Hadronic diffraction as a probe for long-distance effects in QCD

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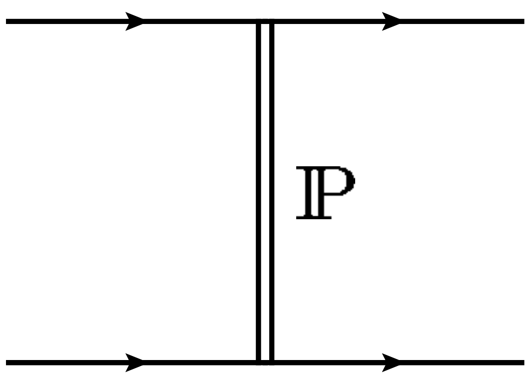
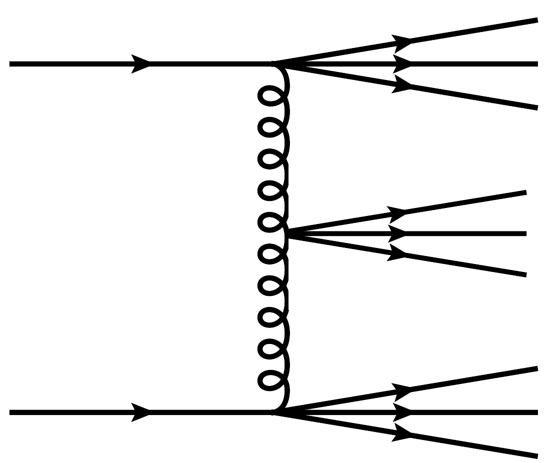
Lund U.

Definition of diffraction

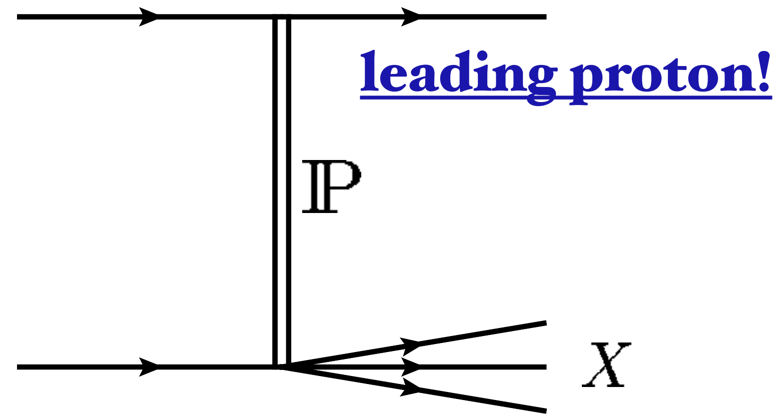
elastic



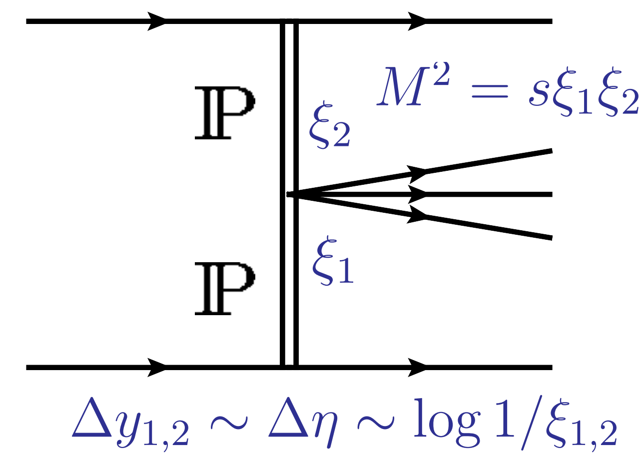
non-diffractive (inclusive)



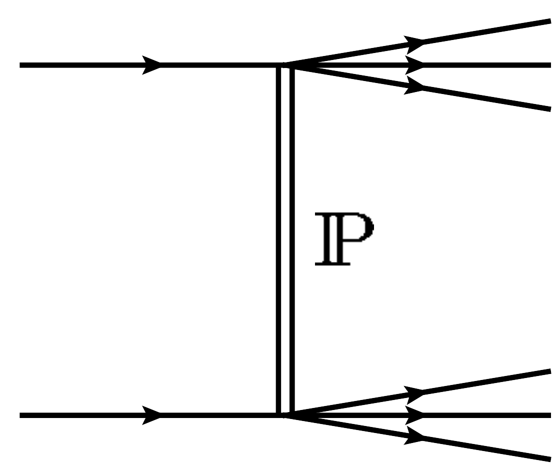
single diffractive



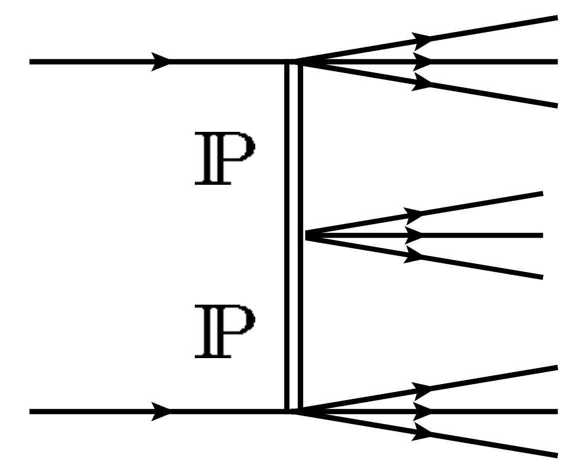
central exclusive



double diffractive



DPE



Basic features of diffraction:

- ★ *no quantum numbers are exchanged*
- ★ *a new (diffractive) state is produced*
- ★ *characterised by large LRGs*
- ★ *mainly peripheral phenomenon (large b)*

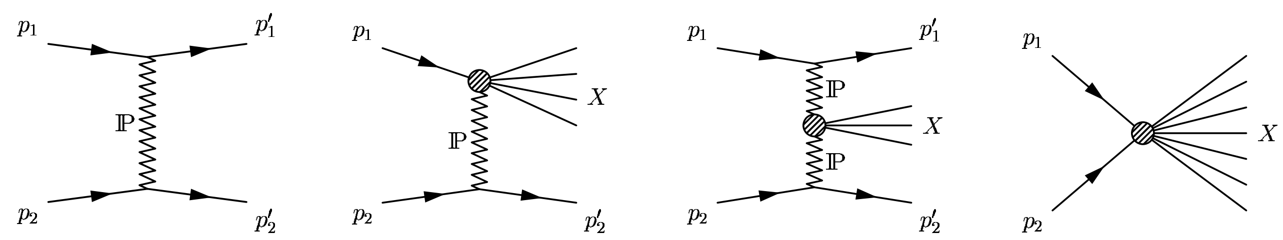
"The diffractive process is caused by **t-channel Pomeron exchange** i.e. by the exchange corresponding to the rightmost singularity in the complex angular momentum plane with vacuum quantum numbers.." A. Martin

Challenges: theory vs experiment

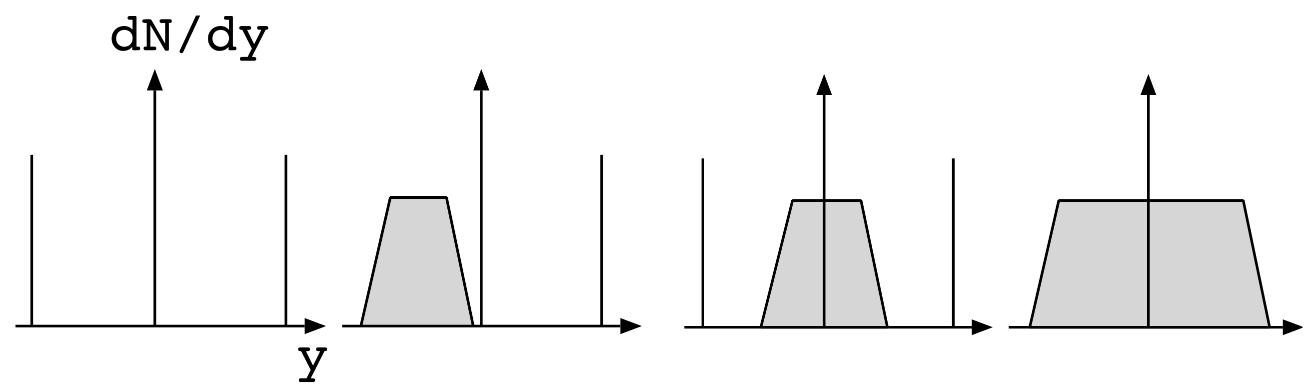
✓ **The definition of diffraction is not unique**

Theoretically:

★ *exchange of vacuum quantum numbers*



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



Experimentally:

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

★ *gap definition*

Rapidity $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

$\approx - \ln \tan \frac{\theta}{2} = \eta$ 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?)*

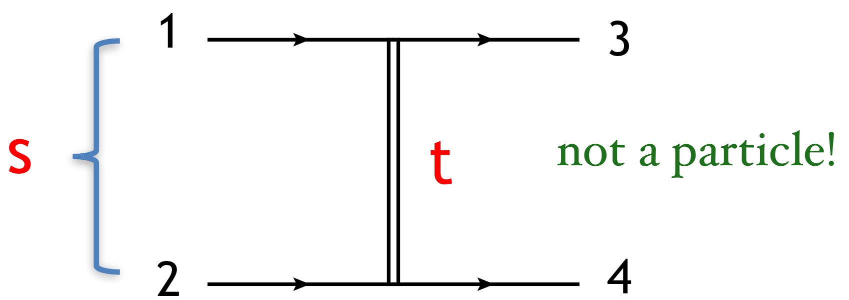
★ *low vs high mass diffractive dissociation*

★ *soft vs hard Pomeron*

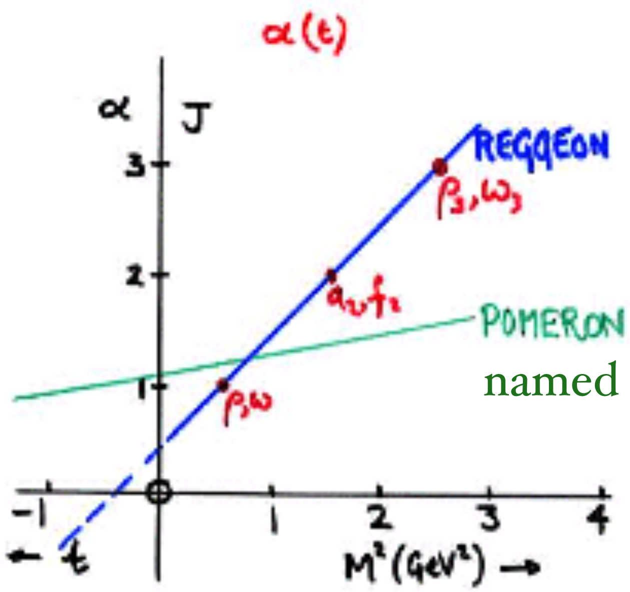
★ *hard-soft factorisation breaking, etc*

huge sensitivity to details!

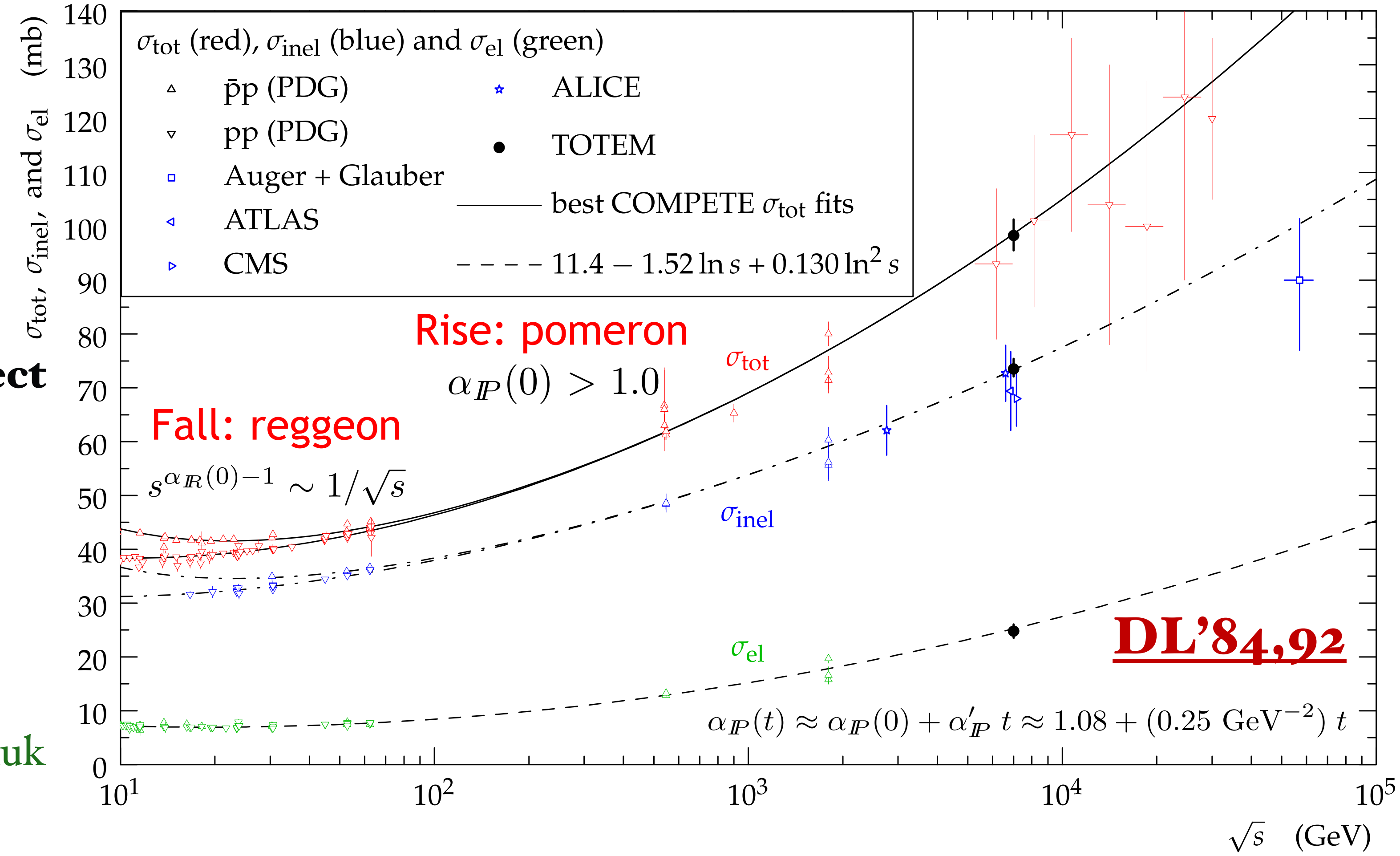
Soft Donnachie-Landshoff Pomeron



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

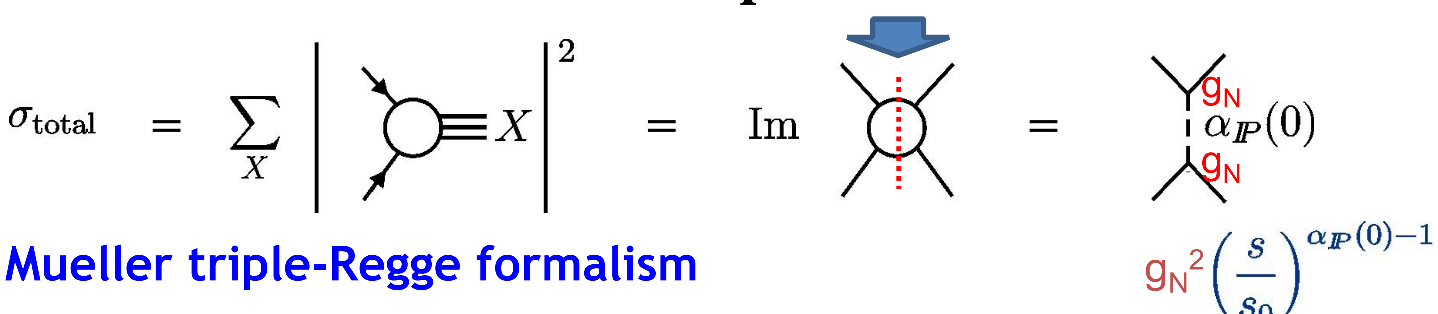


named after Pomeranchuk



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

optical theorem

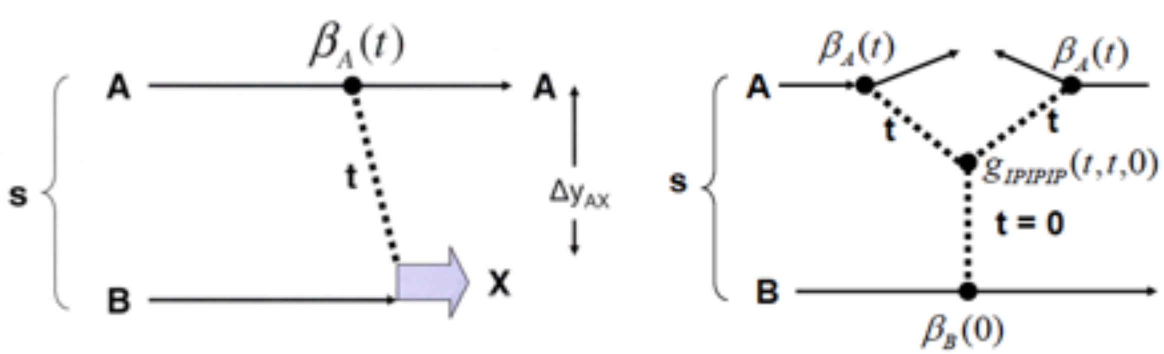


Pomeron "flux"

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

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

Mueller triple-Regge formalism



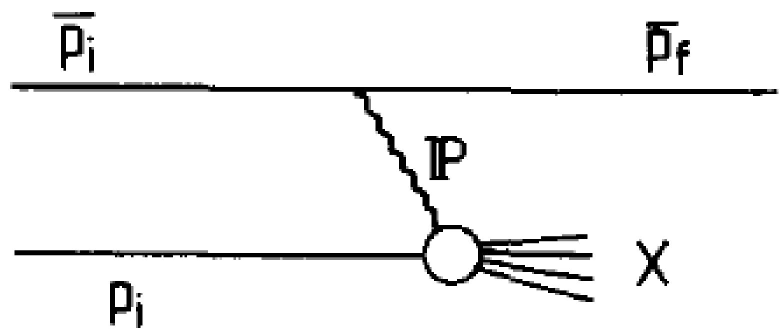
$$\sigma \sim g_{pP}^2(t) g_{pP}(0) g_{3P} \left(\frac{s}{M_X^2}\right)^{2(\alpha(t)-1)} (M_X^2)^{(\alpha(0)-1)}$$

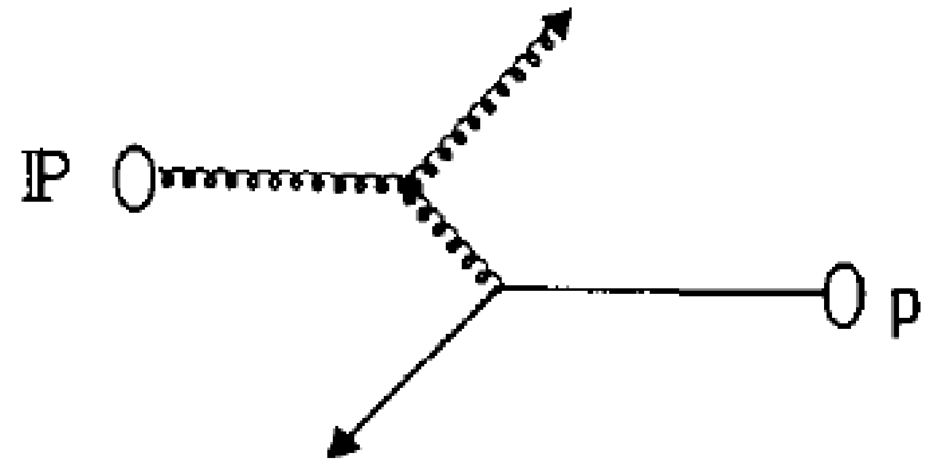
Albrow, Coughlin, Forshaw, Prog.Part.Nucl.Phys 65 (2010) 149

Birth of hard diffraction: QCD modelling of Pomeron

Ingelman-Schlein, Phys. Lett. 1985

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





Monte-Carlo model with effective

$I\!P$ flux $f_{I\!P/p}(x_{I\!P}, t)$

$I\!P$ parton densities $f_{q,g/I\!P}(z, Q^2)$

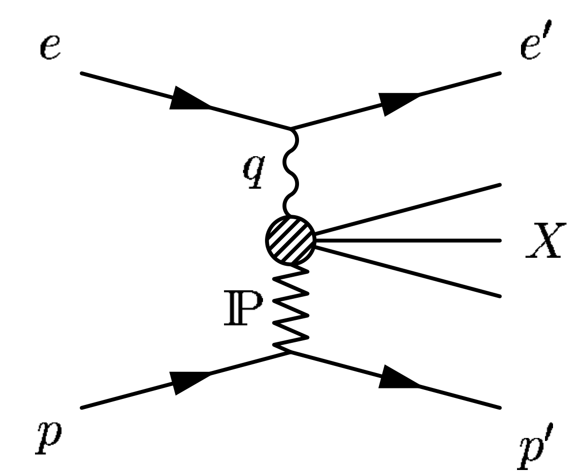
$\Rightarrow$ $d\sigma \sim f_{I\!P/p}\, f_{q,g/I\!P}\, f_{q,g/p}\, d\hat{\sigma}_{\text{pert. QCD}}$

Diffractive factorisation concept

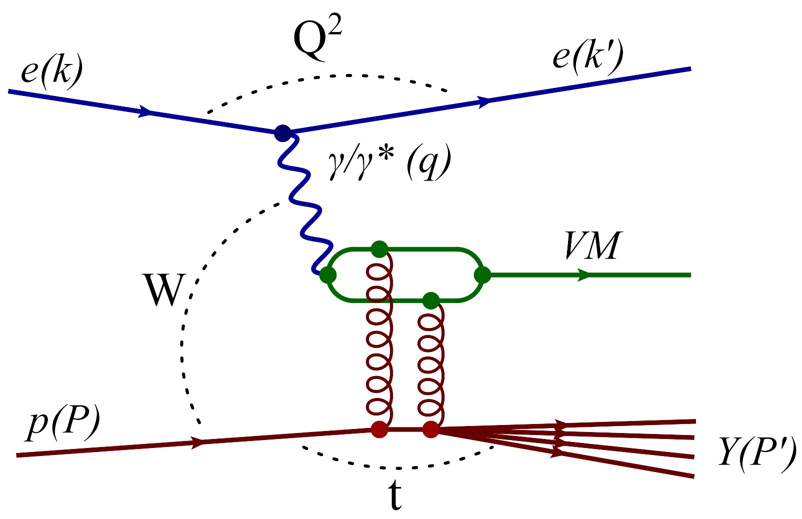
Implemented in POMPYT, CASCADE, and PYTHIA8 MC

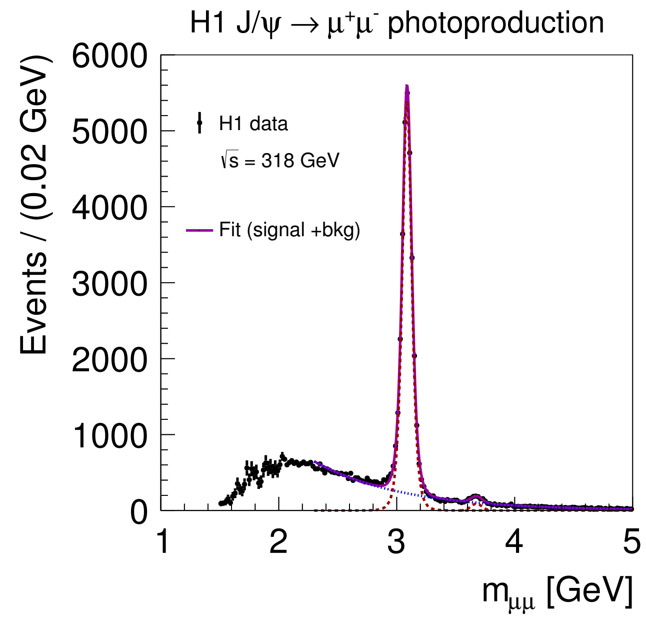
Predictions for

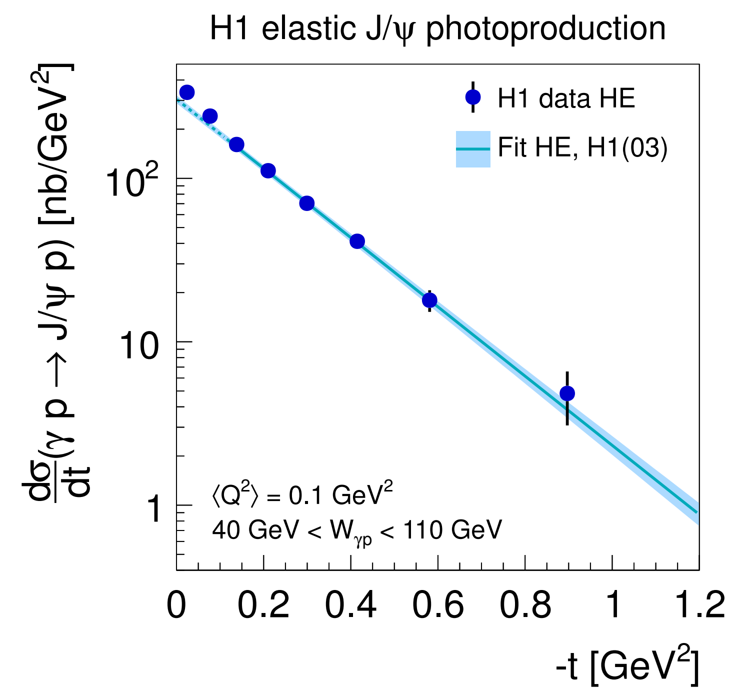
- ★ jets in diffractive $p\bar{p}$ scattering
  - $\Rightarrow$ basis for UA8 experiment
- ★ diffractive DIS at HERA

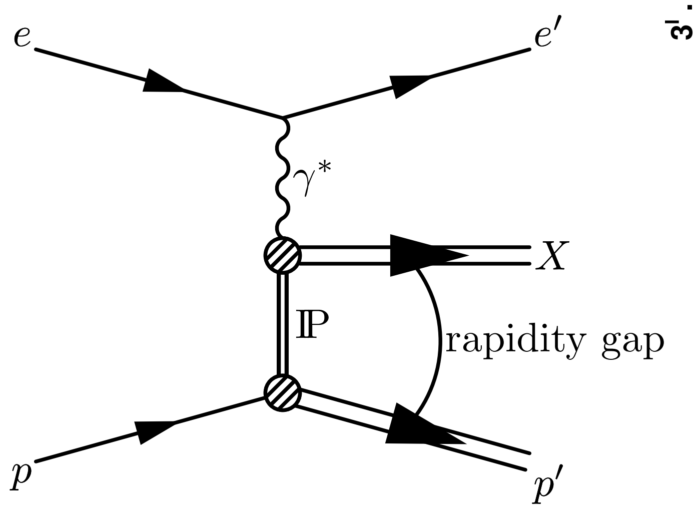


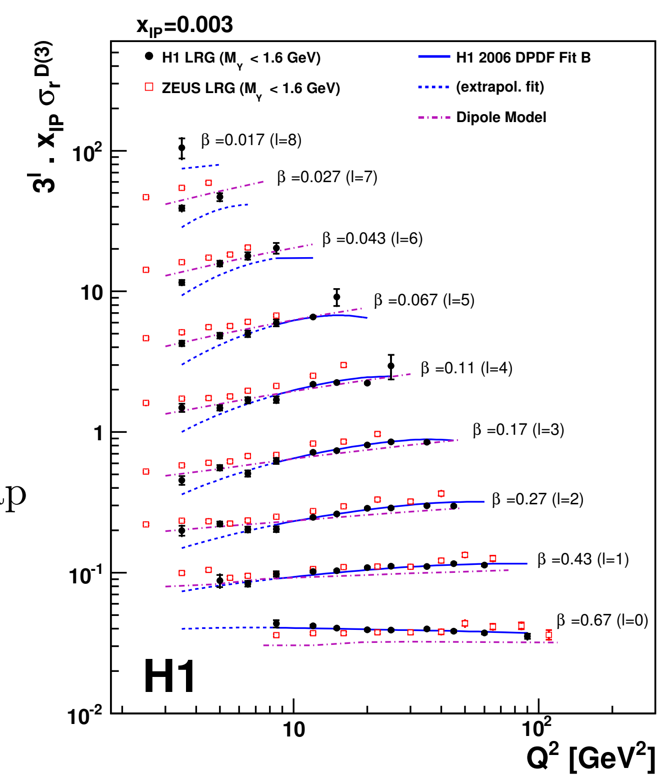
Diffraction at HERA

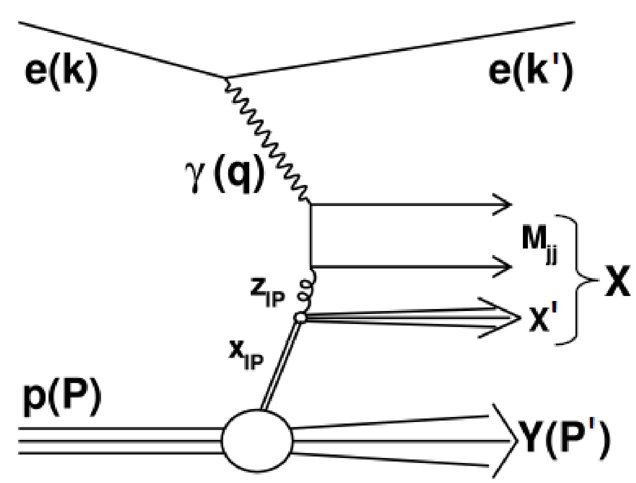


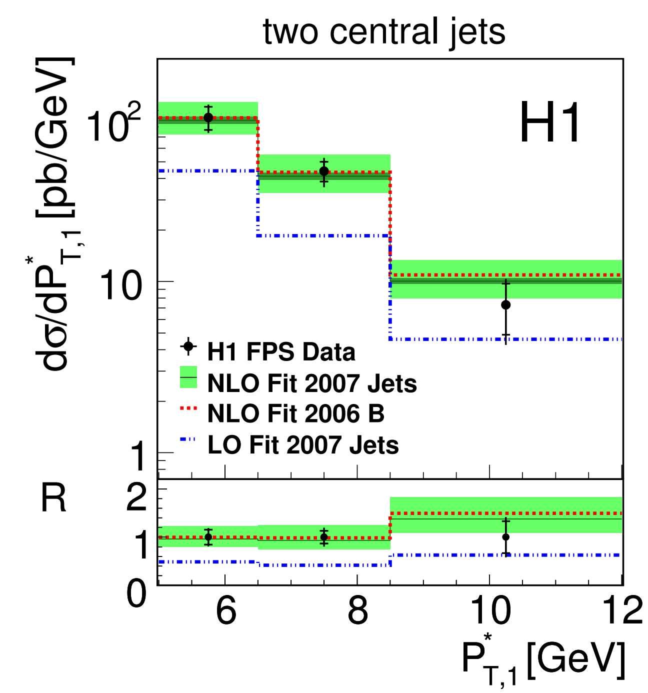






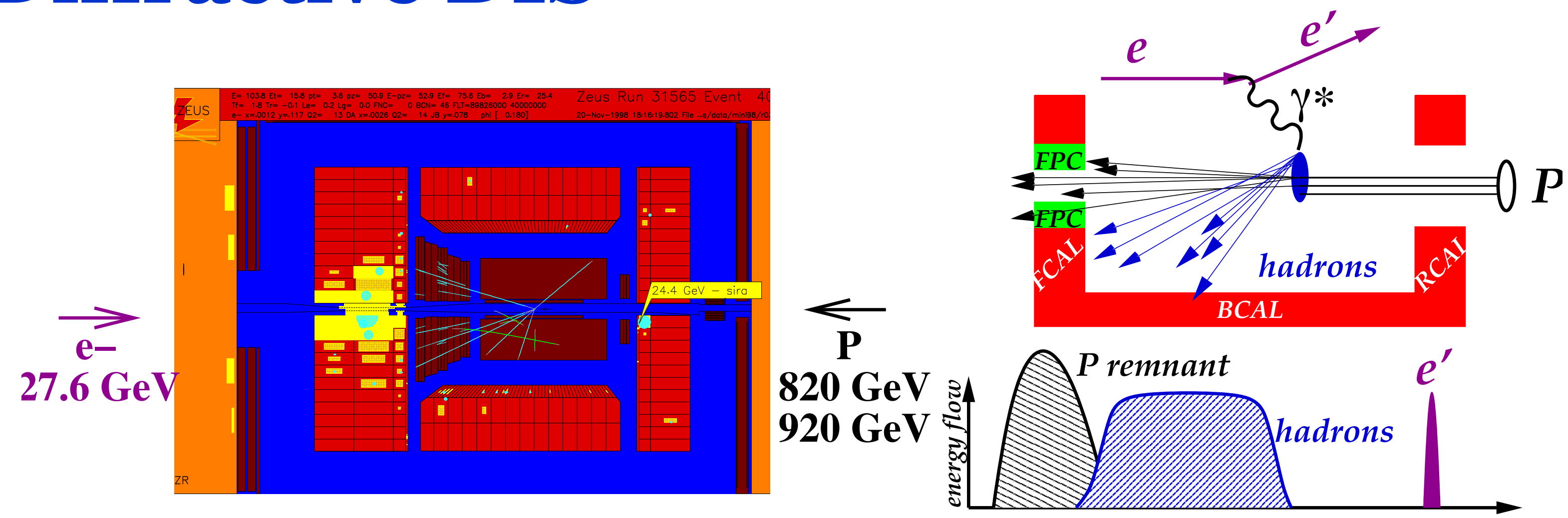






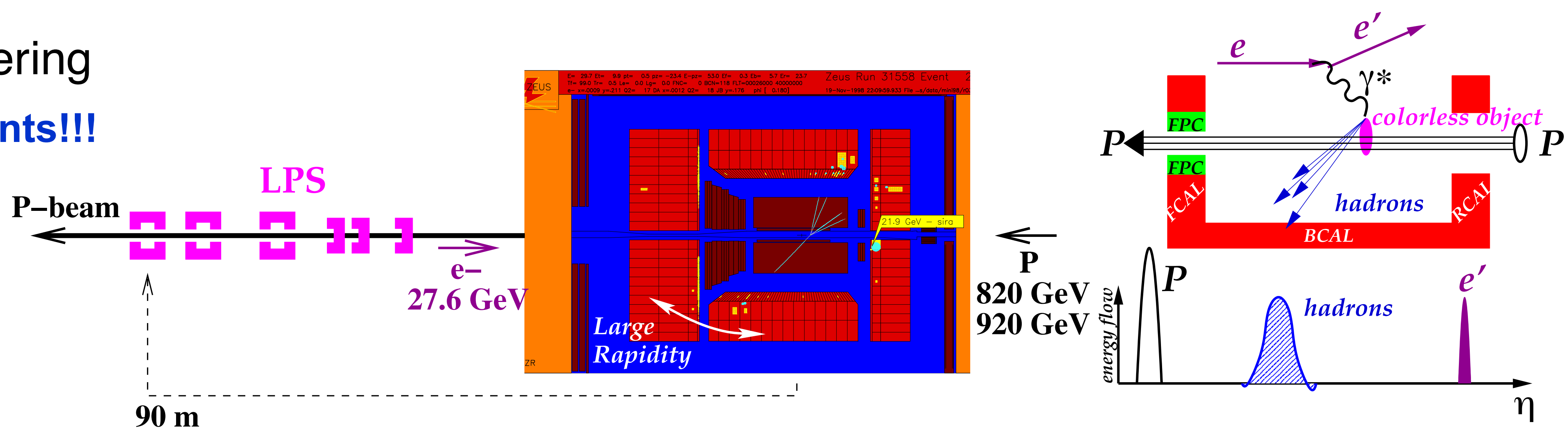
Diffractive DIS

Non-diffractive scattering

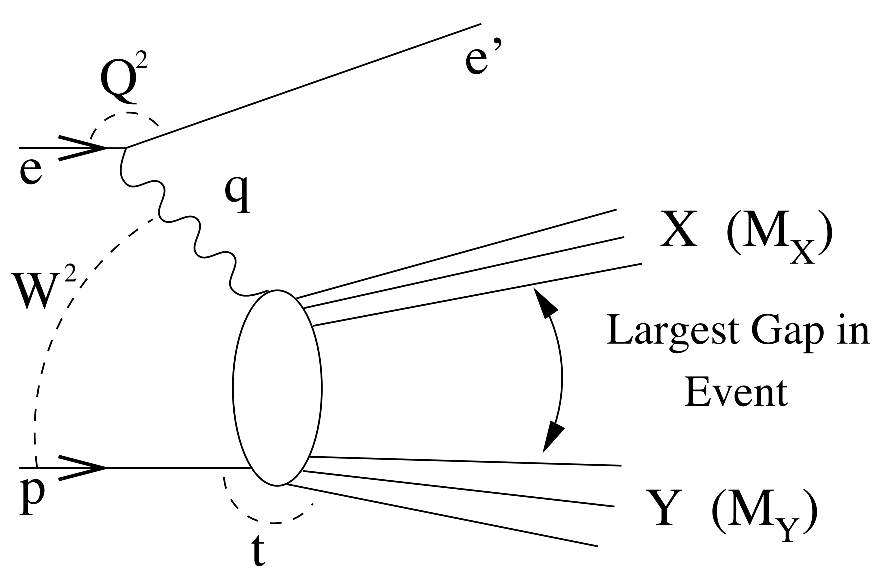


Diffractive scattering

~ 10 % of gap events!!!



$$\frac{d\sigma}{dx\, dQ^2\, dx_{I\!P}\, dt} = \frac{2\pi\alpha^2}{xQ^4}\left(1+(1-y)^2\right) F_2^{D(4)}$$



in terms of diffractive structure function

$$F_2^{D(4)}(x, Q^2, x_{I\!P}, t) = \underbrace{f(x_{I\!P}, t)}_{I\!P\text{ flux}}\ \underbrace{F_2^{I\!P}(\beta, Q^2)}_{I\!P\text{ structure}}$$

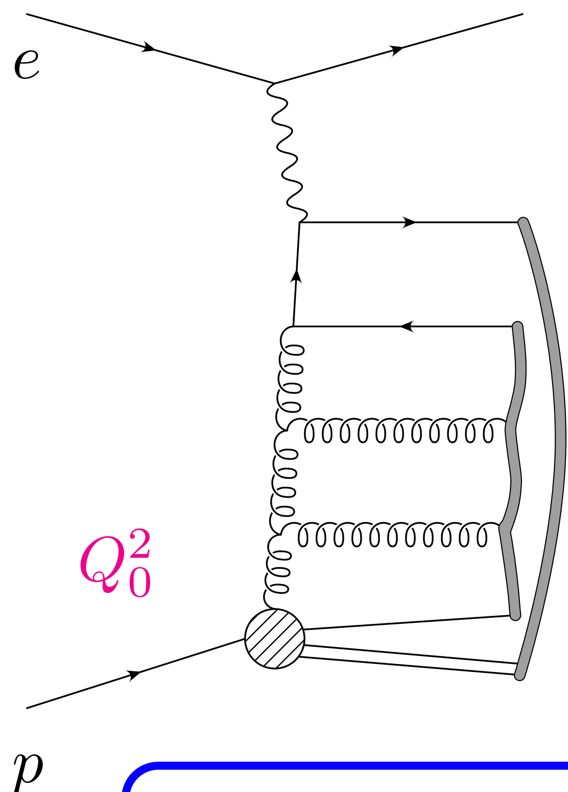
$$\beta = \frac{-q^2}{2q\cdot(p_p - p_Y)} = \frac{Q^2}{Q^2 + M_X^2 - t} \simeq p_{q,g}/p_{I\!P}$$

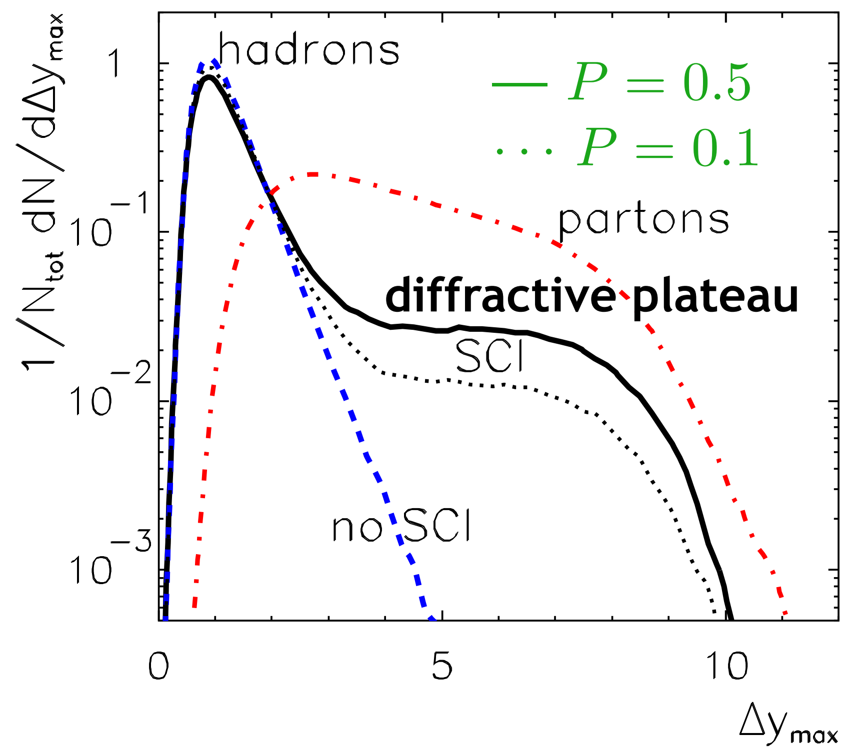
$$x_{I\!P} = \frac{q\cdot(p_p - p_Y)}{q\cdot p_p} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2 - M_p^2} = \frac{x}{\beta} \simeq p_{I\!P}/p_p$$

Sensitivity to the color string topology fluctuations

Edin, Ingelman, Rathsman

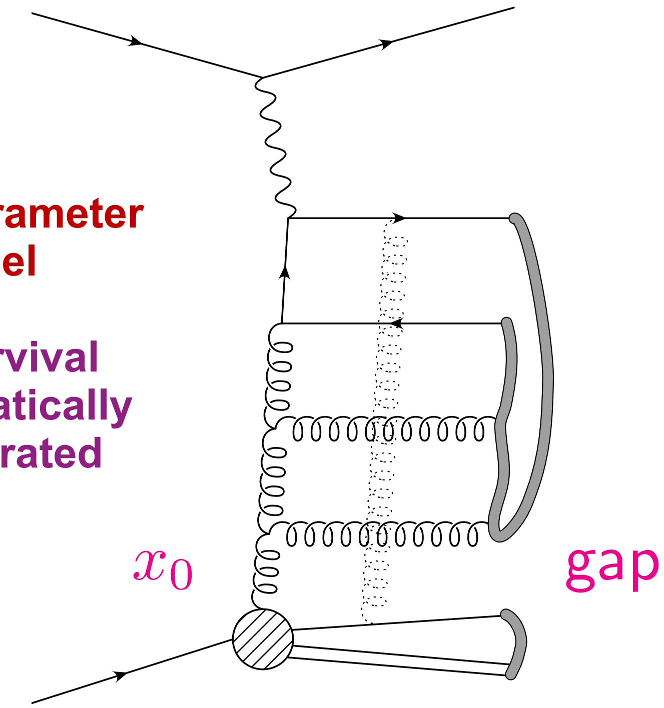
ME + DGLAP PS $> Q_0^2$	$\rightarrow$	SCI model	$\rightarrow$	String hadronisation $\sim \Lambda$
colour ordered parton state		rearranged colour order		modified final state





single parameter model

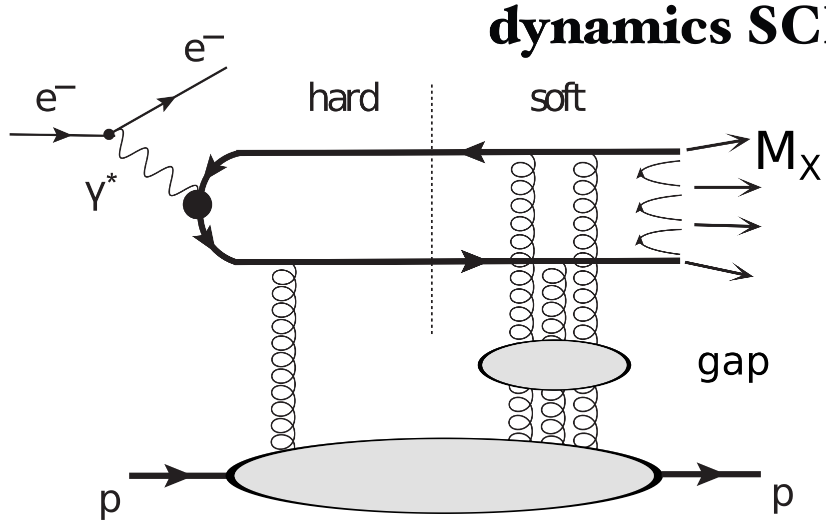
gap survival is automatically incorporated



Single model describing all final states: diffractive $\leftrightarrow$ 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!

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

reconnection probability becomes dynamical

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

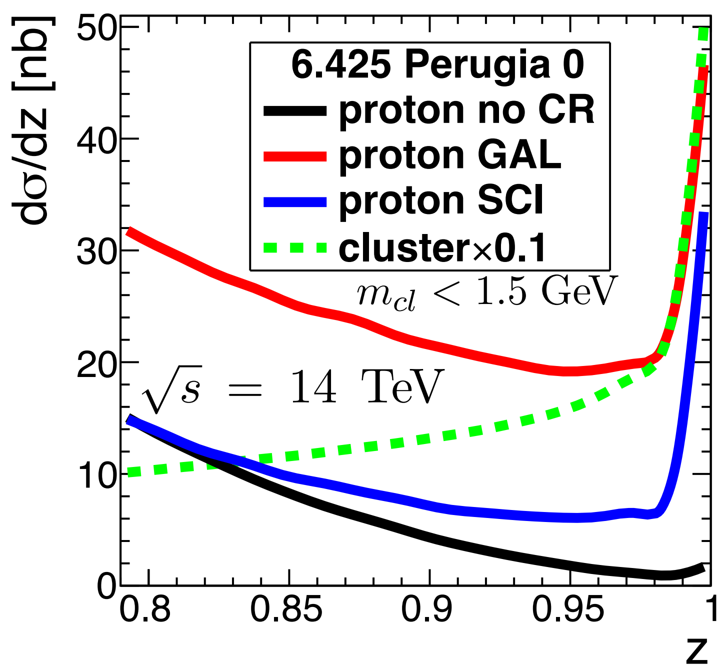
RP, Ingelman, Enberg

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

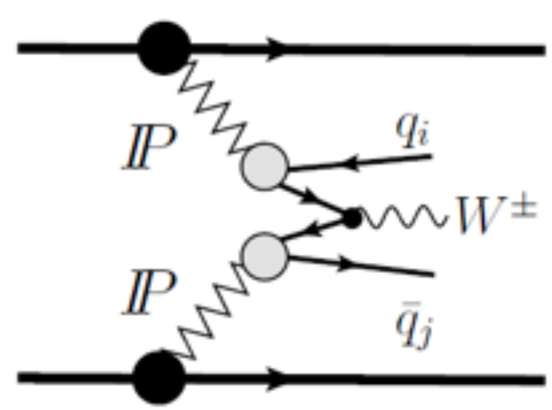
$z = |p_z|/p_{\rm beam} \qquad pp \to p[W^\pm X]$



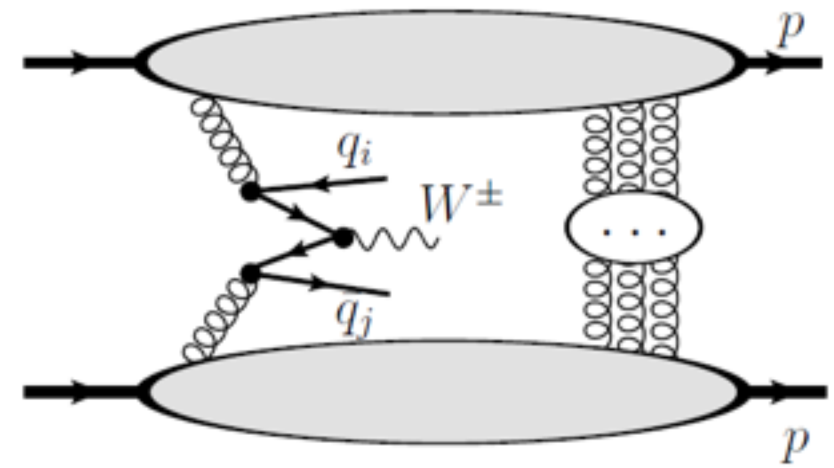
background for anomalous couplings studies with forward detectors see C. Royon

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

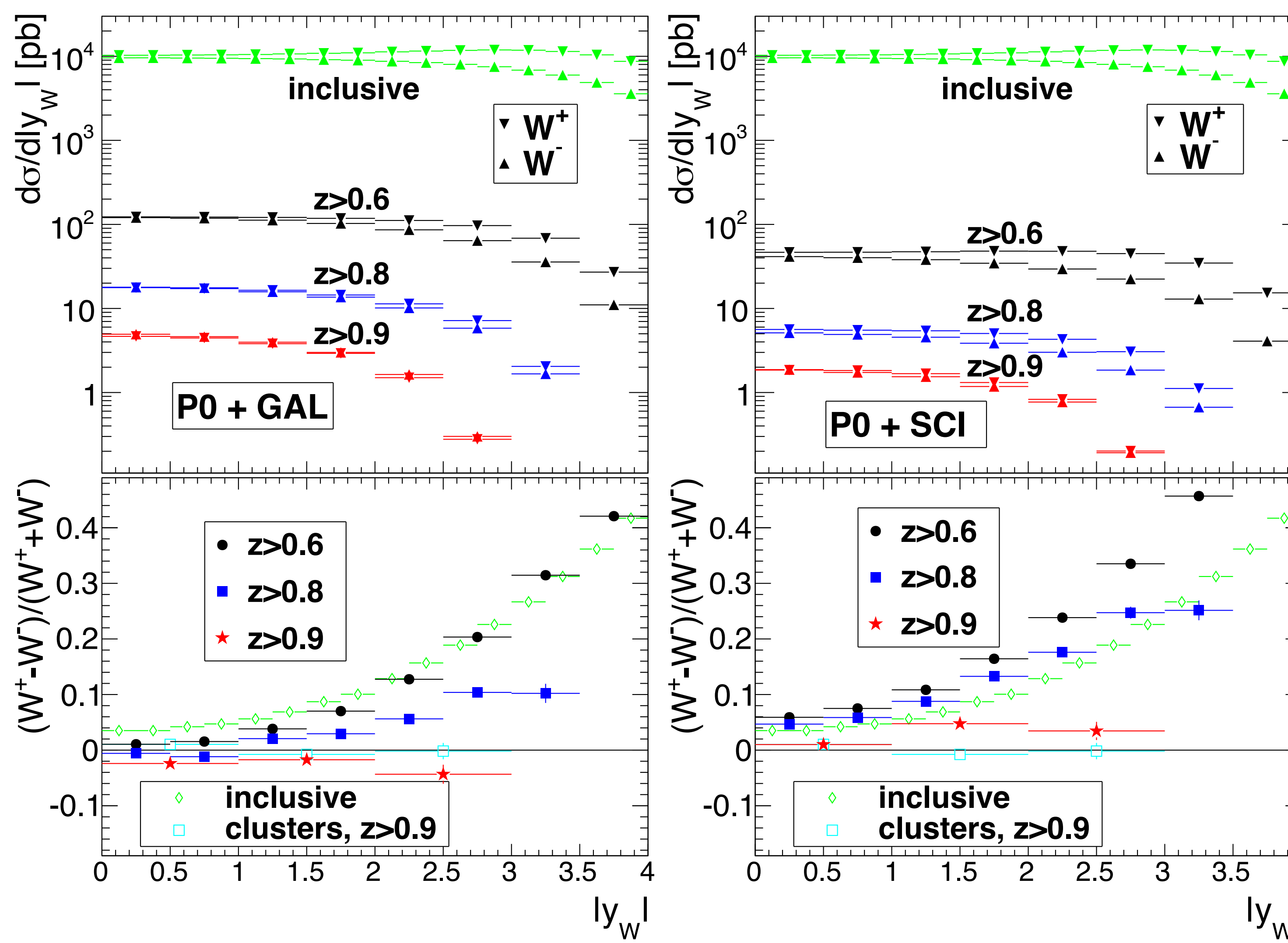
Regge models



QCD inspired models



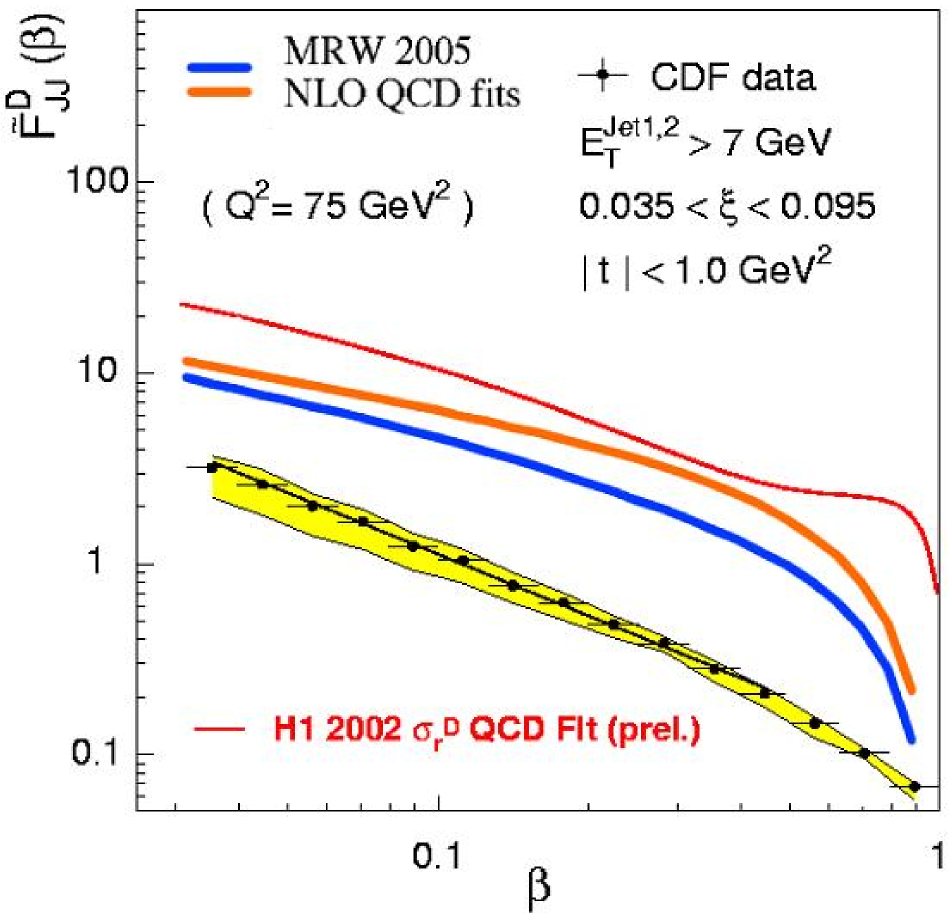
Ingelman, RP, Rathsman, Werder



Mainly gluon-initiated diffraction at large Z!

Diffractive factorisation breaking in pp collisions

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



Sources of diffractive factorisation breaking:

✓ soft survival (=absorptive) effects (Khoze-Martin-Ryskin and Gotsman-Levin-Maor) affecting e.g. the Pomeron flux (Goulianos)

✓ interplay of hard and soft fluctuations in incoming hadron wave function

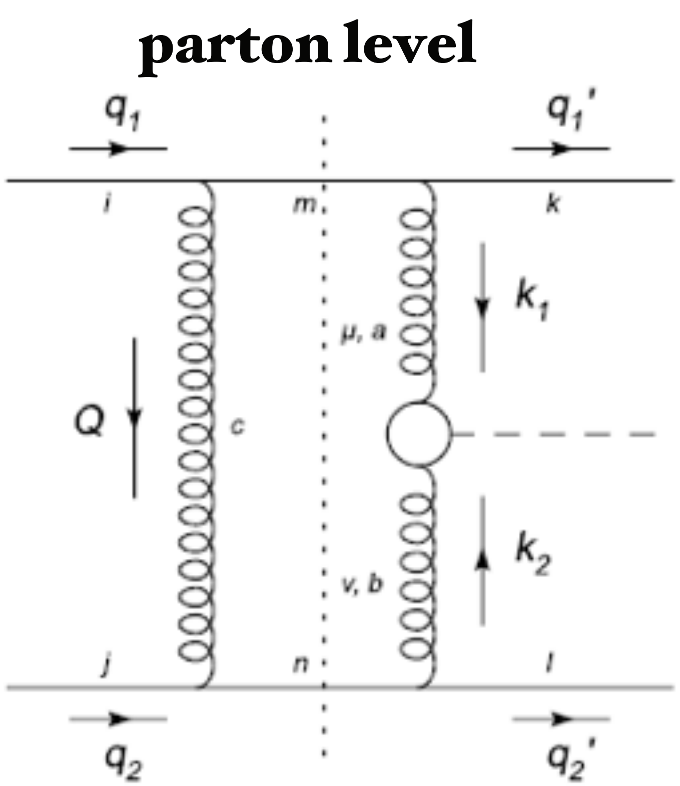
✓ saturated shape of the universal dipole cross section for large dipole sizes

Two distinct approaches treating the above effects:

✓ **Regge-corrected (KMR) approach** — the first source of the factorisation breaking is accounted at the cross section level by "dressing" the factorisation formula by soft Pomeron exchanges

✓ **Color dipole approach** — the universal way of inclusive/diffractive scattering treatment, accounts for all the sources of Regge factorisation breaking at the amplitude level (Kopeliovich, RP et al)

Central exclusive Higgs... etc production



The Durham (KMR) model

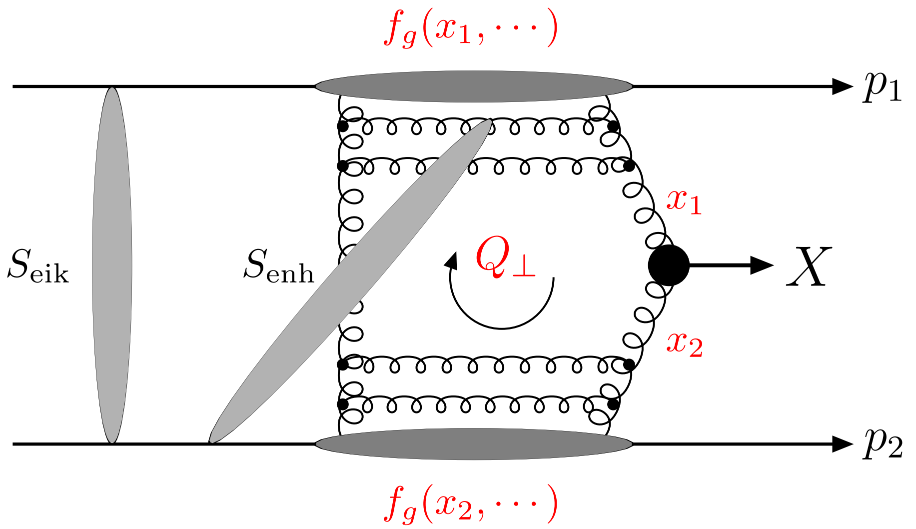
implemented in ExHuME MC

In the forward limit

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

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

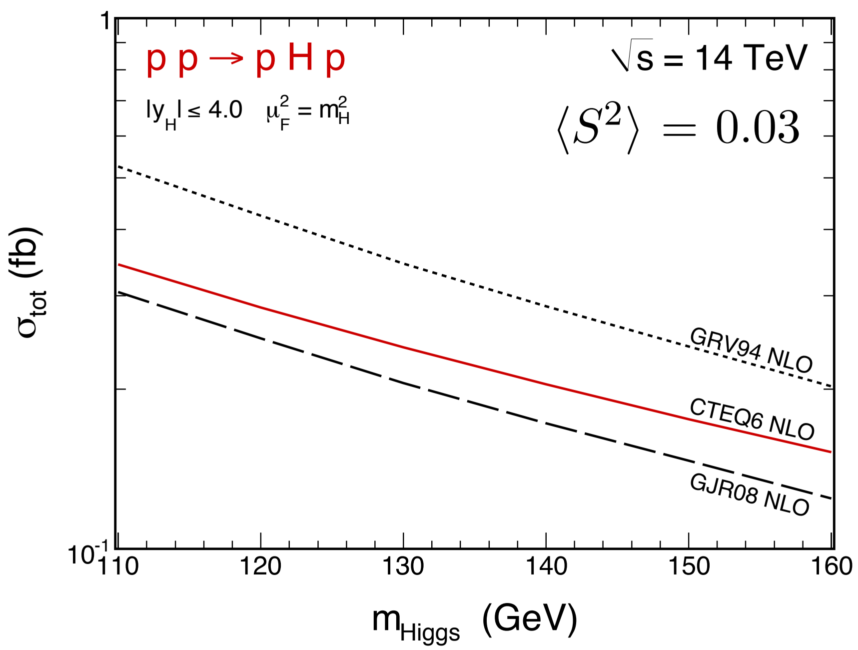
Spin-parity analyser!

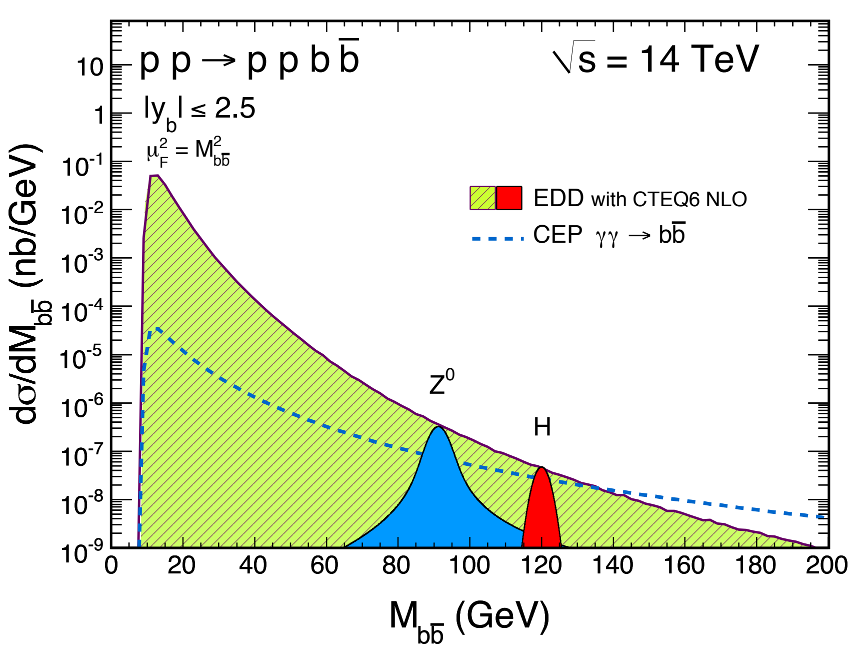


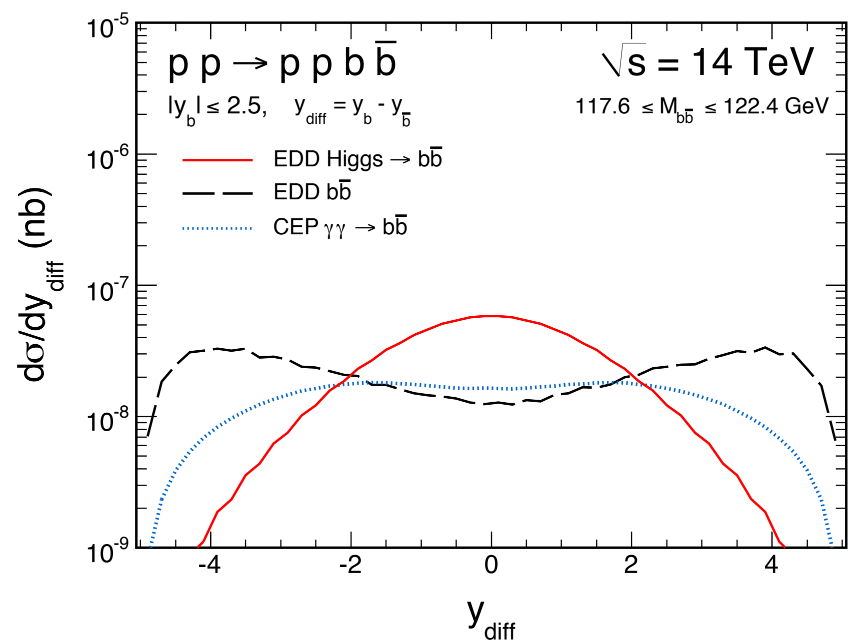
- Correct inclusion of Sudakov factor — JHEP 1001 (2010) 121
- Consistent treatment of 'skewed' gluon PDFs — Phys. Rev. D88 (2013) 034029
- Latest model of soft survival effects — Eur.Phys.J. C73 (2013) 2503

Small CS/large uncertainties

Large irreducible backgrounds







RP + Krakow group

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

Good-Walker picture of diffractive scattering

R. J. Glauber, Phys. Rev. 100, 242 (1955).
E. Feinberg and I. Ya. Pomeranchuk, Nuovo. Cimento. Suppl. 3 (1956) 652.
M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857.

Projectile has a substructure!

Diffractive excitation determined by the fluctuations

Hadron can be excited:
not an eigenstate of interaction!

$$|h\rangle = \sum_{\alpha=1} C_\alpha^h |\alpha\rangle \qquad \hat{f}_{el}|\alpha\rangle = f_\alpha |\alpha\rangle$$

Completeness and orthogonality

$$\langle h'|h\rangle = \sum_{\alpha=1} (C_\alpha^{h'})^* C_\alpha^h = \delta_{hh'}$$

$$\langle \beta|\alpha\rangle = \sum_{h'} (C_\beta^{h'})^* C_\alpha^{h'} = \delta_{\alpha\beta}$$

fluctuations	$\lvert C_\alpha\rvert^2$	σ_α	semi-hard/ semi-soft: $\sigma_{tot} = \sum_{\alpha=soft}^{hard} \lvert C_\alpha\rvert^2 \sigma_\alpha$	soft: $\sigma_{sd} = \sum_{\alpha=soft}^{hard} \lvert C_\alpha\rvert^2 \sigma_\alpha^2$
Hard	~ 1	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^4}$
Soft	$\sim \frac{m_q^2}{Q^2}$	$\sim \frac{1}{m_q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{m_q^2 Q^2}$

Elastic and single diffractive amplitudes

$$f_{el}^{h\to h} = \sum_{\alpha=1} |C_\alpha^h|^2 f_\alpha$$

$$f_{sd}^{h\to h'} = \sum_{\alpha=1} (C_\alpha^{h'})^* C_\alpha^h f_\alpha$$

Single diffractive cross section

$$\sum_{h'\neq h} \left.\frac{d\sigma_{sd}^{h\to h'}}{dt}\right|_{t=0} = \frac{1}{4\pi}\left[\sum_{h'} |f_{sd}^{hh'}|^2 - |f_{el}^{hh}|^2\right]$$

$$= \frac{1}{4\pi}\left[\sum_\alpha |C_\alpha^h|^2 |f_\alpha|^2 - \left(\sum_\alpha |C_\alpha^h| f_\alpha\right)^2\right] = \frac{\langle f_\alpha^2\rangle - \langle f_\alpha\rangle^2}{4\pi}$$

Dispersion of the eigenvalues distribution

Important basis for the dipole picture!

Phenomenological dipole approach

Eigenvalue of the total cross section is the universal dipole cross section

see e.g. B. Kopeliovich et al, since 1981

Eigenstates of interaction in QCD: color dipoles

Dipole:
- cannot be excited
- experience only elastic scattering
- have no definite mass, but only separation
- universal – elastic amplitude can be extracted in one process and used in another

$$\sum_{h'} \frac{d\sigma_{sd}^{h\to h'}}{dt}\bigg|_{t=0} = \sum_{\alpha=1} |C_\alpha^h|^2 \frac{\sigma_\alpha^2}{16\pi} =$$ **SD cross section**

$$\int d^2 r_T |\Psi_h(r_T)|^2 \frac{\sigma^2(r_T)}{16\pi} = \frac{\langle\sigma^2(r_T)\rangle}{16\pi}$$

wave function of a given Fock state

partonic interpretation of a scattering does depend on frame of reference!

total DIS cross section

$$\sigma_{tot}^{\gamma^* p}(Q^2, x_{Bj}) = \int d^2 r_T \int_0^1 dx \, |\Psi_{\gamma^*}(r_T, Q^2)|^2 \sigma_{\bar{q}q}(r_T, x_{Bj})$$

Theoretical calculation of the dipole CS is a challenge

BUT! *Can be extracted from data and used in ANY process!*

Example: Naive GBW parameterization of HERA data

$$\sigma_{\bar{q}q}(r_T, x) = \sigma_0 \left[1 - e^{-\frac{1}{4} r_T^2 Q_s^2(x)}\right]$$

saturates at large separations

$$r_T^2 \gg 1/Q_s^2$$

color transparency $\sigma_{\bar{q}q}(r_T) \propto r_T^2 \qquad r_T \to 0$

QCD factorisation $\sigma_{q\bar{q}}(r, x) \propto r^2 x g(x)$

A point-like colorless object does not interact with external color field!

ANY inclusive/diffractive scattering is due to an interference of dipole scatterings!

Gluon distribution amplitudes and dipole CS

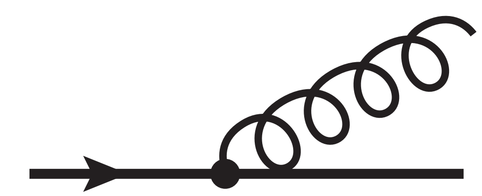
In most cases, a scattering cross section in the target rest frame can be represented in terms of three basic ingredients:

- Gluon to quark-antiquark splitting amplitude:

$$\Phi^T_{Q\bar{Q}} = \sqrt{\alpha_s}\int \frac{d^2\kappa}{(2\pi)^2}\,(\xi^\mu_Q)^\dagger\,\frac{m_Q(\vec{e}_{ini}\cdot\vec{\sigma}) + (1-2\beta)(\vec{\sigma}\cdot\vec{n})(\vec{e}_{ini}\cdot\vec{\kappa}) + i(\vec{e}_{ini}\times\vec{n})\cdot\vec{\kappa}}{\kappa^2+\epsilon^2}\,\tilde{\xi}^{\bar{\mu}}_{\bar{Q}}\,e^{-i\vec{\kappa}\vec{r}}$$

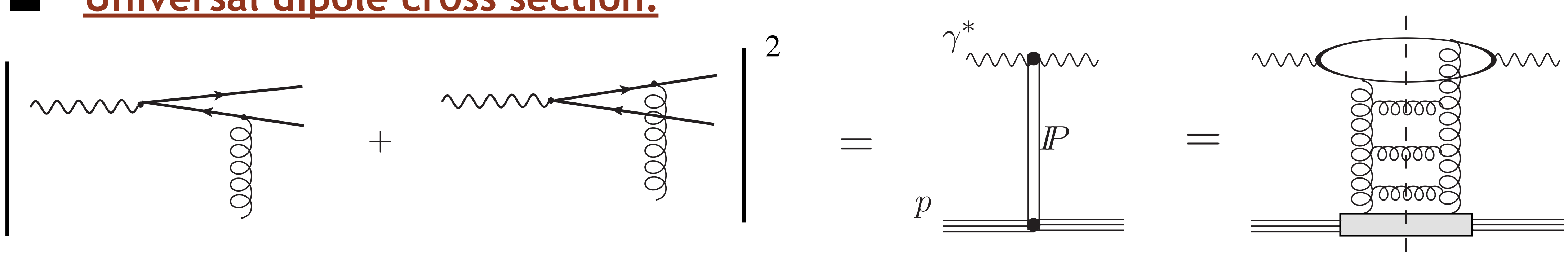
$$= \frac{\sqrt{\alpha_s}}{2\pi}\,(\xi^\mu_Q)^\dagger\Big\{m_Q(\vec{e}_{ini}\cdot\vec{\sigma}) + i(1-2\beta)(\vec{\sigma}\cdot\vec{n})(\vec{e}_{ini}\cdot\vec{\nabla}_r) - (\vec{e}_{ini}\times\vec{n})\cdot\vec{\nabla}_r\Big\}\,\tilde{\xi}^{\bar{\mu}}_{\bar{Q}}\,K_0(\epsilon r)\,,$$

- Gluon Bremsstrahlung off a quark:

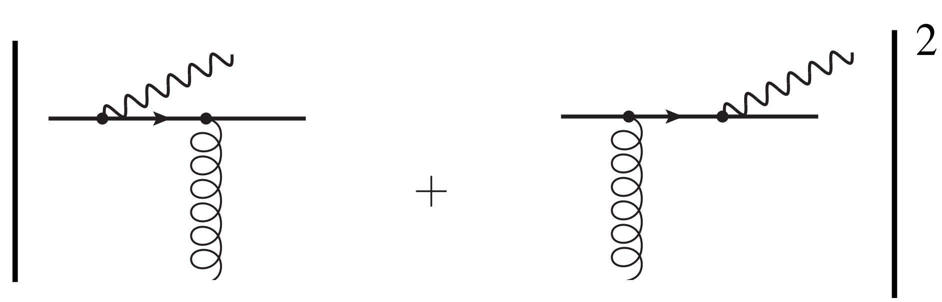


$$\Phi^T_{qG^*}(\alpha,\vec{\pi}) = \sqrt{\alpha_s}\,(\eta^s_Q)^\dagger\,\frac{(2-\alpha)(\vec{e}_*\cdot\vec{\pi}) + i m_q\alpha^2(\vec{n}\times\vec{e}_*)\cdot\vec{\sigma} - i\alpha(\vec{\pi}\times\vec{e}_*)\cdot\vec{\sigma}}{\vec{\pi}^2+\alpha^2 m_q^2}\,\eta^{s'}_Q$$

- Universal dipole cross section:



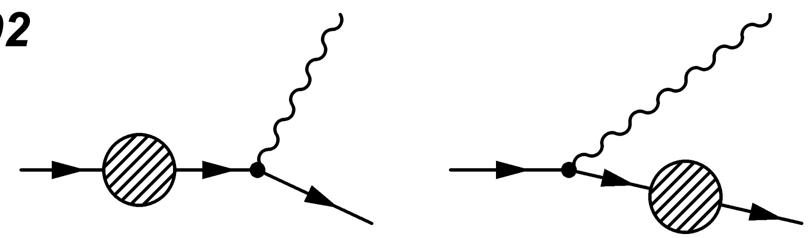
$\propto \quad \sigma_{q\bar{q}}(r,x)$

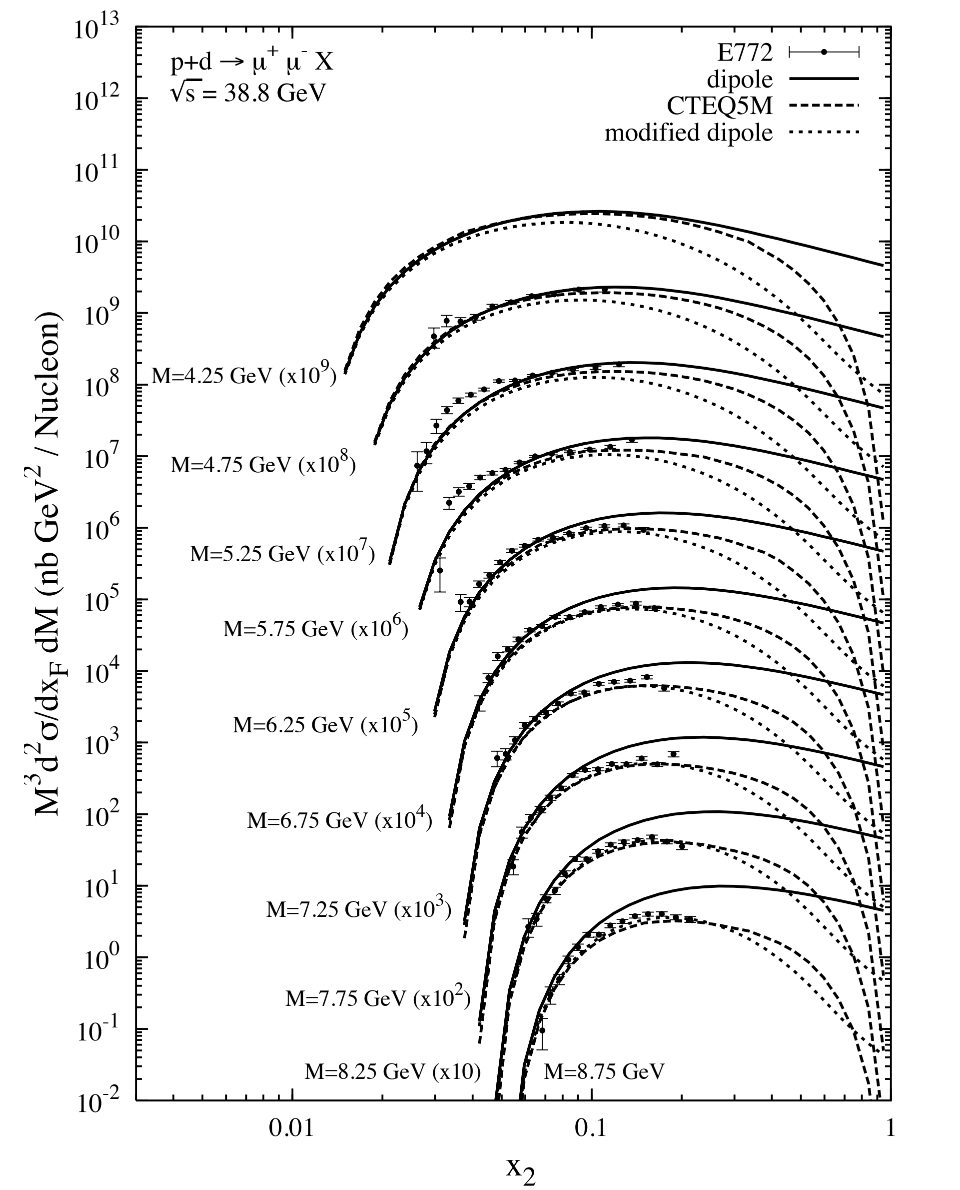


$\propto \quad \sigma_{q\bar{q}}(\alpha r,x)$

Dipole approach vs NLO QCD: Drell-Yan

J. Raufeisen et al, PRD66 2002

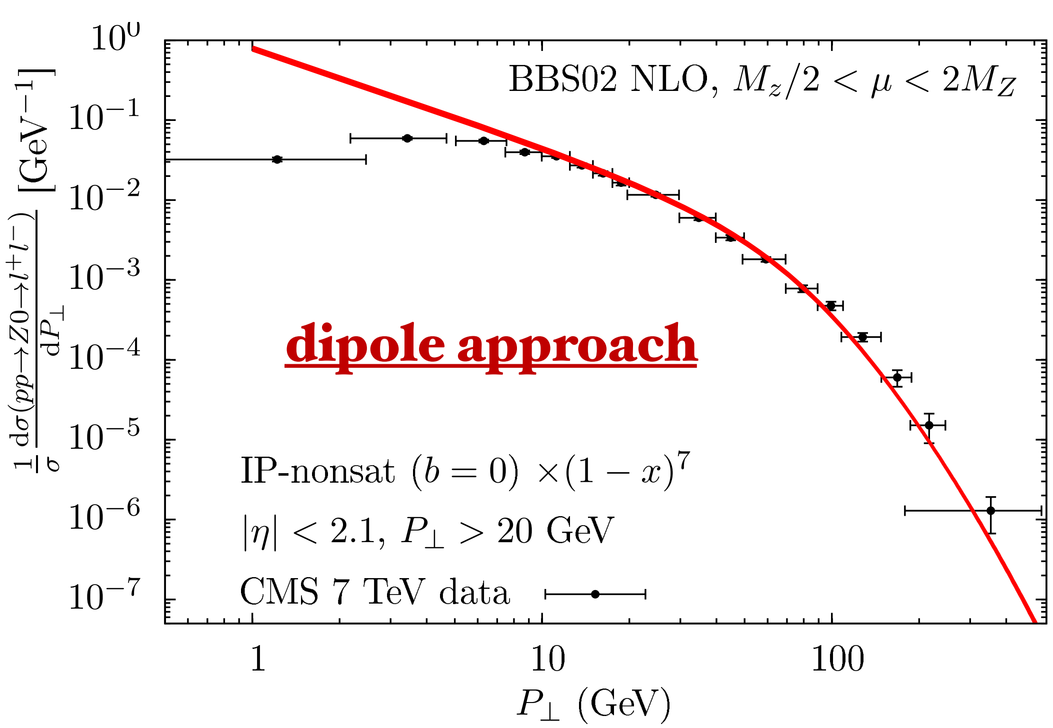


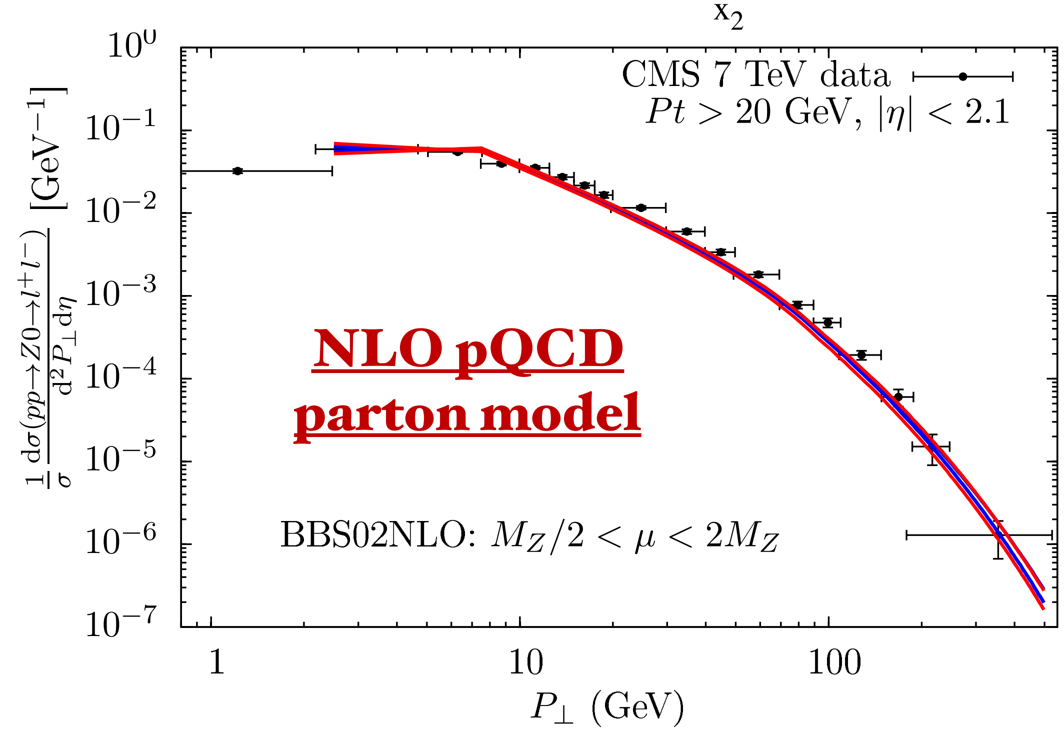


$$\frac{d\sigma(qN \to \gamma^* X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)$$

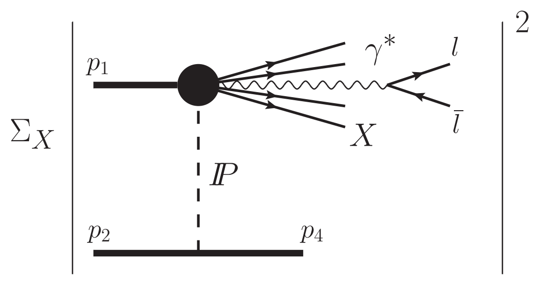
$$\frac{d^2\sigma(pN \to l^+l^-X)}{dM^2 dx_F} = \frac{\alpha_{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_{f=1}^{N_f} Z_f^2 \left[q_f\left(\frac{x_1}{\alpha},\widetilde{Q}\right) + \bar{q}_f\left(\frac{x_1}{\alpha},\widetilde{Q}\right)\right] \times \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)\ .$$

Dipole approach predictions effectively account for higher order QCD corrections!





Diffractive Abelian (e.g. Drell-Yan) radiation via dipoles



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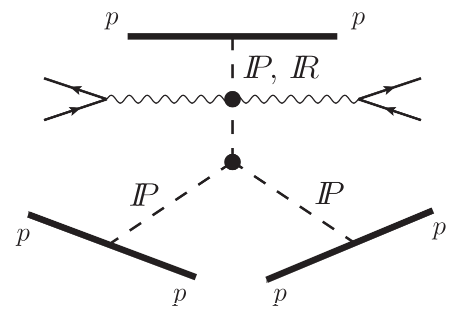
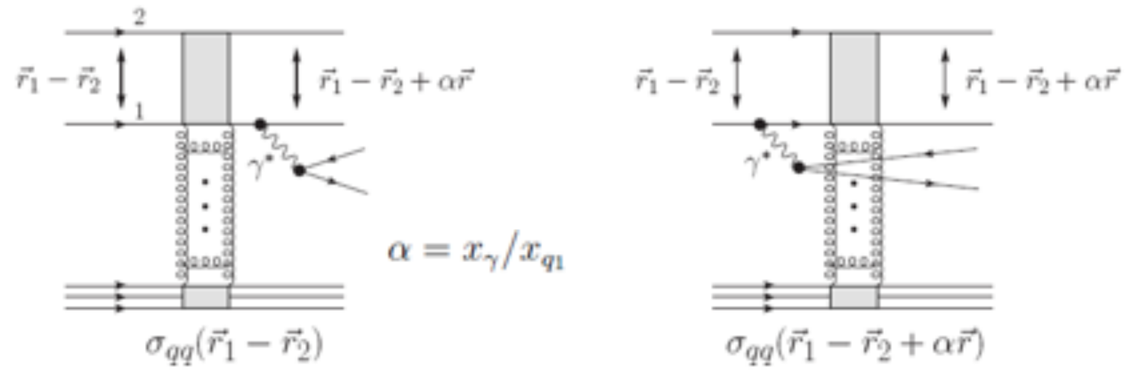


Diffractive Drell Yan (semi-hard)



interplay between hard and soft fluctuations is pronounced!

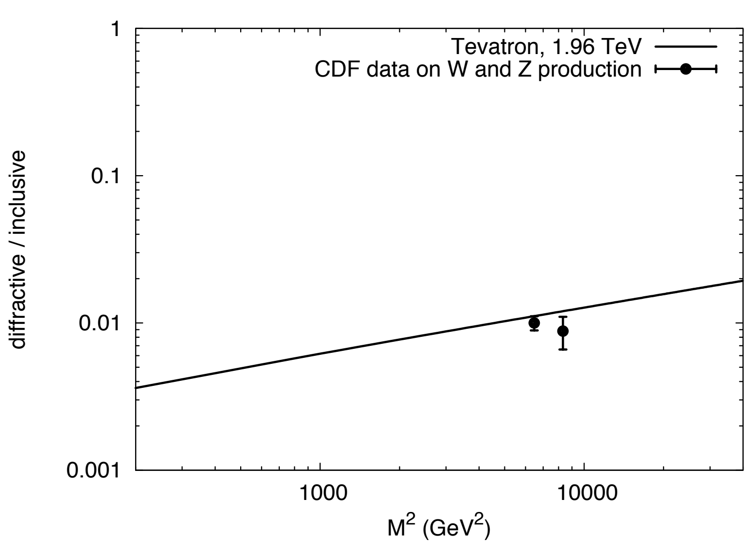
superposition has a Good-Walker structure

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

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

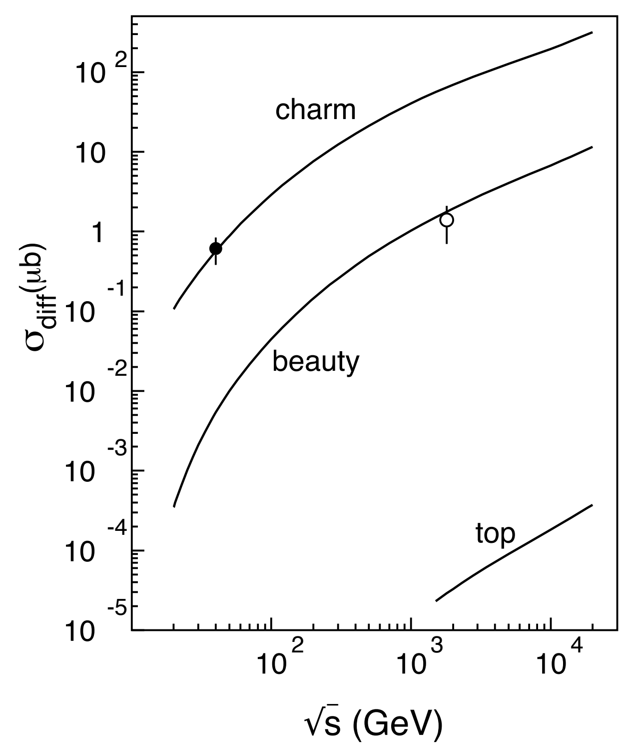
$$r \sim 1/(1-\alpha)M$$

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

Elastic amplitude and gap survival

Dipole elastic amplitude has **eikonal form**:

$$\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2) = 1 - \exp\left[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)\right]$$

$$\sigma_{\bar{q}q}(r_p, x) = \int d^2b\, 2\, \mathrm{Im} f_{el}(\vec{b}, \vec{r}_p) = \sigma_0 (1 - e^{-r_p^2/R_0^2(x)})$$

$$\chi(b) = -\int\limits_{-\infty}^{\infty} dz\, V(\vec{b}, z)$$

potential is nearly imaginary at high energies!

Diffractive amplitude is proportional to

$$\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2 + \alpha\vec{r}) - \mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2) = \exp\left[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)\right]\, \exp\left[i\alpha\, \vec{r} \cdot \vec{\nabla}\chi(\vec{r}_1)\right]$$

$$|\vec{r}_i - \vec{r}_j| \sim b \sim R_p,\ i \neq j$$

Exactly the soft survival probability amplitude

controlled by soft spectator partons

vanishes in the black disc limit!

another source of QCD factorisation breaking

Absorption effect is automatically included into elastic amplitude at the amplitude level

SD-to-inclusive ratio for diffractive gauge bosons production

RP et al 2011,12

$$\mathrm{Im}\, f_{el}(\vec{b}, \vec{R}_{ij} + \alpha\vec{r}) - \mathrm{Im}\, f_{el}(\vec{b}, \vec{R}_{ij}) \simeq \frac{\partial \mathrm{Im}\, f_{el}(\vec{b}, \vec{R}_{ij})}{\partial \vec{R}_{ij}}\, \alpha\vec{r}$$

$$|\Psi_i(\vec{r}_1, \vec{r}_2, \vec{r}_3; x_q, \{x_q^{2,3,\dots}\}, \{x_g^{2,3,\dots})|^2 = \frac{3a^2}{\pi^2} e^{-a(r_1^2+r_2^2+r_3^2)} \rho(x_q, \{x_q^{2,3,\dots}\}, \{x_g^{2,3,\dots}\}) \times \delta(\vec{r}_1 + \vec{r}_2 + \vec{r}_3)\delta(1 - x_q - \sum_j x^j_{q/g}),$$

$$a = \langle r^2_{ch} \rangle^{-1}$$

$$\int d^2r_1 d^2r_2 d^2r_3\, e^{-a(r_1^2+r_2^2+r_3^2)} \delta(\vec{r}_1 + \vec{r}_2 + \vec{r}_3) = \frac{1}{9} \int d^2R_{12} d^2R_{13} e^{-\frac{2a}{3}(R_{12}^2 + R_{13}^2 + \vec{R}_{12}\vec{R}_{13})}$$

$$\frac{d\sigma^{sd}_{\lambda_G}/d^2q_\perp\, dx_1\, dM^2}{d\sigma^{incl}_{\lambda_G}/d^2q_\perp dx_1\, dM^2} = \frac{a^2}{6\pi} \frac{\bar{R}_0^2(M_\perp^2/x_1 s)}{B_{sd}(s)\, \bar{\sigma}_0} \frac{\sigma_0^2(s)}{R_0^4(s)} \frac{1}{A_2} \left[\frac{2}{(A_2 - 4A_1)^2} + \frac{A_2^2}{(A_2^2 - 4A_3^2)^2}\right]$$

$$A_1 = \frac{2a}{3} + \frac{2}{R_0^2(s)}\,, \qquad A_2 = \frac{2a}{3}\,, \qquad A_3 = \frac{2a}{3} + \frac{1}{R_0^2(s)}$$

Hard GBW (small dipoles)

$$\bar{\sigma}_0 = 23.03\,\mathrm{mb}\,, \quad \bar{R}_0(x_2) = 0.4\,\mathrm{fm} \times (x_2/x_0)^{0.144}\,, \quad x_0 = 3.04 \times 10^{-4}$$

diffractive (Regge) slope $B_{sd}(s) \simeq \langle r^2_{ch} \rangle/3 + 2\alpha'_{I\!P} \ln(s/s_0)$

At the leading twist, the dipole approach predicts the same angular correlation in DDY as in inclusive DY!

Soft KST (large dipoles)

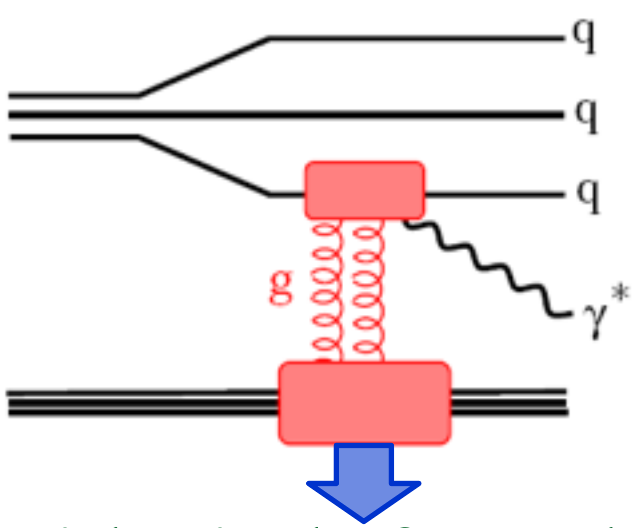
$$R_0(s) = 0.88\,\mathrm{fm}\,(s_0/s)^{0.14}$$

$$\sigma_0(s) = \sigma^{\pi p}_{tot}(s)\left(1 + \frac{3R_0^2(s)}{8\langle r^2_{ch}\rangle_\pi}\right)$$

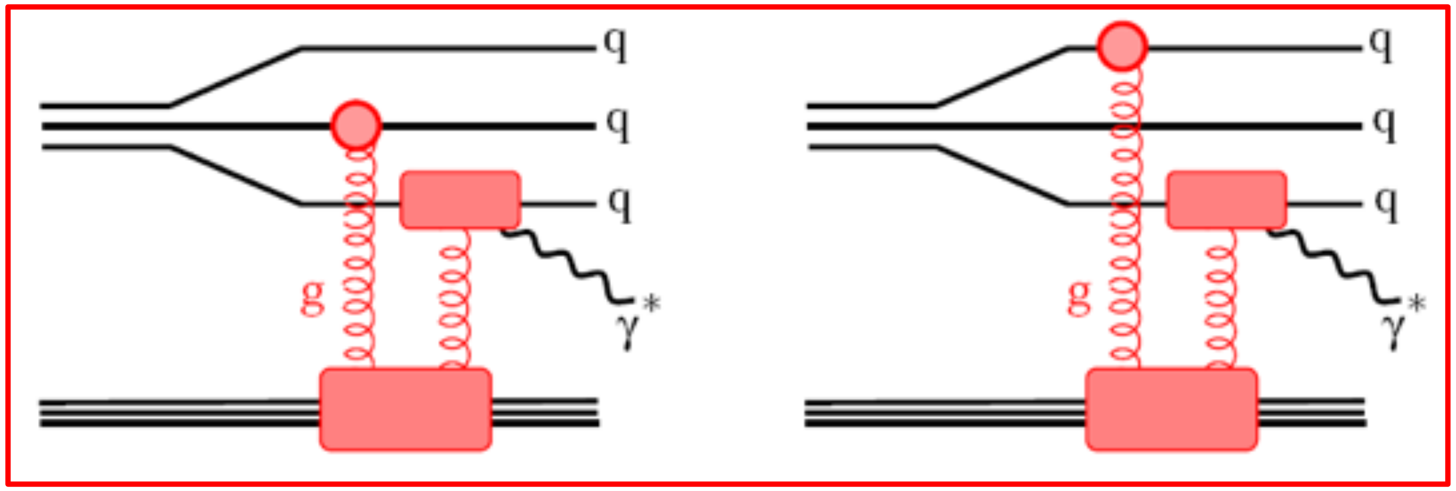
$$\sigma^{\pi p}_{tot}(s) = 23.6(s/s_0)^{0.08}\ \mathrm{mb}$$

$$\langle r^2_{ch}\rangle_\pi = 0.44\ \mathrm{fm}^2$$

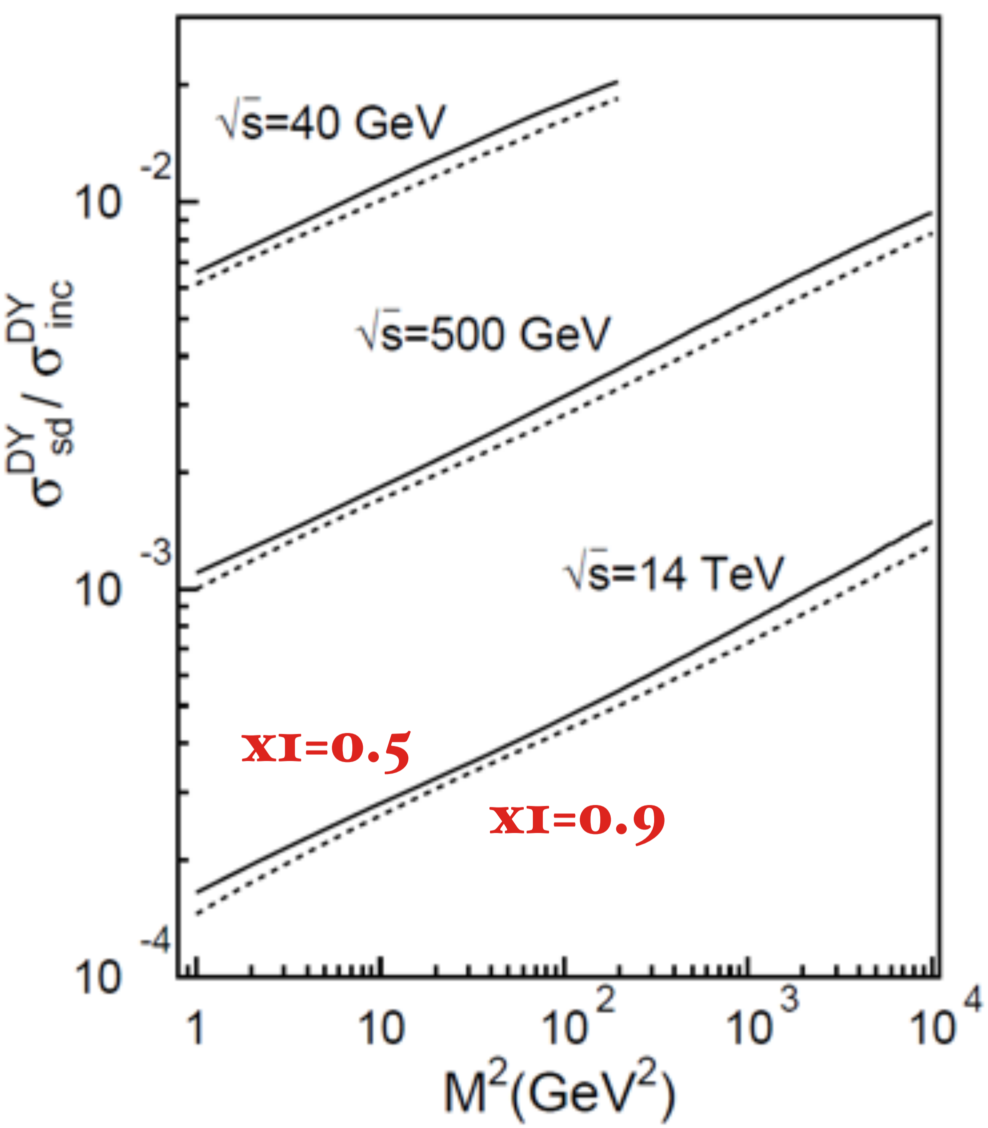
Diffractive factorisation breaking in DDY



vanishes in the forward limit, higher twist effect!



leading twist effect!

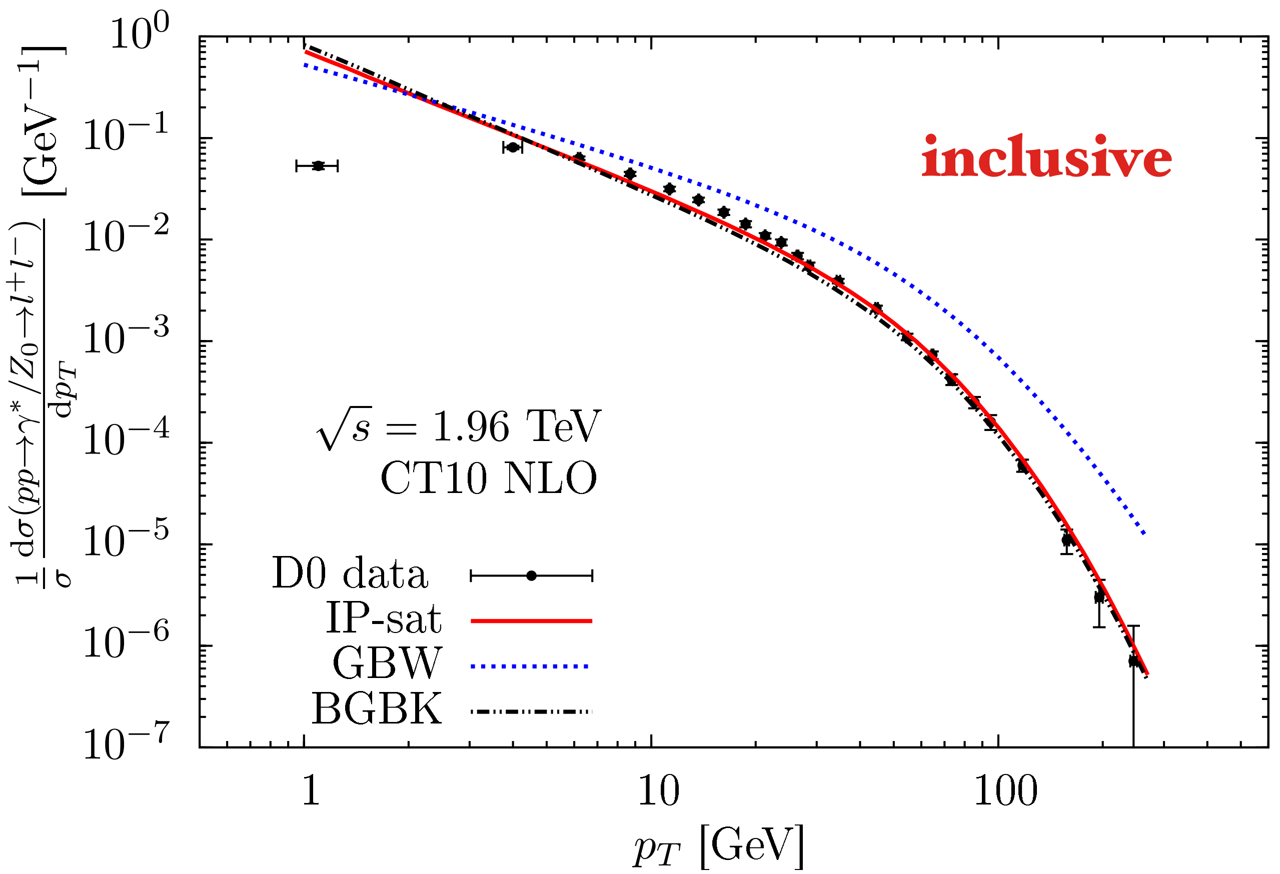


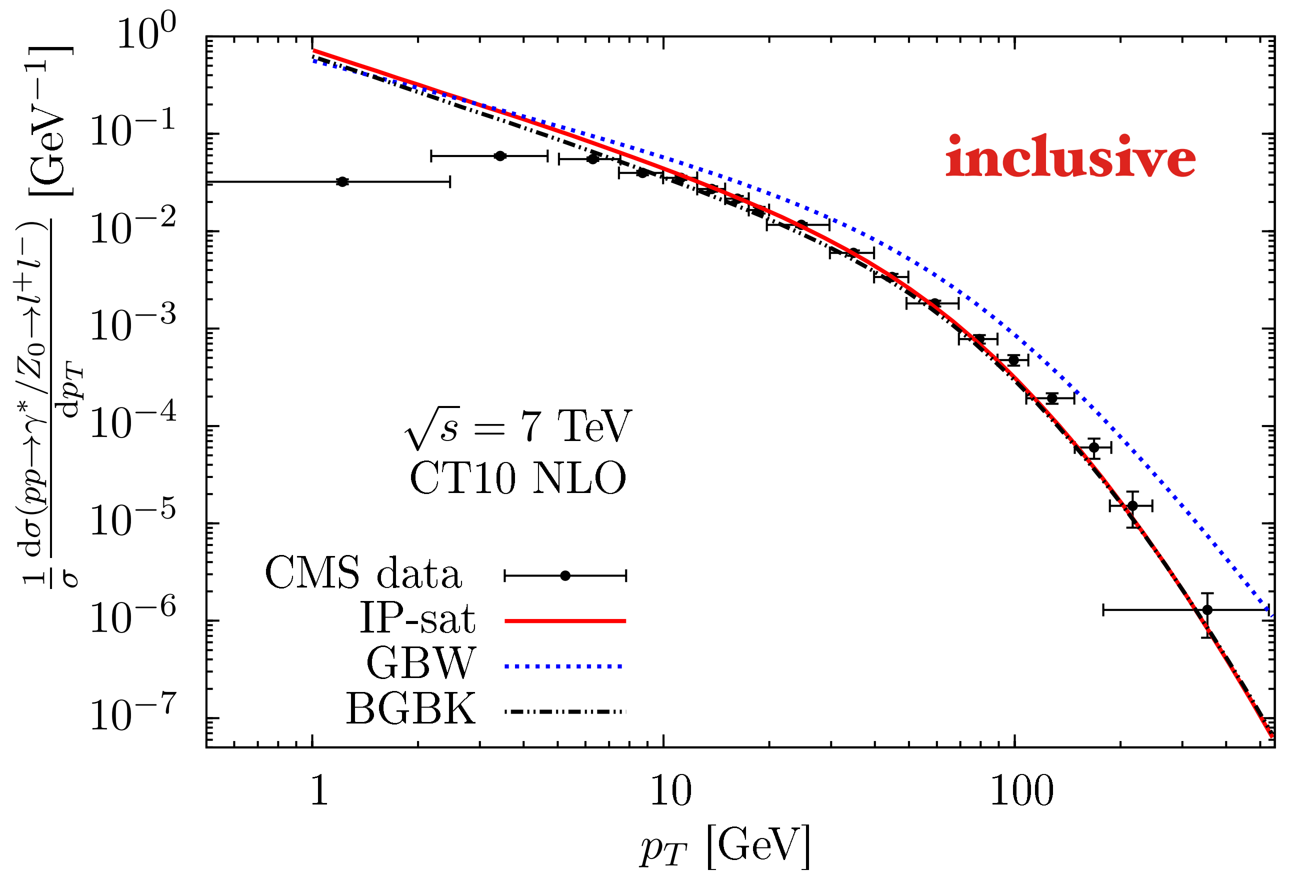
saturated shape of the dipole CS
+
unitarity corrections

Fraction of diffractive events
- steeply falls with energy
- grows with the hard scale

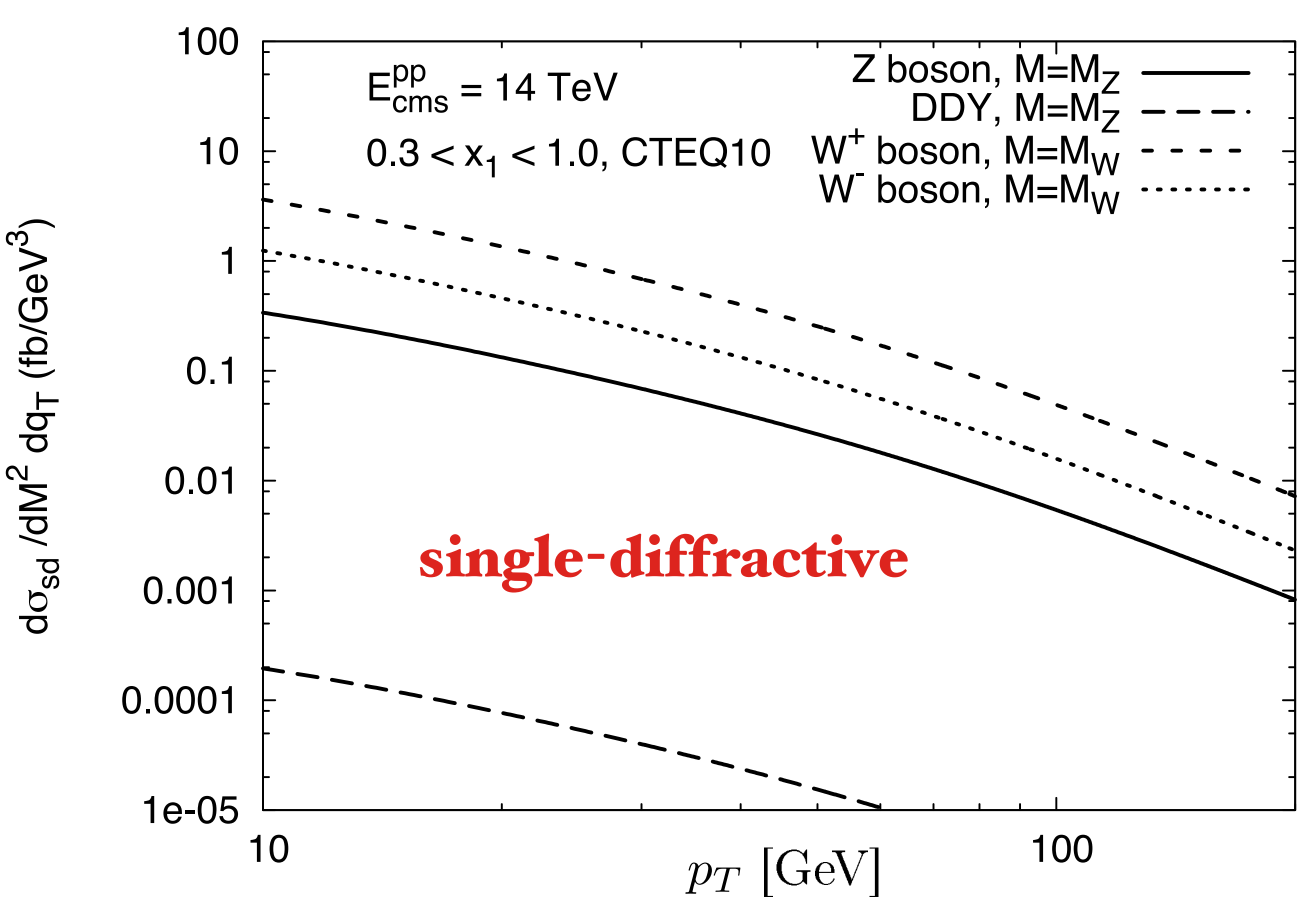
Opposite to factorization-based results (like Ingelman-Schlein)

PT correlations in inclusive and diffractive Drell-Yan



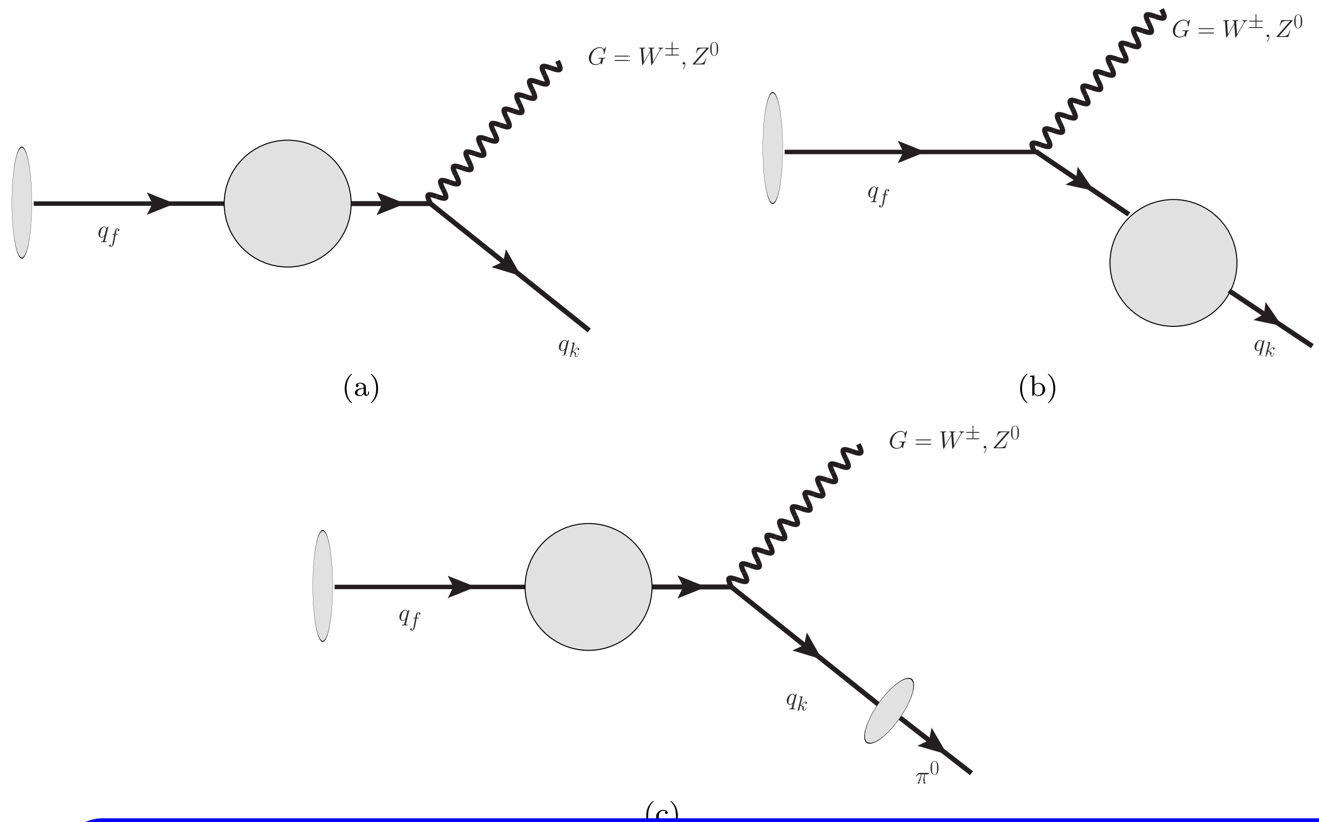


RP et al 2013, 2016

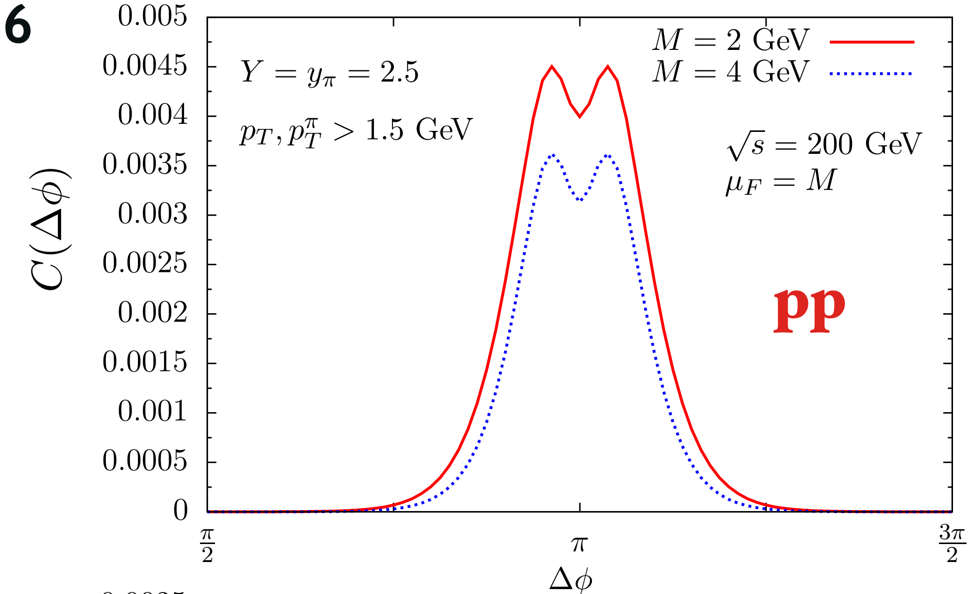


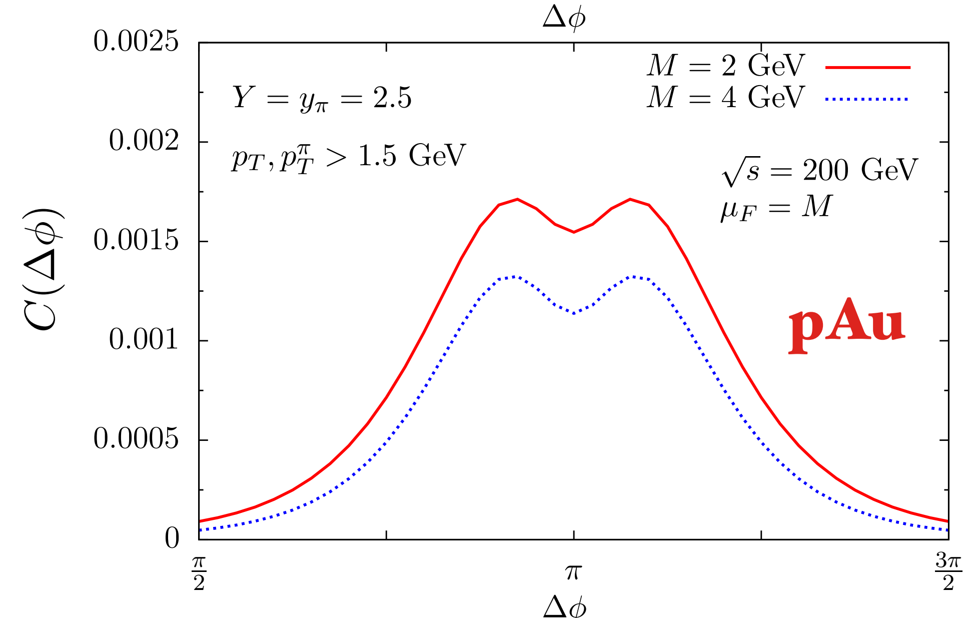
Angular correlations in Drell-Yan as a probe for saturation

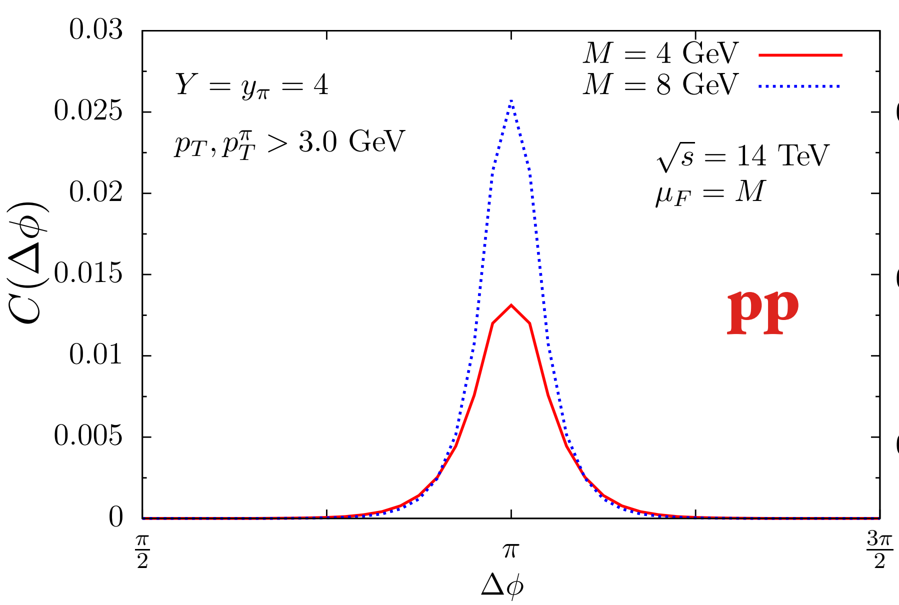
E. Basso, J. Nemchik, RP, M. Sumbera, V. Goncalves PRD93, 2016

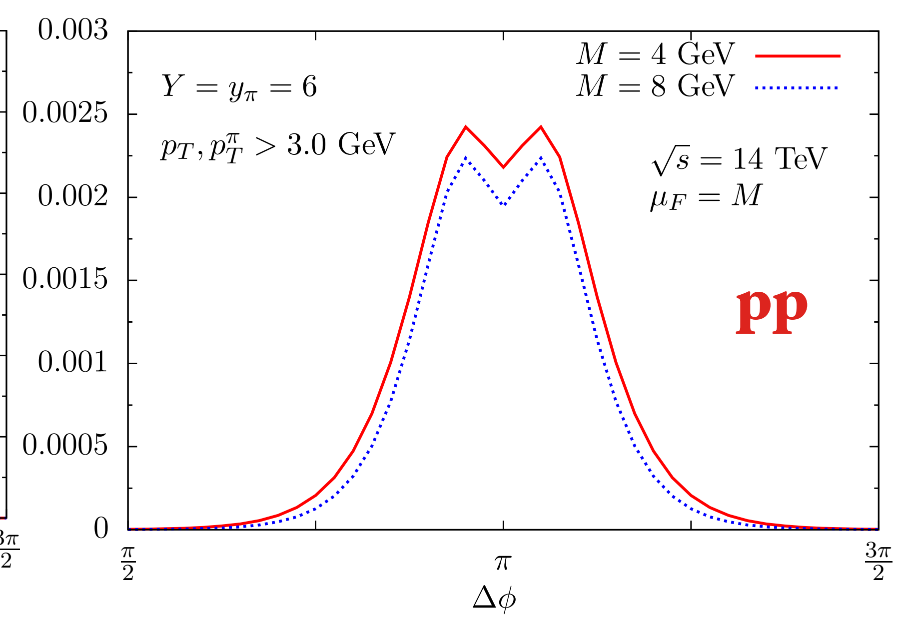


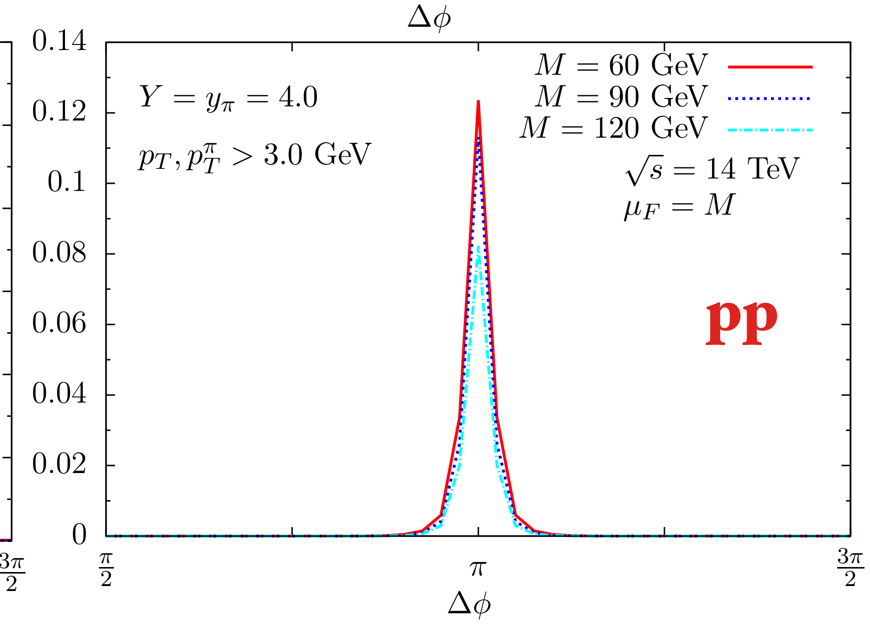
$$C(\Delta\phi) = \frac{2\pi \int_{p_T, p_T^h > p_T^{\rm cut}} dp_T p_T \; dp_T^h p_T^h \; \frac{d\sigma(pp \to h G^* X)}{dY dy_h d^2p_T d^2p_T^h}}{\int_{p_T > p_T^{\rm cut}} dp_T p_T \; \frac{d\sigma(pp \to G^* X)}{dY d^2p_T}}$$











This picture does not change when turning to diffractive Drell-Yan

Heavy flavour production: Bremsstrahlung vs Fusion

Gauge-invariant sub-sets of diagrams

B. Kopeliovich et al, PRD76 2007

"Bremsstrahlung" component

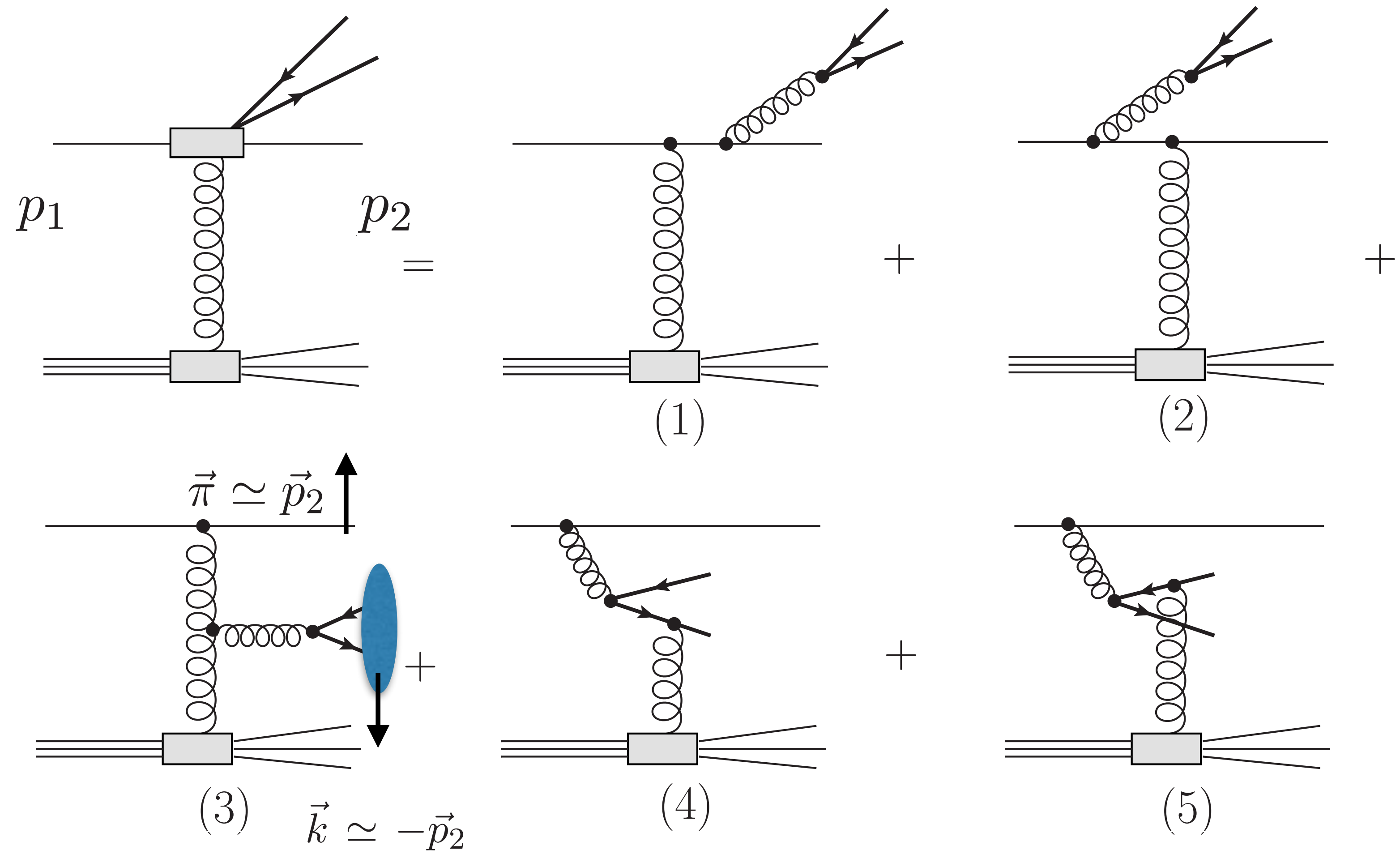
$$M^T_{\rm Br} = M^T_1 + M^T_2 + \frac{Q^2}{M^2+Q^2} M^T_3$$

suppressed by QQ mass!

"Fusion" component

$$M^T_{\rm Pr} = \frac{M^2}{M^2+Q^2} M^T_3 + M^T_4 + M^T_5$$

Dominates!



Gluon virtuality

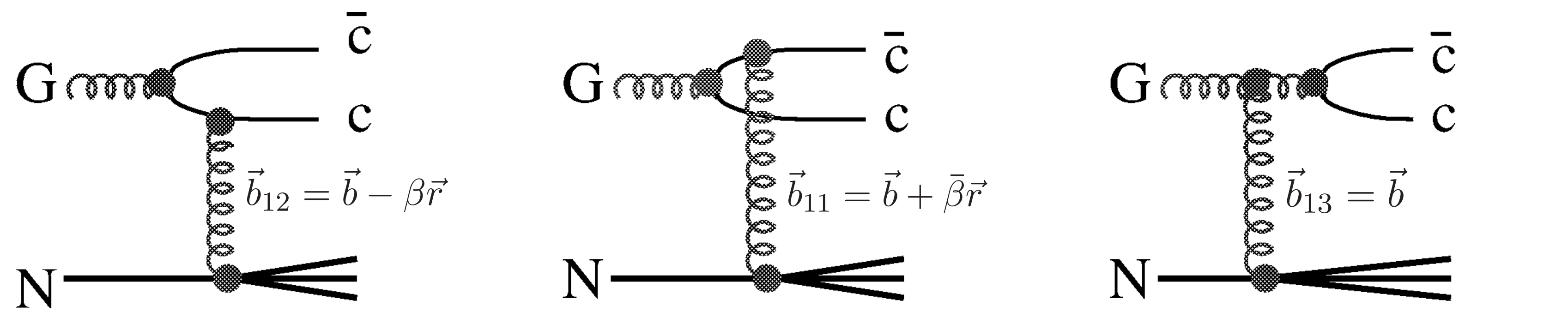
$$(p_2 - p_1)^2 \equiv -Q^2\,, \qquad Q^2 = \frac{\vec{\pi}^2 + \alpha^2 m_q^2}{\bar{\alpha}} \qquad \vec{\pi} = \alpha\vec{p}_2 - \bar{\alpha}\vec{k}\,, \qquad \vec{k} = \sum_i \vec{k}_i$$

Basis for heavy flavour production in the dipole picture

Dipole framework for heavy flavor production

"Fusion" components

$G + N \to \bar{c}c + X$



LC momenta

$$k_1 \simeq \bar{\beta}k - \kappa\,, \qquad k_2 \simeq \beta k + \kappa \qquad \vec{\kappa} = \bar{\beta}\vec{k}_2 - \beta\vec{k}_1$$

impact parameter representation

$$\hat{A}(\vec{s},\vec{r}) = \frac{1}{(2\pi)^4}\int d^2\vec{q}\, d^2\vec{\kappa}\; \hat{A}(\vec{q},\vec{\kappa})\, e^{-i\vec{q}\cdot\vec{s}-i\vec{\kappa}\cdot\vec{r}}$$

$$\hat{A} \simeq \frac{\sqrt{3}}{2}\sum_r \Big\{\tau_r\,\tau_a\langle f|\hat{\gamma}_r(\vec{b}_{11})|i\rangle - \tau_a\,\tau_r\langle f|\hat{\gamma}_r(\vec{b}_{12})|i\rangle - i\sum_c f_{cra}\tau_c\langle f|\hat{\gamma}_r(\vec{b}_{13})|i\rangle\Big\}\Phi_{Q\bar{Q}}(\vec{r},\beta)\,,$$

$$|A|^2 \equiv \frac{1}{8}\frac{1}{2}\sum_{\lambda_*,\mu,\bar{\mu}}\langle\hat{A}^\dagger\hat{A}\rangle_{|3q\rangle_1}$$

$$\sum_X\langle i|\hat{\gamma}_a(\vec{b}_k)\hat{\gamma}_{a'}(\vec{b}_l)|i\rangle_{|3q\rangle_1} = \frac{3}{4}\delta_{aa'}S(\vec{b}_k,\vec{b}_l)$$

The universal dipole cross section

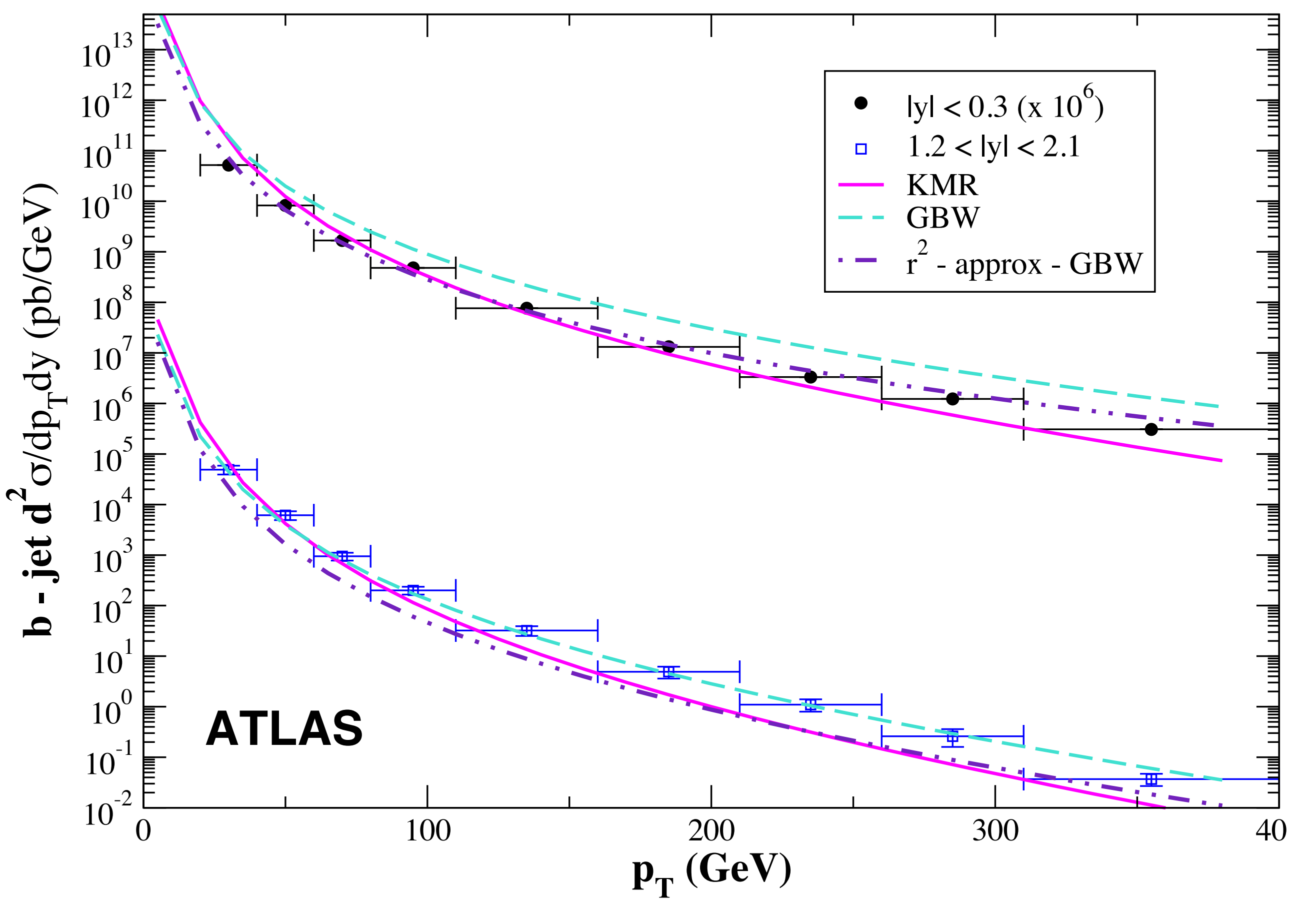
$$\sigma_{\bar{q}q}(\vec{r}_1-\vec{r}_2) \equiv \int d^2b\Big[S(\vec{b}+\vec{r}_1,\vec{b}+\vec{r}_1) + S(\vec{b}+\vec{r}_2,\vec{b}+\vec{r}_2) - 2S(\vec{b}+\vec{r}_1,\vec{b}+\vec{r}_2)\Big]$$

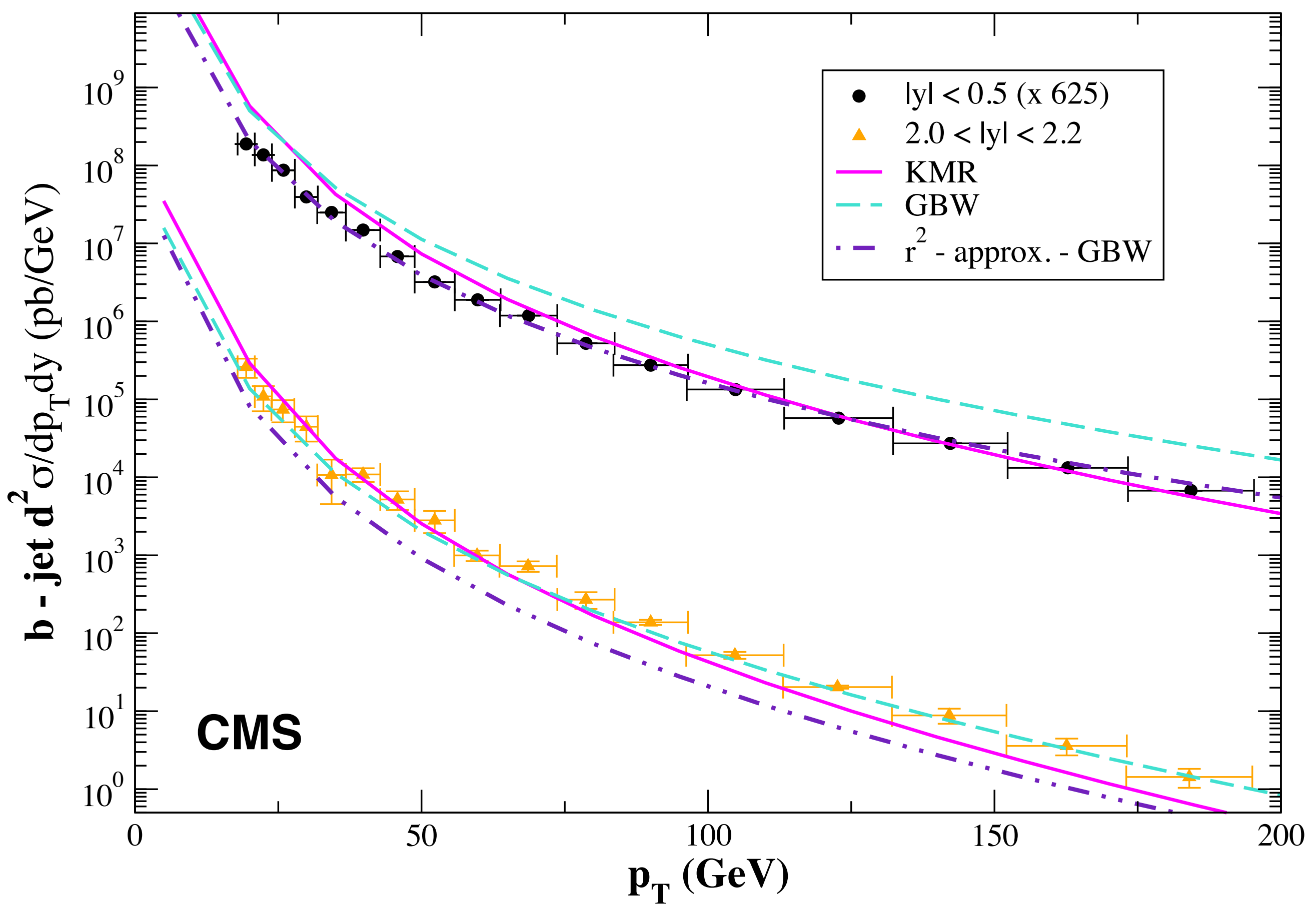
The total cross section

$$\sigma(G+p\to c\bar{c}+X) = \sum_{\mu\bar{\mu}}\int_0^1 d\beta\int d^2r\,\sigma_3(r,\beta,x_2)\,|\Phi_{Q\bar{Q}}(\vec{r},\beta)|^2$$

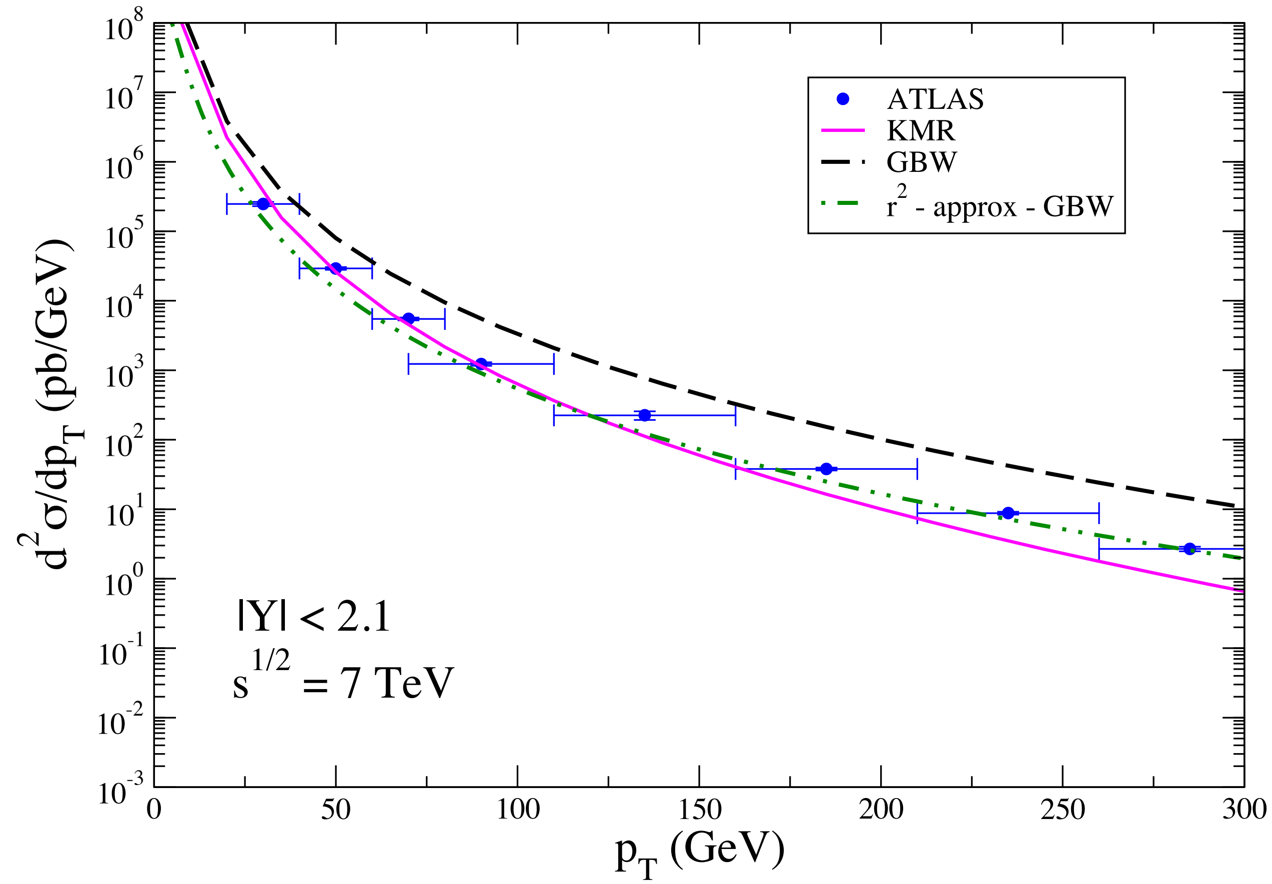
$$\sigma_3(r,\beta,x_2) = \frac{9}{8}\Big(\sigma_{\bar{q}q}(\bar{\beta}r,x_2)+\sigma_{\bar{q}q}(\beta r,x_2)\Big) - \frac{1}{8}\sigma_{\bar{q}q}(r,x_2)\,, \qquad x_2 = \frac{M^2_{c\bar{c}}}{2m_pE_G}$$

Inclusive Q-jet pT distribution in pp collisions vs LHC data



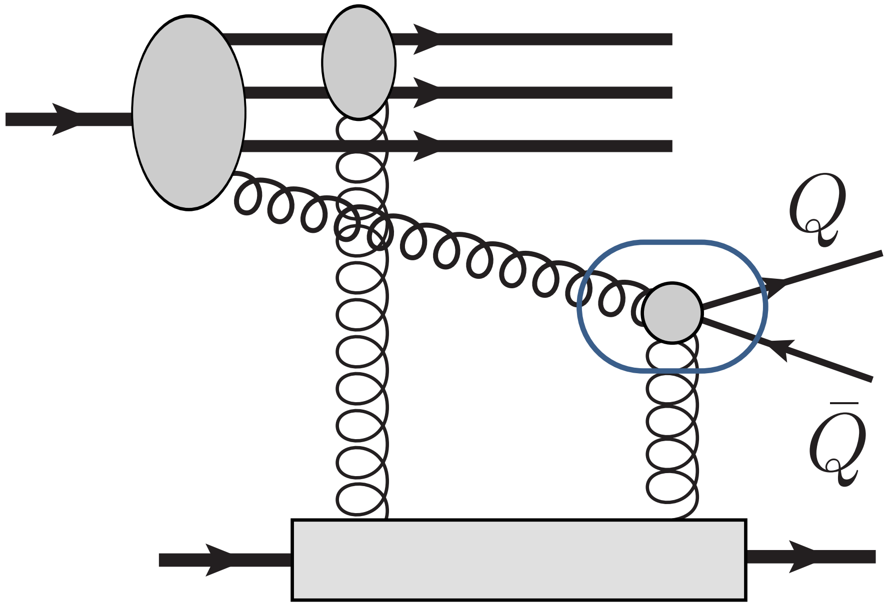


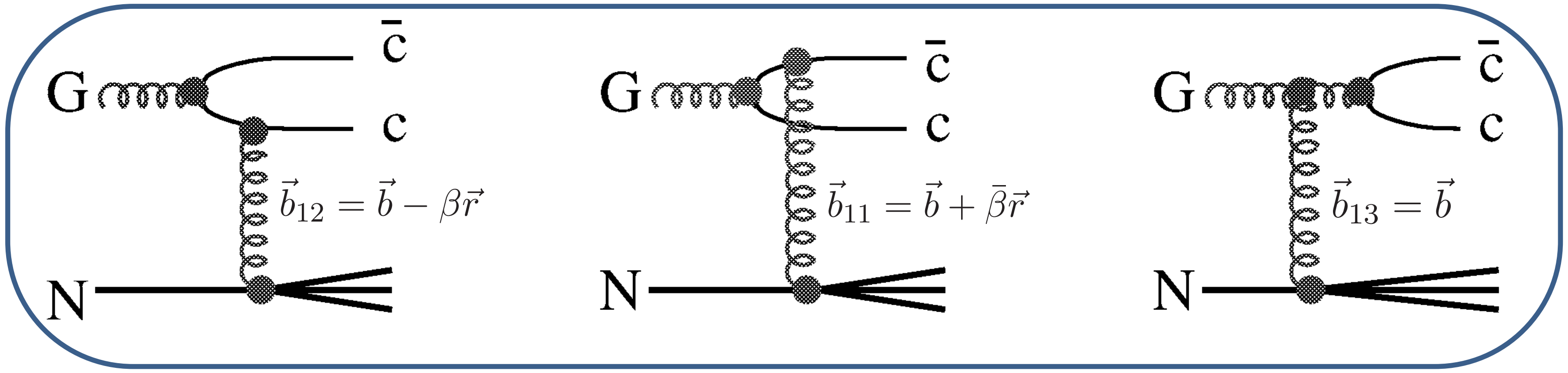
RP, V. Goncalves et al,
in progress



not worse than
in NLO pQCD!

Diffractive non-Abelian (gluon) radiation via dipoles





"skeleton" contributions are subject for "dressing!"

leading twist effect!

B. Kopeliovich et al, 2007

RP et al, in progress

when the LO contributions get generalised to all-order results, ALL possible higher-order (perturbative+nonperturbative) corrections due to NON-RESOLVED emissions are AUTOMATICALLY resumed and accounted for by the dipole formula!

SD amplitude

$$\overline{|A_{\rm SD}|^2} \simeq \frac{3}{256}\,|\Psi_{in}|^2|\Psi_{fin}|^2 \sum_{i,j=1}^{2} \left[\nabla^i \Psi^*_{Q\bar{Q}}(\alpha,\vec{r})\,\nabla^j \Psi_{Q\bar{Q}}(\alpha,\vec{r}')\right]\Omega^{ij}_{\rm soft}$$

"soft color screening" part

$$\Omega^{ij}_{\rm soft} = \left[\nabla^i\sigma_{q\bar{q}}(\vec{r}_{12}) + \nabla^i\sigma_{q\bar{q}}(\vec{r}_{13})\right]\left[\nabla^j\sigma_{q\bar{q}}(\vec{r}_{12}) + \nabla^j\sigma_{q\bar{q}}(\vec{r}_{13})\right]$$

SD-to-inclusive ratio

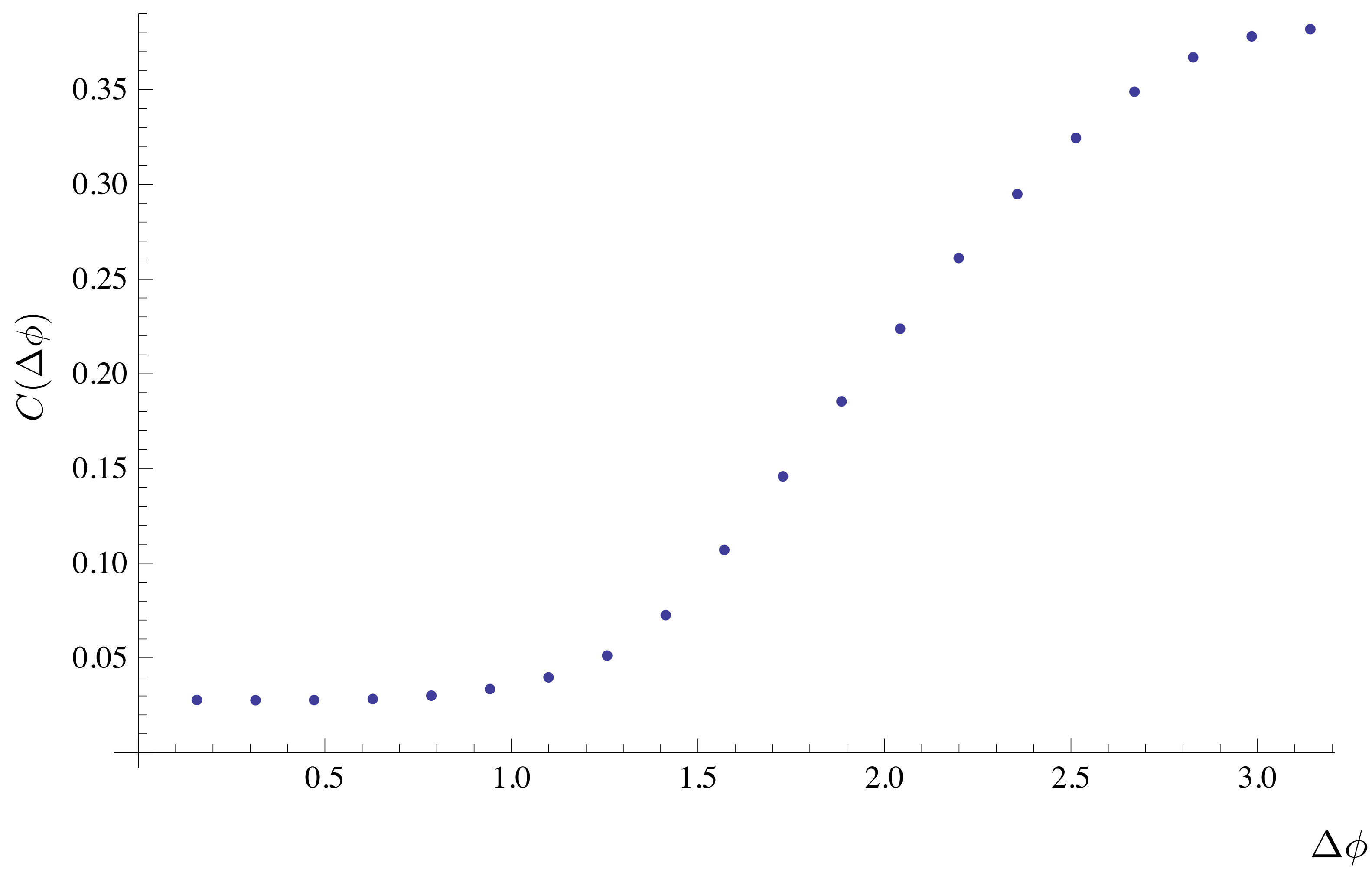
$$\frac{d\sigma_{\rm SD}}{d\Omega} \simeq \frac{\bar{R}_0^2(x_2)}{\bar{\sigma}_0}\left[\alpha^2 + \bar{\alpha}^2 - \frac{1}{4}\alpha\bar{\alpha}\right]^{-1} F_{\rm S}(x_1,s)\,\frac{d\sigma_{\rm incl}}{d\Omega} \qquad F_{\rm S}(x_1,s) \equiv \frac{729\,a^2\sigma_0(x_1 s)^2\,\Lambda(x_1 s)}{4096\,\pi^2\,B_{\rm SD}(s)}$$

The angular correlation is affected by color-screening interaction in higher-twist diffraction but not in the leading twist!

SD vs inclusive: Heavy QQbar angular correlation

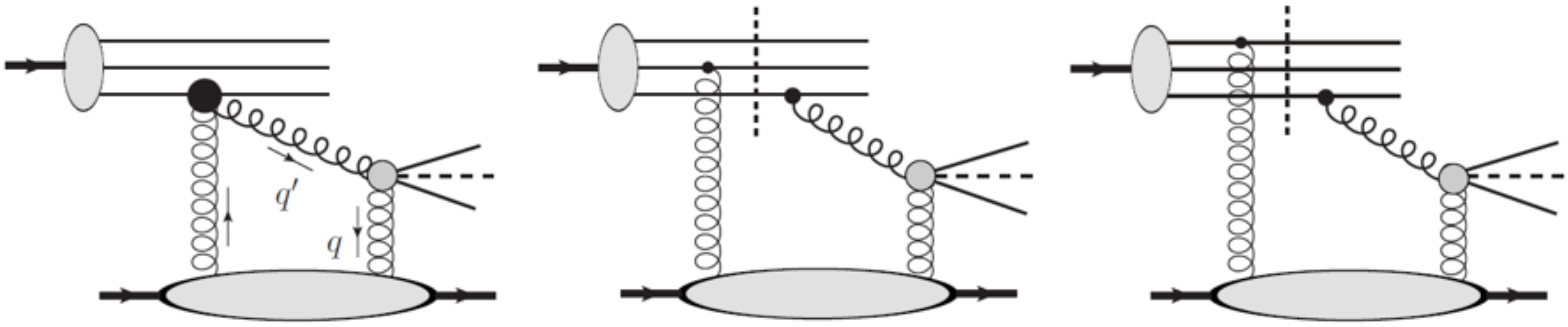
$$\frac{d^3\sigma(G \to Q\bar{Q} + X)}{d(\ln\alpha)d^2p_T} = \frac{1}{6\pi}\int \frac{d^2\kappa_\perp}{\kappa_\perp^4}\alpha_s^2\mathcal{F}(x,\kappa_\perp^2)\times$$

$$\left\{\left[\frac{9}{8}\mathcal{H}_0(\alpha,\bar{\alpha},p_T) - \frac{9}{4}\mathcal{H}_1(\alpha,\bar{\alpha},p_T,\kappa) + \mathcal{H}_2(\alpha,\bar{\alpha},p_T,\kappa) + \frac{1}{8}\mathcal{H}_3(\alpha,\bar{\alpha},p_T,\kappa)\right] + [\alpha \longleftrightarrow \bar{\alpha}]\right\}$$

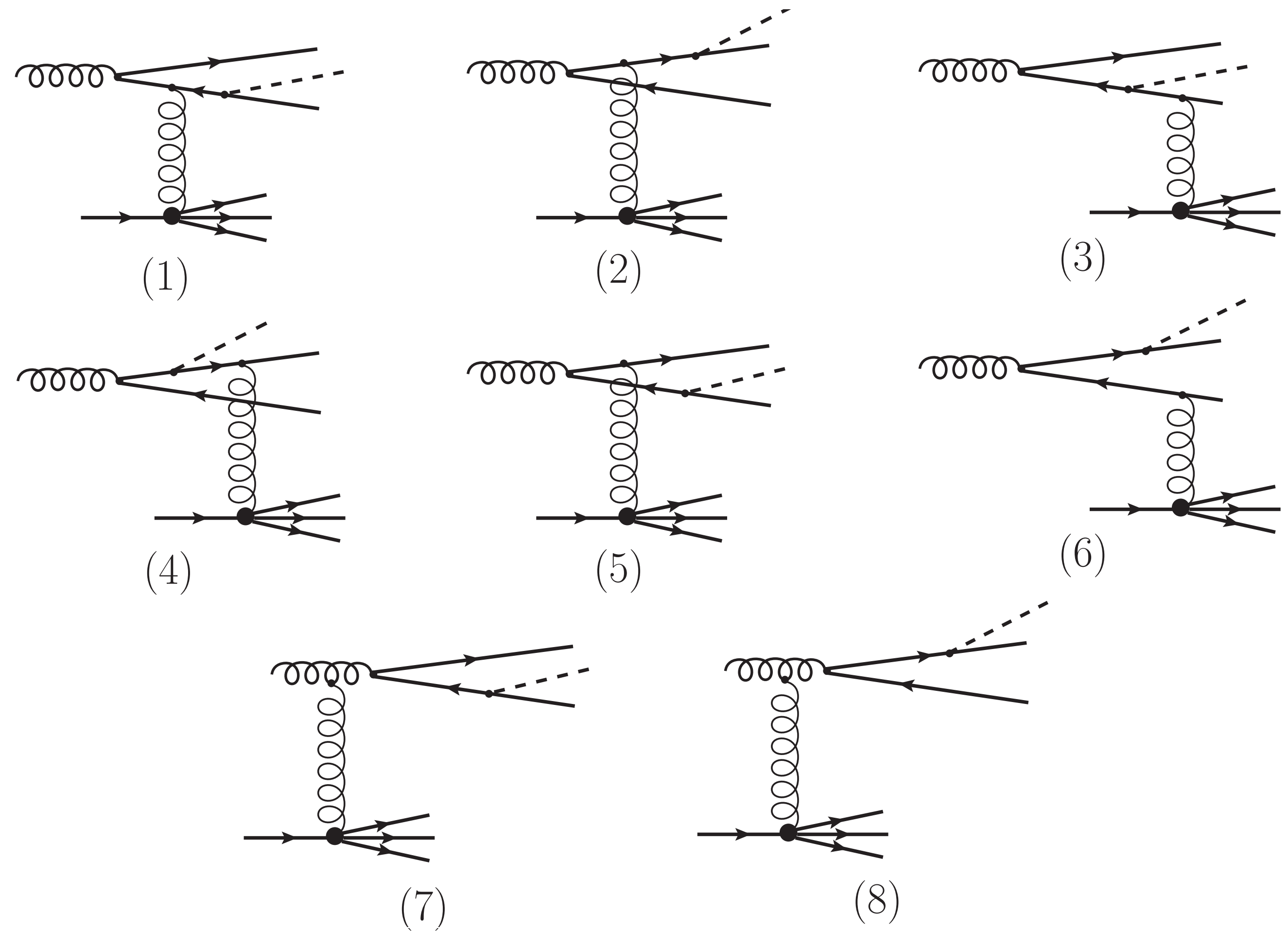


The same for inclusive and leading-twist single-diffractive QQbar production!

Diffractive Higgsstrahlung off heavy quarks



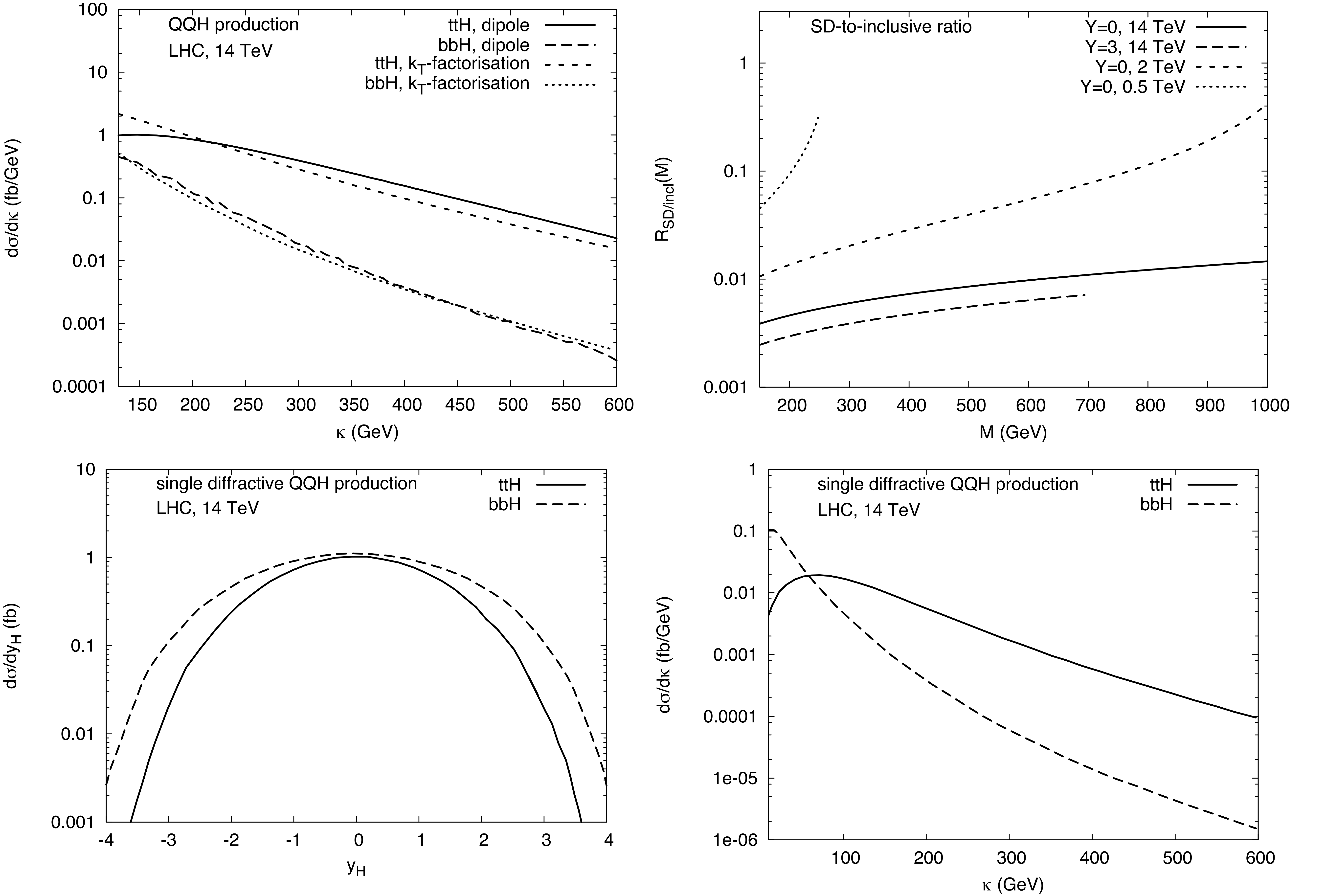
$$p + p \to \bar{Q}Qh + X + p$$



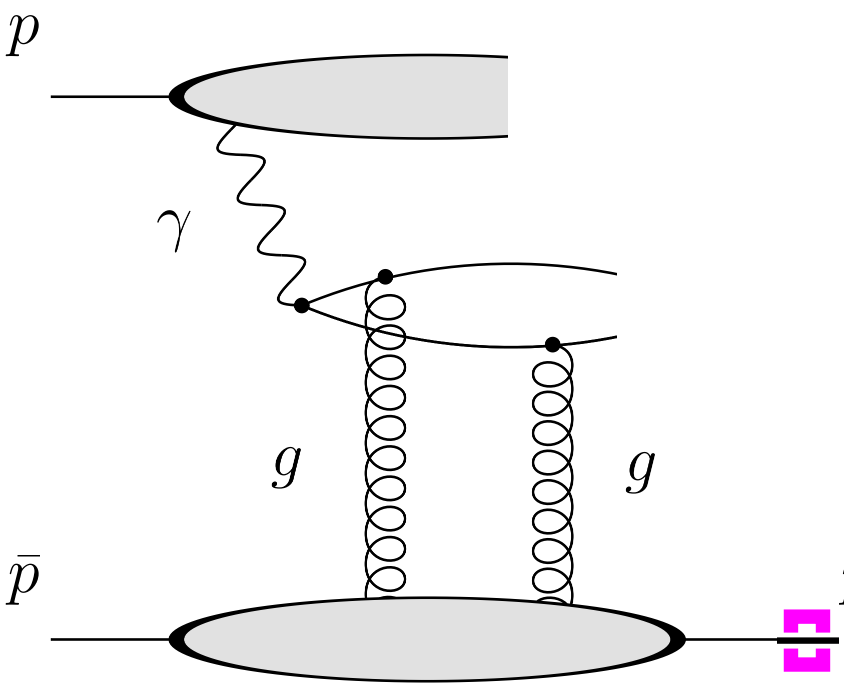
Gluon-Gluon fusion strongly dominates over gluon Bremsstrahlung!

RP, B. Kopeliovich, I. Potashnikova, PRD92 2015

Diffractive Higgsstrahlung off heavy quarks

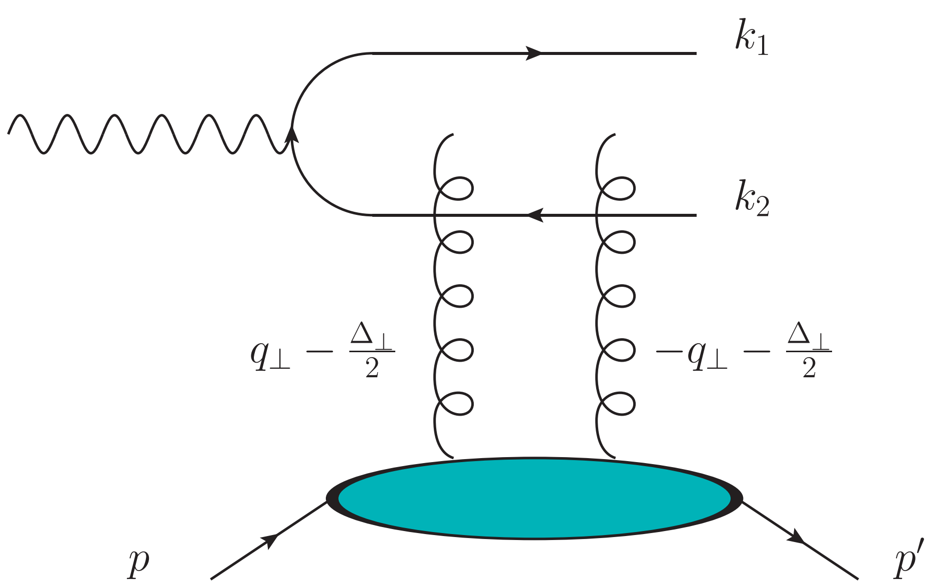


New developments:
probing the dynamical structure of the Pomeron



AFP detector

RP, O. Teryaev and M. Tasevsky, in progress



Wigner function
encodes all the information about nucleon tomography

$$\int (d^2\Delta_\perp/(2\pi)^2) e^{i\Delta_\perp \cdot b_\perp} xG_{\rm DP}(x, q_\perp, \Delta_\perp) \;=\; xW_g^T(x, q_\perp, b_\perp)$$

↑
generalised TMD gluon dipole distribution

elliptic angular correlation

$$xG_{\rm DP}(x, \vec{q}_\perp, \vec{\Delta}_\perp) = x\mathcal{G}_{\rm DP}(x, |\vec{q}_\perp|, |\vec{\Delta}_\perp|) + x\mathcal{G}^{\epsilon}_{\rm DP}(x, |\vec{q}_\perp|, |\vec{\Delta}_\perp|) \cos 2(\phi_{q_\perp} - \phi_{\Delta_\perp})$$

Y. Hatta et al, PRL116, 2016

Summary

- ✓ Hadronic diffraction is one of the most prominent tools for probing the long-distance effects in QCD

- ✓ Major sources of diffractive factorisation breaking in hadron-hadron collisions are (i) the absorptive corrections, and (ii) the hard-soft interplay due to transverse motion of spectators, making the hadronic diffraction of the leading-twist nature

- ✓ The dipole picture provides universal and robust means for studies the inclusive and single-diffractive processes in both pp and pA collisions at large Feynman xF beyond QCD factorisation

- ✓ The universal partial dipole amplitude accounts for the absorptive corrections such that no additional probabilistic fudge factors are necessary in the dipole picture

- ✓ Single-diffractive gauge bosons' (e.g. Drell-Yan) and heavy flavour production at large Feynman xF has been studied beyond diffractive factorisation

- ✓ The SD-to-diffractive ratio affects the scale and rapidity dependence of the leading-twist hadronic diffractive observables compared to the inclusive ones, the angular correlations are the same as in the inclusive case.