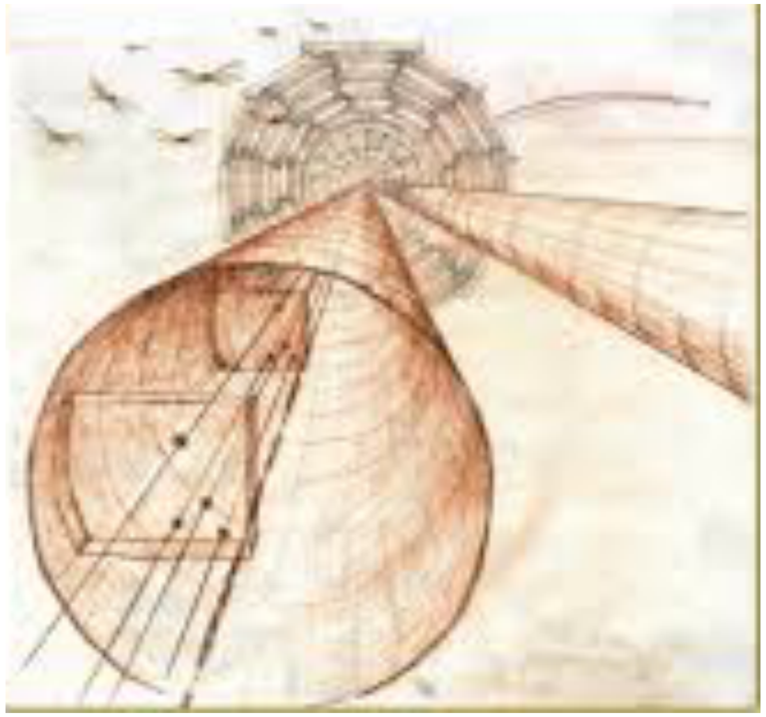
The CMS Precision Proton Spectrometer (PPS)

Past, Present, and Future

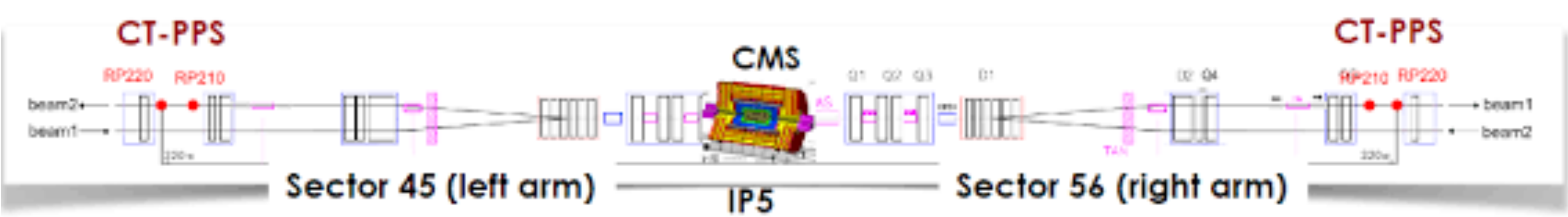
Jonathan Hollar (LIP)

LIP Seminar, Jan. 21, 2021

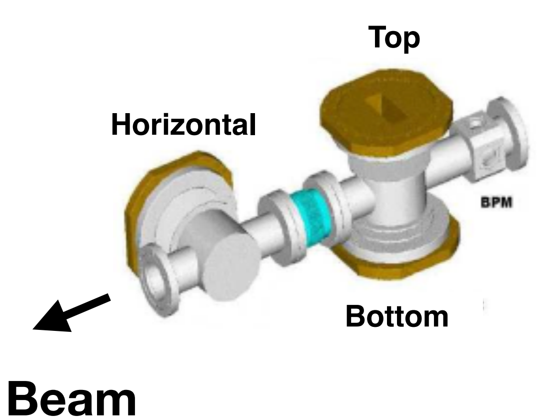


PPS: The Precision Proton Spectrometer

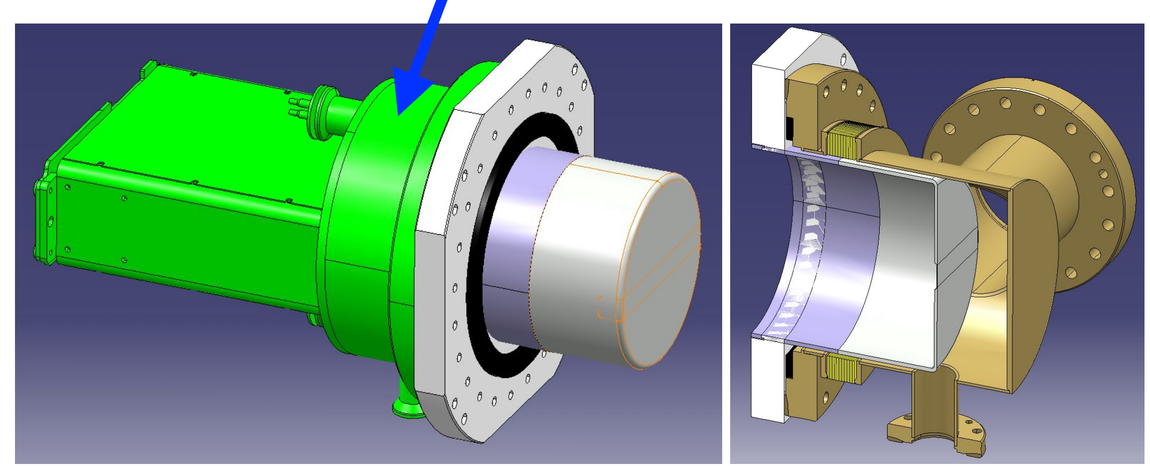
- A series of **very small detectors (few cm^2** active area)
- Located **very far from the central CMS detector (~210m)** at the CERN LHC



Detector package

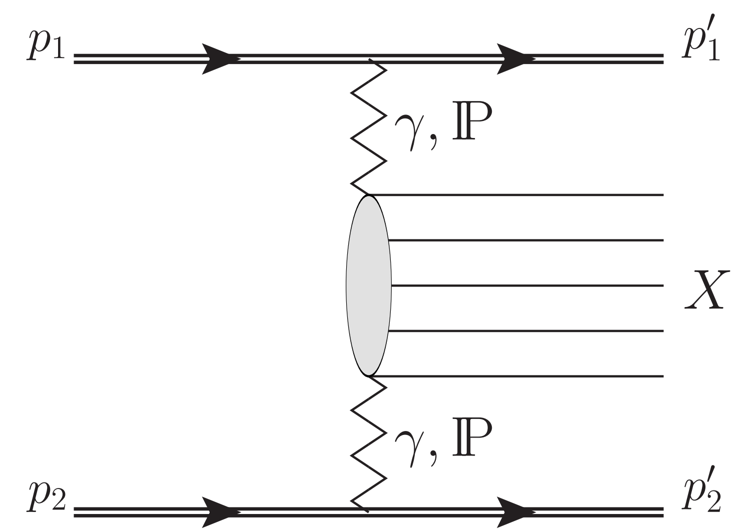


Approaching **very close to the LHC beam (~2 mm)** inside movable "Roman Pot" vessels in every LHC fill



Physics of PPS

- **In a special class of LHC collisions, the protons stay intact and scatter in the far forward direction**
    - γγ or multiple-gluon (“Pomeron”) exchanges



- **Detecting the protons provides a new powerful tool to study γγ collisions at hundreds of GeV to TeV scales**
    - **Operation at high luminosity => sensitivity to a wide range of rare and new processes**

Standard Model Physics

γγ→*ll*
Dijet production
…

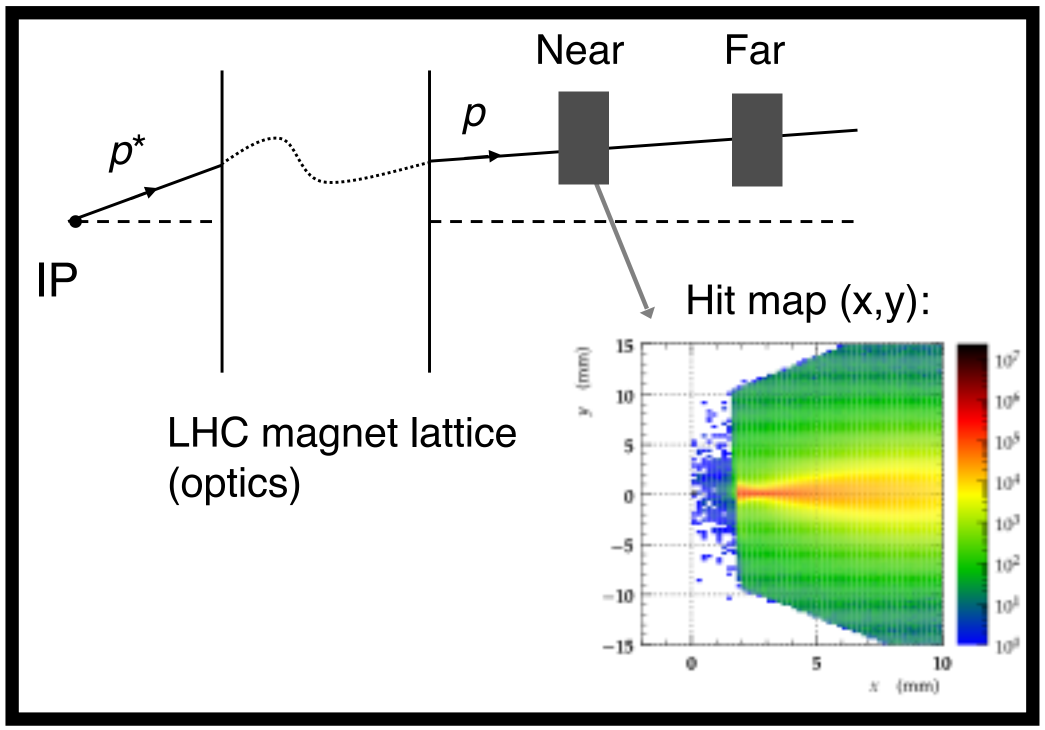
Electroweak and indirect new physics

Anomalous couplings in
γγ→gauge bosons (*WW,ZZ,γγ*),
γγ→top quarks,
γγ→tau leptons…

Direct new physics searches

Resonances, missing mass searches…

Proton reconstruction in space…



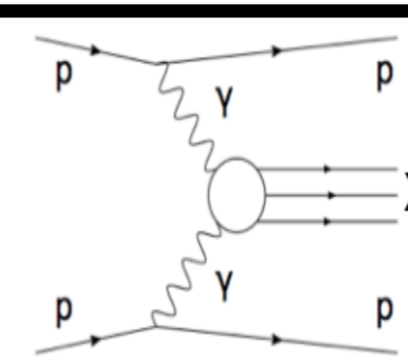
- **Protons are bent through the LHC accelerator magnetic fields, and arrive at the detectors**
  - Detectors measure x,y position
  - Then “reverse engineer” to find the fractional momentum loss (ξ) and 4-momentum transfer squared (t) of the proton at the collision point
  - **Requires very detailed understanding of LHC magnetic fields (“optics”), and alignment of the Roman Pots**

- **For signal events, kinematics are closed**
  - **ξ values are related to the invariant mass and rapidity of the central system “X”**
  - **M_X acceptance roughly 300-2000 GeV**

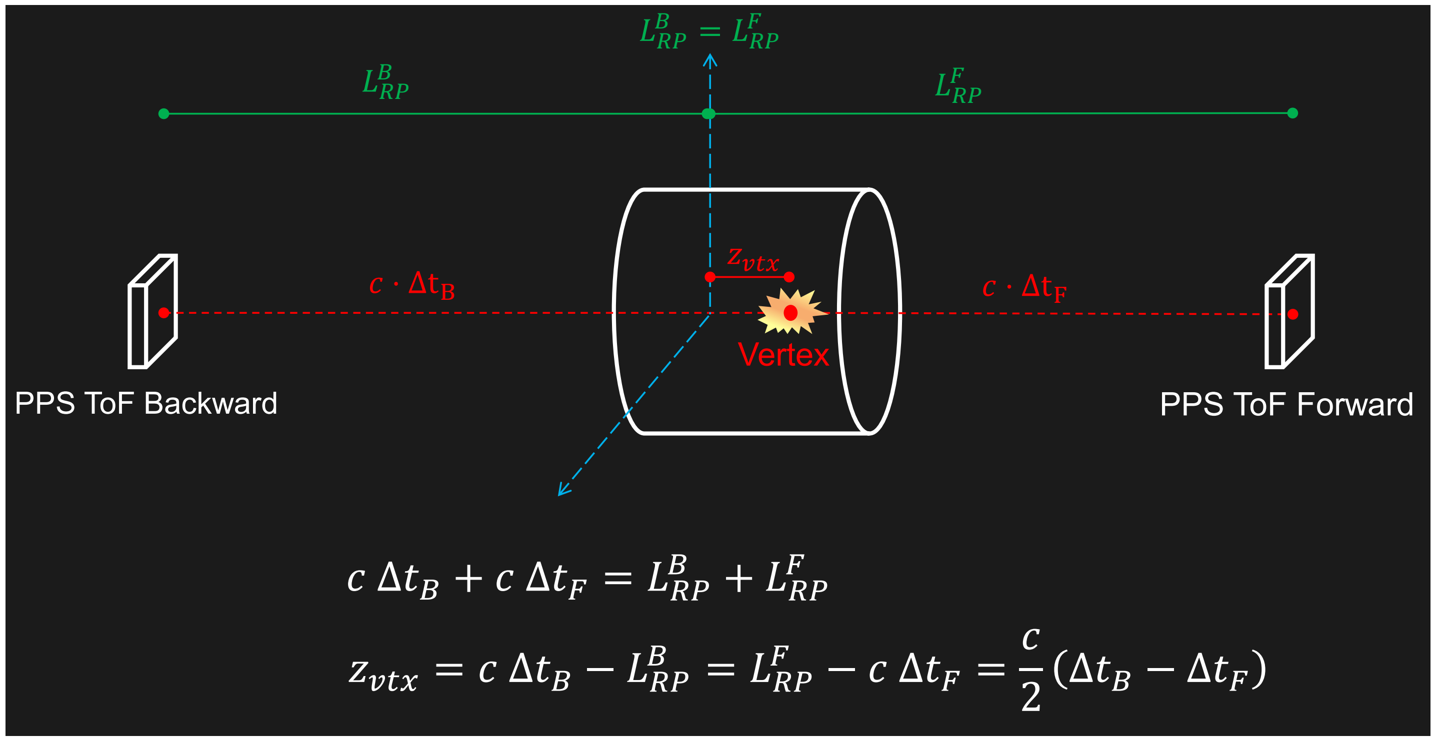
Proton kinematics:

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \quad M_X = \sqrt{s\xi_1\xi_2}$$

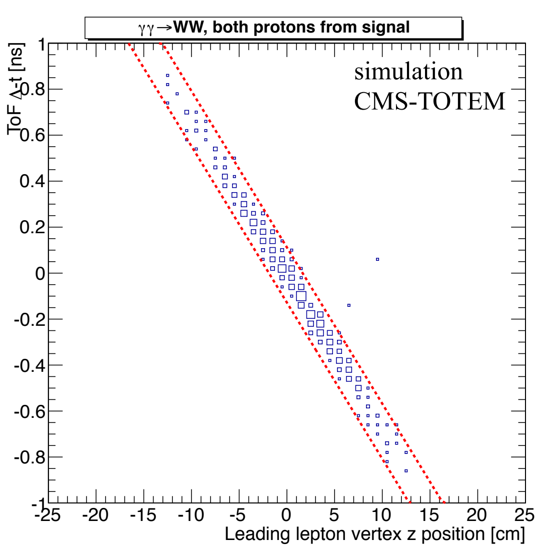
$$t = (p_f - p_i)^2 \quad y_X = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$$



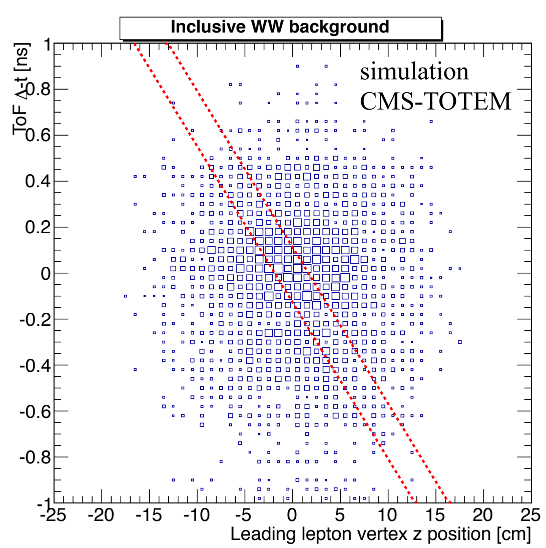
… and in time



- **A major background is due to "pileup" protons, coming from other collisions in the same LHC bunch crossing**
  - Pileup as large as 50-60 in LHC Run 2
- **Mitigated by precisely measuring the arrival time of the protons**
  - For signal, Δt of the 2 protons should be correlated with the longitudinal vertex position measured in the central detector



Simulated signal

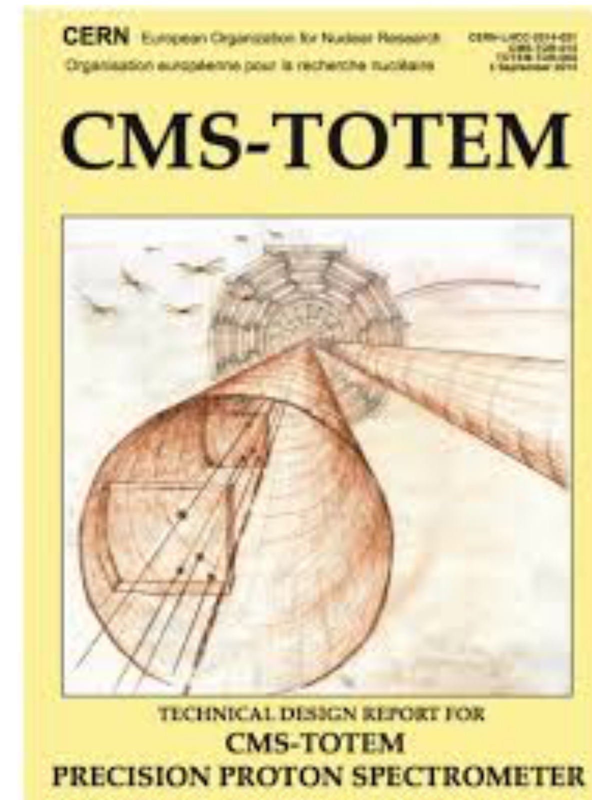


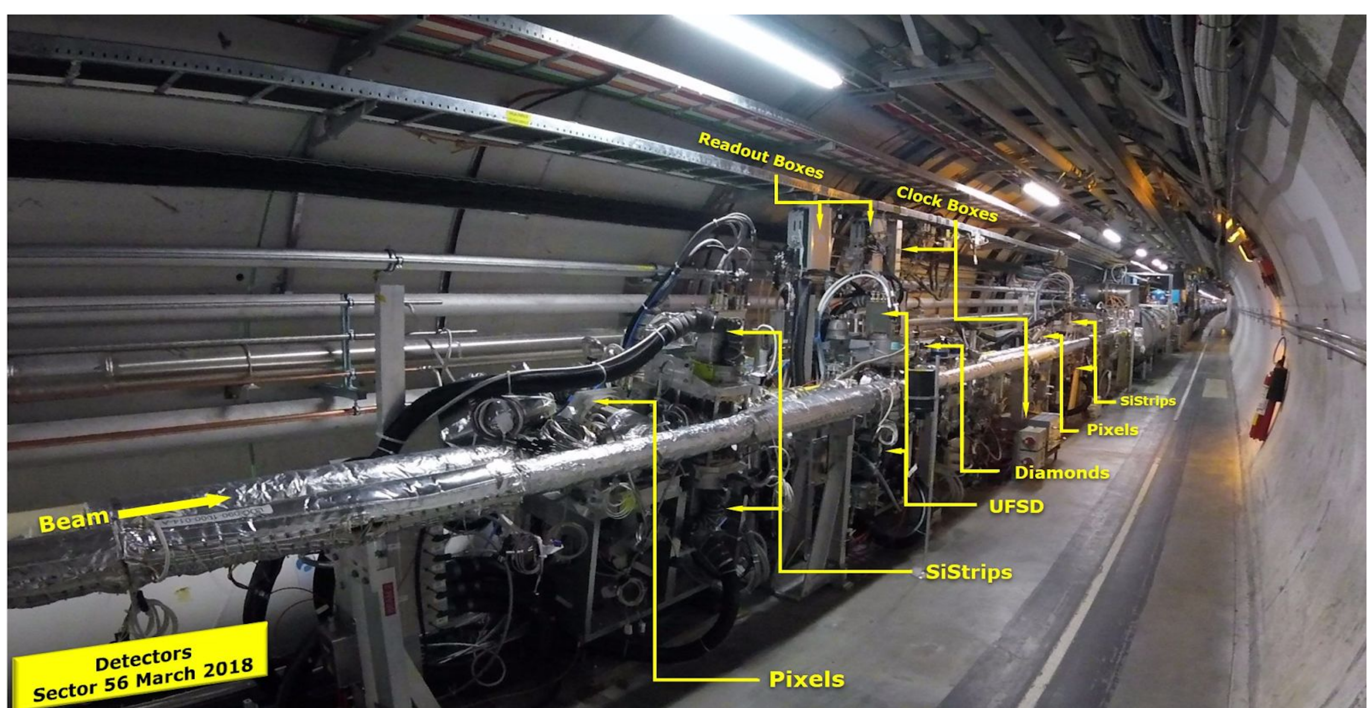
Simulated background

The past: PPS and LHC Run 2

From concept to reality

- **Began as a joint project of the CMS and TOTEM collaborations ("CT-PPS") in 2014**
    - Fully integrated into CMS by 2018 (now just "PPS")
- Reuse of horizontal Roman Pot and tunnel infrastructure installed originally for TOTEM low-luminosity runs
- **Major effort to prepare detectors, electronics, DAQ, for data-taking already in 2016**

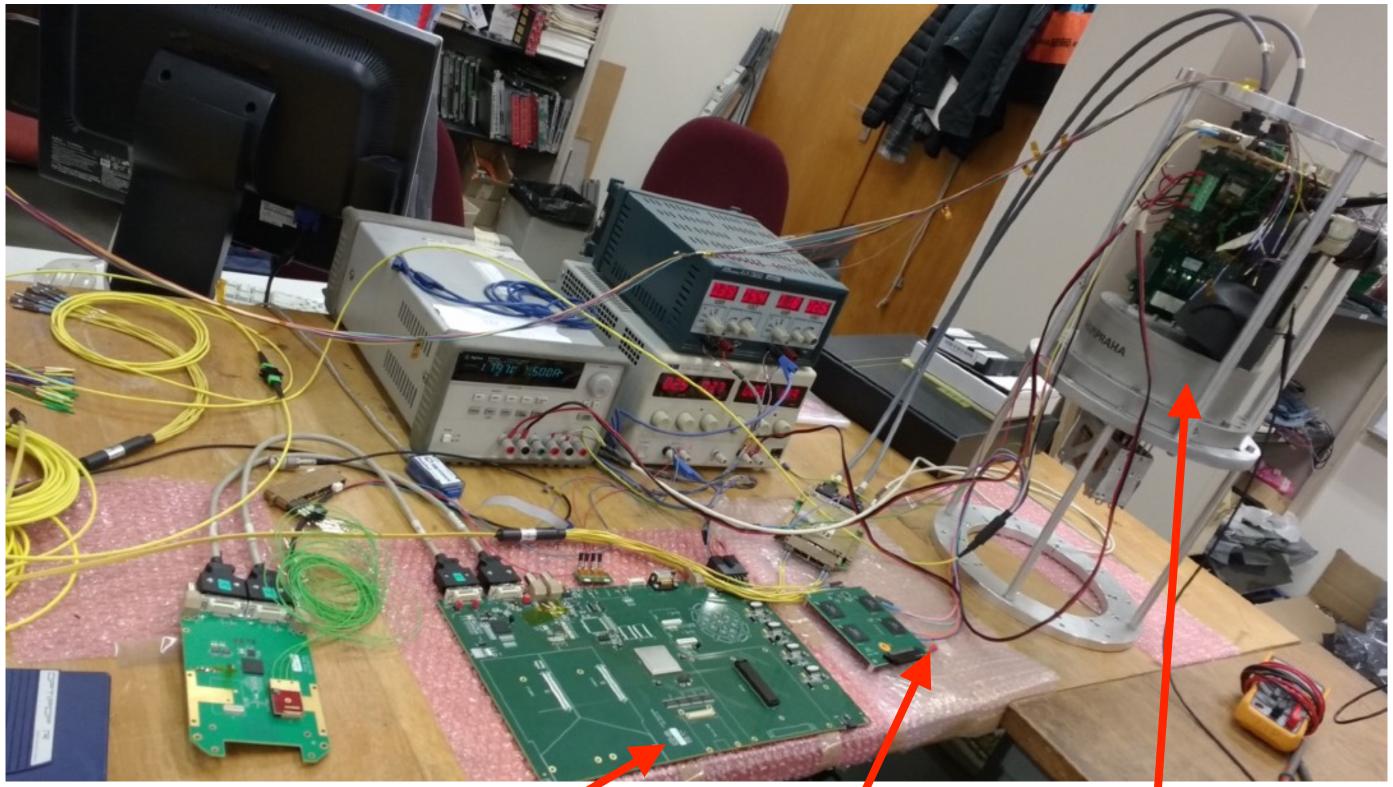




From concept to reality - LIP efforts

- **Leading contribution from the LIP-CMS group on many fronts (not all listed here)**
  - Project management
  - Coordination of timing detectors/electronics, CMS DAQ integration, detector operations
  - Electronics design, firmware, online software/HLT
  - 24-hour "on-call expert" and testbeam shifts
  - Calibration/detector performance studies

LIP lab @CERN B20: Pre-installation tests of electronics chain



Timing: Digitizer motherboard (LIP firmware, control software)

Timing: HPDTC mezzanine board (LIP design)

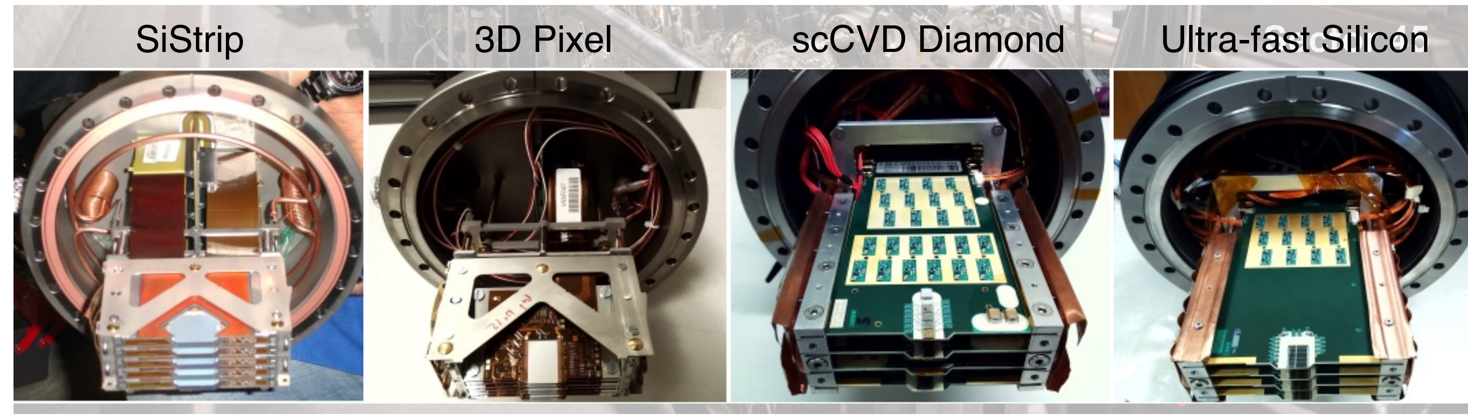
Tracking: Pixel portcard, in RP mechanical assembly (LIP contributions to control software, testing)

LIP Contributions

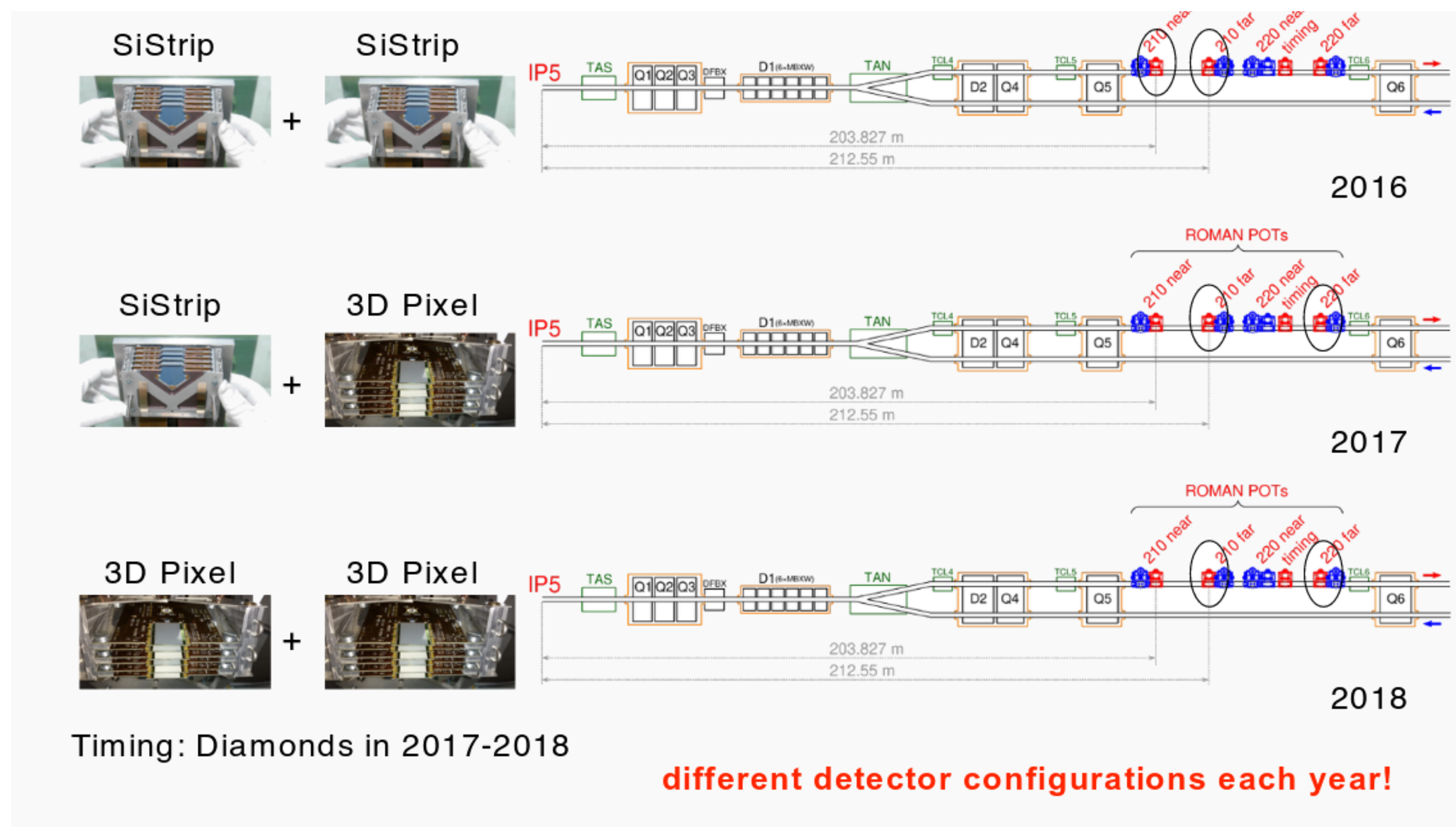
- **Current** and **former** group members
  - Project manager: **J. Varela** (2014-2018)
  - Deputy Project manager: **J. Hollar** (2018-present)
  - Proton Physics Object Group convenor: **K. Shchelina** (2019-present)
  - Timing detector coordinator: **M. Gallinaro** (2014-2018)
  - DAQ and detector operations coordinator: **J. Hollar** (2016-2018)
  - Electronics/firmware/DAQ/online software: **J. Carlos Da Silva**, **C. Carpinteiro**, **L. Llorett**, **B. Galinhas**
  - Proton reconstruction, High-level trigger, tracking performance: **K. Shchelina, M. Araujo**, **M. Pisano**, **C. Da Cruz E Silva**
  - Alignment, timing detector testbeams: **G. Strong, A. Toldayev**
  - Detector on-call shifts: **K. Shchelina, C. Carpinteiro , L. Llorett, J. Hollar**
  - Physics analyses: **K. Shchelina, M. Gallinaro, M. Pisano, H. Silva, B. Ribeiro, L. Llorett, P. Silva**

LHC Run 2: Evolving layout and Detectors

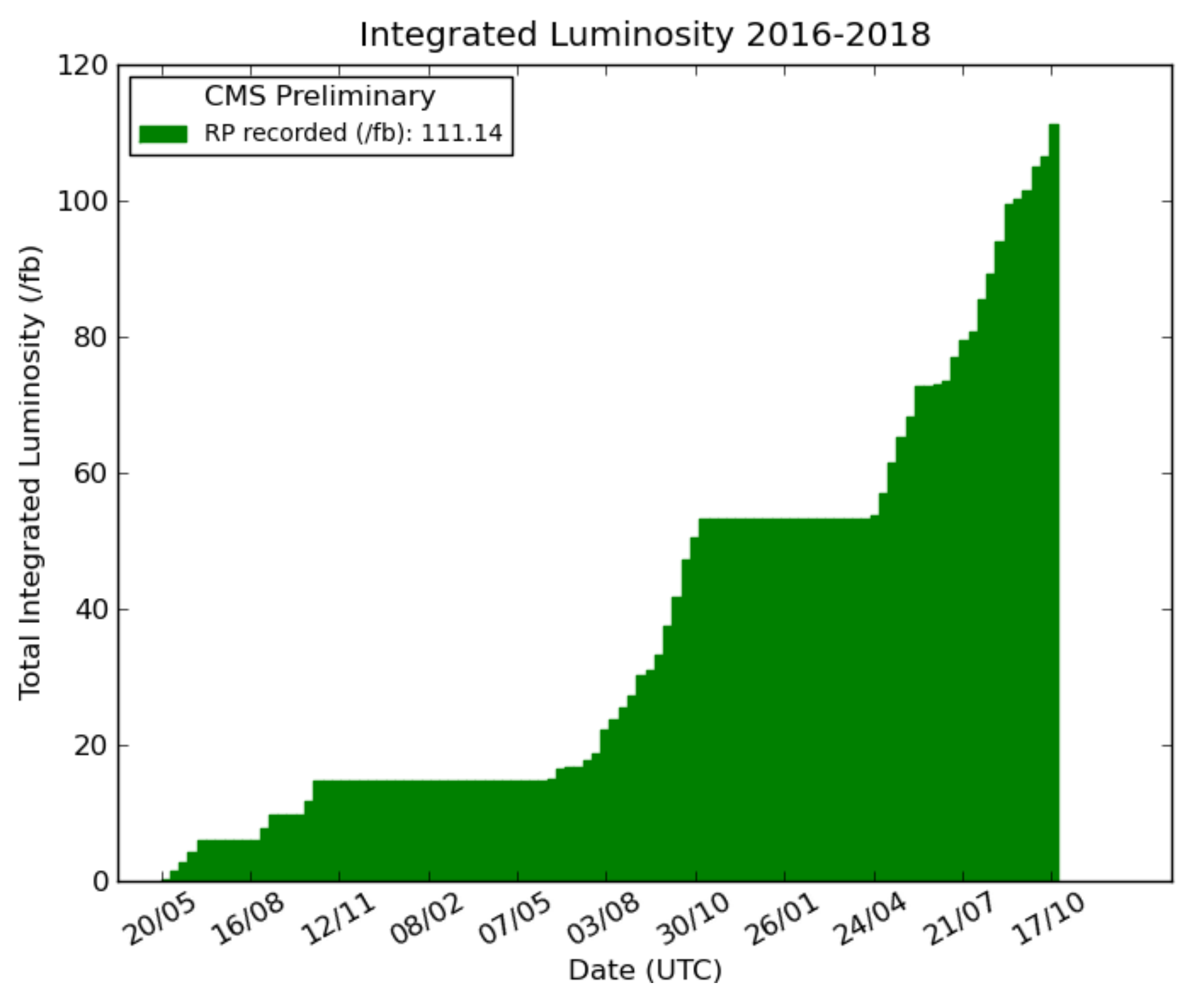
- **Small detectors, relatively fast to replace => variety of technologies used during LHC Run 2**
- Two tracking stations/arm
  - Initially all Si-strips in 2016, inherited from TOTEM
  - By 2018, moved to all 3D Si-pixel tracking (technology considered for CMS HL-LHC inner tracker)
- One timing station/arm in 2017+2018
  - Mainly synthetic diamonds (+ some with fast silicon low gain avalanche)



10 planes | 6 planes | 4 planes | 4 planes



Run 2 PPS data summary



- **>100fb^{-1} recorded with PPS Roman Pots inserted, and taking data together with the rest of CMS**
  - Almost 75% of the Run 2 total recorded by CMS alone
  - (final number for analysis depends on exact quality criteria - presence of timing detectors, etc.)

- **No negative impacts on LHC operations from inserting Roman Pots in almost every fill (beam dumps, luminosity limitations, etc.)**
- **No major problems for CMS data-taking**

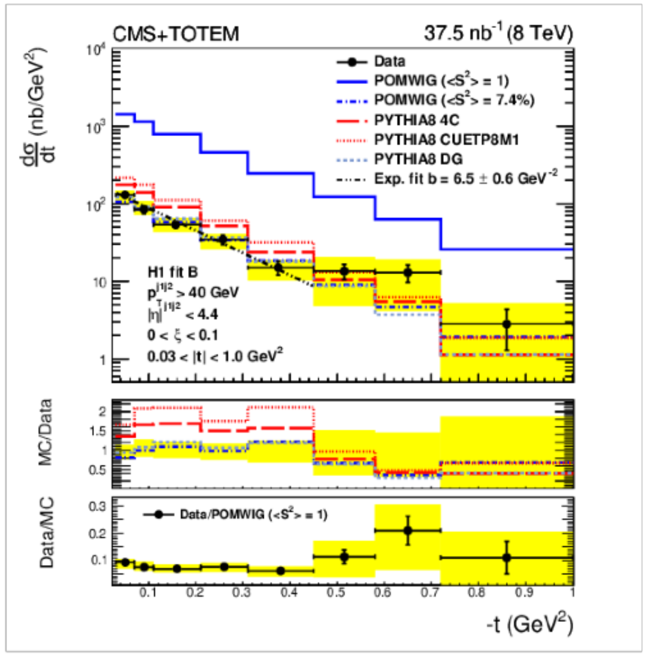
(An aside: special low-pileup/high-β* runs)

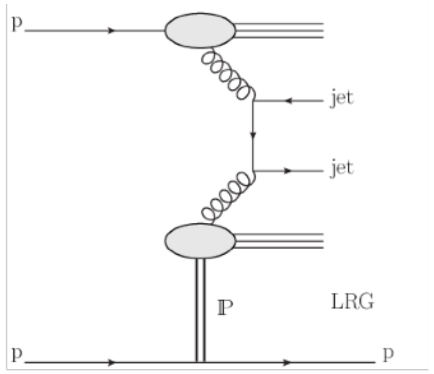
- **Historically - CMS+TOTEM (Roman Pots) also combined data from special low-pileup/high β*(90m) optics runs, dating back to 2012**
  - Even before a common DAQ/software, by exchanging trigger signals and matching events offline (not easy - don't try this at home!)
- Technically not considered part of PPS, though large overlap in people and increasing commonality in other areas
  - CMS+TOTEM high-β* runs now use same integrated DAQ/local reco SW developed for PPS
  - PPS uses the TOTEM vertical Roman Pots for alignment with elastic scattering events
- **I will mostly focus on the high-luminosity PPS program, but will briefly mention some new results with forward protons from the special runs**

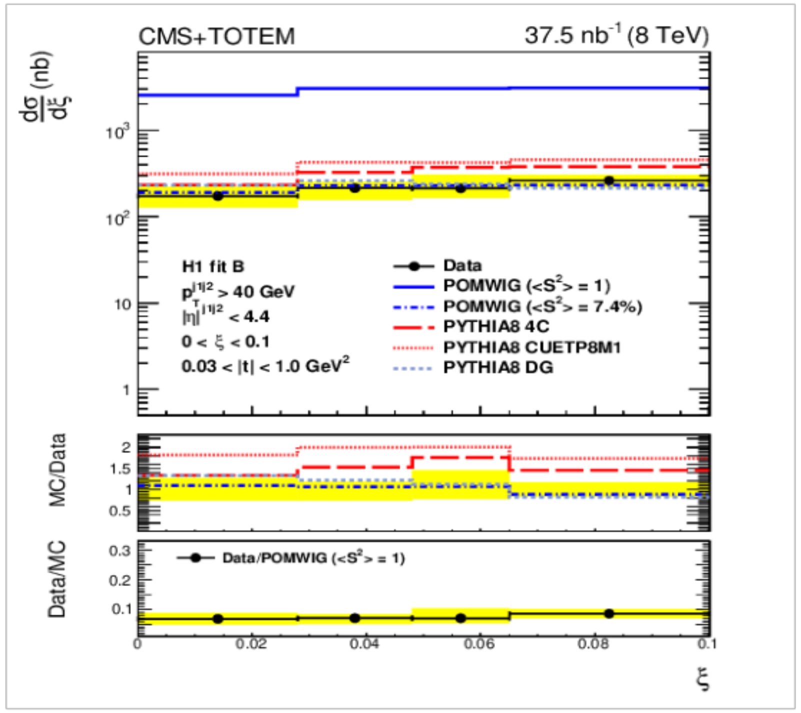
Physics results with forward protons

Physics of special runs: single-diffractive dijets

- **First LHC measurement of hard-scale diffraction with a leading proton**
  - 8 TeV data from 2012/Run 1, before DAQ integration!
- **“t” (proton 4-momentum transfer) slope is consistent with measurements from HERA**
- **Cross sections far (>10x) below predictions of HERA “diffractive PDF’s”**
  - Consistent with similar effect + energy dependence seen at Tevatron:
    - Interpreted in terms of soft rescattering/“survival probability” effects between protons
    - **Pythia8 “dynamic gap” model reproduces this with no ad hoc rescaling**



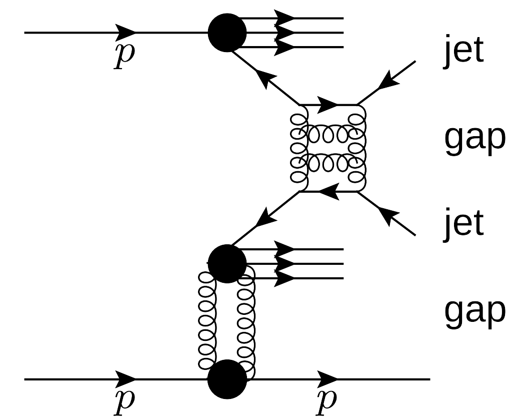


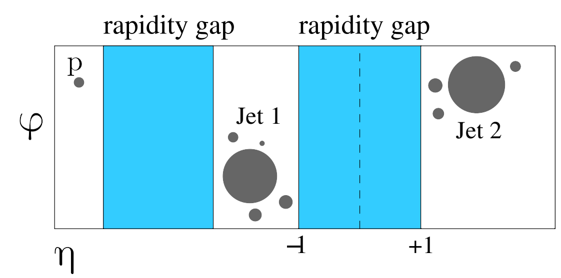


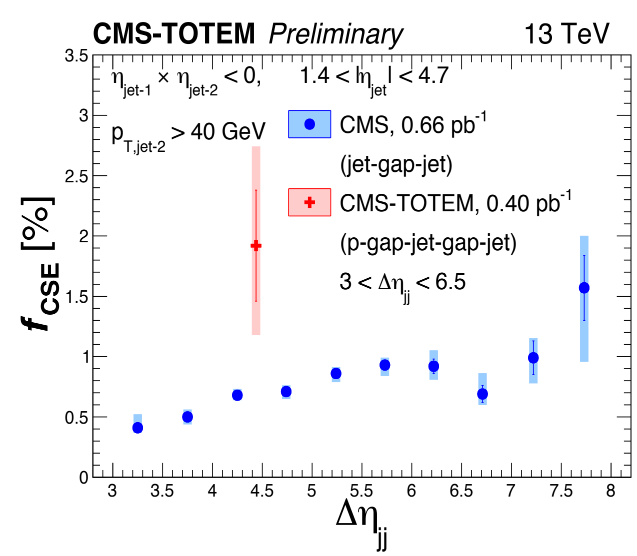
Eur. Phys. J. C 80, 1164 (2020) [arXiv:2002.12146]

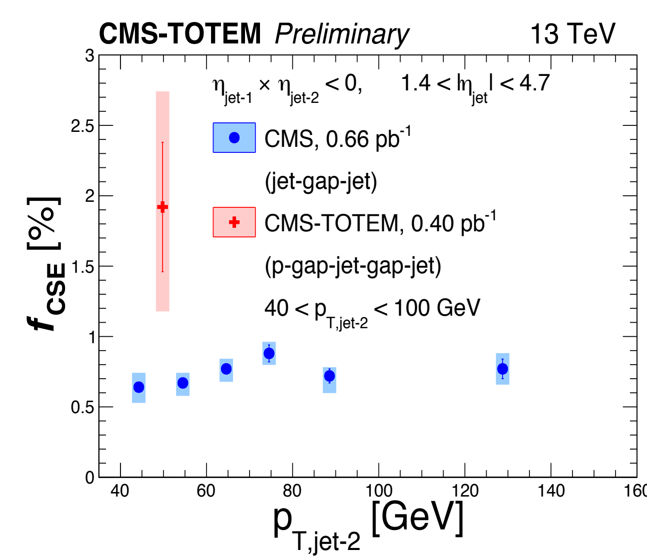
Physics of special runs: jet-gap-jet

- Study of hard color singlet exchange with and without a proton at 13 TeV (2015 data)
  - **Sensitive to BFKL dynamics**
- Excess of events with no activity between jets is observed both with and without a proton
  - **Fraction of events with a central rapidity gap is observed to be almost 3x larger when a proton is detected**
    - Interpreted in terms of reduced spectator parton activity
    - **First measurement of the central gap fraction with a leading proton**





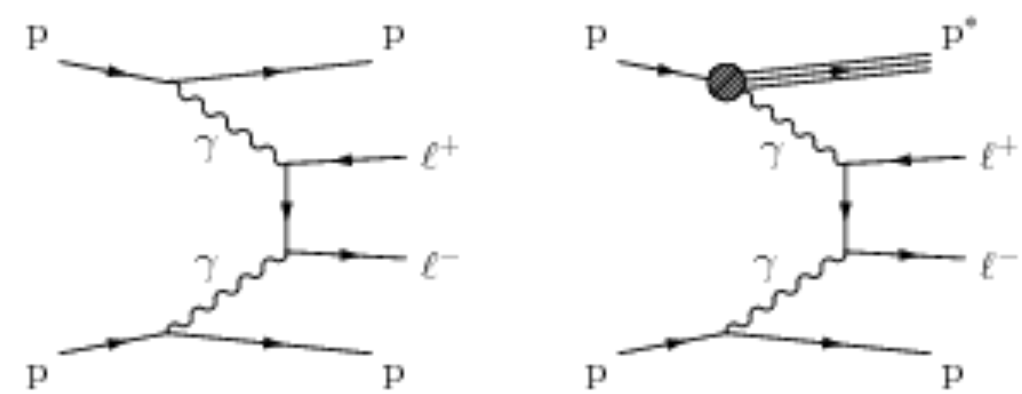


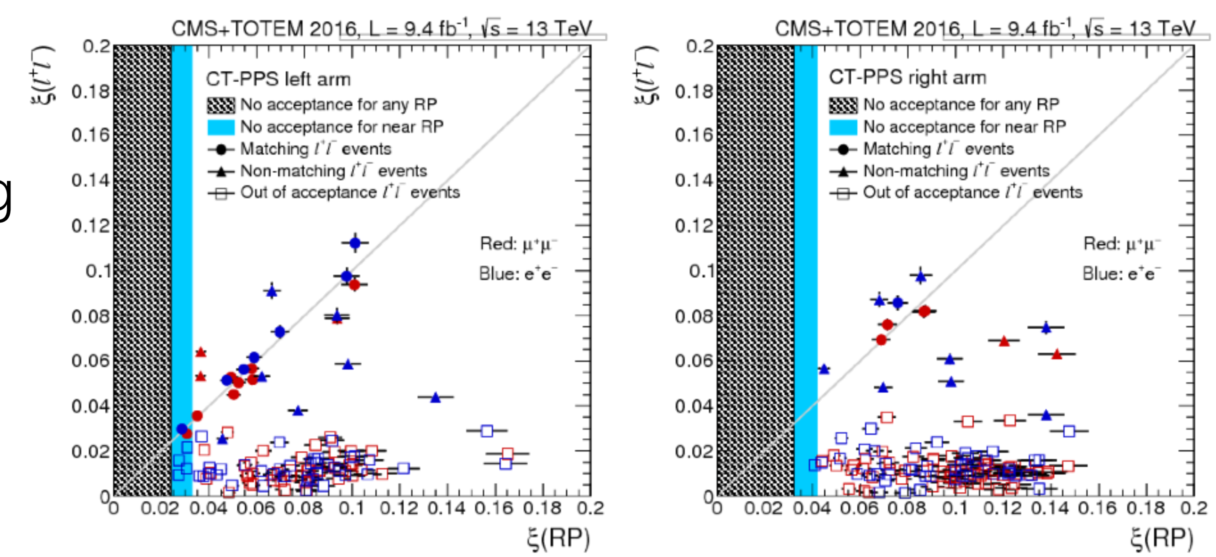


CMS-PAS-SMP-19-006
(to be submitted to PRD this week)

Physics of high-luminosity/PPS: $\gamma\gamma \rightarrow ll$ with single proton tags (2016)

- **Single arm measurement based on <10fb^{-1} of 2016 data**
- Backgrounds estimated by extrapolating from Z control regions, and by event mixing
- Combination of μμ and ee channels
  - Signal appears as 5σ excess of events along the diagonal, where dilepton and proton kinematics match
  - **=> Observation of γγ interactions with a tagged proton at EWK scales**
  - Note: results also from ATLAS-AFP (*Phys.Rev.Lett.* 125 (2020) 26, 261801)



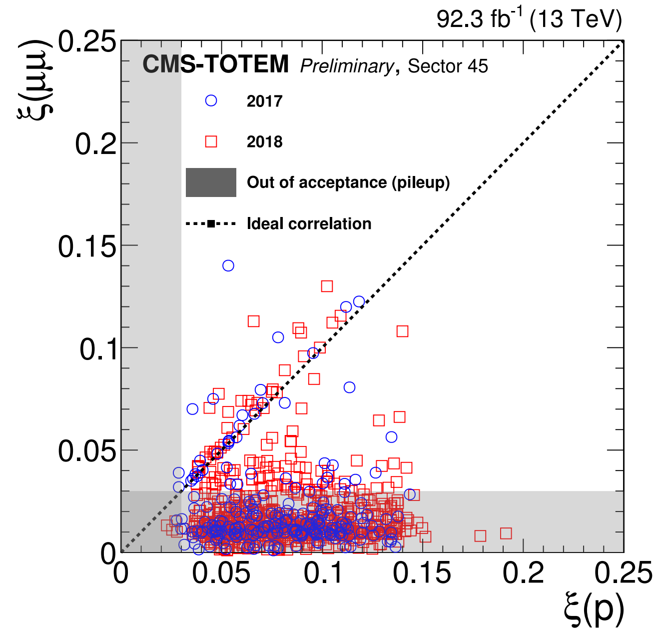


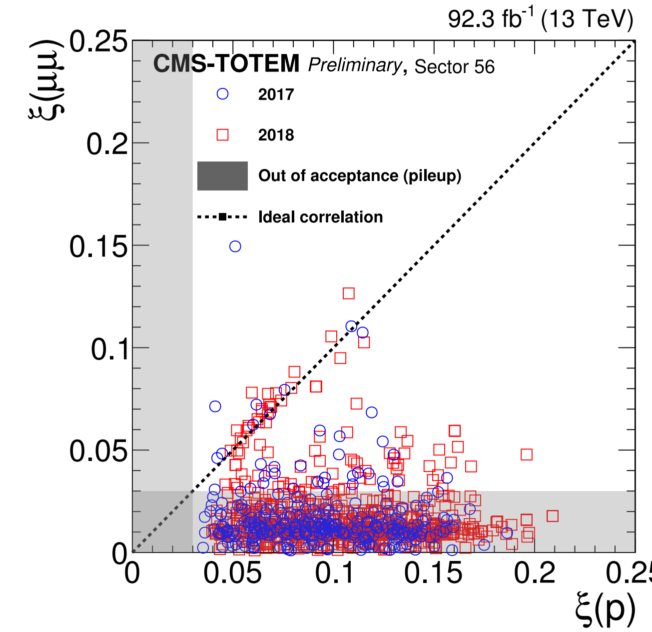
m(*ll*)>110GeV

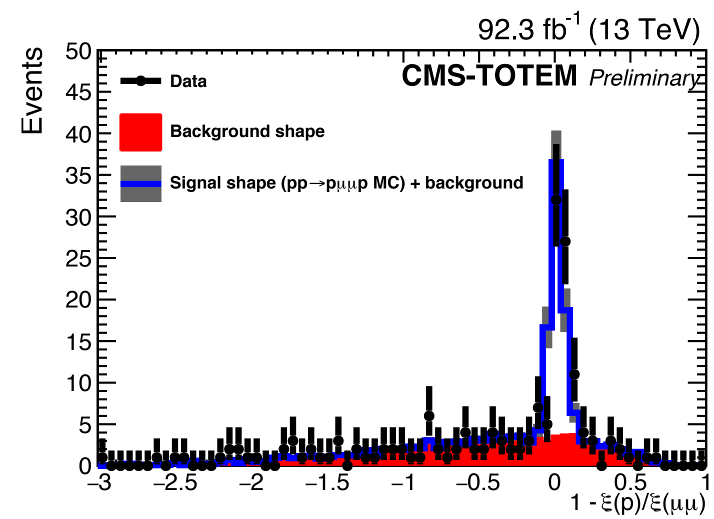
JHEP 07 (2018) 153 [1803.04496]

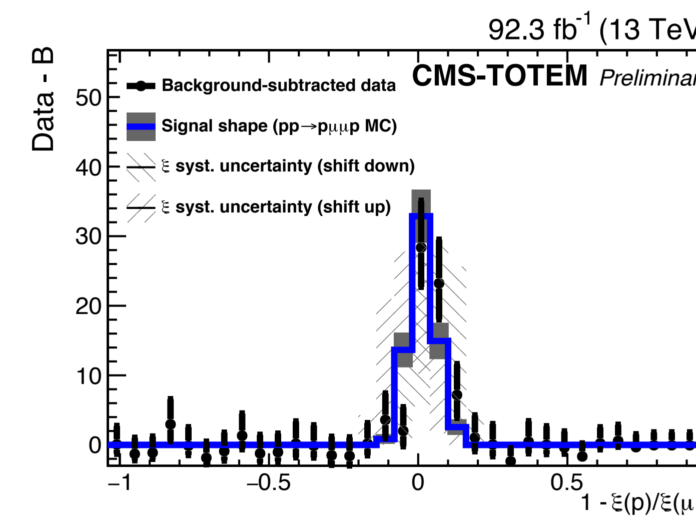
γγ→μμ with single proton tags: Prospects for full Run 2 data (2017+2018)

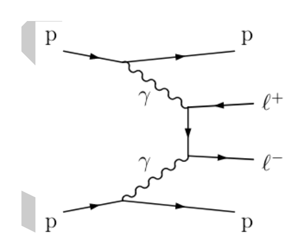
- **Single-arm γγ→μμ events are now used as a control sample for ξ reconstruction in 2017+2018 data**
- **New (“multi-RP”) reconstruction option, with full reco of proton scattering angles/t distribution**
    - Limited low-ξ acceptance, but improved high-ξ resolution
    - “single-RP” reconstruction retained for analyses that need to access lower ξ values
    - Correlation peak widths/resolutions are well-reproduced by the simulation
    - Small offsets are consistent with independently estimated scale systematics
- **SM processes well-established => begin exploring anomalous couplings/BSM physics…**

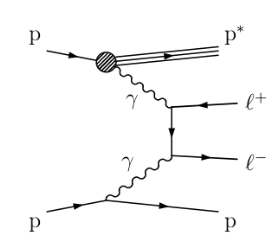










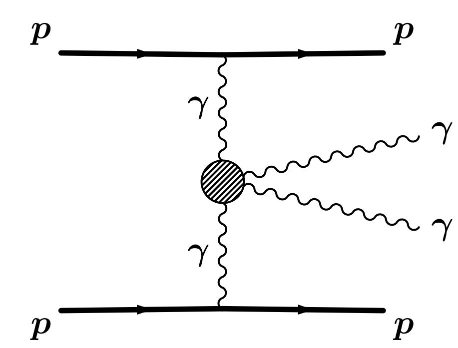


m(μμ)>110GeV
ξ(μμ)>0.04
1 proton/event

CERN-CMS-DP-2020-047.

Physics of high-luminosity/PPS: Search for γγ➝γγ

- γγ➝γγ scattering is sensitive to a wide range of BSM effects
  - Non-resonant: Anomalous Quartic Gauge Couplings, exotic particles at 1-loop level…
  - Resonances: Axion-like particles, others with large couplings to photons

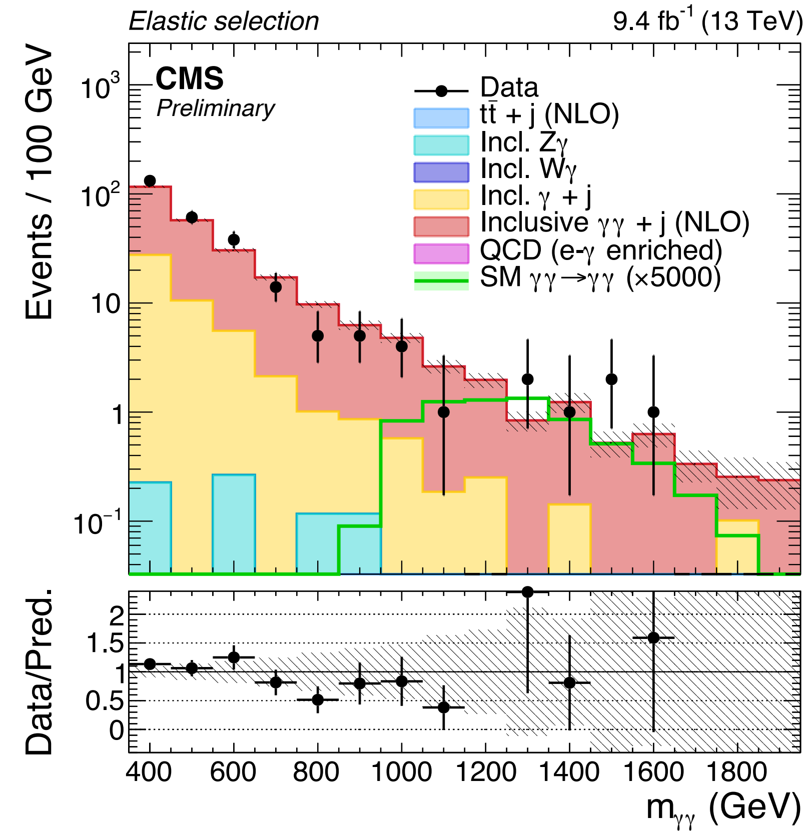


- Large amount of interest surrounding the 750 GeV "diphoton bump" from ATLAS+CMS in ~2015 (not confirmed with more data)
  - Motivation for starting PPS physics program earlier than planned
- **Complementary to "light-by-light" scattering studies in Heavy Ion collisions (PPS probes higher-energy/TeV scale γγ collisions)**

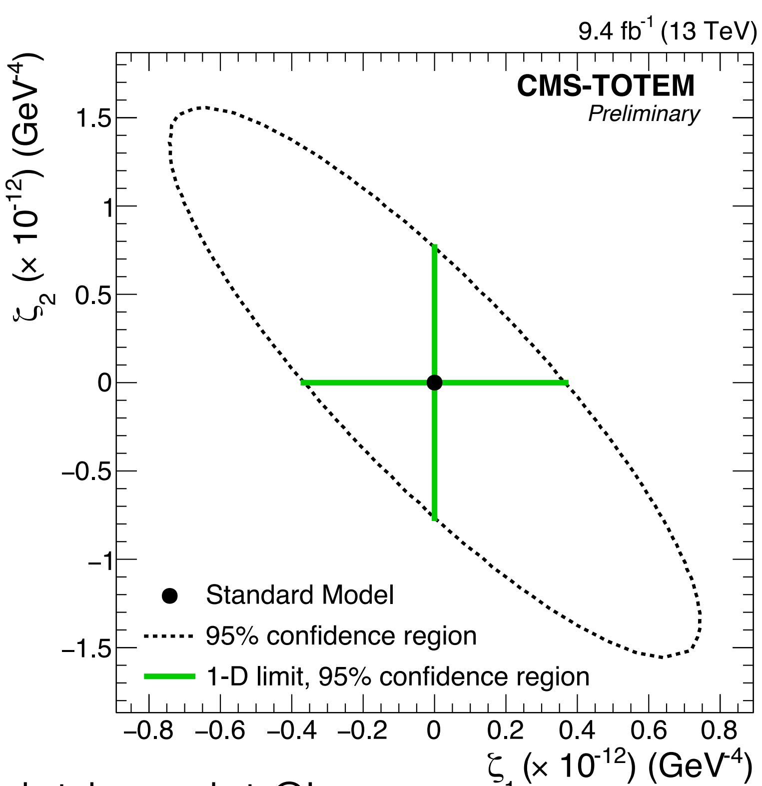
CMS-PAS-EXO-18-014

Physics of high-luminosity/PPS: Search for γγ➝γγ

- Selection mainly adopted from CMS H➝γγ analysis and CMS-PPS dilepton analysis
- Backgrounds estimated from MC constrained in control regions, plus event-mixing of random pileup-like protons
- After diproton-diphoton matching: ~1 background event expected, 0 events observed



Before diproton-diphoton matching



point-by-point CL_s scan

- **First direct collider limits on the anomalous quartic 4-photon couplings**

$$|\zeta_1| < 3.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_2 = 0)$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_1 = 0)$$

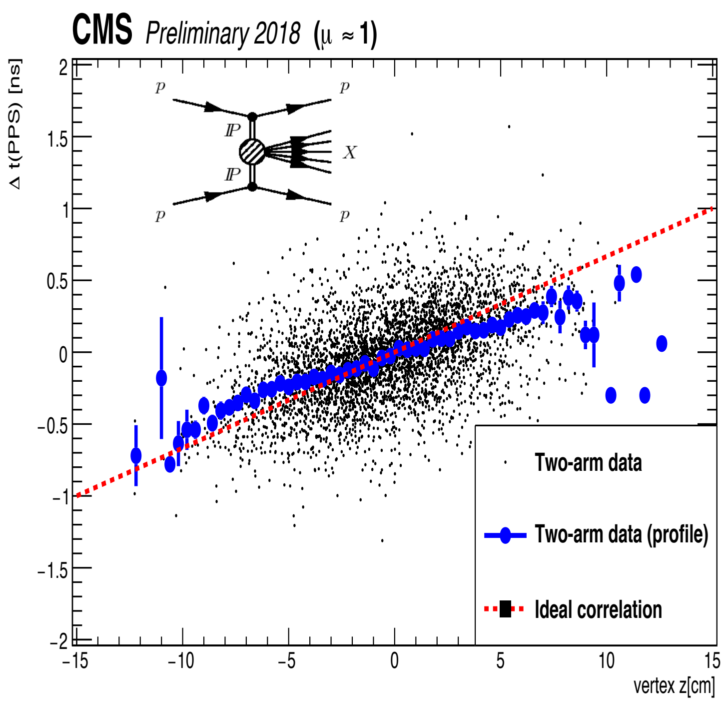
CMS-PAS-EXO-18-014

Prospects for Run 2 physics

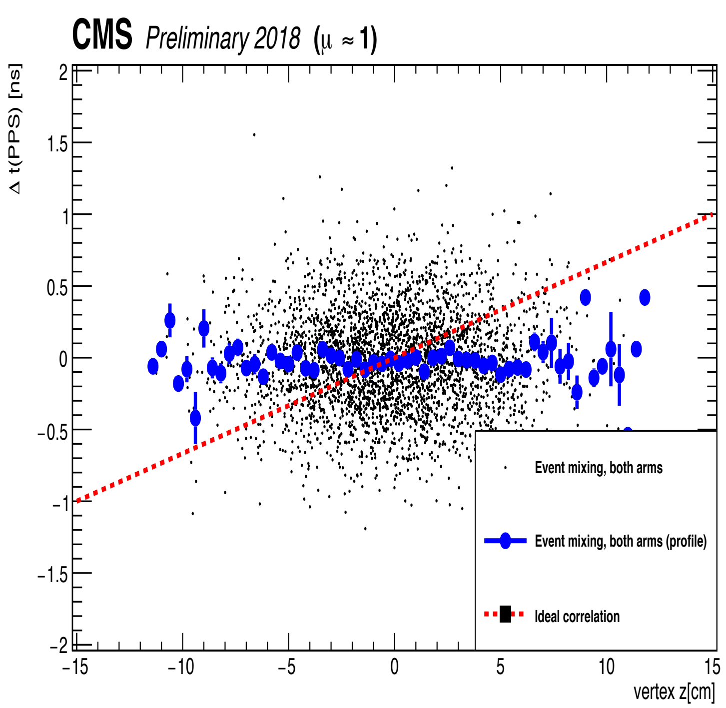
- **Most of the available Run 2 data has not yet been used for physics**
- Existing PPS/high-lumi physics analyses use only ~10 fb^{-1} from first part of 2016
  - **Additional >95 fb^{-1} recorded in the rest of 2016+2017+2018**
    - With improved tracking detectors in 2017+2018
    - With timing detectors in majority of 2017+2018 - not yet used for physics
- Results from high-β*/low-PU special runs use data from 2012+2015
  - ~10x more luminosity recorded in 2018 high-β*/low-PU special run

Physics prospects for 2017+2018 PPS data: timing

2-arm data



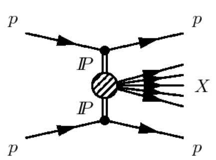
Mixed background



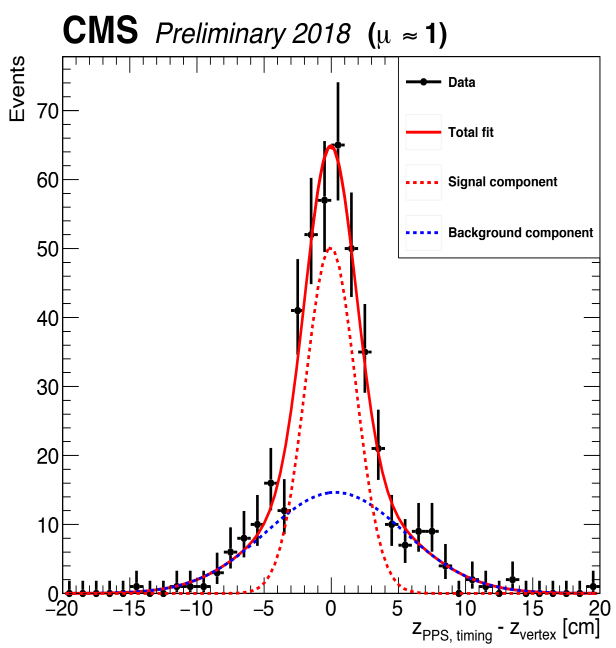
- Timing information available in majority of 2017+2018 data
    - Best calibrations/settings for the last 40fb^{-1} of 2018
- Low pileup (μ~1) 2018 data is used to validate the proton timing performance in Central Diffractive/"Double Pomeron Exchange"-like events
    - Based on comparison of central CMS vertex position vs. Δt of protons in PPS
    - **Strong correlation between z(CMS) and Δt(PPS) visible in events with 1 vertex and protons on both arms**
    - **No correlation present in event-mixing samples (used to model pileup backgrounds)**

CERN-CMS-DP-2020-046.

Physics prospects for 2017+2018 PPS data: timing

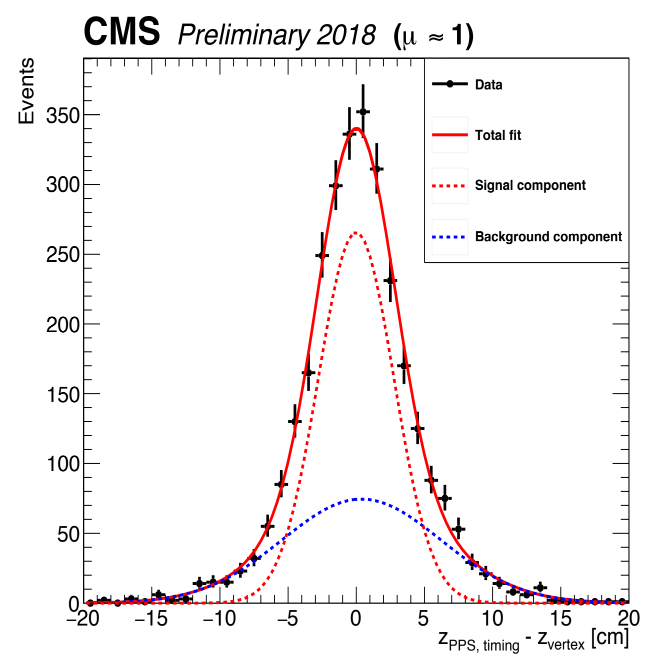


“High-resolution”



Free background
σ(z_{PPS}) = 1.87±0.21 cm
bkg shape variation [1.87-1.93]
sum of single-arm resolutions: 1.83

“High-efficiency”



Free background
σ(z_{PPS}) = 2.77±0.17 cm
bkg shape variation [2.45-2.86]
sum of single-arm resolutions: 2.53

- Distributions fit for resolution in 2 categories
  - High-resolution (time measurements on ~all 4 planes on each arm)
  - High-efficiency (time measurements on at least 2/4 planes on each arm)
- **Results are compatible with the prediction of single-arm resolutions**
  - => No significant effect at this level from sources correlated between the 2 arms (clock distribution, etc.)

The present: Preparations for LHC Run 3

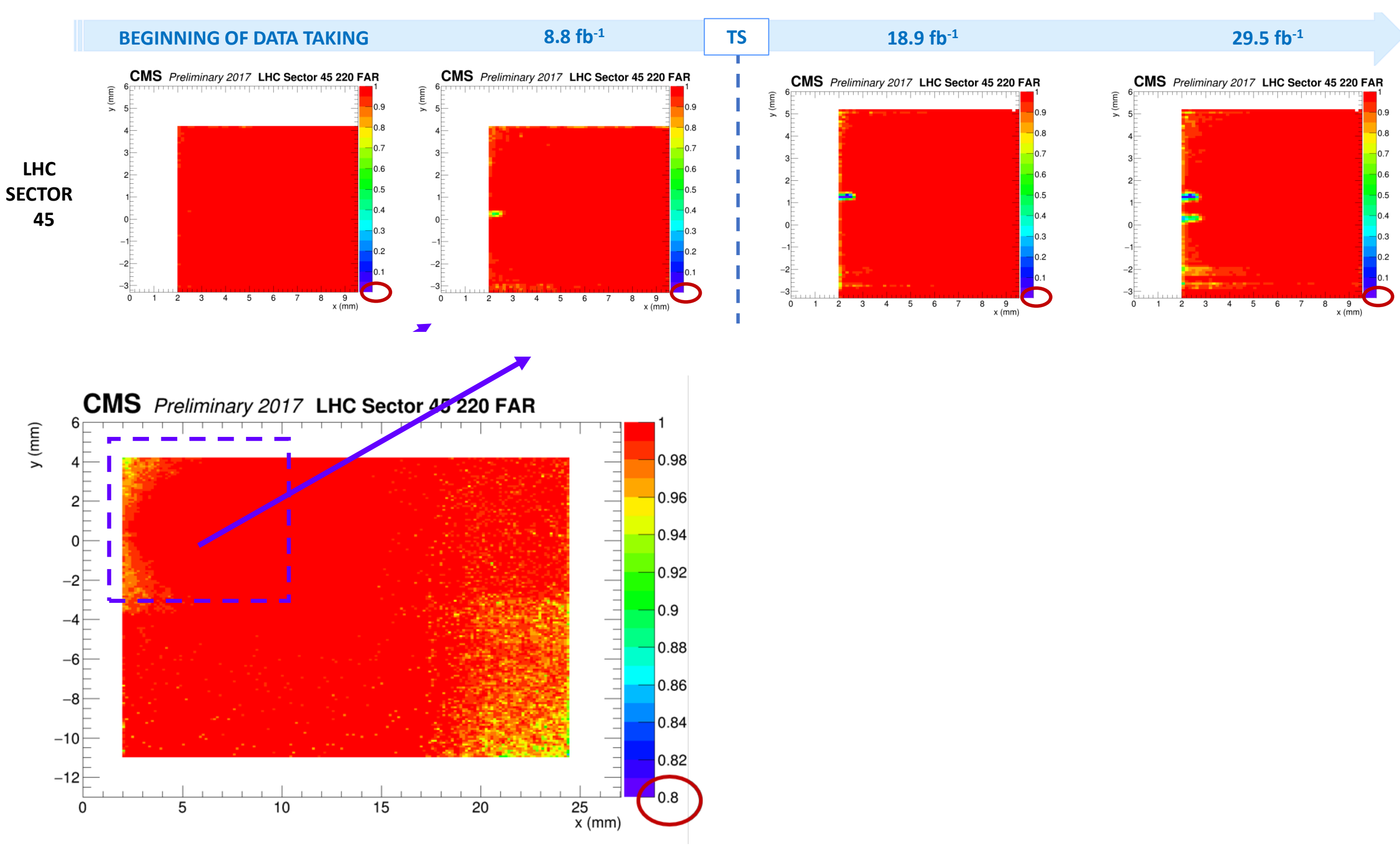
Run 3

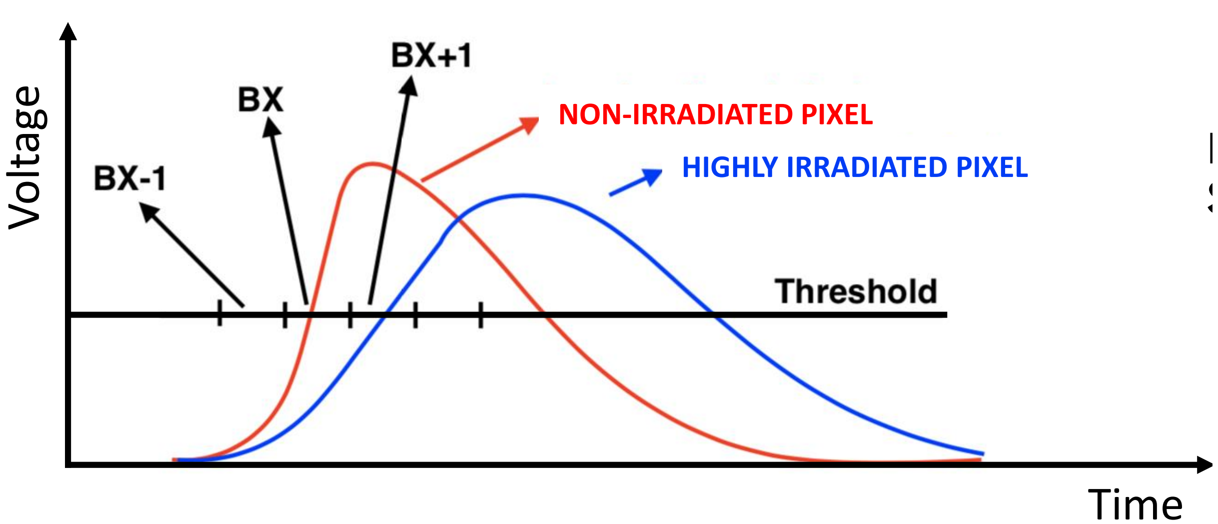
- Most PPS analyses will be statistics-limited, even with full Run 2 data

- **PPS will continue as a standard CMS sub-detector throughout LHC Run 3, beginning in ~~2021~~ 2022**
    - Opportunity to continue analyses with improved/stable detector conditions
        - Building on lessons from Run 2, plus improvements for Run 3
            - Detectors: sensors/electronics (following pages)
            - Automated calibration procedures
            - High-level triggers
            - Improved/GEANT4 simulations

    - **Expect ~300fb^{-1} collected by the end of Run 3**

Run 3: Tracking





- **Generally very good experience with 3D pixels in Run 2, and strong synergy with CMS central pixel detectors**
- Only real issue: highly non-uniform irradiation near the beam leads to some time drift/loss of efficiency from the Readout Chip
  - In Run 2 this was mitigated by manually shifting the pixel detector vertically, during a technical stop
- For Run 3
  - New sensors produced
  - **Small motor system will be installed allowing vertical movements to be performed remotely**

CERN-CMS-DP-2019-036

Run 3: Timing (I)

- **Much more challenging to commission and use timing/diamond detectors**
  - Reasonable efficiency maintained from beginning to end of 2018 run
  - Expected 50ps/plane not yet reached
    - Moderate loss of timing resolution, from early to late 2018 data

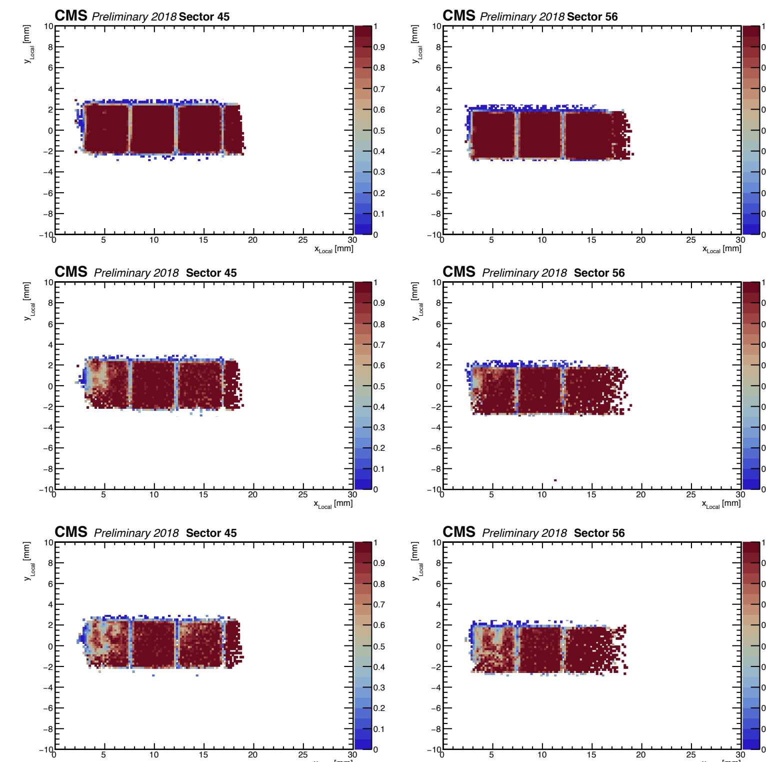
July 2018, low pileup

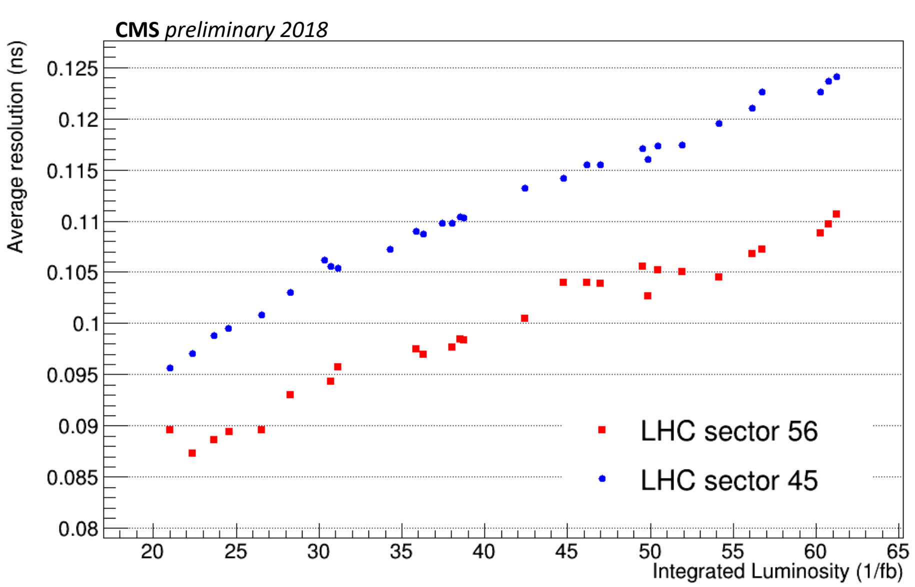
↓

July 2018, high pileup

↓

October 2018, high pileup





1 track in both pixel tracker stations & 4 diamond planes & 1 pad per plane

- **Extensive testbeam campaign was carried out after Run 2, using the irradiated diamonds**
  - With optimized LV/HV settings and ideal readout: no significant loss of efficiency, still close to 50ps resolution

CERN-CMS-NOTE-2020-007
CERN-CMS-DP-2019-034

Run 3: Timing (II)

- **Major campaign to optimize timing for Run 3**
  - Aim approach the 50ps/plane (with 8 planes per arm) obtained in testbeams
- Brute force improvements
  - **Instrument a 2nd RP station for timing: done**
  - All “double-diamond” sensors (2 diamonds connected to each amplification channel), including new production
    - Equivalent increase from ~6 to ~16 timing measurements per track
- Electronics improvements
  - Revised hybrid and discriminator board designs
  - Remote LV control
  - Monitoring/spy channels of signal shapes before digitization

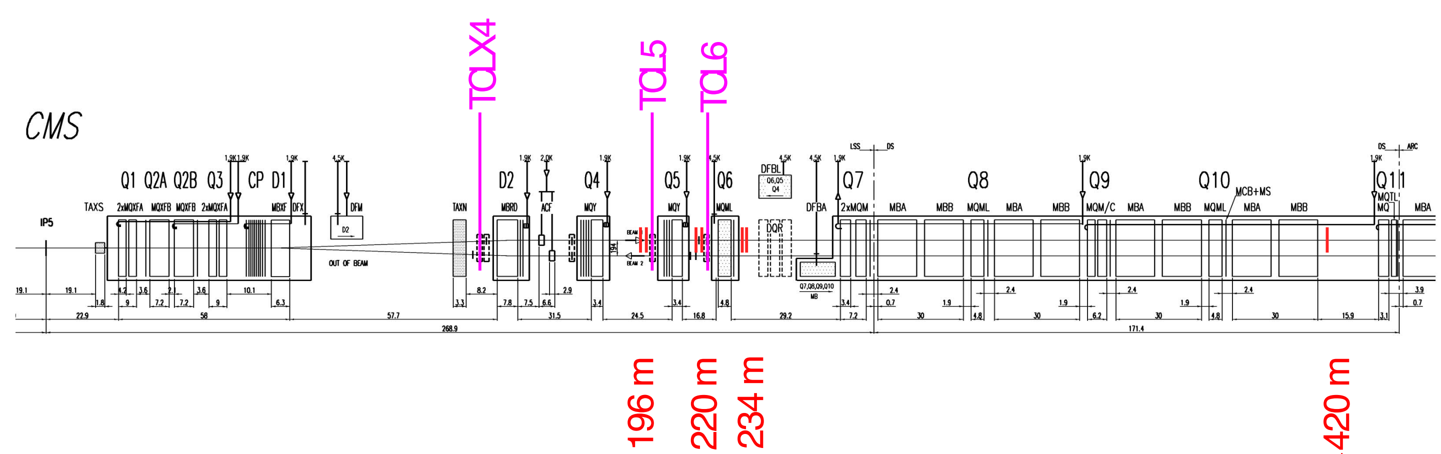
Migration of the Roman Pots, in their natural environment

The future: LHC Run 4 and beyond

After Run 3?

- **After Run 3, all existing Roman Pot installations must be removed to allow reconfiguration for HL-LHC**
    - **In 2018, began exploring possibilities for HL-LHC in CMS, together with LHC machine experts**
    - 4 possible locations identified in the HL-LHC tunnel

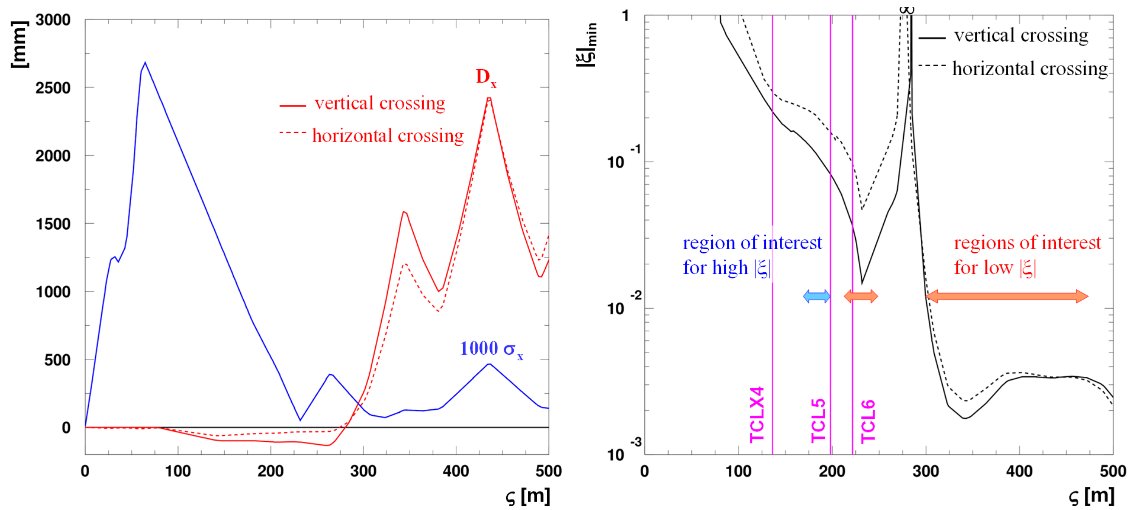
- **“Traditional” (Run 2-like) Roman Pots at 196, 220, 234m from IP5**
- **More challenging region at 420m (devices must be *between* the LHC beampipes, and between cryo-cooled regions)**



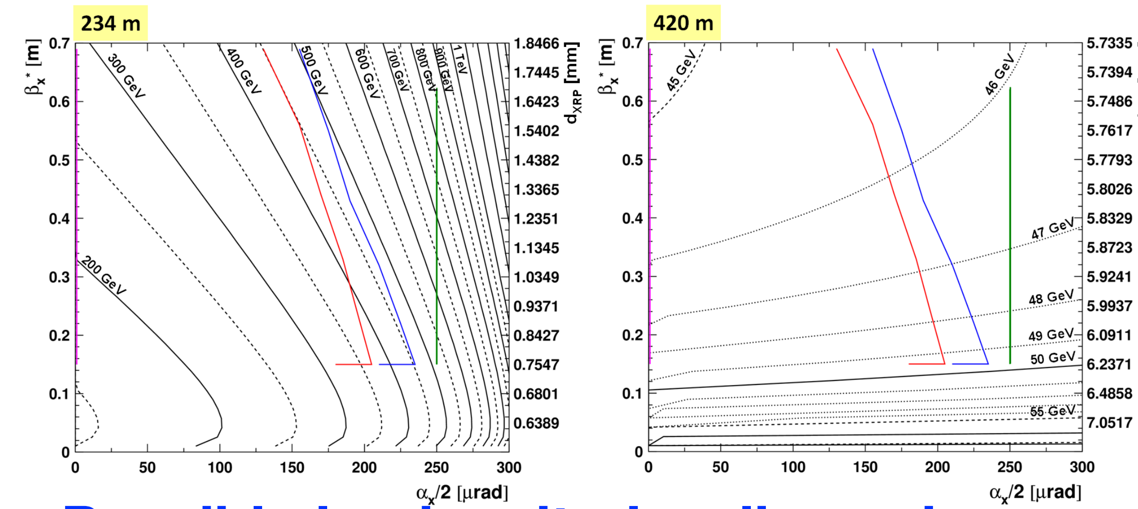
Roman Pot locations

Non-RP location

Suitability of these locations?

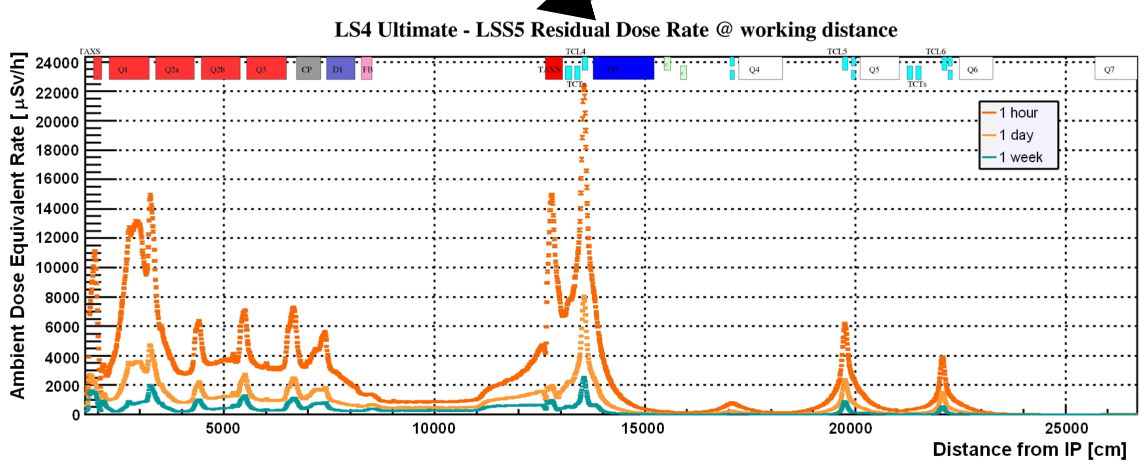


HL-LHC “optics”/crossing angles



Possible luminosity-leveling schemes (change of acceptance during fills)

Detailed studies performed, considering various effects



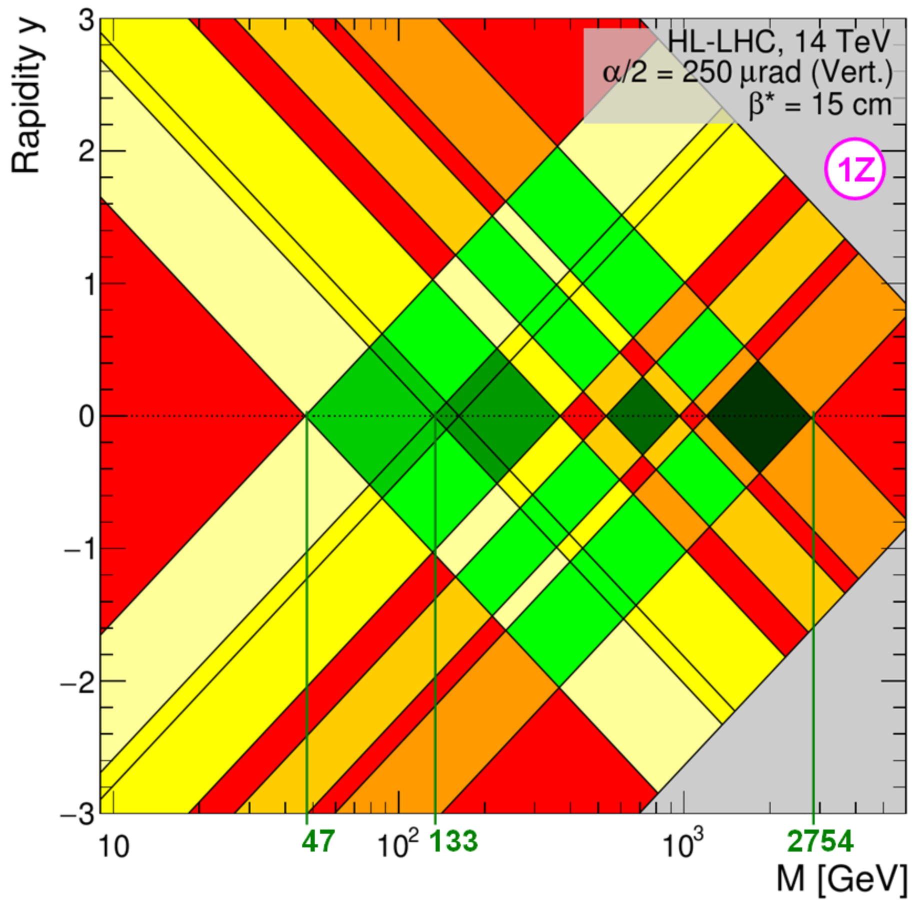
Tunnel radiation levels (HL-LHC simulations) and requirements on detector segmentation

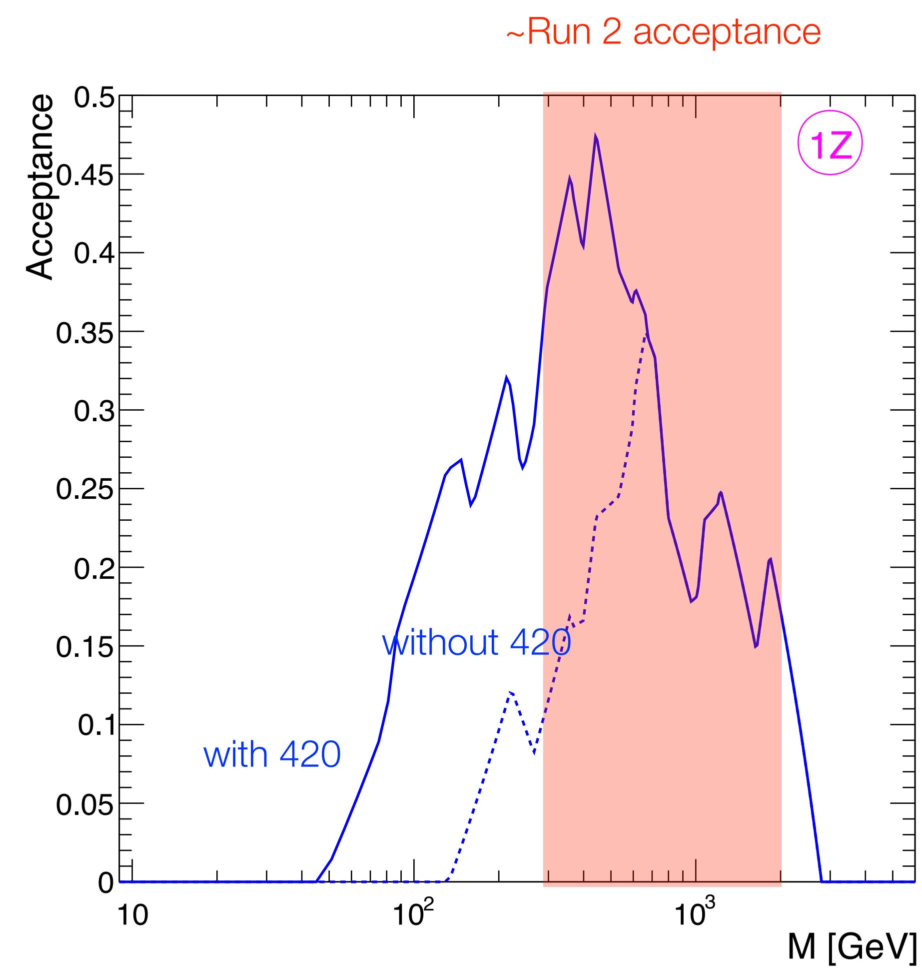
Predicted heat load

Impedance simulations/benchmarks against Run 2 data

Cooling/heat exchanger R&D tests

Acceptance: HL-LHC vs. Run 2/3



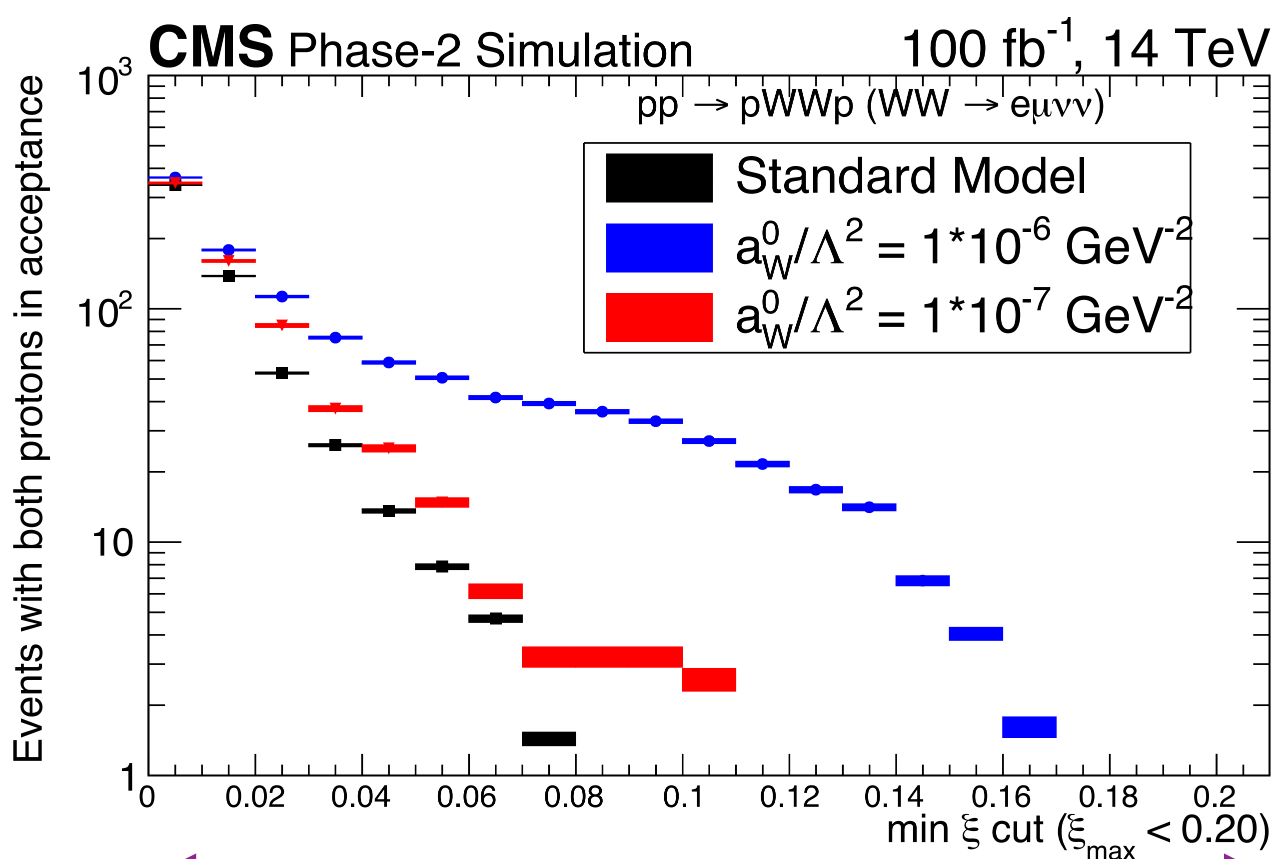


- **Green diamonds (left plot)**: mass-rapidity range where both protons can be detected (end of fill)
- Large (not completely continuous) acceptance between ~50 GeV and 2.7 TeV, and rapidity ±2
    - **Significantly larger than Run 2/3**

Impact on physics

- **Many final states reviewed, at the level of simple generator-level studies or external phenomenological studies**
  - Essentially all physics processes benefit from increased luminosity and/or increased acceptance: example for $\gamma\gamma \rightarrow WW$ with anomalous couplings

Luminosity: increase statistics for rare processes

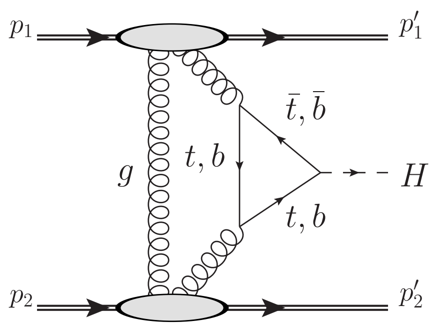


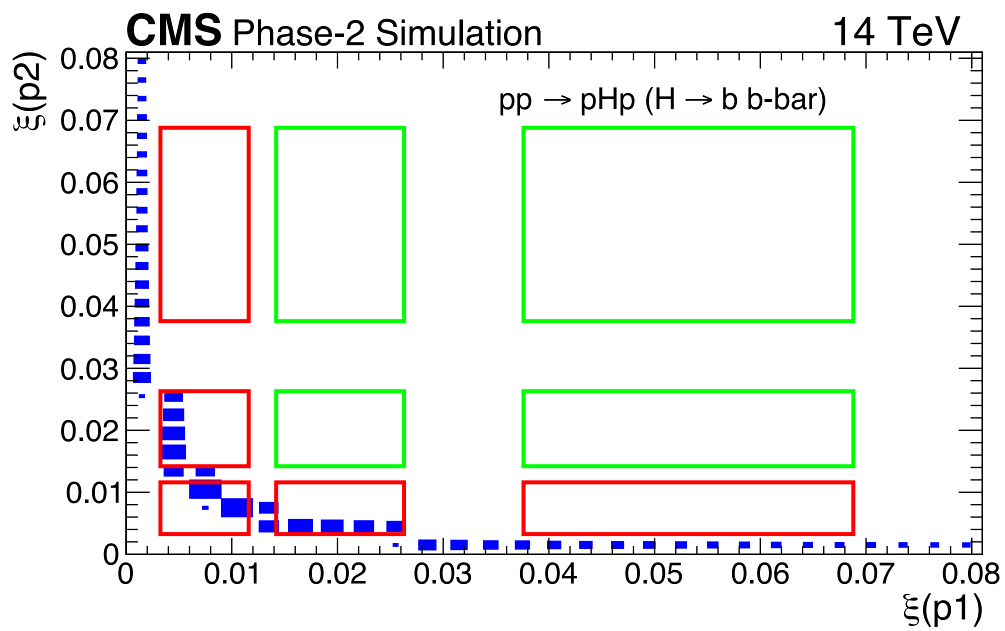
Low ξ/low mass coverage: increase acceptance for SM processes

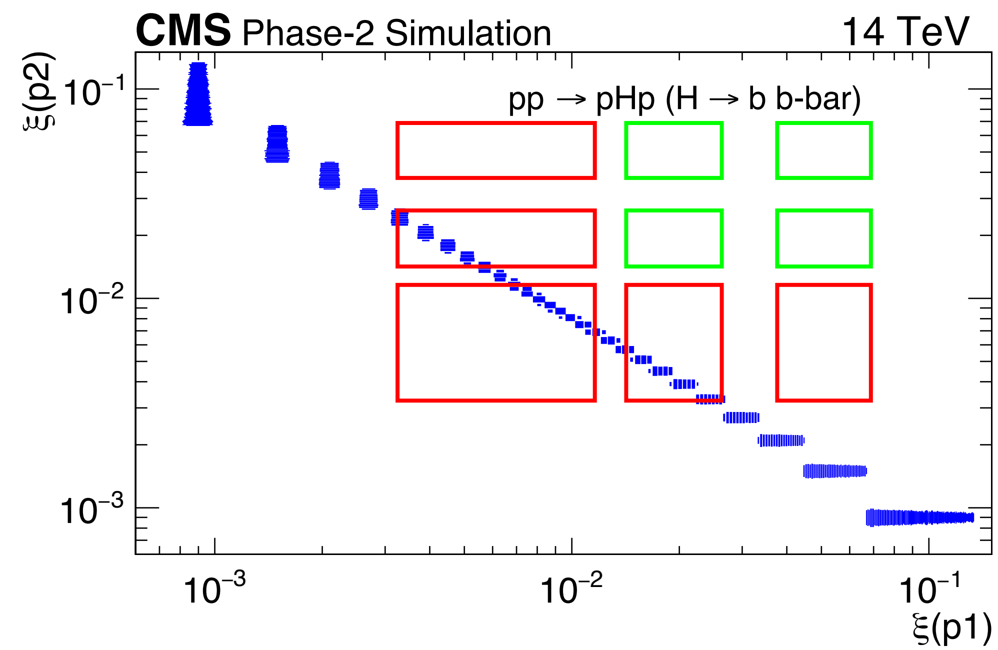
High ξ/high mass coverage: increase acceptance for BSM searches

Impact on physics: very low mass acceptance with 420m

Red: with 420m. Green: without 420m







- Even without 420m station, improved low mass acceptance compared to Run 2/3 helps with most SM processes
  - Addition of 420m further helps by reducing minimum from ~130 GeV to ~50 GeV
  - **Unique feature of the 420m location: only possibility for detecting exclusive production of 125 GeV SM Higgs (pp→pHp)**

420m: Everything old is new again

- **The 420m region was studied in detail by the FP420 R&D collaboration (joint effort of CMS+ATLAS) 12 years ago**
  - Final report published in JINST (176 pages, >275 citations) but the project was not pursued
  - Early studies of mechanics, machine integration, cost, to be revived

JINST 4 (2009) T10001

arXiv:0806.0302v1 [hep-ex] 2 Jun 2008

June 2, 2008

The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC

M. G. Albrow[1], R. B. Appleby[2], M. Arneodo[3], G. Atoian[4], R. Barlow[2], W. Beaumont[5], L. Bonnet[6], A. Brandt[7], P. Bussey[8], C. Buttar[8], J. M. Butterworth[9], M. Carter[10], B.E. Cox[2,], D. Dattola[11], C. Da Via[12], J. de Favereau[6], D. d'Enterria[13], P. De Remigis[11], A. De Roeck[13,5,*], E.A. De Wolf[5], P. Duarte[7,†], J. R. Ellis[13], B. Florins[6], J. R. Forshaw[12], J. Freestone[12], K. Goulianos[14], J. Gronberg[15], M. Grothe[16], J. F. Gunion[17], J. Hasi[12], S. Heinemeyer[18], J. J. Hollar[15], S. Houston[8], V. Issakov[4], R. M. Jones[2], M. Kelly[12], C. Kenney[19], V.A. Khoze[20], S. Kolya[12], N. Konstantinidis[9], H. Kowalski[21], F. Lanni[22], H.E. Larsen[23], S.-L. Liu[24], A. Lyapine[9], F.K. Loebinger[12], R. Marshall[12], A. D. Martin[20], J. Monk[9], I. Nasteva[12], P. Nemegeer[6], M. M. Obertino[3], R. Orava[25], V. O'Shea[8], A. Pal[7], S. Parker[19], J. Pater[12], A.-L. Perrot[26], T. Pierzchala[6], A. D. Pilkington[12], J. Pinfold[24], K. Piotrzkowski[6], W. Plano[12], A. Poblaguev[4], V. Popov[27], K. M. Potter[2], V. Radeka[22], S. Rescia[22], F. Roncarolo[2], A. Rostovtsev[27], X. Rouby[6], M. Ruspa[3], M.G. Ryskin[20], A. Santoro[28], N. Schul[6], G. Sellers[2], A. Solano[23], S. Spivey[7], W.J. Stirling[20], D. Swoboda[26], M. Tasevsky[29], R. Thompson[12], T. Tsang[22], P. Van Mechelen[5], A. Vilela Pereira[23], S.J. Watts[12], M. R. M. Warren[9], G. Weiglein[20], T. Wengler[12], S.N. White[22], B. Winter[10], Y. Yao[24], D. Zaborov[27], A. Zampieri[11], M. Zeller[4], A. Zhokin[5,27]*

FP420 R&D Collaboration

[1]Fermilab, [2]University of Manchester and the Cockcroft Institute, [3]Università del Piemonte Orientale, Novara, and INFN, Torino, [4]Yale University, [5]Universiteit Antwerpen, [6]Université Catholique de Louvain, [7]University of Texas at Arlington, [8]University of Glasgow, [9]University College London (UCL), [10]Mullard Space Science Laboratory (UCL), [11]INFN Torino, [12]University of Manchester, [13]CERN, PH Department, [14]Rockefeller University, NY, [15]Lawrence Livermore National Laboratory (LLNL), [16]University of Wisconsin, Madison, [17]UC Davis, [18]IFCA (CSIC-UC, Santander), [19]Molecular Biology Consortium, Stanford University, [20]Institute for Particle Physics Phenomenology, Durham, [21]DESY, [22]Brookhaven National Lab (BNL), [23]Università di Torino and INFN, Torino, [24]University of Alberta, [25]Helsinki Institute of Physics, [26]CERN, TS/LEA, [27]ITEP Moscow, [28]Universidade do Estado do Rio De Janeiro (UERJ), [29]Institute of Physics, Prague

- **Distributed nature of PPS detectors allows staged installation**
  - Possible approach: 3 well-understood Roman Pot locations target LHC Long Shutdown 3 (2025-2027), more ambitious 420m station targets LS4 (2031-2032)

Detectors: synergies with central CMS upgrades

- PPS pixel tracking detectors are already strongly aligned with the Phase-II tracker upgrade
- Several options for timing detectors: diamonds (current PPS), LGAD (CMS MTD-ETL upgrade)

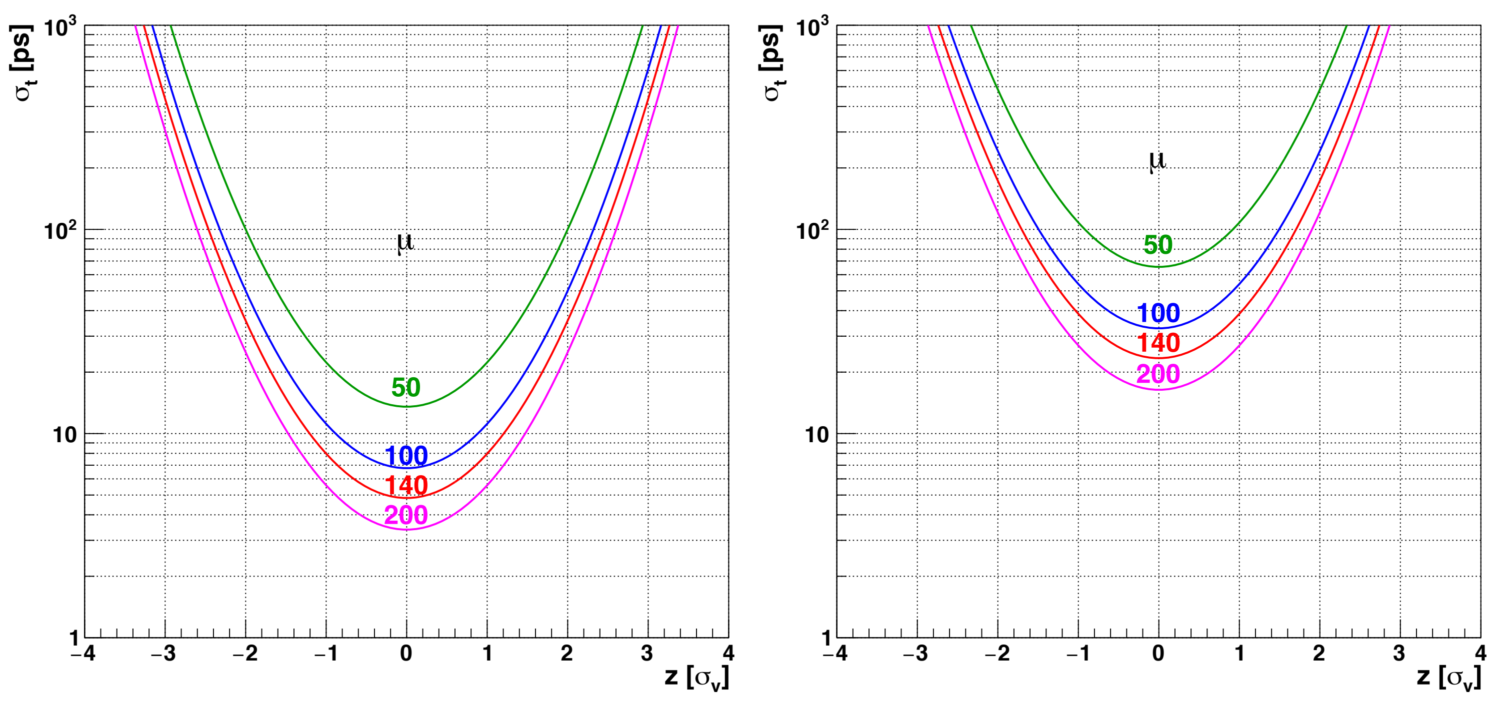


Figure 47: Time resolution required per spectrometer arm to resolve the mean vertex distance at a position z (in units of the longitudinal vertex width σ_v) from the IP centre. Four different pileup multiplicities are shown: $\mu = 50$ (LHC Run 2), 100, 140 (nominal HL-LHC performance), and 200 (ultimate HL-LHC performance). Left: for standalone PPS timing. Right: combining the PPS timing with the MTD system, selecting a time-slice of ± 50 ps around the central bunch crossing time.

- In Run 2/3, the **difference** of PPS proton times is correlated with the vertex position in the CMS Si-tracker
- In Run 4+, CMS will have precise timing in the central region, thanks to the MTD upgrade (LIP leadership in electronics - see Feb. 4 LIP seminar!)
  - The **absolute/sum** of proton times in PPS can be correlated with the vertex time measured in MTD

- PPS could achieve the same level of vertex separation with less stringent timing requirements, thanks to central timing from the MTD

HL-LHC upgrade Expression of Interest

- HL-LHC studies described in a detailed (90 page) “Expression of Interest”, reviewed internally throughout 2020
- **Approved by CMS just before Christmas**
- Initial presentations and discussion of space reservations started with HL-LHC coordination and LHCC
    - **Organizing next steps towards R&D and a TDR**

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, $pp \to pXp$, 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.

The CMS Collaboration intends to pursue the study of central exclusive production (CEP) events, $pp \to pXp$, at the High-Luminosity LHC (HL-LHC) by means of a new near-beam proton spectrometer.

Summary (I): LHC Run 2/3

- **PPS began in 2014, and successfully recorded >100fb^{-1} of data in Run 2 from 2016-2018**
  - First results from Run 2 on SM processes and BSM searches (plus QCD physics from special CMS+TOTEM runs)
  - A factor ~10x more luminosity now available, with good proton reconstruction
- **For Run 3, continue operations with improvements based on Run 2 experience**
  - Remote movement of pixels to mitigate non-uniform irradiation of readout chips
  - Large effort to improve timing performance: additional timing station, modified front-end electronics
- **LIP has been one of the leading institutes in the project since the beginning, and contributed to almost all aspects (hardware/firmware/software/operations/trigger/calibrations/reconstruction/physics…)**

Summary (II): Upgrade

- Beyond Run 3: all existing Roman Pots will be removed, in preparation for the HL-LHC
- **A new Expression of Interest to re-install a PPS-like spectrometer for HL-LHC has just been approved by the CMS collaboration**
    - 4 locations identified in consultation with the machine, near 200m (classic Roman Pots), and at 420m (new technologies) - staging possible
    - Greatly expanded physics program in all dimensions: **Better high-mass acceptance * better low-mass acceptance * increased luminosity**
    - **Possible synergies with other upgrades/future detector developments: PPS was an "Early adopter" of rad-hard tracking and fast timing**
- Encouragement from LHCC and CMS management to continue technical discussions with the machine, physics studies, R&D

Summary of the Summary

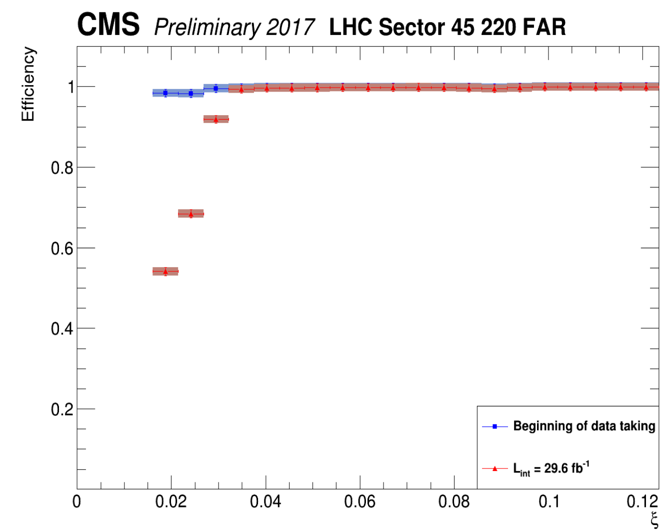
- **PPS presents several unique opportunities**
  - **Chance to work with LHC detectors at the "bleeding edge" of technologies: radiation hardness, timing resolution requirements**
  - **Physics with γ-γ (or IP-IP) interactions at new energies and unprecedented luminosities**
    - Probing anomalous couplings and other new physics in a new way
  - **Demonstrated ability to go from TDR to LHC data-taking in ~2 years (2014-2016)**
    - Timescale of a PhD/postdoc, in contrast to many larger detectors at the LHC

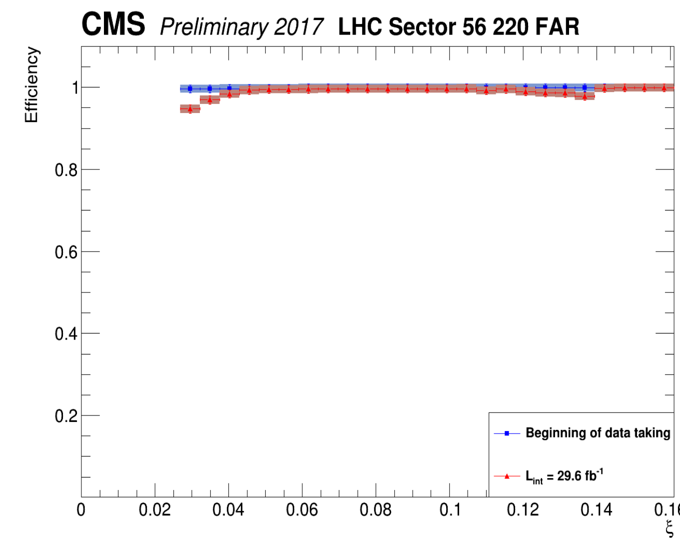
Welcoming new collaborators/institutes

Extra

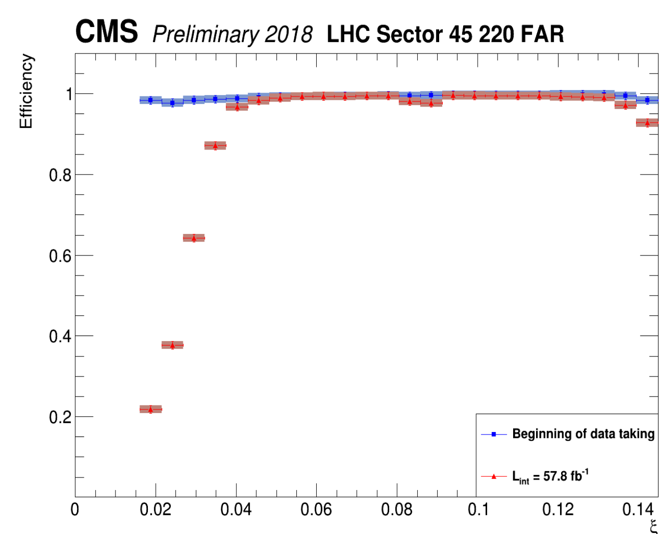
Detector performance - pixel/tracking

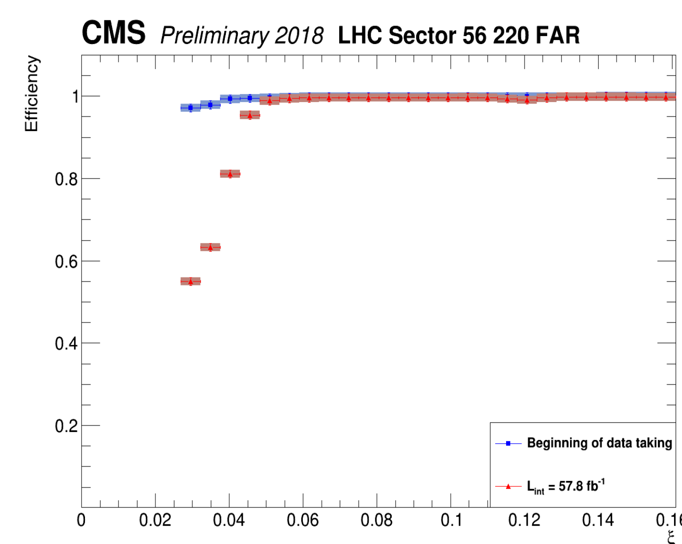
RP efficiency vs ξ (2017)



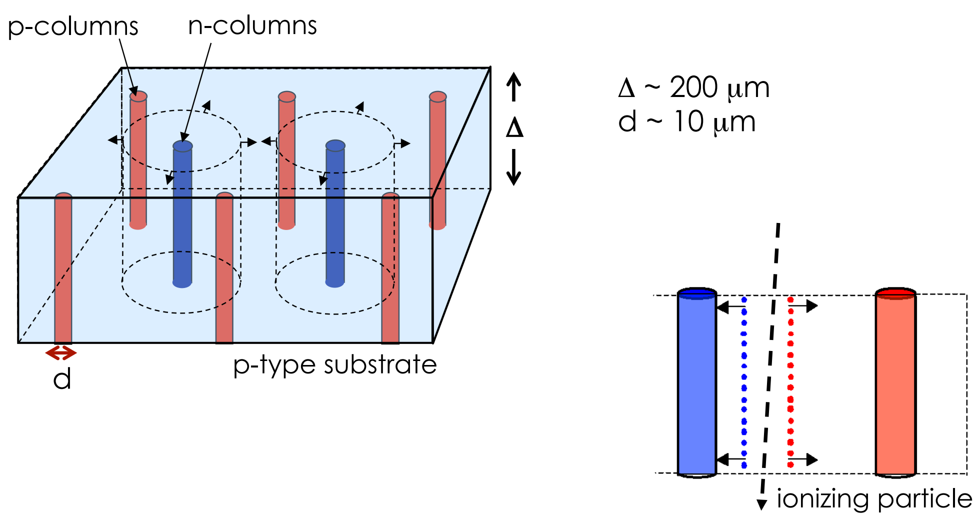


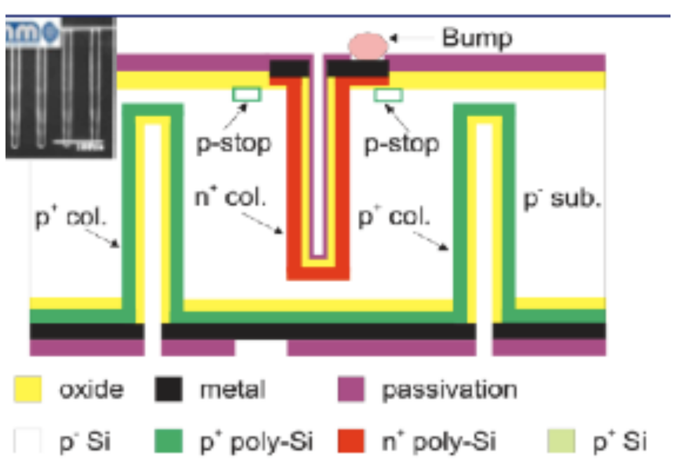
RP efficiency vs ξ (2018)





“3-d” silicon pixels for tracking

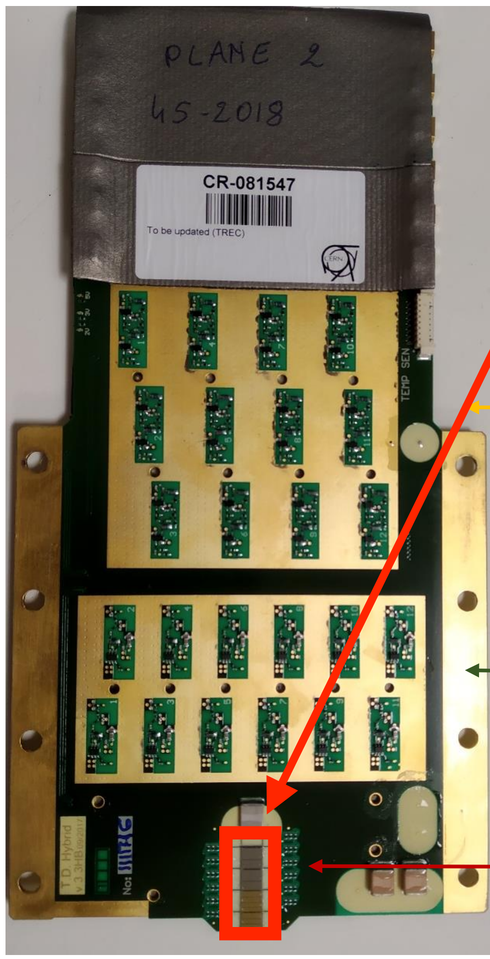




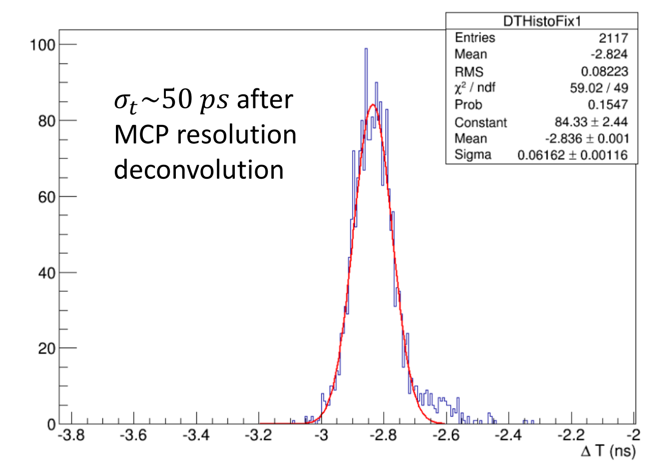
M. M. Obertino

- Electrodes in vertical columns through the substrate, instead of planes
  - Small collection distance without reducing wafer thickness/signal amplitude
  - Low trapping probability - high radiation hardness
    - Est. up to ~$5*10^{15}$ protons/cm^2 in 100 fb^{-1}
  - Low power dissipation
- Efficiency losses mainly due to highly non-uniform irradiation of readout chips, not sensors
  - Mitigated by vertically shifting detectors manually in Run 2, to be automated in Run 3

Diamond timing detectors



- Based on synthetic single-crystal carbon vapor deposit diamonds
- In 2017: 3 planes/arm of "single-diamonds" + 1 plane of ultra-fast silicon sensors
- In 2018: 2 planes of single-diamonds + 2 planes of double-diamonds/arm



Time difference distribution between DD and reference MCP ($\sigma_{t,MCP} \sim 40\ ps$)

E. Bossini

- Double diamonds: signal from 2 diamonds connected to same amplification channel
  - Larger signal amplitude => improved timing resolution
  - Up to 50ps/plane in ideal testbed conditions (oscilloscope readout, nominal LV and HV)
- For Run 3: 8 planes of double-diamonds/arm (in 2 stations)

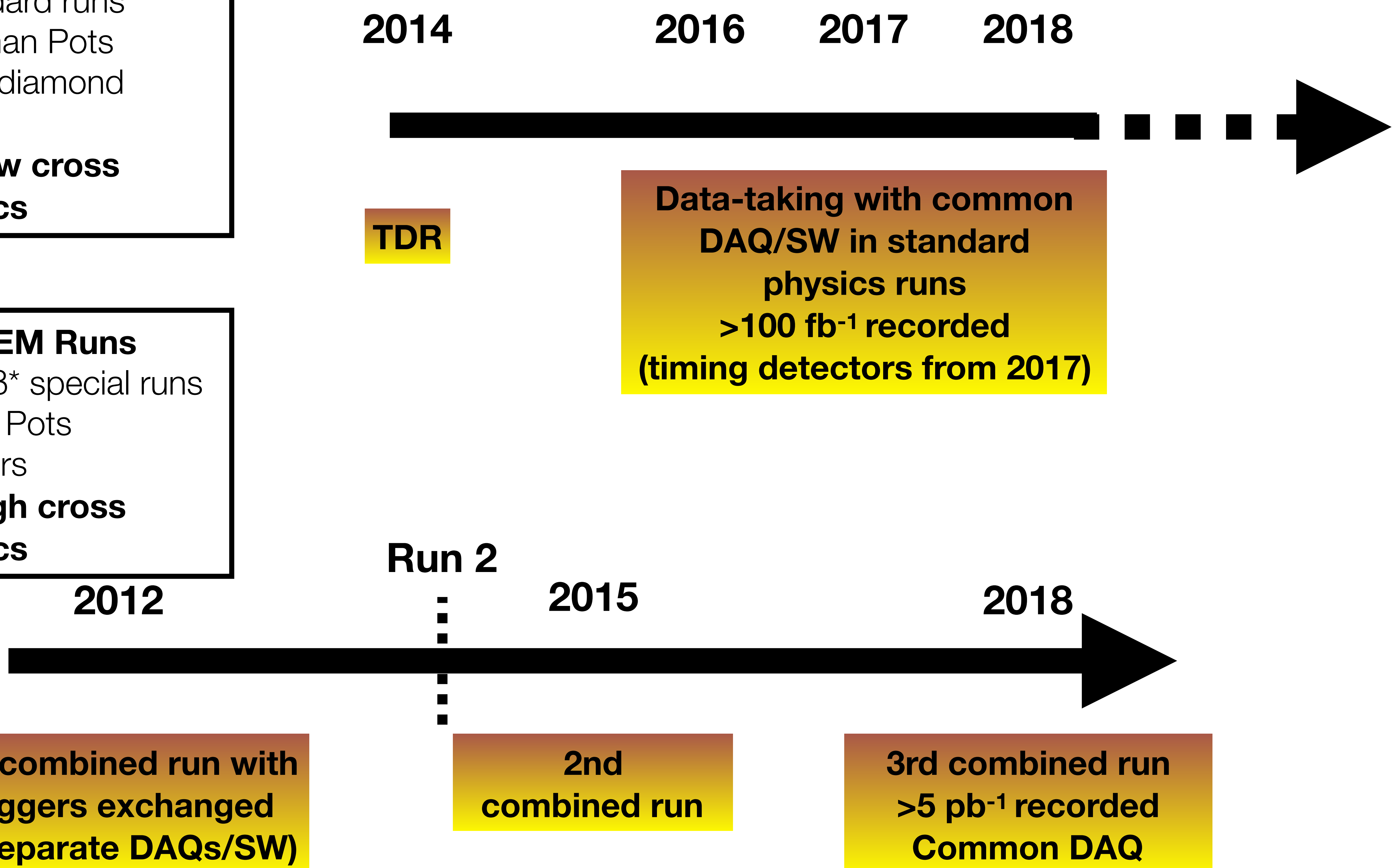
2 paths to combined physics with Roman Pots at P5 (CMS+TOTEM)

(CT-)PPS Project

- High lumi/standard runs
- Horizontal Roman Pots
- Si-pixel/strip & diamond detectors
- **High-mass/low cross section physics**

CMS+TOTEM Runs

- Low lumi/high β* special runs
- Vertical Roman Pots
- Si-strip detectors
- **Low-mass/high cross section physics**



Run 3: Miscellaneous

- **In addition to detector improvements, large efforts in the area of offline SW/ calibrations/trigger**
  - Automatic calibration procedures implemented for fast derivation of RP alignment and timing detector corrections
  - High-level triggers developed, to exploit proton information in exclusive processes
  - Full (GEANT4) and Fast simulation tools integrated in main CMS software