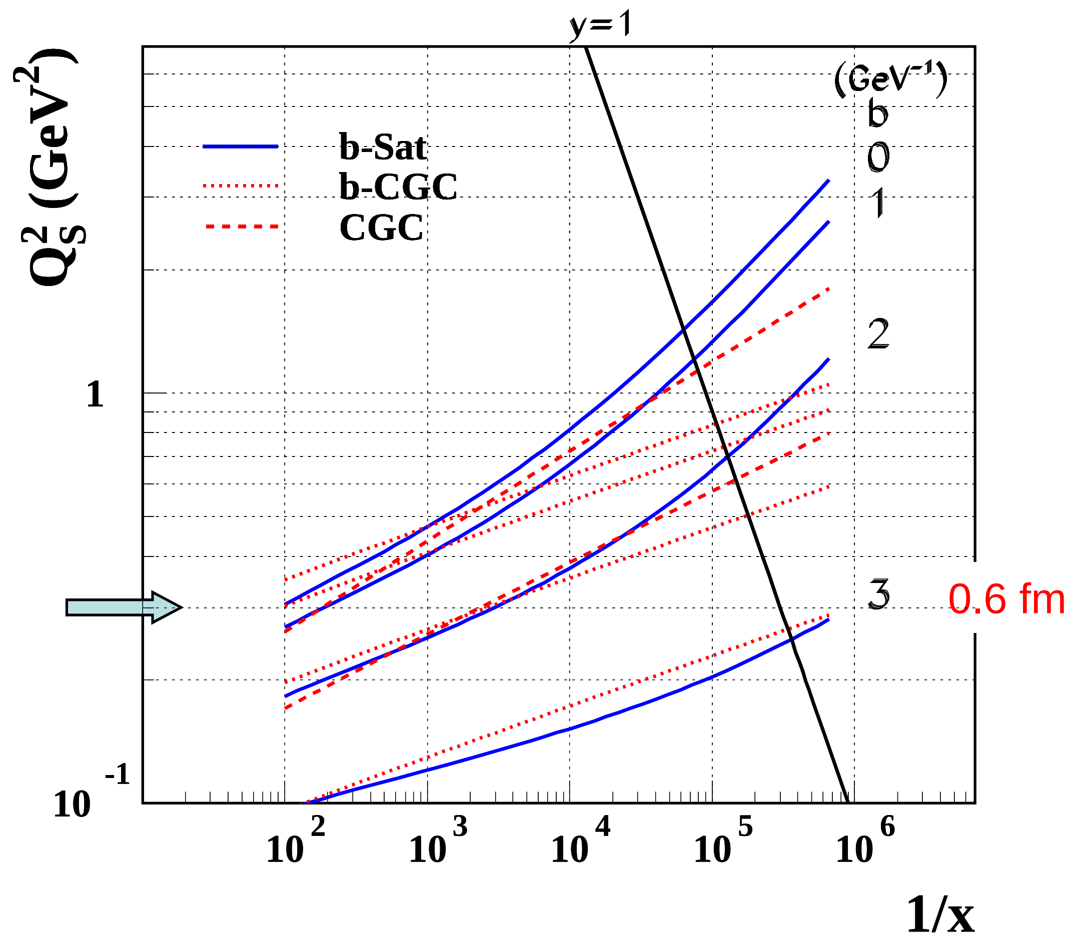
$$\overline{S^2} = \frac{\sum_{i,k} \int d^2b \, |a_{pi}|^2 \; |a_{p'k}|^2 \; |\mathcal{M}_{ik}|^2 \; \exp(-\Omega_{ik}(s,b))}{\sum_{i,k} \int d^2b \, |a_{pi}|^2 \; |a_{p'k}|^2 \; |\mathcal{M}_{ik}|^2}$$

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

→ σ ~ 2 - 3 fb at LHC

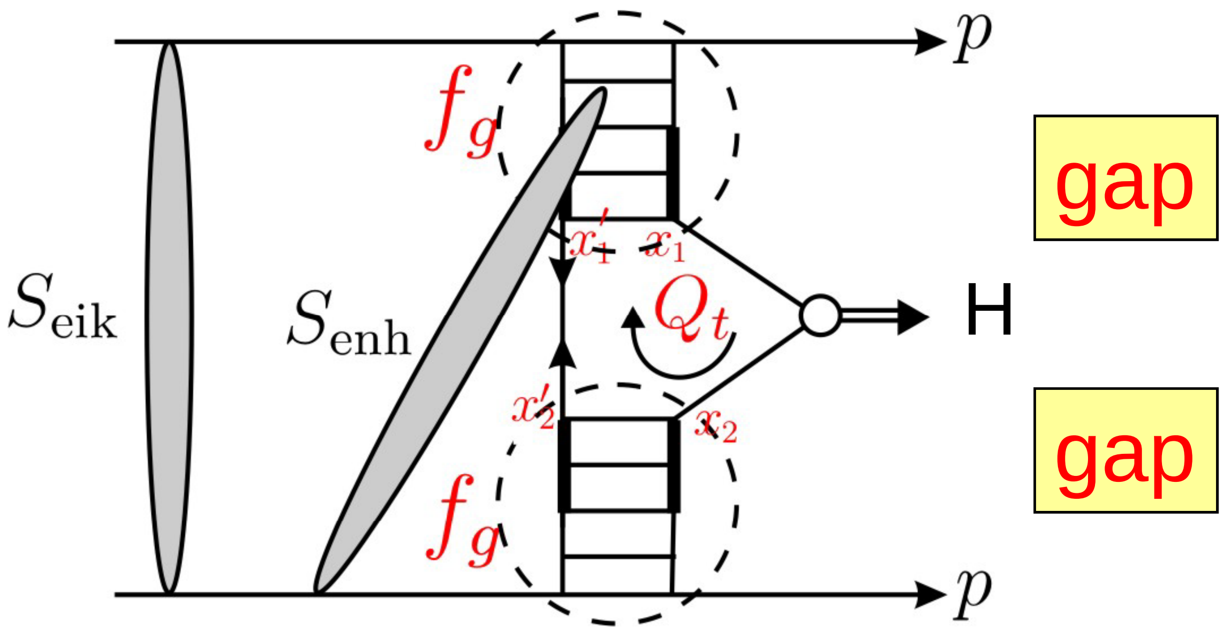
$\langle S_{enh}\rangle^2 = ??$





Watt, Kowalski

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



eikonal rescatt: between protons ← soft-hard factoriz^n conserved

enhanced rescatt: involving intermediate partons ← broken

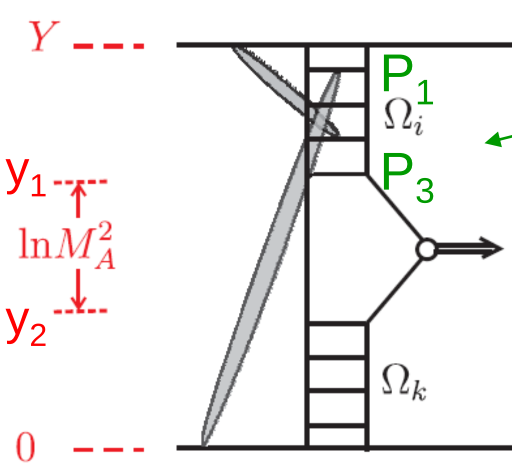
The new soft analysis, with Pomeron q_t structure, enables S^2_{enh} to be calculated model has 4 t-ch. exchanges

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

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

$V_{PiPj} \sim$ BFKL

---

evolve up to y_2

bare pole — absorptive effects

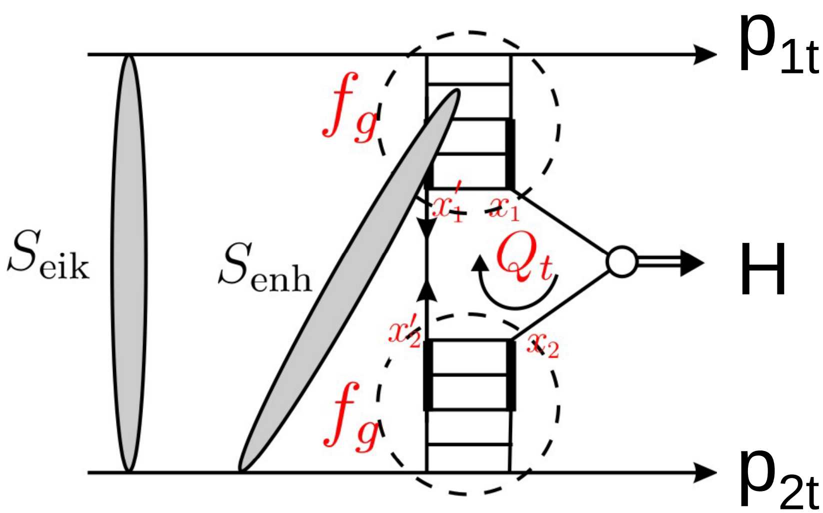
$$\frac{d\Omega^a_{ck}(y)}{dy} = (\Delta + \alpha' \nabla_b^2)\Omega^a_{ck}(y)\ e^{-\lambda\Omega_{ck}(y)/2} e^{-\lambda\Omega_{ic}(y')/2} + V_{aa'}\Omega^{a'}_{ic}(y)$$

$$\frac{d\Omega^a_{ic}(y')}{dy'} = (\Delta + \alpha' \nabla_b^2)\Omega^a_{ic}(y')\ e^{-\lambda\Omega_{ic}(y')/2} e^{-\lambda\Omega_{ck}(y)/2} + V_{aa'}\Omega^{a'}_{ck}(y')$$

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

$$\langle S^2 \rangle_{tot} \langle p^2_t \rangle^2 = \begin{cases} 0.0015 & \text{LHC} \\ 0.0030 & \text{Tevatron} \\ 0.0010 & \text{LHC} \\ 0.0025 & \text{Tevatron} \end{cases}$$

0.0015 LHC, 0.0030 Tevatron: KMR 2000 (no S_{enh})

0.0010 LHC, 0.0025 Tevatron: KMR 2008 (with S_{enh})

see arXiv:0812.2413

Comments on S^2

1. Enhanced rescattering reduces the signal by ~30%

2. However, the quoted values of S^2 are conservative lower limits

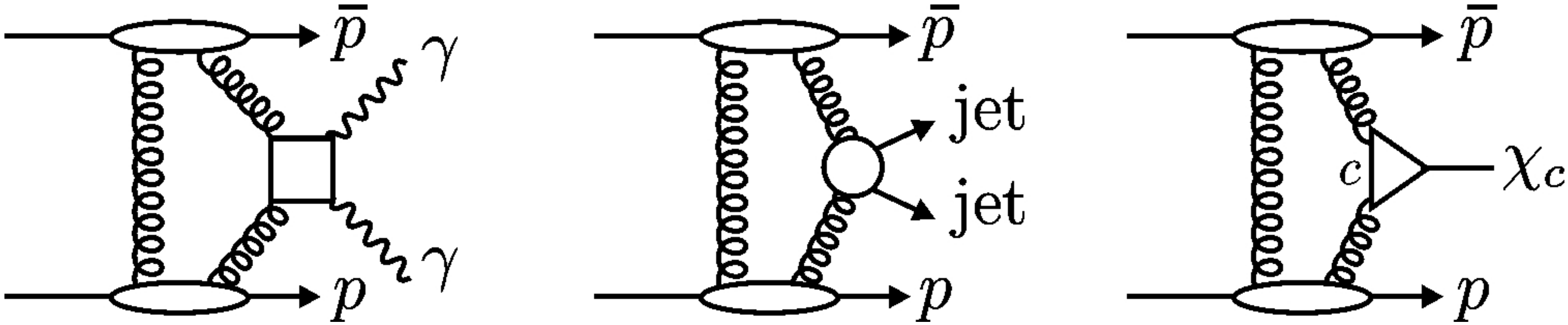
3. The very small values of S^2_{enh} in recent literature are not valid

The arguments are given in arXiv:0903.2980

CDF observation of exclusive processes at the Tevatron offers the first experimental checks of the formalism

Observation of exclusive prod^n, $\bar{p}p \rightarrow \bar{p} + A + p$, by CDF

with A=γγ or A = dijet or A = $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$



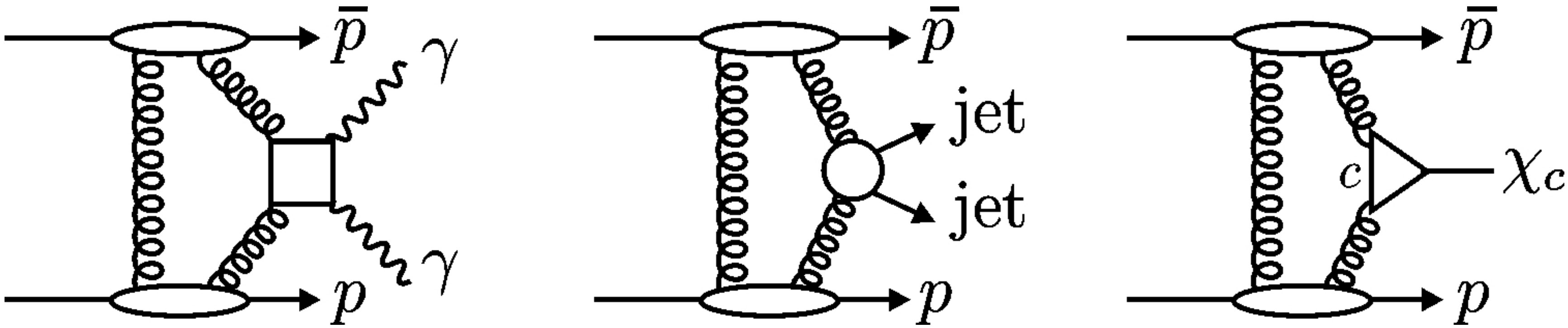
Same mechanism as pp → p+H+p

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

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

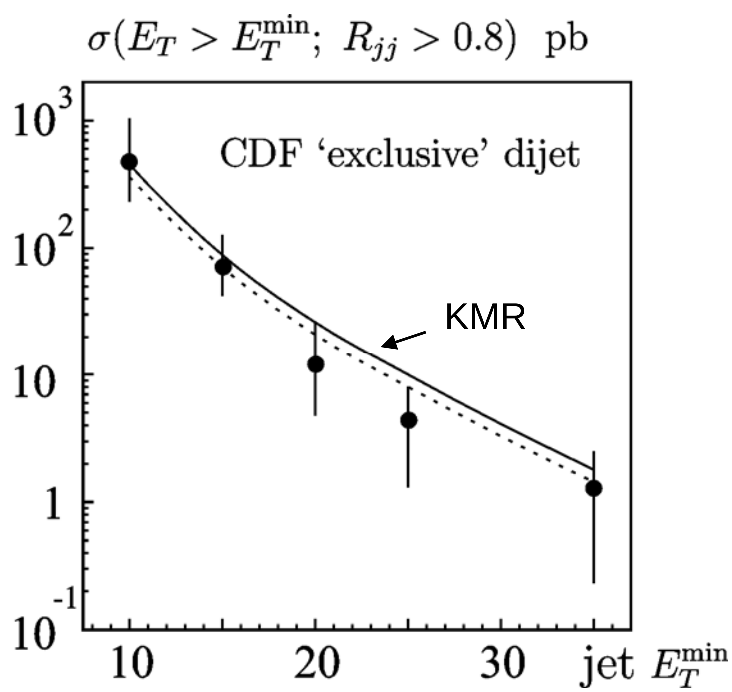
$$T = \exp\left(-\int_{Q_t^2}^{M_A^2} dk_t^2 \ldots\right)$$

Observation of exclusive prod^n, $\bar{p}p \rightarrow \bar{p} + A + p$, at Tevatron



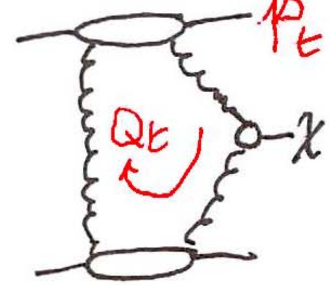
KMR cross section predictions are consistent with CDF data

3 events observed
(one due to $\pi^0 \rightarrow \gamma\gamma$)
$\sigma(\text{excl } \gamma\gamma)_{CDF}$ ~ 0.09pb
$\sigma(\text{excl } \gamma\gamma)_{KMR}$ ~ 0.04pb



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

Exclusive $\bar{p}p \to \bar{p} + \chi_c + p$



CDF: $\chi_c \to J/\psi\,\gamma \to \mu^+\mu^-\gamma$ (0.06)

$$\left.\frac{d\sigma_\chi}{dy}\right|_{y=0} = 76 \pm 14\ \text{nb}$$

B. fractions:

0^{++}	0.013		~ 30 nb
1^{++}	0.36	$\sim \langle p_t^2\rangle / M^2$	"
2^{++}	0.20	$\sim \langle p_t^2\rangle^3 / Q_t^4$	"

even tho' $\dfrac{\chi_0}{\chi_1} \sim \dfrac{\chi_0}{\chi_2} \sim 10\text{-}40$

The KMRS pred^n is reduced by $S^2_{enh} \sim 1/3$ and by 1.45 due to a revised $\Gamma_{tot}(\chi_c(0))$

KMRS: only order-mag. pred^{ns}
(light M_χ, non-pQCD effects)

Better decay channels $\chi_c \to \pi\pi$ or $K\bar{K}$

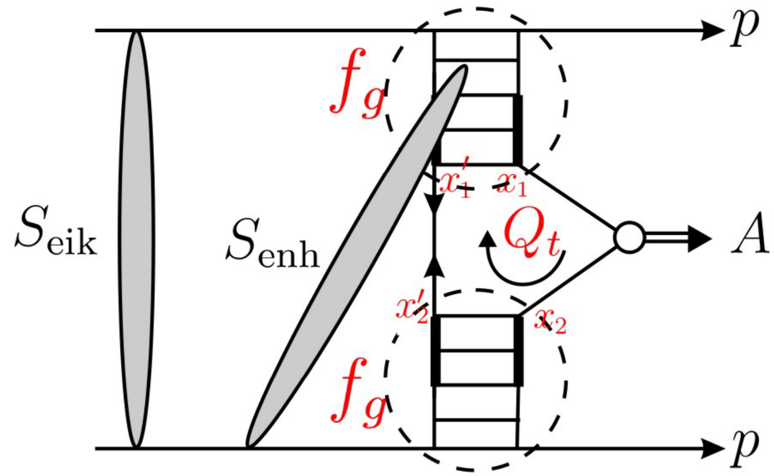
B. fractions

0^{++}	$\sim 1\%$
1^{++}	forbidden
2^{++}	suppressed

χ_b ?

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

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



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

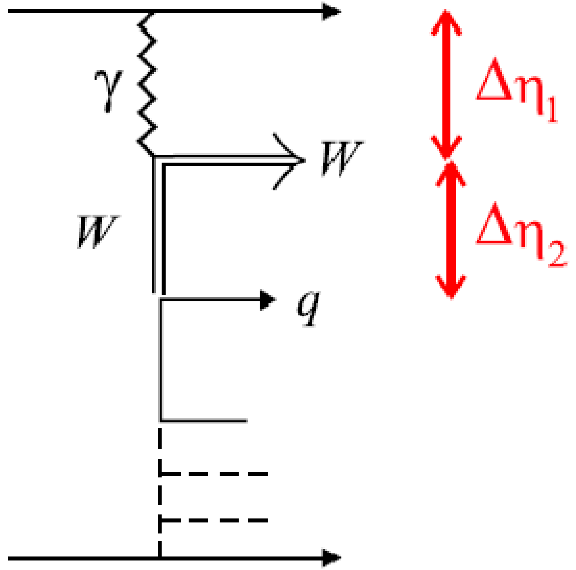
Possible checks of:

(i) survival factor S^2:	W+gaps, Z+gaps
(ii) generalised gluon f_g :	γp →Υp, 3 central jets
(iii) soft-hard factorisation (broken by enhanced absorptive effects)	#(A+gap) evts #(inclusive A) evts with A = W, dijet, Υ…

(arXiv:0802.0177)

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

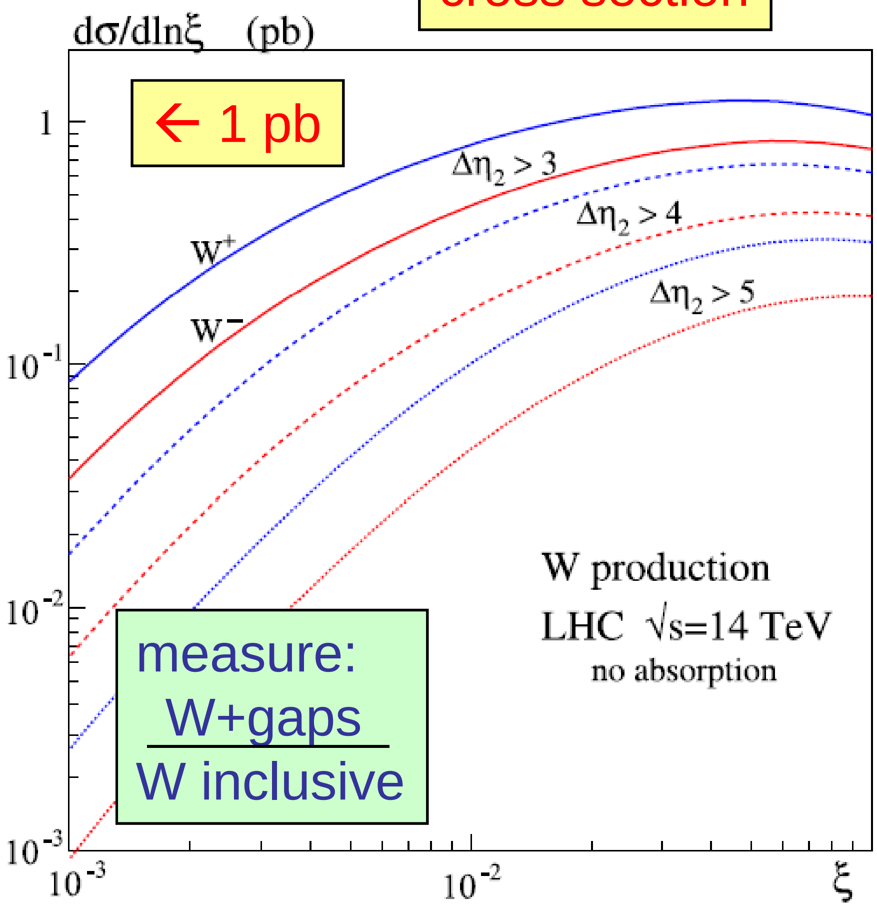
$$\xi = \sum \sqrt{m_i^2 + k_{ti}^2}\ e^{y_i} / \sqrt{s}$$

successfully used by CDF

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

W+gaps

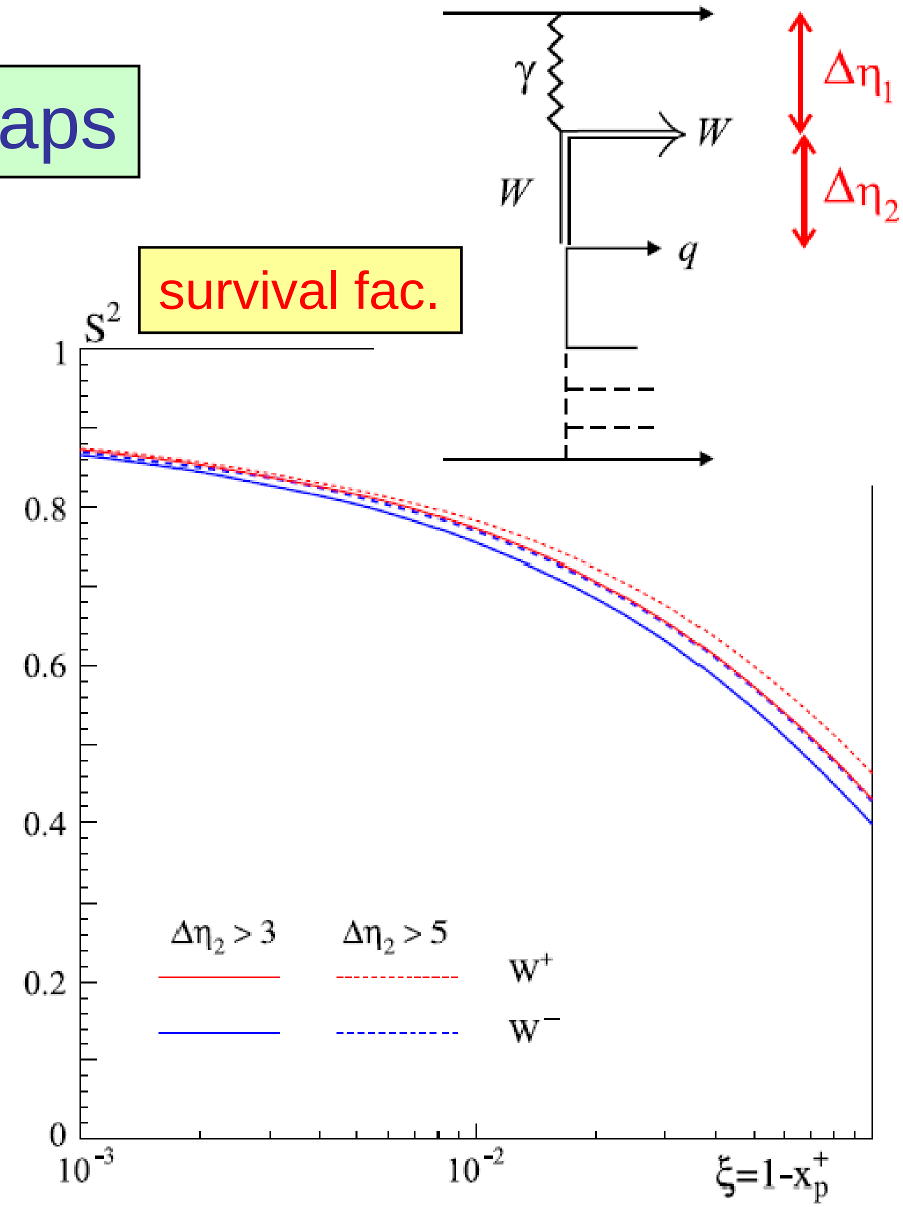
cross section



← 1 pb

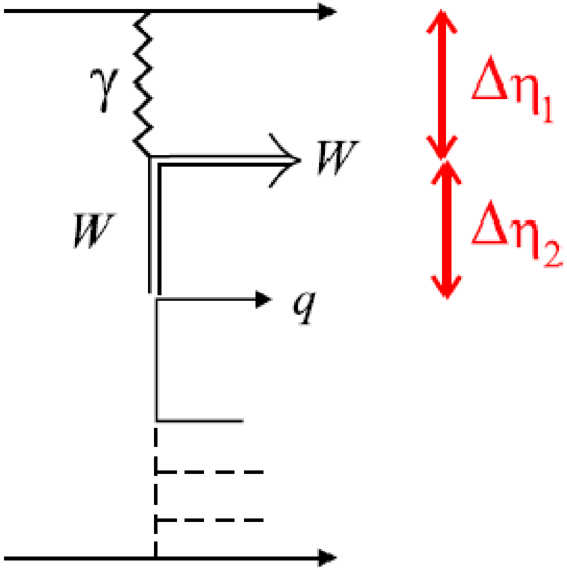
measure: $\frac{\text{W+gaps}}{\text{W inclusive}}$

survival fac.



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

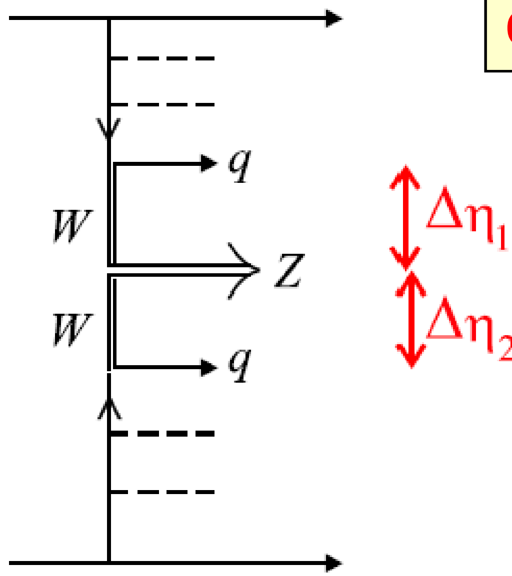
W+gaps has S^2 large, as large b_t for γ exch (small opacity)



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 $Z \to l^+l^-$

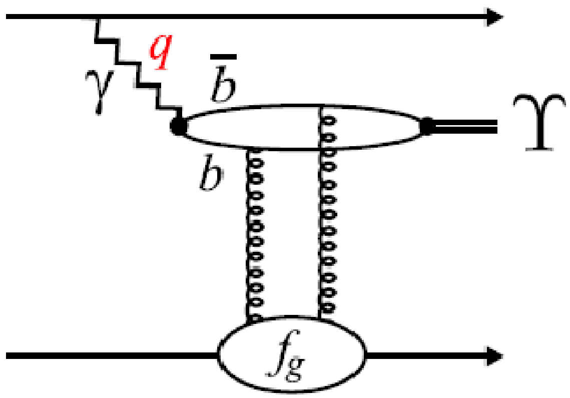
expect S^2~0.3



use track counting veto

Exclusive Υ production as probe of f_g

(a) γ exch

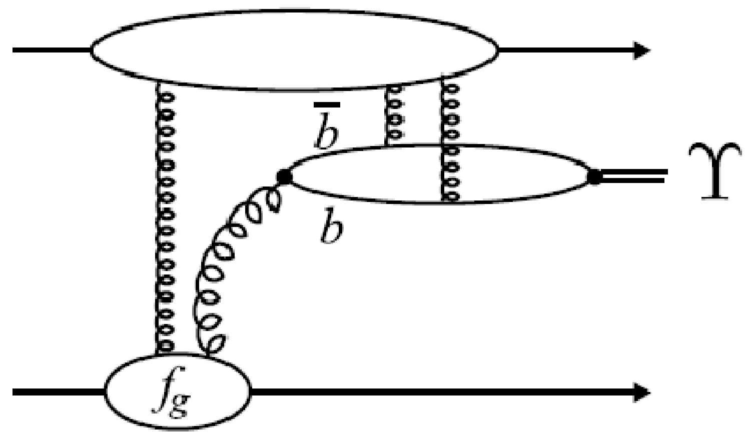


$$\left.\frac{d\sigma^{(a)}}{dy}\right|_{y=0} \simeq 50 \text{ pb}$$

x 0.025 (br for Υ→μμ)

Bzdak, Motyka,Szymanowski,Cudell

(b) odderon exch



comparable ?

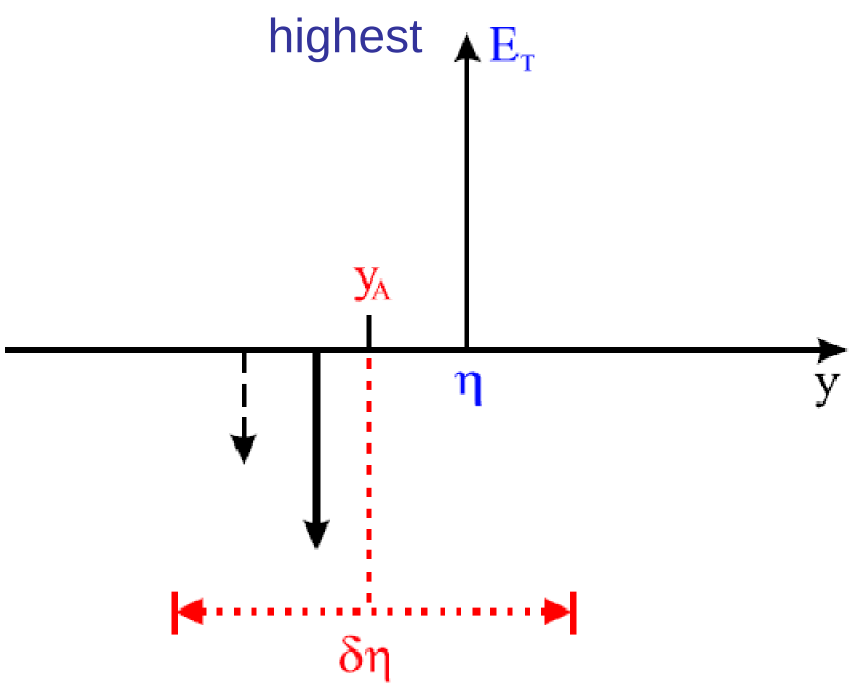
can separate by p_t if a tag of upper proton is done (odderon has larger p_t)

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

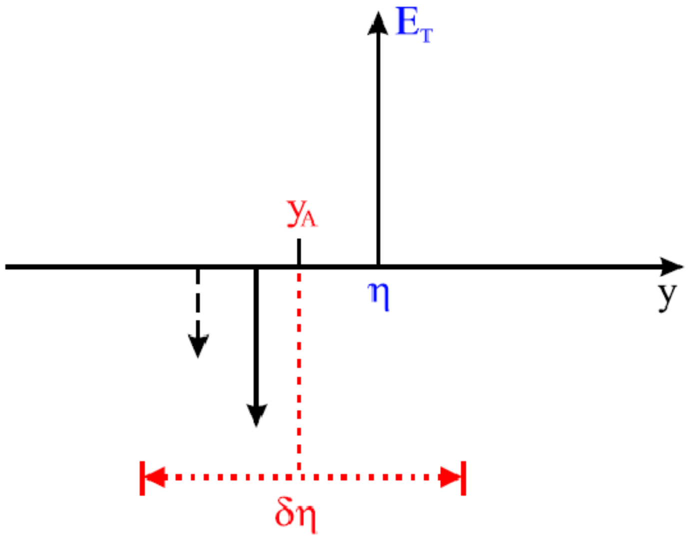


$$R_j = 2E_T(\cosh\eta^*)/M_A$$

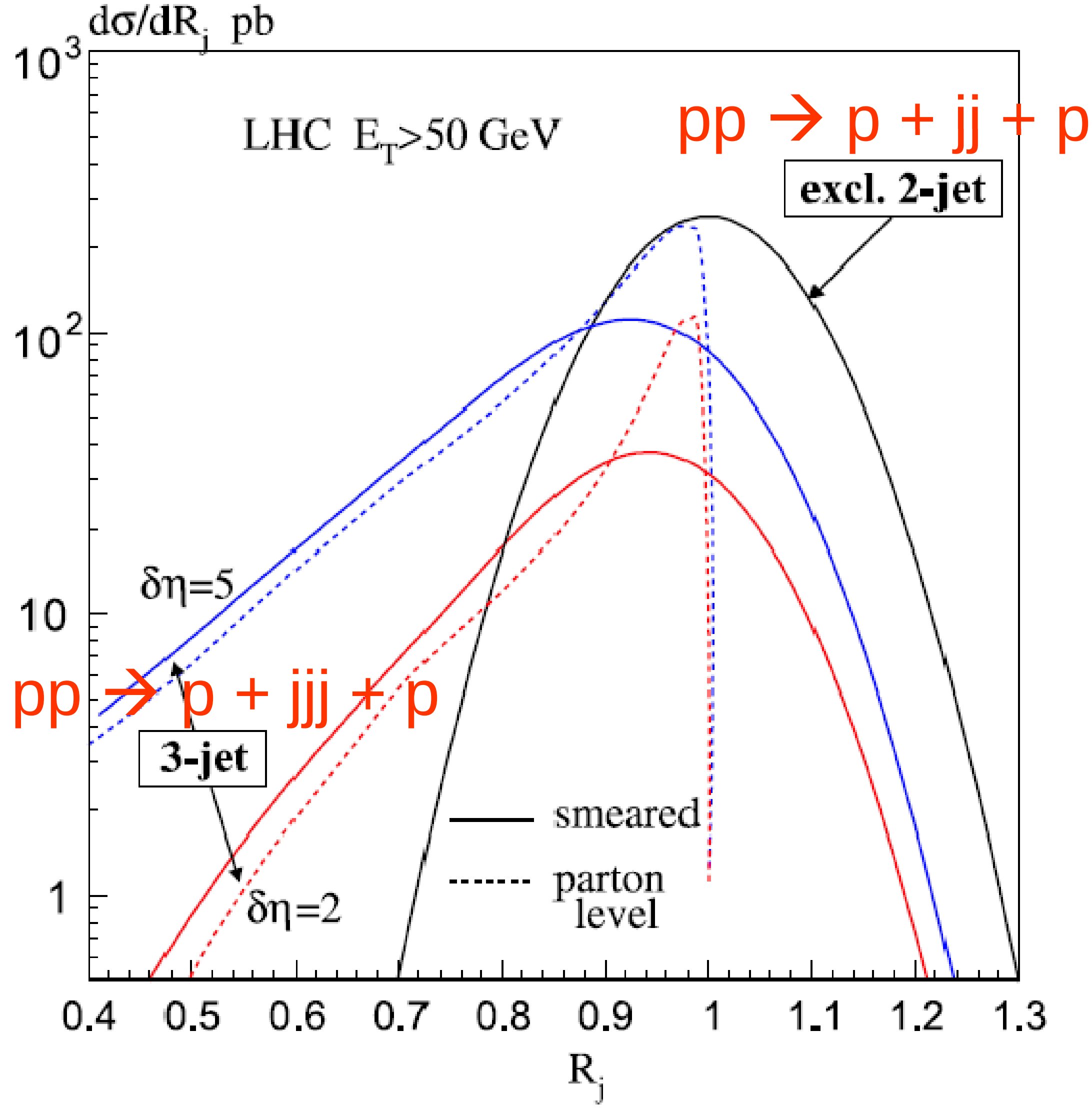
$$M_A = \sqrt{s\,\xi^+\xi^-}$$

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

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



study both $\delta\eta$ and E_T dependence of central 3-jet production

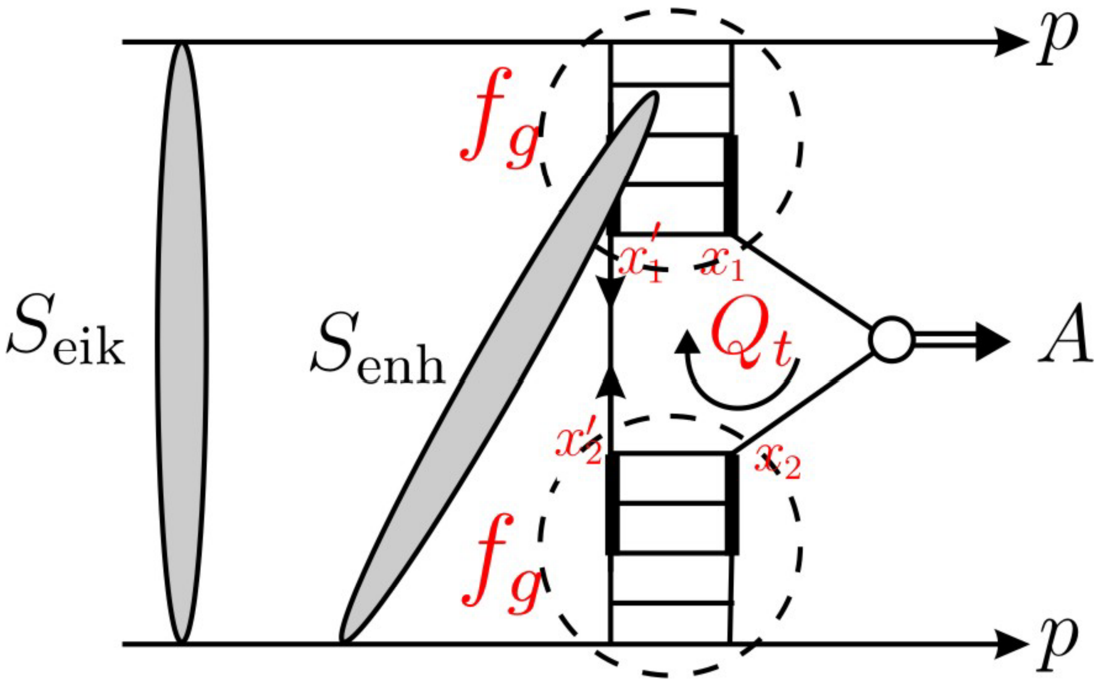


(negligible DPE background)

“Enhanced” absorptive effects

(break soft-hard factorization)

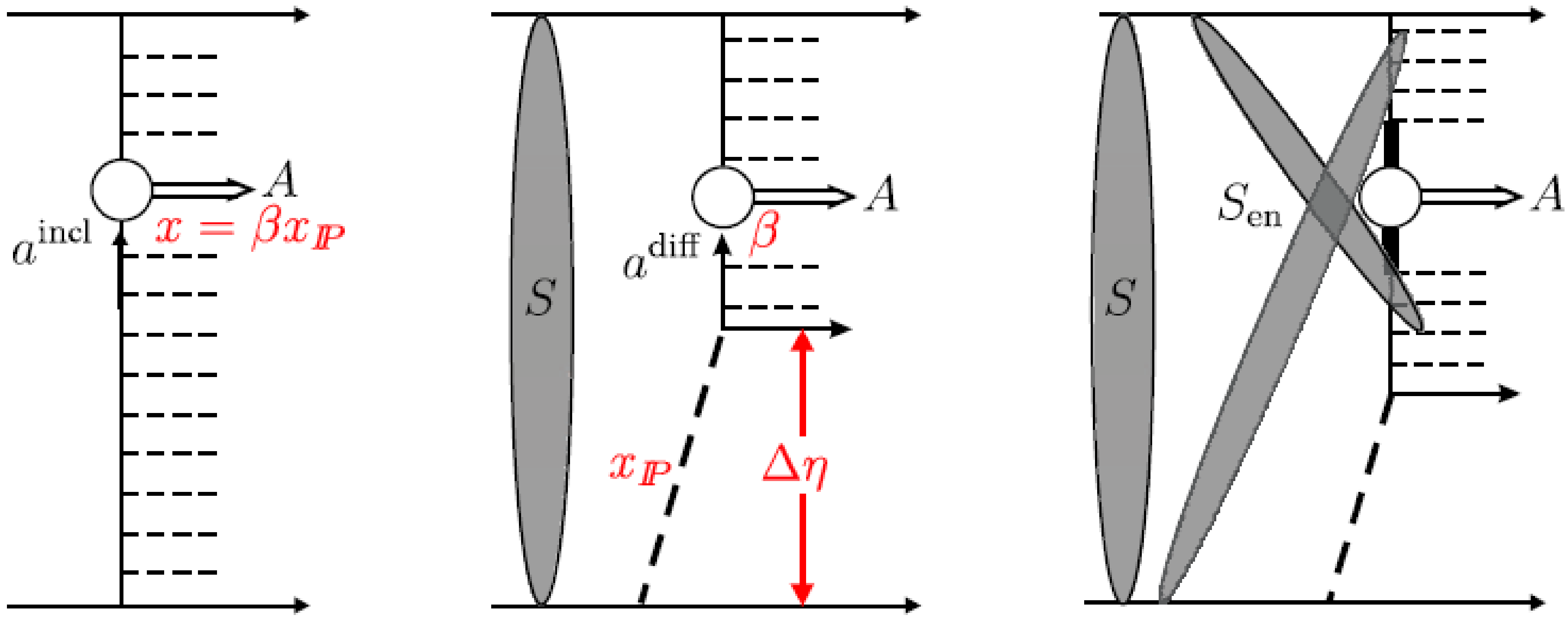
rescattering on an intermediate parton:



can LHC probe this effect ?

inclusive

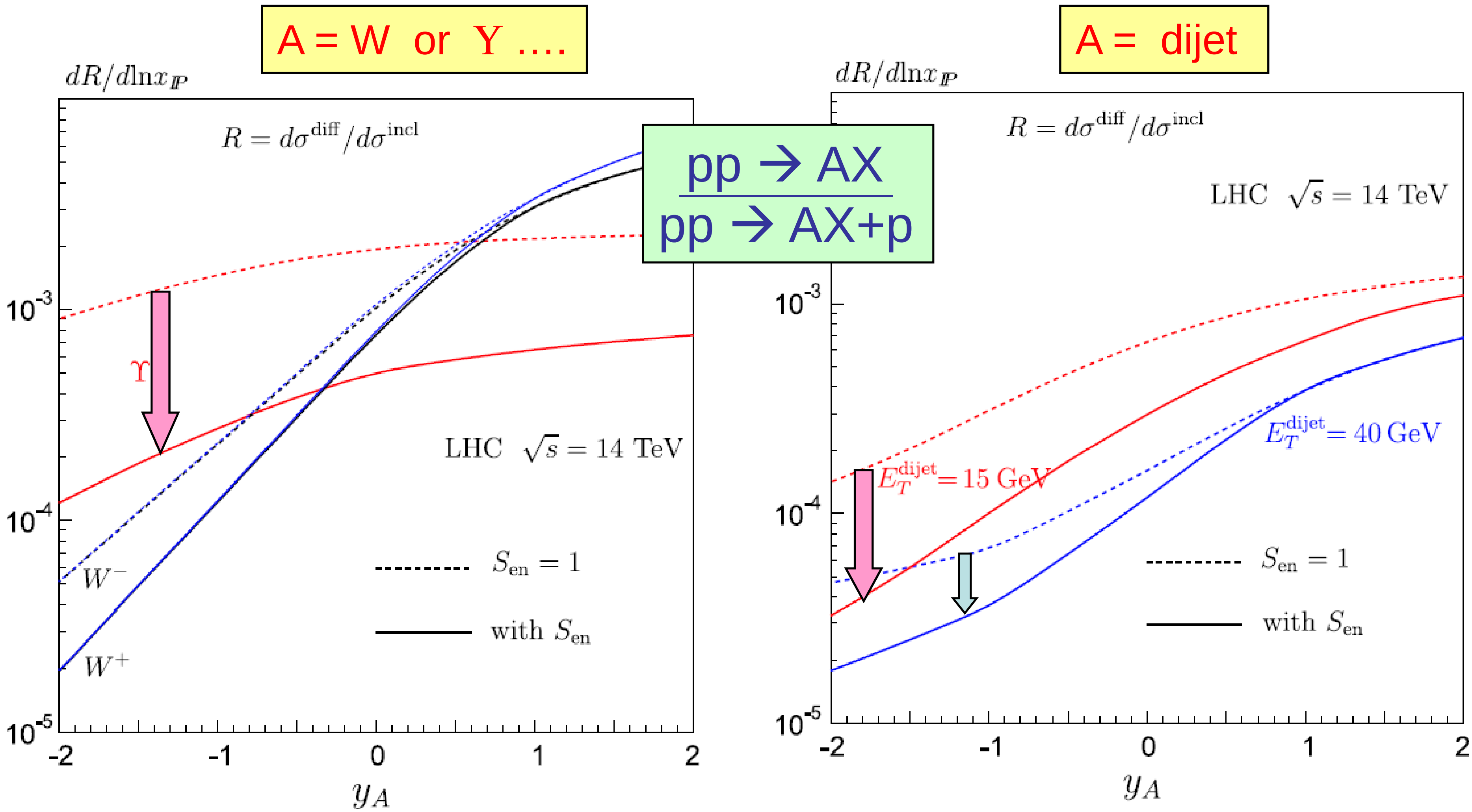
diffractive



A = W or dijet or Y ….

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

known from HERA



rough estimates of enhanced absorption S^2_{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 ….. $\boldsymbol{\sigma_{total}}$ **~ 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 probe "soft" int^{ns} → i.e. probe multi-Pomeron struct.

via long-range rapidity correlations

or via properties of multi-gap events etc.

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