

# Hard Diffraction with Proton Tagging at the LHC

Maciej Trzebiński

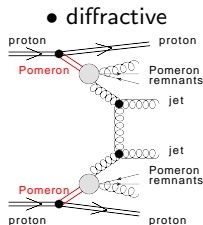
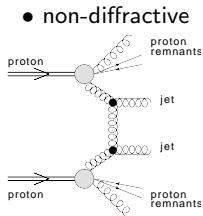
Institute of Nuclear Physics  
Polish Academy of Sciences



**Low-x 2014 Meeting**

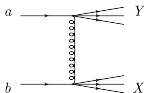
**18<sup>th</sup> June 2014**

■ **hard** – perturbative approach of calculating is valid; small cross-sections:



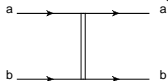
■ **soft** – large cross-sections:

● **non-diffractive:**

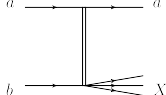


● **diffractive:**

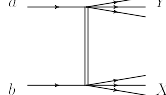
**Elastic Scattering**



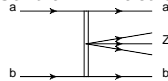
**Single Diffraction**



**Double Diffraction**



**Central Diffraction**



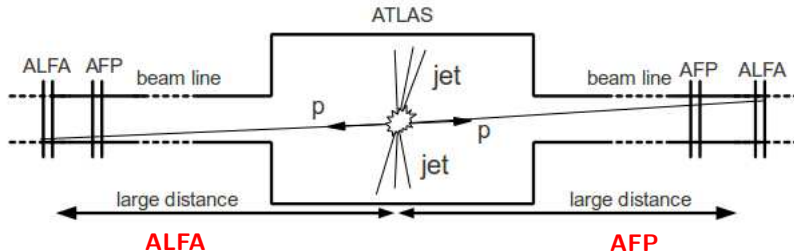
**Diffraction:**

- colour singlet exchanged,
- Pomeron (QCD = two gluons + ...).

Natural ways to seek for diffraction:

- rapidity gaps,
- forward protons.

**Intact protons** → natural diffractive signature → usually scattered at very small angles ( $\mu\text{rad}$ ) → detectors must be located far from the Interaction Point.



- **Absolute Luminosity For ATLAS**
- exist, 240 m from ATLAS IP
- soft diffraction (elastic scattering)
- special runs (high  $\beta^*$  optics)
- vertically inserted Roman Pots
- tracking detectors, resolution:  
 $\sigma_x = \sigma_y = 30 \mu\text{m}$

- **ATLAS Forward Proton**
- planned, 210 m from ATLAS IP
- hard diffraction
- nominal runs (collision optics)
- horizontally inserted Roman Pots
- tracking detectors, resolution:  
 $\sigma_x = 10 \mu\text{m}, \sigma_y = 30 \mu\text{m}$
- timing detectors, resolution:  
 $\sigma_t \sim 20 \text{ps}$

**Similar Devices @ IP5: CMS-TOTEM.**

$$\text{Luminosity: } L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \epsilon \cdot \beta^*} F$$

- $N_1$  and  $N_2$  – number of protons per bunch in beam 1 and 2,
- $n$  – number of bunches per beam,
- $f$  – revolution frequency,
- $\gamma$  – beam Lorentz factor,
- $\epsilon$  – beam emittance,
- $\beta^*$  – **betatron function at the IP**,
- $F$  – luminosity reduction factor due to the crossing angle at the IP.

## Data collecting strategies

hard processes, potential discoveries

↓  
small cross sections

↓  
rare events

↓  
much luminosity needed

↓  
maximise  $N_1$ ,  $N_2$ ,  $n$ ,  $1/\beta^*$

soft processes, elastic scattering

↓  
large cross sections

↓  
clean environment needed

↓  
minimise pile-up, pp interactions within  
a beam and beam divergence

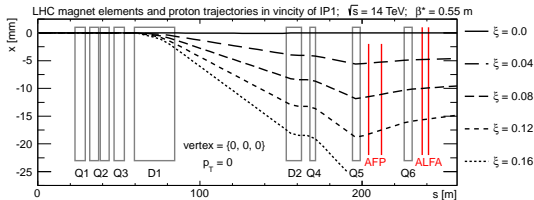
↓  
optimise  $N_1$ ,  $N_2$ ,  $n$ ,  $\beta^*$

forward protons: access to wide range  
of relative energy loss ( $\xi$ )

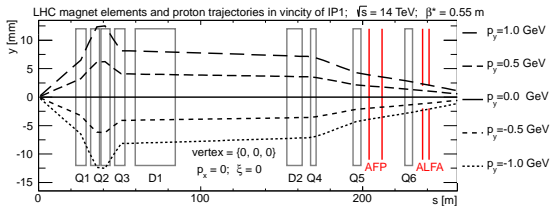
forward protons: access to as low  $t$   
values as possible

Proton trajectory is determined by the LHC magnetic field.

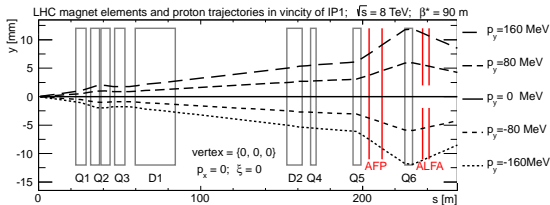
**collision optics,**  
**ALFA and AFP:**  
 trajectory due to  $\xi$   
 $\xi = 1 - E_{proton}/E_{beam}$



**collision optics,**  
**ALFA and AFP:**  
 trajectory due to  $p_y$



**special high- $\beta^*$  optics,**  
**ALFA:**  
 improve acceptance in  
 $p_T$



Ratio of the number of protons with a given relative energy loss ( $\xi$ ) and transverse momentum ( $p_T$ ) that crossed the active detector area to the total number of the scattered protons having  $\xi$  and  $p_T$ .

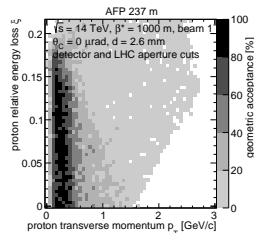
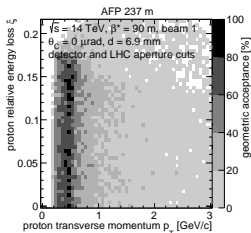
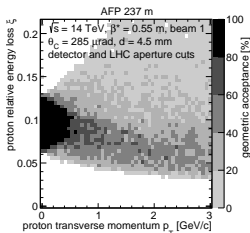
optics

$\beta^* = 0.55$  m  
nominal (*collision*)

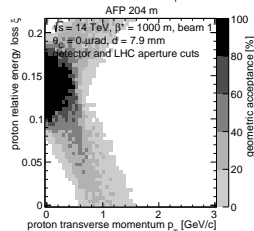
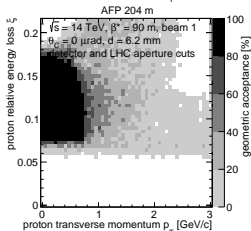
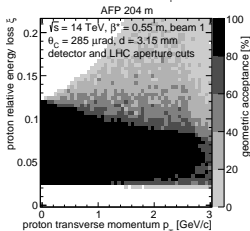
$\beta^* = 90$  m  
special (*high- $\beta^*$* )

$\beta^* = 1000$  m  
special (*high- $\beta^*$* )

ALFA



AFP



## Collected data

- $\sqrt{s} = 7$  TeV,  $\beta^* = 90$  m
- $\sqrt{s} = 8$  TeV,  $\beta^* = 90$  m
- $\sqrt{s} = 8$  TeV,  $\beta^* = 1000$  m

## Future: very low pile-up scenarios ( $\mu \sim 0.05$ )

- detectors: ALFA or AFP
- optics: collision or high  $\beta^*$ , few very low intensity bunches
- goals: measure total cross-section and properties of soft diffraction

## Future: low pile-up scenarios ( $\mu \sim 1$ )

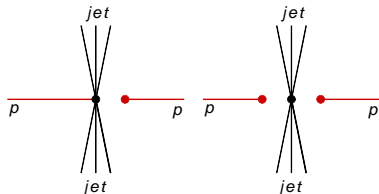
- detectors: ALFA or AFP
- optics: collision or high  $\beta^*$ , low intensity bunches
- goal: measure properties of hard diffraction

## Future: high pile-up scenarios ( $\mu \sim 50$ )

- detectors: AFP
- optics: collision, join all ATLAS runs
- goals: measure exclusive jet production, discovery physics

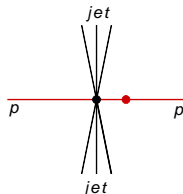
**Signal:** DPE JJ production – two jets in central region + two intact protons

Single Tagged Soft Interaction(ST)



SD JJ + ST    ND JJ + ST + ST

Double Tagged Soft Interaction(DT)



ND JJ + DT

Single Tag (ST) Interactions

	probability				
default	0.18	0.045	–	0.0055	0.038
MBR	0.12	0.040	0.42	0.0054	0.030
	cross section [mb]				
default	2.3	0.40	–	0.32	3.0
MBR	1.3	0.38	0.34	0.30	2.3
	SD	DD	CD	ND	MB

Double Tag (DT) Interactions

	probability [ $10^{-3}$ ]				
default	0.47	0.37	–	0.014	0.13
MBR	0.31	0.36	26.0	0.012	0.37
	cross section [ $\mu\text{b}$ ]				
default	6.1	3.3	–	0.81	10
MBR	3.5	3.4	21	0.67	28
	SD	DD	CD	ND	MB

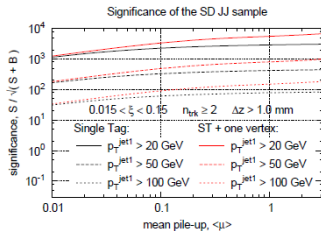
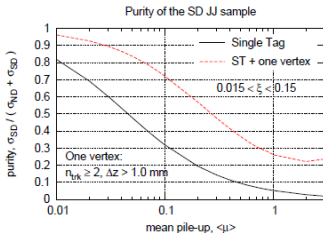
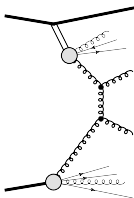
default – Schuler and Sjöstrand (POMFLUX = 1)

MBR – Minimum Bias Rockefeller (POMFLUX = 5)

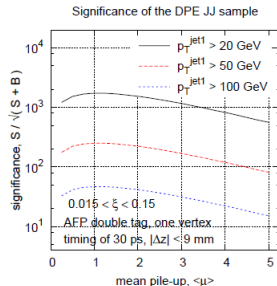
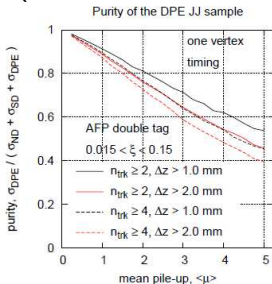
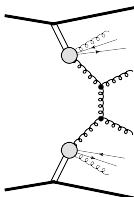


## Motivation: gap survival probability, gluon distribution in Pomeron.

### Single diffractive jets

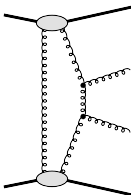


### Central diffractive (double Pomeron exchange) jets



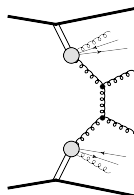
## Exclusive jets

- Two intact protons
- No Pomeron remnants
- All particles measured



## For comparison: CD (DPE) jets

- Two intact protons
- Pomeron remnants
- Remnants escape

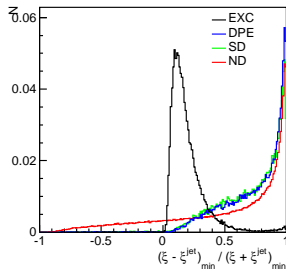


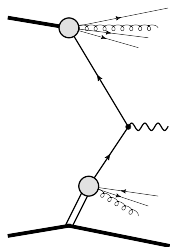
- **Motivation: verification of QCD production models, unintegrated gluon PDFs.**

- Small cross section for exclusive processes  $\rightarrow$  measurement with two proton tags needs high luminosity.

- Low luminosity – use only single tag events, but less pile-up background.

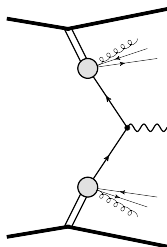
- All particles measured  $\rightarrow$  strong kinematic constraints between central state and each of the forward protons.





## SD W

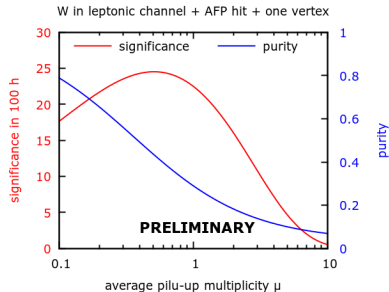
- One intact proton
- One quark from proton, one from Pomeron

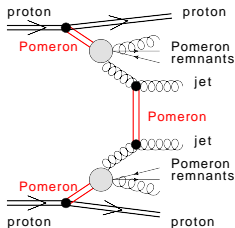


## CD (DPE) W

- Two intact protons
- Both quarks from Pomeron

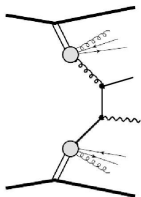
- Sensitivity to quarks in Pomeron.
- SD W – sensitivity to Pomeron flavour composition (via charge asymmetry).
- CD/DPE W – long running at low luminosity needed – unlikely.





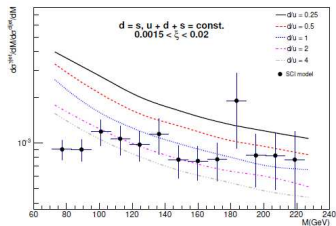
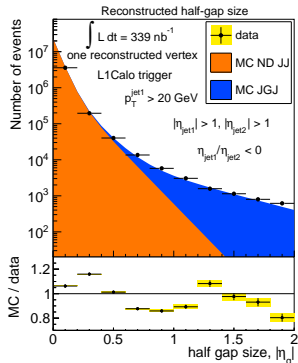
## DPE jet-gap-jet

- Two intact protons and gap between jets.
- Never measured before.
- BFKL dynamics.
- Cleaner than JGG without forward protons.



## DPE photon+jet

- Two intact protons.
- Never measured before.
- Sensitivity to quark in Pomeron and to mechanism of diffraction.



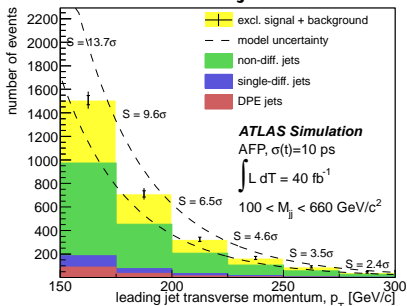
Anomalous couplings of gauge bosons:  $\gamma\gamma WW$ ,  $\gamma\gamma ZZ$ ,  $\gamma\gamma\gamma\gamma$  $\gamma\gamma WW$  and  $\gamma\gamma ZZ$ 

Coupling	OPAL limits [GeV <sup>2</sup> ]	Sensitivity for 200 fb <sup>1</sup>	
		5 $\sigma$	95% CL
$a_0^W/\Lambda^2$	[-0.020, 0.020]	$2.7 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$
$a_C^W/\Lambda^2$	[-0.052, 0.037]	$9.6 \cdot 10^{-6}$	$5.2 \cdot 10^{-6}$
$a_0^Z/\Lambda^2$	[-0.007, 0.023]	$5.5 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$
$a_C^Z/\Lambda^2$	[-0.029, 0.029]	$2.0 \cdot 10^{-5}$	$9.2 \cdot 10^{-6}$

 $\gamma\gamma\gamma\gamma$ 

Coupling (GeV <sup>-4</sup> )	1 conv. $\gamma$		all
	5 $\sigma$	95% CL	95% CL
$\zeta_1$ f.f.	$1 \cdot 10^{-13}$	$7 \cdot 10^{-14}$	$4 \cdot 10^{-14}$
$\zeta_1$ no f.f.	$3 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$
$\zeta_2$ f.f.	$3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8 \cdot 10^{-14}$
$\zeta_2$ no f.f.	$7 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$2 \cdot 10^{-14}$

## Excusive jets



- Quartic Gauge Couplings – testing BSM models.
- Constrained kinematics → low background.
- Reaching limits predicted by string theory and grand unification models ( $10^{-14} - 10^{-13}$  for  $\gamma\gamma\gamma\gamma$ ).
- Exc. jets – high  $p_T$ , double tag.

- Intact protons → **natural diffractive signature** → **usually scattered at very small angles ( $\mu\text{rad}$ )** → **detectors must be located far from the IP.**
- Two forward detectors systems in ATLAS (similar situation in CMS):
  - **ALFA** – **existing** vertical RPs located 240 m from IP1 (**soft diffraction**),
  - **AFP** – **planned** horizontal RPs located 210 m from IP1 (**hard diffraction**).
- **Various data taking strategies (LHC optics):**
  - **very low pile-up ( $\mu \sim 0.05$ ):**
    - detectors: ALFA or AFP,
    - optics: collision or high  $\beta^*$ , few very low intensity bunches,
    - **measure total cross section and properties of soft diffraction,**
  - **low pile-up ( $\mu \sim 1$ ):**
    - detectors: ALFA or AFP,
    - optics: collision or high  $\beta^*$ , low intensity bunches,
    - **measure properties of hard diffraction:**  
SD JJ, SD JGJ, SD W, SD Z, DPE JJ, DPE JGJ, DPE  $\gamma$ +jet,
  - **high pile-up ( $\mu \sim 50$ ):**
    - detectors: AFP,
    - optics: collision, join all ATLAS runs,
    - **measure exclusive production, discovery physics:**  
EXC JJ, **anomalous couplings:**  $\gamma\gamma WW$ ,  $\gamma\gamma ZZ$ ,  $\gamma\gamma\gamma\gamma$ .

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