Rapidity gaps in high energy photoproduction

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Outline

- EIC prospects of rapidity gap measurements : proton tagging vs rapidity gap
- Formalism for VM production at high -t: scattering of Pomeron off a parton
- Comparison with HERA data and tuning the parameters
- Simulations for the EIC

Based on work in collaboration with:

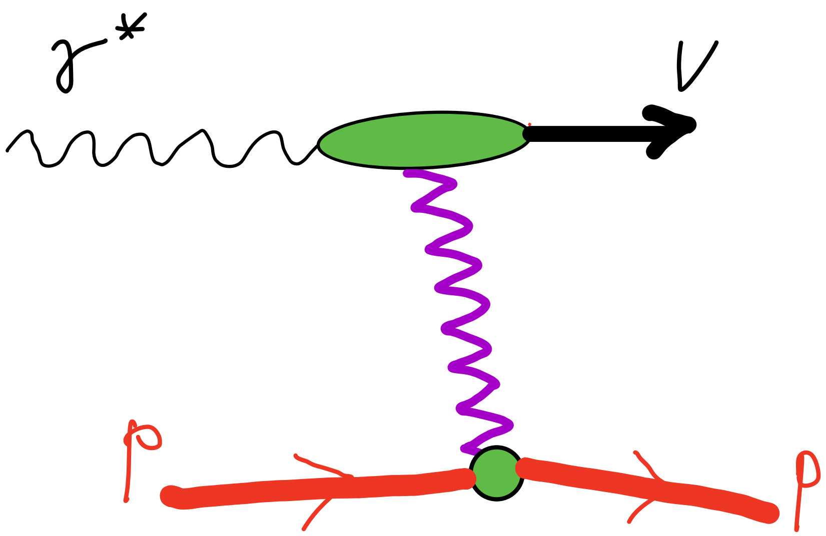
Piotr Kotko, Leszek Motyka, Mariusz Sadzikowski arXiv:1905.00130

Michal Deak, Mark Strikman arXiv:2011.04711

Selected results also appeared in Yellow Report arXiv:2103.05419.

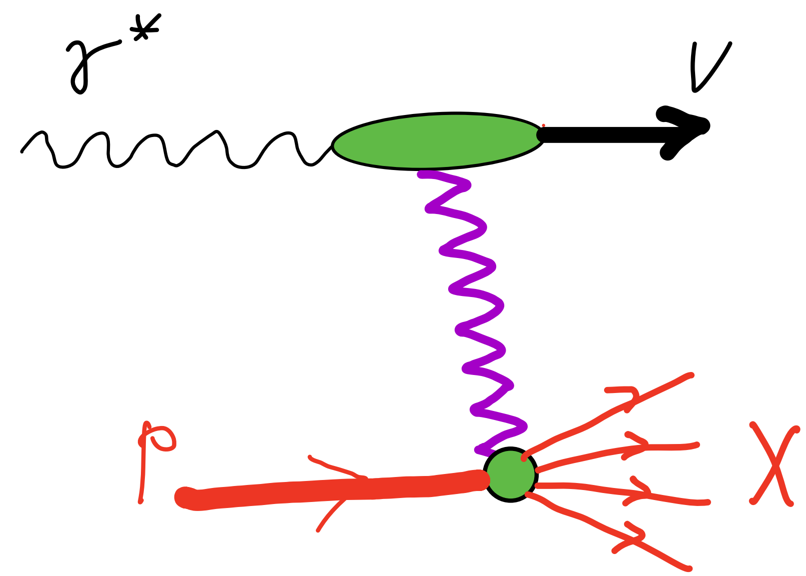
Diffractive VM production

Elastic



Dominates at low -t. Elastic scattering of a small color dipole off a nucleon

Dissociative

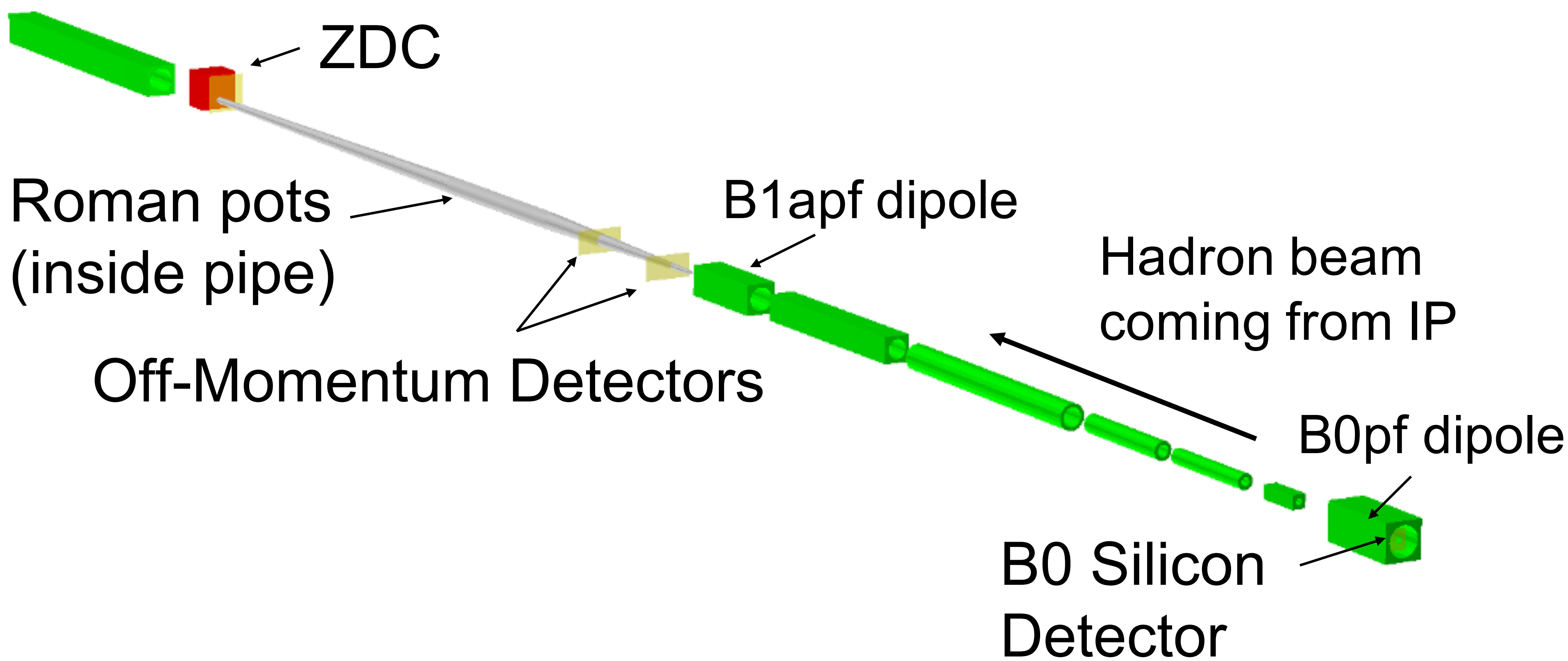


Dominates at high -t. Elastic scattering of a small color dipole off a parton in nucleon

Experimental determination: *proton tagging* or *large rapidity gap* .

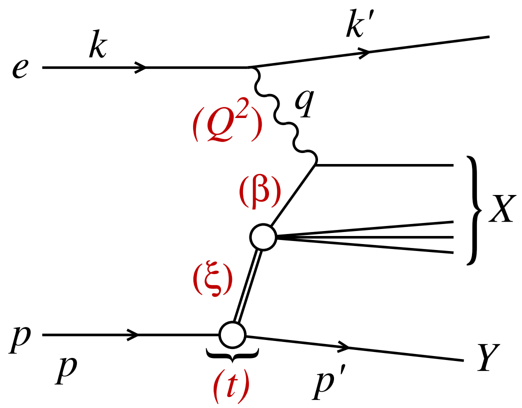
Far forward detectors at EIC

Yellow Report 2021



Detector	Angle	Position [m]
ZDC	θ<5.5 mrad	37.5
Roman Pots	0.5<θ<5.0 mrad	26.0, 28.0
Off-momentum detectors	θ<5.0 mrad	22.5, 25.5
B0	6.0<θ<20.0 mrad	5.4<z<6.4

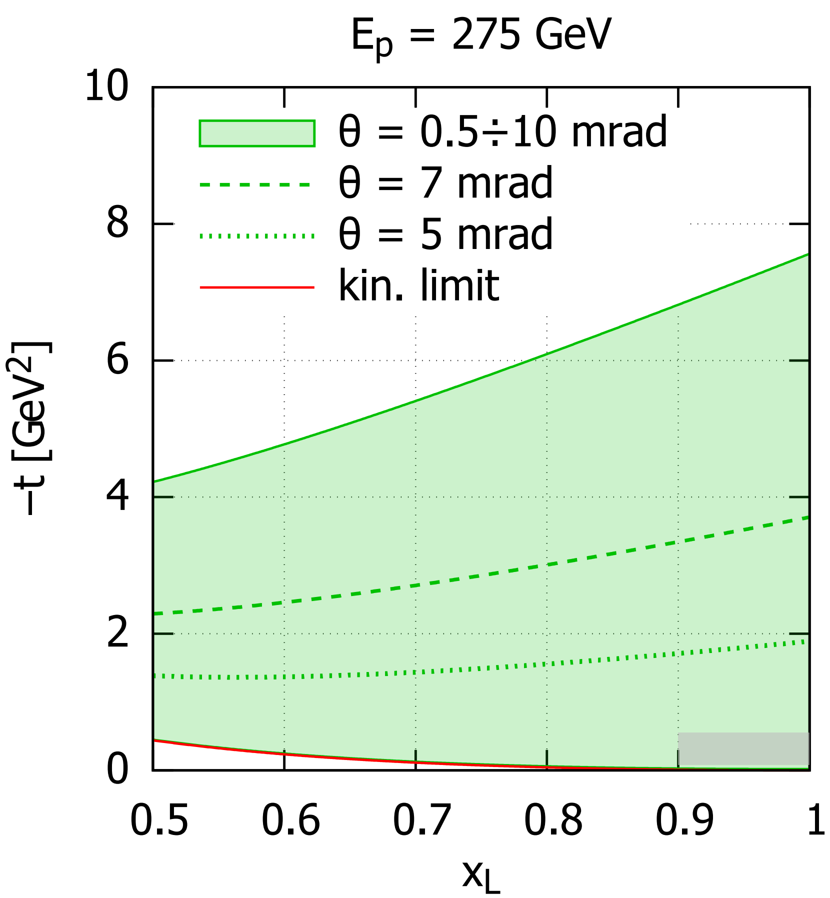
Final proton tagging

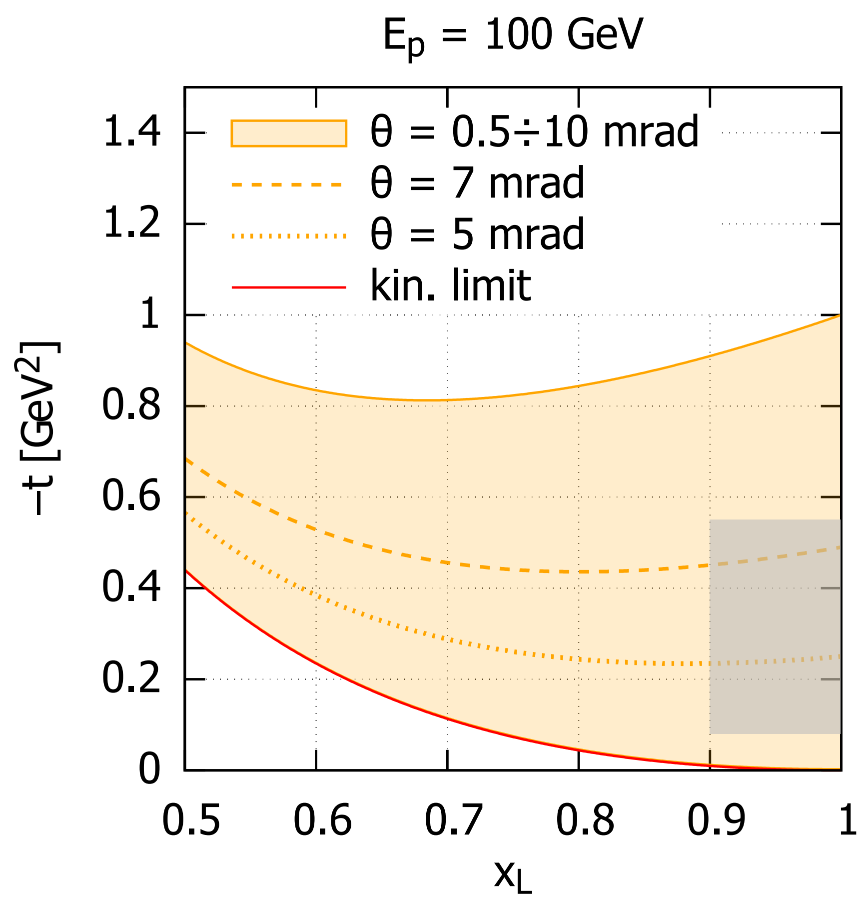


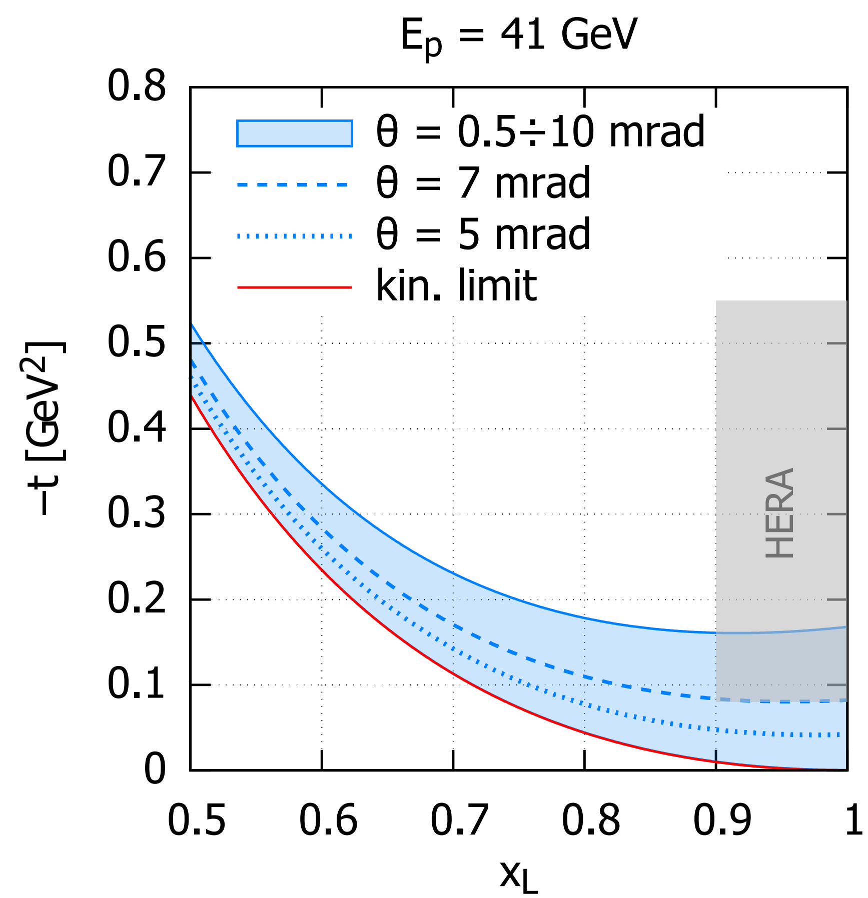
$(x_L, p_\perp)$

Small angle acceptance i.e. Roman pots

$(x_L, p_\perp, \theta)$ measured in LAB, collinear (e,p) frame







Much better than at HERA

Best way to select diffractive events through proton tagging

$$t = -\frac{p_\perp^2}{x_L} - \frac{(1-x_L)^2}{x_L} m_p^2$$

Pseudorapidity distribution

18 GeV x 275 GeV

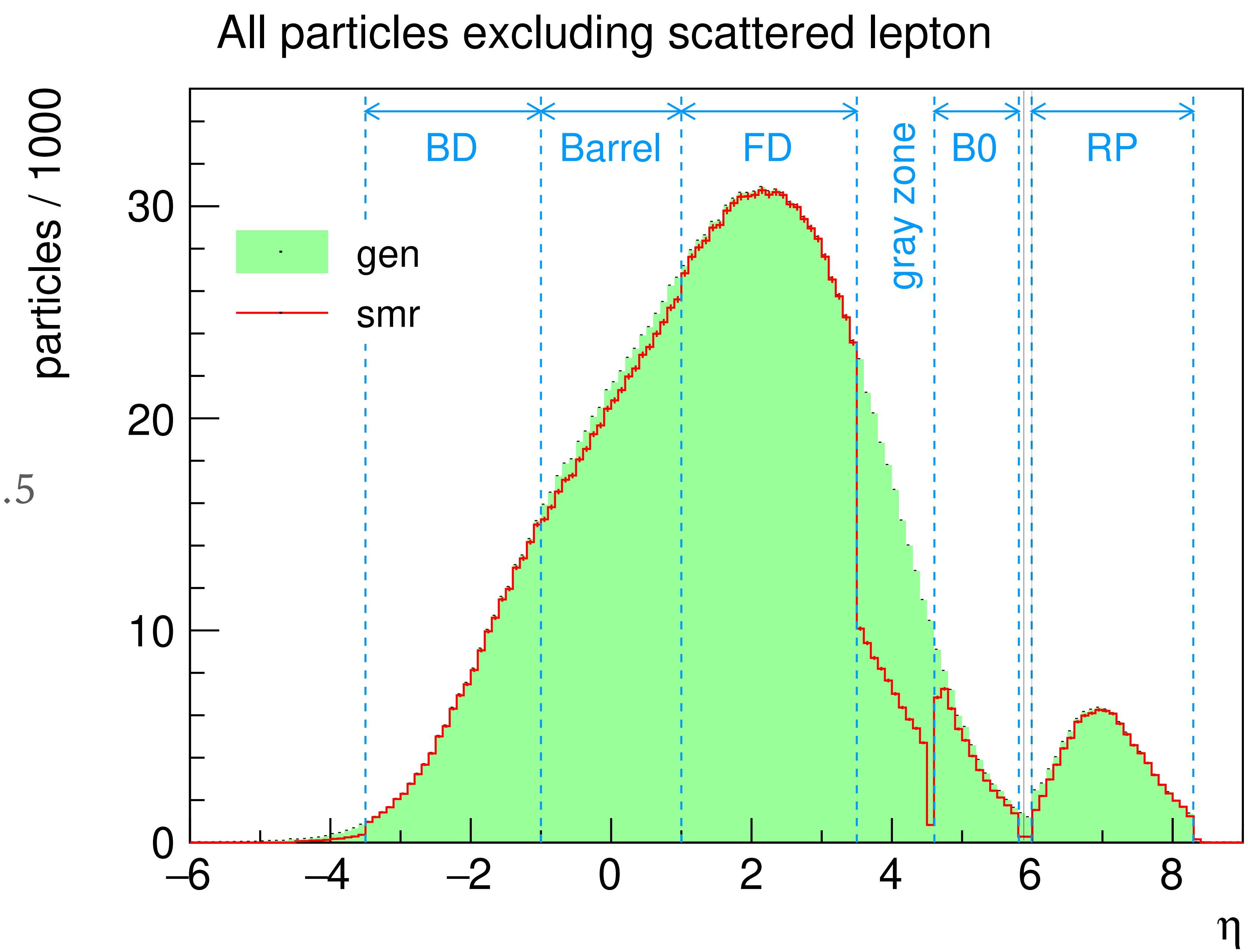
Green histogram: generated from RAPGAP

Red histogram: reconstructed from smeared data

Hadronic calorimetry up to η<3.5

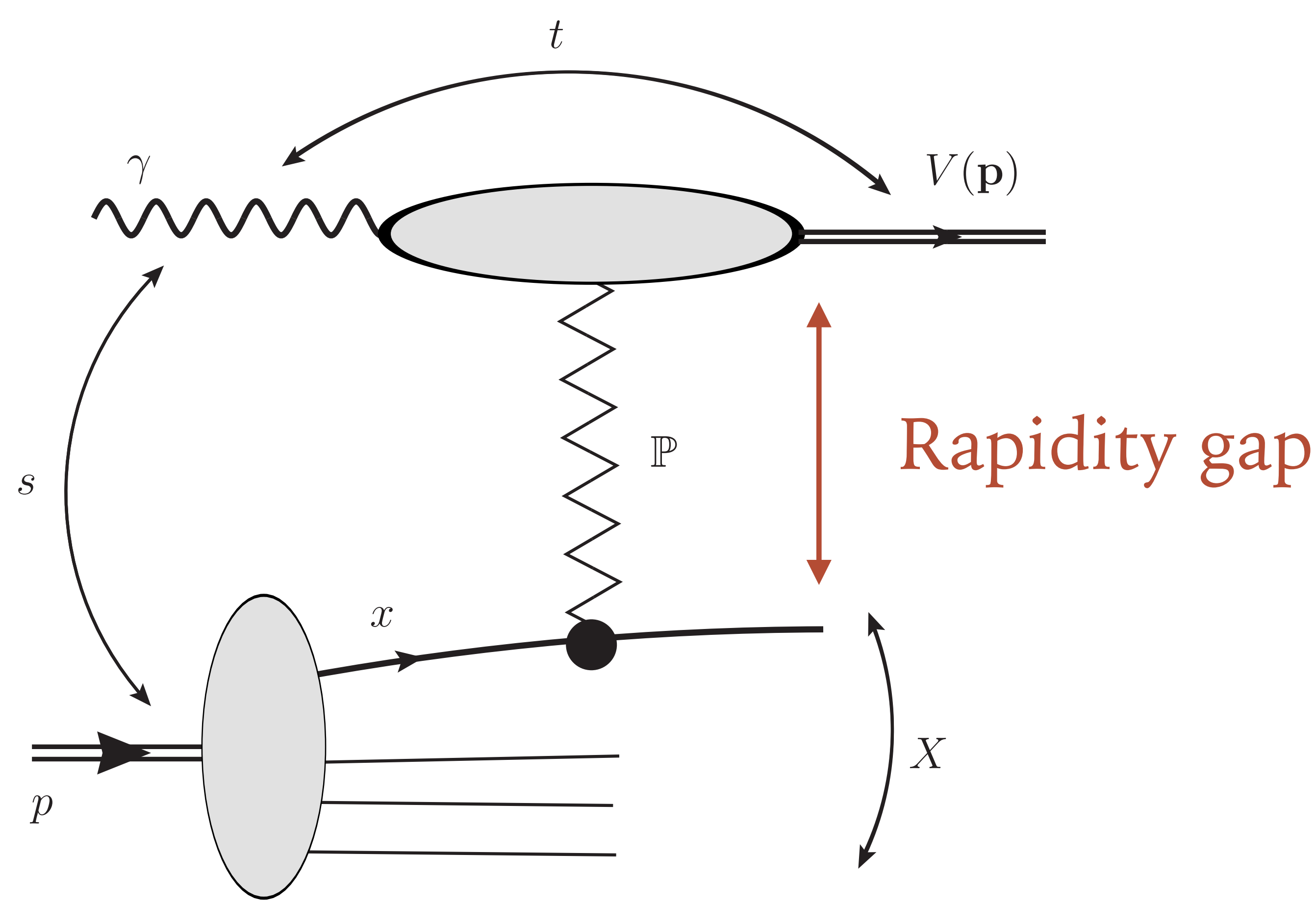
EM calorimetry up to η<4.5

Use of B0 or other dedicated veto detectors could extend this region



Dissociative diffraction with vector mesons

$$\gamma\, p \to V\; X$$



Elastic scattering off a quark

Abramowicz, Frankfurt, Strikman

Forshaw, Ryskin

High energy limit

$$s \gg |t|$$

$$s \gg M_V^2$$

Perturbative QCD

$$|t| \gg \Lambda^2_{QCD}$$

Photoproduction

$$Q^2 \simeq 0$$

Heavy vector meson

$$M_V^2 \gg \Lambda^2_{\rm QCD}$$

High –t diffraction with vector mesons

Factorization of the collinear PDFs and partonic cross section

$$d\sigma = \sum_{i=g,q,\bar{q}} \int dx\, f_i(x,\mu)\, d\hat{\sigma}_{\gamma i}(\hat{s},t,\mu)$$

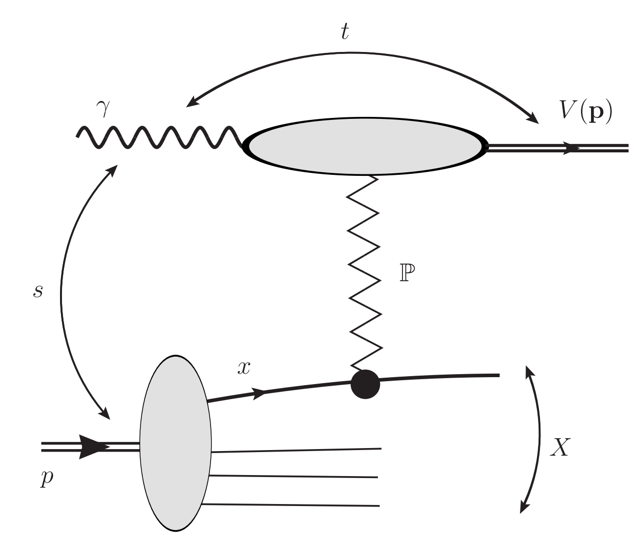
f_i collinear PDF

$d\hat{\sigma}_{\gamma i}(\hat{s},t,\mu)$ partonic cross section

x longitudinal fraction of proton light cone momentum carried by the quark or gluon

$\mu \sim \sqrt{|t|}$ choice of factorization scale

$\hat{s} = xs$ photon-parton invariant mass squared



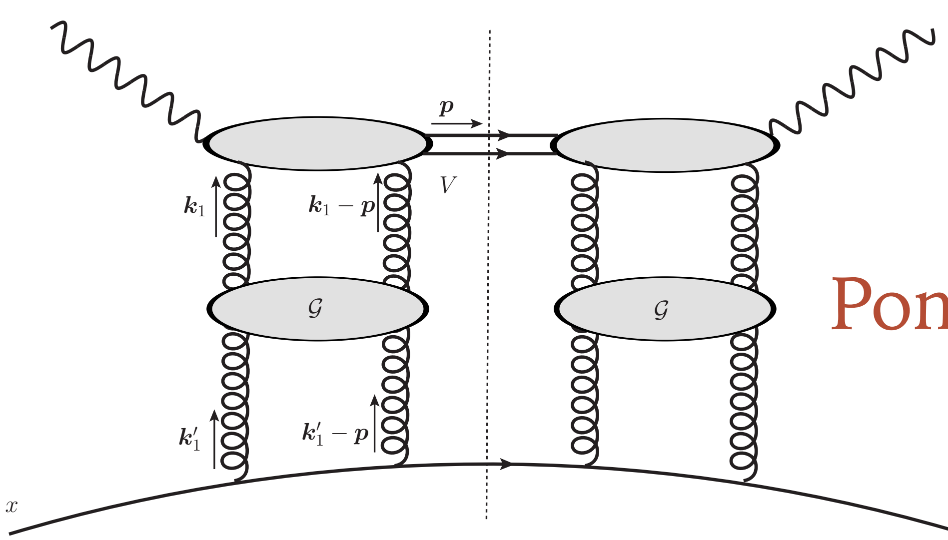
High energy kinematics $t = -\mathbf{p}^2$

Partonic cross section and BFKL Pomeron exchange

$$d\hat{\sigma}_{\gamma i} = C_{\gamma i}\ d\sigma_{1-\mathbb{P}} \qquad\qquad d\sigma_{1-\mathbb{P}} = \frac{1}{16\pi \hat{s}^2}\ \left|\mathcal{A}\left(\hat{s}, t=-p^2\right)\right|^2\ \frac{d^2\boldsymbol{p}}{\pi}$$

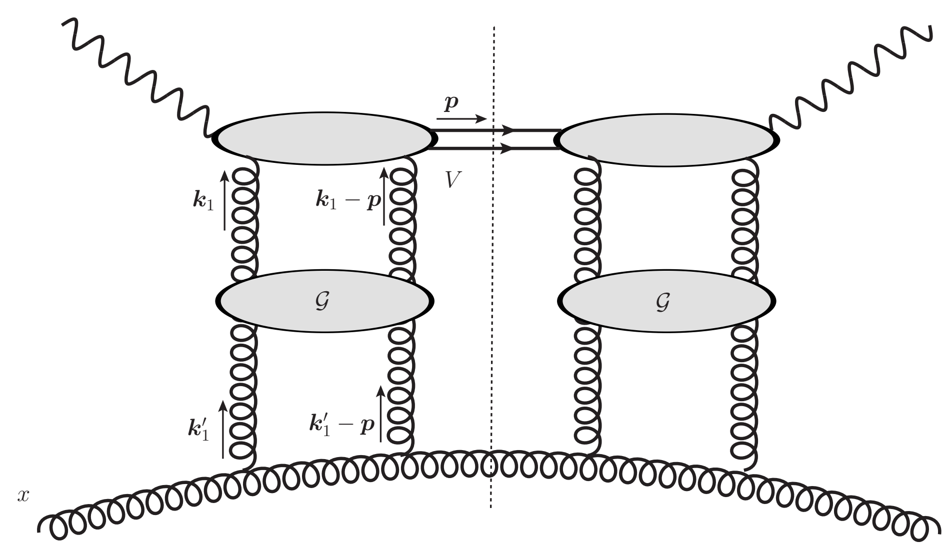
$C_{\gamma i},\ i = q, g$ color factors

$\mathcal{A}$ amplitude to produce the vector meson through single Pomeron exchange



Pomeron

Diffractive scattering off quark



Diffractive scattering off gluon

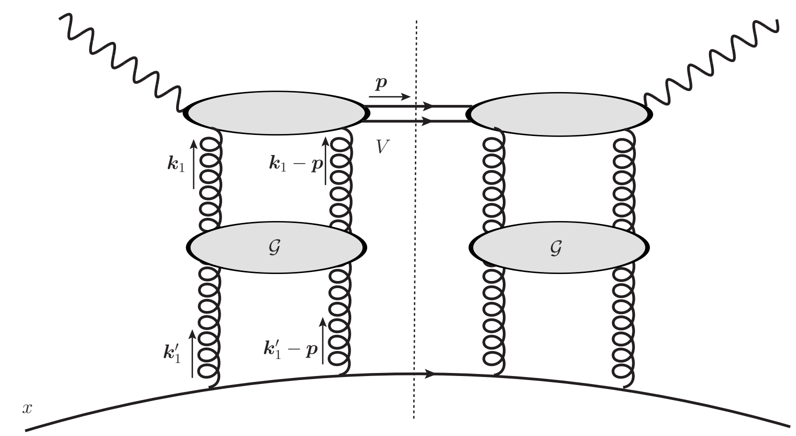
The Pomeron ampliude

Imaginary part of the amplitude

Ginzburg, Ivanov; Forshaw, Poludniowski;

Enberg, Motyka, Poludniowski

$$\mathrm{Im}\,\mathcal{A}\left(\hat{s}, t=-p^2\right) = \hat{s}\int \frac{d^2\boldsymbol{k}_1}{2\pi}\,\frac{\Phi_V\left(\boldsymbol{k}_1,\boldsymbol{p}\right)\Phi_q\left(y,\boldsymbol{k}_1,\boldsymbol{p}\right)}{\left(\boldsymbol{k}_1^2+s_0\right)\left[\left(\boldsymbol{p}-\boldsymbol{k}_1\right)^2+s_0\right]}$$



$\boldsymbol{k}_1$ and $\boldsymbol{p}-\boldsymbol{k}_1 \equiv \boldsymbol{k}_2$ transverse momenta of the exchanged gluons

$\boldsymbol{p}$ transverse momentum carried by the Pomeron

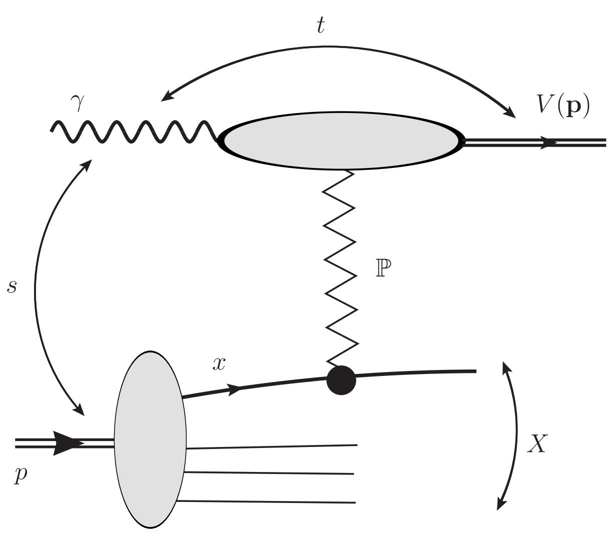
$\Phi_V,\ \Phi_q$ impact factors for vector meson and quark

s_0 phenomenological parameter modeling confinement

$\Phi_q\left(y,\boldsymbol{k}_1,\boldsymbol{p}\right)$ evolved impact factor for quark with rapidity y

Rapidity evolution with BFKL -> energy dependence of the cross section

Definition of the rapidity gap



Essential for the modeling and comparison with data

$$y = y_j - y_V$$

Difference between recoil jet and vector meson rapidity

Different choices in the literature

$$\ln \frac{\hat{s}}{M_V^2}$$

Forshaw, Poludniowski; Enberg, Motyka, Poludniowski

$$\ln \frac{\hat{s}}{M_V^2 + p^2} = \ln \frac{\hat{s}}{M_V^2 - t}$$

Kotko, Motyka, Sadzikowski, Stasto

One can derive more precisely:

$$y = \ln \frac{\hat{s}}{\sqrt{-t(M_V^2 - t)}}$$

Frankfurt, Strikman, Zhalov;

Deak,Stasto, Strikman

Vector meson impact factor

Non-relativistic approximation for the meson wave function.

The impact factor reads

$$\Phi^{ab}_{\gamma V}\left(\boldsymbol{k}_1, \boldsymbol{p}\right) = \Phi_V\left(\boldsymbol{k}_1, \boldsymbol{p}\right)\,\frac{\delta^{ab}}{N_c}$$

Ginzburg, Ivanov

$$\Phi_V\left(\boldsymbol{k}_1, \boldsymbol{p}\right) = 16\pi e e_q \alpha_s M_V g_V \left[\frac{1}{M_V^2 + \boldsymbol{p}^2} - \frac{1}{M_V^2 + (\boldsymbol{p} - 2\boldsymbol{k}_1)^2}\right]$$

$$g_V = \sqrt{\frac{3 M_V \Gamma_{V\to ll}}{16\pi \alpha_{em}^2 e_q^2}}$$

$\Gamma_{V\to ll}$ leptonic decay width

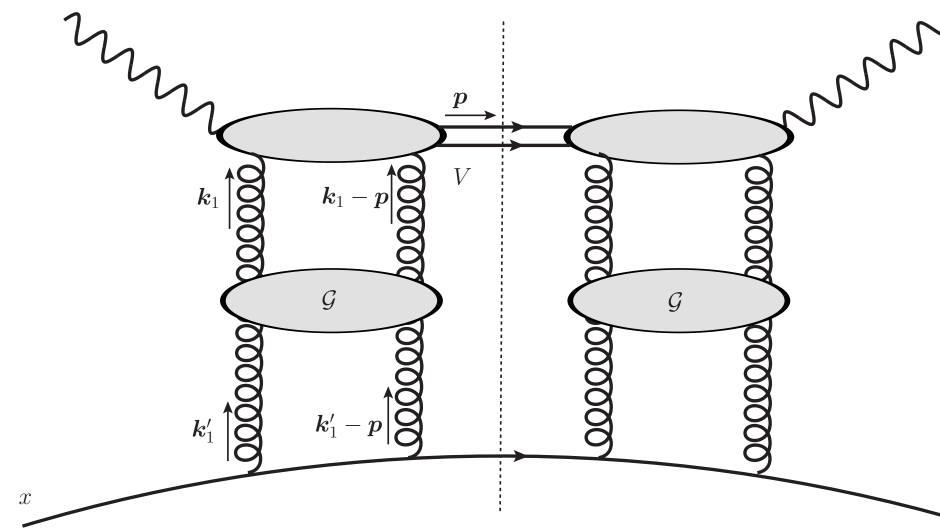
Valid for transverse polarization of the photon and vector meson. Since photon quasi-real its polarization transverse. Amplitude for transverse photon to longitudinally polarized vector meson estimated to be small.

Evolved quark impact factor

Quark and gluon differ only by a color factor

$$\Phi_q^{\mathbf{1},ab}(y,\boldsymbol{k}_1,\boldsymbol{p}) = \Phi_q(y,\boldsymbol{k}_1,\boldsymbol{p})\,\frac{\delta^{ab}}{2N_c}$$

$$\Phi_g^{\mathbf{1},ab}(y,\boldsymbol{k}_1,\boldsymbol{p}) = \Phi_q(y,\boldsymbol{k}_1,\boldsymbol{p})\,\frac{N_c}{N_c^2-1}\,\delta^{ab}$$



Evolved quark impact factor (kinematic part)

with BFKL evolution

$$\Phi_q(y,\boldsymbol{k}_1,\boldsymbol{p}) = \int d^2\boldsymbol{k}_1'\,\Phi_{q,0}(\boldsymbol{k}_1',\boldsymbol{p})\,\mathcal{G}_y(\boldsymbol{k}_1,\boldsymbol{k}_1';\boldsymbol{p})$$

Non-forward gluon Green's function

Non-forward BFKL equation

Balitsky, Fadin, Kuraev, Lipatov

$$\Phi_q(y,\boldsymbol{k}_1,\boldsymbol{p}) = \Phi_{q,0}(\boldsymbol{k}_1,\boldsymbol{p}) + \bar{\alpha}_s\int_0^y dy'\int\frac{d^2\boldsymbol{k}'}{2\pi}\,\frac{1}{(\boldsymbol{k}'-\boldsymbol{k})^2+s_0}$$
$$\Bigg\{\left[\frac{\boldsymbol{k}_1^2}{\boldsymbol{k}_1'^2+s_0}+\frac{\boldsymbol{k}_2^2}{\boldsymbol{k}_2'^2+s_0}-p^2\frac{(\boldsymbol{k}'-\boldsymbol{k})^2+s_0}{(\boldsymbol{k}_1'^2+s_0)(\boldsymbol{k}_2'^2+s_0)}\right]\Phi_q(y',\boldsymbol{k}_1',\boldsymbol{p})$$
$$-\left[\frac{\boldsymbol{k}_1^2}{\boldsymbol{k}_1'^2+(\boldsymbol{k}'-\boldsymbol{k})^2+s_0}+\frac{\boldsymbol{k}_2^2}{\boldsymbol{k}_2'^2+(\boldsymbol{k}'-\boldsymbol{k})^2+s_0}\right]\Phi_q(y',\boldsymbol{k}_1,\boldsymbol{p})\Bigg\}$$

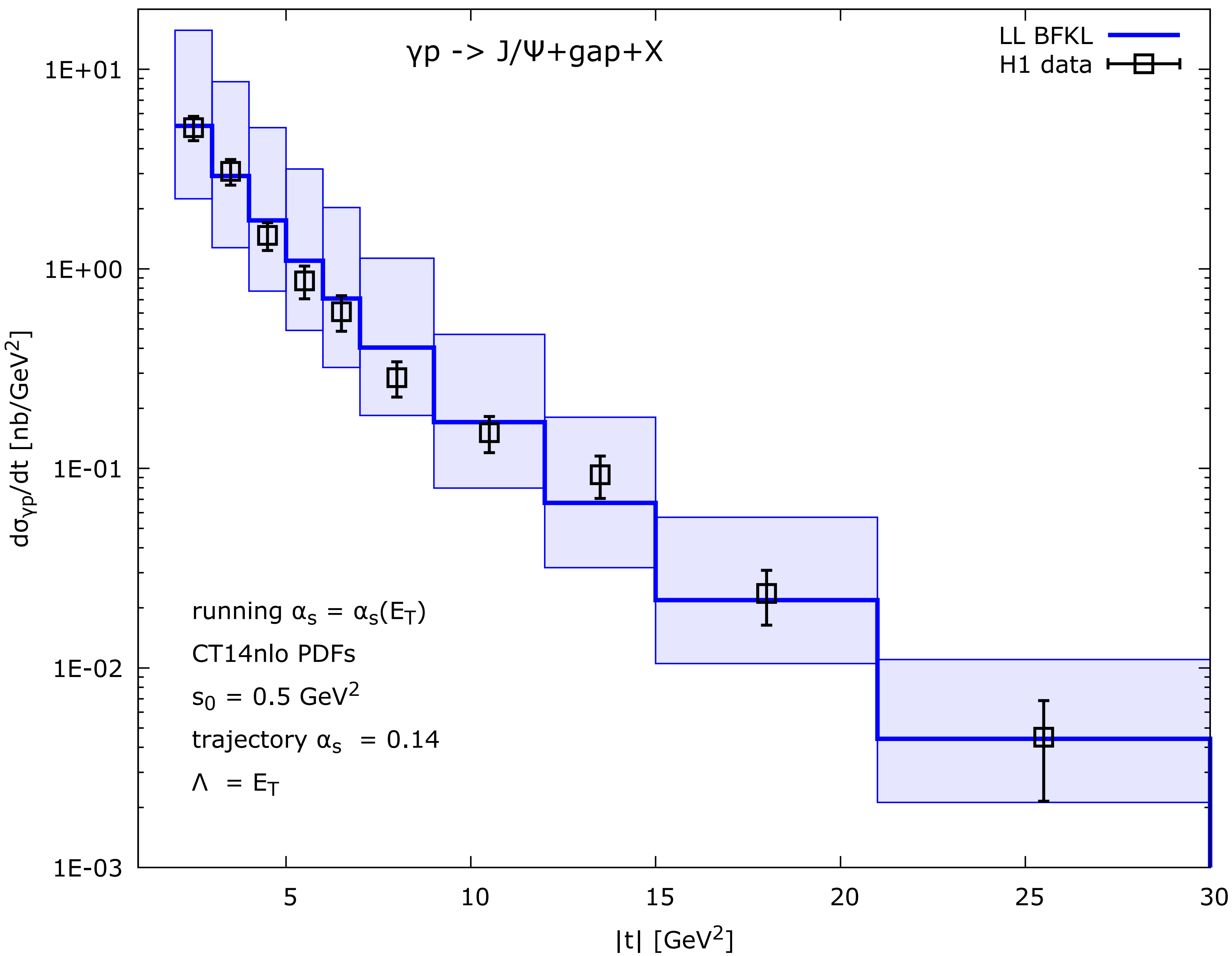
Define the auxilliary momenta

$$\boldsymbol{k} = (\boldsymbol{k}_2-\boldsymbol{k}_1)/2,\ \boldsymbol{k}' = (\boldsymbol{k}_2'-\boldsymbol{k}_1')/2$$

Comparison with HERA data

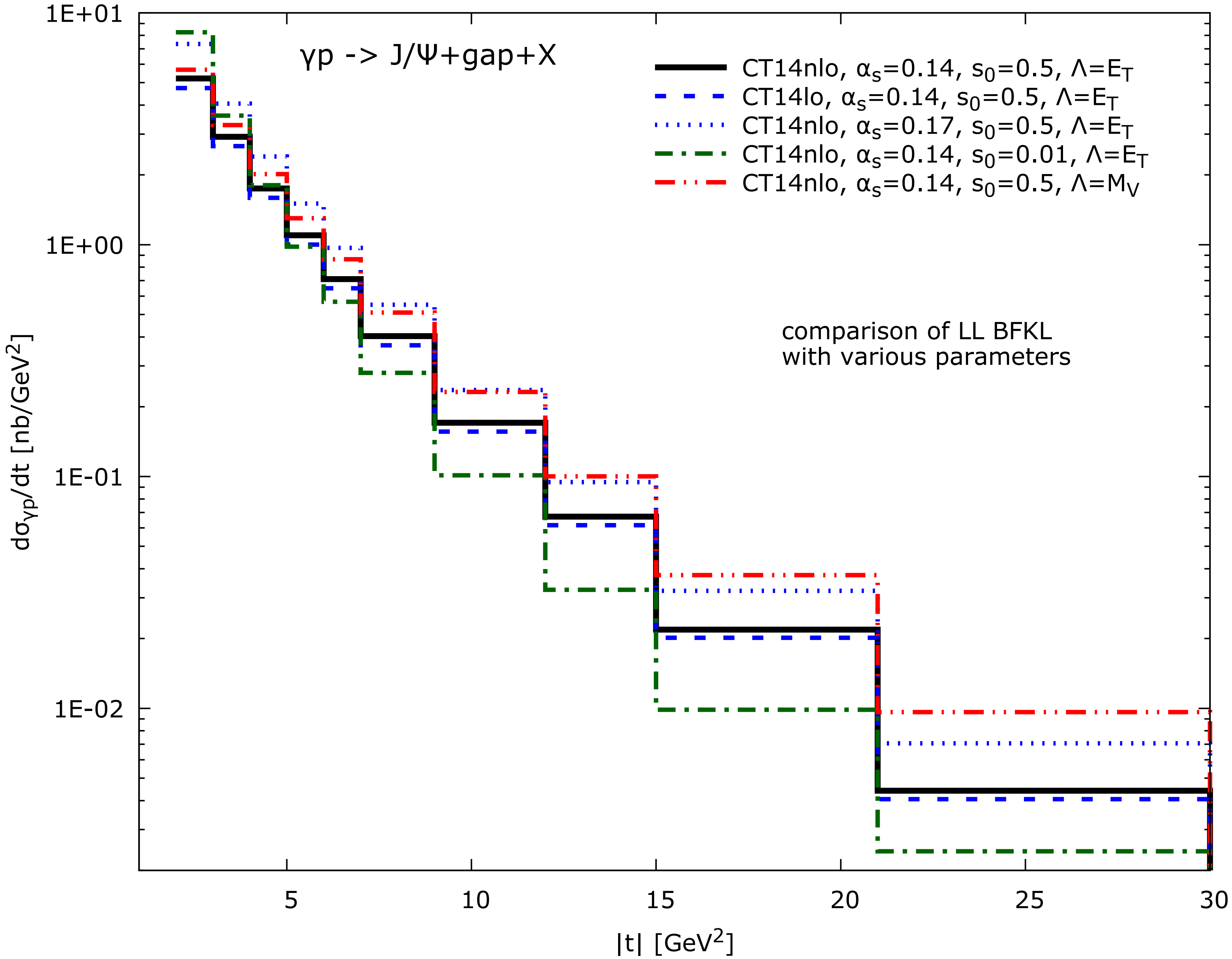
- ZEUS data: $80 < \sqrt{s} < 120\,\mathrm{GeV}$ $|t| < 12\,\mathrm{GeV}^2$
- H1 data: $50 < \sqrt{s} < 200\,\mathrm{GeV}$ $2 < |t| < 30\,\mathrm{GeV}^2$
- Generate explicitly the photon flux
- Cut on the diffractive mass $M_Y^2 < \frac{|t|}{x}$ $M_Y = 30\,\mathrm{GeV}$
- Here we used LL BFKL with adjustable strong coupling, as a fitting parameter
- Vary the non-perturbative parameter $s_0 = 0.5 - 0.01\ \mathrm{GeV}^2$
- Change the scale in the rapidity variable
- PDFs CT14nlo

Comparison with H1 data



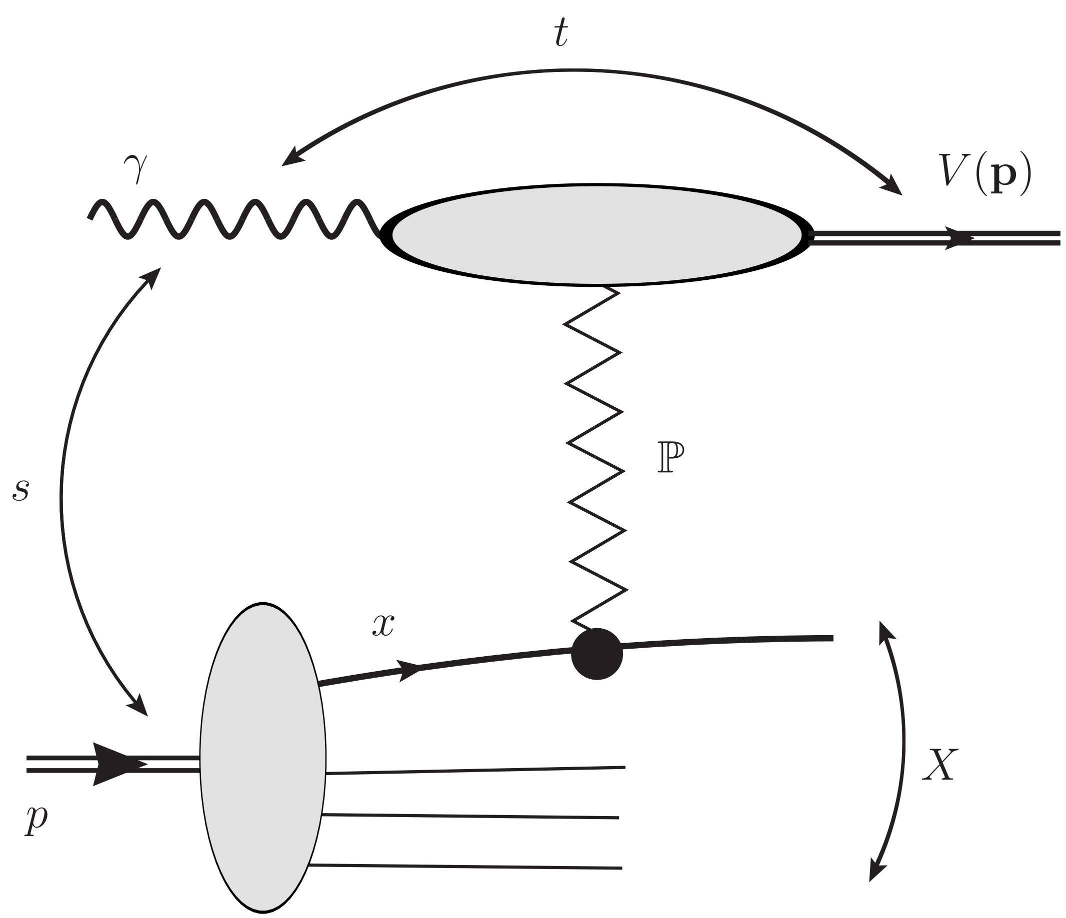
Very good description of the H1 data. Band due to scale change by factor 2 in impact factors.

Comparison with H1 data. Varying the parameters



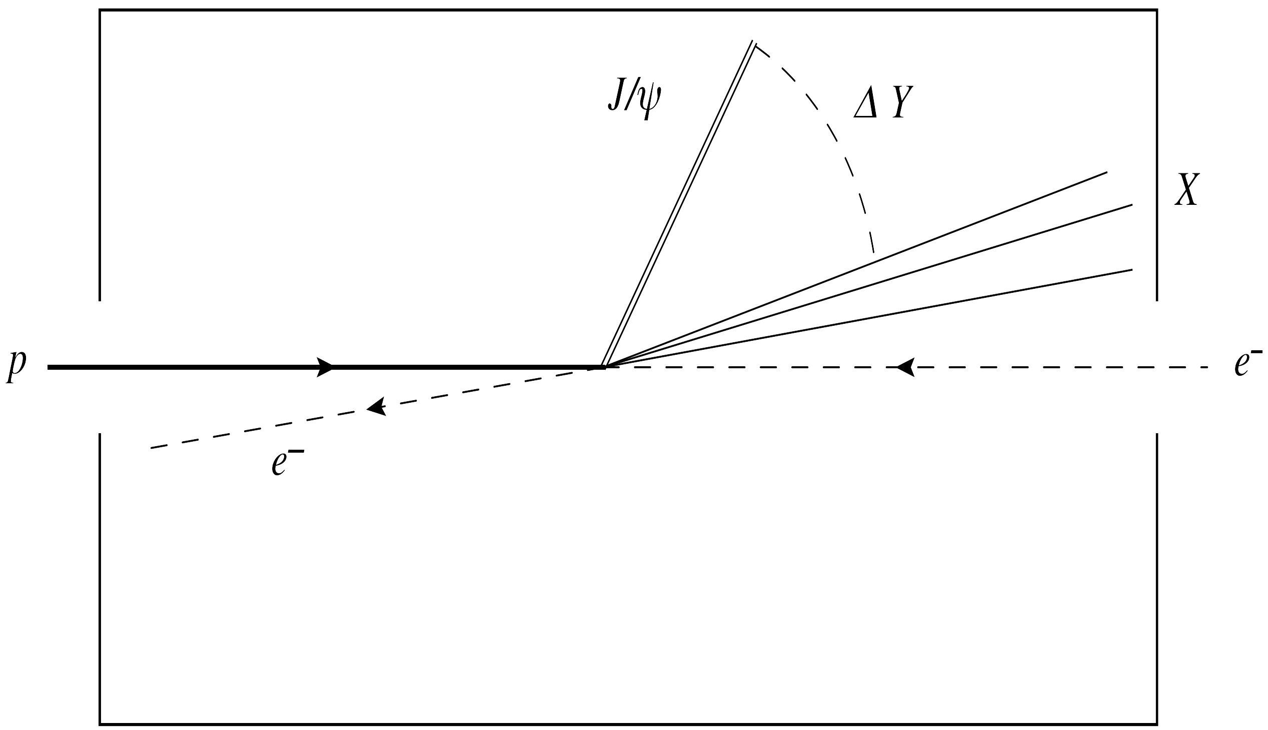
Tests on the variation of the parameters going into the calculation

HERA vs EIC prospects

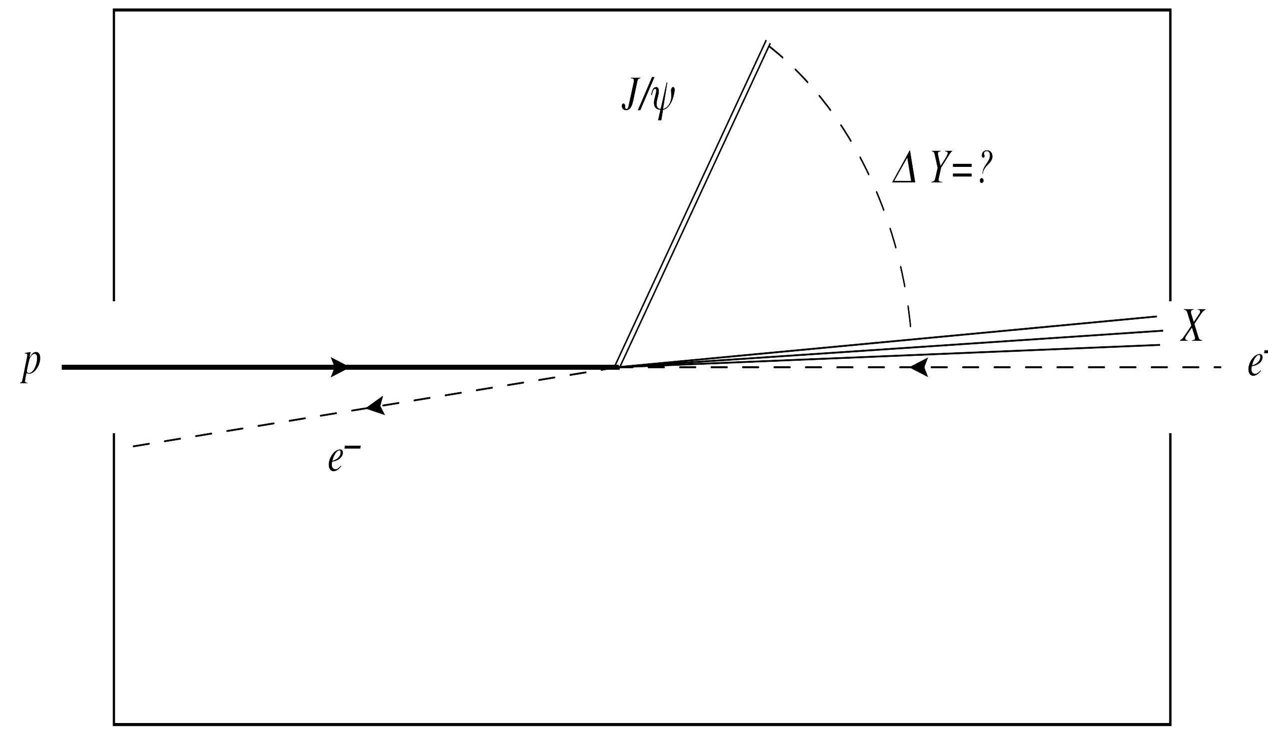


- Due to high -t, it is a good process for tests of the perturbative Pomeron
- Suppression of the diffusion of the transverse momenta along the ladder.
- Suppression of the ordered kinematics.
- Good process to investigate the energy dependence, or the dependence on the rapidity gap
- At HERA, limitations since it was not possible to measure the dependence on the size of the rapidity gap. Integrated over the range of gaps.
- Ideally, one should measure the process by fixing the angle of the recoil jet, and measuring in bins of rapidity
- Simulations performed by fixing x, or the angle of the outgoing particle

Measuring the gap: two scenarios



(a)

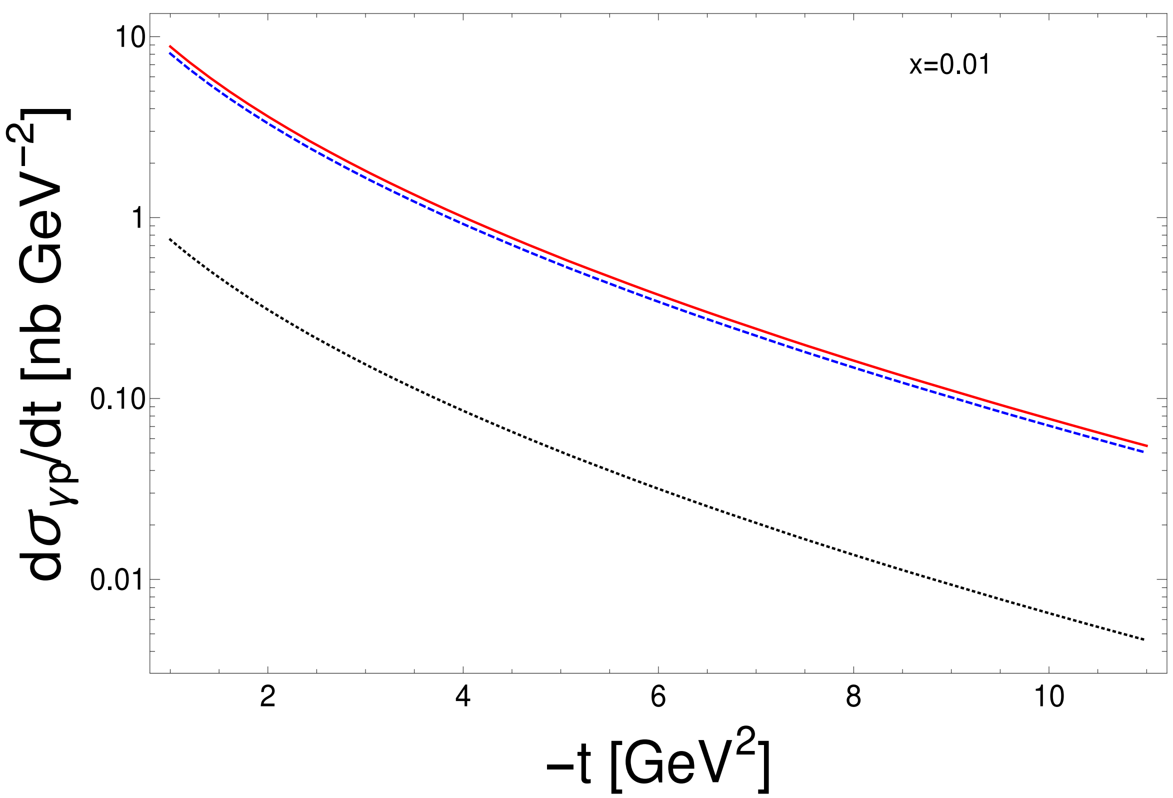


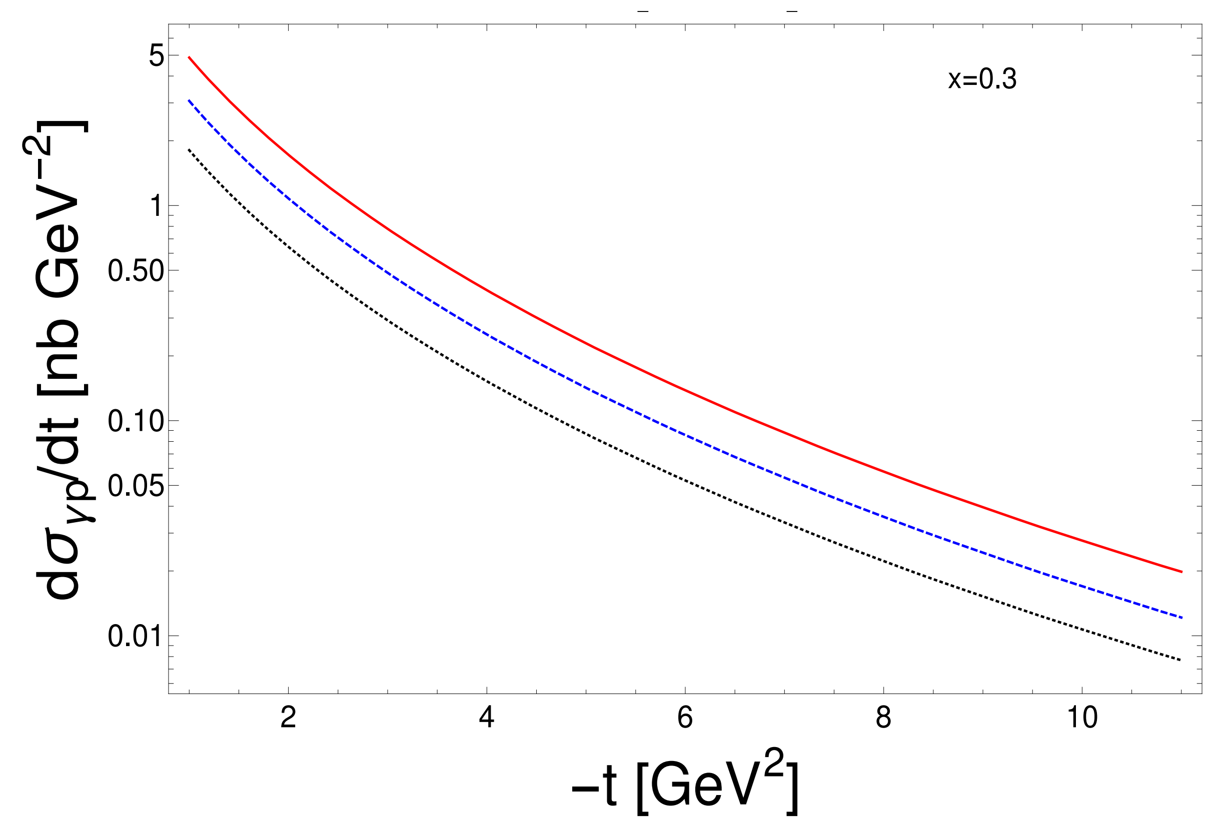
(b)

(a) Request the detection of the J/ψ vector meson, rapidity gap, and the activity in the direction of the proton beam.

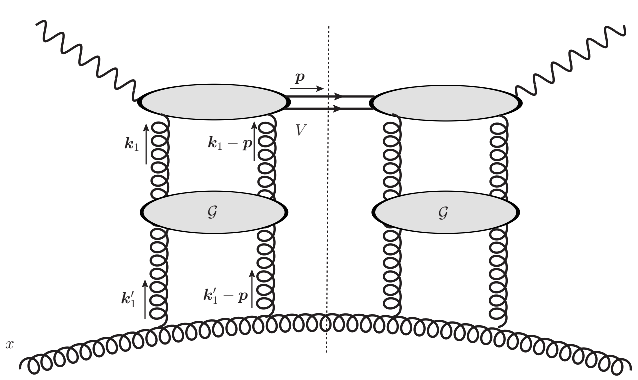
(b) Request detection of the J/ψ vector meson, rapidity gap. No activity in the forward part of the detector. This case has limitations, since the exact size of the rapidity gap is unknown. One needs to integrate over that part.

Dissociative VM diffraction at EIC: γ+p->V+gap+X

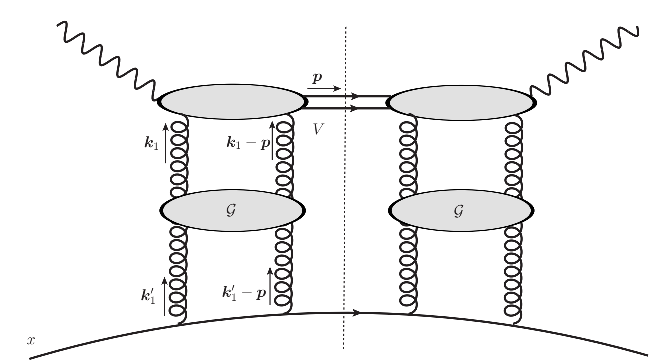




gluon



quark



Dominance of the scattering off gluon, quark negligible except for very large x

Double distribution of events in energy and rapidity

Number of events with rapidity greater than $\Delta Y_{\min}$ integrated over W and in bins of t and x

$$N(\Delta Y_{\min}) = \mathcal{L} \int_{\Delta x} dx \int_{\Delta t} dt \int_{y_{min}}^{y_{max}} dy \, \Theta(\Delta Y - \Delta Y_{\min}) \, \tilde{\Phi}_{\gamma/e}(y) \; \frac{d\sigma_{\gamma^* p}(y)}{dt dx}$$

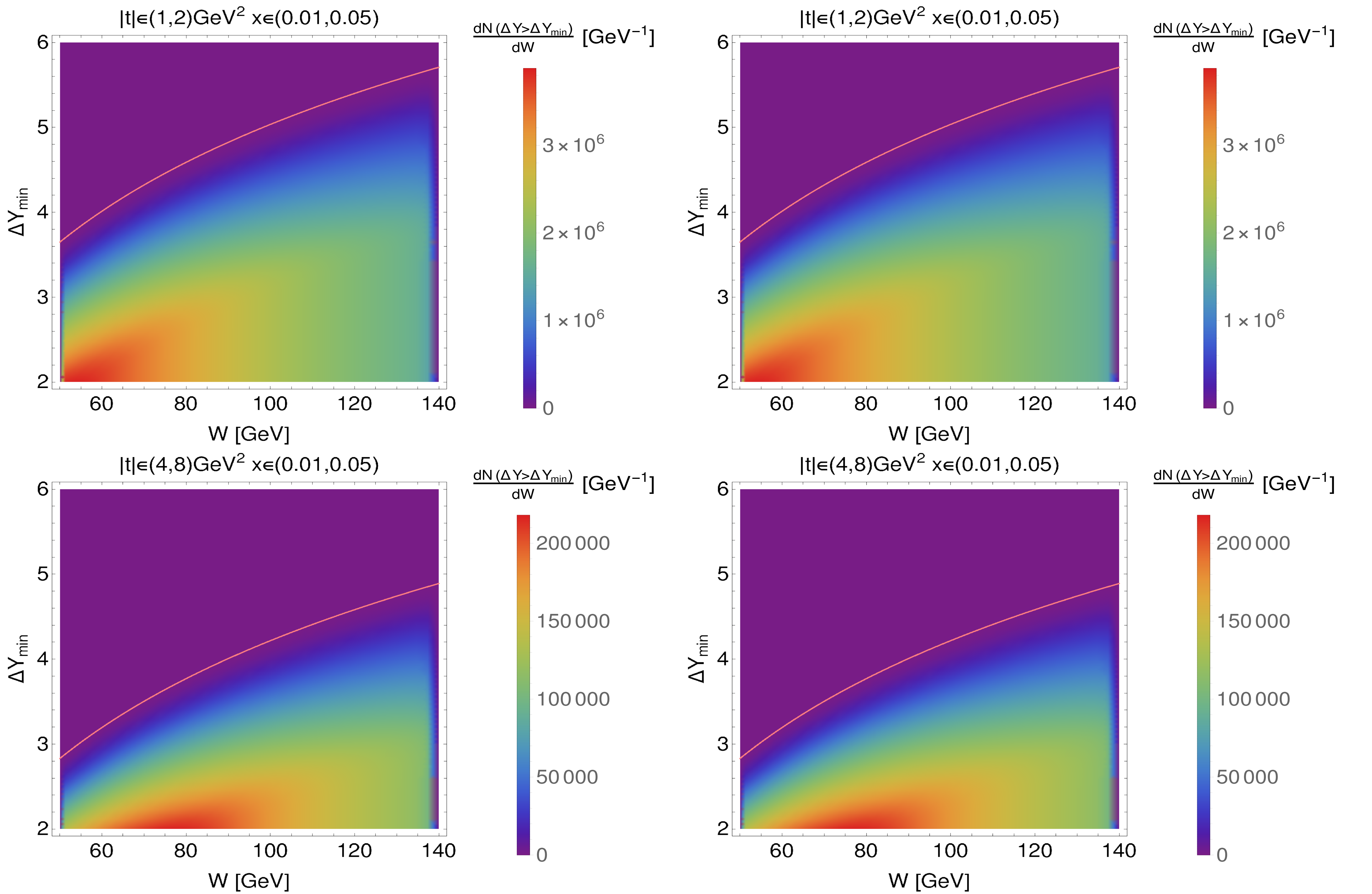
Also, evaluate number of events with rapidity greater than $\Delta Y_{\min}$ as differential in W and in bins of t and x

$$\frac{dN}{dW}(\Delta Y > \Delta Y_{\min})$$

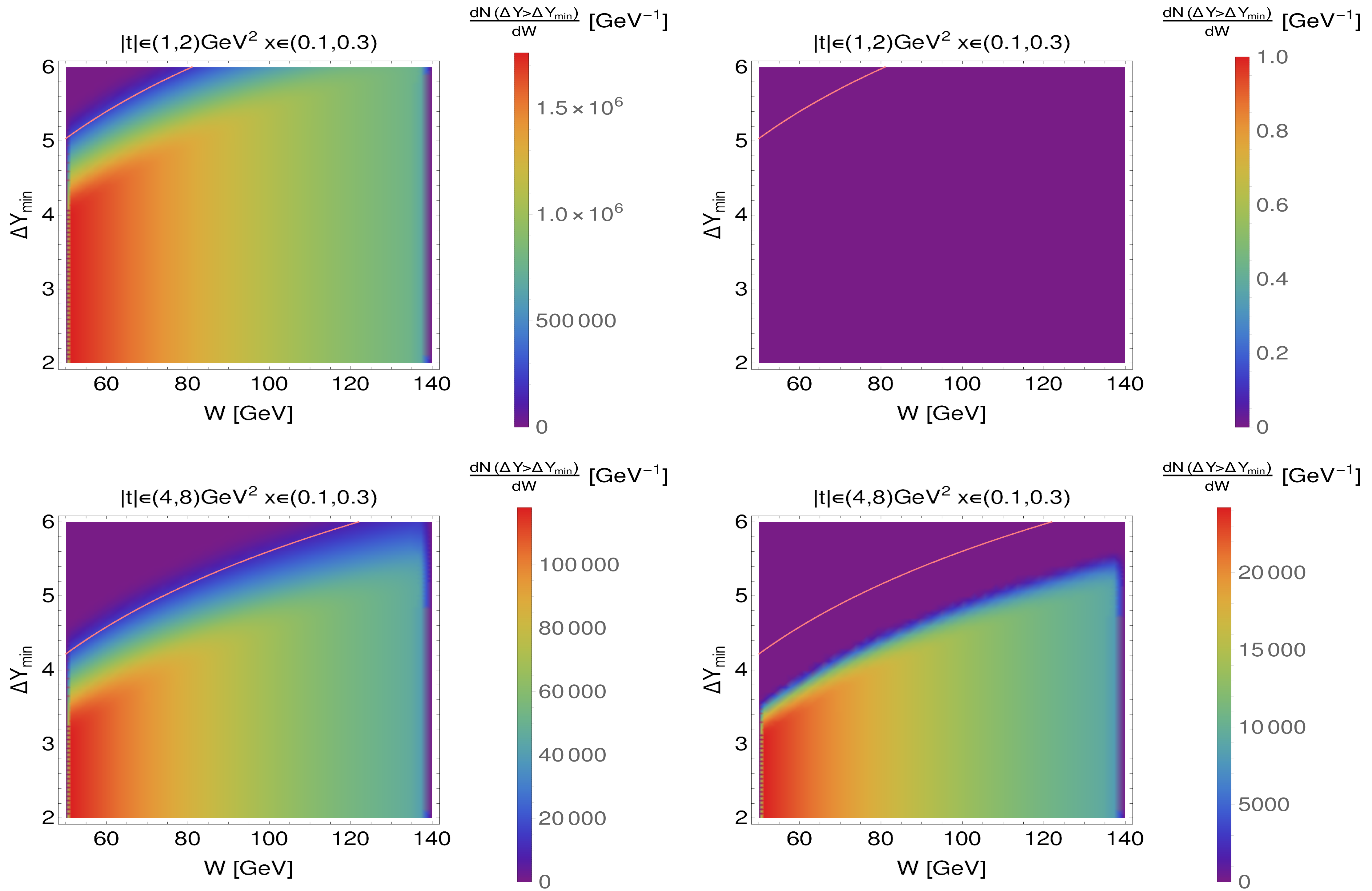
Impose cuts on the angle below which we require activity: 4^o

Corresponds to pseudorapidity 3.3

W and Δy dependence : small(moderate) x



W and Δy dependence : large x



Angular cut most effective on the events with high x and low -t

Summary

- Diffractive vector meson production with rapidity gap measurement
- Good process to test BFKL dynamics, high -t ‘squeezes’ the Pomeron (provides high scale and suppresses the diffusion)
- Sensitive though to preasymptotic effects in BFKL
- Mostly scattering off gluons, only at high x quarks become important. Can one disentangle that ?
- Growth of cross section by a factor of about 1.6 should be accessible at EIC.
- Better measurements of this process would be possible if coverage up to 4.5 in pseudorapidity (Yellow Report: 3.5)
- Outlook: impact of resummation effects in the non-forward Pomeron in this process