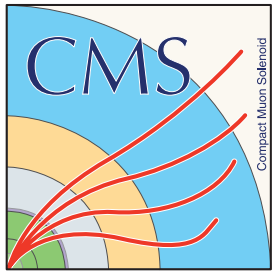


CMS: SM, BSM and Dark Sector Searches with leptons

Simranjit Singh Chhibra (VUB)

on behalf of the CMS collaboration

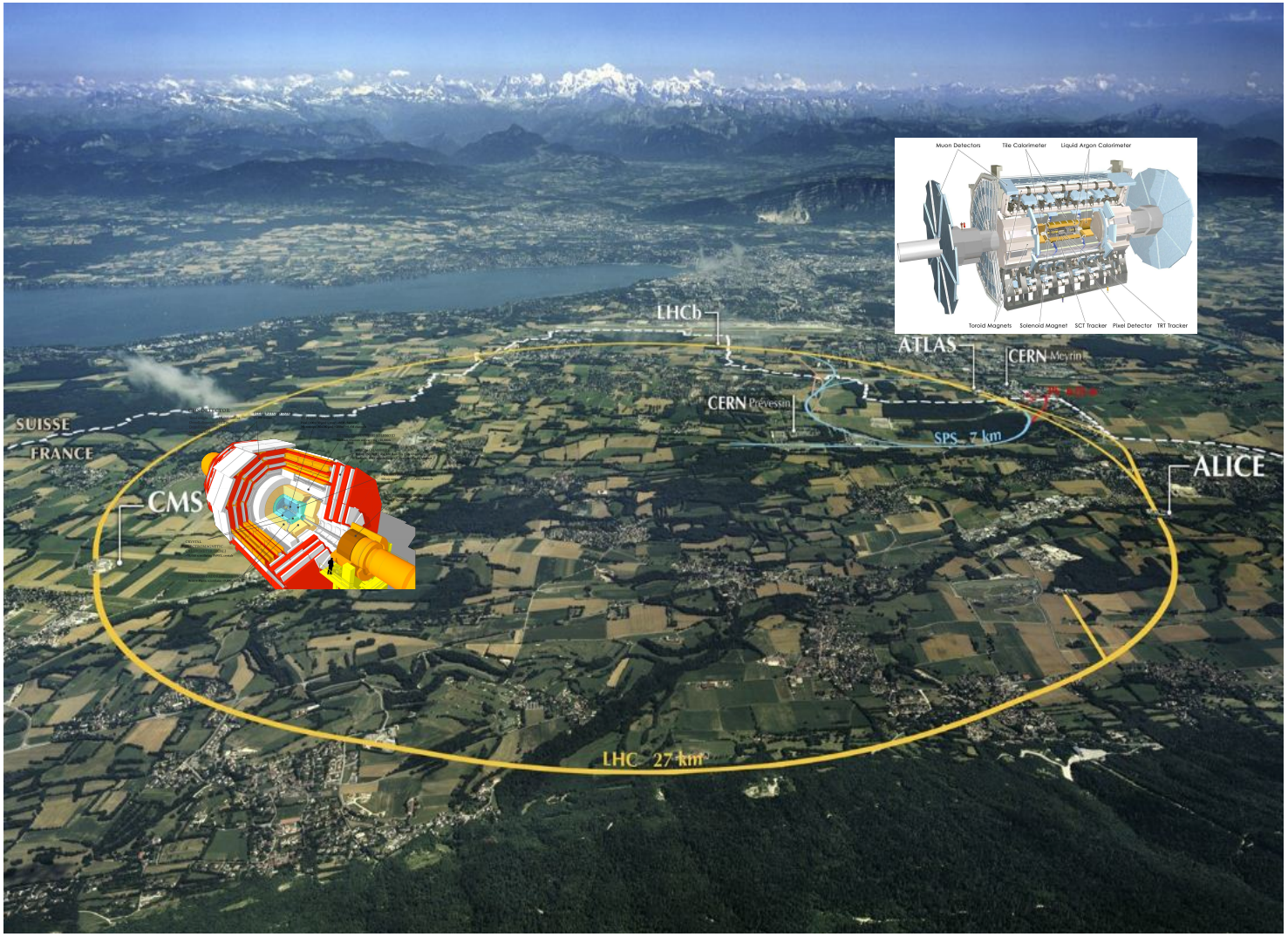
Internal Seminar @ VUB, 01 June 2018

http://indico.iihe.ac.be/indico/conferenceDisplay.py?confId=1184

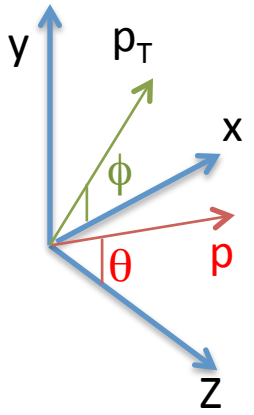
Outline

- The LHC and The CMS Experiment
- Discovery of the SM Higgs boson
- BSM: heavy gauge boson Z’ search
- Dark sector: dark photon search
- Summary

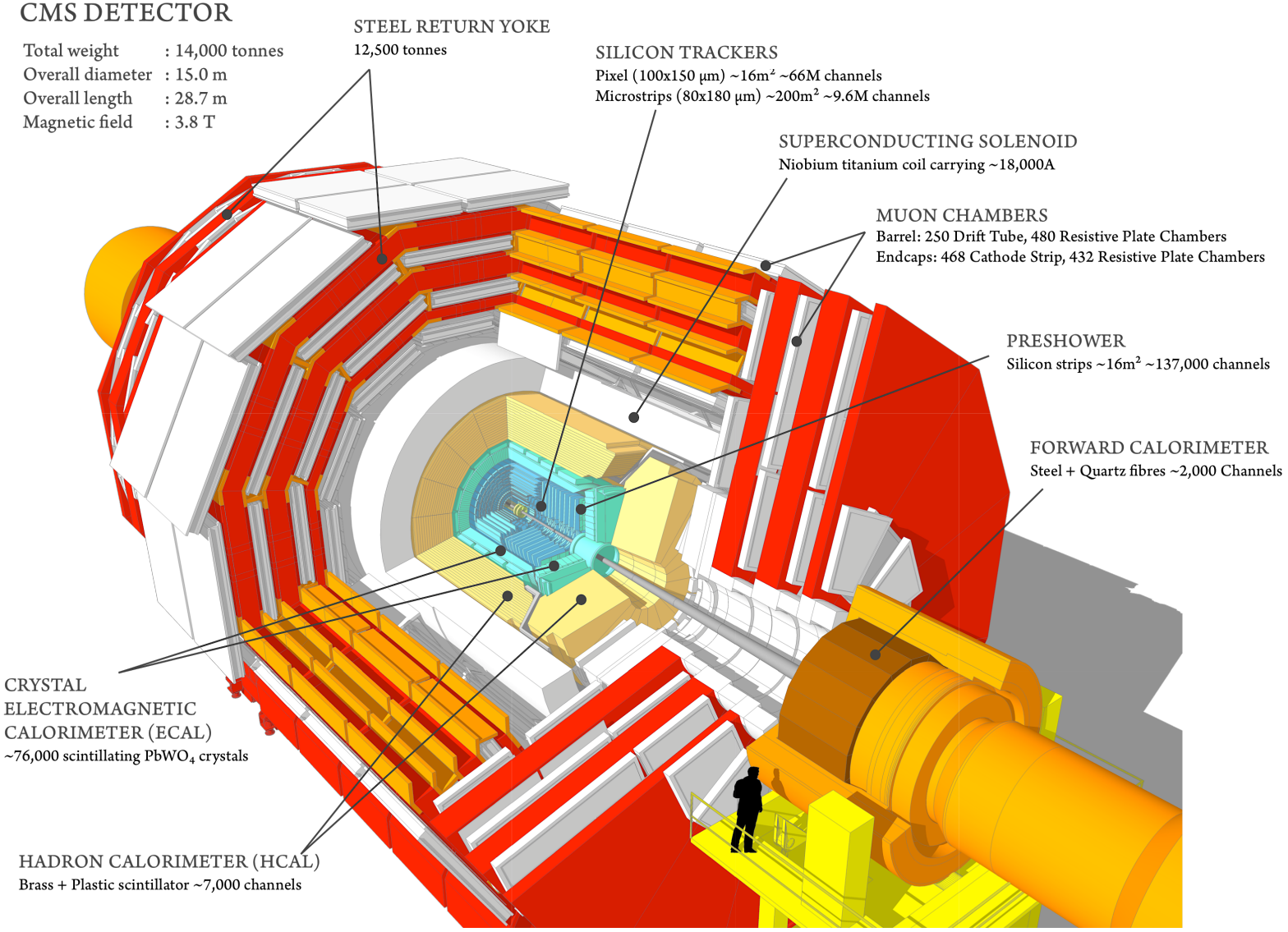
The LHC


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

The CMS experiment



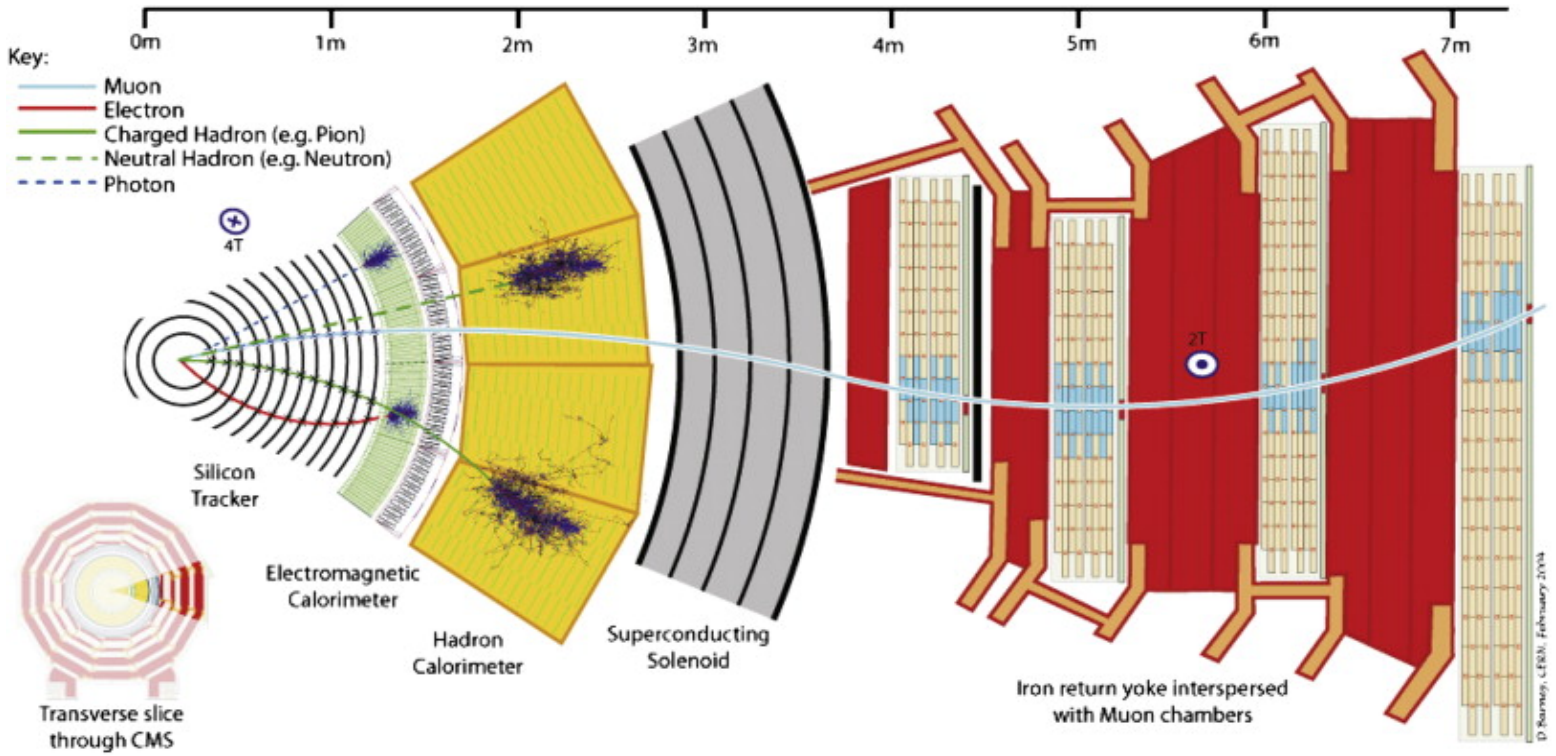
$$\eta = -ln \tan \frac{\theta}{2}$$



The CMS collaboration

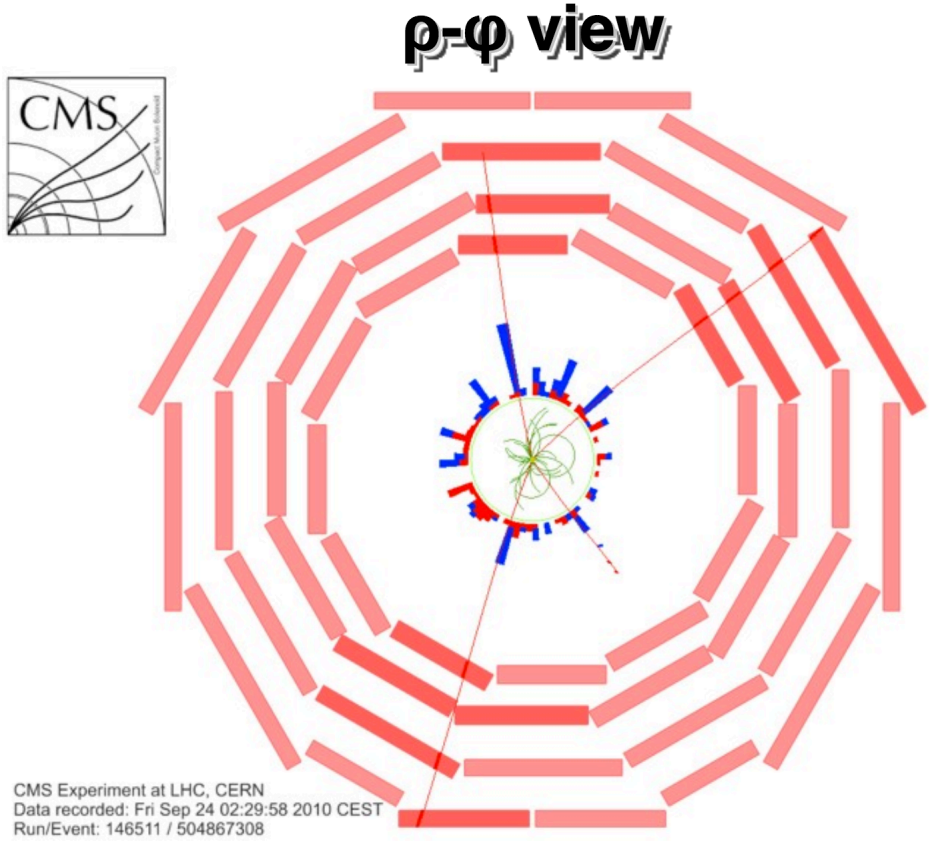
- 4000 particle physicists, engineers, computer scientists, technicians and students from around 200 institutes/universities from more than 40 countries.

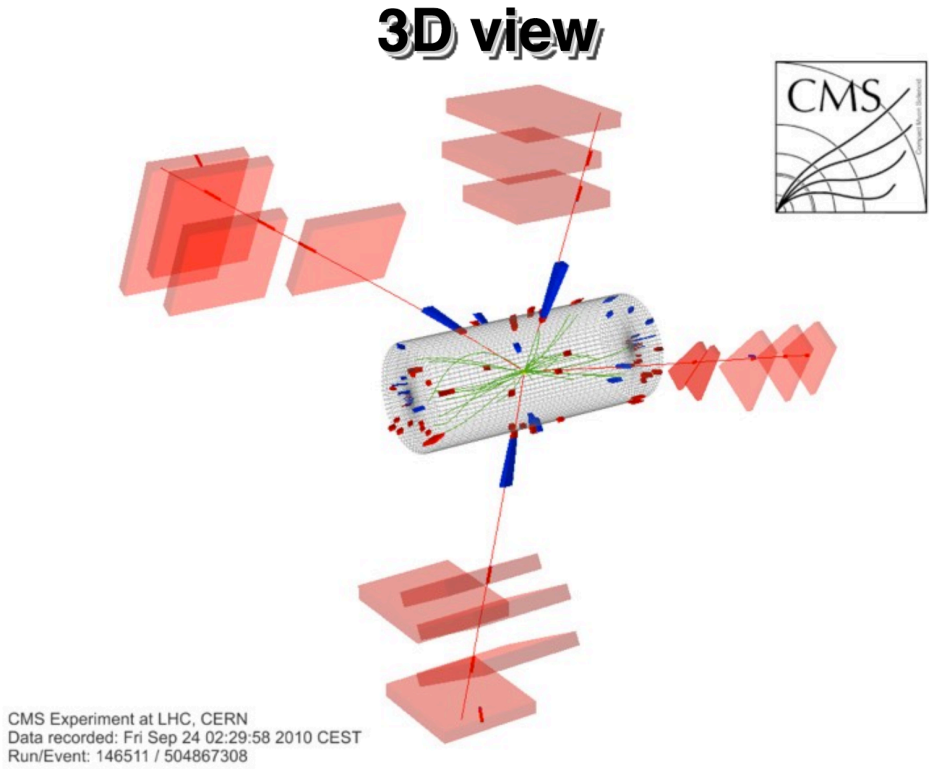
Particles' signature in the CMS detector



First H->ZZ->4μ event in CMS ($m_{4\mu}$ = 201 GeV) [link]

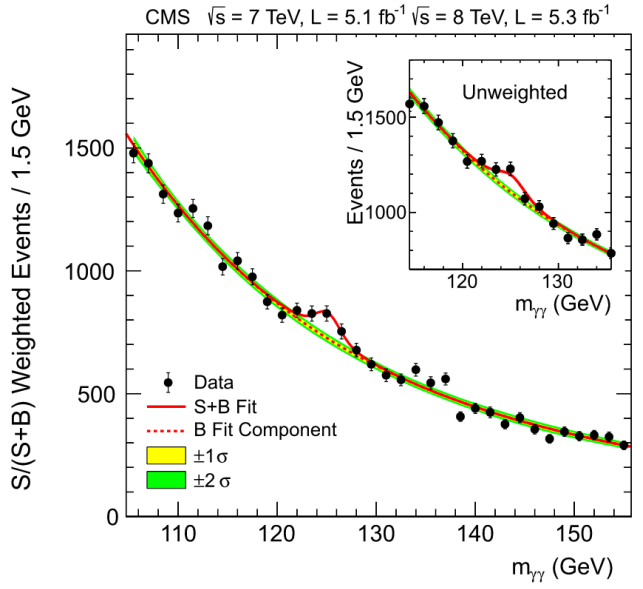
Friday Sep. 24 02:29:58 2010 CEST
Run/Event: 146511/504867308

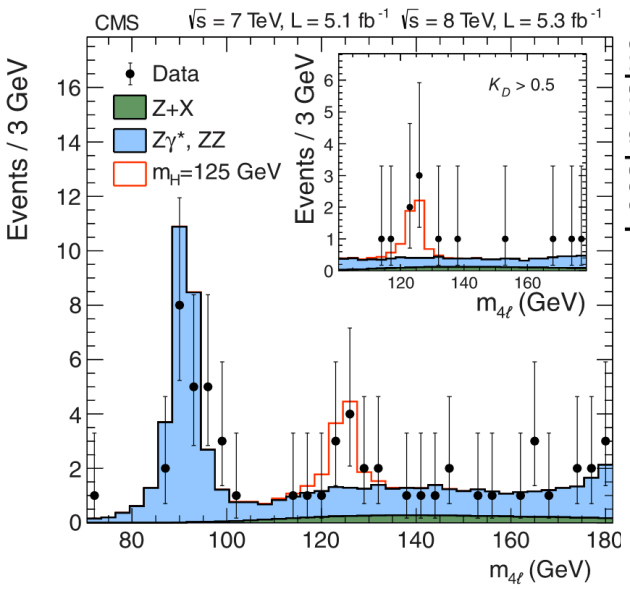


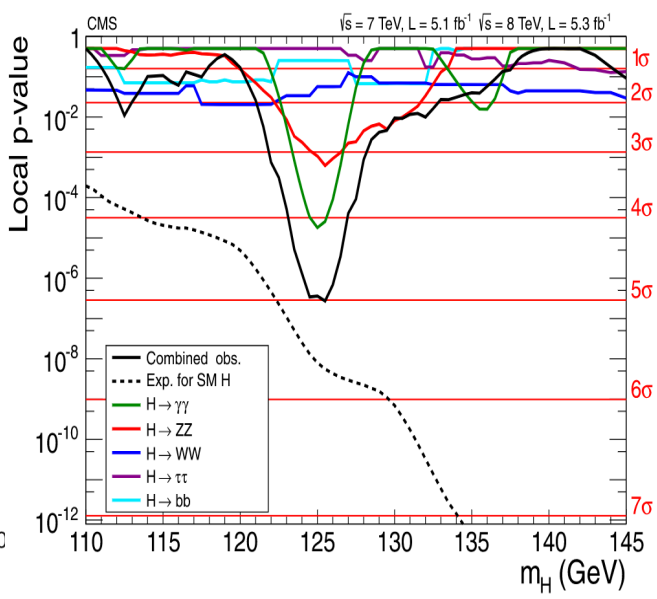


A grand discovery @ LHC: The SM Higgs Boson

- Both ATLAS and CMS observed an excess in their data around mass of 125 GeV with a level of certainty worth a ***"discovery"***
- On 4th July 2012, CERN announced a discovery of a new particle [Phy. Lett. B 716 (2012) 30–61]
- The properties of the new particle was measured: spin-parity, cross-section and couplings to the fermions and gauge bosons, and found compatible with the Higgs boson of the SM
- ***This discovery completed the SM***





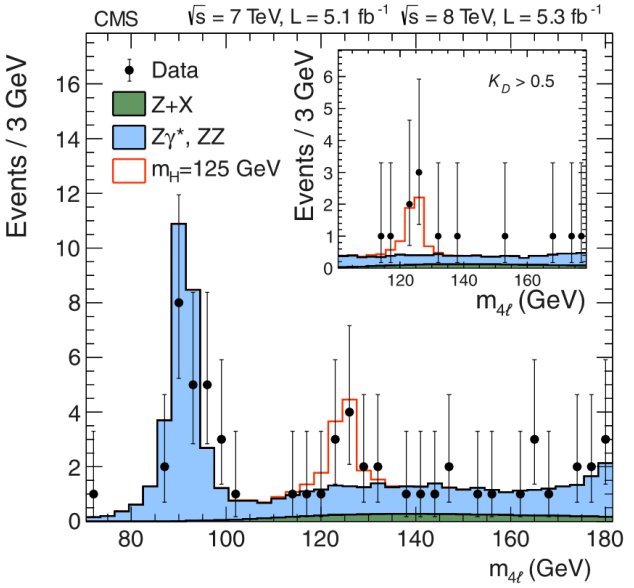


The Nobel Prize in Physics 2013

- Awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN LHC"*

H->ZZ->4l analysis: my main contribution, reported in the Run1 Higgs legacy paper (Eur. Phys. J. C 75 (2015) 212, CMS public twiki)

- *I estimated the contamination of the reducible backgrounds in the signal phase space: Z+jets, WZ+jets and ttbar (Z+X in the plot)*
- It was particularly important since it was impossible to disentangle these backgrounds from signal



- I used the, so-called fake-rate, method to estimate these backgrounds from data itself:
  - **step-1:** define a Z+ jets dominating control region and measure the probability of a jet to fake a lepton
    - FakeRate (*f*) = # jets passing lepton ID and isolation requirements / total # of jets
  - **step-2:** define a phase space with events not passing the ID and isolation requirements and then their normalisation to a factor, *f/(1-f)*, gives the background estimation

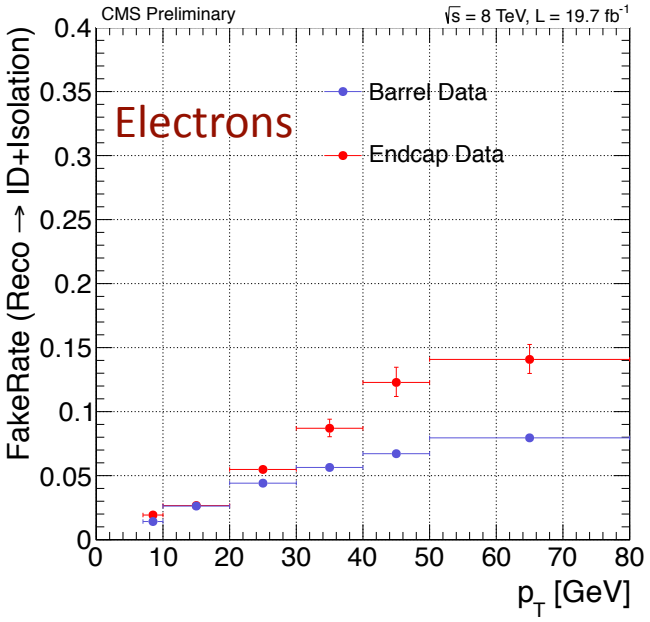
$$f = \frac{N_{jets}^{pass}}{N_{jets}^{tot}}$$

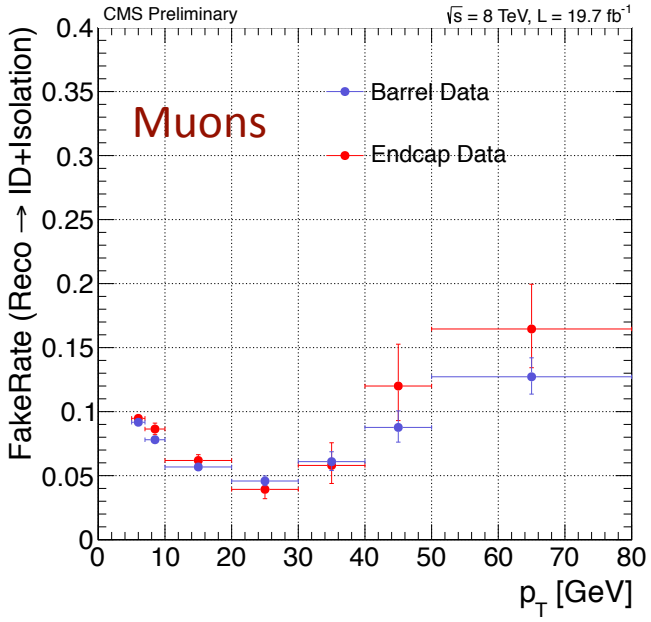
$$N_{jets}^{tot} = N_{jets}^{pass} + N_{jets}^{fail}$$

$$\boxed{N_{jets}^{pass} = \frac{f}{1-f} N_{jets}^{fail}}$$

H->ZZ->4l analysis: Z+X background estimation

$$f = \frac{N_{jets}^{pass}}{N_{jets}^{tot}}$$





L = 5.1/fb @ 7TeV + 19.7/fb @ 8TeV; Mass window = [121.5, 130.5] GeV

$$N_{jets}^{pass} = \frac{f}{1-f} N_{jets}^{fail}$$

Channel	4e	2e2μ	4μ	4l
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
m_H = 125 GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
m_H = 126 GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

Z′->dilepton search

- The SM is a successful theory supported by many experimental evidences but does not explain:
  - mass hierarchy, gravity, dark matter…

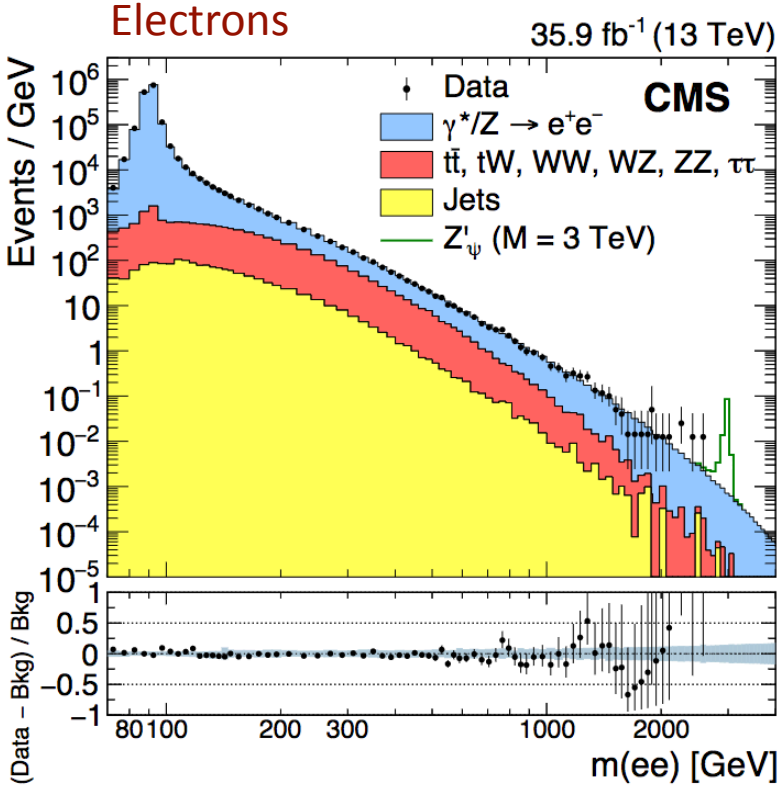
- Many theories beyond the SM address these omissions:
  - Models with extended Higgs sectors
    - e.g. Two-Higgs-Doublet (**2HDM**) model predicts heavy spin-0 resonance
  - Extra dimensional models
    - e.g. Arkani-Hamed, Dimopoulos and Dvali (**ADD**) and Randall-Sundrum (**RS**) models predict heavy spin-2 resonance
  - Superstring-inspired (Z'_{ψ}) models and Sequential Standard Model (**SSM**) predict heavy spin-1 gauge bosons

- **Z' Signal:** two same flavour high-p_T leptons with very low background at high mass
- **Backgrounds:** irreducible Z/γ^* and reducible ttbar, tW and diboson
- **Search Strategy:** search for localised excess in dilepton mass spectrum, up to 5 TeV

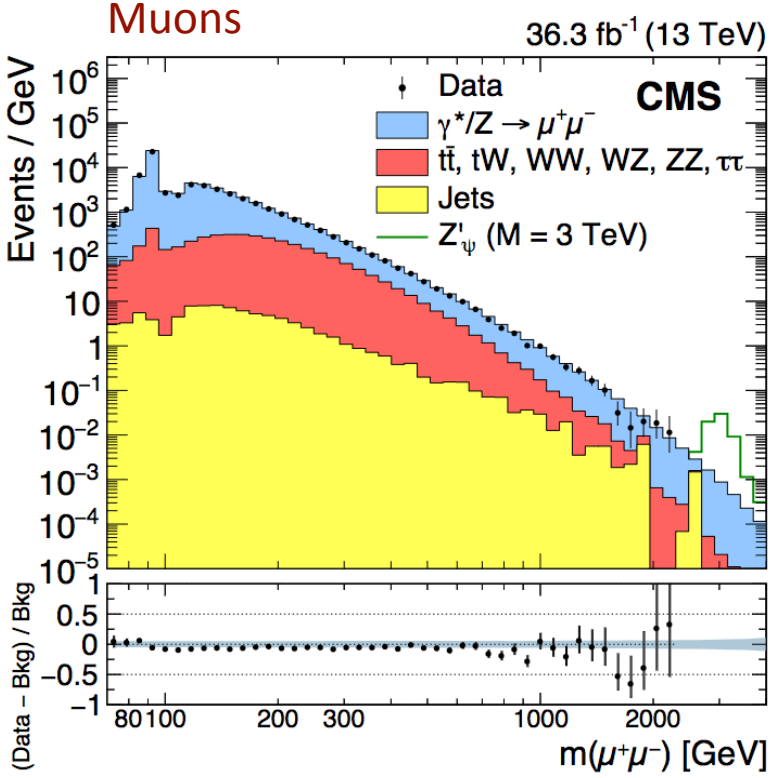
Dilepton mass spectrum

https://arxiv.org/abs/1803.06292

Electrons



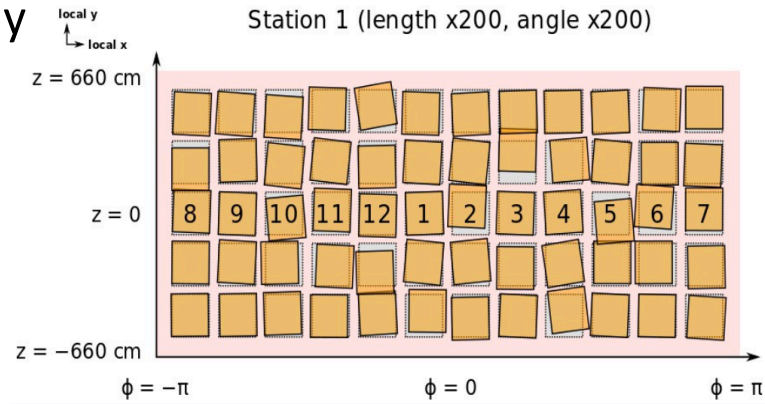
Muons

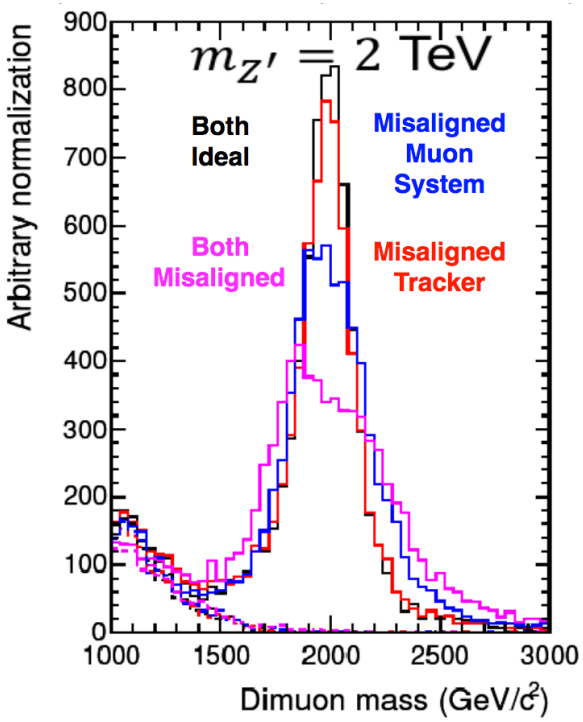


$Z' \to \mu\mu$ search: my main contribution

- The crucial aspect of dimuon search was to precisely reconstruct the muons and measure their momentum -> precise dimuon mass reconstruction
- This search involves very high-momentum muons, p_T >> 200 GeV
  - they do not bend much in the magnetic field
  - tracker is capable to measure momentum with a certain precision only up to 200 GeV
  - for p_T > 200 GeV, the precision in the momentum measurement can be sustained only by adding the muon system information
  - even small misalignments in the muon system screw-up the momentum resolution and hence the mass resolution
- *I improved the muon reconstruction and, in fact, made it more robust by improving the muon sub-detector alignment:* ***by introducing the muon APEs***

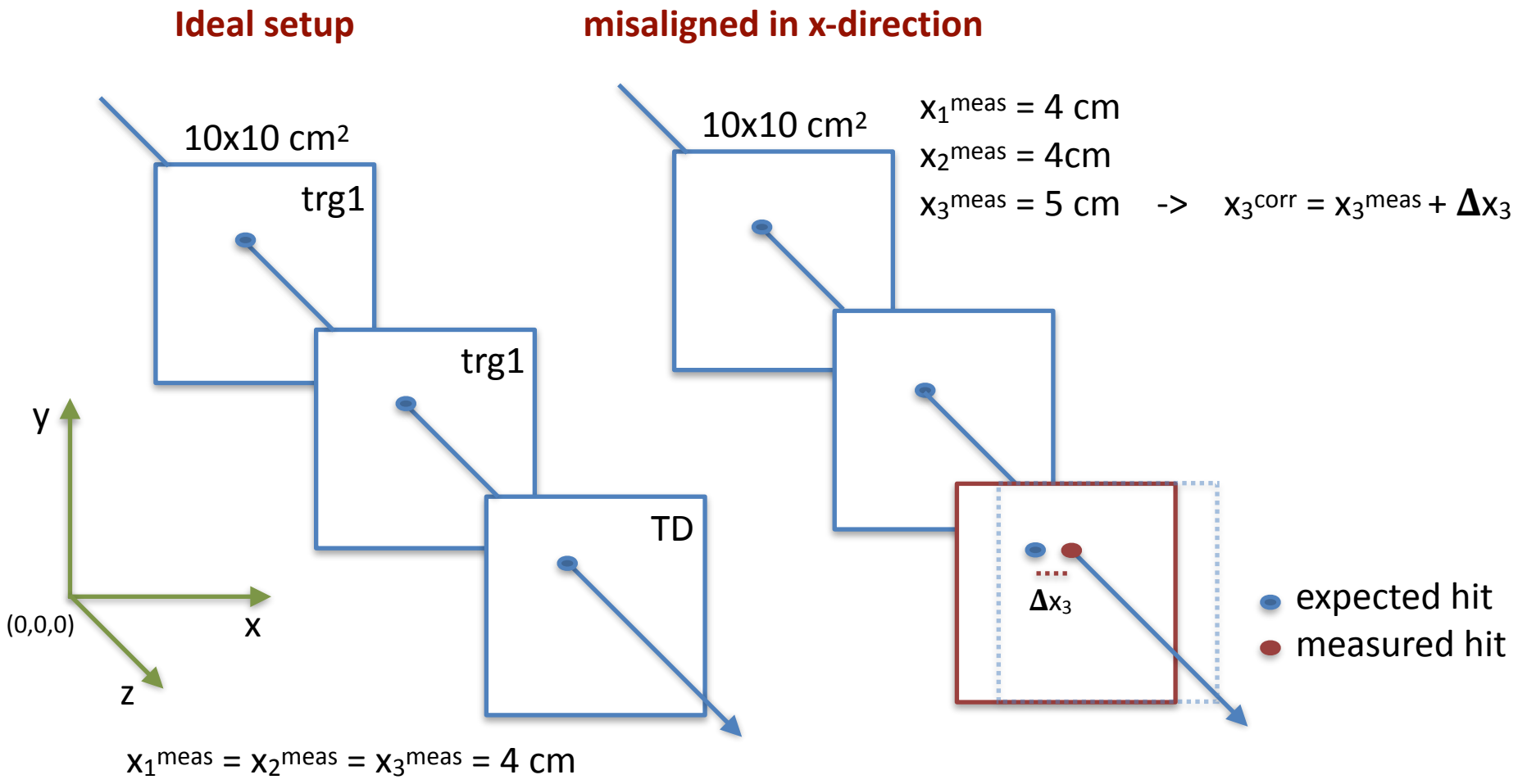
Misaligned Drift tubes





What is “detector alignment”?

- Let’s take a test-beam setup as an example: trigger 1, trigger 2 and a test detector (TD)



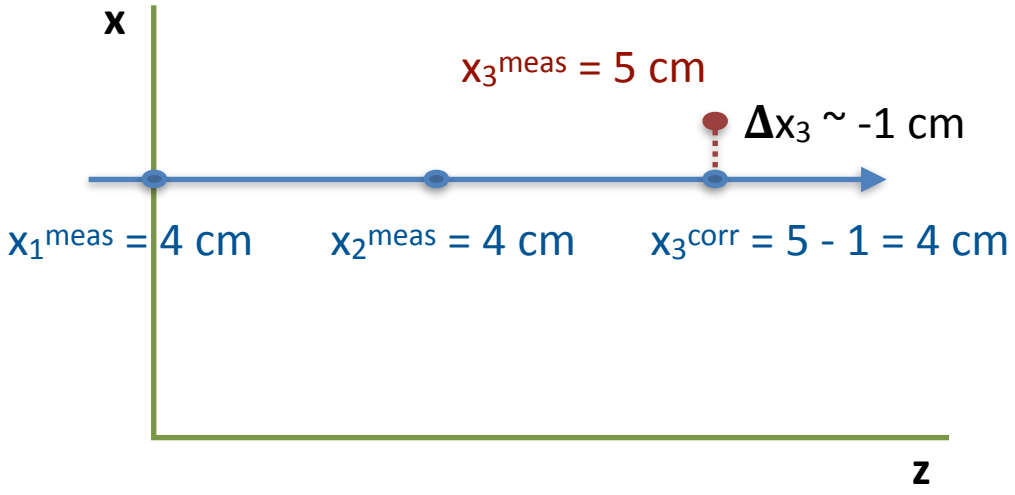
What is “detector alignment”?

$$x_3^{corr} = x_3^{meas} + \Delta x_3$$

this term gives the expected hit

$$\chi^2 = \sum_{j=1}^{Nevents} \frac{(x_{3,j}^{corr} - b_j - a_j x_{3,j})^2}{\sigma_3^2} \qquad (\sigma_3 = \text{hit unc.})$$

- Minimisation of χ^2 gives us the minimised residual Δx_3



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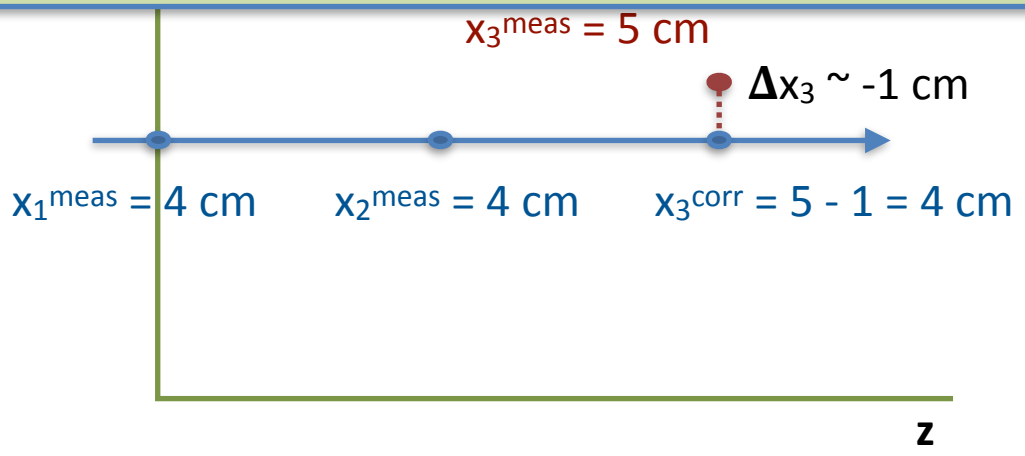
- In real, muon chambers misalign in 6 coordinates: local-x, -y, -z, -ϕ_x, -ϕ_y and -ϕ_z
- Δx is much complicated than simply $x^{corr} - x^{meas}$ (= δx)
- Minimising Δx gives alignment for the coordinates: $\delta x_1, \delta x_2, \delta x_3, \delta\phi_x, \delta\phi_y, \delta\phi_z$



Muon system alignment

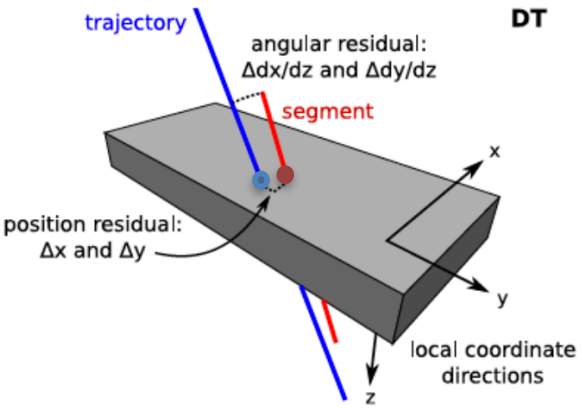
- **Startup alignment:** initial geometry obtained by hardware measurements after the detector is dismounted and remounted
- **Track-based alignment (using data):** final geometry obtained by minimising the residuals of extrapolated inner tracks (expected hit) to matching muon segments (measured hit), chamber by chamber
  - **Drift tubes (DT) (barrel |η| < 0.9):** use local-x and -y residuals; align local-x, -y and -ϕ_z

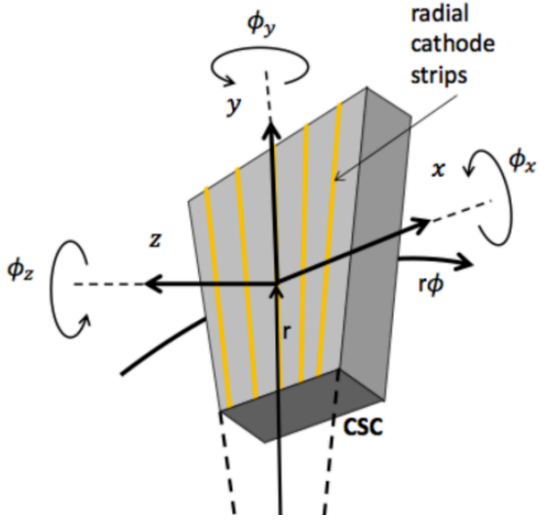
$$\begin{pmatrix} \Delta x \\ \Delta y \\ \Delta\frac{dx}{dz} \\ \Delta\frac{dy}{dz} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & 0 & 0 & -\frac{dx}{dz}\frac{dy}{dz} & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$

  - **Muon cathode strip chambers (CSC (endcaps 0.9 < |η| < 2.4):** use rϕ residual; align local-x and -ϕ_z

$$\begin{pmatrix} \Delta(r\phi) \\ \Delta y \\ \Delta\frac{d(r\phi)}{dz} \\ \Delta\frac{dy}{dz} \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{r}+3\left(\frac{x}{r}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & -\frac{1}{2r}\frac{dx}{dz} & 0 & \left[\frac{x}{r}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$

- expected segment
- measured segment





Muon Alignment Position Errors (APEs)

- The intrinsic uncertainties and the uncertainties due to multiple scattering of a track define the uncertainties on the position of hits/segment reconstructed in a muon chamber
- APEs are the additional uncertainties on the position of muon chambers (and hence on segments) after alignment
    - Size equal to the precision of the alignment measurement

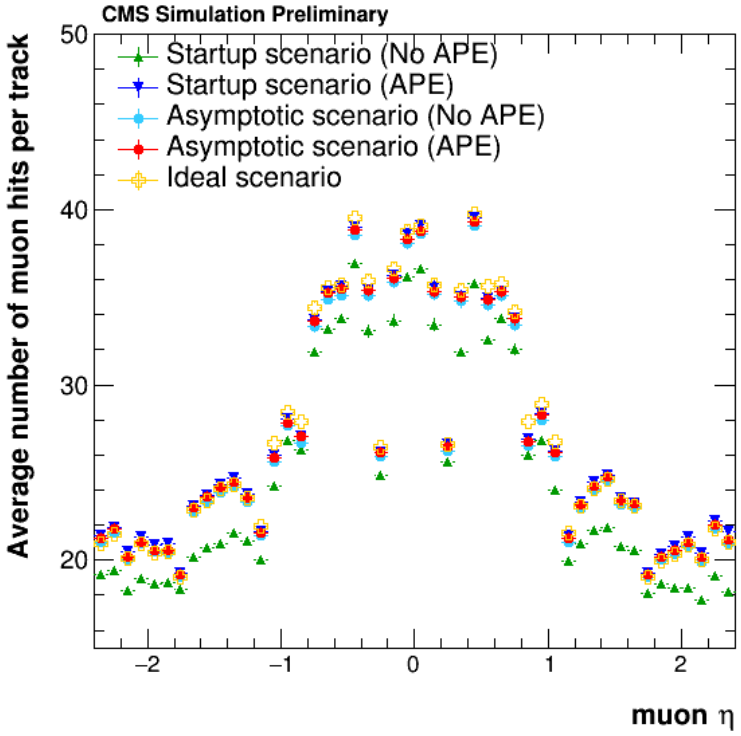
- **What do we expect?**
- **Reconstruction Efficiency:** inclusion of APE -> additional uncertainties -> better pattern recognition (more hits in average) -> higher reconstruction efficiency
- **Track quality:** inclusion of correct-size APEs -> the width of pull distributions (**local-x, q/p etc.**) becomes closer to unity -> better estimate of the χ^2 of track
- **Momentum resolution:** correct weight of muon segments w.r.t inner track by inclusion of APE, resulting in an improved momentum resolution, specially at high momentum, for the tracker plus muon fit

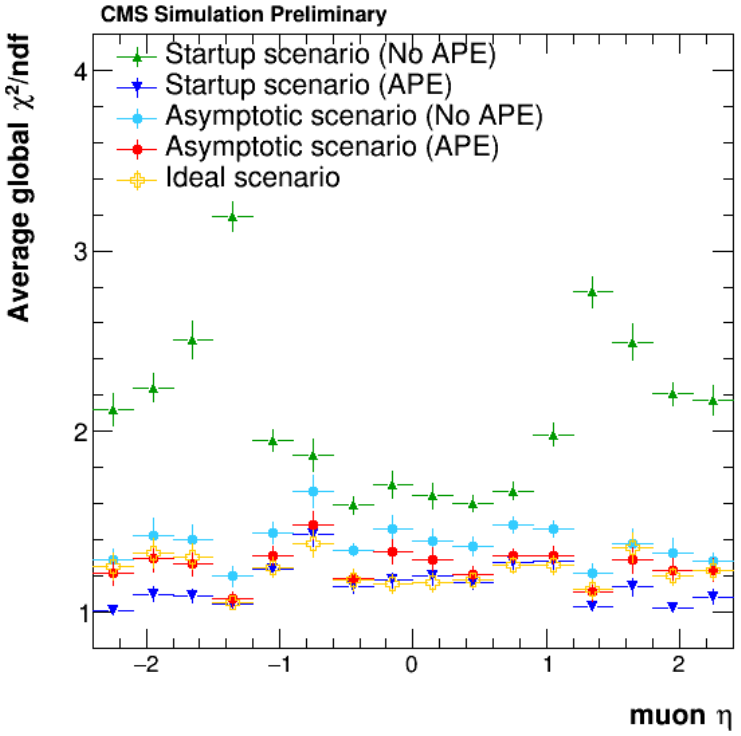
- **Size of APE:**

	Startup APE		Asymptotic APE	
	DTs	CSCs	DTs	CSCs
local-x	0.5-2 mm	2 mm	0.2-0.5 mm	0.1-0.6 mm
local-y	0.9-2 mm	2 mm	0.1-1.3 mm	0.3-0.6 mm
local-z	0.9-2 mm	2 mm	0.6-1.1 mm	2 mm
local-ϕx	0.4-1 mrad	1 mrad	0.3-0.6 mrad	0.5-1 mrad
local-ϕy	0.4-1 mrad	1 mrad	0.3-0.5 mrad	2-2.8 mrad
local-ϕz	0.3-1 mrad	1 mrad	0.05-0.2 mrad	0.04-0.5 mrad

Muon reconstruction performance in simulation

- Muon gun events: back-to-back muons, flat in P, eta and phi





https://cds.cern.ch/record/2229697?ln=es

Muon reconstruction performance in simulation

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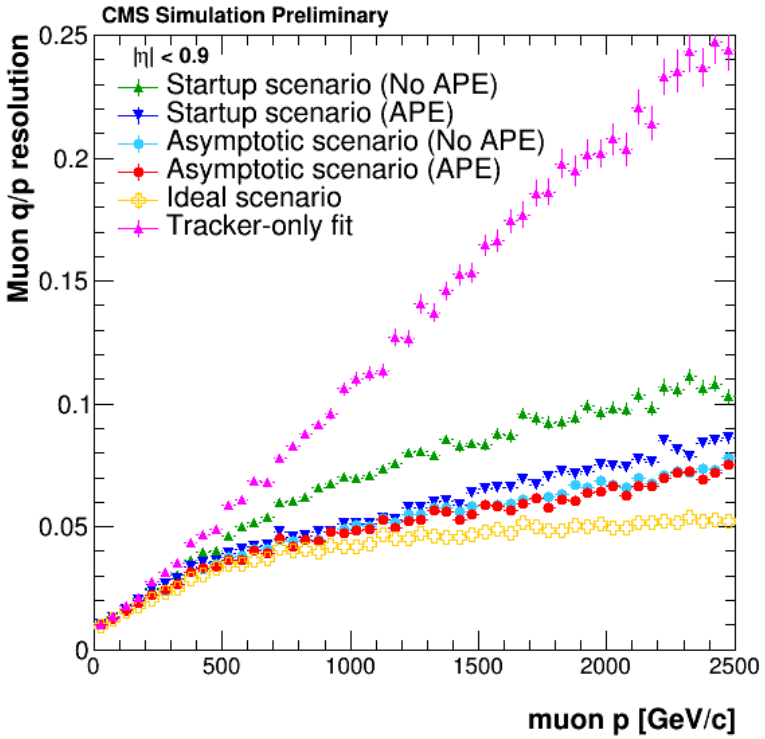
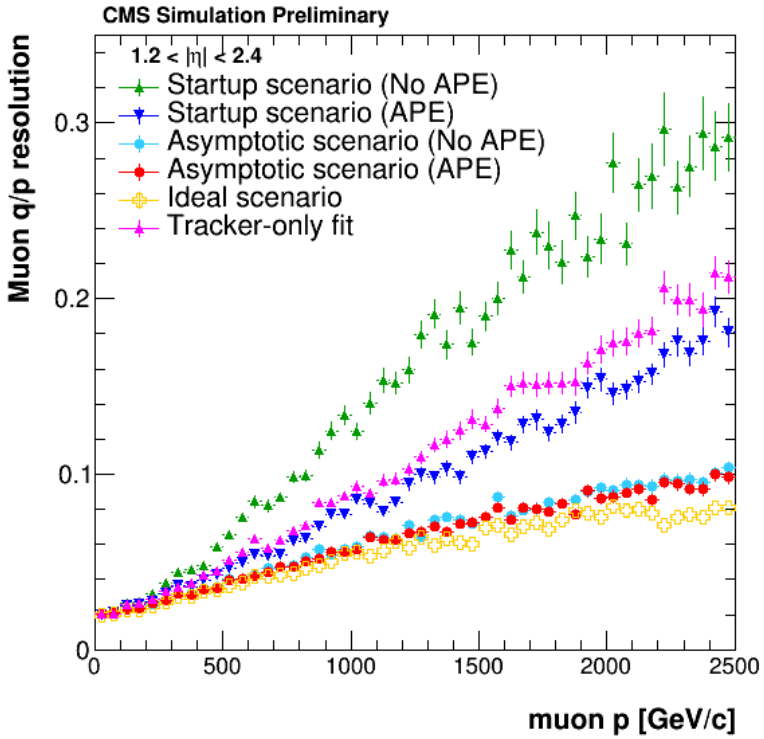
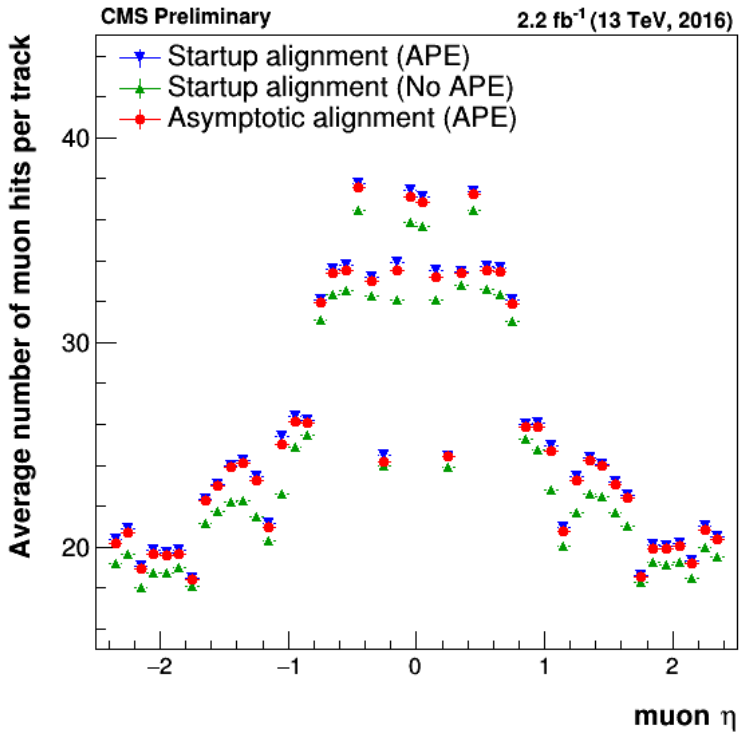


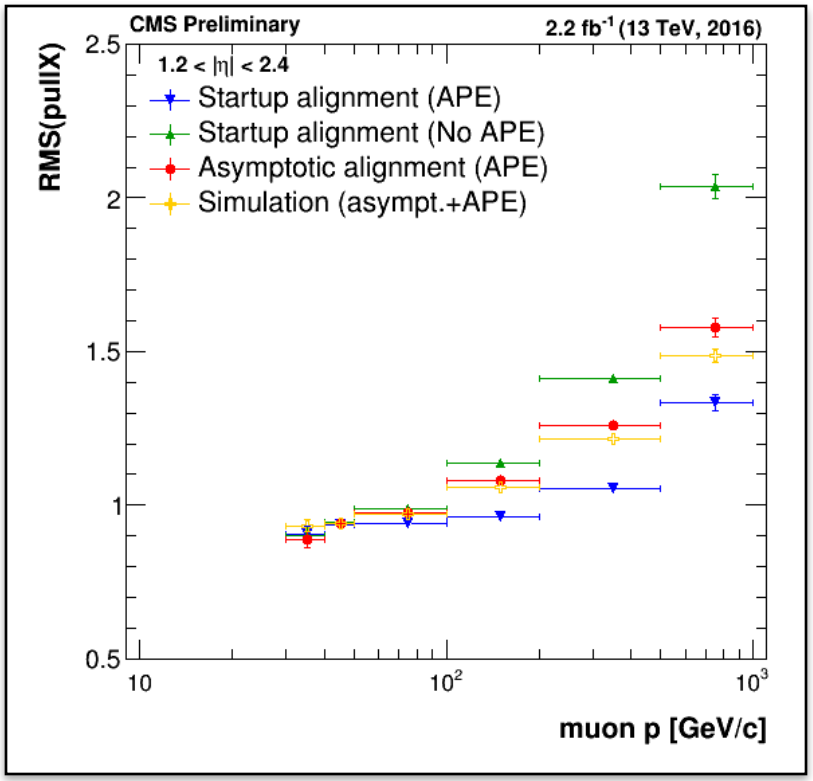


- **Muon q/p resolution:** gaussian sigma of the q/p(reco.-true/true) distribution

Muon reconstruction performance in 2016 data

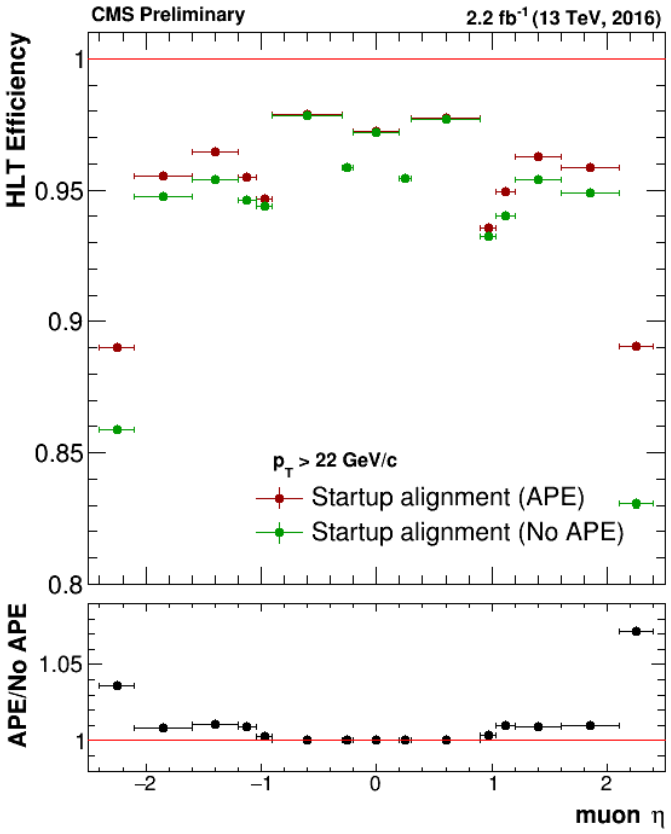
- From the beginning of data collection in 2016, muon reconstruction has been using **non-zero muon APE for the first time ever in CMS**.

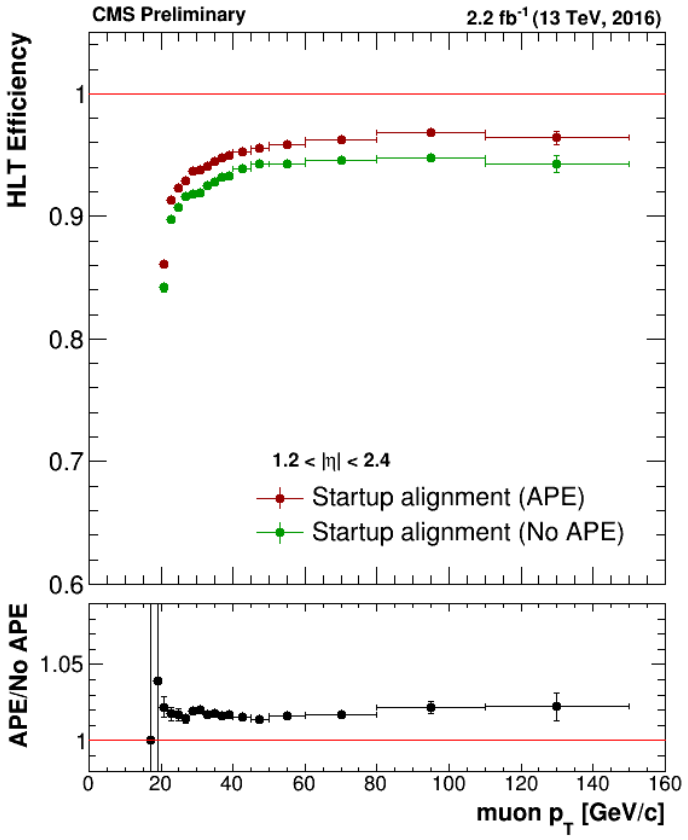




- **pullX: Δx/x-uncertainties**

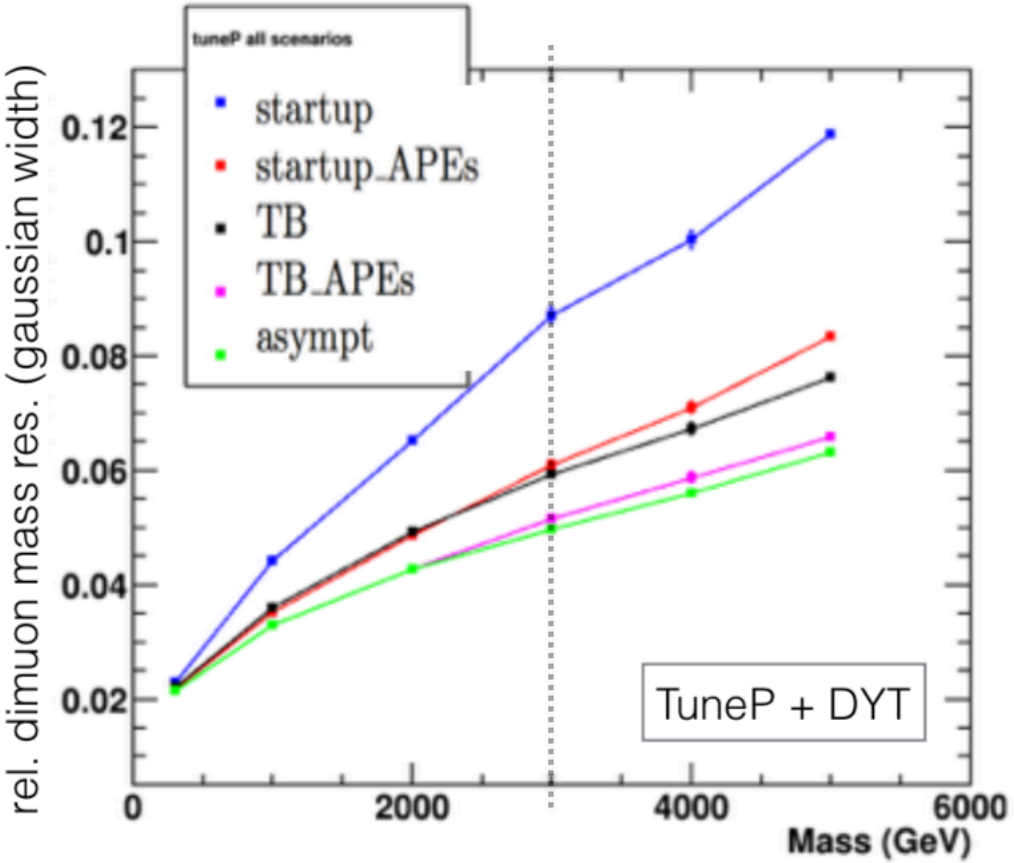
Muon trigger performance in 2016 data





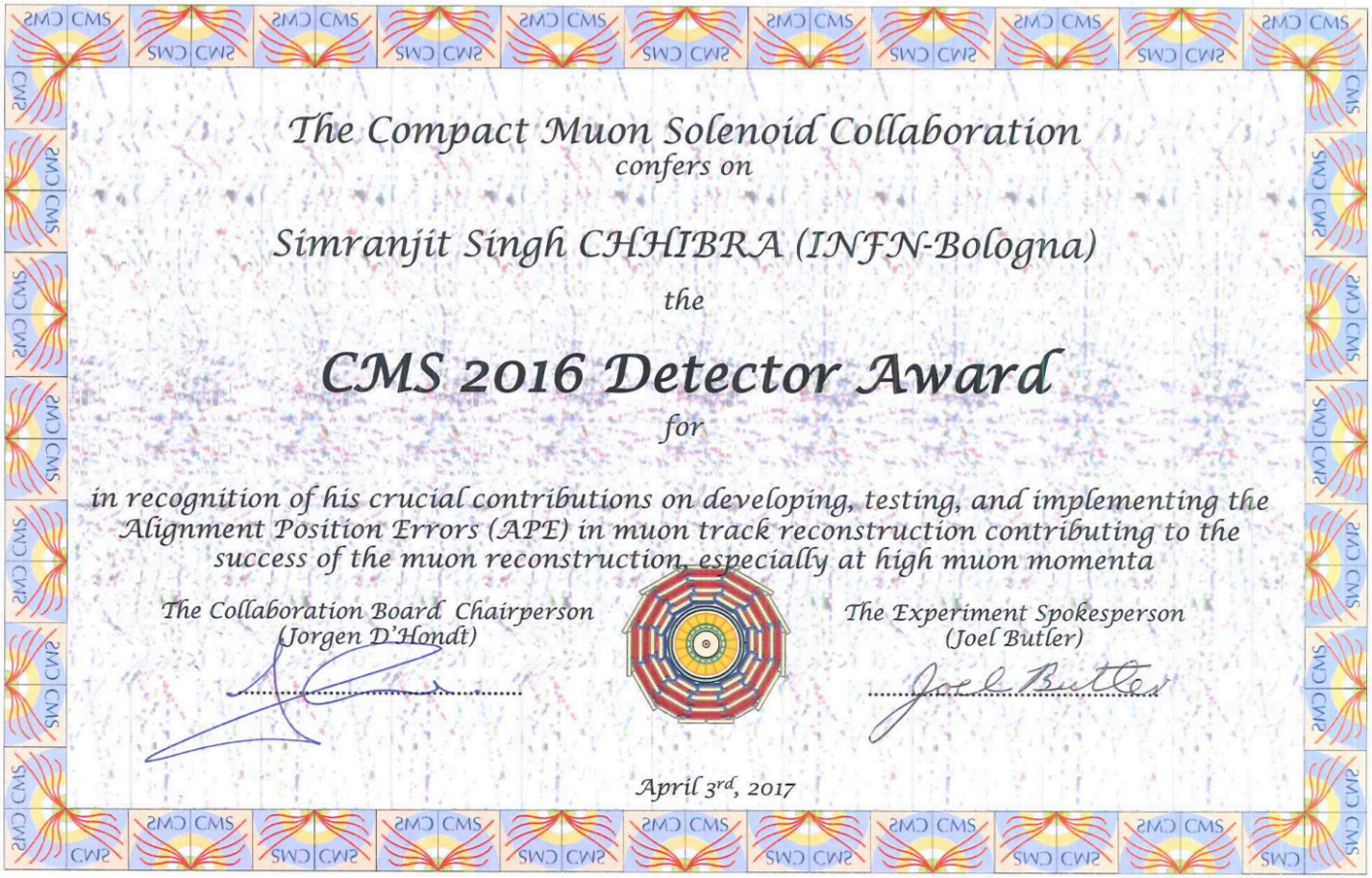
- Non-zero muon startup APE increased the **HLT_IsoMu20 efficiency** by **~ 7% for 2.1 < η < 2.4**, **~ 3.5% for -2.4 < η < -2.1** and **~ 1% over the remaining endcap regions**

Dimuon mass resolution



- Non-zero muon startup APE has improved the dimuon mass resolution by ~ 30% for mass = 3TeV

CMS Detector Award 2016



The Compact Muon Solenoid Collaboration
confers on

Simranjit Singh CHHIBRA (INFN-Bologna)

the

CMS 2016 Detector Award

for

in recognition of his crucial contributions on developing, testing, and implementing the Alignment Position Errors (APE) in muon track reconstruction contributing to the success of the muon reconstruction, especially at high muon momenta

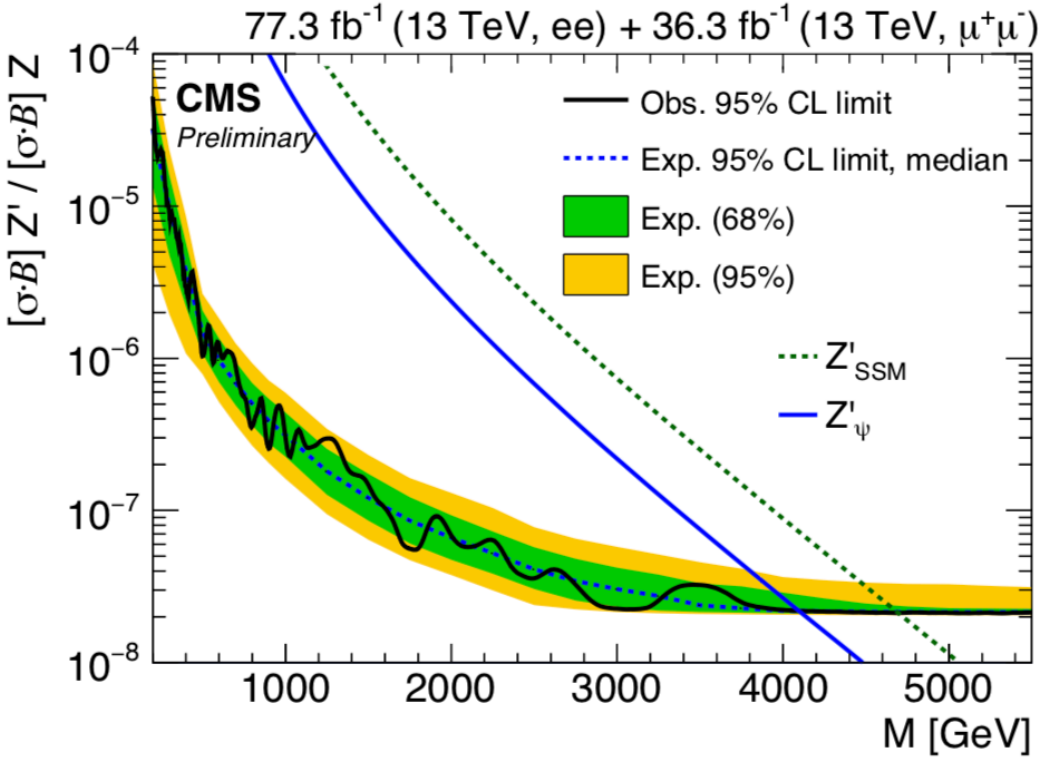
The Collaboration Board Chairperson
(Jorgen D'Hondt)

The Experiment Spokesperson
(Joel Butler)

April 3rd, 2017

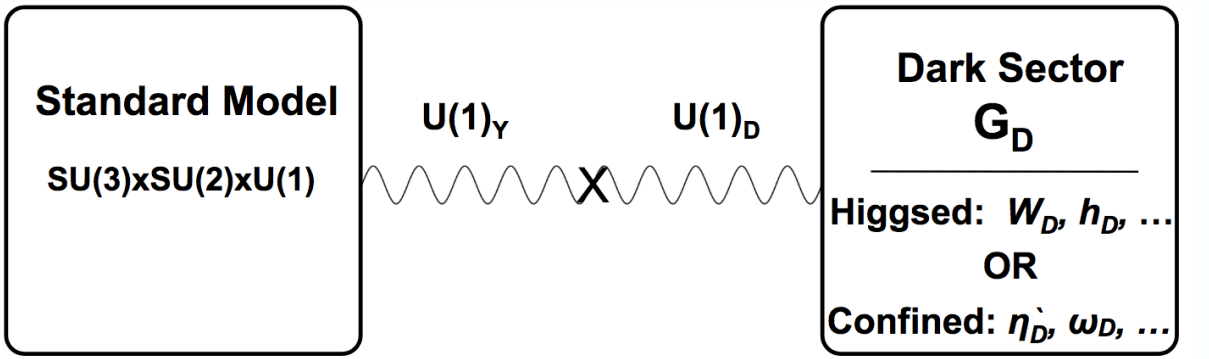
Upper limits on R = $\sigma_{Z'}/\sigma_Z$

Electrons + Munos



Channel	Model	Obs. limit [TeV]	Exp. limit [TeV]
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

Dark photon searches: my current analysis



- Dark photon, Z_D, represents a new $U(1)_D$ symmetry of nature (https://arxiv.org/abs/1608.08632)
- Often seen as a connection between the SM and the dark sector
- Dark photon talks to the SM particles through the kinetic mixing term in the Lagrangian

$$\mathcal{L} \subset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \boxed{\frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu}} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu}$$

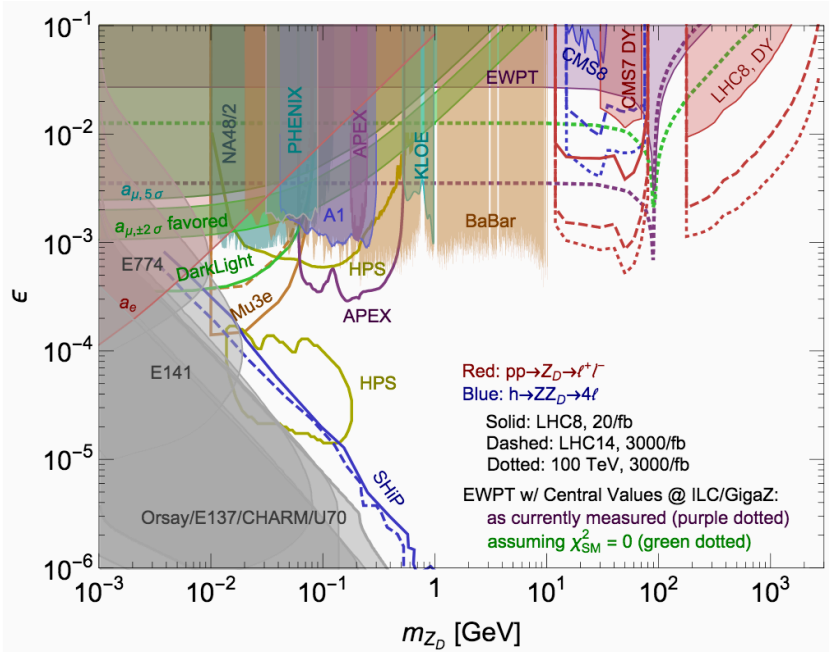
ϵ: kinetic mixing coefficient

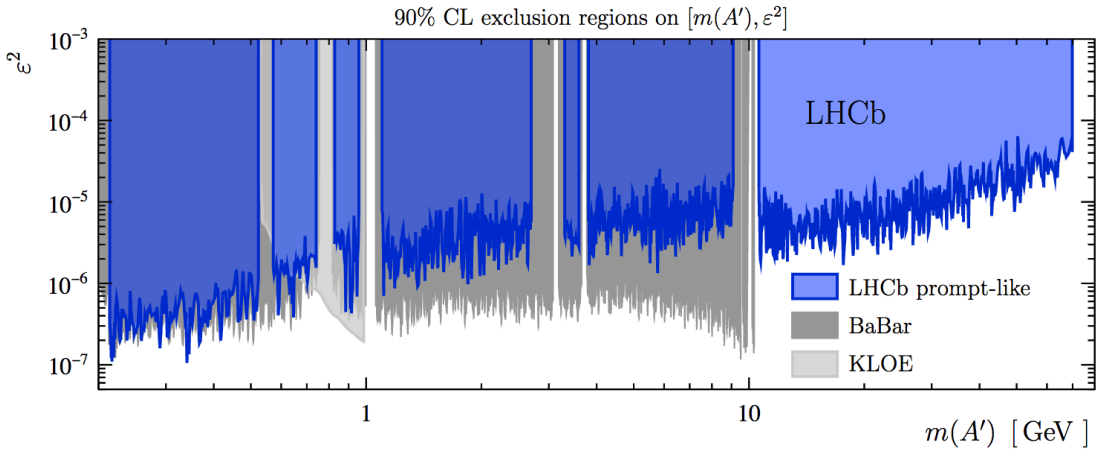
Gauge invariant, renormalizable, dimension 4 operator

- Z_D interactions with fermions is similar to that of γ/Z and coupling is proportional to ϵ^2

Present constraints in [ϵ, m_{Z_D}] parameter space

- **Babar:** $\epsilon \sim 10^{-3}$ mass < 10 GeV
- **EWPT:** $\epsilon \sim 3 \times 10^{-2}$ for mass > 10 GeV
- **LHCb:** $\epsilon \sim 10^{-3}$ for mass [0.2, 70] GeV ([Phys. Rev. Lett. 120, 061801 (2018)])



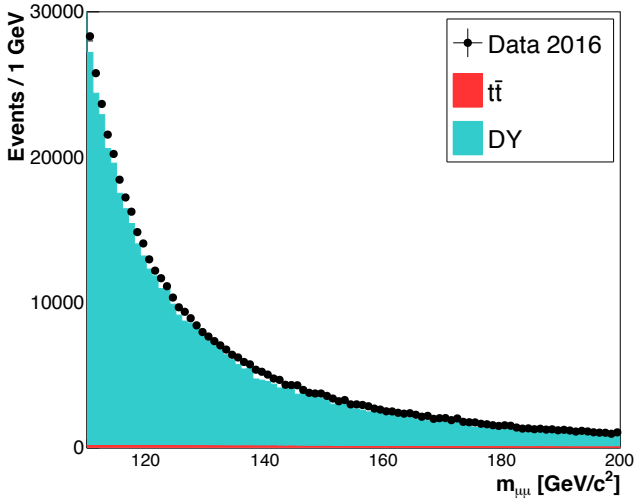


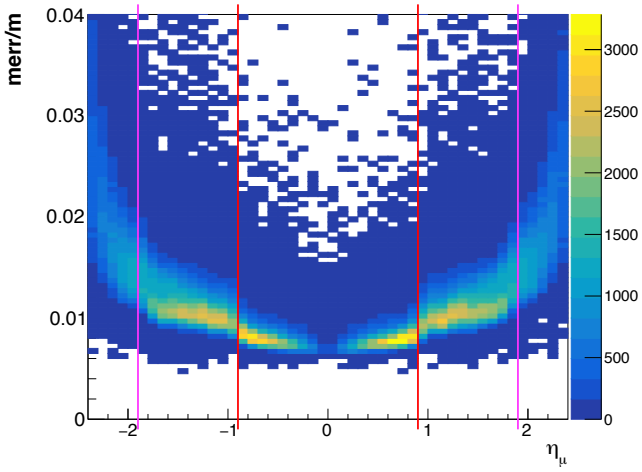
Z_D search with CMS

Preliminary Results

- **Signal:** two same flavour leptons
- **Backgrounds:** irreducible Z/γ* and reducible ttbar, tW and diboson
- **Search Strategy:** search for localised excess in dilepton mass spectrum, in the mass range of [0.1, 200] GeV

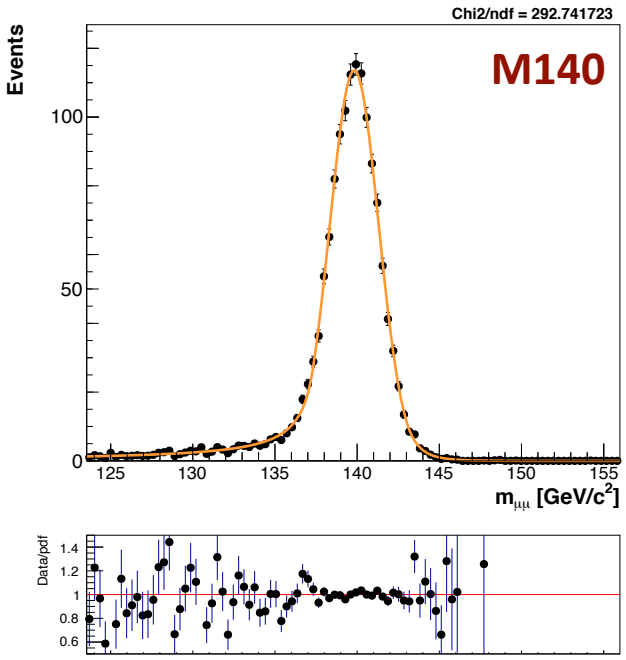
- *Steven and I have started the Z_D search using 2016 dimuon data in the mass range of [110, 200] GeV (the mass range not covered by Z' search)*
- The Z_D signal has similar kinematics as of the DY process
  - Provide no handles to separate out signal from the background
- Events are categorised in three eta categories to enhance the sensitivity
  - **Barrel:** |eta| < 0.9
  - **Overlap:** 0.9 < |eta| < 1.9
  - **Endcap:** 1.9 < |eta| < 2.4
- To extract the signal, the background modelling is performed using data in a mass window of +-10 sigma around the nominal Z_D mass

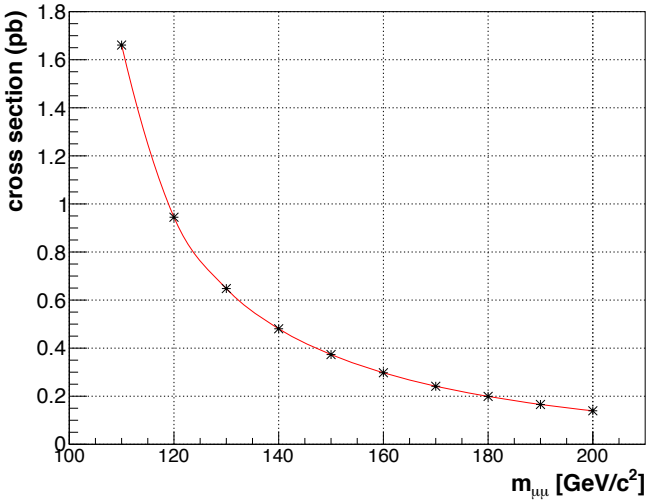




Signal MC generation

- Privately generated Z_D signal samples at LO with madgraph generator for $\epsilon = 0.02$
  - Generated mass points: [110, 200] GeV with a mass-step of 10 GeV



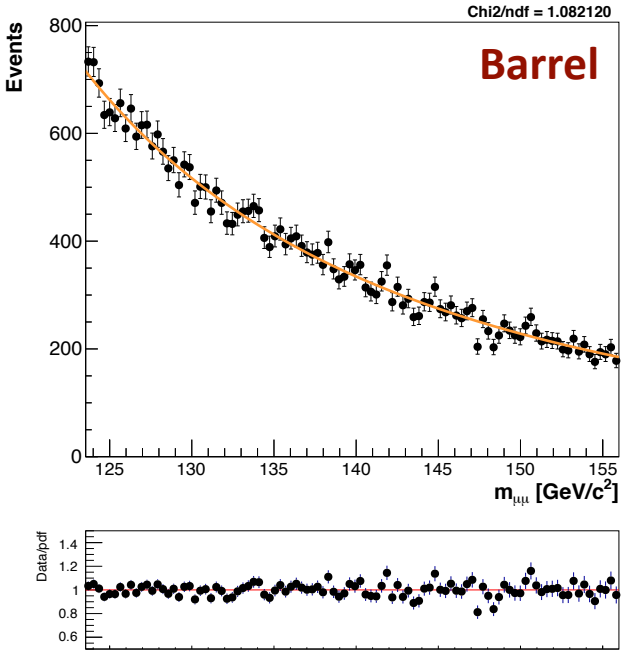


	xsec (pb)
M110	1.661e+00
M120	9.447e-01
M130	6.479e-01
M140	4.806e-01
M150	3.733e-01
M160	2.976e-01
M170	2.414e-01
M180	1.992e-01
M190	1.656e-01
M200	1.394e-01

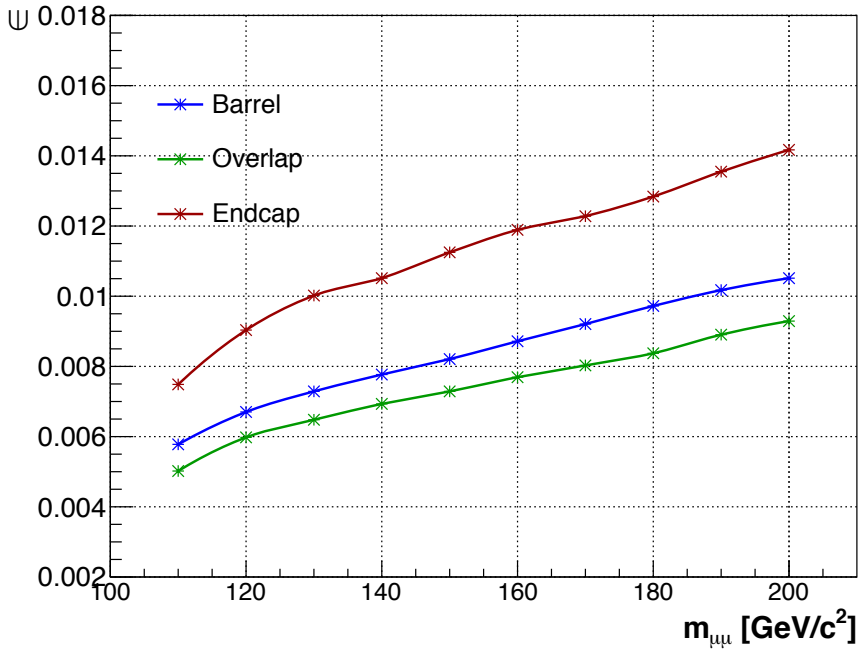
Expected limits in [ϵ, m_{ZD}] parameter space

Bkg. model: modified Breit-Wigner

$$B(x) = \frac{e^{a_2 x + a_3 x^2}}{(x-\mu_z)^{a1} + (\frac{\sigma_Z}{2})^{a1}}$$



ϵ ~ 0.006 - 0.01



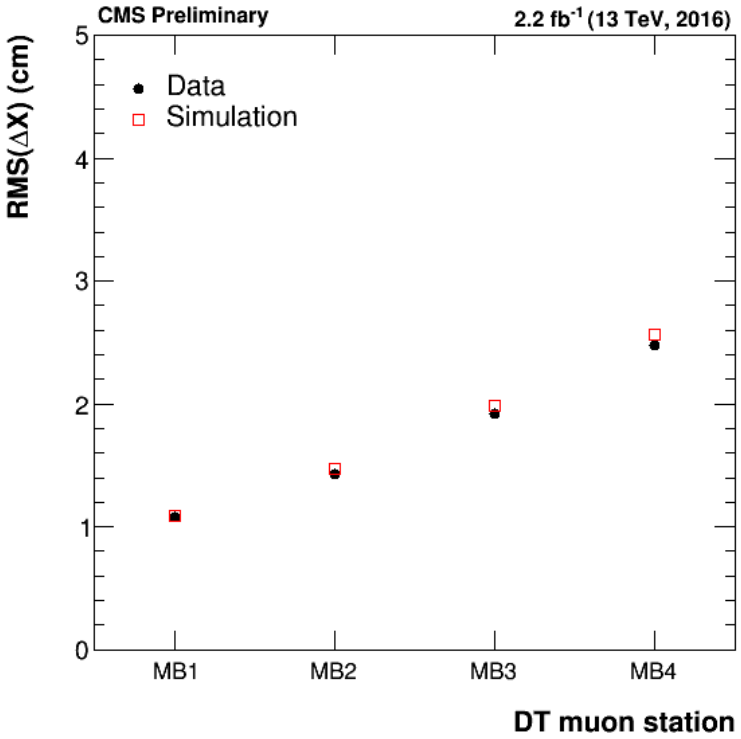
- Once the muon analysis is finalised, we will add the electron channel and the 2017 data
- We plan to then extend the analysis in the low-mass range, below Z mass

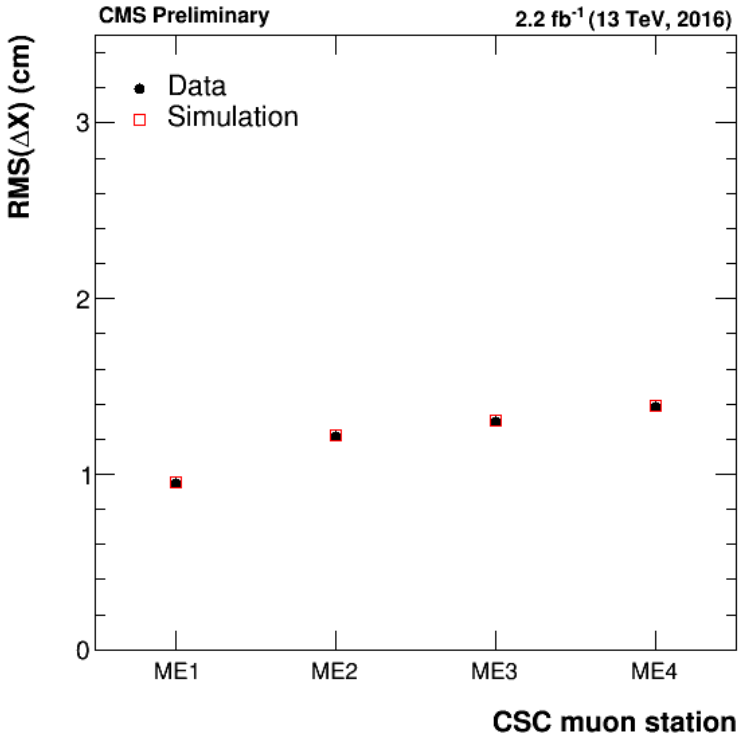
Summary

- We have talked about the LHC and the CMS experiment
- We have discussed the SM Higgs boson discovery at LHC
- We have discussed the BSM Z' search: analysis strategy, improvements in muon reconstruction by adding APEs, and the upper exclusion limits
  - Combining 2016-17 data for electrons and 2016 data for muons channels
    - Z'_{SSM}: excluded in the mass range of [0.2, 4.7] TeV
    - Z'_{ψ}: excluded in the mass range of [0.2, 4.1] TeV
- I have introduced the concept of Z_D search with CMS
  - with 2016 dimuon analysis: able to exclude $\epsilon \sim 0.006$ - 0.01 in the mass range of [110, 200] GeV

Backup

local-x residuals of track-to-segment matches after track-based alignment





- We can only achieve minimum RMS(**Δ**x) ~ 1-2 cm; data and MC agrees pretty good

Z_D search: signal and background modelling

- **Signal Model:** Double crystal ball function
- **Background Models:** several functions have been considered (as in HIG-17-019 analysis)

$$\text{Sum of exponentials (Sum Exp)}: B(x) = \sum_{i=1}^{n} \beta_i e^{\alpha_i x}$$

$$\text{Breit–Wigner}: B(x) = \frac{e^{ax}\sigma_z}{(x-\mu_z)^2 + (\frac{\sigma_z}{2})^2}$$

$$\text{Modified Breit–Wigner (mBW)}: B(x) = \frac{e^{a_2 x + a_3 x^2}}{(x-\mu_z)^{a_1} + (\frac{\sigma_z}{2})^{a_1}}$$

$$\text{BWZGamma: } B(x) = f\frac{e^{ax}\sigma_z}{(x-\mu_z)^2 + (\frac{\sigma_z}{2})^2} + (1-f)\frac{e^{ax}}{x^2}$$

Used by ATLAS [1] in H to dimuon analysis -> $P_{\mathrm{B}}(m_{\mu\mu}) = f \times [\mathrm{BW}(m_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}) \otimes \mathrm{GS}(\sigma^{\mathrm{B}}_{\mathrm{GS}})](m_{\mu\mu}) + (1-f) \times \mathrm{e}^{A \cdot m_{\mu\mu}}/m^3_{\mu\mu},$

[1] PRL 119, 051802 (2017)