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Search for high mass resonances decaying in 2 muons at CMS

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Outline

- Introduction
- Analysis strategy
- CMS experiment
- Muon reconstruction
- Event selection
- Results
- Conclusions

Introduction

The existence of an high-mass neutral gauge boson, the Z', is predicted from some theories extending the Standard Model:

Sequential Standard Model (Z'_{SSM})

- Coupling to fermions are the same of the SM Z boson
- Used as benchmark
- Intrinsic Z' width is the 3% of its mass

E6 Grand Unification Model

- E6 gauge group breaks into SU(5) and two additional U(1) groups
- Physical states are given by

$$Z'(\theta_{E_6}) = Z'_{\psi} \cos\theta_{E_6} + Z'_{\chi} \sin\theta_{E_6}$$

Randall-Sundrum Model of extra dimensions

- solution to the hierarchy problem by diluting gravity in a warped additional dimension
- Predict excitations of the gravitational field (spin 2 Kaluza-Klein gravitons) separated by a characteristic mass scale

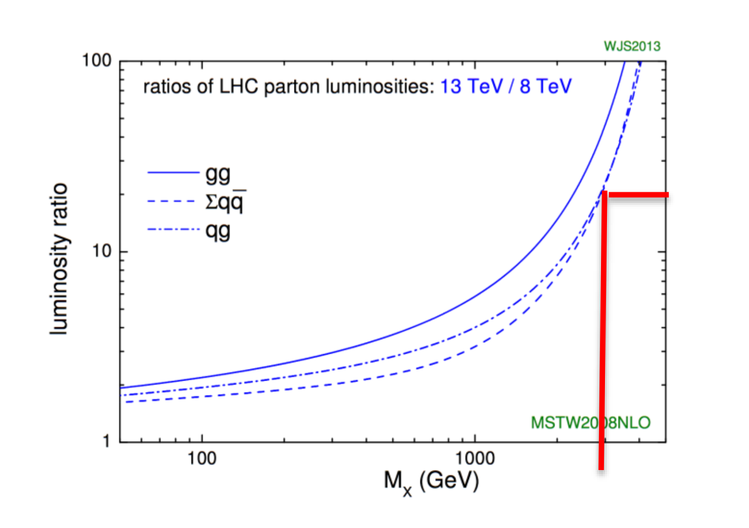
History in CMS

- **1993-97**: **pioneering studies** by C.-E. Wulz and M. Dittmar
- **2002-2009**: more and more realistic and detailed studies (full simulation, detector misalignment, systematic uncertainties, 2nd-order backgrounds, well-defined statistical techniques). **Foundation for the analysis of today.**
  - 2006: Z′ → μμ was one of several analyses studied "in full detail" for Physics TDR, including distinguishing among Z′ models using A_{FB} and discriminating between different spin hypotheses
  - 2009: mock-up paper on Z′ discovery (with 50 pb^{-1} of data at √s=10 TeV)

- **2010-2012:** cranking out theses, PASes, and papers
  - Limits on $M(Z_{SSM})$: 1.1 TeV (40 pb^{-1}@7 TeV) → 1.9 TeV (1 fb^{-1}@7 TeV) → 2.3 TeV (5 fb^{-1}@7 TeV) → 2.6 TeV (5 fb^{-1}@7 TeV + 4 fb^{-1}@ 8 TeV) → 2.9 TeV (20 fb^{-1}@8 TeV).

- **LHC Stop**
  - Upgrade of the CMS muon system
  - 13 TeV collisions
  - Increased parton luminosity

    ≈20 times for Mz = 3 TeV
  - 20 fb^{-1}@8 TeV ≈ 1 fb^{-1}@13 TeV



History in CMS

- **2015** paper (strong Italian contribution from INFN, Pisa, Bologna, Padova, Roma1 and Bari Universities)
  - Limits on $M(Z_{SSM})$: 3.4 TeV (3 fb^{-1}@ 13 TeV + 20 fb^{-1}@8 TeV)
  - Spin-2 interpretation

- 2016: ongoing master thesis in Frascati (A.Alfonsi)
  - Limits on $M(Z_{SSM})$: 4 TeV (13 fb^{-1}@ 13 TeV)
  - Work is ongoing to publish result on the full data taken up to now (37 fb^{-1}@ 13 TeV)

- 2017: LHC stop, the data taking is expected to start in some weeks

Strategy

The analysis follows the long-established approach of a **shape-based search** for a resonance in the dilepton mass spectrum

- Avoid constraints on the absolute background level: fit assumes that only B shape is known
- Keep the fit range reasonably narrow
- Check that the limits are robust against variations in B shape, fit range, etc.

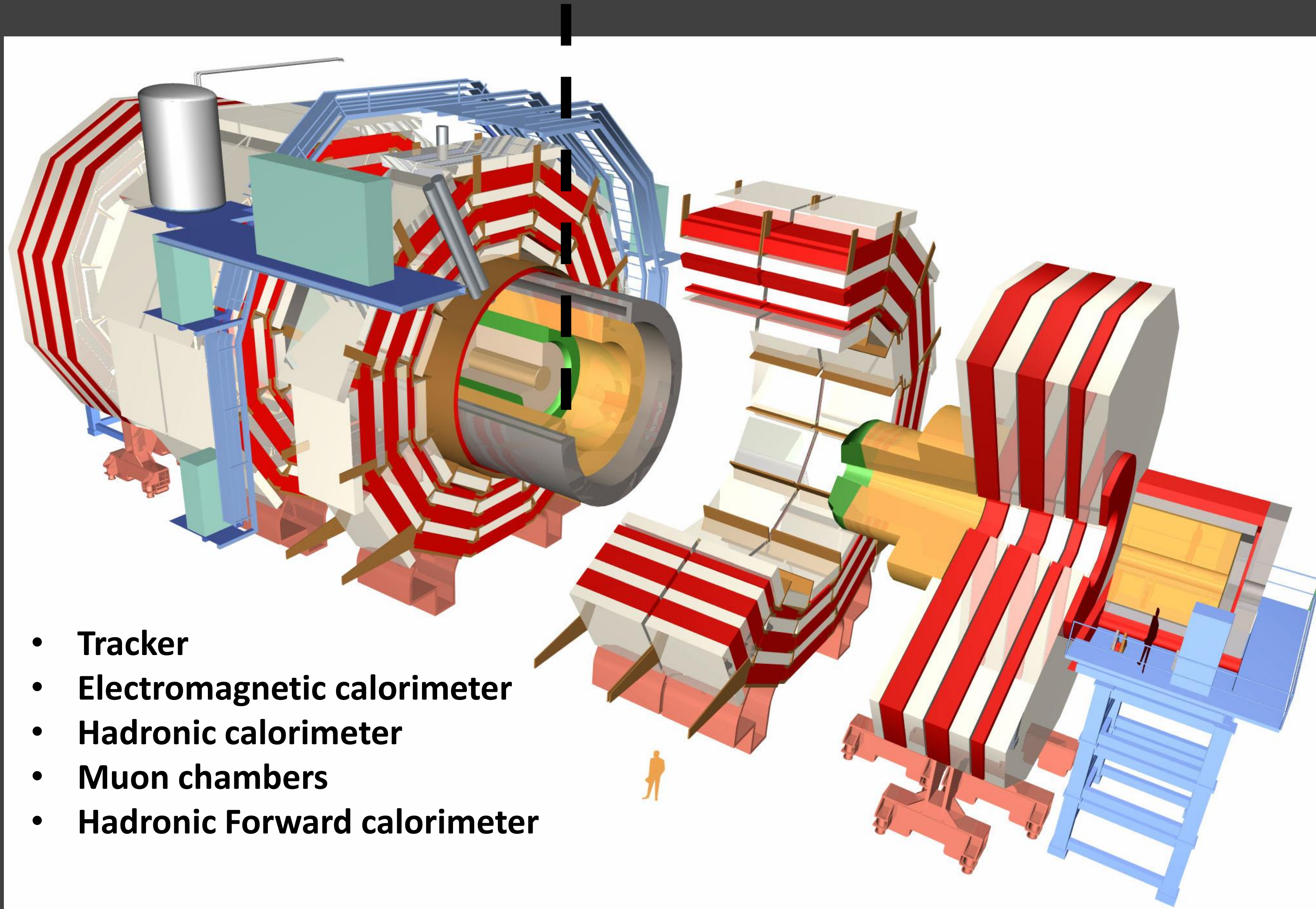
- Existence (or lack) of a signal is established by performing **unbinned maximum likelihood** fits to the observed spectrum

- We interpret the results in terms of a **cross-section ratio**

$$R_\sigma = \frac{\sigma(\mathrm{pp} \to \mathrm{Z}' + \mathrm{X} \to \mu^+\mu^- + \mathrm{X})}{\sigma(\mathrm{pp} \to \mathrm{Z} + \mathrm{X} \to \mu^+\mu^- + \mathrm{X})} = \frac{N(\mathrm{Z}' \to \mu^+\mu^-)}{N(\mathrm{Z} \to \mu^+\mu^-)} \times \frac{A(\mathrm{Z} \to \mu^+\mu^-)}{A(\mathrm{Z}' \to \mu^+\mu^-)} \times \frac{\epsilon(\mathrm{Z} \to \mu^+\mu^-)}{\epsilon(\mathrm{Z}' \to \mu^+\mu^-)},$$

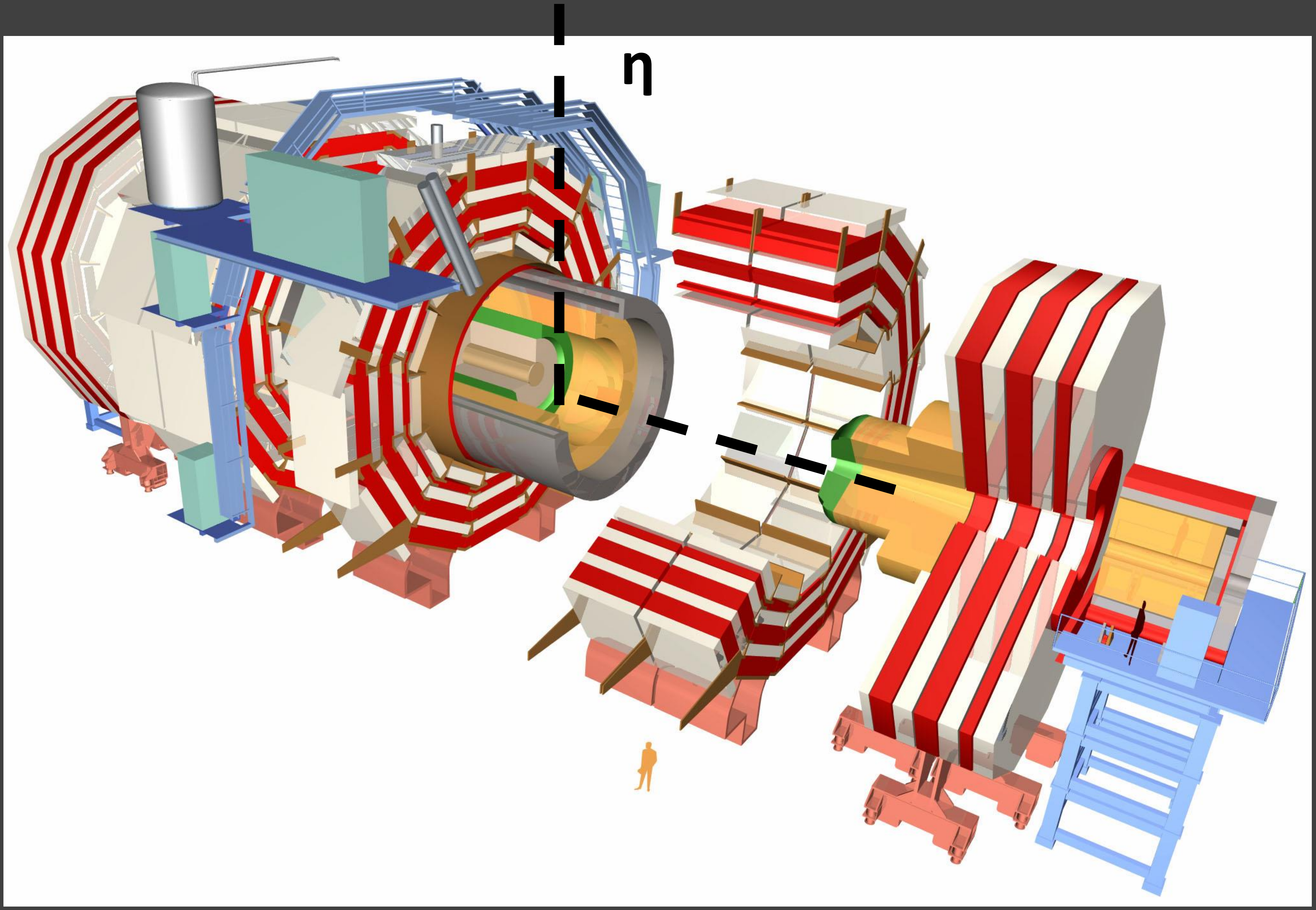
which makes many known and unknown systematic uncertainties cancel

CMS detector

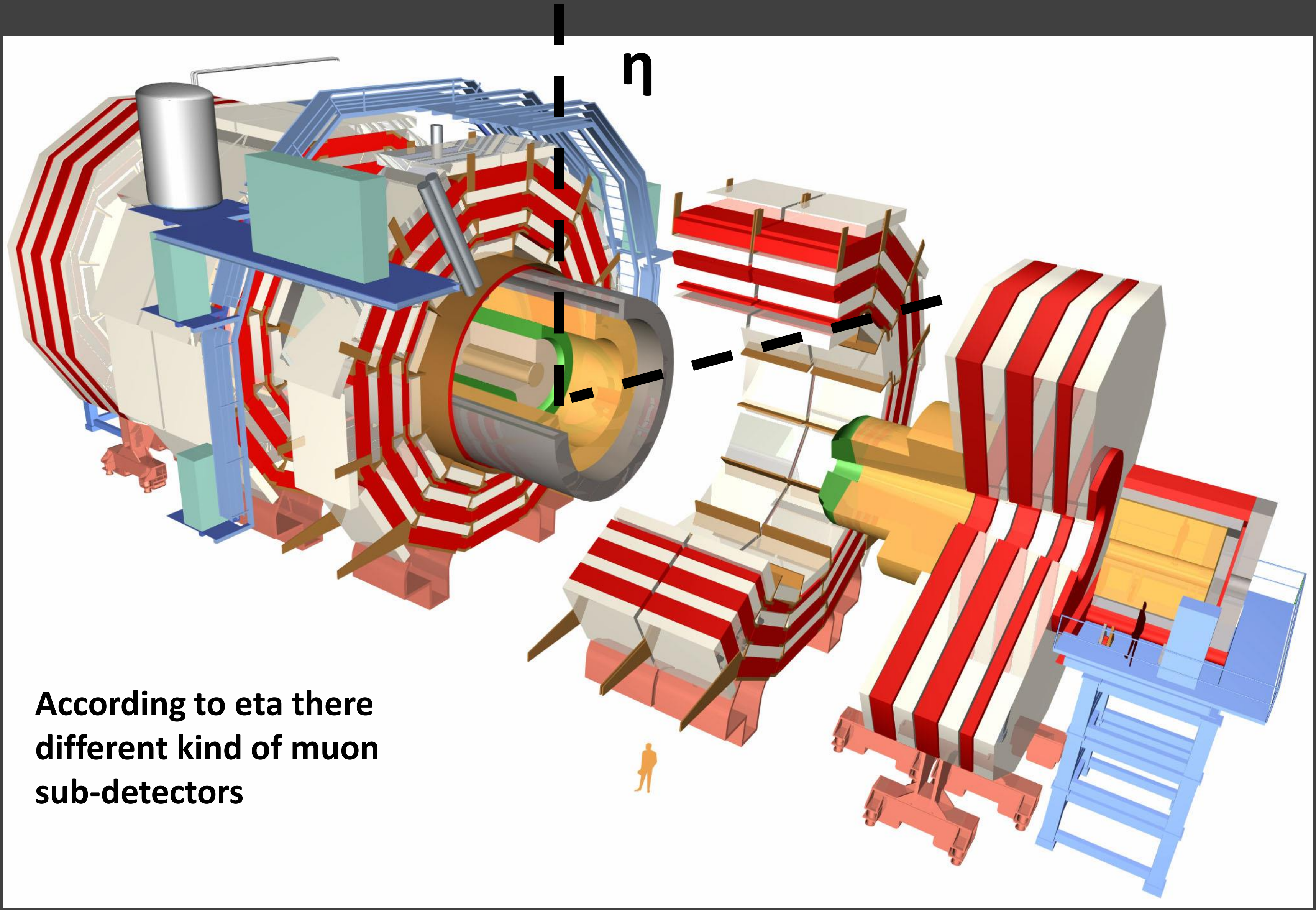


- Tracker
- Electromagnetic calorimeter
- Hadronic calorimeter
- Muon chambers
- Hadronic Forward calorimeter

CMS detector

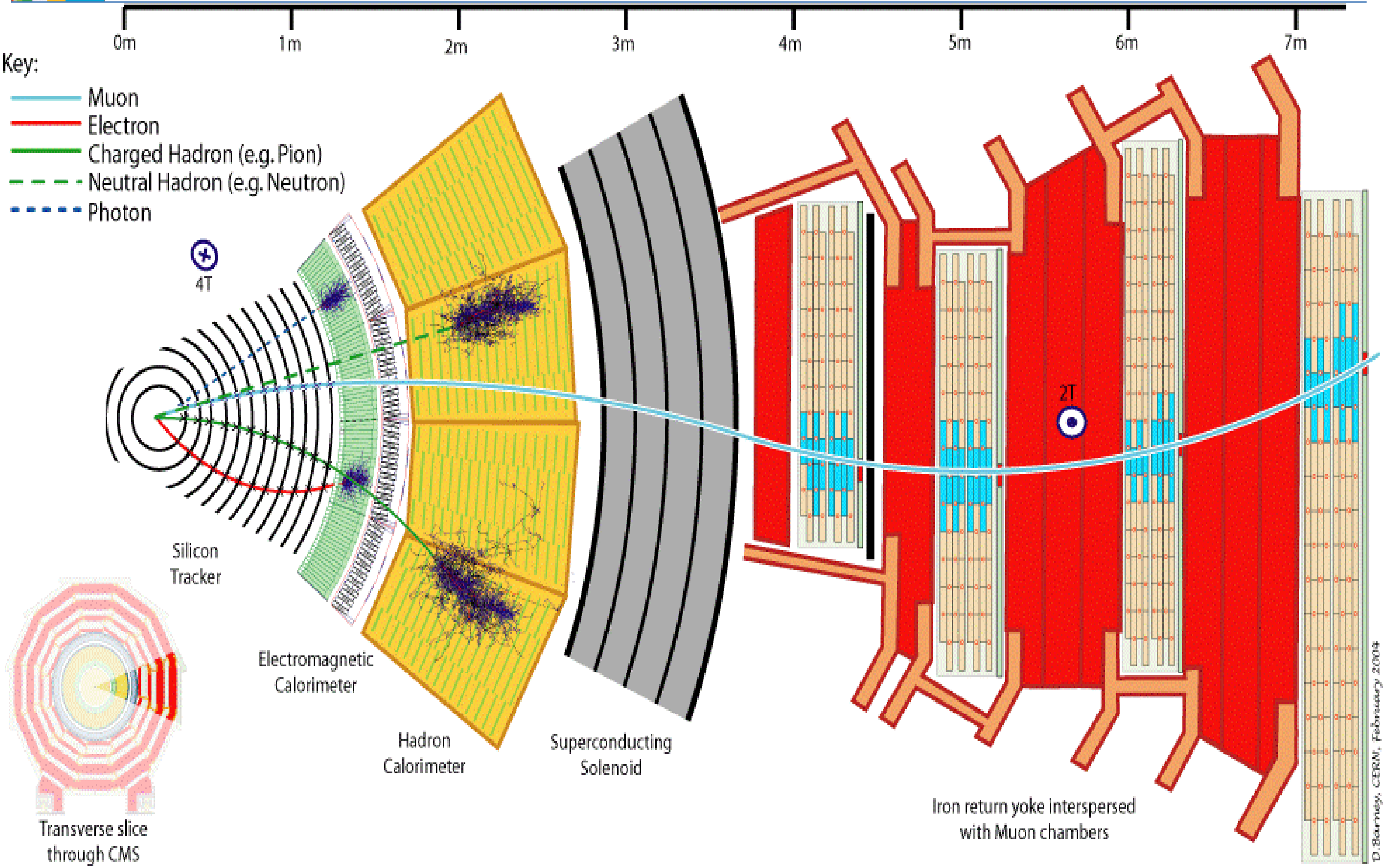


CMS detector



According to eta there different kind of muon sub-detectors

CMS detector



High-pT Muon Reconstruction

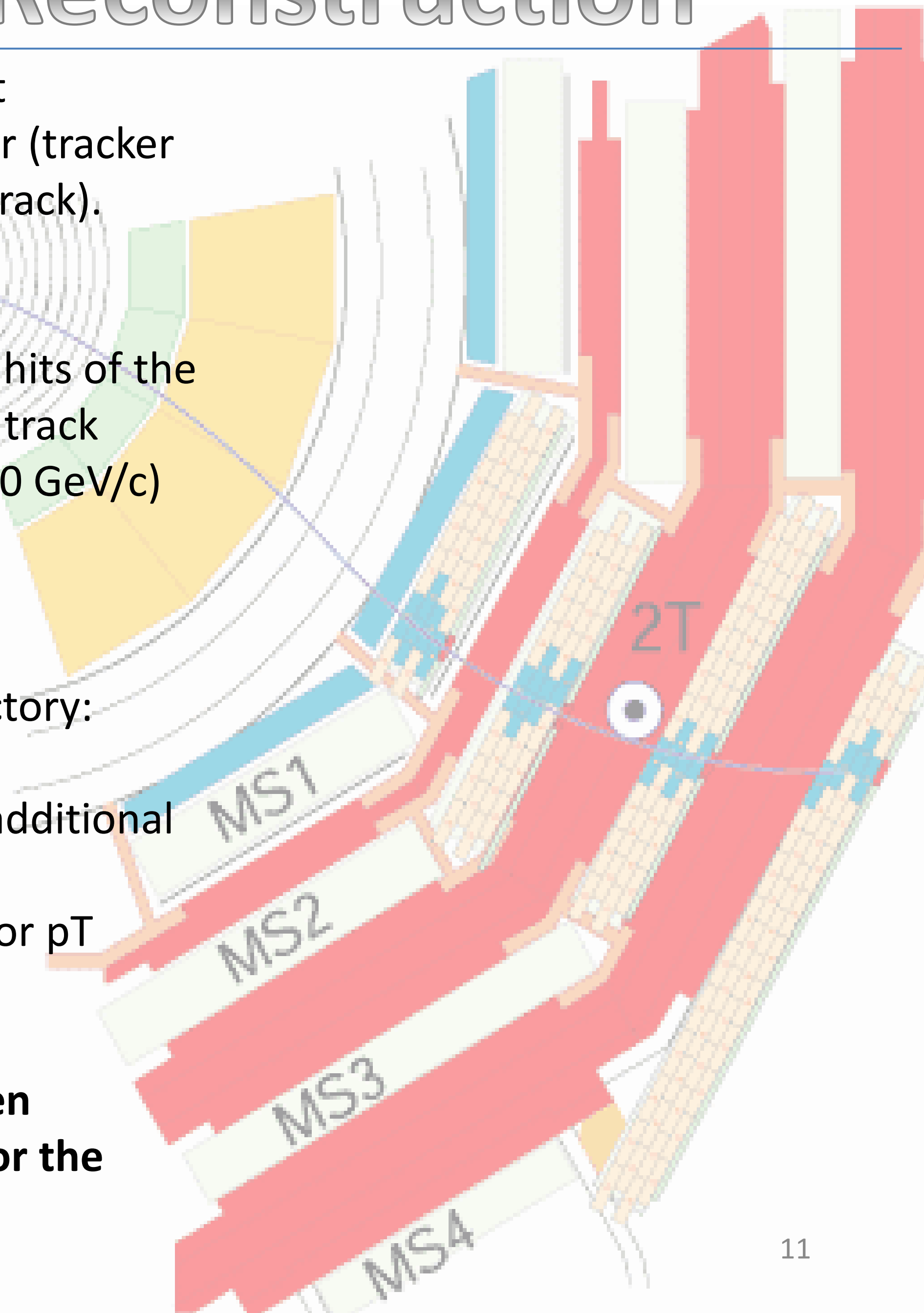
To reconstruct a muon candidate, tracks are first reconstructed independently in the inner tracker (tracker track) and the muon system(standalone-muon track).

Global Muons:
The Kalman-filter technique is used to fit all the hits of the standalone muon tracks and a matched tracker track (improved measurement of muons with pT > 200 GeV/c)

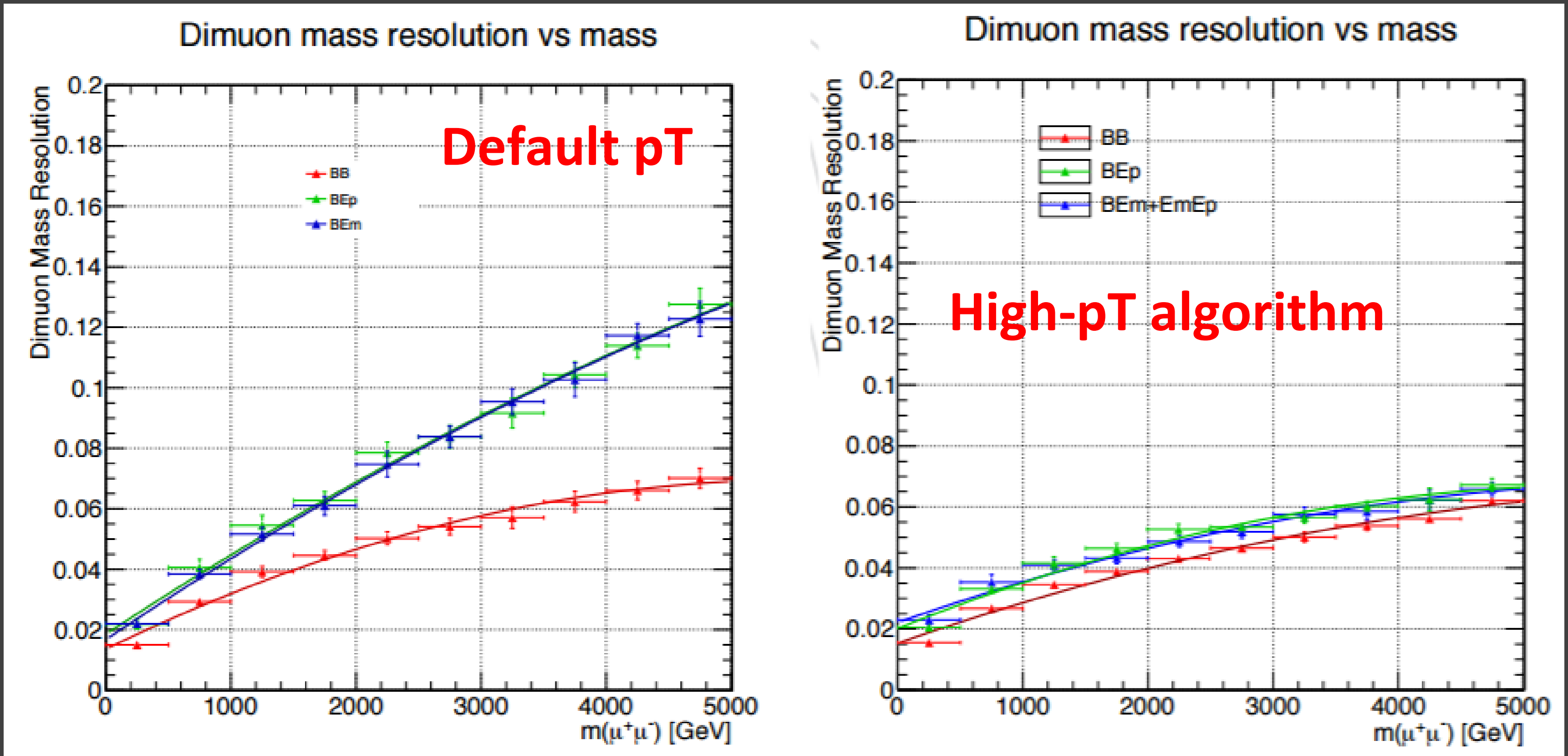
High-pT challenges:

- multiple scattering (minor impact)
- radiative processes can alter the muon trajectory:
  - large energy losses
  - electromagnetic showers giving rise to additional hits in the muon chambers.
- dedicated algorithms have been developed for pT assignment

A good understanding of the alignment between the tracker and the muon chambers is crucial for the Muon momentum resolution



Mass resolution



An accurate measurement of the muon momentum is crucial to achieve the best mass resolution and the highest sensitivity

Event selection

Search for <u>narrow</u> resonance in the dimuon invariant mass distribution above the SM background

<u>Online selection</u>

- at least 1 muon firing the high-pT trigger
- at least 1 muon firing the low-pT trigger (normalization factor at Z peak)

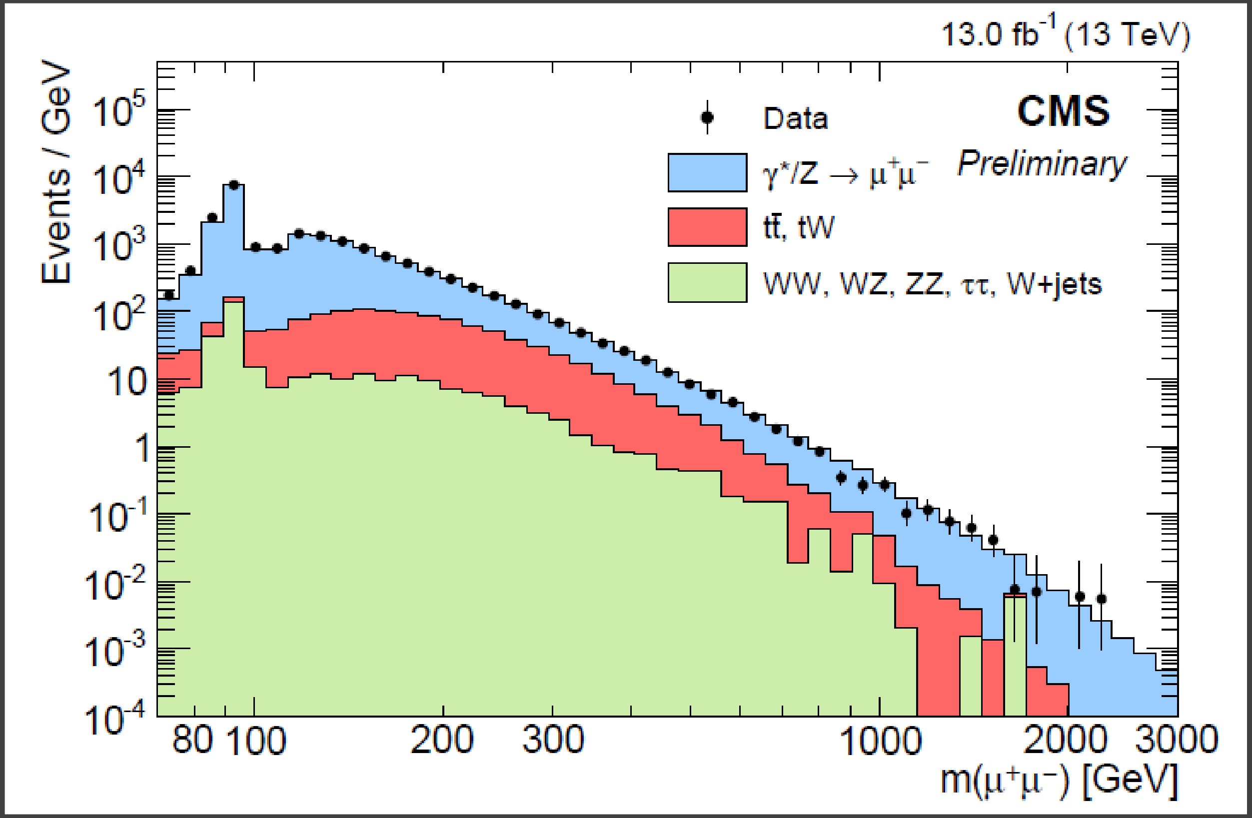
<u>Offline selection</u>

- at least 2 opposite charged muons
- pT > 53 GeV (plateau of trigger turn-on)
- |η| < 2.4 (geometrical acceptance)
- Detector quality cuts
- Isolation(0.3 cone) $\frac{\sum pT}{pT}$ < 10% (measured in the tracker system only)
- Common vertex fit
- 3D angle between the muons < π-0.02 (to suppress muons from cosmic rays)
- If more than one pair is selected the one with highest pT is chosen

<u>3 different categories to isolate detector alignment and calibration effects</u>

<u>better resolution allows to have an higher sensitivity</u>

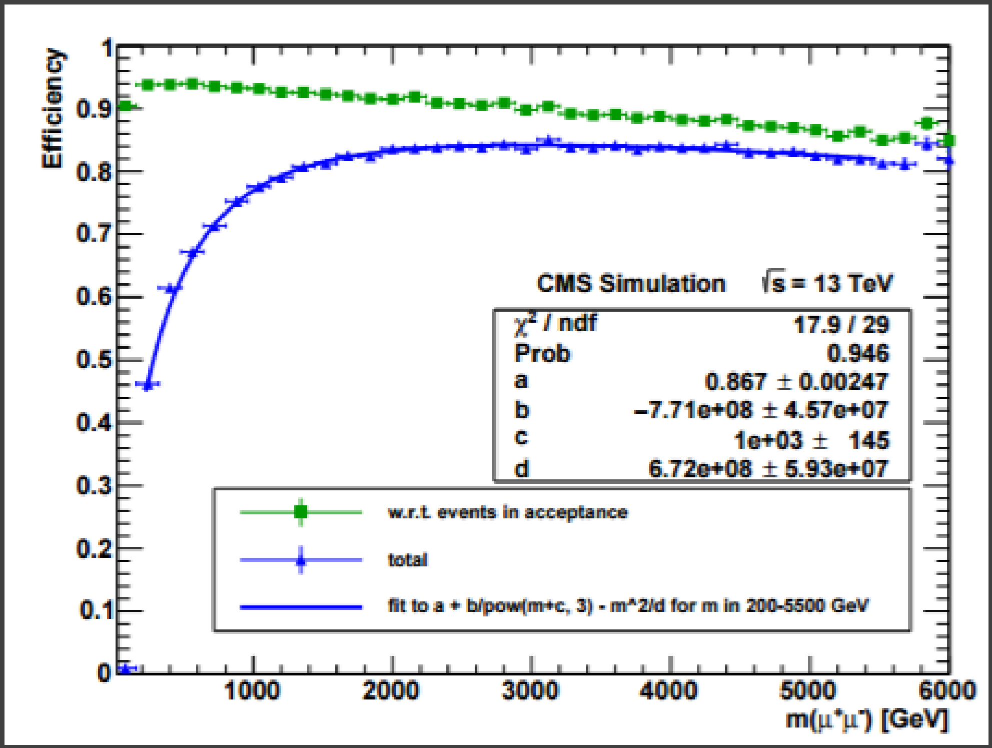
Invariant mass



Background is estimated using MC:

- DY is the main and irreducible (NLO cross section corrected by a k-factor for QCD NNLO effects and other QED NLO effects)
- Prompt leptons from ttbar, tW, dibosond
- Fake leptons from W+jets and QCD

Selection efficiencies



- **Drell-Yan MC samples**
- **Acceptance is defined by**
  - pT > 53 GeV (plateau of trigger turn-on)
  - |η| < 2.4 (geometrical acceptance)
- **Green squares represent the selection efficiency w.r.t the events in the acceptance**
- **Blue triangles represent the acceptance X efficiency**

Blue triangles are fitted (blue curve), and this function is used to describe the Z' acceptance X efficiency in the statistical analysis (all spin-1 particles are expected to behave in the same way).

Statistical analysis

A shape analysis is done using an unbinned likelihood fit:

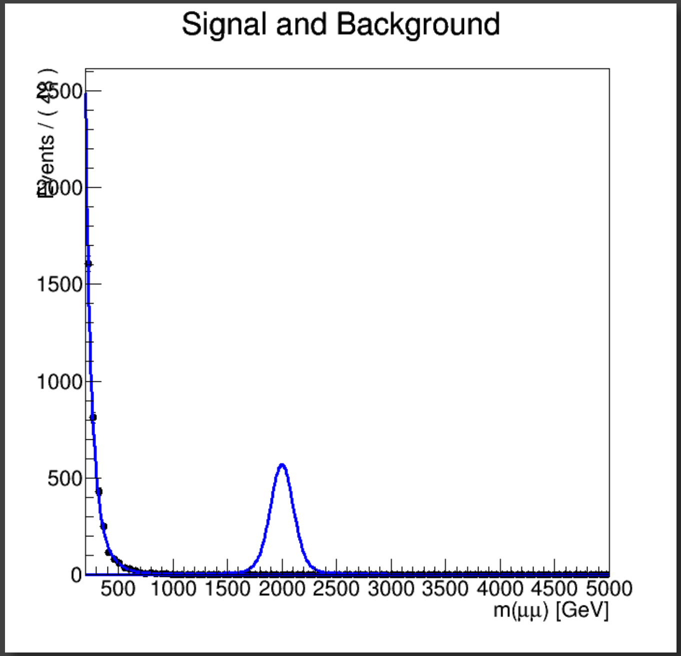
$$\mathcal{L}(x|\theta,\nu) = \frac{\mu^N e^{-\mu}}{N!} \cdot \prod_{i=1}^{N} \left(\frac{\mu_{SIG}(\theta,\nu)}{\mu} f_{SIG}(x_i|\theta,\nu) + \frac{\mu_{BG}(\theta,\nu)}{\mu} f_{BG}(x_i|\theta,\nu) \right),$$

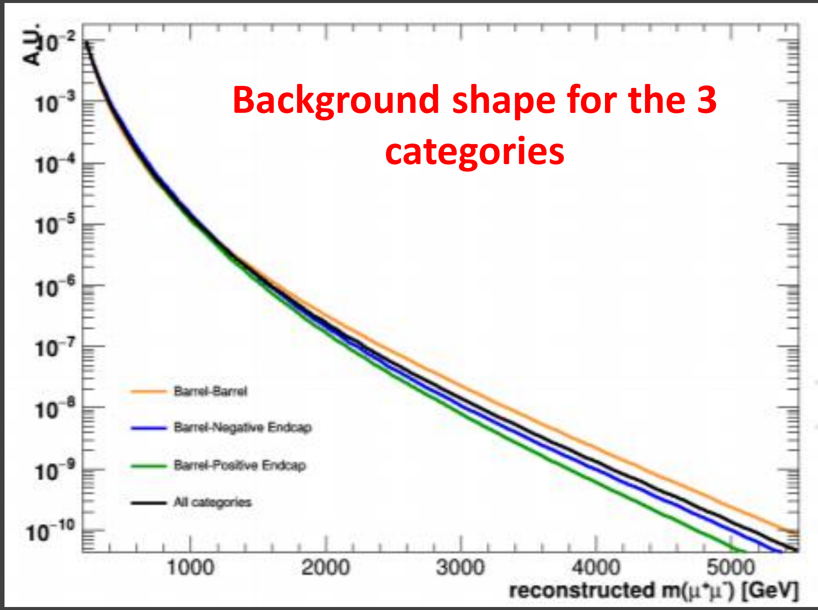
$$f_{SIG}(m|\Gamma,\sigma) = \mathrm{BW}(m|\Gamma) \otimes \mathrm{Gauss}(m|\sigma),$$

$$f_{bkg} = e^{a+b\times m+c\times m^2+d\times m^3} m^e$$

- **Breit-Wigner describes the resonance of mass m and width Γ**
- **The Gaussian accounts for the detector resolution σ**

The background has been estimated by fitting the MC distribution





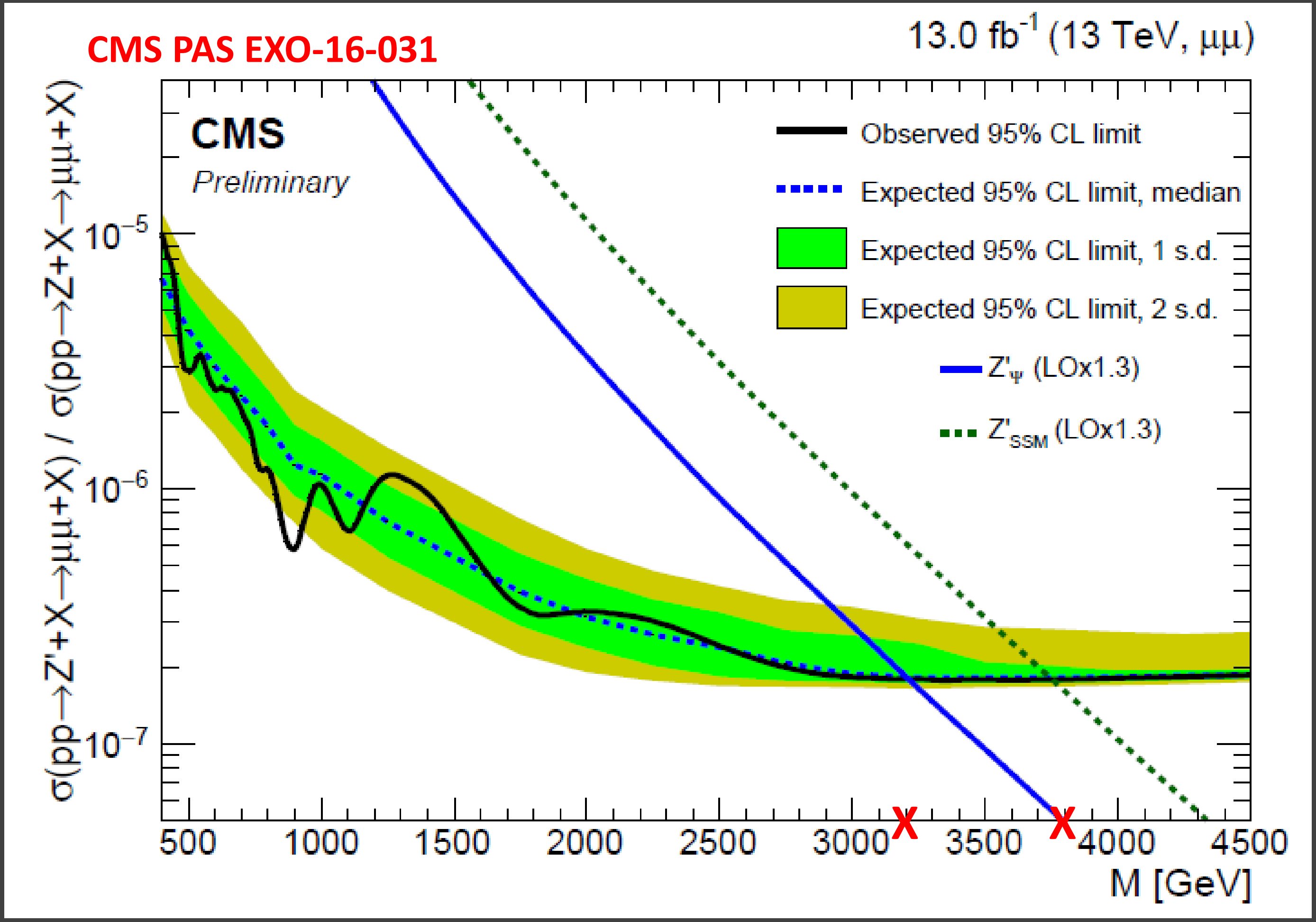
Systematic uncertainties

The limits are calculated in narrow width approximation:

- **Small Breit-Wigner intrinsic width Γ compared to the detector resolution σ**
- **Variations of the width have small impact on the limits**
- **Resolution is taken from MC (5.5%-8.5% according to the categories), a systematic of 20%**
- **The uncertainty on the signal efficiency is mass dependent (1-4% up to 30% according to the categories)**
- **1% of uncertainties is considered for the mass scale**

- **The uncertainty in the background shape is dominated by the statistical uncertainty in the background amplitude (10-50%)**
- **Variation of the background shape has a negligible effect on the limits**

Results for dimuon search

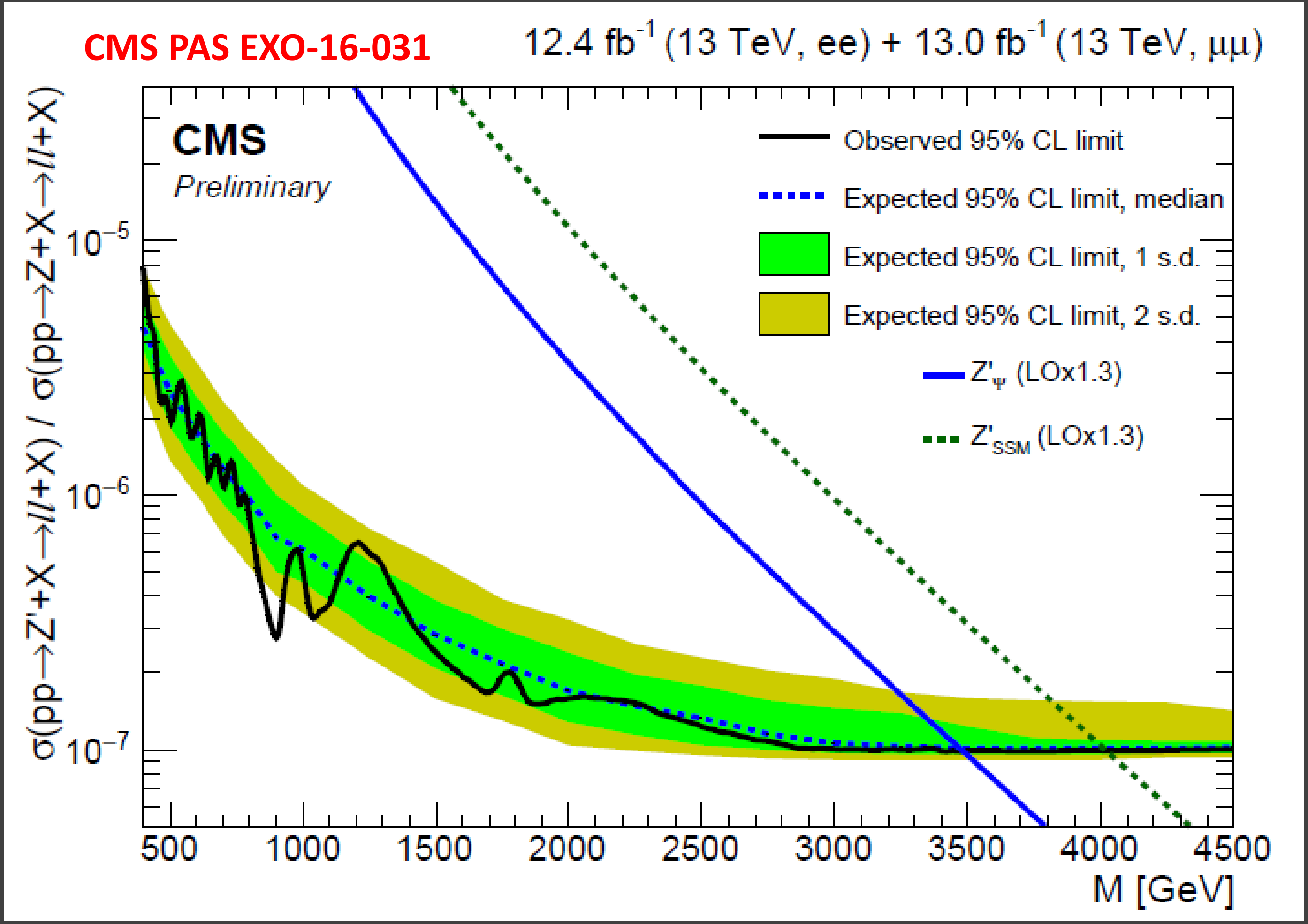


Limits on $R_\sigma = \sigma_{Z'}/\sigma_Z$:

excluded a Sequential Standard Model Z'_{SSM} resonance lighter than 3.8 TeV and superstring-inspired Z'_ψ lighter than 3.2 TeV

Results for dilepton search

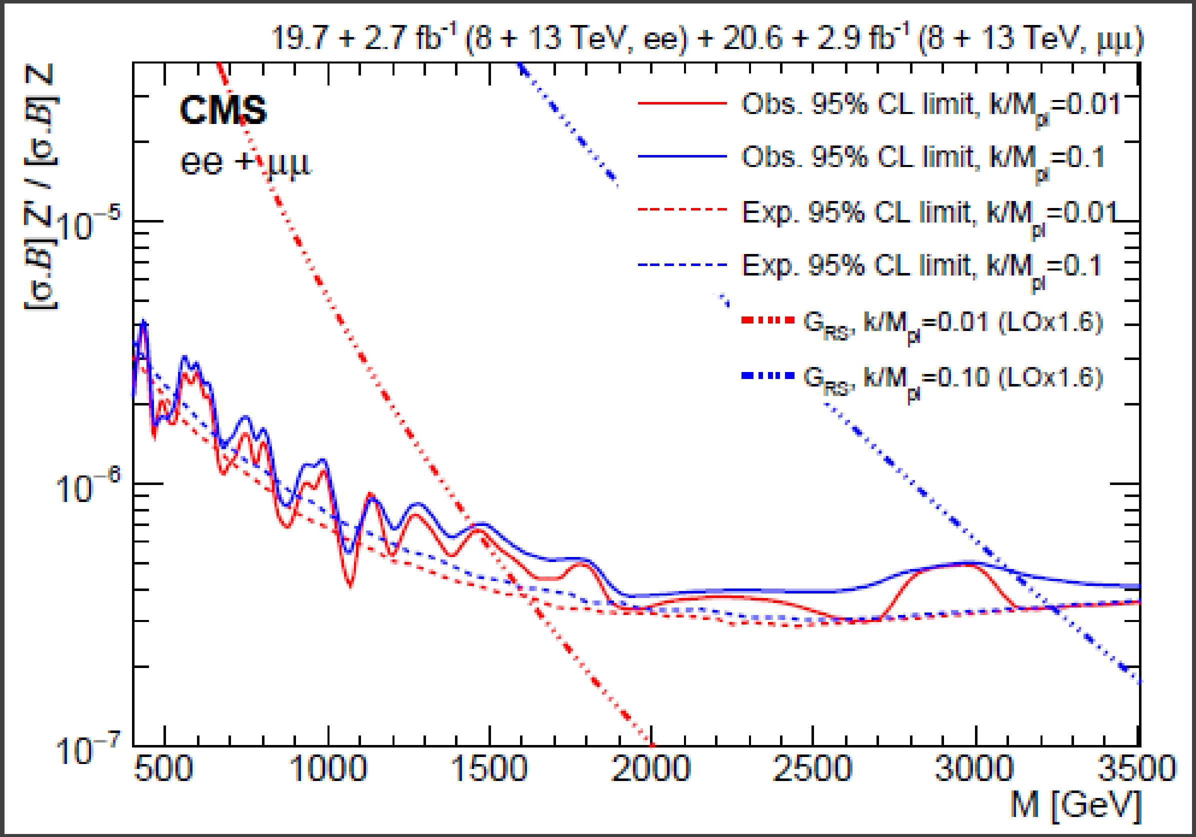
CMS PAS EXO-16-031



More sensitive limits adding also the dielectron channel:
excluded a Sequential Standard Model Z'_{SSM} resonance lighter than 4 TeV and superstring-inspired Z'_ψ lighter than 3.5 TeV

Results for dilepton search

CMS EXP-15-005



Spin-2 interpretation has been performed using the combination of dimuon and dielectron channel @ 8+13 TeV:

excluded a Randall-Sumdrum Model Z'_{RS} resonance lighter than 3.1 (1.5) TeV with k/M_{Pl} = 0.1 (0.01)

Conclusions

- The latest results about the search for a heavy resonance decaying to a pair of muons have been presented
- The results of the combination to the dielectron channel have been also shown
- No signal excess has been found in 13 fb^{-1} of data at 13 TeV
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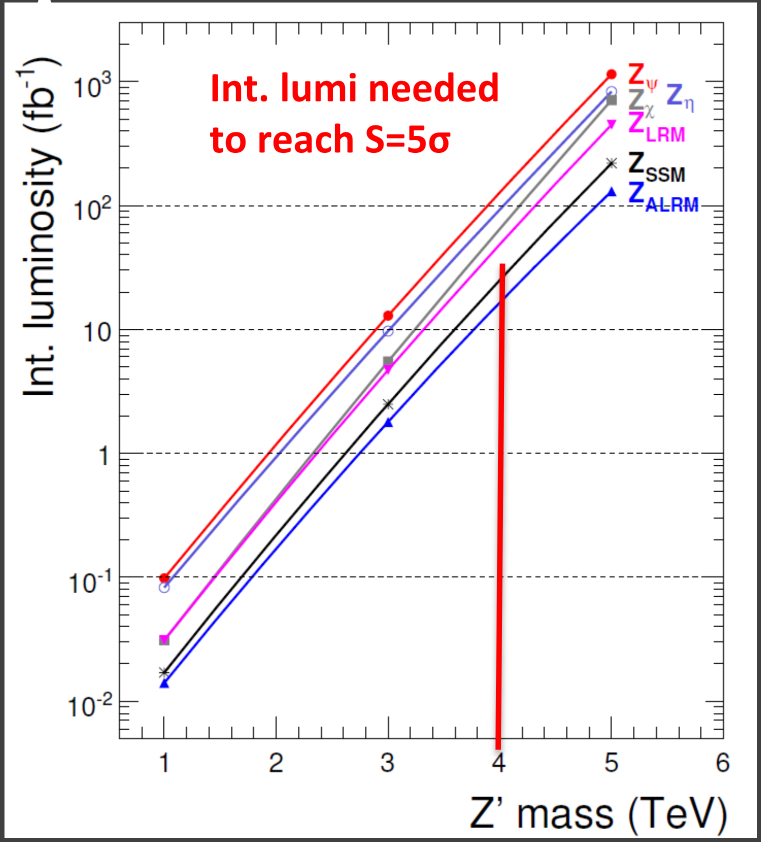

and maybe we need to graduate a lot of students before claiming a discovery, or a few less to start to see something…