Multiple Interactions, Saturation, and Final States in *pp* Collisions and DIS

LUND UNIVERSITY

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Epiphany 2009, Krakow 5-7 Jan.
Dedicated to the memory of Jan Kwieciński

Work done with
Emil Avsar, Christoffer Flensburg, and Leif Lönnblad

Outline

Introduction

Minimum bias and Underlying event

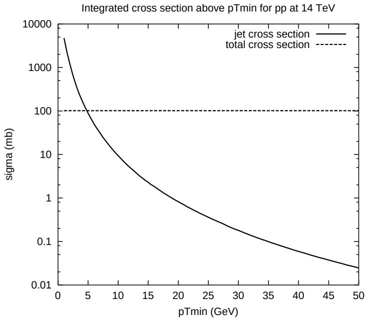
Eikonal formalism and Dipole cascades

Introduction

- Minijet cross section $>> \sigma_{tot}$ in high energy *pp* collisions
  $\Rightarrow$ Multiple subcollisions important feature
- Formulation in transverse coordinate space and eikonal approximation suitable for saturation and mult. coll.
- Successfully applied to $\gamma^\star p$ collisions: total and diffr. scatt.
- Final states: Best model PYTHIA. Extensive tunes to CDF data (R. Field)
- Problems:
  - How to hadronize? Fit to data needs color reconnections.
  - Correlations and fluctuations difficult in momentum space cascades
- New approach based on Mueller's dipole cascade

Minimum bias and Underlying event

Inclusive parton scattering cross section diverges like $\mathrm{d}\hat{\sigma}/\mathrm{d}p_{\perp}^{2} \approx 1/p_{\perp}^{4}$ for $p_{\perp} \to 0$.

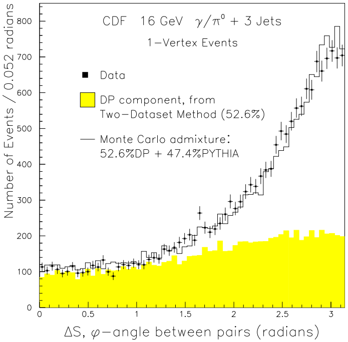


Integrated cross section

Average *pp* collisions has several hard subcollisions

Direct observation:

Four-jet events with pairwise back-to-back jets: AFS (ISR), UA2($Sp\bar{p}S$ collider), CDF(Tevatron)



CDF 3-jet + prompt photon analysis

Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

Early suggestion:

Increasing cross setion driven by minijets. Minimum bias events dominated by (semi)hard parton subcollisions.

Assumption behind the PYTHIA model
(T. Sjöstrand - M. van Zijl - P. Skands)

Cutoff needed for small $p_\perp$

Hadrons are color neutral $\Rightarrow$ Coulomb potential screened for large impact parameters or small $p_\perp$.

Fits to data $\Rightarrow$ cutoff $\approx$ 2 GeV.

(Similar cutoff obtained in $k_\perp$-factorization formalism.)

Typically 2 - 3 interactions/event at the Tevatron,
4 - 5 at the LHC

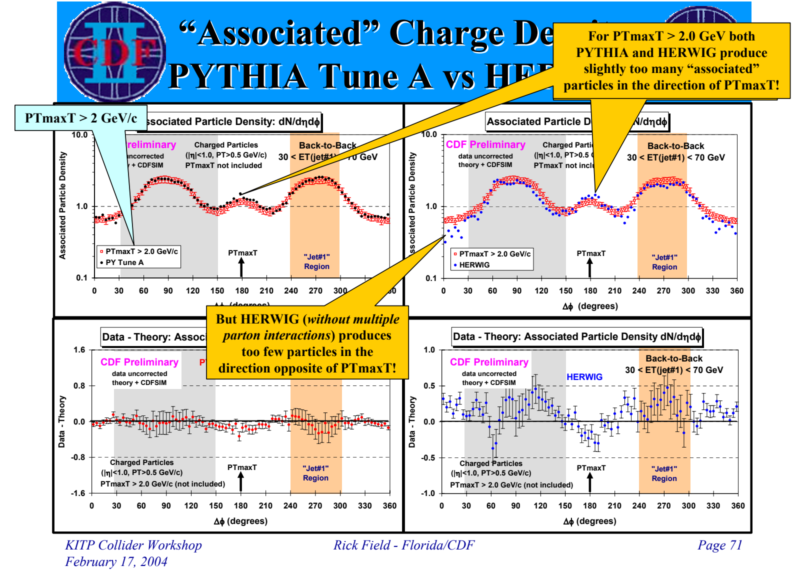
However: Subcollisions are correlated.

Central collsions have many interactions

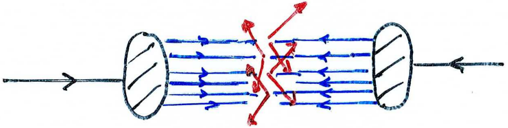
Peripheral collisions have few interactions

$$\sigma_{\text{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \quad \text{for } A \neq B \quad \Longrightarrow \sigma_{\text{eff}} \approx 14.5 \text{ mb}$$

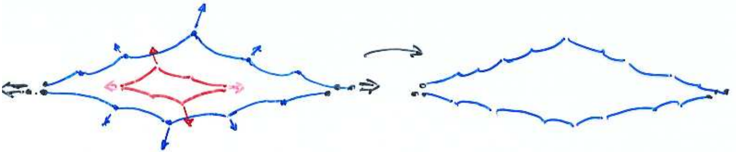
Strong enhancement


"Associated" Charge De
PYTHIA Tune A vs HE
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!
PTmaxT > 2 GeV/c
Associated Particle Density: dN/dηdφ
Charged Particles (|η|<1.0, PT>0.5 GeV/c) PTmaxT not included
Back-to-Back 30 < ET(jet#1) < 70 GeV
CDF Preliminary
data uncorrected
theory + CDFSIM
PTmaxT > 2.0 GeV/c
PY Tune A
HERWIG
PTmaxT
"Jet#1" Region
Associated Particle Density
Δφ (degrees)
But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of PTmaxT!
Data - Theory: Associated Particle Density dN/dηdφ
Data - Theory
Charged Particles (|η|<1.0, PT>0.5 GeV/c) PTmaxT > 2.0 GeV/c (not included)
KITP Collider Workshop
February 17, 2004
Rick Field - Florida/CDF
Page 71

Questions:



Hadronization of many-parton system. Fit needs maximum color reconnection



Correlations between impact parameter and momentum distributions expected, but not included

Eikonal formalism

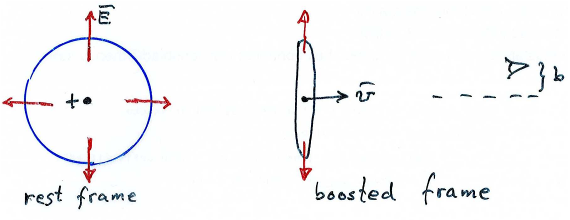
Transverse coordinate space suitable for rescattering and multple collisions

Convolution in $\mathbf{k}_\perp$-space $\rightarrow$ Product in **b**-space

$S(b) = S_1(b)S_2(b)S_3(b)$

$S_i = e^{-\eta_i(b)} \quad \Rightarrow \quad S = e^{-\sum \eta_i}$

Weizsäcker-Williams: Method of virtual quanta



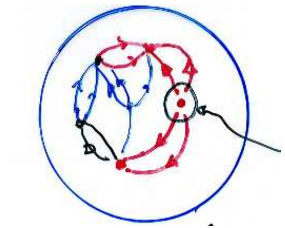
$\mathbf{E}_\perp \sim g\frac{\mathbf{r}}{r^2}$

short pulse

$$I(t) \sim E_\perp B_\perp \sim g^2 \frac{1}{r^2}\delta(t)$$

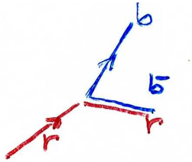
$$I(\omega) \propto g^2 \frac{d^2r}{r^2} \cdot 1$$

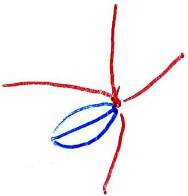
$$dn \sim g^2 \frac{d^2r}{r^2}\frac{d\omega}{\omega} \sim g^2 \frac{d^2q_\perp}{q_\perp^2}\frac{d\omega}{\omega}$$



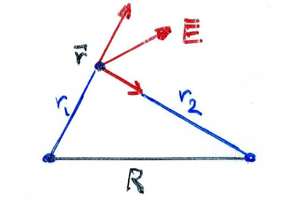
Coulomb field for $r < 0.1\,\mathrm{fm} \Rightarrow k_\perp > 2\,\mathrm{GeV}$

Gluon emission $\Rightarrow$ dipole field





Mueller Dipole model

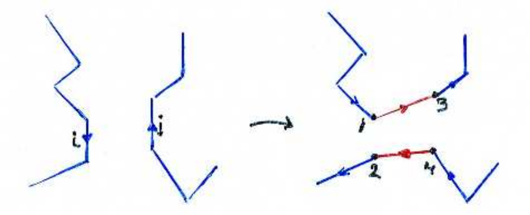


$$\mathrm{E}^2 \sim g^2 \frac{R^2}{r_1^2 r_2^2}; \qquad \frac{d\mathcal{P}}{dy} = \bar{\alpha} \frac{d^2 r}{2\pi} \frac{R^2}{r_1^2 \, r_2^2}$$

Cascade:

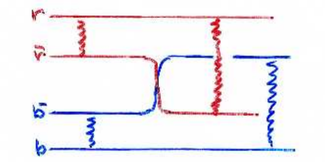
Reproduces LL BFKL evolution

Dipole-dipole scattering



$$f_{ij} = \frac{\alpha_s^2}{2} \ln^2 \left(\frac{r_{13} r_{24}}{r_{14} r_{23}} \right),$$

Single gluon exhange ⇒ Color reconnection



Eikonal approximation → Unitarity

Total, diffractive and elastic cross sections:

$$\sigma_{tot} \sim d^2b < 2(1 - e^{-\sum f_{ij}}) >$$
$$\sigma_{diff} \sim d^2b < (1 - e^{-\sum f_{ij}})^2 > \quad \text{(incl. elastic)}$$
$$\sigma_{el} \sim d^2b(< 1 - e^{-\sum f_{ij}} >)^2$$

The result is sensitive to fluctuations

Problems

1. LL BFKL not good enough
2. Non-linear effects
3. Massless gluon exchange violates the Froissart bound
4. Fluctuations and correlations. BK eq. $\sim$ mean field theory
5. Exclusive final states
6. Analytic calculations applicable at extreme energies

Monte Carlo

Salam: Dipole splitting diverges for small r.

Cross section finite but numerical difficulties

New approach:

- Include NLL BFKL effects
- Include Nonlinear effects in evolution
- Remove virtual emissions $\rightarrow$ Final states

NLL effects

3 major contributions:

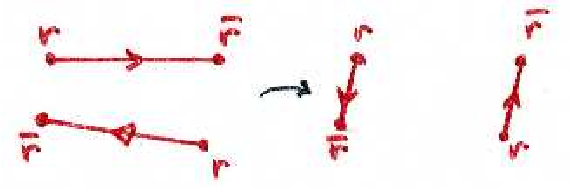
- *Running coupling*
- *Non-singular terms in splitting function (suppresses large z-values)*
  Mostly included by energy conservation and the constraint that a daughter must not be faster than her recoiling parent
- *Projectile-target symmetry (Energy-scale terms)*
  Fixed by p_--conservation (equivalent to consistency constraint)

Includes effects beyond NLL: λ_{eff} is not negative for large α_s

Non-linear effects, Saturation

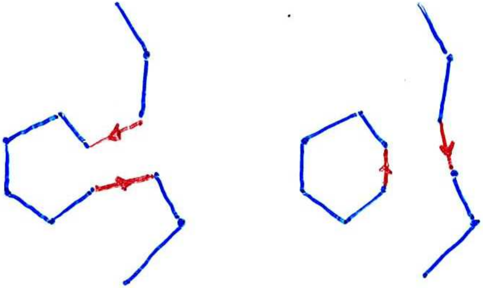
Color suppressed relative to dipole splitting. Two dipoles with same color:

Quadrupole. Better approximated by smaller dipoles



Dipole swing

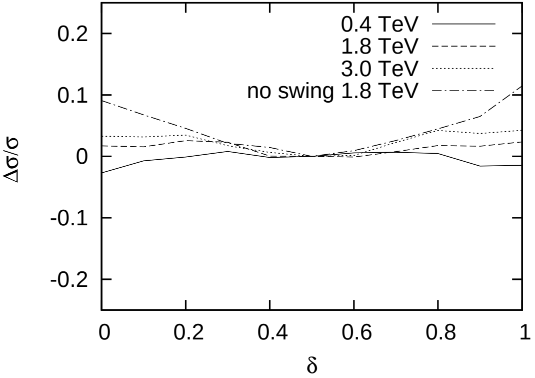
The swing ⇒ Recoupling of the dipole chain



Dipole loop ∼ Pomeron loop

Similar recouling effect from gluon exchange

Almost frame independent result



Note: Number of dipoles not reduced. Saturation effect because smaller dipoles have smaller cross section.

Confinement

Effective gluon mass $\Rightarrow \frac{1}{k_\perp^2} \;\to\; \frac{1}{k_\perp^2+m^2}$

Dipole splitting: $\mathbf{E} \sim \frac{\mathbf{r}}{r^2} \to \frac{\mathbf{r}}{r\, r_{max}} K_1(r/r_{max}), \qquad r_{max} = 1/m$

Dipole scattering: $\ln(1/r) \to K_0(r_{max}/r)$

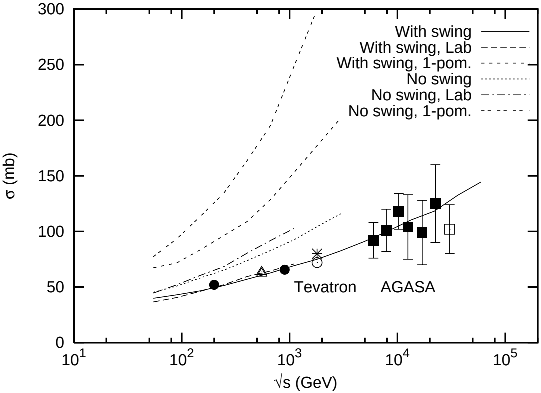
Reduced spread to wider dipole distribution

$\Rightarrow$ Froissart bound satisfied. (E. Avsar)

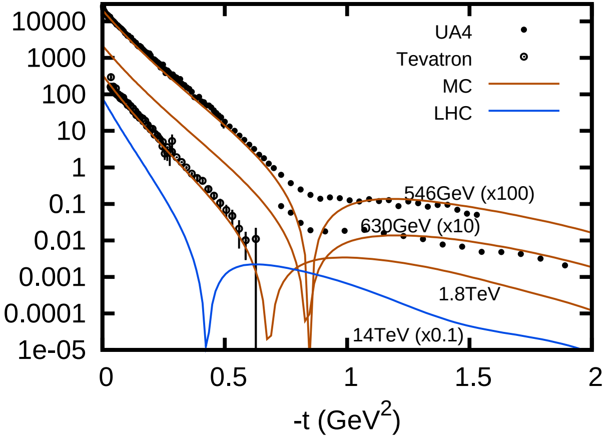
Applications

pp Scattering

Simple model for proton wave function: Triangle with 3 dipoles



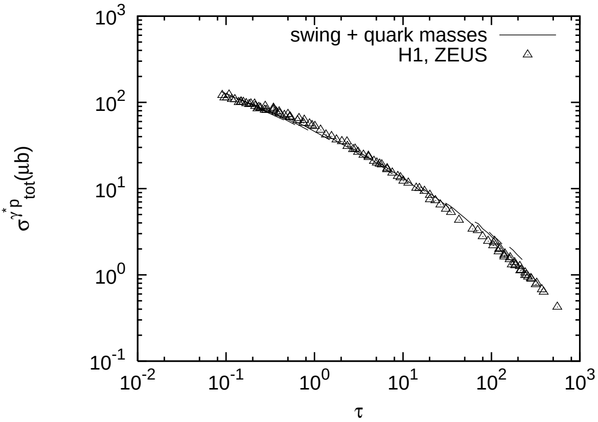
Elastic cross section $d\sigma/dt$



Energy variation of the dip fixed by the evolution

$\gamma^{\star}p$ scattering

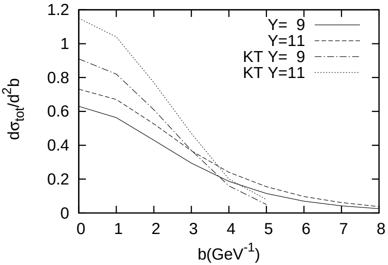
Geometric scaling



Diffraction

Sensitive to fluctuations and correlations

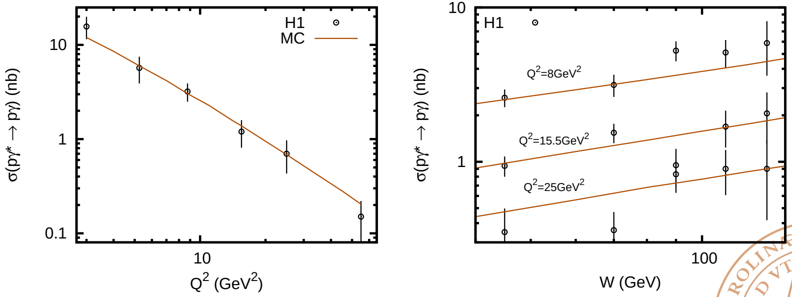
Fluctuations within the cascade ⇒ Less fluctuations needed in impact parameter profile. *pp* scattering more gray and less black/white.

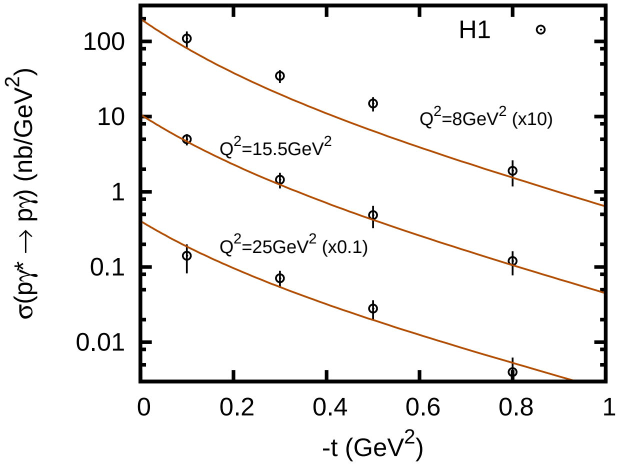


Diffractive excitation also reproduced.

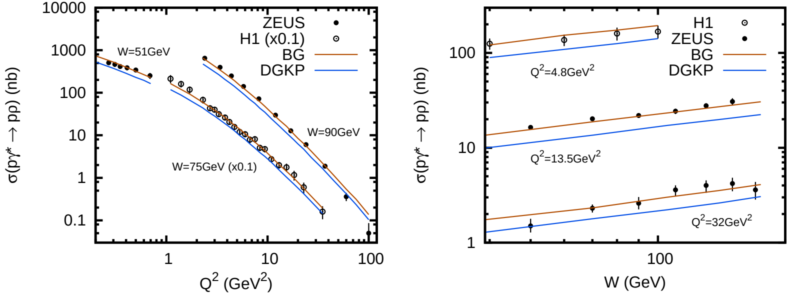
DVCS and $\gamma^\star p \to Vp$

Quasi-elastic $\gamma^\star p \to \gamma p$ scattering




H1
100
10
1
0.1
0.01
0
0.2
0.4
0.6
0.8
1
Q^2=8GeV^2 (x10)
Q^2=15.5GeV^2
Q^2=25GeV^2 (x0.1)
$\sigma(p\gamma^* \to p\gamma)$ (nb/GeV^2)
-t (GeV^2)

$\gamma^{\star} p \longrightarrow \rho p$

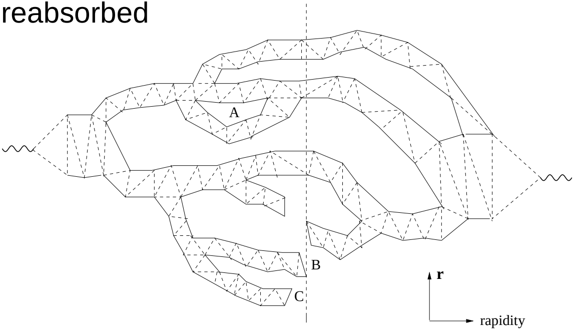


Also t-dependence look good. As well as ϕ-production.

(BG = Boosted Gaussian wave function,
DGKP = Dosch, Gousset, Kulzinger, Pirner)

Final States

Dipoles which do not interact have to be treated as virtual and reabsorbed



Total number of loops: Tevatron 3.5 (0.65+2.2+0.65), LHC 5

FSR has to be added

Work in progress

$p_\perp - n_{ch}$ correlation

Problem in present MCs. Fits to $p_\perp$-multiplicity correlation for hadrons need maximum color reconnection

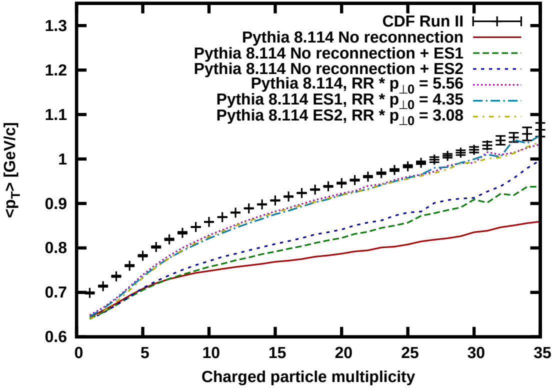
Dipole cascade adds contribution from $p_\perp$-multiplicity correlation for partons

Cascade with many dipoles $\Rightarrow < r >$ small

$\Rightarrow$ Stronger screening $\Rightarrow$ Smaller effective cutoff $p_{\perp 0}$

$\Rightarrow$ larger $< p_\perp >$ in events with many hadrons

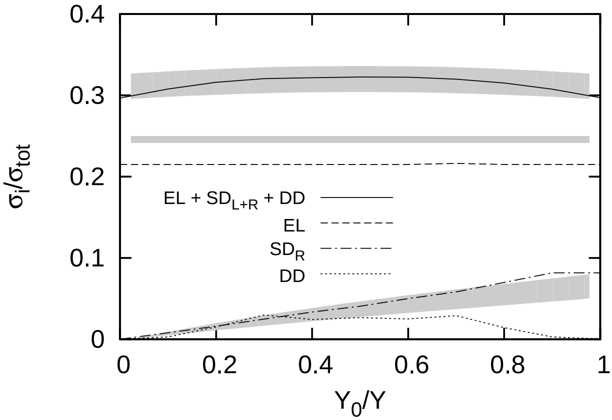
Toy model result (R. Corke)

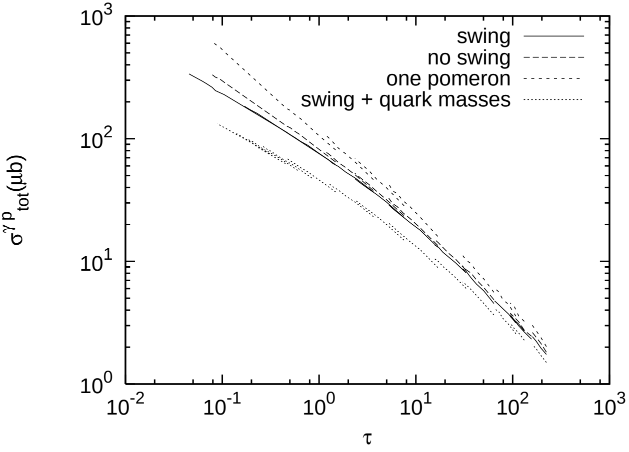


Summary

- Dipole formulation of high energy collisions in transverse coordinate space
- Main ingredients:
  - NLL contributions to BFKL
  - Non-linear effects: Saturation and multiple subcollisions
  - Confinement effects
  - Includes momentum-impact parameter correlations
  - Simple proton and photon model
  - MC implementation
- Fair description of data:
  - Total cross sections for *pp* and $\gamma^\star p$
  - (Quasi-) Elastic scattering in *pp* and $\gamma^\star p$
  - Diffractive excitation
- To come: Final states
- Wanted: Understanding the connection to *t*-channel picture of pomeron loops

Extras




swing
no swing
one pomeron
swing + quark masses
10^3
10^2
10^1
10^0
10^-2
10^-1
10^0
10^1
10^2
10^3
τ
σ^γ*p_tot(μb)

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