Theory and Experiment in High Energy Physics
V4-HEP workshop

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Hard diffraction in ATLAS

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Outline

Introduction

Phenomenology overview

Experimental methods

Diffractive charm

Diffractive jets

Introduction

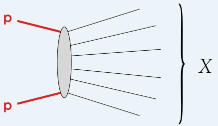
Usual proton-proton collisions at the LHC

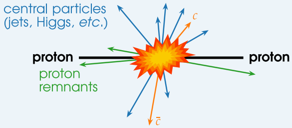
→ protons collide head-on

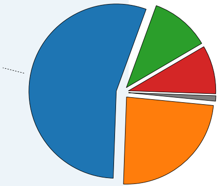
→ both protons break up

→ collision products are emitted in the central region

→ proton remnants may be found in the forward regions







Collisions at LHC

COLLISIONS AT LHC

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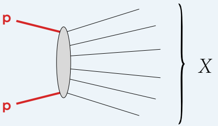
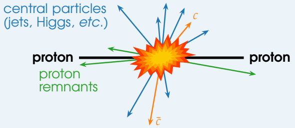
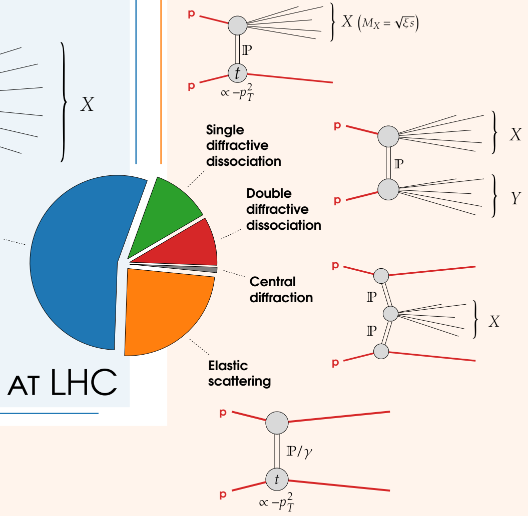
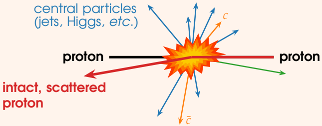






How can proton(s) remain intact?



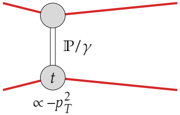
Proton can exchange objects that do not change its quantum numbers:

→ photon (γ) – via electromagnetic interactions

→ Pomeron ($\mathbb{P}$) – via strong nuclear force

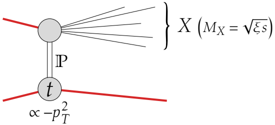
Forward proton scattering in a diverse physics program!

Soft diffraction



Elastic scattering

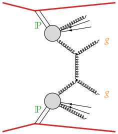
ATLAS EPJC 83 (2023) 441
ATLAS PLB 761 (2016) 158



Single diffractive dissociation

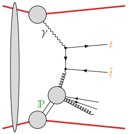
ATLAS JHEP 02 (2020) 042

Hard diffraction



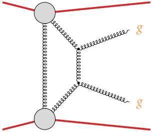
Diffractive jets

ATL-PHYS-PUB-2017-012



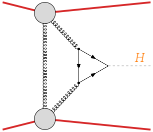
Heavy quarks

Goncalves et al 2007.04565
Howarth 2008.04249



Exclusive jets

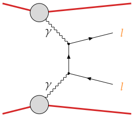
Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018



Higgs boson

Cox et al 0709.3035
Heinemeyer et al 0708.3052

$\gamma + \gamma$ processes



Leptons

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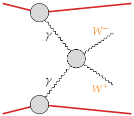

W bosons

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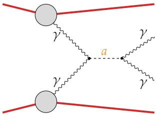

Axion-like particles

Fichet et al 1312.5153
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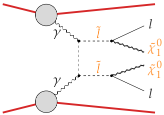

SUSY dark matter

Beresford & Liu 1811.06465
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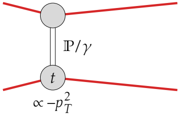
Soft diffraction



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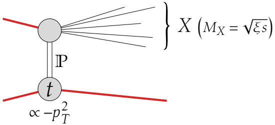

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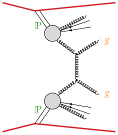
Hard diffraction

today!



Diffractive jets

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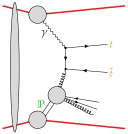

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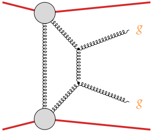

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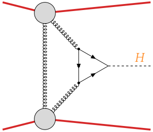

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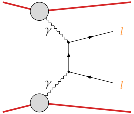

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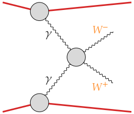

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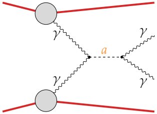

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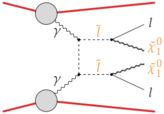

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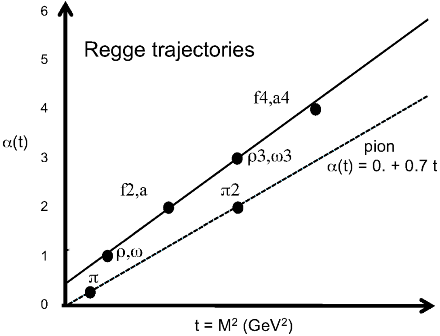
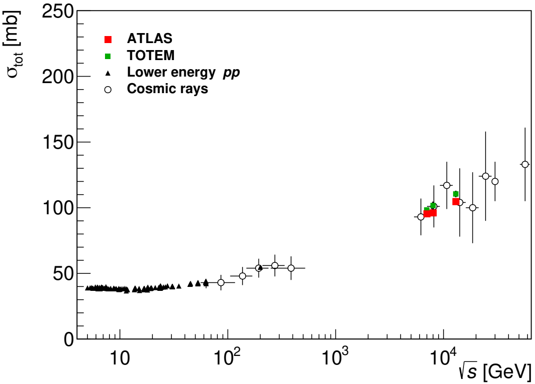
Phenomenology overview

- What is a Pomeron?
- Models of diffraction
- Hard diffraction
- Factorization and its breaking ...and its restoration

Pomeron in Regge theory





- In **Regge theory** scattering interpreted as exchanges of **Regge trajectories** (rather than individual particles)
- Chew & Frautschi (1961, 1962) plotted the spins of low lying mesons against square mass and noticed that they lie in a straight line:

$$a(t) = a(0) + a' t$$

- Total hadronic cross section (asymptotic behavior):

$$\sigma_{\text{tot}} \sim s^{\alpha(0)-1}$$

- Rising with $\sqrt{s}$

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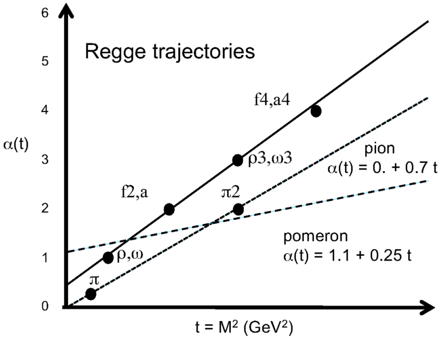

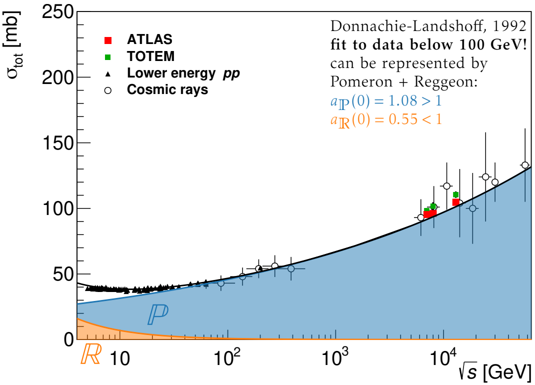

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- Total hadronic cross section (asymptotic behavior): $$\sigma_{tot} \sim s^{\alpha(0)-1}$$
- Rising with $\sqrt{s}$
  $\implies$ there must exist a trajectory with $a(0) > 1$
  a Pomeron trajectory!

Models of diffraction

What is a **Pomeron** in QCD?

- *"diffraction appears to be mediated by the exchange of low-x partons subject to color constraints"* [hep-ph:0407035]
- vacuum quantum numbers $\left(J^{\mathrm{PC}} = 0^{++}\right)$
- simplest picture – two gluons in a color singlet

3 main categories of effective models of diffraction:

- Resolved Pomeron
- Two-gluon (dipole) exchange
- Soft Color Interaction

Resolved Pomeron

- Ingelman-Schlein model
- Two different types of factorization:

1. Collinear factorization

The cross section given by a convolution of the partonic sub-process
→ the same as in inelastic DIS – and
diffractive parton distribution functions (DPDF) of the proton:

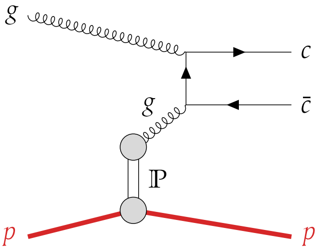
$$d\sigma = f_i^D(x, Q^2, x_{\mathbb{P}}, t) \otimes d\sigma_{\text{sub}}(x, Q^2)$$

proton DPDF — partonic sub-process

2. Proton-vertex factorization

Pomeron flux and its partonic structure:

$$f_i^D(x, Q^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \cdot f_i(x/x_{\mathbb{P}}, Q^2)$$



[Phys.Lett.B 152 (1985) 256-260]
[Eur.Phys.J.C18:167-179,2000]
[AIP Conf.Proc. 1105 (2009) 1, 248-251]

Color dipole framework

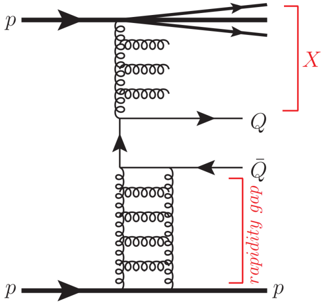
Two relevant scenarios
(note that different proton remains intact):

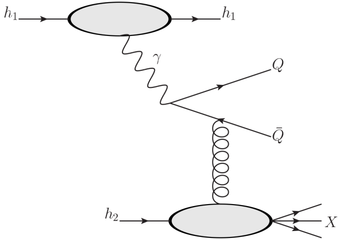
1.

- Fluctuation of the incoming virtual **gluon** into a heavy $q\bar{q}$ pair
- Subsequent **elastic scattering of the $q\bar{q}$ dipole** on the target proton

2.

- Fluctuation of the incoming virtual **photon** into a heavy $q\bar{q}$ pair
- Subsequent **interaction of the $q\bar{q}$ dipole with the parton** inside the proton (proton breaks up)



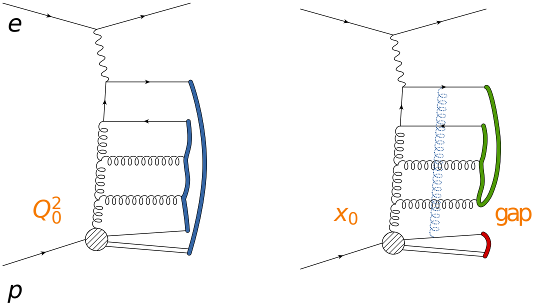


[Phys.Lett.B 379 (1996) 239-248]
[Phys.Lett.B 386 (1996) 389-396]
[Phys.Lett.B 406 (1997) 171-177]
[Phys.Rev.D 102 (2020) 7, 076020]

Soft Color Interaction

- **Soft color exchange** may change the topology of the created color string
- Hard process remains unaffected
- Natural emergence of rapidity gaps
- Similar concept used in the Generalized Area Law model (soft color exchange happens between the strings)
- SCI model has been compared to data with good agreement:
  - **diffractive DIS** [Edin, Ingelman, Rathsman, hep-ph/9508386, hep-ph/9602227, hep-ph/9605281, hep-ph/9912539]]]
  - **hard diffraction in hadron–hadron coll. at the Tevatron** [RE, Ingelman, Tîmneanu; hep-ph/0106246, hep-ph/0210408]

  The SCI model reproduces diffractive rates in both DIS and hadron-hadron!
- Unified approach to both hard and soft diffractive events
- However, due to the complexity of soft interactions the model remains primarily qualitative



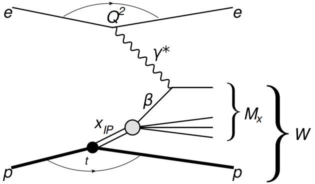
[Phys.Lett. B366 (1996) 371-378]
[Phys.Rev. D64 (2001) 114015]

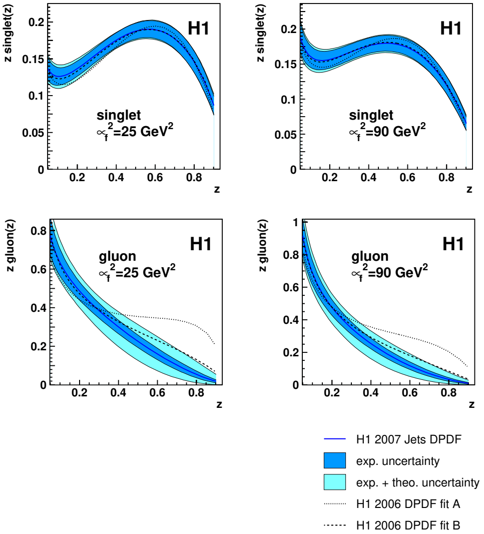
Hard diffraction

- Unlike "soft" diffraction (low p_T), "hard" diffraction involves **partonic interactions**
- Final states: high-energy jets, vector bosons, or heavy quarks.
- First observation: UA8 at SPS, $\sqrt{s} = 630$ GeV
  $\rightarrow$ Jet distributions **similar to inelastic parton-parton scattering**
  $\rightarrow$ suggesting the **parton scattering underneath**
  $\rightarrow$ but the **scattered protons were detected** in forward spectrometers!
- **Ingelman and Schlein** (1985) – “hard Pomeron” that features a partonic structure
- It may be a different Pomeron:
  The probability to emit a pomeron governed by the same Regge-type formulae,
  $\rightarrow$ but the trajectory $\alpha(t)$ can be different.

Diffractive PDFs at HERA, kinematics of hard diffraction

- Hard diffraction measured at HERA *ep* collider
- Diffractive deeply inelastic scattering (DDIS)
- Scattering of the electron off a parton inside a pomeron emitted from the proton
- $\rightarrow$ Possible to measure the diffractive structure functions F_2^D
- Depends not only on x and Q^2, but also on the proton kinematics: t and $x_{\mathbb{P}}$

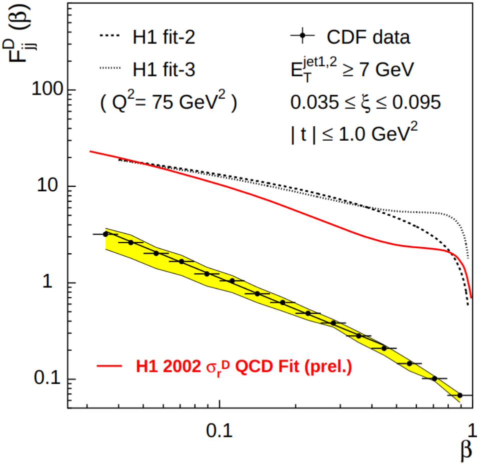




- Q^2: minus the square of the four-momentum exchanged by the electron
- t: squared four-momentum exchanged by the proton (intact).
- M_X: invariant mass of the diffractively produced system.
- x: fraction of the proton carried by the struck quark.
- $x_{\mathbb{P}} = \xi$: momentum fraction lost by the proton.
- $\beta = \frac{x}{\xi}$: fraction of the Pomeron momentum carried by the struck parton.

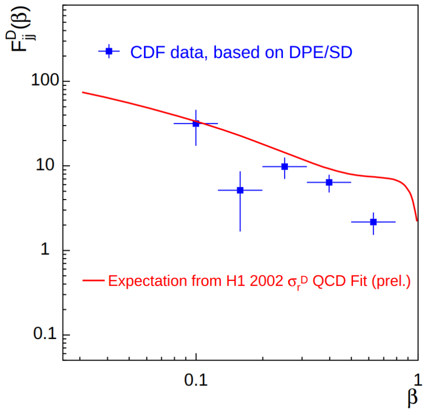
Factorization breaking

- CDF at Tevatron: **factorization does not hold** in hadron-hadron collisions
- **Additional soft interactions** (either in the initial or final states) may spoil the rapidity gap and break up the outgoing proton
- **Overall suppression factor** – little dependence on the kinematics of the interaction or its type
- Suppressed approximately by a factor of 10 at the Tevatron with respect to HERA.



Gap survival

- **Soft survival probability factor** $\langle S \rangle^2$ ≡ probability that the event with rapidity gaps survives the soft exchanges
- (Mostly) **independent on the details of the process** (i.e. does not depend on ξ, t, β, Q^2)
- Gap survival probability estimate is crucial for hard diffraction
- **Non-perturbative nature**: model-dependent, difficult to obtain for all processes.

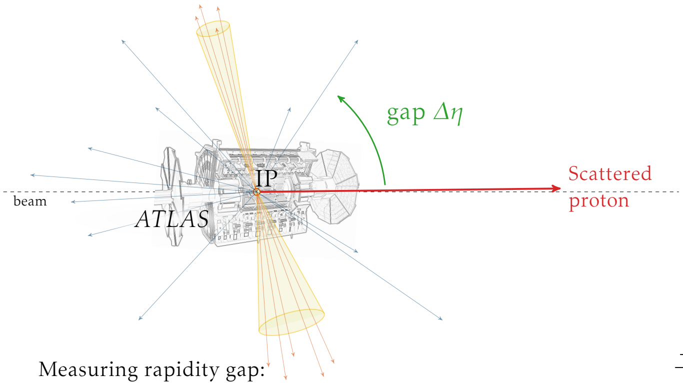


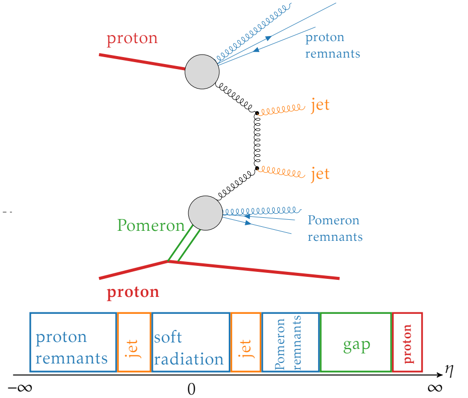
Restoring the factorization

- If an additional soft exchange between the protons occurs, it **spreads over the whole rapidity region**
- For events with **two rapidity gaps** (DPE):
  – either both rapidity gaps survive, or
  – both are spoiled at the same time
- The structure function measured in DPE **events where already one gap was present** agreed with the HERA expectation
  → **no factorization breaking!**

Experimental methods

How to identify diffractive events?





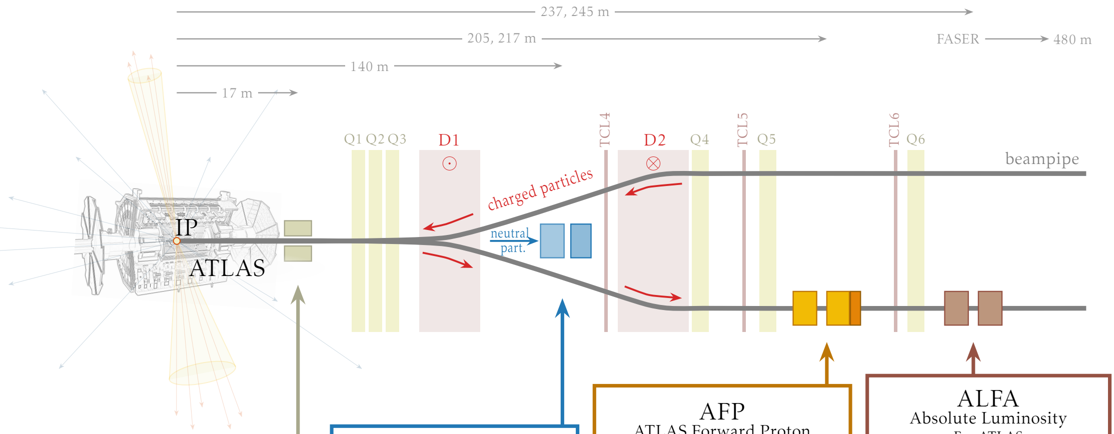
Measuring rapidity gap:

- \+ historically used for diffractive pattern recognition
- \+ no need for additional detectors
- – **gap is frequently destroyed** (pile-up, rescattering)
- – **gap may be out of acceptance**
- – **gap may be a statistical fluke**

[ATLAS, Eur.Phys.J.C 72 (2012) 1926]
[ATLAS, Phys.Lett.B 754 (2016) 214-234]

Measuring forward protons:

- \+ **Protons measured directly** (deflection→$\vec{p}, E$)
- \+ **Suitable for pile-up environment**
- – Protons are scattered at very small angles
- – **Additional detectors required** → far downstream.



LUCID

Luminosity Cherenkov Integrating Detector

$5.6 < |\eta| < 5.9$

For luminosity measurement

ZDC + LHCf

Zero Degree Calorimeter
LHC Forward

Low-μ, $|\eta| > 8.0$

For cosmic-ray & heavy-ion physics

AFP

ATLAS Forward Proton

Low & high μ

$0.02 < \xi < 0.12$

soft & hard diffraction, $\gamma + \gamma$

- 4 Roman Pots, 2-4 mm from beam
- tracker: 3D sillicon pixel sensor
- spatial resolution $\sigma_x = 6\mu$m
- ToF: 16 Quartz Cherenkov bars
- **timing resolution $\sigma_t \approx 25$ ps**

ALFA

Absolute Luminosity
For ATLAS

Low-μ, $0 < \xi < 0.2$

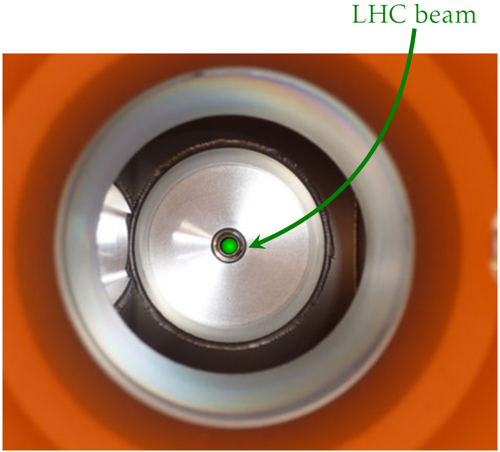
special high-$\beta^\star$ optics

Elastic scattering, soft diffraction

- 8 Roman Pots in 4 stations
- **<1 mm from beam**
- layered Scintilating Fibers
- spatial resolution $\sigma_y = 30\mu$m
- Multi-Anode-Photo-Multipliers

Roman Pot in action

Roman Pot in action



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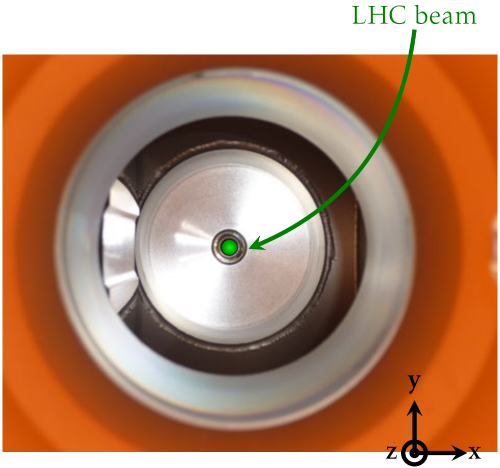

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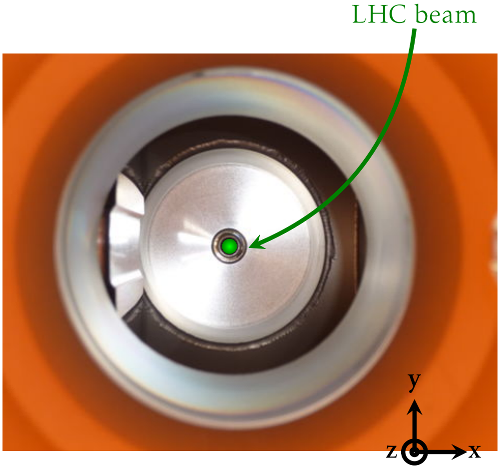

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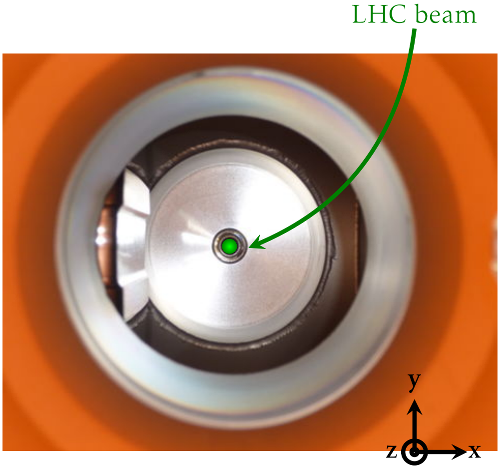

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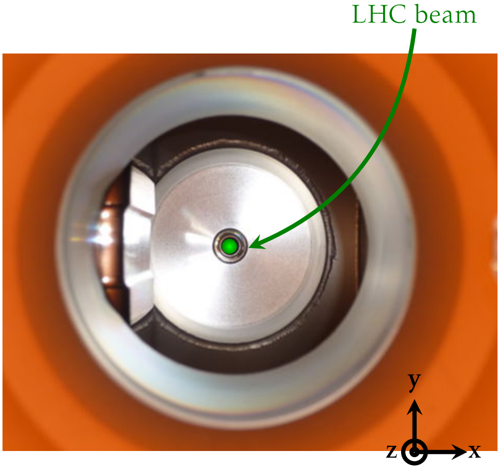

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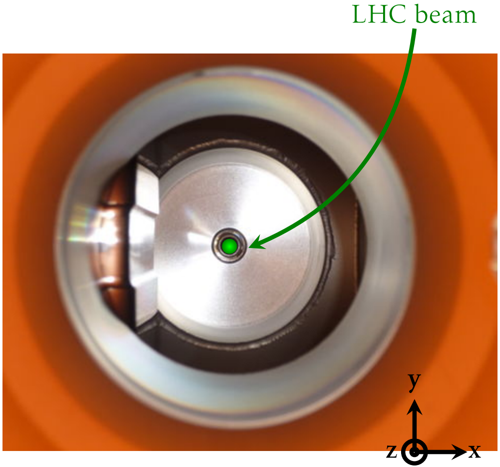

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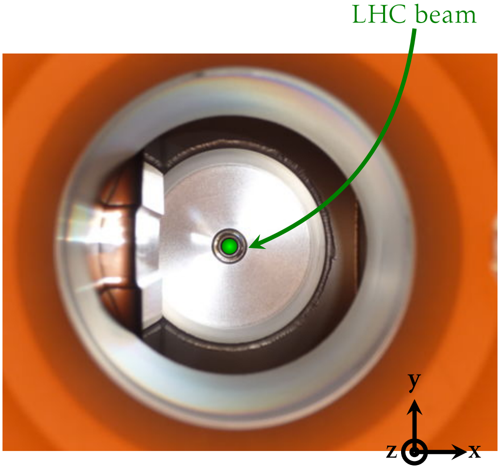

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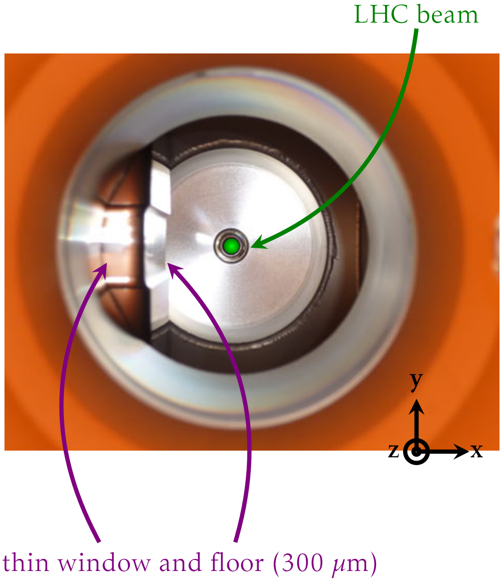

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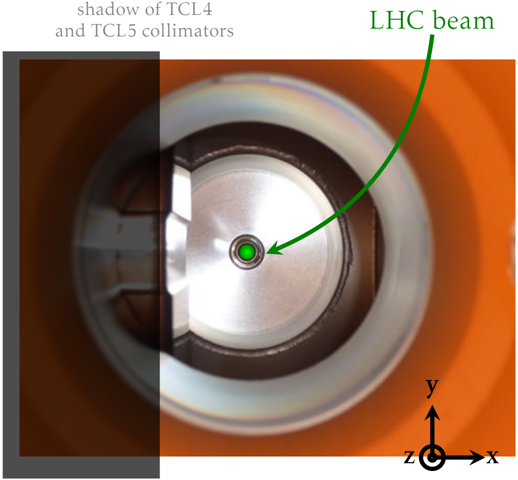

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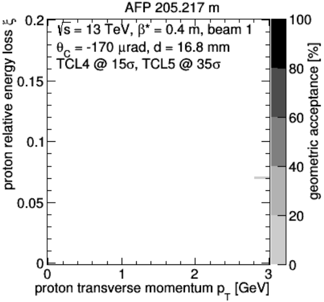

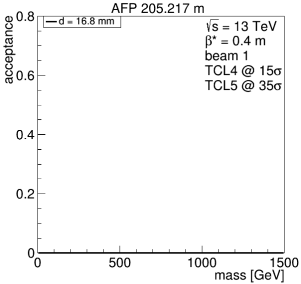

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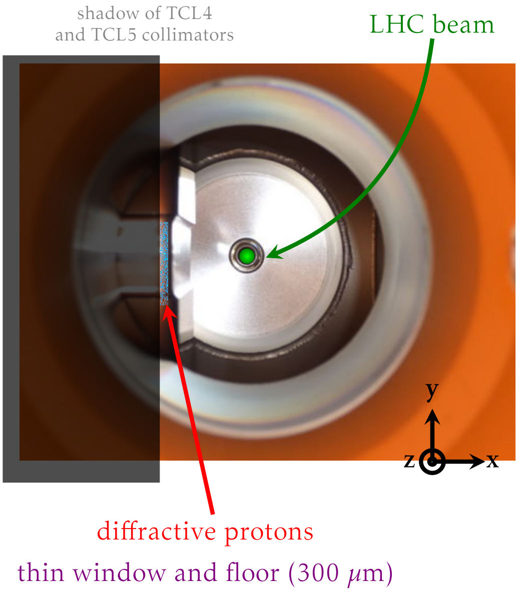

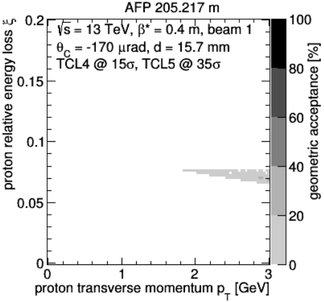

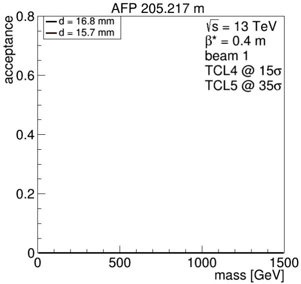

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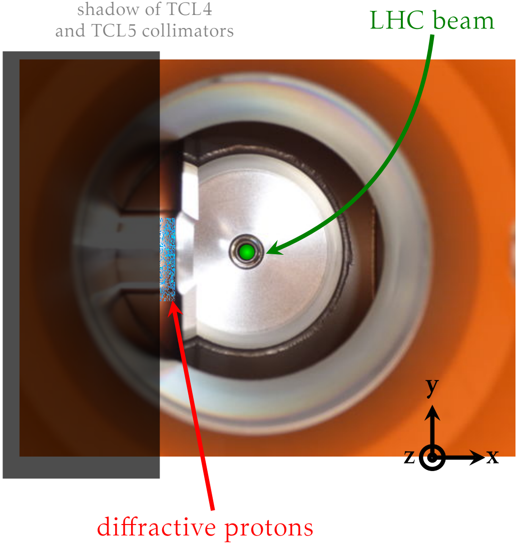

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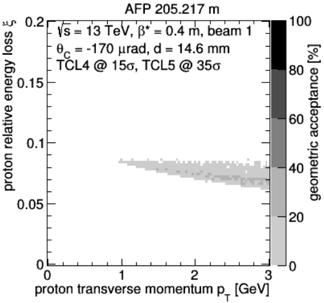

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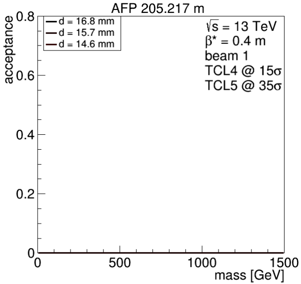

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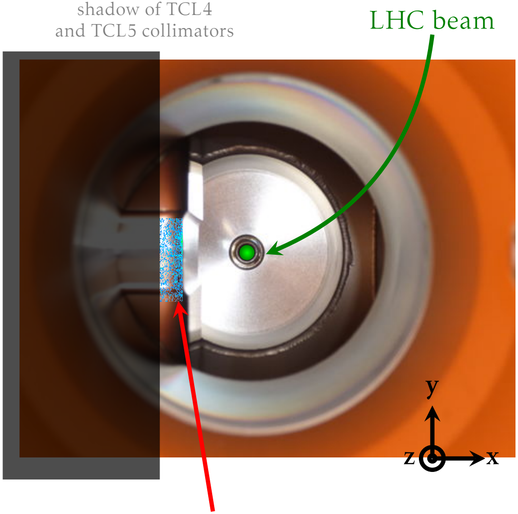

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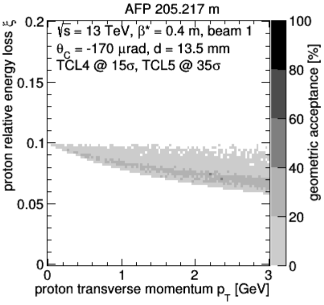

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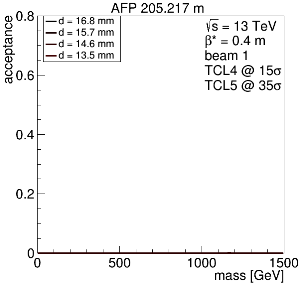

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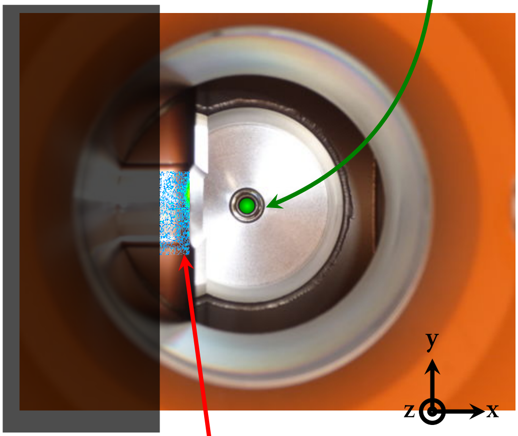

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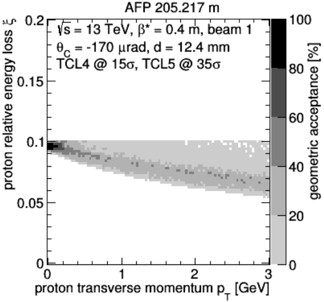

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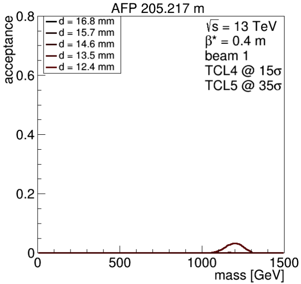

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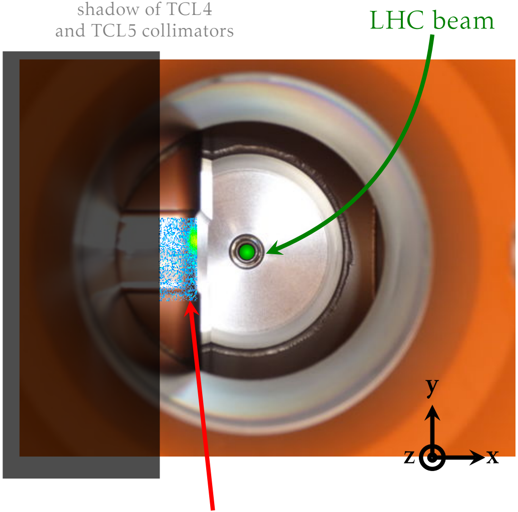

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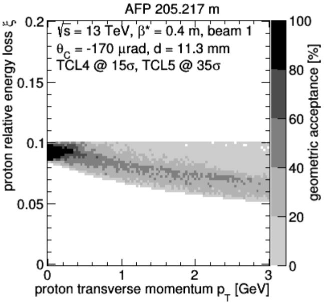

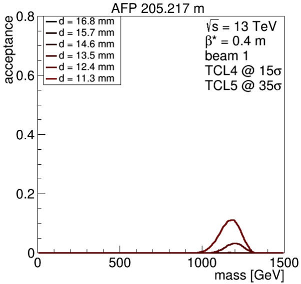

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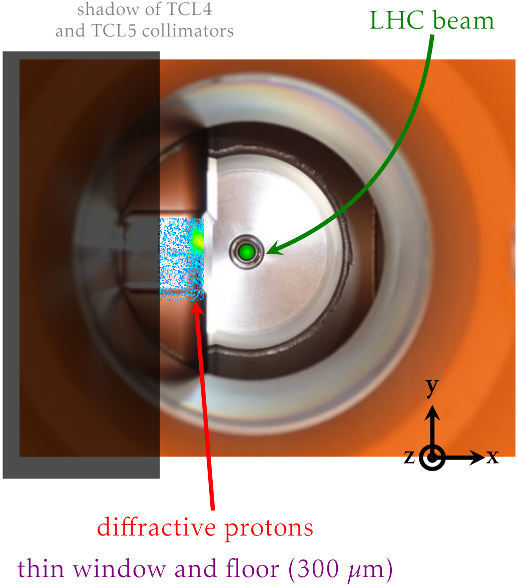

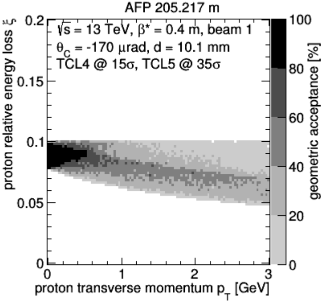

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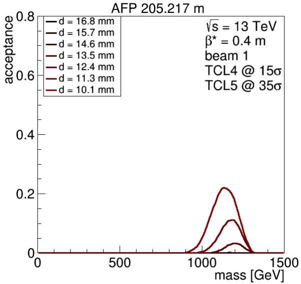

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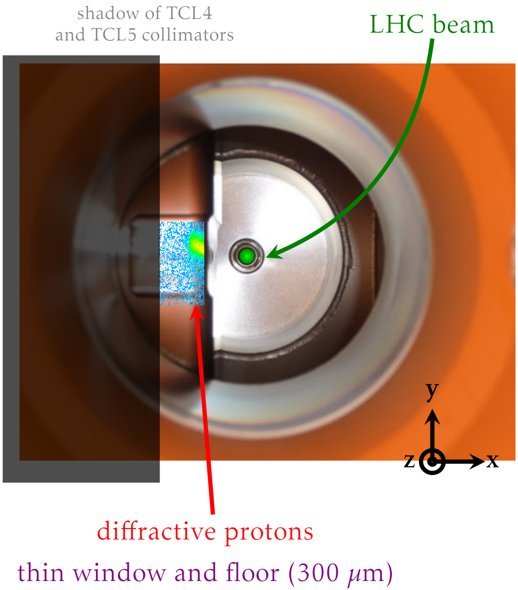

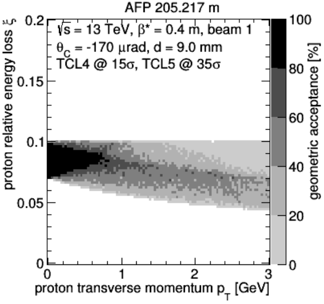

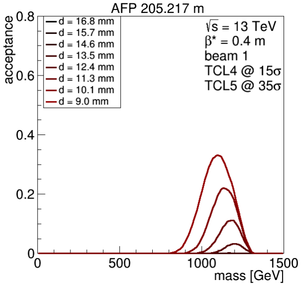

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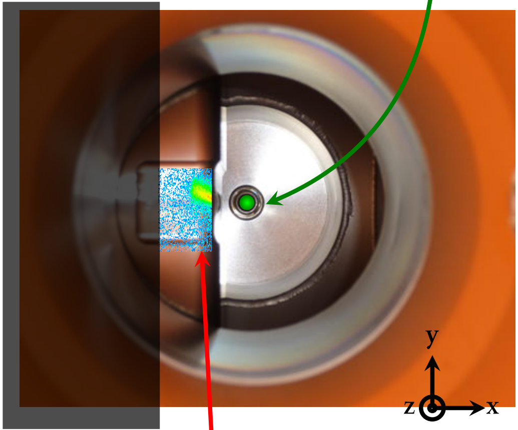
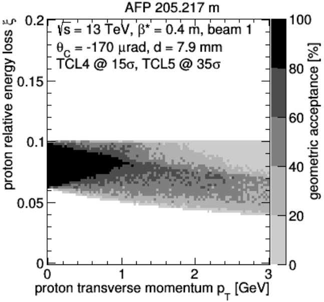
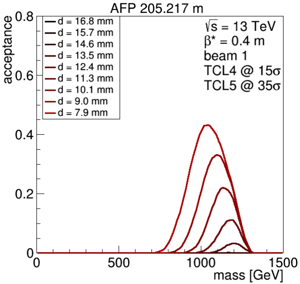


diffractive protons

thin window and floor (300 μm)





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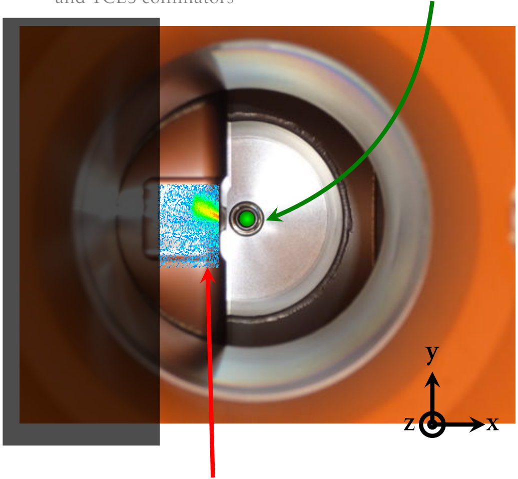

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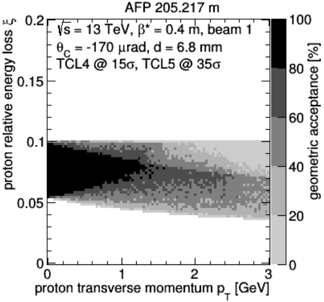

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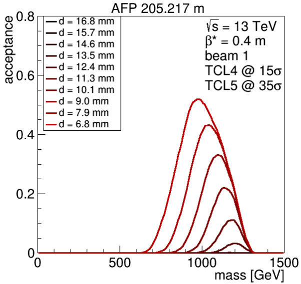

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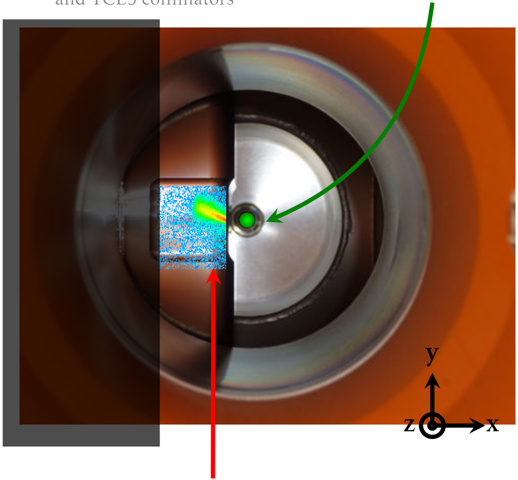

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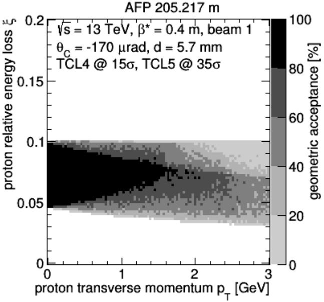

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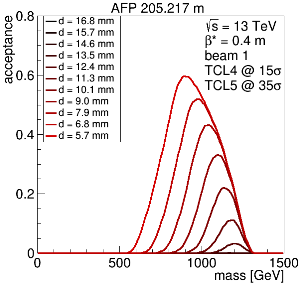

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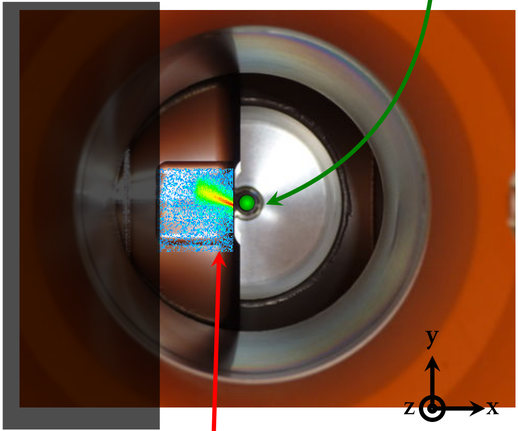

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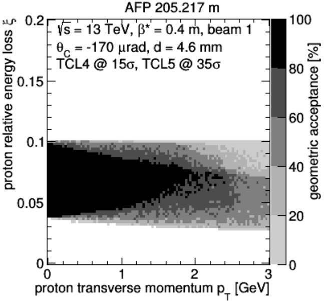

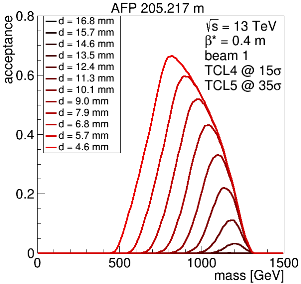

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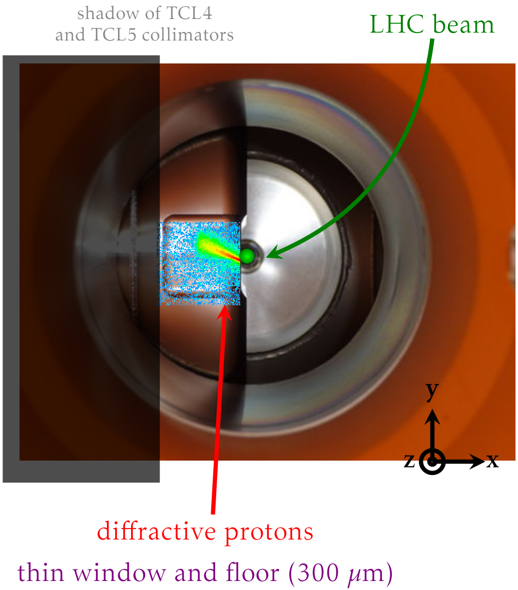

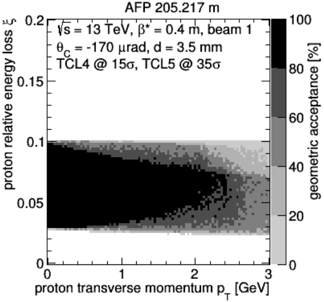

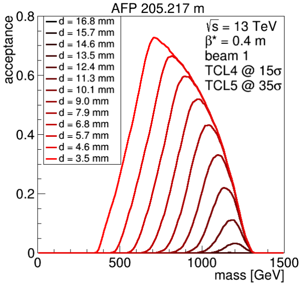

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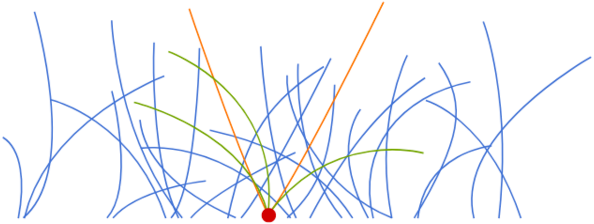
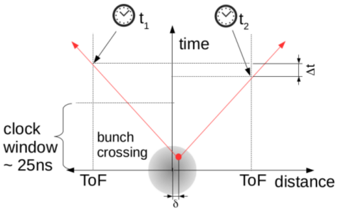
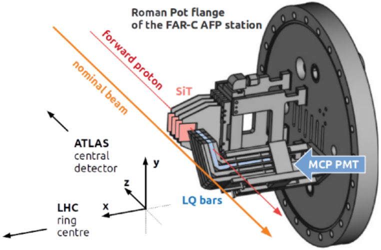
Backgrounds and its reduction

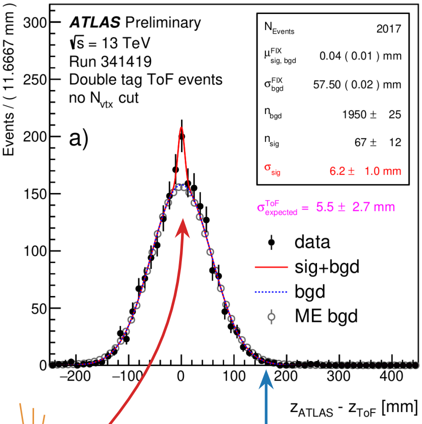


- Multiple $p+p$ collisions happening in the ATLAS detector at the same time (pile-up).
- **Background**: in a pile-up environment there are usually multiple diffractive events happening.
- Which vertex corresponds to the measured forward proton?
- Main tools for background suppression:
  - data taking in special **low-pile-up runs** (price is statistics),
  - **ToF measurement** (only for double-tag events),
  - **kinematic match** of forward proton and central system (only for exclusive processes).

Reducing physics background with ToF

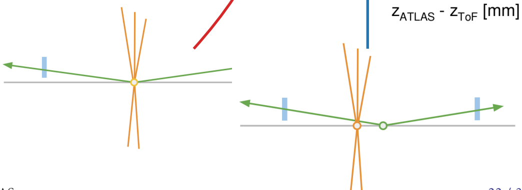






For events with double proton tag:

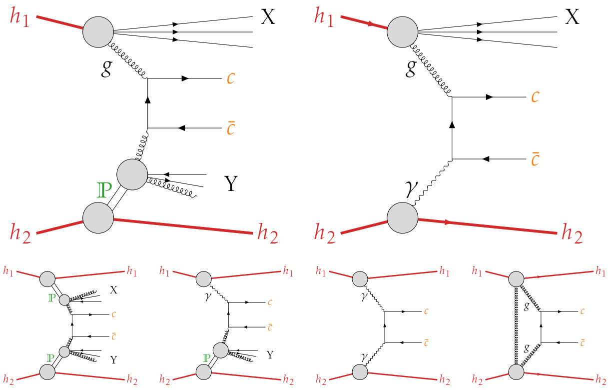
- Measure ToF difference: $\Delta t = (t_A - t_C)/2$
- Calculate vertex position: $z_{\text{ToF}} = \frac{c}{2}\Delta t$
- Compare z positions reconstructed by ATLAS and AFP ToF:



Diffractive charm

Why open charm?

- $c\bar{c}$ production – lowest-mass process involving **hard-scale**
- Probing the **nature of Pomeron**, testing alternative approaches (e.g. Soft Color Interaction)
- Testing the **factorization theorem**
- Diffractive events identified with **forward proton tag with AFP**



Unique class of events:

i) accessible within **perturbative QCD framework**,

ii) characterized by **high exepected cross-section**,

iii) possible to be studied in a clean, **low background** experimental environment – low pile-up

Phenomenology perspective

Specifics of **charm production**:

- At LHC, **large cross-sections** are expected from QCD.
  → background can be reduced with special, **low pile-up runs**
  → identification of diffractive events possible with **intact protons**
- Lesson from data on inclusive charm production:
  QCD LO collinear approach works rather poorly – higher order corrections are needed
  (e.g. k_t factorization).
- There exists a **wide range of model predictions** (next slides).

Discovery potential:

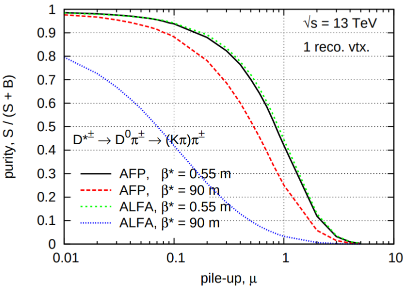
- Tests of **factorization theorem(s)**.
- Probing the **nature of the Pomeron**.
- Measurement of diffractive charm production may **pin down the mechanism of diffractive production** – large differences in predicted cross-sections.

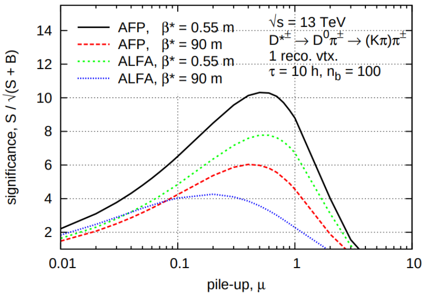
Measurement Feasibility

Excellent data to be studied:

- LHC Run 2 (2017):
  100 nb^{-1} at $\mu \sim 0.05$,
  500 nb^{-1} at $\mu \sim 0.3$,
  650 nb^{-1} at $\mu \sim 1$,
  150 pb^{-1} at $\mu \sim 2$.
- LHC Run 3 (2022):
  0.46 nb^{-1} at $\mu \sim 0.005$
  34.6 nb^{-1} at $\mu \sim 0.05$
  170 nb^{-1} at $\mu \sim 0.02$
- LHC Run 3 (2023):
  175 nb^{-1} at $\mu \sim 1$
  29 nb^{-1} at $\mu \sim 0.2$
  61 nb^{-1} at $\mu \sim 0.05$

- Feasibility studied with simulations (JHEP 02 (2017) 089)

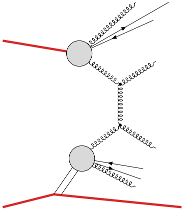




- Dedicated triggers:
  track with min. $p_T = 2, 4, 6, 8$ GeV/c, single-side tag in AFP
  track with min. $p_T = 2, 4, 6, 8$ GeV/c, double-sides tag in AFP

Diffractive jets

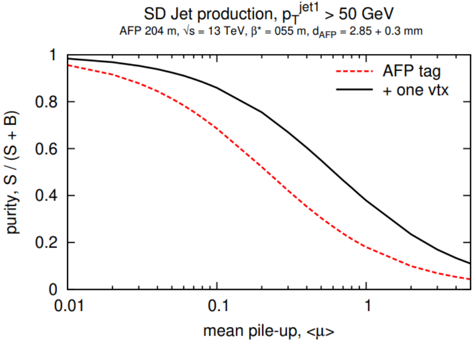
Single Diffractive Jet Production

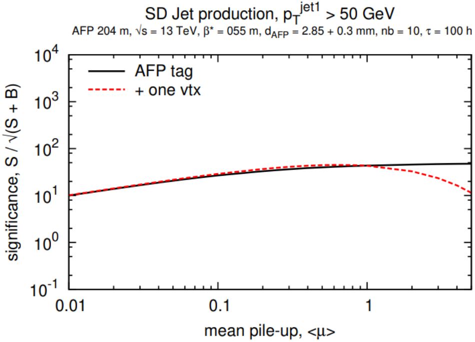


Motivation:

- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- check Pomeron universality between ep and pp colliders

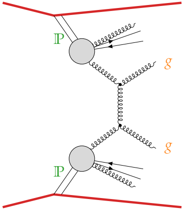
Measurements from CMS already available (8 TeV): EPJC 80 (2020) 1164





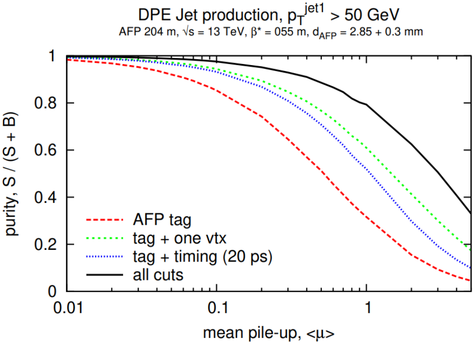
[J. Phys. G: Nucl. Part. Phys. 43 (2016) 110201]

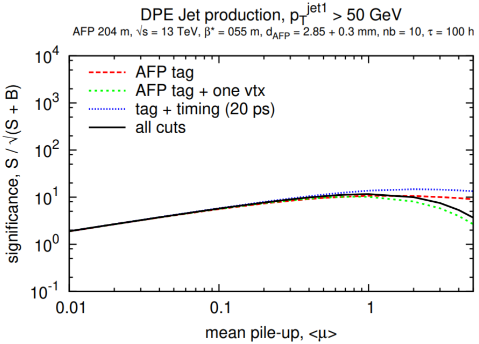
Double Pomeron Exchange Jet Production



Motivation:

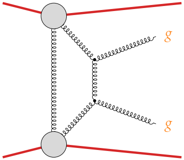
- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- investigate gluon structure of the Pomeron.





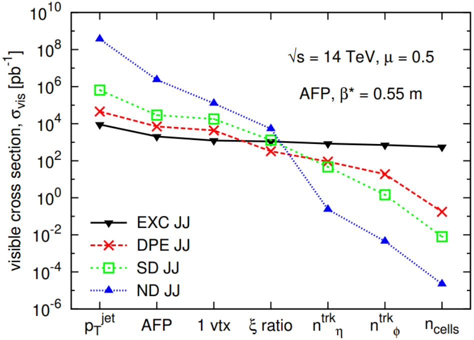
[J. Phys. G: Nucl. Part. Phys. 43 (2016) 110201]

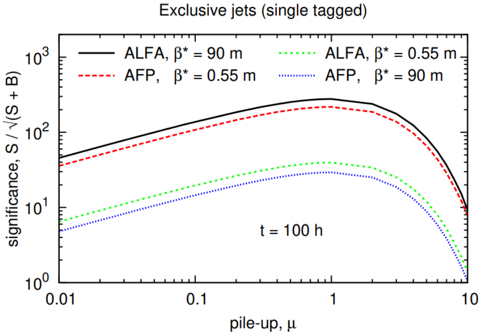
Exclusive Jet Production



Motivation:

- cross section measurement,
- constrain other exclusive productions (e.g. Higgs)





[Eur. Phys. J. C 75 (2015) 320, Acta Phys. Pol. B 47 (2016) 1745]

Thank you for your attention!

Backup Slides

Elastic and diffractive processes are intimately linked to our basic understanding of physics:

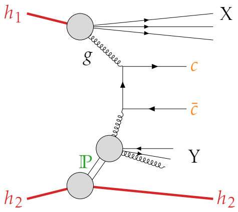
Fundamental questions:

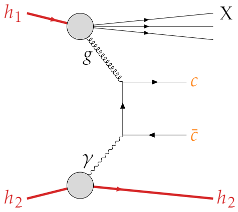
- Color Confinement
- Hadronic mass generation
- Non-perturbative vs perturbative degrees of freedom
- Strong / weak coupling and super-gravity

Practical concerns:

- Modelling pile-up at the LHC
- Luminosity monitoring
- Modelling cosmic ray air showers

Single Diffraction





1. Singe diffraction, $\mathbb{P}$-p process

$$\sigma(h_1 h_2 \to XQ\bar{Q}Y \sqcup h_2) = \int dx_1 \int dx_2 \;\; g_1(x_1,\mu^2) \;\; g_2^D(x_2,\mu^2) \;\; \hat{\sigma}(gg \to Q\bar{Q})$$

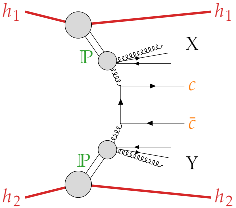
- The dominant contribution in SD processes at the LHC.
- Gay Ducati *et al.*, Phys.Rev.D 81 (2010) 054034
  14 TeV, Resolved Pomeron, $\sigma_{\gamma p}$ = 178 μb ($R_{c\bar{c}} = 2.3\%$)
- Kopeliovich *et al.*, Phys.Rev.D 76 (2007) 034019:
  Dipole, Leading Twist Mechanisms
- Łuszczak *et al.*, Phys. Rev. D 91, 054024 (2015):
  Resolved Pomeron, 14 TeV, $|y| < 2.5$, $p_T > 3.5$ GeV, $D^0 + \bar{D^0}$, $\sigma_{\mathbb{P}p}$ = 3555 nb.
- Łuszczak *et al.*, JHEP 02 (2017) 089:
  k_t-factorization, 13 TeV, $|y| < 2.1$, $p_T > 3.5$ GeV, $D^0 + \bar{D^0}$, $\sigma^{SD}_{\mathbb{P}p}$ = 3–4 μb
- Siddikov *et al.*, Phys.Rev.D 102 (2020) 7, 076020:
  Dipole Model, 13 TeV, $R_{c\bar{c}}$=1.6% $\to \sigma_{\mathbb{P}p} \approx 135\mu$b
  predictions regarding charged particle multiplicity dependence

2. Single diffraction, γ-p process

$$\sigma(h_1 h_2 \to XQ\bar{Q} \sqcup h_2) = \int dx_1 \int dx_2 \;\; g_1(x_1,\mu^2) \;\; \gamma_2(x_2,\mu^2) \;\; \hat{\sigma}(\gamma g \to Q\bar{Q})$$

- Strong electromagnetic fields arising around the proton due to relativistic effects may interact directly with the partons inside the proton.
- Goncalves *et al*, Nucl.Phys.A 976 (2018) 33-45:
  13 TeV, $|y| < 10$, Dipole Model, $\sigma_{\gamma p}$ = 1030 (b-CGC) — 1140 (IP-SAT) nb

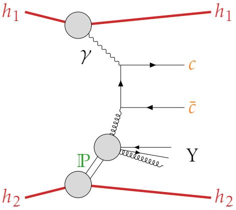
Central Diffraction



3. Central diffraction with double $\mathbb{P}$ exchange

$$\sigma(h_1 h_2 \to h_1 \sqcup XQ\bar{Q}Y \sqcup h_2) = \int dx_1 \int dx_2 \;\; g_1^D(x_1,\mu^2) \;\; g_2^D(x_2,\mu^2) \;\; \hat{\sigma}(gg \to Q\bar{Q})$$

- Gay Ducati, *et al.*, Phys. Rev. C 83, 014903 (2011):
  14 TeV, Resolved Pomeron $\sigma_{\mathbb{P}\mathbb{P}} = 13.6\ \mu$b ($R_{c\bar{c}} = 0.17\%$)
- Łuszczak *et al.*, Phys. Rev. D 91, 054024 (2015):
  14 TeV, Resolved Pomeron, $|y| < 2.5$, $p_T > 3.5$ GeV, $D^0 + \bar{D}^0$, $\sigma_{\mathbb{P}\mathbb{P}} = 177$ nb.

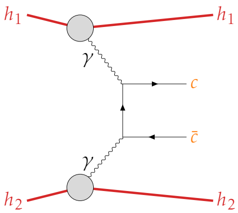


4. Central diffraction in $\gamma, \mathbb{P}$ exchange

$$\sigma(h_1 h_2 \to h_1 \sqcup Q\bar{Q}Y \sqcup h_2) = \int dx_1 \int dx_2 \;\; \gamma_1(x_1,\mu^2) \;\; g_2^D(x_2,\mu^2) \;\; \hat{\sigma}(\gamma g \to Q\bar{Q})$$

- Goncalves *et al*, Nucl.Phys.A 1000 (2020) 121862:
  pp @ 13 TeV, Exclusive, $|\eta| < 2.5$, Dipole Model
  $\sigma_{\gamma\mathbb{P}} = 83.2$–$117.9$ nb
- Goncalves *et al*, Phys.Rev.D 85 (2012) 054019:
  pp @ 14 TeV, Dipole Model, $\sigma_{\gamma\mathbb{P}} = 161$ nb
  pp @ 14 TeV, Resolved Pomeron, $\sigma_{\gamma\mathbb{P}} = 1208$ nb

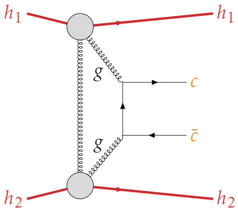
Central Diffraction (contd.)



5. Central exclusive production in the electromagnetic channel

$$\sigma(h_1 h_2 \to h_1 \sqcup Q\bar{Q} \sqcup h_2) = \int dx_1 \int dx_2 \;\; \gamma_1(x_1, \mu^2) \;\; \gamma_2(x_2, \mu^2) \;\; \hat{\sigma}(\gamma\gamma \to Q\bar{Q})$$

- The term $\hat{\sigma}(\gamma\gamma \to Q\bar{Q})$ is heavily suppressed due to presence of two EM vertices, thus it is not expected to contribute significantly to the signal measured experimentally.

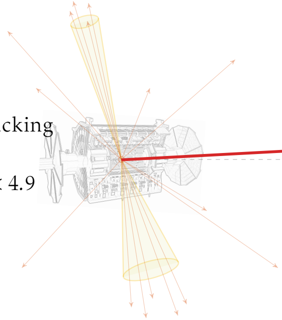


6. Central exclusive production in the strong channel

$$\sigma(h_1 h_2 \to h_1 \sqcup Q\bar{Q} \sqcup h_2) \propto \;\; \hat{\sigma}(gg \to Q\bar{Q})$$

- Maciuła *et al.*, Phys.Lett.B 685 (2010) 165-169:
  2 TeV: $R_{c\bar{c}} = 1\%$
- Gay Ducati, *et al.*, Phys. Rev. C 83, 014903 (2011):
  14 TeV: $\sigma_{\mathbb{PP}} = 0.53\ \mu$b ($R_{c\bar{c}} = 0.007\%$)

Measurement

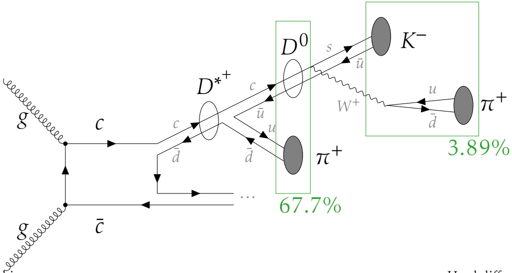


ATLAS

- Low-p_T charged particle tracking (down to 100 MeV)
- Calorimeter acceptance $|\eta| < 4.9$ (rapidity gaps)
- Dedicated triggers
- Advanced vertex & track reconstruction software

AFP

- Forward proton tagging with Roman Pot technology
- 3D pixel silicon tracker → precise reco. of kinematics
- Acceptance: $0.02 \lesssim \xi = 1 - E_{\text{proton}}/E_{\text{beam}} \lesssim 0.15$
- High efficiency, low background



Targeted decay modes:

- $D^{*\pm} \to D_0\pi \to K\pi\pi$
- $D^{\pm} \to K\pi\pi$
- $D_s^{\pm} \to KK\pi$
- $\Lambda_C \to pK\pi$