Upgrades and studies of aging of the CMS muon system in preparation of HL-LHC

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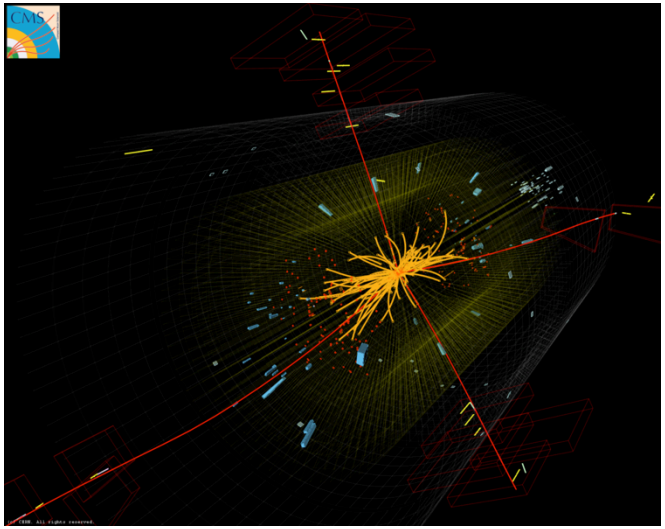
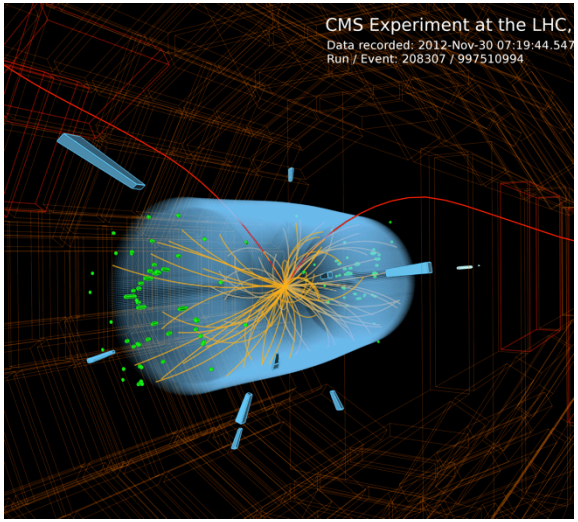
on behalf of the CMS Muon Group

Muons

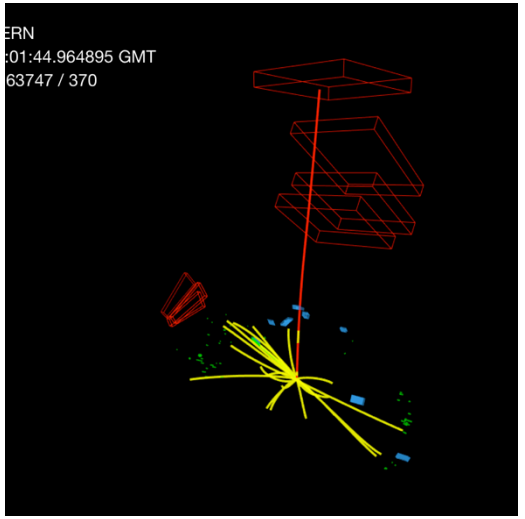
- **Muon? "Who ordered that!?"**
- **HEP experimentalists!**
  - Searches and measurements using muons are among the cleanest in high energy physics
  - CMS stands for **Compact Muon Solenoid**



H→ZZ→4μ (golden channel)

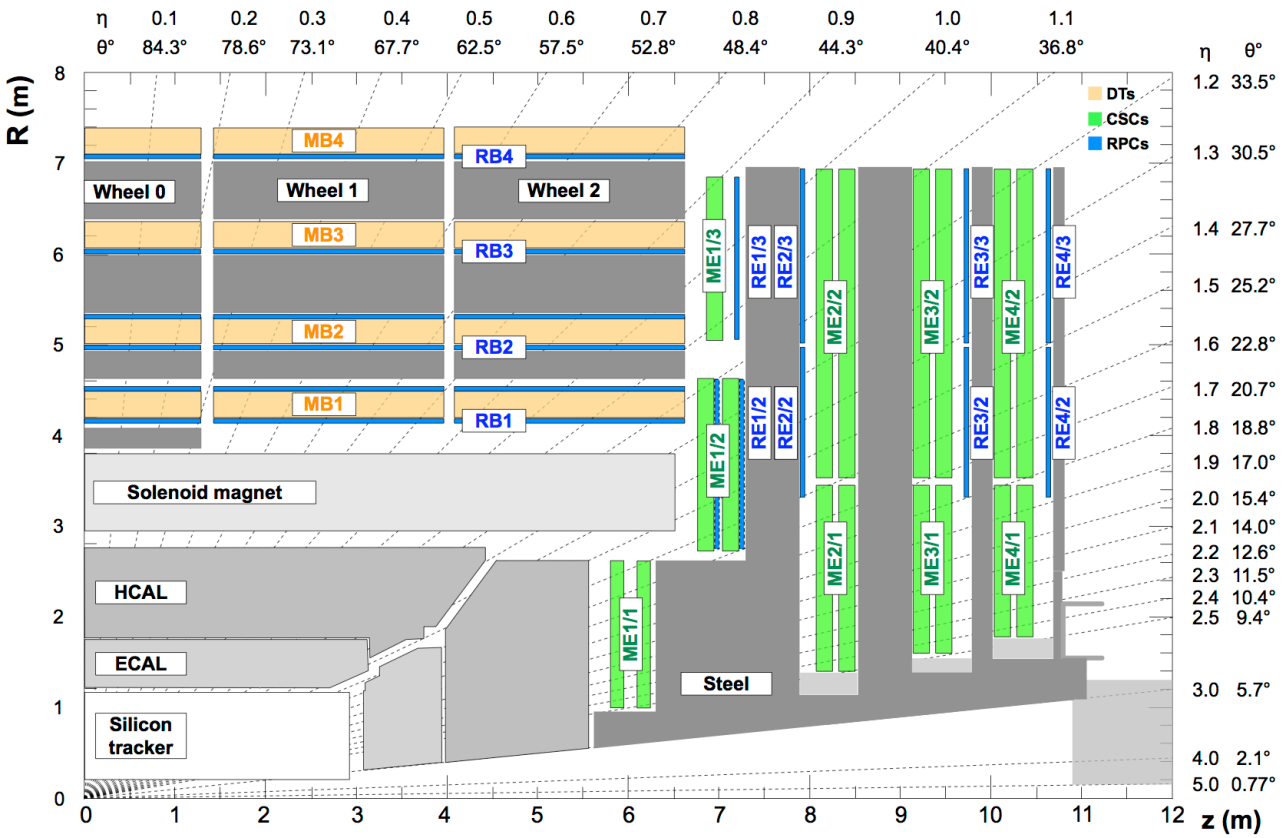


B_s→2μ (BSM search)



W→μν (precision W mass)

Current CMS Muon System



DT (drift tubes):
trigger, precision, low rate

CSC (cathode strip chambers):
trigger, precision, high rate

RPC (resistive plate chambers):
trigger, fast

Redundancy (4 stations with 2 detector technologies on the path of a muon in ≈any direction) ensure

- robust trigger
- efficient reconstruction

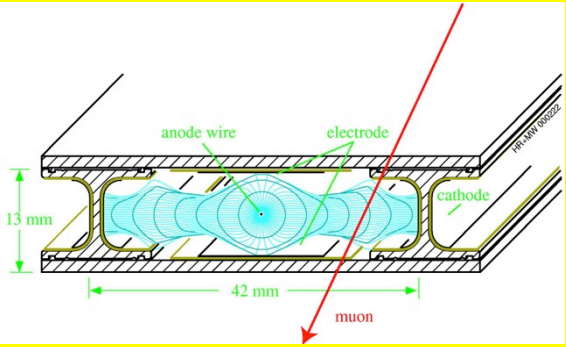
Acceptance: $|\eta| < 2.4$

L1 Trigger: $p_T > 25$ GeV (μ); $p_T > 4$ GeV ($\mu^+\mu^-$, $\Delta R<1.2$)

Reconstruction: $p > 3$ GeV (yes, p), $\delta p_T/p_T \approx$ 1-2% (with the Tracker)

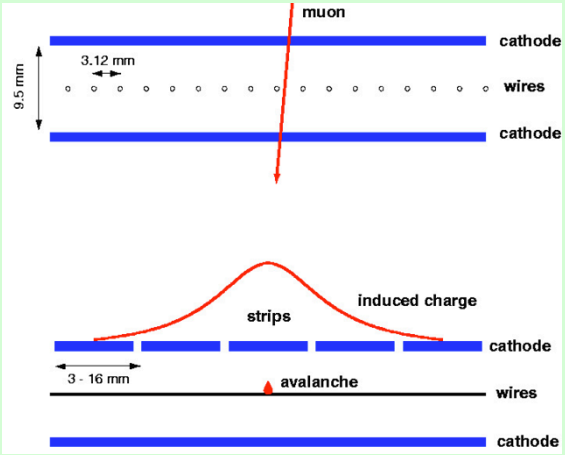
Three technologies

DTs



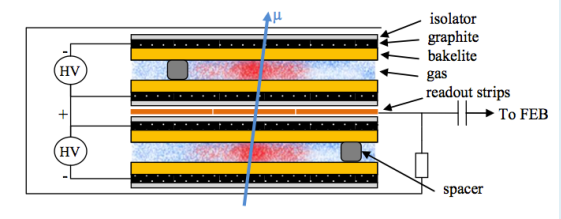
Sensitive layers area: **18,500 m^2**
Number of channels: **172K**

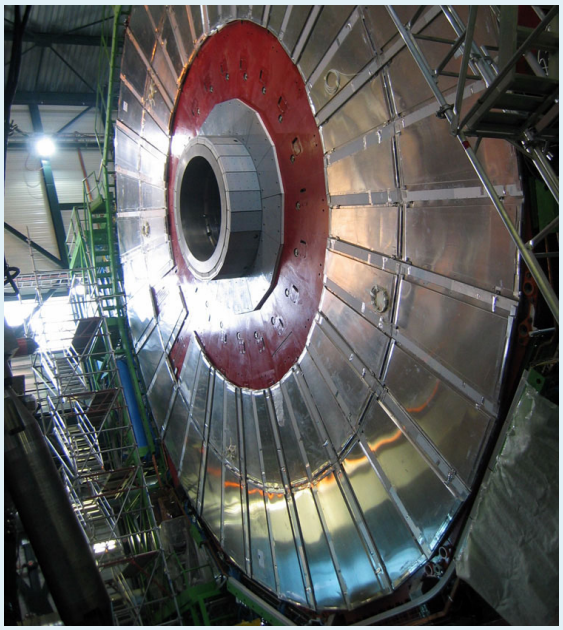
CSCs



Sensitive layers area: **6,300 m^2**
Number of channels: **477K**

RPCs





Sensitive layers area: **4,000 m^2**
Number of channels: **137K**

HL-LHC vs LHC

		LHC	HL-LHC
Collider	instantaneous luminosity ($cm^{-2}s^{-1}$)	10^{34}	**5×10^{34}**
	pileup collisions	30	**150**
	integrated luminosity (fb^{-1})	300	**3000**
CMS	L1 trigger (kHz)	100	**750**
	L1 trigger latency (μs)	3.6	**12.5**
	Muon System DAQ Bandwidth		**×10**

All LHC experiments were designed for the LHC specs

New specs require detector upgrades

CMS Muon System Upgrade Concept

- **CONFIRM longevity of detectors/electronics to stay at HL-LHC**
  (NB: all present day detectors will stay)

- **REPLACE some electronics expected to fail HL-LHC requirements**

- **ENHANCE the muon system robustness:**
  - **new RPC electronics (1.5 ns sampling time, instead of 25 ns)**
    - **suppress out-of-time background**
  - **additional detectors in the very forward direction**
    - **keep trigger rates under control**
    - **improve muon identification efficiency and purity (trigger and offline)**

BONUS: enhancements will also open new physics opportunities

CMS Muon System Upgrade Concept

this talk

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this talk

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this talk

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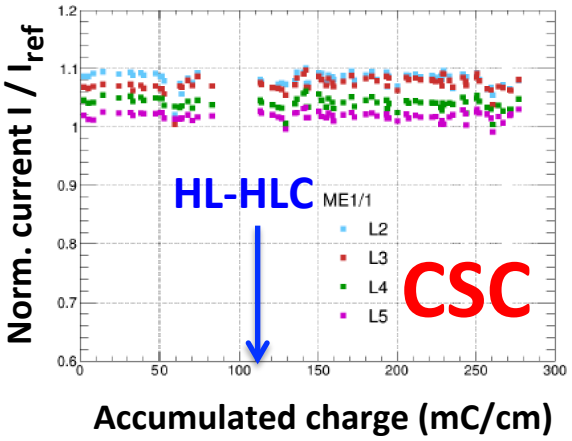
Present detector longevity

- **Full-size DTs, CSCs, RPCs are exposed to high rates at the CERN Gamma Irradiation Facility (GIF++)**
- **DTs (Ar : CO_2)**
  - **about 15%** of chambers, most exposed to background, will see noticeable gas gain loss
  - efficiency per layer may drop **as low as 50%**
  - muon reconstruction will **remain high**, thanks to multiple layers of DTs on the path of a muon
  - aging mitigation measures are being explored
- **CSCs (Ar : CO_2 : CF_4)**
  - no noticeable gas gain loss up to **2.5 × HL-LHC**
  - tests continue
- **RPCs (i-C_4H_{10} : $C_2H_2F_4$: SF_6)**
  - tests are on-going



Eco-friendlier gas

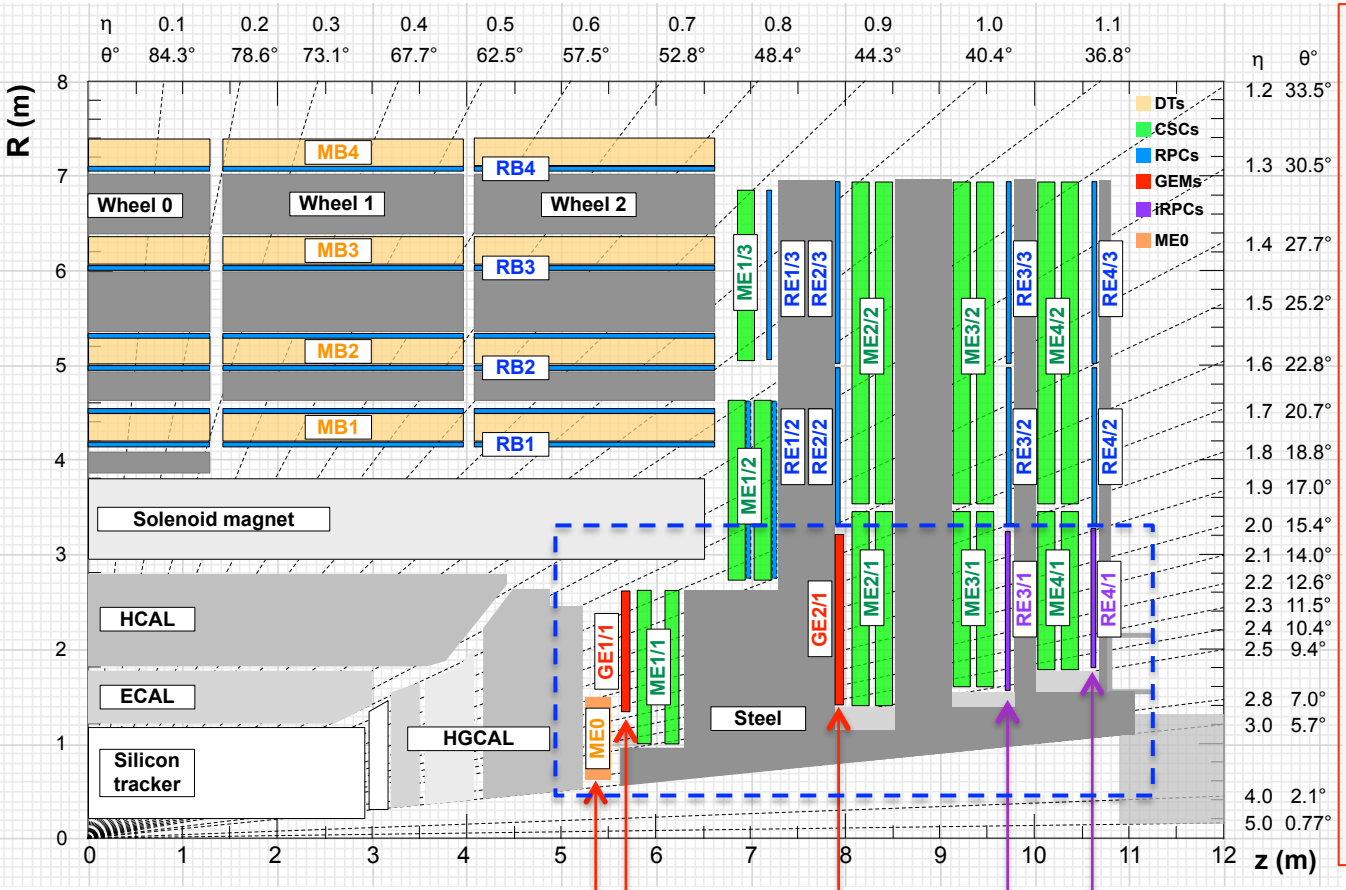
- **New regulations**

  *In 2014, the European Commission adopted a new regulation limiting the total amount of important **fluorinated greenhouse gases (F-gases)** that can be sold in the EU from 2015 onward and phasing them down in steps to **one-fifth of 2014 sales in 2030***

- **CSC and RPC F-gas footprint**
  - **1700 m^3/hr of CO_2 equivalent (yearly, ≈12K cars)**
    - CSCs use **10% CF_4**: 274 m^3/hr of CO_2 equivalent
    - RPCs use **95.2% $C_2H_2F_4$** and **0.3% SF_6**: 1440 m^3/hr of CO_2 equivalent
  - **F-gases used by CSCs and RPCs prevent aging and ensure reliable operation**

- **Solutions**
  - **new eco-friendlier gas options** → RPCs explore operation with **CF_3I, $C_3H_2F_4$** (GWP ≈ 0, 4)
  - **F-gas consumption reduction** → CSCs explore operation with **2% CF_4**
  - **Other measures being explored:**
    - improved recuperation (currently, CSCs only and ~40% efficient)
    - add an "abatement" system to burn off F-gases on the exhaust into harmless compounds

Enhance system in forward direction



Very challenging region:

- trigger
- offline reconstruction

<u>High rates</u>: random hits, punchthrough, muons

<u>Small bending</u> of muons by magnetic field

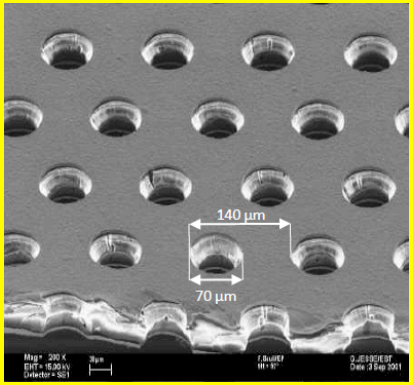
UPGRADE: augment the system by adding new detectors

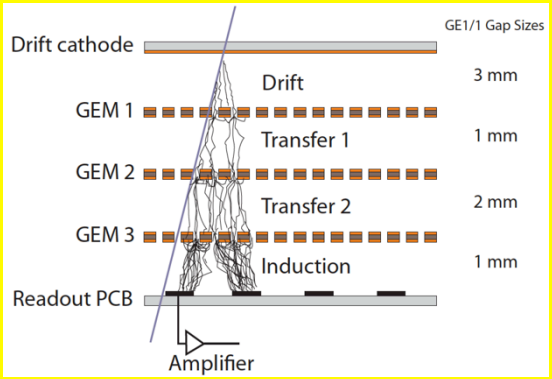
improved RPC (iRPC)

GEM detectors

New detectors in the forward direction

GEM – gas electron multiplier





Avalanches in strong electric field concentrated in pin holes

Triplet GEM: **gas gain 10^4**

Operate well in **high rate**

Tests show **excellent longevity**

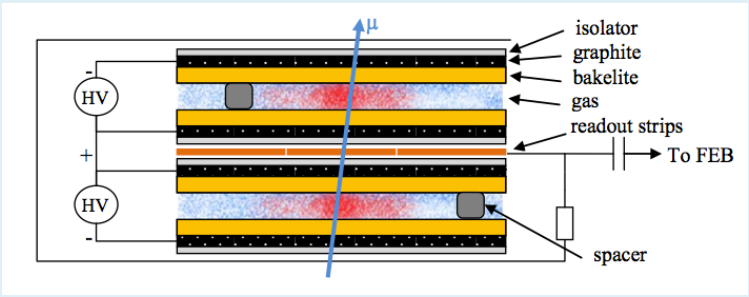
GE1/1, GE2/1 stations: 2 layers of triplet-GEM units

ME0: 6 layers of triplet-GEM units

Overall area (triplet-GEM): **220 m^2**

Number of channels: **1.5M**

improved RPC



Improvements:

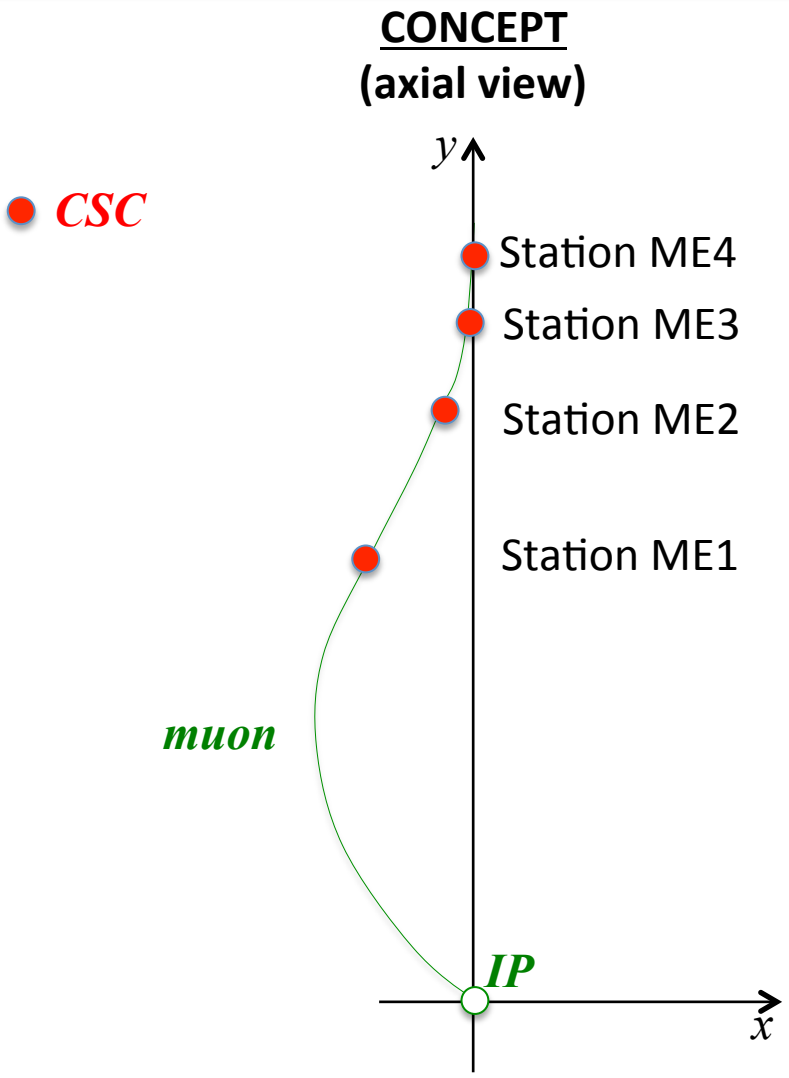
- higher rate capability (lower resistivity, smaller gas gain)
- two-ended strip readout

RE3/1 and RE4/1 stations: double-layer RPC units

Overall area: **90 m^2**

Number of channels: **14K**

L1 Trigger: p_T measurement and rate



CSCs alone provide short segments with low-precision info on segment direction

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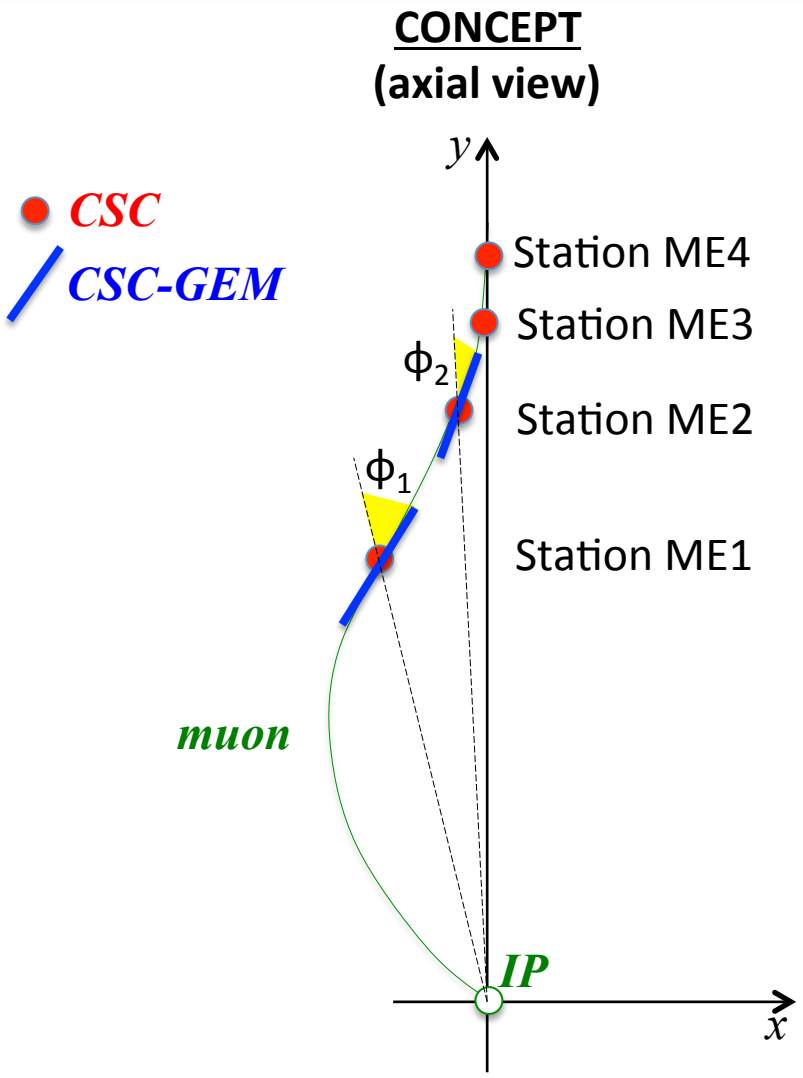

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GEM-CSC tandems in ME1 and ME2 stations give accurate measurement of muon "local" direction sensitive to muon p_T

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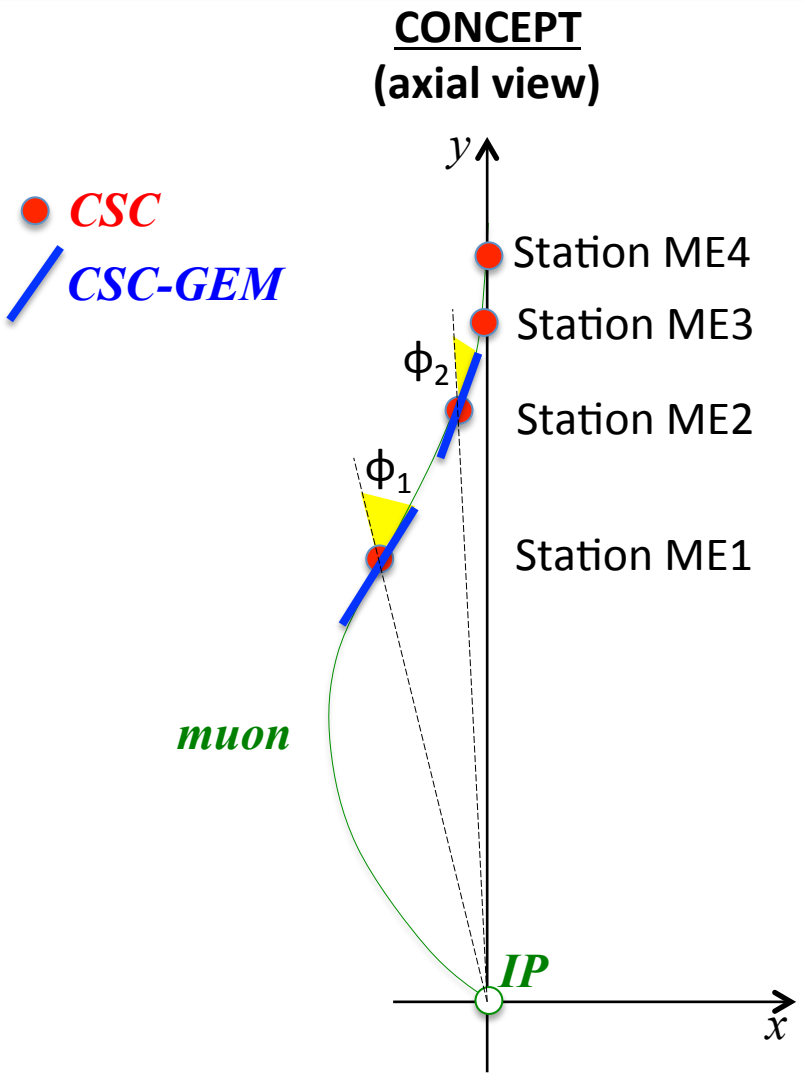

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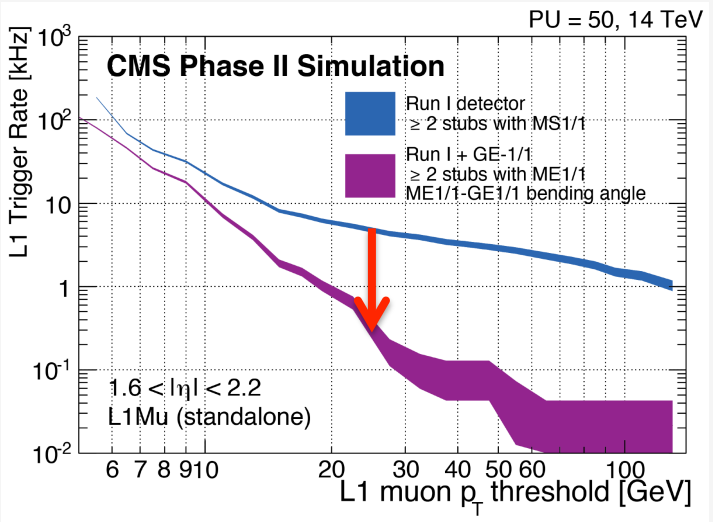
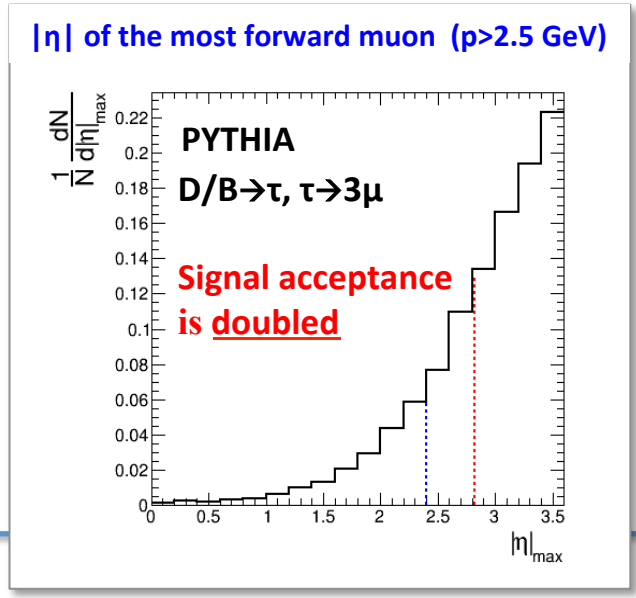
GEM-CSC tandems in ME1 and ME2 stations give accurate measurement of muon "local" direction sensitive to muon p_T

p_T measurement improves and, hence, the L1-trigger rate drops by a factor of 10



New physics search bonuses

- **Trigger on slow-moving muon-like particles**
  - heavy "colorless" charged particles with very long lifetimes: hits in the muon system can be considerably delayed and spread in time
  - **Upgraded RPC electronics** with **precision timing** can trigger on such slow "muons"
- **Trigger on displaced muons**
  - long-lived exotic particles can decay into muons O(1) m away from interaction point
  - **GEM+CSC packages in ME1 and ME2** stations provide **long lever arms** and allow one to trigger on displaced muons in the forward direction without an interaction point constraint
- **Extended muon acceptance**
  - many BSM searches and SM measurements benefit from "very forward" muon acceptance (e.g., τ→3μ)
  - **ME0 chambers** extend muon η coverage: **2.4 → 2.8**



Summary: CMS Muon System Upgrade

- **CONFIRM longevity of detectors/electronics to stay at HL-LHC**
- **REPLACE some electronics expected to fail HL-LHC requirements**
- **ENHANCE the muon system robustness:**
  - **new faster RPC electronics**
  - **additional detectors, GEMs and iRPCs, in the very forward direction**

BONUS: enhancements will also open new physics opportunities