Diffraction in QCD

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Outline

- Diffraction in the pre-QCD era: triple-Regge description

- Soft diffraction: hadronic collisions, diffractive DIS

- "Hard diffraction", diffractive abelian and non-abelian radiation

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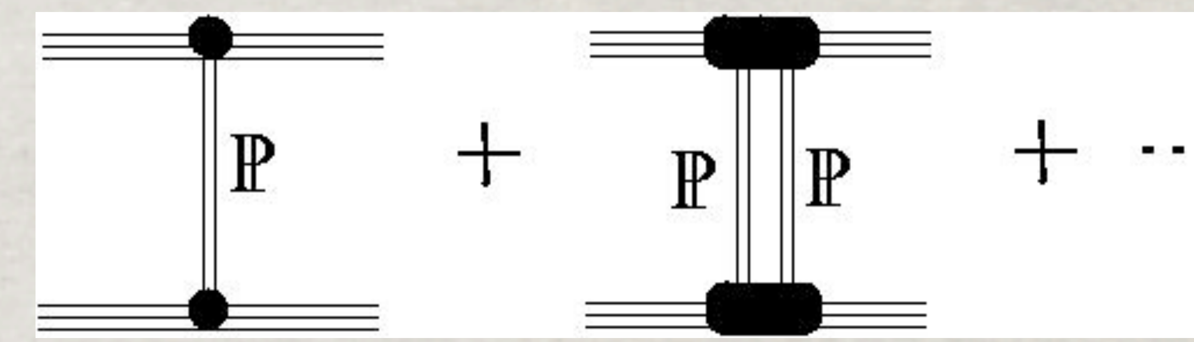
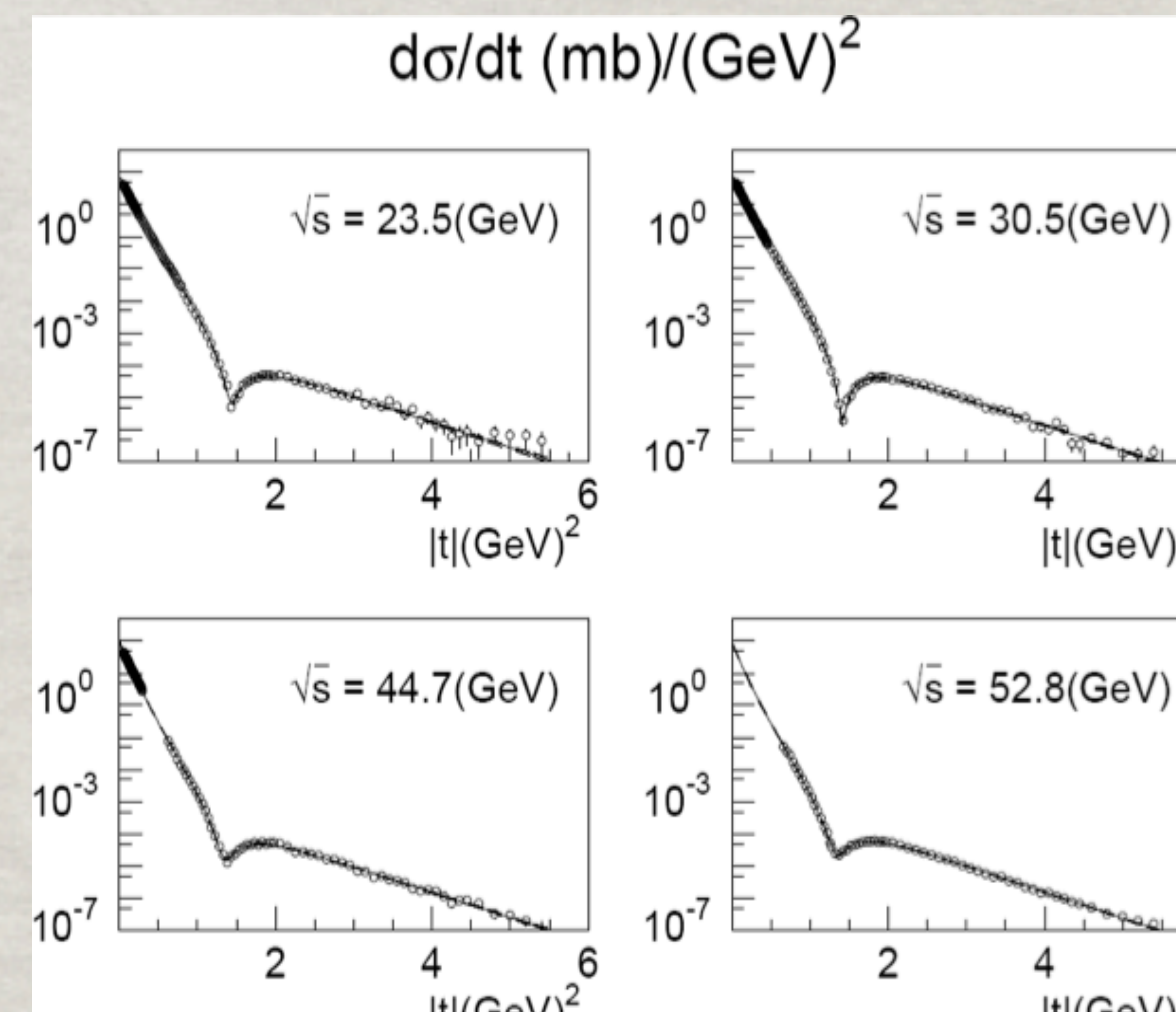
Diffractive high-energy collisions

Optical theorem: elastic diffraction is a shadow of inelastic interactions

$$2\,\mathrm{Im}\, f_{el}(0) = \sigma_{tot}$$



This quantum mechanical effect has been known in classical optics.
The angular distribution of elastic diffraction has characteristic minima and maxima, for hadrons as well.



This diffraction is soft, since the main bulk of inelastic collisions is soft.

In the Regge approach this dip results from the interference of single and double Pomeron exchanges

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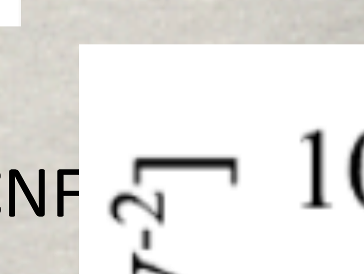

Good-Walker mechanism of inelastic diffraction (1964)

Glauber, 1955; Fainberg-Pomeranchuk, 1956

How to interpret inelastic (or quasi-elastic) diffraction, a+b -> X+b ?

Hadrons are eigenstates of the mass matrix, but not of the interactions.
So they can be expanded of the eigenstate of interaction $|\mathbf{h}\rangle = \sum_{\mathbf{l}=1} \mathbf{C}^{\mathbf{h}}_{\mathbf{l}} |\mathbf{l}\rangle$

$$\sum_{\mathbf{h}'\neq\mathbf{h}} \left. \frac{d\sigma_{sd}^{\mathbf{h}\to\mathbf{h}'}}{dt} \right|_{t=0} = \frac{1}{4\pi}\left[\sum_{\mathbf{l}} |\mathbf{C}^{\mathbf{h}}_{\mathbf{l}}|^2\,|\mathbf{f}_{\mathbf{l}}|^2 - \left(\sum_{\mathbf{l}} |\mathbf{C}^{\mathbf{h}}_{\mathbf{l}}|\mathbf{f}_{\mathbf{l}}\right)^2\right] \equiv \frac{\langle \mathbf{f}^2_{\mathbf{l}}\rangle - \langle \mathbf{f}_{\mathbf{l}}\rangle^2}{4\pi}$$

Diffractive excitation occurs only due to diversity of the elastic eigen amplitudes.
As far as different components interact differently (i.e. make different shadows), the final state wave packet is modified and can be projected to a new hadronic state.

In the black-disk regime all the partial eigen amplitudes reach the unitarity limit, $\mathrm{Im}\,\mathrm{f}_{\mathrm{l}} = 1$, and single diffraction is vanishes.

Since in the Froissart regime R ∝ ln(s), so $\sigma_{tot} \propto \sigma_{el} \propto \ln^2(s)$; $\sigma_{sd} \propto \ln(s)$,

i.e. asymptotically $\sigma_{sd}/\sigma_{tot} \propto 1/\ln(s)$

Such a falling energy dependence of diffraction has not been seen in data yet.

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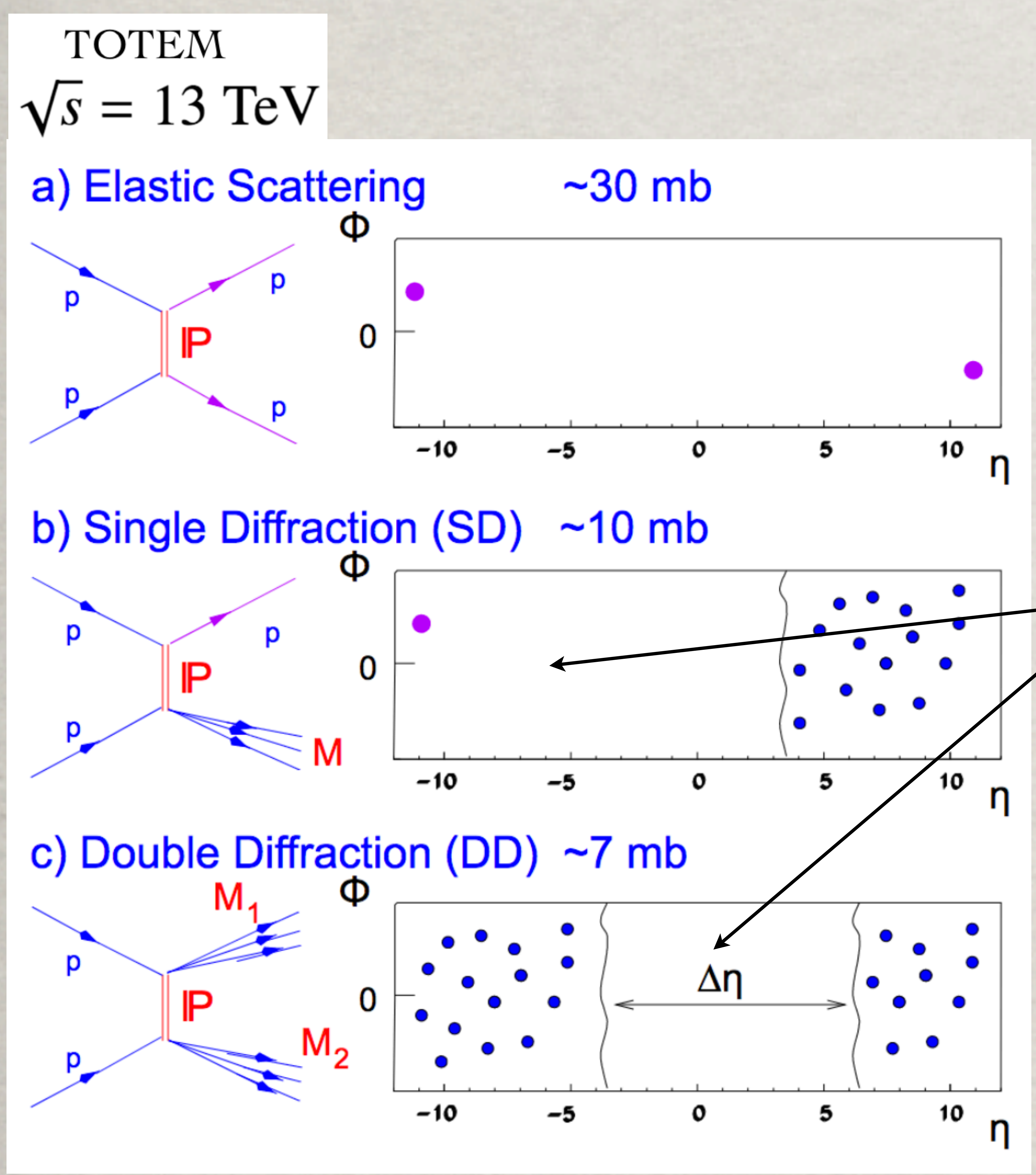
Diffraction in experiment

$$\eta = \ln(2/\theta)$$



The main signature of diffraction is a large rapidity gap.

Experimentally diffraction looks like a large rapidity gap event. Particles are produces only at small angles relative the beam or/and target directions. Nothing is produced in between.

B. Kopeliovich, ICNFP 2019

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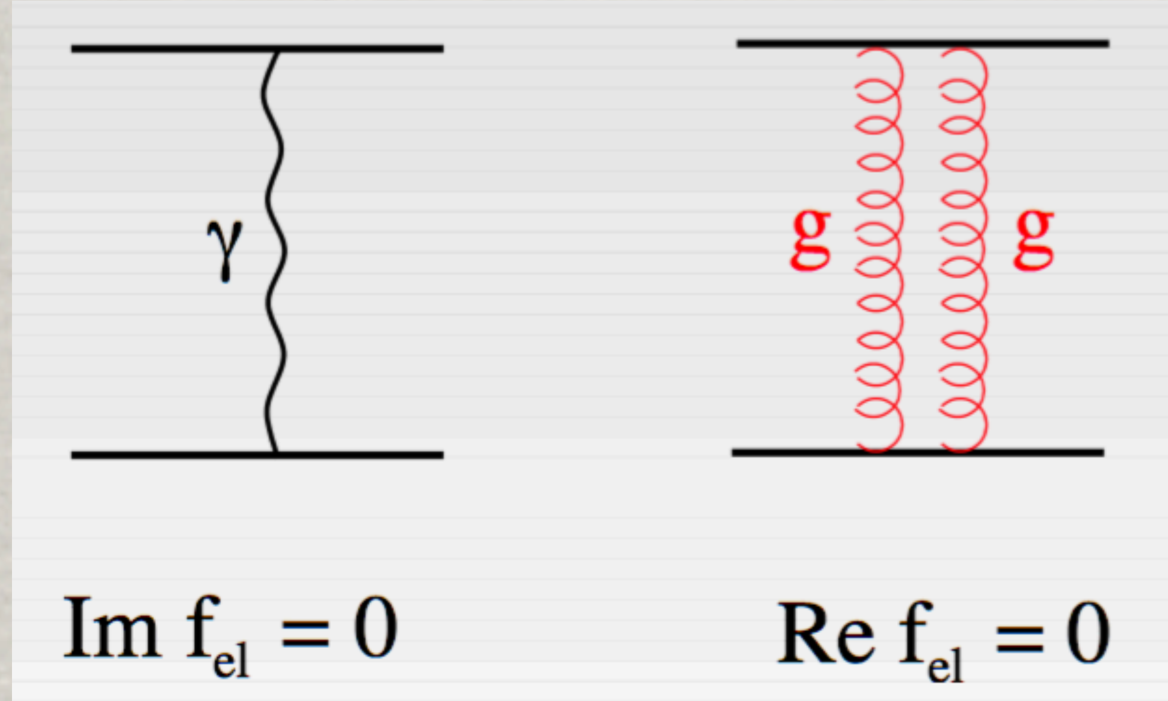
How rapidity gap appears

In an abelian theory (QED) one could simply exchange a photon, which provides a gap in rapidity with no particle production. And the gap probability will be independent of the rapidity interval.



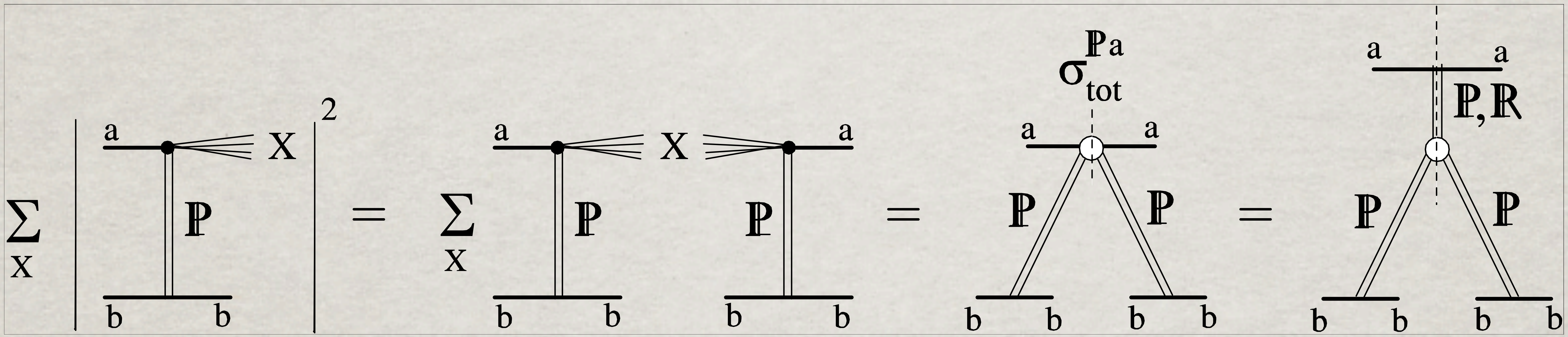
In a nobabelian theory (QCD) gluons are color-charged and gluon echange would ruin the gap. Minimum two gluons in a colorless state must be exchanged. This helps one easily identify whether the undelying theory is abelian or not.

In the former case the elastic amplitude is real, while in the latter case it is imaginary. Experiment decides in favor of non-abelian dynamics (QCD).

In Born approximation the elastic amplitude is energy independent and pure imaginary. Gigher order corrections make it rising with energy and supply with a small real part. Such a colorless exchange dominating at high energies is called Pomeron.

Triple Regge phenomenology

Diffractive excitation of a hadron: a+b->X+b

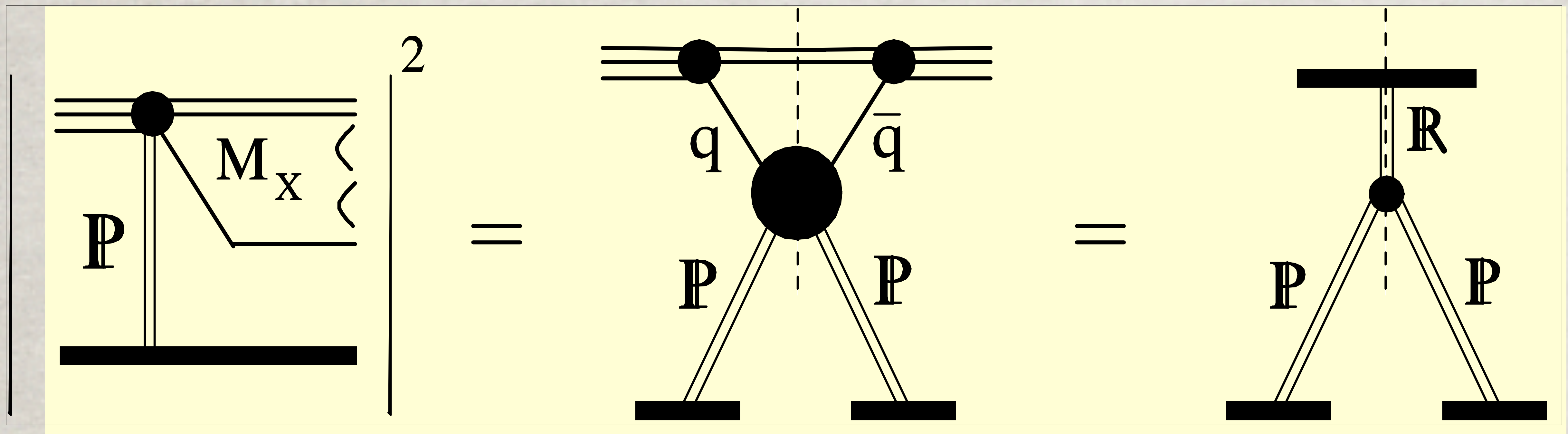


Kinematics: $s_o \ll M_X^2 \ll s;$ $x_F \equiv \frac{2p_b^*}{\sqrt{s}} = 1 - \frac{M_X^2}{s}$

$$\frac{d\sigma_{sd}^{ab\to Xb}}{dx_F\,dt} = \sum_{i=\mathbb{P},\mathbb{R}} G_{\mathbb{P}\mathbb{P}i}(t)(1-x_F)^{\alpha_i(0)-2\alpha_{\mathbb{P}}(t)}\left(\frac{s}{s_0}\right)^{\alpha_i(0)-1}$$

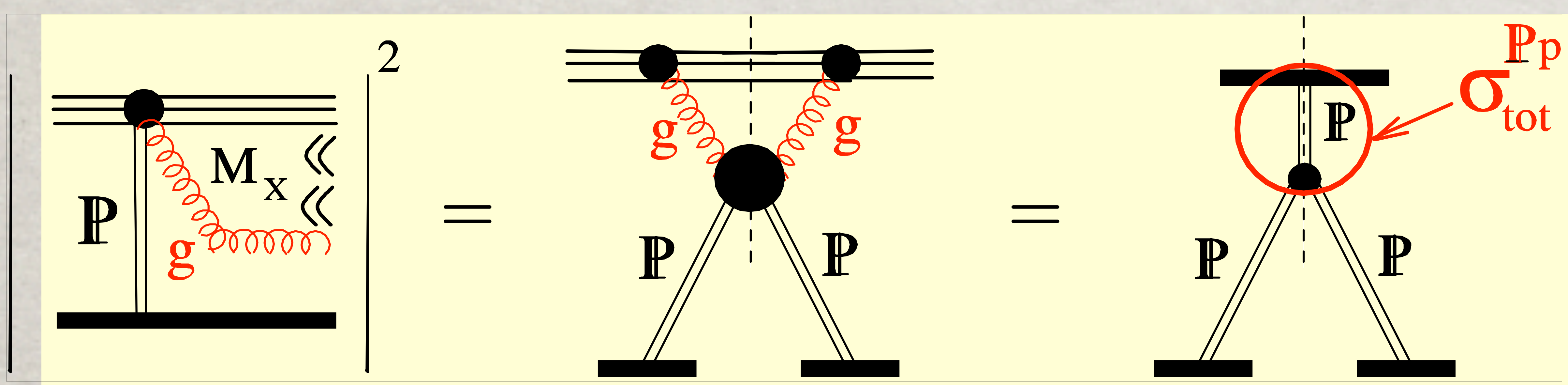
The triple-Regge couplings G_{PPP}, G_{PPR} are fitted to data.

The graph PPR corresponds to excitation of the valence quark skeleton



$$\left.\frac{d\sigma_{sd}}{dM_X^2}\right|_{PPR} \propto \frac{1}{M_X^3}$$

The triple-Pomeron graph corresponds to diffractive gluon radiation

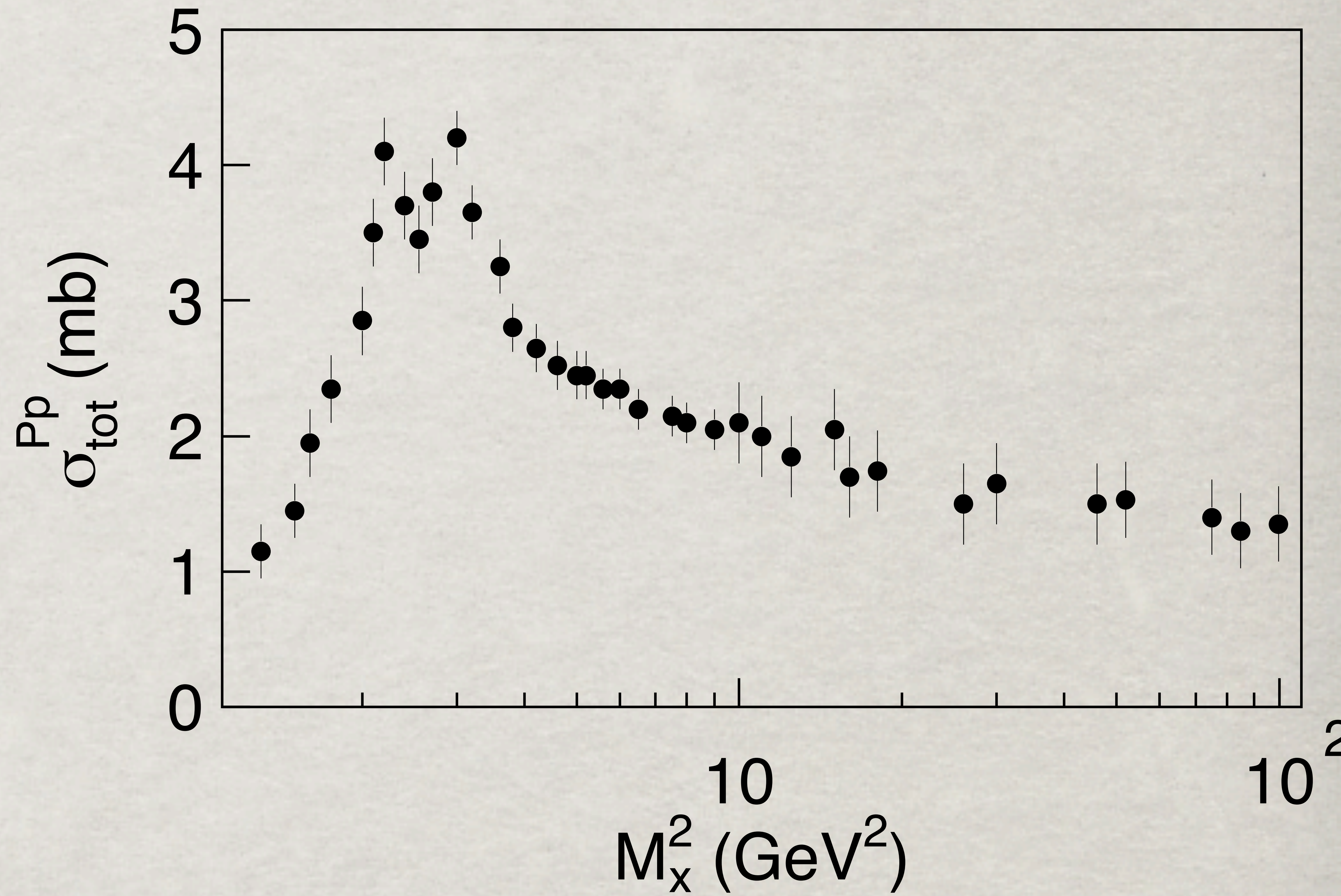


$$\left.\frac{d\sigma_{sd}}{dM_X^2}\right|_{PPP} \propto \frac{1}{M_X^2}$$

One can discriminate the two mechanisms via their M_X-dependence and find the **Pomeron-proton cross section** from data.

Since the Pomeron is a gluonic object, it should interact stronger than a quark-antiquark meson, so one could expect

$$\sigma_{Pp}^{tot} \approx \frac{9}{4}\sigma_{\pi p}^{tot} \approx 50mb$$



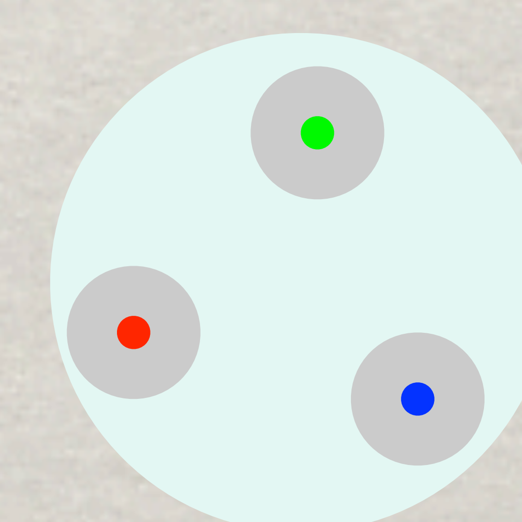
However, diffractive data reveal a much smaller value

$$\sigma_{Pp}^{tot} = \frac{M_x^2/s}{\left(g_{pp}^{P}(t)\right)^2} M_x^2 \frac{d^2\sigma}{dM_x^2 dt} \approx 2mb$$

The only solution is to assume that the Pomeron is a small size object, and its cross section is small due to Color Transparency.

BK, A.Schafer & A.Tarasov, PRD 62(2000)054022

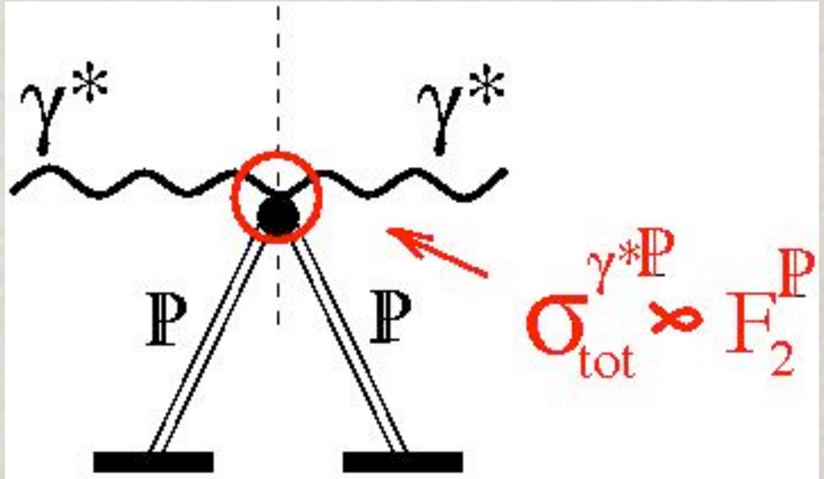
BK, B.Povh, I.Schmidt, PRD 76(2007)094029



This means that gluons in the proton are located within small spots of radius r ~0.3 fm.

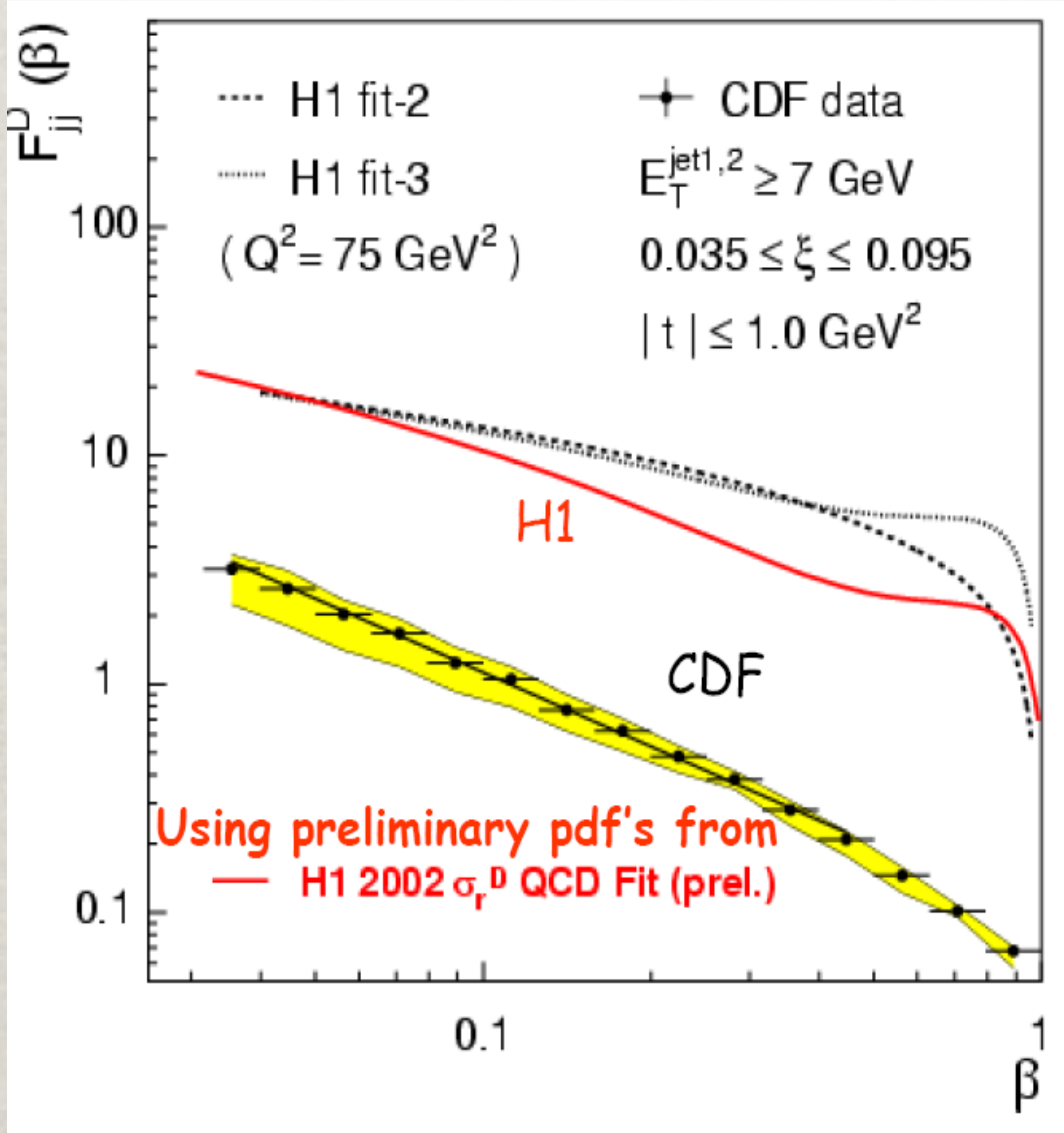
Breakdown of QCD factorization in diffraction

The triple-Regge graph for diffractive DIS, can be interpreted as a way to measure the structure function (PDFs) of the Pomeron. (Ingelman-Schlein)



Once the parton densities in the Pomeron are known and factorization is at work, one can try to predict the cross section of any hard hadronic diffraction.

However, the attempts to use this diffractive PDFs of the Pomeron for diffractive di-jet production failed badly: data from the Tevatron contradict the predictions by an order of magnitude (more later)



Factorization is broken for hard hadronic diffraction.

“Hard” diffractive processes

- **Diffractive DIS is soft-dominated**

  BK & B.Povh, Z.Phys. A354(1997)467

- **Diffractive Drell-Yan is semi-soft, semi-hard**

  BK, I.Potashnikova, I.Schmidt & A.Tarasov, PRD 74(2006)114024

  R.Pasechnik & BK, EPJ C71(2011)1827

- **Diffractive heavy flavors**

  BK, I.Potashnikova, I.Schmidt & A.Tarasov, PRD 76(2007)034019

- **Diffractive gauge bosons**

  R.Pasechnik, I.Potashnikova & BK, PRD 86(2012)114039

- **Diffractive Higgsstrahlung**

  R.Pasechnik, I.Potashnikova & BK, PRD 92(2015)094014

- **Diffractive bremsstrahlung**

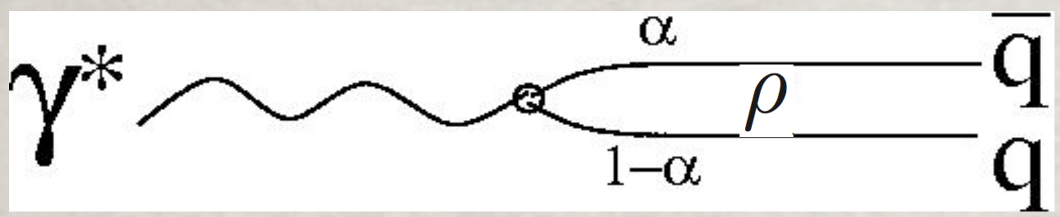
  BK, A.Schafer & A.Tarasov, PRD 62(2000)054022

  R.Pasechnik, I.Potashnikova & BK, Adv.HEP 2015(2015)701467

- **Diffractive dijets**

  R.Pasechnik, I.Potashnikova & BK, PRD98(2018)114021

Diffraction in DIS



At high energies dipoles with a certain separation are the eigenstates of interaction.

$$\langle \rho^2 \rangle \sim \frac{1}{\varepsilon^2} \sim \frac{1}{Q^2 \alpha (1-\alpha) + m_q^2}$$

Fluctuation	$W_h^{\gamma *}$	σ_{tot}^{hN}	$W_h^{\gamma *}\sigma_{tot}^{hN}$ (incl)	$W_h^{\gamma *}(\sigma_{tot}^{hN})^2$ (diff)
Hard	~ 1	$\sim 1/Q^2$	$\sim 1/Q^2$	$\sim 1/Q^4$
Soft	$\sim \mu^2/Q^2$	$\sim 1/\mu^2$	$\sim 1/Q^2$	$\sim 1/\mu^2 Q^2$

Q. Is inclusive DIS hard or soft reaction?
A. - Both

Q. Is diffractive DIS hard or soft?
A. - Soft !

The aligned-jet dipole configurations dominate diffractive DIS.
This explains why the fractional cross section is nearly Q^2 independent

$$\frac{\sigma_{\rm diff}^{\rm DIS}}{\sigma_{\rm incl}^{\rm DIS}} \approx {\rm Const}$$

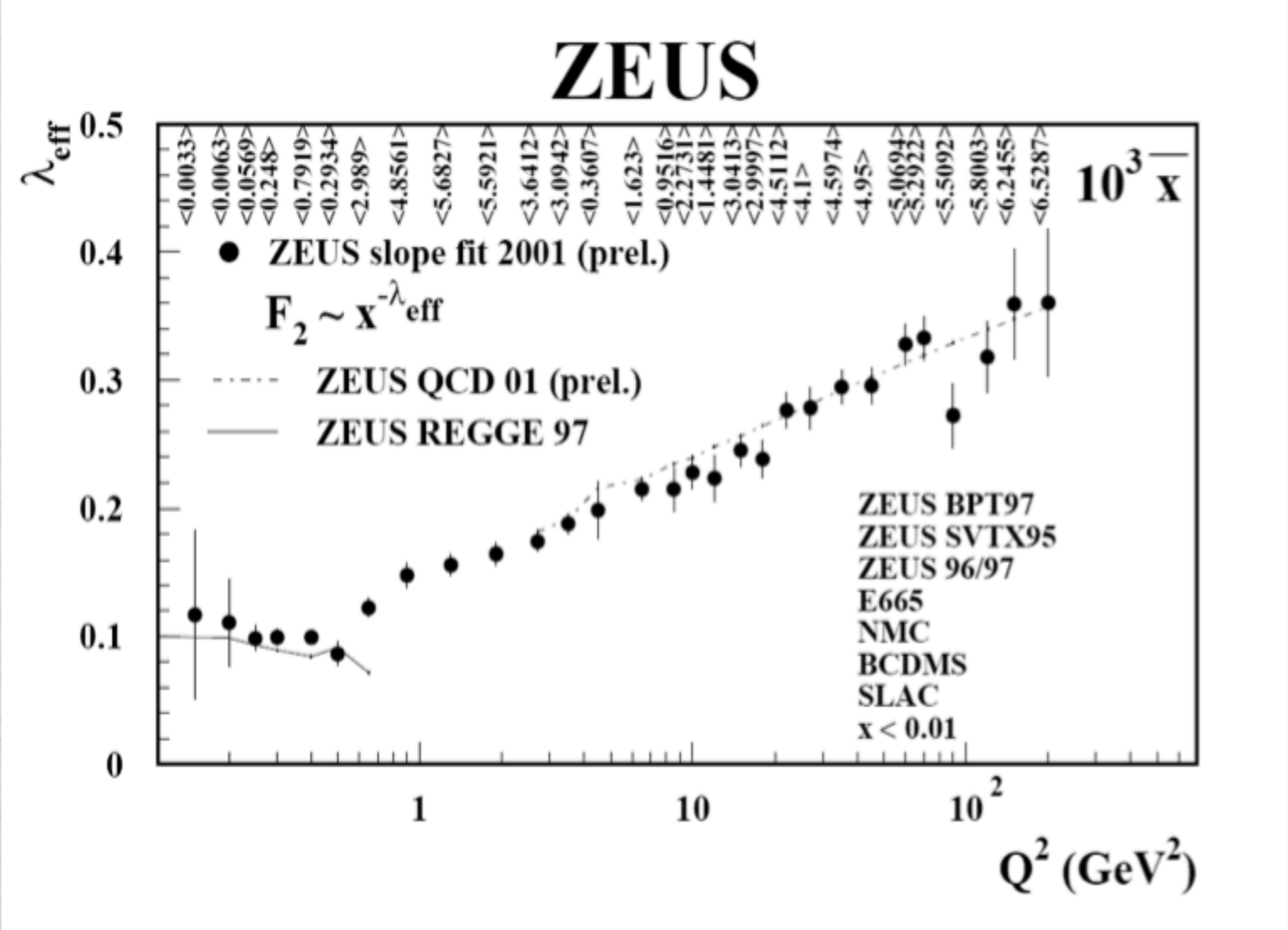
Diffraction in DIS

- Naively one could expect $\sigma_{\mathrm{diff}} \propto 1/Q^4$, but it is $1/Q^2$, like σ_{incl}
- Naively one could expect $\sigma_{\mathrm{diff}} \propto W^{4\Delta}$ vs $\sigma_{\mathrm{incl}} \propto W^{2\Delta}$ but in diffraction

$$\Delta \Rightarrow \Delta_{\mathrm{soft}} \sim 0.1$$

$$\sigma_{tot}^{\gamma^* p}(x,Q^2) \propto F_2(x,Q^2) \propto \left(\frac{1}{x}\right)^{\lambda_{eff}(Q^2)}$$

$$\alpha_P(0) - 1 = \lambda_{eff}(Q^2)$$



Data show that in inclusive DIS the Pomeron intercept is moving with Q up to higher values. However, in diffractive DIS does not rise, stays at the soft value.

Diffractive Drell-Yan

Differently from DIS diffractive Drell-Yan gets the main contribution from the interplay of soft and hard scales

The quark radiating the heavy photon gets a shift in its location by $\mathbf{r} \sim 1/M$

The diffractive amplitude has the Good-Walker structure,

$$\sigma(\tilde{\mathbf{R}}) - \sigma(\tilde{\mathbf{R}} - \tilde{\mathbf{r}}) = \frac{2\,\sigma_0}{\mathbf{R}_0^2(\mathbf{x}_2)}\, \mathbf{e}^{-\mathbf{R}^2/\mathbf{R}_0^2(\mathbf{x}_2)} \left(\tilde{\mathbf{r}} \cdot \tilde{\mathbf{R}}\right) + \mathbf{O}(\mathbf{r}^2)$$

hadronic soft scale ($\tilde{\mathbf{R}}$) **recoil shift** ($\tilde{\mathbf{r}}$) **hard-soft** ($\tilde{\mathbf{r}} \cdot \tilde{\mathbf{R}}$)

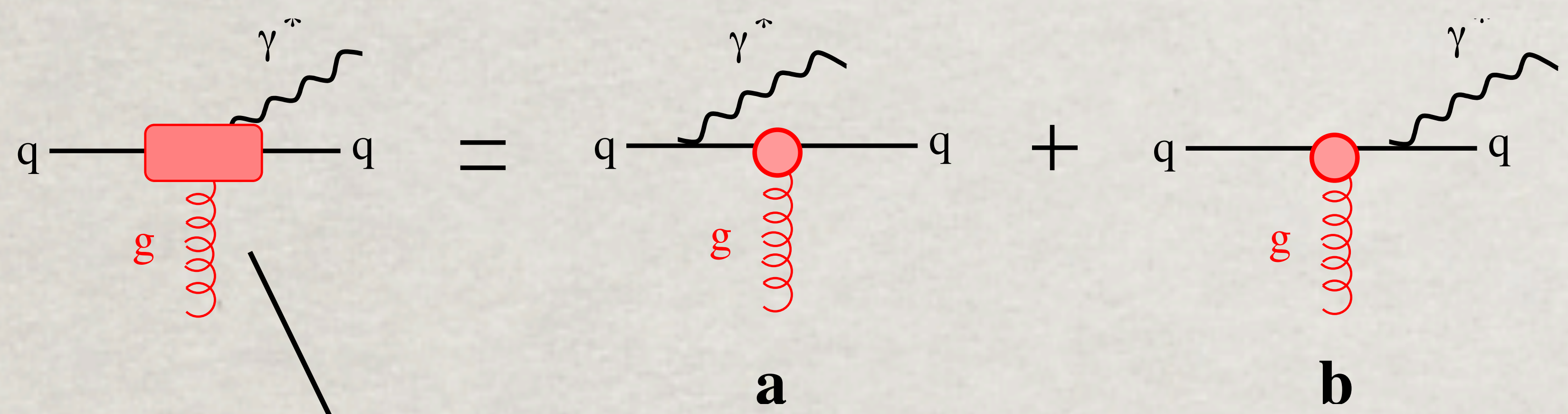
GBW: $\sigma(\mathbf{r}) = \sigma_0 \left(1 - \mathbf{e}^{-\mathbf{r}^2/\mathbf{R}_0^2}\right)$ $\quad\quad$ $\mathbf{R}_0(\mathbf{x}_2) = \mathbf{0.4}\,\mathrm{fm} \times (\mathbf{x}_2/\mathbf{x}_0)^{\mathbf{0.144}}$

- The diffractive amplitude is not quadratic in r like in DIS, but linear. Therefore, the soft part of the interaction is not enhanced in Drell-Yan diffraction, which is as semi-hard, semi-soft, like inclusive DIS.
- Such a structure of the diffractive amplitude includes all absorptive corrections (gap survival amplitude), provided that the dipole cross section is adjusted to data.

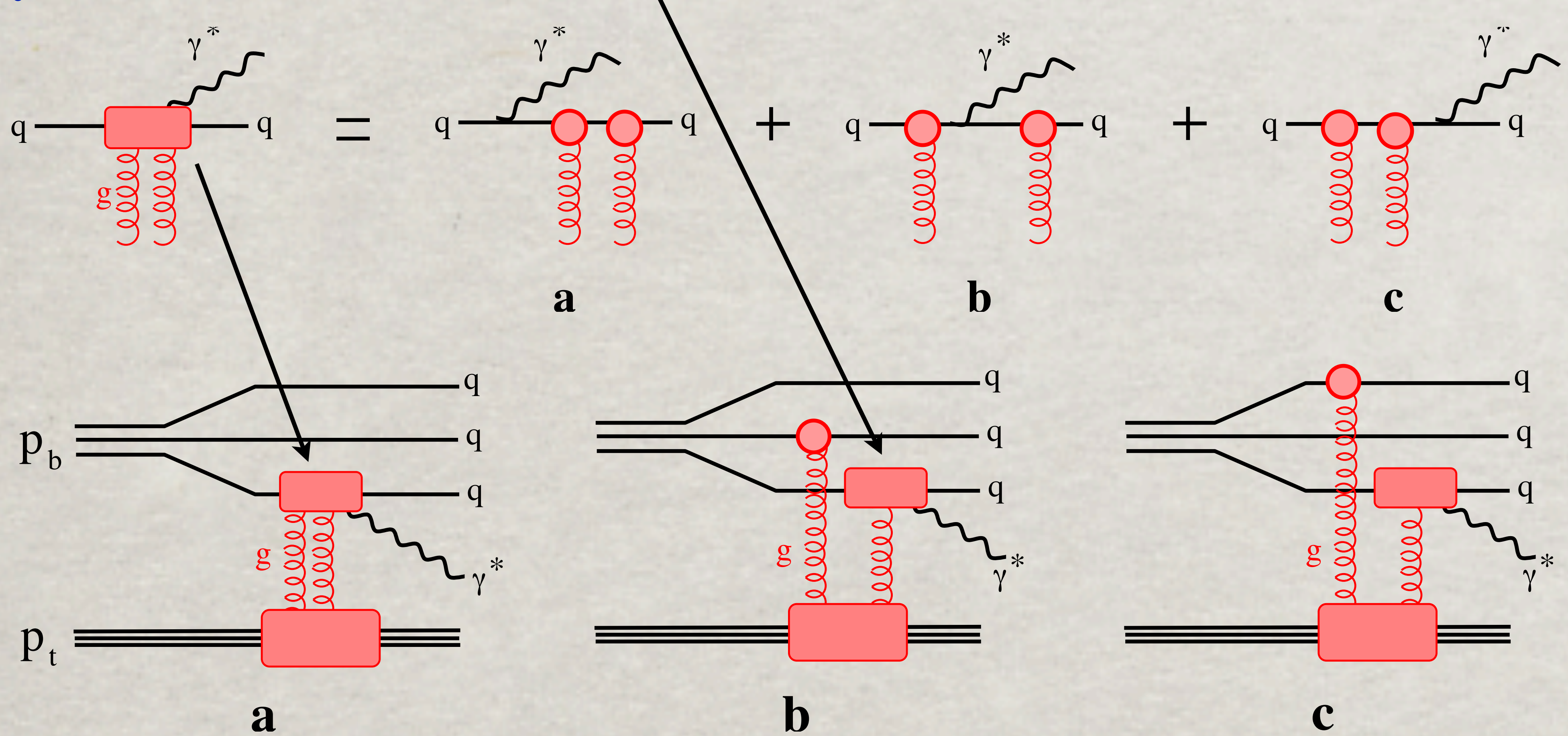
Diffractive Drell-Yan

- Diffractive Drell-Yan is semi-soft, semi-hard

Inclusive:

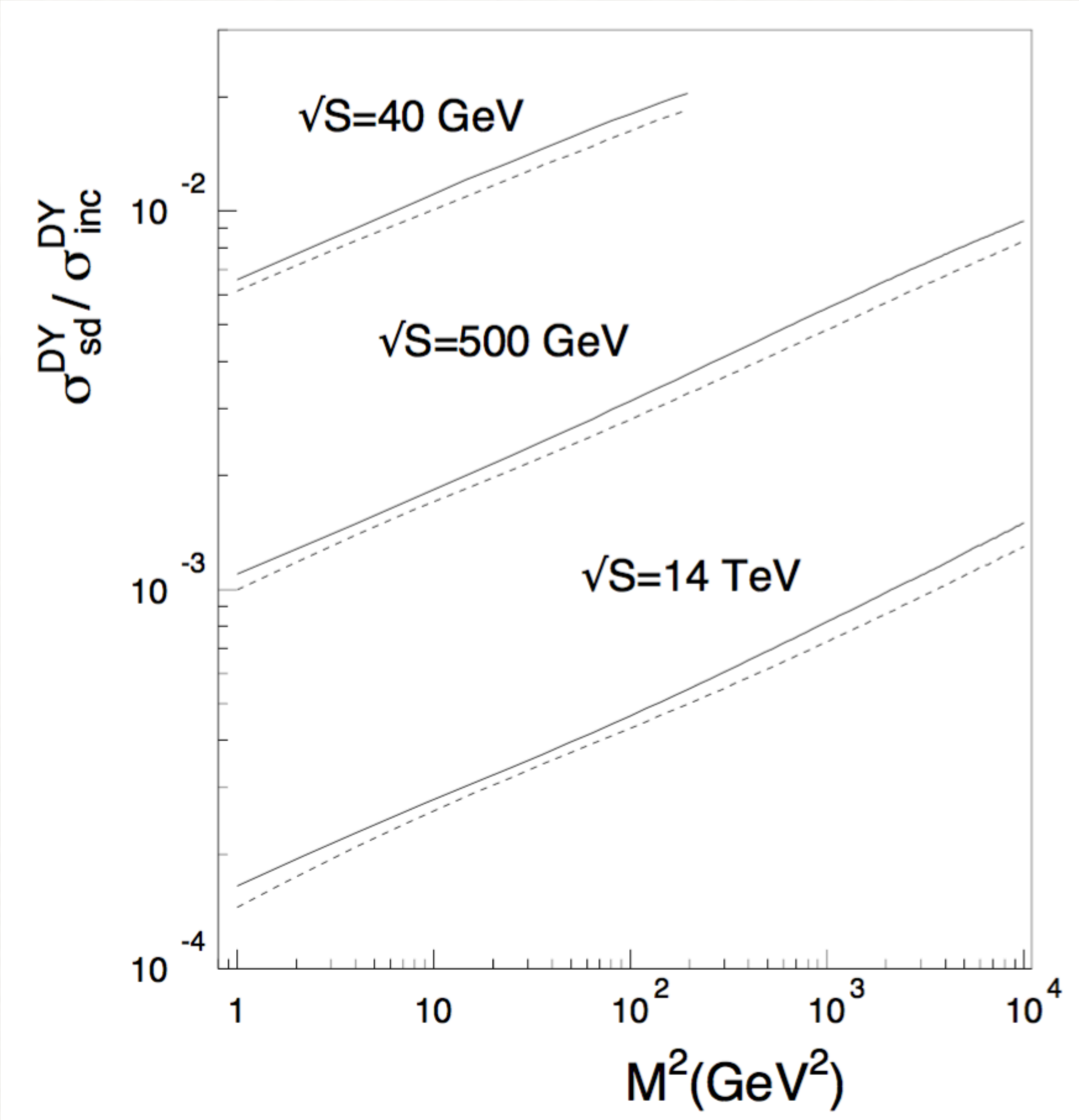


Diffractive:



Diffractive radiation of a heavy photon (any gauge boson) by a quark vanishes in the forward direction

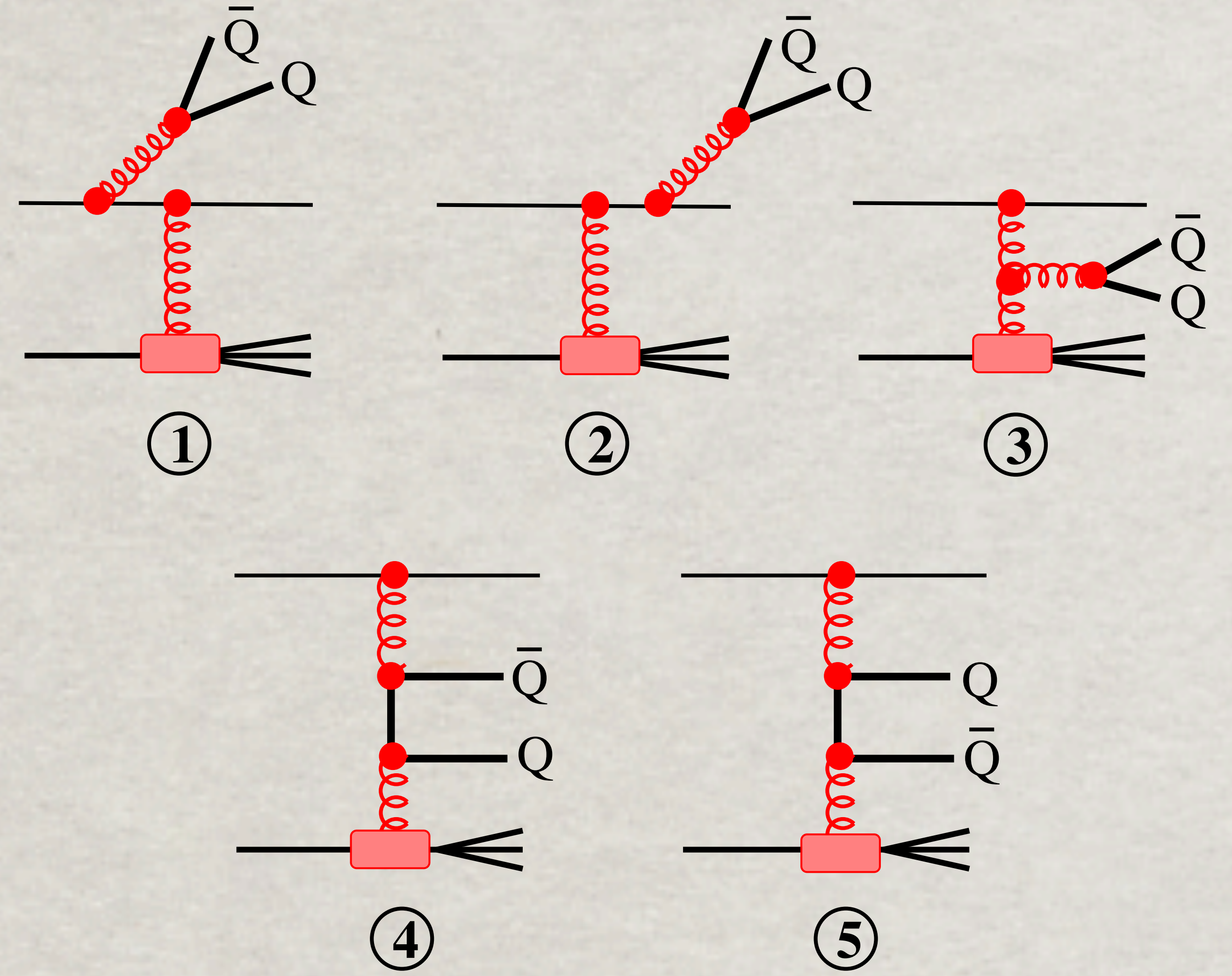
$$\left.\frac{d\sigma^{DY}_{inc}(qp\to\gamma^* qp)}{d\alpha\, dM^2}\right|_{p_T=0} = 0 \qquad !!!$$

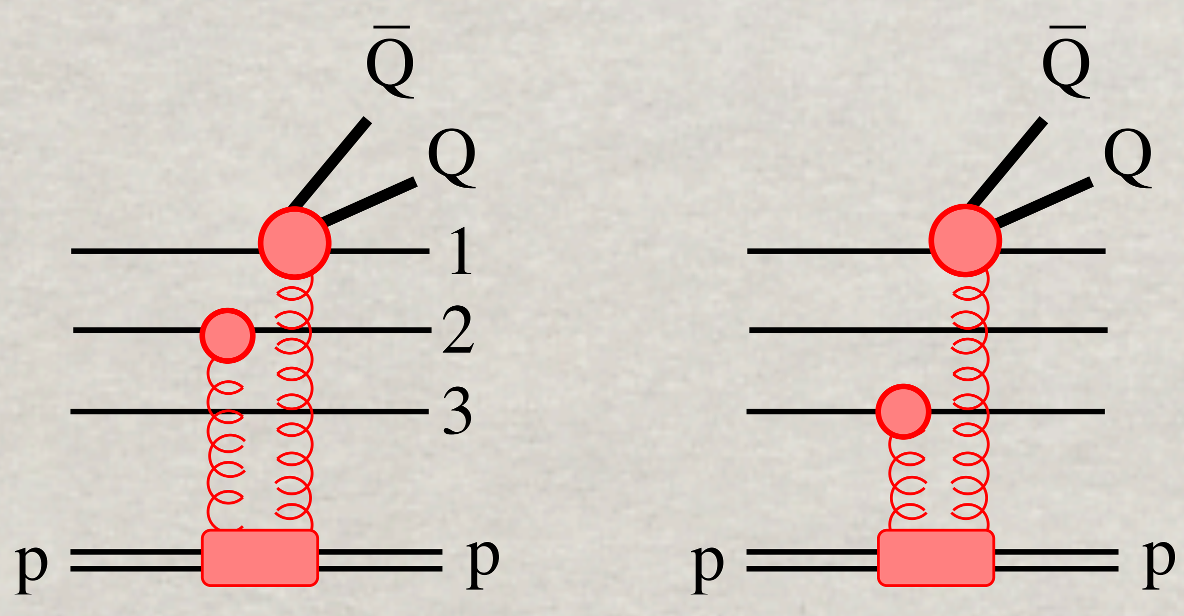


The fraction of diffractive Drell-Yan cross section is steeply falling with energy, but rises with scale, because of saturation.

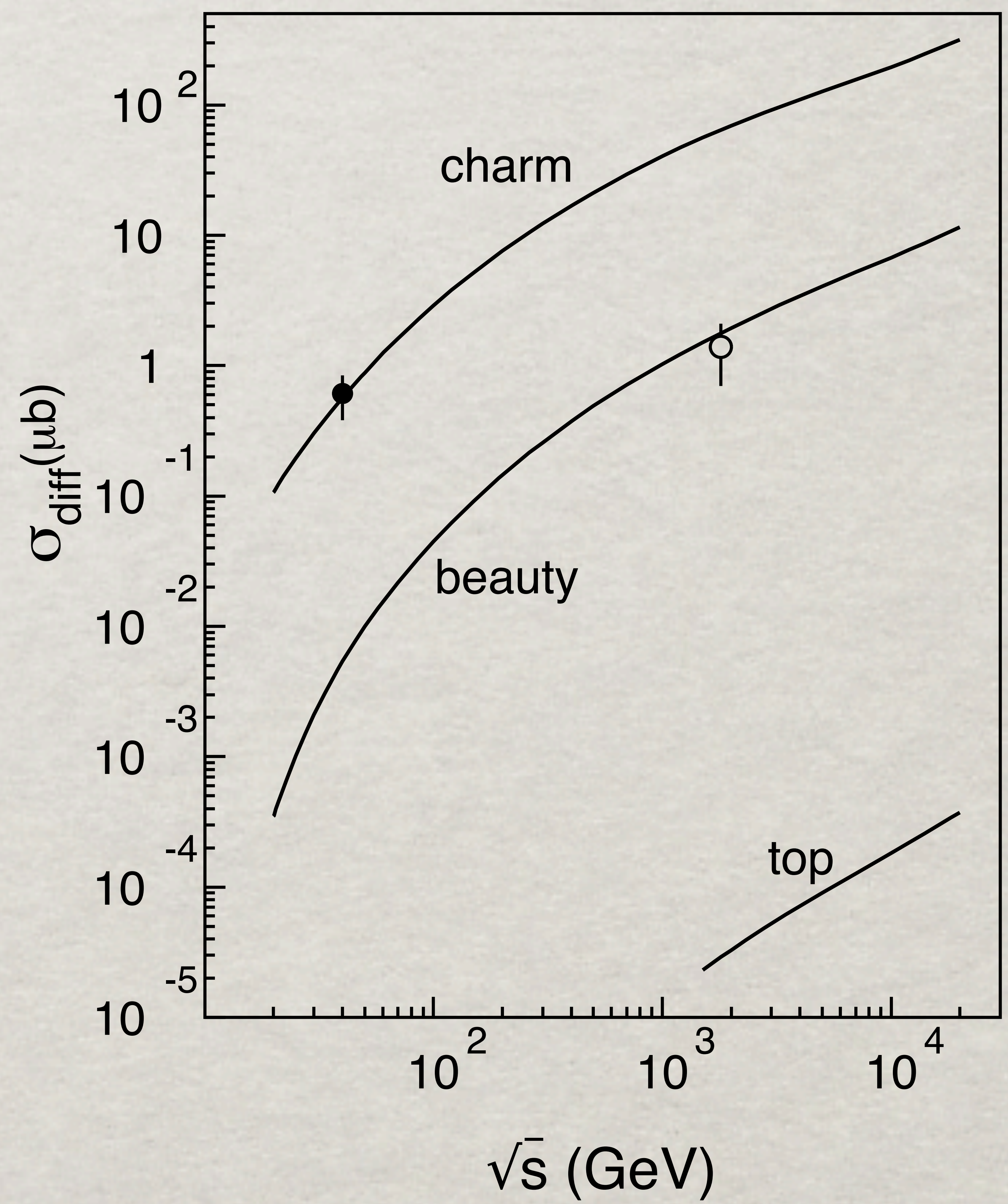
$$\frac{\sigma^{DY}_{sd}}{\sigma^{DY}_{incl}} \propto \frac{\exp(-2R^2/R_0^2)}{R_0^2}$$

Diffractive heavy flavors





Test of the scale dependence:



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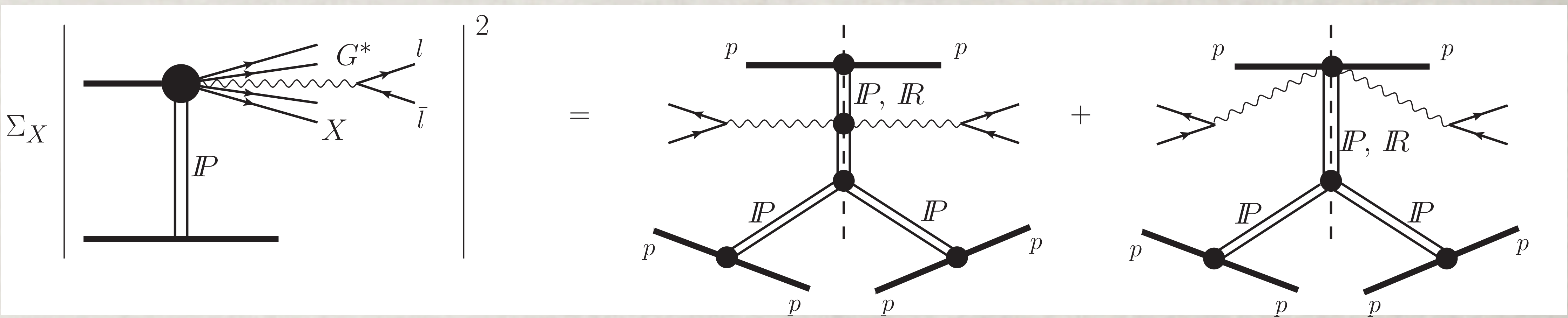
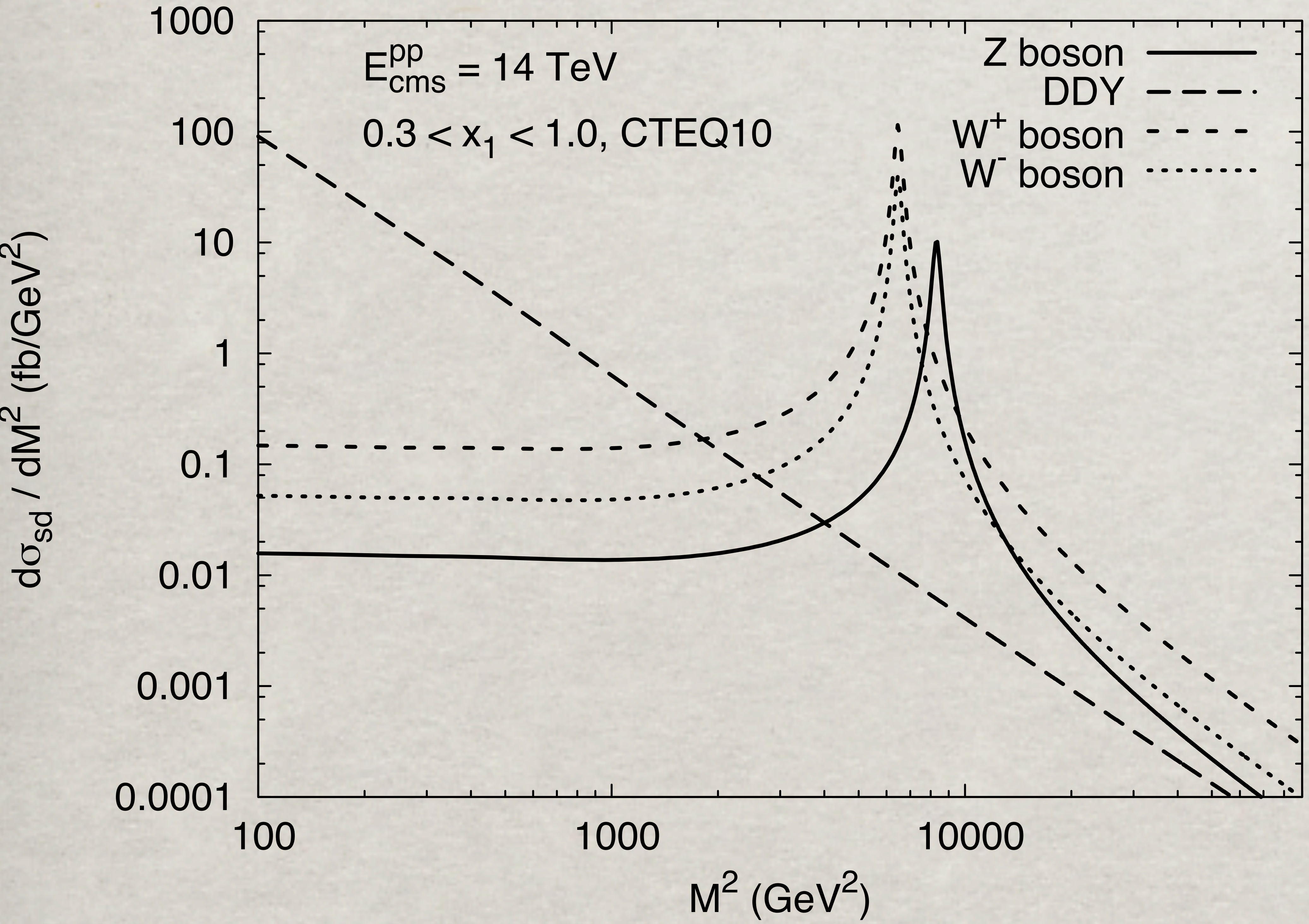
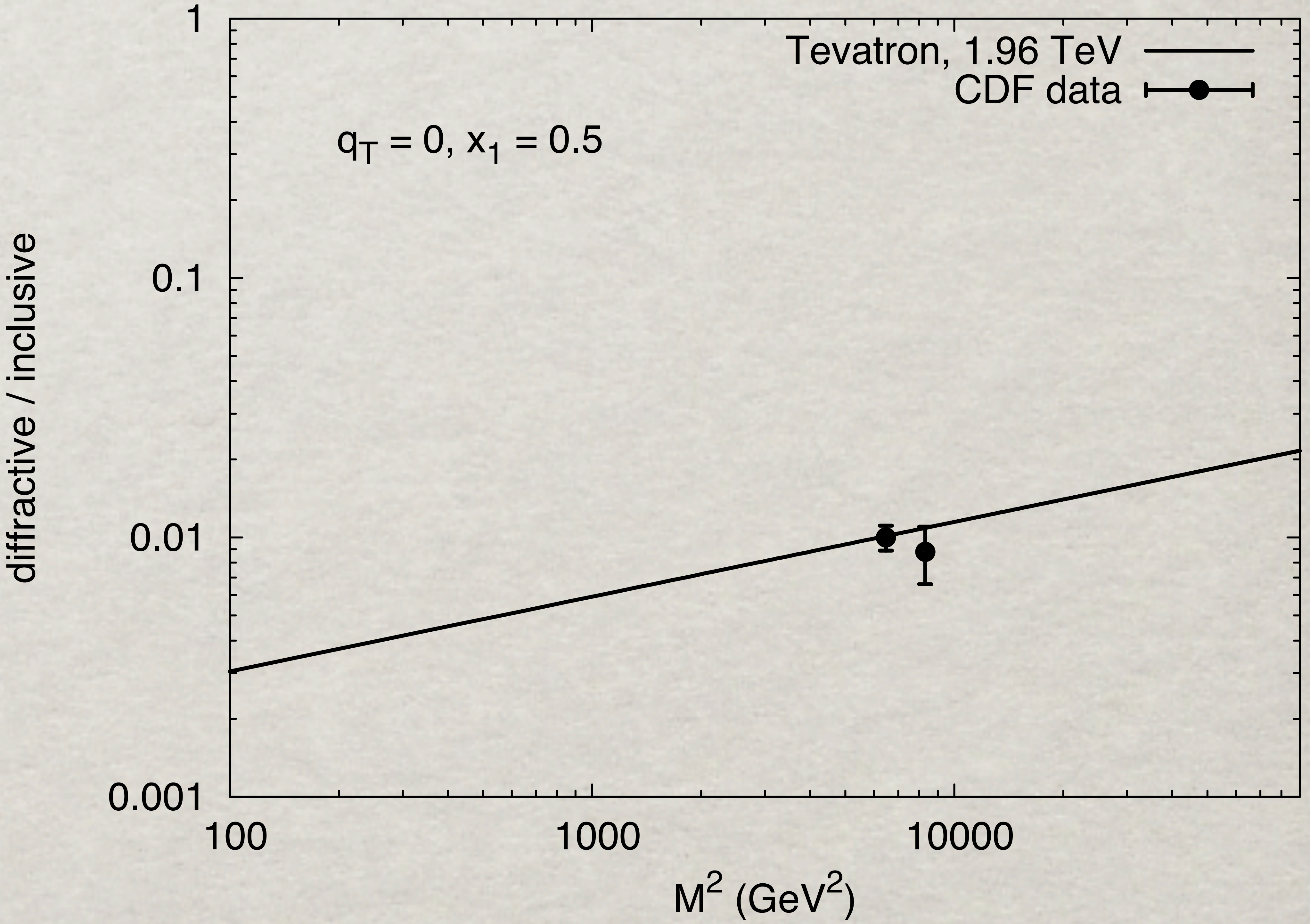
More tests of scale dependence: diffractive Z and W

Abelian diffractive radiation of any particle is described by the same Feynman graphs, only couplings and spin structure may vary.







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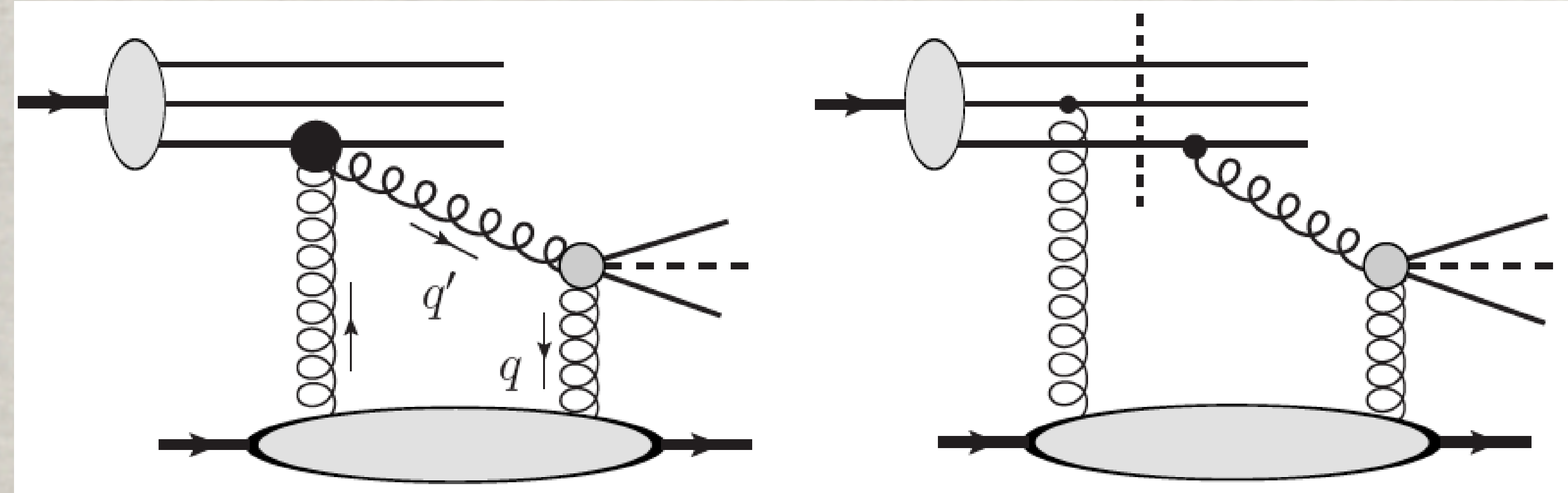
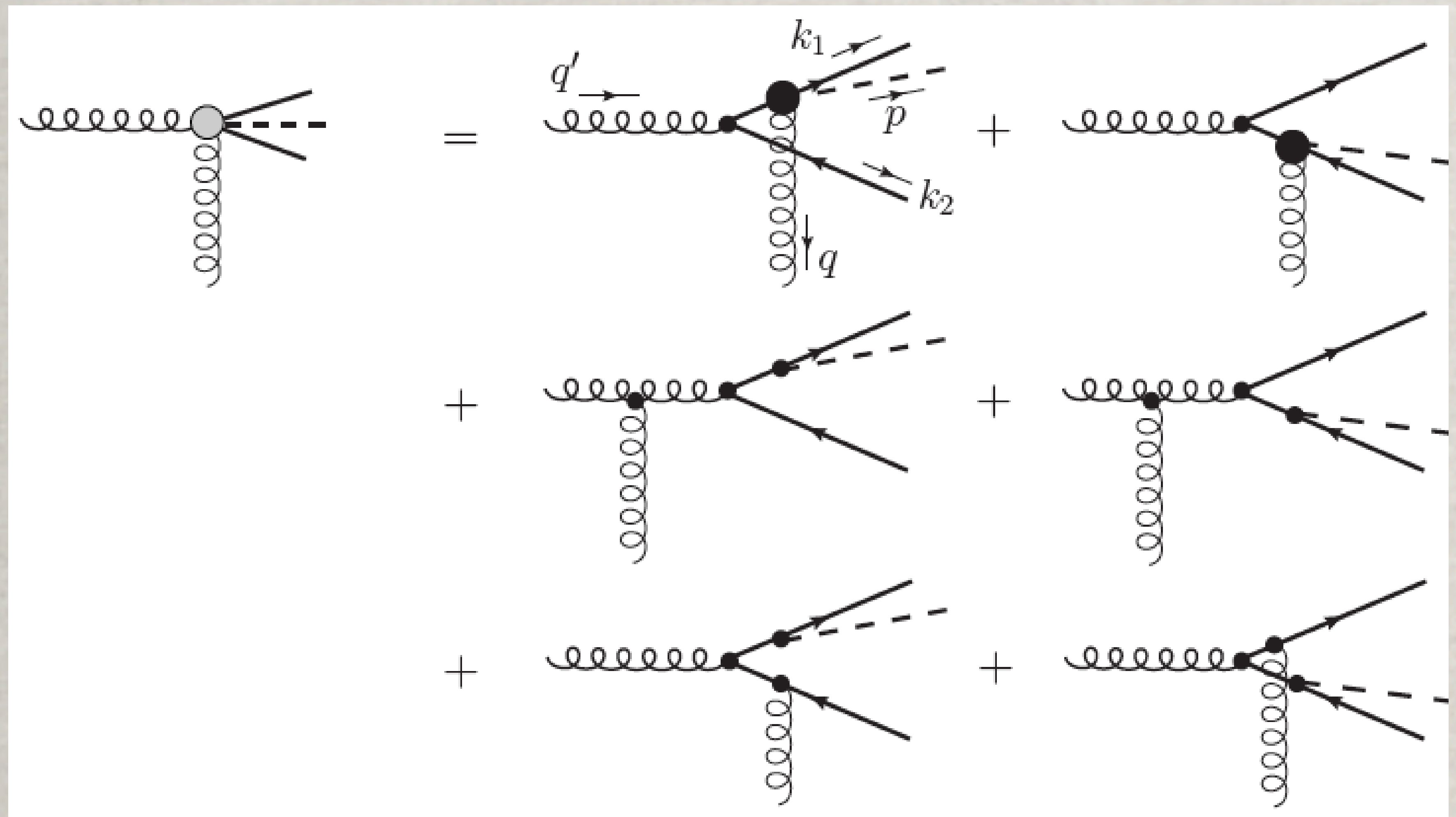
Diffractive Higgsstrahlung

Light quark do not radiate higgs directly, only via production of heavy flavors. Therefore the mechanism is the same as for non-abelian diffractive quark production.

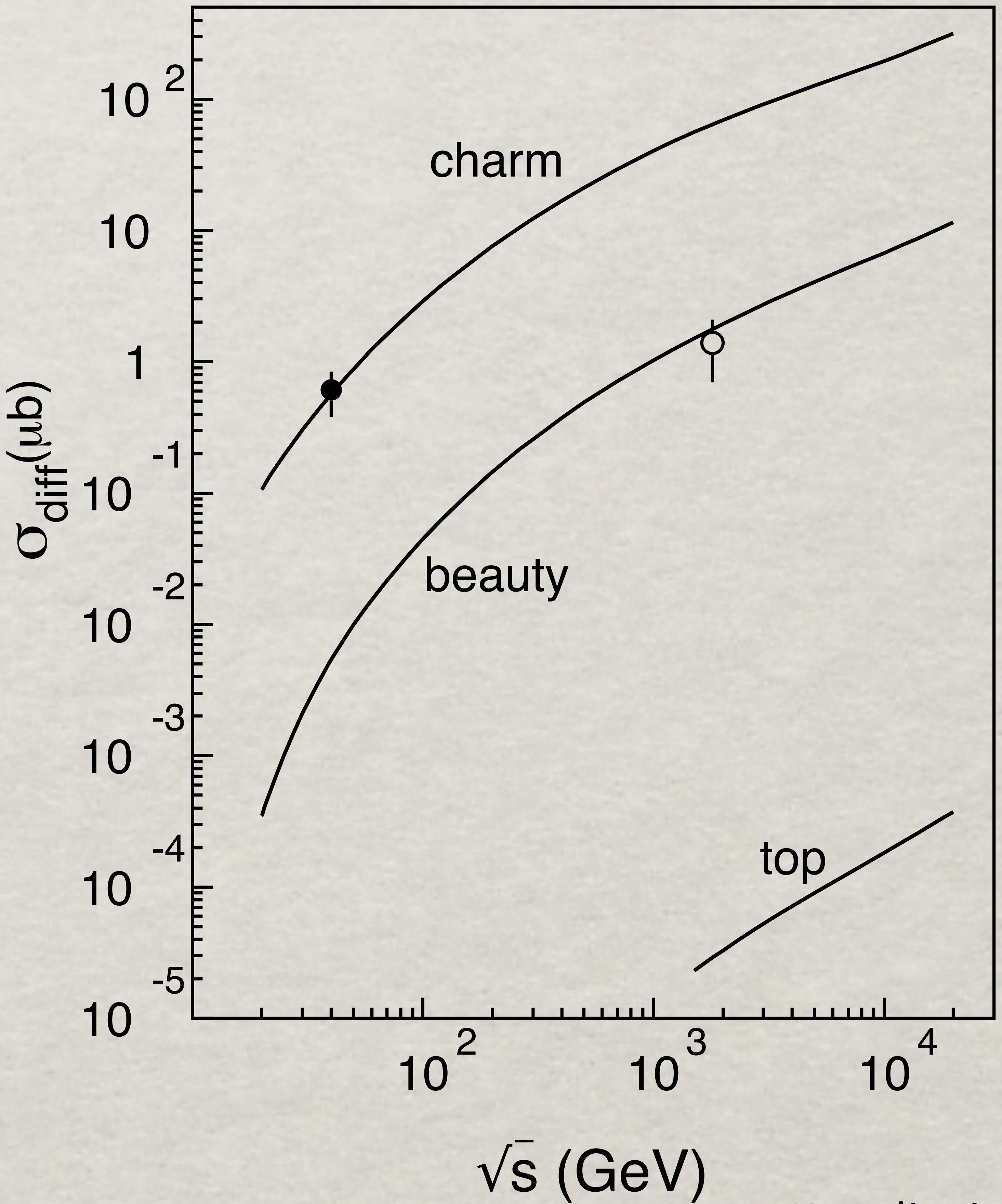
R.Pasechnik, I.Potashnikova, B.K. 2014.





The diffractive cross section is a leading twist, $1/m_Q^2$, confirmed by CDF data

I.Potashnikova, I.Schmidt, A.Tarasov, B.K. 2006



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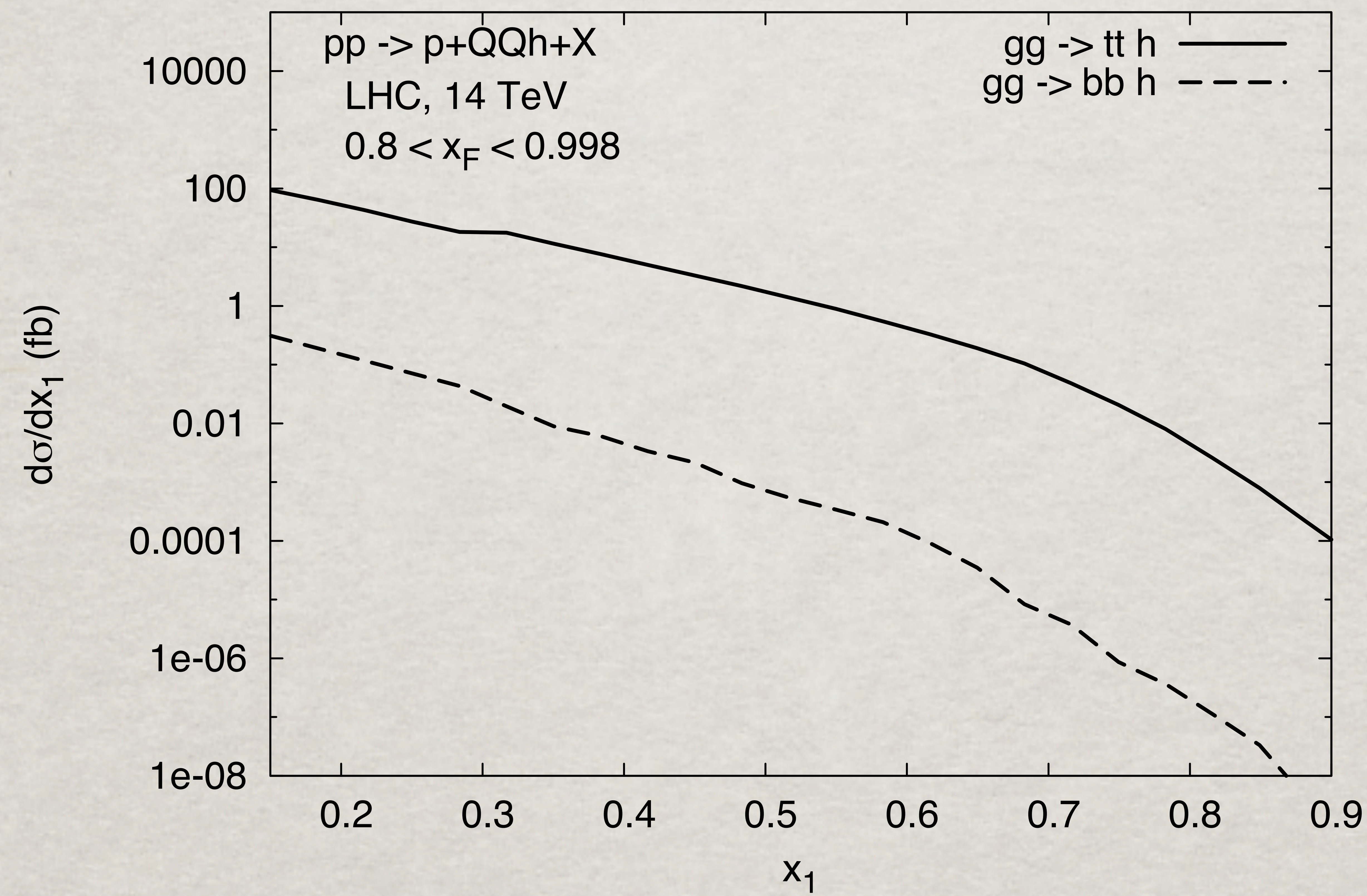
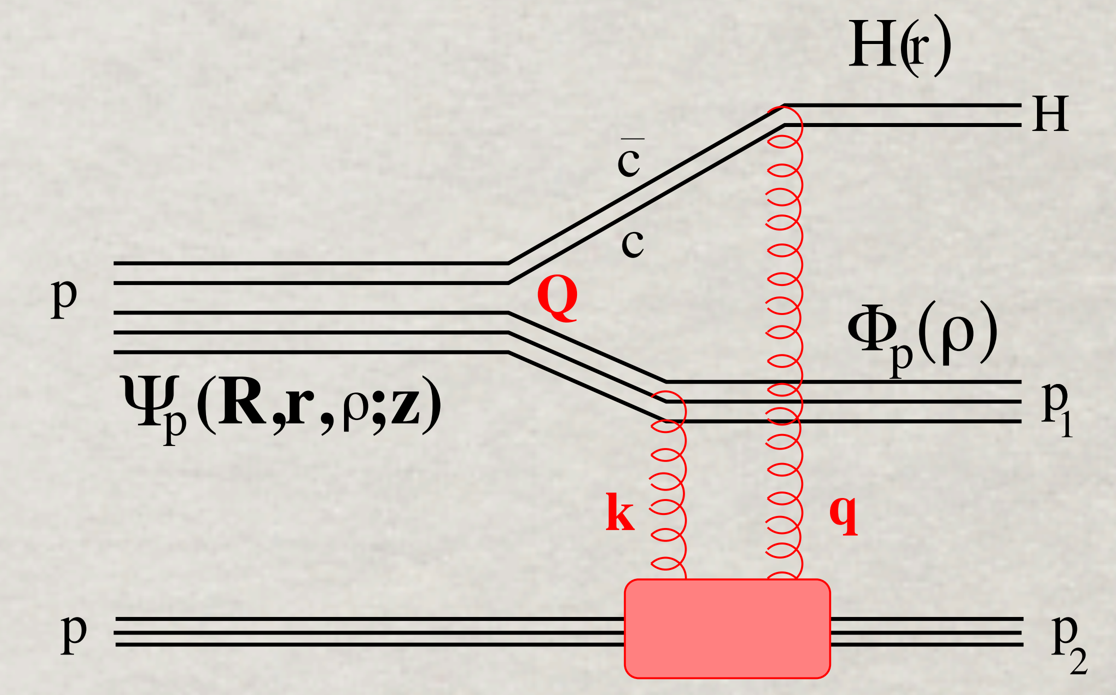
Diffractive Higgsstrahlung



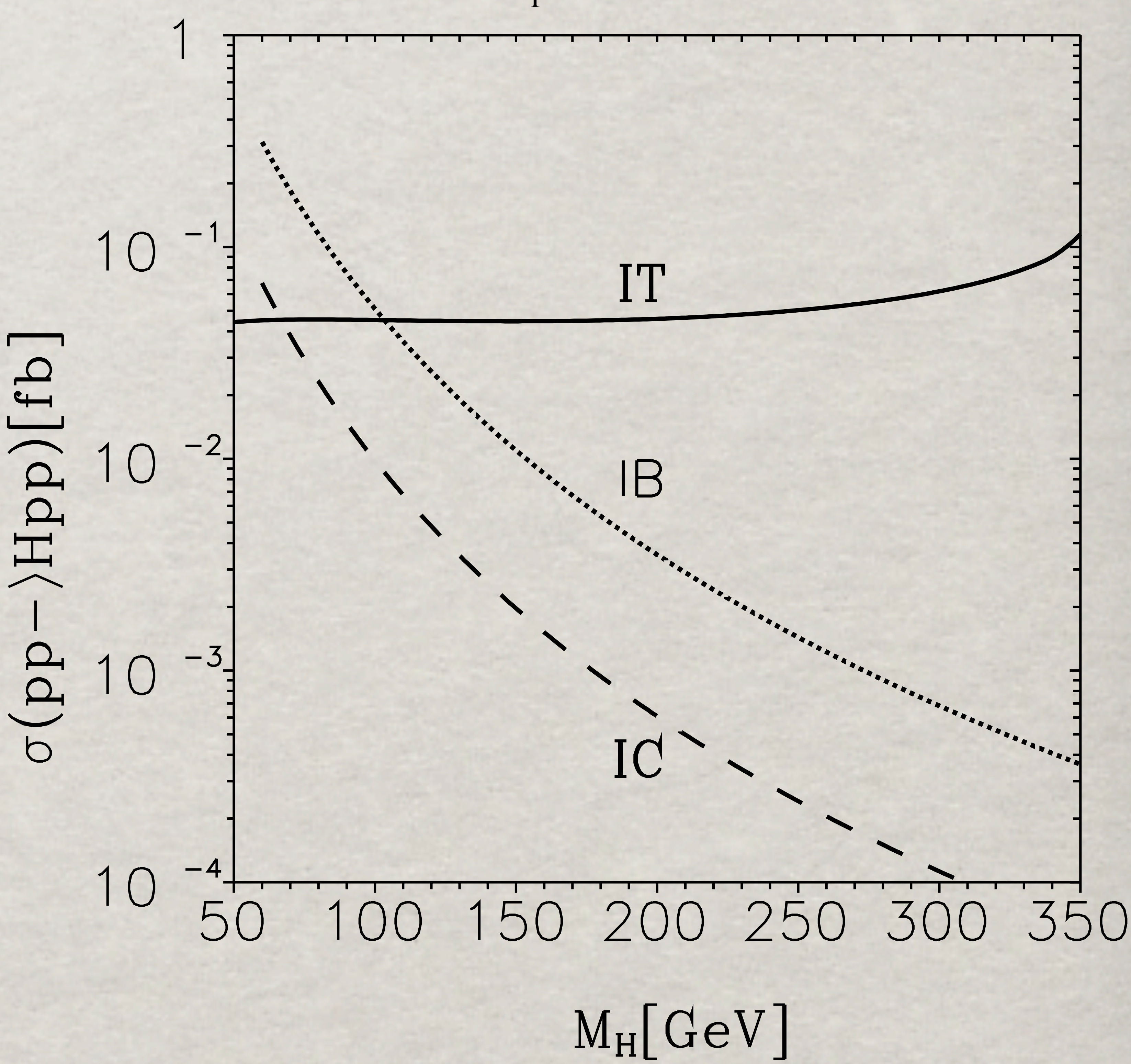
Diffractive Higgs from heavy flavored sea.

Diffractive Higgsstrahlung is similar to diffractive DY. Z, W, since in all cases the radiated particle does not participate in the interaction. However, the Higgs decouples from light quarks, so the cross section of higgsstrahlung by light hadrons is small.



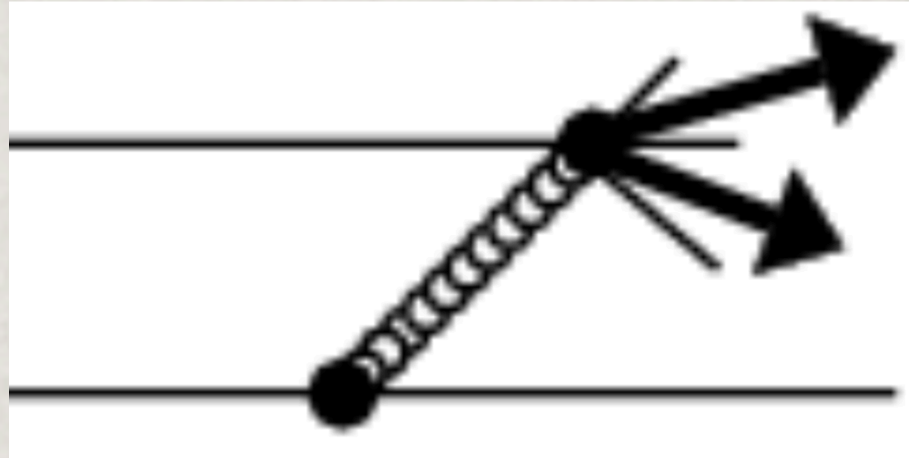
A larger cross section may emerge due to admixture of heavy flavors in light hadrons. Exclusive Higgs production, pp→ Hpp, via coalescence of heavy quarks, $\mathbf{Q\bar{Q} \to H}$

S.Brodsky, B.K., I.Schmidt, J.Soffer 2006;
S.Brodsky, A.Goldhaber, B.K., I.Schmidt 2009.



The cross section of Higgs production was evaluated assuming 1% of intrinsic charm, and that heavier flavors scale as $1/m_Q^2$ [M.Franz, M.Polyakov, K.Goeke 2000]. At the Higgs mass 125 GeV intrinsic bottom and top give comparable contributions.

Diffractive dijets



Notations:

$$\xi \equiv 1 - x_F = \frac{M_X^2}{s}$$

xF is the fractional longitudinal momentum of the recoil p

$$x_{Bj} = \frac{1}{\sqrt{s}} \sum_{i=1}^{3\,\text{jets}} E_T^i e^{-\eta_i}$$

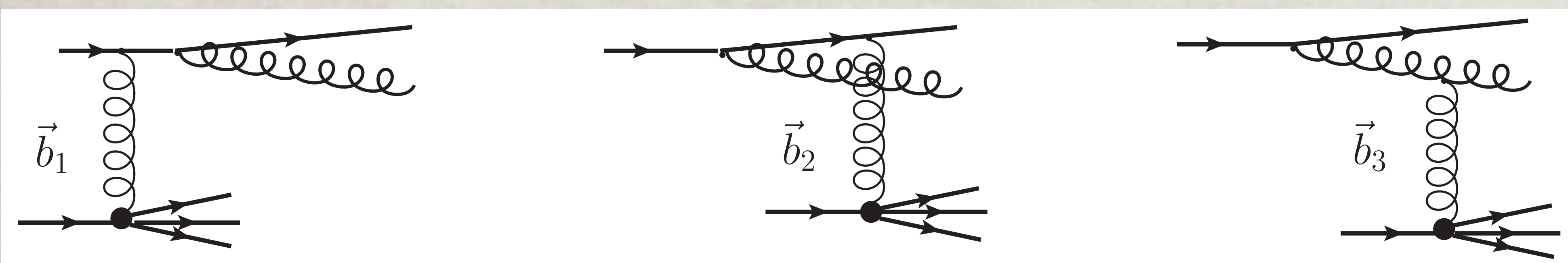
The fractional LC momentum of the target parton (analog of x2 in Drell-Yan)

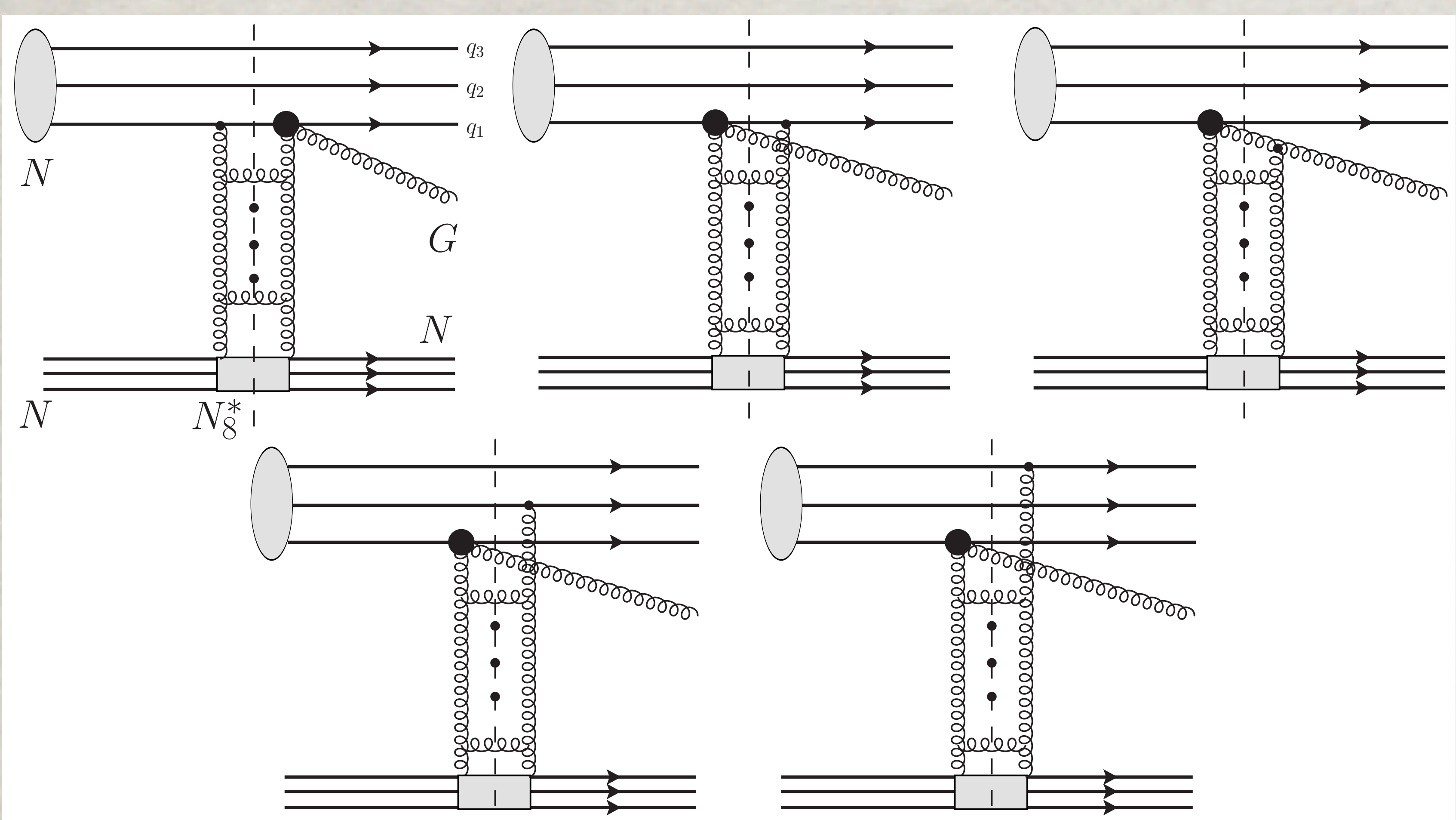
$$Q^2 = \frac{(E_T^1 + E_T^2)^2}{4}$$

The characteristic scale

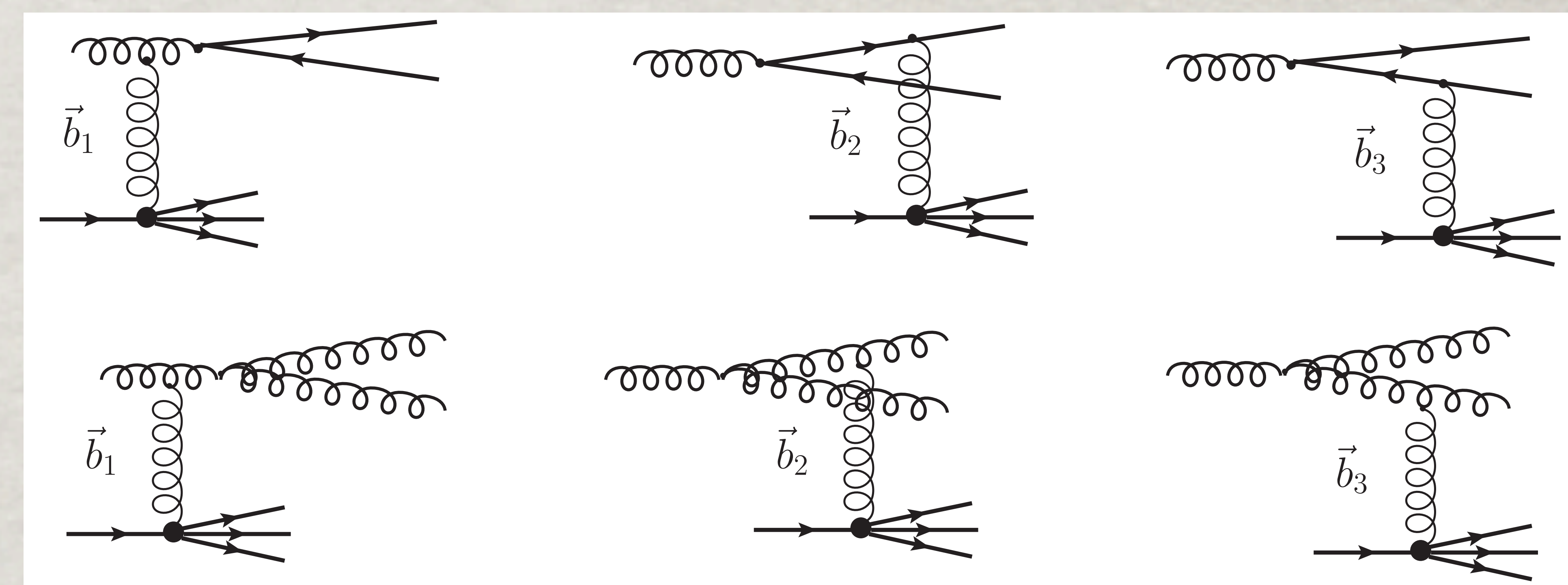
Diffractive dijets

- quark-gluon dijets



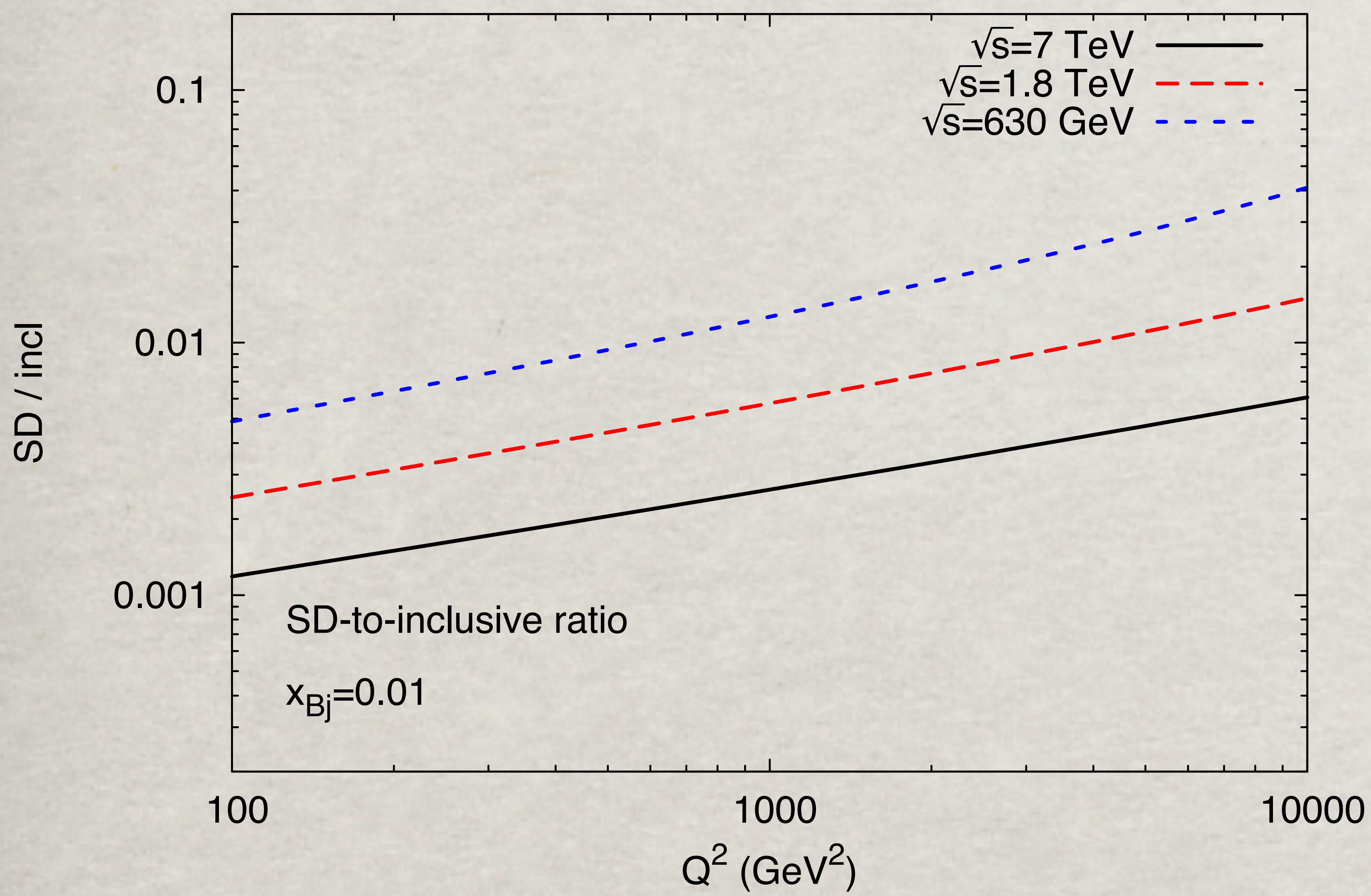


- quark-antiquark dijets

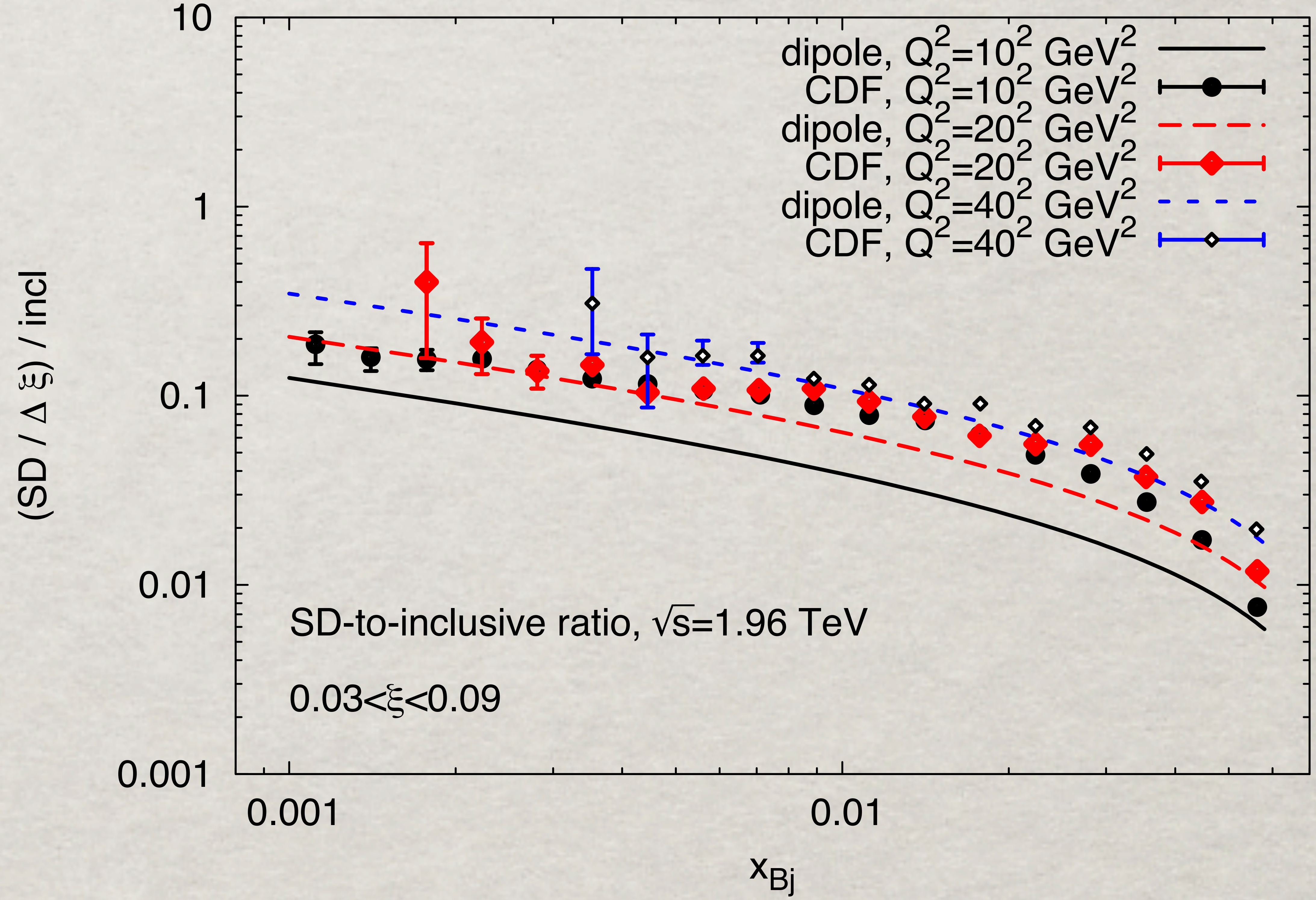


Diffractive dijets

Scale dependence:



CDF data



Conclusions

- Diffractive DIS is dominated by soft aligned-jet configuratopns of the

- This explains why the naive expectations, $\sigma_{\rm diff} \propto W^{4\Delta}$ vs $\sigma_{\rm incl} \propto W^{2\Delta}$, like $\sigma_{\rm diff} \propto 1/Q^4$, or are not correct.

- The mechanisms of hadron-induced hard diffraction are different,they are half-hard, half-soft, and have the leading twist behavior.