Challenges and first results venturing into uncharted territory with forward proton tags

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CP3 Seminar

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Outlook

The Large Photon Collider

The CMS-Totem Precision Spectrometer

Venturing into uncharted territory with CT-PPS

Other recent results and next chapters

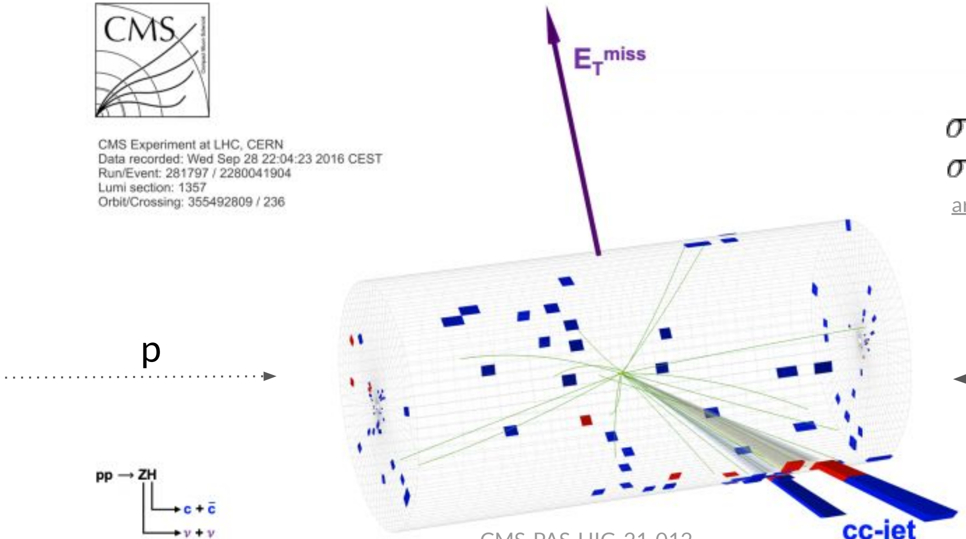
Summary

A large photon collider

Large Hadron Collider

It is a discovery machine colliding protons or heavy ions

- in each inelastic collision the constituents, carrying a fraction of the beam momentum, interact
- large phase covered for the momentum transfer (Q^2)
- interesting physics ranging “from the charm quark to the BEH boson” and beyond
- new states of matter, possibly new fields



$$\sigma_{\text{tot}} = 111 \text{ mb}$$
$$\sigma_{\text{inel}} \sim 72\%$$

arXiv:1712.06153

CMS-PAS-HIG-21-012

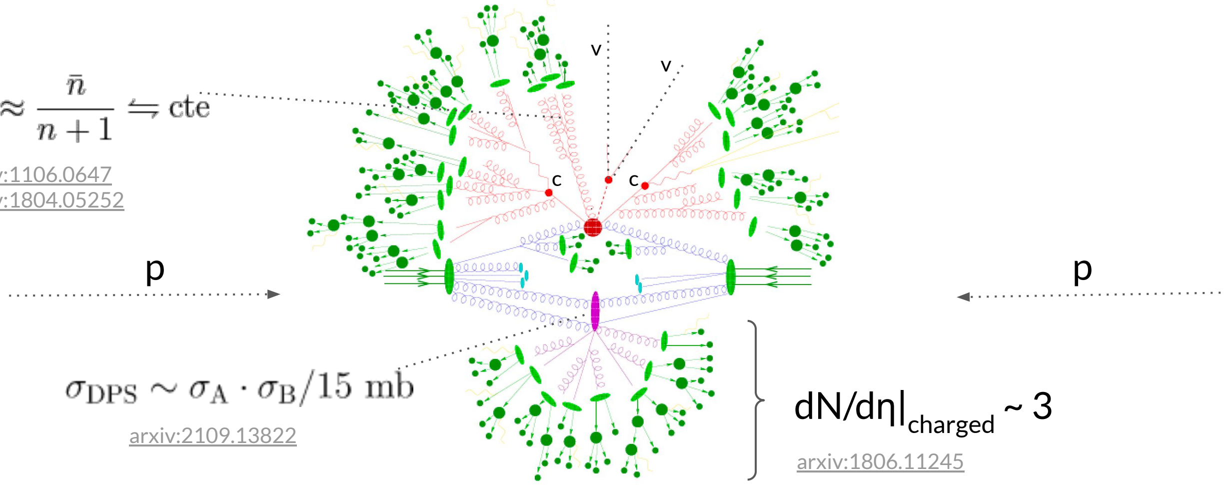
Large Hadron Collider

It is a discovery machine colliding protons or heavy ions

- in each inelastic collision the constituents, carrying a fraction of the beam momentum, interact
- large phase covered for the momentum transfer (Q^2)
- interesting physics ranging "from the charm quark to the BEH boson"
- new states of matter, possibly new fields
- but also proton remnants, multi-parton interactions, initial/final state radiation...

$$\frac{\sigma_{n}^{incl}}{\sigma_{n-1}^{incl}} \approx \frac{\bar{n}}{n+1} \leftrightharpoons cte$$

arXiv:1106.0647
arXiv:1804.05252



$$\sigma_{DPS} \sim \sigma_A \cdot \sigma_B / 15 \text{ mb}$$

arxiv:2109.13822

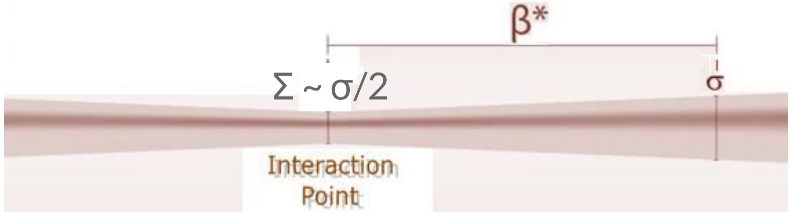
$dN/d\eta|_{charged} \sim 3$

arxiv:1806.11245

Energy and intensity at the LHC

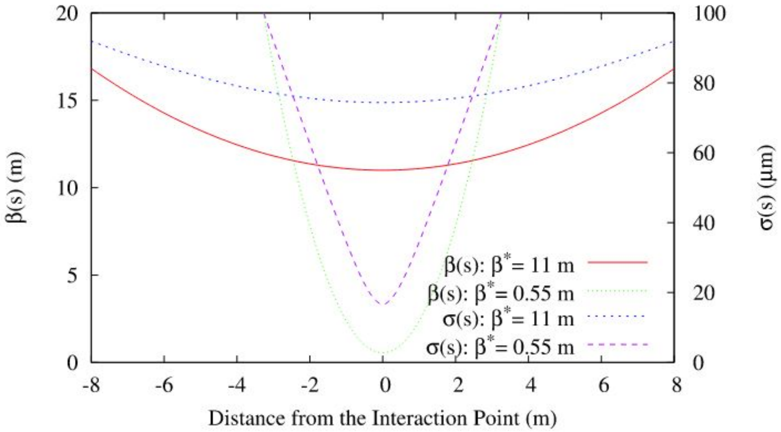
The LHC maximizes the discovery potential by

- pushing the energy frontier every new run: 7 - 13.6 TeV
- pushing the intensity/luminosity (ℒ) frontier



Higher luminosity involves typically

- increasing the number of bunches in the machine (N)
- increasing the separation factor
- increasing the geometric factor (~σ_x / Σ_x) keeping the beams as squeezed as possible (small σ)

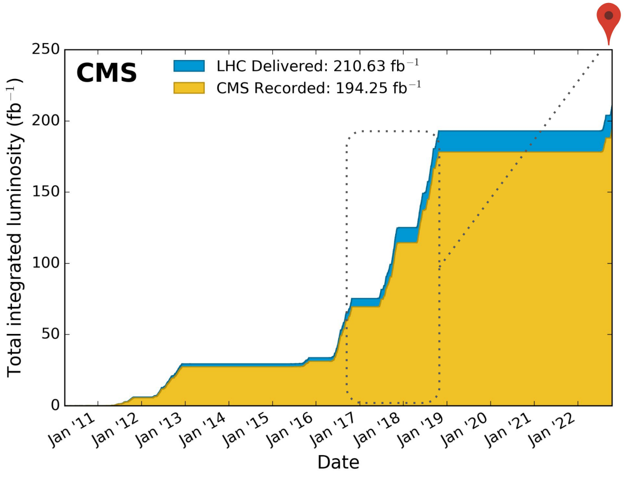


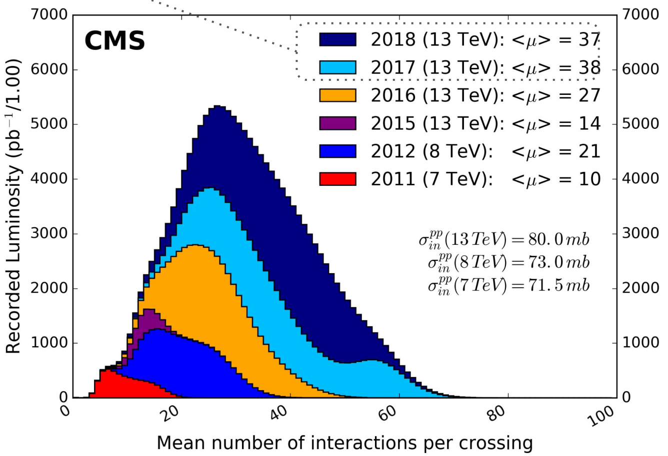
The amplitude function (□) and the crossing angle (α) are two relevant parameters steering the size at the IP

$$\Sigma_x^2 = \frac{2\varepsilon}{\beta^*}\cos^2(\alpha/2) + 2\sigma_z^2 \sin^2(\alpha/2)$$

Large pileup collider

this talk





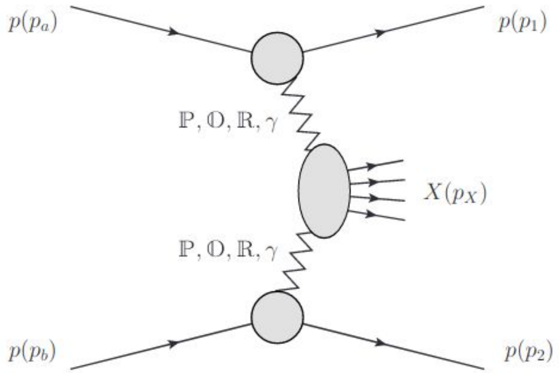
Most of LHC Run 2 data was taken at $s^{1/2}$=13 TeV with an average pileup of 38 pp collisions

- excellent performance of the machine and the detectors (CMS had >92% data taking efficiency)
- several new techniques developed to cope with pileup: *CMS DPS 2015-016*, arXiv:2003.00503
  - multi-bunch pulse fits in calorimeters
  - tracker-driven association of the charged particles: applied to jets (CHS), lepton isolation (δβ)
  - luminosity-driven probabilistic interpretation of the particle fluxes (PUPPI)
  - multivariate classifiers (PU jet id, deep jet) and regressors, and jet substructure techniques

Singling out photon (and gluon) collisions at the LHC

In rare occasions (typically <100 fb) a peculiar effect happens: the electrically charged beams stay intact and exchange a QCD color singlet

- at lower masses, $<\mathcal{O}(200\ \text{GeV})$, QCD color singlets dominate (|P, pomerons)
- at higher masses, $>\mathcal{O}(200\ \text{GeV})$, QED dominates (ɣ, photons)



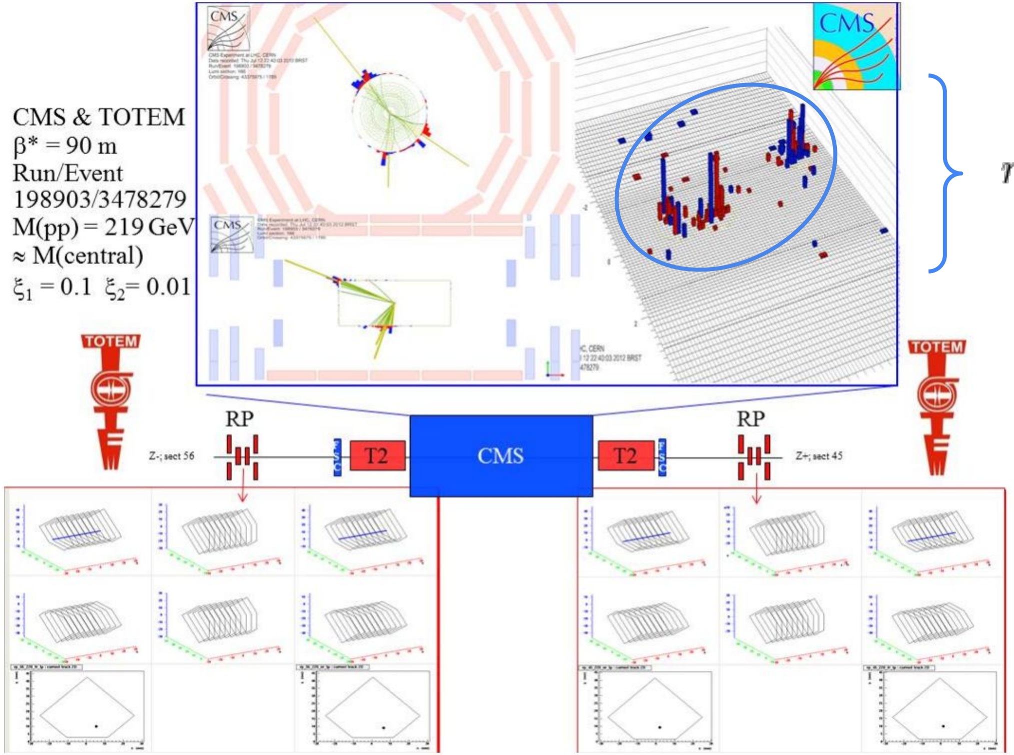
$$p(p_a) + p(p_b) \longrightarrow p(p_1) + X(p_X) + p(p_2)$$

The central state X

- production “filtered for” $J_z^{PC} = 0^{++}$
- is accompanied by two large rapidity gaps (i.e. additional QCD emissions are suppressed)

Full event reconstruction in central exclusive events

If the energy loss of the protons is measured ($\xi = \Delta p/p$) ⇒ no missing degrees of freedom



TOTEM-TDR-003

Central system

$$m_X = 2E_{\text{beam}}\sqrt{\xi_+\xi_-}$$

$$y_X = \frac{1}{2}\log\frac{\xi_+}{\xi_-}$$

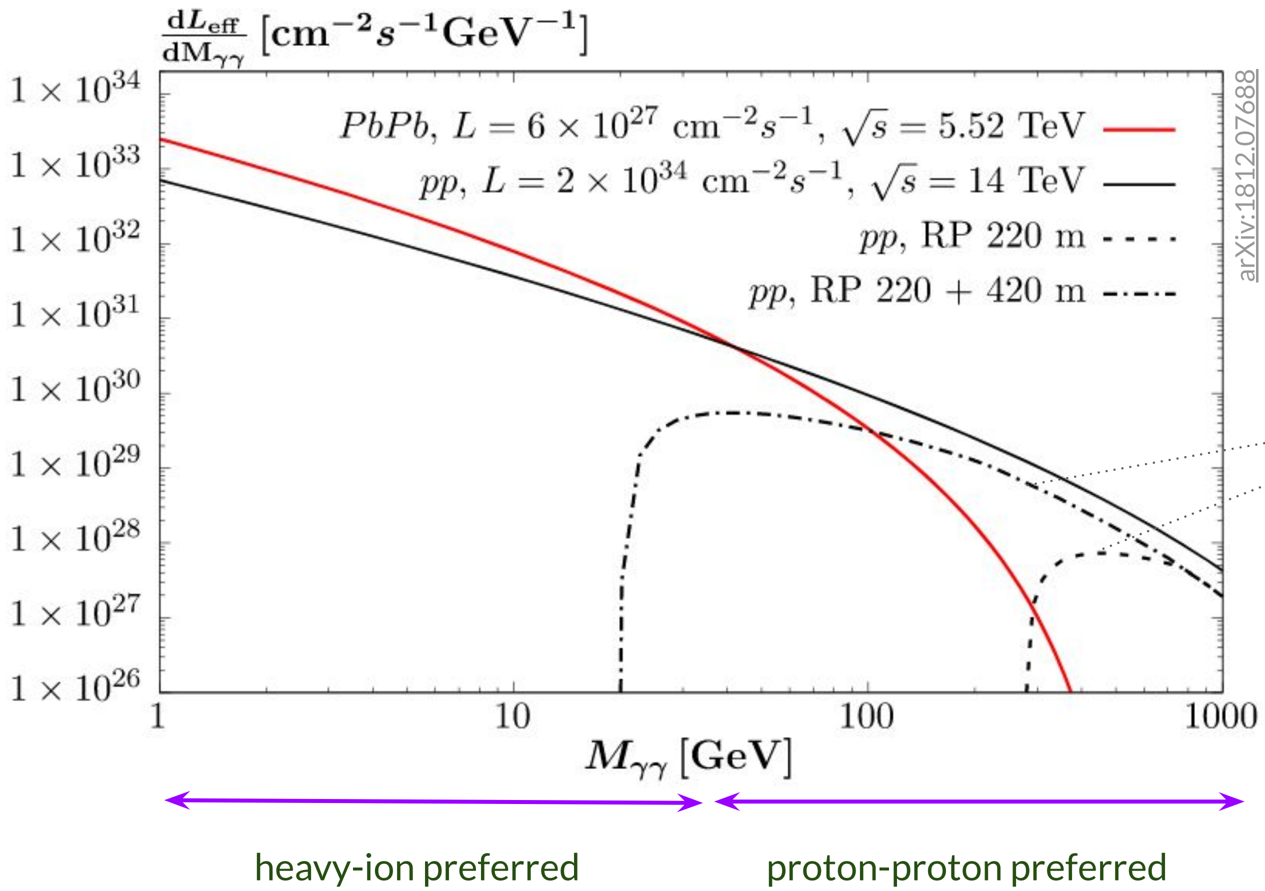
Can use forward protons to recover what the central detector missed!

Forward protons

$$\xi_\pm = \sum \frac{E_X \pm p_{z,X}}{2E_{\text{beam}}}$$

arXiv:9705393

Effective photon-photon luminosities at the LHC



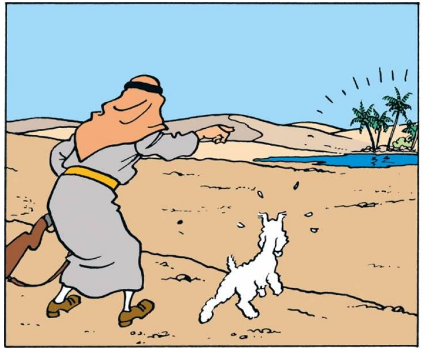
placement of the Roman Pots (RP) to measure protons will dictate final acceptance

Heavy-ions and proton-proton are complementary

At the LHC each collision type covers distinct phase spaces

Beam	**Heavy-ions**	**Proton**
Advantages	Photon flux enhanced by Z^4 Clean signature of ultra-peripheral coll. (UPC) No pileup	Energy and intensity frontier LHC prime time Full reconstruction of outgoing protons with detectors housed in RP
Drawbacks	Lower $\sqrt{s_{NN}}$ Limited LHC runs (1-2 weeks) No detection of outgoing ion	Lower photon fluxes Large pileup including diffractive processes with outgoing protons
Target	<20 GeV low mass UPC processes light BSM	>200-300 GeV heavy final states heavy BSM

The CMS-Totem Precision Spectrometer



The experimental apparatus

CT-PPS is composed of small tracking and timing detectors inside the LHC tunnel

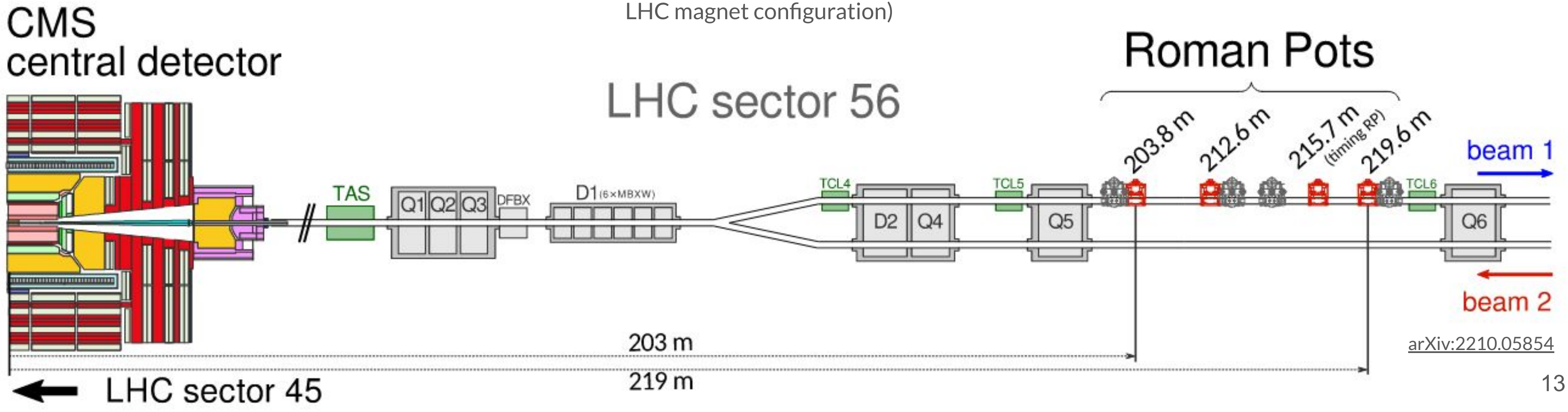
- ~200 m from CMS allows to detect protons scatter at small angles (rad)
- in the beam pipe the LHC magnets will bend the protons along the way
- protons reconstructed at a given position can be correlated to a fractional momentum loss (ξ)

$$\mathbf{d}(l) = T(l,\xi) \cdot \mathbf{d}^*$$

measured track in the RP located at a distance *l*

transport matrix (depends on LHC magnet configuration)

production state in IP5 ($x,\Theta_x,y,\Theta_y,\xi$)



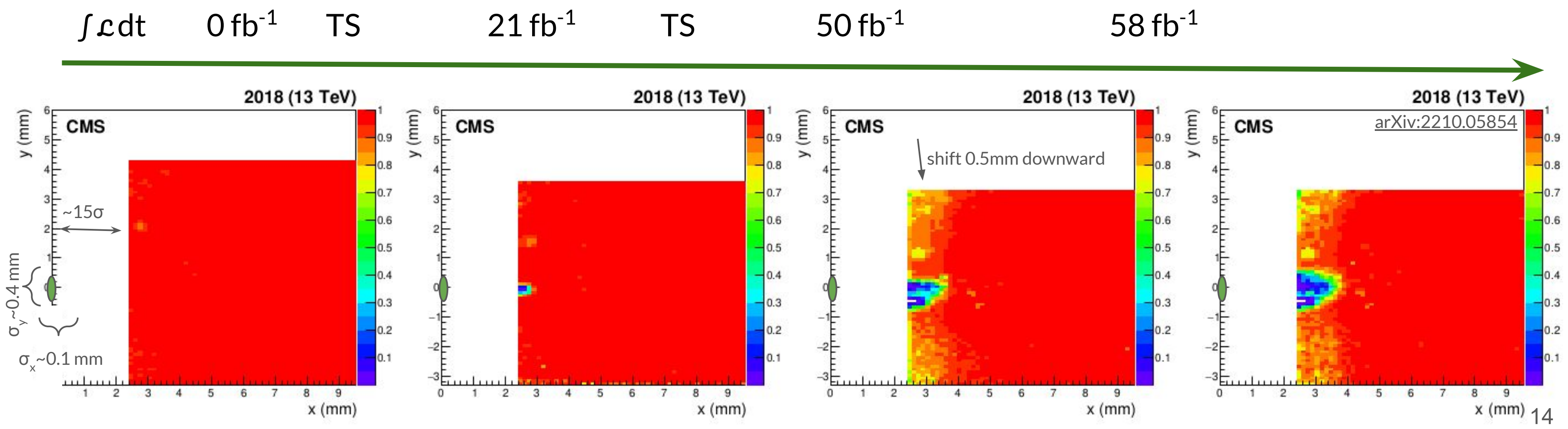
arXiv:2210.05854

The sensors

Solid-state sensors are used: Si (pixels and strips) and diamond

- evolution from Si strip to fully equipped 3D pixel stations throughout 2016-2018
- 10 μm tracking resolution sustained with proton fluxes up to $5 \times 10^{15} cm^{-2}$ and fluences up to $10^{12} n_{eq}/cm^2$
- electronics chain similar to CMS Tracker (e.g. RPix used as in CMS Phase I pixel upgrade)

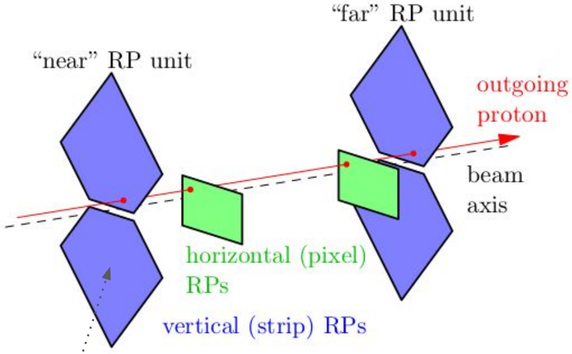
Although efficiency nears 100%, electronics affected by harsh radiation environment

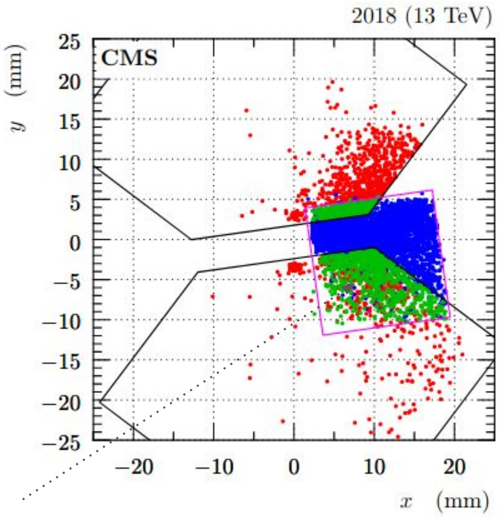


Alignment

The detectors are housed in RPs and lowered to their positions once beams are stable

- alignment of the detectors is needed using a special fill (2–3 bunches per beam)
- safer to bring sensors closer to beam (~6σ) increasing the overlap
- protons from elastic scattering (ξ=0) are used as candle for alignment
- align with iterative track fitting starting with $\mathcal{O}$(100 μm) tolerance and progressing to $\mathcal{O}$(10 μm)
- for physics runs, the distribution of proton tracks is matched to that of the reference run
- final absolute/relative alignment is obtained with a $\mathcal{O}$(150 μm) / $\mathcal{O}$(10 μm) uncertainty





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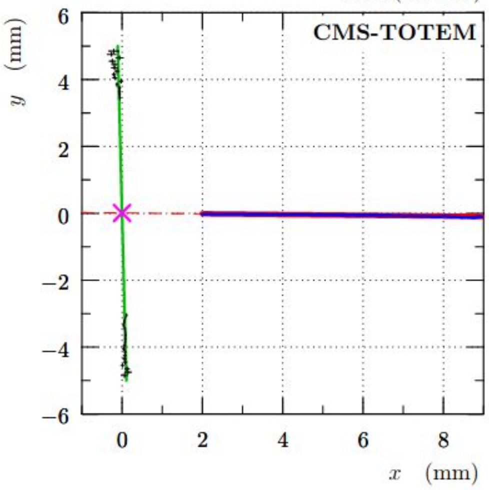


used for alignment fills

common hits

Calibration (main terms)

$$x = x_0 + D_x \cdot \xi + L_x(\xi) \cdot \theta_x^* + v_x(\xi) \cdot x^*$$
$$y = y_0 + D_y \cdot \xi + L_y(\xi) \cdot \theta_y^* + v_y(\xi) \cdot y^*$$

optical dispersion (main term)

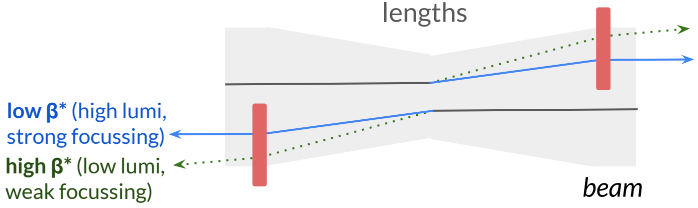
beam magnification factors

effective lengths

The transport equation can be reduced to a "few" terms

These require input from the LHC optics model and fill conditions

- LHC optics can be calculated using MAD-X



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optical dispersion (main term)

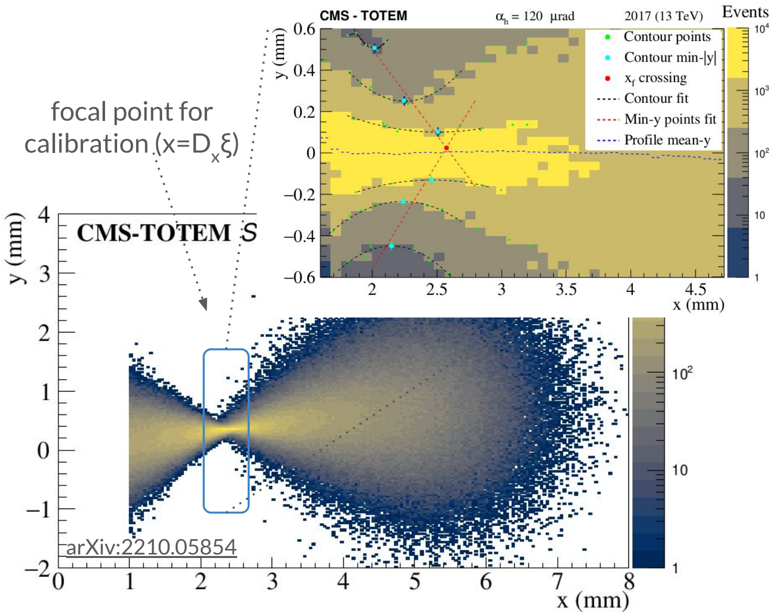
effective lengths

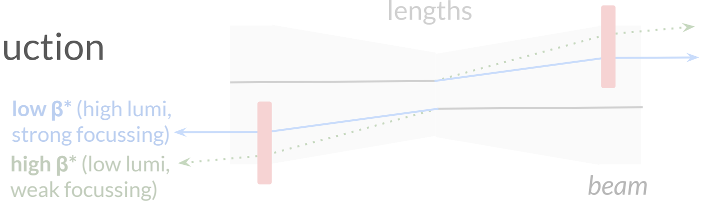
beam magnification factors

The transport equation can be reduced to a "few" terms

These require input from the LHC optics model and fill conditions

- LHC optics can be calculated using MAD-X
- use "vanishing" $L_y(\xi \simeq 4\%)$ point in min. bias collisions
- combine with measurement using semi-exclusive dilepton production





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optical dispersion (main term)

effective lengths

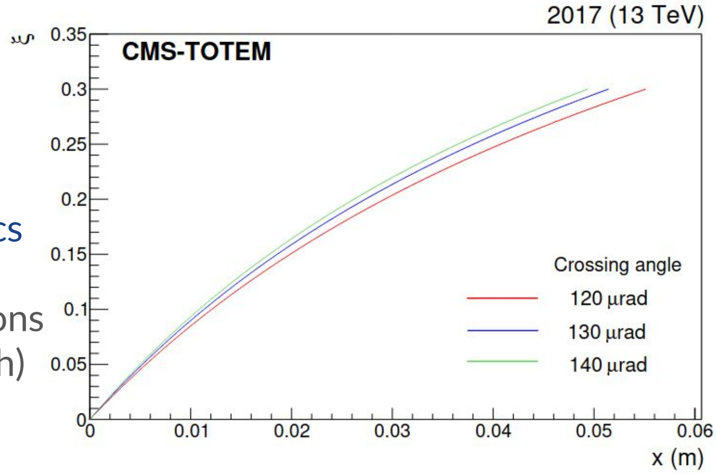
beam magnification factors

The transport equation can be reduced to a “few” terms

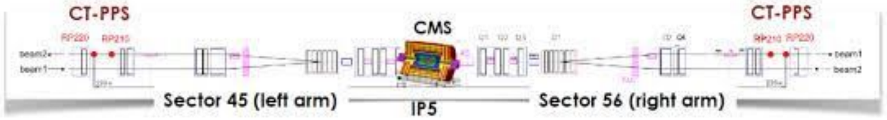
These require input from the LHC optics model and fill conditions

- LHC optics can be calculated using MAD-X
- use “vanishing” $L_y(\xi \approx 4\%)$ point in elastic collisions as reference
- combine with measurement using semi-exclusive dilepton production

Constraint further dispersion values varying the most relevant LHC optics (crossing angle, quadrupole positions and kicker strength)

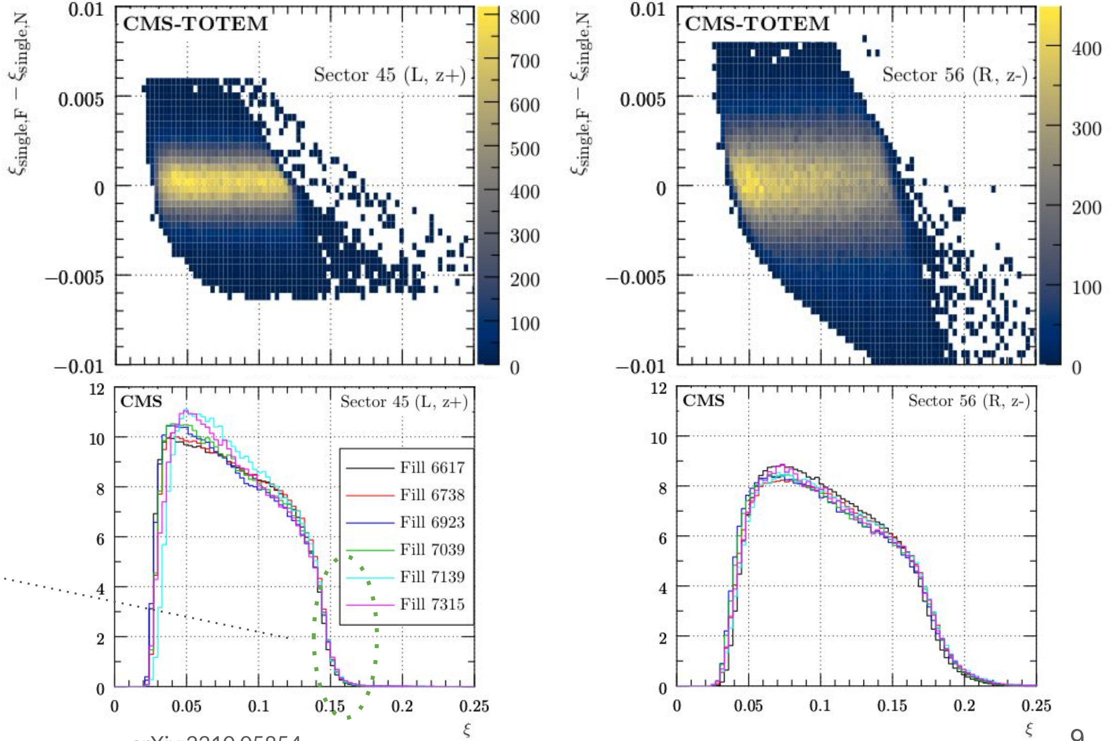


Proton reconstruction



Protons can be reconstructed from individual (single) or combining several (multi) RPs

- linear trajectory (B=0)
- overall unbiased and uncertainty < 1% (dominated by D_x calibration)
- multi-RP has optimal resolution < 5‰! (limited by detector spatial resolution)
- multi-RP larger systematics for ξ>0.15 (alignment, dispersion)
- … and reduced acceptance/efficiency from aperture constraints (collimators, beam screens, etc.)



arXiv:2210.05854

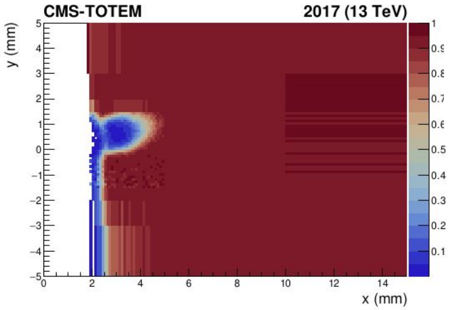
Tracking efficiency

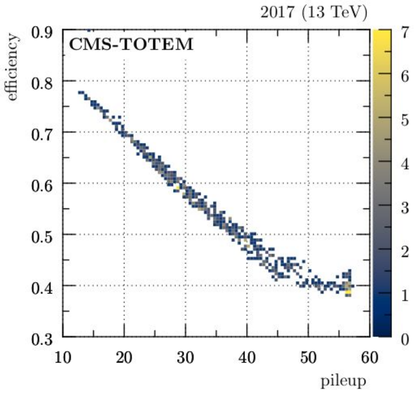
Besides inefficiency from radiation effects (s.14) additional effects compete

- Si strips become inefficient when hit by multiple protons
- matching between near and far stations depends on overlap and straight propagation
- availability of the detectors not uniform throughout each year! often (at least) one RP missing

These effects depend on the data-taking period and beam conditions (mostly crossing angle)

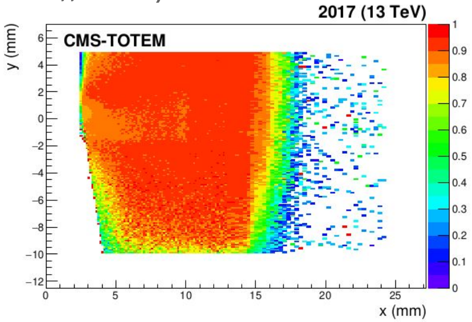
Strip tracking efficiency

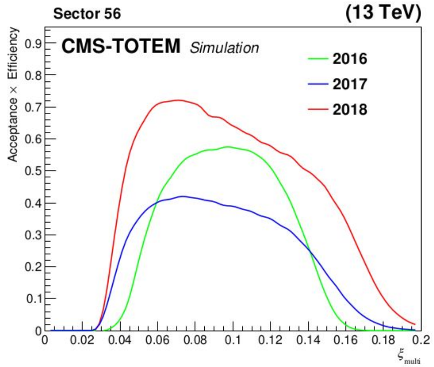




Strip multi-track inefficiency

multi-RP matching efficiency

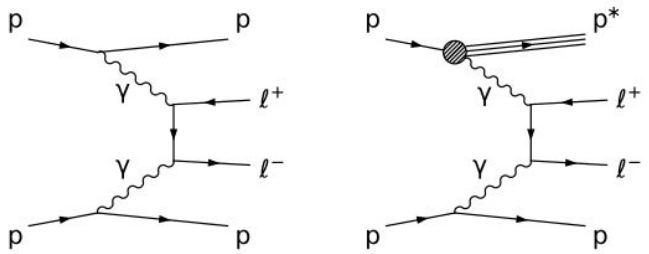




Combined acceptance x efficiency

arXiv:2210.05854

Validation with data



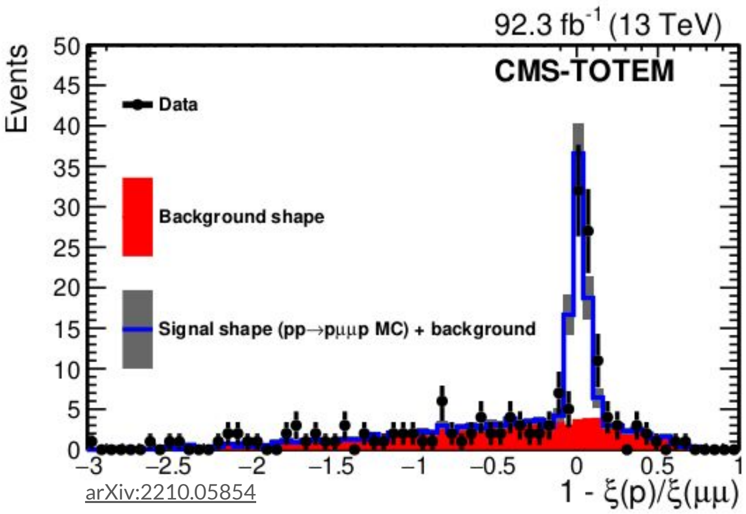
Exclusive di-muon production with at least one intact proton

- SM candle can be used to validate proton reconstruction
- full match between $\mu^+\mu^-$ kinematics and reconstructed proton

$$\xi(\mu^+\mu^-) = \frac{1}{\sqrt{s}}\left[p_{\mathrm{T}}(\mu^+)\mathrm{e}^{\pm\eta(\mu^+)} + p_{\mathrm{T}}(\mu^-)\mathrm{e}^{\pm\eta(\mu^-)}\right]$$

Control confirms both bias and resolution are under-control

- here shown for multi-RP reconstruction



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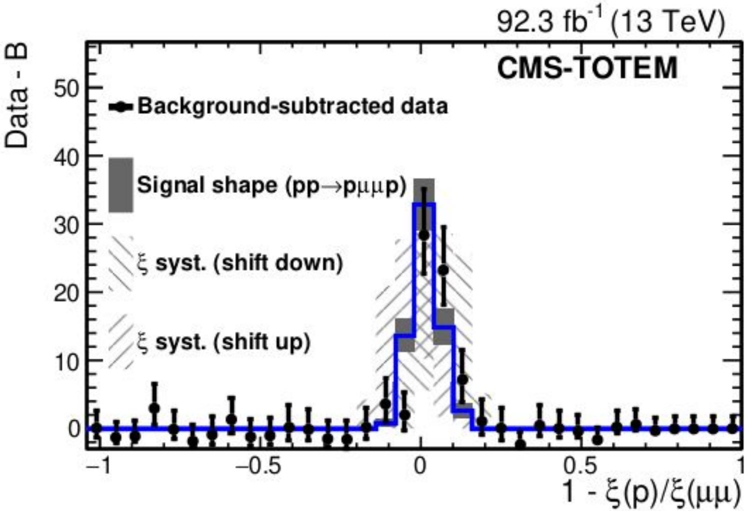
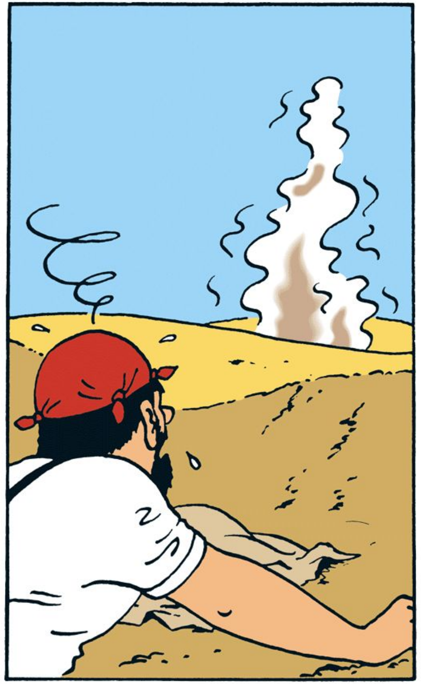


$m(\mu^+\mu^-)>100$ GeV
$\xi(\mu^+\mu^-)>0.04$
$1-|\Delta\phi(\mu^+\mu^-)|/\pi<0.009$

Venturing into uncharted territory



A simple idea

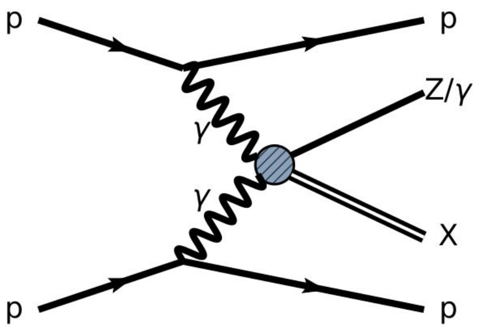
Let’s say we are looking for Z produced in association with a system X (not resolved)

X can be another Z or a g, a DM candidate, …

If such events can be produced from photon-photon collisions

$$m^2_{\mathrm{miss}} = \left[\underbrace{(P^{\mathrm{in}}_{p_1} + P^{\mathrm{in}}_{p_2})}_{LHC} - (\underbrace{P_V}_{CMS} + \underbrace{P^{\mathrm{out}}_{p_1} + P^{\mathrm{out}}_{p_2}}_{PPS})\right]^2$$

- use Z-triggered events with two proton tags
- reconstruct the missing mass in the event (X is not necessarily specified)
- m_{miss} is a typical LEP estimator (also used in B-physics)



Although no theory model behind, the resolution of final state objects is a competitive factor to perform a bump hunt

Modelling of a possible signal I

Without a specific MC generator experimentalists opted to perform a phase space scan

- focus on the acceptance region of the detector: $m_{ZX} = m_X + \mathcal{O}(m_Z) + \varepsilon$ where $\varepsilon \sim e^{-0.04\, m_{VX}}$
- the p_Z distribution of the system is obtained using the equivalent photon approximation Phys. Rep. 15 (1975), 181
- ZX generated with an isotropic distribution in its rest frame (as well as the Z decay products)

The results are fairly consistent for variations of these assumptions

With a signal at hand could evaluate best sensitivity

- use multi-RP with fallback on single-RP categories if multi-RP failed
- migration between categories needed however correct emulation of the time-dependent efficiencies
- in practice there were 4 crossing angles x 2 data-taking eras simulated per mass point

There was no full simulation of the signal : folding procedure was adopted

- lepton and photon efficiencies well established in CMS
- proton fast simulation included mostly acceptance and tracking emulation

Modelling of a possible signal II

Inclusion of pileup protons and emulation of inefficiencies reliable by mixing with data

- procedure makes use of the LHC fill-/angle-dependent efficiencies discussed back in slide 18
- additional efficiency correction needed to mix correctly events with 0 observed protons ("pure 0" state) - non-negligible effect with up to 70% loss in the high pileup runs of 2017

To emulate all selection categories each signal event is projected into 12 possible states

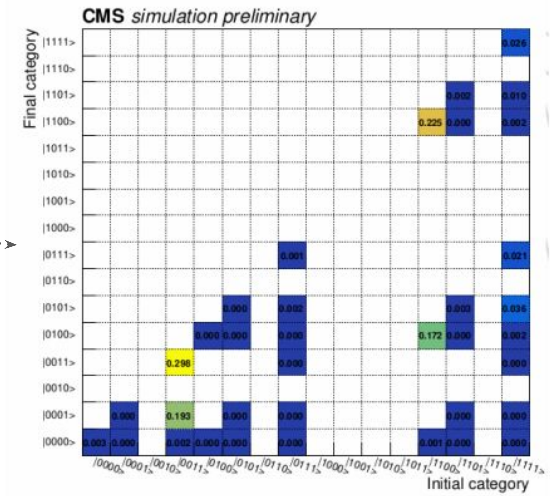
- corresponding to different reconstruction algorithms used in each of the CT-PPS arms

$$|m_- \; p_- \; m_+ \; p_+\rangle = |m_- \; p_-\rangle |m_+ \; p_+\rangle$$

Neg. arm — pos. arm — Multi? 0/1 — Pixel? 0/1

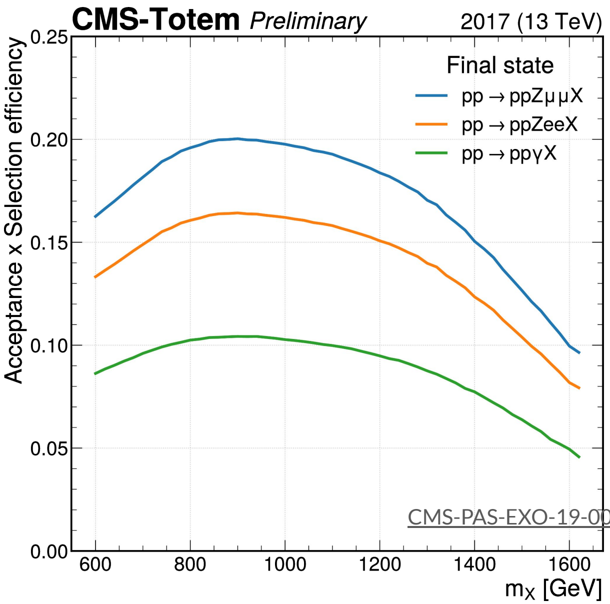
$$\begin{pmatrix} |11\rangle \\ |10\rangle \\ |01\rangle \\ |00\rangle \end{pmatrix} = \begin{pmatrix} \varepsilon_m \cdot \varepsilon_p & 0 & (1-\varepsilon_m)\cdot\varepsilon_p & (1-\varepsilon_m)\cdot(1-\varepsilon_p) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \varepsilon_p & (1-\varepsilon_p) \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} |11\rangle \\ |10\rangle \\ |01\rangle \\ |00\rangle \end{pmatrix}$$

\+ pileup protons



Acceptance of the analysis

Modelling of the time dependency is crucial to estimate the Acceptance x Efficiency ($A \cdot \varepsilon$)



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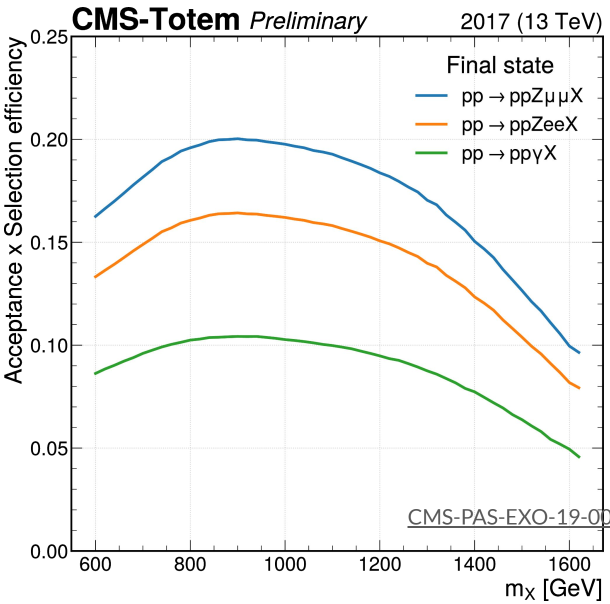
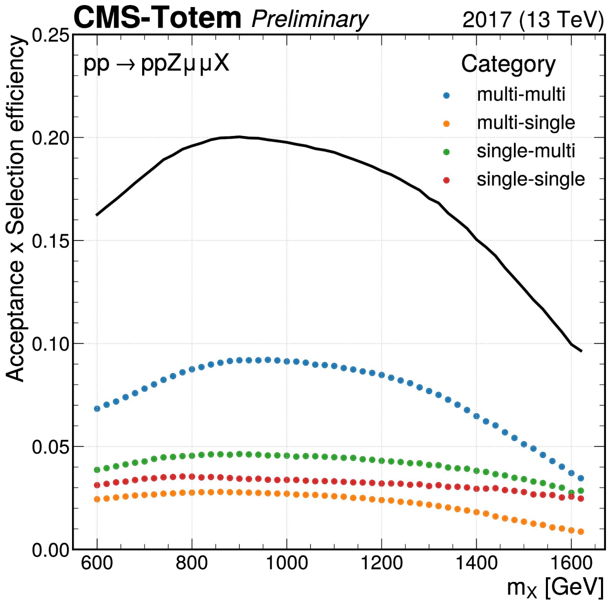
Acceptance of the analysis

Modelling of the time dependency is crucial to estimate the Acceptance x Efficiency (A · ε)

- most events are expected to be found in the golden category “multi-multi”
- fallback categories with single-RP increase A · ε by factor of 2!
  (but they lose unavoidably resolution when compared to multi-RP)





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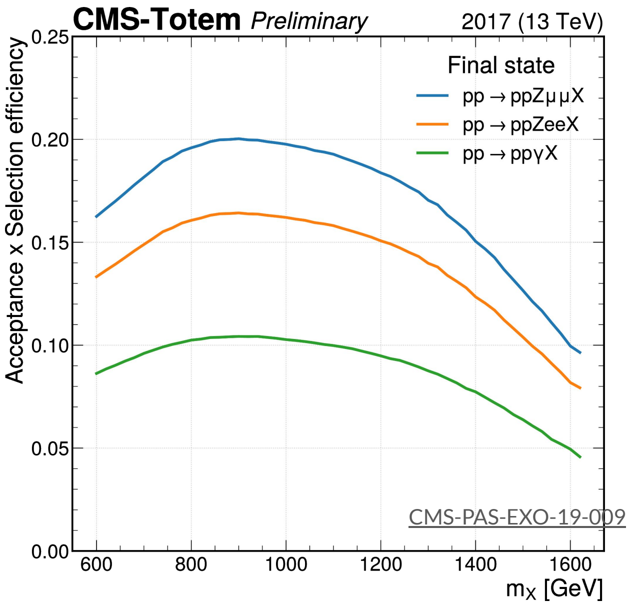
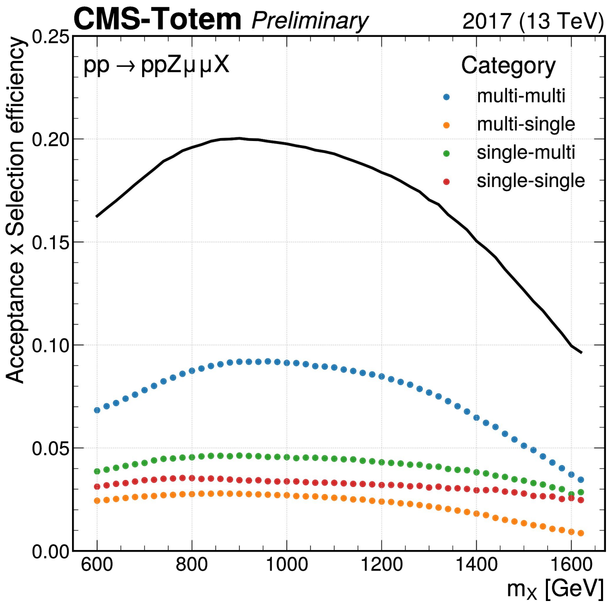
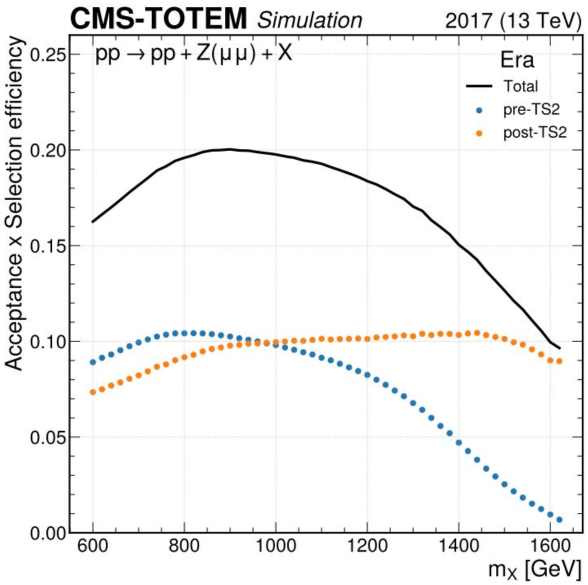
- most events are expected to be found in the golden category “multi-multi”
- fallback categories with single-RP increase A · ε by factor of 2!
  (but they lose unavoidably resolution when compared to multi-RP)
- partial availability of the detectors yields unbalanced contributions of fallback categories







Event selection adopted

Based on the toy MC baseline the event selection is defined

- relaxed cuts to increase significance
- moderate boost expected for boson
- protons limited to fiducial region of the detector

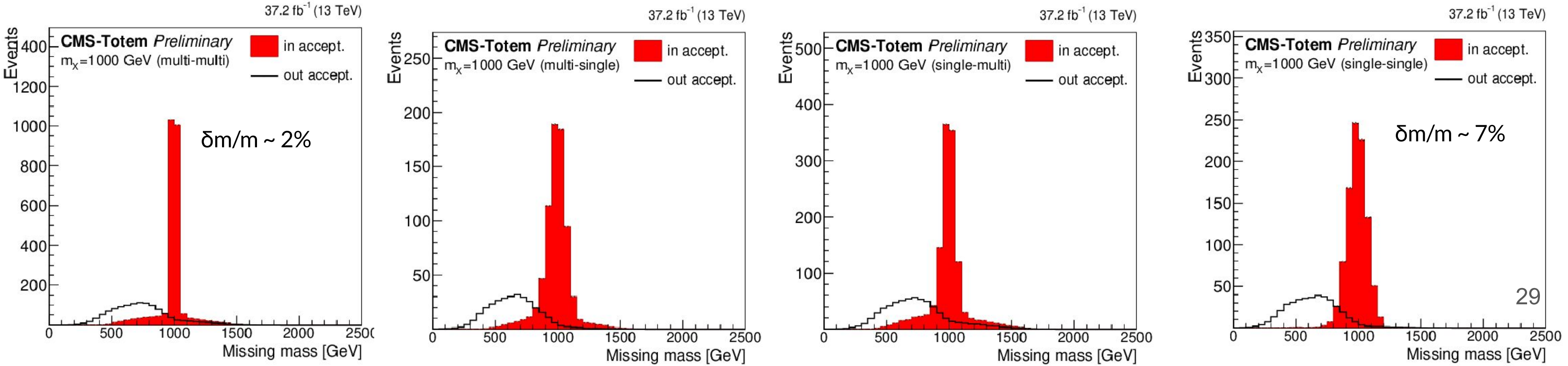
Convention "σ_{th}=1pb" in the fiducial region →

Selection / Analysis	$Z \to e^+e^-/Z \to \mu^+\mu^-$	γ
Leptons/Photons	≥ 2 same flavor leptons (e or μ) opposite electric charge $p_T(\ell_1/\ell_2) > 30/20$ GeV $\|\eta(\ell)\| < 2.4$ $\|m(\ell_1\ell_2) - m_Z\| < 10$ GeV	=1γ within $\|\eta(\gamma)\| < 1.4442$
Boson p_T	$p_T(Z) > 40$ GeV	$p_T(\gamma) > 95$ GeV
Protons	$0.02 < \xi_+^{gen} < 0.16$	$0.03 < \xi_-^{gen} < 0.18$

Toy MC yields in addition the possibility to estimate a signal-induced background component

- signal events in which at least one proton fails to be reconstructed/selected

CMS-PAS-EXO-19-009



Background modelling

Main source of the background is combinatorial

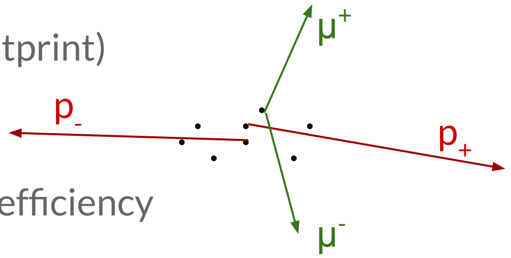
- with an average 38 pileup interactions: single diffractive, elastic collisions etc. generate several protons
- probability of a Z+jets event reconstructed with random coincident proton tags is high

Without timing commissioned/available, proton pileup reduction is challenging

- in case of multiple proton candidates disambiguation introduces additional combinatorial background
- multivariate analysis tried to correlate vertex activity, forward energy of the calorimeters with proton tags
- in the end adopted a simple approach of categorizing by crossing angle and vertex multiplicity

Background modelled with event mixing technique

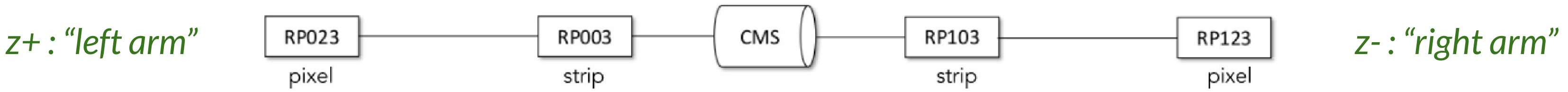
- select proton candidates in Z events with $p_T(Z)<10$ GeV (reduced UE footprint)
- combine protons with pre-selected Z (or γ)
- preserve LHC fill- and crossing angle- of the two mixed events
  ⇒ uniform sampling of data taking conditions, detector acceptance and efficiency

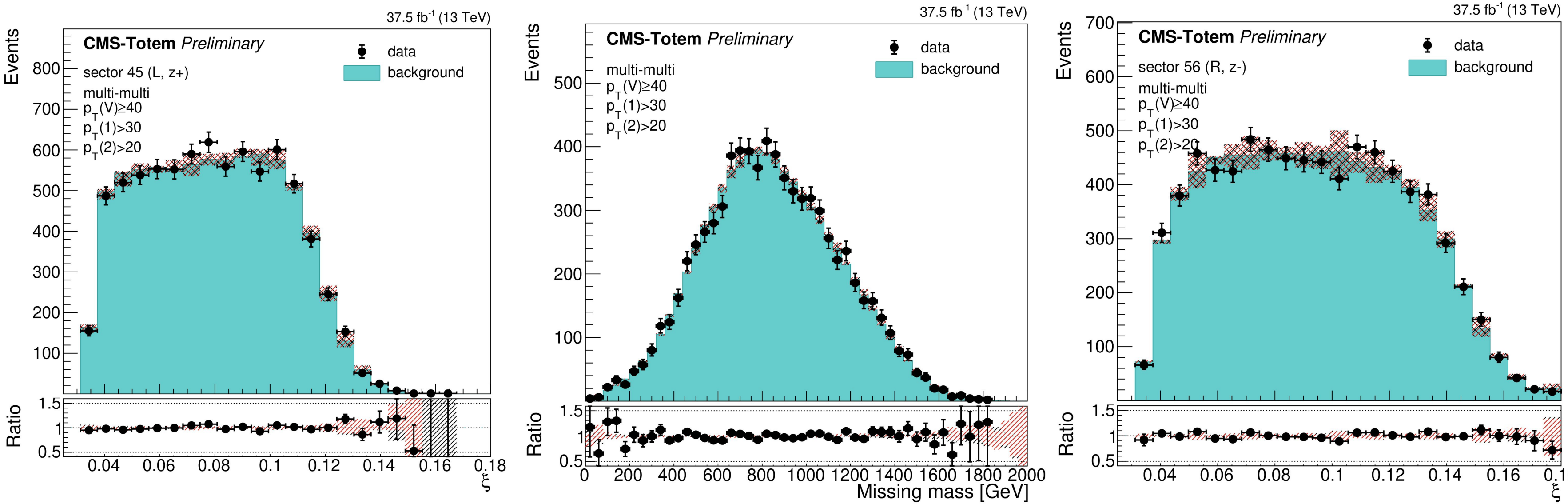


Background validation I

eμ events where no signal expected used to validate procedure

- Good agreement found over >90 different categories, giving confidence in the procedure





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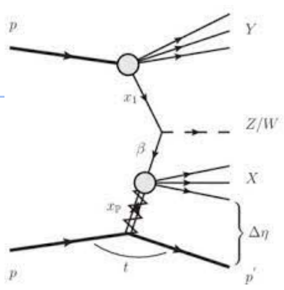
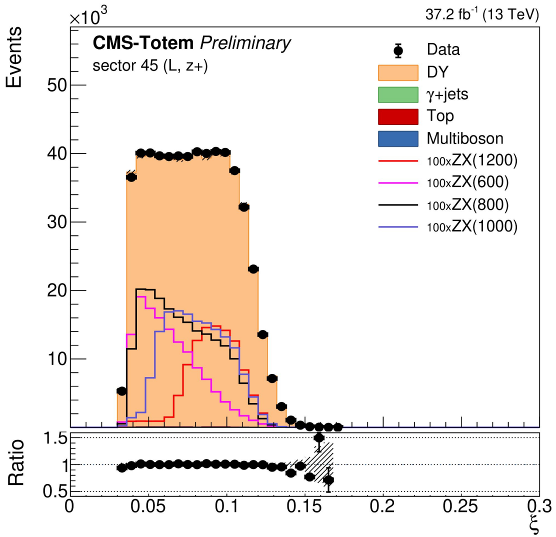
Background validation II

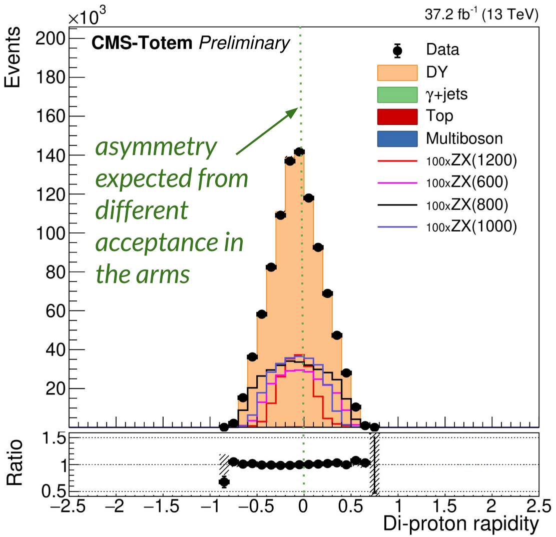


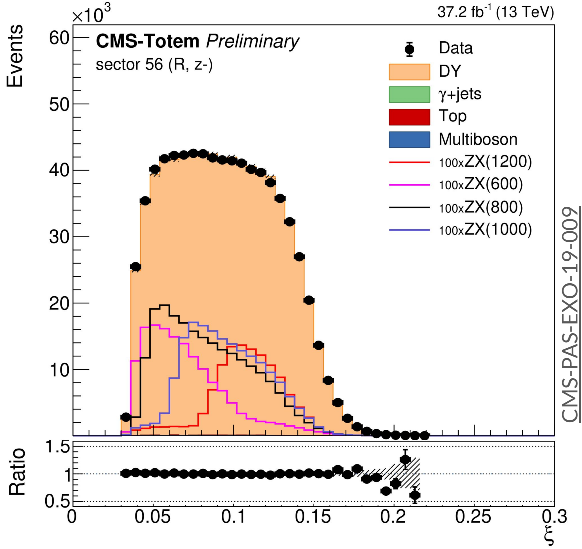
Other processes are expected to be negligible or under control with event mixing

- *single diffractive Z*: although distinct shape and large σ, modelled with single proton mixing
- *central exclusive events*: small cross section and acceptance after Z window requirement

Mixing using “standard” MC events (neglecting processes above): good agreement with data







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Statistical analysis

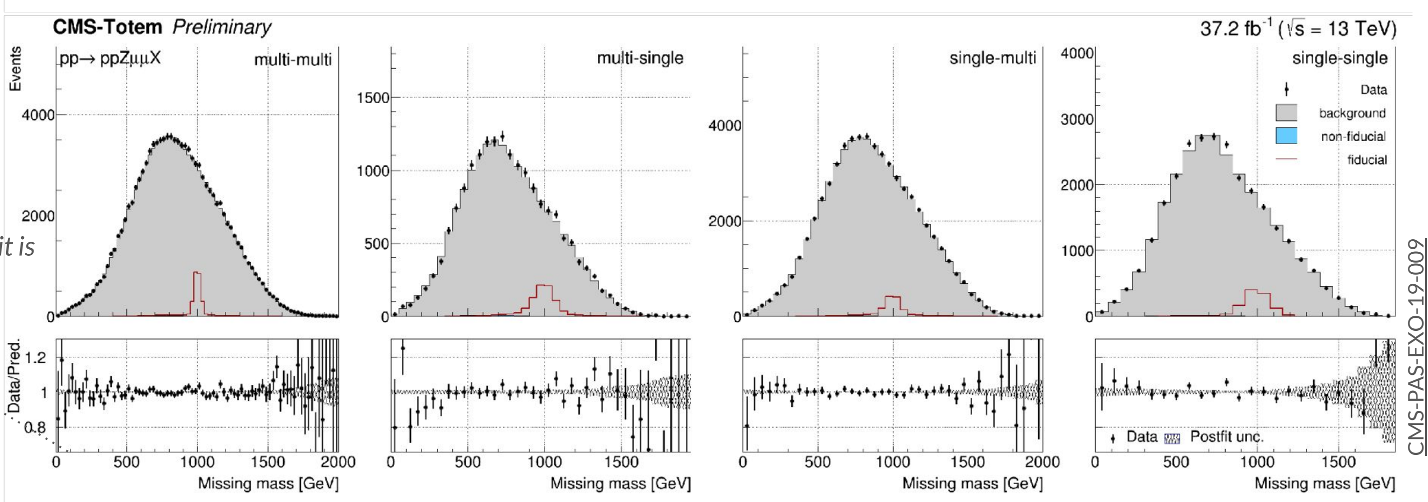
Based on a profile likelihood test statistics with the following systematics

- *signal*: pileup, lepton, photon and proton efficiencies, time-dependency, integrated luminosity, pz(pp) modelling and limited statistics
- *background*: single diffractive component, source of pileup protons (floats freely in each category)
- *signal-induced background*: left floating freely (correlated between different categories)

Best sensitivity with a simultaneous fit to the missing mass spectra in a total of 96 categories

(4 beam crossing angles, 4 proton reconstruction categories, 2 vertex multiplicity, 3 final states)

binning depends on category resolution but it is fixed for all mass scan (reduce look elsewhere effect)



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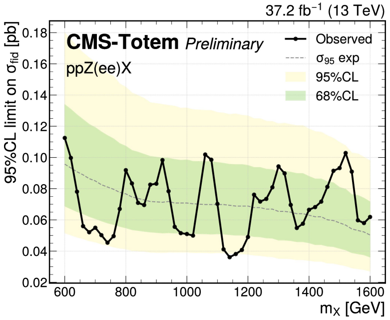
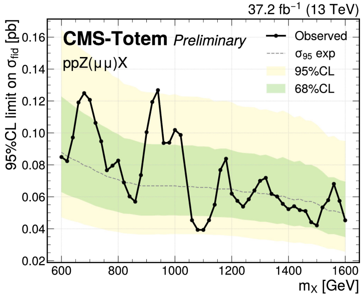
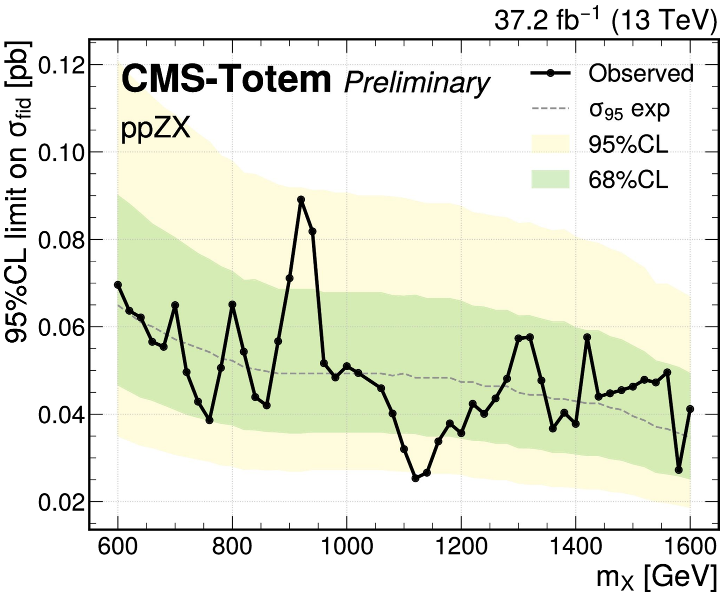
Limits

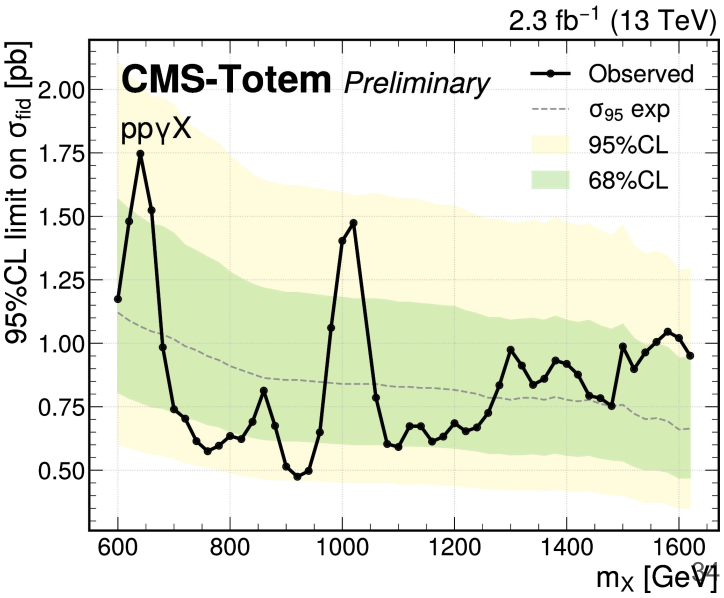
Good agreement with background-only hypothesis

- observed limits within 2σ expectation
- oscillations are fully consistent with resolution









Other recent results and next chapters

Searches for pp → pp VV

Di-boson final states with protons: interesting as they are sensitive to quartic gauge couplings

- V=W,Z,γ
- selection of events at the 0.6-2 TeV scale just from current CT-PPS acceptance
- complementary to VBS type of searches as γγVV vertices are singled out
- can use to probe dim-8 operators in an EFT context

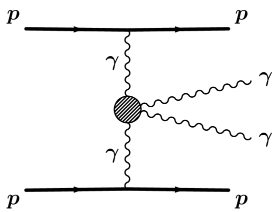
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

arXiv:1309.7890

- in addition specific scenarios such as axion-like particles (ALPs) can be probed

Limits on aQGC



Using single photon triggers

p_T >75-100 GeV m(γγ)>350 GeV
0.02<ξ(γγ)<0.2   1-δφ/π<0.0025
PPS matching in mass and rapidity

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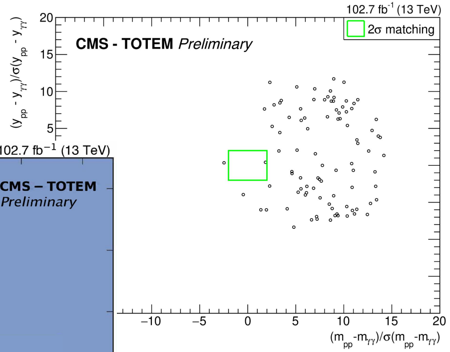
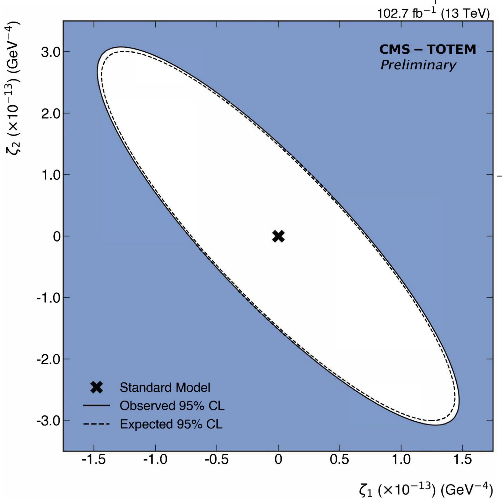
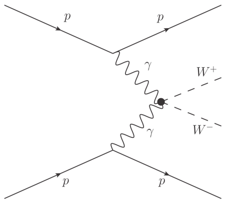
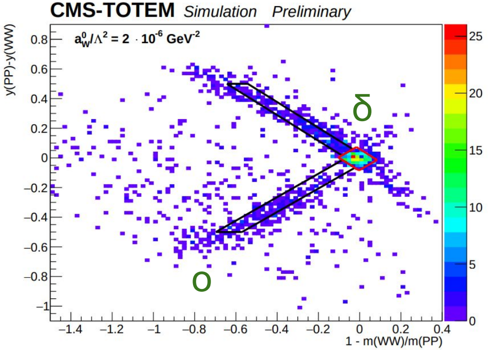






Using boosted (R=0.8) jet topology

p_T(V)>200 GeV m(VV)>1.126 TeV
Δη(V,V')<0.3 1-δφ/π<0.01
Categorize in fully matched (δ) and singly-matched (o) categories



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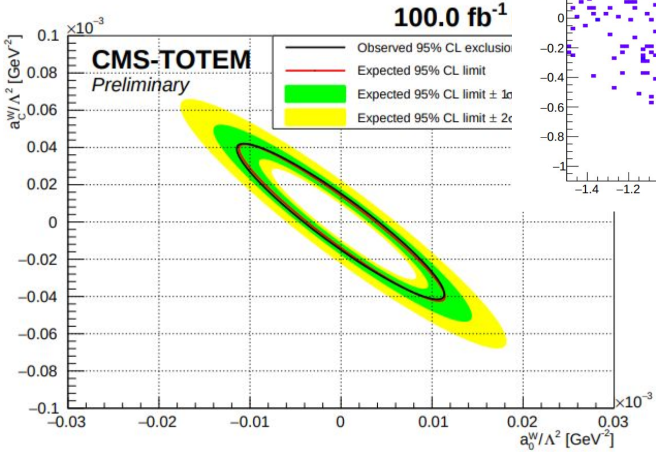
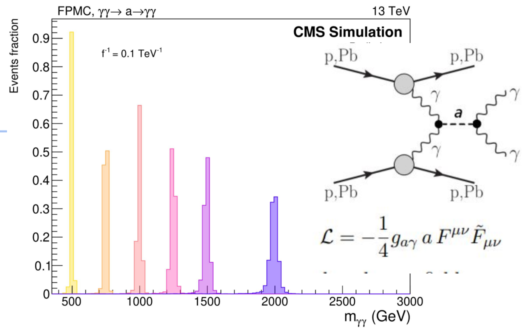


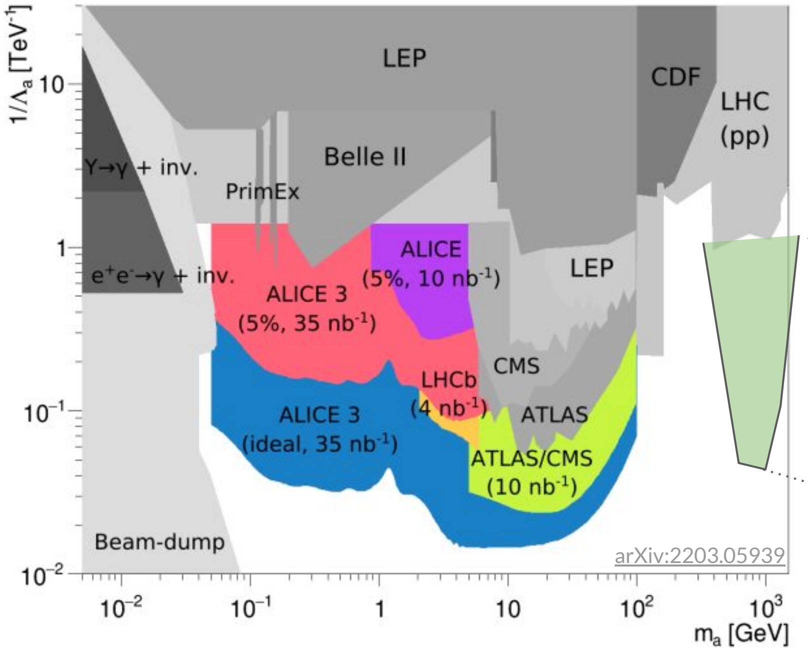
$$(\mathbf{a}/\Lambda^2) \sim (gv)^2 (\mathbf{f}/\Lambda)^4$$

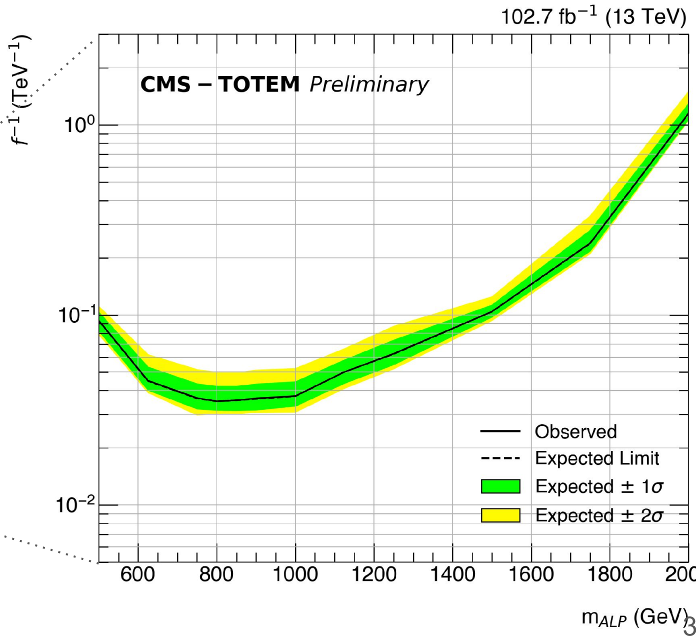
Limits on (high-mass) ALPs



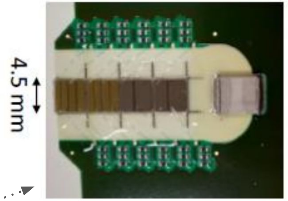
Re-cast the γγ analysis for a resonant scenario

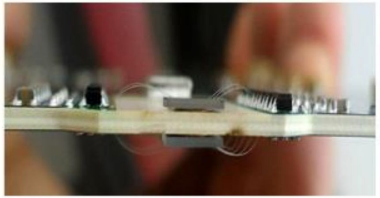
- result reduces significantly the phase space allowed for high mass ALPs
- clear complementarity of CT-PPS-driven searches to LbL in PbPb





PPS in LHC Run 3...

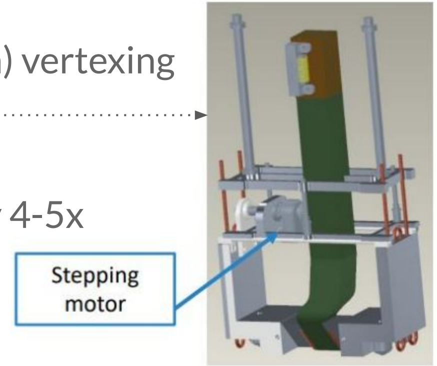




Several upgrades took place for current run

- Timing detectors: two new stations,
- Double-Diamond detectors in all planes targeting a resolution $\mathcal{O}(30\text{ ps}) \Rightarrow \mathcal{O}(1\text{cm})$ vertexing
- New Si pixel tracker with internal motion (increased efficiency to lower ξ)
- Dedicated high level trigger with proton tag (hadronic WW / multijet events)

$\Rightarrow$ 2x more luminosity in Run 3, potential to increase sensitivity of proton analyses by 4-5x



PPS in LHC Run 3... and beyond

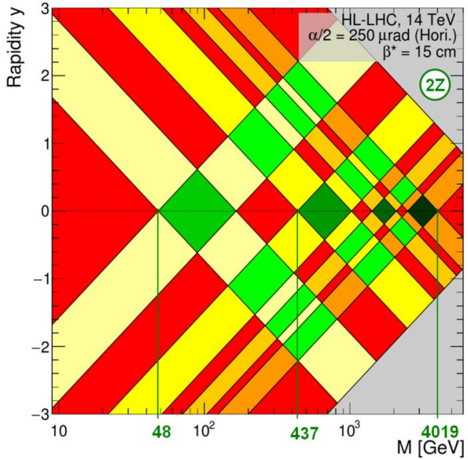
Several upgrades took place for current run

- Timing detectors: two new stations,
- Double-Diamond detectors in all planes targeting a resolution $\mathcal{O}$(30 ps) ⇒ $\mathcal{O}$(1cm) vertexing
- New Si pixel tracker with internal motion (increased efficiency to lower ξ)
- Dedicated high level trigger with proton tag (hadronic WW / multijet events)

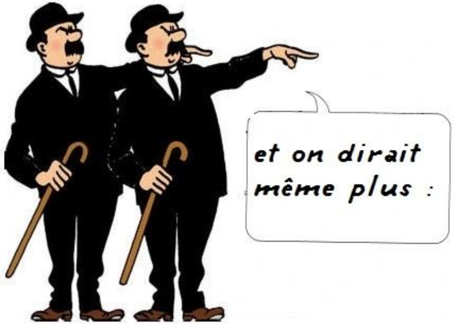
⇒ 2x more luminosity in Run 3, potential to increase sensitivity of proton analyses by 4-5x

An expression of interest has been submitted for the HL-LHC - arXiv:2103.02752

- expands LHC programme on WW, di-τ, top, ALPs, SUSY, Higgs, …
- staggered installation at 196 m, 220 m, 234 m and 420 m from CMS
- expanding acceptance to the $\mathcal{O}$(40 GeV) – $\mathcal{O}$(4 TeV) range
- 1-2 MCHF (costs spread overtime with staggered installation)



Summary



Summary

LHC: likely to be the best (and cheapest) high energy photon collider available for a long time

First analyses with proton tags from Run 2 have provided, among others:

- first "missing mass" searches for resonances in V+X final states
- first+best collider constraints on anomalous quartic gauge couplings in $\gamma\gamma \to \gamma\gamma$
- best limits on ALPs at the TeV scale
- new constraints on anomalous quartic gauge couplings in $\gamma\gamma \to WW$, $\gamma\gamma \to ZZ$

… complemented with heavy ion $\gamma\gamma$ physics program, not covered here

Photon collisions should be maximally exploited for SM and BSM physics in Run 3 and beyond