Hard diffraction and proton tagging at the LHC

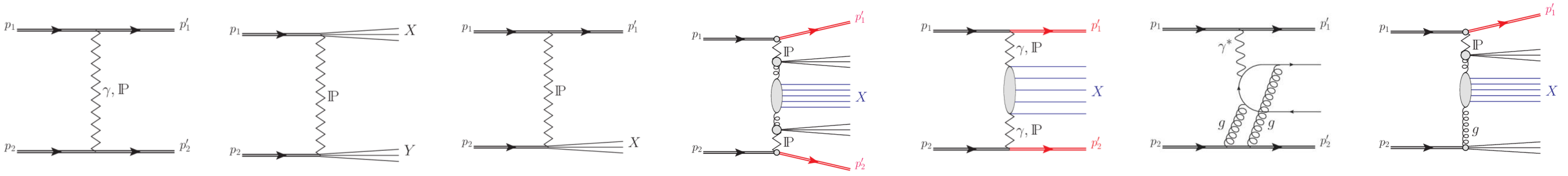
24 October 2022

C. Baldenegro, A. Bellora, M. Pitt, C. Royon

Introduction

Diffractive processes in *pp* collisions at the LHC

- t-channel exchange of color neutral particles (QED, QCD)



Elastic scattering — Single/double diffractive dissociation — Double pomeron exchange — Central exclusive production — Exclusive photoproduction — Single-diffraction with central system

- Spans over large kinematic region (MeV – TeV), and large cross-section range
- Provide a rich scientific program for LHC experiments
- Sometimes protons loose substantial fraction (~ a few%) of their kinetic energy but emerge intact

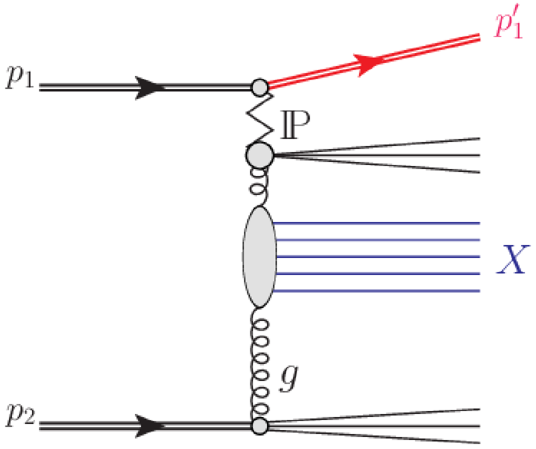
  – **Hard diffraction with forward protons**

Factorization in hard-diffraction

Example: Production cross-section of single diffractive events

$$\frac{d\sigma}{d\xi dt} = F_{IP/p}(\xi, t) \sum_{a\,b} \int dx_g d\frac{x_b}{\xi} f_{b/P}(x_b, Q^2) f_{a/IP}\left(\frac{x_b}{\xi}, Q^2\right) \hat{\sigma}_{ab\to X}$$

Pomeron flux — dPDF, PDF — Hard-scatter Xsec



Where:

$F_{IP/p}(\xi, t)$ is the pomeron flux

ξ is proton fractional momentum loss, t is the square of the four-momentum transfer

x_a, x_b proton momentum fraction caried by the struck partons ($x_b \equiv x_{bj}$, $\beta \equiv \frac{x_{bj}}{\xi}$)

$f_{a/P}, f_{b/IP}$ parton distribution function of proton (PDF) or pomeron (dPDF) respectively

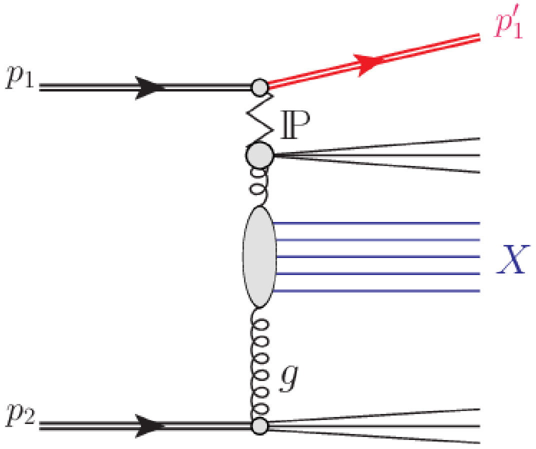
Q^2 – factorization scale of order of transverse energy of the hard scattering

Factorization in hard-diffraction

Example: Production cross-section of single diffractive events

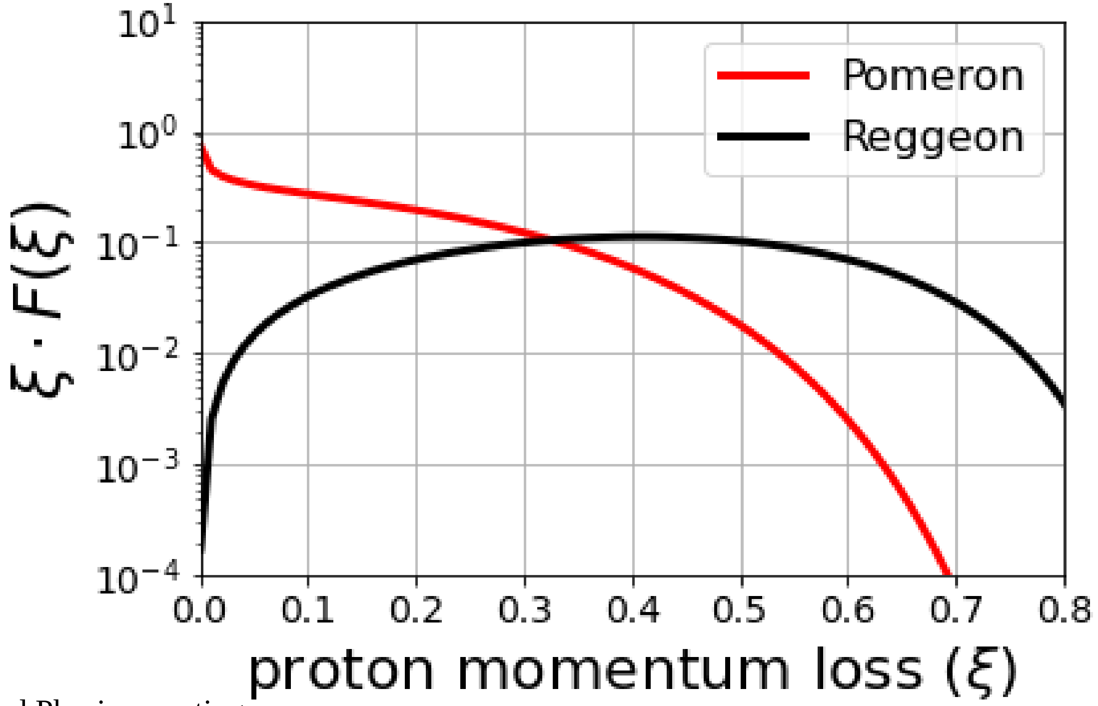
$$\frac{d\sigma}{d\xi dt} = F_{IP/p}(\xi,t) \sum_{a\,b} \int dx_g\, d\frac{x_b}{\xi} f_{b/P}(x_b,Q^2) f_{a/IP}\left(\frac{x_b}{\xi},Q^2\right) \hat{\sigma}_{ab\to X}$$

Pomeron flux — dPDF, PDF — Hard-scatter Xsec



Fluxes:

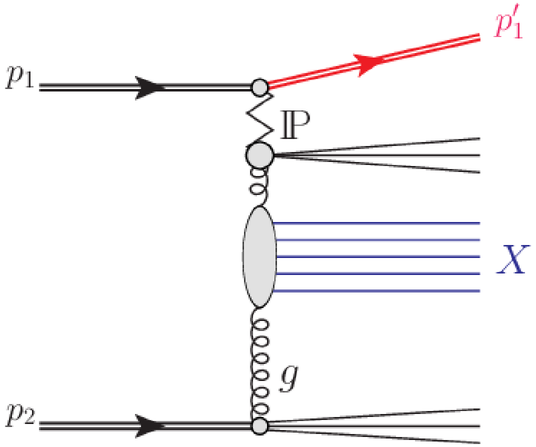
- H1 parametrized fluxes: $A_{IP} \frac{e^{B_{IP}t}}{\xi^{2\alpha_{IP}(t)-1}}$
- Reggeon contributions are not constrained at LHC/Tevatron
- Testing the fluxes at ξ>10% could give a first hint on the Reggeon contributions at LHC (?)



Factorization in hard-diffraction

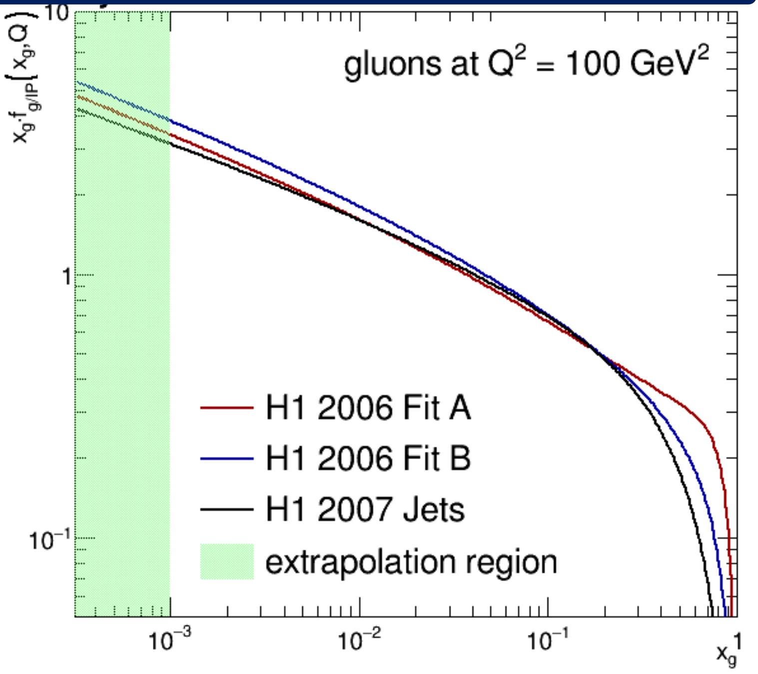
Example: Production cross-section of single diffractive events

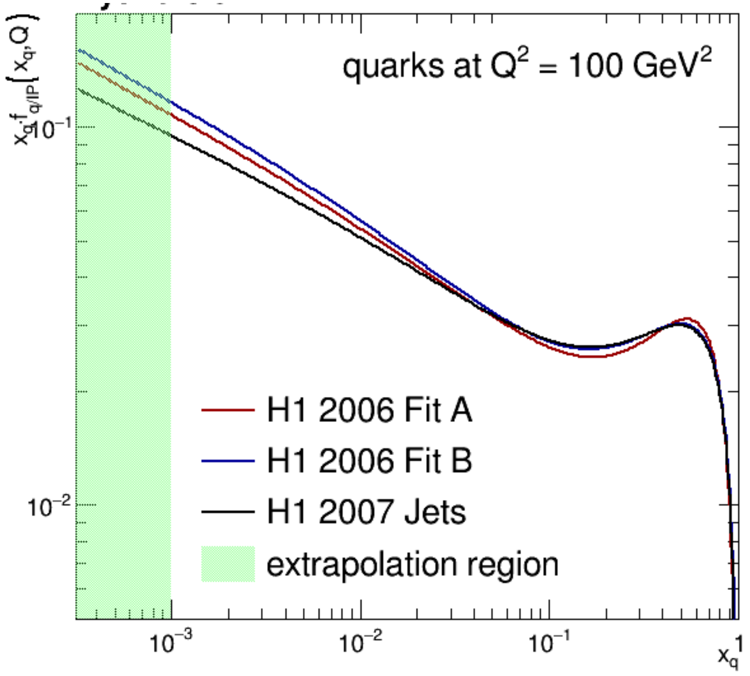
$$\frac{d\sigma}{d\xi dt} = \underbrace{F_{IP/p}(\xi,t)}_{\text{Pomeron flux}} \sum_{a\,b} \underbrace{\int dx_g\, d\frac{x_b}{\xi}\, f_{b/P}(x_b,Q^2) f_{a/IP}\left(\frac{x_b}{\xi},Q^2\right)}_{\text{dPDF, PDF}} \underbrace{\hat{\sigma}_{ab\to X}}_{\text{Hard-scatter Xsec}}$$



<u>Diffractive terms</u>:

- Structure functions are fitted using H1 data[1]
- Dominated by gluons
- No fits from Tevatron/LHC
- H1 assumption of flavor universality (never tested)

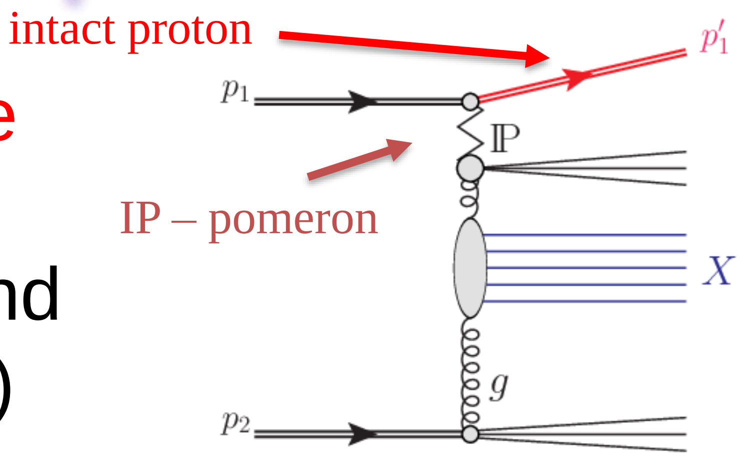




[1] Eur. Phys. J. C48 (2006) 715 [hep-ex/0606004]

Diffraction with tagged protons

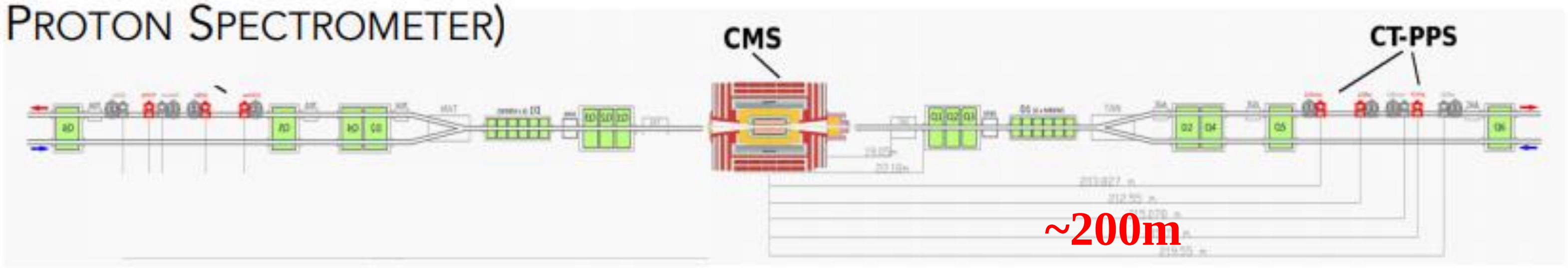
- In diffractive events, occasionally, protons emerge intact from the pp collisions
- The protons are deflected away from the beam and measured by forward proton detectors (PPS/AFP)

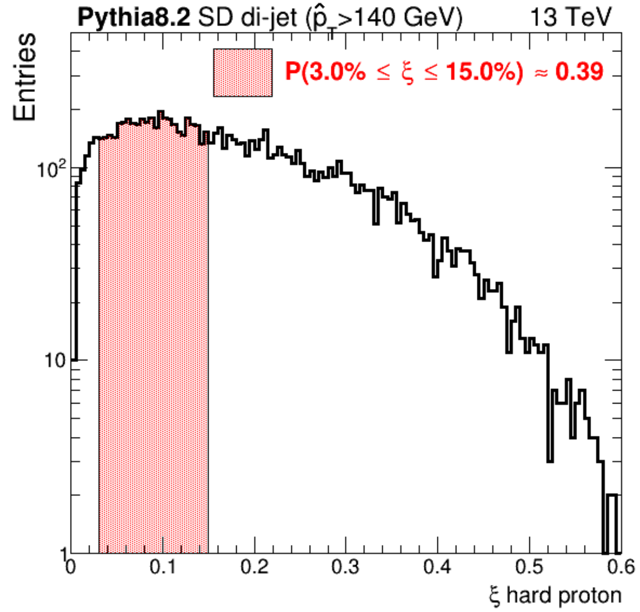


Displacement of the protons from the beam determines the proton momentum loss $\xi = \frac{\Delta p}{p}$ and p_T, can be measured by LHC detectors in the range of ξ ~ 3 – 15% and p_T up to a few GeV

One of the examples of proton tagging at LHC – PPS:

(Precision Proton Spectrometer)

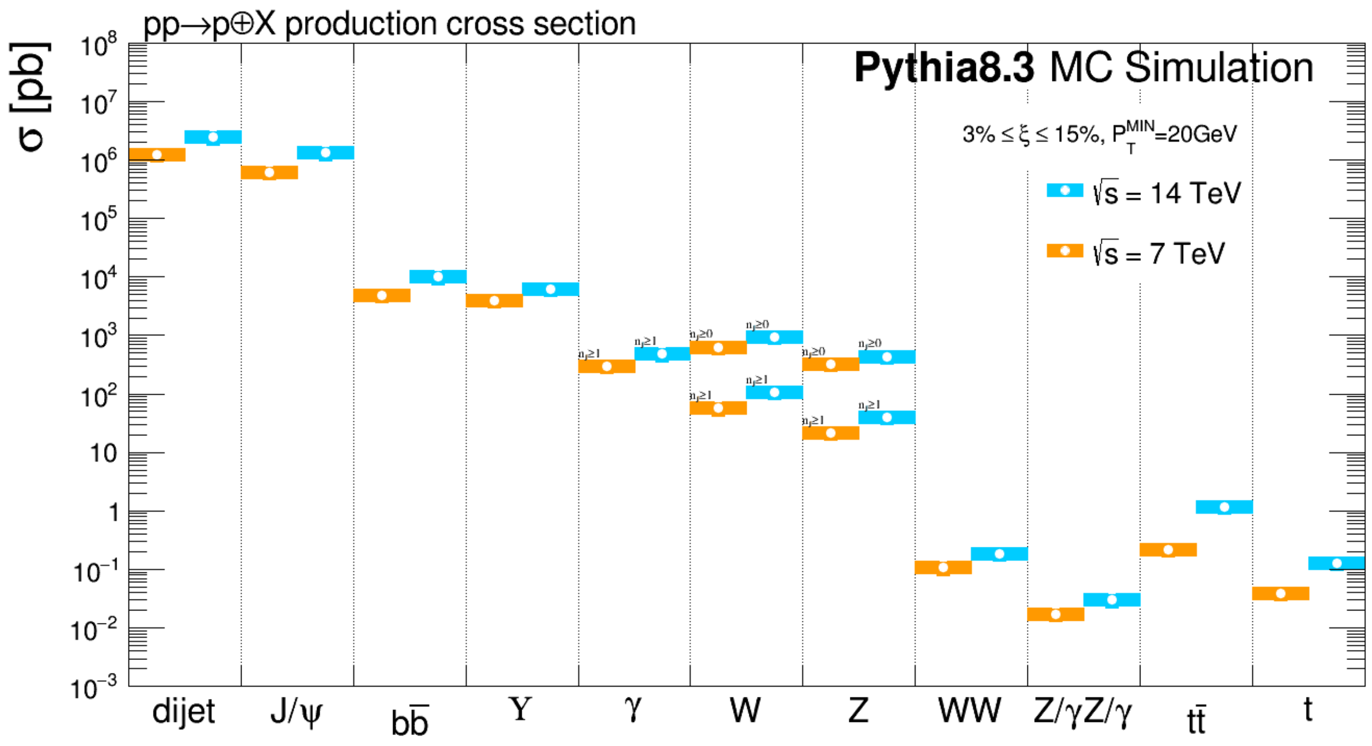


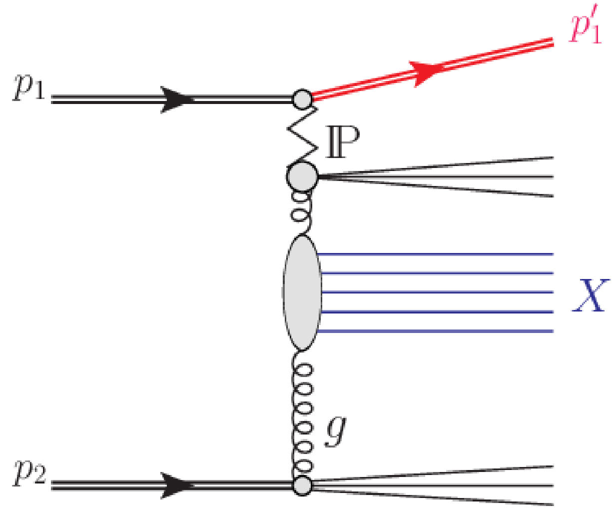


Single diffraction in pp

Single diffraction (SD) with high mass central system (jets, bosons, …)

- Production of hard process + a diffractive proton
- Hard SD events comprise up to a few % of the inclusive σ
- Could have impact in precision measurement at the HL-LHC



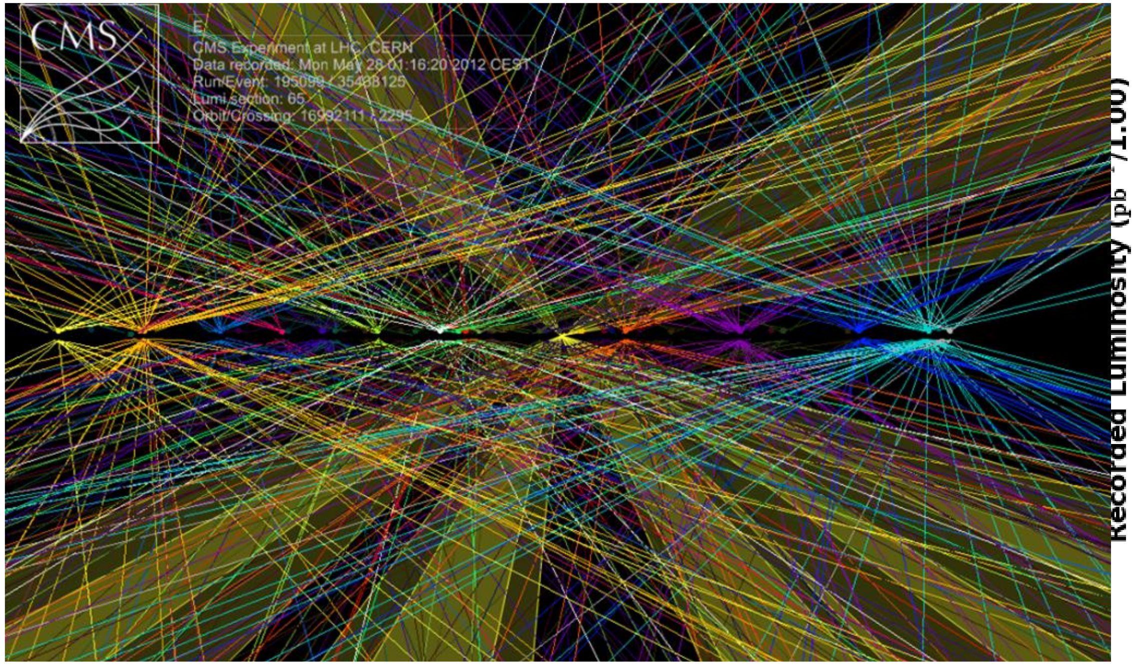


Large fraction of SM processes are accessible by the LHC experiments

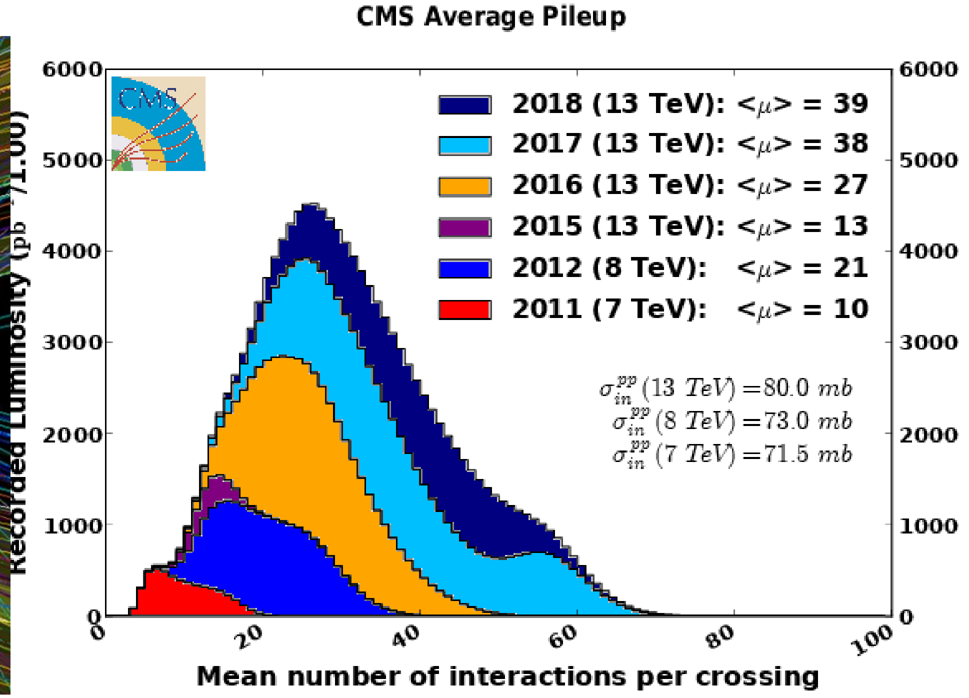
SD with tagged protons

Challenge (backgrounds):

- In the standard LHC runs tens of interactions occur per bunch crossing

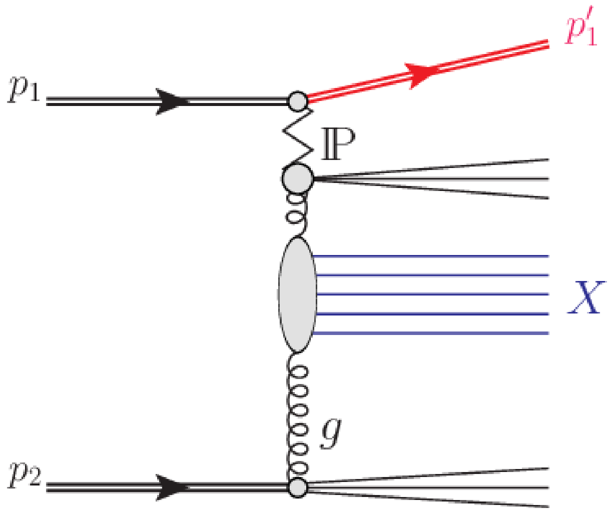


https://cds.cern.ch/record/2746227



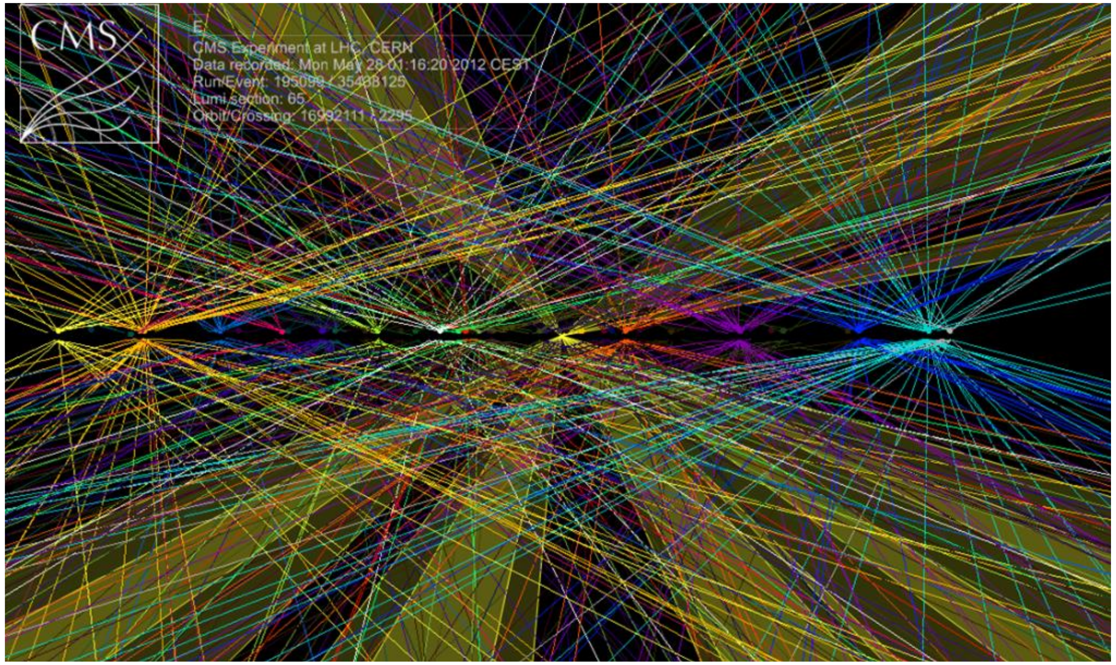
https://cds.cern.ch/record/2654205

SD with tagged protons

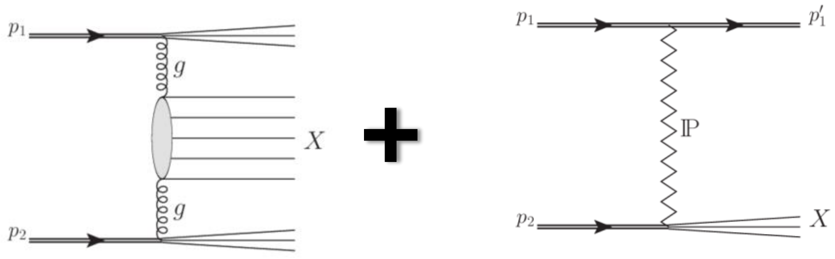


Challenge (backgrounds):

- Multiple pp collision can fake the signal:



https://cds.cern.ch/record/2746227

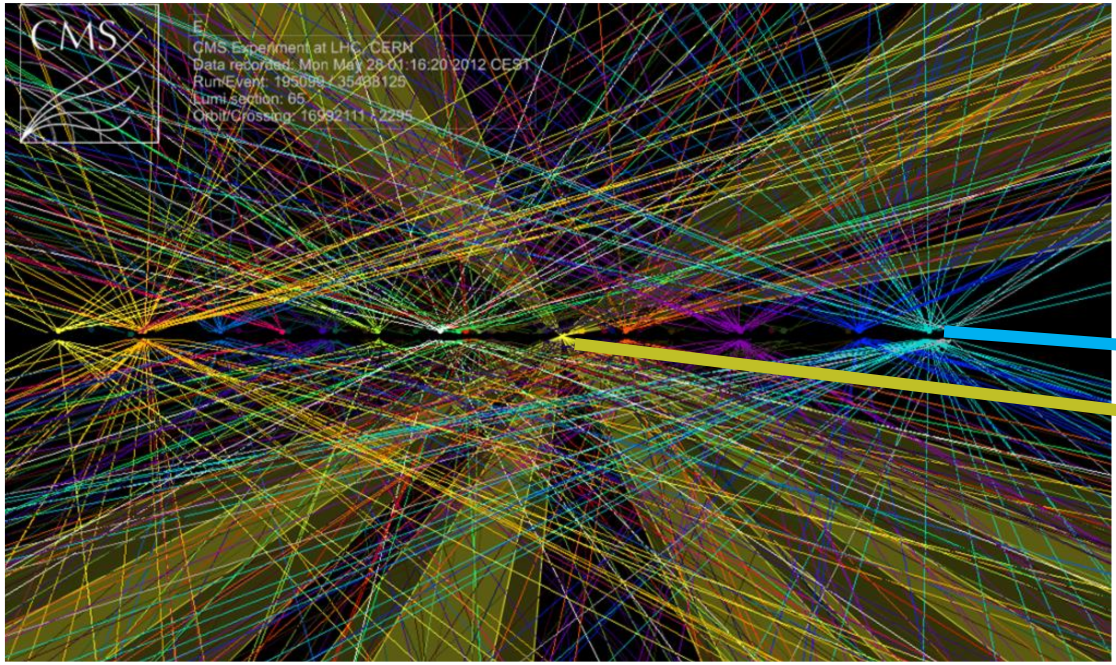


Diffractive protons produced ~20% of non-elastic pp collisions

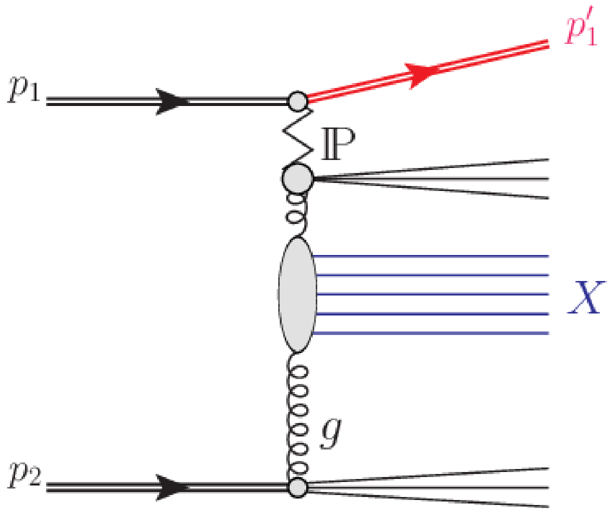
SD with tagged protons

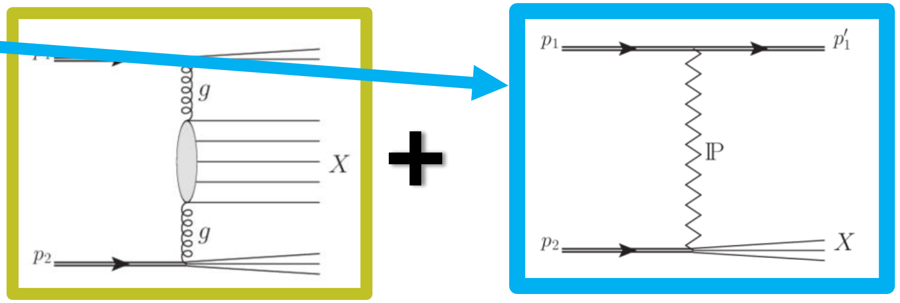
Challenge (backgrounds):

- Multiple pp collision can fake the signal:



https://cds.cern.ch/record/2746227



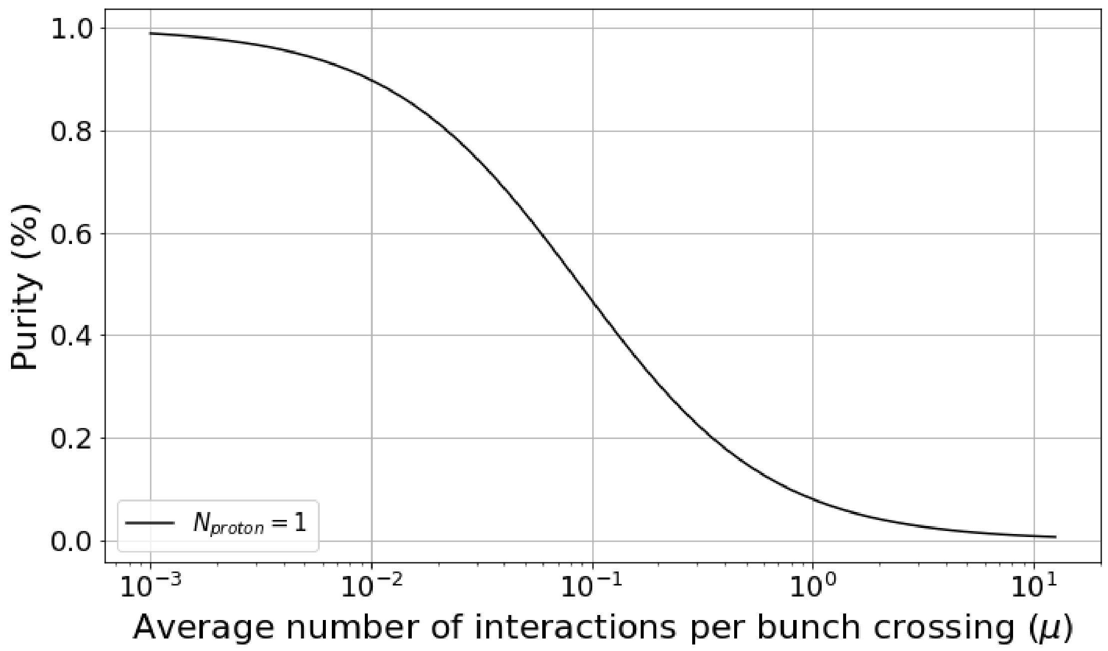


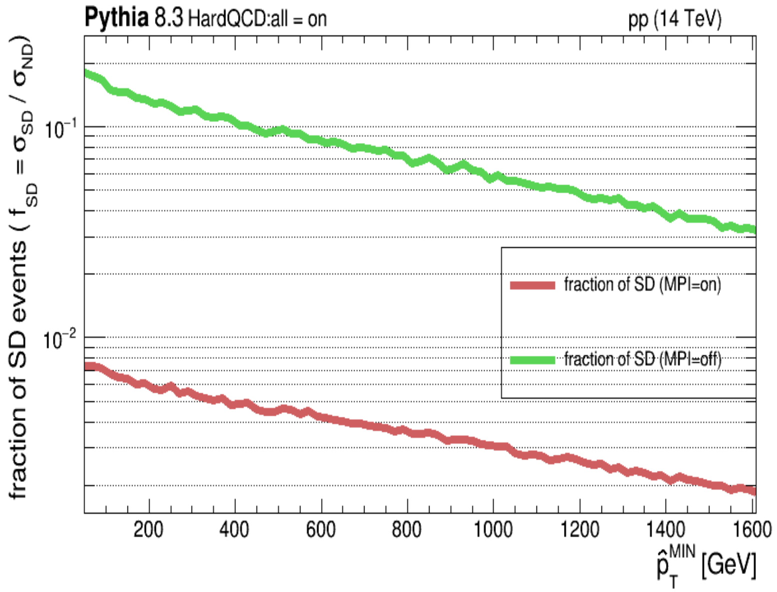
Diffractive protons produced ~20% of non-elastic pp collisions

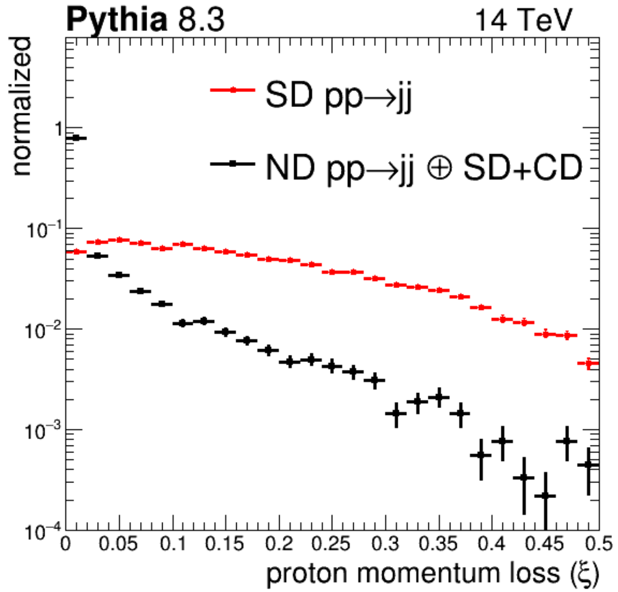
SD with tagged protons

Background rates and event purity. Assume:

- 0.5% fraction of diffractive events (σ_{SD}/σ_{ND})
- 2.2% (40%) of soft-diffractive (signal) events have proton $\xi \in (3\%, 15\%)$



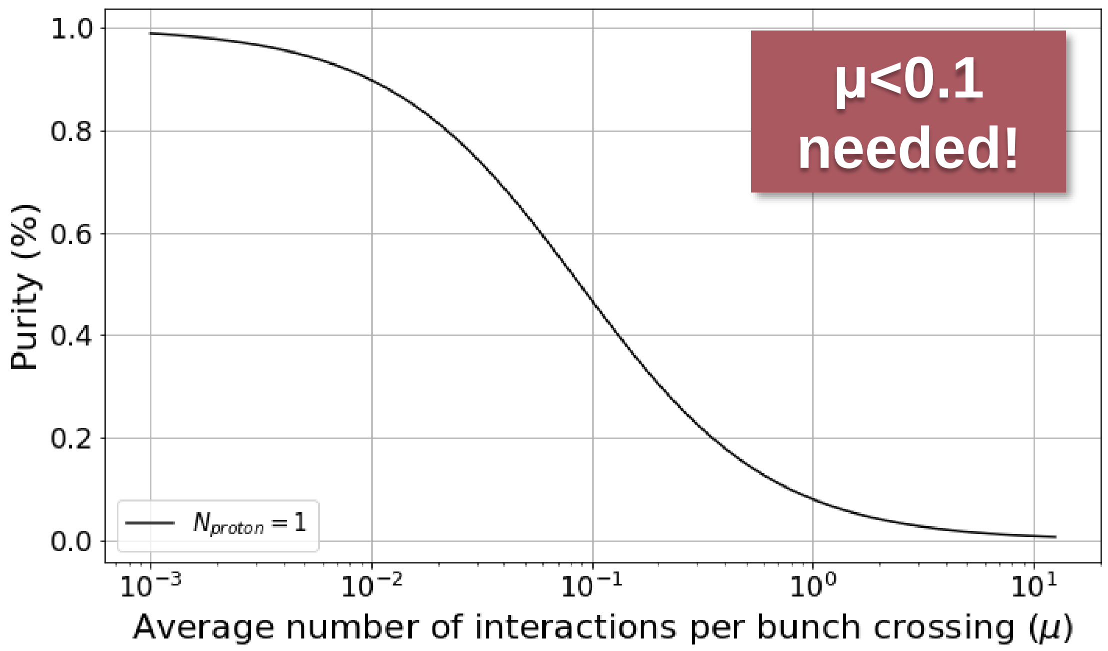


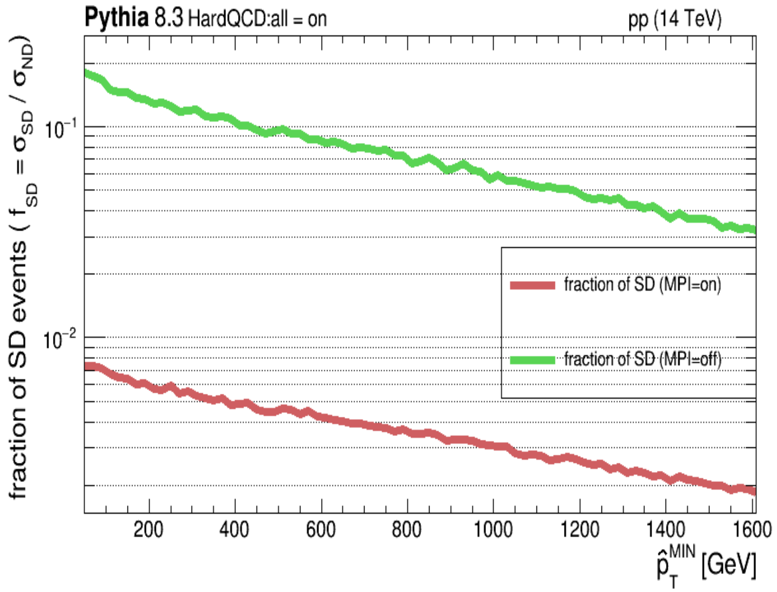


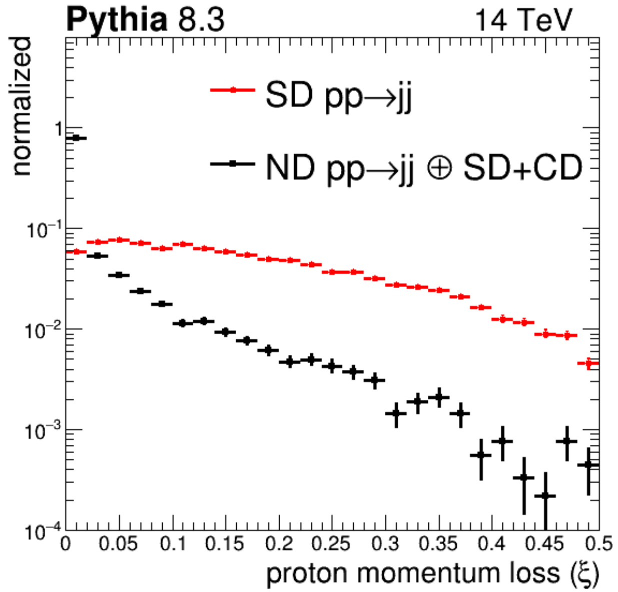
SD with tagged protons

Background rates and event purity. Assume:

- 0.5% fraction of diffractive events $(\sigma_{SD}/\sigma_{ND})$
- 2.2% (40%) of soft-diffractive (signal) events have proton $\xi \in (3\%, 15\%)$

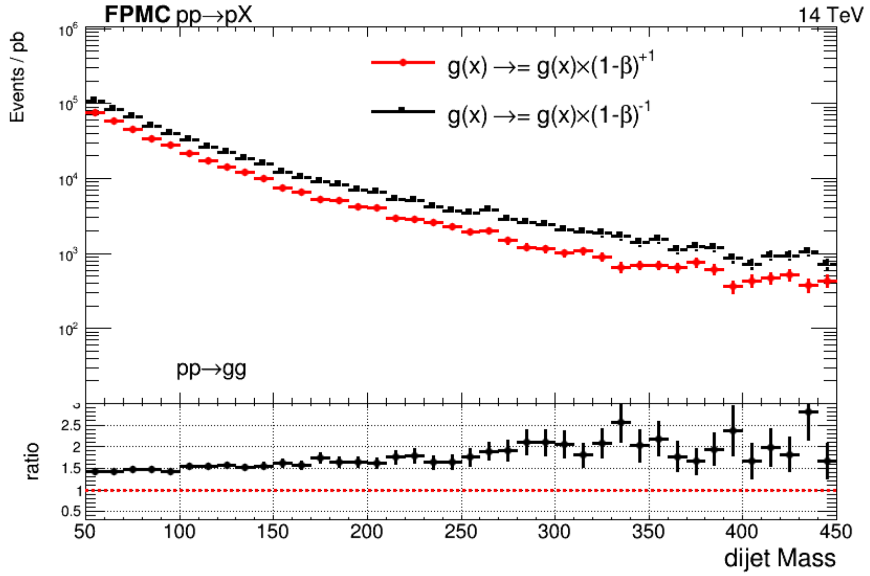


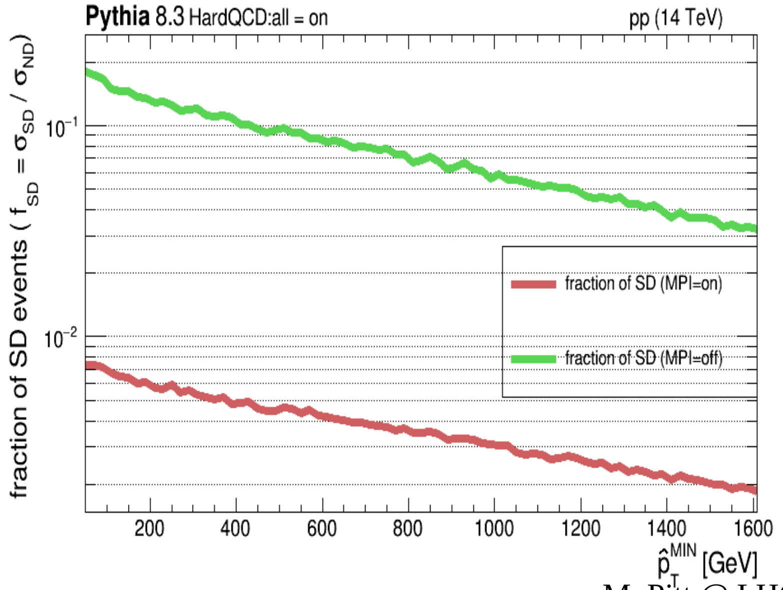


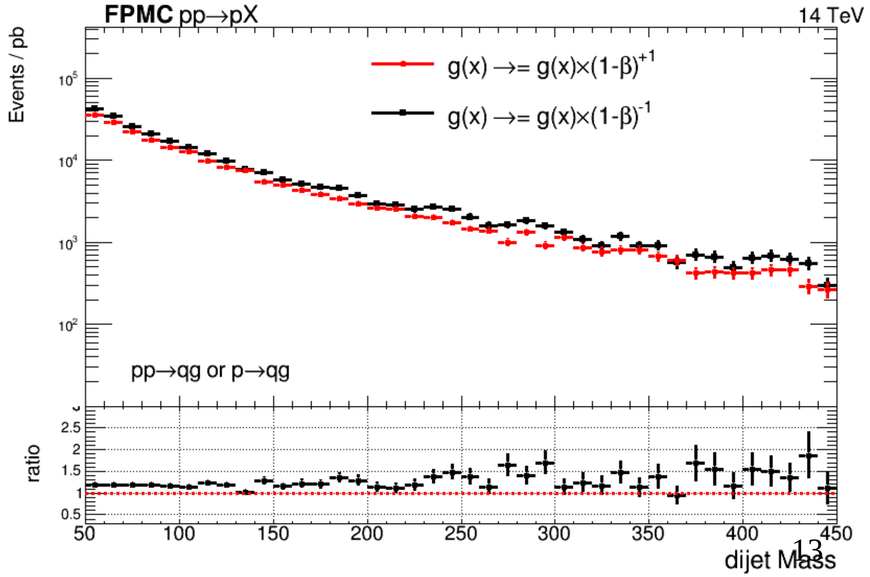


Probing diffractive di-jet events

- The highest cross-section (~nb)
- Sufficient statistics to measure survival probabilities
- Using gluon/quark tagging gluon contribution to structure functions can be probed at high x



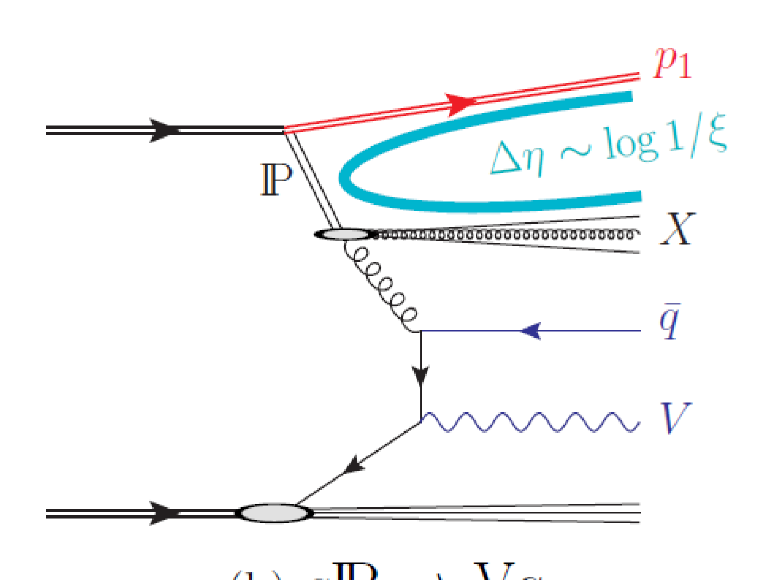




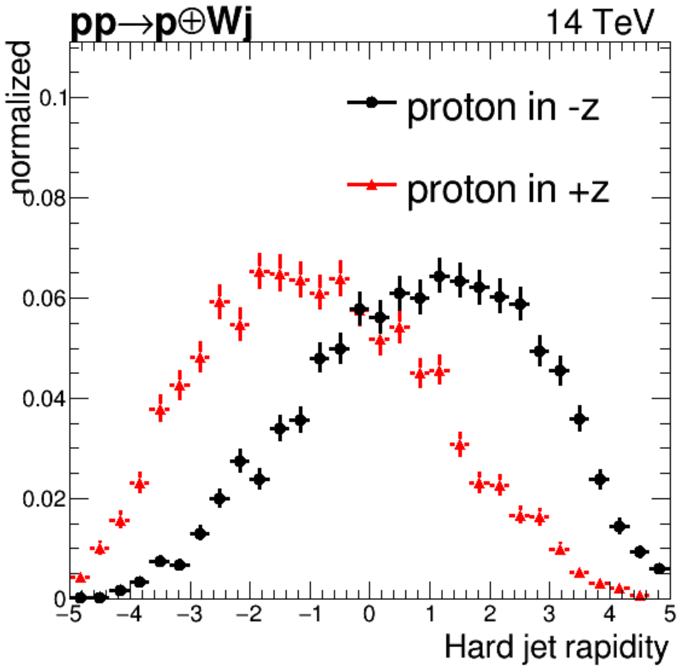
Probing diffractive V+jets

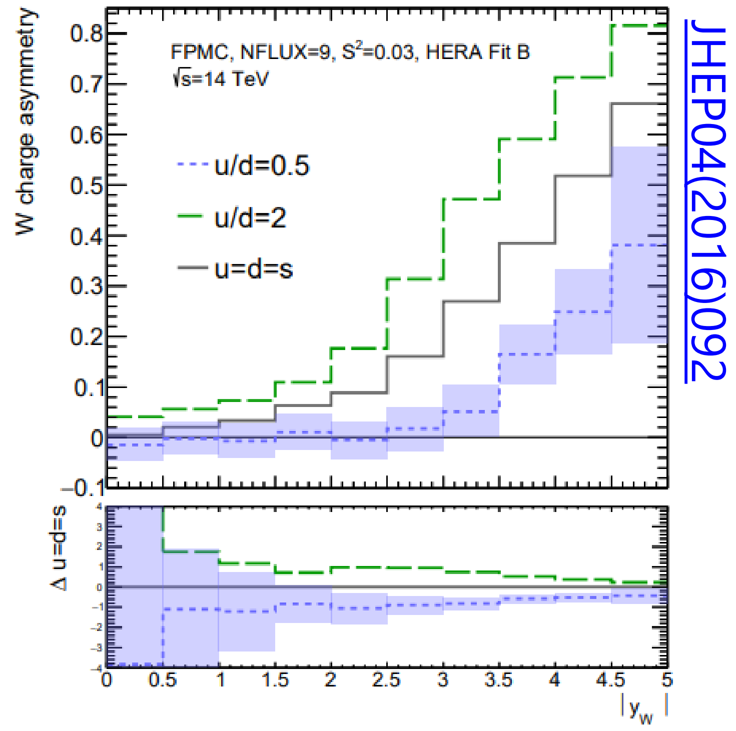
Z/W+jet diffractive production, with q/g/c tagging

Charge asymmetry in diffractive W production



(b) $q\mathbb{P} \rightarrow$ Vq



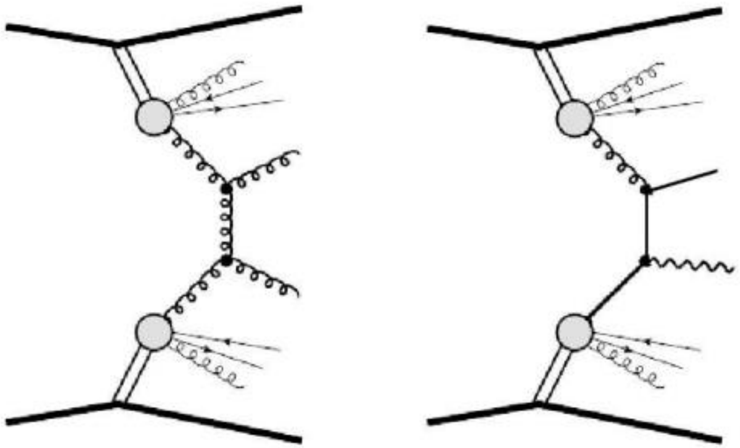


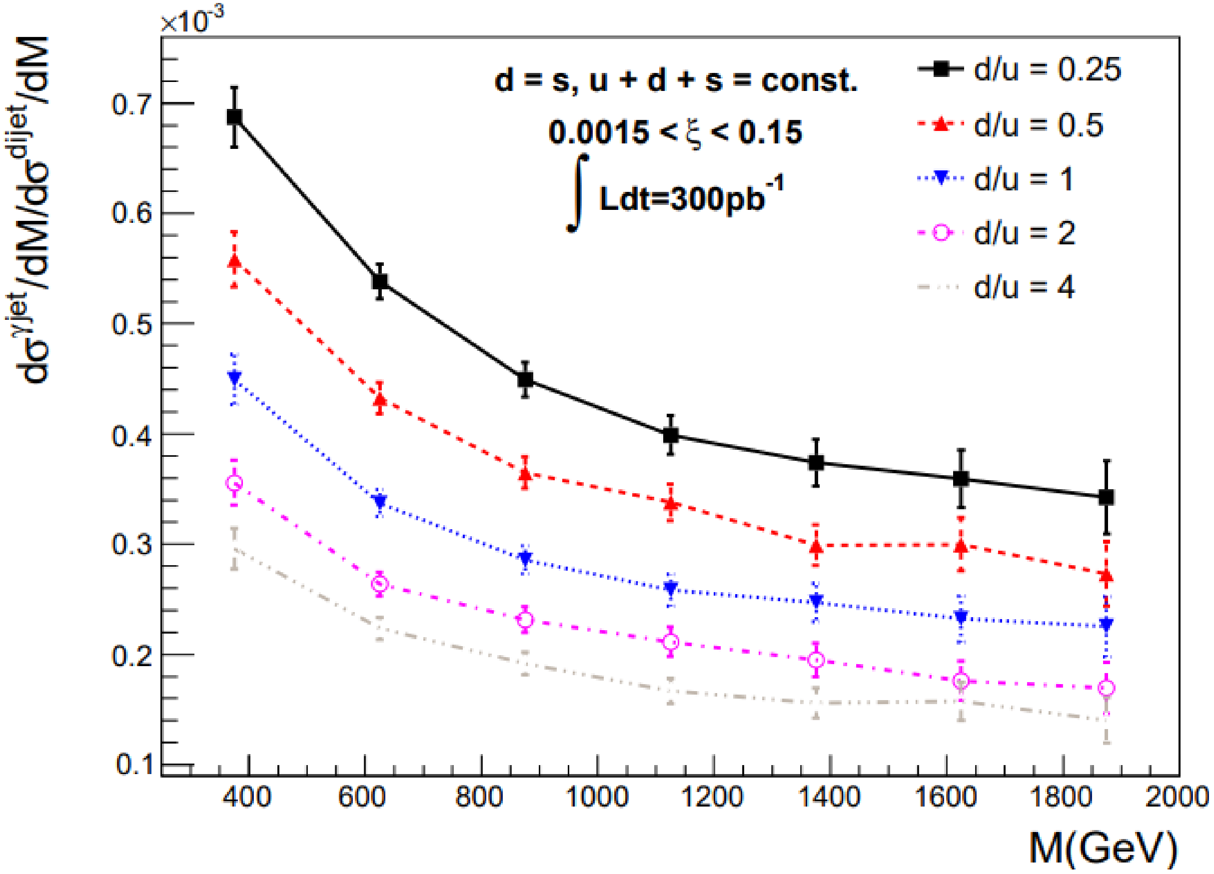
(b) W rapidity

Probing diffractive V+jets

Photon+jet diffractive production, using ration to dijet

- Similarly to W/Z+jet, photon+jet sensitive +jet can be used to probe quark content of dPDF

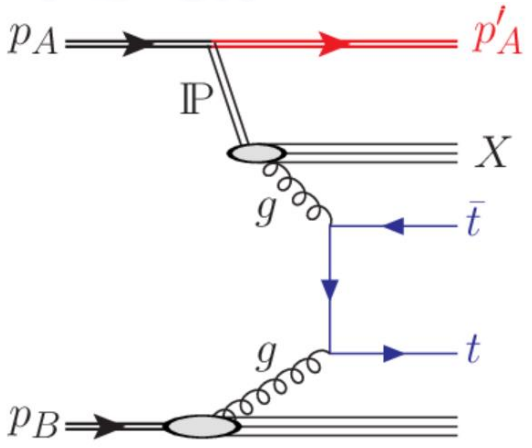


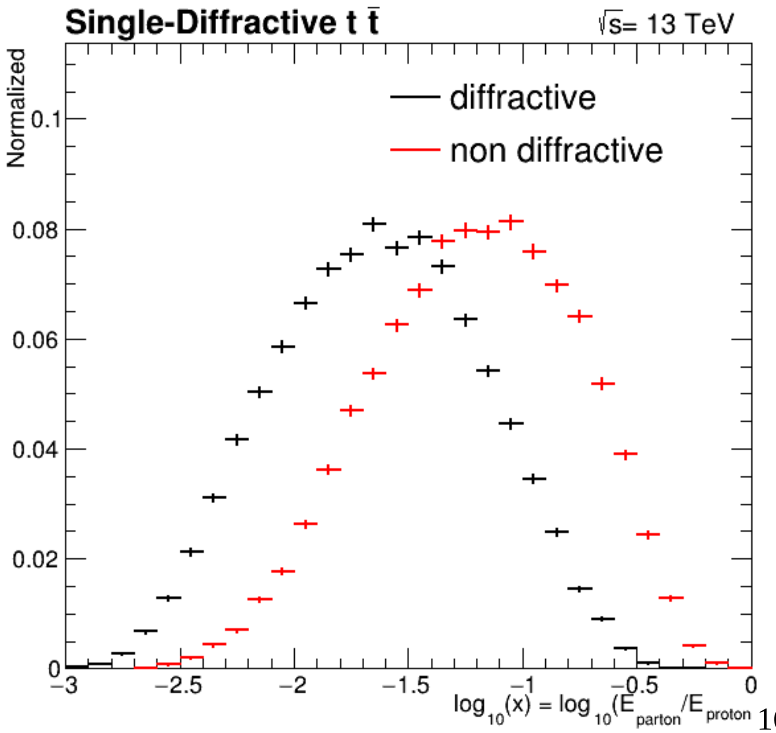


PRD **88**, 074029

Probing diffractive ttbar

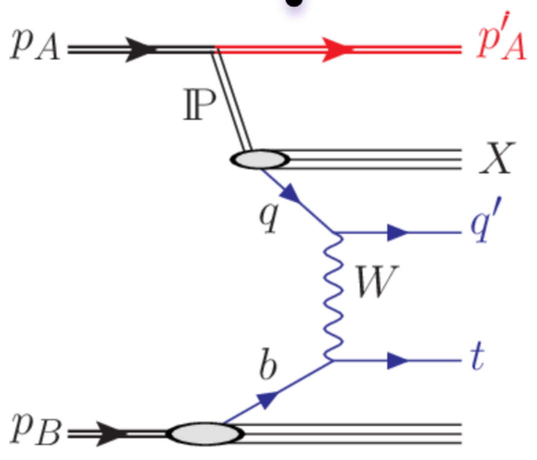
- ttbar is a common SM process produced at the largest scale (σ~800pb, $\sqrt{\hat{s}} > m_{tt} \approx 350$ GeV)
- SD ttbar is expected to be of the order of a few pb
- Dominated by gluon-fusion
- Can have visible effects near the m_{tt} threshold
- Different structure functions manifest in different event topologies (true for all SD processes)

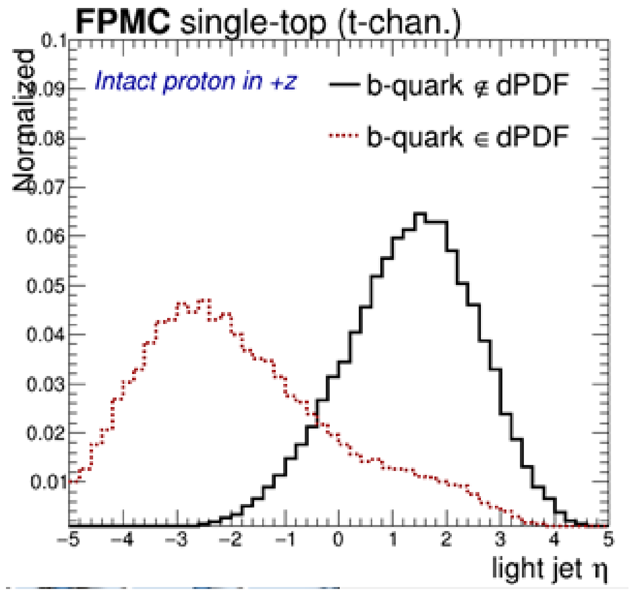




Probing diffractive single top

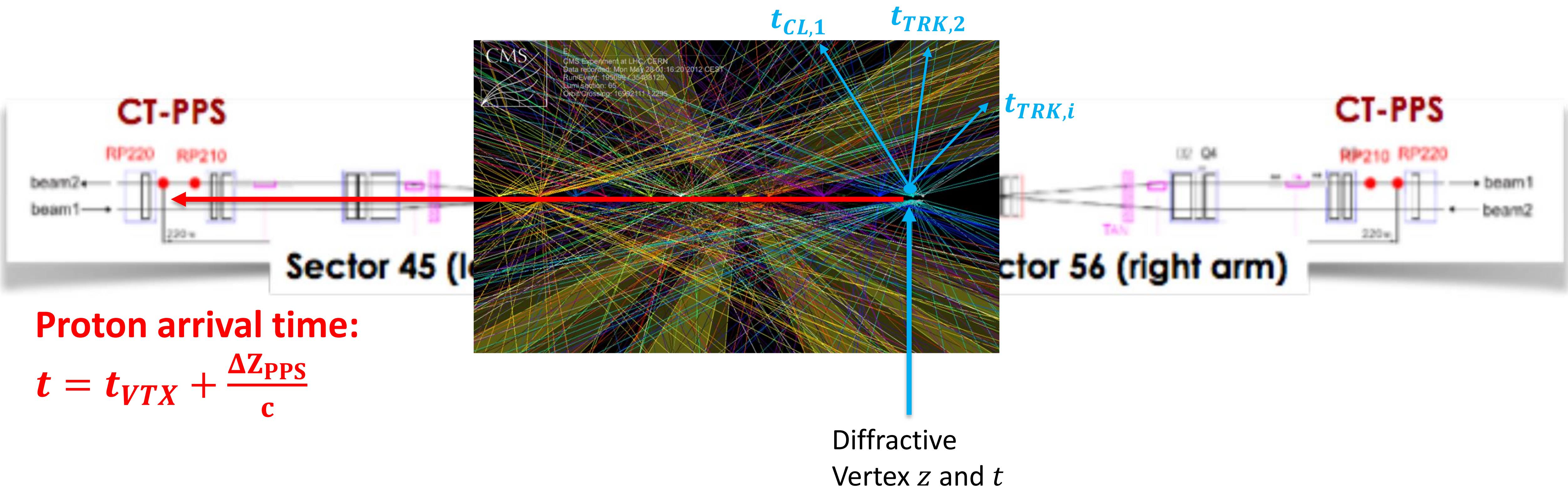
- Non-diffractive production of the single top is common at LHC (160pb), diffractive single top expect to have a low fraction (0.3pb)
- Although the low cross-section, single top production is sensitive to b-quark content of proton/pomeron
- dPDF(b) assume to be zero / not constrained
- Strong asymmetry in the light jet kinematics
- **The process can be used to probe pomeron b-quark content**





Proton tagging with timing

- When bunches cross, collisions take place, and multiple vertices are created
- Central detector equipped with timing detectors, mostly used to suppress out of time pileup, and used for physics (e.g. long lived particles).

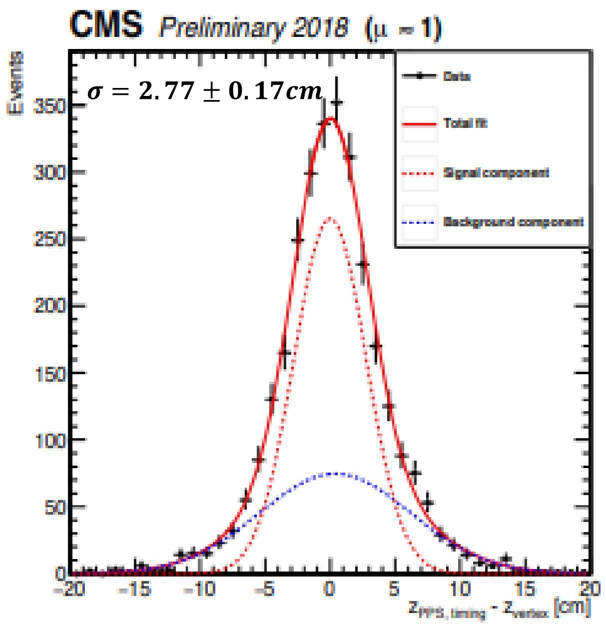


Proton arrival time:

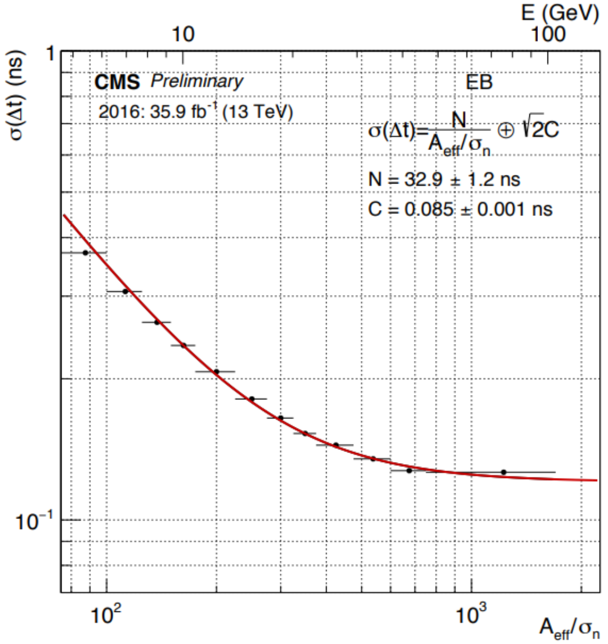
$$t = t_{VTX} + \frac{\Delta Z_{PPS}}{c}$$

Proton tagging with timing?

Example from CMS in Run 2: Forward detectors $\sigma \sim 90ps$. Central ECAL, neighboring crystals (CMS) $\sigma > 100\ ps$



CMS-DP-2020-046



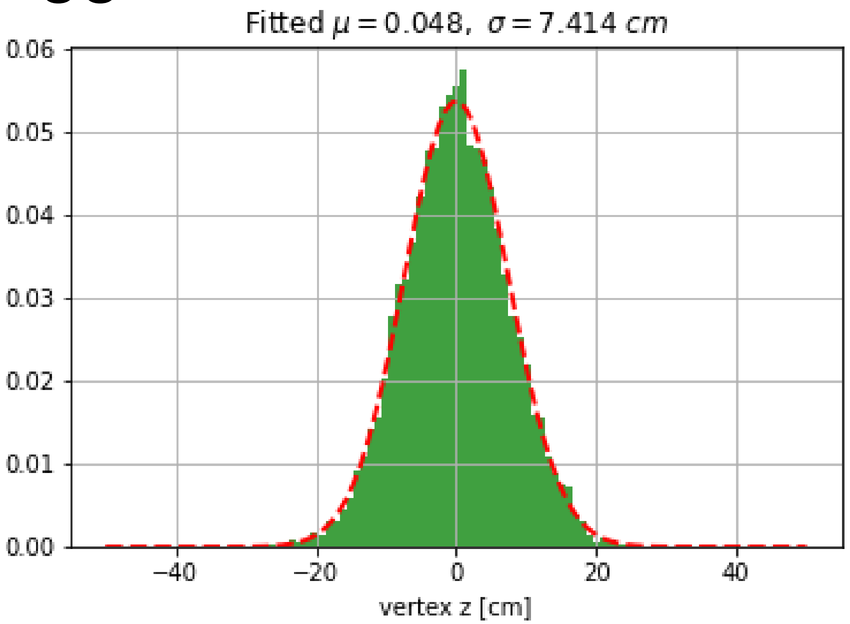
CMS-DP-2019-021

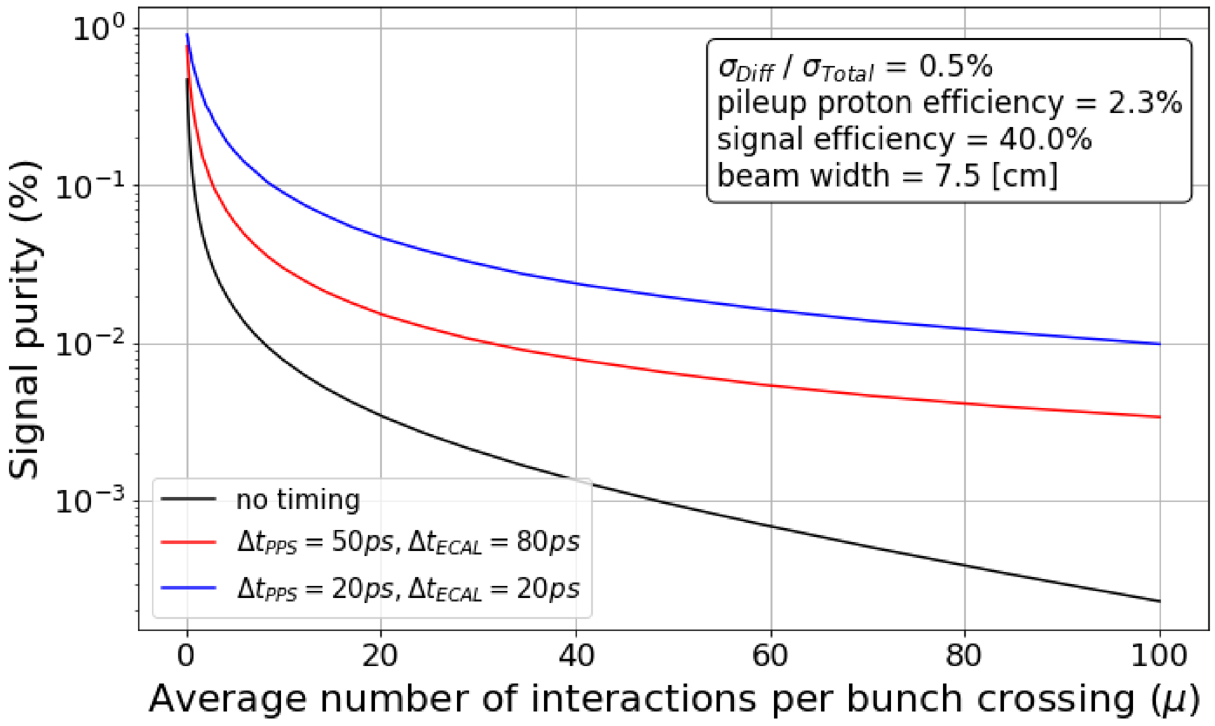
Run 4: Central detector resolution expected to improve well bellow 50ps, similar expectation from the forward detectors

Proton tagging with timing

Background rates and event purity using timing information:

- 0.5% diffractive component is enhanced using time correlation
- Timing detectors can improve background rejection for any single tagged events*





---

*Not only SD, but single tagging also include also low mass CEP processes(!)

Summary

- Hard SD production processes can be used to constrain diffractive models at LHC
- Low-PU data is required to measure SD events ($\mu<0.1$)
- In Run 3 low-PU runs are possible, several tools exist to enhance diffractive fraction – dedicated triggers, analysis tools, or improved timing detectors

Backup

Probing diffractive di-jet events

- The highest cross-section (~nb)
- Sufficient statistics to measure survival probabilities
- Using gluon/quark tagging gluon contribution to structure functions can be probed at high x
- gg/qq fractions (slightly different from non-diffractive events) could probe pomeron structure
- Potential to probe Reggeon contributions