LHCP Boston 2024

The CMS Precision Proton Spectrometer at the HL-LHC

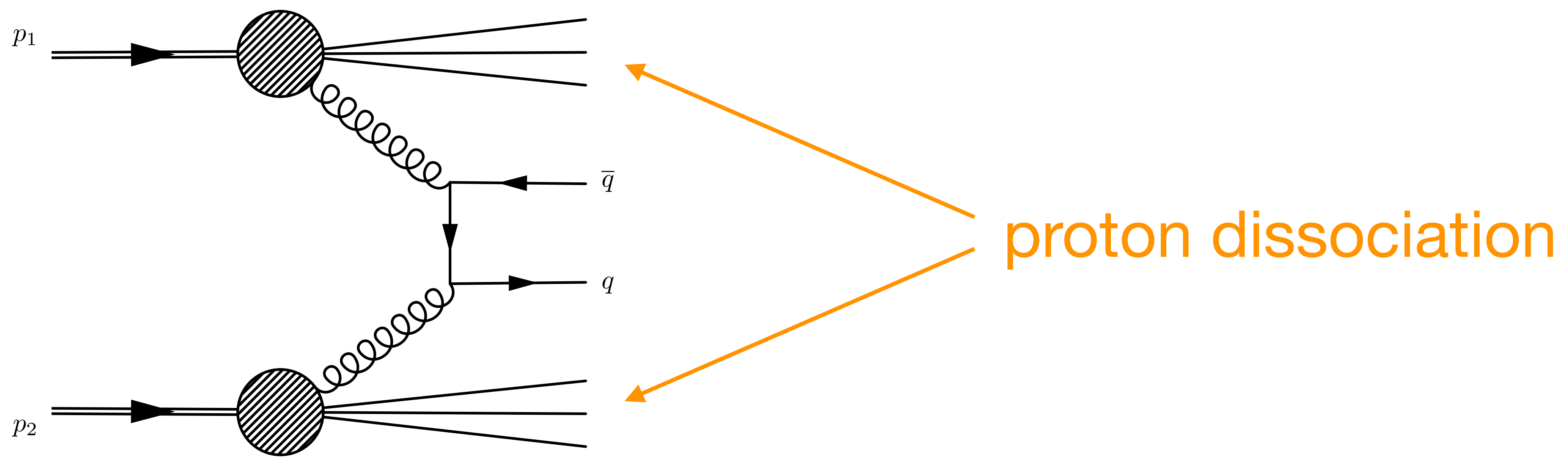
Enrico Robutti (INFN Genova)
on behalf of the CMS Collaboration

CMS Compact Muon Solenoid

INFN Istituto Nazionale di Fisica Nucleare

Events with intact protons

Typical hard scattering event at LHC:



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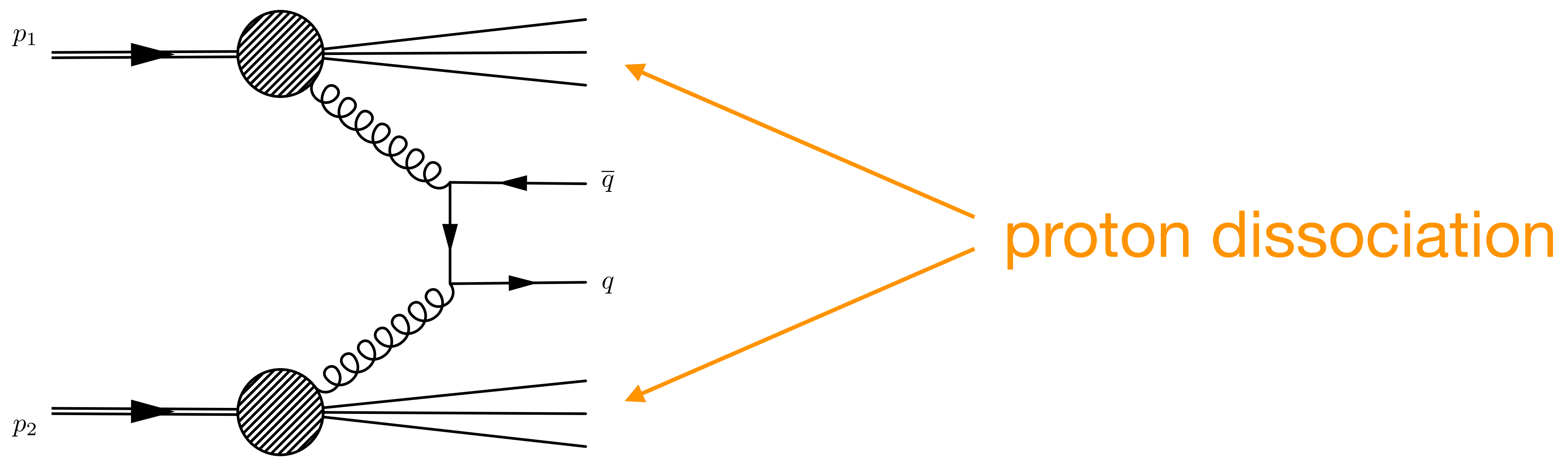
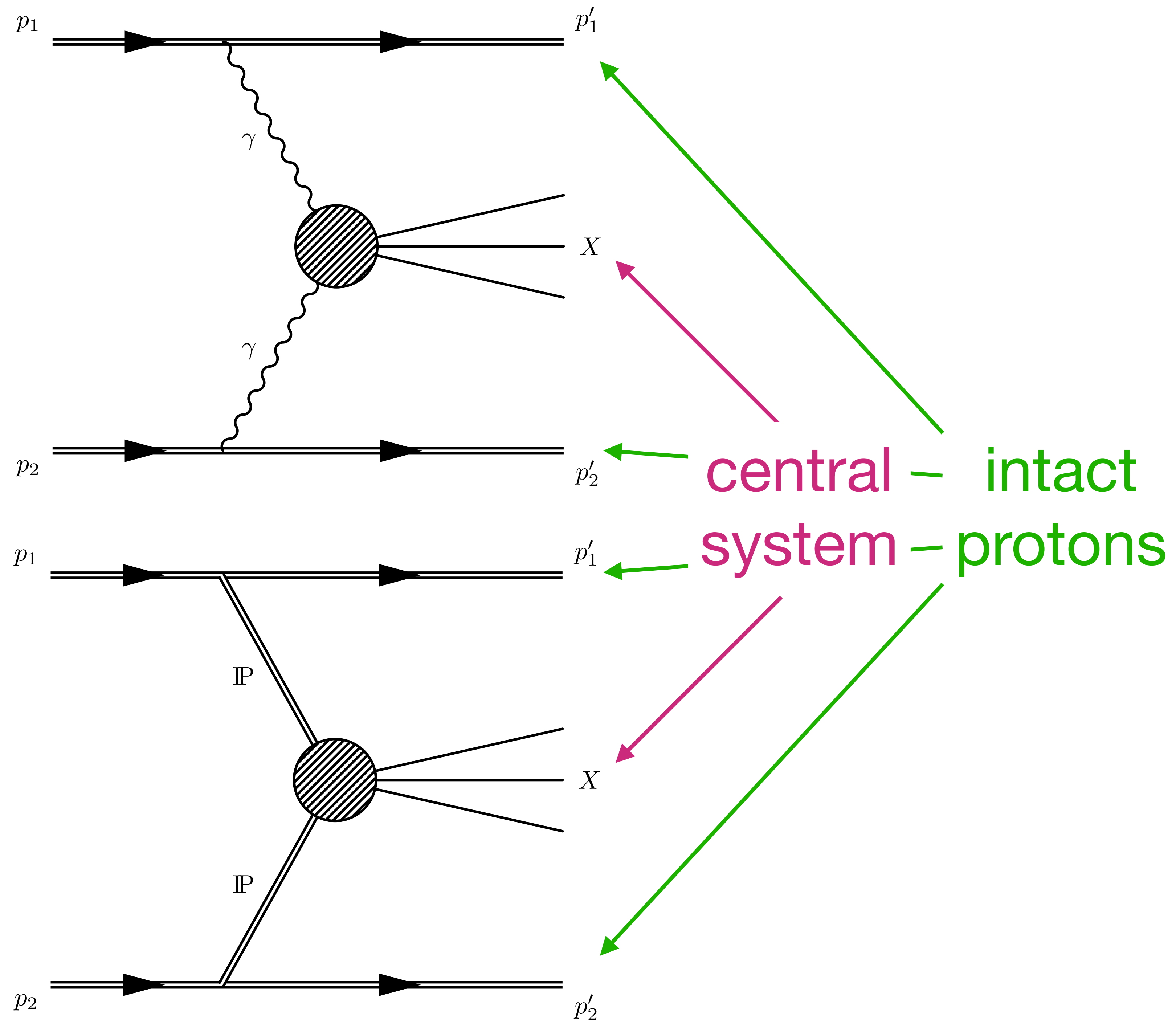


One or both protons may remain intact in the interaction



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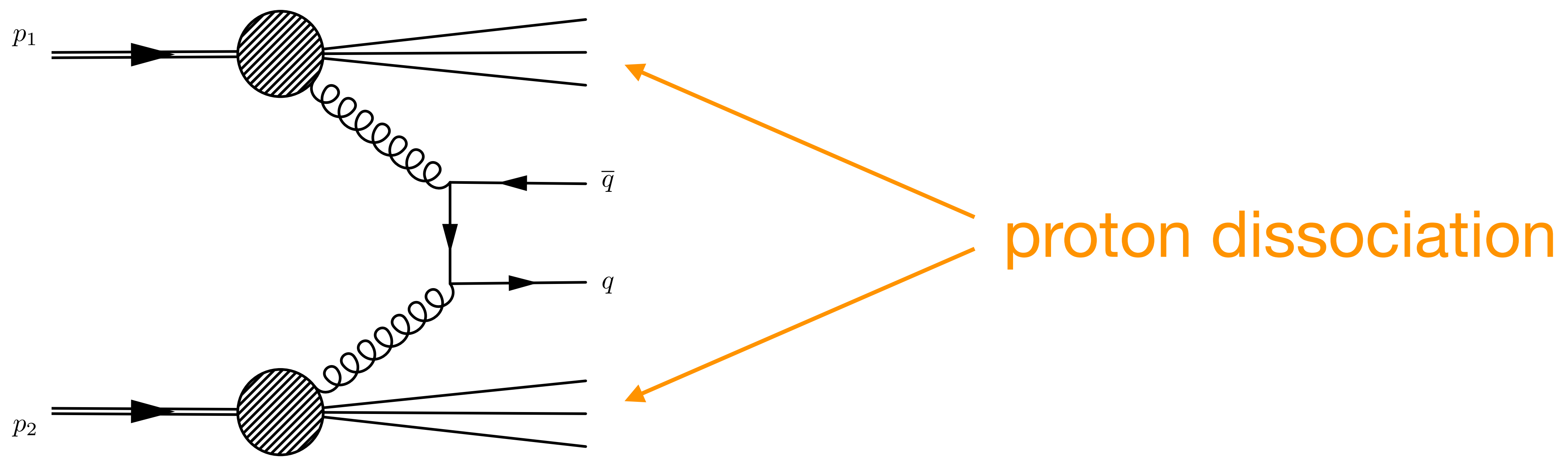

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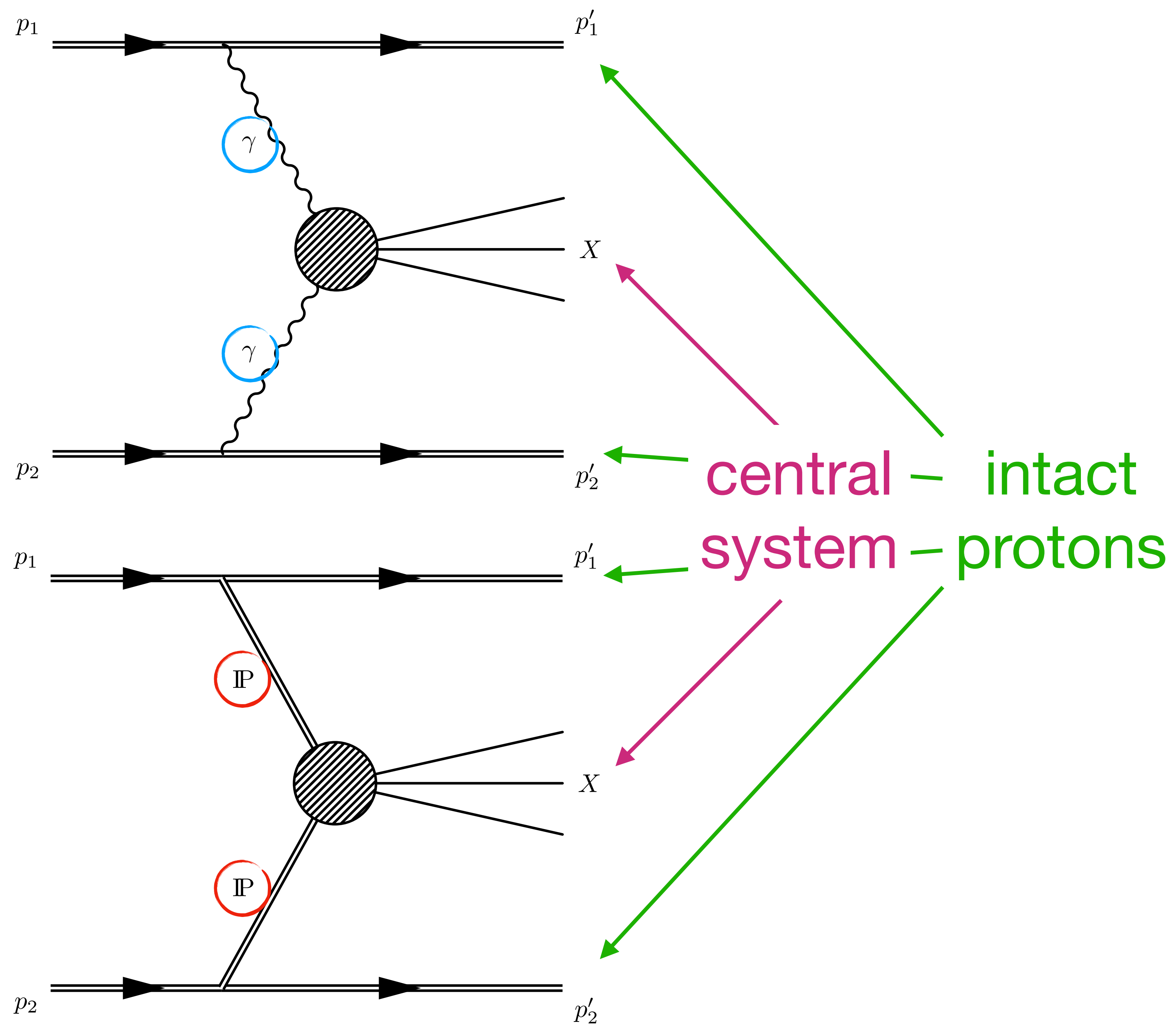
- Intact protons interact via QCD (pomerons) or QED (photons) color singlet exchange
- Energy lost by protons goes into the creation of particles in the central rapidity region
- Reduced track activity in the central detector
- Scattered protons travel along the beam pipe and can be traced by dedicated near-beam detectors



Physics opportunities

Tagging intact protons after the interaction allows the study of very rare processes

In particular, detecting both protons allows to study Central Exclusive Production (CEP)

- proton kinematics characterised by fractional momentum loss, $\xi \equiv (|\boldsymbol{p}_i| - |\boldsymbol{p}_f|)/|\boldsymbol{p}_i|$
- kinematic closure of the whole event by match with reconstructed central system $\begin{cases} m_X = \sqrt{s\xi_1\xi_2} \\ y_X = \frac{1}{2}\ln(\frac{\xi_1}{\xi_2}) \end{cases}$

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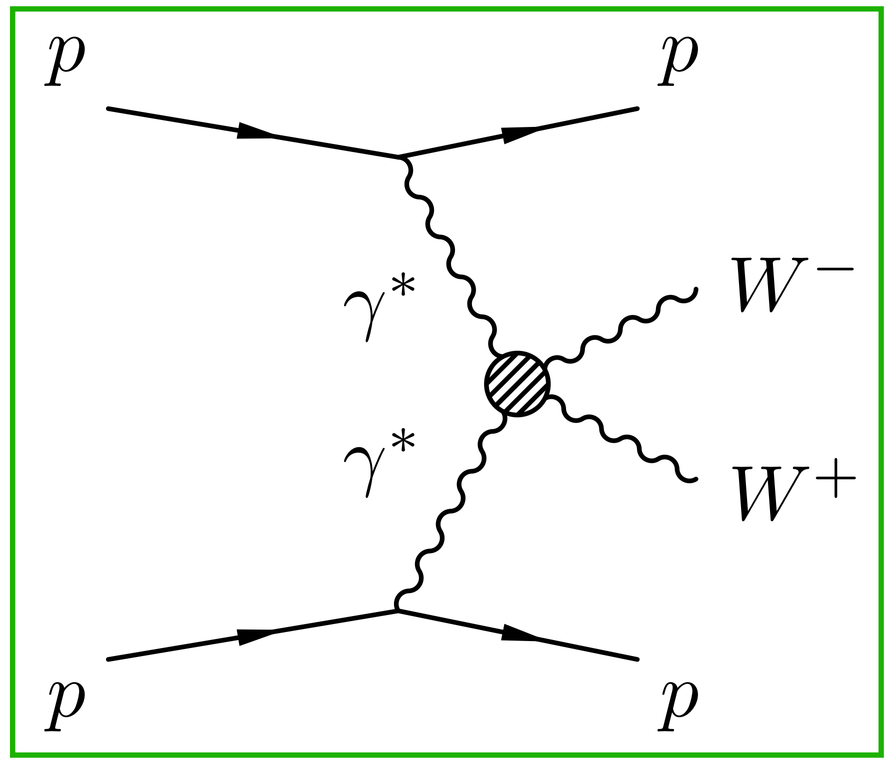
LHC can be used as a $\gamma\gamma$ collider:

- anomalous gauge couplings in $\gamma\gamma \to W^+W^-$ ($\gamma\gamma$, γZ, ZZ);
- direct search for DM via resonances in $\gamma\gamma \to X \to \gamma\gamma$;
- direct search for new particles (BSM), via resonances (e.g. $t\bar{t}$) or with missing mass techniques



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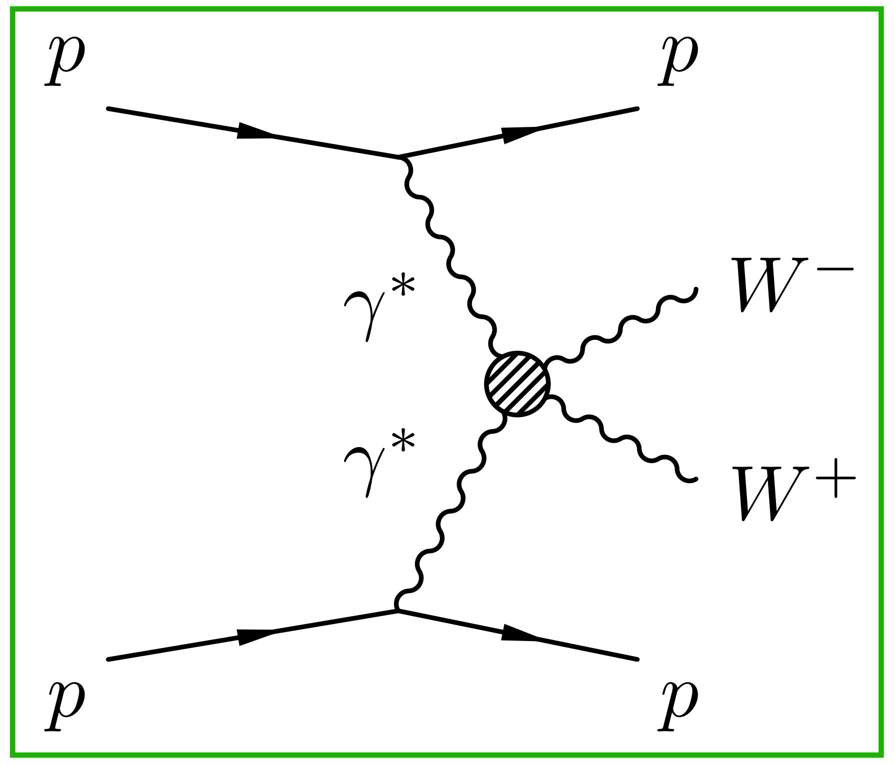
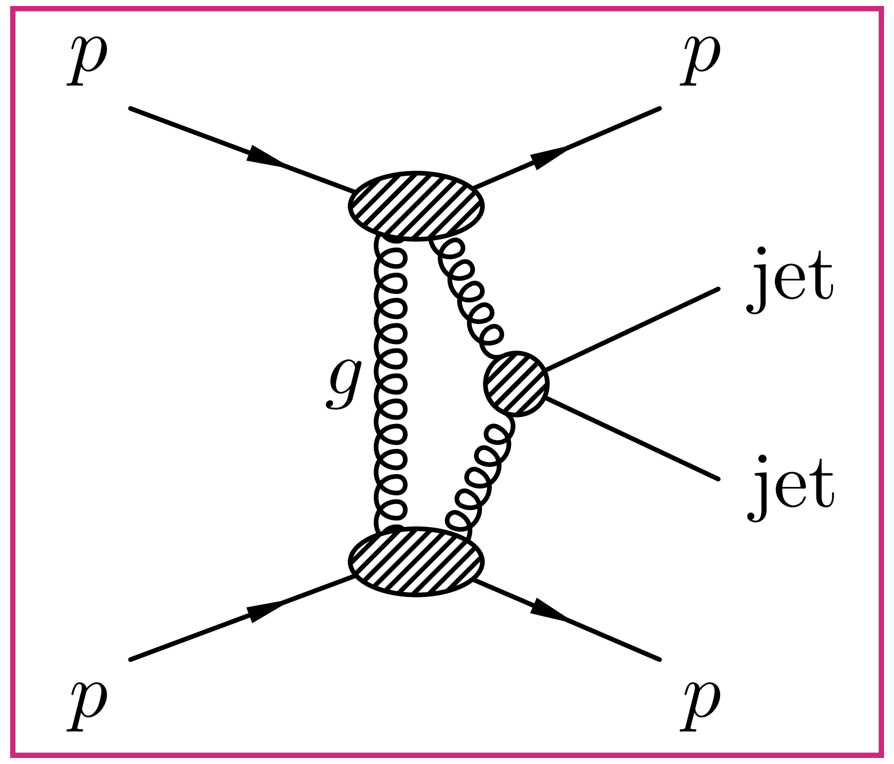
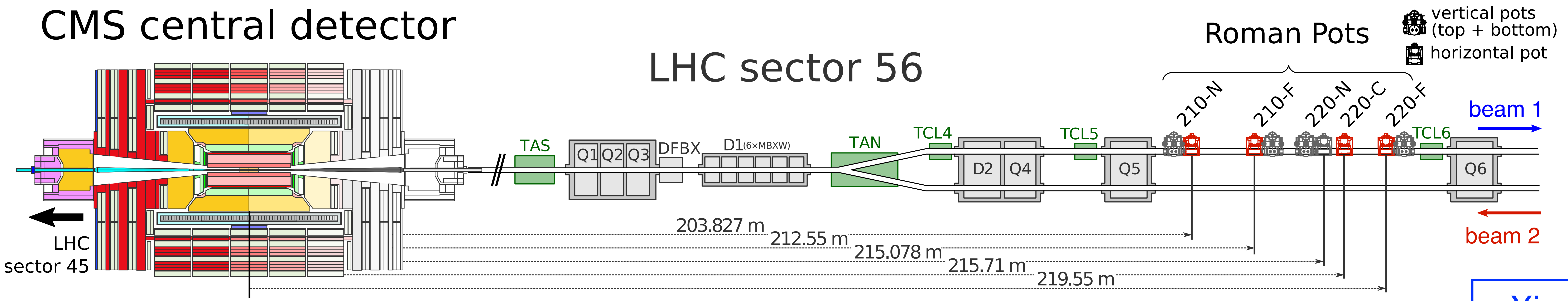


QCD physics: most dijet events from $gg \to gg \Longrightarrow$ gluon jet factory



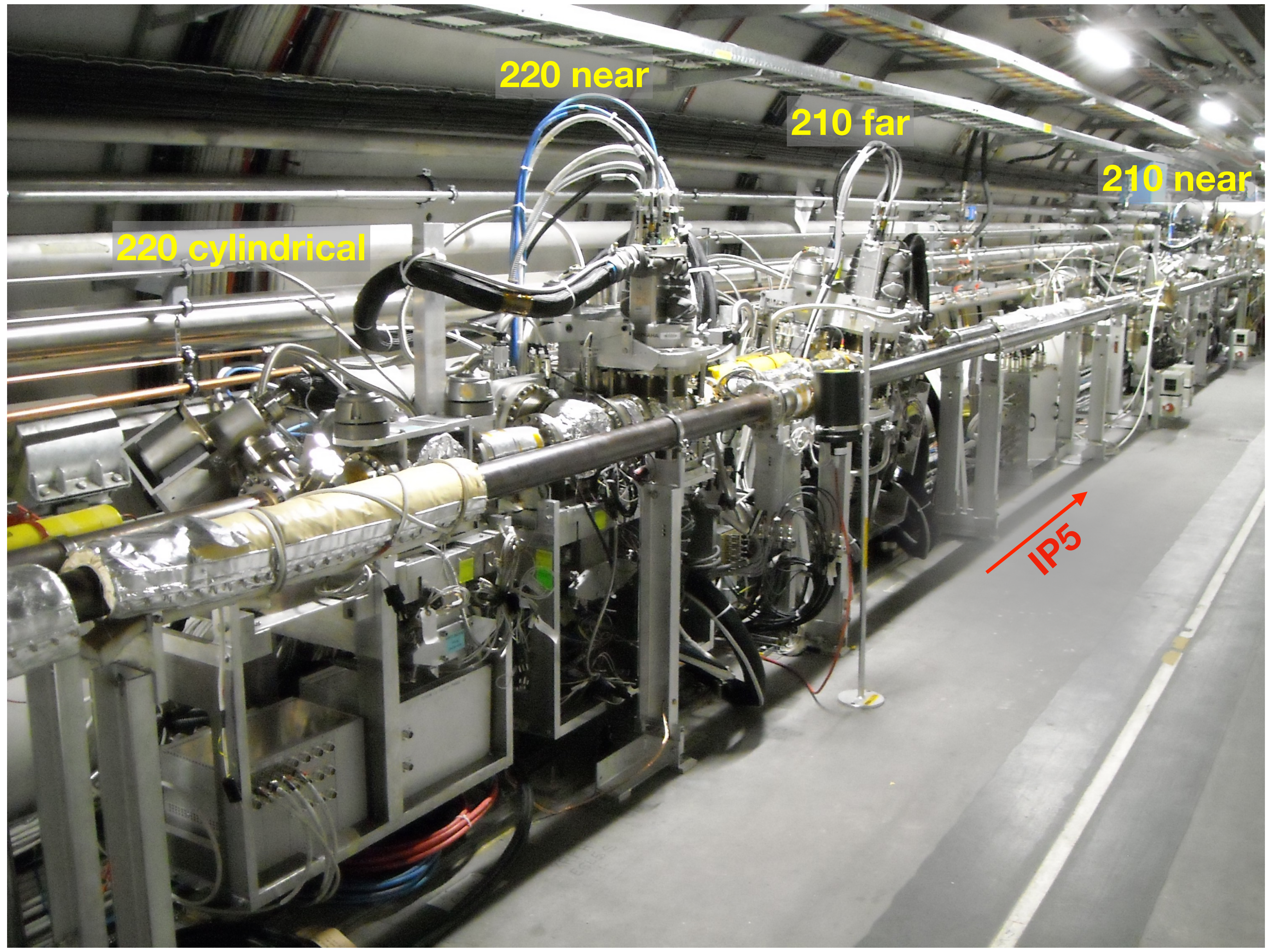
The CMS Precision Proton Spectrometer



arXiv:2309.05466

The CMS Precision Proton Spectrometer (PPS), originally conceived as a joint CMS-TOTEM project, is designed to detect intact protons after the interaction, in standard LHC running conditions

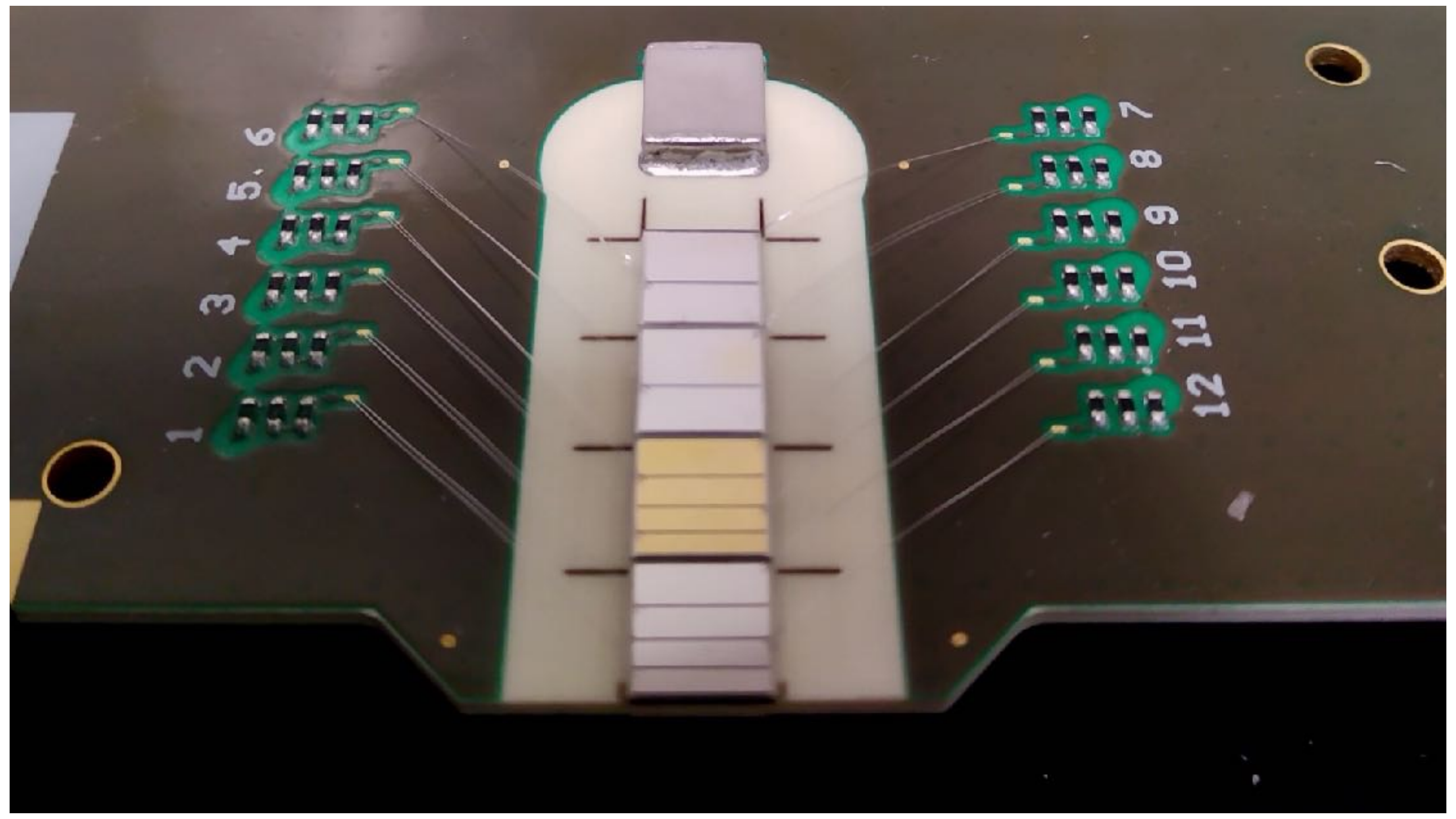
- tracking and timing detectors located along the LHC beam line, at ±~200 m from the CMS interaction point
- detectors hosted in horizontal roman pots, allowing sensor approach to the beam (in the LHC plane) down to few mm

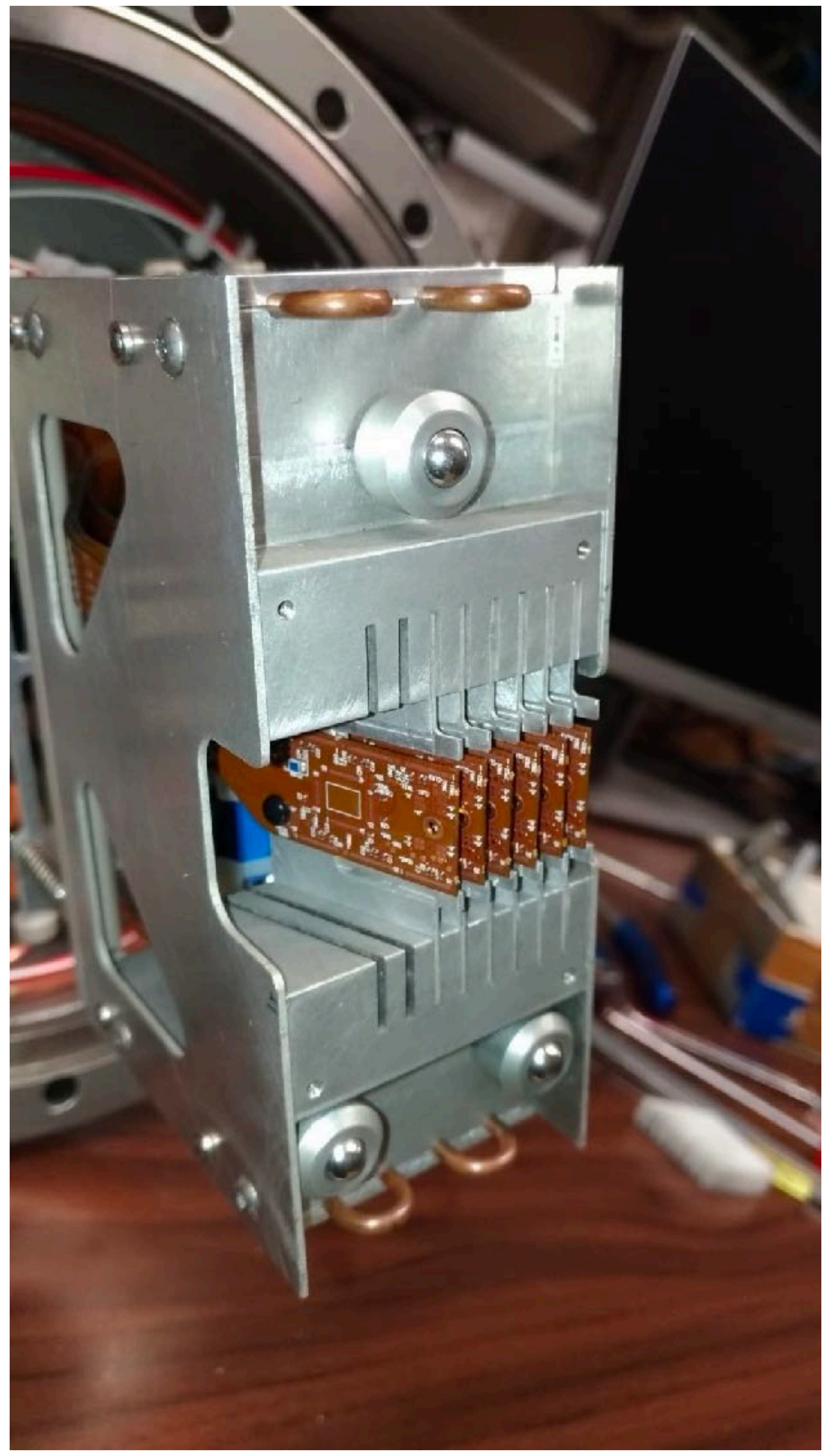


PPS in Run 2 and Run 3

Various detector configurations starting from 2016:

- two tracking stations per arm; silicon strips, then replaced by 3D silicon pixels;
- one timing station per arm, two from 2023; CVD diamond sensors;
- major update to all detectors for Run 3





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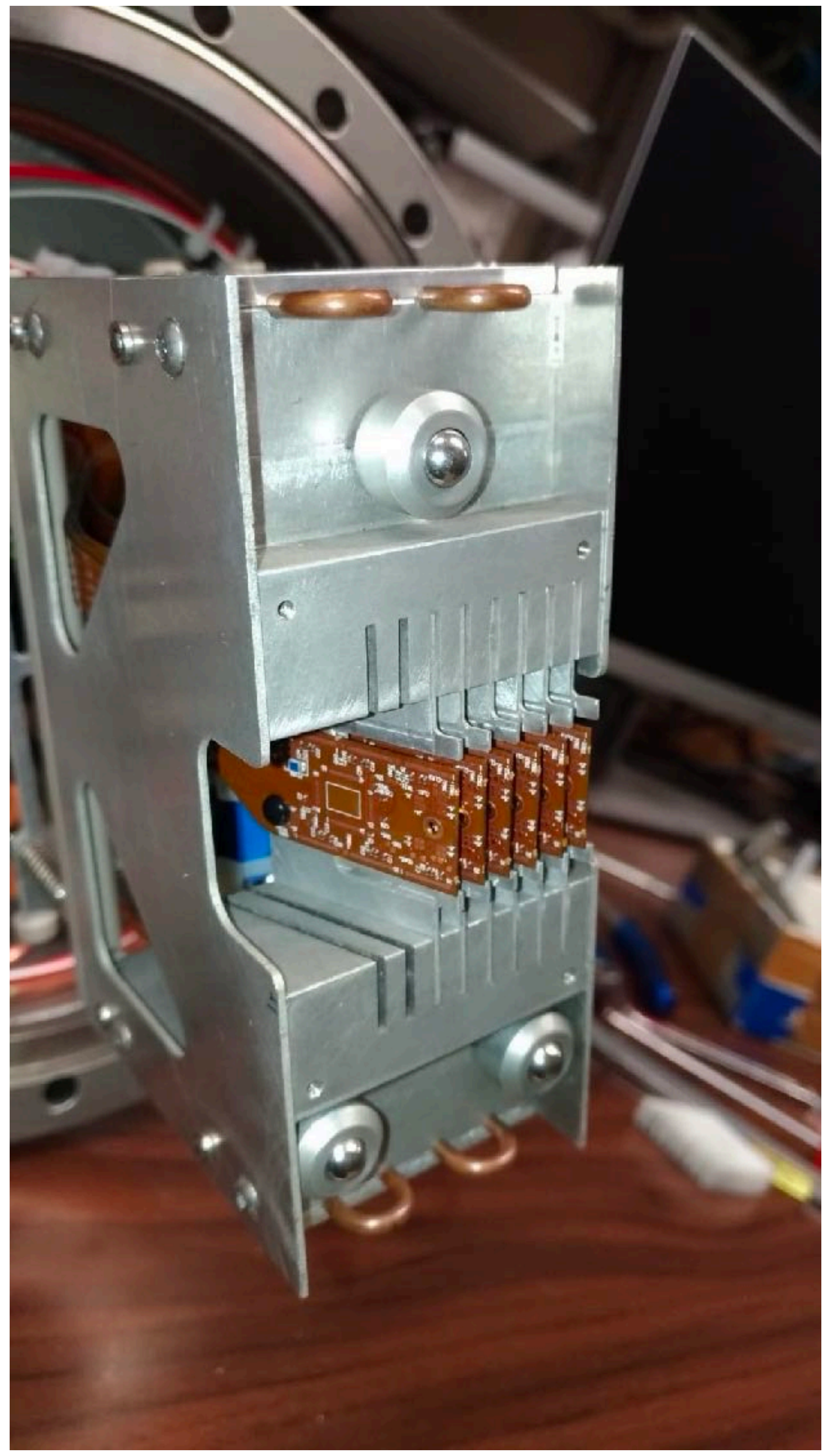
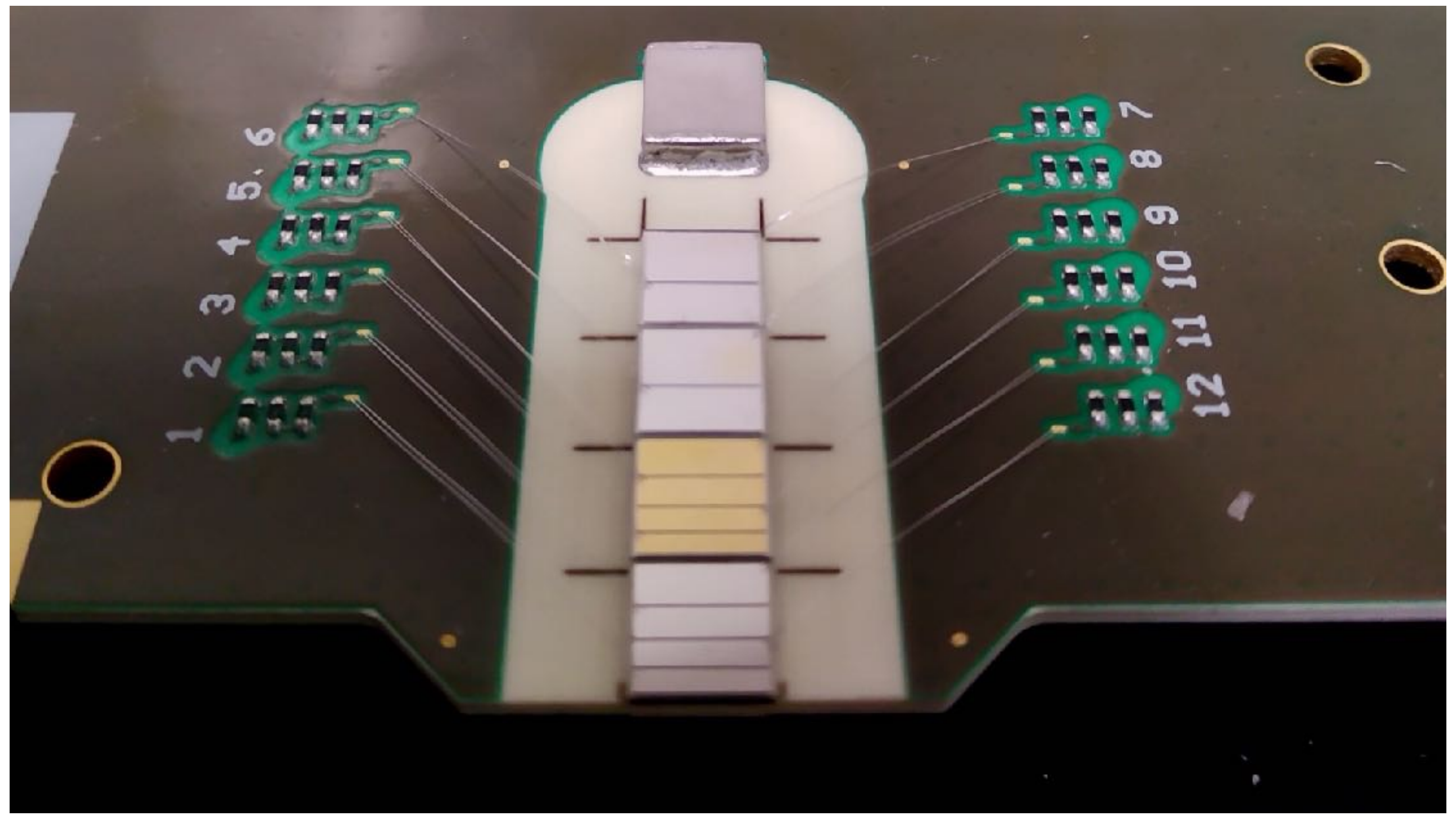
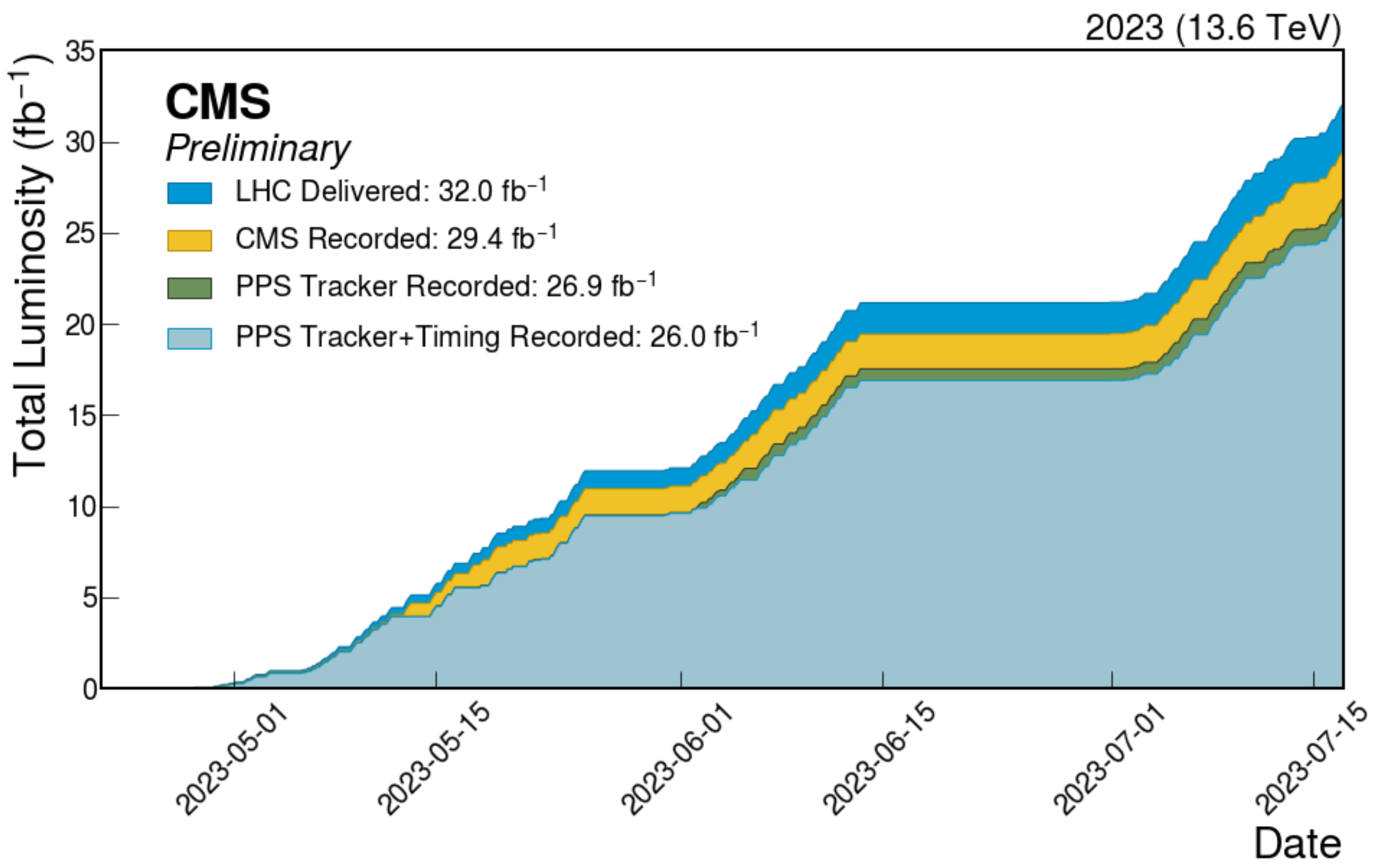


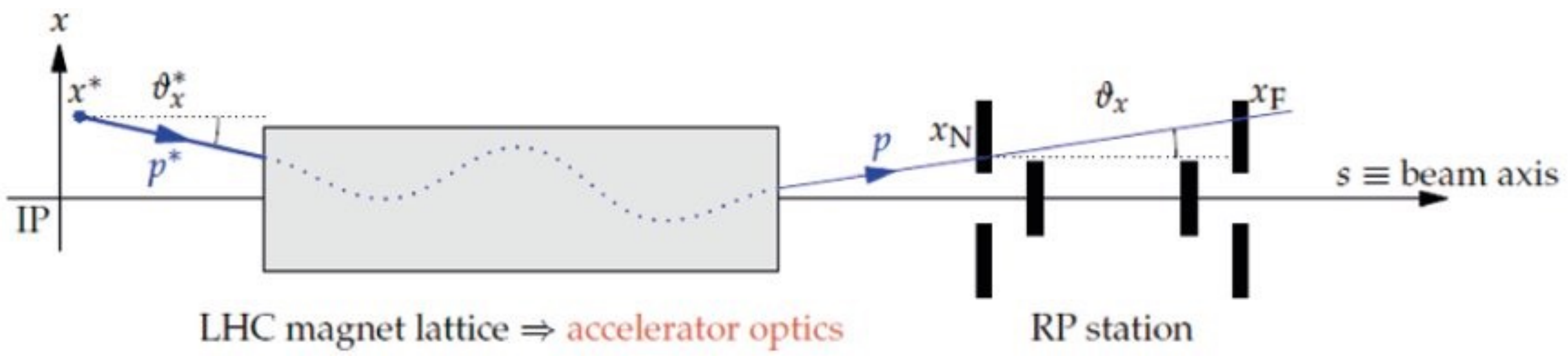


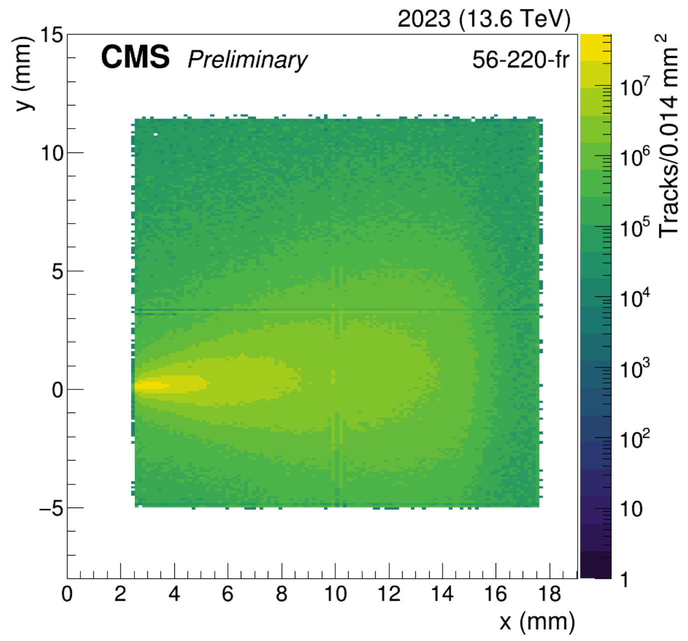


Detectors operational for most part of Run 2 and Run 3:

- 110 fb^{-1} collected in Run 2
- >50 fb^{-1} collected in Run 3

Proton reconstruction





Proton kinematics obtained from reconstructed tracks in PPS

- Standard reconstruction: multi-RP tracks (tracks in 2 stations)

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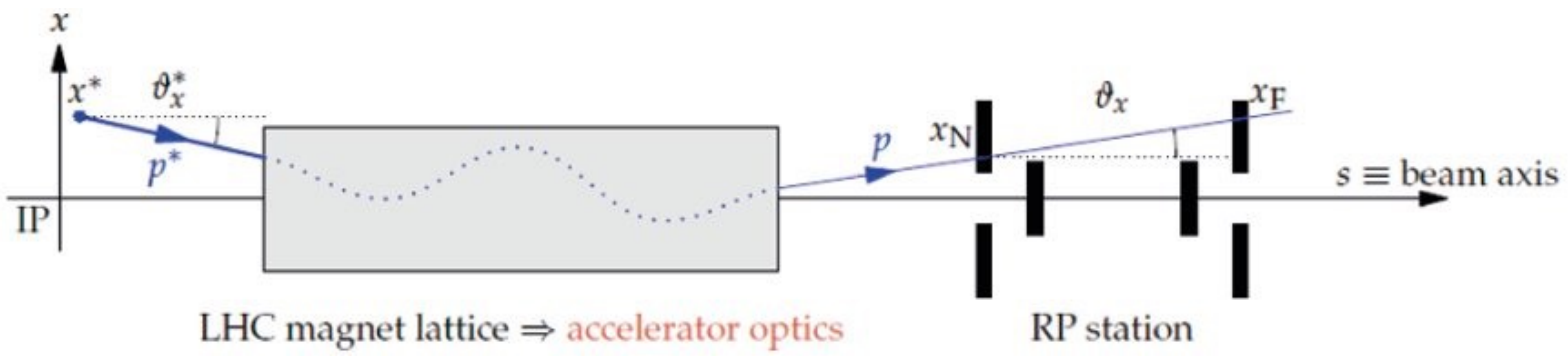
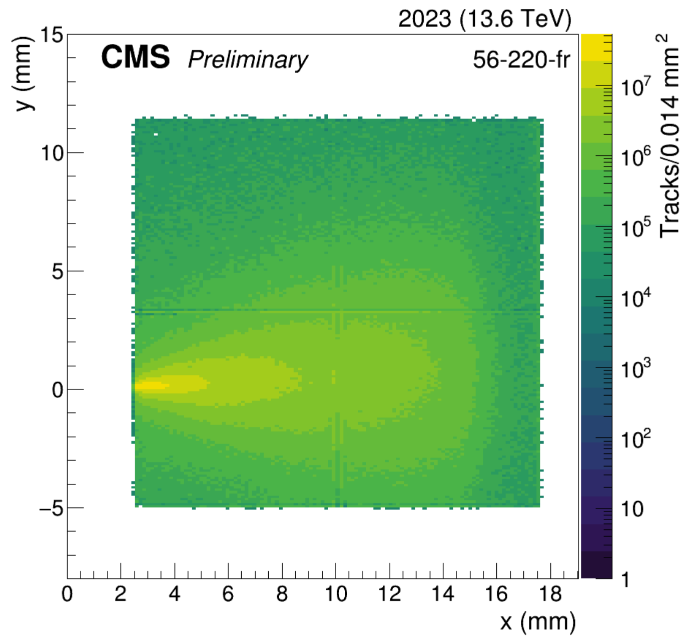
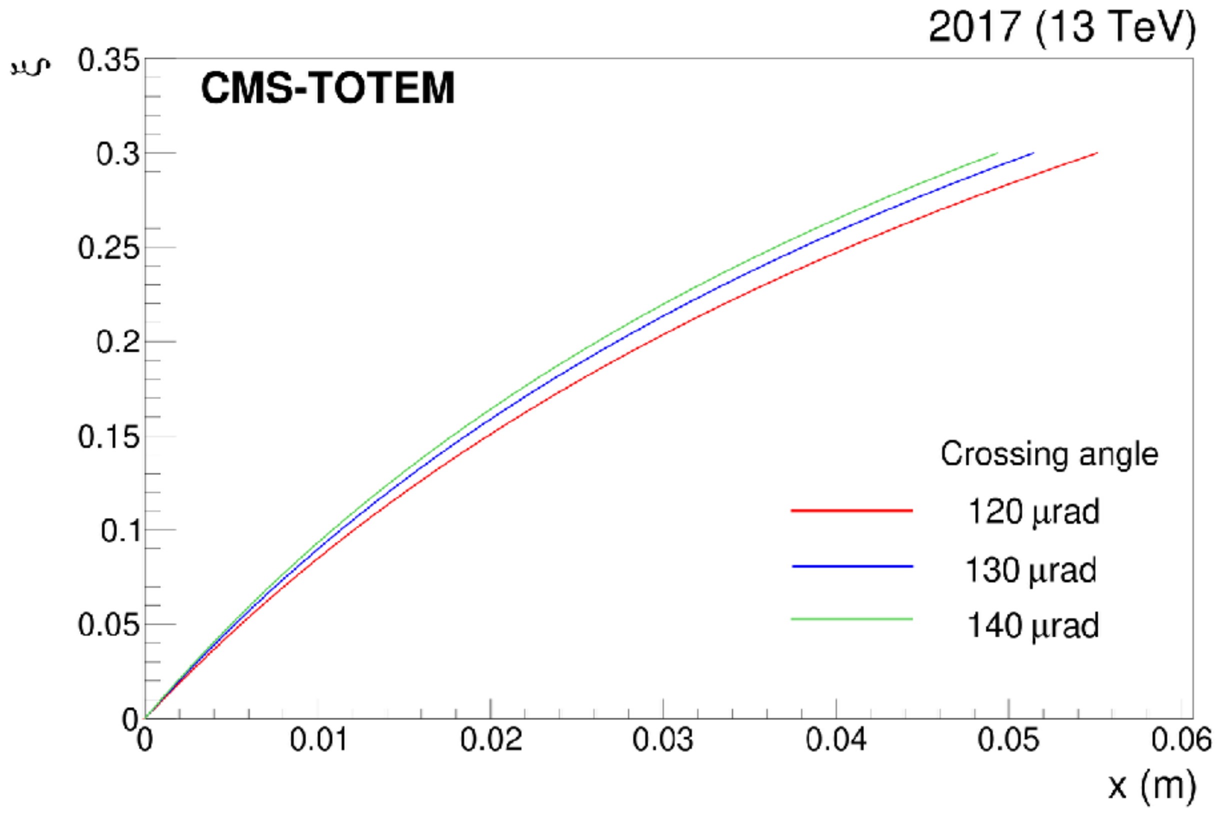
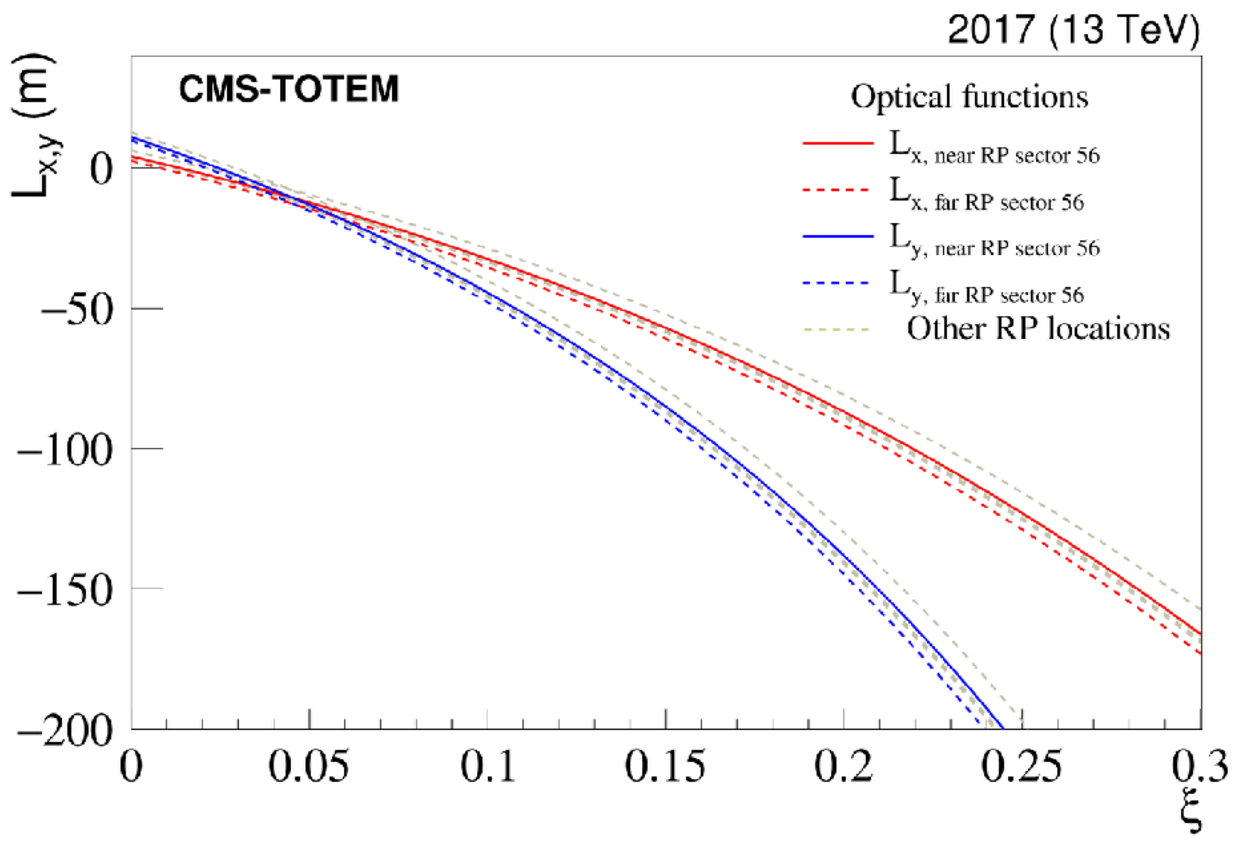




[JINST 18 (2023) 09, P09009](#)





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Kinematics at the IP using LHC optics transport matrix

- Main terms:

$$x = D_x(\xi) \cdot \xi + L_x(\xi) \cdot \theta_x^*$$
$$y = D_y(\xi) \cdot \xi + L_y(\xi) \cdot \theta_y^* + v_y(\xi) \cdot y^*$$

- Optics parameters depend on LHC running conditions; in particular from β^* and beam crossing angle α_X

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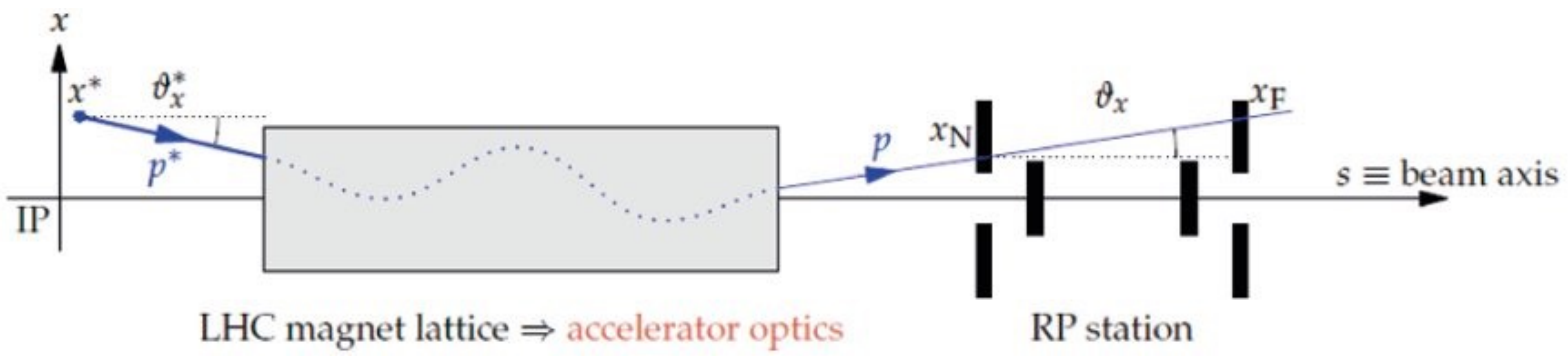

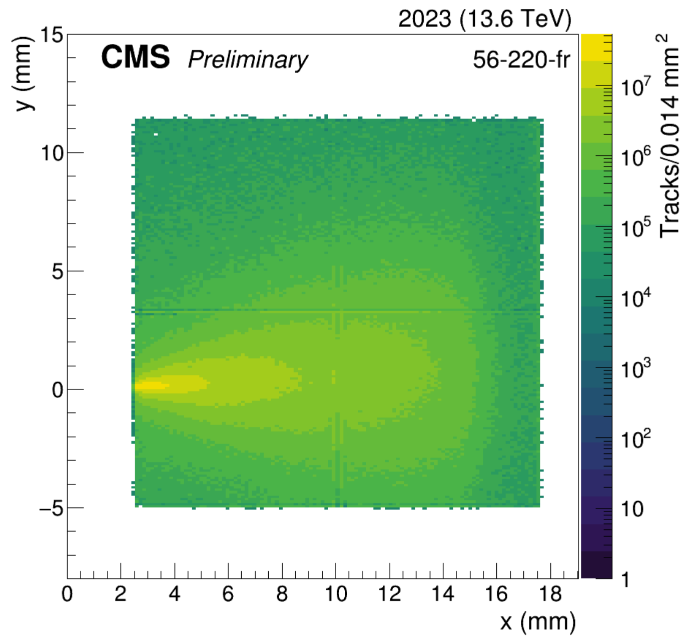

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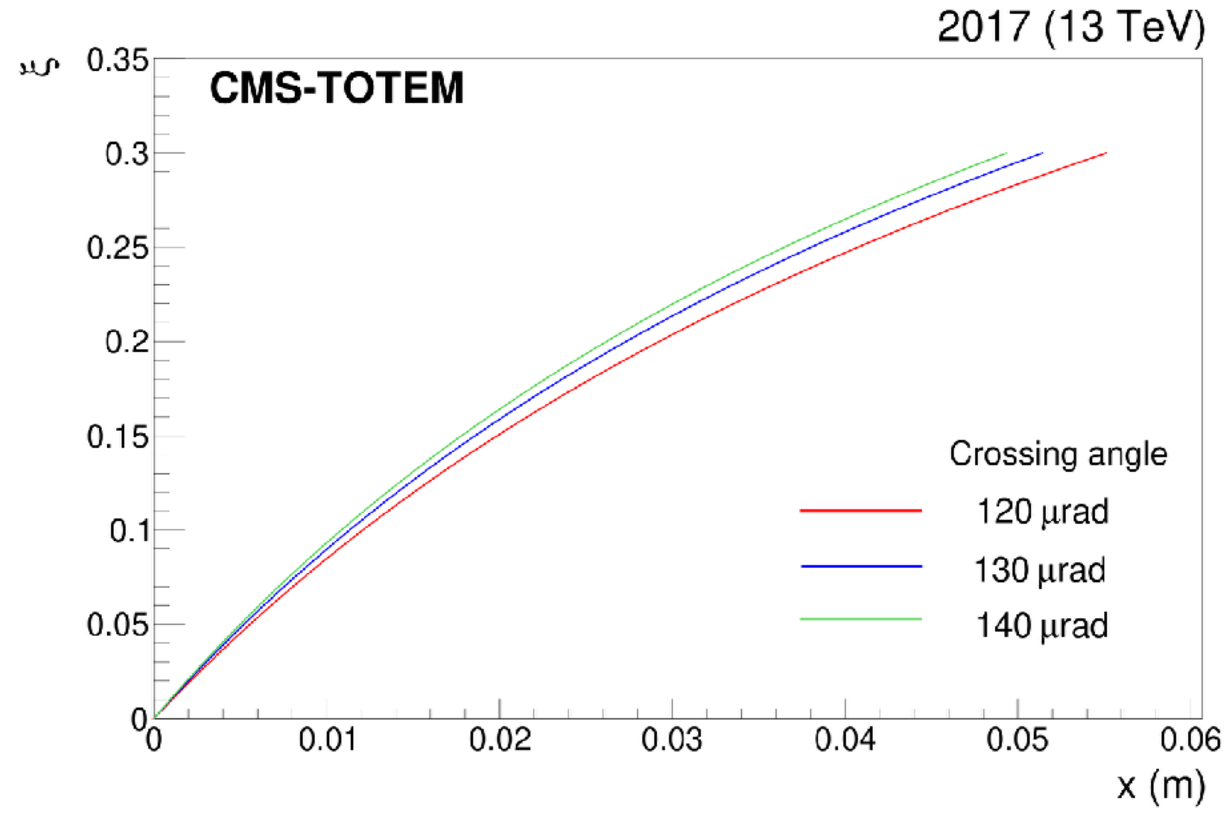

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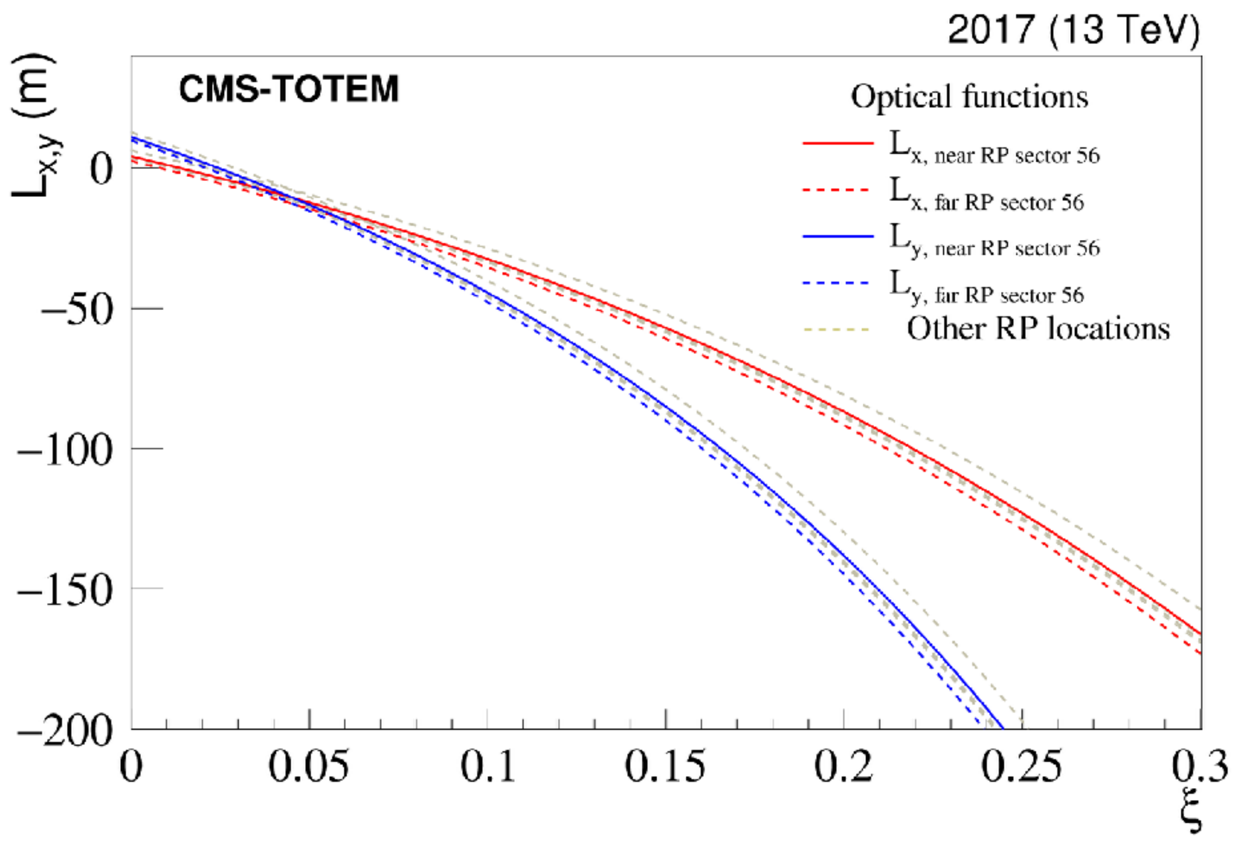
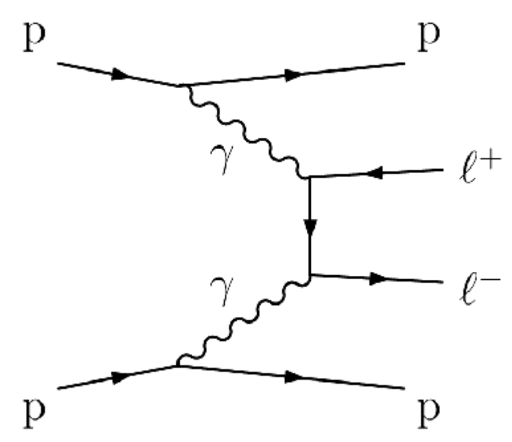


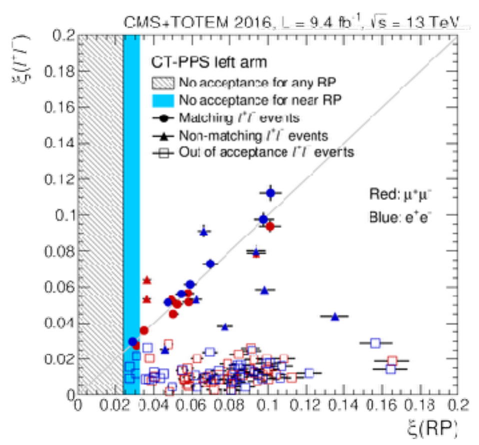
Precision timing helps to fight background from pileup (uncorrelated protons from other interactions in the same bunch crossing)

Physics results from Run 2

Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs

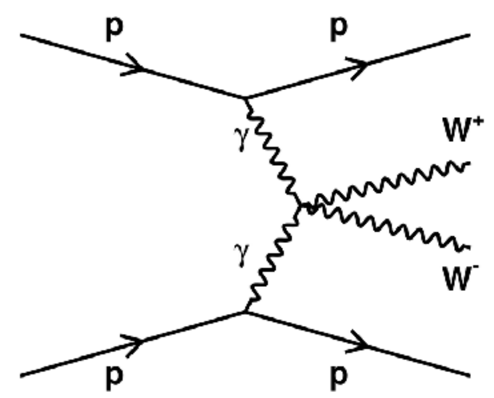
[JHEP 07 (2018) 153]

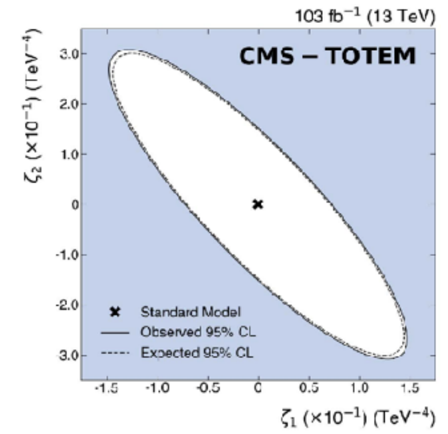




Search for high-mass exclusive $\gamma\gamma \to WW$ and $\gamma\gamma \to ZZ$ production

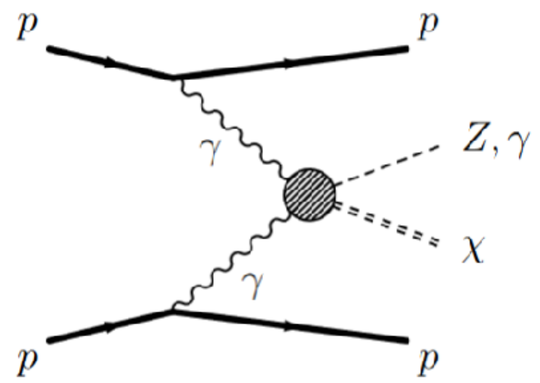
[JHEP 07 (2023) 229]

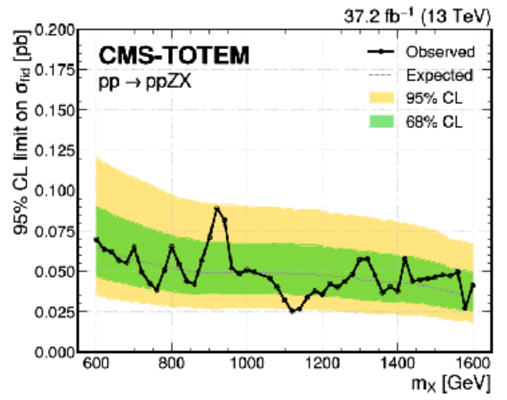




Search for new physics in central exclusive production using the missing mass technique in $pp \to p\,(Z,\gamma)\,X\,p$

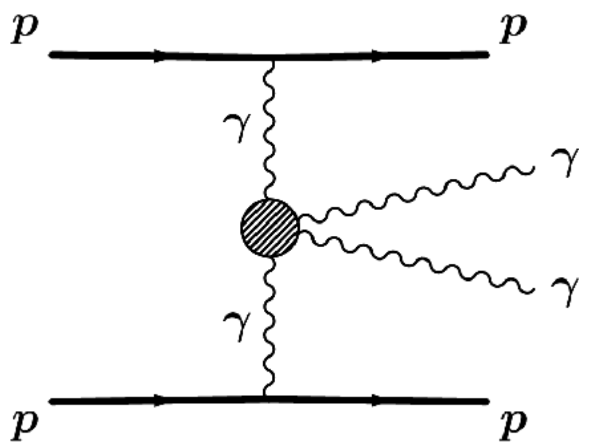
[Eur. Phys. J. C 83 (2023) 827]

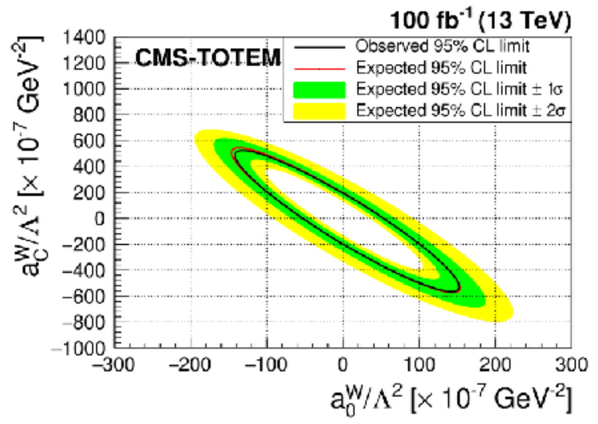




Search for high-mass exclusive diphoton production with tagged protons

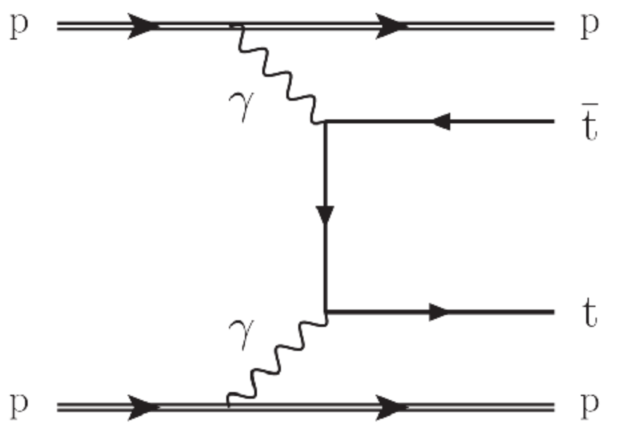
[Phys. Rev. Lett. 129 (2022) 011801] [arXiv:2311.02725]

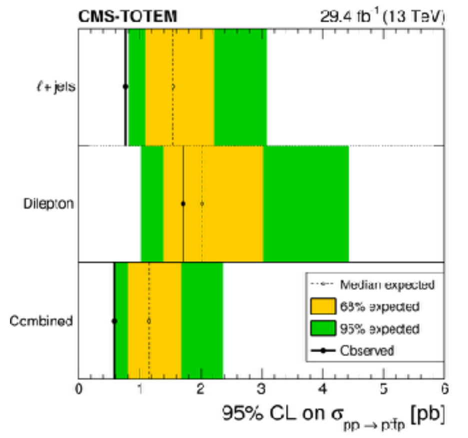




Search for central exclusive production of top quark pairs with tagged protons

[arXiv:2310.11231]





PPS at the HL-LHC

Extension of the PPS program in HL-LHC would significantly improve physics reach:

More integrated luminosity

- Results from Run 2 and Run 3 limited by statistical uncertainties

Broader m_X ($\sqrt{s_{\gamma\gamma}}$) range

- Current acceptance in the range ~350 GeV - 2 TeV (when both protons detected)
- In HL-LHC configuration, upper limit up to ~4 TeV (with horizontal beam crossing), lower limit down to ~200 GeV (with vertical beam crossing)

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Expression of interest submitted in 2021 arXiv:2103.02752

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Proposal approved by CERN Research Board in September 2023

- PPS2 included in HL-LHC baseline; design of detector vessels and detector units started

PPS2 physics reach: low mass

Several standard model processes can be probed, mainly in $\gamma\gamma$, to measure couplings and check theory predictions

Process	**Fiducial cross section [fb]**	
	2 tags	**1 tag**
jj	2	219
bb	0.04	6.3
W^+W^-	15	152
$\mu\mu$	1.3	172
tt	0.1	0.65
H	0	0.23
HW^+W^-	0.01	0.06
ZZ	0.03	0.23
$Z\gamma$	0.02	0.15
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SM cross sections
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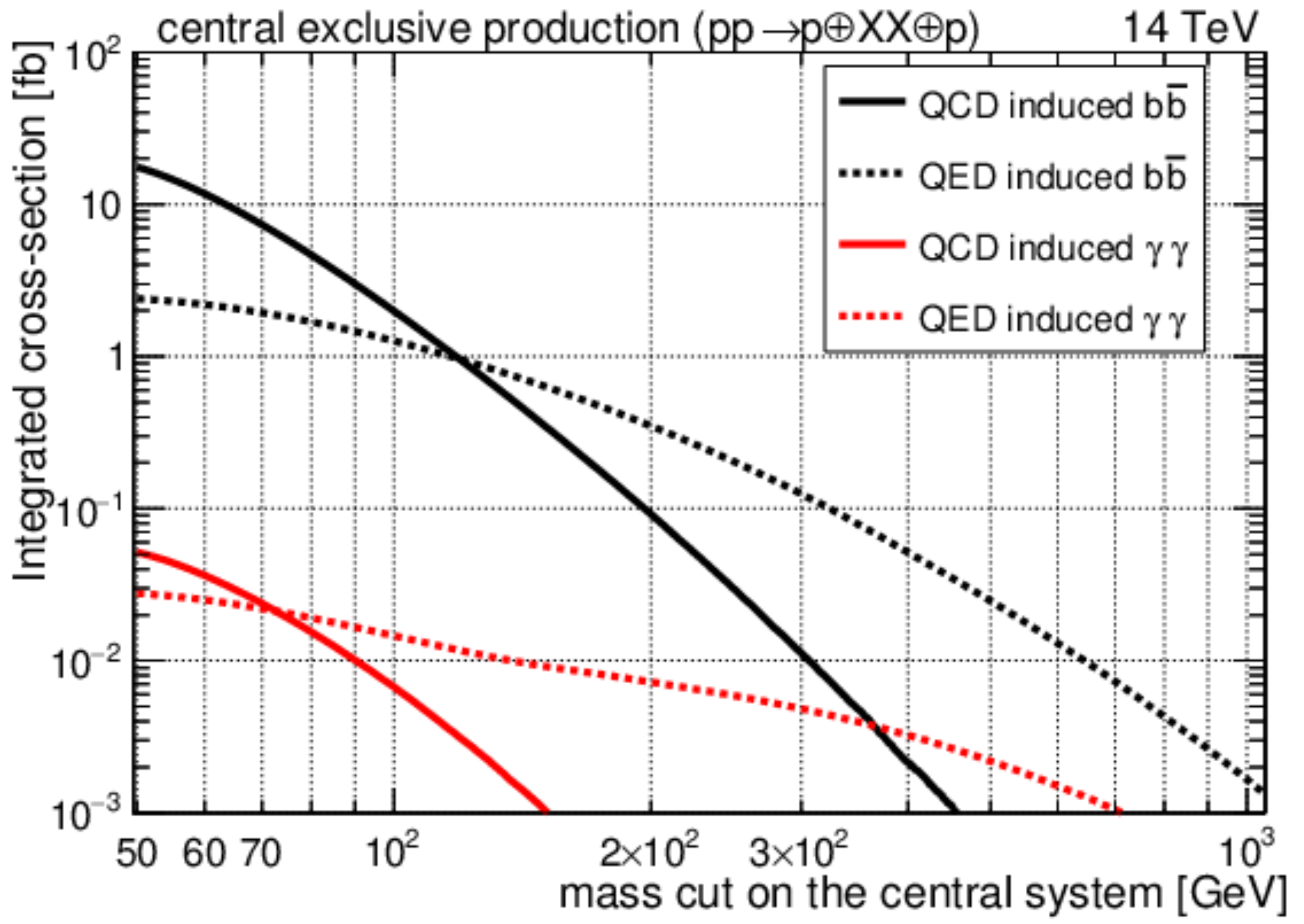
$pp \to p\, b\bar{b}\, p$, $pp \to p\, \gamma\gamma\, p$, QCD and QED contributions



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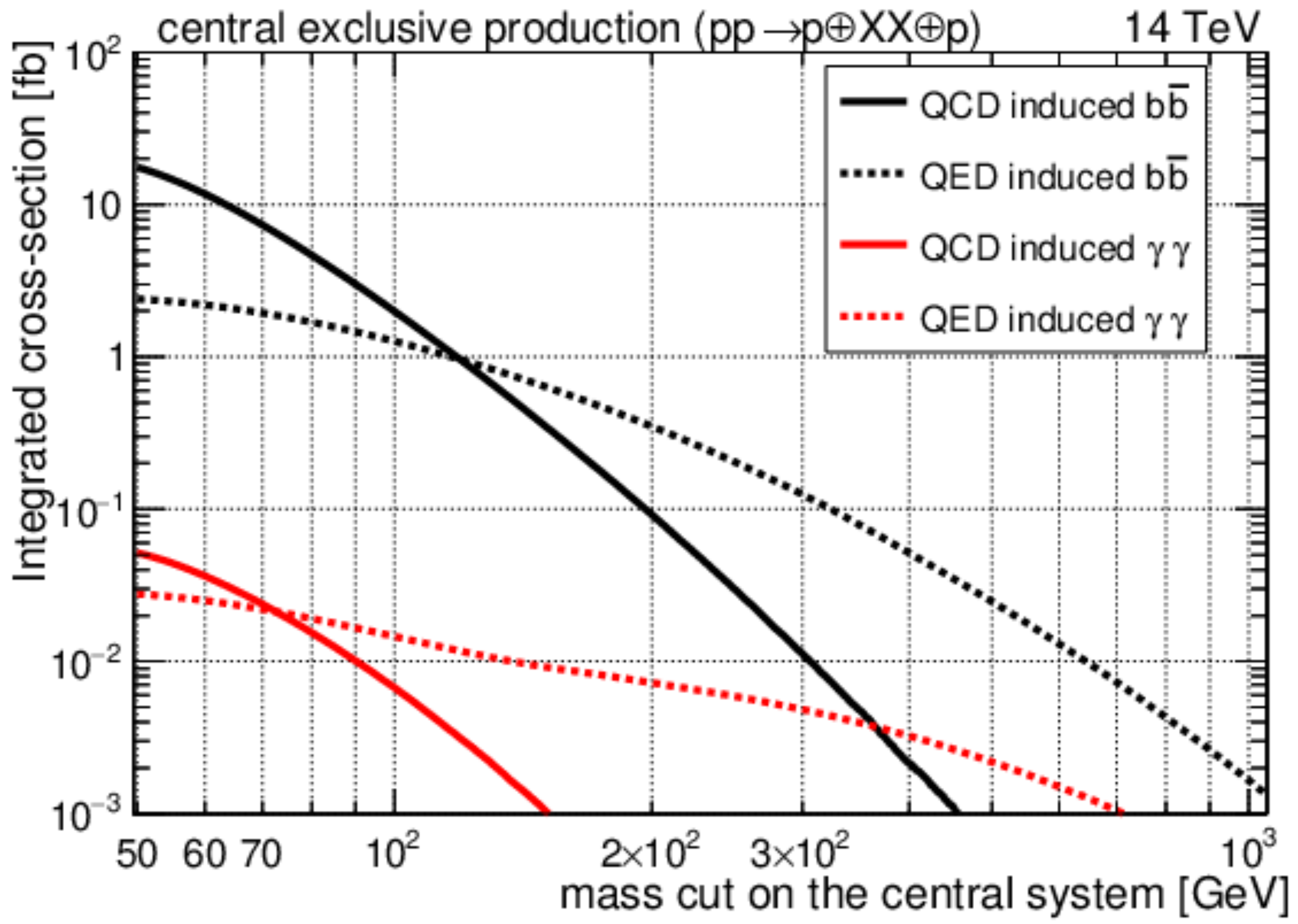

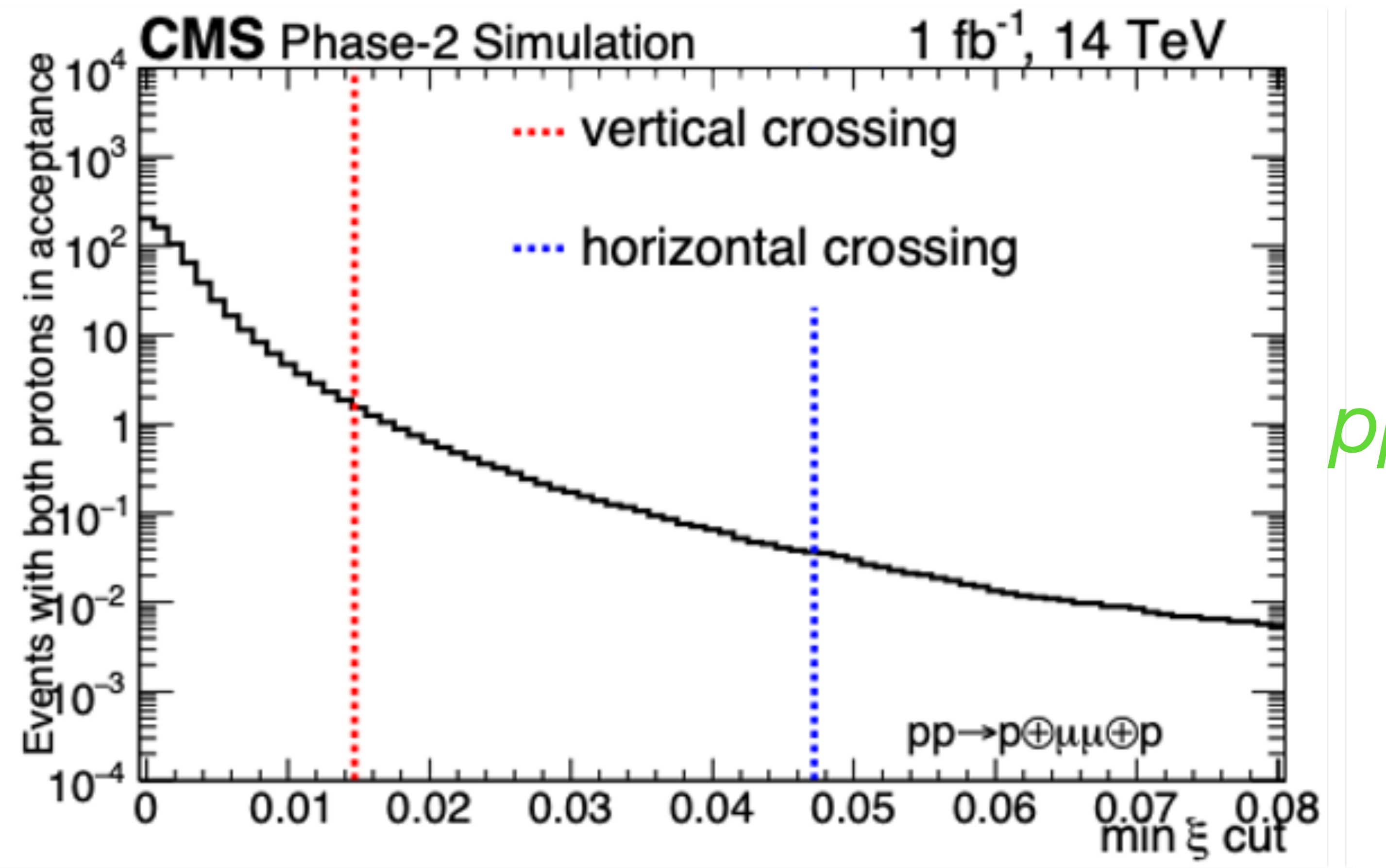

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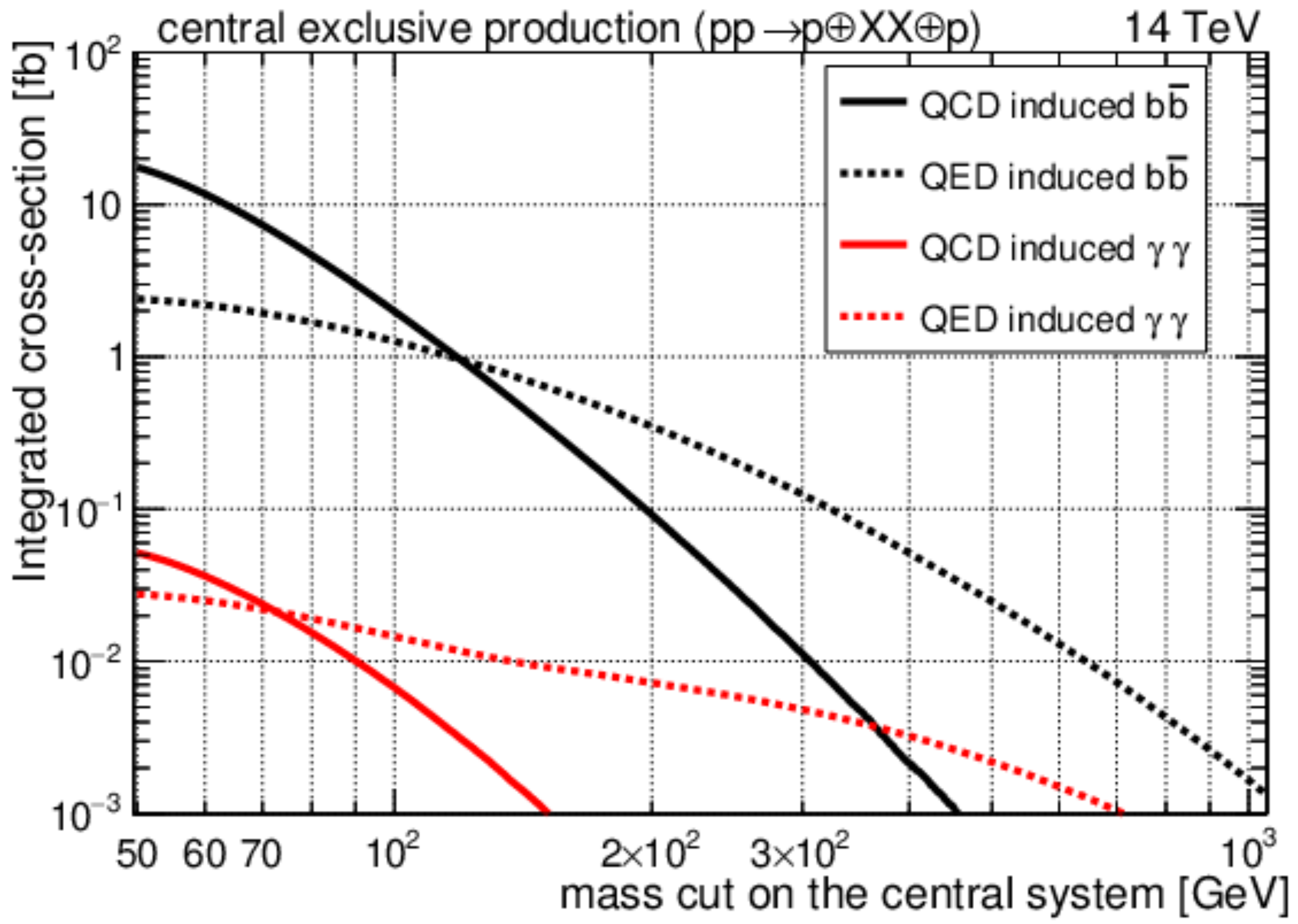
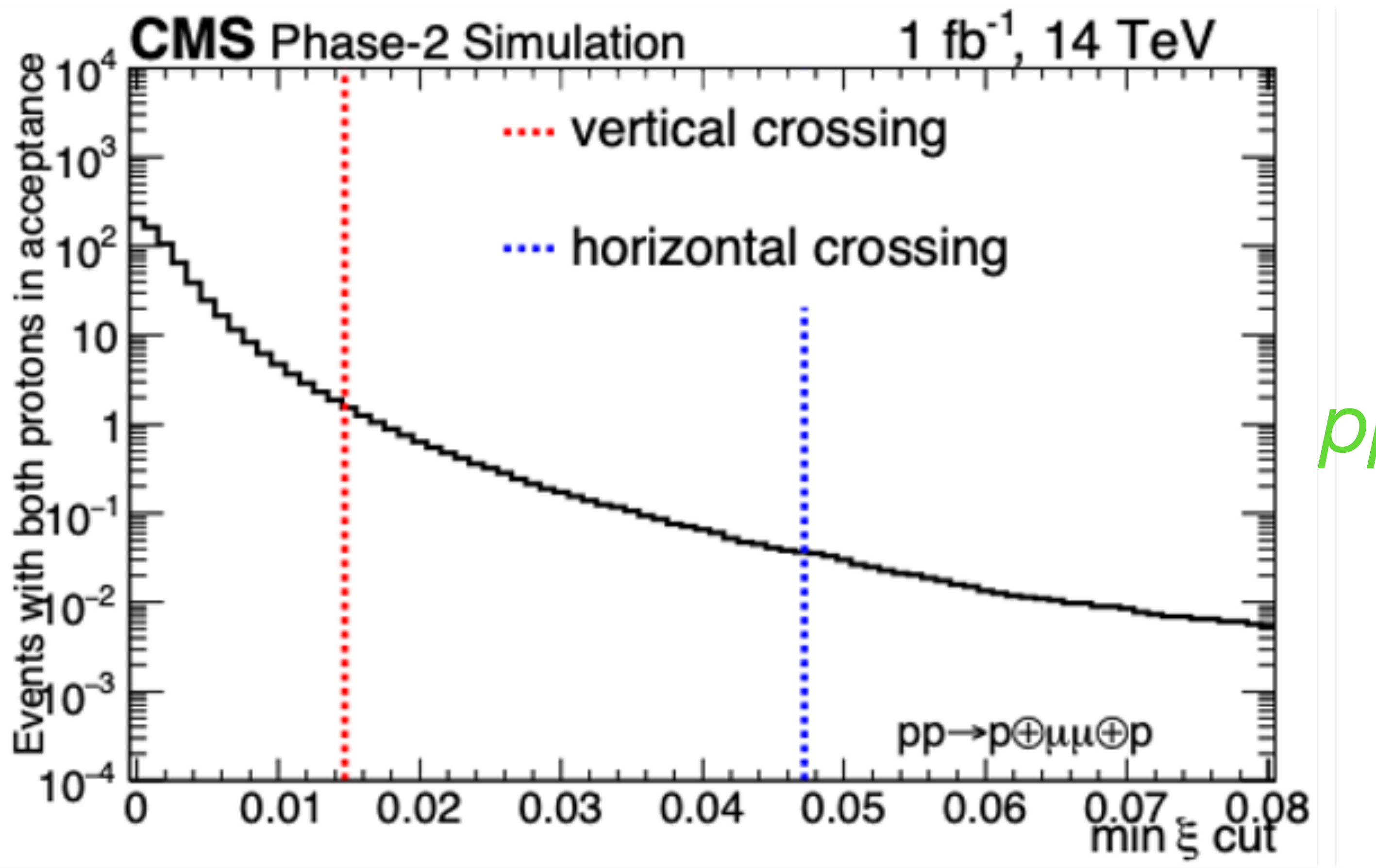
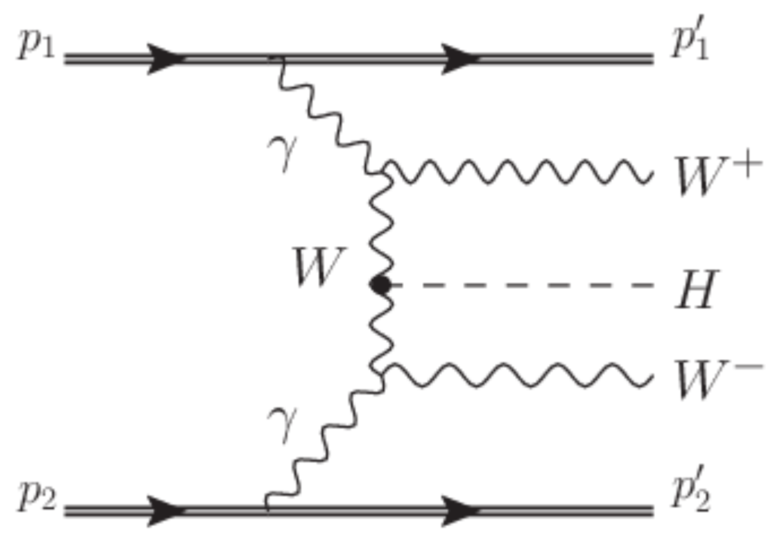


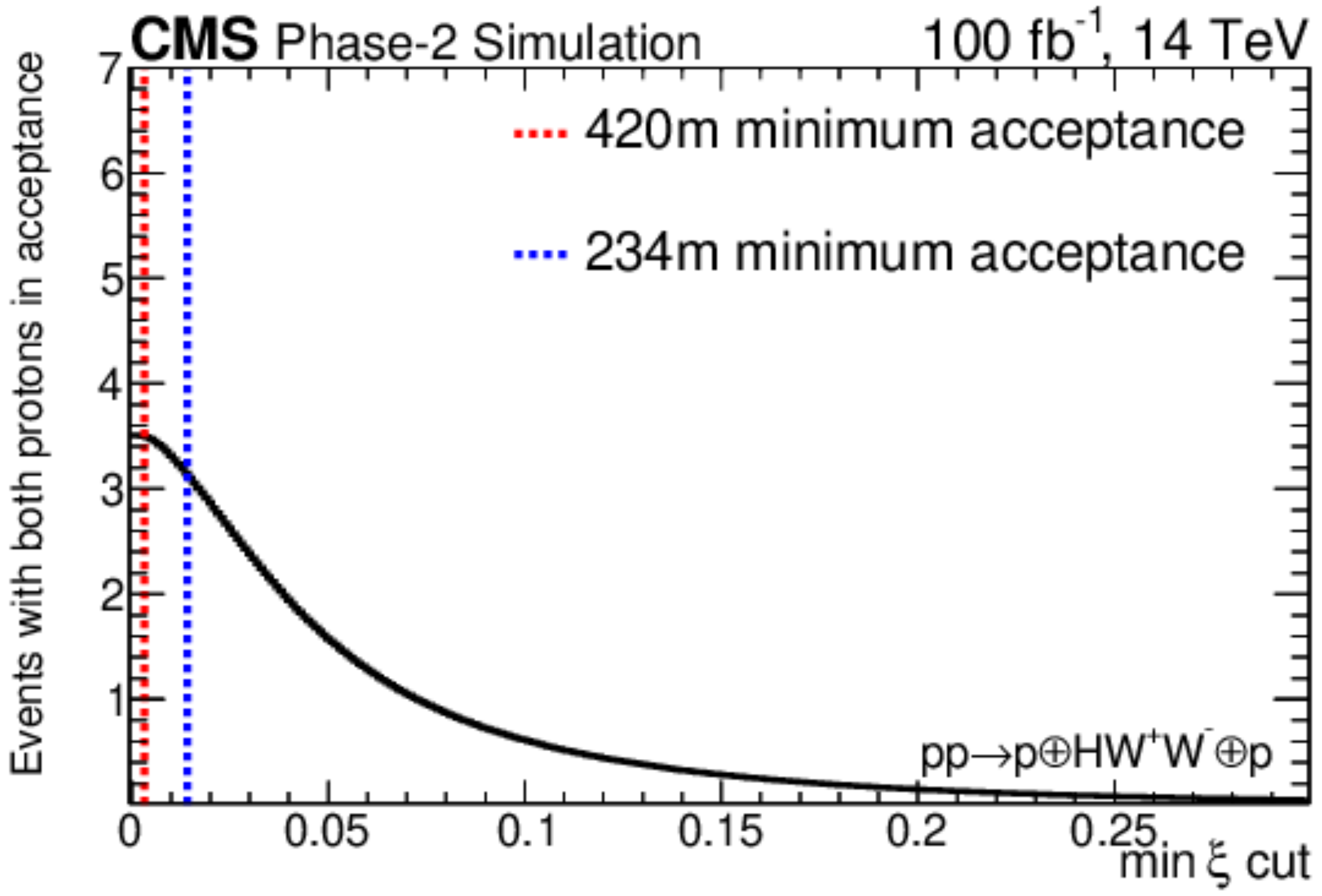


$pp \to p\, \mu^+\mu^-\, p$

$pp \to p\, HW^+W^-\, p$

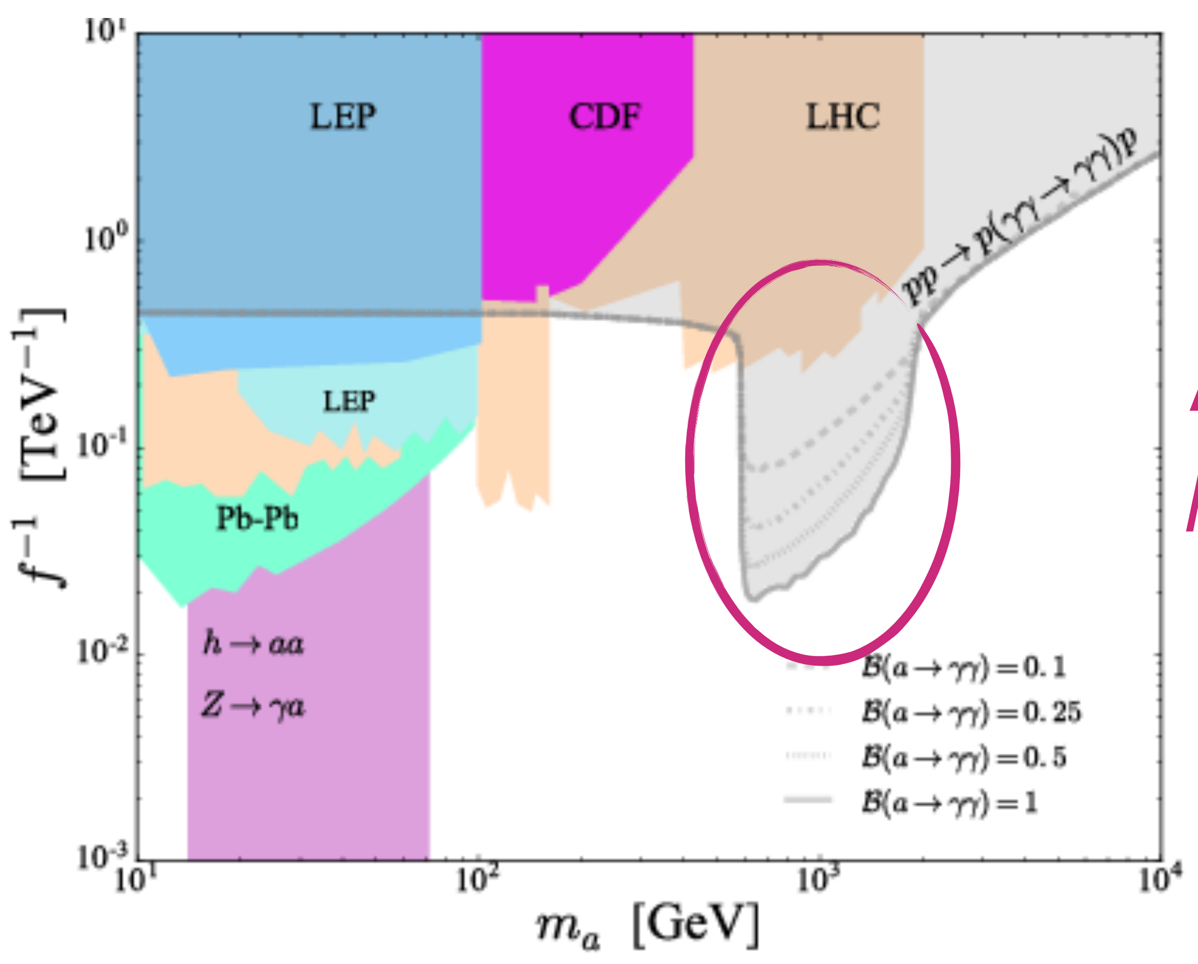


Decay-mode-inclusive, using missing mass technique



PPS2 physics reach: high mass

Tagged protons may be a powerful tool in studying various BSM scenarios where new particles are produced in $\gamma\gamma$ interactions



ALP search in
$pp \to p\,X\,p,\ X \to \gamma\gamma$

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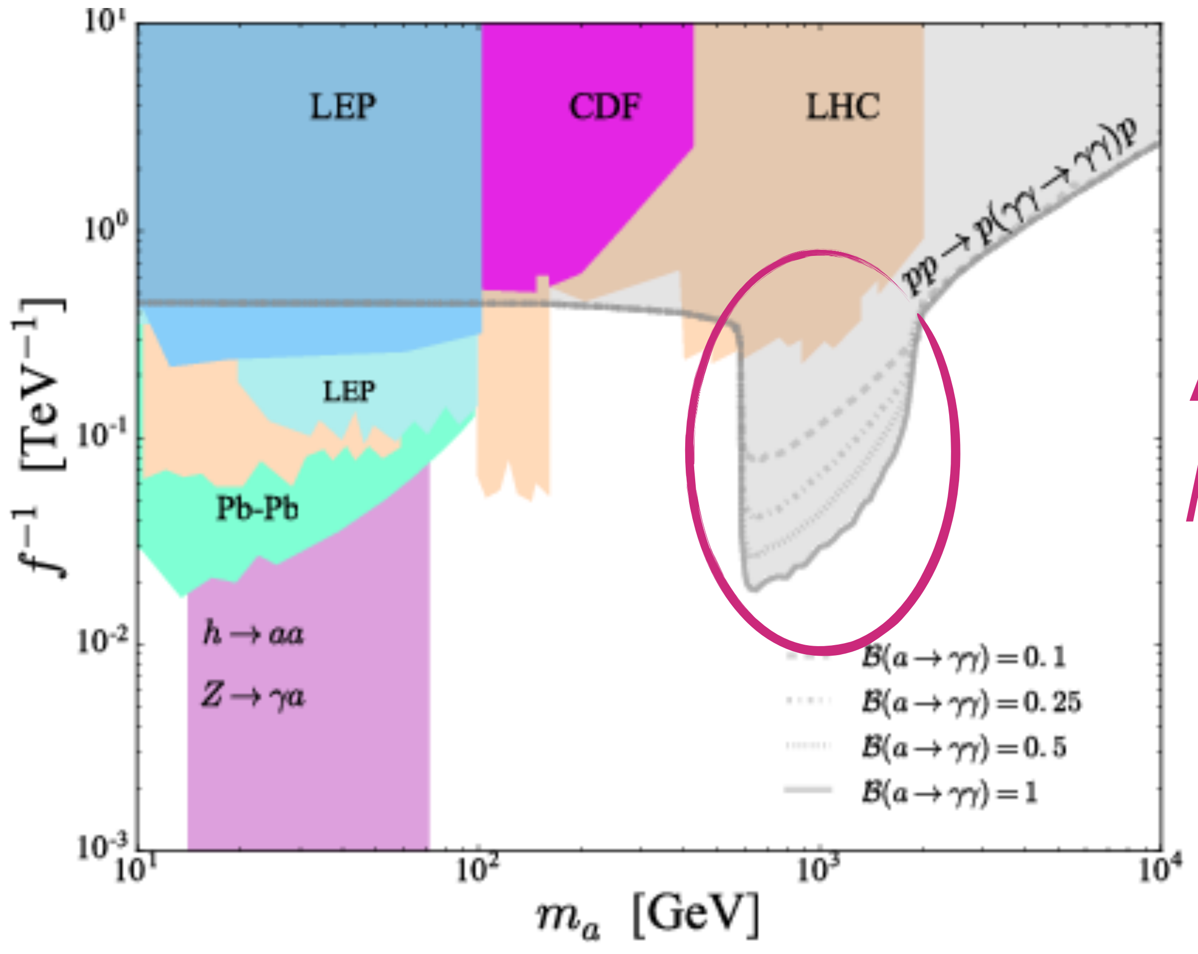
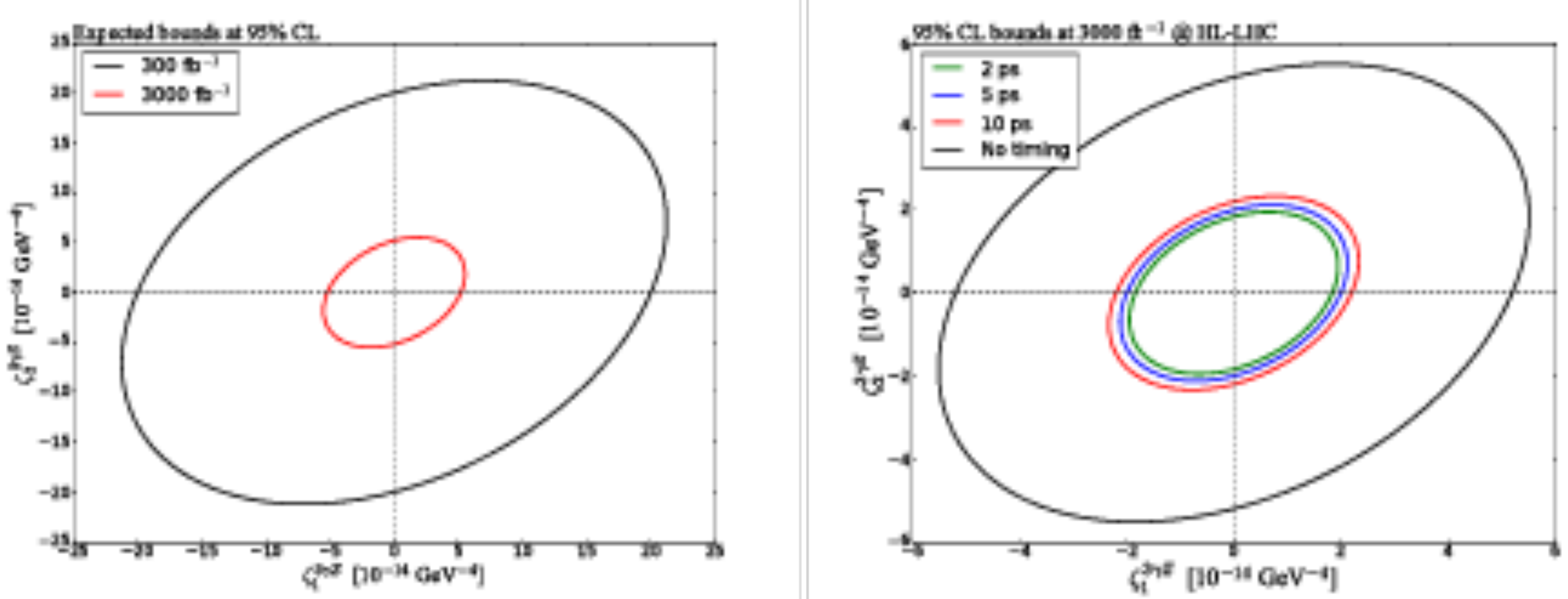


ALP search in $pp \to p\, X\, p,\ X \to \gamma\gamma$

AQGC in $pp \to p\, \gamma Z\, p$



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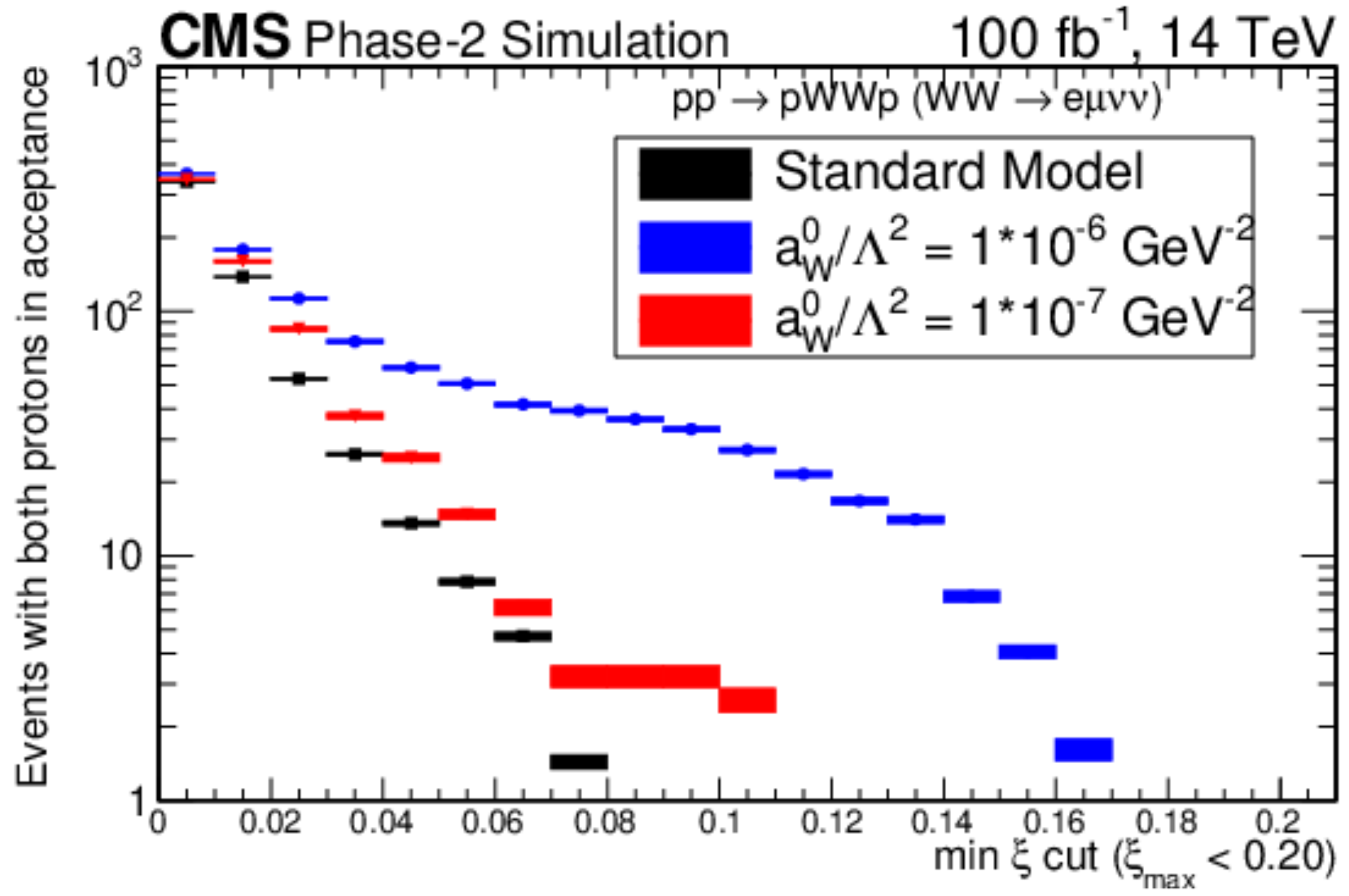

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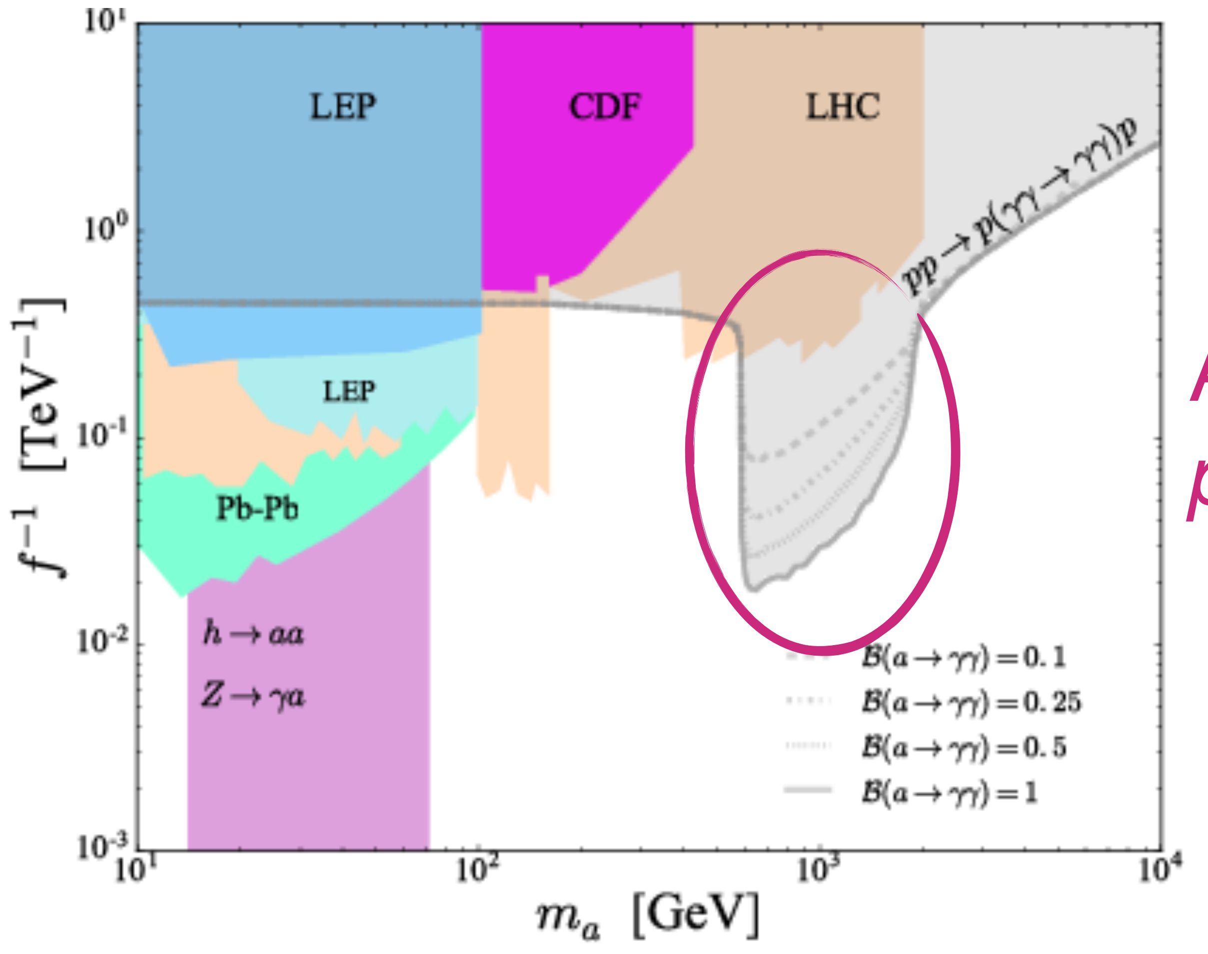
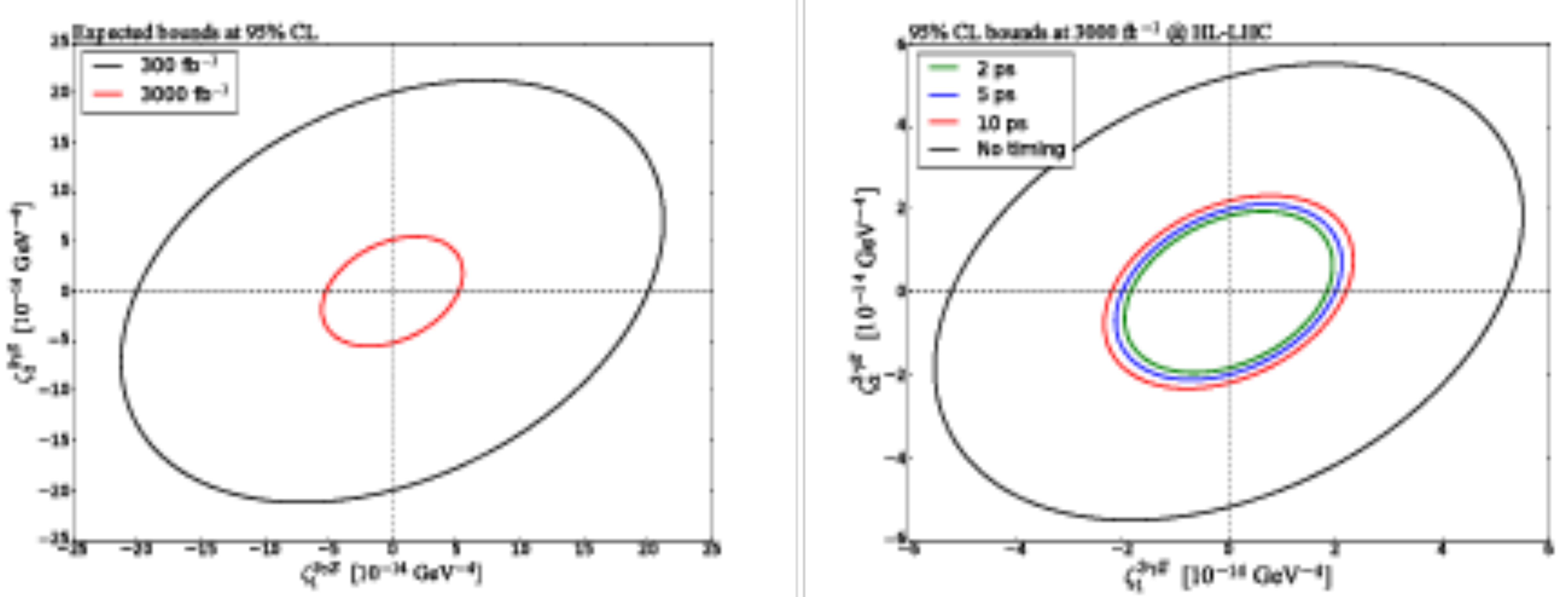
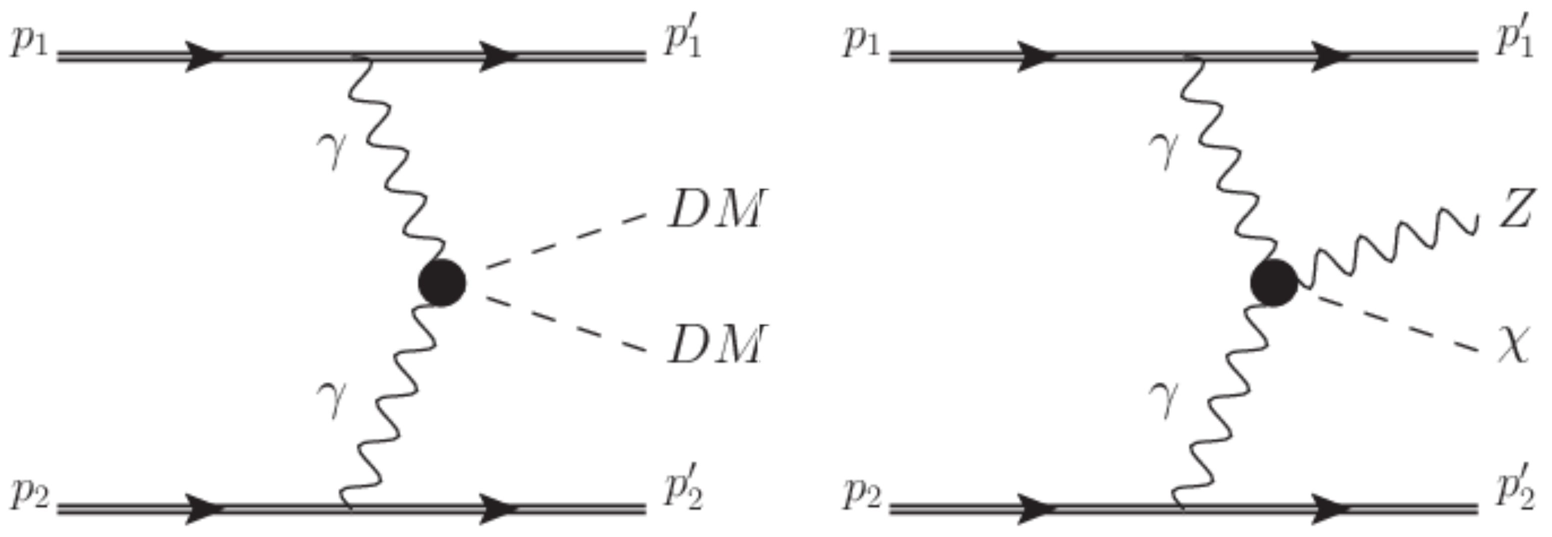


ALP search in
$pp \to p\,X\,p,\ X \to \gamma\gamma$

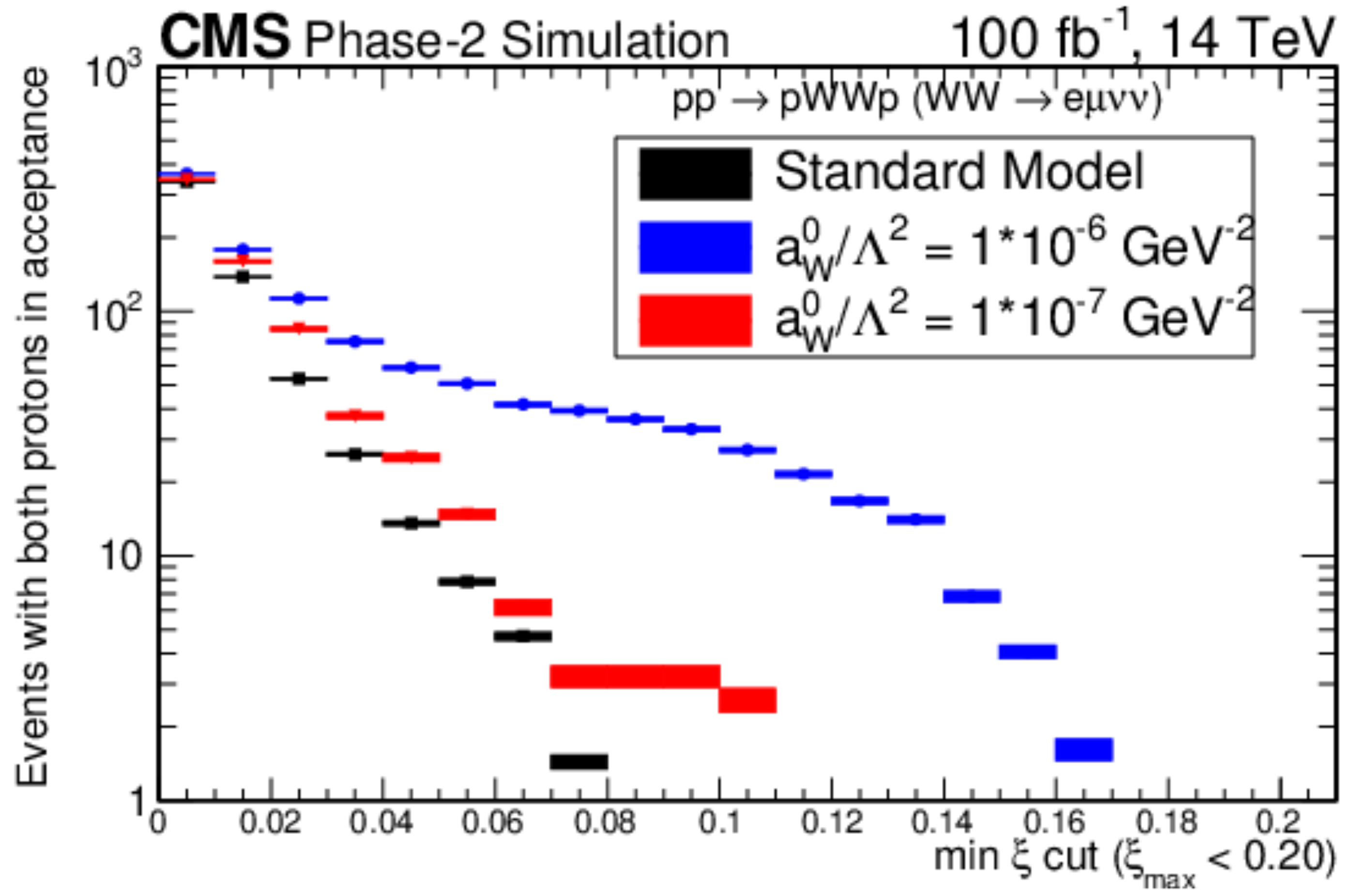
AQGC in $pp \to p\,\gamma Z\,p$



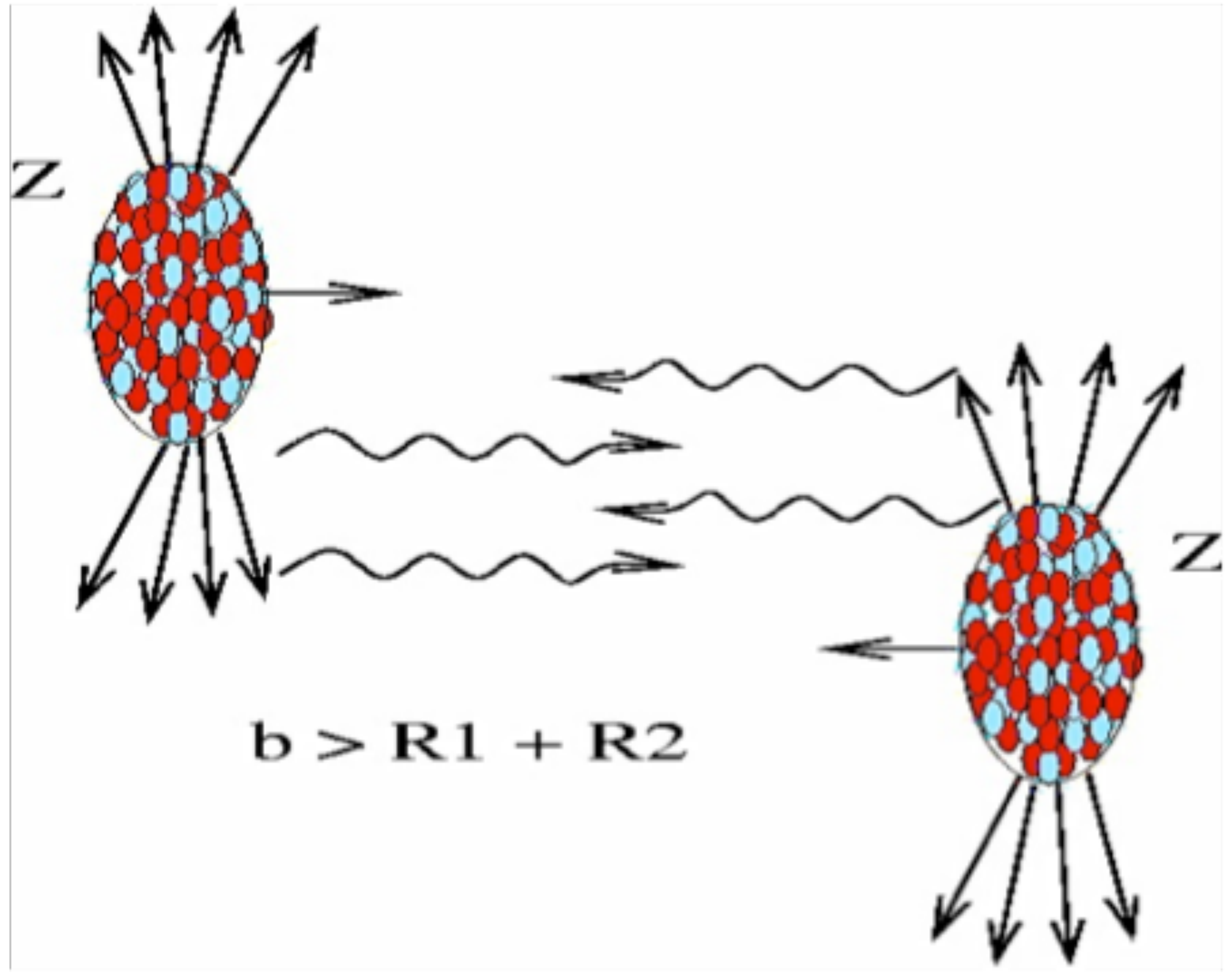


DM searches with
missing mass technique

AQGC in $pp \to p\,W^+W^-\,p$

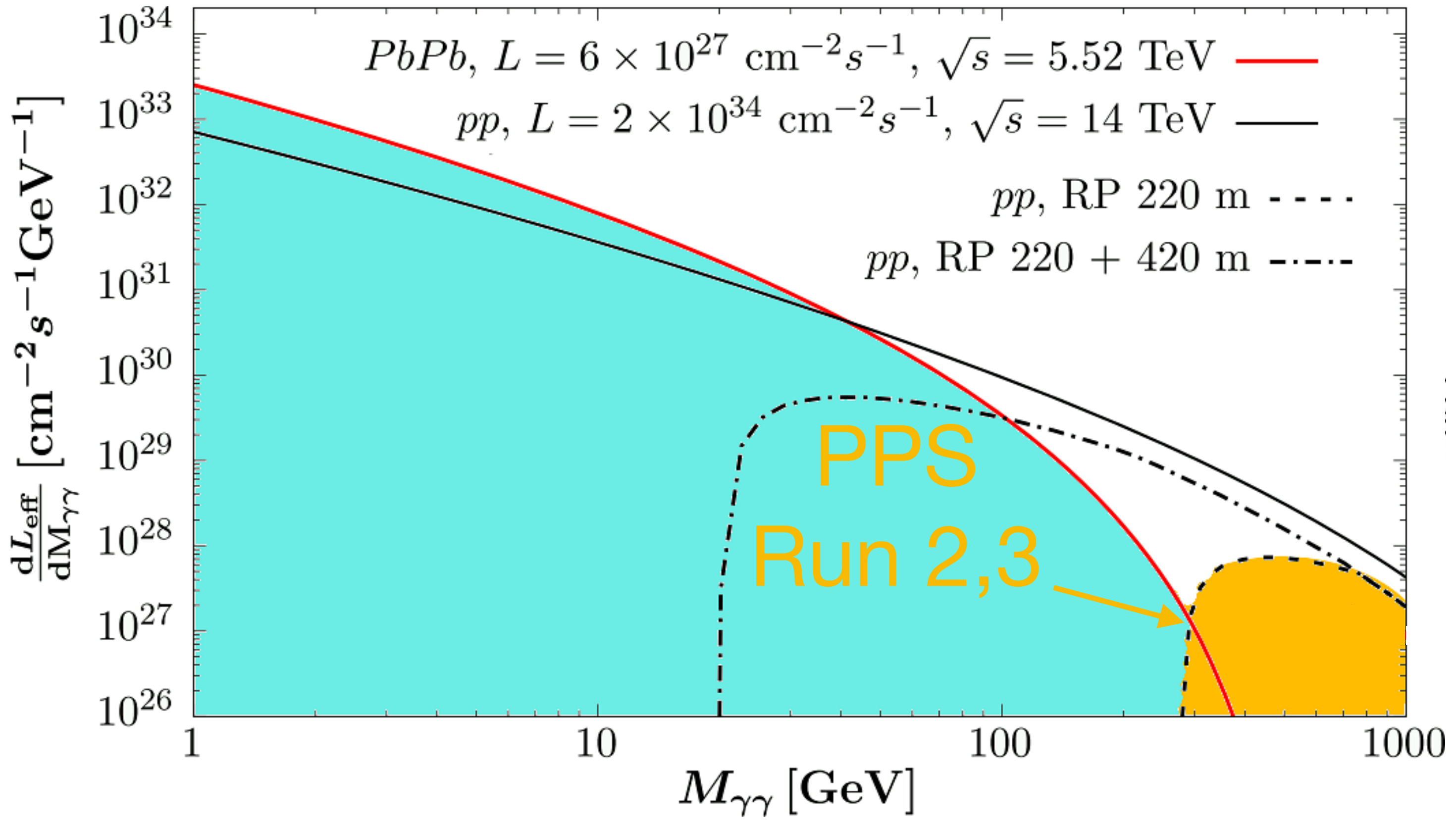


PPS2 physics reach: complementarity



Ultra-peripheral collisions in heavy ion interactions are a copious source of $\gamma\gamma$ interactions

- High photon flux proportional to Z^4, lower luminosity wrt. *pp*
- Large cross sections in the low mass range, $m_{\gamma\gamma} \lesssim 300$ GeV for Pb-Pb
- Low pileup conditions



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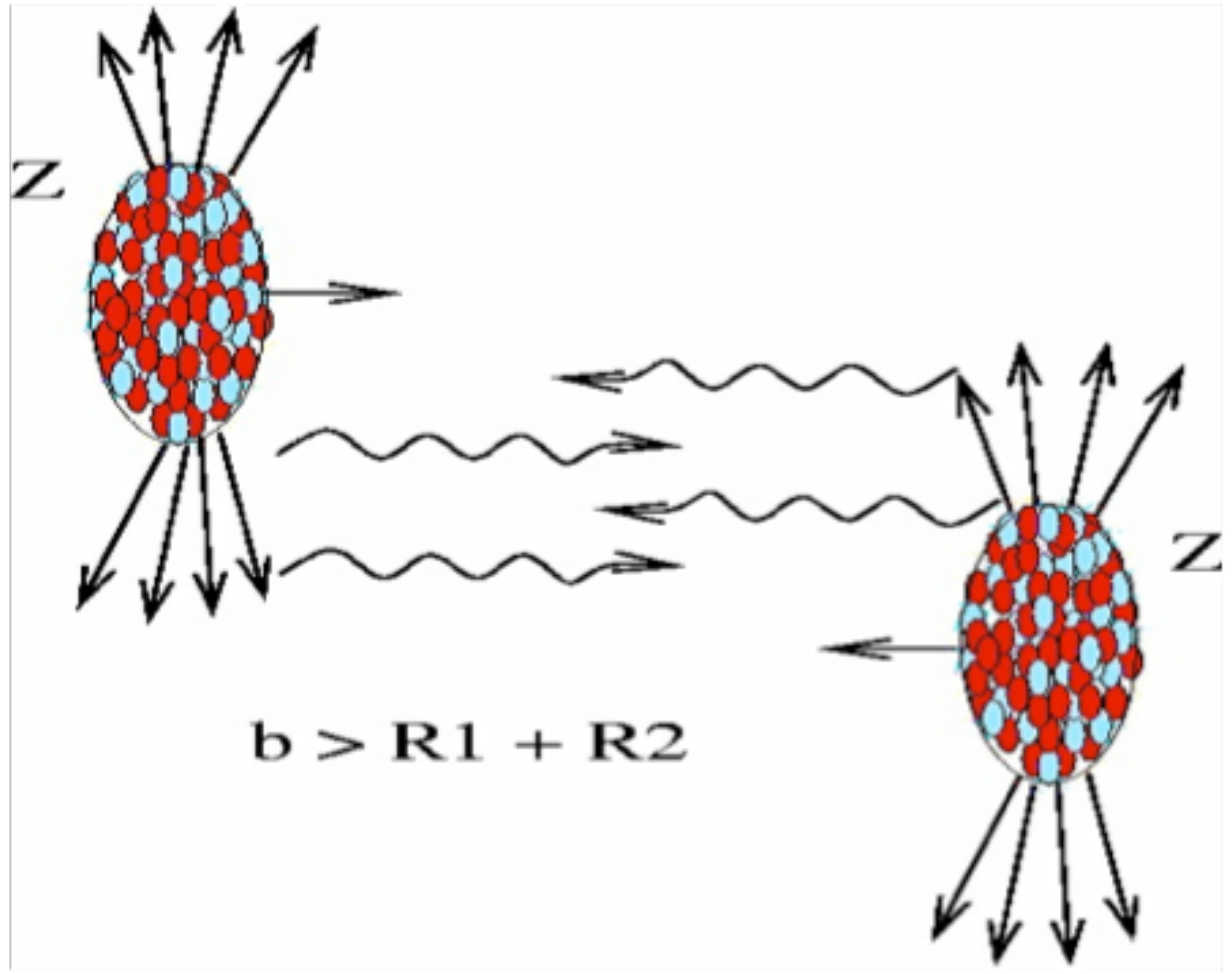

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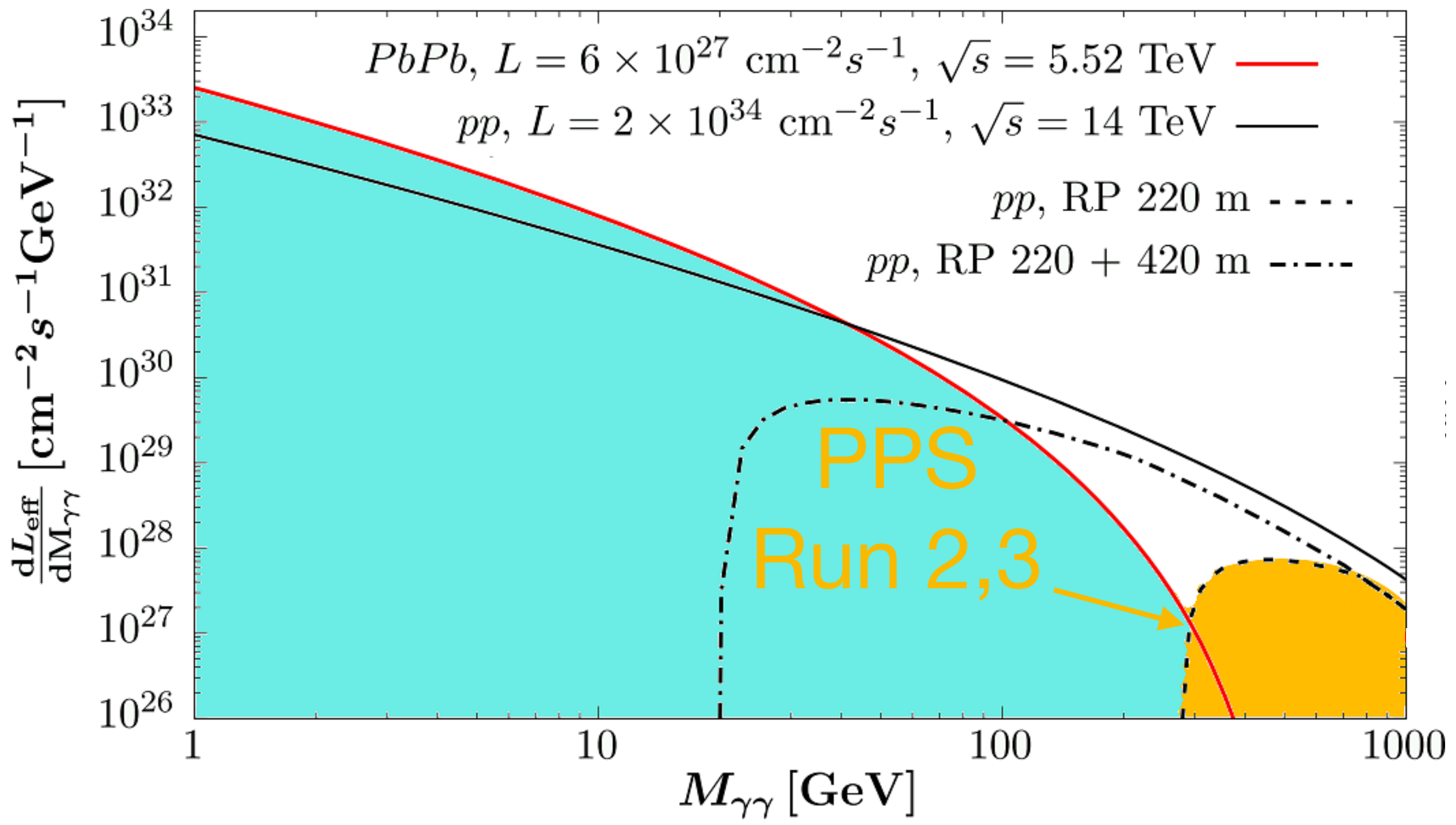

PPS2 may be able to tag protons in *pA* interactions

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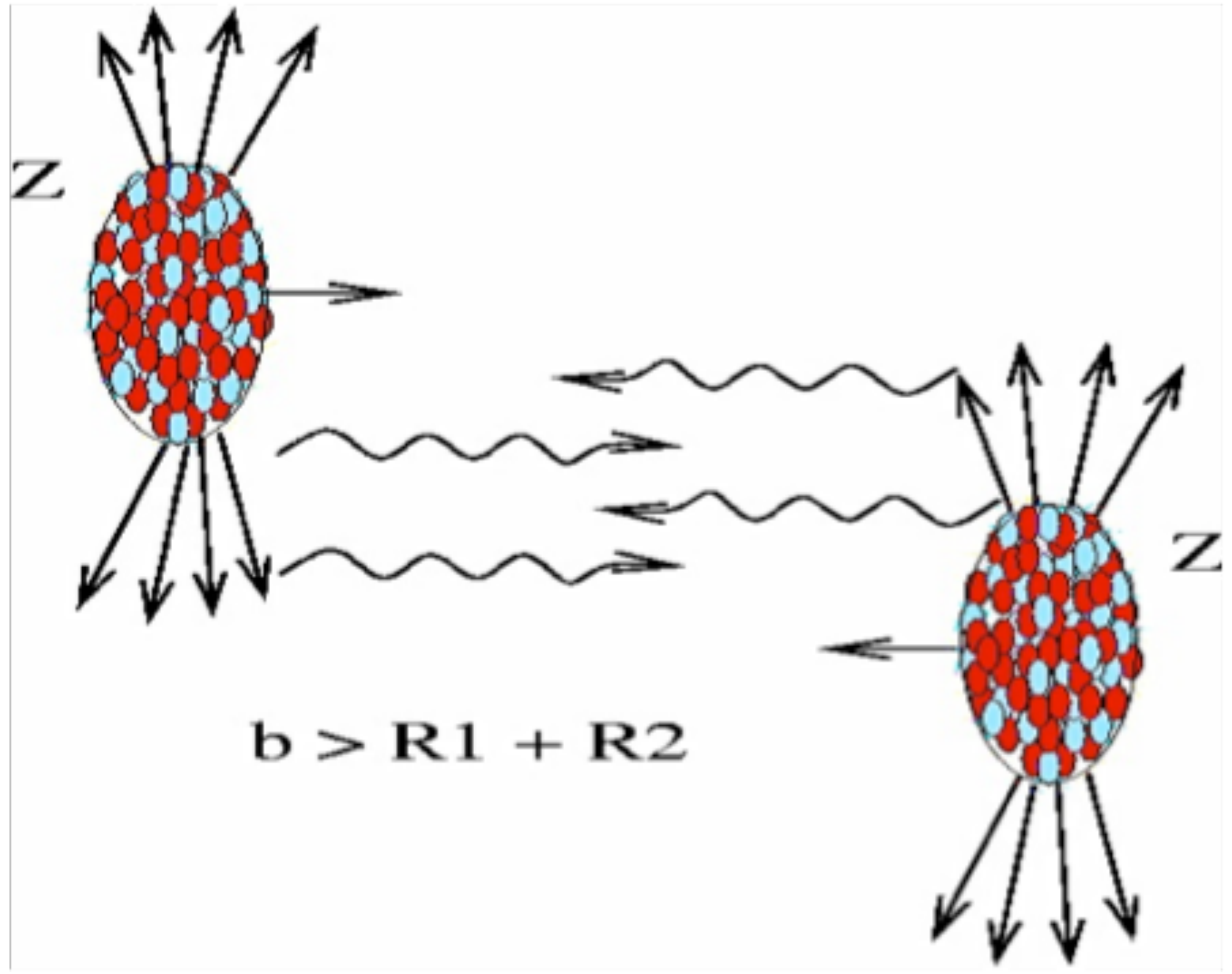

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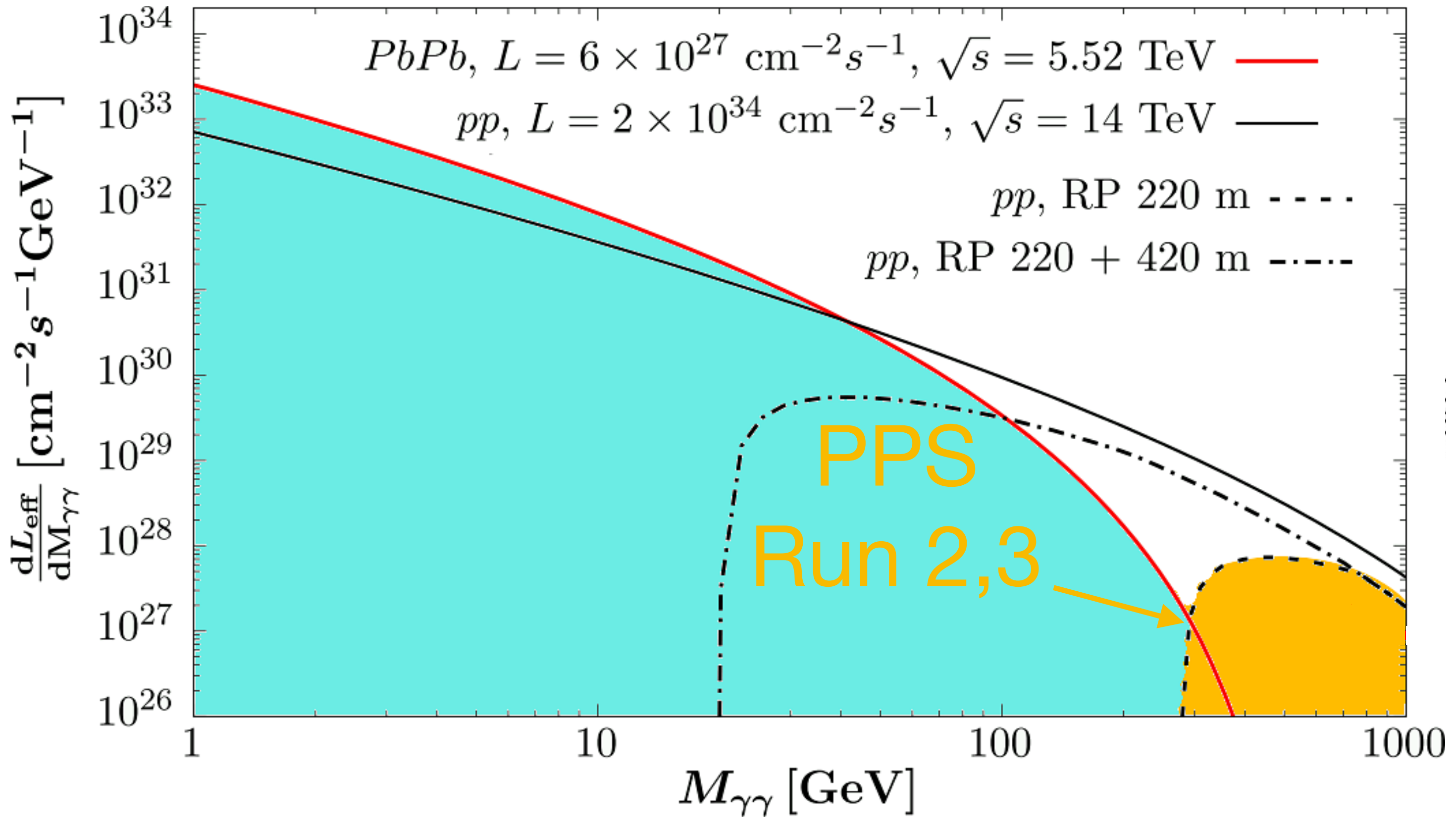

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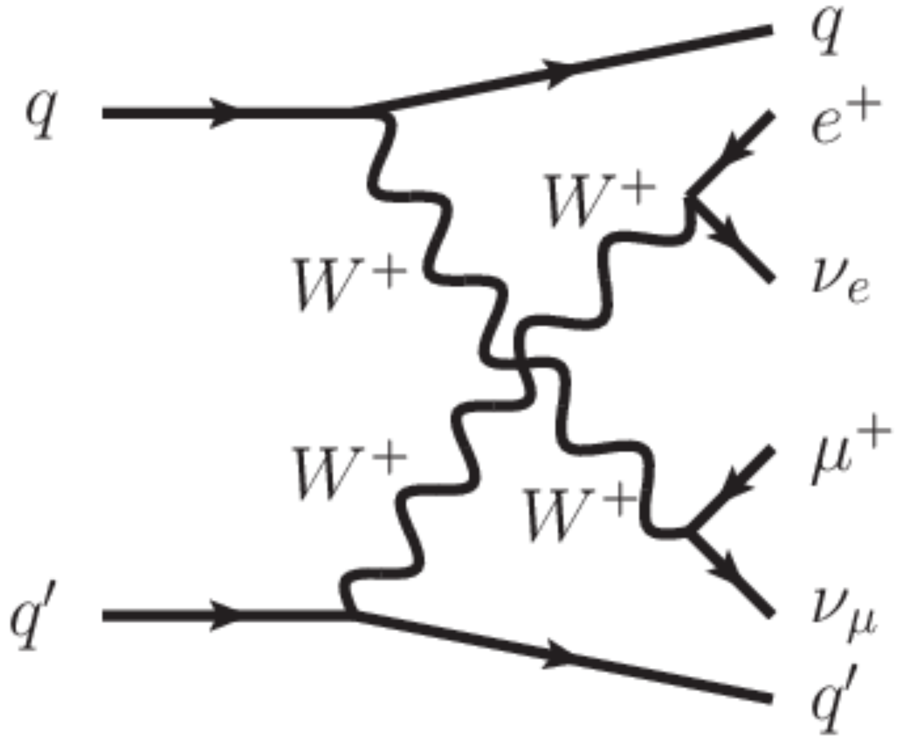
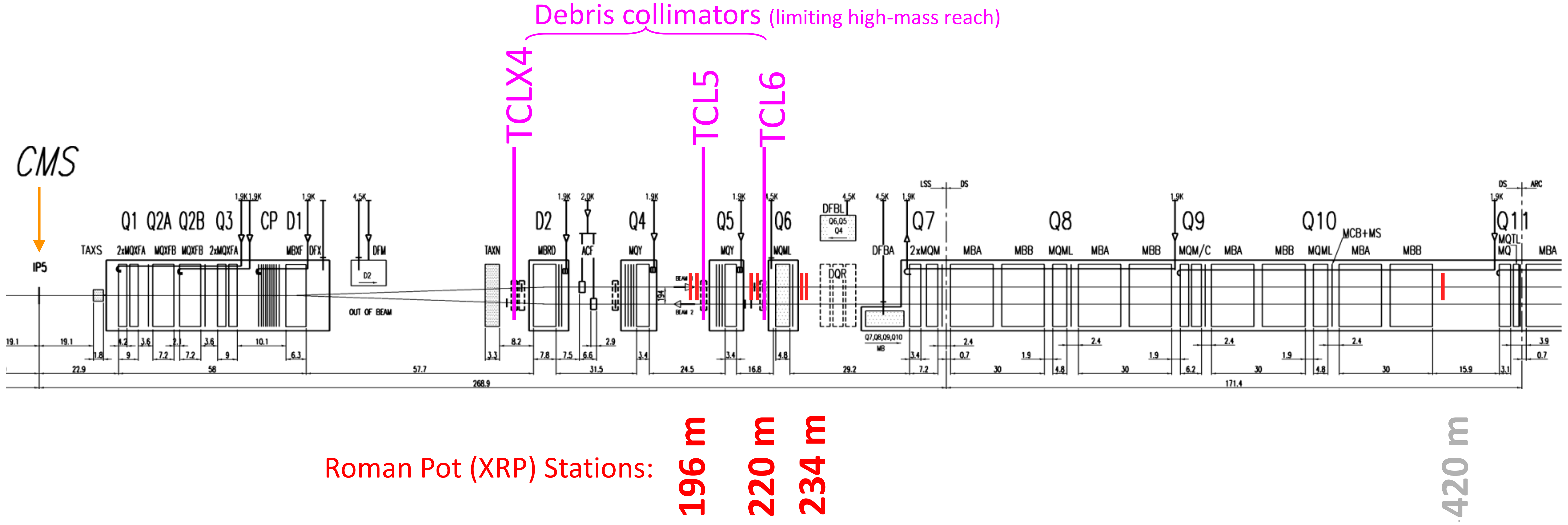


Phase-2 CMS upgrade will enhance the coverage in the forward region

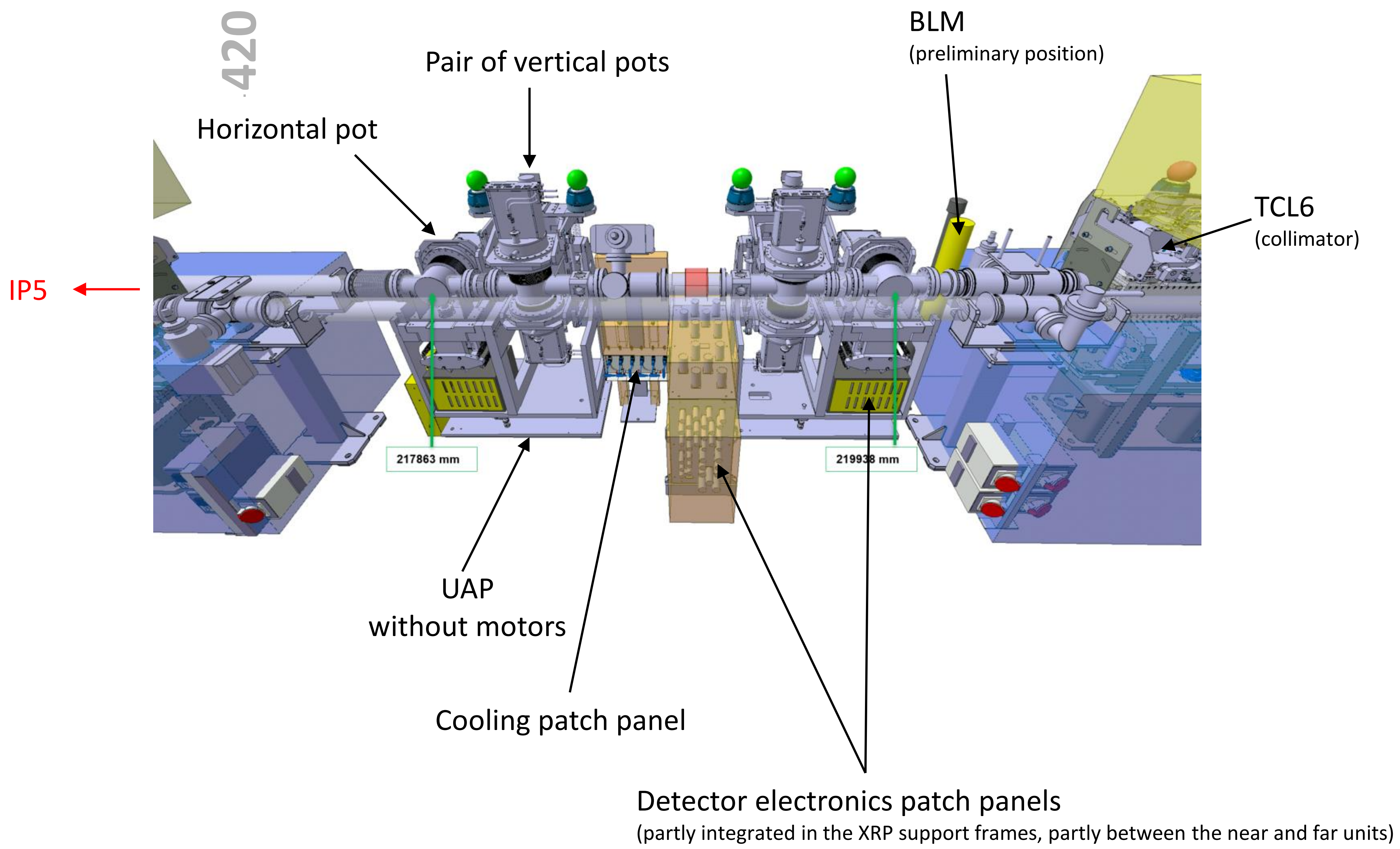
- LHC as a vector-boson collider, complementary to $\gamma\gamma$
- VBF/VBS events tagged by forward jets
- Similar events with intact protons may be tagged by PPS2

Detector locations

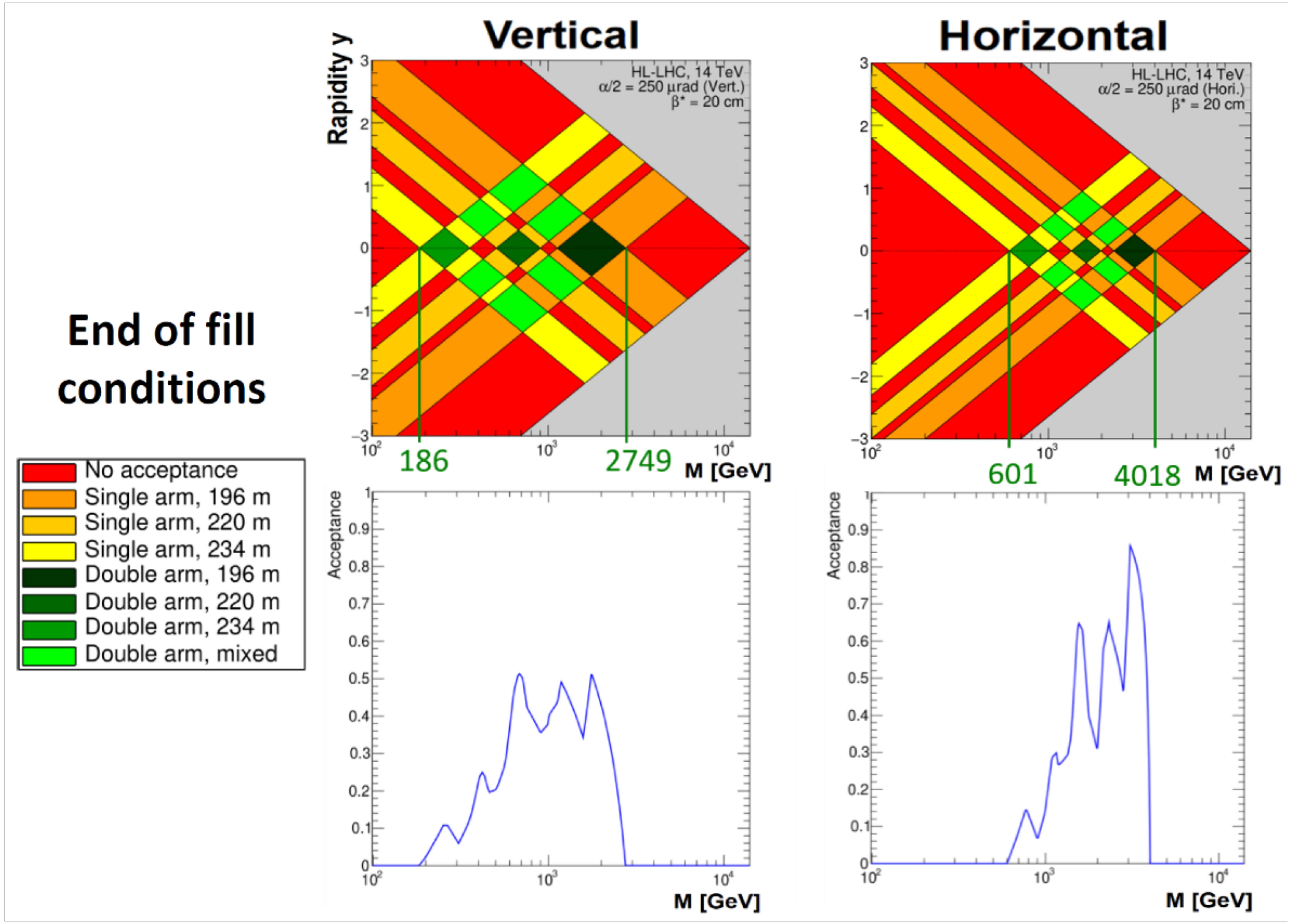


Three locations selected per side, with available space, in the LHC straight section

- In each location, two horizontal roman pots
- At 220 m, two additional pairs (top-bottom) of vertical roman pots, for detector alignment
- All positions precisely defined, including patch panels and all services



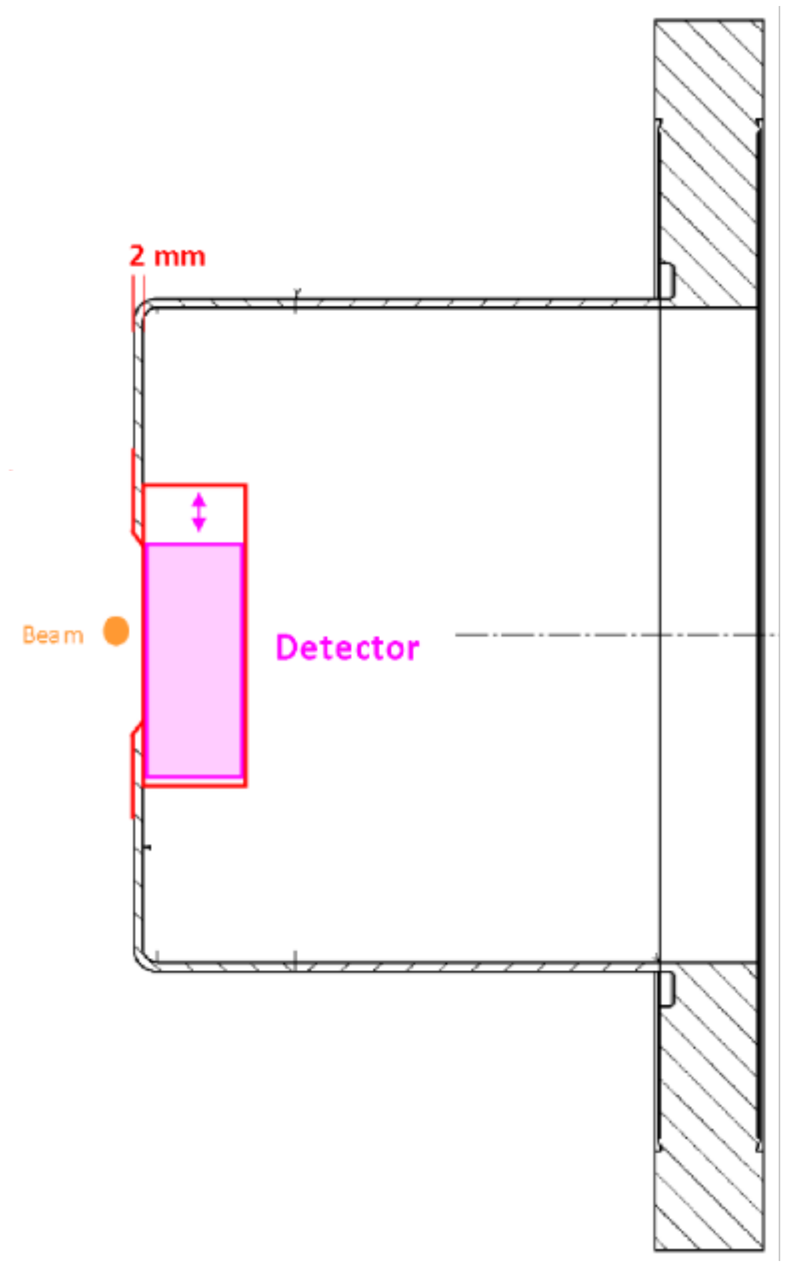
Detector acceptance

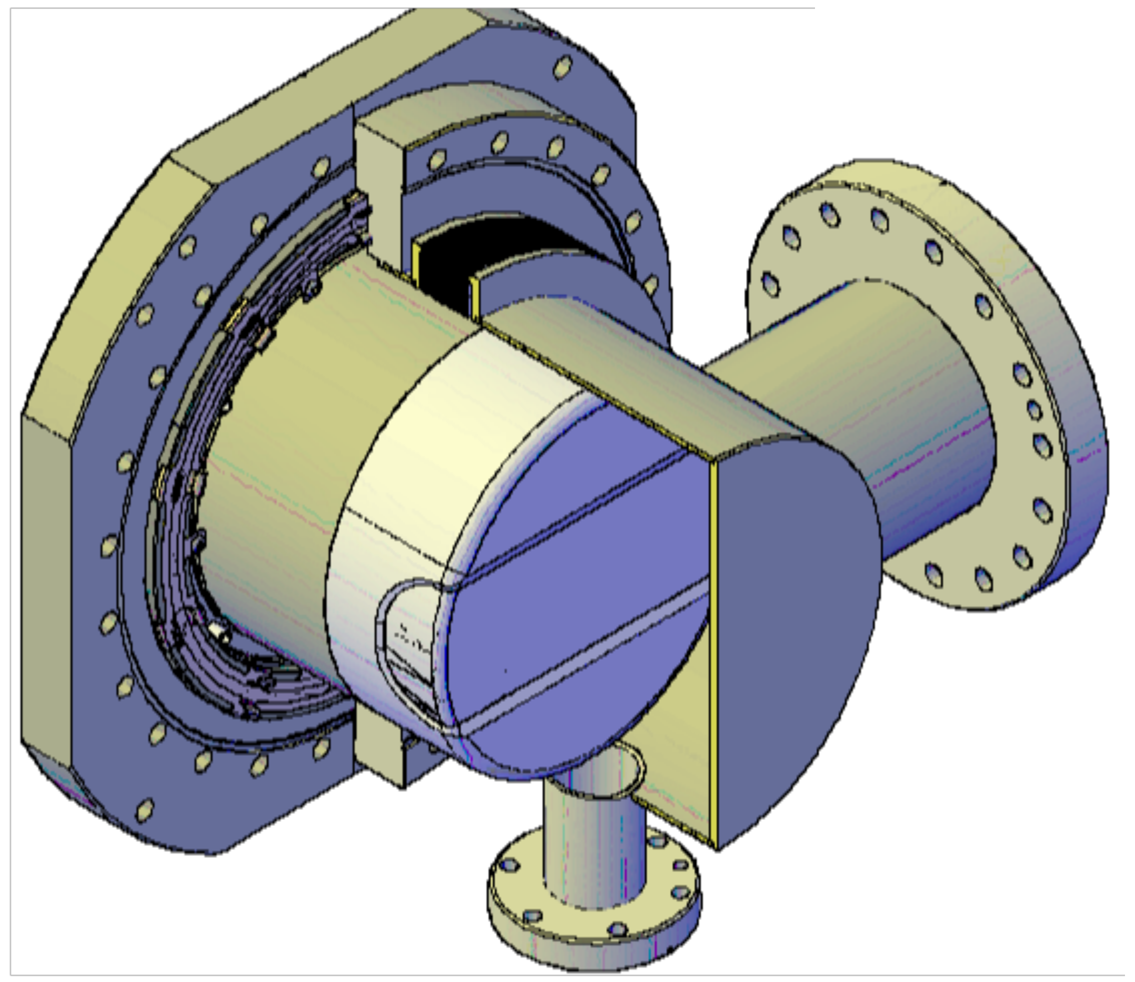


Two different beam crossing schemes in the IP foreseen during LHC operations

- ⟹ different proton acceptance in the two cases
- Double proton tag can use different stations on the two sides
- Larger combined m_X acceptance compared to current setup

Detector packages



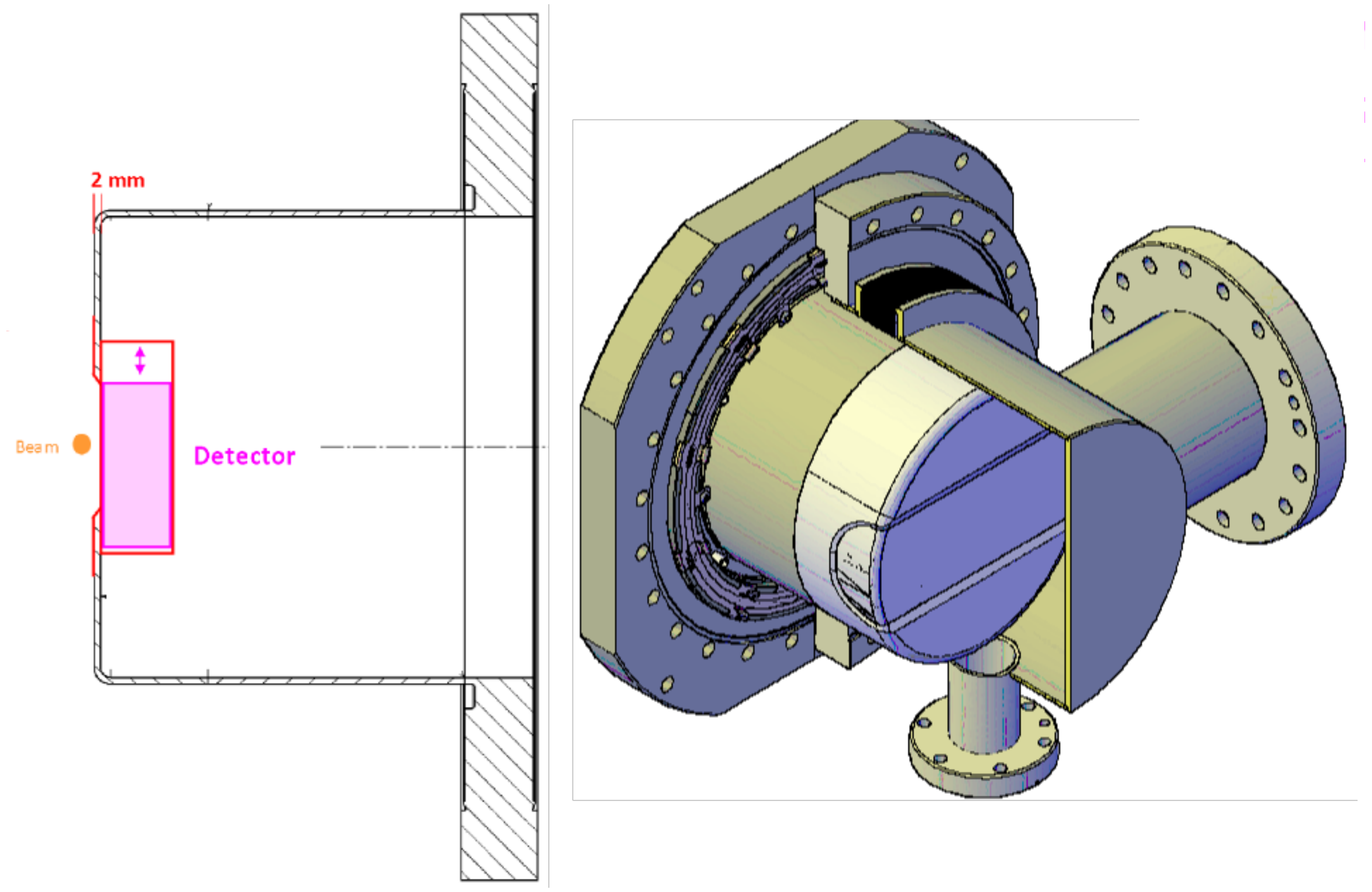


Each roman pot will host both tracking and timing detectors (or 4D detectors)

New design for detector vessels

- Cylindrical housing, maximising available space
- Larger thin window

Detector packages



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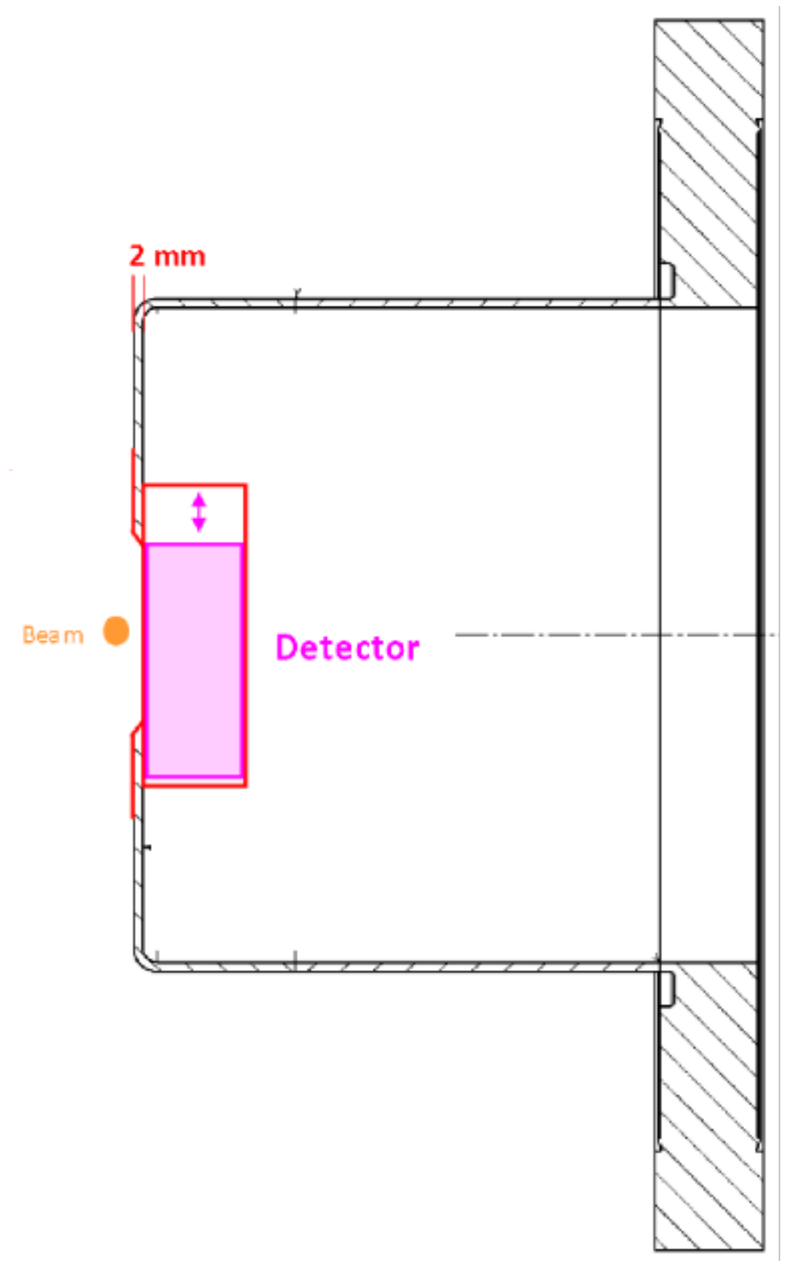

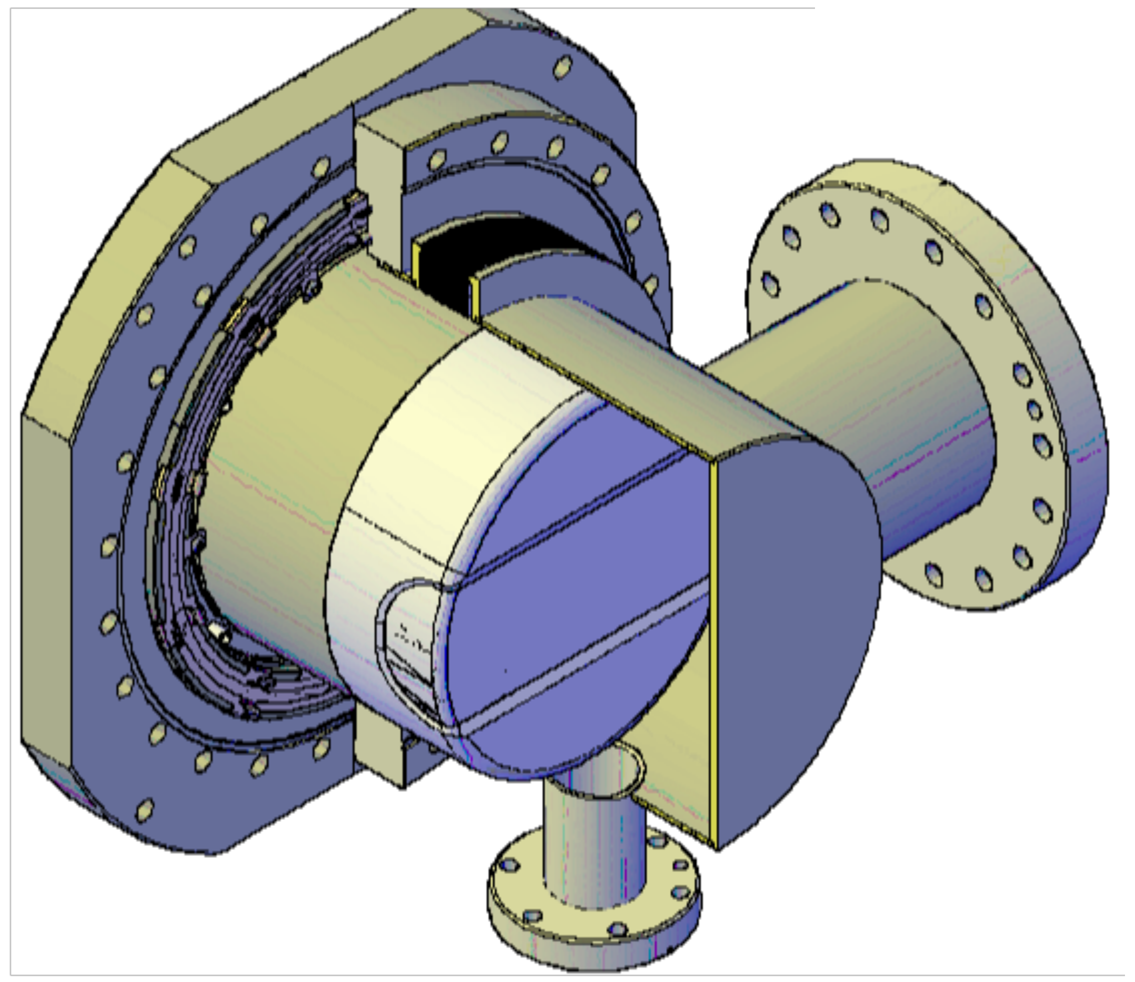

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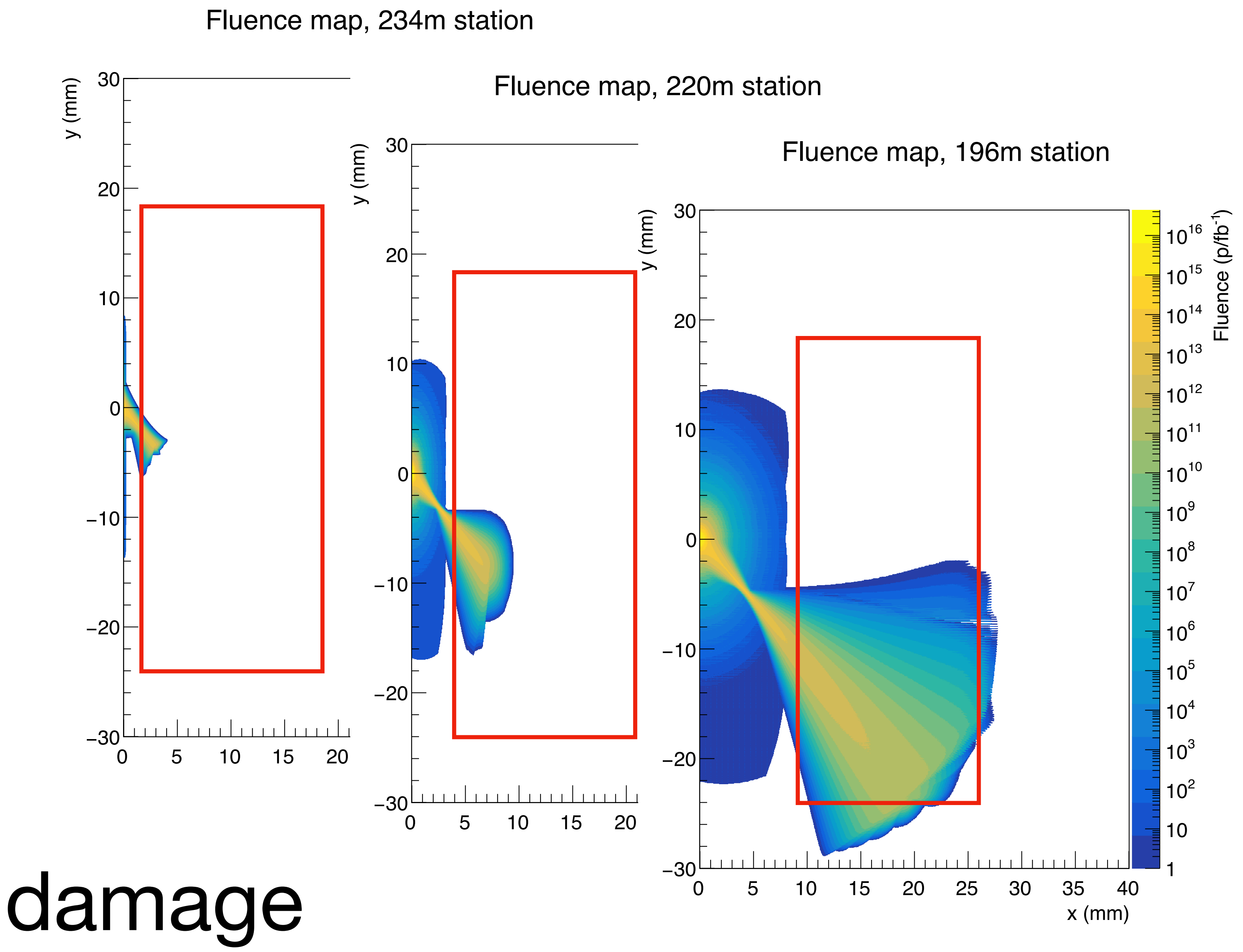

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Proton fluence highly non-uniform over the detector area

- ⟹ internal vertical shift system necessary to distribute radiation damage

Detector technologies

Baseline design exploiting detectors being developed for CMS Phase 2

- Similar position and timing resolution required
- Similar radiation doses expected, although much less uniformly distributed
- Smaller occupancy wrt. hottest regions in CMS
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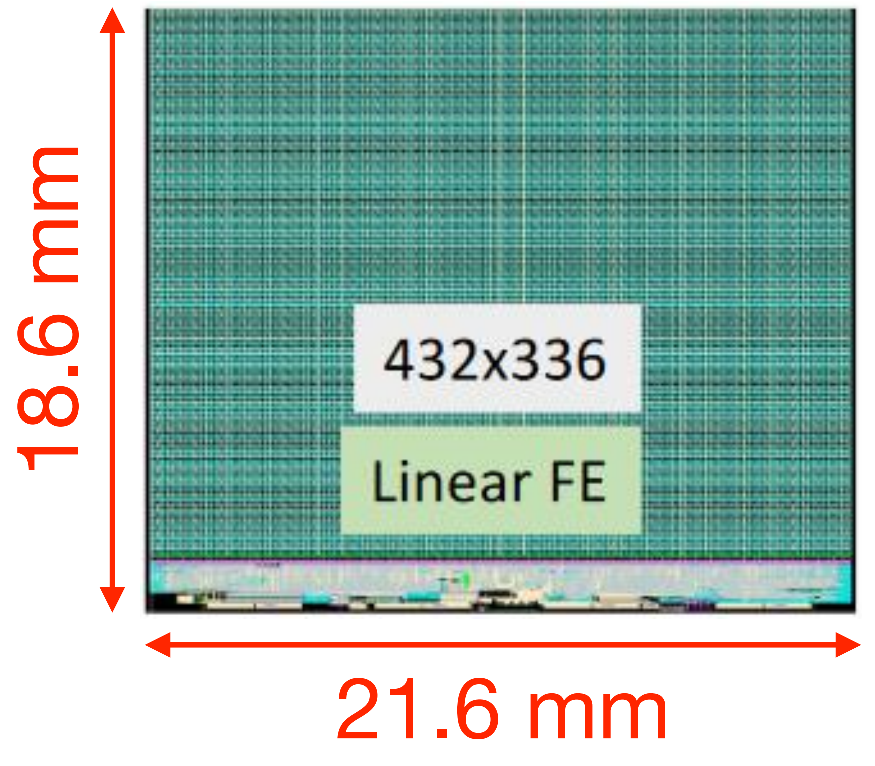
Tracking

- Based on Inner Tracker design
- 6 planes of 3D silicon pixels
- Front-end: CROC
  $\Longrightarrow$ 50×50 μm^2 pixels
- 2 or 3 chips/module



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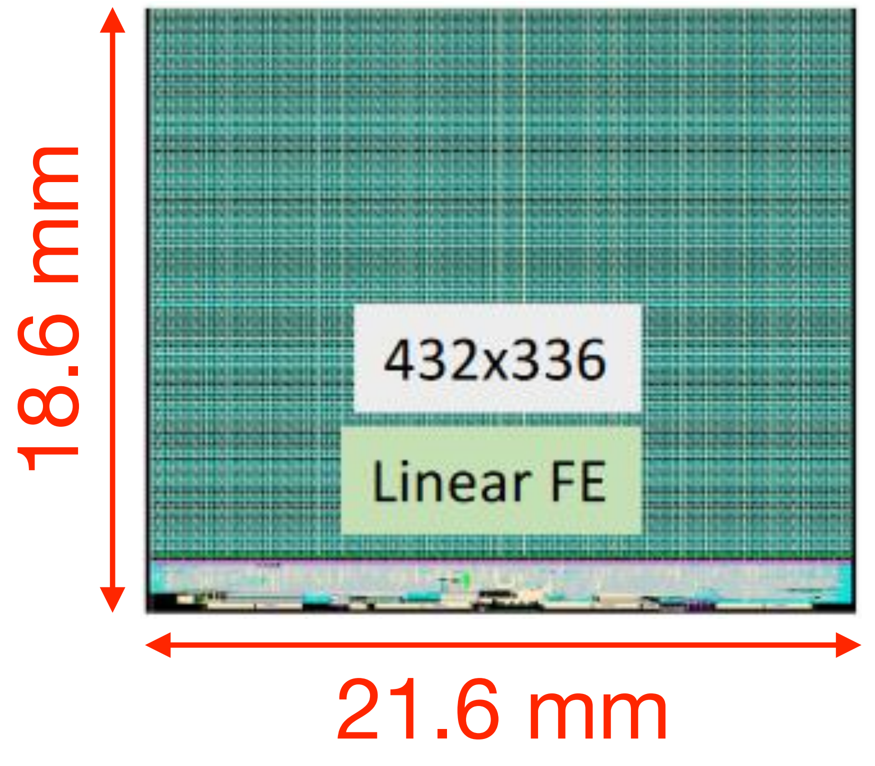
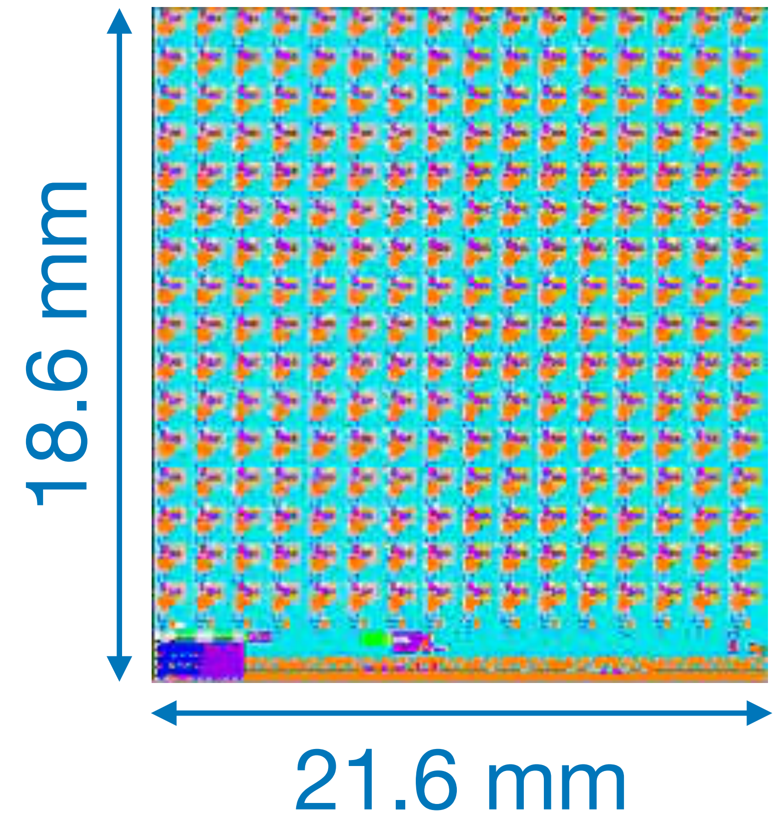


Timing

- Based on Endcap Timing Layer design
- 5 double-layer planes of LGADs
- Front end: ETROC
  $\Longrightarrow$ $1.3\times1.3\ mm^2$ pads
- 2 or 3 chips/module



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Aiming to be ready for the start of HL-LHC operations!