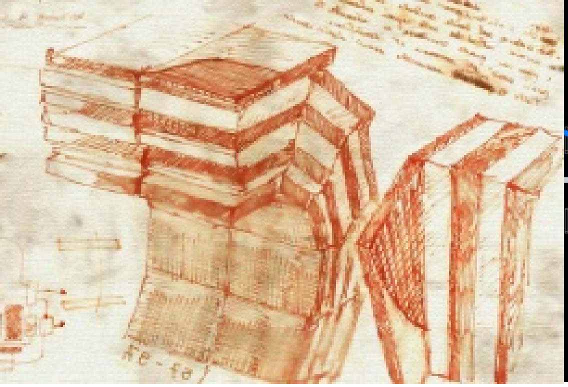
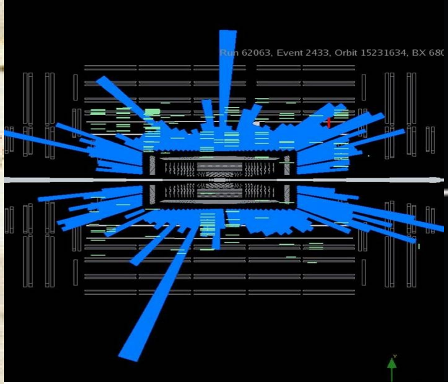
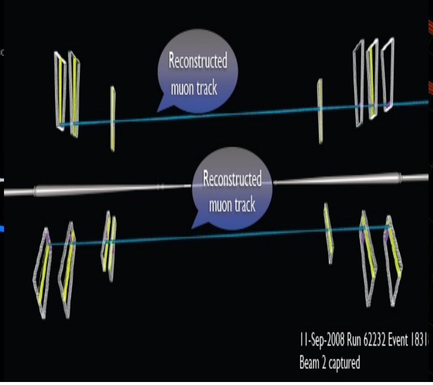
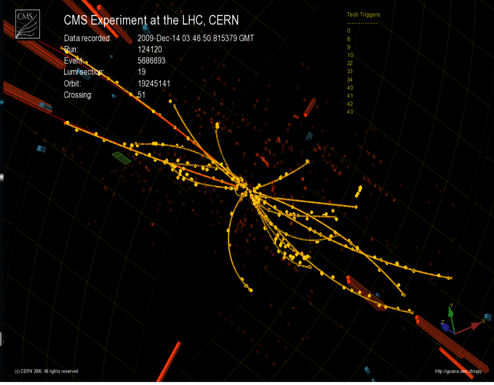








Prospects for multi-lepton studies in CMS

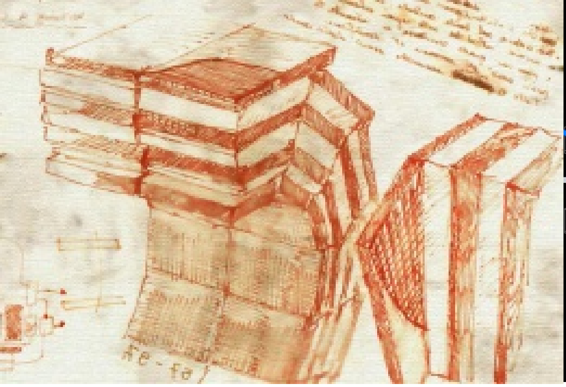
Martijn Mulders (CERN)

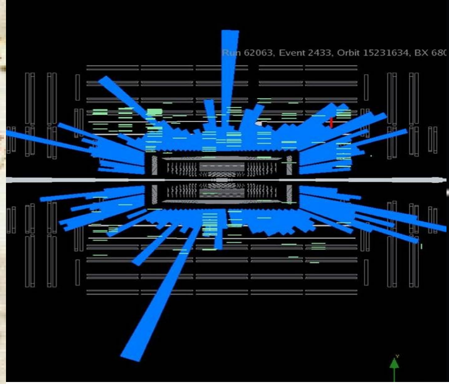
Workshop on

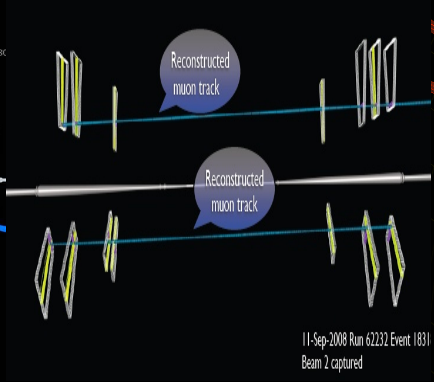
"Multi-lepton Final States in the Search for New Physics at the LHC"

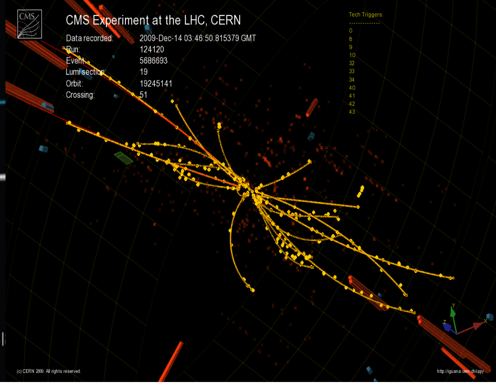
Lisbon, March 25, 2010

European Organization for Nuclear Research









Prospects for multi-lepton studies in CMS

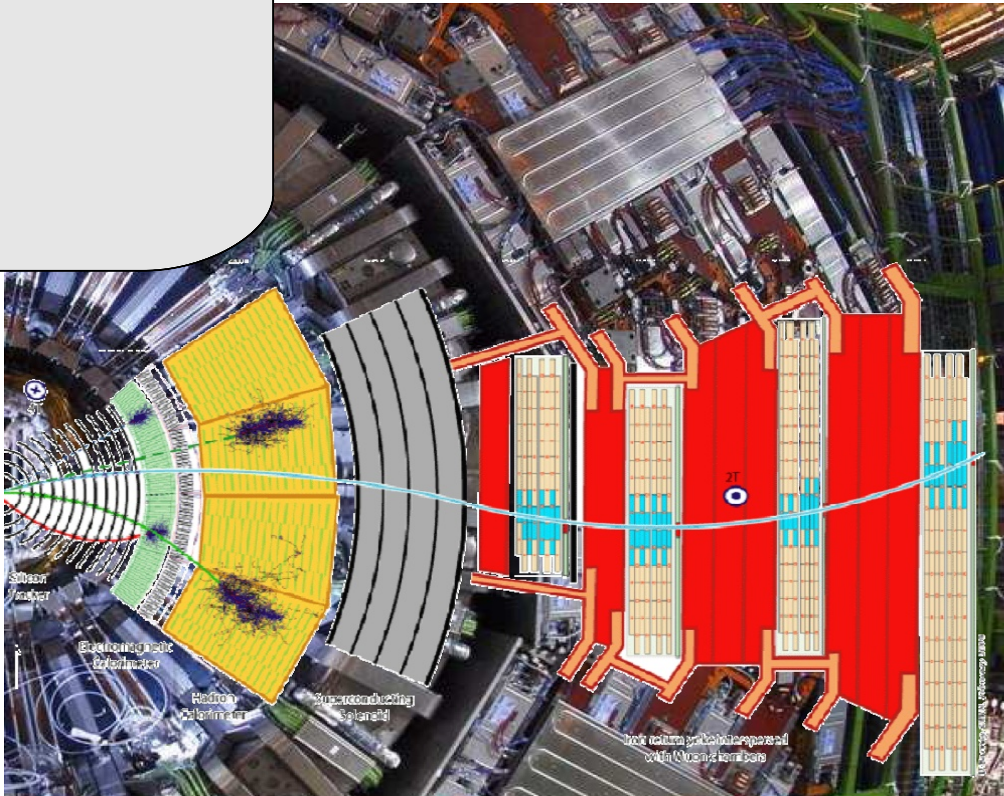
- CMS design
- Lepton Identification algorithms in CMS
- Lepton Commissioning… so far
  - Cosmics
  - Collisions
- Multi-lepton Prospects

CMS: designed with leptons in mind

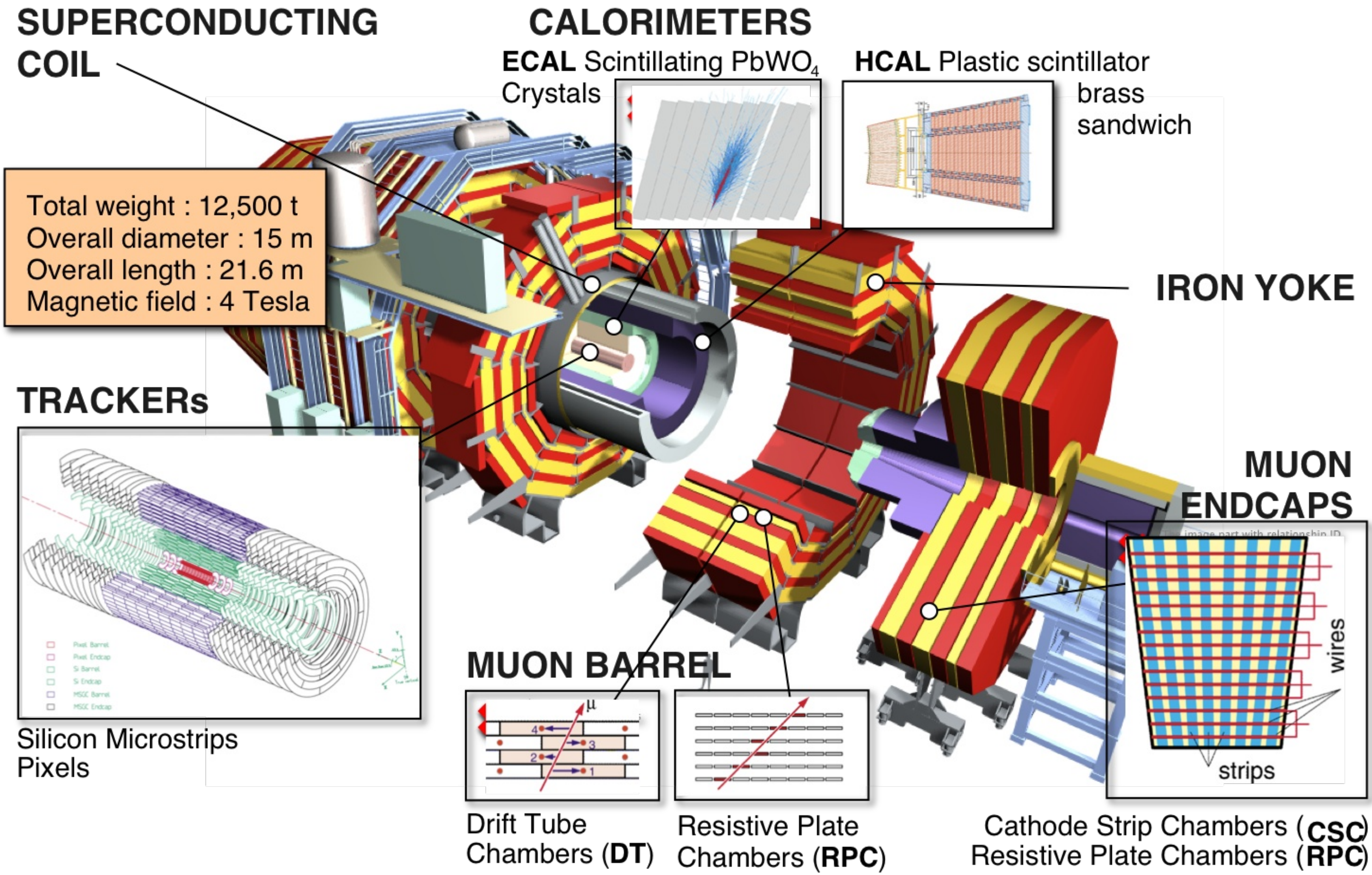
Compact Muon Solenoid

The design goals of CMS (Evian 1992):

1. A robust and redundant Muon system
2. The best possible e/gamma calorimeter consistent with 1)
3. A high quality central tracking consistent with 1) and 2)
4. A hermetic calorimeter system
5. A financially affordable detector

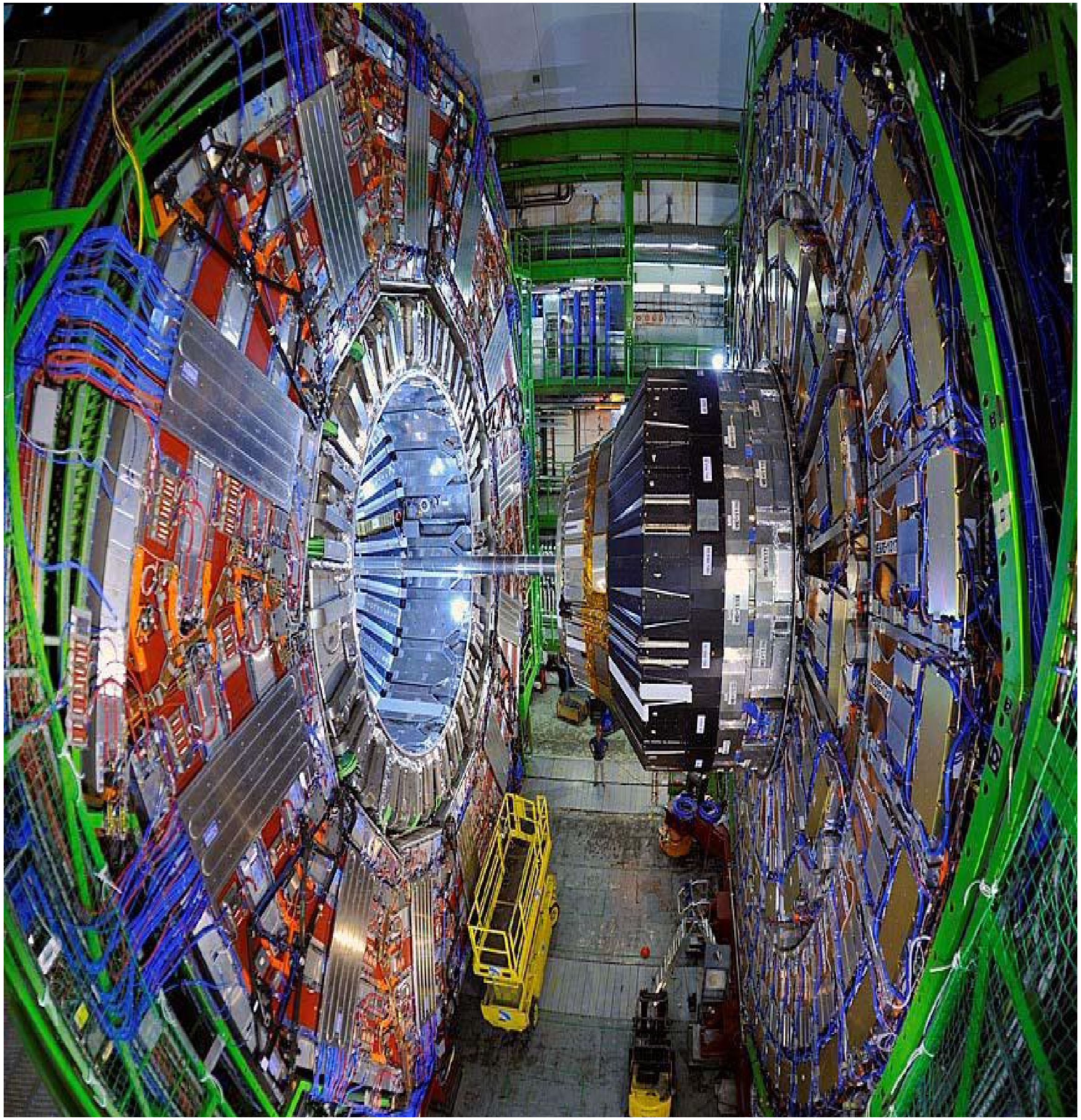


CMS design



SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator brass sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
Silicon Microstrips
Pixels
MUON ENDCAPS
MUON BARREL
μ
wires
strips
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Expected Performance



$|\eta|<2.5$: *Tracker*

$\sigma / p_T \approx 10^{-4} p_T \oplus 0.005$

$|\eta|<4.9$: *EM Calorimeter*

$\sigma / E \approx 0.03 / \sqrt{E} + 0.003$

$|\eta|<4.9$: *HAD Calorimeter*

$\sigma / E \approx 1.0 / \sqrt{E} + 0.05$

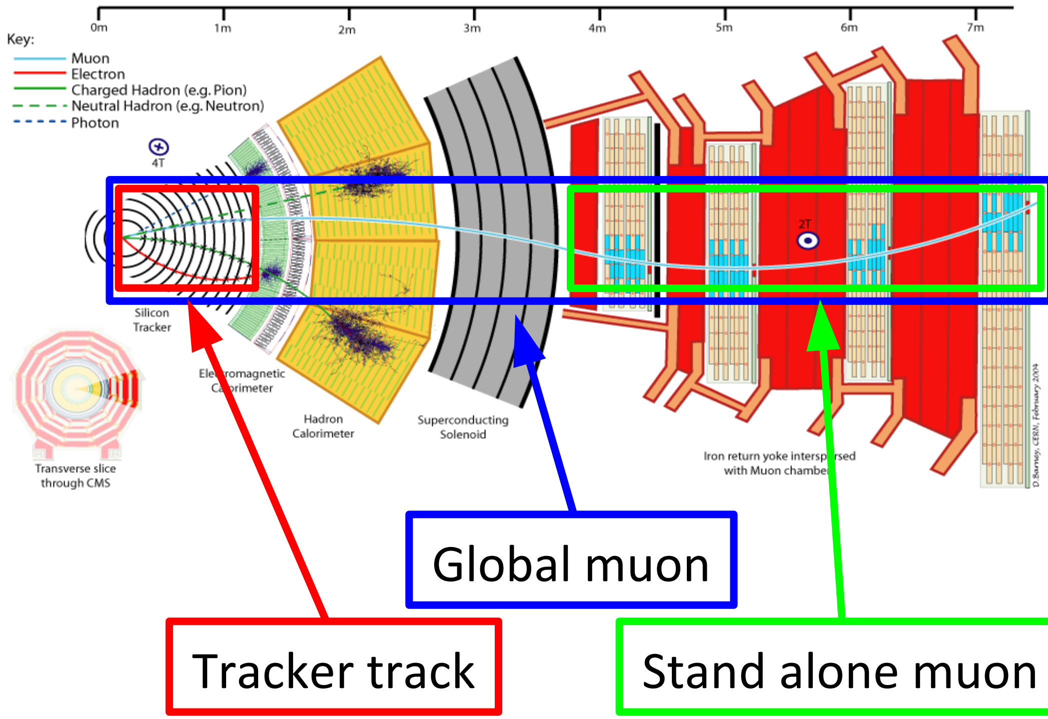
$|\eta|<2.4$: *Muon spectrometer*

$\sigma / p_T \approx 0.10$ *(1TeV muons)*

Lepton Identification in CMS

Muon Identification

- <u>Two complementary approaches</u> for a unique collection of muons
  - Stand alone muon based (outside-in)
  - Tracker based (inside-out)
- <u>Both</u> use reconstructed segments and hits in the muon system
  - Outside-in: fits all muon hits and search for a compatible tracker track to build a global muon
  - Inside-out: try to match tracks in the tracker with muon segments and identify tracker tracks which are muons

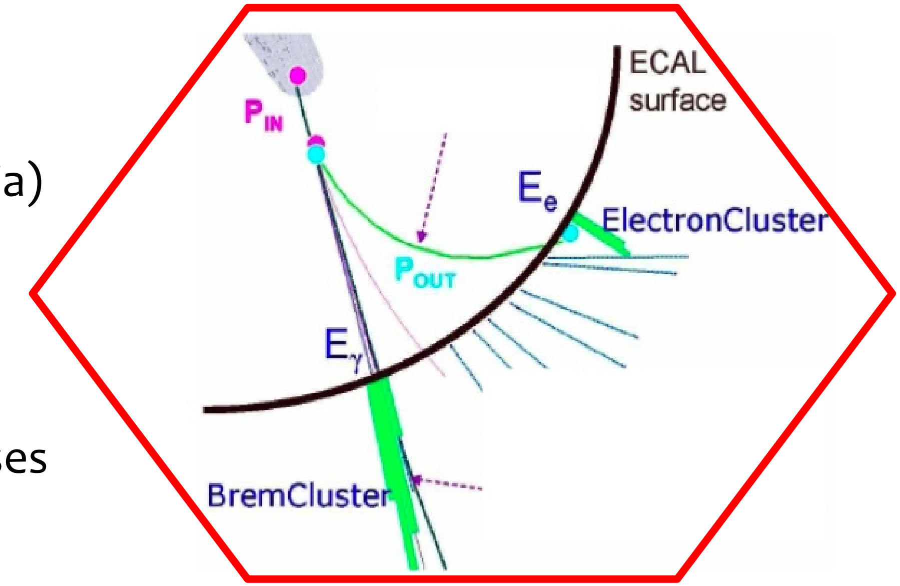


- By-product: a set of muon identification variables are computed, using also calorimeter energy deposits

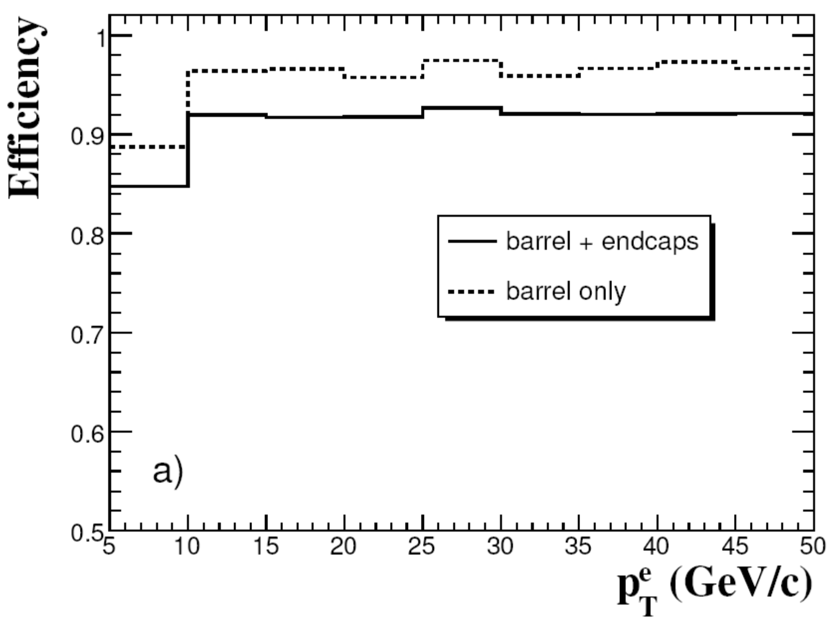
The two algorithms "cooperate" after they have individually performed their choices (eg: a high quality muon will have the information from both the strategies)

Electron Identification

- Reconstruction (outside-in and inside-out):
  - Start form ECAL cluster and then match it with the tracker seeds (with loose criteria)
  - Build the tracks from matched seeds with loose χ^2, electron hypothesis for energy loss, final fit with Gaussian Sum Filter
  - (inside-out) track seeded approach increases efficiency for low pT electrons (<10 GeV)

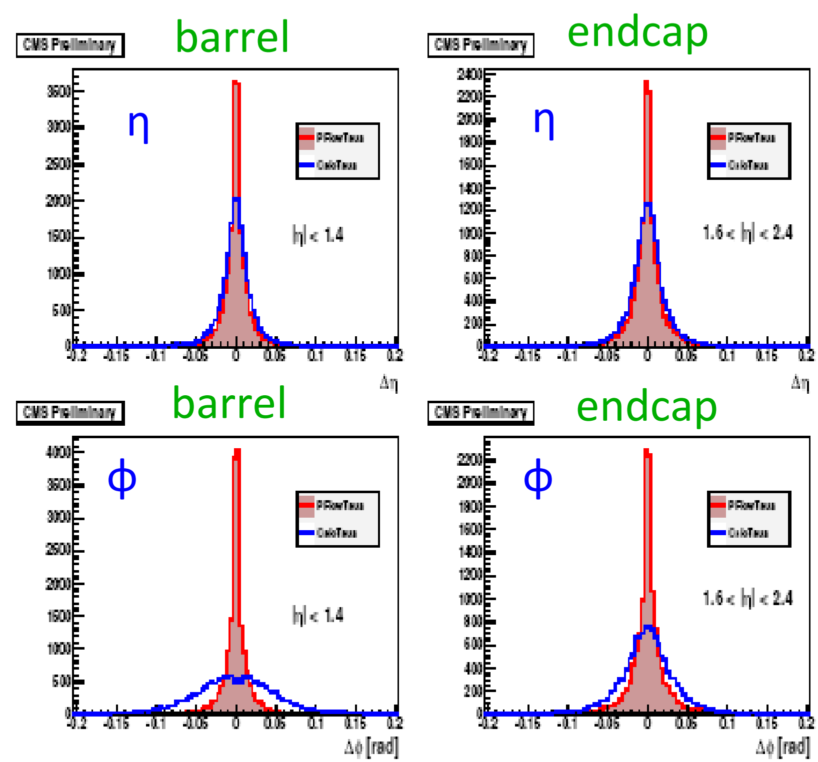


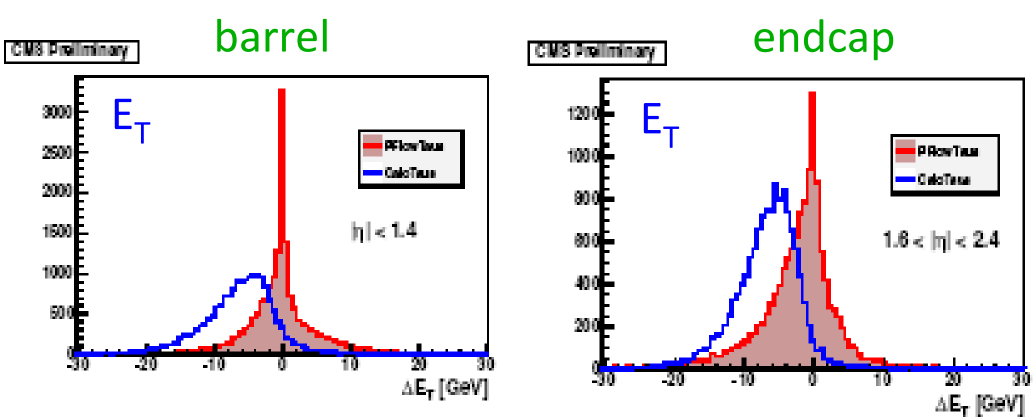
- Identification:
  - 10^3-10^5 rejection power needed against jets (depending on physics analysis)
  - Start-up: robust cut-based approach; later multivariate technique will be applied
  - Further rejection against jets can be achieved using isolation cuts in tracker, ECAL and HCAL → expect further improvements from Particle-Flow approach



Tau identification

- Tau is reconstructed in hadronic channel (main products: γ and charged pions)
  - 1 prong ($1\ \pi\pm + n\ \pi 0$) ~50%, 3 prong ($3\ \pi\pm + n\ \pi 0$) ~ 15%
- Tau reconstruction and identification is based on Particle-Flow technique (PF)
- All reconstructed particles in the event (including pions and photons) from any possible hadronic tau decay products, are clustered into jets using a cone algo
  - PF-tau reconstruction combines tracker and calorimeter information
  - Better energy and angular resolution than calorimeter-based algorithm
- (Pre-)Select the tau-jets applying momentum cuts and isolation requirements

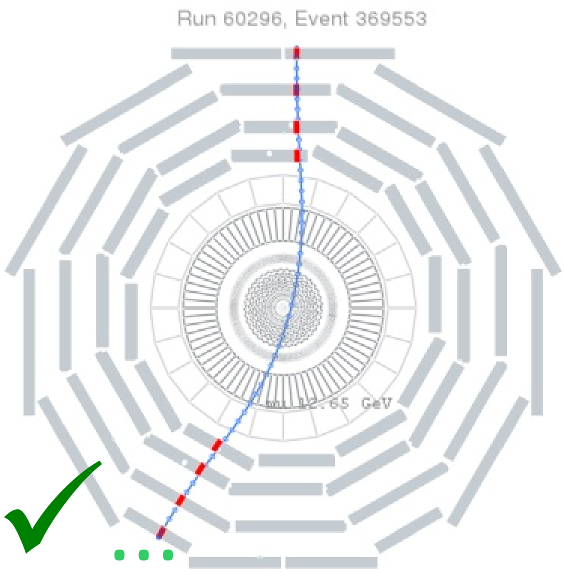


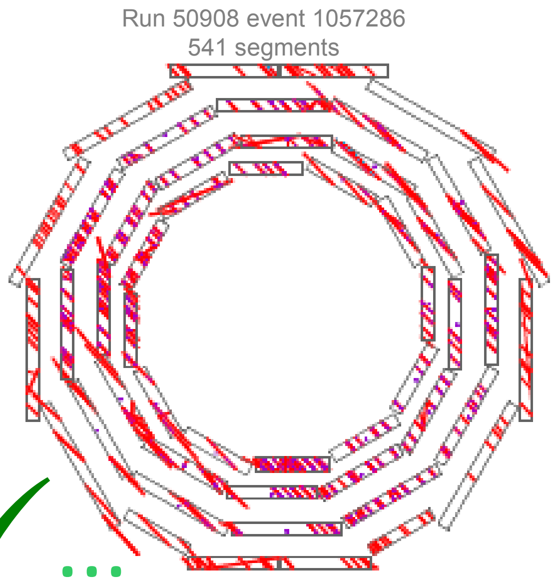


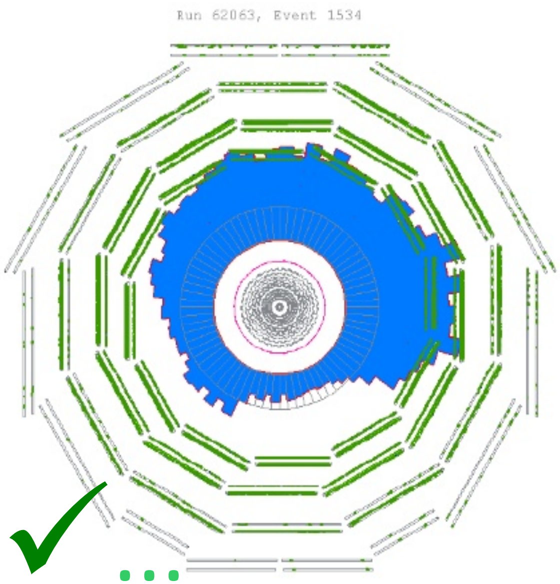
Commisioning (multi-)lepton identification with Cosmics….

Multi Lepton events?

In 2006-2009 CMS invested maximum effort to understand detector performance before LHC start-up... using muons:







✔ ...

Cosmic / Beam Halo
O(1) muon

Analysis using: tracks
cosmic charge ratio

✔ ...

Cosmic Shower
O(10-100) muons

... segments
shower origin

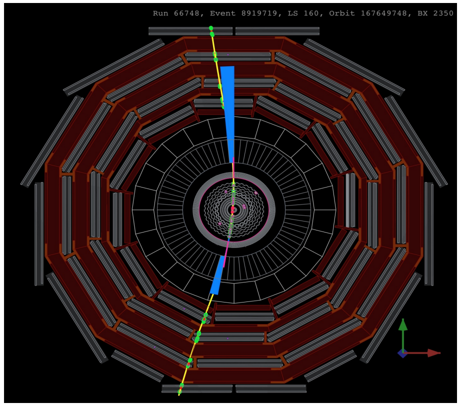
✔ ...

Beam "splash" event
O(10^5) muons

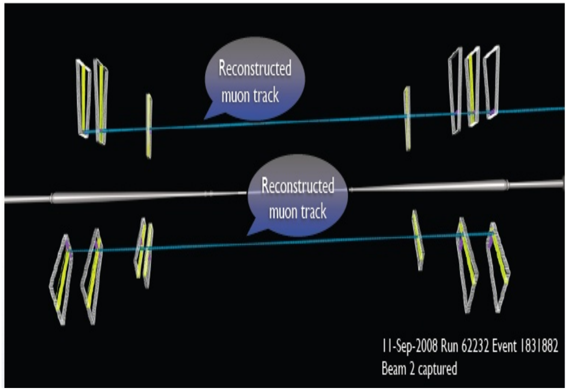
... hits
shower energy and shape

Muon datasets

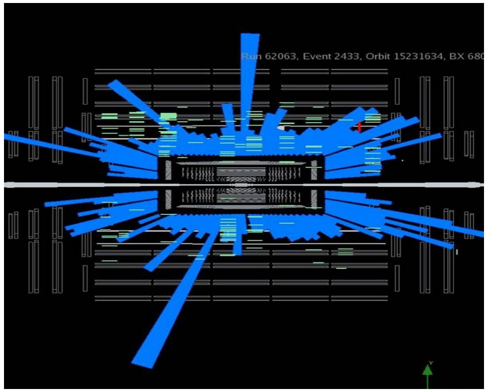
> 1 billion cosmics



> 1 million beam halo



> 1000 beam splash (*)

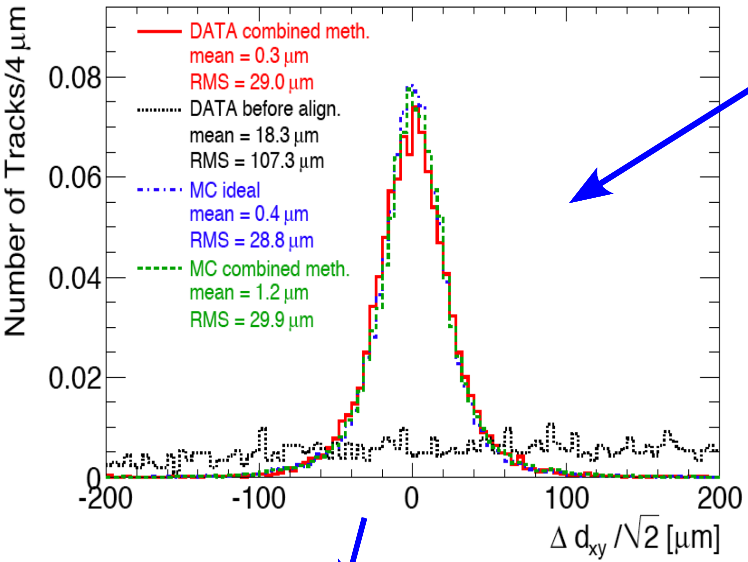


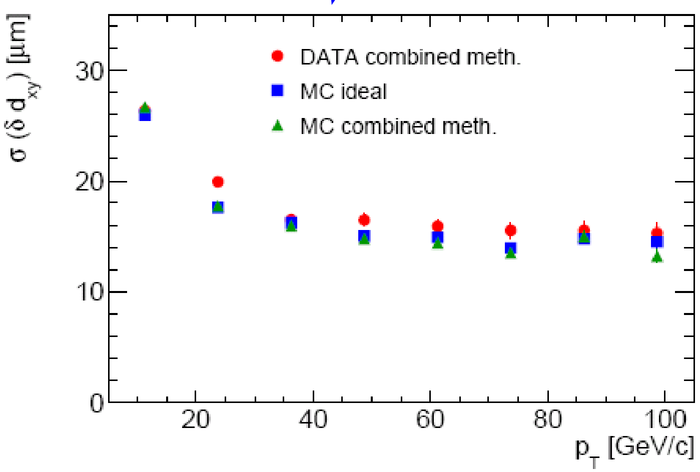
- Cosmic Runs at Four Tesla (CRAFT) in Fall 2008 and Summer 2009: two month-long cosmic data taking campaigns → 2x 300M events with full detector and B field on
- Beam halo (Sep 2008 and March 2010) → alignment of End Caps
- Beam splash (17 in 2008, 1105 in 2009, 51 in 2010) → synchronization of detector, uniformity of response

(*) LHC sector test dumping beam on collimator 150m away from CMS → O(100k) muons

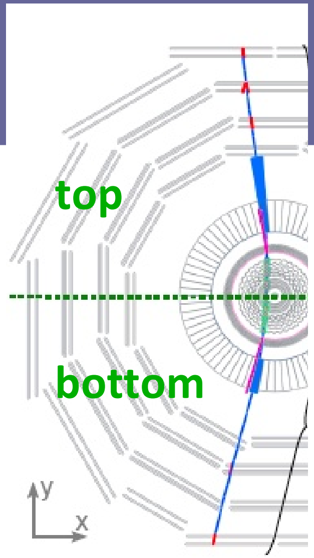
CRAFT: Alignment

http://arxiv.org/abs/0910.2505





Tracking performance evaluated by comparing top and bottom half of cosmic muon, reconstructed independently

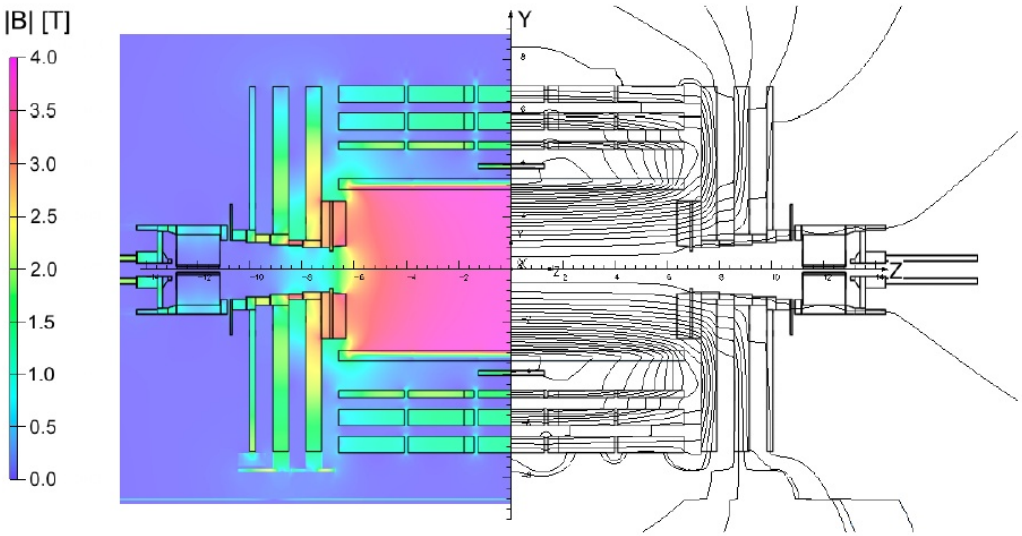


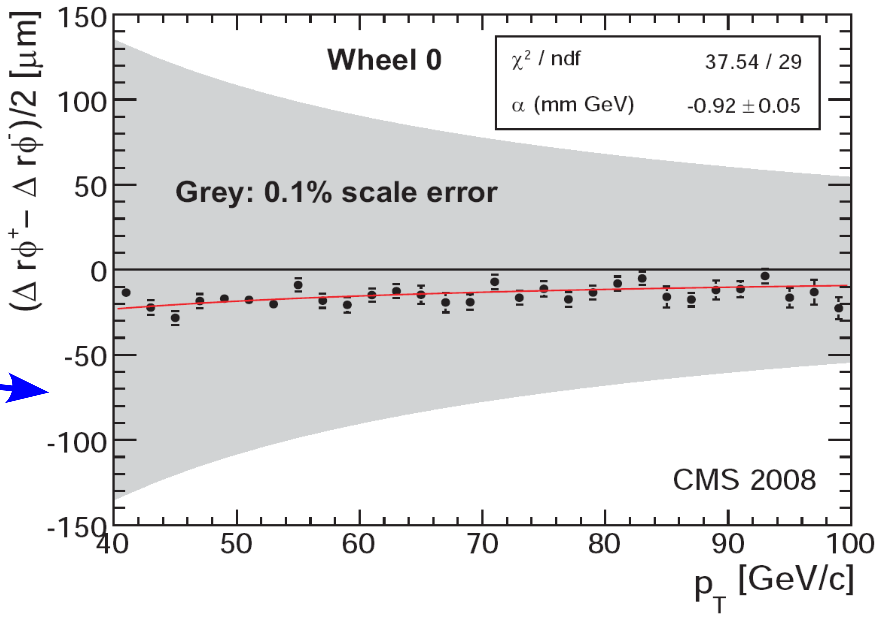
- Alignment achieved with CRAFT data gives tracking performance close to MC with perfect alignment
- 16027/16588 (97%) of silicon detector modules aligned
  - 3-4 µm in barrel
  - 3-14 µm in endcap
- Internal alignment barrel muon chambers ~80 µm and positions relative to tracker: 200-700 µm

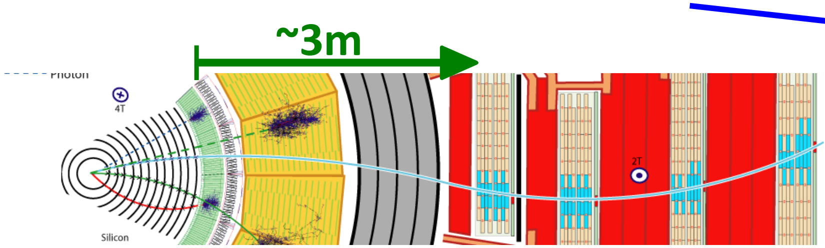
http://arxiv.org/abs/0911.4022

CRAFT: Magnetic Field

- Field in Tracker Volume mapped by probes in 2006 to excellent precision of 0.5*10^{-4}
- Yoke: field in yoke over-estimated by 20% ..!
  - Too tight boundaries used in finite element model
  - New map provided with 3-8% accuracy in barrel yoke (more than sufficient for physics)
- From tracker to muon system: cosmic tracks confirm ∫B*dl to better than 0.1% in the barrel





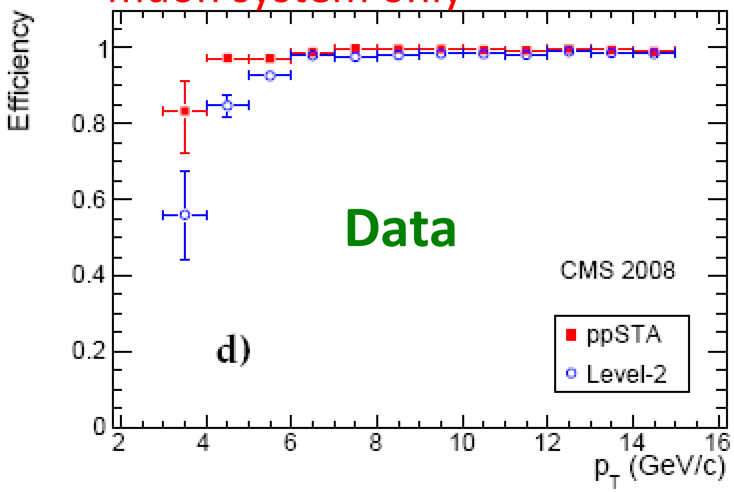


CRAFT: Muon ID

http://arxiv.org/abs/0911.4994

Muons studied in great detail

muon system only



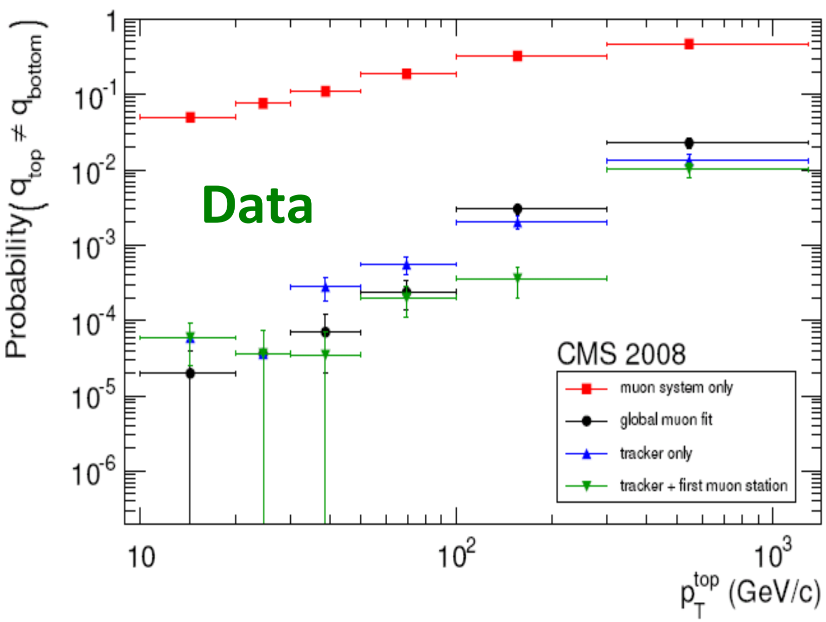
Efficiencies (one example)

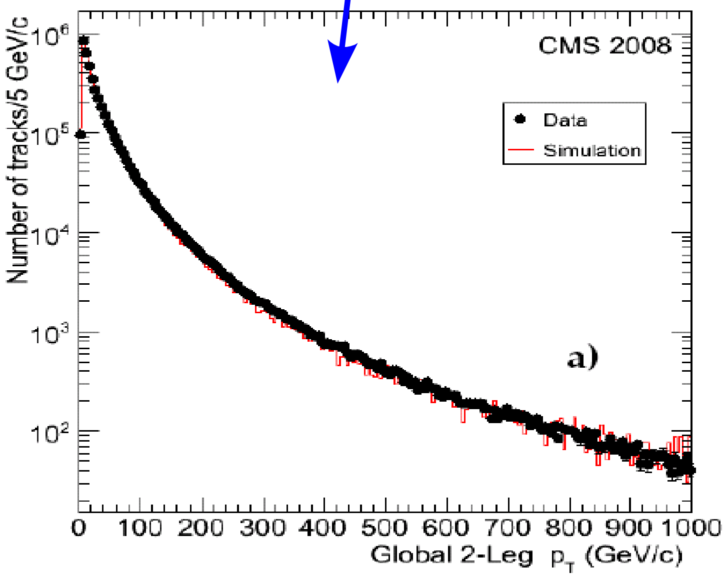
Charge mis-ID

<0.01% below 20 GeV/c

~1% at 0.5 TeV

Large momentum range

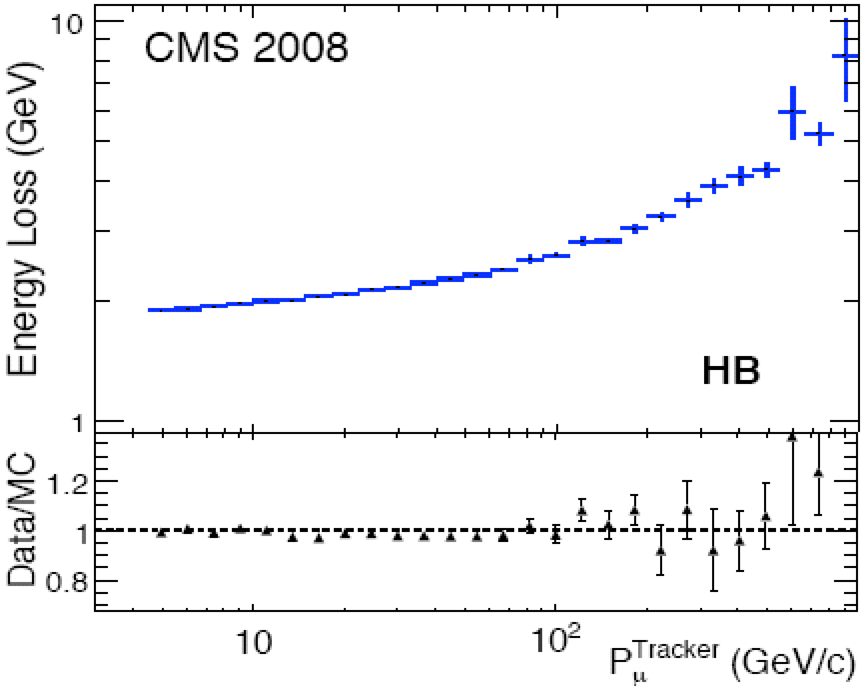




CRAFT: Muons in calorimeters

An excellent understanding of muon response in calorimeters

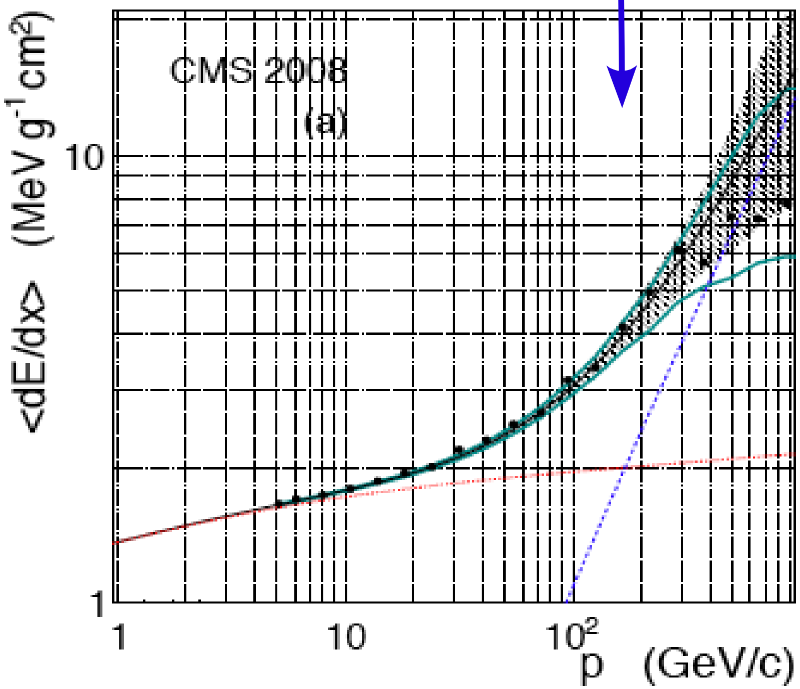
- Hadronic calorimeter: good agreement data and simulation over large momentum range



- Crystal calorimeter: first measurement of muon critical energy in Lead Tungstate:

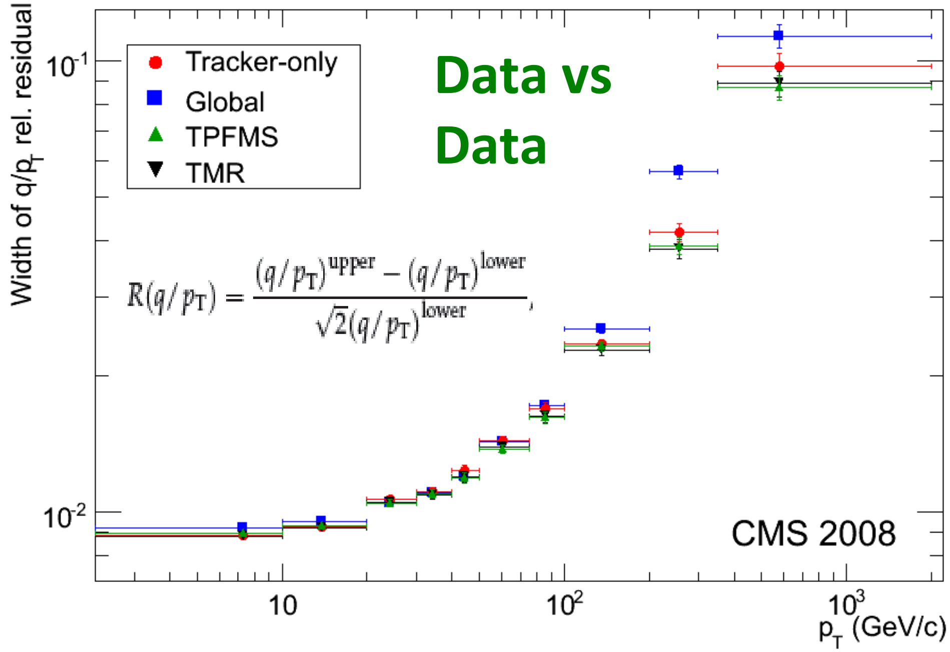
$160^{+5}_{-6} \pm 8$ GeV,

For a typical energy deposit of 250 MeV!



CRAFT: Muon pT resolution

muon system + tracker combined



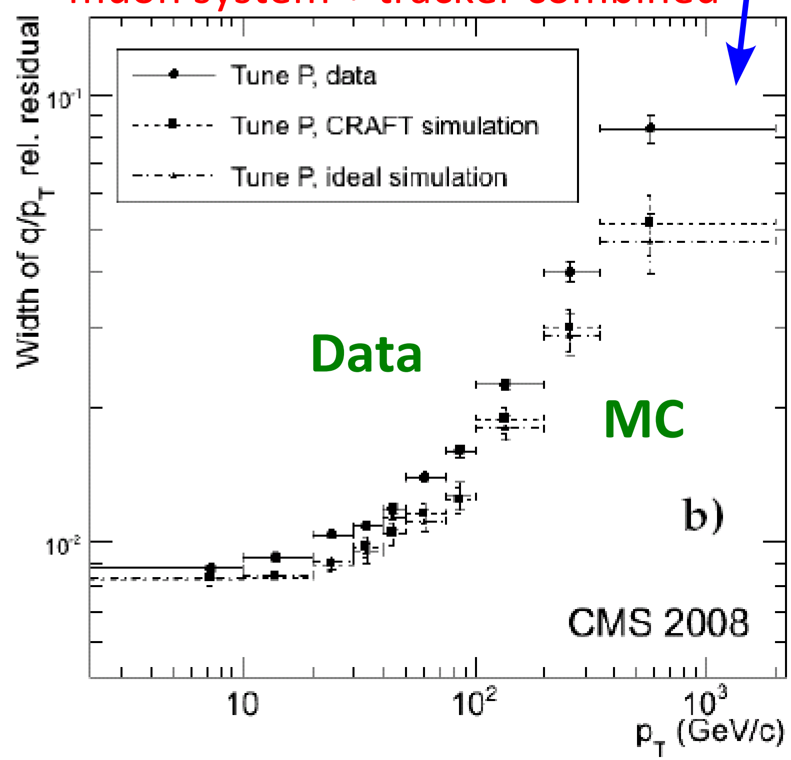
Relative pT resolution

<1% below 20 GeV/c

~8% at 0.5 TeV/c

Agreement data – MC

muon system + tracker combined

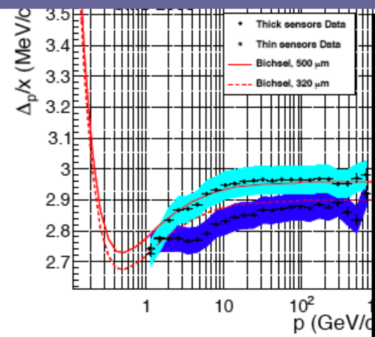


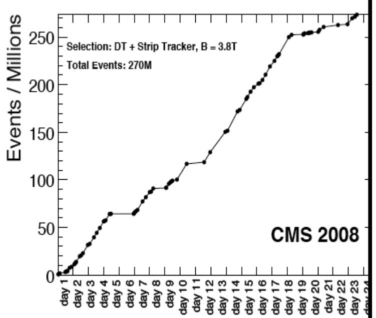
- ▲ TPFM = Tracker Plus First Muon Station
- ▼ TMR = Truncated Mean Reconstructor (pick up Tracker or TPFM on chi2 basis)

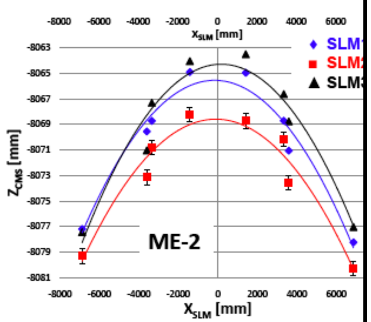
Specialized combined fits exceed resolution of silicon tracker alone thanks to accuracy of alignment and B field reached with CRAFT tracks

23 papers published in JINST

http://iopscience.iop.org/1748-0221/focus/extra.proc6

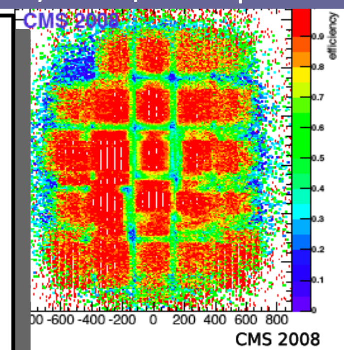


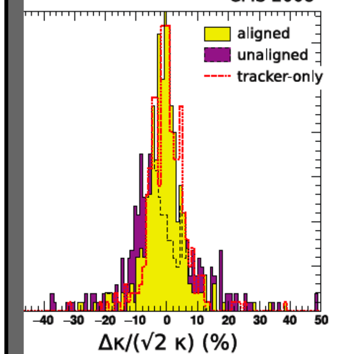


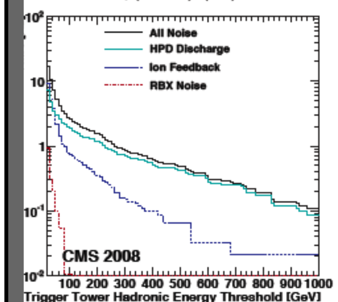


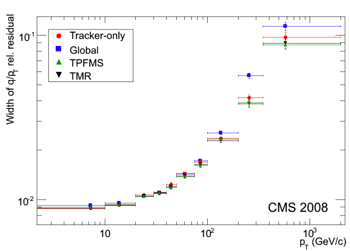
- Experience with sustained operation of CMS as an integrated experiment
- Excellent alignment already at start-up
- Improved understanding magnetic field
- Muon reconstruction studied up to 1 TeV

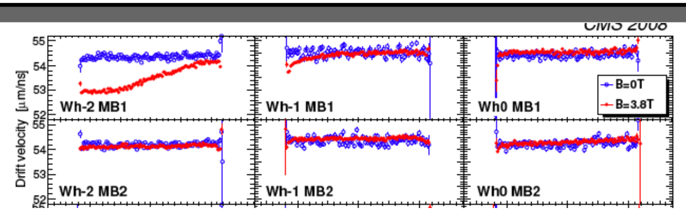
And: detector simulation with realistic conditions (mis-alignment, calibrations) ready for LHC start-up → used for analysis of first LHC collision data without further tuning

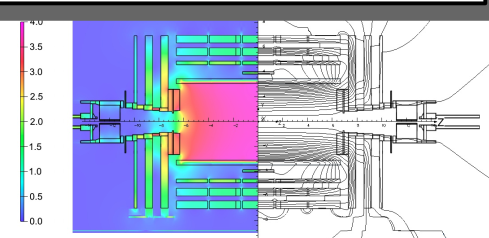


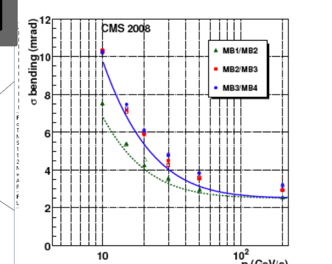




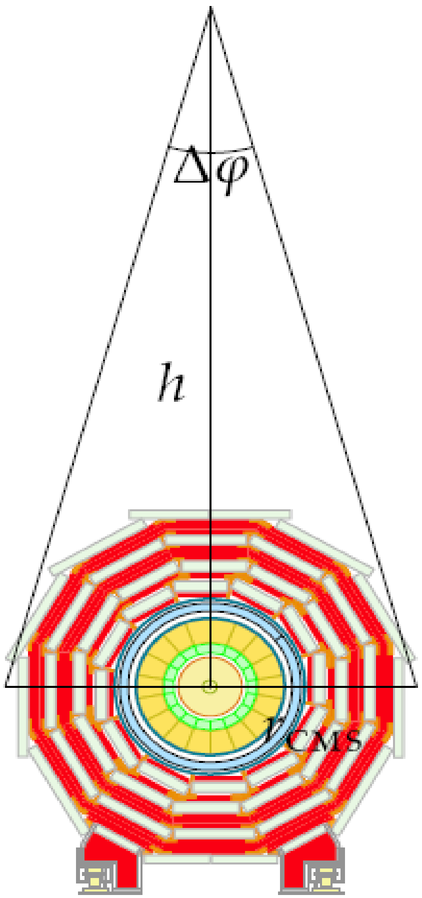








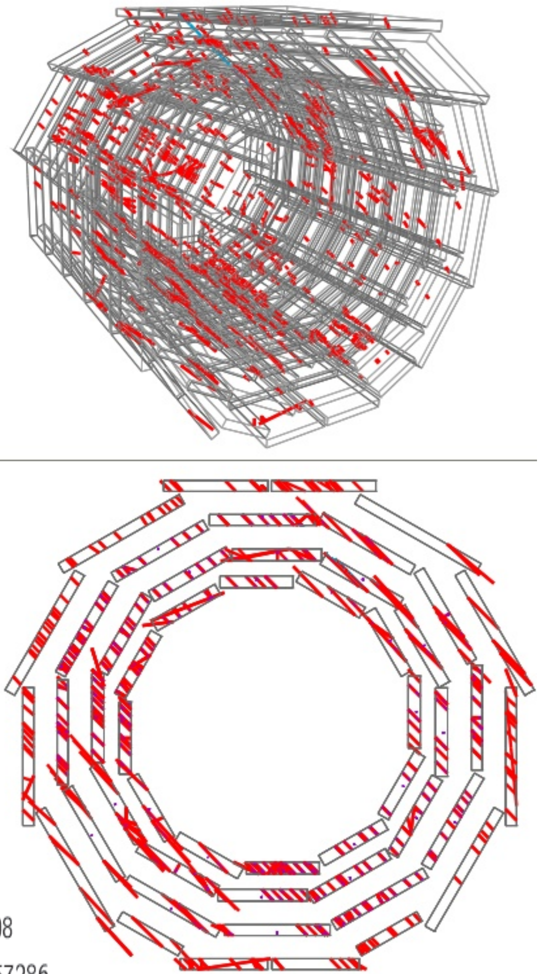
For fun: multi-muon events 2008



- 0.02% rate of cosmic events with >100 segments
- Cross-check of CMS "pointing" accuracy
- Analysis using segments only
- Estimate of (minimum) distance shower origin

$$\Delta\varphi \approx 0.01\pi$$
$$\Rightarrow \quad h \gtrsim 500\,\mathrm{m}$$

$$\tfrac{1}{2}\Delta\varphi \approx \tan\tfrac{1}{2}\Delta\varphi = \frac{r_{\mathrm{CMS}}}{h}$$

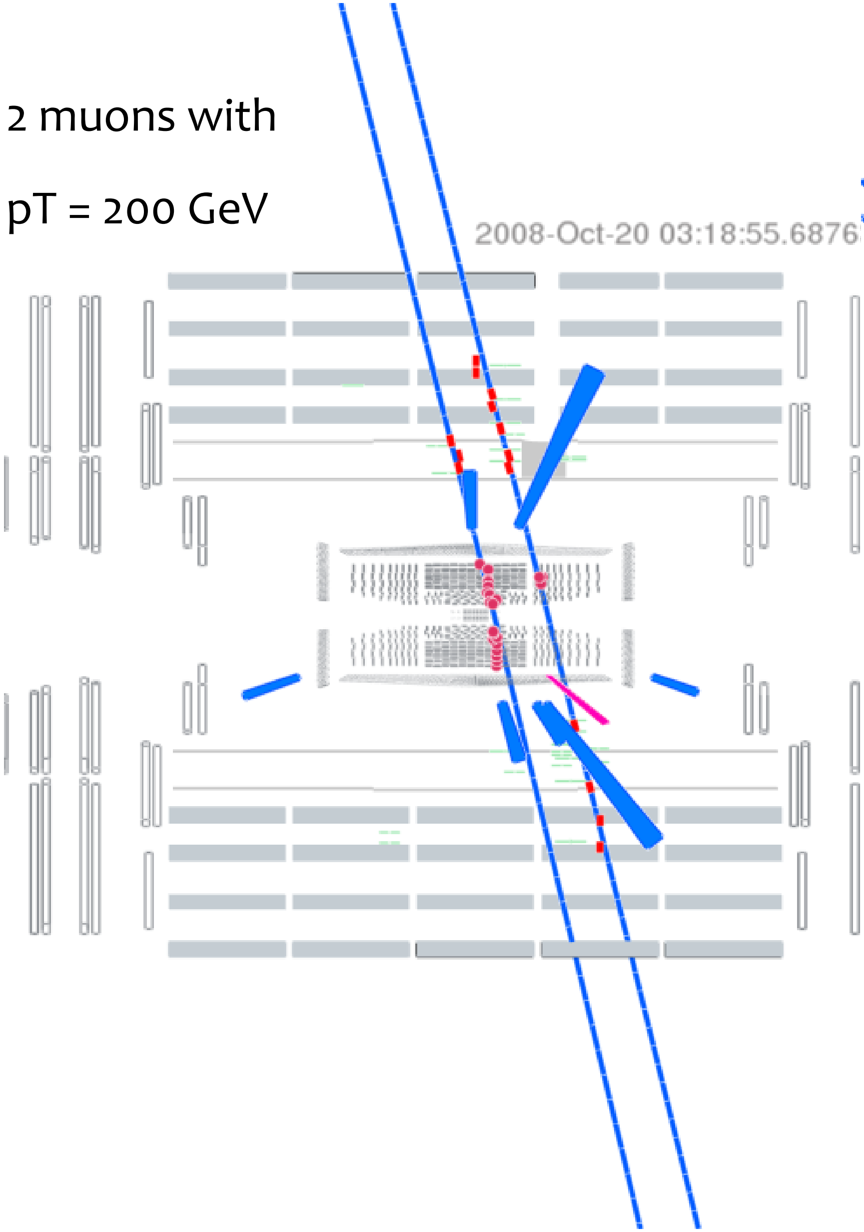


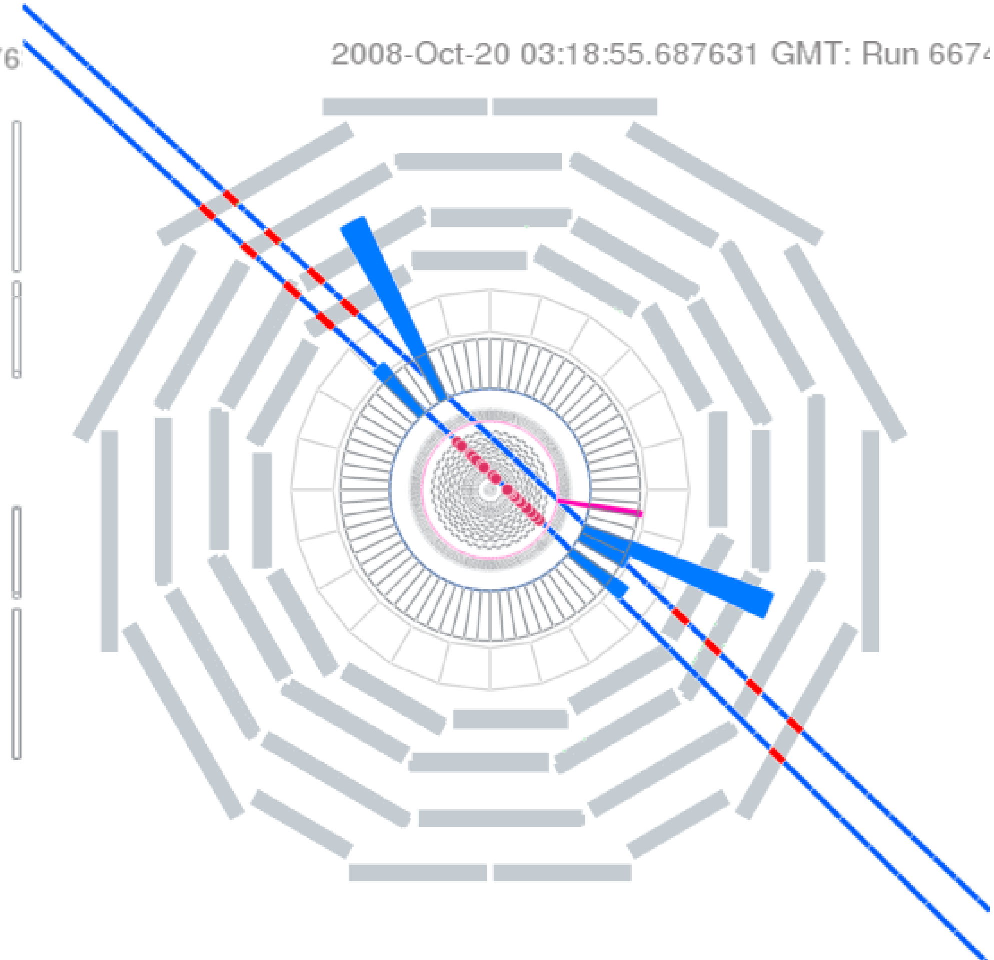
- Run 50908
- event 1057286
- 541 segments

CRAFT'09 event (B on)

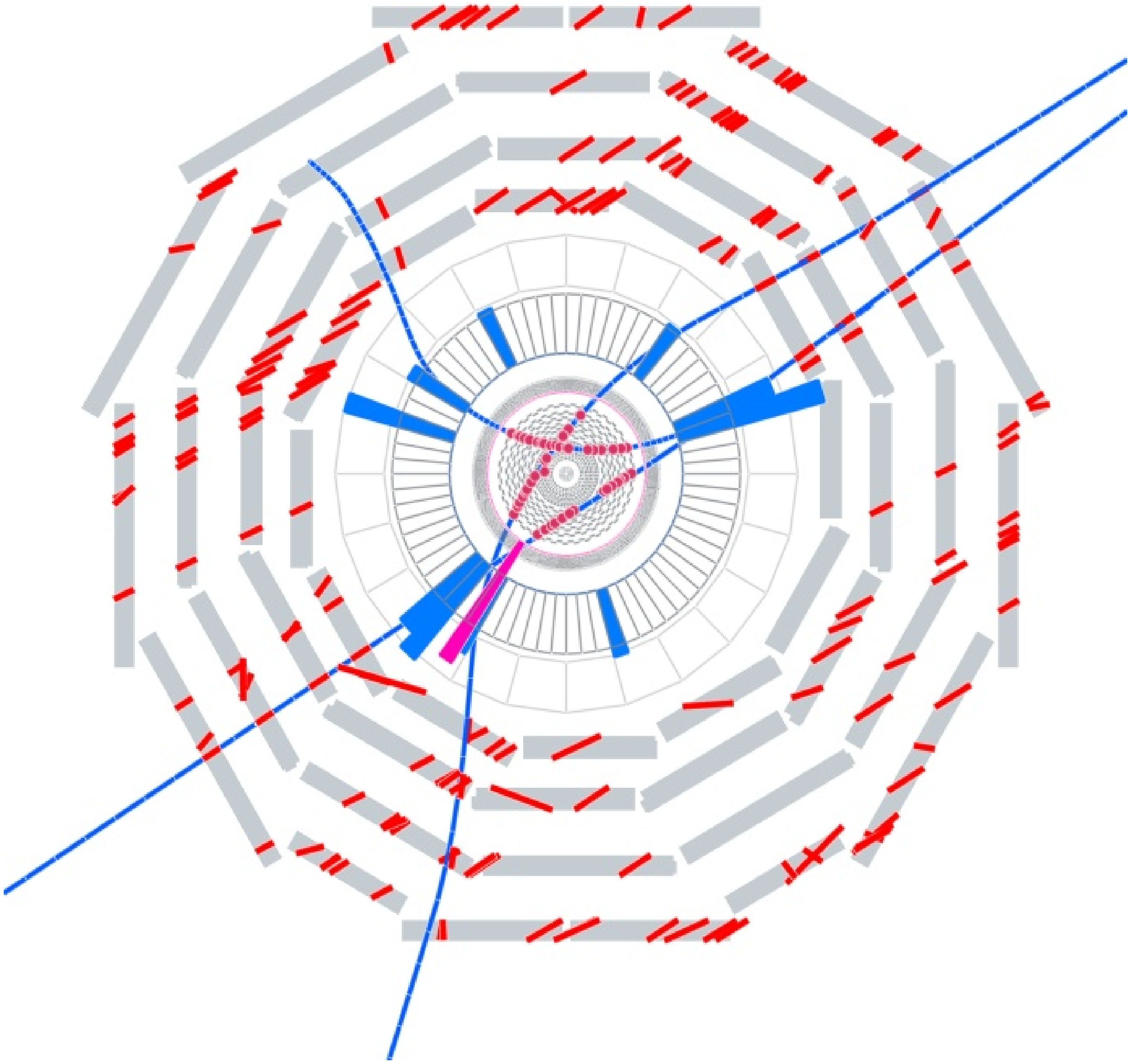
2 muons with

pT = 200 GeV





CRAFT'09 event (B on)

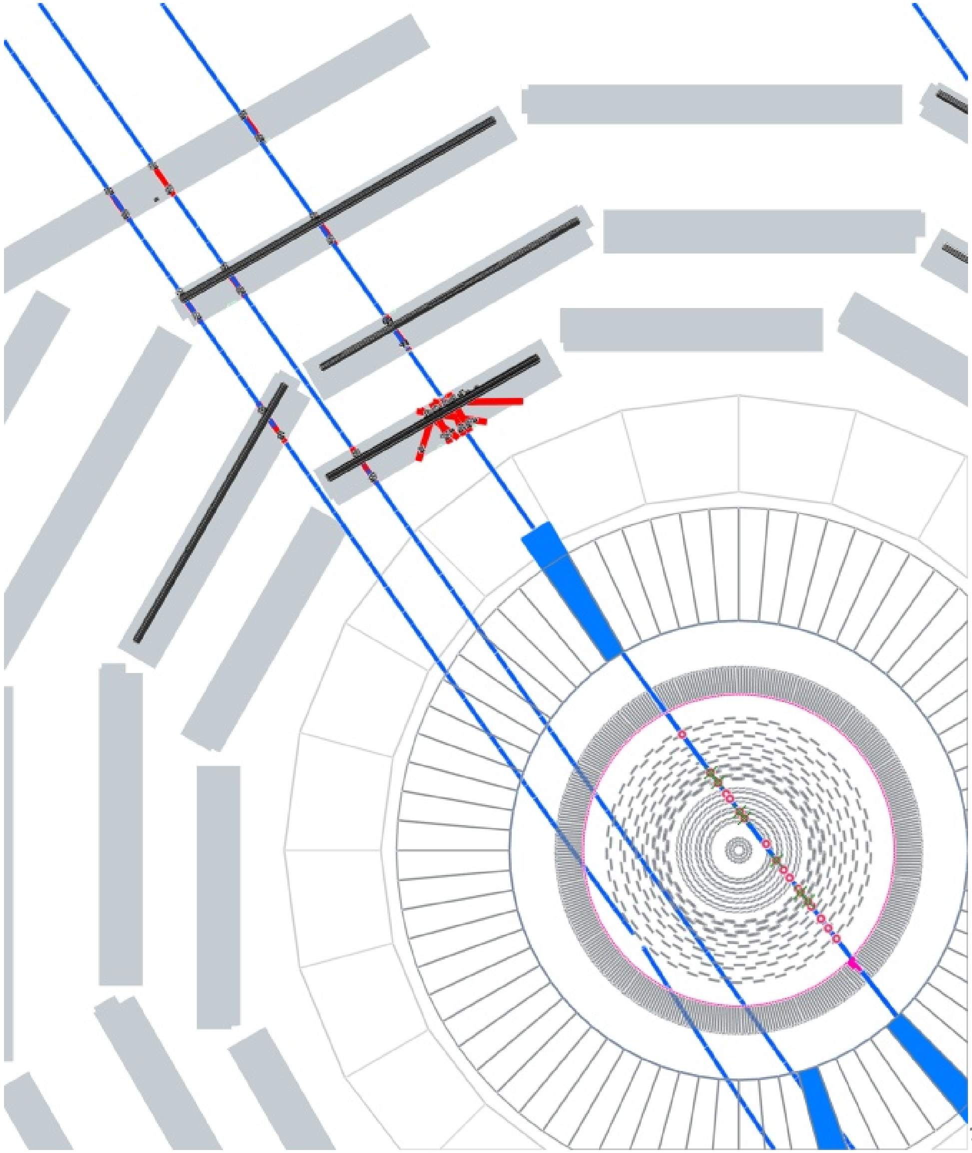


CRAFT'09 event (B on)

>3 parallel muons

100 GeV muon with

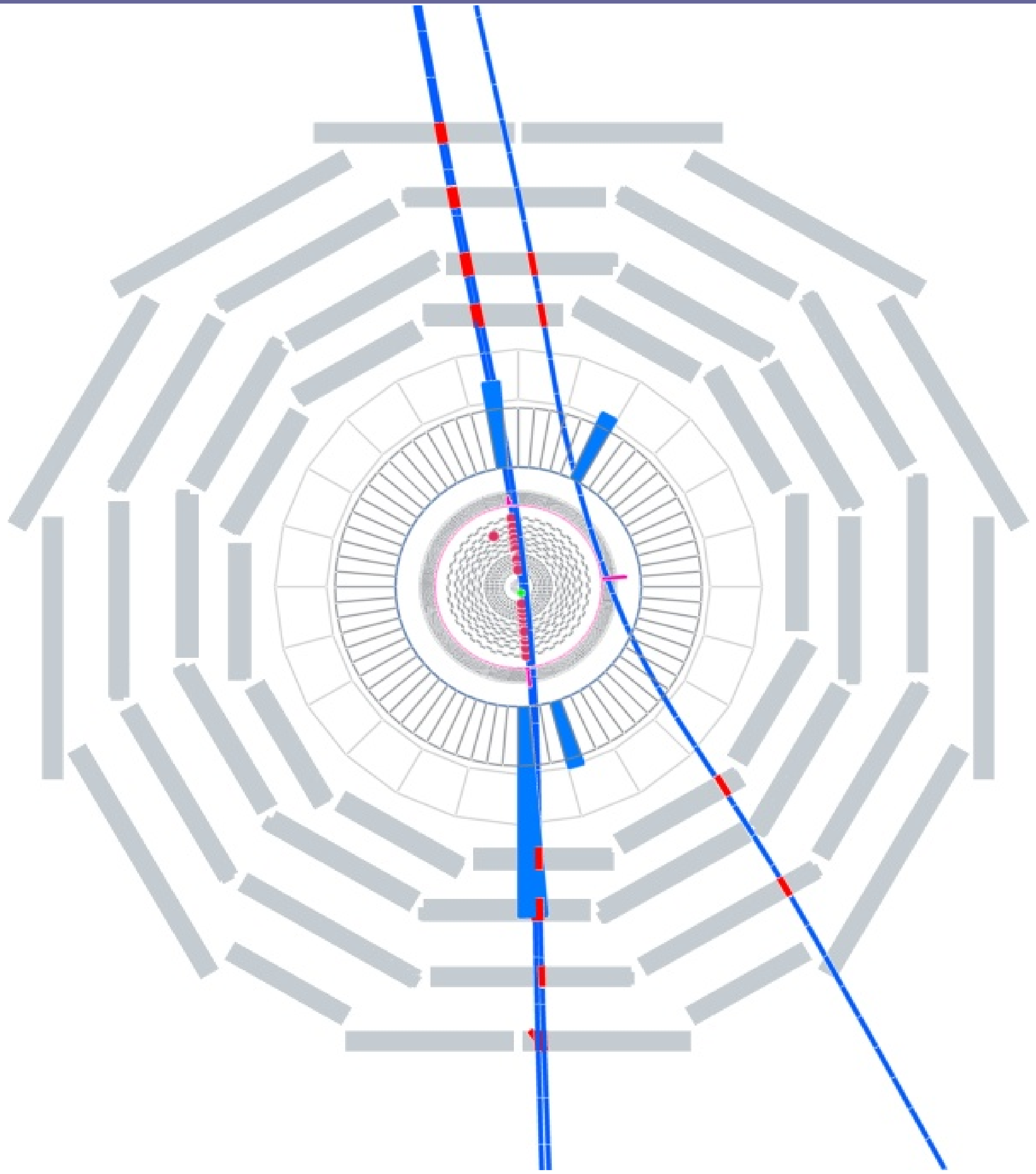
shower in Drift Tube:



CRAFT'09 event (B on)

Run 66739

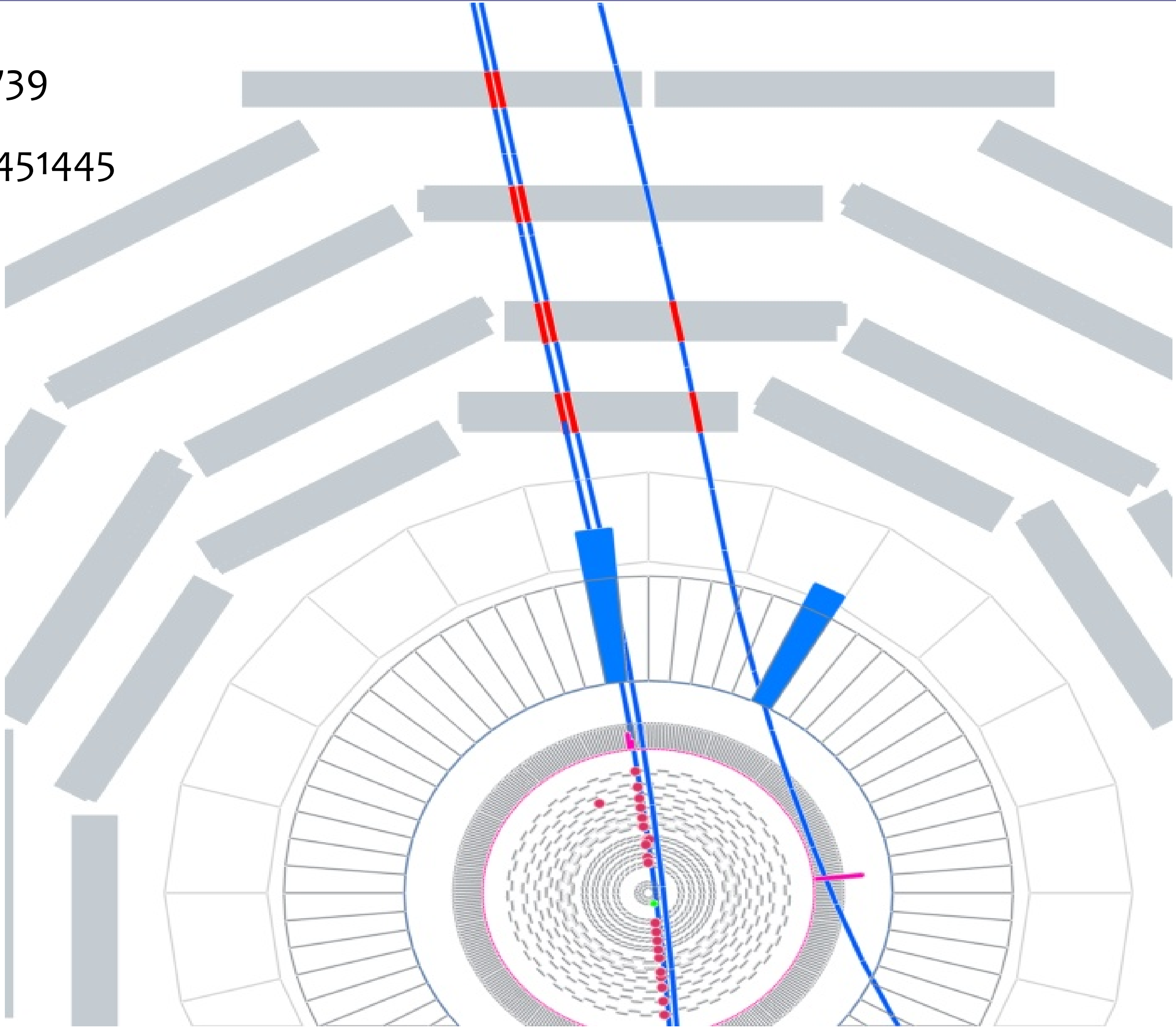
Event 9451445



CRAFT'09 event (B on)

Run 66739

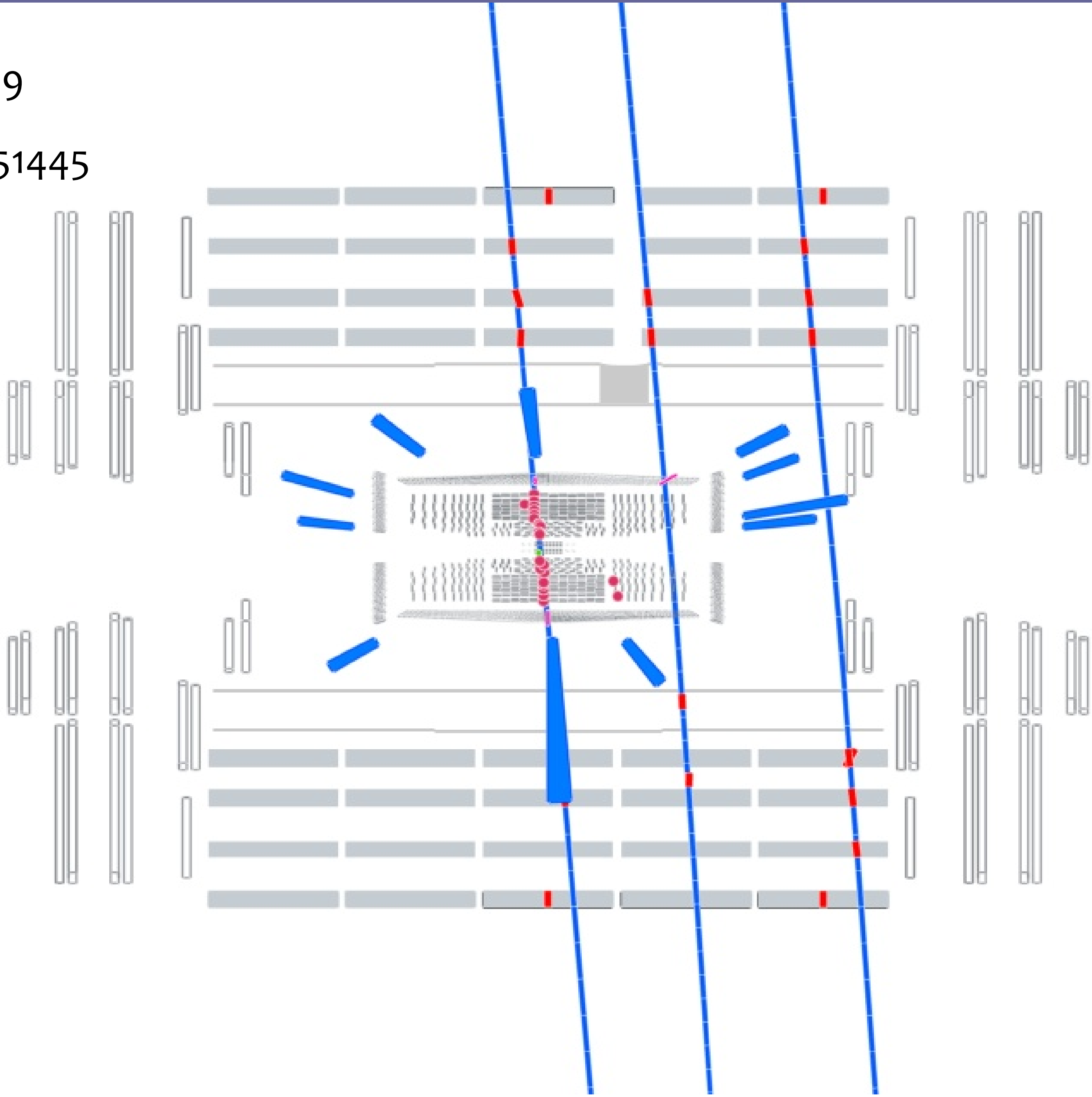
Event 9451445



CRAFT'09 event (B on)

Run 66739

Event 9451445



Finally:
LHC proton-proton Collisions…!

LHC re-start Nov 2009

November 21, 2009

BBC NEWS

Scientists at Cern in Geneva have restarted the Large Hadron Collider (LHC) experiment, which hopes to shed light on the origins of the universe.

First LHC p-p collisions

First collisions 23 November
First stable beams 6 December
First 2.36 TeV collisions 14 December

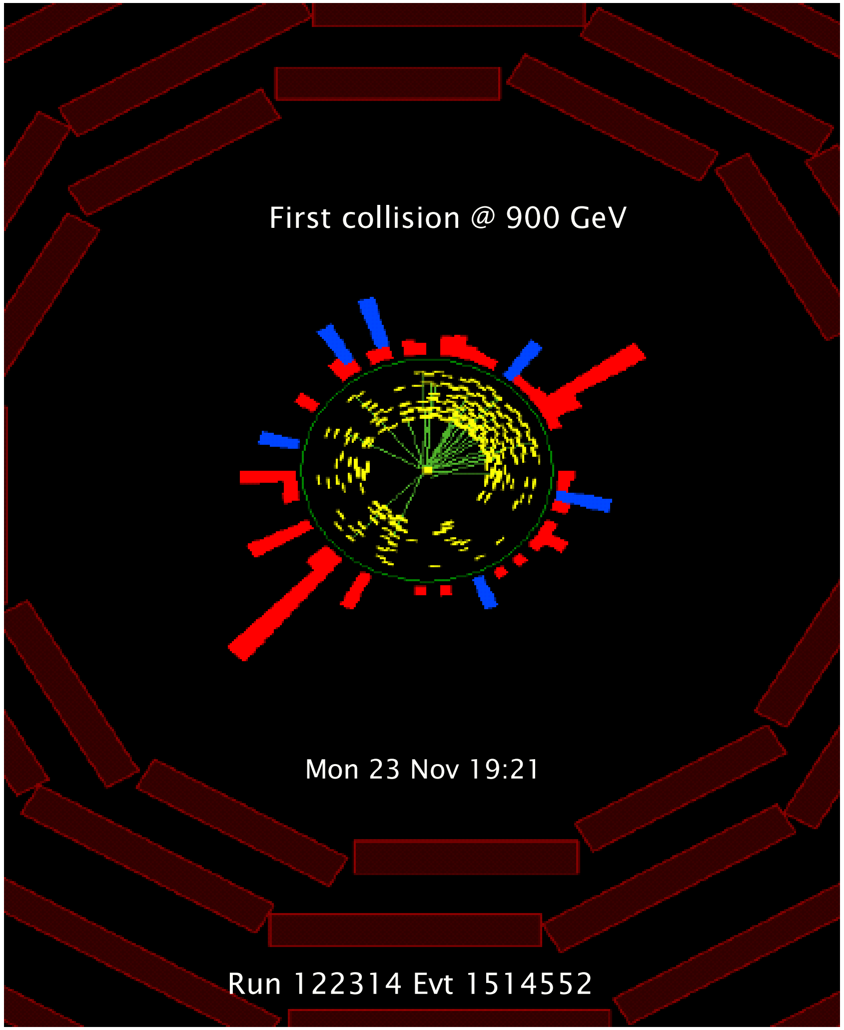
Recorded **85% of delivered luminosity**

Number of collected events:

$3.9 \times 10^5 \approx$ 10 μb^{-1} @ 900 GeV
$2.0 \times 10^4 \approx$ 0.4 μb^{-1} @ 2360 GeV
Tracker on, beam background rejected

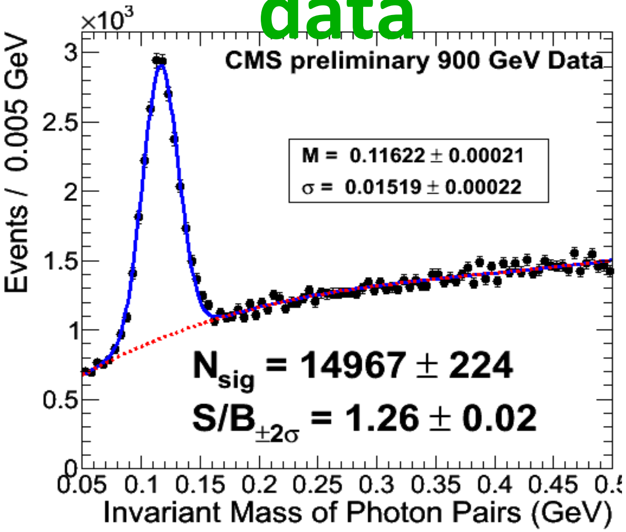
Fully 'open' trigger
Minimum Bias trigger rate 0.5-15 Hz

Quick analysis delivered preliminary results within hours/days

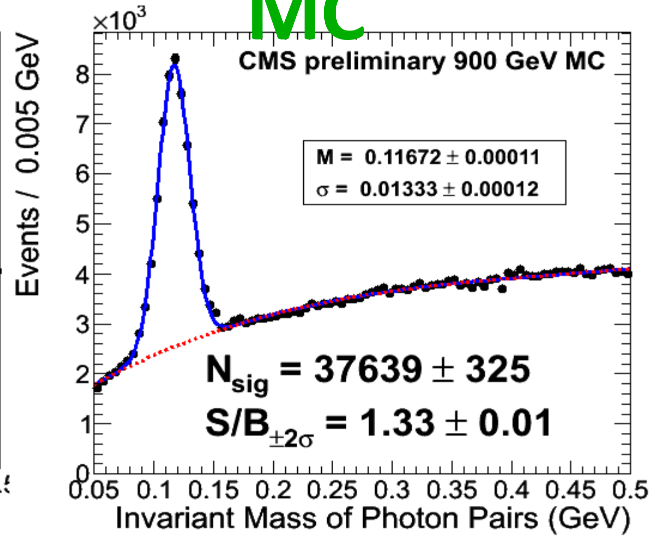


π⁰ and η in ECAL:

data



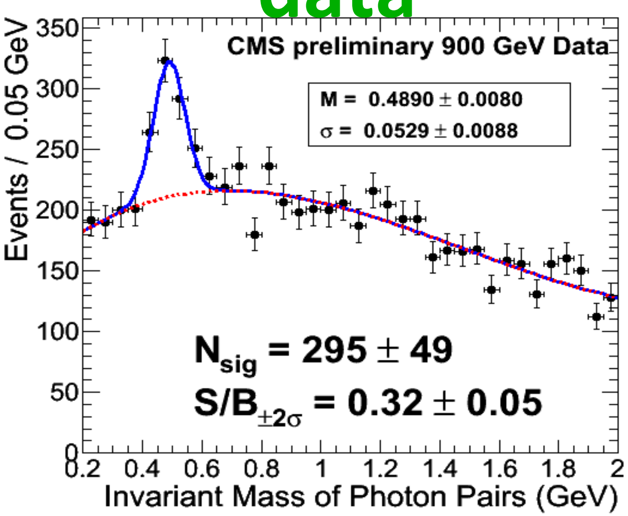
MC



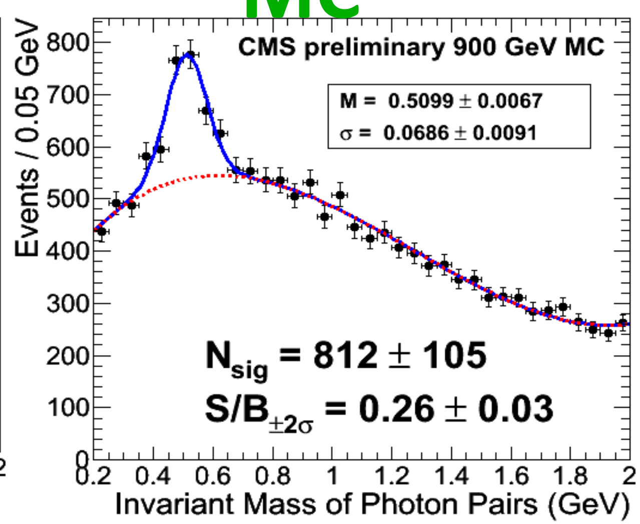
Only ECAL barrel (|η|<1.479)
pT(γ) > 300 MeV
pT(π0) > 900 MeV
shower shape

No corrections for shower containment, thresholds, energy loss upstream of ECAL → mass is a bit low

data



MC



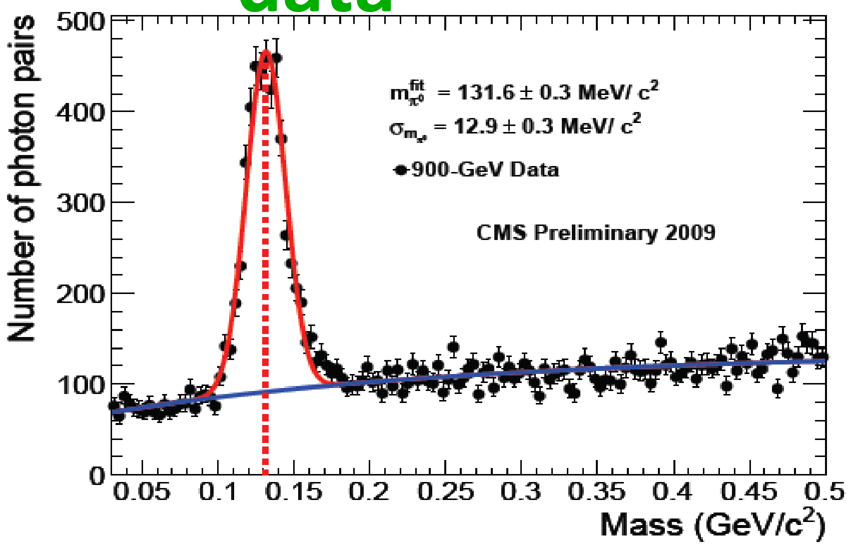
Photon pairs in barrel
ET(γ)>400 MeV;
ET(η)>2.0 GeV;
shower shape

Good agreement data and MC: peak position and S/B

→ energy scale in data and MC agree within 2% (even at these low energies!)

More π^0's, and electrons too!

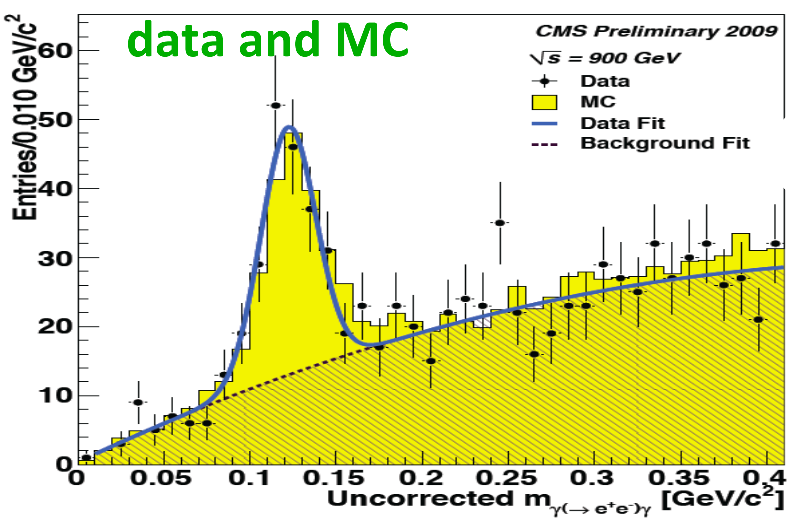
data

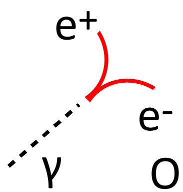


→ ***mass within 2% of known π^0 mass (PDG: 135 MeV)***

Photon pairs in the ECAL barrel (|η|<1)
E(γ) > 400 MeV
E(π0) > 1.5 GeV

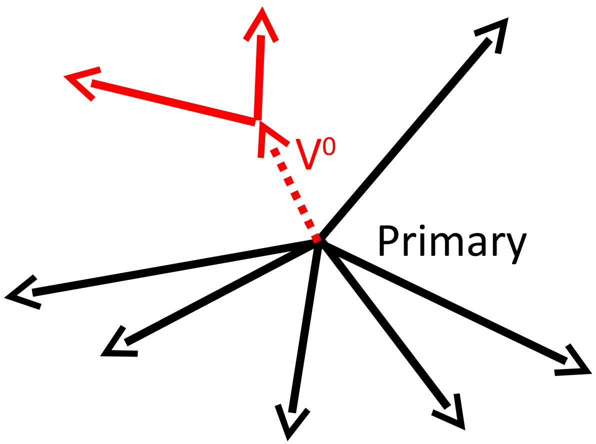
Monte-Carlo based correction of photon cluster energy is applied



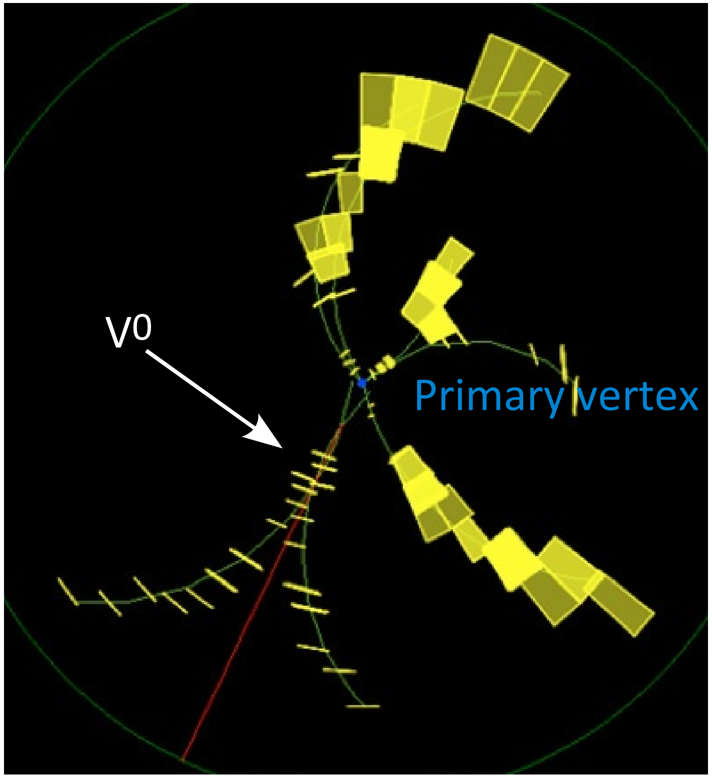


One photon in the ECAL barrel (|η|<1.479)
ET(γ) > 300 MeV
Second photon reconstructed as e+e- pair, using tracker only
pT(π0) > 1.5 GeV

V^0 decays in the Tracker



- Like photon conversions, look more generally for neutral particles that decay far away (> 1 cm or so) from primary vertex, to a pair of oppositely charged tracks
- Useful to find weak decays of Ks (and Λ^0) to $\pi^+\pi^-$ (or $p\pi^-$)



Track requirements: ≥6 hits and χ^2/dof < 5
$d_0/\sigma(d_0) > 0.5$.
Vertex requirements: χ^2/dof < 7, $>15\sigma$ separation from beam spot in radial direction. No daughter track hits $>4\sigma$ inside of vertex

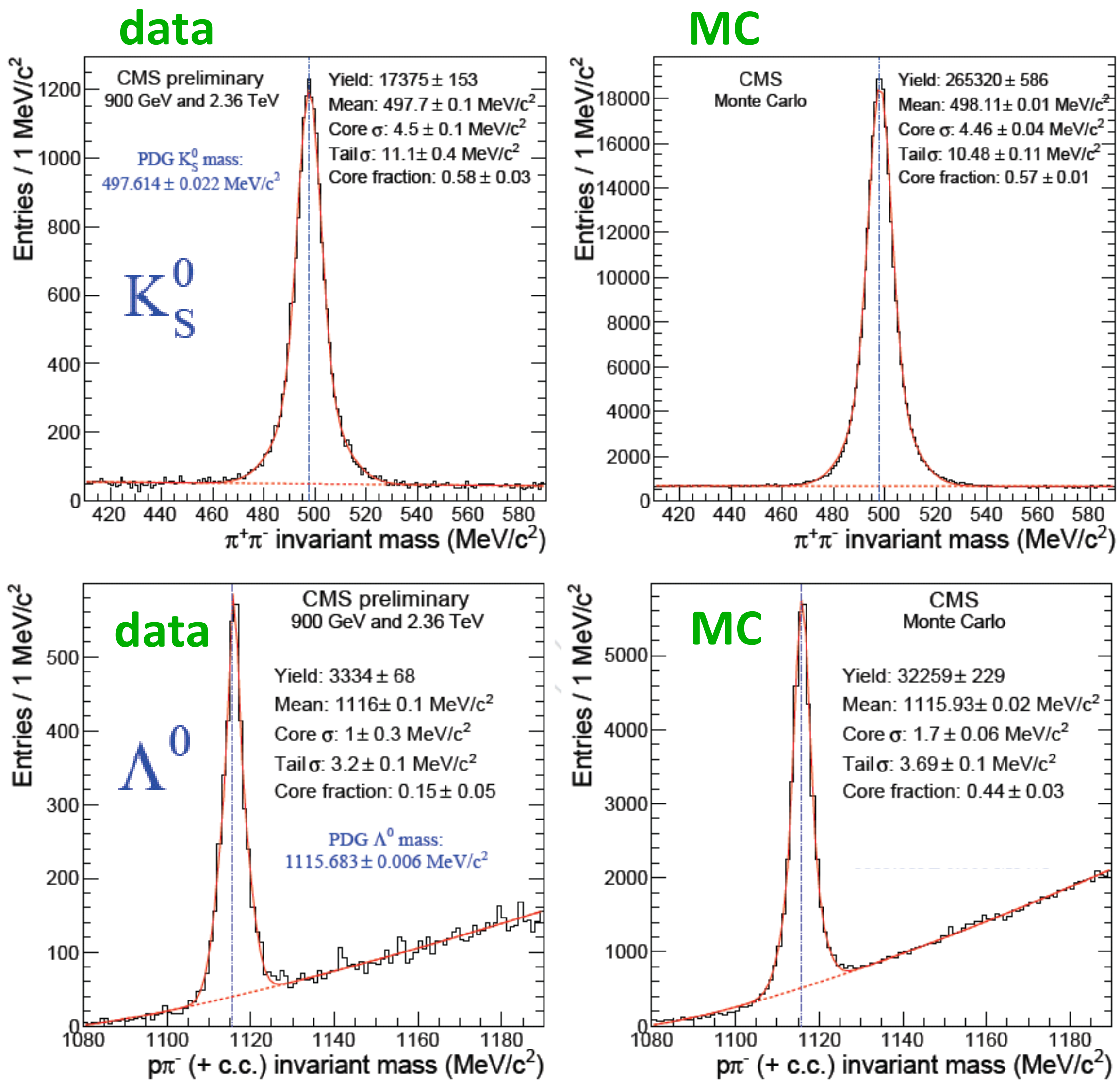
Strange particles in the Tracker

First K and Λ peaks presented within hours after first 900 GeV run with magnet on!

Peak shape and S/B agree beautifully between data and MC

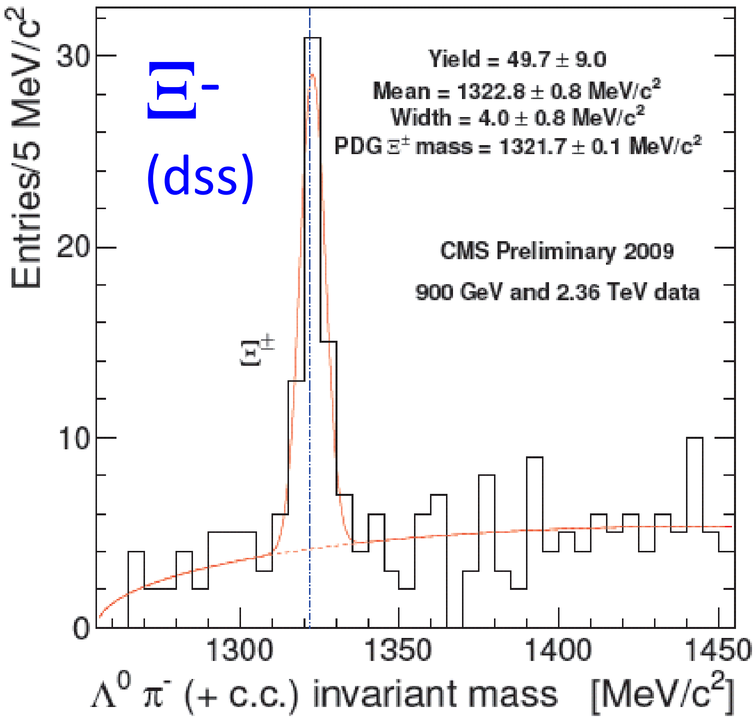
Momentum scale correct to better than 0.1% (PDG/data and data/MC)

→ confirms excellent knowledge of B field

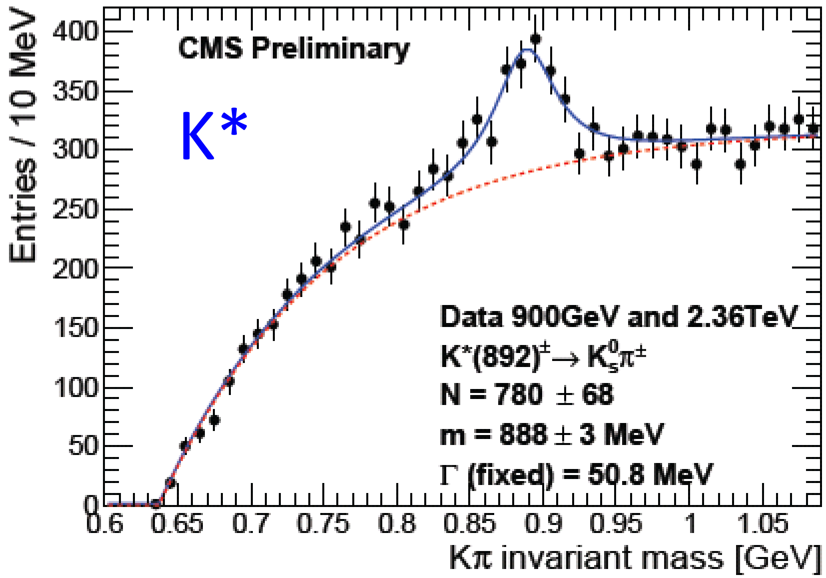


Cascade baryon and K*(892)

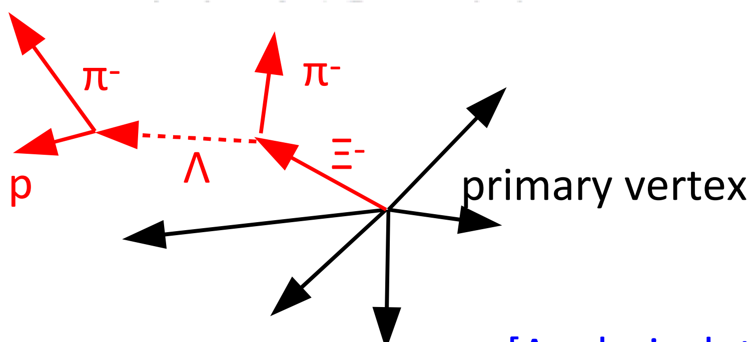
data *single Gaussian fit*

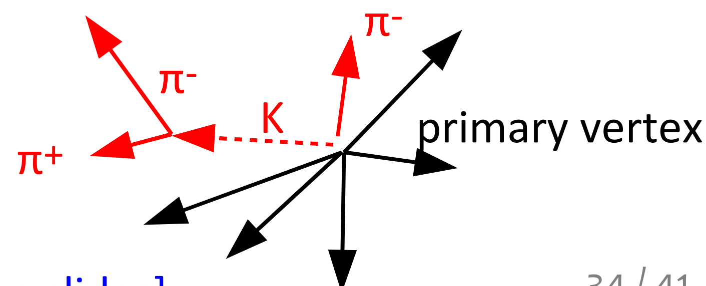


data *Fit : Gaussian and Breit-Wigner*



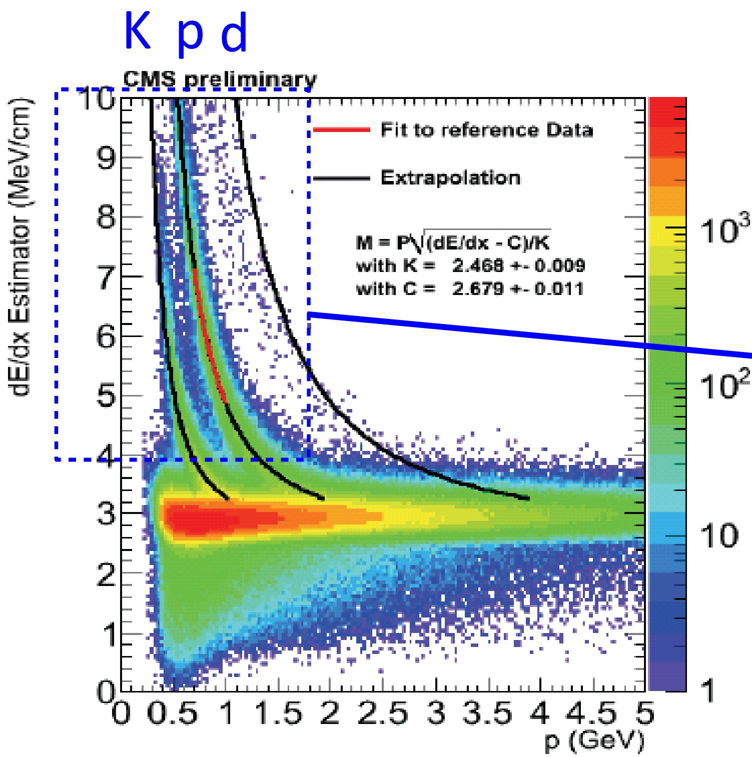
Again: excellent agreement peak position with PDG mass

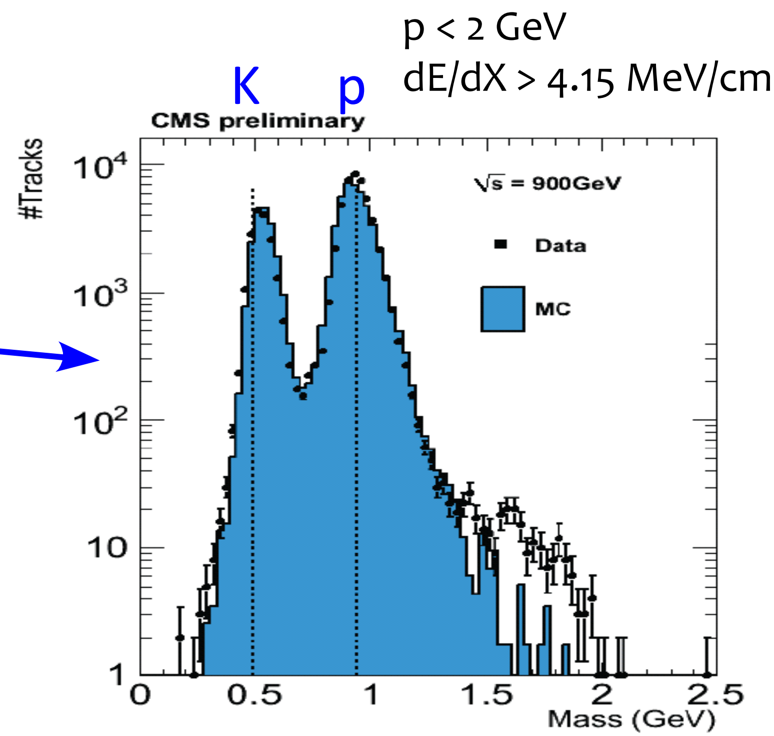




[Analysis details in backup slides]

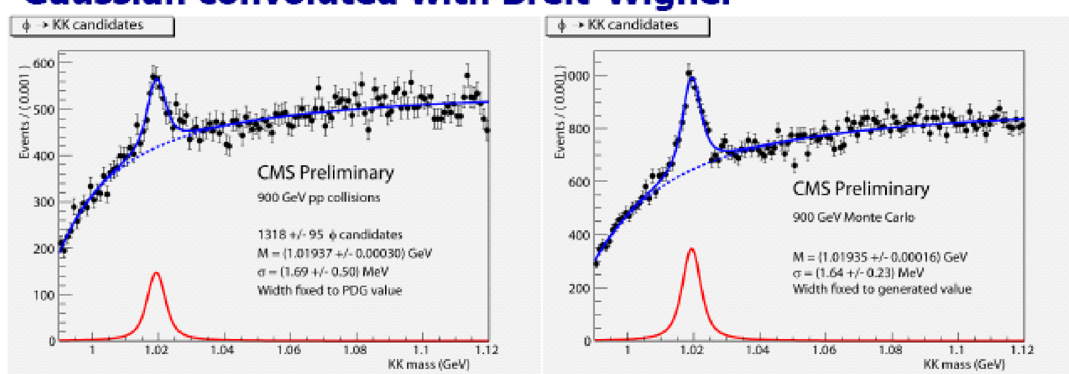
dE/dx in the Tracker





dE/dx estimated from charge deposited in silicon tracker hits (analog readout)
used for paricle ID at low momentum

φ →KK
Gaussian convoluted with Breit-Wigner



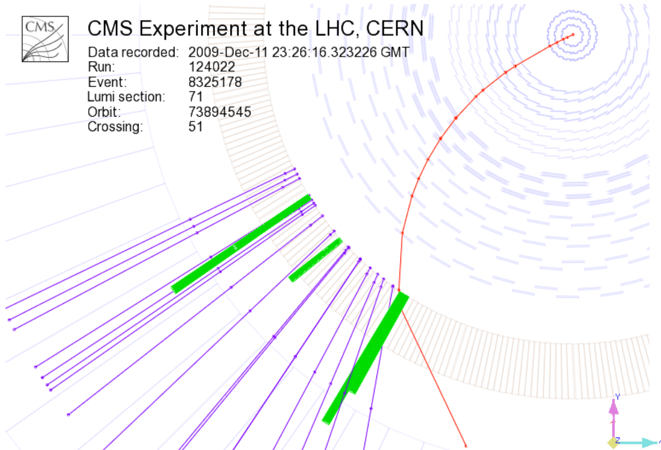
Intermediate Summary

- Good understanding EM calorimeter: energy scale for low-pT photons and electrons correct to 2% level
- Beautiful performance of the tracker → momentum scale for low-pT tracks (B field) correct to 0.1% level:

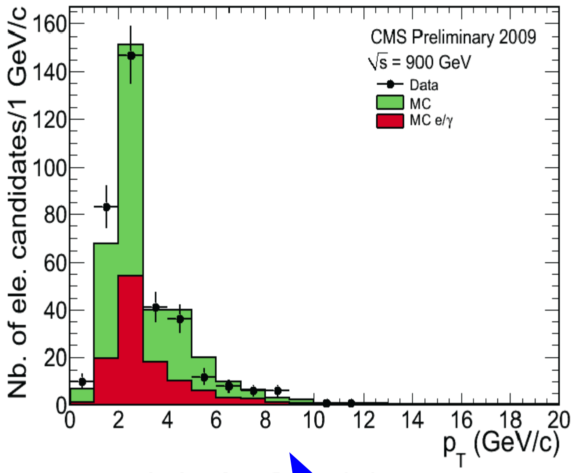
Mass bias	K_S	Λ	Ξ^-	K^{*+}	Φ
$(mass_{data} - mass_{PDG}) - (mass_{MC} - mass_{Gen})$	-0.37 ± 0.07 MeV	0.04 ± 0.06 MeV	0.0 ± 0.9 MeV	-4.0 ± 3.1 MeV	-0.22 ± 0.26 MeV

Ready for electrons…

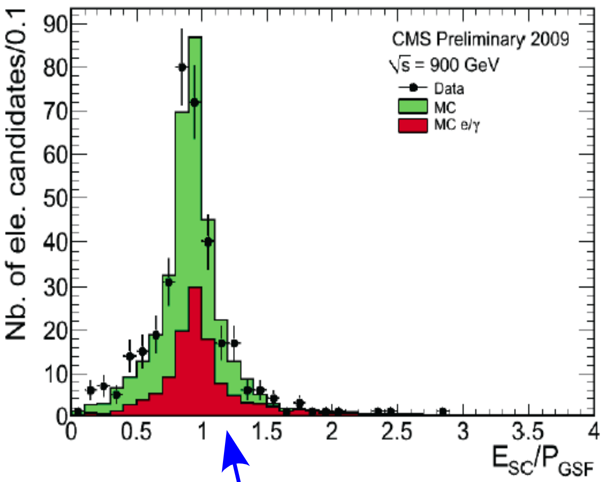
Electron (candidates)



2.5 GeV electron candidate with bremsstrahlung



low pT



Good agreement
Track and
Calorimeter cluster

Low statistics for signal in these data

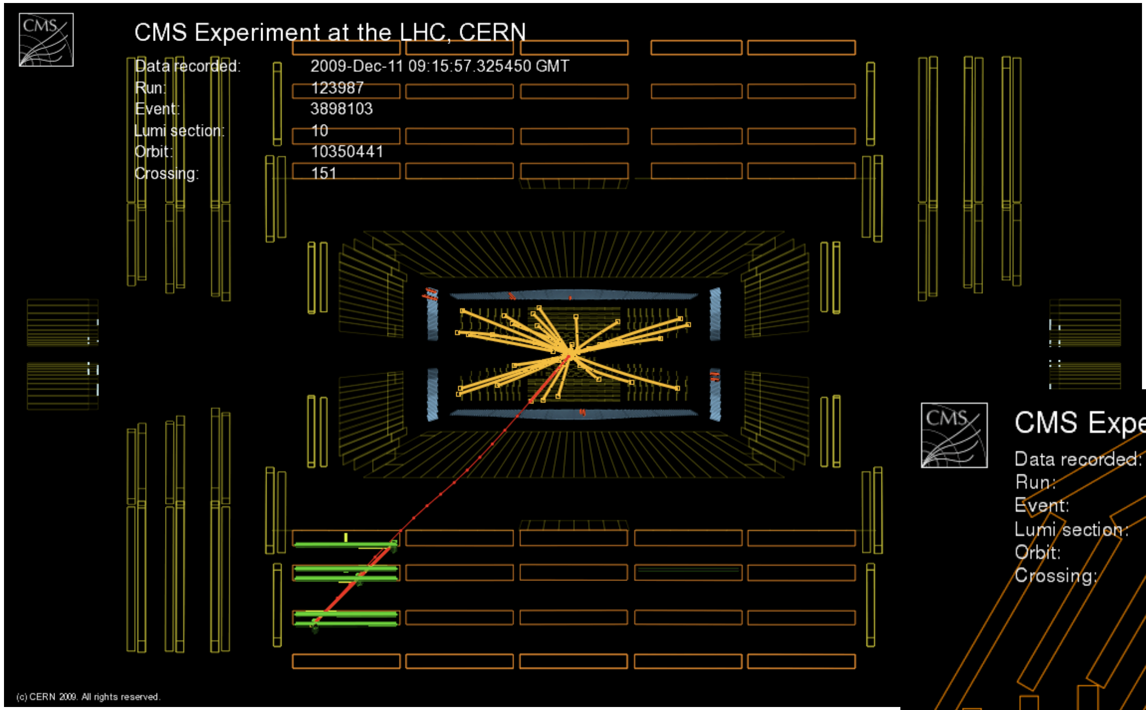
Comparison with MC performed mainly for background (only 1/3 of electron candidates are electrons, mostly from conversions)

Commissioning will continue in the next run
Agreement with MC is promising

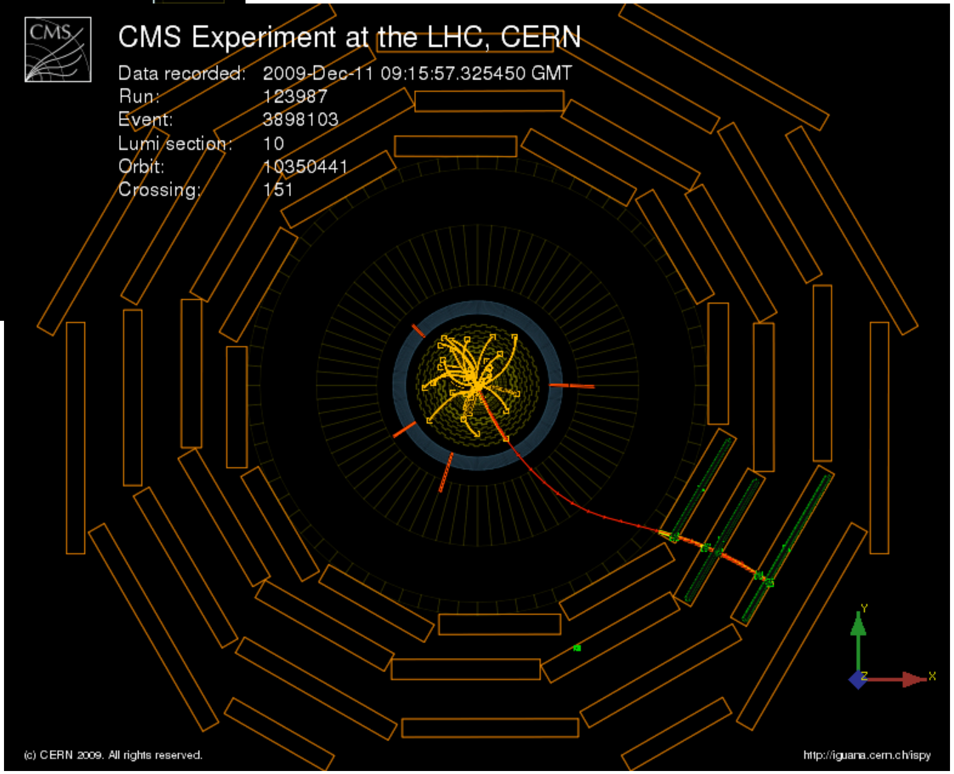
Reconstructed electrons candidates combining two seeding algorithms

- "ecal driven" optimized for W/Z electrons, starting from clusters of energy > 4 GeV
- "tracker driven" more suitable for low p_T electrons and electrons in jets

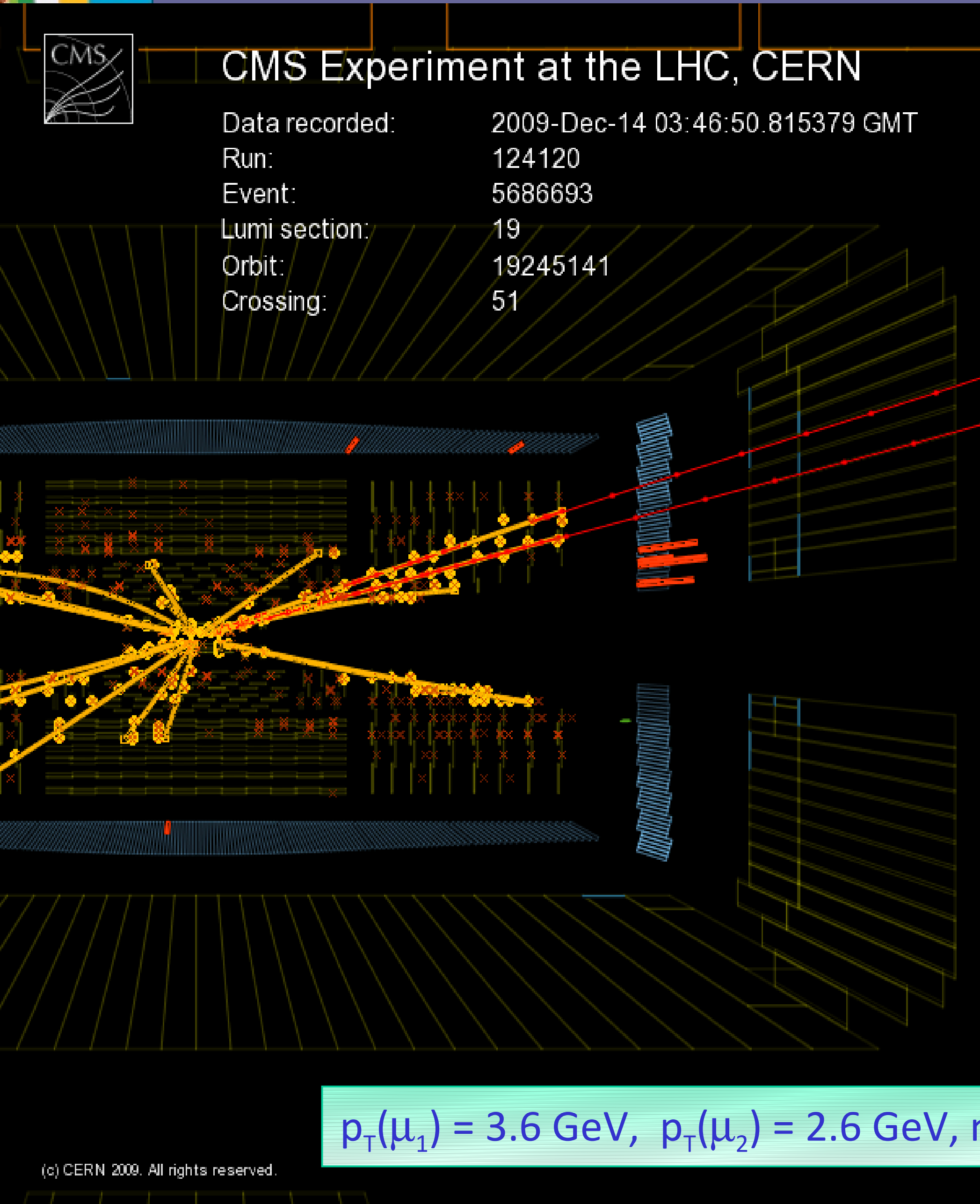
And Muons



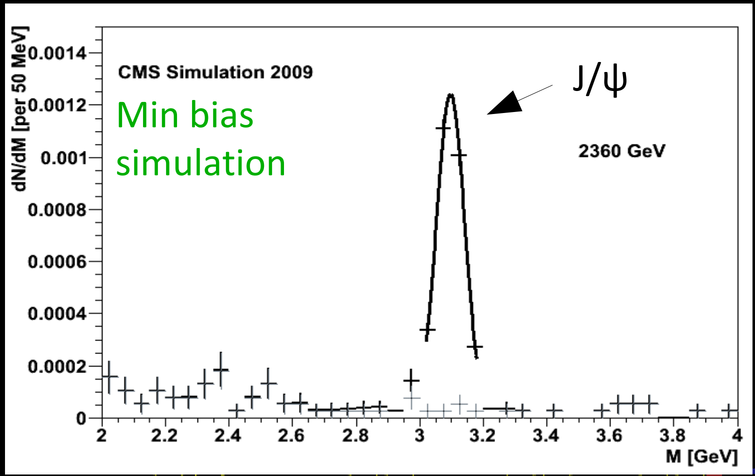
A rare muon in the barrel…



Di-muon event in the EndCaps



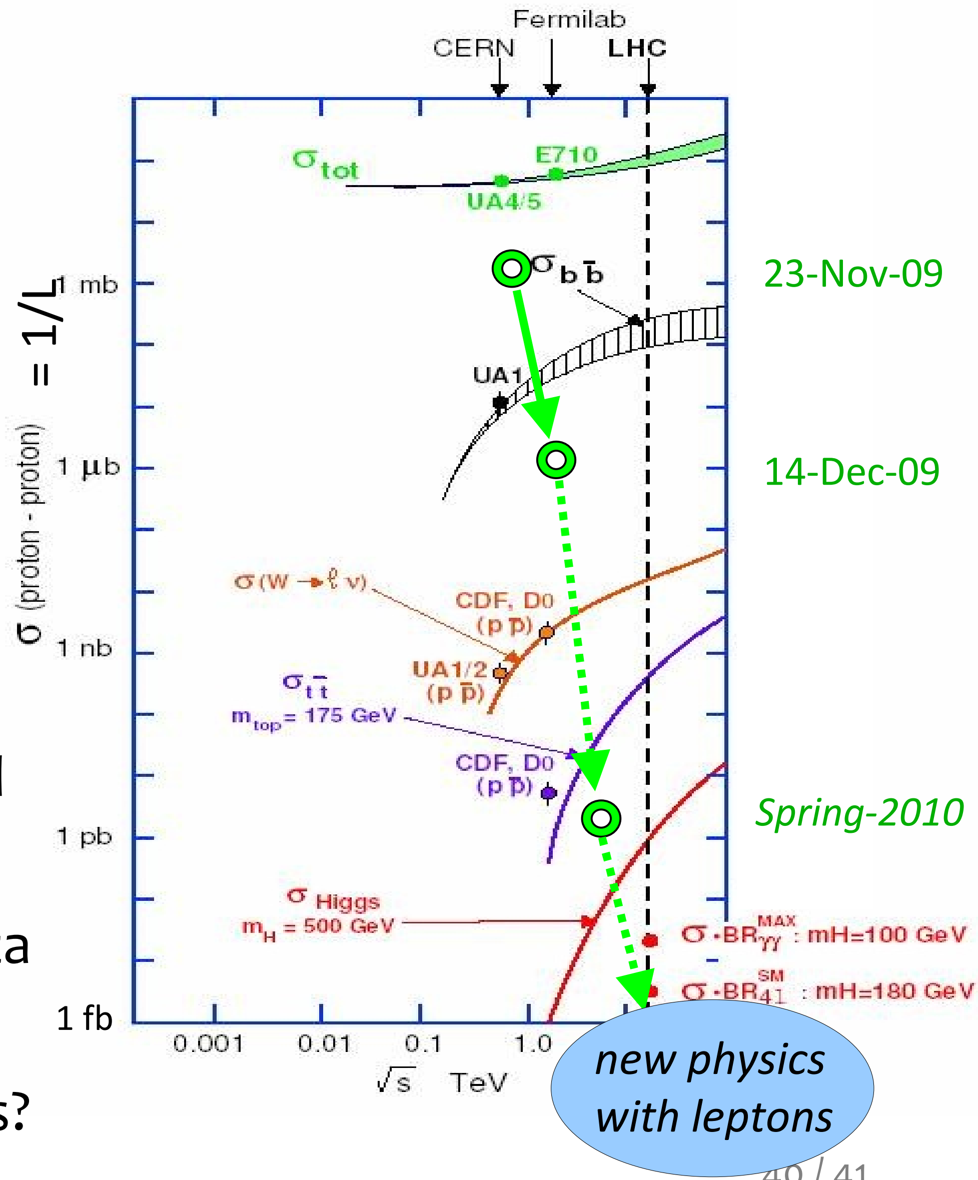
1 event observed in mass window 2-4 GeV
S/B between 3.0 and 3.2 GeV ~ 16/1



$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

Summary and Prospects

- CMS design and sophisticated algorithms promise unprecedented multi-lepton identification capabilities
- Started testing key ingredients for physics with cosmics and first (~10μb-1) of pp data
- Amazing results so far
- But: still many orders of magnitude away from normal physics operation
- Expect a million times more data (~10pb-1) very soon!
- Ready for multi-lepton searches?



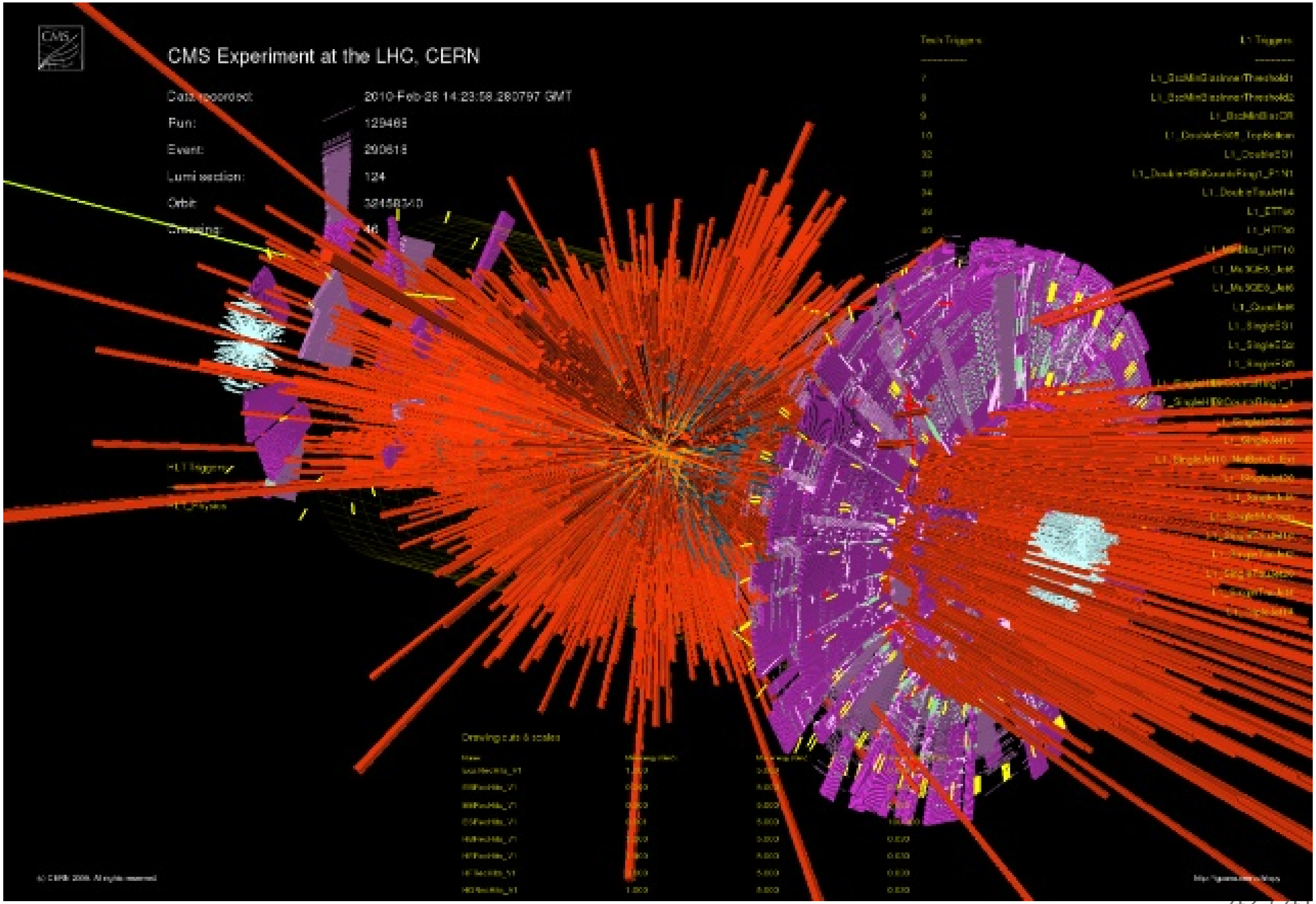
Conclusion

- CMS has studied (mostly single) muon reconstruction and identification in great detail using cosmics. With Nov'09 data, started commissioning electrons and taus (not shown)
- November 2009 LHC data great opportunity to study lepton reconstruction in collision data, but:
  - More background than signal (study fakes)
  - Very low pT and very low statistics
- In next months we expect a million times more data, to study:
  - Single- and multi-lepton trigger performance
  - Commissioning with more statistics muon, electron and tau reconstruction and identification...

The prospects for multi-lepton studies in CMS are excellent !

BACKUP SLIDES

Beam splash Event February 28, 2010



More Information:

CMS overview of published and preliminary physics results:
http://cms-physics.web.cern.ch/cms-physics/CMS_Physics_Results.htm

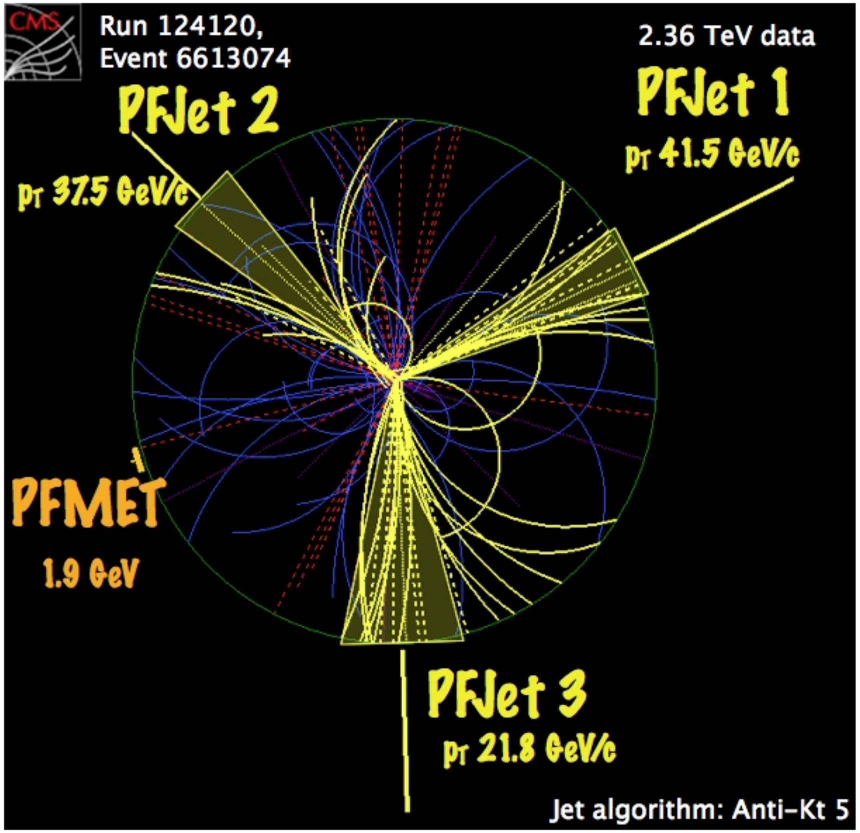
23 CRAFT papers published in JINST: http://iopscience.iop.org/1748-0221/focus/extra.proc6

09-001	Commissioning and Performance of the CMS Pixel Tracker with Cosmic Rays	http://arxiv.org/abs/0911.5434
09-002	Commissioning and Performance of the CMS Silcon Strip Tracker with Cosmic Ray Muons	http://arxiv.org/abs/0911.4996
09-003	Alignment of the CMS Silicon Tracker During Commissioning with Cosmic Ray Particles	http://arxiv.org/abs/0910.2505
09-004	Performance and Operation of the CMS Electromagnetic Calorimeter	http://arxiv.org/abs/0910.3423
09-005	Measurement of the muon stopping power of Lead Tungstate	http://arxiv.org/abs/0911.5397
09-006	Time Reconstruction and Performance of the CMS Electromagnetic Calorimeter	http://arxiv.org/abs/0911.4044
09-007	CMS Data Processing Workflows During an Extended Cosmic Ray Run	http://arxiv.org/abs/0911.4842
09-008	Commissioning of the CMS Experiment and the Cosmic Run at Four Tesla	http://arxiv.org/abs/0911.4845
09-009	Performance of the CMS Hadron Calorimeter with Cosmic Rays and Accelerator Produced Muons	http://arxiv.org/abs/0911.4991
09-010	Performance study of Barrel CMS Resistive Plate Chambers with Cosmic Rays	http://arxiv.org/abs/0911.4045
09-011	Performance of the CMS Cathode Strip Chambers with Cosmic Rays	http://arxiv.org/abs/0911.4992
09-012	Performance of the CMS Drift Tube Chambers with Cosmic Rays	http://arxiv.org/abs/0911.4855
09-013	Performance of the CMS Level-1 Trigger during Commissioning with Cosmic Rays	http://arxiv.org/abs/0911.5422
09-014	Performance of CMS Muon Reconstruction in Cosmic-Ray Events	http://arxiv.org/abs/0911.4994
09-015	Precise Mapping of the Magnetic Field in the CMS Barrel Yoke using Cosmic Rays	http://arxiv.org/abs/0910.5530
09-016	Alignment of the CMS Muon System with Cosmic-Ray and Beam-Halo Muons	http://arxiv.org/abs/0911.4022
09-017	Aligning the CMS Muon Chambers with the Muon Alignment System during an Extended Cosmic Ray Run	http://arxiv.org/abs/0911.4770
09-018	Performance of CMS Hadron Calorimeter Timing and Synchronization using Cosmic Ray and LHC Beam Data	http://arxiv.org/abs/0911.4877
09-019	Identification and Filtering of Uncharacteristic Noise in the CMS Hadron Calorimeter	http://arxiv.org/abs/0911.4881
09-020	Commissioning of the CMS High-Level Trigger with Cosmic Rays	http://arxiv.org/abs/0911.4889
09-022	Performance of the CMS Drift-Tube Chamber Local Trigger with Cosmic Rays	http://arxiv.org/abs/0911.4893
09-023	Calibration of the CMS Drift Tube Chambers and Measurement of the Drift Velocity with Cosmic Rays	http://arxiv.org/abs/0911.4895
09-025	Fine Synchronization of the CMS Muon Drift-Tube Local Trigger using Cosmic Rays	http://arxiv.org/abs/0911.4904

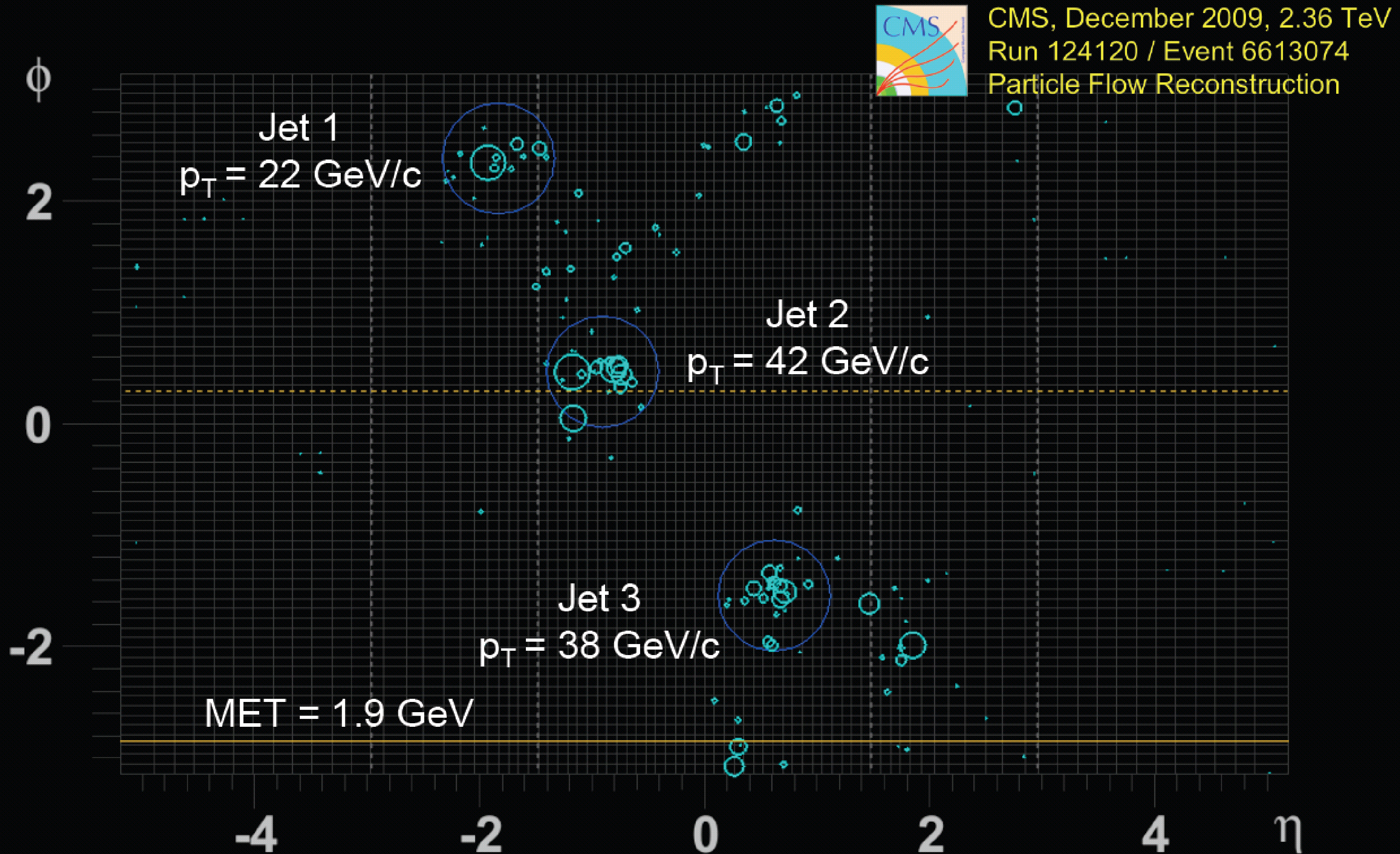
Unification of calorimetry and tracking

(to further improve the capability of CMS to measure ElectroWeak processes and detect potential new signatures of Unified Theories)

- Particle Flow approach: link tracks to calorimeter clusters to reconstruct individual photons, charged and neutral hadrons → to optimize energy resolution and particle ID
- CMS is ideally suited:
  - Powerful B field+ tracker
  - EM calorimeter with fine granularity



Eta-phi view

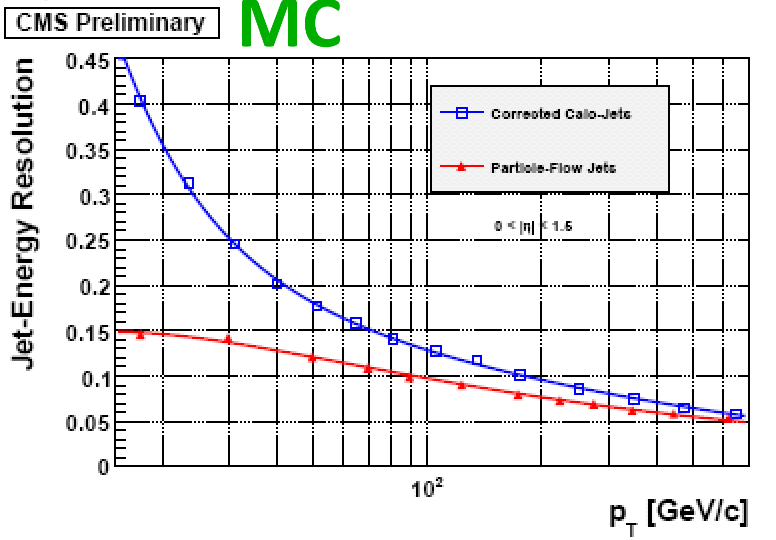


(η,φ) view of a particle-flow reconstructed event. Reconstructed particles are represented as circles with a radius proportional to their pT. The direction of the MET computed from all particles is drawn as a solid horizontal straight line. Particle-based jets with pT> 20 GeV/c are shown as thinner circles representing the extension of the jet in the (η,φ) coordinates.

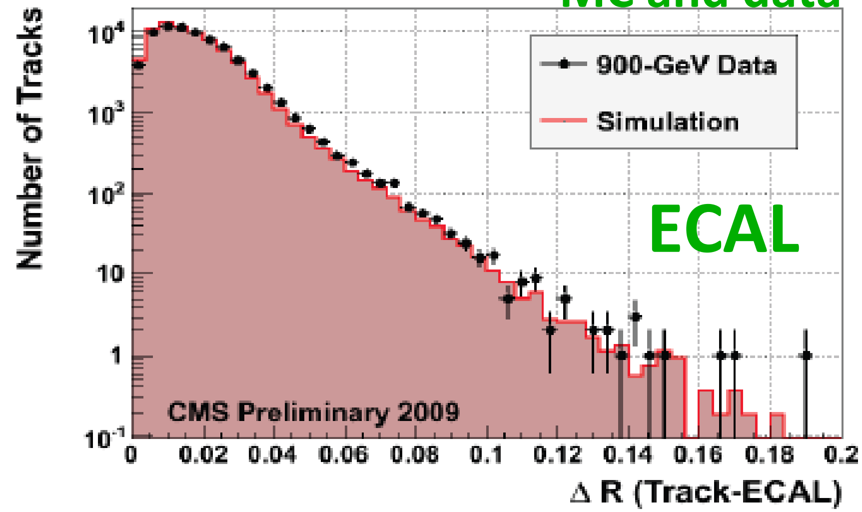
Linking tracks to Calo-clusters

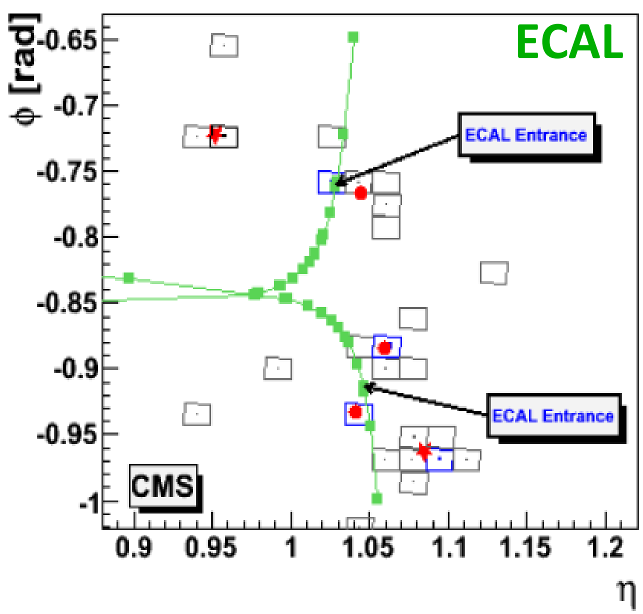
The goal: improved jet (and MET) resolution, especially at low pT

MC



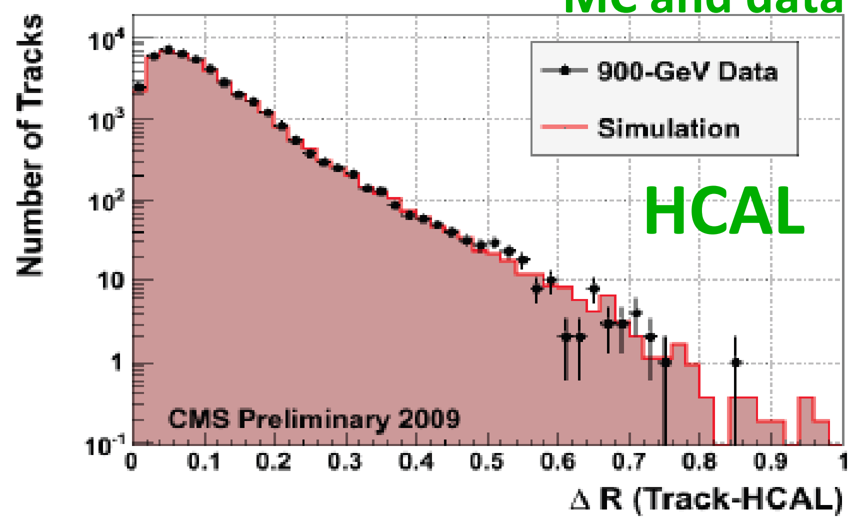
MC and data



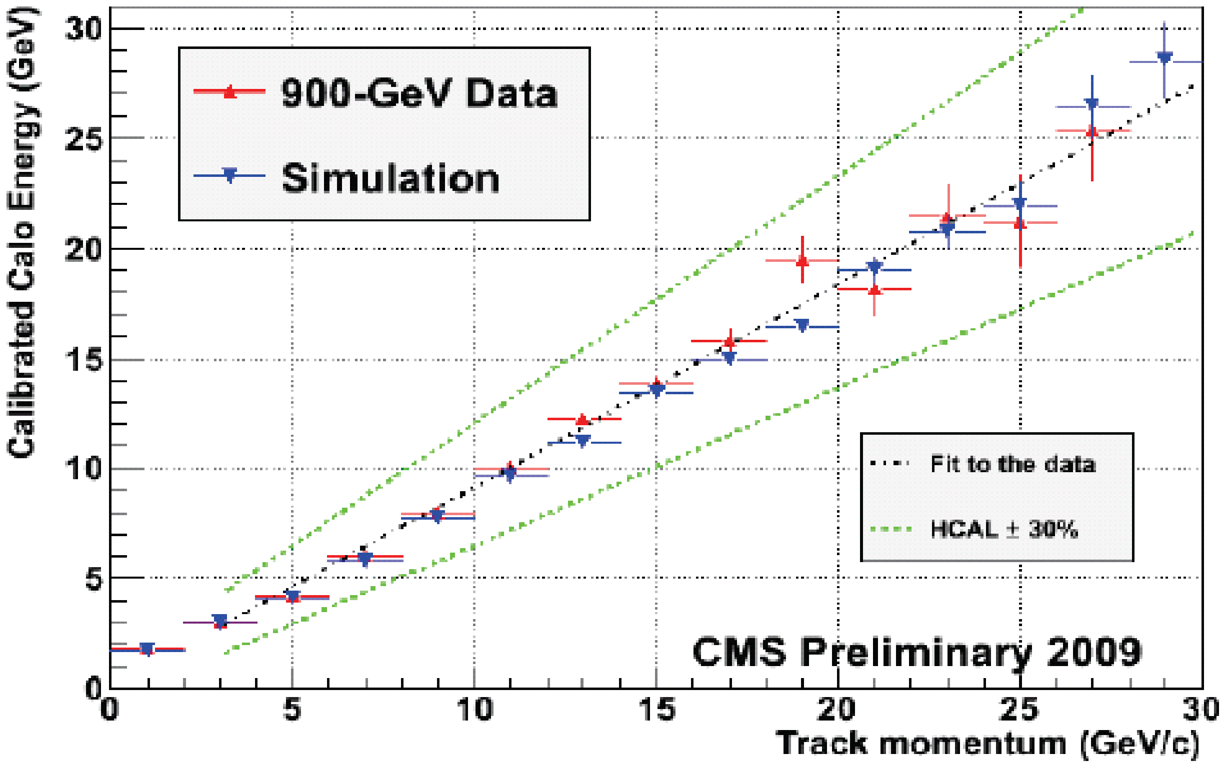


ΔR between tracks (pT > 1GeV) and closest linked calorimeter cluster

MC and data

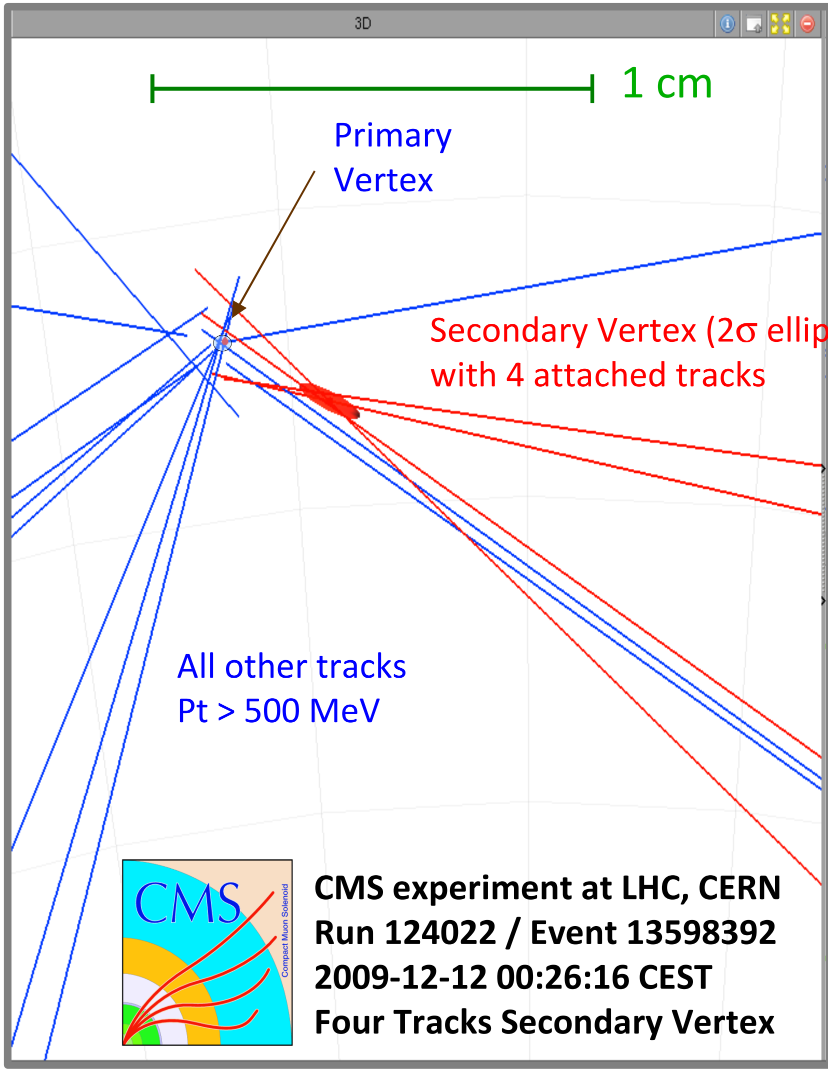


Particle Flow and HCAL calibration



- Compare calorimeter cluster energy to track momentum
  (integrated over full tracker acceptance $|\eta| < 2.4$)
- Calibration in simulation and data agree to 1.5 ± 4%
- This implies that HCAL calibration scale agrees within ~5%

Towards b-tagging:



Getting closer to the primary vertex

Secondary vertex with 4 tracks

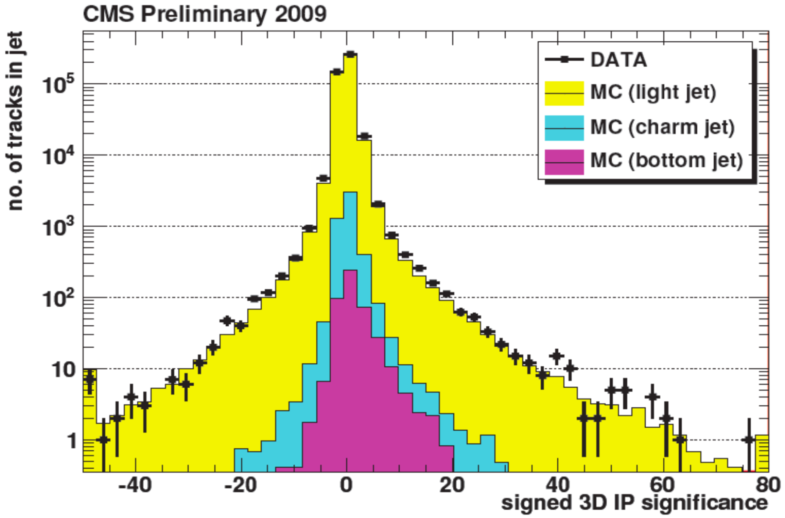
Vertex χ^2/ndf = 1.67 / 5

Vertex mass: 1.64 GeV/c^2

Transverse decay length significance: L_{xy}/σ = 0.12 / 0.019 [cm] = 6.6

3D decay length significance: L_{3D}/σ = 0.26 / 0.037 [cm] = 7.0

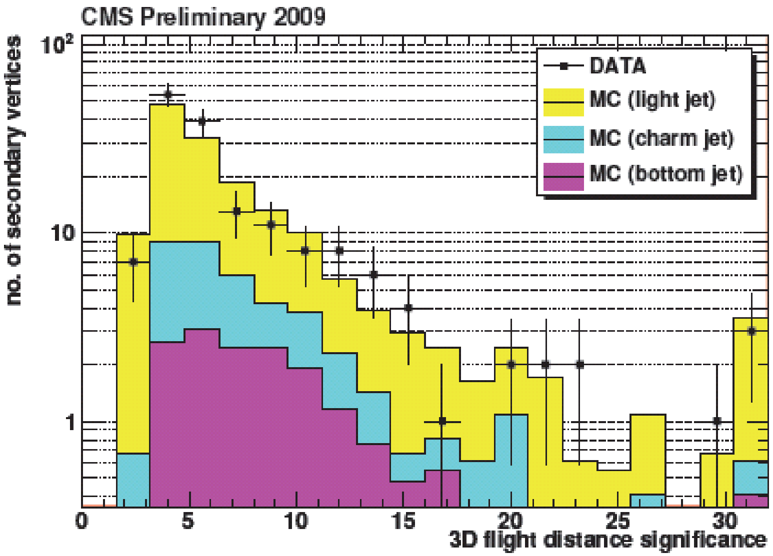
B-tagging variables



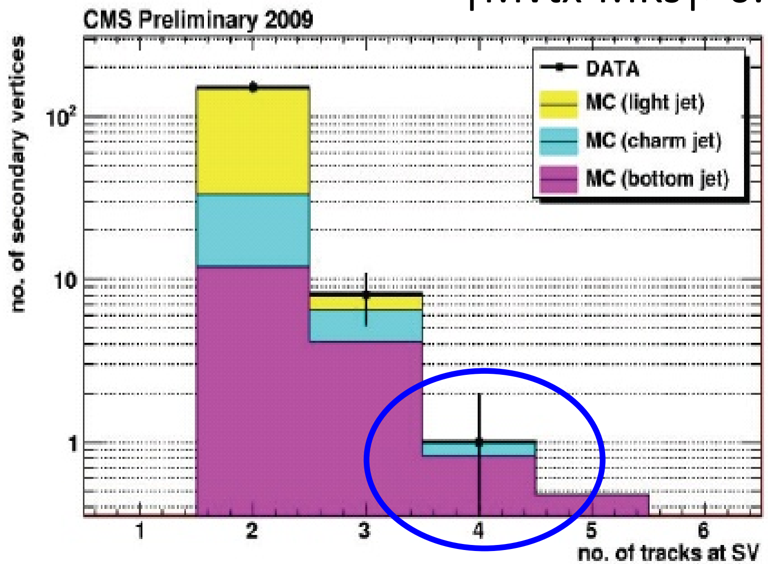
basic variables relevant for b-tagging are well described by simulation

Signed 3D impact parameter for tracks, with ≥7 hits, associated to a jet. Impact parameter with respect to primary vertex.

Secondary vertices with above tracks, after K rejection: Lxy< 2.5cm, |Mvtx-MKs|>0.015 GeV



Vertex 3D decay length significance



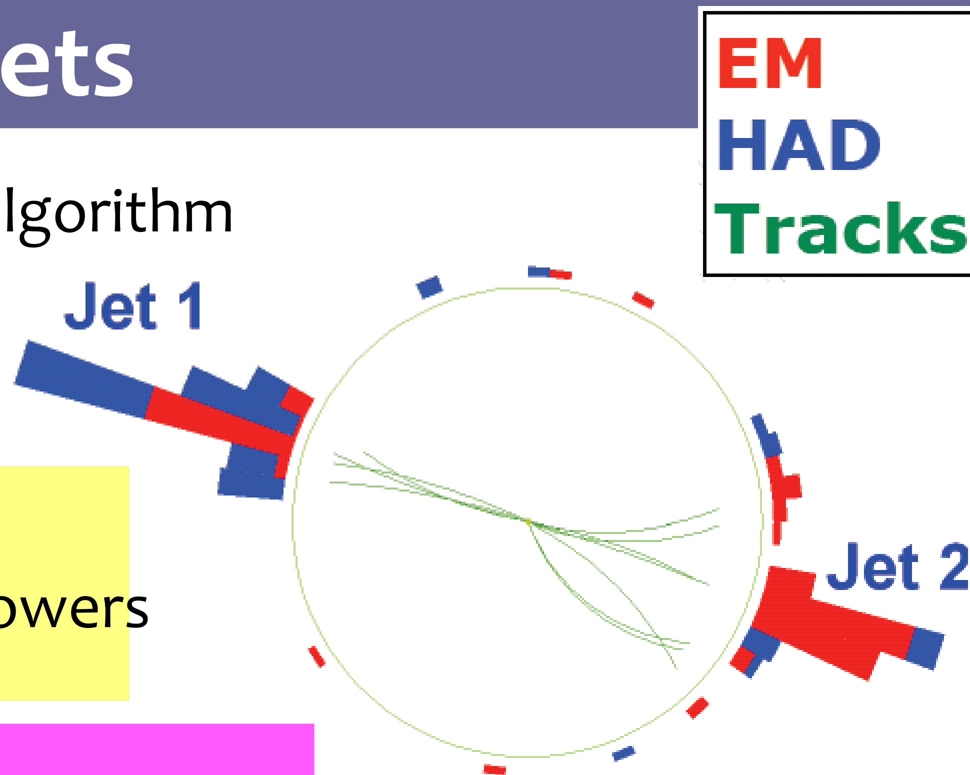
Number of tracks in Vertex

Jets

Using the anti-kT (R=0.5) jet algorithm

Three kinds of inputs:

- Calorimeter Jets
  - Inputs: Calorimeter Towers
  - E_T tower thresholds
- Jets-Plus-Tracks (JPT) Jets
  - Inputs: Calorimeter Jets, corrected with tracks
  - Single-pion calorimeter response map
- Particle-Flow (PF) Jets
  - PF candidate particles



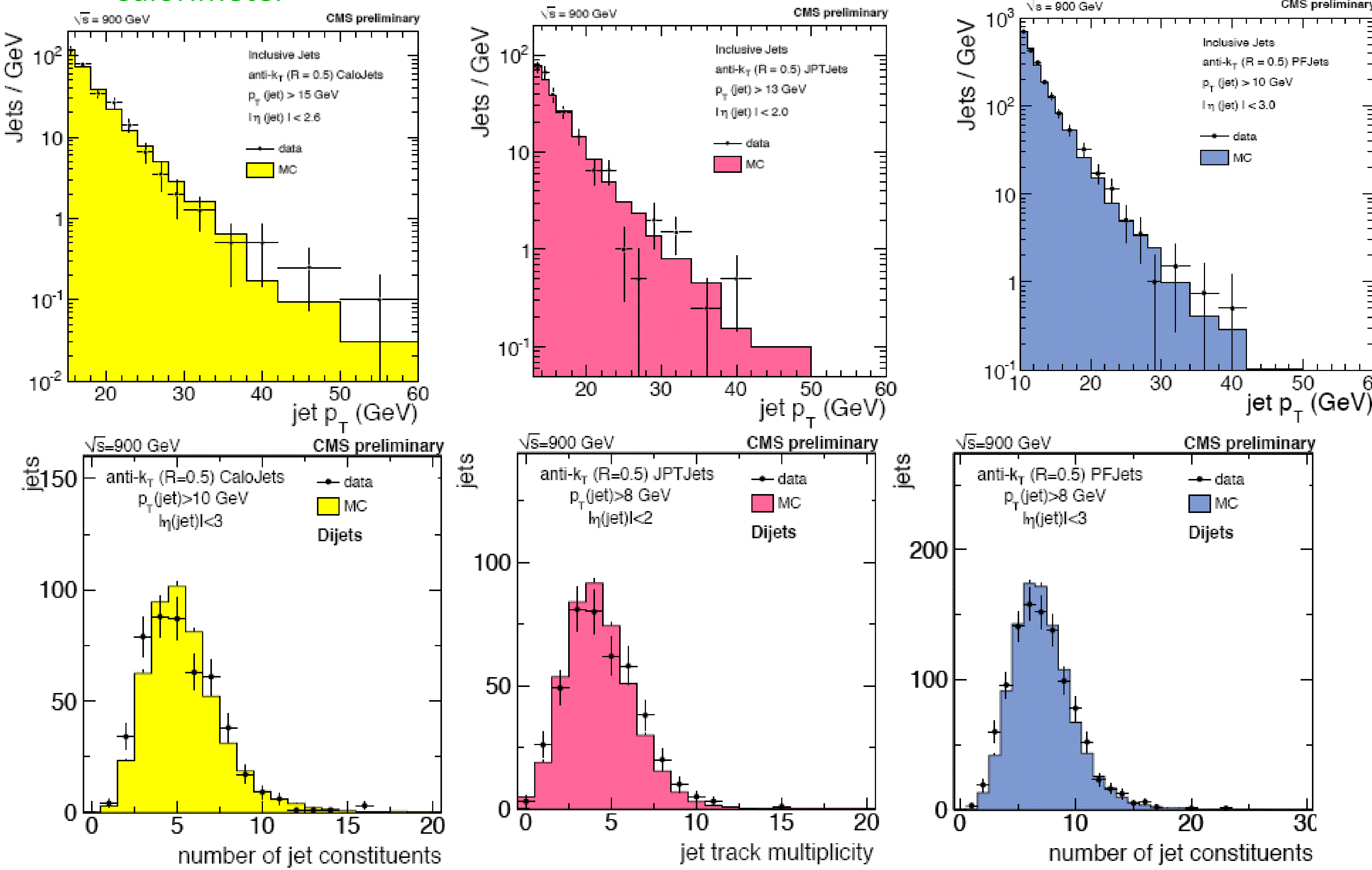
run 124009: evt 10872958

→ Use superior resolution of tracker (at low pT) to improve jet resolution

→ Combine tracking and calorimetry for *all* particles in the event

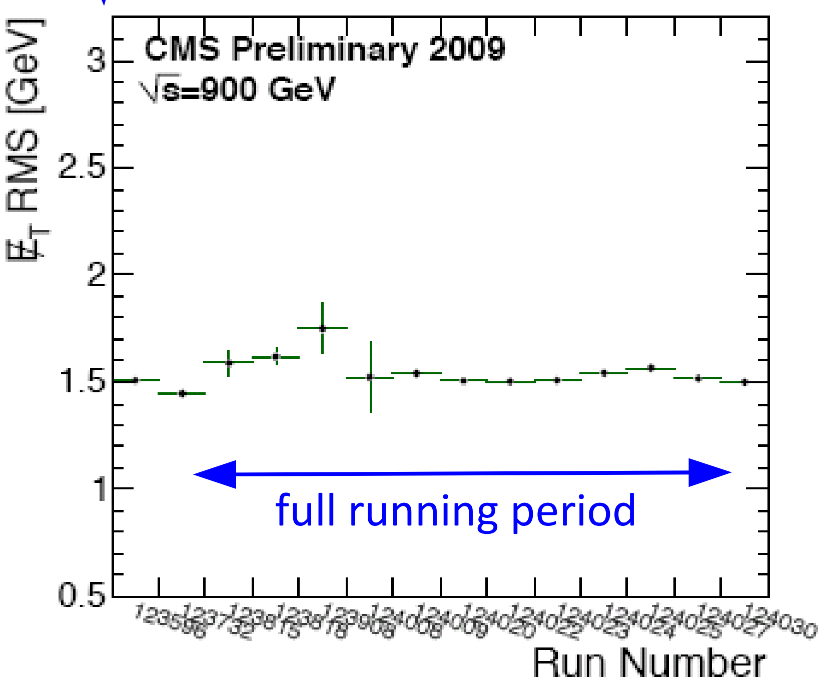
Jet pT and composition

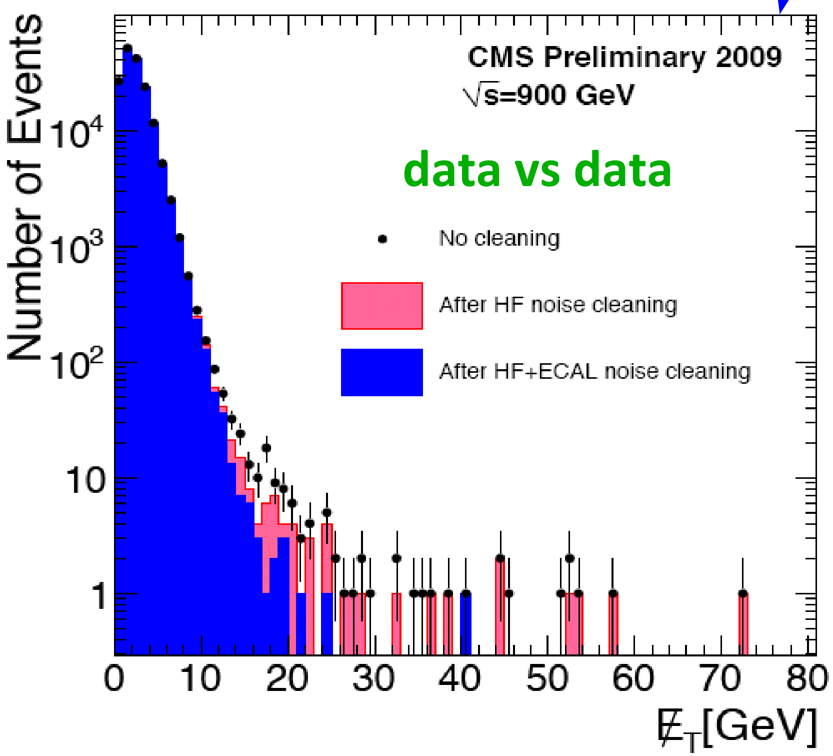
Calorimeter | Jets-plus-tracks | Particle Flow



Missing E_T

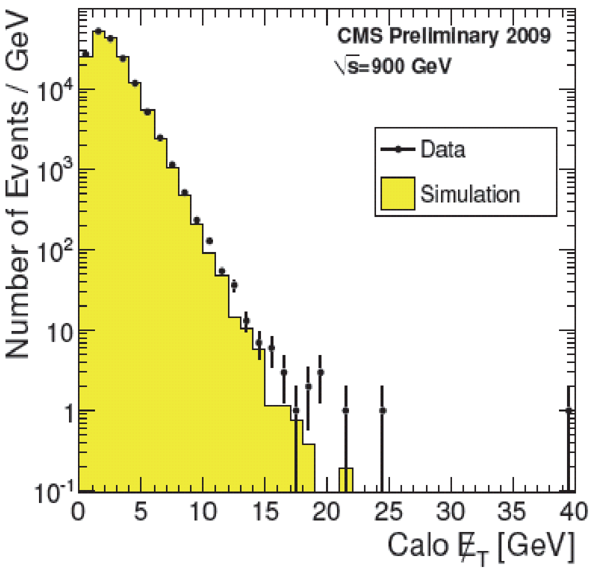
- Raw calorimeter missing E_T is already rather stable vs time
  - Investigation of outliers → identification and cleaning of 3 types of noise: HF (particle hits PMT window), correlated HCAL noise (specific pattern) and occasional ECAL single hot channel:



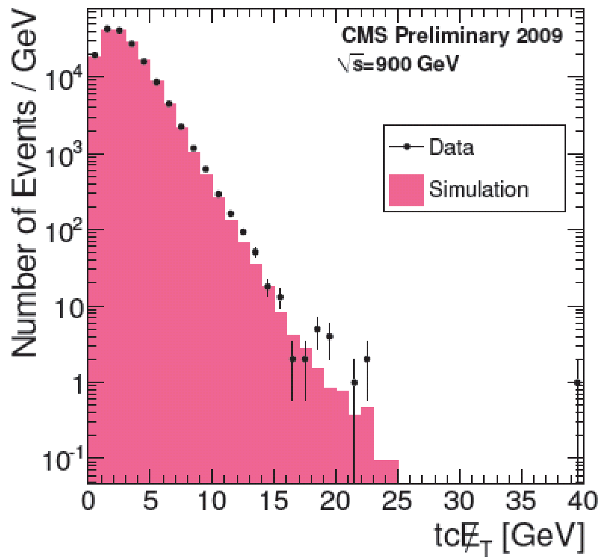


Missing E_T

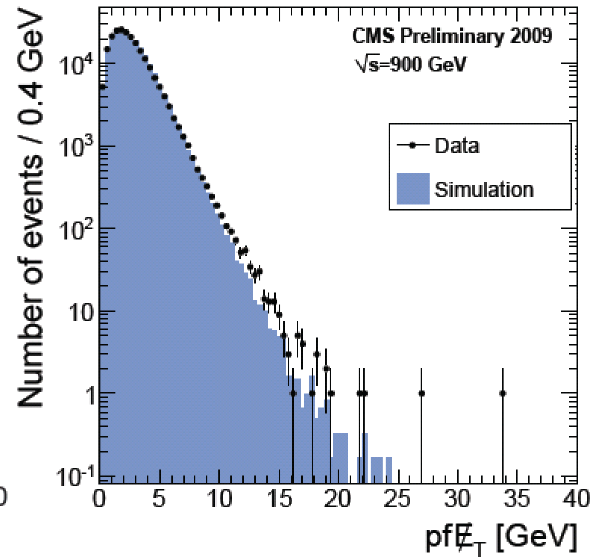
Calorimeter



Track-corrected MET



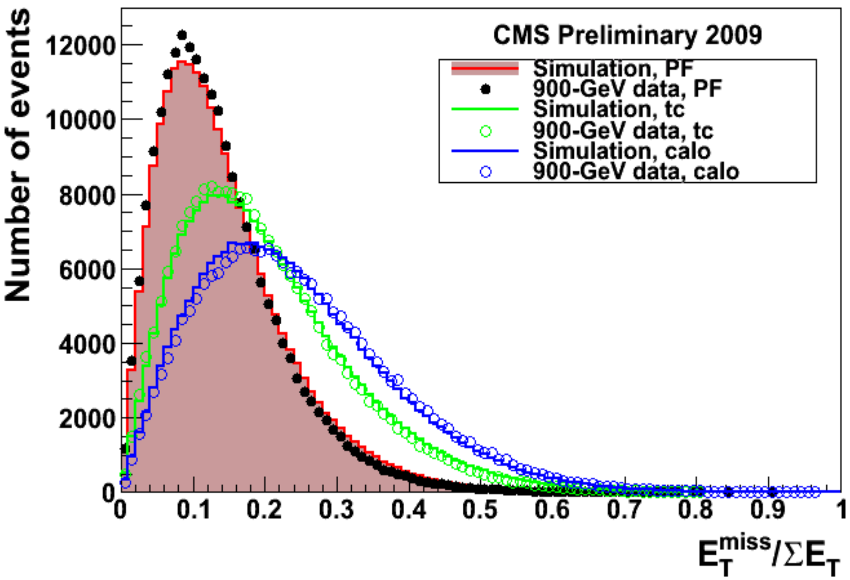
Particle Flow

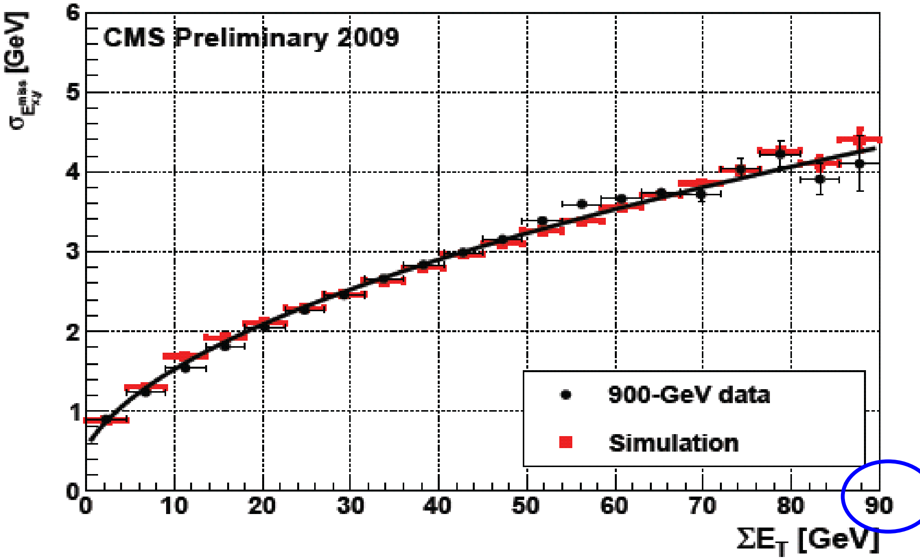


Even in this early stage, without final detector calibration, the missing E_T is well described in simulation, and tails are small !

Missing E_T significance

In these events, no real MET (from neutrino's or other invisible particles) is expected, so any observed MET is a measure of the resolution:





$\text{Sum}E_T > 3$ GeV

Particle-flow based MET relative resolution is about twice as good as for Calorimeter-only MET

$$\sigma(E_{x,y}^{\text{miss}}) = a \oplus b\sqrt{\sum E_T}$$

Particle-flow based MET:

a = 0.55 GeV

b = 45%

The First CMS physics paper

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Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV

CMS Collaboration

ABSTRACT: Measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions are presented for proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The data were collected with the CMS detector during the LHC commissioning in December 2009. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be 0.46 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 0.9 TeV and 0.50 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 2.36 TeV, for pseudorapidities between -2.4 and $+2.4$. At these energies, the measured pseudorapidity densities in the central region, $dN_{ch}/d\eta|_{|\eta|<0.5}$, are 3.48 ± 0.02 (stat.) $\pm$ 0.13 (syst.) and 4.47 ± 0.04 (stat.) $\pm$ 0.16 (syst.), respectively. The results at 0.9 TeV are in agreement with previous measurements and confirm the expectation of near equal hadron production in p$\bar{\text{p}}$ and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

KEYWORDS: Hadron-Hadron Scattering

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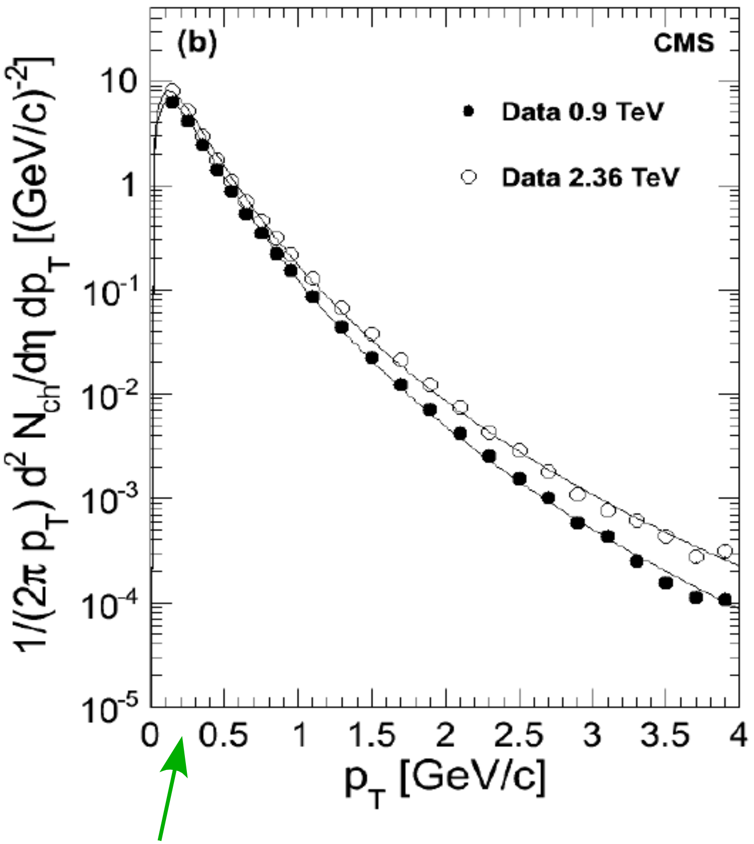
http://www.springerlink.com/content/t35h6211438476k0/

Charged hadron dN/dη and dN/dp$_T$

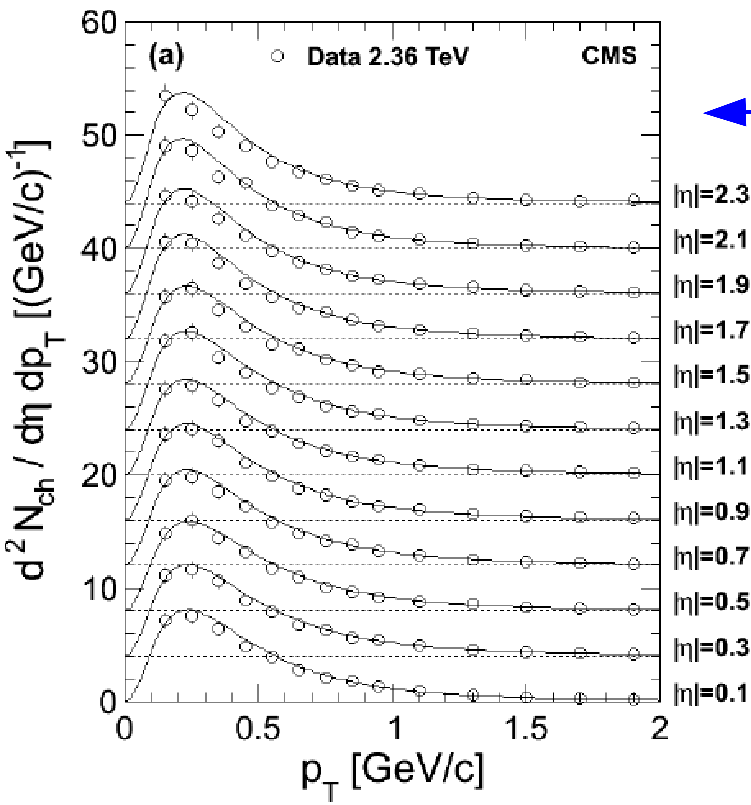
- Hadron production in soft pp collisions cannot be calculated perturbatively and has to be measured in data and modeled phenomenologically
- Important for high-luminosity LHC runs with pile-up and relevant as reference for heavy ion physics
- Various processes involved: elastic, single-diffractive, and non-single-diffractive (NSD)= double diffractive + non-diffractive → aim to measure the NSD component



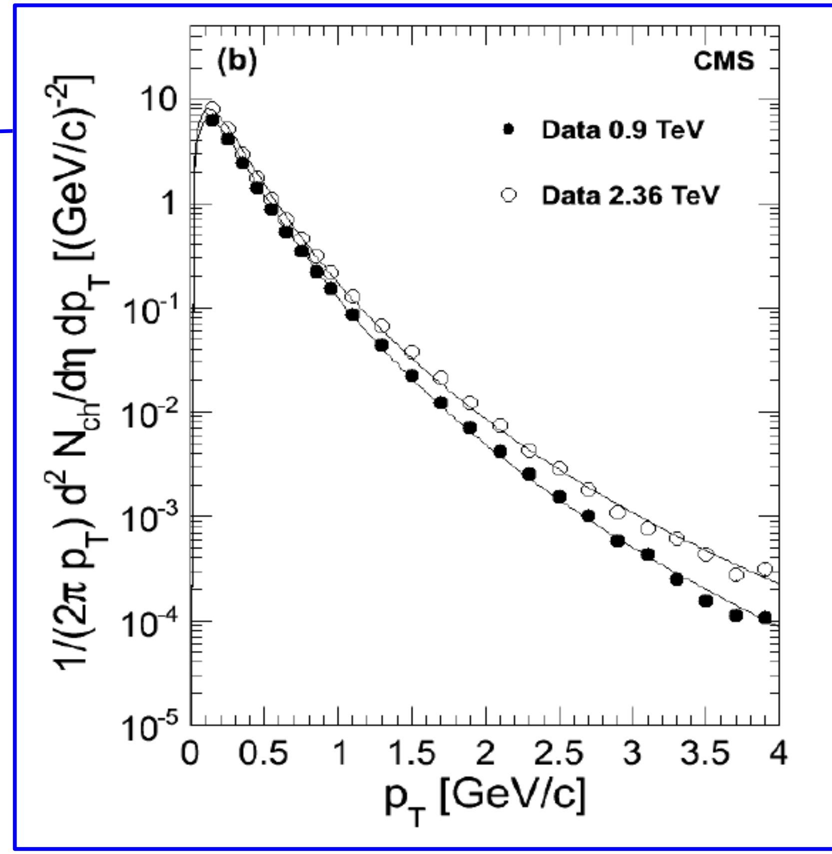
Very low p$_T$ = a big challenge for tracking: 0.1 GeV/c in a B field of 3.8T corresponds to a bending radius of ~8 cm

dN/dp_T results

dN/dpT in bins of eta:



Integral for |η|<2.4



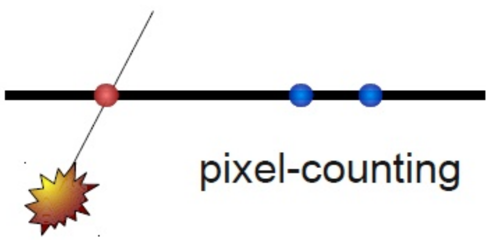
Fitted with the empirical Tsallis function (exponential at low p_T, power law at high p_T). Integral used for dN/dη particle count (5% correction at low p_T)

$\langle p_T \rangle$ = 0.46 ± 0.01(stat) ± 0.01(syst) @0.9TeV

$\langle p_T \rangle$ = 0.50 ± 0.01(stat) ± 0.01(syst) @2.36TeV

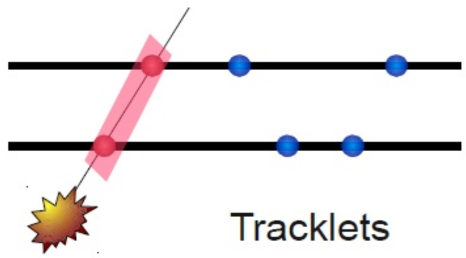
Three methods for dN/dη

Pixel detector: 53.3cm long,
3 layers with radii: 4.4, 7.3, 10.2 cm



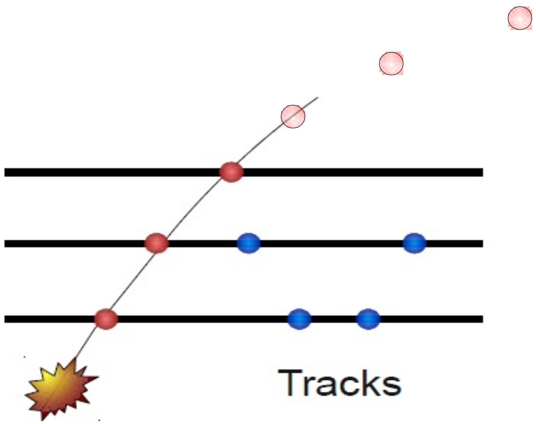
p_T > 30 MeV/c

Clusters per layer
|η|<2
3 measurements of dN/dη
Immune to mis-alignment
Simplest method
Requires noise-free detector



p_T > 75 MeV/c

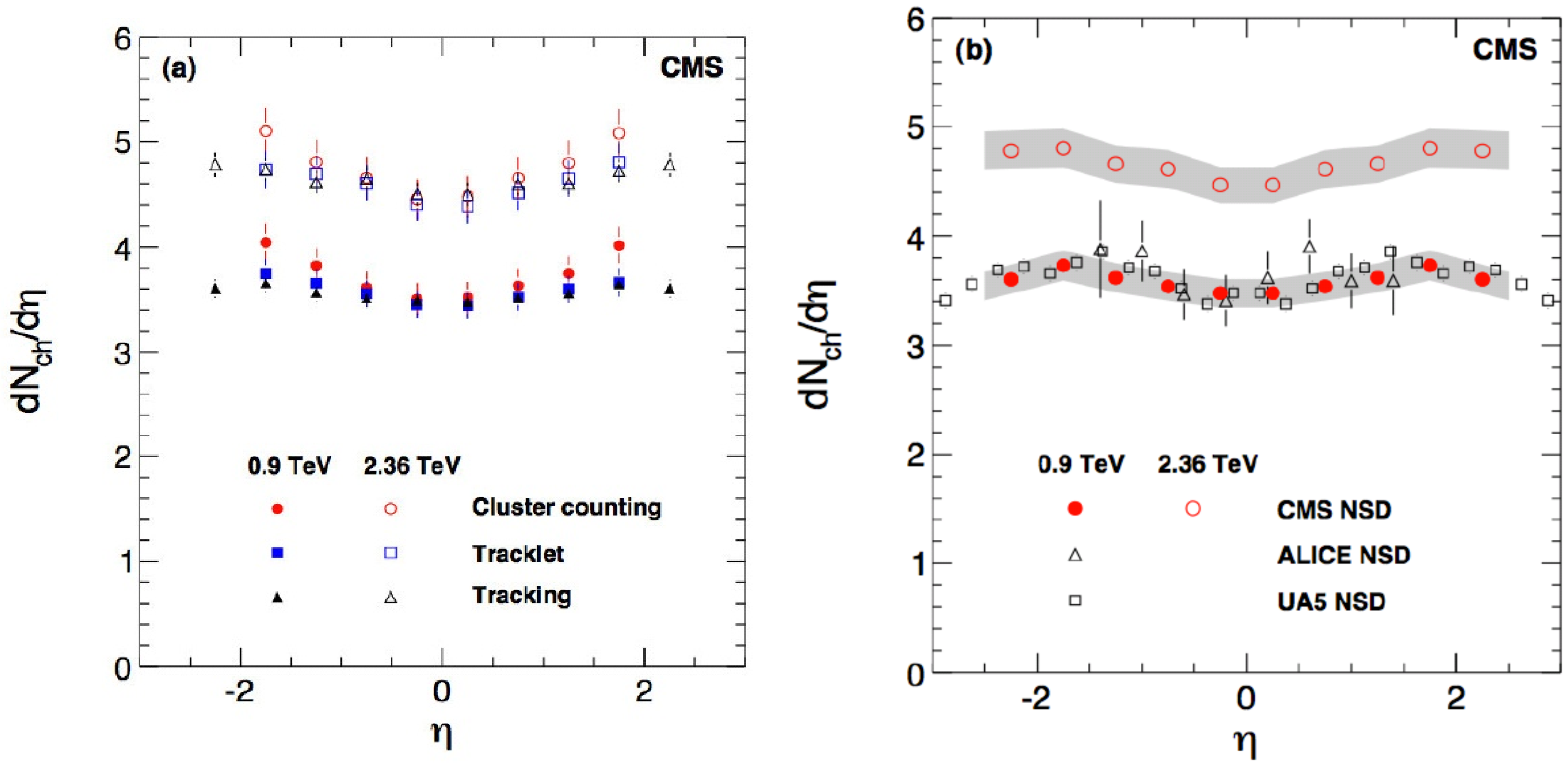
2 of 3 pixel layers
|η|<2
3 measurements of dN/dη
Sensitive to mis-alignment



Over 50% Efficient for p_T >
0.1, 0.2, 0.3 GeV/c for π, K, p

Full tracks (pixel and strips)
|η|<2.4
dN/dη and dN/dp_T
Sensitive to mis-alignment
Most complex

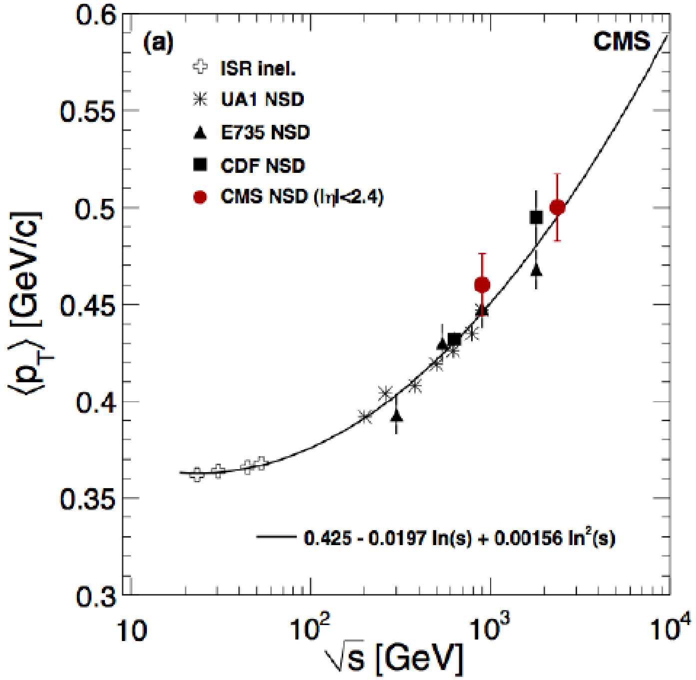
dN/dη Results



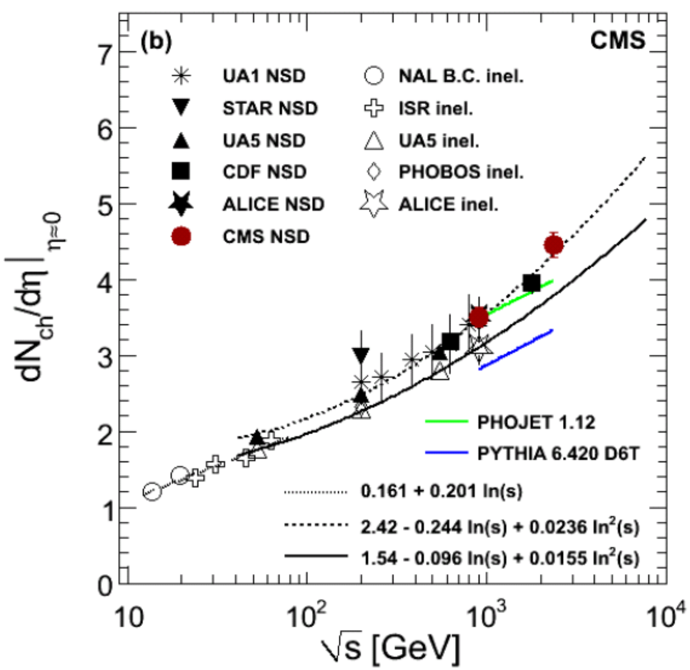
3 methods give consistent results. Error bars show systematic errors (ranging from 4.4% to 2.4%), excluding common contributions

The 3 CMS methods are averaged. Shaded band indicates systematic error, of which largest part is due to uncertainty in SD/DD contamination (2%). UA5 and CMS results are symmetrized in η. UA5 and ALICE errors are statistical only

Results: scaling with Energy



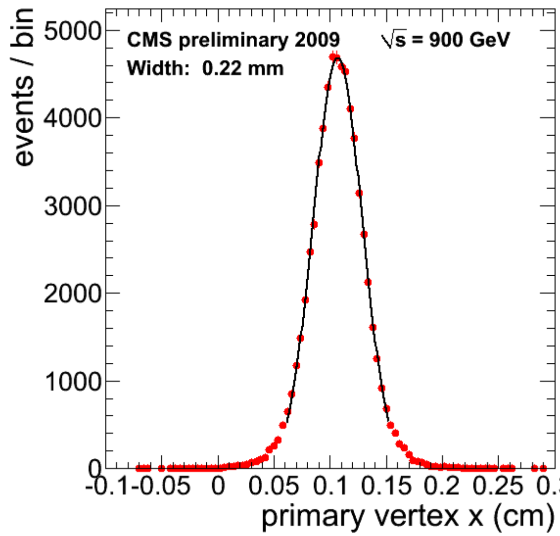
Variation of average transverse momentum with center-of-mass energy

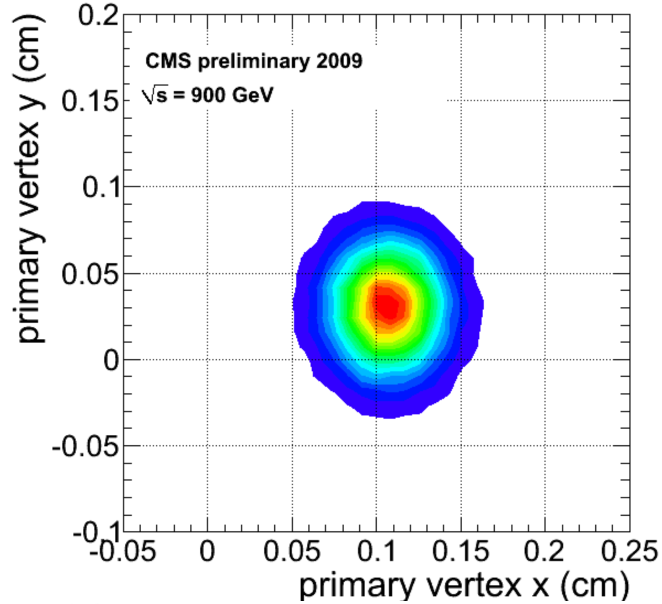


Variation of dN/dη with center-of-mass energy.
dN/dη(@2.36TeV)/dN/dη(@0.9TeV) =
$(28.4 \pm 1.4 \pm 2.6)\%$
significantly larger then prediction from PYTHIA&PHOJET tunes used in the analysis 18.4% & 14.5%

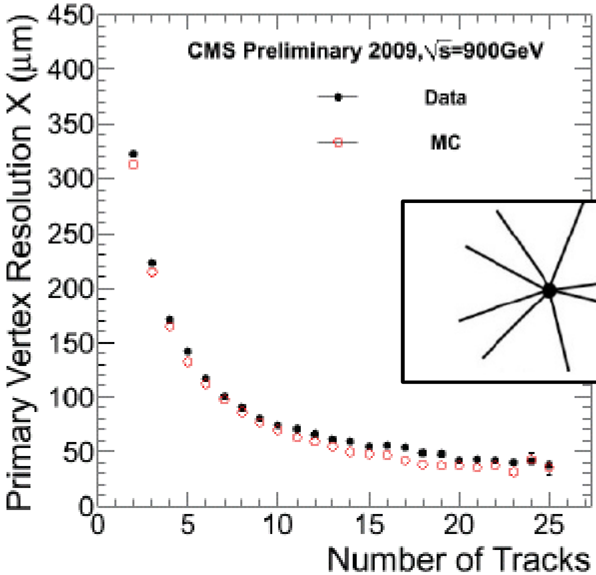
Primary Vertexing

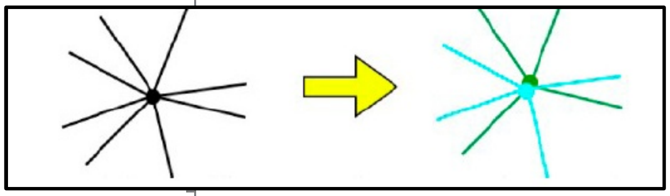
Primary vertex distribution for a single run: clean Gaussian distributions

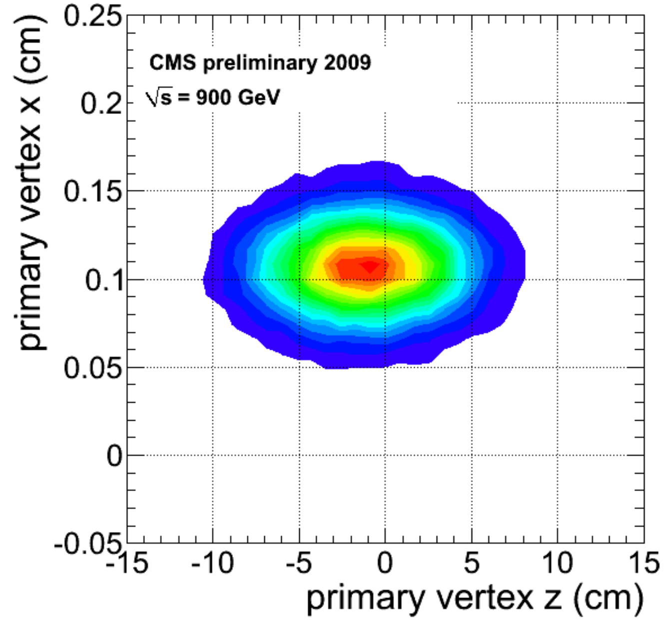




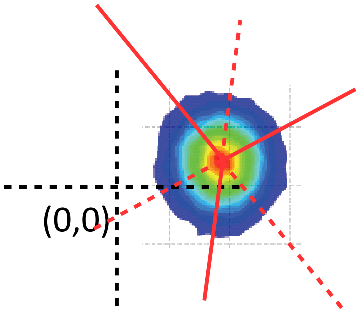
Resolution estimated by splitting vertices in 2 and comparing fits:

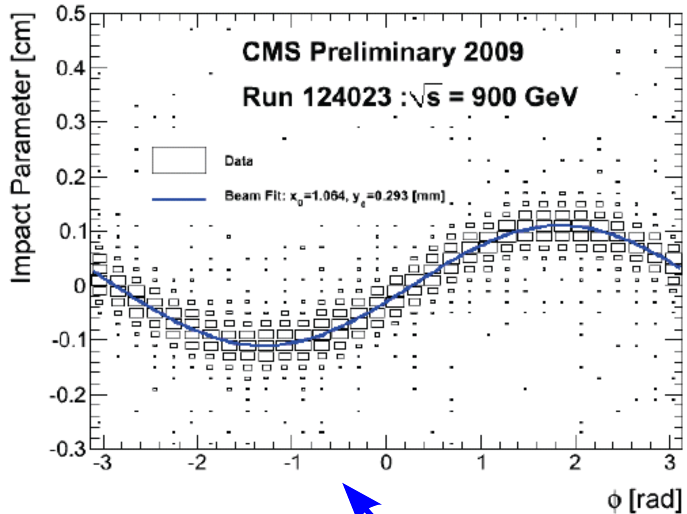


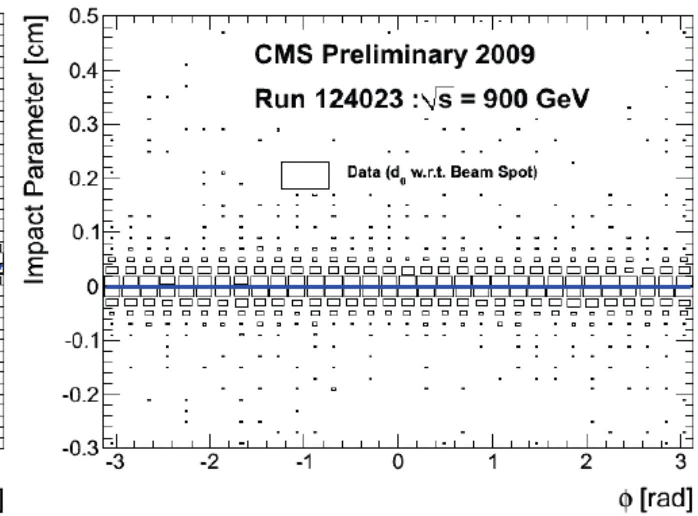




LHC beam spot

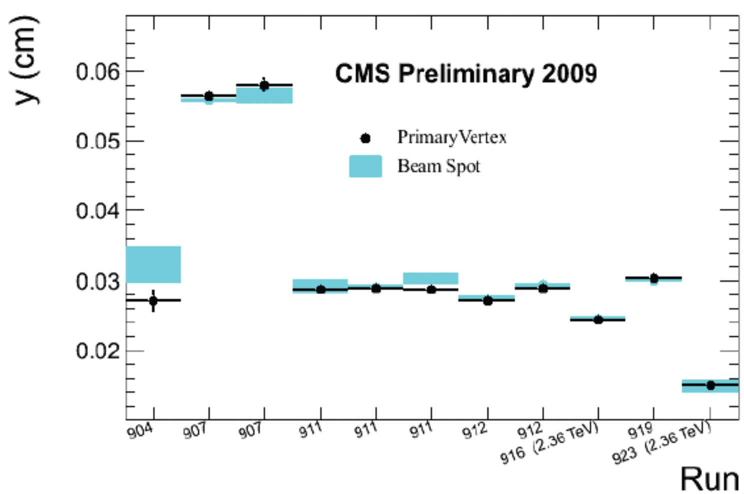






Commissioned method for determination of LHC beam spot, important for:

- Initial guess of interaction point, before primary vertex fit
- As vertex constraint in High Level Trigger



Mean of primary vertex distribution and beam spot positions are consistent

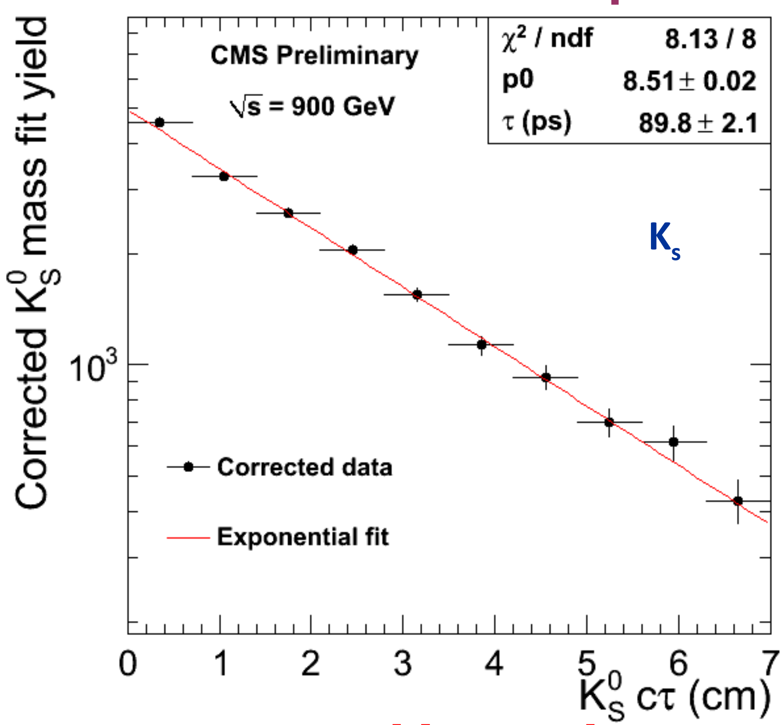
Lifetime Measurements

Monte Carlo is simulated with the same conditions as in data.

- Data and MC are split into bins of cτ and a fit for the yield is performed in each bin.
- Divide MC yields by true (exponential) distribution to obtain correction factor.
- Correct data and fit for lifetime.

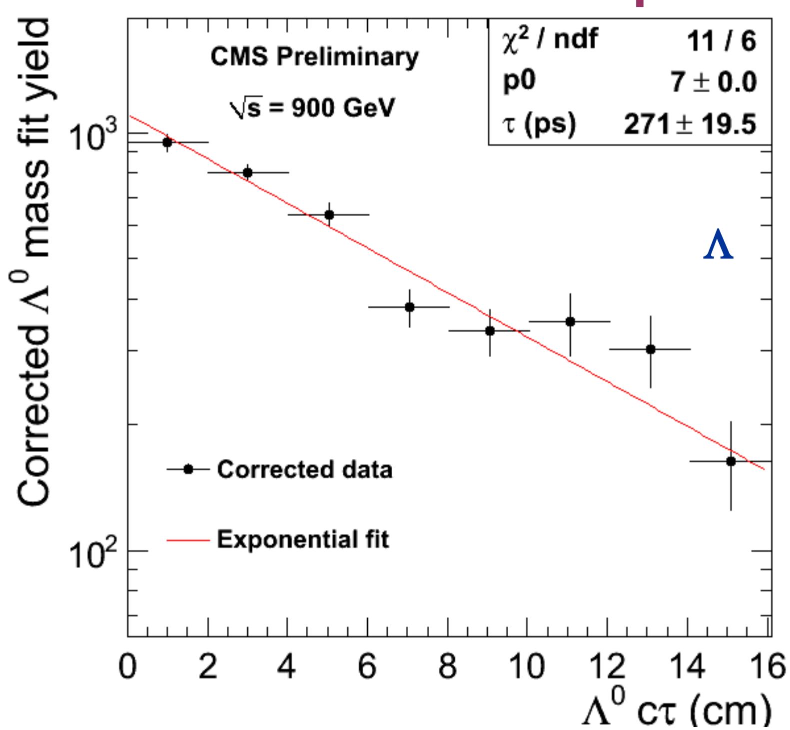
PDG: 89.53 ± 0.05 ps

CMS: 89.80 ± 2.10 ps



PDG: 263.1 ± 2.0 ps

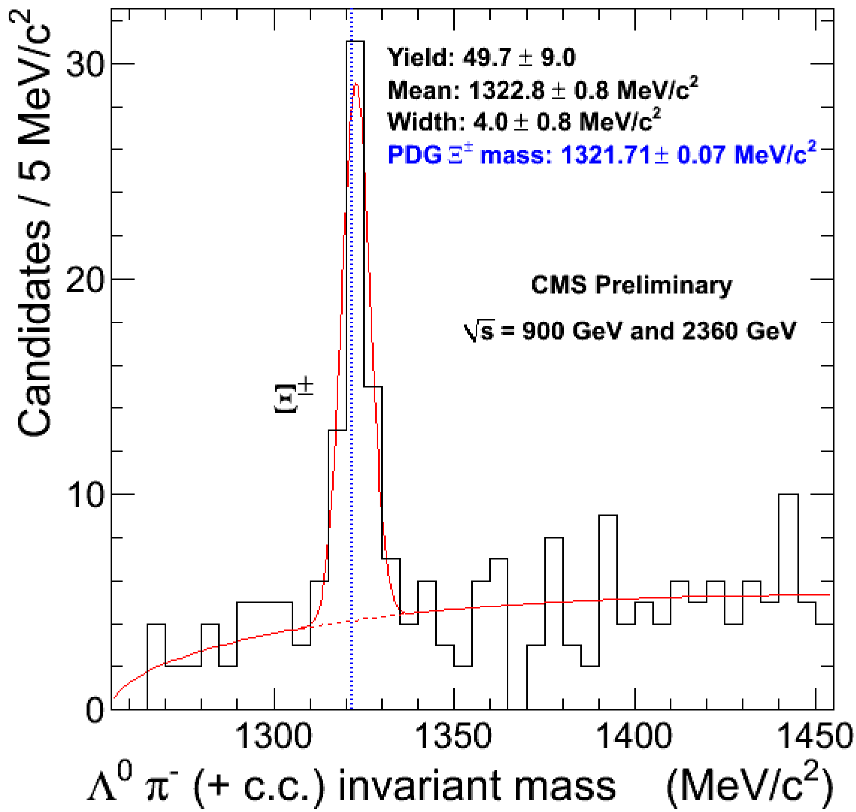
CMS: 271.0 ± 20 ps



➔ accurate tracking and vertex simulation, even outside the beam region

Cascade Baryon signal

- All 3 tracks must have ≥ 6 hits and miss primary by 3σ (in 3D).
- Λ^0 vertex must be separated by 10σ radially from beam spot, have $\chi^2 < 7$, and track hits no more than 4σ inside.
- Λ^0 candidates must be within 8 MeV of PDG mass.
- Constrain Λ^0 mass in vertex fit. Fit probability > 1%.



- Data mass 1322.8 ± 0.8 MeV is consistent with PDG value (1321.71 ± 0.07 MeV).
- Data width 4.0 ± 0.8 MeV similar to MC (3.6 ± 0.1 MeV).

K*(892) signal

Basic idea: combine K_S candidates with charged tracks from the primary vertex.

K_S requirements:

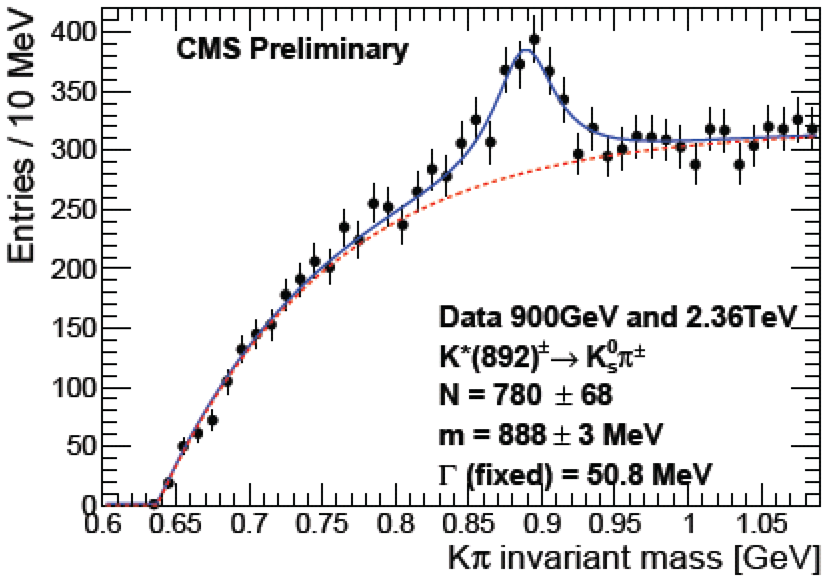
- Tracks have ≥ 6 hits, normalized $\chi^2 < 5$, $d_0/\sigma(d_0) > 2$.
- Vertex is > 15σ from beam spot (radially), does not have track hits > 4σ inside of position, has $\chi^2 < 7$.
- K_S 3D momentum vector passes < 2 mm of primary.
- Invariant mass within 20 MeV/c^2 of PDG value.

Pion requirements:

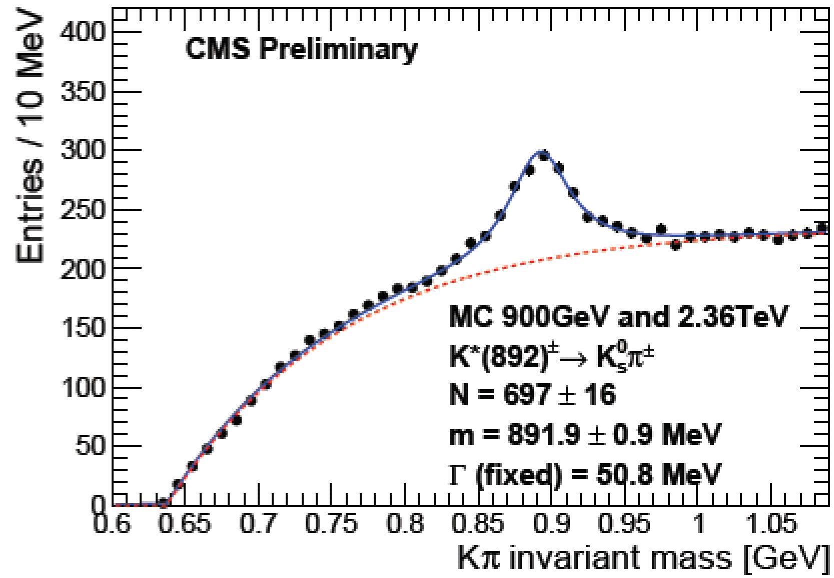
- Normalized $\chi^2 < 2$ with ≥ 7 hits and ≥ 2 pixel hits.
- $p_T > 0.5$ GeV/c, $|\eta| < 2$, $d_{xy} < 2$ mm, $|d_z| < 3$ mm.

The K*(892) resonance

data



MC



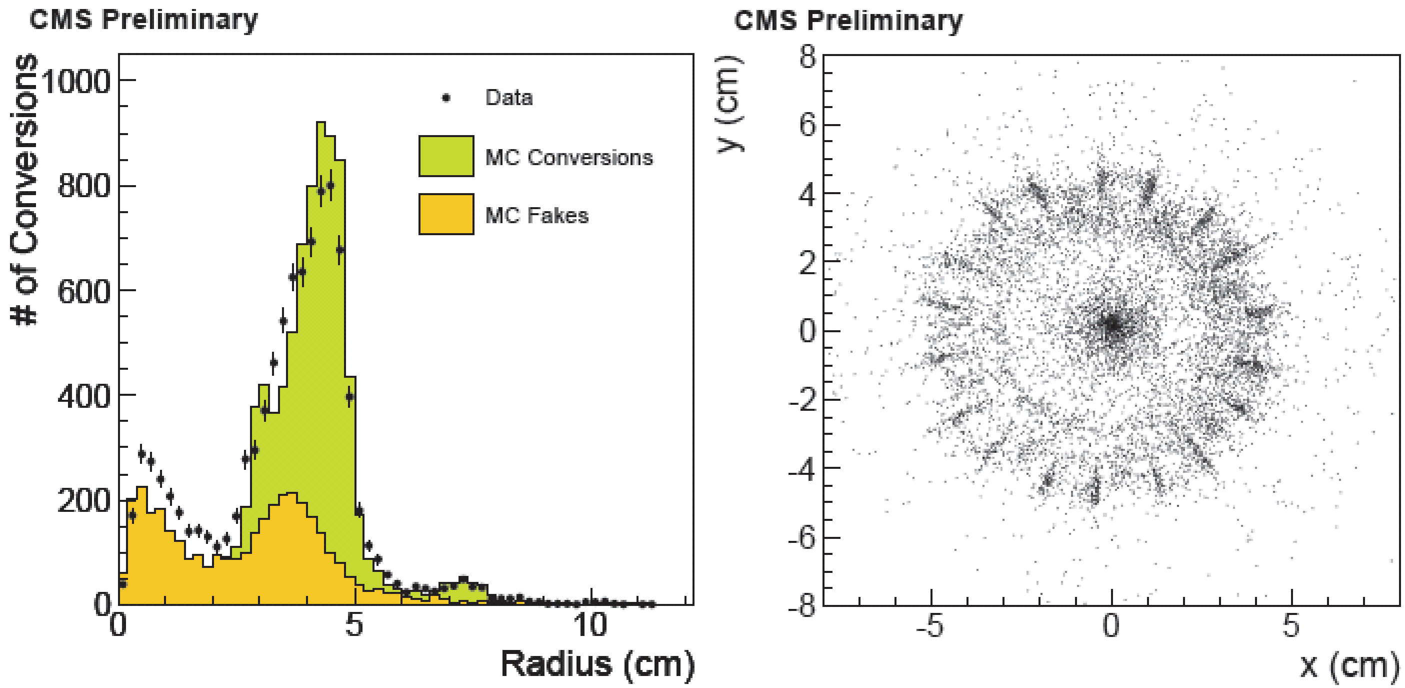
- Relativistic Breit-Wigner for signal with the width fixed to PDG value.

$$\frac{1}{\left(m^2 - M^2\right)^2 + \Gamma^2 M^2}$$

- Background function:

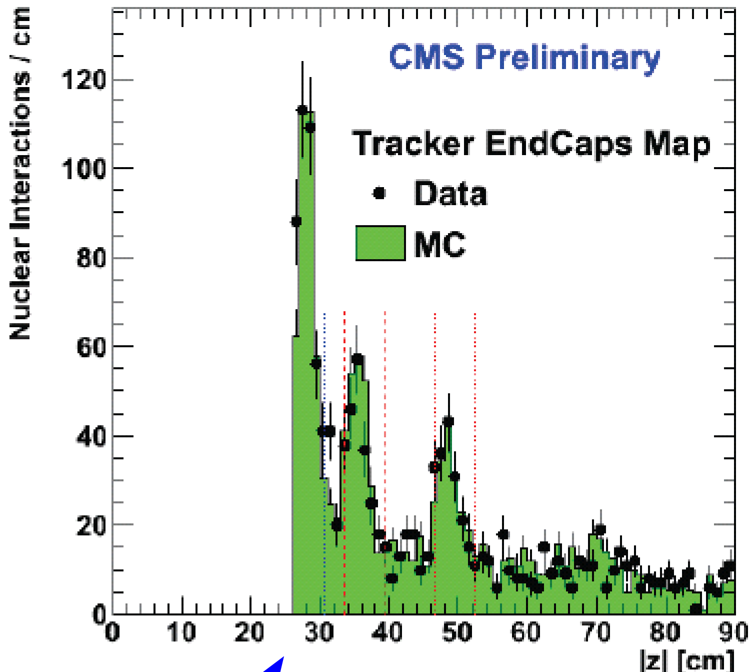
$$A\left(1 - \exp\left(\frac{m_K + m_\pi - m}{B}\right)\right)$$

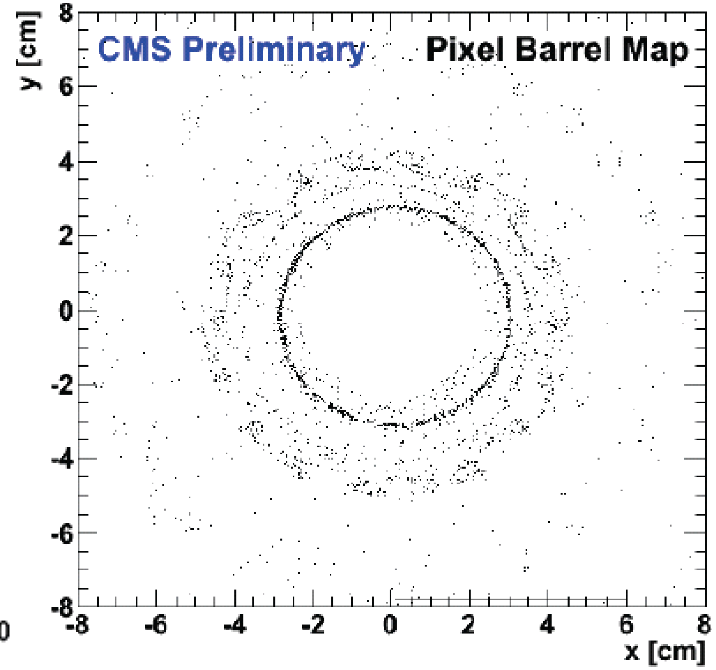
Photon Conversions



18-fold structure is from cooling pipes
Smeared by radial resolution ~ 0.5cm

Nuclear Interactions





Resolution of the vertex ~ 500 µm

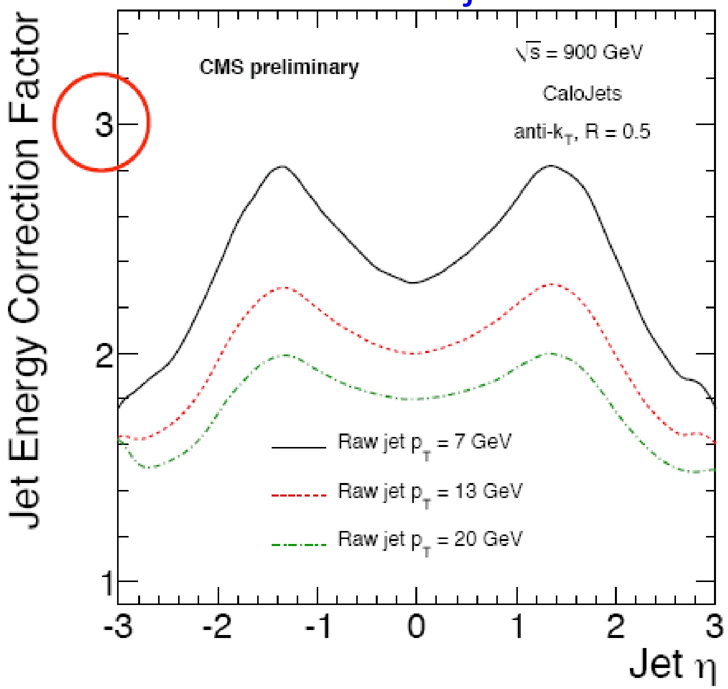
Good agreement between data and MC
means a good understanding of the material budget

Jet Corrections

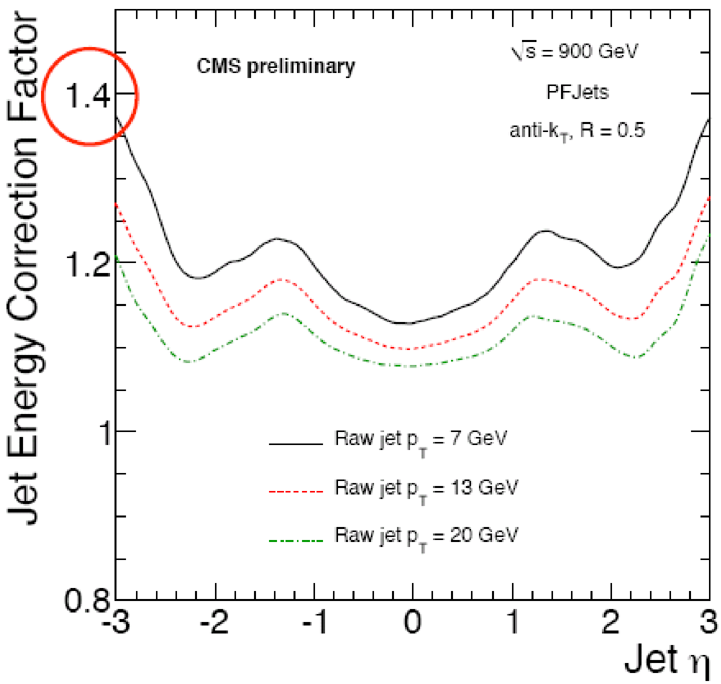
- Derived from Pythia QCD simulation @ 900 GeV and 2360 GeV
- Derived for and applied to calorimeter jets & particle-flow jets

Jet Energy correction factor is function of jet pT and η:

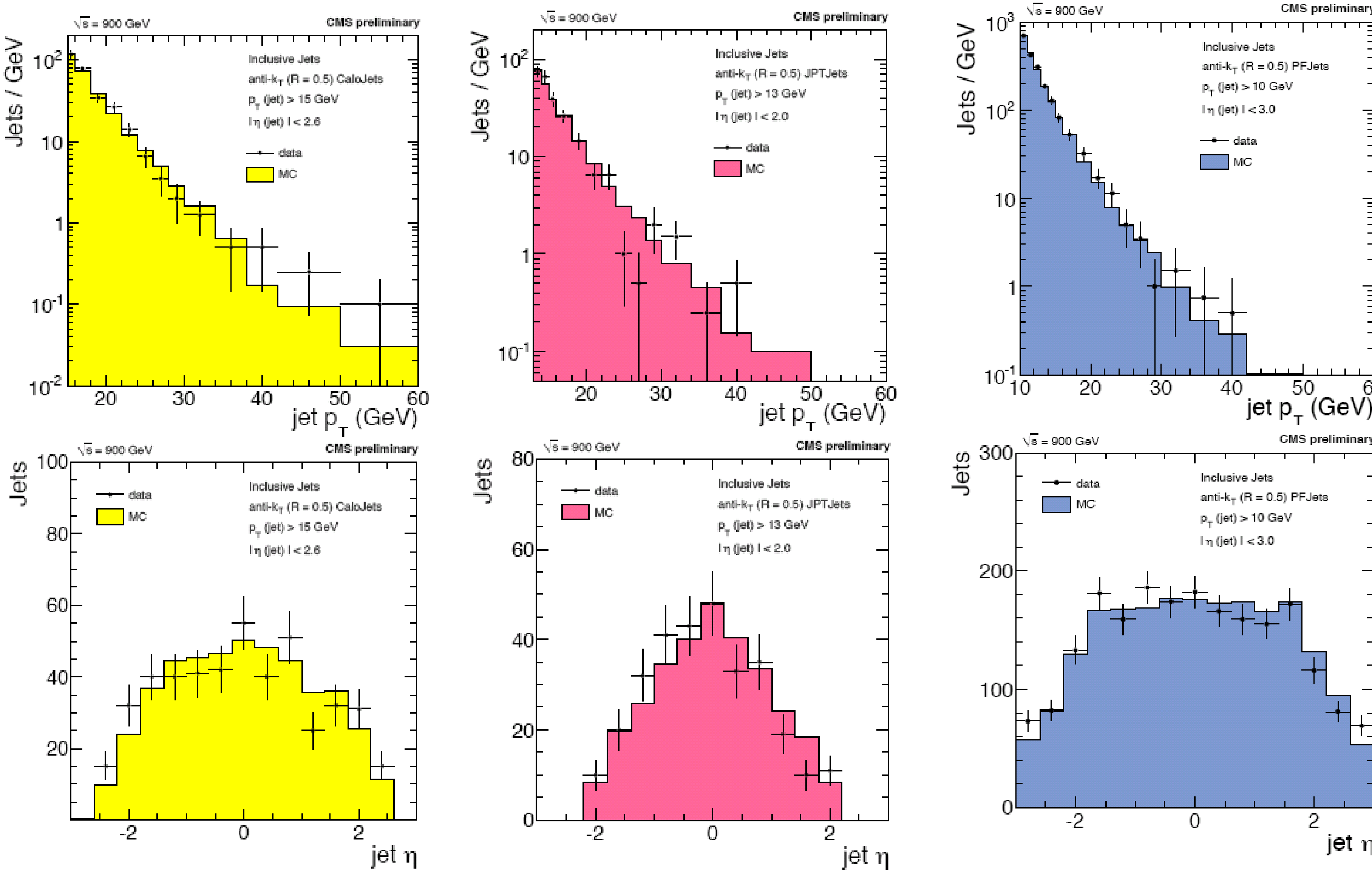
Calorimeter jets



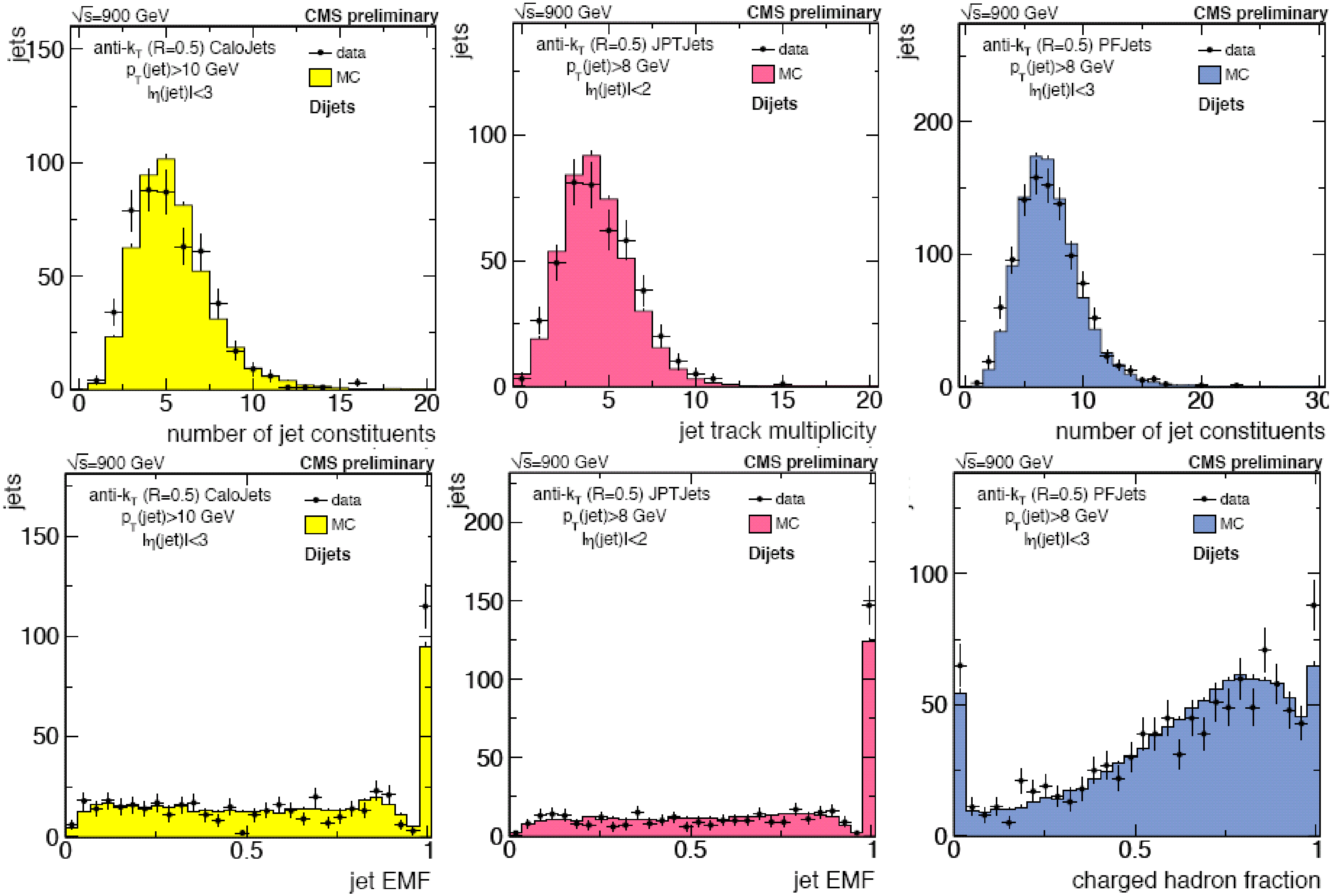
Particle Flow jets



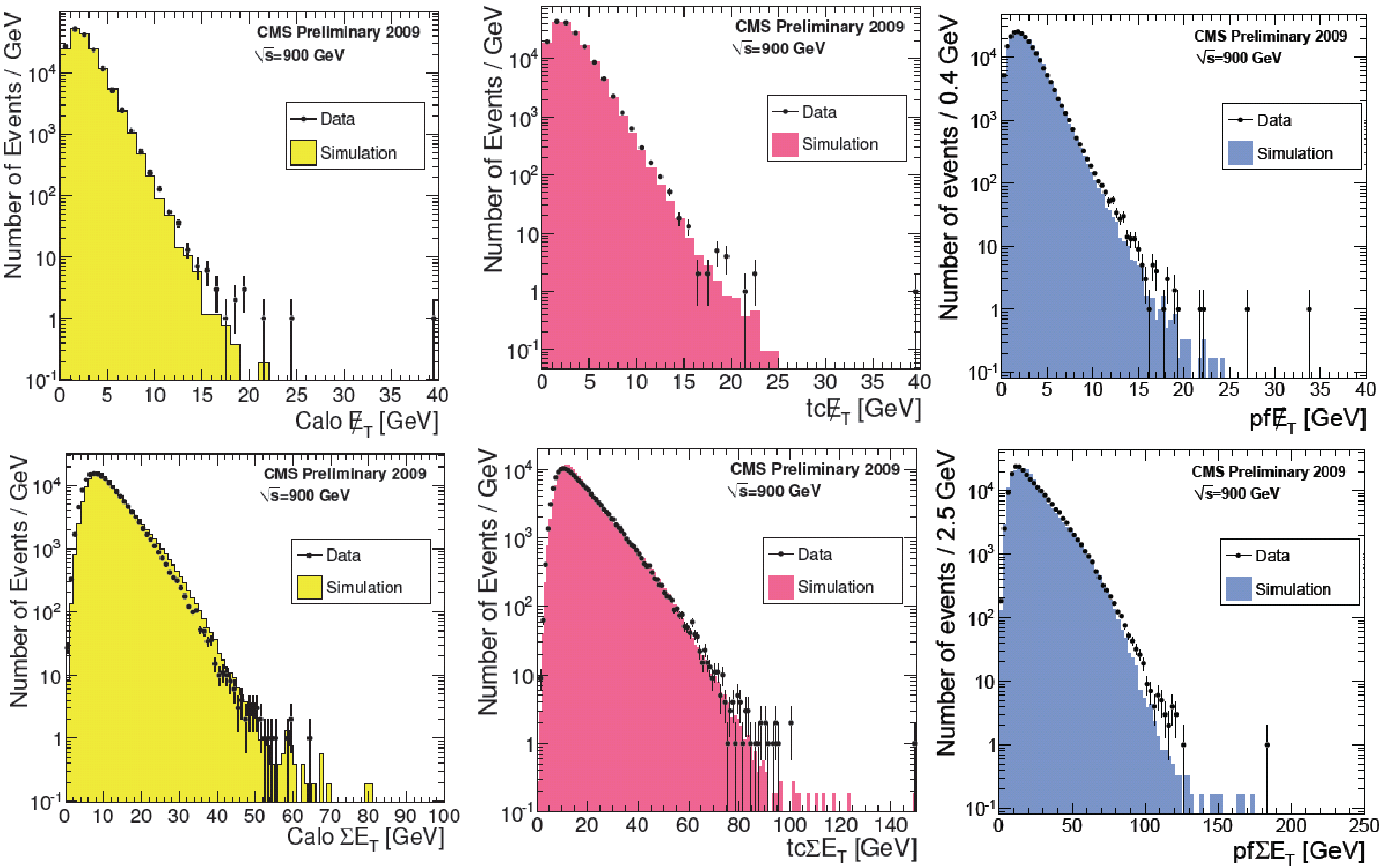
Inclusive Jet pT and η



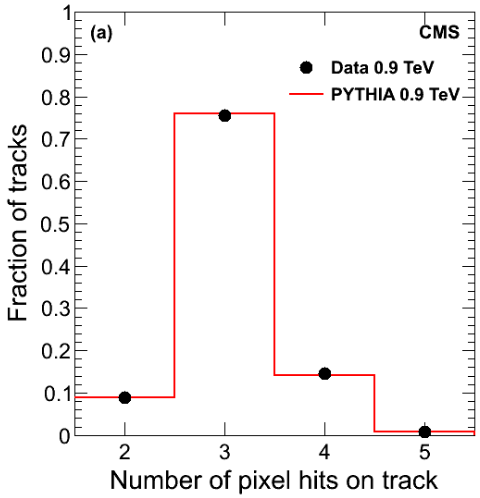
Di-jet events: Jet composition

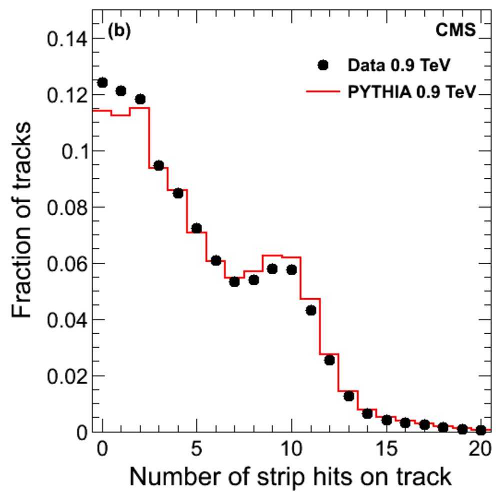


Missing ET and Sum ET



Tracking Quality dN/dη



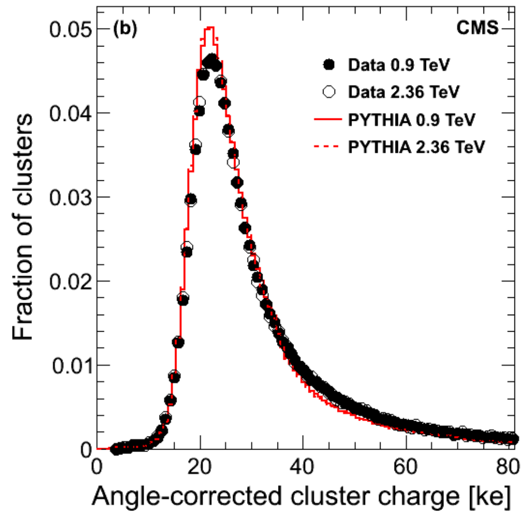


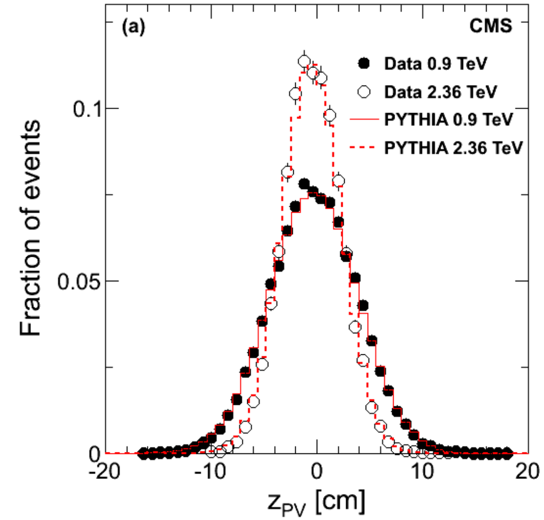
Good understanding of tracker performance was crucial to quickly produce final results

Hits on track

Cluster charge

Vertex distribution with no tails – beam spot in simulation Matched to data





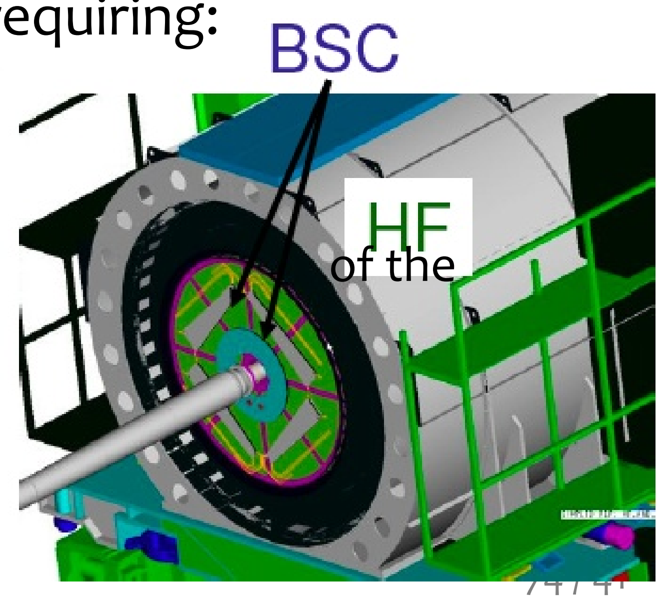
Event Selection dN/dη

- Aimed at selecting NonSingleDiffractive events with high efficiency (rejecting a large fraction of SingleDiffractive).

  Efficiencies:
  - NSD: ≈ 86%
  - SD: ≈ 19%
  - DD: ≈ 34%

  NSD are chosen to minimize effect of model dependence of the corrections and allow comparison with previous experiments

- ≈ 10 Hz collision rate (pile-up probability < 2 x 10^{-4})
- Event selection common to the 3 methods requiring:
  - Trigger level: at least 1 hit in Beam scintillation counters AND coincidence with beam pickups (BPTX)
  - >3GeV total energy on both sides Forward calorimeter (HF)
  - Beam halo rejection
  - Beam background rejection
  - A collision vertex



dN/dη: systematic uncertainties

Table 3: Summary of systematic uncertainties. While the various sources of uncertainties are largely independent, most of the uncertainties are correlated between data points and between the analysis methods. The event selection and acceptance uncertainty is common to the three methods and affects them in the same way. The values in parentheses apply to the $\langle p_T \rangle$ measurement.

Source	Pixel Counting [%]	Tracklet [%]	Tracking [%]
Correction on event selection	3.0	3.0	3.0 (1.0)
Acceptance uncertainty	1.0	1.0	1.0
Pixel hit efficiency	0.5	1.0	0.3
Pixel cluster splitting	1.0	0.4	0.2
Tracklet and cluster selection	3.0	0.5	-
Efficiency of the reconstruction	-	3.0	2.0
Correction of looper hits	2.0	1.0	-
Correction of secondary particles	2.0	1.0	1.0
Misalignment, different scenarios	-	1.0	0.1
Random hits from beam halo	1.0	0.2	0.1
Multiple track counting	-	-	0.1
Fake track rate	-	-	0.5
p_T extrapolation	0.2	0.3	0.5
Total, excl. common uncertainties	4.4	3.7	2.4
Total, incl. common uncert. of 3.2%	5.4	4.9	4.0 (2.8)

dN/dη: DD/SD/NSD fractions

Table 2: Expected fractions of SD, DD, ND and NSD processes ("Frac.") obtained from the PYTHIA and PHOJET event generators before any selection and the corresponding selection efficiencies ("Sel. Eff.") determined from the MC simulation.

	PYTHIA				PHOJET			
Energy	0.9 TeV		2.36 TeV		0.9 TeV		2.36 TeV	
	Frac.	Sel. Eff.	Frac.	Sel. Eff.	Frac.	Sel. Eff.	Frac.	Sel. Eff.
SD	22.5%	16.1%	21.0%	21.8%	18.9%	20.1%	16.2%	25.1%
DD	12.3%	35.0%	12.8%	33.8%	8.4%	53.8%	7.3%	50.0%
ND	65.2%	95.2%	66.2%	96.4%	72.7%	94.7%	76.5%	96.5%
NSD	77.5%	85.6%	79.0%	86.2%	81.1%	90.5%	83.8%	92.4%

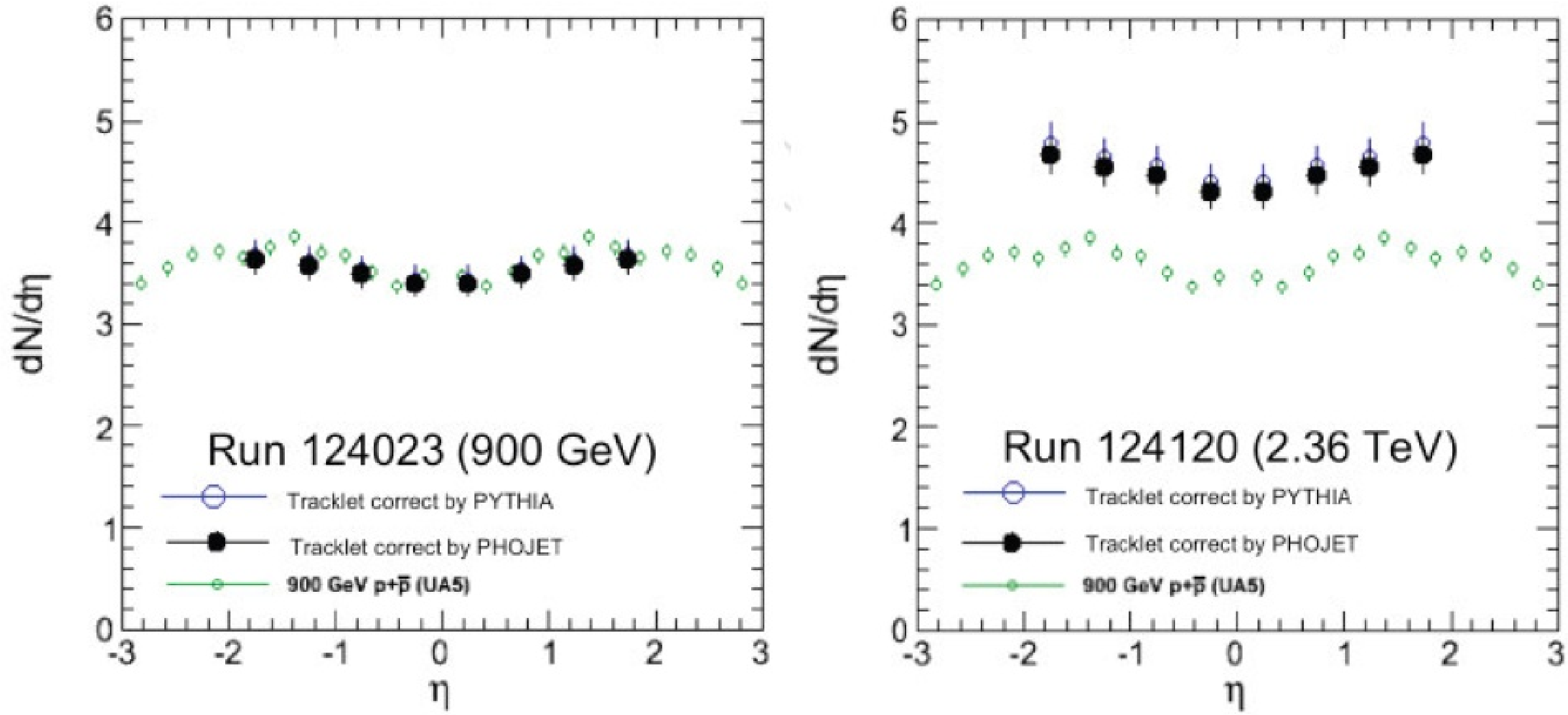
dN/dη: Tsallis Function

$$E\frac{d^3N_{ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$

Limits:

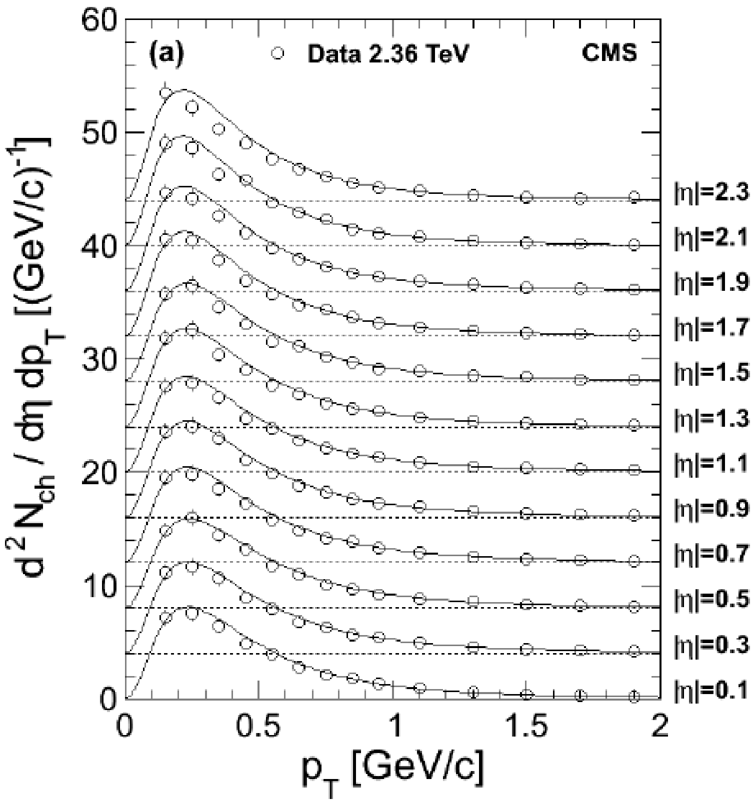
- exponential at low p_T
- power-law at high p_T

dN/dη: Model Dependence

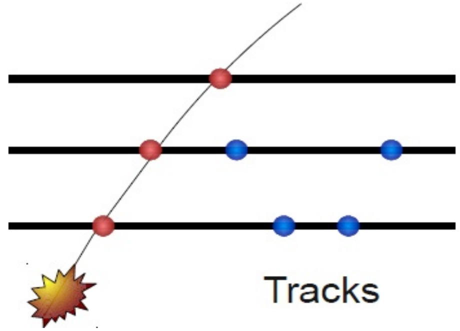


Corrections based either on PYTHIA or on PHOJET event generators yield the same final result

Tracking Method

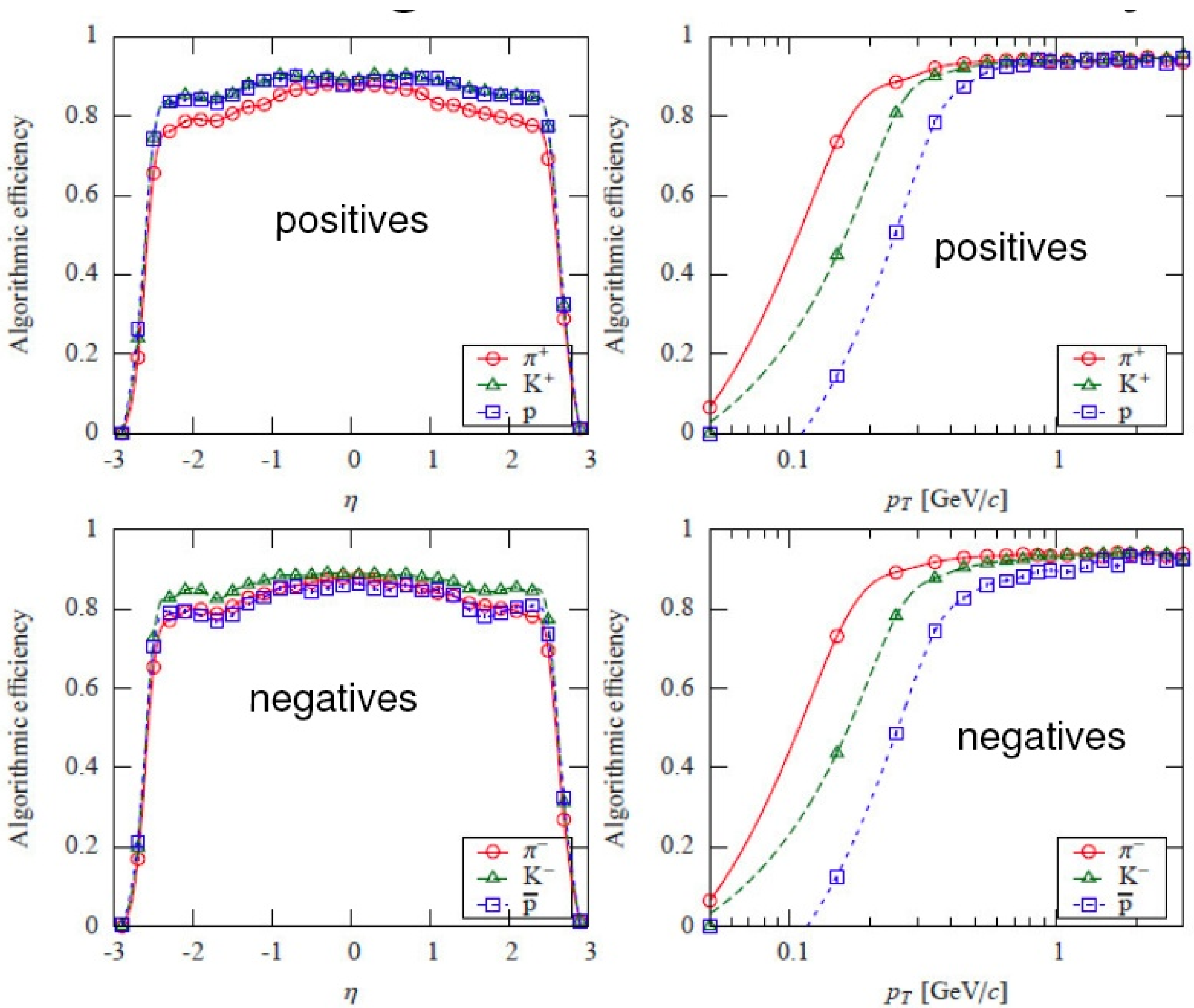


Differential yield of charged hadrons in different η bins (vertically shifted by 4 units). Points fitted with the empirical Tsallis function (exponential at low pT, power law at high pT) ——► Integral gives hadron count (a 5% correction)

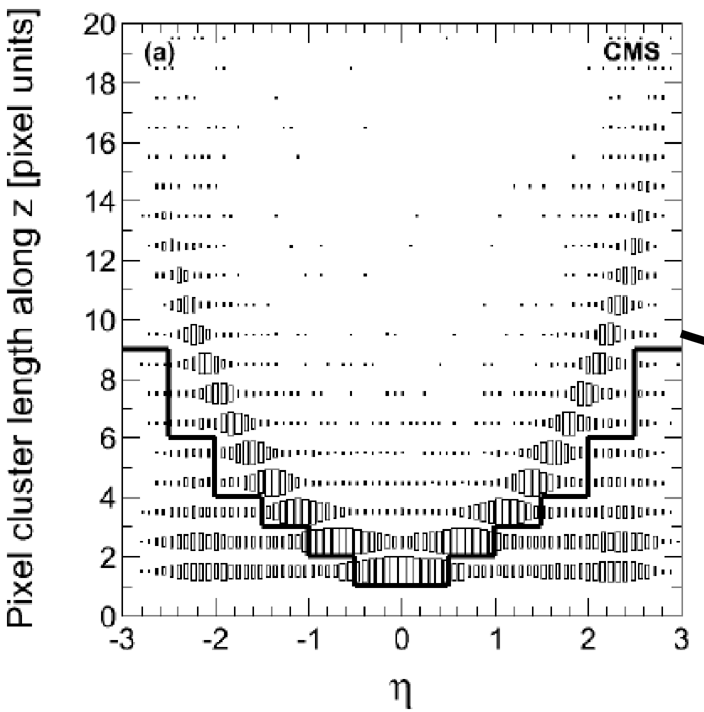


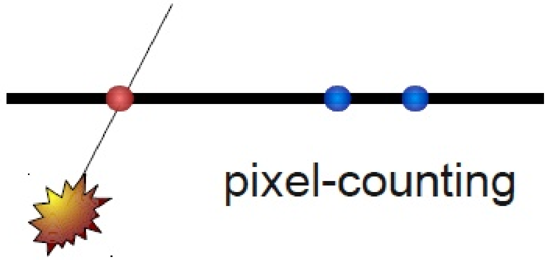
- Use all pixel & strip layers
- Acceptance (|η|<2.4, >50% for $p_T \approx 0.1, 0.2, 0.3$ for π,K,p)
- Compatibility with beam spot and primary vertex is required
- Low fake rate (<1%) achieved with additional cleaning on cluster shapes
- Immune to beam background
- More sensitive to beam spot & alignment

Tracking Method: efficiency



Pixel Cluster Counting





Counting clusters of pixel hits in pixel barrel layers (acceptance p_T>30 MeV/c $|\eta|<2$)

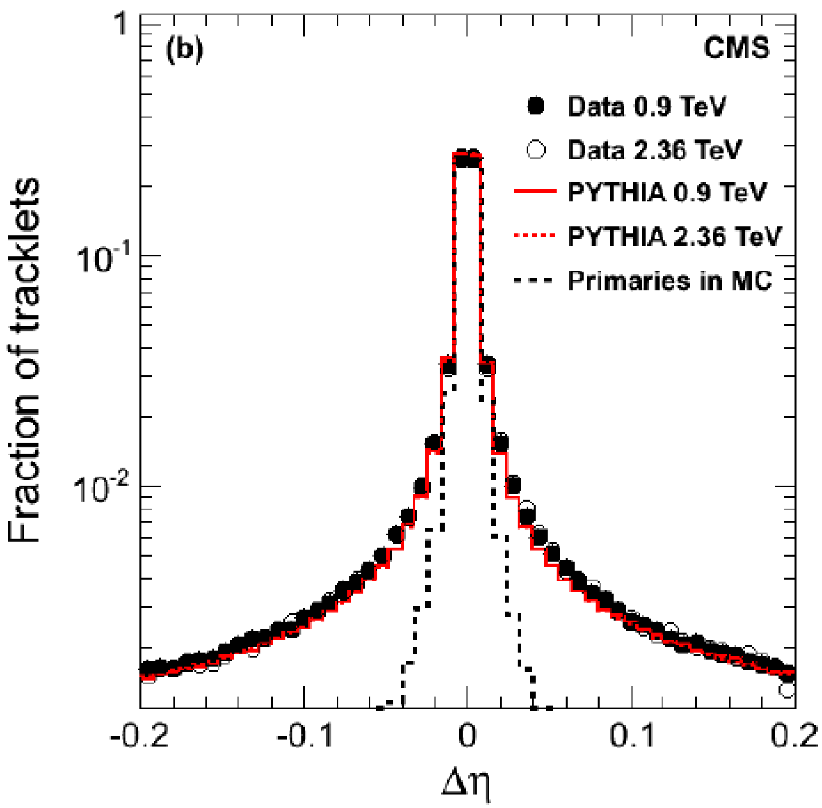
Applying a cut on cluster length ≈ $|\sinh(\eta)|$ to eliminate loopers and secondaries (shorter clusters)

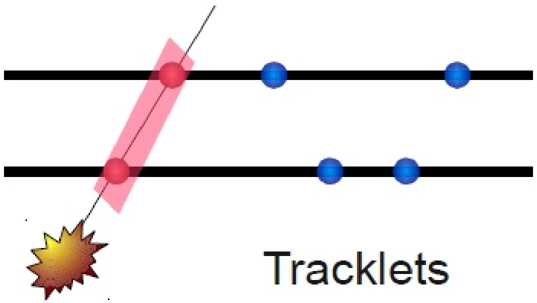
Corrections for loopers, weak decays, secondaries

Independent results for the 3 layers agree

Insensitive to detector misalignment, sensitive to beam background

Tracklets Method





Tracklets: pairs of clusters in 2 different pixel barrel layers (acceptance p_T>75 MeV/c $|\eta|$<2)

$|\Delta\eta|$ and $|\Delta\varphi|$ between clusters are used to select signal from primaries

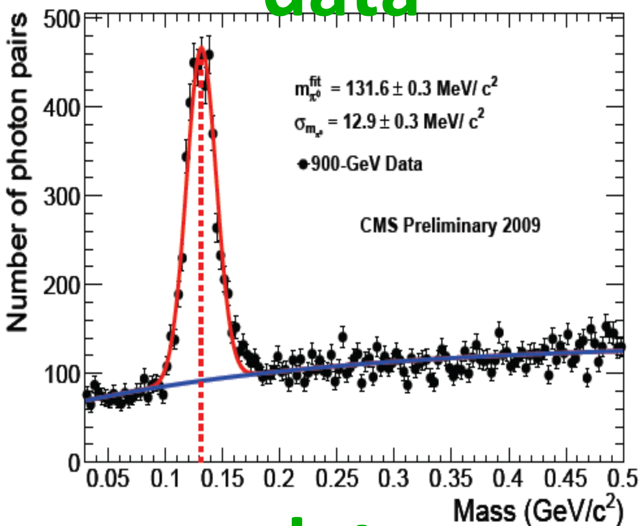
Combinatorial background is subtracted using $\Delta\varphi$ sidebands

Corrections are applied for efficiency, secondaries, weak decays

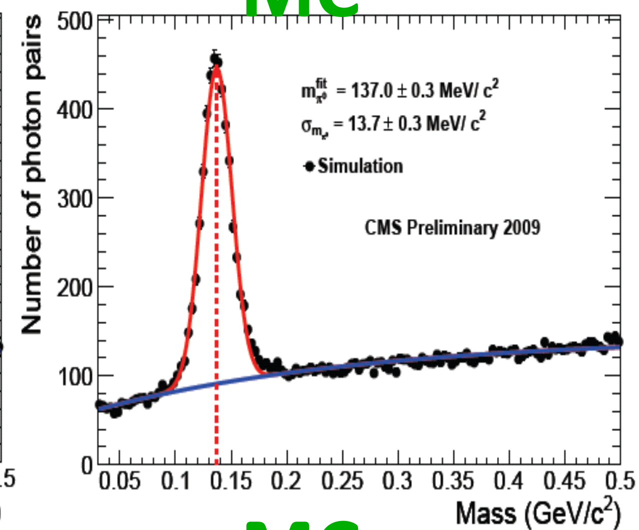
Less sensitive to beam background

π^0 and η in ECAL:

data



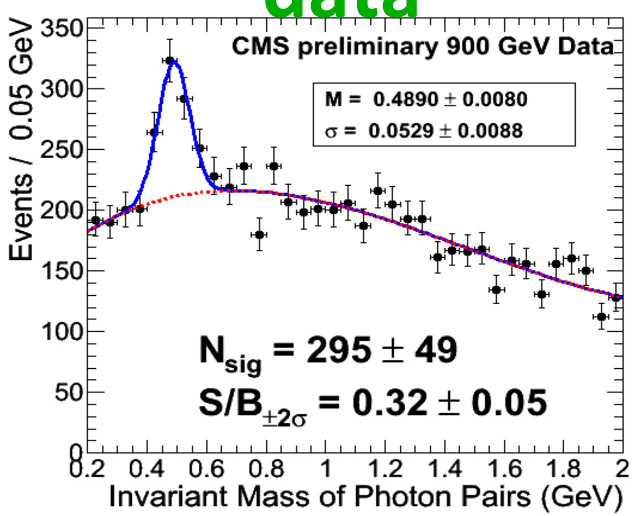
MC



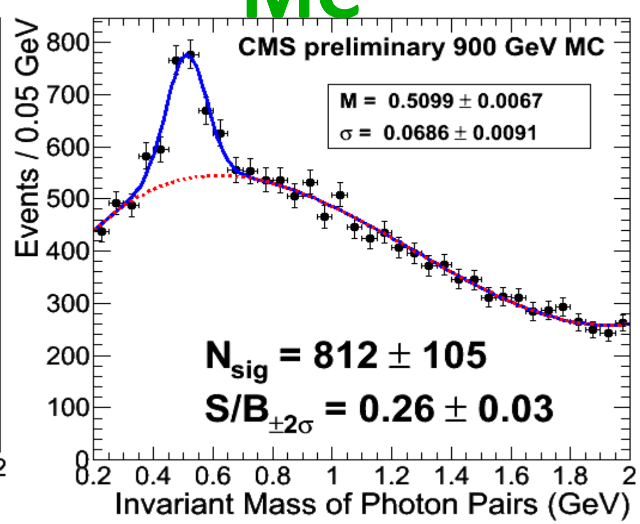
Photon pairs in the
ECAL barrel (|η|<1)
E(γ) > 400 MeV
E(π0) > 1.5 GeV

Monte-Carlo based correction of photon cluster energy is applied

data



MC

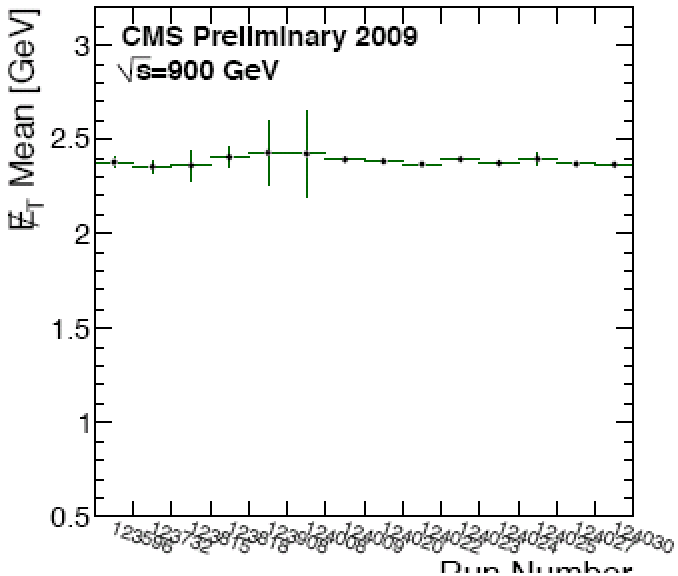


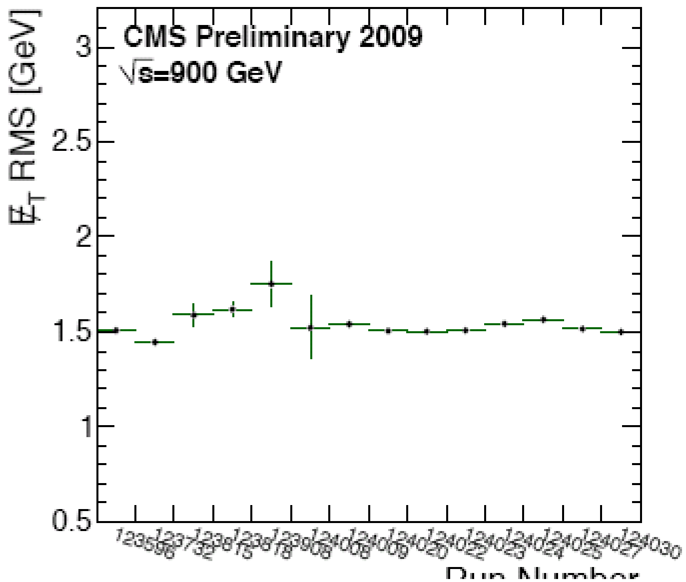
Photon pairs in barrel
ET(γ)>400 MeV;
ET(η)>2.0 GeV;
shower shape

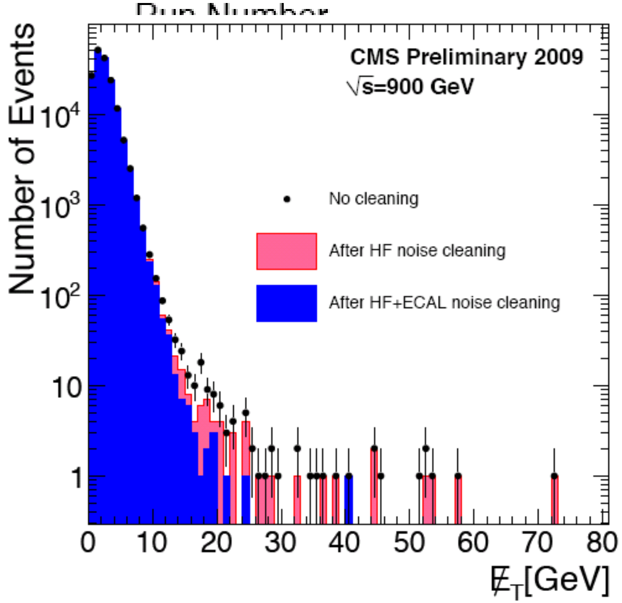
No corrections applied

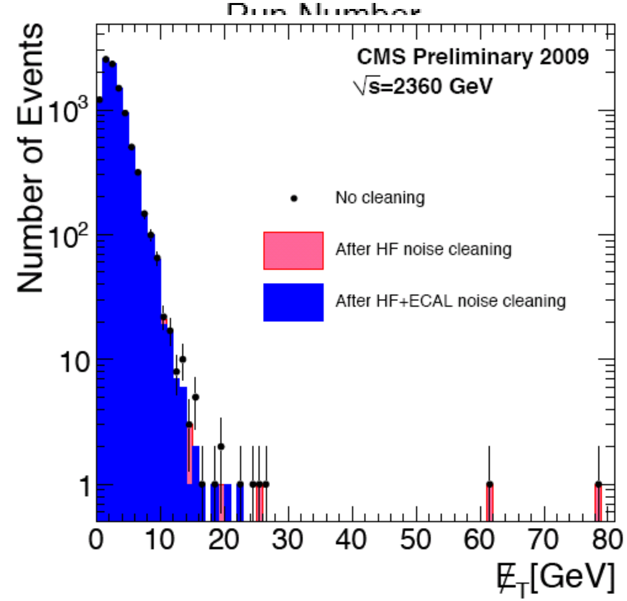
Good agreement data and MC: peak position and S/B

Missing ET


CMS Preliminary 2009
√s=900 GeV
$\not{E}_T$ Mean [GeV]
3
2.5
2
1.5
1
0.5


CMS Preliminary 2009
√s=900 GeV
$\not{E}_T$ RMS [GeV]
3
2.5
2
1.5
1
0.5


CMS Preliminary 2009
√s=900 GeV
No cleaning
After HF noise cleaning
After HF+ECAL noise cleaning
Number of Events
10^4
10^3
10^2
10
1
0 10 20 30 40 50 60 70 80
$\not{E}_T$[GeV]


CMS Preliminary 2009
√s=2360 GeV
No cleaning
After HF noise cleaning
After HF+ECAL noise cleaning
Number of Events
10^3
10^2
10
1
0 10 20 30 40 50 60 70 80
$\not{E}_T$[GeV]