CMS Alignment and Calibration

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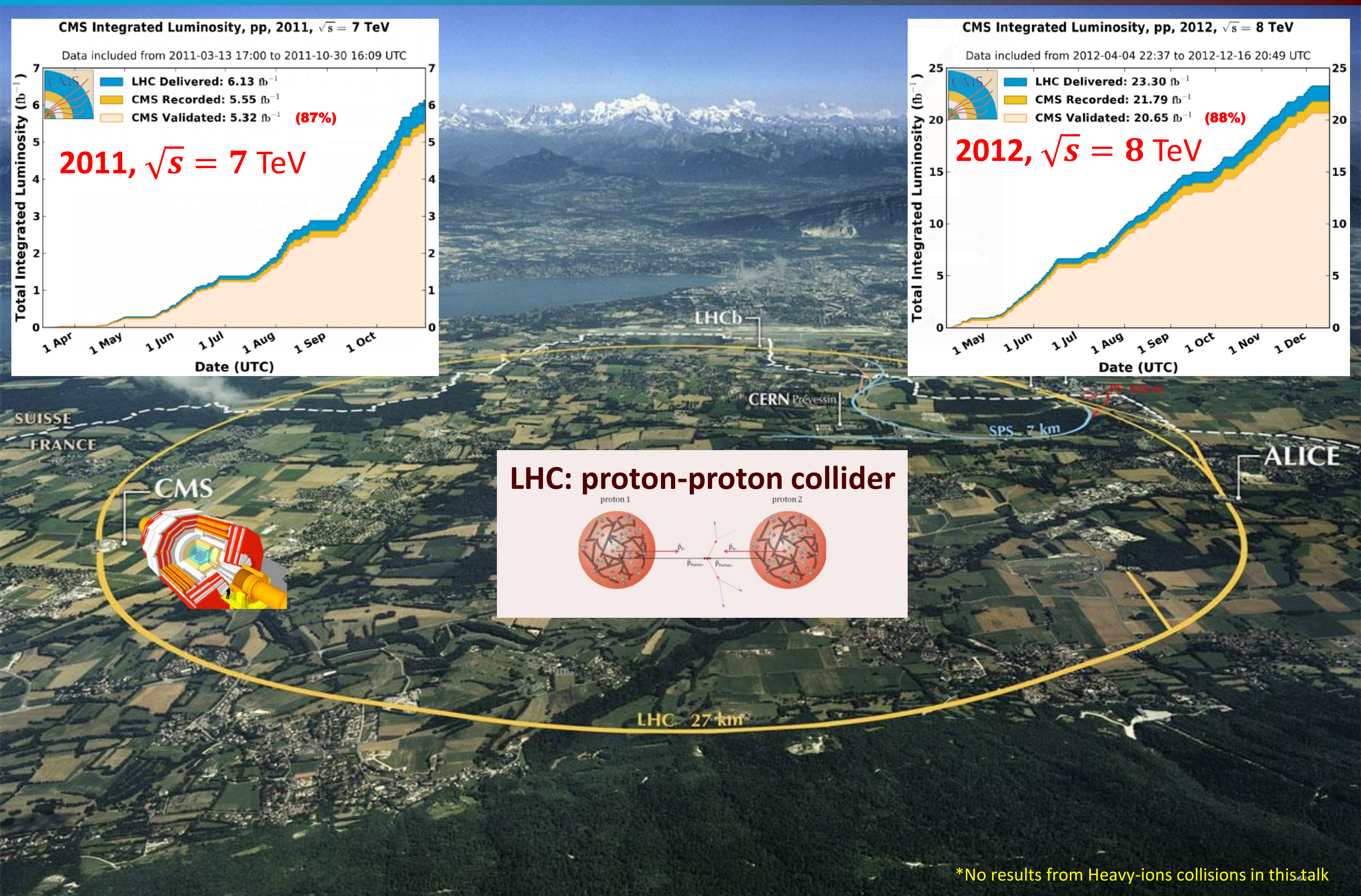
on behalf of CMS Collaboration

The International Conference on Instrumentation for Colliding Beam Physics **(INSTR 2014)**

February 24 — March 1, 2014
BINP, Novosibirsk, Russia

CMS Detector at LHC



*No results from Heavy-ions collisions in this talk

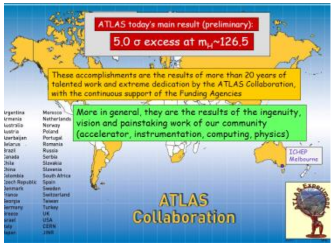
Higgs Boson: from original idea to observation

✓ Higgs boson observation: July 4th, 2012

- Reports from CMS and ATLAS on special event at CERN
- http://indico.cern.ch/conferenceDisplay.py?confId=197461

In summary

We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !



✓ It took almost 50 years to find Higgs

VOLUME 13, NUMBER 9 — PHYSICAL REVIEW LETTERS — 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

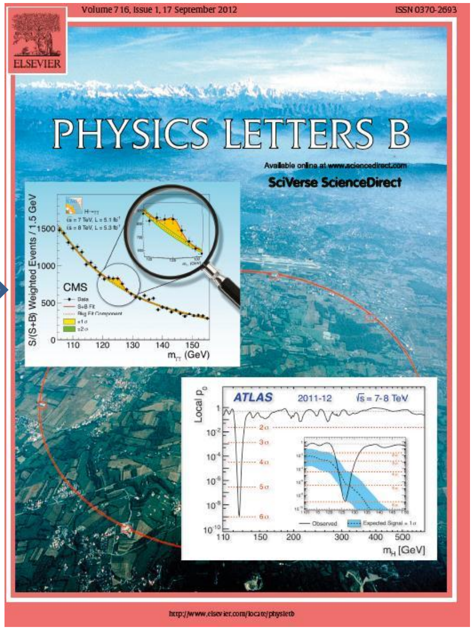
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

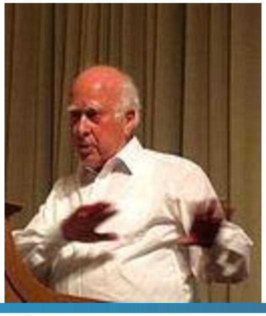
VOLUME 13, NUMBER 20 — PHYSICAL REVIEW LETTERS — 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

1964 → 2012





Detector Calibration and Alignment

- ✓ No discoveries possible without perfectly working detector
- ✓ Smooth road to the discoveries essentially depends on calibration and alignment of the detector sub-systems internally and with respect to each other

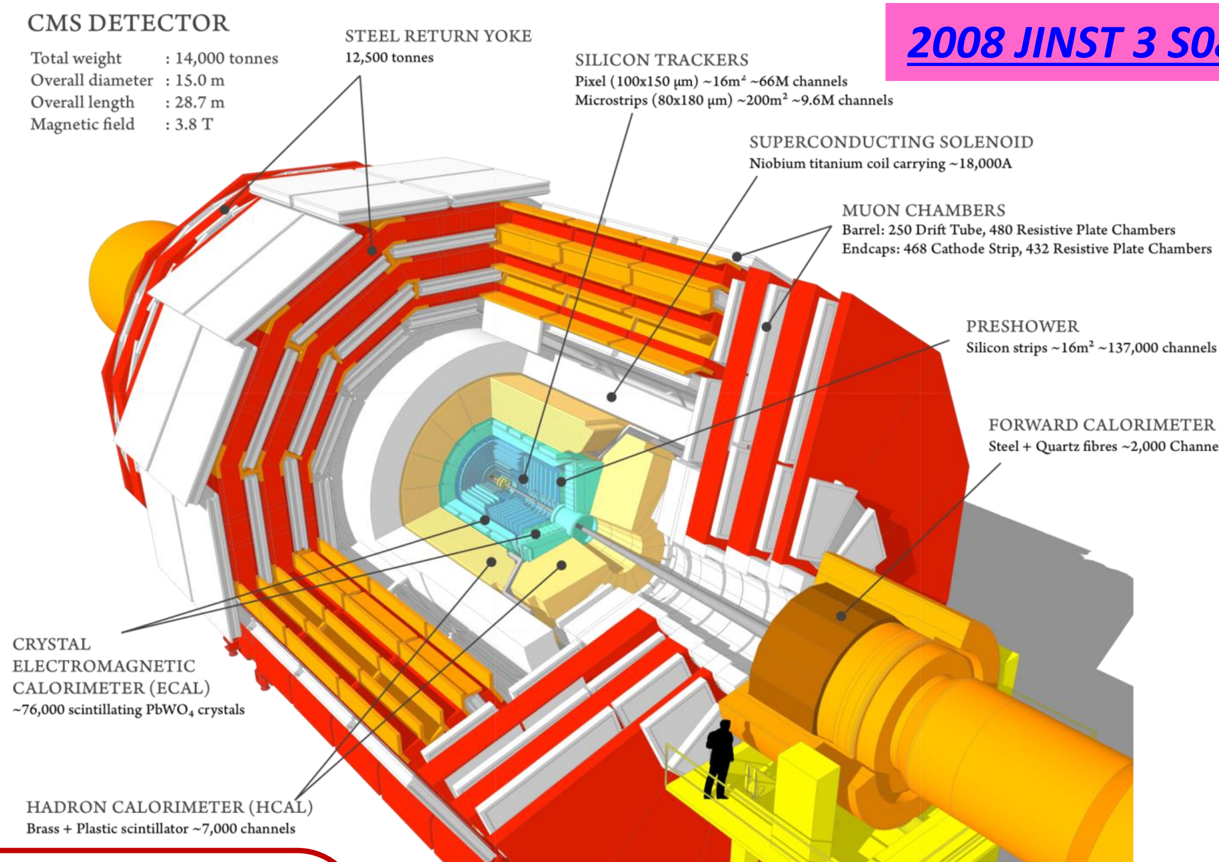
Sorry, not today

In spotlight of this talk!

CMS Detector “Onion” Structure

Total weight: 12,500 t
Diameter: 15 m
Overall Length: 22 m
Magnetic field: 4 Tesla

2008 JINST 3 S08004



CMS is a complex detector:

- Largest silicon tracker (~76M channels)
- Homogeneous ECAL (76k crystalls)
- Multilayers muon system (25k m^2)
- Largest superconducting magnet (B=4 T)

Muon system:

- momentum resolution: $\left.\frac{\delta p_T}{p_T}\right|_{25\,GeV} \sim 1\%$
- acceptance $|\eta| < 2.4$

Calorimetry:

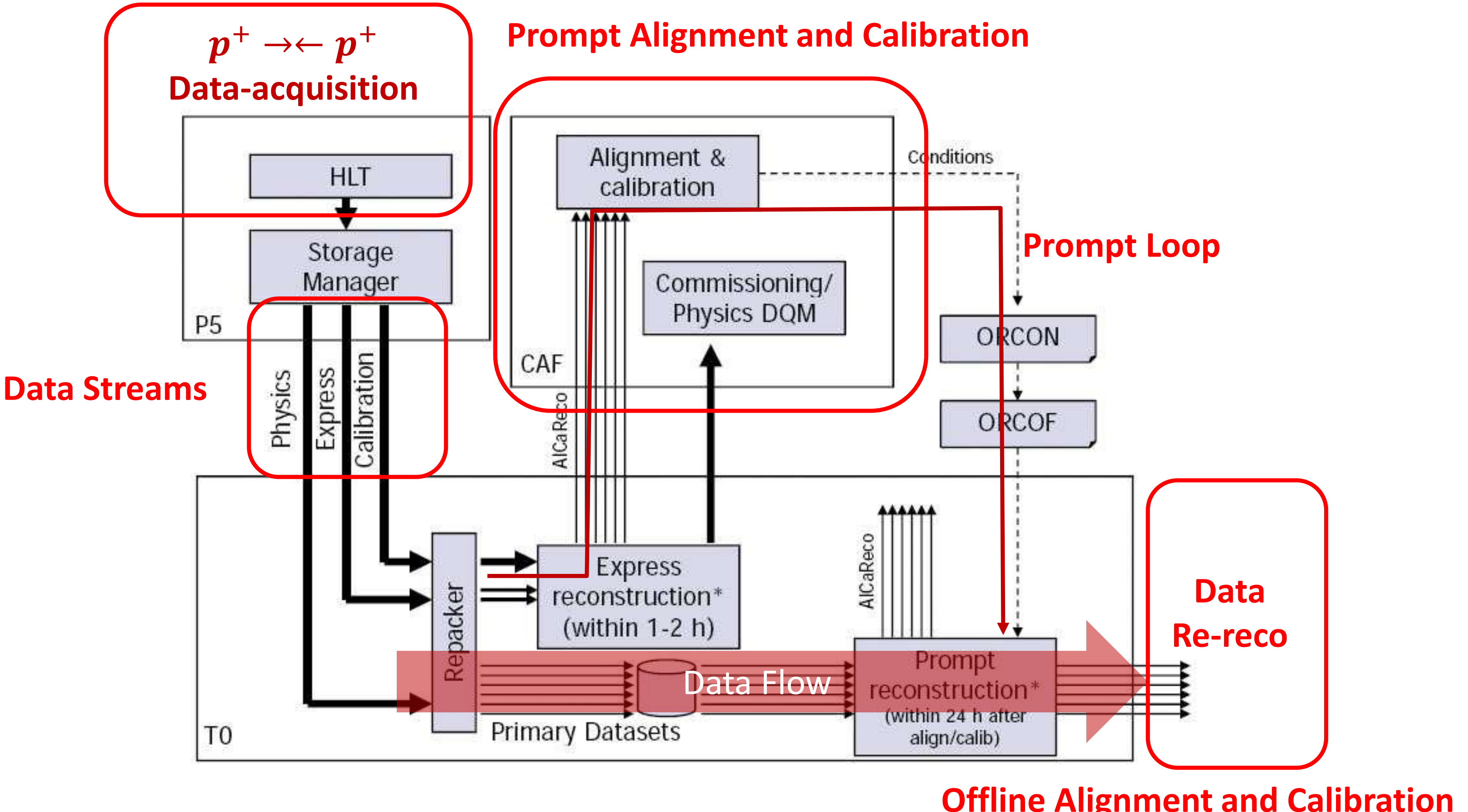
- Hadron |η|<5.0, δE/E ~ 100% / √E + 5%
- Electromagnetic |η|<3.0, δE/E ~ 2.8% / √E + 0.3%

Alignment and Calibration Strategy

- ✓ Searches for new physics demand excellent knowledge of detector in terms of resolution
- ✓ Near-detector calibration constants (pedestals, gains, etc.) are determined online
- ✓ Rapidly changing detector conditions derived synchronously with data-taking and promptly used in first processing of data
  - derived within ~24-48 hours after data collection
  - important for fast physics analyses
- ✓ Stable and improved conditions determined with state-of-the-art event-based alignment algorithms utilizing data sample accumulated over a longer range of time and used for data re-processing
  - usually derived within ~1 month after data collection
  - internal dependencies between alignment and calibration of different subsystems are accounted
- ✓ Large data rate requires robust computing framework to handle alignment and calibration workflows utilizing special data formats to reduce bandwidth and disk space (AlCaReco)

Alignment and Calibration Workflow

✓ Two main alignment and calibration frames: prompt and offline



Prompt Alignment and Calibration

✓ Low latency workflows run immediately after the data-taking:

- Beam-spot position: measured frequently (every Luminosity Section)
- ECAL response corrections: frequently measured with laser pulses

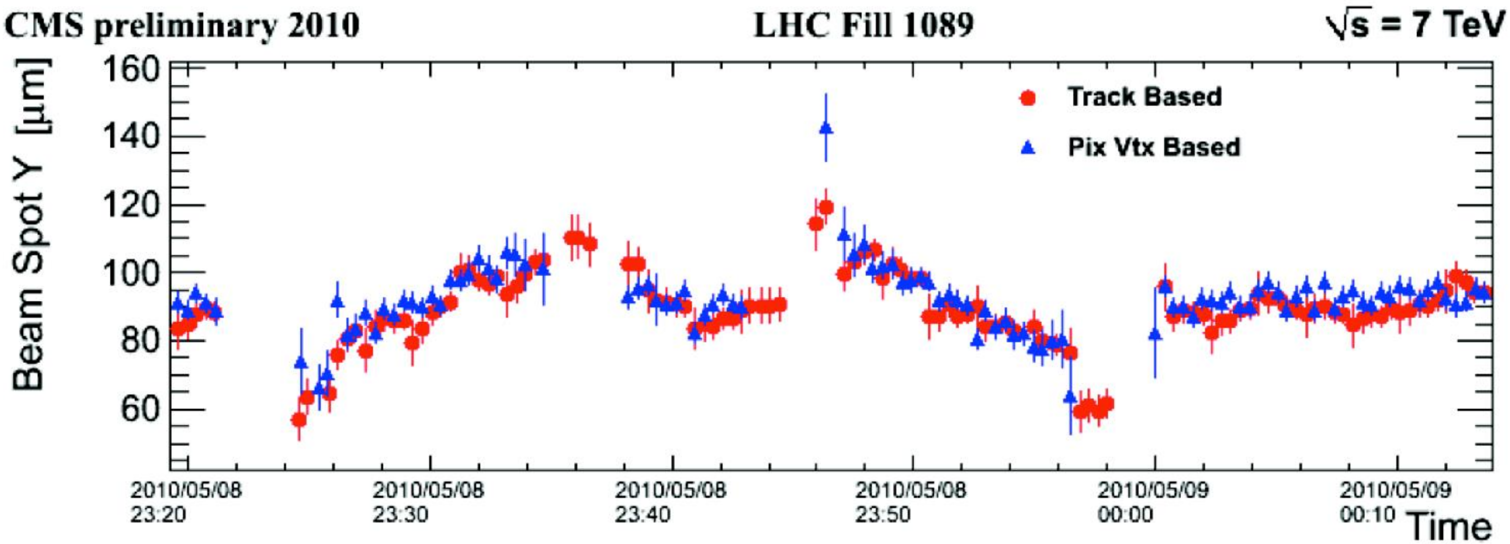
✓ Monitor conditions (update if necessary):

- Tracker problematic channels: HV trips/noise
- Calorimeter problematic channels: mask hot channels
- Pixel alignment: monitor movements of large structures using tracks

✓ Use delay between express and prompt reconstruction to include derived conditions in first data processing

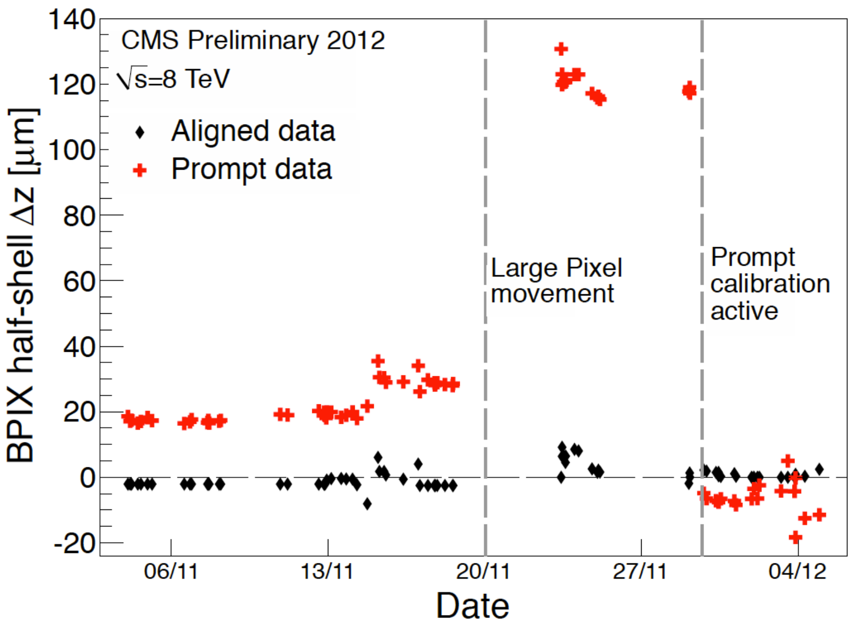
Calibrate Beam-spot Position

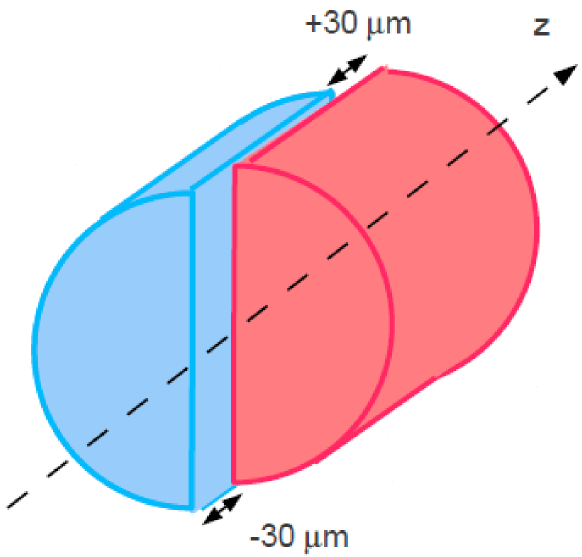
- ✓ A value is measured every Luminosity Section (23 s)
  - use tracks from express stream
- ✓ Position of the beam-spot in transverse plain (x, y) and slopes determined from fit using reconstructed minimum bias tracks
- ✓ Beam width (σ_x and σ_y), length (σ_z) and position (z) come from fit to primary vertices
- ✓ The calibration strongly dependent on alignment of Pixel detector
  - Beam-spot is recomputed offline every time Pixel alignment is updated



Monitor Movements of Pixel Large Structures

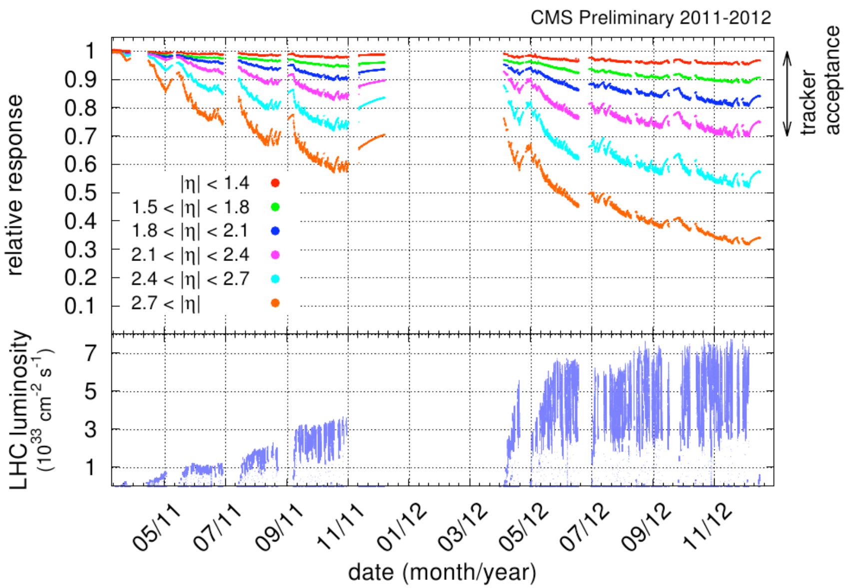
- ✓ Cylindrically symmetrical Pixel detector is physically separated into two half barrels
- ✓ Corrections for relative displacements along z between the barrels are time-dependent
- ✓ Monitor longitudinal separation (within mechanical tolerance) using unbiased track-to-vertex residuals
  - done for every run ($\sim 20k$ events) using express strem
- ✓ Time dependence of pixel structure alignment accounts for separation as a function of time
  - b-tagging algorithms insensitive to remaining 10 μm effect

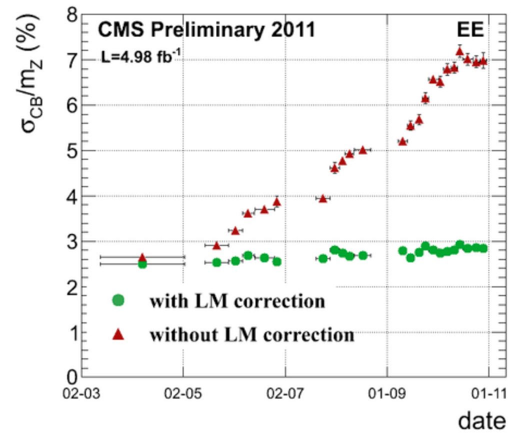




Monitoring the ECAL Response

- ✓ ECAL $PbWO_4$ crystals temporary change transparency due to irradiation
  - less significant in barrel, more pronounced in endcaps (where photo-detectors get conditioned by strong irradiation)
- ✓ Damage/recovery cycles monitored by laser pulses (447 nm, 100 Hz in LHC abort gaps) and photo-detectors measuring the response variation to the laser light
  - continuous monitoring, the whole ECAL measured in 40 min
  - use dedicated stream at trigger
- ✓ Corrections derived within 48 h and applied to prompt reconstruction

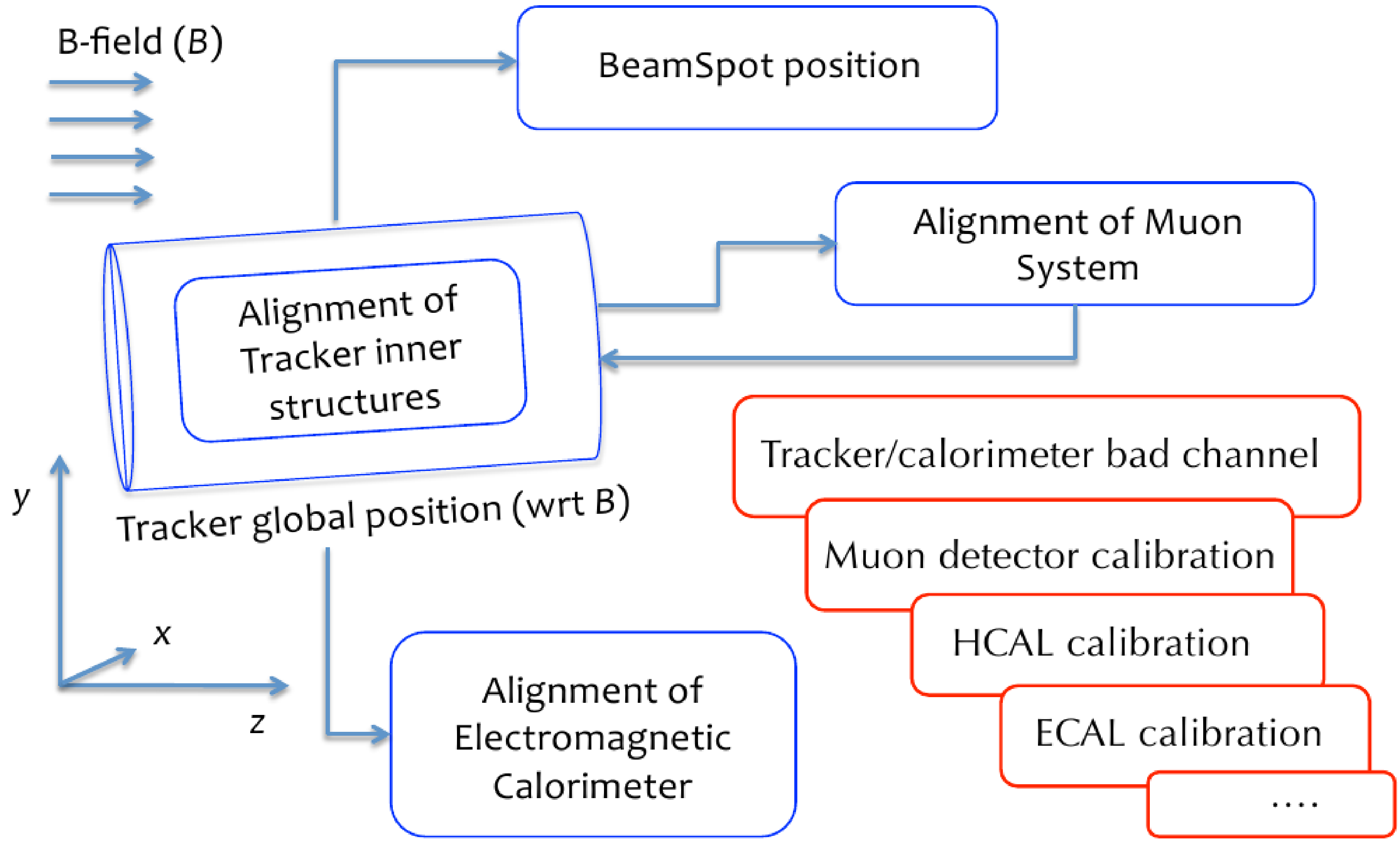




Stable $Z \rightarrow ee$ mass resolution

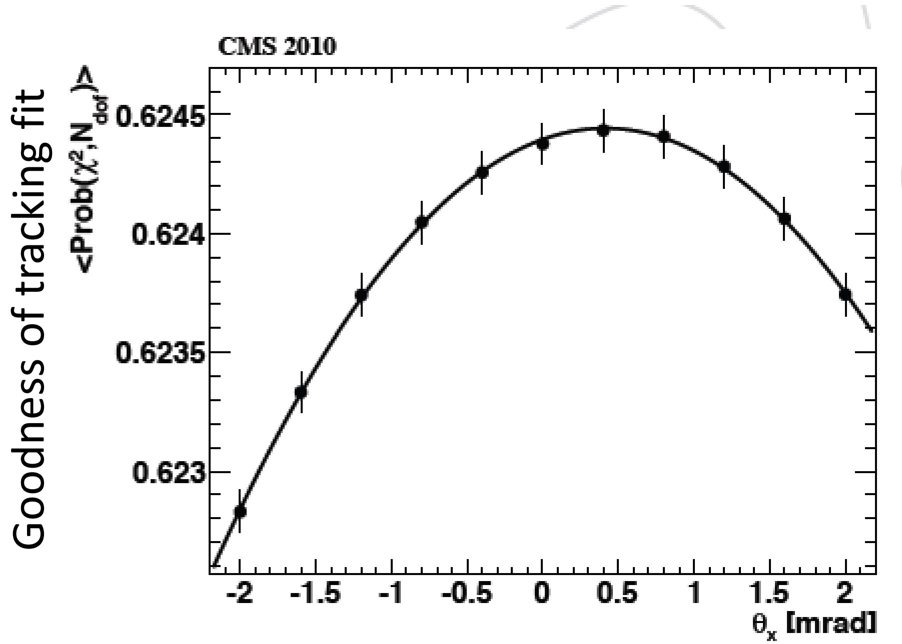
Offline Alignment and Calibration

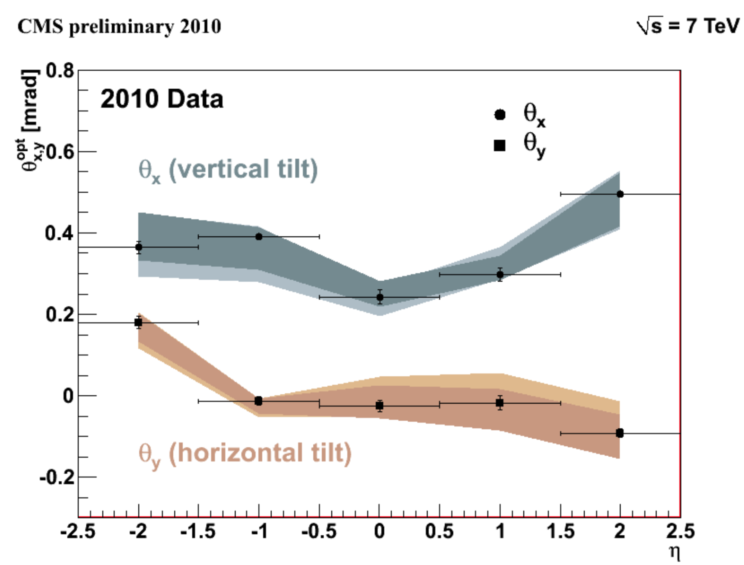
✓ All subsystems are aligned and calibrated offline



Tracker Orientation w.r.t. $\vec{B}$-field

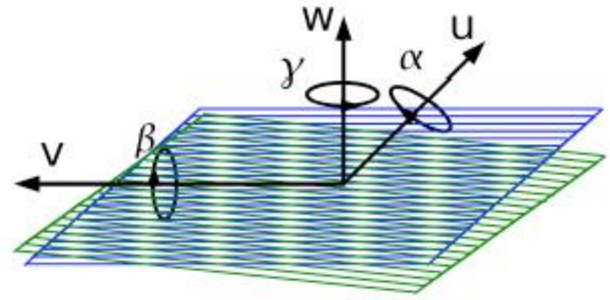
- ✓ Tilts of the Tracker relative to magnetic field (flux along global z) could result in biases of the reconstructed track parameters
  - need to be corrected
- ✓ The global Tracker orientation is described by the angles θ_x and θ_y that correspond to rotation around global x and y axis of the CMS
- ✓ Goodness of track fit scans for various tilt angles
  - $\theta_y \sim 0$ mrad, $\theta_x \sim 0.3$ mrad

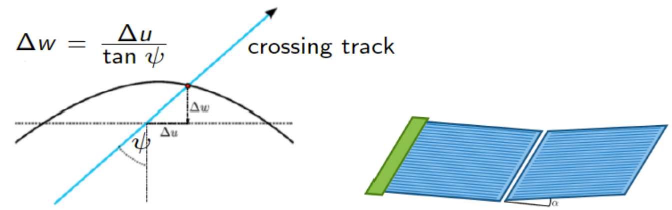




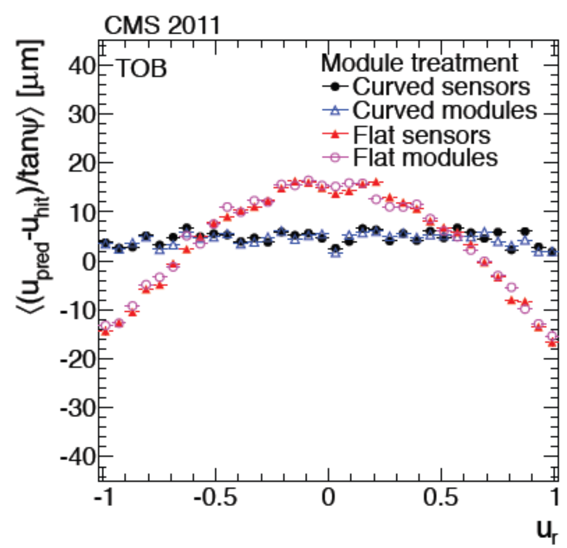
Tracker Alignment with Tracks

- ✓ The track-based alignment with MillePedeII minimization algorithm expected to provide $< 10\ \mu m$ precision
- ✓ The CMS Tracker is a complex system:
  - 24k sensors in total
  - $O(200k)$ free parameters per sensor (a sensor depends on other sensors)
    - 5(6) rigid body + 3 bow parameters for each sensor
- ✓ Example: the 2011 alignment campaign with 1 fb^{-1} o reconstructed data
  - inputs: 15M loosely selected isolated muon tracks
  - 3M low momentum tracks
  - 3.6M cosmic ray tracks
  - 375k muon track pairs from Z
  - Z-mass measurement as a constraint
  - Fitting sensor bows and kinks
  - Time dependent (9 intervals) rigid body alignment for large pixel structures
- ✓ Enormous computing task!
- ✓ Precision estimated from the RMS of the Distribution of the Medians of the Residuals for each module
  - more robust against Multiple Scattering



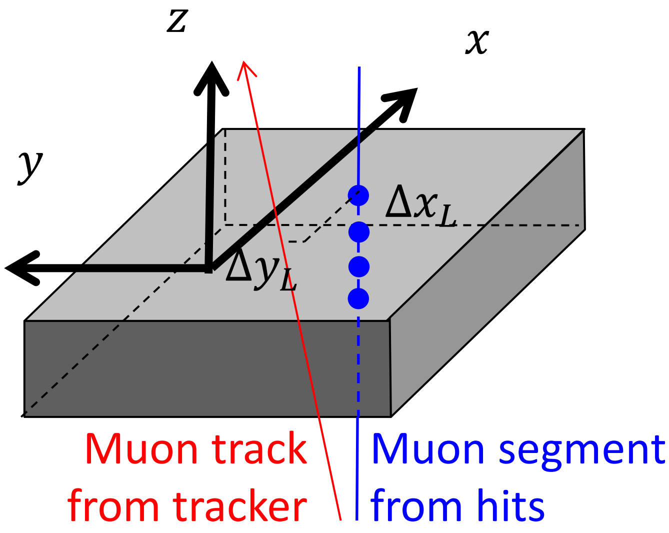


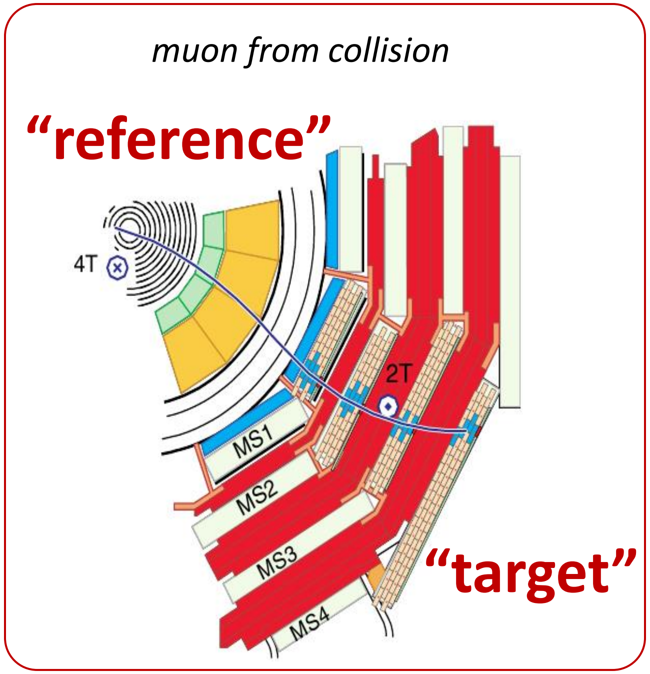
Visualization of bows and kinks

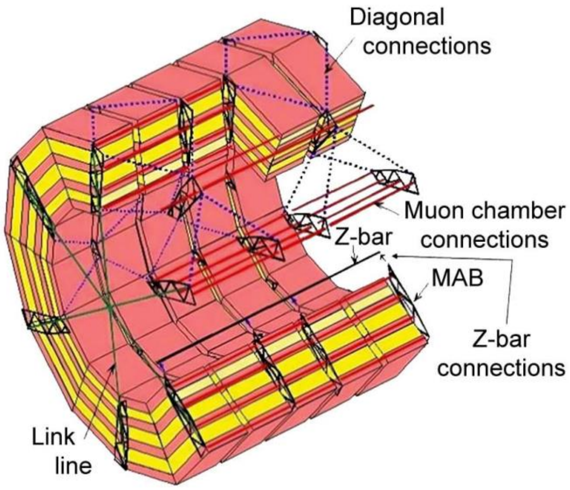


Muon System Alignment

- ✓ **Hardware based**: measures positions of all chambers with respect to a floating network of rigid reference structures (σ_x and $\sigma_y \sim 1$ mm)
  - provides physically bound constraints on track-based alignment
- ✓ **Track based**: minimizing the residuals which are the differences between measured (with segments) and predicted (propagated from Tracker) position of the muon in the chamber ($\sigma_{R\phi} \sim 100 - 150\ \mu$m)
  - **more details in poster session**
- ✓ Combination (and comparison) of the methods

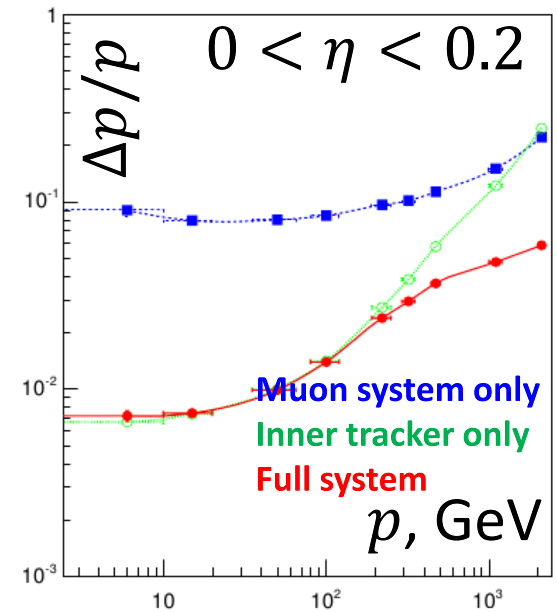






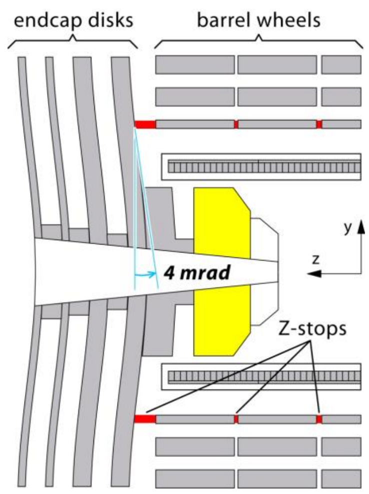
Why the Muon Alignment Important?

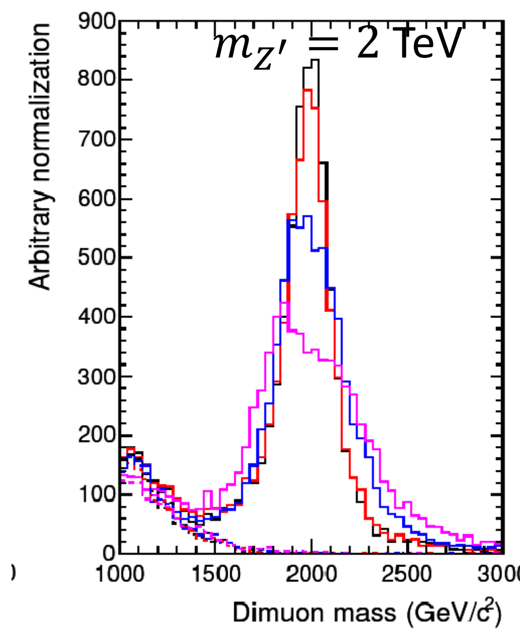
- ✓ Beyond 200 GeV, the muon system can contribute significantly to overall momentum resolution due to large lever arm
- ✓ Precise muon alignment becomes essential for searches with high p_T muons (e.g., $Z' \to \mu\mu$)



Why the Muon System Misaligned?

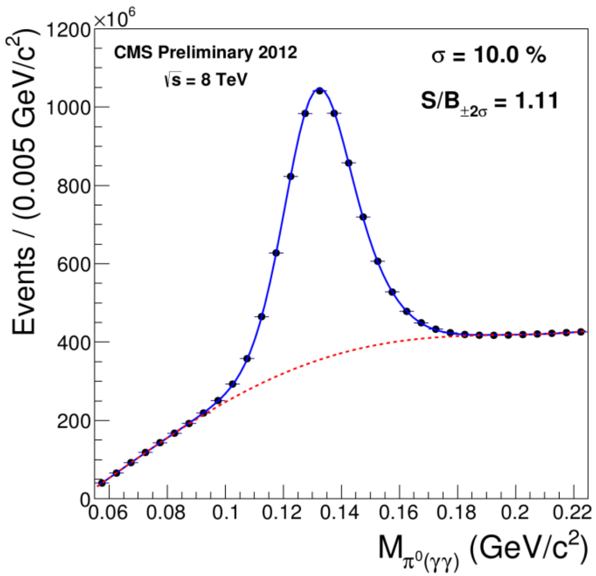
- Deformations due to gravity force (~10 mm)
- Barrel shrinks & endcaps bend due to magnetic force (~10 mm)
- Repositioning after detector open/close operations (~1 mm)
- Imperfect positioning during installation (sub-mm)
- Temperature effects (sub-mm)

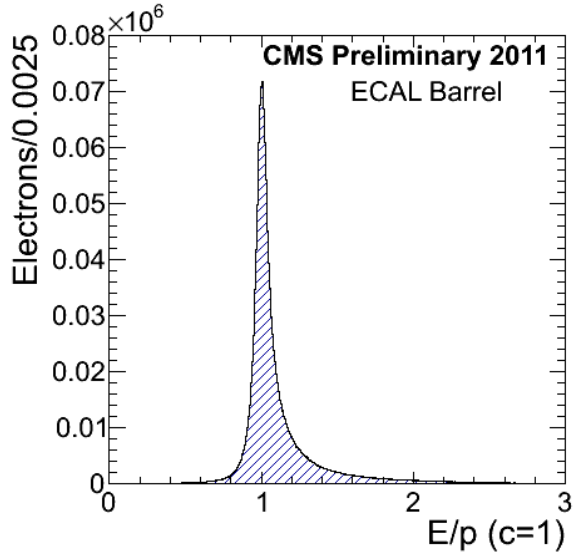


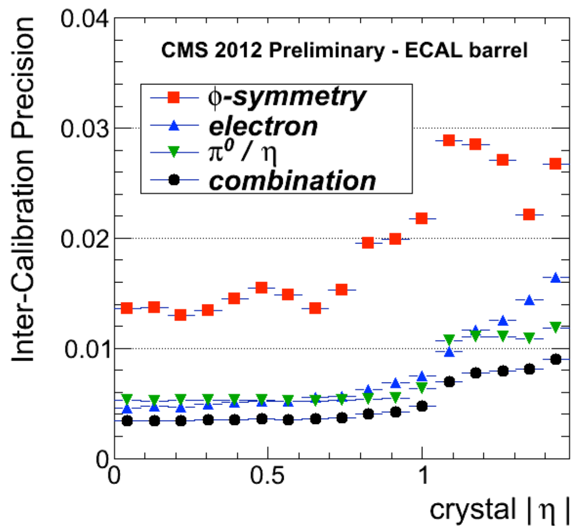


Offline ECAL Calibration

- ✓ Inter-calibration of crystals located within the same η ring:
  1. ϕ-symmetry of the energy flow trough the ECAL crystal (~3-4 days)
  2. $\pi^0/\eta \to \gamma\gamma$ invariant mass peak (~1.5 months)
  3. $E_{ECAL}/p_{tracker}$: high energy electrons from $W \to e\nu_e$ and $Z \to ee$ decays (once in a year)
- ✓ Key feature: dedicated streams at HLT with reduced event content
  - ~1.5 kHz of ZeroBias events for ϕ-symmetry and a total of ~7 kHz for π^0/η
- ✓ Combination: weighted average of the 3 methods
- ✓ The calibration determines energy scale and resolution



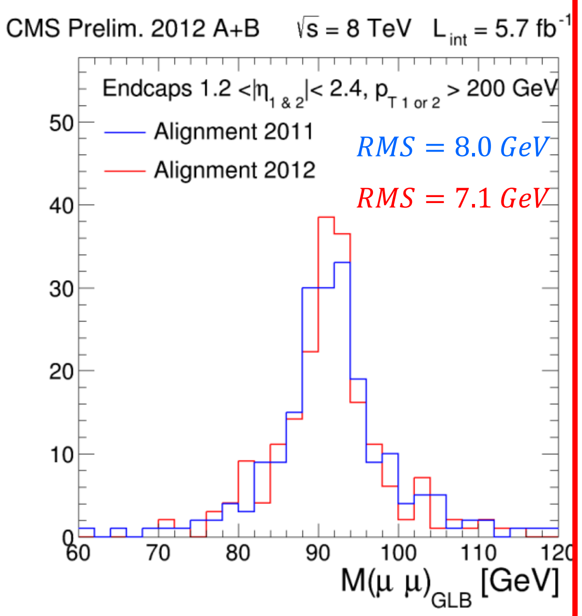




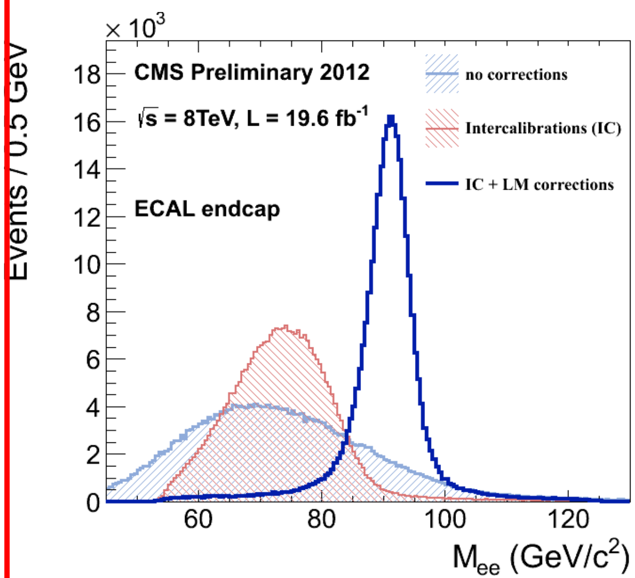
Validation

- All offline alignment and calibration constants are thoroughly validated before injection for data reprocessing
  - "standard candle" process $Z \rightarrow ee/\mu\mu$ used by many system

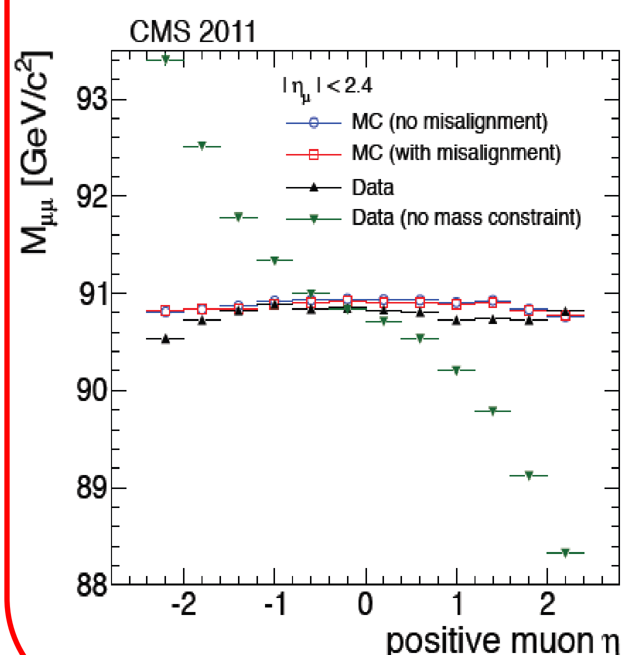
Muon System



ECAL

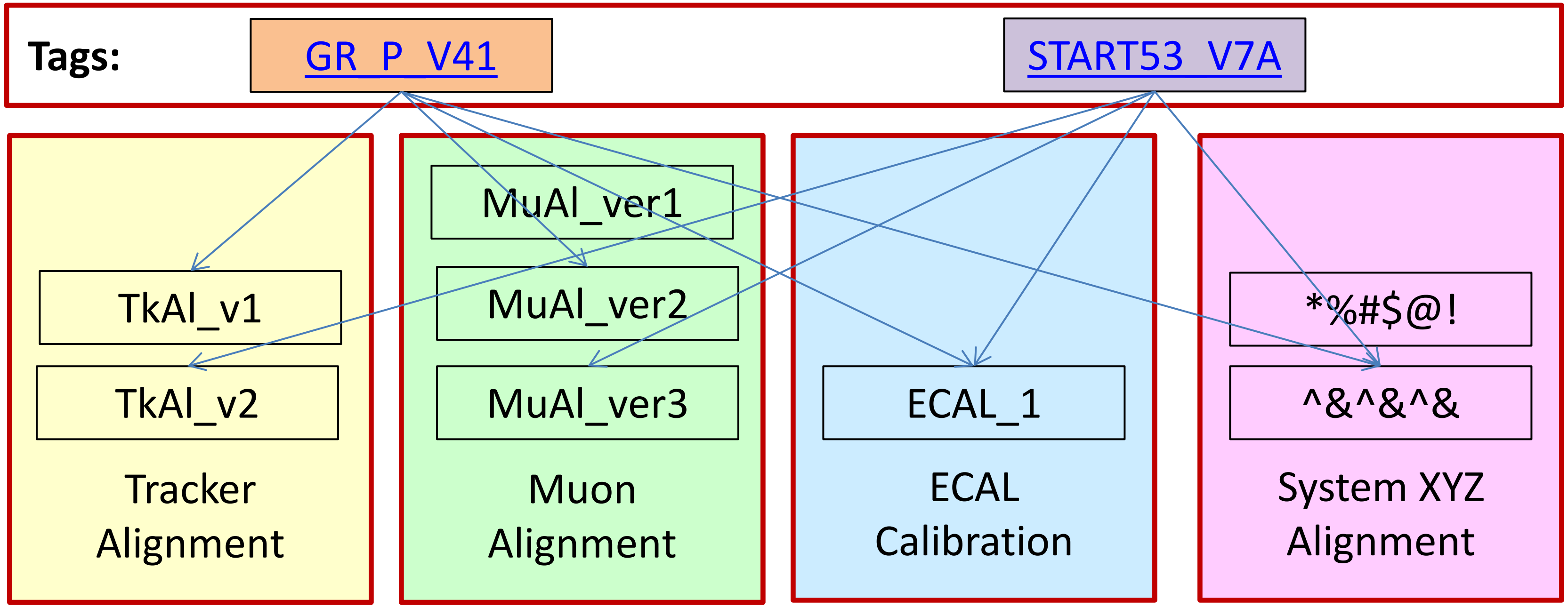


Tracker



Alignment and Calibration Constants Storage

- ✓ All constants stored in SQL Data Base for global access by data processing computing jobs from all over the World
  - All CMS Tiers must use the same conditions
- ✓ Set of matching constants is identified via “tag”
  - complete and consistent as required for data processing
  - simple access for non-expert users (undergraduates and distinguished professors)
  - experts can customize used constants



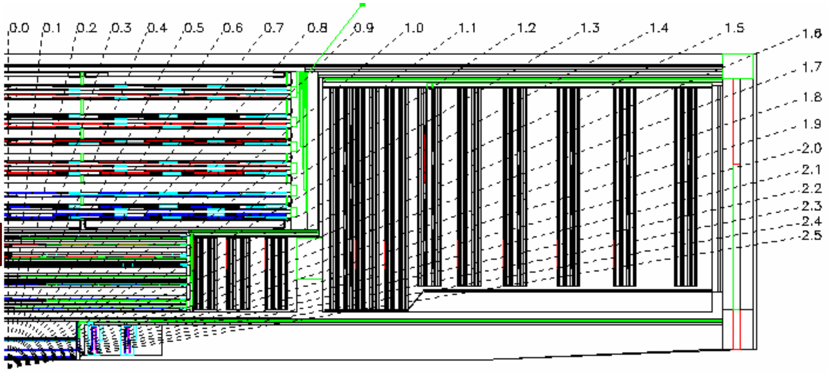
Summary

- ✓ The CMS alignment and calibration infrastructure proved to be efficient and effective for a fast analysis turn-around during data taking in 2011 and 2012
- ✓ The *prompt* alignment and calibration mechanism:
  - Designed for low latency workflow run smoothly during Run1
  - Better quality of physics reconstructed objects already during very first processing of data
- ✓ The *offline* calibration and alignment procedure:
  - Increasing time/space granularity of the calibrations and thus precision
  - Delivering to reconstruction the best knowledge of detector performance based on state-of-the-art algorithms
  - Account for inter-dependencies among the different systems and workflows
- ✓ Calibration and alignment has been crucial step towards the successful physics program of CMS during 2010-- 2012
- ✓ Revision of main workflow is under study
  - Goal is to keep the high standard
- ✓ Looking forward to Run2 in 2015 and possible discoveries!

Back-up Slides

CMS Inner Tracker

- ✓ Pixel detector: 66M channels
  - pixel size $100 \times 150\ \mu\mathrm{m}^2$
  - 3 barrel layers, 2×2 endcap wheels
  - span to beam $4.7 < R < 10.2$ cm
- ✓ Strip detector: 10M channels
  - 10 layers and $> 200\ m^2$ of silicon
  - largest silicon tracker!
  - span to beam $20 < R < 116$ cm



Barrel

Endcap wheel

Residuals in Track-based Muon Alignment

✓ Muon residual is difference between measured (with hits) and predicted (i.e. propagated from Tracker) position of the muon in the chamber

✓ Residuals calculated in chamber's local frame

- hit (layers) based muon re-fit is used
- local residual x = track local x – hit local x
- scattering in iron → width of residual distribution
- chamber misalignment → non-zero mean of distribution