First Results & Performance of The CMS Experiment

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on behalf of the CMS Collaboration

Aspen Particle Physics Conference

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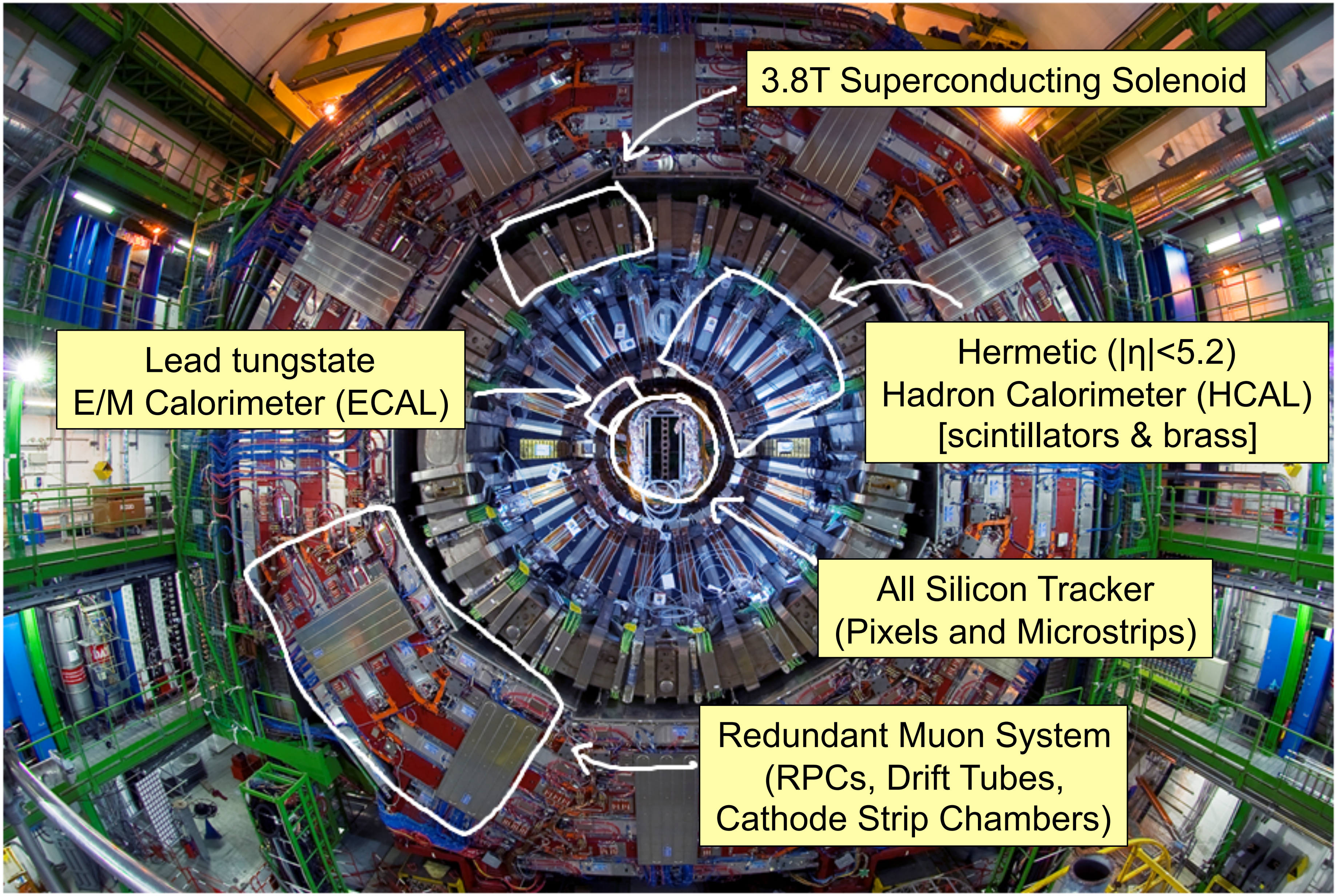
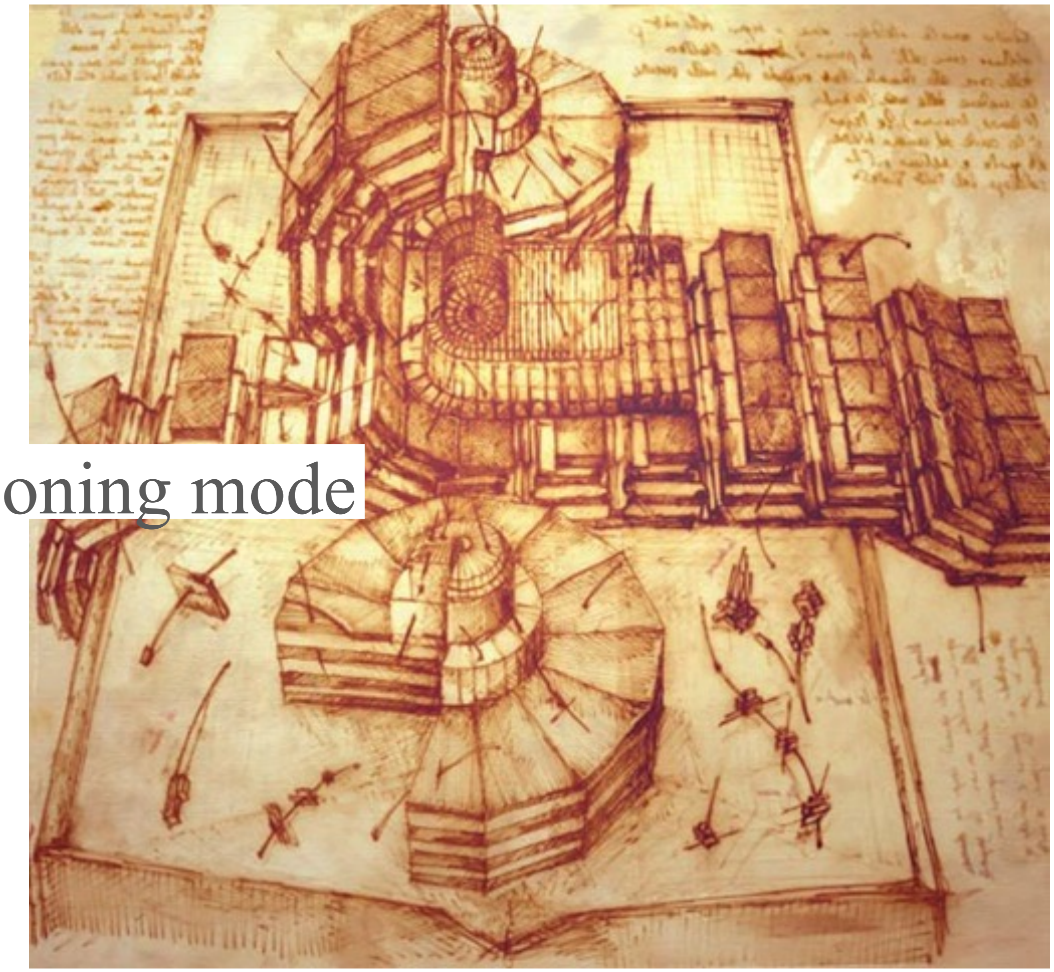
Aspen, Colorado

The Detector



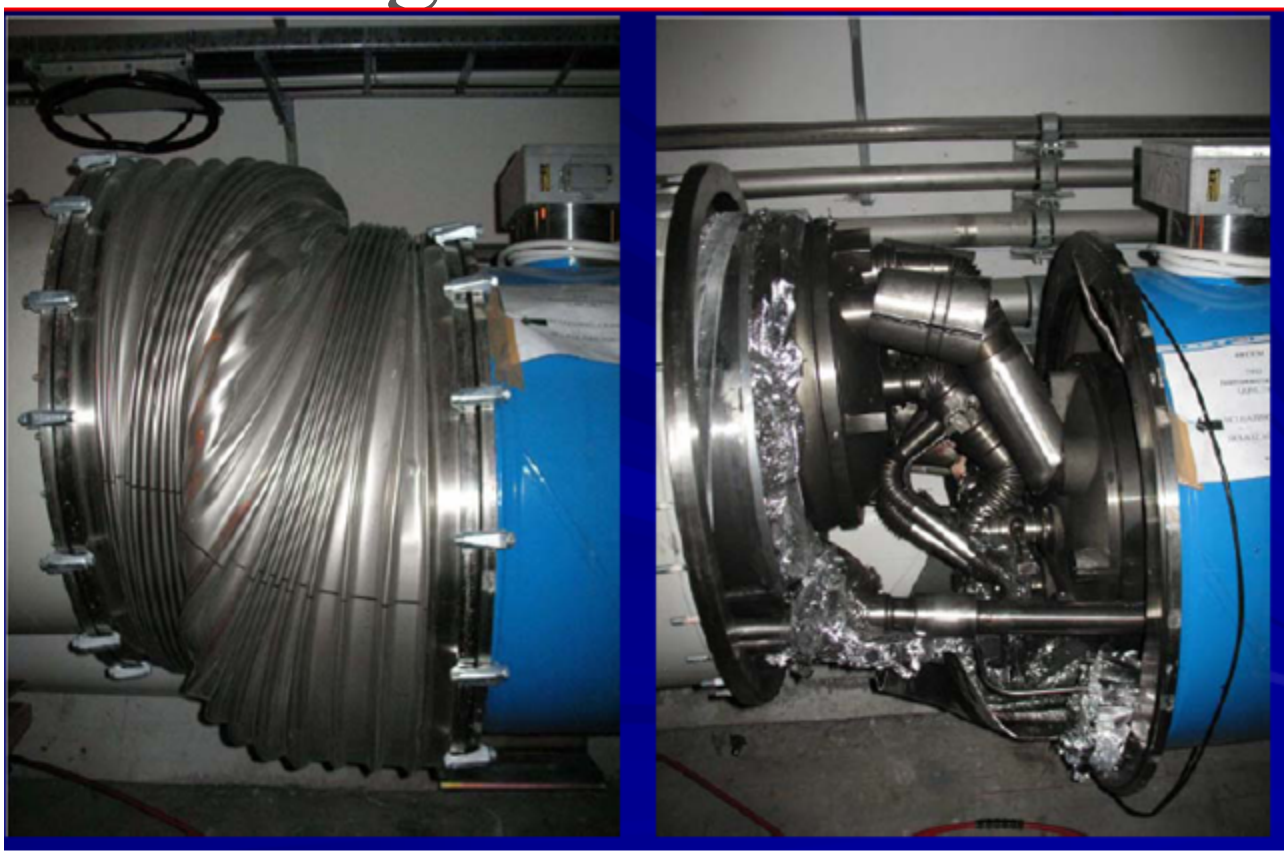
Overview

After 20 years of R&D, Detector Building,
Commissioning and Preparation



- LHC is up & running
- CMS:
  - Is in physics commissioning mode
  - Detector performance is according to design
- First Collision Results

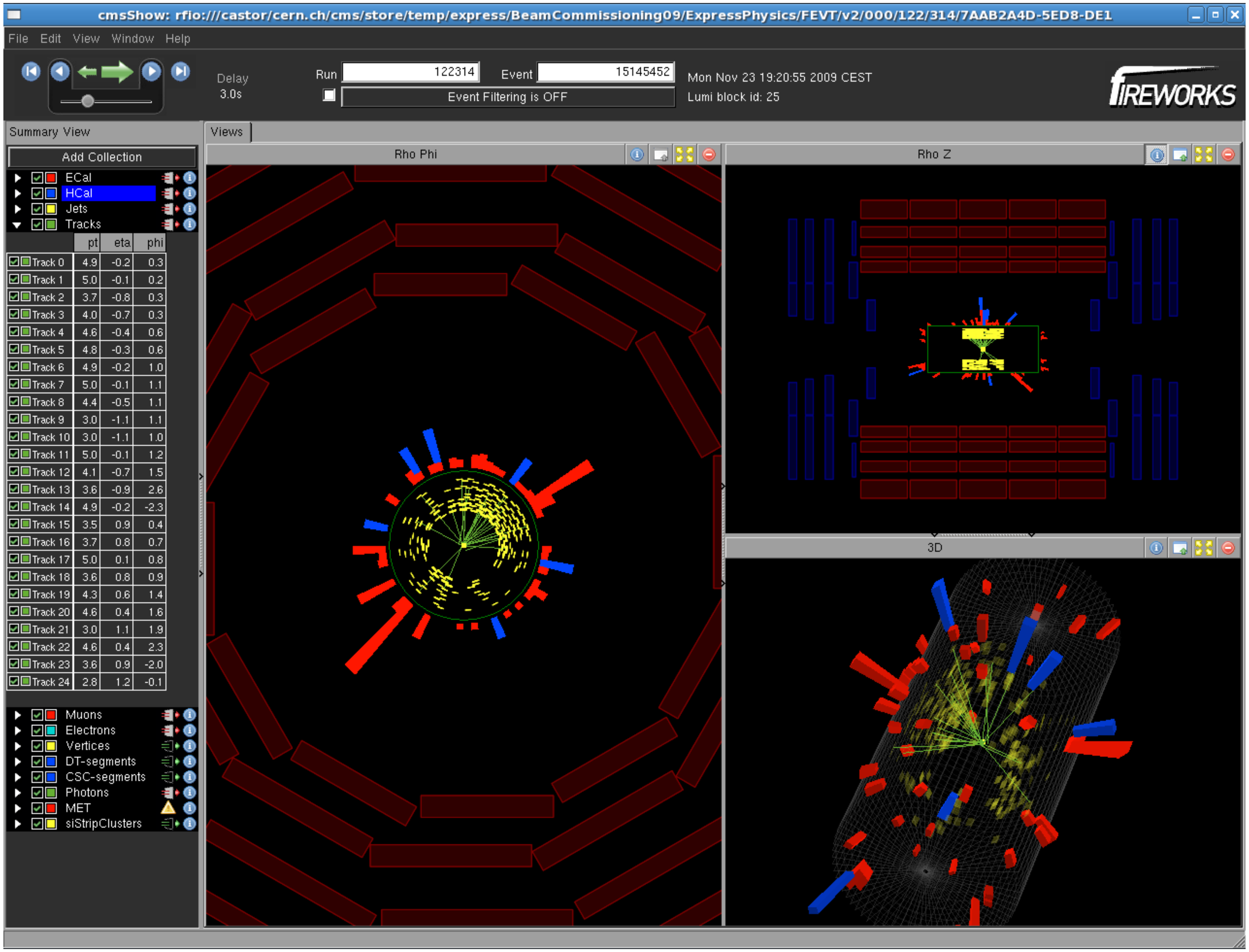
A review of how we managed to go from this



19 September 2008 (*)

(*) Picture released in December 2008

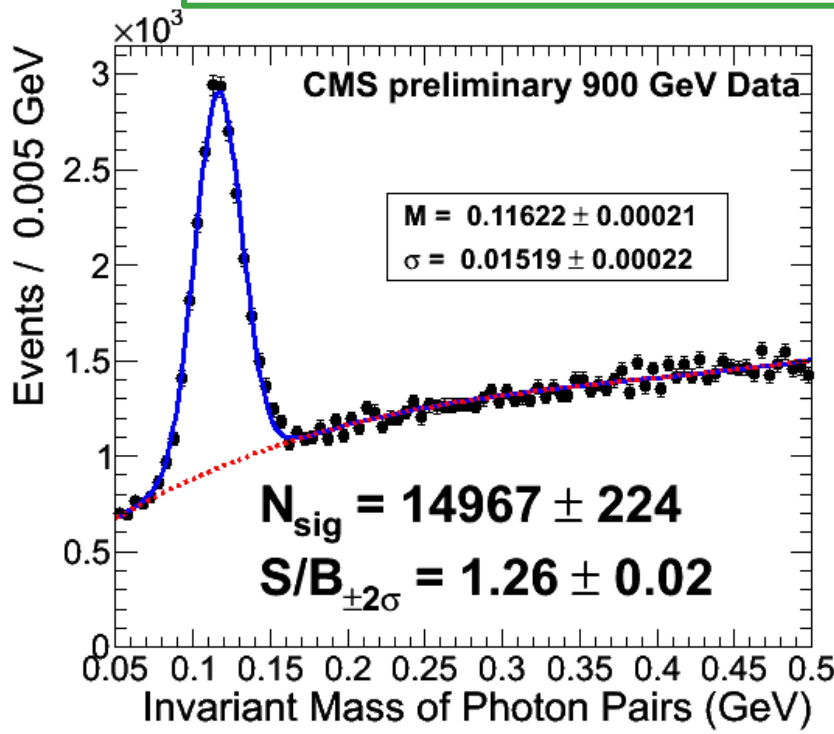
…to this



First collisions in CMS – Monday, 23 November 2009

…but also this, just two days later!

Photon pair invariant mass



First CMS results shown publicly at CERN – Thursday, 26 November 2009

Status Quo

What happened last December

- Collision data taken at
  - 900 GeV (350 k min. bias events or 10 μb^{-1}), and
  - 2.36 TeV (20k min. bias events or $< 1\ \mu b^{-1}$)
    - Collider energy world record

- CMS has taken good quality data
  - > 99% of detector channels operational
  - High data-taking efficiency (> 80%)
  - Data can be analyzed very quickly
  - First results in pipeline

What happens next

- LHC will resume collision running in March
  - ➢ Starting at $\sqrt{s} = 7$ TeV for a few months (maybe up to ~30-40 pb^{-1})
- Then ramp up to 10 TeV (*)
  - ➢ Expecting ~ ~~200~~ 500 (!) pb^{-1} till Fall of 2010
- The year will end with a short heavy-ion run

(*) Or somewhat less

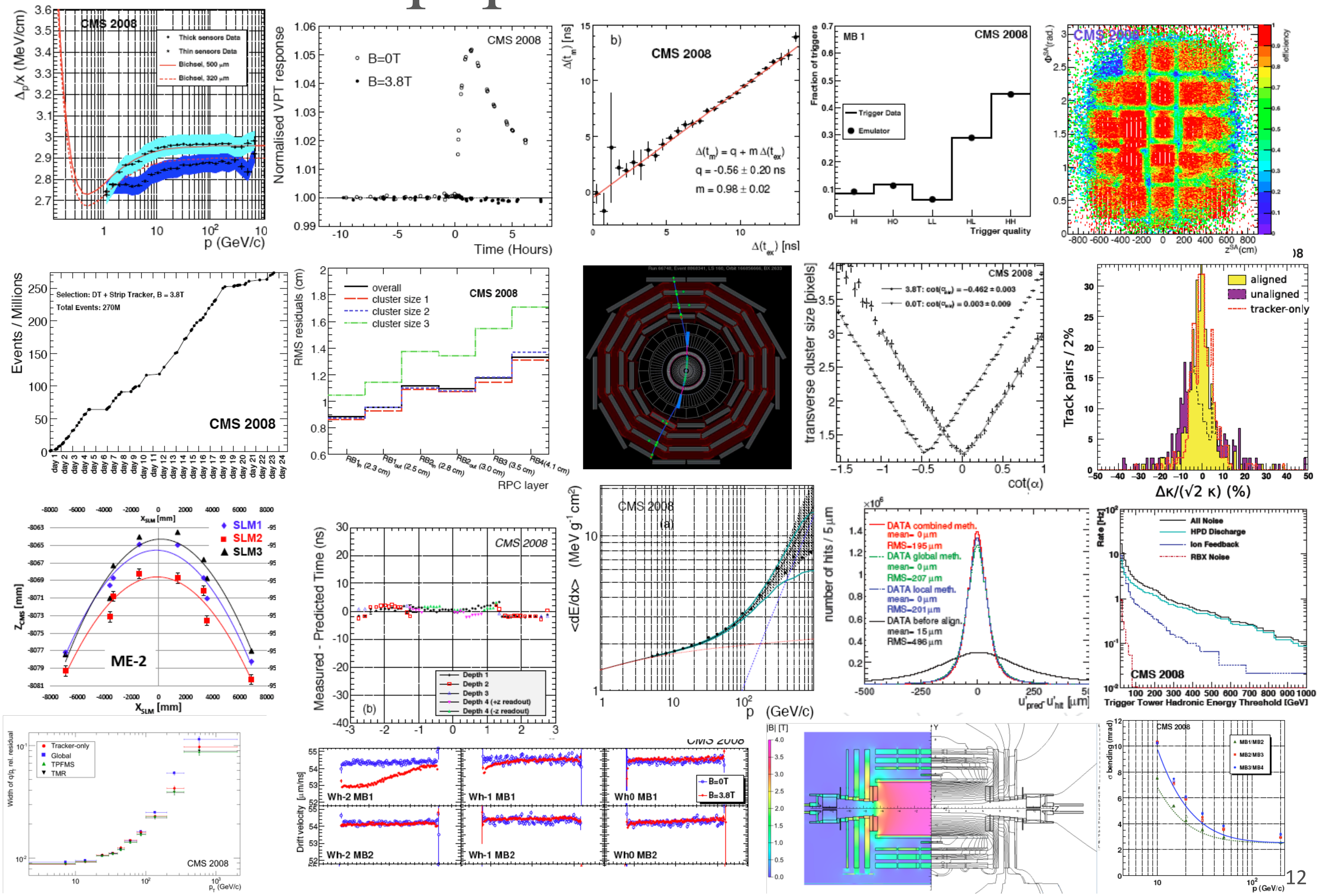
Sept 08 – Nov 09 Shutdown

Life during the shutdown

- Continuous preparation while waiting for LHC to get repaired (and beam!)
  - Cosmic Runs At Four Tesla (aka CRAFT)
    - October 08 and August 09: 600M events logged!
    - Reconstruction: tuning & improved robustness
    - Validation of Software & Computing workflows
    - Alignment & calibration: exercised with real data

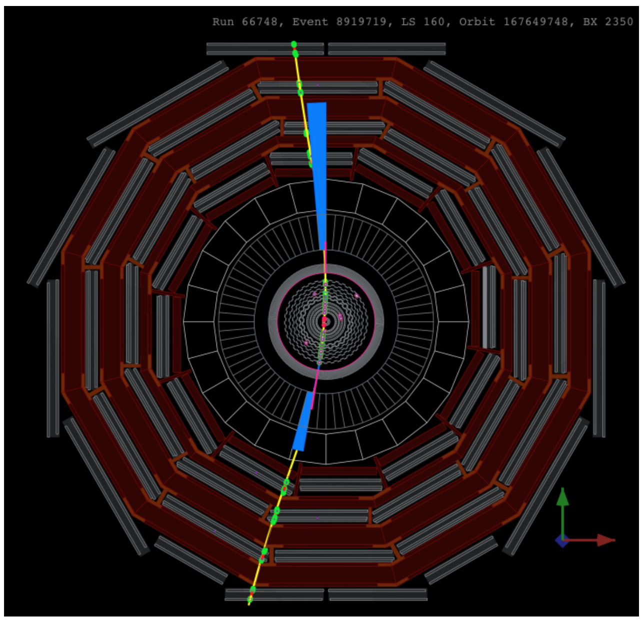
- Extensive documentation of detector performance
- Feedback into *realistic* simulation

23 CRAFT papers submitted to JINST



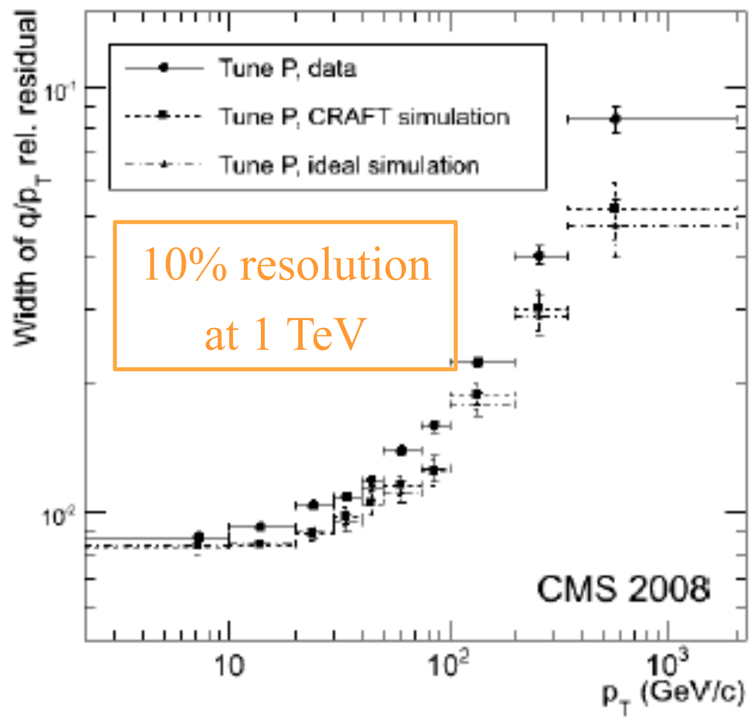
Muon p_T resolution with cosmics

600M events of (mostly muon) cosmic events collected make muons the best understood reconstructed object in CMS



$$R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2}(q/p_T)^{\text{lower}}}$$

Compare muon p_T in upper, lower detector halves to evaluate resolution



MC studies: what to expect in 2010

- Last year, we re-evaluated the CMS performance for the 2009-10 run: 10 TeV, 200-300 pb^{-1}

http://cms-physics.web.cern.ch/cms-physics/CMS_Physics_Results.htm

- 2010 *discovery potential* - Some highlights:
  - W charge asymmetry: constrain PDF (100 pb^{-1})
  - SUSY & opposite-sign 2μ: reach exp. limit (200 pb^{-1})
  - Leptoquarks in e/μ + jet: 300-500 GeV (100 pb^{-1})
  - b partner in $b' \rightarrow cWbZ$: 200 GeV (200 pb^{-1})
  - b partner in $b' \rightarrow tW$: 500 GeV (300 pb^{-1})
  - Majorana neutrinos in 2ℓ+2j: 150 GeV (200 pb^{-1})
  - Large Extra dimensions in 2γ: 2.5 TeV, n=4 (100 pb^{-1})

Detector understanding

- "Why should we believe that the simulation correctly describes the detector performance?"
- Excellent question!
- TeVatron experience: it takes a *long* time to commission & understand collider experiments
  - Accelerator, detector, trigger, background, underlying event, software: *very* complicated problems

Claim:

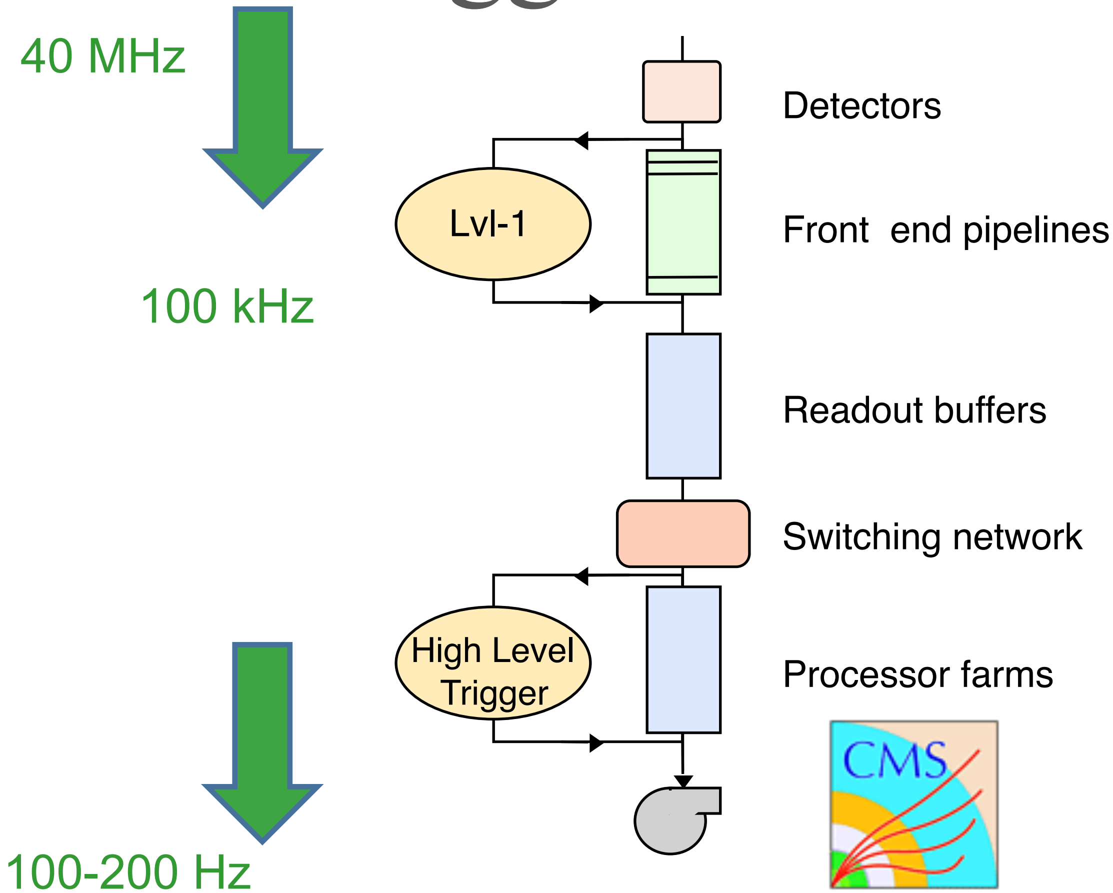
- The CRAFT exercise has made a difference
- First data distributions agree well with simulation

The
20 November – 16 December 2009
Revolution

The Trigger

"The Trigger does not determine which Physics Model is Right. Only which Physics Model is Left."

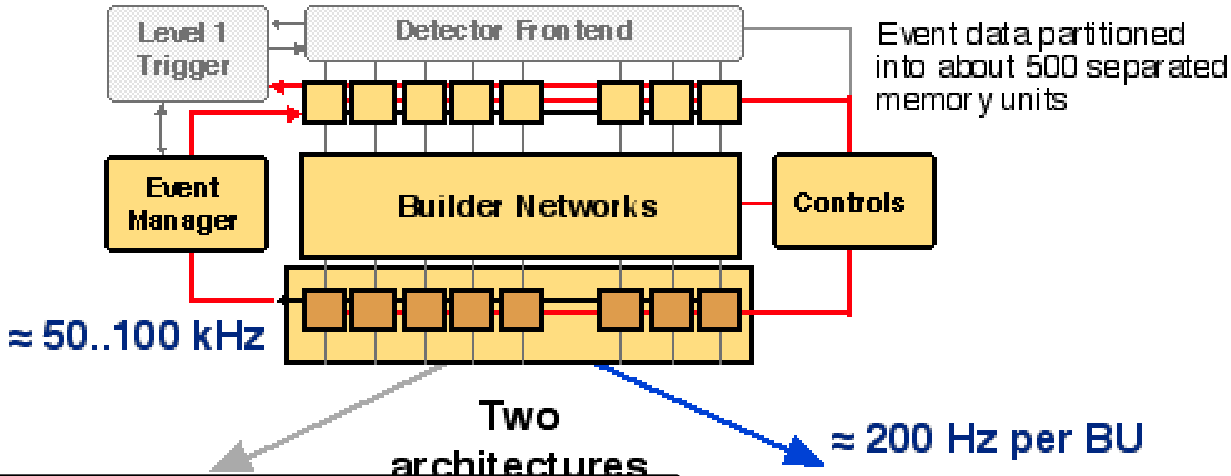
The CMS Trigger at 10/14 TeV



CMS

- Two-tier trigger system
- L1: hardware & firmware
- L2, L3: merged into High-Level Trigger (HLT)

The CMS High Level Trigger



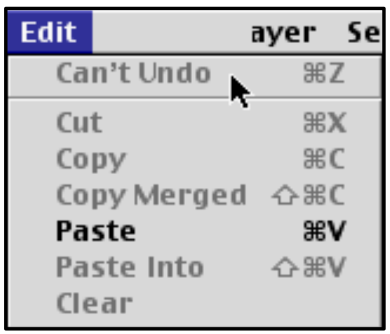
- L2 and L3 merged into High Level Trigger (HLT)
- HLT (~5000 CPUs) accesses full event info (full granularity) seeded by L1 objects using "off-line quality" algorithms
- L1 latency: 3.2 µs
- Average HLT processing time: 40 ms

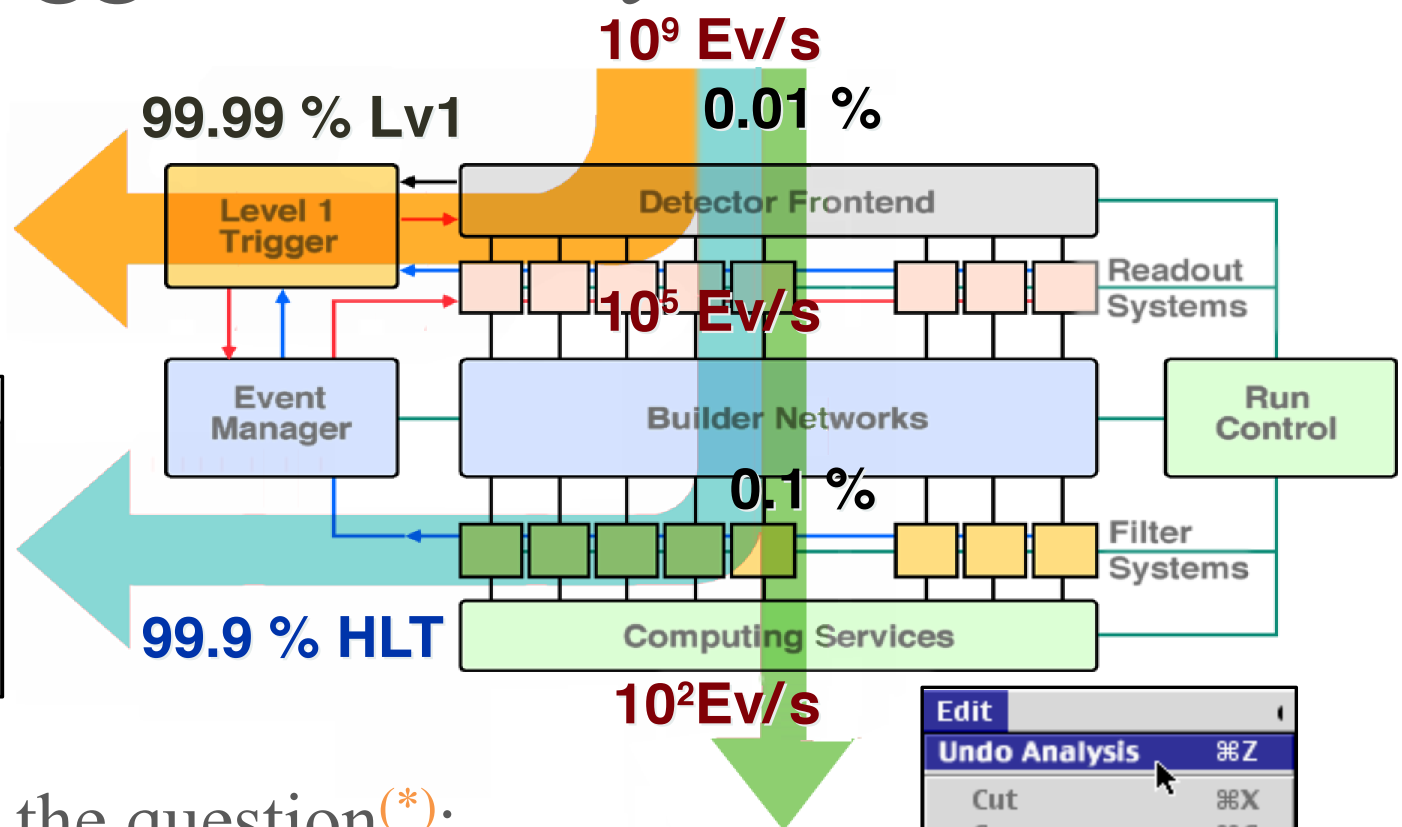
Farm of processors

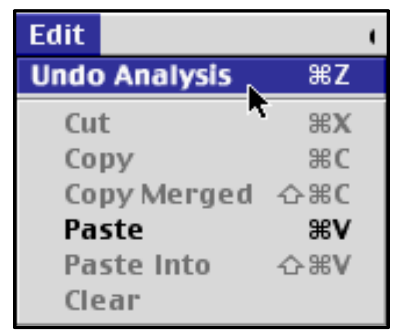
ONE event, ONE processor

- High latency (larger buffers)
- Simpler I/O
- Sequential programming

Trigger: A tricky business







Which begs the question(*):

Will <u>your</u> favorite new physics signal be included in the small fraction of selected events?

(*) LHC upgrade: 1B CHF, CMS detector: 0.6B CHF

The 2009 Trigger Strategy

- Adapt to *rapidly* changing conditions
  - Beam “splashes” & circulating beam
  - Two (unstable) beams with magnetic field off
  - Two (stable) beams with magnetic field (and tracker) on

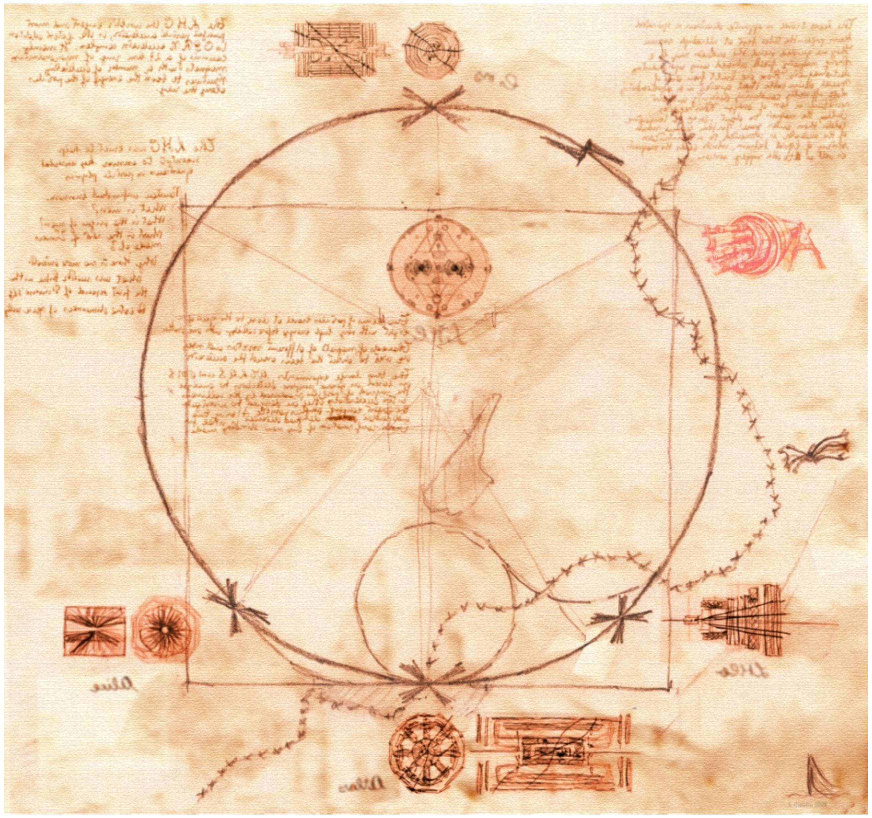
- Write out as many events as possible
  - Thou Shalt Not Unnecessarily Reject Events
  - Thou Shalt Capture as many bunches with protons as possible (rate: from 11 to 88 kHz)
  - Thou Shalt Capture All Events with Any Detector Activity (rate: up to 600 Hz)

The CMS Trigger: 900 GeV, 2.36 TeV

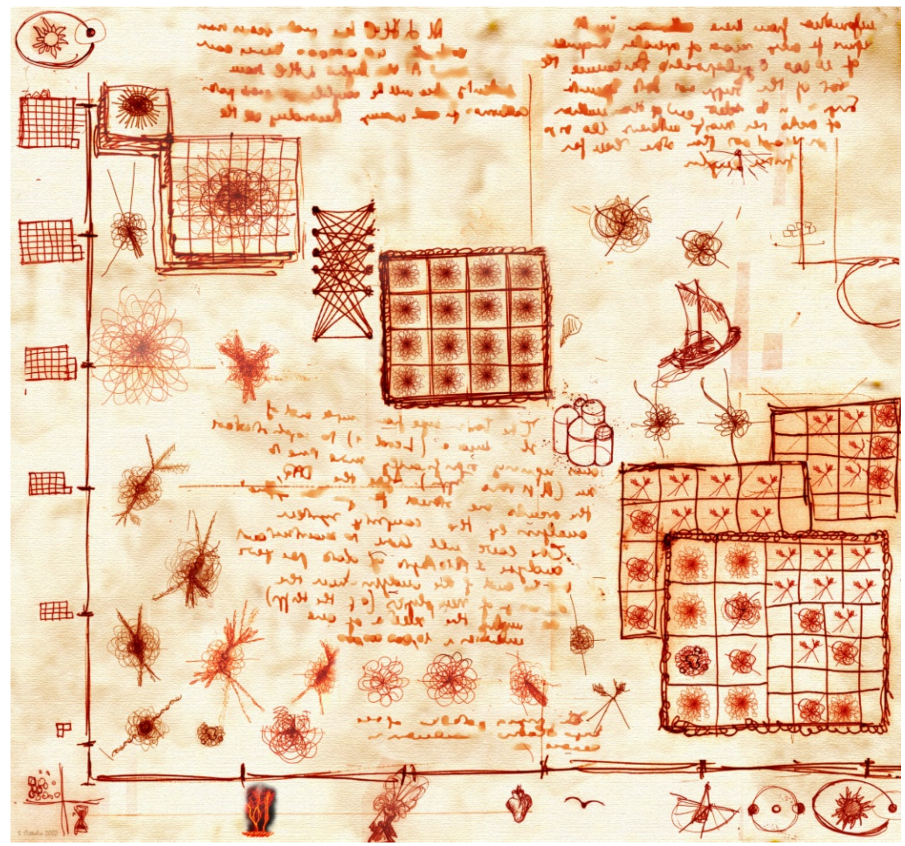
- The Early Collision menu
  - ➢ Zero-bias (i.e. filled bunch coincidence), beam-gas (i.e. unpaired filled bunch): ***Prescaled***
  - ➢ Suite of minimum bias triggers
    - o Based on beam scintillators, HCAL, ECAL, pixels: ***unprescaled***
  - ➢ "Level-1 Activity"
    - o Accept ***any*** event for which L1 has fired within ±2 bxs of filled bunch coincidence signal
  - ➢ "HLT Activity" (ECAL, HCAL, Muon, Pixels, …)
    - o Accept ***any*** event for which HLT finds detector activity above noise
    - o Catch events which L1 may have missed (sync or other rare problem)
  - ➢ Disable HLT paths with a L3 (i.e. tracking) component
    - o Not really exercised with CRAFT data

- Trigger Rate for MB: 0.5 – 15 Hz
- Efficiency > 90%

LHC has delivered

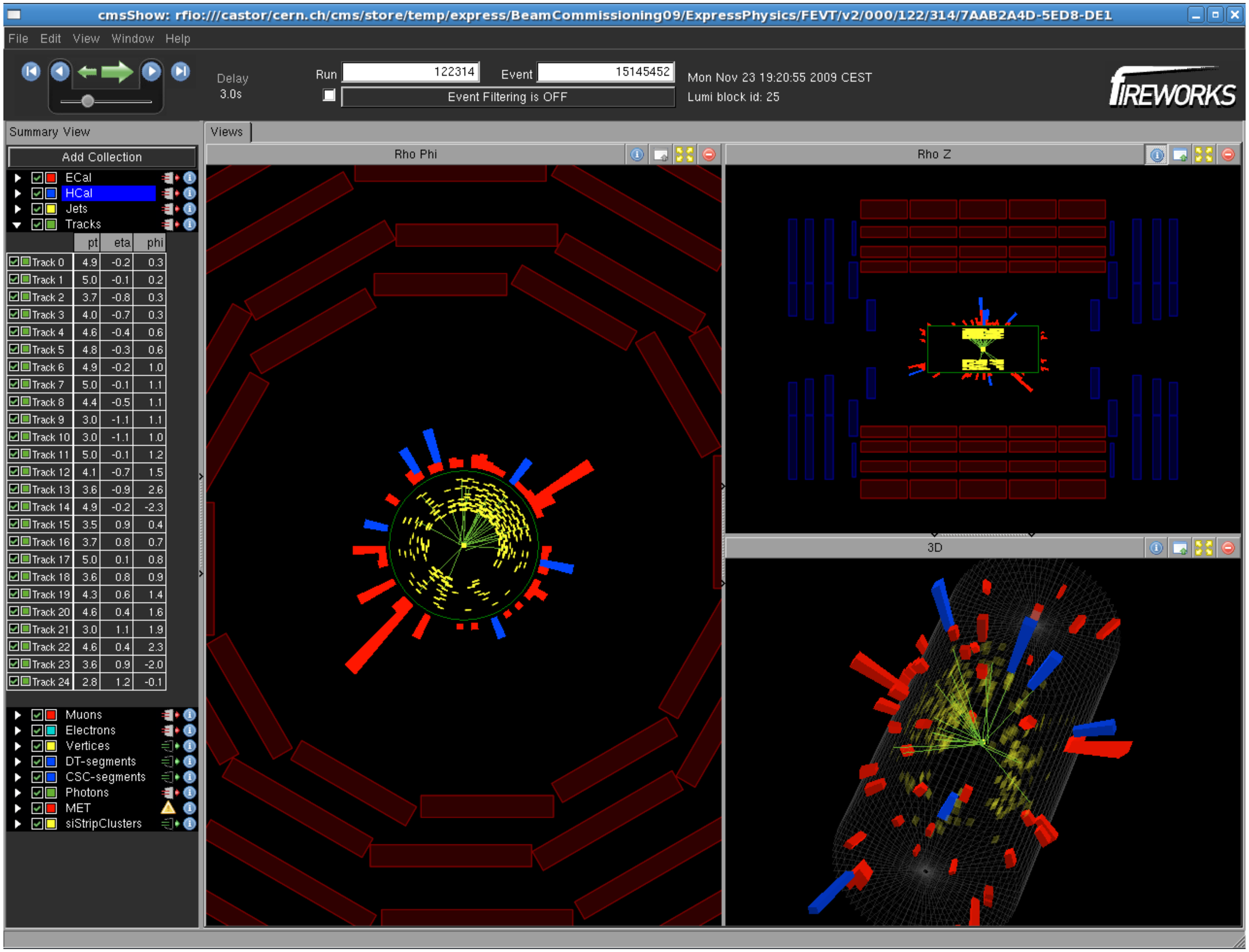


Trigger has accepted

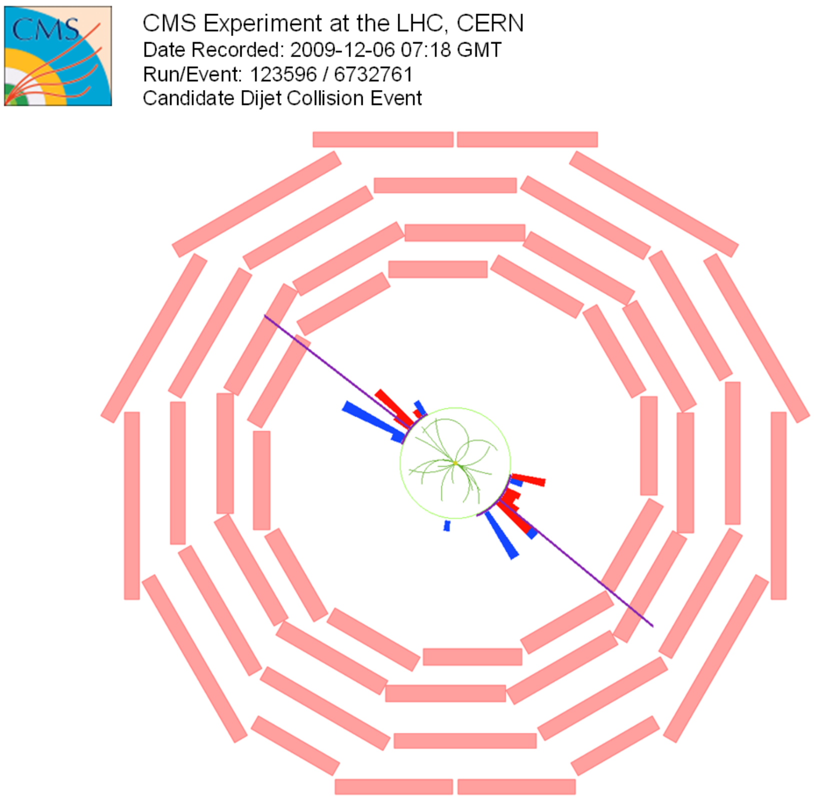


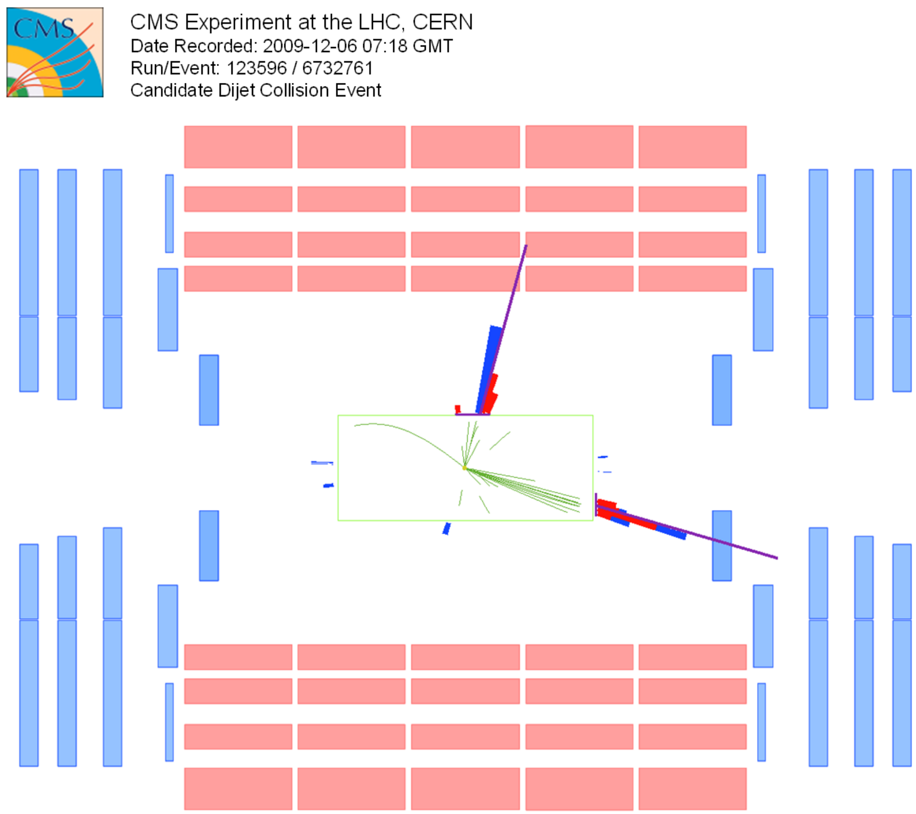
CMS will analyze

First collisions in CMS – Monday, 23 November 2009

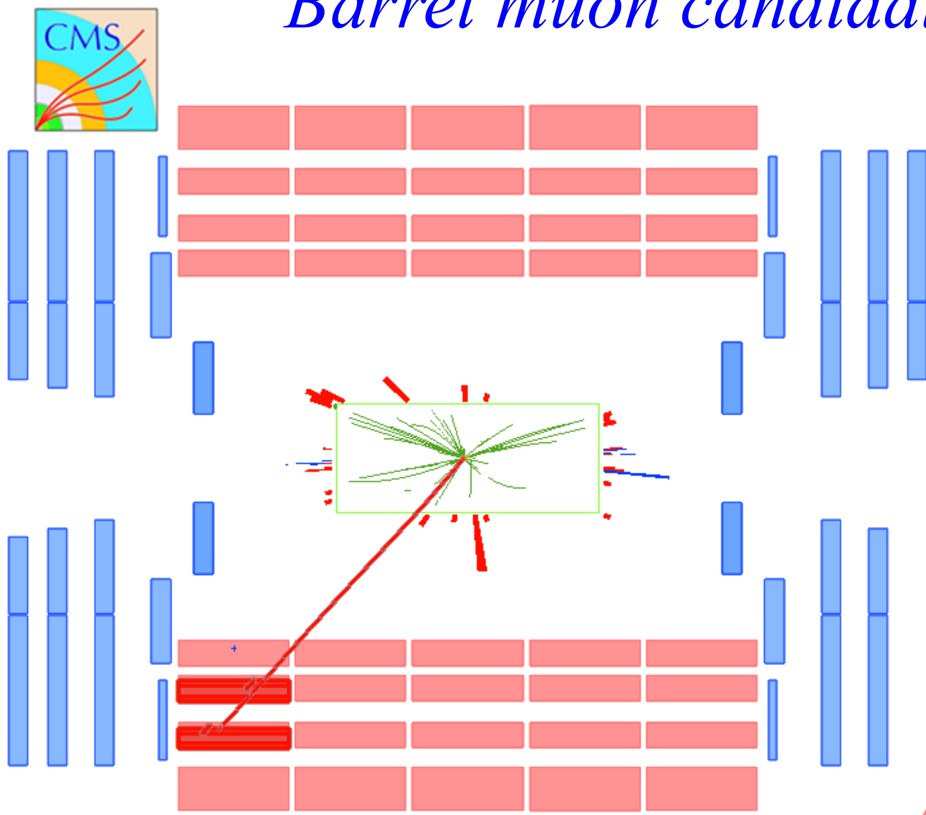


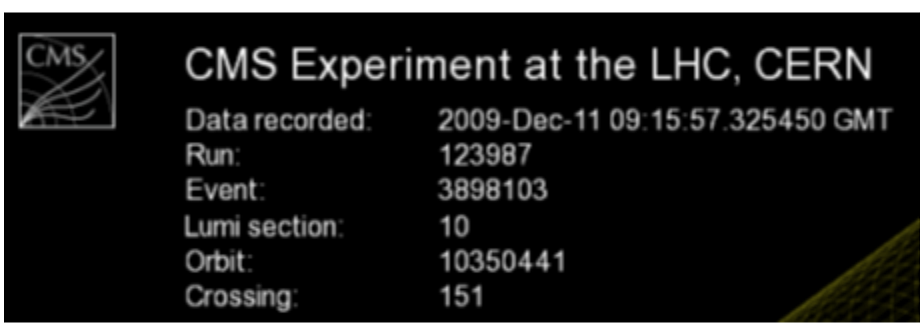
Dijet candidate – 6 December 2009

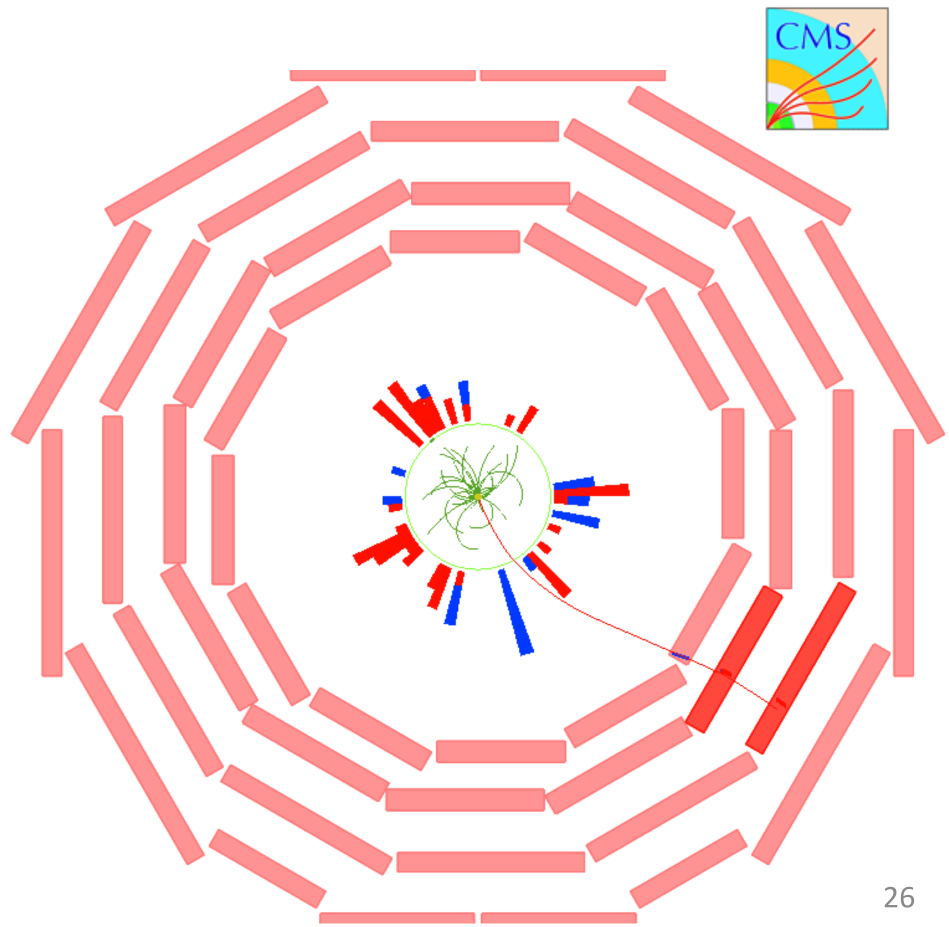




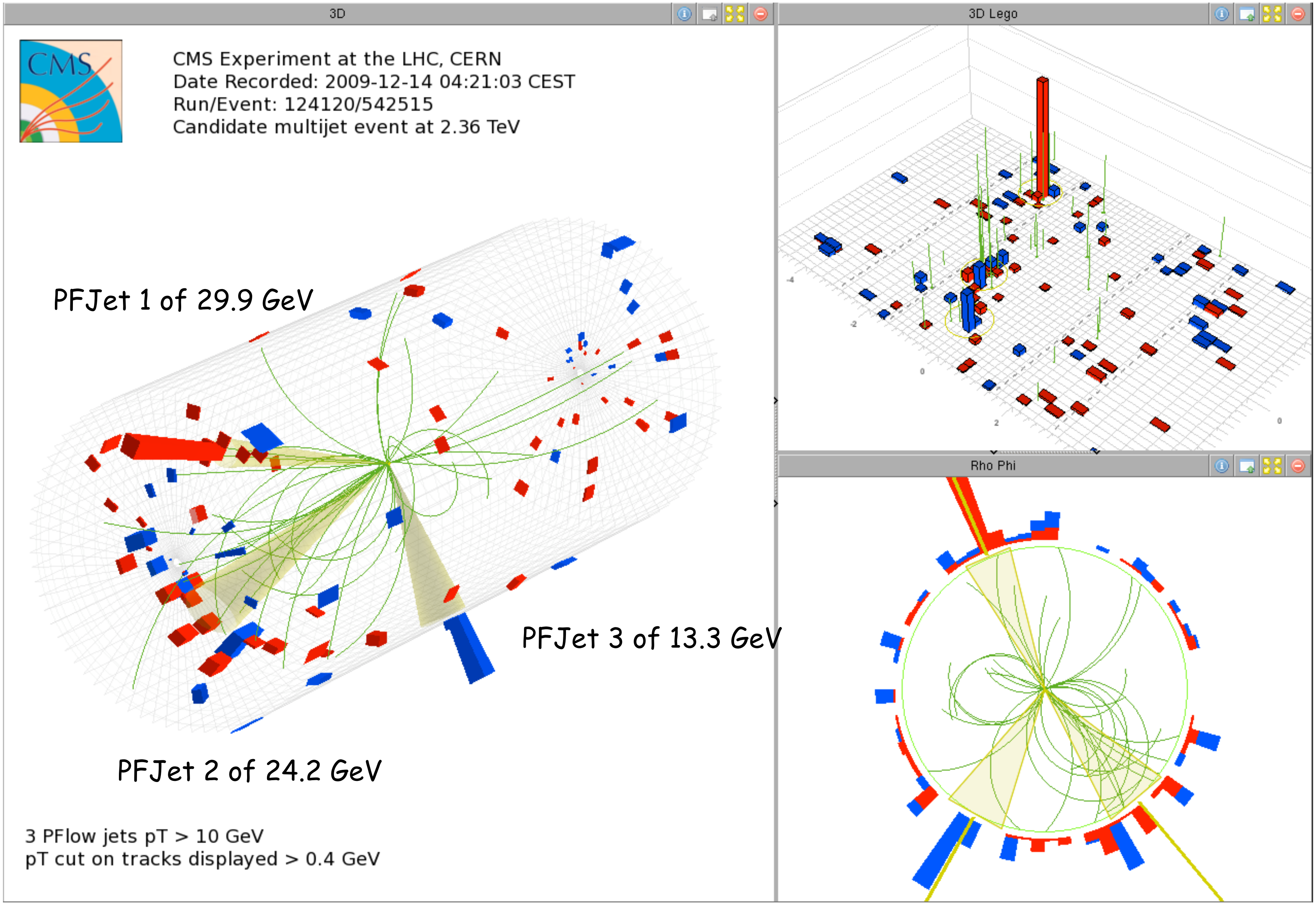
Barrel muon candidate – 11 December 2009







Multijet at 2.36 TeV – 14 December 2009



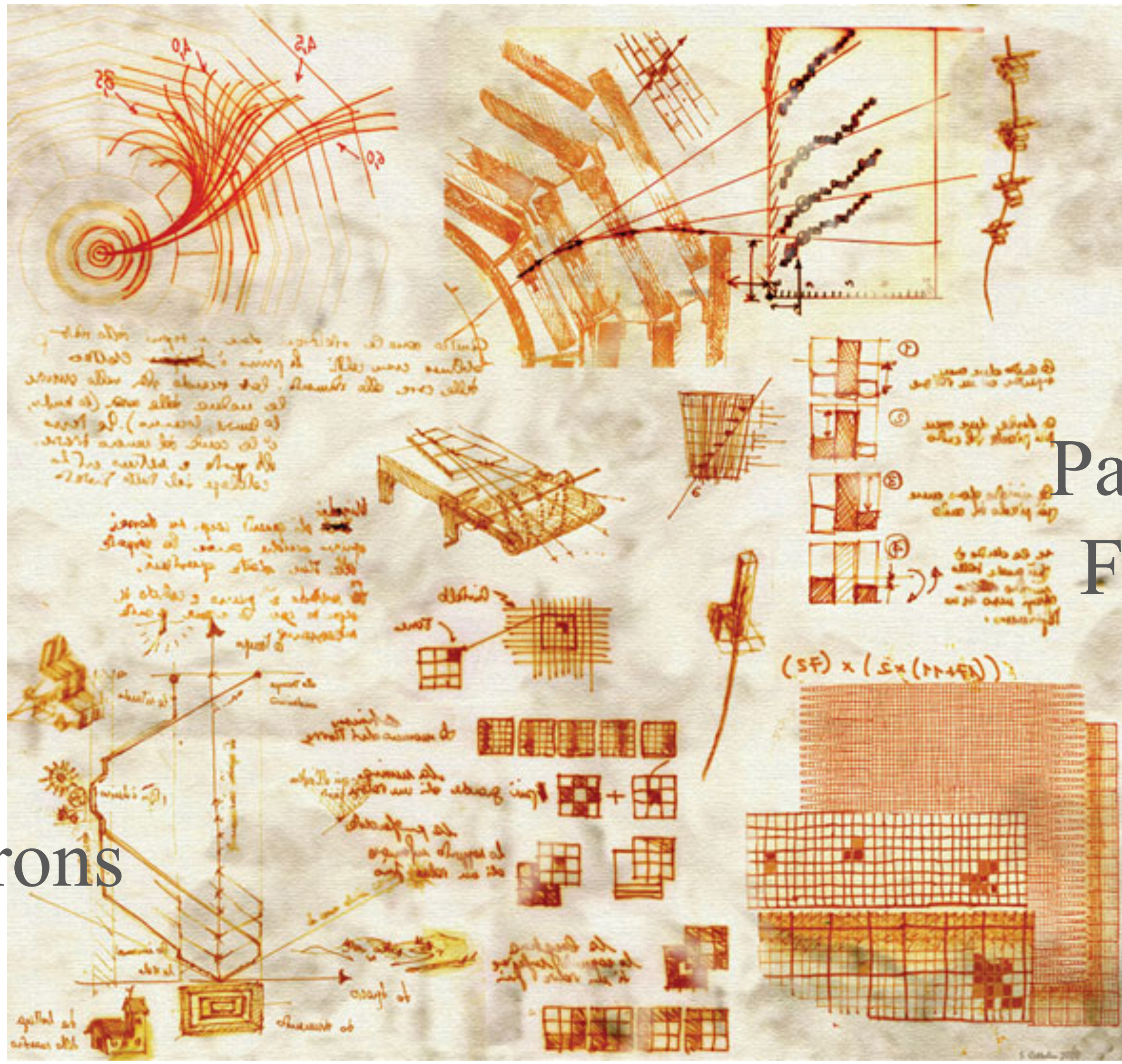
Detector Performance

Calorimetry

Jets

Tracking

Particle-ID



Muons

Particle Flow

Electrons

Detector Performance

Calorimetry

Jets

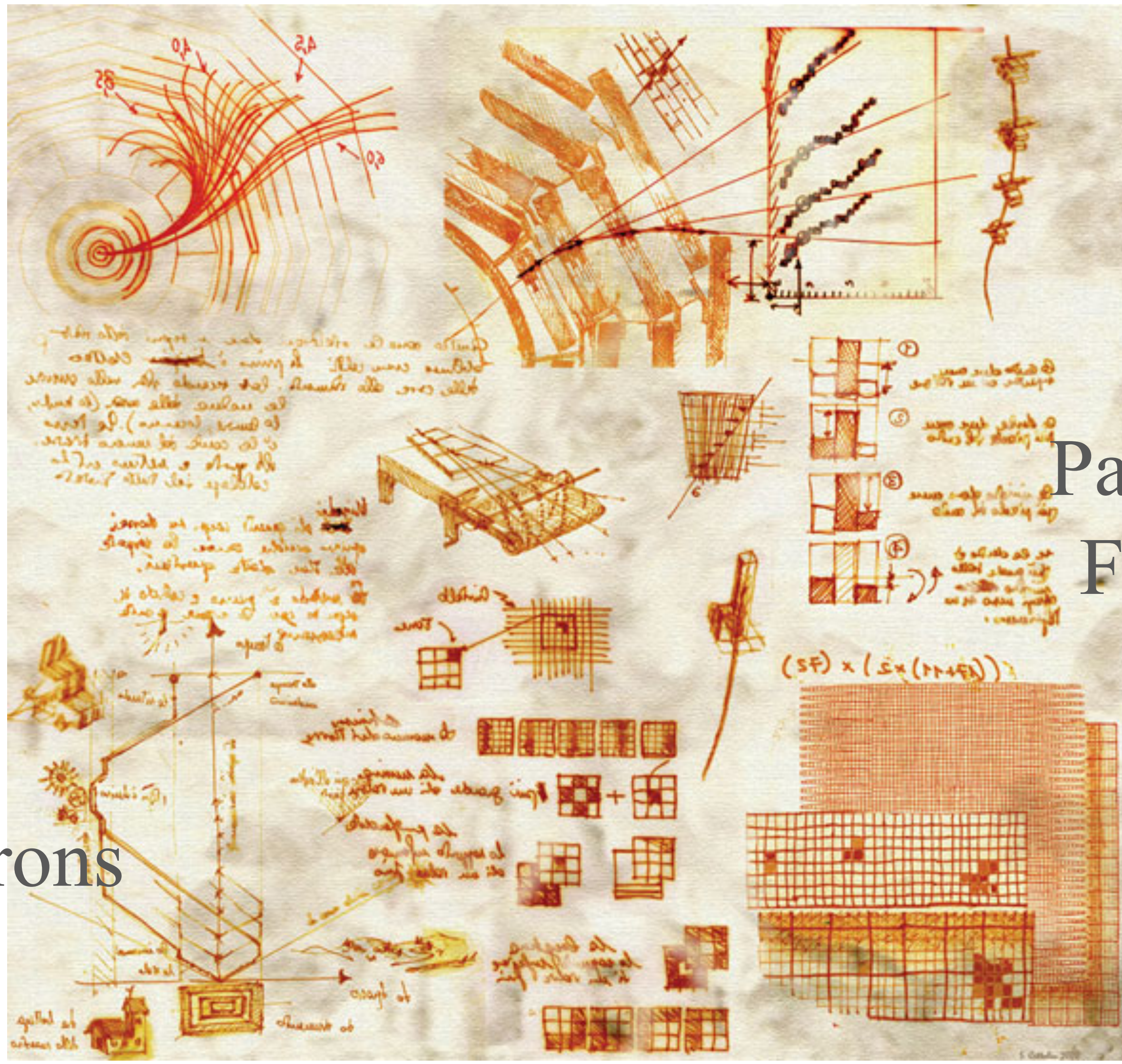
Tracking

Particle-ID

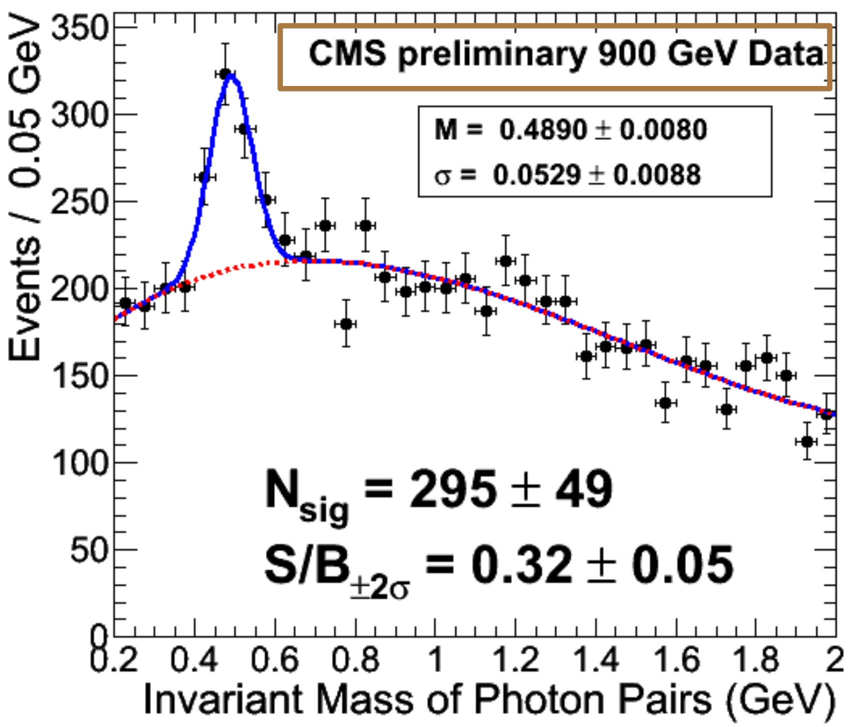
Muons

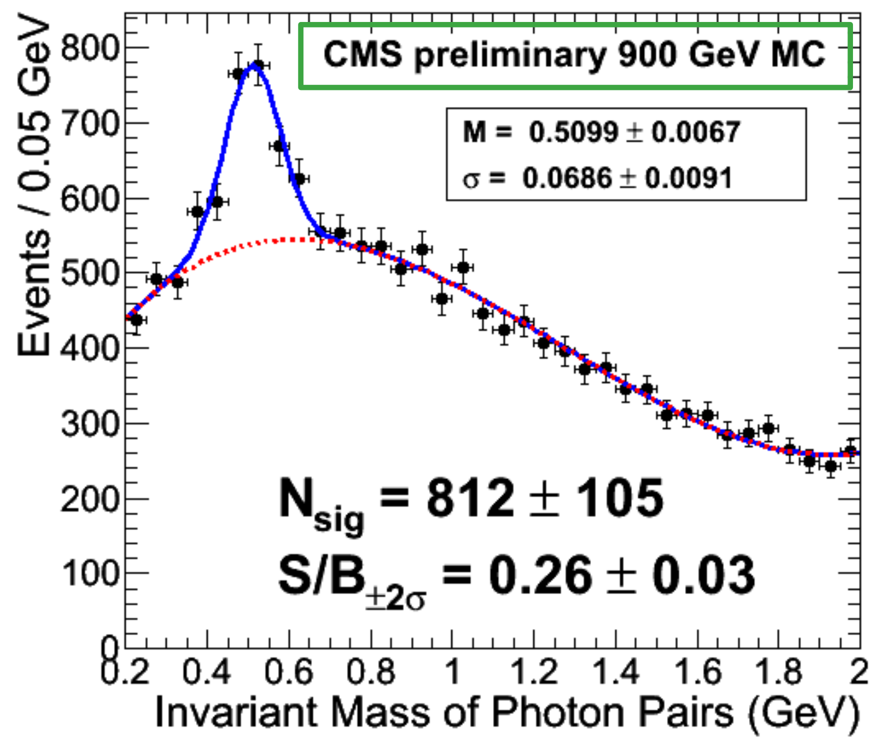
Particle Flow

Electrons



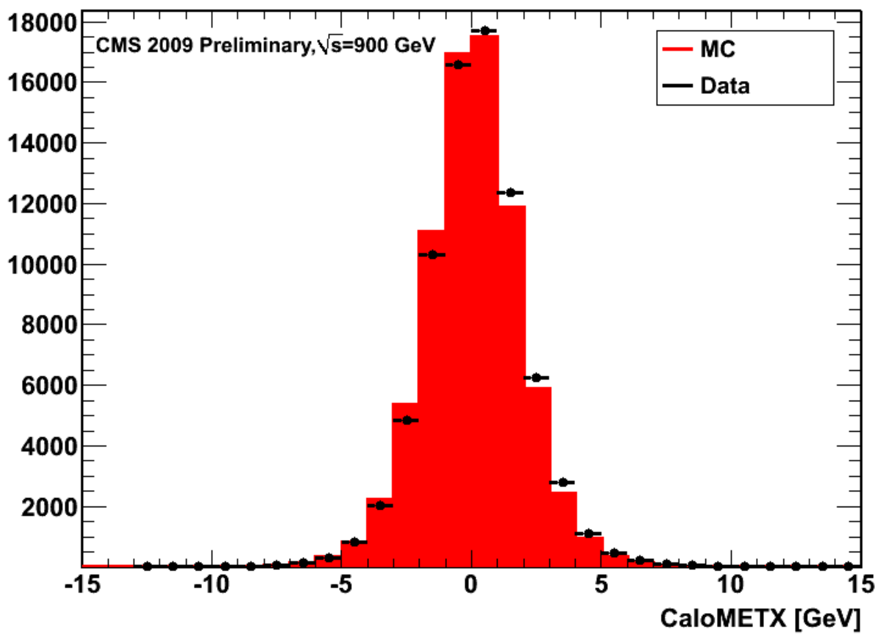
Calorimetry: $\eta \rightarrow \gamma\gamma$



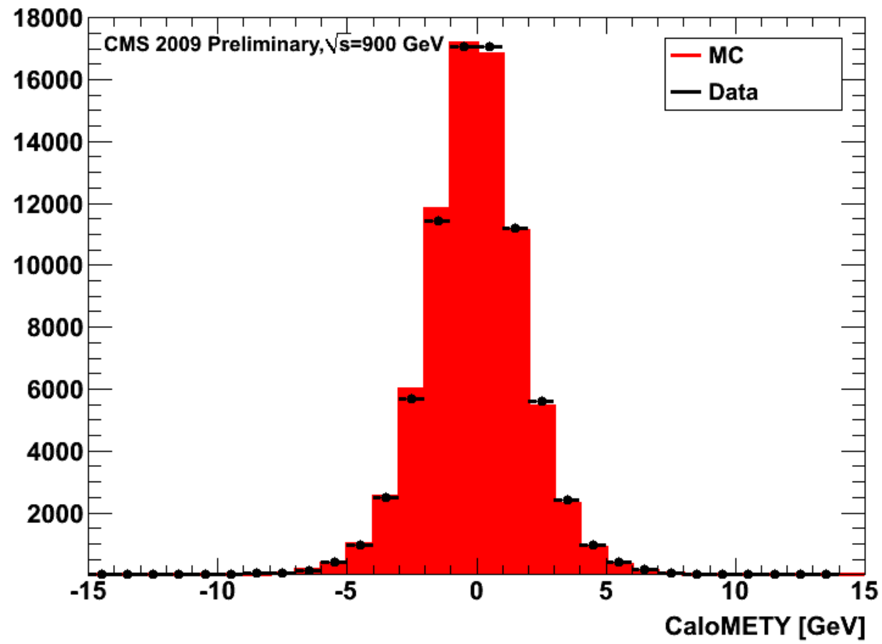


- Mass and width compatible with MC
- η yield scale as expected (π^0 candle)
  - $N(\eta) / N(\pi^0) = 0.020 \pm 0.003$ DATA (left)
  - $N(\eta) / N(\pi^0) = 0.021 \pm 0.003$ MC (right)

Calorimetry: Missing E_T



MET_x (GeV)



MET_y (GeV)

Detector Performance

Calorimetry

Jets

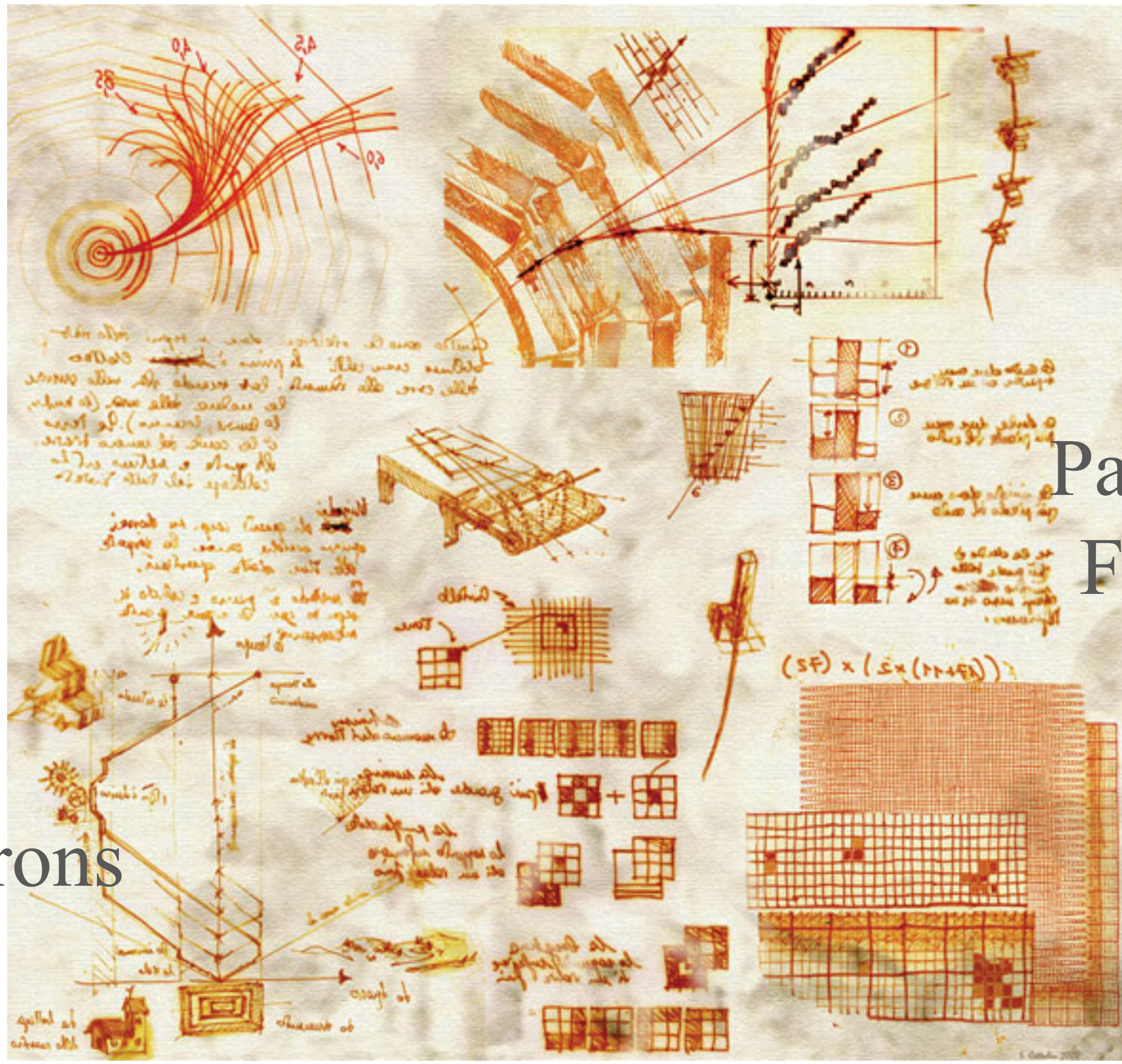
Tracking

Particle-ID

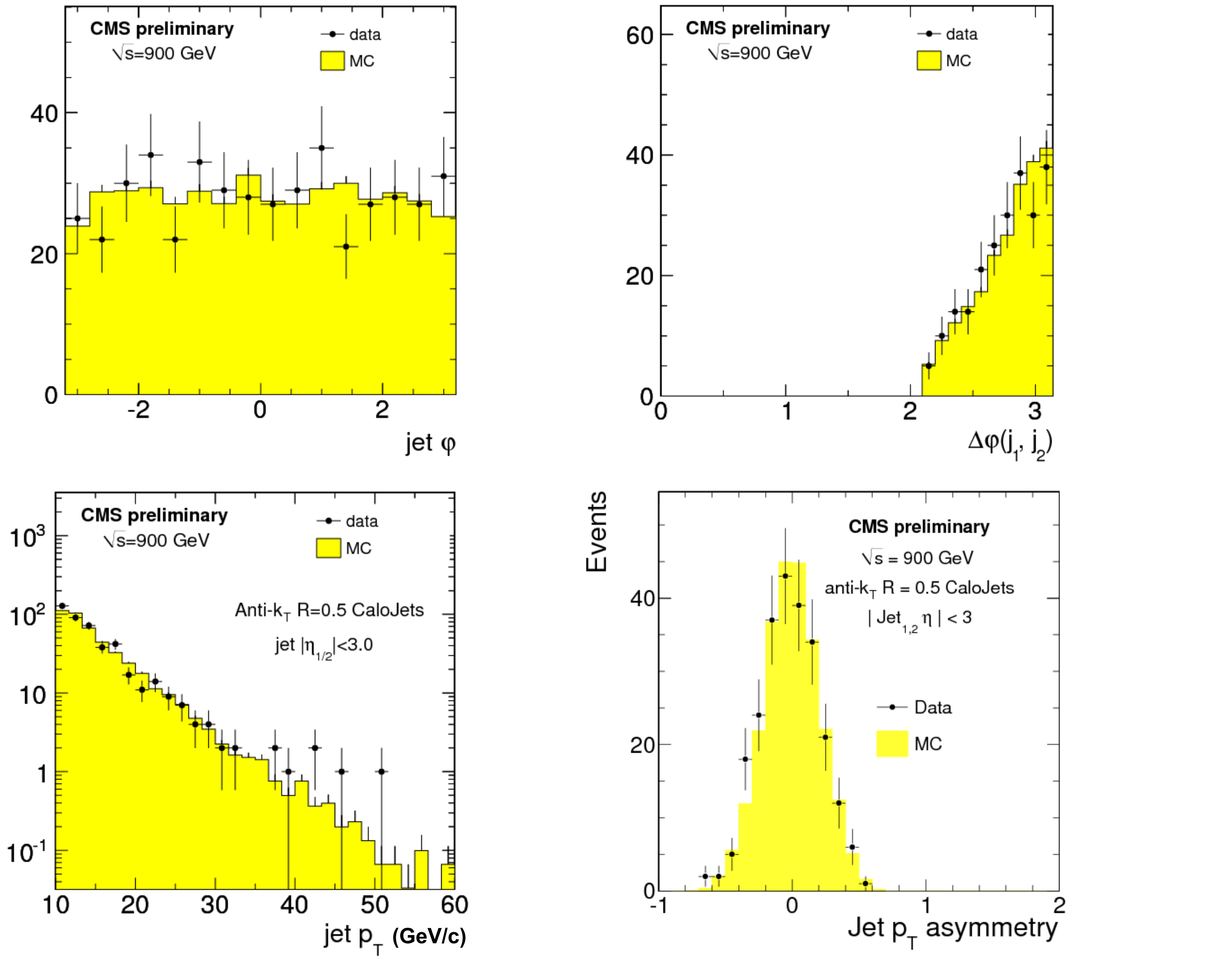
Muons

Particle Flow

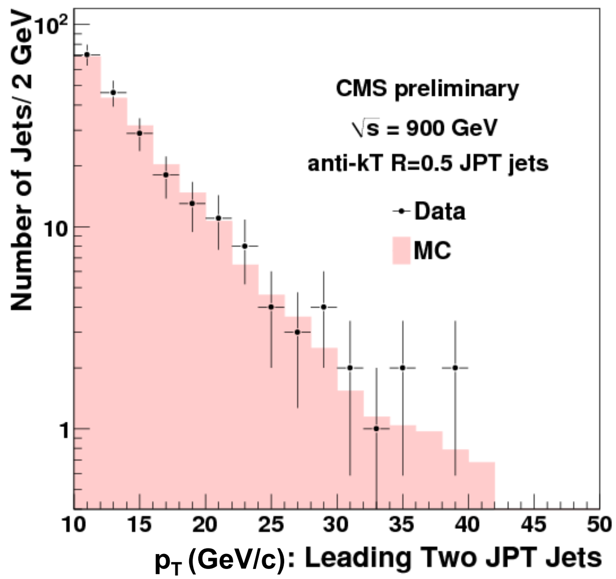
Electrons

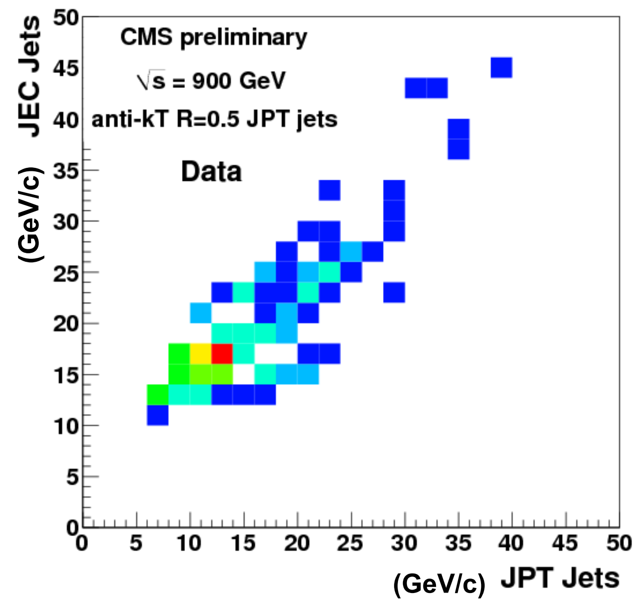


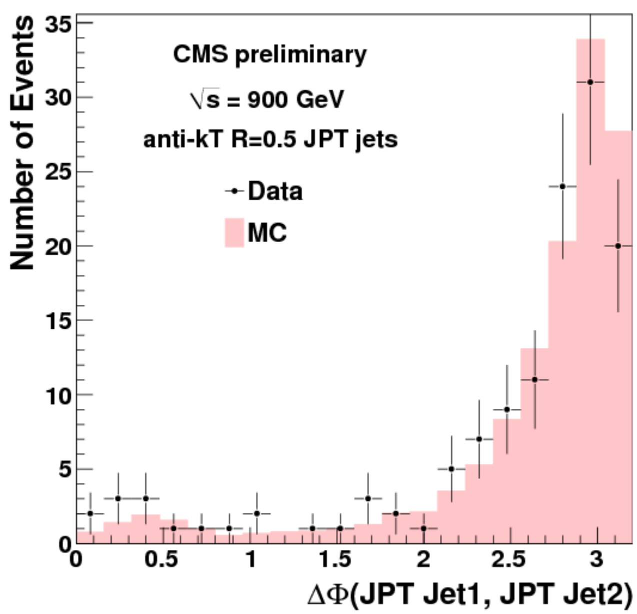
Calorimetric di-jet events

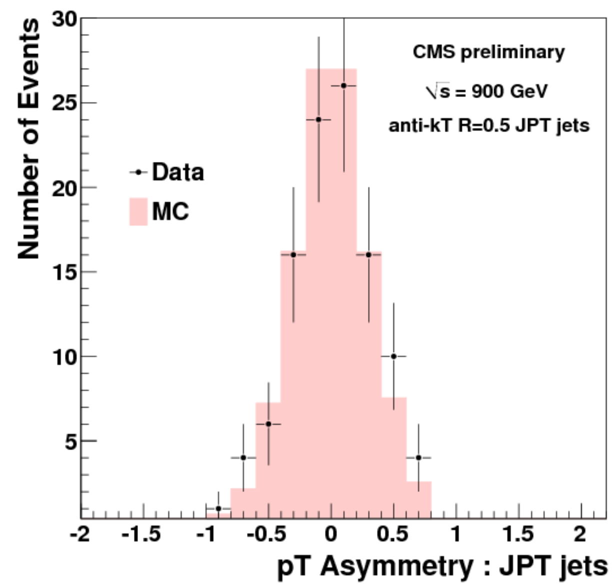


Calorimetric di-jet events plus tracks







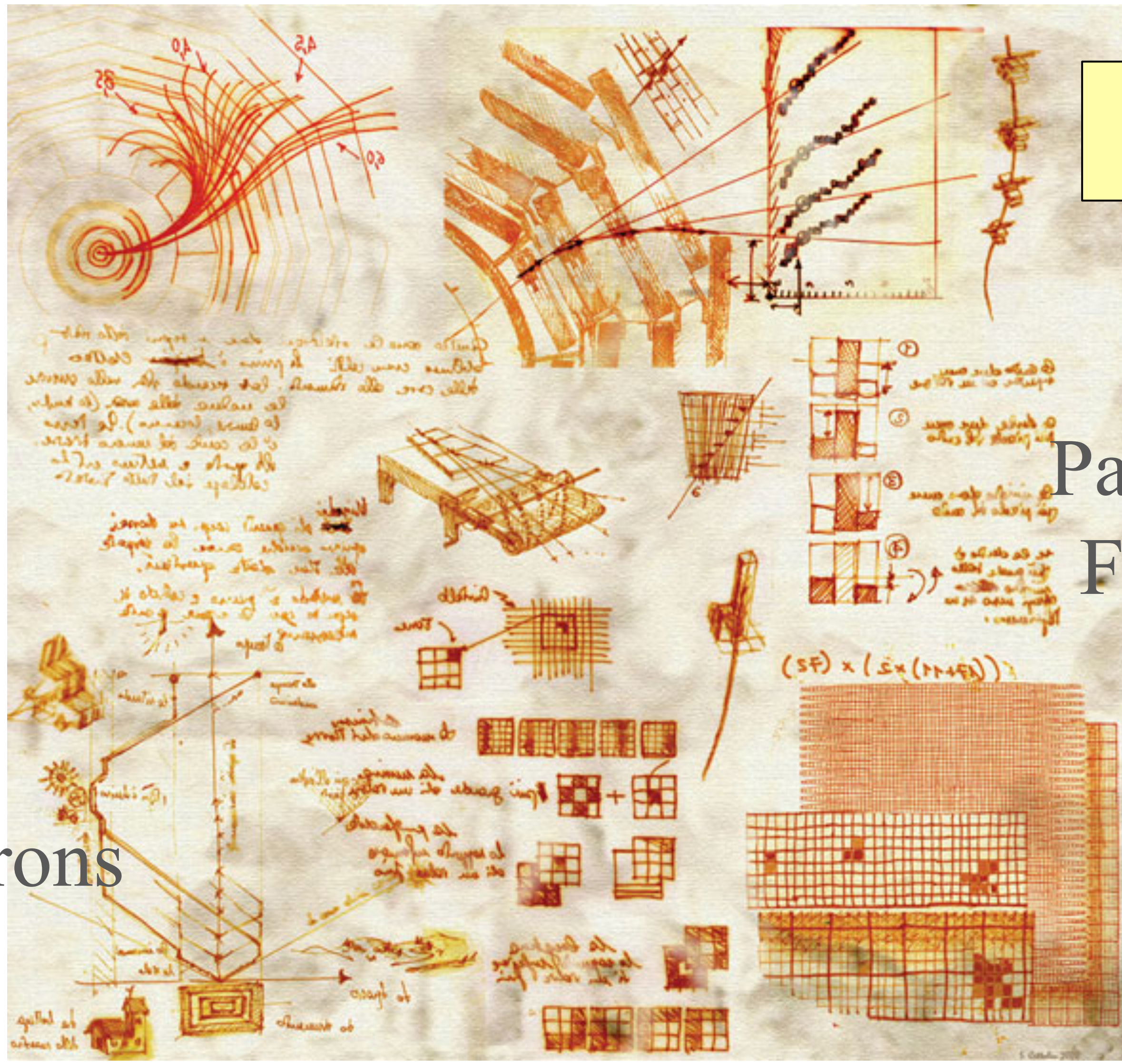


Detector Performance

Calorimetry Jets

Tracking

Particle-ID

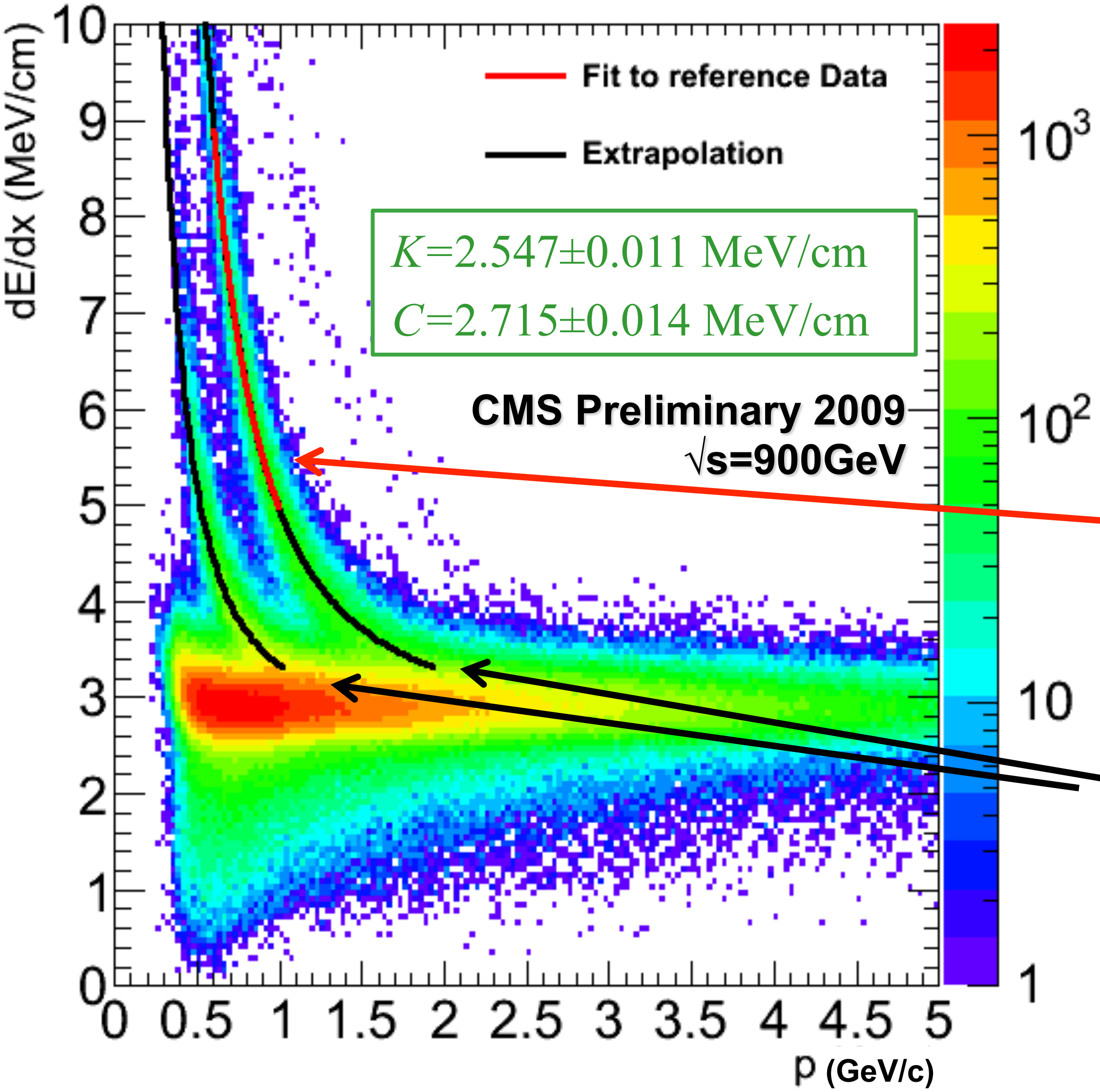


Muons

Particle Flow

Electrons

Tracker dE/dx as Particle-ID

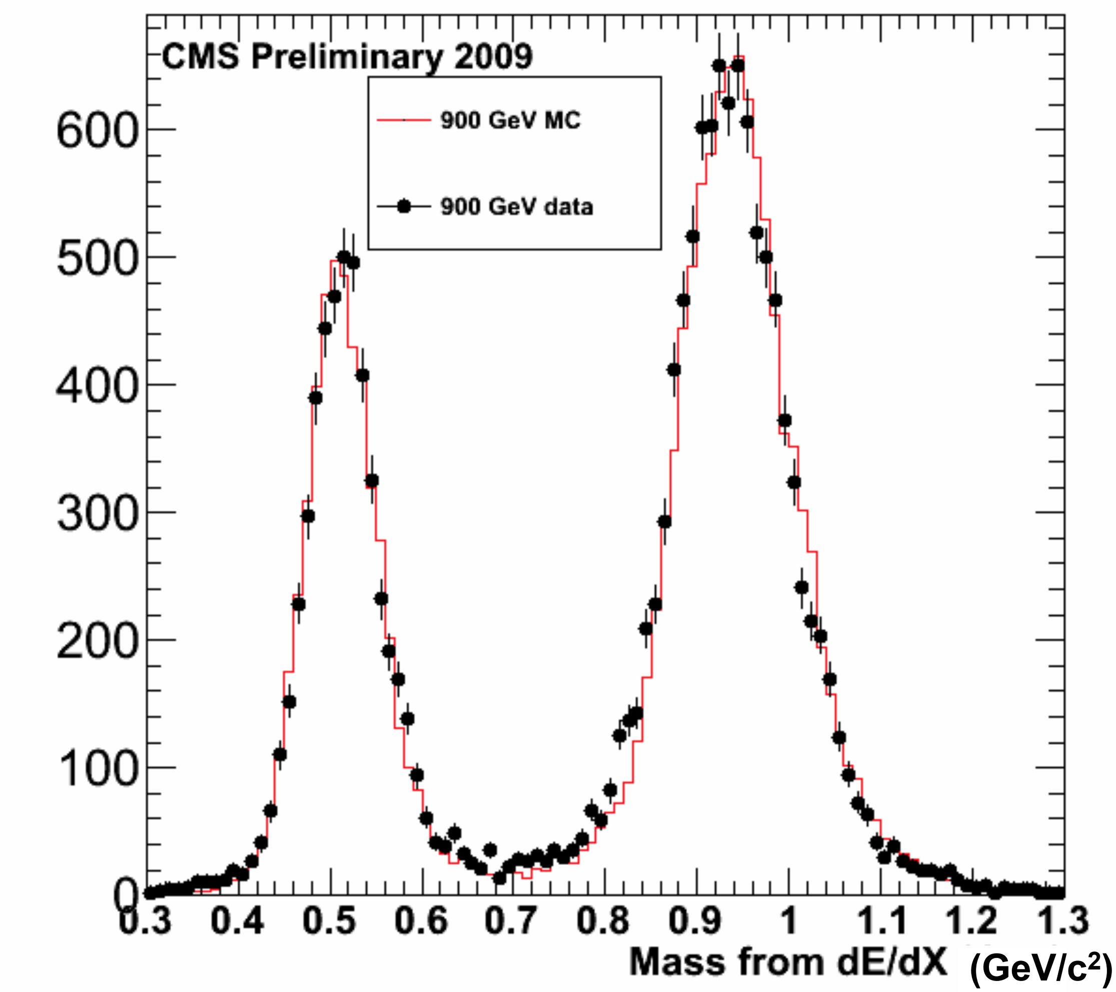


- dE/dx distribution can be fitted for various particles (p, *K*)

$$\frac{dE}{dx} = K\frac{M^2}{p^2} + C$$

- Use reference data for protons (red line)
- Extrapolate behavior for kaons & protons at higher momentum (black lines)
- Calculate mass by using dE/dx, p and reverting formula

Tracker dE/dx as Particle-ID



Tracks with

- $P < 2$ GeV/c
- # Silicon Strip hits > 10
- $|d_0| < 2$ cm, $dz < 15$ cm

$$M = p\sqrt{\left(\frac{dE}{dx} - C\right)K^{-1}}$$

Mass distribution of particles with dE/dx>4.15 MeV/cm

Protons and kaons clearly separated

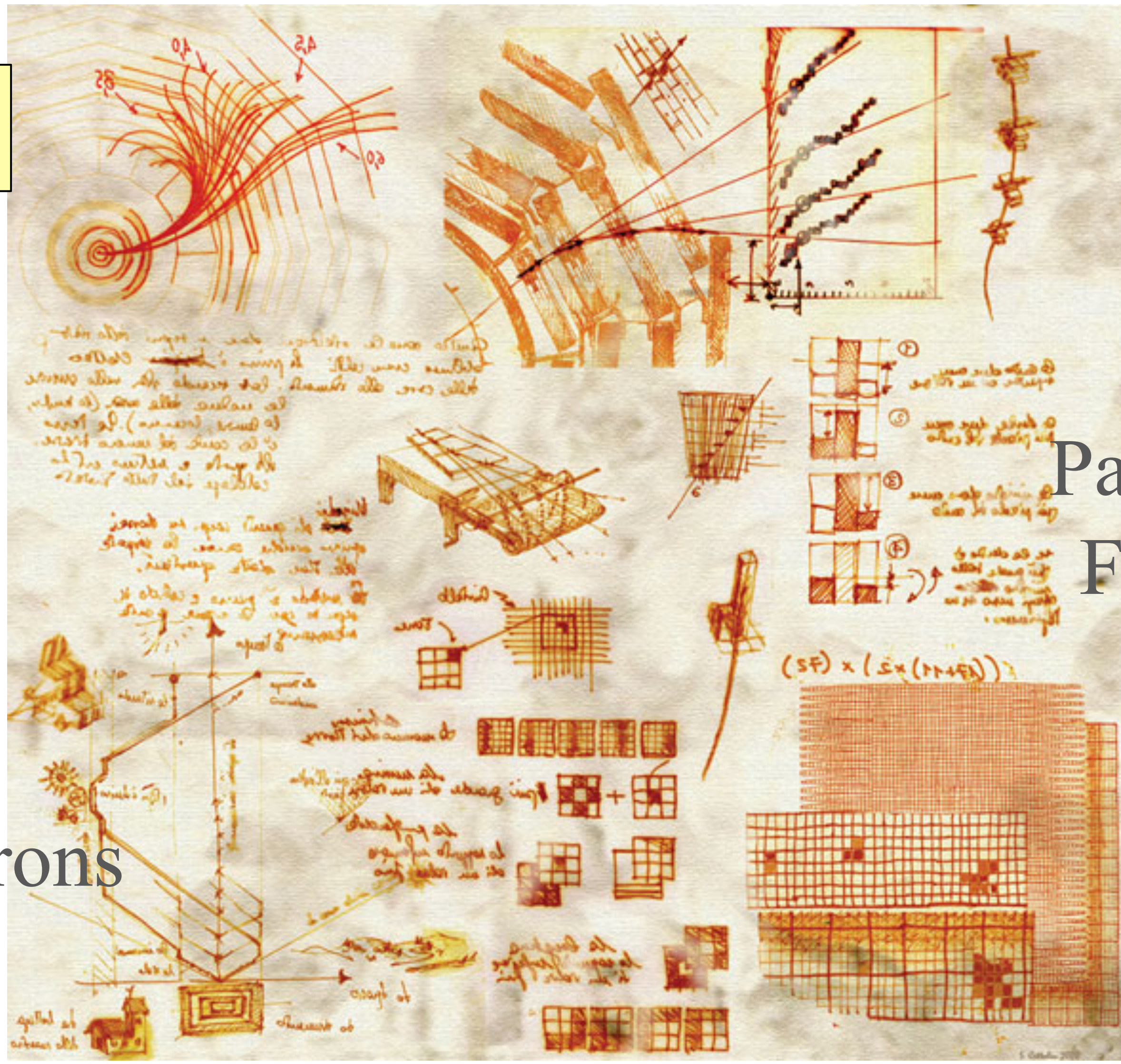
Detector Performance

Calorimetry

Jets

Tracking

Particle-ID



Muons

Particle Flow

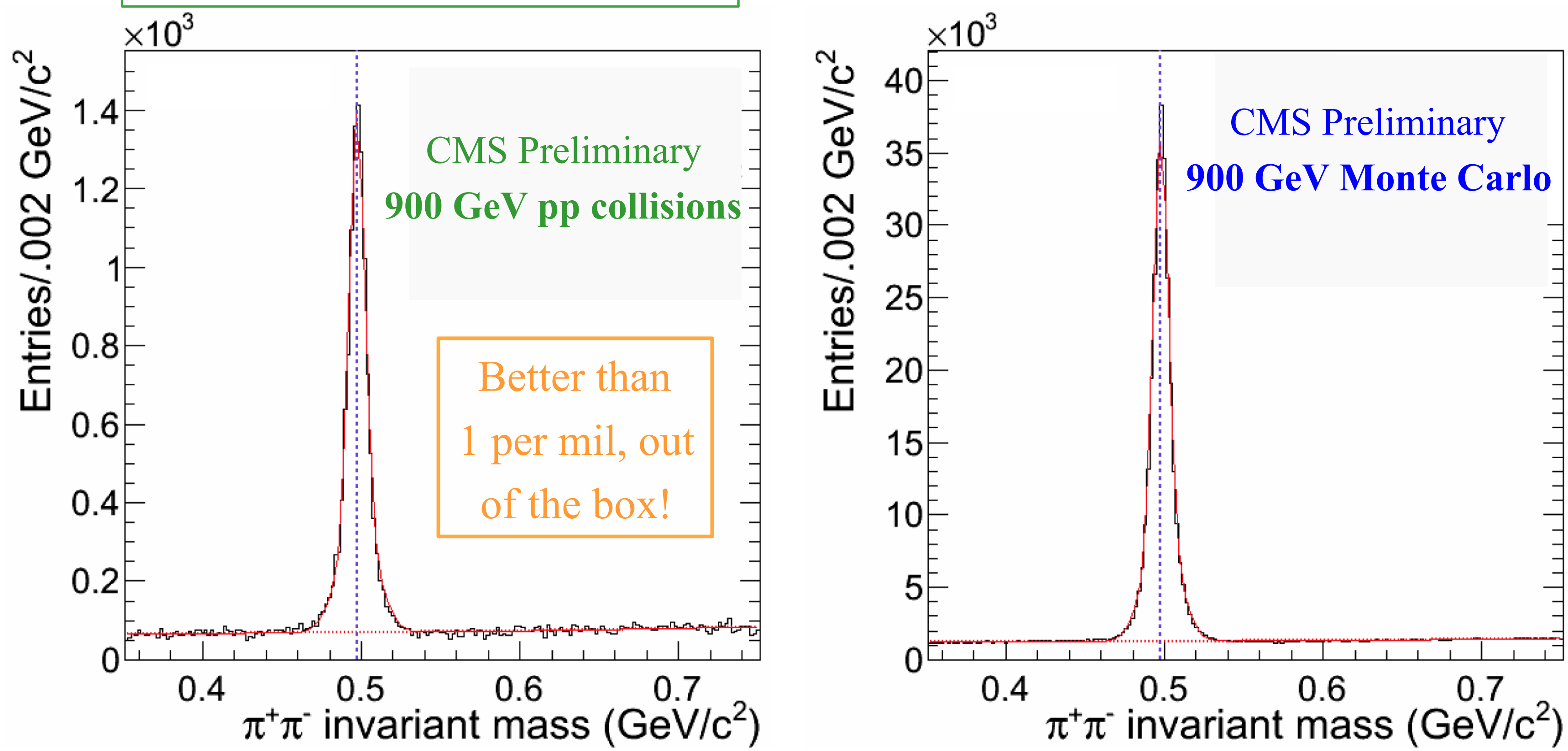
Electrons

Resonances

K_S

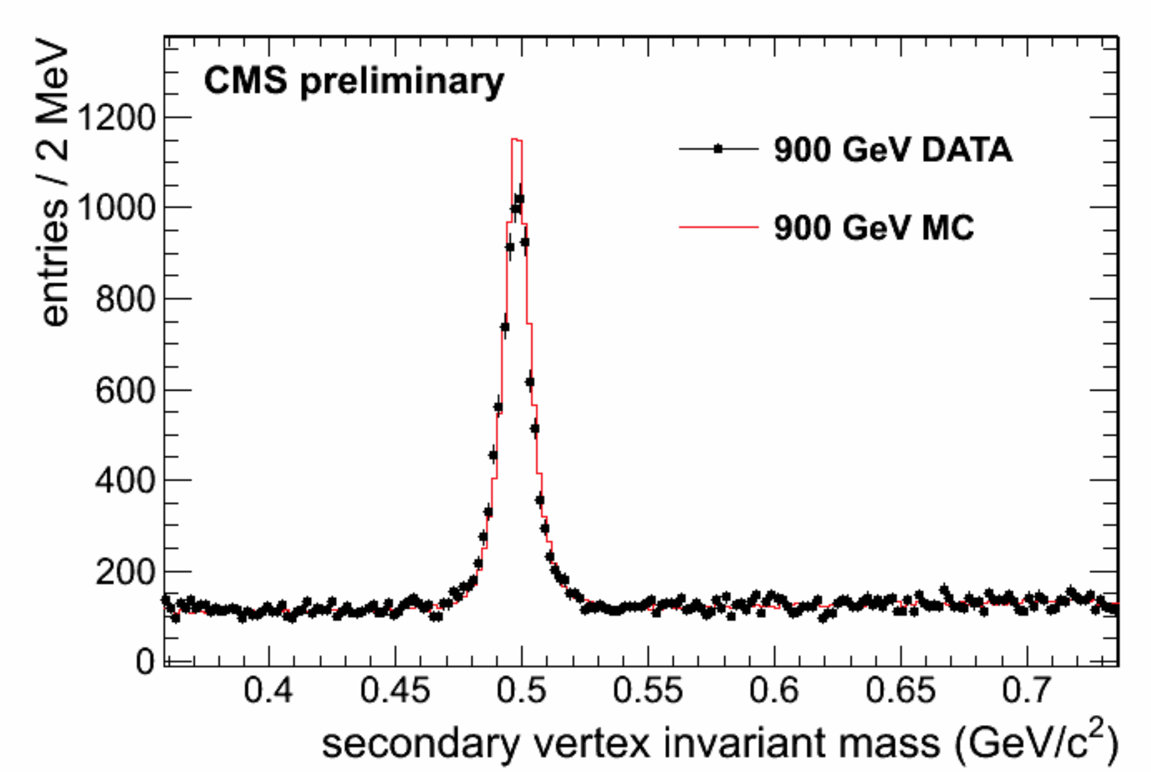
CMS Preliminary
900 GeV pp collisions
$M = (497.58 \pm 0.07)$ MeV/c^2
$\sigma_1 = (4.74 \pm 0.16)$ MeV/c^2
$\sigma_2 = (11.57 \pm 0.57)$ MeV/c^2

CMS Preliminary
900 GeV Monte Carlo
$M = 497.97$ MeV/c^2
$\sigma_1 = 4.4$ MeV/c^2 , $\sigma_2 = 10.4$ MeV/c^2

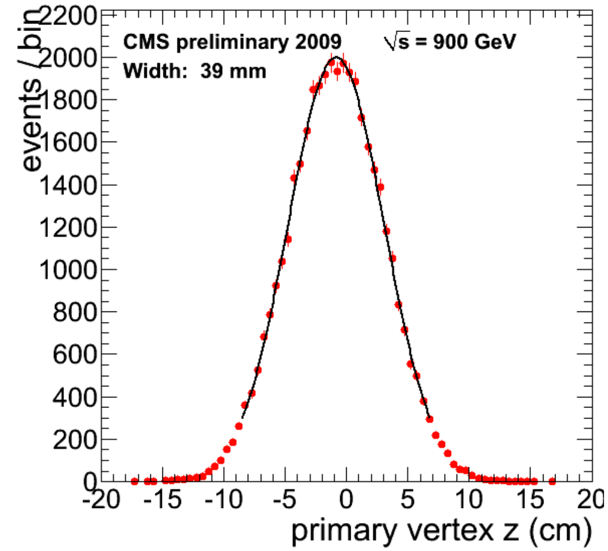


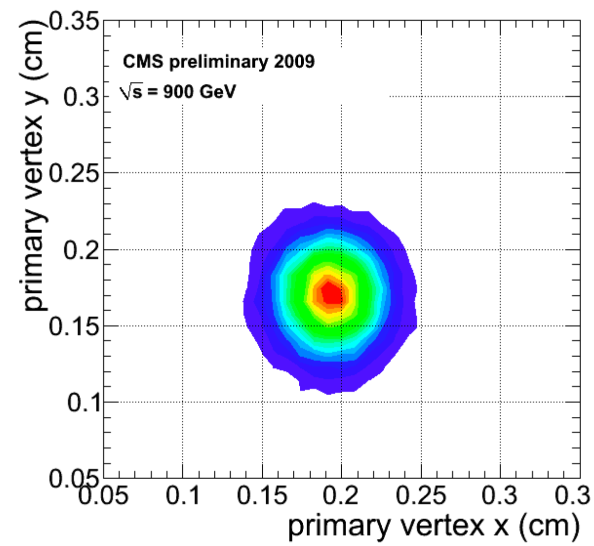
Double Gaussian Fits (From a sample of ~240k minimum bias events)

K^o_s for physics commissioning



Primary Vertex





K_s as vertexing & *b*-tagging commissioning tool

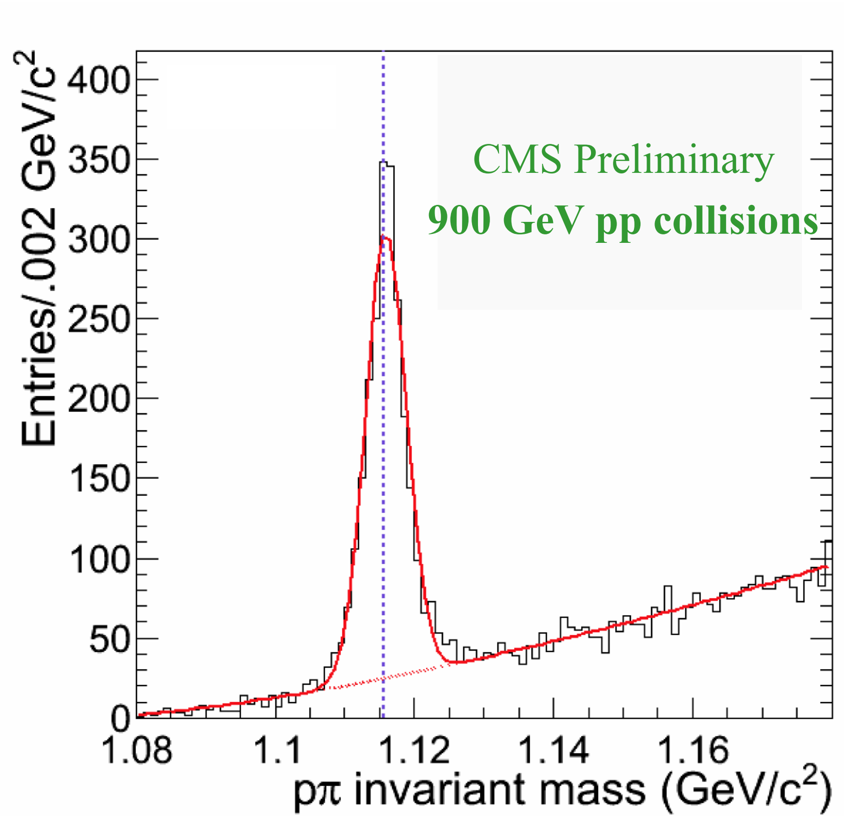
- Invariant mass of ≥2 track vertices found by Secondary Vertex *B* tagger
- Low background → low mistag rate

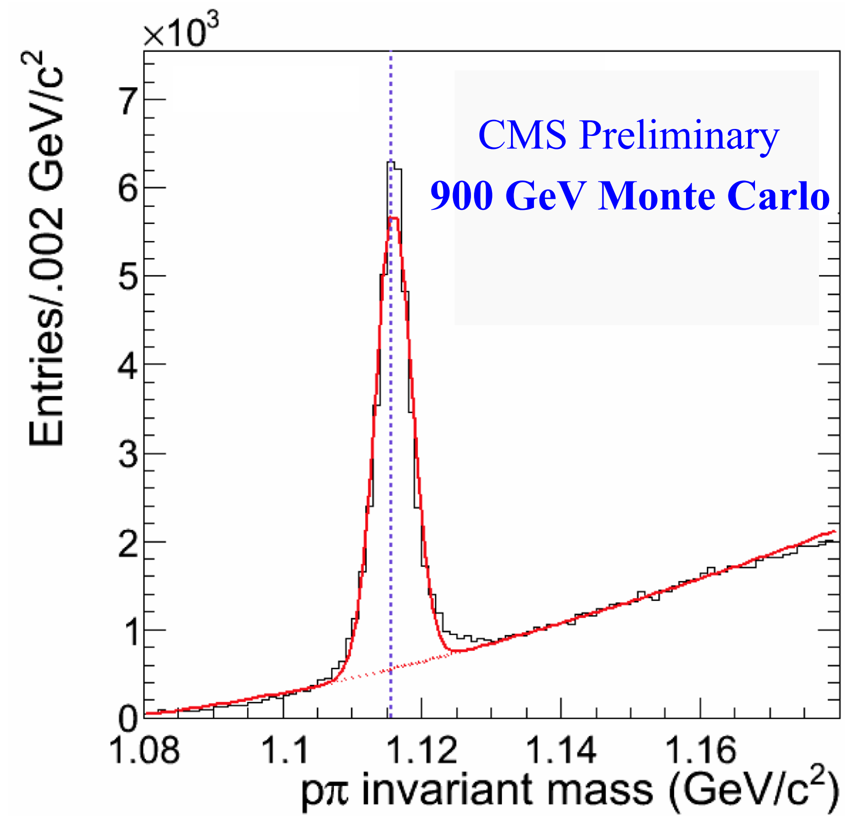
Λ

CMS Preliminary
900 GeV pp collisions
M = (1115.9 ± 0.1) MeV/c^2
σ = (2.93 ± 0.08) MeV/c^2

Uses dE/dx information to reduce background

CMS Preliminary
900 GeV Monte Carlo
M = 1116 MeV/c^2
σ = 2.6 MeV/c^2





Single Gaussian Fits (From a sample of ~240k minimum bias events)

$\phi \to K^+K^-$

- Fit: Gaussian convoluted with Breit-Wigner
- Uses dE/dx information to reduce background

CMS Preliminary: **900 GeV pp collisions**

1318 ± 95 ϕ candidates

$M = (1.01937 \pm 0.00030)$ GeV/c^2

$\sigma = (1.69 \pm 0.50)$ MeV/c^2

Γ: fixed at PDG2009 value (4.260 MeV/c^2)

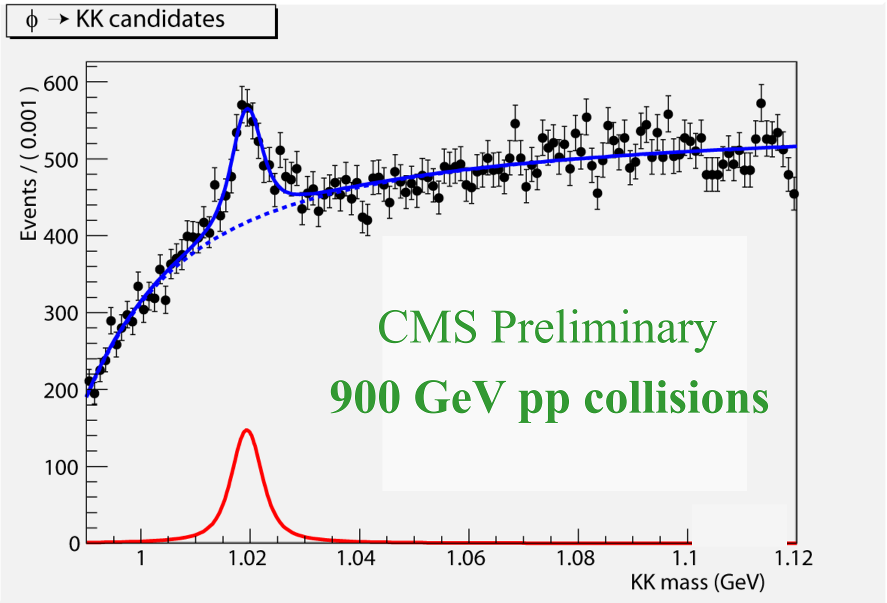
CMS Preliminary: **900 GeV Monte Carlo**

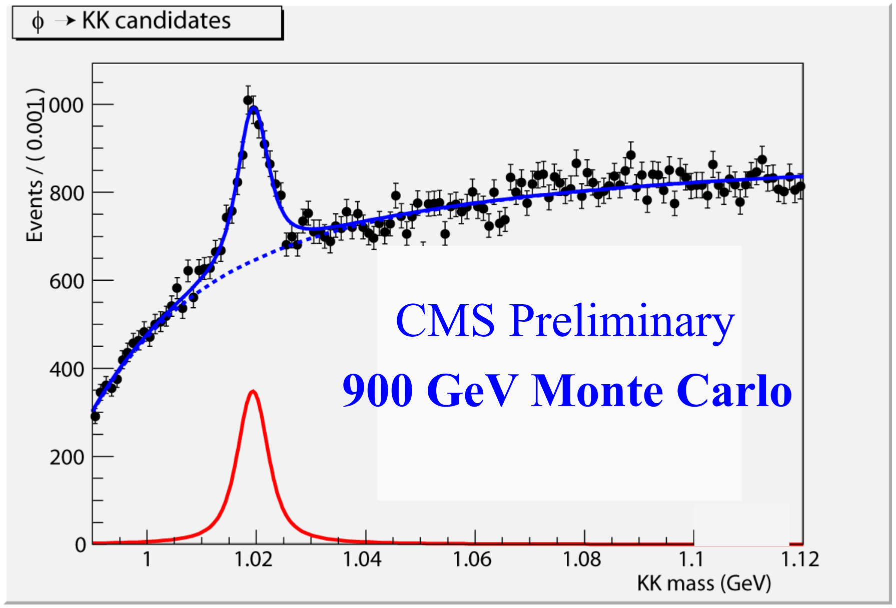
$M = (1.01935 \pm 0.00016)$ GeV/c^2

$\sigma = (1.64 \pm 0.23)$ MeV/c^2

Γ: fixed at PDG2001 value (4.458 MeV/c^2)

[used to generate Monte Carlo sample]

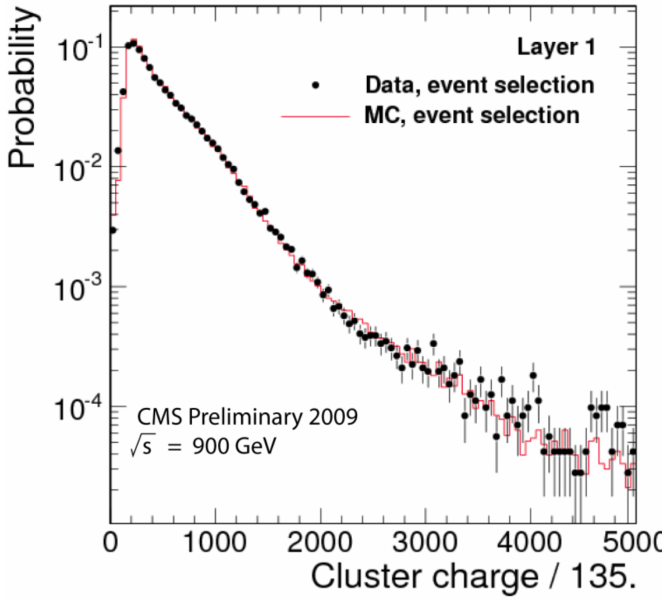


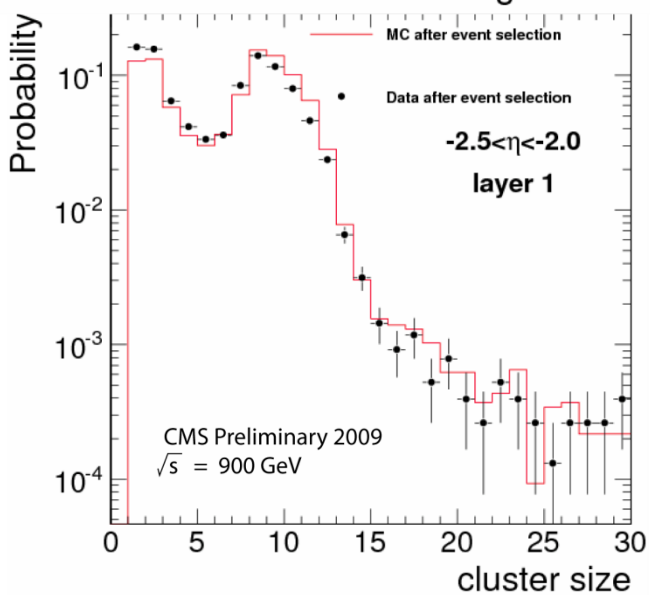


Tracking distributions

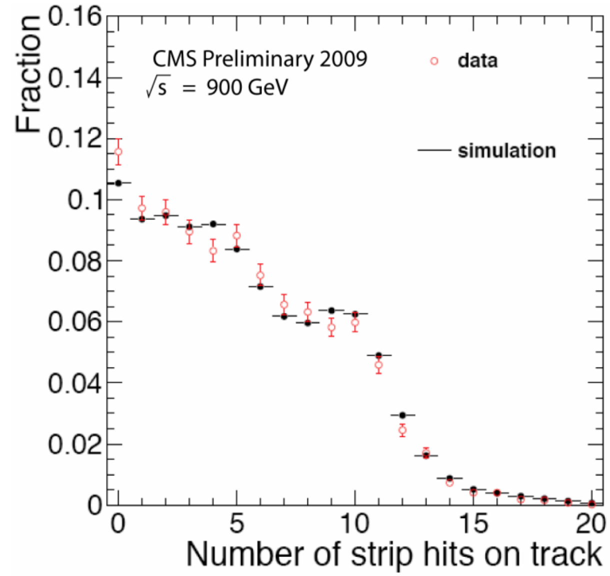
Tracking distributions

Pixels Clusters

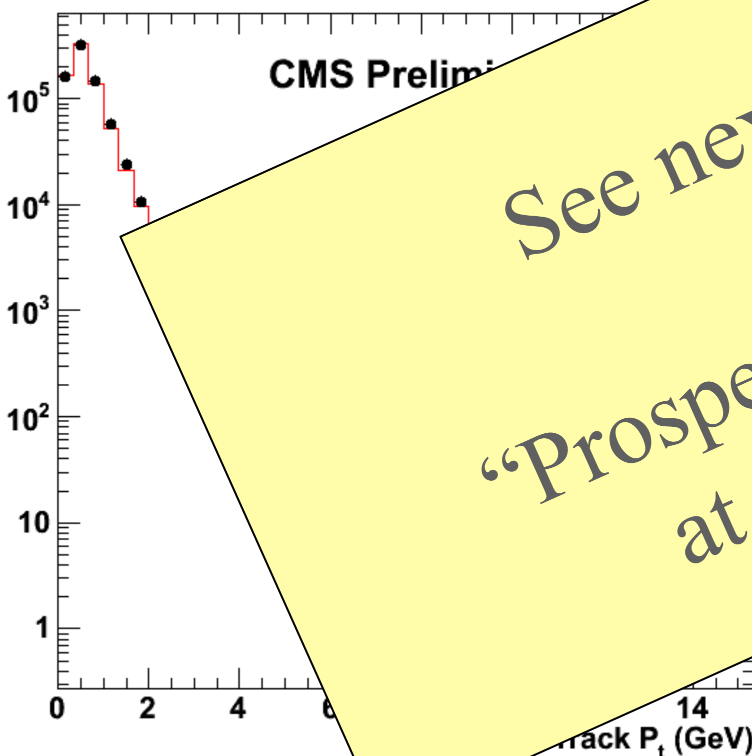




Strip Tracker



Tracking P_T distributions



See next talk:

"Prospects for QCD at the LHC"

00 tracks

flag

10%

on η or p_T

Tracking P_T distributions

Charged Particle Multiplicity

Average p_T

See next talk:

"Prospects for QCD at the LHC"

Detector Performance

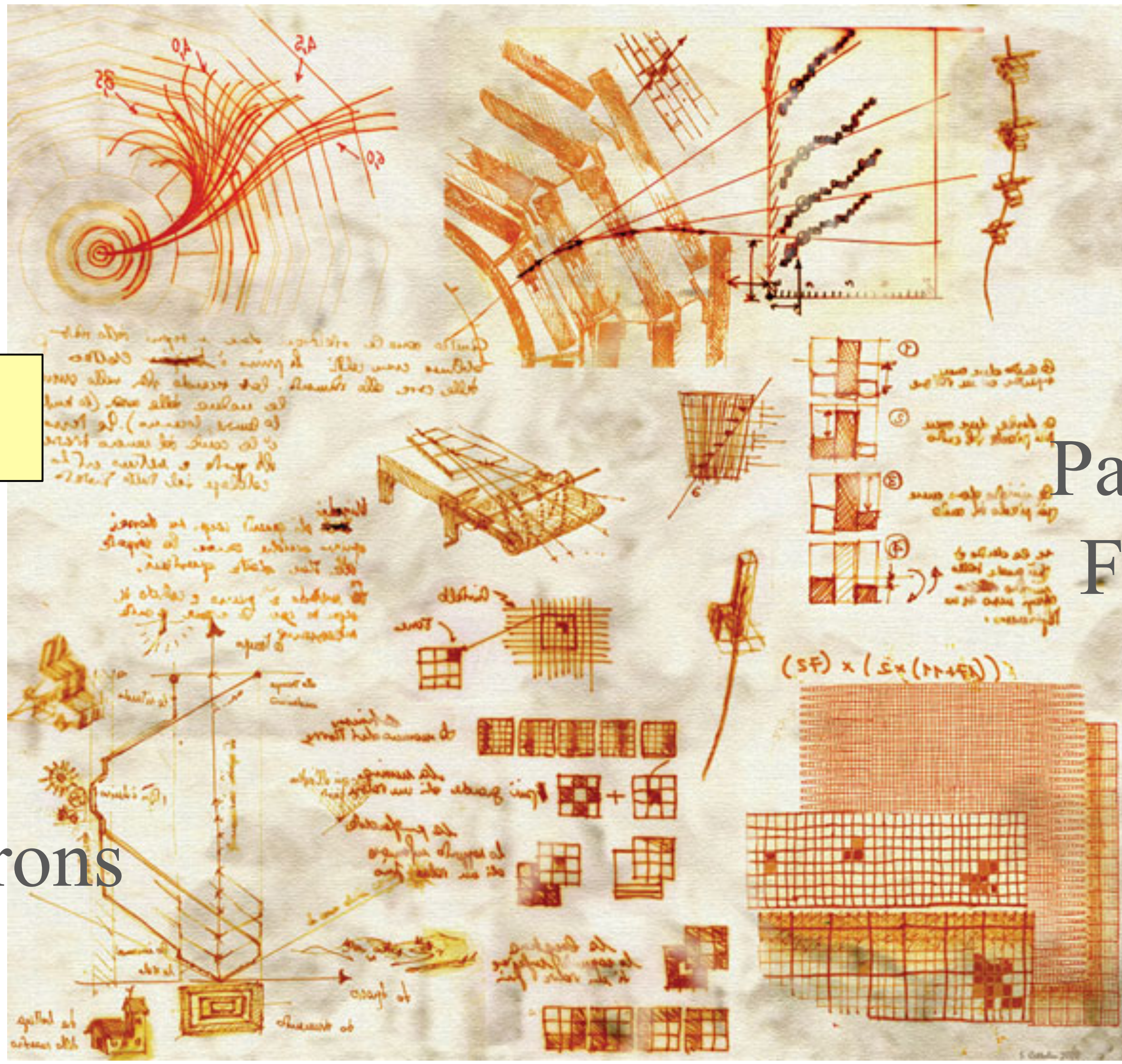
Calorimetry

Jets

Tracking

Particle-ID

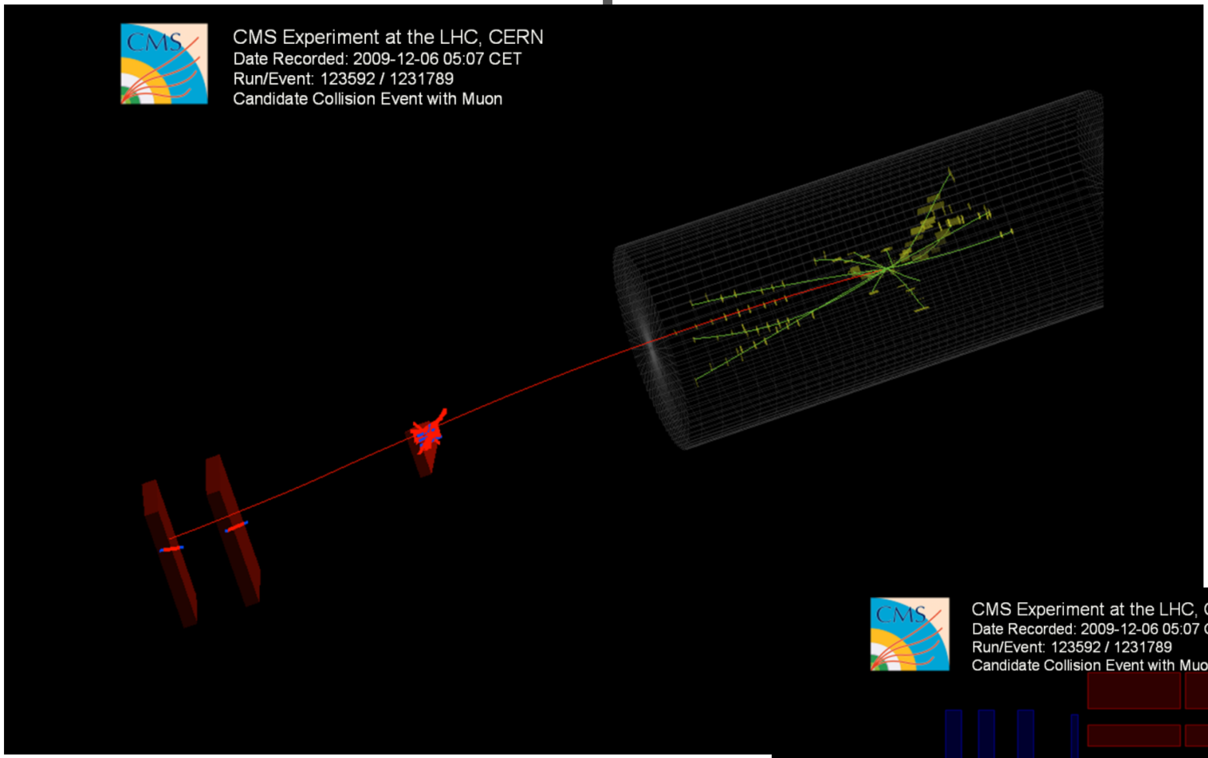
Muons

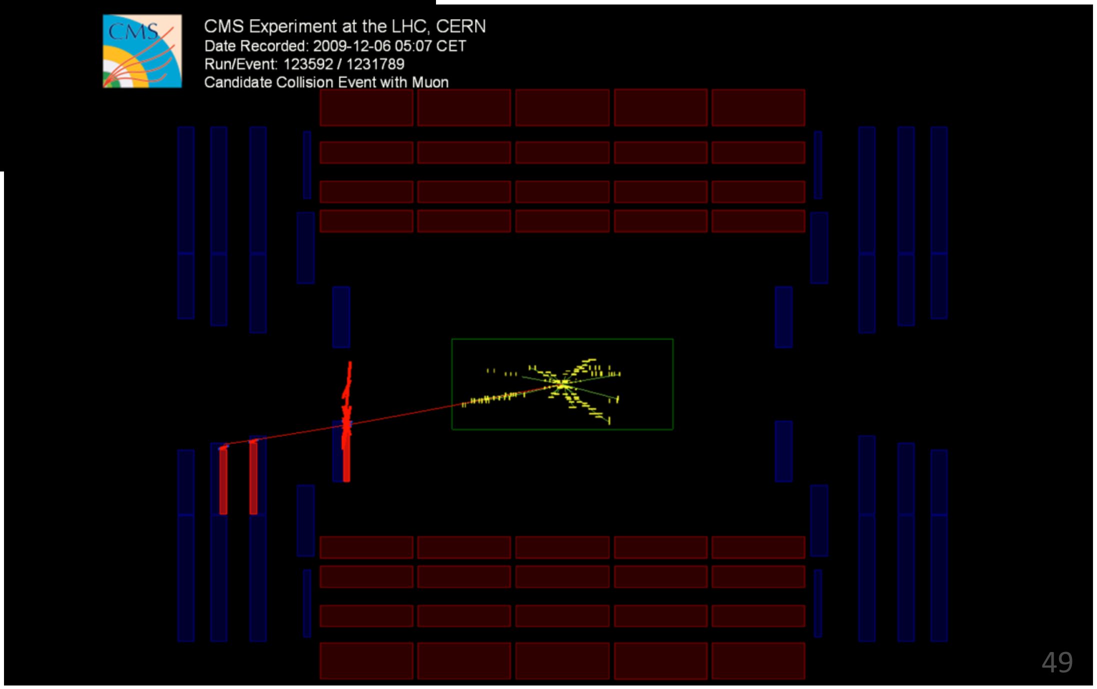


Particle Flow

Electrons

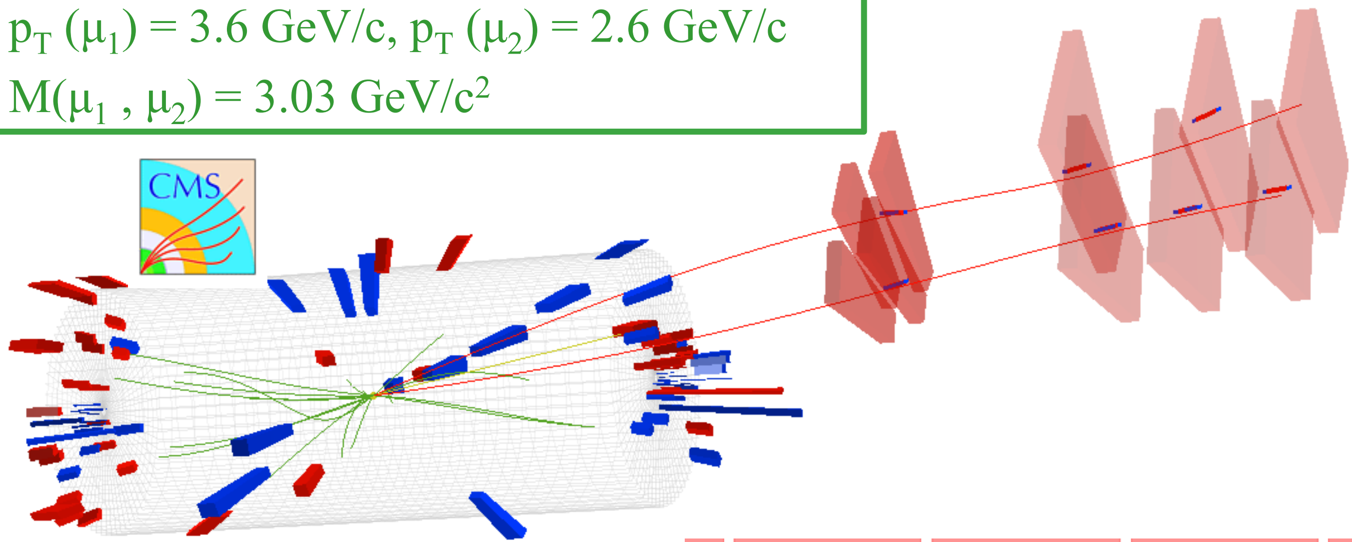
Endcap Muon Candidate

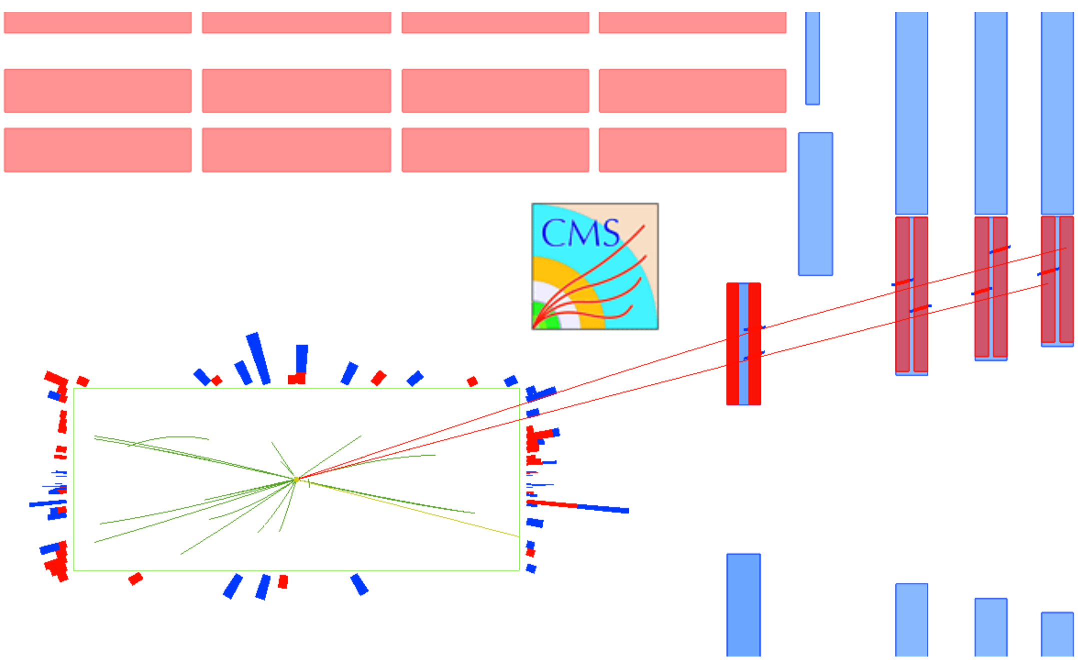




Dimuon Event at 2.36 TeV

- $p_T(\mu_1) = 3.6$ GeV/c, $p_T(\mu_2) = 2.6$ GeV/c
- $M(\mu_1, \mu_2) = 3.03$ GeV/c^2

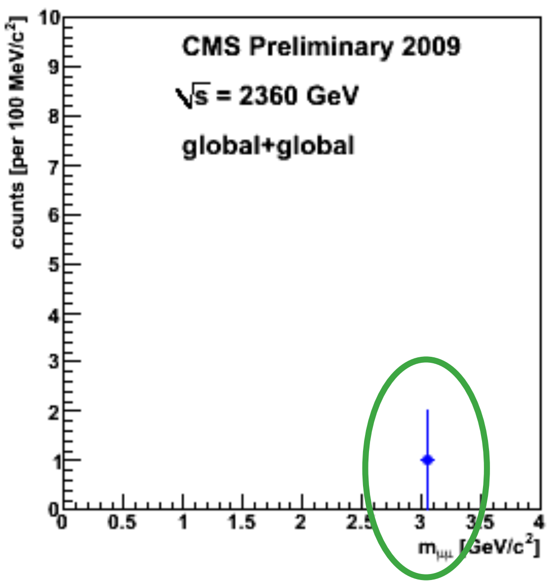




Dimuon Events at 2.36 TeV

- Expected one $J/\psi \rightarrow \mu\mu$ event in 500k min.bias events at 2.36 TeV

- Got one $J/\psi \rightarrow \mu\mu$ candidate in 20k events



- S/B ratio: 16/1 in [3.0, 3.2] GeV/c^2 region (background: ~ 0)

Detector Performance

Calorimetry

Jets

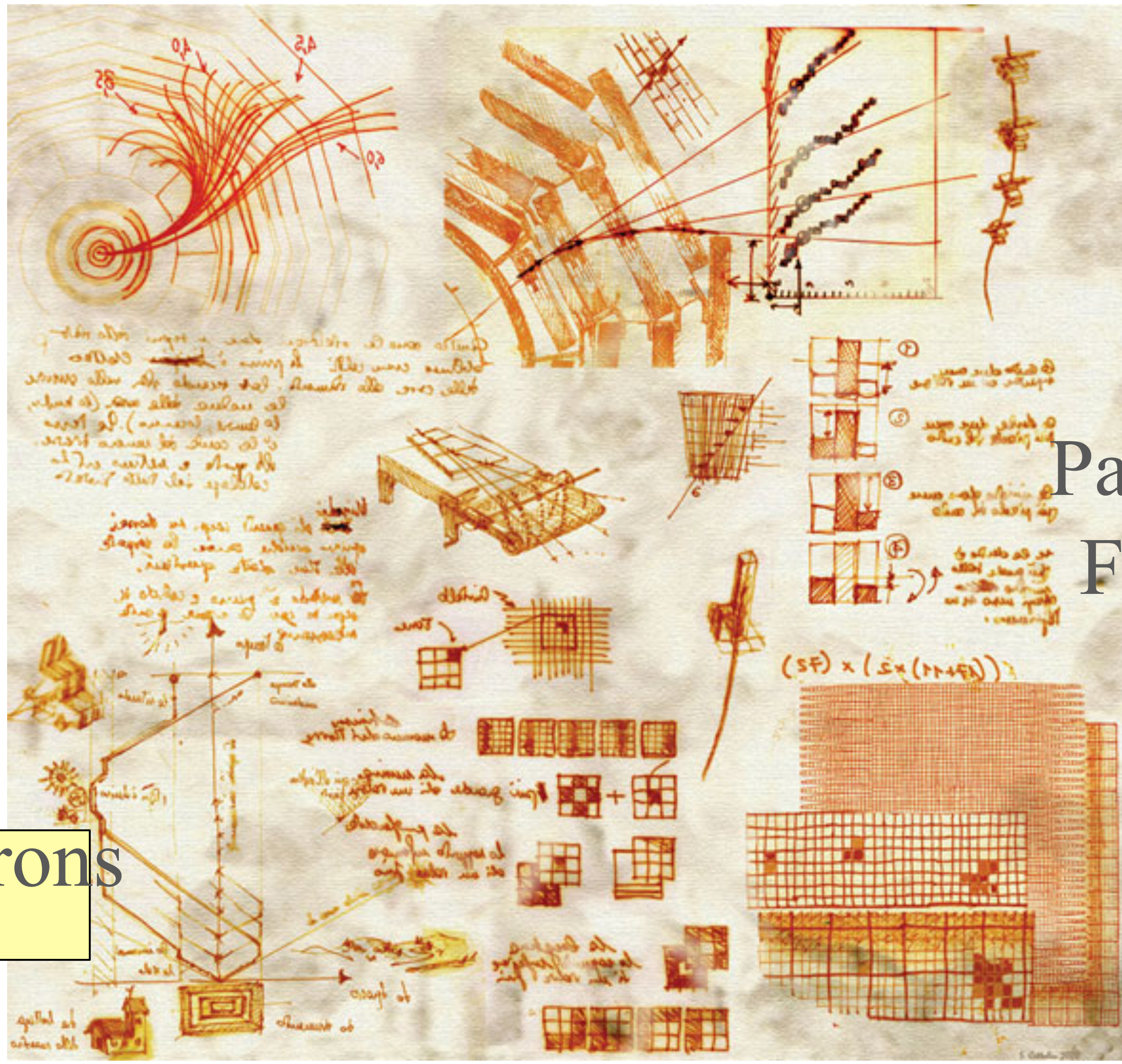
Tracking

Particle-ID

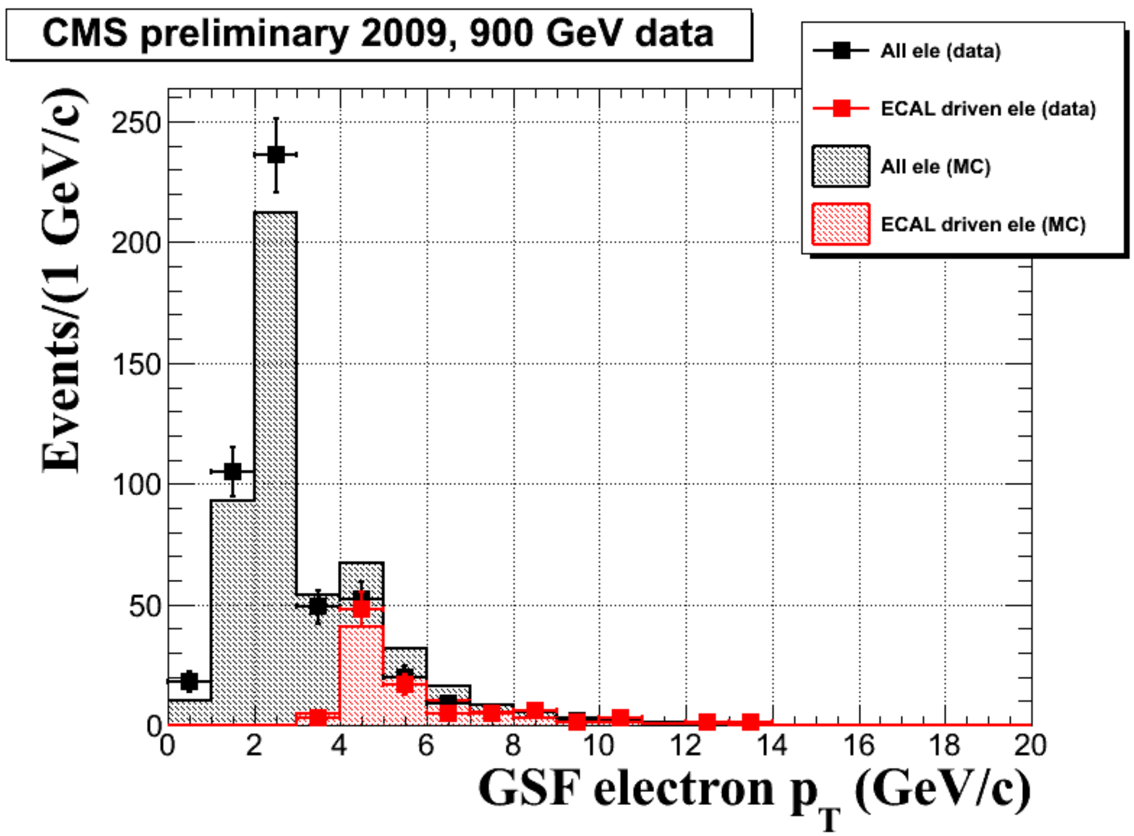
Muons

Particle Flow

Electrons



Electron p_T spectrum



Electron transverse momentum distribution as reconstructed in 900 GeV data (points) and 900 GeV MC (filled histos)

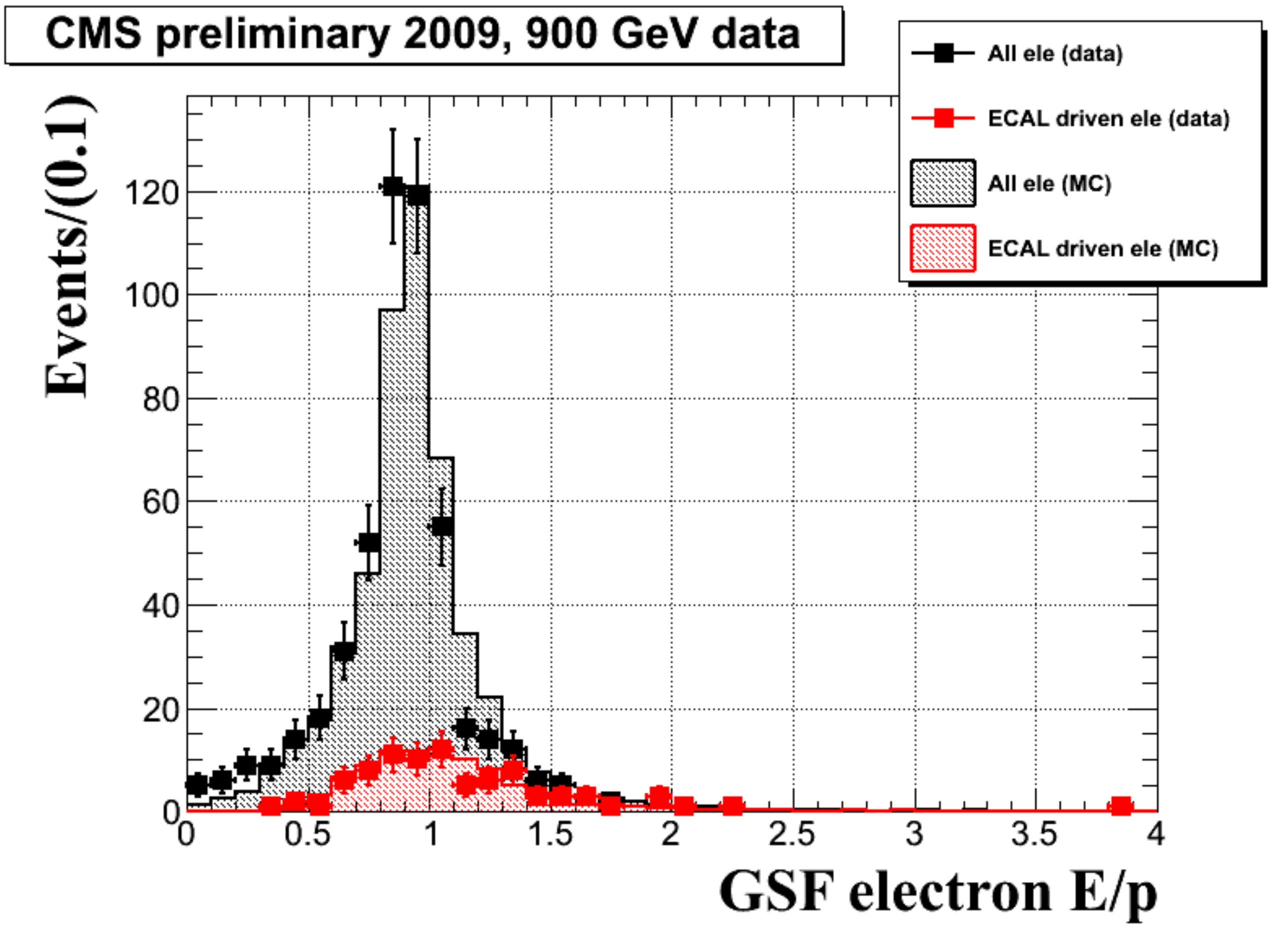
In black: all electrons (tracker driven + ECAL driven)

In red: only ECAL driven

MC is normalized to the same number of entries

Gaussian Sum Filter: R. Frühwirth, T. Speer: Nucl. Instrum. Methods Phys. Res., A 534 , 1-2 (2004) 217-221

Electron *E*/*p*



E / p distribution for electrons in 900 GeV data (points) and 900 GeV MC (filled histos)

In black: all electrons (tracker driven + ECAL driven)
In red: only ECAL driven

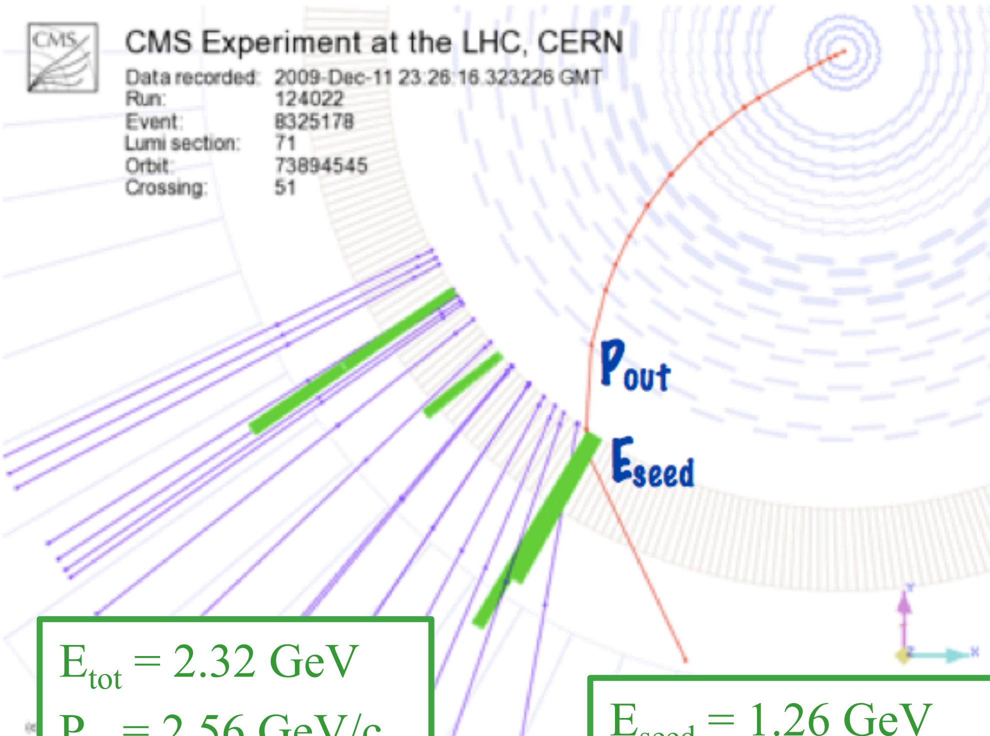
MC is normalized to the same number of entries

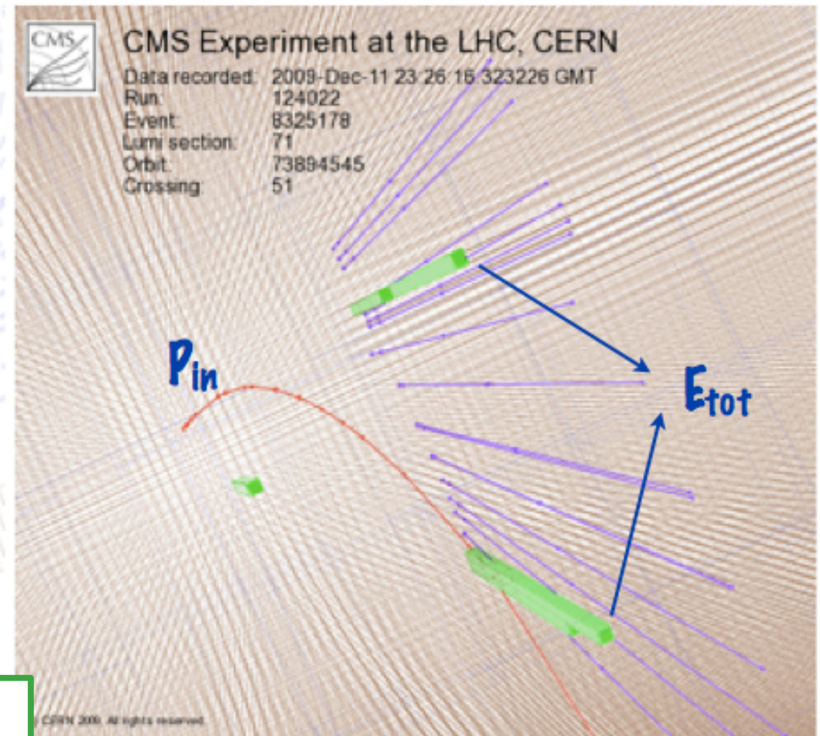
* Gaussian Sum Filter: R. Frühwirth, T. Speer: Nucl. Instrum. Methods Phys. Res., A 534 , 1-2 (2004) 217-221

Electron candidates in Particle Flow

For each tracker layer: use tangent extrapolation to find associated electron and Brem clusters

900 GeV data





$E_{tot} = 2.32$ GeV
$P_{in} = 2.56$ GeV/c
$E_{tot}/P_{in} = 0.91$

Initial electron parameters (in)

$E_{seed} = 1.26$ GeV
$P_{out} = 1.18$ GeV/c
$E_{seed}/P_{out} = 1.07$

Final electron parameters (out)

$E_{brem} = 1.06$ GeV
$P_{in} - P_{out} = 1.38$ GeV/c

Brem evaluation: calorimeter vs tracking

Detector Performance

Calorimetry

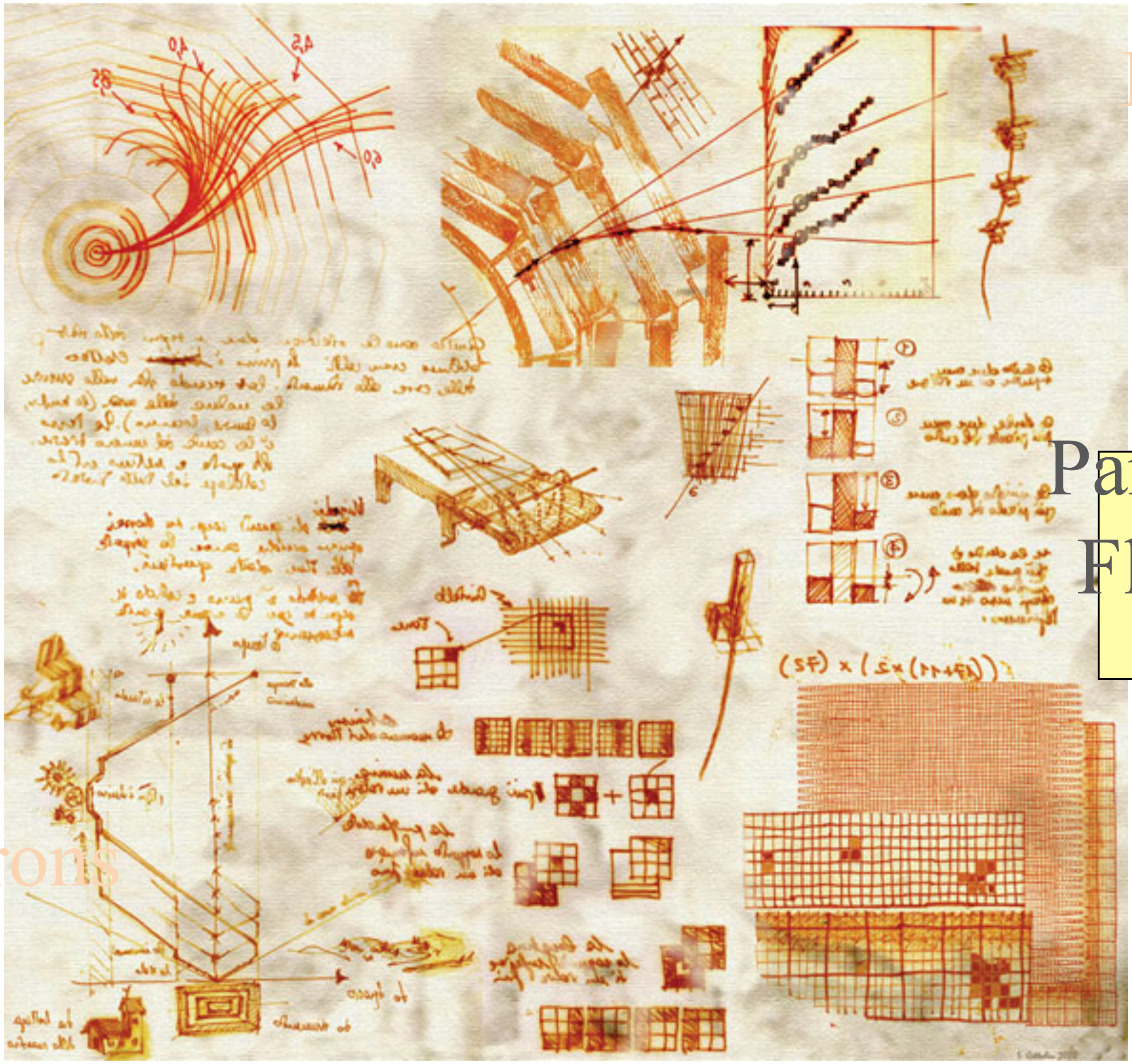
Jets

Tracking

Particle-ID

Muons

Electrons



Particle Flow

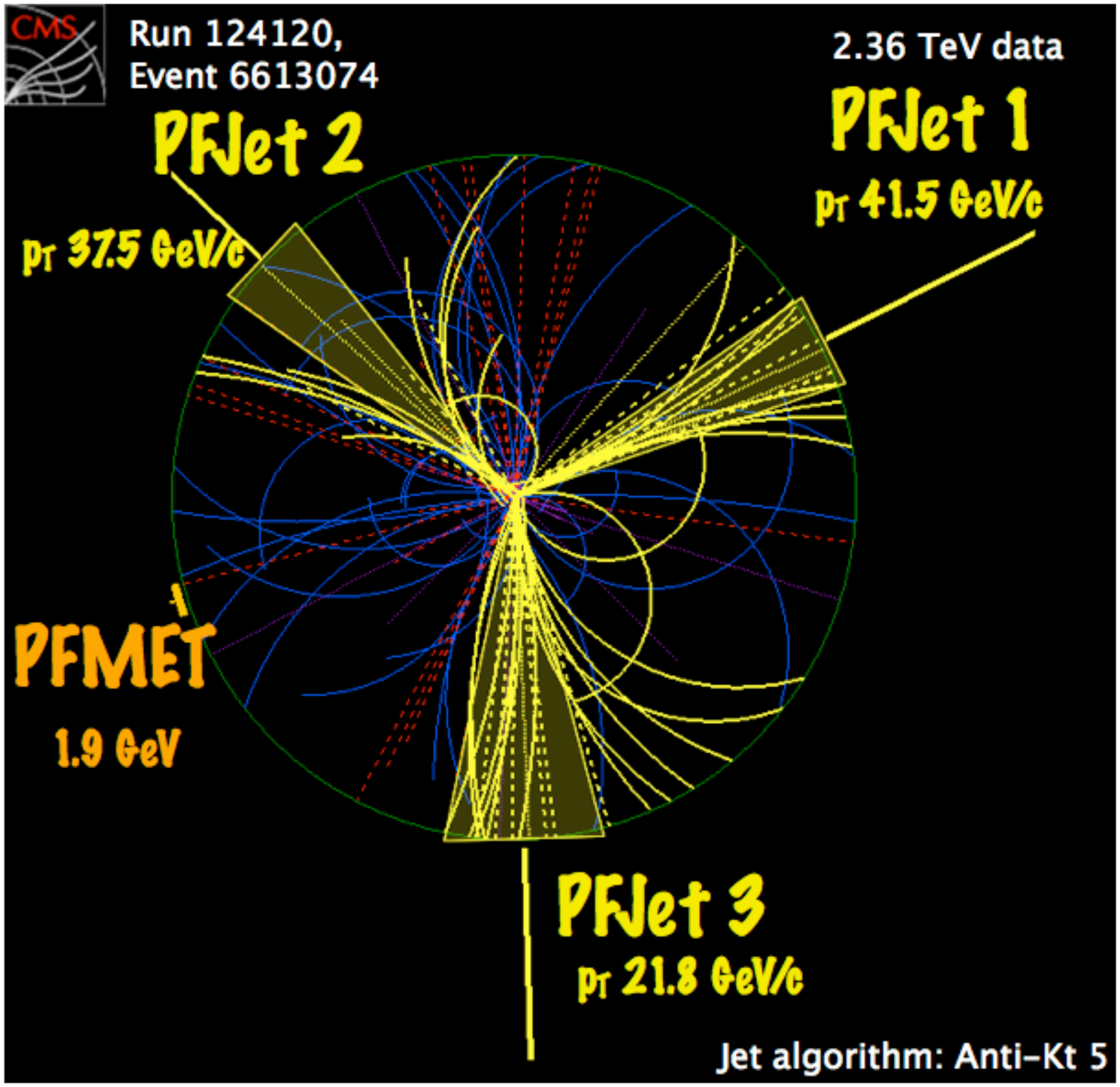
Particle Flow

- Particle Flow: Full Event reconstruction
  - Topological matching between charged particle momenta measured with tracker with clusters in calorimeter
  - Corrects for energy loss along trajectories
  - Better precision, full event info

- High-level object: requires holistic detector view
  - Excellent tracker
  - High E/M calorimeter granularity (0.017×0.017)
  - Strong magnetic field to separate tracks

- CMS very well suited for P-Flow reconstruction

Multi jet event @ 2.36 TeV



PFJets with (uncorrected) p_T > 20 GeV/c

Particle inside the jet:

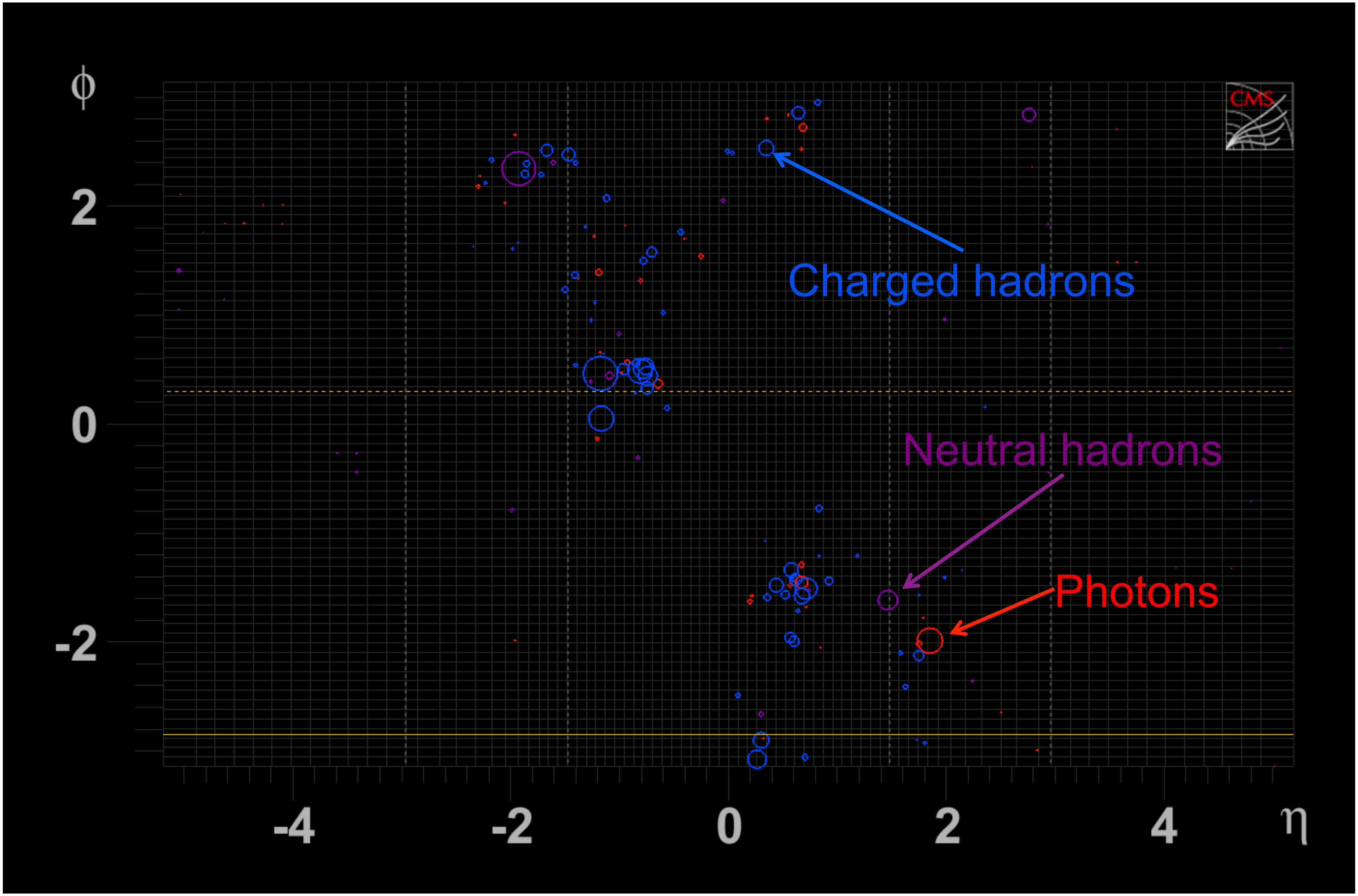
- Charged hadrons
- Photons
- Neutral hadrons

Particles outside the jet:

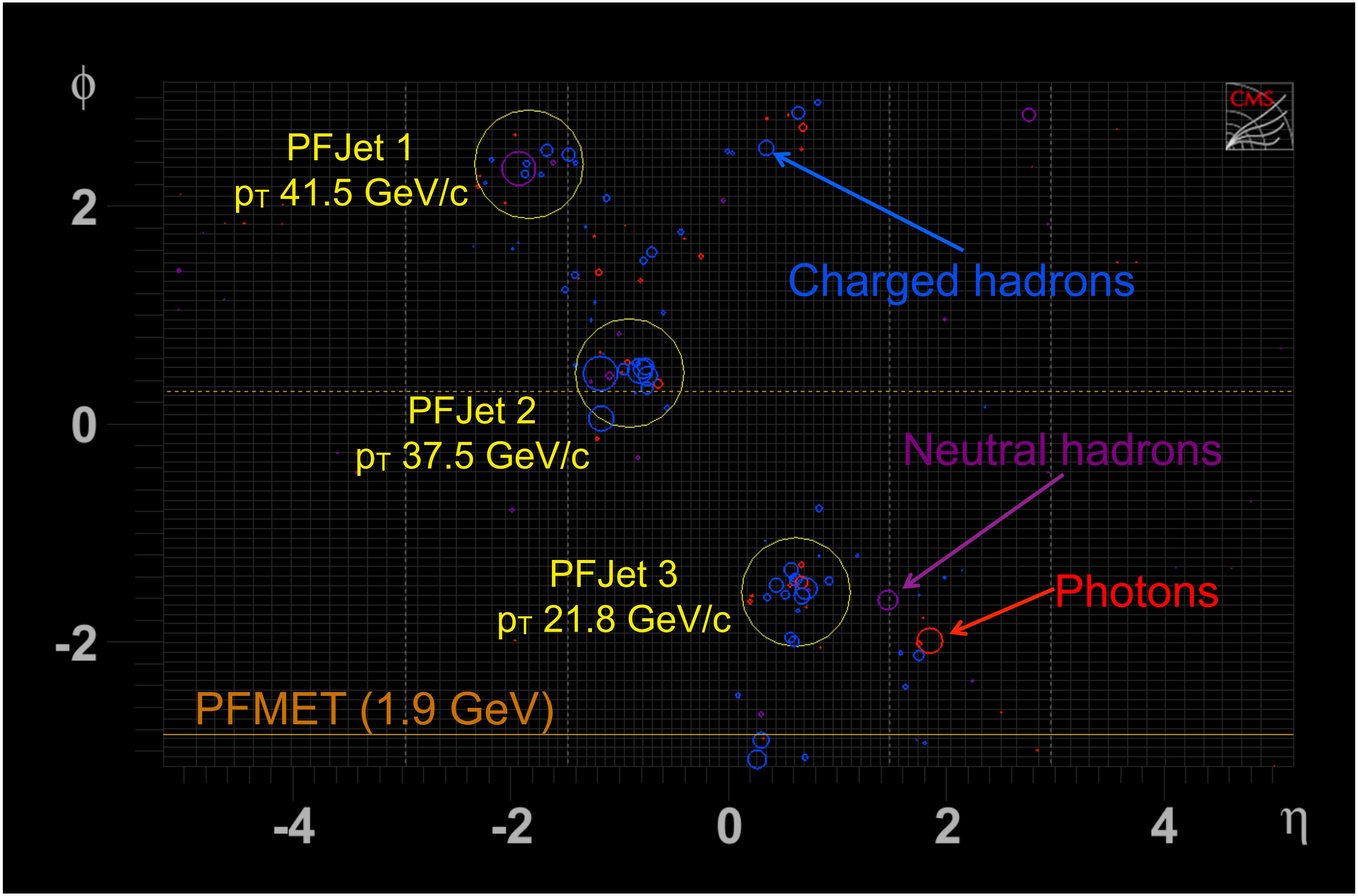
- Charged hadrons
- Photons
- Neutral hadrons

PFMET (1.9 GeV)

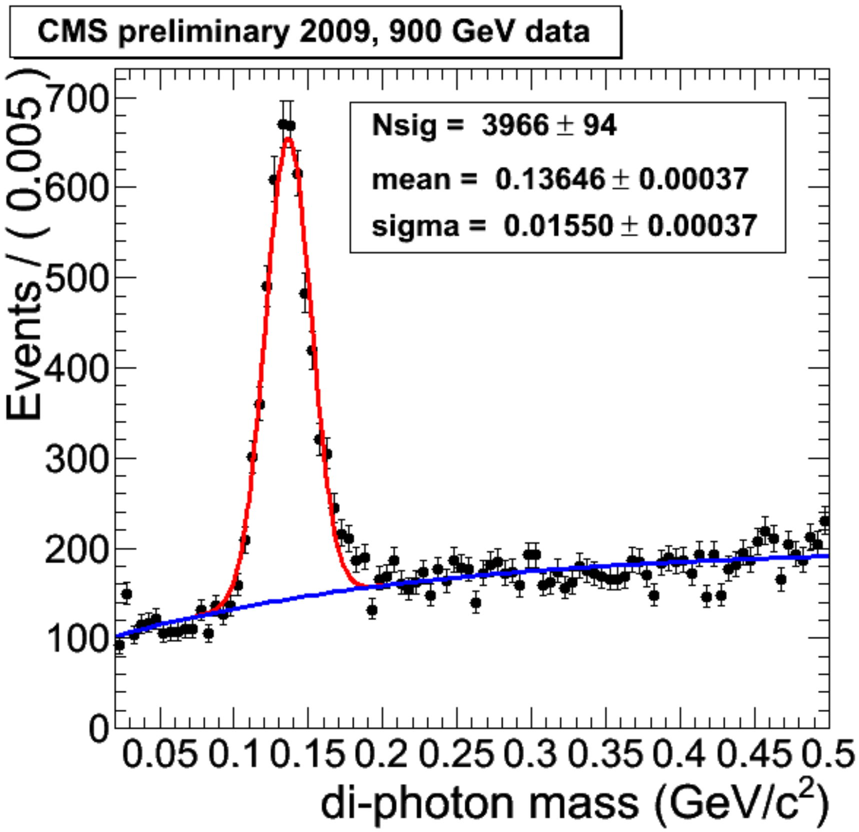
Multi jet event @ 2.36 TeV



Multi jet event @ 2.36 TeV

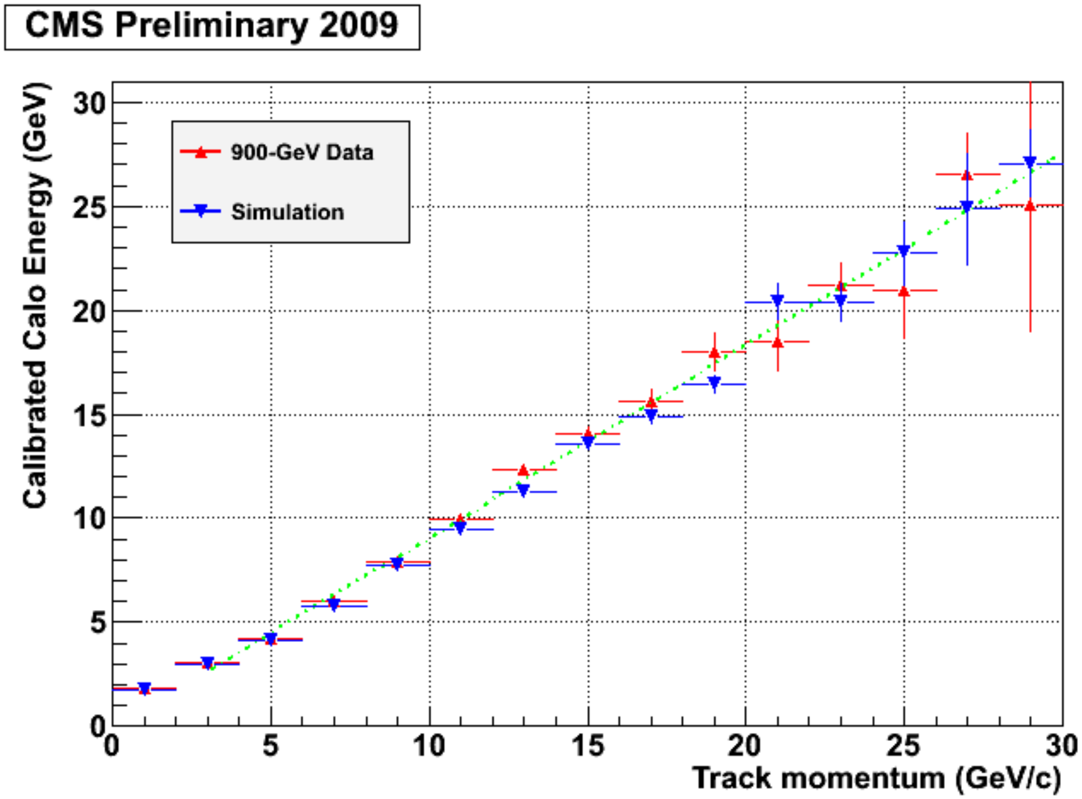


Calibration: $\pi^0 \to \gamma\gamma$



Using "out of the box" corrections to account for readout threshold (100 MeV/crystal) and conversions

Charged hadron response



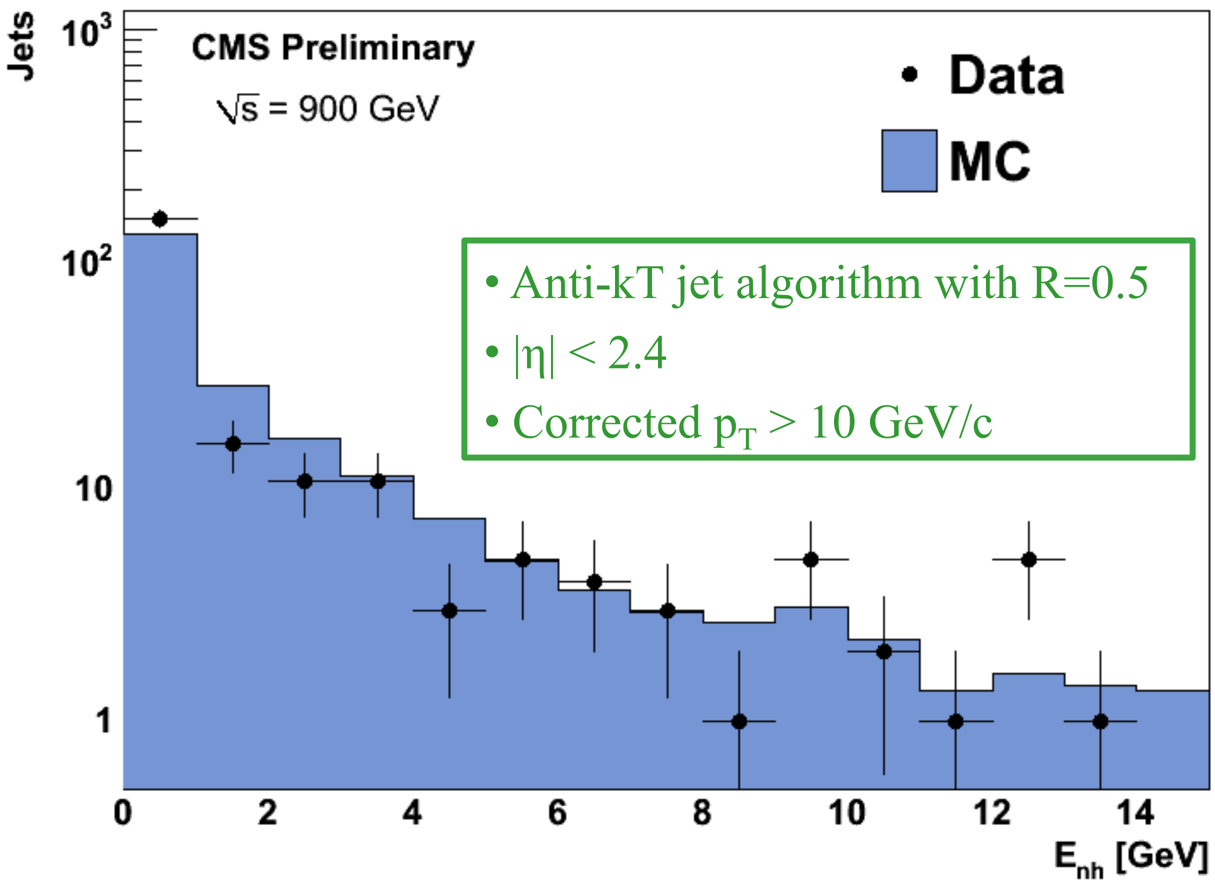
Selection:

- Tracks with $p_T > 1$ GeV/c and $|\eta| < 2.4$
- # hits > 14 and # of pixel hits > 1
- HCAL hits associated with track
- Only one track associated with Jet

Linear fit on data above 3 GeV/c

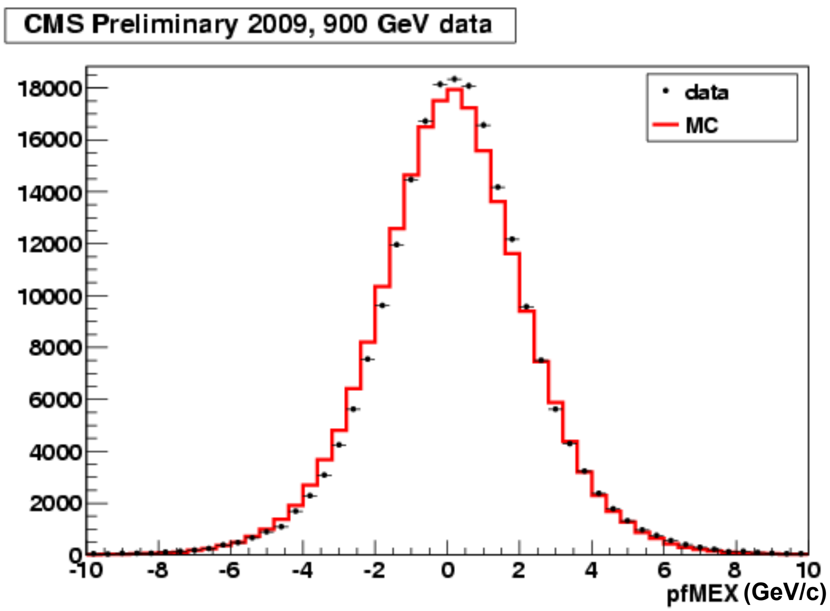
- Out of the box MC-based calibration is validated

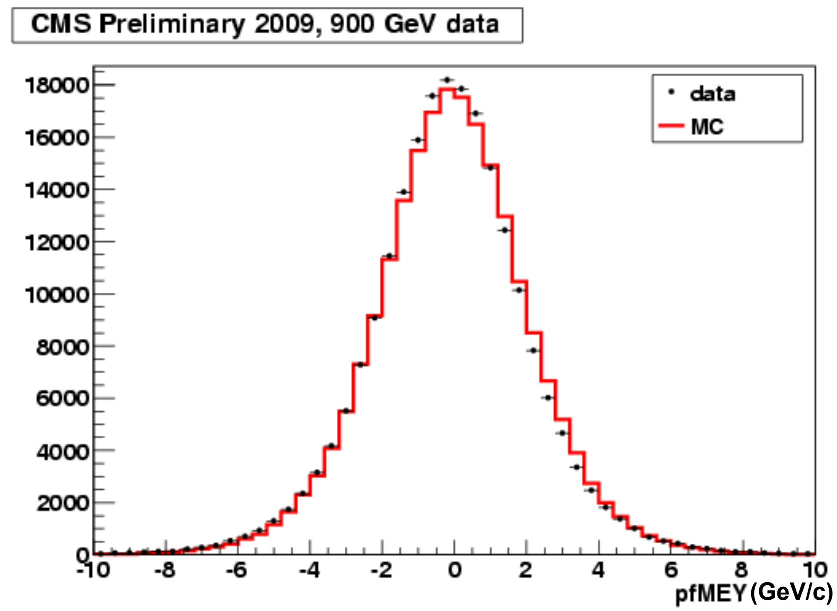
Neutral hadron energy distribution in jets

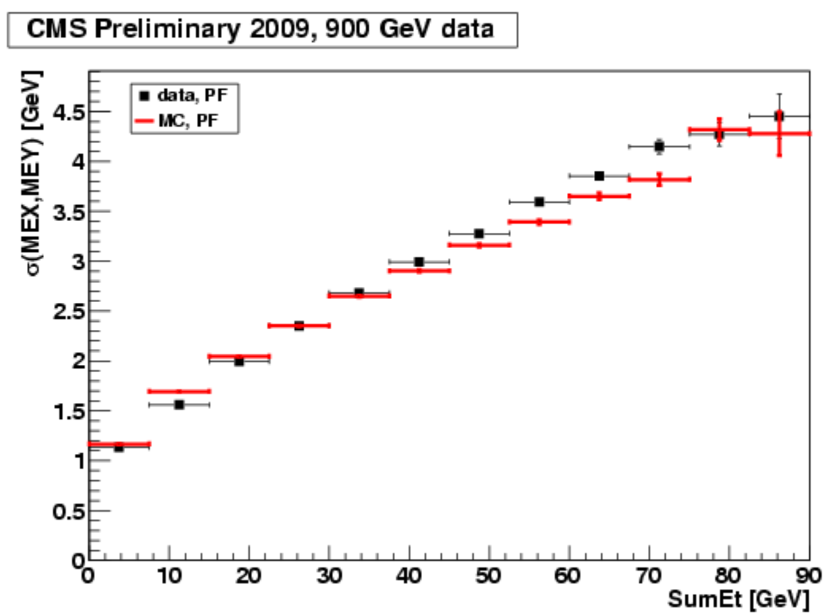


A calibrated calorimeter provides the possibility to extract the neutral hadron composition of jets using particle flow

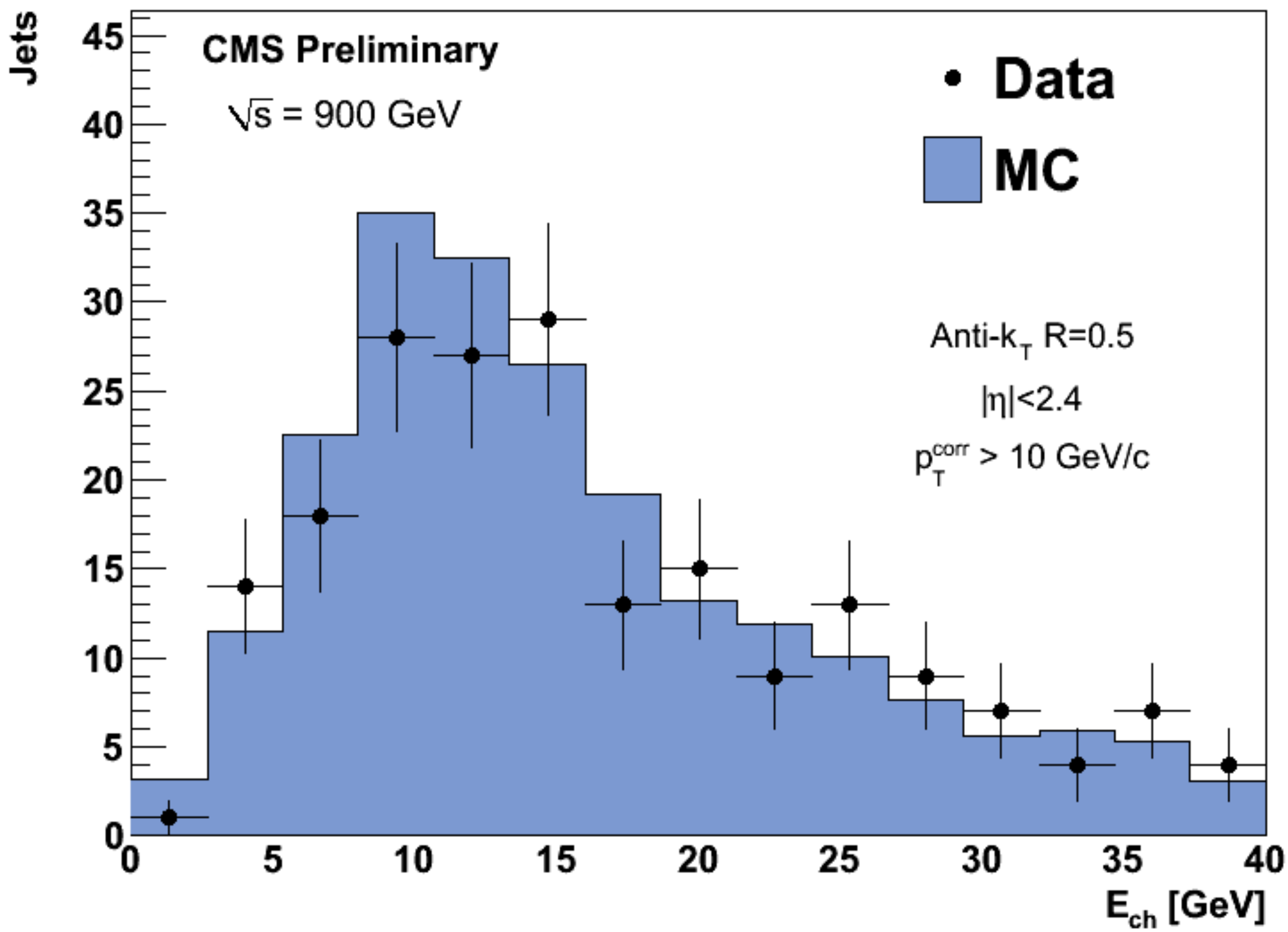
Particle Flow MET







Pflow Jet Composition



Summary

2009: A very successful year!

- The CMS detector is working beautifully
  - Its performance is according to design
  - Its behavior can be reproduced in Monte Carlo simulation
  - Our level of understanding for this early commissioning phase is very advanced
- The highest collider energy ever, combined with the expected integrated luminosity puts us in the best position for new discoveries as early as the end of this year

Epilogue

- The technology of the LHC accelerator and experiments is unprecedented

- Massive amount of work and preparation invested in building and commissioning hardware & software
- But: a lot of work remains to be done!

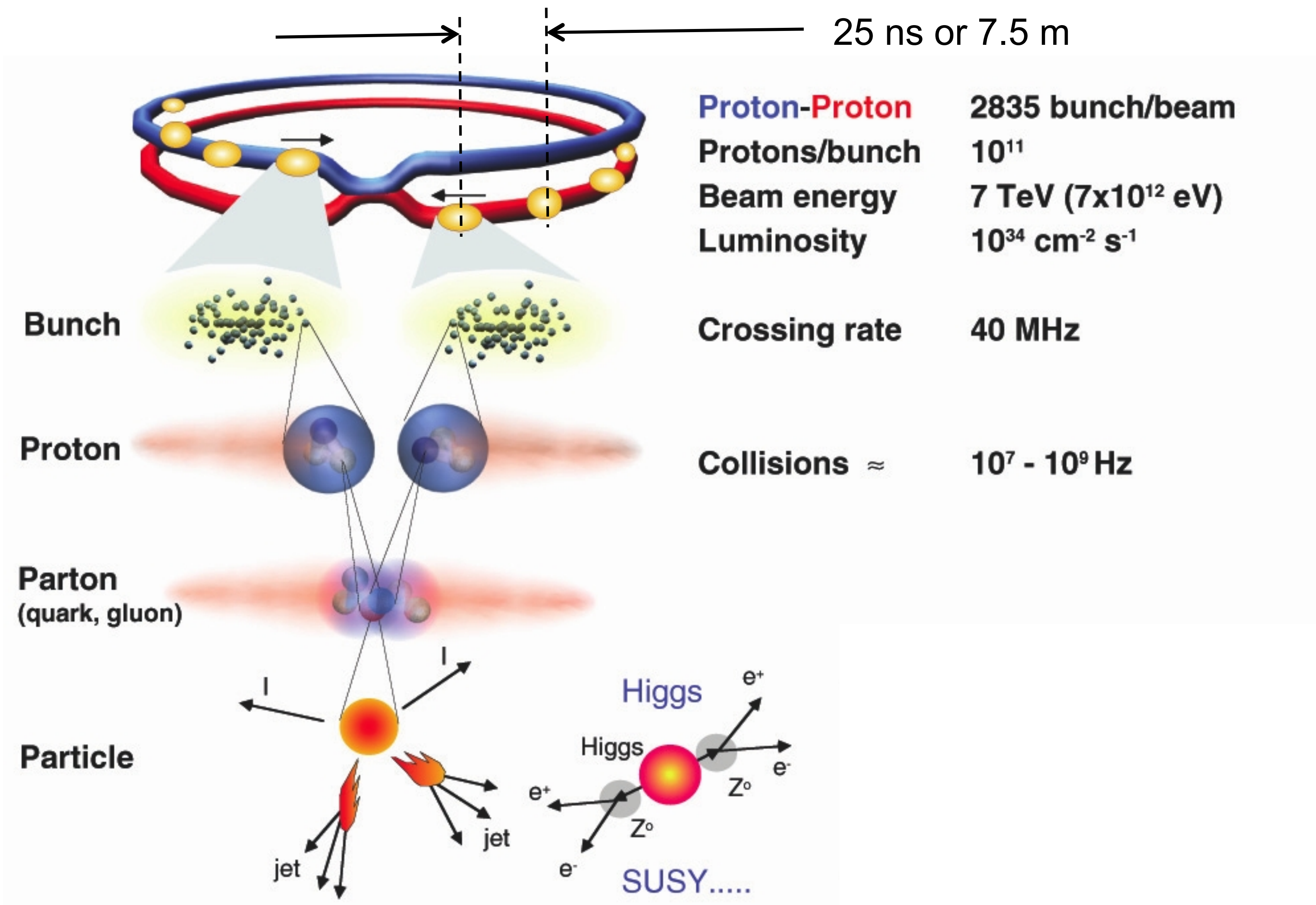
- A truly exciting period has just started

The Beginning of The Journey

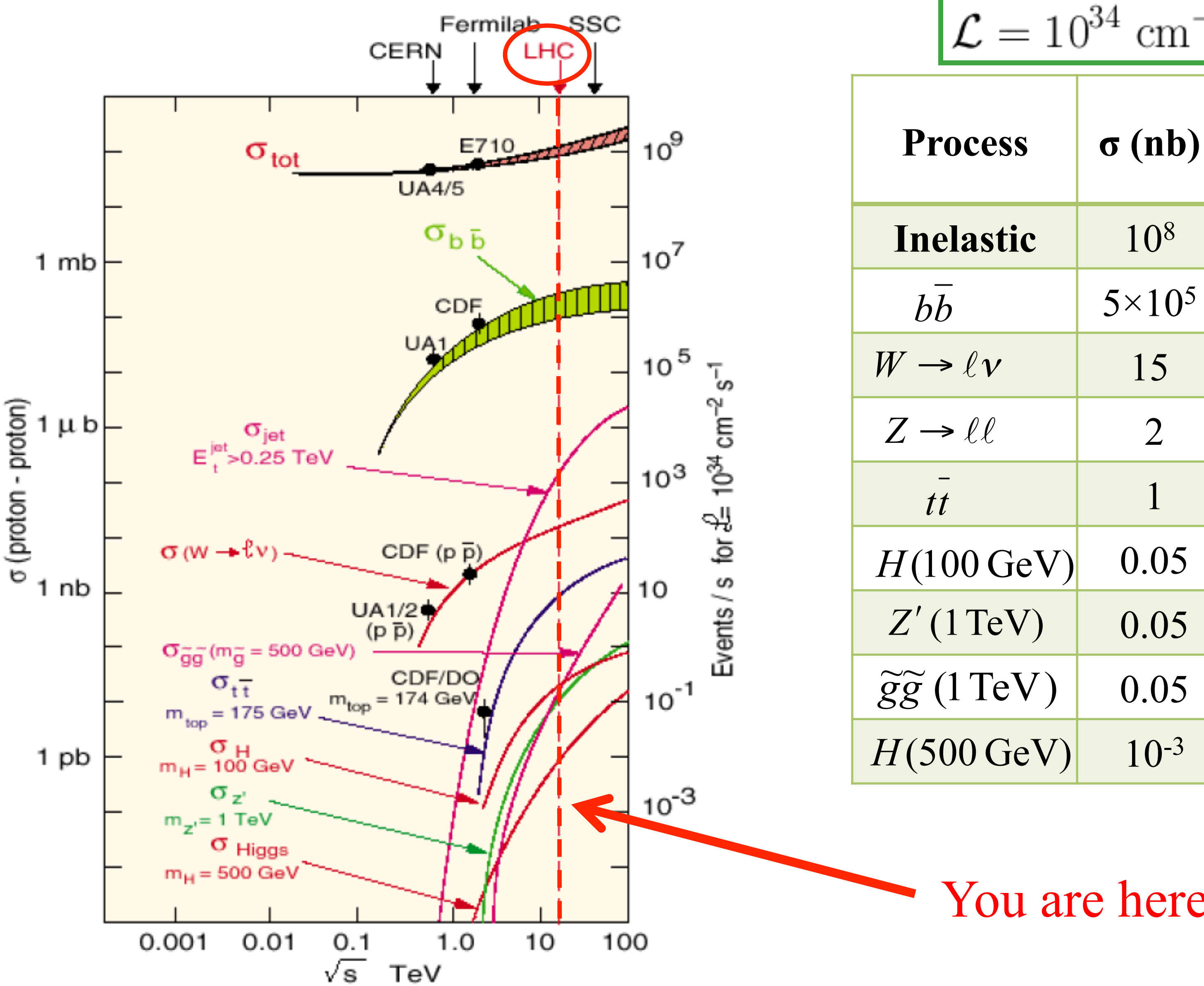
Credit for "Da Vinci" drawings: Sergio Cittolin

Backup

LHC reference numbers



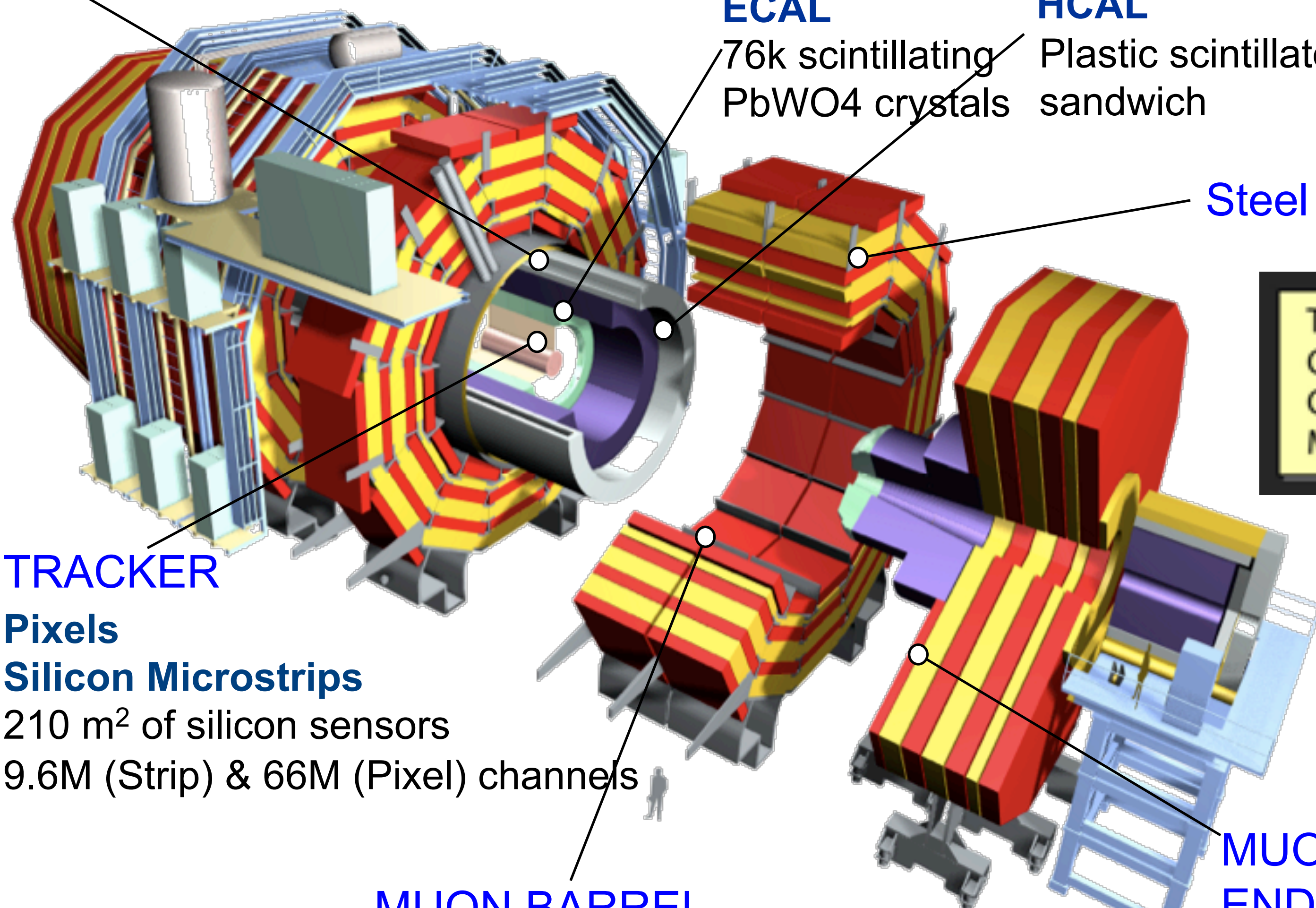
The New Physics



$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Process	σ (nb)	Production rates (Hz)
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	100
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
H(100 GeV)	0.05	0.1
Z' (1 TeV)	0.05	0.1
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.1
H(500 GeV)	10^{-3}	10^{-2}

The CMS Detector



ATLAS *vs.* CMS Triggers

- More traditional, safer design
- Concrete steps & requirements for each of Level-2, Level-3 steps of selection
- Accesses fraction of event at L2 (small throughput)
- But: Custom controls and separate farms for L2, L3

- More flexibility
  - Full event info (and offline reconstruction) as early as L2
  - HLT: continuous software environment in single farm
- But:
  - Large data throughput (and switching network) needed
  - Risky design decision (at the time)

ATLAS *vs*. CMS Triggers

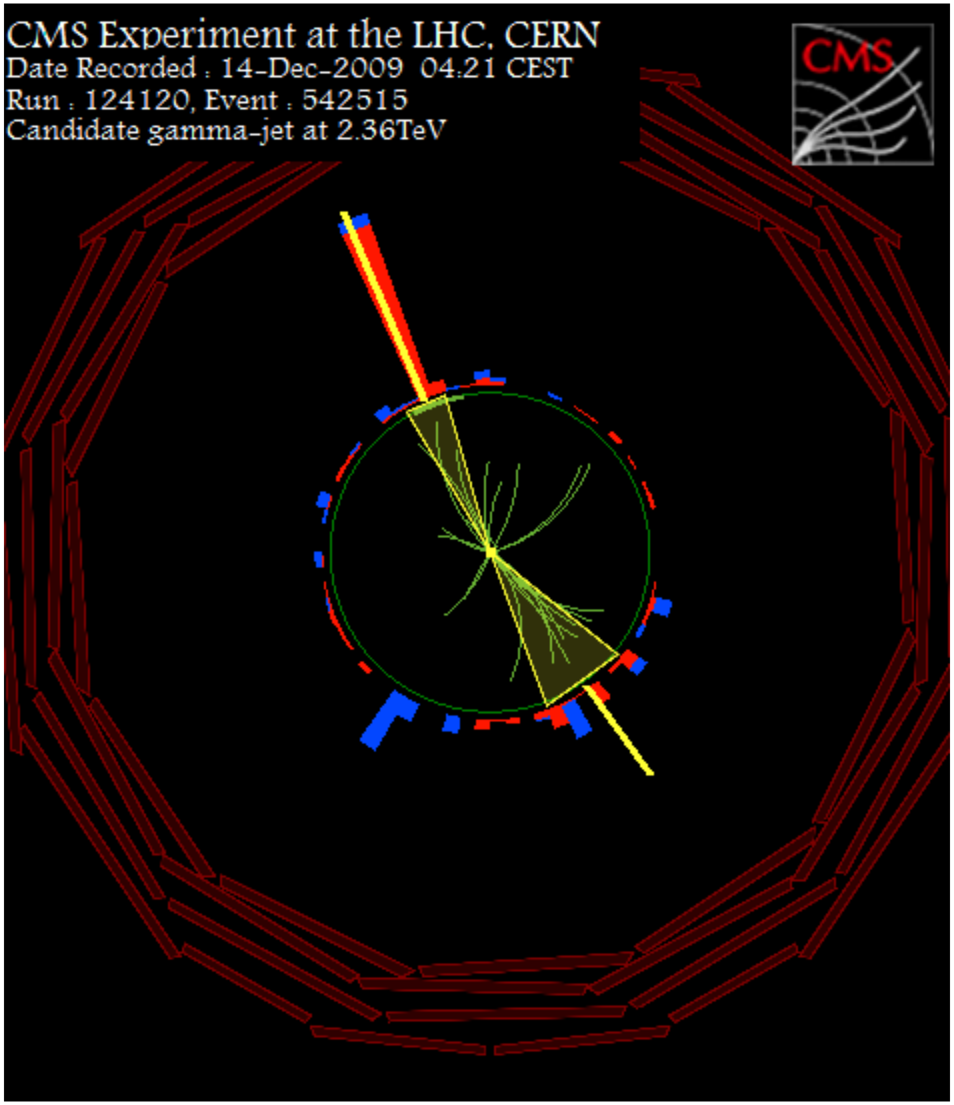
Overall:

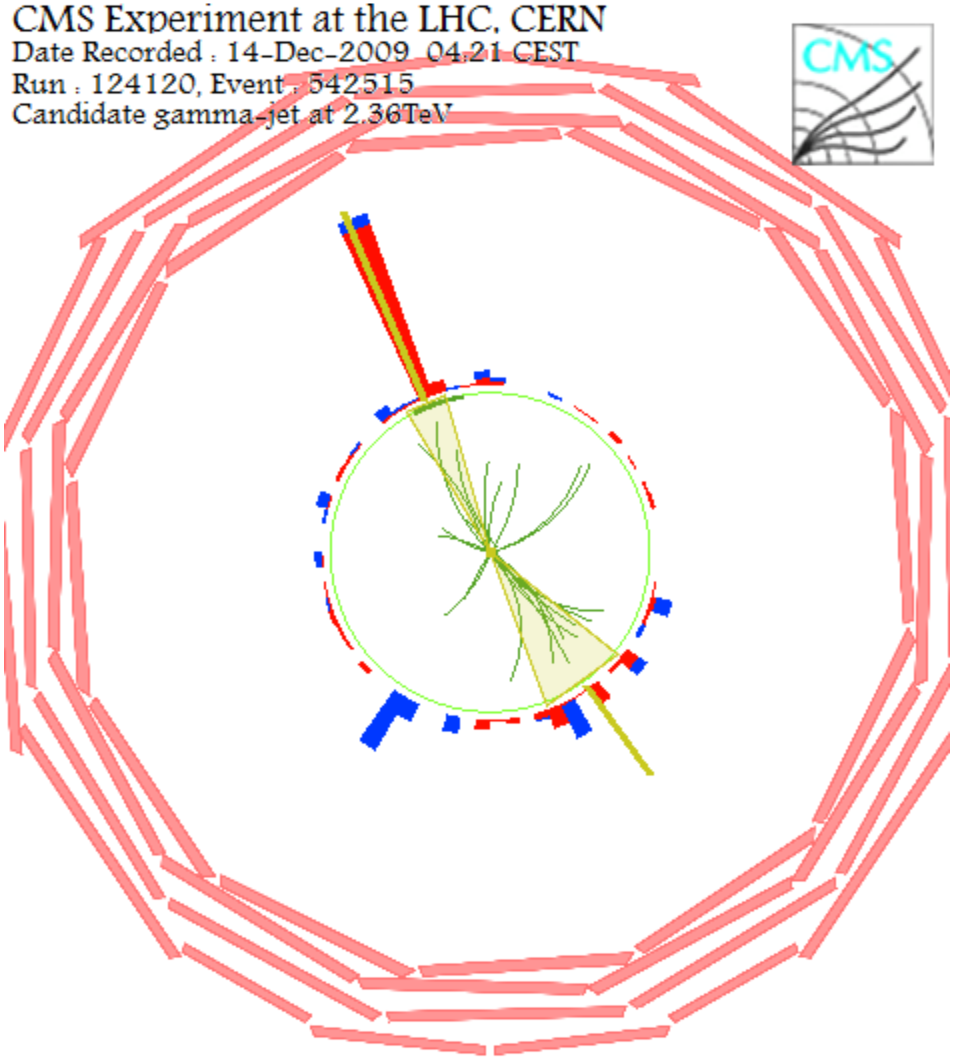
- Very similar performances
- Trigger bandwidth determined by detectors and physics programs, not trigger design
- Systems still differ (two farms vs. single farm at HLT) so: commissioning and debugging also different

Colliding 2/4/8 Bunches

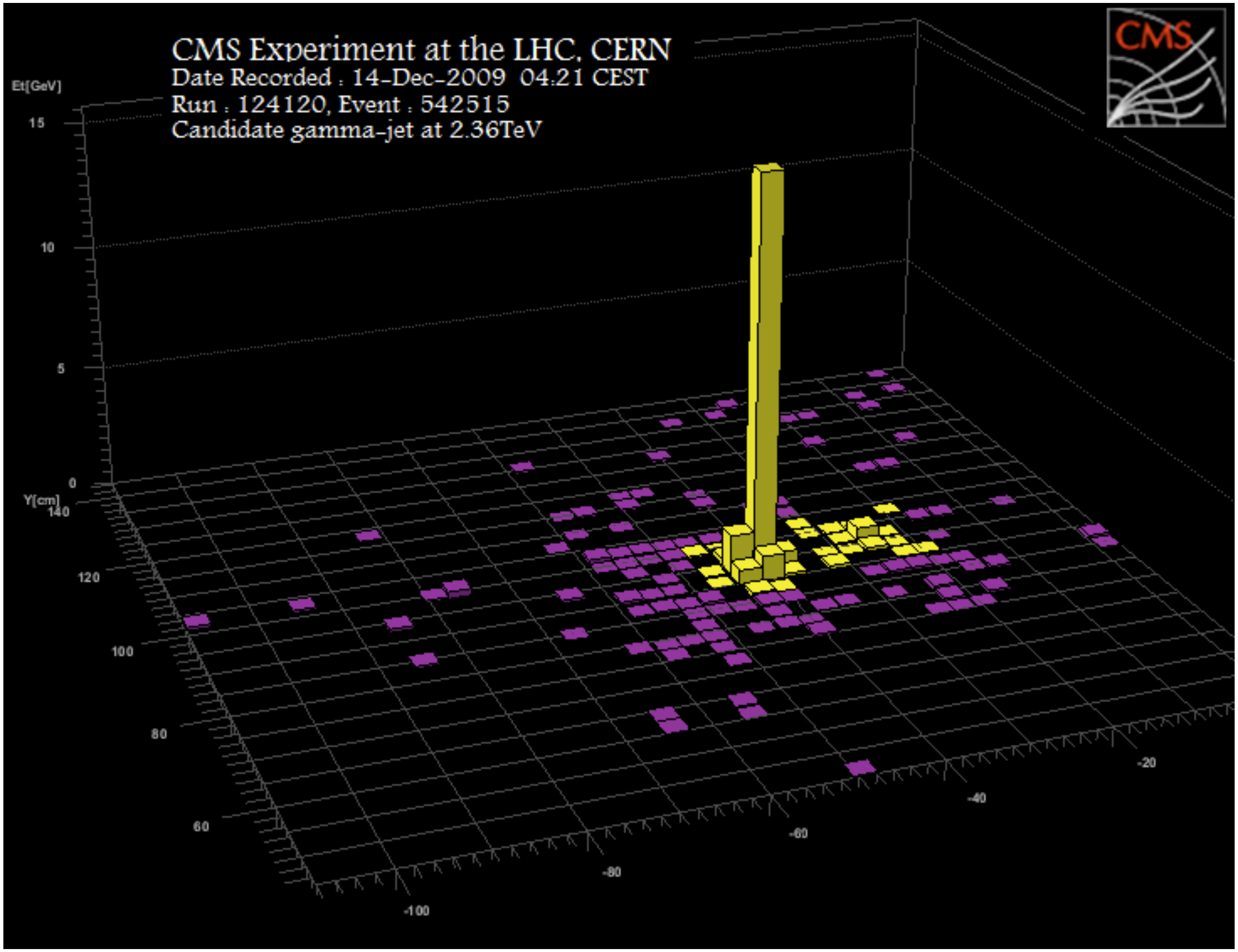
- If 2x2, lumi = 6×10^{27}:
  - Total cross section interaction rate ~100 Hz
  - Crossing rates ~22 kHz
- If 4x4, lumi = 1.3×10^{28}:
  - Total cross section interaction rate ~ 300 Hz
  - Crossing rates ~44 kHz
- If 8x8, lumi = 3×10^{28}:
  - Total cross section interaction rate ~ 600 Hz
  - Crossing rates ~88 kHz
- L1A:
  - Trigger on ***all*** BPTX (till rest of L1 bits has been synchronized)
  - Tag on all physics L1 triggers (but do not use them for L1 Accept)
- HLT:
  - Can write out all MinBias, as much Zero Bias (BPTX) as needed
  - Physics (i.e. interesting) triggers expected to output < 1 Hz
  - Tracking triggers not really needed for first runs

Rho-Phi View of γ candidate

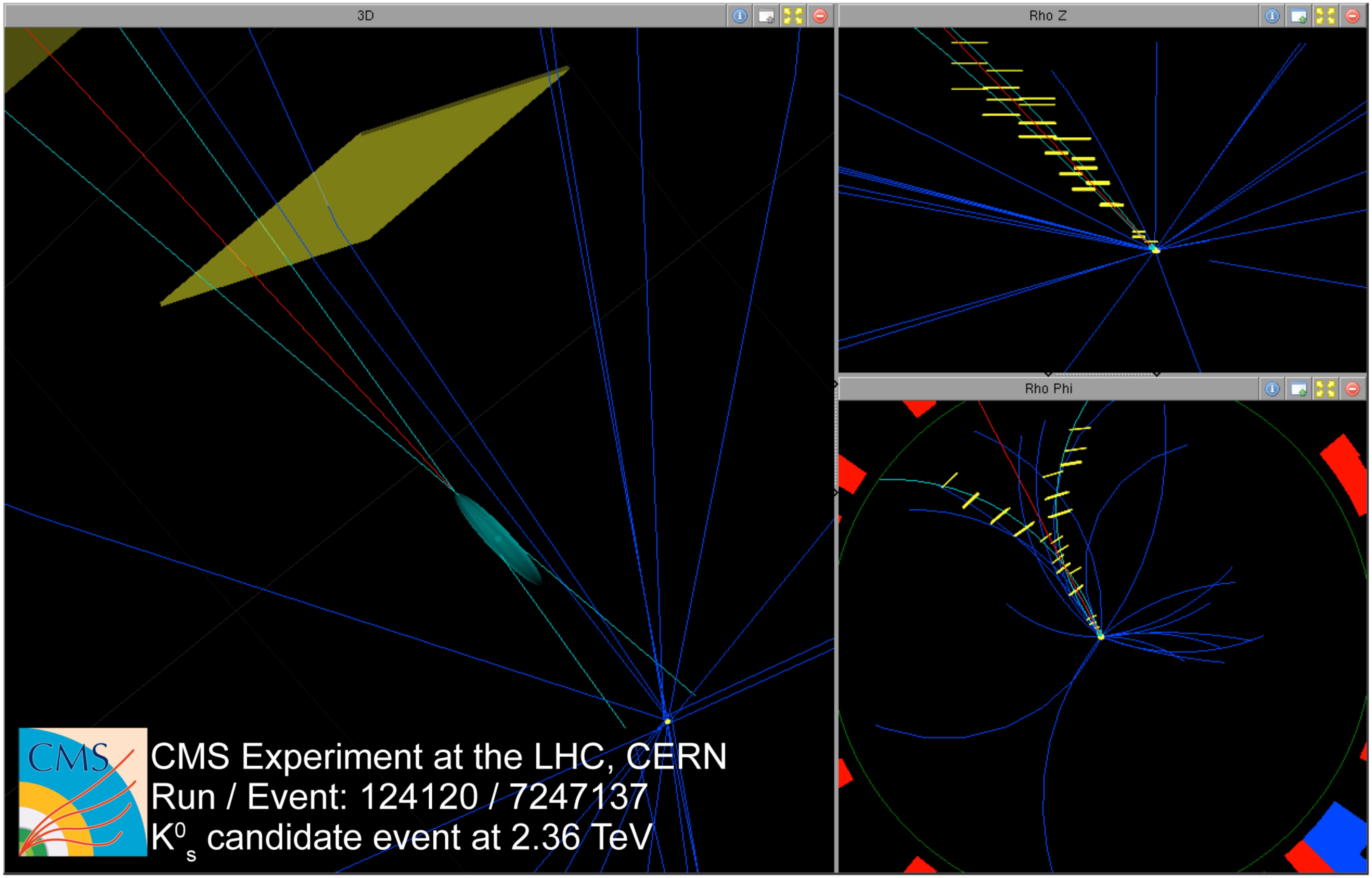




3D Lego View of γ candidate



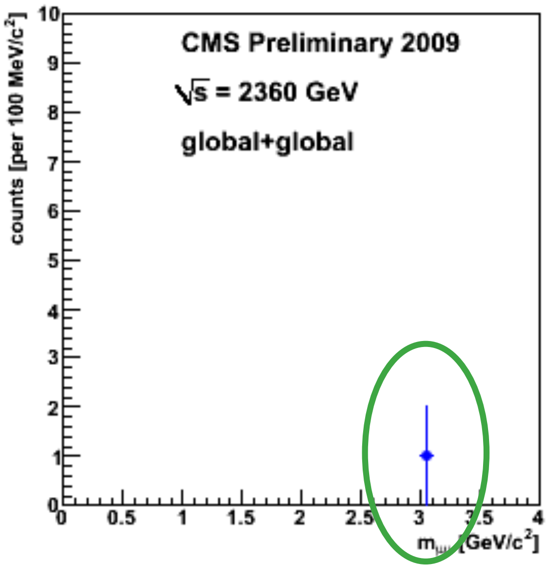
K^0_s candidate event at 2.36 TeV

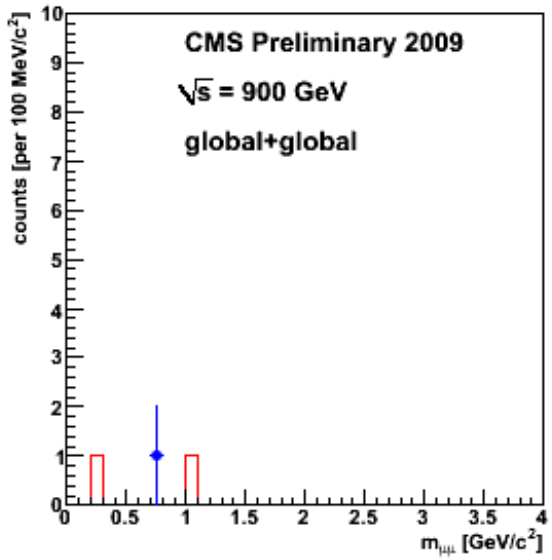


Dimuon Events at 2.36 TeV

Analysed: 12k min. bias events at 2.36 TeV and 321k events at 900 GeV

- Expected # of opposite-sign dimuons between 2 and 4 GeV/c^2:
  0.01 events at 2.36 TeV and 0.69 events at 900 GeV
- Expected # of $J/\psi \rightarrow \mu\mu$ events in 2.36 TeV data sample:
  0.005 events
- S/B ratio: 16/1 in [3.0, 3.2] GeV/c^2 region (background: ~ 0)





blue points: opposite-sign pairs
red line: same-sign pairs

- Probability that both muons come from a common vertex: 90%
- ct = (- 31 ± 46) mm → most likely a dimuon coming from the primary vertex

Jet + Track corrections for dijet (event 6732761)

Step #1: ZSP correction to jet #1

	p_T^{jet}	η	φ
Raw	**12**	0.27	2.5
ZSP	**16**	0.27	2.5

Step #2: "in-cone" tracks (purple, x2)

#	p_T^{trk}	E_{calo}	ΔE
1	4.2	-2.7	1.5
2	5.1	-3.2	1.9

Step #3: "out-of-cone" tracks (orange, x6)

#	p_T^{trk}	E_{calo}	ΔE
1	1.7	-	1.7
2	1.2	-	1.2
3	0.3	-	0.3
4	0.6	-	0.6
5	0.4	-	0.4
6	0.8	-	0.8

Step #4: efficiency

	ΔE
In-cone	0.1
Out-of-cone	0.4

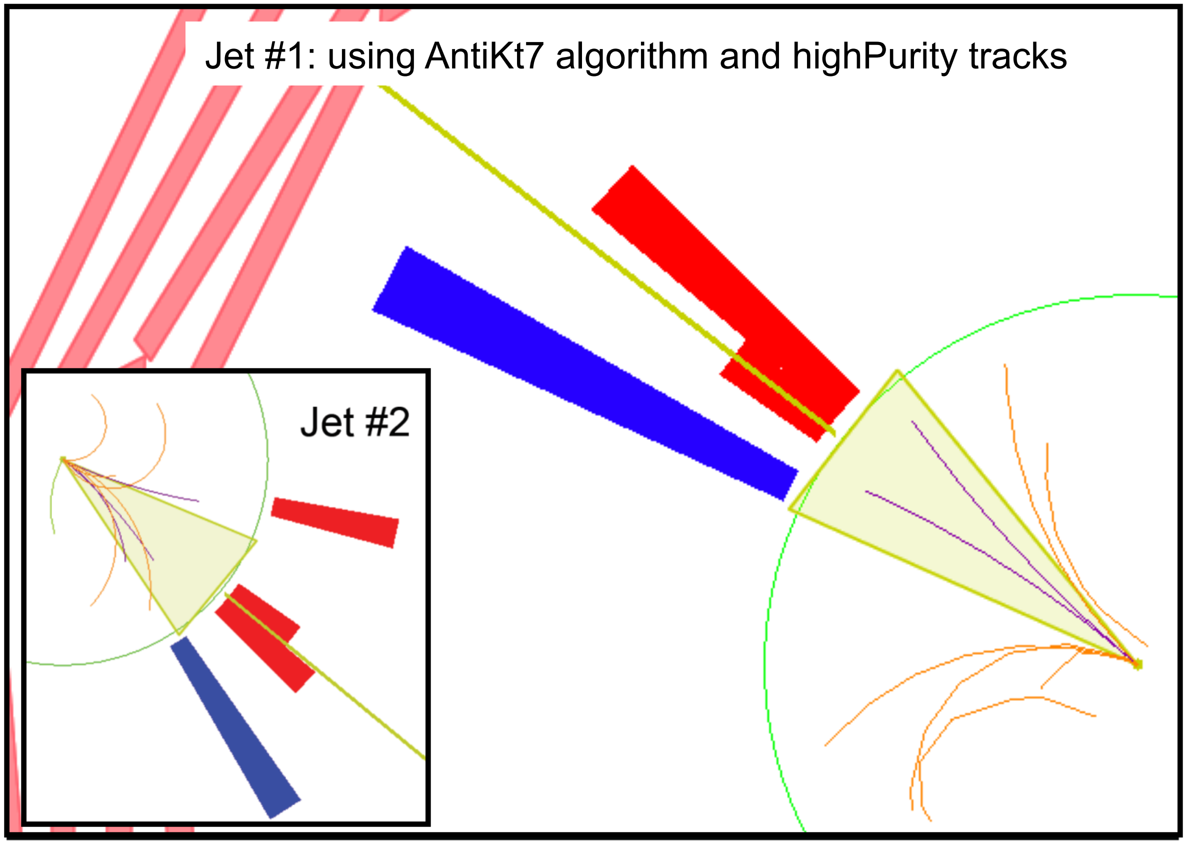
Corrected p_T for jet #1

	p_T^{jet}	η	φ
JPT	**24**	0.23	2.5

Direction correction

Δφ (uncorrected) = 3.1

Δφ (corrected) = 3.0



Corrected p_T of 24 and 25 GeV when including tracks.

Corrected p_T for jet #2

	p_T^{jet}	η	φ
RAW	13	2.0	-0.69
ZSP	17	2.0	-0.69
JPT	25	1.9	-0.55