Origin and Properties of Forward Protons at the LHC

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III Workshop on QCD and Diffraction at the LHC
joint with
LHC Forward Physics and Diffraction WG meeting

Cracow, 18 – 20 November 2013

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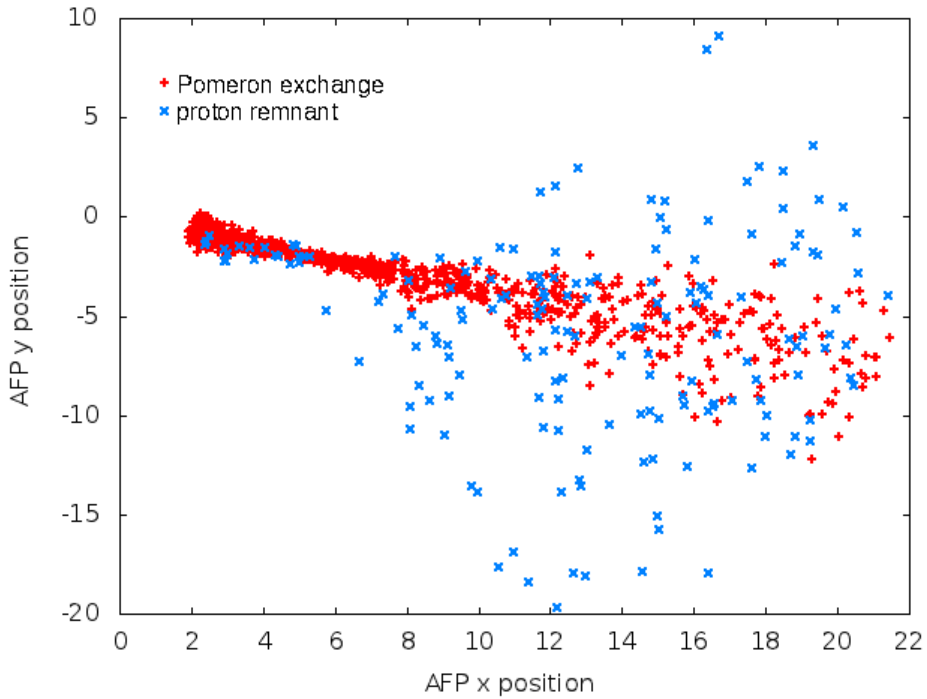
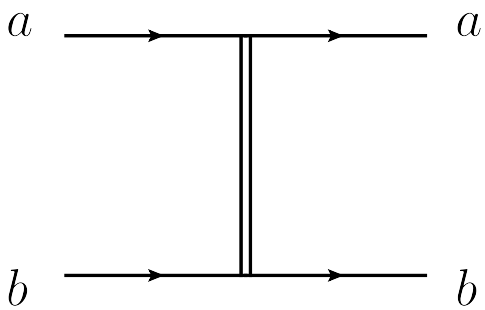
Non-Intact Protons



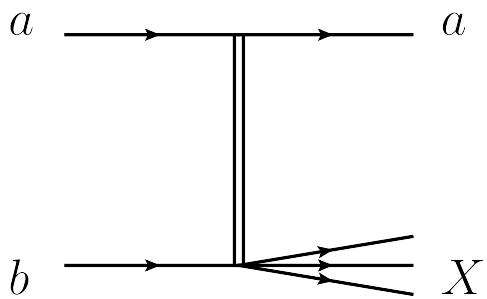
- AFP detectors: planned for ATLAS, around 220 m from ATLAS IP, after several LHC magnets
- AFP aim – measure protons origiating from diffractive or electromagnetic interaction
- Other protons can be seen, if energy large enough

Intact and Non-Intact Protons

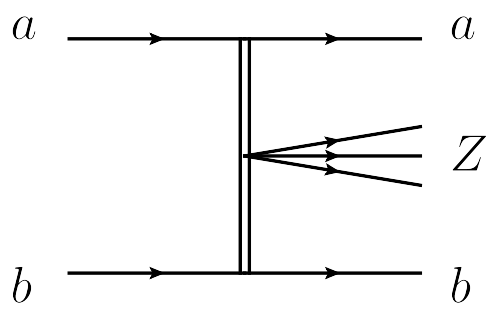
Elastic:



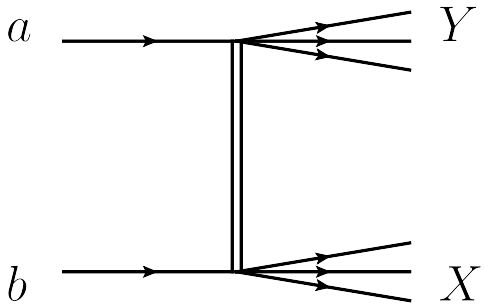
Single diffractive:



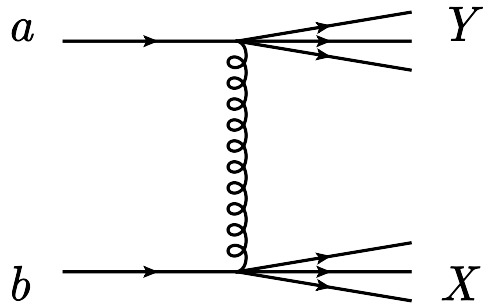
Central diffrractive:



Double diffrractive:



Non-diffractive:



- Intact protons in: elastic (EL), single diffractive (SD) and central diffractive (CD) processes
- Proton remnants (or dissociates states) present in: single diffractive, double diffractive and non-diffractive processes
- Possible to find a proton in the remnant (recombination)

Probability of AFP Tag

σ (mb)	ND	SD	DD	CD	Total
Pythia 6	55	14	10	–	79
Pythia 8	58	13	9	–	79
Phojet	68	11	4	1	84

Now, new diffraction model in Pythia 8 – MBR (Minimum-Bias Rockefeller) – contains also the central diffractive component.

- AFP acceptance: $0.02 < \xi < 0.12$
- Double tag: protons on both sides from a single interaction

	ND	SD	DD	CD	Total
AFP single tag probability (%)					
Pythia 6	0.4	11.0	3.2	–	2.8
Pythia 8	0.2	11.0	2.4	–	2.2
Phojet	1.7	13.0	2.0	38	3.6
AFP double tag probability (%)					
Pythia 6	0.004	0.4	0.01	–	0.06
Pythia 8	0.001	0.07	0.05	–	0.02
Phojet	0.1	0.6	0.03	11	0.29

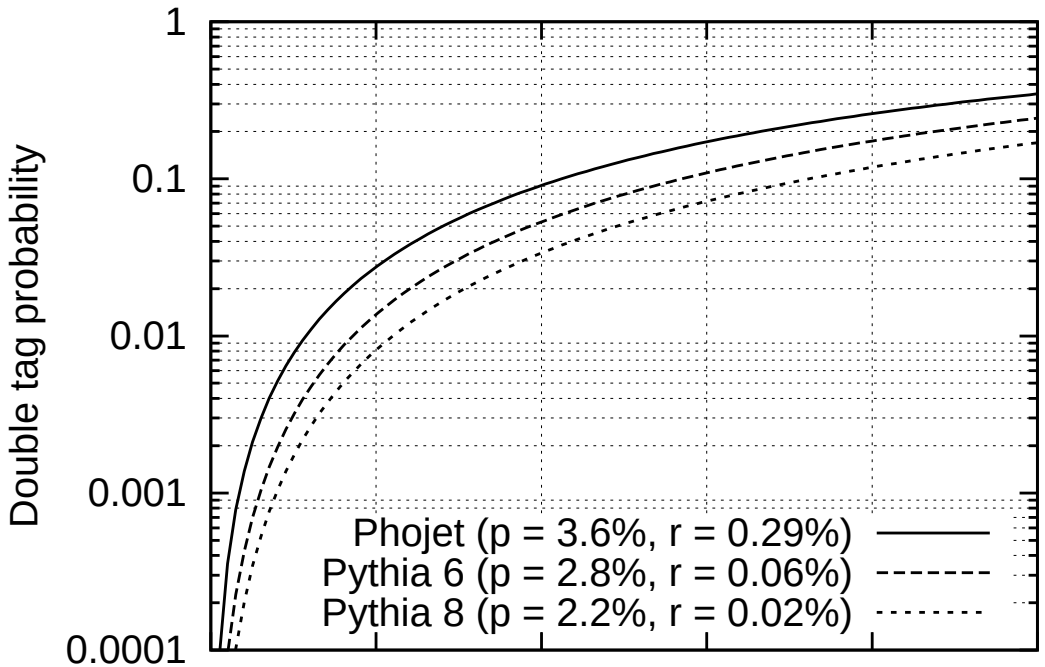
Double Tag Probability With Pile-up

Probability of having a double tag event for average pile-up multiplicity μ (combinatorial formula convoluted with a Poisson distribution):

$$P(\mu) = 1 - 2e^{-\mu p} + e^{-\mu(2q-r)}$$

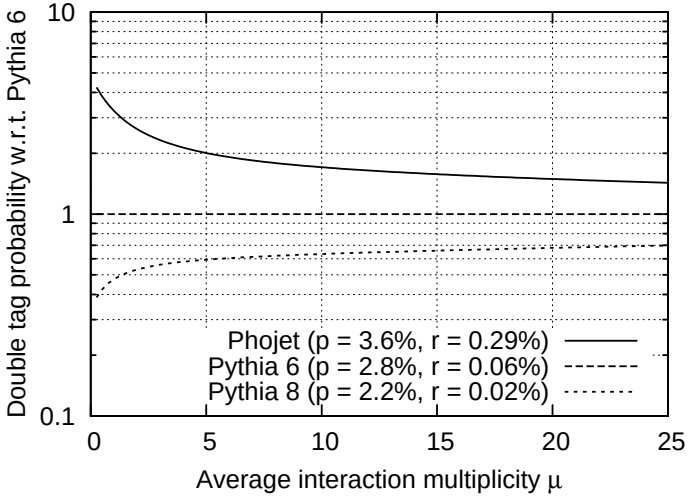
where

- p – single tag probability
- r – double tag probability
- Background to hard DPE processes



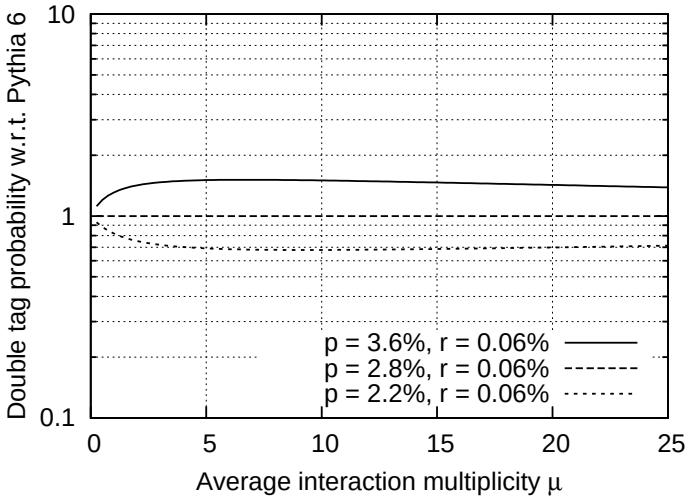
Pile-up

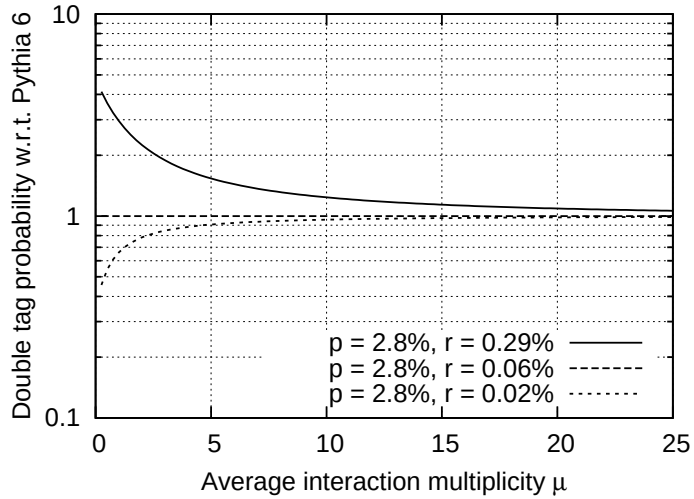
Predictions from different generators:



- Single tag probability important at high μ
- For special runs double tag probability dominant
- Non-intact protons may affect measurements with double tag

Effects of p and r:





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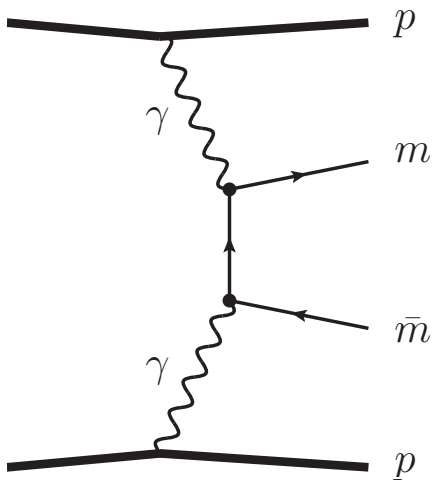
Direct Background to Hard Diffraction

- Previous slides – pile-up (overlay) background: diffractive hard process mimicked by non-diffractive hard process overlaid with soft processes with forward protons
- Non-intact protons can lead to background more directly: proton is present in proton remnants of a hard process
- ND $\rightarrow$ SD
- May become a problem when $\sigma_{\mathrm{ND}} \gg \sigma_{\mathrm{SD}}$
- Experimentally indistinguishable from hard diffraction (rapidity gap too small)
- Similarly, SD $\rightarrow$ DPE
- Unlike for pile-up background, timing detectors do not help

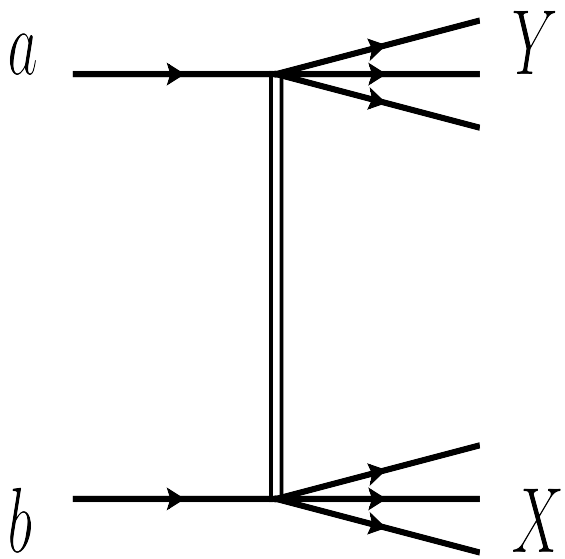
Magnetic Monopoles – Introduction

- Symmetrization of Maxwell equations
- Existence of magnetic monopoles implies electric charge quantisation: $q_m q_e = \frac{1}{2}\hbar c$
- $q_e = 1/\sqrt{137} \quad \rightarrow \quad q_m = 68.5$
- Large charge – large coupling to photons
- Possible to produce in two-photon exchange
- Perturbative calculations not valid

- Final state:
  - annihilation to 2γ
  - form a monopolium state (can also annihilate)
  - trapped in beam pipe material
  - escape undetected
- Invisible monopoles – forward protons + empty all other detectors



Background to Invisible Monopoles – Double Diffraction



- Large Rapidity Gap $\rightarrow$ central detector does not see anything
- Protons both in X and Y states
- Probability between 10^{-5} and 10^{-4}
- Huge cross section compared to any hard process, including monopoles

Event Record Example


```
-------- PYTHIA Event Listing  (complete event)  -----------------------
 no      id  name      status     p_x     p_y         p_z          e      m
 1    2212  (p+)         -12   0.000   0.000   7000.000   7000.000  0.938
 2    2212  (p+)         -12   0.000   0.000  -7000.000   7000.000  0.938
 3 9902210  (p_diffr+)   -15  -0.158   0.026   7000.000   7000.000  2.832
 4 9902210  (p_diffr+)   -15   0.158  -0.026  -7000.000   7000.000  2.362
 5       2  (u)          -23  -0.002   0.000     97.398     97.399  0.325
 6    2101  (ud_0)       -63  -0.156   0.026   6902.601   6902.601  0.650
 7       1  (d)          -23   0.003  -0.001   -143.670    143.670  0.325
 8    2203  (uu_1)       -63   0.155  -0.026  -6856.330   6856.330  0.650
 9    -211  pi-           83   0.315   0.025   -195.506    195.506  0.140
10    2224  (Delta++)     -84  -0.157  -0.052  -6804.493   6804.494  1.123
11     211  pi+           83   0.037   0.406    202.600    202.601  0.140
12    -211  pi-           84   0.117  -0.093    752.369    752.369  0.140
13    2212  p+            84  -0.312  -0.288   6045.030   6045.031  0.938
14    2212  p+            91  -0.071  -0.069  -6219.013   6219.013  0.938
15     211  pi+           91  -0.086   0.017   -585.481    585.481  0.140
-------- End PYTHIA Event Listing  -----------------------------------
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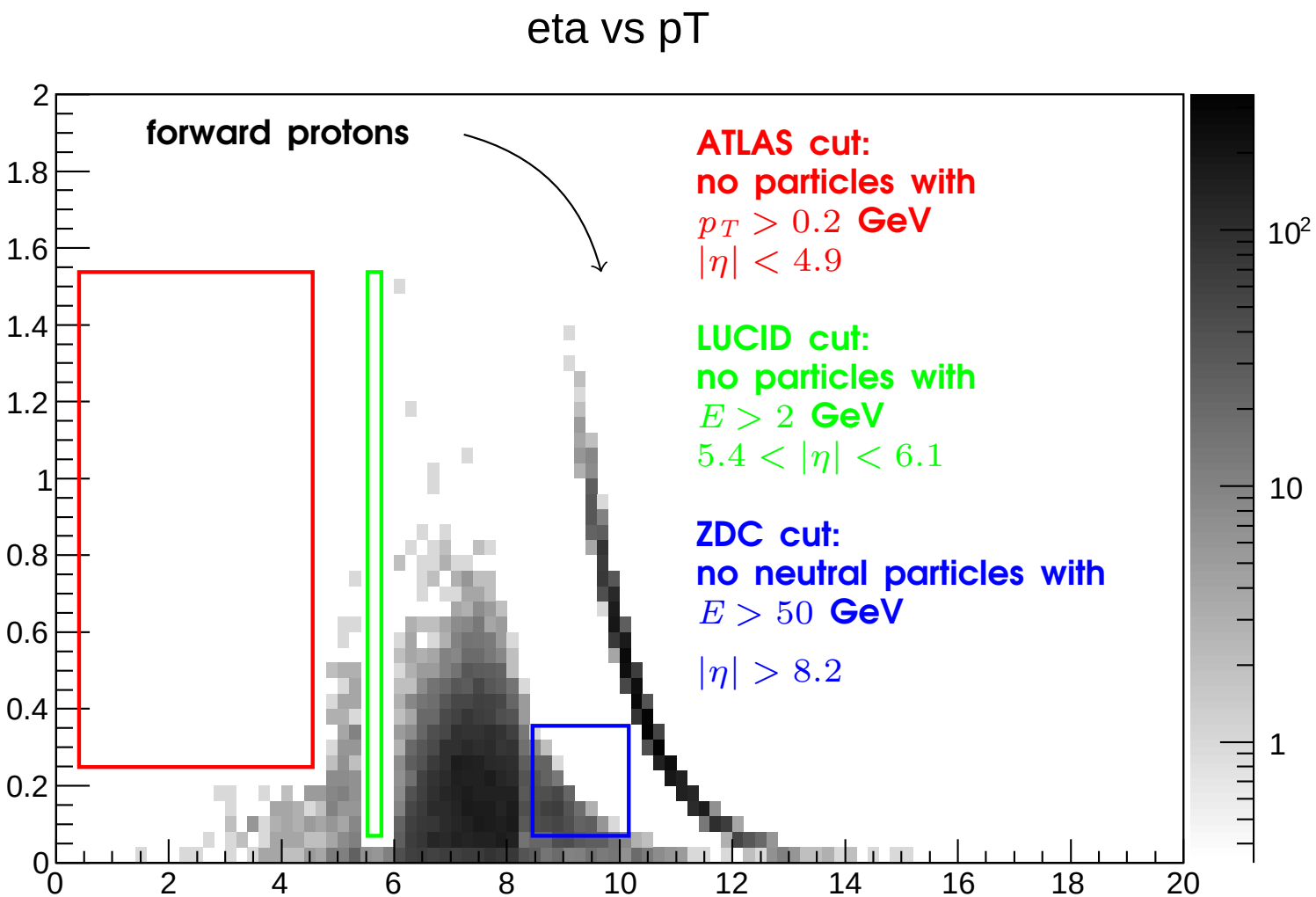
Particle Flow



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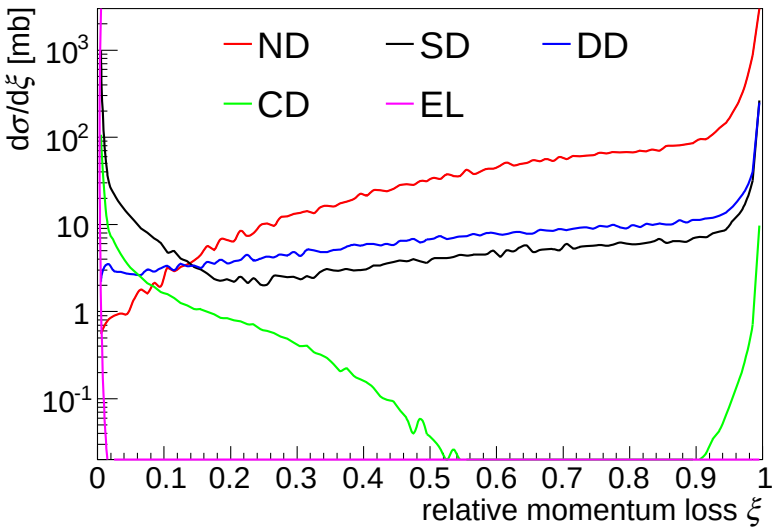
Kinematics of the Forward Proton

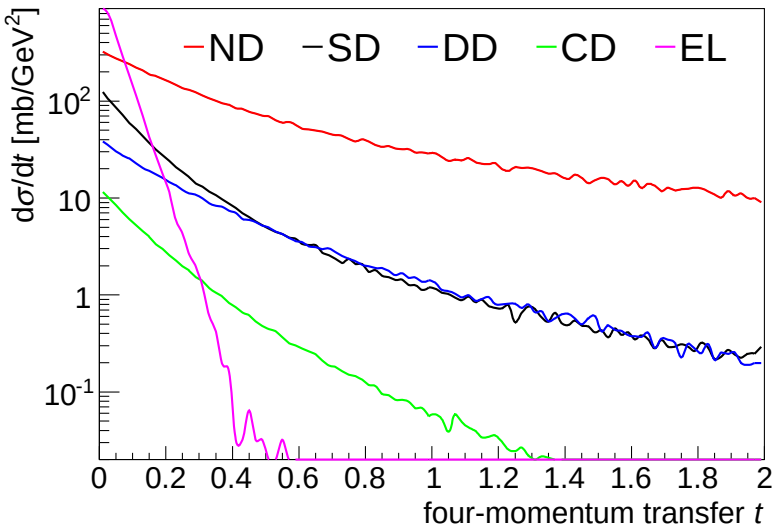
- Dimensionless fractional momentum loss ξ:

$$\xi = \frac{p_0 - p}{p_0},$$

  where p_0 – beam momentum
- $\xi = 0$ for elastic protons ($p = p_0$)
- $0 < \xi < 1$ for diffraction
- ξ distribution steeply falling (typically $\sim 1/\xi$)
- For central production $M = \sqrt{s\xi_1\xi_2}$
- One is interested in relatively small values of ξ, *e.g.* ALFA: $\xi < 0.2$, AFP: $0.02 < \xi < 0.12$
- Interpretation as "momentum loss" only for diffractive protons, but mathematically valid for all particles

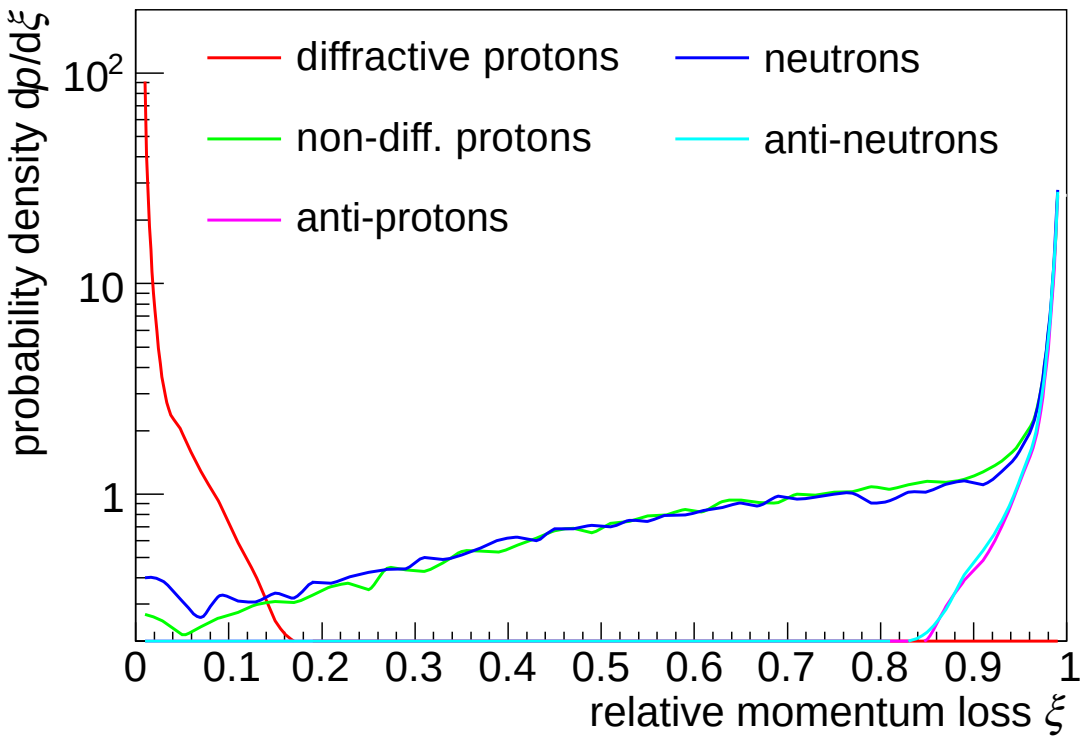
Proton Production in pp Interactions





- Diffractively scattered protons – peak at $\xi = 0$
- All processes – peak at $\xi = 1 \rightarrow$ non-intact protons
- t distribution steeper for diffractive processes

Protons in SD

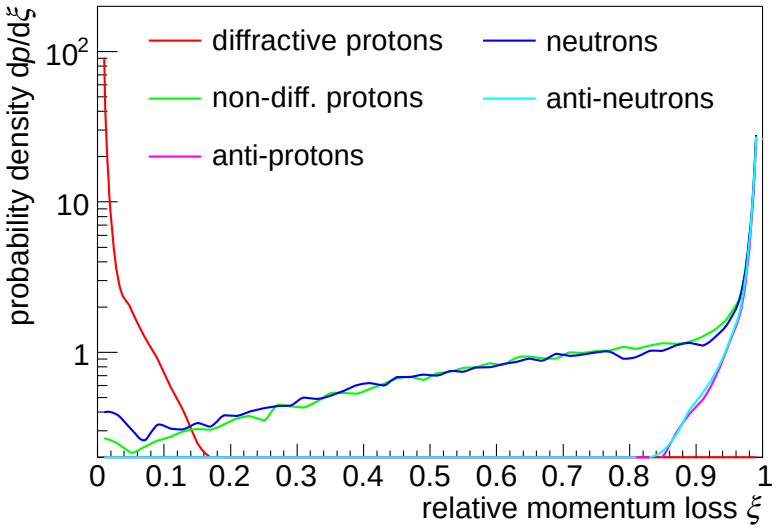


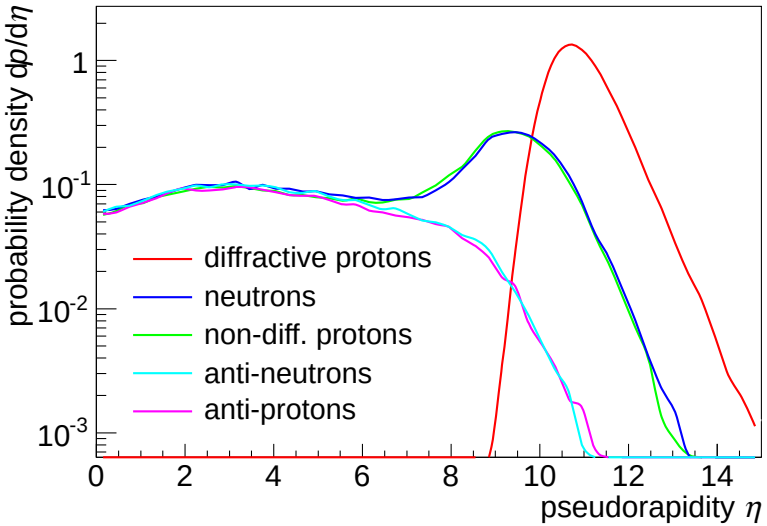
Diffractive (intact) vs non-diffractive (non-intact) proton – MC information

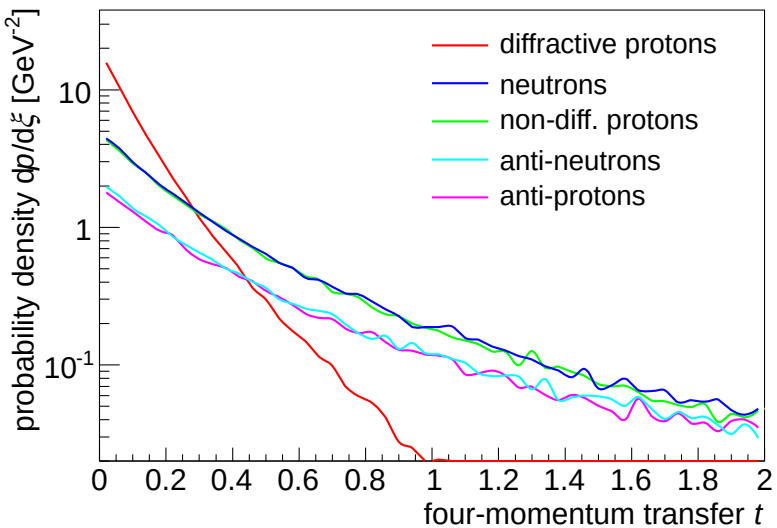
Distributions for non-diffractive protons and neutrons equal – isospin symmetry (similarly for anti-protons and anti-neutrons)

Distributions of all barions at $\xi \to 1$

Protons in SD





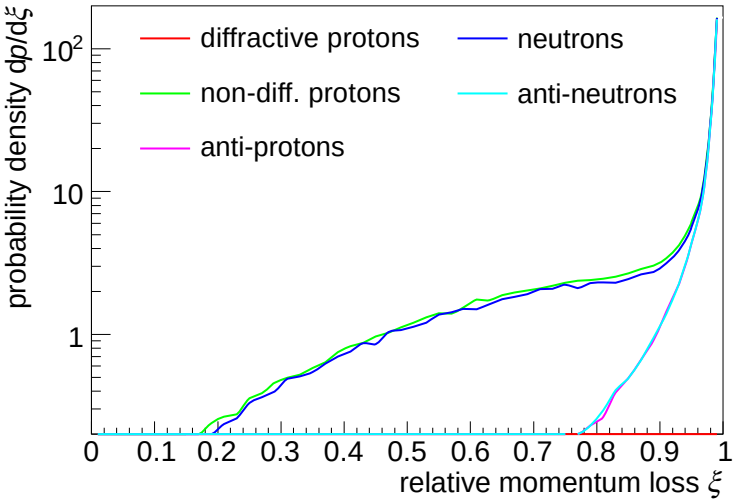


Three mechanisms of production:

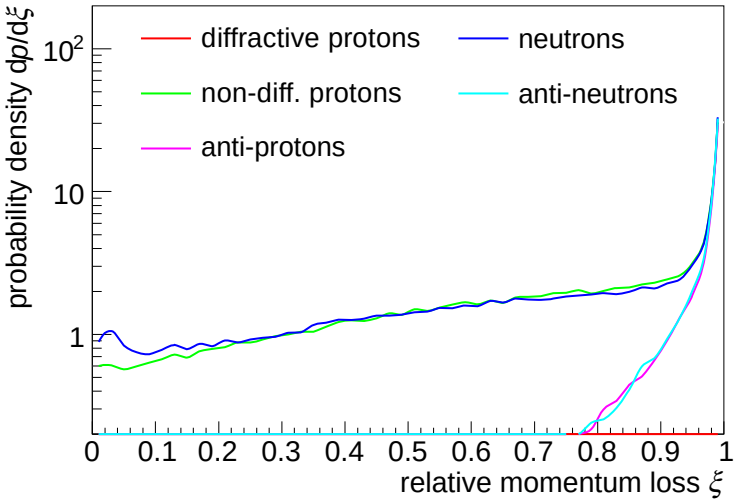
- diffractive
  ($\xi < 0.1, \eta \sim 11$)
- "baryon conservation"
  ($0.1 < \xi < 0.9, \eta \sim 10$)
- "pair production"
  ($\xi > 0.9, \eta < 9$)

ξ Distribution in Different Processes

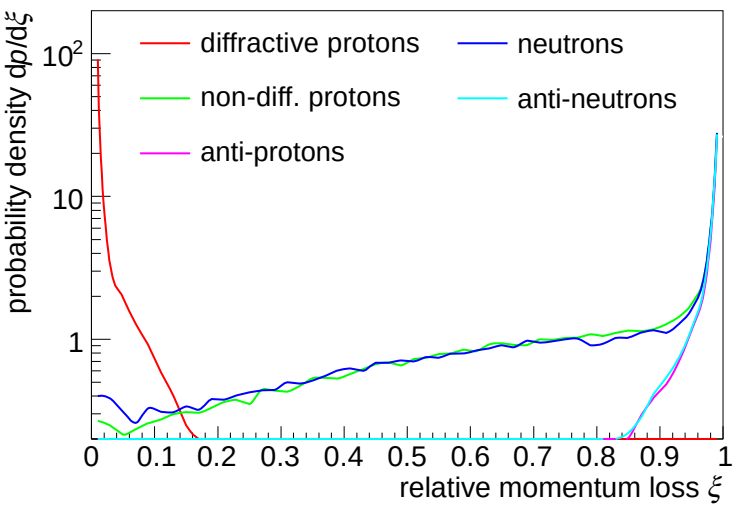
ND:



DD:



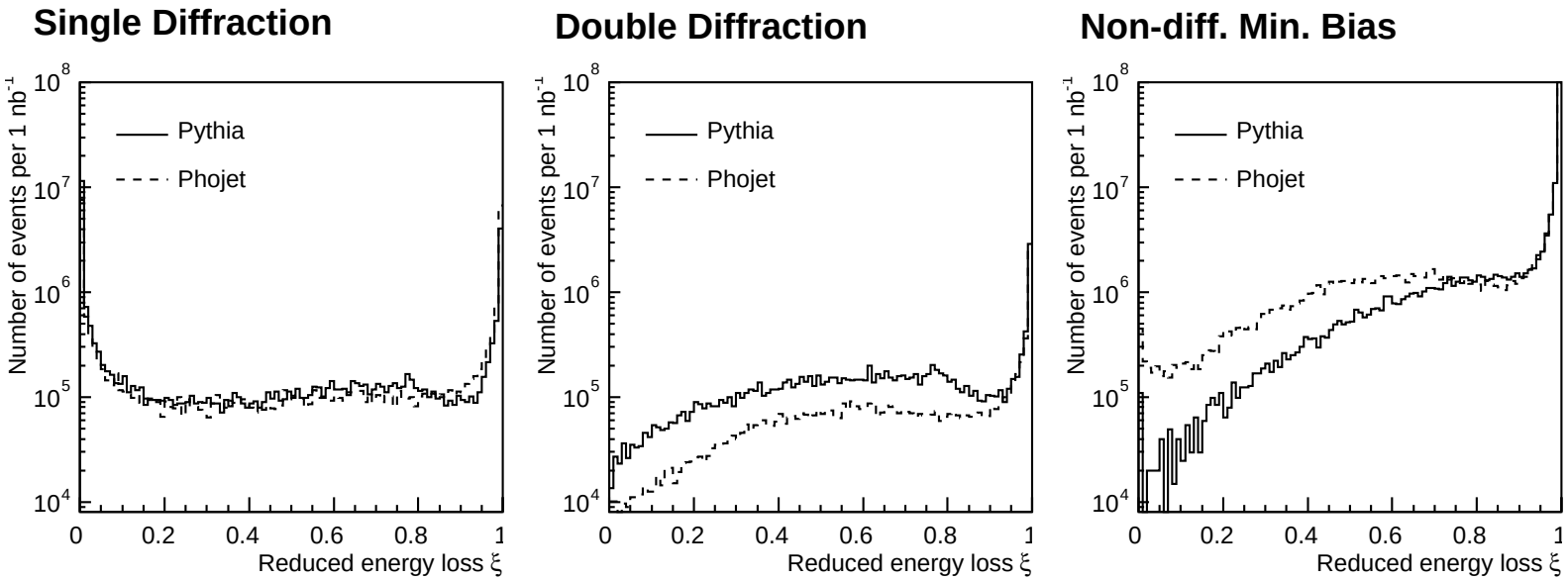
SD:



Non-intact proton distribution in SD and DD similar

Steeper distribution in ND – more difficult to recombine back to a proton

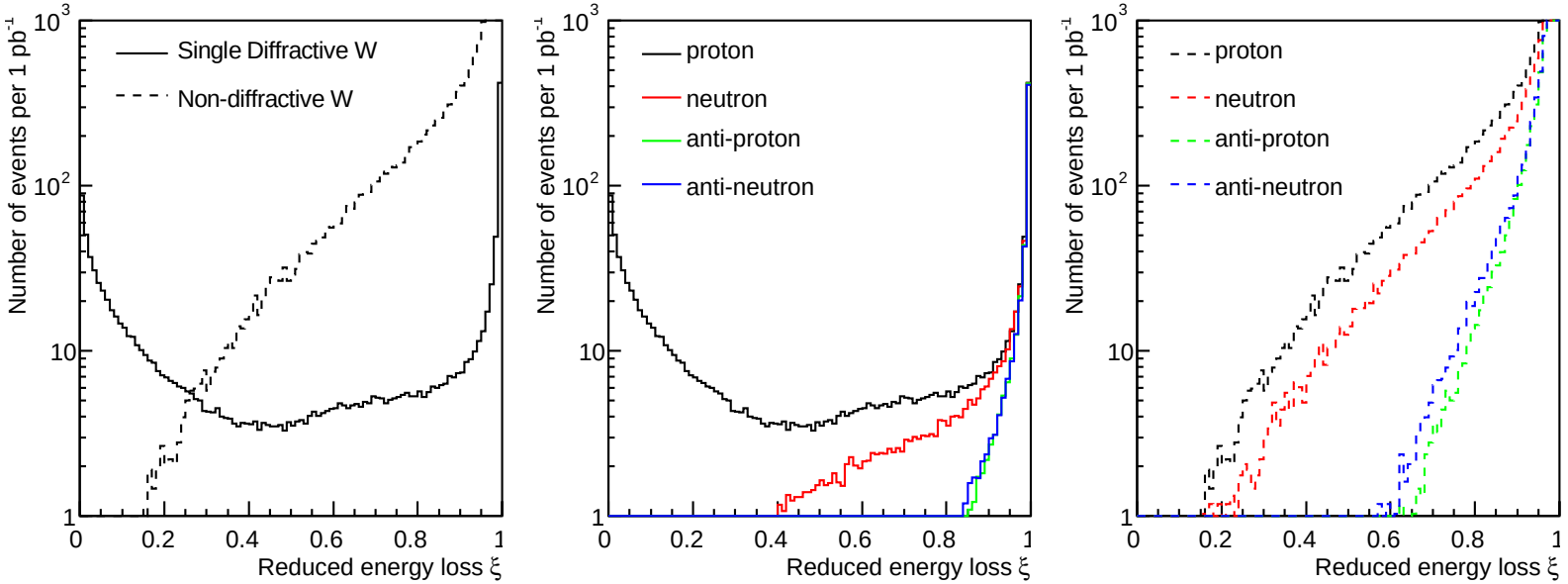
Difference Between Generators



- Large impact of hadronisation model
- To be studied in more detail …

Hard Processes

Non-diffractive W Single diffractive W



- ND W – Pythia 6, SD W – Herwig++
- Distribution steeper than before, because W is produced from quarks – even more difficult to recombine
- Important background for $\xi > 0.2$
- May be negligible at LHC, but probably large uncertainty

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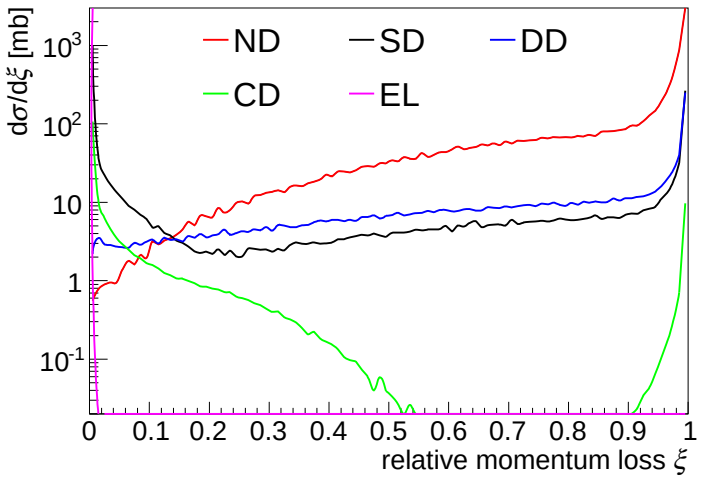
Summary and Conclusions



- Three mechanism for proton production
- For $\xi > 0.1$ non-diffractive mechanism shows up
- Single and double tag events
- Gap too small to distinguish from true diffractive events

- Interesting, but difficult to measure – timing detectors probably needed to reject backgrounds
- Plans:
  - sensitivity to hadronisation models
  - invisible magnetic monopoles (or other particles)
  - cosmic air shower physics?