Measurement of the Muon Charge Ratio in Cosmic Ray Events with the CMS Experiment at the LHC

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on behalf of the CMS collaboration

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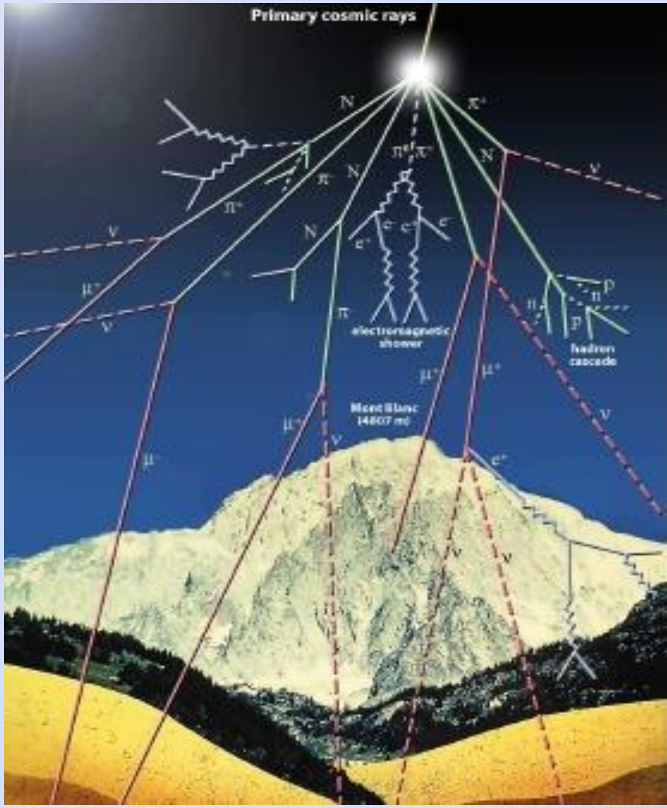
The Muon Charge Ratio R: the ratio of positive to negative atmospheric muons arriving at the earth surface

Atmospheric muons are mostly produced in the decay of pions and kaons produced in hadronic interactions of the primary cosmic rays with nuclei in the upper atmosphere.



Primary cosmic radiation is **positively charged**

→ positive **meson** production is favoured

⬇

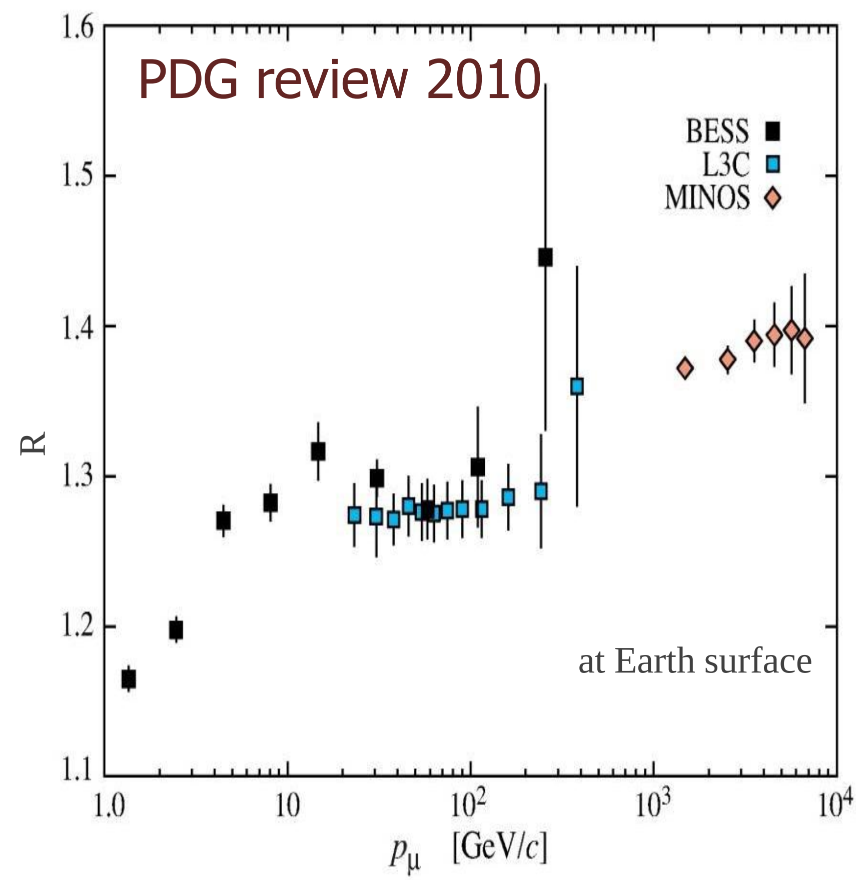
positive **muon** production is favoured: **R > 1**

R vs p_μ depends on the production, the interaction cross section and the decay length of charged π and K and on the excess of π^+/K^+ vs π^-/K^-

Its measurement can better constrain hadronic interaction models, and to better predict the atmospheric ν flux

Expectations for the Muon Charge Ratio R

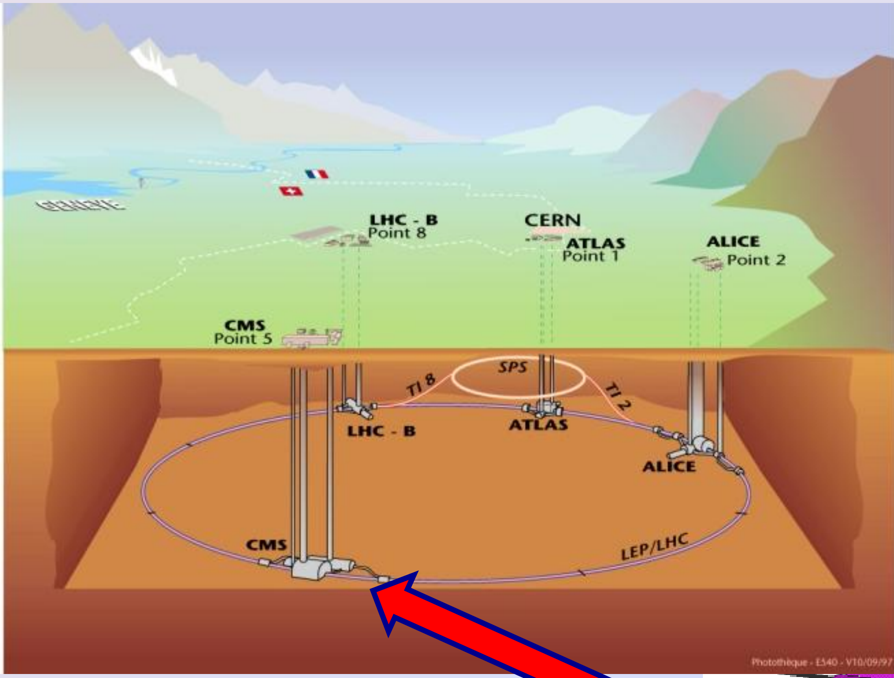
Previous measurements show a rather **constant R for p_μ ~ 200 GeV**, and **then an increase vs p_μ** , consistent with the predicted rise of the fraction of muons from kaon decays ($K^+\Lambda$ favoured w.r.to K^+K^-)



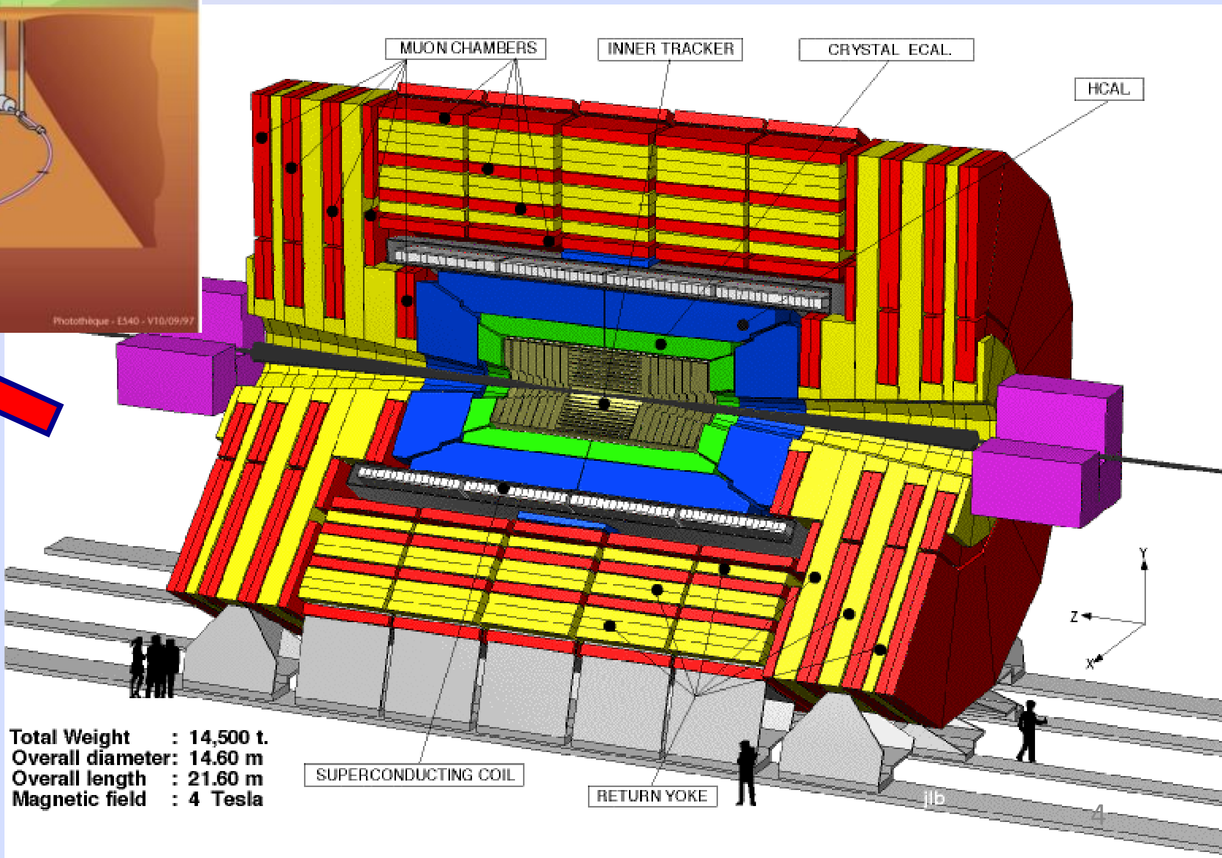
Above the critical momentum of 115 GeV, pions start to interact before they decay.
Similarly for Kaons at 850 GeV

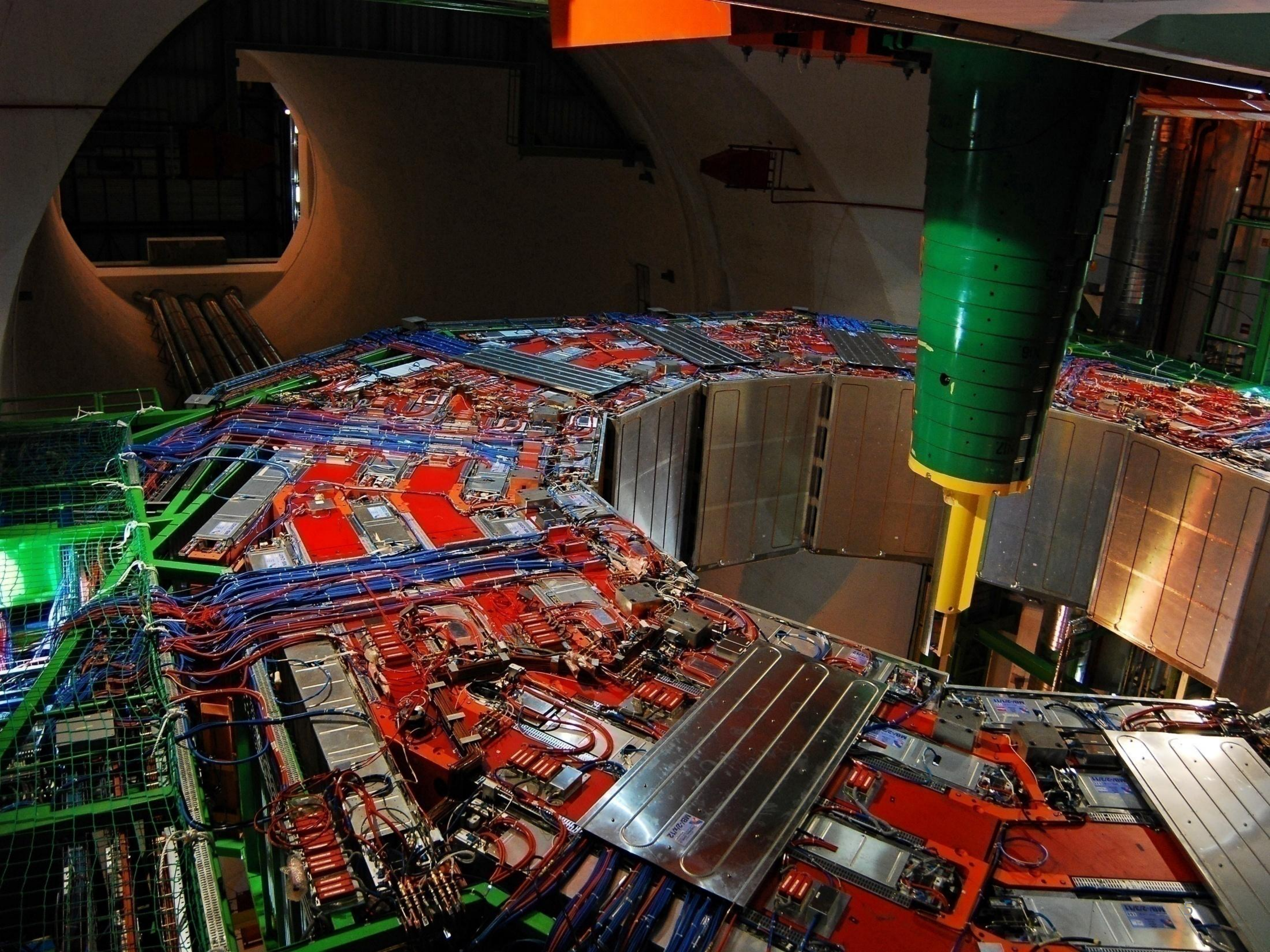
→ **a change in R between 100 GeV and 1 TeV is expected.**

The Compact Muon Solenoid (CMS) Detector



located 89 m below Earth`s surface
(420 above sea level)





Measurement of the Muon Charge Ratio R

Make use of the large number of cosmic ray muons collected by the CMS experiment during the commissioning of the detector.

~ **25 M events collected on earth surface**
~ **270 M events collected underground**

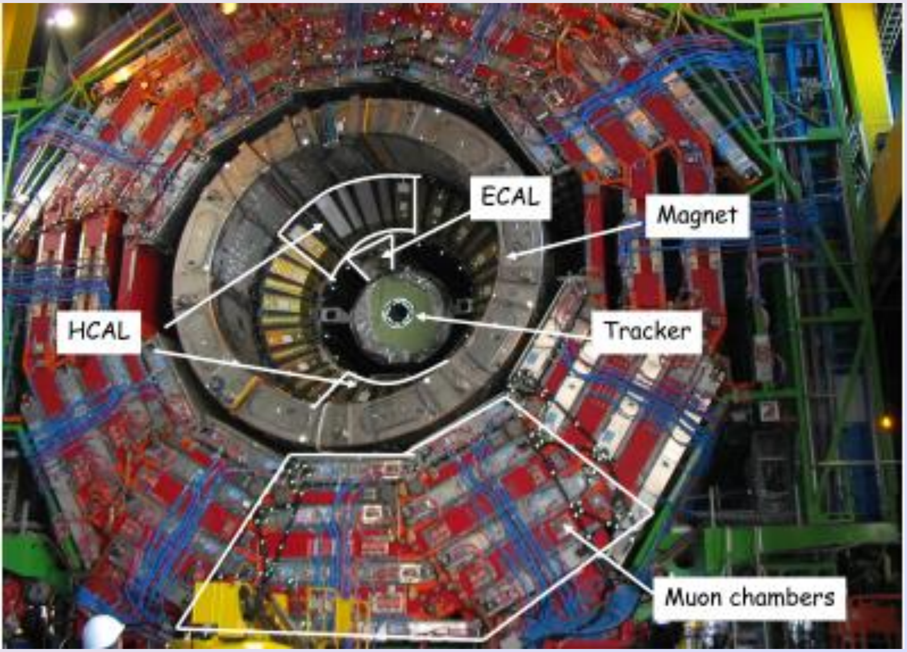
- **Using Muon Tracks Detected on Earth Surface**

  Data collected during the detector assembly.
  Not the complete detector

- **Using Muon Tracks Detected Underground**

  Two separate analyses, using two different muon samples

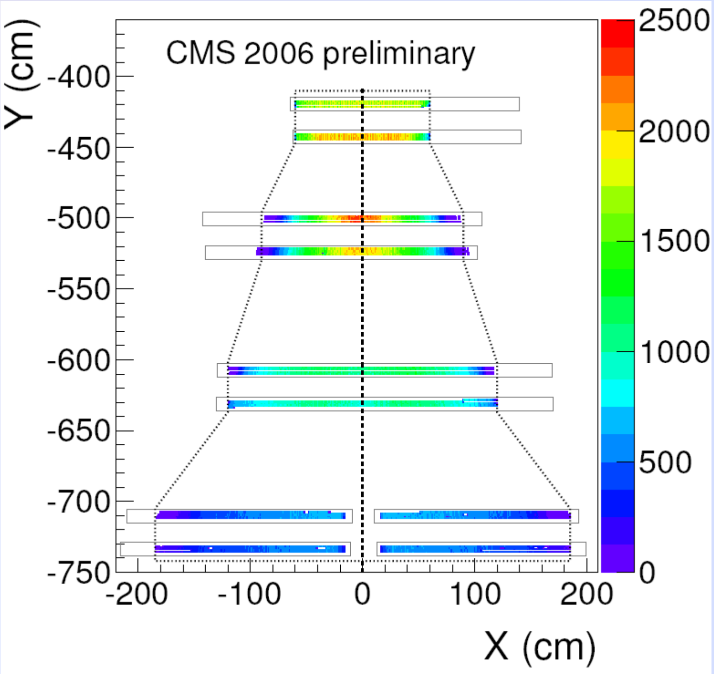
Cosmic Muons in CMS: earth surface (called MTCC)

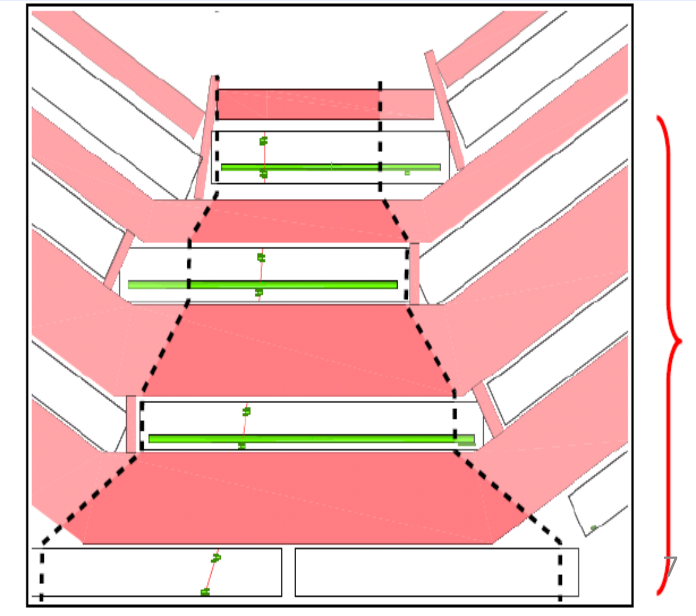


Standalone Muons taken during the detector assembly : **325 K events**

- Access to low momentum muons
- Charge-asymmetric detector

A left-right symmetric fiducial volume is defined, and only hits in this volume are accepted

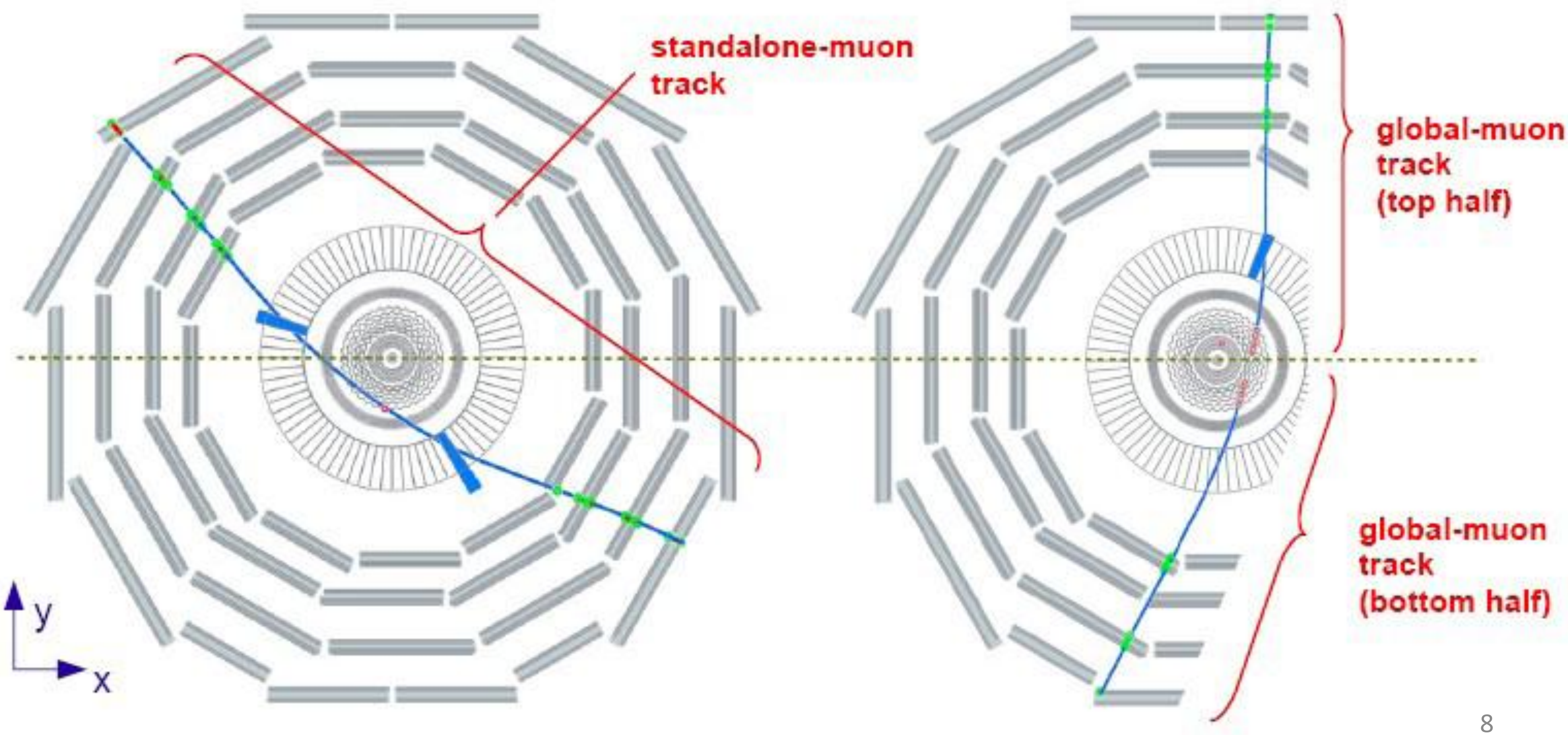




Cosmic Muons in CMS: underground

Standalone Muons (STA): Muon Detector Only.
1-leg standalone muon analysis: **1.6 M events**
- Large statistics, good p resolution due to the large lever arm.
- More dependent on simulation

Global Muons (GLB): Tracker + Muon Detector
2-legs global muon analysis: **245 K events**
- Fully data driven procedure to estimate momentum resolution and charge mis-assignment

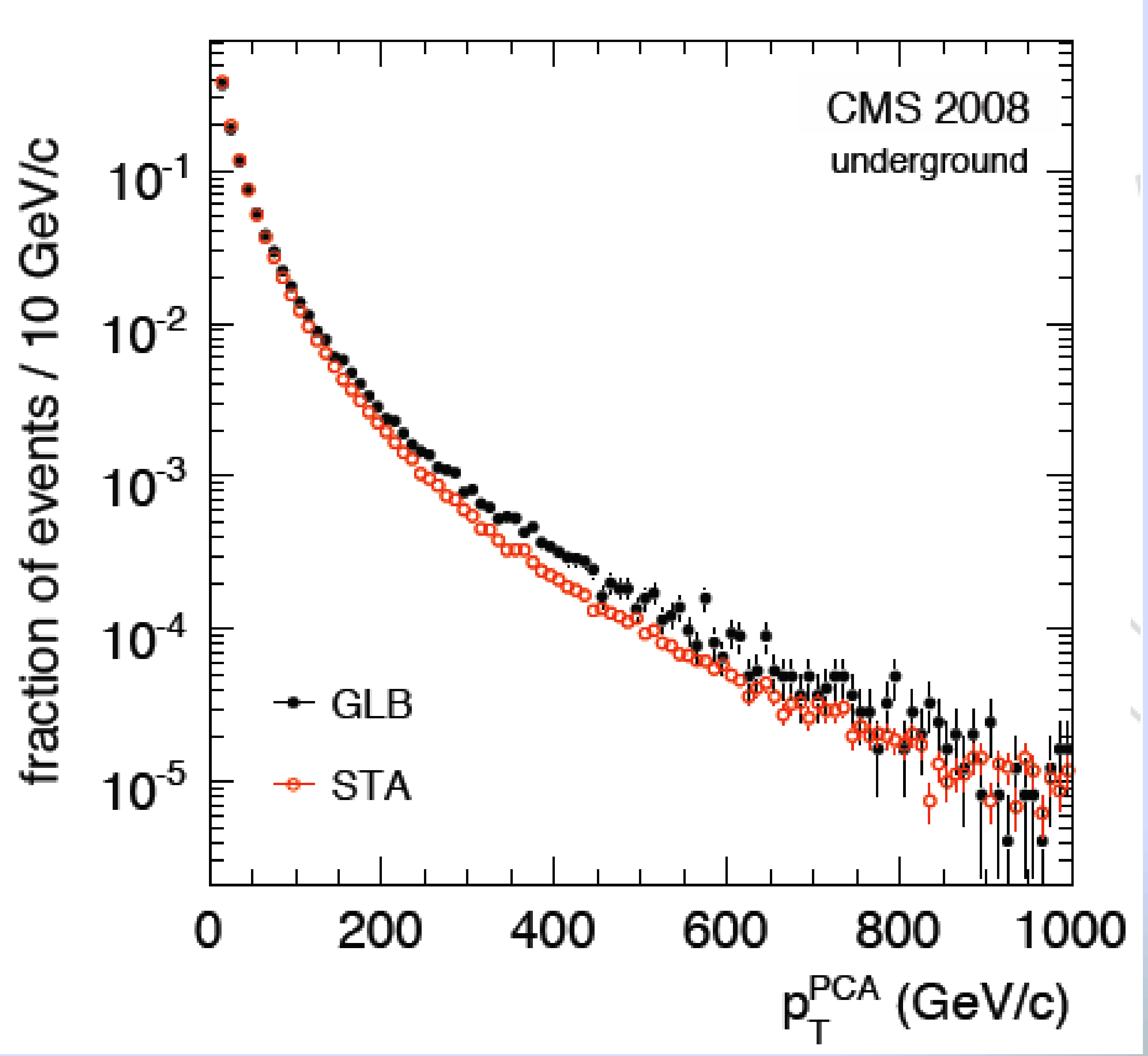


Raw momentum distribution underground

Normalized distributions for observed Standalone (**STA**) and Global Muons (**GLB**) underground.

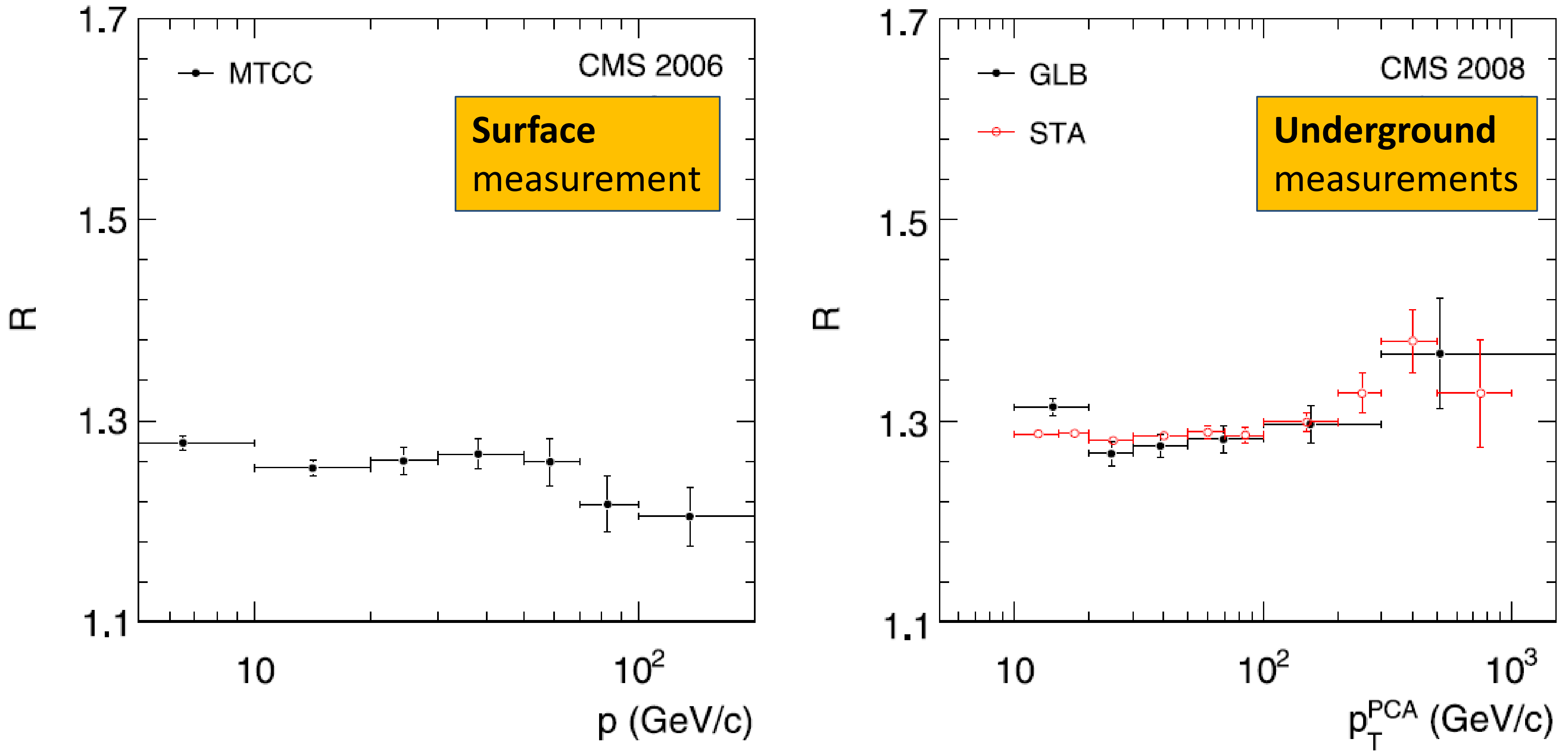
Differences are expected due to different momentum resolution and acceptance

A wide range of muon momenta, from few tens of GeV to ~ 1 TeV



Muon transverse momentum measured underground

RAW (uncorrected) measurements of R



Transverse Momentum at the Point of Closest Approach (PCA) to the interaction point

Raw R → Corrected R

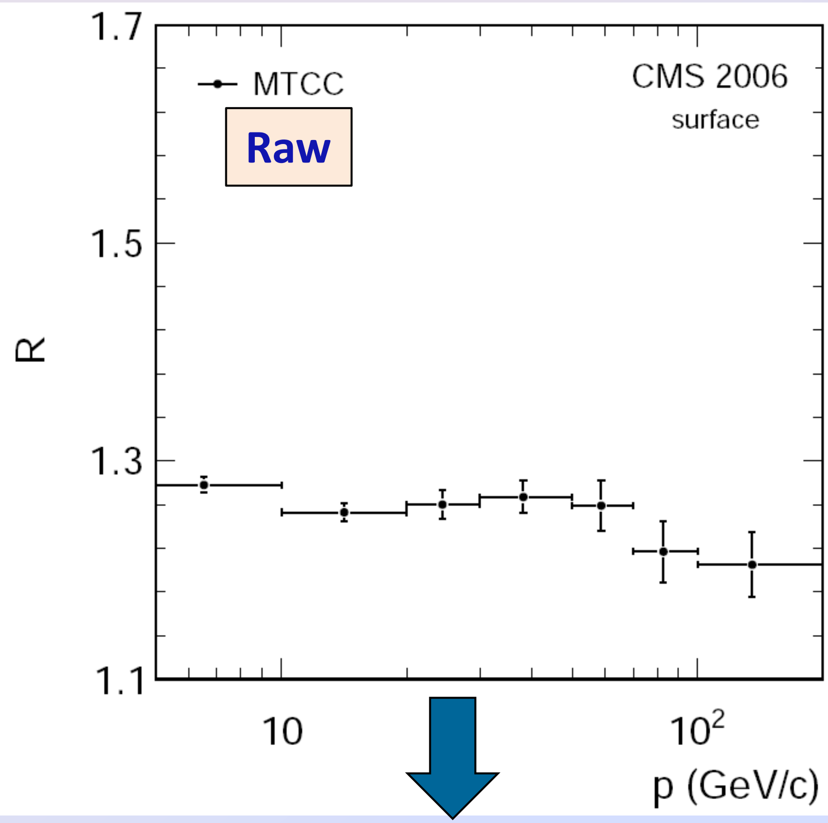
To measure **R** **at the earth surface**, as a function of the **true momentum** of the muons:

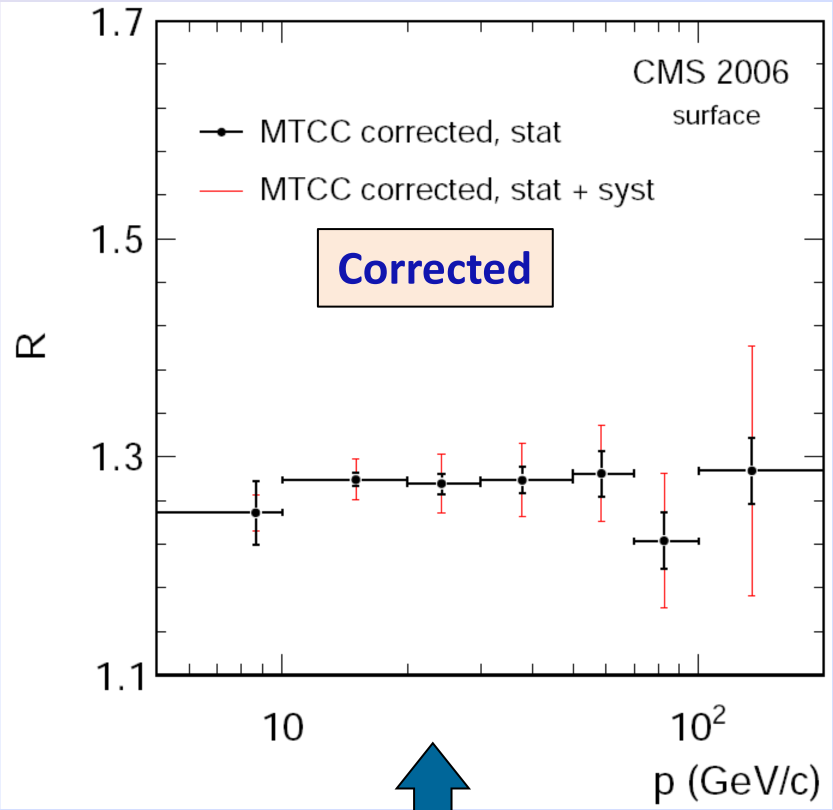
- Correct the measured momentum for the expected energy loss in the rock and in the detector
- Correct for detector effects (momentum resolution and charge mis-assignment)
- Estimate Systematic Uncertainties:

  alignment, momentum scale, trigger, material modelling,
  detector asymmetry, muon rate losses, event selection etc...

R measurement at the earth surface (MTCC analysis)

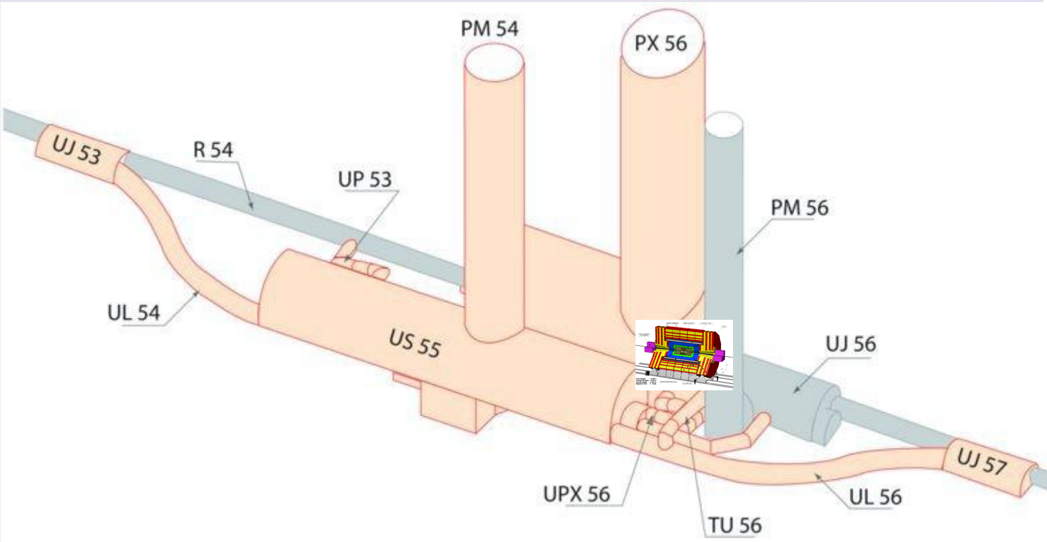
Only Muons with p < 200 GeV are considered

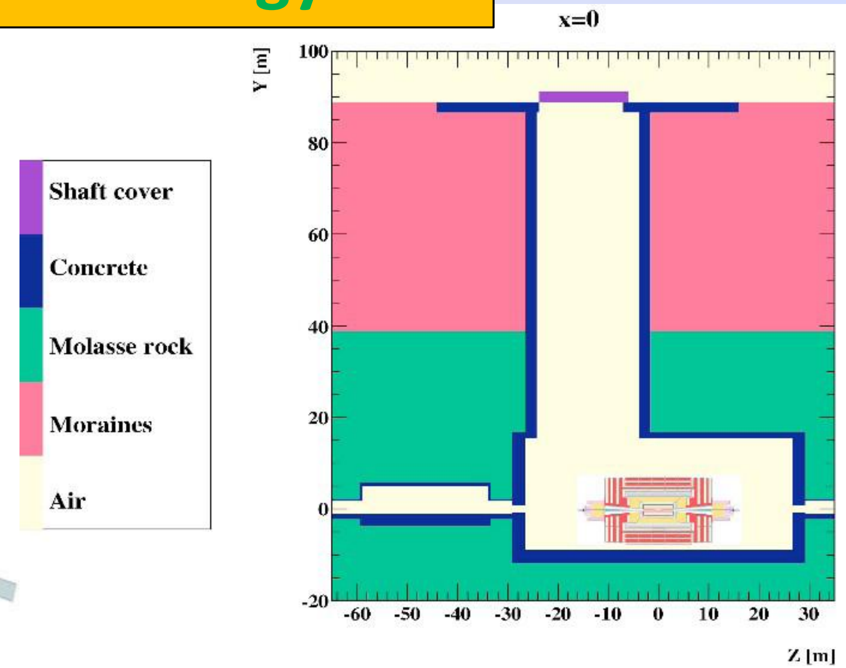




- **Applying correction for**
  - energy loss traversing CMS (few GeV)
  - charge mis-assignment estimated from simulation (small at low p)

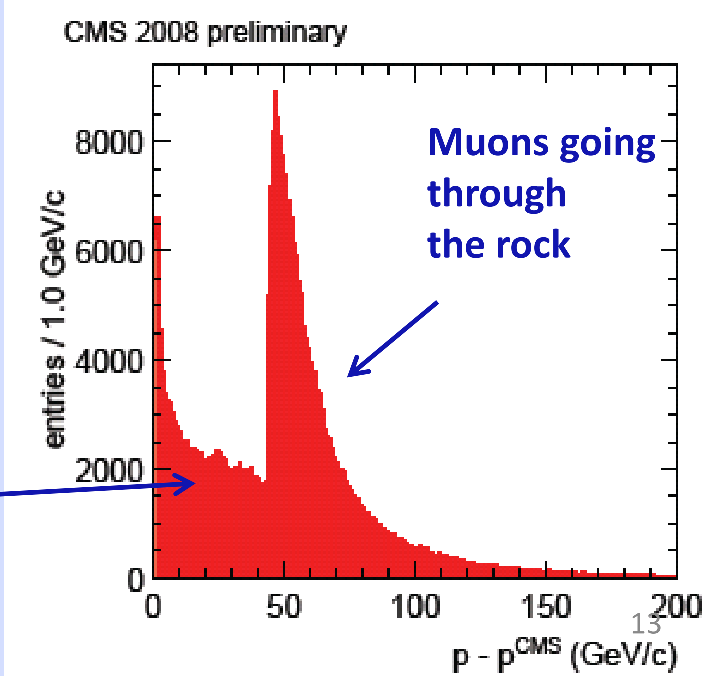
R underground measurement: energy loss





Correction for energy loss:
muons are propagated back to the surface, considering the expected differences between μ^+ and μ^- energy loss (0.15 % higher for positive muons, and < 0.3 % effect on R)

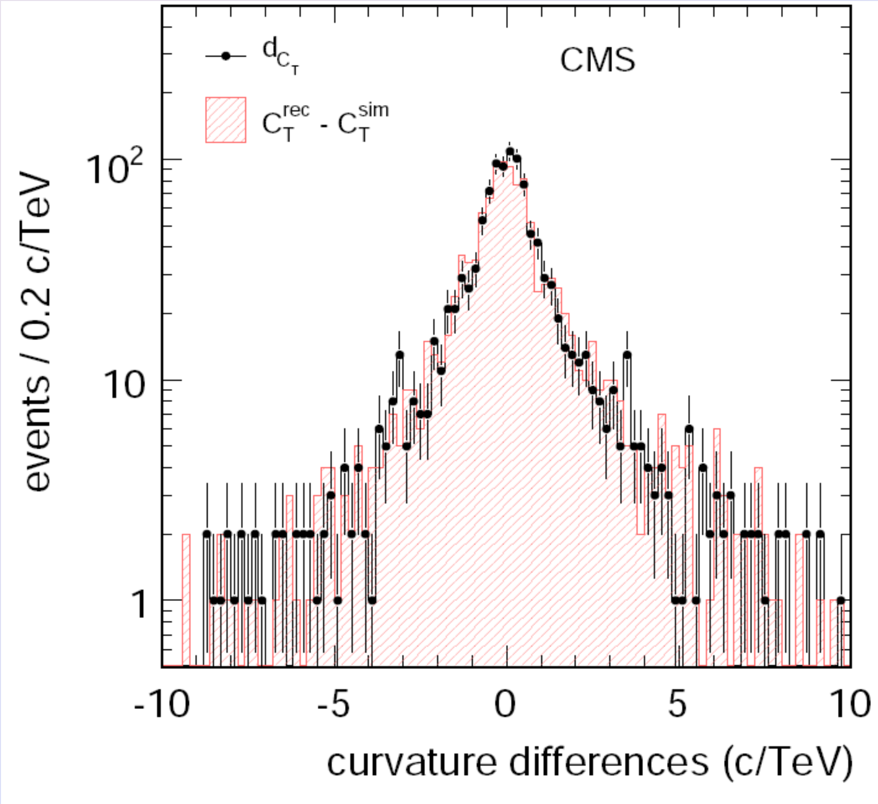
Muons going through the shaft

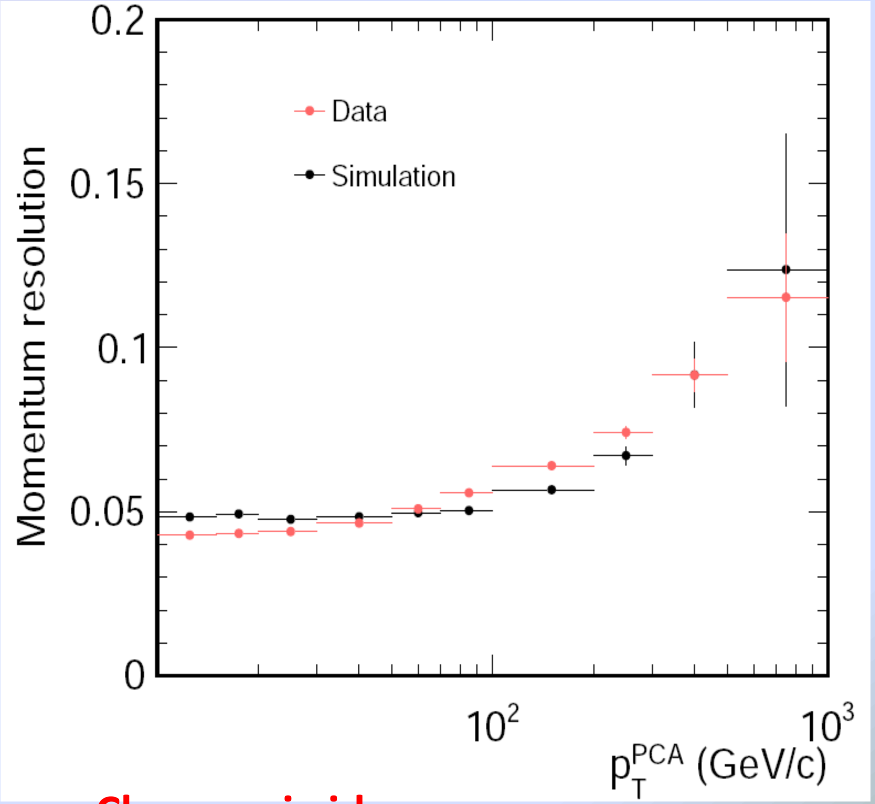


R underground measurement: p resolution and charge mis-id

2-legs global muons allow to measure **from data** both momentum resolution and charge mis-id (comparing the **curvature difference** between the two legs)

1-leg standalone muons:
resolution is measured from **simulation,** and cross-checked on **data** in a sub-sample of tracks that include the tracker track.





Also well modelled by simulation (in pink), which is not used anyway

Charge mis-id:
<1 % for p < 500 GeV, 1.5 % above, x-checked on data

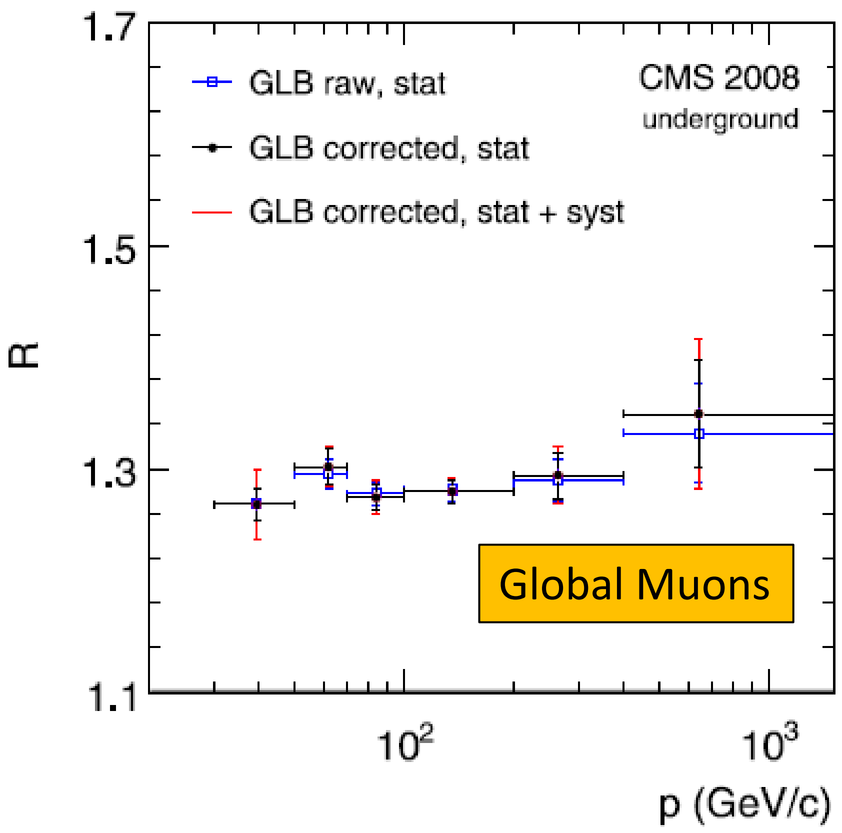
An **unfolding technique** is used to go from the measured momentum to the true momentum, after the tracks are propagated to the earth surface

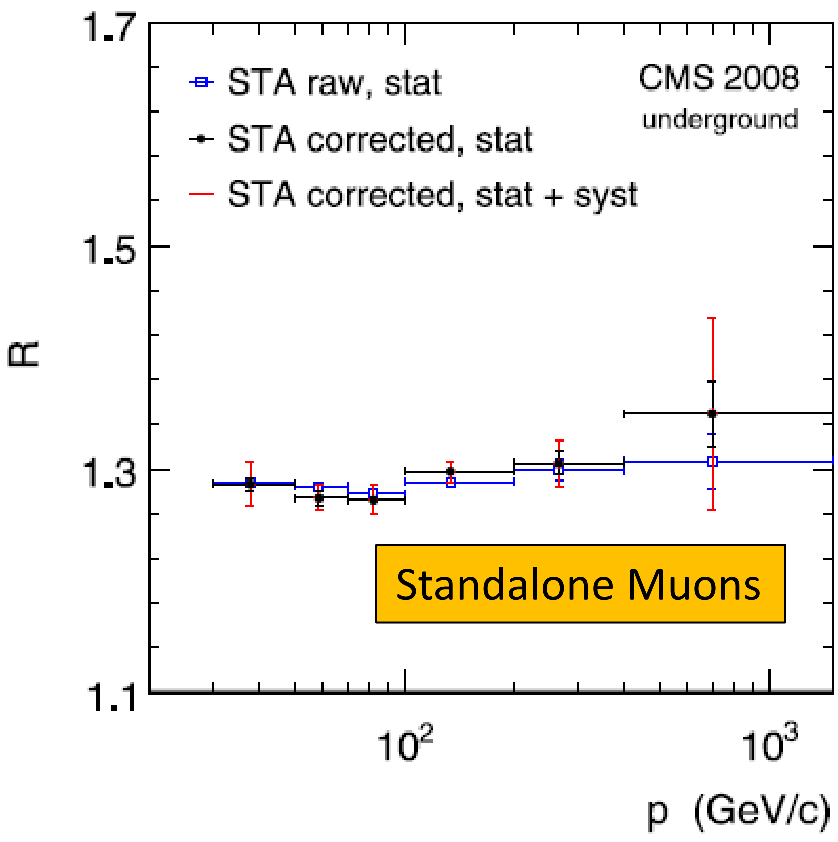
A resolution matrix $\mathbf{M}_{ij}$ is built, in q/p bins, from data for Global Muons, and from simulation for Standalone Muons.

$$N_i^{measured} = \sum_j M_{ij} N_j^{true}$$

The momentum binning was chosen to keep the spill-over between bins < 15 %.

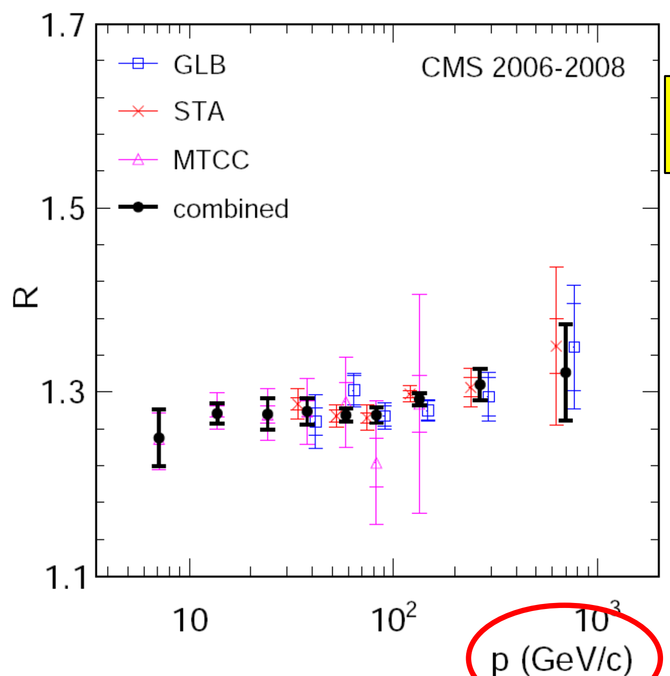
R **corrected** results (underground measurements)

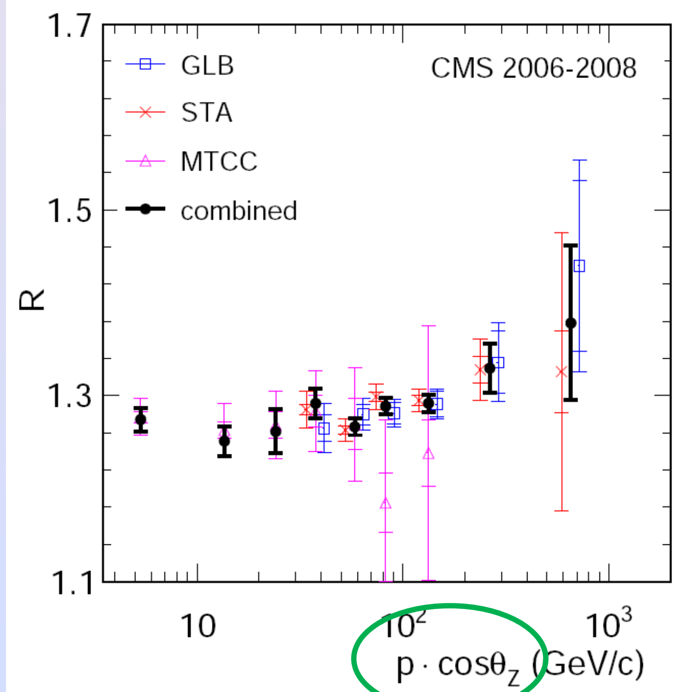




Raw and **corrected** measurements are superimposed

CMS Results





Combining the three measurements below 100 GeV

(and taking into account bin-to-bin and among-analyses correlations of sys. uncertainties)

p : $R = 1.2766 \pm 0.0032(\text{stat}) \pm 0.0032(\text{sys})$, with $\chi2/\text{ndf} = 7.3/11$

$p{\cdot}\cos\theta_z$: $R = 1.2772 \pm 0.0032(\text{stat}) \pm 0.0036(\text{sys})$, with $\chi2/\text{ndf} = 15.3/11$

Fitting the region $p{\cdot}\cos\theta_z < 70$ GeV

$R = 1.2728 \pm 0.0039$ (stat) ± 0.0040(sys) with $\chi2/\text{ndf} = 4.0/8$

Previous results:

L3+C: $R=1.285 \pm 0.003$ (stat) ± 0.019 (sys)

MINOS: $R=1.266 \pm 0.001$ (stat) ± 0.015 (sys) (near detector)

Systematic Uncertainties

Surface: mostly alignment, charge mis-id and scale of the B-field
Global Muons: knowledge of absolute momentum scale (high p)
charge dependent effects on muon rate (low p)
Standalone Muons: knowledge of absolute momentum scale, alignment,
charge mis-id (high p)
charge dependent effects on muon rate (low p)

p range	2006 surface			2008 global-muon			2008 standalone-muon		
	R	stat.	syst.	R	stat.	syst.	R	stat.	syst.
5 – 10	1.249	2.3	1.3	–	–	–	–	–	–
10 – 20	1.279	0.5	1.5	–	–	–	–	–	–
20 – 30	1.276	0.7	2.1	–	–	–	–	–	–
30 – 50	1.279	0.9	2.6	1.268	1.2	2.1	1.287	0.5	1.5
50 – 70	1.285	1.6	3.4	1.302	1.2	0.6	1.274	0.5	0.8
70 – 100	1.223	2.1	5.1	1.274	0.9	0.7	1.272	0.4	0.9
100 – 200	1.287	2.4	8.9	1.280	0.8	0.3	1.298	0.3	0.6
200 – 400	–	–	–	1.295	1.6	1.3	1.305	0.8	1.4
> 400	–	–	–	1.349	3.5	3.5	1.350	2.2	6.0

Pion-Kaon Fit Model

R vs p·cosΘ$_z$ increases due to the increase of the Kaon contribution

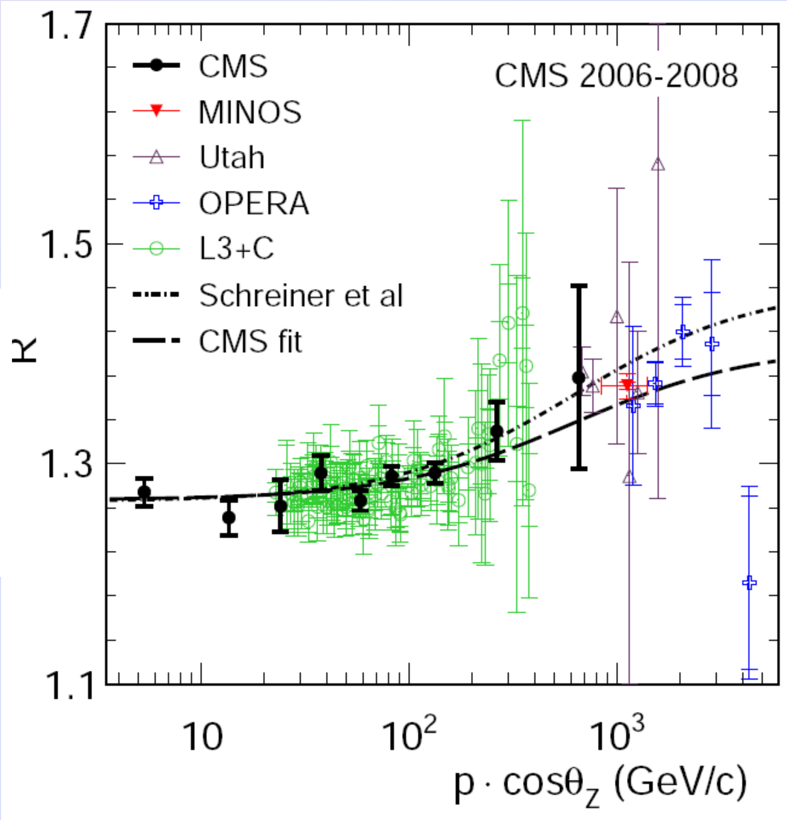
Pion-Kaon (PiKa) **Model:**

$$R = \frac{\left\{\frac{f_\pi}{1 + 1.1 E_\mu \cos\theta/115\ \text{GeV}} + \frac{\eta\times f_K}{1 + 1.1 E_\mu \cos\theta/850\ \text{GeV}}\right\}}{\left\{\frac{1-f_\pi}{1 + 1.1 E_\mu \cos\theta/115\ \text{GeV}} + \frac{\eta\times(1-f_K)}{1 + 1.1 E_\mu \cos\theta/850\ \text{GeV}}\right\}}$$

η: ratio of K to π rates contributing to $\mu^\pm$ rate

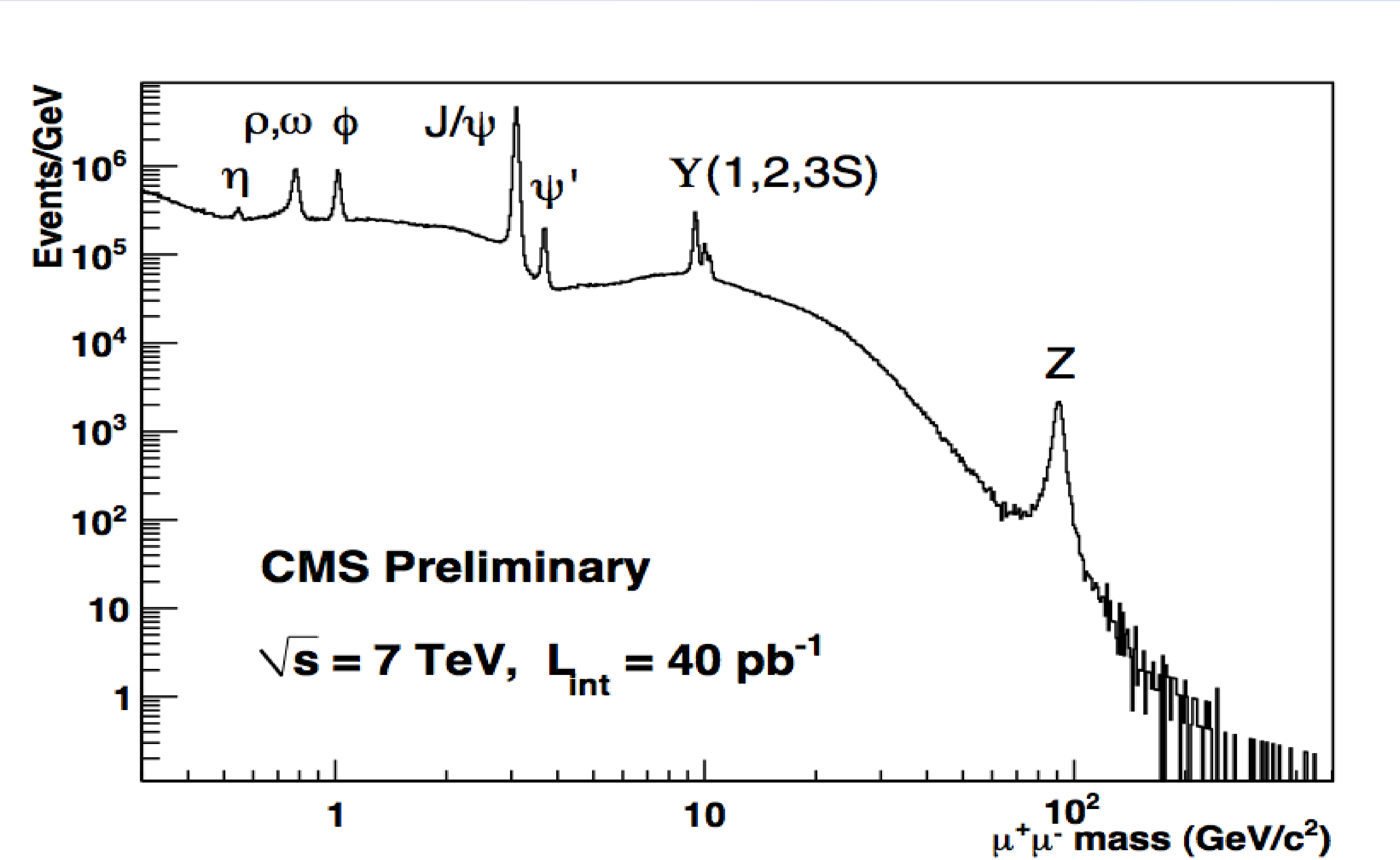
f_k (f_π): fraction of positive K(π)

f_k grows with momentum ($K^+\Lambda$ favoured w.r.to K^+K^-)



- Fit of the Pion-Kaon model to the CMS data in the entire p·cosθz region
  - f_π=0.553 ± 0.005 f_K=0.66 ± 0.06 χ2/ndf=7.8/7 (assuming a fixed amount of kaons)

Now CMS is using muons for a more LHC-like physics



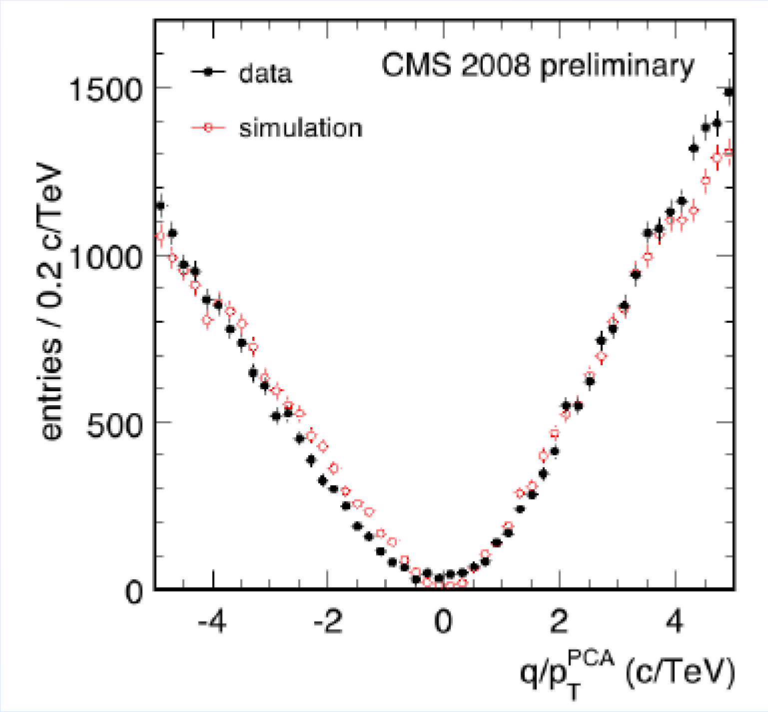
Back-up Slides

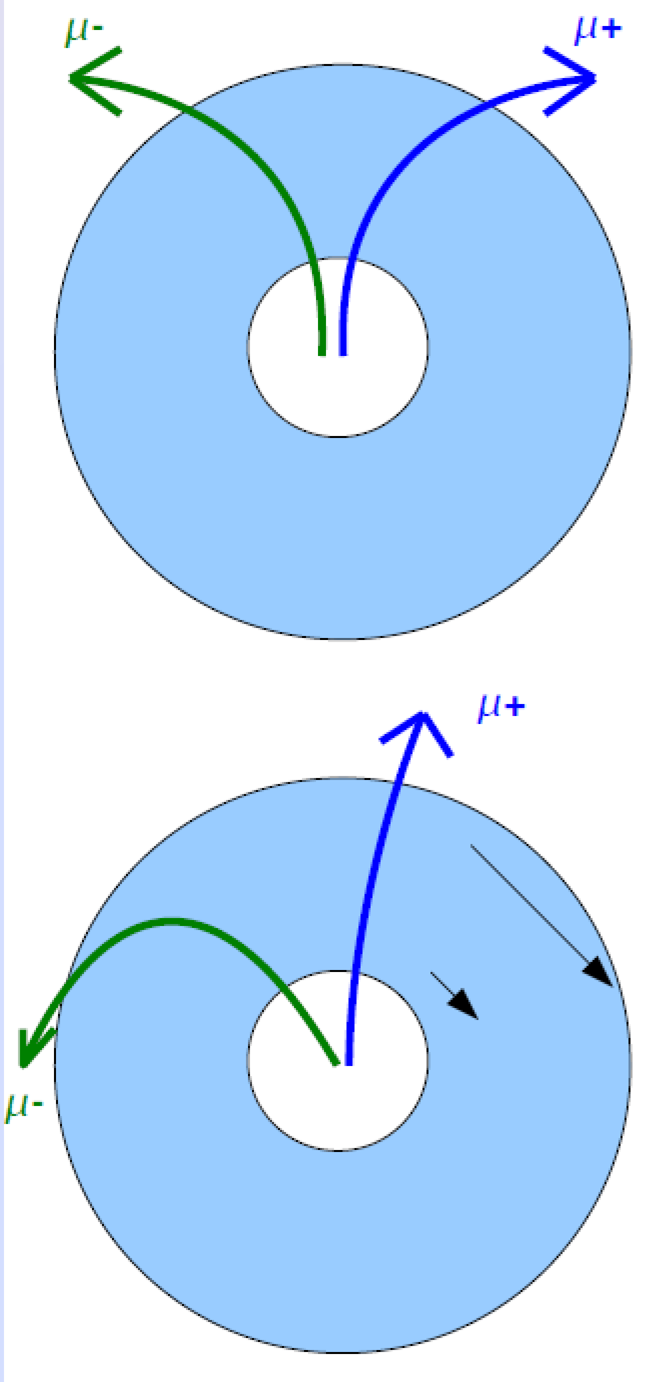
Alignment: weak modes

It affects momentum determination but not the fit quality (χ^2 invariant)

Main concern: charge dependent ?

q/p_T distribution → 0 as $p_T \rightarrow \infty$
A weak mode will move the endpoint away from 0
From data: shift = (4.3 ± 2.2) % /TeV





Acceptance cuts: underground

A non phi-symmetric muon distribution is a problem due to the B-field: muons from symmetric areas are removed to avoid shafts effects.