Forward physics prospects

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LHC Forward Physics

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Forward Physics: theory topics

- ✓ **Low-x QCD phenomenology**

  Measurements: hard 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 …

- ✓ **Elastic pp scattering and 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, long-range fluctuations, diffractive factorisation breaking, color-screening effects, initial-state interactions, intrinsic heavy flavor, hadronisation, nucleon tomography, quarkonia production mechanisms, UE structure …

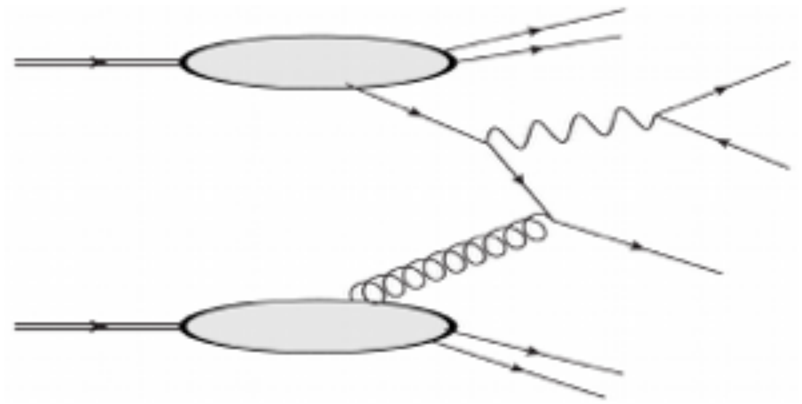
- ✓ **Central exclusive particle production and New Physics phenomenology**

  Measurements: CEP cross sections with two LRGs and two tagged protons

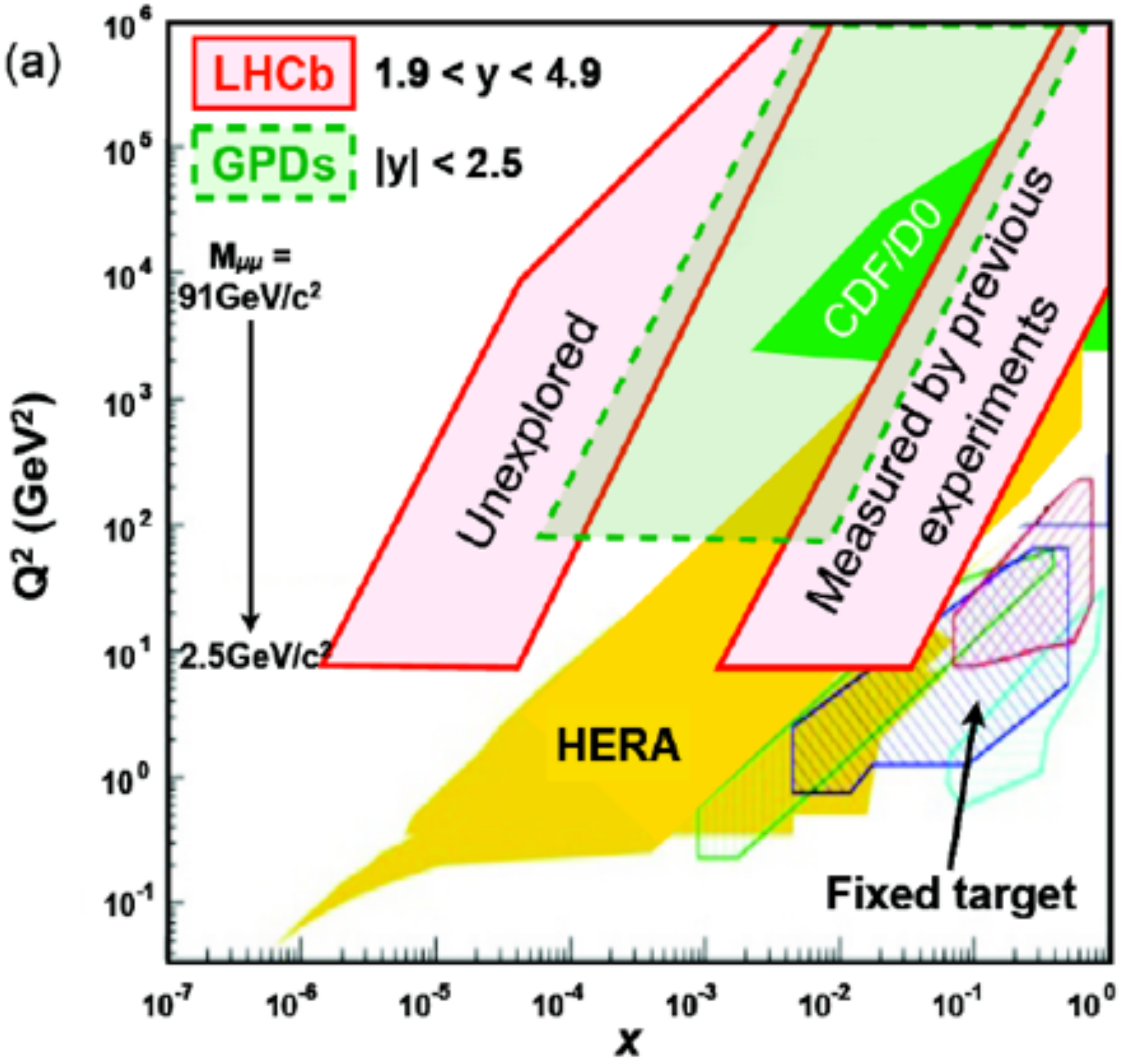
  Theory issues: QCD mechanism for CEP and gap survival, spin-parity analyser, search for new (e.g. di-photon) resonances, Higgs partners, composite sector, Dark Matter and anomalous gauge couplings studies in clean environment …

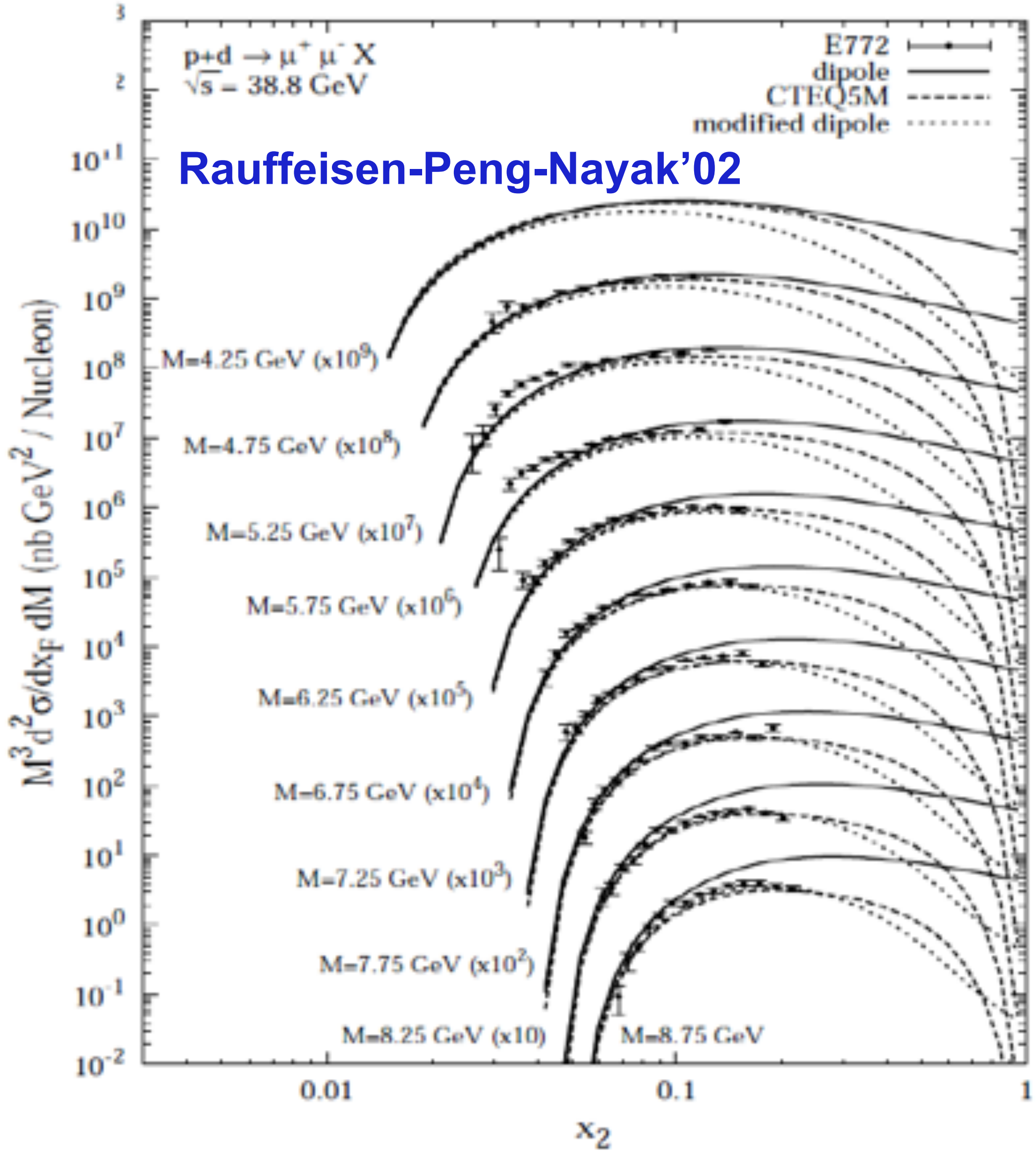
Probing low-x gluon: forward Drell-Yan

JHEP 2015, 2017



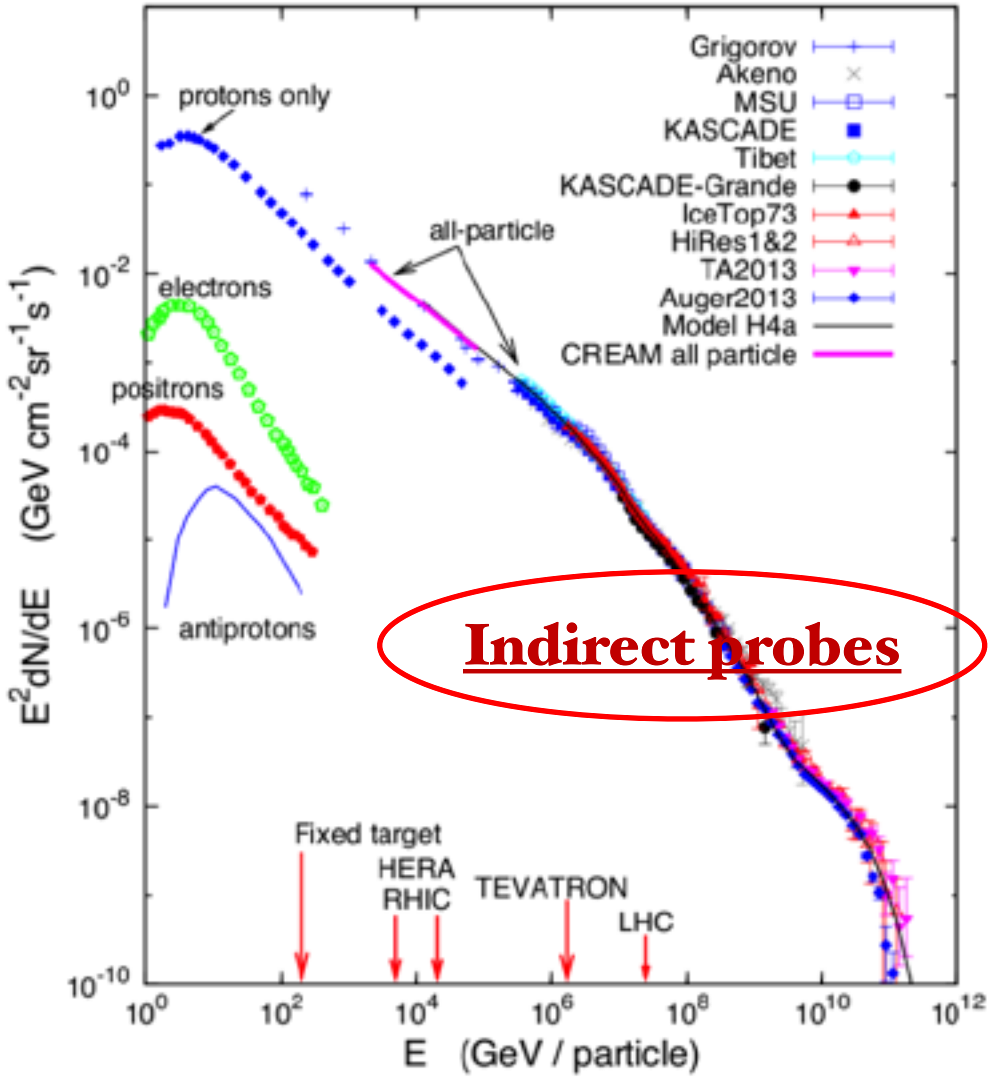
- ★ *asymmetric kinematics x1 >> x2*
- ★ *probing small-x2 gluons and large-x1 quarks*
- ★ *strong effects from small-x resummation*
- ★ *for small mass: multiple scattering/higher twists affecting low-x PDFs determination*
- ★ *sensitivity to primordial quark kT*





Rauffeisen-Peng-Nayak'02

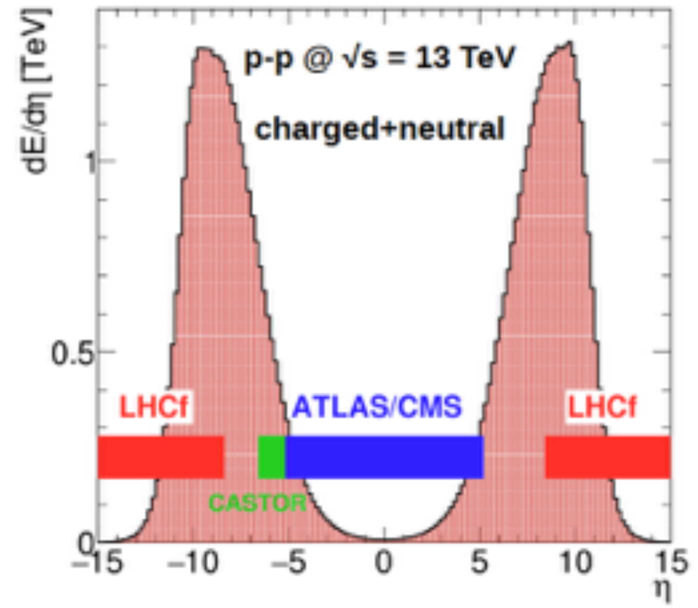
Forward Physics prospects for UHE CRs



Indirect probes

CR measurements are expected to provide:

- ★ *CRs spectrum*
- ★ *composition*
- ★ *sources distribution*

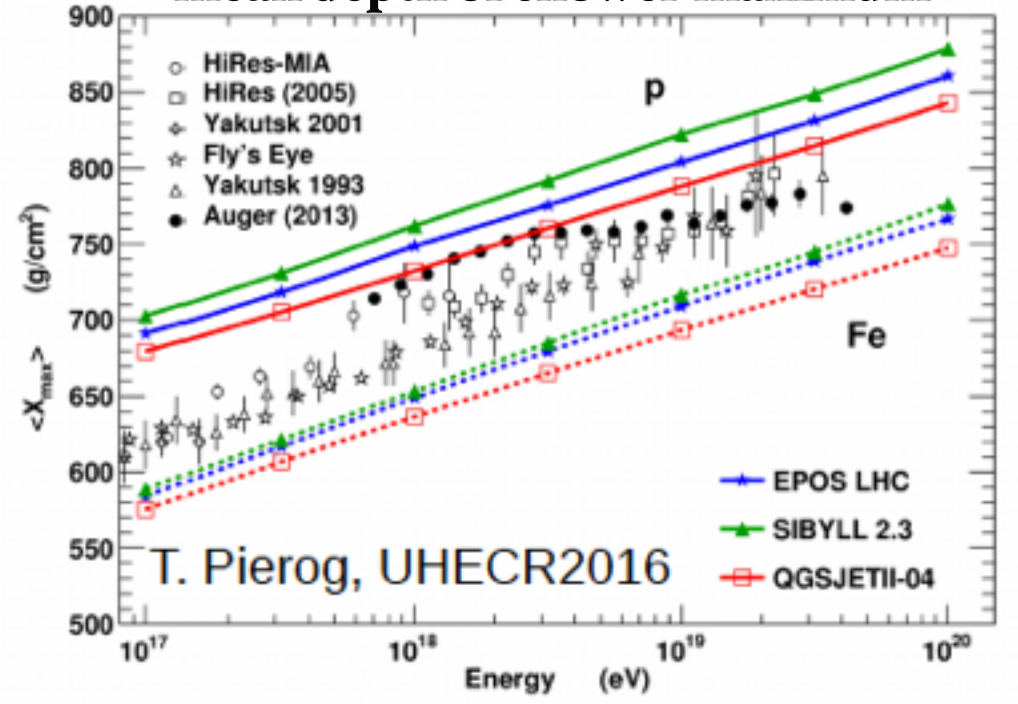


Forward physics issues:

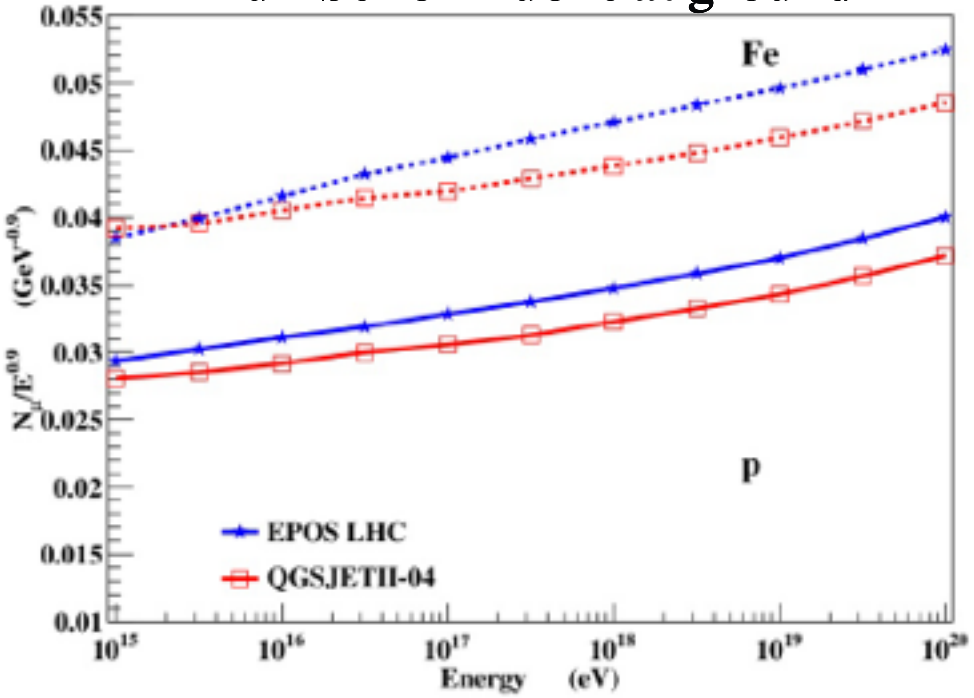
- ★ *forward energy spectrum*
- ★ *forward multiplicity distributions*
- ★ *nuclear effects*
- ★ *inelastic cross section*
- ★ *soft QCD fluctuations*

Dominate theoretical uncertainties of MC simulations of air showers

mean depth of shower maximum



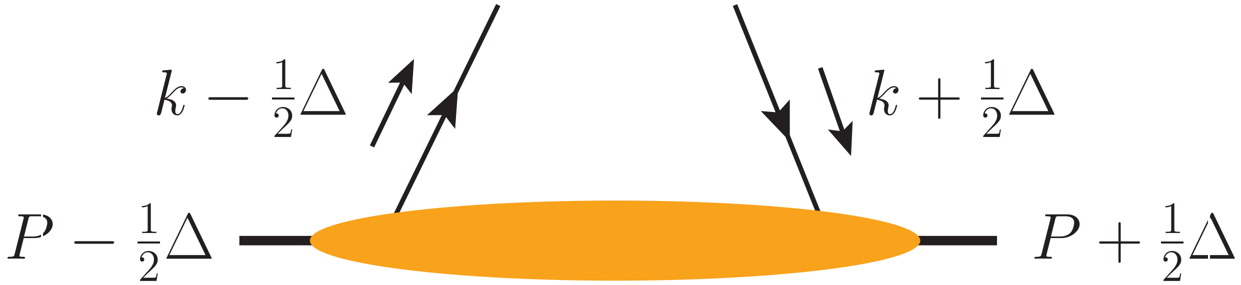
number of muons at ground



Forward LHC (e.g. LHCf) measurements provide important means for constraining hadron interaction models

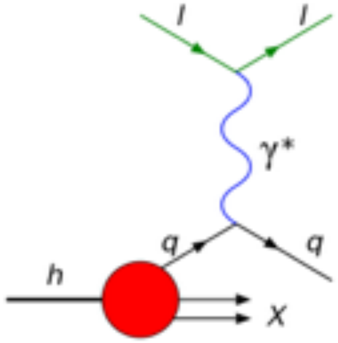
Nucleon tomography: phase space distributions

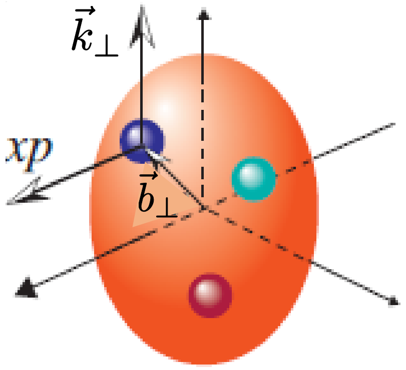
What do we know about the nucleon?



It is a complicated object!

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





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

$$\begin{tikzcd}
 & & & & & & H(k,P,\Delta)\ \text{parton correlation function} \arrow[dlllll, "\Delta=0"'] \arrow[dd, "\int dk^-"] \\
 & f(k,P)\ \text{parton correlation function} \arrow[dddd, "\int dk^-"', "\text{TMD}"' near end] & & & & & \\
 & & & & & H(x,\boldsymbol{k},\xi,\boldsymbol{b}) \arrow[r, leftrightarrow, "\text{FT}", "\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp"'] \arrow[dlll, "\xi=0"'] & H(x,\boldsymbol{k},\xi,\boldsymbol{\Delta})\ \text{GTMD} \arrow[dd, "\int d^2\boldsymbol{k}"] \\
 & & W(x,\boldsymbol{k},\boldsymbol{b})\ \text{Wigner distribution} \arrow[ddl, "\int d^2\boldsymbol{b}"] \arrow[ddr, "\int d^2\boldsymbol{k}"] & & & & \\
 & & & & & H(x,\xi,\boldsymbol{b}) \arrow[r, leftrightarrow, "\text{FT}"] \arrow[dll, "\xi=0"'] & H(x,\xi,\Delta^2)\ \text{GPD} \arrow[dd, "\int dx\, x^{n-1}"] \\
f(x,\boldsymbol{z}) \arrow[r, leftrightarrow, "\text{FT}"] & f(x,\boldsymbol{k}) \arrow[ddr, "\int d^2\boldsymbol{k}"] & & f(x,\boldsymbol{b})\ \text{impact parameter distribution} \arrow[ddl, "\int d^2\boldsymbol{b}"'] \arrow[ddr, "\int dx\, x^{n-1}"] & & & \\
 & & & & & & \sum_{k=0}^{n} A_{nk}(\Delta^2)\,(2\xi)^k\ \text{GFFs} \arrow[dl, "\xi=0"'] \\
 & & \underset{\text{PDF}}{f(x)} & & F_n(\boldsymbol{b}) \arrow[r, leftrightarrow] & \underset{\text{form factor}}{F_n(\Delta^2)} &
\end{tikzcd}$$

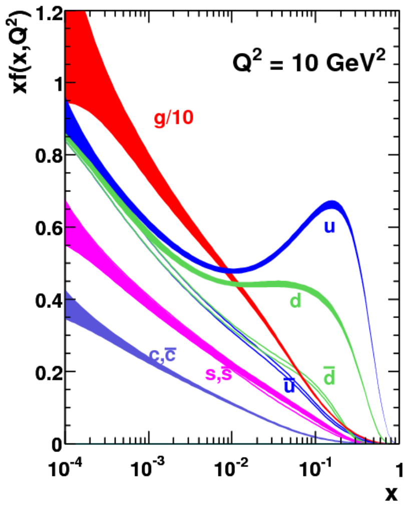
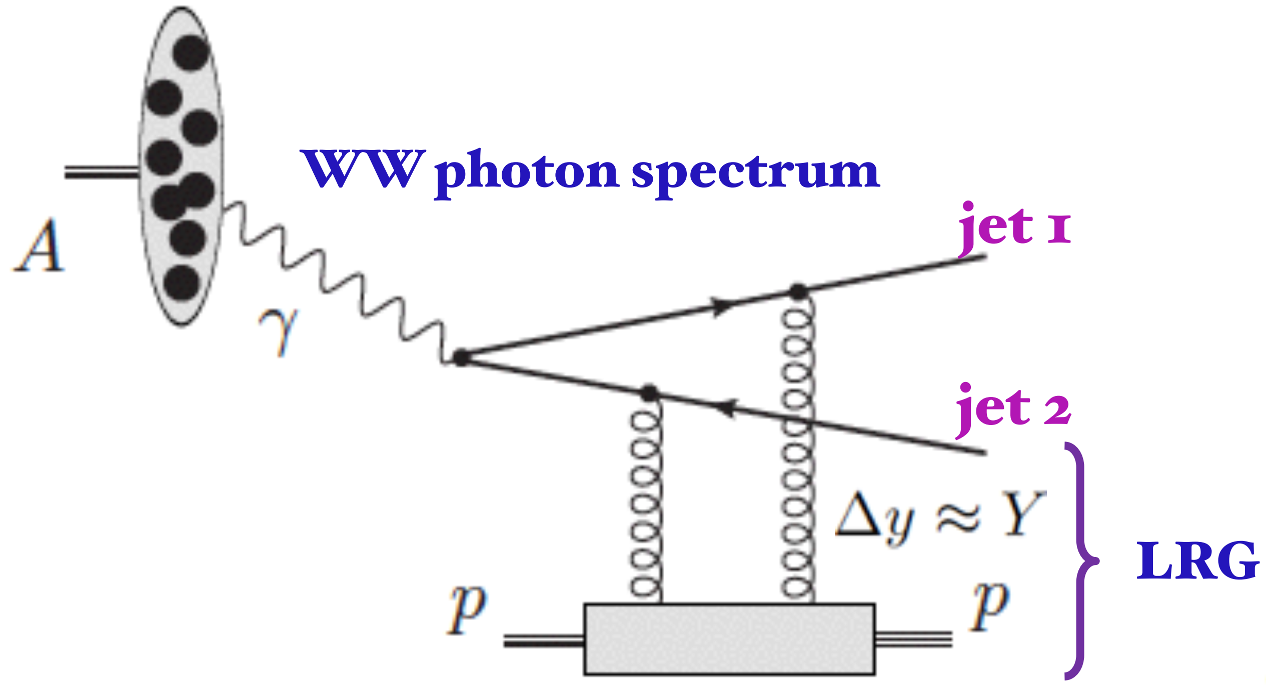


Figure from Ref.
M. Diehl, arXiv: 1512.01328

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:

$$\frac{d\sigma^{p\gamma}}{dy_1dy_2d^2\vec{k}_{1\perp}d^2\vec{k}_{2\perp}}=N_c\alpha_{em}(2\pi)^2q^+\delta(k_1^++k_2^+-q^+)\sum_f e_f^2 2z(1-z)(z^2+(1-z)^2)|\vec{M}|^2 \qquad z=\frac{k_{1\perp}e^{y_1}}{k_{1\perp}e^{y_1}+k_{2\perp}e^{y_2}}$$

Nucleus-target cross section:

$$\boxed{\frac{d\sigma^{pA}}{dy_1dy_2d^2\vec{k}_{1\perp}d^2\vec{k}_{2\perp}}\approx\underset{\text{photon flux}}{\omega\frac{dN}{d\omega}}\frac{2(2\pi)^4N_c\alpha_{em}}{P_\perp^2}\sum_f e_f^2z(1-z)(z^2+(1-z)^2)(\bigcirc\!\!\!\!\!A^2+2\cos 2(\phi_P-\phi_\Delta)\bigcirc\!\!\!\!\!\!AB)}$$

$$\left.\begin{aligned}S_0(P_\perp,\Delta_\perp)&=-\frac{1}{P_\perp}\frac{\partial}{\partial P_\perp}A(P_\perp,\Delta_\perp)\\ \tilde{S}(P_\perp,\Delta_\perp)&=-\frac{\partial B(P_\perp,\Delta_\perp)}{\partial P_\perp^2}+\frac{2}{P_\perp^2}\int_0^{P_\perp^2}\frac{dP_\perp'^2}{P_\perp'^2}B(P_\perp',\Delta_\perp)\end{aligned}\right\}$$

Separate measurements of A and B

full information about the gluon Wigner!

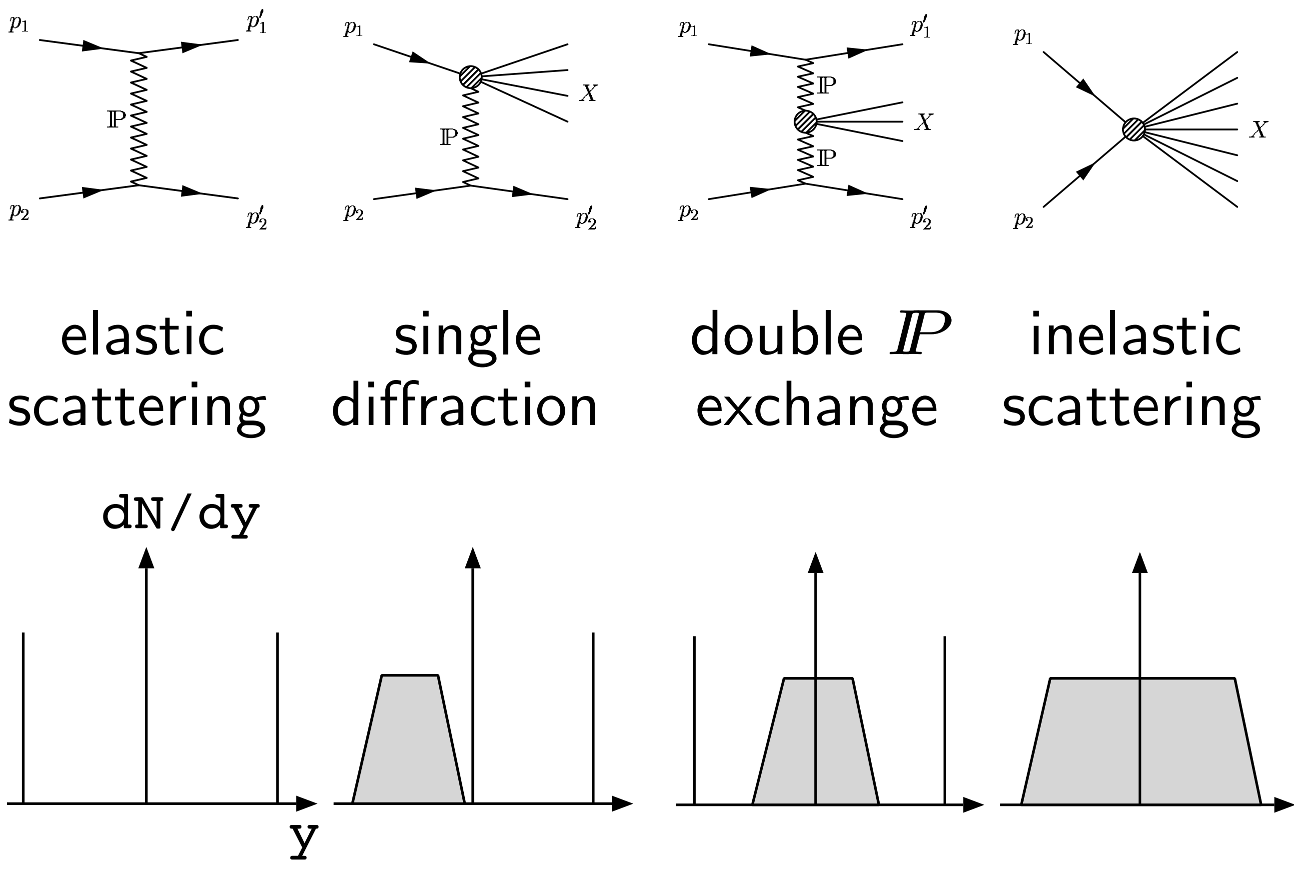
Diffraction: theory vs experiment

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

peripheral phenomenon!

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



elastic scattering | single diffraction | double $I\!P$ exchange | inelastic scattering

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?)*

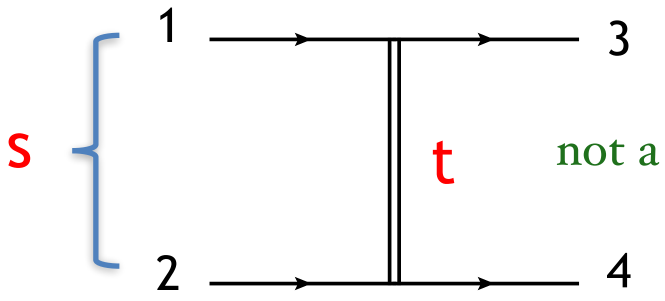
★ *low vs high mass diffractive dissociation*

★ *soft vs hard Pomeron*

★ *hard-soft factorisation breaking, etc*

huge sensitivity to details!

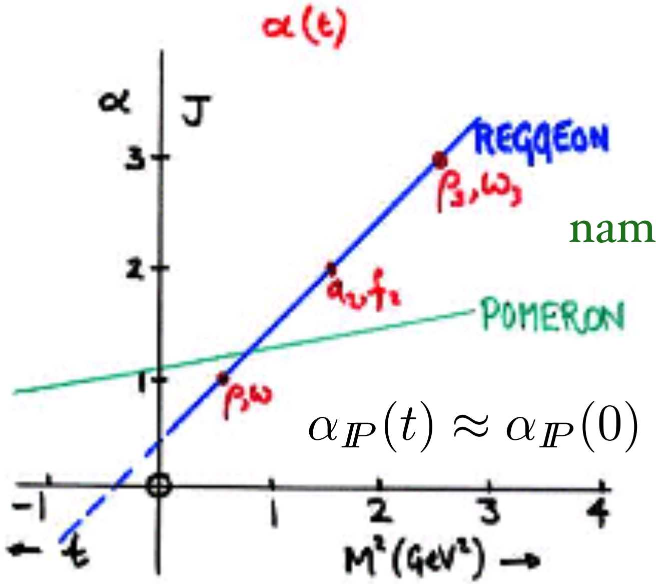
Soft Pomeron



not a particle!

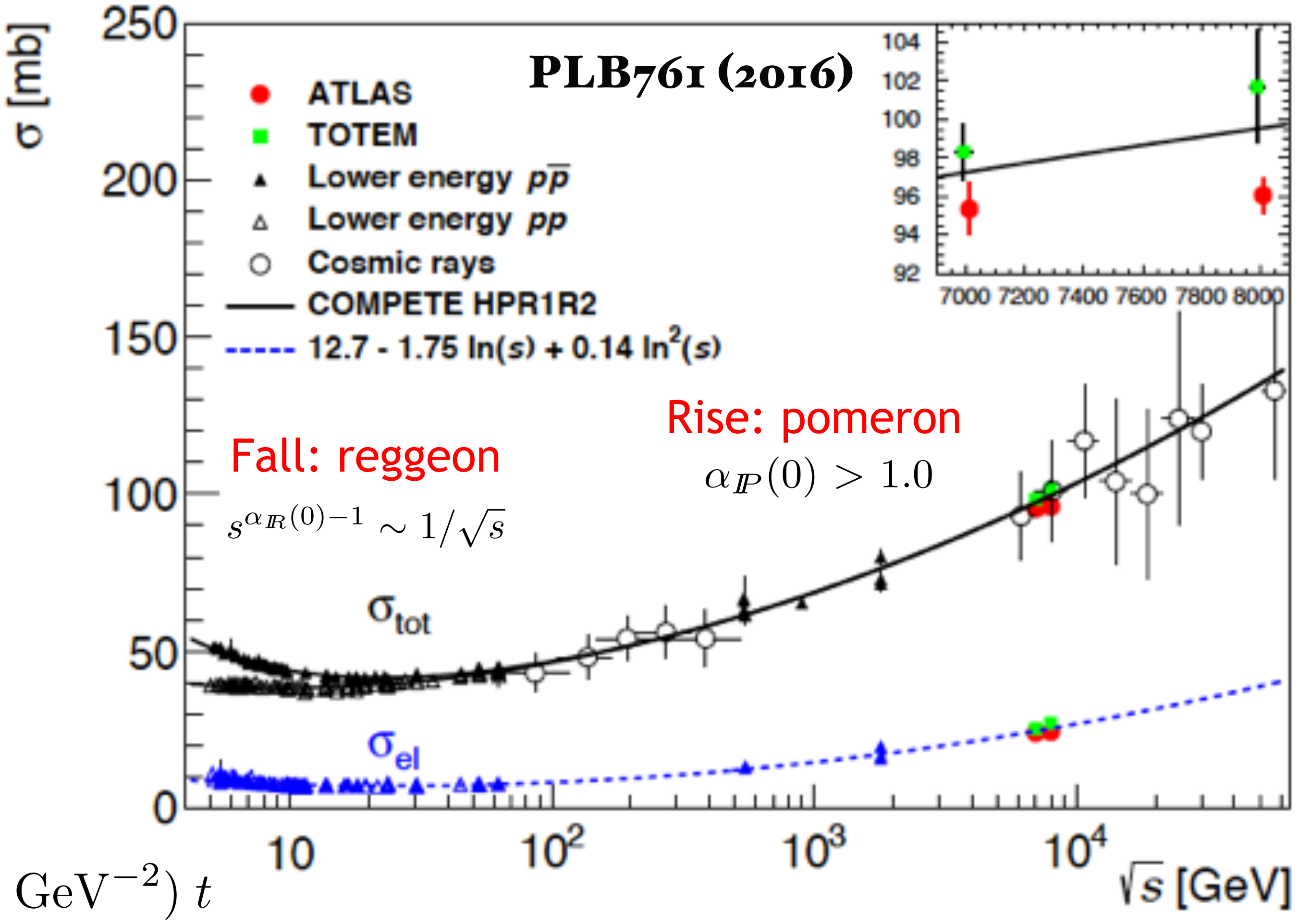
DL'84,92

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



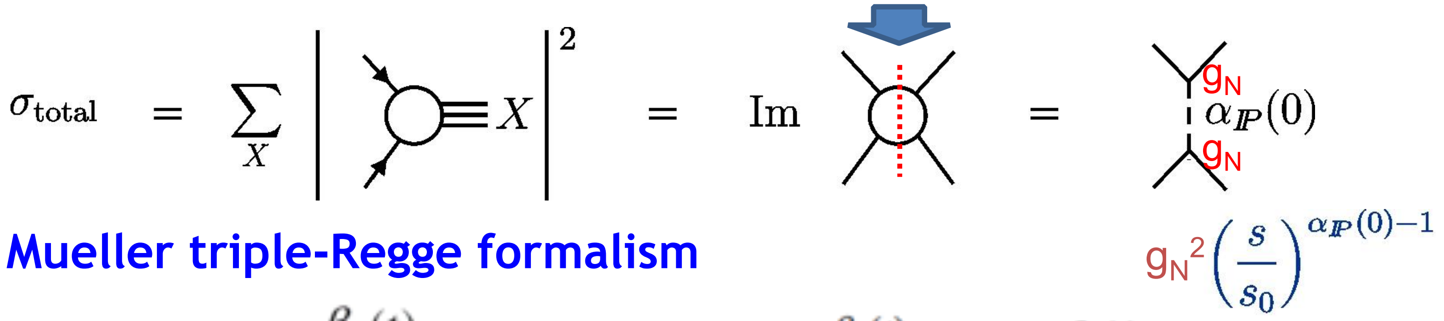
named after Pomeranchuk

$$\alpha_{I\!P}(t) \approx \alpha_{I\!P}(0) + \alpha'_{I\!P}\, t \approx 1.08 + (0.25\ \mathrm{GeV}^{-2})\, t$$



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

optical theorem

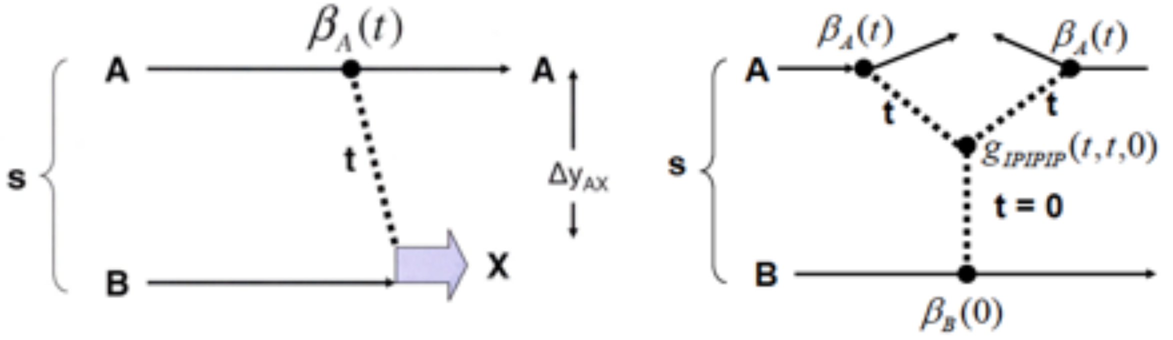


Pomeron "flux"

$$\frac{d\sigma}{dt\, d\xi} = f_{I\!P/A}(\xi, t)\, \sigma_{BI\!P}(M_X^2, t) \quad M_X^2 = \xi s$$

$\sigma_{BI\!P}(M_X^2, t) \propto (M_X^2)^{\alpha_{I\!P}(0)-1}$ **at large** M_X

Mueller triple-Regge formalism



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

Albrow, Coughlin, Forshaw, Prog.Part.Nucl.Phys 65 (2010) 149

Unitarity corrections

DL Pomeron breaks the unitarity bound at small b at a few TeV already

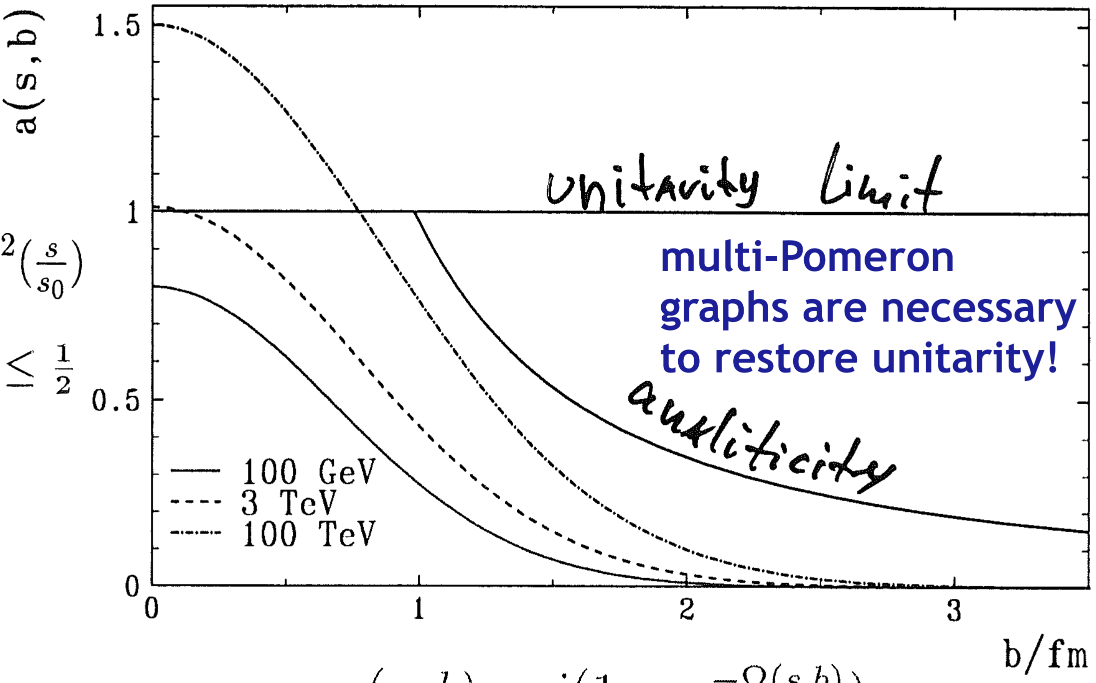
$\sigma_{tot} \propto s^{0.08}$

$\sigma_{el/diff} \propto s^{0.16+0.5t}$

violate bounds

Froissart $\sigma_{tot} \leq \sigma^{\mathrm{FR}} = \frac{\pi}{m_\pi^2} \ln^2(\frac{s}{s_0})$

Pumplin $(\sigma_{el} + \sigma_{diff})/\sigma_{tot} \leq \frac{1}{2}$



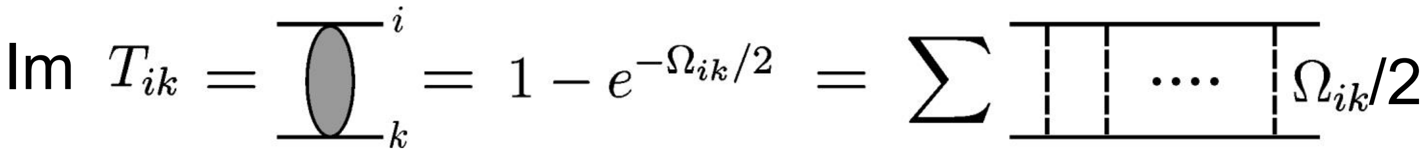
multi-Pomeron graphs are necessary to restore unitarity!

$a(s,b) = i(1 - e^{-\Omega(s,b)})$

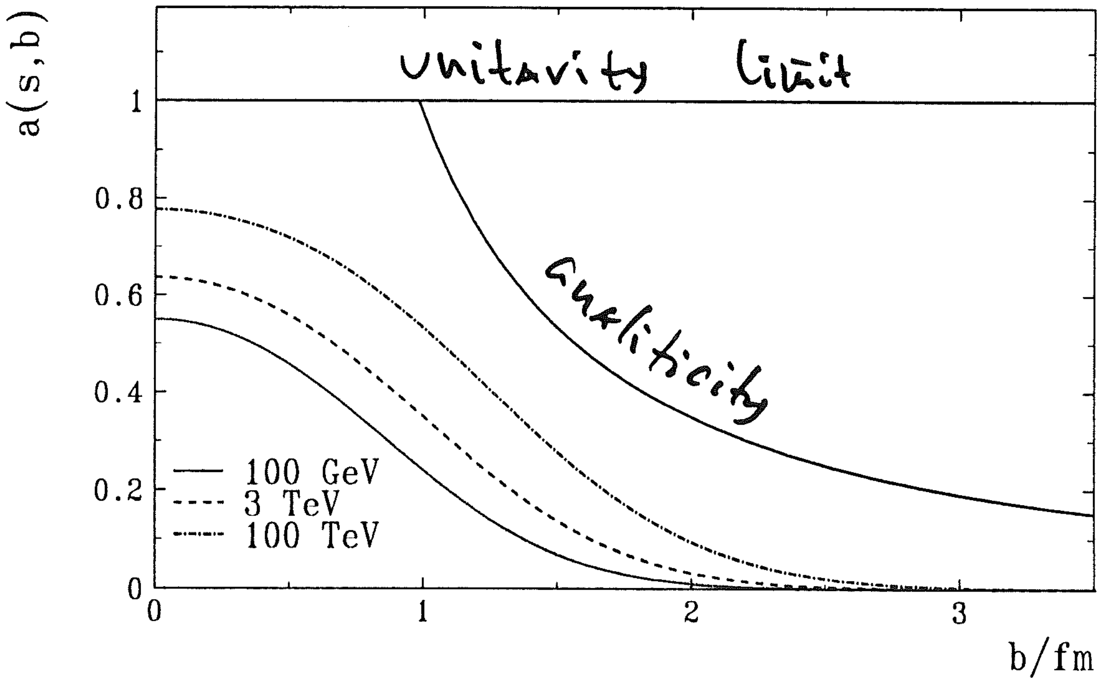
Unitarity can be restored by eikonalisation!

Reggeon Field Theory, Gribov- 1986

in terms of diffractive eigenstates ϕ_i, ϕ_k which undergo only elastic scatterings

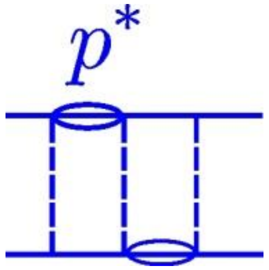


$$\mathrm{Im}\ T_{ik} = \quad = 1 - e^{-\Omega_{ik}/2} = \sum \quad \Omega_{ik}/2$$

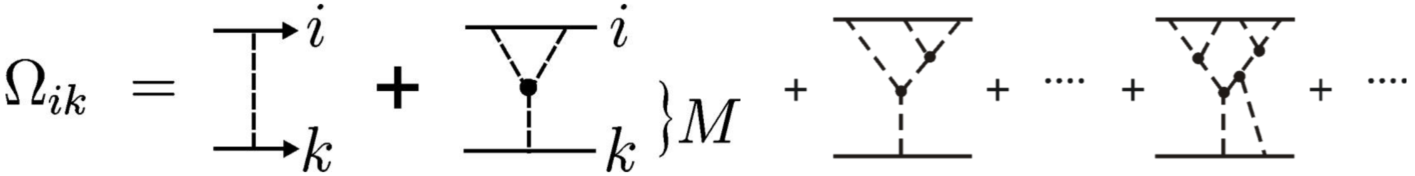


Low-mass diffractive dissociation

multichannel eikonal model



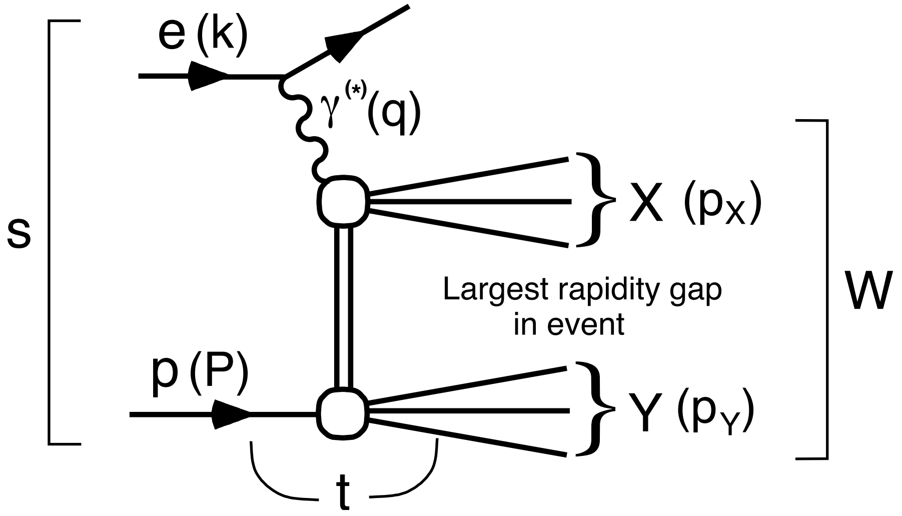
high-mass diffractive dissociation



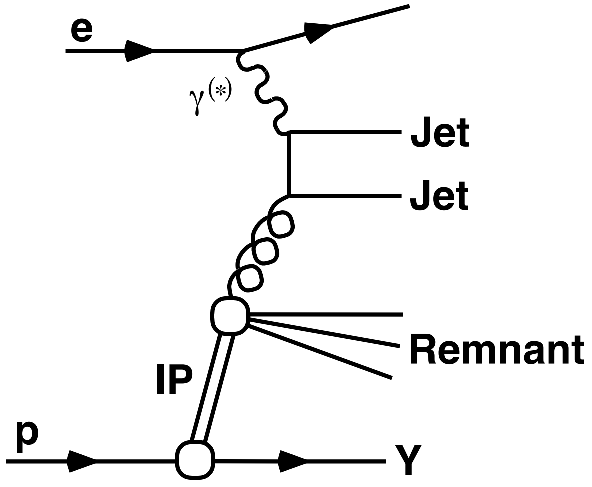
Ostapchenko (based on Kaidalov et al)
Durham (KMR group)
Tel Aviv (GLM group)

Birth of hard diffraction: QCD modelling of Pomeron

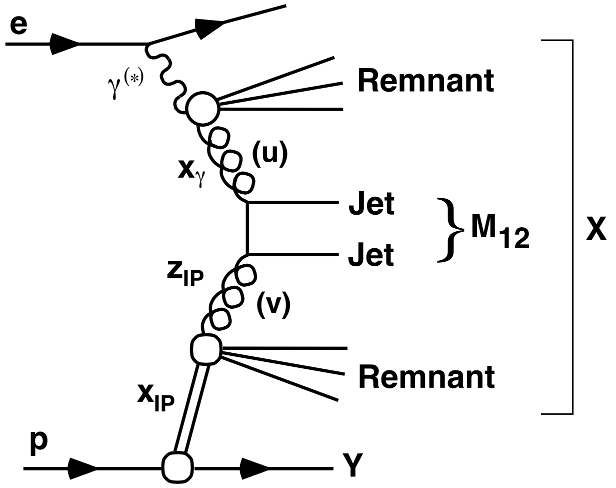
generic diffractive scattering at HERA



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

$$\boxed{\begin{aligned} d\sigma(ep \to e + 2\,\text{jets} + X' + Y) \;&= \sum_{i,j} \int dy\; f_{\gamma/e}(y) \int dx_\gamma\; f_{j/\gamma}(x_\gamma, \mu_F^2) \;\times \\ &\times \int dt \int dx_{I\!P} \int dz_{I\!P}\; d\hat{\sigma}(ij \to 2\,\text{jets})\; f_i^D(z_{I\!P}, \mu_F^2, x_{I\!P}, t), \end{aligned}}$$

- ✓ **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

Pomeron PDFs

DPDF $$f_i^D(z_{I\!P}, \mu_F^2, x_{I\!P}, t) = f_{I\!P}(x_{I\!P}, t)\; f_{i,I\!P}(z_{I\!P}, \mu_F^2)$$

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)

$x_{I\!P} > 0.01$

$$\ldots + f_{IR}(x_{IP},t)\, f_i^{IR}(z,Q^2)$$

Reggeon PDFs taken from pion (GRV)

Fit z and Q^2 dependence at fixed x_{IP} and t

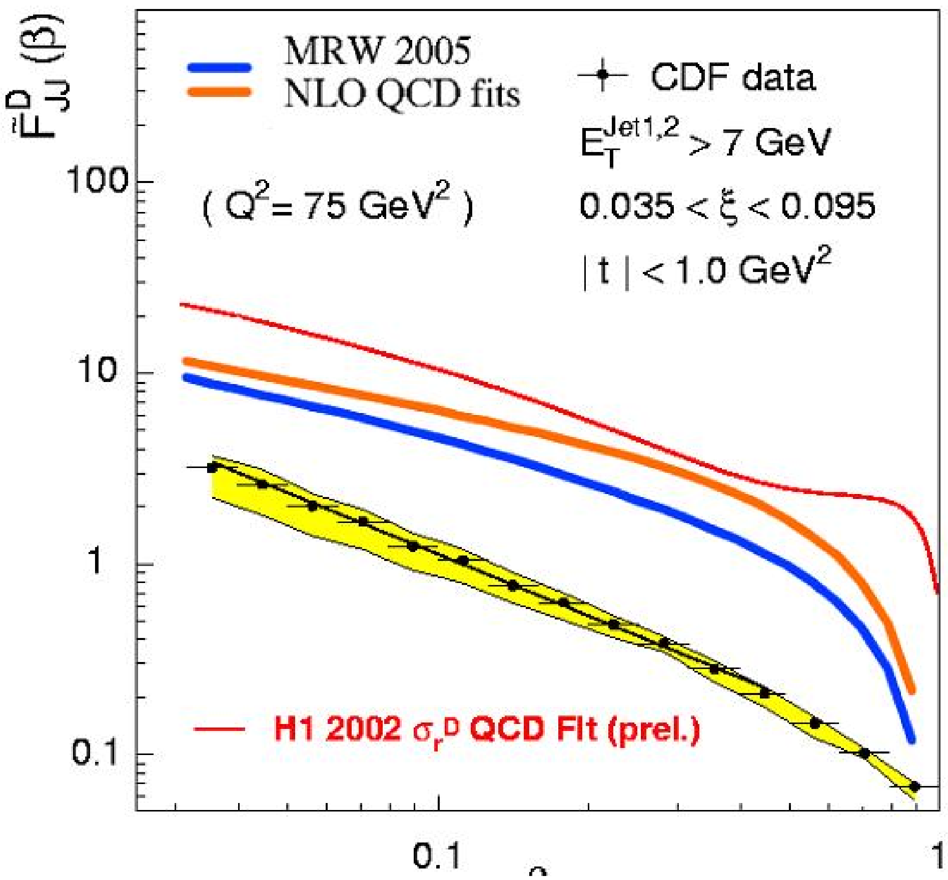
Flux parametrisation

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

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

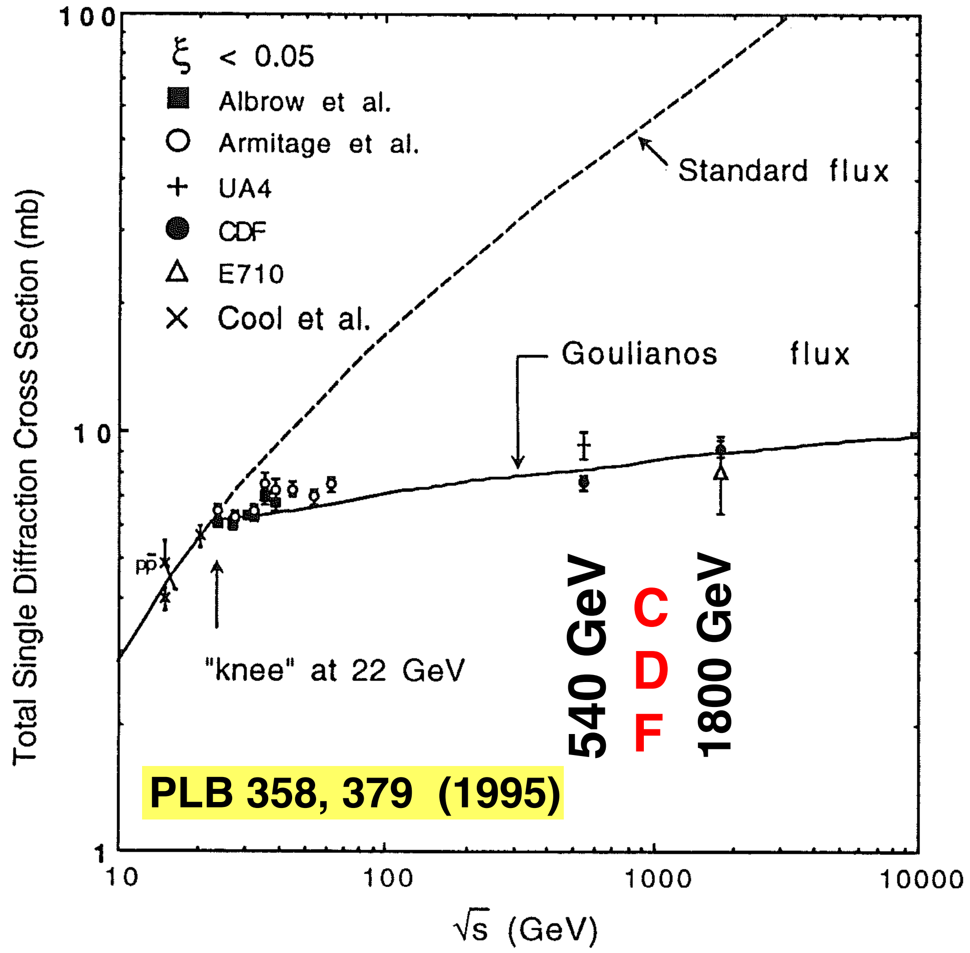
HERA

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

Non-universality!

$q_{I\!P}(x,Q^2)$ and $g_{I\!P}(x,Q^2)$ fitted to DIS F_2^D

factor 10 too large diffractive cross section at Tevatron!



PLB 358, 379 (1995)

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

factorisation is broken by gap survival effects!

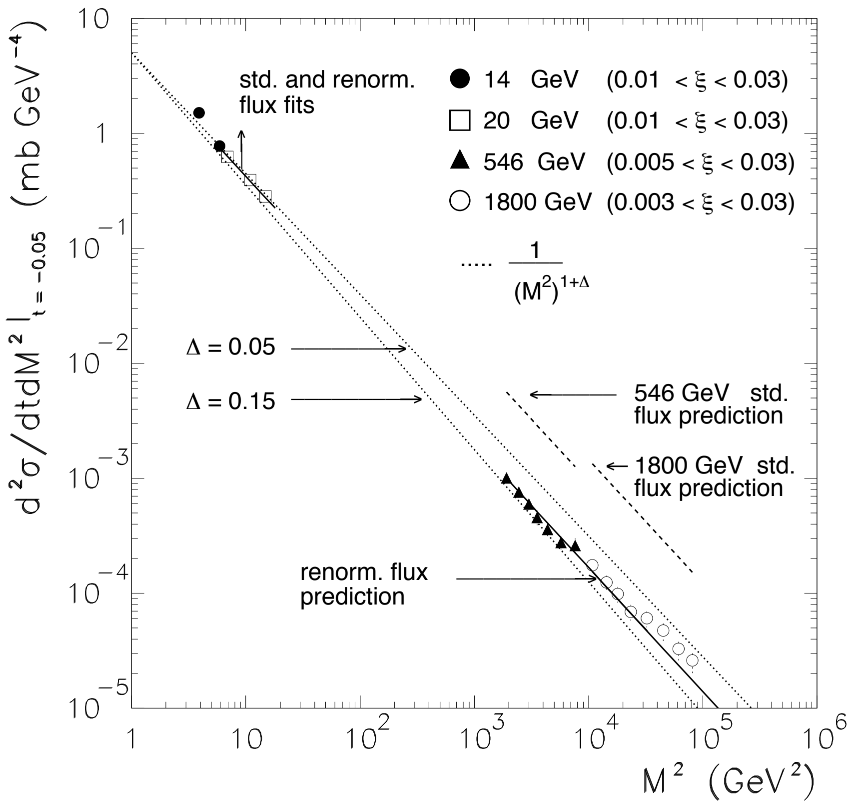
Factor of ~8 (~5) suppression at $\sqrt{s}$ = 1800 (540) GeV

Pythia 8-MBR implementation

Rockefeller Model (by K Coulianos)

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

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

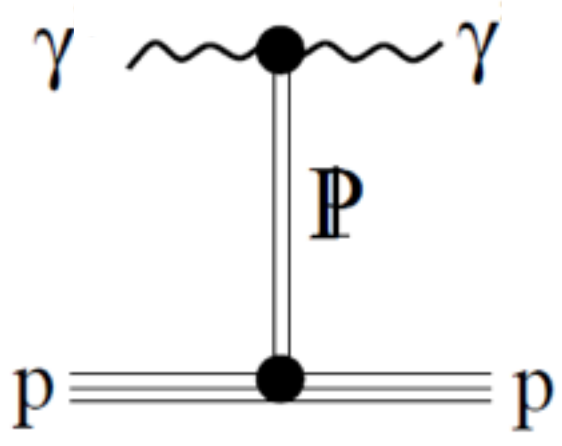


Soft vs hard Pomeron: KMR'14 model

Soft diffraction

only soft scales $R \sim 1\ \mathrm{fm}$

elastic scattering, low mass diffraction etc

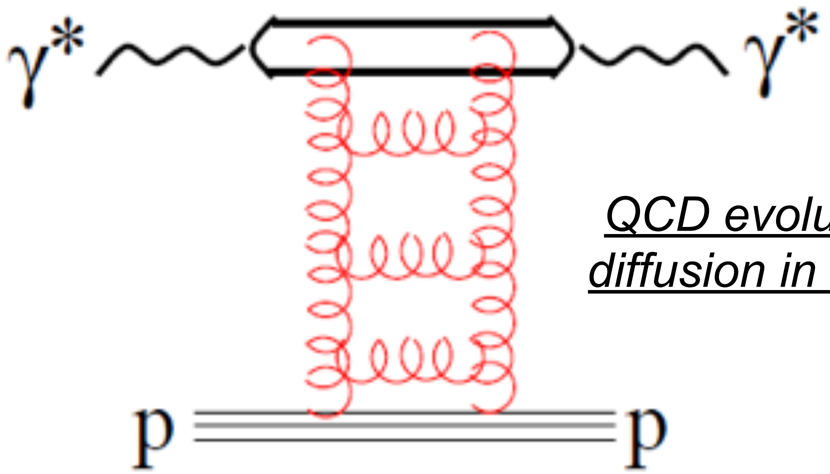


Regge Field Theory with
phenomenological DL Pomeron
$\alpha_P^{\mathrm{eff}} \sim 1.08 + 0.25\,t$

Continuous matching is necessary!

Hard diffraction

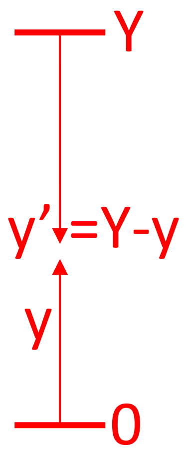
at least, one hard scale $\mu^{-1} \ll R$



QCD evolution: diffusion in log kt

perturbative QCD
(BFKL) "bare" Pomeron
$\alpha_P^{\mathrm{bare}} \sim 1.35 + 0\,t$

Rapidity evolution of opacity in absorptive background of both hadrons



BFKL kernel

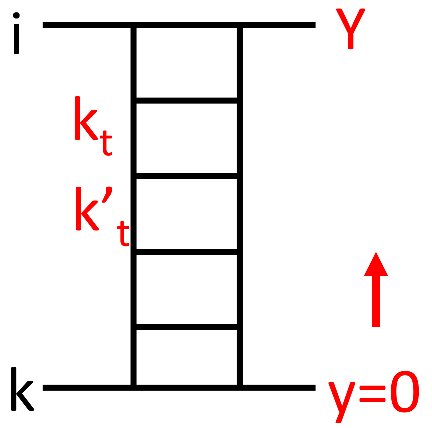
$$\frac{\partial\Omega^b(y,k_t)}{\partial y}=\frac{\alpha_s(k_t)}{2\pi}\int dk_t'^2\,S(y,y',k_t,k_t')\mathcal{K}(k_t,k_t')\Omega^b(y,k_t')$$

absorptive factor

$$\frac{\partial\Omega^a(y',k_t)}{\partial y'}=\frac{\alpha_s(k_t)}{2\pi}\int dk_t'^2\,S(y,y',k_t,k_t')\mathcal{K}(k_t,k_t')\Omega^a(y',k_t')$$

$$y' = Y_k = \ln(s/k_t'^2) \qquad \Omega(y) = \int_{k_t^2}\Omega(y,k_t')\frac{dk_t'^2}{k_t'^2}$$

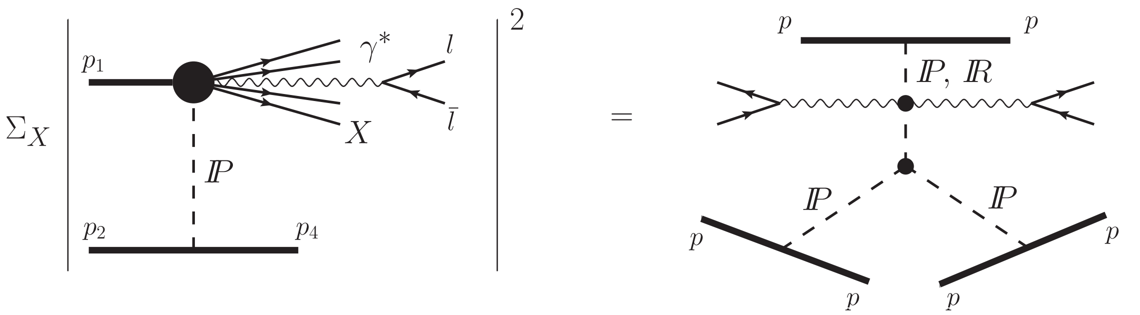
flattening low kt dependence! Further tests are required..



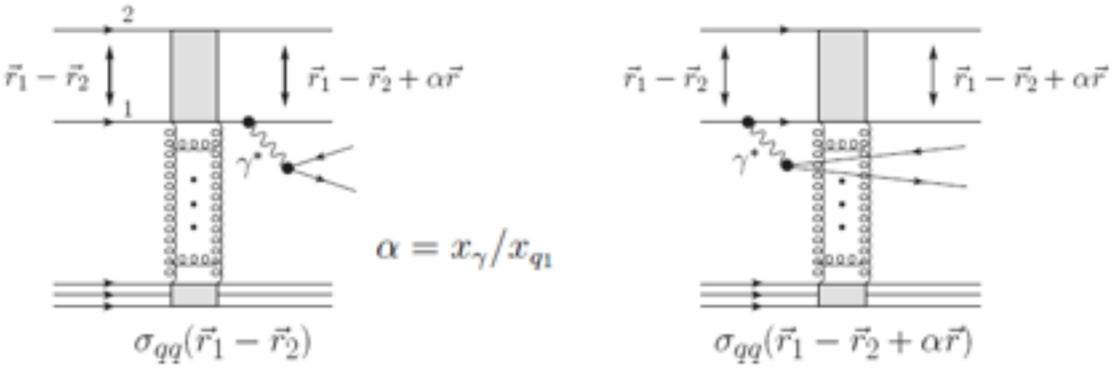
$\lambda = N_c\alpha_S(k_t)\Theta(k_t'-k_t)$ LLx 3P coupling

$$\lambda\Omega^b(y,k_t') = N_c\pi^2\alpha_s(k_t')\frac{f^b(y,k_t')}{16\pi k_t'^2\,B_g}$$

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

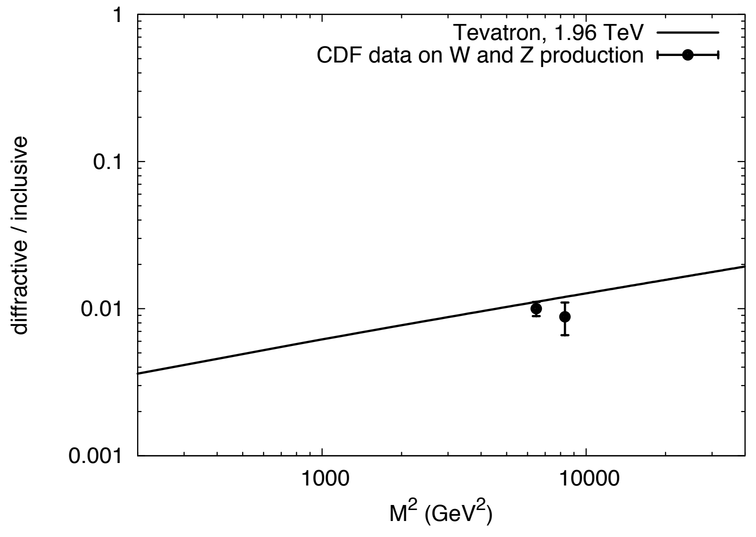
superposition has a **Good-Walker structure**

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

interplay between hard and soft fluctuations is pronounced!

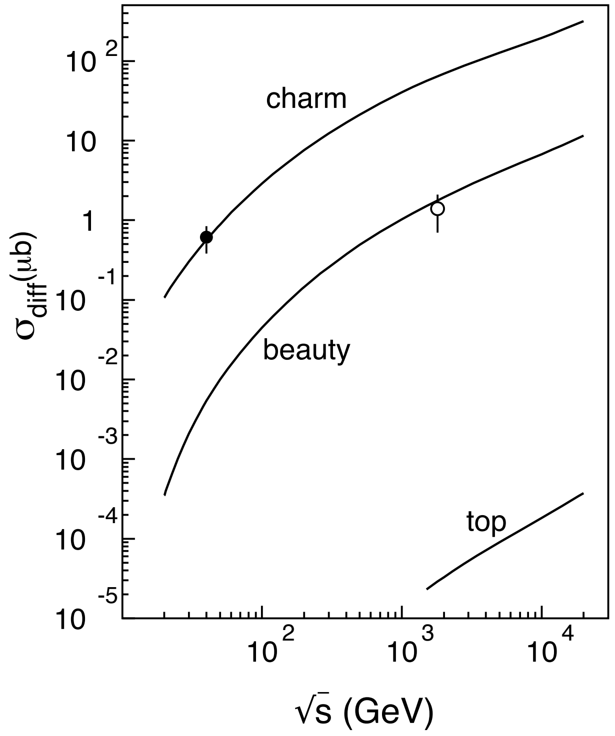
Diffractive DIS $\propto r^4 \propto 1/M^4$ **vs diffractive DY** $\propto r^2 \propto 1/M^2$

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*

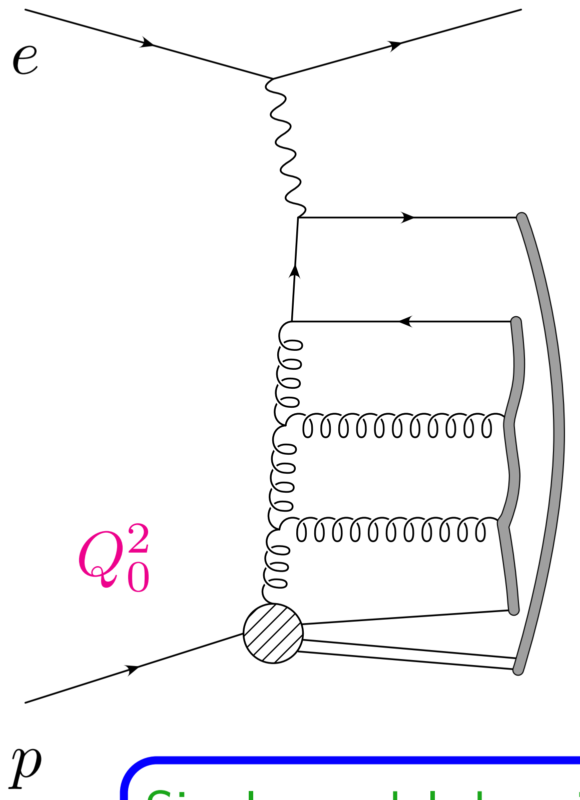
Sophisticated dipole cascades are being put into MC: Lund Dipole Chain model (DIPSY)
Ref. G. Gustafson, and L. Lönnblad

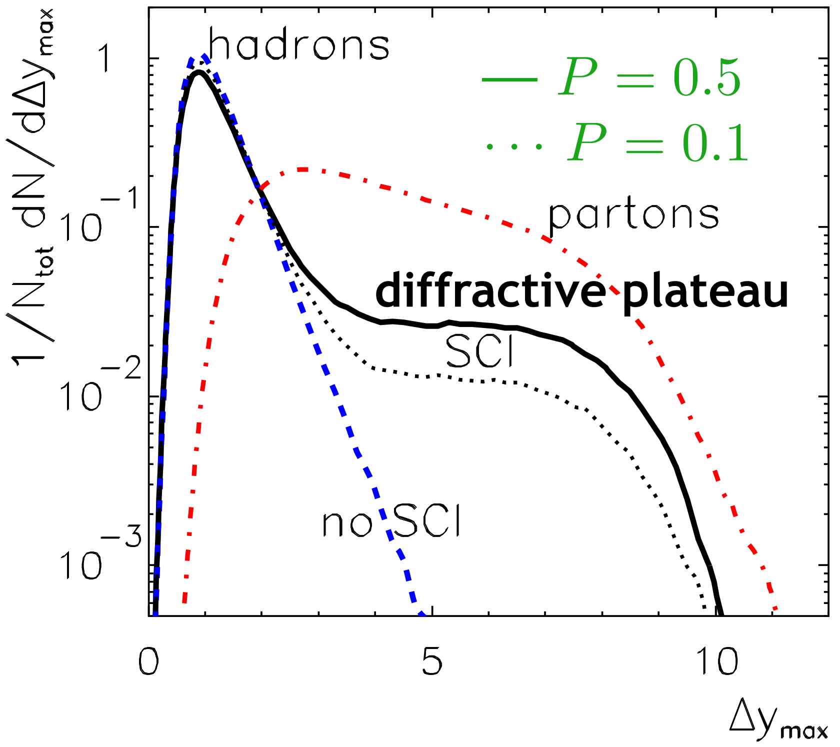
Sensitivity to the color string topology fluctuations

Edin, Ingelman, Rathsman

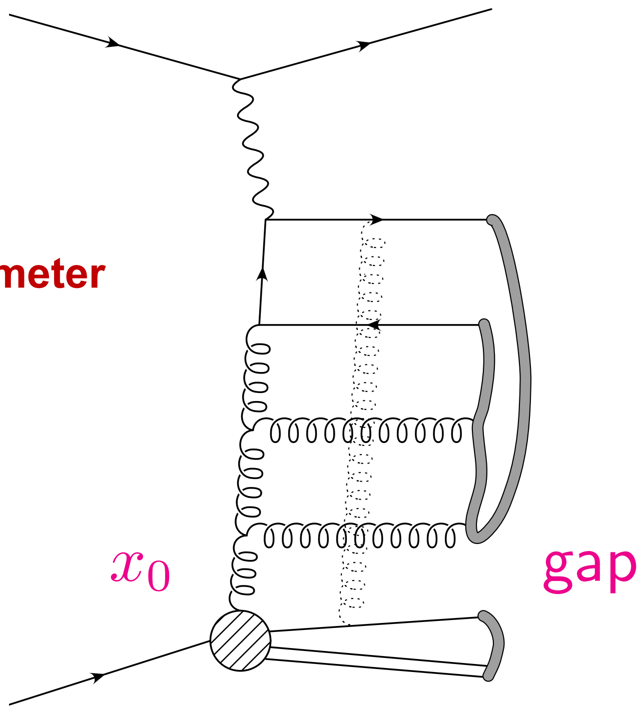
ME + DGLAP PS > Q_0^2 → SCI model → String hadronisation ~ Λ

colour ordered parton state → rearranged colour order → modified final state





single parameter model

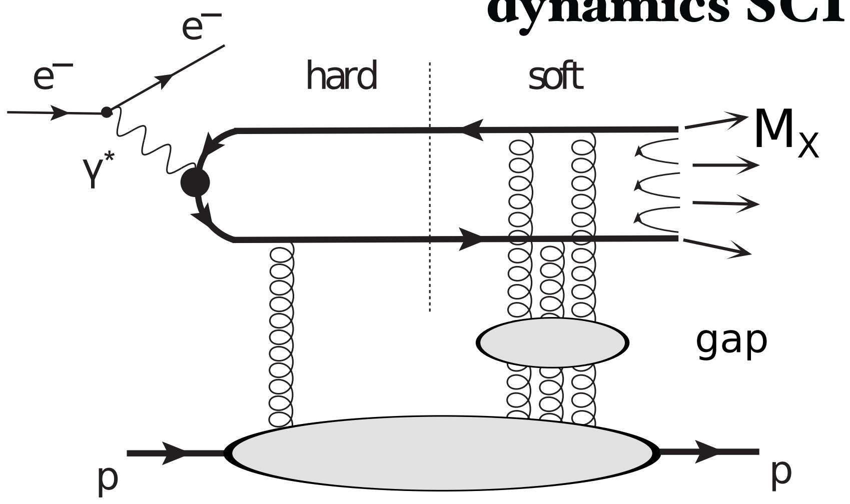


Single model describing all final states: diffractive ↔ nondiffractive

Gap events not 'special', but fluctuation in colour/hadronisation

diffractive events from fluctuations in color string topology!

dynamics SCI



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

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

reconnection probability becomes dynamical

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

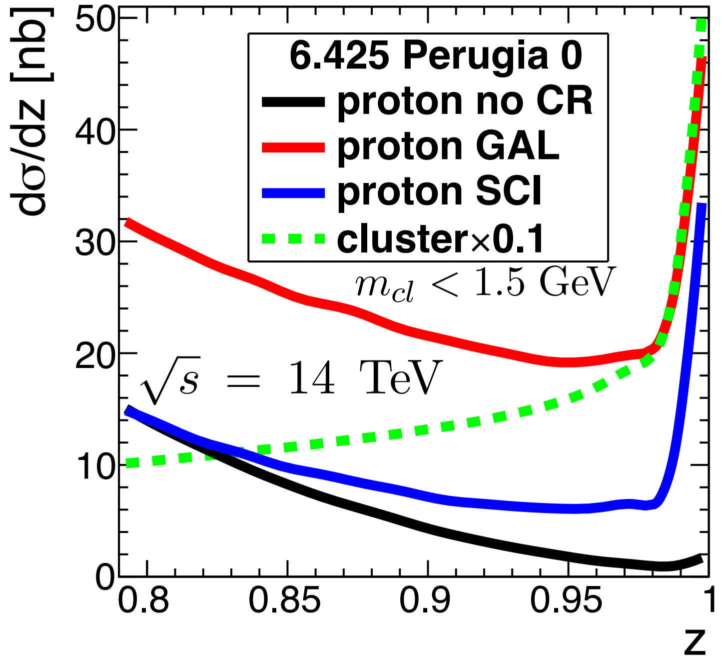
RP, Ingelman, Enberg

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

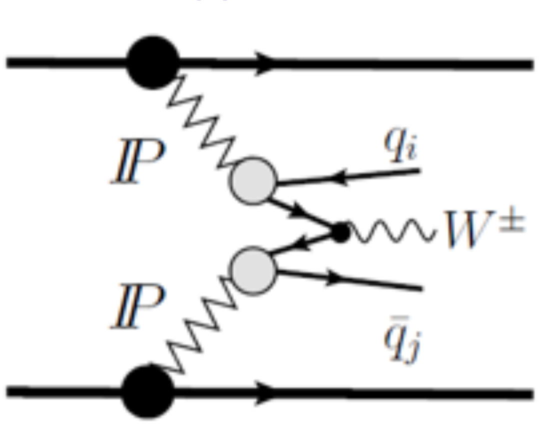
$$z = |p_z|/p_{\rm beam} \qquad pp \to p[W^{\pm}X]$$



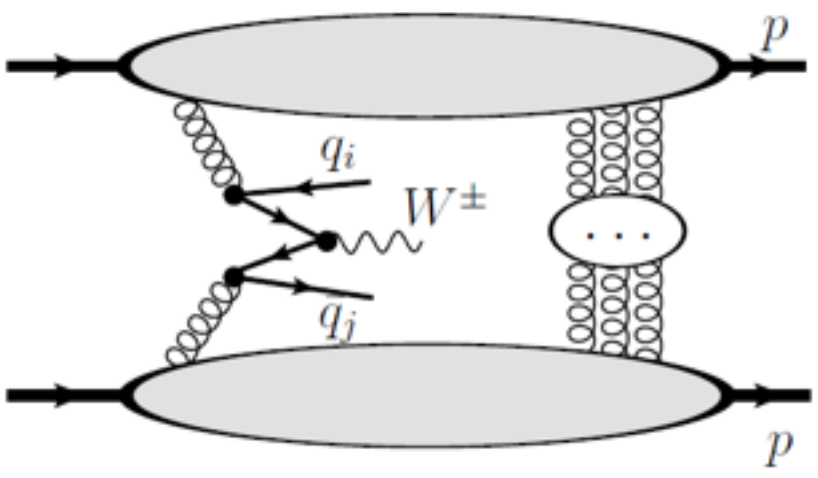
background for anomalous couplings studies with forward detectors
see C. Royon

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

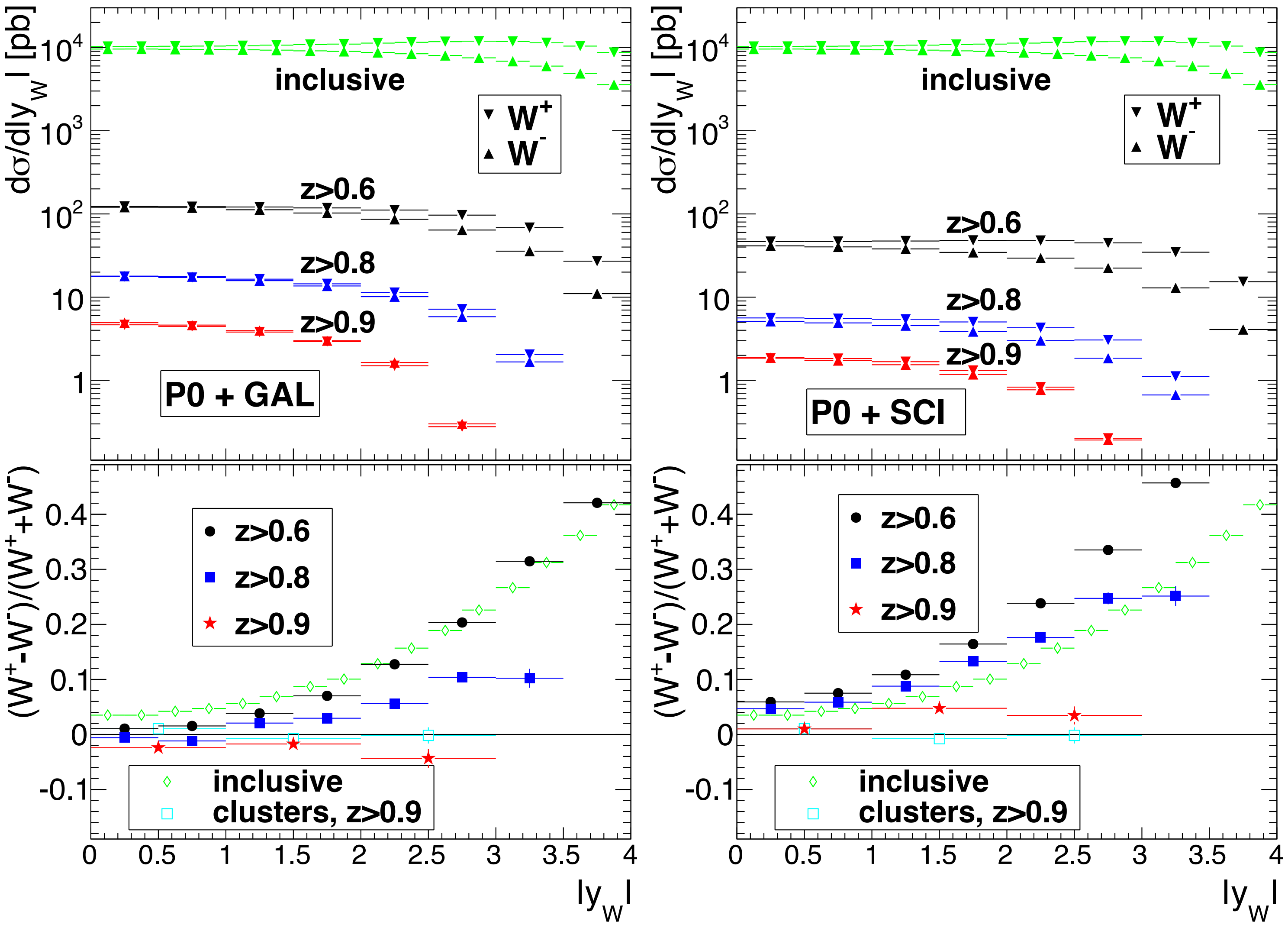
Regge models



QCD inspired models

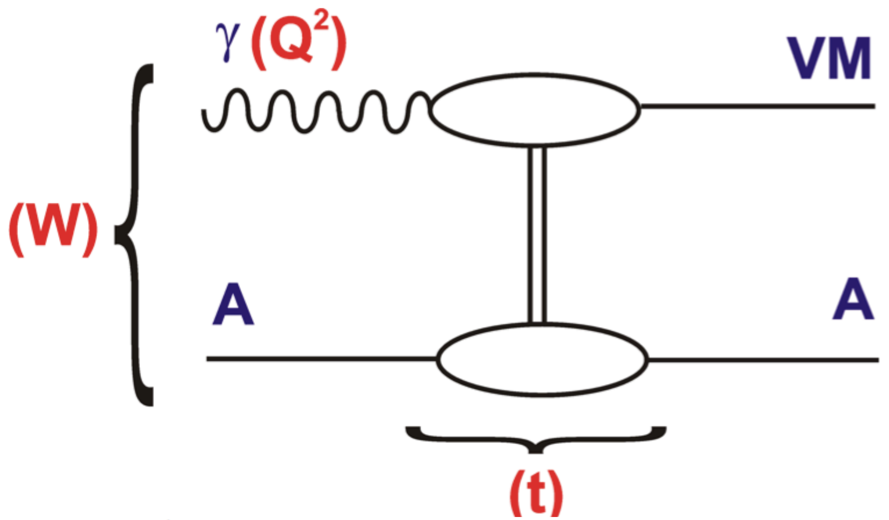


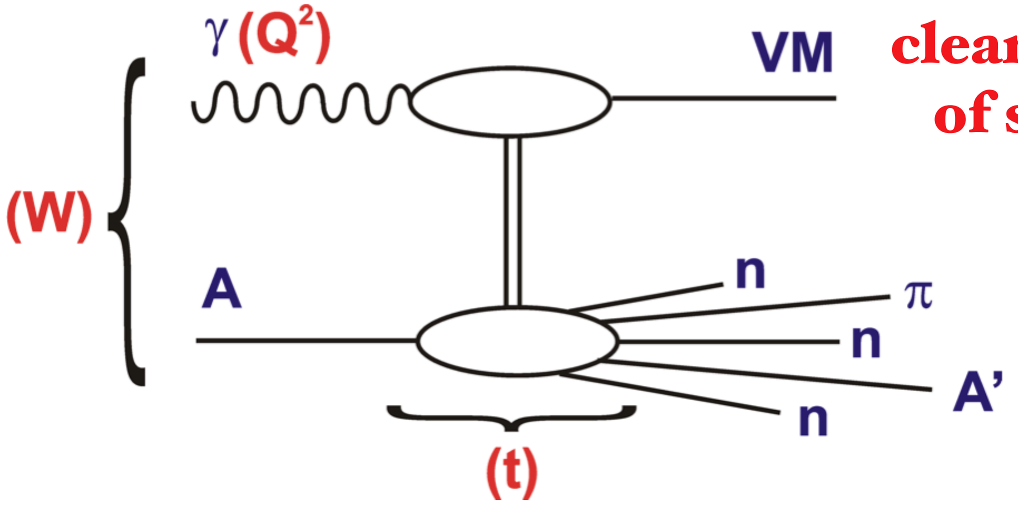
Ingelman, RP, Rathsman, Werder



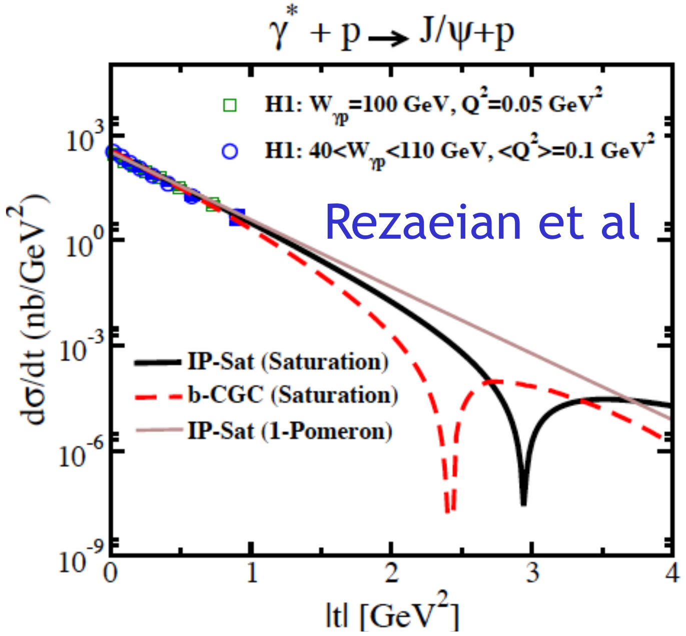
Mainly gluon-initiated diffraction at large Z!

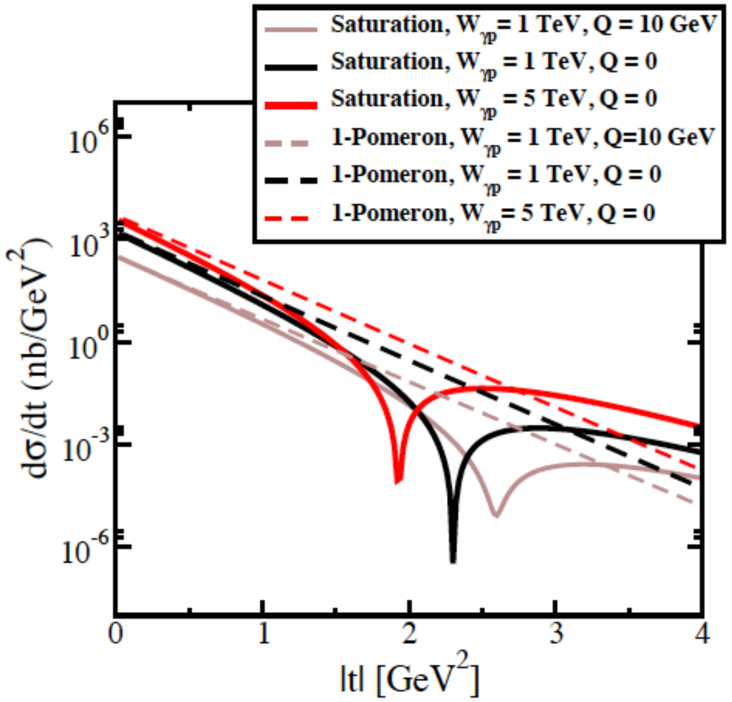
Saturation studies via coherent diffraction

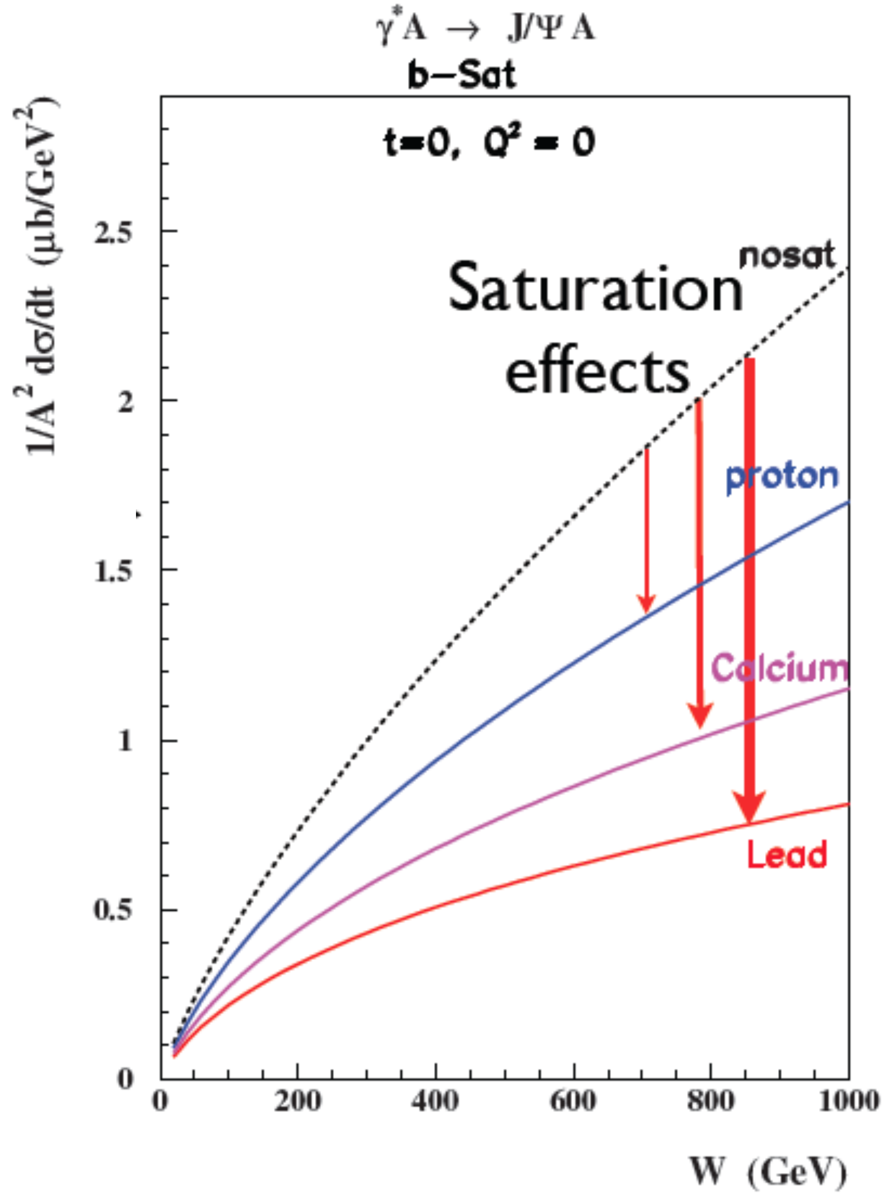


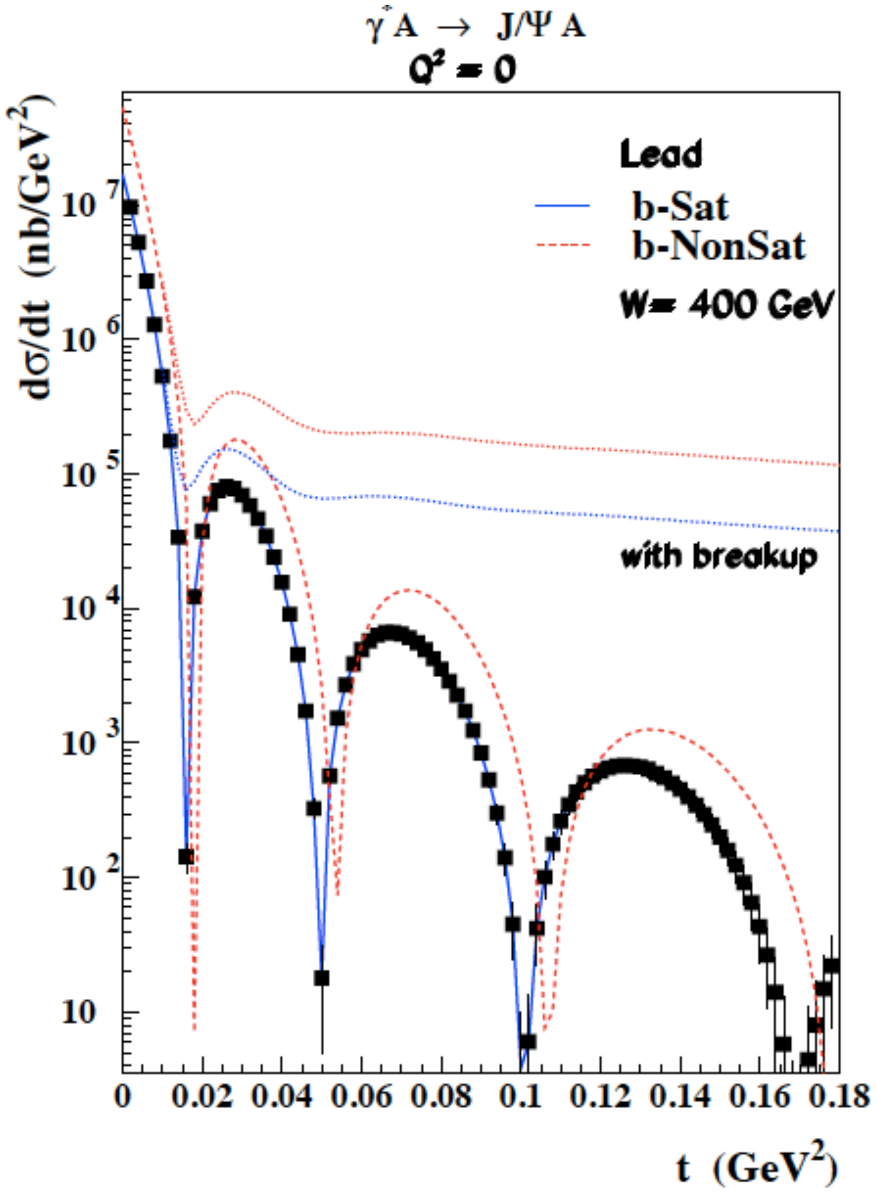


clean signatures of saturation



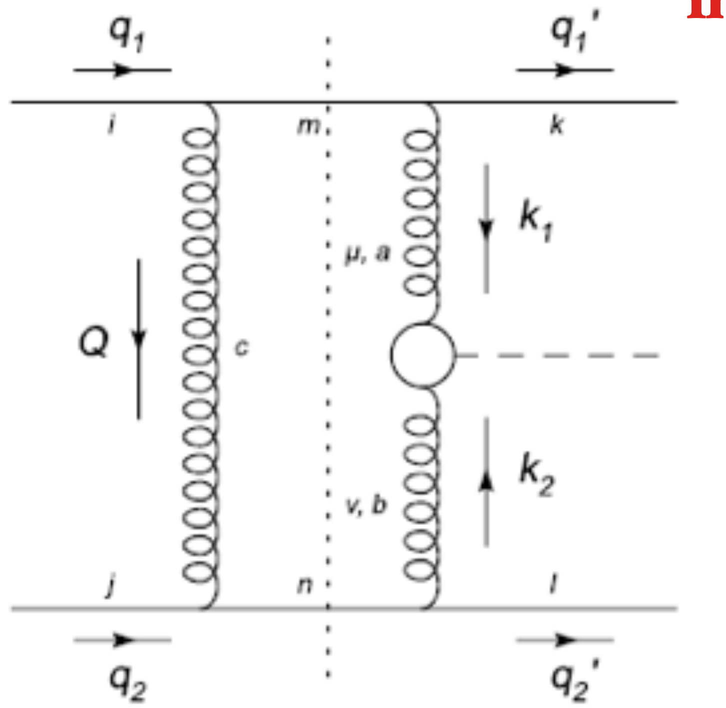






Central exclusive Higgs... etc production

parton level



The Durham (KMR) model

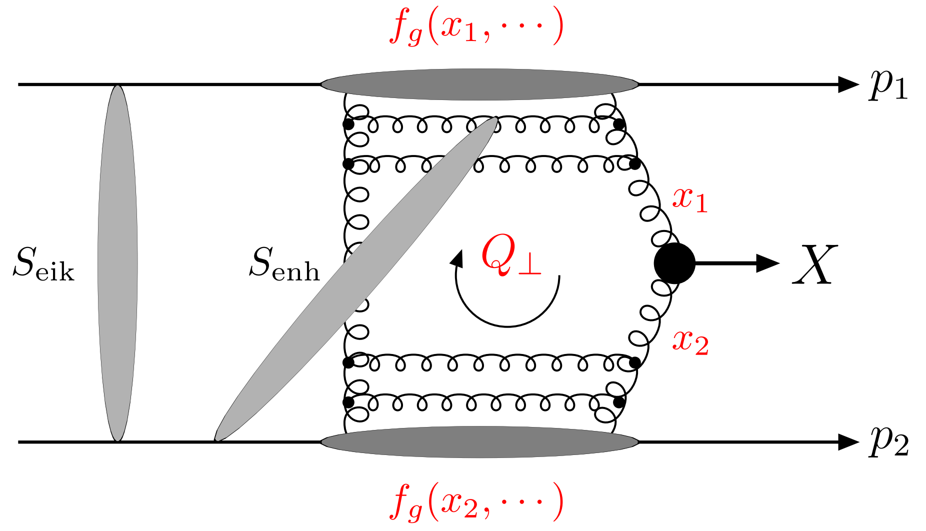
implemented in ExHuME MC

In the forward limit

$$\epsilon_i \sim k_{it}$$

$$Q_t = -k_{1t} = k_{2t}$$

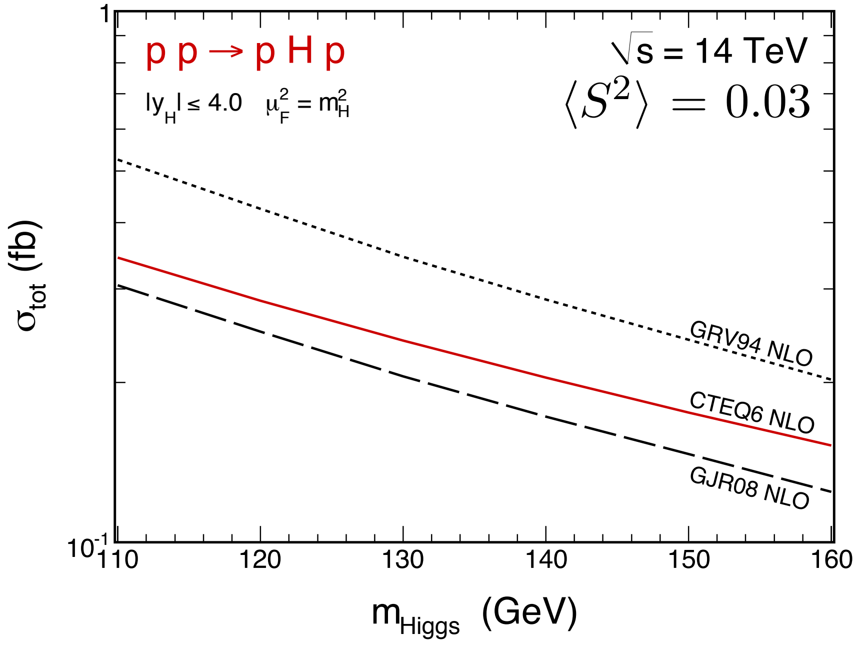
Spin-parity analyser!

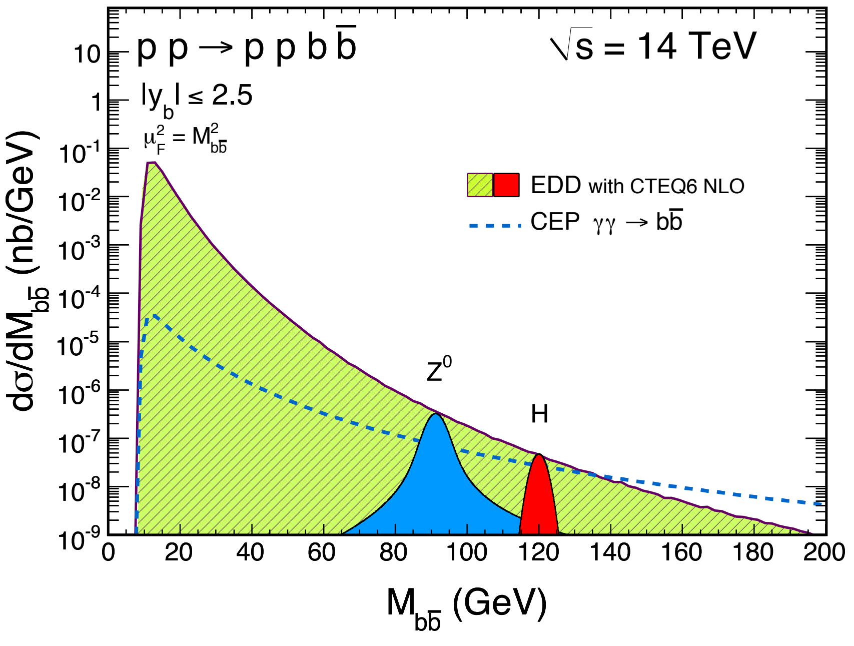


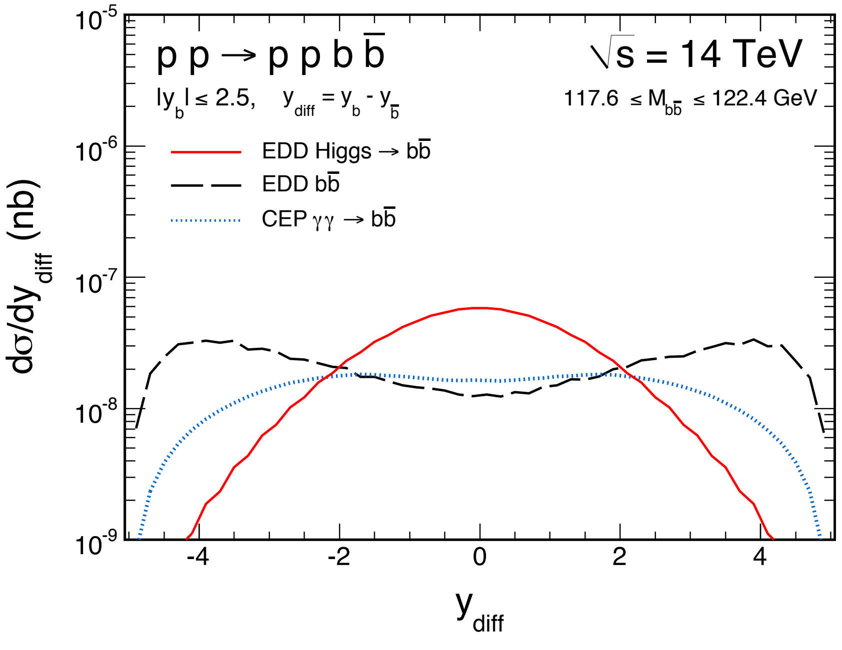
- Correct inclusion of Sudakov factor — JHEP 1001 (2010) 121
- Consistent treatment of ‘skewed’ gluon PDFs — Phys. Rev. D88 (2013) 034029
- Latest model of soft survival effects — Eur.Phys.J. C73 (2013) 2503

Small CS/large uncertainties

Large irreducible backgrounds







RP + Krakow group

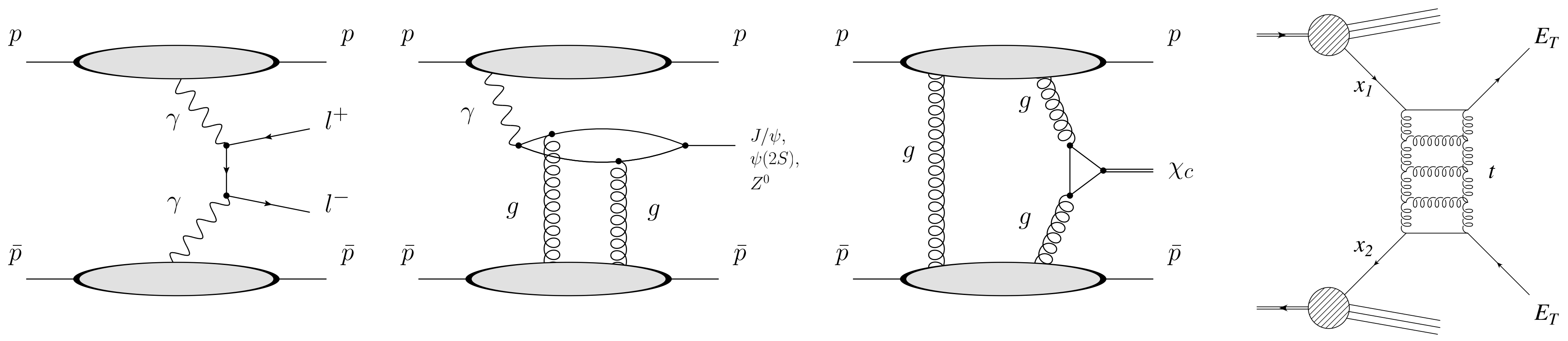
Higgs CEP was proven to be hardly feasible at the LHC...

More exclusive/diffractive reactions...

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

Examples of typical exclusive reactions studied so far...

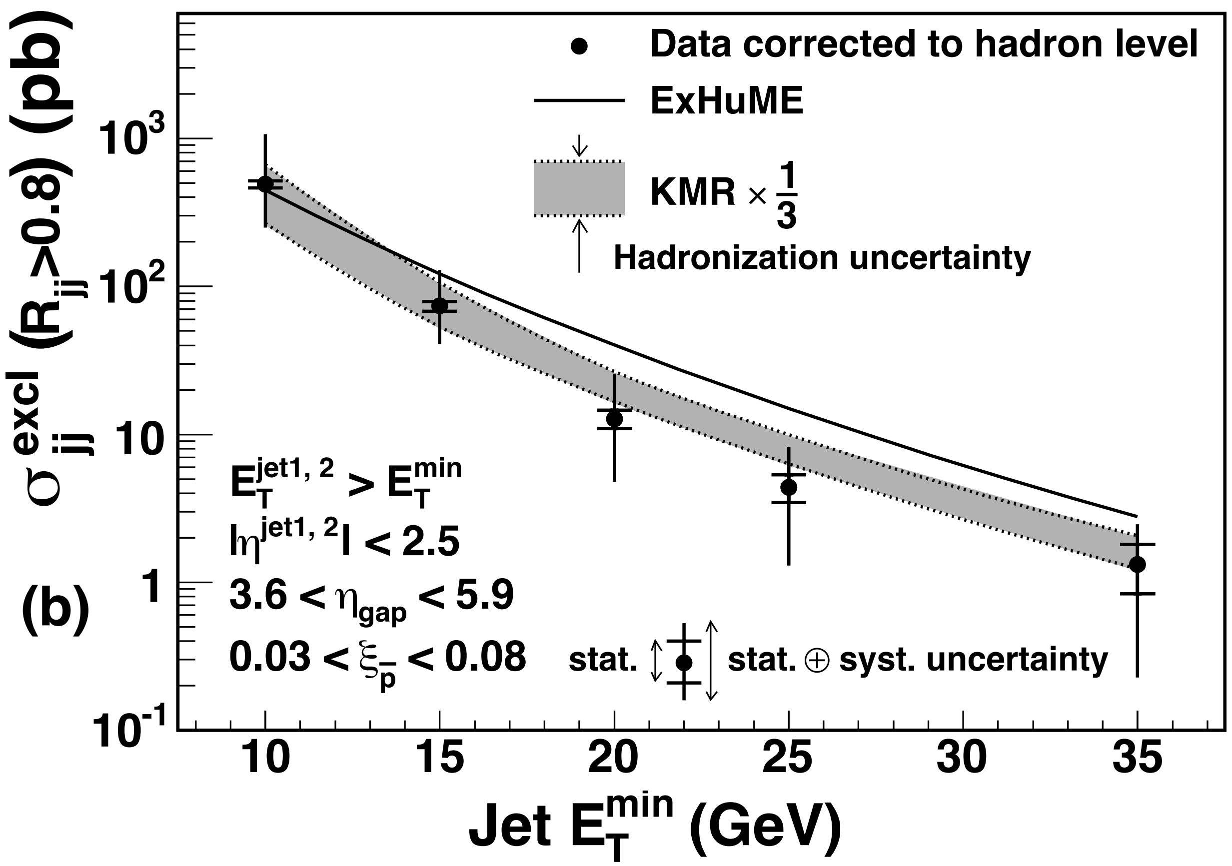
many covered in SuperChic and FPMC Monte Carlo generators



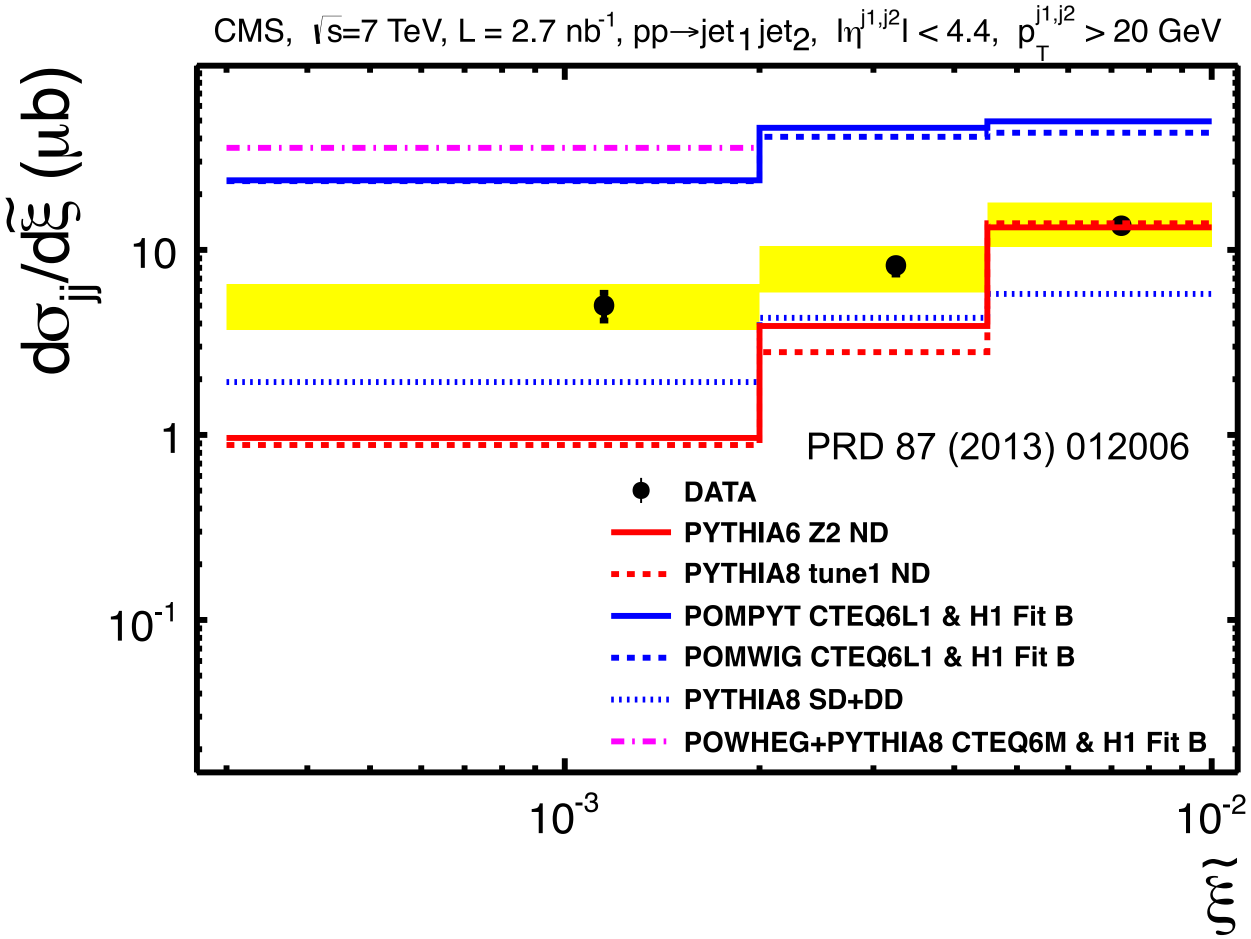
L. Harland-Lang + Durham group

Example: Diffractive di-jets at Tevatron

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



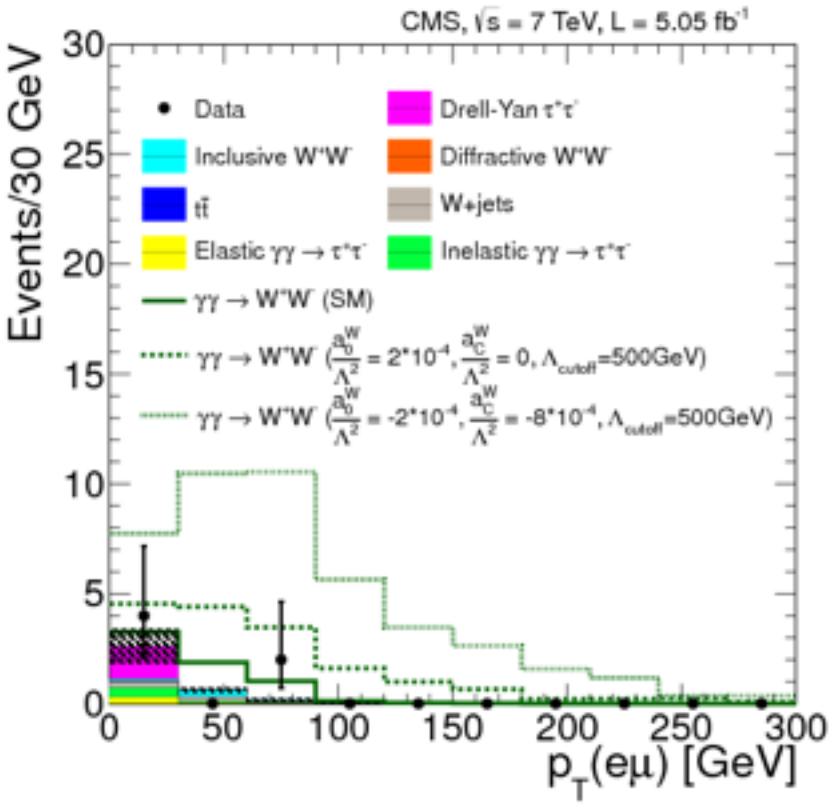
Example: Diffractive di-jet at the LHC

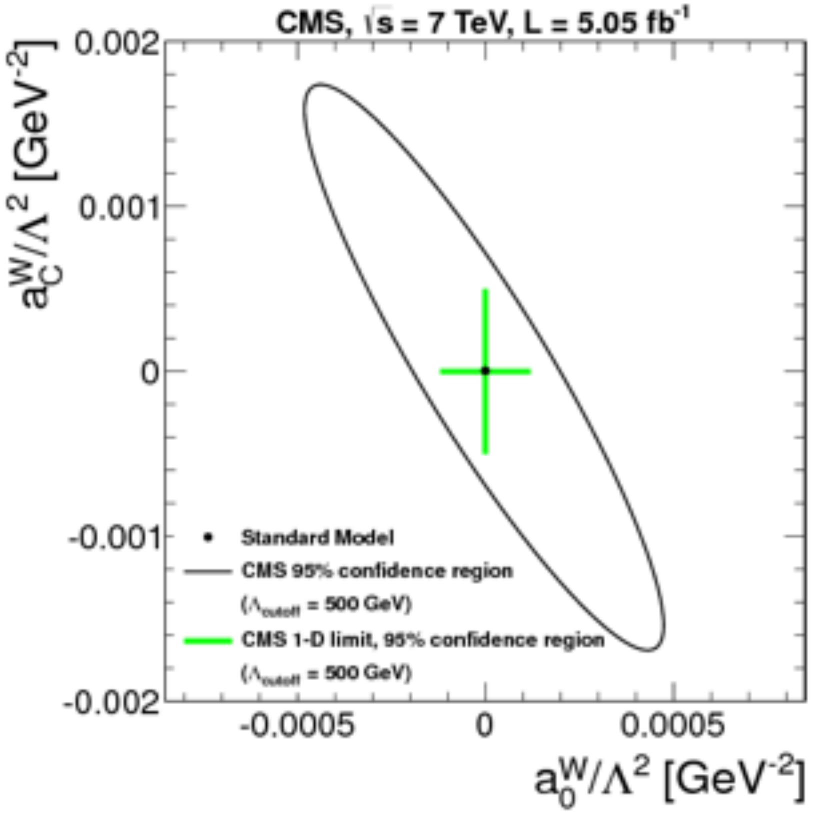


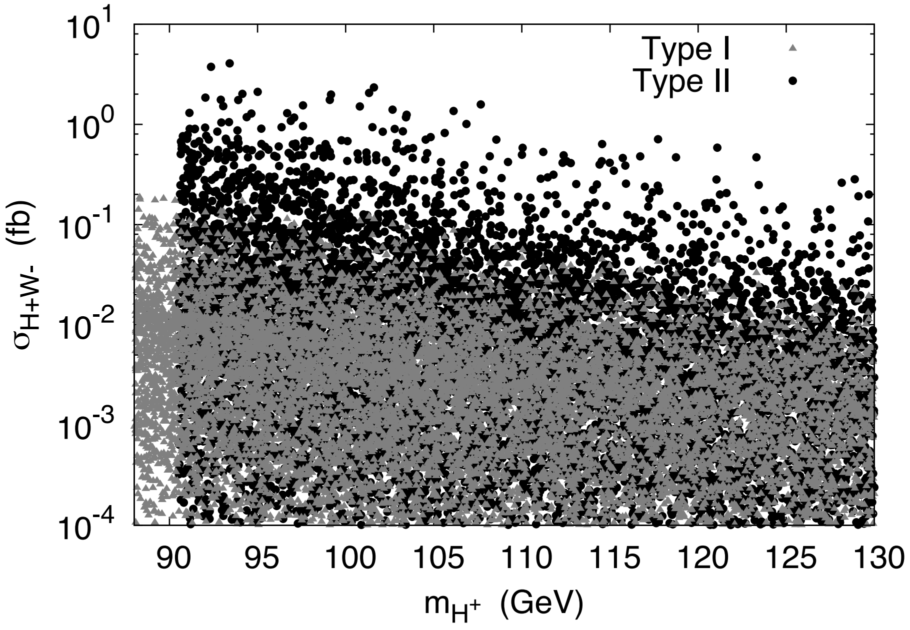
New Physics via CEP

anomalous couplings JHEP 1307 (2013) 116

charged Higgs+W CEP



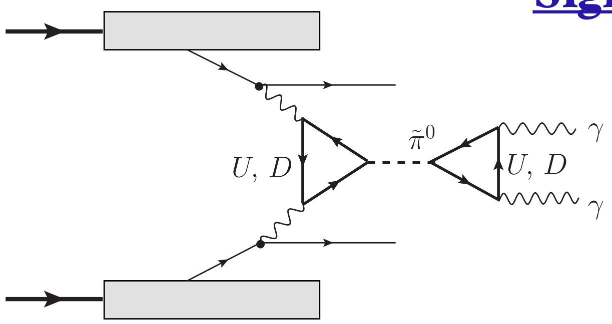


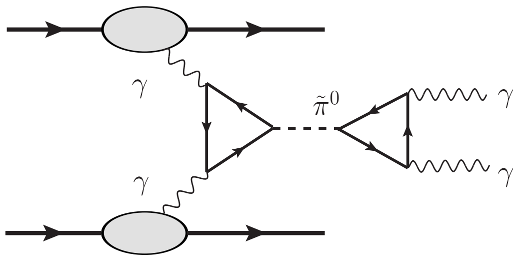


RP, R. Enberg PRD'11

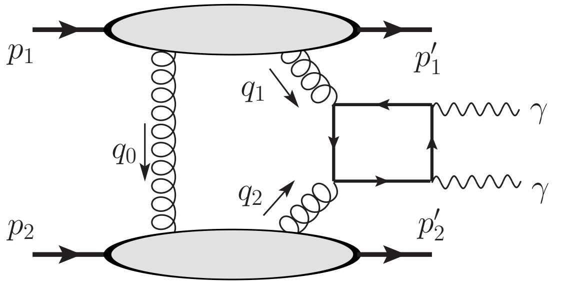
RP, Szczurek, Lebiedowicz, NP881, 288 (2014)

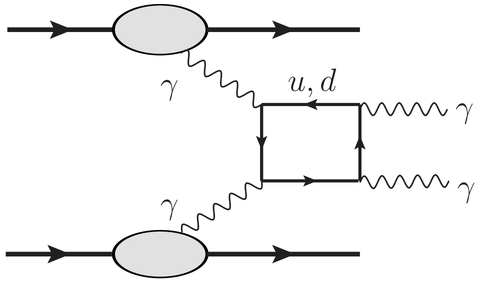
Signal

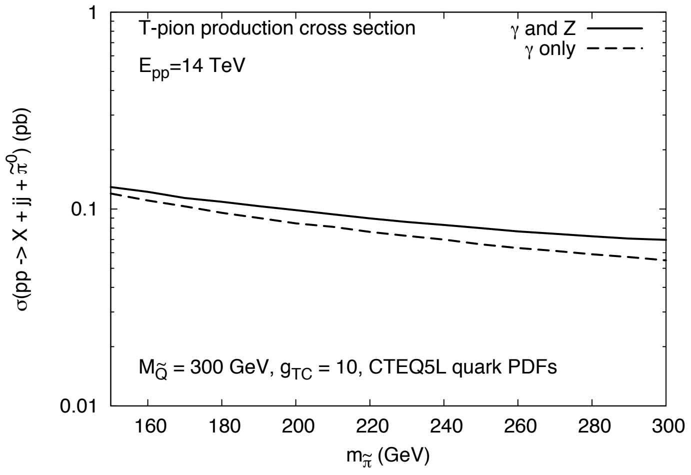


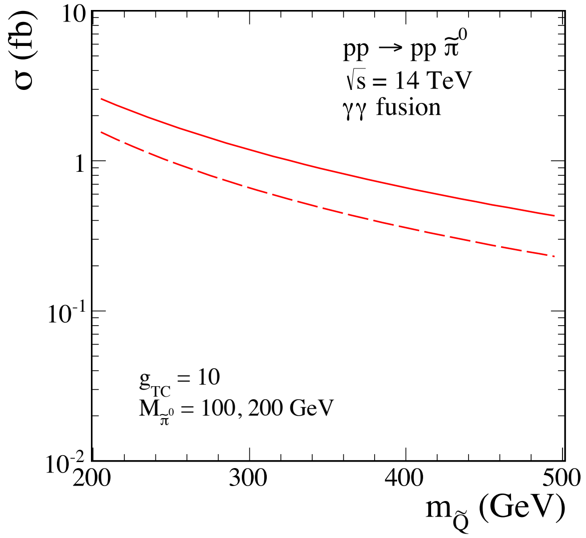


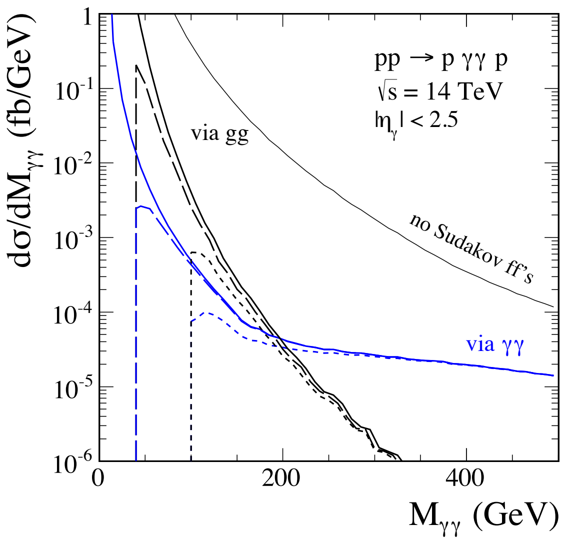
Background











see also Royon

Summary: 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
- ✓ Exclusive diffraction opens up new opportunities for New Physics searches due to reduced backgrounds