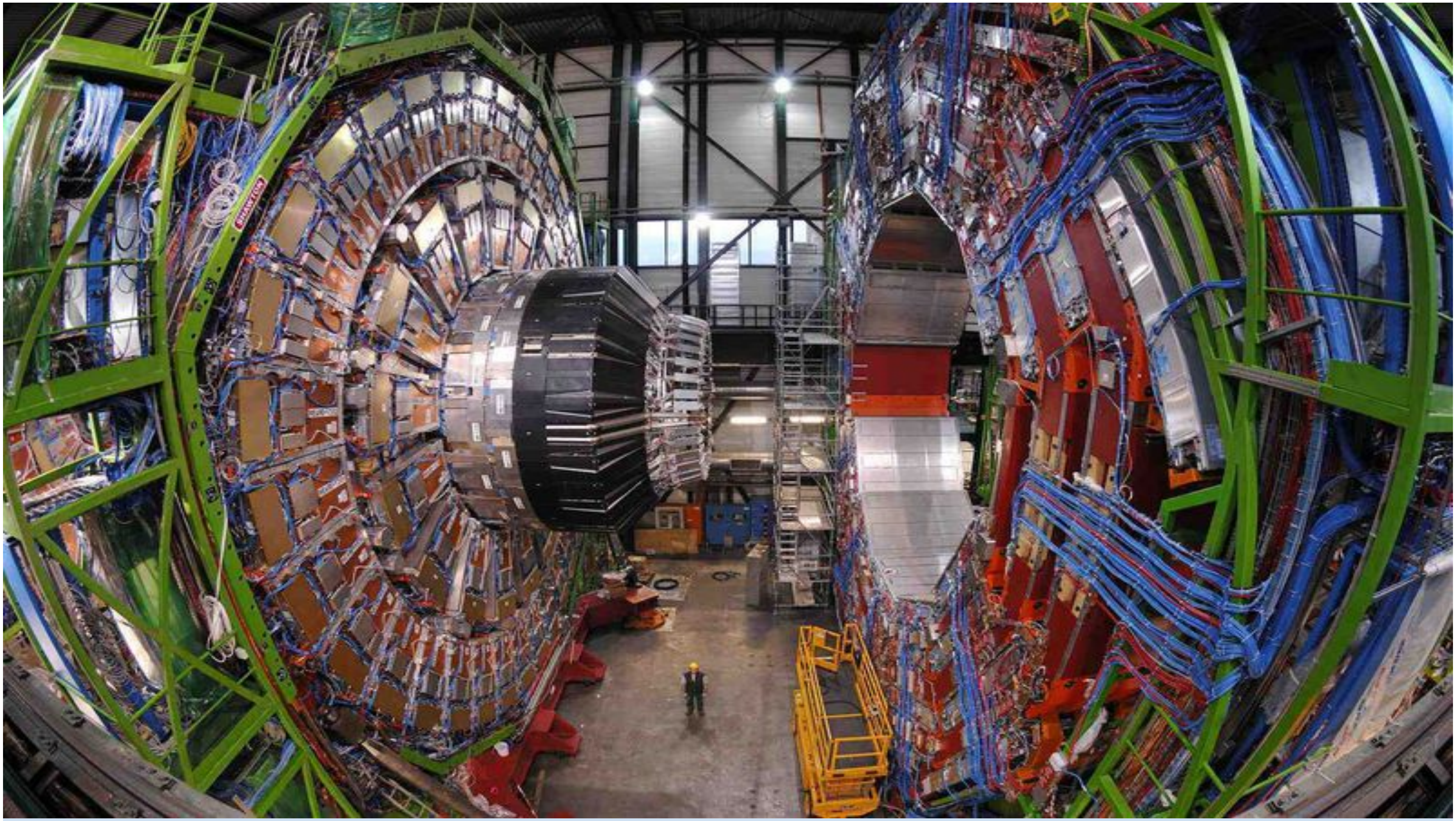
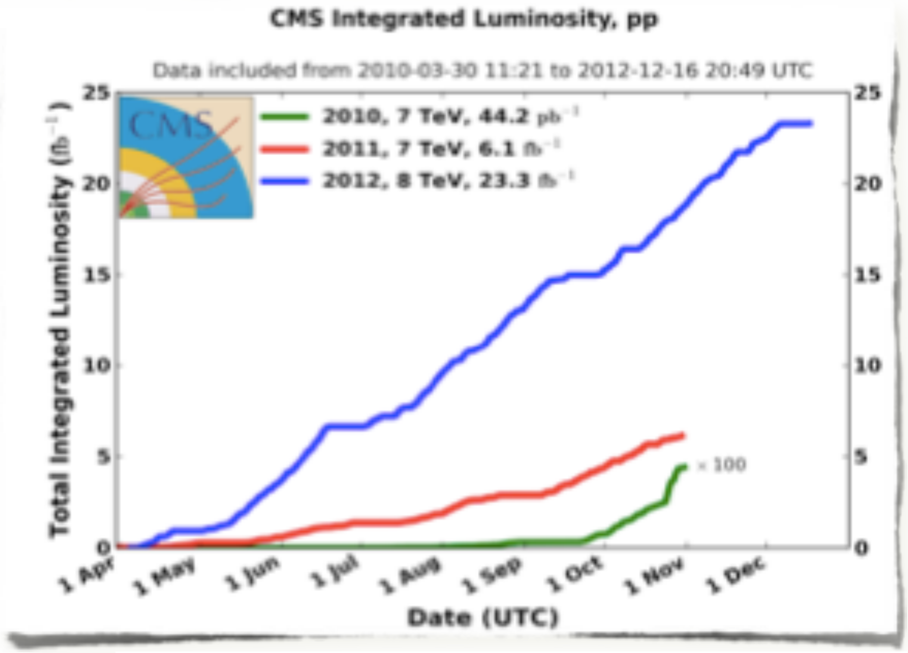


Status of the CMS Muon system

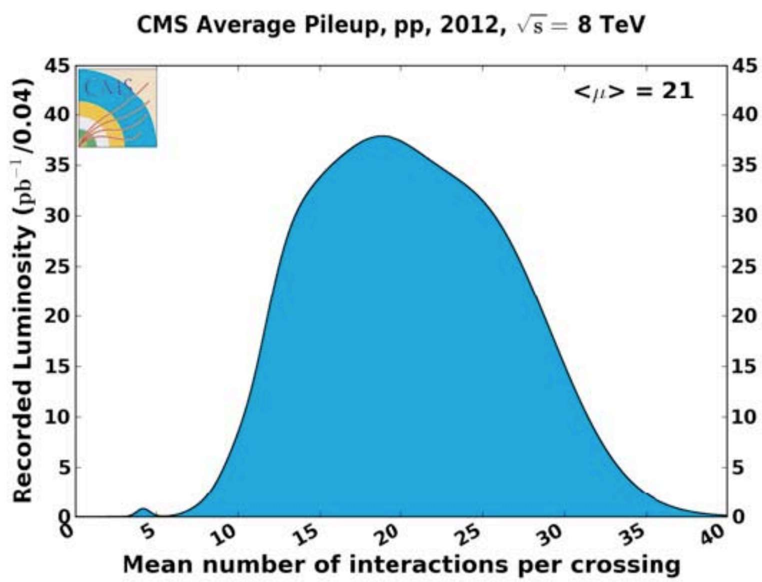
Guenakh Mitselmakher
University of Florida

LHC performance, CMS pp-collisions

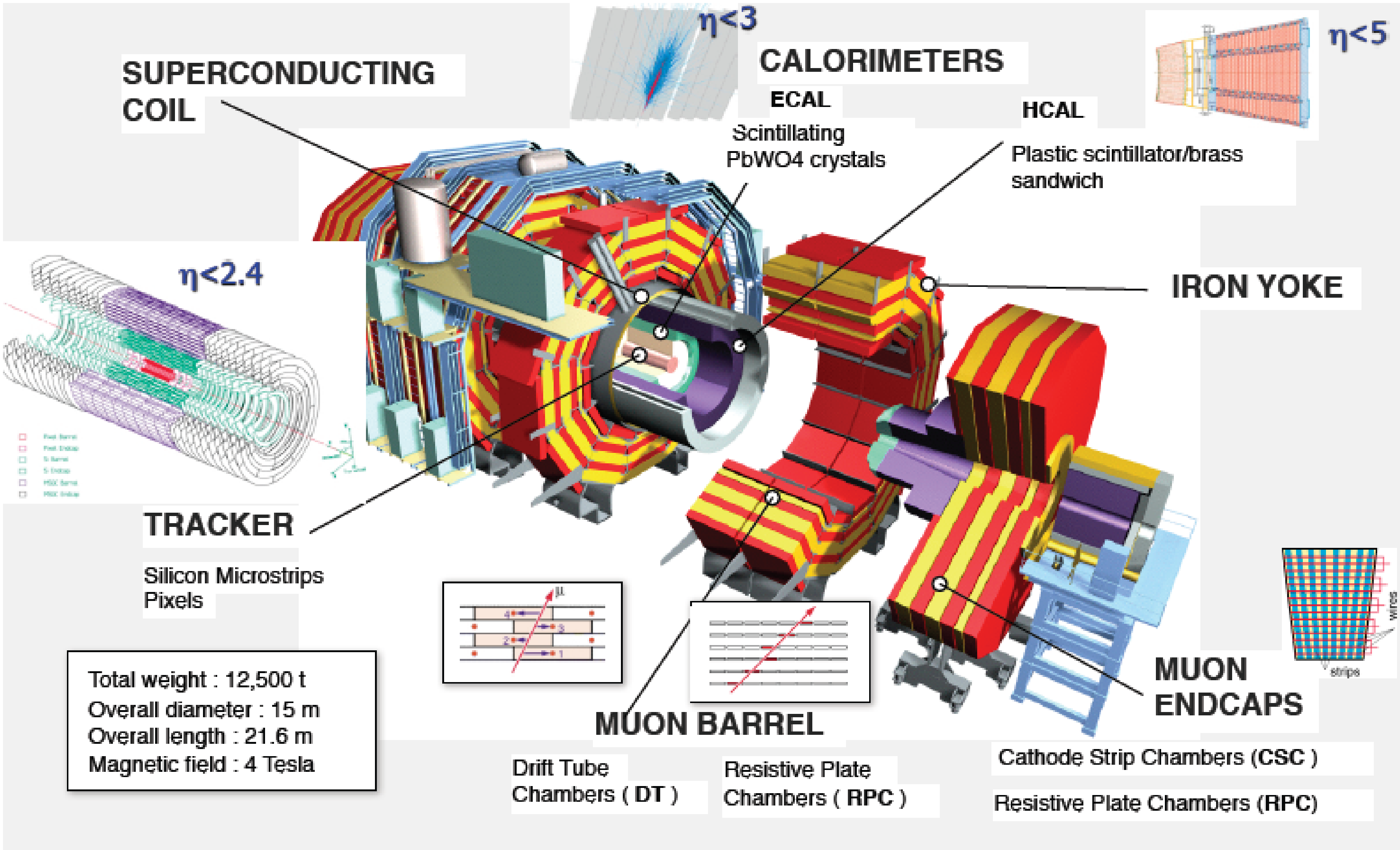
pp collisions in CMS
2010: ~44 pb^{-1} @ 7 TeV
2011: ~6 fb^{-1} @ 7 TeV
2012: ~23 fb^{-1} @ 8 TeV



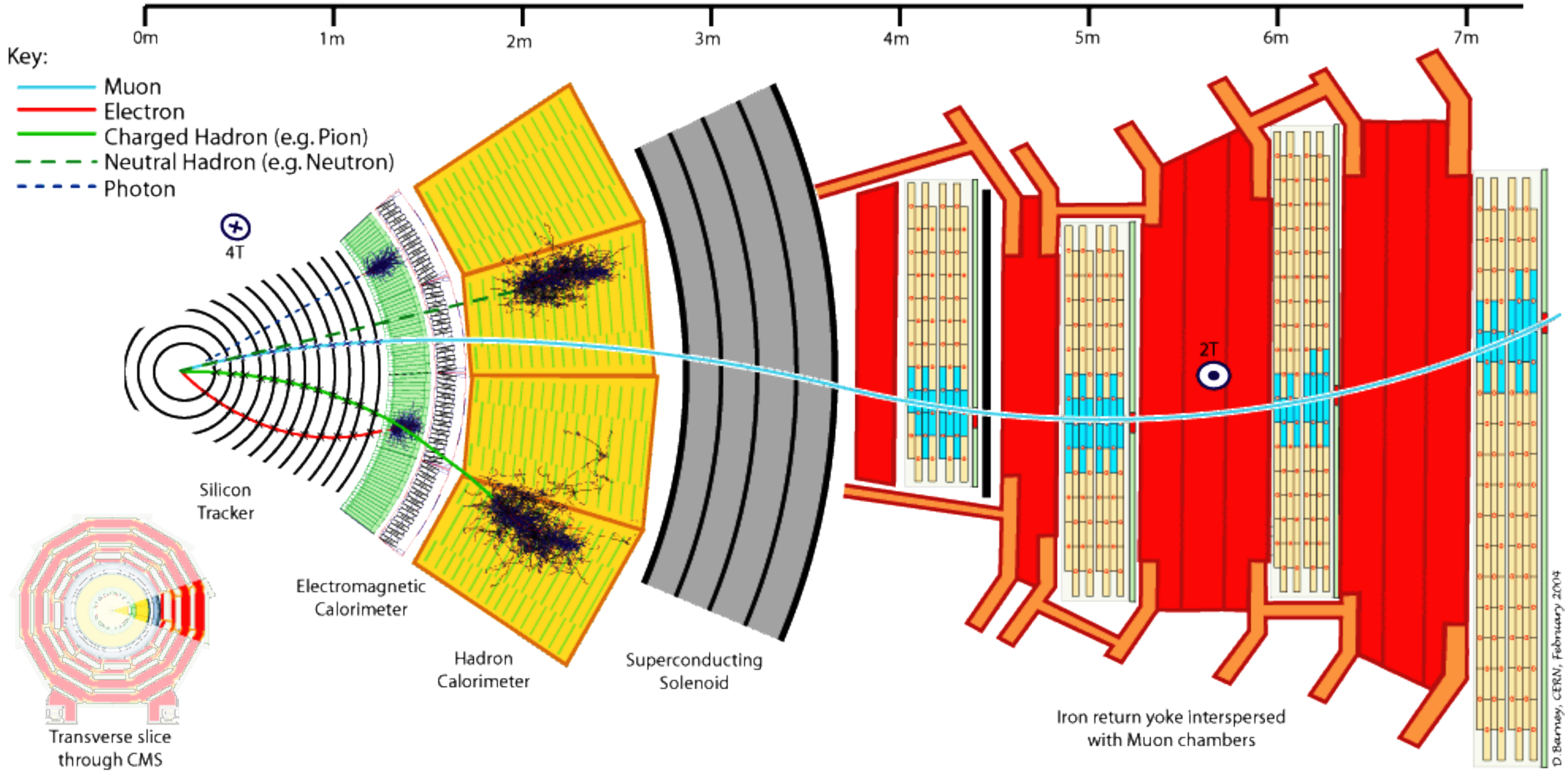
In 2012: reached ~ design luminosity but at 50 nsec bunch spacing (instead of 25 nsec). pilep > design



The Compact Muon Solenoid



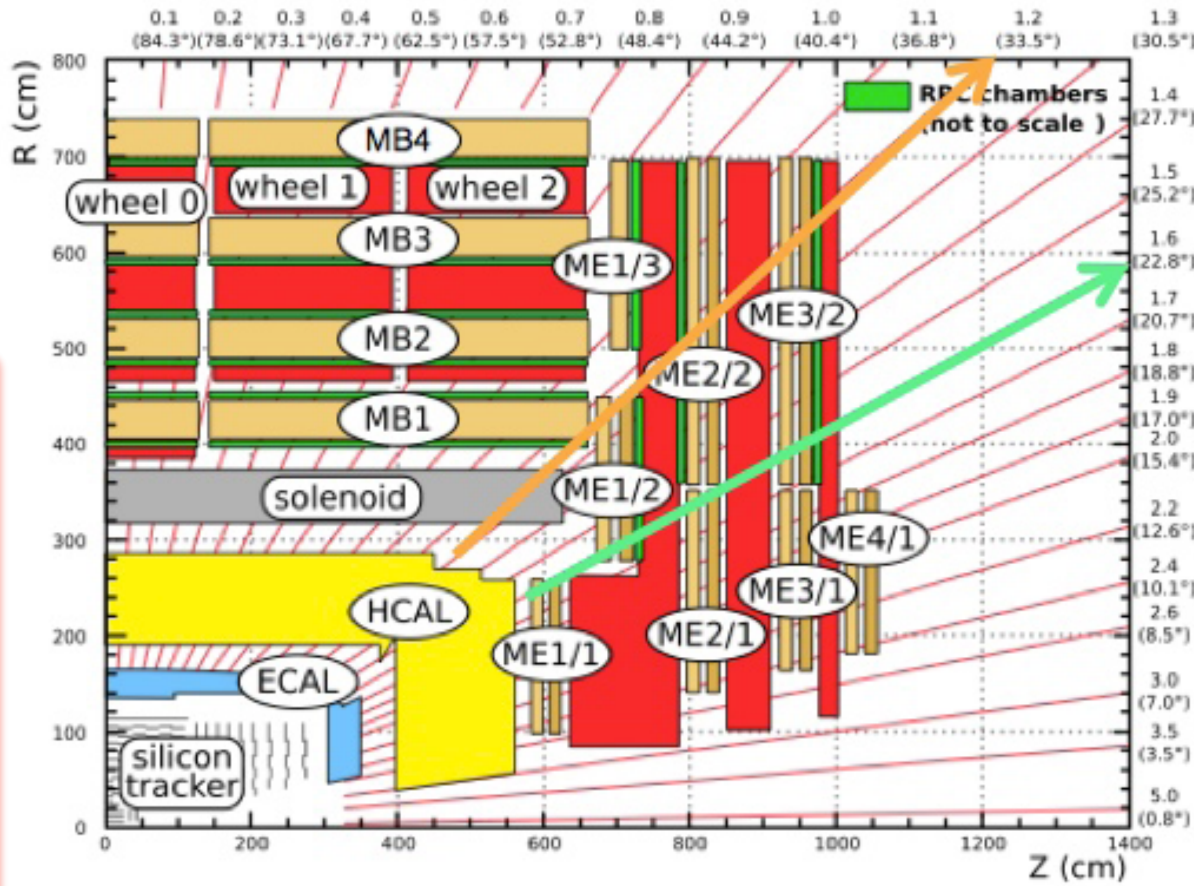
Particle identification in CMS



CMS Muon chambers

- Robust, efficient and redundant muon system design
- 4 stations interleaved with iron return yoke

- Cylindrical barrel region:
  - 4 coaxial stations. Chambers are grouped into 5 wheels of 12 azimuthal sectors
  - Equipped with Drift Tubes (DT) and Resistive Plate Chambers (RPC)



- Planar endcap region:
  - 4 planar stations (4th station completion in 2014)
  - Equipped with a Cathode Strip Chambers (CSC) and RPC

CMS Detector Requirements for the Muon System (TDR)

Primary Functions

- **Muon identification;**
- **Muon momentum measurement;**
- **Muon triggering;**

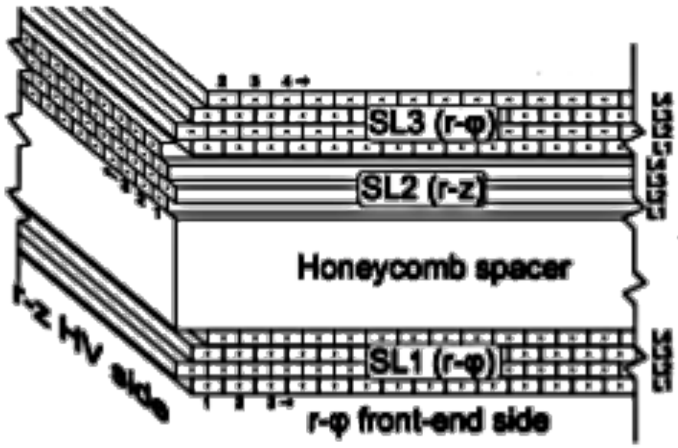
- **Muon momentum resolution over a wide range of momenta in the region $|\eta| < 2.5$:**

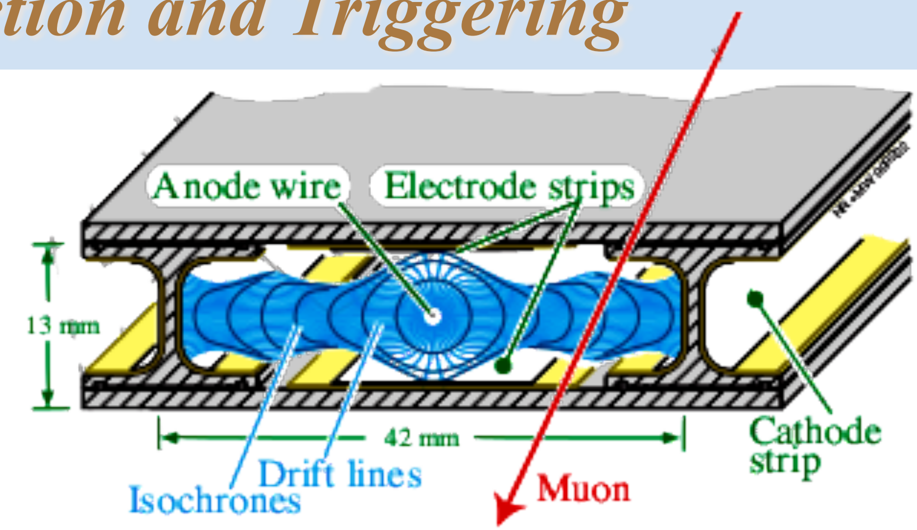
  - **Muon system - 8–15% at 10 GeV/c, 20–40% at 1 TeV/c;**
  - **Tracker and muon system - 1–1.5% at 10 GeV/c, 6–17% at 1 TeV/c;**

- **A good dimuon mass resolution (1% at 100 GeV/c^2);**
- **Charge misassignment - less than 0.1% at muon p_T = 100 GeV/c;**
- **Trigger on single- and multi-muon events with well defined thresholds from a few to 100 GeV/c;**

Drift Tubes – DT
Reconstruction and Triggering

$|\eta| < 1.2$





Barrel part - 5 wheels;
4 stations per wheel;
12 sectors per wheel;

DT chamber
8 layers in the (r-φ) plane
4 layers in the (r-z) plane

spatial resolution
(r-φ) ~ 100 μm (depends on the muon impact angle) (r-z) ~ 150 μm

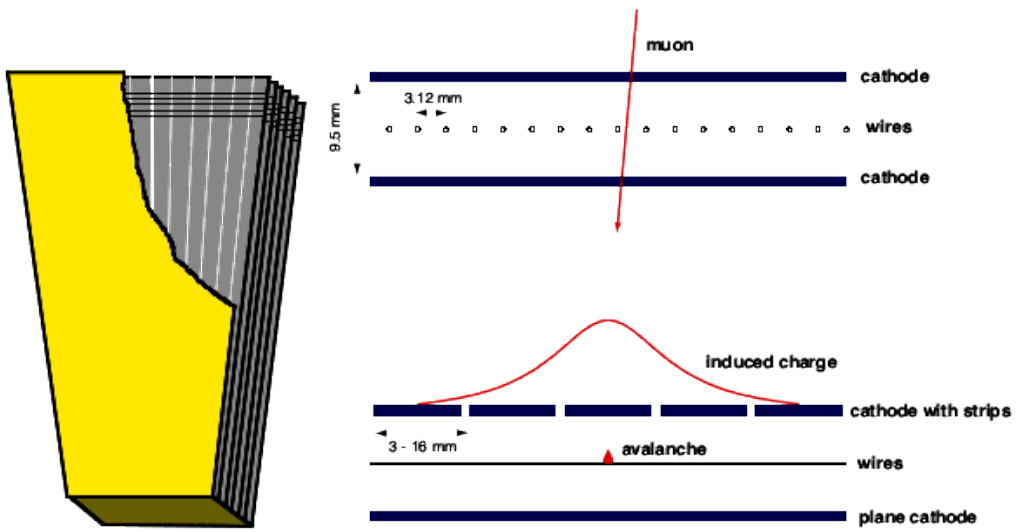
Drift cell - 42 × 13 mm^2;
Anode wire – d = 50 μm, HV = +3600 V;
Gas mixture – 85% Ar, 15% CO_2;
Drift velocity ~ 55 μm/ns;
Max drift time ~ 400 ns;

2 Cathode strips – HV = -1.8 kV;
2 Electrode srips – HV = +1.8 kV

Length ~ 2.5 m;
Transverse size – 1.9 m (MB1) – 4.1 m (MB4)

Cathode Strip Chambers – CSC Reconstruction and Triggering

0.9 < |η| < 2.4



4 stations per endcap

spatial resolution
(r-φ) 75 (ME1/1) - 150 μm
(depends on the muon impact angle)

6 layers per chamber;
80 cathode strips per layer :

Anode wires: ME 1/1:
d = 30 μm; spaced by ~ 2.5 mm;
HV 2900 V;
All the other chambers:
d = 50 μm; spaced by ~3.5 mm;
HV = 3600 V;

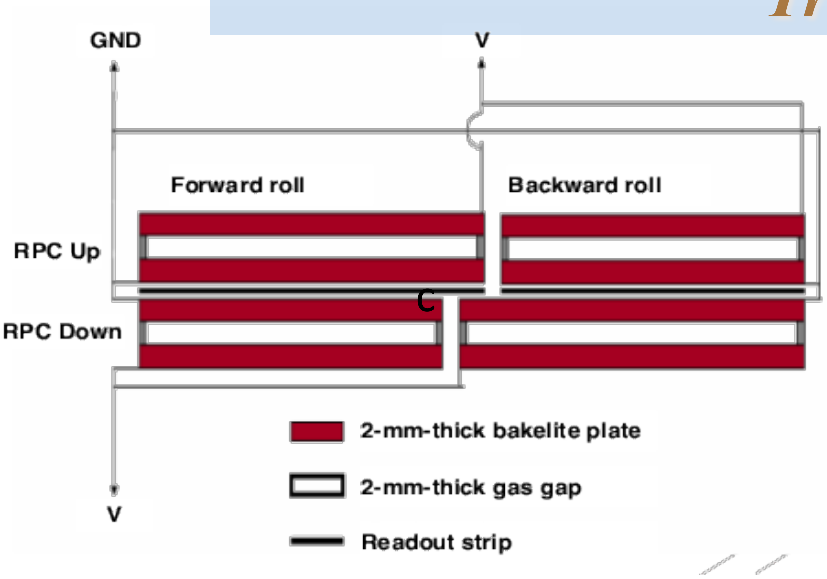
Groups of 5 to 16 wires, with widths from 16 to 51 mm, which limits the position resolution in the wire coordinate direction.

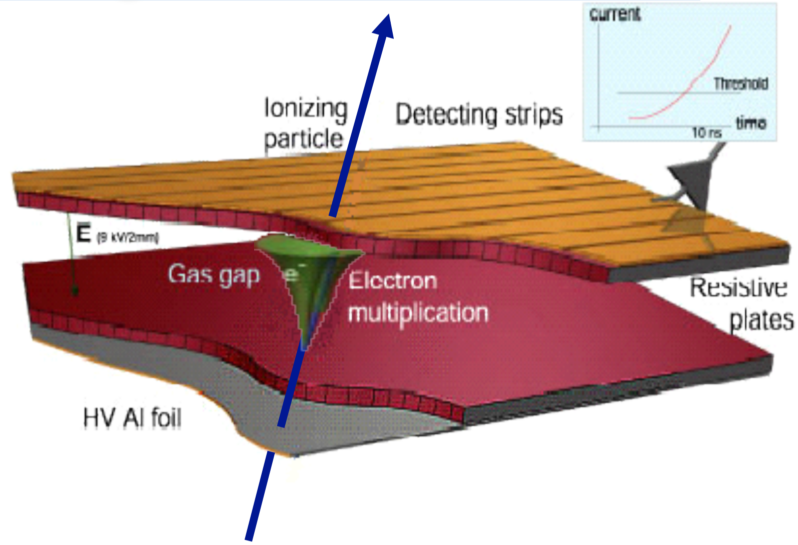
Gas mixture:
50% CO_2 , 40% Ar, and 10% CF_4

Chamber length – from 1.7 m to 3.4 m

Resistive Plate Chambers – RPC Triggering

$|\eta| < 1.6$



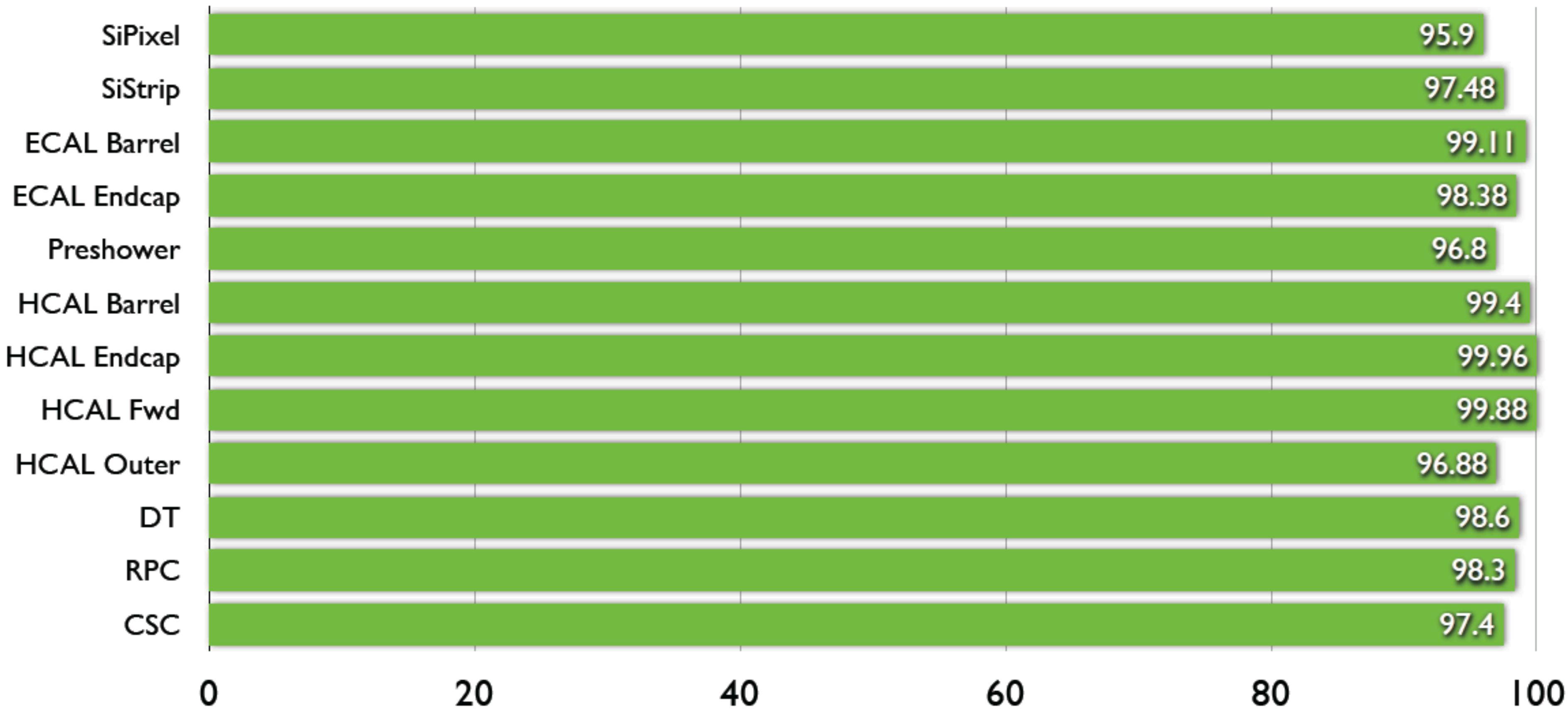


Resistive Plates	**Bakelite with bulk resistivity (1 - 2). 10^{10} Ω.cm**
Gas gap	**2 mm ± 20 µm wide**
Gas mixture	**95,2% $C_2H_2F_4$(Freon), 4,5 % iC_4H_{10} (Isobutan), 0,3 % SF_6**
Detecting copper strips	**pitch 2.3 – 4.1 cm (barrel); 1.7 – 3.6 cm (endcap)**
Avalanche mode	**ability to work at a high rate of ionizing particles ~ 1 kHz/cm²**
Trigger	**time resolution < 2 ns – bunch crossing assignment**
Operating HV	**9.4 - 9.8 kV**
Linseed oil treatment	

Design Parameters of the Muon system

Muon subsystem	Drift Tubes (DT)	Cathode Strip Chambers (CSC)	Resistive Plate Chambers (RPC)
Function	Tracking, p_T trigger, BX ID	Tracking, p_T trigger, BX ID	p_T trigger, BX ID
$\|\eta\|$ range	0.0 - 1.2	0.9 – 2.4	0.0 – 1.6
№ of stations	4	4 (no ME4/2 ring)	Barrel 4; Endcap 3
№ of layers per station	r-φ:8, z:4	6	2 in RB1 and RB2; 1 elsewhere
№ of chambers	250	468	Barrel 480; Endcap 432
№ of channels	172000	Strips 220000; Wire groups 183000	Barrel 68000; Endcap 41000

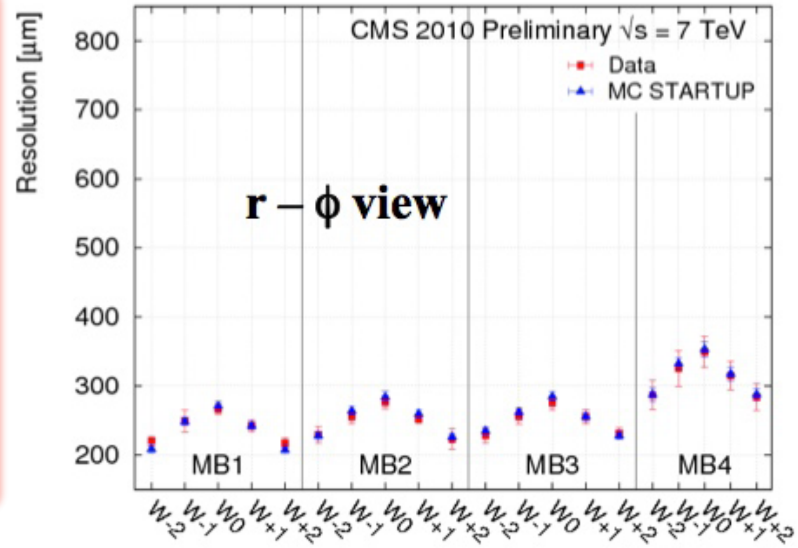
CMS Subsystems performance: reliability data

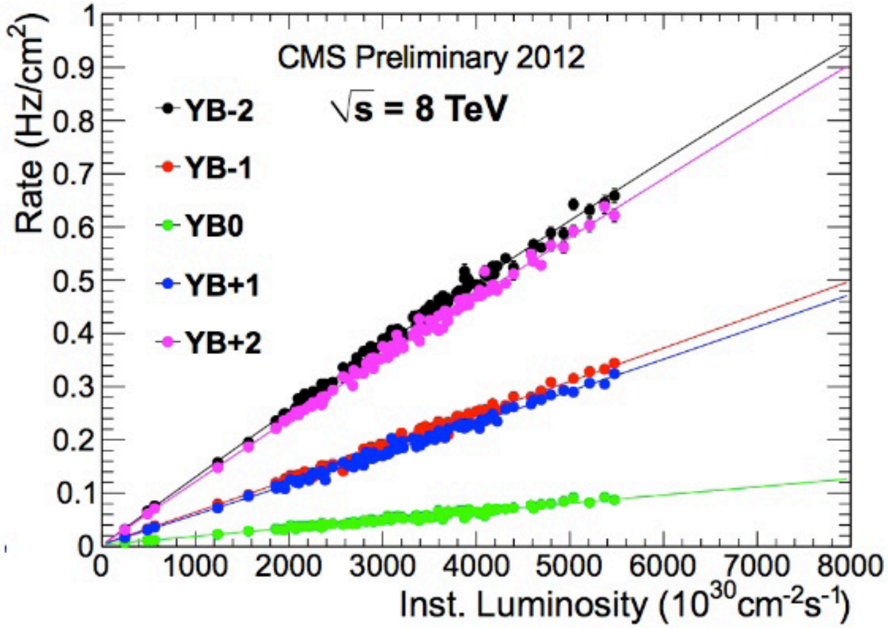


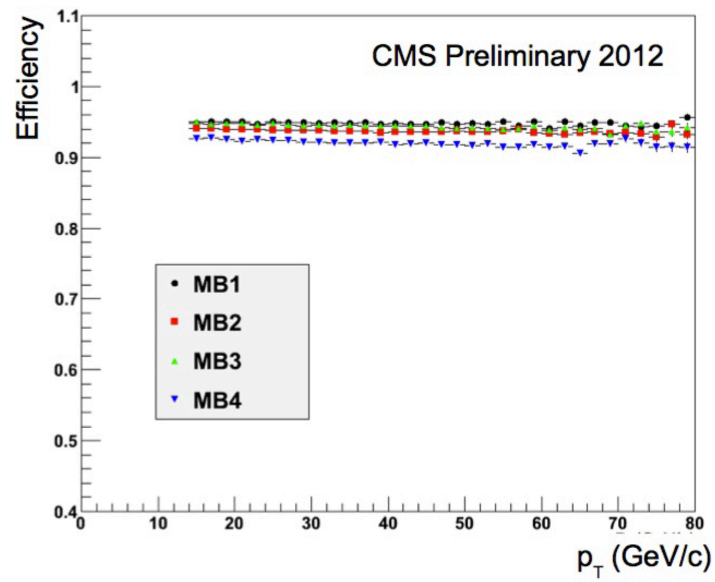
Fraction of working channels > 98%

Muon performance : DTs

- Hit resolution ~250 um
- Good DT Local Trigger efficiency (including Bunch Crossing identification BX-ID)
- DT Background measurement
  - In agreement with neutron hit rate simulations

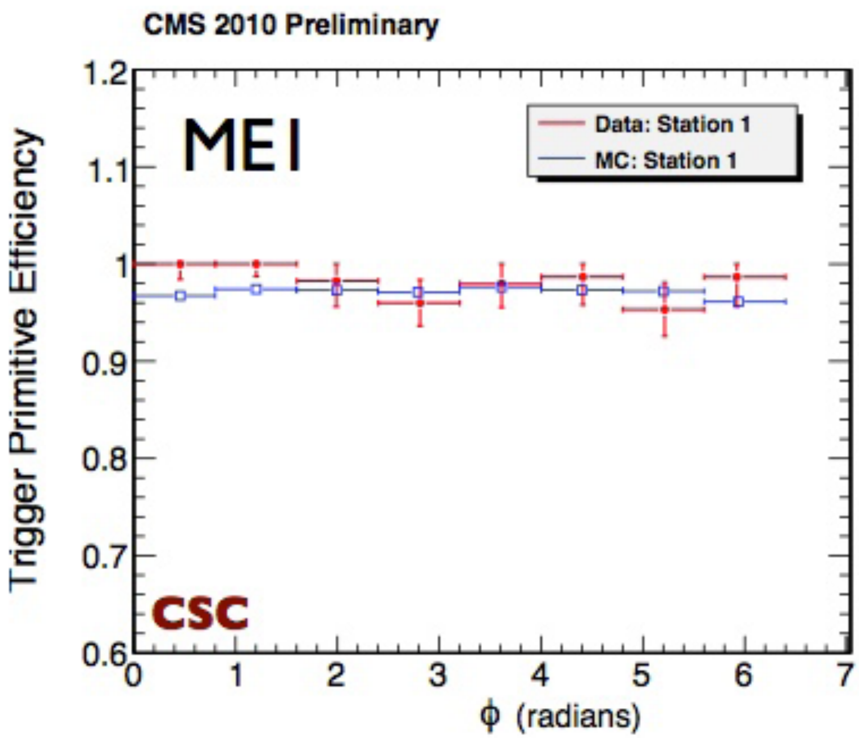


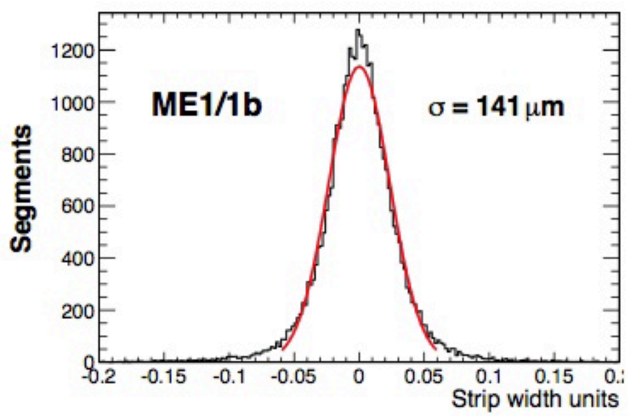


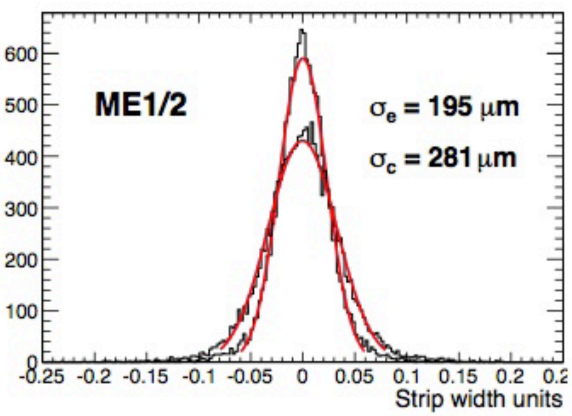


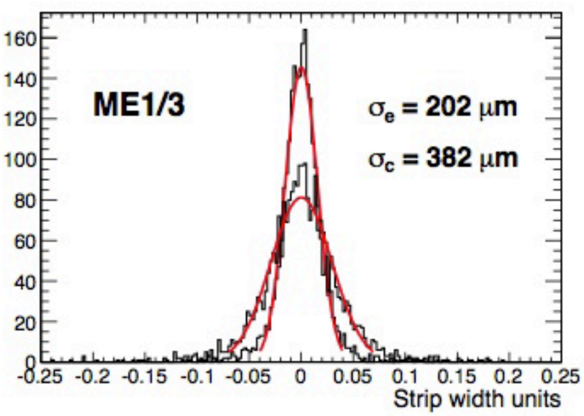
Muon performance: CSC

- High efficiency for ME1 trigger primitives
  - Similar result for other stations
- Resolutions for various chamber types
  - Better than design specification

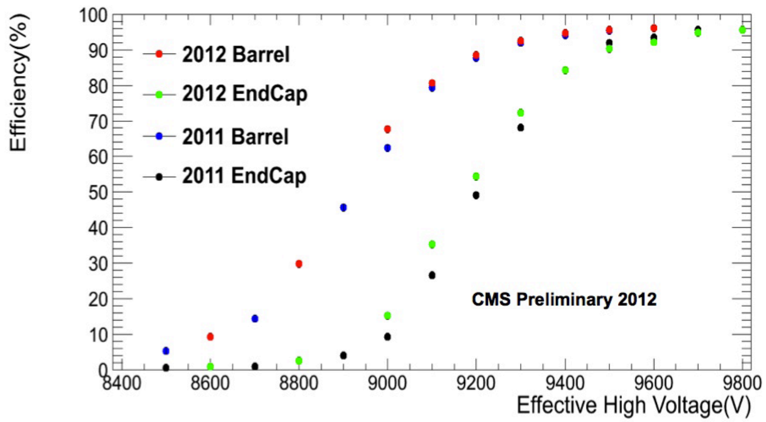


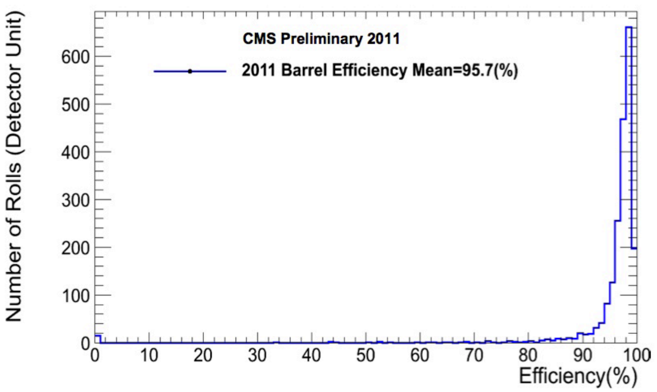






Muon performance: RPC





- HV scans:
  - System stability in time confirmed

- RPC chamber efficiency (Barrel)
  - Average > 95% efficiency

RPC spatial resolution (driven by the strip size):
Barrel: σ = 0.81 cm inner, to σ = 1.32 cm outer station.
Endcap: σ = 0.86 cm in the inner, to σ = 1.28 cm in the outer ring

Muon triggering

All Muon detector systems (DT, CSC, RPC) participate in Triggering:
Level 1 (hardware) and High Level Trigger (software algorithms)

Level 1 trigger (L1)

Local triggers:

DT local trigger (DTLT):

Up to 2 trigger segments on the x-y plane (φ view) and 1 in z direction (θ view);

Tracker finder – collects and combines the DTLT information, forms the muon track and assigns the p_T value;

CSC local trigger (CSCLT):

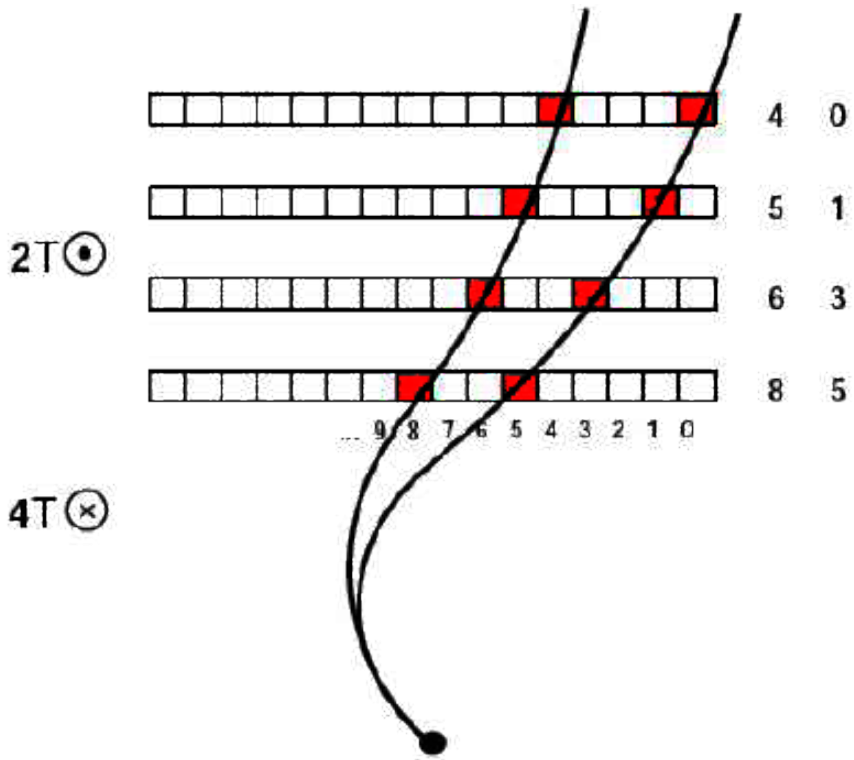
Muon track segments are found separately in the nearly orthogonal cathode and anode planes. Up to 2 cathode and 2 anode local track projections can be found in each chamber at any BX.

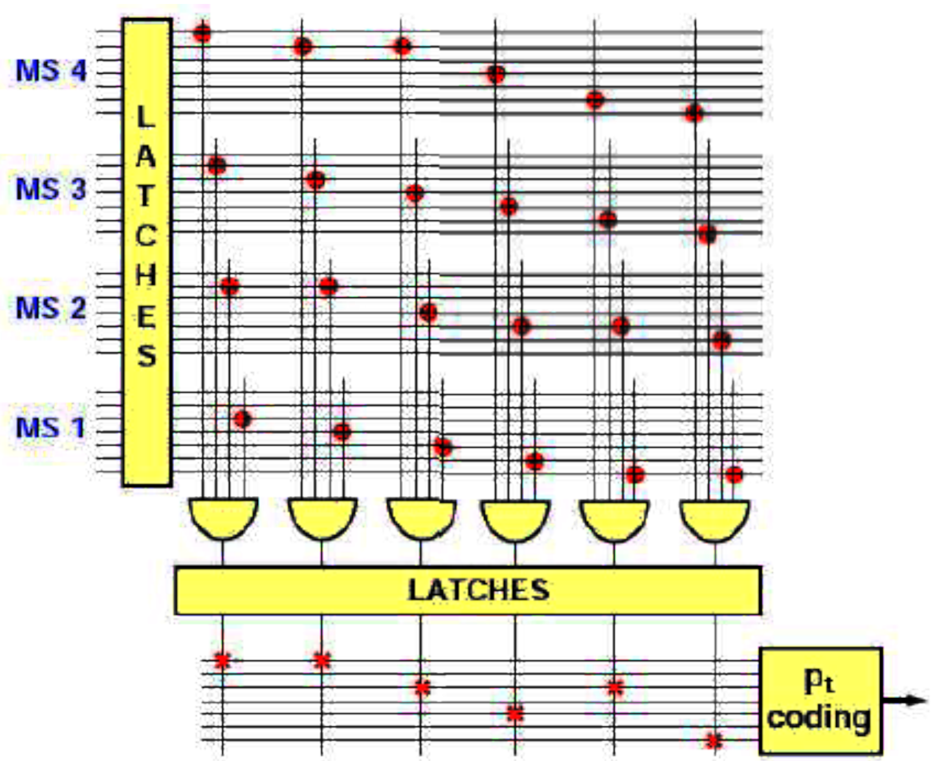
The local track projection are combined into 3D tracks by requiring a timing coincidence in the trigger electronics device.

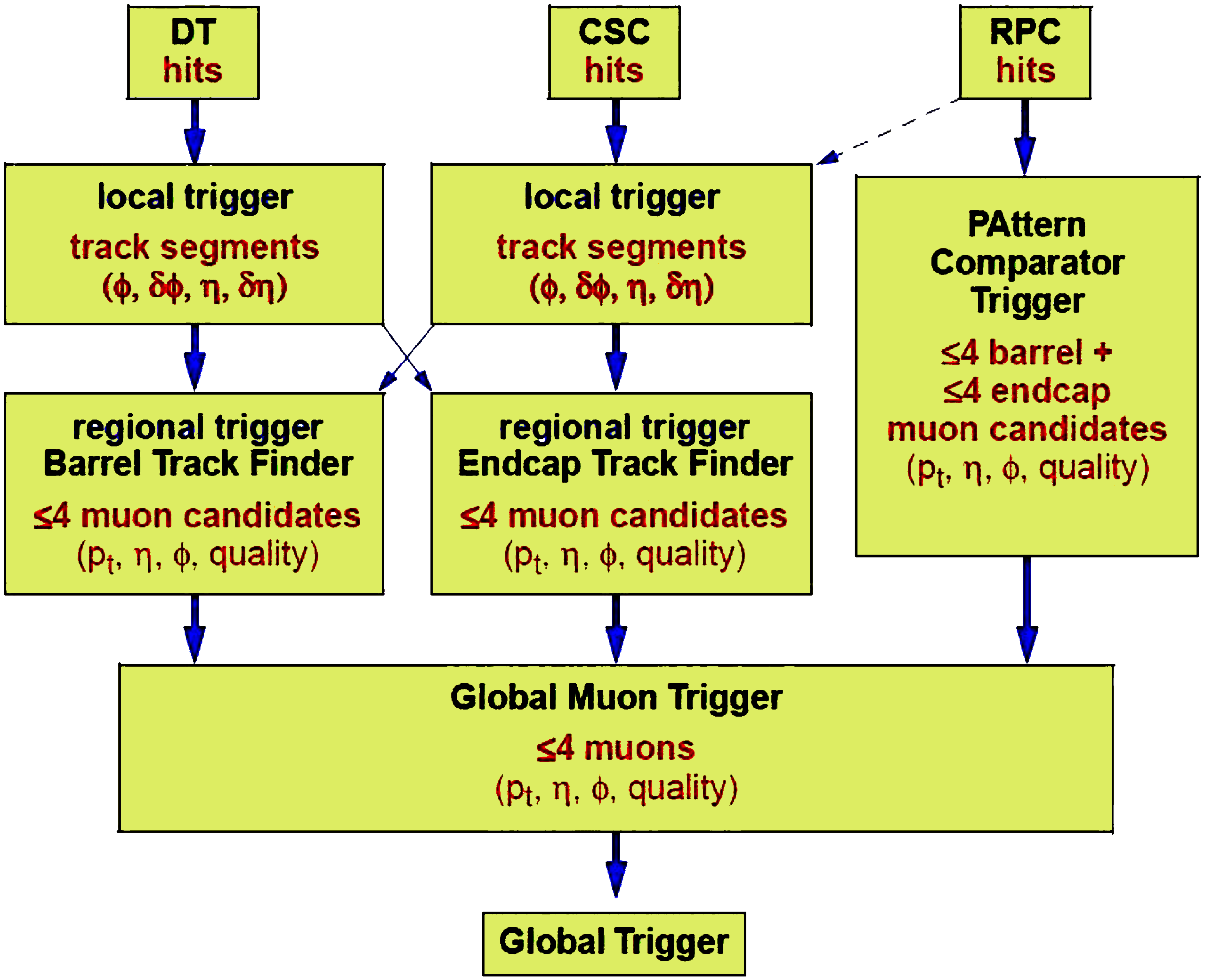
Muon triggering

RPC – PAttern Comparator Trigger (PACT)

Trigger processors compare the observed hit pattern within a segment with predefined patterns corresponding to certain p_T values.
If the observed hits match multiple patterns, the muon candidate with the highest quality and highest p_T is selected.



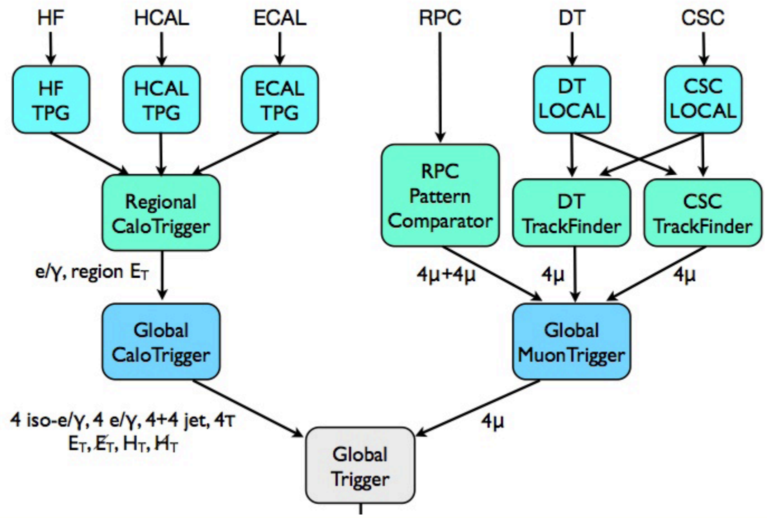




All candidates are first sorted by quality, then by p_T. The L1 regional triggers deliver the 4 best muon candidates in the barrel and the 4 best muon candidates in the endcap to the global muon trigger (GMT).

Level1+HLT	Z→μ+μ- Eff.[%] Data/MC	Single isolated μ Eff.[%] Data/MC	Single μ in b jets Eff.[%] Data/MC
$\lvert\eta\rvert < 2.1$	92.5±0.3 0.972±0.003	90.8±0.9 0.959±0.013	88.9±0.4 0.953±0.004
$\lvert\eta\rvert < 0.9$	95.0±0.3 0.978±0.003	93.3±1.1 0.967±0.015	92.5±0.4 0.967±0.005
$0.9 < \lvert\eta\rvert < 2.1$	89.9±0.4 0.966±0.004	88.5±1.4 0.952±0.020	83.5±0.8 0.931±0.008

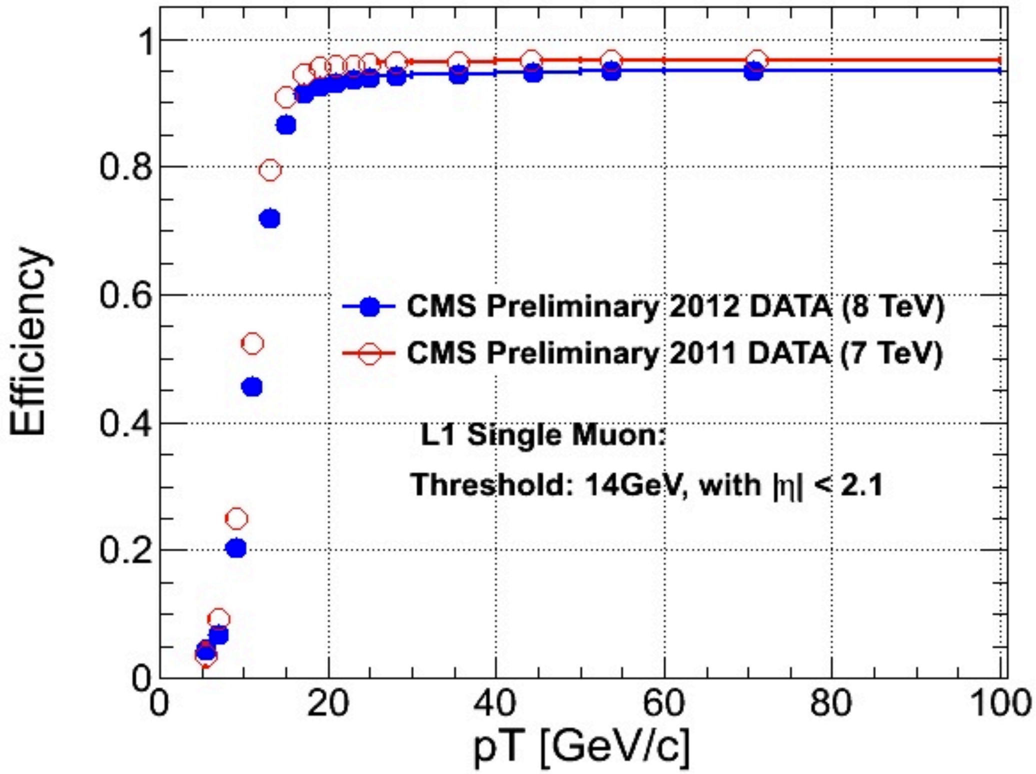
CMS L1 Trigger: Muons + Calorimeters



Trigger	Threshold (GeV)	Rate (kHz)	Physics
Single e/γ	20	13	Higgs, SM, EXO
Double e/γ	13,7	8	Higgs, SM, SUSY, EXO
Single μ	14 ($\|\eta\|<2.1$)	7	Higgs, SM, SUSY, EXO
Double μ	10, 0	6	Higgs, SM, EXO
e/γ + μ	12, 3.5	3	SM, SUSY, EXO
μ + e/γ	12, 7	1.5	SM, SUSY, EXO
Single Jet	128	1.5	SM, EXO
Quad Jet	36	3.5	SM, SUSY, EXO
H_T	150	5	SUSY, EXO
E_T^{miss}	36	8	SUSY, EXO

- Typical L1 trigger table for running in 2012
- Main single and multi-object triggers shown
- Rates reported for luminosity ~6.6×10^{33}

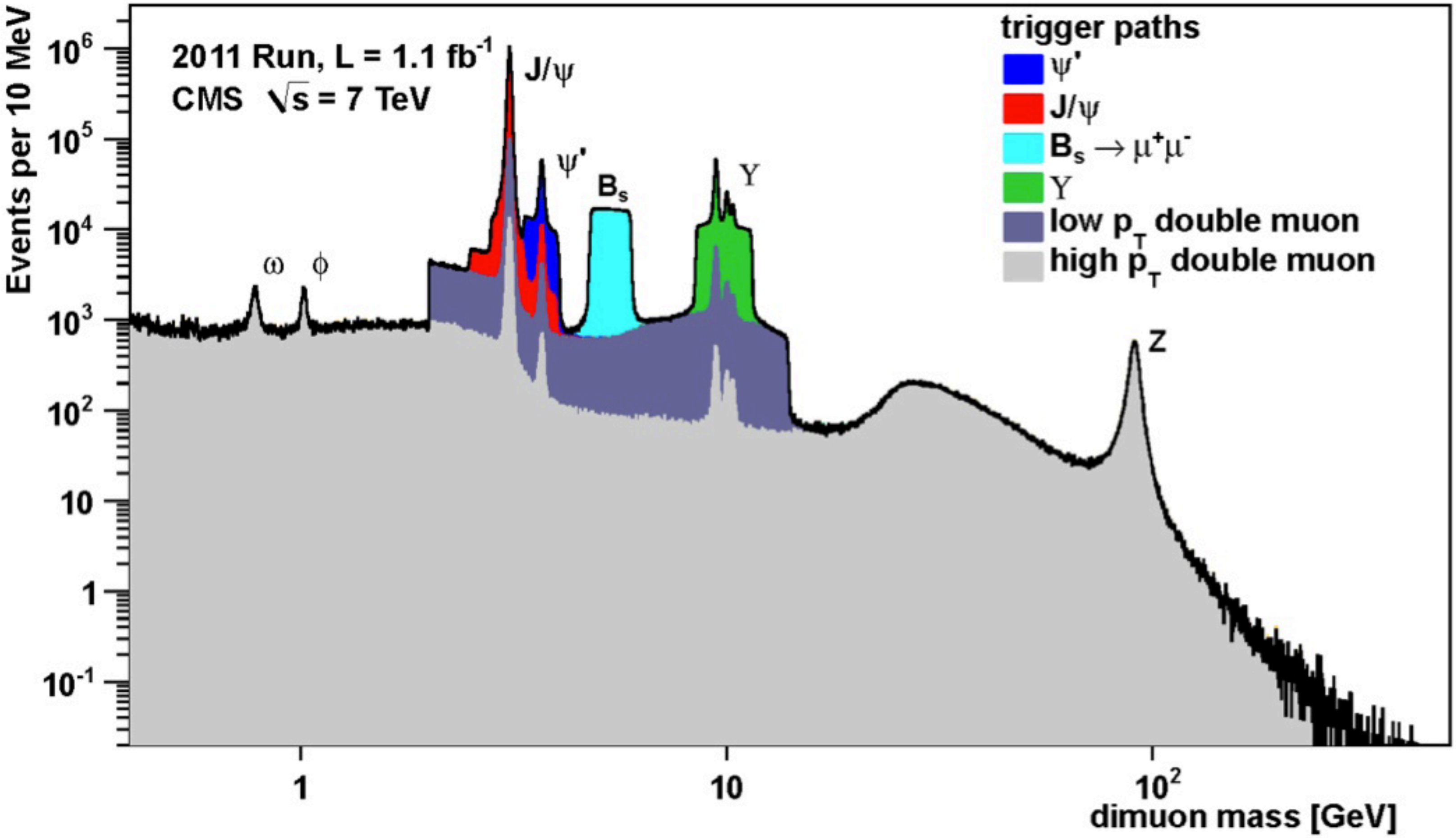
Muon L1 trigger performance: single muon



Rate improvements in 2012:

- CSCTF tighter Pt assignment
- Improvement in Global Muon Trigger pt merging
- About 50% rate reduction, for few % efficiency cost

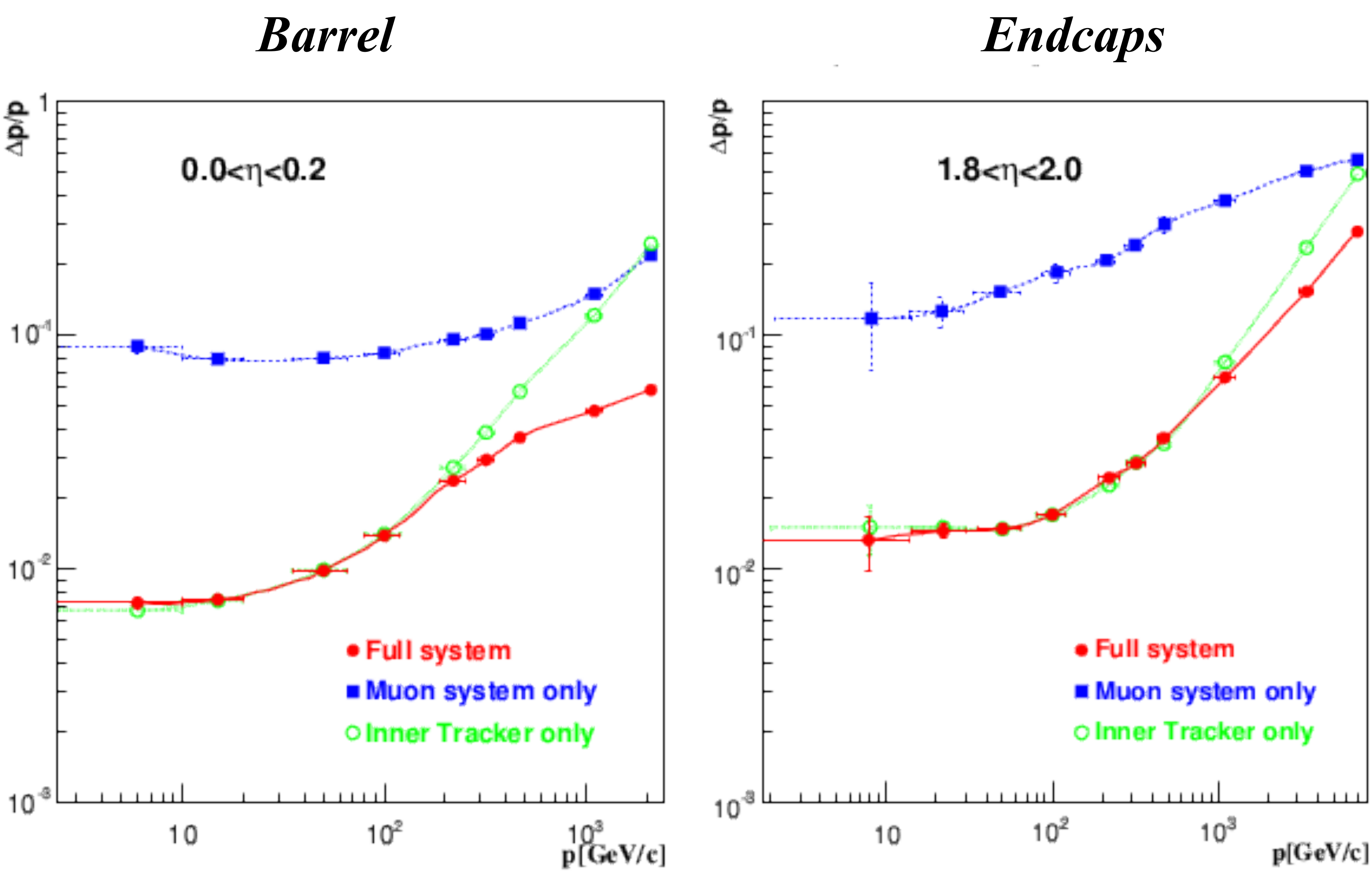
High Level Trigger (HLT) performance



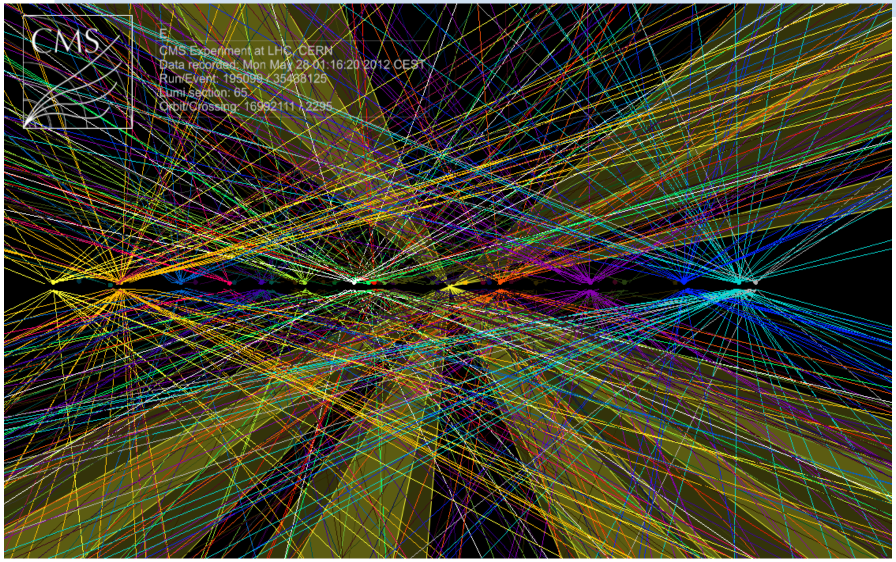
CMS di-muon mass spectrum divided into different HLT selections

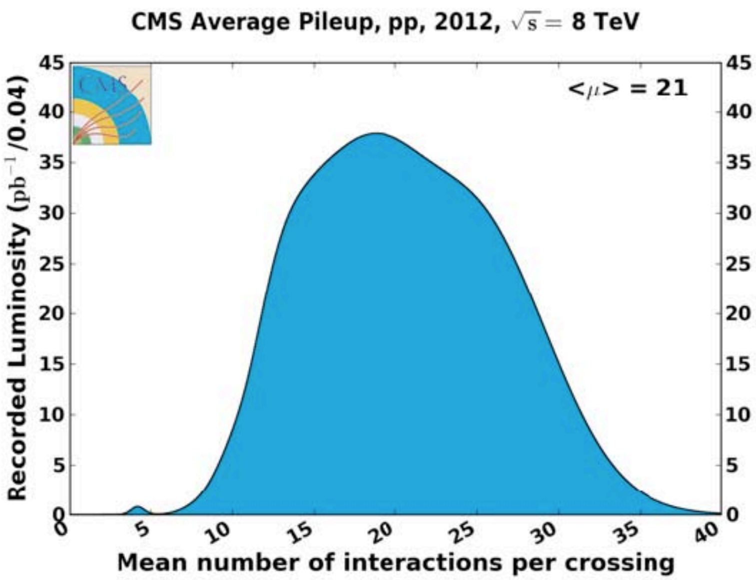
- Muon triggers for Heavy Flavor exploits vertex, mass and momentum constraints

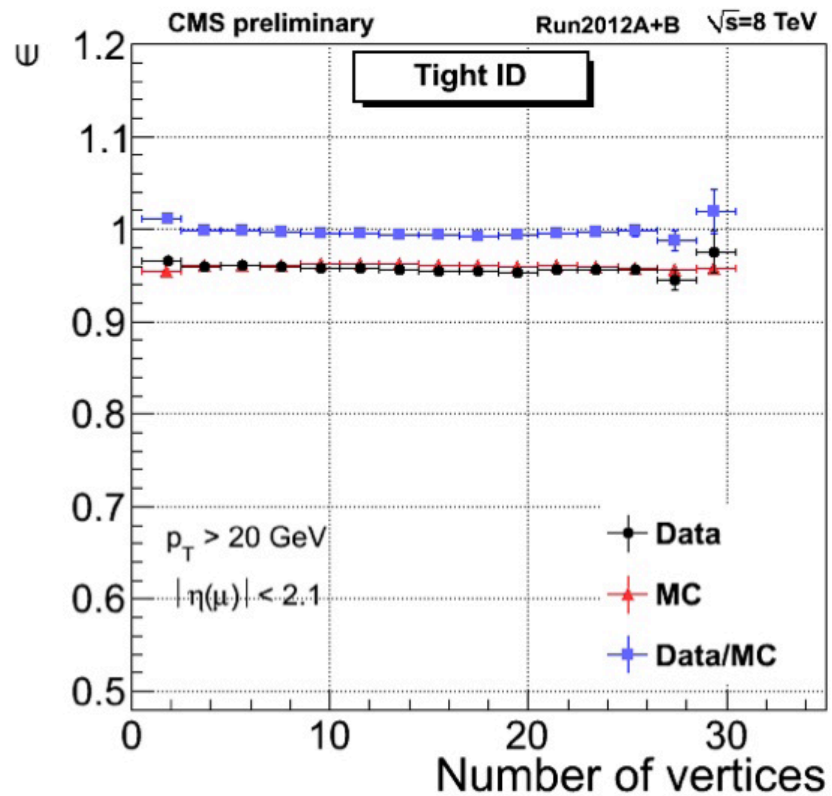
Muon momentum resolution



Muon performance: ID stability vs pilup

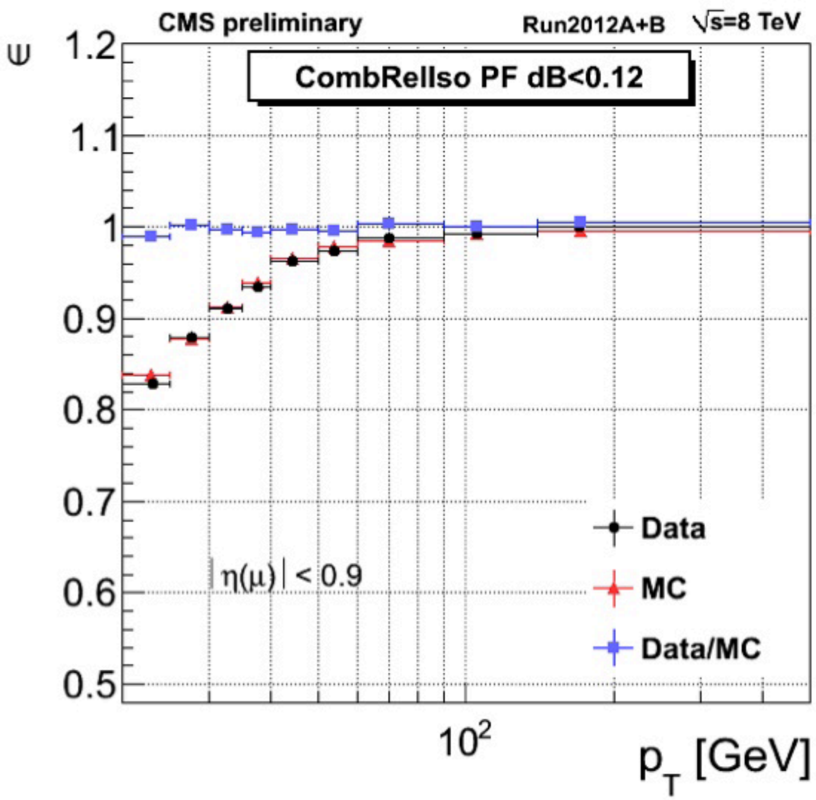


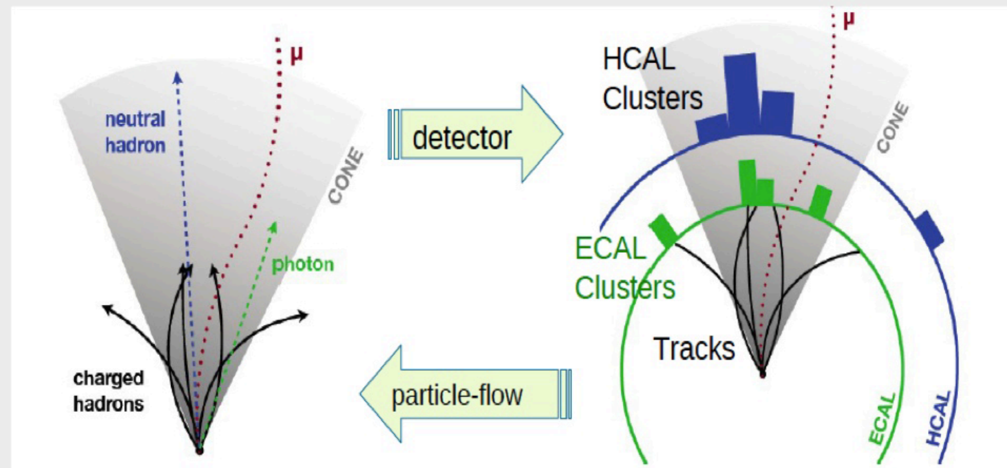




Muon ID vs pileup

Muon performance: isolation (Particle Flow algorithm)

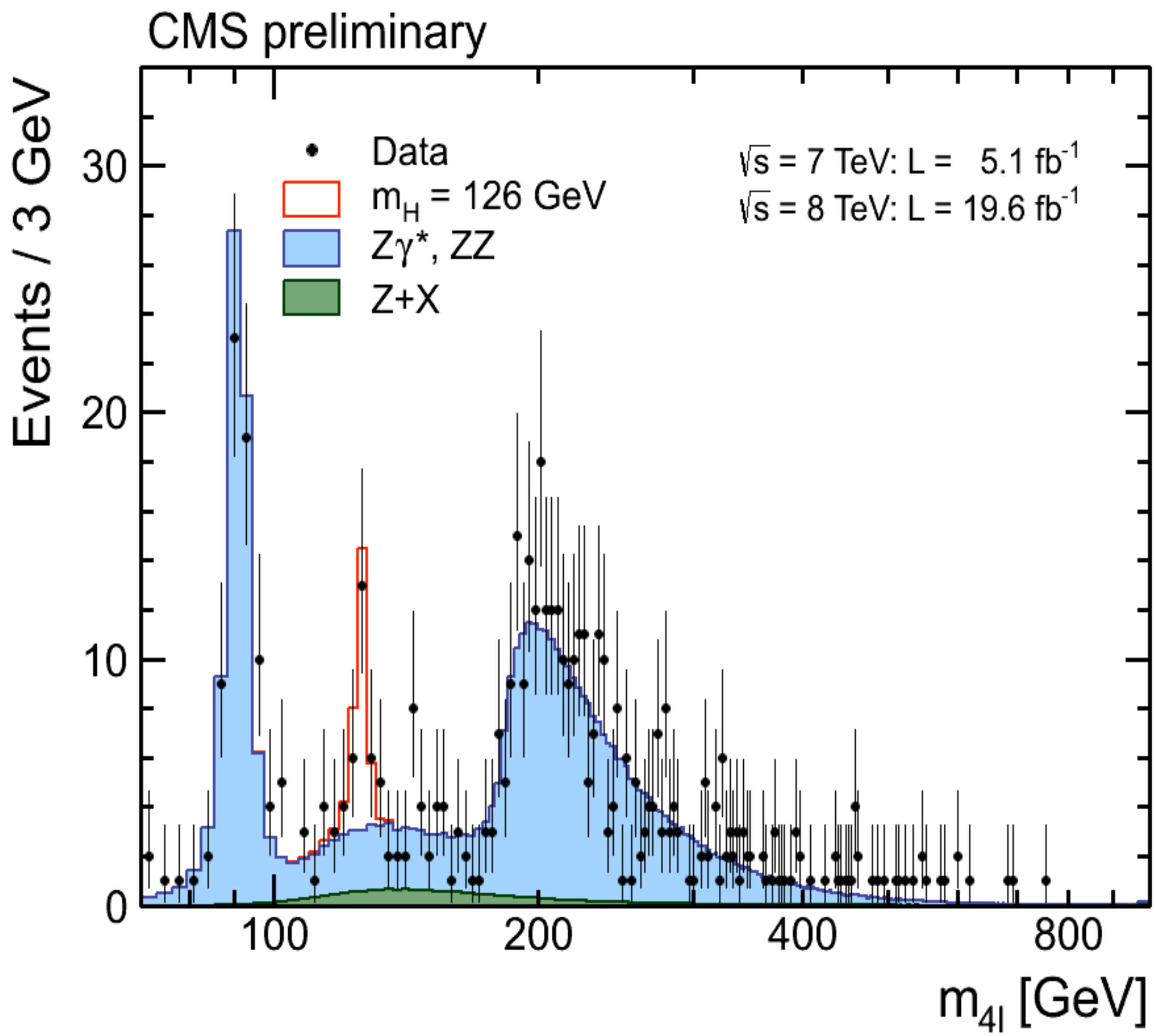




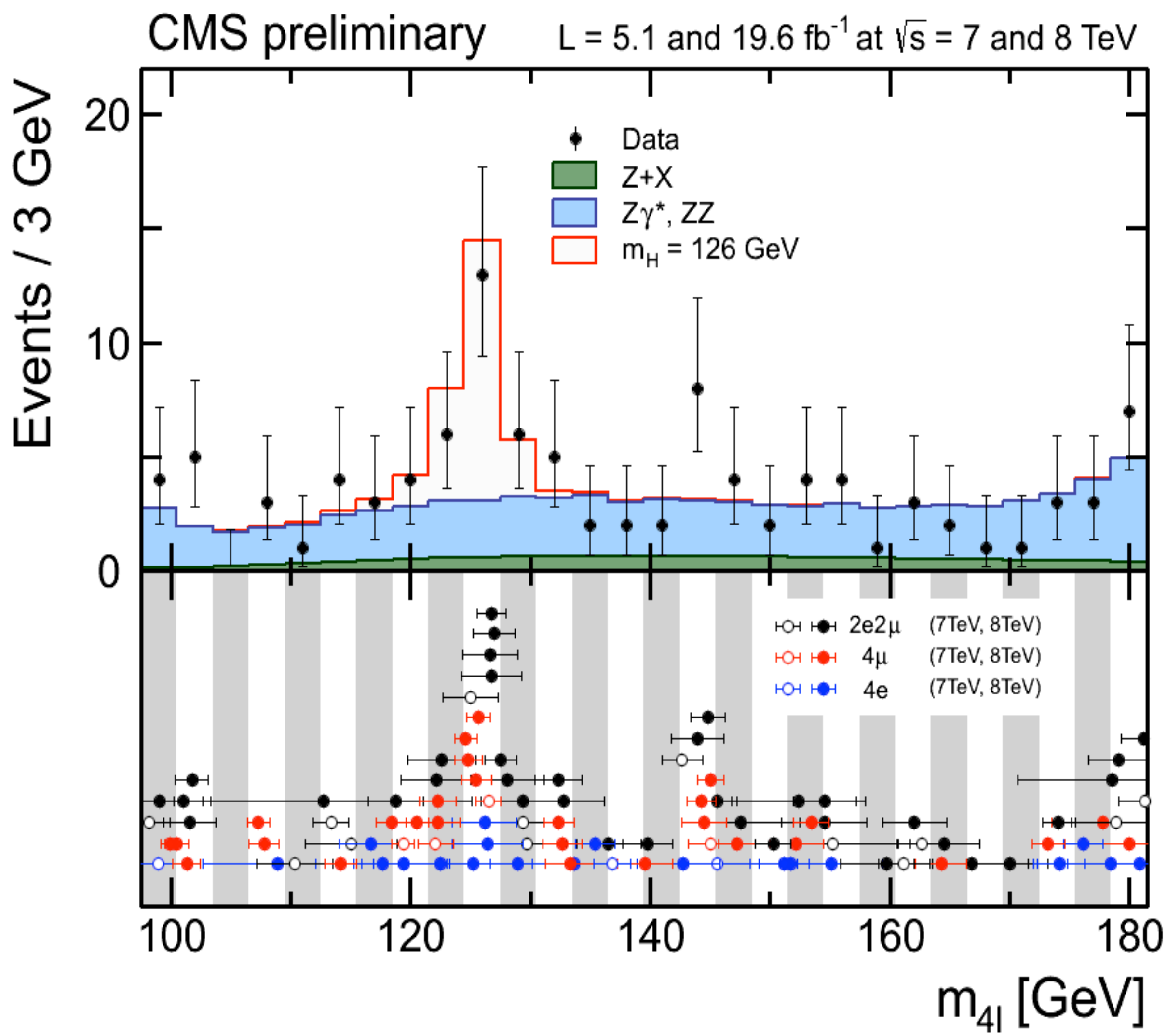
- Charged particles well separated in large tracker volume & 3.8T B field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution
- In multijet events, only 10% of the energy goes to neutral (stable) hadrons

Muon Isolation efficiency vs Pt (Particle Flow algorithm)

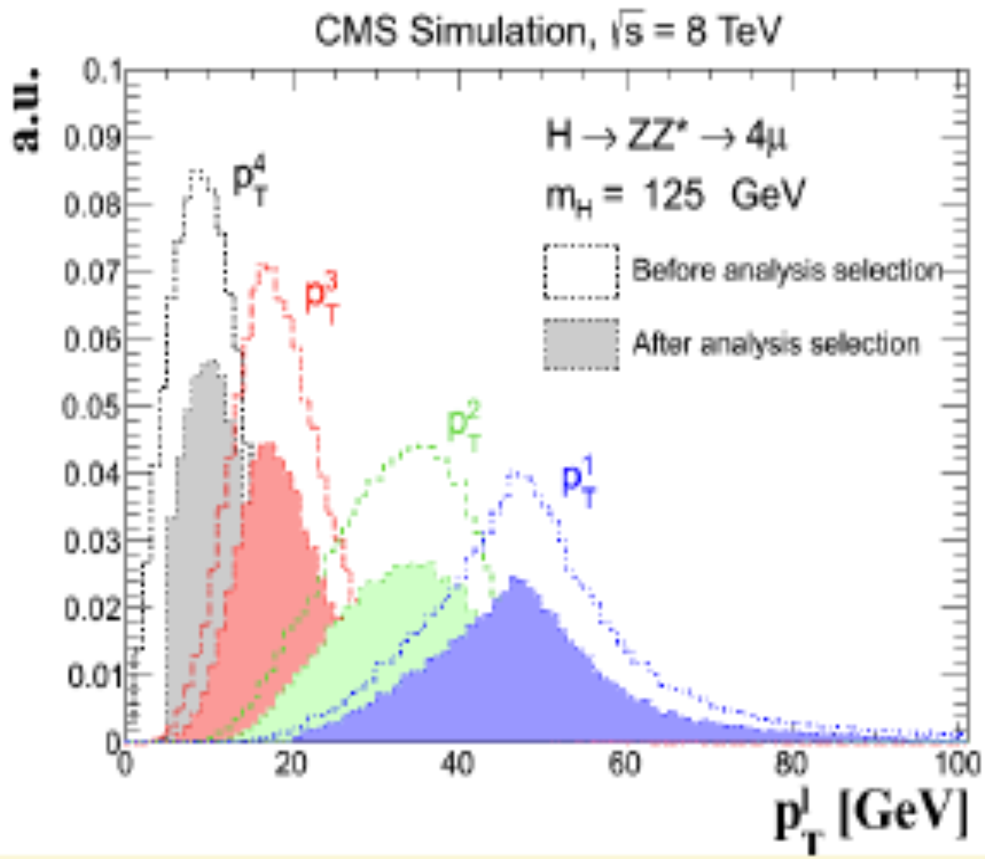
Higgs peak in 4leptons decay channel



Higgs mass distribution, including per-event errors: 4μ events have smallest invariant mass errors

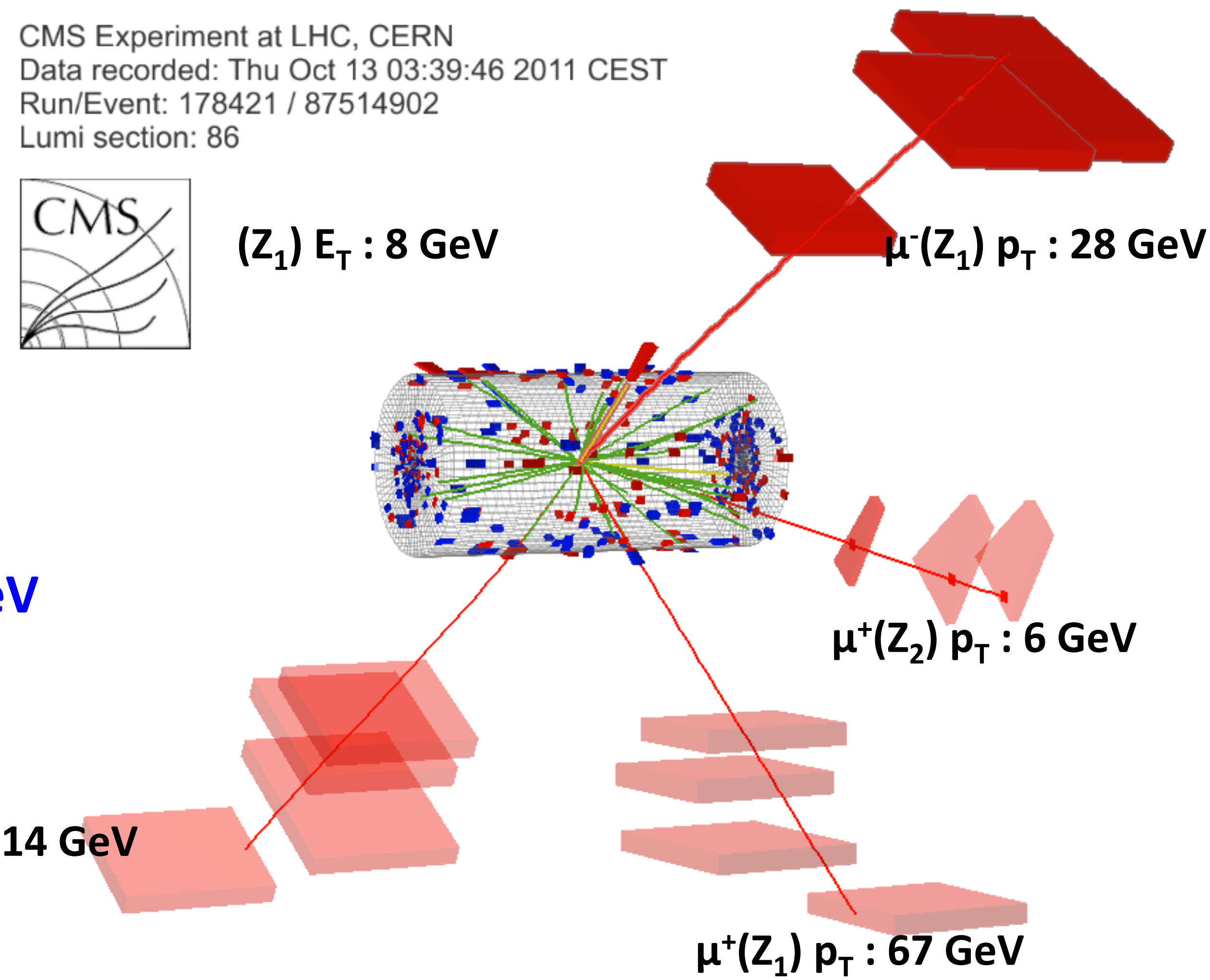


A challenge: 4 Leptons selection efficiency



- Almost 50% of leptons from low mass Higgs →4l have pT less than 10 GeV
- A challenge for the lepton selection in the analysis
- Control of background rate is difficult at low pT
- Control of lepton selection efficiencies is also a challenge at low pT

Higgs candidate event in CMS



7 TeV DATA

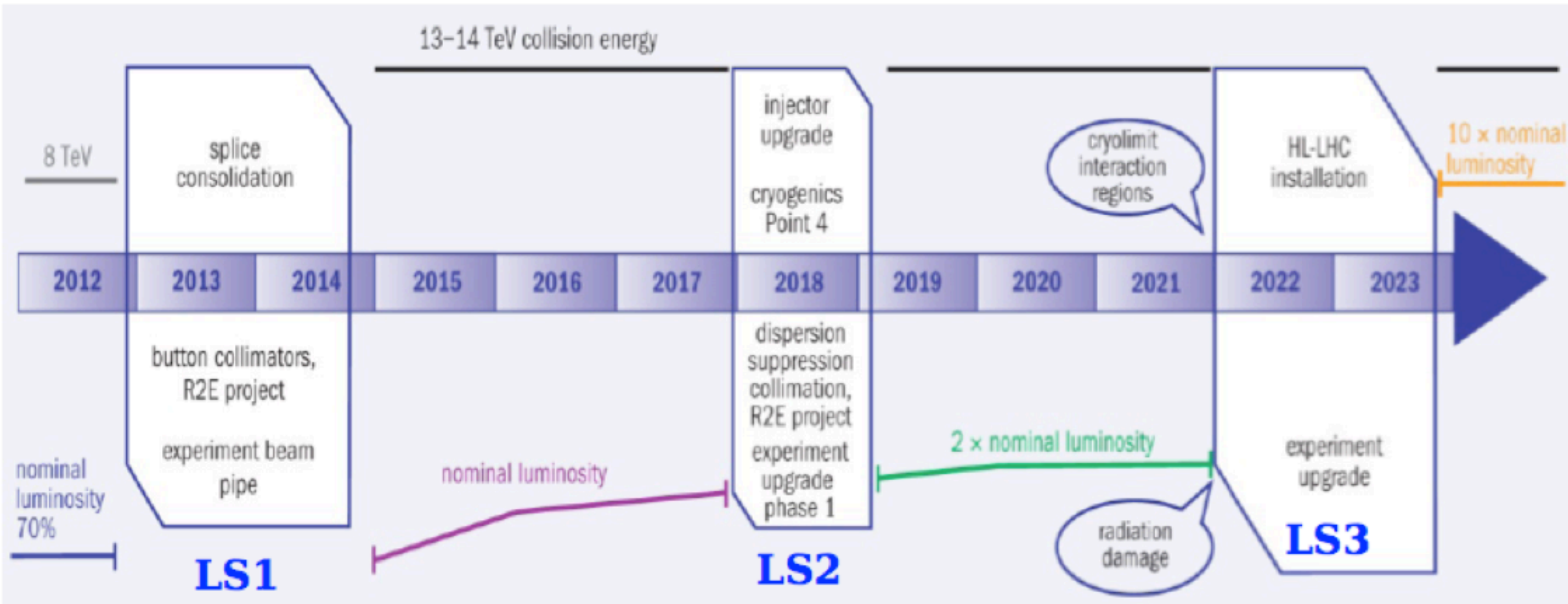
$4\mu+\gamma$ Mass : 126.1 GeV

LHC schedule

Lucio Rossi and Oliver Brüning (CERN): HL-LHC

Krakow symposium, Sep 2012

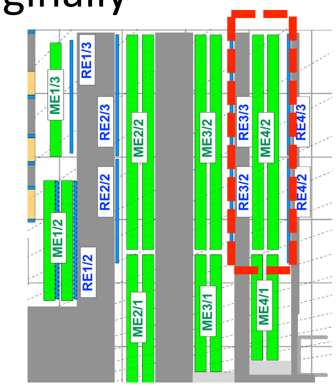
https://indico.cern.ch/contributionDisplay.py?contribId=153&confId=175067



~ 8.10^{33} ~ 10^{34} ~ 2.10^{34} ~ 8.10^{33}

LS1: Detector consolidation

Install originally planned ME4/2 + RE4/2

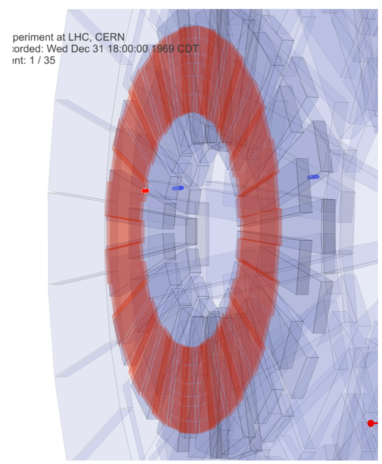


Partially move DT electronics from detector to cavern and redesign in uTCA technology.

Upgrade ME1/1 electronics.

LS2: Anticipated phase-2 upgrades

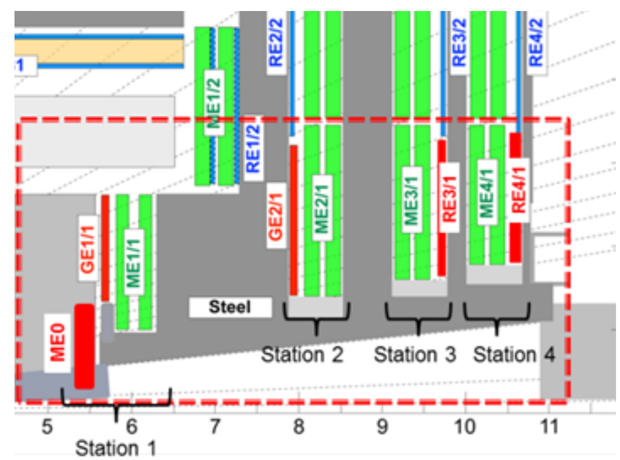
Installation of GE1/1 Combined CSC+GEM trigger



LS3: HL upgrades

Muon trigger: Additional detectors in forward region of all 4 stations

Rapidity extension of tracker, calo, muon to $|\eta|$~4



Redesign of DT on-chamber electronics

Ongoing Muon Upgrades (2013-2014)

Trigger performance: significantly lower threshold for same rate

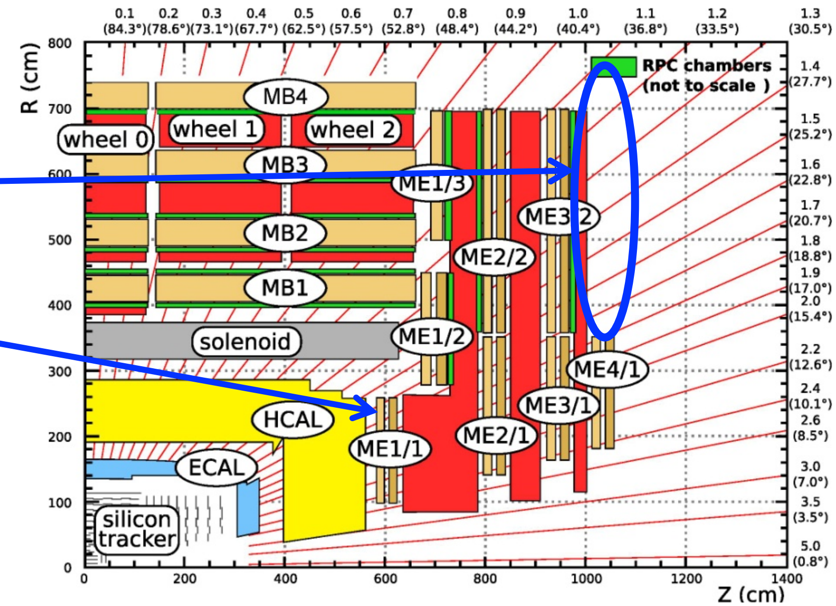
CSC and RPC: ME4/2 (1.25<|η|<1.8)

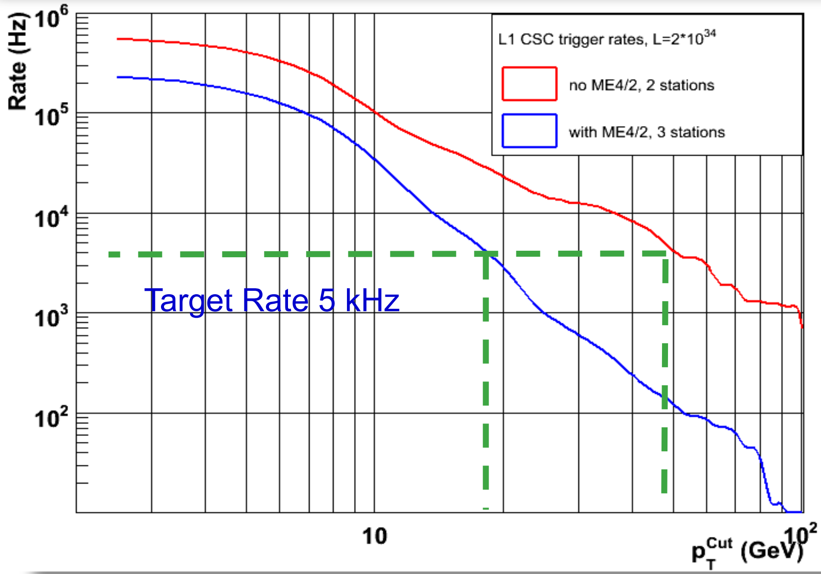
More hits, lower rates

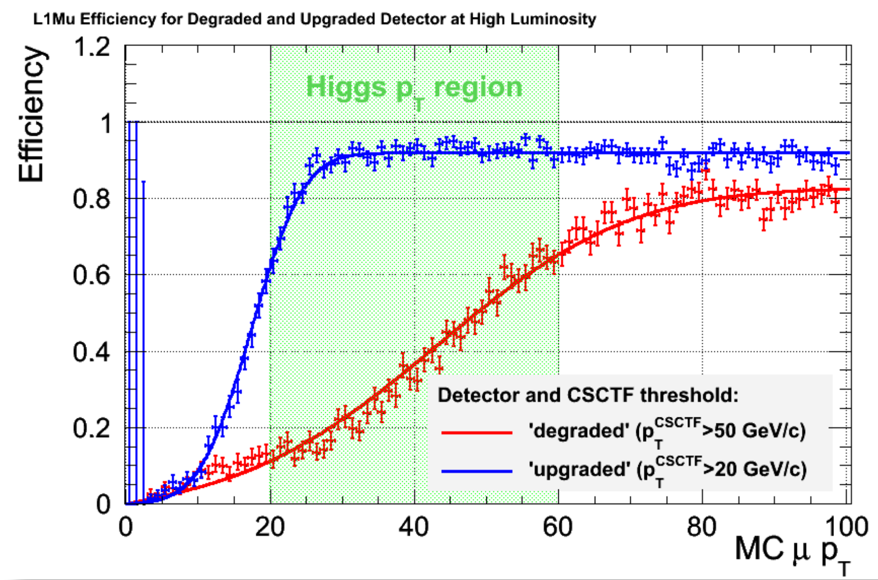
CSC: ME1/1 (2.1<|η|<2.4) new digital boards and trigger cards : higher strip granularity

Electronics reliability

DT: new trigger readout board and relocation of sector collector from UXC55 to USC55 (more accessible, using new optical links)



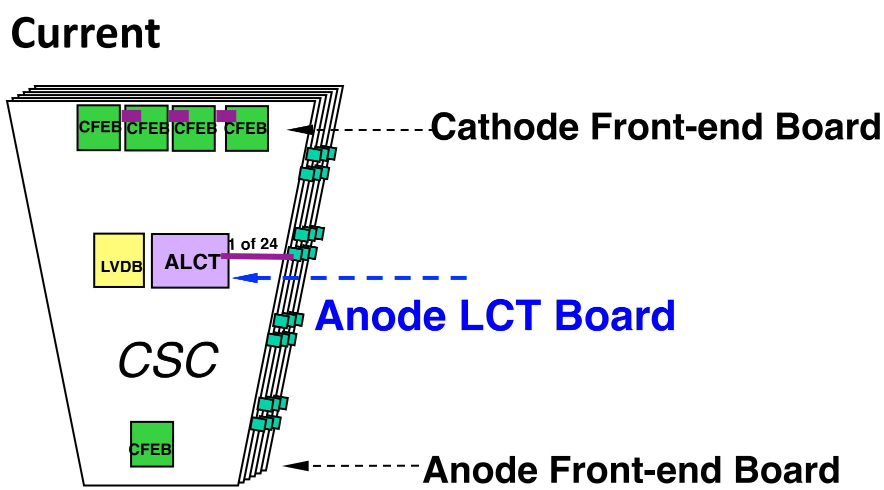


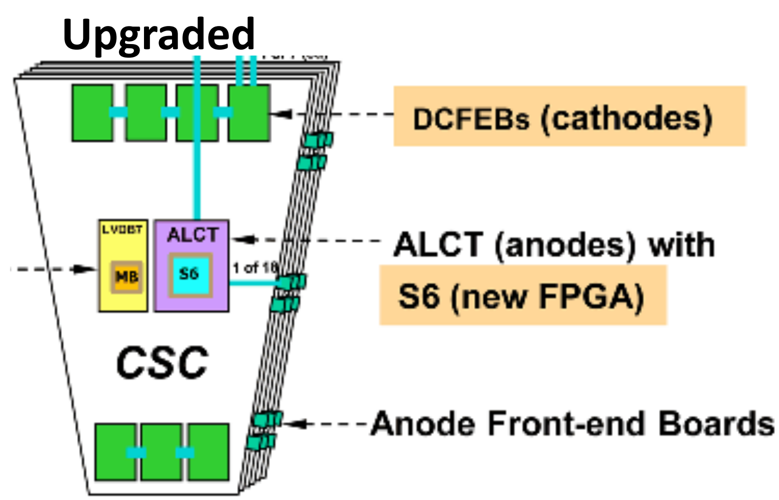



ME4/2 CSC production at CERN
FR4 bar bonding
wire winding
wire soldering
components soldering
Wire pitch and tension HV testing
chamber assembly
chamber integration
chamber testing
chamber installation

ME-1/1 On-Chamber Electronics Upgrade

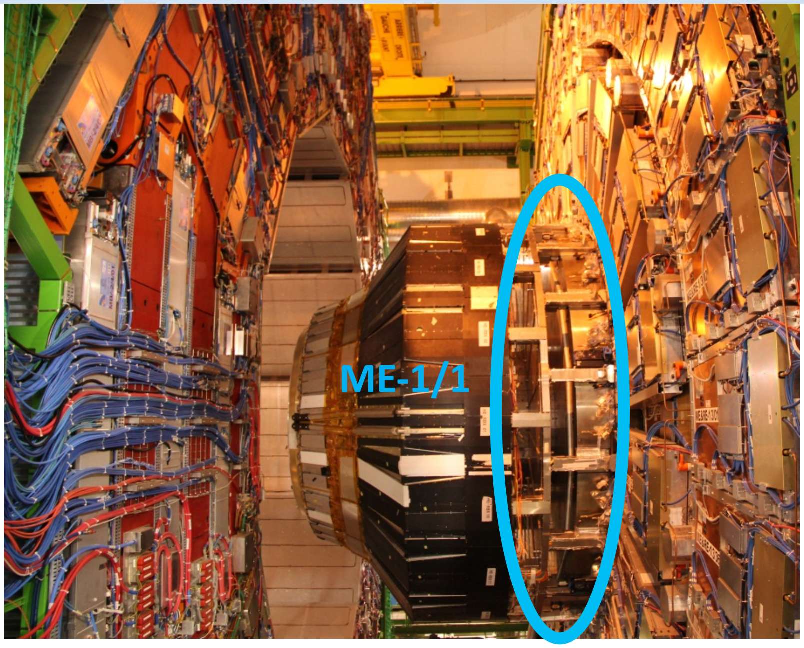
- Remove triple-strip-ganging in ME1/1a region (5→7 CFEB)
  - Suppress mis-measured muons
  - Reduces ambiguities due to combinatorics
- New anode readout board
  - FPGA Virtex E → Spartan 6
  - New, faster FPGA to handle rates
- New Low Voltage Distribution Board and Low Voltage Mezzanine Board (monitoring,control)

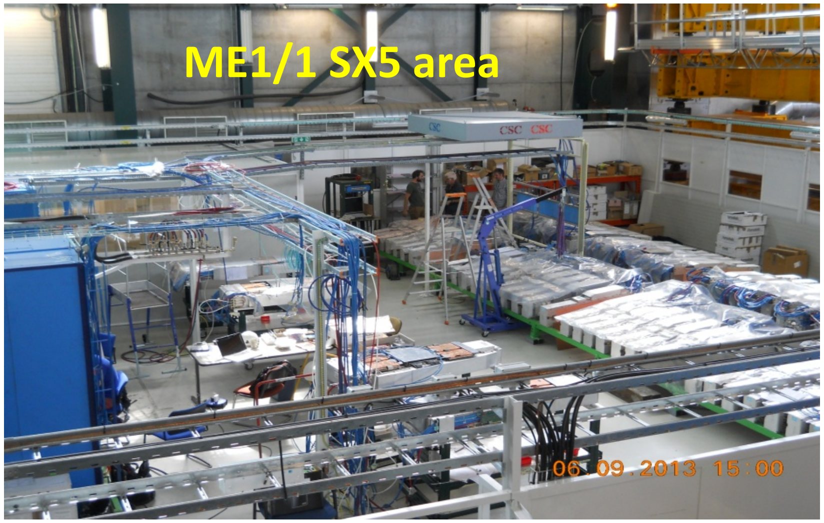




Innermost ME1/1 CSCs Electronics Upgrade

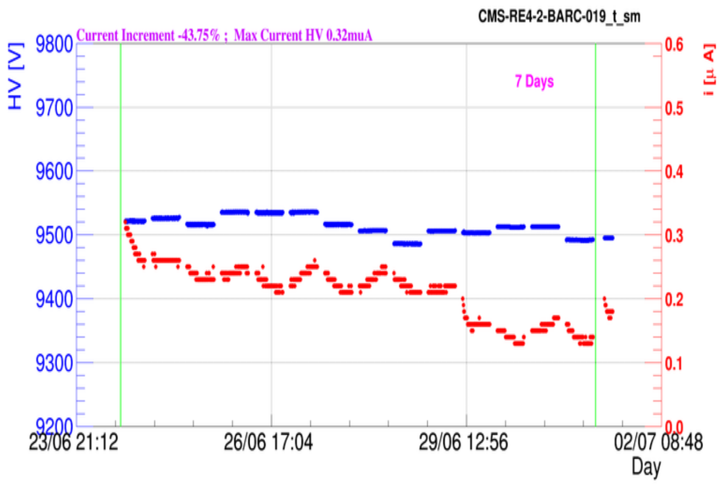
- All ME-1/1 CSC Chambers have been removed from and taken to the SX5 (surface building)
- On-chamber elecronics refurbished and retested
  - The old electronics already used for the ME-4/2 system

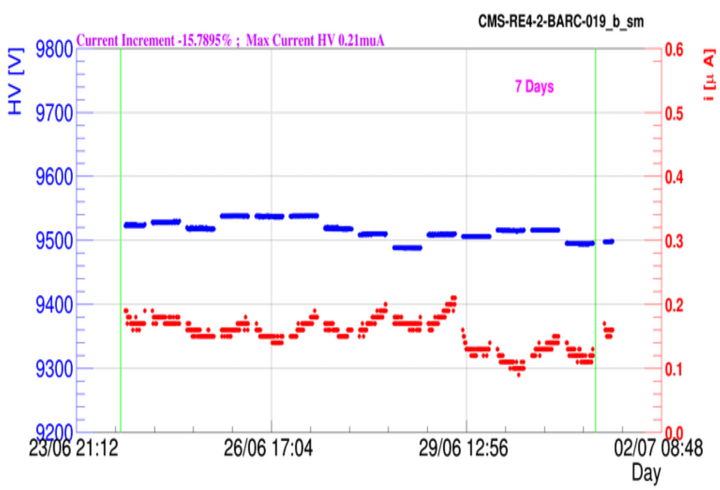




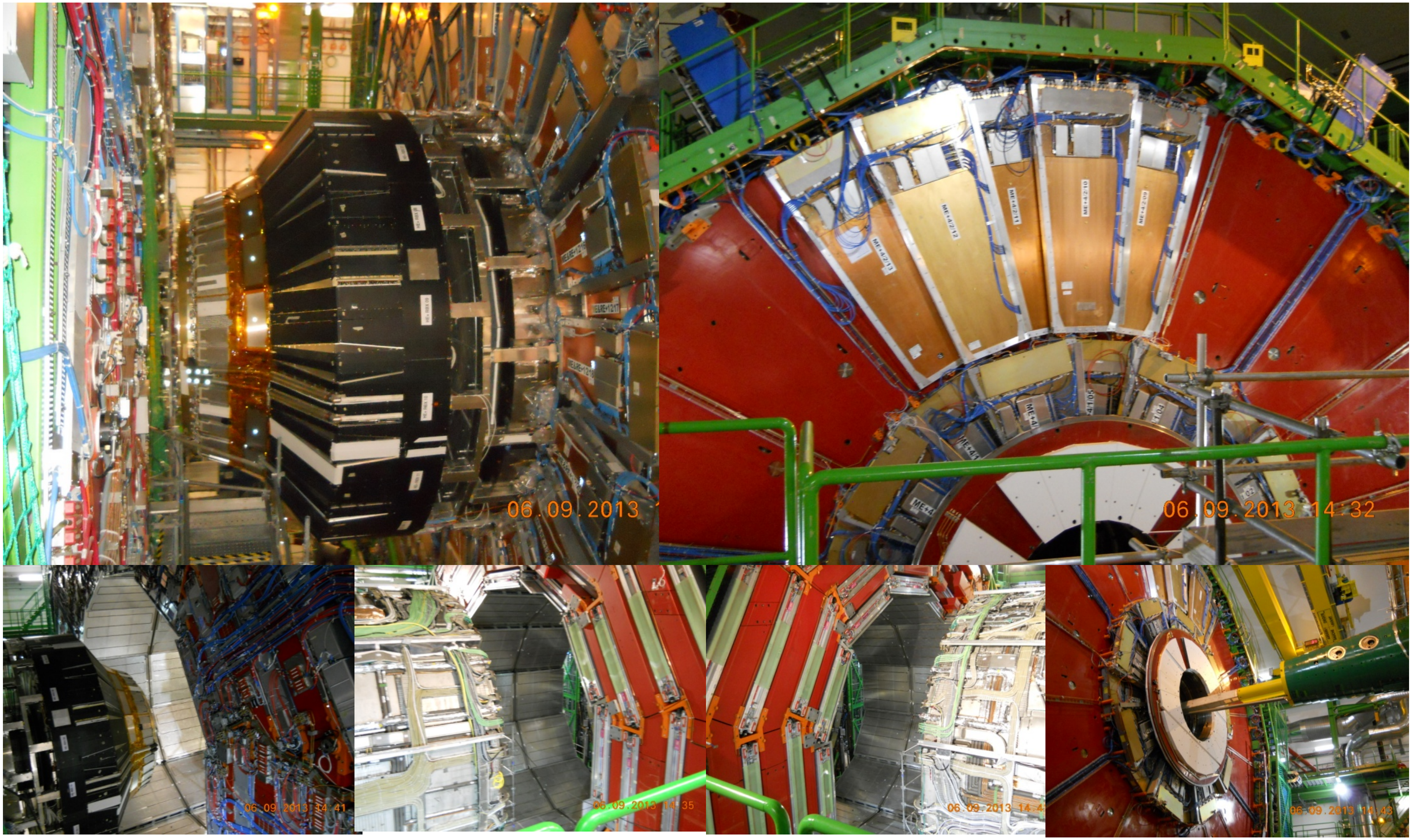
CMS RPC upgrade: 4th Encap station construction

QC-4 & Super Module Assembly at 904, CERN





CMS views (September 2013)



Conclusions

- CMS Muon system performed very reliably in Run 1, meeting specifications for efficiency, precision and triggering capability
- Played a key role in many physics studies, including the Higgs discovery
- Currently undergoing upgrades for Run 2, on schedule . Long term upgrades planned (see also other talks at this conference)

HL Muon Challenges

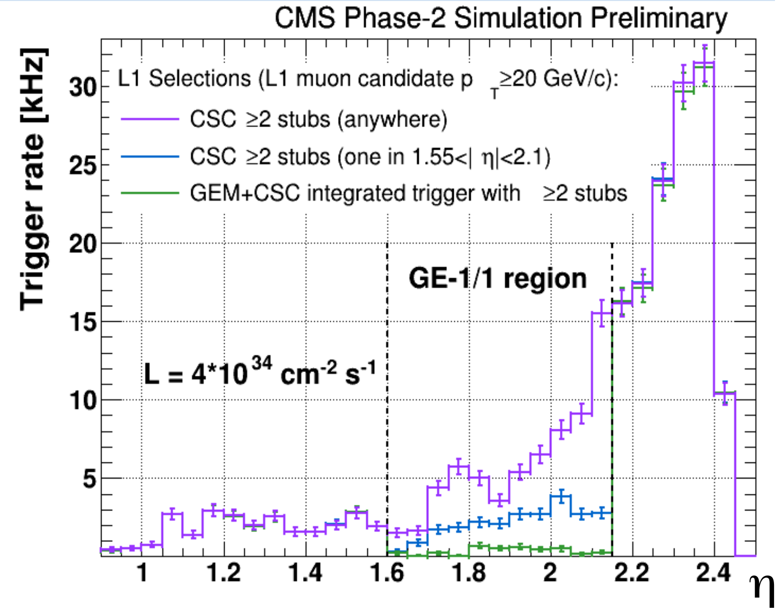
Robust muon triggering and identification are major discovery drivers at the LHC

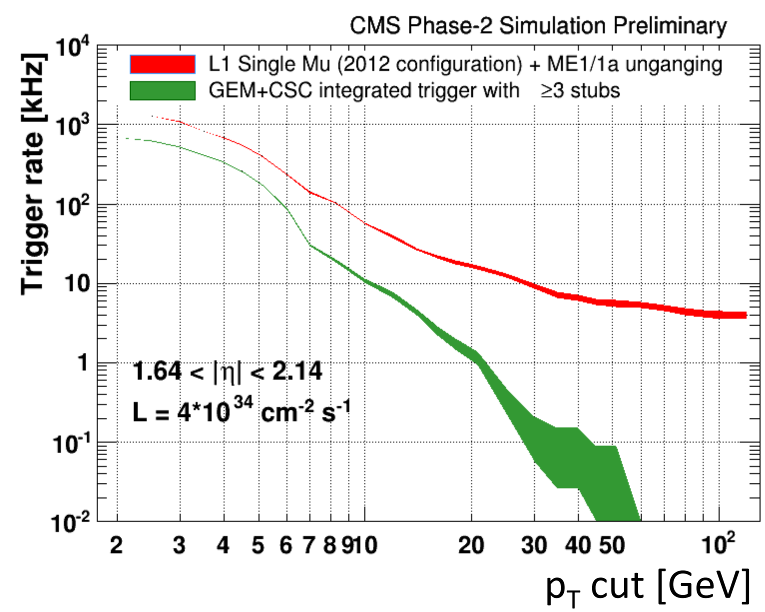
HL affects muon system performance. Forward region |η|≥2.0 especially challenging.

- Rates up to MHz/cm^2 and growing with η
- Reduced resolution and longevity issues
- Exceeds capabilities of existing electronics
- p_T mis-measurements and multiple scattering in iron yoke cause rate flattening

Focus on **maximizing the potential** of large datasets to be collected at HL-LHC

- Maintain current performance (η, p_T)
- Seek acceptance gains where possible





Phase-2 Muon Trigger Challenges

Not loosing trigger coverage is the key

- p_T mis-measurement drives trigger rate. Increasing threshold would not help.
- Level-1 track trigger helps, but has reduced performance in high-η “corner”

Phase-2 objectives:

1) Increase purity, reduce p_T mis-measurements
2) Sharpen trigger turn-on
3) Keep trigger threshold even at HL (Higgs physics → relatively soft leptons, e.g. H2Tau)

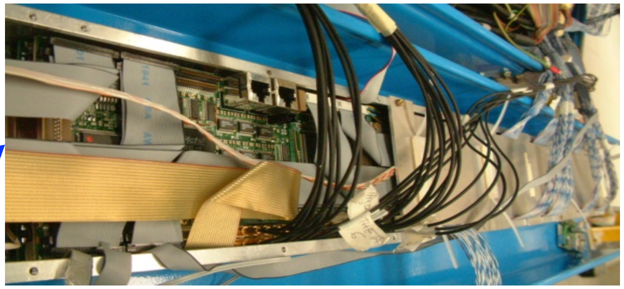
Large rate reduction using bending angle in forward region (already done in barrel)

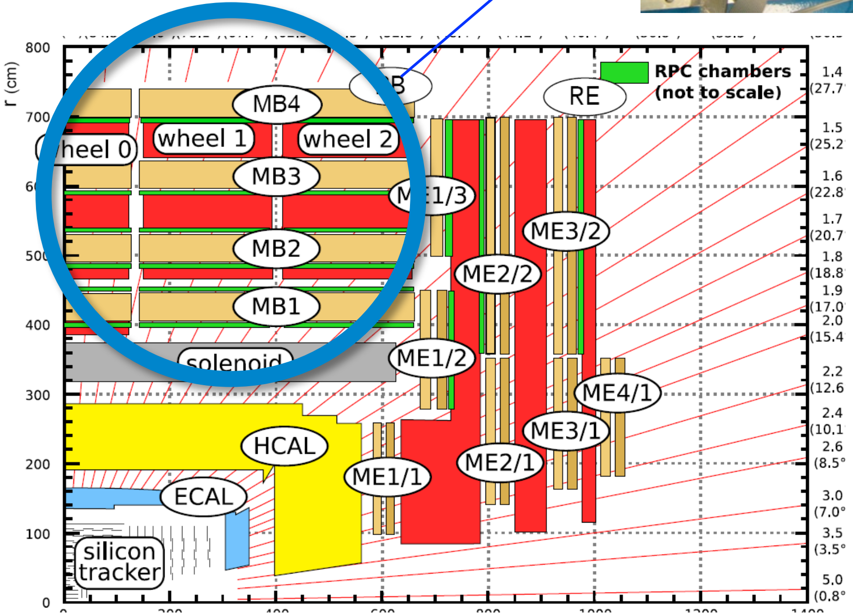
- Need good spatial resolution and rate capability
- Larger lever arms using new detectors and existing CSC chambers in the same station
- Must measure bending angle in station 1. Else radial B-field and multiple scattering quickly diminish discrimination.
- Expect x5-10 rate reduction with new detectors.

Impact of CMS Trigger Upgrade on Muon Electronics

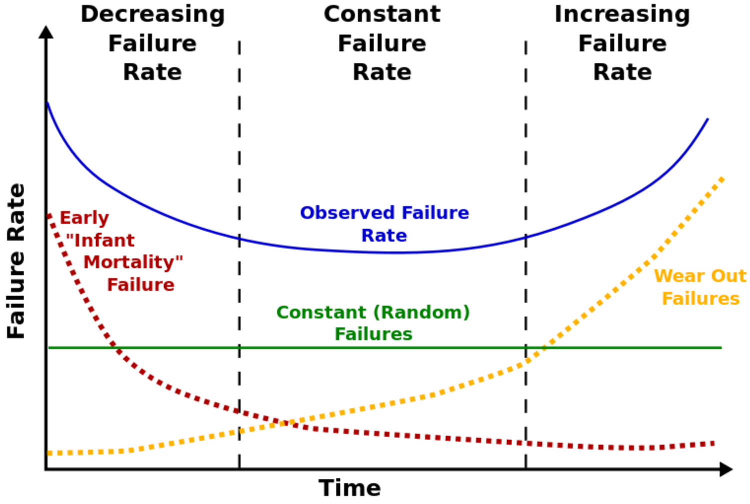
Concept of tracking trigger impacts needed latency and rate	**Level 1 Latency from 3 μs**	⇨	**10 μs**
	Level 1 Rate from 100 kHz	⇨	**1 MHz**

L1 rate needs replacement of the DT on-chamber electronics





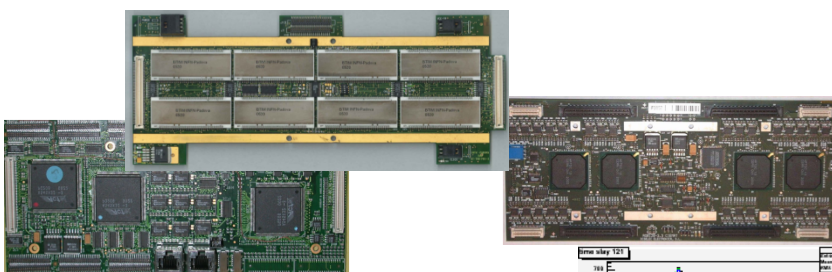
Another argument: electronics is old. Wear-out failure may increase

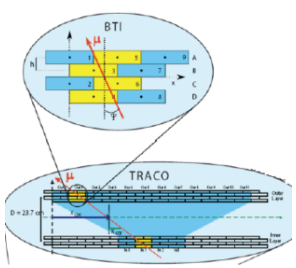


Upgrade of DT on-chamber electronics

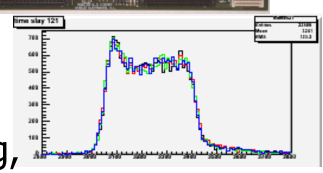
Present Minicrates

- Highly integrated and complex system
- Many boards with various ASICs for specific tasks
- Trigger primitive generation performed inside each chamber
- Filtered information sent to counting room





Trigger
segment finding, angle measurement=> single chamber trigger generation



Readout
Time digitization
Event matching

Phase-2 Minicrates

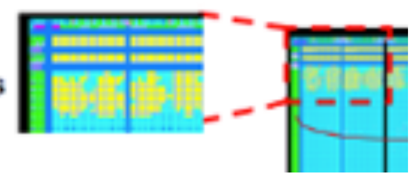
- On-chamber electronics performs time digitization of all chamber signals
- Digital information sent through optical link to the counting room
- Complexity is brought into the counting room

R&D started

Radiation tolerant FPGAs which perform 1 ns time digitization (no filtering)

GBT link for data forwarding

Zoom of first 4 TDC channels



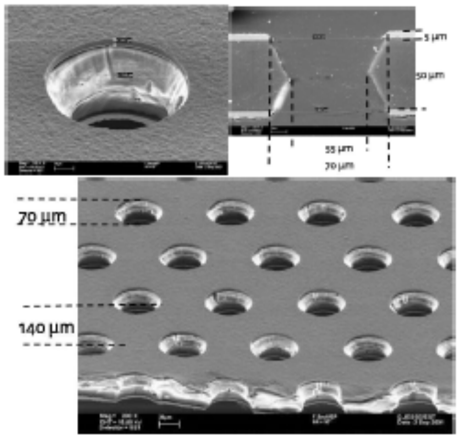
* Allows readout at 1 MHz Level 1 and 20 us latency

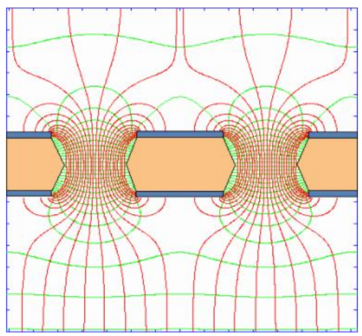
* Trigger primitive generation:

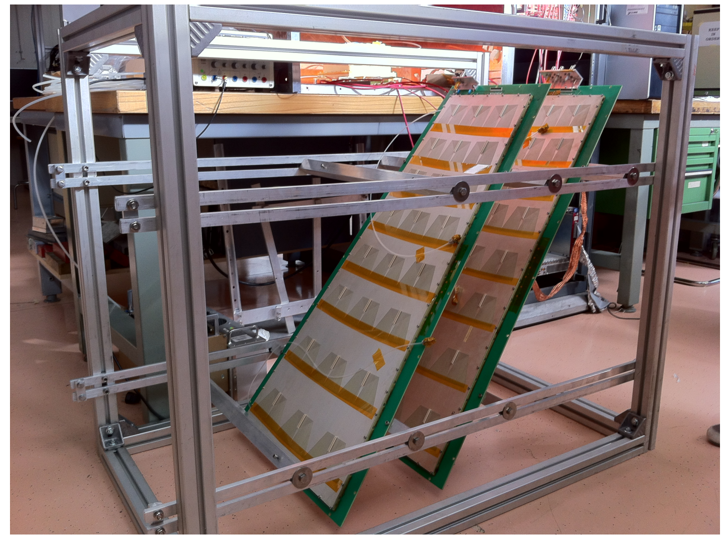
-maximum chamber resolution
-room for pt resolution increase

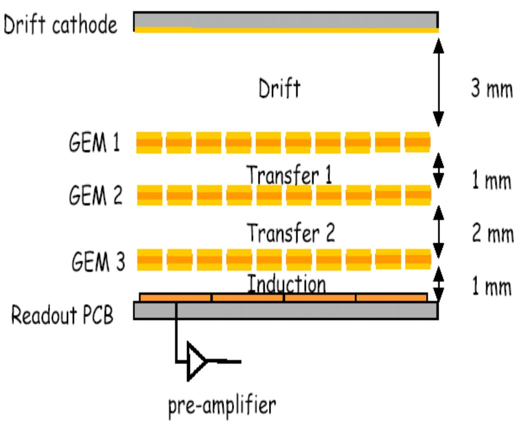
Triple GEM Detectors for CMS

GEM foil using PCB manufactering techniques. **Large areas ~1m x 2m to be developed.** Several large-size prototypes assembled and tested in testbeams.

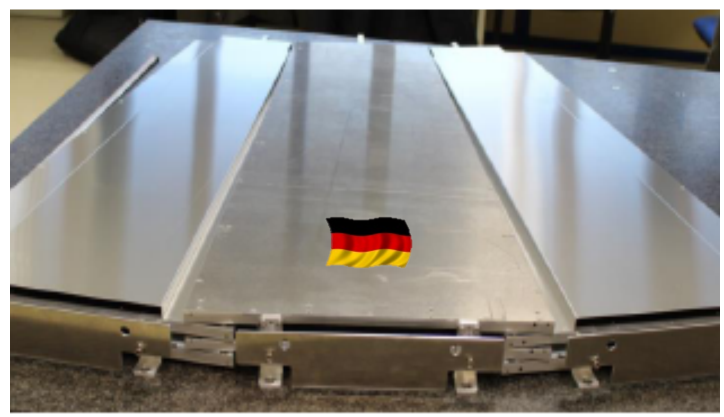






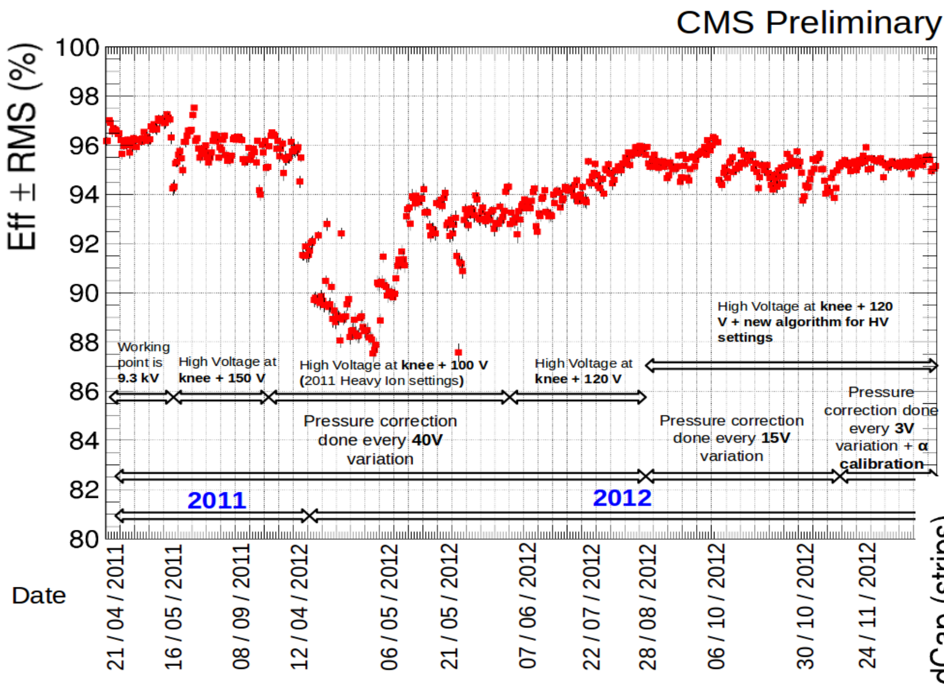


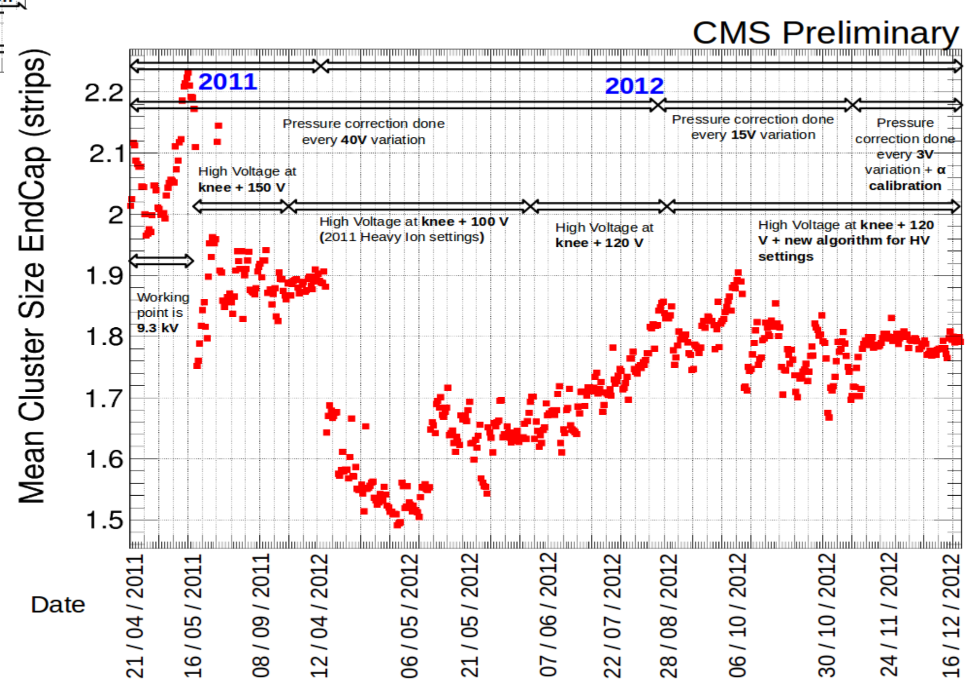
Smaller size GEM detectors operate e.g. in LHCb



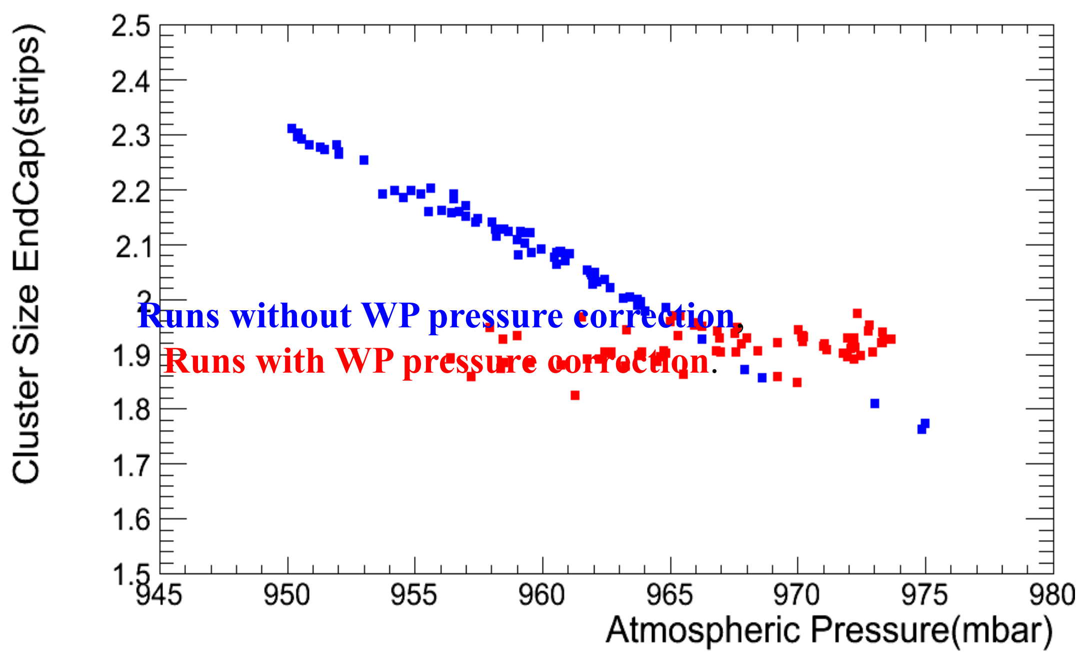
For safe operation and high amplification use 3 layers to form a triple GEM.

RPC Endcap performance





RPC Chamber performance: cluster size



Higgs →4l : Signal/Background ratio ~ 2:1 observed: 25 events total (S+B)

For 121.5 < m4l < 130.5 GeV

	4e	4μ	2e2μ
H(126) expected	3.0	6.7	8.9
ZZ expected	1.2	2.7	3.5
Z+X & top expected	0.6	0.5	0.9
Total Bkg	1.8	3.2	4.4
Signal+Bkg expected	4.8	9.9	13.3
Observed	5	8	12