High Luminosity LHC Optics

Feasibility Studies for: ATLAS, ALICE and LHCb

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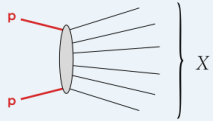
Usual proton-proton collisions at the LHC

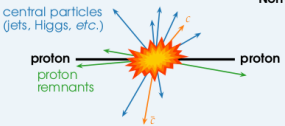
→ protons collide head-on

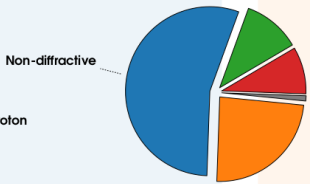
→ both protons break up

→ collision products are emitted in the central region

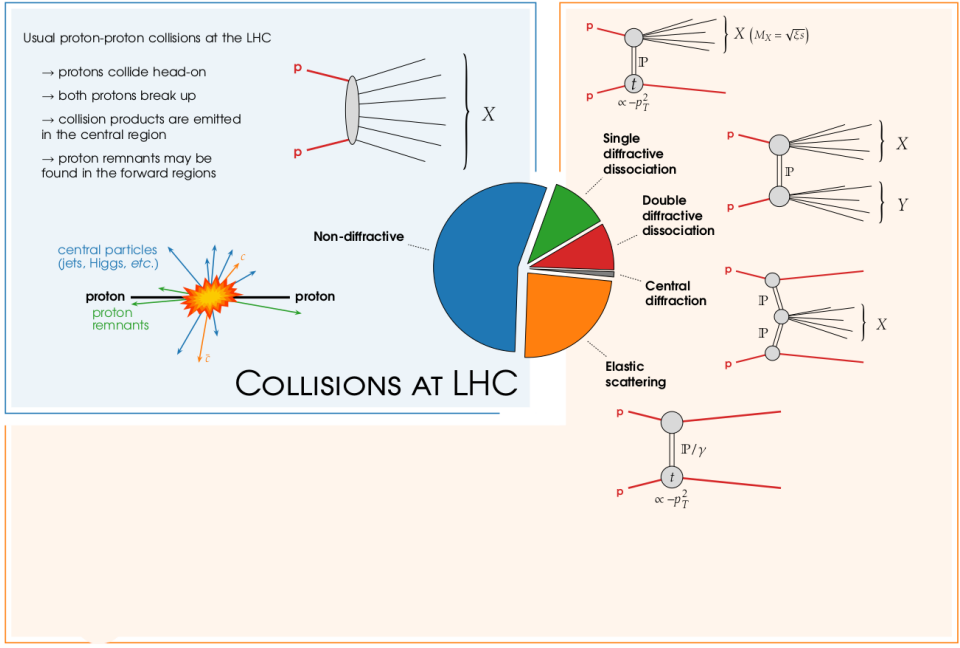
→ proton remnants may be found in the forward regions







COLLISIONS AT LHC


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
p
p
X
central particles (jets, Higgs, efc.)
proton
proton
proton remnants
c
c̄
Non-diffractive
Single diffractive dissociation
Double diffractive dissociation
Central diffraction
Elastic scattering
COLLISIONS AT LHC
p
p
$\mathbb{P}$
t
$\propto -p_T^2$
$X\ (M_X = \sqrt{\xi s})$
X
Y
$\mathbb{P}/\gamma$

Usual proton-proton collisions at the LHC

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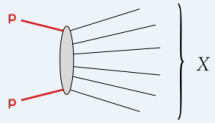
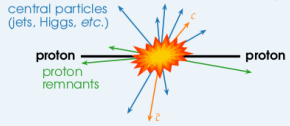
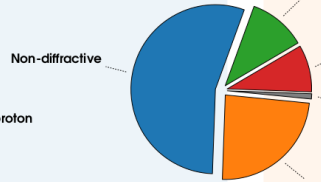
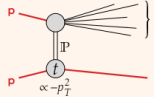
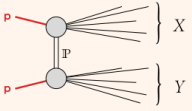
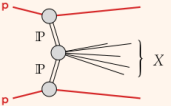


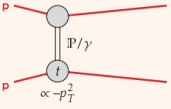




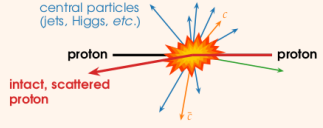








How can proton(s) remain intact?



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

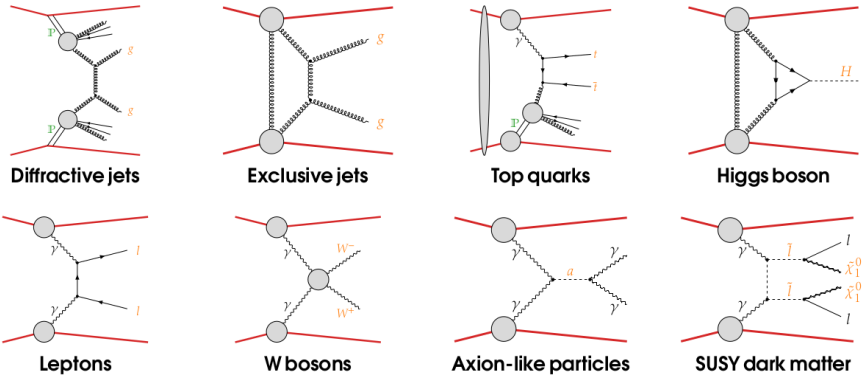
→ photon (γ) – via electromagnetic interactions

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

COLLISIONS AT LHC

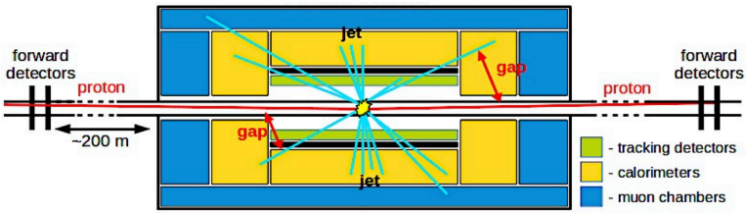
Physics Processes

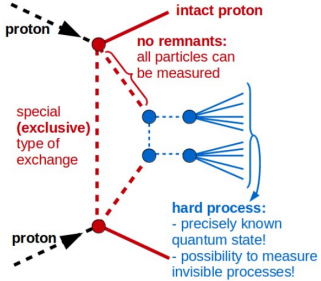
- Wide range of physics processes predict **forward proton scattering**:



- At HL-LHC high pile-up environment the main focus would be on **photon induced processes** and **Beyond Standard Model searches**.

Measurement Methods



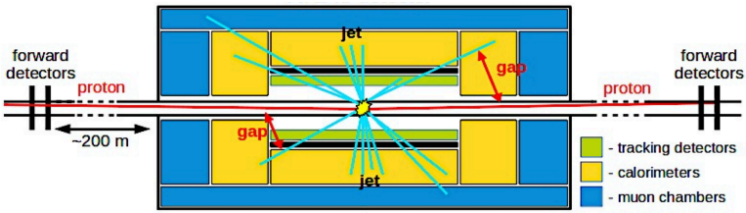


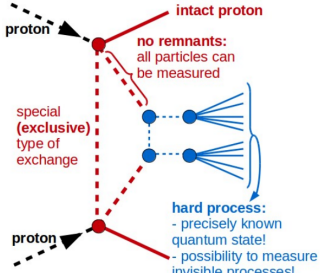
- Characteristic topology: presence of rapidity gap between the proton(s) and the "central" system;

Measuring rapidity gap:

\+ "classically" used for diffractive pattern identification
\+ no need for additional detectors
– gap is frequently destroyed due to pile-up background
– gap may be out of acceptance of "central" detector

Measurement Methods





- Characteristic topology: presence of rapidity gap between the proton(s) and the "central" system; one or both interacting proton(s) remain intact.
- Intact protons scattered at very small angles → very close to the beam after the interaction → detectors must be located far from the Interaction Point (IP) → LHC magnetic fields (**optics**) must be considered.

Measuring rapidity gap:

+ "classically" used for diffractive pattern identification
+ no need for additional detectors
– gap is frequently destroyed due to pile-up background
– gap may be out of acceptance of "central" detector

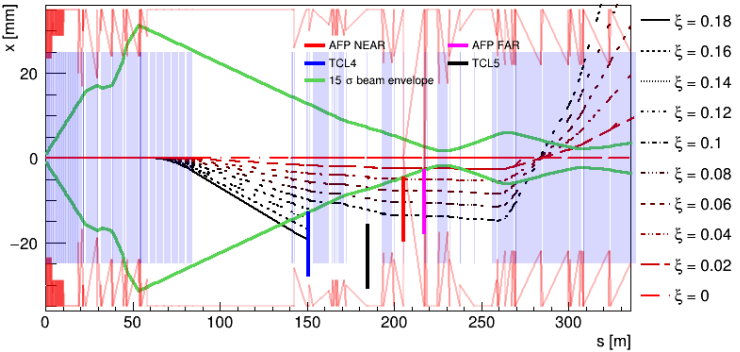
Measuring forward protons:

+ protons measured directly
+ suitable for pile-up environment
– protons are scattered at very small angles
– additional detectors required far downstream

Case: ATLAS Detector

- Space in the LHC tunnel is "occupied" by accelerator equipment: magnets, collimators, beam position monitors, *etc.*
- A few places are possible for detectors, *e.g.* at 195.5 (RP1A), 198.0 (RP1B), 217.0 m (RP2A), 219.5 (RP2B), 234.0 (RP3A), 237.0 (RP3B), 245.0 (RP3C) or 420 (RP4) meters from IP.
- **Knowledge of proton behaviour along the LHC beamline is central for feasibility studies**:

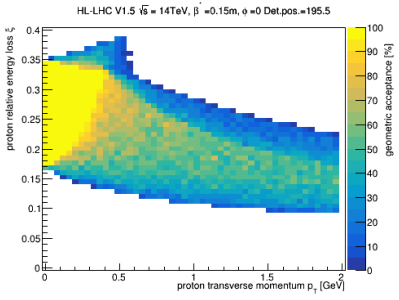
- collision point at $(x, s) = (0, 0)$,
- positive x towards LHC ring center,
- blue rectangles – LHC elements,
- thin red lines – beampipe aperture,
- thick solid red line – nominal proton trajectory (*i.e.* 7 TeV proton beam),
- solid green lines – $15\sigma_{beam}$ beam envelope (rough indication of the smallest detector-beam distance),
- thick black and blue line ∼200 m – collimators,



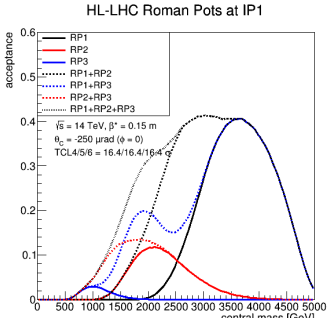
- dashed/dotted red/brown/black lines – trajectories of scattered protons having transverse momentum $p_T = 0$ and certain relative energy loss, $\xi = 1 - E_{proton}/E_{beam}$.

Case: ATLAS Detector

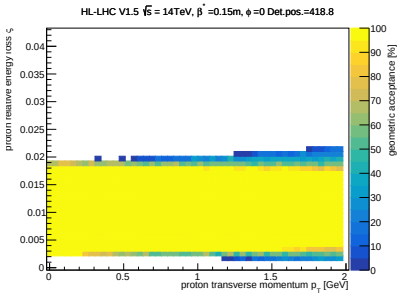
geometric acceptance for RP1A:



mass acceptance for RP1-RP3 stations:

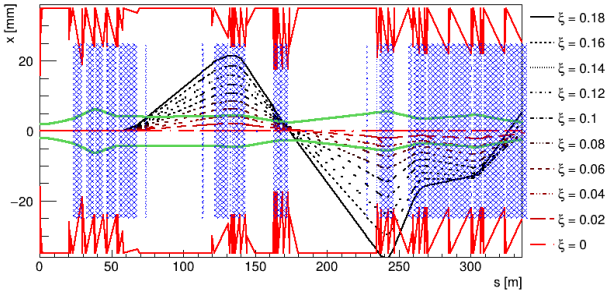


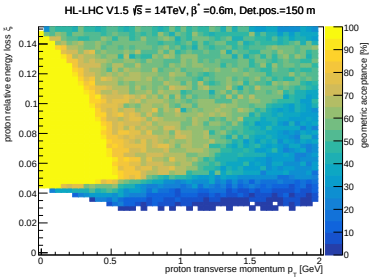
geometric acceptance for RP4:



- Plane of crossing angle, θ_C, must be opposite at IP1 and IP5: vertical θ_C at IP5 means horizontal at IP1.
- Vertical crossing angle results in acceptance for lower masses – the choice for CT-PPS (CMS) at Run 4.
- Mass acceptance depends on pot location – stations closer to IP have acceptance towards higher masses.
- Combination of stations (*e.g.* RP1+RP2) assumes installation of more pots (cost to be considered) to provide "enchanced" acceptance (dashed and dotted lines on right plot):
  - RP1 means combination two stations RP1A and RP1B on both sides of IP: proton measured in all of them.
  - RP1+RP2 means: [(RP1A & RP1B on side A) | (RP2A & RP2B on side A)] & [(RP1A & RP1B on side C) | (RP2A & RP2B on side C)].
- Detectors located at 420 m have acceptance for very low masses.

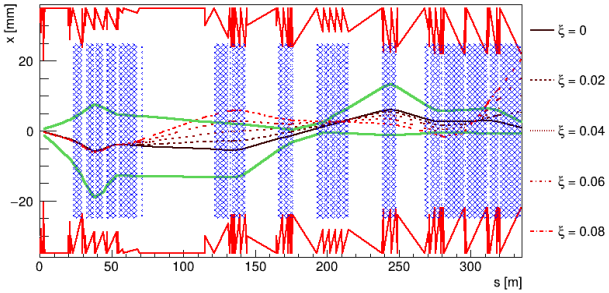
Case: ALICE Detector

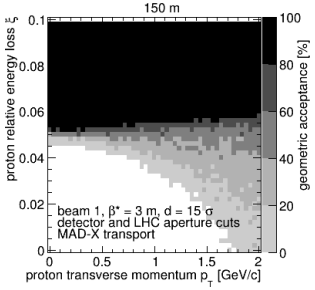


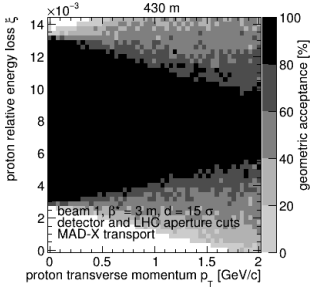


- Left: trajectories in vicinity of ALICE detector.
  - Note: collimators and beam aperture are not considered.
- Right acceptance for detectors placed around 150 m from the ALICE IP:
  - $0.04 \lesssim \xi \lesssim 0.14 \rightarrow 280 \lesssim M_X \lesssim 980$ GeV.
- Acceptance for the detectors located at 430 m under investigation.

Case: LHCb Detector







- Top left: trajectories in vicinity of LHCB detector.
- Top right acceptance for detectors placed around 150 m from the LHCb IP:
  - $0.05 \lesssim \xi \lesssim ?? \rightarrow 350 \lesssim M_X$ GeV.
- Bottom right 430 m case:
  - $0.003 \lesssim \xi \lesssim 0.013 \rightarrow 21 \lesssim M_X \lesssim 91$ GeV.
- More details in: Acta Phys. Pol. B **51**, 1577 (2020).

Summary

- HL-LHC layout for Run 4 (2027 – 2029) is already fixed:
  - only CMS experiment will be equipped with a set of dedicated forward proton detectors installed in region 195 – 240 m: CERN-CMS-NOTE-2020-008.

- Option to have forward proton detectors for Run 5 and beyond (2031+) is opened for all LHC experiments.

- Knowledge of proton acceptance at possible detector locations is a starting point for feasibility studies needed to build the physics case.

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