Physics studies with cosmic muons in CMS

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Introduction

CMS experiment at CERN: ambitious physics programme, from the measurement of Standard Model (SM) parameters to the discovery of new physics beyond the SM.

Potential of CMS to cover this physics programme: established by detailed studies based on simulated events (latest calculations, state-of-the-art Monte Carlo programs).

Since 2006, CMS has collected large amounts of data from cosmic ray muons, whose analysis has allowed for commissioning both the CMS detector and the reconstruction and analysis software.

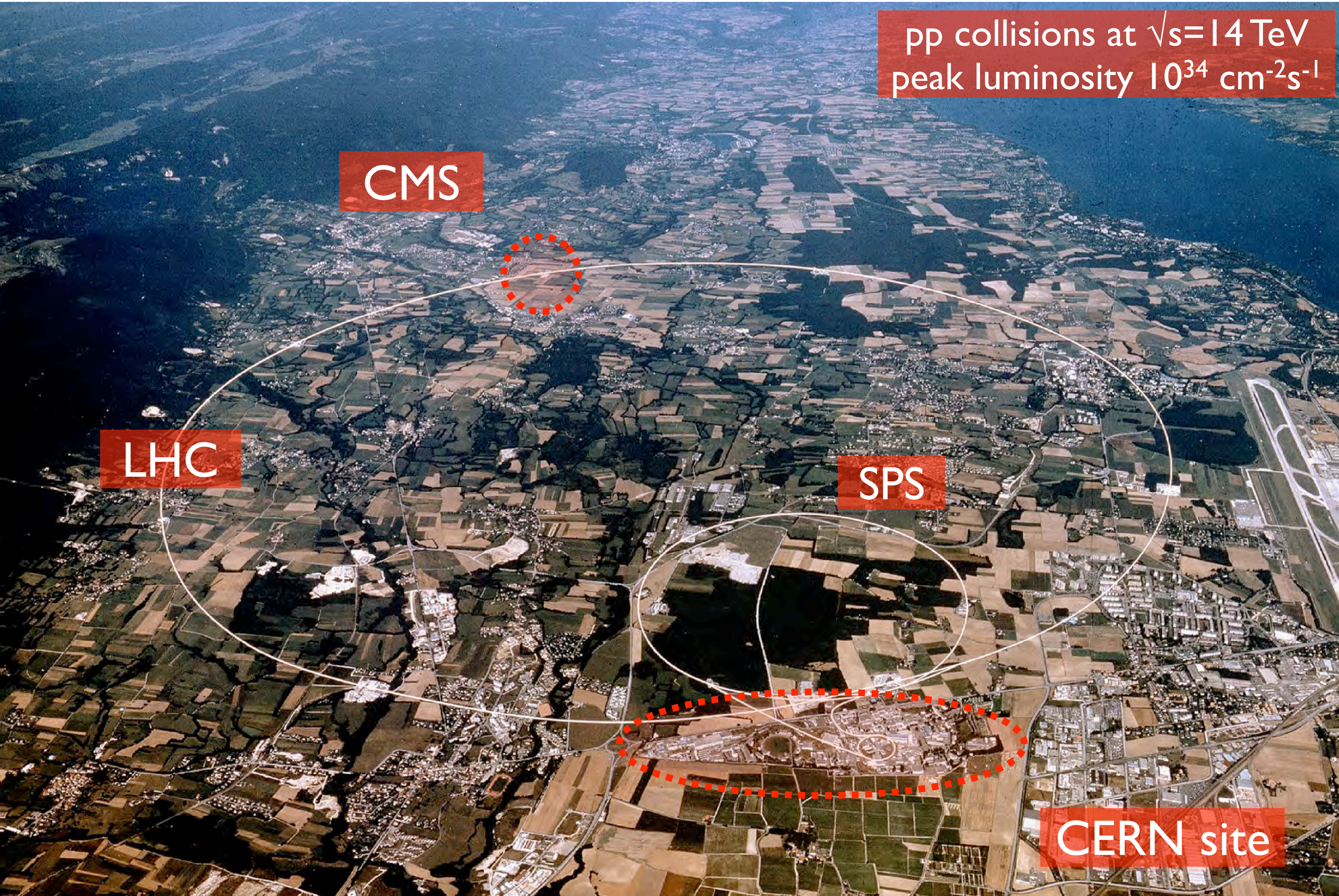
Introduction II

The analysis of cosmic muons is not part of the physics programme of CMS: it provides high quality measurements that probe the capabilities of our detector and reconstruction algorithms.

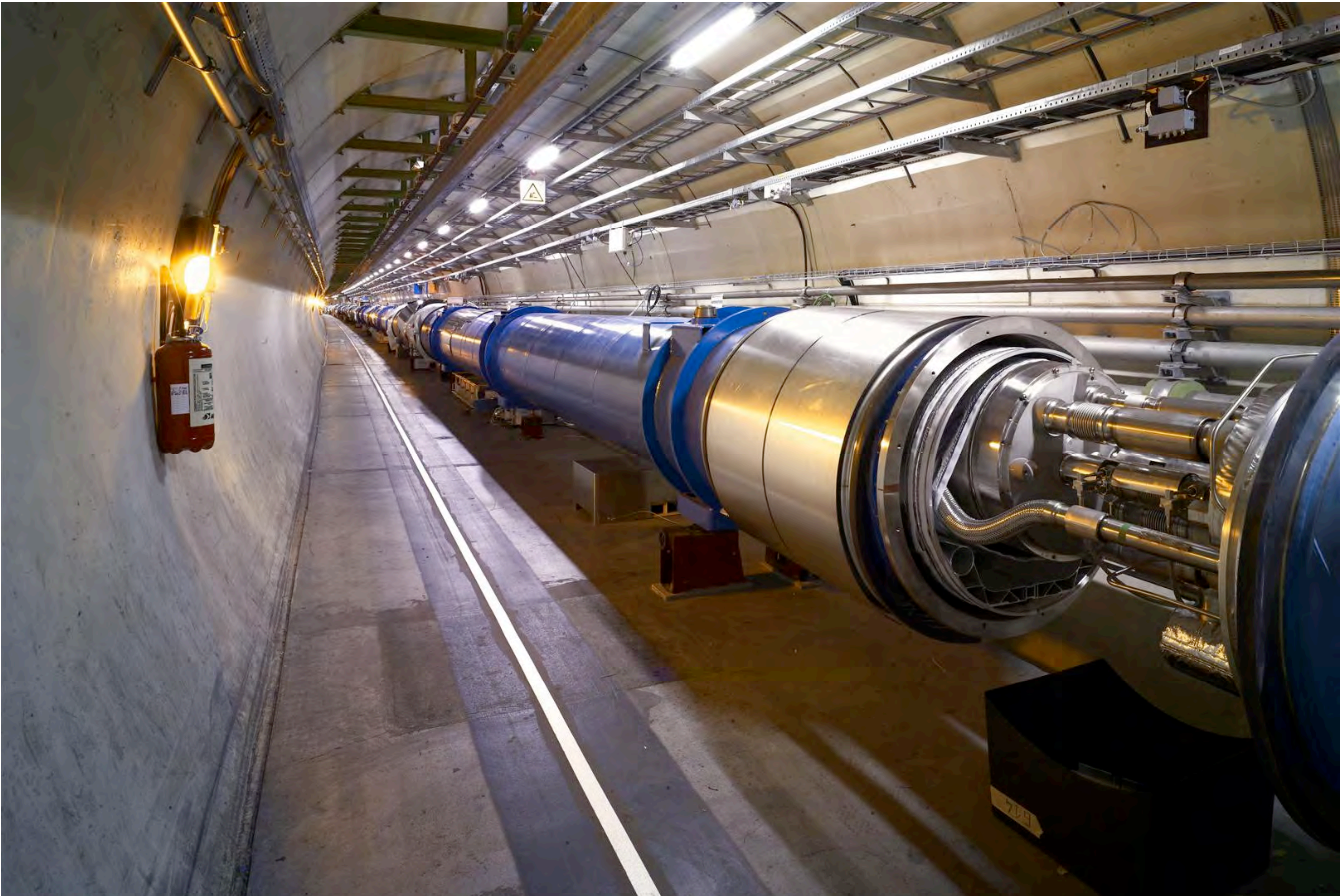
Measurement of the ratio of positive- to negative-charge cosmic muons, *charge asymmetry*, as a function of the muon momentum, using the data collected by CMS; the first measurement of a physical parameter performed by the CMS experiment. Other measurements: absolute muon flux.

Detector studies assess performance of CMS (including alignment and calibration) at a level previously expected after ≈ 10 pb^{-1} to 100 pb^{-1} of LHC data. Impressive !!!

Setting the scene...



Large Hadron Collider



Compact Muon Solenoid

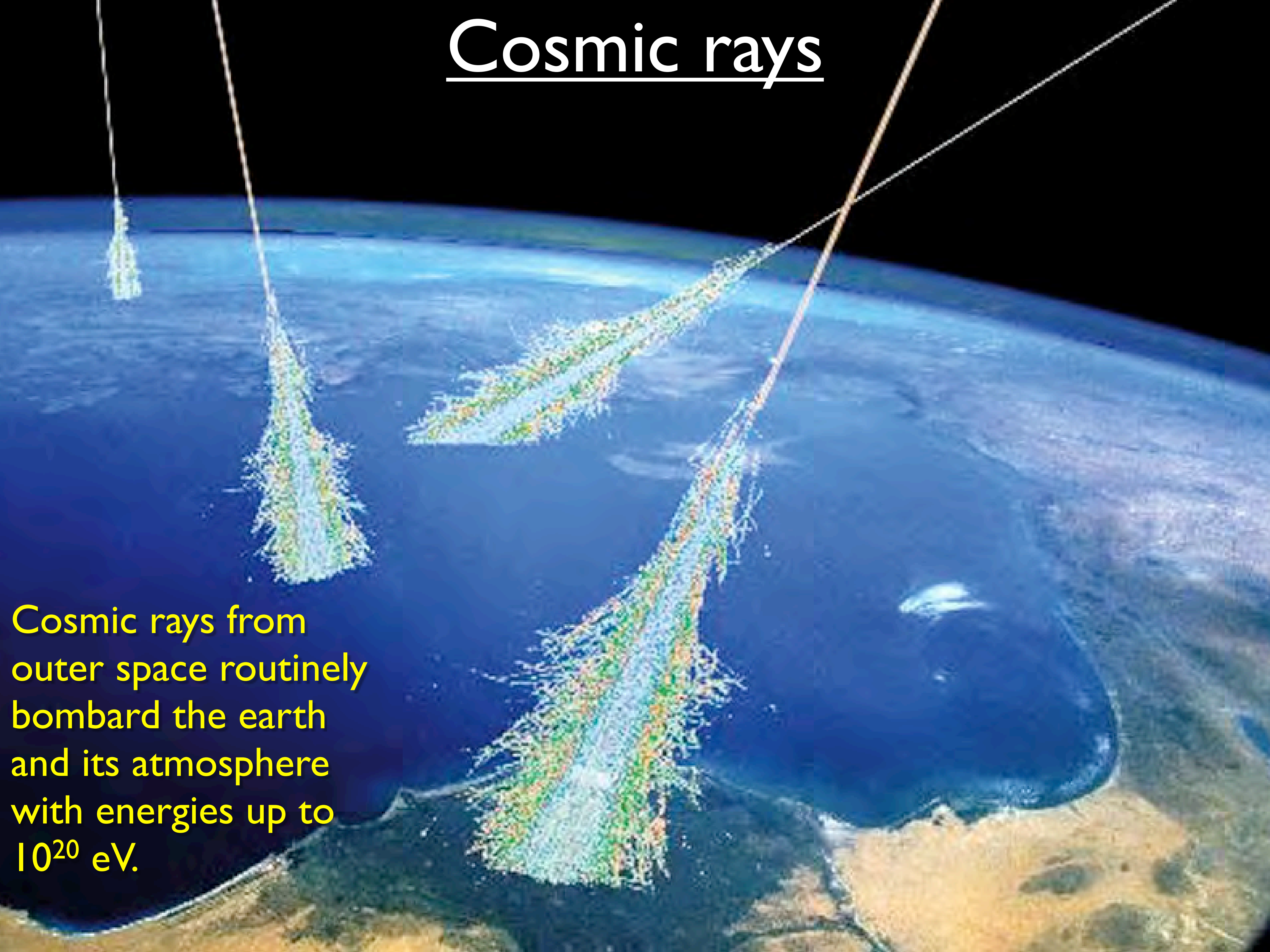
- CMS is a huge 80 Mpixel "3D" (2x2D) digital camera (not impressive), spread over a 3700 m^3 volume, weighing 12500 Ton.

- Operating at B = 3.8 T, supplied by a super-conducting magnet (impressive).

- Very high precision in the pixel/hit positions: from 20 μm to 200 μm.

- This camera works at 40 Mhz (this IS impressive too).

Cosmic rays



Cosmic rays from outer space routinely bombard the earth and its atmosphere with energies up to 10^{20} eV.

Atmospheric Muons

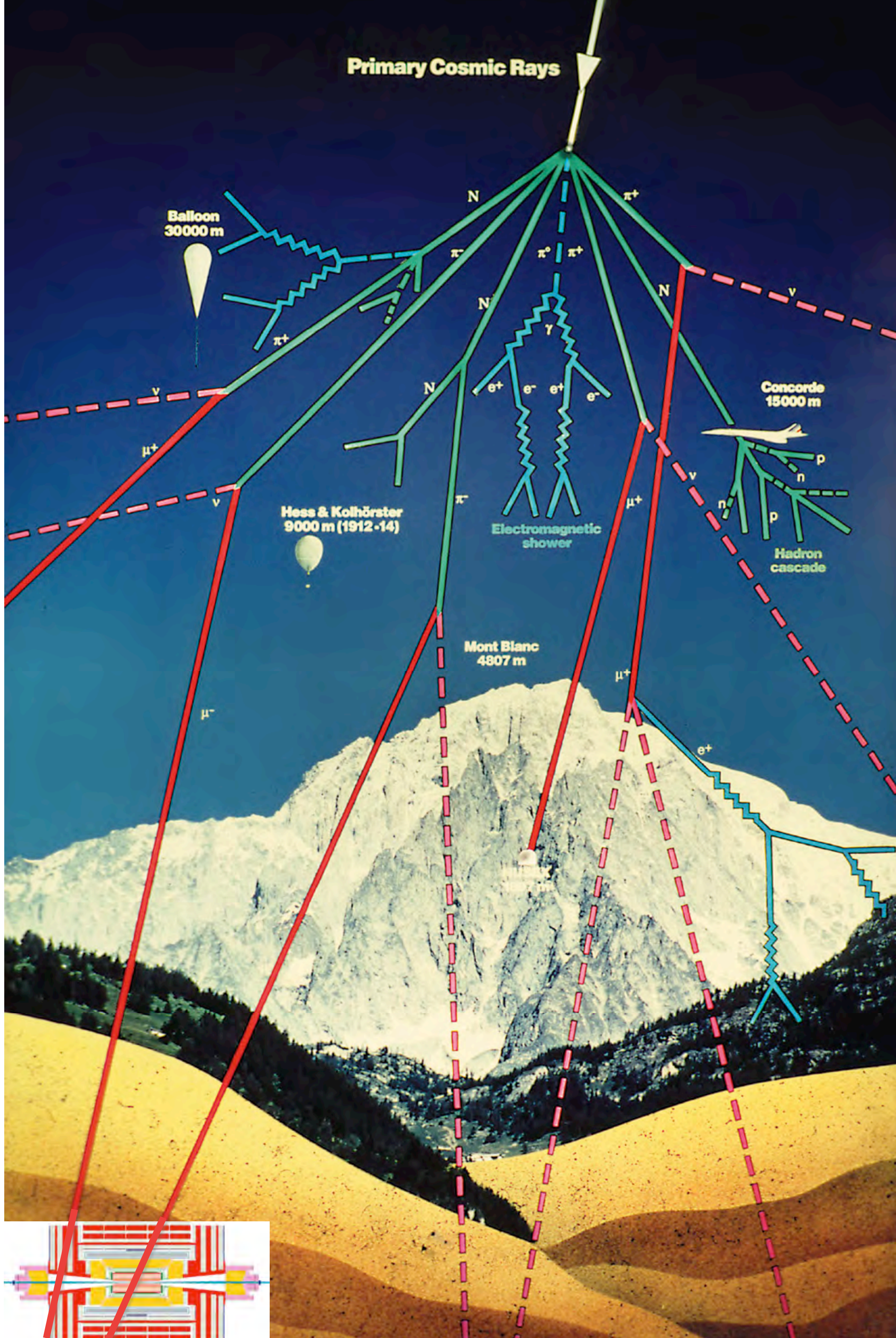
Stem from cosmic ray showers, produced via interactions of high-energy cosmic-ray particles (nuclei), entering the upper layers of the atmosphere, with air nuclei:

(p, He, ..., Fe) $\rightarrow$ hadrons, $e^{\pm}\gamma$

$(\pi^{\pm}, K^{\pm}) \rightarrow \mu^{\pm}\, \nu_{\mu}\, (\bar{\nu}_{\mu})$ and

$\mu^{\pm} \rightarrow e^{\pm}\, \nu_e\, \bar{\nu}_{\mu}\, (\bar{\nu}_e\, \nu_{\mu})$

Long-lived muons cross the overburden and reach CMS.



Cosmic muon charge ratio

- Muon energy spectrum underground (vertical muons, cosθ=1):

$$\frac{[dN]}{[dE_\mu]} = A\left\{\frac{1}{1+\frac{1.1E_\mu\cos\theta}{\epsilon_\pi}} + \frac{0.054}{1+\frac{1.1E_\mu\cos\theta}{\epsilon_K}}\right\} \qquad A \equiv \frac{0.14E_\mu^{-2.7}}{\mathrm{cm}^2\ \mathrm{s\ sr\ GeV}}$$

- Both π and K contribute, ϵ is the energy where the probability of meson interaction and decay are equal: ϵ_π = 115 GeV and ϵ_K = 850 GeV.

- Generalizing for μ^+ and μ^-, the measured charge ratio on surface is:

$$\frac{N^{\mu^+}}{N^{\mu^-}} = \left\{\frac{f_\pi}{1+\frac{1.1E_{\mu^+}\cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054\times f_K}{1+\frac{1.1E_{\mu^+}\cos\theta}{850\ \mathrm{GeV}}}\right\} \Big/ \left\{\frac{1-f_\pi}{1+\frac{1.1E_{\mu^-}\cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054\times(1-f_K)}{1+\frac{1.1E_{\mu^-}\cos\theta}{850\ \mathrm{GeV}}}\right\}$$

- From L3+C, f_π = 0.555(2) and f_K = 0.667(7). These values imply the muon charge asymmetry induced by π and K is

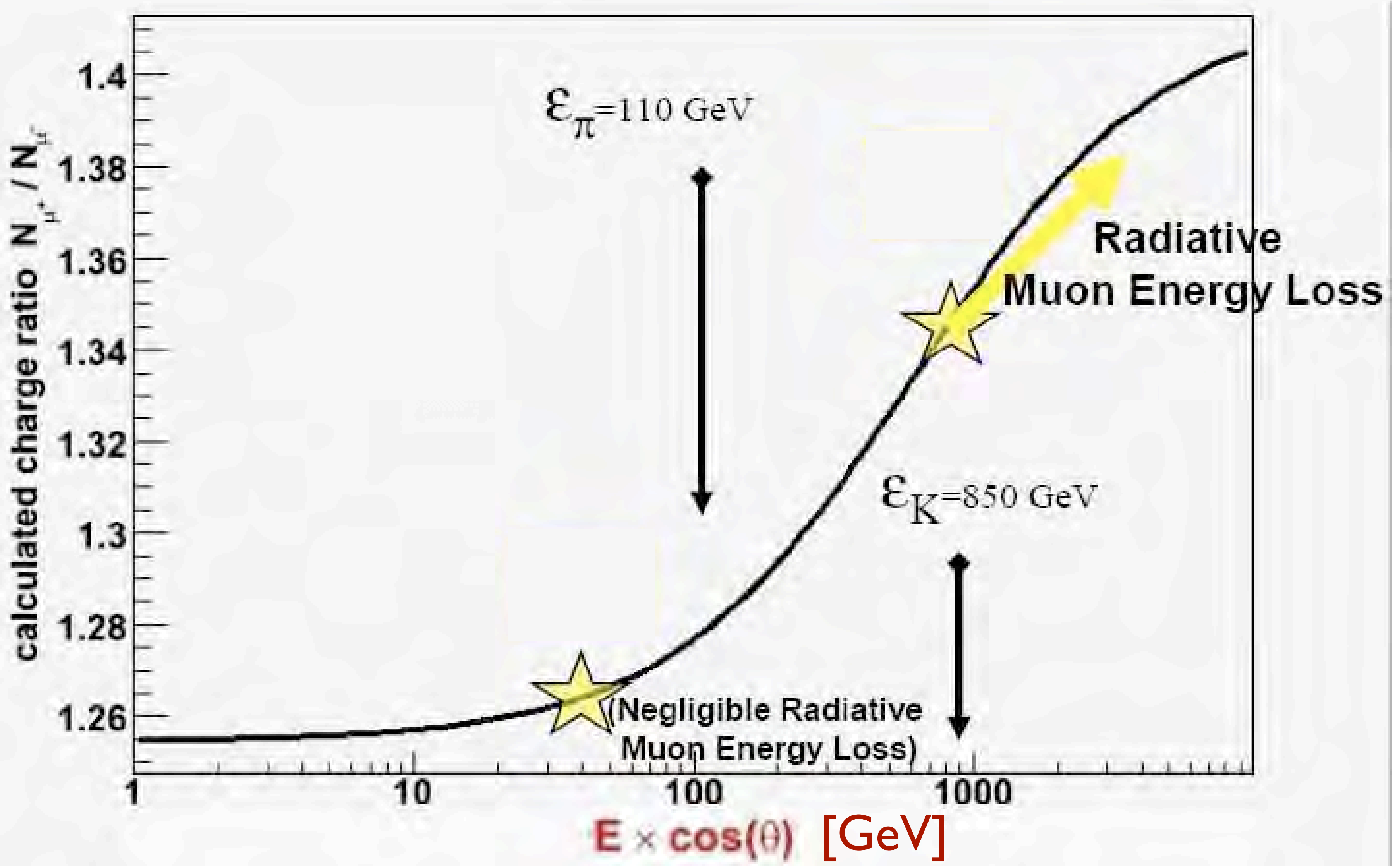
$$r_\pi = f_\pi / (1-f_\pi) = 1.25 \quad \text{and} \quad r_K = f_K / (1-f_K) = 2$$

Schreiner, Goodman (MINOS), arXiv:0706.0538v1 [hep-ex]

Cosmic muon charge ratio

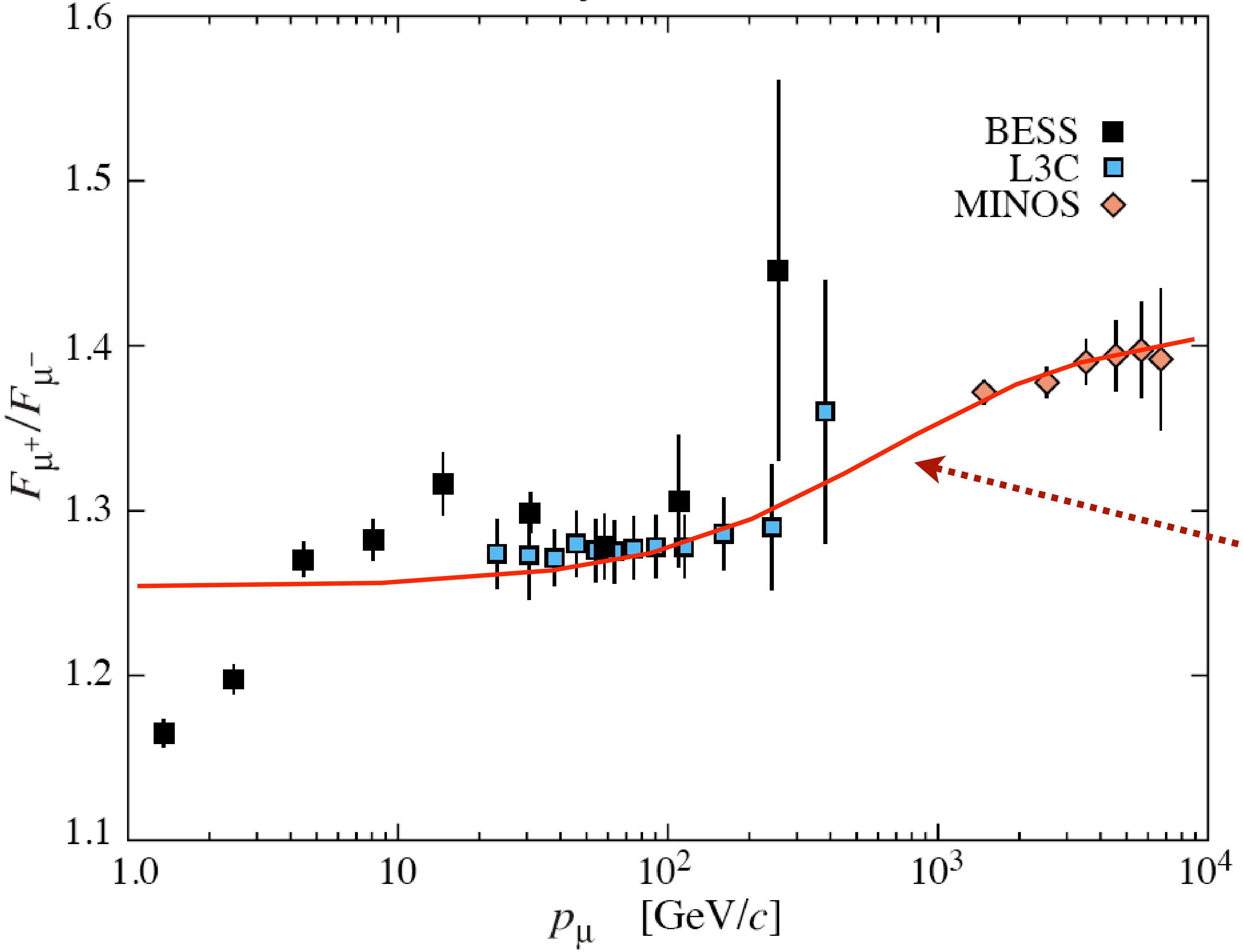
Schreiner, Goodman (MINOS), arXiv:0706.0538v1 [hep-ex]

Expected charge ratio vs. E×cosθ, from previous slide



Previous measurements

C. Amsler et al., Physics Letters B667, 1 (2008)

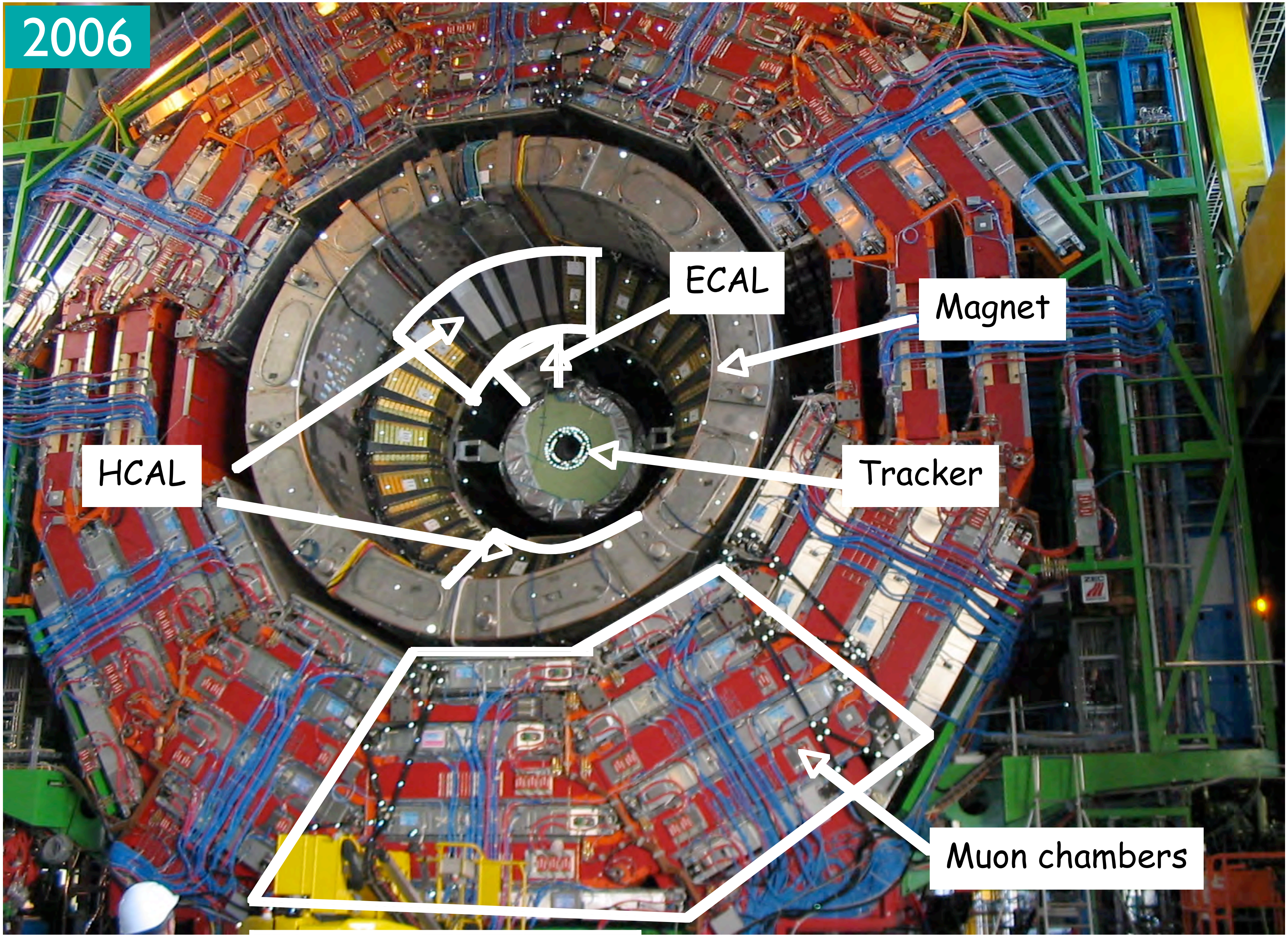


The momentum range 200 GeV/c to 1 TeV/c is sparsely covered by measurements.

Measurement of the charge ratio in CMS

- In 2006, CMS is closed for the first time, on the *surface hall*.
- A major test of the magnet at 4 T is performed, the Magnet Test and Cosmic Challenge (MTCC):
  - testing and commissioning the superconducting magnet, measuring the magnetic field map,
  - data from cosmic muons are collected to test the whole system: detector, DAQ, alignment, event filtering and processing;
  - combined test of the sub-detectors available: 60° slice of CMS !!
- Use CMS data collected at the MTCC to perform a physics measurement: the cosmic muon charge asymmetry.

Experimental setup at MTCC

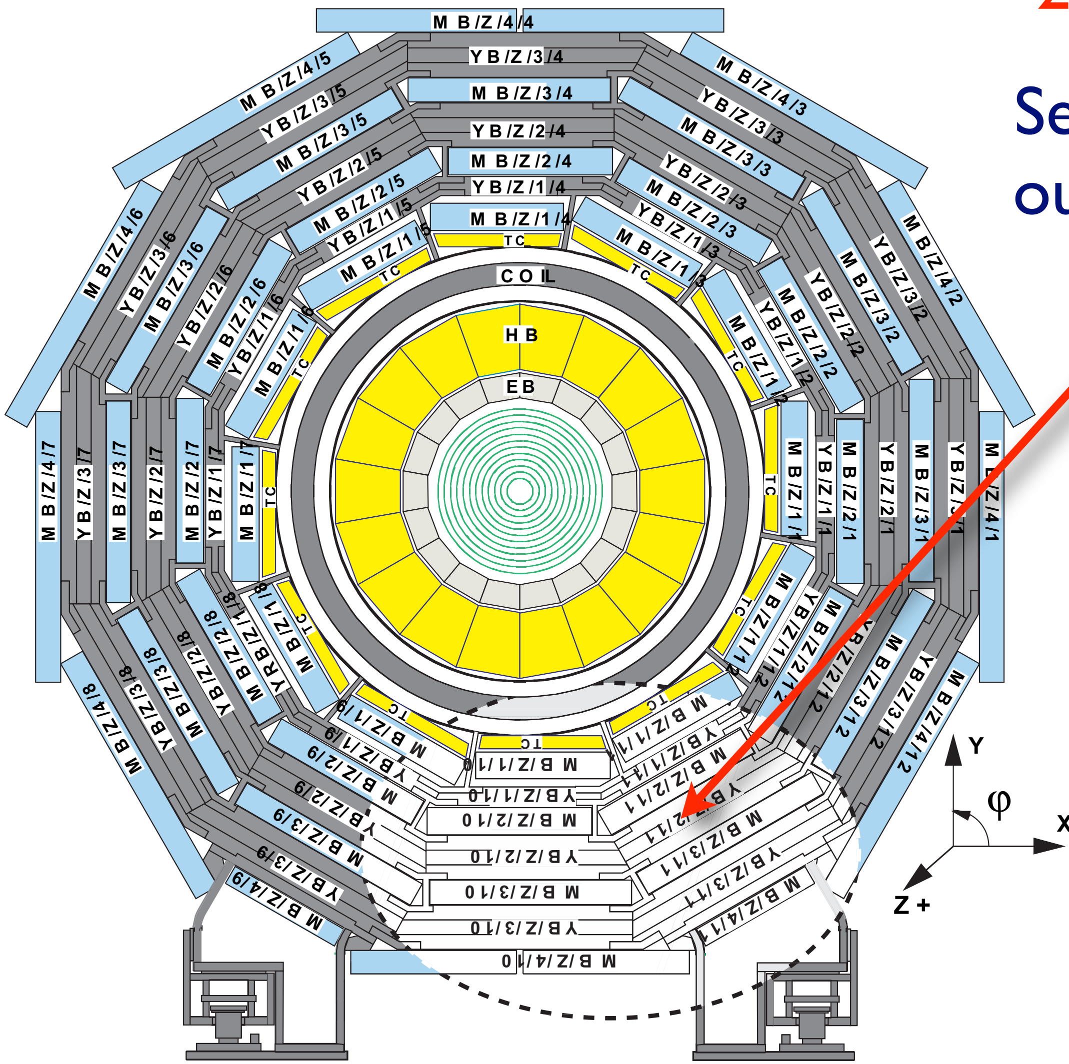


Schematic setup at MTCC

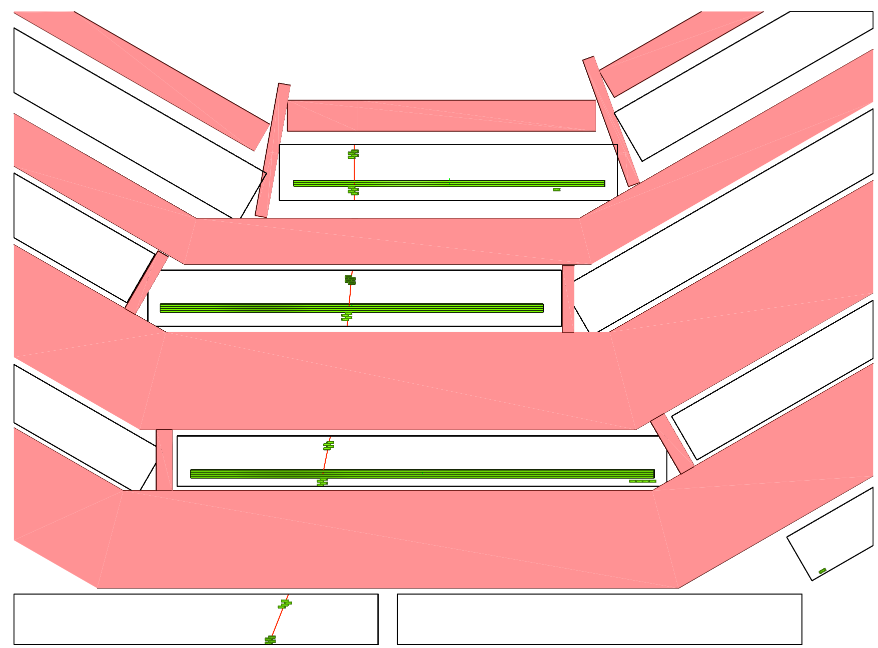
CMS detector on surface: high μ rate

25 Mevents on DTs, 15 M at B≥3.8 T

Sector 10 (sector 11 not used), in two out of five wheels (YB+1 and YB+2) of DT chambers



Barrel wheels YB+2 (S10, S11) and YB+1 (S10)



Data samples

Five runs with similar trigger conditions, ~ 9 M events.
Run at B=0 used for cross checks.

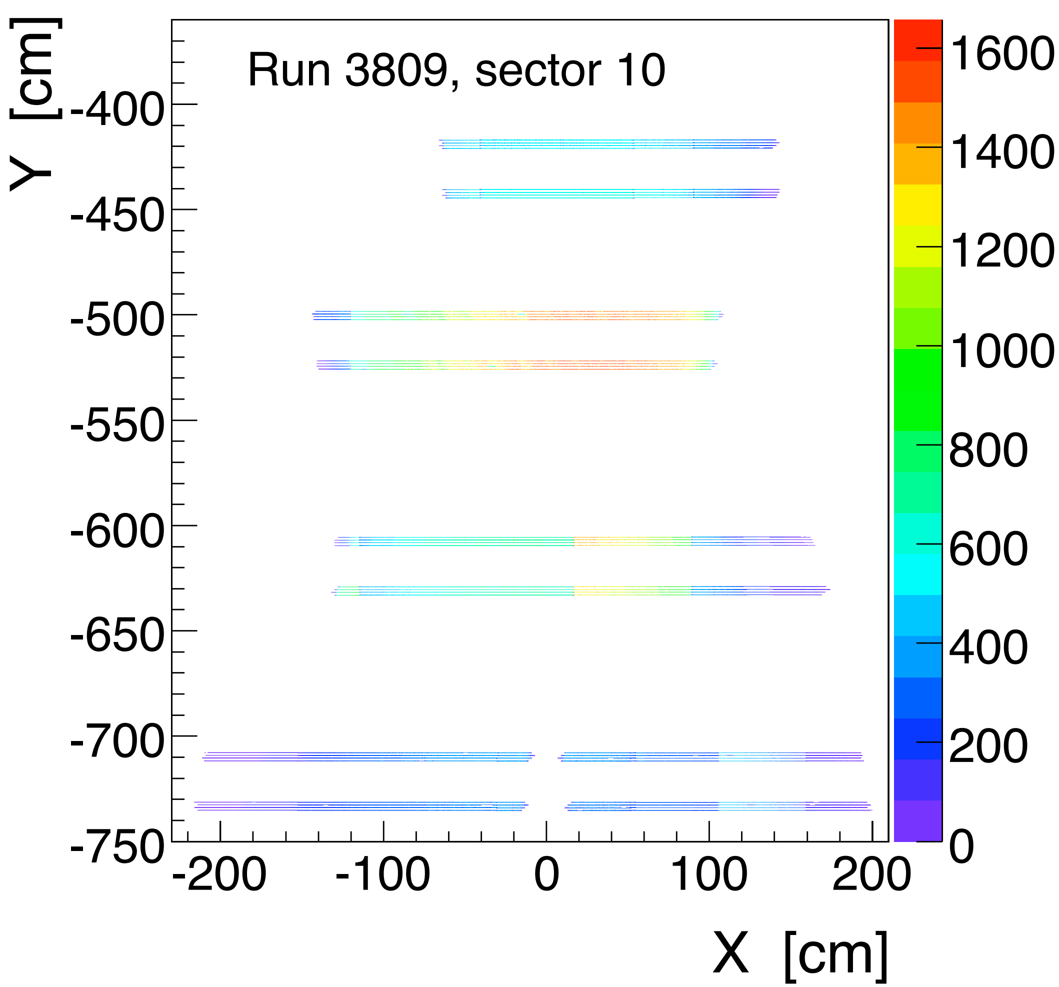
Run	B (T)	Trigger conditions	Events	DT trigger rate
2377	3.67	DT (MB2, MB3), CSC (first 160703 events); CSC, DT, RPC (from event 160704)	613 174	20 %
4045	3.8	DT (MB1, MB2, MB3) OR CSC	3 110 980	32 %
4406	4	DT (MB2, MB3) OR CSC	1 825 273	23 %
4407	4	DT (MB2, MB3) OR CSC	1 665 440	23 %
4409	4	DT (MB2, MB3) OR CSC	2 563 020	23 %
3809	0	any two DT chambers coincidence	611 407	99 %

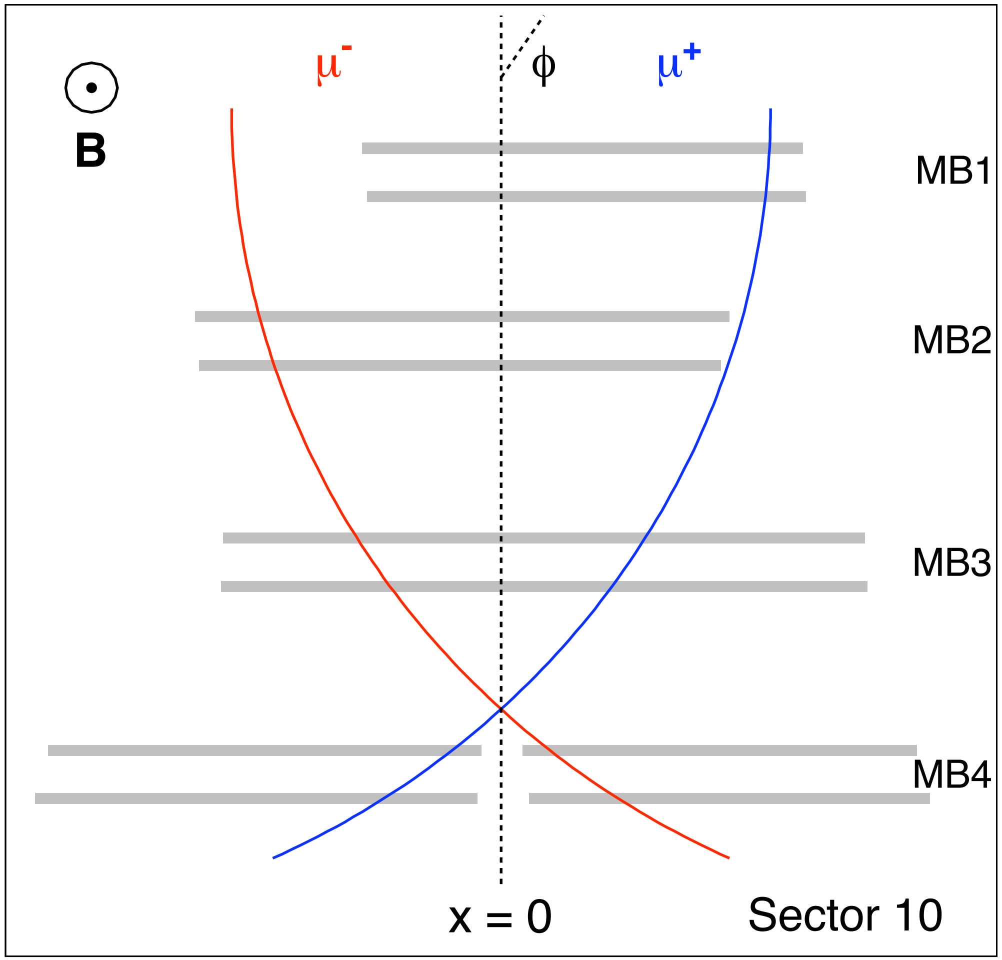
The DT trigger rate is normalized to the global trigger rate.

Symmetric fiducial geometry

Detector geometry asymmetric for μ^+ and μ^-: LR symmetry enforced

Key ingredient of the analysis (no MC efficiency corrections)





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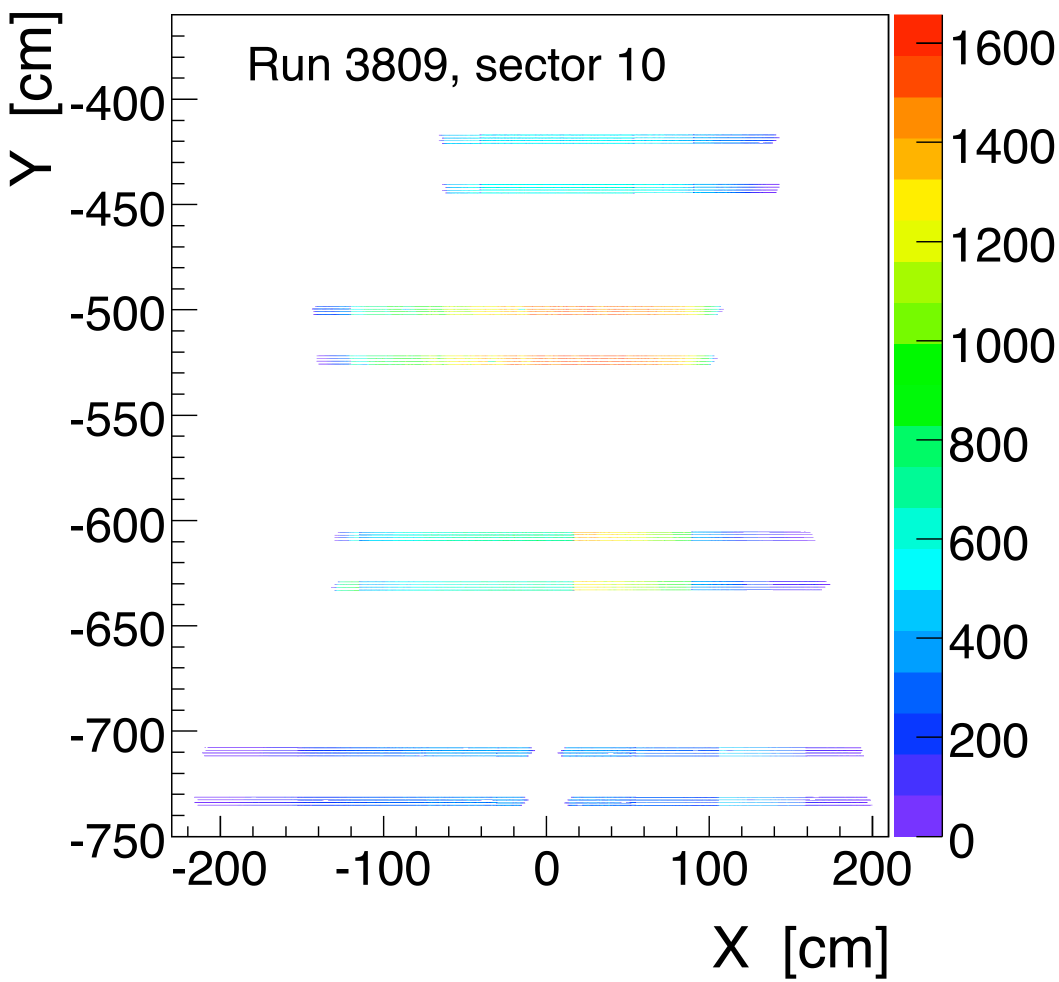
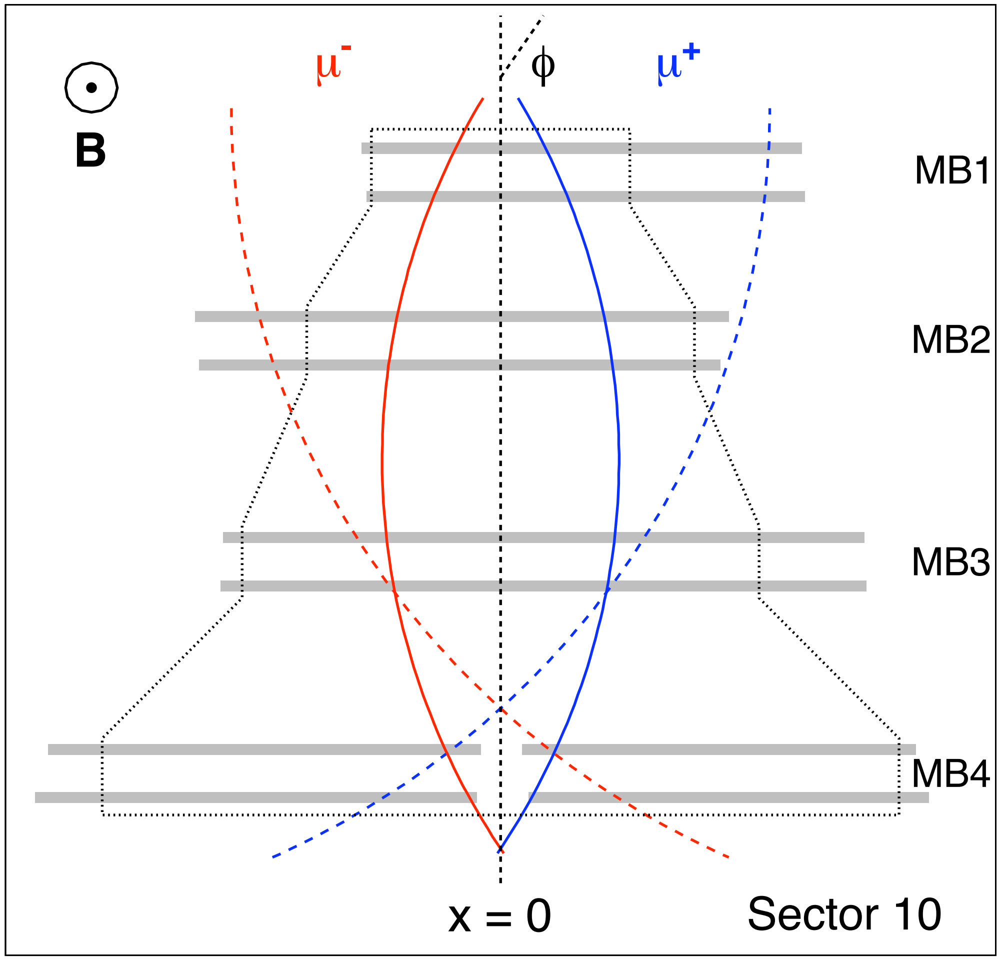
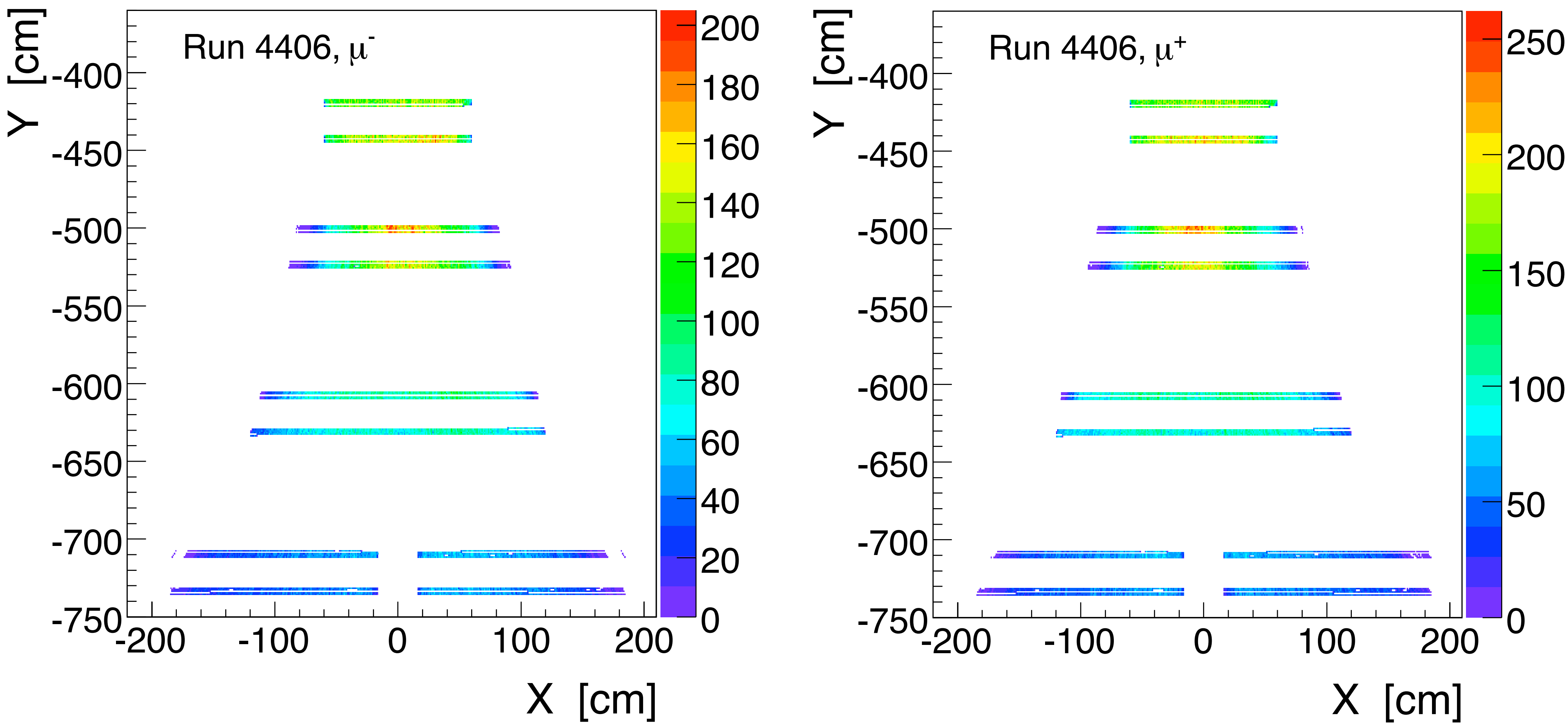




Event selection

Distribution of hits, global XY coordinate, after selection cuts (3 or 4 DT stations, sector 10, same wheel, p_T>3 GeV/c): illumination of DTs is LR symmetric



Selection efficiencies

PRESELECTION

Preselection		
Run	Events	Relative efficiency
2377	40 650	33 %
4045	280 165	28 %
4406	147 471	35 %
4407	135 209	35 %
4409	207 985	35 %
Total	811 480	29 %

Preselection, track quality criteria:

one muon track with ≥10 hits in DTs,
at least 6 in MB2 and MB3.

SELECTION

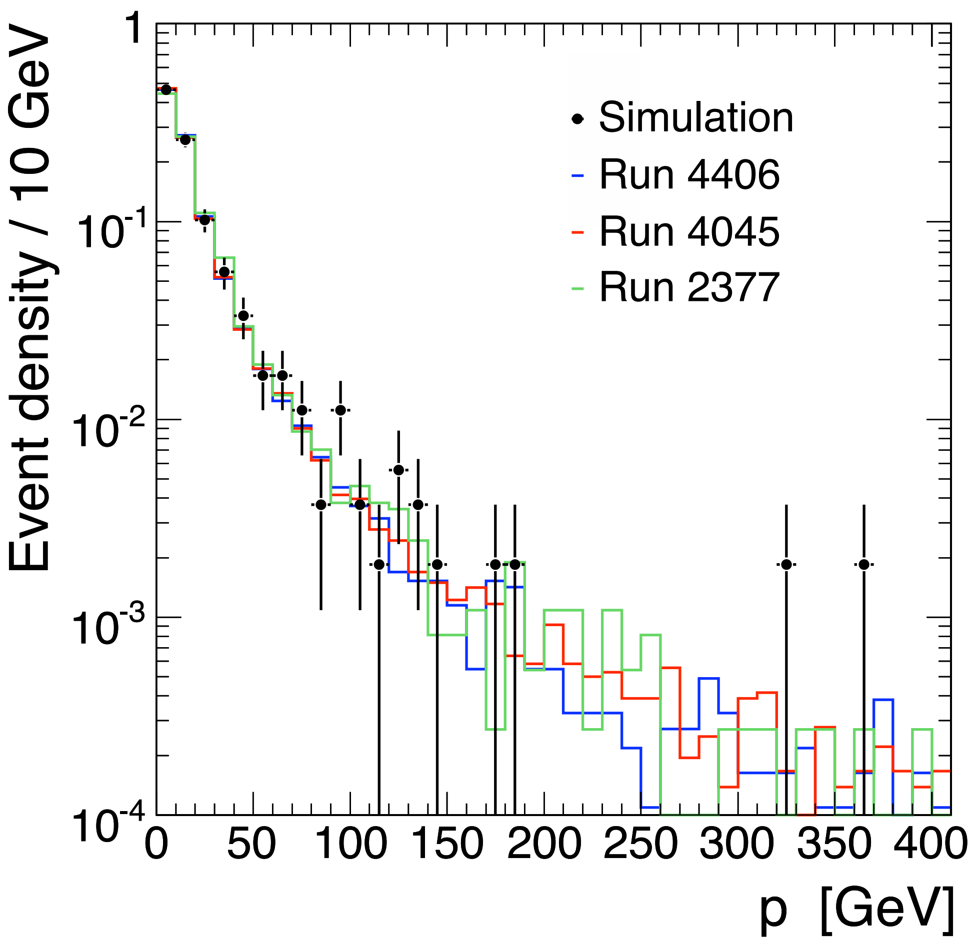
Selection			
Run	Events	Relative efficiency	Q/(Q+T)
2377	16 908	42 %	54.9 %
4045	123 916	44 %	78.5 %
4406	59 227	40 %	79.2 %
4407	54 028	40 %	79.2 %
4409	83 036	40 %	78.9 %
Total	337 115	42 %	77.6 %

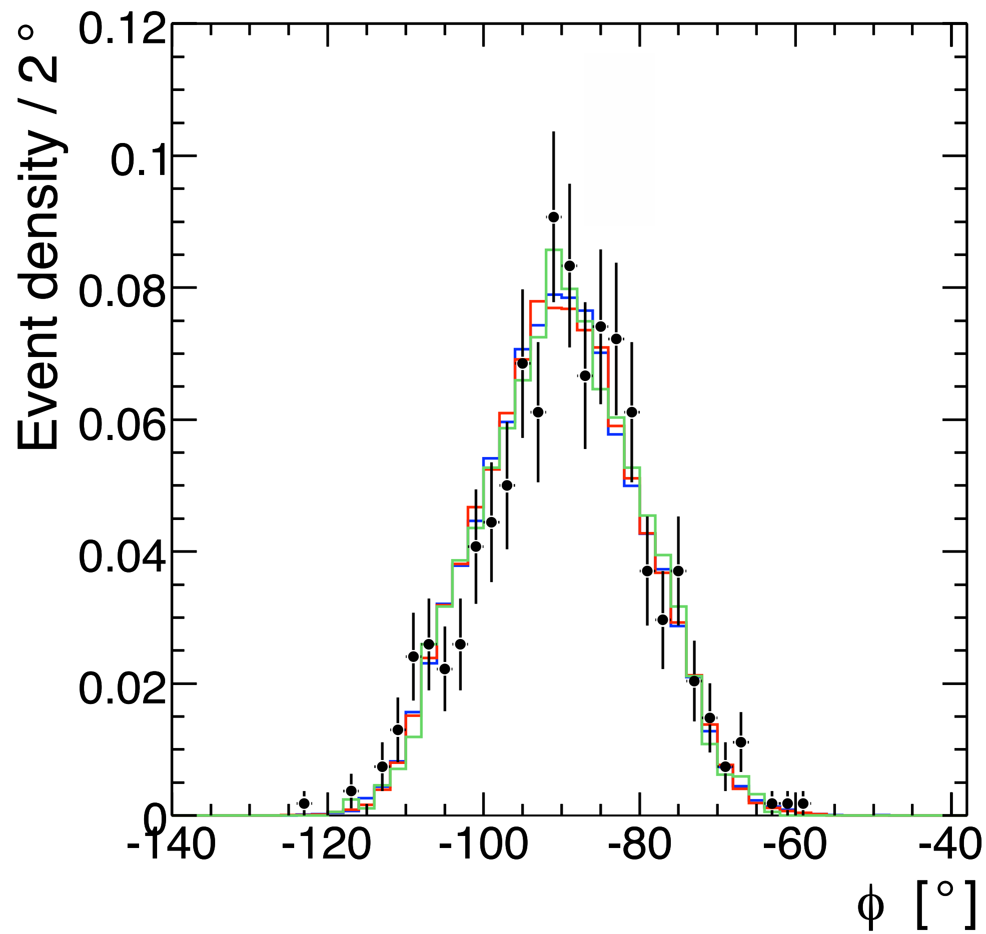
Selection, unbiased sample, high quality muons:

p_T>3 GeV/c,
3 or 4 segments in DTs, sector 10,
LR-symmetric fiducial region.

Distributions after selection

Track momentum and ϕ, after selection cuts are applied, for three data runs and for simulated events (very few).

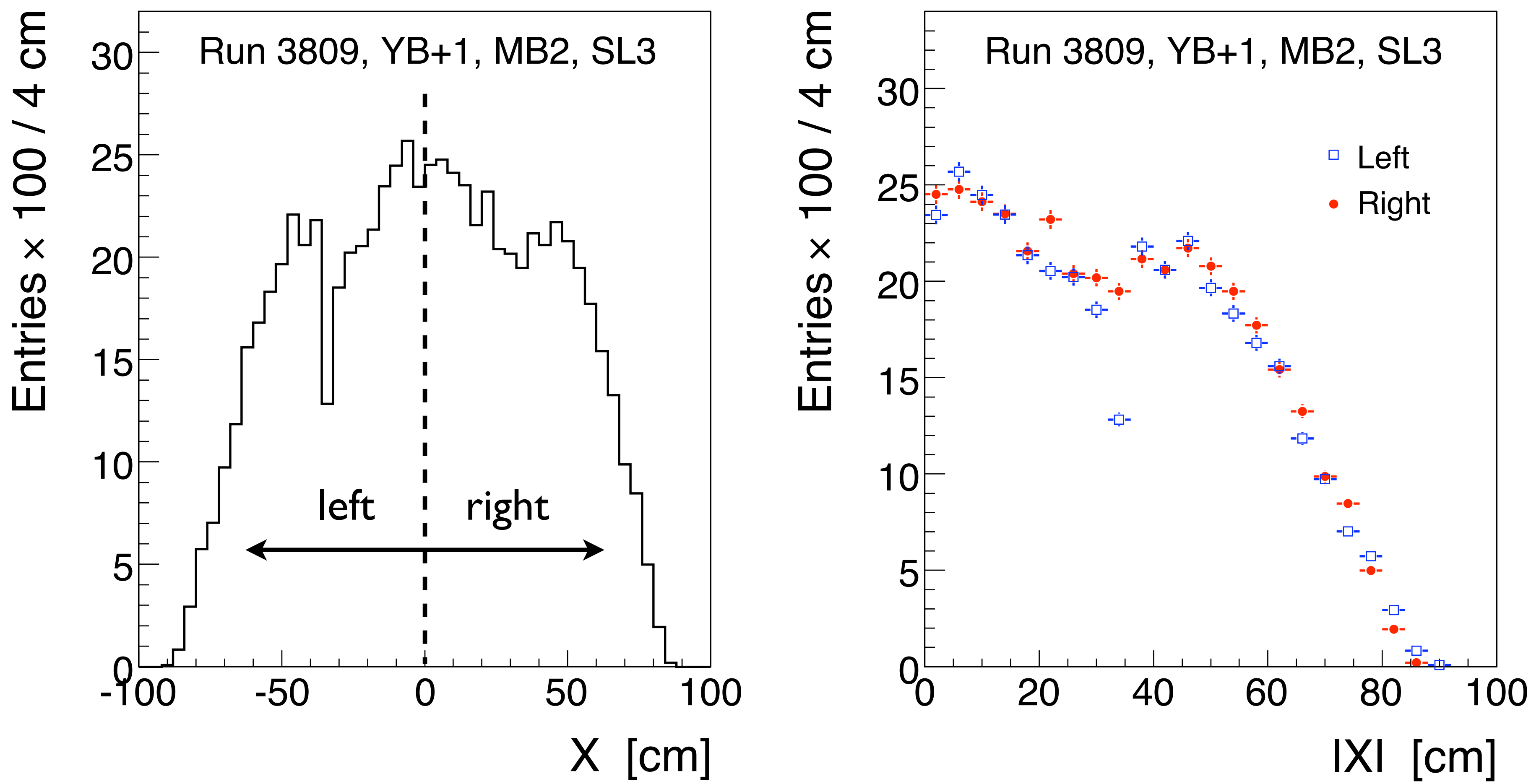




Detector performance

LR symmetry of the performance key of the analysis.

Distribution of hits in the fiducial geometry for one SL.
Data collected at B=0, independent of muon charge.



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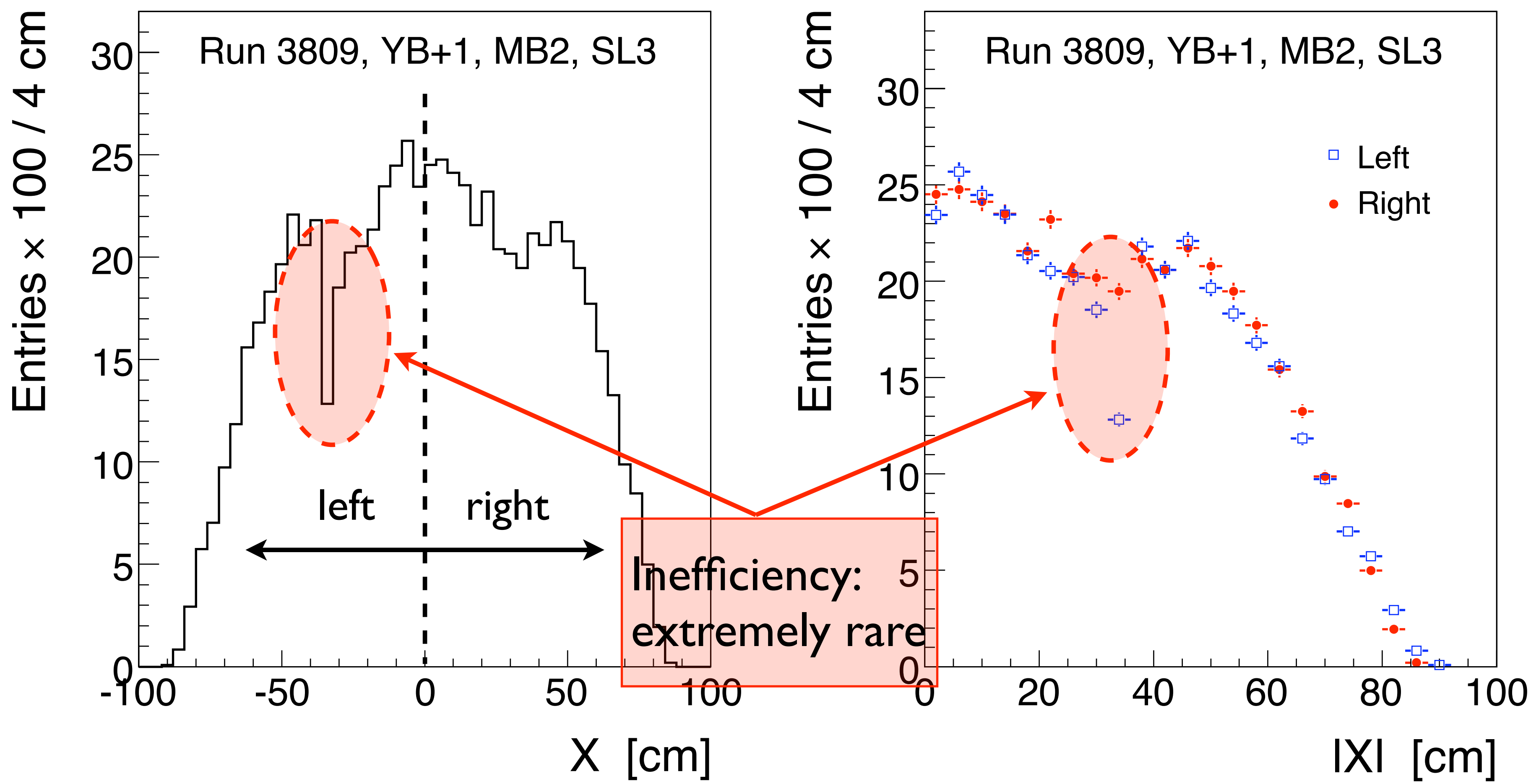
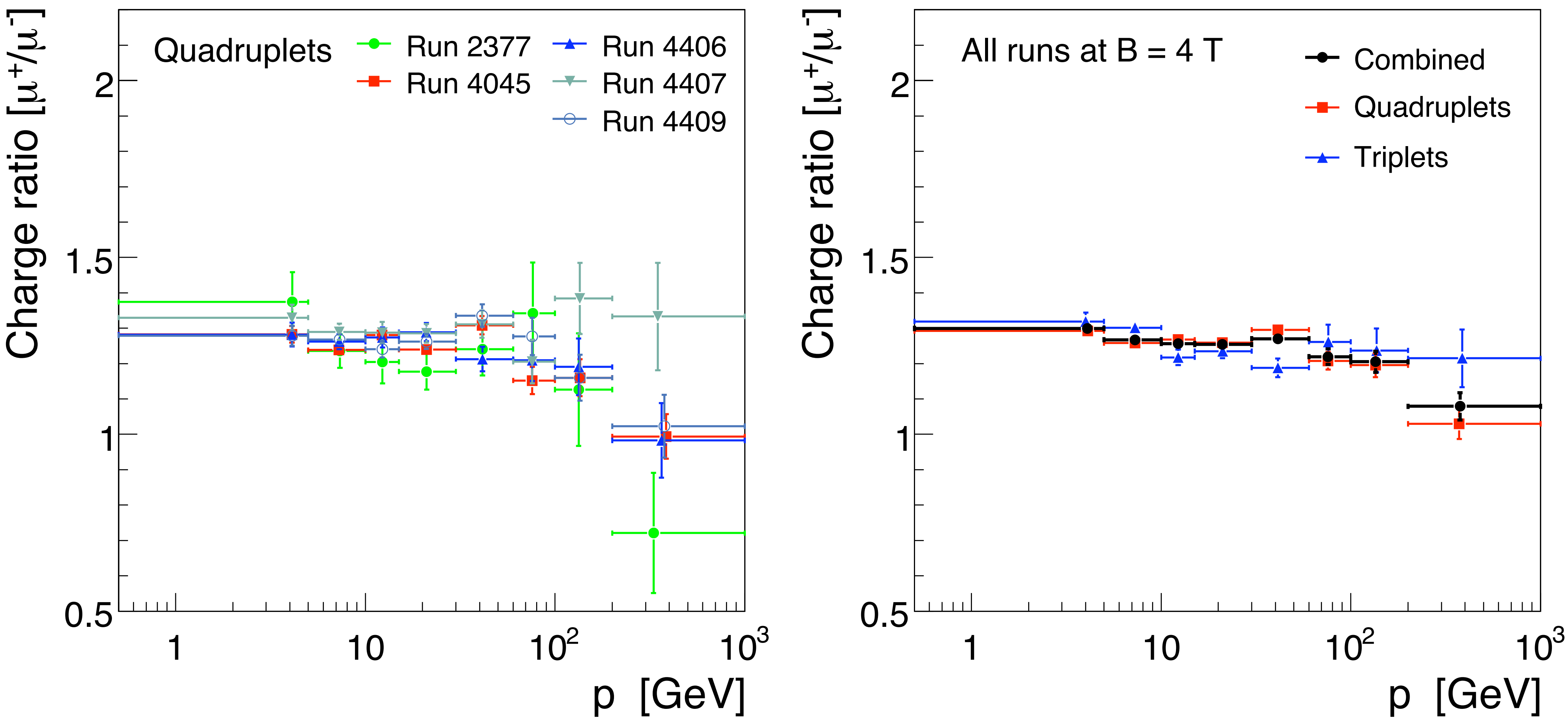


Consistency of the measurements

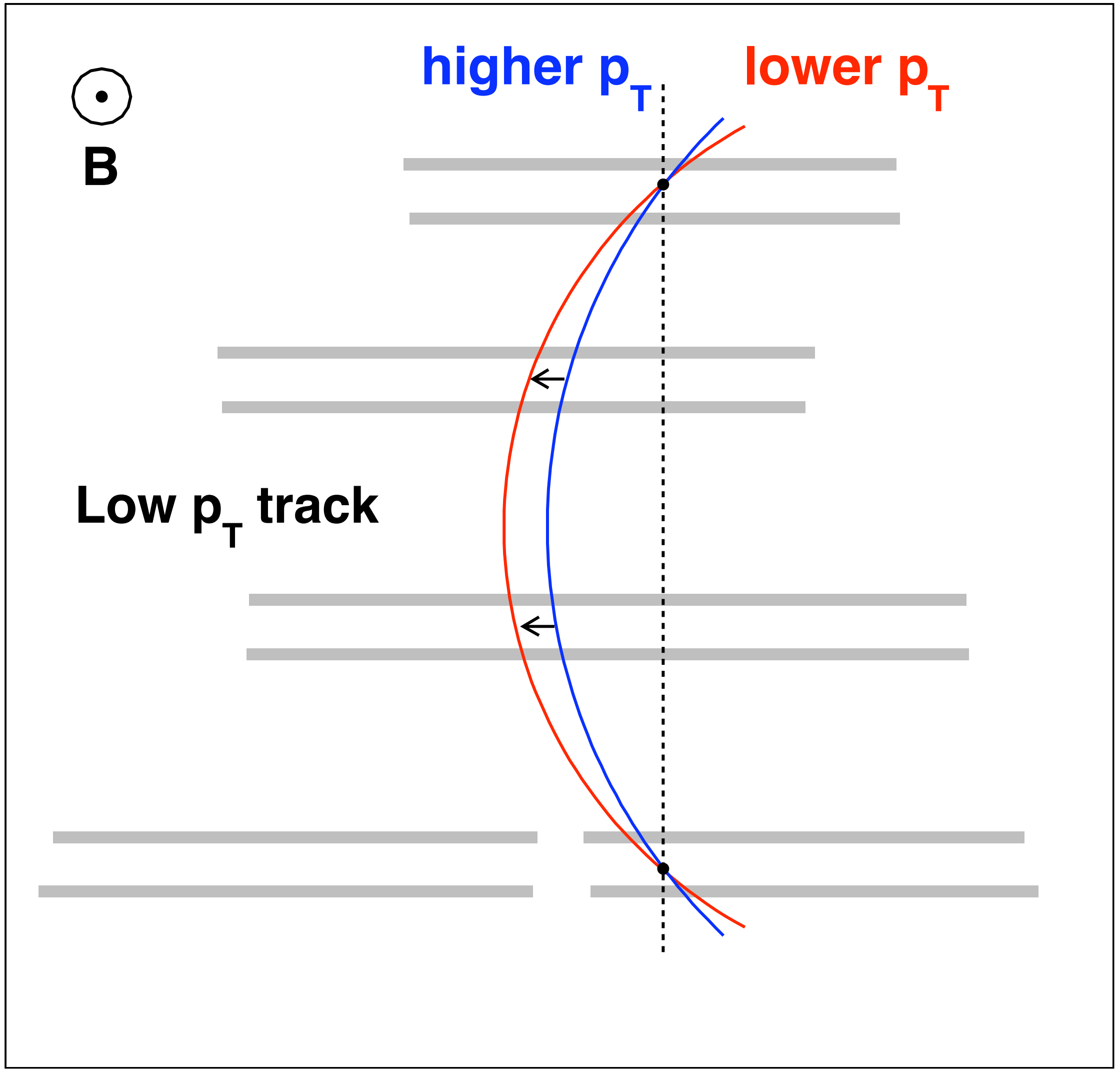
Measurements are consistent among runs and for different track qualities (number of 4D segments)



Misalignment induces bias

Deviation of the position of the chambers from their ideal position introduces a momentum-dependent bias in the momentum (charge) determination, antisymmetric for μ^+ and μ^-.

Most important systematic uncertainty, in particular at hight p_T.



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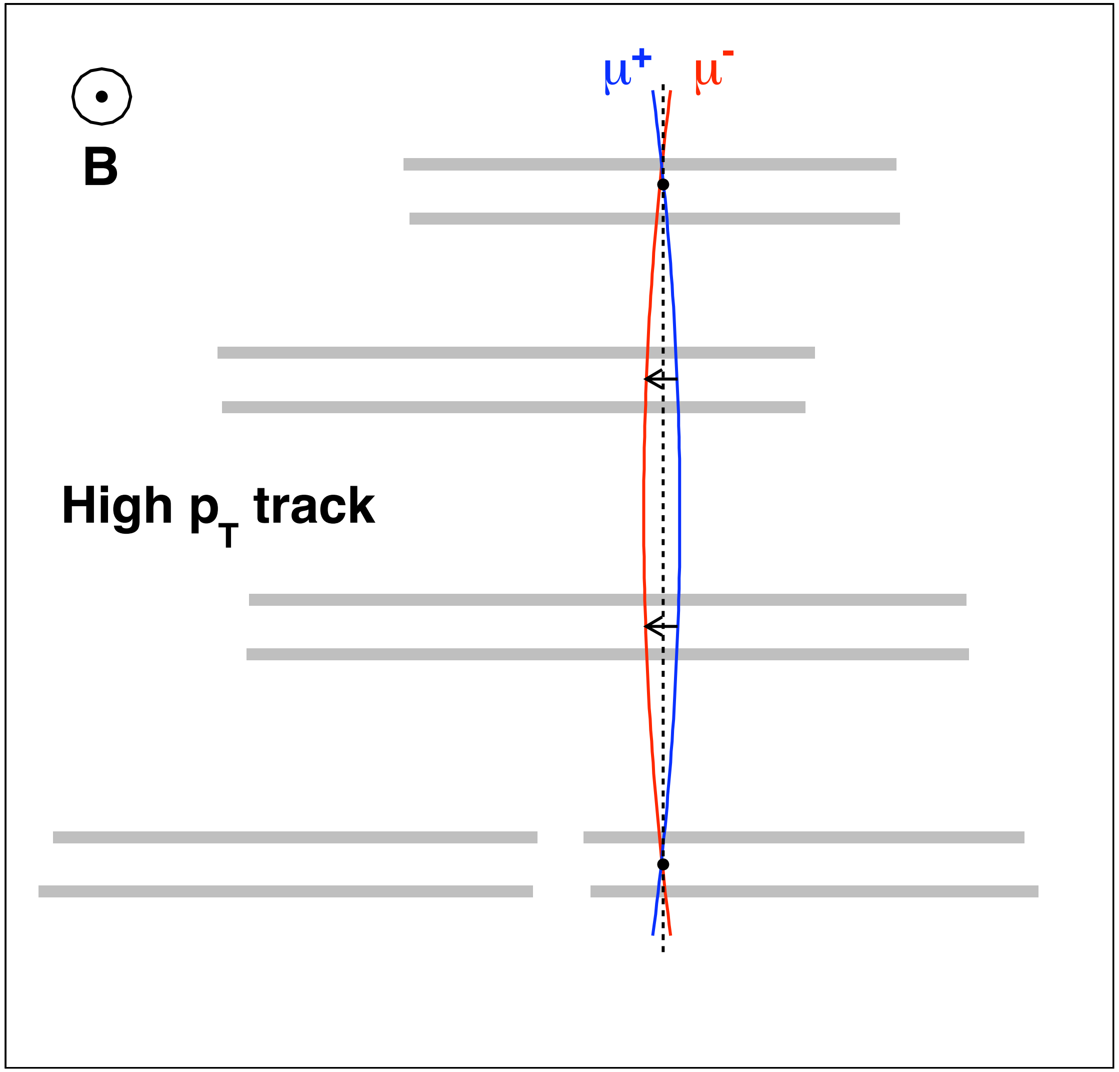
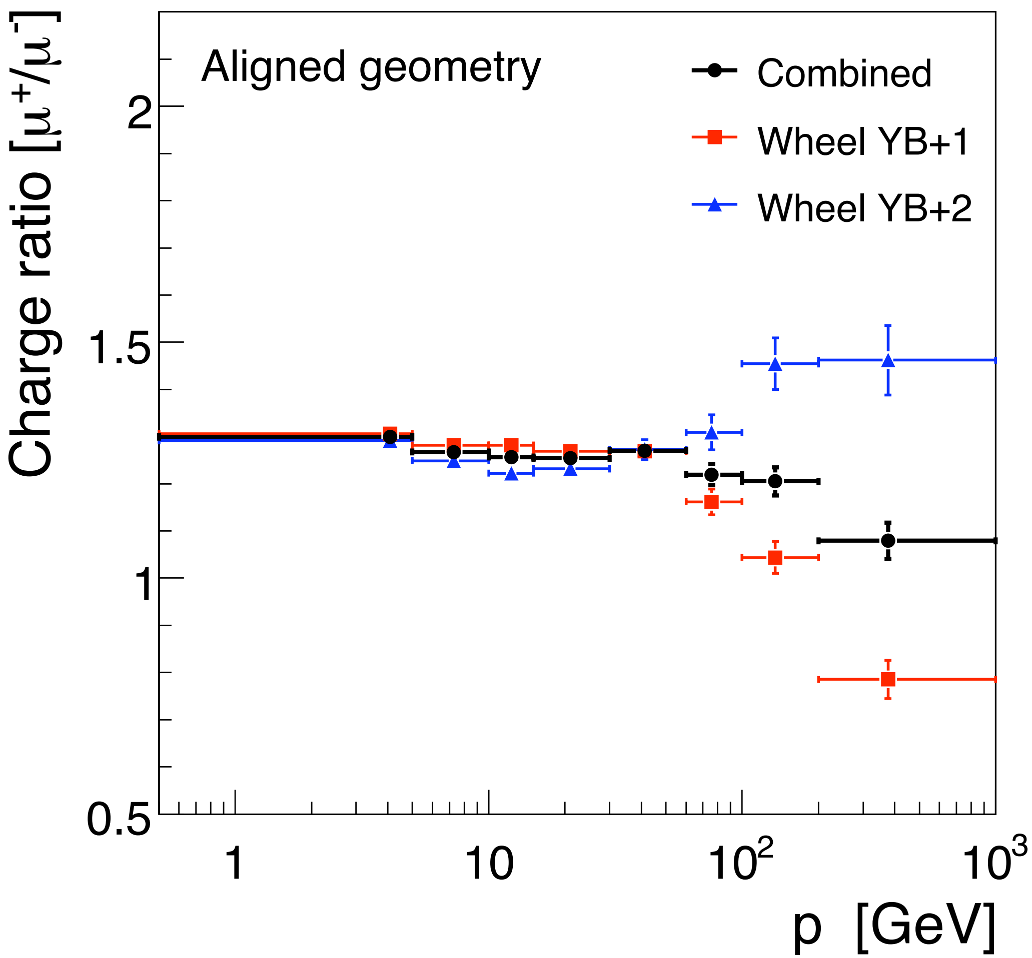
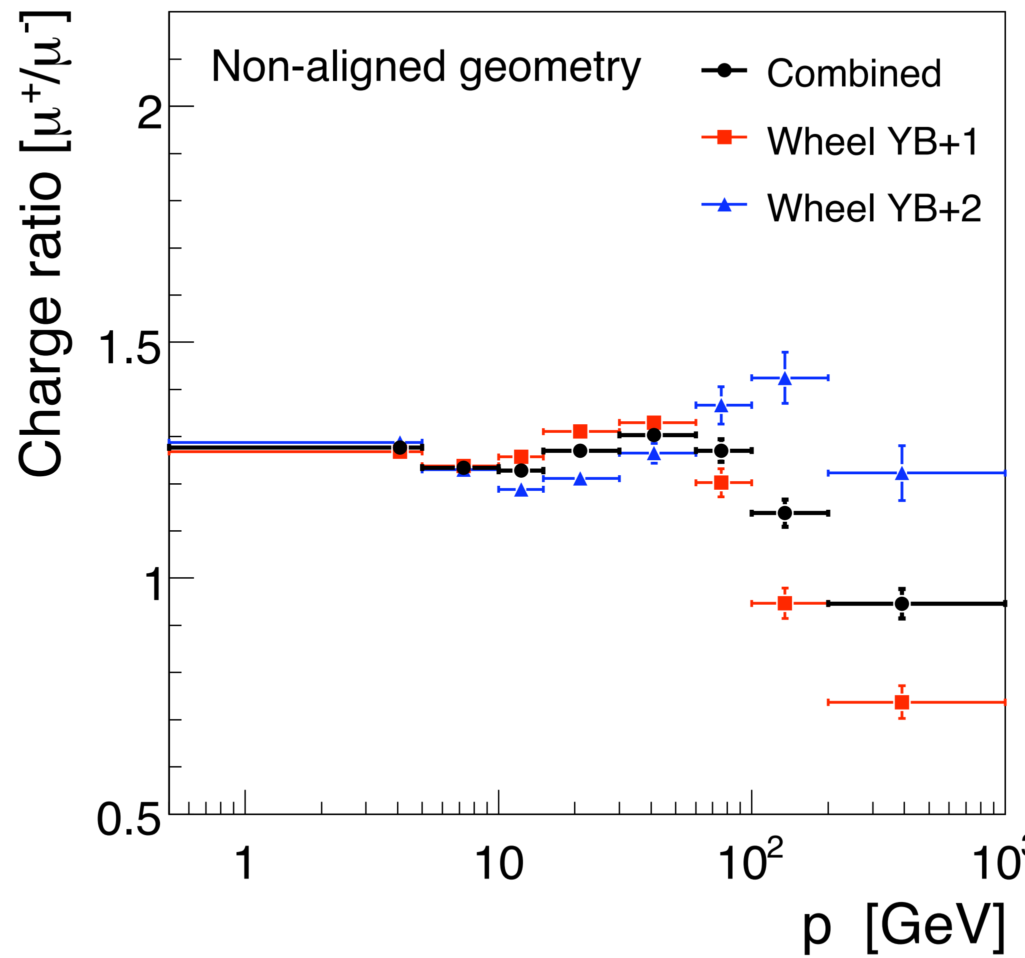


Alignment corrections

Alignment corrections from survey: large discrepancy between two wheels. Consistent with accuracy of parameters: toy MC.

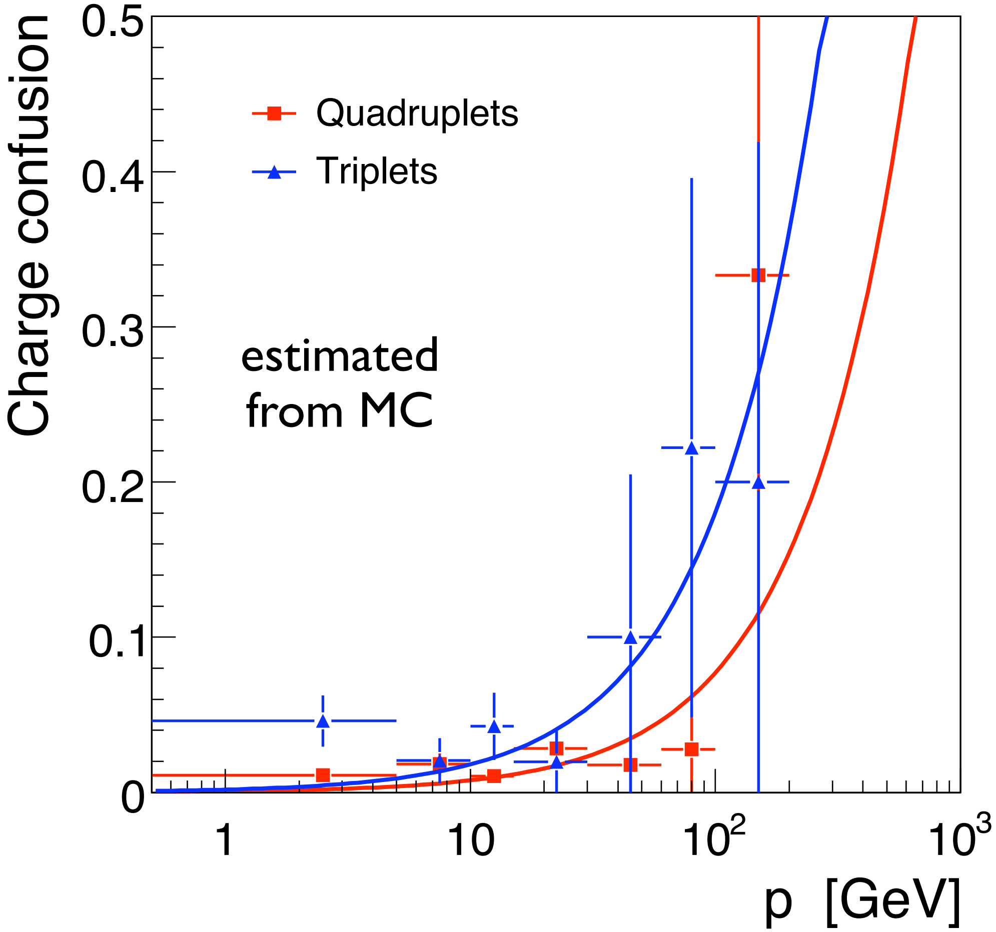


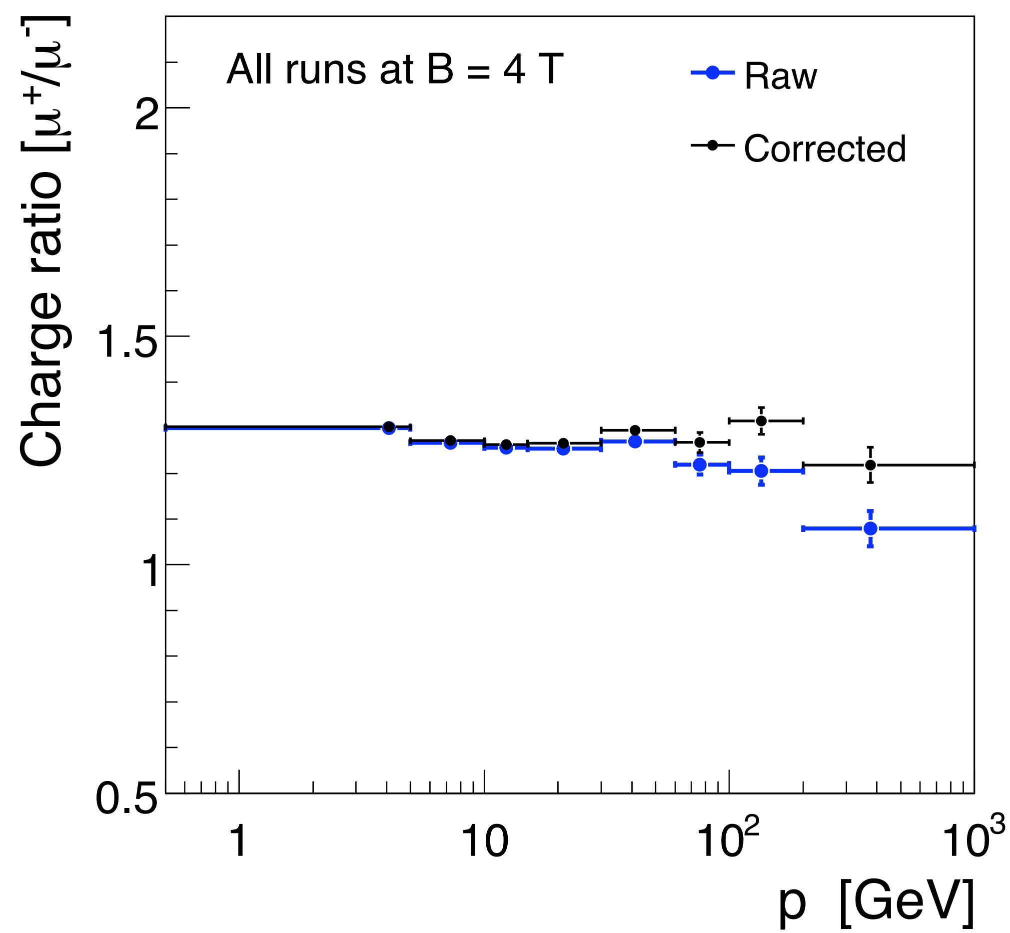


Charge misidentification

Limited detector resolution yields a momentum-dependent charge misidentification probability:

$$N_{\mu^\pm} = (1 - C)\, N^\circ_{\mu^\pm} + C\, N^\circ_{\mu^\mp}, \quad R^\circ = \frac{R - C\,(1+R)}{1 - C\,(1+R)}.$$



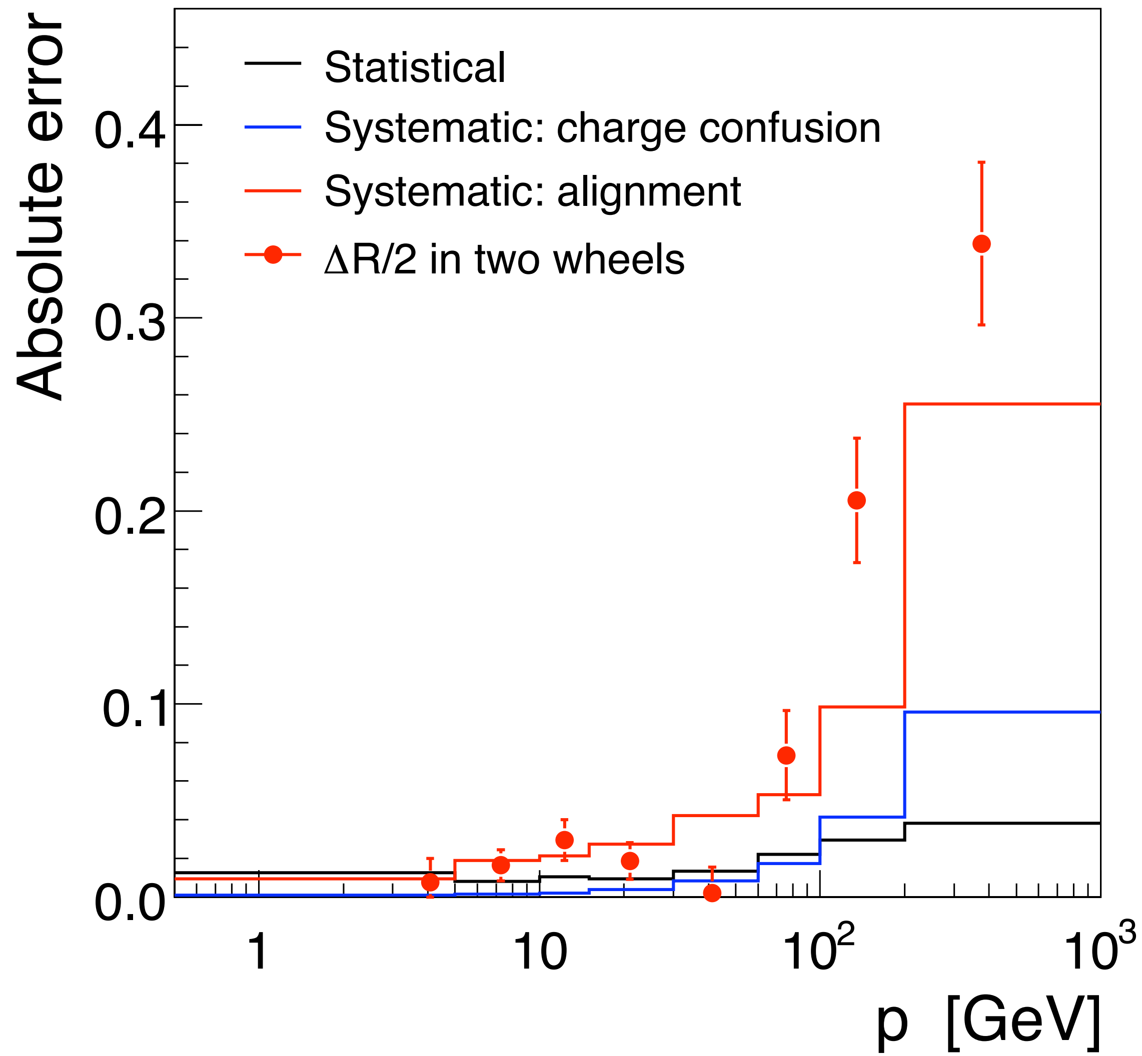


Systematic uncertainties

Systematic uncertainties significantly increase at p_T above 100 GeV/c.

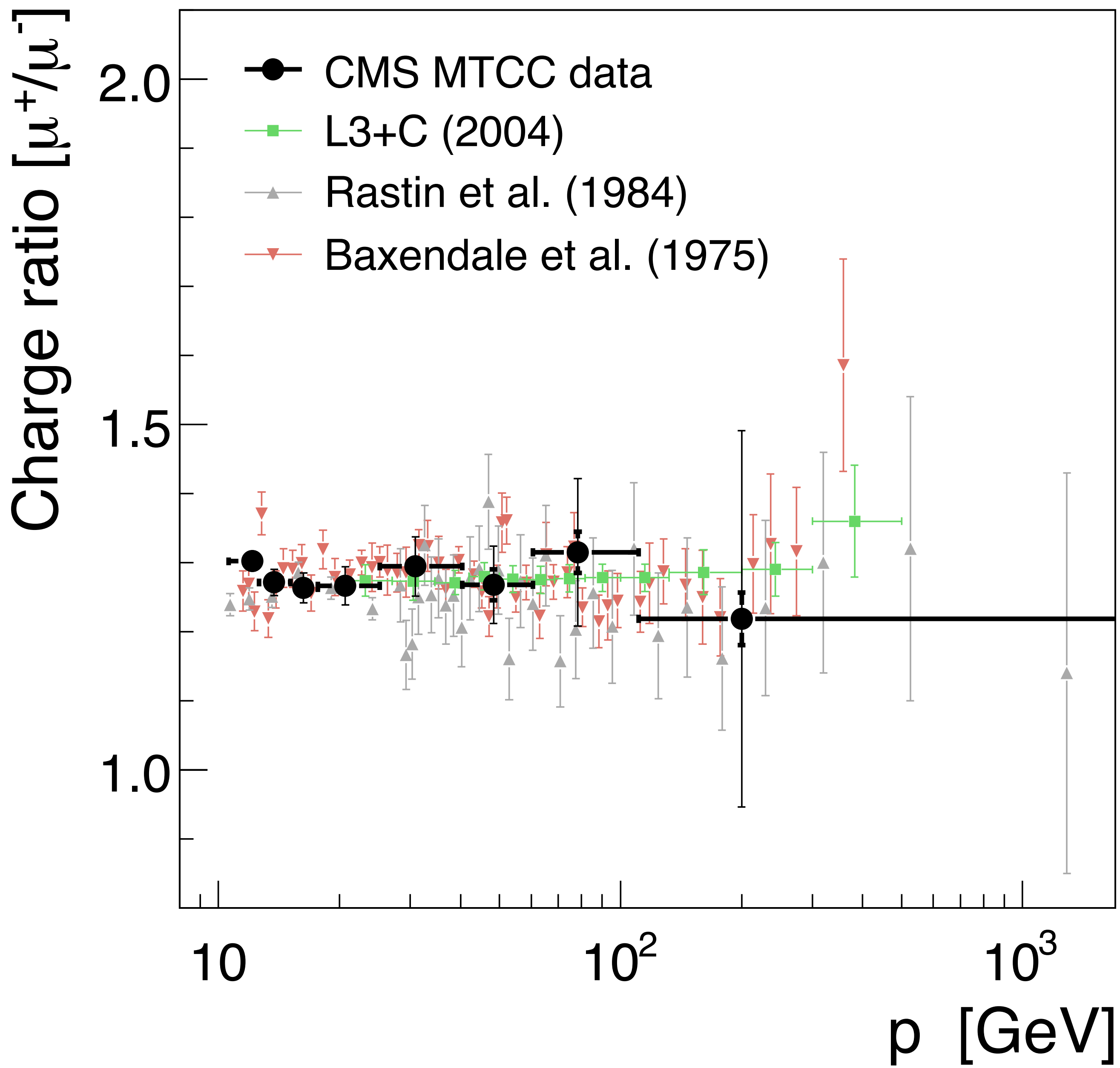
This is consistent with the resolution of the DT chambers, without the vertex constraint (unlike for pp collision data).

During normal operation of CMS, muon tracks *are* reconstructed with much higher accuracy and precision: tracker, vertex.



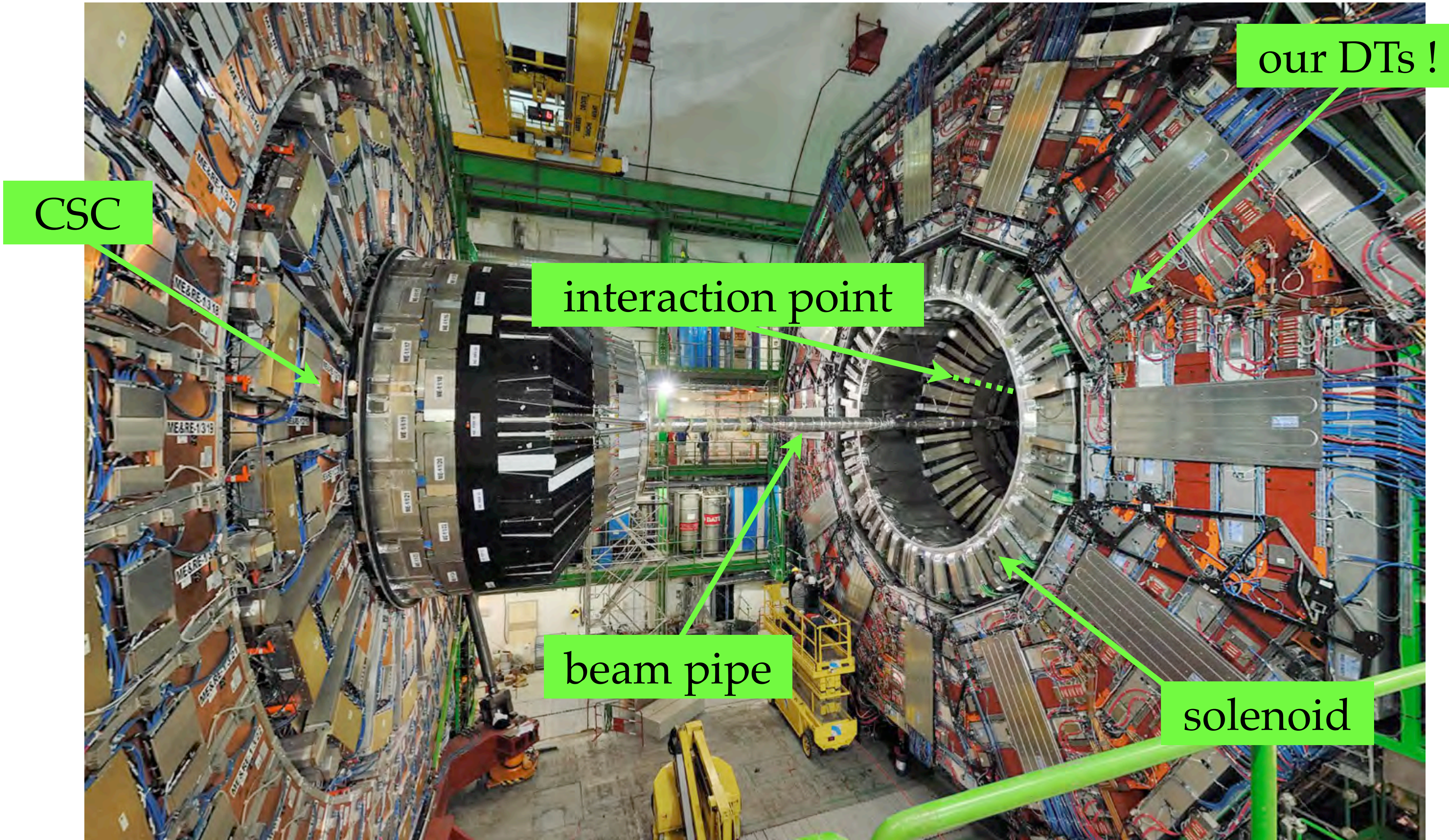
Measurement of R°

- The CMS result compares to results from other experiments.
- Large systematic uncertainties at high momentum.
- Crucial for understanding and verifying alignment of muon chambers.
- Ph.D. thesis of M. Aldaya, CMS NOTE 2008/016.

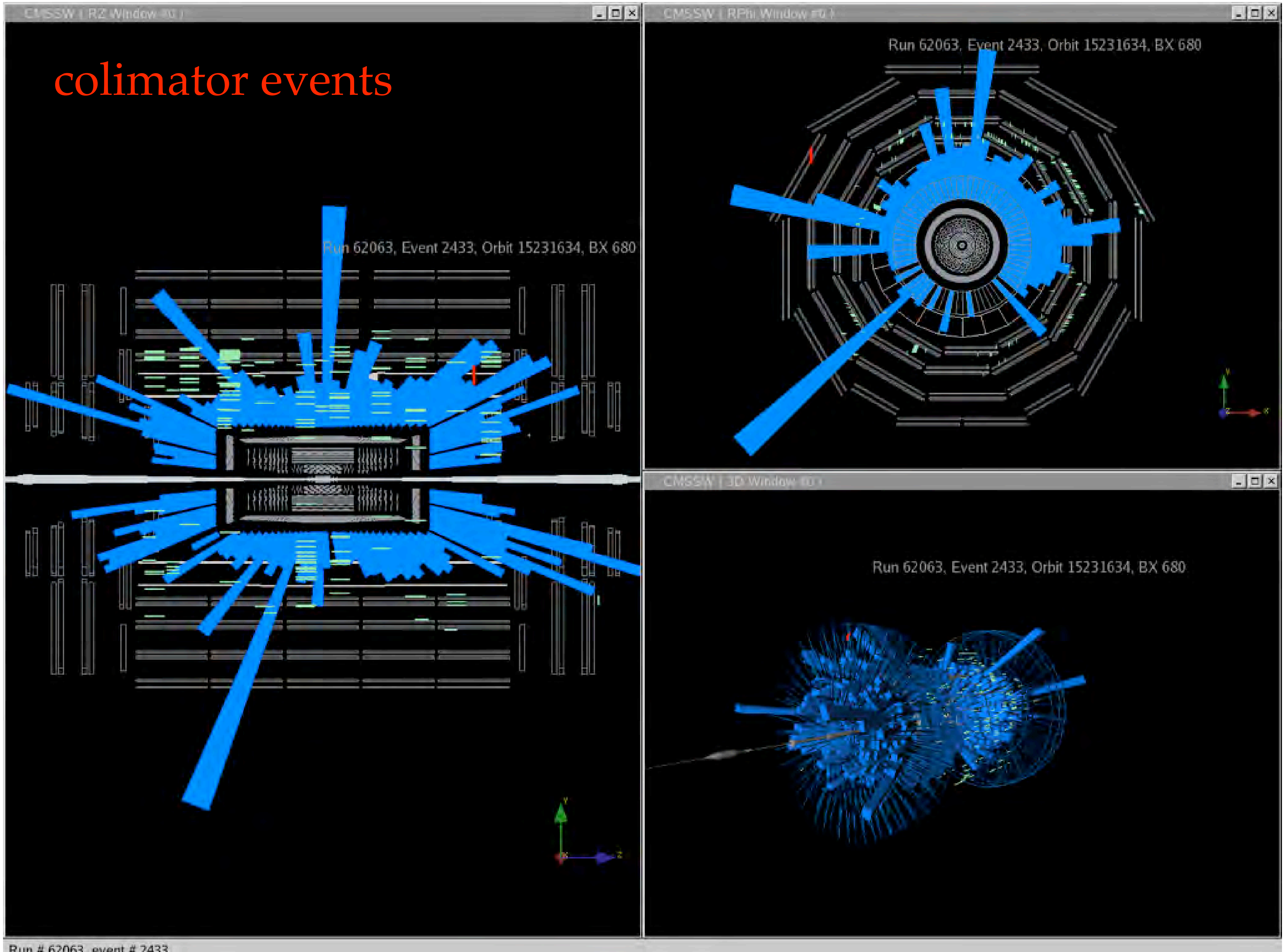


CMS in August '08

Detector complete and installed in the P5 experimental area since Aug. '08



First LHC beams on Sep. 10



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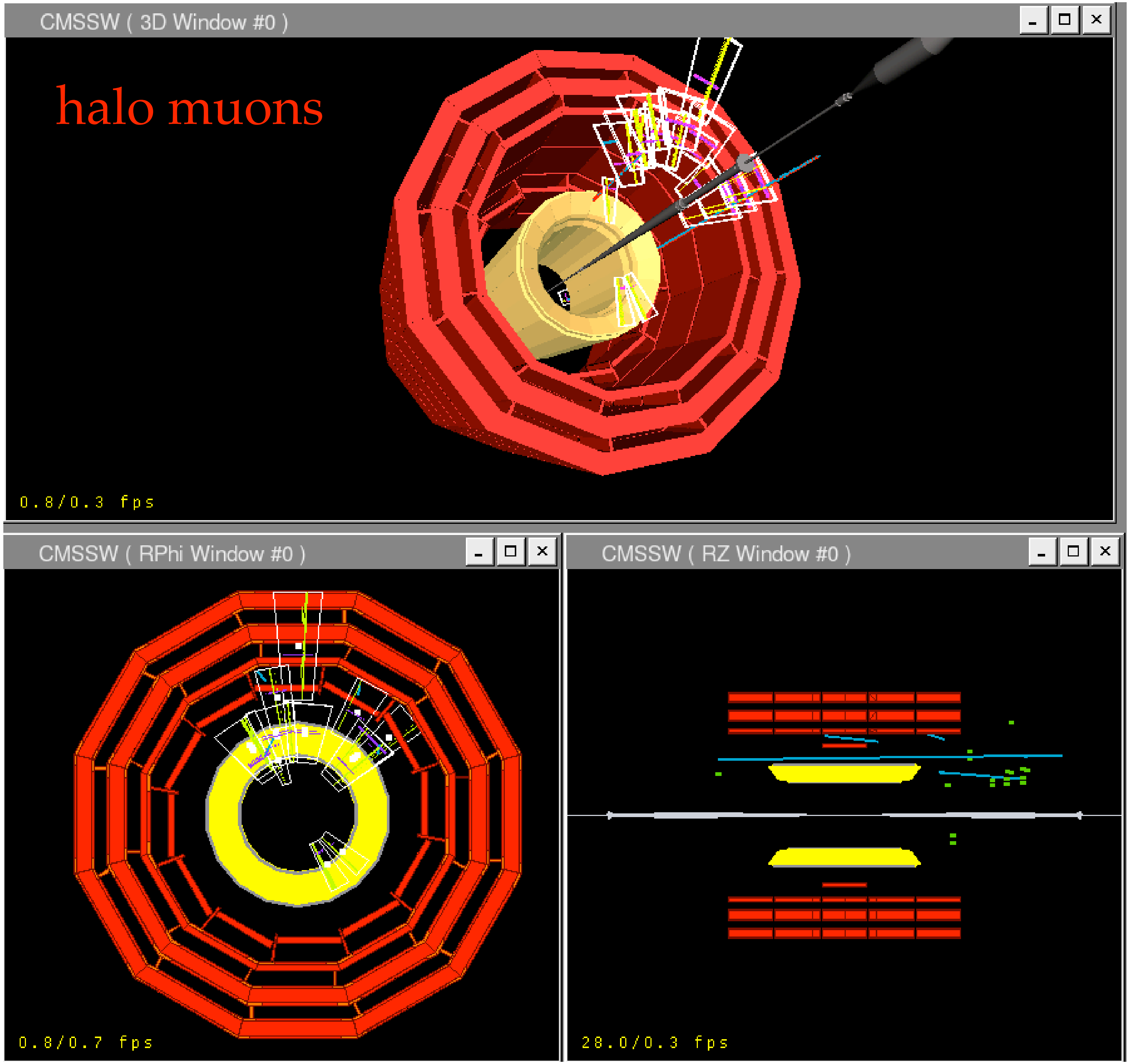


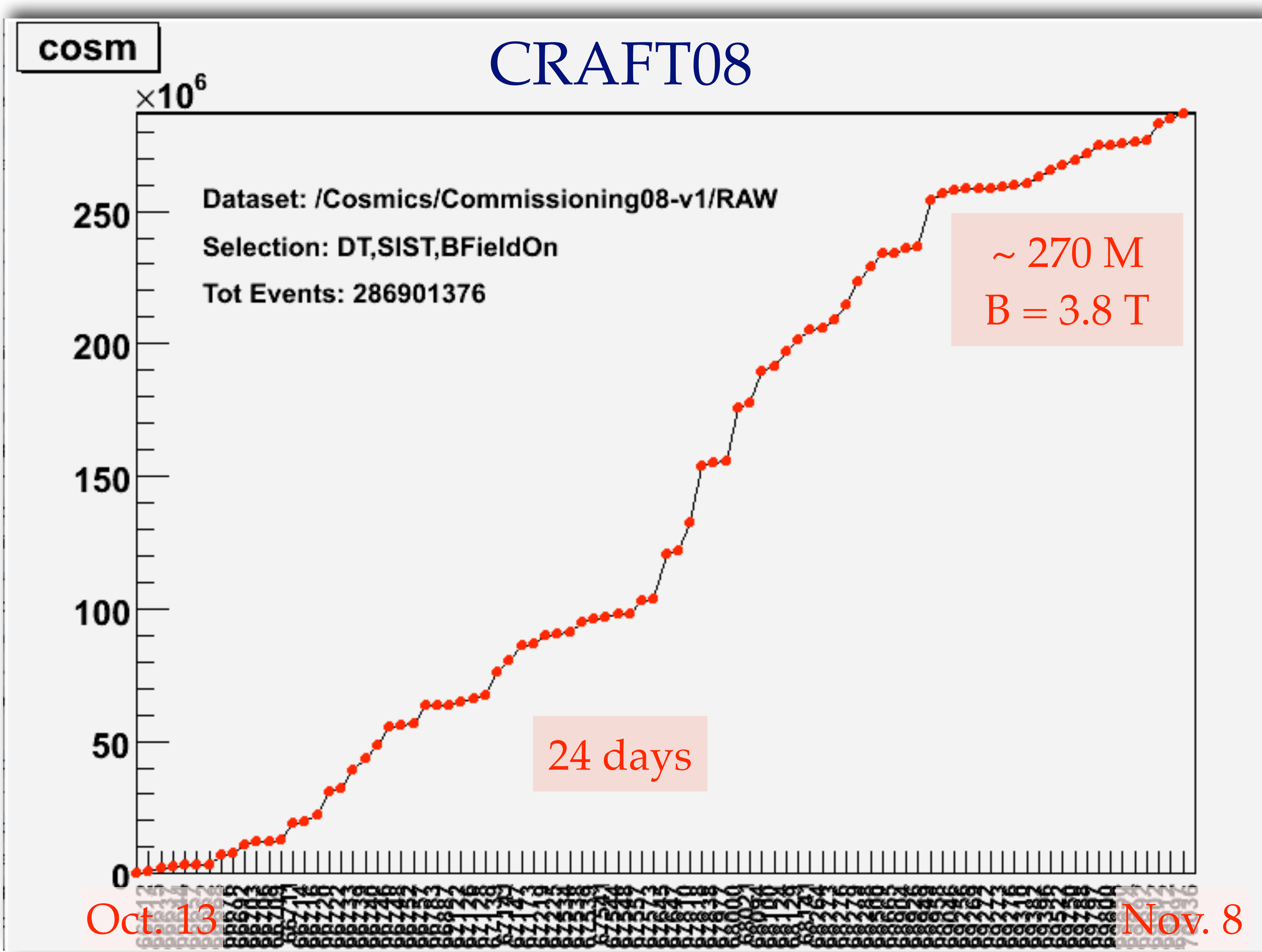
Incident at the LHC

Sep. 19: “faulty electrical connection between two of the accelerator’s magnets. This resulted in mechanical damage and release of helium from the magnet cold mass into the tunnel”.

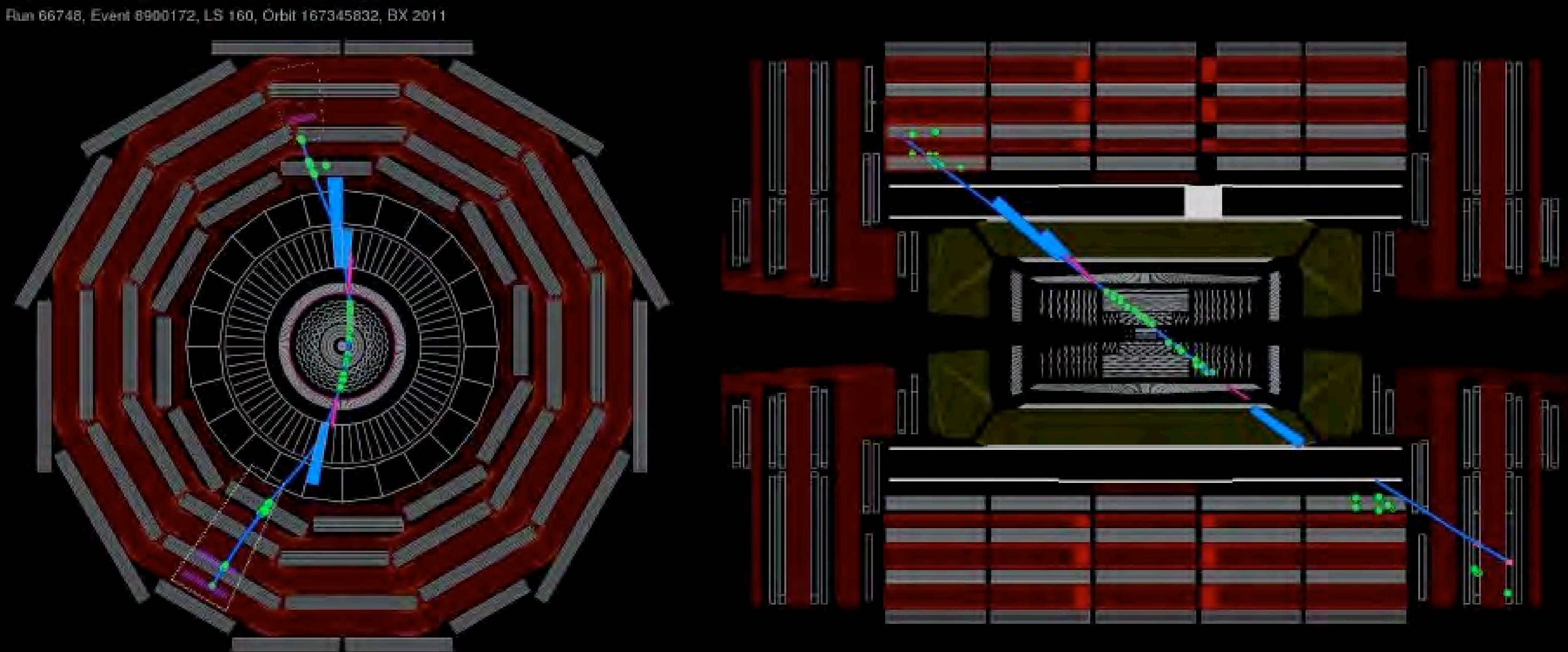
New plans of CMS

- LHC will restart on fall 2009...
- CMS closed and ready for beam September ’09.
- In the mean time, keep CMS alive, up and running:
  - commissioning of magnet, hardware (DAQ, L1, DQM) and software (HLT, reconstruction),
  - conditions workflows → alignment and calibration.
- Cosmic muon runs, with full detector operational.

Cosmics runs at 4 T

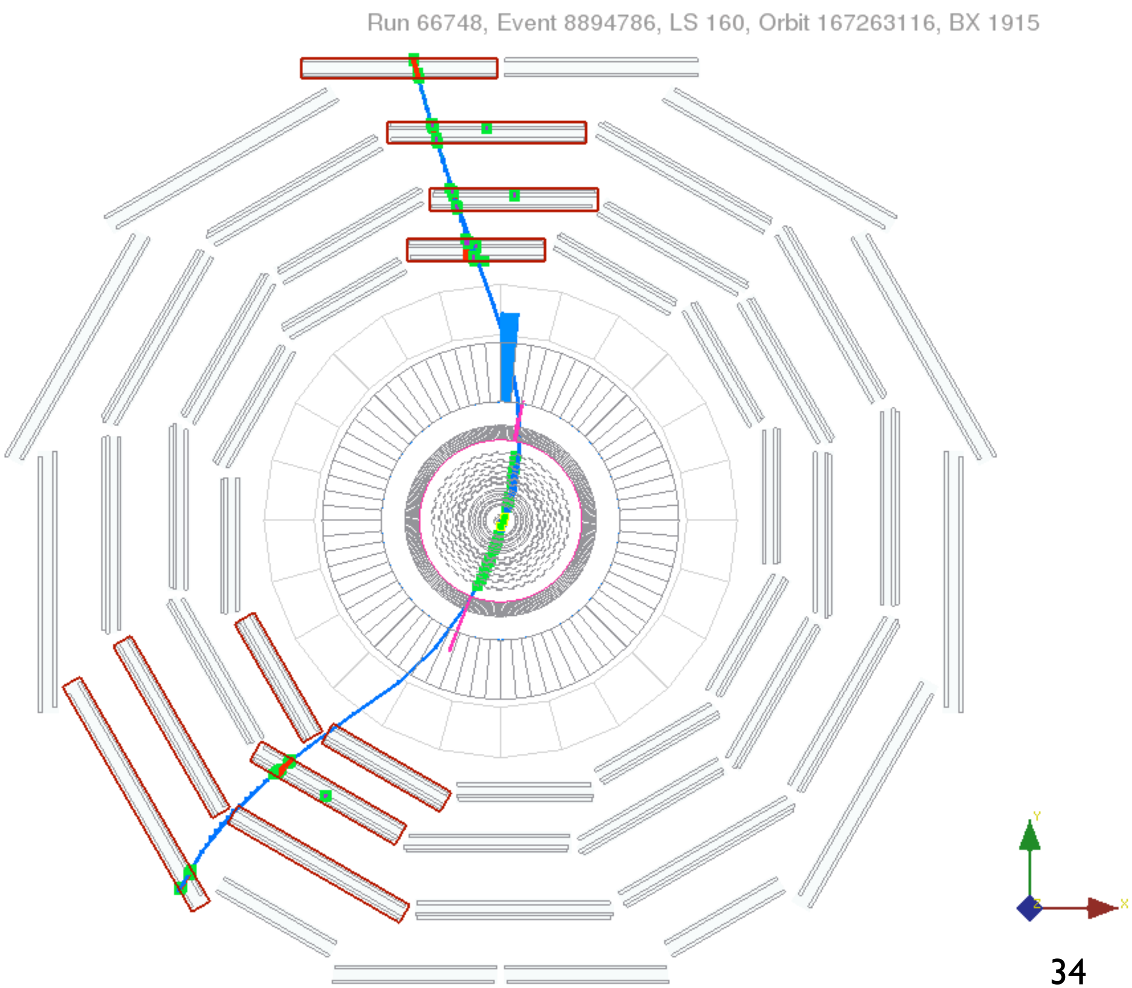


Typical cosmic muon event



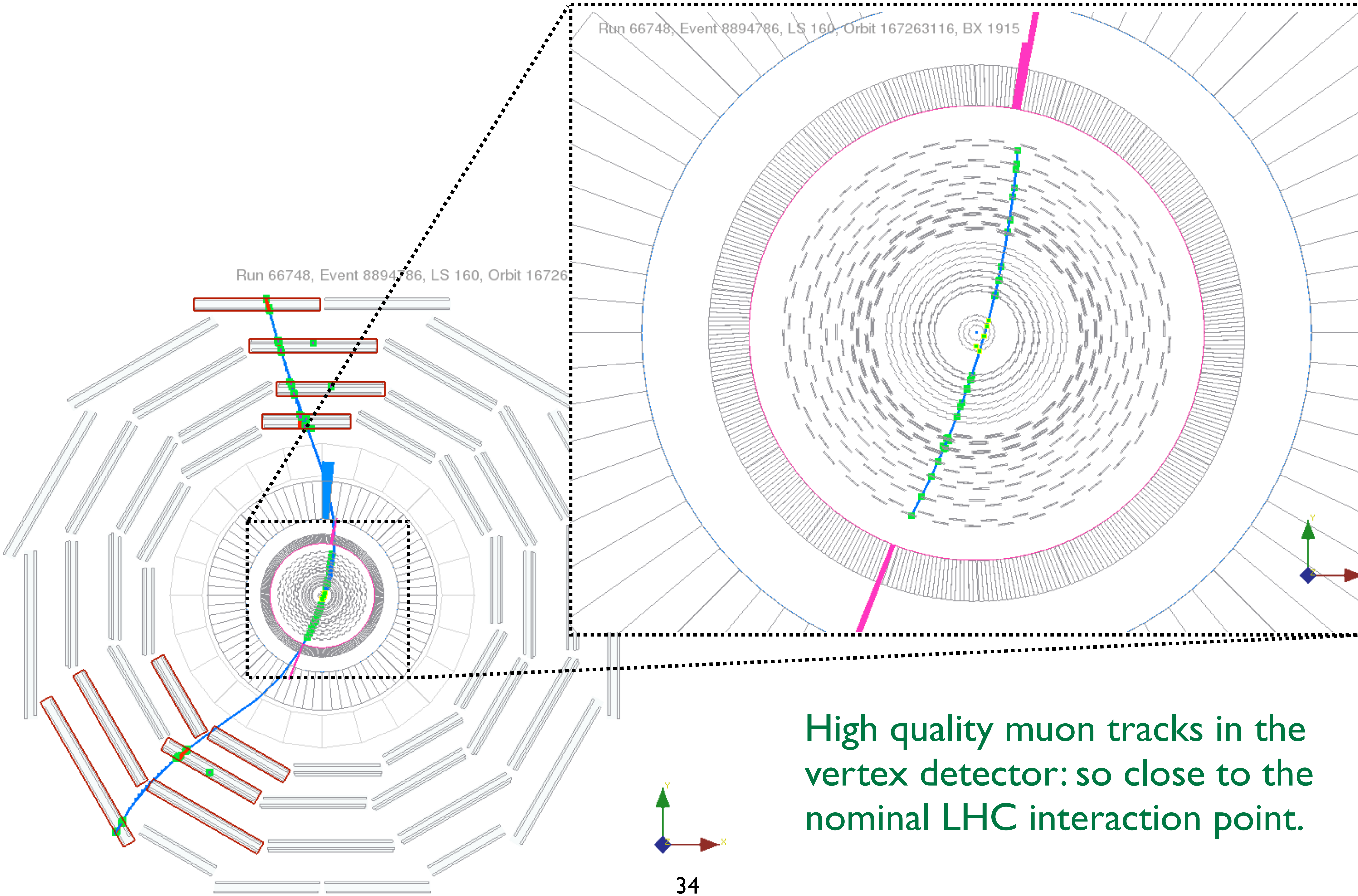
High quality muon tracks in all subdetectors, similar to those expected from pp interactions.

Detail of a tracker track



High quality muon tracks in the vertex detector: so close to the nominal LHC interaction point.

Detail of a tracker track



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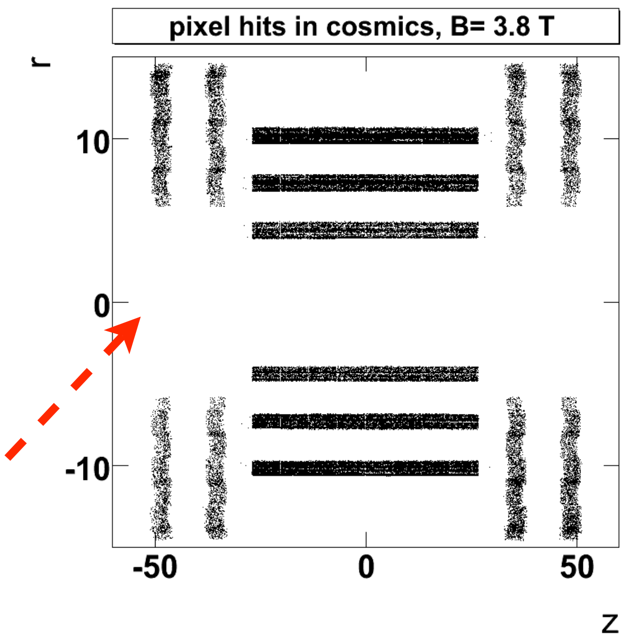
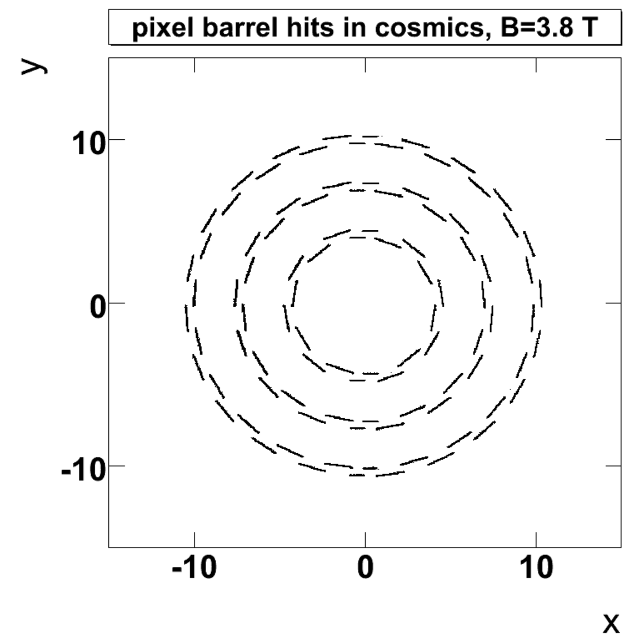
Tracker occupancy map

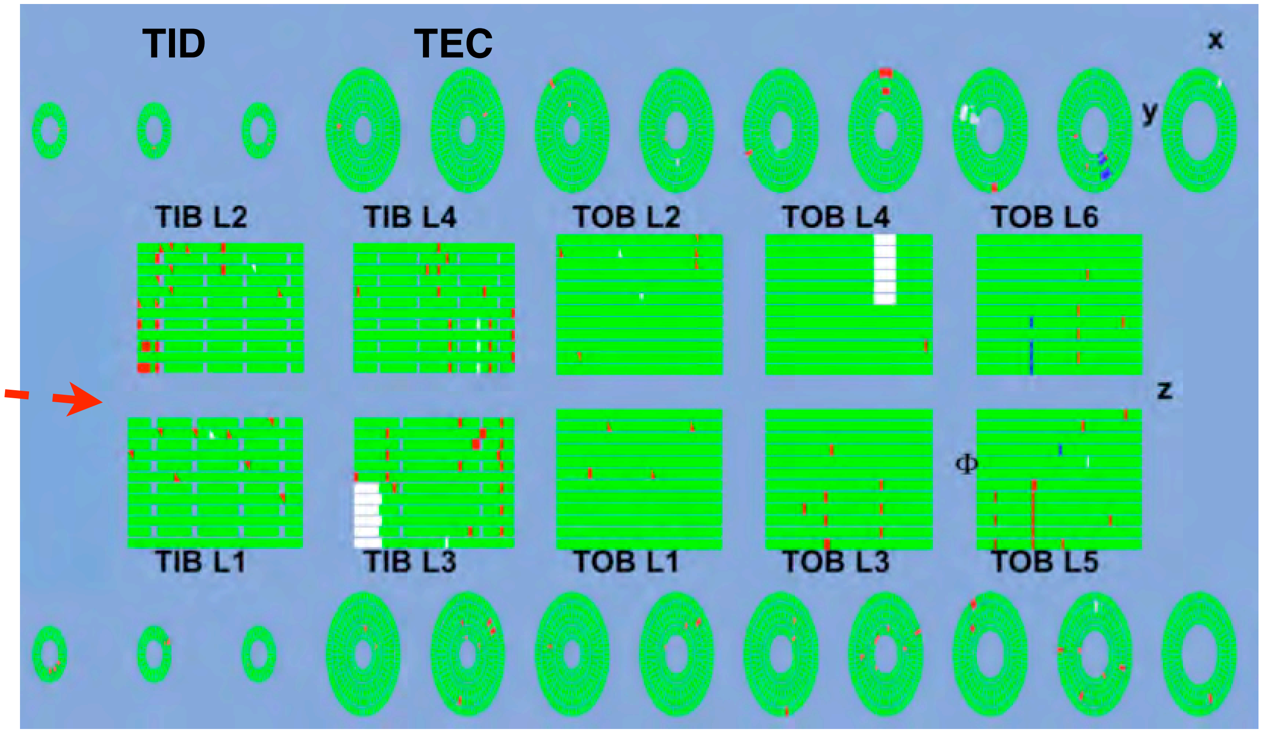
Large number of cosmic muons allows us to probe the whole detector.

Pixel detector

Silicon tracker

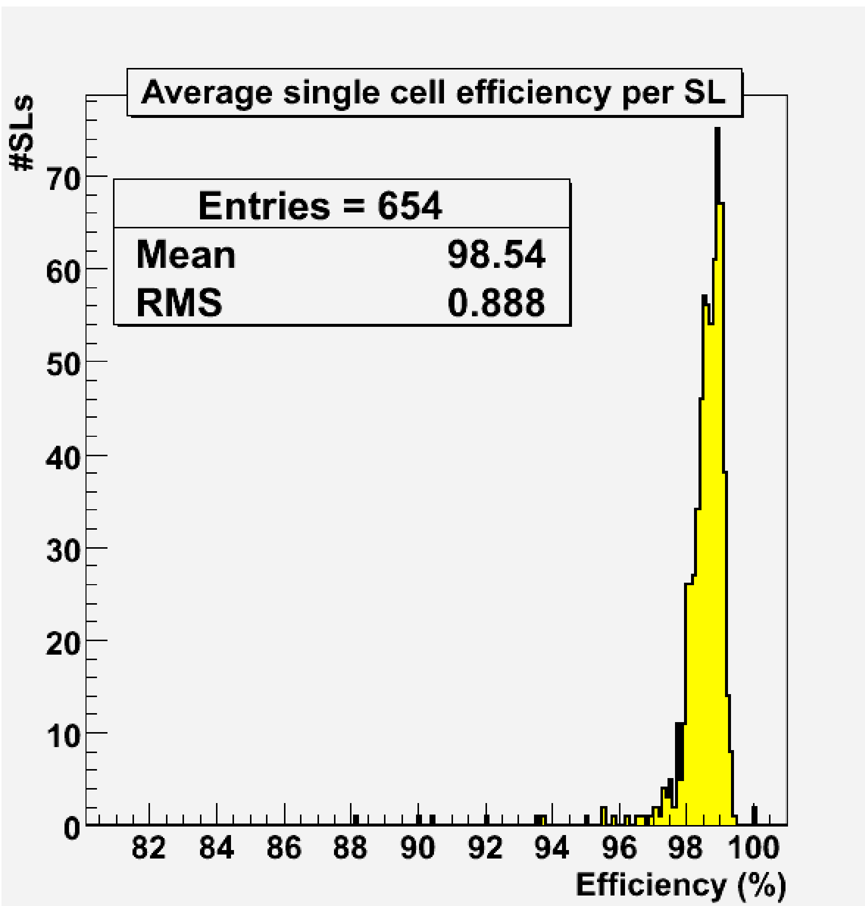


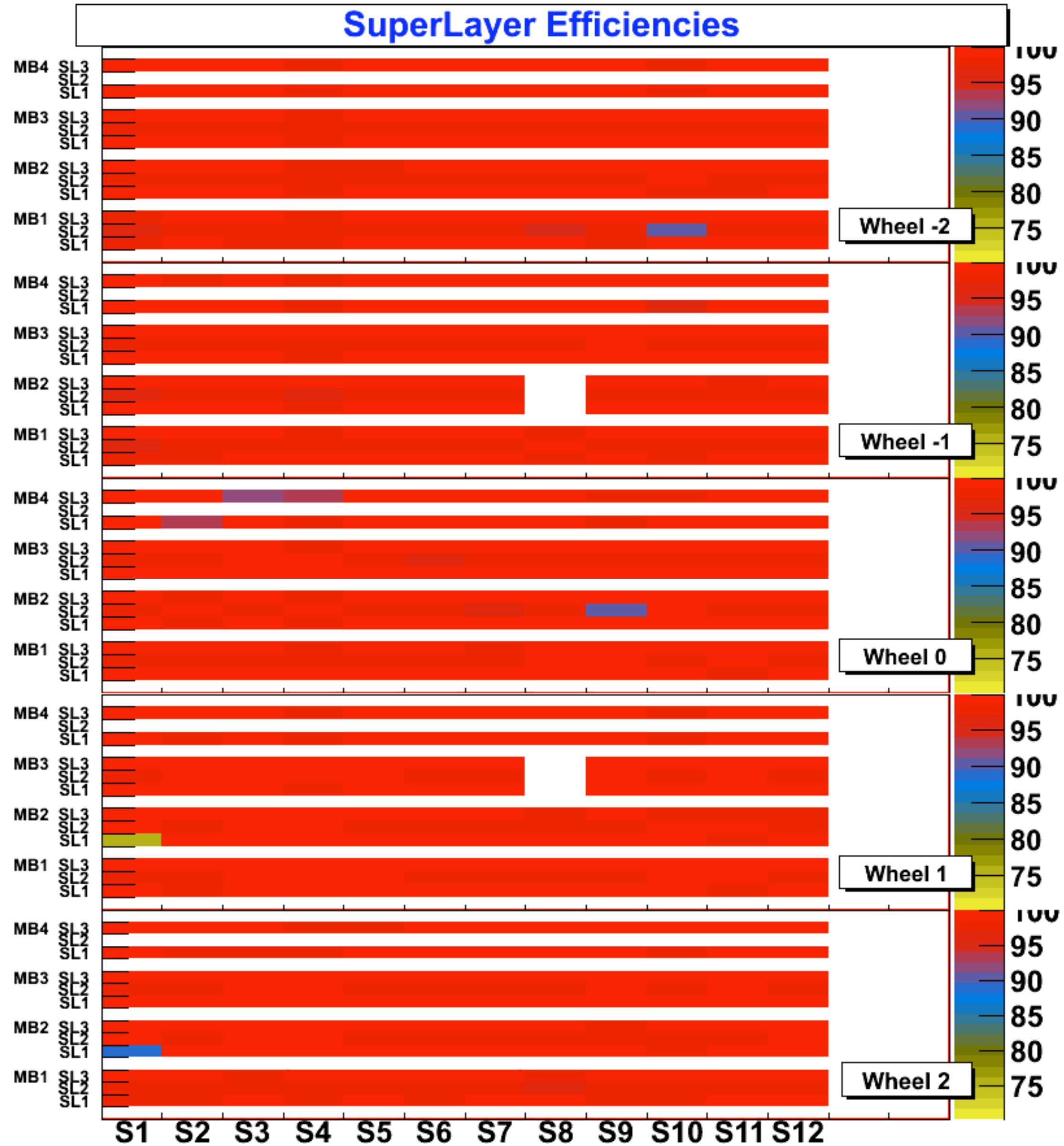




DT (muon) cell efficiency

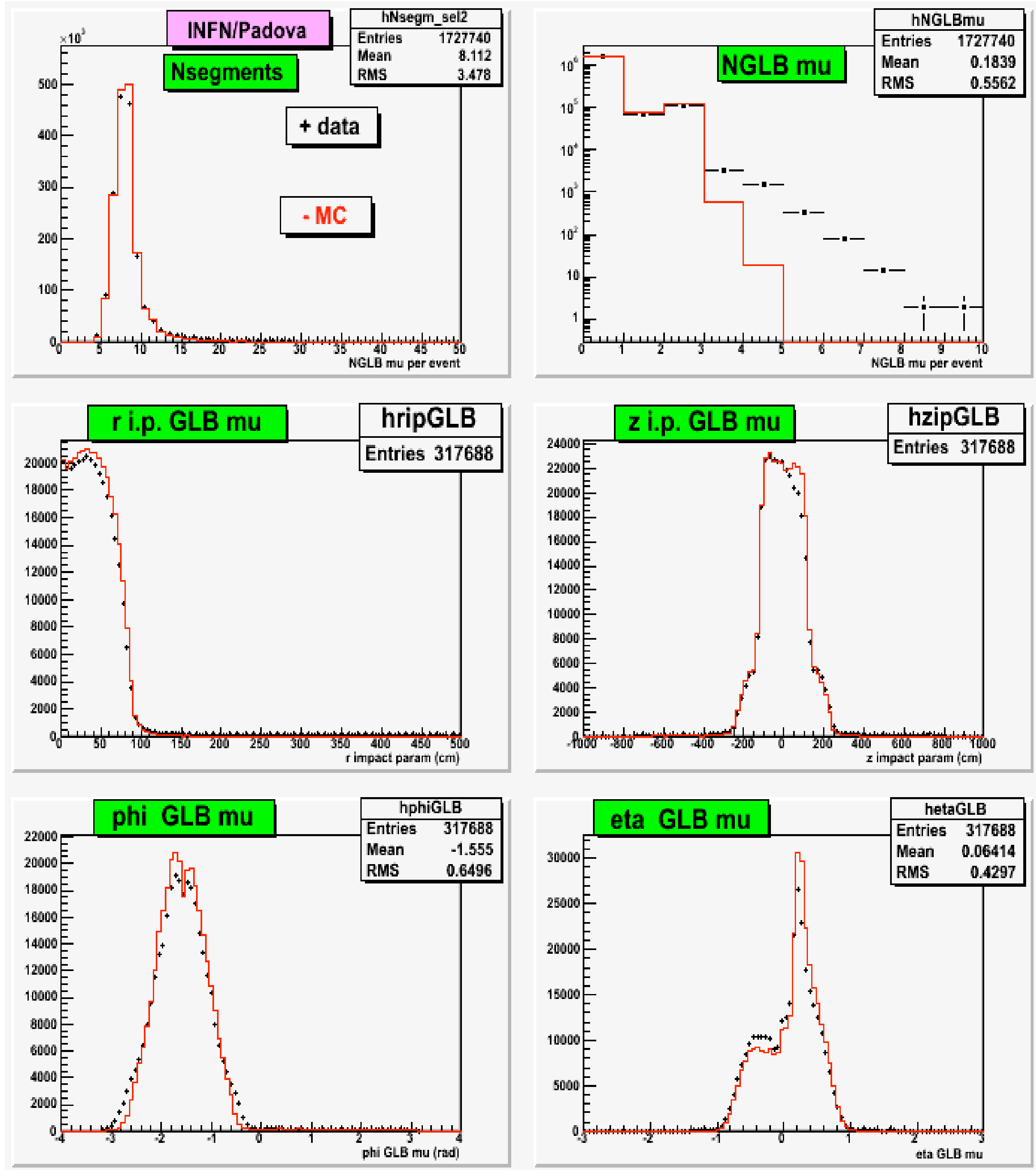
High efficiency of the muon detector: above 98 %





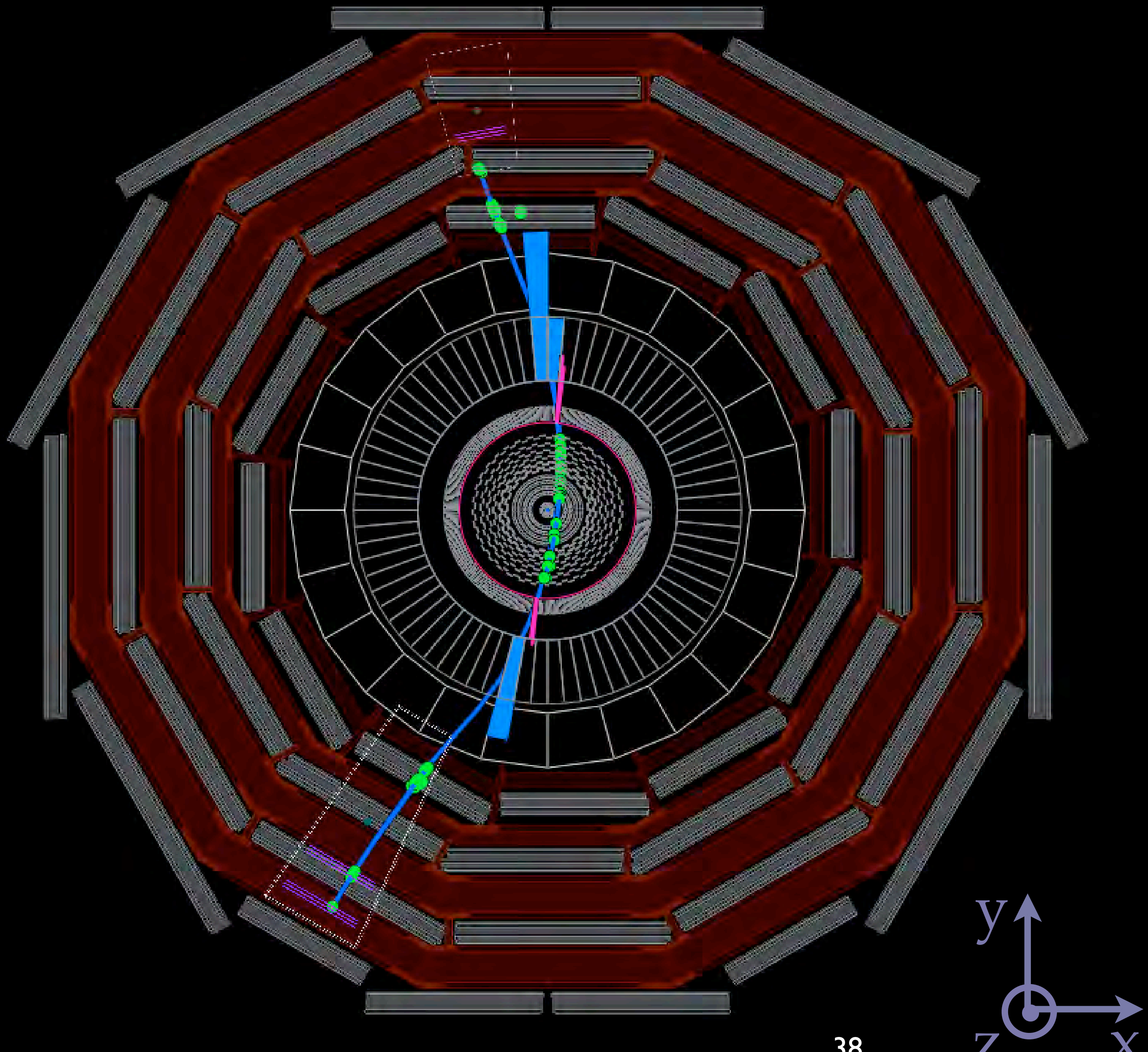
Data vs. simulations in barrel

- Very simple muon selection.
- Plots normalized to the number of selected events.
- Simulation does not include multiple muon events.
- Overall good agreement.



pp-like muon event

⊙ B



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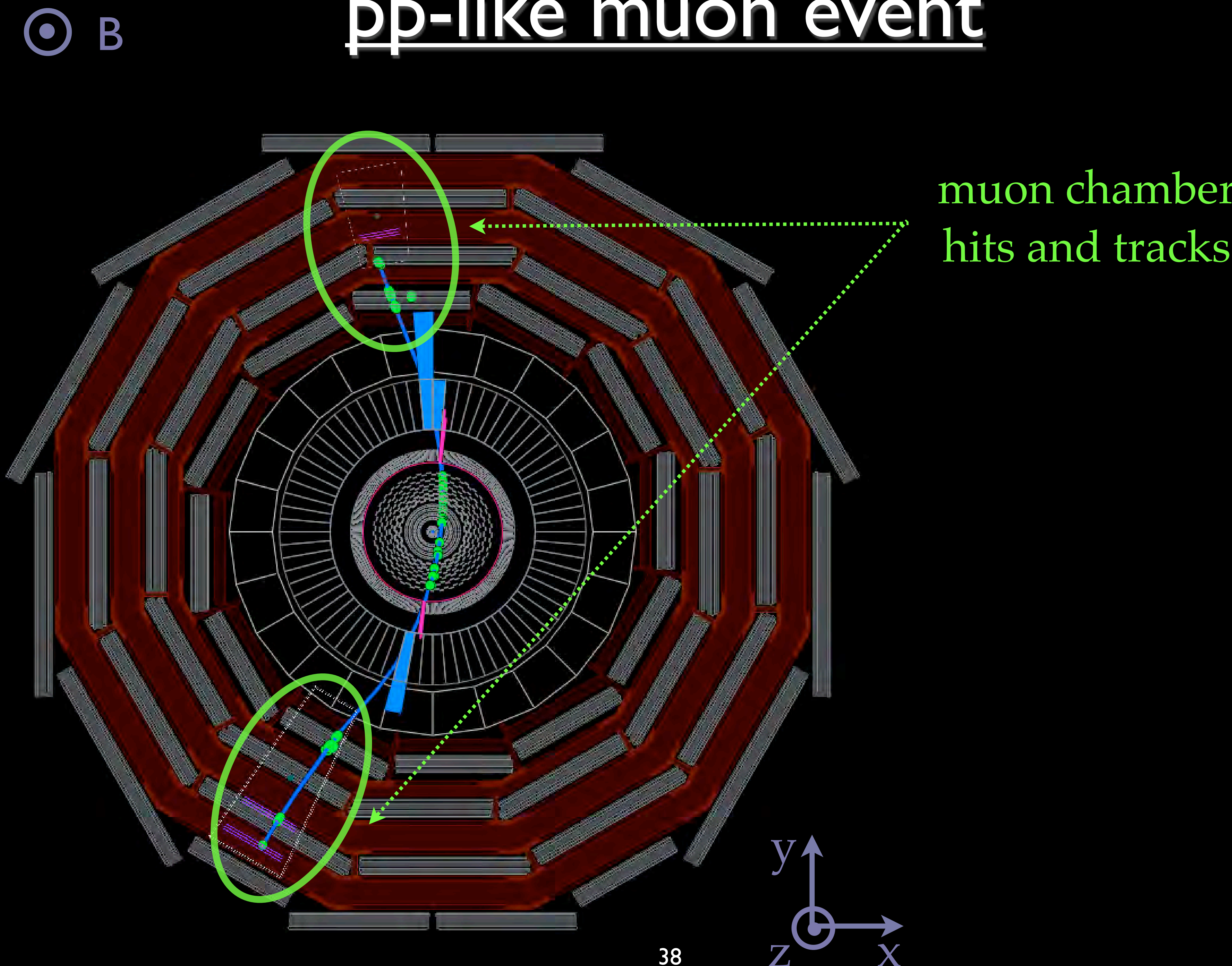

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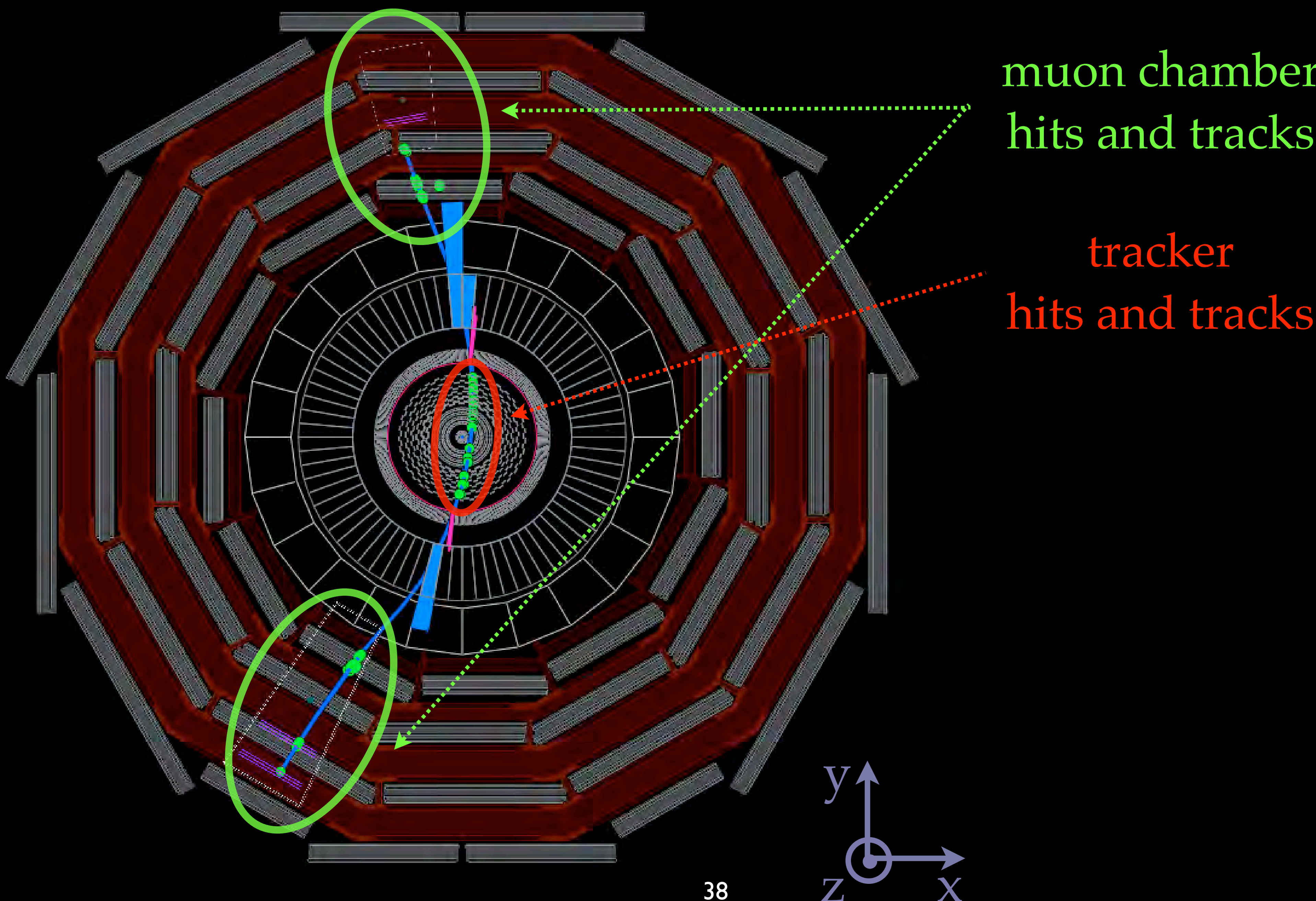

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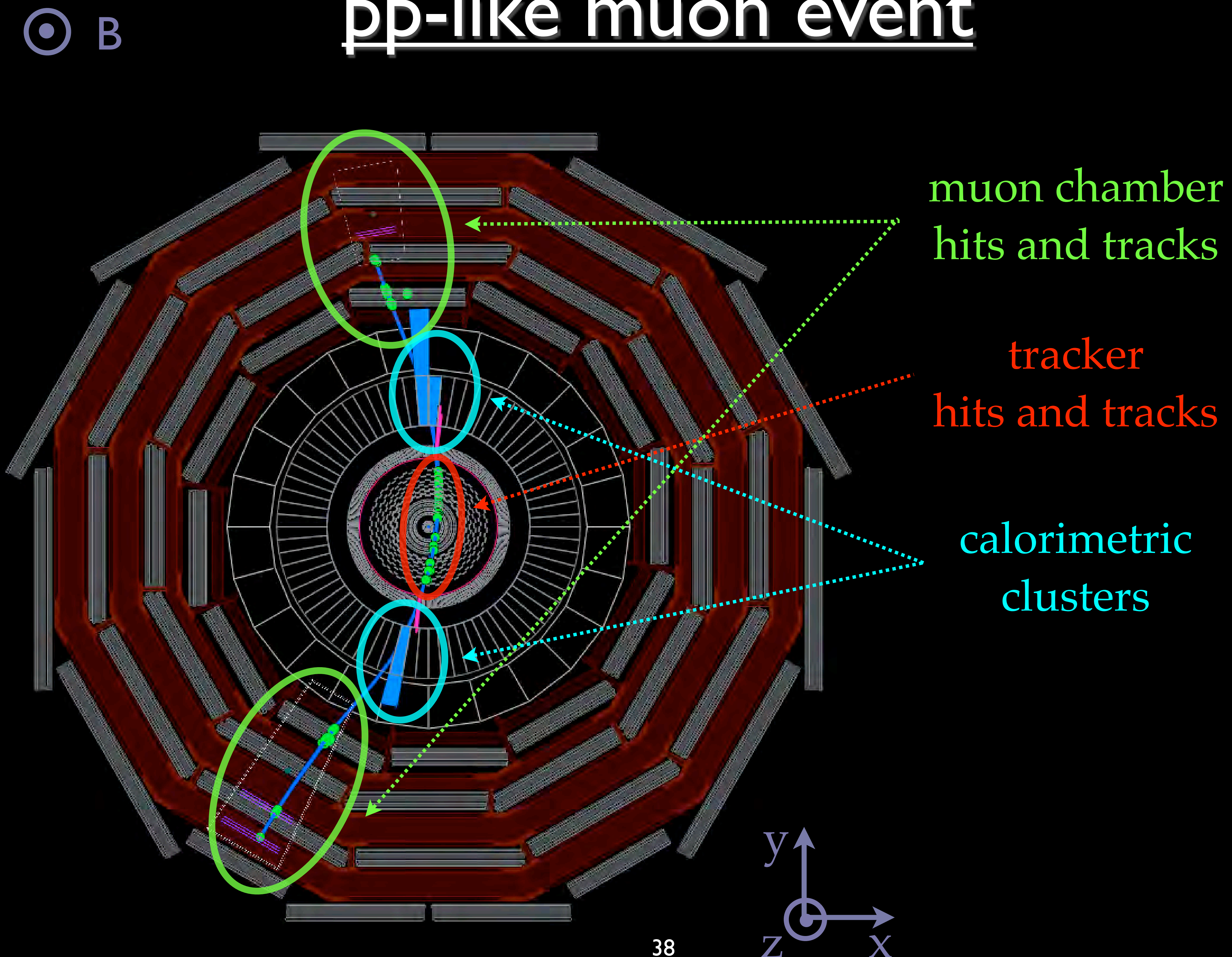

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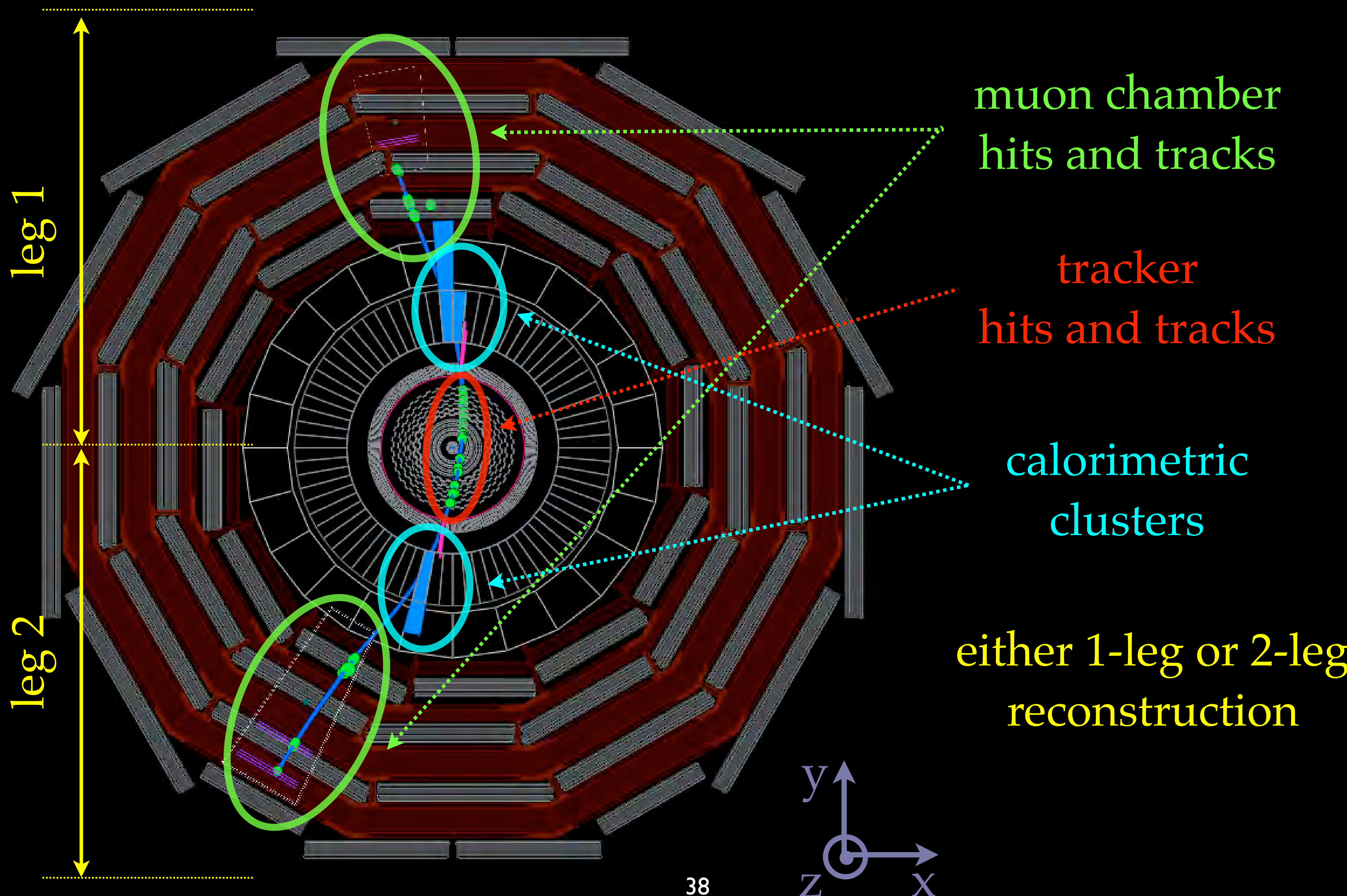
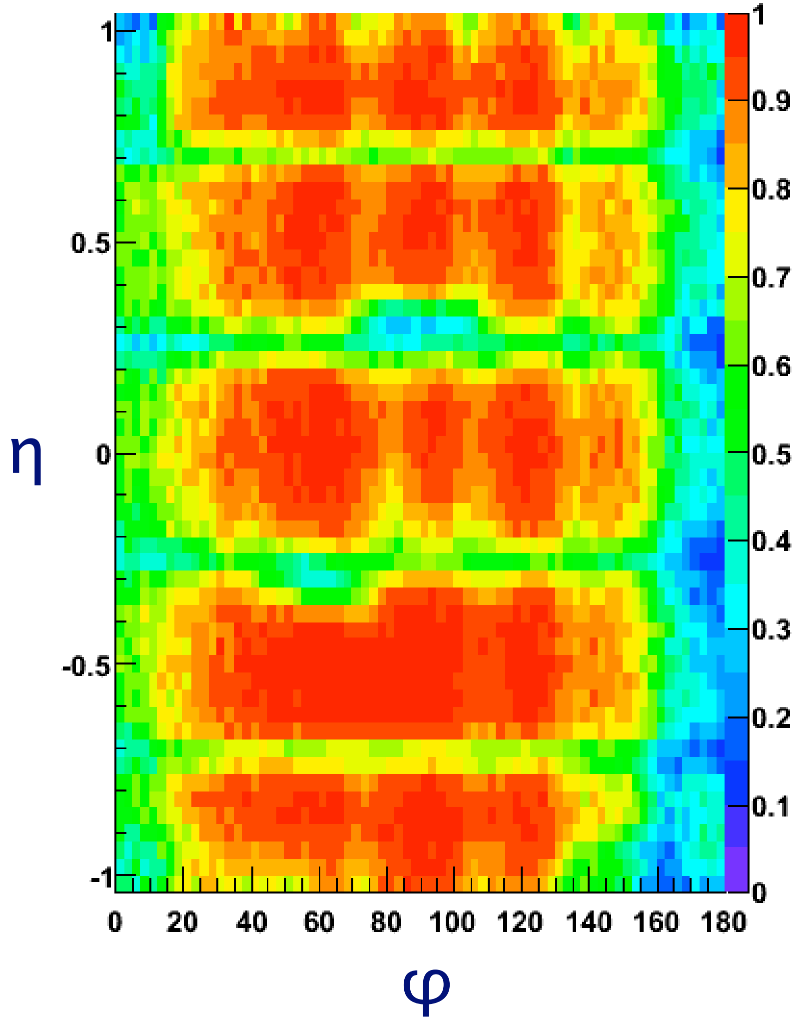
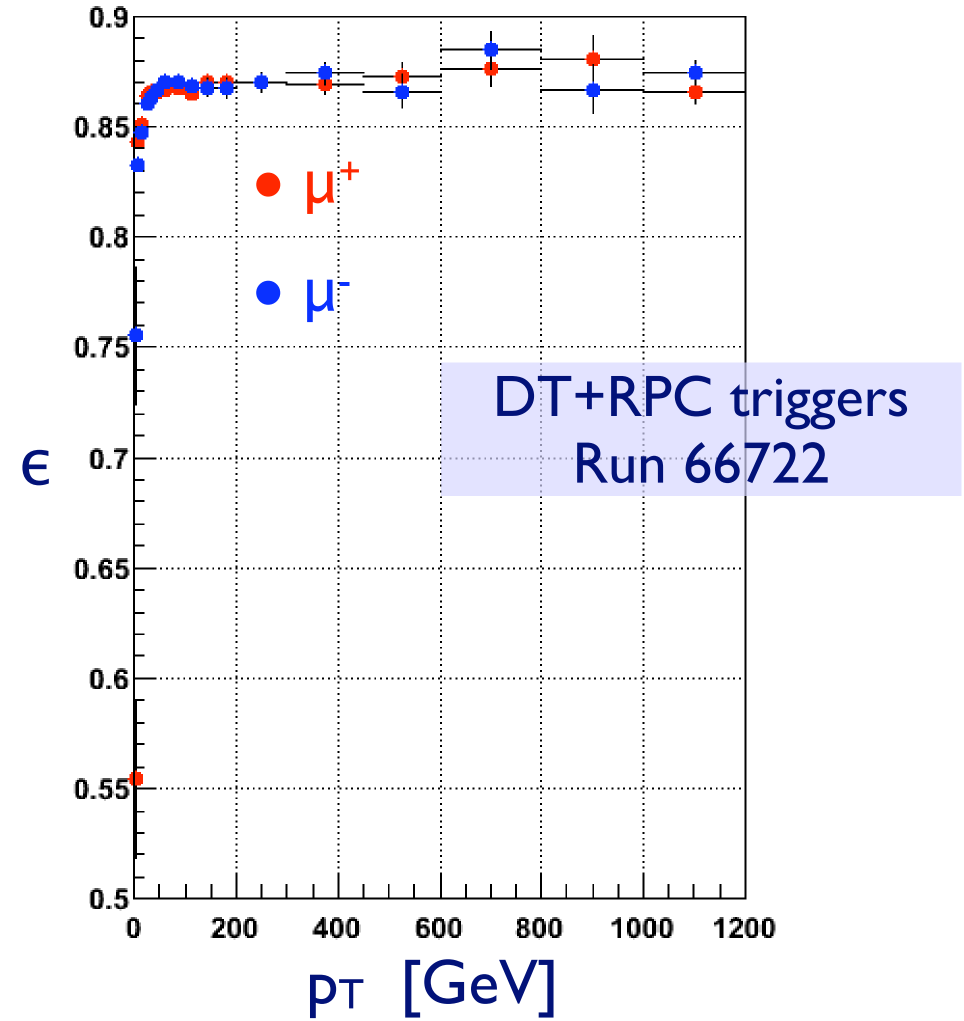


L1 muon trigger efficiency

Measured vs. p_T using tag and probe, standalone or tracker muons.





Very high trigger efficiency. Most inefficiencies have local character: chimneys, wheel gaps.

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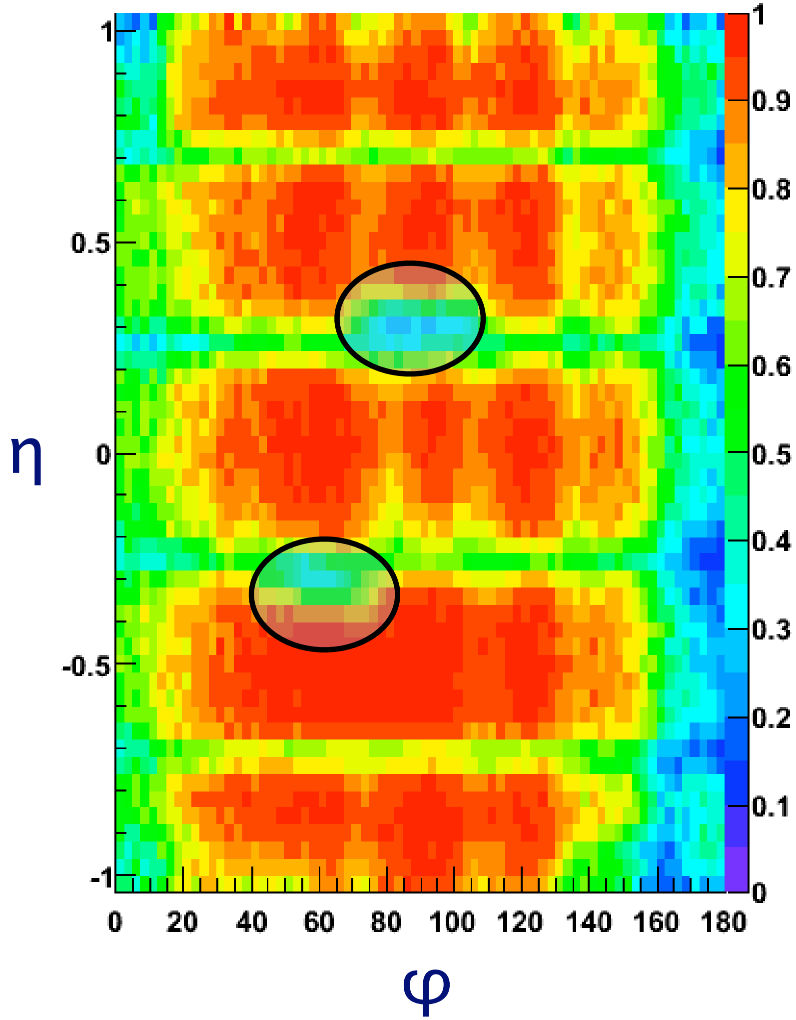
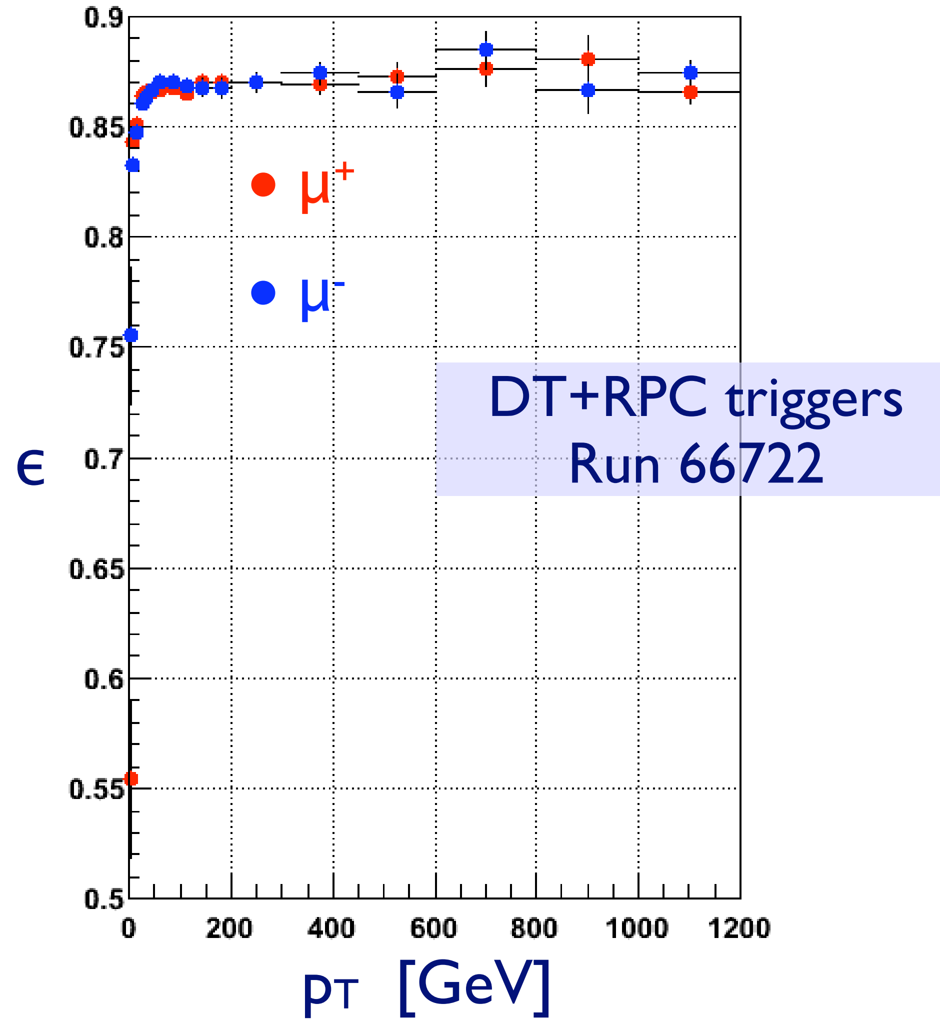
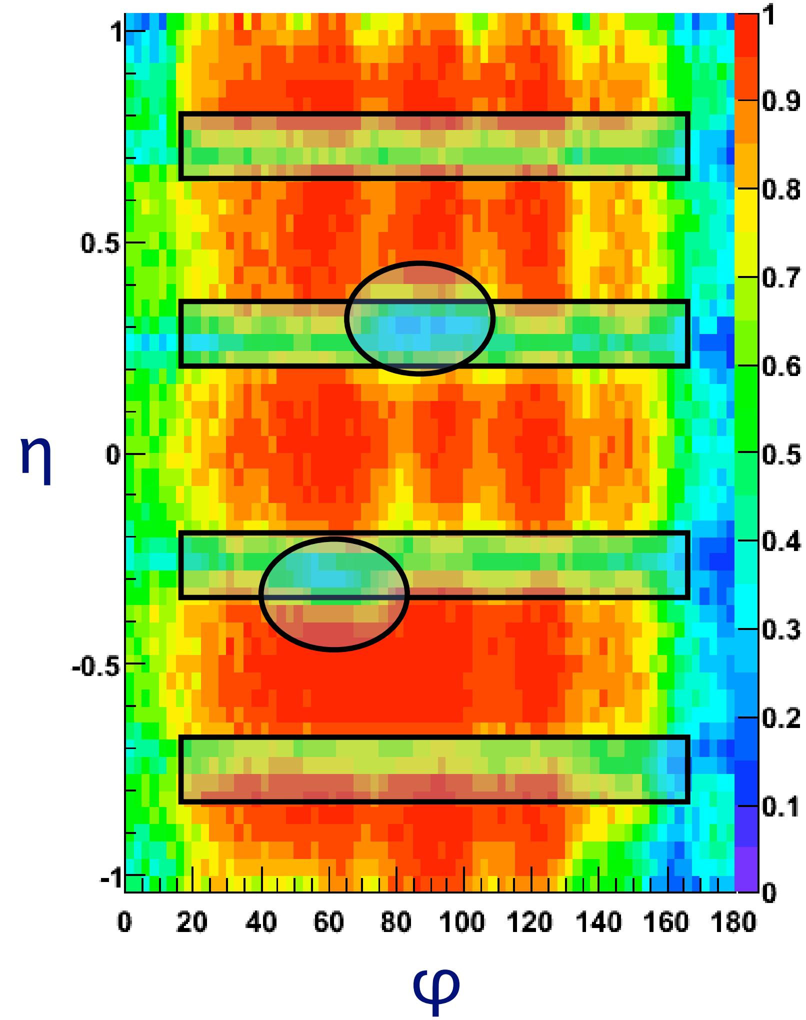


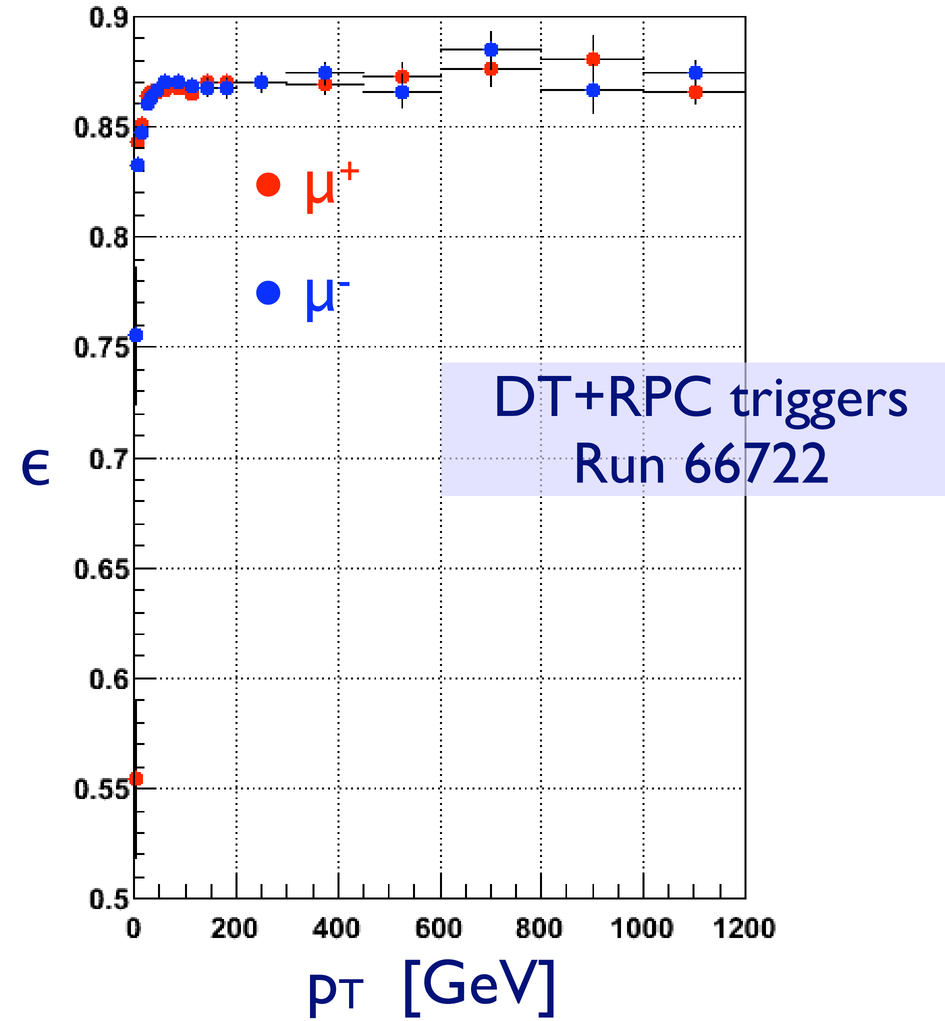


Very high trigger efficiency. Most inefficiencies have local character: chimneys, wheel gaps.

L1 muon trigger efficiency

Measured vs. p_T using tag and probe, standalone or tracker muons.

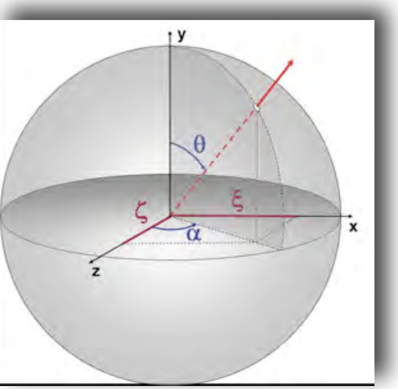


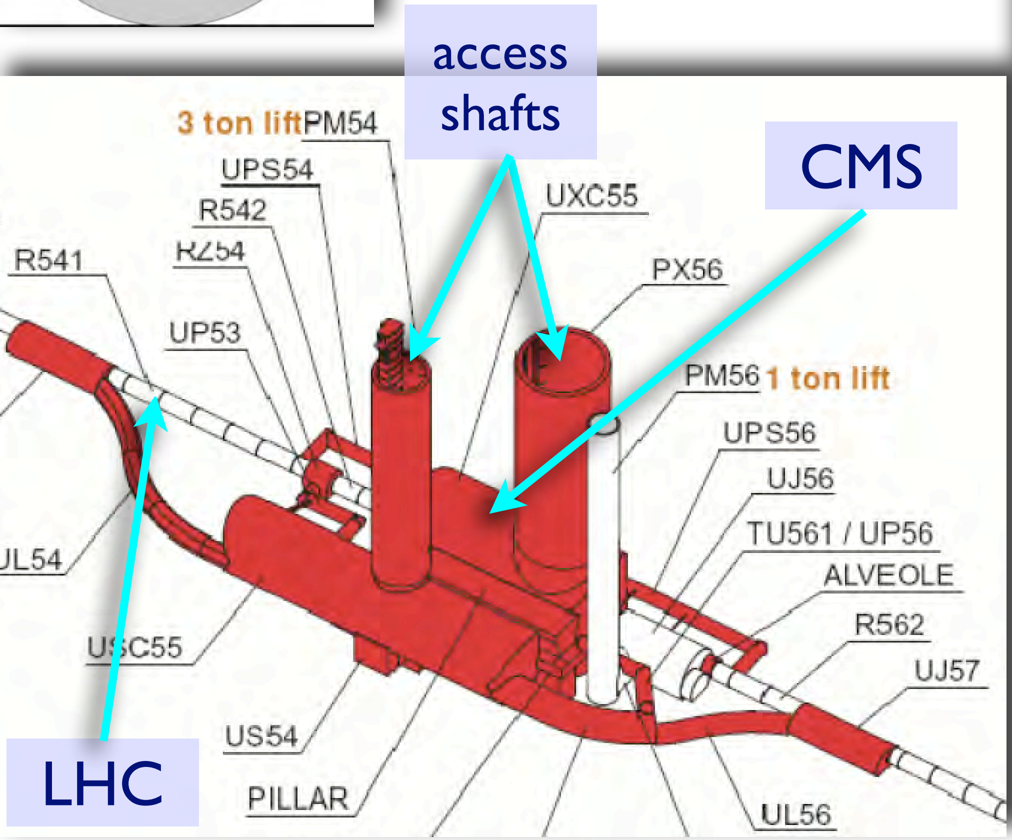


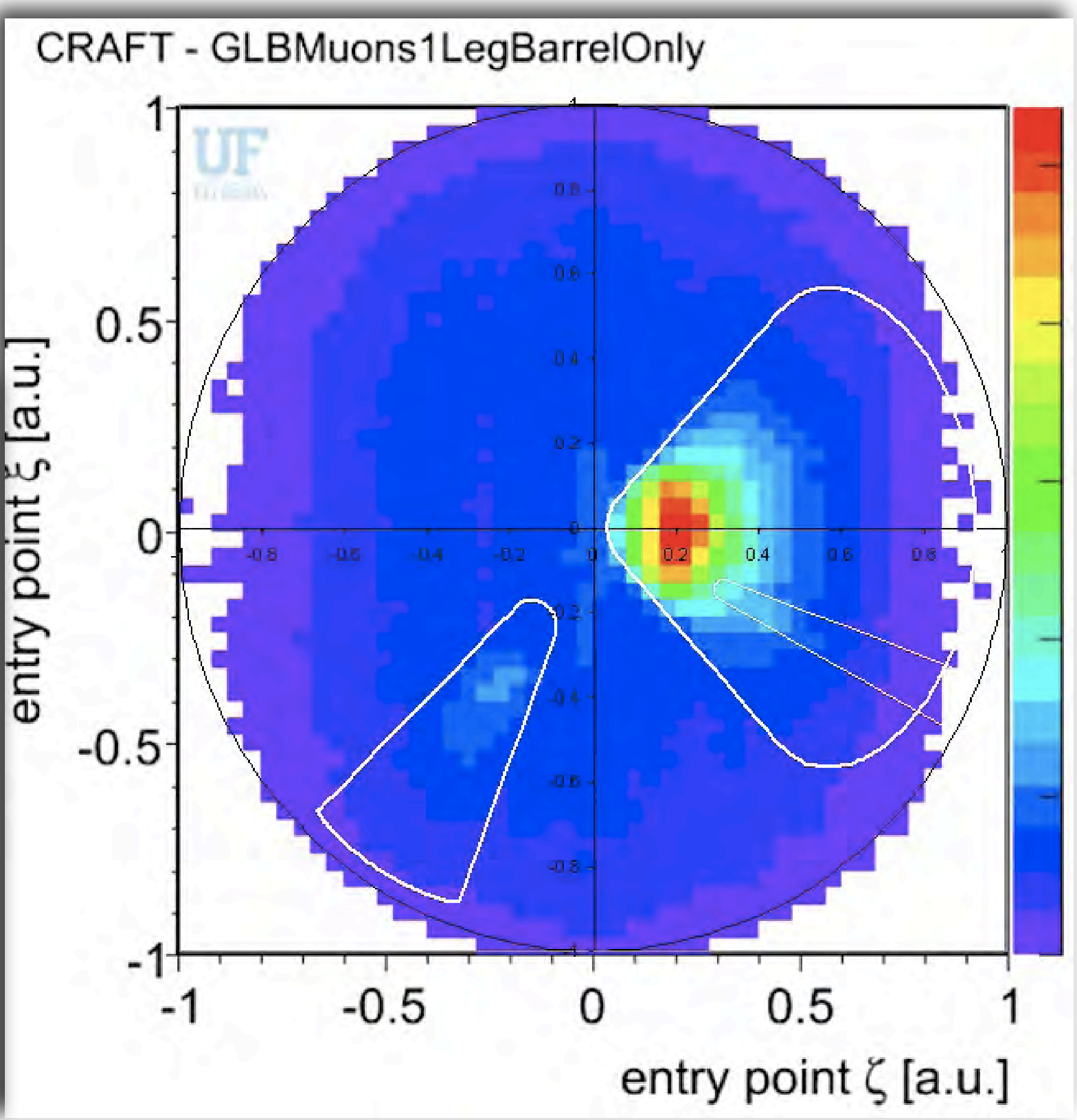
Very high trigger efficiency. Most inefficiencies have local character: chimneys, wheel gaps.

Exposure of CMS

Incidence of cosmic muons as seen from IP. Relevant for astrophysics studies.







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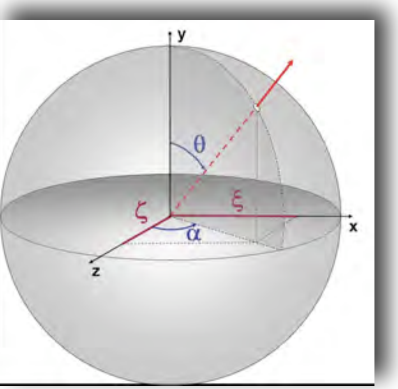
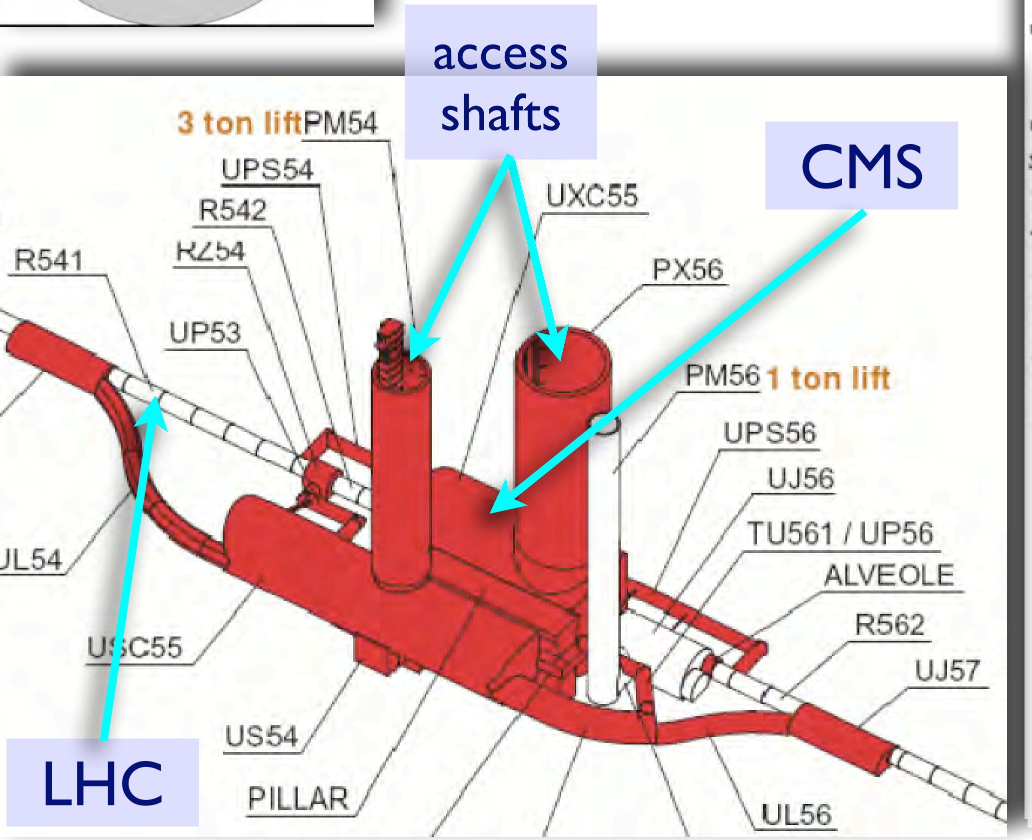
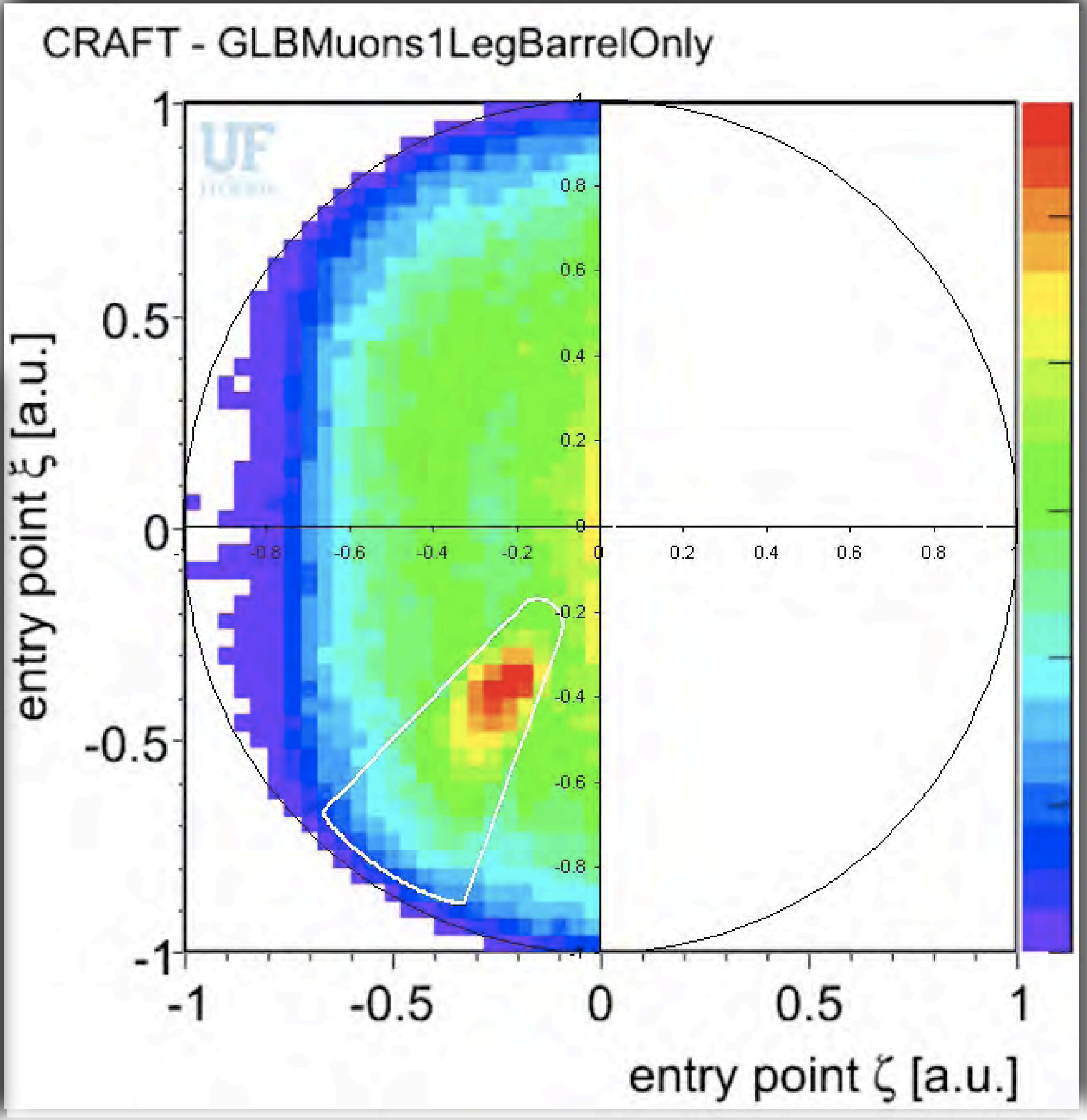


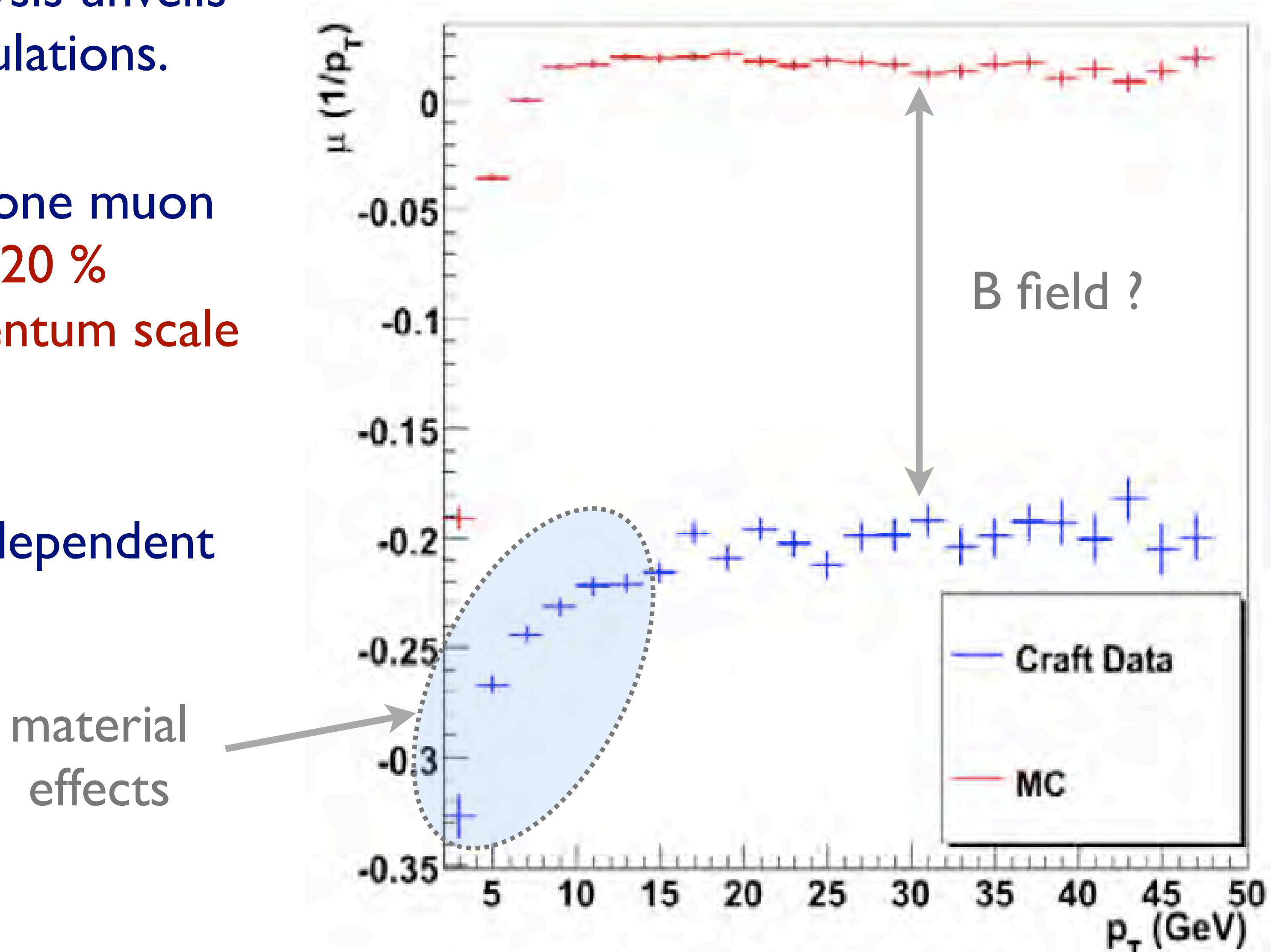




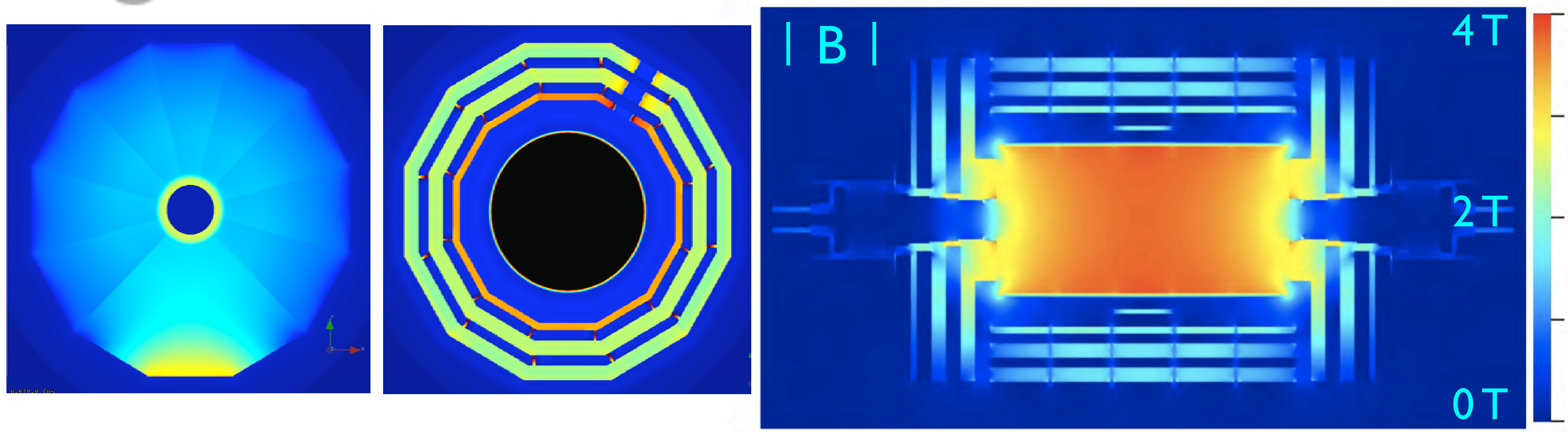
Muon momentum scale

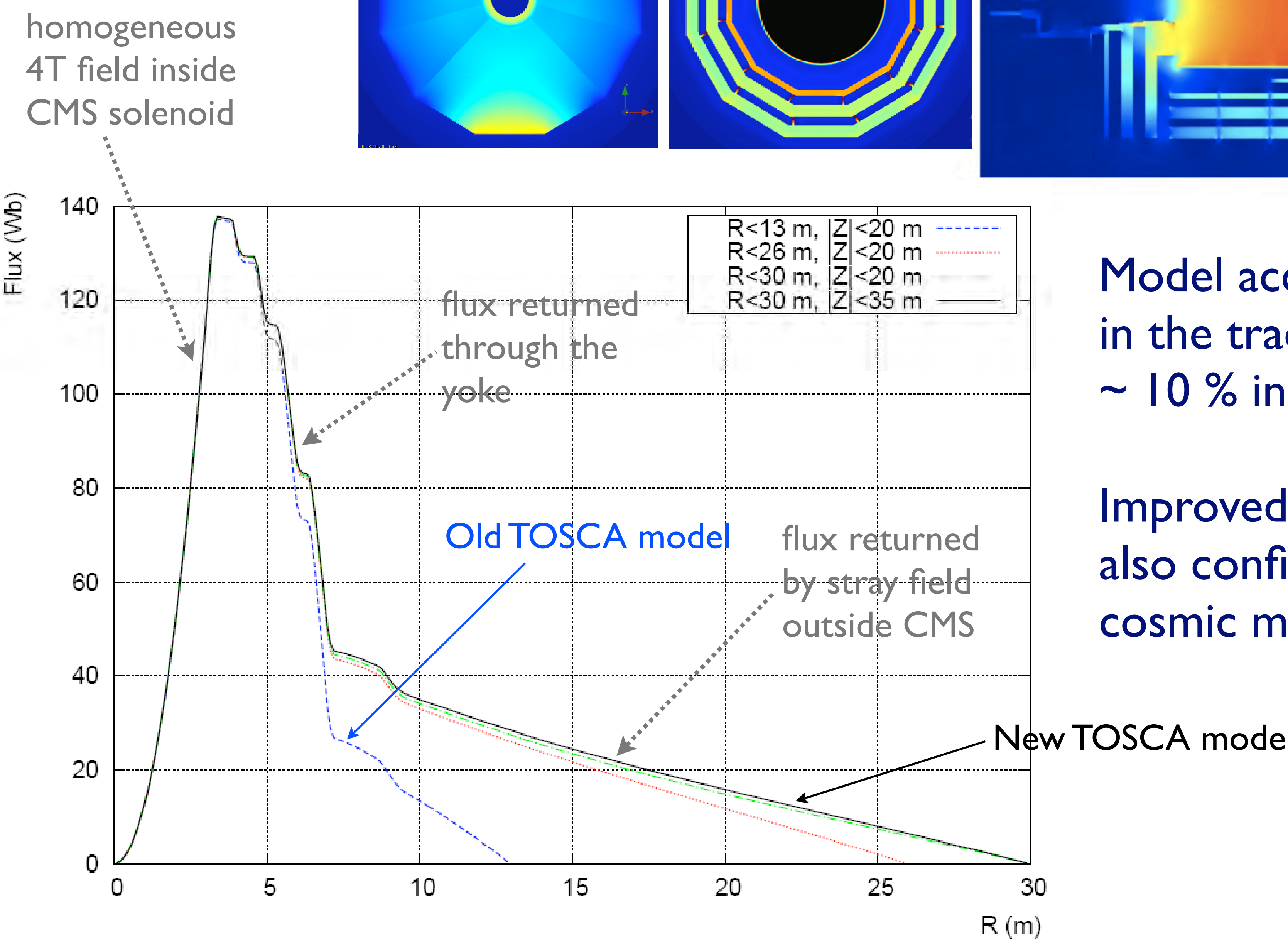
- Cosmic muon analysis unveils inaccuracies in simulations.
- Comparing standalone muon and tracker tracks: 20 % difference in momentum scale between them !!
- Confirmed by 3 independent analyses.

Observed during CRAFT08



Probing B field with cosmic muons



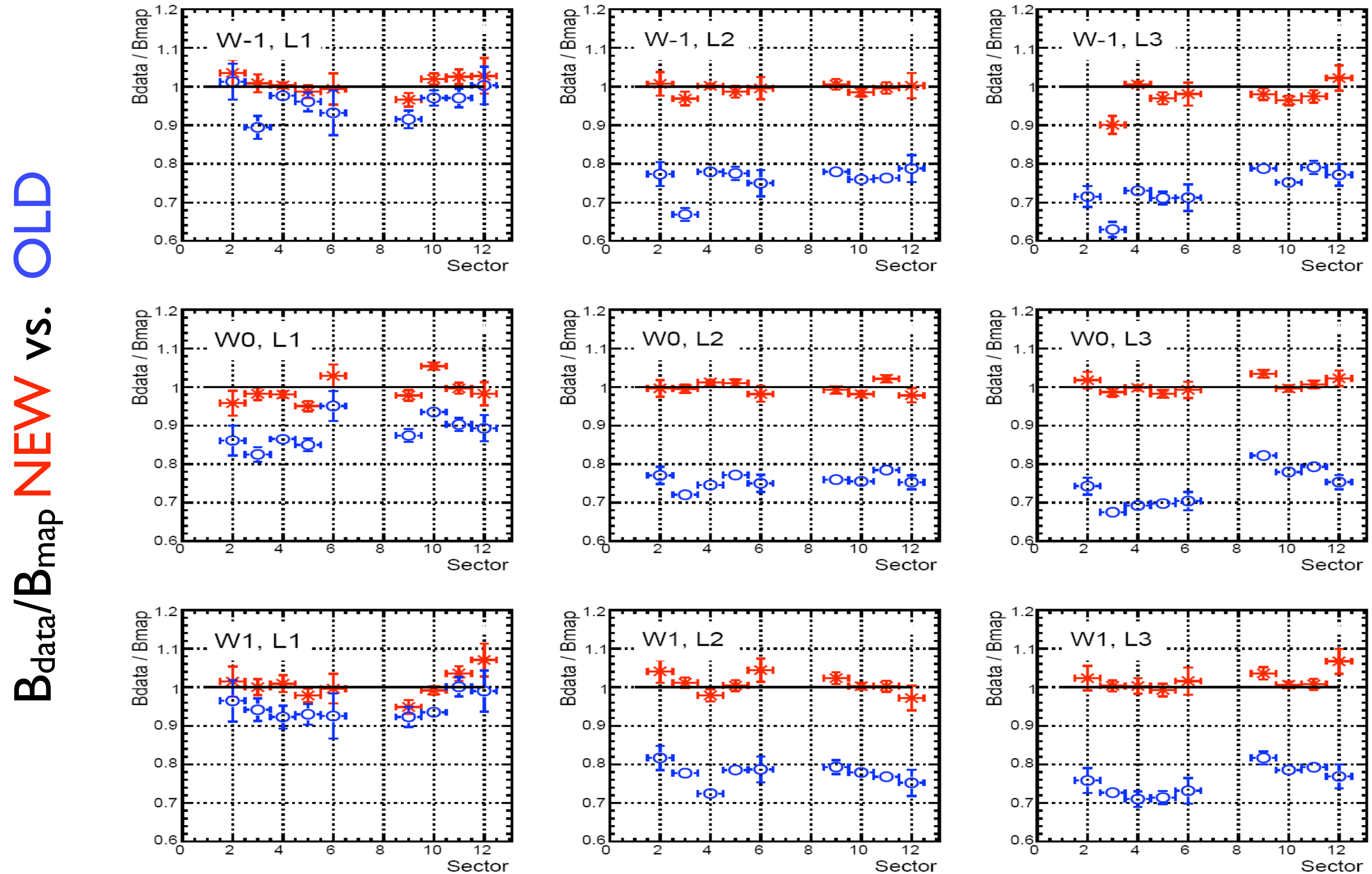


Model accuracy < 0.1 % in the tracker region, ~ 10 % in the iron yoke.

Improved B field model, also confirmed by cosmic muon analysis.

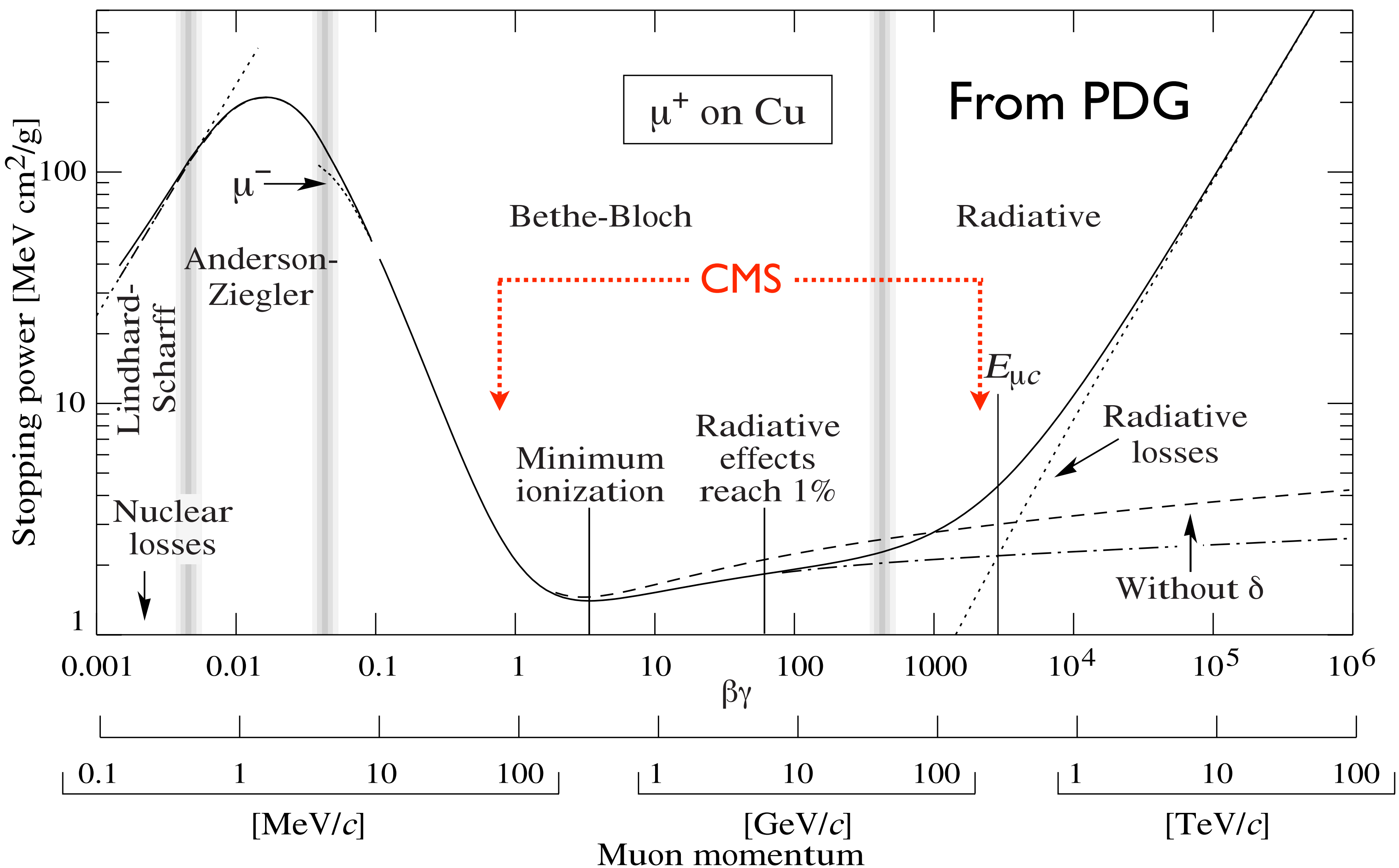
Improvement in B field map

Ratio B_{data}/B_{map} for 12 sectors of the muon detector, sensitive mostly to B_Z. B_{data} is estimated with tracks in CRAFT data, B_{map} is the simulated B field map.



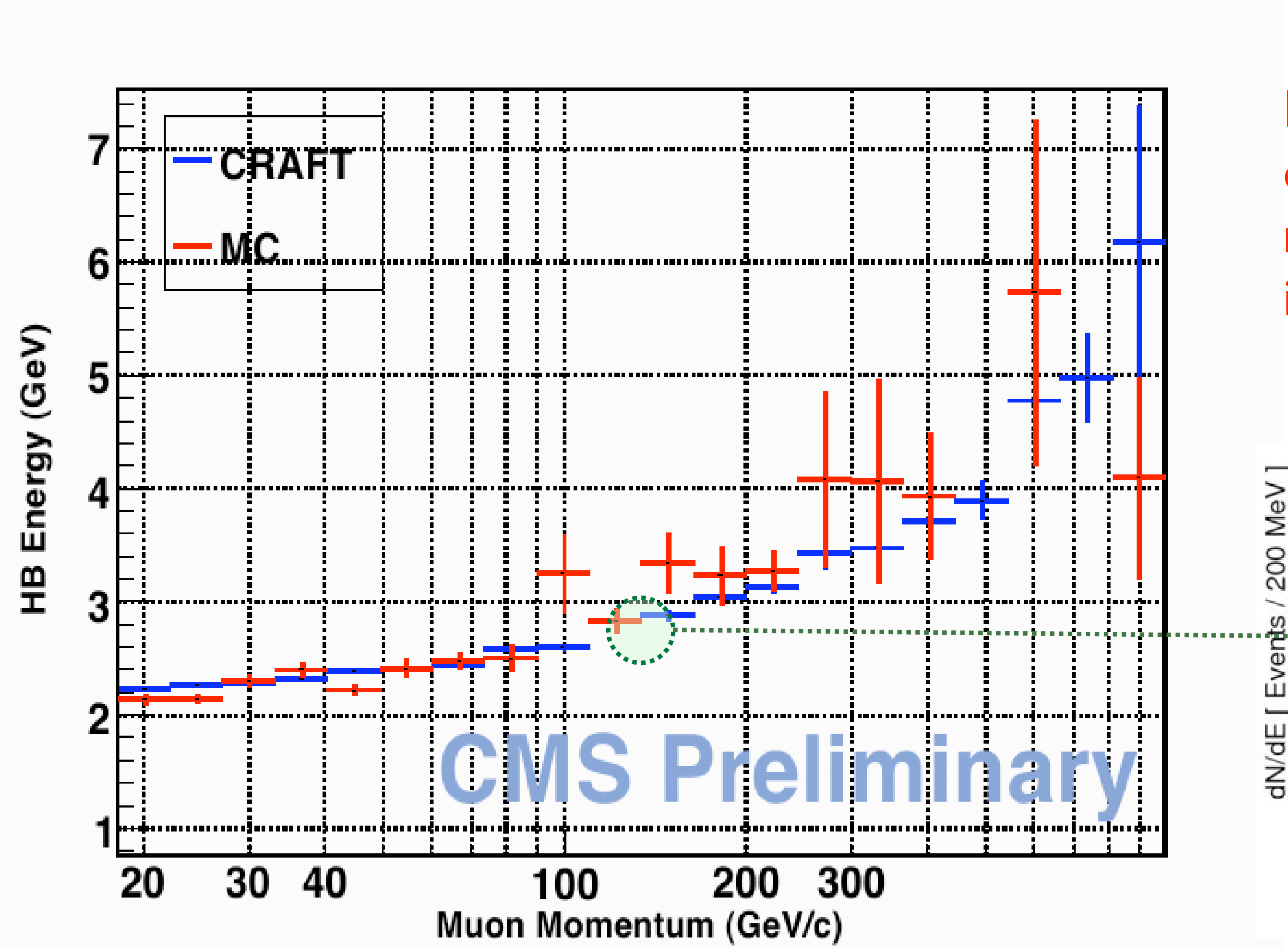
Stopping power of muons

Potential interest for studying the calorimeter response in CMS.

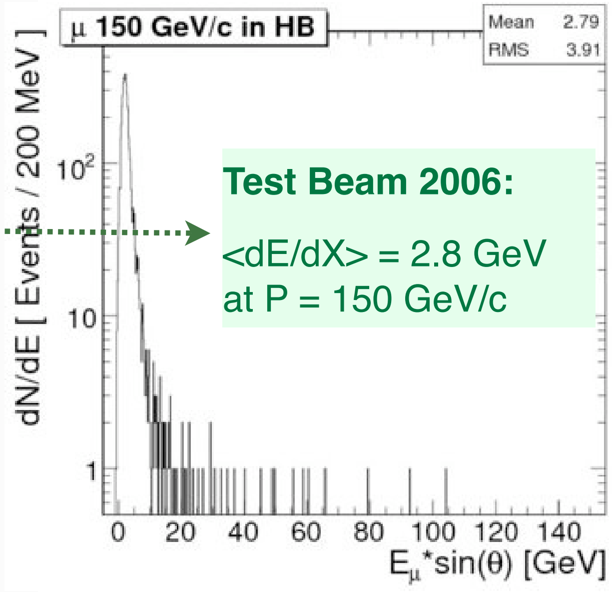


Energy loss in HCAL

Overall data vs. simulation agreement, almost PDG like.
Deviations under investigation.



HCAL energy corrected for muon path length in the calorimeter.



Cosmic muon analysis at CRAFT

- CMS data collected at CRAFT are being used to perform physics measurements:
  - cosmic muon charge asymmetry and absolute muon flux.
- Differences with respect to MTCC:
  - The full CMS detector is underground.
  - muons: large energy loses, eventually absorbed, lower rates;
  - muons cross all CMS: better momentum resolution;
  - more sub-detectors involved: tracker.
  - propagate CMS measurements to measurements at Earth surface.

Cosmic muon analysis at CRAFT

- Some issues are being thoroughly reviewed:
  - event selection: final selection for analysis → quality cuts for defining/ selecting good muons;
  - fiducial geometry: is the full CMS detector LR symmetric ? Are charge dependent efficiency corrections necessary ?
  - performance of the detector: muon momentum scale, alignment and charge confusion, as function of the muon momentum.
  - efficiencies: L1 trigger and reconstruction efficiencies.
- Analyses exploit different reconstruction algorithms: standalone muon vs. tracker based, 1-leg vs. 2-leg, etc.
  - High quality measurements, systematics well under control.

Conclusions from CRAFT

Cosmic muon analyses in CMS are well advanced. Useful lessons learned from them (can't make them public yet ☹).

Publications (JINST) on detector performance and analysis coming out.

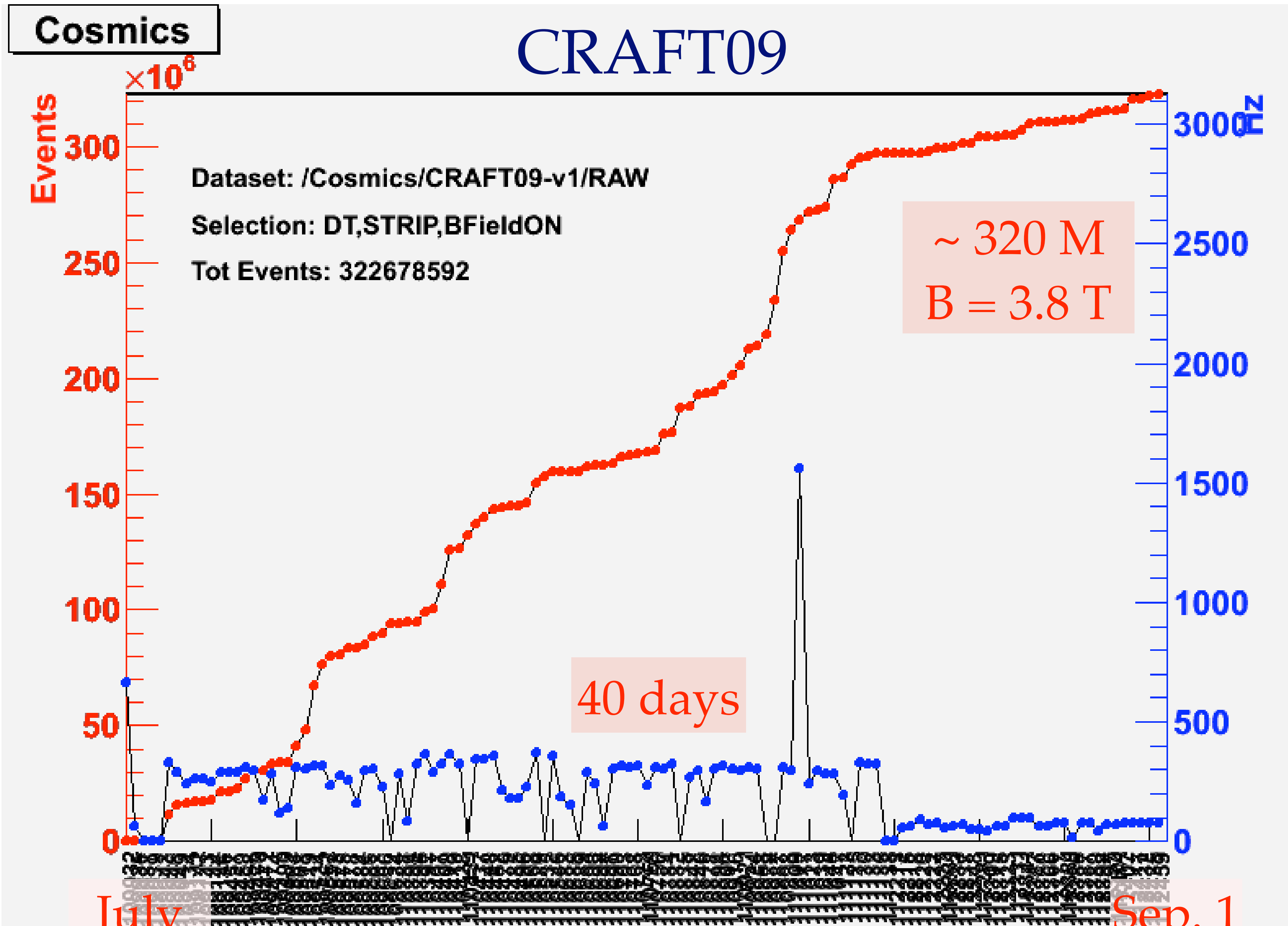
Cosmic Muon Analysis group aims to publish the first CMS physics paper(s) before LHC collisions:

"measurement of the cosmic muon charge asymmetry"

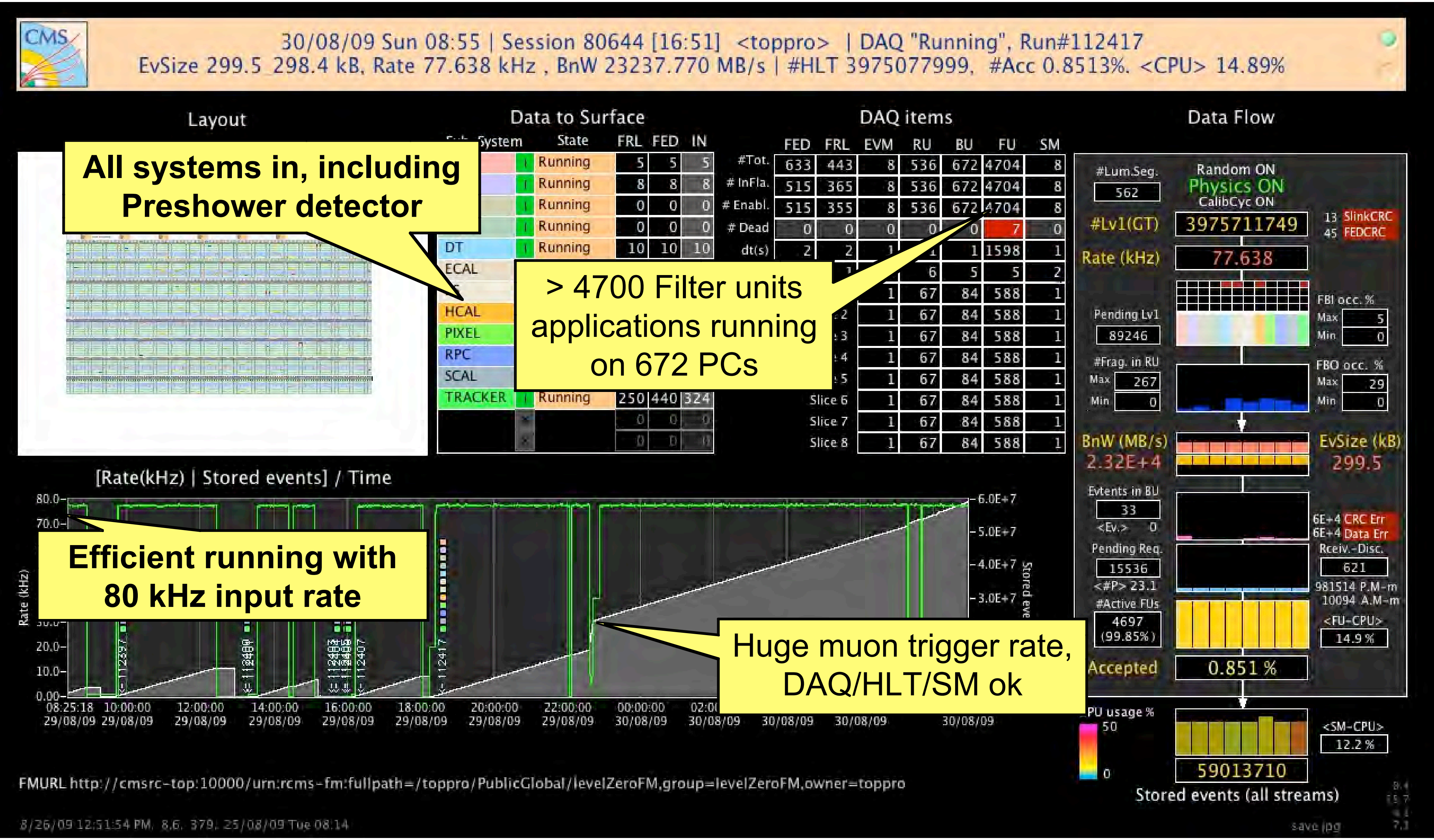
"measurement of the absolute muon flux"

Readiness of CMS: Aug. '09

CMS ready for LHC collisions.
CRAFT09 re-assessed the good performance of the detector.



CRAFT09 DAQ


30/08/09 Sun 08:55 | Session 80644 [16:51] <toppro> | DAQ "Running", Run#112417
EvSize 299.5 298.4 kB, Rate 77.638 kHz , BnW 23237.770 MB/s | #HLT 3975077999, #Acc 0.8513%, <CPU> 14.89%
Layout
Data to Surface
DAQ items
Data Flow
All systems in, including Preshower detector
> 4700 Filter units applications running on 672 PCs
Efficient running with 80 kHz input rate
Huge muon trigger rate, DAQ/HLT/SM ok
[Rate(kHz) | Stored events] / Time
#Lum.Seg. 562
Random ON
Physics ON
CalibCyc ON
#Lv1(GT) 3975711749
Rate (kHz) 77.638
BnW (MB/s) 2.32E+4
EvSize (kB) 299.5
#Active FUs 4697 (99.85%)
Accepted 0.851 %
59013710
Stored events (all streams)
FMURL http://cmsrc-top:10000/urn:rcms-fm:fullpath=/toppro/PublicGlobal/levelZeroFM,group=levelZeroFM,owner=toppro

Conclusions

Current analyses of cosmic ray muons confirm the readiness of CMS for pp collision data, from data acquisition (DAQ) to end-user analysis. In particular, it endorses the capability of CMS to successfully covering its physics program.

Eagerly waiting for LHC to delliver pp collisions.