Diffraction at the LHC:
From the shadows to light
- Phenomenology -

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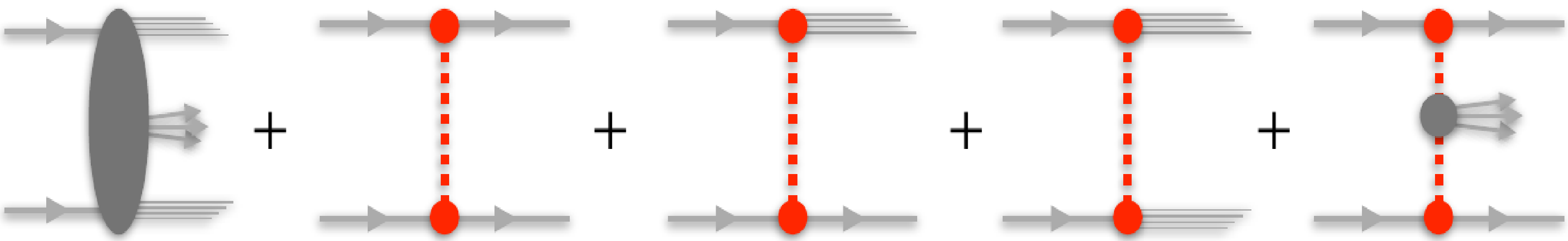
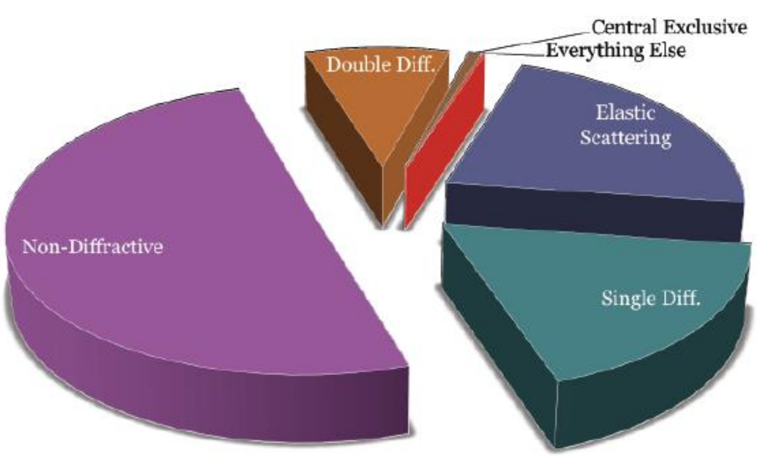
Proton - Proton Collisions

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

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



LHC is:

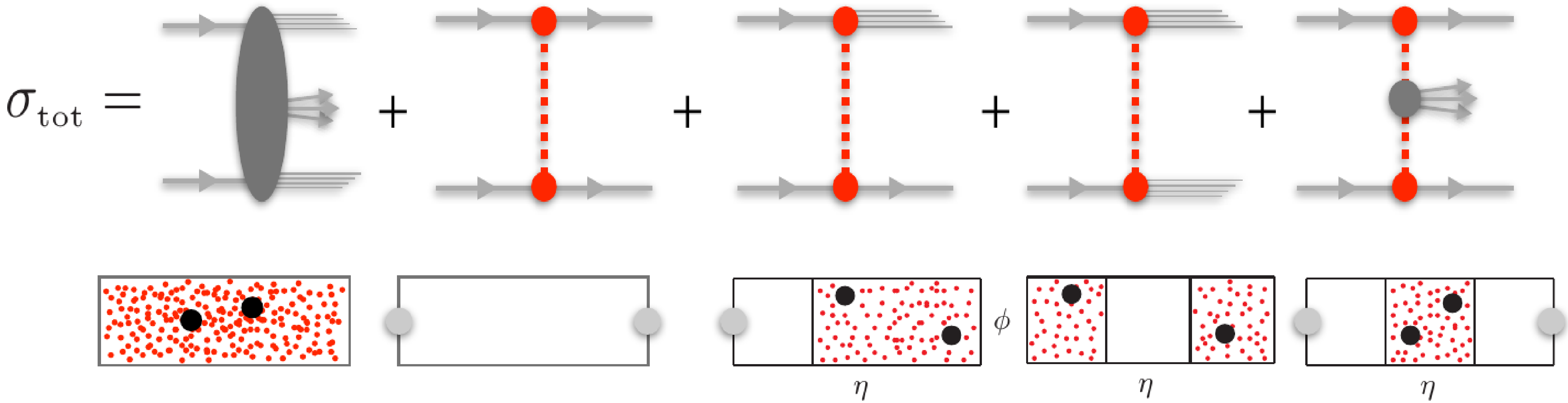
- Discovery Machine
- QCD machine (QCD is always present!)

Diffraction is:

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

Diffraction in Particle Physics

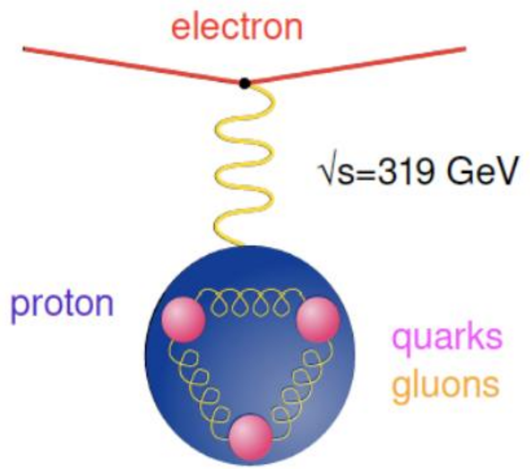
- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles

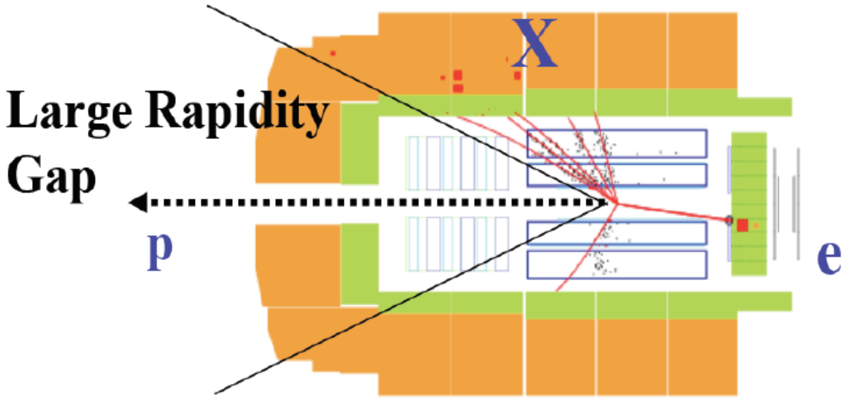


- Identified by the presence of an intact leading particle or a large rapidity gap (LRG).

Diffraction in 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).

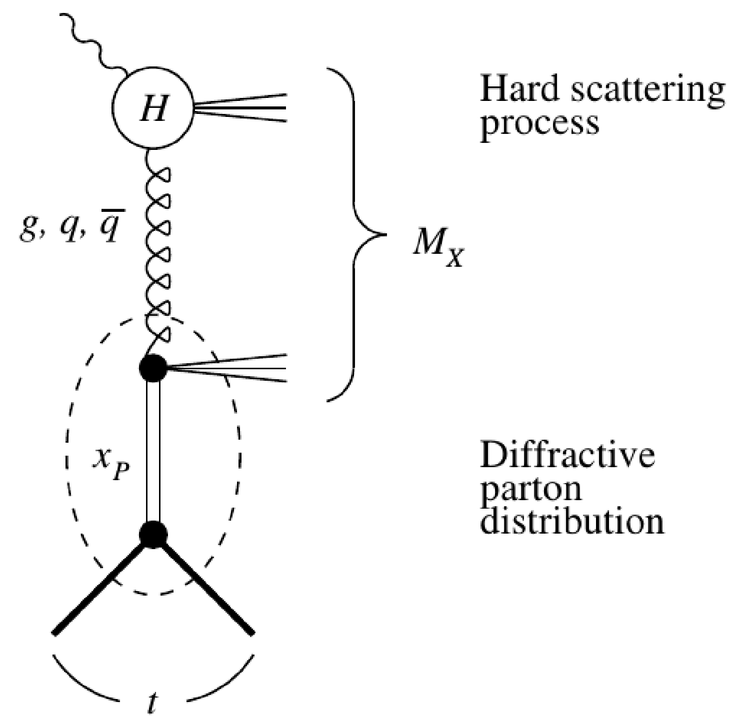
Leading-twist collinear factorization in DDIS

Diffractive structure function (integrated over t):

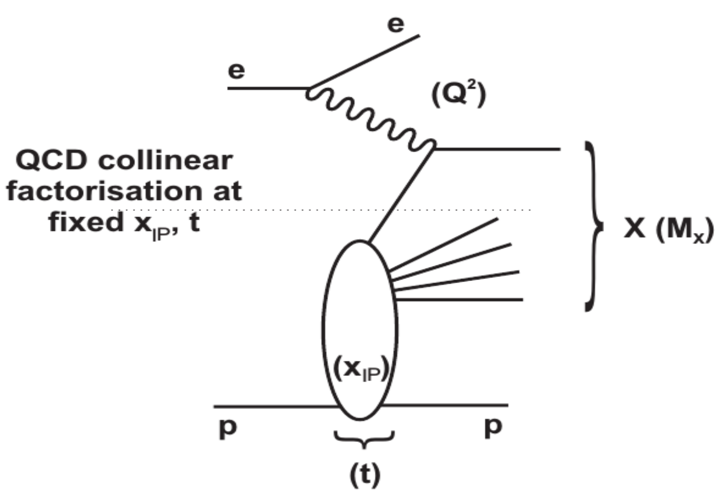
$$F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2) = \sum_{a=q,g} \beta \int_\beta^1 \frac{dz}{z} C_{2,a}\left(\frac{\beta}{z}\right) f_{a/p}^{D}(x_{\mathbb{P}}, z, \mu_F^2)$$

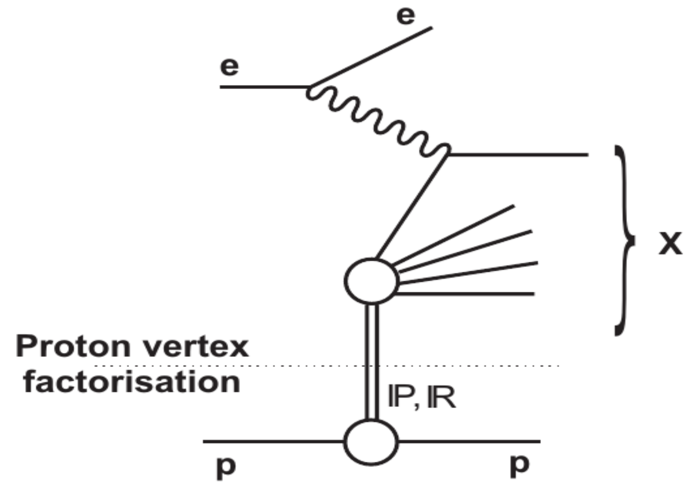
$$= \sum_q e_q^2 \, \beta f_{q/p}^{D}(x_{\mathbb{P}}, \beta, \mu_F^2) \quad \text{at LO.}$$

- $C_{2,a}$ 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.

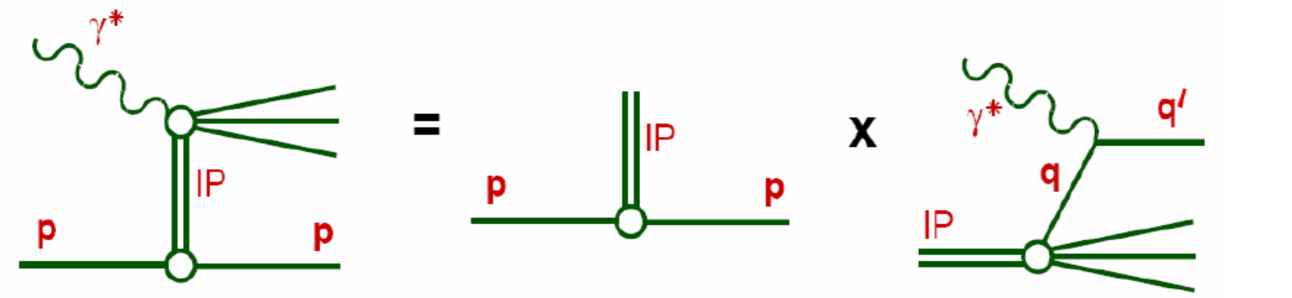


Proton vertex factorization





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

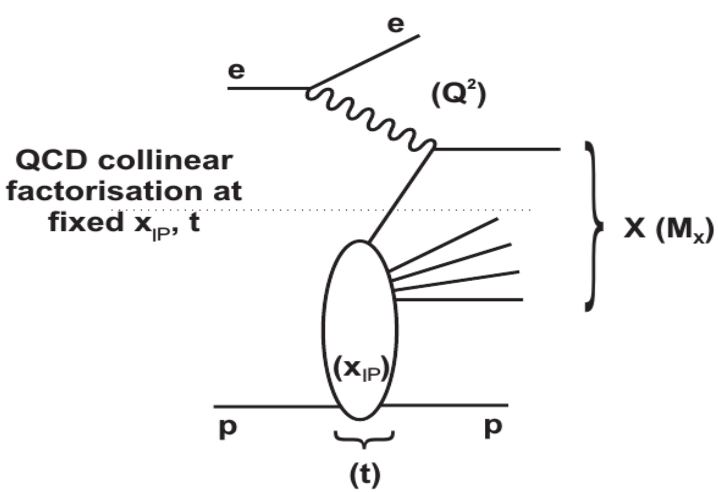


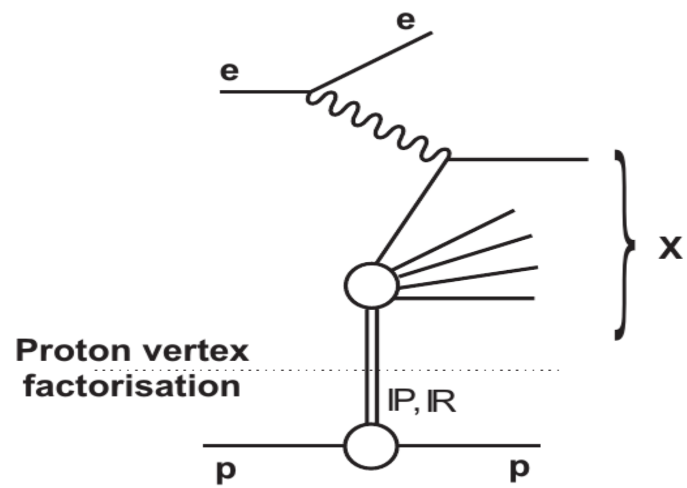
$$f^D_{a/p}(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \cdot f_{a/IP}(\beta, Q^2)$$

Pomeron flux

Probability for a hadron to radiate off a Pomeron

Proton vertex factorization





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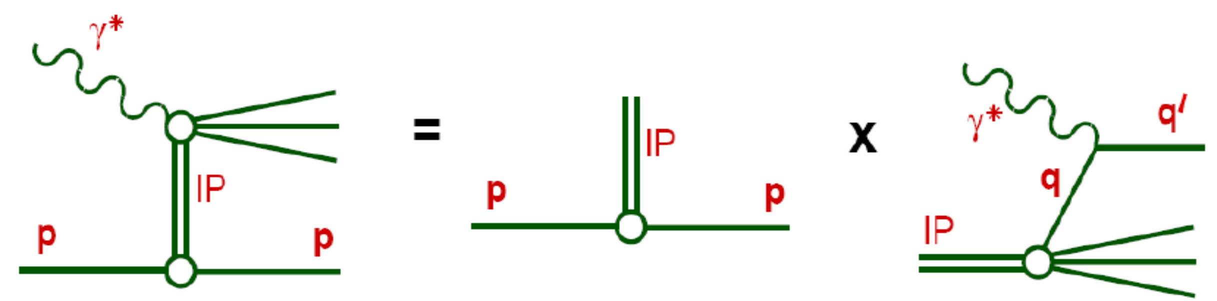

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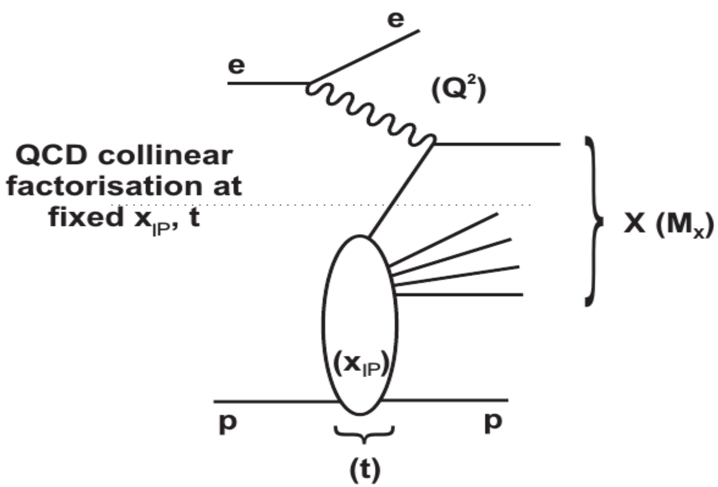
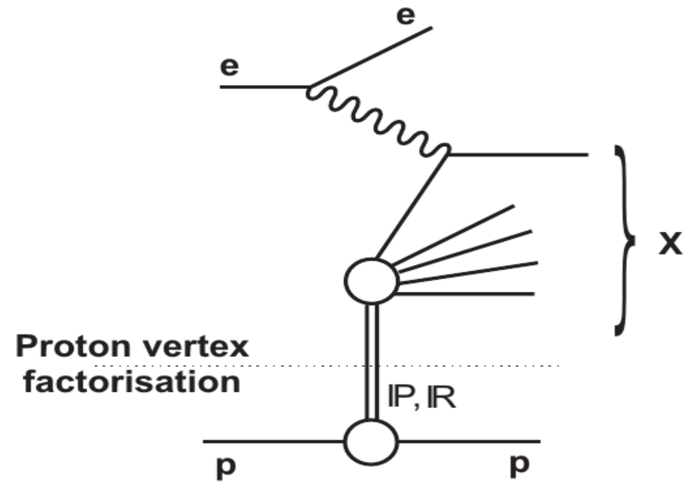
Pomeron PDFs

Proton vertex factorization





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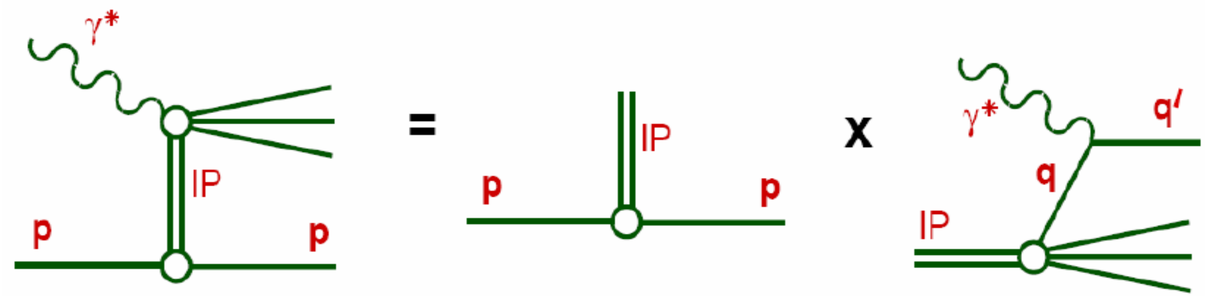


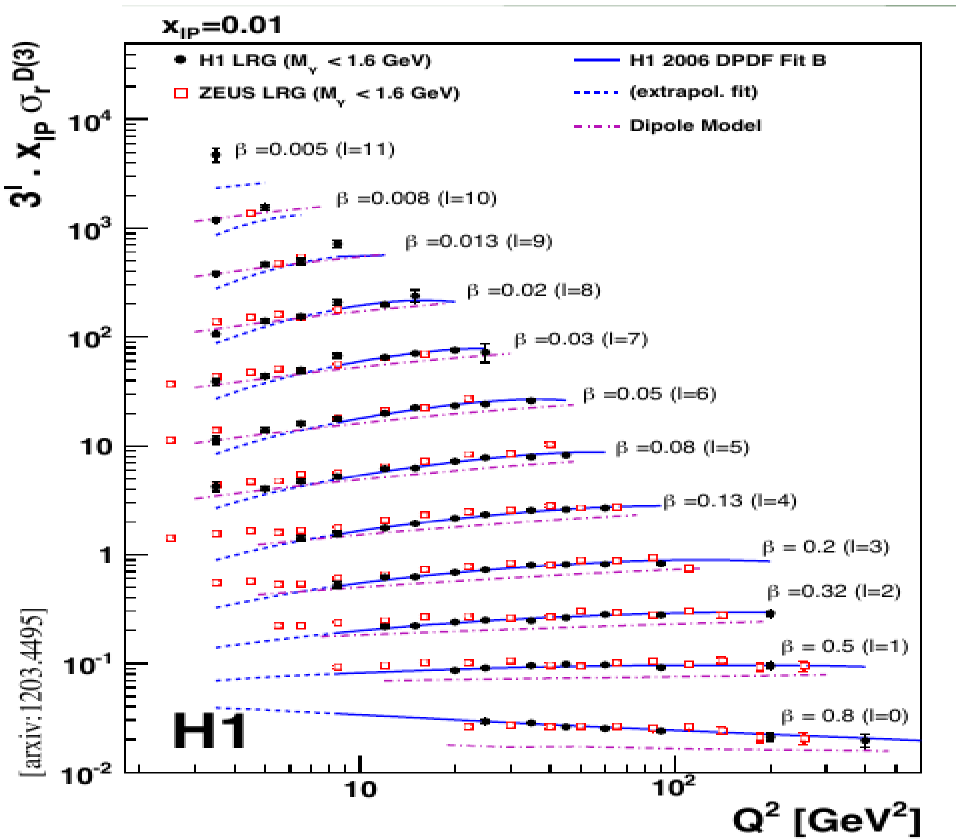
$$f^D_{a/p}(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \, . \, f_{a/IP}(\beta, Q^2)$$

Pomeron flux

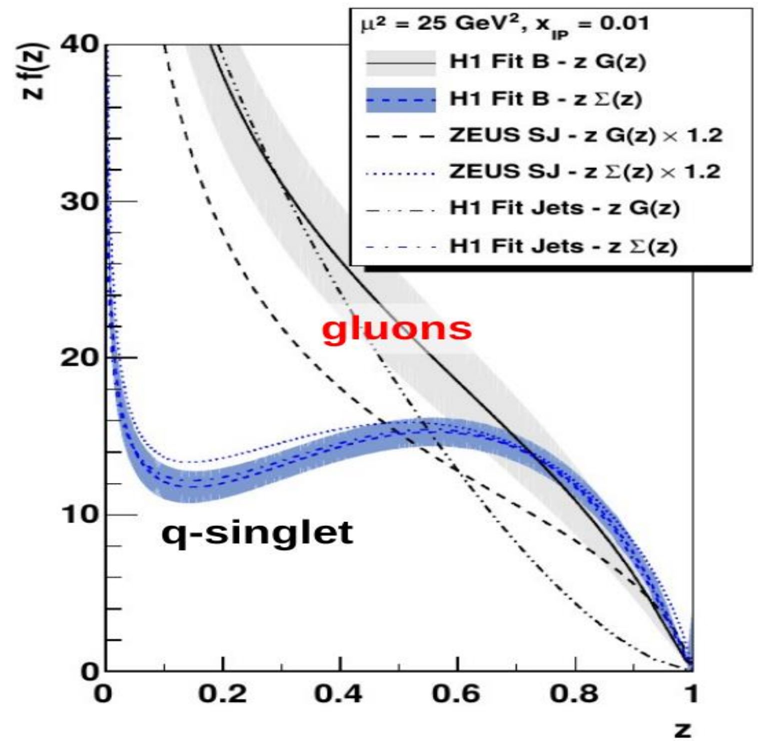
Pomeron PDFs

No QCD basis,
consistent with data

Pomeron PDFs

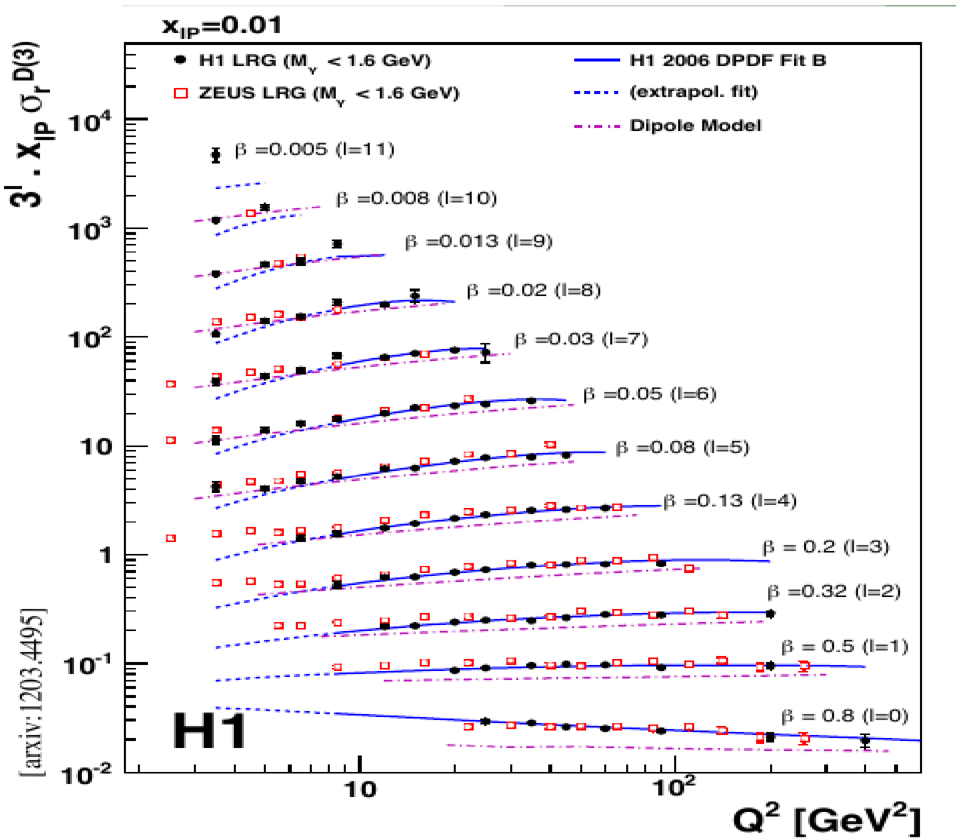


DGLAP Evolution Equations

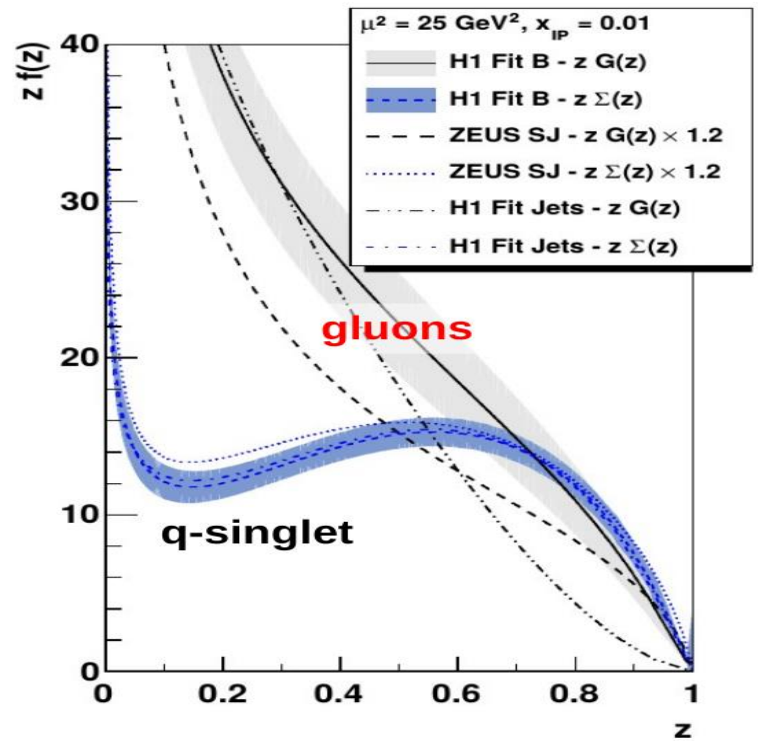


- Gluon dominates the Pomeron structure (60% of the exchanged momentum carried by gluons) ;
- Gluons weakly constrained in the high z region;

Pomeron PDFs

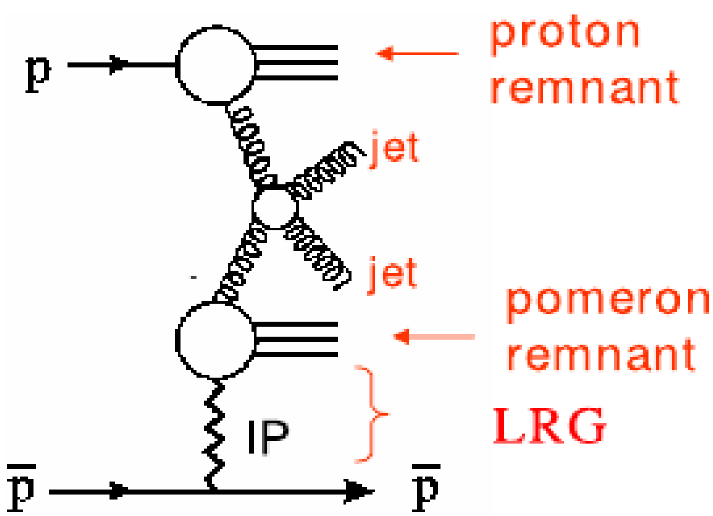


DGLAP
Evolution
Equations

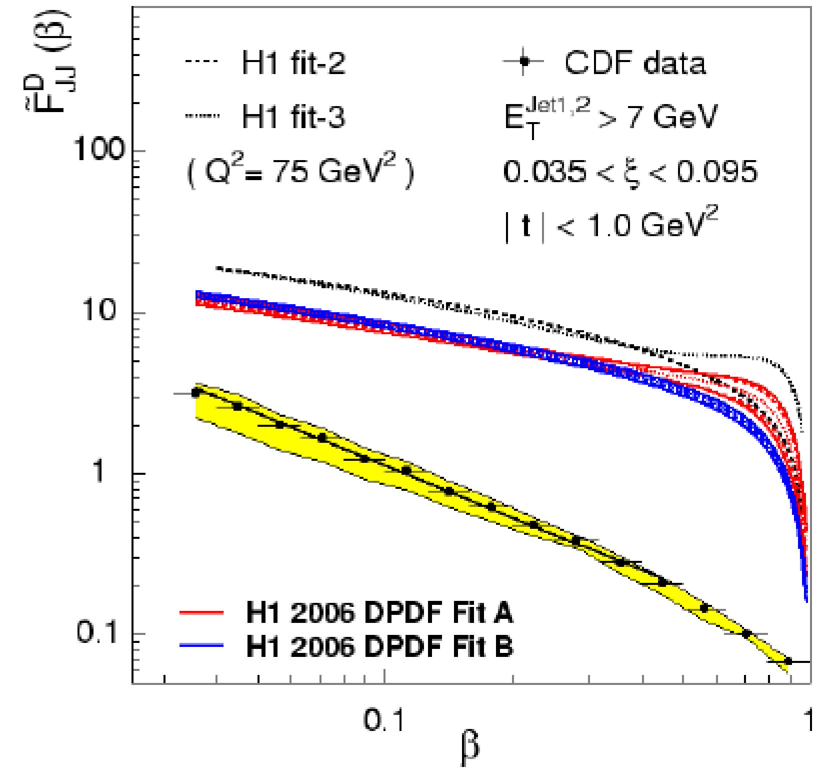


- Gluon dominates the Pomeron structure (60% of the exchanged momentum carried by gluons) ;
- Gluons weakly constrained in the high z region;
- Cross check: Use the resulting DPDFs as input in the calculations of other diffractive observables measured at HERA and hadronic colliders (Tevatron and LHC)

Diffractive Di-jet Production at the Tevatron



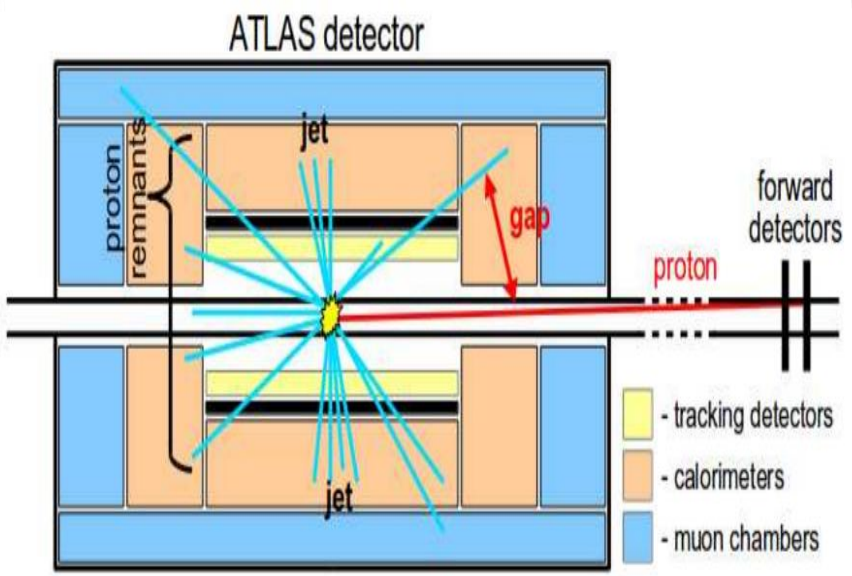
$$\sigma(\bar{p}p \to \bar{p}X) \approx F_{jj} \otimes F_{jj}^{D} \otimes \hat{\sigma}(ab \to jj)$$

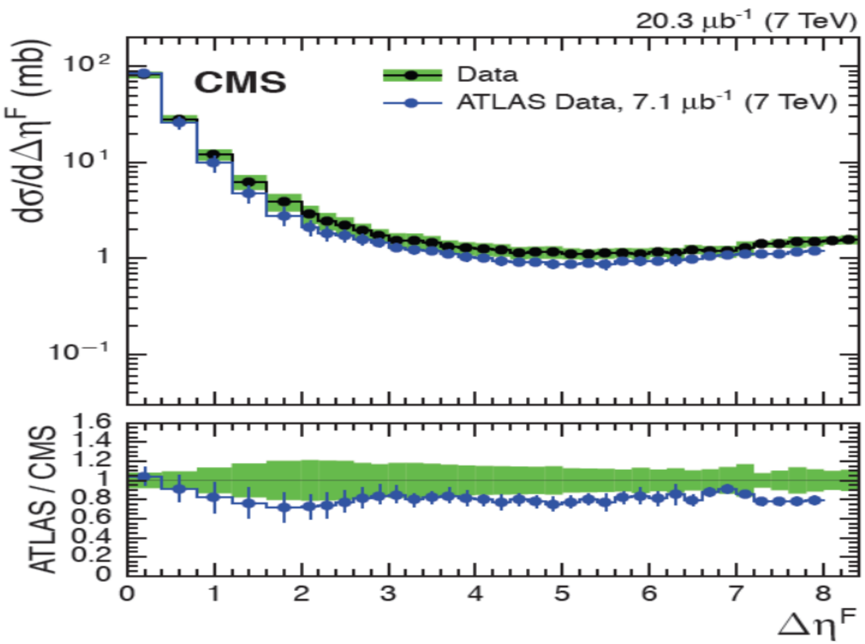


- Predictions obtained using the HERA DPDFs fail by factor 5 - 7;
- **Note**: QCD factorization has not been proven for hadron – hadron collisions.
- Final state interaction between proton remnant and antiproton possible.

  Gap survival probability is not equal to one !

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 ...?

Hard Diffraction at the LHC

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

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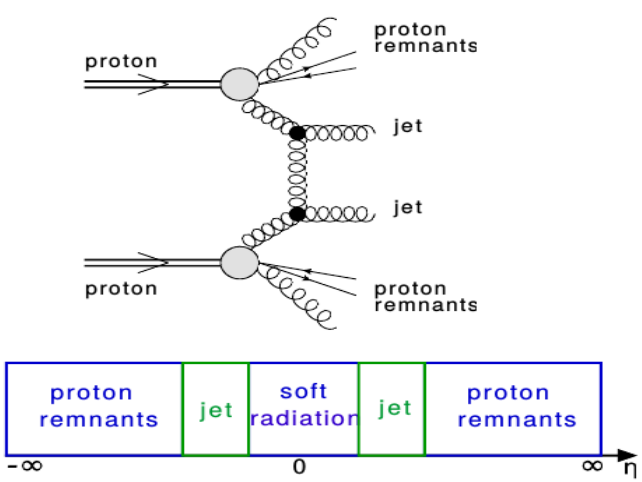
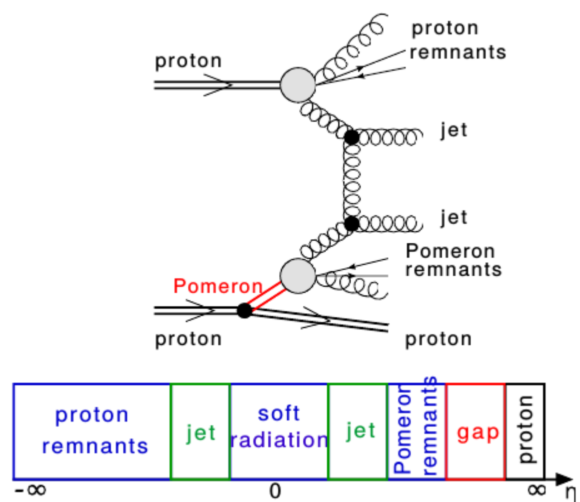
❖ Di-jet production (*)

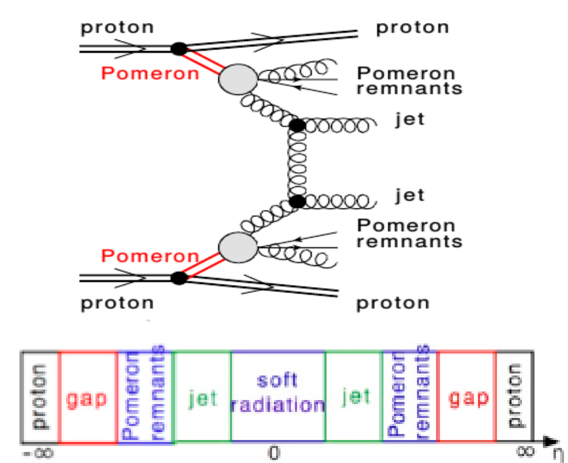
Inclusive



Single Diffraction



Double Diffraction



Main goal: Probe of the gluon DPDF

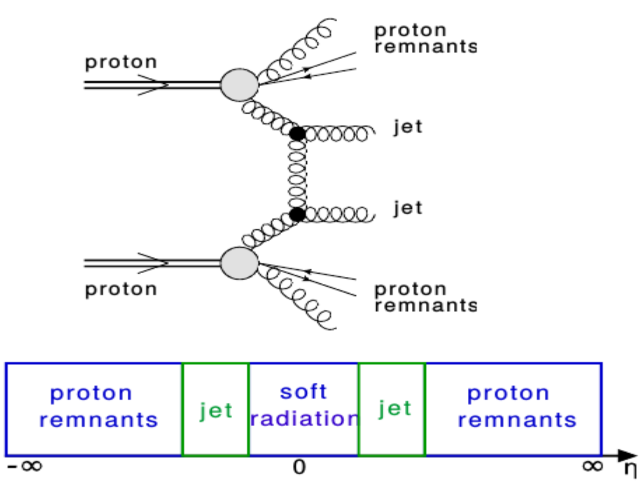
(*) Marquet, Royon, Sampert, Werder, PRD88, 074029 (2013)

Hard Diffraction at the LHC

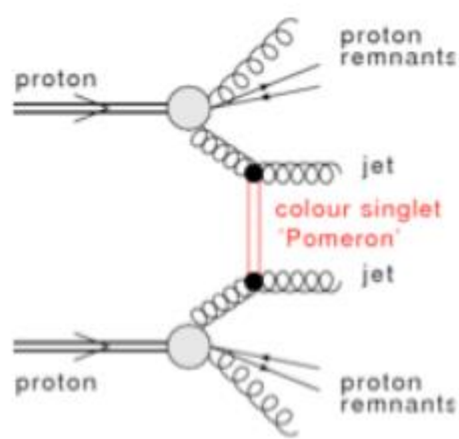
- ❑ Hard processes, calculable in perturbative QCD
- ❑ Measure proton structure, QCD at high parton densities, Discovery physics
- ❑ Some few examples:

❖ Di-jet production (**)

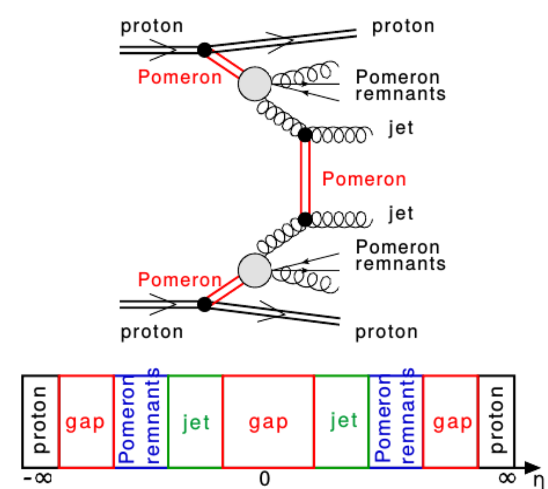
Inclusive



Jet – Gap – Jet



DPE with jet – gap - jet



Main goal: Probe the BFKL evolution between the hard scale set by the two jets

(**) C. Royon et al, PRD83, 034036 (2013); PRD87, 034010 (2013)

Hard Diffraction at the LHC

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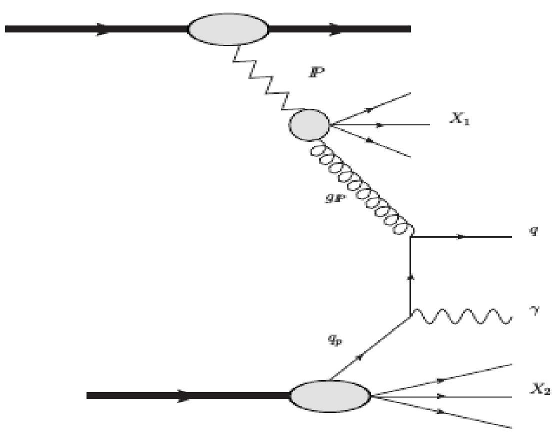
- Some few examples:

❖ Photon + jet production (*)

Single Diffraction



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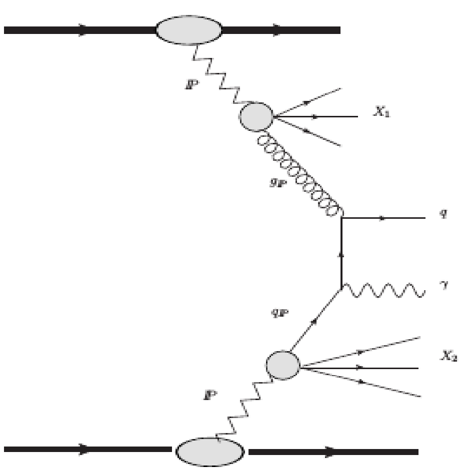

Main goal: Probe of the quark DPDF

(*) VPG,Brenner Mariotto, PRD88, 074023 (2013)
Marquet, Royon, Sampert, Werder, PRD88, 074029 (2013)

Hard Diffraction at the LHC

- ❑ Hard processes, calculable in perturbative QCD
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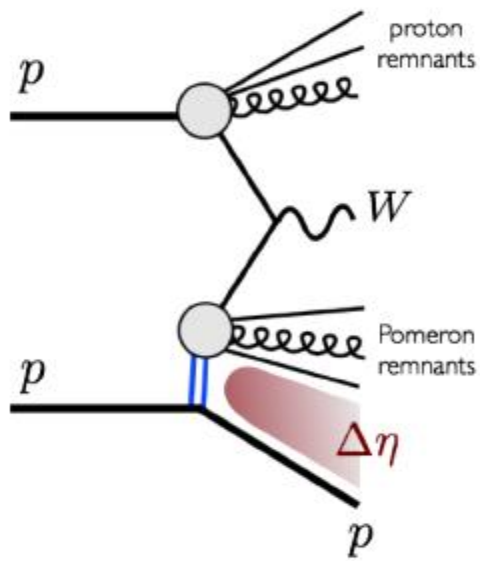
- ❑ Some few examples:

❖ W, Z production (*)



Main goal: Probe of the quark DPDF and Pomeron Flavour symmetry

(*) Gay Ducati et al, PRD 75, 1140013 (2007);
Golec – Biernat et al., PRD 81, 014009 (2010);
Royon et al., JHEP, 092 (2016)

Hard Diffraction at the LHC

- Hard processes, calculable in perturbative QCD
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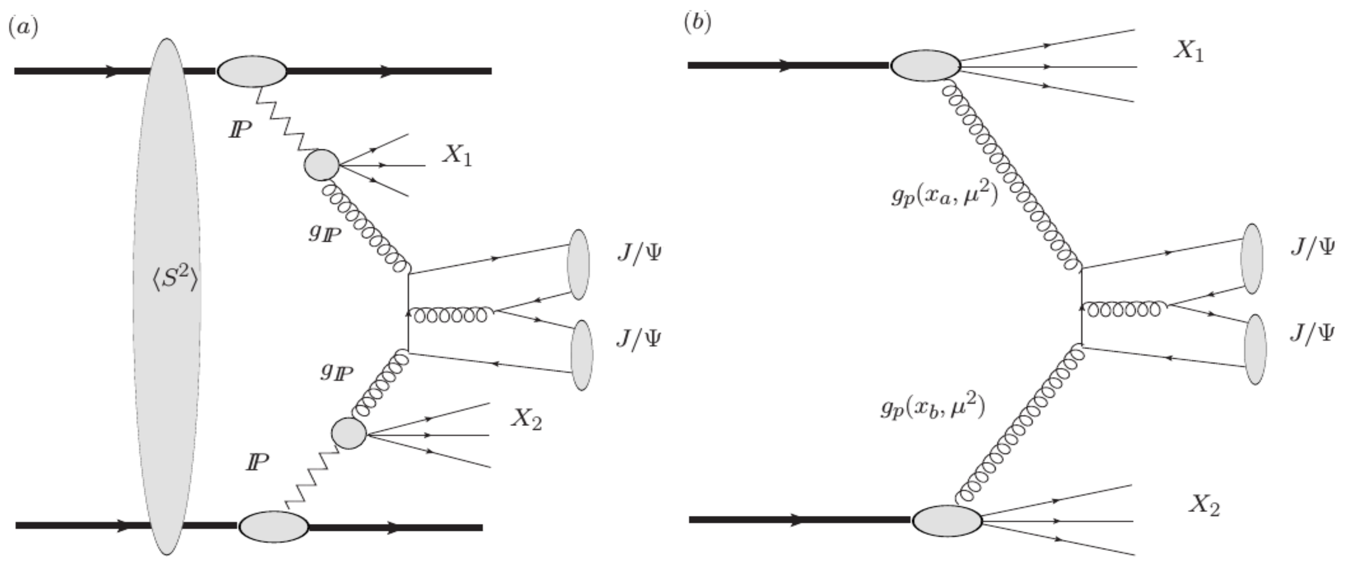
- Some few examples:

❖ DPE with Double J/ψ production (**)



Main goal: Probe of the quarkonium production mechanism

(**) VPG, Brenner Mariotto, PRD91, 114002 (2015)

Hard Diffraction at the LHC

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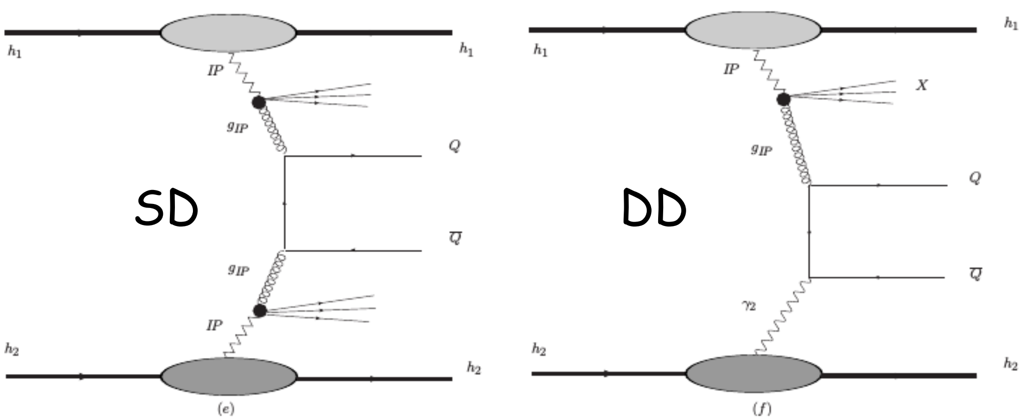
- ❑ Some few examples:

❖ Heavy quark production



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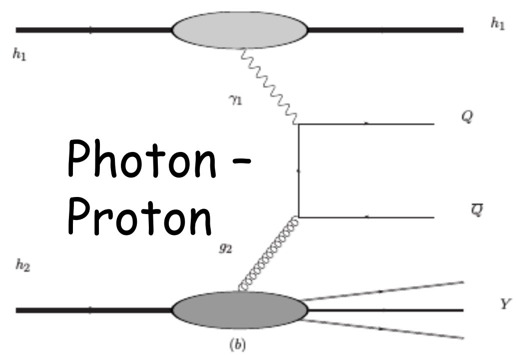

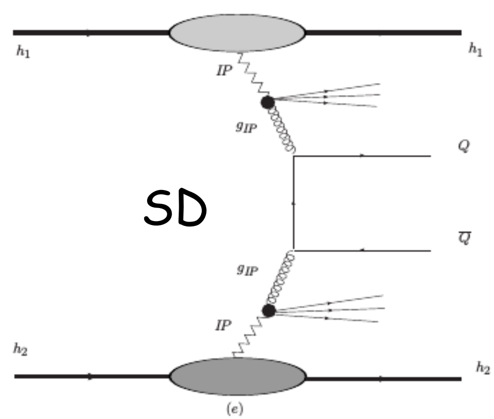

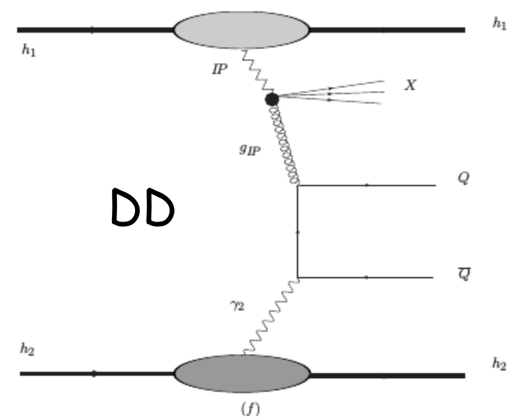

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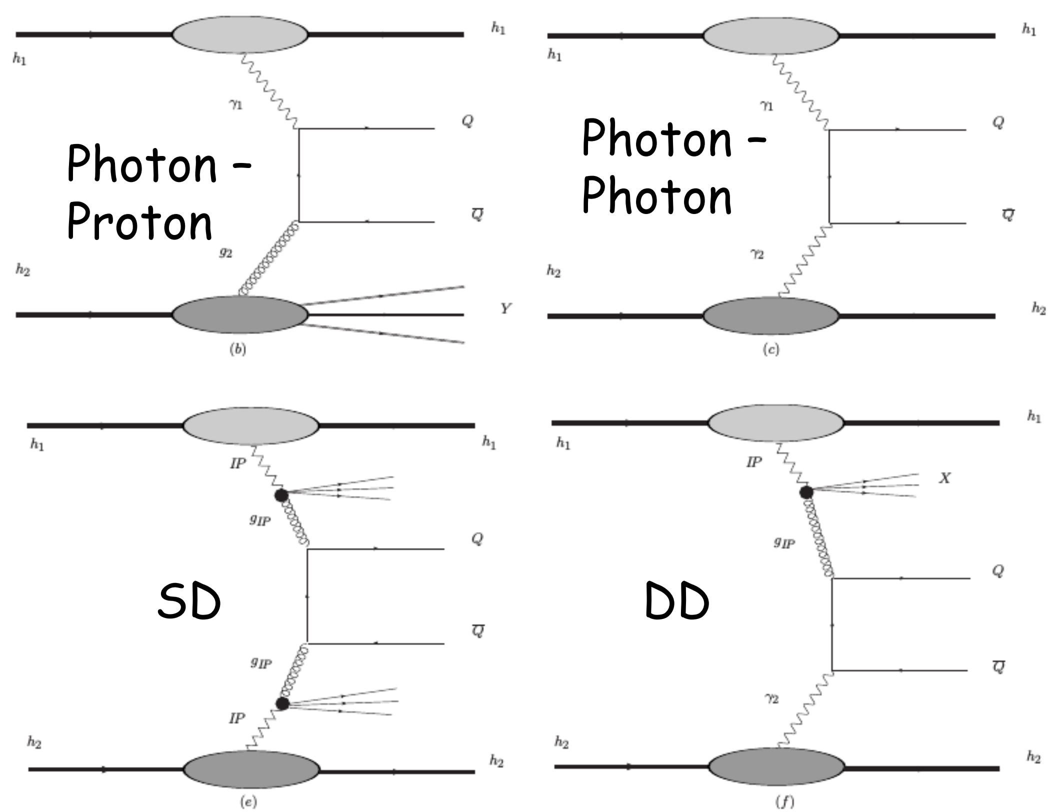

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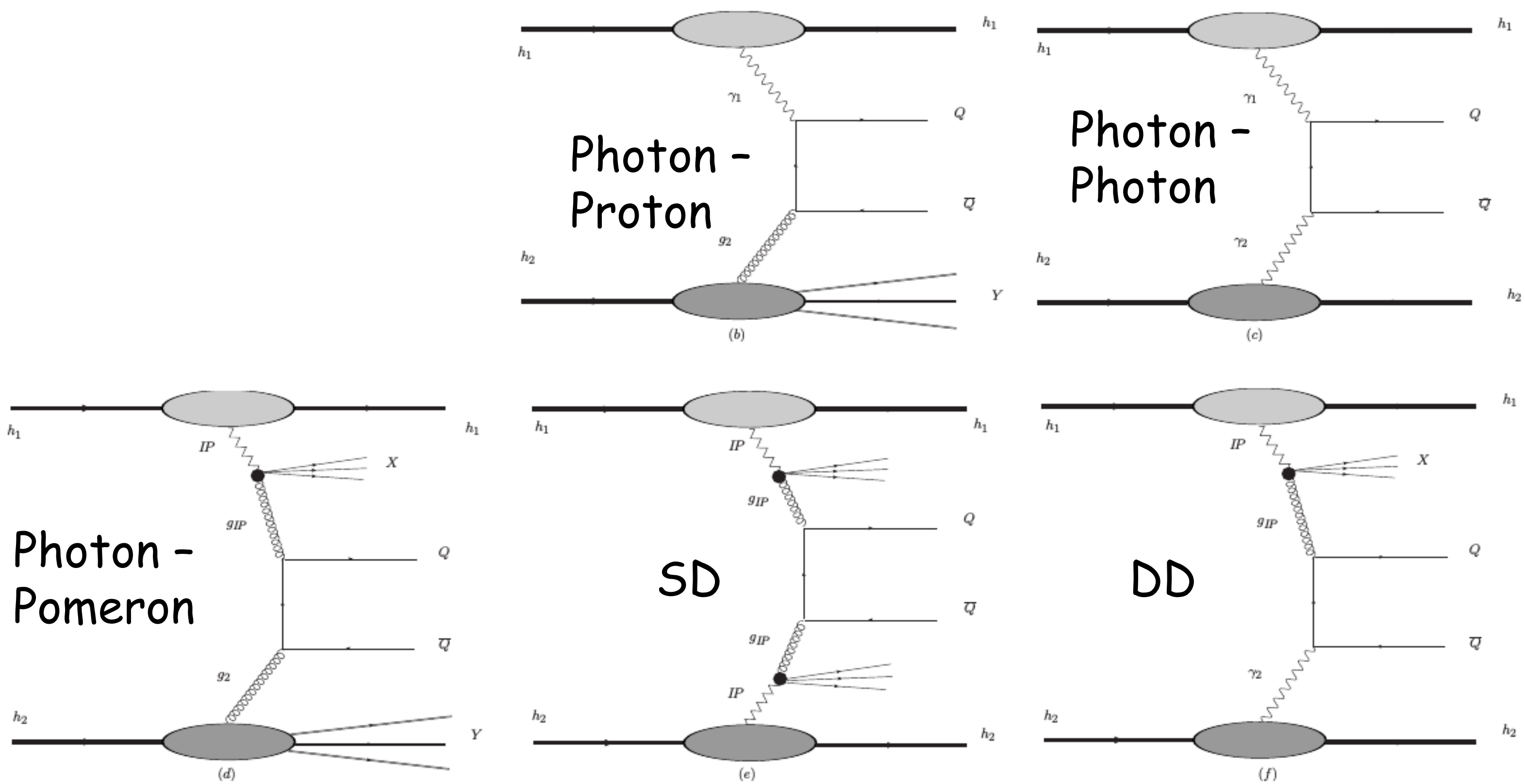

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- Hard processes, calculable in perturbative QCD
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- Some few examples:

- Heavy quark production (*)
  - All contributions were included inside a MC generator: Forward Physics Monte Carlo (FPMC)

(*) VPG, Potterat, Rangel, PRD93, 034038 (2016)

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	pp	$p\mathbb{P}$	$\mathbb{P}\mathbb{P}$	γp	$\gamma\mathbb{P}$	$\gamma\gamma$
LHC	3.59×10^{8}	2.63×10^{7}	1.51×10^{6}	11474.80	1744.91	0.11
LHCb	1.53×10^{7}	210036.10	1846.33	3065.27	573.14	7.97×10^{-7}
LHCb gap	3725.05	59392.50	518.22	932.01	189.37	7.97×10^{-7}

TABLE I: Total cross sections in pb for the bottom production in inclusive pp collisions and and $p\mathbb{P}$, $\mathbb{P}\mathbb{P}$, γp, $\gamma\mathbb{P}$ and $\gamma\gamma$ interactions. The LHCb gap line represents the results obtained considering the detector acceptance with a rapidity gap requirement in the LHCb experiment.

> ➢ The requirement that the bottom quarks are produced in the LHCb acceptance, ($2.0 < \eta < 5.0$) and no charged particles are produced in the backward region of $-4.5 < \eta < -1.5$ suppress the inclusive contribution.
>
> ➢ SD becomes dominant !

(*) VPG, Potterat, Rangel, PRD93, 034038 (2016)

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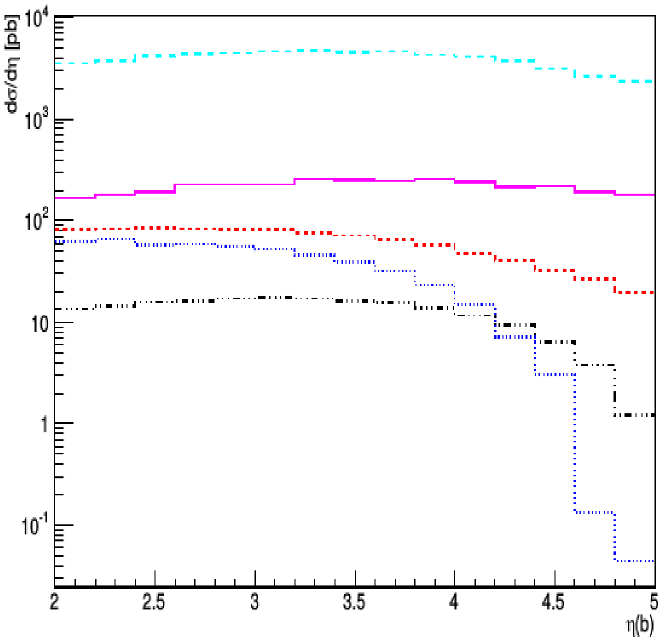
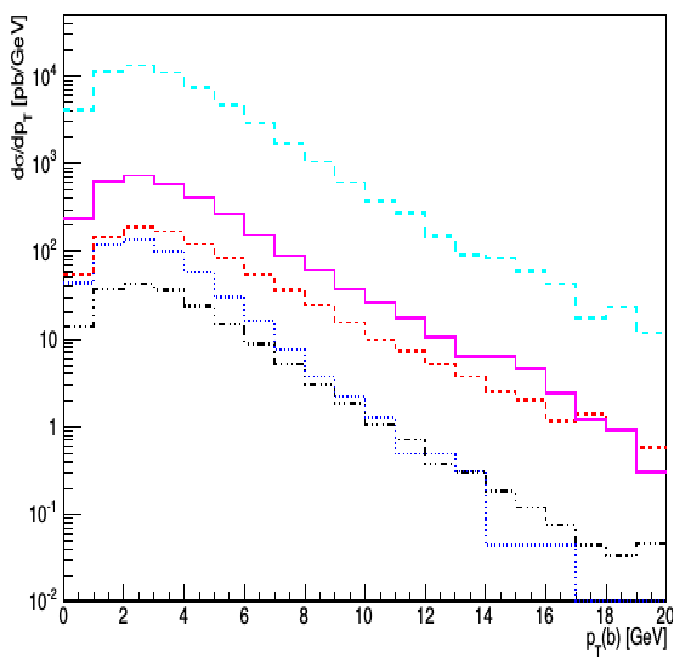
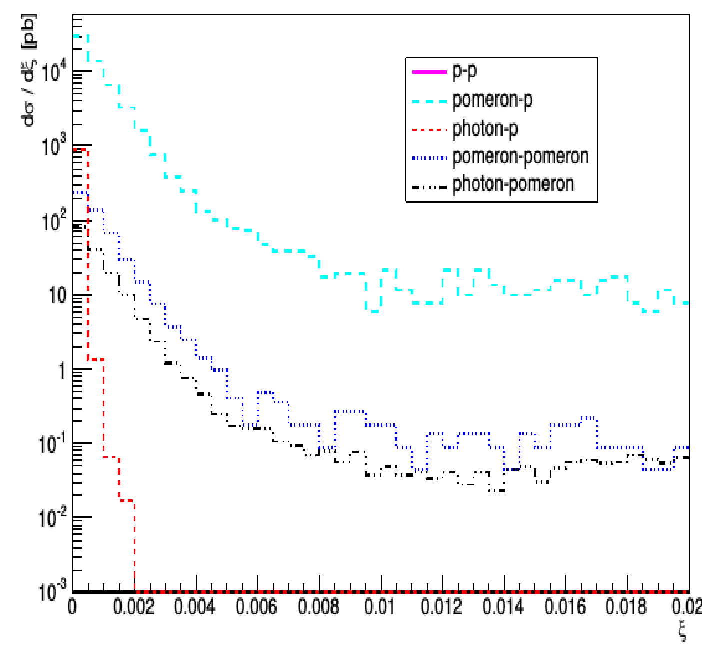


η distribution



p_T distribution

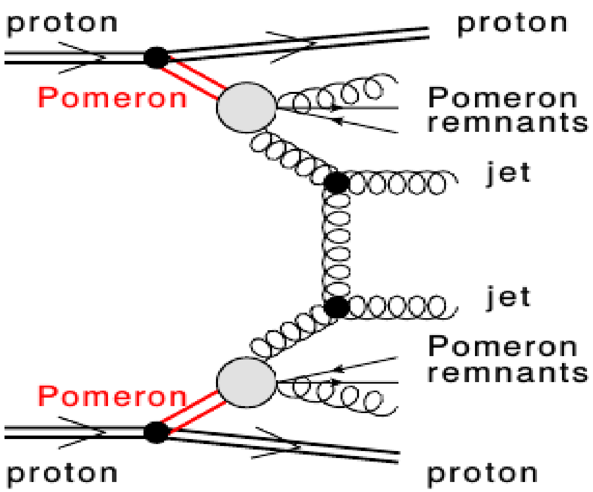


ξ distribution

(*) VPG, Potterat, Rangel, PRD93, 034038 (2016)

Exclusive Diffraction at the LHC

❑ Inclusive Diffraction: Pomeron remnants are present



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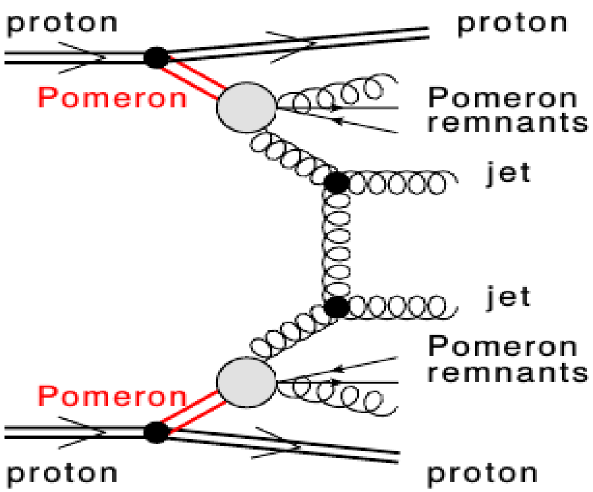
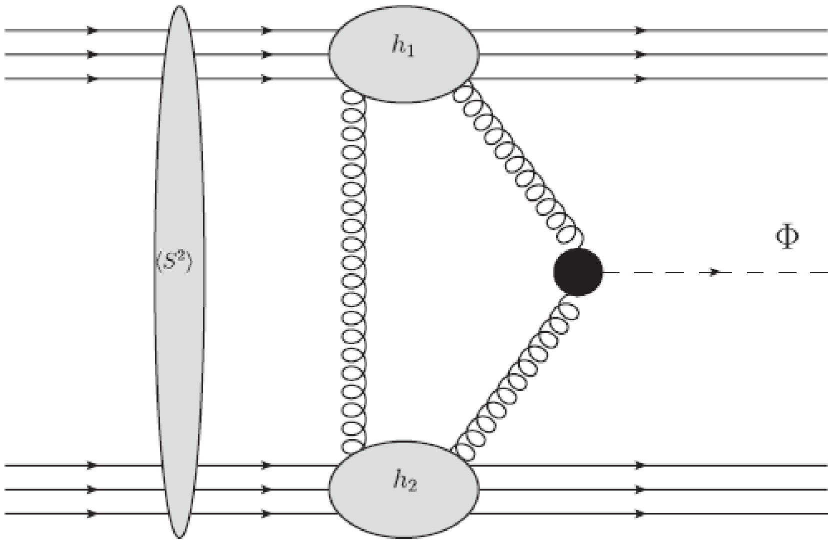


- Exclusive Diffraction: Pomeron remnants are NOT present and ALL particles can be measured in the final state



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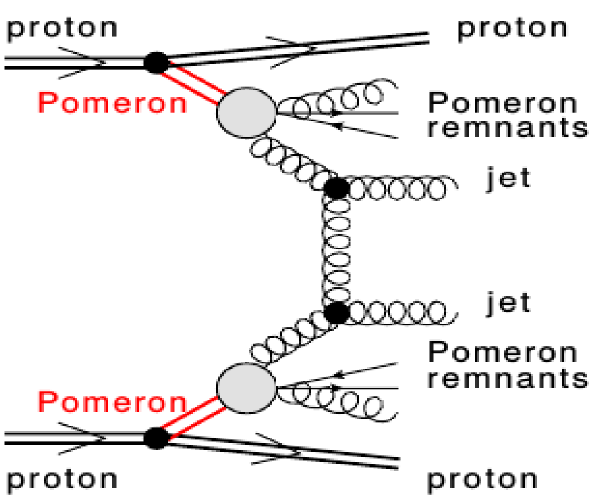

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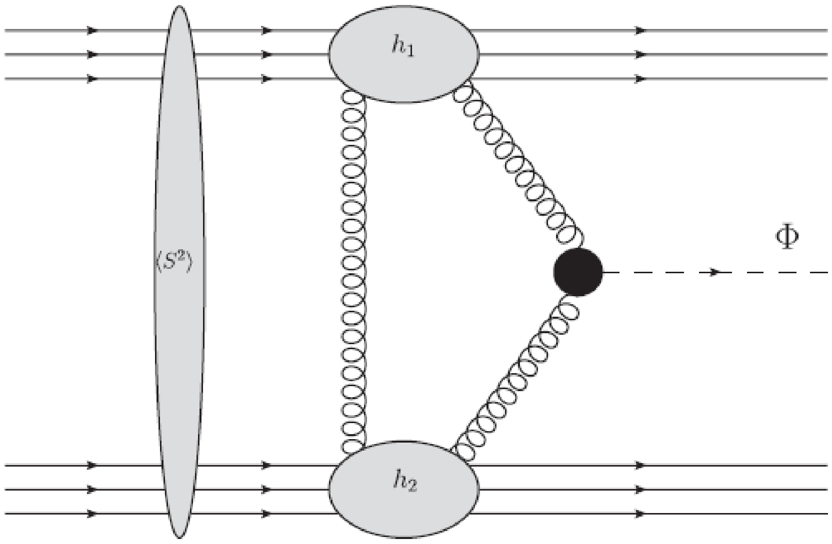

- It is possible to reconstruct the properties of the object produced exclusively from the tagged proton since the system is completely constrained.

Exclusive Diffraction at the LHC

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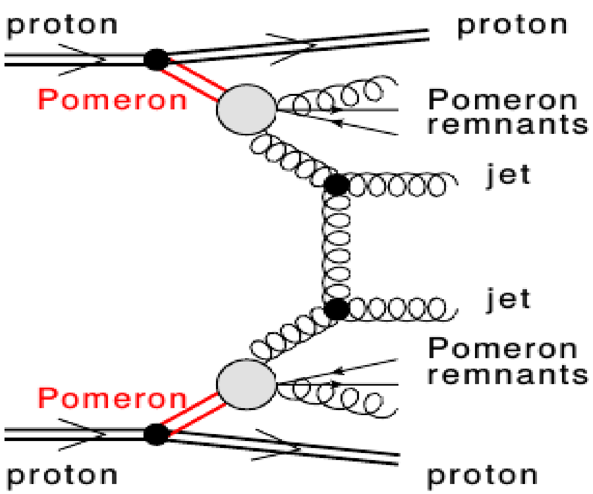

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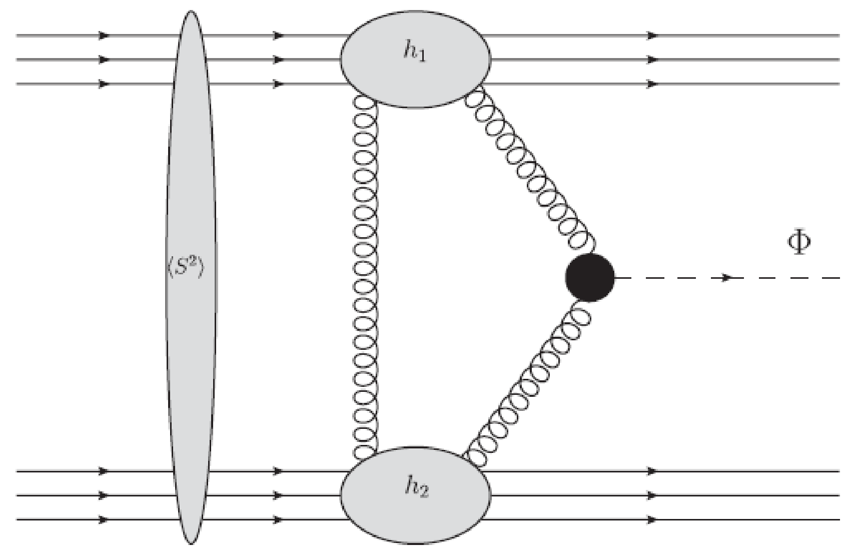
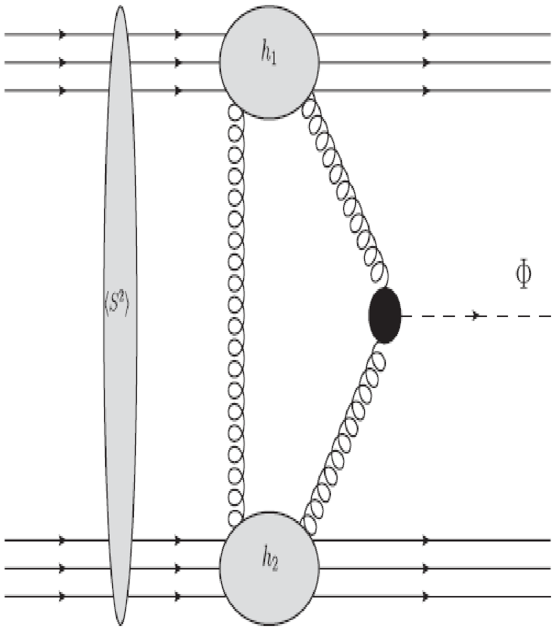


- It is possible to reconstruct the properties of the object produced exclusively from the tagged proton since the system is completely constrained.

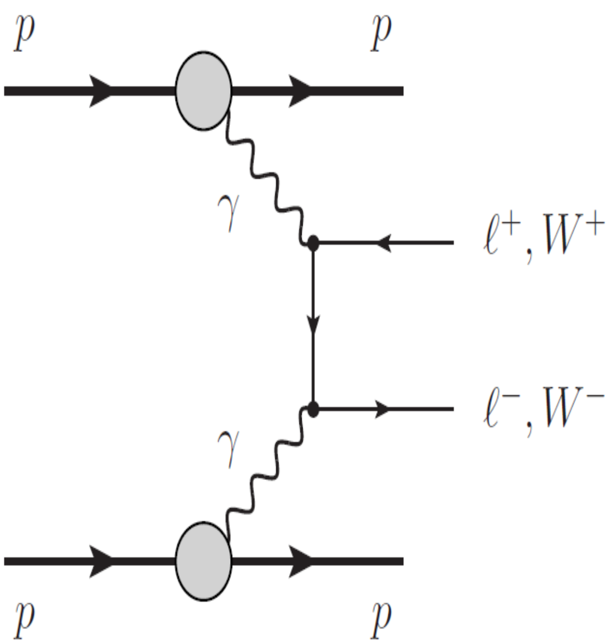
- Final state characterized by intact protons and two rapidity gaps.

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

Pomeron - Pomeron:



Photon – Photon:



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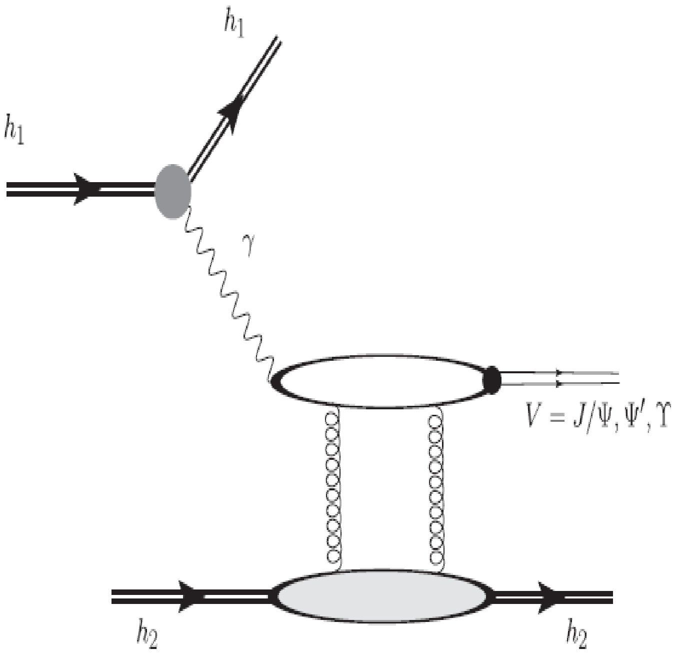

Exclusive Processes at the LHC:
Exclusive Diffraction and Photon Exchange Processes

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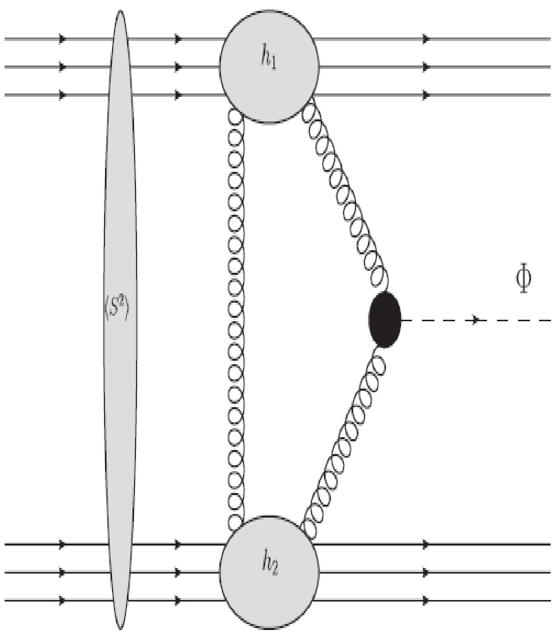

- Spin - parity analyser: only a subset of resonant states can be produced. In particular 0^{++} but not, for example, 1^{++}.
- Sensitive to the description of diffraction.
- Very sensitive to beyond Standard Model Physics.

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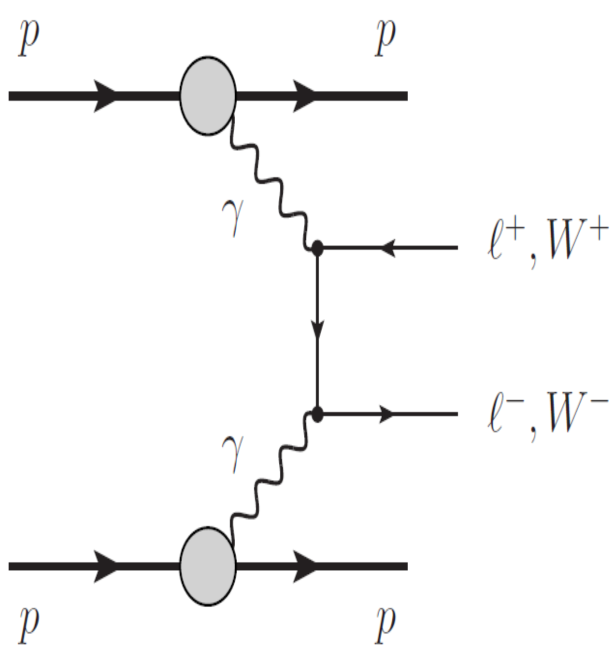

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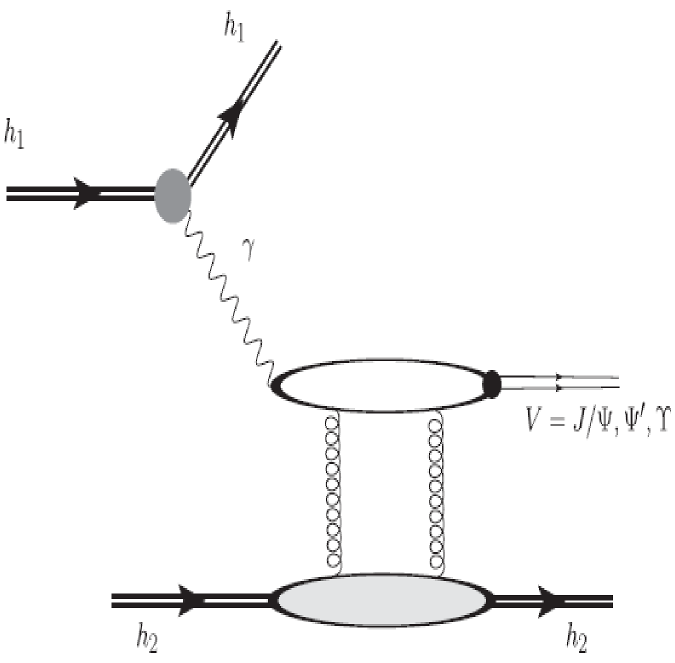

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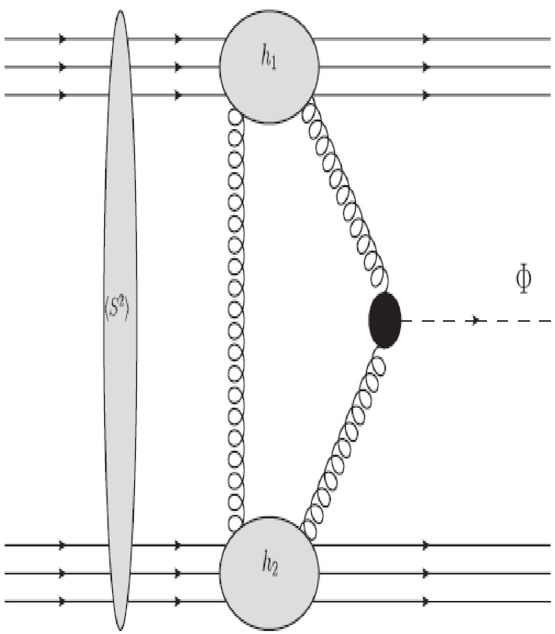

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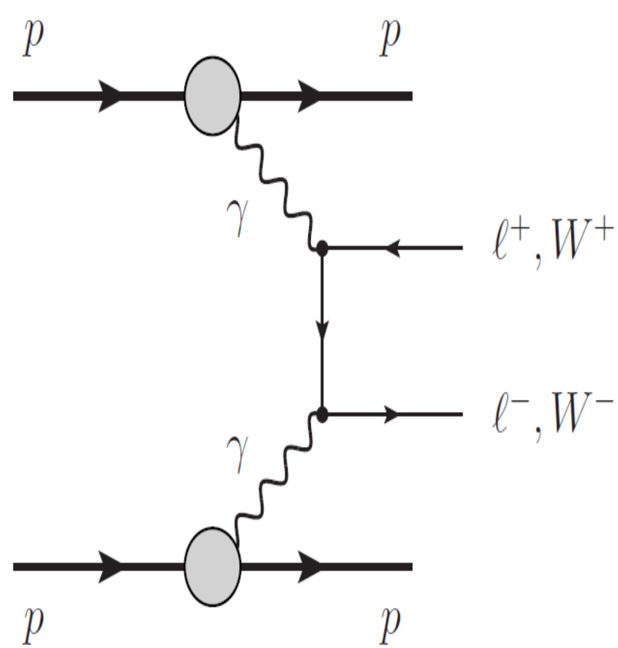

- Very clean processes: Central production with forward hadrons
- Accessible measurements:

1. Luminosity via dilepton production ($\gamma\gamma \to \mu^+\mu^-$);
2. Anomalous quartic gauge - couplings ($\gamma\gamma \to W^+W^-$);
3. SUSY/Radion/Dilaton production

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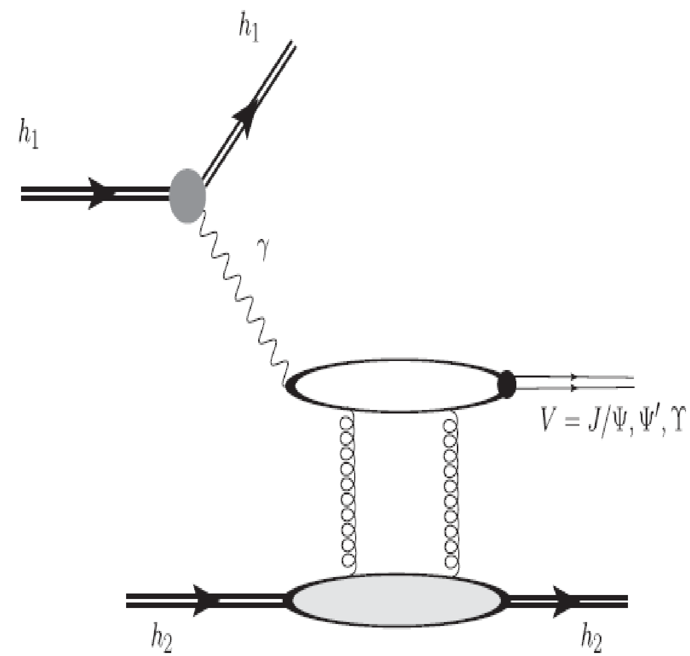

Exclusive Processes at the LHC:
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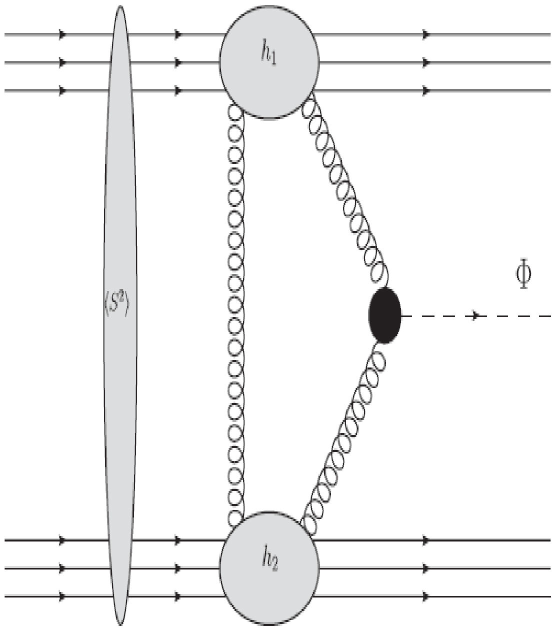

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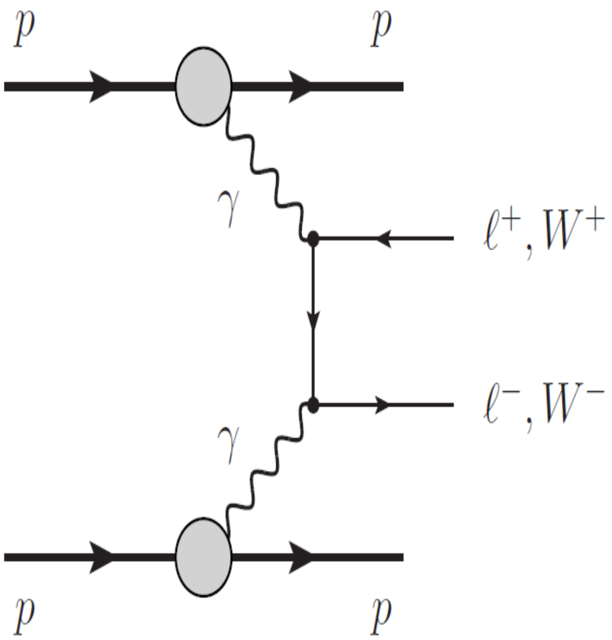

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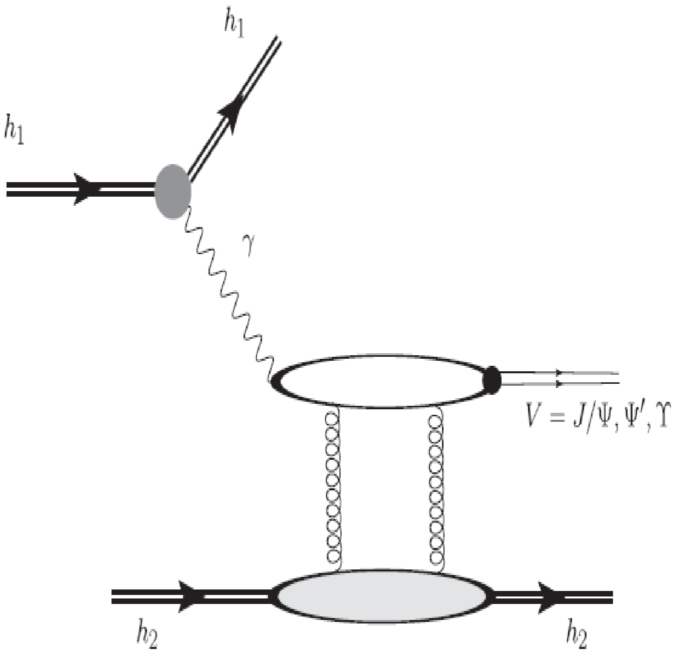
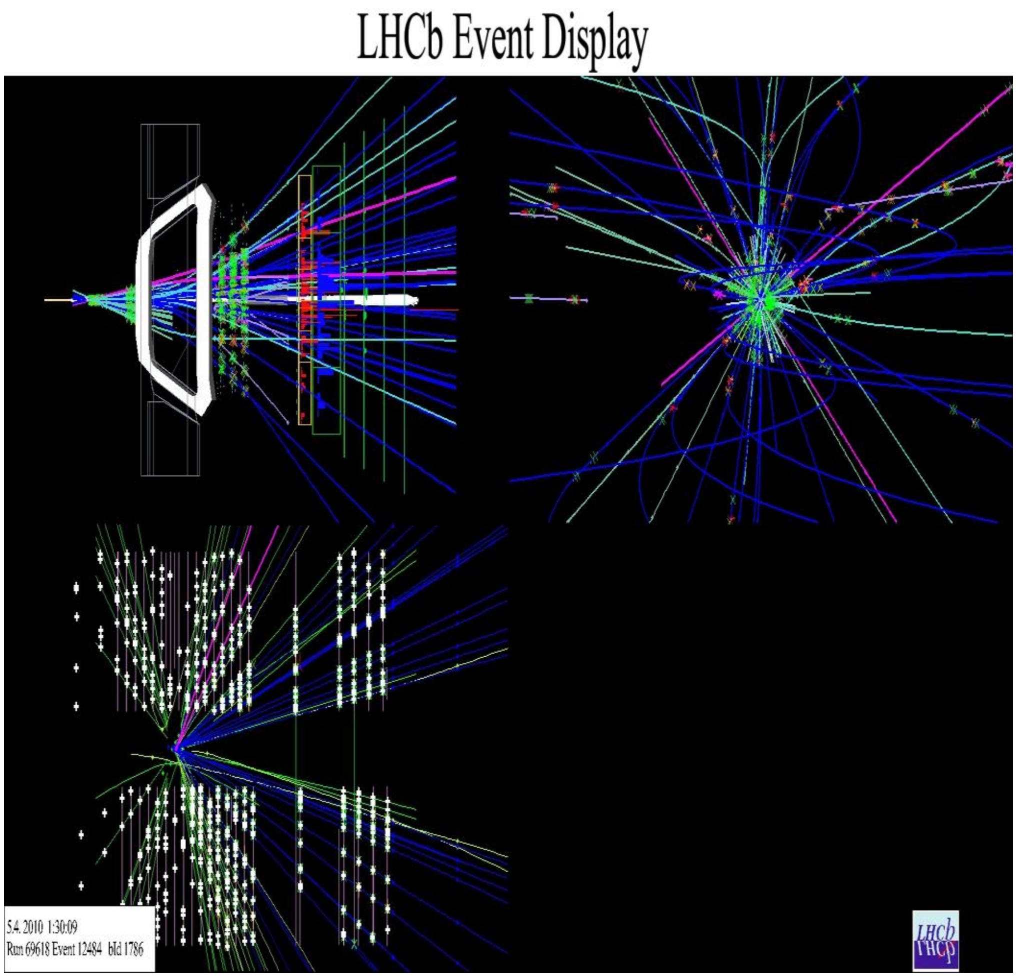


- Allow us to study the QCD dynamics at small-x.
- Sensitive to the description of diffraction.
- Determination of the gluon distribution and the magnitude of the shadowing effects.
- Search for saturation effects.
- Search for Odderon, Charmoniumlike exotic states, ...

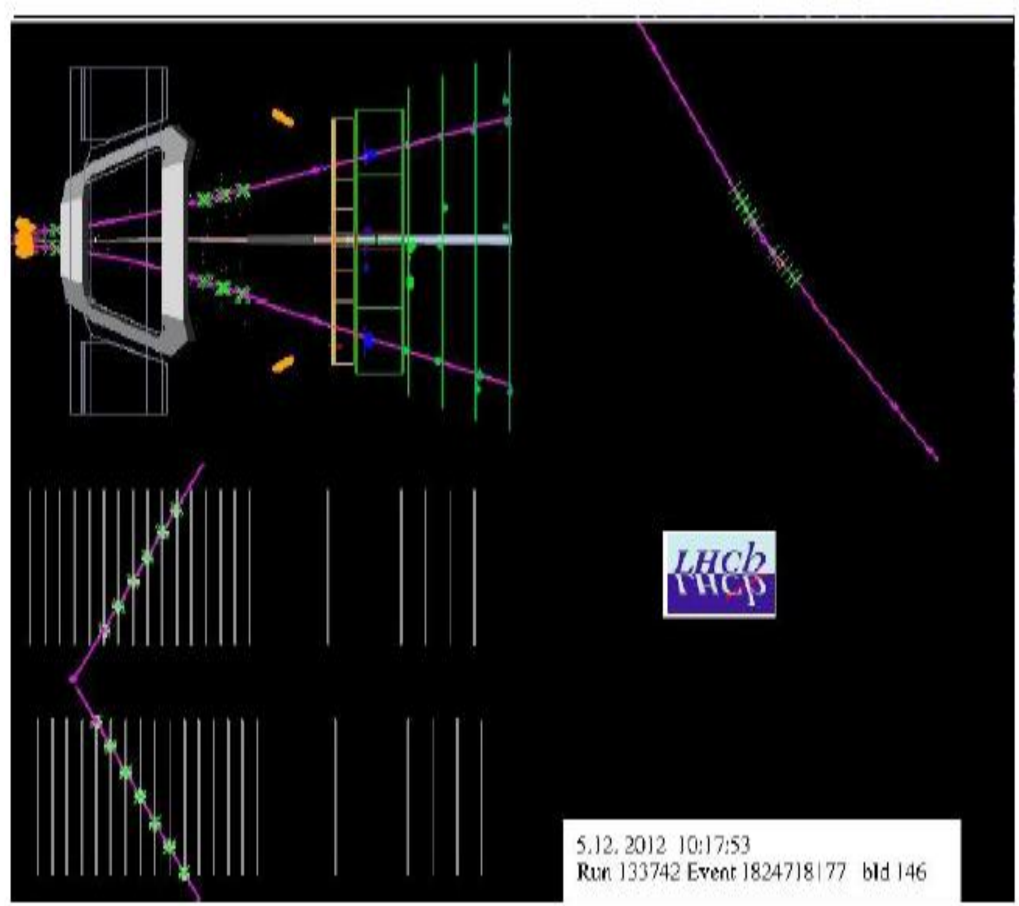
Exclusive Processes at the LHC:
Exclusive Diffraction and Photon Exchange Processes

- **Typical *pp* events:**



Many tracks + high pT particles

- **Exclusive events:**



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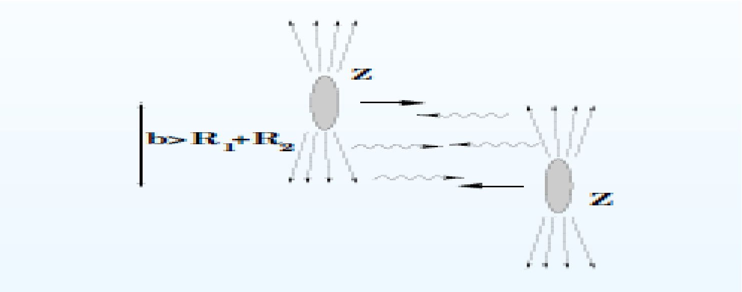
Photon - induced interactions at the LHC:



1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

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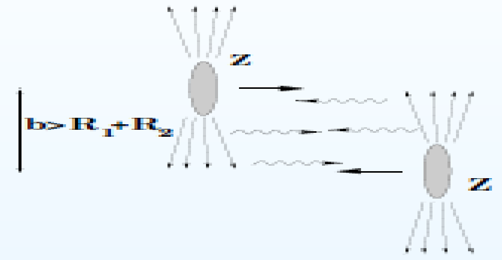

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Center of mass energies

LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$W_{\gamma\gamma} \lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

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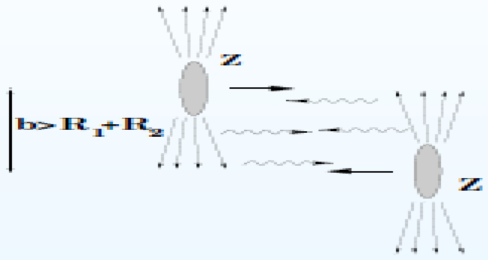

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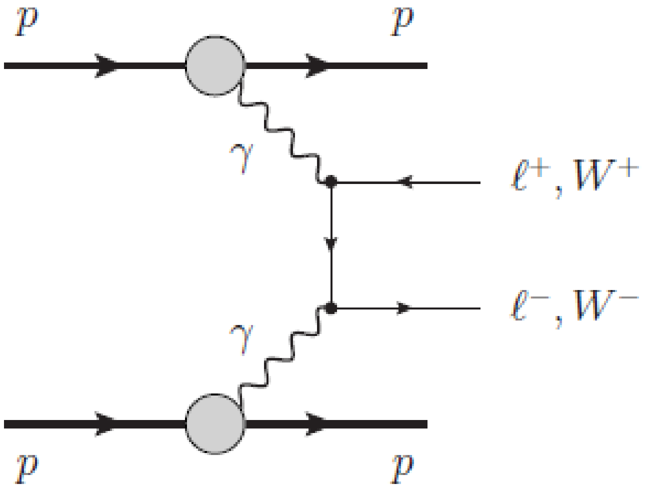
- The LHC is the world´s most powerful collider not only for proton and lead ions but also for γγ and γh collisions.

Photon - Photon Interactions at the LHC



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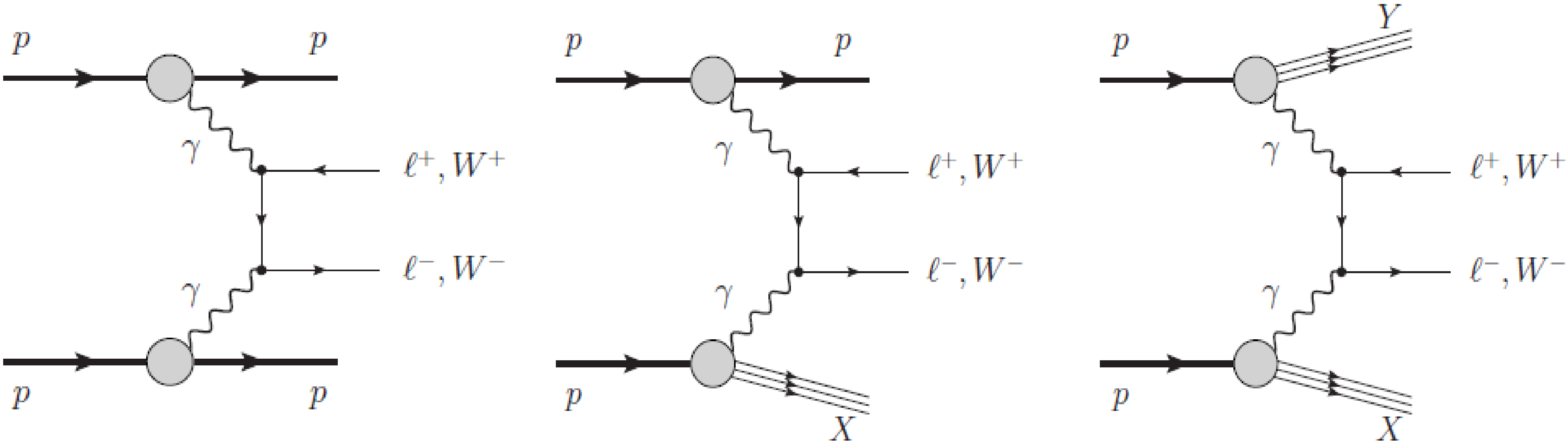

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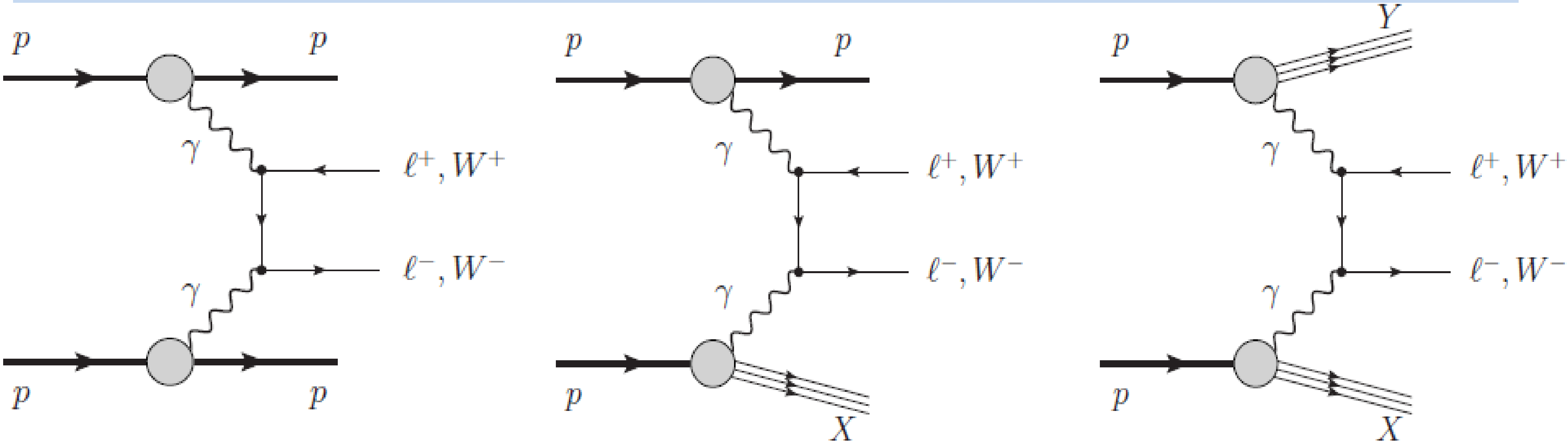
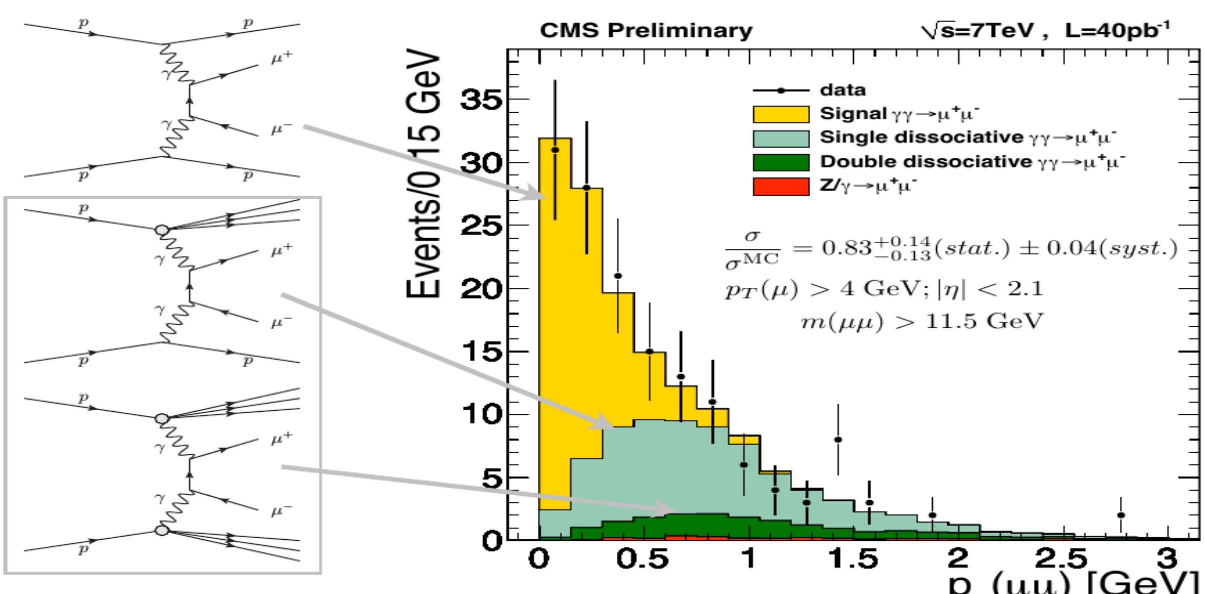
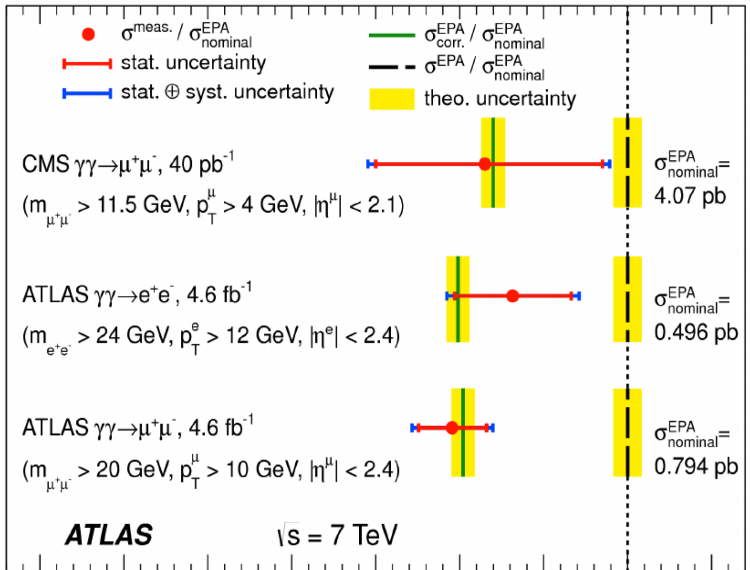
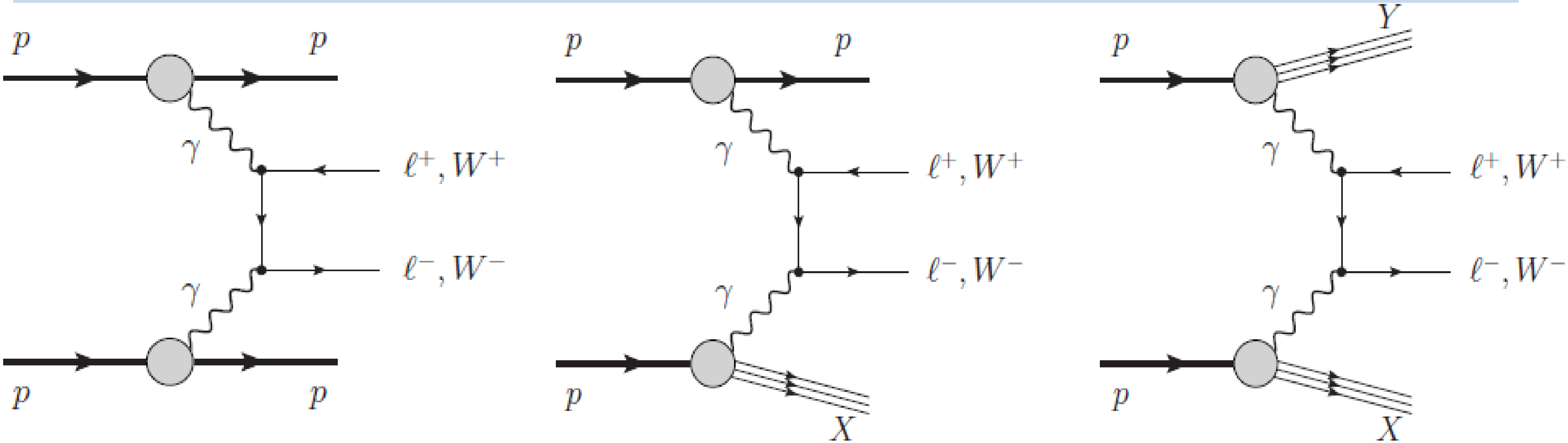
Photon - Photon Interactions at the LHC

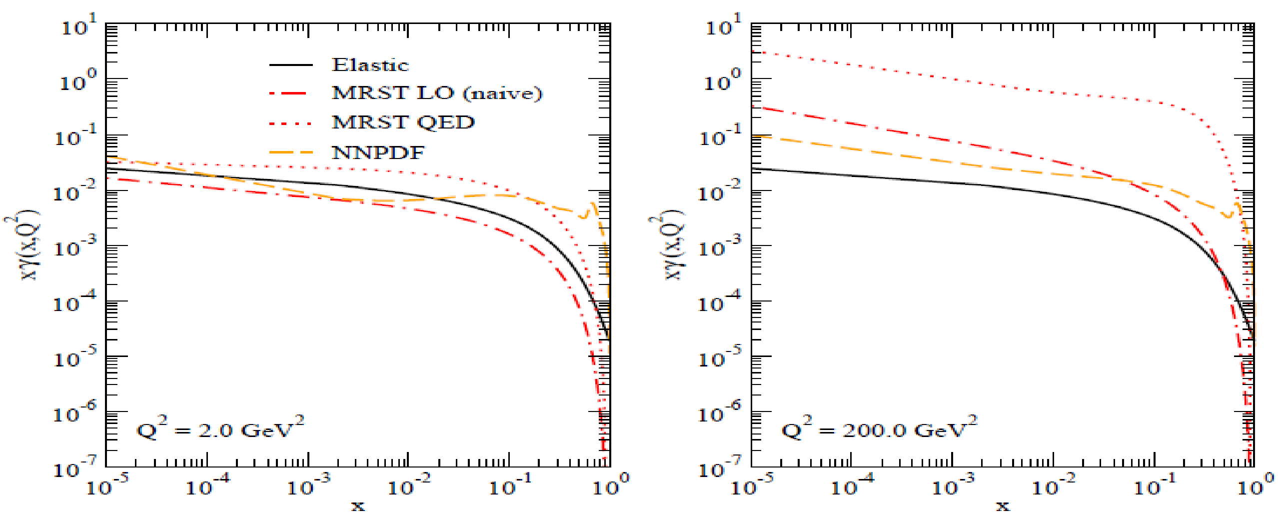






Photon - Photon Interactions at the LHC: Probing the Photon Distribution of the Proton





VPG, da Silveira, PRD92, 014013 (2015)

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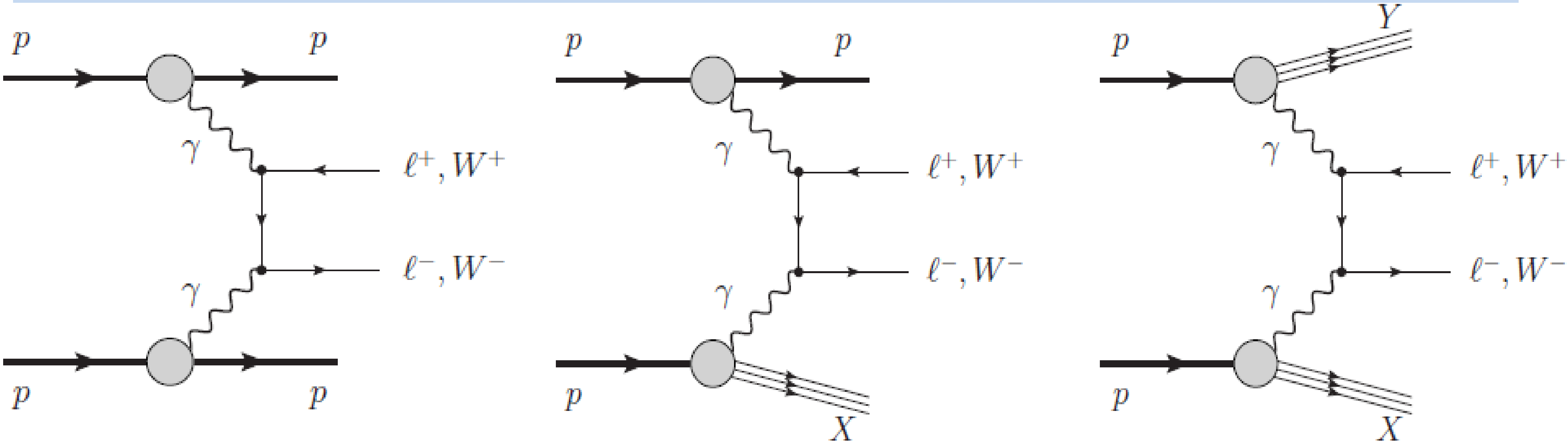

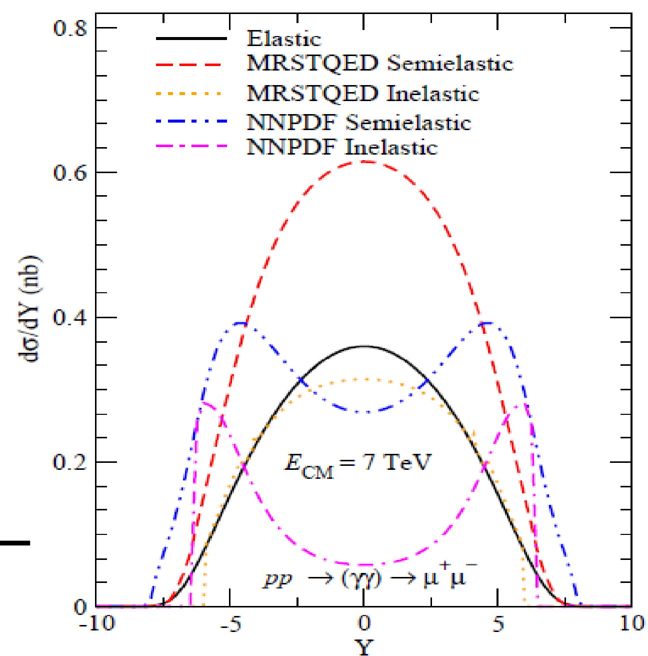

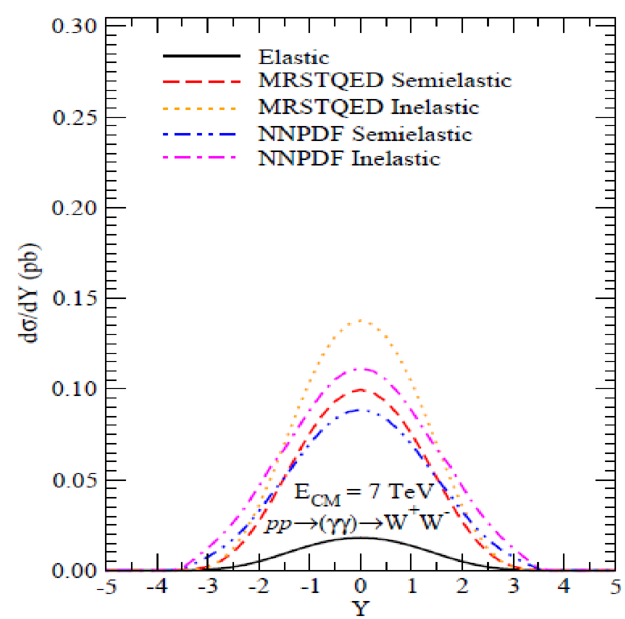

VPG, da Silveira, PRD92, 014013 (2015)

Photon - Hadron Interactions at the LHC

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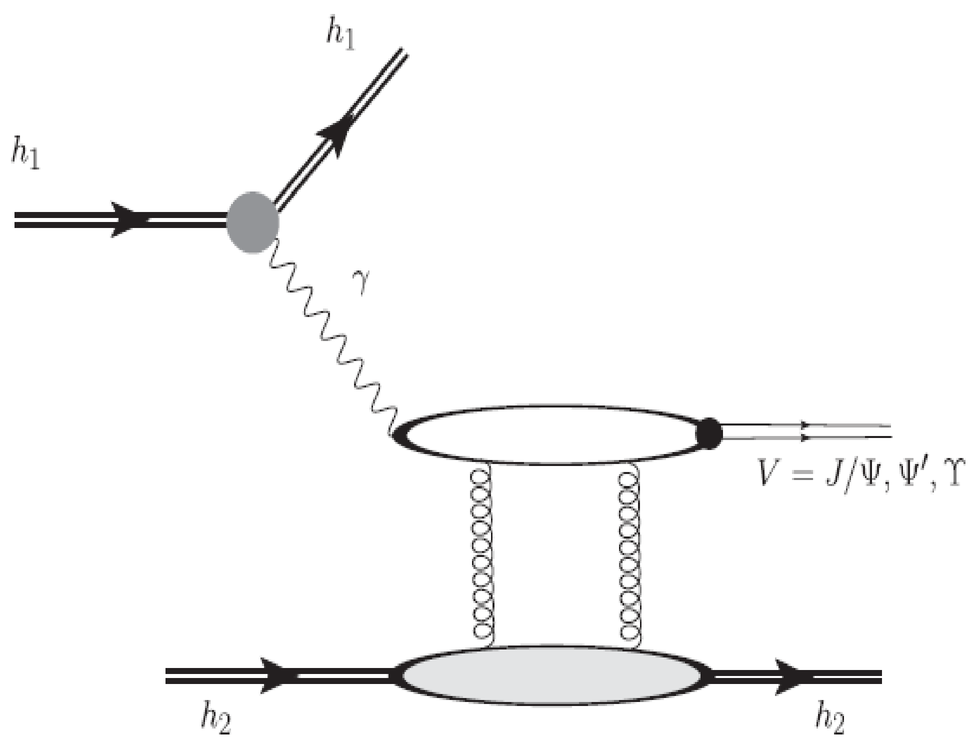
Photon - Hadron Interactions at the LHC

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

- Diffractive vector meson photoproduction at the LHC



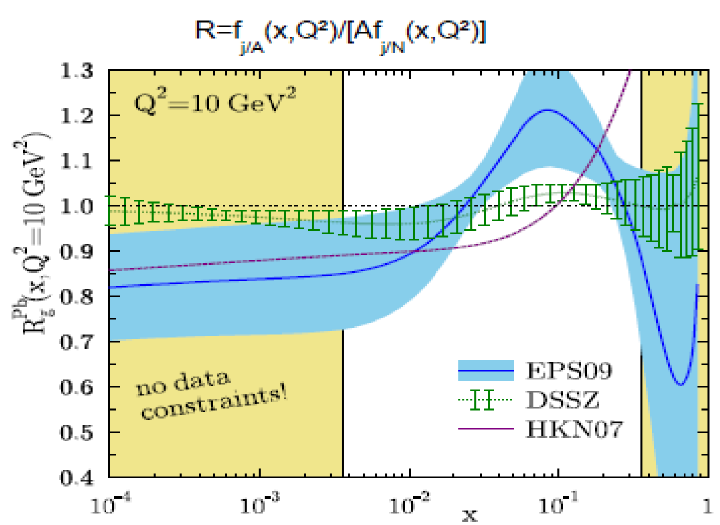
- Coherence condition implies $Q^2 \approx 0$.
- At leading logarithmic approximation the cross section is proportional to the square of the target gluon distribution.
- Diffractive vector meson photoproduction in hadronic colliders can be used as a probe of the gluon distribution[a].

[a] VPG, Bertulani, PRC65, 054905 (2002)

Diffractive vector meson photoproduction at the LHC
Probing the nuclear gluon distribution

$$R_g \equiv \frac{xg_A(x,Q^2)}{A \cdot xg_p(x,Q^2)}$$

- No nuclear effects: $R_g = 1$



Eskola, Puukkunen, arXiv:1401.2345

- The current eA experimental data does not constrain the small-x behaviour.
- Large theoretical uncertainty present in the kinematical range probed by LHC.

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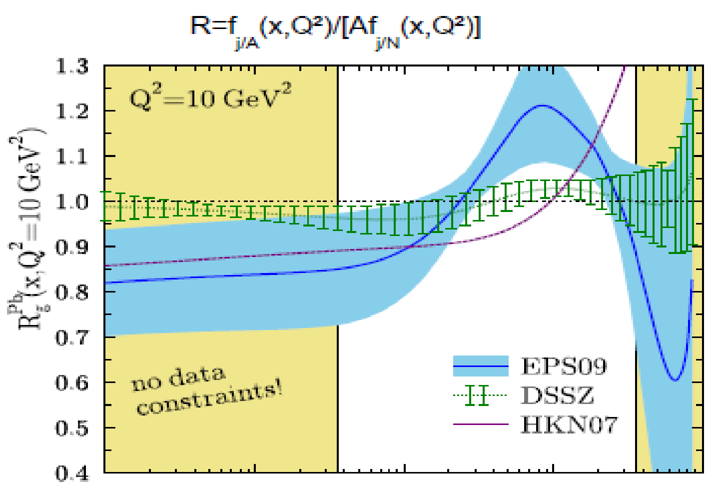

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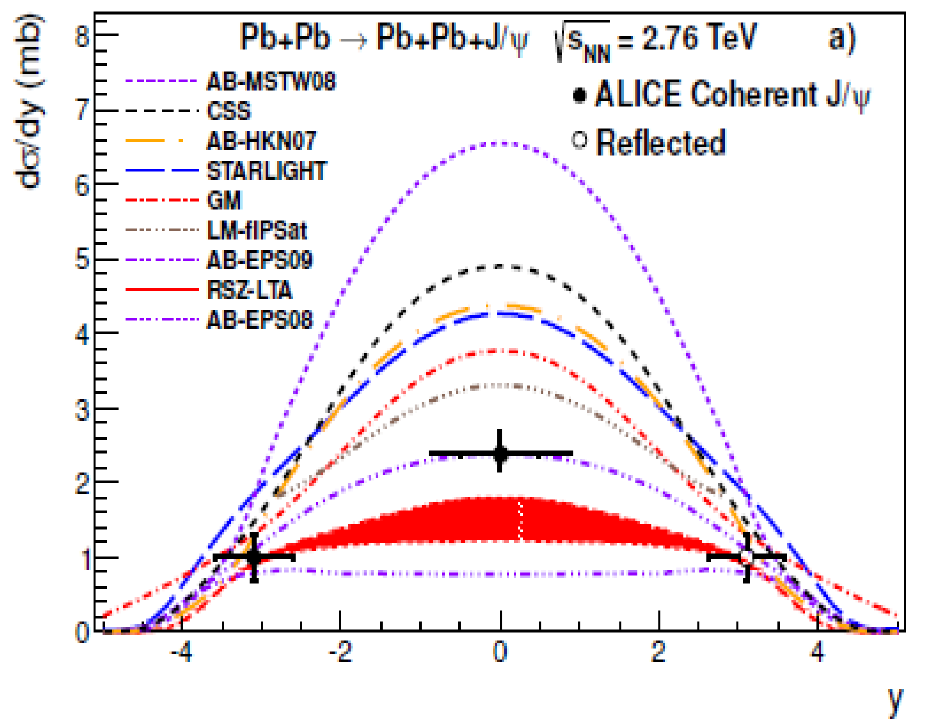


- Since $x = (M_{J/\psi}/s^{1/2}).\exp(-y)$ one have:

$$y = -3 \Rightarrow x = 0.02$$

$$y = 0 \Rightarrow x = 0.001 \text{ in } x g_A(x,Q^2).$$

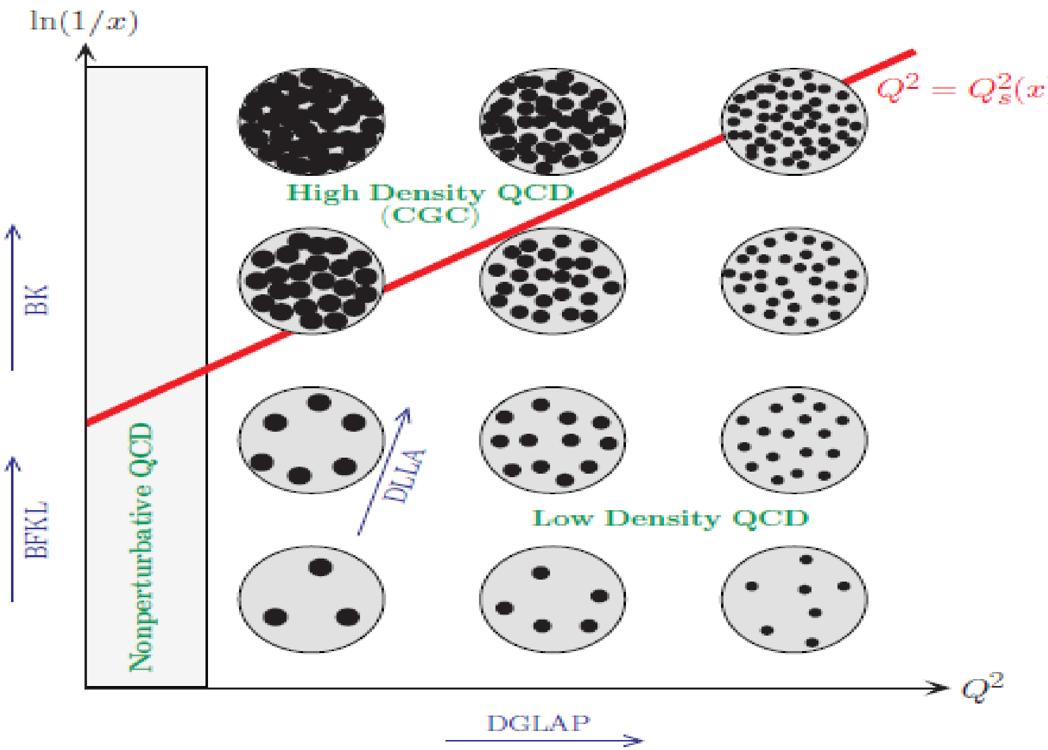
- First evidence of a strong nuclear shadowing at small - x

Diffractive vector meson photoproduction at the LHC
Probing the QCD dynamics at high energies

- At high energies we expect the breakdown of the leading logarithmic approximation and that the contribution of the nonlinear linear effects for the QCD dynamics become important.

- The description of the diffractive vector meson photoproduction should taken into account these effects.

- The study of this process in photon – induced interactions can be used as a probe of the **nonlinear effects** in the QCD dynamics and the **vector meson wave function** [a].



- Linear QCD evolution equations predict a power growth of gluon distribution as $x \to 0$ (violates unitarity).
- Number of gluons in the nucleon becomes so large that gluon recombine ⇒ Nonlinear effects
- Saturation scale Q_s (energy and atomic number dependent) defines the onset of nonlinear QCD dynamics.

[a] VPG, Machado, EPJC 40, 519 (2005)

Diffractive vector meson photoproduction at the LHC: Color Dipole Formalism

$$\frac{d\sigma\,[h_1+h_2\to h_1\otimes V\otimes h_2]}{d^2b dy} = \left[\omega N_{h_1}(\omega,b)\,\sigma_{\gamma h_2\to V\otimes h_2}(\omega)\right]_{\omega_L} + \left[\omega N_{h_2}(\omega,b)\,\sigma_{\gamma h_1\to V\otimes h_1}(\omega)\right]_{\omega_R}$$

$$\sigma(\gamma h\to Vh) = \int_{-\infty}^{0}\frac{d\sigma}{dt}\,dt = \frac{1}{16\pi}\int_{-\infty}^{0}|\mathcal{A}_T^{\gamma h\to Vh}(x,\Delta)|^2\,dt$$

$$\mathcal{A}_T^{\gamma h\to Vh}(x,\Delta) = i\int dz\,d^2\boldsymbol{r}\,d^2\boldsymbol{b}_h e^{-i[\boldsymbol{b}_h-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}}\,(\Psi^{V*}\Psi)_T\;2\mathcal{N}_h(x,\boldsymbol{r},\boldsymbol{b}_h$$

Overlap functions for Vector Mesons:

$$(\Psi_V^*\Psi)_T = \frac{\hat{e}_f e}{4\pi}\frac{N_c}{\pi z(1-z)}\{m_f^2 K_0(\epsilon r)\phi_T(r,z) - [z^2+(1-z)^2]\epsilon K_1(\epsilon r)\partial_r\phi_T(r,z)\}$$

Diffractive vector meson photoproduction at the LHC: Color Dipole Formalism

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Forward dipole – hadron scattering amplitude: Determined by the QCD dynamics

Diffractive vector meson photoproduction at the LHC: Color Dipole Formalism

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Forward dipole – hadron scattering amplitude: Determined by the QCD dynamics

- Proton: Constrained by Hera data for inclusive and exclusive processes taking into account the nonlinear effects
- Nucleus:

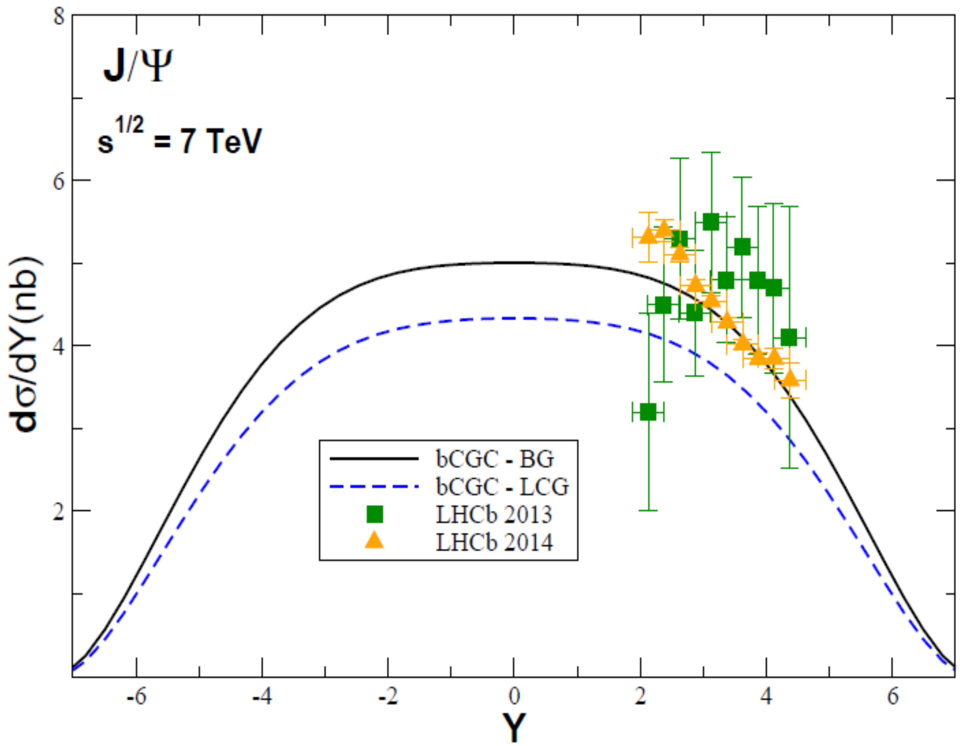
$$\mathcal{N}_A(x,\boldsymbol{r},\boldsymbol{b}_A) = 1-\exp\left[-\frac{1}{2}\,\sigma_{dp}(x,\boldsymbol{r}^2)\,T_A(\boldsymbol{b}_A)\right]$$

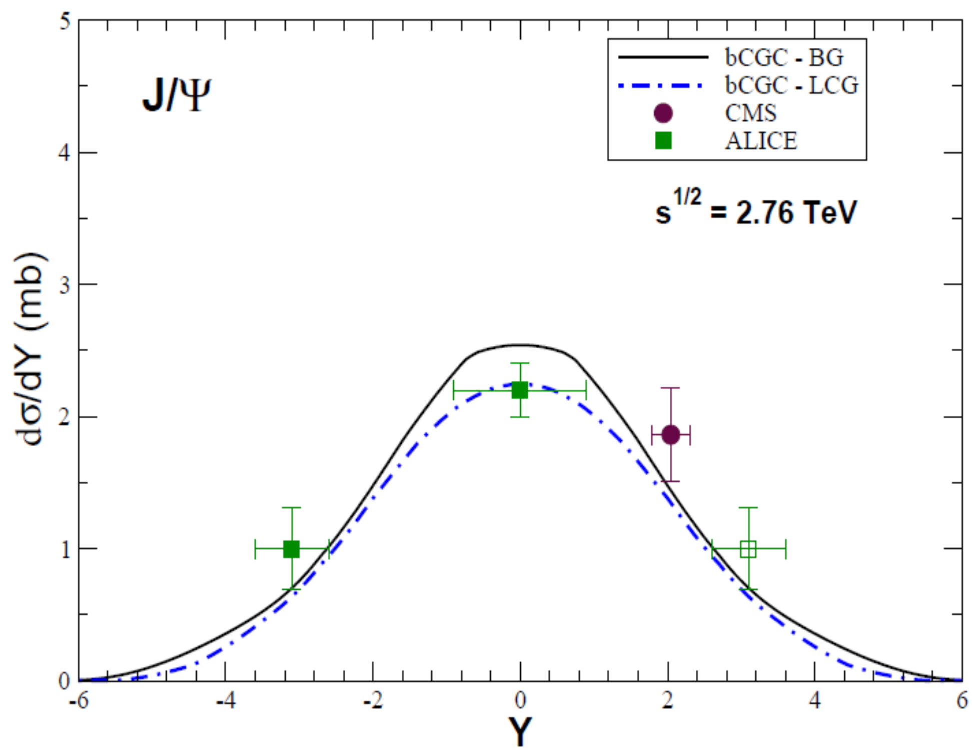
Sums all multiple elastic rescatterings of the dipole

$$\sigma_{dp}(x,\boldsymbol{r}^2) = 2\int d^2\boldsymbol{b}_p\,\mathcal{N}_p(x,\boldsymbol{r},\boldsymbol{b}_p)$$

Diffractive vector meson photoproduction at the LHC: Comparison with the Run I data

- Diffractive J/Ψ photoproduction in hadronic collisions [a]

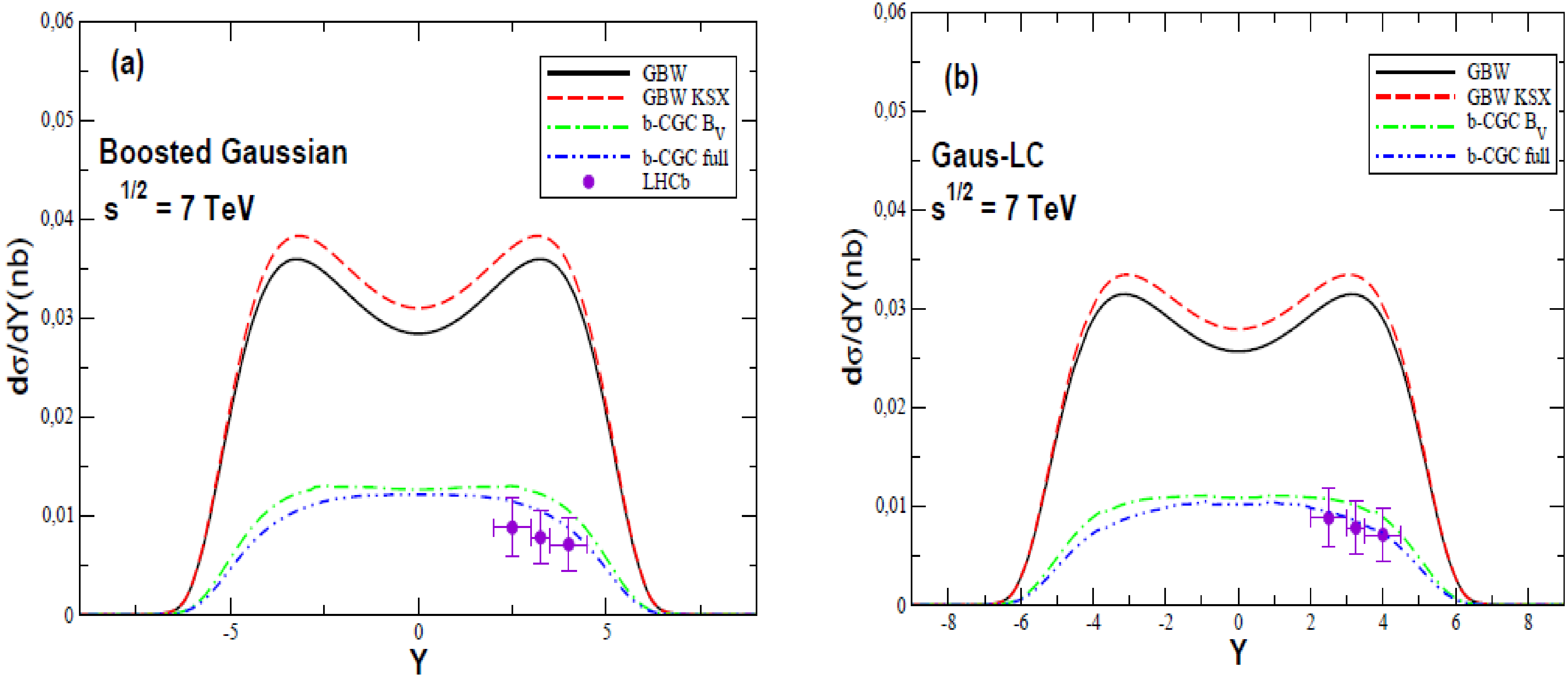




(a) VPG, Moreira, Navarra, PRD90, 15203 (2014)

Diffractive vector meson photoproduction at the LHC: Comparison with the Run I data

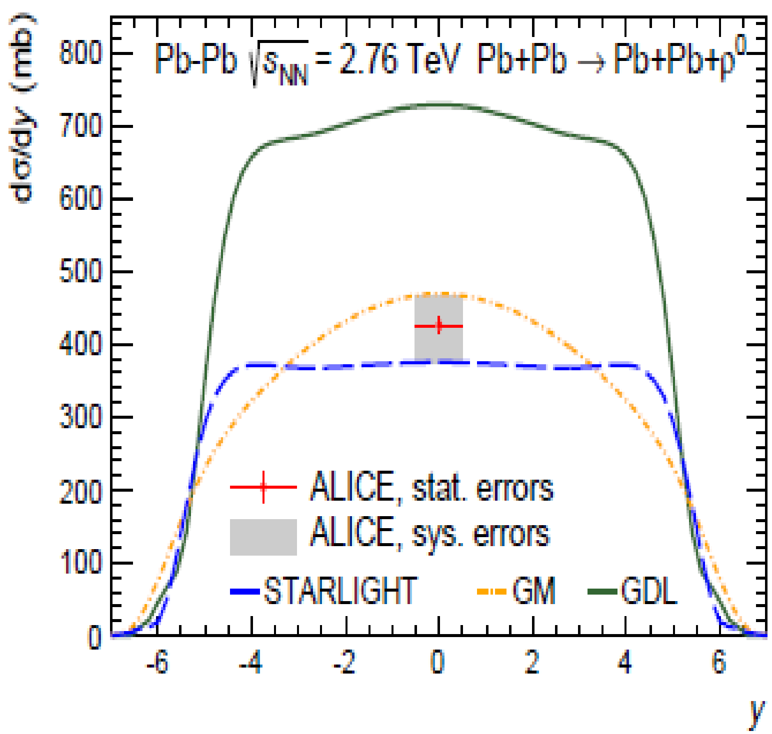
- Diffractive Υ photoproduction in hadronic collisions [b]

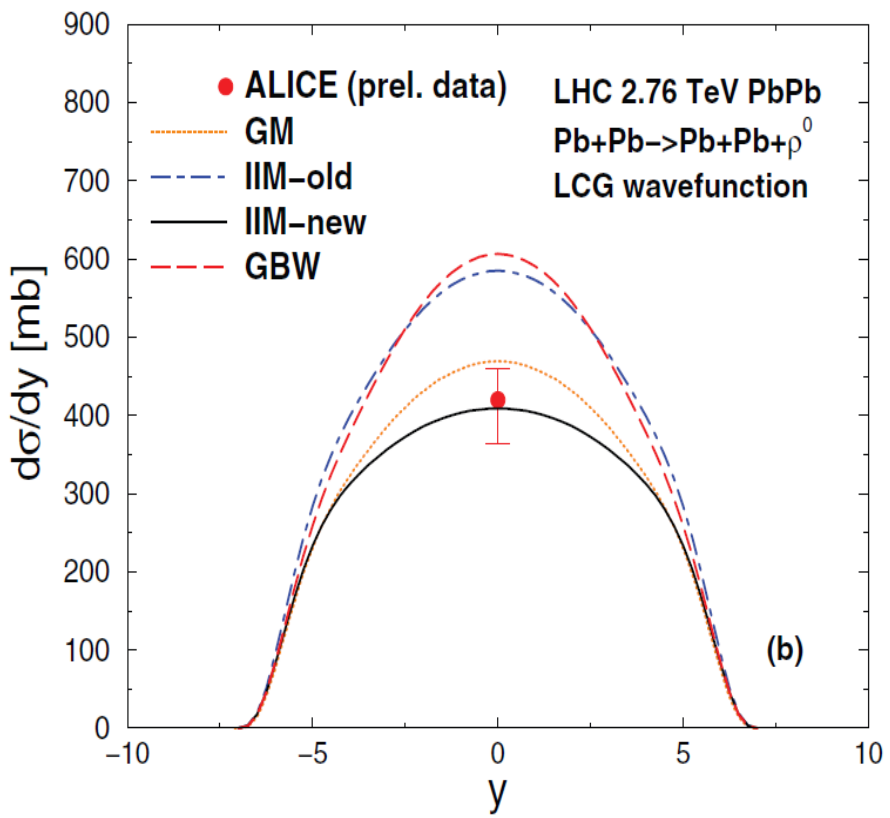


[b] VPG, Moreira, Navarra, PLB 472, 172 (2015)

Diffractive vector meson photoproduction at the LHC:
Comparison with the Run I data

- Diffractive ρ photoproduction in hadronic collisions [c]





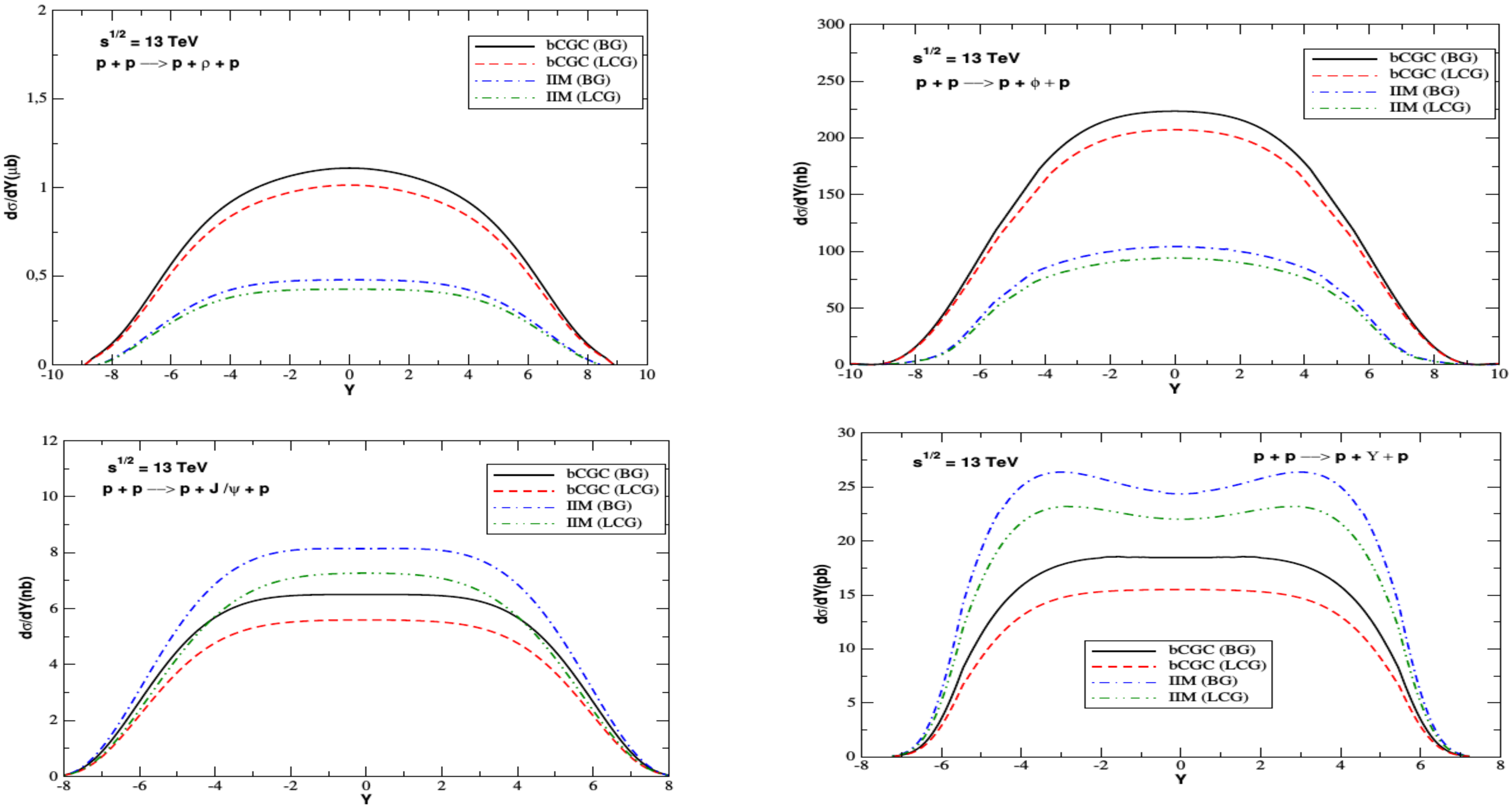
(c) VPG, Machado, EPJC 40, 519 (2005); PRC80, 054901 (2009); PRC84, 011902 (2011) Machado, dos Santos, PRC91, 025203 (2015)

Diffractive vector meson photoproduction at the LHC: Predictions for the Run II

(*) VPG, Machado, Moreira, Navarra, dos Santos (paper in preparation)

Diffractive vector meson photoproduction at the LHC: Predictions for the Run II

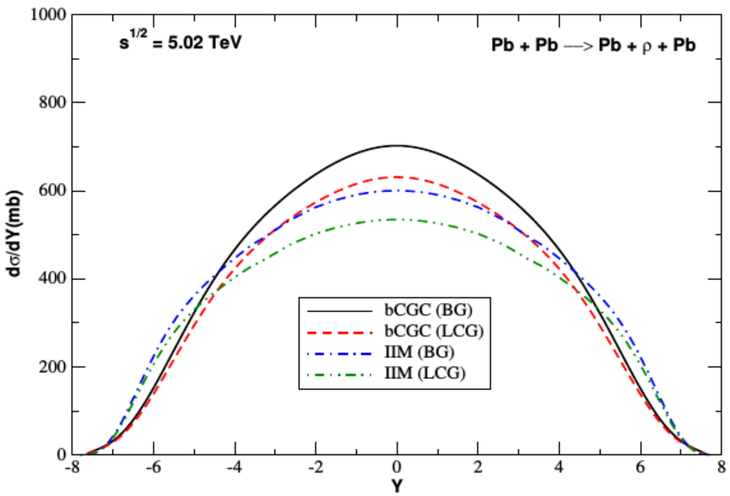
- Diffractive vector meson photoproduction in proton – proton collisions

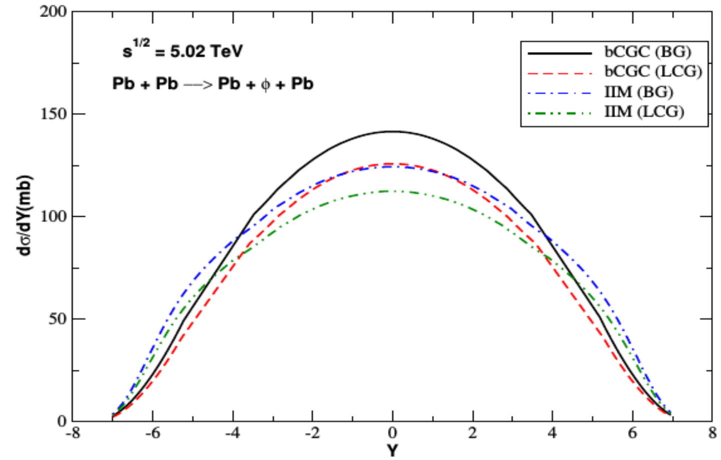


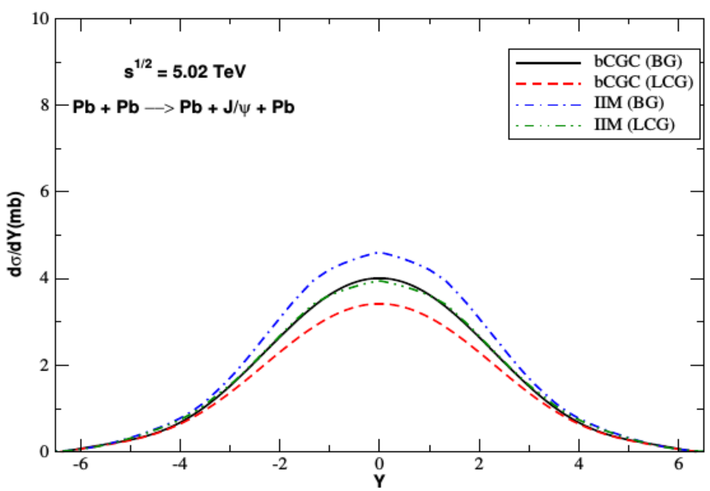
(*) VPG, Machado, Moreira, Navarra, dos Santos (paper in preparation)

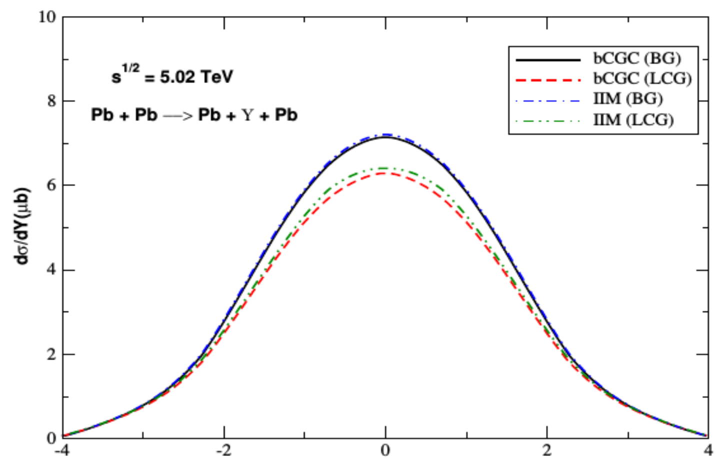
Diffractive vector meson photoproduction at the LHC: Predictions for the Run II

➢ Diffractive vector meson photoproduction in nucleus - nucleus collisions





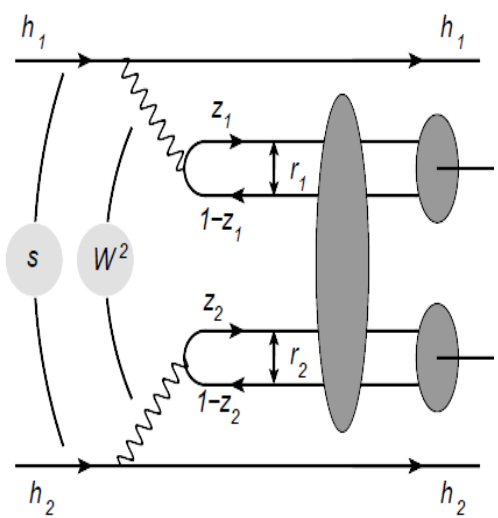


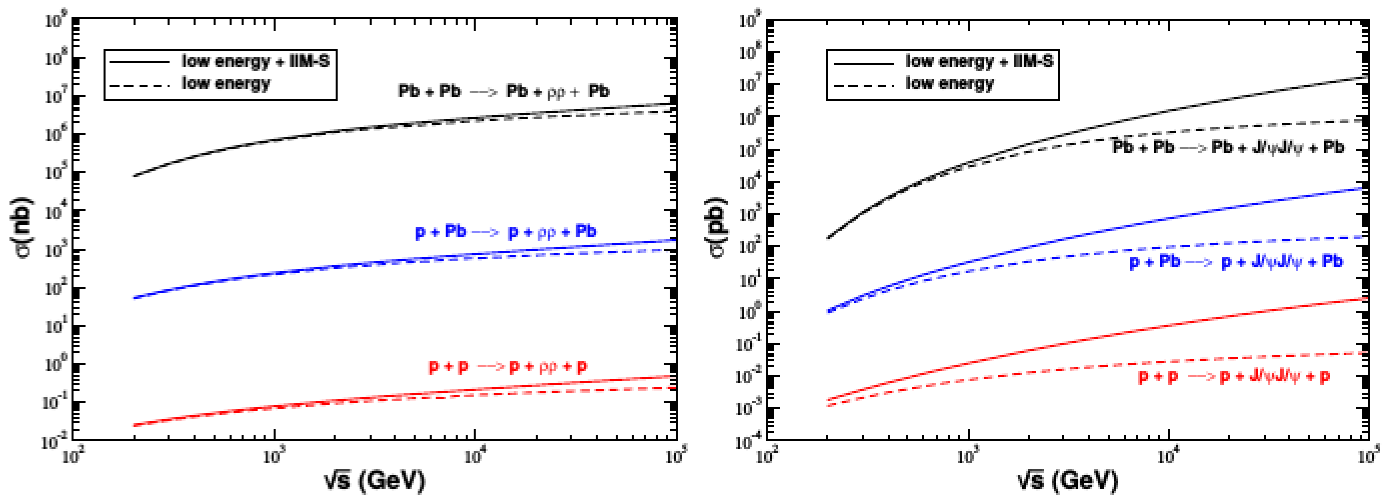


(*) VPG, Machado, Moreira, Navarra, dos Santos (paper in preparation)

Diffractive vector meson photoproduction at the LHC: Complementary studies in the Run II

➢ Double Vector Meson production in photon - photon interactions (*)



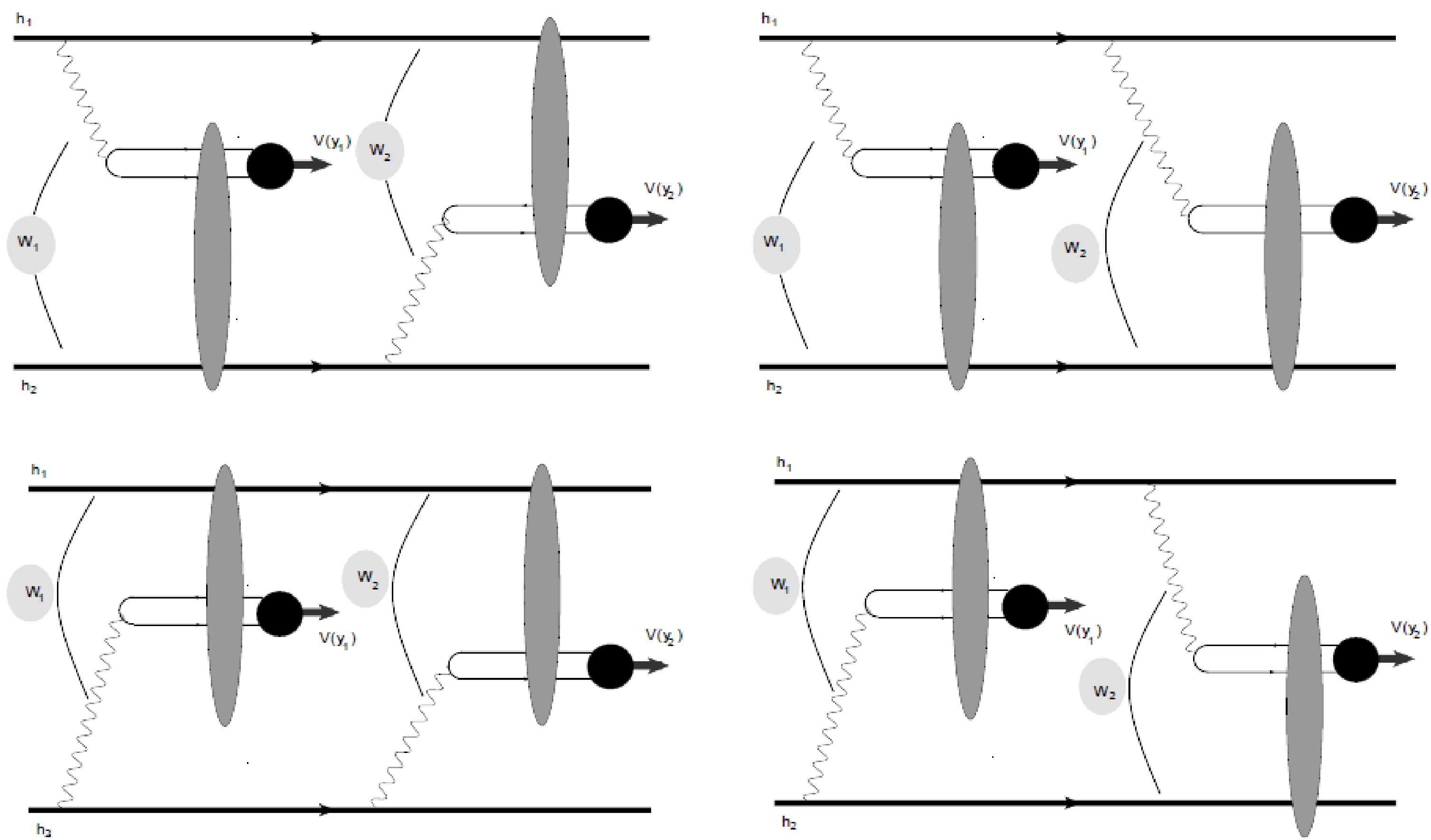


➢ The contribution associated to the description of the QCD dynamics at high energies contributes significantly for the double J/Ψ production.

(*) VPG, Moreira, Navarra, EPJC 76, 103 (2016)

Diffractive vector meson photoproduction at the LHC: Complementary studies in the Run II

➢ Double Vector Meson production in double photon - hadron interactions



(**) VPG, Moreira, Navarra, EPJC 76, 388 (2016)

Diffractive vector meson photoproduction at the LHC: Complementary studies in the Run II

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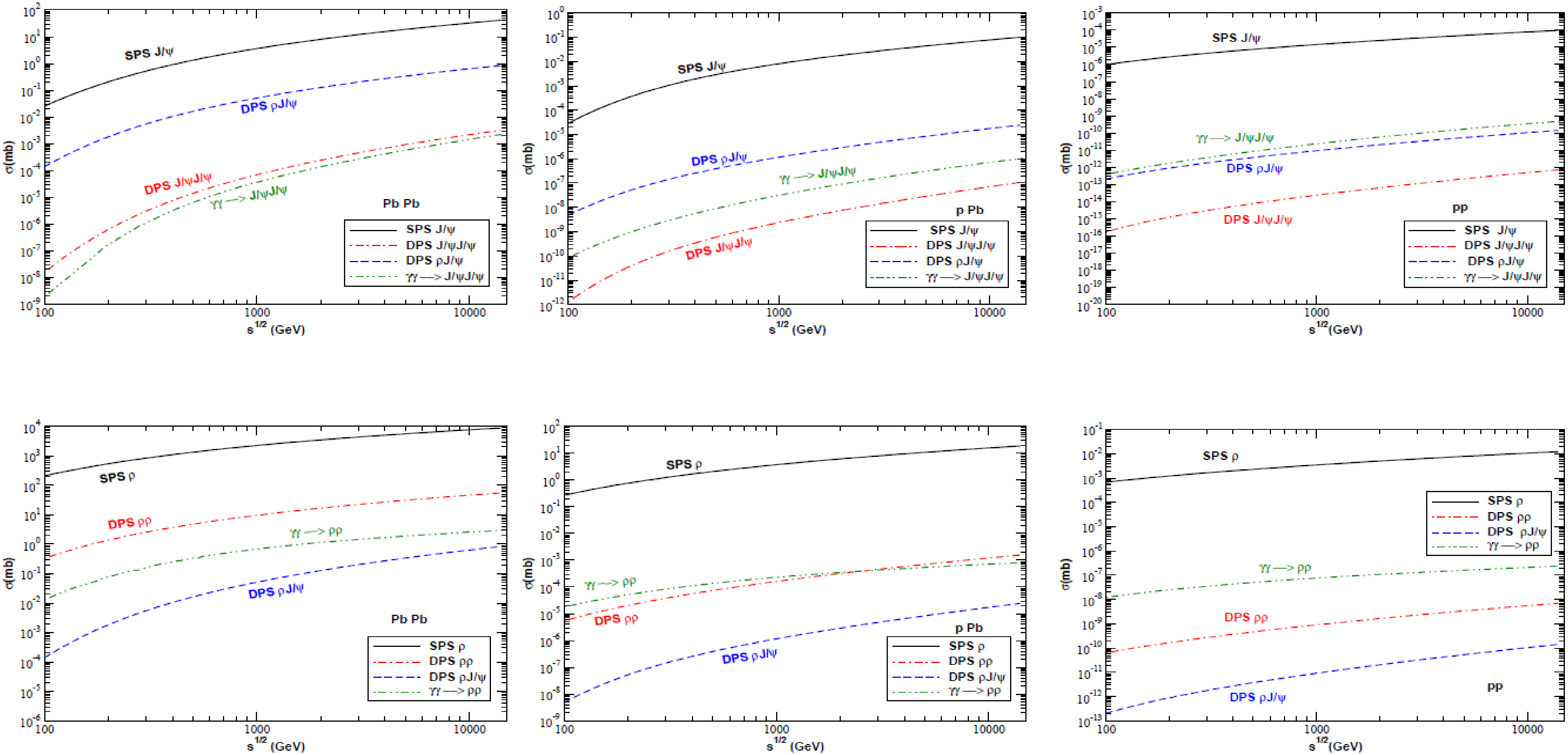


(**) VPG, Moreira, Navarra, EPJC 76, 388 (2016)

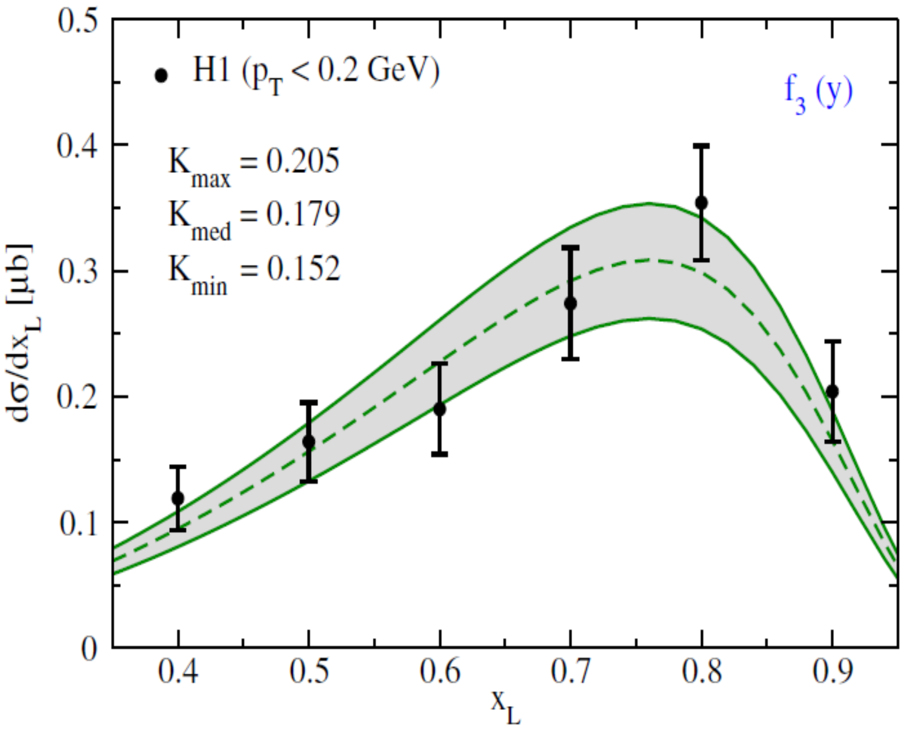
Diffractive vector meson photoproduction at the LHC: Complementary studies in the Run II

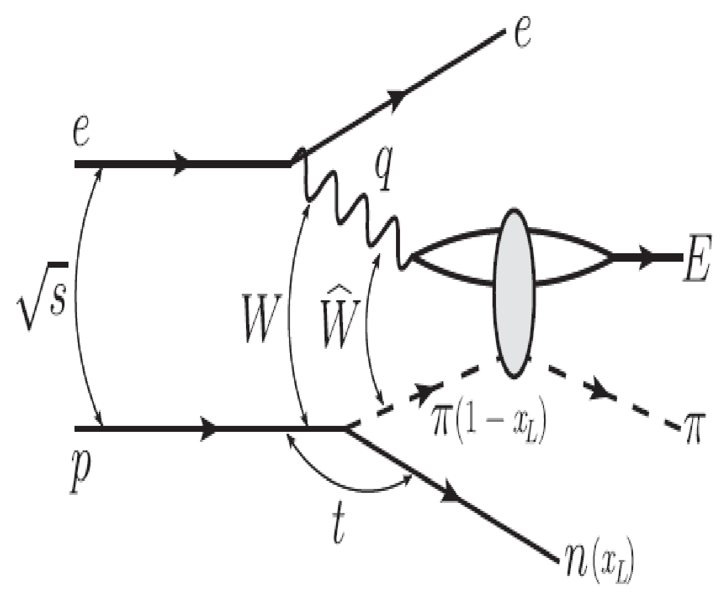
- Vector Meson photoproduction with a leading neutron

Diffractive vector meson photoproduction at the LHC: Complementary studies in the Run II

➢ Vector Meson photoproduction with a leading neutron at HERA (***)

$$\gamma p \to \rho^0 \pi^+ n$$



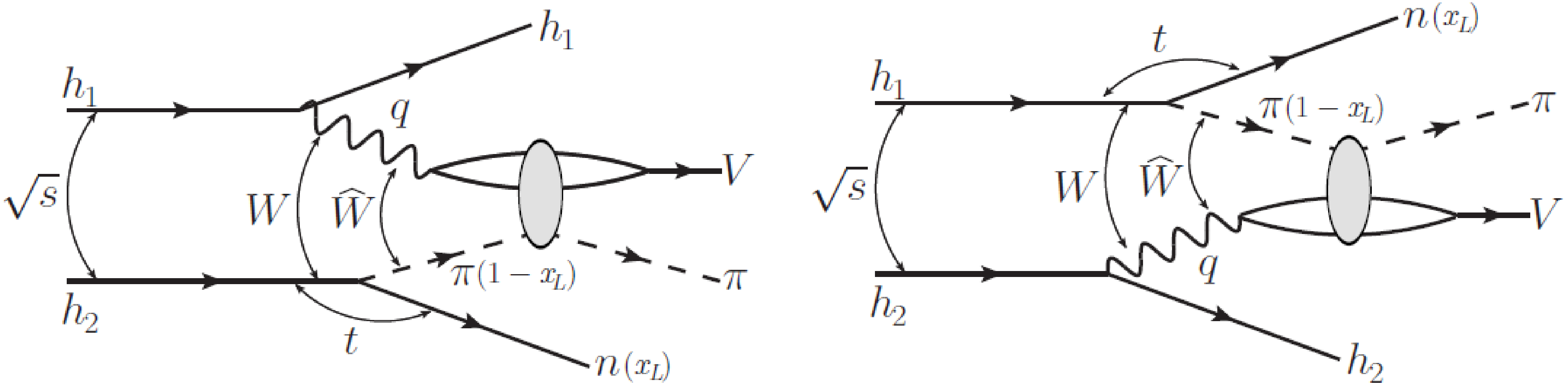


$$\sigma_{\gamma p \to V \otimes \pi + n}(W^2) = K \cdot \int dx_L dt \, f_{\pi/p}(x_L, t) \cdot \sigma_{\gamma\pi \to V \otimes \pi}(\hat{W}^2)$$

(***) VPG, Navarra, Spiering, PRD 93, 054025 *(2016)*

Diffractive vector meson photoproduction at the LHC: Complementary studies in the Run II

- Vector Meson photoproduction with a leading neutron at the LHC (**)



(**) VPG, Moreira, Navarra, Spiering PRD94, 014009 (2016)

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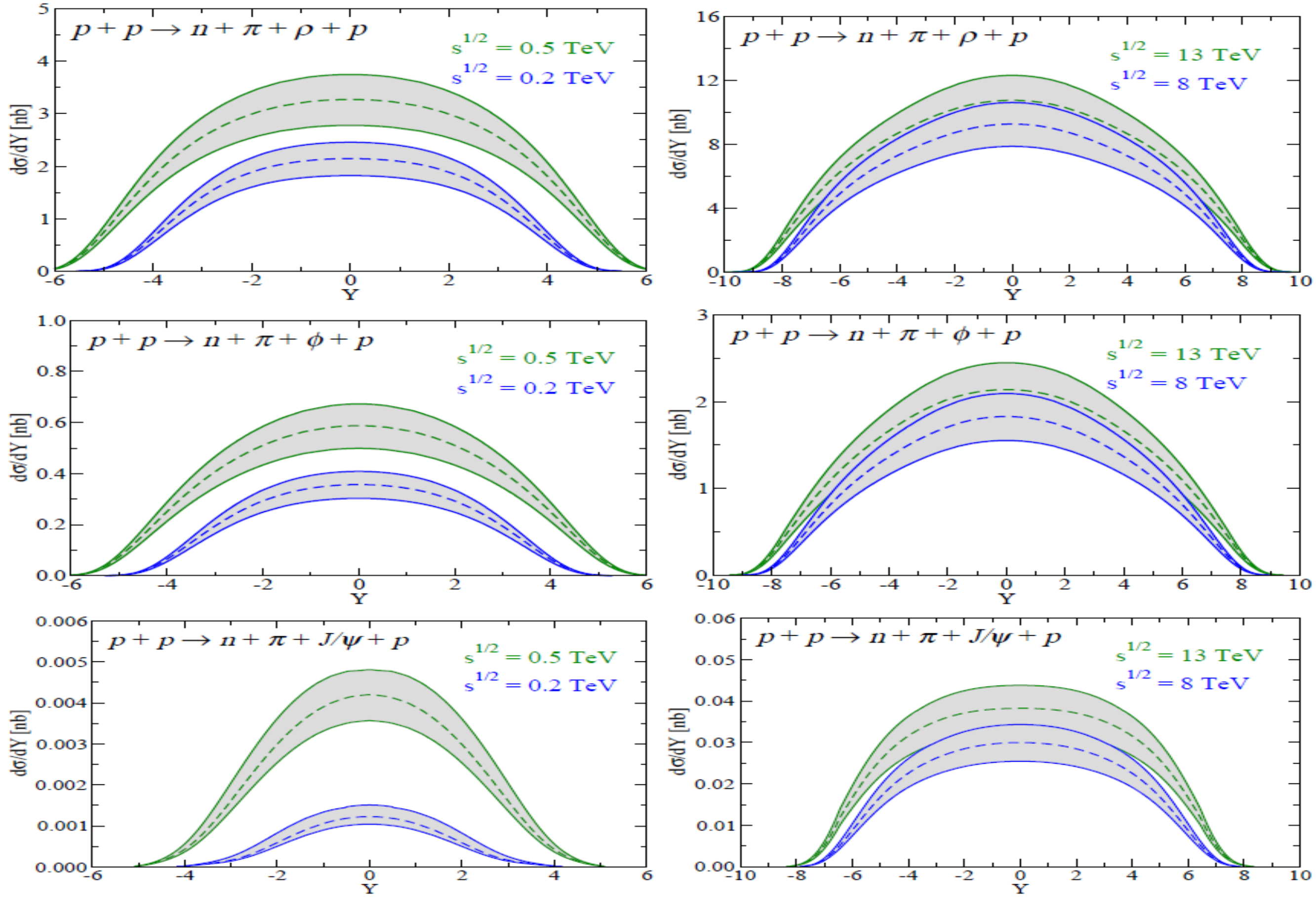

(**) VPG, Moreira, Navarra, Spiering PRD94, 014009 (2016)

Pomeron - Pomeron Interactions at the LHC

- Allows to search for Beyond Standard Model Physics in a clean environment.
- Some few examples:

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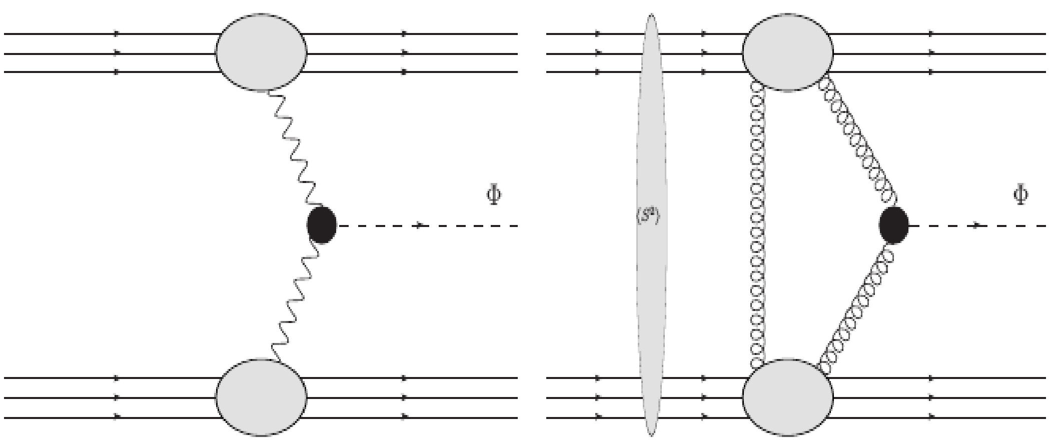
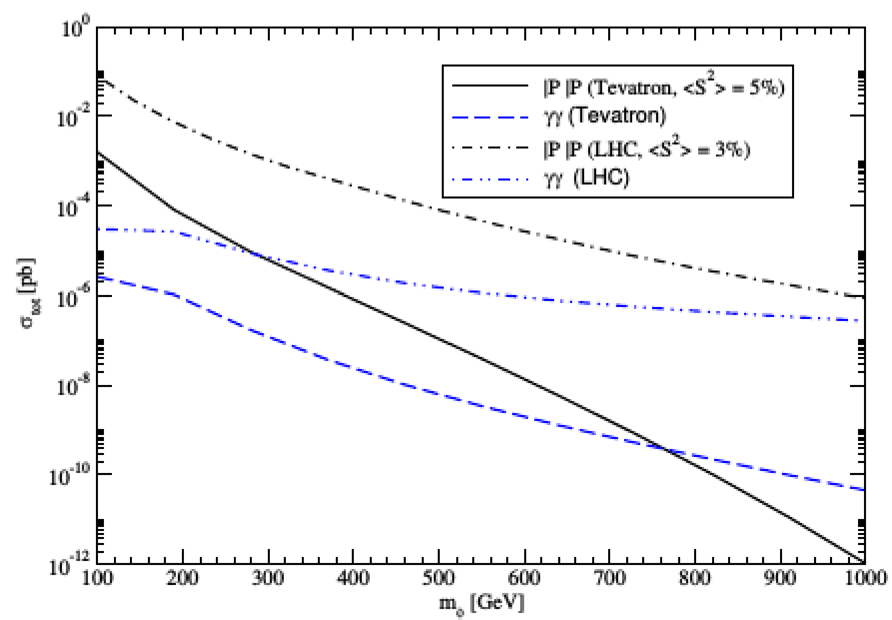
- ❑ Some few examples:

❖ Probing the Radion in Central Exclusive Processes (*)

- ➢ In the Randall-Sundrum (RS) scenario the compactification radius of the extra dimension is stabilized by the radion, which is a scalar field lighter than the graviton Kaluza-Klein states.





(*) VPG, Sauter, PRD89, 076003 (2014)

Pomeron - Pomeron Interactions at the LHC

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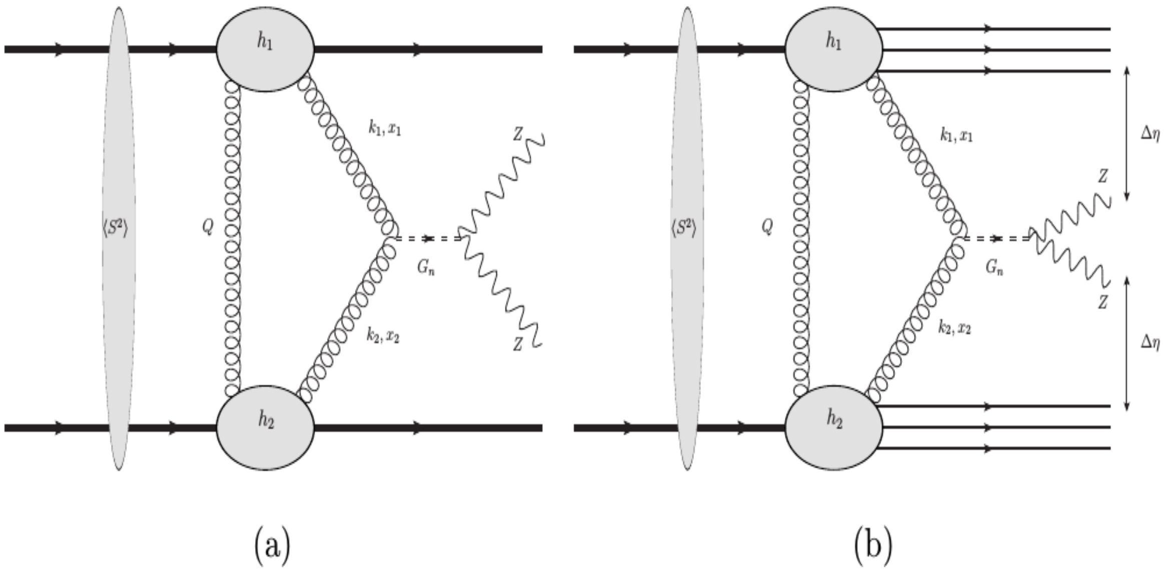
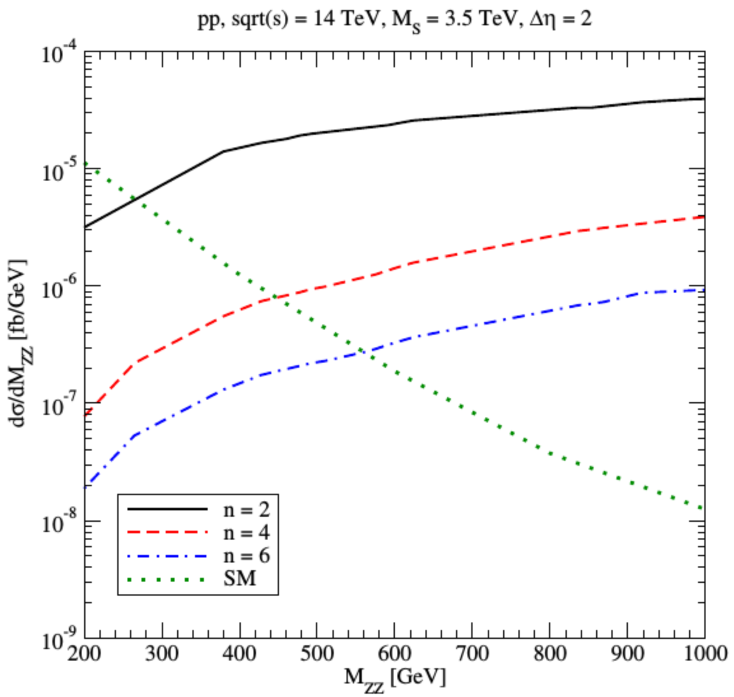
❖ Double Z production in the large extra dimensions scenario (**)





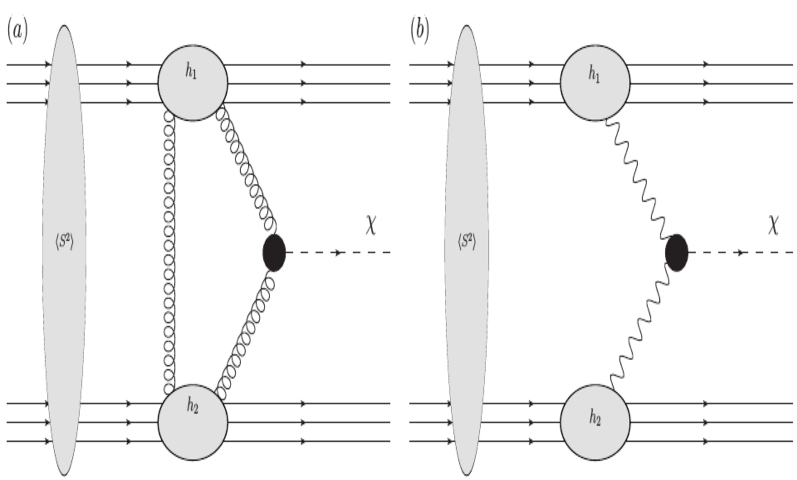
(**) VPG, Thiel, Sauter, PRD89, 076003 (2014)

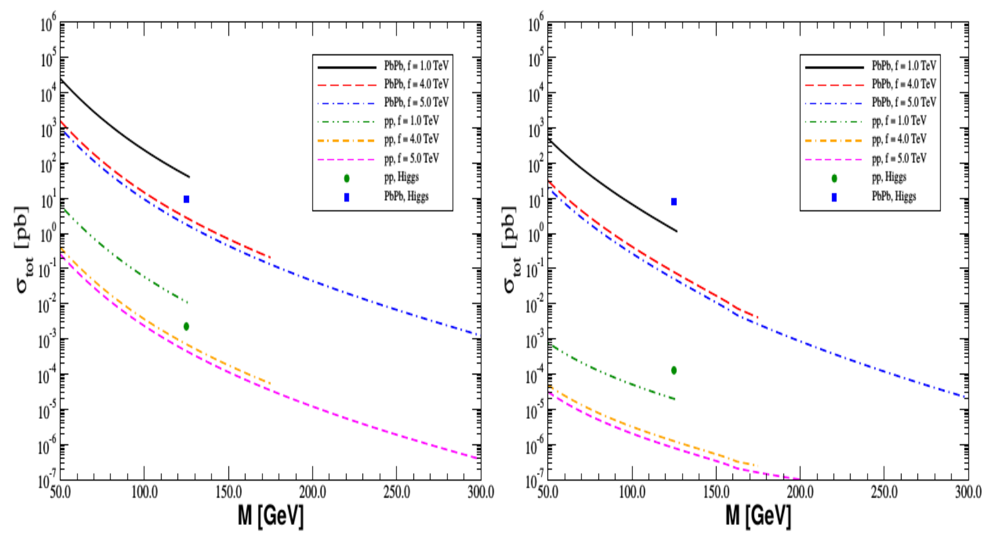
Pomeron - Pomeron Interactions at the LHC

- Allows to search by Beyond Standard Model Physics in a clean environment.
- Some few examples:

❖ Probing the Dilaton in Central Exclusive Processes at the LHC (***)

- The existence of a dilaton as a pseudo-Nambu-Goldstone boson in spontaneous breaking of scale symmetry is predicted in beyond standard model theories in which electroweak symmetry is broken via strongly coupled conformal dynamics.





(***) VPG, Sauter, PRD91, 035004 (2015)

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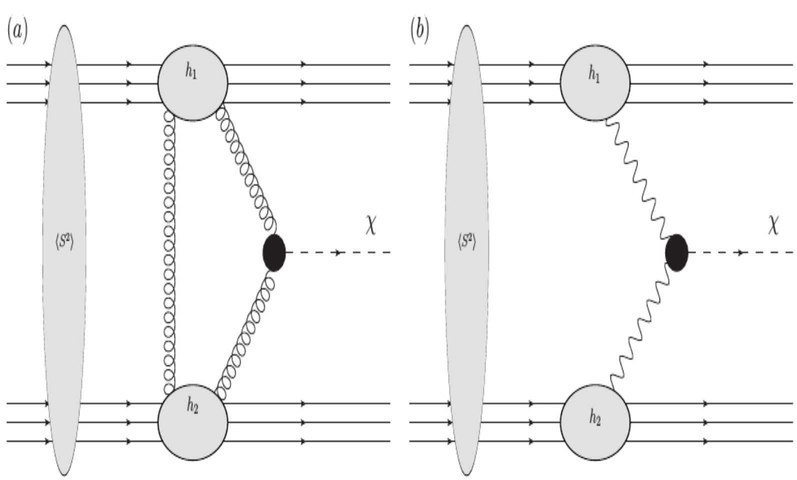
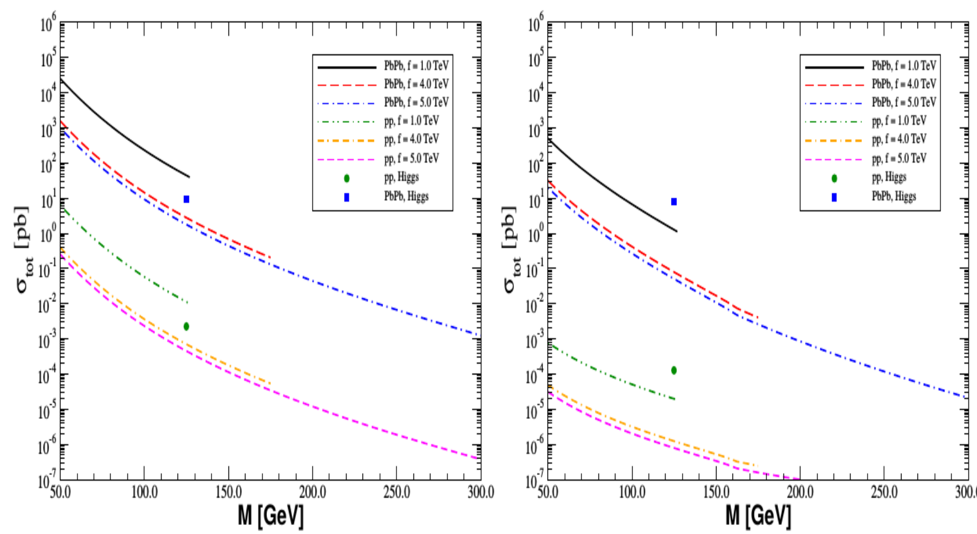
➢ Our results indicated that if the dilaton is massive ($M_\chi \geq 2\ M_W$), the study of dilaton production by IP IP interactions in pp collisions can be useful to determine its mass and the conformal energy scale.





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Summary

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LHC Forward Physics

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

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(in press)

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Thank you for your attention !

Extras

Diffraction in Hadronic Collisions: Definitions

y - rapidity

η - pseudorapidity

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

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

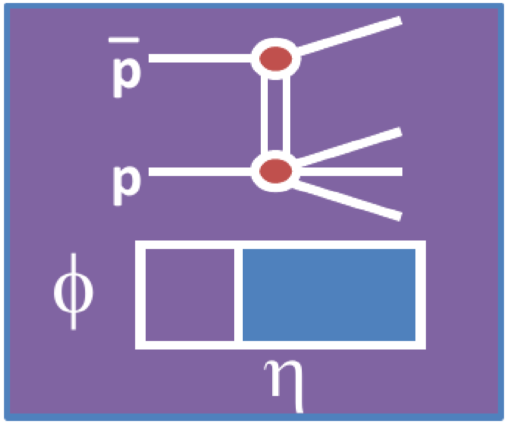
t - four-momentum transfer squared

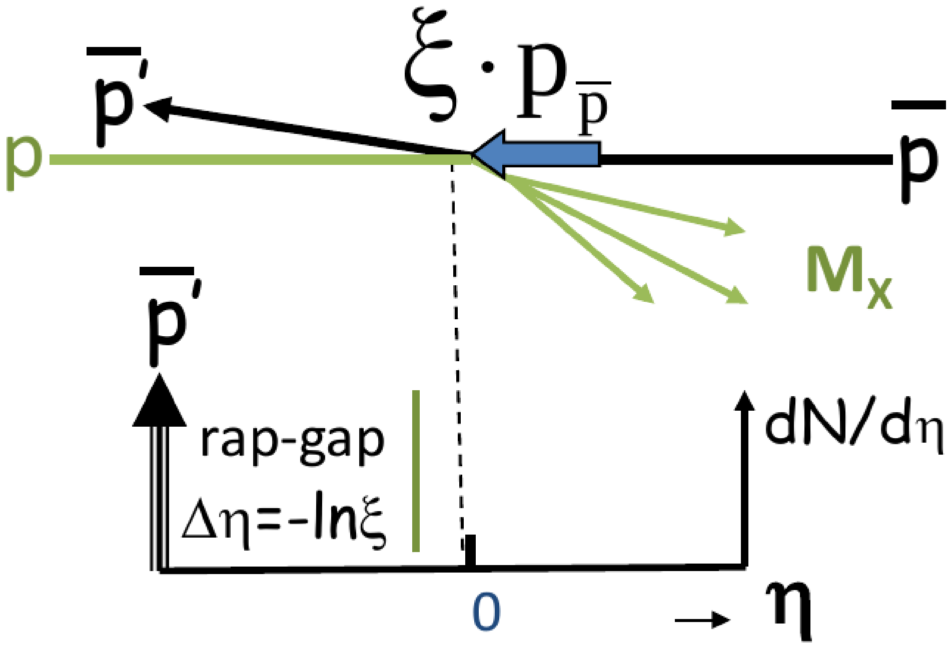
ξ - fractional momentum loss of pbar

M_X - mass of diffractive system X

$\xi = M_X^2/s$

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

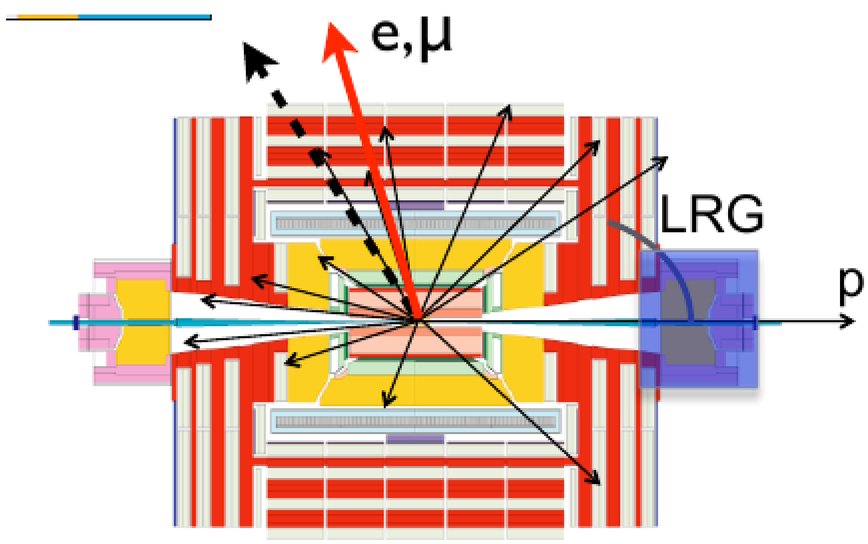


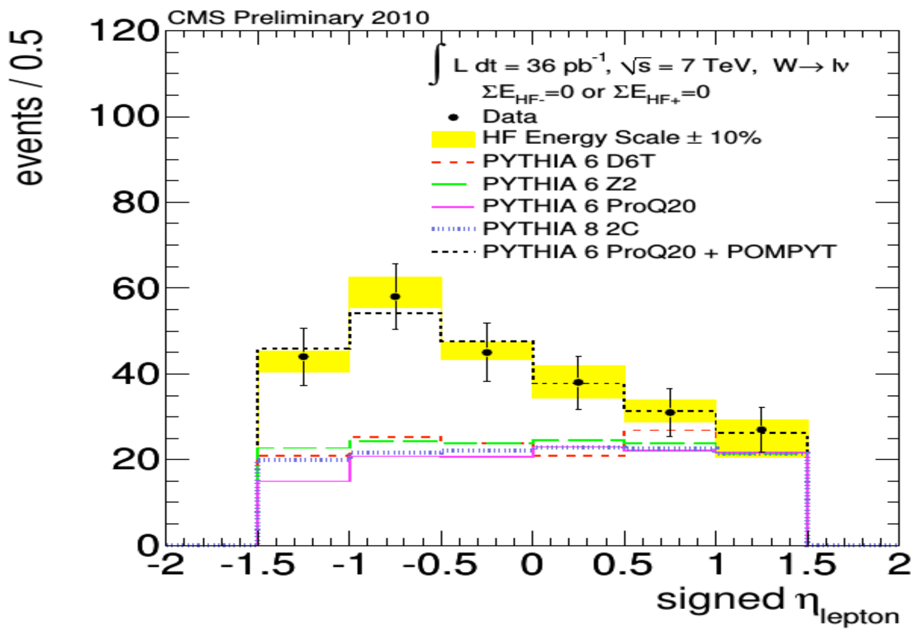


Hard Diffraction at the LHC

- ❑ 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

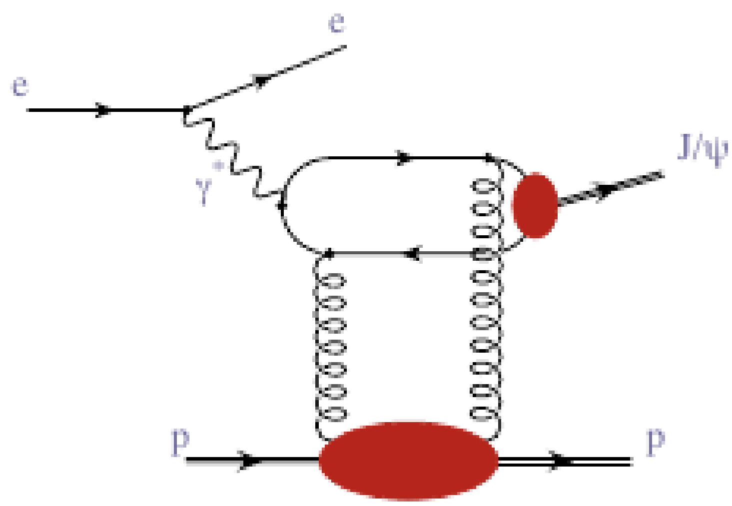
- **Exclusive events:**

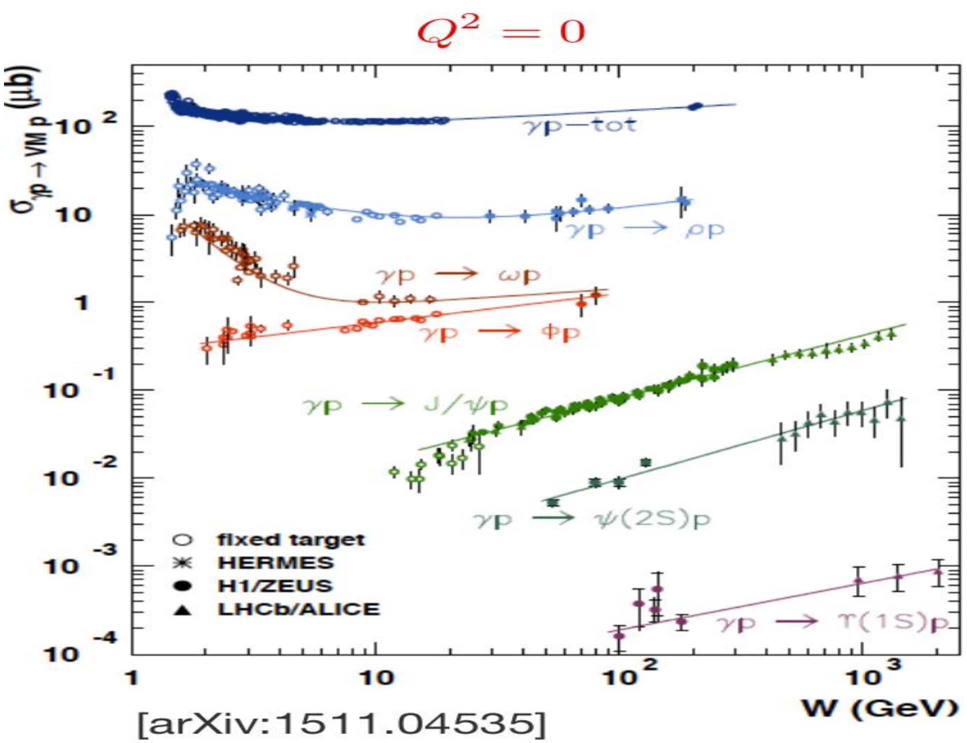
Few tracks + low pT particles

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

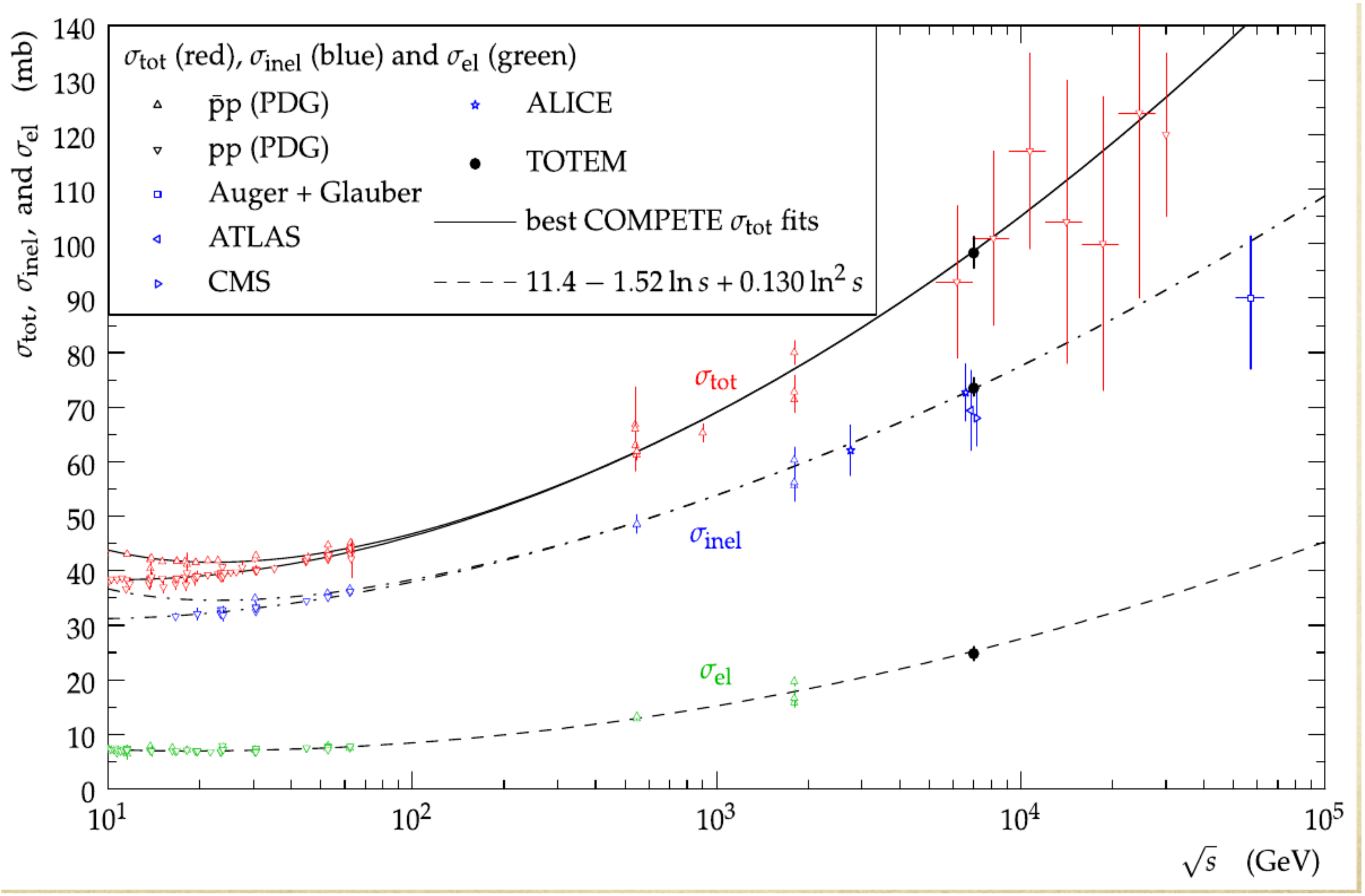




[arXiv:1511.04535]

- ➢ 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



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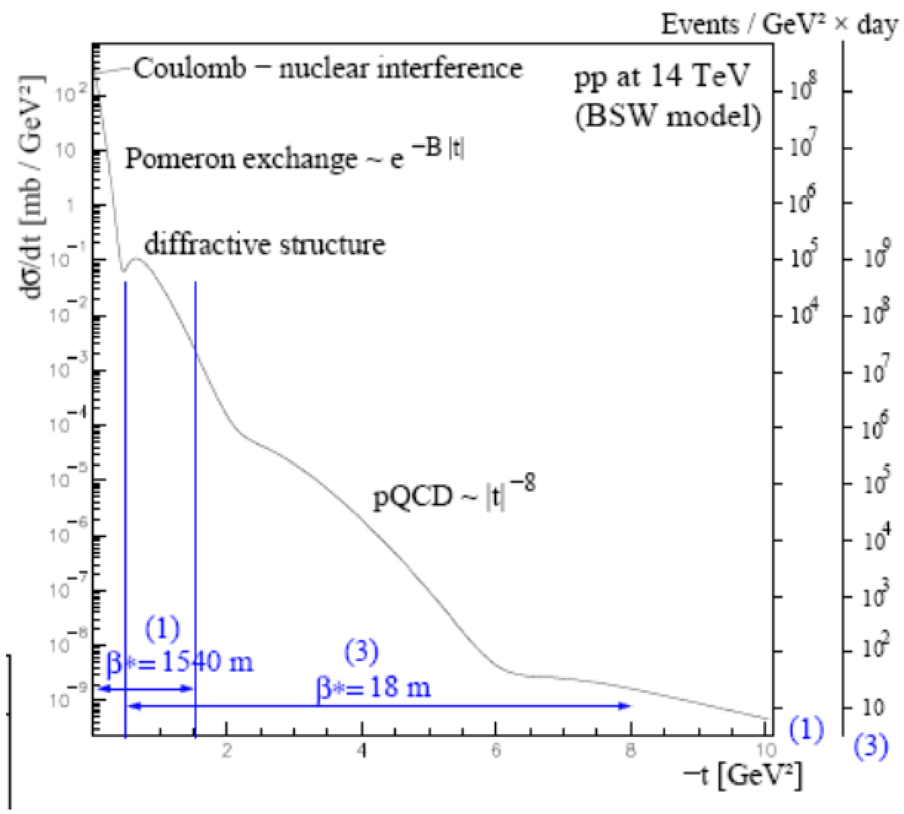

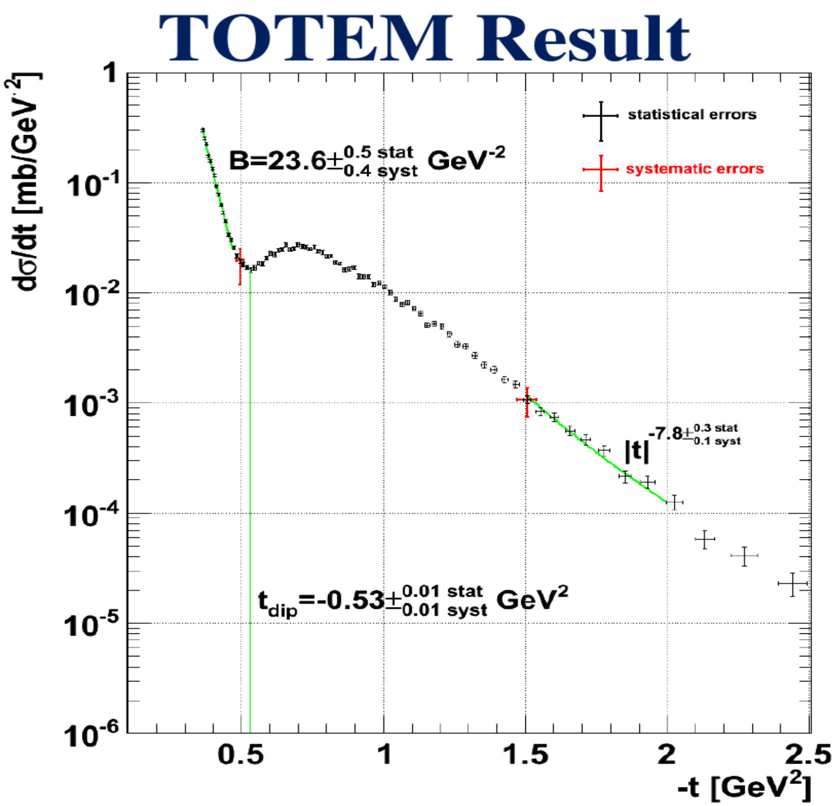

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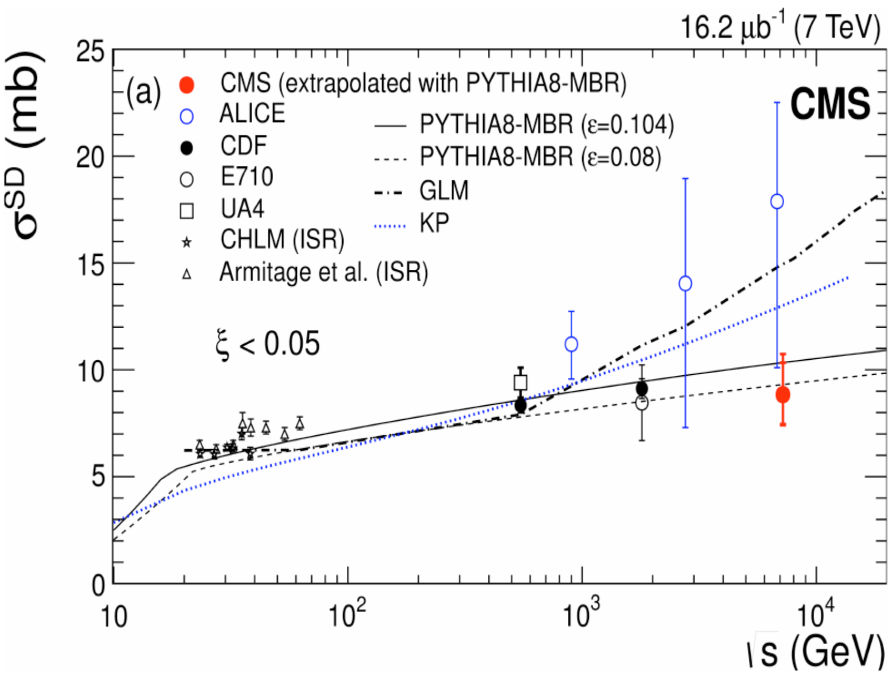
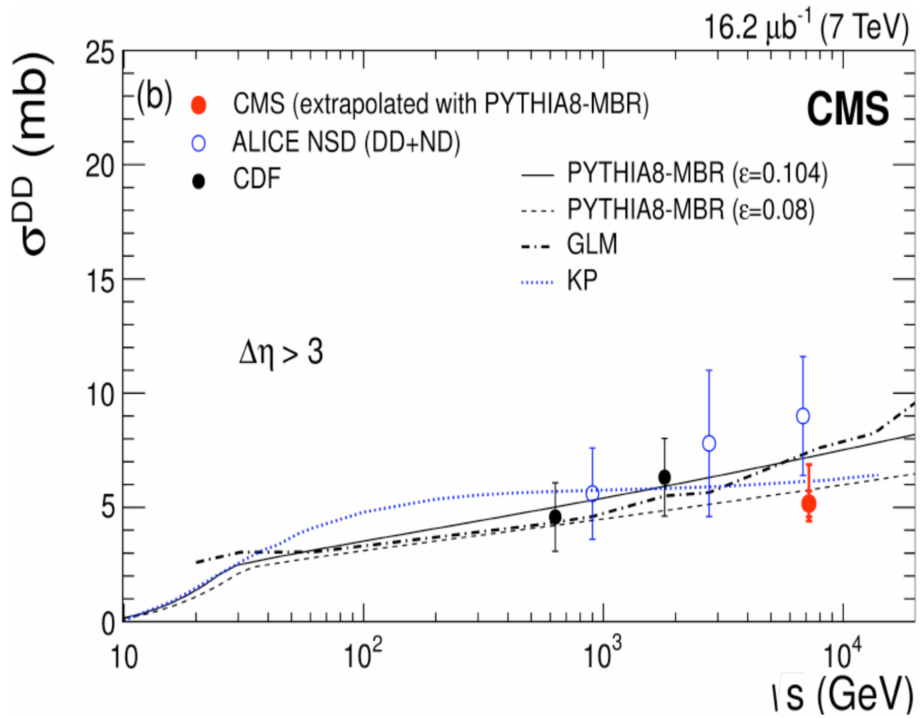
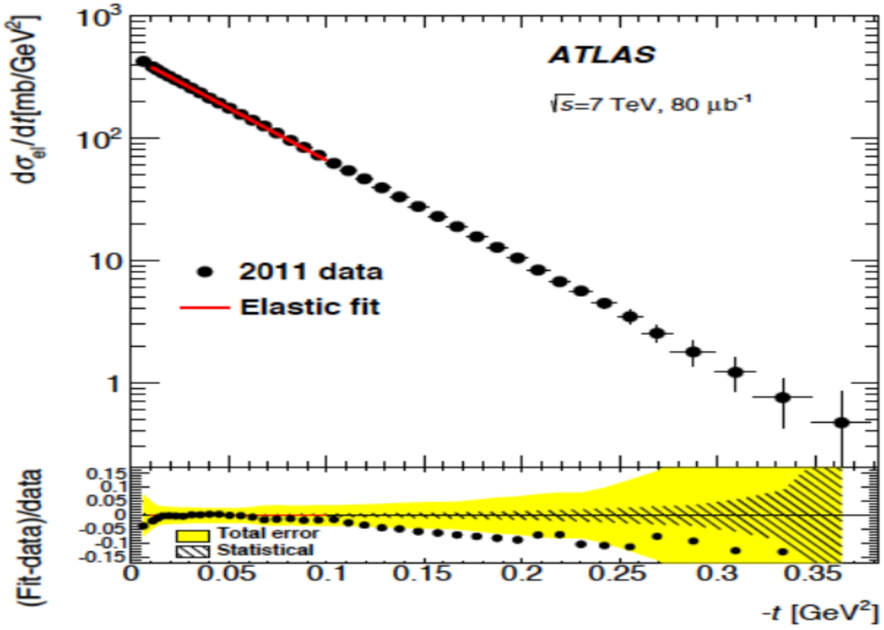




Soft Diffraction: Selected results

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