BUAP

Física de Astropartículas en el CERN

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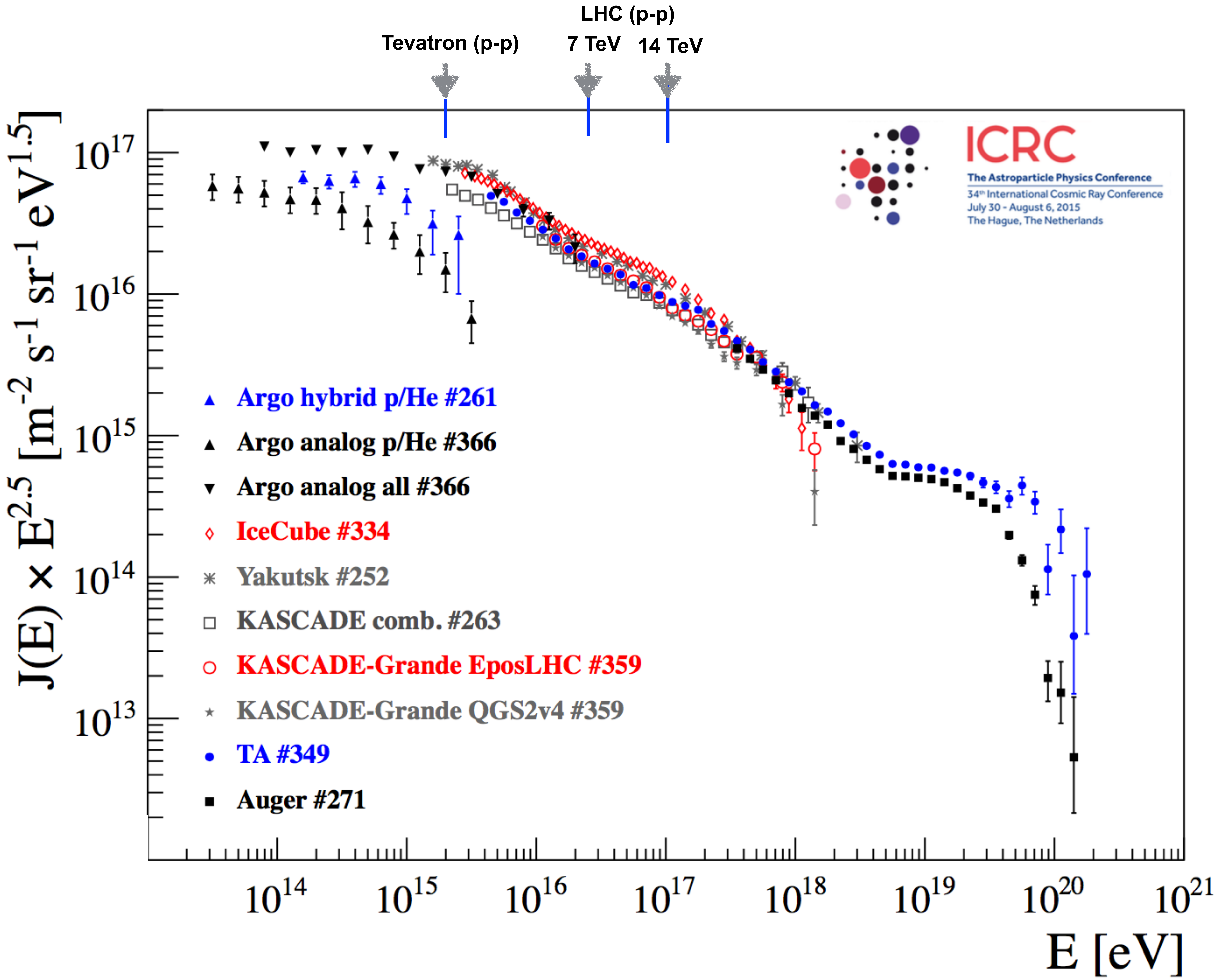
Reunión General de la Red FAE

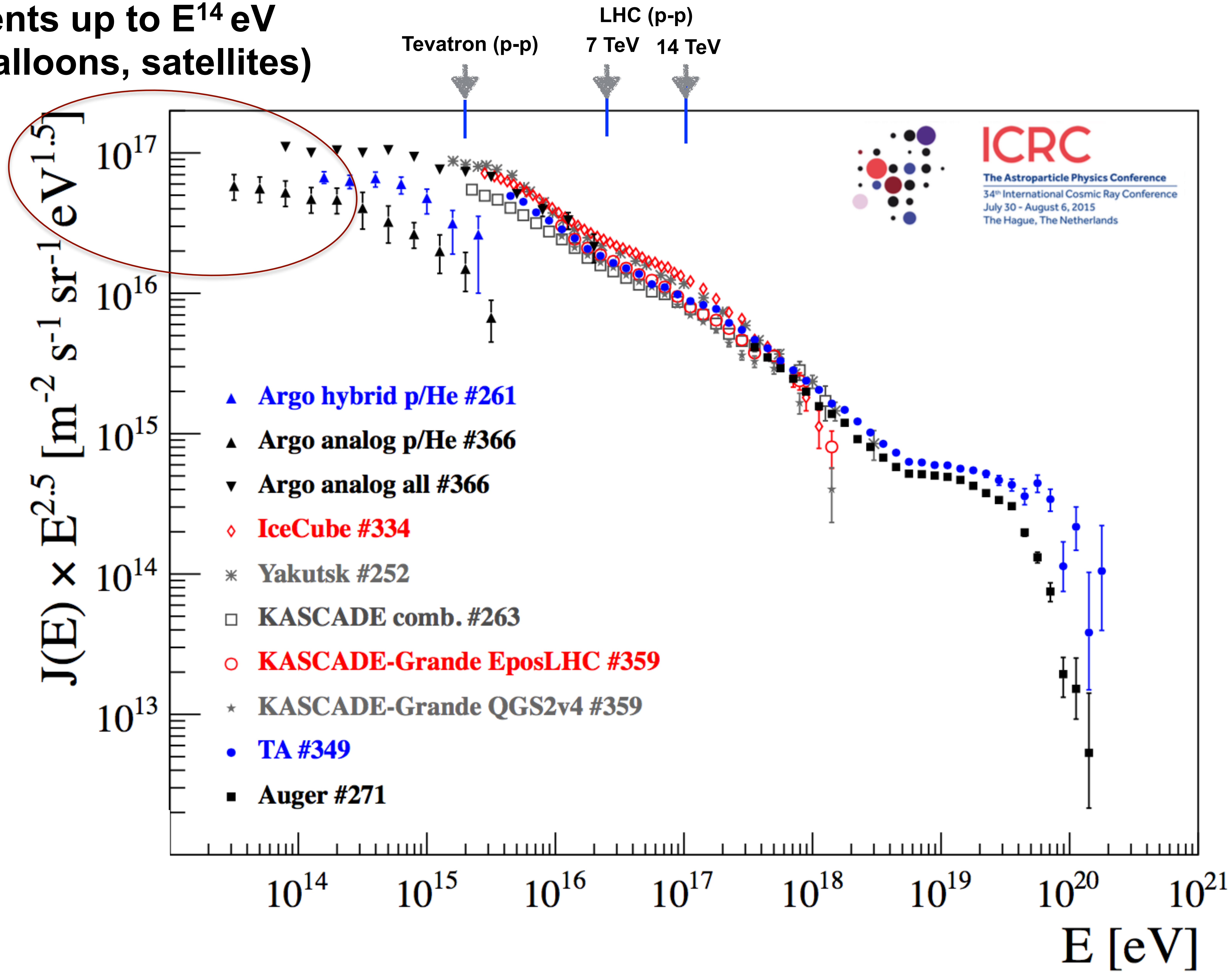
28/09/2017

PLAN OF THE TALK

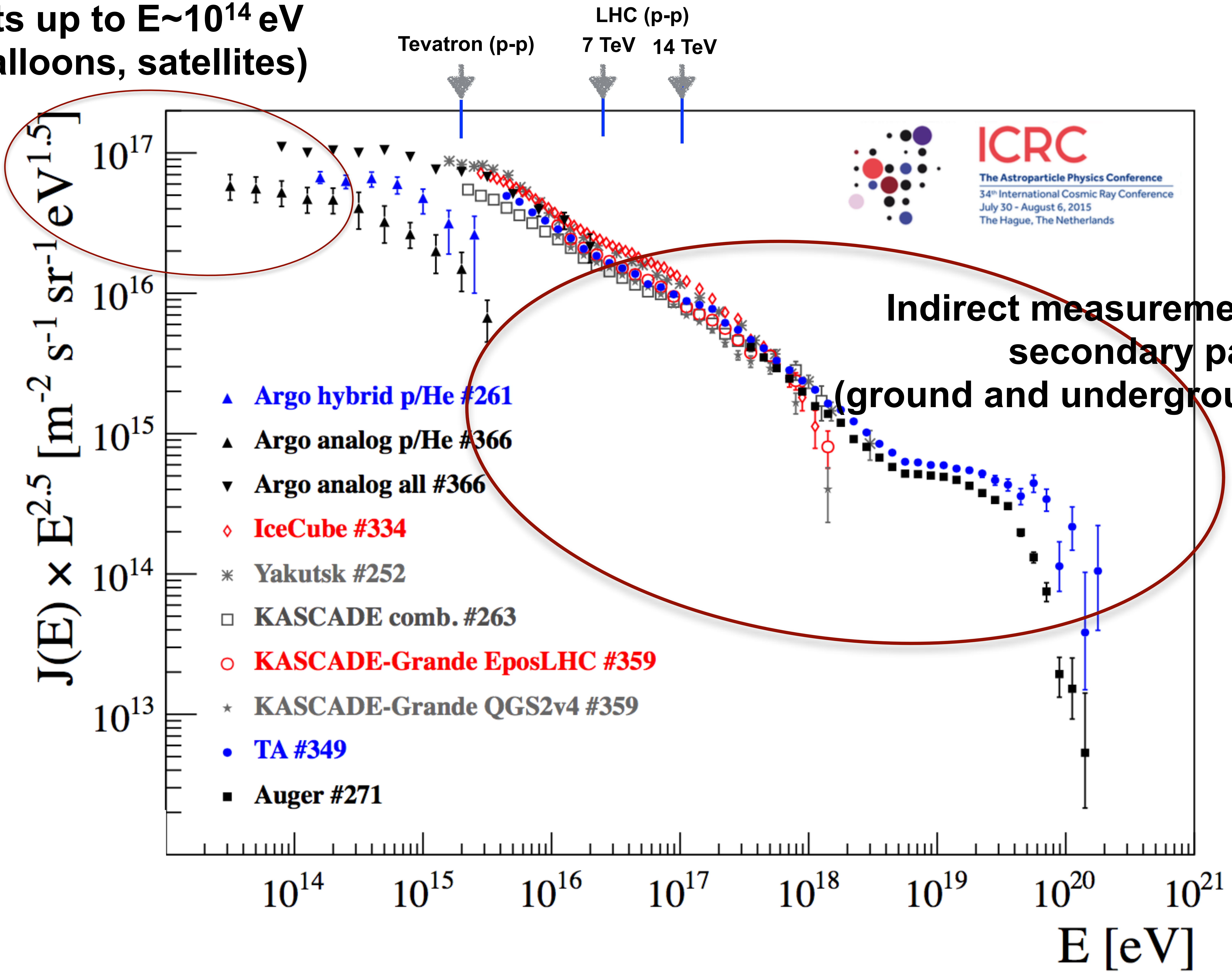
- Cosmic-ray physics with accelerator apparatus
- LEP results
- CERN results (LHC, Run 1)
- CERN plans (Run 3, HI Run)
- Final comments


LHC (p-p)
Tevatron (p-p)
7 TeV
14 TeV
ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands
$J(E) \times E^{2.5}$ [m^{-2} s^{-1} sr^{-1} $eV^{1.5}$]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
▲ Argo hybrid p/He #261
▲ Argo analog p/He #366
▼ Argo analog all #366
◊ IceCube #334
✳ Yakutsk #252
□ KASCADE comb. #263
○ KASCADE-Grande EposLHC #359
⋆ KASCADE-Grande QGS2v4 #359
● TA #349
■ Auger #271
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E [eV]

Direct measurements up to E^{14} eV primary particles (balloons, satellites)

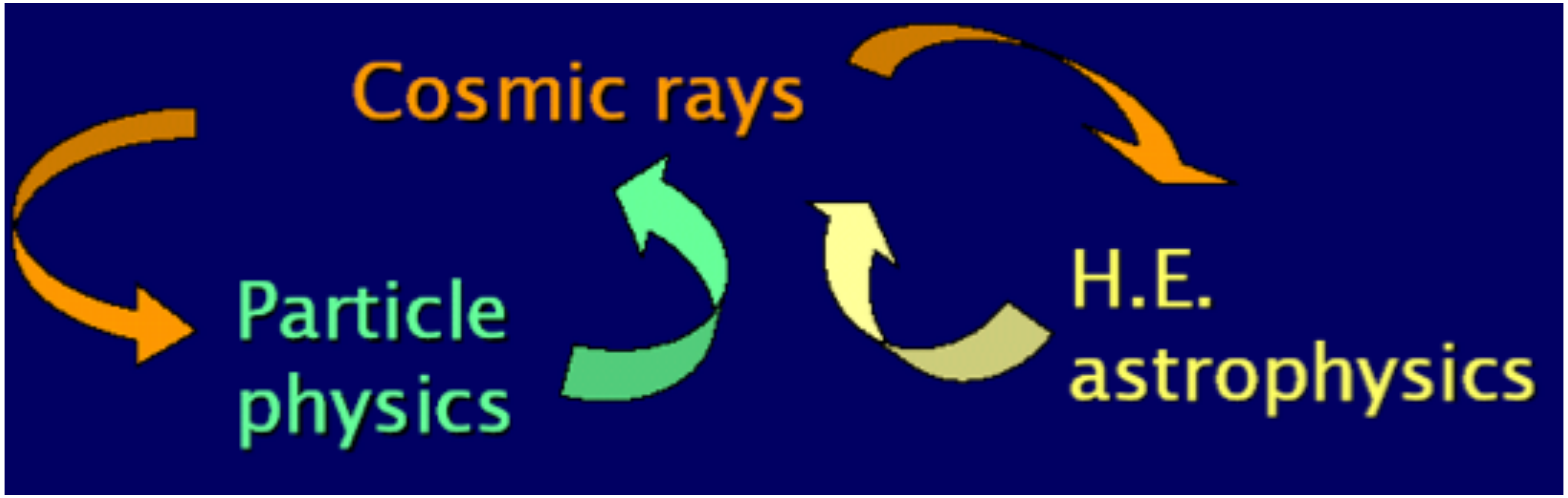


Direct measurements up to E~10^{14} eV primary particles (balloons, satellites)



Indirect measurements E>10^{14} eV secondary particles (ground and underground experiments)

Particle detection



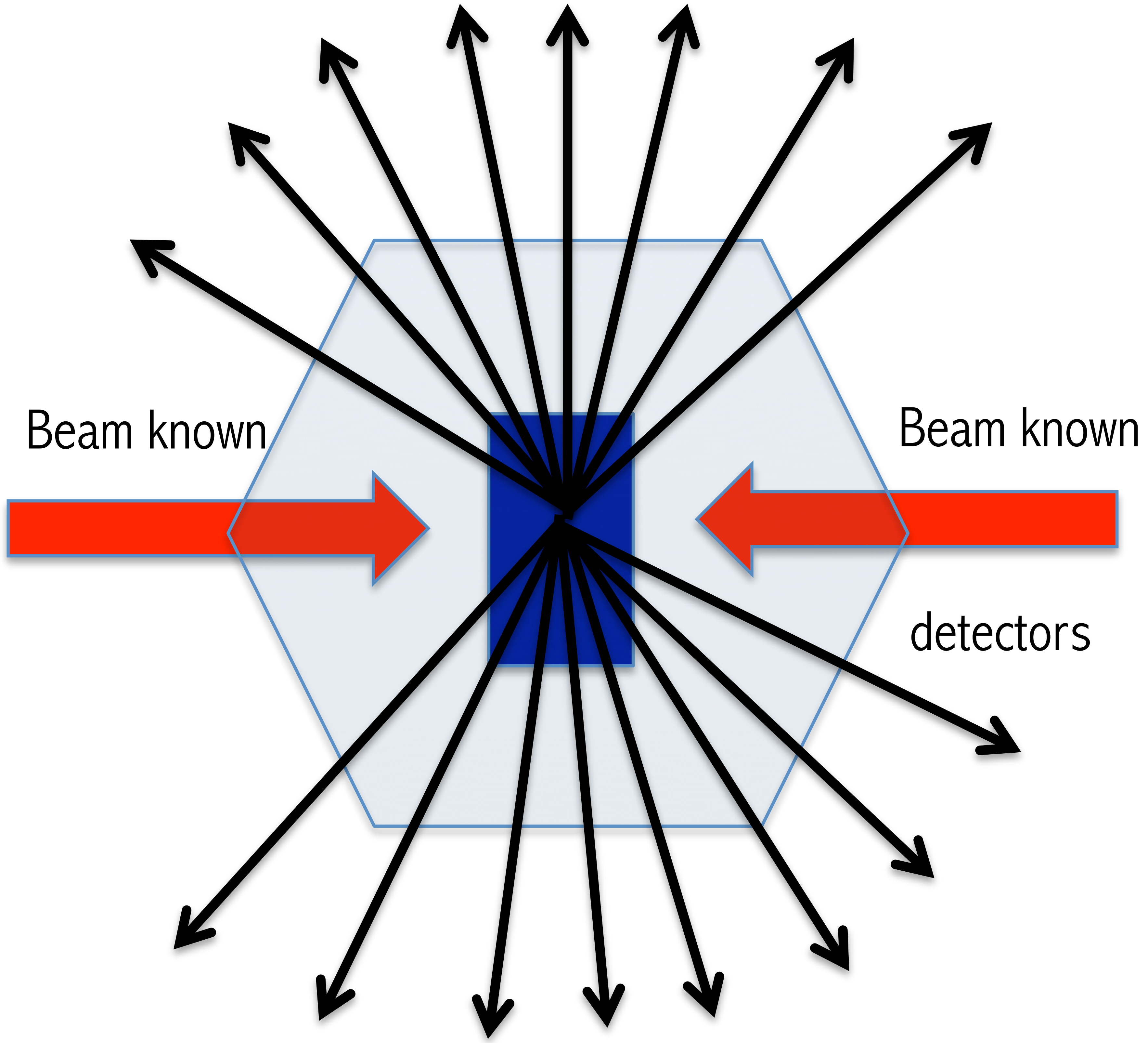
- DETECTION AND STUDY OF COSMIC RAY
- STUDY OF HIGH ENERGY INTERACTIONS IN p-p, Pb-Pb COLLISIONS TO EXTRAPOLATE INFORMATION FOR COSMIC RAY PHYSICS (hadronic interactions)

Particle detection

ACCELERATOR PHYSICS:

BEAM KNOWN → DETECTION OF THE SECONDARIES

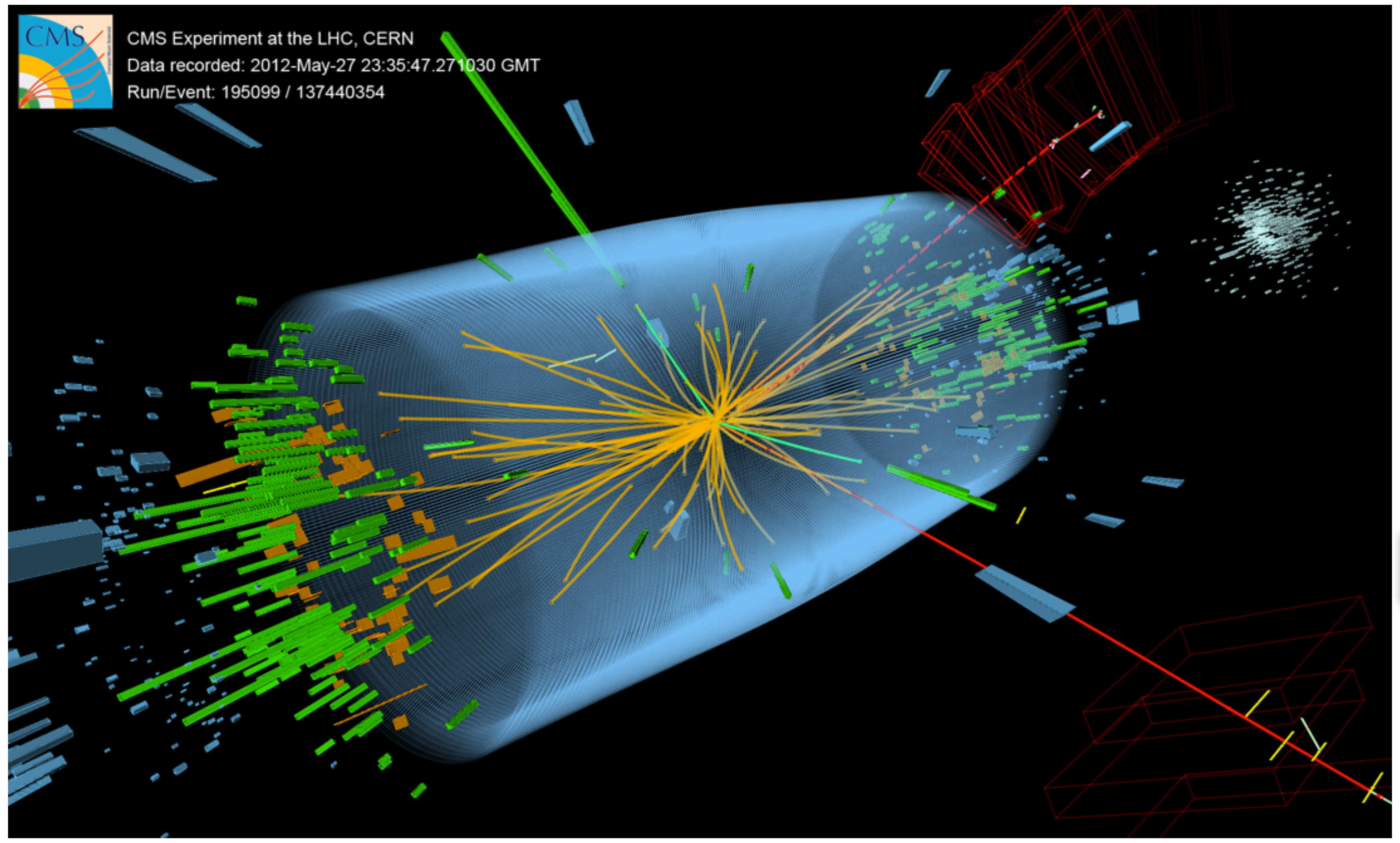
→ STUDY OF THE INTERACTIONS

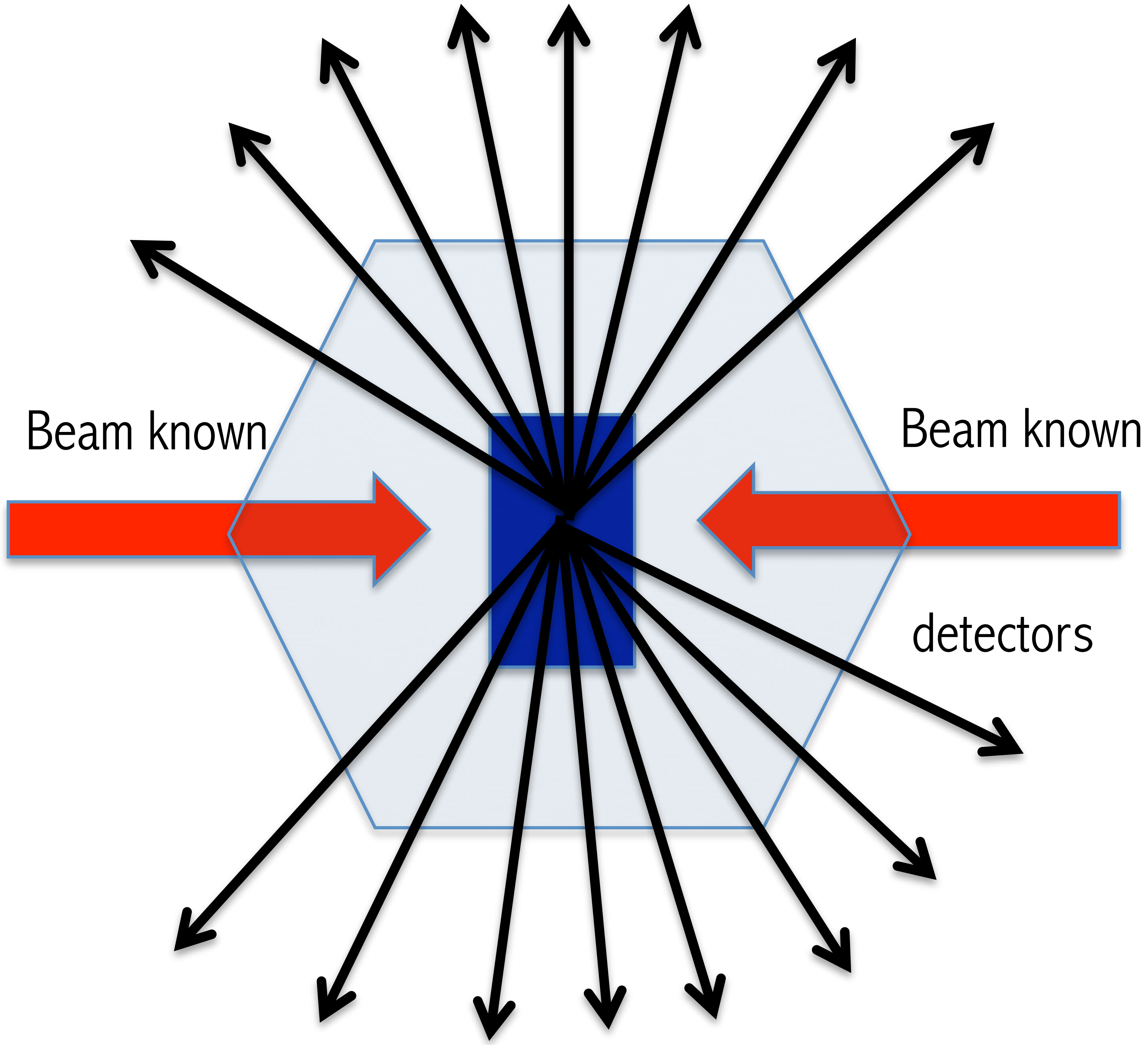


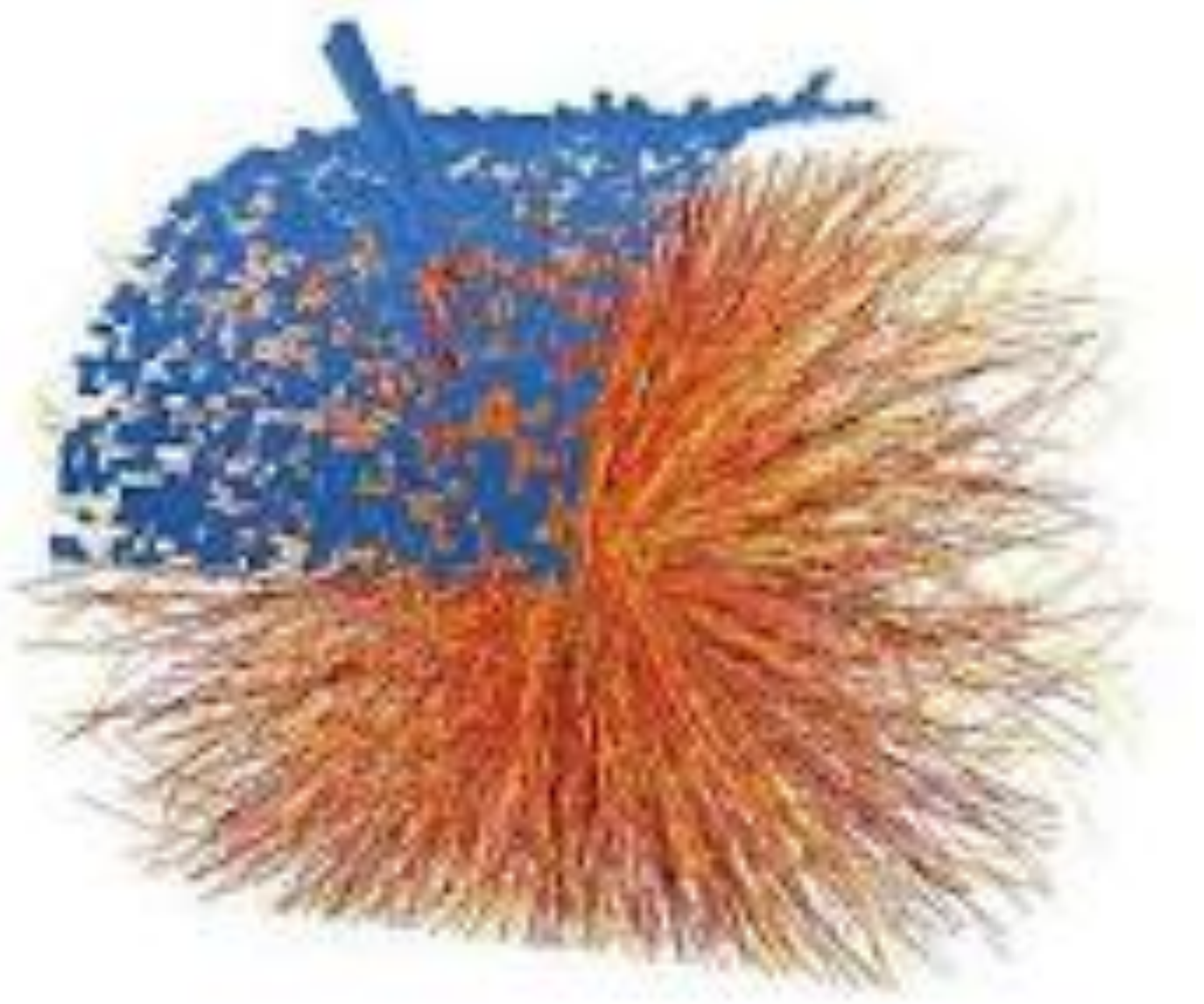
Particle detection

ACCELERATOR PHYSICS:

BEAM KNOWN → DETECTION OF THE SECONDARIES
→ STUDY OF THE INTERACTIONS





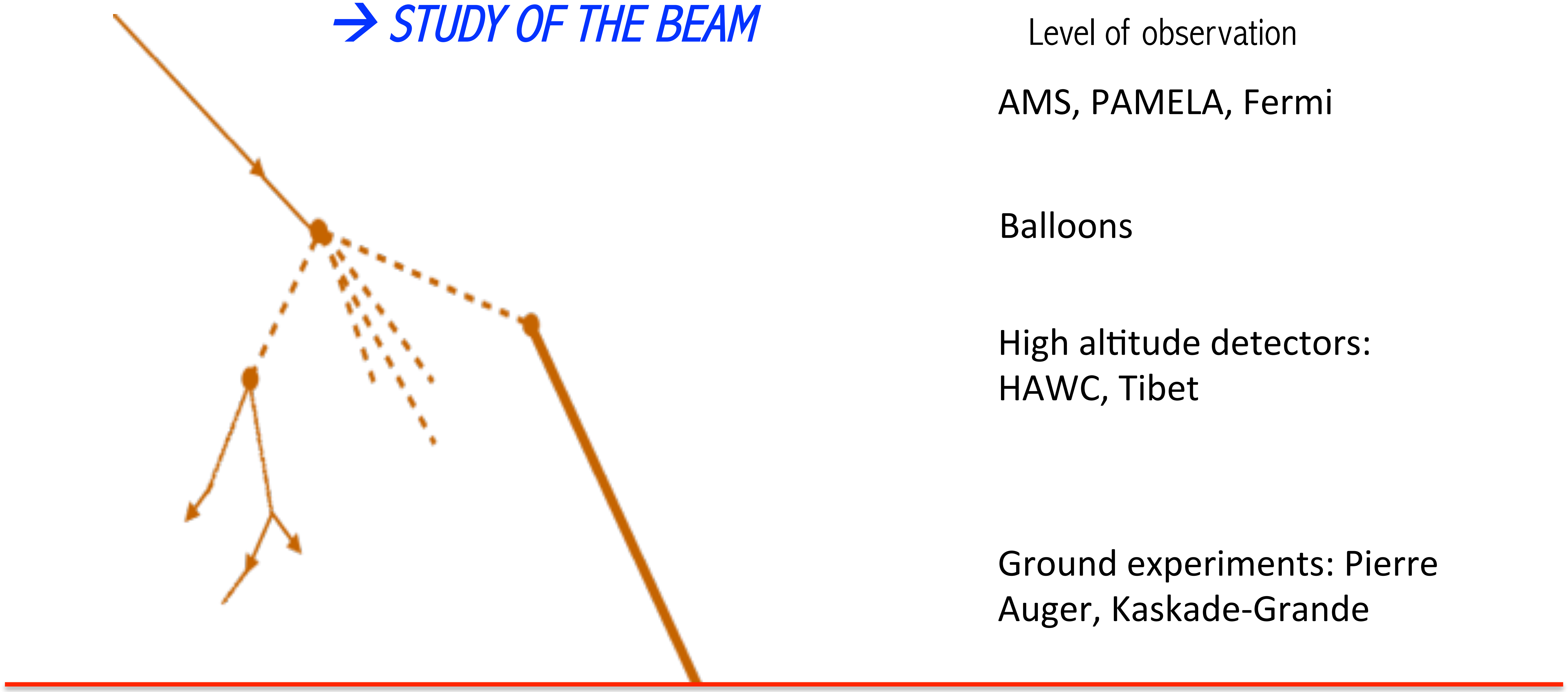


Particle detection

COSMIC RAY PHYSICS WITH EAS:

BEAM UNKNOWN → DETECTION OF THE SECONDARIES ARRIVING AT GROUND

→ *STUDY OF THE BEAM*



Level of observation

AMS, PAMELA, Fermi

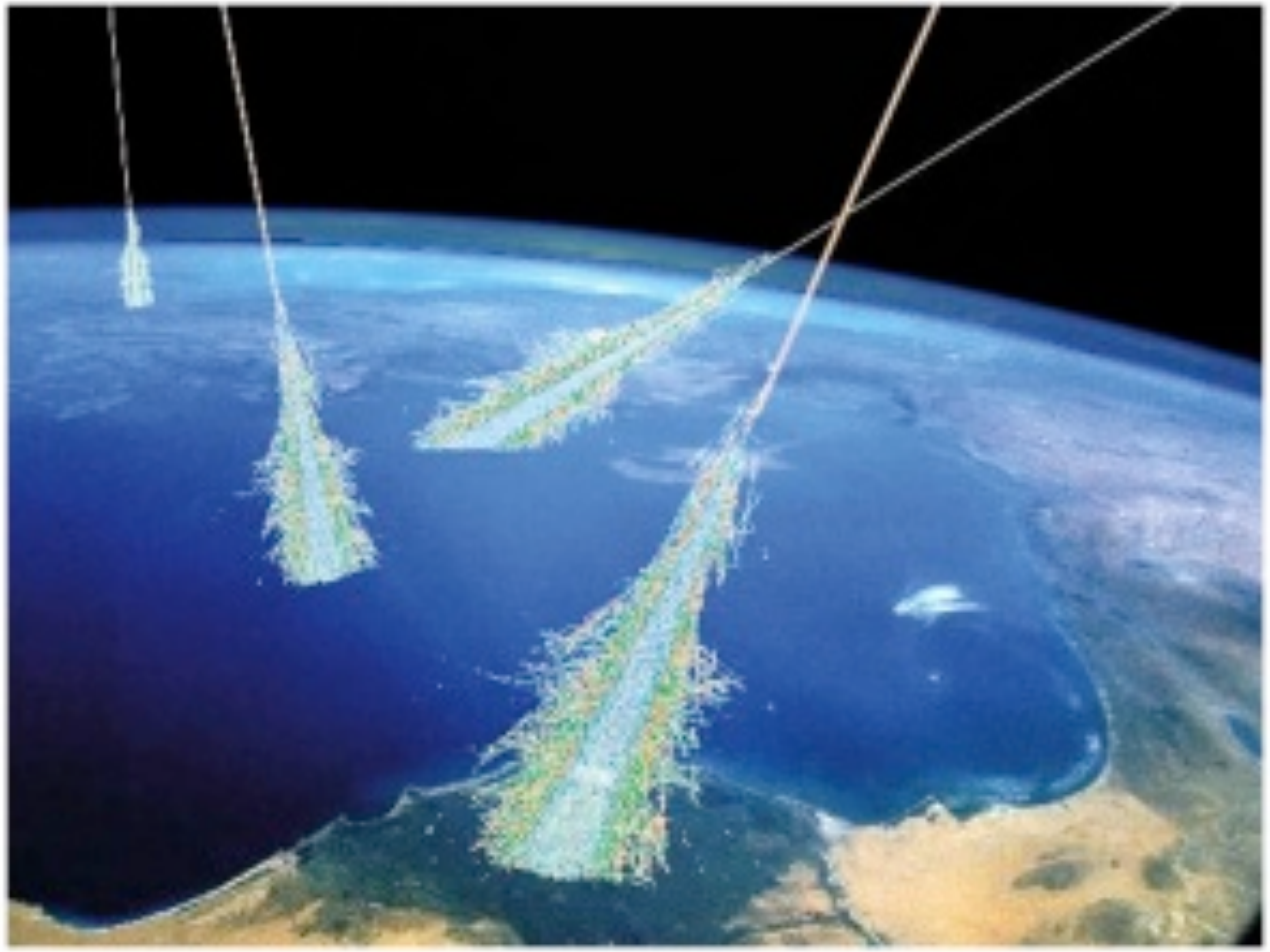
Balloons

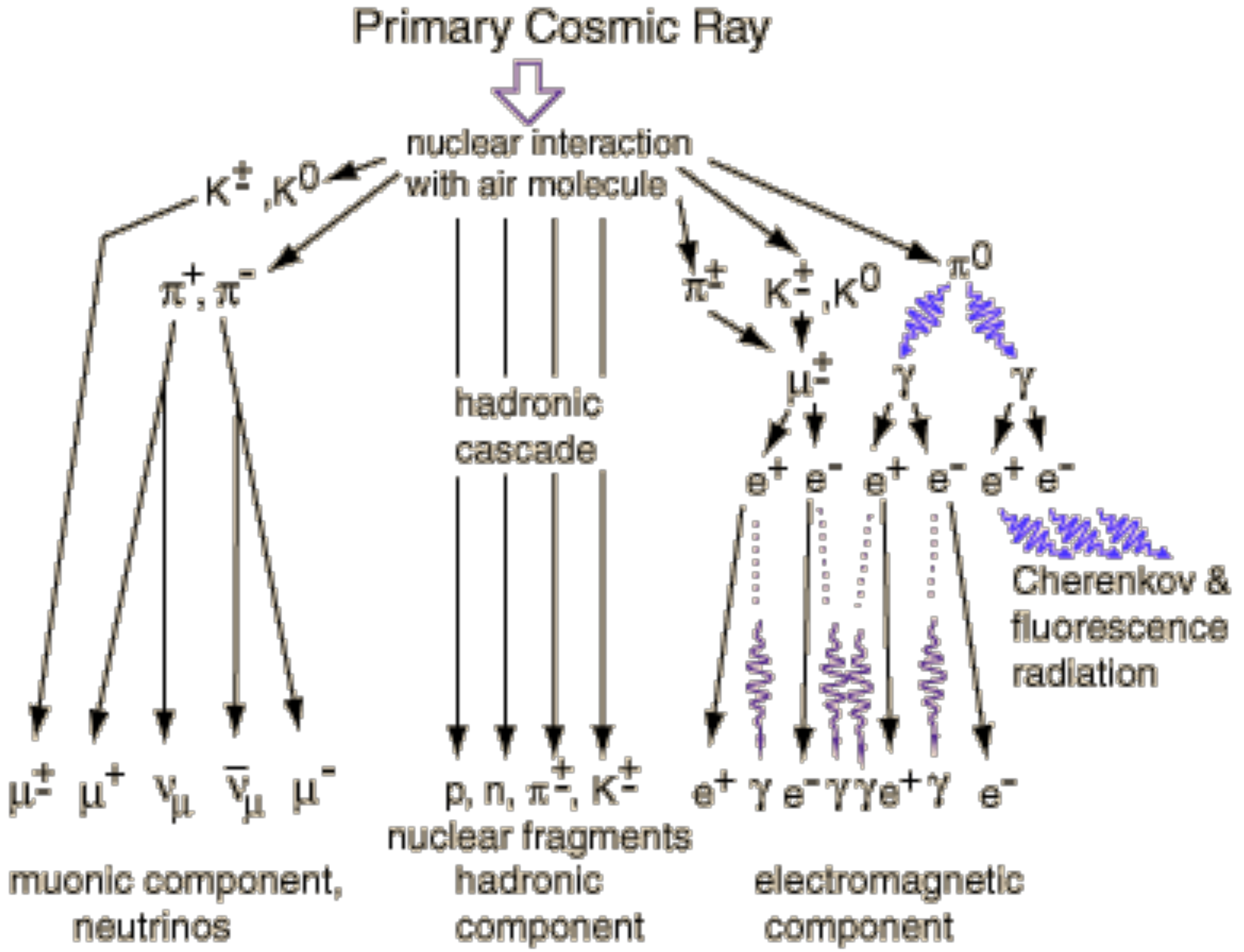
High altitude detectors:
HAWC, Tibet

Ground experiments: Pierre Auger, Kaskade-Grande

Under-ground experiments:
Ice cube, Macro, LEP&LHC experiments

Particle detection





Primary Cosmic Ray

nuclear interaction with air molecule

$K^{\pm}, K^{0}$

π^{+}, π^{-}

$\pi^{\pm}$

$K^{\pm}, K^{0}$

π^{0}

$\mu^{\pm}$

γ

γ

hadronic cascade

e^{+} e^{-} e^{+} e^{-} e^{+} e^{-}

Cherenkov & fluorescence radiation

$\mu^{\pm}$ μ^{+} ν_{μ} $\bar{\nu}_{\mu}$ μ^{-}

$p, n, \pi^{\pm}, K^{\pm}$

nuclear fragments

e^{+} γ e^{-} γ γ e^{+} γ e^{-}

muonic component, neutrinos

hadronic component

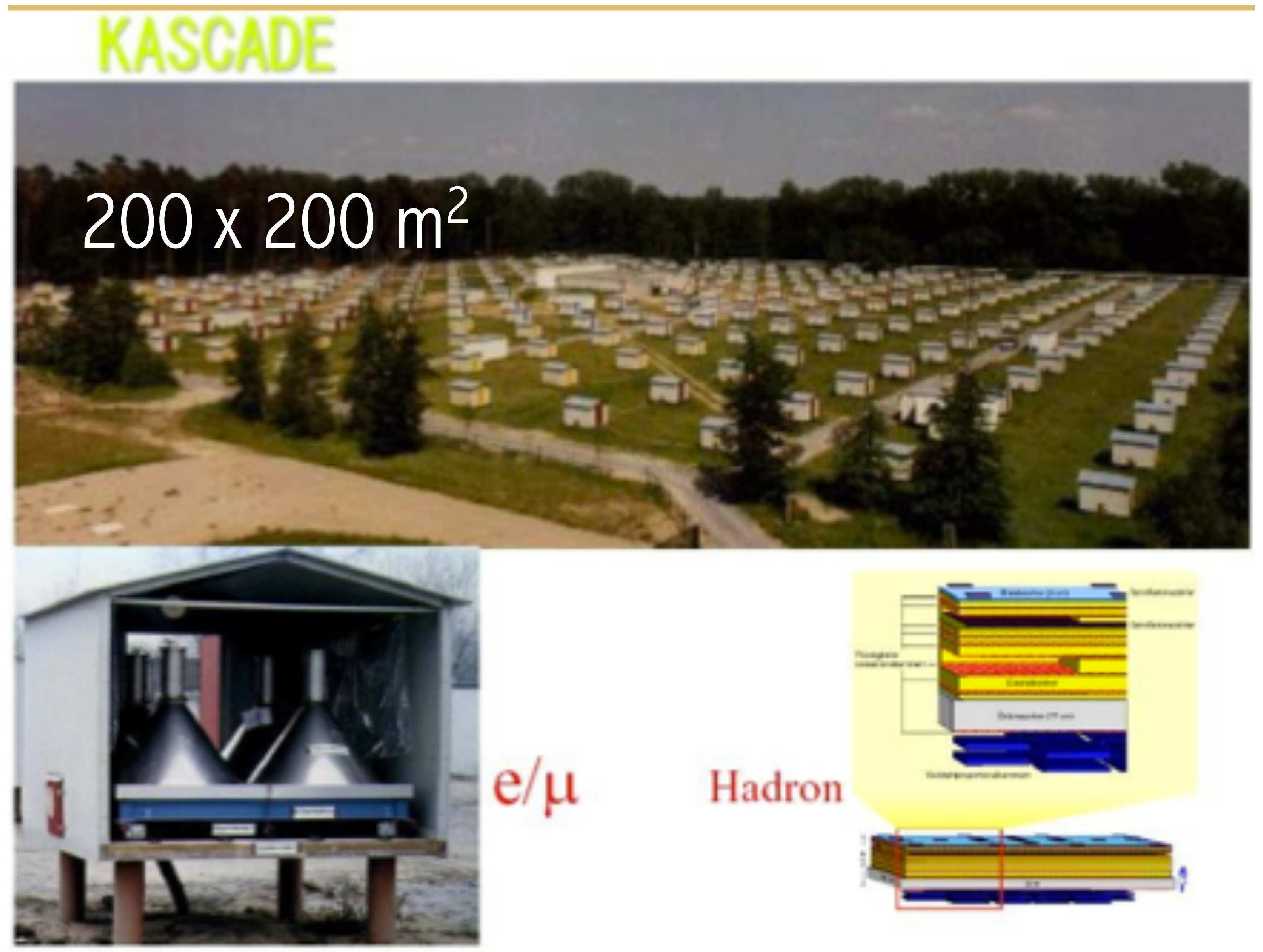
electromagnetic component

Direct measurements up to E ~ 10^{14} eV

- Primary particles (balloons, satellites)

Indirect measurements with (under)ground experiments to E > 10^{14} eV

- ☆ Cosmic ray interactions with atmosphere and Extensive Air Showers (EAS)
- ☆ Measurements around the knee (Eas-Top, Kaskade, Casa …) and beyond (Kaskade-Grande)
- ☆ Ultra high energy cosmic rays (Auger, HiRes)
- ☆ Underground experiments (Macro, Emma)
- ☆ **COSMIC RAY PHYSICS AT CERN (LEP: L3+C, ALEPH, DELPHI; LHC: CMS, ALICE)**



- ✧ Small apparatus
- ✧ Low underground
- ✧ Detection of muons crossing the rock

★ These apparatus are not designed for cosmic ray physics ☹ :

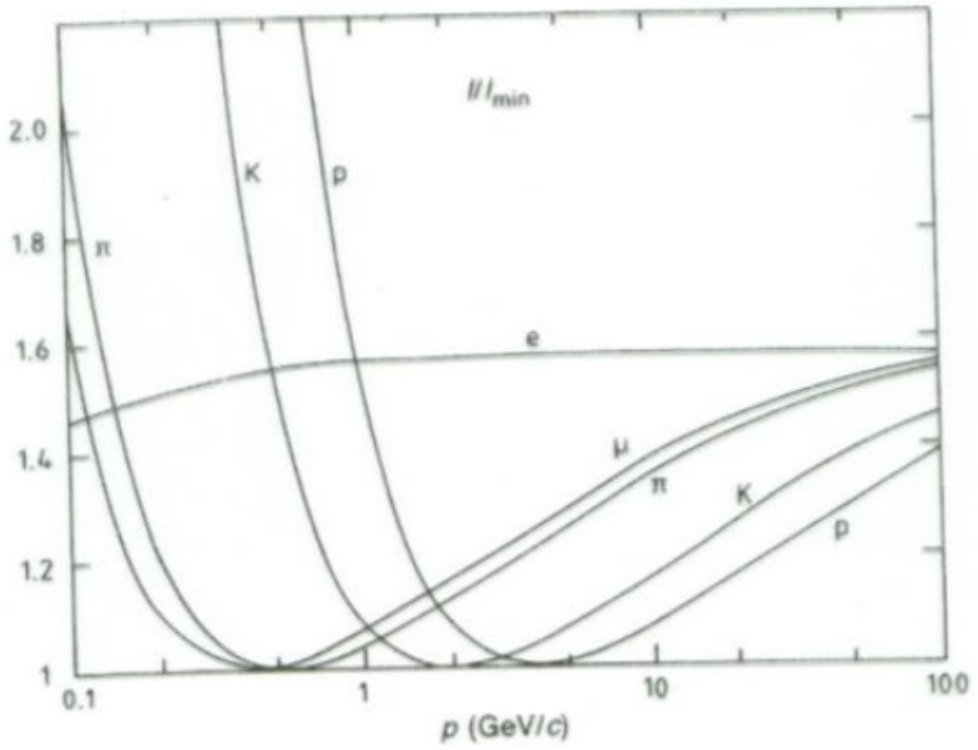
❑ Small detectors compared with the standard cosmic ray apparatus:

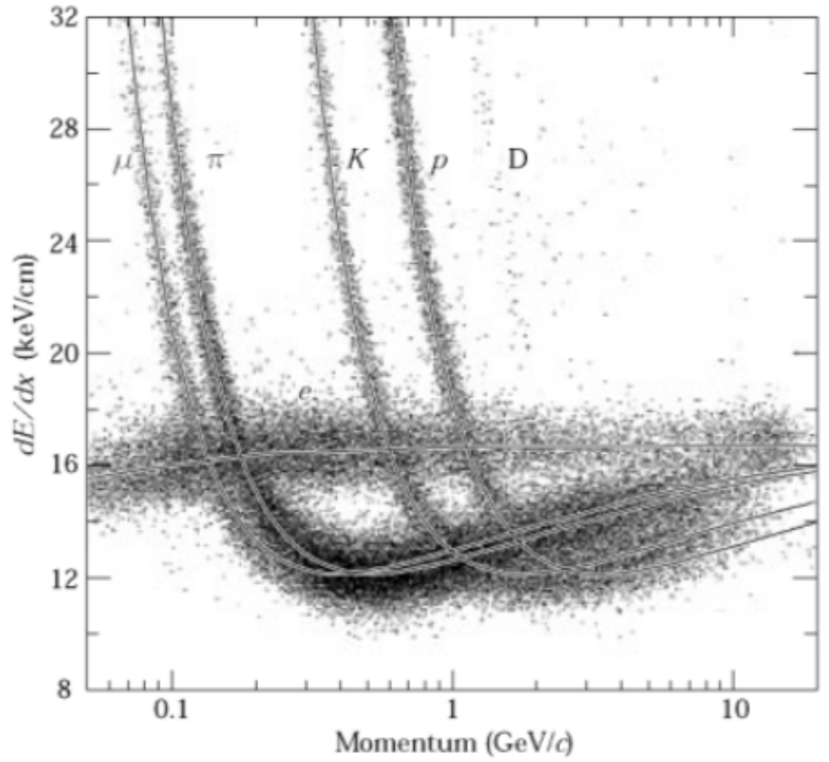
  - ✧ Only muons are detected
  - ✧ Short live time of data taking

- ✓ Advantage: detectors with very high performances, presence of magnetic field ☺
- ✓ Why to study cosmic ray events with dedicated accelerator experiments? → remember that the only result out of LEP that did not agree "perfectly" with the Standard Model was the observation of too many multiplicity muon bundles.

Particle detection

Energy Loss as a Function of the Momentum



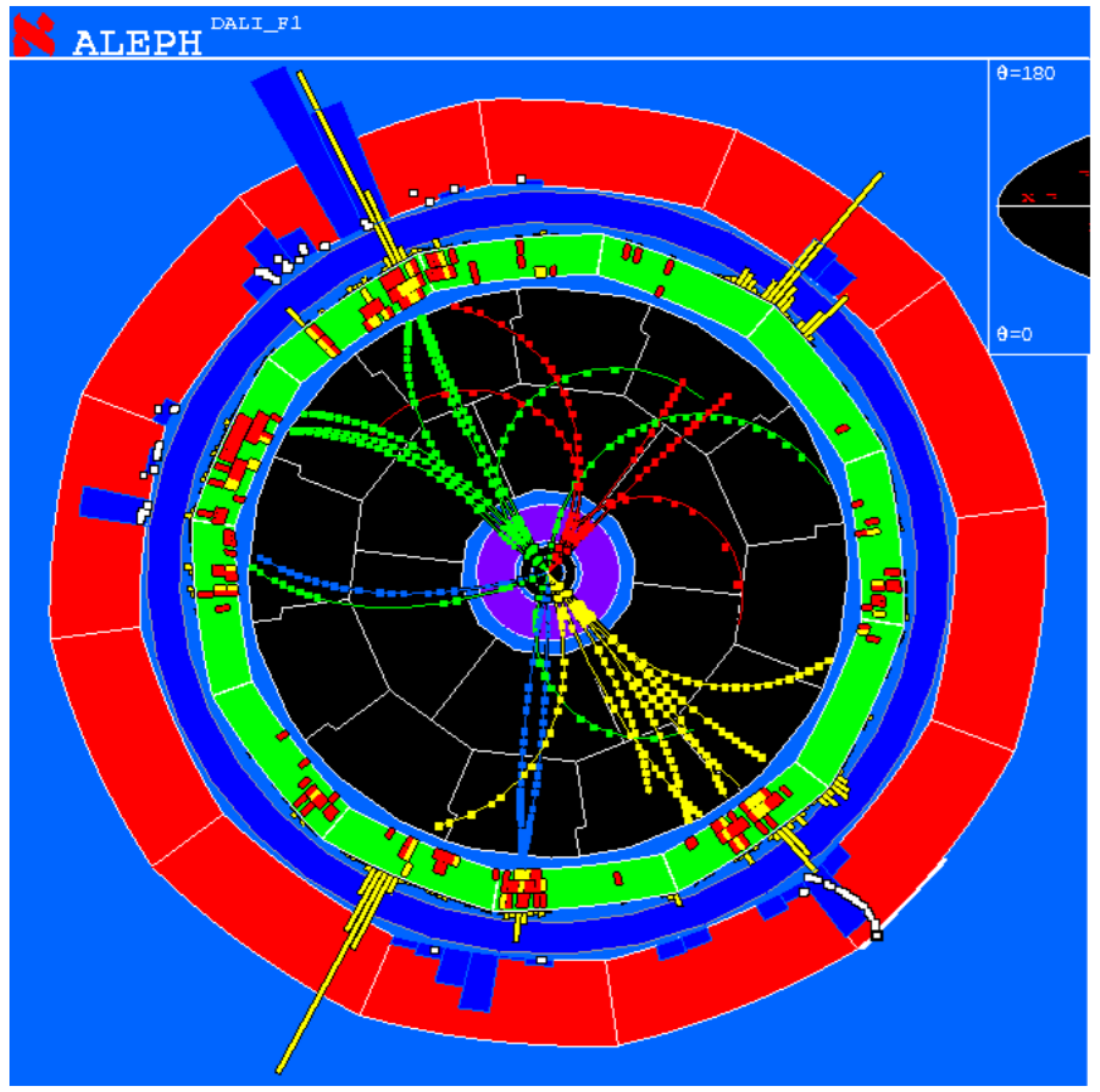


Energy loss depends on the particle velocity and is ≈ independent of the particle's mass M.

The energy loss as a function of particle Momentum P= Mcβγ IS however depending on the particle's mass

By measuring the particle momentum (deflection in the magnetic field) and measurement of the energy loss on can measure the particle mass

→ Particle Identification !



Measure momentum by curvature of the particle track.

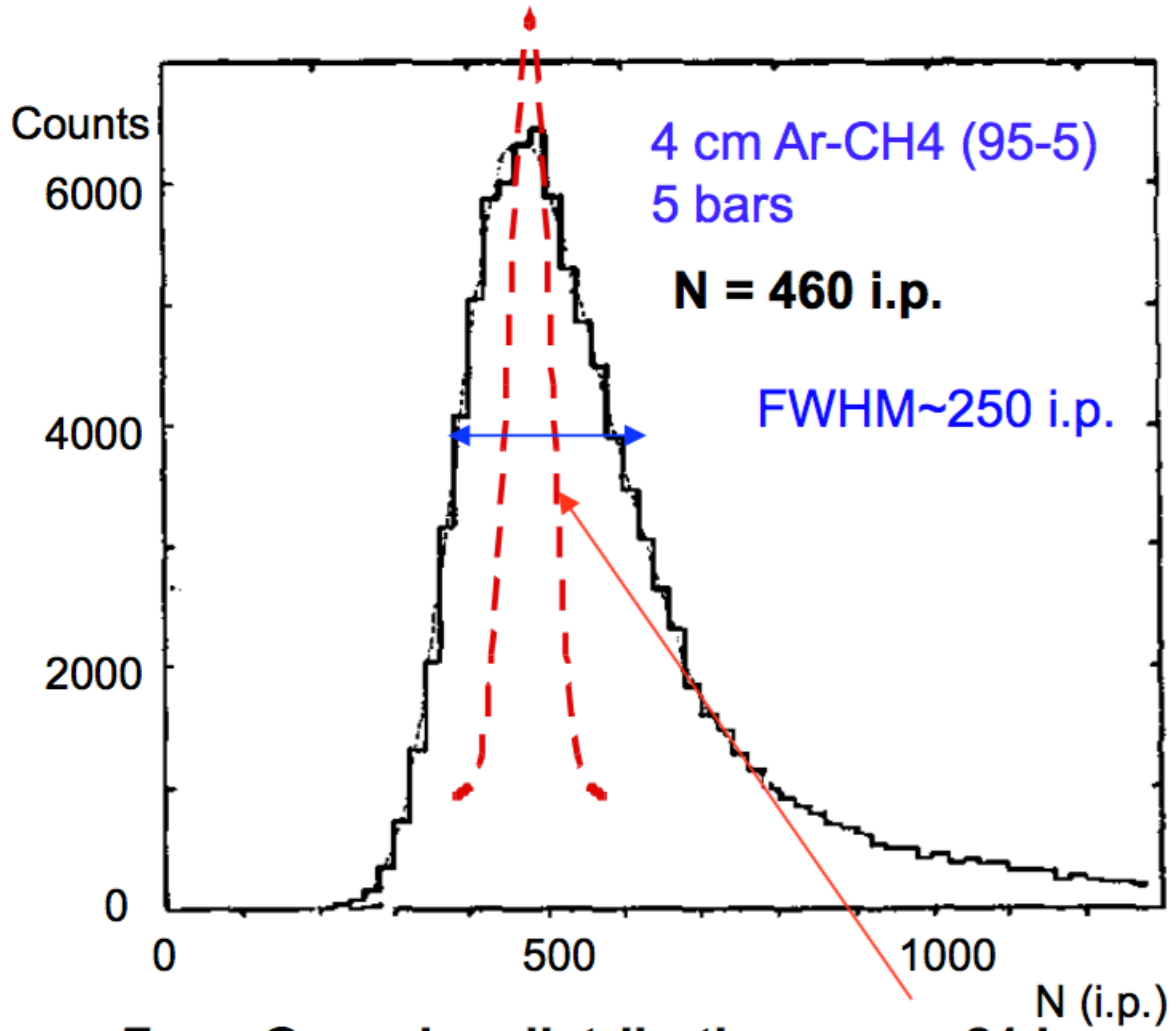
Find dE/dx by measuring the deposited charge along the track.

→Particle ID

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, Z_1^2 \frac{p^2 + M^2c^2}{p^2} N_A \frac{Z}{A}\left[\ln \frac{2m_e c^2 F}{I}\frac{p^2}{M^2c^2} - \frac{p^2}{p^2 + M^2c^2}\right]$$

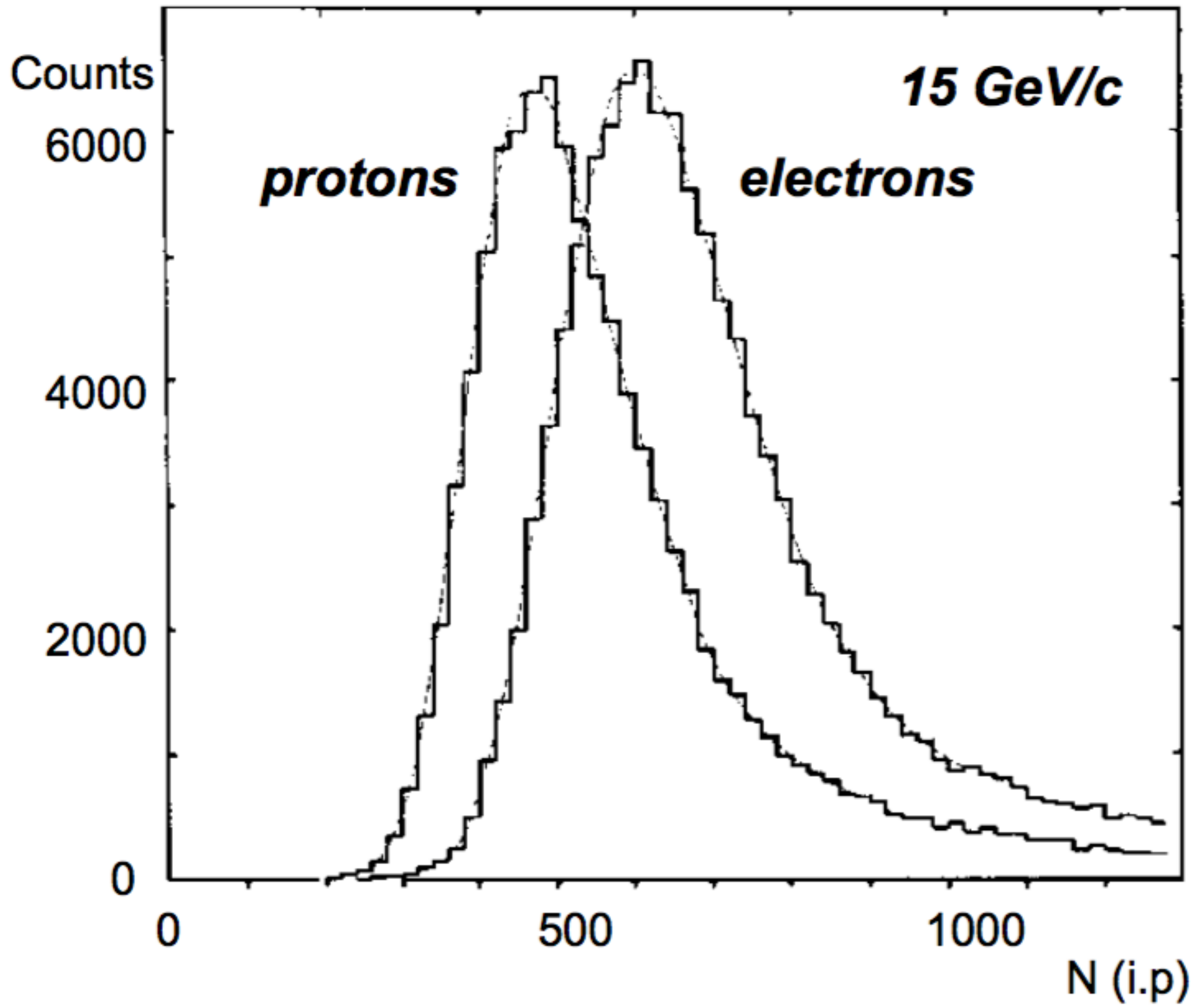
Particle detection

LANDAU DISTRIBUTION OF ENERGY LOSS:



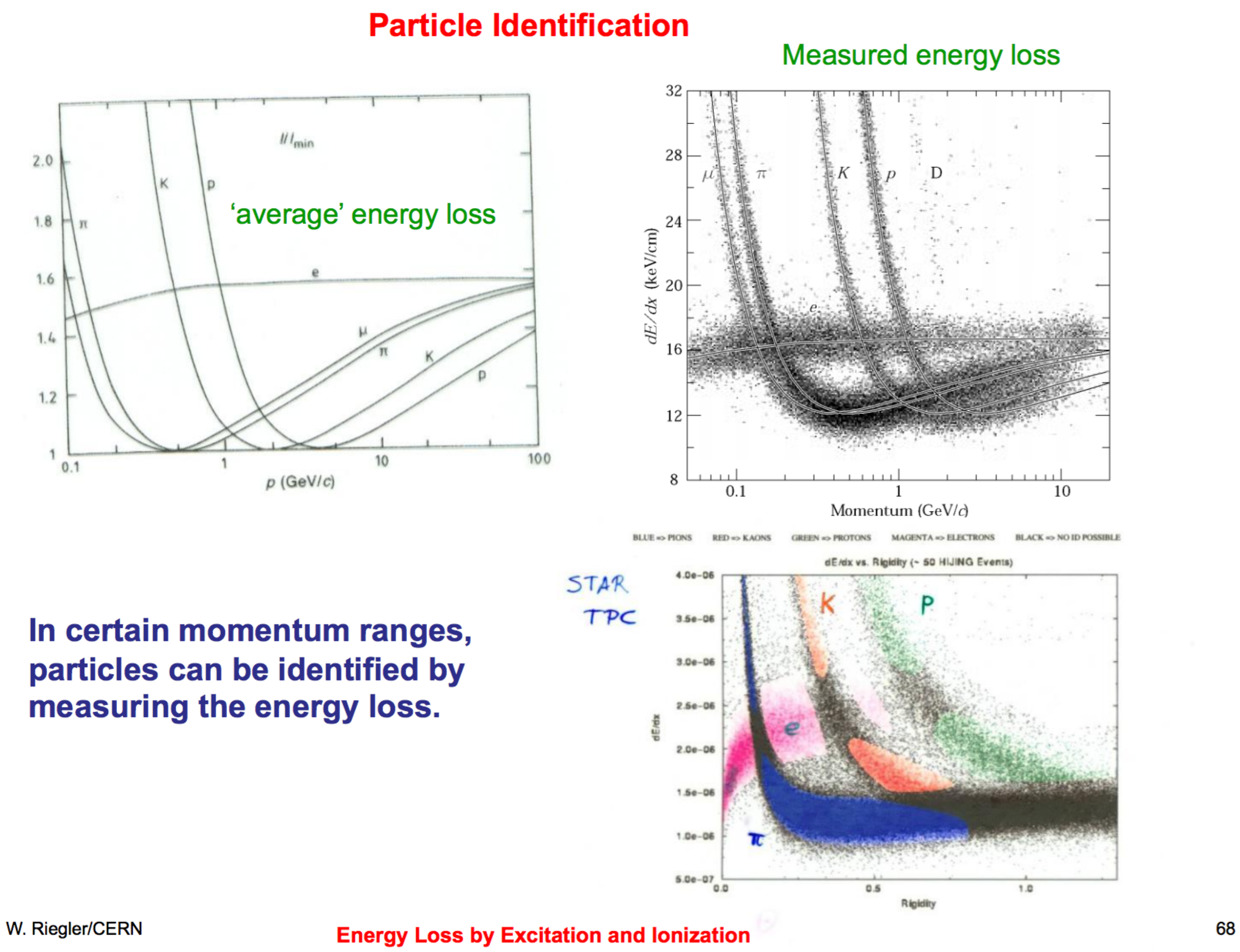
For a Gaussian distribution: **σ_N ~ 21 i.p.**
FWHM ~ 50 i.p.

PARTICLE IDENTIFICATION
Requires statistical analysis of hundreds of samples



I. Lehraus et al, Phys. Scripta 23(1981)727

Particle detection



Particle Identification

Measured energy loss

'average' energy loss

In certain momentum ranges, particles can be identified by measuring the energy loss.

STAR TPC

W. Riegler/CERN

Energy Loss by Excitation and Ionization

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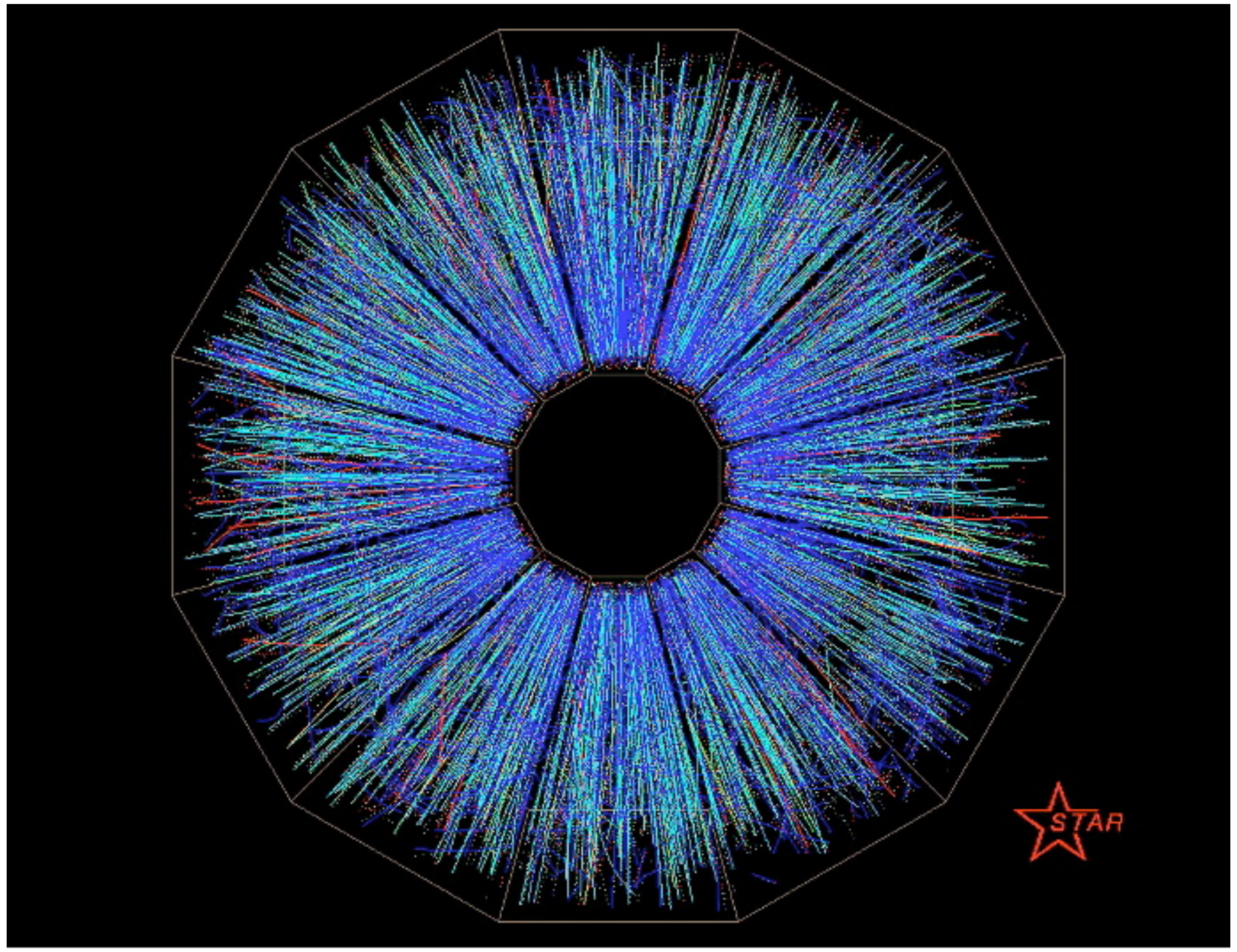
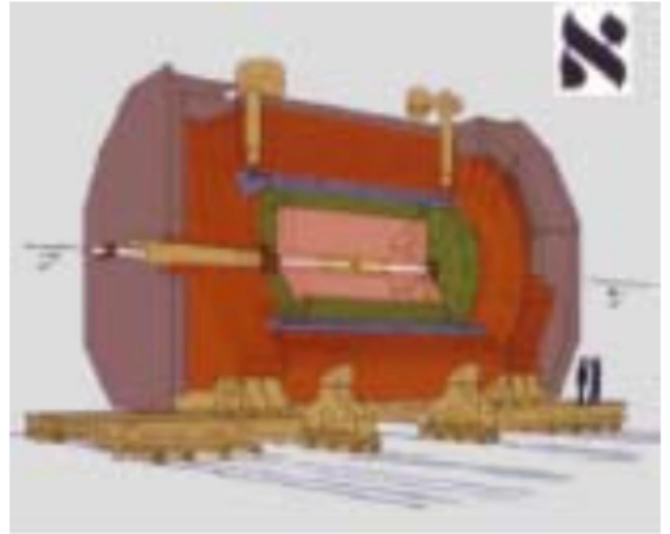


LEP RESULTS

Experiments II



Cosmo-ALEPH

130 m underground

Hadron calorimeter

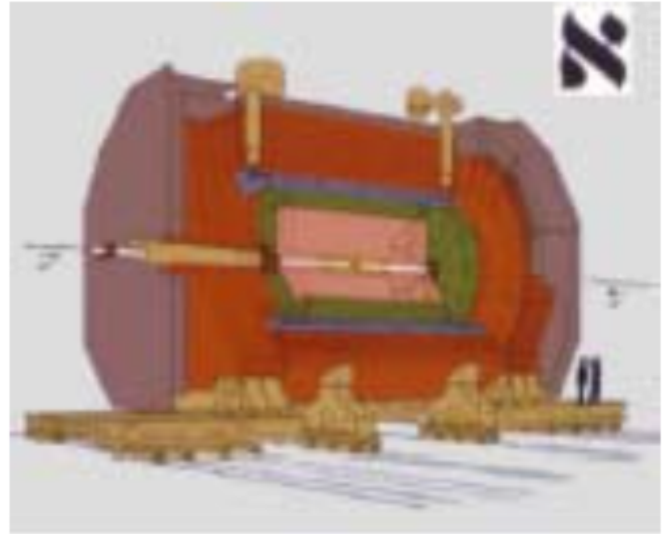
TPC + 5 scintillator stations

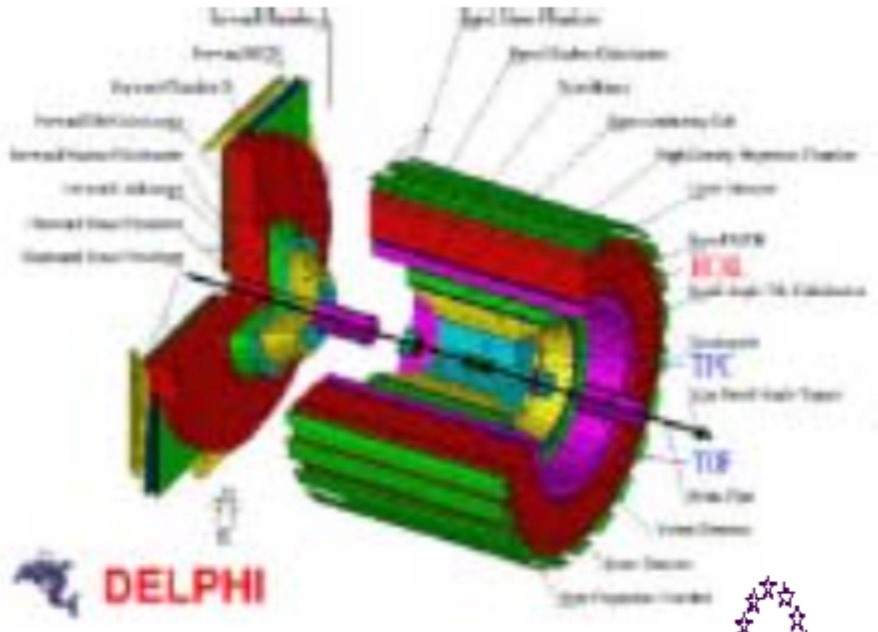
Muon energy spectrum

Charge ratio

Multiplicity, lateral distributions, sources

Experiments II





Cosmo-ALEPH

130 m underground

Hadron calorimeter

TPC + 5 scintillator stations

Muon energy spectrum

Charge ratio

Multiplicity, lateral distributions, sources

DELPHI

100 m underground

Hadron calorimeter

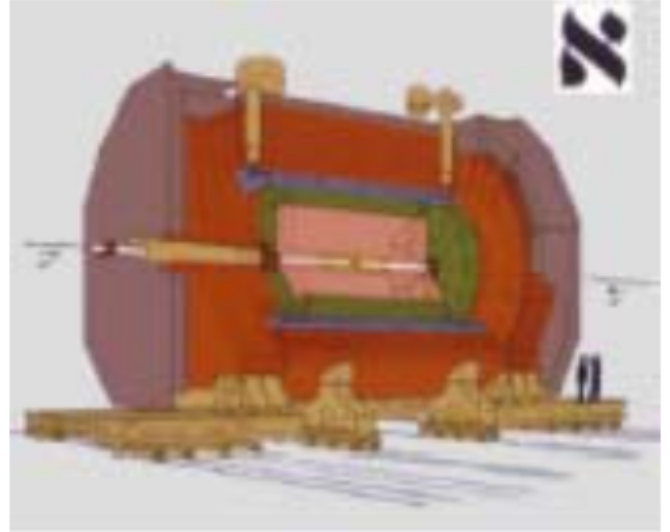
TPC, TOF, muon chambers

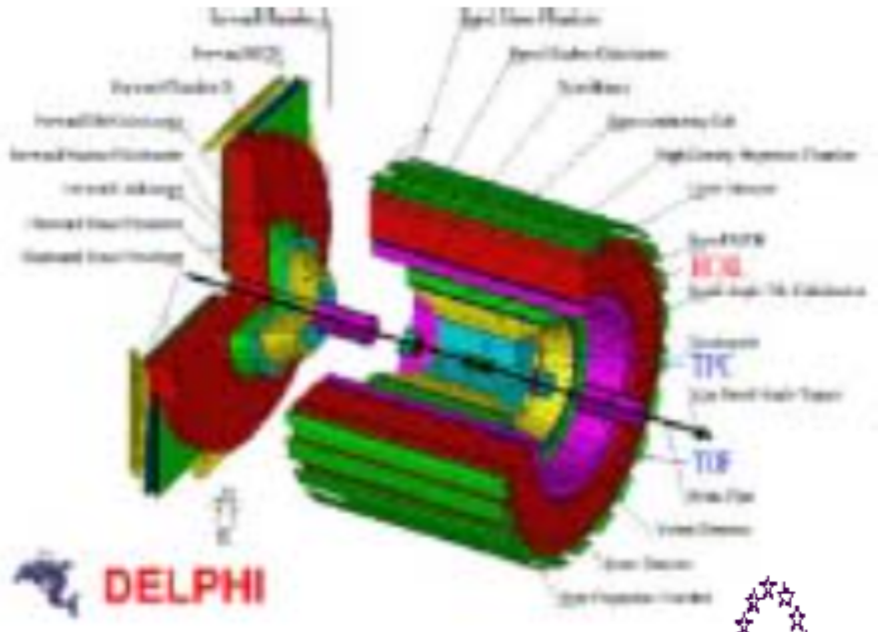
Multiplicity,

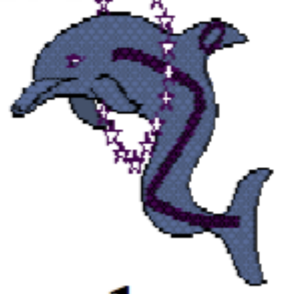
sources

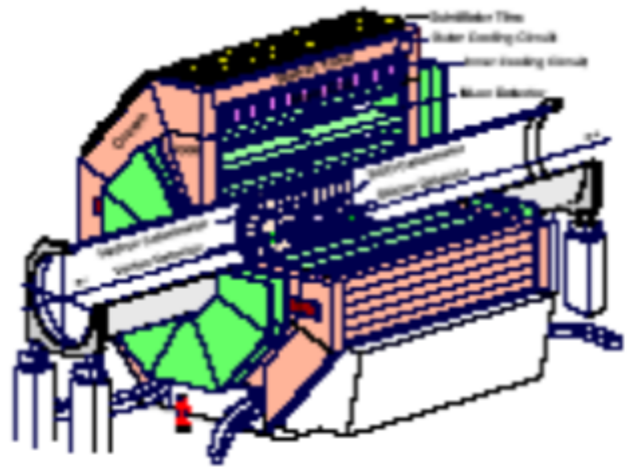
Experiments II

From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005









Cosmo-ALEPH

130 m underground

Hadron calorimeter

TPC + 5 scintillator stations

Muon energy spectrum

Charge ratio

Multiplicity, lateral distributions, sources

DELPHI

100 m underground

Hadron calorimeter

TPC, TOF, muon chambers

Multiplicity,

sources

L3+C

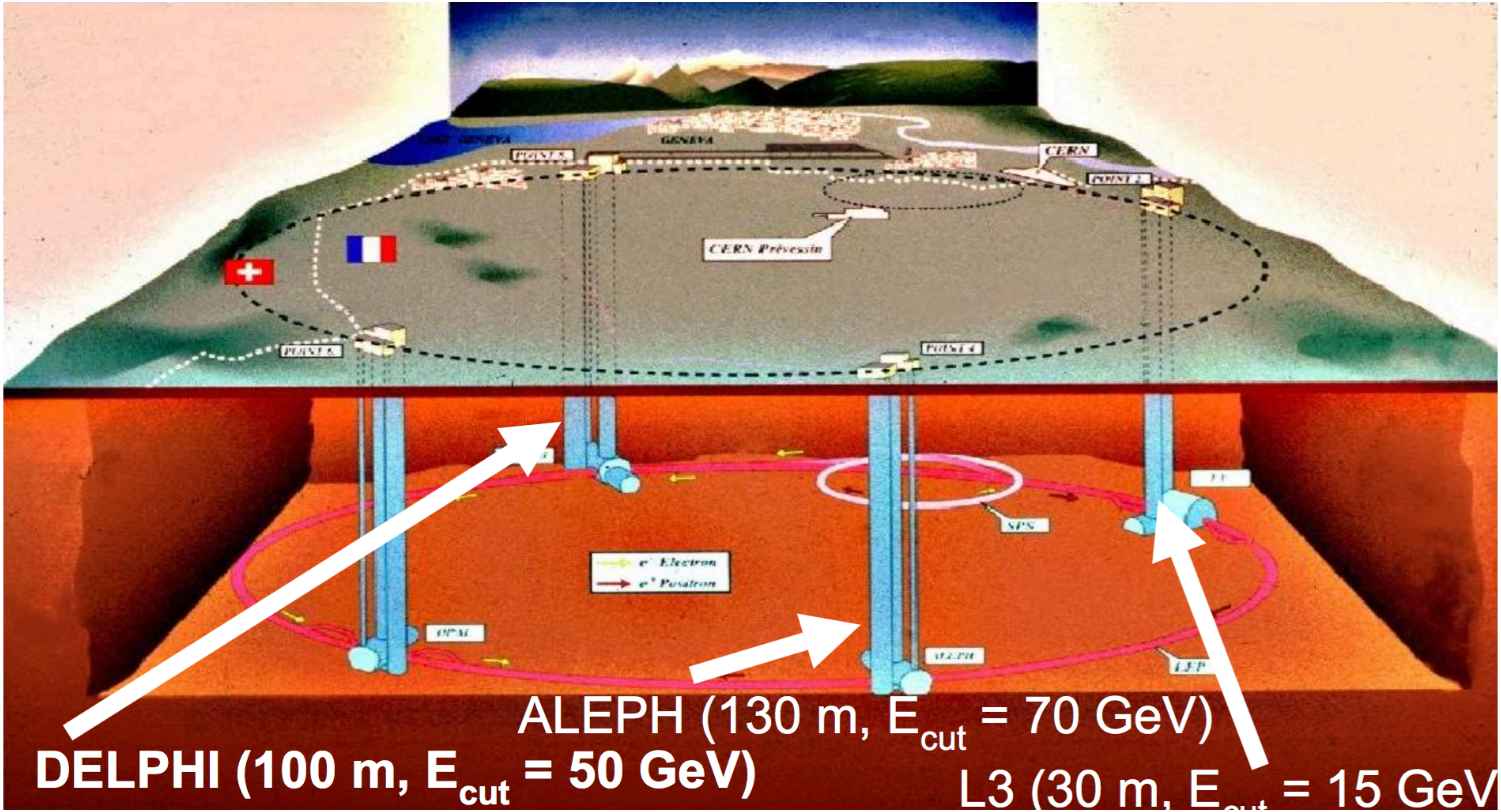
40 m underground

Drift chambers

Timing scintillators, surface array, dedicated trigger

Muon spectrum, charge ratio, antiproton limit, sources, flares …, multiplicity

LEP:Large Electro-Positron collider



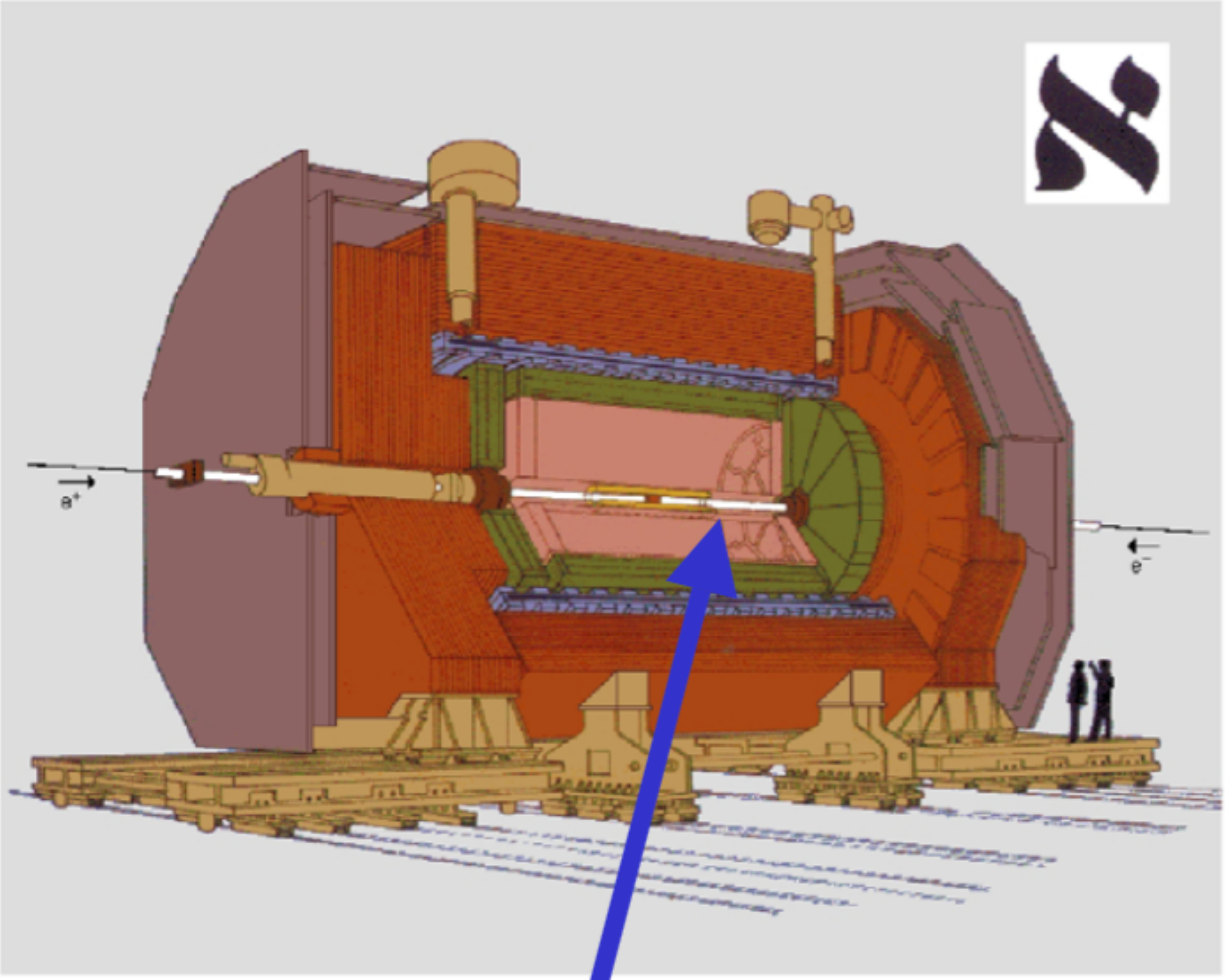
ALEPH (130 m, E_{cut} = 70 GeV)

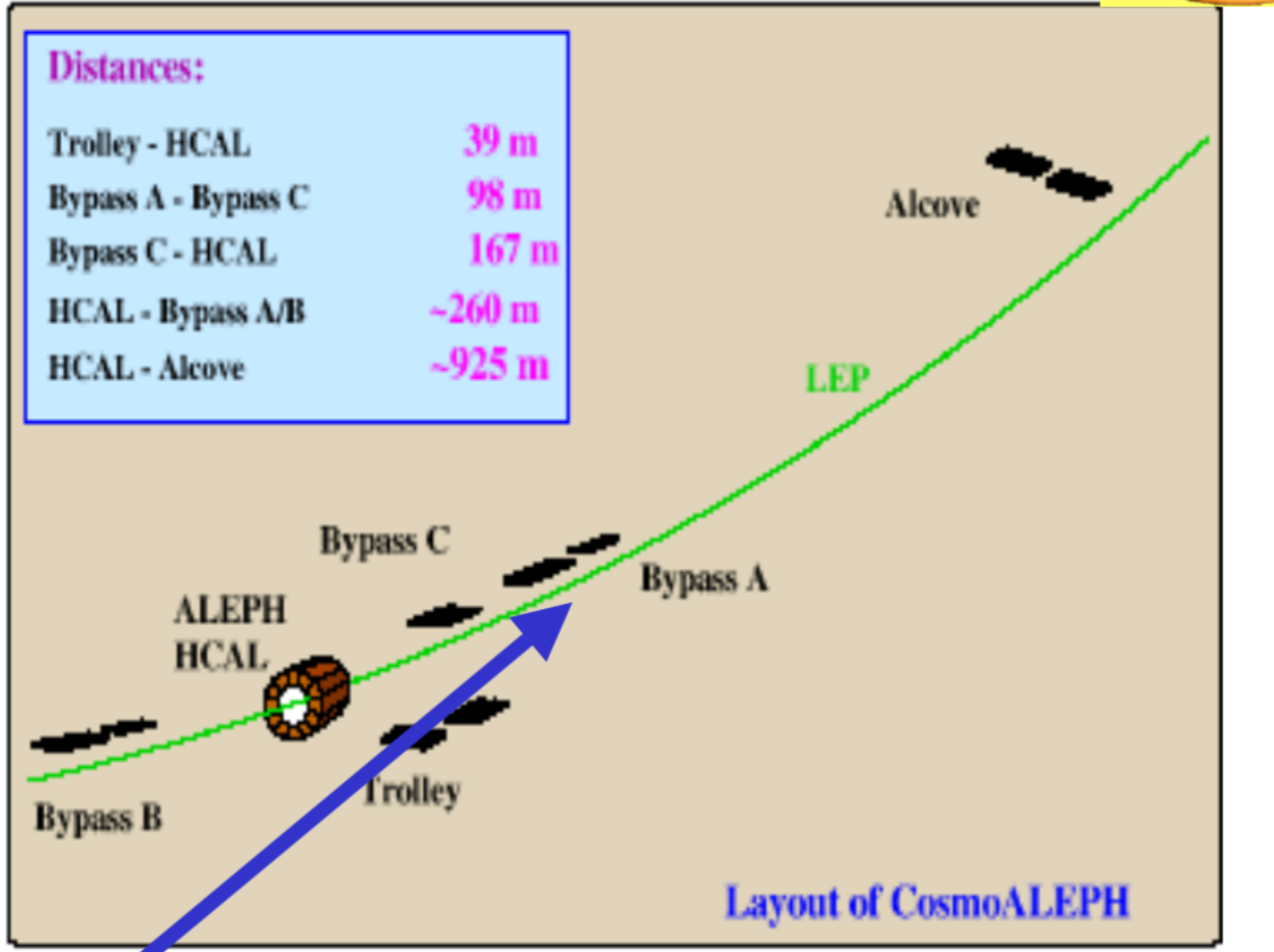
DELPHI (100 m, E_{cut} = 50 GeV)

L3 (30 m, E_{cut} = 15 GeV

Cosmo-ALEPH

From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005





Distances:

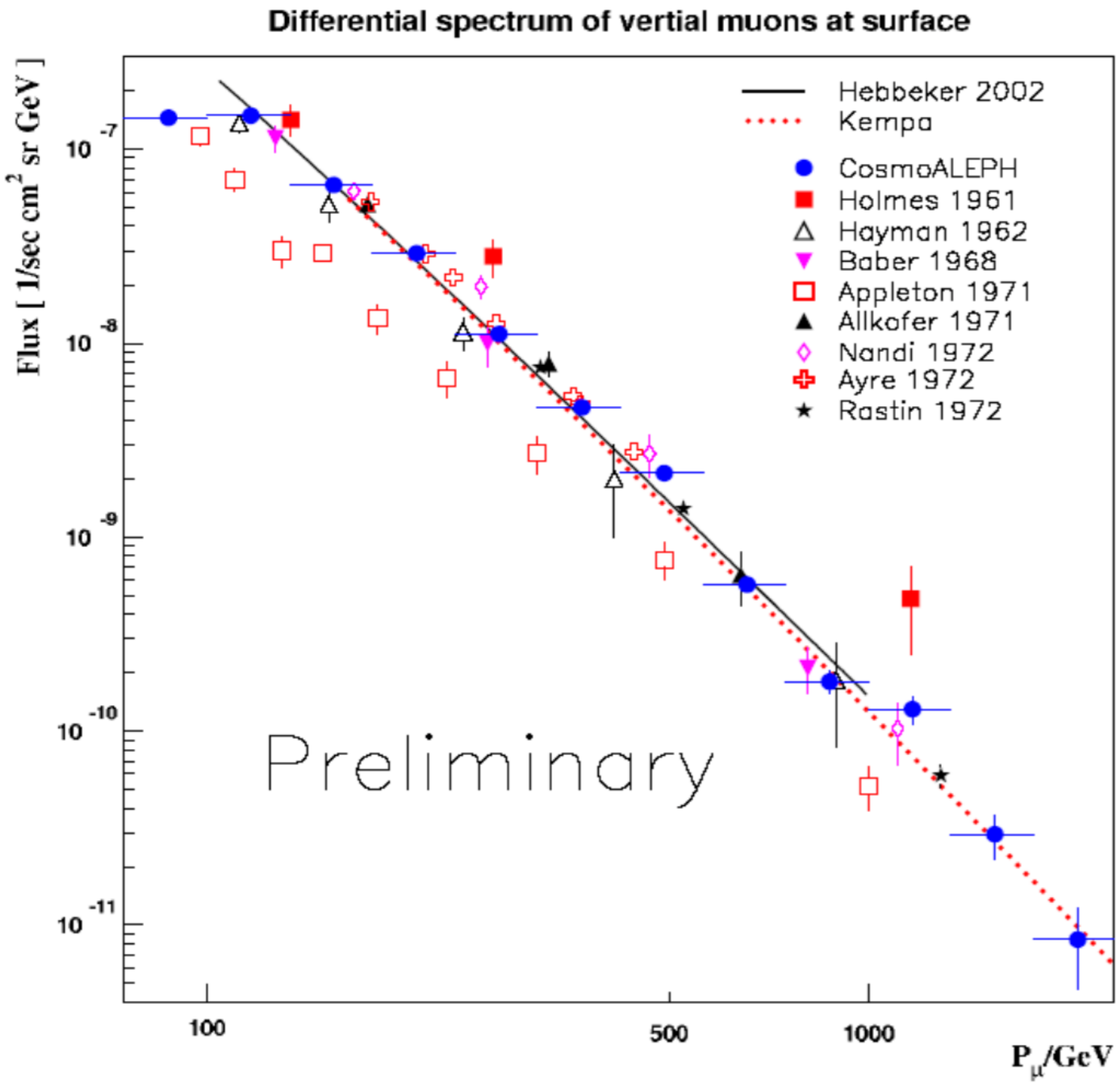
Trolley - HCAL	39 m
Bypass A - Bypass C	98 m
Bypass C - HCAL	167 m
HCAL - Bypass A/B	~260 m
HCAL - Alcove	~925 m

Layout of CosmoALEPH

16 m^2 TPC, array of 5 scintillators, experiment running with respect to beam crossing frequency => 11 % duty cycle. Also dedicated runs without beams in accelerator (CosmoALEPH trigger from HCAL)

maximal detectable momentum 3 TeV

Cosmo-ALEPH
Momentum spectrum of vertical muons



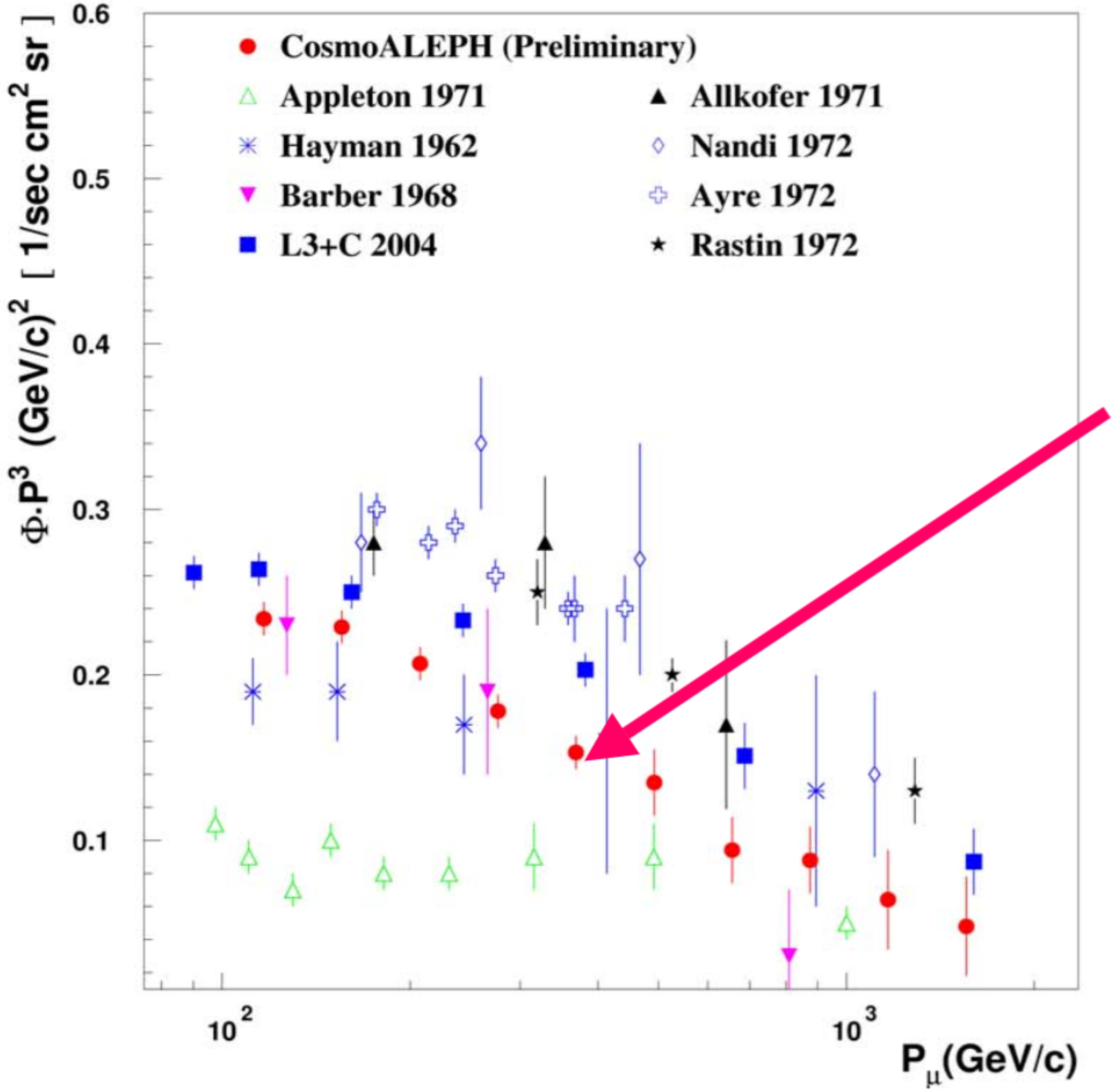
Normalized at 200 GeV to world average

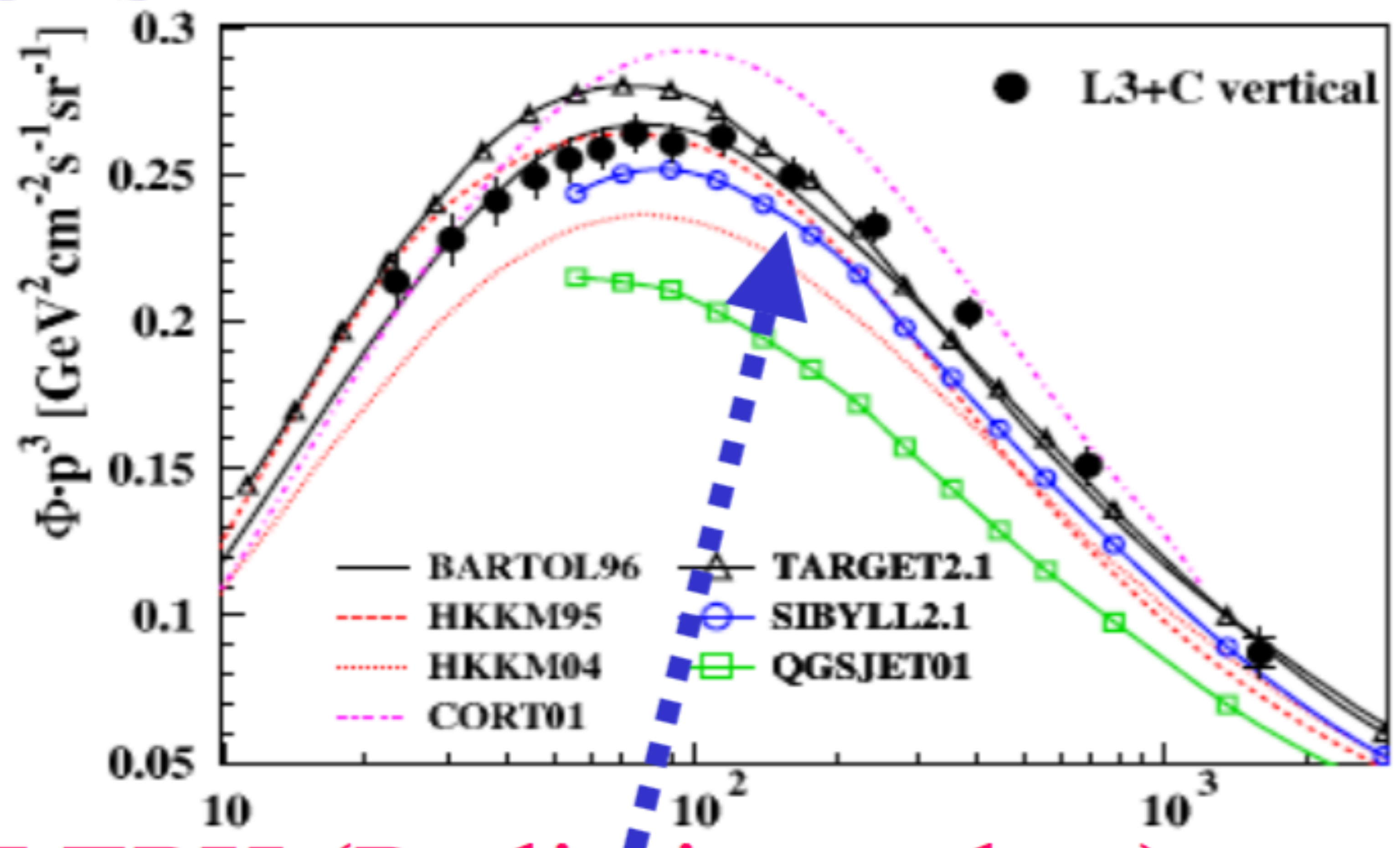
Conversion from underground momentum to ground energy according to energy loss formula:

$dE/dx = -a - bE$ ($a = 0.21$ GeV/m.w.e, $b = 4 \times 10^{-4}$ m.w.e.$^{-1}$)

Cosmo-ALEPH

Momentum spectrum of vertical muons





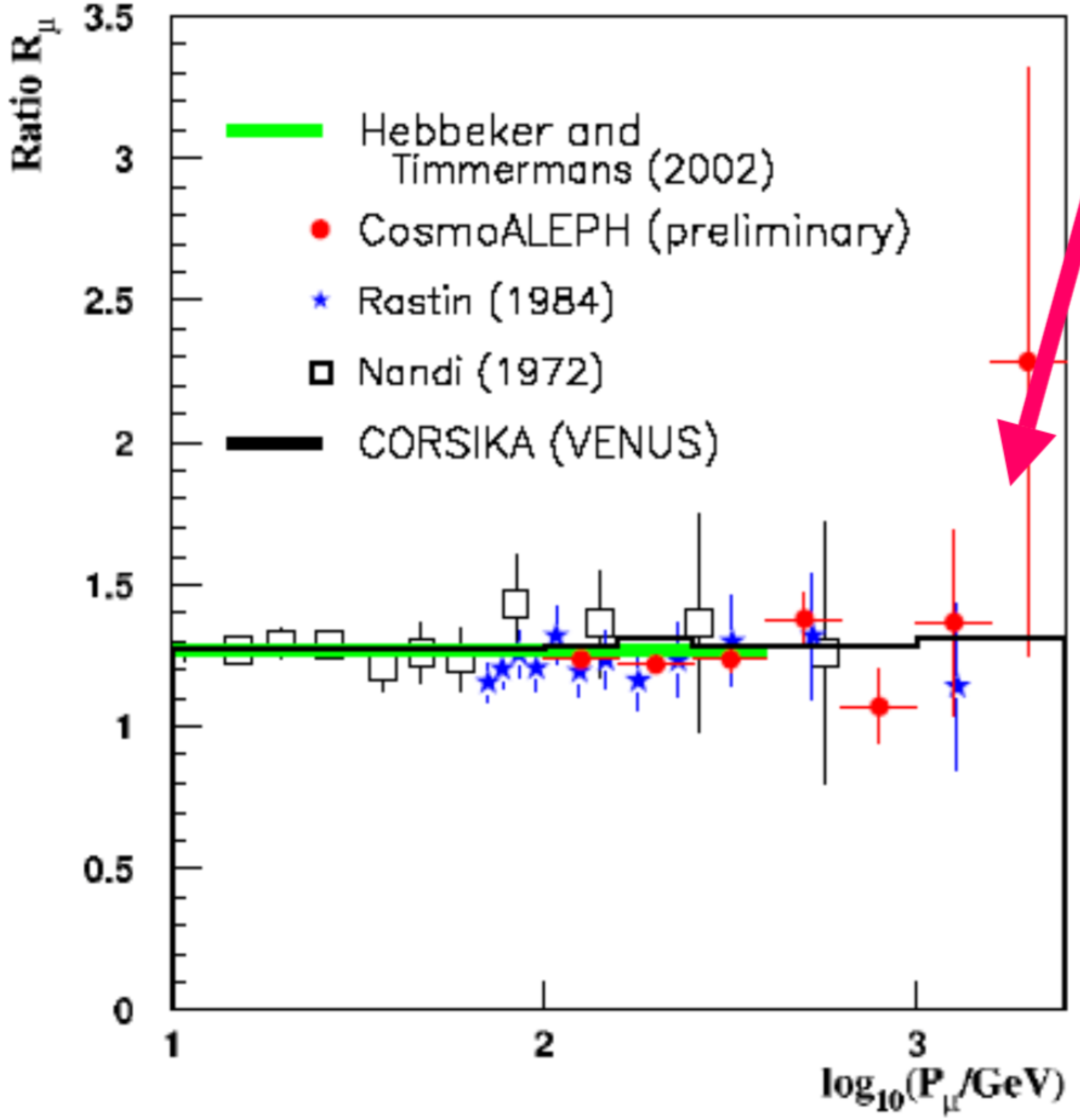
ALEPH (Preliminary data) as compared to other data.

For a given primary flux and composition this result will test interaction models and help to constrain their parameters (like in L3+C case – Lawrence Jones talk). It also constrains calculations of atmospheric neutrino flux.

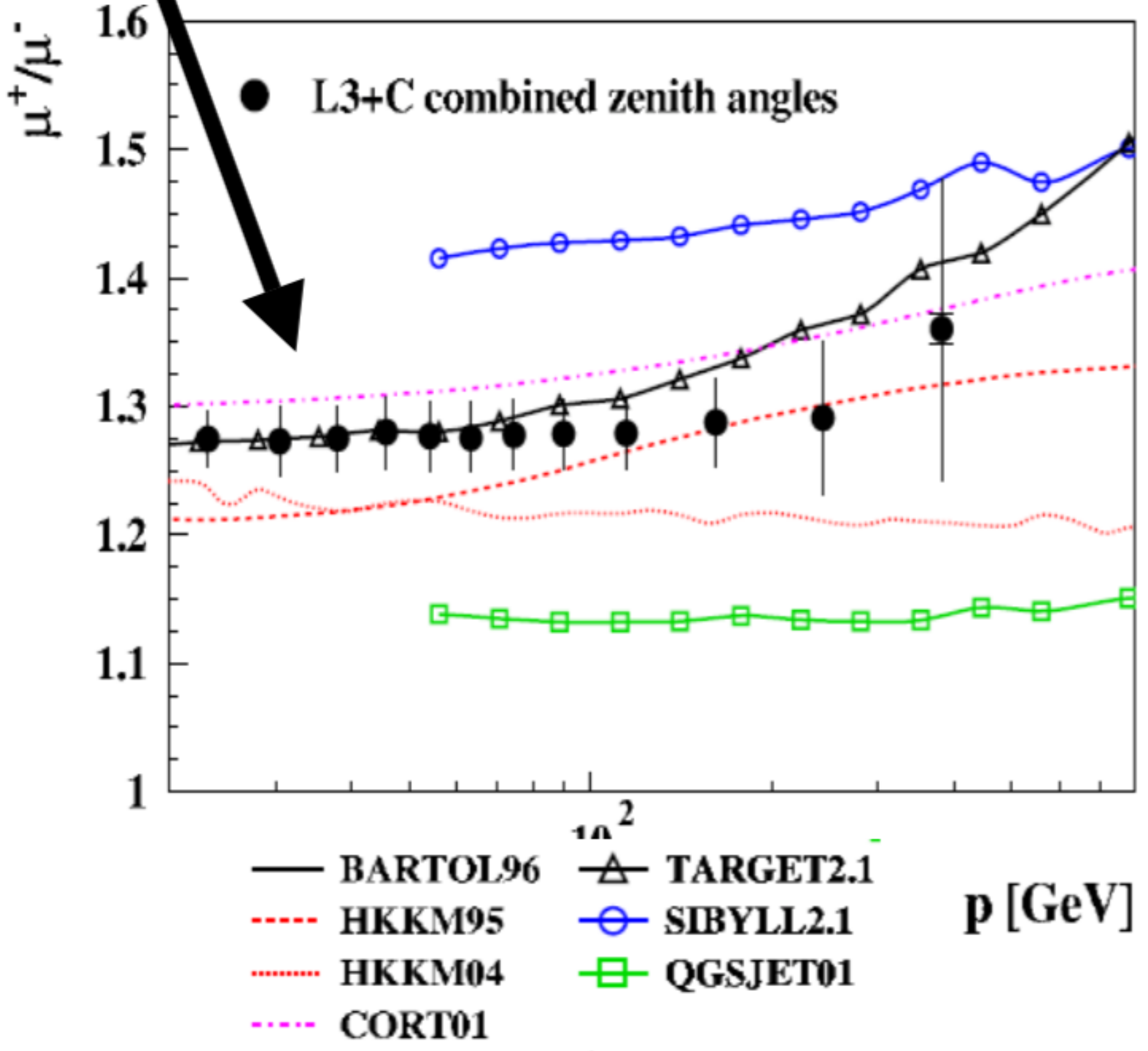
Cosmo-ALEPH
Charge ratio

From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005

ALEPH (Preliminary data)



another test of interactions models (has been done with L3+C data, see Lawrence Jones talk)



Cosmo-ALEPH
Multi-muon bundles

Sensitive to primary energies $10^{14} - 10^{16}$ eV

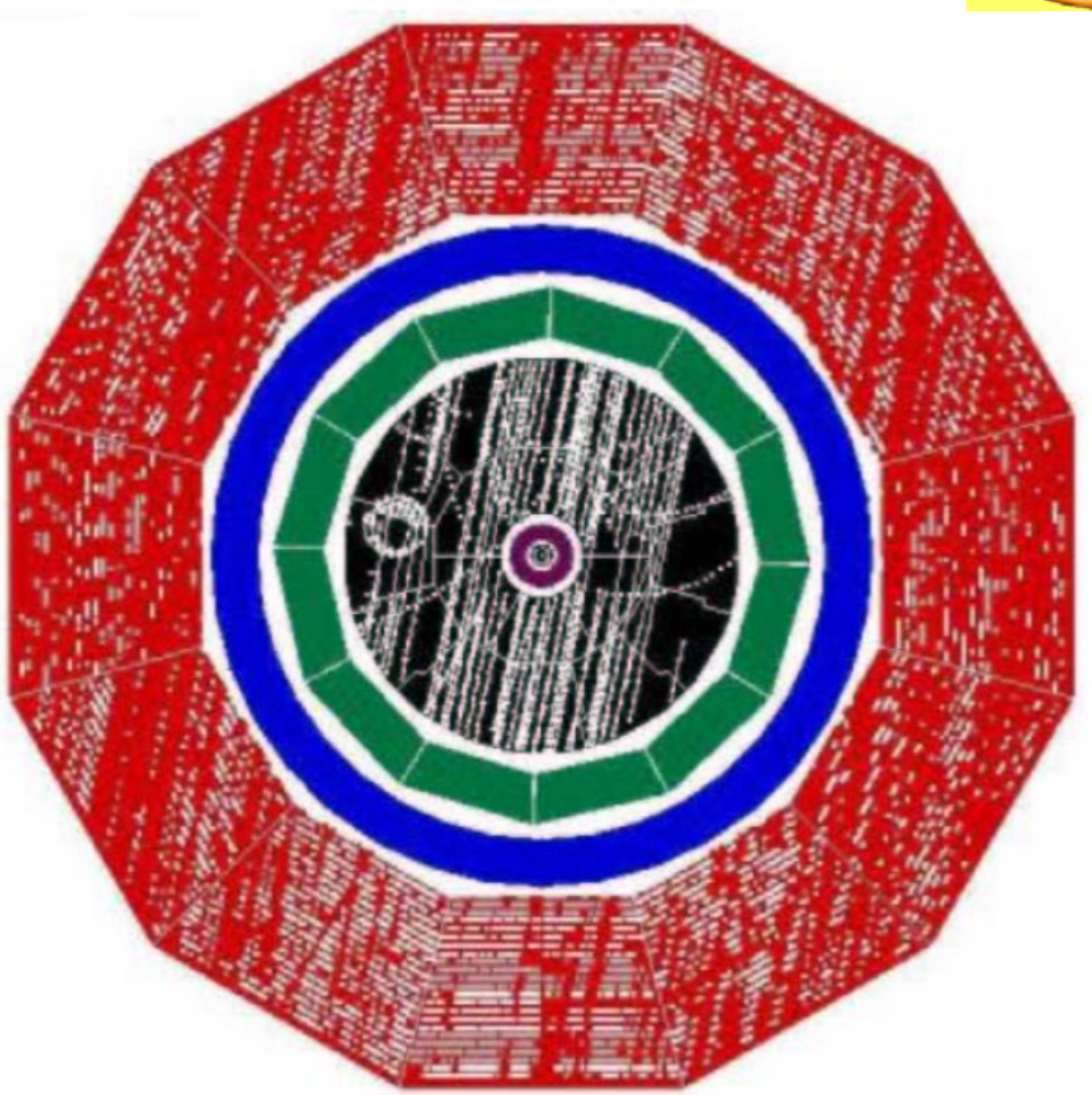
For E>10^{14} eV at given energy more muons for heavier nuclei

High energy muons (E >70 GeV) are sensitive to dynamics of the first interactions

Test of interaction models

Simulation: CORSIKA, QGSJET

Difficulty: unknown core position (small detectors) => scattering of shower centers over some area (200x200 m^2) in MC



Multiplicities up to 150 in 16 m^2

TPC

Cosmo-ALEPH
Multi-muon bundles

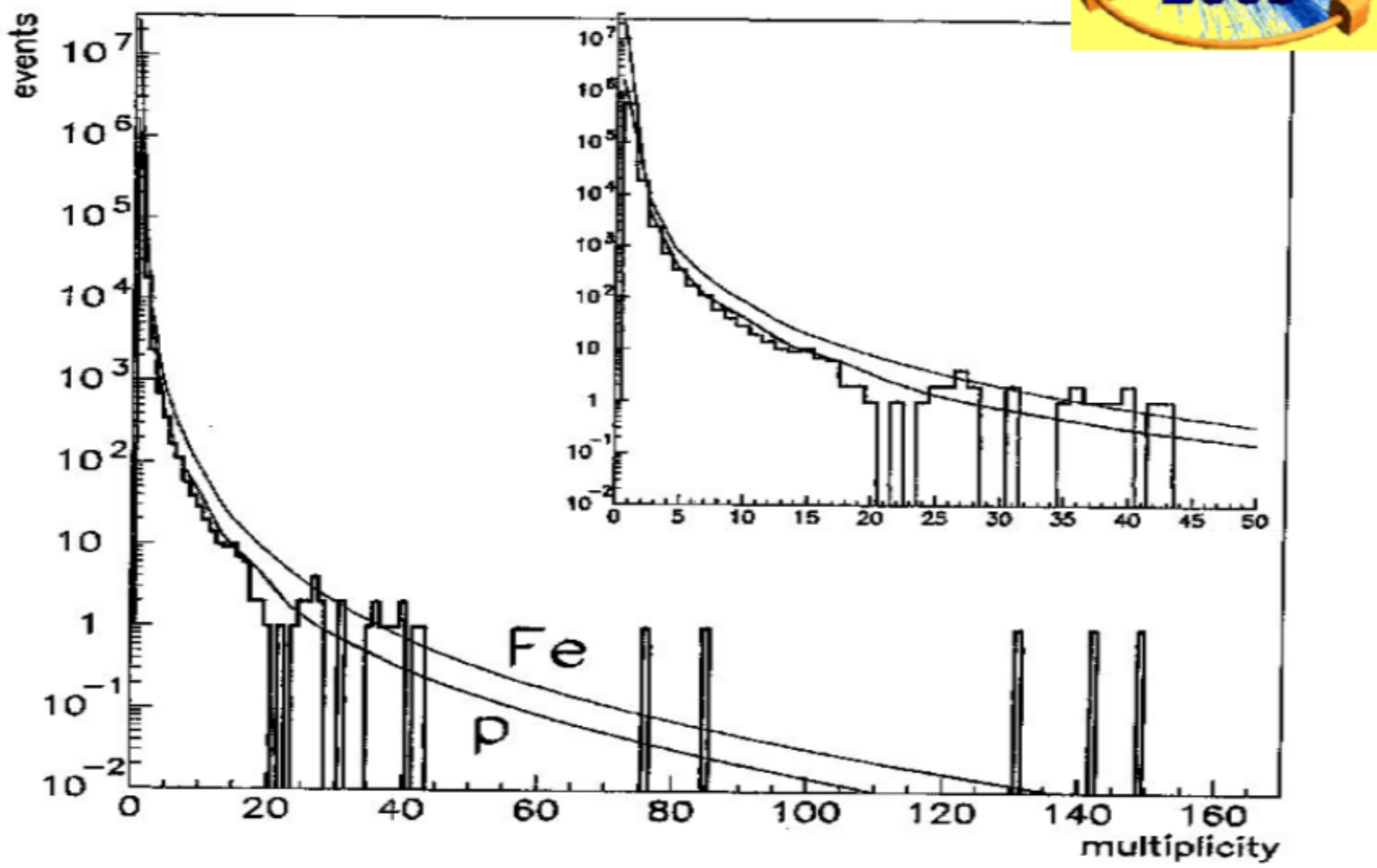
From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005

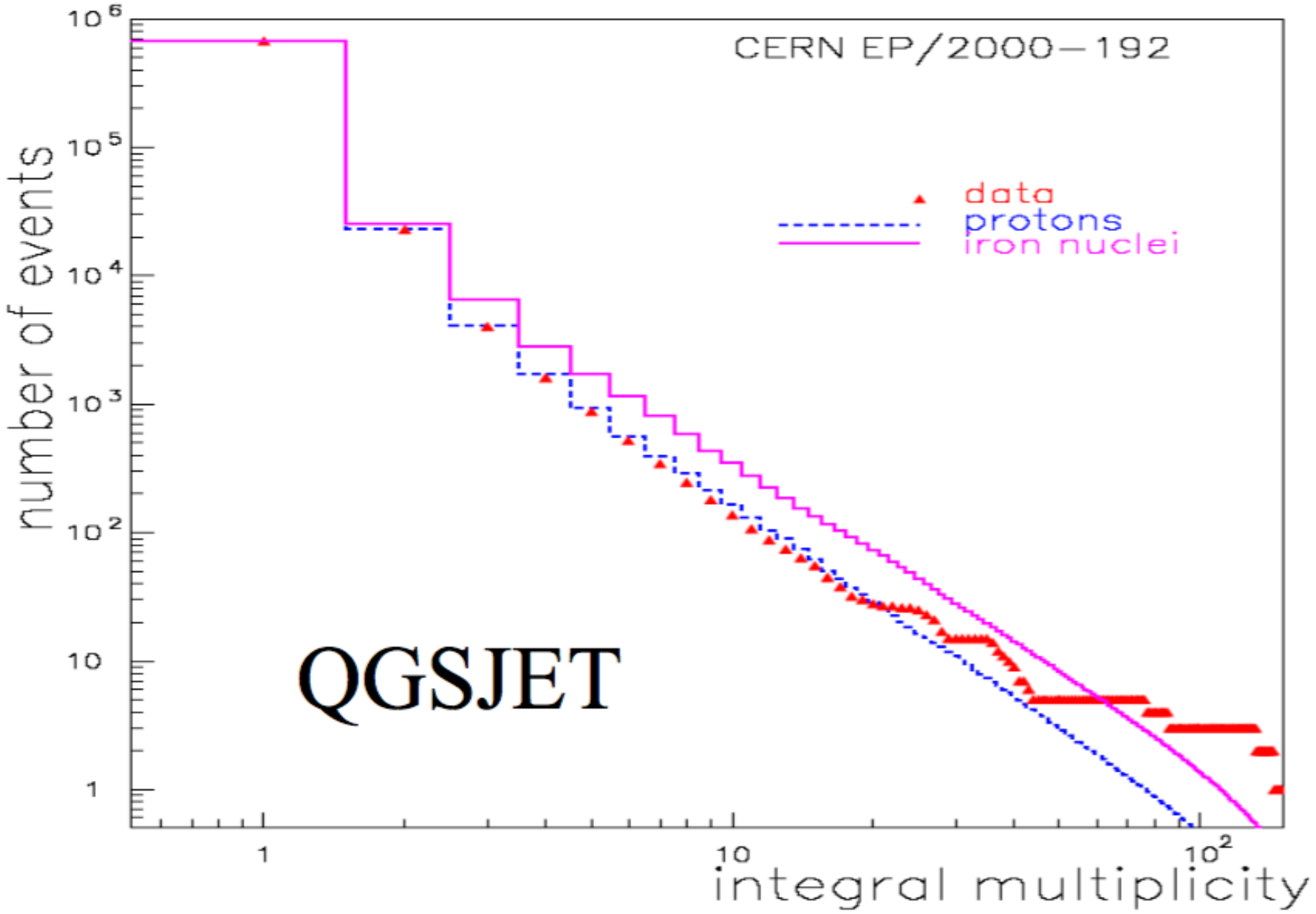
Composition unknown => two assumptions: all particles are p or Fe, data should be somewhere in the middle of the two predictions

Low multiplicities (low energies): proton like

Medium multiplicities: transition to heavier nuclei

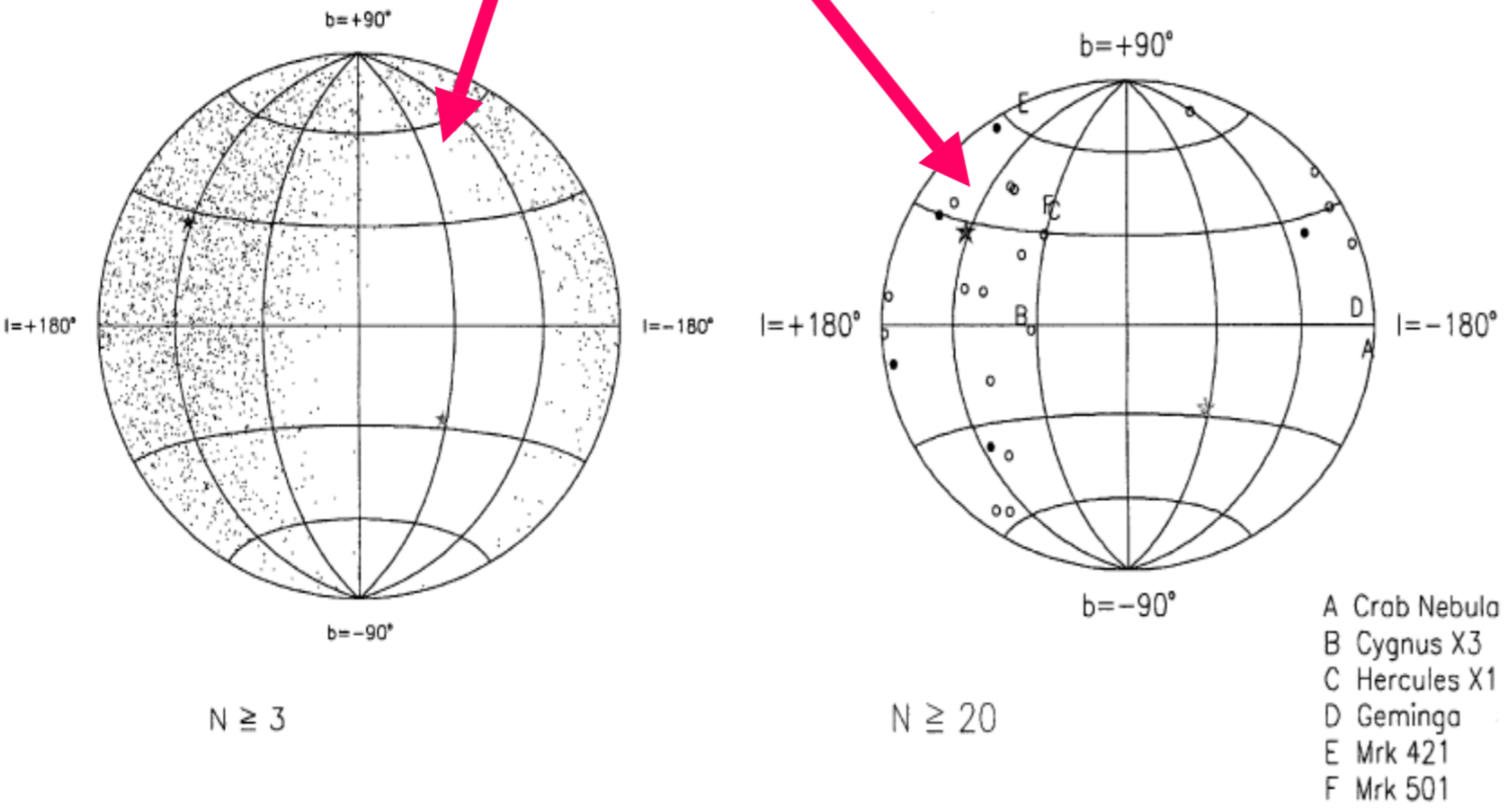
Some excess of events at the highest multiplicities compared to MC with iron





Cosmo-ALEPH
Multi-muon bundles, sources

Events with more than 3 and 20 muons, no apparent clustering around known sources:



N ≥ 3

N ≥ 20

DELPHI

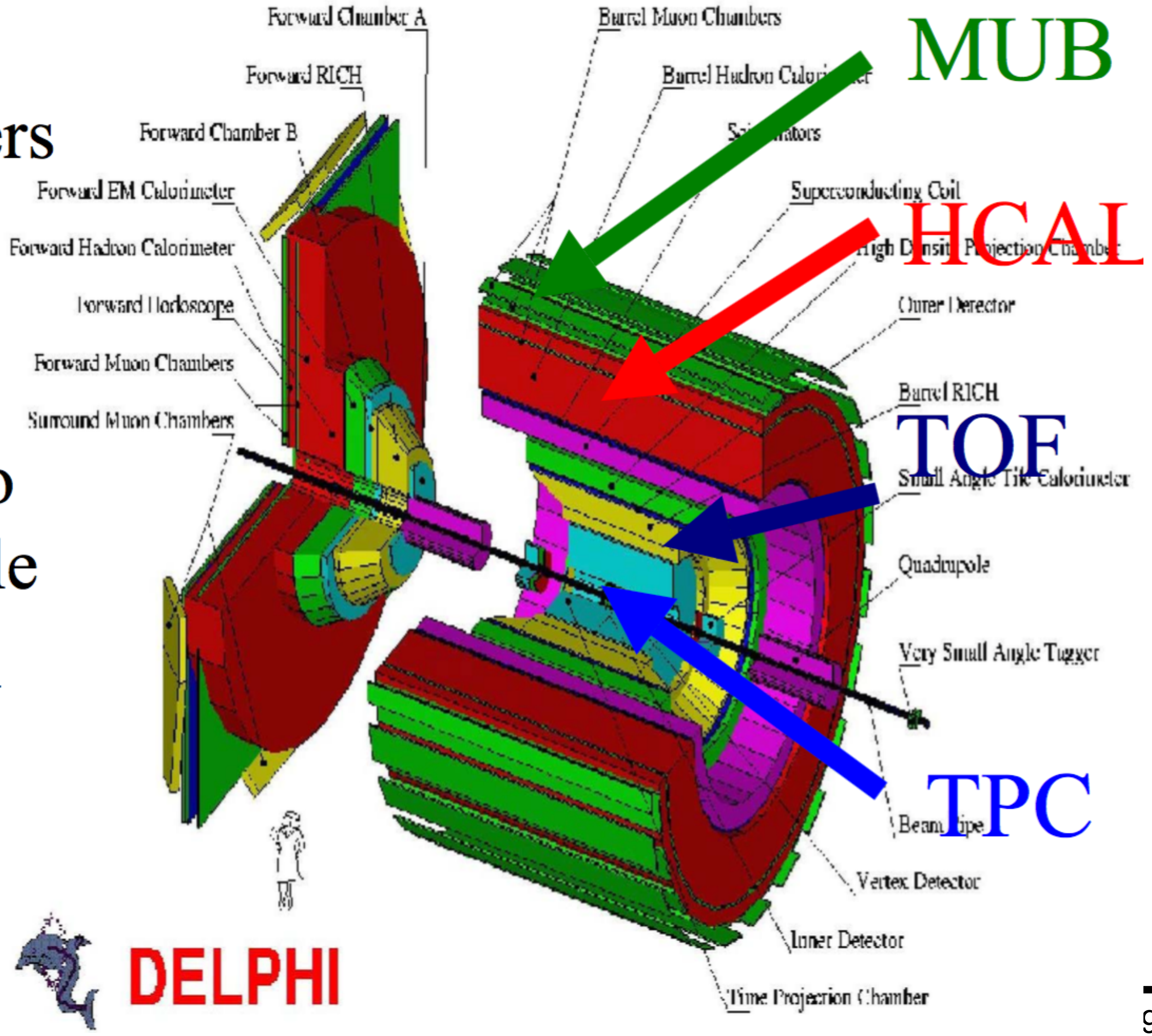
Main detector - 75 m^2 HCAL

TPC and muon chambers partly used

TOF served as trigger

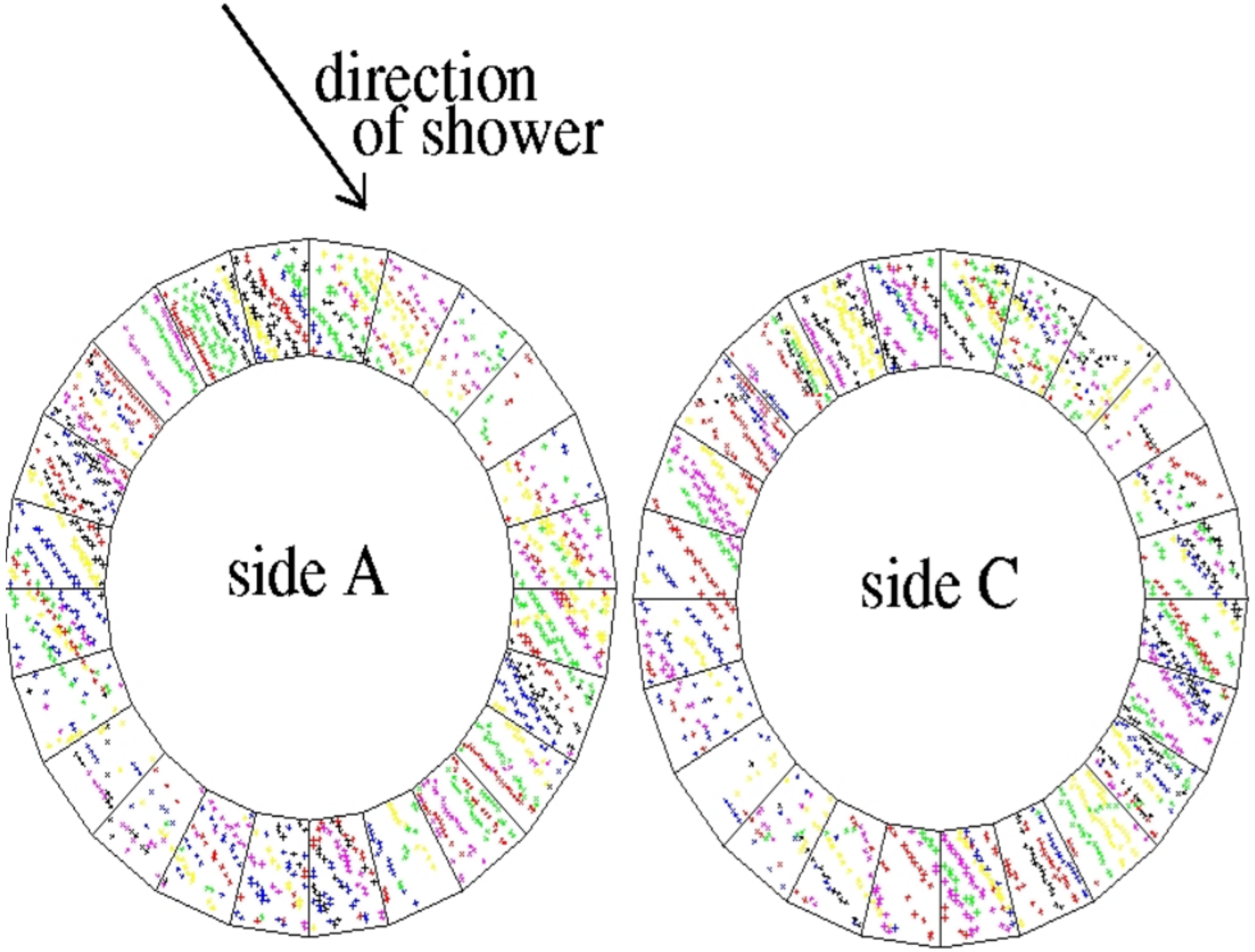
Running with respect to BCO => 18% duty cycle

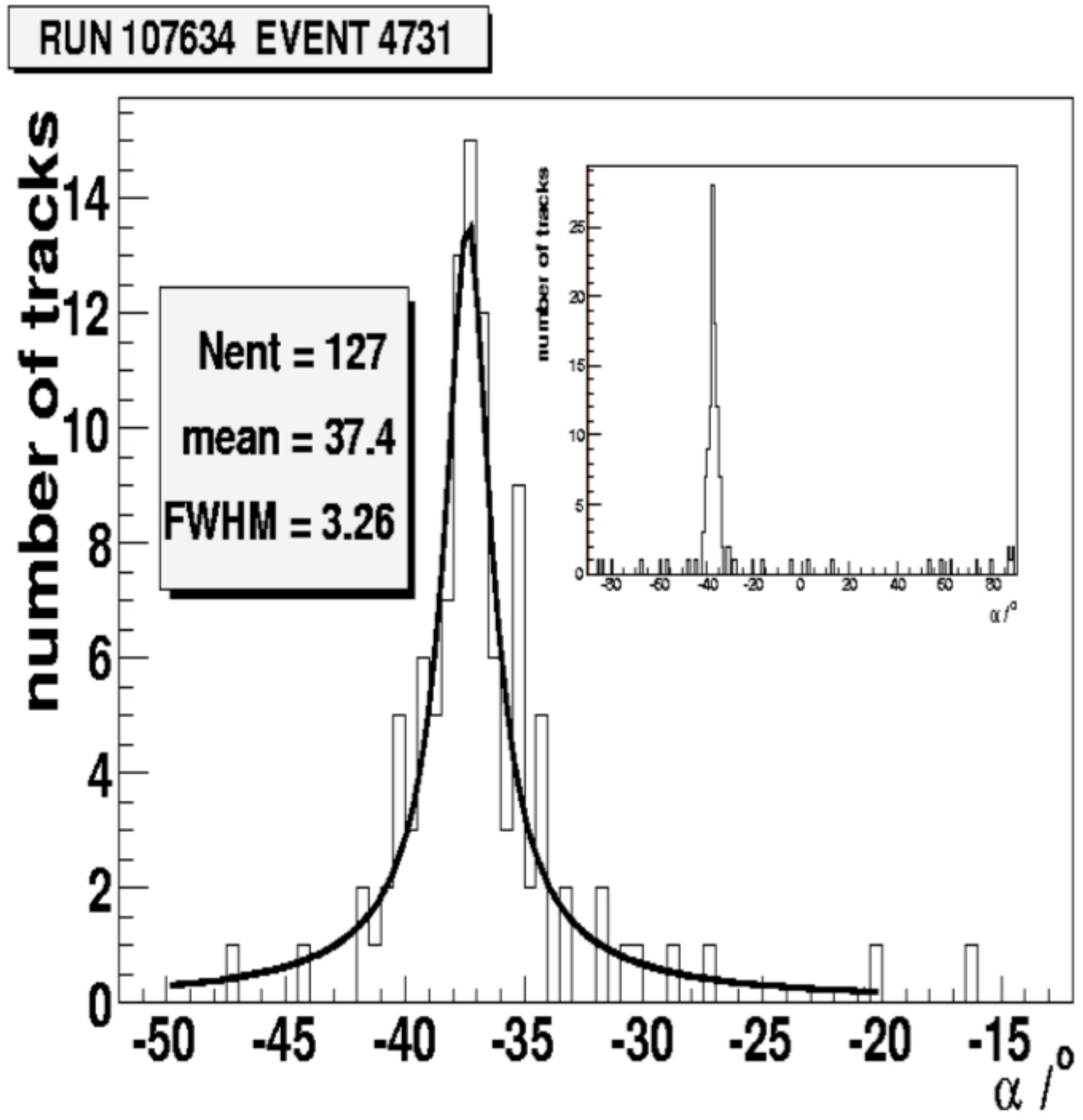
Fine HCAL granularity allowed analysis of multi-muon bundles



DELPHI
High multiplicity event

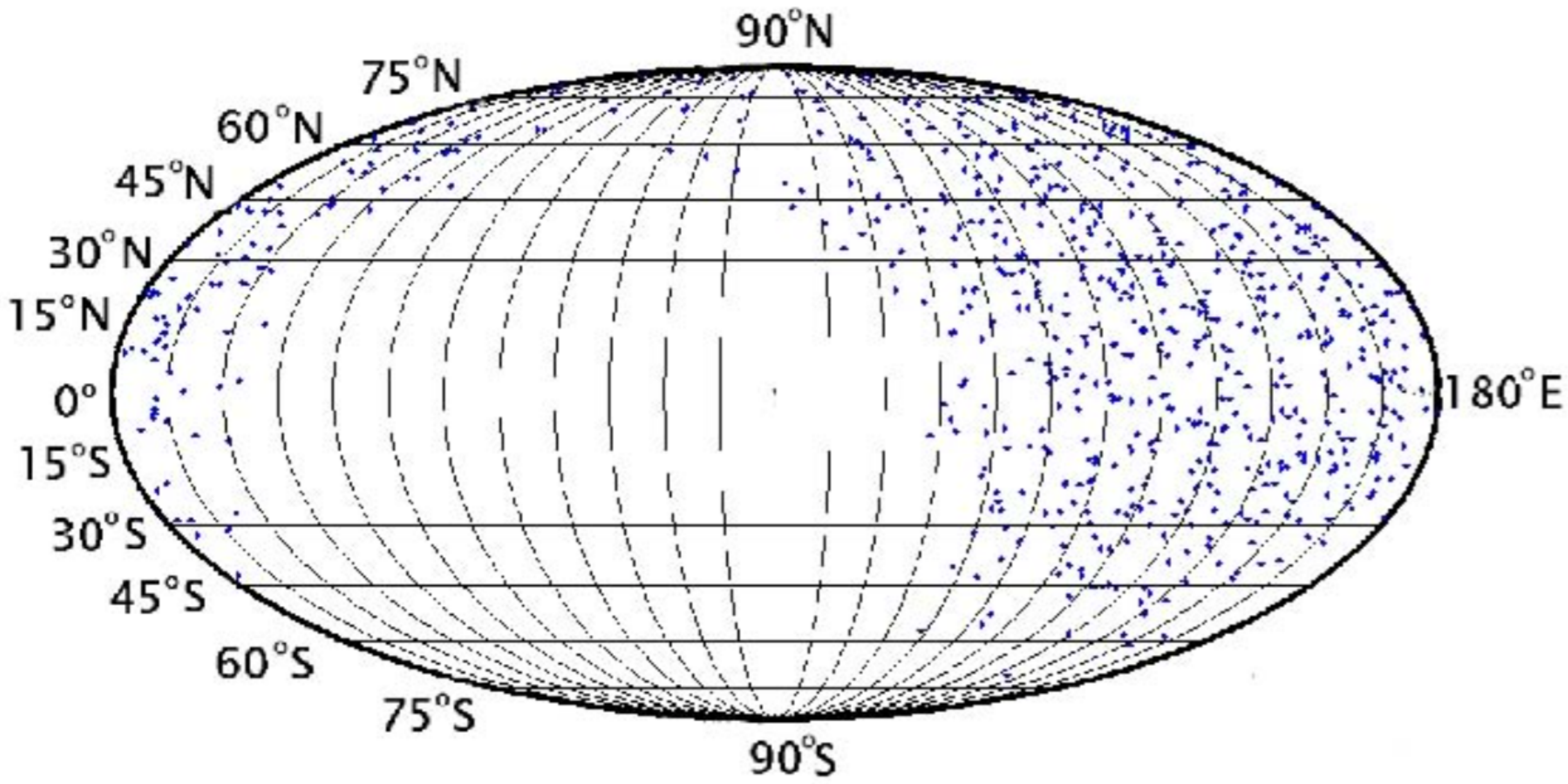
Reconstruction up to multiplicity 130





DELPHI
Point sources

No event clustering for high multiplicity events, N(HCAL)>15, N(TPC)>5



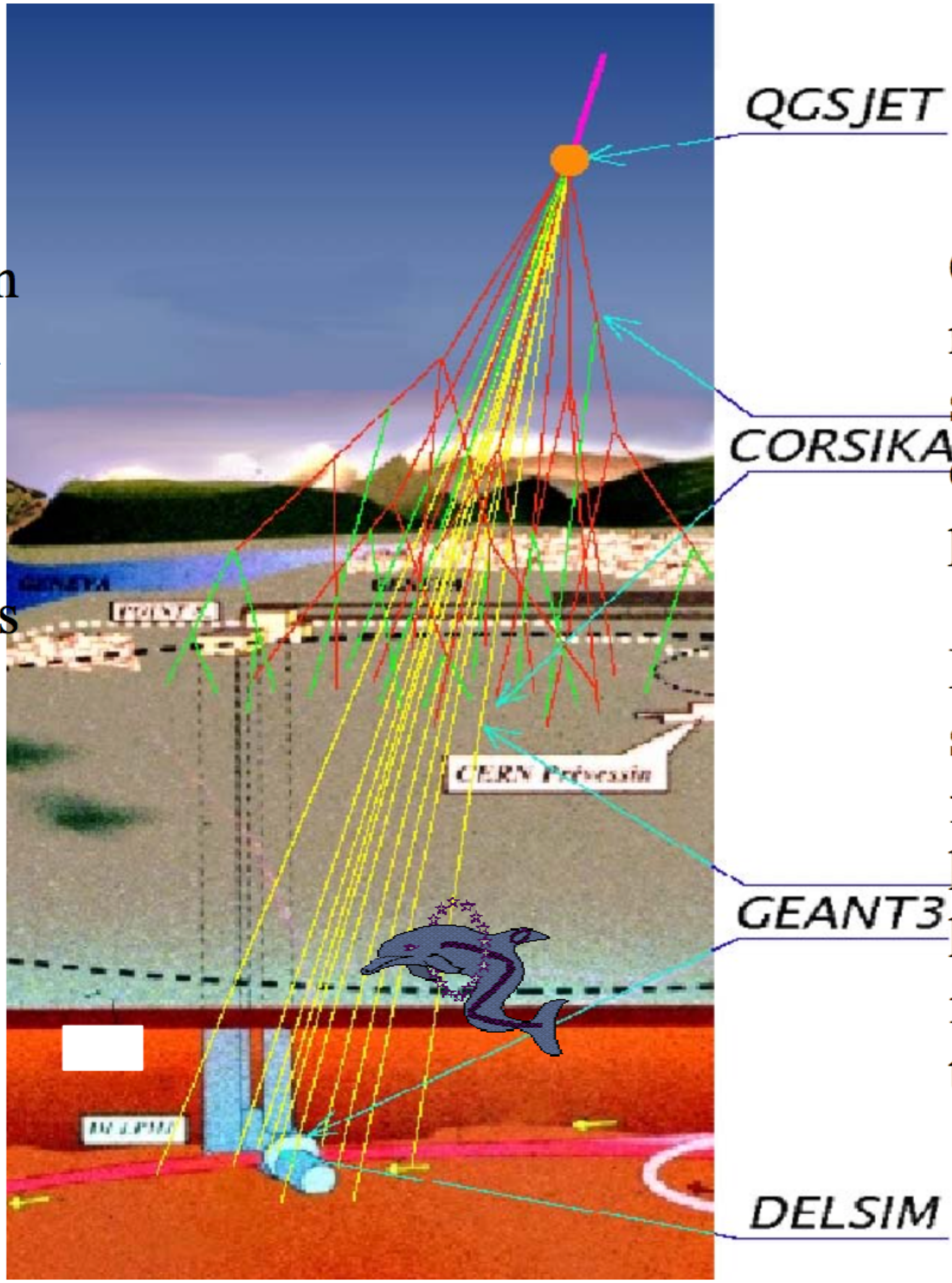
From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005

DELPHI
Motivation

Measurement

Detection of multi-muon bundles originated from cosmic rays in the DELPHI detector.

Not many measurements from medium depth underground.

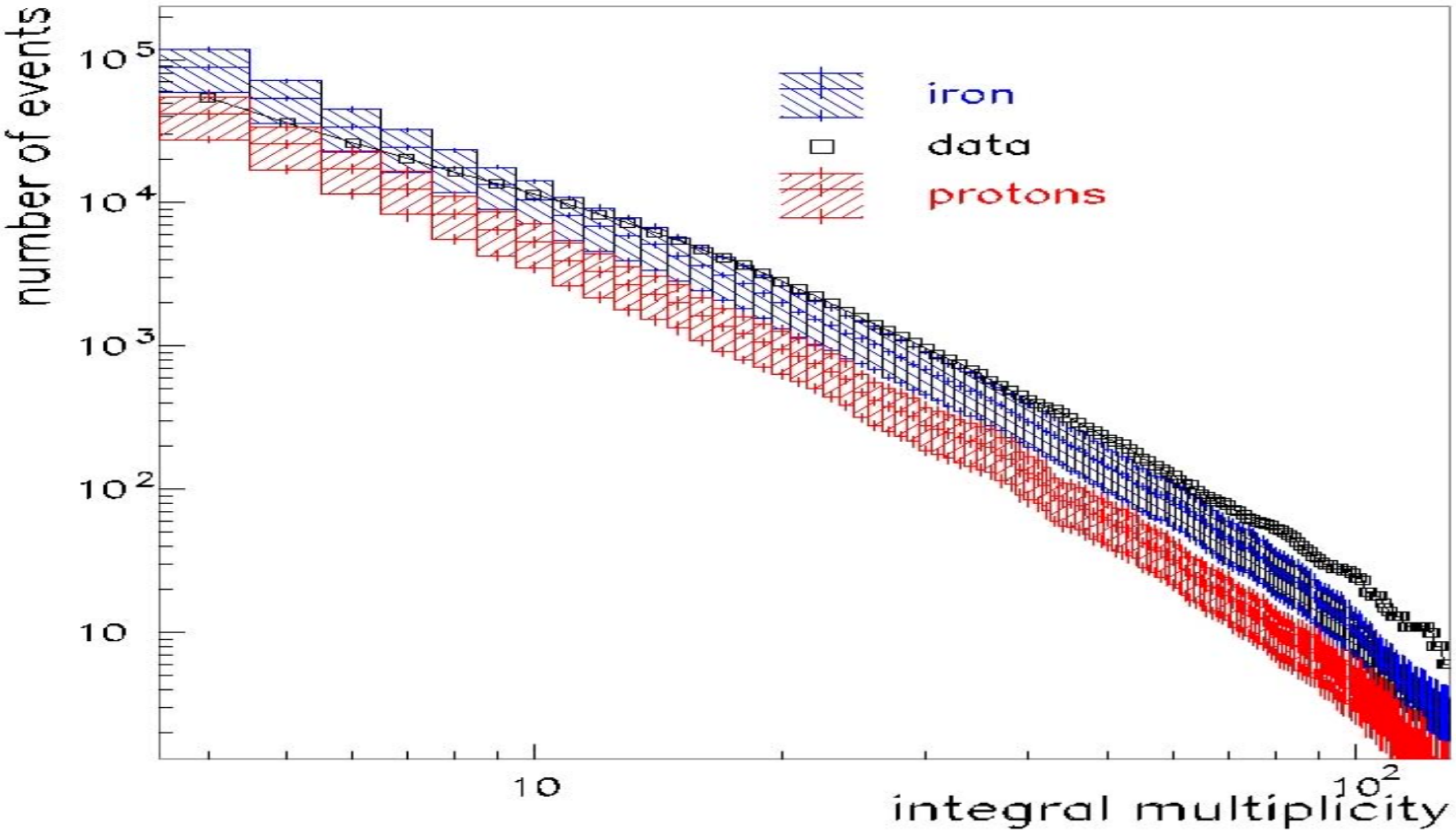


Simulation

Comparison of the measurement with MC simulations describing cosmic ray shower propagation.

High energy muons are sensitive to dynamics of first interactions. The high energy model of hadron-hadron interactions is in fact tested.

DELPHI
Results II –different flux



flux 1, 2, 3- influence of the flux of primary particles

L3+C

Air shower detector:

50 scintillators, S = 30 x 54 m^2

Muon detector

30 m underground,magnet (0.5 Tesla)

High precision drift chambers

202 m^2 of scintillators

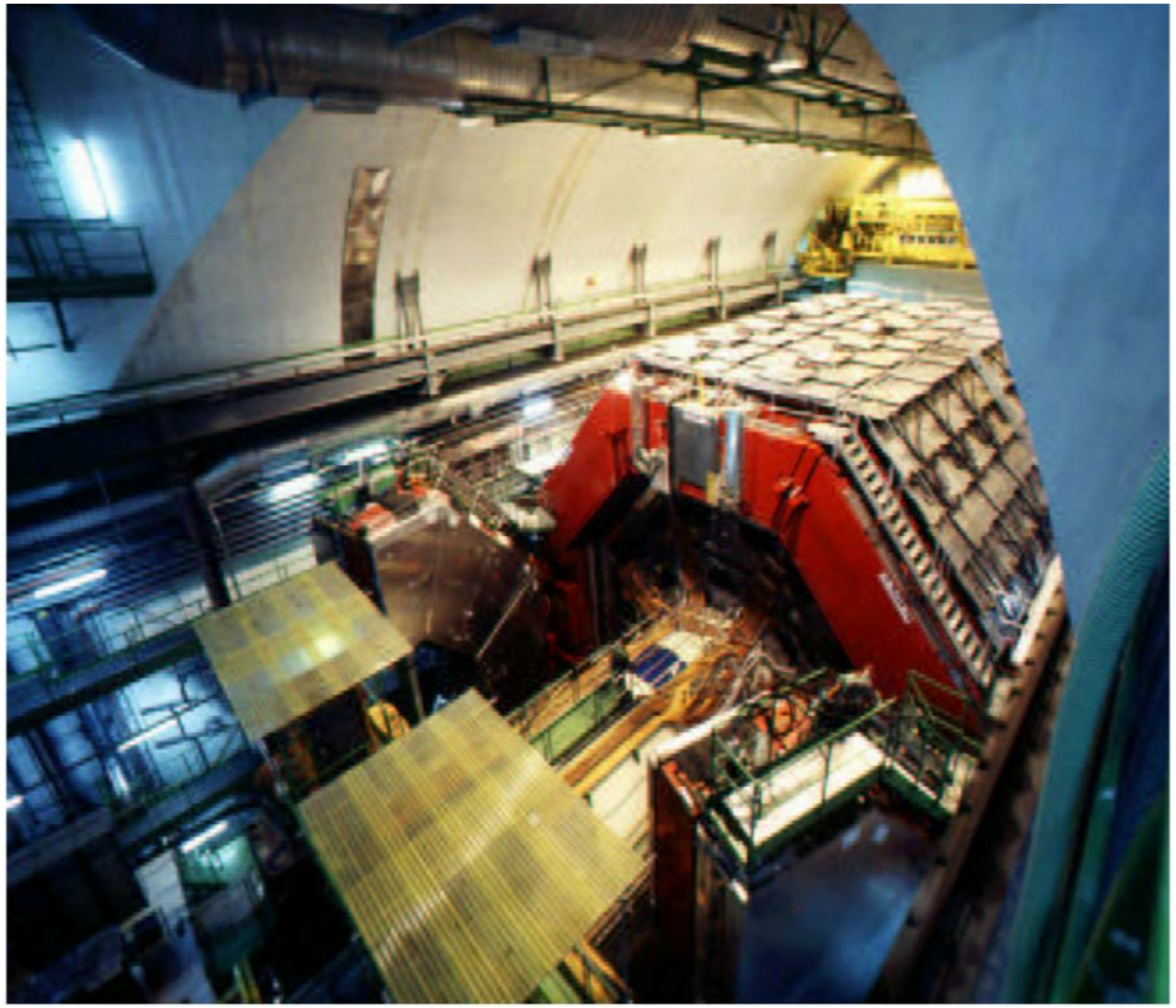
Trigger and DAQ: independent of L3

Geom. acceptance: 200 m^2sr

Energy threshold:15 GeV

Mom. resol.: = 7.6 % at 100 GeV/c

Ang. resol.: 3.5 mrad above 100 GeV



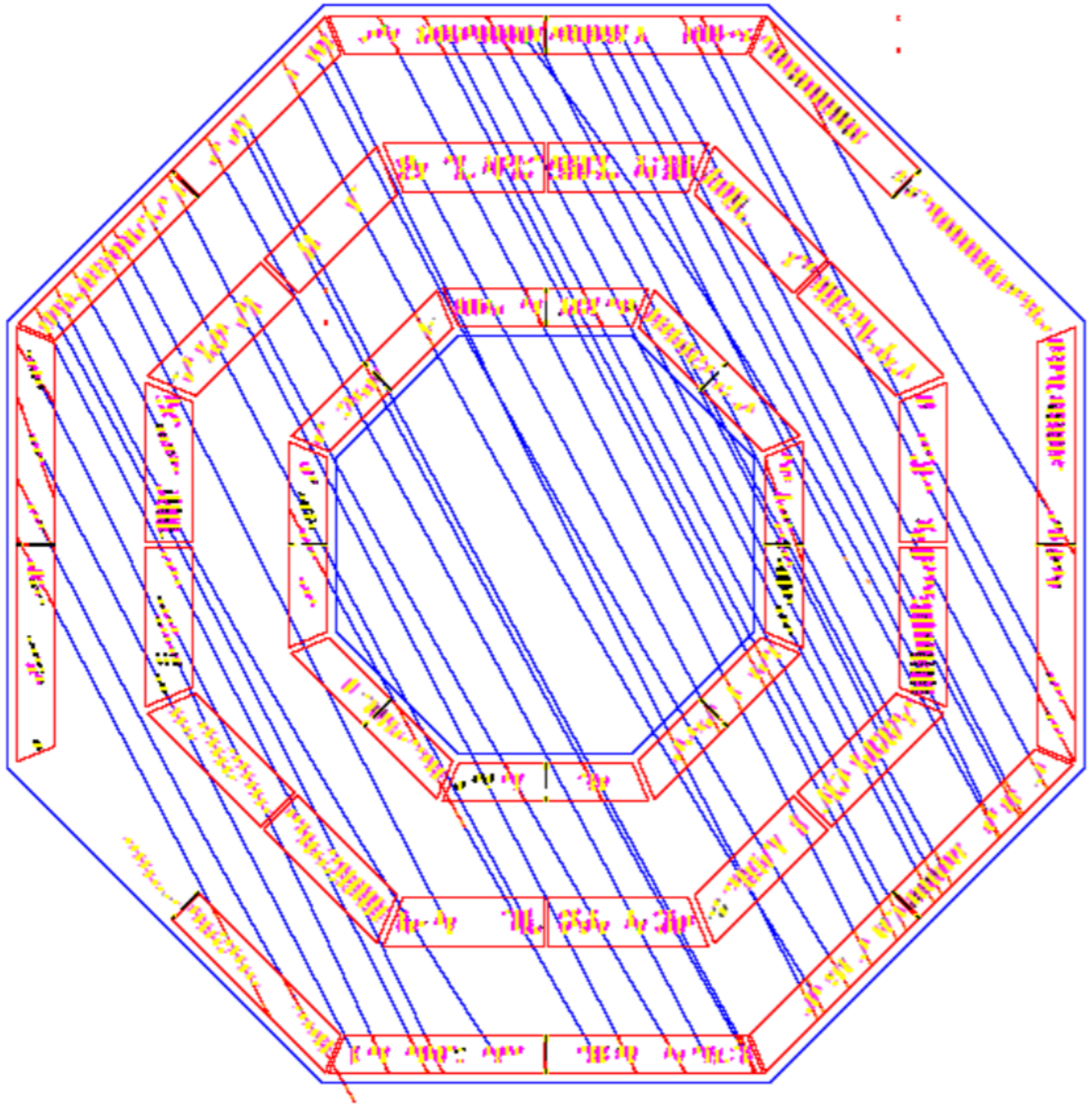
L3+C
Composition, Multi-muon bundles

L3+C can study multi-muon events also in coincidence with surface array.

Muon multiplicity can be studied as a function of shower size.

Muon momentum can be measured for individual muons in the bundle.

Analysis of the abovementioned items is still in progress …



L3+C
Composition, Multi-muon bundles

Some results:

Muon multiplicity in events with:

E>30TeV (surface array),

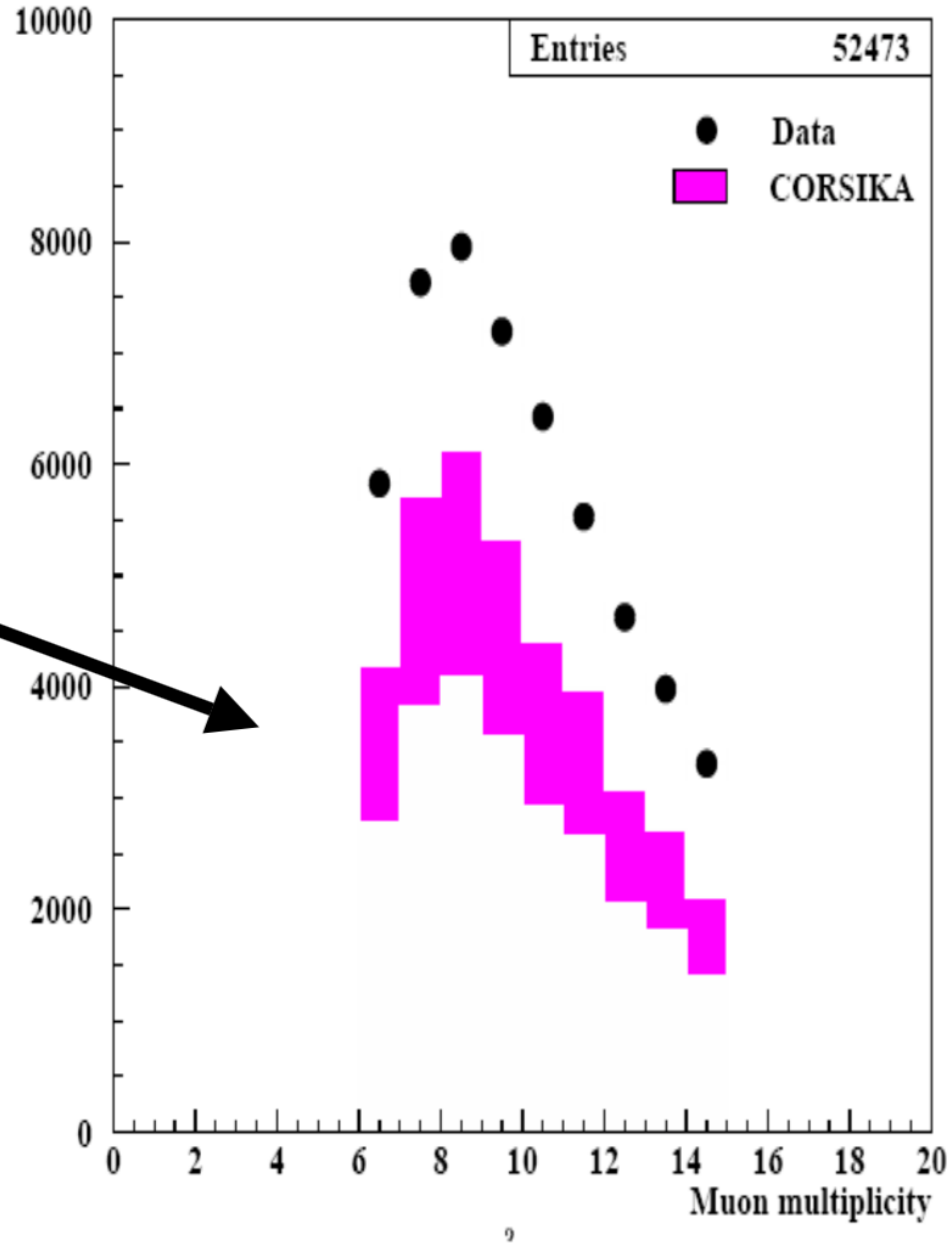
14>N(muons)>5,

N(muons, E>100GeV)>5

MC assuption:

p:He:CNO:Fe=2:2:1:1

Analysis indicates deviation from prediction of MC models (surplus of multi-muon data with large muon energies compared to MC simulation)



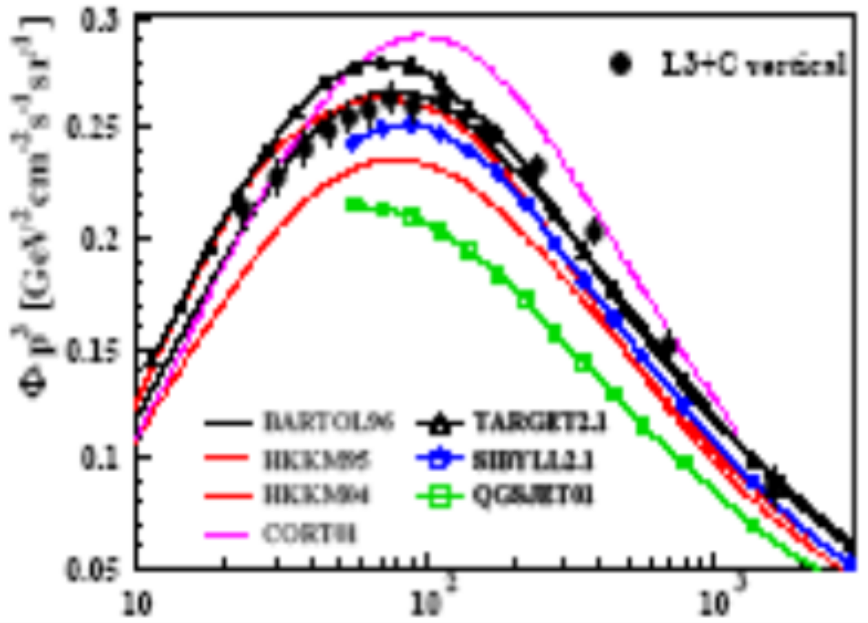
LEP - Conclusions I

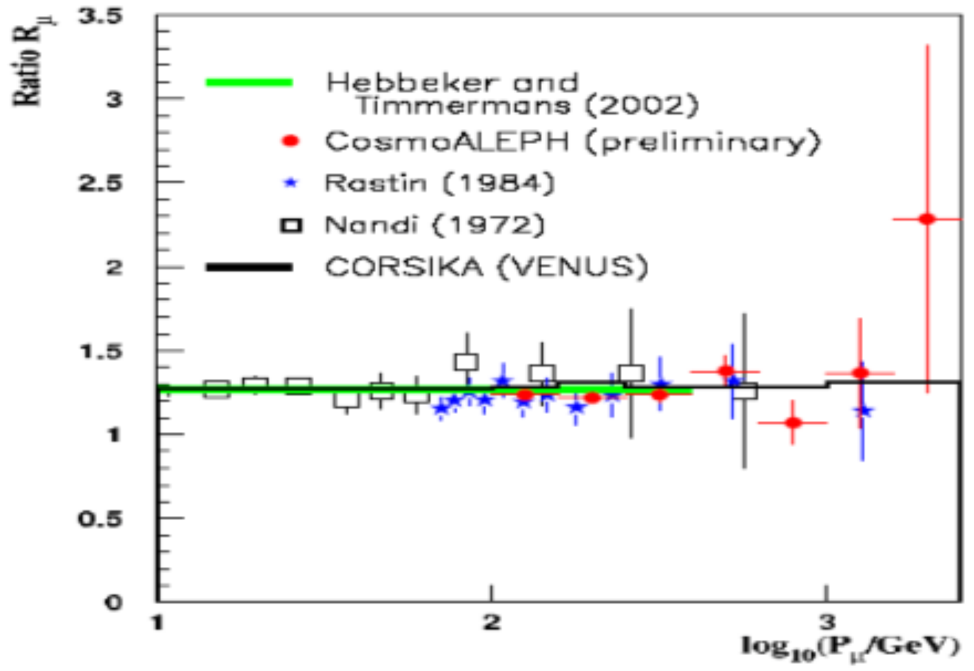
From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005

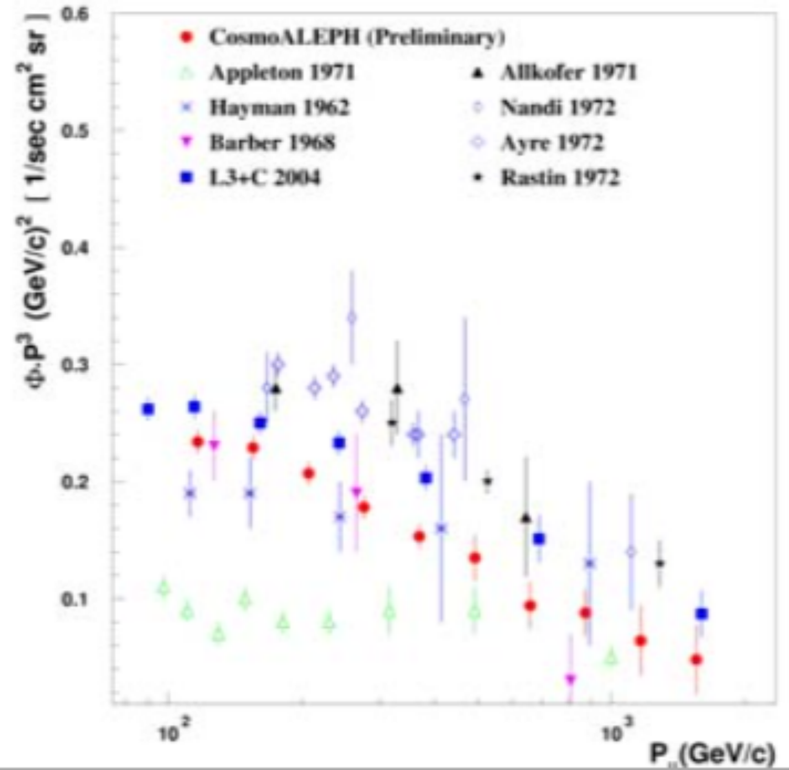
LEP experiments provided important results in the field of cosmic ray physics (HE interactions, source searches, composition …)

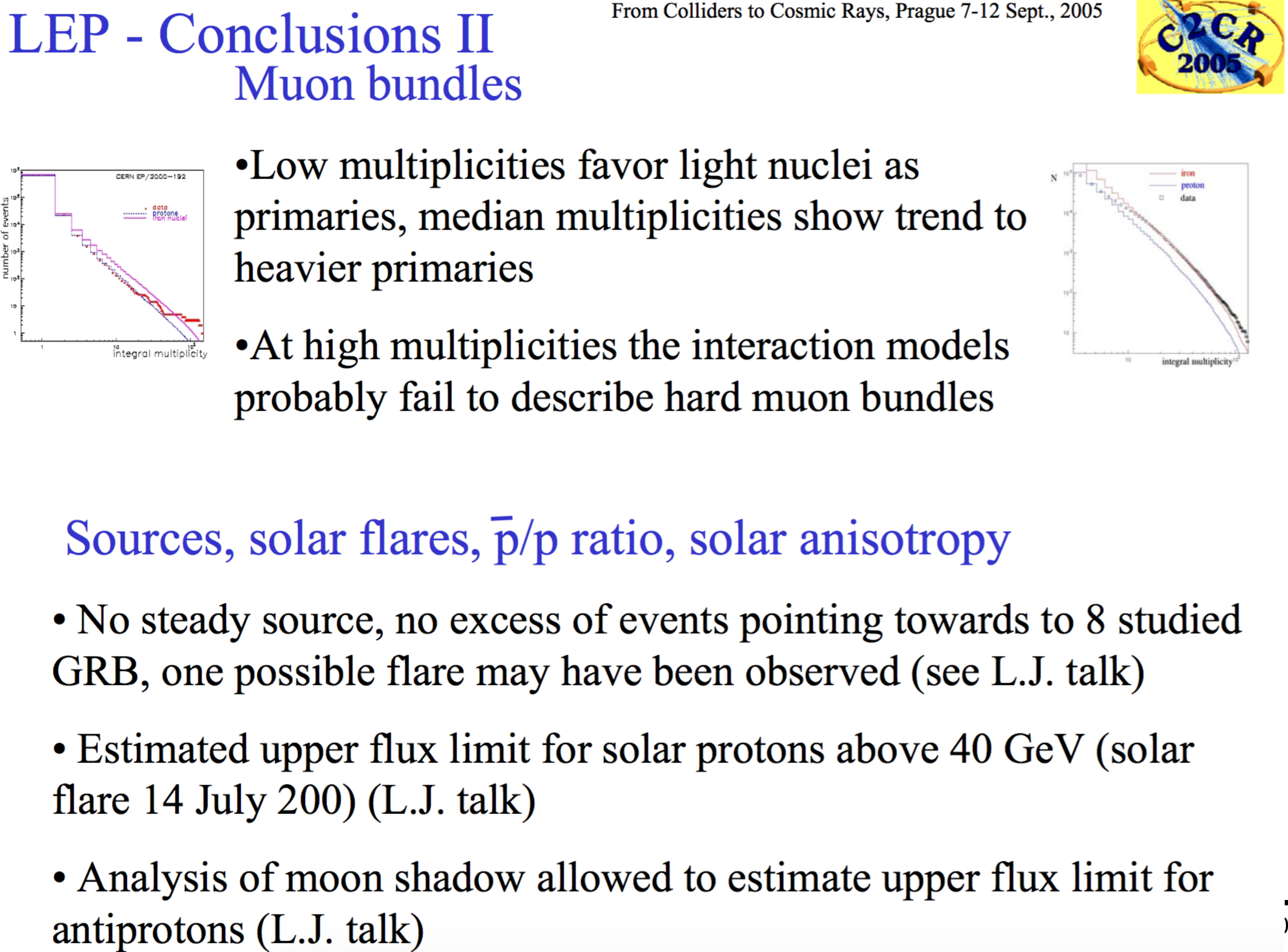
Atmospheric muon energy spectrum, charge ratio (and angular dependencies of both items)

- Hadronic interaction models cannot describe observed muon spectrum and charge ratio (for given CR composition)
- Atmospheric neutrino spectra can be better constrained
- Impact also to the field of neutrino astronomy: neutrino induced muon background can be better defined









From Colliders to Cosmic Rays, Prague 7-12 Sept., 2005

LEP - Conclusions II

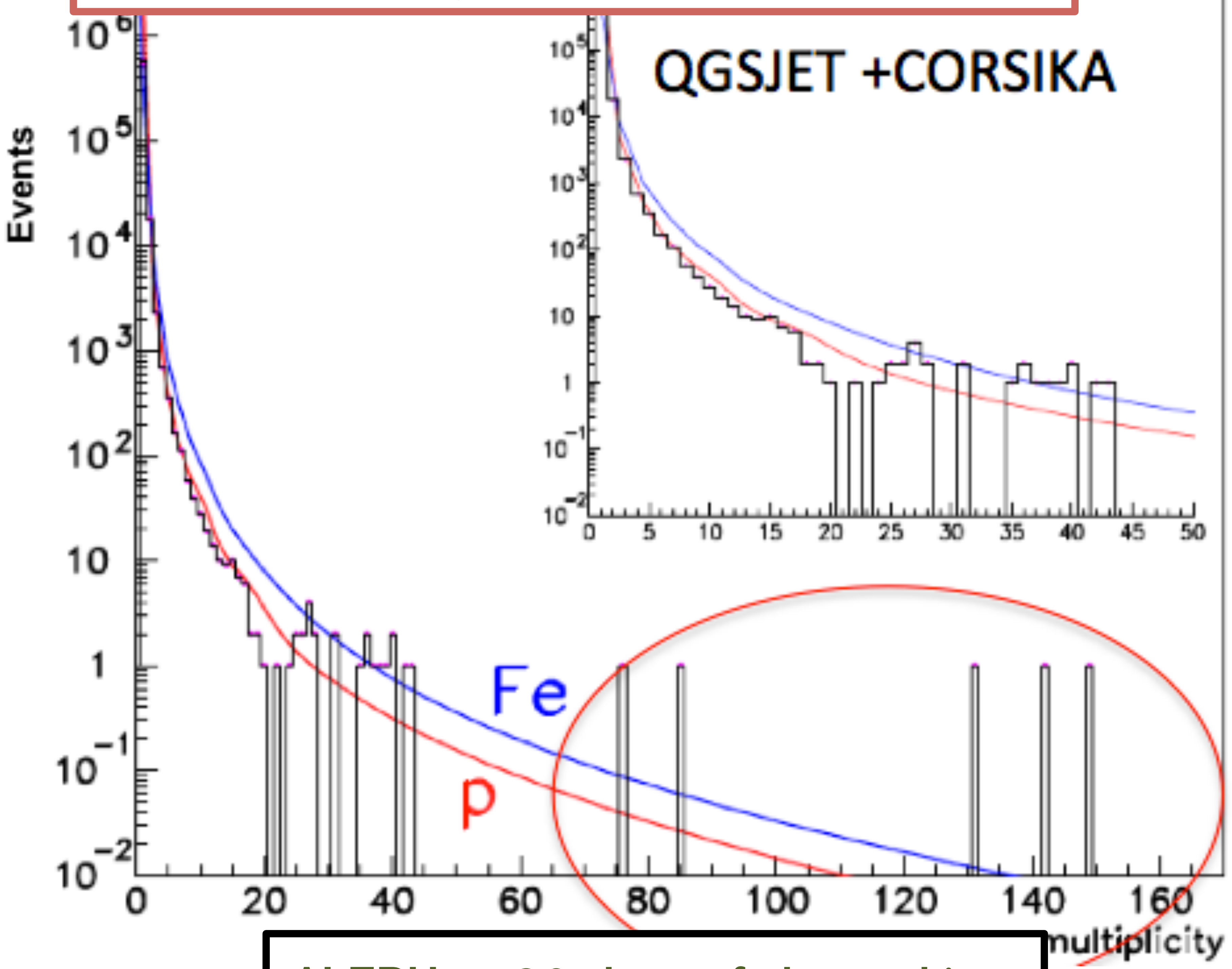
Muon bundles

- Low multiplicities favor light nuclei as primaries, median multiplicities show trend to heavier primaries
- At high multiplicities the interaction models probably fail to describe hard muon bundles

Sources, solar flares, $\bar{p}$/p ratio, solar anisotropy

- No steady source, no excess of events pointing towards to 8 studied GRB, one possible flare may have been observed (see L.J. talk)
- Estimated upper flux limit for solar protons above 40 GeV (solar flare 14 July 200) (L.J. talk)
- Analysis of moon shadow allowed to estimate upper flux limit for antiprotons (L.J. talk)

Astroparticle Physics 19 (2003) 513–523



ALEPH: ~20 days of data taking

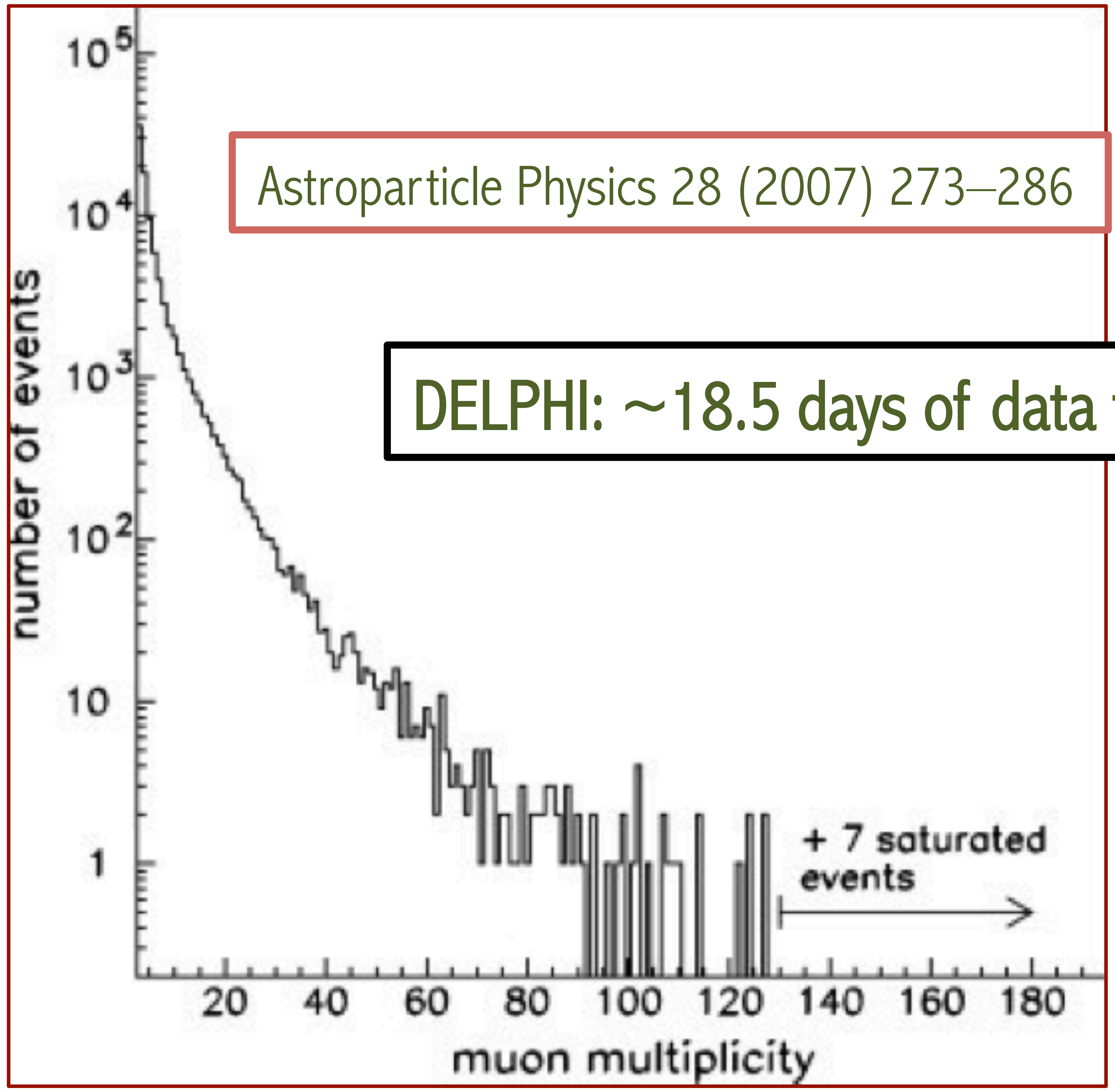
Data indicate that heavier component is needed to explain higher multiplicity muon bundles

These muon bundles are not well described (almost an order of magnitude above the simulation)

The conclusion is similar to Aleph :

However, even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events.

Astroparticle Physics 28 (2007) 273–286



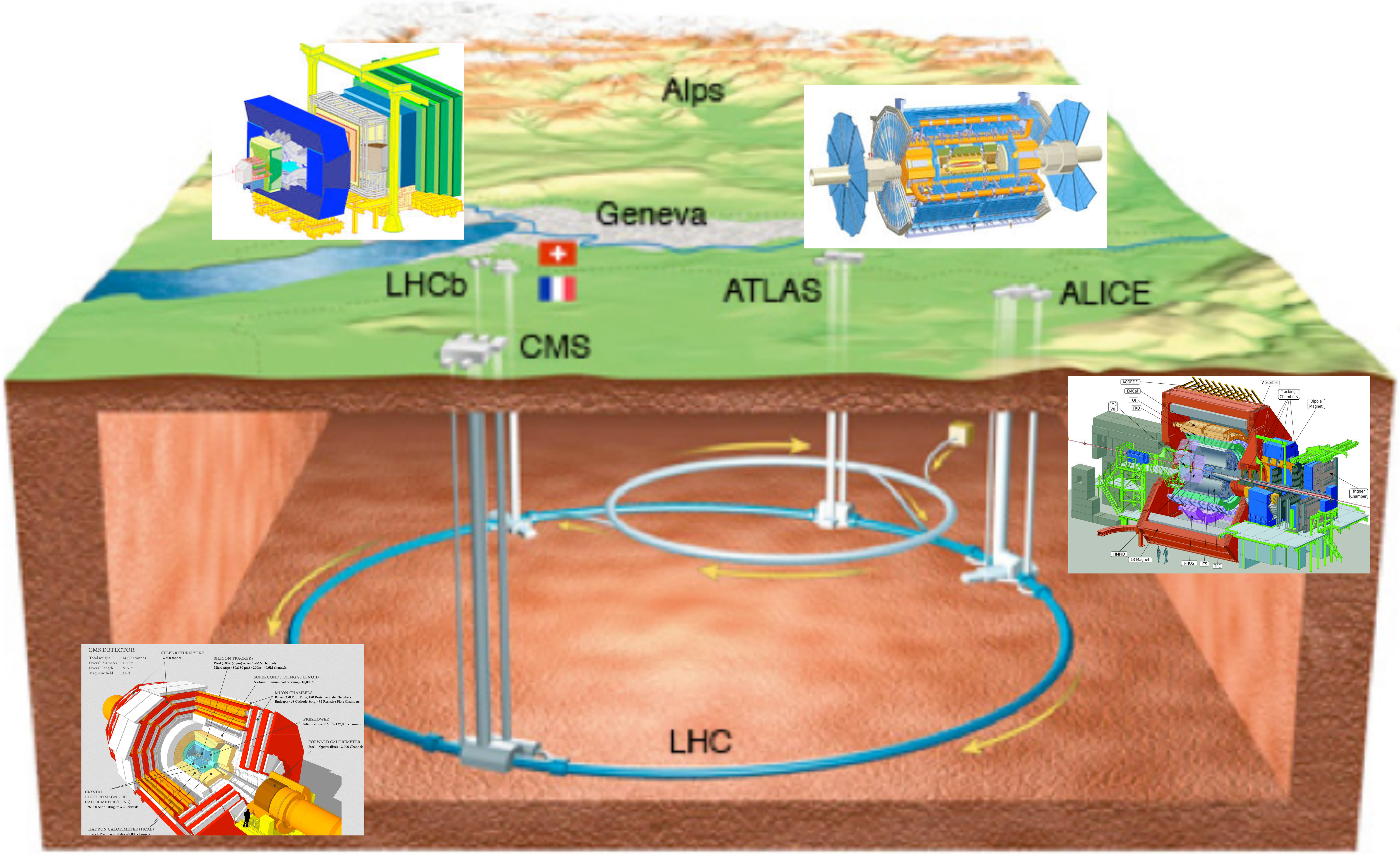
DELPHI: ~18.5 days of data taking

LHC RESULTS

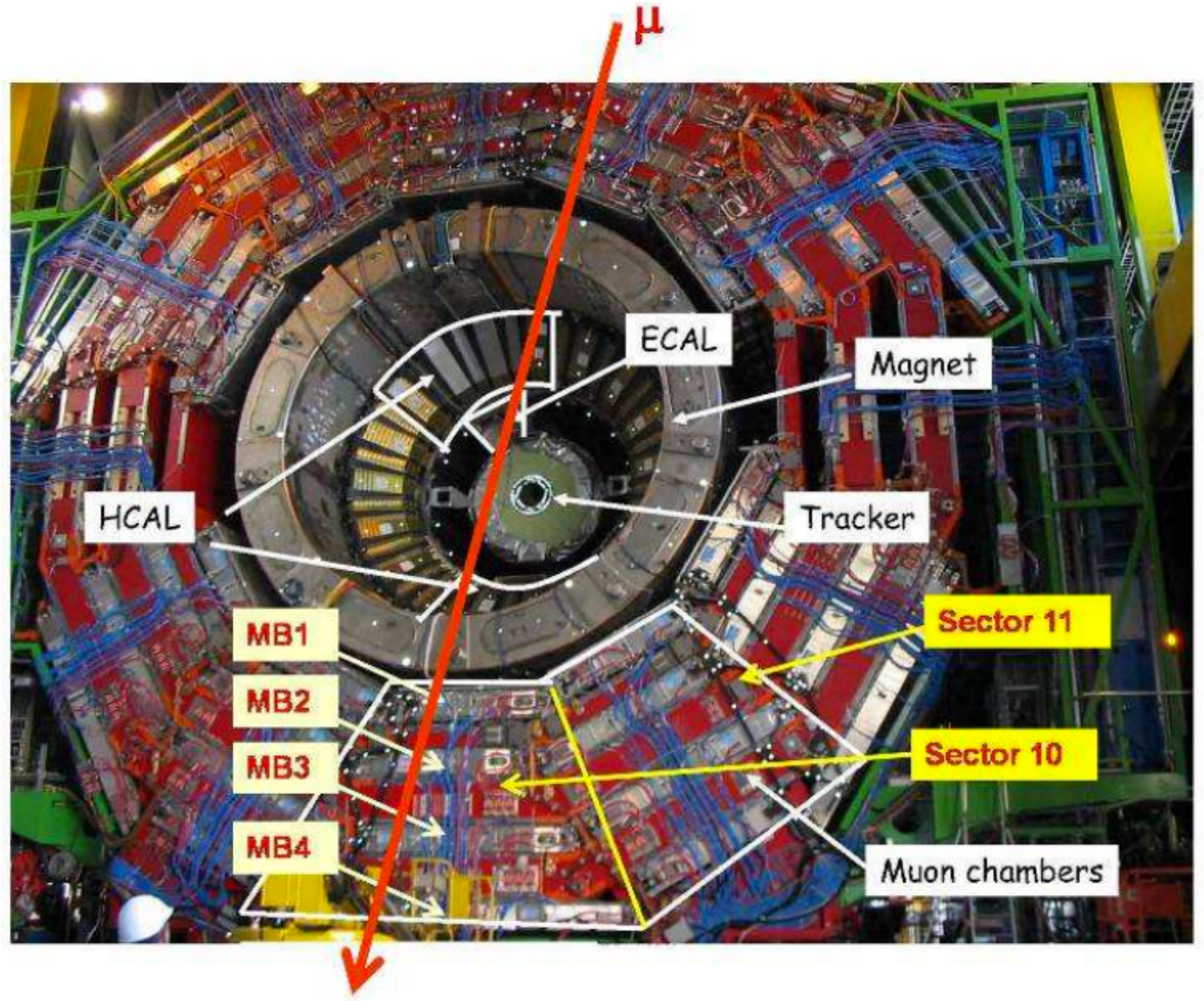
LHC conditions

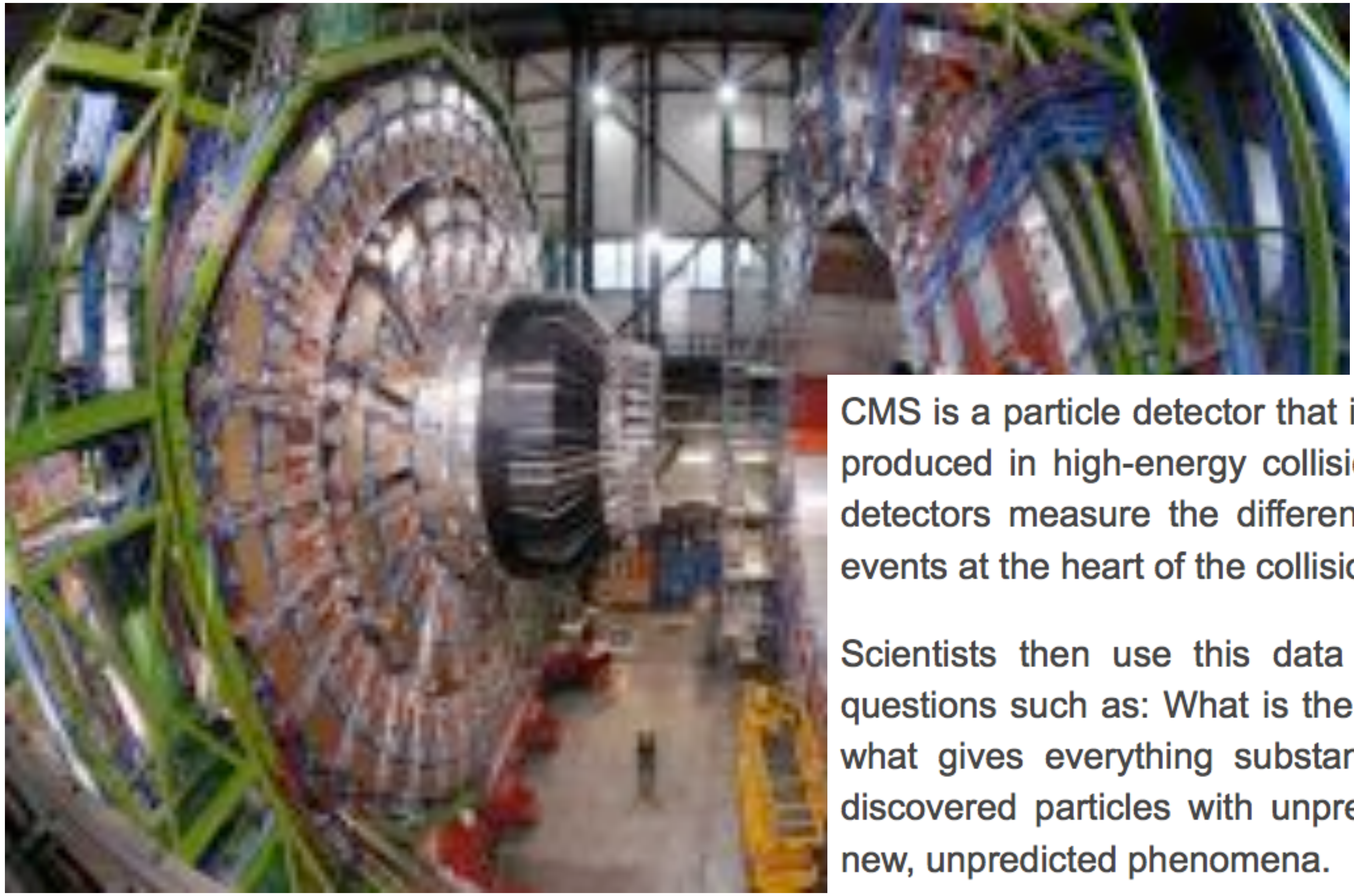
- Large QGP temperature, volume, energy density and lifetime.
- Large cross section for hard probes: high pT, jets, heavy quarks.
- Small net-baryon density at mid rapidity corresponding to the conditions in the early Universe.
- First principle methods (pQCD, Lattice Gauge Theory) more directly applicable
- New generation of detectors: ATLAS, CMS, ALICE and LHCb (for p-Pb runs)

LHC


Alps
Geneva
LHCb
CMS
ATLAS
ALICE
LHC
ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

COMPACT MUON SOLENOID

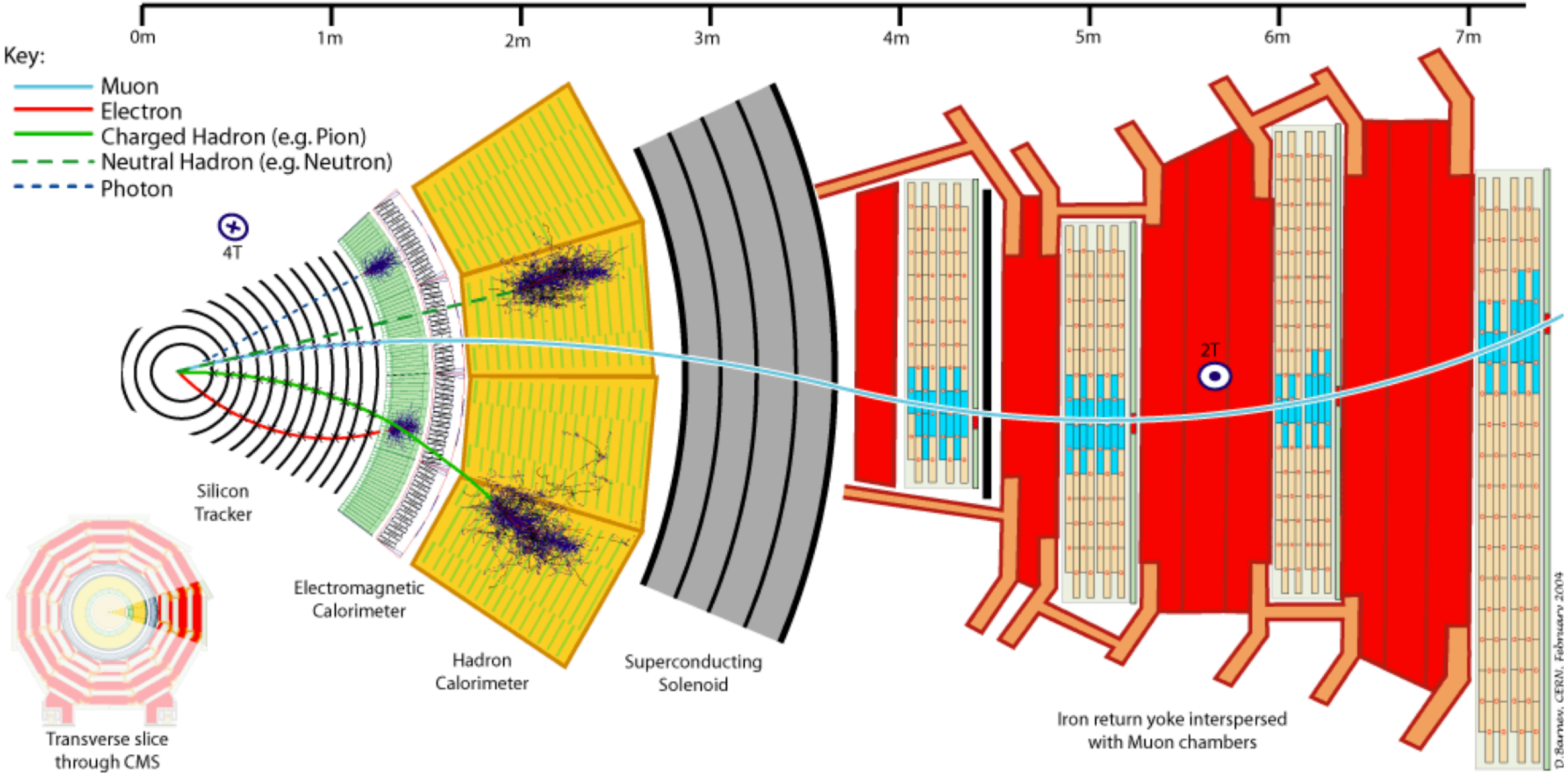




CMS is a particle detector that is designed to see a wide range of particles and phenomena produced in high-energy collisions in the LHC. Like a cylindrical onion, different layers of detectors measure the different particles, and use this key data to build up a picture of events at the heart of the collision.

Scientists then use this data to search for new phenomena that will help to answer questions such as: What is the Universe really made of and what forces act within it? And what gives everything substance? CMS will also measure the properties of previously discovered particles with unprecedented precision, and be on the lookout for completely new, unpredicted phenomena.

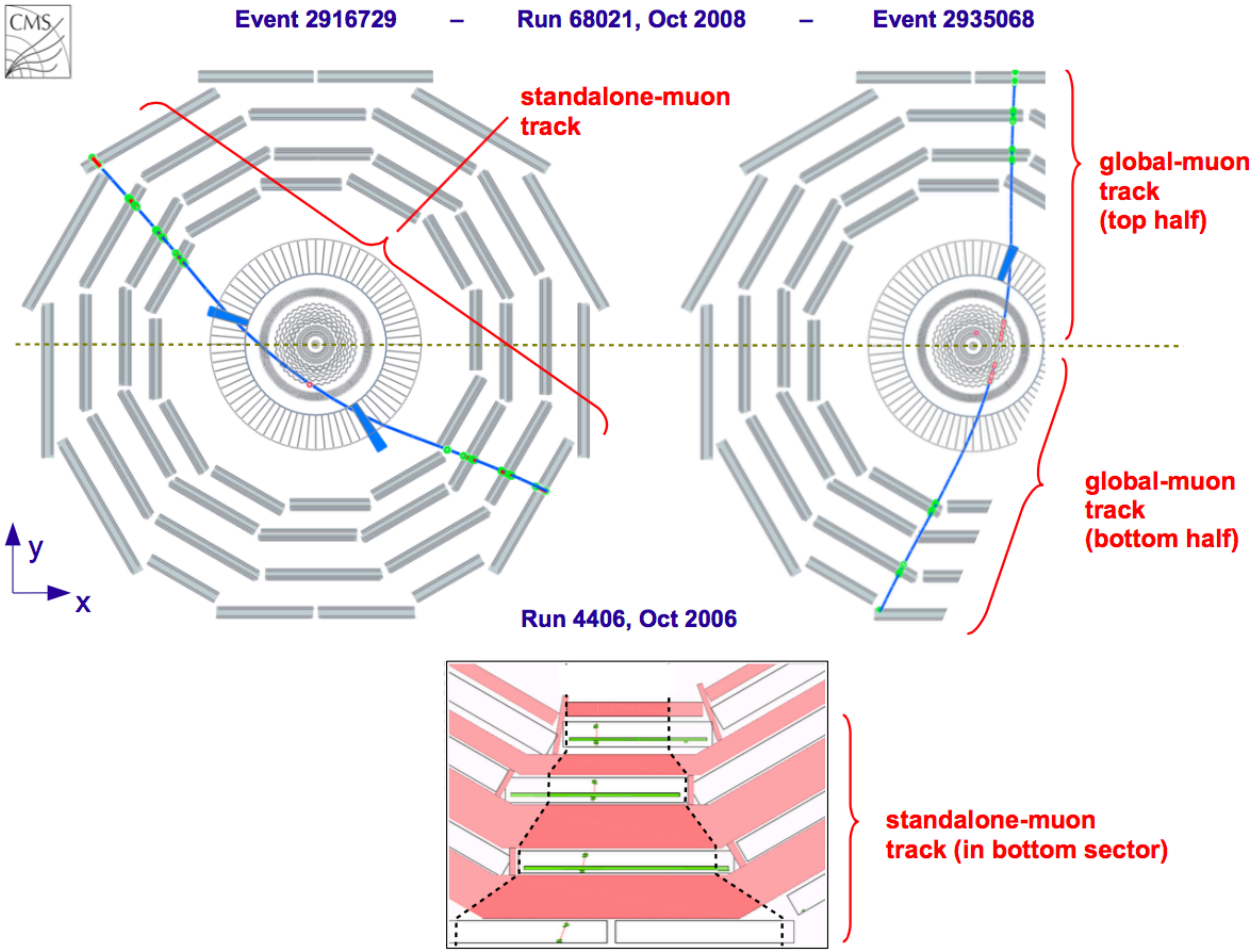
CMS

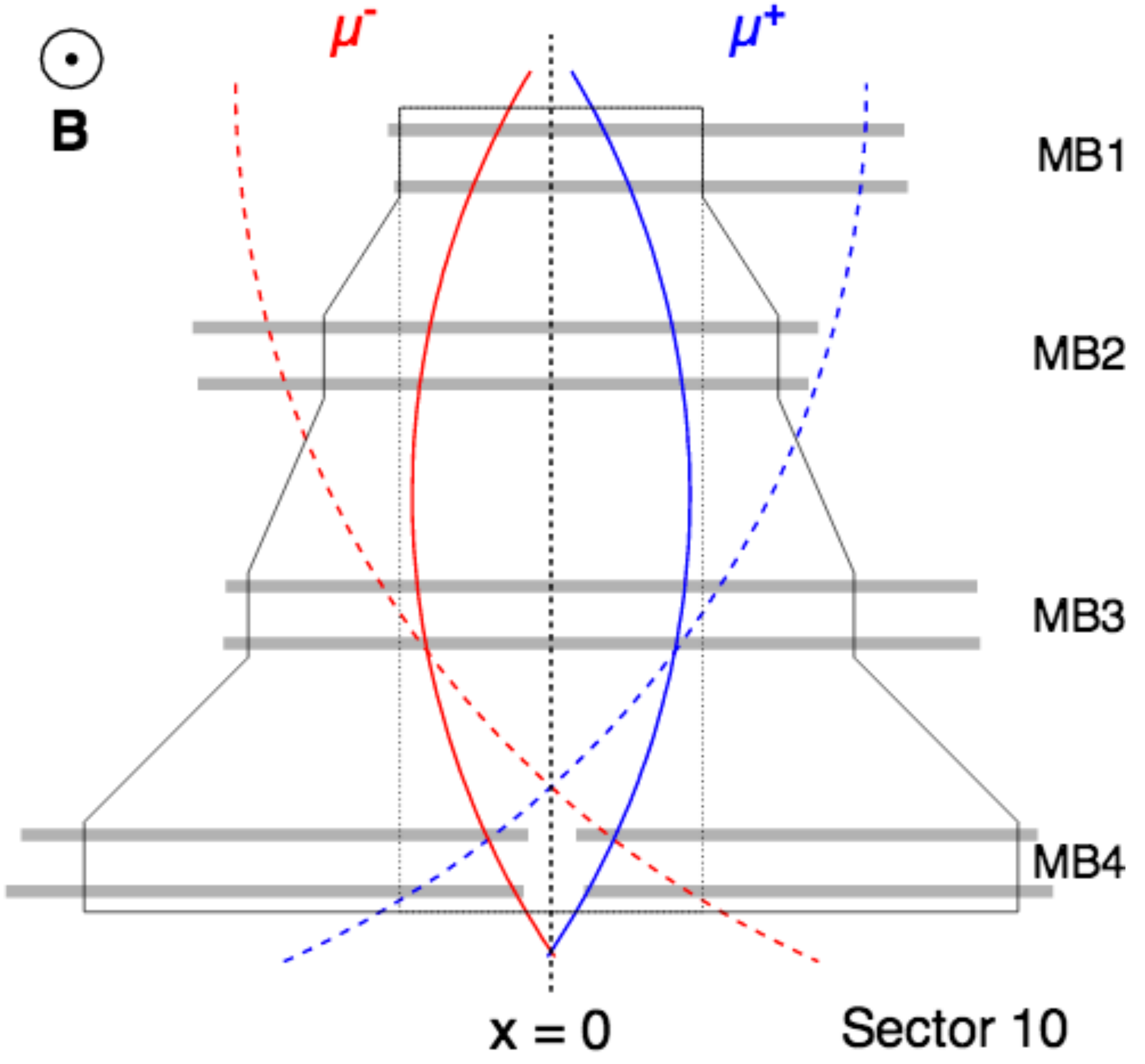

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Indeed, the first publication of an LHC experiment with a physical measurement was done by CMS: cosmic charge ratio

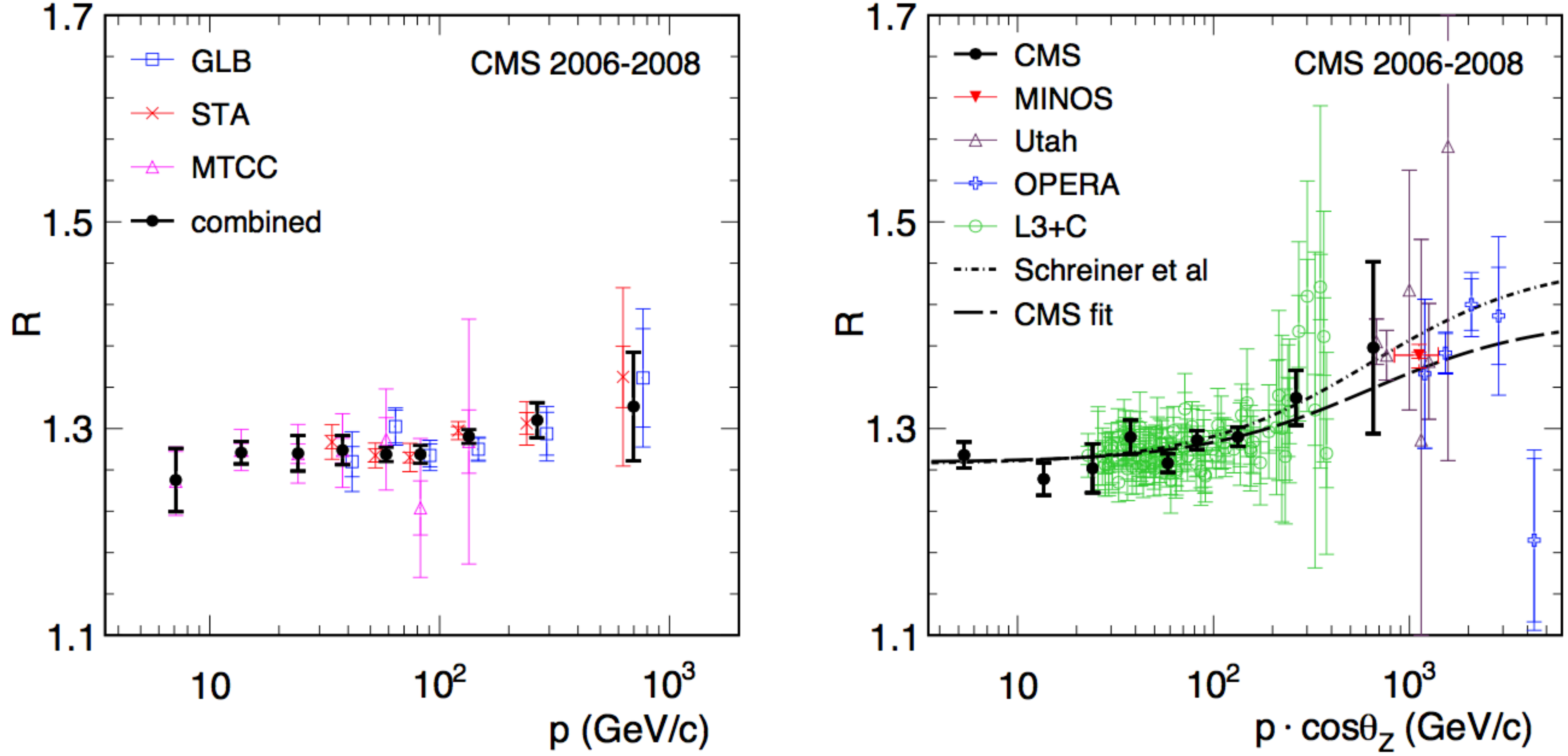
CMS

CERN-PH-EP-2010-011 2010/05/31



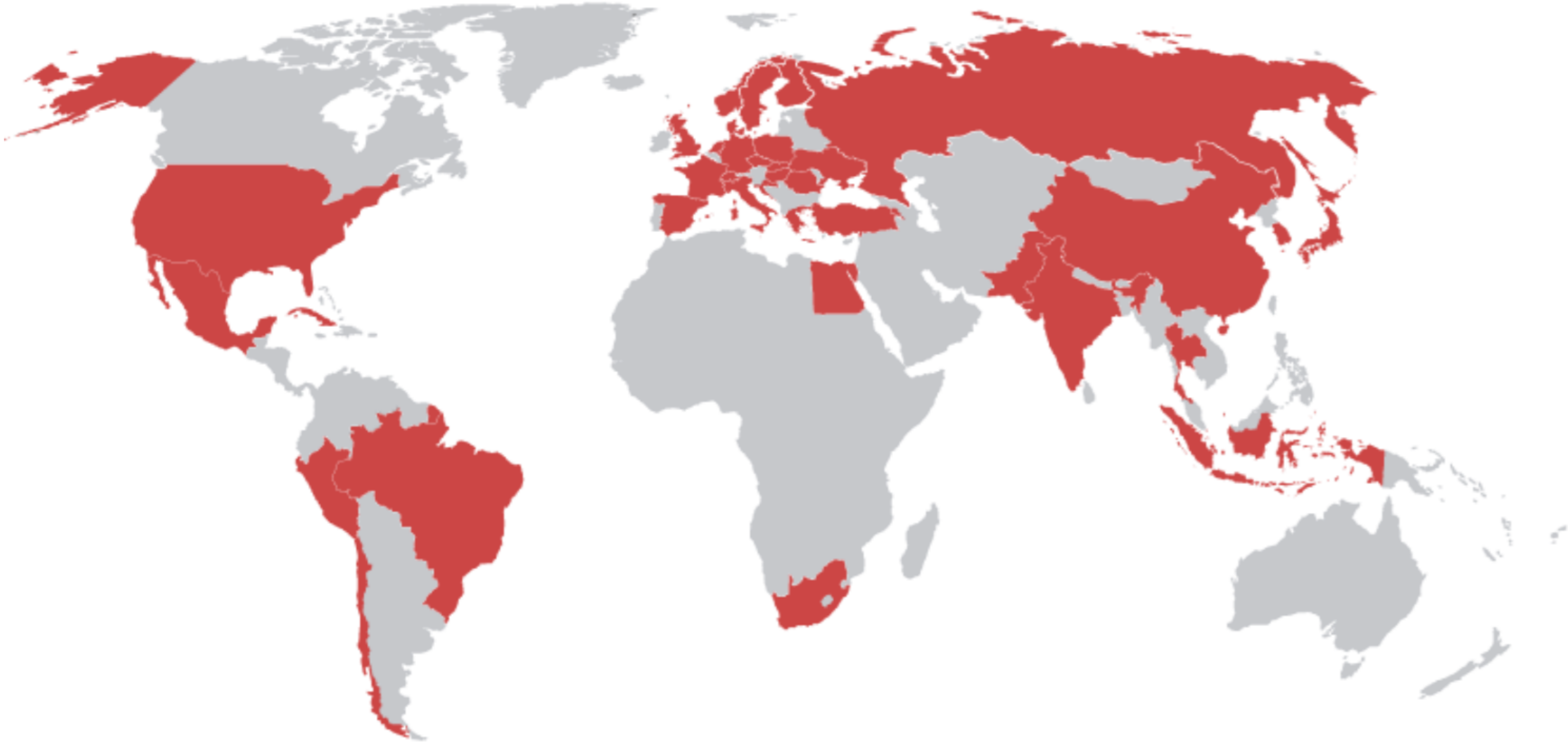


CMS



CMS has measured the flux ratio of positive- to negative-charge cosmic ray muons, as a function of the muon momentum and its vertical component. The result is in agreement with previous measurements by underground experiments. This is the most precise measurement of the charge ratio in the momentum region below 0.5 TeV/c. It is also the first physics measurement using muons with the complete CMS detector.

A Large Ion Collider Experiment

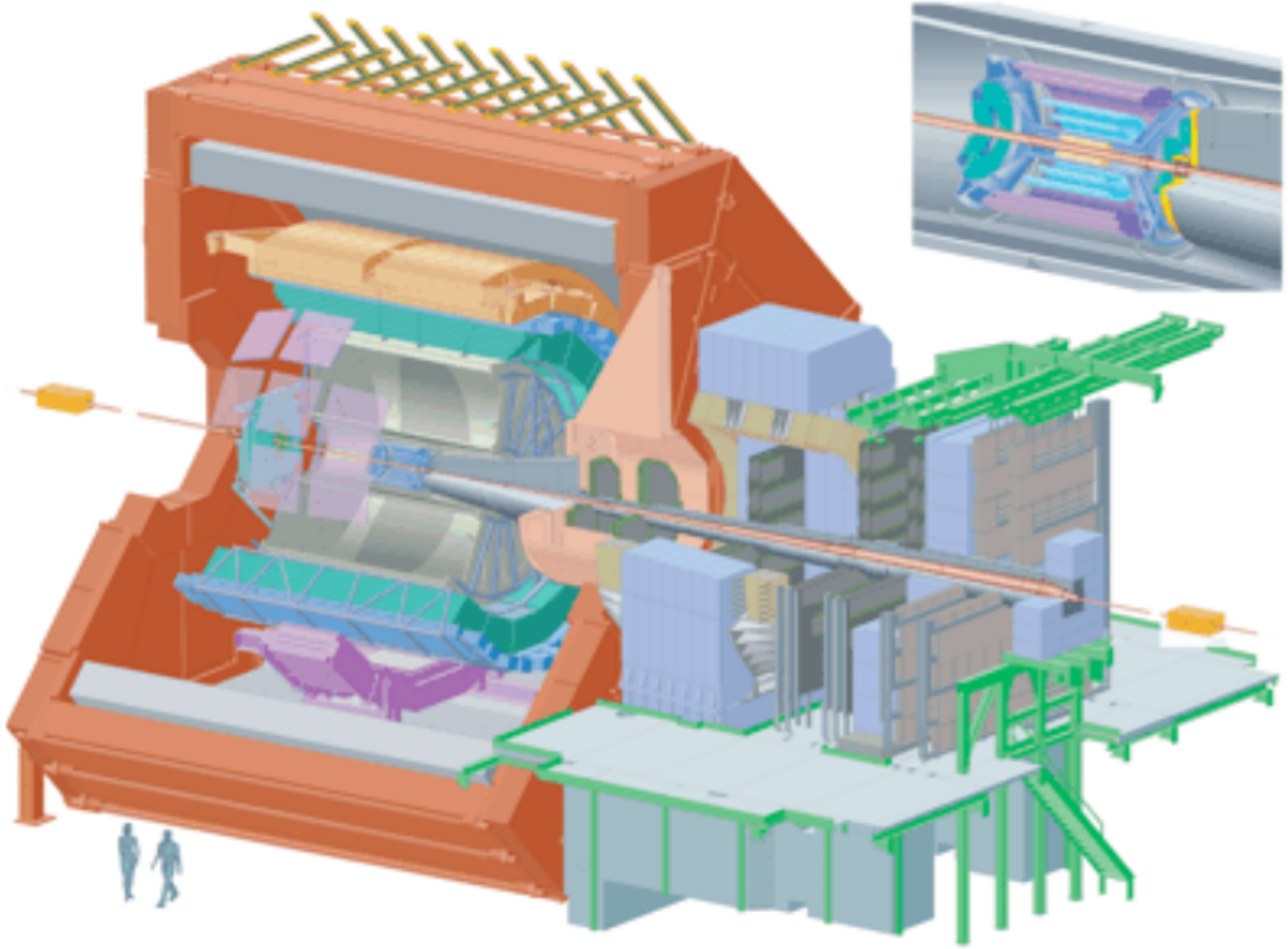


37 countries, 151 institutes, 1550 members

http://aliceinfo.cern.ch/

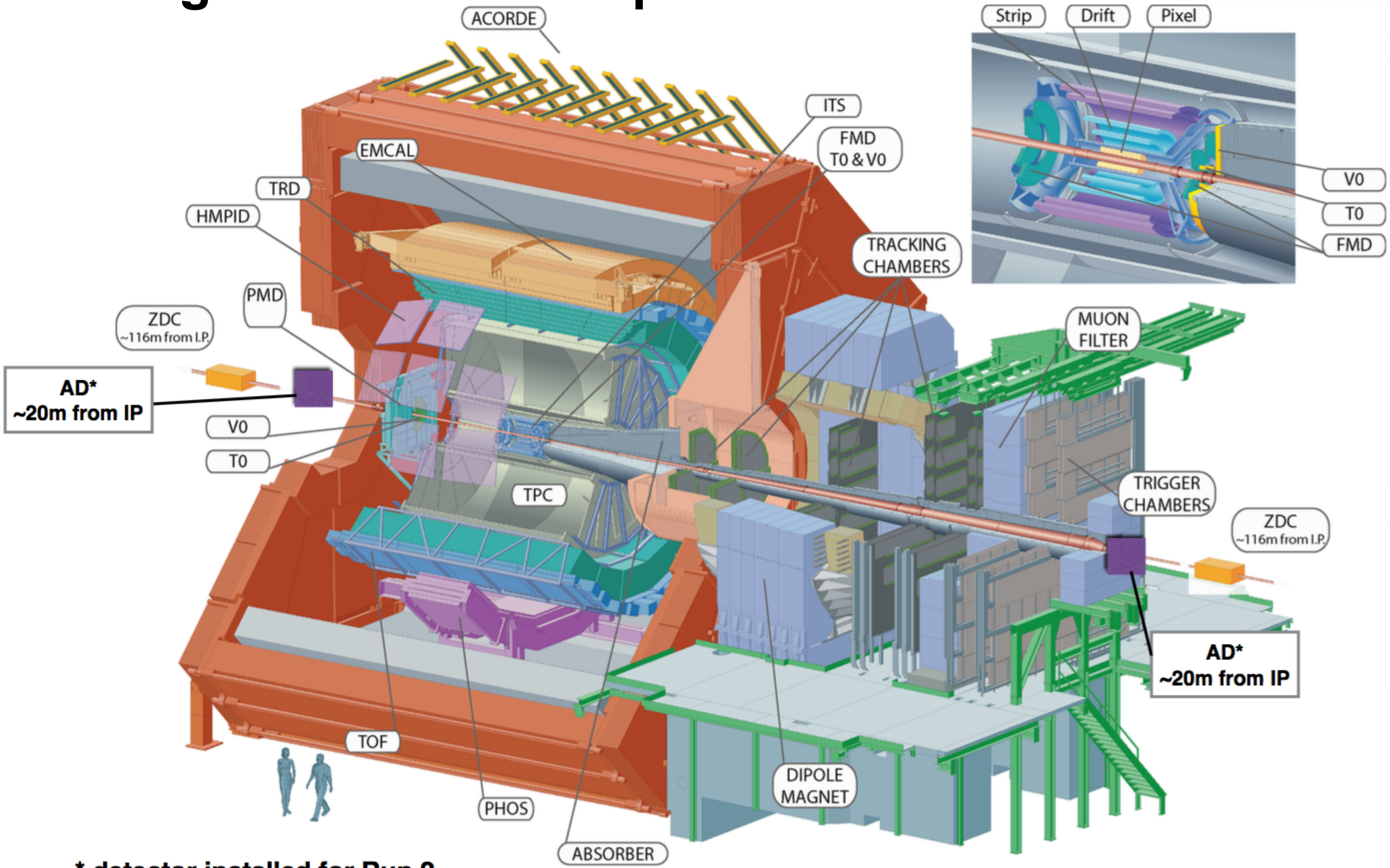
ALICE: A Large Ion Collider Experiment

BUAP

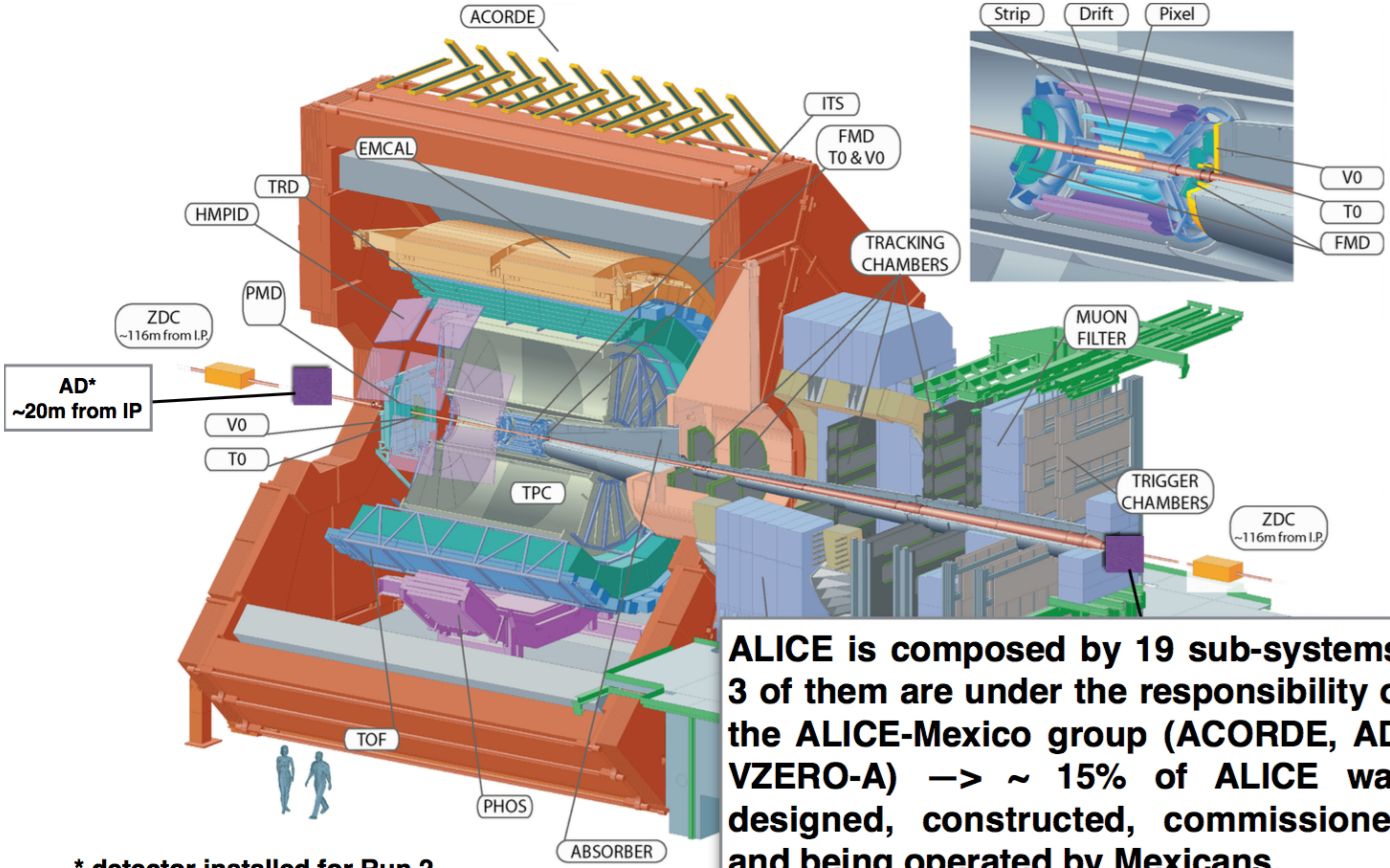


The ALICE Collaboration has built a **dedicated heavy-ion detector** to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies. Our **aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma**, is expected. The existence of such a phase and its properties are key issues in QCD for the **understanding of confinement and of chiral-symmetry restoration.** For this purpose, we are carrying out a comprehensive study of the hadrons, electrons, muons and photons produced in the collision of heavy nuclei. **ALICE is also studying proton-proton collisions both as a comparison with lead-lead collisions and in physics areas where ALICE is competitive** with other LHC experiments.

ALICE: A Large Ion Collider Experiment

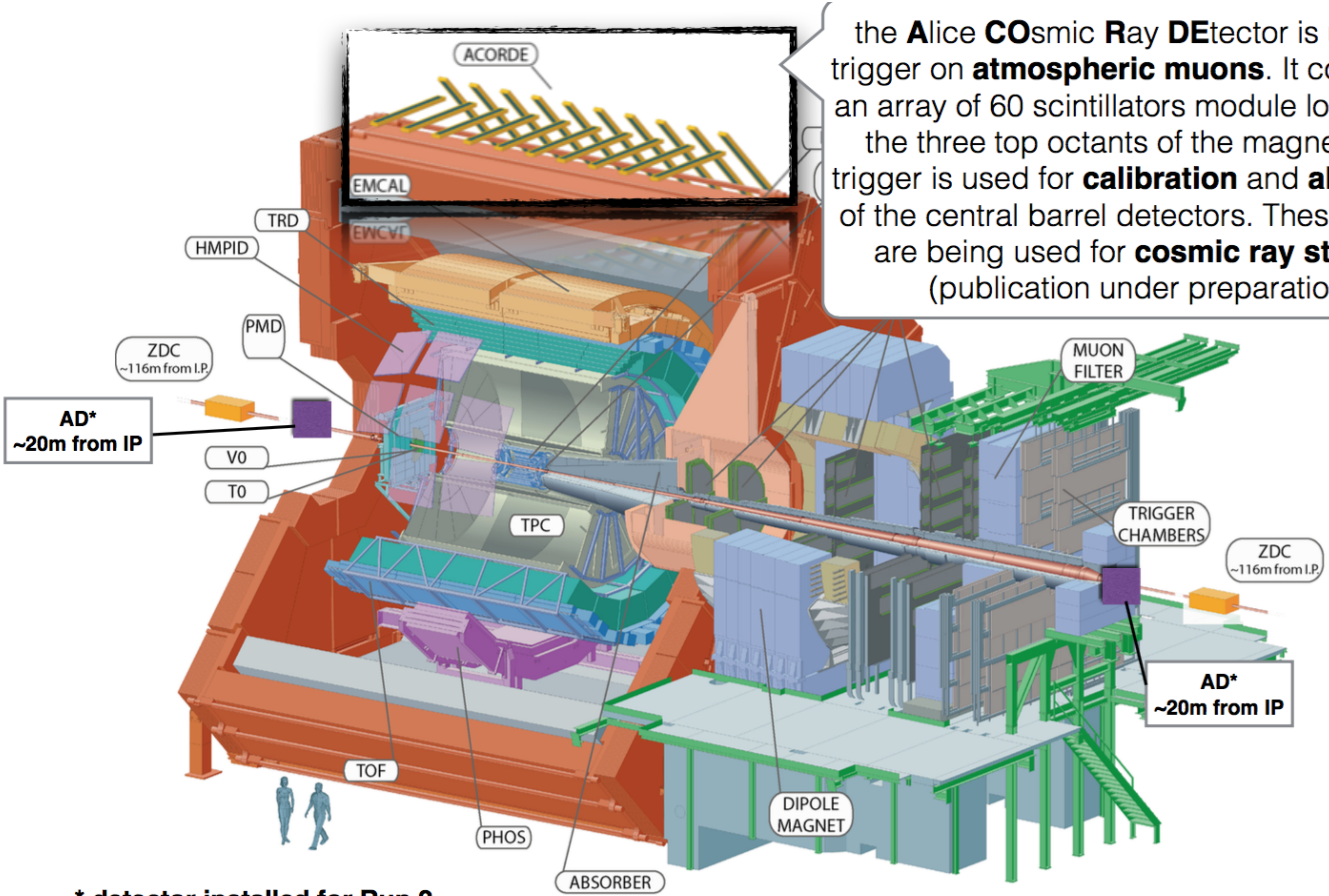


*** detector installed for Run 2**



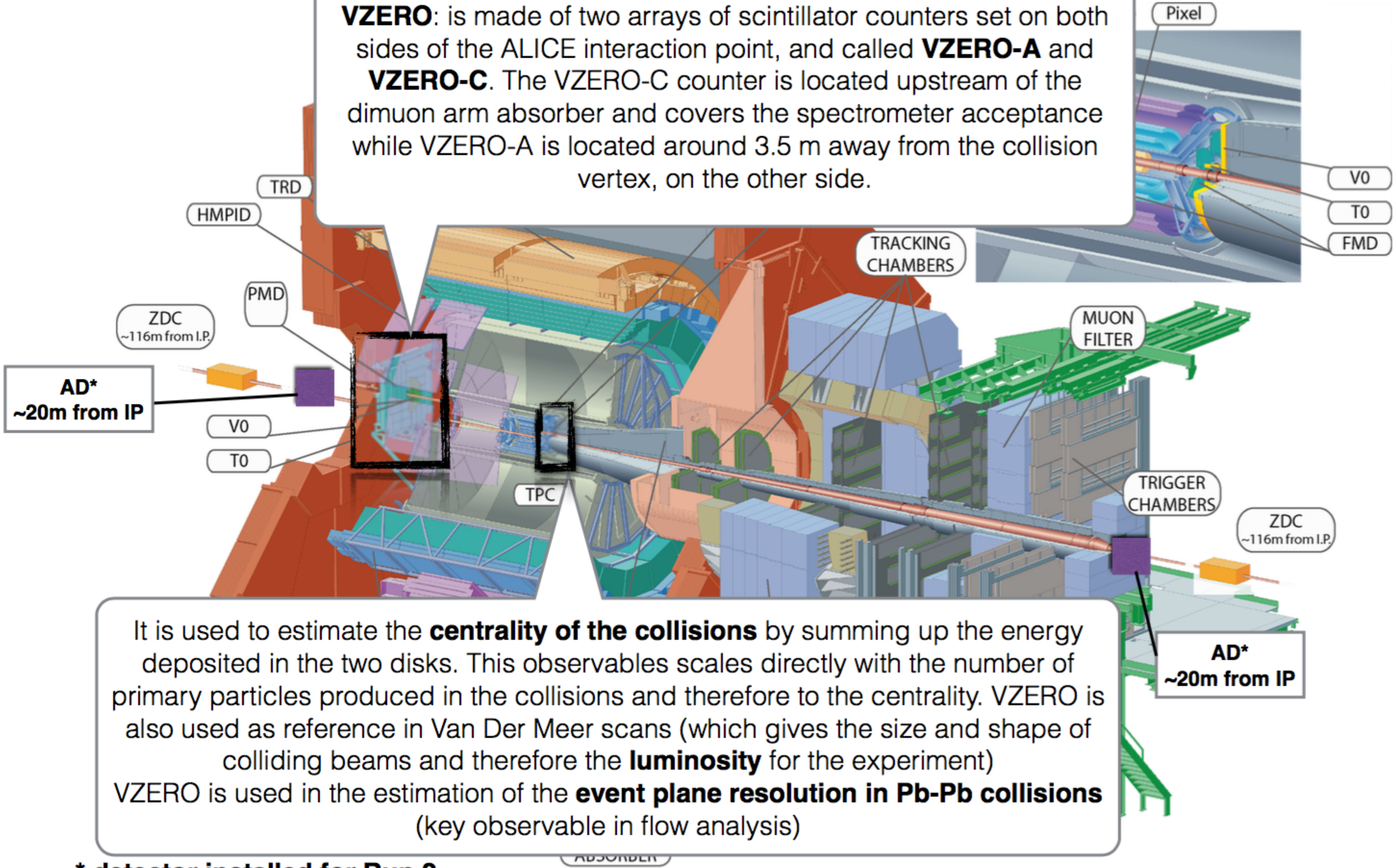
ALICE is composed by 19 sub-systems, 3 of them are under the responsibility of the ALICE-Mexico group (ACORDE, AD, VZERO-A) —> ~ 15% of ALICE was designed, constructed, commissioned and being operated by Mexicans.

*** detector installed for Run 2**



the **A**lice **CO**smic **R**ay **DE**tector is used to trigger on **atmospheric muons**. It consists of an array of 60 scintillators module located on the three top octants of the magnet. This trigger is used for **calibration** and **alignment** of the central barrel detectors. These events are being used for **cosmic ray studies** (publication under preparation)

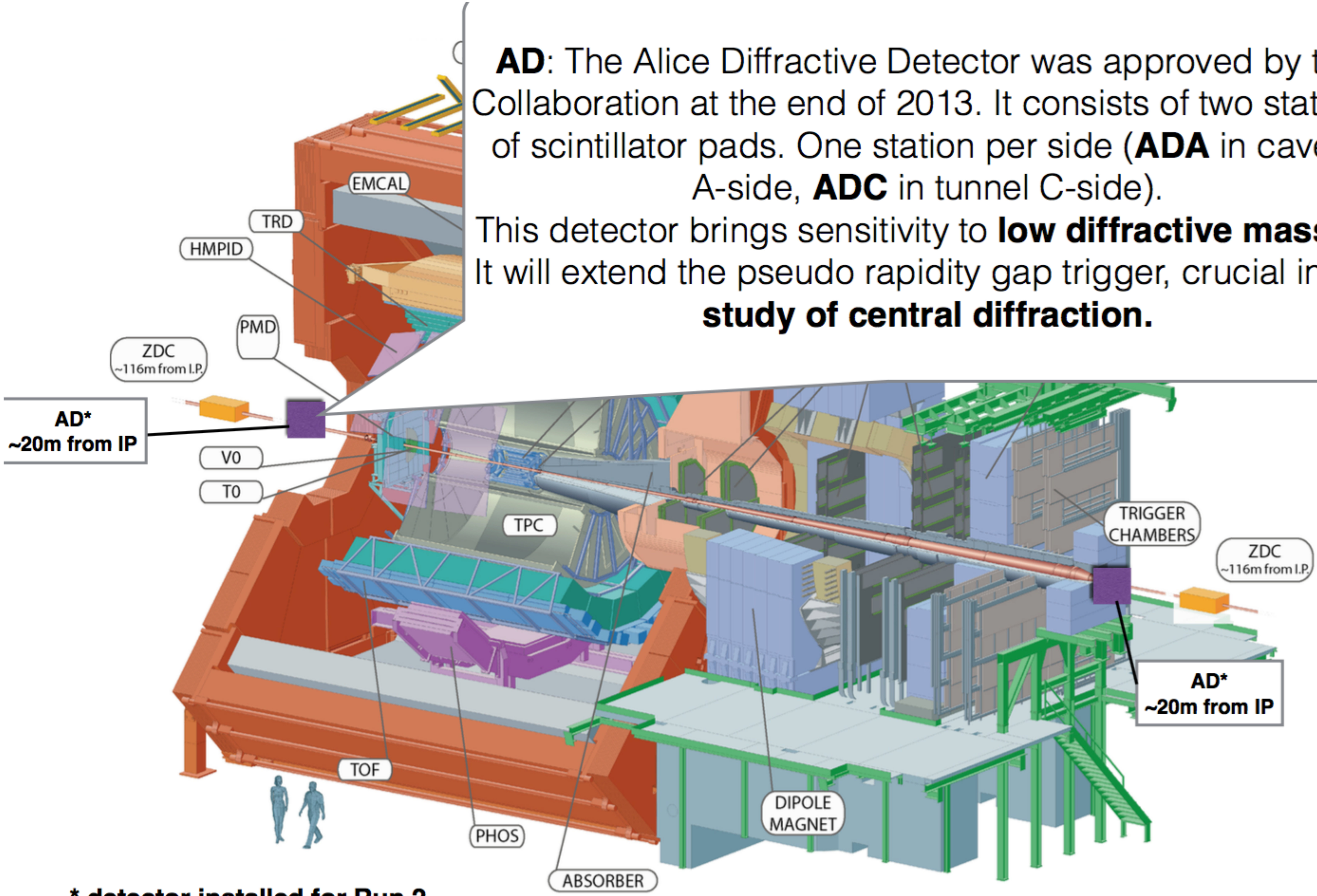
*** detector installed for Run 2**



VZERO: is made of two arrays of scintillator counters set on both sides of the ALICE interaction point, and called **VZERO-A** and **VZERO-C**. The VZERO-C counter is located upstream of the dimuon arm absorber and covers the spectrometer acceptance while VZERO-A is located around 3.5 m away from the collision vertex, on the other side.

It is used to estimate the **centrality of the collisions** by summing up the energy deposited in the two disks. This observables scales directly with the number of primary particles produced in the collisions and therefore to the centrality. VZERO is also used as reference in Van Der Meer scans (which gives the size and shape of colliding beams and therefore the **luminosity** for the experiment)
VZERO is used in the estimation of the **event plane resolution in Pb-Pb collisions** (key observable in flow analysis)

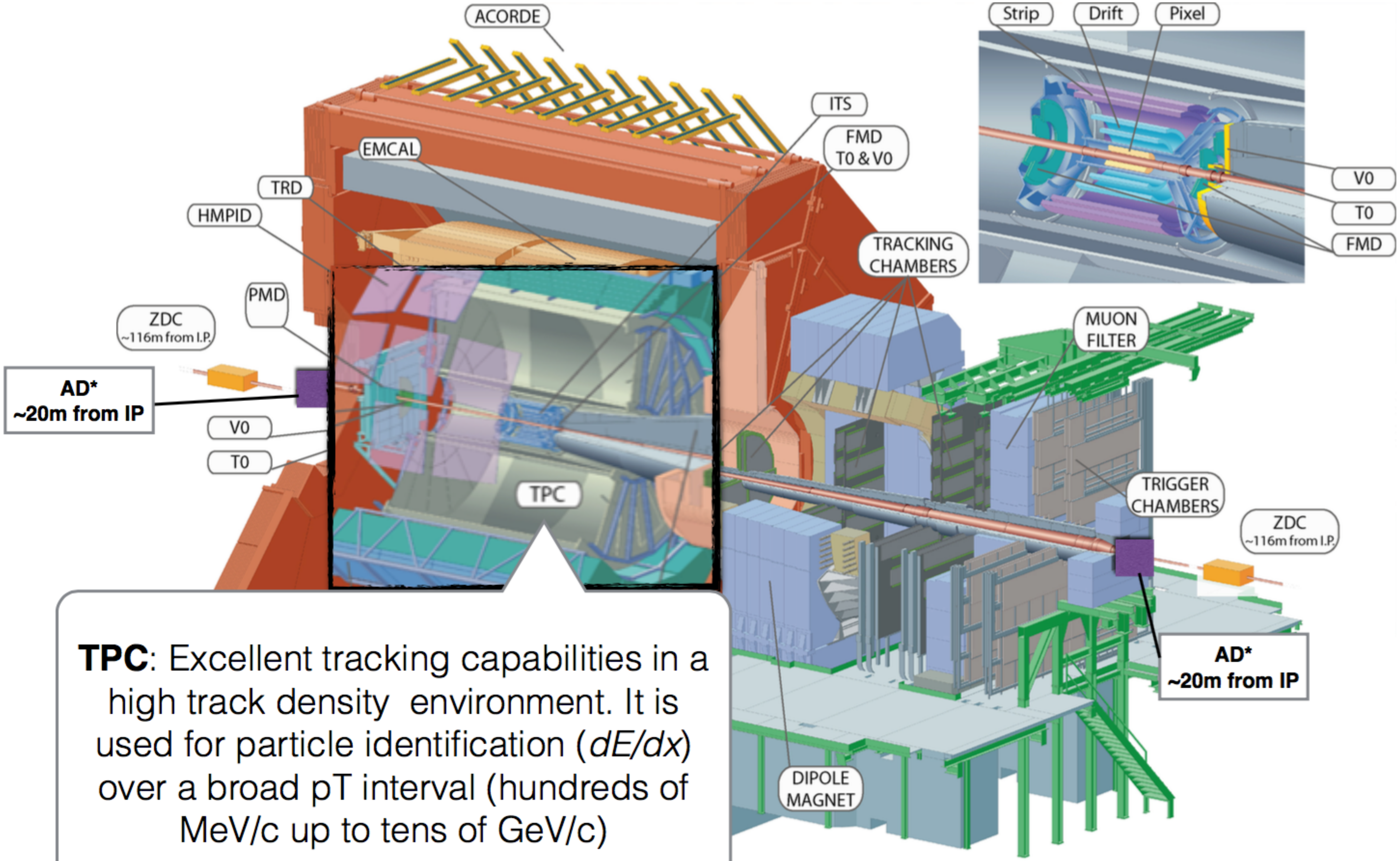
*** detector installed for Run 2**



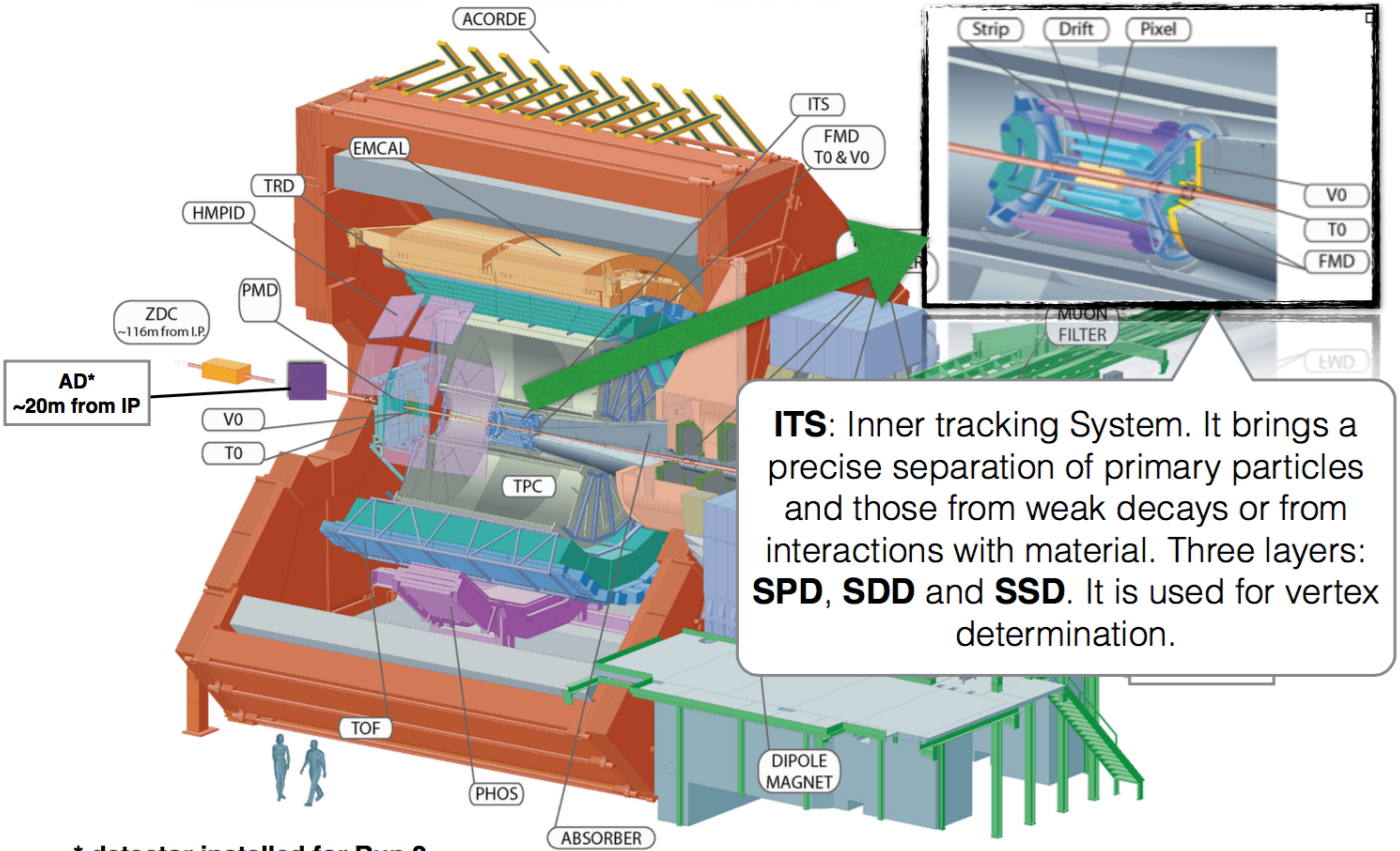
AD: The Alice Diffractive Detector was approved by the Collaboration at the end of 2013. It consists of two stations of scintillator pads. One station per side (**ADA** in cavern A-side, **ADC** in tunnel C-side).

This detector brings sensitivity to **low diffractive masses.** It will extend the pseudo rapidity gap trigger, crucial in the **study of central diffraction.**

*** detector installed for Run 2**

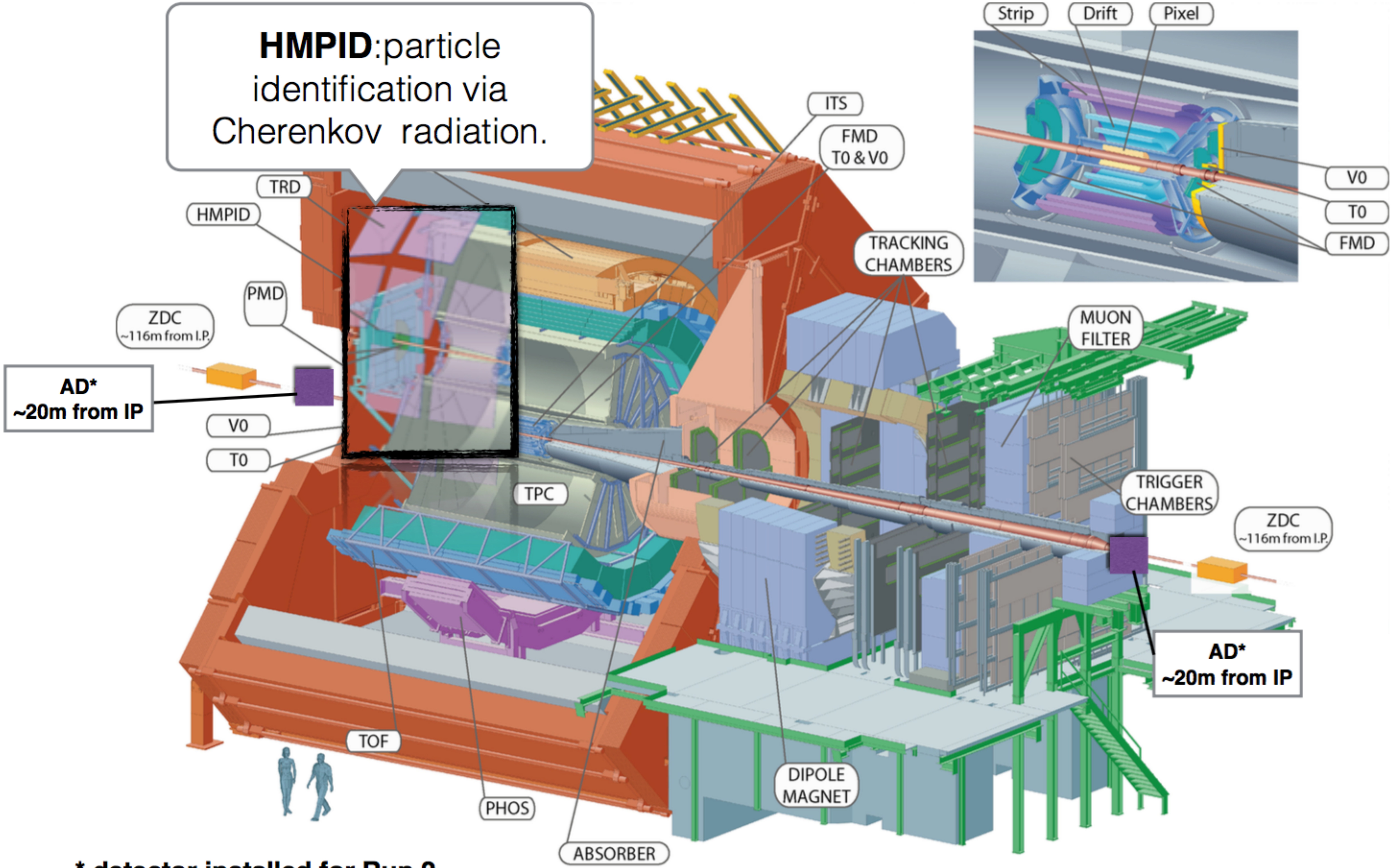


TPC: Excellent tracking capabilities in a high track density environment. It is used for particle identification (*dE/dx*) over a broad pT interval (hundreds of MeV/c up to tens of GeV/c)



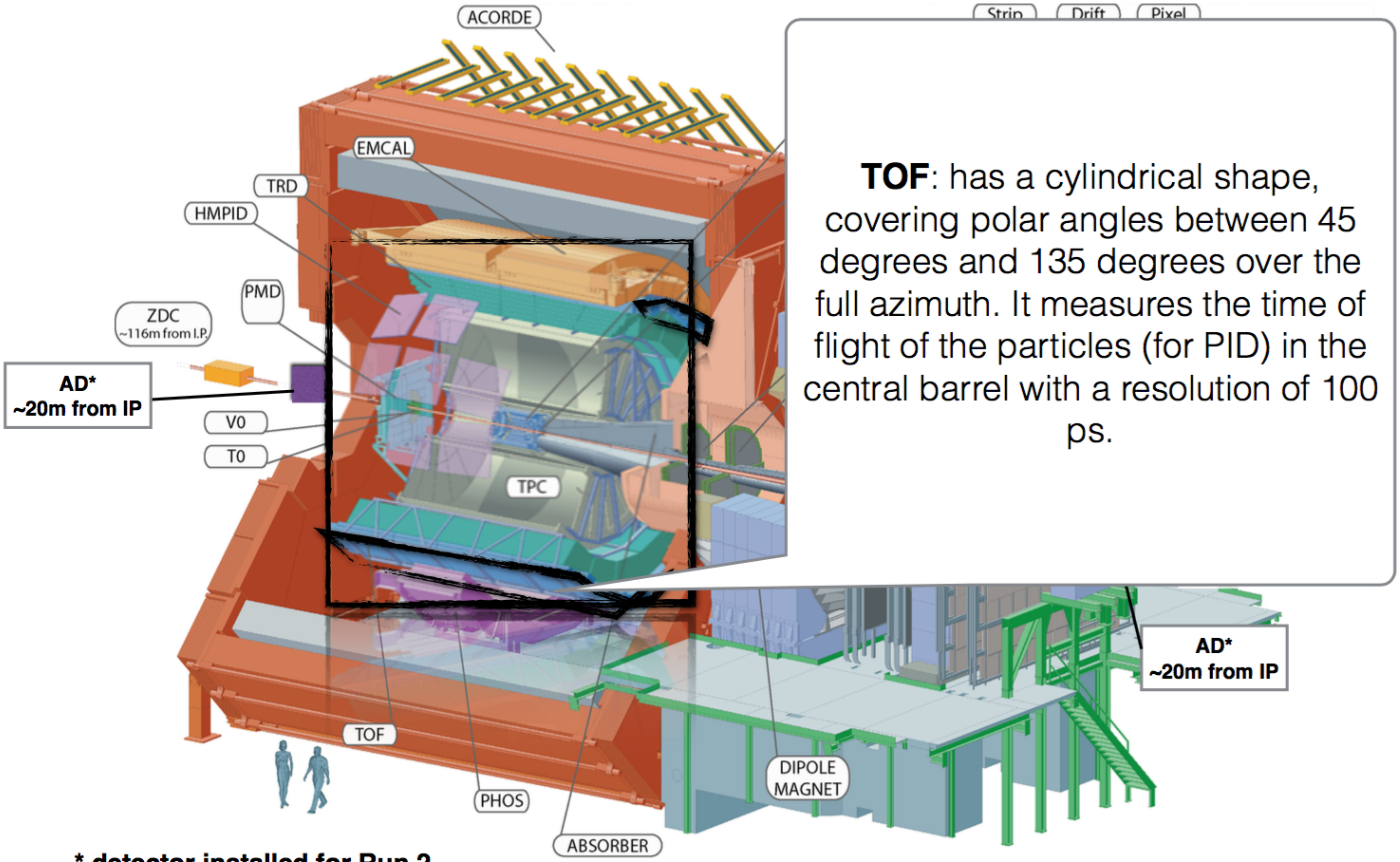
ITS: Inner tracking System. It brings a precise separation of primary particles and those from weak decays or from interactions with material. Three layers: **SPD**, **SDD** and **SSD**. It is used for vertex determination.

*** detector installed for Run 2**



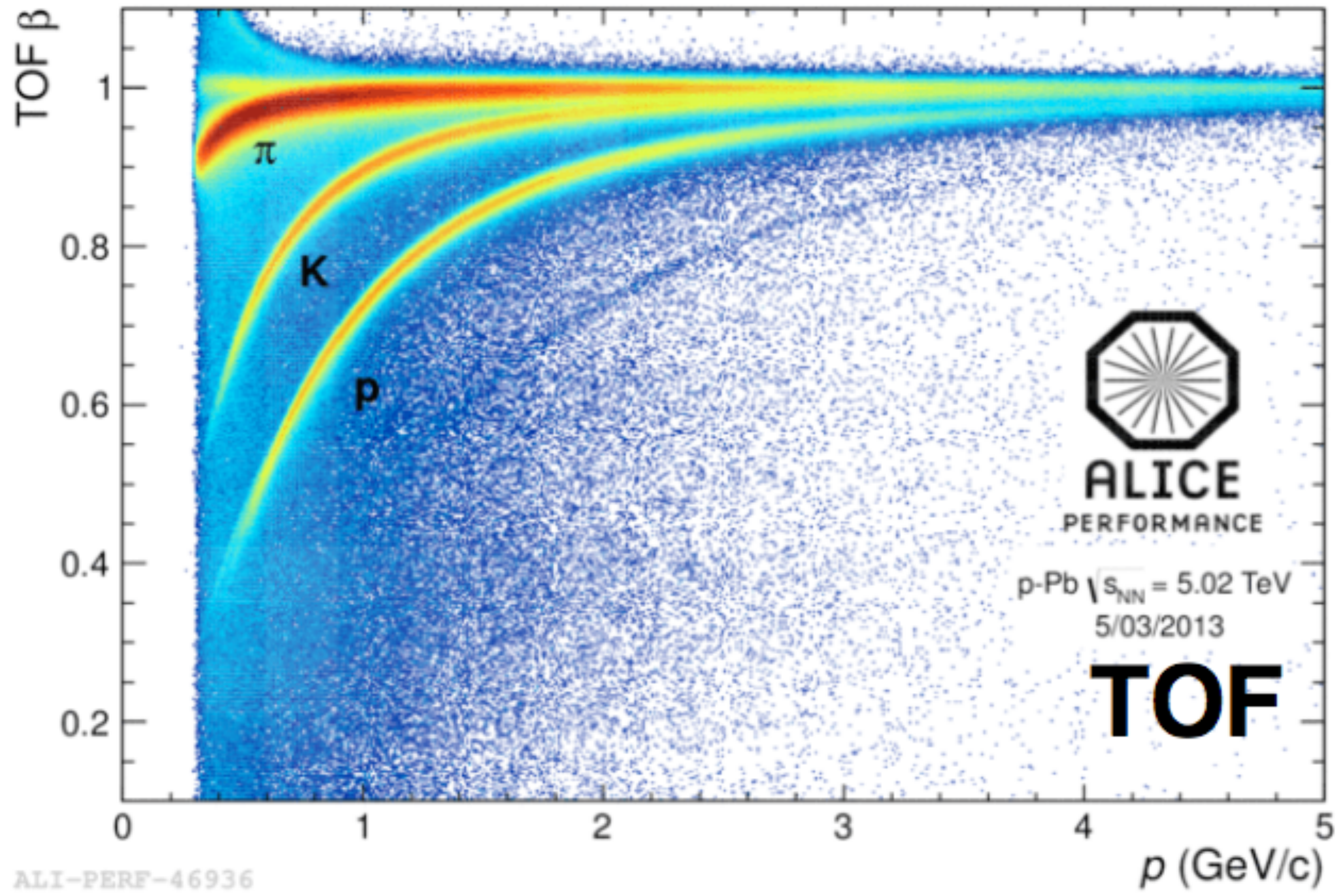
HMPID:particle identification via Cherenkov radiation.

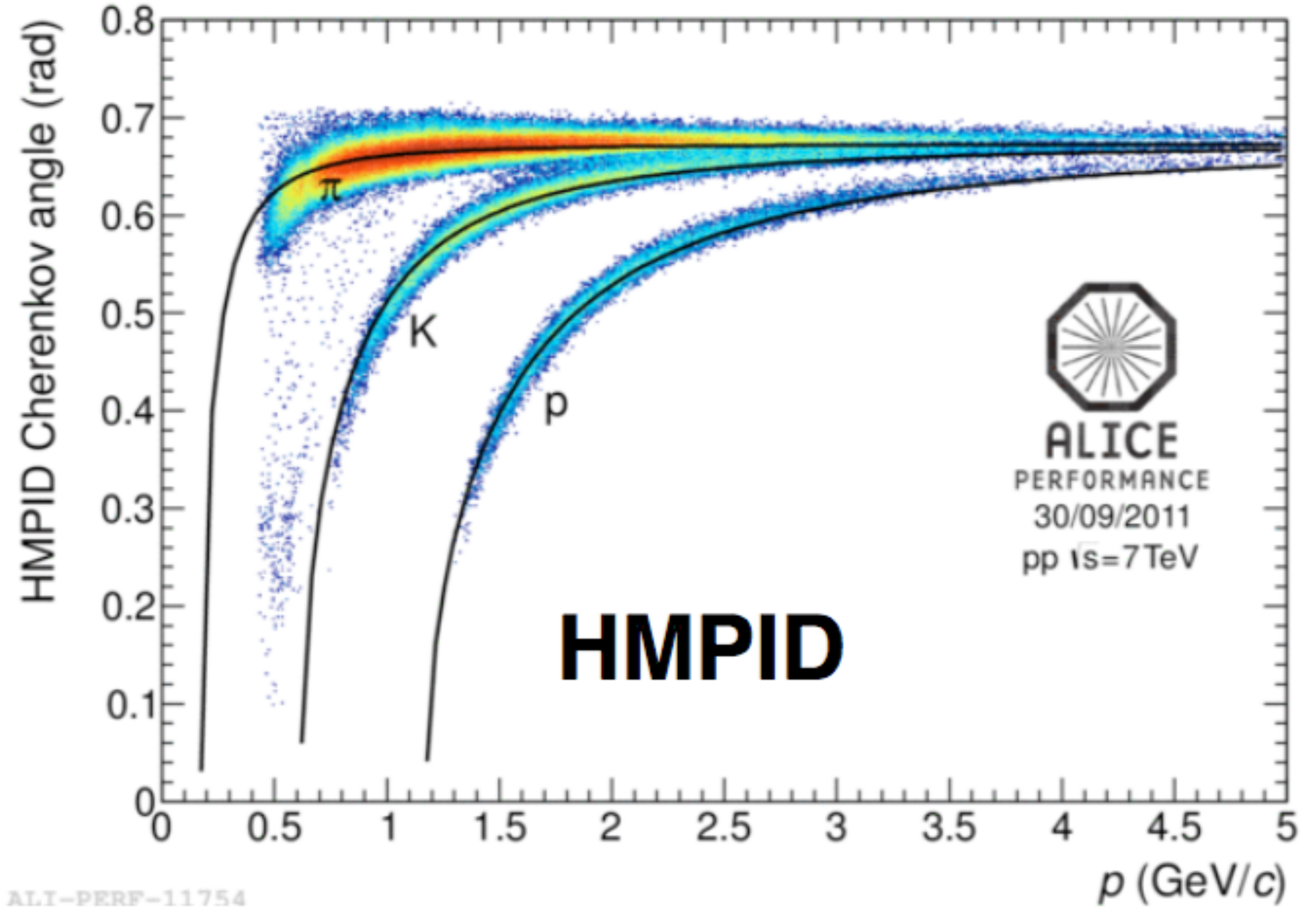
* detector installed for Run 2

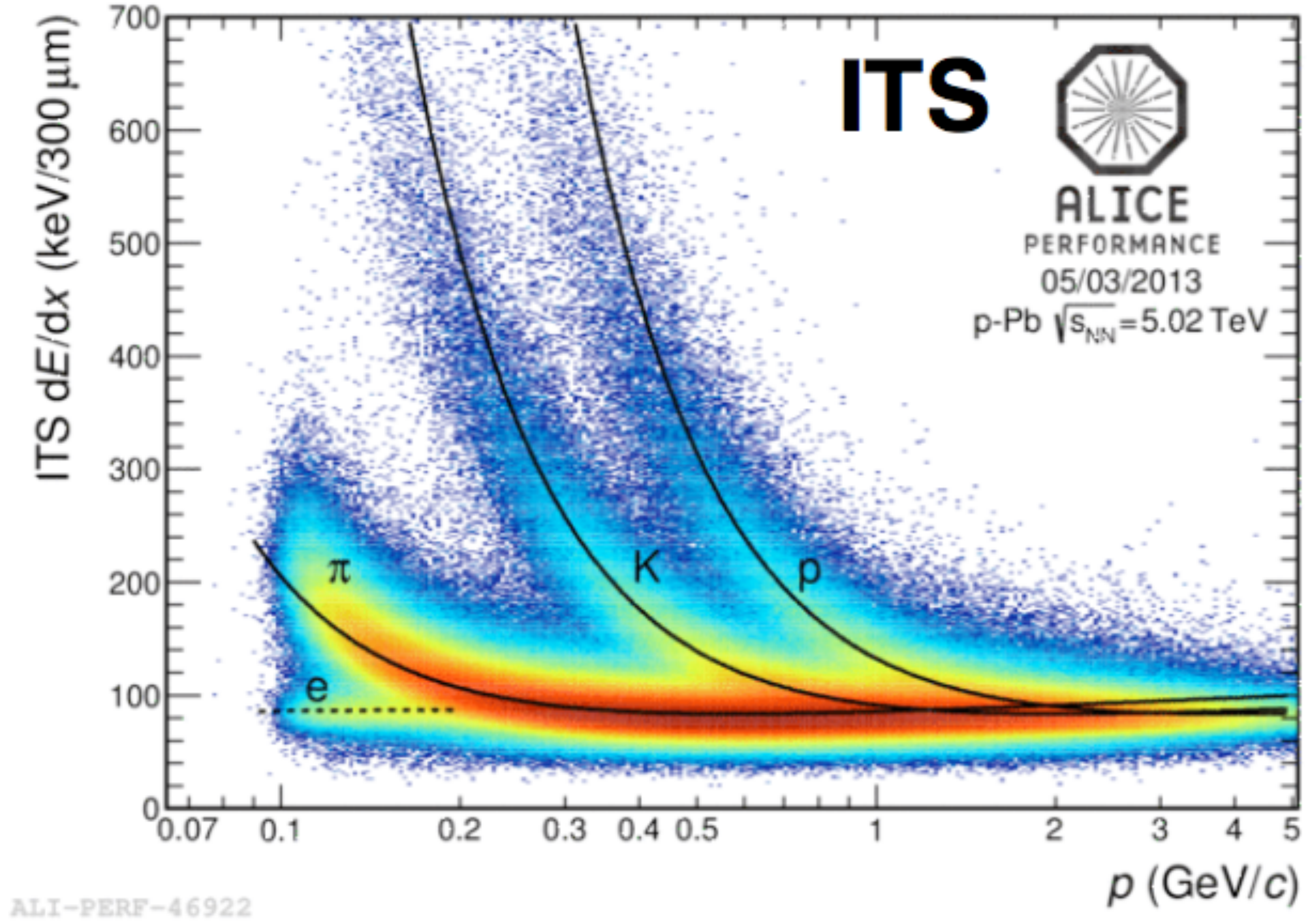


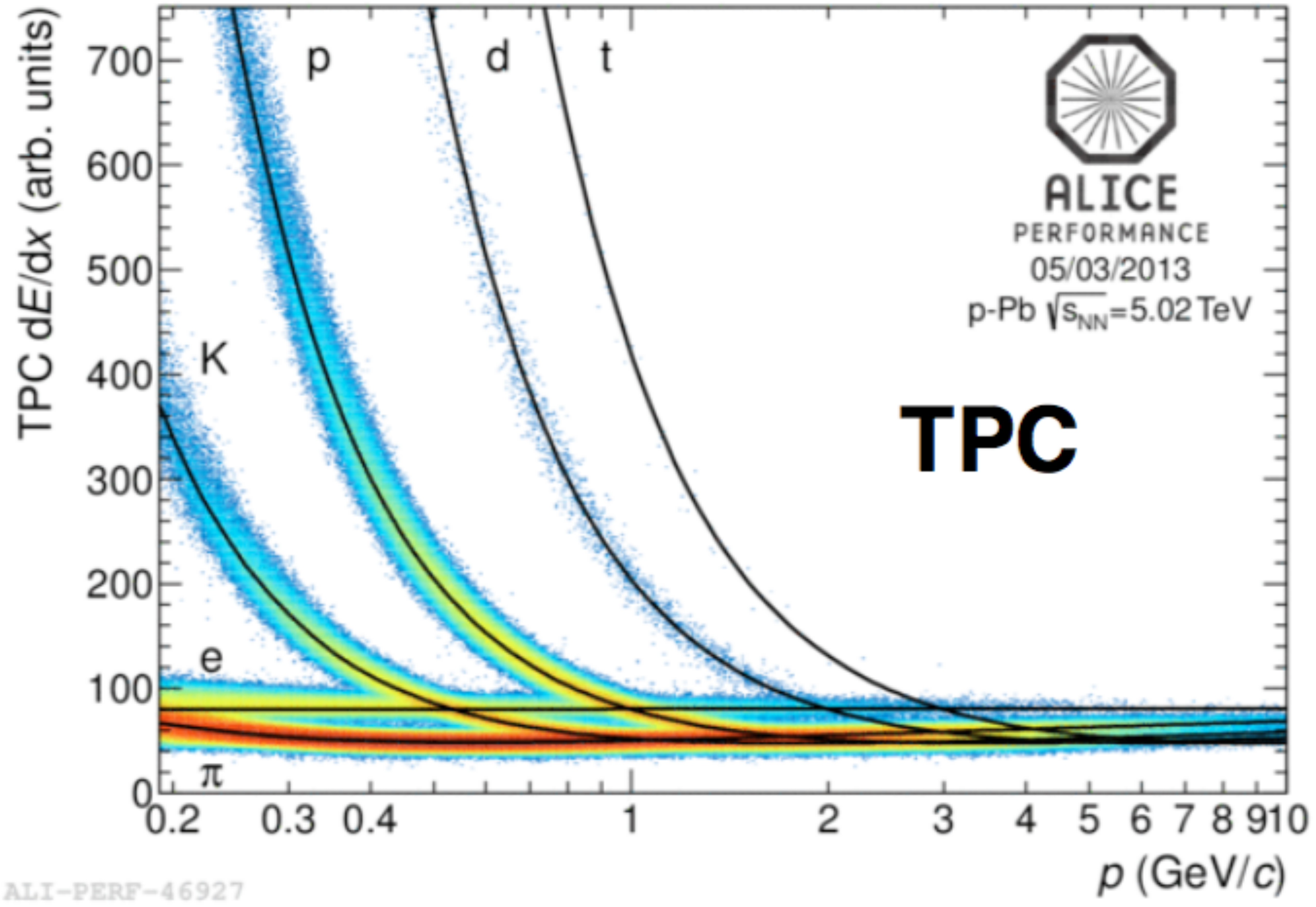
TOF: has a cylindrical shape, covering polar angles between 45 degrees and 135 degrees over the full azimuth. It measures the time of flight of the particles (for PID) in the central barrel with a resolution of 100 ps.

*** detector installed for Run 2**









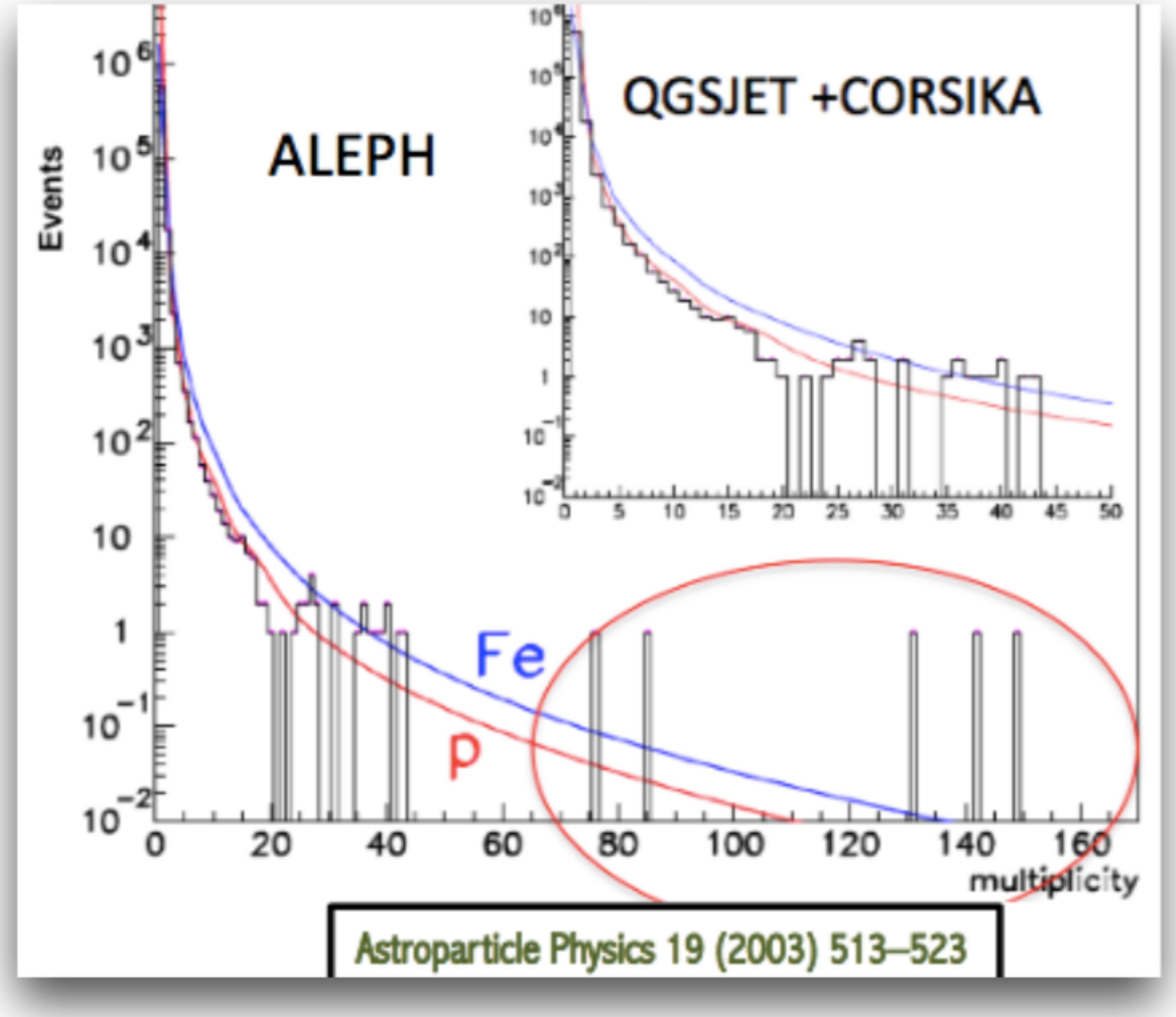
Several PID methods are used in ALICE.

COSMIC-RAY PHYSICS

LEP experiments were pioneers in the study of atmospheric muon bundles with underground apparatus used in particle accelerators: ALEPH, **Astro-particle Physics 19 (2003) 513–523 and** DELPHI, **Astro-particle Physics 28 (2007) 273–286**

- These muon bundles are well described at low intermediate multiplicity, but not the high muon multiplicity events.

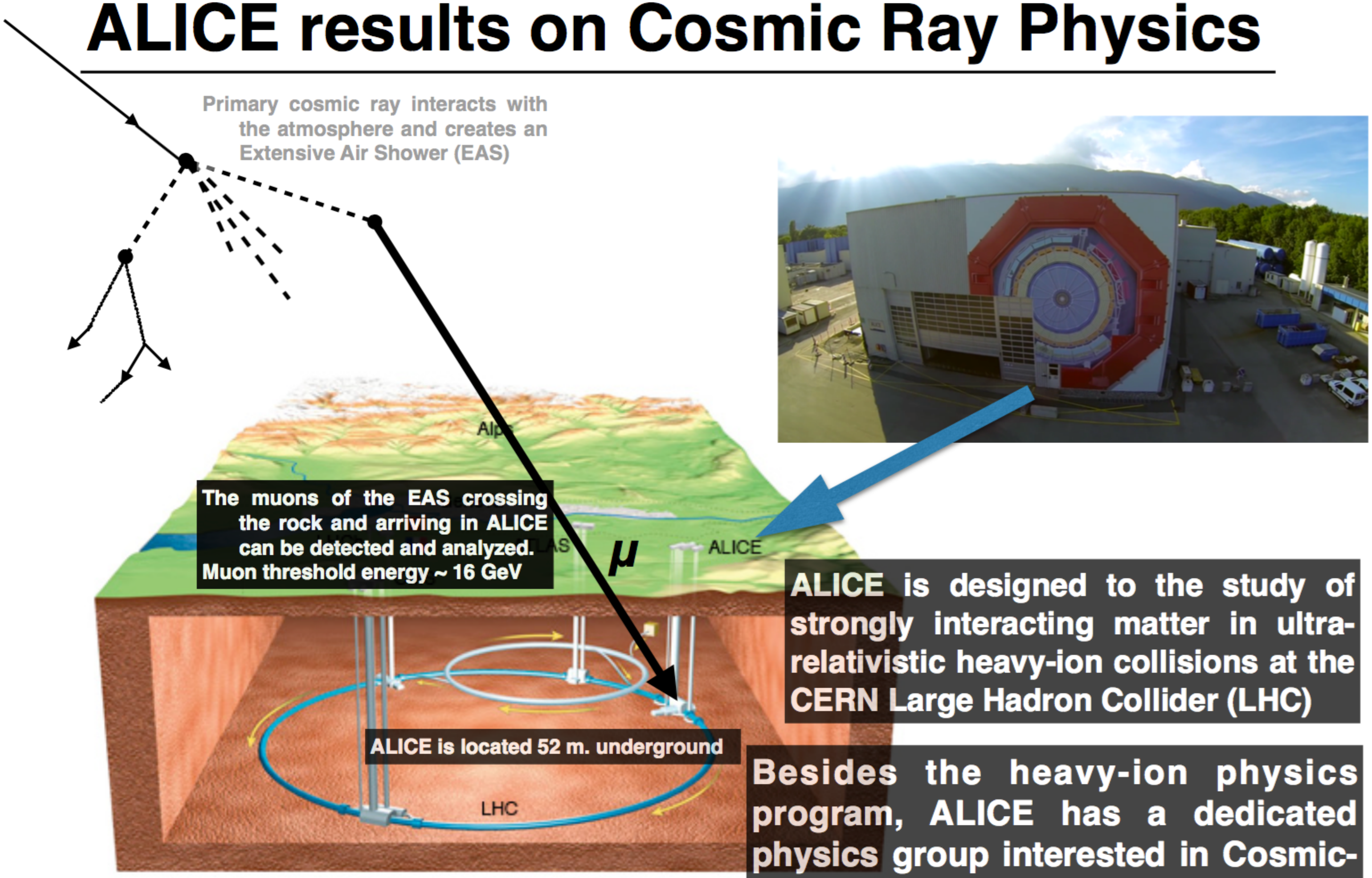
- Delphi conclusion: "*Even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events*".



Astroparticle Physics 19 (2003) 513–523

Cosmic-ray energy coverage: 10^{13} - 10^{18} eV

ALICE results on Cosmic Ray Physics



Primary cosmic ray interacts with the atmosphere and creates an Extensive Air Shower (EAS)

The muons of the EAS crossing the rock and arriving in ALICE can be detected and analyzed.
Muon threshold energy ~ 16 GeV

ALICE is located 52 m. underground

ALICE is designed to the study of strongly interacting matter in ultra-relativistic heavy-ion collisions at the CERN Large Hadron Collider (LHC)

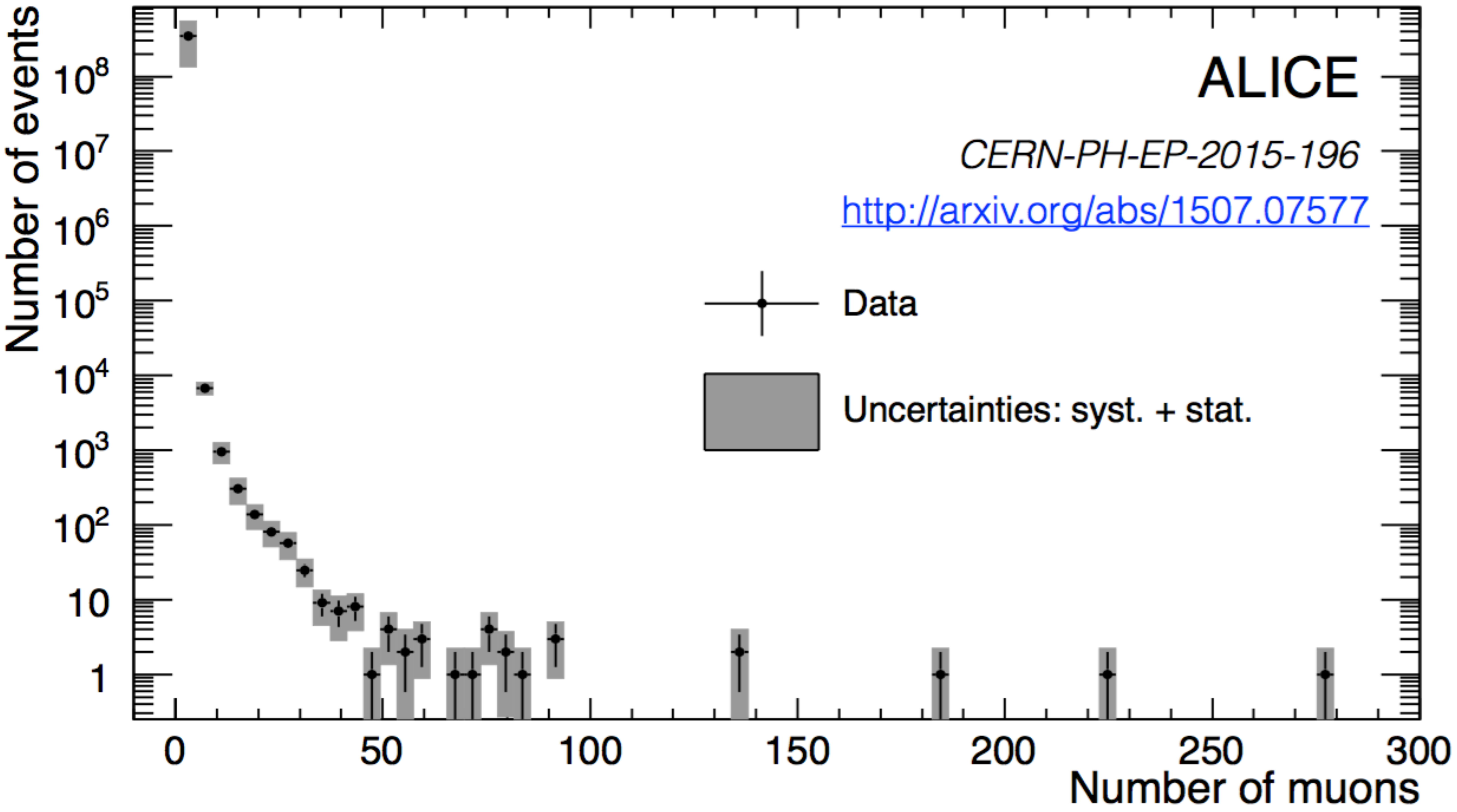
Besides the heavy-ion physics program, ALICE has a dedicated physics group interested in Cosmic-ray physics.

ALICE results on Cosmic Ray Physics

- Between 2010 and 2013, ALICE collected 30.8 days of dedicated cosmic-ray data during downtime of LHC.

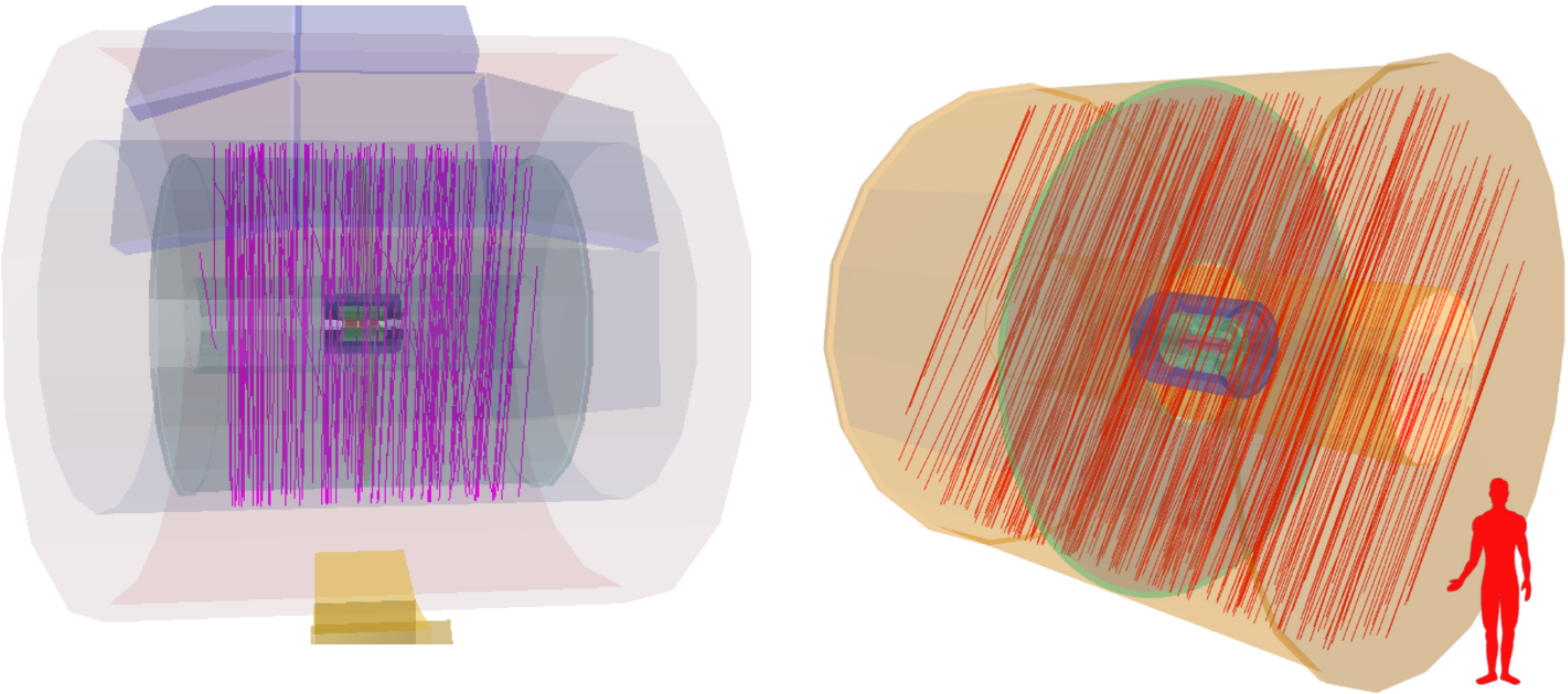
- A logical **OR** among the trigger signals of ACORDE, TOF and SPD was configured to generate the cosmic-ray trigger of ALICE.

ALICE results on Cosmic Ray Physics



We find a smooth distribution up to #μ < 70 and 5 events with more than 100 atmospheric muons (HMM)

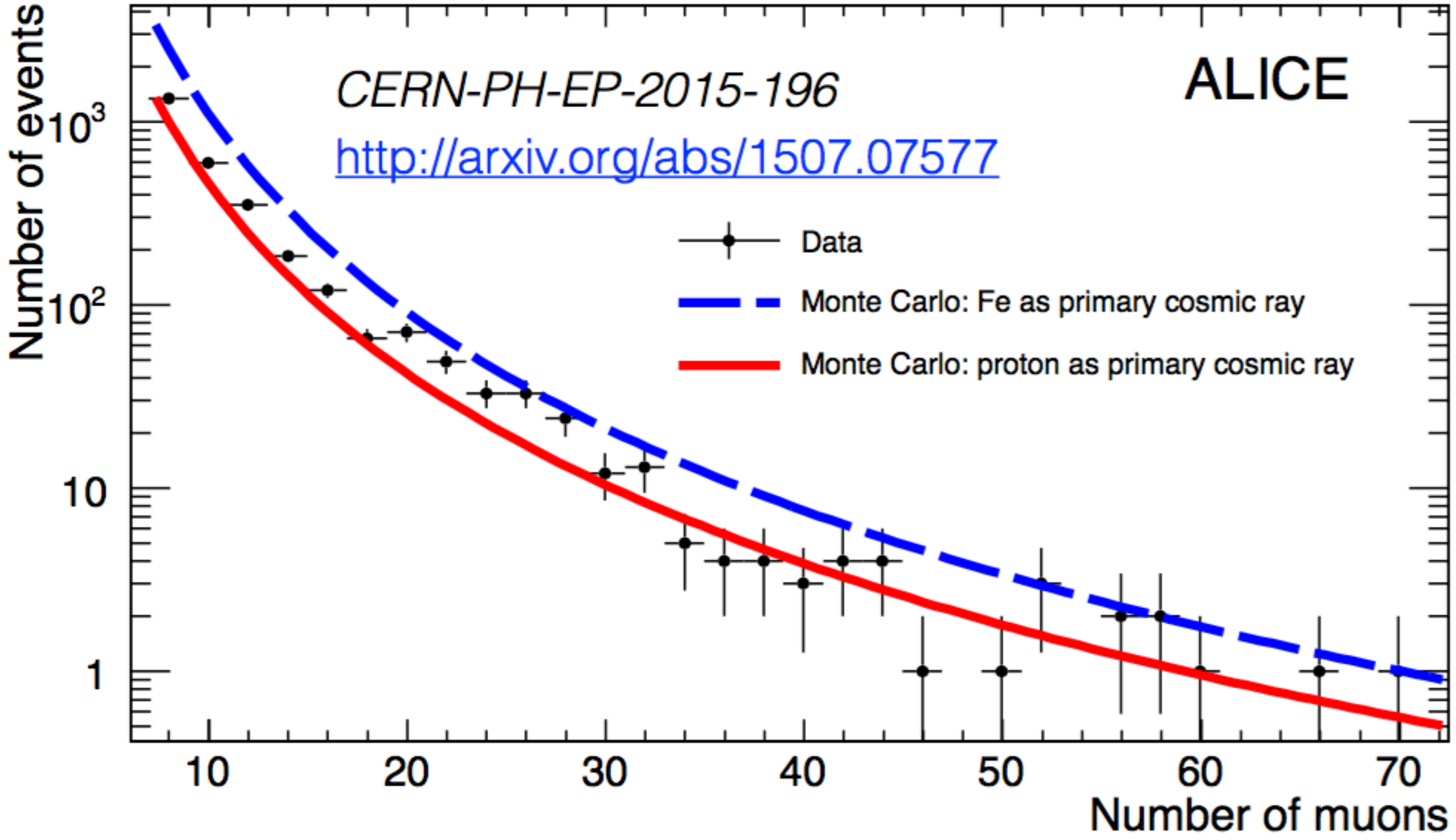
ALICE results on Cosmic Ray Physics



ALICE collected 5 events with more than 100 atmospheric muons during 30.8 days of data taking

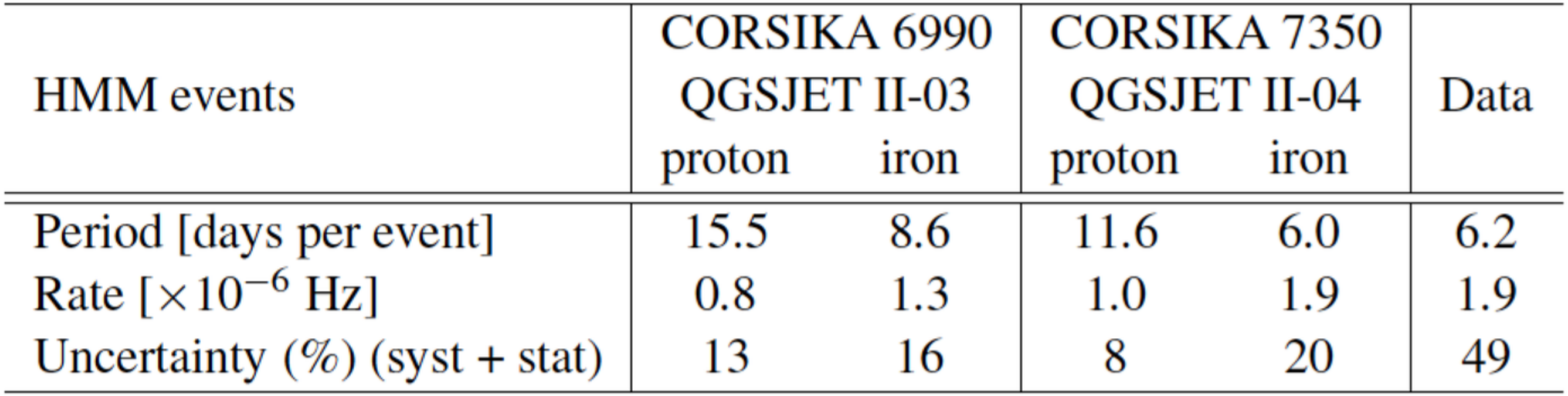
ALICE results on Cosmic Ray Physics

To compare the data with MC, the simulated distributions obtained with proton and iron primary cosmic-rays were fitted with a power-law function.



The data approach the proton curve (low multiplicities). High multiplicity data lie closer to the iron curve. This suggests that the average mass of the primary cosmic-ray flux increases with increasing energy.

ALICE results on Cosmic Ray Physics

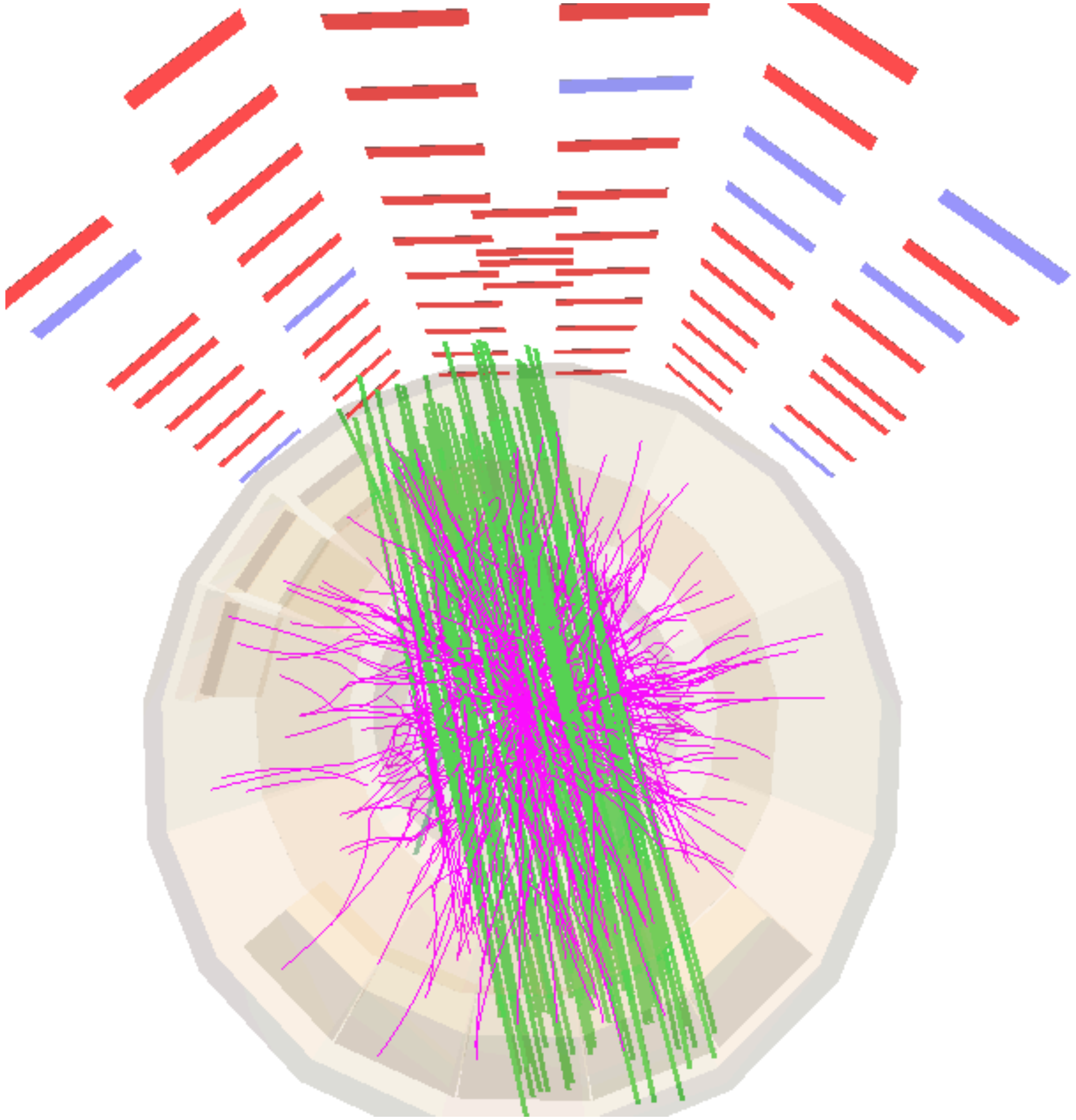


HMM events	CORSIKA 6990 QGSJET II-03		CORSIKA 7350 QGSJET II-04		Data
	proton	iron	proton	iron	
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [$\times 10^{-6}$ Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (%) (syst + stat)	13	16	8	20	49

- Pure **iron** sample simulated with **QGSJET II-04** model reproduces HMM event rate in close agreement with the measured value.
- Independent of the version model, the rate of HMM events with pure proton cosmic-ray composition is more difficult to reproduce.
- This result is compatible with recent measurements which suggest that the composition of the primary cosmic-ray spectrum with energies larger than 10^{16} eV is dominated by heavier elements: Phys. Rev. Lett. **107** (2011) 171104.

COSMIC TRIGGER DURING p-p RUNS

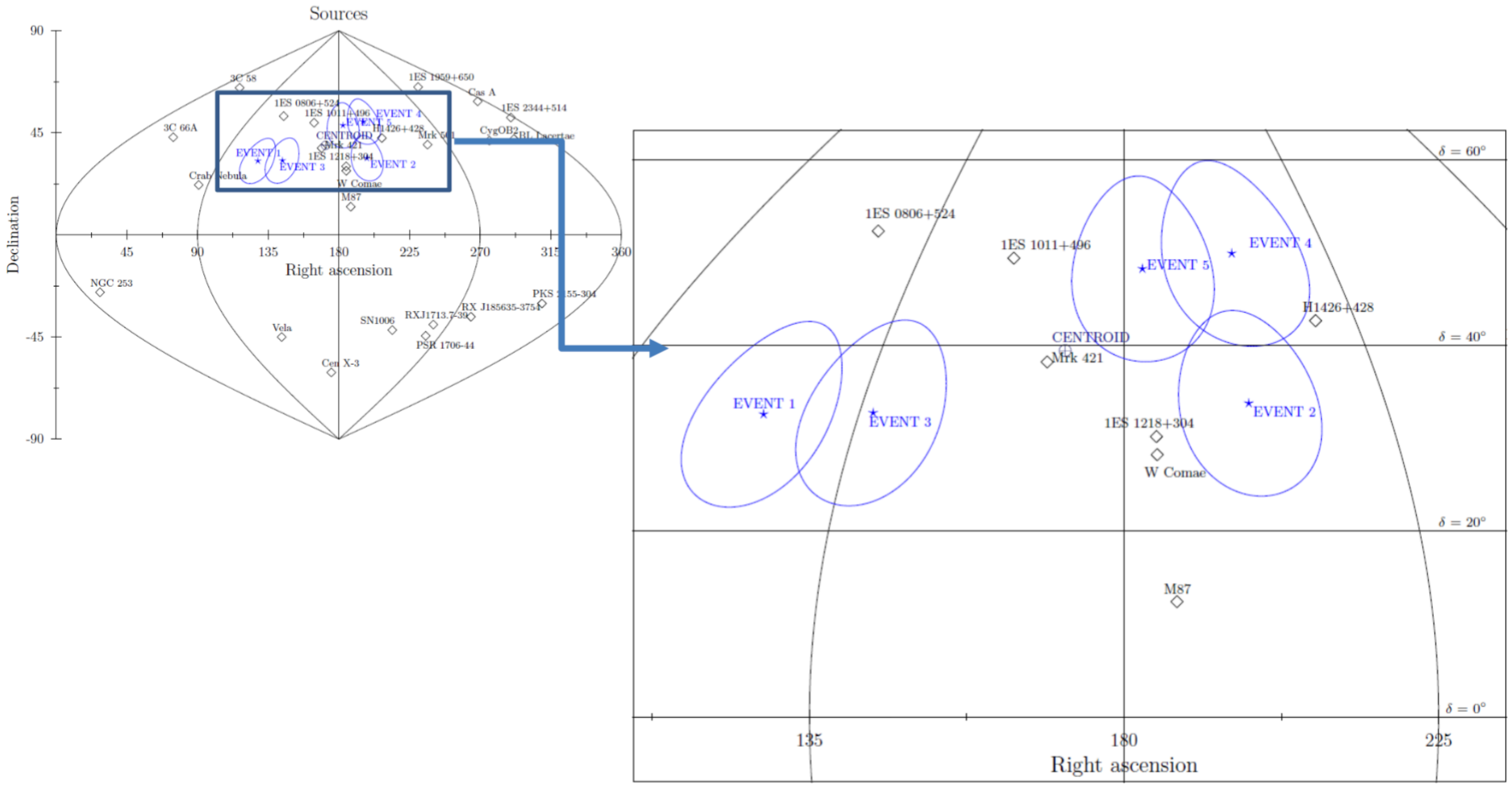
68 atm. Muons
MCN: 51



WHERE DO THE MUON BUNDLES COME FROM?

From Maciej Rybczyński, ISMD 2017

Anisotropy of arrival directions

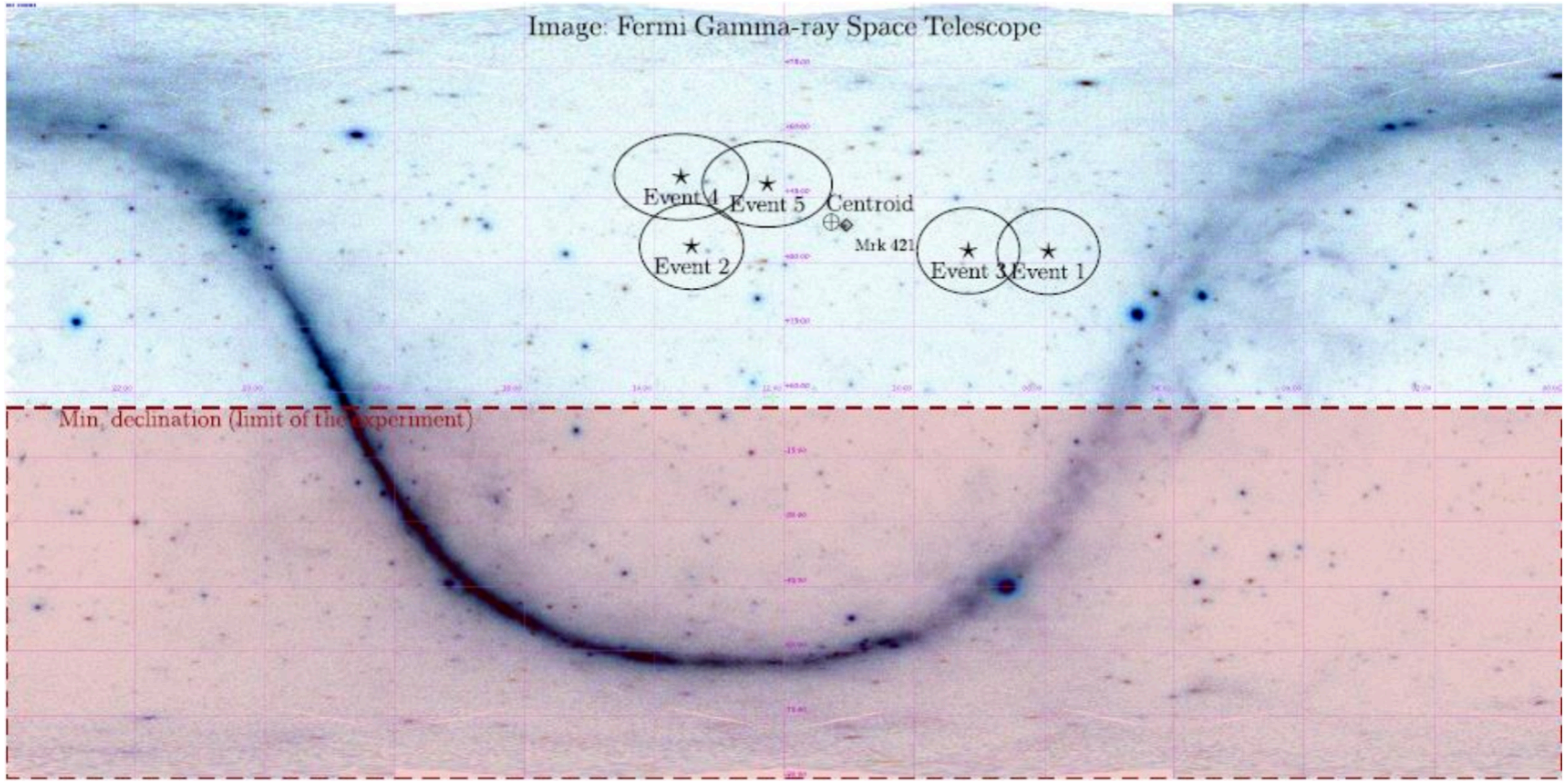


Five high-multiplicity muon events in the equatorial reference frame (α, δ).
Most known extragalactic TeV Sources (blazars, SNRs, radio galaxies) in the sky [Horan and Weekes, New Astr. Rev. 48 (2004) 527], [Turley et al., arXiv:1608.08983] are also shown (note that **the Mrk 421 blazar** is the source located very close to the centroid of the five considered events).

WHERE DO THE MUON BUNDLES COME FROM?

From Maciej Rybczyński, [ISMD 2017]

Anisotropy of arrival directions



Five high-multiplicity muon events. All events are located close to the galactic pole (far from the galactic plane). Background: Inverted (negative) image of the Fermi telescope mosaic. The minimum declination limit (due to the restricted zenith angle in the experiment) is marked by a horizontal line. The area in the southern sky not covered by the experiment is marked by a rectangle (filled).

WHERE DO THE MUON BUNDLES COME FROM?

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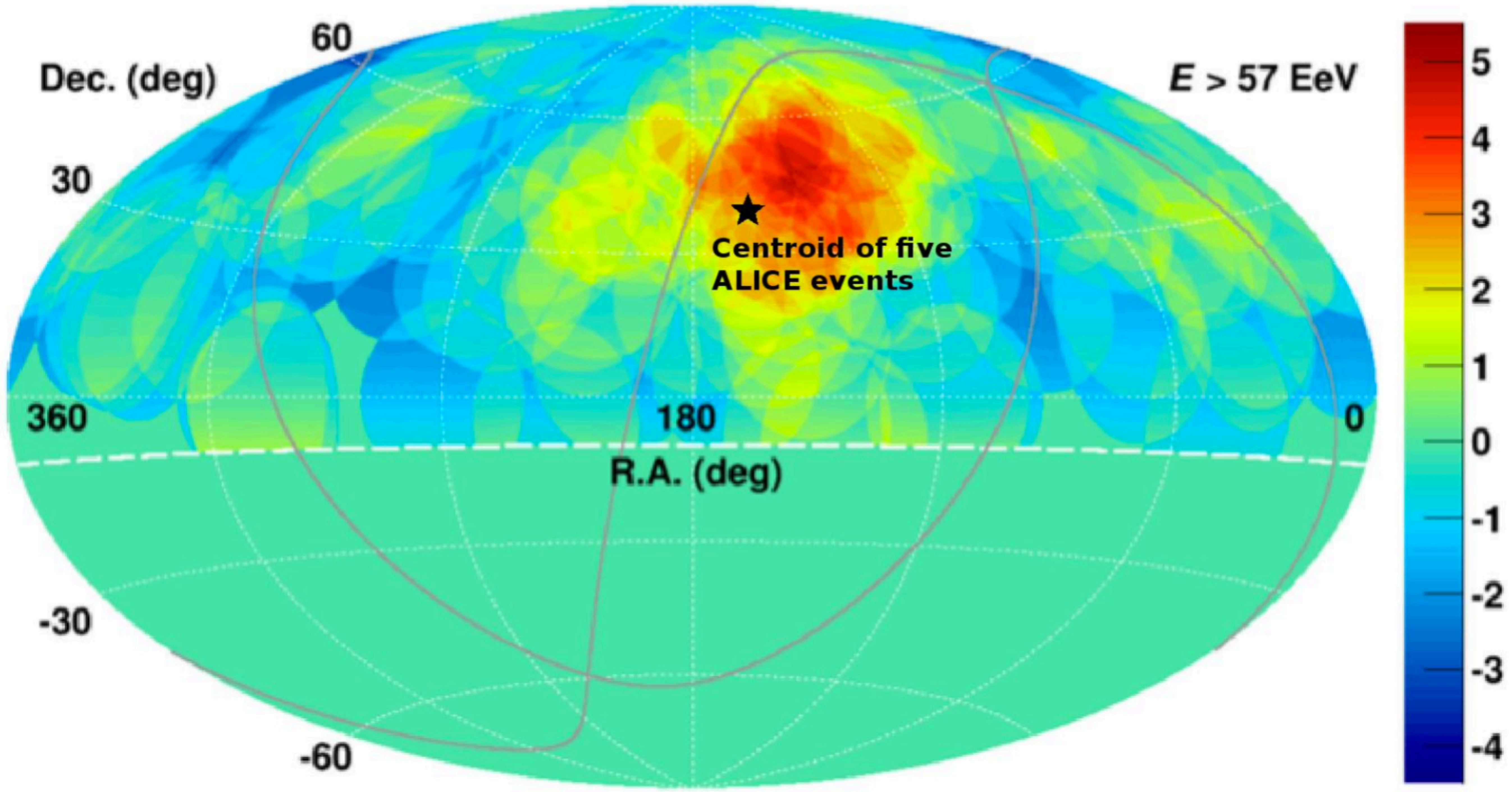
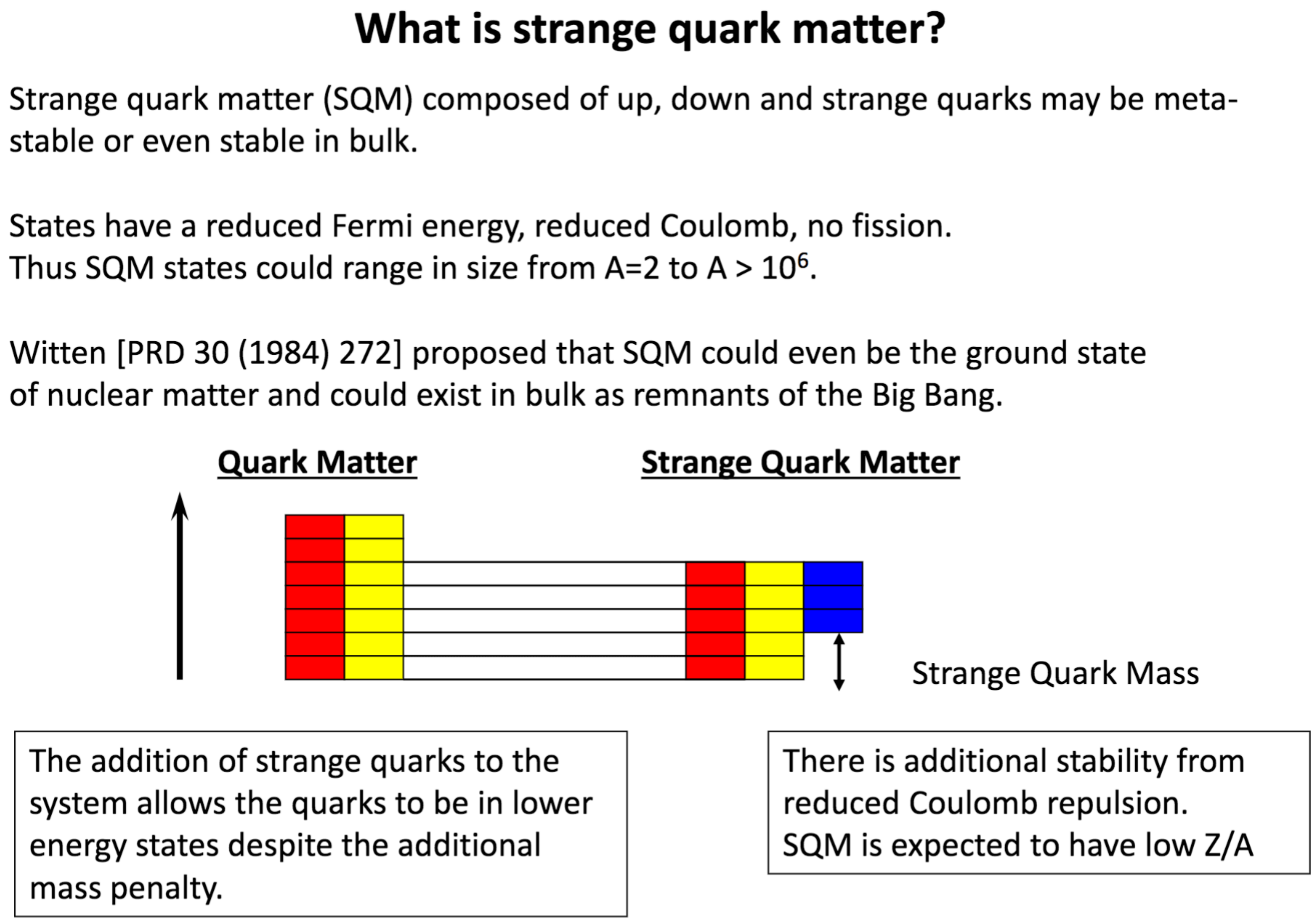
Anisotropy of arrival directions



Aitoff projection of the UHECR map in equatorial coordinates taken from Telescope Array Collaboration data **[The Astrophysical Journal Letters 790 (2014) L21]**

WHERE DO THE MUON BUNDLES COME FROM?

From Maciej Rybczyński, ISMD 2017



What is strange quark matter?

Strange quark matter (SQM) composed of up, down and strange quarks may be meta-stable or even stable in bulk.

States have a reduced Fermi energy, reduced Coulomb, no fission.
Thus SQM states could range in size from A=2 to A > 10^6.

Witten [PRD 30 (1984) 272] proposed that SQM could even be the ground state of nuclear matter and could exist in bulk as remnants of the Big Bang.

Quark Matter **Strange Quark Matter**

Strange Quark Mass

The addition of strange quarks to the system allows the quarks to be in lower energy states despite the additional mass penalty.

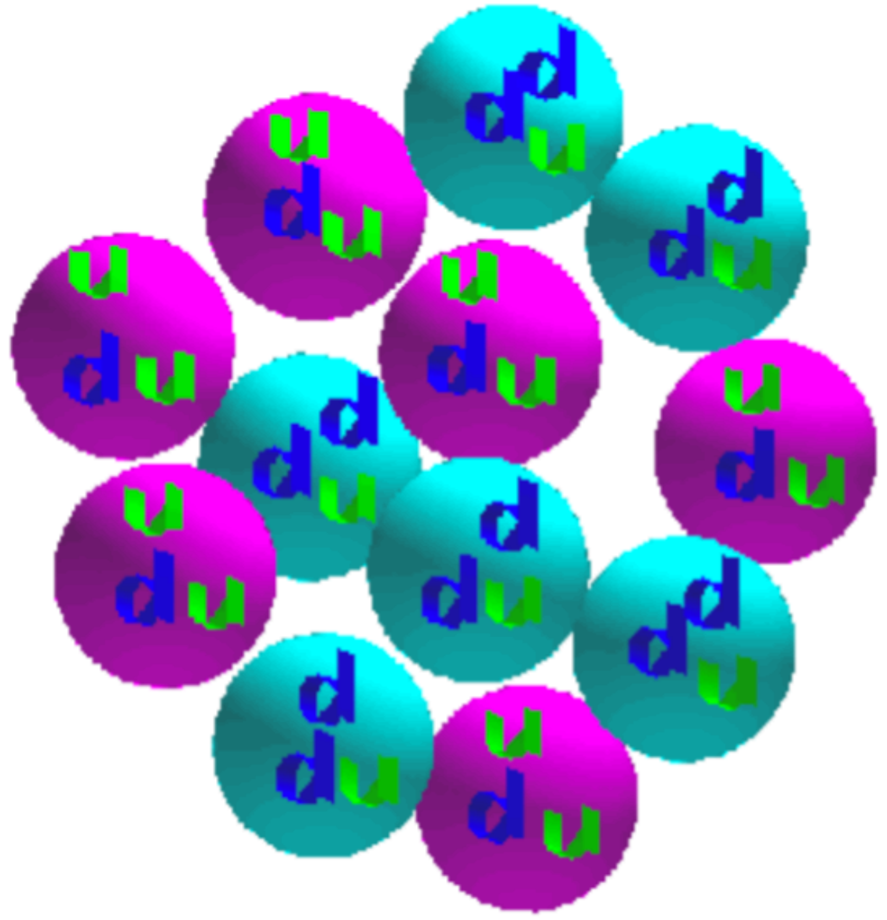
There is additional stability from reduced Coulomb repulsion.
SQM is expected to have low Z/A

WHERE DO THE MUON BUNDLES COME FROM?

From Maciej Rybczyński, ISMD 2017

Strange quark matter

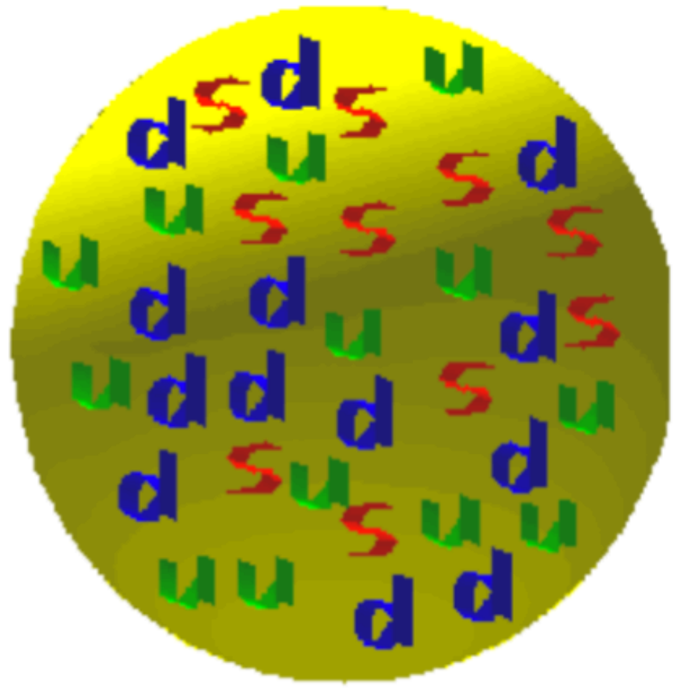
Roughly equal numbers of u, d, s quarks in a single 'bag' of cold hadronic matter.



Nucleus (^{12}C)

Z=6, A=12

Z/A = 0.5



Strangelet*

A=12 (36 quarks)

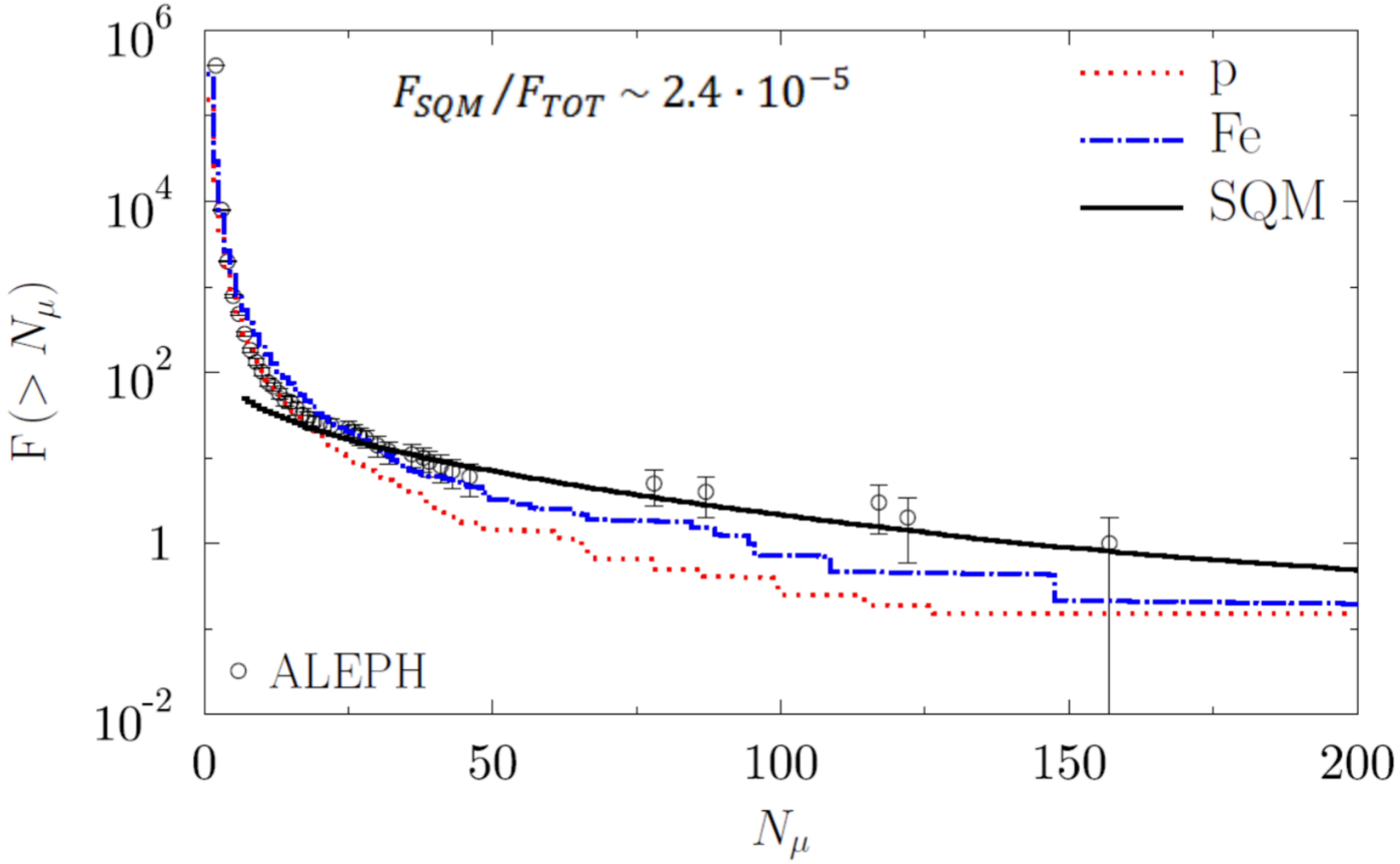
Z/A = 0.083

*small lump of Strange Quark Matter

WHERE DO THE MUON BUNDLES COME FROM?

From Maciej Rybczyński, ISMD 2017

High multiplicity muon bundles from strange quark matter



Integral multiplicity distribution of muons the ALEPH data (circles) published in Astr. Phys. 19 (2003) 513. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux.

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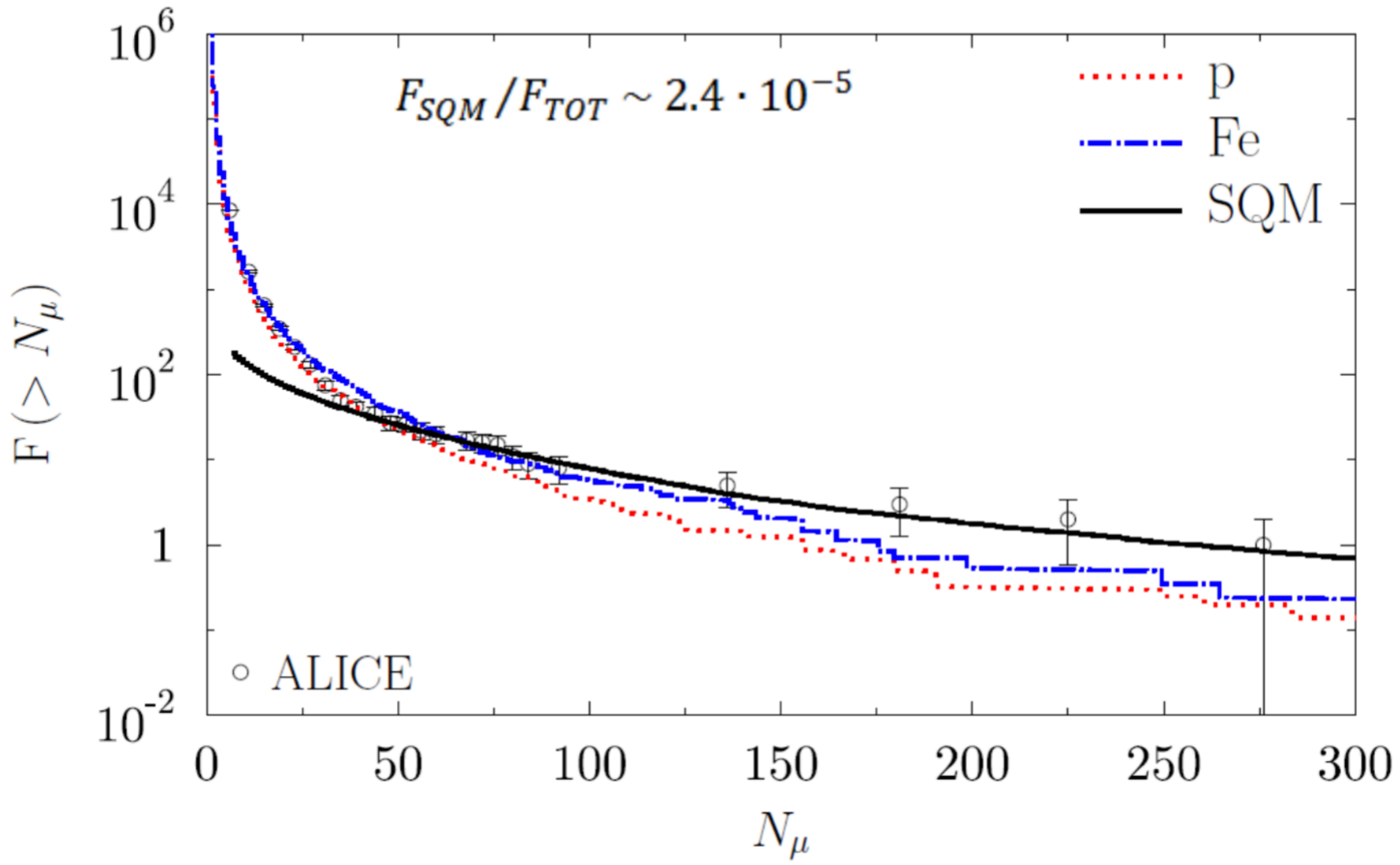

Integral multiplicity distribution of muons for the ALICE data (circles) published in JCAP 01 (2016) 032. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux.

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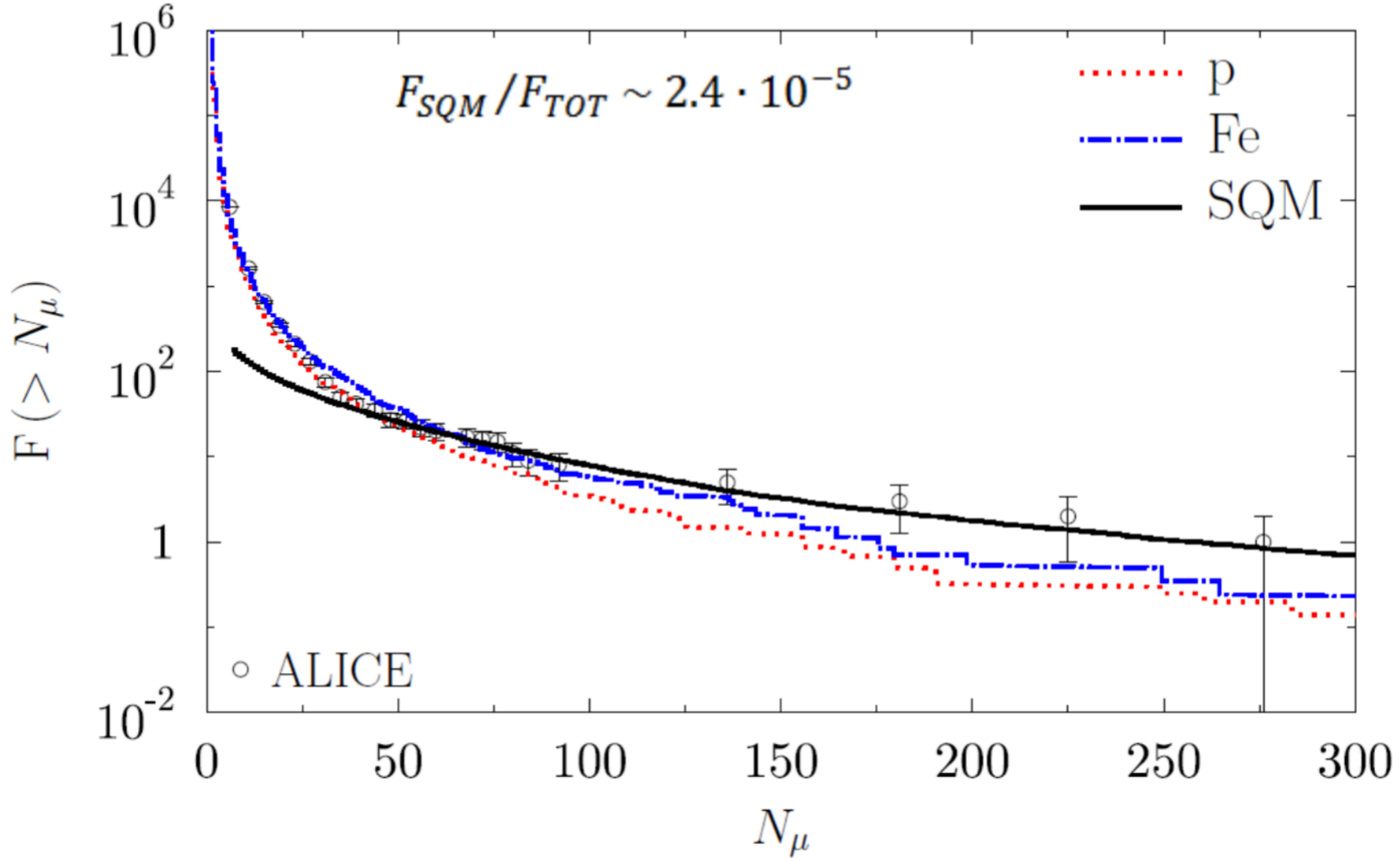

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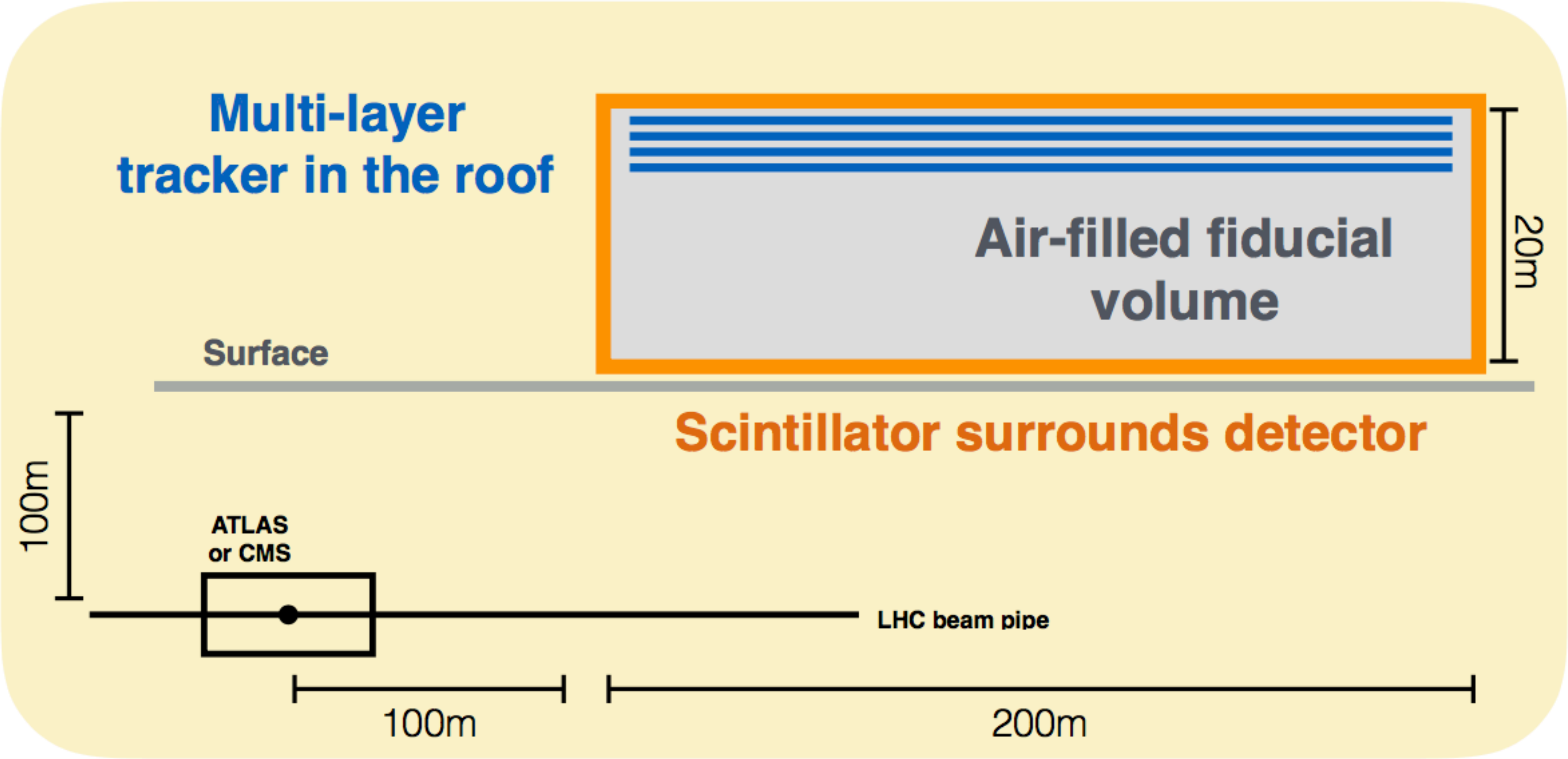
PLANS FOR THE RUN 3 AND HI

The MATHUSLA Detector

MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

A proposal for big tracker with a with a gigantic (~ 200x200x20m) fiducial volume on the surface above ATLAS or CMS at the HL-LHC



hou, DC, Lubatti 1606.06298

The MATHUSLA Detector

MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

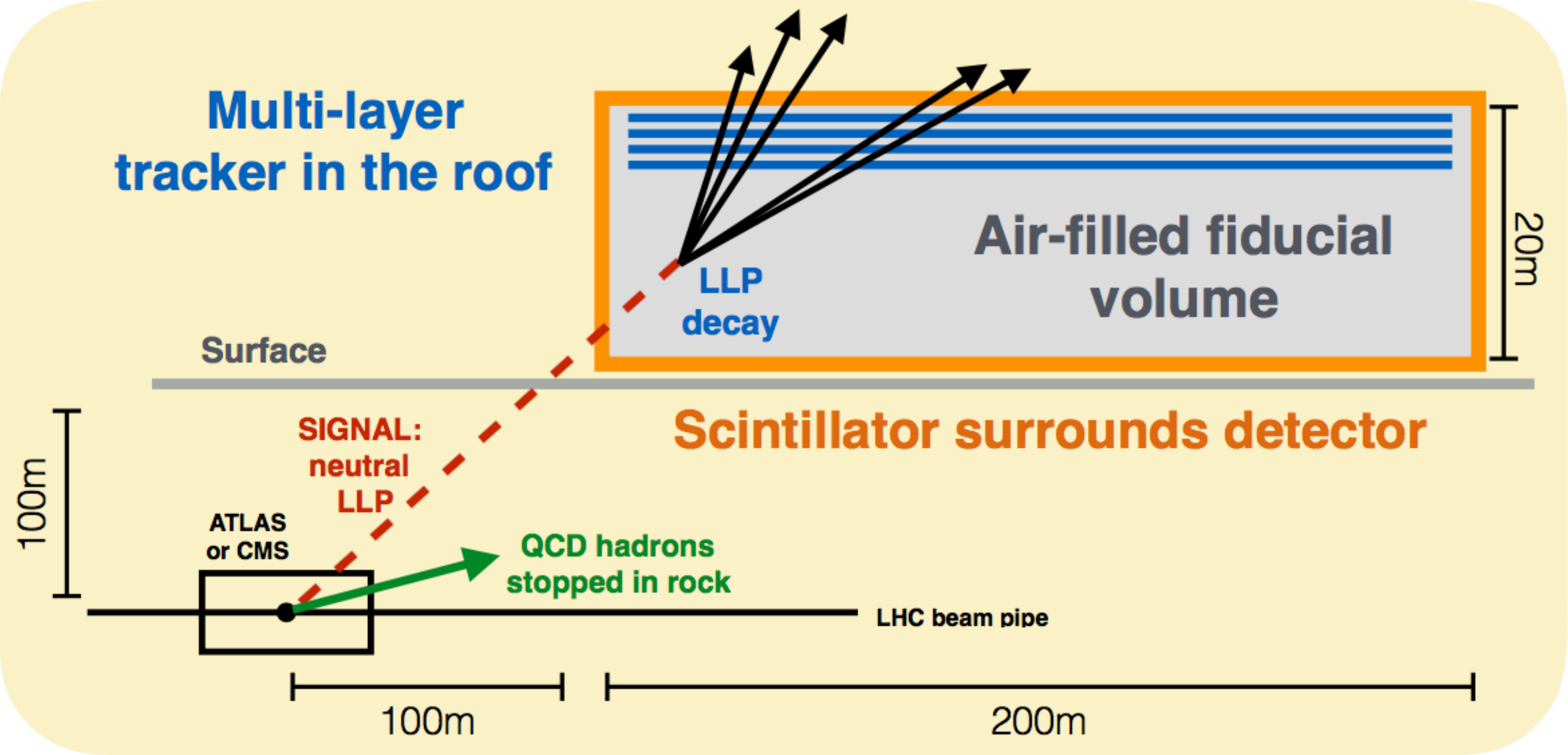
A proposal for big tracker with a with a gigantic (~ 200x200x20m) fiducial volume on the surface above ATLAS or CMS at the HL-LHC

Aim: observe **BSM Long-Lived Particles (LLPs)** produced in LHC collisions

LLPs are difficult to see in LHC main detectors.
MATHUSLA does not suffer from collision-related backgrounds.

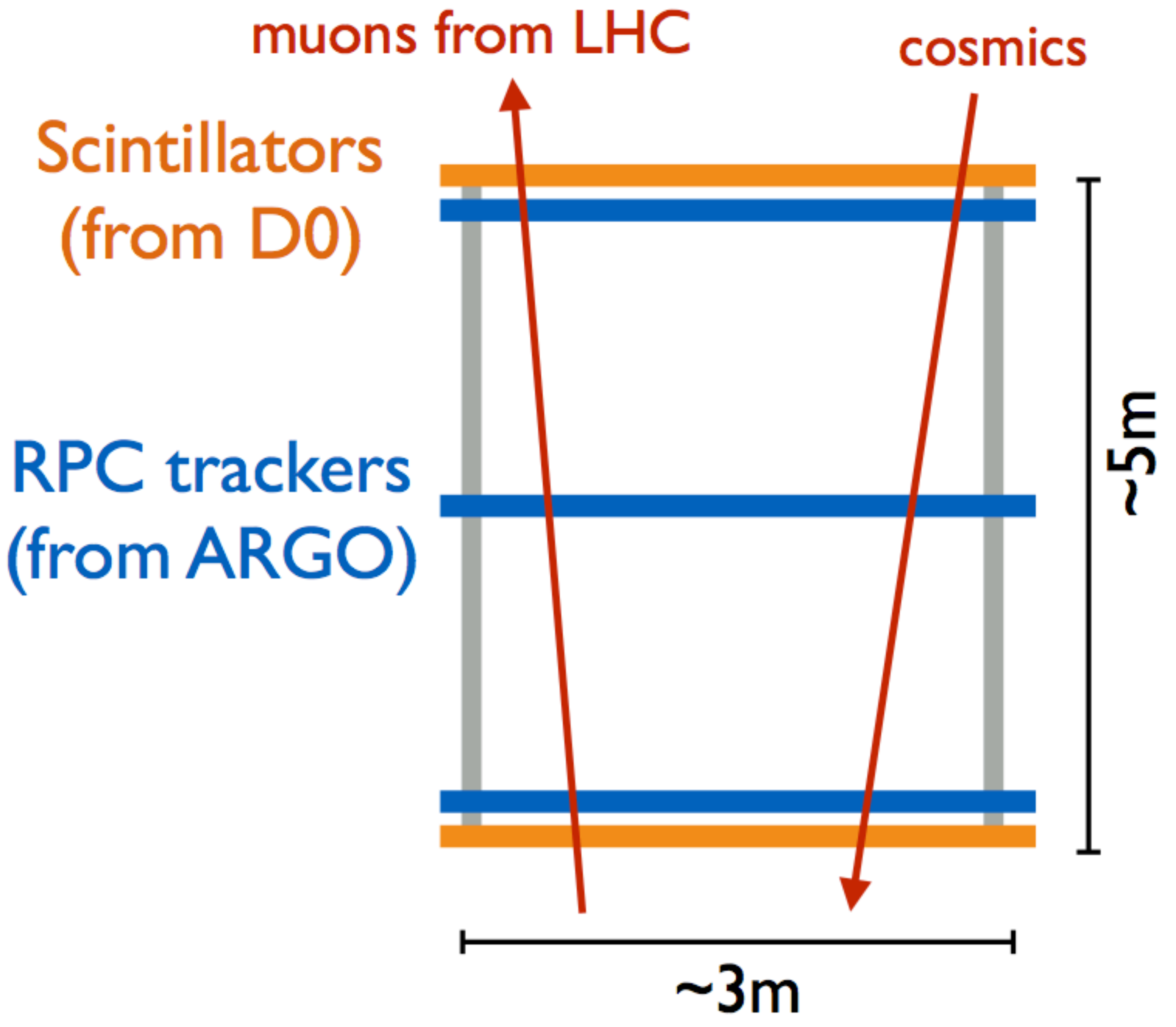
→ MATHUSLA is up to 10^3 x more **sensitive** to BSM LLP production ATLAS/CMS alone!

Chou, DC, Lubatti 1606.06298



Status of MATHUSLA experiment

~ 40 experimentalists from ~ 10 institutions joined effort,
including CR groups from **ALICE** and **ARGO-YBJ**



A small-scale
Test Stand
to demonstrate
operation of a
MATHUSLA-like
detector is
currently under construction at CERN!

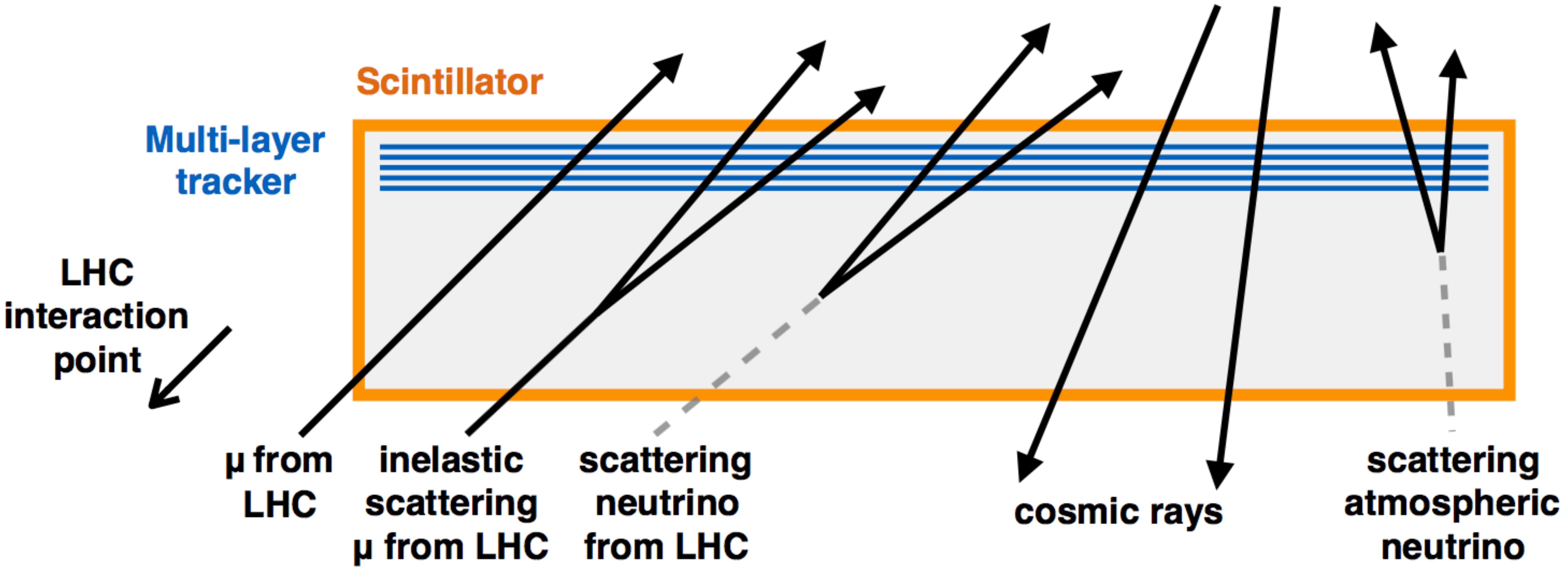
Start taking data in a few months with beam on & off!

Cosmic Rays @ MATHUSLA

1. Cosmic Rays as Background to LLP decays

2. A dedicated Cosmic Ray Physics program at MATHUSLA?

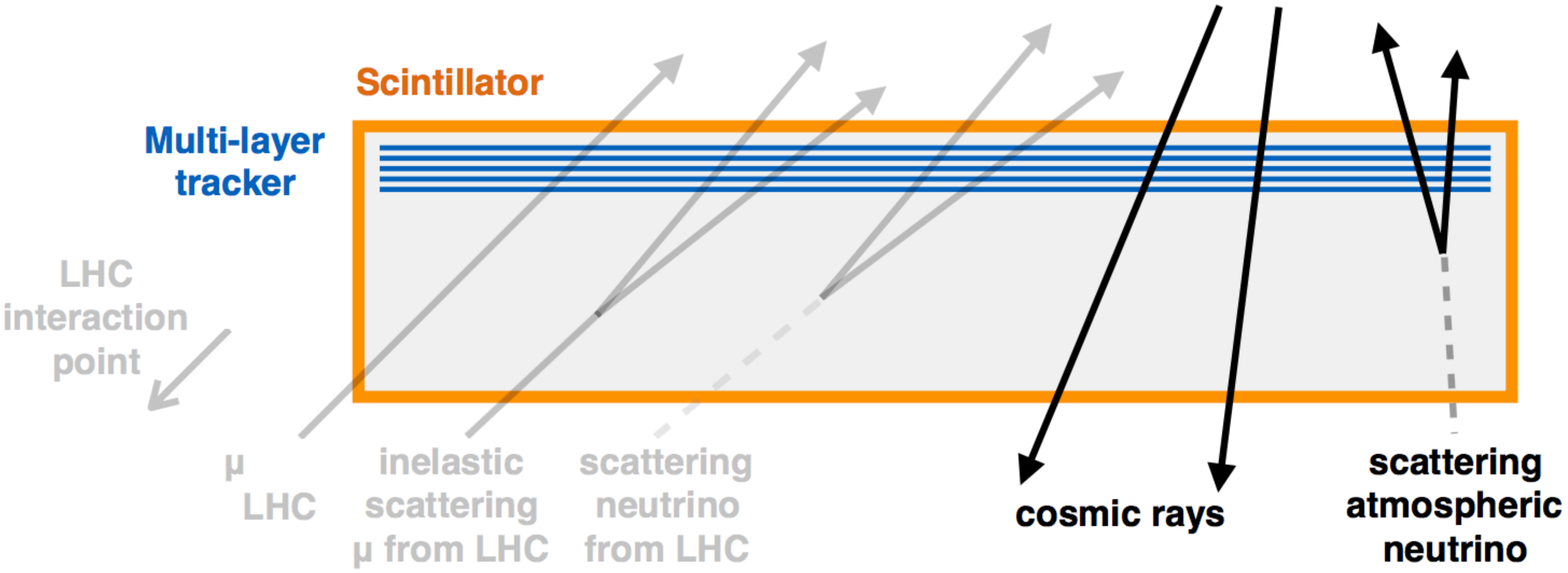
Background to LLP Detection



Claim: all of those can be rejected using geometry and timing of charged particle trajectory measurements

LLP decay signal is *highly distinctive*: many charged particles emerging from single point in space & time

Background to LLP Detection



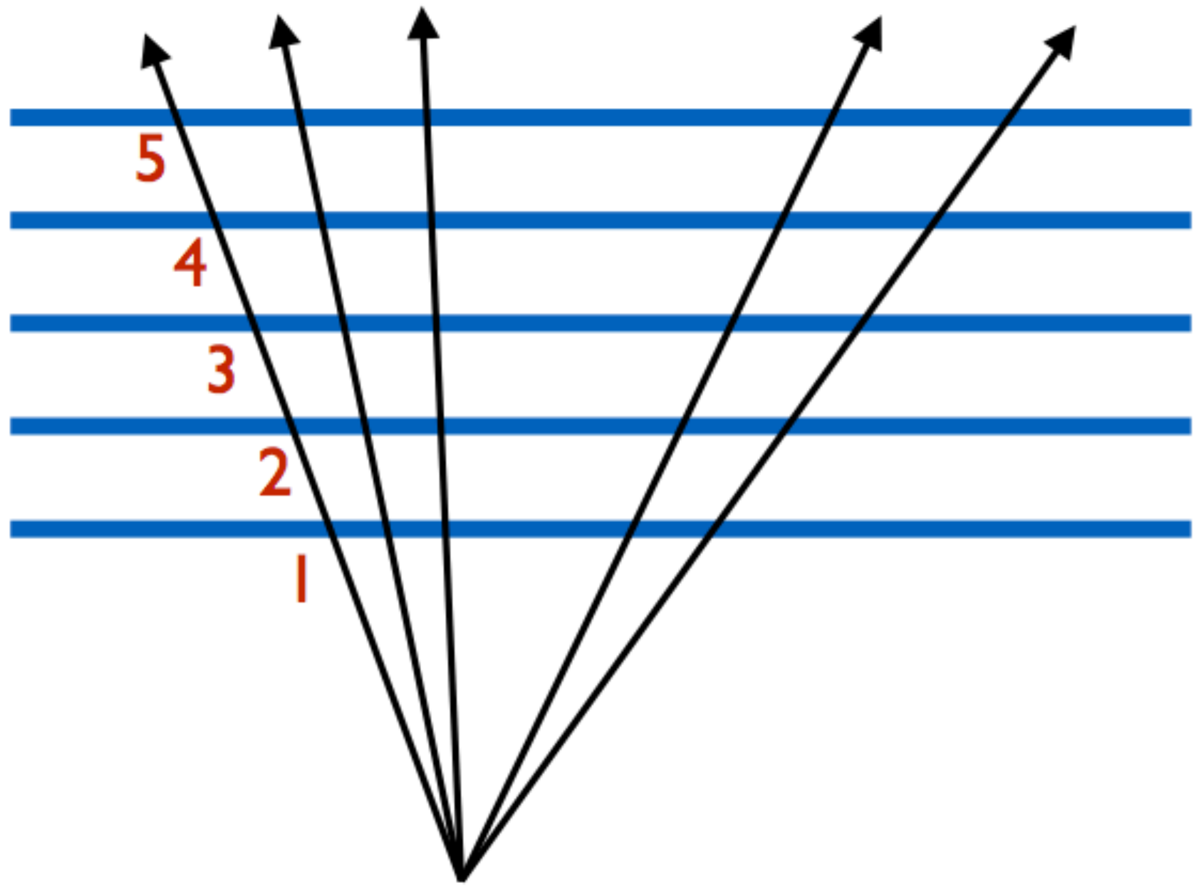
Consider cosmic ray related backgrounds

Rejecting Cosmic Rays

Chou, DC, Lubatti
1606.06298

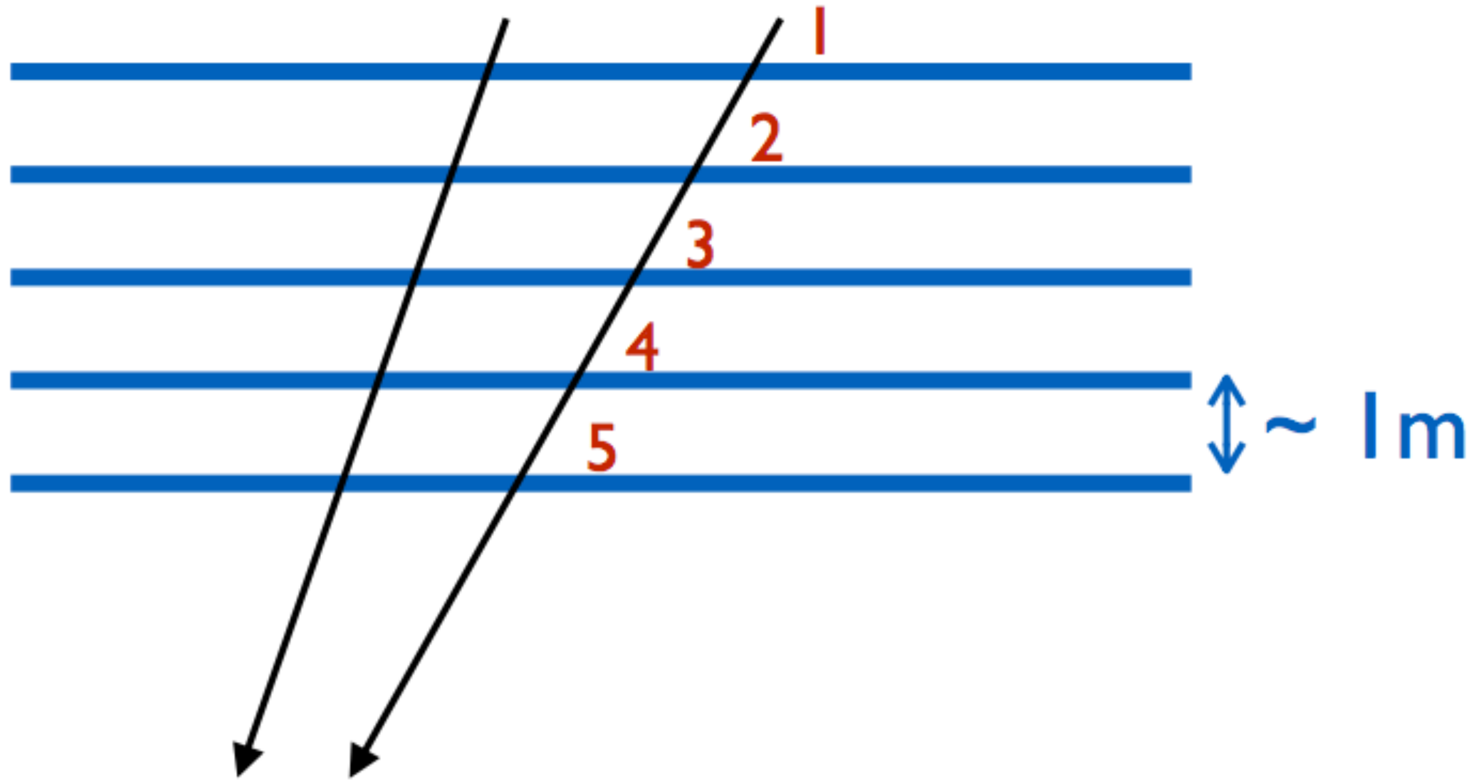
BUAP

LLP Signal



(say) 5
tracking
layers
with
~ ns, cm
resolution

Cosmic Ray: ~ 10^{14}/year



Stringent signal requirements:
→ hits in all (!) tracking layers
→ all tracks in region-of-interest must converge on displaced vertex (DV)
→ timing of track hits used to verify charged particles emerged from DV at same *instant in time!*
→ require otherwise relatively "empty" detector

Even if only 3 layers fire, rate of confusing single down-wards going CR for upwards-going charged particle is < 10^{-15}.

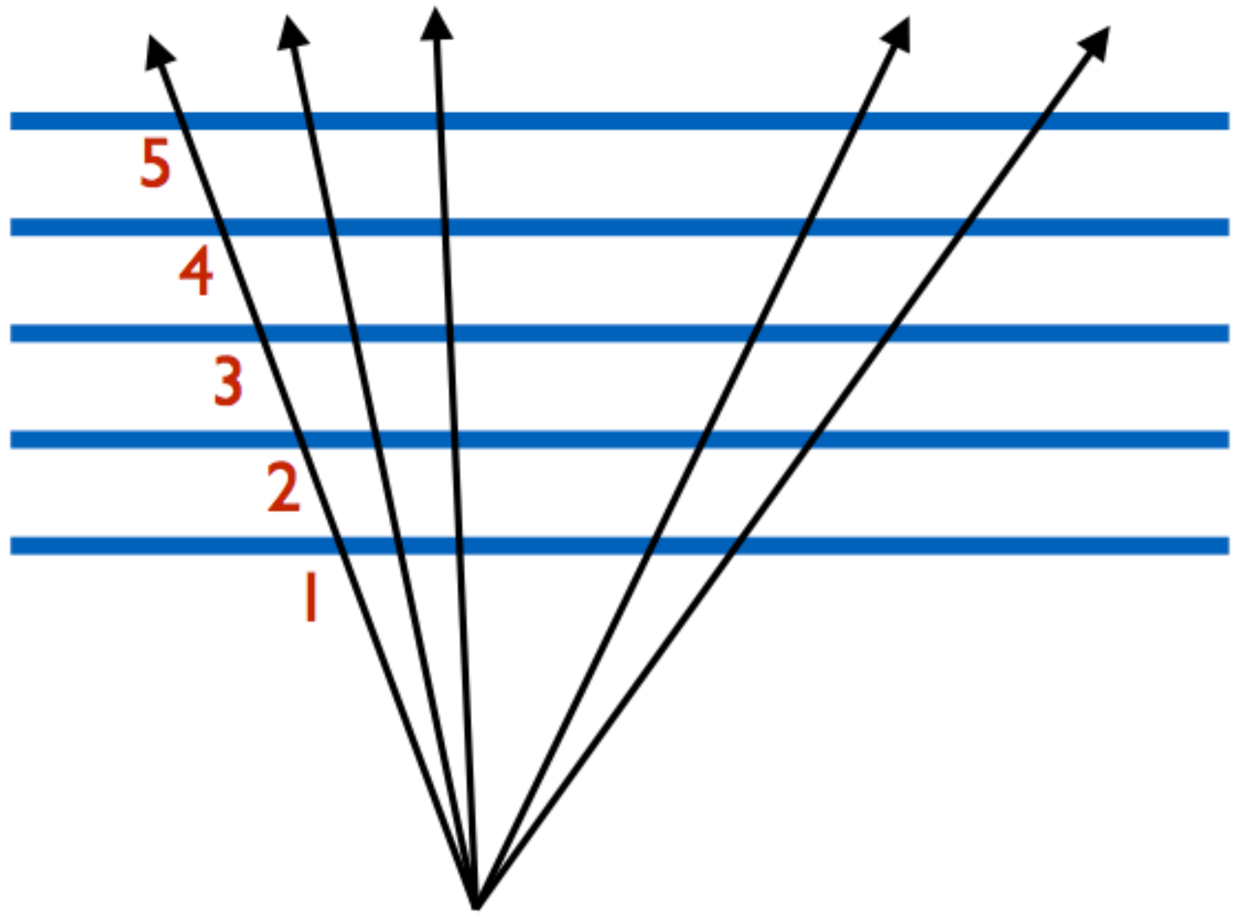
Only need 10^{-8} to reject fake DVs.

Could imagine (??) fake DVs from high-multiplicity CR events, but those are easy to reject.

Rejecting Neutrinos

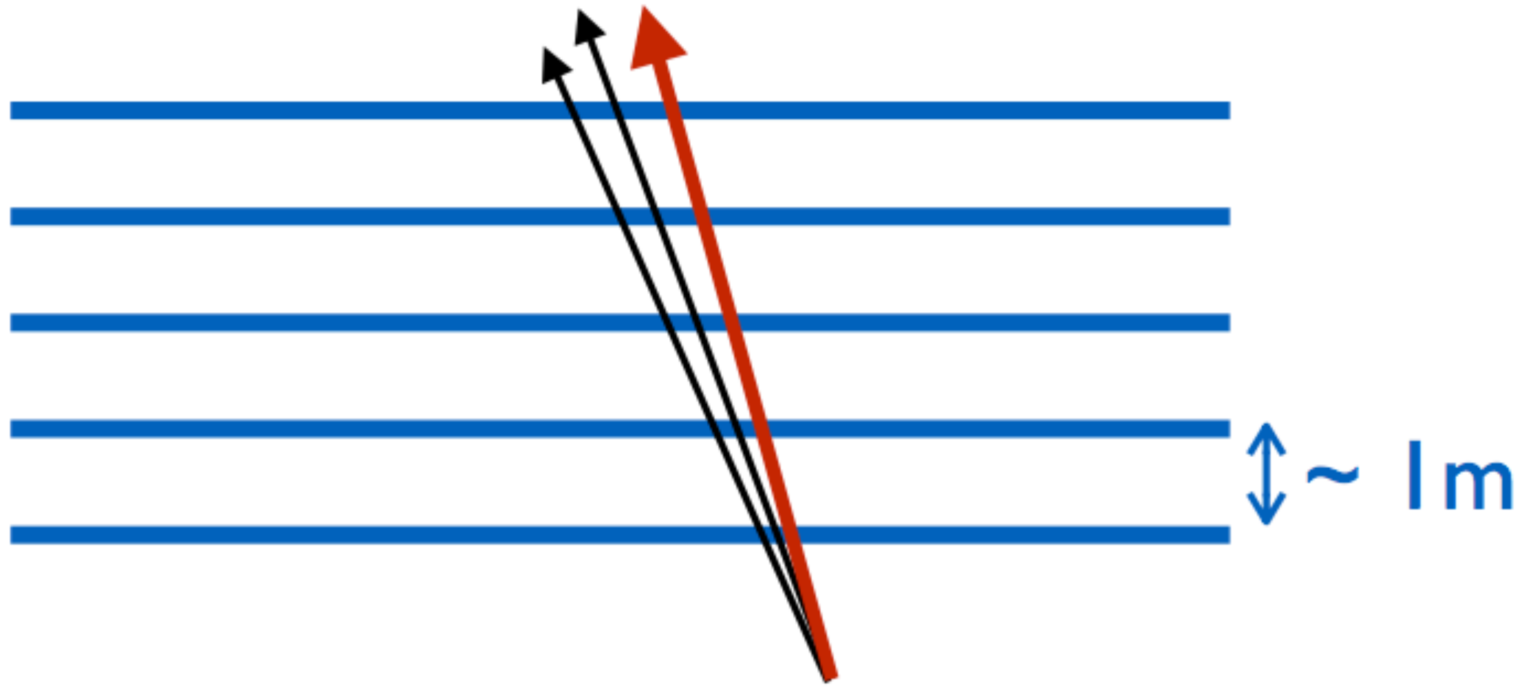
Chou, DC, Lubatti
1606.06298

LLP Signal



(say) 5
tracking
layers
with
~ ns, cm
resolution

Neutrino Scattering: ~70/year



Stringent signal requirements:

→ hits in all (!) tracking layers

→ all tracks in region-of-interest must converge on displaced vertex (DV)

→ timing of track hits used to verify charged particles emerged from DV at same *instant in time!*

→ require otherwise relatively "empty" detector

Narrow opening angle, does not point back to LHC collision point.

Can be rejected with simple timing cuts, e.g. **90% have NR proton in final state, different from LLP signal**

Rejection of cosmic ray background looks *plausible* to allow background-free LLP detection.

Obviously, much more study is needed!
How many tracking layers are needed? 3? 7?

Requires full simulations & **data from the test stand!**

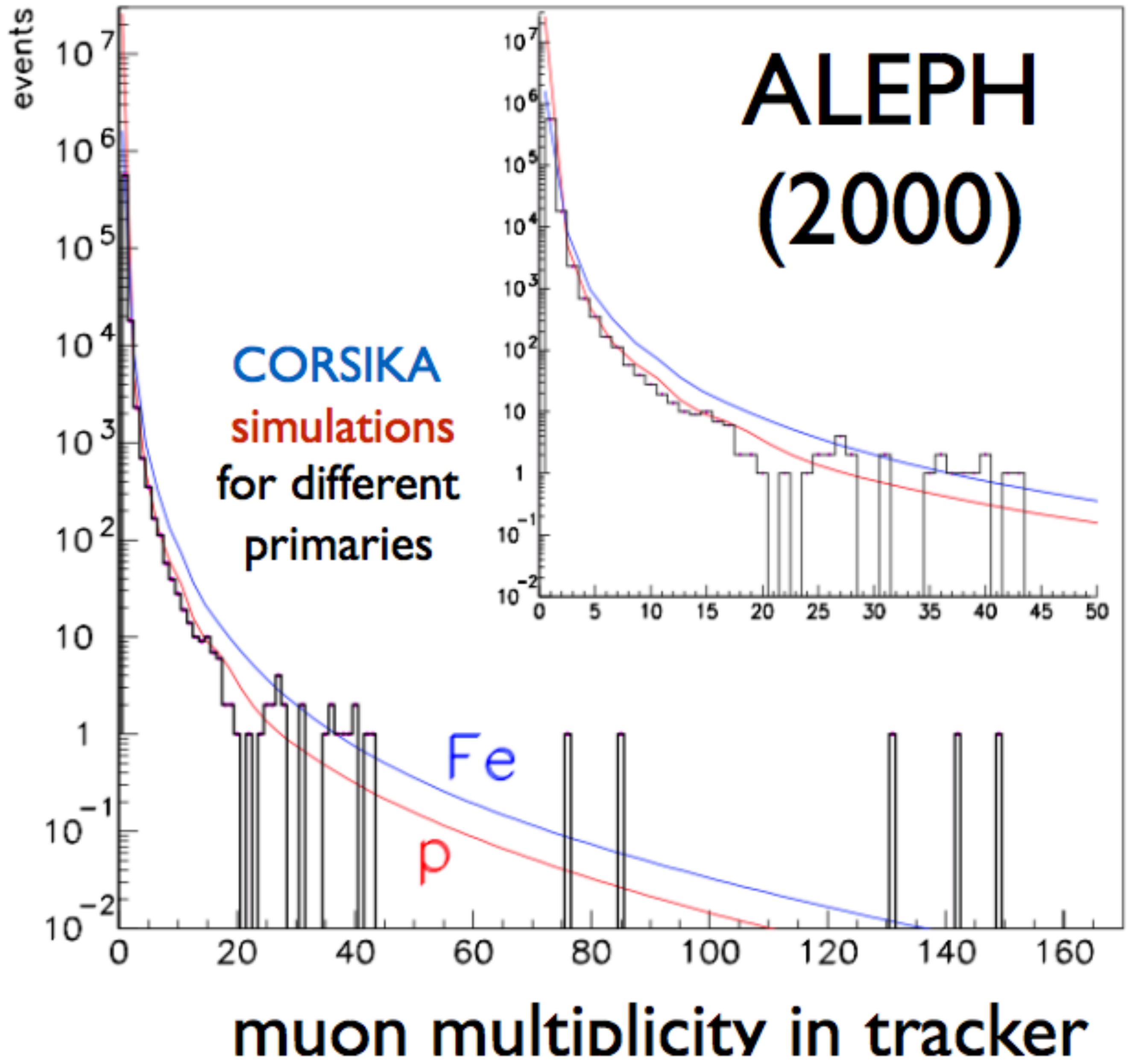
Hope to sort this out in time for letter-of-intent in 2018!

Join us if you're interested!

1. Cosmic Rays as Background to LLP decays

2. A dedicated Cosmic Ray Physics program at MATHUSLA?

High-Multiplicity Muon Bundles



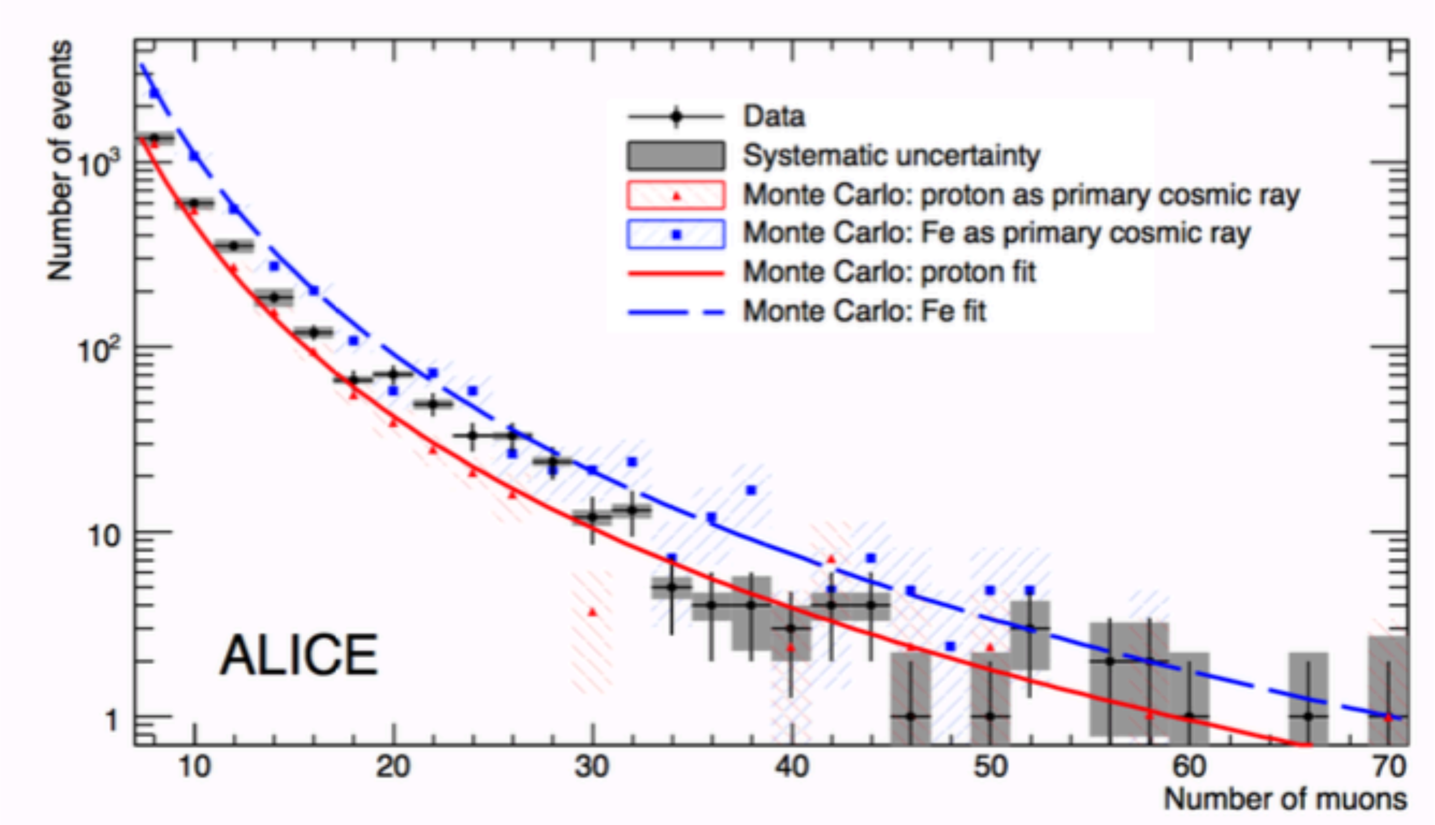
Measurement shows excess compared to CORSIKA - QGSJET of the time, even for pure Fe primaries

Connected to CR primary composition above the "knee", E > 10^{16} eV

Hints of high-E high-multiplicity muon excess at other experiments (NEVOD-DECOR, AUGER, IceCube)

ALICE did a similar measurement (1507.07577) with **E_μ > 16 GeV** which can be made to agree with **UPDATED CORSIKA - QGSJET** with large Fe primary fraction* above the knee, but uncertainties are large. **Need more data!**

*e.g. KASCADE-GRANDE PhysRevLett.107.171104

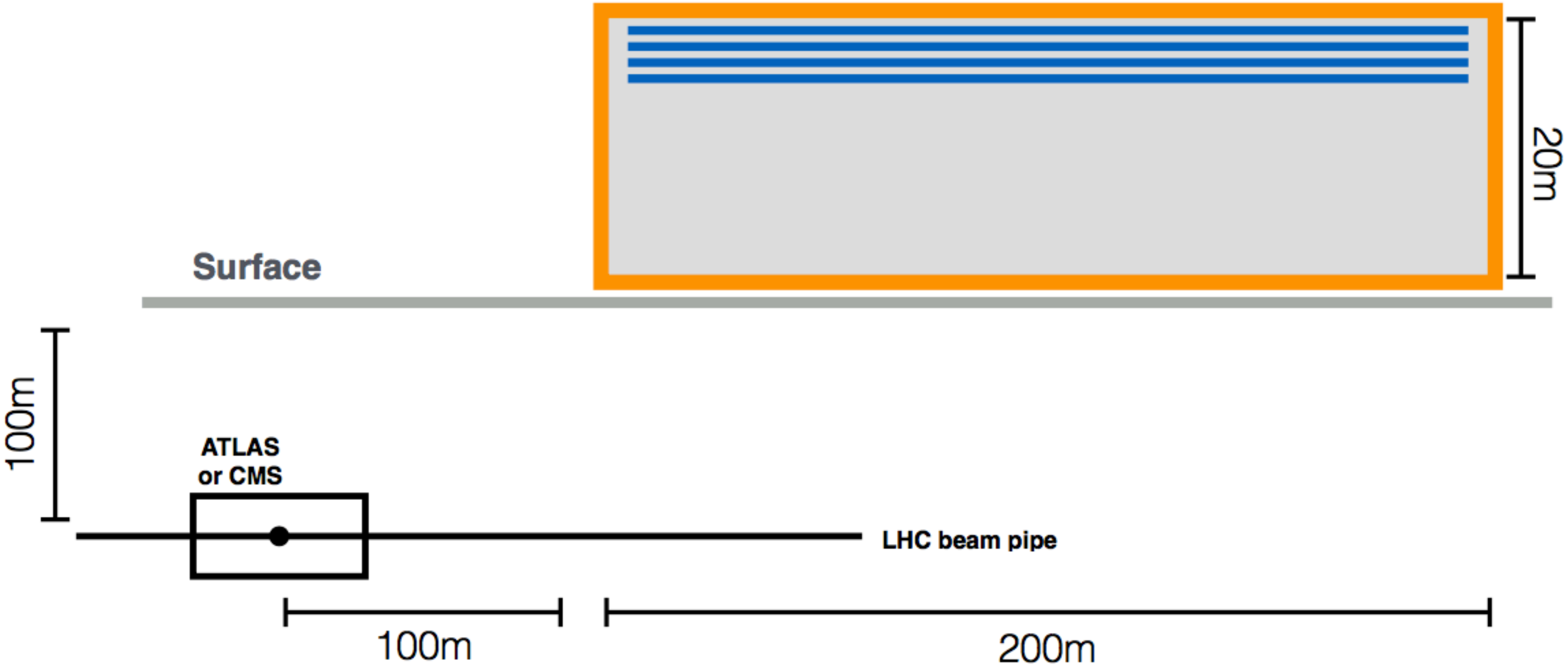


Explanations?

Significant uncertainties in models of CR primary composition & hadronic interaction!

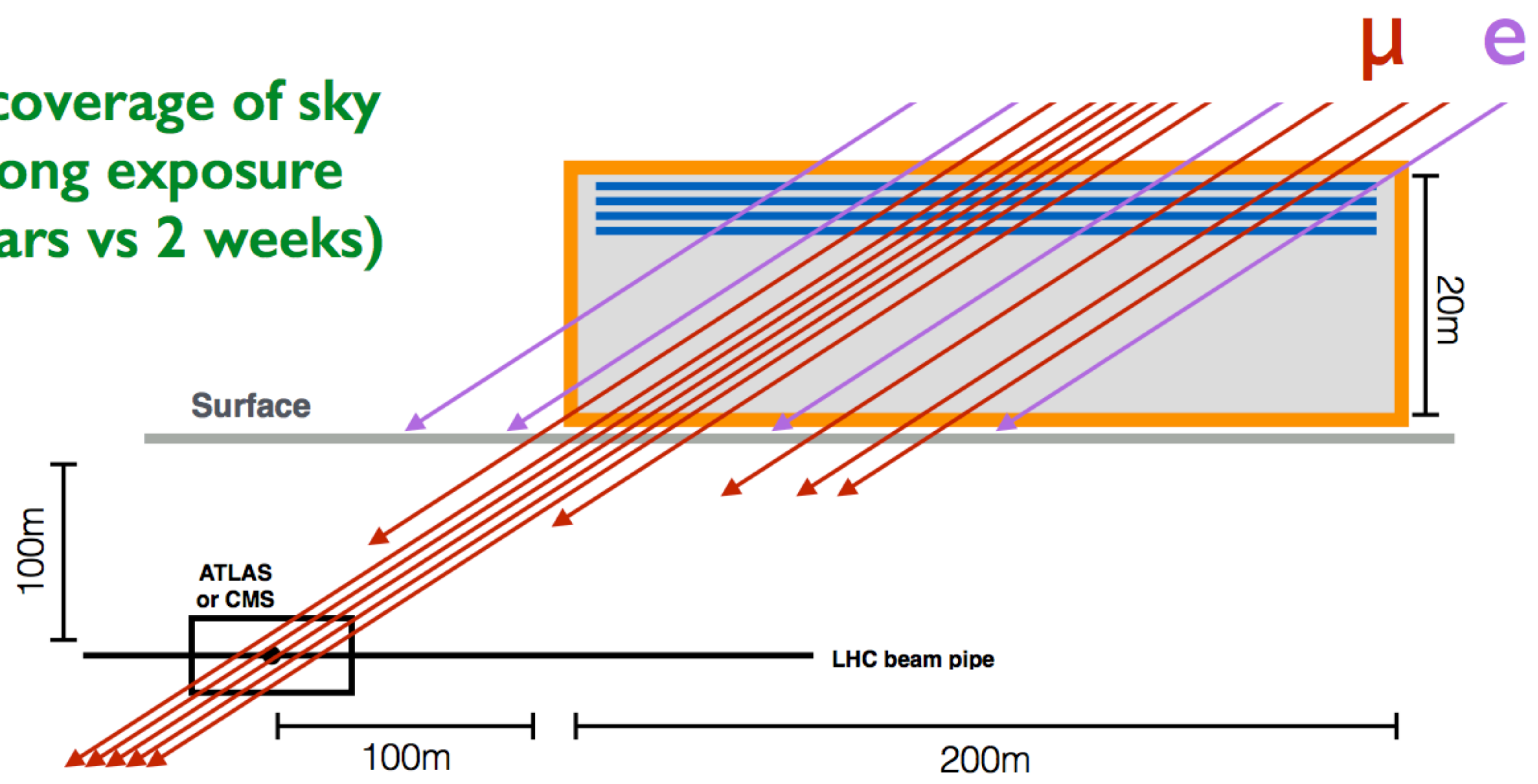
Nuclear Effects?	Klein nucl-ex/0611040
Quark-Gluon Plasma?	Ridky hep-ph/0012068
Strangelets?	Rybczynski, Wlodarczyk, Wilk hep-ph/0410064
Quark-Gluon Matter?	Petrukhin, Nucl.Instrum.Meth.A742 (2014) 228-231

Can MATHUSLA Help?



Can MATHUSLA Help?

~ 5% coverage of sky
but long exposure
(10 years vs 2 weeks)



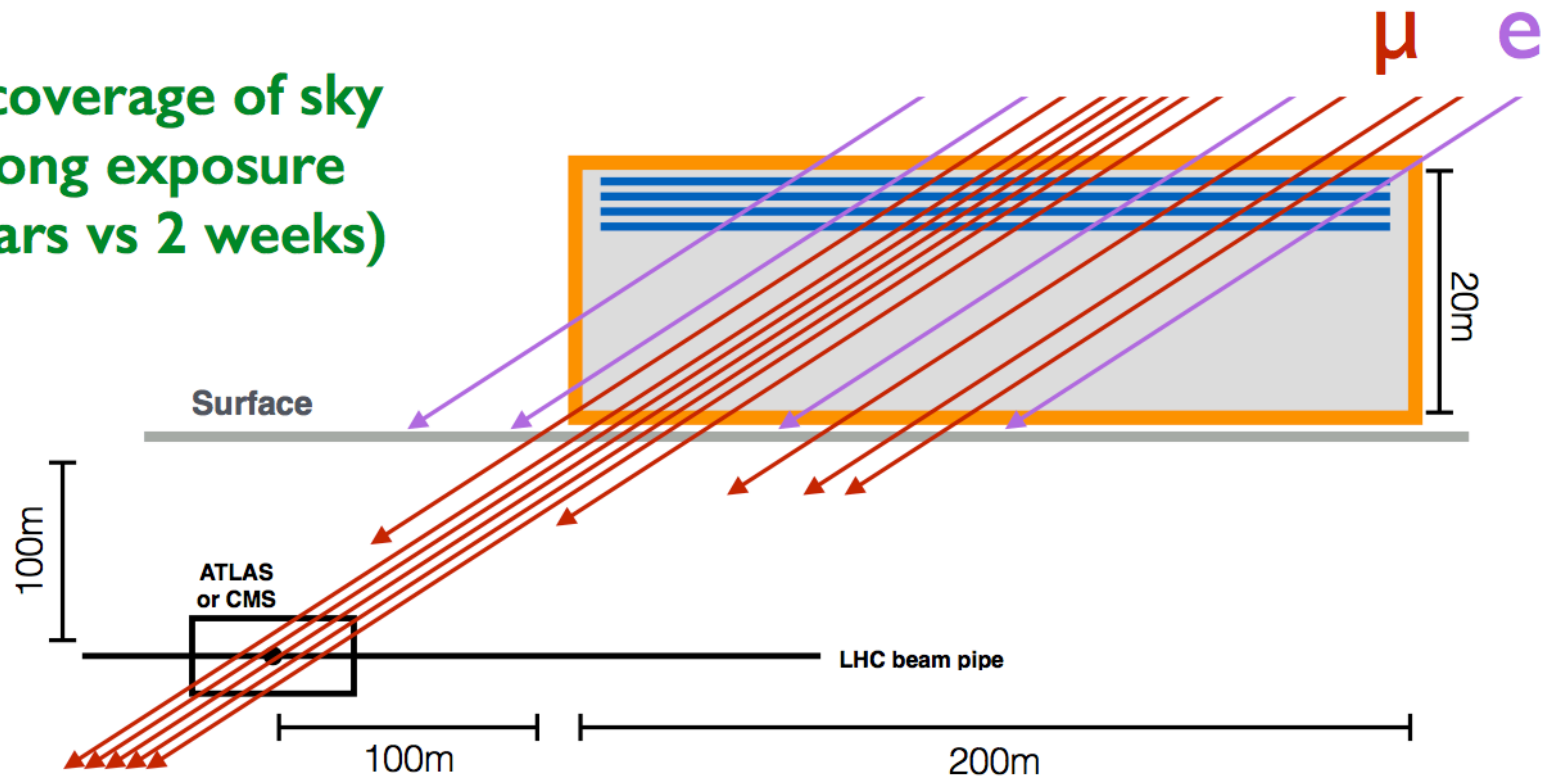
Main detector can measure core of muon bundle (multiplicity, direction, spatial distribution, momentum)

MATHUSLA measures correlated e/μ (distinguish?) direction, spatial distribution at surface

Would require dedicated CR trigger at main detector
(new hardware? not sure yet…)

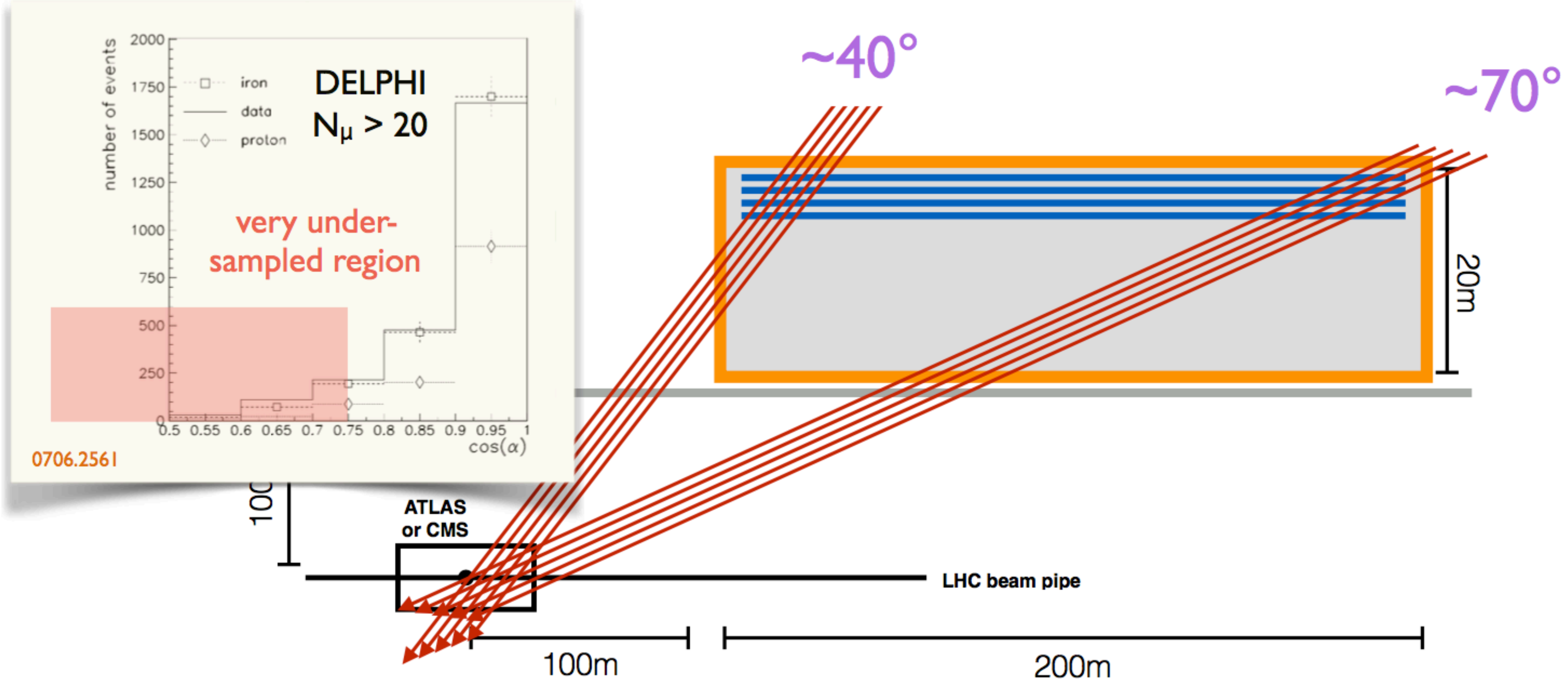
Can MATHUSLA Help?

~ 5% coverage of sky
but long exposure
(10 years vs 2 weeks)



In this energy range, correlating **underground data on muon bundle core (e.g. multiplicity, decoherence function)** with **shower data from surface** could provide **new sensitivity to hadronic interaction model or exotic bundle explanations**?!

Can MATHUSLA Help?



MATHUSLA's **large size**, **vertical offset** from main detector, and **high exposure** also means you can probe detailed **muon bundle properties** at **large range of inclination up to > 60°**, which has never been probed with high statistics before.

Astropart.Phys. 14 (2000) 109-120

Will supply important information on primary CR composition above knee!

May even be able to see **ultra-high-energy neutrino primaries!**

MATHUSLA is a proposed BSM Long-Lived Particle surface detector for the HL-LHC.

LLP searches are highly motivated, and MATHUSLA improves main detector sensitivity by x 1000

Rejection of Cosmic Ray Backgrounds for LLP search is plausible but needs much more study.

MATHUSLA + ATLAS/CMS together may provide new data to probe CR primary composition above the knee and understand cause of high-multiplicity/high-energy CR muon excesses!

Thoughts? Suggestions?

Join us!

FINAL COMMENTS

- **LEP RESULTS**: provided important results in the fiel of cosmic rays (HE interactions, sources searches, composition, …), they opened a new window of physics analysis with accelerator detectors
- **LHC RESULTS** revealed that these rare events can only be produced by primary cosmic rays with energies higher than 10,000 TeV.
  - the observed detection rate of one event every 6.2 days can be reproduced quite well by the simulations, assuming that all cosmic rays were due to iron nuclei (heavy composition). For proton nuclei (light composition) the expected rate would be of one event every 11.6 days.
  - the rate of these rare events has been satisfactorily reproduced using conventional hadronic-interaction models. However, the large error in the measured rate (50%) prevents us from drawing a firm conclusion on the exact composition of these events, with heavy nuclei being, on average, the most likely candidates. This conclusion is in agreement with the deduced energy of these primaries being higher than 10,000 TeV, a range in which the heavy component of cosmic rays prevails.
- **STUDIES OF COSMIC-RAY EVENTS ALLOW TO TEST HADRONIC INTERACTION MODELS**

FINAL COMMENTS

- **STUDIES OF COSMIC-RAY EVENTS ALLOW TO TEST HADRONIC INTERACTION MODELS**

Results from LEP and LHC have revealed interesting properties of atmospheric muons. This type of studies are useful to test to the interaction hadronic models post-LHC. They have attract the attention from theoretical colleagues to propose alternative interpretations of LEP/LHC data.

New ideas are brewing inside the LHC experiments. Besides ALICE, people from CMS and ATLAS are interested in developing cosmic-ray physics studies:

- Muon multiplicity, study of muon bundles, testing of hadronic interaction models (important input from LHC results to cosmic-ray interaction models)
- Charge ratio for single and multi-muon events
- study of horizontal events (not discussed here, but LHC experiments are willing to have a deep look on this data.)

Mathusla project aims to be a project involving ATLAS and CMS experiments searching for LLP particles. Mathusla is developing a proposal for cosmic-ray physics studies (ATLAS+CMS+ALICE?)