

Probing soft QCD with exclusive reactions

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XIV Hadron Physics 2018, Florianopolis

Soft QCD: theory topics

✓ **Low-x QCD phenomenology**

Measurements: hard (inclusive/exclusive) QCD cross sections in the forward region

Theory issues: Parton saturation, non-linear QCD evolution, small-x (u)PDFs, quarkonia production mechanisms, kt-factorisation, multi-parton scattering, factorisation-breaking effects, testing ground for UHE CRs interactions in the atmosphere ...

✓ **Hard/soft diffraction**

Measurements: Total pp cross section, hard diffraction cross sections (heavy-Q, di-jets, Drell-Yan, vector bosons, quarkonia) and exclusive photoproduction (with forward p/n tagging)

Theory issues: Pomeron structure, gap survival, long-range fluctuations, diffractive factorisation breaking, color-screening effects, initial-state interactions, intrinsic heavy flavor, hadronisation, nucleon tomography, quarkonia production mechanisms, UE structure ...

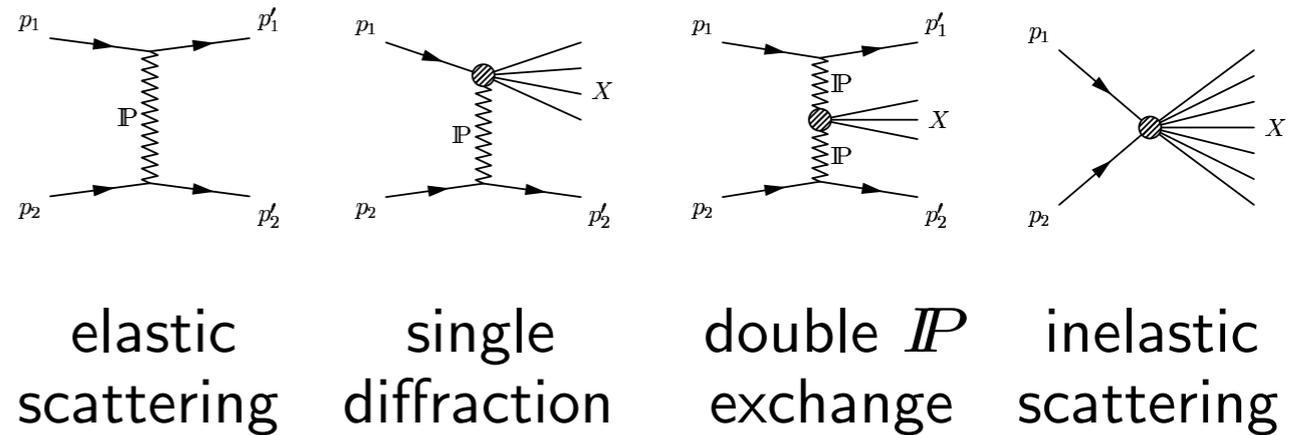
Diffraction: theory vs experiment

✓ **The definition of diffraction is not unique**

Theoretically:

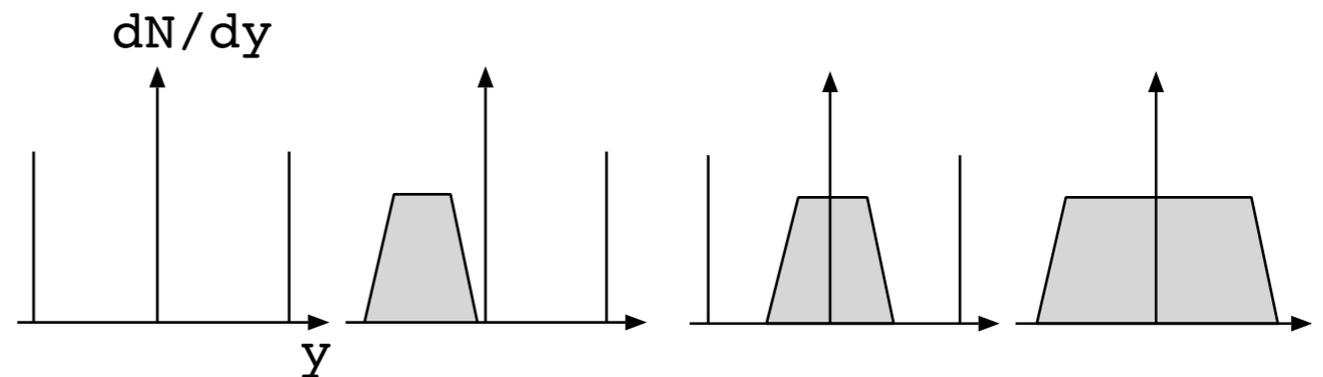
“The diffractive process is caused by **t-channel Pomeron exchange** i.e. by the exchange corresponding to the rightmost singularity in the complex angular momentum plane with vacuum quantum numbers..” A. Martin

peripheral phenomenon!



Experimentally:

- ★ *intact protons and/or rapidity gaps (no hadron activity)*
- ★ *gap definition*



$$\text{Rapidity } y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z} \approx -\ln \tan \frac{\theta}{2} = \eta \text{ pseudorapidity}$$

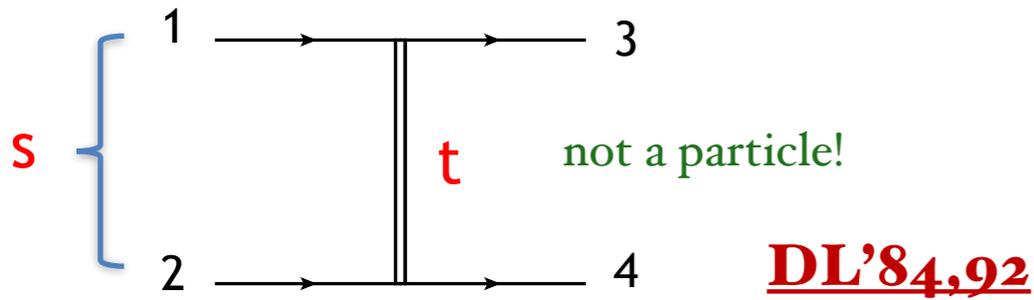
mapping is not one to one!

✓ **QCD modelling of diffraction is a major problem**

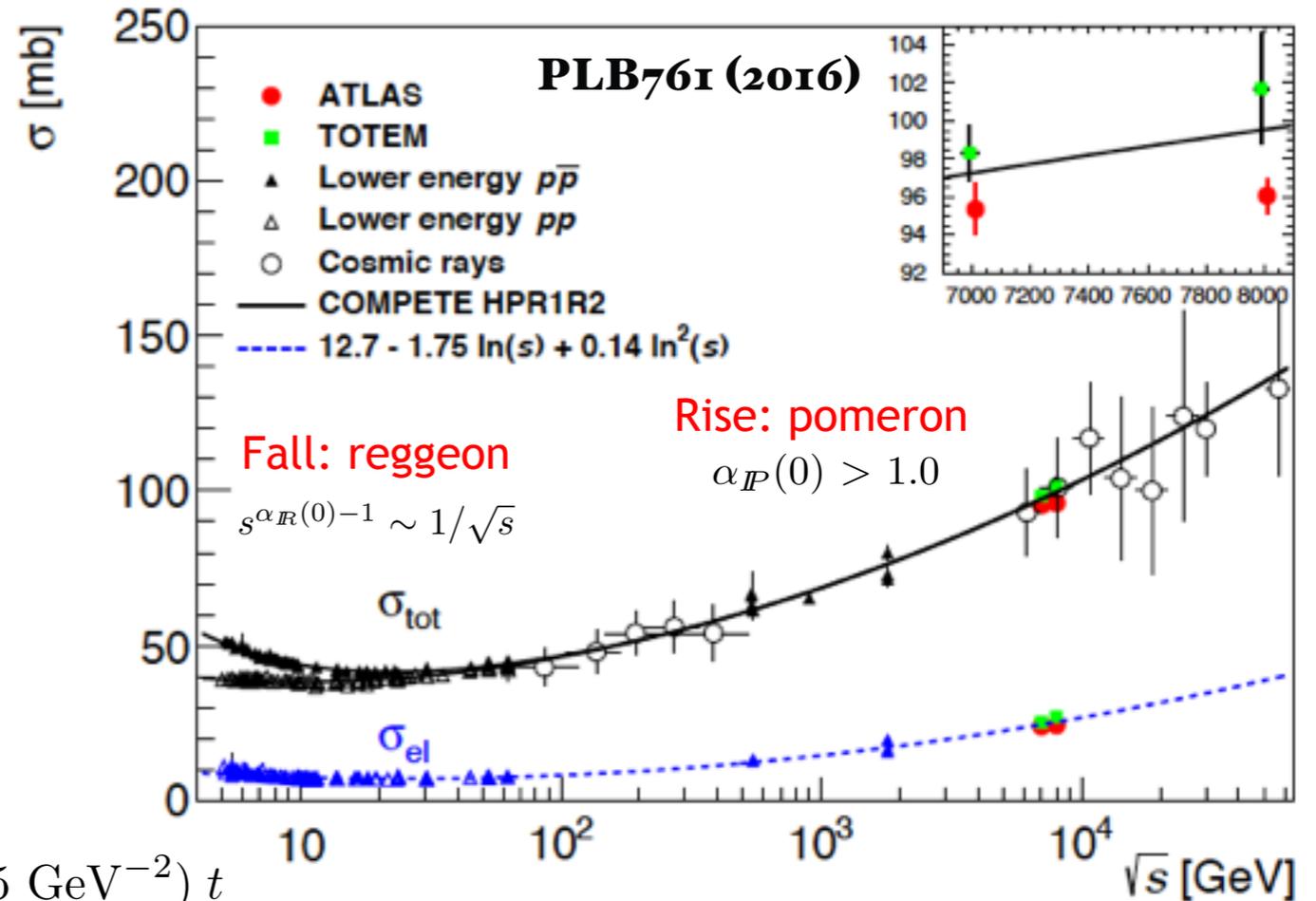
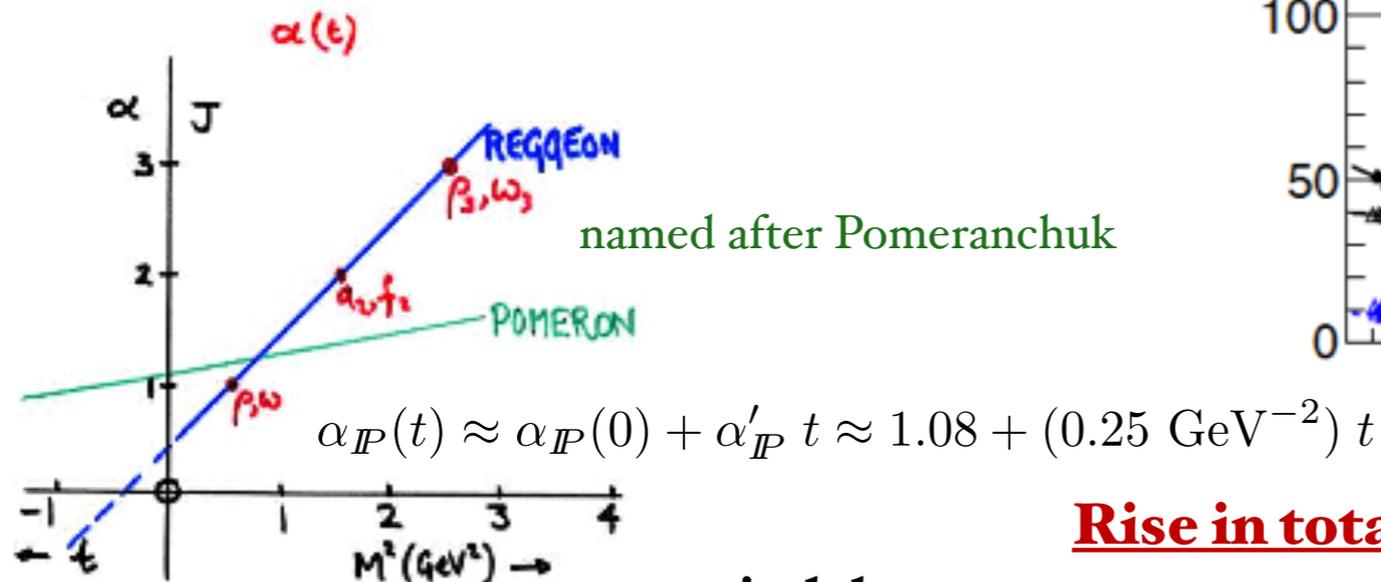
- ★ *fluctuations during the hadronisation process (protons from recombination? gap size?)*
- ★ *low vs high mass diffractive dissociation*
- ★ *soft vs hard Pomeron*
- ★ *hard-soft factorisation breaking, etc*

huge sensitivity to details!

Soft Pomeron



- interpreted in QCD as a >two gluon exchange
- not a simple pole but enigmatic non-local object

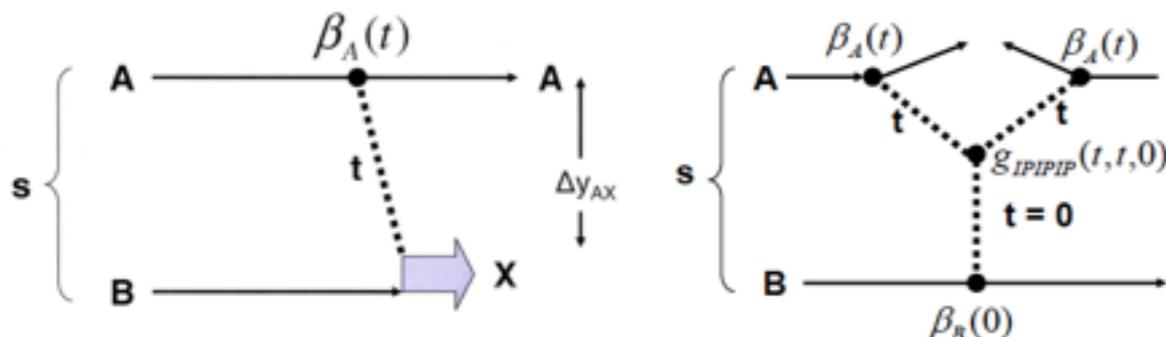


Rise in total and elastic CS: "discovery" of Pomeron!

optical theorem

$$\sigma_{\text{total}} = \sum_X \left| \text{Diagram} \right|^2 = \text{Im} \left[\text{Diagram} \right] = g_N^2 \left(\frac{s}{s_0} \right)^{\alpha_{IP}(0)-1}$$

Mueller triple-Regge formalism



Pomeron "flux"

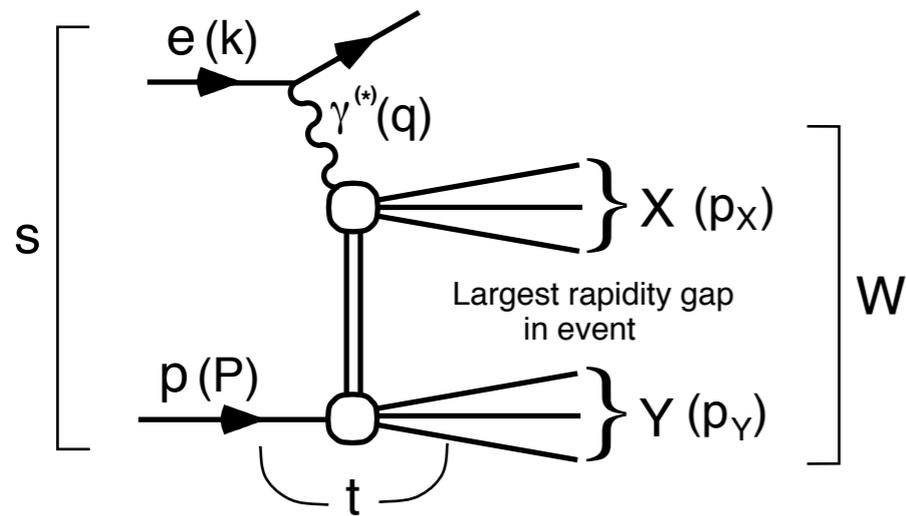
$$\frac{d\sigma}{dt d\xi} = f_{IP/A}(\xi, t) \sigma_{BP}(M_X^2, t) \quad M_X^2 = \xi s$$

$$\sigma_{BP}(M_X^2, t) \propto (M_X^2)^{\alpha_{IP}(0)-1} \quad \text{at large } M_X$$

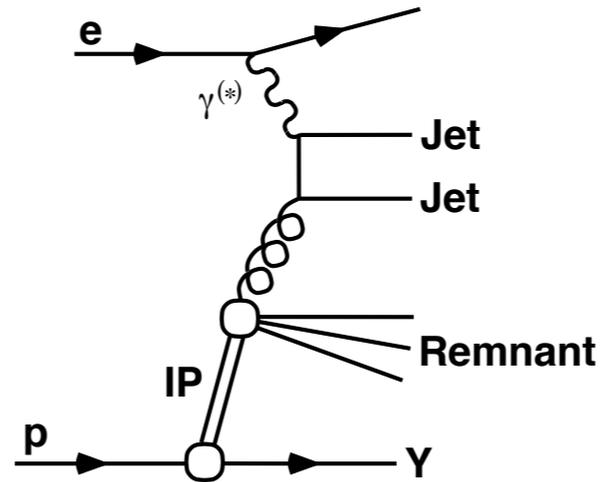
$$\sigma \sim g_{pP}^2(t) g_{pP}(0) g_{3P} \left(\frac{s}{M_X^2} \right)^{2(\alpha(t)-1)} (M_X^2)^{(\alpha(0)-1)}$$

Birth of hard diffraction: QCD modelling of Pomeron

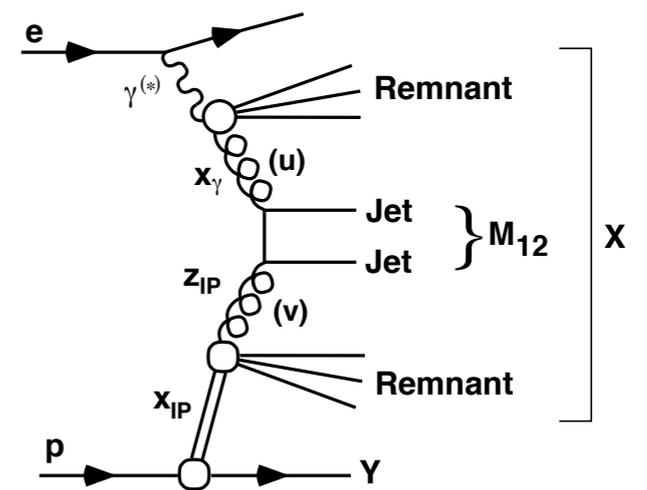
generic diffractive scattering at HERA



LO di-jet (photon-gluon)



LO di-jet (gluon-gluon)



Ingelman-Schlein, Phys. Lett. 1985

Introduce a hard scale to probe “parton skeleton” of the Pomeron!

Access to gluon content of the Pomeron!

factorisation
formula

$$d\sigma(ep \rightarrow e + 2 \text{ jets} + X' + Y) = \sum_{i,j} \int dy f_{\gamma/e}(y) \int dx_\gamma f_{j/\gamma}(x_\gamma, \mu_F^2) \times \\ \times \int dt \int dx_{IP} \int dz_{IP} d\hat{\sigma}(ij \rightarrow 2 \text{ jets}) f_i^D(z_{IP}, \mu_F^2, x_{IP}, t)$$

- ✓ Diffractive PDFs are non-universal
- ✓ They can not be exported to describe other hard diffractive processes (e.g. in pp)
- ✓ We need to calculate the survival probability of the LRG's which is process-dependent

Regge factorisation scheme

One considers **two different factorisations**:

- diffractive fact.n: proven by Collins for a hard diffractive scattering (hep-ph/9709499)
- Regge fact.n: relates the power of $x_{\mathbb{P}}$ in diffractive DIS to the power of S in hadron-hadron elastic scattering and can be broken

DPDF

$$f_i^D(z_{\mathbb{P}}, \mu_F^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}}(x_{\mathbb{P}}, t) f_{i,\mathbb{P}}(z_{\mathbb{P}}, \mu_F^2)$$

Pomeron PDFs

soft and hard scales are separated!

Berera, Soper PRD'96

universal (soft) Pomeron flux in the proton (Regge theory)

DGLAP-evolved parton density in the Pomeron

At larger x subleading "Reggeon" is to be included

fit to inclusive diffraction data by H1 (2006) and ZEUS (2009)

$$x_{\mathbb{P}} > 0.01$$

$$\dots + f_{IR}(x_{\mathbb{P}}, t) f_i^{IR}(z, Q^2)$$

Reggeon PDFs taken from pion (GRV)

Fit z and Q^2 dependence at fixed $x_{\mathbb{P}}$ and t

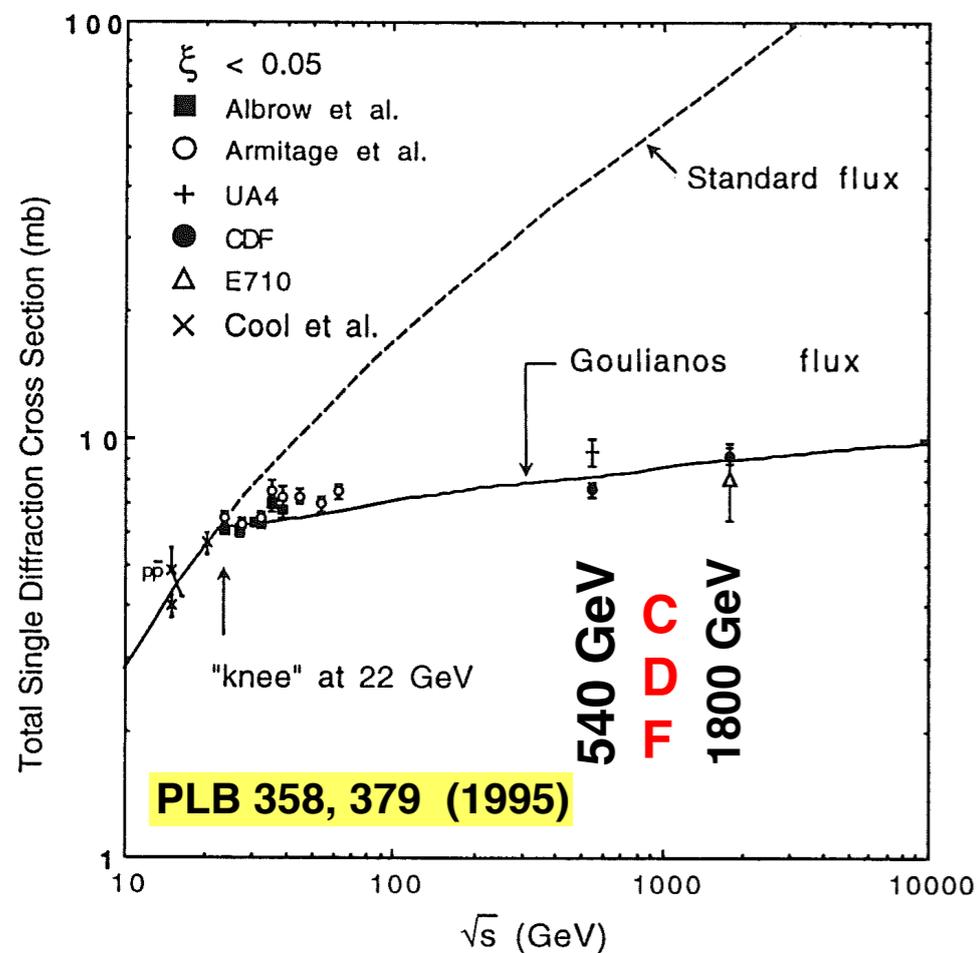
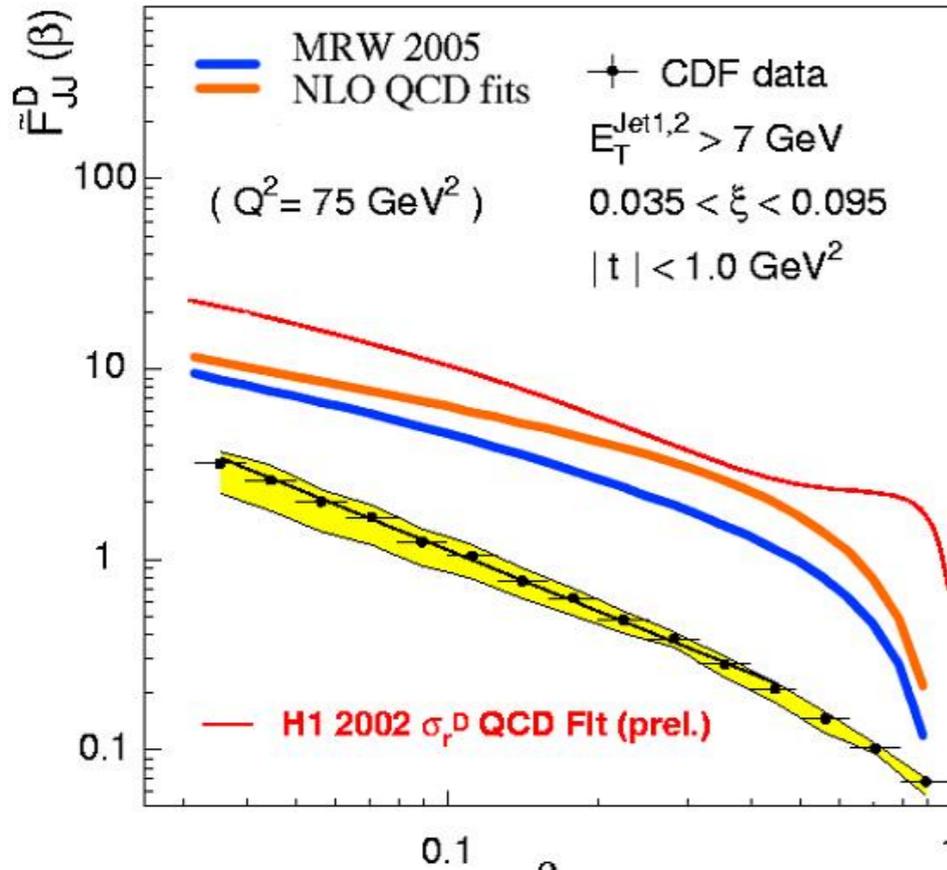
Flux parametrisation

$$f(x_{\mathbb{P}}, t) = \frac{Ae^{Bt}}{x_{\mathbb{P}}^{2\alpha(t)-1}}$$

with $\alpha(t) = \alpha(0) + \alpha't$

- ✓ DPDFs are extracted from global NLO fits of inclusive diffraction data at HERA
- ✓ Predictions based upon extracted DPDFs are fairly consistent with theoretical models
- ✓ Important tool for diffractive factorisation breaking studies (especially in had-had coll.)

Single diffractive pp cross section at high energies



Tevatron

HERA

$$\frac{\sigma(\text{hard diffraction})}{\sigma(\text{hard})} \sim 1\% \ll 10\% \sim \frac{\sigma(\text{diffractive DIS})}{\sigma(\text{DIS})}$$

Non-universality!

$$q_{IP}(x, Q^2) \text{ and } g_{IP}(x, Q^2) \text{ fitted to DIS } F_2^D$$

factor 10 too large diffractive cross section at Tevatron!

interpret flux as gap formation probability that saturates when it reaches unity

factorisation is broken by gap survival effects!

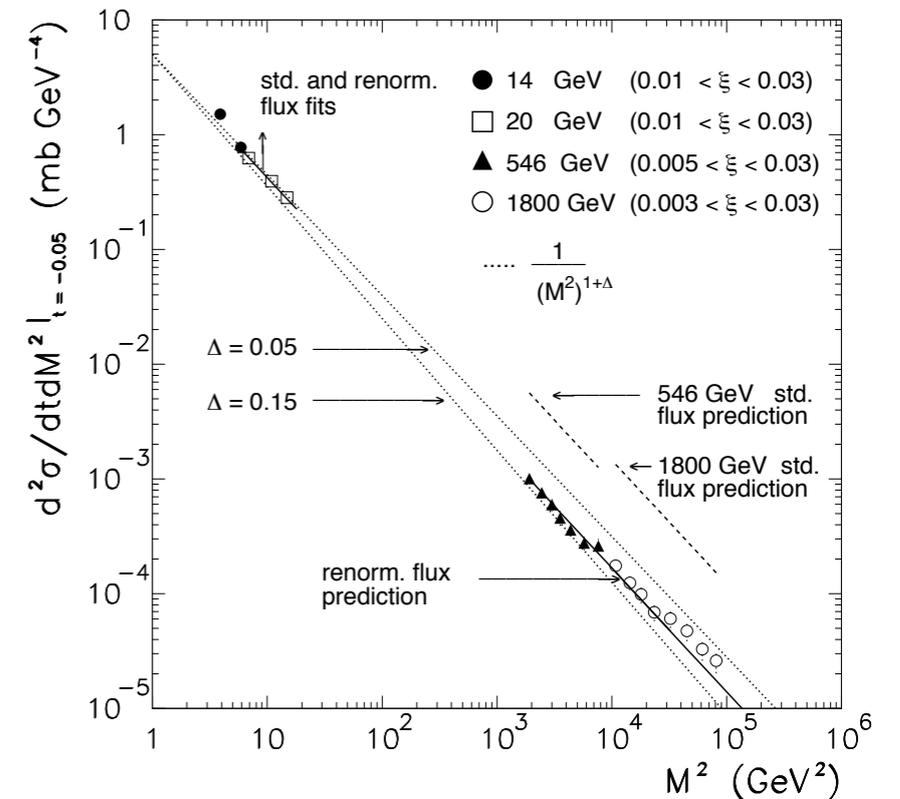
Factor of ~8 (~5) suppression at $\sqrt{s} = 1800$ (540) GeV

Pythia 8-MBR implementation

Rockefeller Model (by K Coulianos)

$$f_{IP/p}(\xi, t) \Rightarrow N_s^{-1} \cdot f_{IP/p}(\xi, t)$$

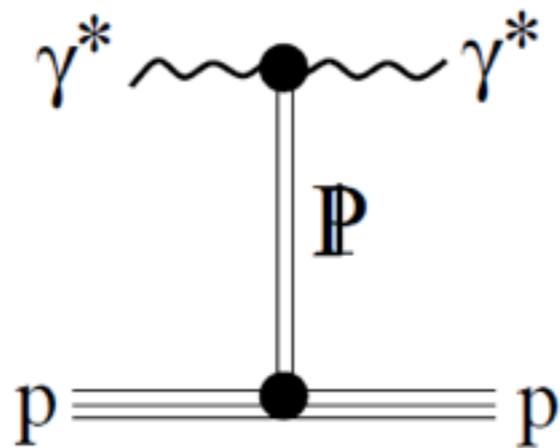
$$N_s \equiv \int_{\xi(\min)}^{\xi(\max)} d\xi \int_{t=0}^{-\infty} dt f_{IP/p}(\xi, t) \sim s^{2\epsilon}$$



Soft vs hard Pomeron

Soft diffraction

only soft scales $R \sim 1$ fm
 elastic scattering, low mass diffraction etc

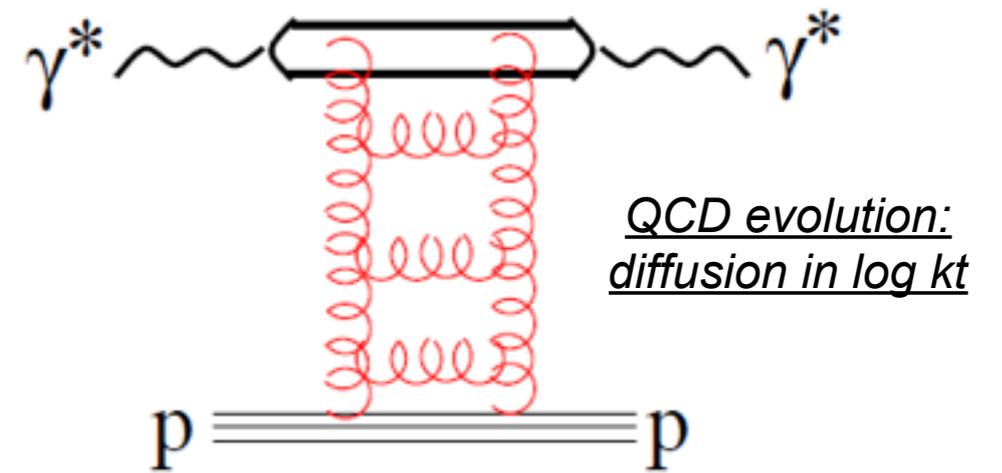


Continuous matching
is necessary!



Hard diffraction

at least, one hard scale $\mu^{-1} \ll R$



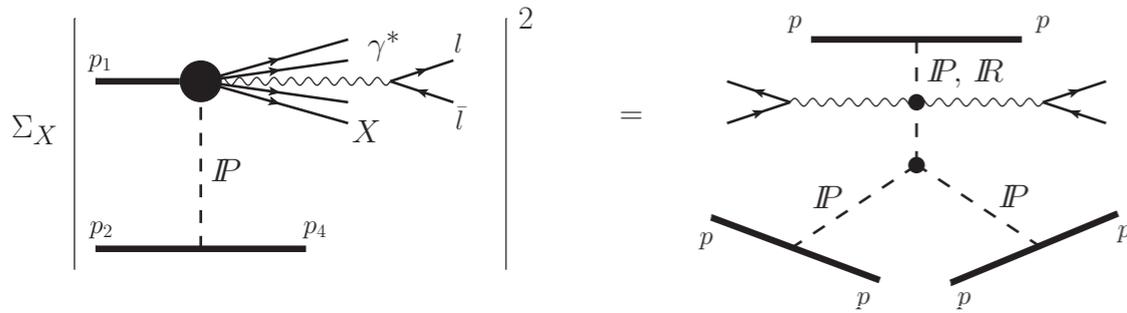
**Regge Field Theory with
 phenomenological DL Pomeron**

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

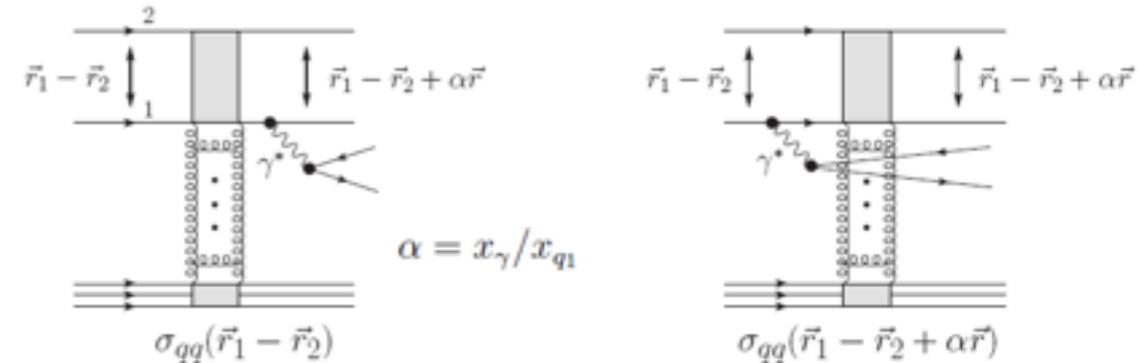
**perturbative QCD
 (BFKL) "bare" Pomeron**

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

Beyond factorisation: hadronic diffraction via dipoles



Diffractive Drell Yan (semi-hard)



Incoming hadrons are **not elementary** – experience soft interactions dissolving them leaving **much fewer rapidity gap events** than in ep scattering

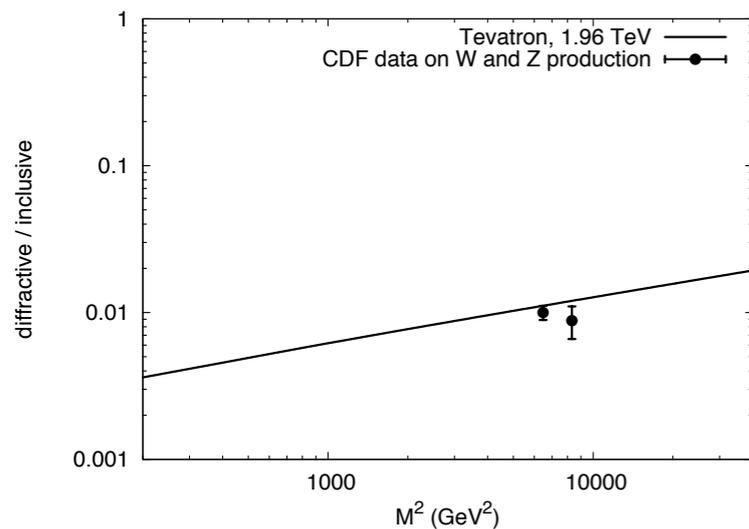
superposition has a **Good-Walker structure**

$$\propto \sigma(\vec{R}) - \sigma(\vec{R} - \alpha\vec{r}) = \frac{2\alpha\sigma_0}{R_0^2(x_2)} e^{-R^2/R_0^2(x_2)} (\vec{r} \cdot \vec{R}) + O(r^2)$$

interplay between hard and soft fluctuations is pronounced!

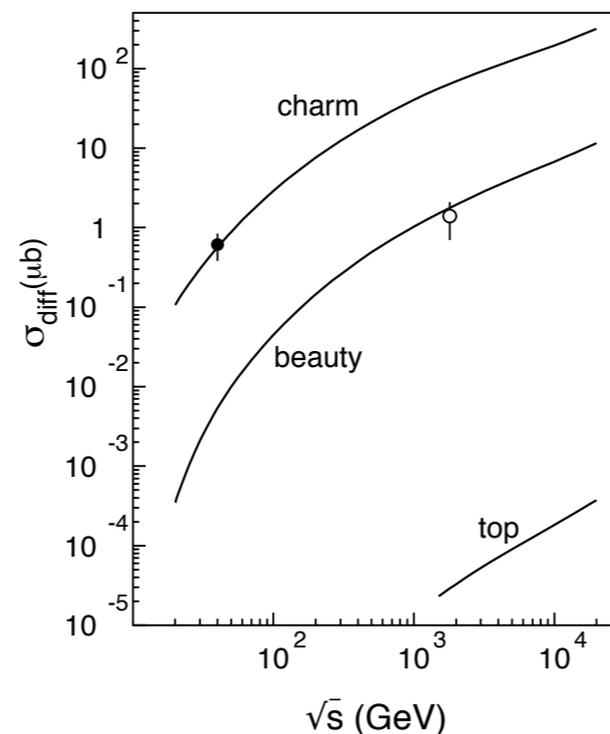
Diffractive DIS $\propto r^4 \propto 1/M^4$ vs **diffractive DY** $\propto r^2 \propto 1/M^2$

SD DY/gauge bosons



RP et al 2011,12

SD heavy quarks



Kopeliovich et al 2006

- ★ *diffractive factorisation is automatically broken*
- ★ *any SD reaction is a superposition of dipole amplitudes*
- ★ *gap survival is automatically included at the amplitude level on the same footing as dip. CS*
- ★ *works for a variety of data in terms of universal dip. CS*

Sophisticated dipole cascades are being put into MC: **Lund Dipole Chain model (DIPSY)**
Ref. G. Gustafson, and L. Lönnblad

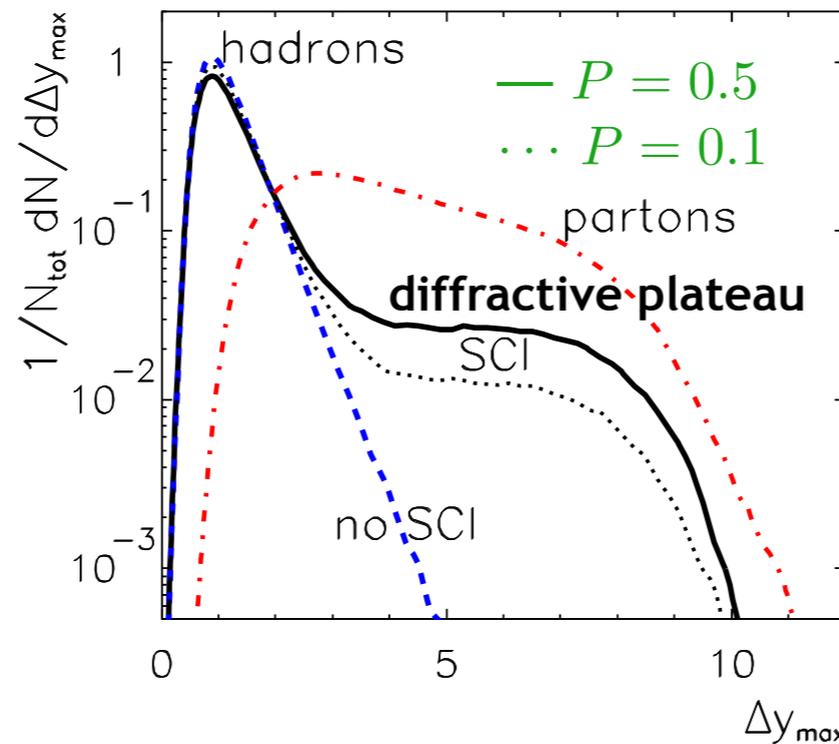
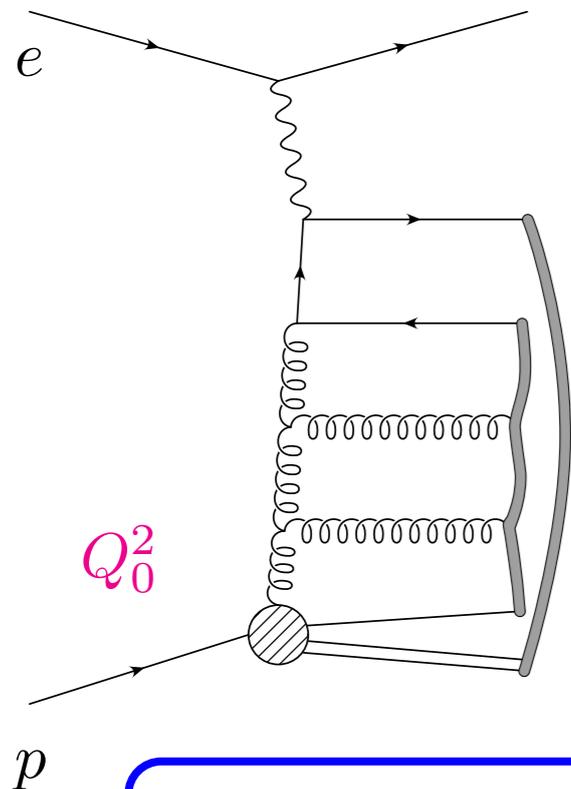
Sensitivity to the color string topology fluctuations

Edin, Ingelman, Rathsman

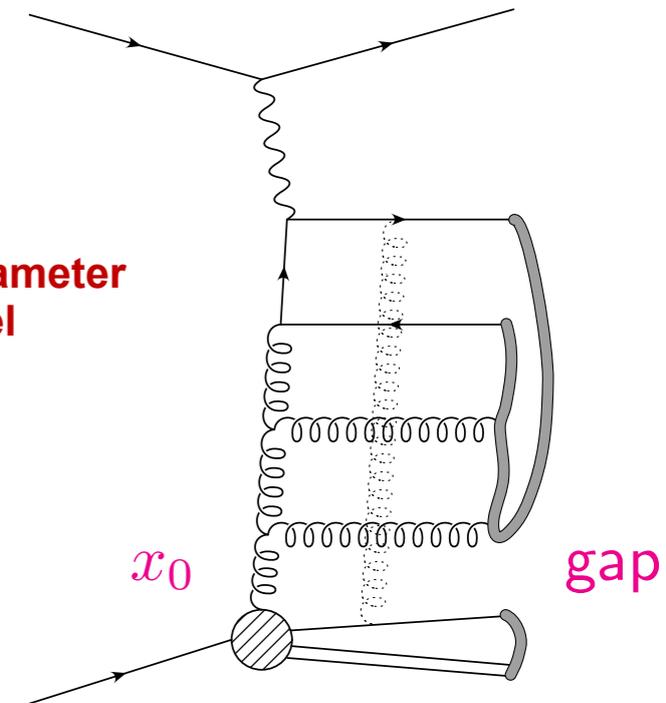
ME + DGLAP PS $> Q_0^2$
colour ordered parton state

SCI model
rearranged colour order

String hadronisation $\sim \Lambda$
modified final state

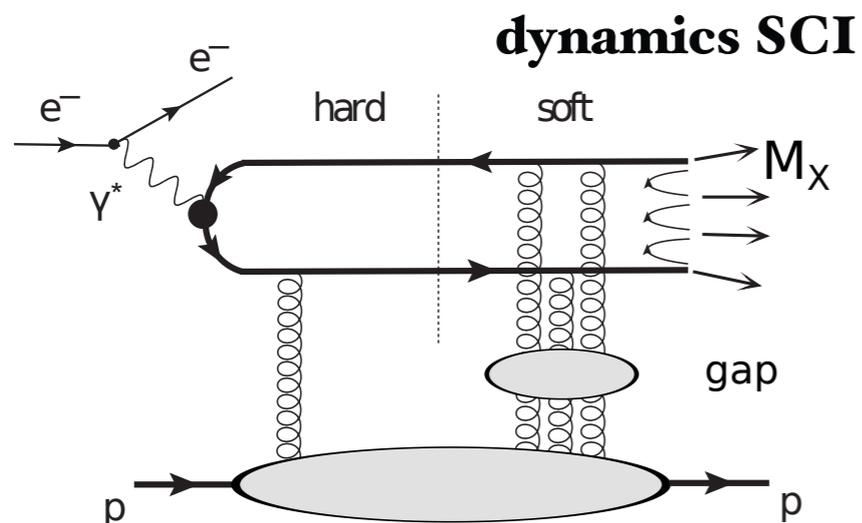


single parameter model



diffractive events from fluctuations in color string topology!

Single model describing all final states: diffractive \leftrightarrow nondiffractive
Gap events not 'special', but fluctuation in colour/hadronisation



Soft gluons can only change phase of propagating quark and it's color – should be resumed!

$$M(\delta) = \int d^2b \exp^{-i\delta b} \hat{M}^{\text{hard}}(b) \hat{M}^{\text{soft}}(b)$$

$$\hat{M}^{\text{soft}}(\mathbf{b}, \mathbf{r}) \propto \left(1 - e^{A \ln \frac{|\mathbf{b}-\mathbf{r}|}{|\mathbf{b}|}}\right)$$

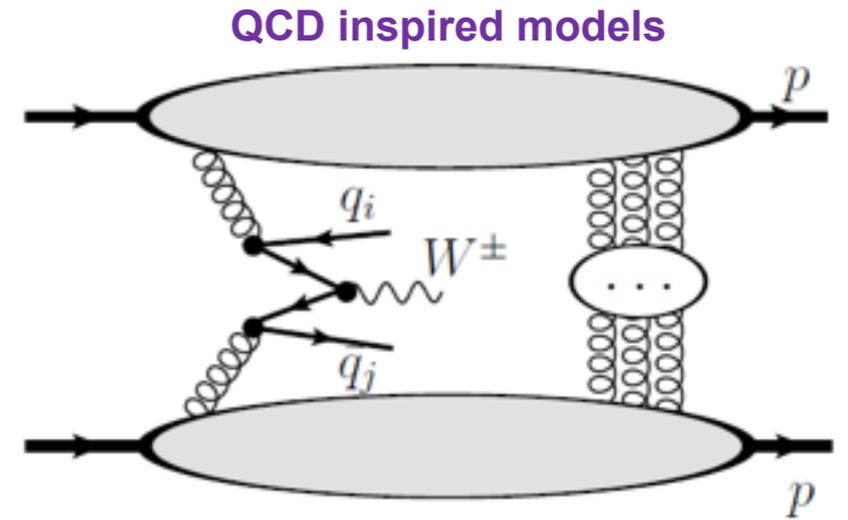
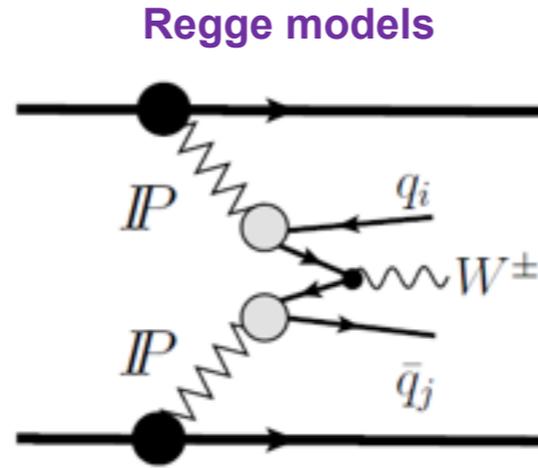
reconnection probability becomes dynamical

RP, Ingelman, Enberg

Diffractive W production in high-energy pp collisions

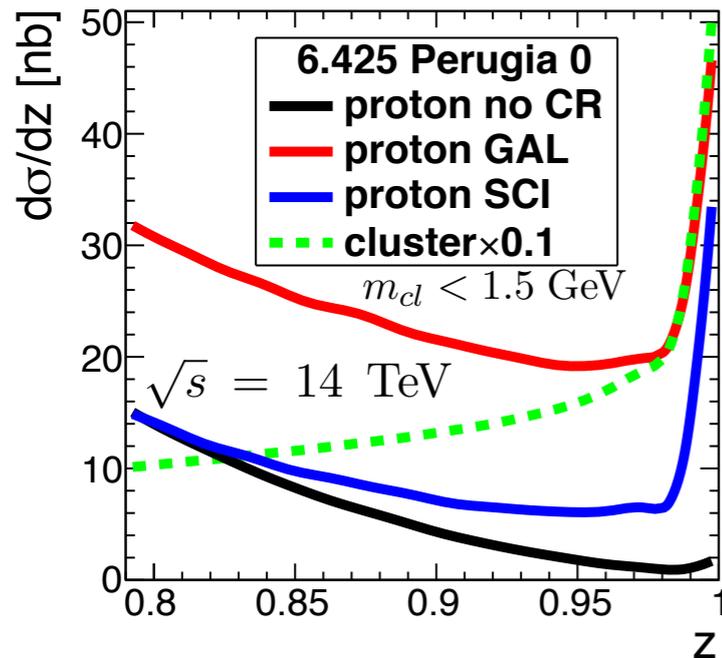
Features:

- ✓ clean environment (**color singlet**)
- ✓ well-defined hard scale (**tests of QCD factorisation**)
- ✓ high sensitivity to the **production mechanism**
- ✓ **large enough cross section** to be experimentally observed and tested



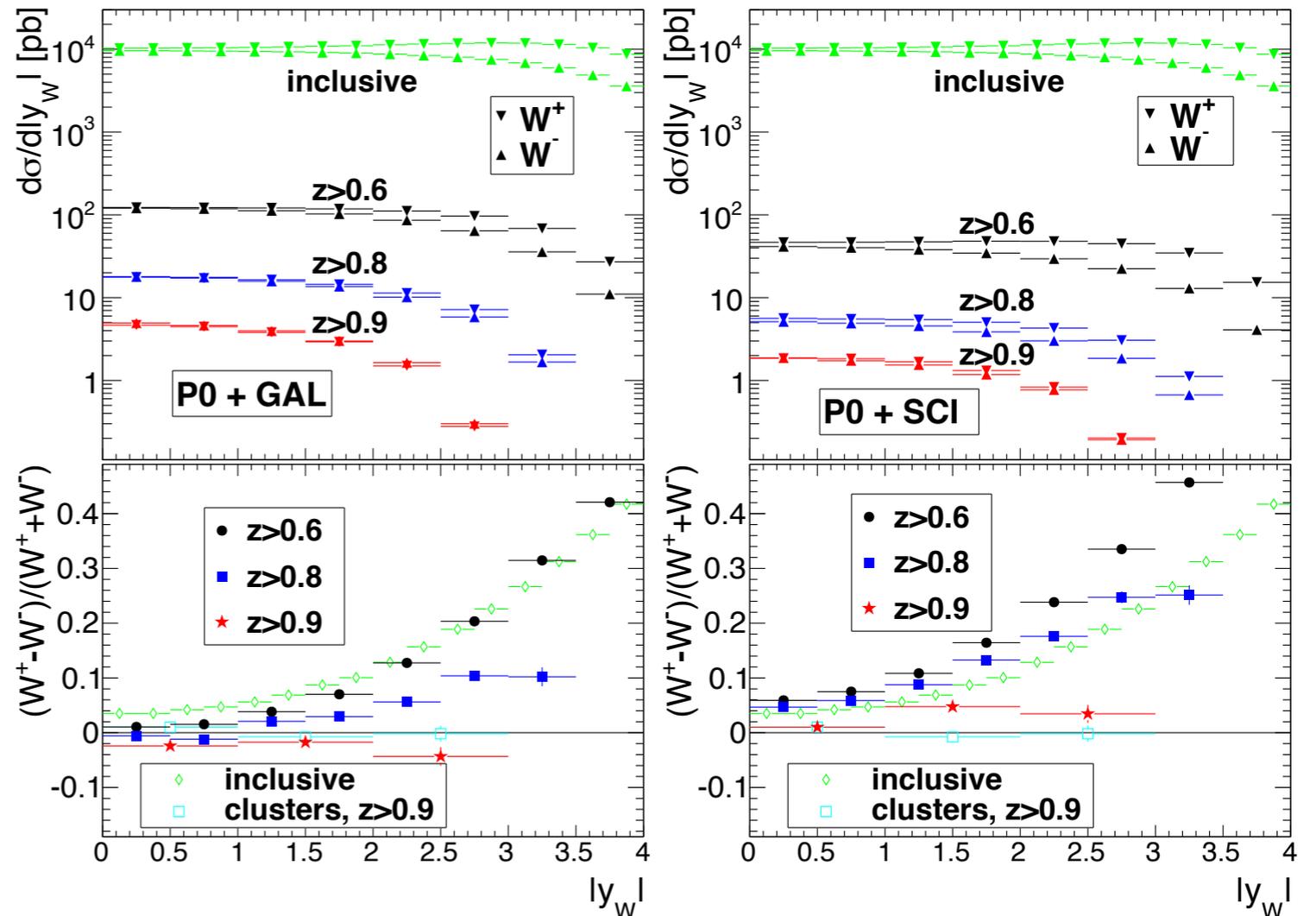
$$z = |p_z|/p_{\text{beam}} \quad pp \rightarrow p[W^\pm X]$$

Ingelman, RP, Rathsman, Werder



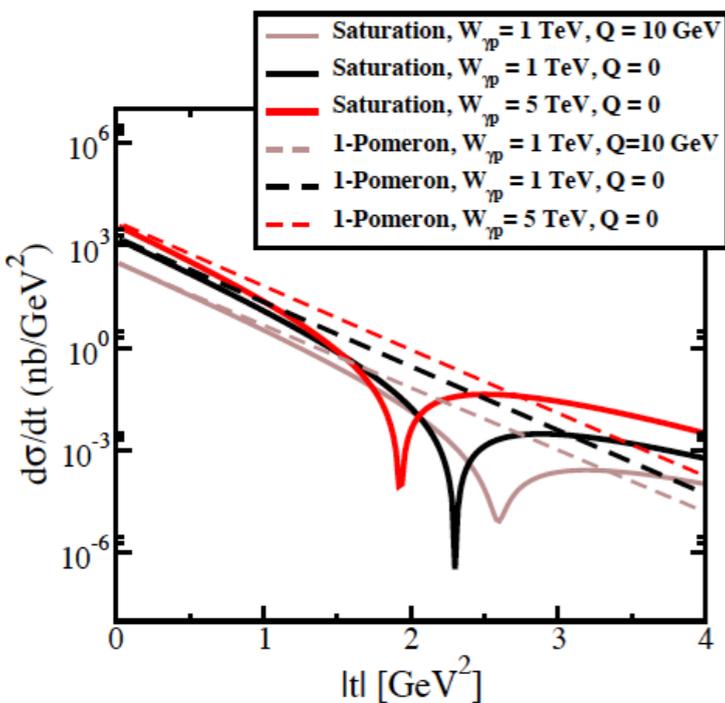
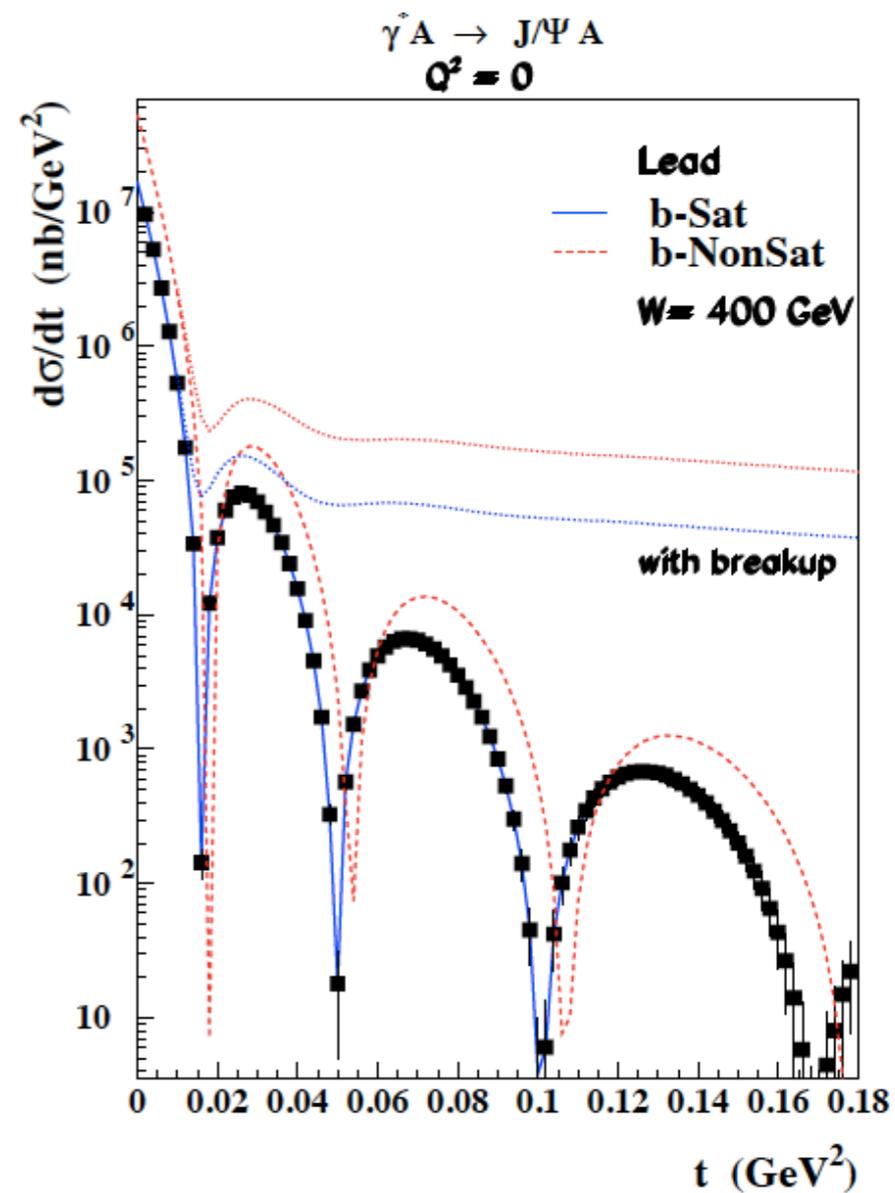
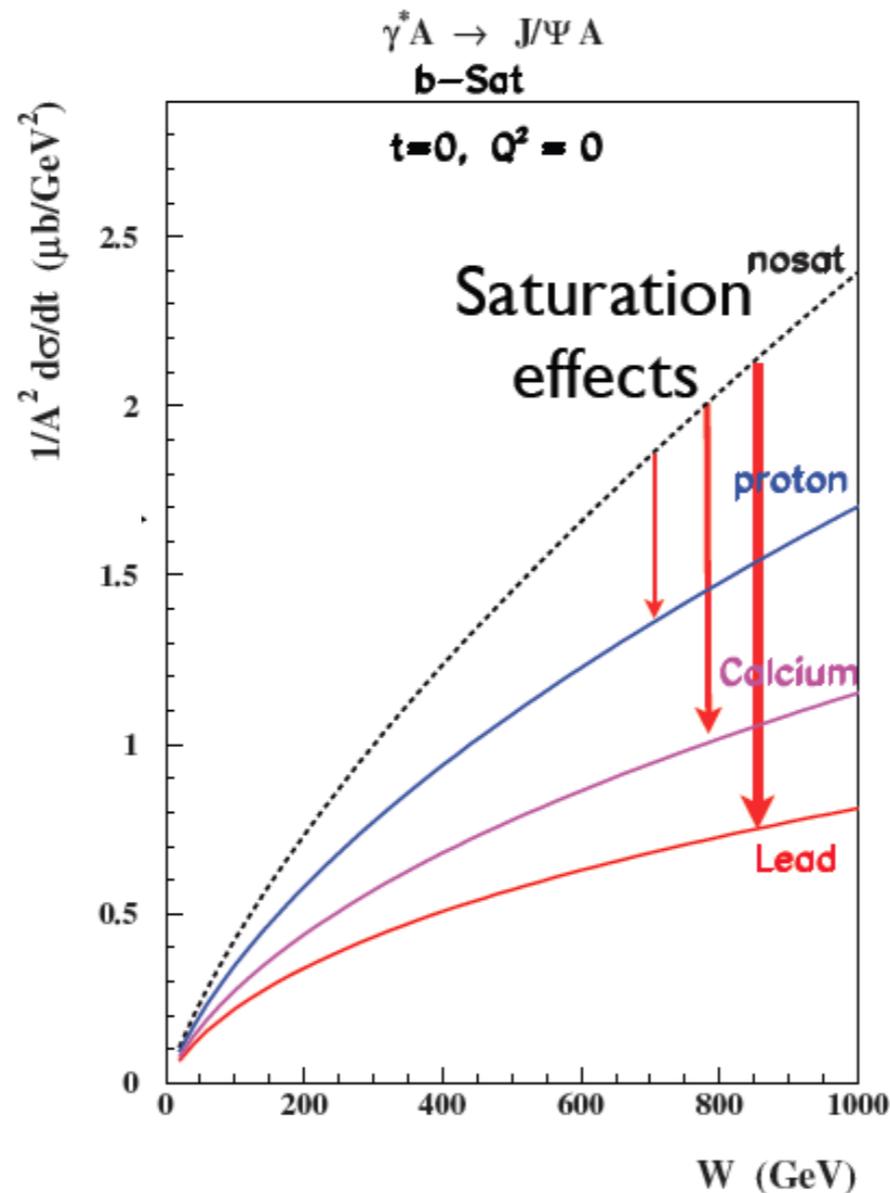
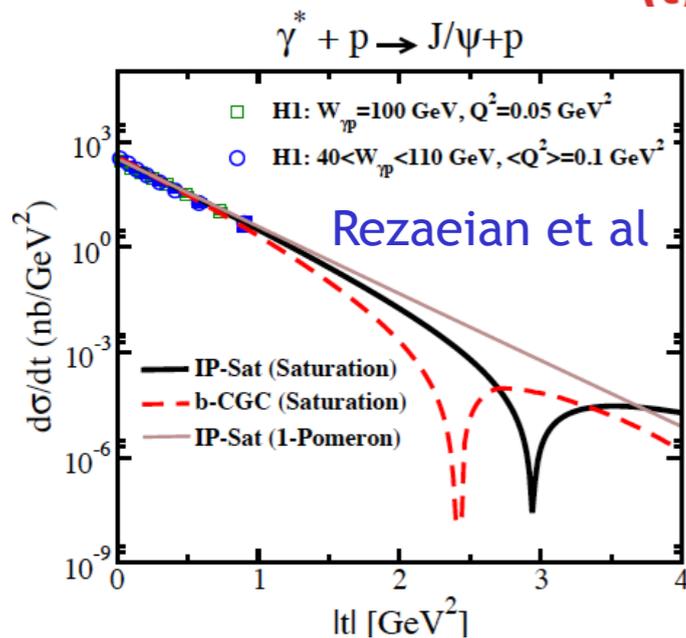
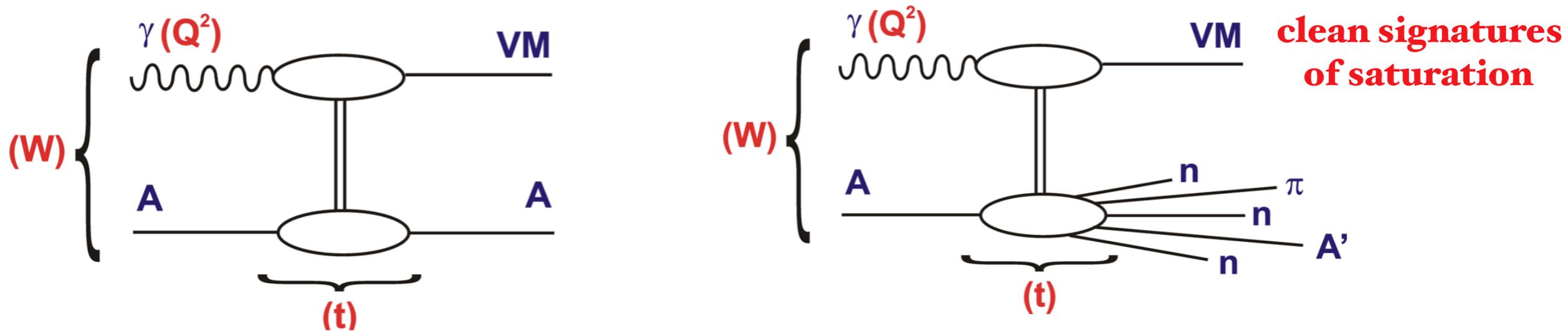
background for anomalous couplings studies with forward detectors see C. Royon

SD/ND ~ 1 % for SCI/GAL close to Tevatron data!



Mainly gluon-initiated diffraction at large Z!

Saturation studies via coherent diffraction

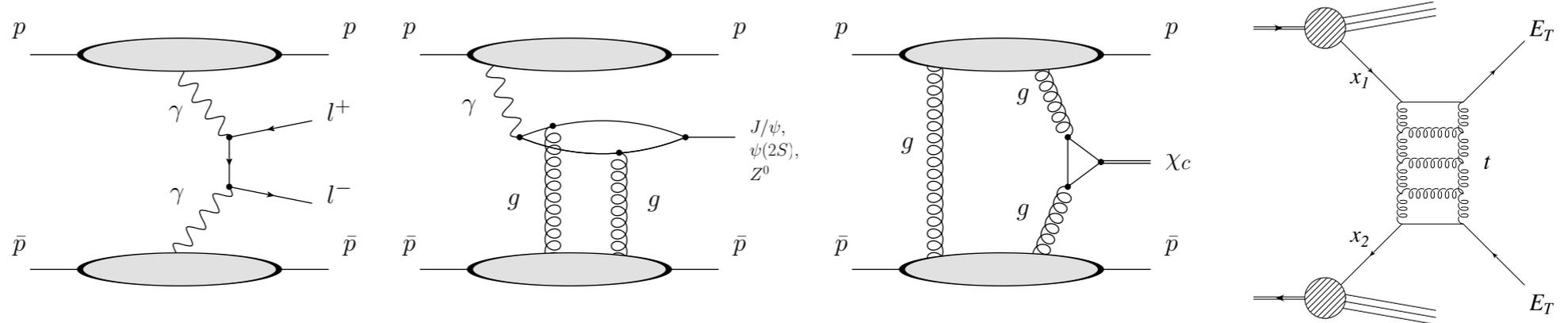


More exclusive/diffractive reactions...

Examples of typical exclusive reactions studied so far...

many covered in SuperChic and FPMC Monte Carlo generators

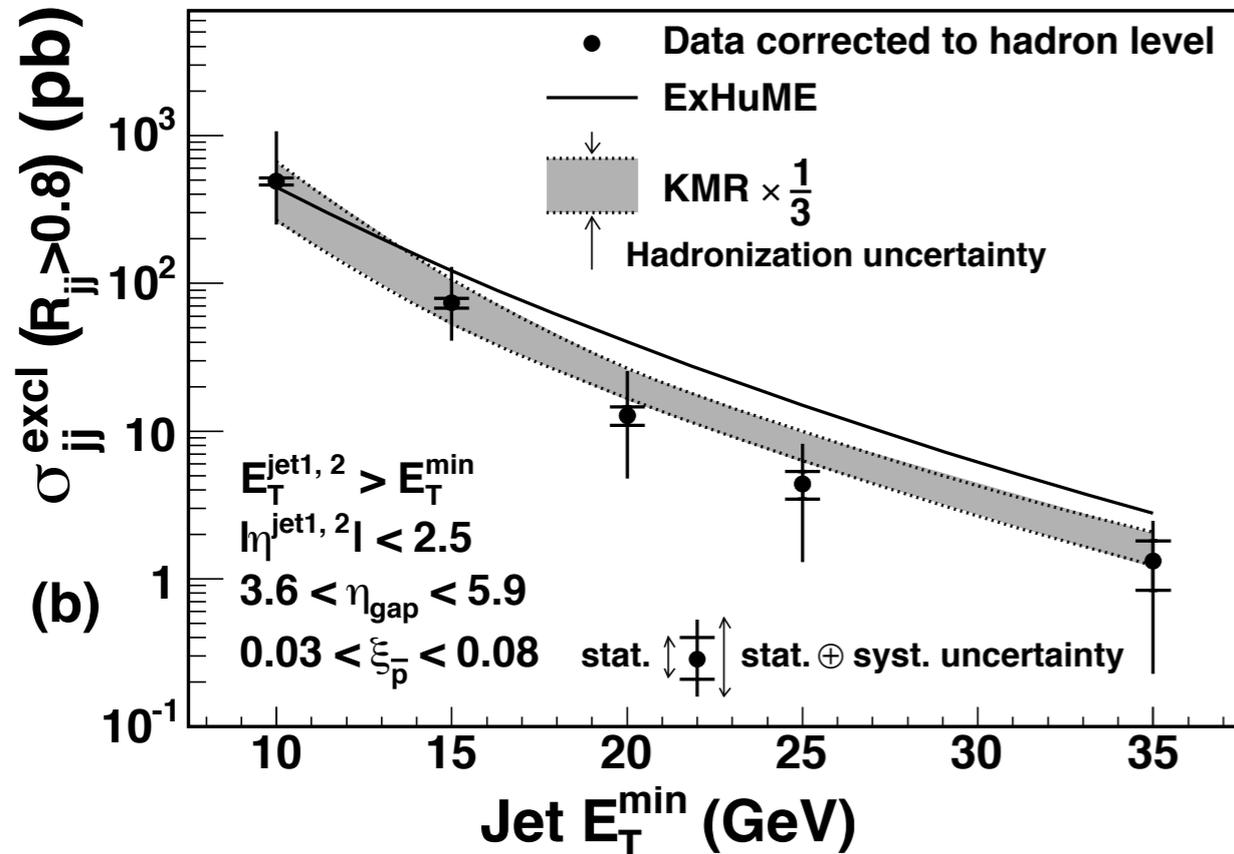
Laboratory of quarkonia, meson pair, exotics, gauge bosons, New Physics... production



L. Harland-Lang + Durham group

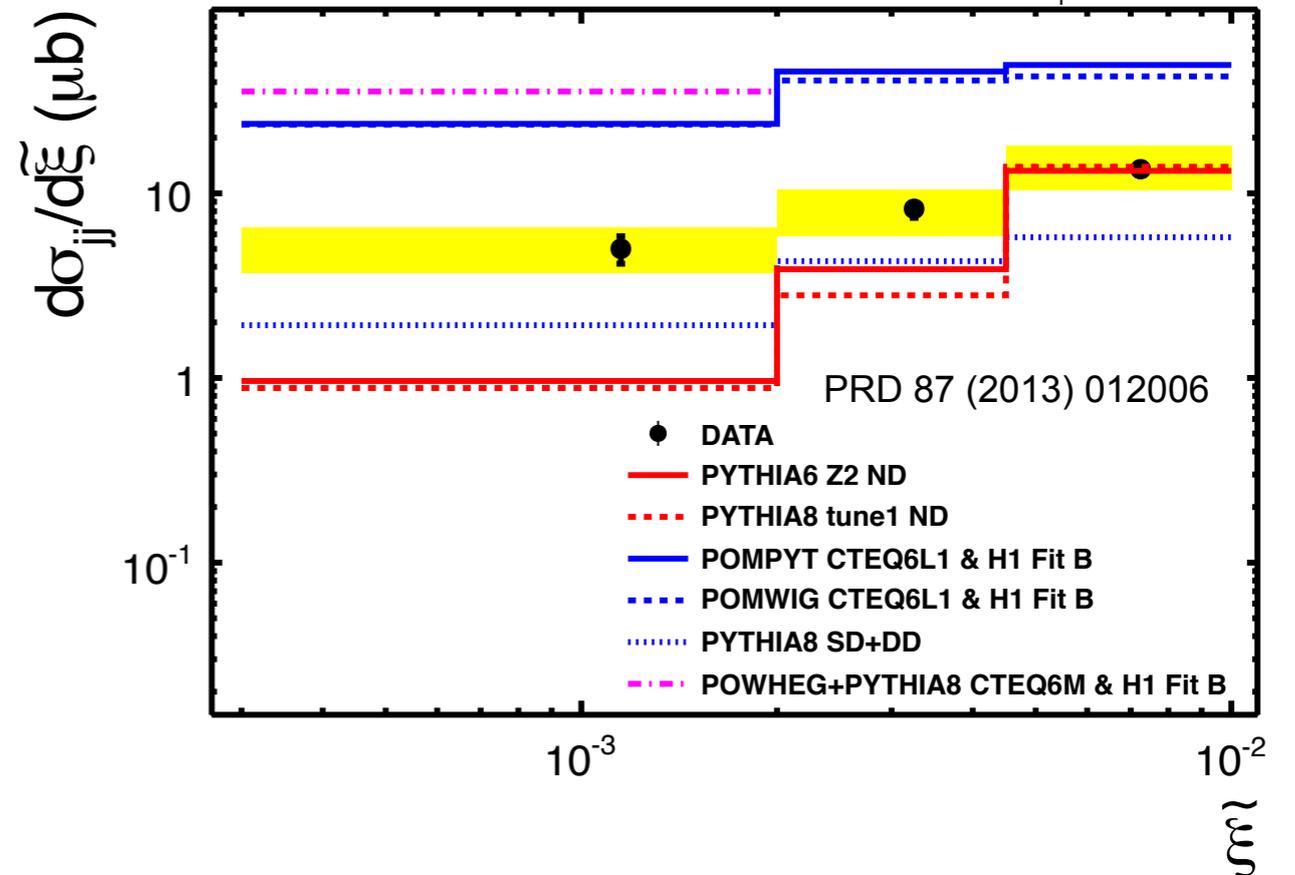
Example: Diffractive di-jets at Tevatron

CDF Collab., Phys.Rev.D77:052004,2008



Example: Diffractive di-jet at the LHC

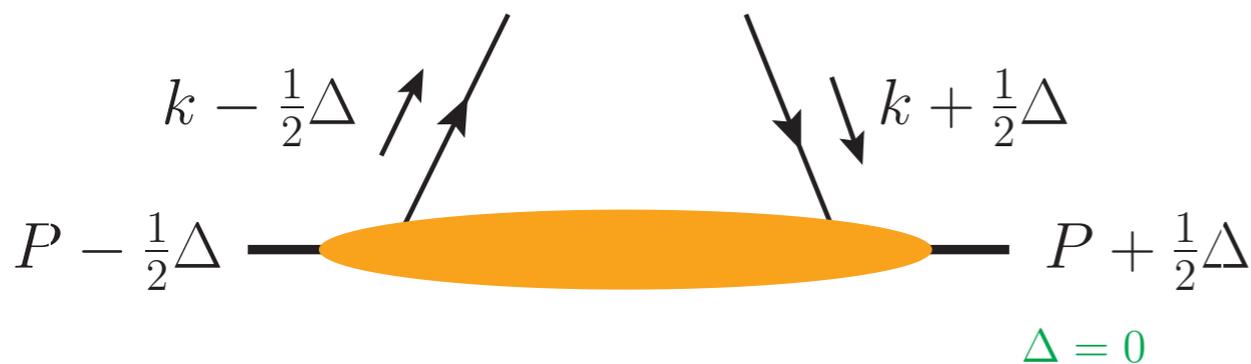
CMS, $\sqrt{s}=7$ TeV, $L = 2.7 \text{ nb}^{-1}$, $pp \rightarrow \text{jet}_1 \text{ jet}_2$, $|\eta^{j1,j2}| < 4.4$, $p_T^{j1,j2} > 20$ GeV



Nucleon tomography: phase space distributions

What do we know about the nucleon?

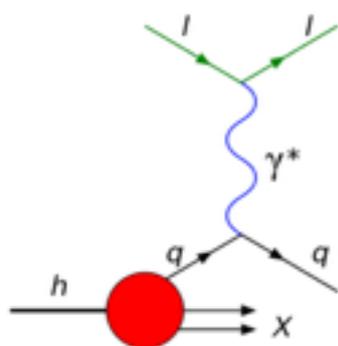
It is a complicated object!



$$H(k, P, \Delta) = (2\pi)^{-4} \int d^4 z e^{i z k} \times \langle p(P + \frac{1}{2} \Delta) | \bar{q}(-\frac{1}{2} z) \Gamma q(\frac{1}{2} z) | p(P - \frac{1}{2} \Delta) \rangle$$

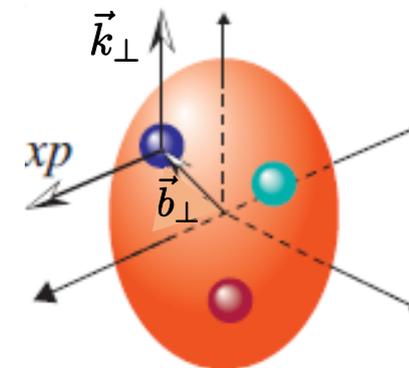
parton correlation function

Partons also experience a transverse motion at a given impact parameter!



$f(k, P)$ parton correlation function

$H(k, P, \Delta)$



GTMD

$\int dk^-$

$W(x, k, b)$ Wigner distribution

$H(x, k, \xi, b) \leftrightarrow H(x, k, \xi, \Delta)$

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

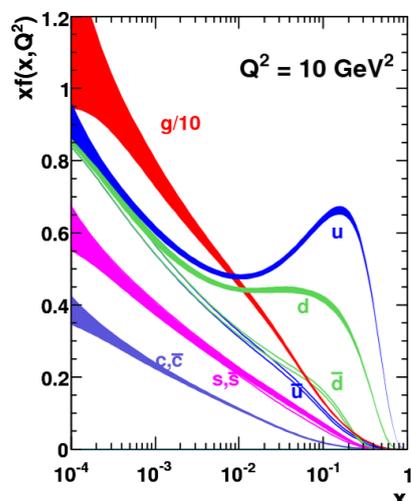
TMD

$f(x, z) \leftrightarrow f(x, k)$

$f(x, b)$ impact parameter distribution

$H(x, \xi, b) \leftrightarrow H(x, \xi, \Delta^2)$ GPD

$\int dx x^{n-1}$



$f(x)$ PDF

$F_n(b) \leftrightarrow F_n(\Delta^2)$ form factor

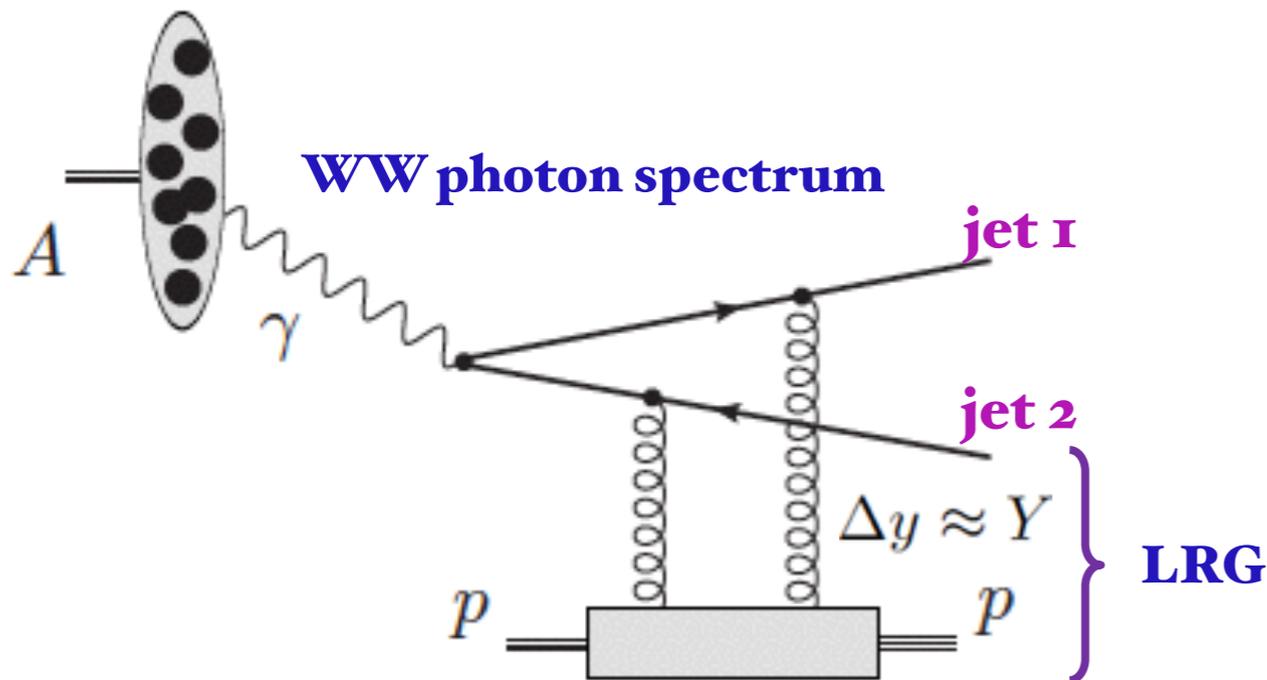
$\sum_{k=0}^n A_{nk}(\Delta^2) (2\xi)^k$

GFFs

Figure from Ref. M. Diehl, arXiv: 1512.01328

Accessing the gluon Wigner from exclusive dijets in UPC

Y. Hagiwara, Y. Hatta, RP, M. Tasevsky, O. Teryaev,
PRD 96, 034009 (2017)



photon-target diffractive amplitude

$$\vec{M}(\vec{P}_\perp, \vec{\Delta}_\perp) = \int \frac{d^2 \vec{q}_\perp}{2\pi} \frac{\vec{P}_\perp - \vec{q}_\perp}{(\vec{P}_\perp - \vec{q}_\perp)^2} S(\vec{q}_\perp, \vec{\Delta}_\perp)$$

“Isotropic”

“Elliptic”

$$S(\vec{q}_\perp, \vec{\Delta}_\perp) = S_0(q_\perp, \Delta_\perp) + 2 \cos 2(\phi_q - \phi_\Delta) \tilde{S}(q_\perp, \Delta_\perp)$$

Photon-target cross section:

$$\frac{d\sigma^{P\gamma}}{dy_1 dy_2 d^2 \vec{k}_{1\perp} d^2 \vec{k}_{2\perp}} = N_c \alpha_{em} (2\pi)^2 q^+ \delta(k_1^+ + k_2^+ - q^+) \sum_f e_f^2 2z(1-z)(z^2 + (1-z)^2) |\vec{M}|^2 \quad z = \frac{k_{1\perp} e^{y_1}}{k_{1\perp} e^{y_1} + k_{2\perp} e^{y_2}}$$

Nucleus-target cross section:



$$\frac{d\sigma^{PA}}{dy_1 dy_2 d^2 \vec{k}_{1\perp} d^2 \vec{k}_{2\perp}} \approx \omega \frac{dN}{d\omega} \frac{2(2\pi)^4 N_c \alpha_{em}}{P_\perp^2} \sum_f e_f^2 z(1-z)(z^2 + (1-z)^2) (A^2 + 2 \cos 2(\phi_P - \phi_\Delta) AB)$$

photon flux

$$S_0(P_\perp, \Delta_\perp) = -\frac{1}{P_\perp} \frac{\partial}{\partial P_\perp} A(P_\perp, \Delta_\perp)$$

$$\tilde{S}(P_\perp, \Delta_\perp) = -\frac{\partial B(P_\perp, \Delta_\perp)}{\partial P_\perp^2} + \frac{2}{P_\perp^2} \int_0^{P_\perp^2} \frac{dP_\perp'^2}{P_\perp'^2} B(P_\perp', \Delta_\perp)$$

Separate measurements
of A and B



full information
about the gluon Wigner!

LHC Forward Physics working group



September 3 2015

CERN-PH-LPCC-2015-001
SLAC-PUB-16364
DESY 15-167

J. Phys. G43 (2016) 110201

LHC Forward Physics

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The LHC Forward Physics Working Group

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Forward Physics as a QCD laboratory

- ✓ Definition of diffraction is not unique but understood
- ✓ We have seen the Pomeron at work both in soft and hard regimes, as well as in the transition region — marginal agreement with data is achieved despite large uncertainties
- ✓ Matching between “soft” DL and “hard” BFKL Pomerons is a big challenge, but there is a progress
- ✓ Many theoretical developments in QCD-ish modelling of soft/hard Pomeron
- ✓ Diffraction is highly sensitive to small-x/long distance and multiple exchange physics
- ✓ Such effects as Regge/diffractive factorisation breaking, fluctuations in hadronisation, color screening need a proper universal treatment
- ✓ Further MC development/improvements and measurements are required