Search for Heavy Stable Charged Particles in the CMS Experiment using the RPC phase II upgraded detectors

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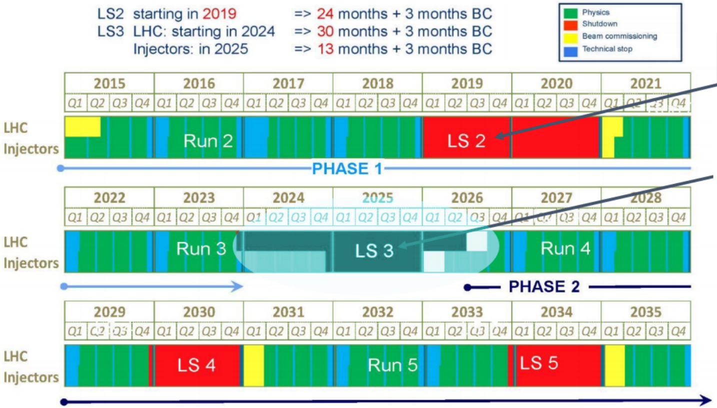
Phase-2 upgrade

LHC time scale:

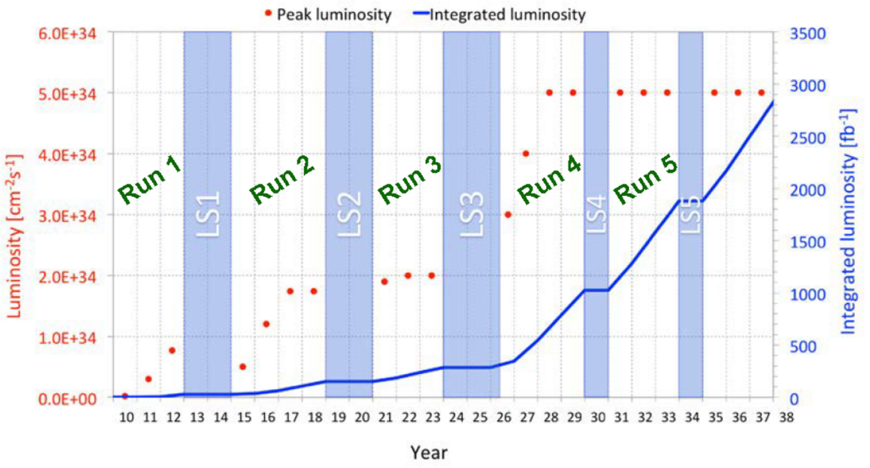


LS2:on-chamber electronics

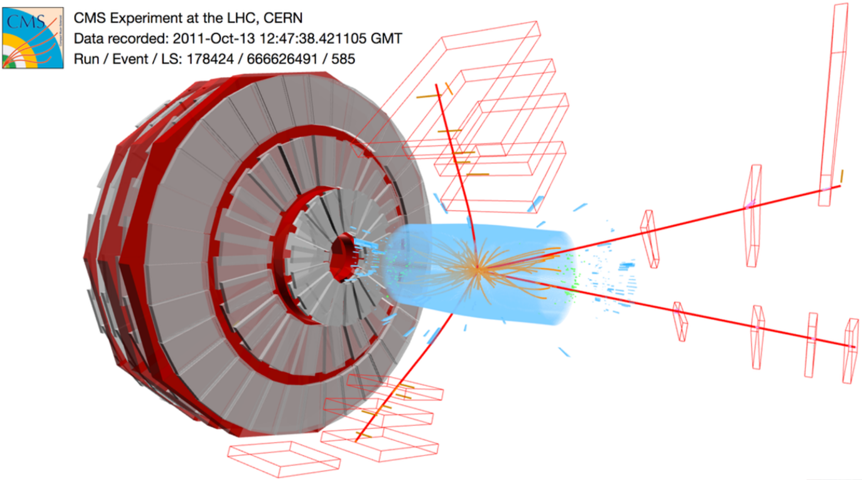
Here the Phase-2 upgrade will happen

Focus on upgrades being installed in LS2

Less than 10% of the LHC integrated luminosity by the end of Run2!



Why the Muon System? the M in CMS stands for Muon!



Probably a higgs boson decaying into 4 muons.

Why the Muon System? the M in CMS stands for Muon!

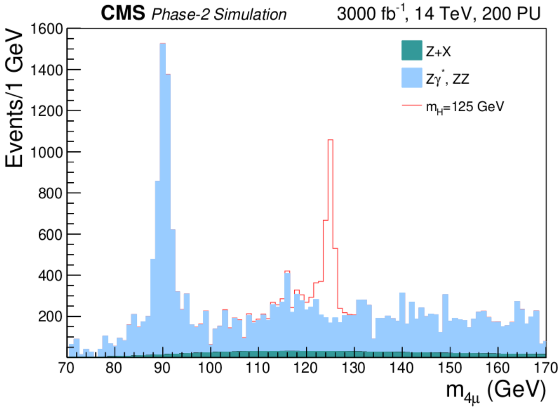


Figure 1.27: Four-muon invariant mass distribution for $H \to ZZ \to 4\mu$ signal, and for irreducible ($Z\gamma^*, ZZ$) and reducible backgrounds ($Z + X$). The peak near 90 GeV comes from rare $Z \to 4\mu$ decays.

Subdectors of the CMS Muon System

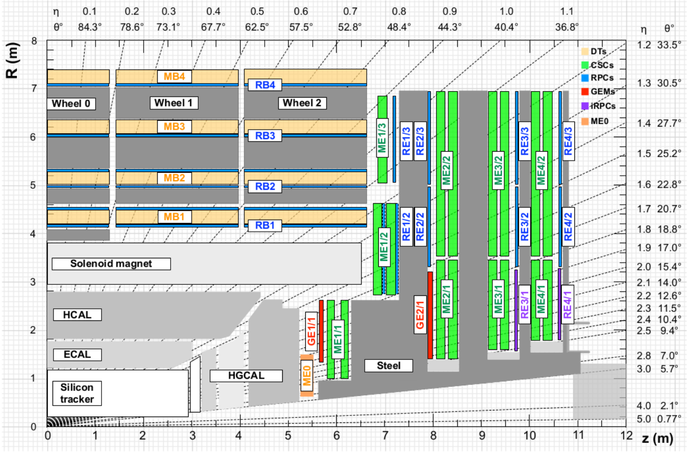


Figure 1.4: An *R*-*z* cross section of a quadrant of the CMS detector, including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0). The acronym iRPCs in the legend refers to the new improved RPC chambers RE3/1 and RE4/1. The interaction point is at the lower left corner. The locations of the various muon stations are shown in color (MB = DT = Drift Tubes, ME = CSC = Cathode Strip Chambers, RB and RE = RPC = Resistive Plate Chambers, GE and ME0 = GEM = Gas Electron Multiplier). M denotes Muon, B stands for Barrel and E for Endcap.

Recently published Technial Design Report (TDR) document for the Muon System

Official CERN link:

`https://cds.cern.ch/record/2283189/files/CMS-TDR-016.pdf`

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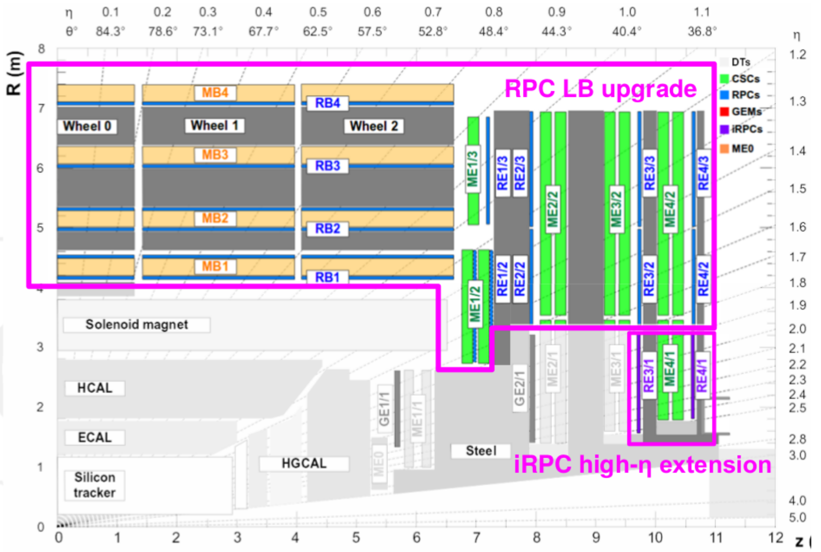
Very short editor lists (4000 people in the CMS collaboration). The book will be printed in the following months (367 pages)

RPC phase-2 upgrade (hight η new detectors)

- New Link Board system: $\rightarrow$ RPC system **time resolution**: from 25 ns to 1.5 ns
  - $\rightarrow$ Better muon time measurement.
  - $\rightarrow$ New searches for Physics BSM, HSCPs (slow moving particles).
- Extend η **acceptance**: from 1.8 to 2.4
  - $\rightarrow$ Fully redundant CMS muon system (Trigger & Reconstruction)
  - $\rightarrow$ Possibility for Tracker + RPC standalone Trigger

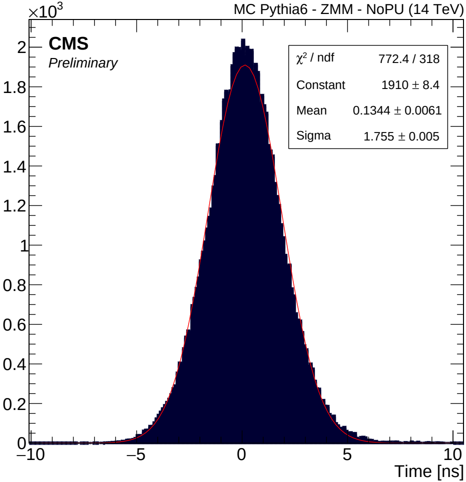
Improvement in all detector time resolution $\approx 1.5ns$[1]



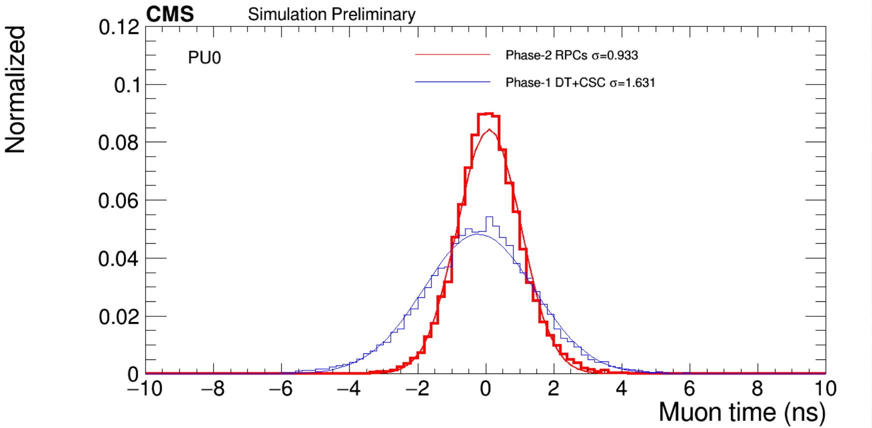
[1]intrinsic time resolution

Single hit time resolution improvement 25ns $\rightarrow$ 1.5ns:

- In **phase-1** 1 time window per bunch-crossing $\approx$ **25ns**, limited by Link Board system.
- In **phase-2** 16 (4bits) time windows per bunch-crossing $\approx$ **1.5ns**, with phase-2 LB system.
- **phase-2** RPC will provide the **most precise single hit time resolution** in the CMS muon system.



Muon Time measurement



- To measure the muon time, **all hits included in the fit are taken into account** (like for instance 6 RPC hits in the barrel).
- Phase-2 RPCs alone performs better (50%) than phase-1 DT+CSC combined for muon time measurement.

But, what are HSCPs?

- **Heavy**
  Slow particle → β<1

- **Stable → Long-lived**
  1) Reach the tracker → cτ > O(0.1)m
  2) Escape the detector → cτ > O(10)m
  3) Stop in → Asynchronous decay → cτ > O(100)m

- **Charged**

IONIZATION:

Electric	→	lepton-like
		|Q|<<e, |Q|<e, |Q|=e, |Q|>e, |Q|>>e
Color	→	hadron-like → R-hadron properties ?!
		(gluinoball, charge flip, interaction w/ matter, etc.)
Magnetic	→	monopoles, dyons
Exotic	→	quirks, …

Terminology : HSCP=SMP=ChaMP=CmLLP=…

Experimental signatures.

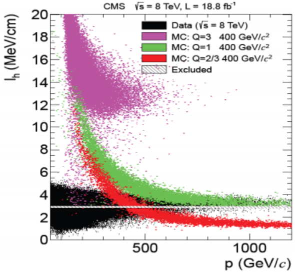
IONIZING

⇩

dE/dx

$$\frac{dE}{dx} \approx Q^2 \left(\frac{A}{\beta^2} + B\right) \text{ for } \beta << 1$$

Magnetic charge g_D → Q ~ 68.5e



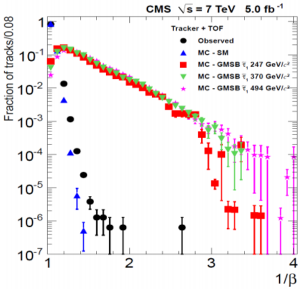
dE/dx resolution improves with #layers, sensor thickness and readout electronics

SLOW

⇩

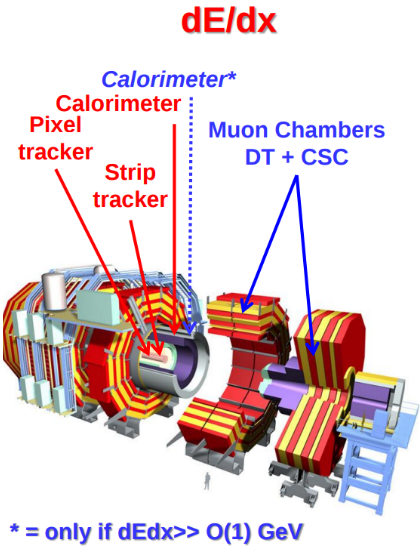
Time Of Flight

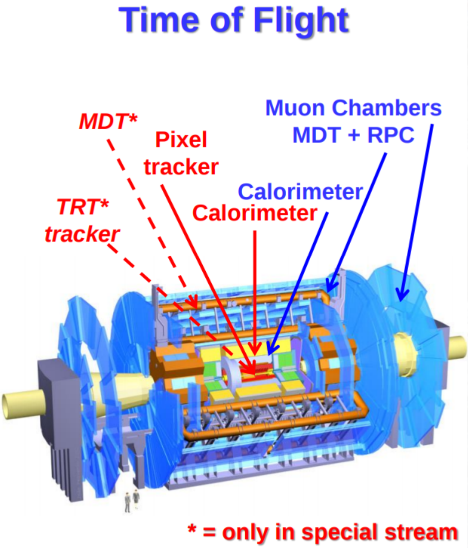
$$1/\beta = 1 + \frac{c\delta_t}{L} \quad \text{with } \delta_t = \text{delay}$$



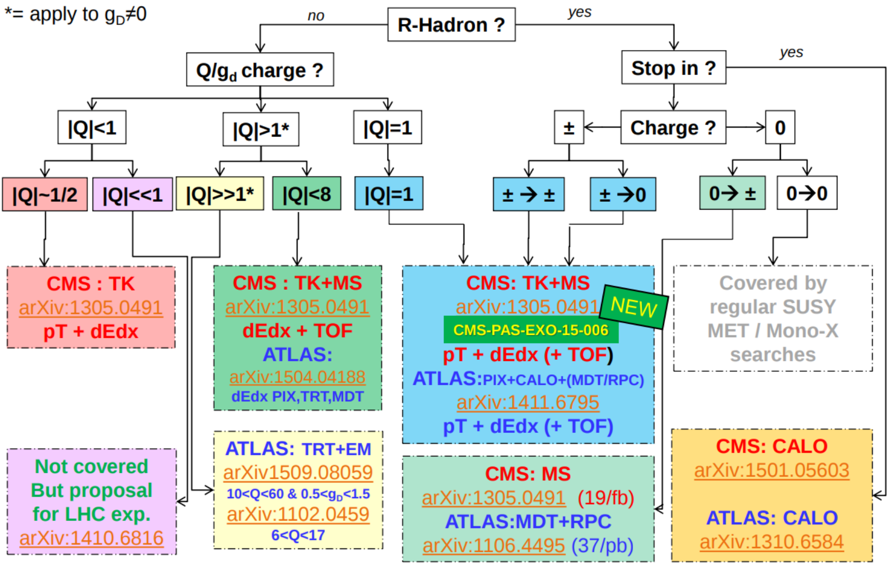
β resolution improves with time resolution (δt) and with lever arm (L)

Many searches ongoing in the LHC experiments

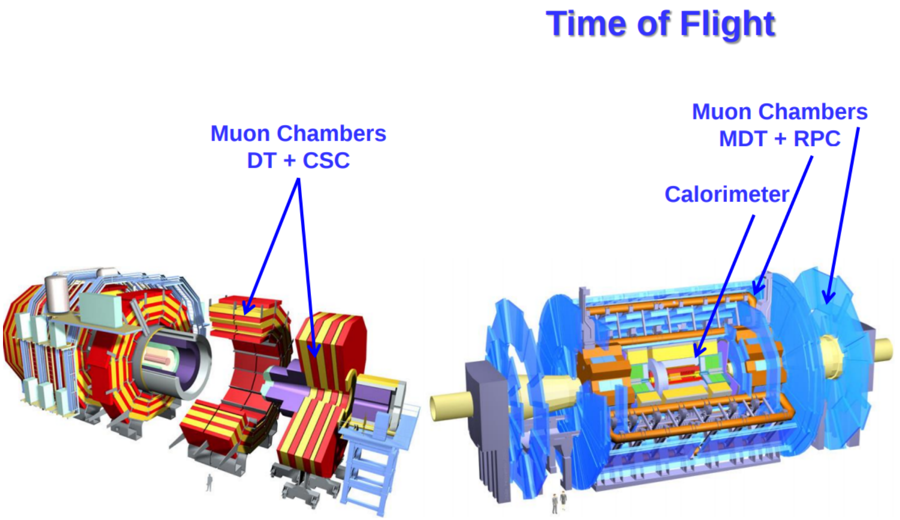




Many searches ongoing in the LHC experiments



Focus in the ToF Technique



In Phase-2 dE/dx technique drastically affected:

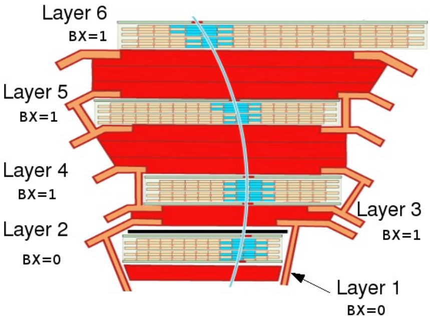
- Completely new tracker for HL-LHC
- (Challenging) Requirements for the Phase-II tracker (from the Phase-II TP)
    - Radiation tolerance
    - Increased granularity
    - Improved two-track separation
    - Reduced material in the tracking volume
    - Robust pattern recognition
    - Compliance with the L1 trigger upgrade
    - Extended tracking acceptance

- Inner (pixel) Tracker
    - No significant changes regarding the HSCP

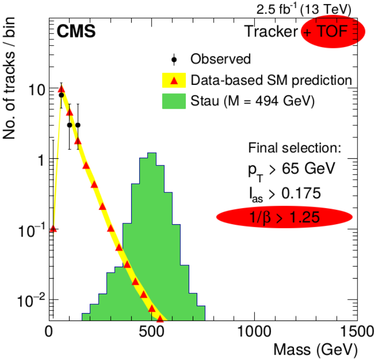
- Outer Tracker
    - Analogue readout of the charge on silicon is not affortable anymore
        - Electronics, bandwith, trigger, etc.
        - → No dE/dx information from the (outer) silicon tracker
        - Drastically affecting the HSCP sensitivity

Search for HSCP with the ToF technique

Run-1 RPCHit BX for an HSCP

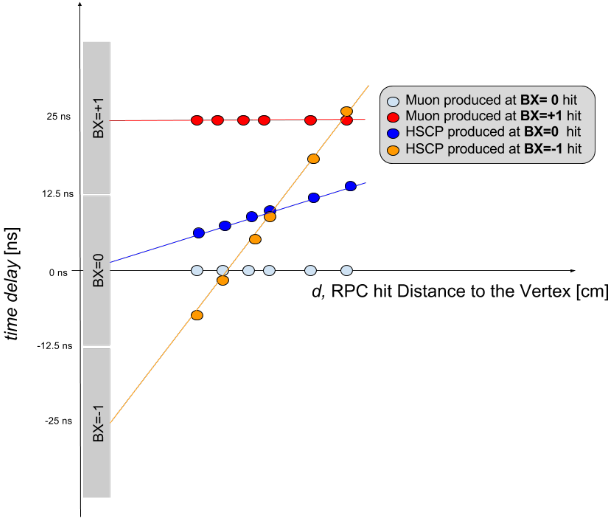


latest HSCP publication



- Due to their high mass: $\beta_{HSCP} < 1 \rightarrow$ "late" arrival to the muon system.
- The signature of HSCP: **coherent out-of-time set of hits in the muon system**
- If the ToF is measured the speed of the particle can be estimated for trigger or analysis.
- With better time resolution the RPC-contribution can be drastically improved.

RPC-HSCP trigger strategy for phase-2



Algorithm to trigger HSCPs with the RPC ToF technique using phase-2 new LB time information.

A linear fit is not demanding in computing time and can be implemented in the Phase-2 track finders

RPC-HSCP trigger strategy for phase-2

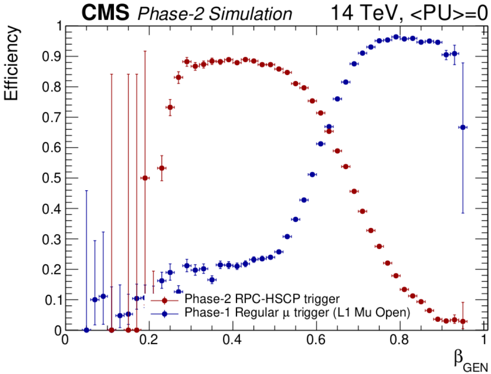


Figure 1.24: L1 Trigger efficiency as a function of an HSCP velocity β for the 'regular' trigger (assuming the muon to come from the primary vertex, blue points) and a dedicated HSCP trigger, fully exploiting the improved timing of the upgraded RPC link system (red points).

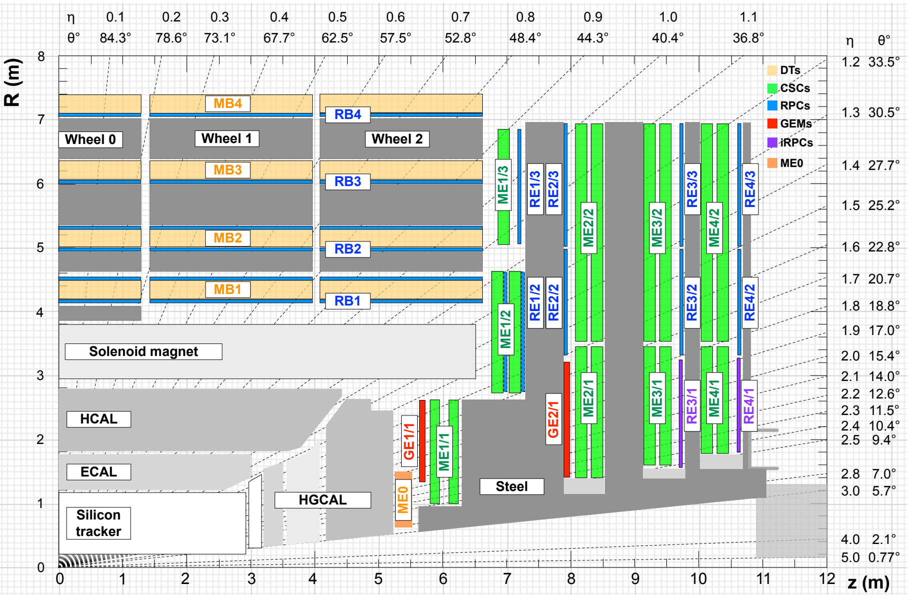
Conclusions/Summary

- **CMS Muon detectors** have proven **excellent performance during run-1 and run-2** (efficiency stability)
- phase-2 muons will benefit from the improved time measurement of the new RPC Link Board system in the **full η range**.
- New subdetectors will extend the acceptance and redundancy in the full η range, the CMS Muon System will warranty muon trigger and reconstruction redundancy for CMS.
- phase2 HSCP-RPCs trigger proposal will ensure that we don't miss BSM LLP signatures for the remainder of the LHC program (90% of the total LHC will come data after LS3).
- HSCP and Dark Matter: Stable Massive Particles at Colliders `https://arxiv.org/abs/hep-ph/0611040`

Backup

Backup

CMS Muon system quadrant



HSCP publication with HSCP-RPC trigger

4. Trigger and data selection

Events were selected using a trigger requiring a muon with high transverse momentum ($p_T > 40$ GeV/c) with $|\eta| < 2.1$, or a trigger requiring large missing transverse energy ($E_T^{miss} >$ 150 GeV). The latter quantity was computed online using jets reconstructed with a particle-flow algorithm [53]. Jet clustering was performed using the anti-k_T algorithm [54] with a size parameter of 0.5. Triggering on E_T^{miss} allows the recovery of events with HSCPs failing muon identification or emerging mainly as neutral particles after traversing the calorimeters. The L1 muon trigger accepts tracks that produce signals in the RPC detectors either within the 25 ns time window corresponding to the collision bunch crossing, or within the following 25 ns time window. This operation mode is particularly suited for detecting late tracks in the muon system. It was designed to cater for this analysis, and is tenable as long as collisions are separated by 50 ns or more, which was the case for the 2011 LHC running period. The DT and CSC L1 triggers were used only for detecting particles produced in the collision bunch crossings. Track reconstruction in the muon HLT assumes particles traveling at the speed of light and produced within the triggered bunch crossing. However, the requirements on the quality of the muon segments are loose enough to allow tracks from late particles to be reconstructed with reasonably high efficiency. Events with pair produced $\tilde{\tau}_1$, and with the fastest $\tilde{\tau}_1$ having β as low as 0.6, would be selected by the muon trigger with 75% efficiency. The muon trigger efficiency would become less than 10% for events where the fastest $\tilde{\tau}_1$ had $\beta \leqslant 0.45$.

Single hit time resolution improvement:

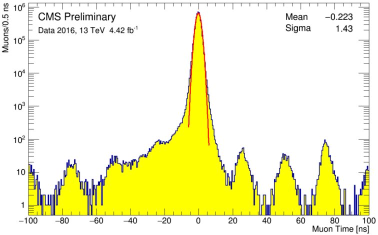


Figure 11: Time-at-vertex distribution for standalone muons in the barrel, using the tir
sured from DT chambers in 2016 data.

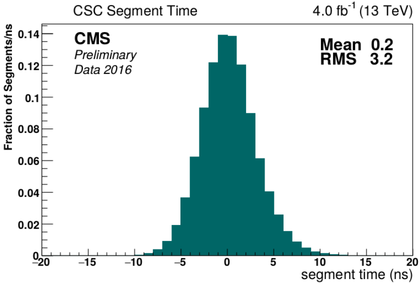
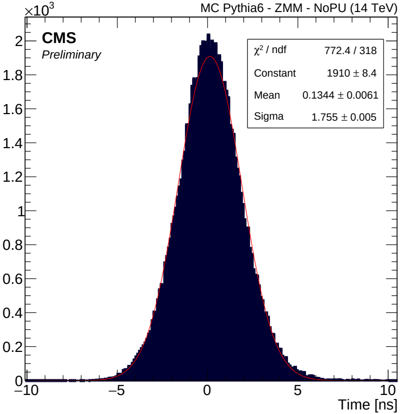


Figure 10: Distribution of times from reconstructed CSC segments using 2016 data.



HSCP searches

HSCP searches

HSCP Theoretical predictions

SUSY

SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}^0_1$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}^0_1$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}^+_1$	$\tilde{\chi}^0_1$	MSSM	$m_{\tilde{\chi}^+_1} - m_{\tilde{\chi}^0_1} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}^0_1$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}^0_1$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

EXOTIC

Q_{em}	C_{QCD}	S	Model(s)
0	**8**	1	Universal Extra Dimensions (KK gluon)
± 1	**1**	$\frac{1}{2}$	Universal Extra Dimensions (KK lepton)
			Fat Higgs with a fat top (ψ fermions)
			4th generation (chiral) fermions
			Mirror and/or vector-like fermions
		0	Fat Higgs with a fat top (ψ scalars)
$\pm\frac{4}{3}$	**3**	$\frac{1}{2}$	Warped Extra Dimensions with GUT parity (XY gaugino)
		0	5D Dynamical SUSY-breaking (xyon)
$-\frac{1}{3},\frac{2}{3}$	**3**	$\frac{1}{2}$	Universal Extra Dimensions (KK down, KK up)
			4th generation (chiral) fermions
			Mirror and/or vector-like fermions
			Warped Extra Dimensions with GUT parity (XY gaugino)
$\epsilon < 1$	**1**	$\frac{1}{2}$	GUT with $U(1) - U(1)'$ mixing
			Extra singlets with hypercharge $Y = 2\epsilon$
			Millicharged neutrinos
?	?	$0/\frac{1}{2}/1$	"Technibaryons"

+++ other more exotic models/particles (monopoles, quirks, dyons, etc.)

arXiv:hep-ph/0611040 **Fairbairn et al.**

The Drift Tubes phase-2 upgrade

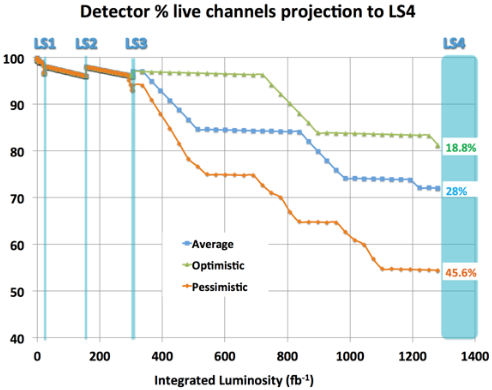


Figure 1.8: Extrapolated fraction of live channels as a function of integrated luminosity if the MiCs would not be replaced in LS3. Note that the horizontal scale covers only 1/3 of the HL-LHC luminosity, up to the first LS in the HL-LHC running period. The three aging scenarios shown (optimistic, pessimistic, average) result from different assumptions on the uncertainties coming from irradiation tests and on the expected dose profile.

The Drift Tubes phase-2 upgrade

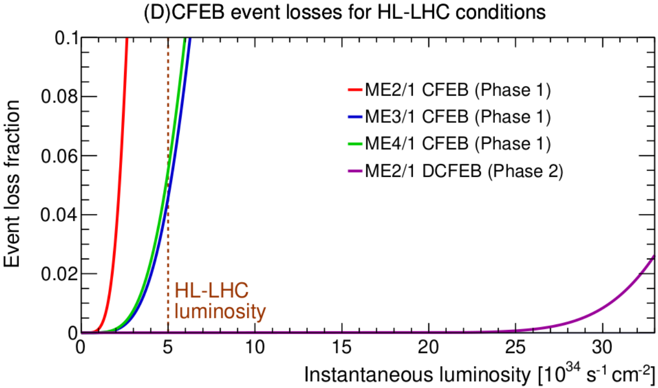


Figure 1.10: CFEB (Phase-1) and DCFEB (Phase-2) event loss fractions for HL-LHC conditions in the inner CSC rings ME2/1, ME3/1, and ME4/1 as a function of instantaneous luminosity. The design HL-LHC luminosity of 5×10^{34} cm^{-2}s^{-1} is marked by the dashed brown vertical line. The event loss fraction for the upgraded electronics, the curve in magenta, is negligible for all CSC stations at the HL-LHC luminosity.

Summary forward region

Table 1.11: Properties of the new CMS muon detectors installed as part of the HL-LHC upgrade. The RE3/1 and RE4/1 detectors are double-gap iRPC chambers. The GE1/1 and GE2/1 detectors comprise two layers of triple-GEM chambers, referred to as superchambers. The ME0 detectors are made of six layers of triple-GEM chambers, referred to as stacks. The quoted intrinsic spatial and time resolutions refer to a chamber for RPCs, to a superchamber for GE1/1 and GE2/1, and to a stack for ME0. Note that GE1/1 is not part of this TDR.

Muon subsystem Detector technology	RE3/1 + RE4/1 iRPC	GE1/1 GEM	GE2/1 GEM	ME0 GEM
$\lvert\eta\rvert$ range	1.8–2.4	1.6–2.15	1.6–2.4	2.0–2.8
Number of chambers	36 + 36	144	72	216
Number of channels	13 824	442 368	442 368	663 552
Number of layers/station	1	2	2	6
Surface area of all layers	$93\,m^2$	$54\,m^2$	$105\,m^2$	$64\,m^2$
spatial resolution	~ 0.3 cm	200–340 μm	200–410 μm	160–390 μm
time resolution	1.5 ns	8 ns	8 ns	8 ns