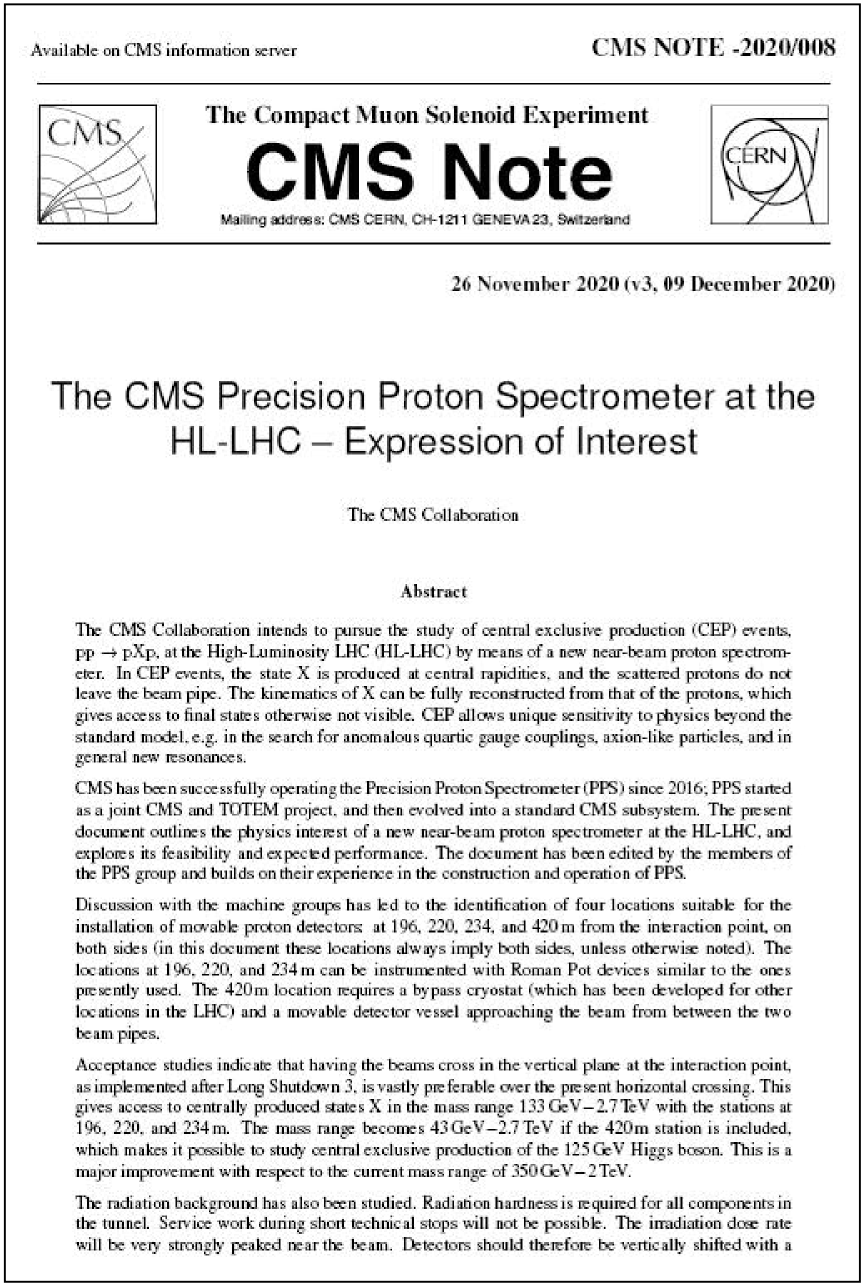
The CMS Precision Proton Spectrometer Project for the HL-LHC

Low-x Workshop
La Biodola, Isola d’Elba

30 September 2021

Mario Deile (CERN)
on behalf of
The CMS Collaboration

Expression of Interest for a PPS Spectrometer at HL-LHC



Available on CMS information server

CMS NOTE -2020/008

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2020 (v3, 09 December 2020)

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

The CMS Collaboration

Abstract

The CMS Collaboration intends to pursue the study of central exclusive production (CEP) events, pp → pXp, at the High-Luminosity LHC (HL-LHC) by means of a new near-beam proton spectrometer. In CEP events, the state X is produced at central rapidities, and the scattered protons do not leave the beam pipe. The kinematics of X can be fully reconstructed from that of the protons, which gives access to final states otherwise not visible. CEP allows unique sensitivity to physics beyond the standard model, e.g. in the search for anomalous quartic gauge couplings, axion-like particles, and in general new resonances.

CMS has been successfully operating the Precision Proton Spectrometer (PPS) since 2016; PPS started as a joint CMS and TOTEM project, and then evolved into a standard CMS subsystem. The present document outlines the physics interest of a new near-beam proton spectrometer at the HL-LHC, and explores its feasibility and expected performance. The document has been edited by the members of the PPS group and builds on their experience in the construction and operation of PPS.

Discussion with the machine groups has led to the identification of four locations suitable for the installation of movable proton detectors at 196, 220, 234, and 420 m from the interaction point, on both sides (in this document these locations always imply both sides, unless otherwise noted). The locations at 196, 220, and 234 m can be instrumented with Roman Pot devices similar to the ones presently used. The 420 m location requires a bypass cryostat (which has been developed for other locations in the LHC) and a movable detector vessel approaching the beam from between the two beam pipes.

Acceptance studies indicate that having the beams cross in the vertical plane at the interaction point, as implemented after Long Shutdown 3, is vastly preferable over the present horizontal crossing. This gives access to centrally produced states X in the mass range 133 GeV – 2.7 TeV with the stations at 196, 220, and 234 m. The mass range becomes 43 GeV – 2.7 TeV if the 420 m station is included, which makes it possible to study central exclusive production of the 125 GeV Higgs boson. This is a major improvement with respect to the current mass range of 350 GeV – 2 TeV.

The radiation background has also been studied. Radiation hardness is required for all components in the tunnel. Service work during short technical stops will not be possible. The irradiation dose rate will be very strongly peaked near the beam. Detectors should therefore be vertically shifted with a

Since 2018:

- HL-LHC Studies based on present-day PPS experience
- regular interactions with machine integration and optics teams.
- presentations to HL-LHC coordination group

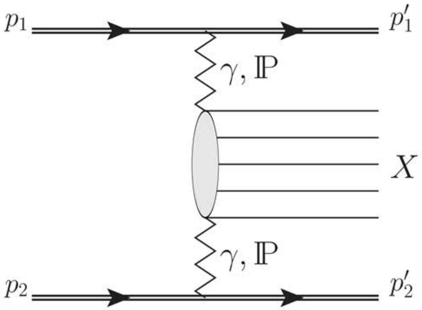
2020:

- September: presentation in the LHCC focus session on CMS PPS / Forward Physics at HL-LHC
- December: publication as CMS NOTE-2020/008, available on CDS and arXiv:

https://cds.cern.ch/record/2750358

http://arxiv.org/abs/2103.02752

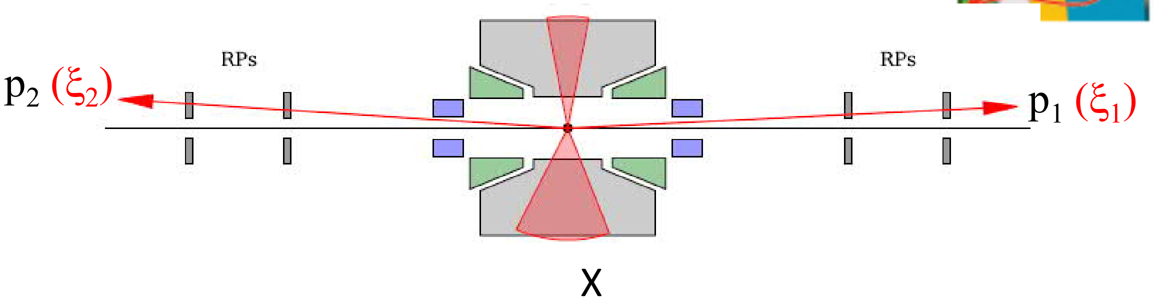
Central Exclusive Production (Reminder)



($\xi_1 = \Delta p_1 / p$)

(mass M)

($\xi_2 = \Delta p_2 / p$)



Measurable kinematic variables of the leading protons:

- **Fractional momentum losses (ξ_1, ξ_2) via proton tracking**

  → Reconstruction of mass and rapidity of central system

$$\boxed{M_X^2 = \xi_1 \, \xi_2 \, s} \qquad \boxed{y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}}$$

- **Transverse momenta ($p_{T,1}$, $p_{T,2}$) via proton tracking**

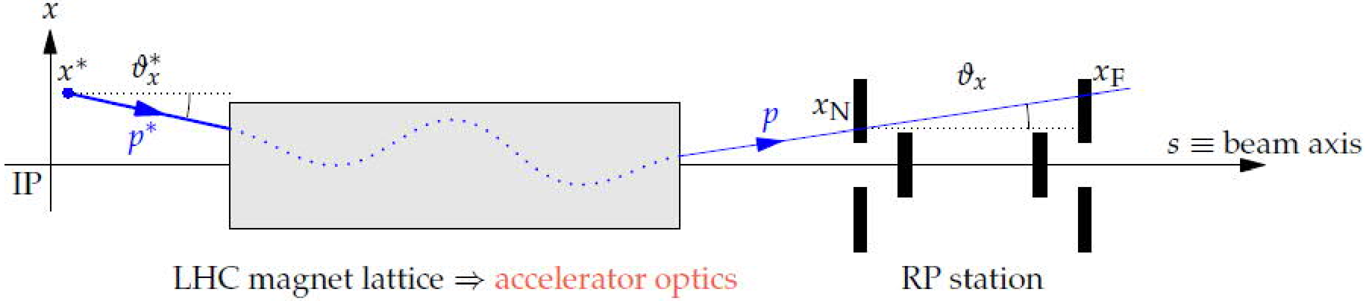
→ momentum balance with central system useful for event selection:

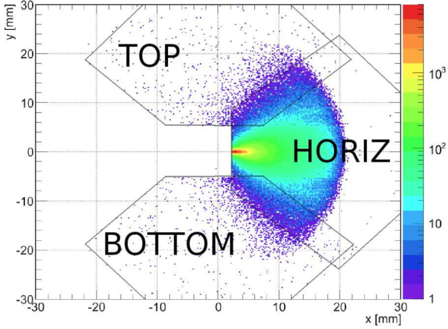
$$\mathbf{p_{T,X} + p_{T,1} + p_{T,2} = 0}$$

- **Longitudinal vertex position via proton time of flight (ToF)**

→ important for resolving pileup (up to μ = 200 at the HL-LHC)

Proton Measurements in Space and Time



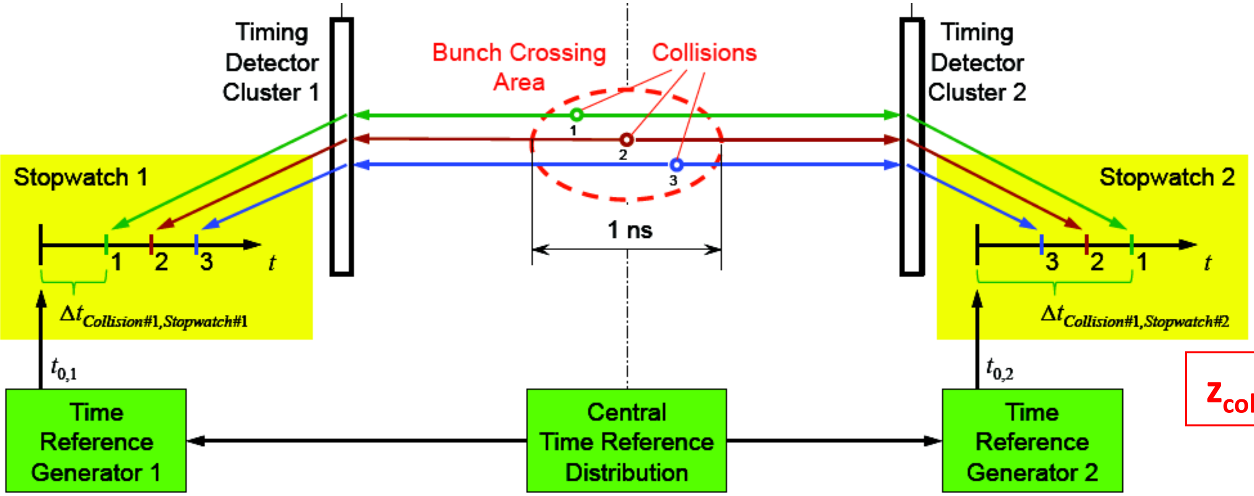


Proton kinematics in RP

$$\begin{pmatrix} x\\ \Theta_x\\ y\\ \Theta_y\\ \Delta p/p\end{pmatrix}_{\mathbf{RP}} = \underbrace{\begin{pmatrix} v_x & L_x & 0 & 0 & D_x\\ v'_x & L'_x & 0 & 0 & D'_x\\ 0 & 0 & v_y & L_y & 0\\ 0 & 0 & v'_y & L'_y & 0\\ 0 & 0 & 0 & 0 & 1\end{pmatrix}}_{\text{Product of all lattice element matrices}} \begin{pmatrix} x^*\\ \Theta^*_x\\ y^*\\ \Theta^*_y\\ \Delta p/p\end{pmatrix}_{\mathbf{IP5}}$$

Values at IP5 to be reconstructed

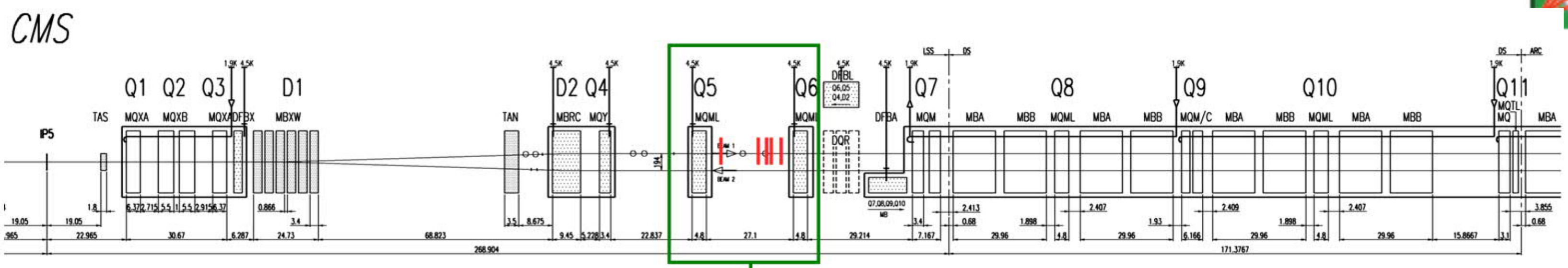
Longitudinal Vertex Position Measurement via Time-of-Flight Difference



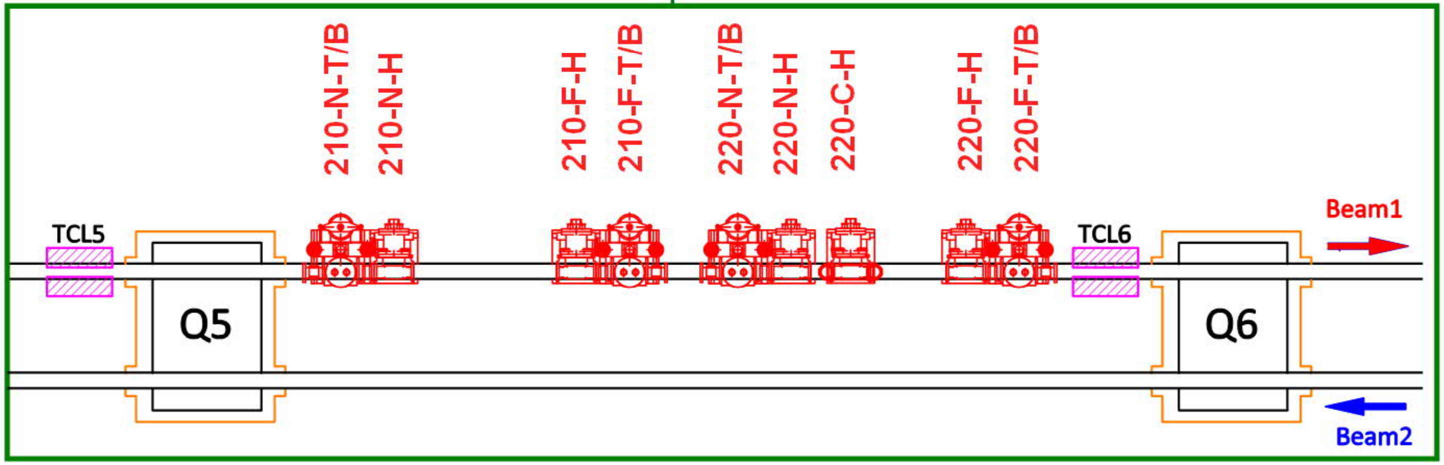
$\mu \leq 200$!

$$z_{\mathrm{collision}} = \tfrac{1}{2}\,(t_{\mathrm{stopwatch\ 2}} - t_{\mathrm{stopwatch\ 1}})$$

Experience in Proton Tagging: The Run 2+3 PPS Apparatus



Roman Pots (movable detector vessels)



+ mirror-symmetric subsystem on the left side of IP5

- PPS created after LS1 (initially “CT-PPS”) merging TOTEM and CMS expertise: TDR in 2014
- tracking detectors: initially TOTEM edgeless silicon strip sensors, later 3D pixel sensors
- timing detectors: UFSD (briefly), diamond sensors

→ Collection of > 100 fb^{-1} by LS2, hope for a total of ~ 300 fb^{-1} by LS3

HL-LHC: 300 fb^{-1} per year (total for Runs 4 + 5 + 6: ~ 3000 fb^{-1})

Search for Detector Locations (1)

LS3: Long Straight Section in IR5 to be redesigned, all present Roman Pots removed

→ **new spectrometer to be built**

Objective from physics programme:

Maximise mass acceptance for centrally produced states measured via leading protons.

Minimum mass: $M_{min} = |\xi|_{min} \sqrt{s}$,

$$\xi \equiv \frac{\Delta p_{\mathrm{proton}}}{p_{\mathrm{proton}}} = \frac{x_{\mathrm{track}}}{D_x}$$

← track displacement from beam @ detector

← dispersion @ detector

$$M_{\min} = \frac{d_{\min}}{D_x}\sqrt{s}$$

Closest approach of detector to beam: $d_{min} = (n_{TCT} + 3)\,\sigma_x + 0.3$ mm (collimation hierarchy)

→ look for locations with small $\frac{\sigma_x}{D_x}$ (σ_x = beam width)

Maximum mass: $M_{max} = |\xi|_{max} \sqrt{s}$:

determined by the tightest aperture limitation (usually a TCL debris collimator):

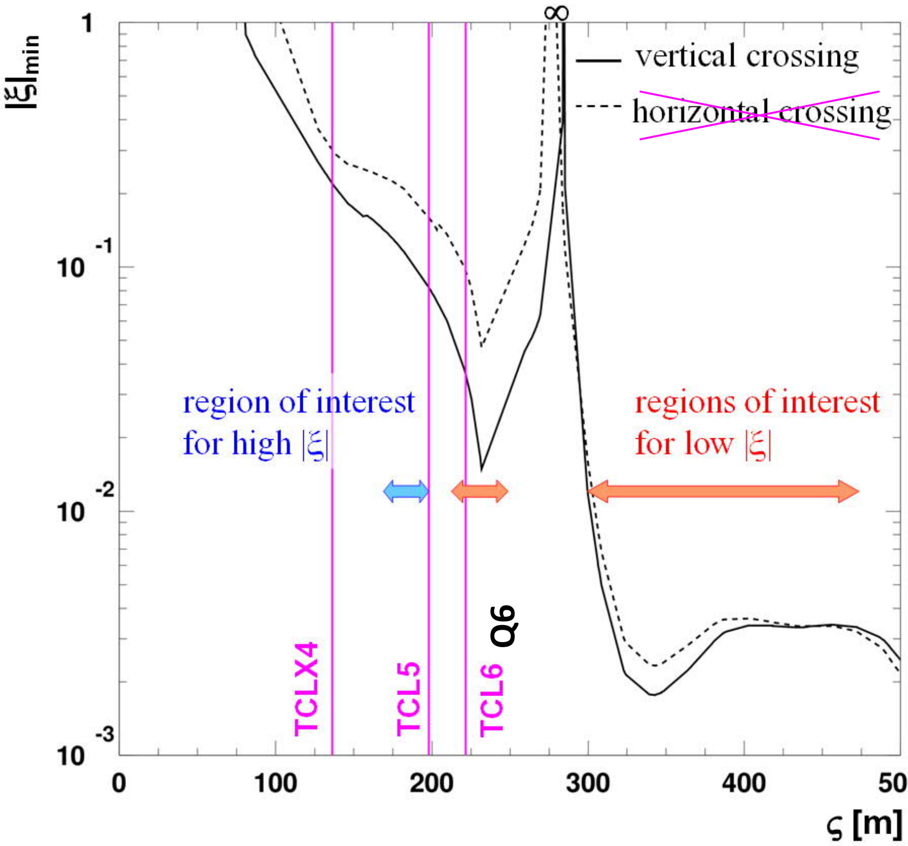
$$M_{\max} = \frac{d_{\mathrm{TCL}}}{D_{\mathrm{TCL}}}\sqrt{s}$$

→ look for locations just before TCL collimators

Search for Detector Locations (2)

- HL-LHC optics version 1.3
- for (crossing-angle $\alpha/2$, β^*) = (250 μrad, 15 cm)
- Roman Pots @ (12.9 + 3) σ + 0.3 mm

$$|\xi|_{min} = (15.9\,\sigma_x + 0.3\text{ mm}) / D_x$$



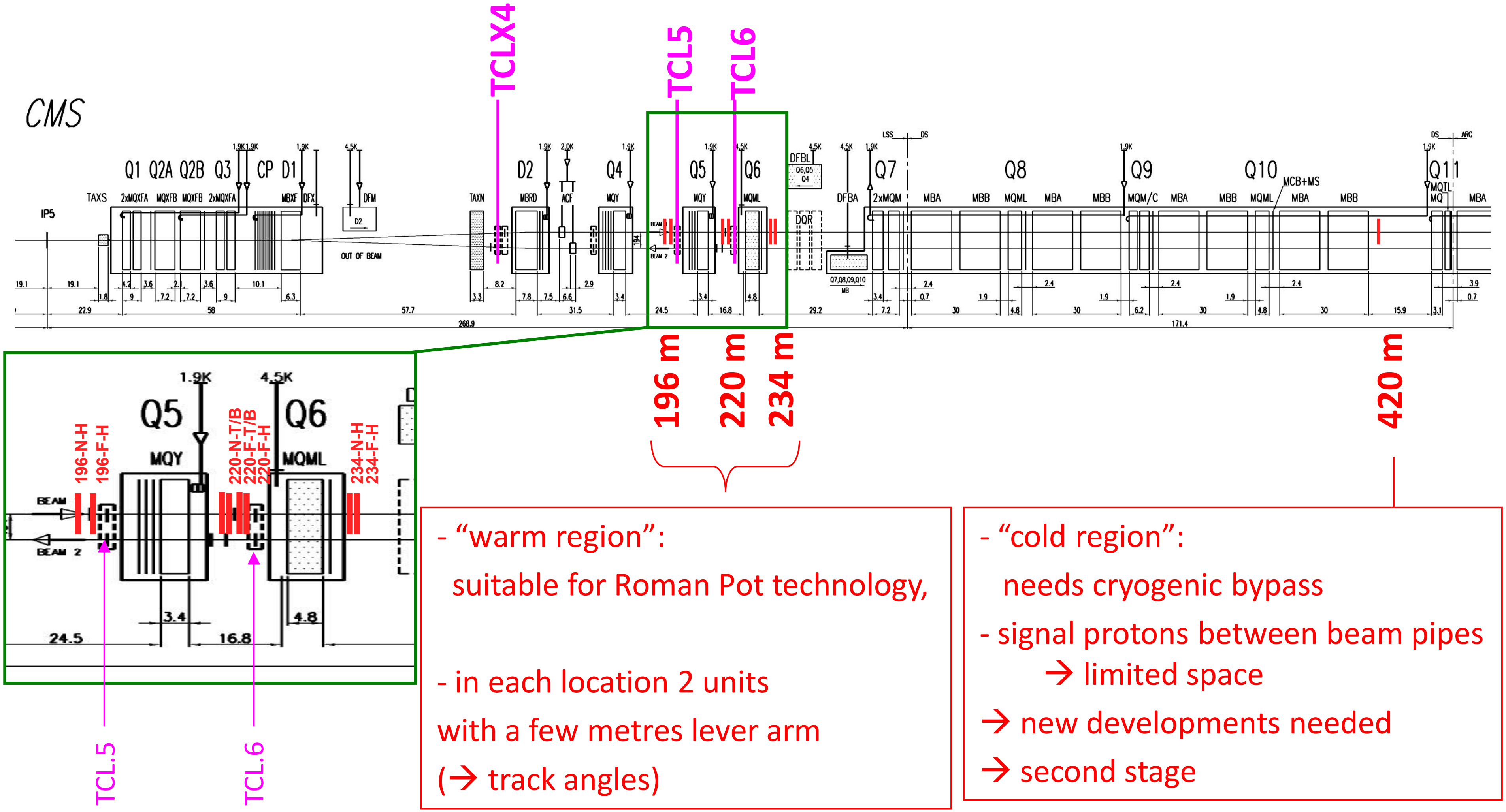
Crossing plane in IP5:
Both orientations (horizontal, vertical) studied and discussed in the EoI
→ strong preference for vertical crossing
→ CMS request in December 2018

June 2020: machine decision for vertical crossing in IP5

→ All figures in this presentation for vertical crossing

Layout Overview with Proposed Stations

Free locations identified in discussions with the LHC layout team:



- “warm region”:

  suitable for Roman Pot technology,

- in each location 2 units

with a few metres lever arm

(→ track angles)

- “cold region”:

  needs cryogenic bypass

- signal protons between beam pipes

  → limited space

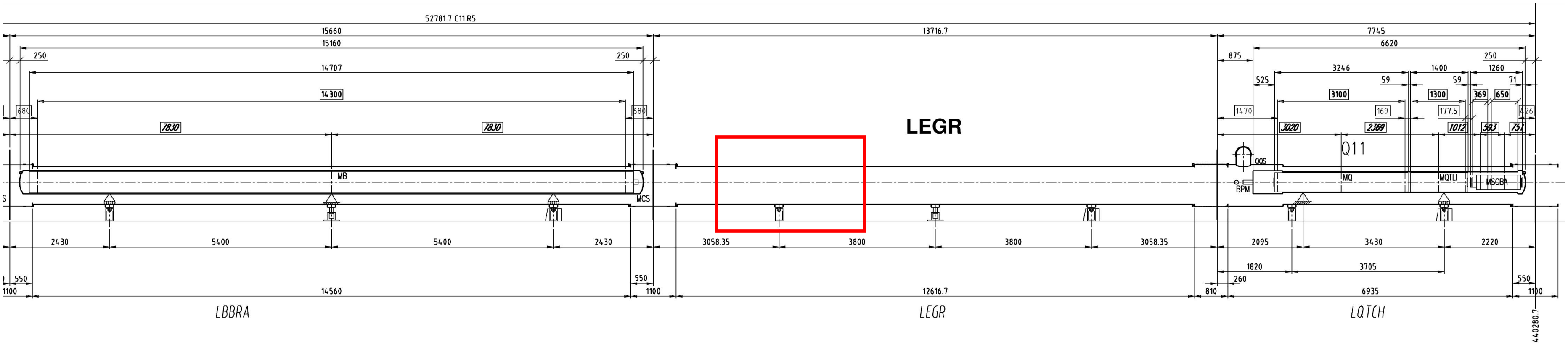
→ new developments needed

→ second stage

Feb. 2020: Tentative space reservations at the 28th HL-LHC Coordination Group Meeting

Dec. 2020: Consolidation of reservation: layout drawings with space holders in preparation

The 420 m Station

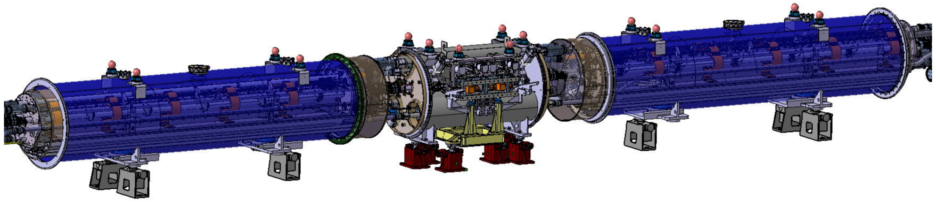


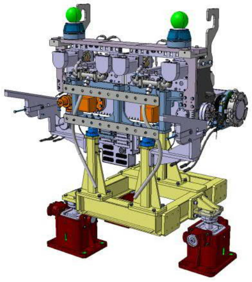
- Region with an empty cryostat (“missing magnet”)
- Signal proton tracks are between the 2 beampipes (positive dispersion)

→ Not suitable for present Roman Pot technology → needs special development

Ideas:

- Reuse connection cryostat from TCLD integration or cryostat designed for the old FP420 project
- Detector vessel options:
  - mini Roman Pot
  - modified TCLD
  - moveable beampipe

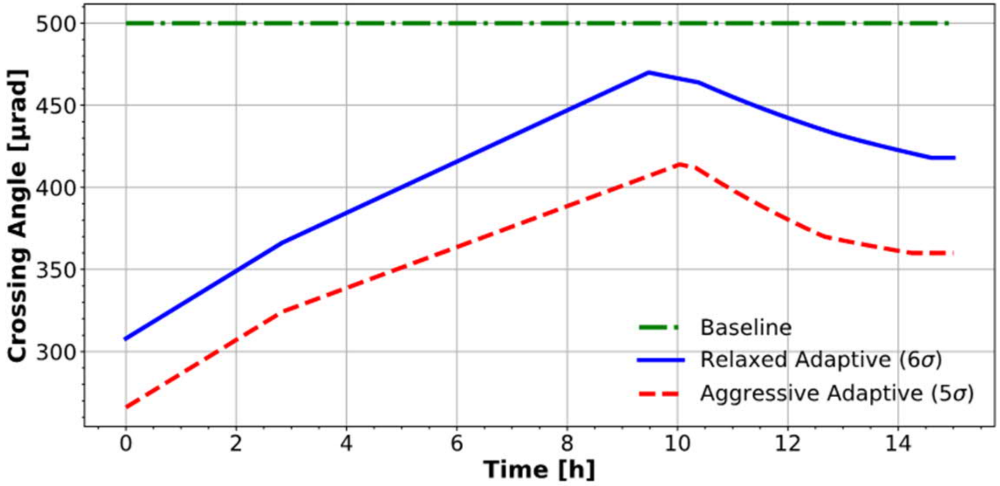




TCLD

Evolution of Acceptance during a Fill

Luminosity levelling: concurrent variation of crossing-angle ($\alpha/2$) and optics (β^*)



Crossing-angle in IP5 can – in principle – be horizontal (Runs 1 – 3) or vertical (HL-LHC)

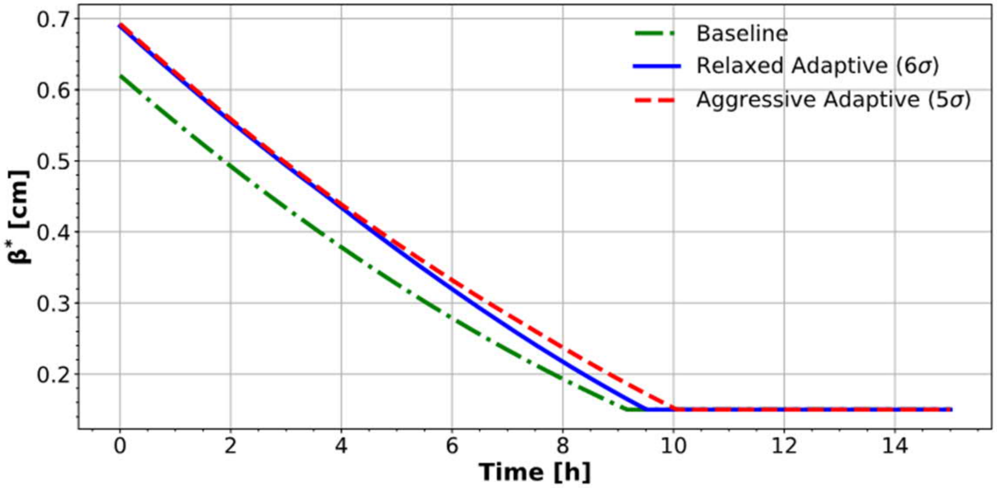
Linear dependence of dispersion on X-angle:

$D_x = D_x(0) - D_x' \; \alpha_x/2$ (X-angle **reduces** D_x !)

$D_y = \qquad D_y' \; \alpha_y/2$

Acceptance depends mainly on D_x, less on D_y:

→ choice of crossing plane very important

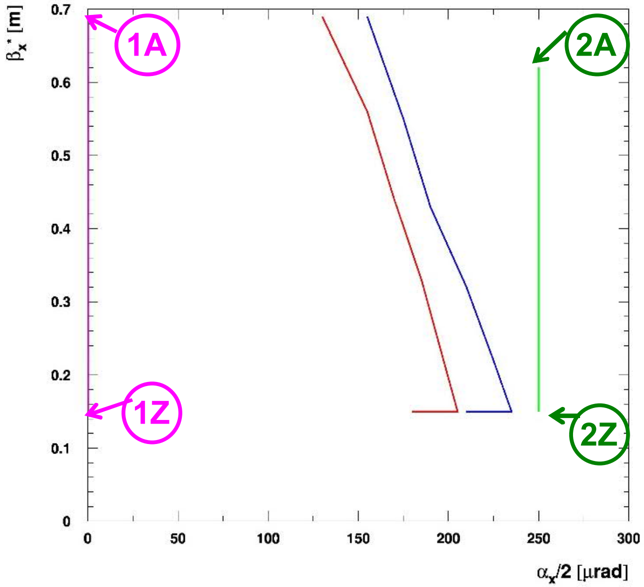


β^* determines beam width,

hence RP distance

All performance parameters to be studied along a "levelling trajectory" in the ($\alpha_x/2$, β^*) plane.

Acceptance in the Mass – Rapidity Plane



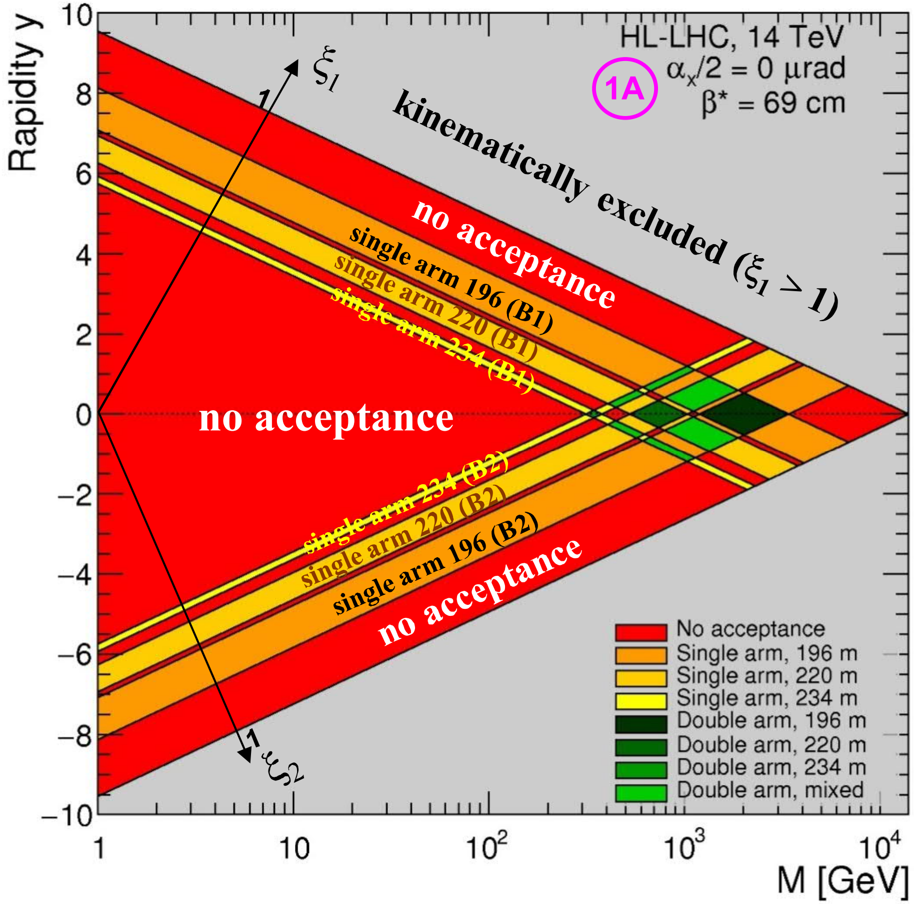
Labels (1A), (1Z), (2A), (2Z)
= start and end points of any vertical
and the simplest horizontal trajectory

For each point ($\alpha_x/2$, β_x^*):

Acceptance for central exclusive events is defined in 2-dim space (ξ_1, ξ_2) or equivalently – after basis rotation – in (M, y):

$$M^2 = \xi_1 \xi_2 s \qquad y = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$

$$\boxed{\ln \frac{M}{\sqrt{s}} = \tfrac{1}{2}(\ln \xi_1 + \ln \xi_2)} \qquad \boxed{y = \tfrac{1}{2}(\ln \xi_1 - \ln \xi_2)}$$



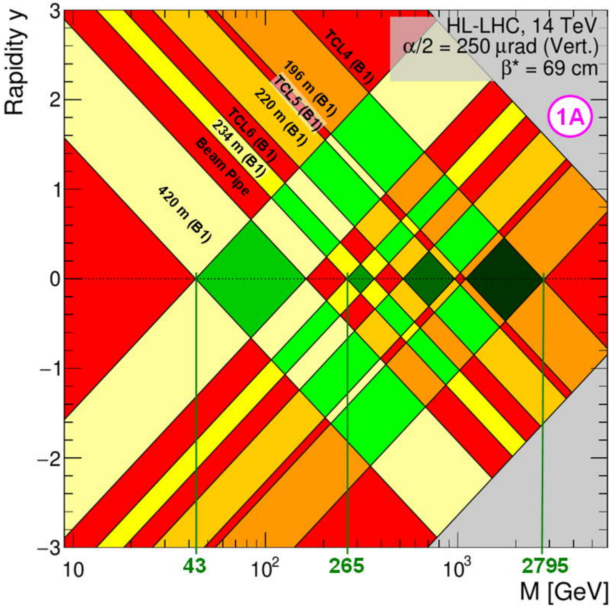
Note on p_T:
The M-y plot is for proton $p_{T,1} = p_{T,2} = 0$
Fixed non-zero p_T would shift the contours.

Acceptance in Mass – Rapidity Plane

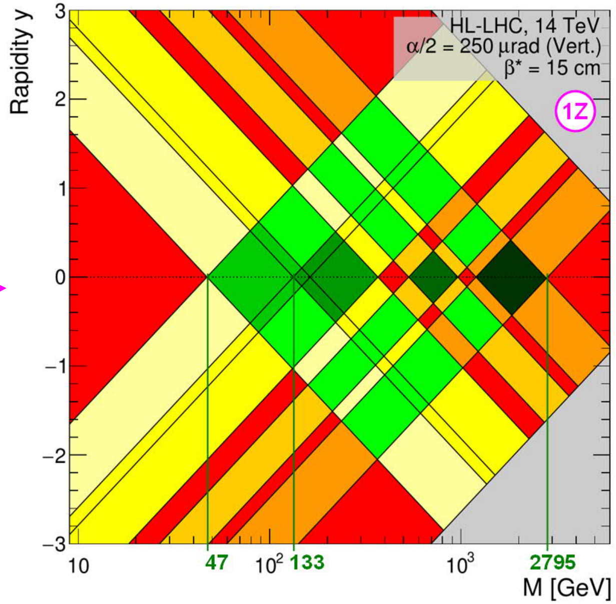
Vertical crossing in IP5

$$\ln\frac{M}{\sqrt{s}} = \tfrac{1}{2}(\ln\xi_1 + \ln\xi_2)$$

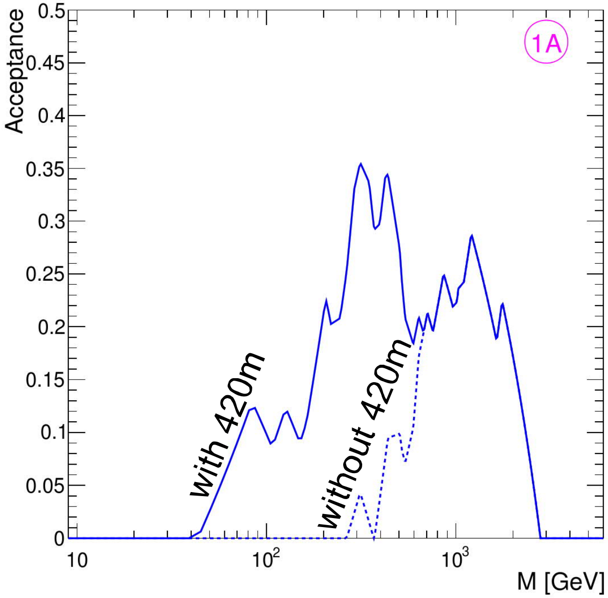
$$y = \tfrac{1}{2}(\ln\xi_1 - \ln\xi_2)$$



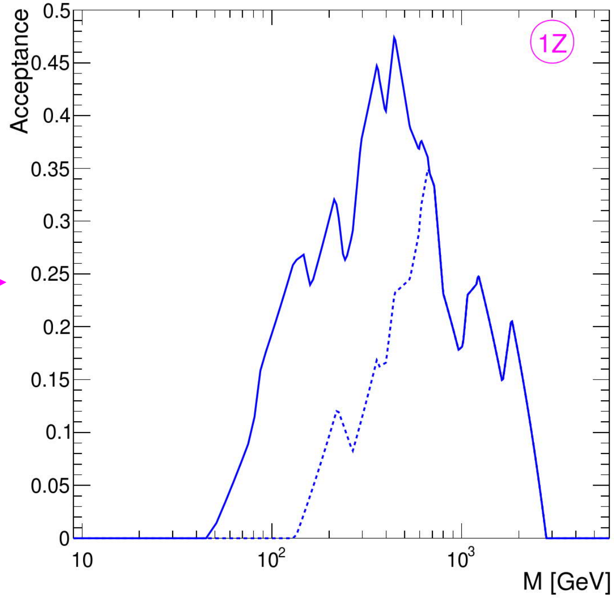
Fill →



Projection on M
assuming flat
y distribution
(in kinematically
allowed region)

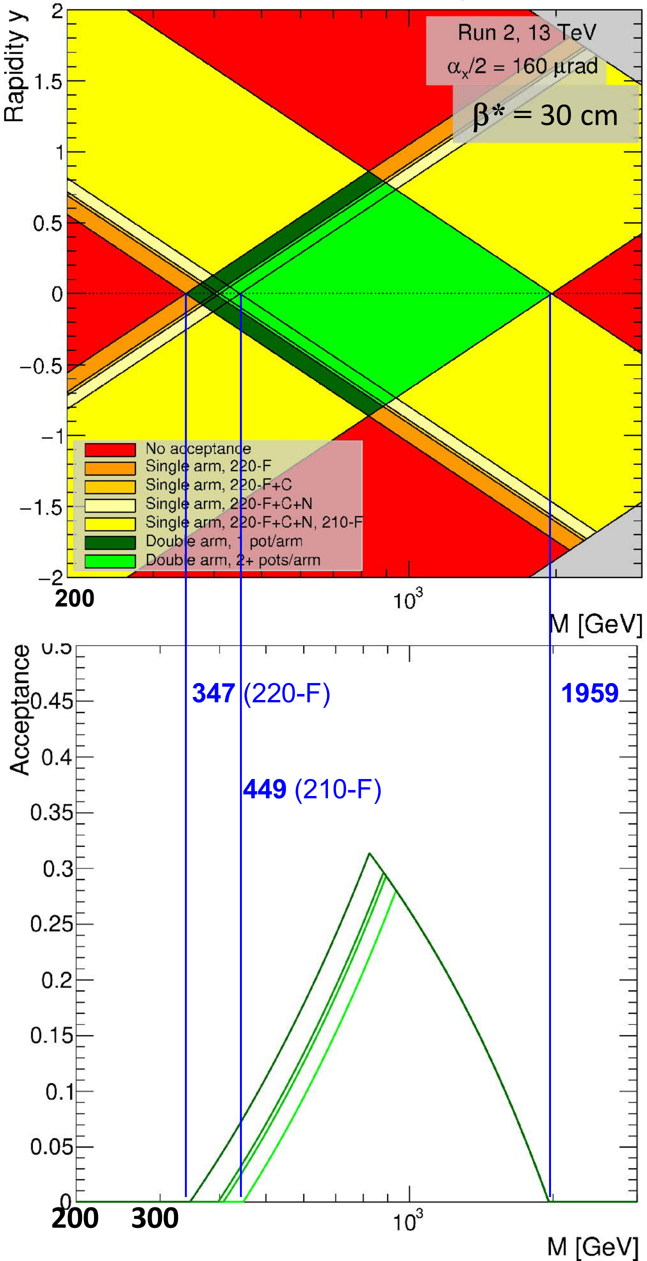


Fill →



Comparison Mass-Rapidity Acceptance Run 2 / HL-LHC

2018 Nominal Optics



HL-LHC (vertical crossing):

without 420 m: 133 GeV – 2.7 TeV
with 420 m: 43 GeV – 2.7 TeV

Physics programme allows
a staged installation (420 m later)

Physics Perspectives

The physics section anticipates:

- integrated lumi: 300 fb^{-1}/year [nominal ÷ ultimate peak: (5 ÷ 7.5) x 10^{34} cm^{-2} s^{-1}]
- pileup multiplicity: nominal ÷ ultimate = 140 ÷ 200
- detector stations at +- 196 m, +-220 m, +-234 m, (+-420 m)
- vertical crossing-angle in IP5

Central exclusive production at different mass scales

0 – few 10 GeV	**45 – few 100 GeV**	**few 100 GeV – 2.7 TeV**
very low mass	**low mass**	**high mass**
(mesonic resonances, glueballs)	(SM: e.g. QCD, Higgs, top, electro-weak, photoprod.)	(BSM searches: Axion-like particles, missing mass, anomalous couplings)
needs special high β^* optics		
→ **not for HL-LHC, not discussed here**	**420 m stations important or even necessary**	**196 m, 220 m, 234 m stations sufficient**

→ staged installation possible

Most recent physics talk: Michael Pitt @ LHC Forward Physics Meeting (March 2021): https://indico.cern.ch/event/955960/

Physics Examples

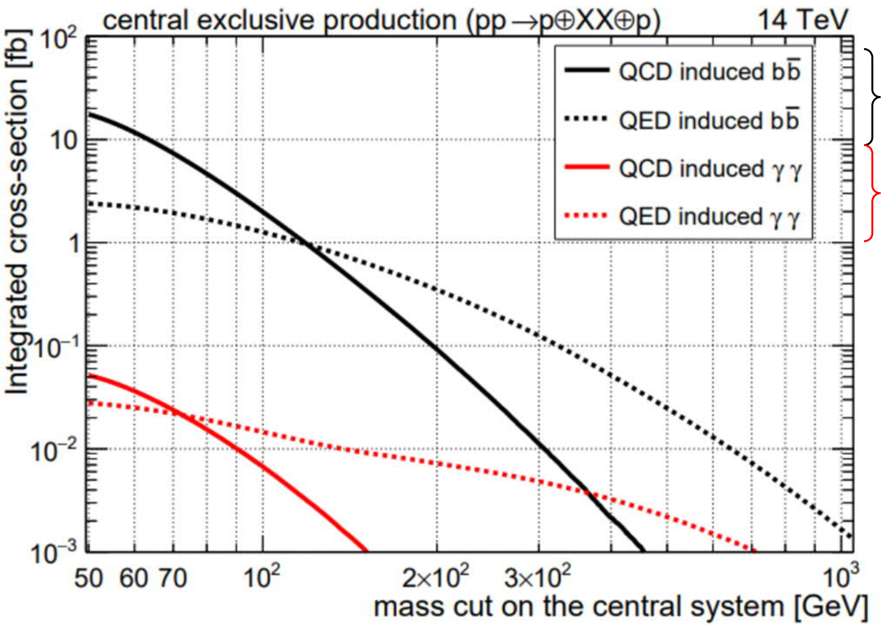
Low masses: QCD dominant

→ study exclusive jj

(screening effects; bb as Higgs backg.)

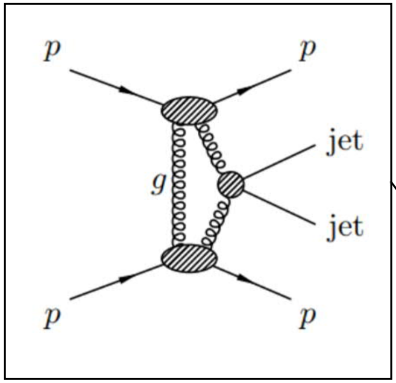
High masses: QED dominant

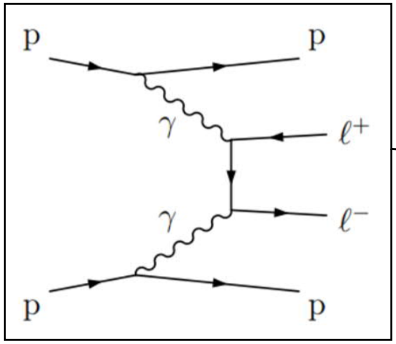
→ study heavy objects, anomalies



FPMC generator

SuperChic_v4 generator





Fiducial cross-sections (2-arm tagged) of CEP SM processes @ √s = 14 TeV with and without the 420 m stations

[FPMC generator, p_T > 20 GeV for all objects generated, survival prob. = 3% (QCD) and 90% (QED)]

Process	fiducial cross section [fb]			
	all stations		w/o 420	
	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

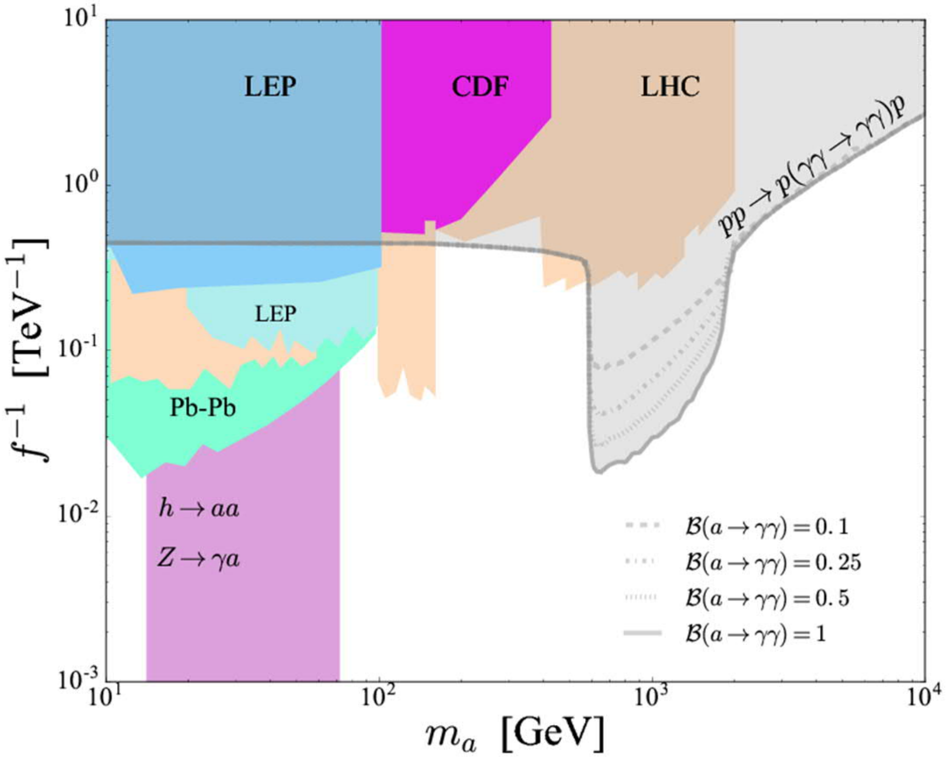
needs 420 m stations

Physics Examples: Direct Searches at High Mass

Search for Axion-Like Particles

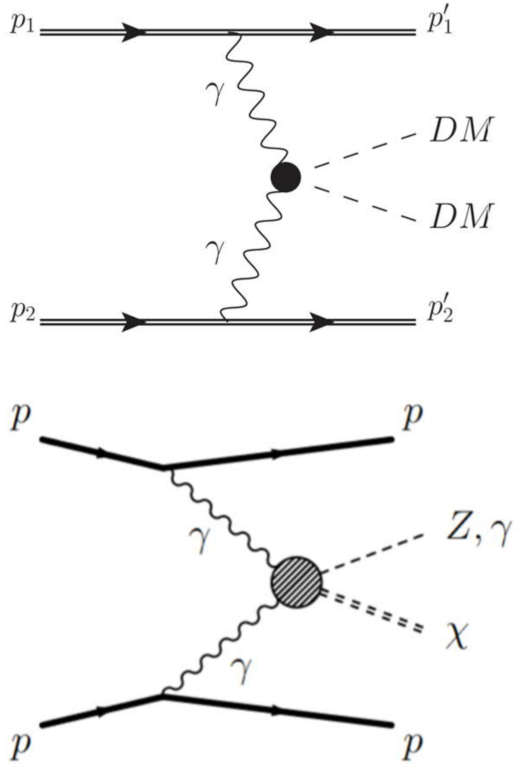
via $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$

95% CL exclusion regions



Light grey shaded: PPS @ LHC for 300 fb^{-1}

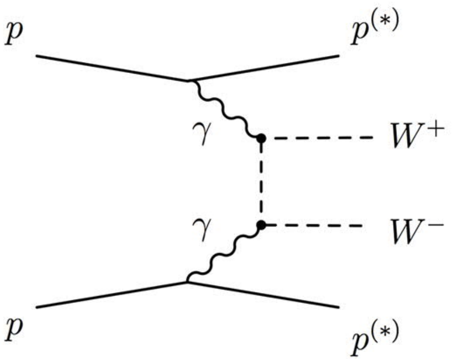
Search for invisible particles ("missing mass")



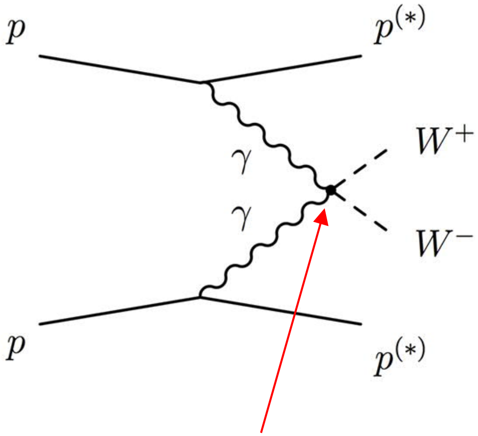
Total central mass measured via protons !

Physics Examples: Anomalous Gauge Couplings ($\gamma\gamma$WW)

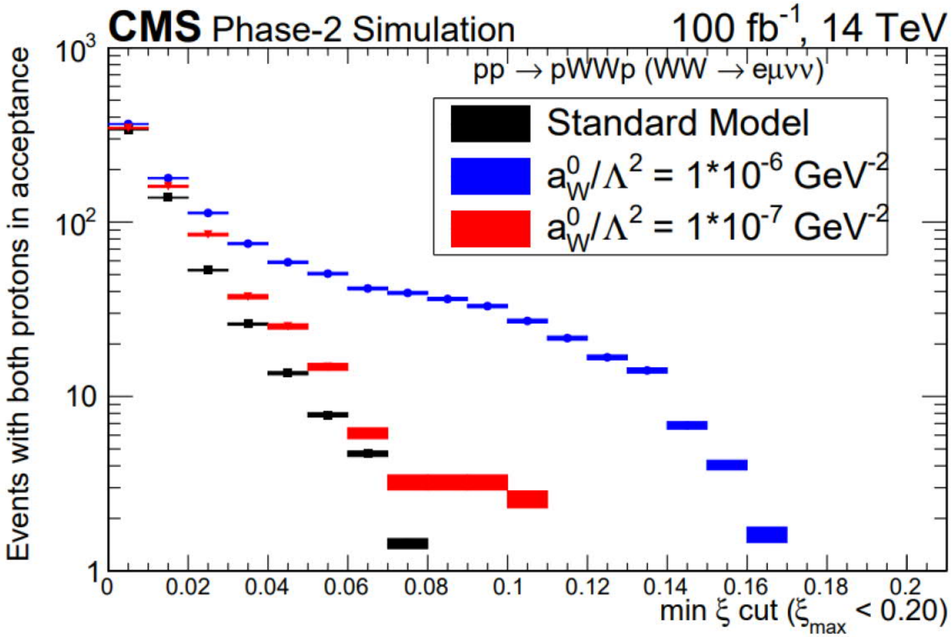
Triple Gauge Couplings



Quartic Gauge Coupling



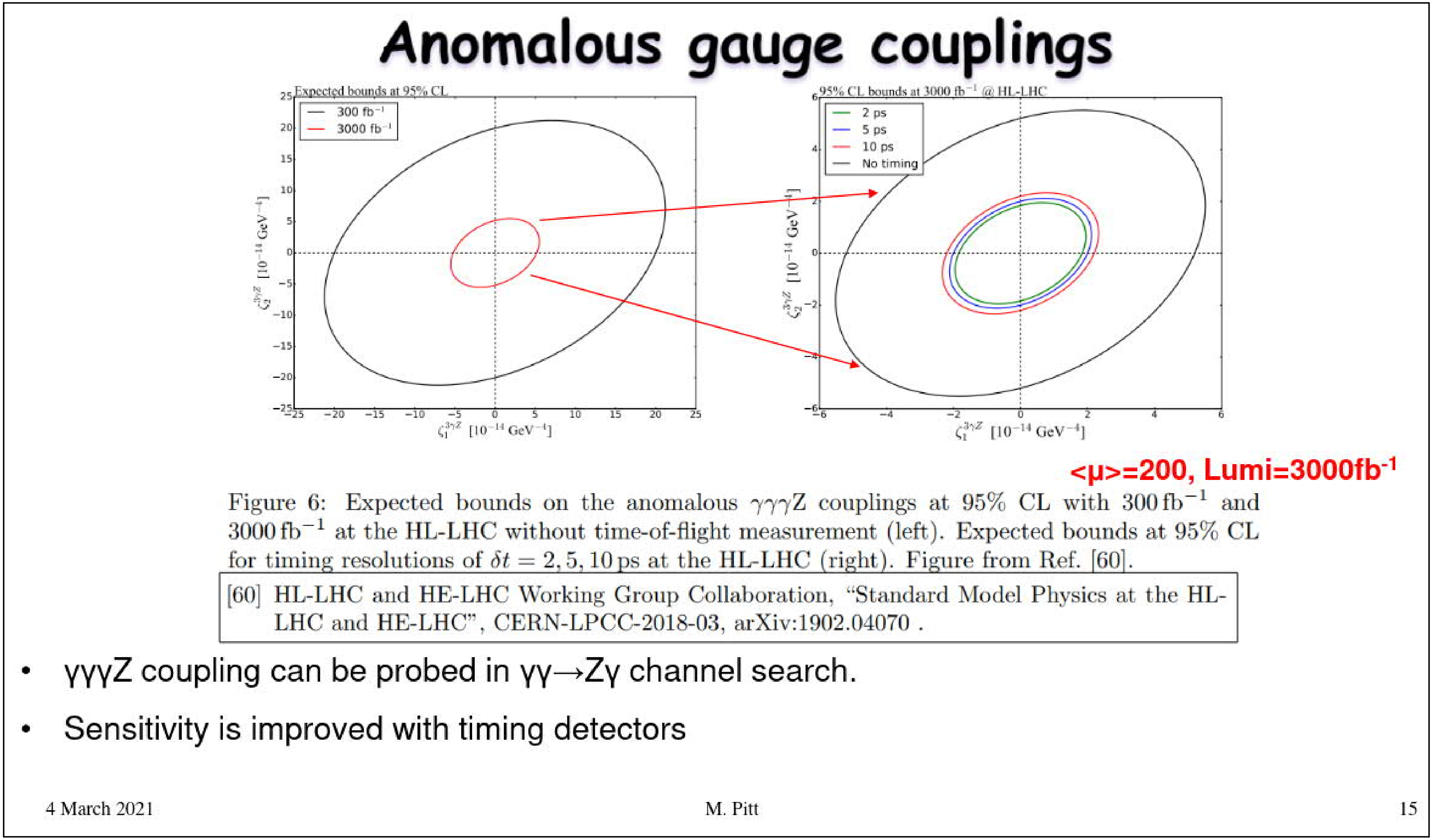
anomalous contributions (AQGC)?



(generator level)

Deviations due to AQGC expected to be visible at high masses

Physics Examples: Anomalous Gauge Couplings (γγγZ)



Anomalous gauge couplings

<μ>=200, Lumi=3000fb^{-1}

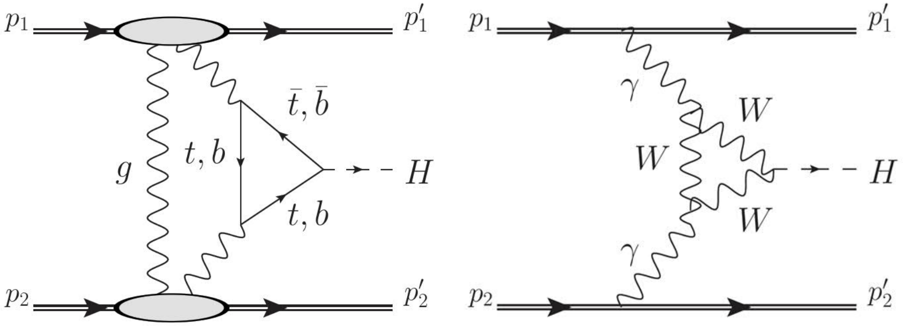
Figure 6: Expected bounds on the anomalous γγγZ couplings at 95% CL with 300 fb^{-1} and 3000 fb^{-1} at the HL-LHC without time-of-flight measurement (left). Expected bounds at 95% CL for timing resolutions of $\delta t = 2, 5, 10$ ps at the HL-LHC (right). Figure from Ref. [60].

[60] HL-LHC and HE-LHC Working Group Collaboration, "Standard Model Physics at the HL-LHC and HE-LHC", CERN-LPCC-2018-03, arXiv:1902.04070 .

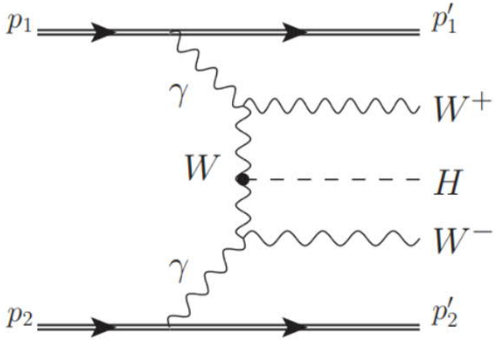
- γγγZ coupling can be probed in γγ→Zγ channel search.
- Sensitivity is improved with timing detectors

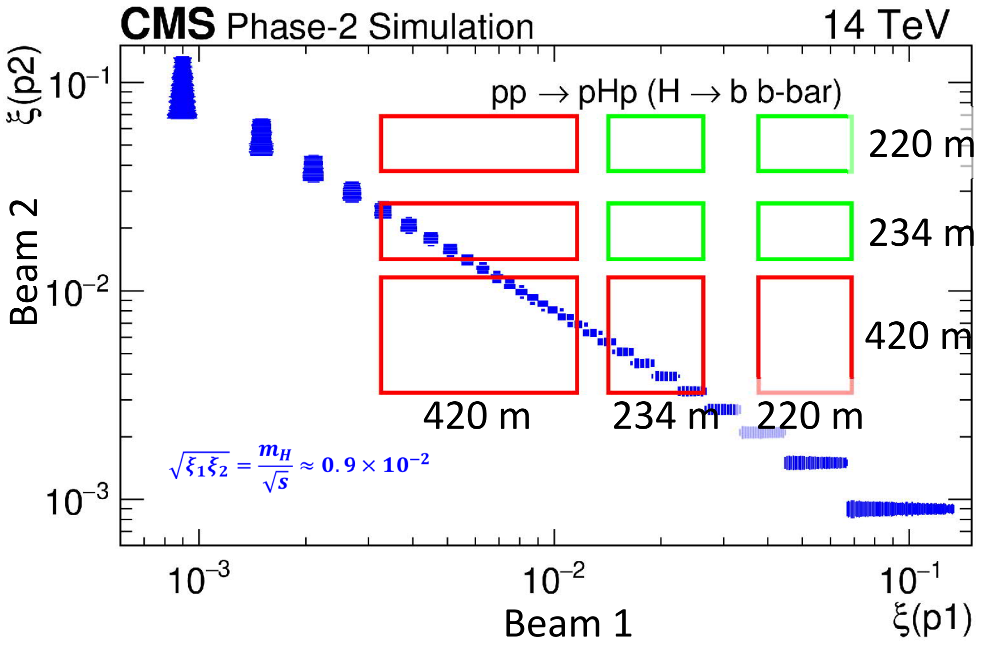
Similar study for γγγγ coupling (light-by-light scattering) by CT-PPS close to journal submission [CMS-PAS-EXO-18-014].

Physics Examples: Higgs Boson

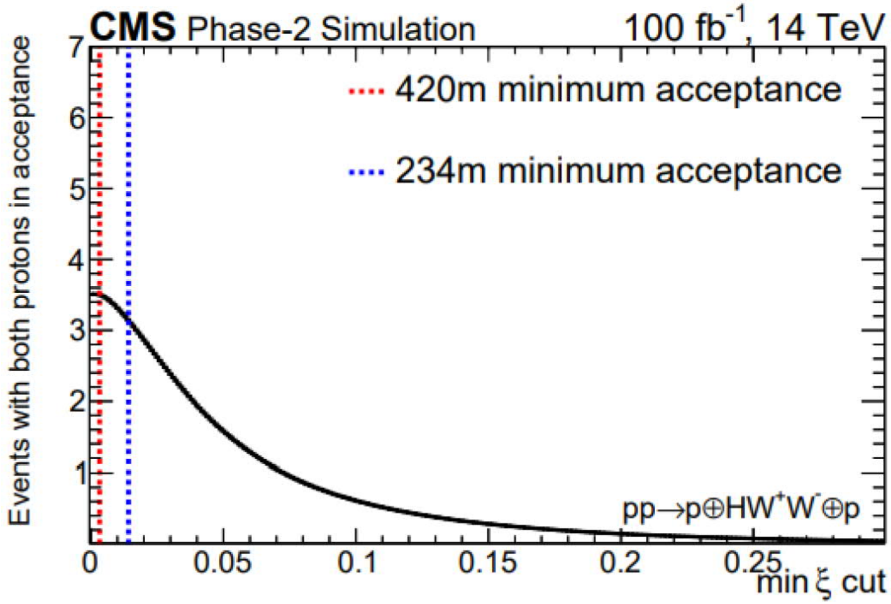


Associated Production





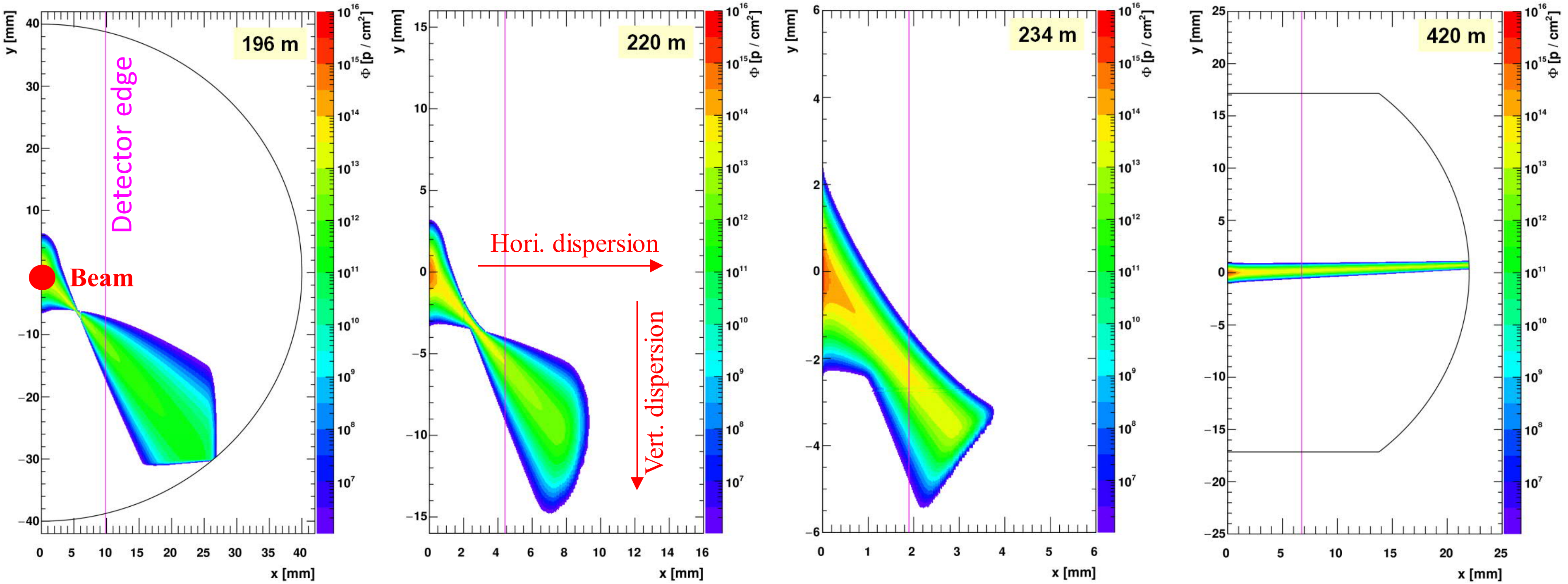
- needs 420 m stations
- 60 events per 100 fb^{-1}
  (all decay channels, no experimental cuts)



- feasible without 420 m stations
  (large total central mass!)
- 3 events per 100 fb^{-1}
  (all decay channels, no experimental cuts)

Detector Requirements:
Fluence Maps in Detector Planes

Calculation for Single Diffractive protons (dominant background)



- strongly peaked irradiation

- **Signal distributions similar:**
  → required sensitive areas much larger than at present
  → needs larger thin window (challenge!) but present pot size is appropriate

- occupancy
  → impact on segmentation

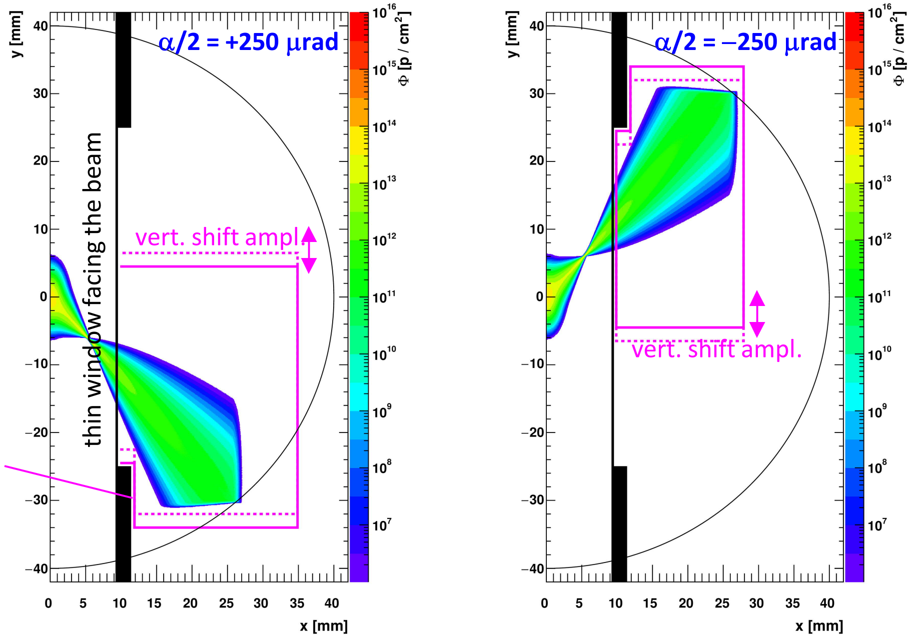
Peak fluence after 1 year

Station	x_{peak} [mm]	y_{peak} [mm]	$\Phi[\text{p/cm}^2]$ $(300\,\text{fb}^{-1})$
196 m	9.9	-11.6	$5.4\ (5.7) \times 10^{14}$
220 m	4.5	-5.7	$2.9\ (3.0) \times 10^{15}$
234 m	2.3	-2.7	$1.4\ (1.3) \times 10^{16}$
420 m	6.8	0.2	$6.0\ (6.0) \times 10^{15}$

Design Considerations

- **Detector Area:**
  - from hit maps
  - extension for vertical shifts to dilute irradiation peak
    (calculated from hit maps and radiation hardness of detectors and electronics)
  - detectors covering one polarity of vertical crossing-angle
    but housings for both polarities to allow for annual X-angle flips
    → replace detectors once a year

196 m station:
Hitmap, beam pipe,
thin window and
detector area:



- **Detector Segmentation:**
  - spatial resolution (most crucial for tracking)
  - occupancy (most crucial for timing):
    - * hit maps: different in the 4 stations
    - * deadtime
    - * acceptable level of proton pileup
  - → different for tracking and timing

Detector Technologies

Ideas based on present-day PPS experience and other CMS developments.

Presently explored:

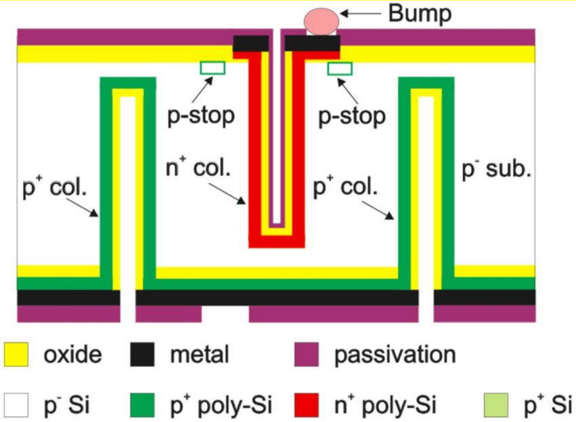
1. **Tracking:**
   3D silicon pixel detectors:
   - used by PPS and CMS tracker in Runs 2 & 3
   - improved HL-LHC developments for CMS tracker (sensors and electronics)

2. **Timing:**
   - Diamond:
     - own developments by TOTEM+PPS, operating in Runs 2 & 3 (very small areas)
     - for equipping larger areas: new electronics developments needed
   - Ultra-Fast Silicon Detectors (UFSD a.k.a LGAD) from CMS MTD-ETL
     (Mip Timing Detector – Endcap Timing Layer)
     - maximal use of synergy with ETL system (sensors & ETROC electronics)
     - some adaptations in segmentation and area needed

No separate pots for tracking and timing

→ combined detector packages (about 10 timing + 6 tracking planes)

3D Pixel Silicon Tracking Detectors



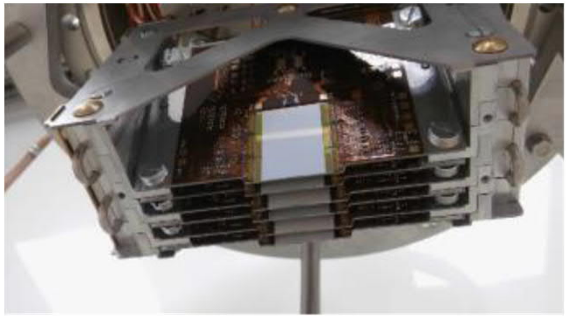
- **Spatial resolution:**

  Present sensors (150 x 100 μm^2 pixels, inclination of 18^o w.r.t. beam): $\sigma_x = 25\ \mu m$
- **"Slim Edge" technology:** 200 μm edge → 50 μm insensitive margin
- **Radiation hardness:**

  - sensors: present generation: 5 x 10^{15} p/cm^2
  future (CMS tracker phase 2): 2 x 10^{16} p/cm^2
  → sufficient

  - electronics chip bonded to sensor: degraded in the irradiation peak, fine elsewhere
  → move detector vertically by 0.5 mm after 20 fb^{-1} to displace the peak
  - Run 2: manually in short technical stops
  - Run 3 and HL-LHC: remotely controlled piezo-electric motors

  At HL-LHC use new pixel readout chips being developed for CMS



- **Possible use for timing:**

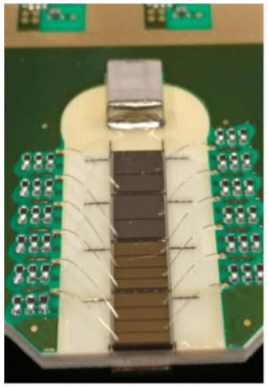
  Recent tests yield time resolutions of 20 – 30 ps

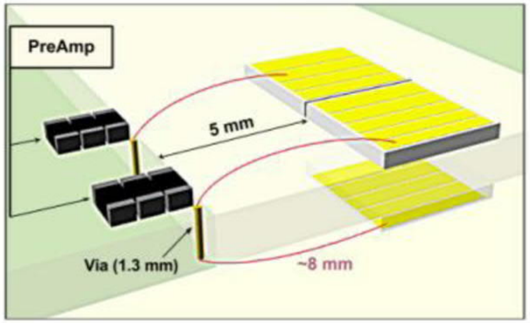
Diamond Timing Detectors

Presently used in PPS: “Double Diamonds” (DD)

(2 layers of scCVD diamond → 1 amplifier)

[single crystal chemical vapour deposited]





Time resolution per DD plane:

ideal conditions (testbeam): **50 ps**

LHC Run 2 (non-perfect readout & biassing): 100 – 150 ps

With present technology: expected achievable time resolution ~ 50 – 60 ps / plane

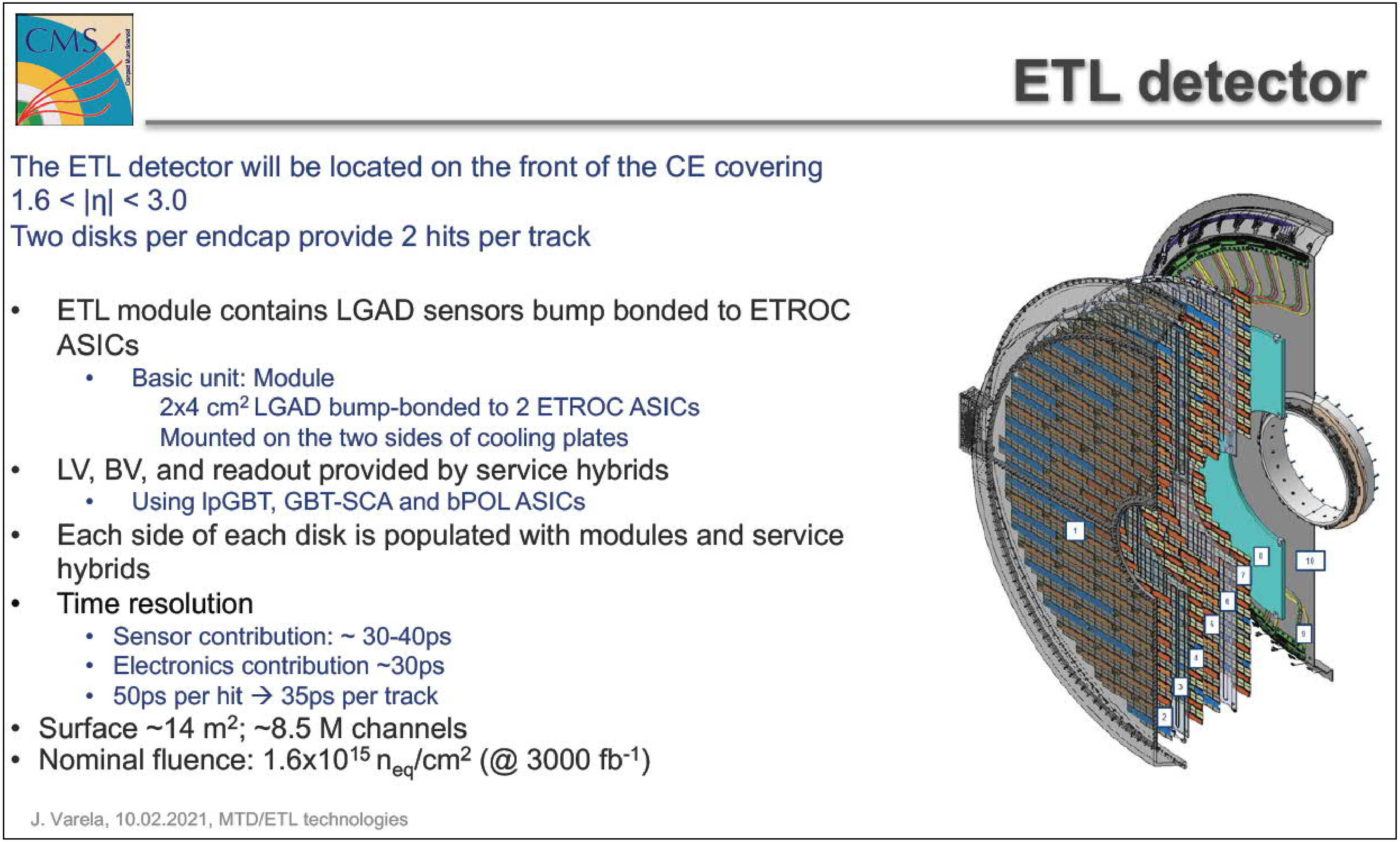
→ with ~ 10 planes per spectrometer arm: **15 – 20 ps / arm**

Radiation hardness:

after 100 fb^{-1} (5 x 10^{15} p/cm^2):

- mainly deterioration of electronics,
- only minor deterioration of the **sensors in the tiny irradiation peak near the beam**

ETL Detector



ETL detector

The ETL detector will be located on the front of the CE covering
$1.6 < |\eta| < 3.0$
Two disks per endcap provide 2 hits per track

- ETL module contains LGAD sensors bump bonded to ETROC ASICs
  - Basic unit: Module
    2x4 cm^2 LGAD bump-bonded to 2 ETROC ASICs
    Mounted on the two sides of cooling plates
- LV, BV, and readout provided by service hybrids
  - Using lpGBT, GBT-SCA and bPOL ASICs
- Each side of each disk is populated with modules and service hybrids
- Time resolution
  - Sensor contribution: ~ 30-40ps
  - Electronics contribution ~30ps
  - 50ps per hit → 35ps per track
- Surface ~14 m^2; ~8.5 M channels
- Nominal fluence: $1.6 \times 10^{15}\ n_{eq}/cm^2$ (@ 3000 fb^{-1})

J. Varela, 10.02.2021, MTD/ETL technologies

Conclusions and Outlook

- CMS Expression of Interest for a new PPS spectrometer at HL-LHC:
  extend central production to lower cross-sections and wider mass range

- 4 relevant locations on both sides of IP5 :
  - just before TCL5 (~ 196 m): high masses
  - just before TCL6 (~ 220 m): intermed. masses
  - just after Q6 (~ 234 m): lower masses
  - 420 m: lowest masses

Station	M_{min} [GeV] @ $y = 0$	M_{max} [GeV] @ $y = 0$
196 m	1100.87–1197.80	2754.27
220 m	519.89–533.18	962.70
234 m	264.96–132.80	368.11
420 m	43.38–47.04	162.66

- Detector technologies presently studied:
  - Tracking: 3d silicon pixel detectors
  - Time of Flight (to resolve pileup with multiplicity $\mu \le 200$):
    - Diamond detectors (like present PPS)
    - UFSD (LGAT) from CMS MTD-ETL

- **Next step: TDR(s):**
  First priority: detector vessel (warm stations), machine integration, services
  Staged approach: 420 m station in a second step
  Physics studies ongoing

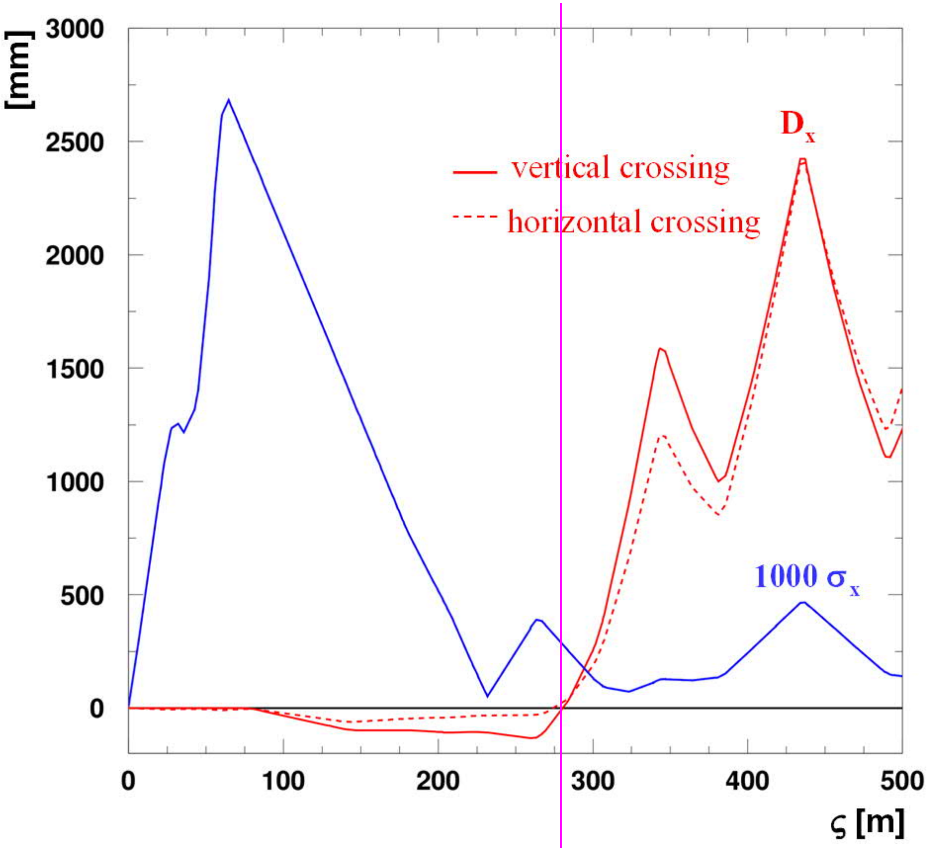
The End.

Appendix

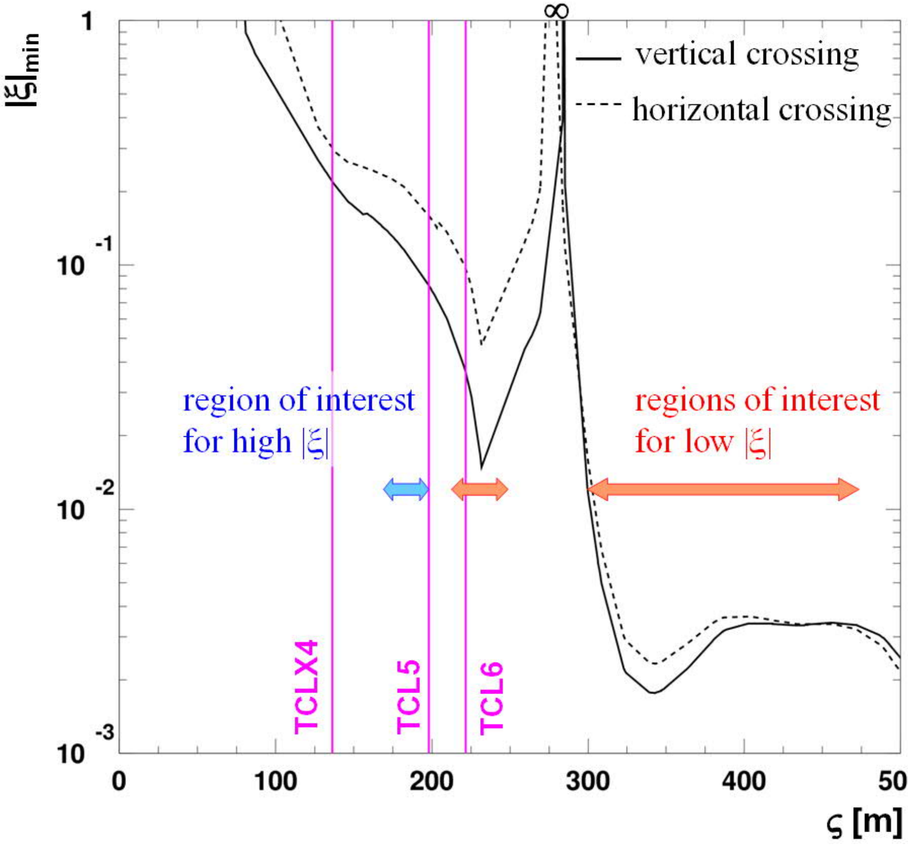
Parameter	Nominal LHC (design report)	HL-LHC (standard)	HL-LHC (BCMS)#
Beam energy in collision [TeV]	7	7	7
Particles per bunch, N [10^{11}]	1.15	2.2	2.2
Number of bunches per beam	2808	2748	2604
Number of collisions in IP1 and IP5*	2808	2736	2592
N_{tot} [10^{14}]	3.2	6.0	5.7
Beam current [A]	0.58	1.09	1.03
Crossing angle in IP1 and IP5 [μrad]	285	510	510
Minimum normalized long-range beam–beam separation [σ]	9.4	12.5	12.5
Minimum β^* [m]	0.55	0.2	0.2
ε_n [μm]	3.75	2.50	2.50
ε_L [eVs]	2.50	2.50	2.50
R.M.S. energy spread [0.0001]	1.13	1.08	1.08
R.M.S. bunch length [cm]	7.55	8.1	8.1
IBS horizontal in collision [h]	80→106	18.8	18.8
IBS longitudinal in collision [h]	61→60	20.6	20.6
Piwinski parameter	0.65	2.5	2.5
Total reduction factor R_0 without crab cavities at min. β^*	0.836	0.369	0.369
Total reduction factor R_1 with crab cavities at min. β^*	(0.981)	0.715	0.715
Beam–beam tune shift/IP	0.0031	0.01	0.01
Peak luminosity without crab cavities L_{peak} [10^{34} cm^{-2} s^{-1}]	1.00	6.52	6.18
Peak luminosity with crab cavities $L_{\mathrm{peak}} \times R_1/R_0$ [10^{34} cm^{-2} s^{-1}]	(1.18)	12.6	11.9
Events/crossing without levelling and without crab cavities	27	172	172
Levelled luminosity for μ =140 [10^{34} cm^{-2} s^{-1}]	-	5.32†	5.02†
Events/crossing μ (with levelling and crab cavities)‡	27	140	140
Maximum line density of pile-up events during fill [events/mm]	0.21	1.3	1.3
Levelling time [h] (assuming no emittance growth)‡	-	5.23	5.23
Number of collisions in IP2/IP8	2808	2452/2524**	2288/2396**
N at injection [10^{11}]††	1.20	2.30	2.30
Maximum number of bunches per injection	288	288	288
N_{tot}/injection [10^{13}]	3.46	6.62	6.62
ε_n at SPS extraction [μm]‡‡	3.50	2.00	<2.00***

Search for Detector Locations (2)

- HL-LHC optics version 1.3
- for (crossing-angle $\alpha/2$, β^*) = (250 μrad, 15 cm)
- Roman Pots @ (12.9 + 3) σ + 0.3 mm



$|\xi|_{min} = (15.9\ \sigma_x + 0.3\ \text{mm}) / D_x$

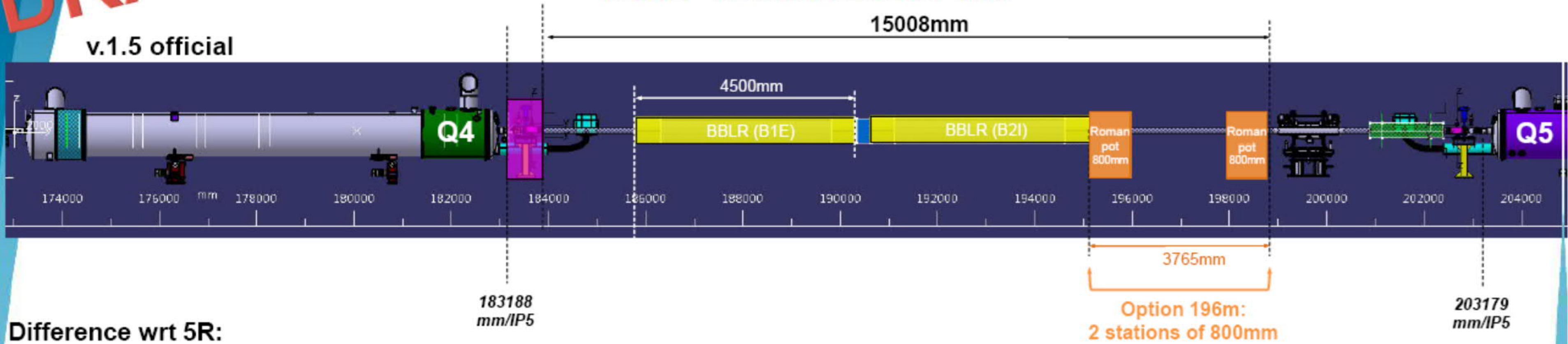


for s > ~270 m : $D_x > 0$
→ protons with momentum loss are between the beam pipes
→ no standard Roman Pot possible → needs new technology
Free only around 420 m.

Region of interest: 180-200m/IP5 → 196m

LSS5R - MACHINE LAYOUT v.1.5

v.1.5 official

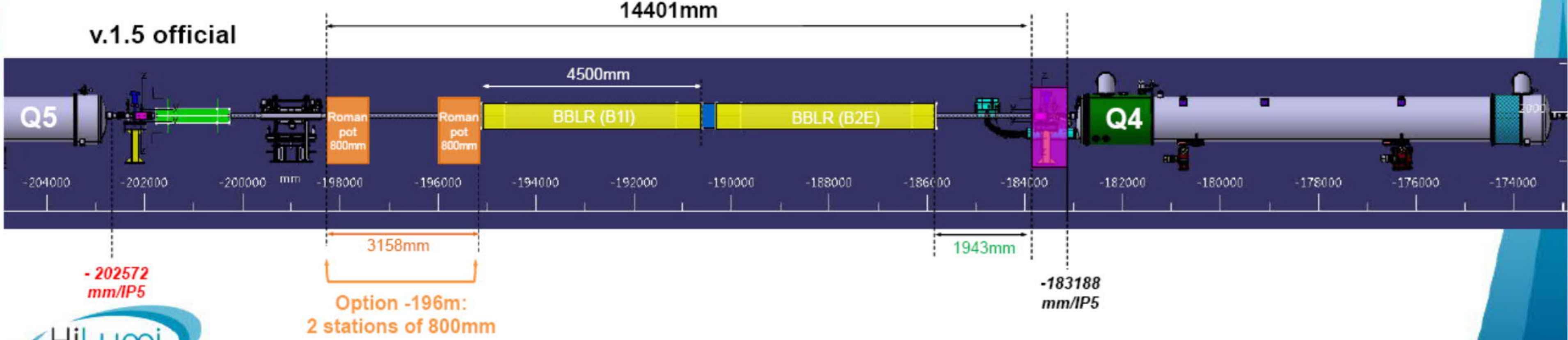


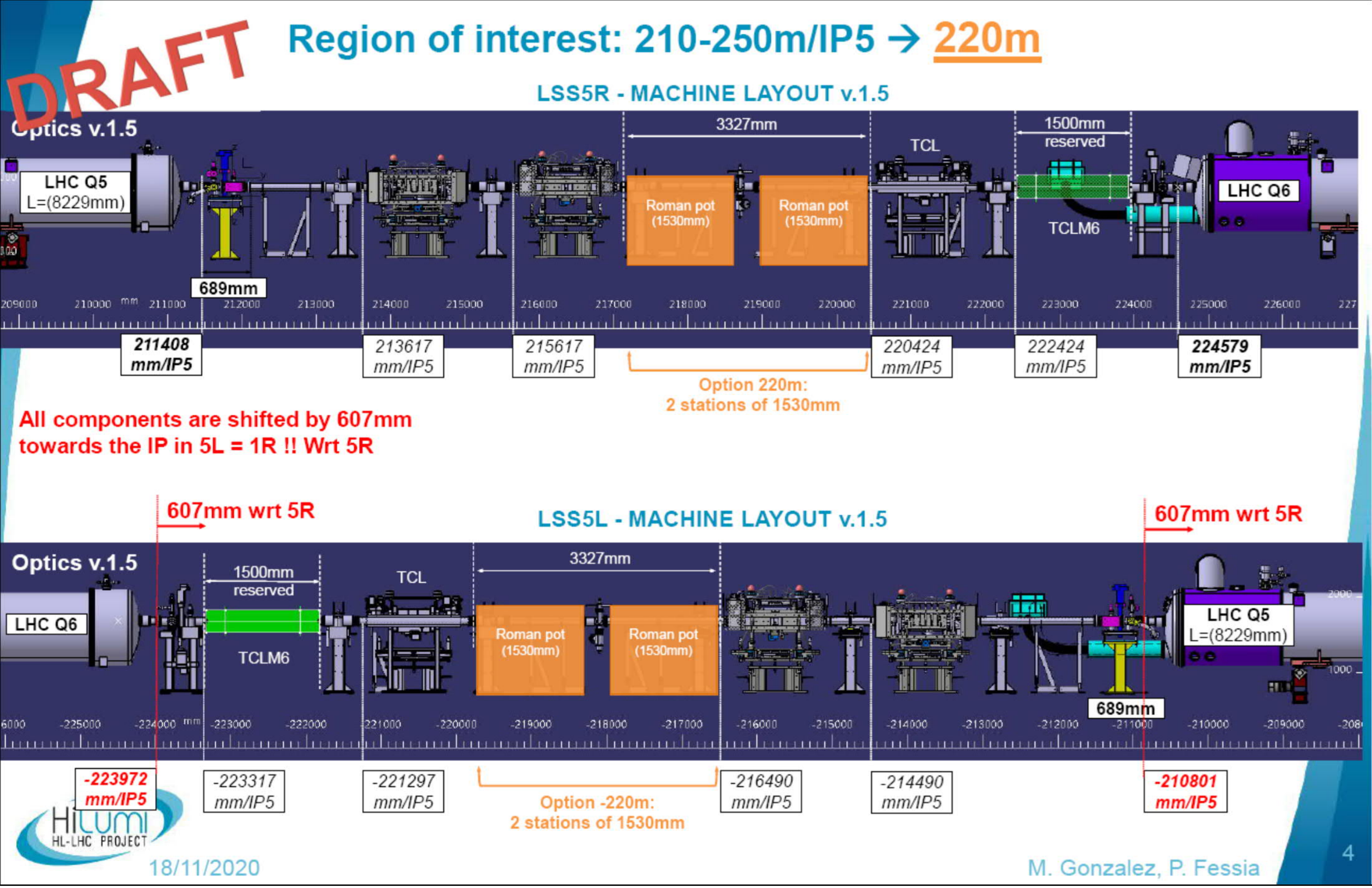
Difference wrt 5R:
203179 - *202572* = 607mm

There is 607mm less space in 5L = 1R !!

LSS5L - MACHINE LAYOUT v.1.5

v.1.5 official





DRAFT

Region of interest: 210-250m/IP5 → 220m

LSS5R - MACHINE LAYOUT v.1.5

Option 220m:
2 stations of 1530mm

All components are shifted by 607mm
towards the IP in 5L = 1R !! Wrt 5R

LSS5L - MACHINE LAYOUT v.1.5

Option -220m:
2 stations of 1530mm

HL-LHC PROJECT

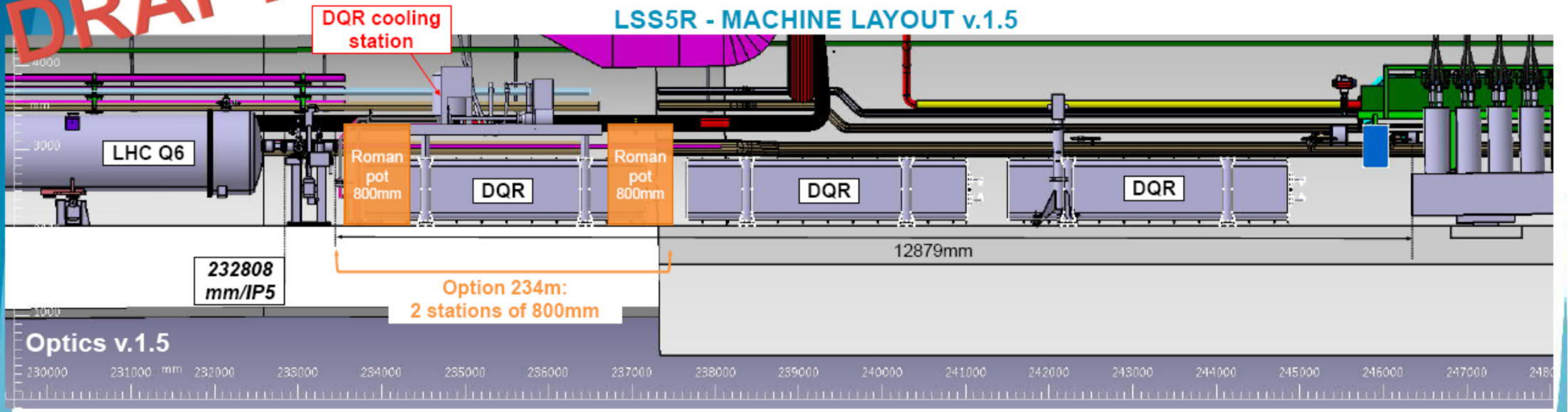
18/11/2020

M. Gonzalez, P. Fessia

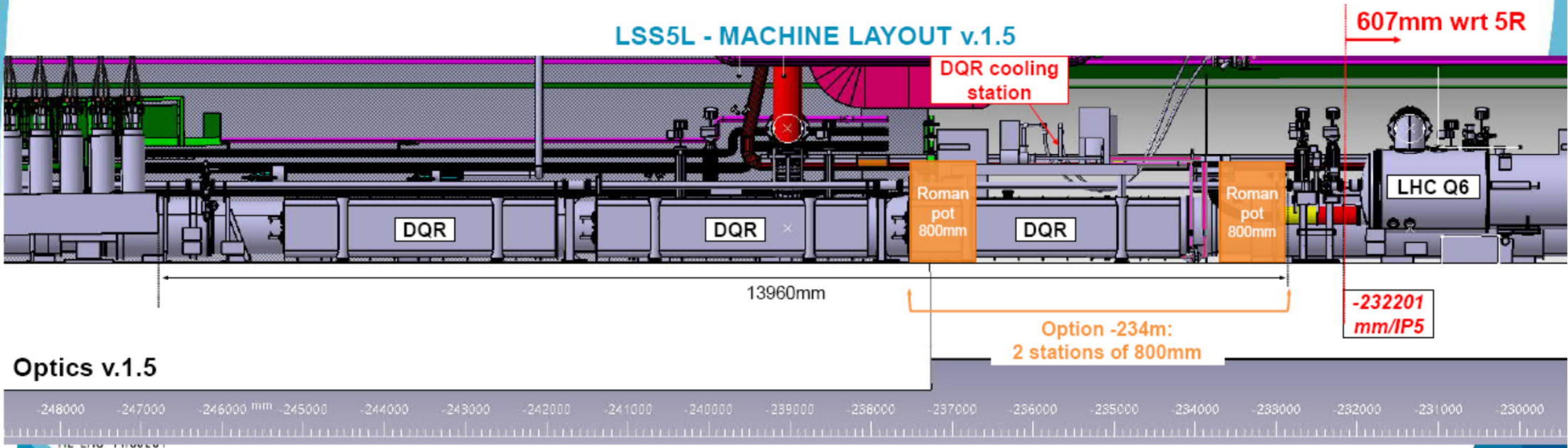
Only in this station: vertical units for alignment and optics calibration

Region of interest: 210-250m/IP5 → 234m

LSS5R - MACHINE LAYOUT v.1.5



LSS5L - MACHINE LAYOUT v.1.5



XRP Insertion Distance vs. β*

Assume insertion rule: $d_{\mathrm{XRP}} = (n_{\mathrm{TCT}} + 3)\sigma_{\mathrm{XRP}} + 0.3\ \mathrm{mm}$

Collimation scheme presently foreseen:

$d_{\mathrm{TCT}} = \mathrm{const.}$ → $n_{\mathrm{TCT}}(\beta^*) = n_{\mathrm{TCT}}(\beta_0^*)\sqrt{\dfrac{\beta^*}{\beta_0^*}}$

$$\sigma_{\mathrm{XRP}} = \sqrt{\frac{\varepsilon_n \beta_{\mathrm{XRP}}}{\gamma}}$$

We need $\beta_{\mathrm{XRP}}(\beta^*)$!

ATS invariance of optical functions: $v_{\mathrm{XRP}} = \sqrt{\dfrac{\beta_{\mathrm{XRP}}(\beta^*)}{\beta^*}}\cos\mu_{\mathrm{XRP}}(\beta^*)$: magnification independent of β^*

$L_{\mathrm{XRP}} = \sqrt{\beta_{\mathrm{XRP}}(\beta^*)\,\beta^*}\,\sin\mu_{\mathrm{XRP}}(\beta^*)$: eff. length independent of β^*

$$\Rightarrow \left\{ \begin{aligned} \tan\mu_{\mathrm{XRP}}(\beta^*) &= \frac{L_{\mathrm{XRP}}}{v_{\mathrm{XRP}}}\frac{1}{\beta^*} \\ \beta_{\mathrm{XRP}}(\beta^*) &= \frac{L_{\mathrm{XRP}} v_{\mathrm{XRP}}}{\sin\mu_{\mathrm{XRP}}(\beta^*)\cos\mu_{\mathrm{XRP}}(\beta^*)} \end{aligned} \right\} \Rightarrow \beta_{\mathrm{XRP}}(\beta^*) = v_{\mathrm{XRP}}^2 \beta^* + \frac{L_{\mathrm{XRP}}^2}{\beta^*}$$

$$\sigma_{\mathrm{XRP}} = \sqrt{\frac{\varepsilon_n}{\gamma}\left(v_{\mathrm{XRP}}^2\beta^* + \frac{L_{\mathrm{XRP}}^2}{\beta^*}\right)}$$

$$\boxed{d_{\mathrm{XRP}} = \left(n_{\mathrm{TCT}}(\beta_0^*)\sqrt{\frac{\beta^*}{\beta_0^*}} + 3\right)\sqrt{\frac{\varepsilon_n}{\gamma}\left(v_{\mathrm{XRP}}^2\beta^* + \frac{L_{\mathrm{XRP}}^2}{\beta^*}\right)} + 0.3\ \mathrm{mm}}$$

Mass Acceptance Calculation

Calculate mass limits: $M_{\min/\max} = \xi_{\min/\max}\sqrt{s}$ in (α/2, β*) plane
(for symmetric optics in Beam 1 / Beam 2 with $\xi_{1\ \min/\max} = \xi_{2\ \min/\max}$)

Cannot simulate every (α/2, β*) point → analytical approach:

gap + insensitive XRP detector margin

$$M_{\min} = \xi_{\min}\sqrt{s} \quad \text{with} \quad \xi_{\min} = \frac{d_{\mathrm{XRP}}(\beta^*) + \overset{\downarrow}{\delta}}{D_{x,\mathrm{XRP}}(\frac{\alpha_x}{2}, \xi_{\min})} \quad \text{resolved for } \xi_{\min}$$

d_{XRP}: detector distance from beam centre:
analytical expression depending on
TCT collimator settings
and optics properties

D_{XRP}: hori. dispersion @ detector location,
parametrisation in (α/2, ξ) from MAD-X

$$M_{\max} = \xi_{\max}\sqrt{s} = \frac{d_{\mathrm{A}}}{D_{\mathrm{A}}(\frac{\alpha}{2}, \xi_{\max})}\sqrt{s}$$

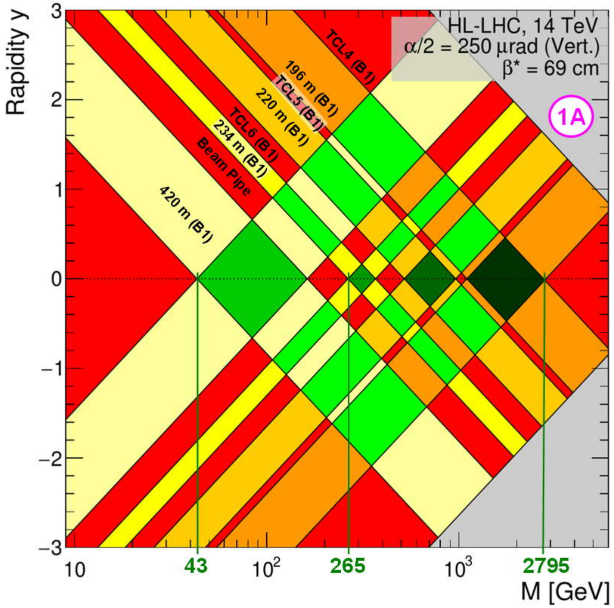
Based on full aperture study

d_{A}: aperture limitation (hori. or vert.) upstream,
in most cases: TCLs

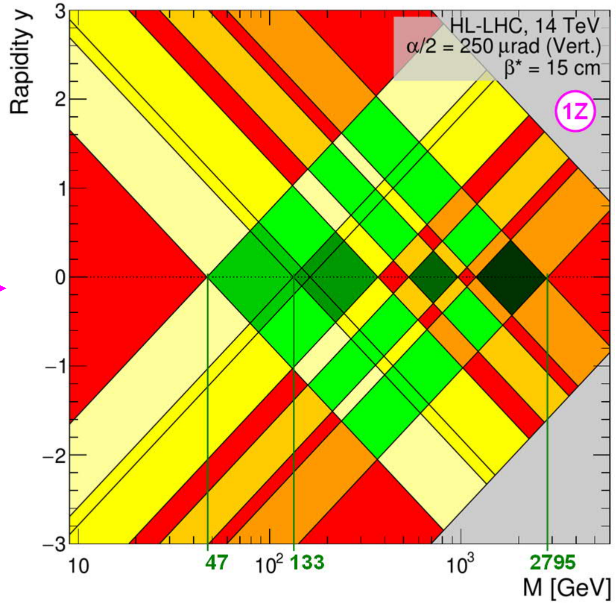
D_{A}: dispersion (hori. or vert.) @ aperture limit.,
parametrisation in (α/2, ξ) from MAD-X

Acceptance in Mass – Rapidity Plane

Vertical crossing in IP5

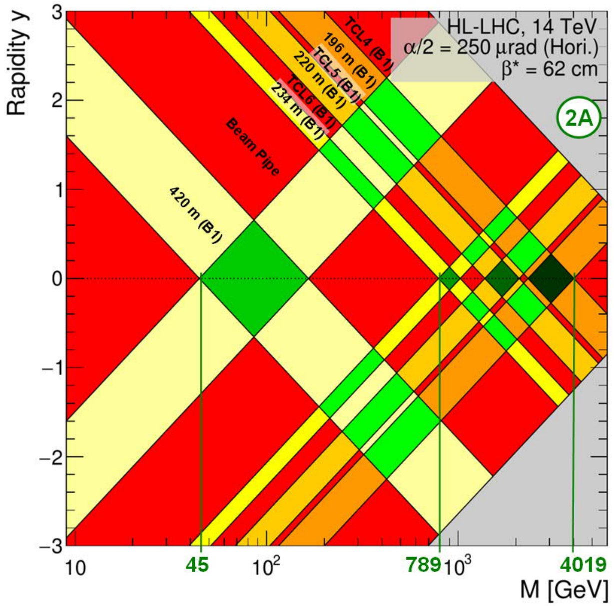


Fill →

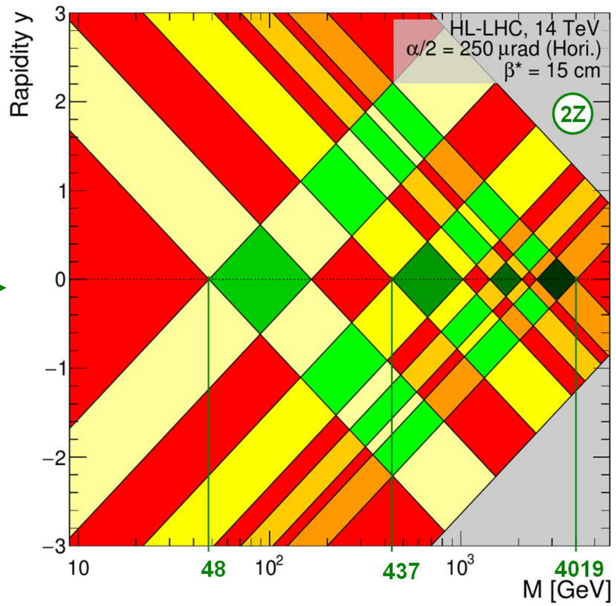


Horizontal crossing in IP5

Large gaps !



Fill →



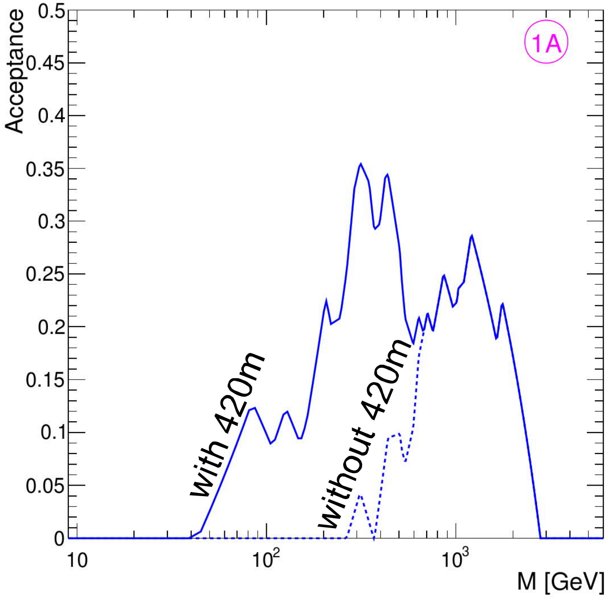
$$\ln\frac{M}{\sqrt{s}} = \tfrac{1}{2}(\ln\xi_1 + \ln\xi_2)$$

$$y = \tfrac{1}{2}(\ln\xi_1 - \ln\xi_2)$$

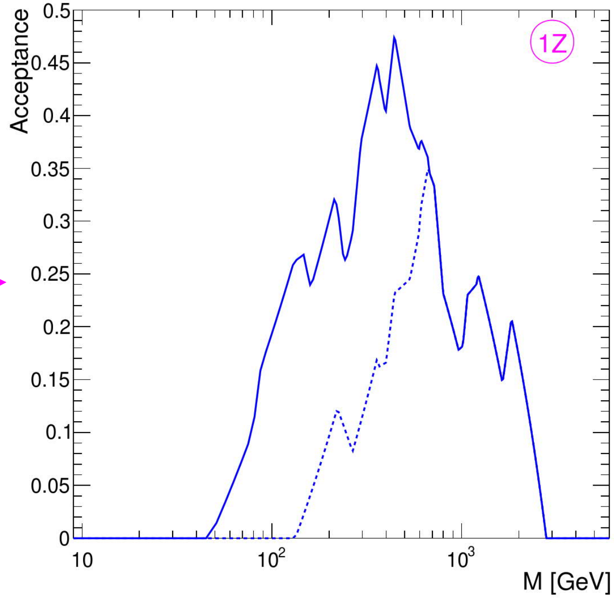
Mass Acceptance

projections on M axis assuming flat rapidity distribution

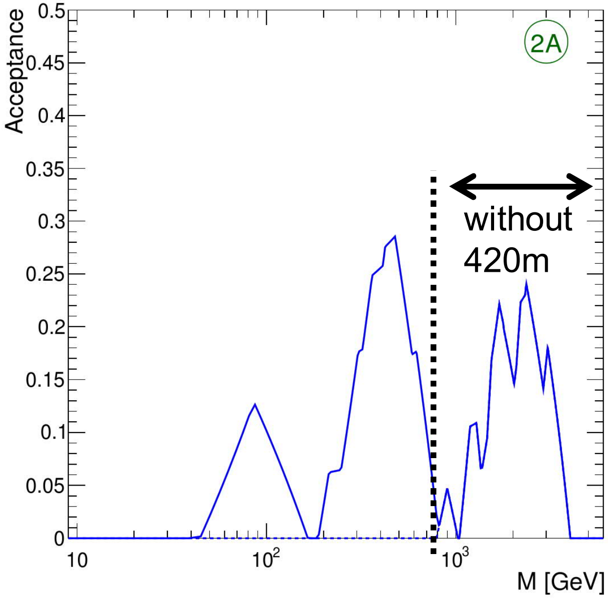
Vertical crossing in IP5



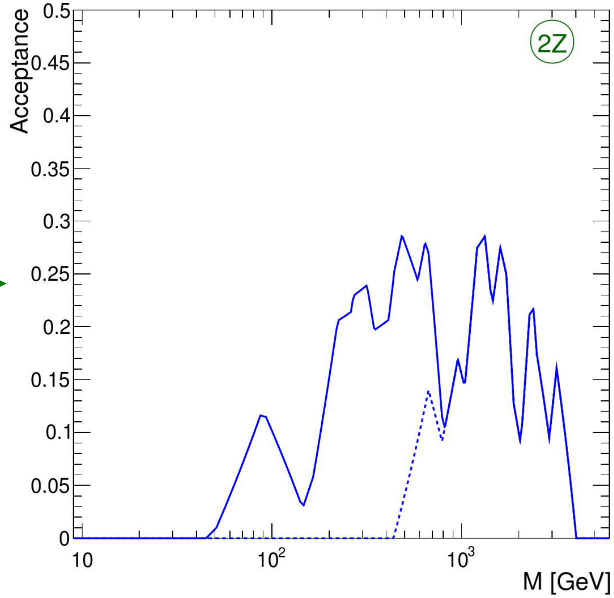
Fill →



Horizontal crossing in IP5



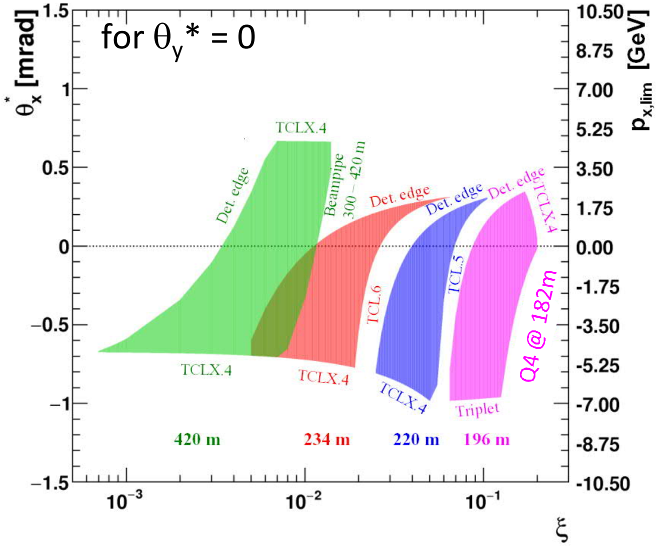
Fill →

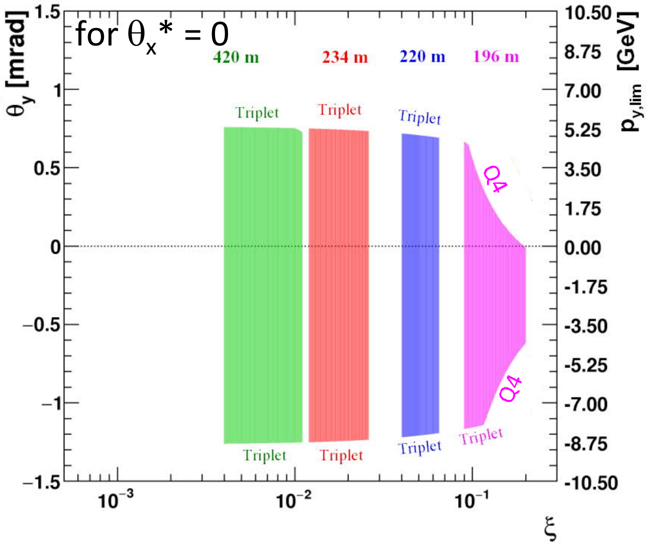


Single-Arm Proton Acceptance (Non-Zero p_T)

Acceptance numbers in EoI are taking into account all aperture limitations upstream of XRPs but assuming full instrumentation of the scoring planes.

Physics Runs



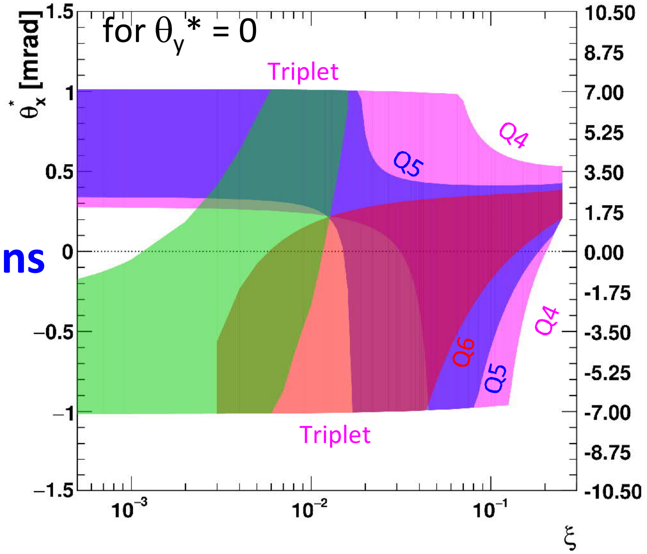


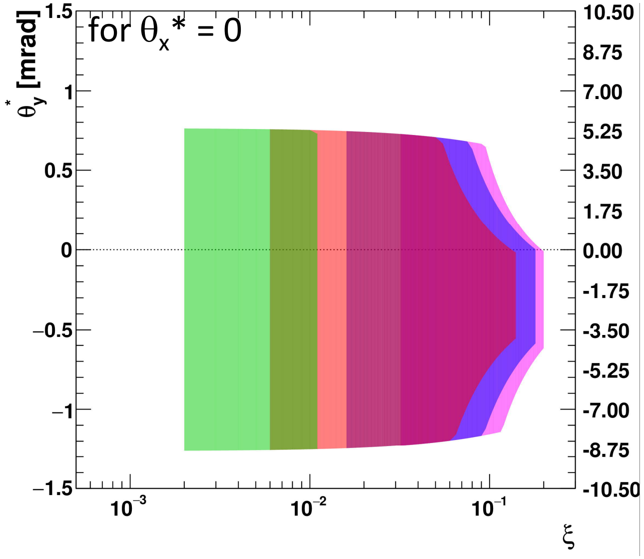
These plots are for $\alpha/2 = +250\ \mu$rad

Continuous variation of $\alpha/2$ during the fill shifts the θ_y^* acceptance blocks (approx.) up and down

Calibration Runs

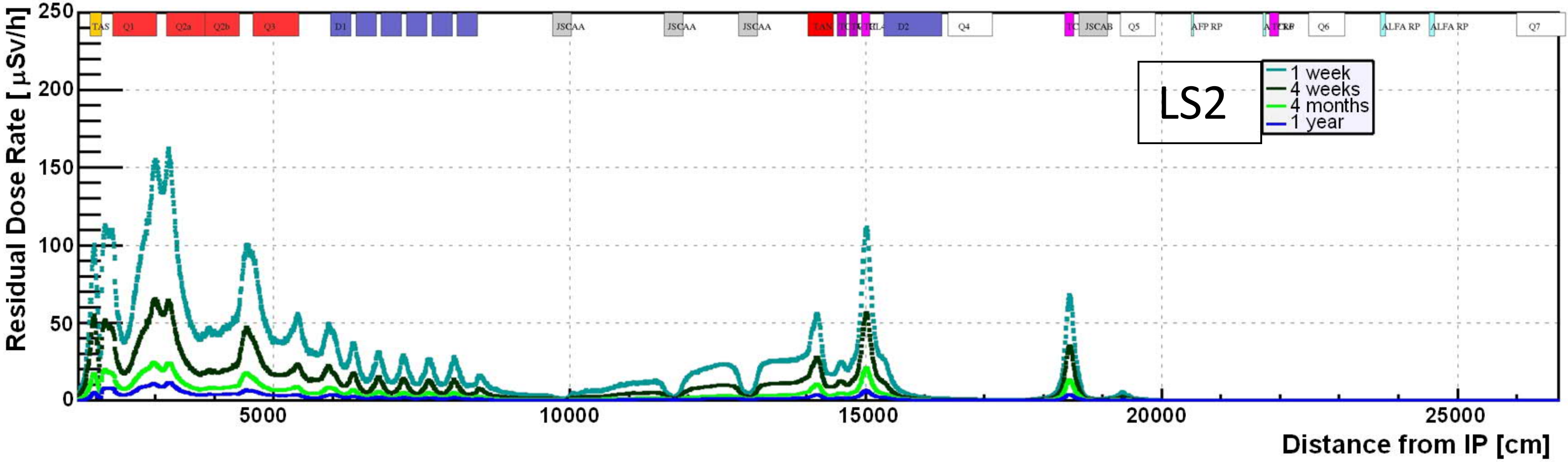
- RPs at 5 σ from beam
- no TCLs

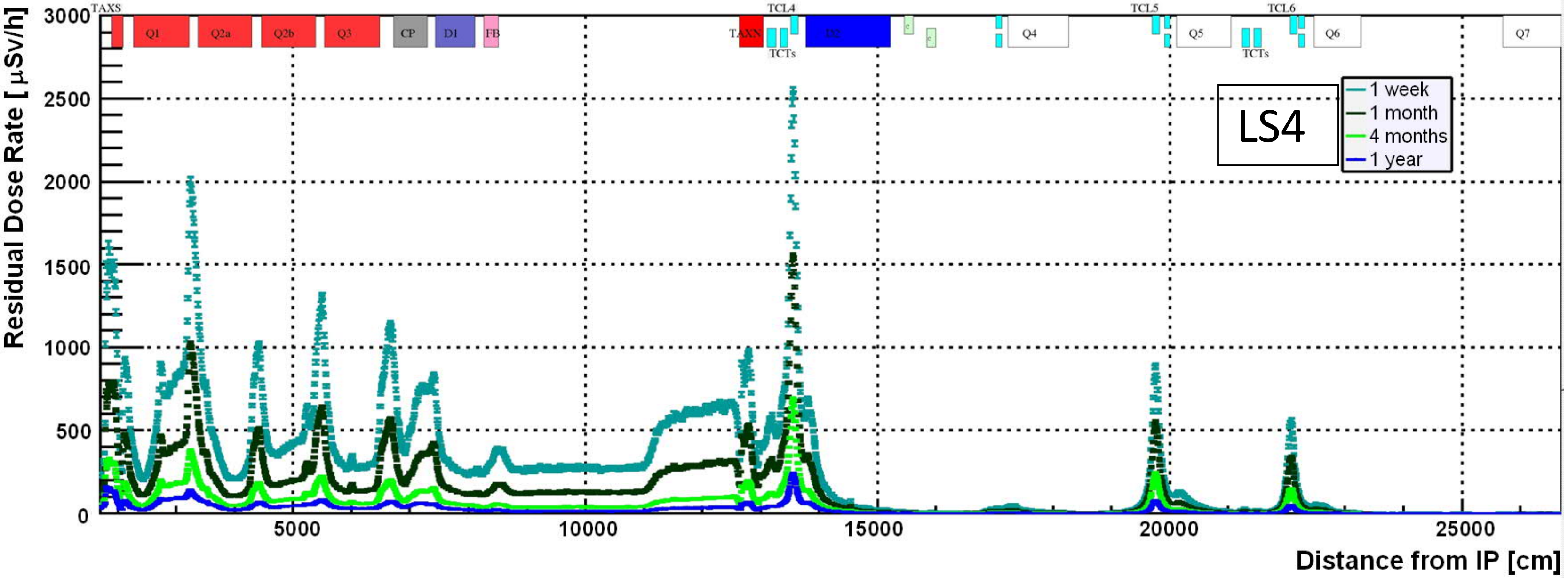




$\alpha/2$

Radiation Environment





Cooling times: after 1 week in LS2: same level as after 17 months in LS4
→ no access during short technical stops → no exchange of sensors

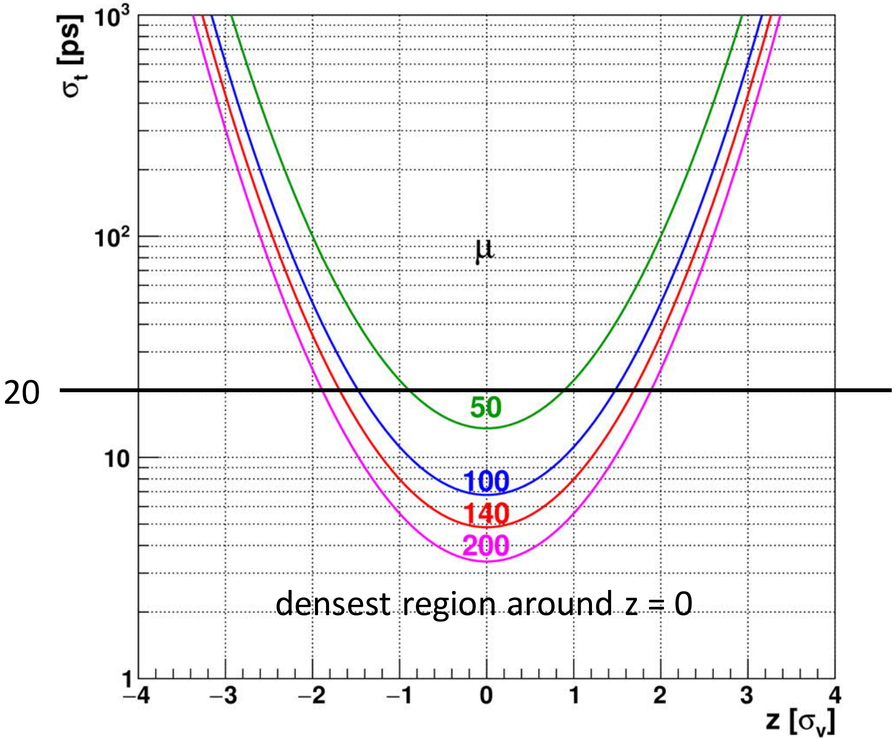
ToF and Vertex Resolution

With present technology: expected time resolution ~ 50 – 60 ps / plane

→ with ~ 10 planes per spectrometer arm: 15 – 20 ps / arm

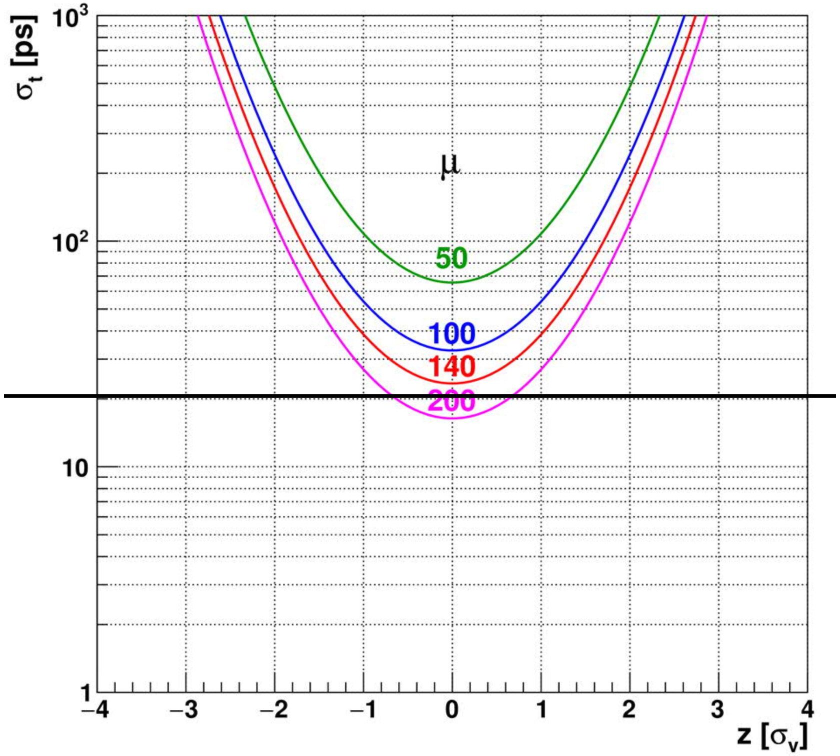
Required time resolution per arm to resolve mean vertex distance:

PPS alone



densest region around z = 0

Combined with MTD timing



For μ = 140 (200):

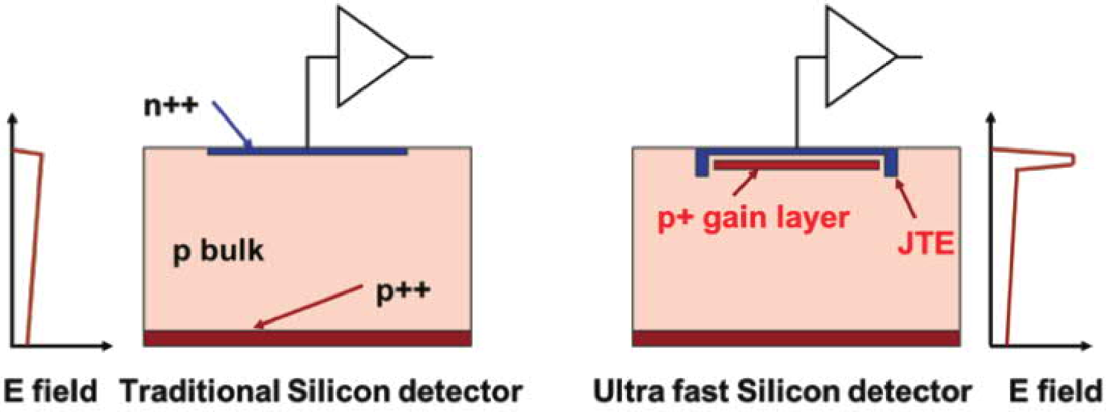
resolves vertices only outside 1.7 (1.9) σ

But: event topology selections reduce eligible vertices!

to be studied in detail

Low gain avalanche diodes

- The LGAD sensors, as proposed and first manufactured by CNM
- High field obtained by adding an extra doping layer
- E ~ 300 kV/cm, close to breakdown voltage
- Gain is the key ingredient to good time resolution

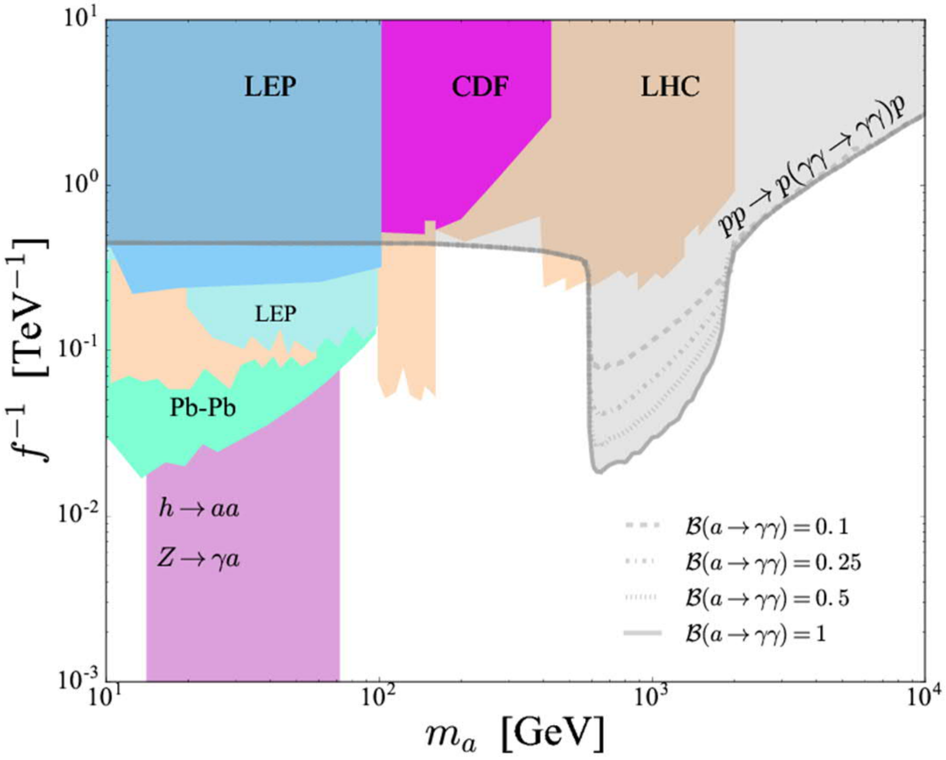


Physics Examples: Direct Searches at High Mass

Search for Axion-Like Particles

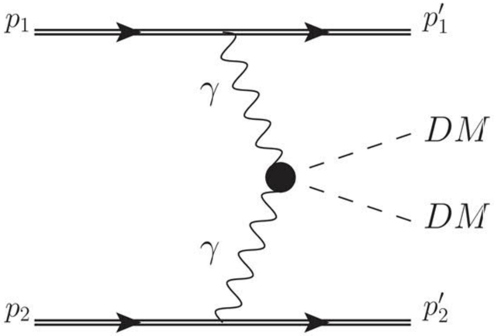
via $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$

95% CL exclusion regions



Light grey shaded: PPS @ LHC for 300 fb^{-1}

Search for invisible particles ("missing mass")

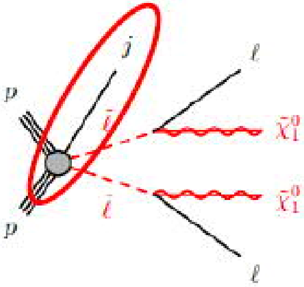


Example: SUSY searches in compressed mass scenario

$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$

Conventional search: need ISR jets to boost neutralinos → high missing E_T

[PRD 101 (2020), 052005]



Central production:

measure $m_{\tilde{\ell}\tilde{\ell}}$ via protons!

[JHEP 1904, 010 (2019); PRL 123 (2019) 141801]