Diffraction at the LHC: From the shadows to light - Basic Concepts -

Victor P. Goncalves

High and Medium Energy Group

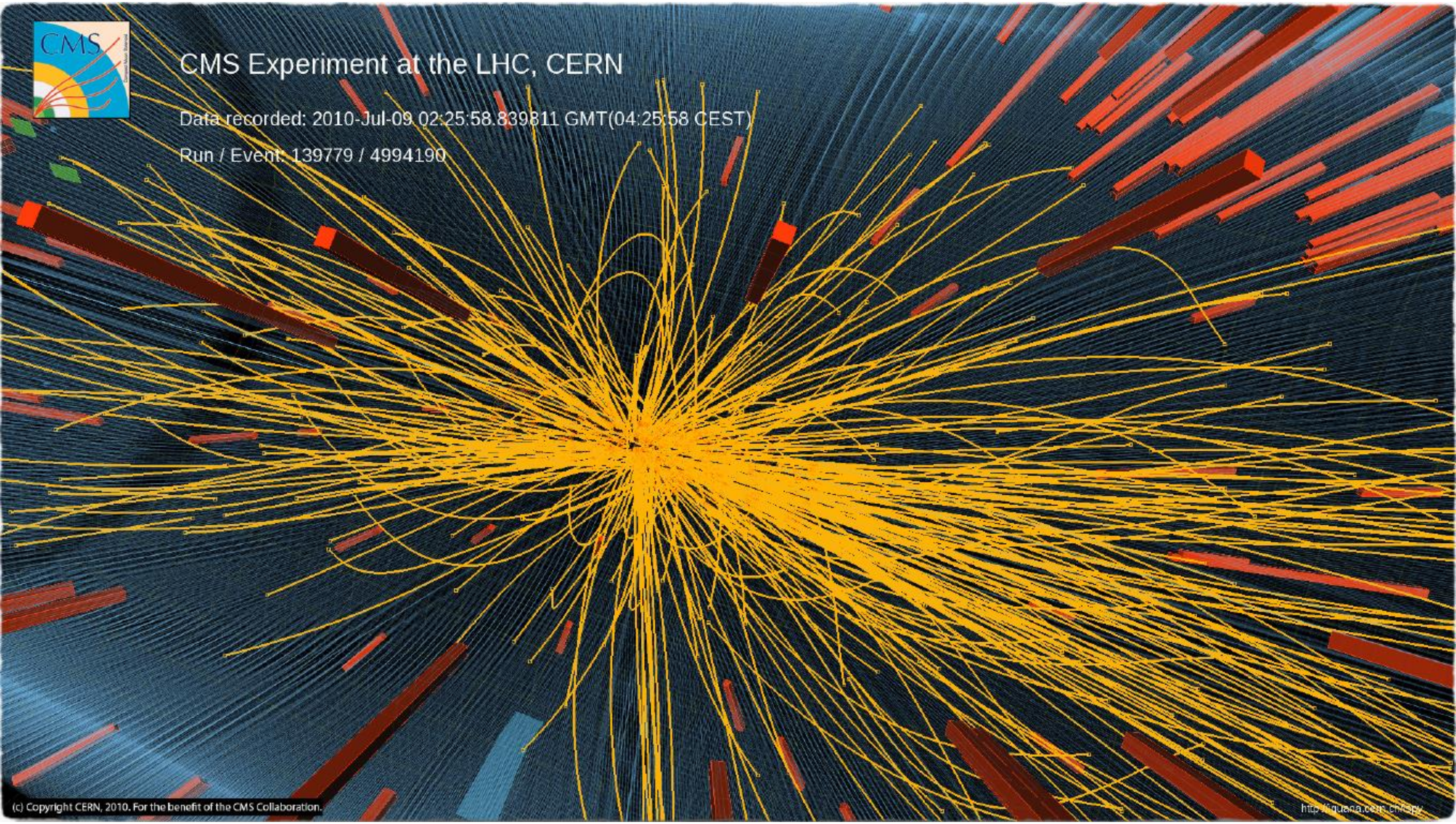
Universidade Federal de Pelotas (UFPel)

Pelotas – RS – Brazil

barros@ufpel.edu.br

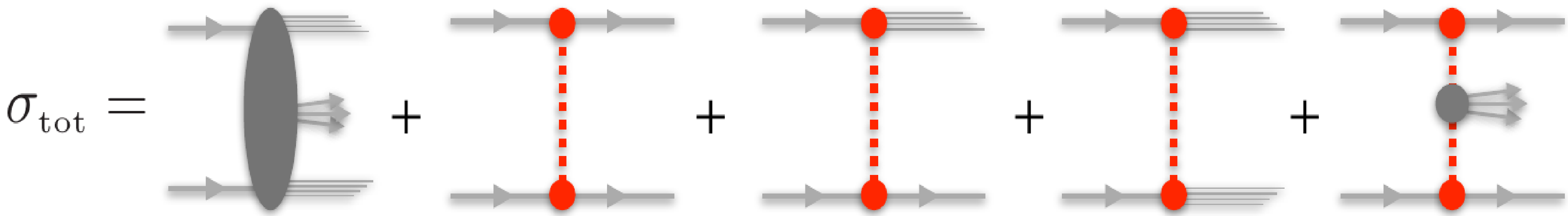
Pelotas
16 Sep 2016

What happens when hadrons collide?



Proton - Proton Collisions

$$\sigma_{\text{tot}} = \sigma_{\text{ND}} + \sigma_{\text{elastic}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}}$$

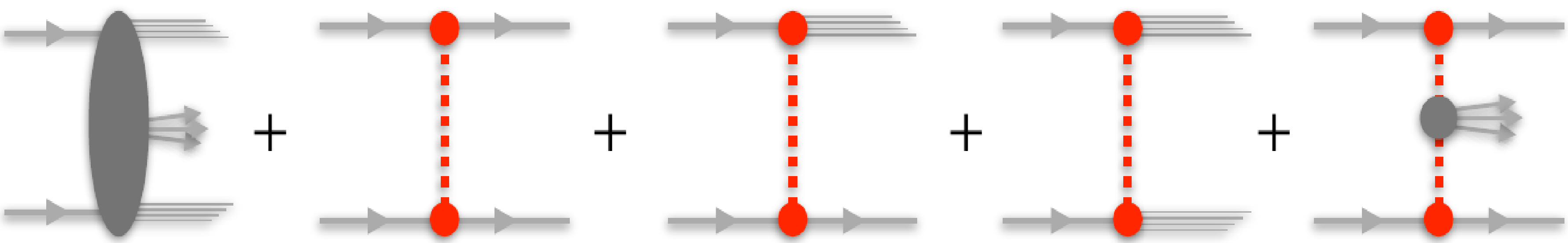


Proton - Proton Collisions

Non - Diffractive

$$\sigma_{\text{tot}} = \boxed{\sigma_{\text{ND}}} + \sigma_{\text{elastic}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}}$$

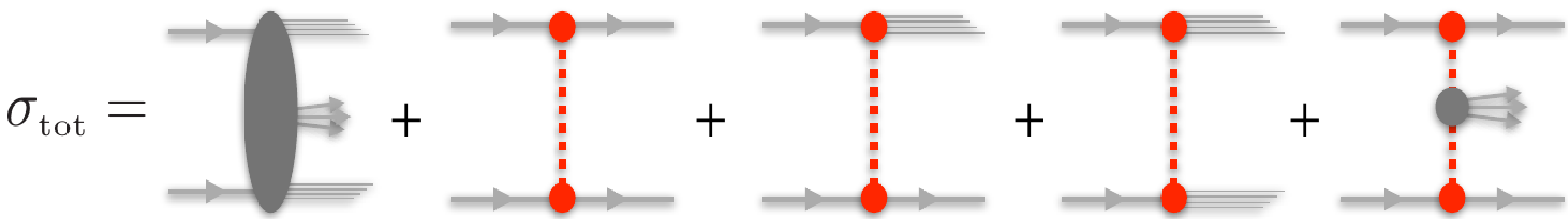
$\sigma_{\text{tot}} =$

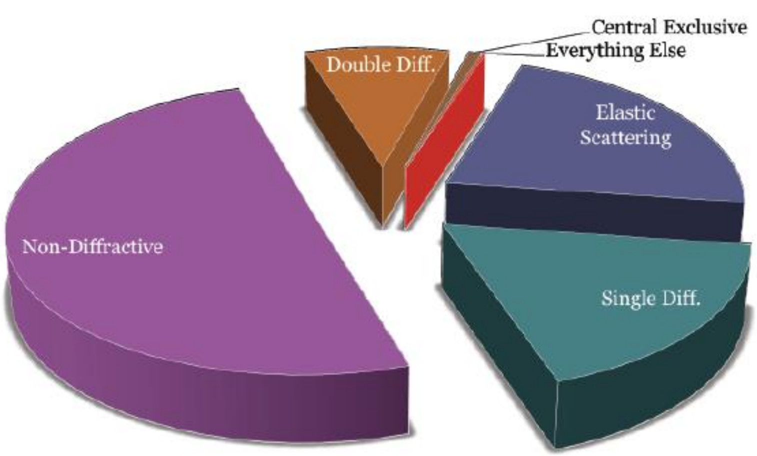


Proton - Proton Collisions

Non - Diffractive

$$\sigma_{\mathrm{tot}} = \boxed{\sigma_{\mathrm{ND}}} + \sigma_{\mathrm{elastic}} + \sigma_{\mathrm{SD}} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{CD}}$$

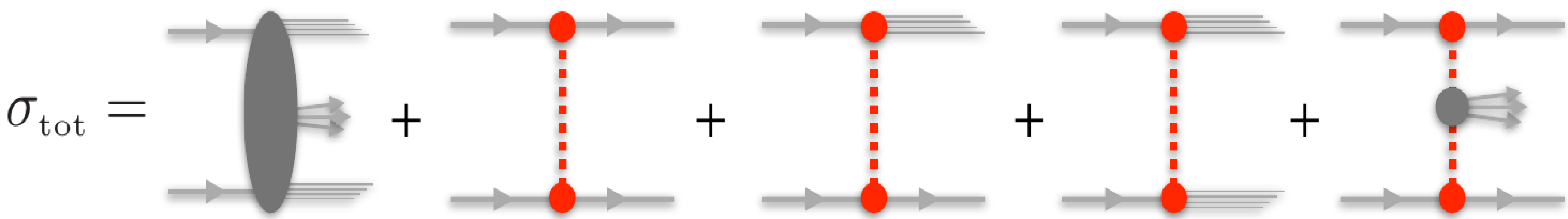


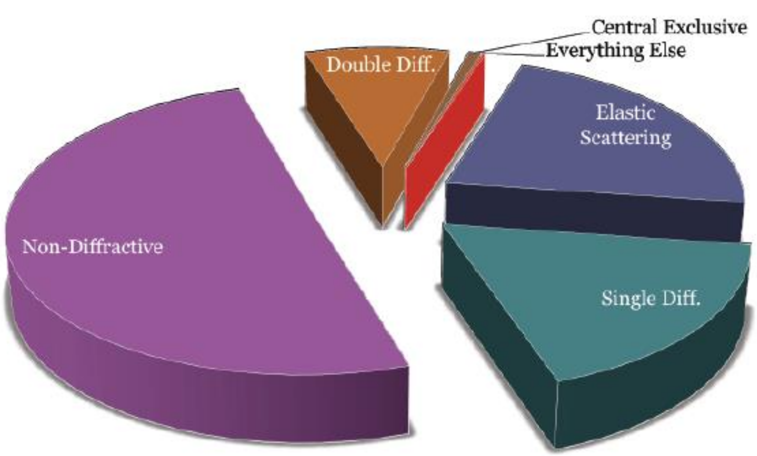


Proton - Proton Collisions

Diffractive

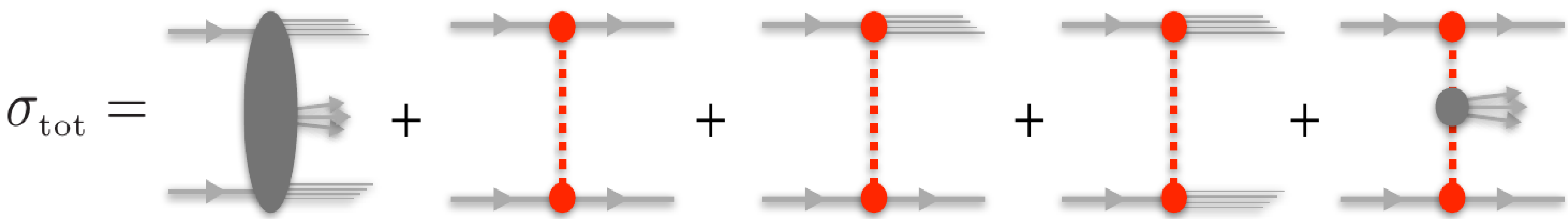
$$\sigma_{\text{tot}} = \sigma_{\text{ND}} + \sigma_{\text{elastic}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}}$$

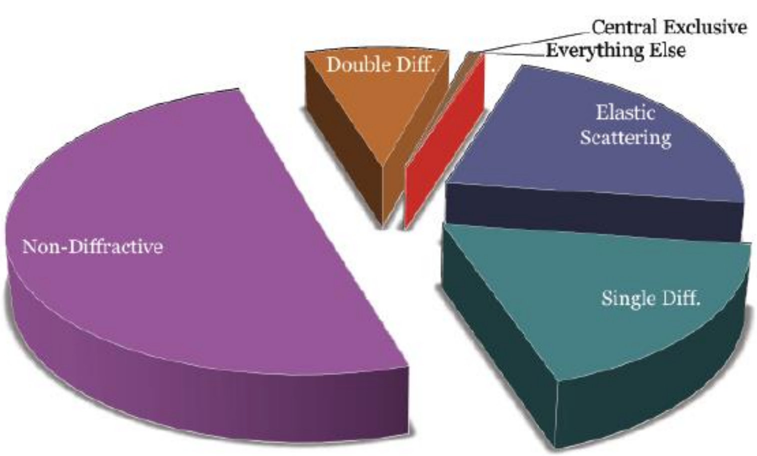




Proton - Proton Collisions

$$\sigma_{\rm tot} = \sigma_{\rm ND} + \boxed{\sigma_{\rm elastic} + \sigma_{\rm SD} + \sigma_{\rm DD} + \sigma_{\rm CD}}$$





LHC is:

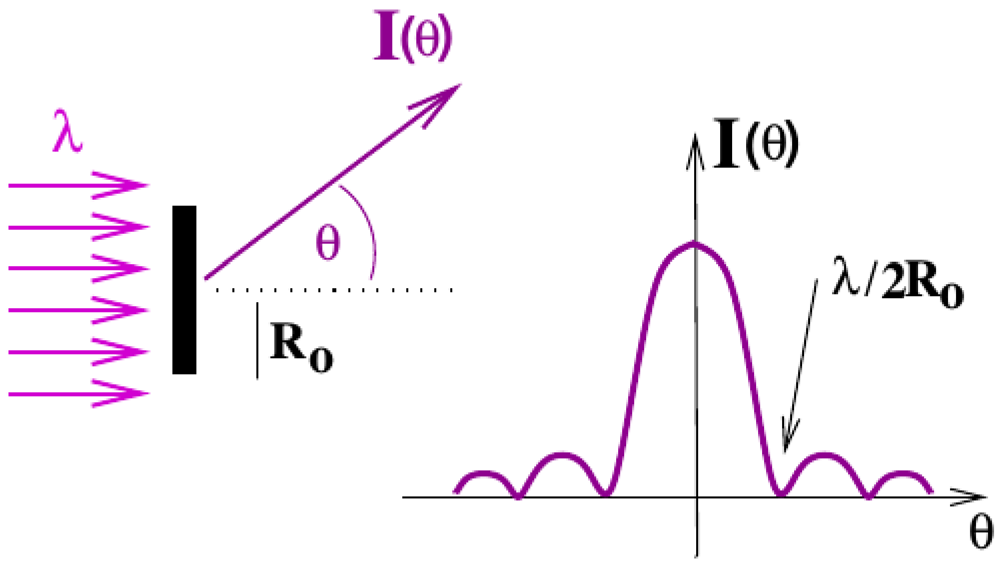
- Discovery Machine
- QCD machine (QCD is always present!)

Diffraction is:

- Vital aspect of QCD
- Place to look for New Physics

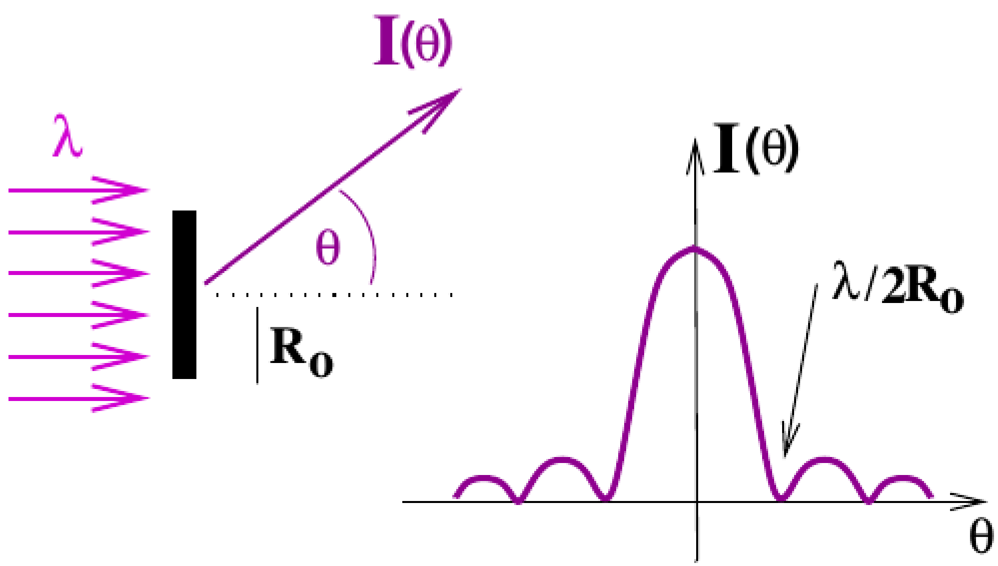
Diffraction in Optics

- Diffraction of light of wavelength λ from a circular target of size R_0



Diffraction in Optics

- Diffraction of light of wavelength λ from a circular target of size R_0



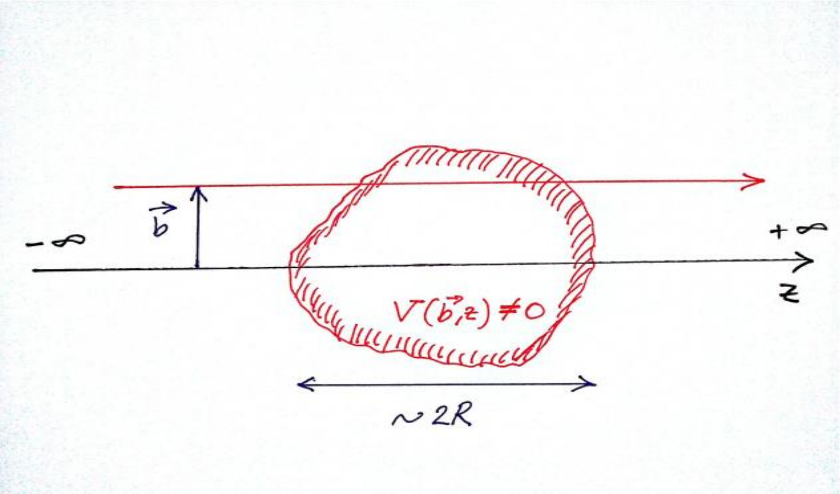
$$\frac{I(\theta)}{I(\theta=0)} = \frac{[2J_1(x)]^2}{x^2} \simeq 1 - \frac{R_0^2}{4}(k\theta)^2$$

$$x = kR_0 \sin\theta \simeq kR_0\,\theta$$

- The diffraction pattern is related to the size of the target and to the wavelength of the light beam.

Diffraction in Particle Physics

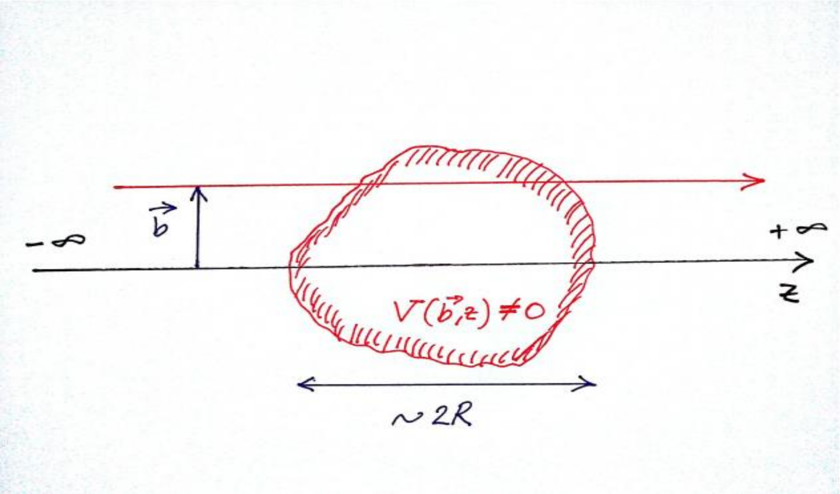
- Scattering theory in the short wavelength limit (high energies): Eikonal approximation



- Eikonal phase:
  $$\delta(\boldsymbol{b}) = -\frac{1}{2v}\int_{-\infty}^{\infty} dz V(\boldsymbol{b}, z)\,,\ v = k/m$$
- scattered wave $\psi(\boldsymbol{b}, +\infty) = S(\boldsymbol{b})\psi(\boldsymbol{b}, -\infty)$, $S(\boldsymbol{b}) = \exp(2i\delta(\boldsymbol{b}))$
- profile function: $\Gamma(\boldsymbol{b}) \equiv 1 - S(\boldsymbol{b})$.
- scattering amplitude:
  $$f(\boldsymbol{q}) = \frac{ik}{2\pi}\int d^2\boldsymbol{b}\, \exp[-i\boldsymbol{q}\boldsymbol{b}]\Gamma(\boldsymbol{b})$$

Diffraction in Particle Physics

- Scattering theory in the short wavelength limit (high energies): Eikonal approximation



- Eikonal phase:
  $$\delta(\boldsymbol{b}) = -\frac{1}{2v}\int_{-\infty}^{\infty} dz V(\boldsymbol{b},z)\,,\; v = k/m$$
- scattered wave $\psi(\boldsymbol{b},+\infty) = S(\boldsymbol{b})\psi(\boldsymbol{b},-\infty)$, $S(\boldsymbol{b}) = \exp(2i\delta(\boldsymbol{b}))$
- profile function: $\Gamma(\boldsymbol{b}) \equiv 1 - S(\boldsymbol{b})$.
- scattering amplitude:
  $$f(\boldsymbol{q}) = \frac{ik}{2\pi}\int d^2\boldsymbol{b}\,\exp[-i\boldsymbol{q}\boldsymbol{b}]\Gamma(\boldsymbol{b})$$

✓Elastic cross section:

$$\frac{d\sigma_{\rm el}}{d\Omega} = |f(\boldsymbol{q})|^2 = \frac{k^2}{4\pi^2}\int d^2\boldsymbol{b}d^2\boldsymbol{b}'\exp[-i\boldsymbol{q}(\boldsymbol{b}-\boldsymbol{b}')]\,\Gamma(\boldsymbol{b})\Gamma^*(\boldsymbol{b}')$$

✓Integrated cross sections:

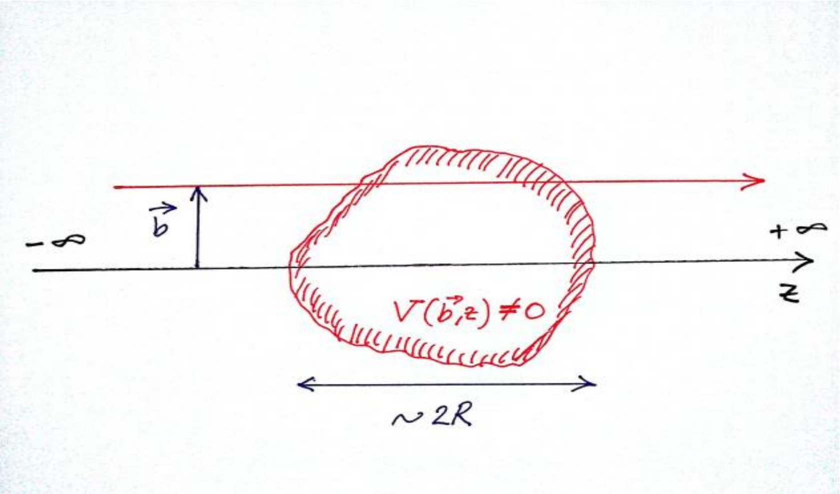
$$\sigma_{\rm tot} = \frac{4\pi}{k}\Im m\, f(0) = 2\int d^2\boldsymbol{b}\,\Re e\,\Gamma(\boldsymbol{b})$$

$$\sigma_{\rm el} = \int d^2\boldsymbol{b}\,|\Gamma(\boldsymbol{b})|^2$$

$$\sigma_{\rm inel} = \int d^2\boldsymbol{b}\left(2\Re e\,\Gamma(\boldsymbol{b}) - |\Gamma(\boldsymbol{b})|^2\right)$$

Diffraction in Particle Physics

❑Scattering theory in the short wavelength limit (high energies): Eikonal approximation



- Eikonal phase:
  $$\delta(\boldsymbol{b}) = -\frac{1}{2v}\int_{-\infty}^{\infty} dz V(\boldsymbol{b},z)\,,\; v = k/m$$
- scattered wave $\psi(\boldsymbol{b},+\infty) = S(\boldsymbol{b})\psi(\boldsymbol{b},-\infty)$, $S(\boldsymbol{b}) = \exp(2i\delta(\boldsymbol{b}))$
- profile function: $\Gamma(\boldsymbol{b}) \equiv 1 - S(\boldsymbol{b})$.
- scattering amplitude:
  $$f(\boldsymbol{q}) = \frac{ik}{2\pi}\int d^2\boldsymbol{b}\,\exp[-i\boldsymbol{q}\boldsymbol{b}]\Gamma(\boldsymbol{b})$$

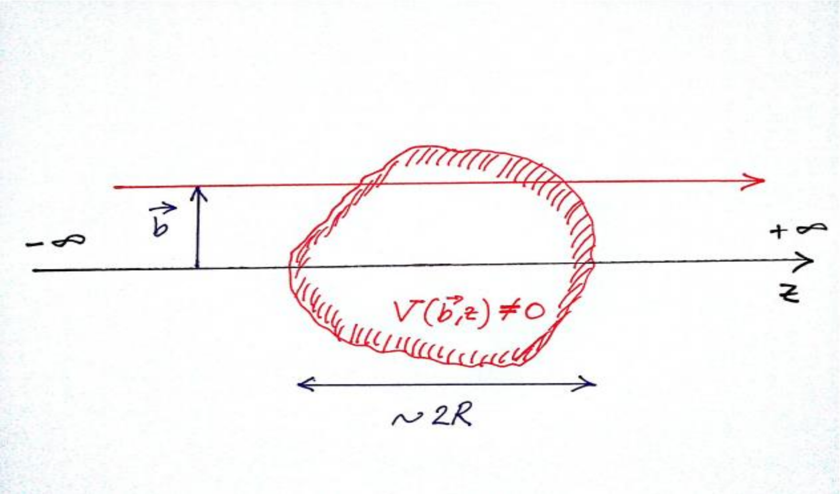
✓**Black disc**:
No scattering outside a disc of radius R and strong absorption for |b| < R

$$\delta(\boldsymbol{b}) = 0 \text{ for } |\boldsymbol{b}| > R,\;, \Im m\delta(\boldsymbol{b}) \gg 1 \text{ for } |\boldsymbol{b}| < R\,.$$

$$S(\boldsymbol{b}) = \theta(|\boldsymbol{b}| - R) \;\Rightarrow\; \Gamma(\boldsymbol{b}) = \theta(R - |\boldsymbol{b}|)\,.$$

Diffraction in Particle Physics

❑Scattering theory in the short wavelength limit (high energies): Eikonal approximation



- Eikonal phase:
  $$\delta(\boldsymbol{b}) = -\frac{1}{2v}\int_{-\infty}^{\infty} dz V(\boldsymbol{b},z)\,,\; v = k/m$$
- scattered wave $\psi(\boldsymbol{b},+\infty) = S(\boldsymbol{b})\psi(\boldsymbol{b},-\infty)$, $S(\boldsymbol{b}) = \exp(2i\delta(\boldsymbol{b}))$
- profile function: $\Gamma(\boldsymbol{b}) \equiv 1 - S(\boldsymbol{b})$.
- scattering amplitude:
  $$f(\boldsymbol{q}) = \frac{ik}{2\pi}\int d^2\boldsymbol{b}\,\exp[-i\boldsymbol{q}\boldsymbol{b}]\Gamma(\boldsymbol{b})$$

✓**Black disc**:
No scattering outside a disc of radius R and strong absorption for |b| < R

$$\delta(\boldsymbol{b}) = 0 \text{ for } |\boldsymbol{b}| > R,\;, \Im m\delta(\boldsymbol{b}) \gg 1 \text{ for } |\boldsymbol{b}| < R\,.$$

$$S(\boldsymbol{b}) = \theta(|\boldsymbol{b}| - R) \Rightarrow \Gamma(\boldsymbol{b}) = \theta(R - |\boldsymbol{b}|)\,.$$

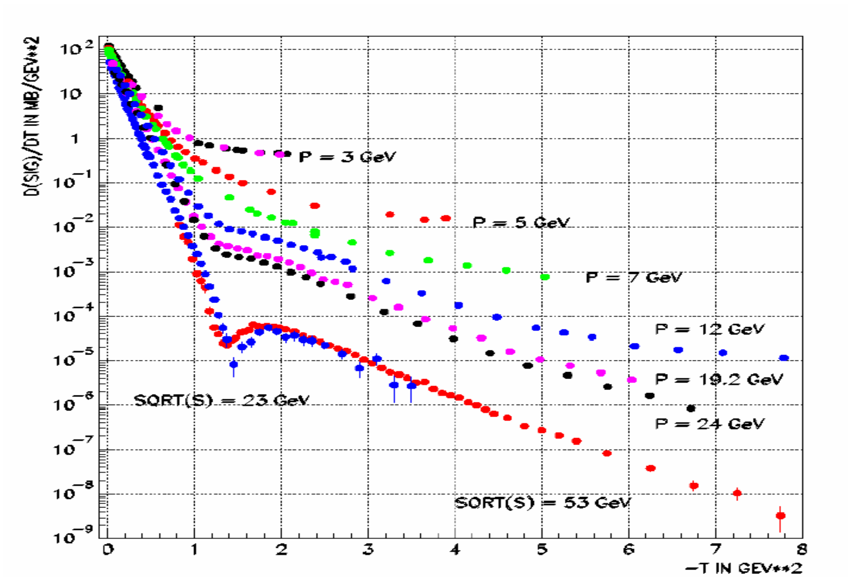
$$f(\boldsymbol{q}) = ikR^2\frac{J_1(qR)}{qR}$$

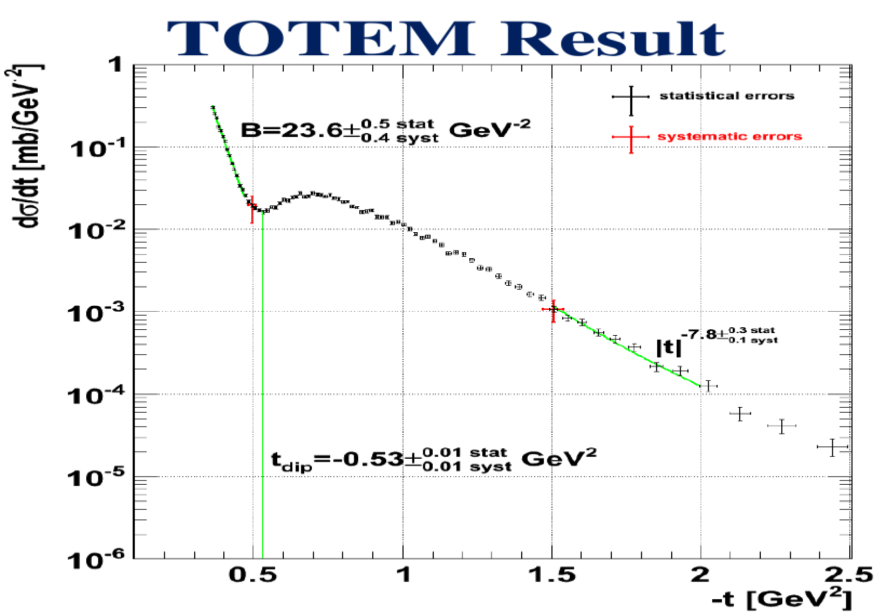
$$\sigma_{\text{tot}} = 2\int d^2\boldsymbol{b}\,\Re e\,\Gamma(\boldsymbol{b}) = 2\pi R^2$$

$$\sigma_{\text{el}} = \int d^2\boldsymbol{b}\,|\Gamma(\boldsymbol{b})|^2 = \pi R^2 = \frac{1}{2}\sigma_{\text{tot}}$$

$$\sigma_{\text{inel}} = \int d^2\boldsymbol{b}\left(2\Re e\,\Gamma(\boldsymbol{b}) - |\Gamma(\boldsymbol{b})|^2\right) = \pi R^2$$

Diffraction in Particle Physics





- ✓ $|t| \approx (P\,\theta)^2$ is the absolute value of the squared four-momentum transfer. P is the incident proton momentum and θ is the scattering angle .

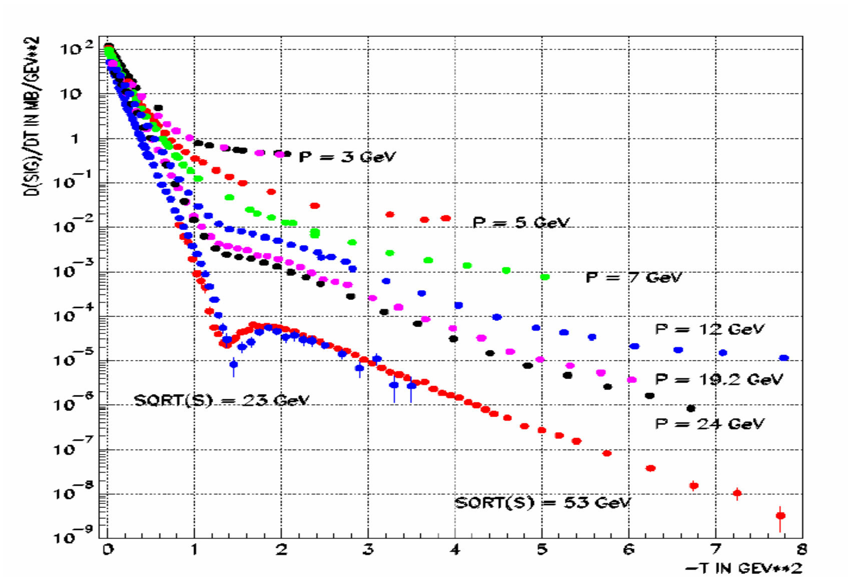
- ✓ One have that:

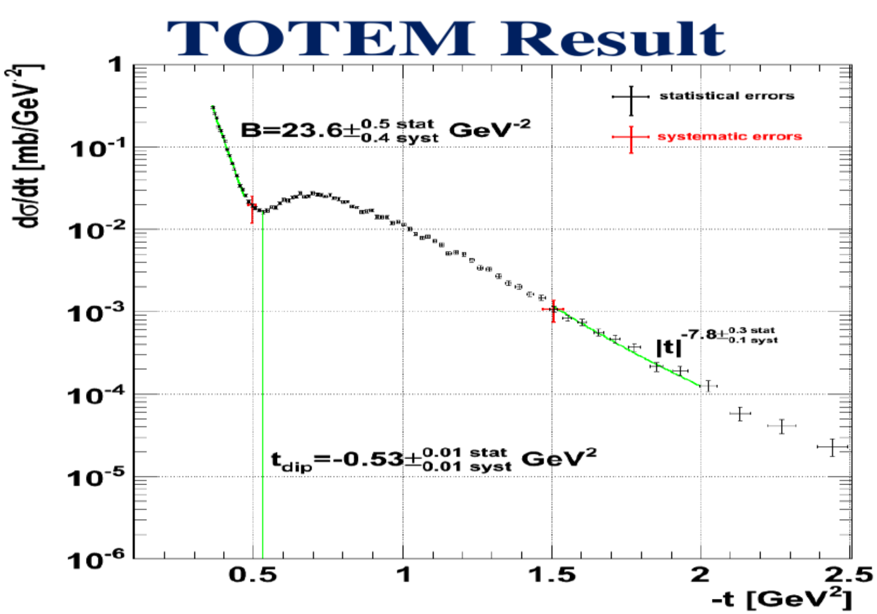
$$\frac{\frac{d\sigma}{dt}(t)}{\frac{d\sigma}{dt}(t=0)} \simeq e^{-b|t|} \simeq 1 - b\,(P\theta)^2$$

The t-slope can be written as $b = R^2/4$, where once again R is related to the target size.

- ✓ A dip followed by a secondary maximum has also been observed, with the value of |t| in which the dip appears decreasing with increasing proton momentum.

Diffraction in Particle Physics





✓ $|t| \approx (P\,\theta)^2$ is the absolute value of the squared four-momentum transfer. P is the incident proton momentum and θ is the scattering angle .

✓ One have that:

$$\frac{\frac{d\sigma}{dt}(t)}{\frac{d\sigma}{dt}(t=0)} \simeq e^{-b|t|} \simeq 1 - b\,(P\theta)^2$$

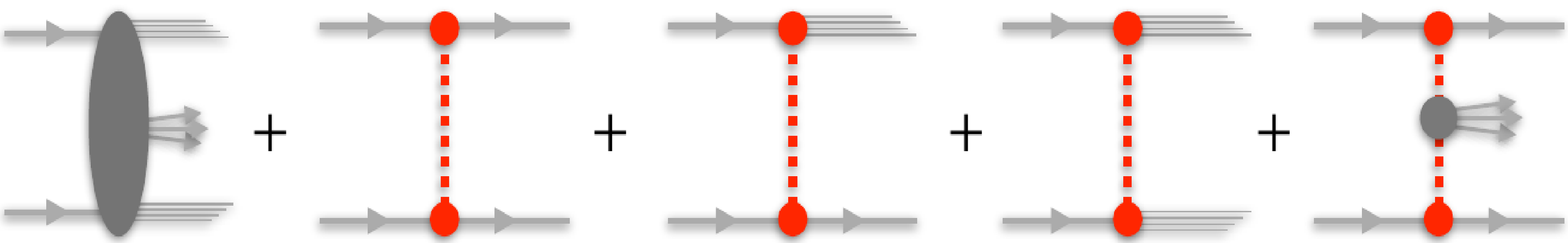
The t-slope can be written as $b = R^2/4$, where once again R is related to the target size.

✓ Similar t distributions has been observed for the other diffractive reactions mentioned before, leading to the use of the term **diffraction** for all such processes.

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

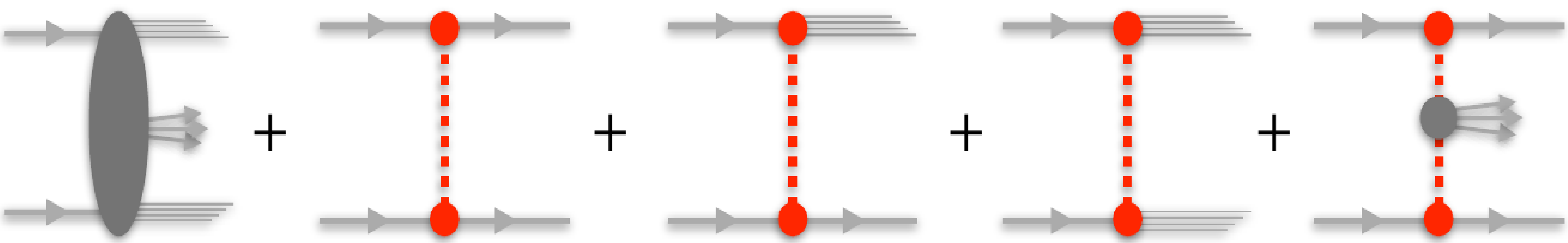
$\sigma_{\mathrm{tot}} =$

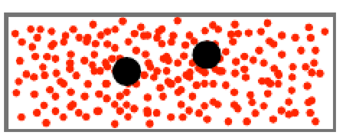


Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

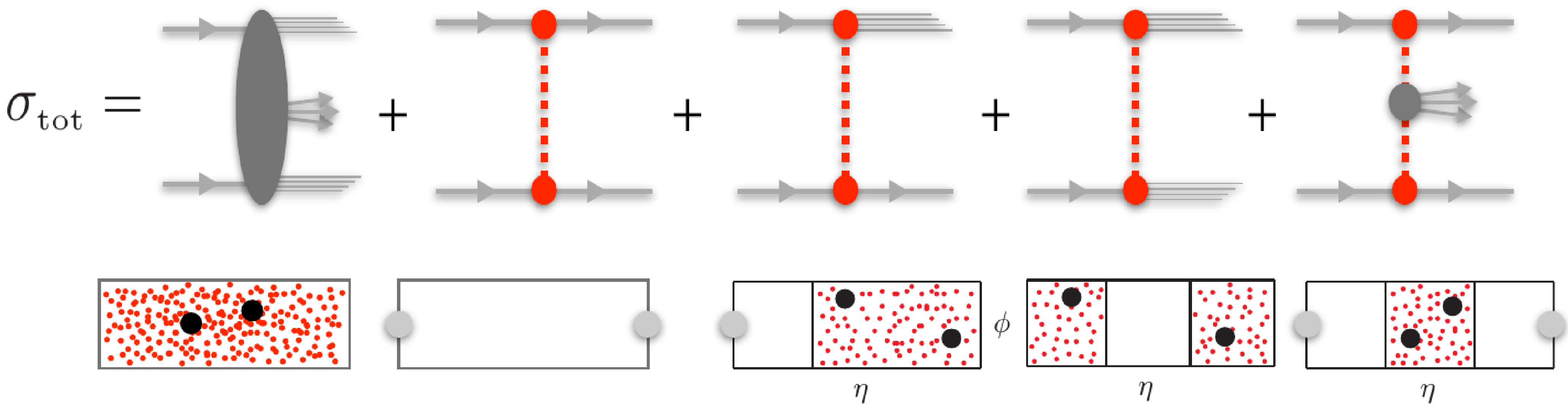
$$\sigma_{\text{tot}} =$$





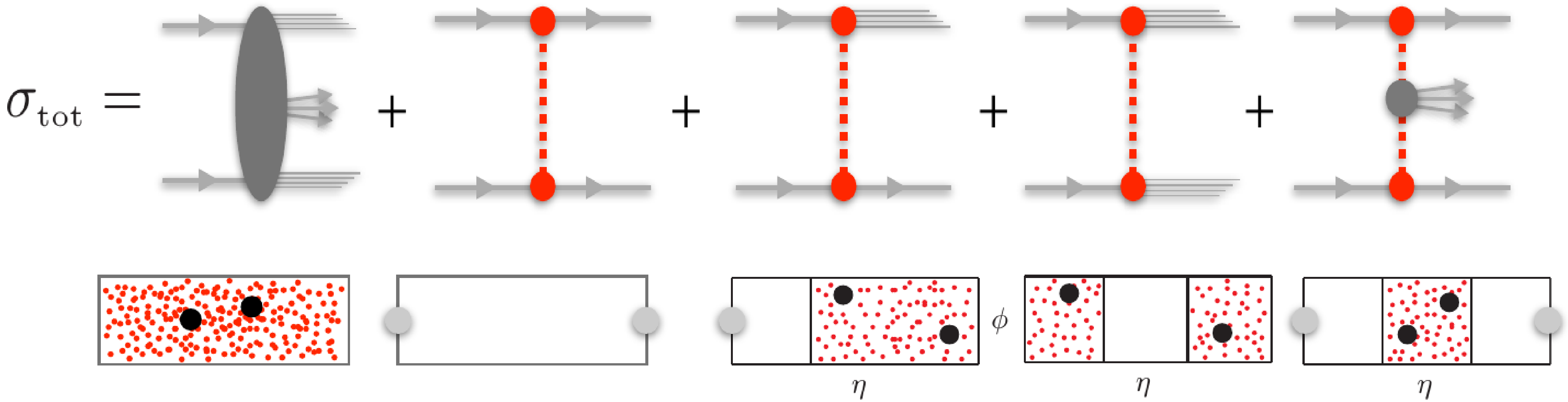
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles



Diffraction in Particle Physics

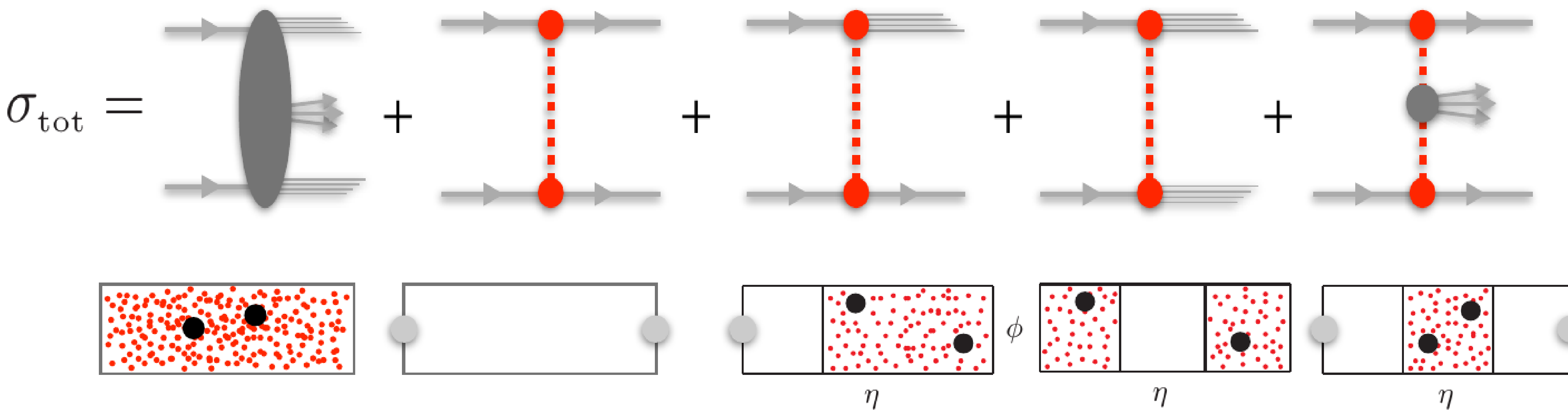
- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles



- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

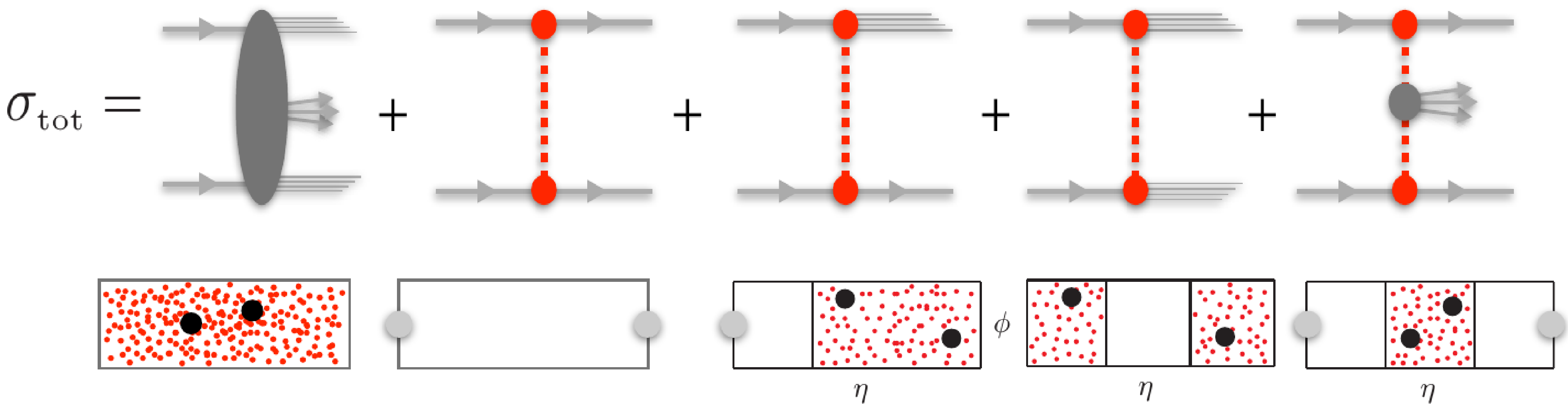


- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

Caveats: - The rapidity gap(s) can be very forward and outside of the detector acceptance;

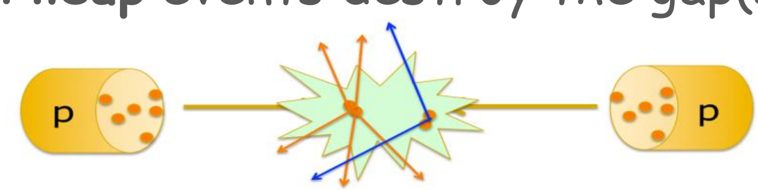
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles



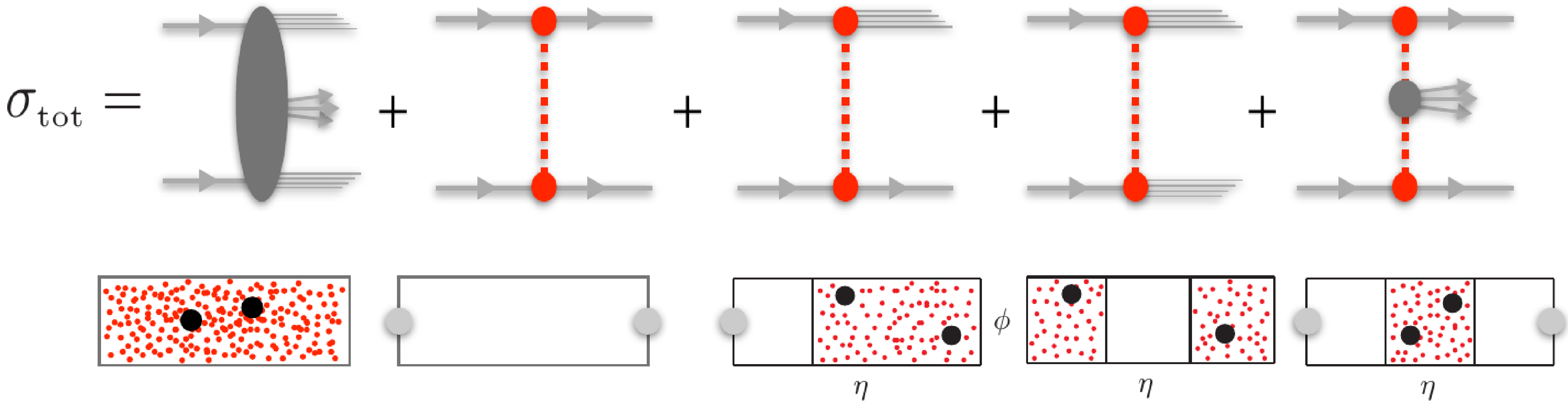
- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

Caveats: - **Pileup** events destroy the gap(s).



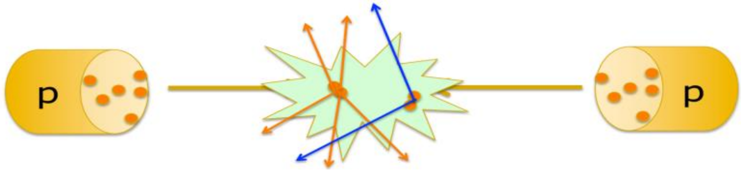
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles



- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

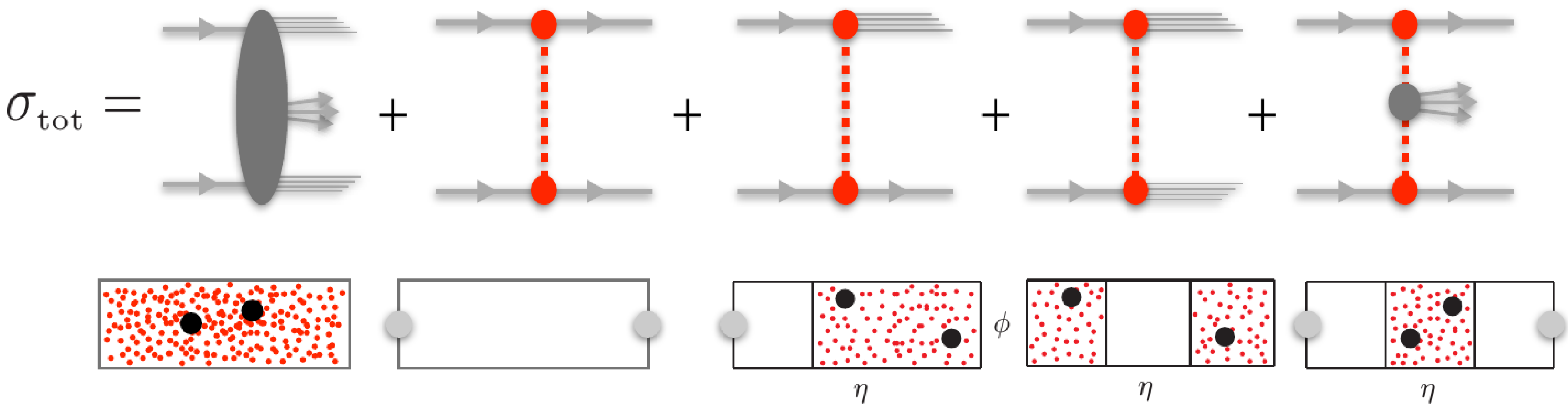
Caveats: - **Pileup** events destroy the gap(s).



CMS/ATLAS (2012): $\langle\mu\rangle \approx 30$

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

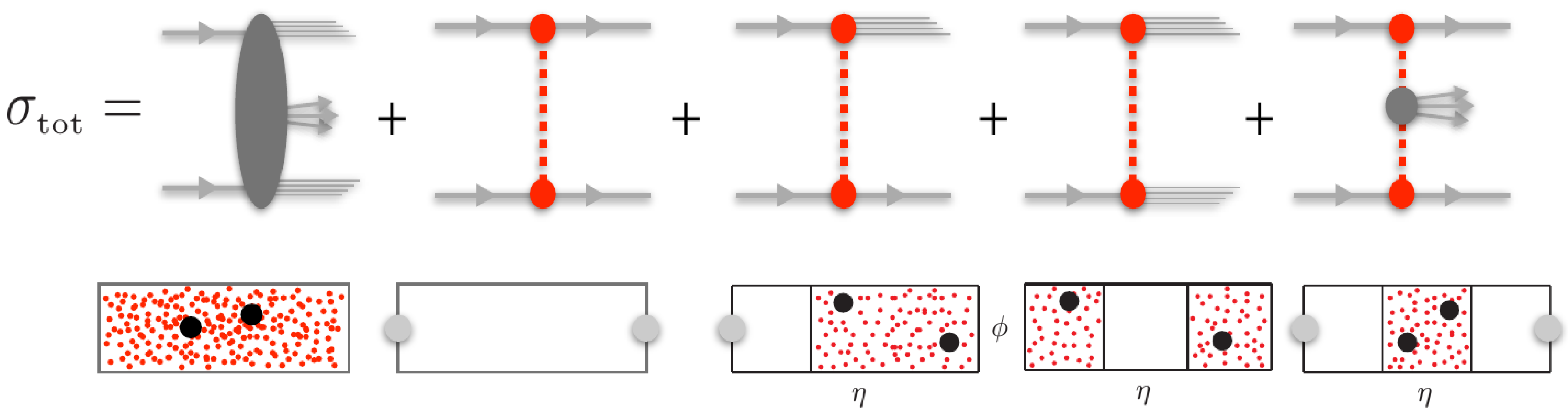


- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

Caveats: ⇒ **LRG** not always usable!

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles



- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

Alternative : Proton tagging (and timing) detectors e.g. CMS/Totem – PPS; ATLAS - AFP

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

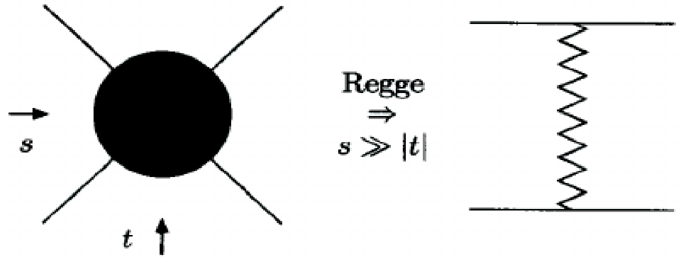
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Regge Theory:



- IP is a Regge trajectory:

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'.t$$

- $\sigma_{tot} \approx s^{\alpha_{IP}(0)}$
- Donnachie – Landshoff fit (92):

$\alpha_{IP}(0) = 1.08$ and $\alpha' = 0.25\ GeV^{-2}$

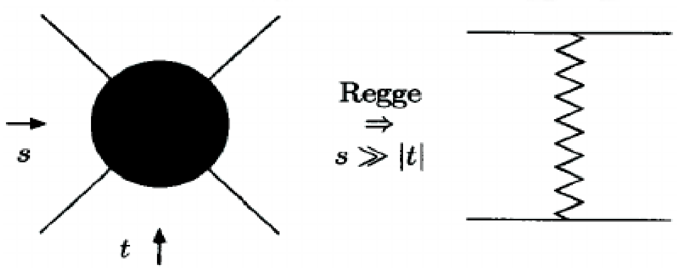
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Regge Theory:



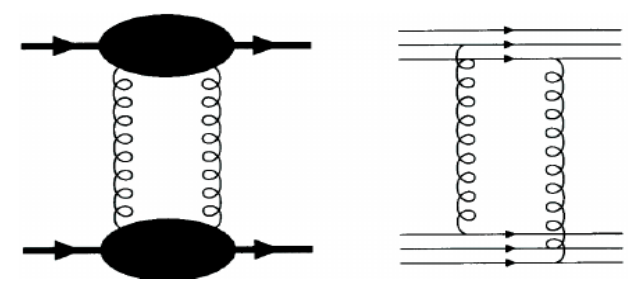
- IP is a Regge trajectory:

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'.t$$

- $\sigma_{tot} \approx s^{\alpha_{IP}(0)}$
- Donnachie – Landshoff fit (92): $\alpha_{IP}(0) = 1.08$ and $\alpha' = 0.25\ GeV^{-2}$

Perturbative QCD:

- Lowest order: Two – gluon exchange (Low – Nussinov)



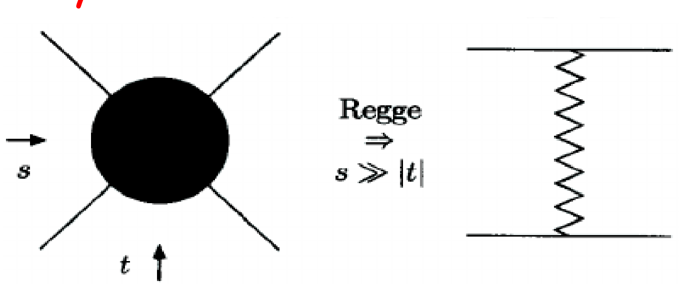
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Regge Theory:



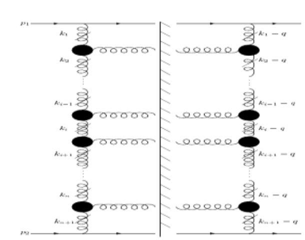
- IP is a Regge trajectory:

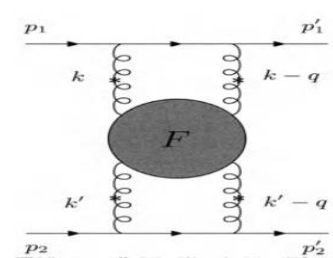
$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'.t$$

- $\sigma_{tot} \approx s^{\alpha_{IP}(0)}$
- Donnachie – Landshoff fit (92):
  $\alpha_{IP}(0) = 1.08$ and $\alpha' = 0.25\ \mathrm{GeV}^{-2}$

Perturbative QCD:

- In the leading log(1/x) approximation:





- *F* satisfies the Balitsky – Fadin – Kuraev – Lipatov (BFKL) equation
- At leading order: $\boldsymbol{\alpha_{IP}(0) = 1.5}$

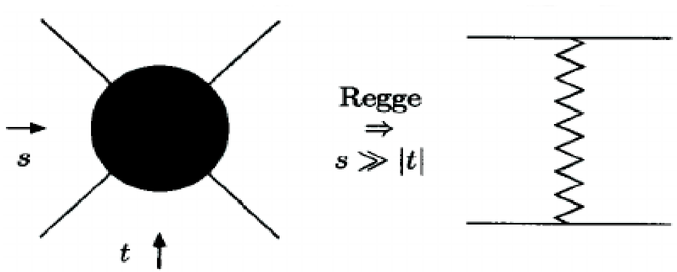
Diffraction in Particle Physics

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Regge Theory: (Soft Pomeron)



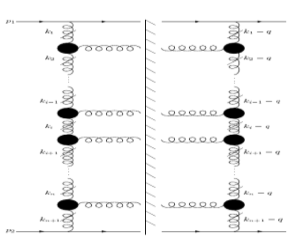
- IP is a Regge trajectory:

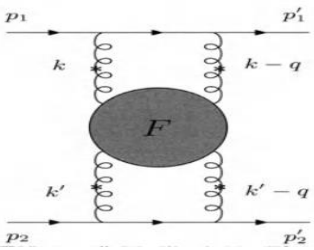
$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'.t$$

- $\sigma_{tot} \approx s^{\alpha_{IP}(0)}$
- Donnachie – Landshoff fit (92):
  $\alpha_{IP}(0) = 1.08$ and $\alpha' = 0.25\ GeV^{-2}$

Perturbative QCD: (Hard Pomeron)

- In the leading log(1/x) approximation:





- F satisfies the Balitsky – Fadin – Kuraev – Lipatov (BFKL) equation
- At leading order: $\alpha_{IP}(0) = 1.5$

Diffraction in Particle Physics

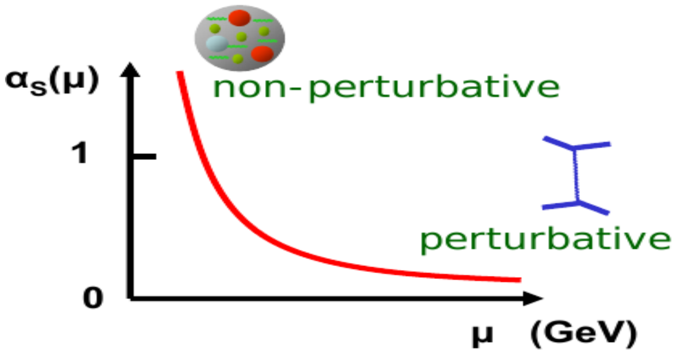
- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Perturbative QCD:

- **Caveat:** pQCD is inadequate to describe (soft) processes where the energy scale is of the order of the hadron size (≈ 1 fm)



Diffraction in Particle Physics

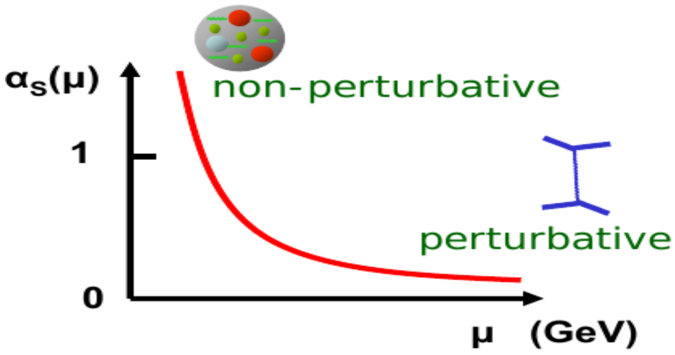
- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Perturbative QCD:

- **Caveat:** pQCD is inadequate to describe (soft) processes where the energy scale is of the order of the hadron size (≈ 1 fm)



- Diffractive processes mostly belongs to soft processes (Ex. Total SD/DD cross sections) - **Soft Diffraction**
- However, if a hard scale is present, perturbative methods can be applied to describe the diffrative process (Ex. Dijet, Heavy quark, W, Z production) - **Hard diffraction**

Diffraction in Particle Physics

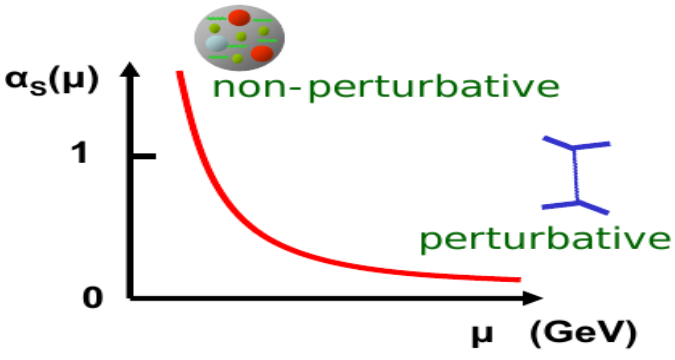
- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

✓ The exchanged object should be in a Colour Singlet State (Vacuum quantum numbers).
✓ At high energies: Pomeron (IP) exchange

What is the Pomeron (IP) ?

Perturbative QCD:

- **Caveat:** pQCD is inadequate to describe (soft) processes where the energy scale is of the order of the hadron size (≈ 1 fm)

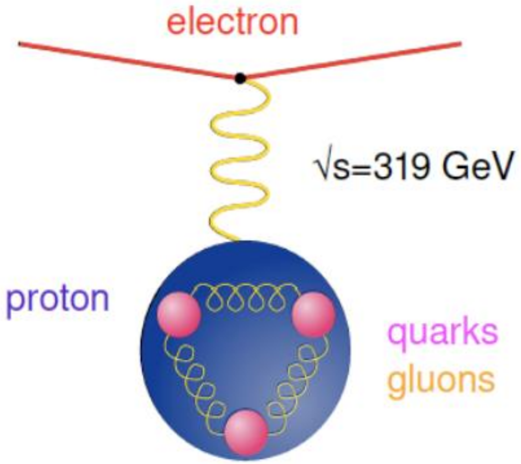


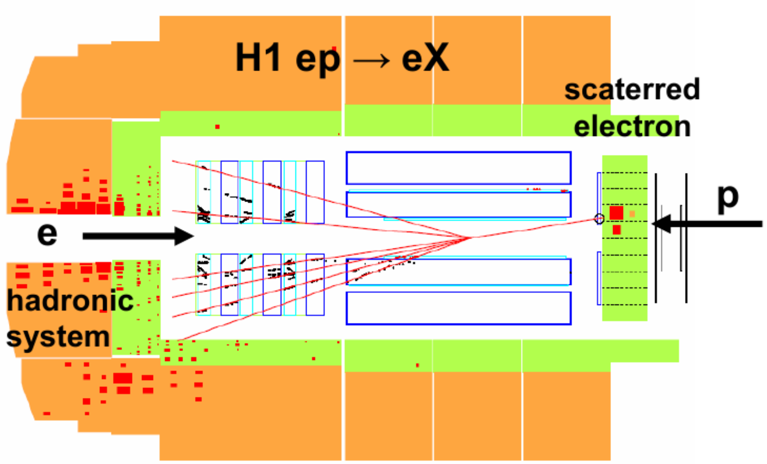
- Diffractive processes mostly belongs to soft processes (Ex. Total SD/DD cross sections) - **Soft Diffraction**
- However, if a hard scale is present, perturbative methods can be applied to describe the diffrative process (Ex. Dijet, Heavy quark, W, Z production) - **Hard diffraction**

- **Diffraction allows to bridge the gap between the hard and soft regimes of Strong interactions.**

Diffraction in electron – proton collisions

- Deep-inelastic electron-proton scattering (DIS) at DESY - HERA:

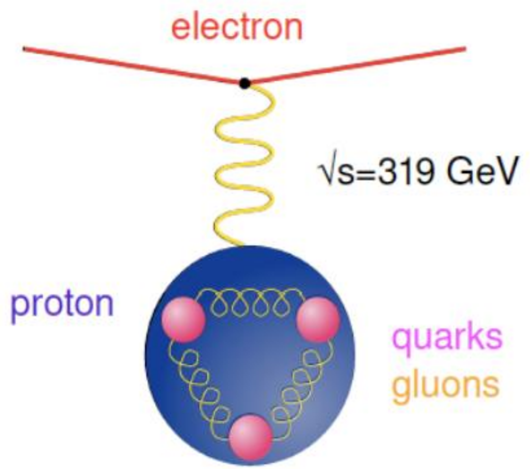


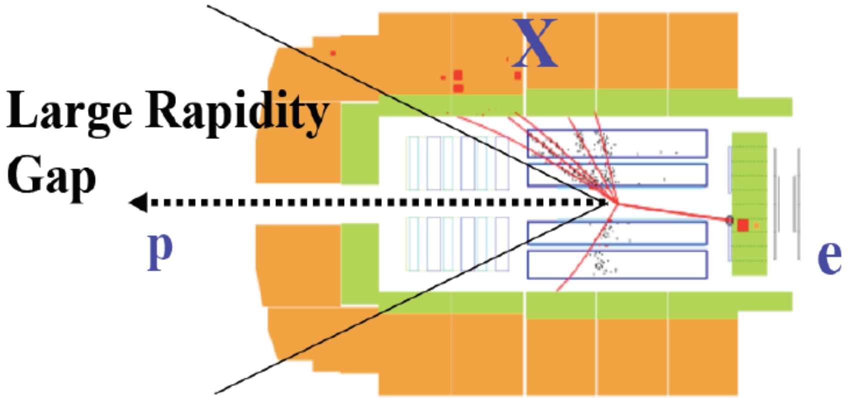


✓ Main goal of HERA was the investigation of the structure of the proton;

Diffraction in electron – proton collisions

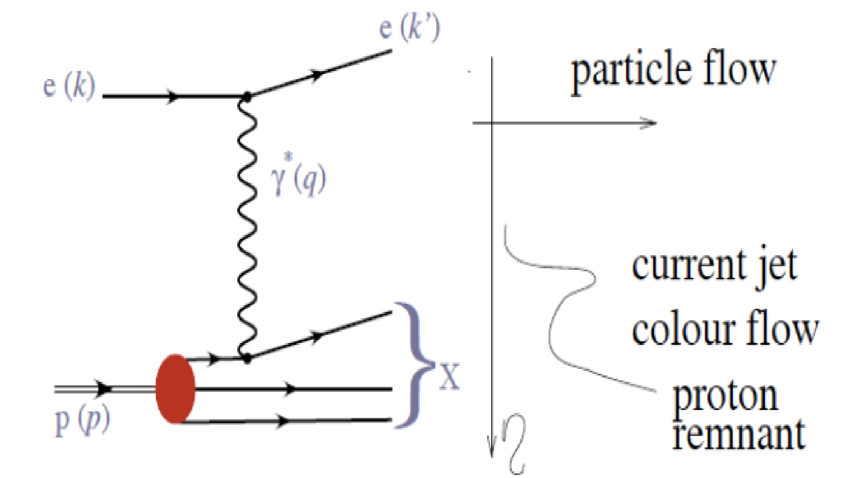
- Deep-inelastic electron-proton scattering (DIS) at DESY - HERA:





- ✓ Main goal of HERA was the investigation of the structure of the proton;
- ✓ Unexpectedly, in 1993 HERA saw that in 10 % of the DIS events there was a large gap where there were NO particle produced between the struck quark and the proton: Diffractive deep inelastic scattering (DDIS).

DDIS - Definitions



Deep Inelastic Scattering $ep \to eX$

Q^2 $= -q^2$ - virtuality of the exchanged photon

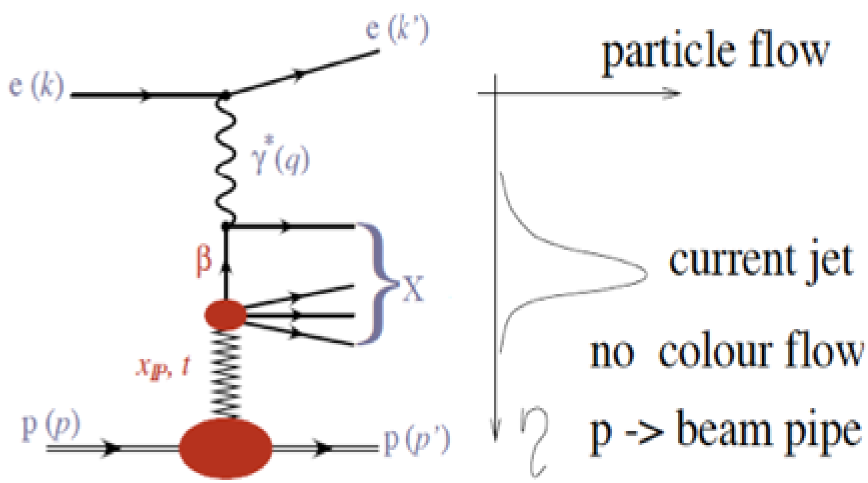
W $\gamma^* - p$ system energy

x Bjorken-x: fraction of proton's momentum carried by the struck quark

y γ^* inelasticity : $y = Q^2/s\,x$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{x\,Q^4} Y_+ F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

$Y_+ = 1 + (1-y)^2$



Diffractive Scattering $ep \to eXp$

$x_{I\!P}$ fraction of proton's momentum of the colour singlet exchange

$x_{I\!P} \simeq \frac{Q^2+M_X^2}{Q^2+W^2}$ = ξ at Tevatron and LHC

β fraction of $I\!P$ carried by the quark "seen" by the γ^* $\beta = x/x_{I\!P}$

t $= (p-p')^2$, 4-momentum squared at the p vertex

$$\frac{d^4\sigma^D}{d\beta\; dQ^2\; dx_{I\!P} dt} = \frac{2\pi\alpha^2}{\beta Q^4}\; Y_+ F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t) - \frac{y^2}{Y_+} F_L^{D(4)}$$

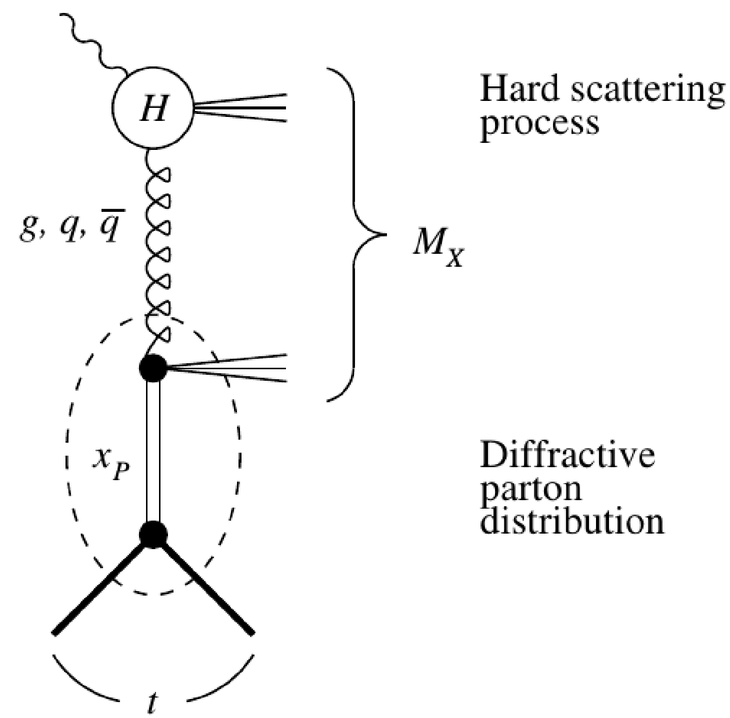
Leading-twist collinear factorization in DDIS

Diffractive structure function (integrated over t):

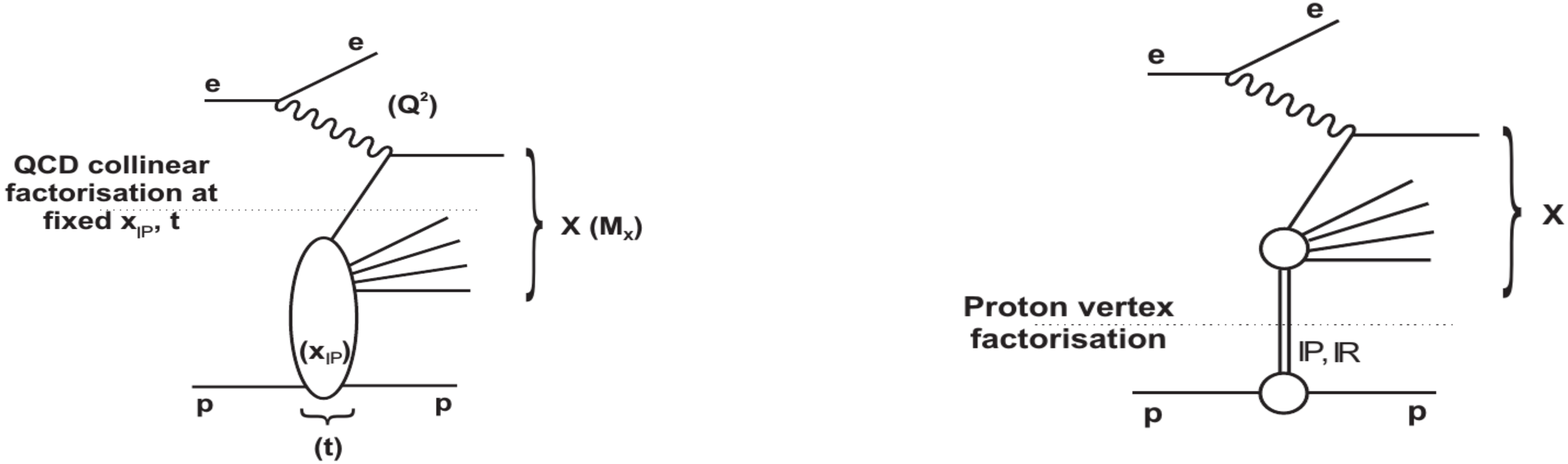
$$F_2^{\mathrm{D}(3)}(x_{\mathbb{P}}, \beta, Q^2) = \sum_{a=q,g} \beta \int_\beta^1 \frac{\mathrm{d}z}{z}\, C_{2,a}\left(\frac{\beta}{z}\right)\, f_{a/p}^{\mathrm{D}}(x_{\mathbb{P}}, z, \mu_F^2)$$

$$= \sum_q e_q^2\, \beta f_{q/p}^{\mathrm{D}}(x_{\mathbb{P}}, \beta, \mu_F^2) \quad \text{at LO.}$$

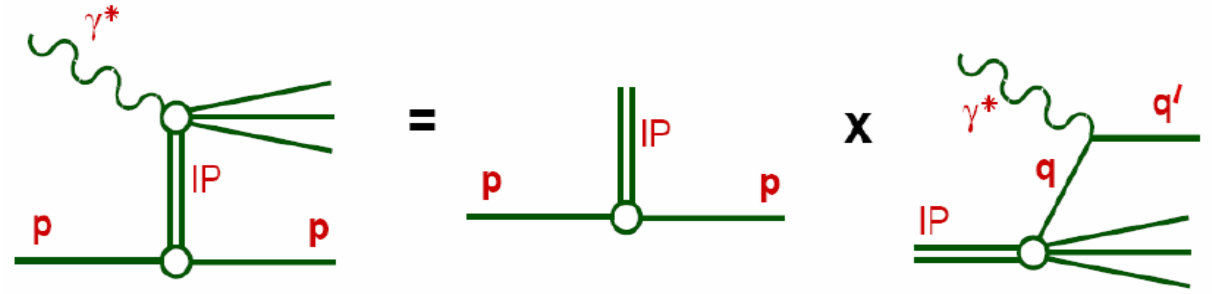
- $C_{2,a}$ are the same coeficiente functions as in inclusive DIS;
- Diffractive PDFs $f^{D}_{a/p}$ satisfy DGLAP evolution;
- Proven by J. Collins [hep-ph/9709499] to hold up to power-suppressed corrections.



Proton vertex factorization



- Proton vertex factorization (Ingelman, Schlein – 1985) separate x_{IP} from the (β, Q^2) dependences:

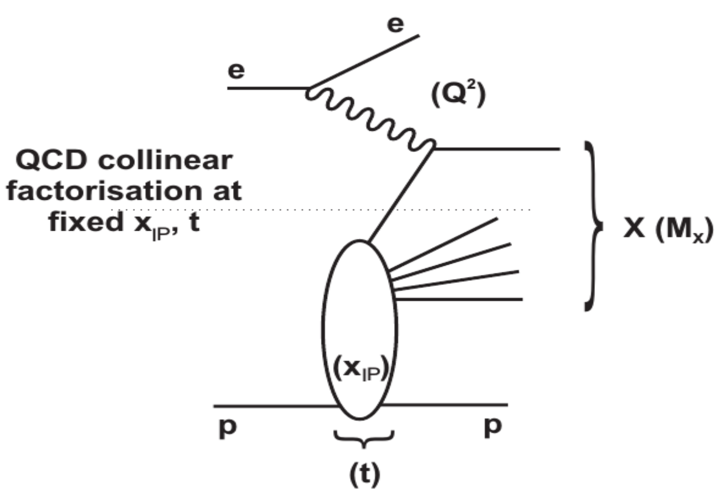


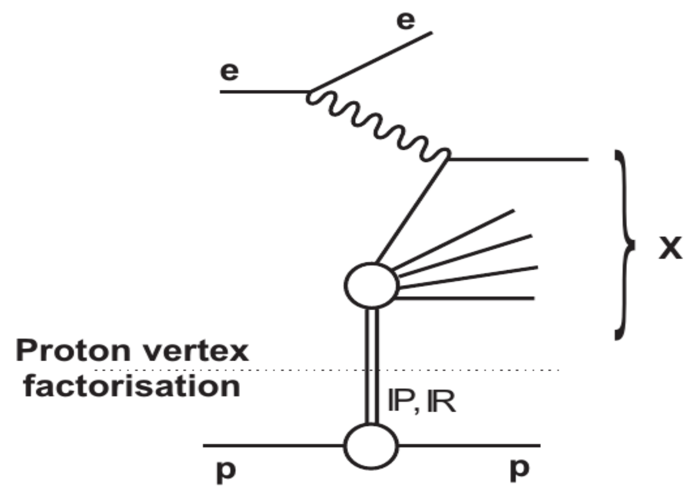
$$f^D_{a/p}(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \cdot f_{a/IP}(\beta, Q^2)$$

Pomeron flux

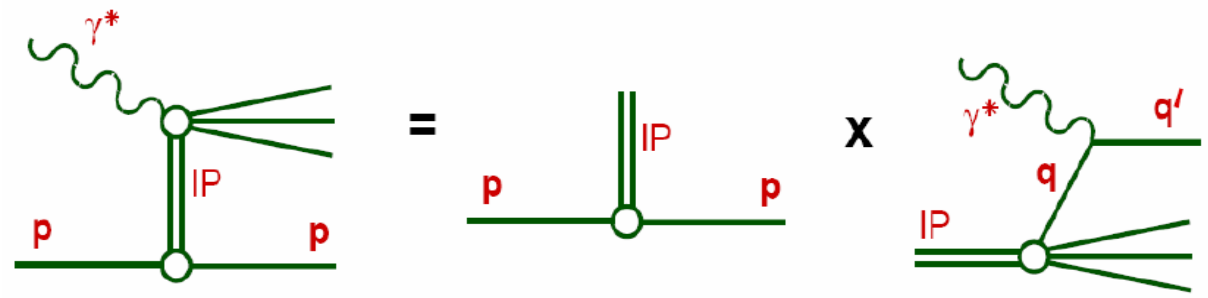
Probability for a hadron to radiate off a Pomeron

Proton vertex factorization





- Proton vertex factorization (Ingelman, Schlein – 1985) separate x_{IP} from the (β, Q^2) dependences:

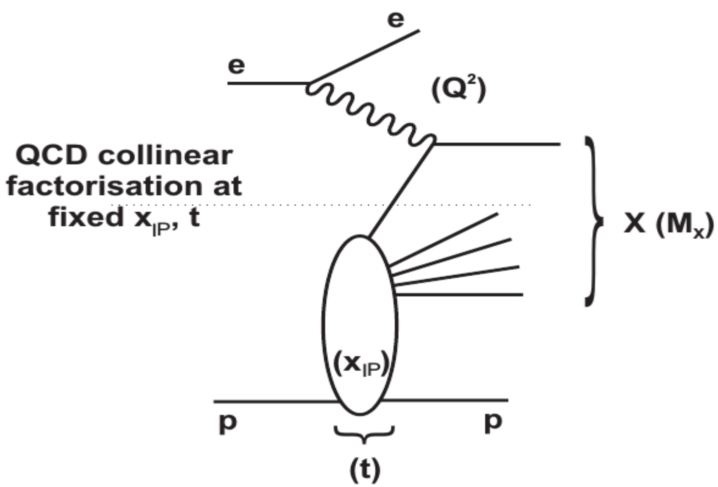


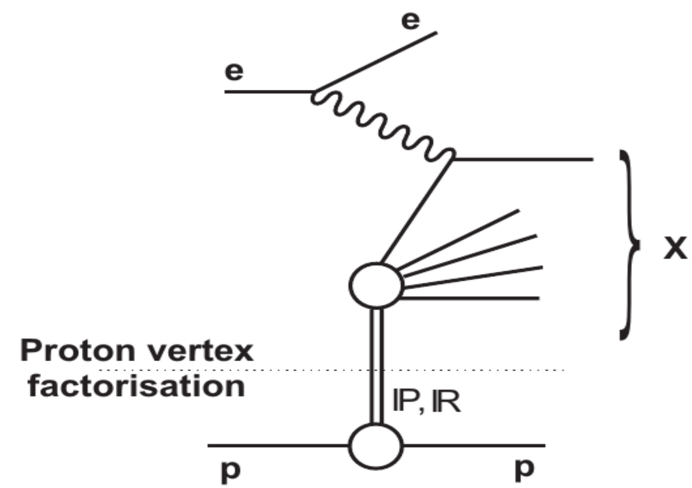
$$f^D_{a/p}(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \cdot f_{a/IP}(\beta, Q^2)$$

Pomeron flux

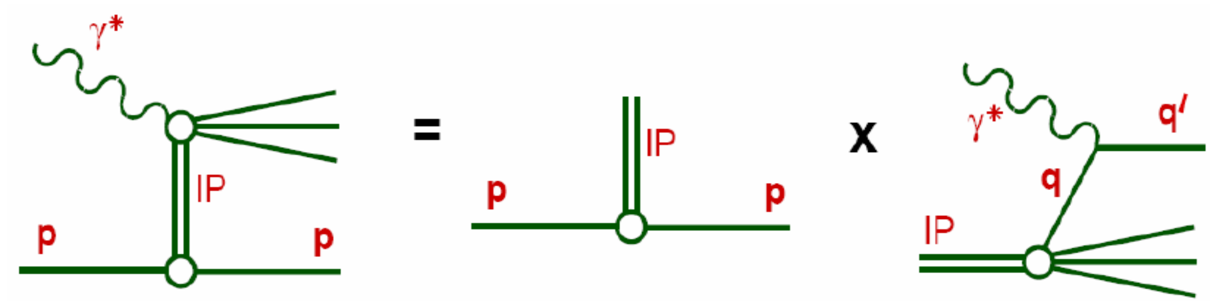
Pomeron PDFs

Proton vertex factorization





- Proton vertex factorization (Ingelman, Schlein – 1985) separate x_{IP} from the (β, Q^2) dependences:



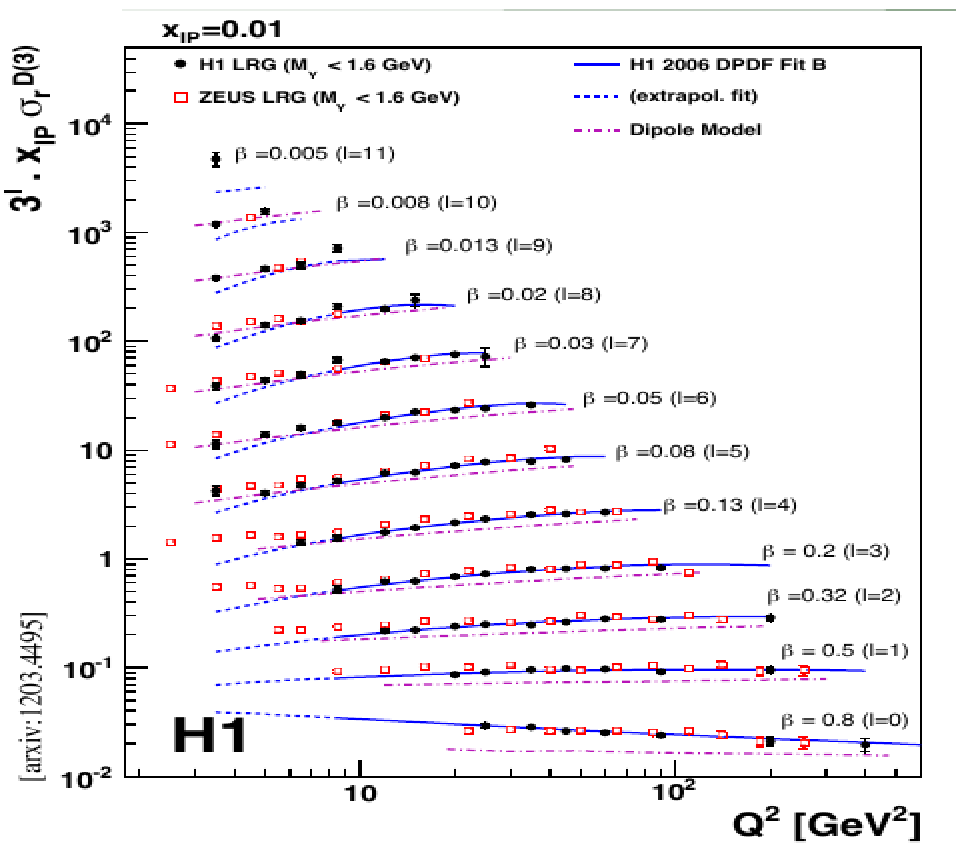
$$f^D_{a/p}(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \cdot f_{a/IP}(\beta, Q^2)$$

Pomeron flux

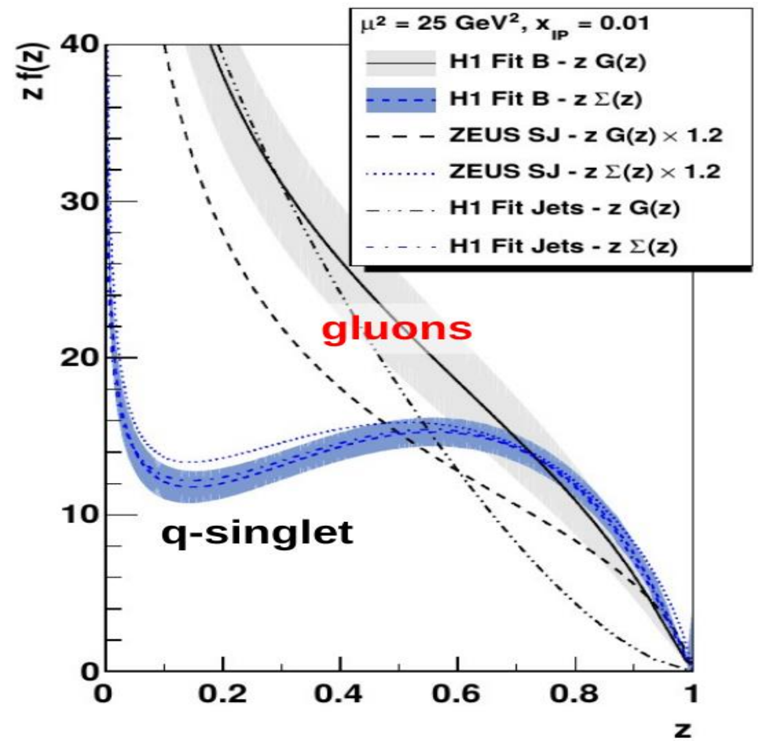
Pomeron PDFs

No QCD basis, consistent with data

Pomeron PDFs

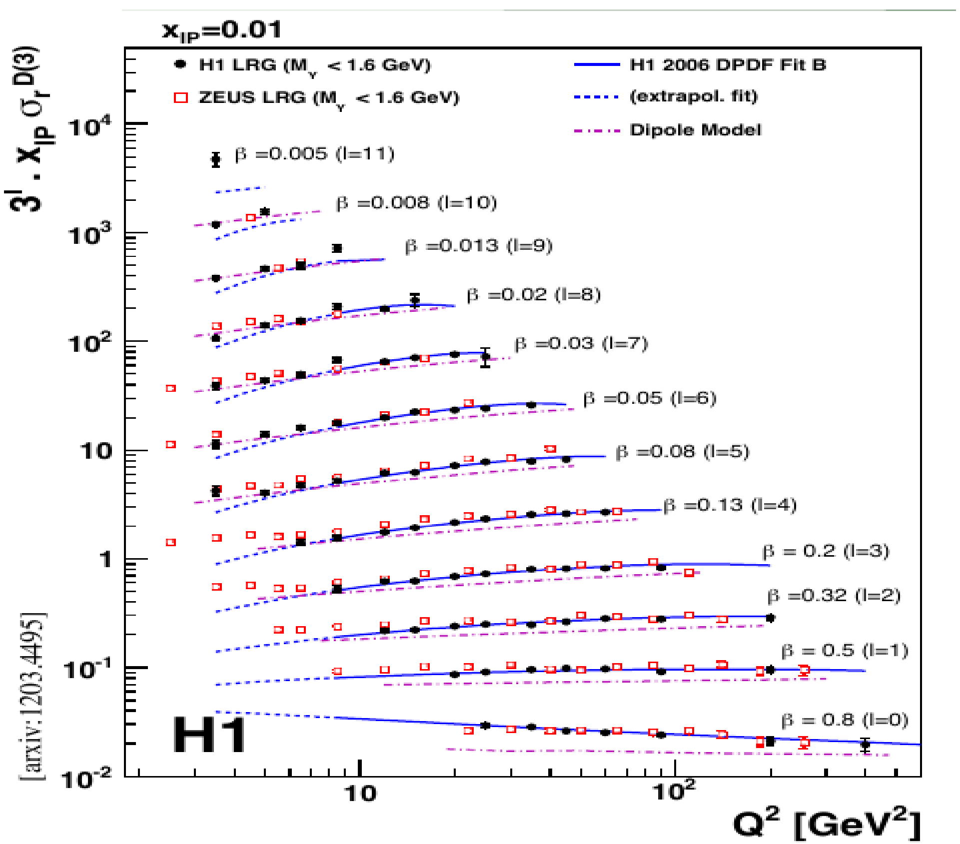


DGLAP
Evolution
Equations

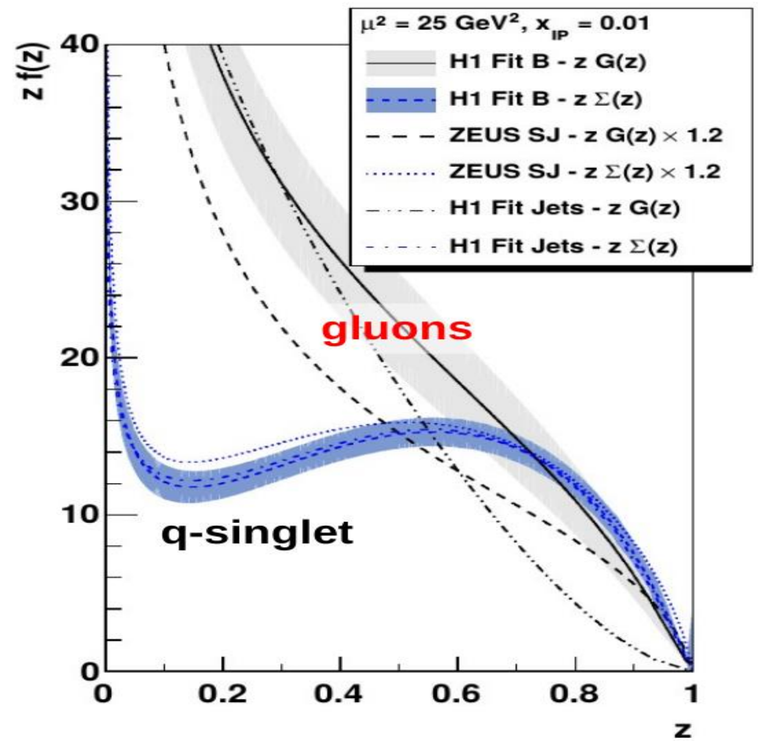


- Gluon dominates the Pomeron structure (60% of the exchanged momentum carried by gluons) ;
- Gluons weakly constrained in the high z region;

Pomeron PDFs

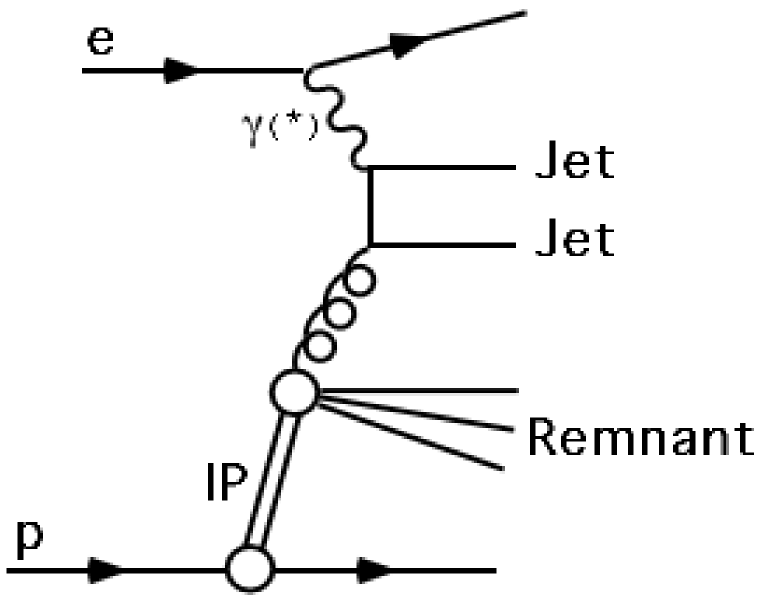


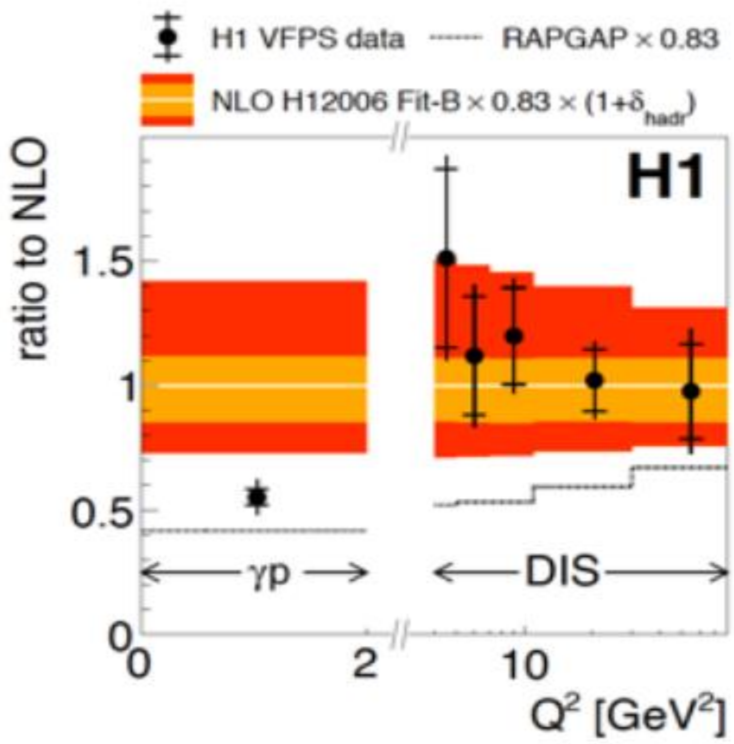
DGLAP
Evolution
Equations



- Gluon dominates the Pomeron structure (60% of the exchanged momentum carried by gluons) ;
- Gluons weakly constrained in the high z region;
- Cross check: Use the resulting DPDFs as input in the calculations of other diffractive observables measured at HERA and hadronic colliders (Tevatron and LHC)

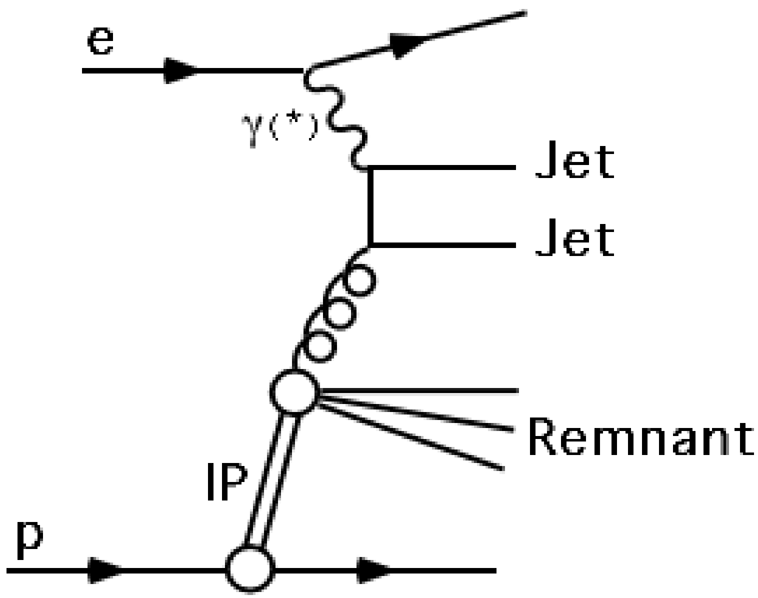
Diffractive Di-jet Production at the HERA

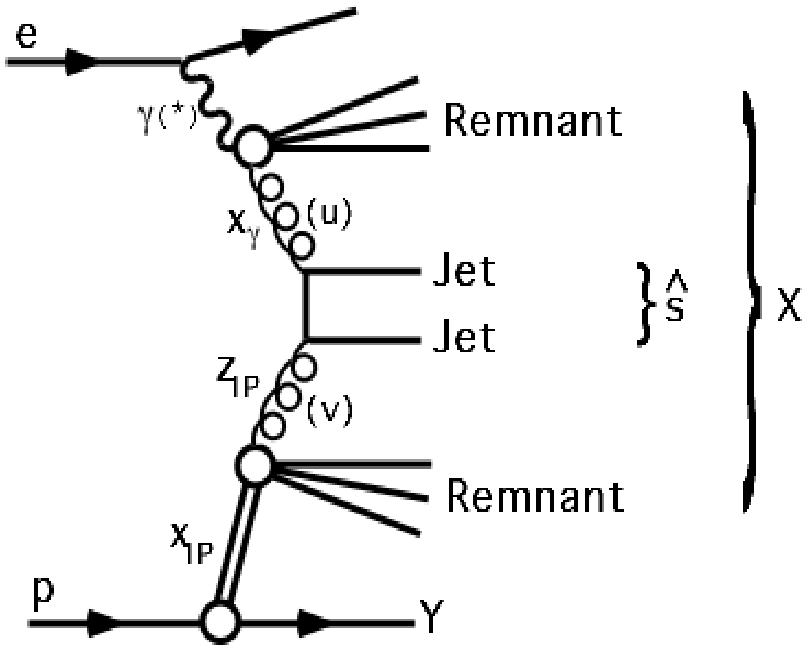




- Diffractive Di-jet production is sensitive to the gluon DPDF;
- Factorization is OK in DIS but not at $Q^2 = 0$!

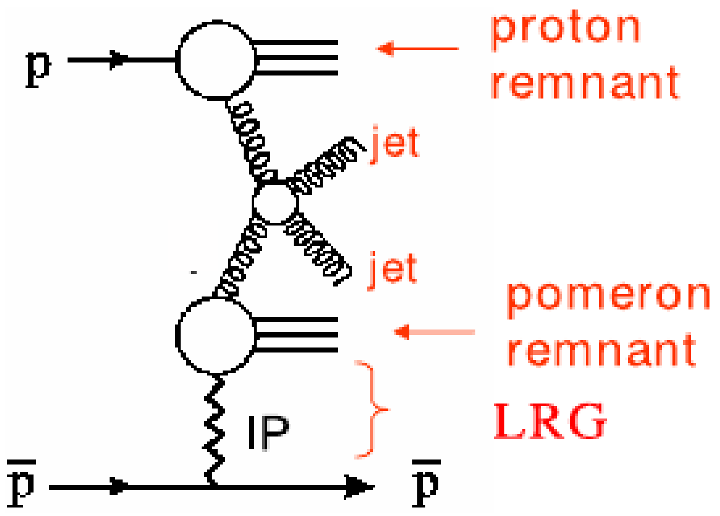
Diffractive Di-jet Production at the HERA





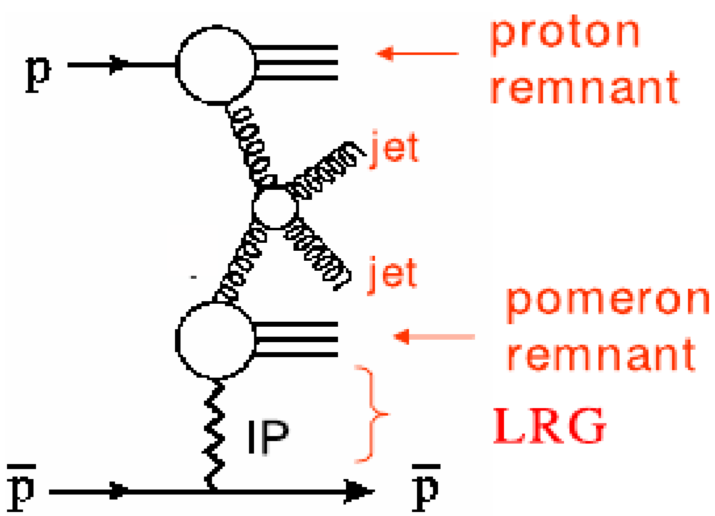
- Diffractive Di-jet production is sensitive to the gluon DPDF;
- Factorization is OK in DIS but not at $Q^2 = 0$!
- Contribution associated to the resolved structure of the photon is important at low Q^2.

Diffractive Di-jet Production at the Tevatron

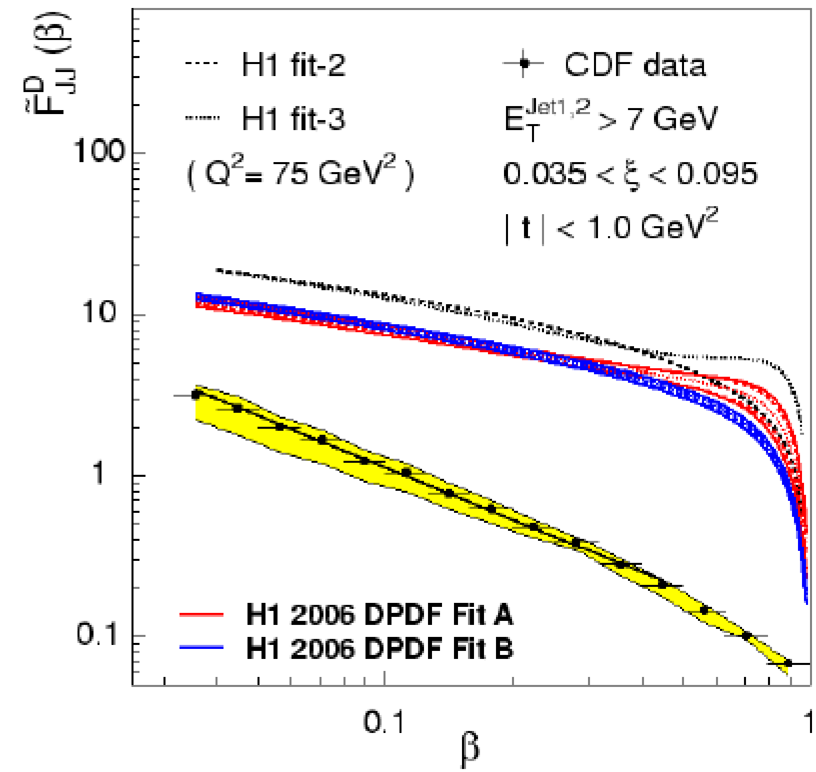


$$\sigma(\bar{p}p \to \bar{p}X) \approx F_{jj} \otimes F_{jj}^{D} \otimes \hat{\sigma}(ab \to jj)$$

Diffractive Di-jet Production at the Tevatron

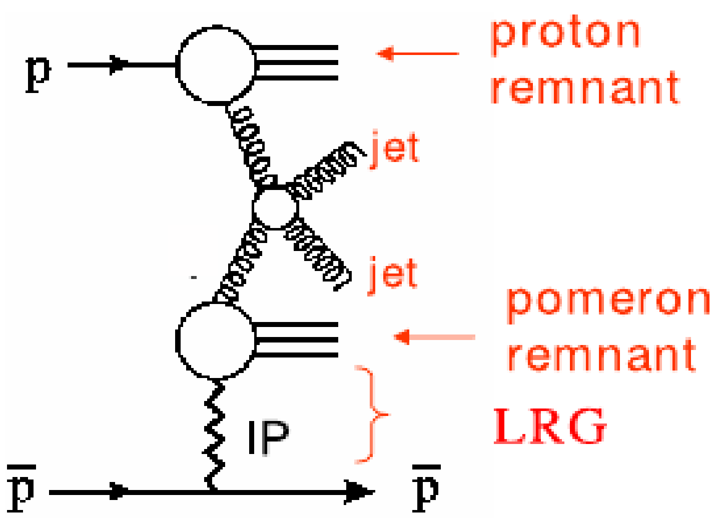


$$\sigma(\bar{p}p \to \bar{p}X) \approx F_{jj} \otimes F_{jj}^{D} \otimes \hat{\sigma}(ab \to jj)$$

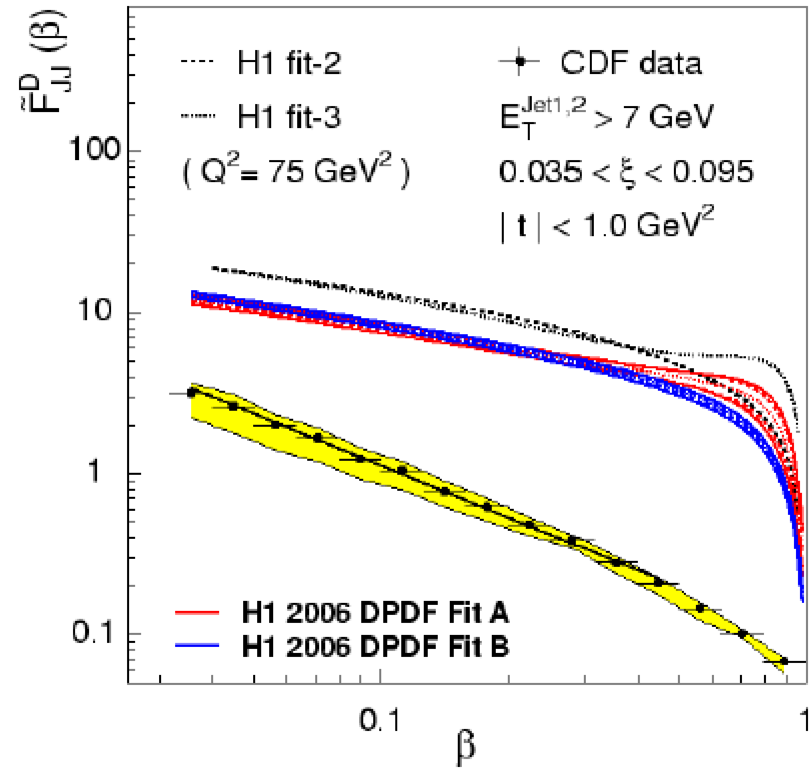


- Predictions obtained using the HERA DPDFs fail by factor 5 - 7;
- **Note**: QCD factorization has not been proven for hadron – hadron collisions.

Diffractive Di-jet Production at the Tevatron



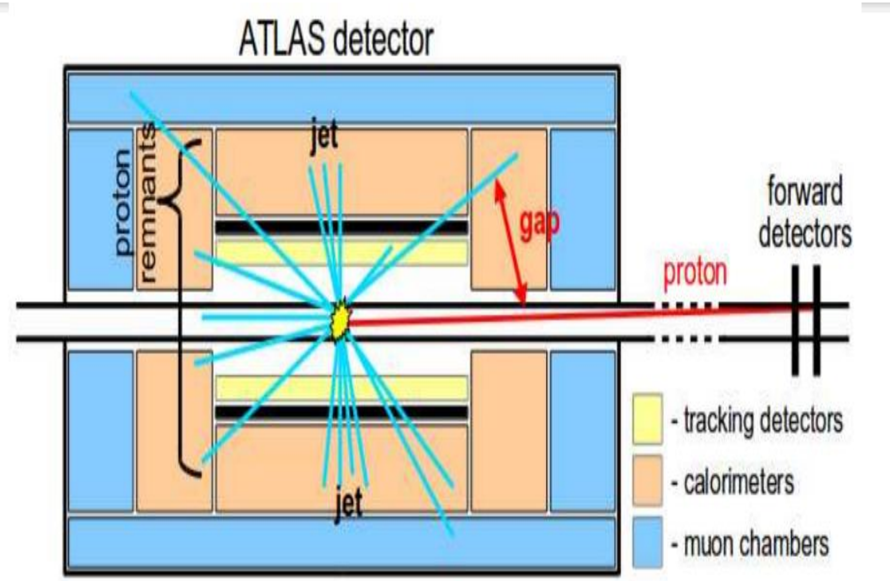
$$\sigma(\bar{p}p \rightarrow \bar{p}X) \approx F_{jj} \otimes F_{jj}^{D} \otimes \hat{\sigma}(ab \rightarrow jj)$$

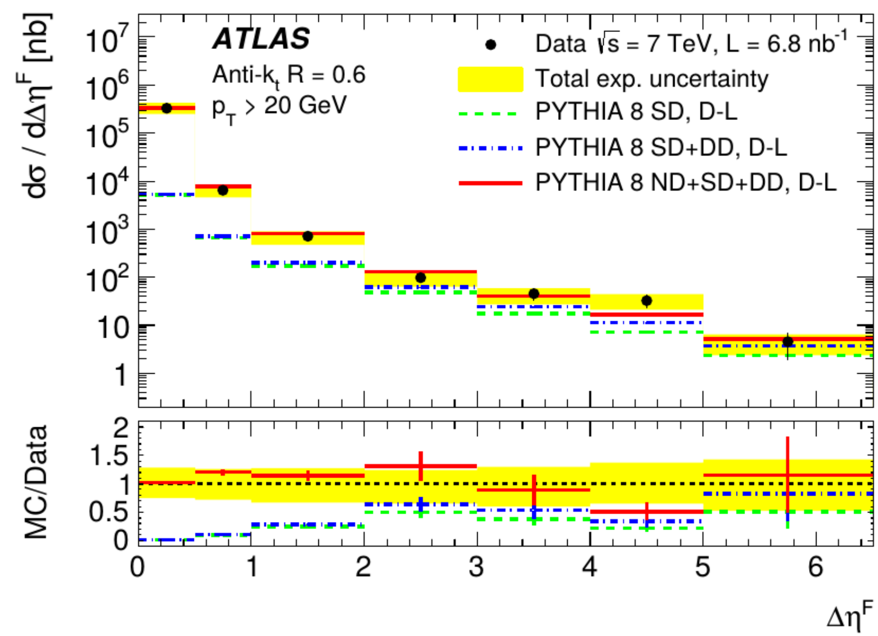


- Predictions obtained using the HERA DPDFs fail by factor 5 - 7;
- **Note**: QCD factorization has not been proven for hadron – hadron collisions.
- Final state interaction between proton remnant and antiproton possible.

  Gap survival probability is not equal to one !

Diffractive Di-jet Production at the LHC

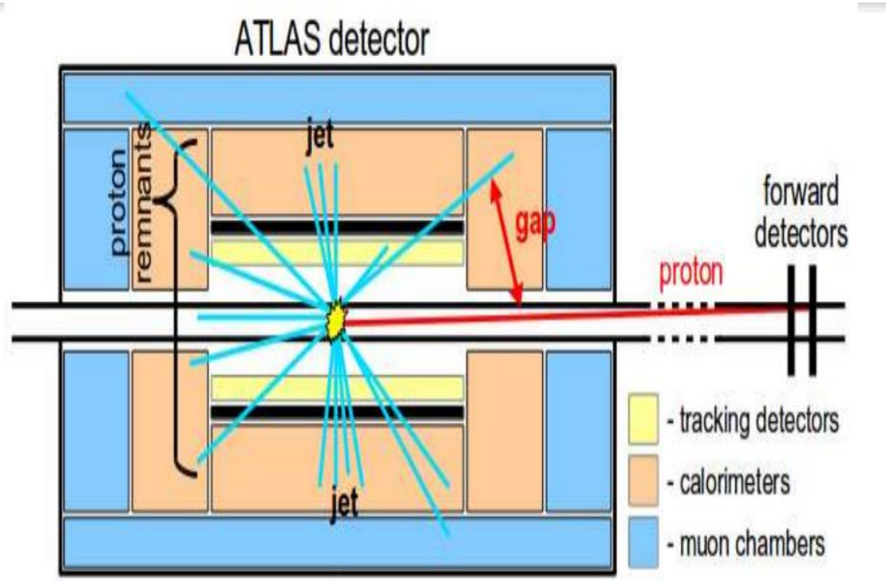


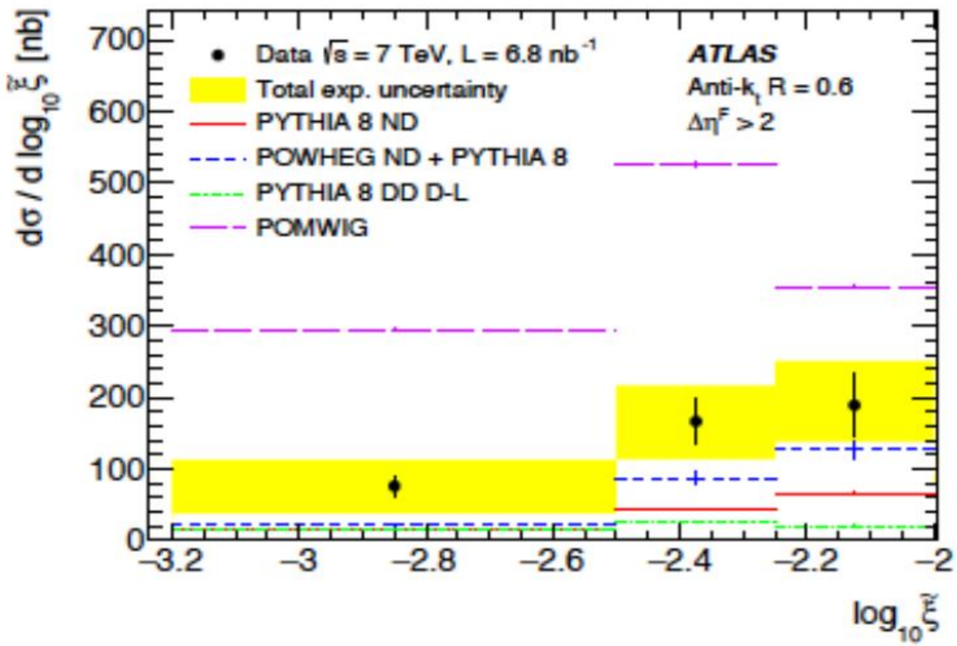


ATLAS, PLB 754 (2016) 214

- Diffractive component is required for more complete description of data;

Diffractive Di-jet Production at the LHC

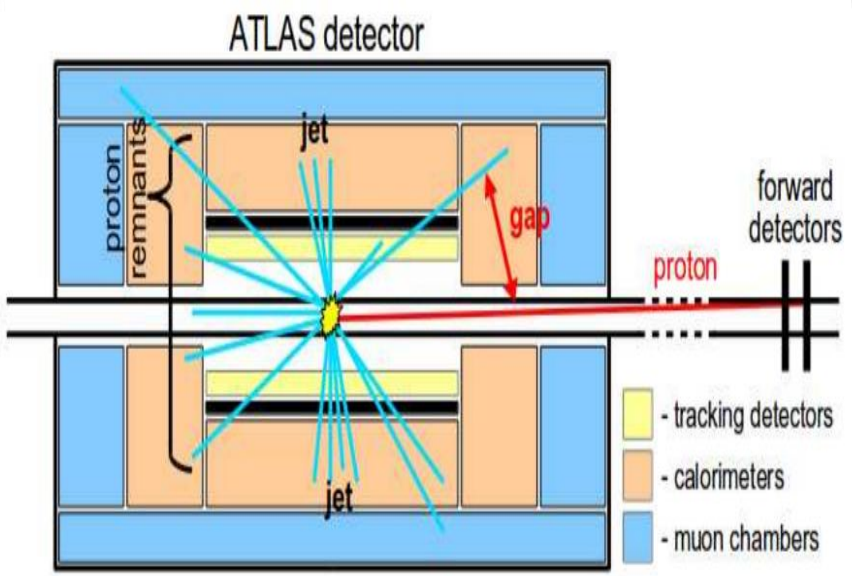


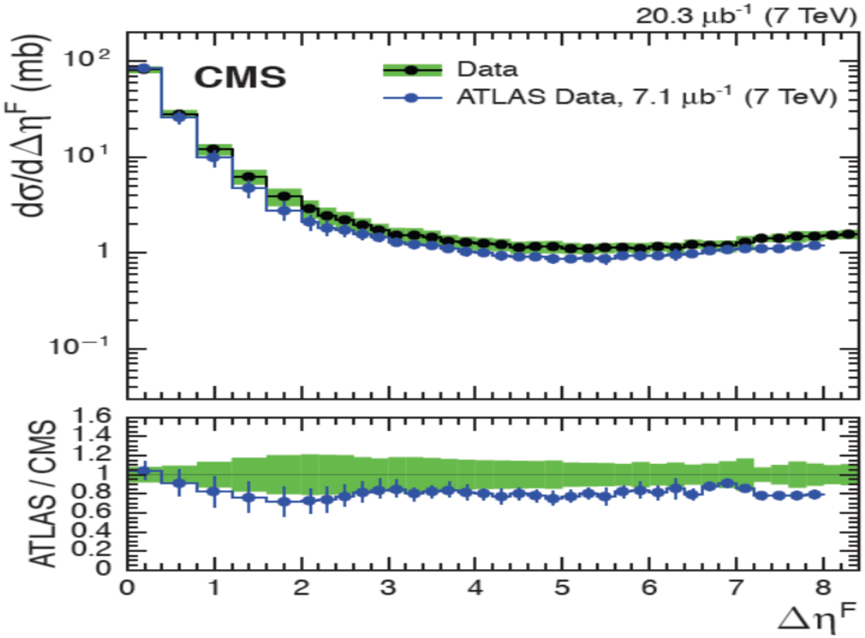


ATLAS, PLB 754 (2016) 214

- Diffractive component is required for more complete description of data;
- Rapidity gap survival factor (Probability of non – emission by other soft processes into gap): **S^2 = 0.16 ± 0.04 (stat) ± 0.08 (exp. Syst.)**

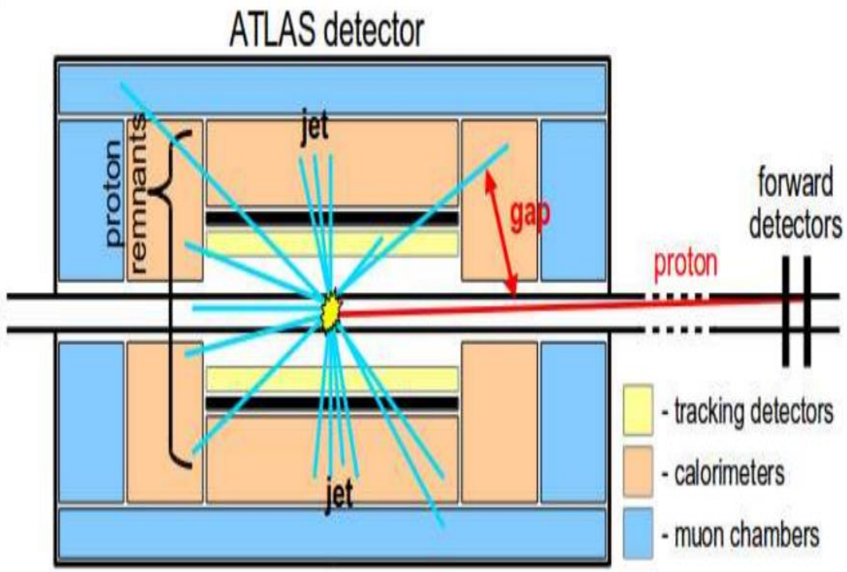
Diffractive Di-jet Production at the LHC

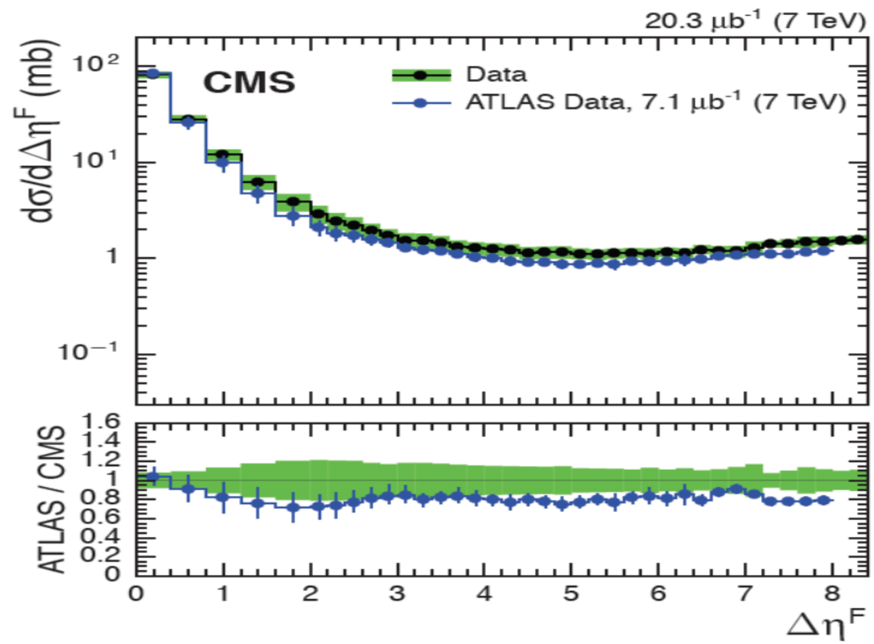




- Diffractive component is required for more complete description of data;
- Rapidity gap survival factor (Probability of non – emission by other soft processes into gap): **S^2 = 0.16 ± 0.04 (stat) ± 0.08 (exp. Syst.)**

Diffractive Di-jet Production at the LHC





- ➢ Diffractive component is required for more complete description of data;
- ➢ Rapidity gap survival factor (Probability of non – emission by other soft processes into gap): **S^2 = 0.16 ± 0.04 (stat) ± 0.08 (exp. Syst.)**

- ❑ The inclusion of **S^2** is fundamental to describe the experimental data from hard diffractive processes.
- ❖ Associated to soft reinteractions -> Nonperturbative physics !
- ❖ Main theoretical uncertainty in hard diffraction ! Universal? Depends on $s^{1/2}$, η ...?

Summary

- Diffraction offer us a unique opportunity to study the hard and soft regimes of QCD and its interplay in unusual settings.
- Such studies are difficult:
  - ✓ On the experimental side because the complexity of the environment makes it difficult to separate the diffractive events;
  - ✓ On the theoretical side, the subject can become highly technical, involving sophisticated formalisms (e.g. Regge theory x QCD at high energies) whose mutual relations are not always visible.
- However, important experimental and theoretical progress has been achieved in the recent years and much more is expected in the coming years.

Summary

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

September 3 2015

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

K. Akiba[21], M. Akbiyik[1], M. Albrow[2], M. Arneodo[3,4], V. Avati[5,6], J. Baechler[6], O. Villalobos Baillie[87], P. Bartalini[7], J. Bartels[8], S. Baur[1], C. Baus[1], W. Beaumont[9], U. Behrens[10], D. Berge[11], M. Berretti[6,12], E. Bossini[12], R. Boussarie[13], S. Brodsky[14], M. Broz[15], M. Bruschi[16], P. Bussey[17], W. Byczynski[81], J. C. Cabanillas Noris[18], E. Calvo Villar[19], A. Campbell[10], F. Caporale[22], W. Carvalho[21], G. Chachamis[22], E. Chapon[23], C. Cheshkov[24], J. Chwastowski[25], R. Ciesielski[26], D. Chinellato[83], A. Cisek[25], V. Coco[6], P. Collins[6], J. G. Contreras[15], B. Cox[27], D. de Jesus Damiao[21], P. Davis[28], M. Deile[6], D. D'Enterria[6], D. Druzhkin[29,6], B. Ducloué[30,31], R. Dumps[6], R. Dzhelyadin[82] P. Dziurdzia[6], M. Eliachevitch[1], P. Fassnacht [6] F. Ferro[32], S. Fichet[33], D. Figueiredo[21], B. Field[34], D. Finogeev[35], R. Fiore[29,36], J. Forshaw[27], A. Gago Medina[19], M. Gallinaro[37], A. Granik[82], G. von Gersdorff[33], S. Giani[6], K. Golec-Biernat[25,38], V. P. Goncalves[39], P. Göttlicher[10], K. Goulianos[26], J.-Y. Grosslord[24], L. A. Harland-Lang[40], H. Van Haevermaet[9], M. Hentschinski[41], R. Engel [1], G. Herrera Corral[42], J. Hollar[37], L. Huertas[21], D. Johnson[6], I. Katkov[1], O. Kepka[43], M. Khakzad[44], L. Kheyn[45], V. Khachatryan[46], V. A. Khoze[47], S. Klein[48], M. van Klundert[9], F. Krauss[47], A. Kurepin[35], N. Kurepin[35], K. Kutak[49], E. Kuznetsova[1], G. Latino[12], P. Lebiedowicz[25], B. Lenzi[6], E. Lewandowska[25], S. Liu[28], A. Luszczak[25,38], M. Luszczak[25], J. D. Madrigal[50], M. Mangano[6], Z. Marcone[34], C. Marquet[51], A. D. Martin[47], T. Martin[52], M. I. Martinez Hernandez[53], C. Martins[21], C. Mayer[25], R. Mc Nulty[54], P. Van Mechelen[7], R. Macula[25], E. Melo da Costa[21], T. Mertzimekis[55], C. Mesropian[26], M. Mieskolainen[31], N. Minafra[6,56], I. L. Monzon[18], L. Mundim [21], B. Murdaca[20,36], M. Murray[57], H. Niewiadowski[58], J. Nystrand[59], E. G. de Oliveira[60], R. Orava[31], S. Ostapchenko[61], K. Osterberg[31], A. Panagiotou[55], A. Papa[20], R. Pasechnik[62], T. Peitzmann[63], L. A. Perez Moreno[53], T. Pierog[1], J. Pinfold[28], M. Poghosyan[64], M. E. Pol[65], W. Prado[21], V. Popov[66], M. Rangel[67], A. Reshetin[35], J.-P. Revol[68], M. Rijssenbeek[34], M. Rodriguez [5]3, B. Roland[10], C. Royon[25,43,57], M. Ruspa[3,4], M. Ryskin[47,69], A. Sabio Vera[22], G. Safronov[66], T. Sako[70], H. Schindler[6], D. Salek[11], K. Safarik [6], M. Saimpert[71], A. Santoro[21], R. Schicker[73], J. Seger[64], S. Sen[73], A. Shabanov[35], W. Schafer[25], G. Gil Da Silveira[39], P. Skands[74], R. Soluk[28], A. van Spilbeeck[9], R. Staszewski[25], S. Stevenson[75], J. Stirling[86], M. Strikman[76], A. Szczurek[25,38] L. Szymanowski[77], J.D. Tapia Takaki,[57] M. Tasevsky[43], K. Taesoo[78], C. Thomas[75], S. R. Torres[18], A. Tricomi[79], M. Trzebinski[25], D. Tsybychev[34], N. Turini[12], R. Ulrich[1], E. Usenko[35], J. Varela[37], M. Lo Vetere[80], A. Villatoro Tello[53], A. Vilela Pereira[21], D. Volyanskyy [84], S. Wallon[13,85], G. Wilkinson[75], H. Wöhrmann[1]. K. C. Zapp[6], Y. Zoccarato[24].

Journal of Physics G
(in press)

Summary

- ❑ Diffraction offer us a unique opportunity to study the hard and soft regimes of QCD and its interplay in unusual settings.
- ❑ Such studies are difficult:
  - ✓ On the experimental side because the complexity of the environment makes it difficult to separate the diffractive events;
  - ✓ On the theoretical side, the subject can become highly technical, involving sophisticated formalisms (e.g. Regge theory x QCD at high energies) whose mutual relations are not always visible.
- ❑ However, important experimental and theoretical progress has been achieved in the recent years and much more is expected in the coming years.

Thank you for your attention !

Extras

Diffraction in Hadronic Collisions: Definitions

y - rapidity

η - pseudorapidity

$y = 1/2 \ln((E+p_z)/E-p_z))$

$\eta \equiv y\big|_{m=0} = -\ln\tan(\vartheta/2)$

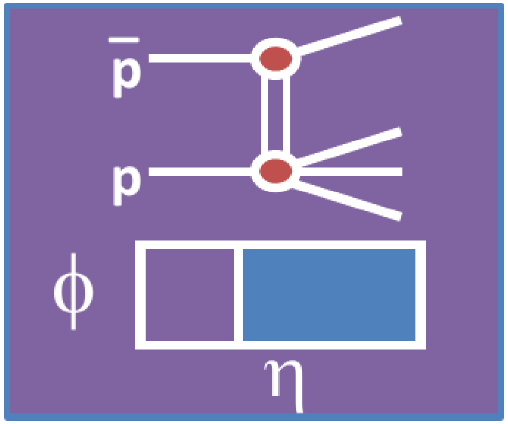
t - four-momentum transfer squared

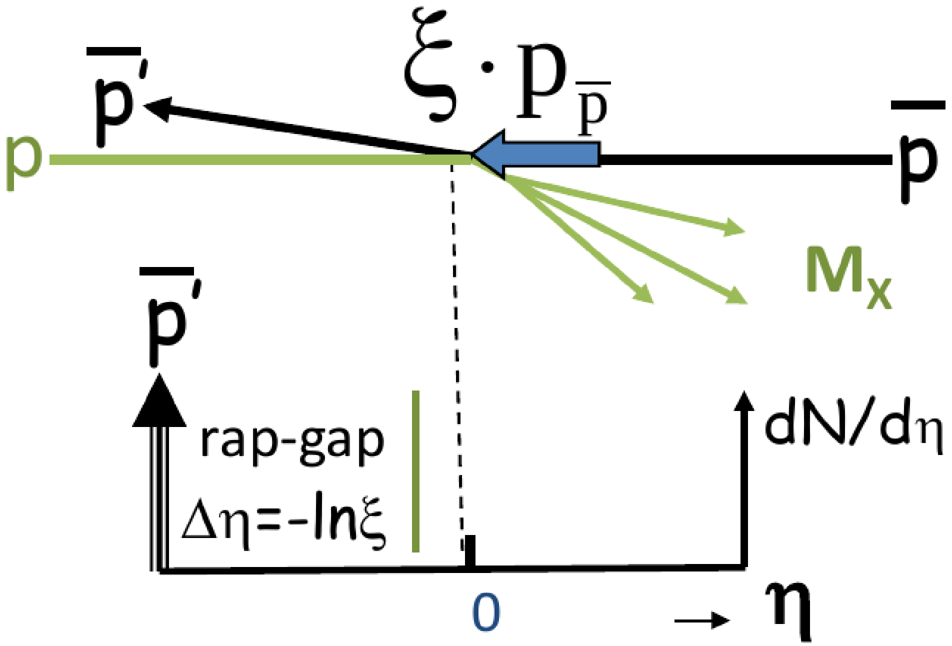
ξ - fractional momentum loss of pbar

M_X - mass of diffractive system X

$\xi = M_X^2/s$

$\Delta\eta \approx \ln(s/M_X^2)$

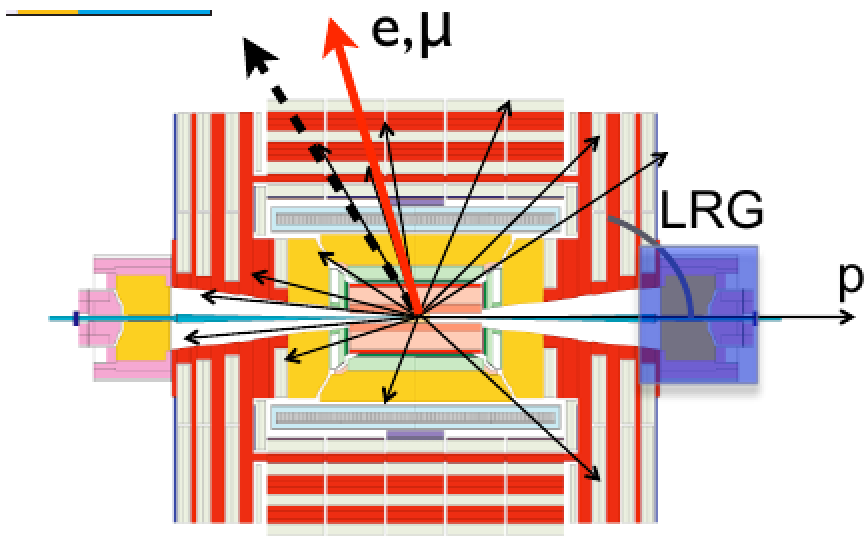


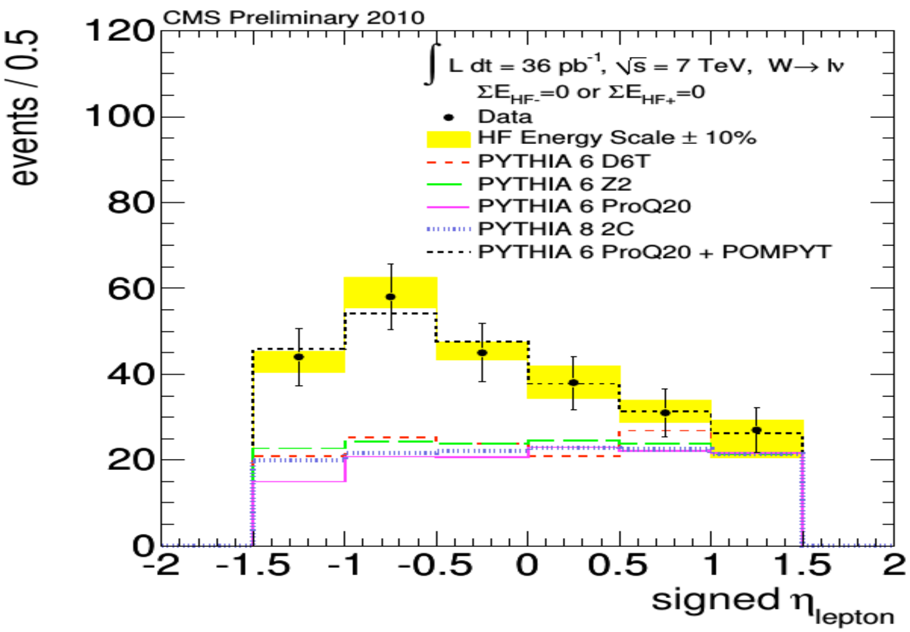


Hard Diffraction at the LHC

- ❑ Hard processes, calculable in perturbative QCD
- ❑ Measure proton structure, QCD at high parton densities, Discovery physics
- ❑ Some few examples:

❖ W, Z production





- ➢ Flat for non-diffractive, asymmetric for diffractive events;
- ➢ Evidence of diffractive W production in the data.

Exclusive Processes at the LHC:
Exclusive Diffraction and Photon Exchange Processes

- **Typical *pp* events:**

Many tracks + high pT particles

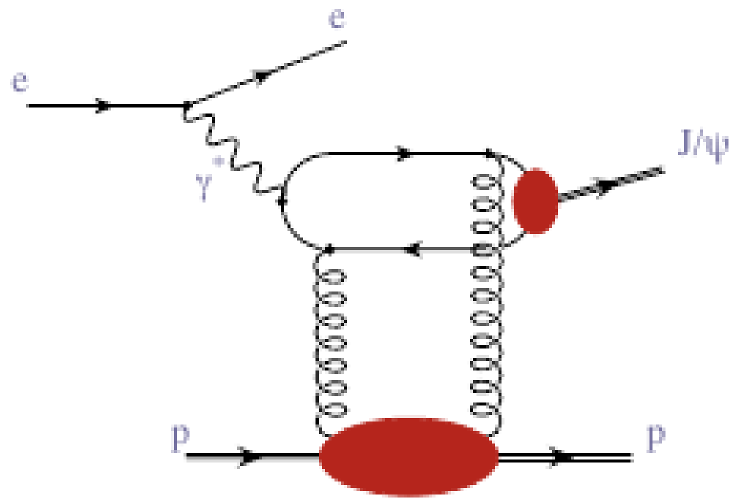
- **Exclusive events:**

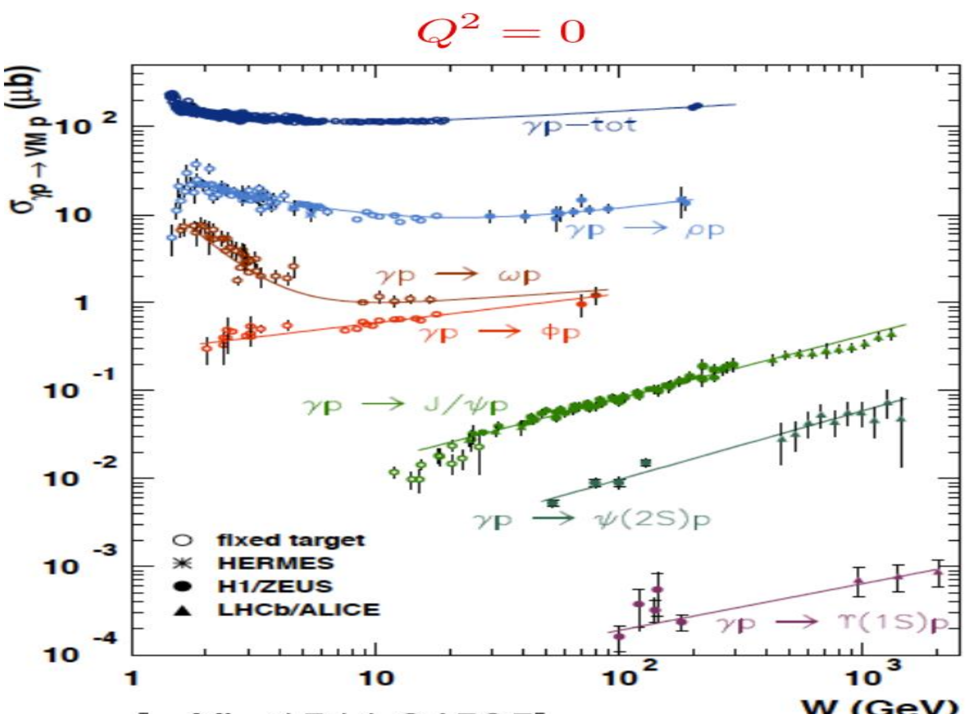
Few tracks + low pT particles

Photon - Hadron Interactions at the LHC

$$\gamma h \text{ Processes: } \sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$$

- ❑ Diffractive vector meson photoproduction at HERA

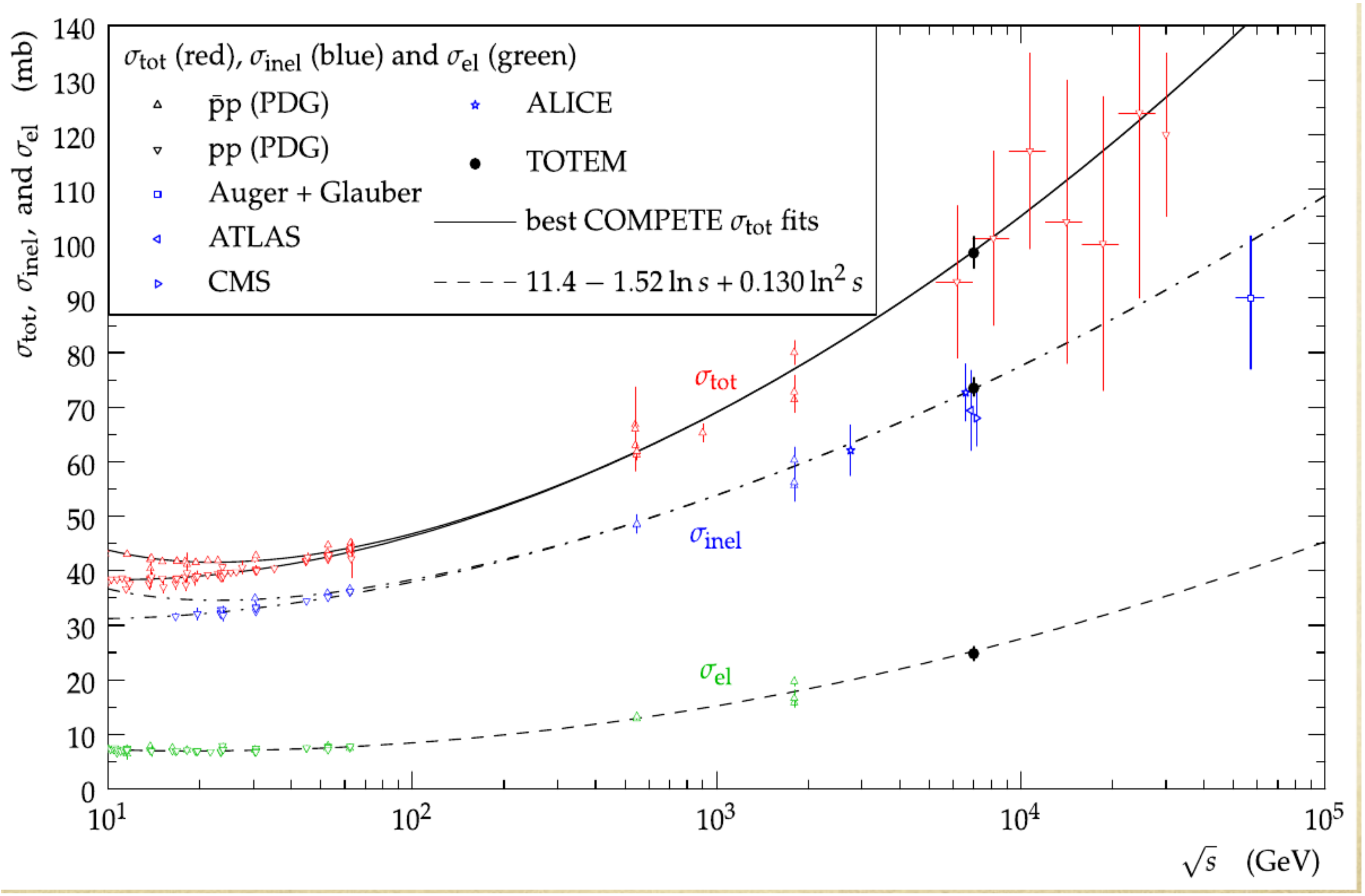




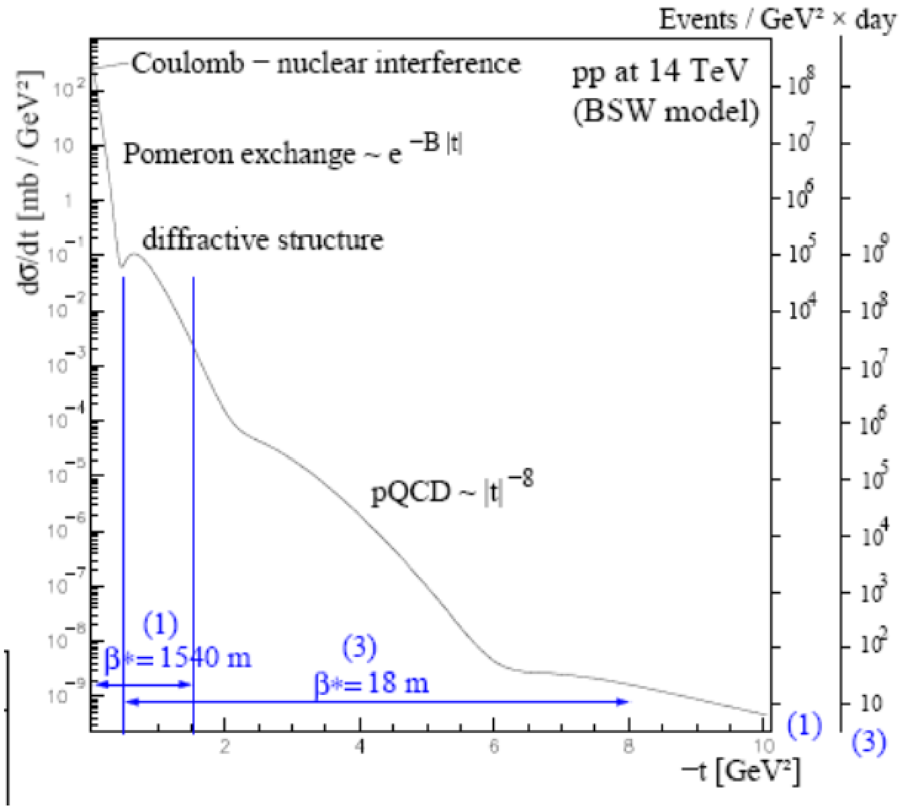
[arXiv:1511.04535]

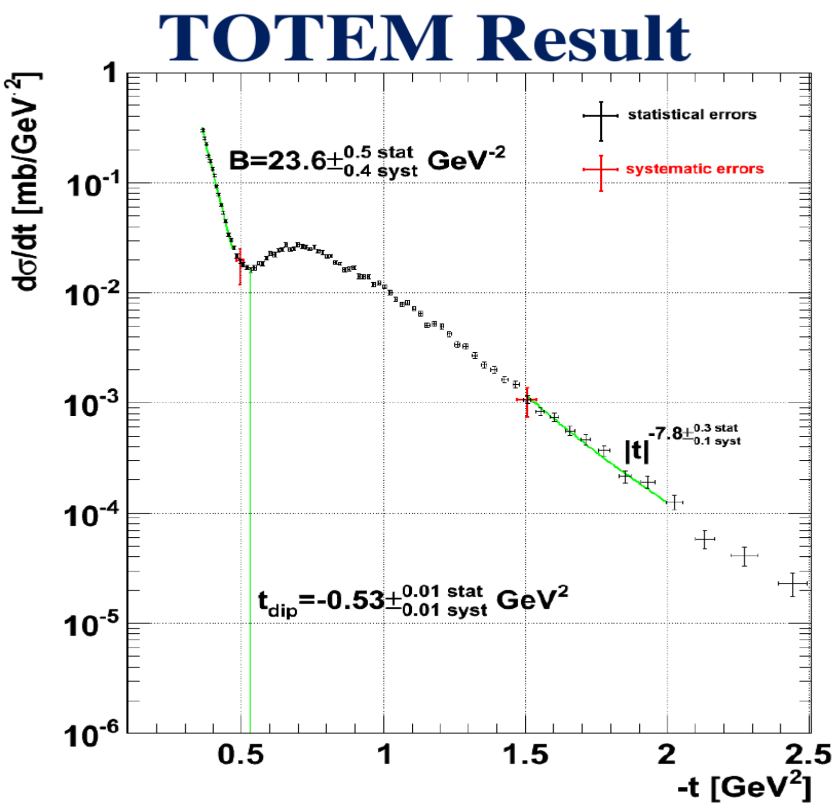
- ➢ Transition soft to hard regime with masses of the vector mesons.
- ➢ The photoproduction of heavy vector mesons can be calculated using perturbative QCD

Soft Diffraction: Selected results

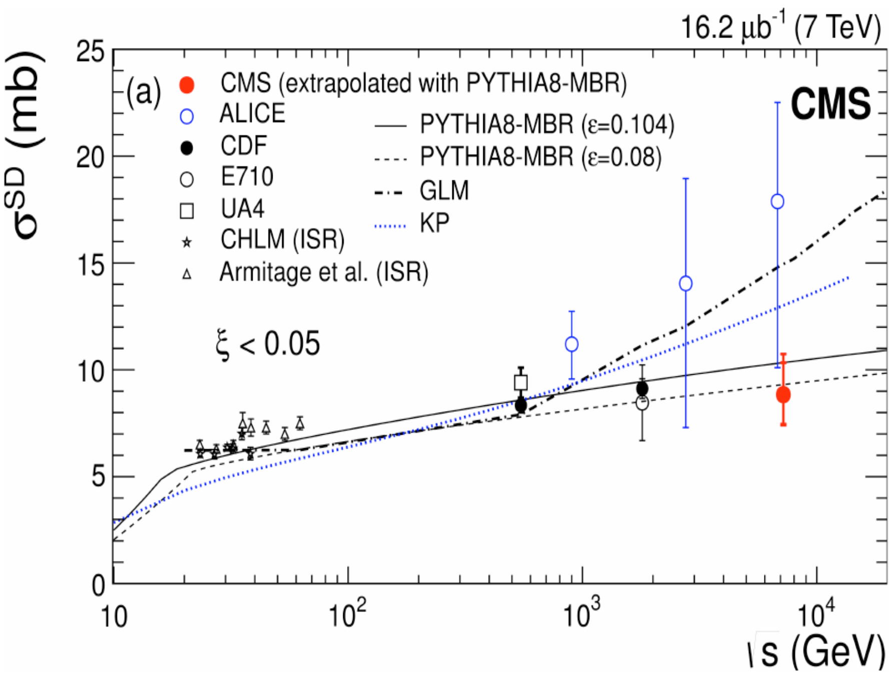


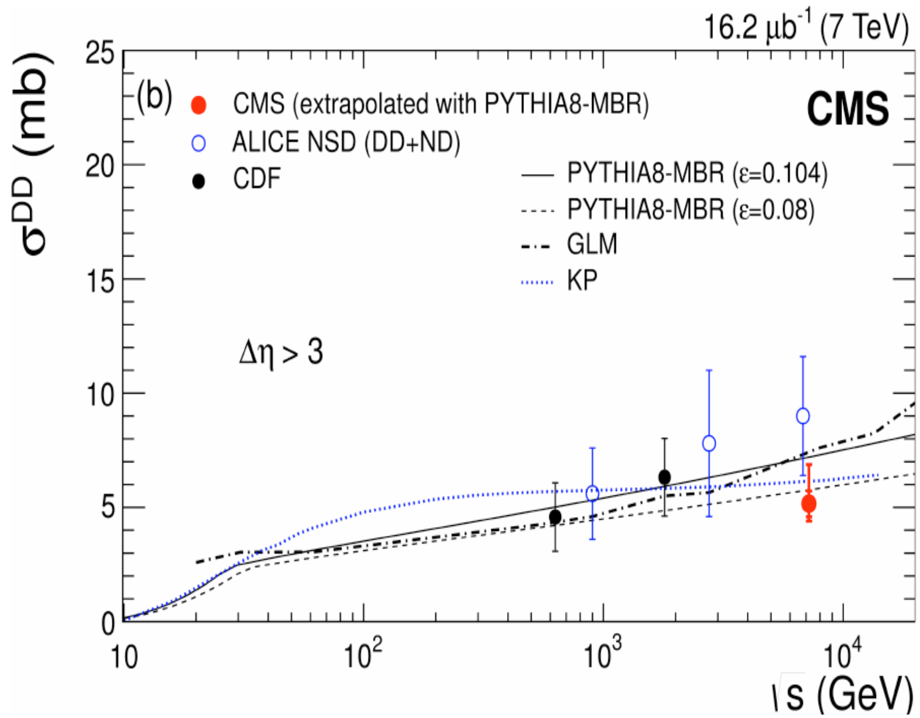
Soft Diffraction: Selected results





Soft Diffraction: Selected results

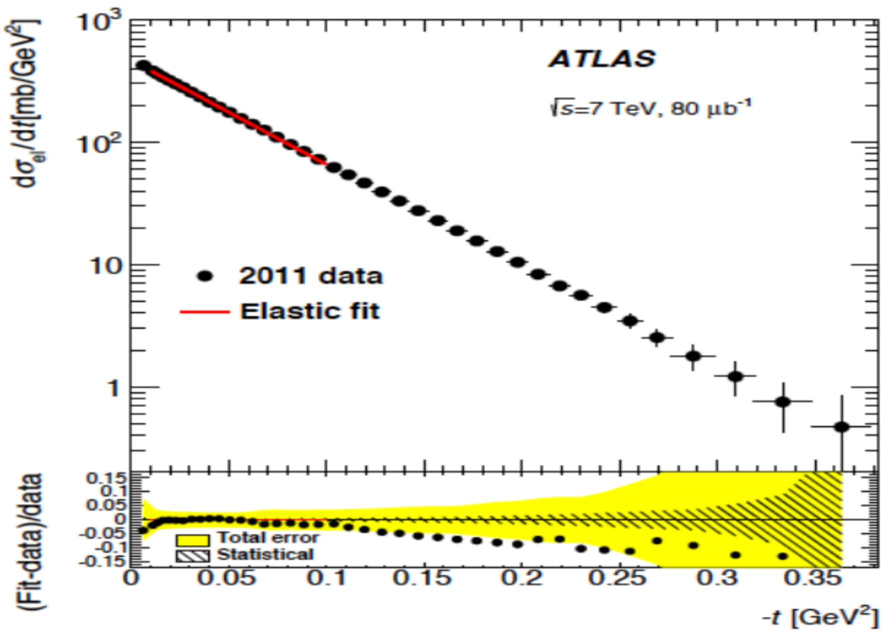




Soft Diffraction: Selected results

Motivation: Total and elastic cross sections

Measurements of the elastic cross section and its t-dependence (eg in ALFA) determine total cross section via optical theorem



Nucl Phys B889 (2014), 486

At fixed s: $$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

B=19.73±0.24 GeV^{-2} (ALFA)

$$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

[ρ~0.1 = phase of Coulomb-nuclear interference at t=0]

P. Newman, Low-x 2016