Cosmic ray inspired searches
at the LHC

Searching for New States of Matter
by Unconventional Signatures

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Exotic phenomena observed in cosmic ray experiments in the LHC energy domain

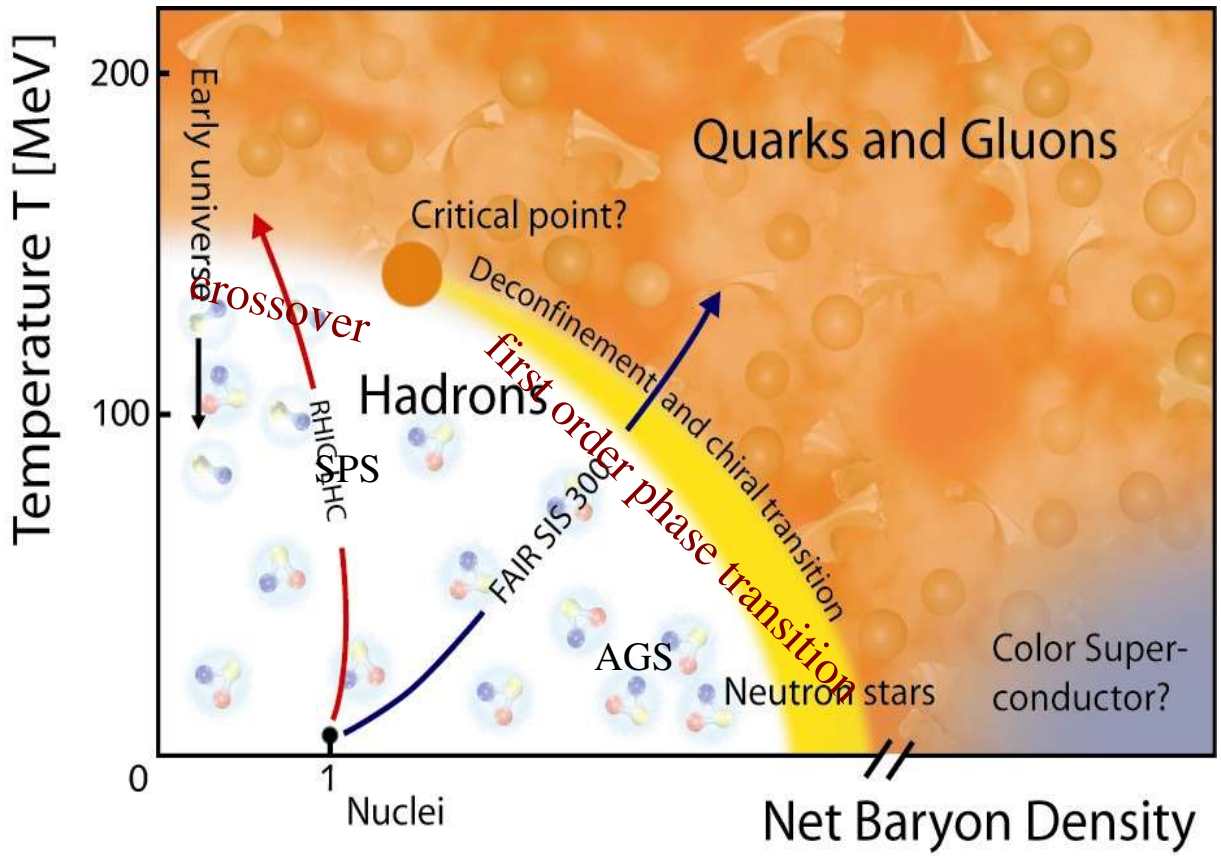
- **Centauro-related phenomena**
  -> Strange Quark Matter ?
- **Strongly penetrating component**
- **Ring-like events -> Cherenkov gluons?**
- **Multi-photon events -> Magnetic monopoles?**

Should we look for them at the LHC

and in which way?

MOTIVATION

www.gsi.de/fair/experiments/CBM



Transition between QGP and ordinary hadronic matter is a crossover at small μB, and is thought to become first order for μB greater than that of a critical point in the phase diagram.

Strong fluctuations are expected in vicinity of the critical end-point

Rich structure of the phase diagram in regions of large μB and moderate T motivates a search in heavy ion collisions at the LHC for exotic phenomena observed in cosmic rays.

First LHC results triggered interest in the cosmic-ray community

ALICE Coll., 2010, *EPJ C68:345-354*

- $\mathbf{N_{ch}}$ in pp collisions at midrapidity ($-1<\eta<1$) appears to be **rising with energy** ($\sqrt{s}$ = 0.9; 2.36; 7 TeV -> $E_{lab} \sim 10^{14}$-10^{16} eV) **faster than expected from commonly used models –**
- Shape of the multiplicity distribution is not reproduced well by standard simulations.

First LHC data confirm cosmic ray multiplicity observations ! -> should trigger interest of LHC community in studies of other cosmic ray phenomena

CERN Courier, June 2010 –

Letters by A. Erlykin and A. Wolfendale

- **N_{ch} at central rapidity is following a simple power law in energy**
- **power law exponent is the same as α = 0.11 found at E_{lab} ~ 1.5×10^3-1.5×10^5 GeV *(Erlykin, ICRC 1983)* and close to α = 0.13 found at lower energies E_{lab} ~ 10-1.5×10^3 GeV *(Wdowczyk&Wolfendale, N.C. 1979)***

CENTAURO RELATED PHENOMENA

at Mt Chacaltaya (5200 m) and Pamir (4300 m)

CENTAURO SPECIES:

Abnormal hadron dominance

(in N and E), high p_T, low multiplicity

- **CENTAUROS** of original type (5 "classical" Chacaltaya + others)
  $N_h \sim 100$, $P_T \sim 1.75$ GeV/c
- **MINI-CENTAUROS**
- **CHIRONS**

Review:

E.G.-D. Phys. Part. Nucl. 34(2003)285

STRONGLY PENETRATING COMPONENT:

cascades, clusters, halos, frequently accompanying hadron-rich events

CENTAURO RELATED PHENOMENA – until 2003

- **convincing evidence** *(Review: E.G.-D. Phys. Part. Nucl. ,2003)*
- **unexplained by fluctuations in "usual" hadronic interactions and/or development of normal hadronic cascades** *(Tamada, Ohsawa...)*
- **many models** *(QGP, DCC, isospin violation, SQM ..., by Bialas, Bjorken, Morozov, McLerran, Rajagopal, Wilczek, Zelevinsky...)* **explain hadron-rich composition**
- **Only STRANGE QUARK MATTER scenario** *(Panagiotou, E.G-D., Wlodarczyk...)* **offers simultaneous explanation of all Centauro-related phenomena:**

production of SQM fireball -> decay into baryons and strangelets -> strangelets = strongly penetrating component

First **CENTAURO** accompanied by the **STRONGLY PENETRATING CASCADES**

PAMIR - thick Pb chamber

S = 9 m2, d = 60 cm Pb

59 layers (1cm Pb + X-ray film)

Hadron-rich event

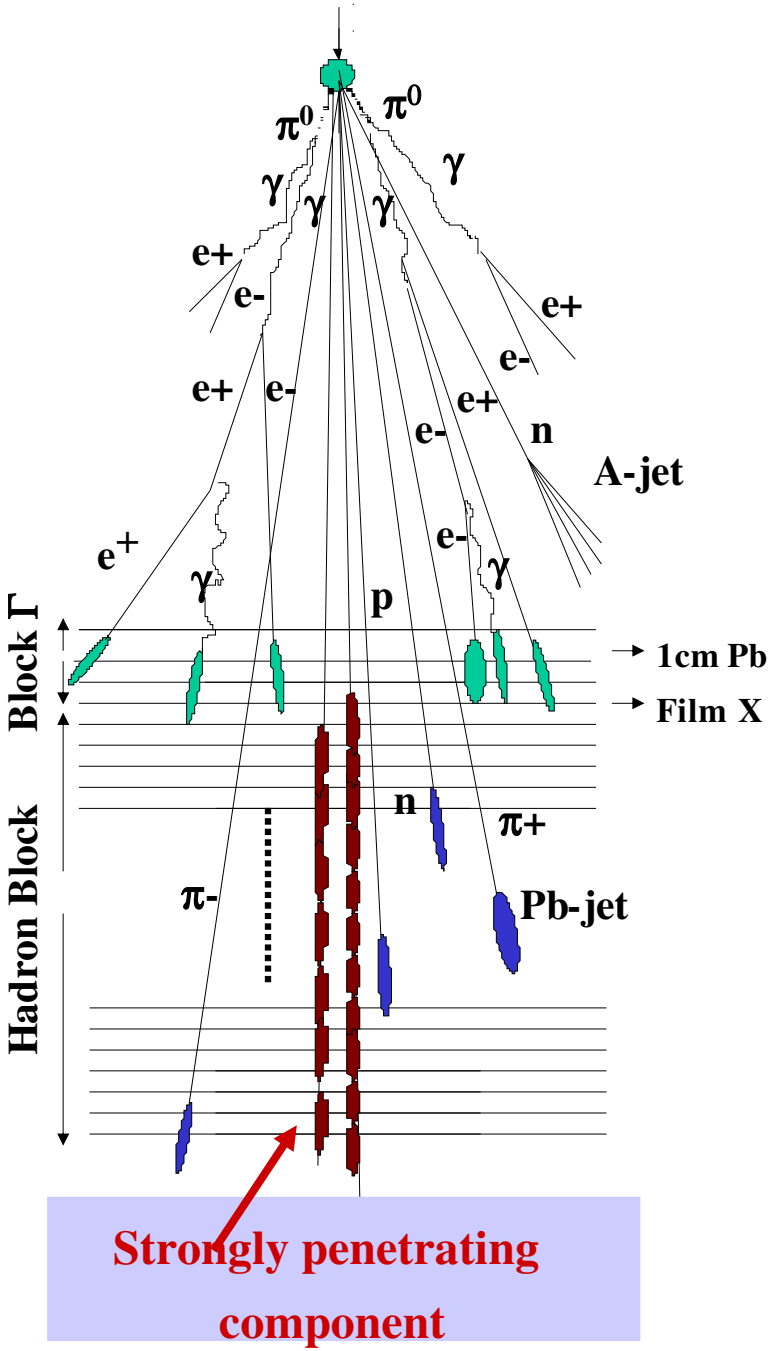
Nh = 55, Nγ = 74, ΣEh = 382 TeV, ΣEγ =305 TeV

Two long many-maxima cascades

no	start [c.u.]	end [c.u]	**range [c.u.]**	**no peaks**
197.08	12	121	**109**	**11**
748.01	48	121	**72**	**5**

passed and escaped through the bottom of the chamber

Cracow group, presented by E.G-D., ICRC, Paris, 1981



STRONGLY PENETRATING CASCADES in Pb CHAMBERS

STRANGELETS???

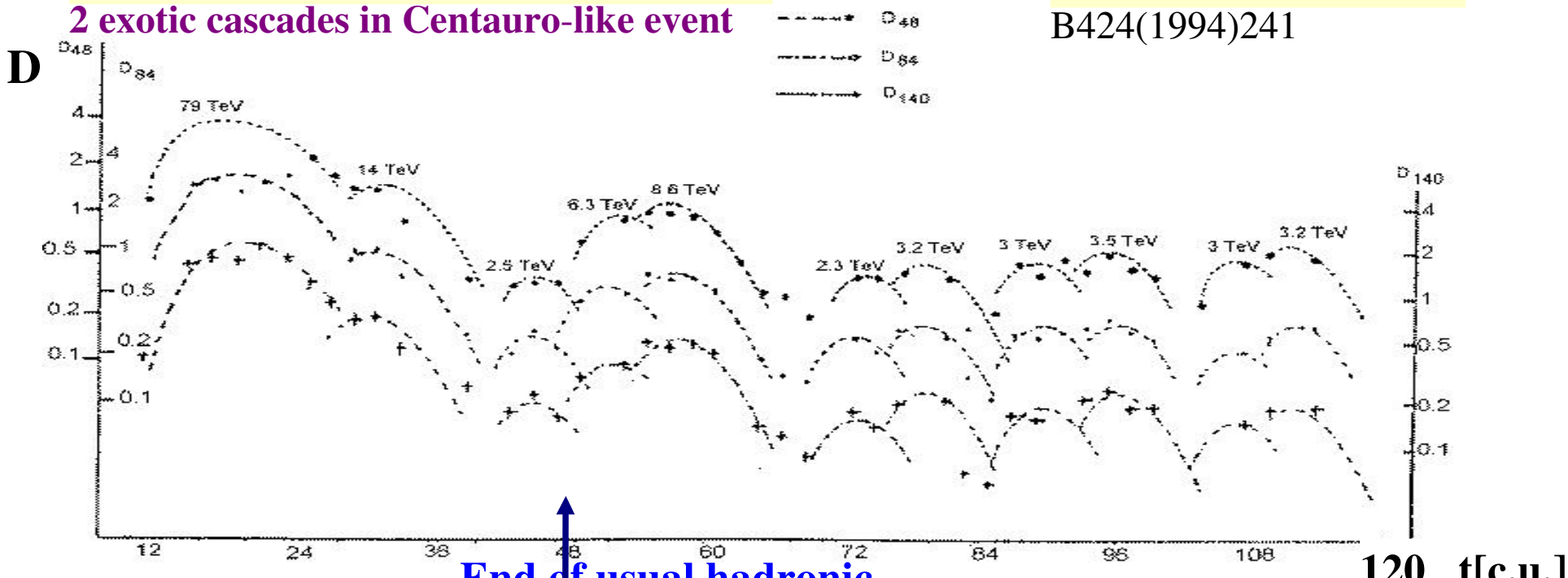
First observation:

Krakow group, by E.G.-D. 17th ICRC, 1981

2 exotic cascades in Centauro-like event

Other events

Arisawa et al.,Nucl. Phys. B424(1994)241



End of usual hadronic cascade ~1.5 λint

60 cm Pb~3.6 λ int

Cascades passed through the chamber practically without attenuation and revealed many-maxima character with small distances between humps

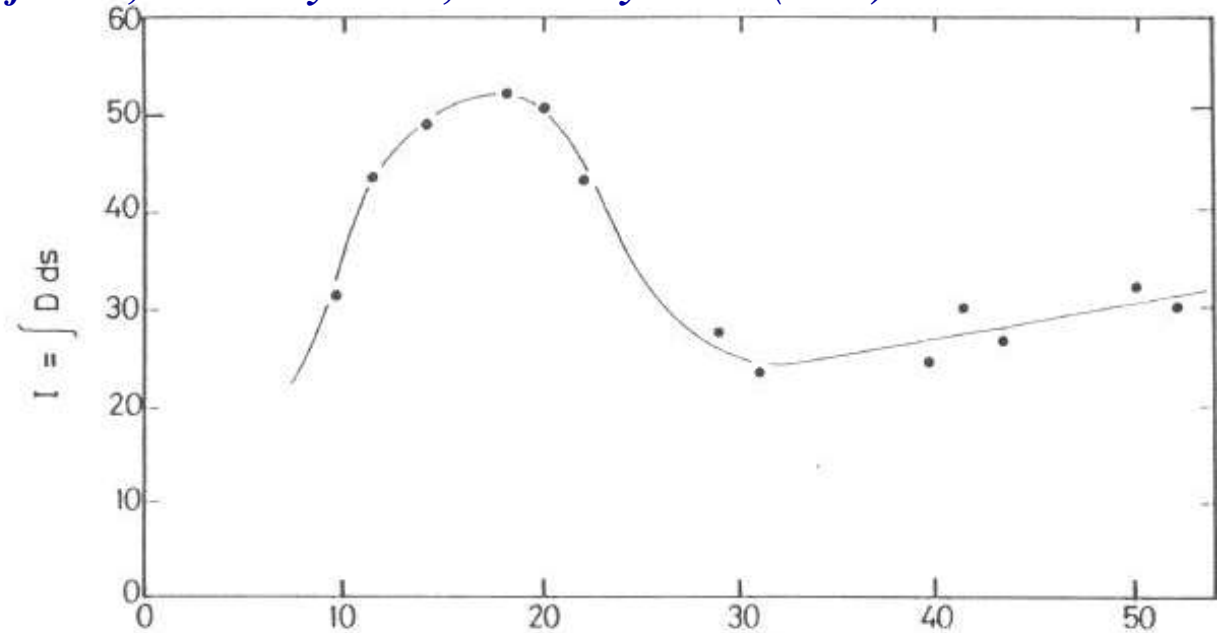
Penetrating halo in the center of family "Татьяна" – in thick carbon chamber (26 cm Pb + 4 C layers (320 cm)) -

Pamir Coll., Mt. Fuji Coll., Chacaltaya Coll., Nucl. Phys. B191(1981)1

CONFIRMATION

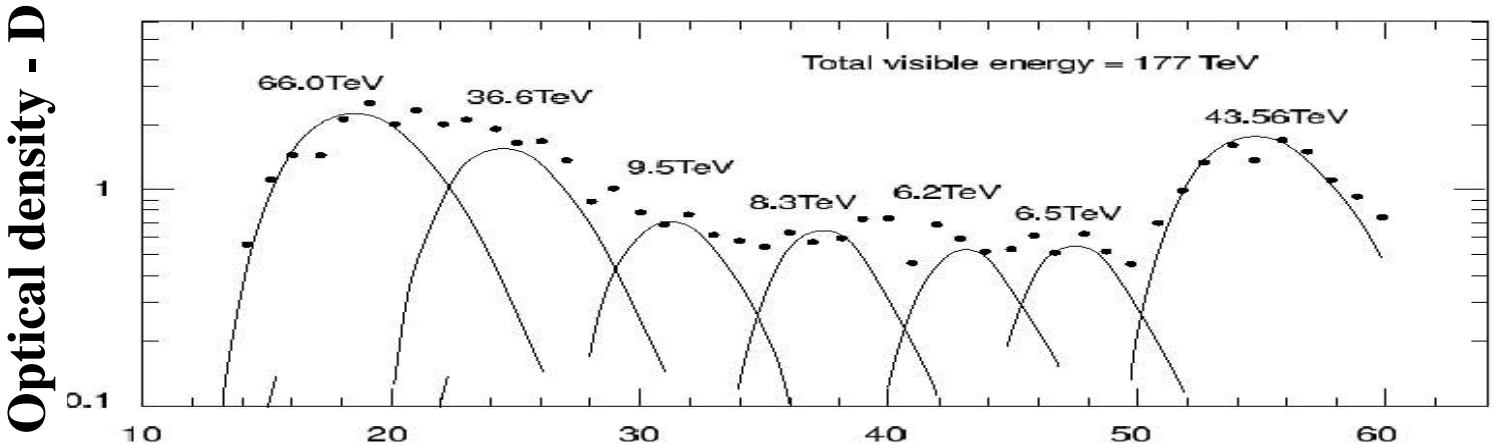
Other examples of exotic cascades in thick Pb chambers:

Chacaltaya-Pamir Coll., Nucl. Phys. B424(1994)241



t [c.u.]

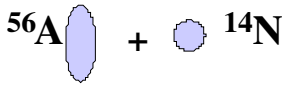
50 c.u.~5 Λ_{int}



Depth [cm Pb]

120 c.u.~3.6 Λ_{int}

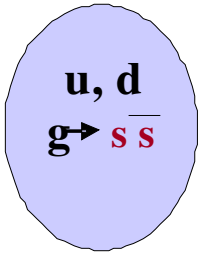
CENTAURO FIREBALL EVOLUTION



CENTRAL COLLISION

at the top of the atmosphere

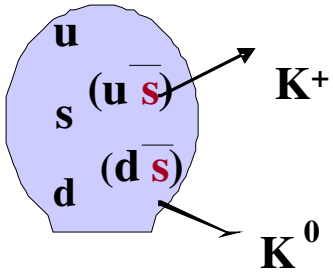
E_p ~ 1740 TeV



QUARK MATTER FIREBALL

in the baryon-rich fragmentation region

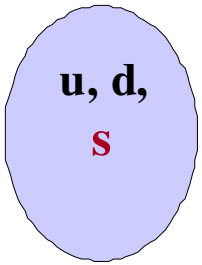
High μ_q suppresses production of $(u\,\bar{u})$, $(d\,\bar{d})$, favoring $g \rightarrow s\,\bar{s}$



(pre-equilibrium)
KAON EMISSION

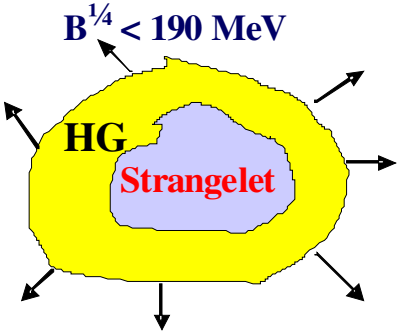
K^+, K^0 carry out:

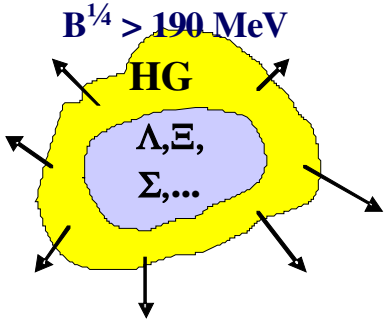
anti-strangeness , positive charge, entropy



SQM FIREBALL

Stabilizing effects of s quarks
→ long lived state





EXPLOSION

~75 non strange baryons + strangelet (A ~ 10 -15)

Strangeness distillation mechanisn

Estimates for "Chacaltaya" and LHC Centauro

- Energy density
  ~ (2.4) 3 - 25 GeV/fm^3,
- Temperature
  T ~ (130)130 - 300 MeV
- Baryo-chemical potential
  μ_b ~ (1.8)0.9 - 1.8 GeV/fm^3

sufficient for phase transition

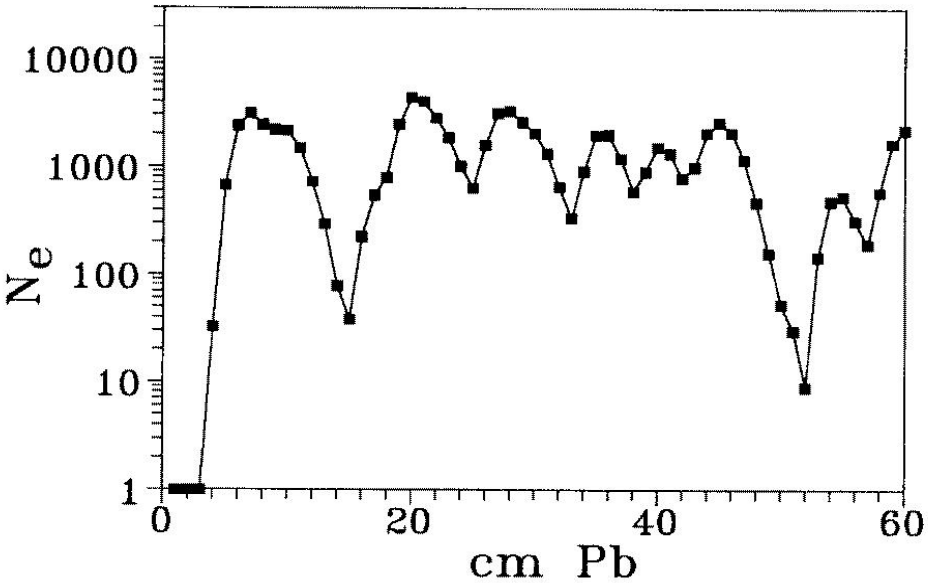
possible STRANGELET formation

CNGEN

Centauro&Strangelet Generator

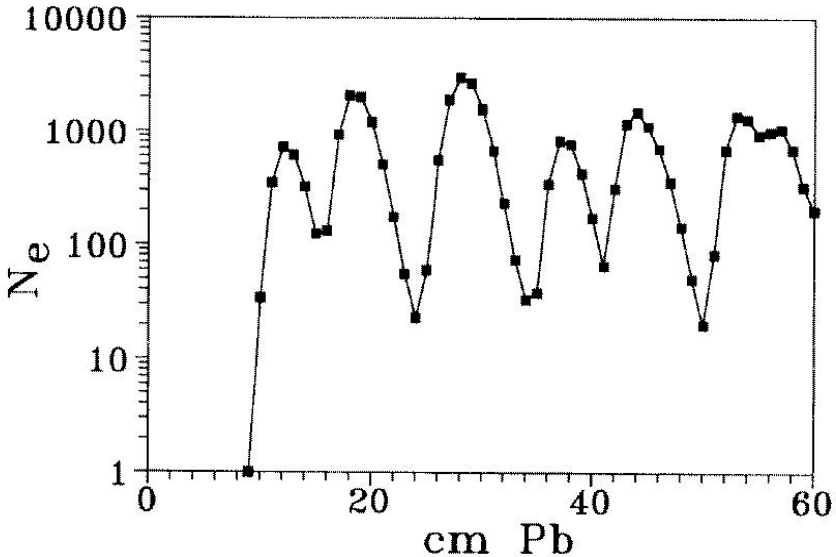
Phys. Rev. D45(1992)3134 Astr. Phys. 2 (1994)167; Astr. Phys. 13(2000)173; Phys. Atom. Nucl. 67(2004)396

Strangelet passage through the Pb emulsion chamber



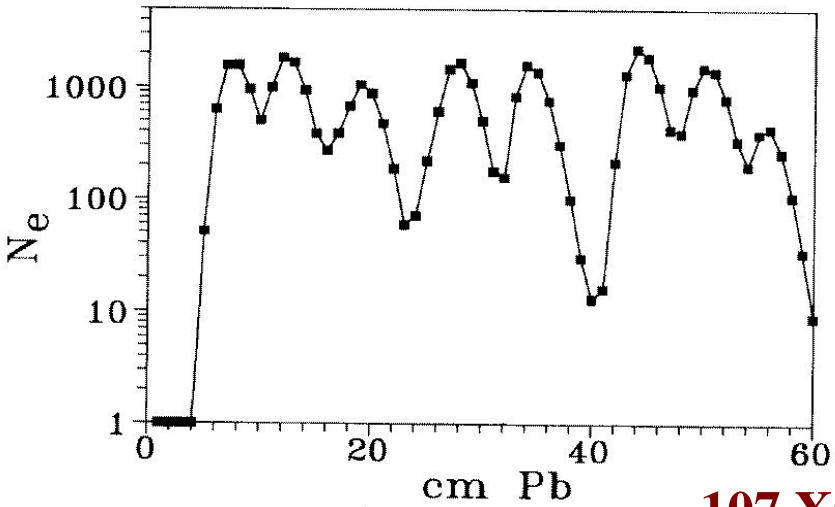
Unstable strangelet decaying into a bundle of 7 n

(En ~ Estr/Astr ~ 200 TeV)



Metastable strangelet

(Astr=15, Estr~200ATeV, $\tau \sim 10^{-15}$ s)



Long-lived strangelet **~107 X0, ~3.5 Λ int**

(Astr=15, μq = 600MeV)

Simulated transition curves resemble the observed long many-maxima cascades

E. G.-D. and Z. Wlodarczyk,

J. Phys., Nucl. Part. Phys. G23 (1997)2057

1. NEW EXPERIMENTAL FINDINGS

(= troubles)

2. NEW QUESTIONS – could any other objects

(muons, magnetic monopoles, SUSY long lived particles)

produce long-range many-maxima cascades?

↓

NEW IDEAS

and

NEW EXPERIMENTS

EMBARRASSMENT I -> CENTAURO I PUZZLE

remeasurement -> NO CASCADES in the upper chamber ?

- ***Kopenkin, Fujimoto, Sinzi***, *Phys. Rev. D68, -52007 (2003)*
  - differences in arrival angles of cascades in upper (7 showers) and lower (43 showers) chambers -> no upper -lower correspondence -> **usual atmospheric family** that passed in the gap between chamber units ?

- ***Ohsawa, Tamada, Shibuya*** , Phys. Rev.C70, 074028 (2003)
  - **– exclude the gap-passing hypothesis** - reanalysis confirms the hadron rich composition of Centauro I – **EVENT** seems to be even **MORE EXOTIC ?!**

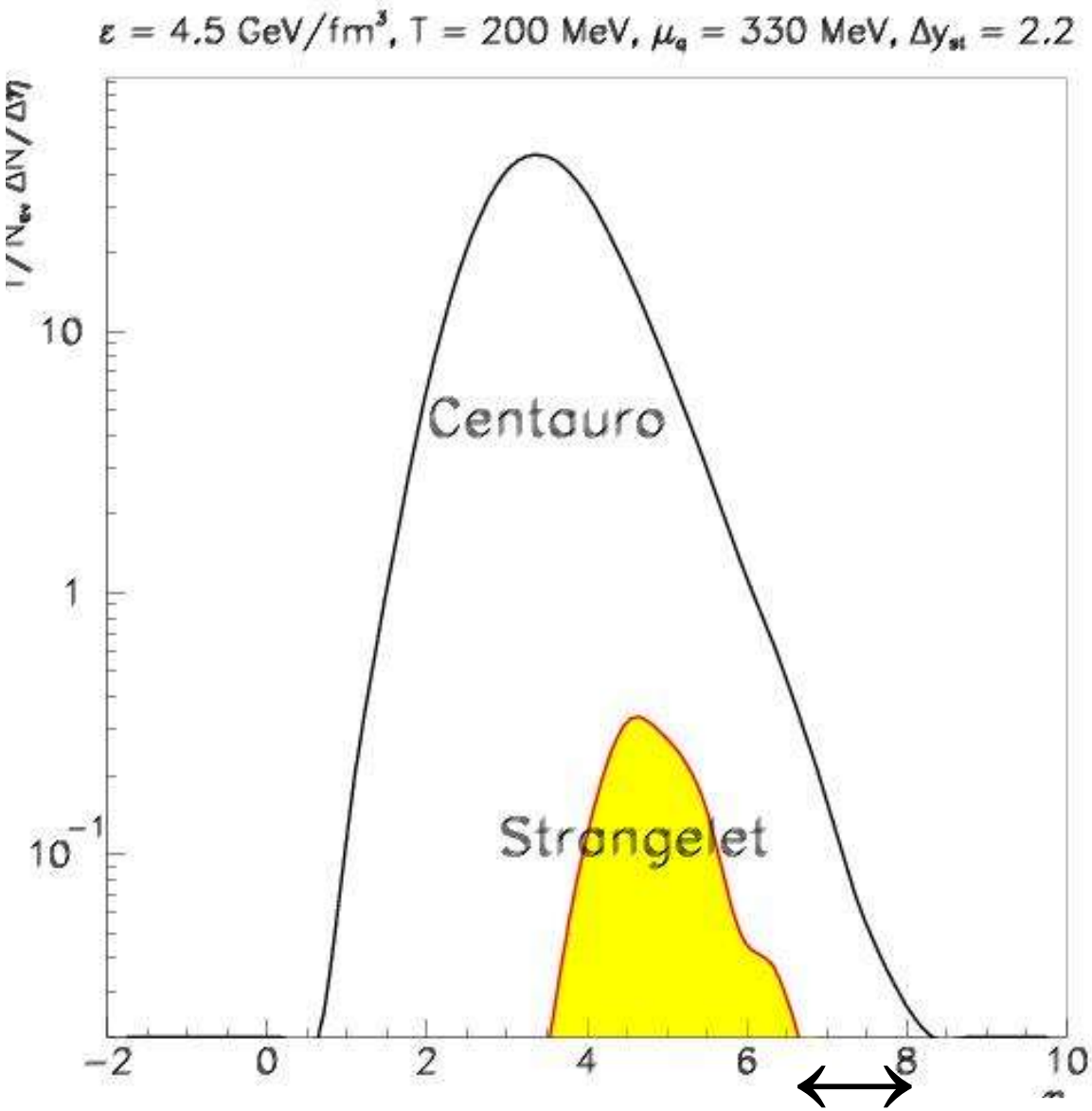
- > confirmation of the SQM scenario

- **simple arguments against "passing in the gap" hypothesis:**

- many other hadron-rich events and related phenomena: mini-clusters, strongly penetrating component etc. (1997 - second clean Centauro, 2008 – reanalysis of old Centauro V -> "authentic Centauro") can not be explained by apparatus effects

- the same gap between blocks in all 6 layers of upper chambers?

EMBARRASSMENT II



STAR

η

strangelets in central Au+Au at RHIC (*E.G.-D. - CNGEN*)

- ***2 strangelet candidates by AMS - 2002***
- ***no strangelets at RHIC -2007***

Maximum of strangelet distribution beyond geometrical acceptance (~ 6.5 < η < 8.0 for neutral strangelets) of the detector used by *STAR Coll., Phys. Rev. C76, 011901(R) (2007)*

Negative results of strangelet searches – too forward rapidity region for strangelet formation ??

STRANGELETS -> NEW IDEAS

- **STRANGELETs – decay products of large quark globs present in the primary cosmic rays**

  - confirmation of our SQM scenario

  Ohsawa, Tamada, Shibuya , Phys. Rev. C70, 074028 (2003)

- **STRANGELETS - modified spectator matter**

  - produced in peripheral nucleus-nucleus collisions

  - enhancement of strange quarks after absorbing K^- produced in QGP ***Norbeck and Onel, J. Phys., Conf. Series 230 (2010)012044***

  this scenario explains the negative result of strangelet searches by STAR – strangelets should be looked for in peripheral (not in central) collisions

CENTAURO –

new explanations based on extra dimensions

Mini Black Holes

- ***Mironov, Morozov, Tomaras – hep-ph/0311318 , 2004***
  suppression of EM component in Centauros caused by evaporation of MBH (all particles of the SM are produced with equal probability) –> low photon/hadron ratio

- ***E. G.-D., Z. Wlodarczyk - "Black holes versus strange quark matter", hep-ph/0405115, Nova Science Publishers, 2006***
  extremely high pT (~ 1 TeV) of MBHs decay products could be responsible for the group of particles with a little different arrival angles and explain the Centauro I puzzle ?

Why one associates CENTAUROS with R – HADRONS ?

Hunting gluinos at the Auger - *Anchordoqui et al, Phys Rev D 77,023009,2008*

R - hadron originates through confinement of a supersymmetric particle (long-lived gluino, squark) with quarks, anti-quarks, gluons

R-hadrons produce the peculiar air showers and CENTAUROS because

- energy loss is by a multiple low-inelasticity collisions of gluino with nucleons

- very low inelasticity implies that leading particle retains most of its energy all the way, while secondary particles produce an ensemble of mini-showers strung smoothly along the trajectory of the leading particle

- **strongly penetrating clusters and cascades**
- **hadron-rich showers since at the detector level (~5200 m) the EM component of subshowers would be mostly filtered out, while the superposed hadronic showers would survive**

NEW experiments

- **Pamir – Chacaltaya International Scientific Research Centre** (ISRC) – established in 2009
- 2-storied deep X-ray chamber put under exposure -Ar-Arkhar, Pamir, 4400 m a.s.l. -to study a penetrating hadronic component, possibly caused by charm particles or **strange matter (strangelets) – similar experiment as the CASTOR**-CMS
- Proposal of global network of high altitude research stations

CENTAUROS and STRANGELETS at the LHC

where and how to look for them?

Search for Centauro-like phenomena

CENTAURO via event-by-event fluctuations –
wide interval, preferably in the more forward region

- *low multiplicity and characteristic particle composition*
- *high pT*
- *low $N\gamma/Nh$, $\Sigma E\gamma/\Sigma Eh$*
- *characteristic η distribution*

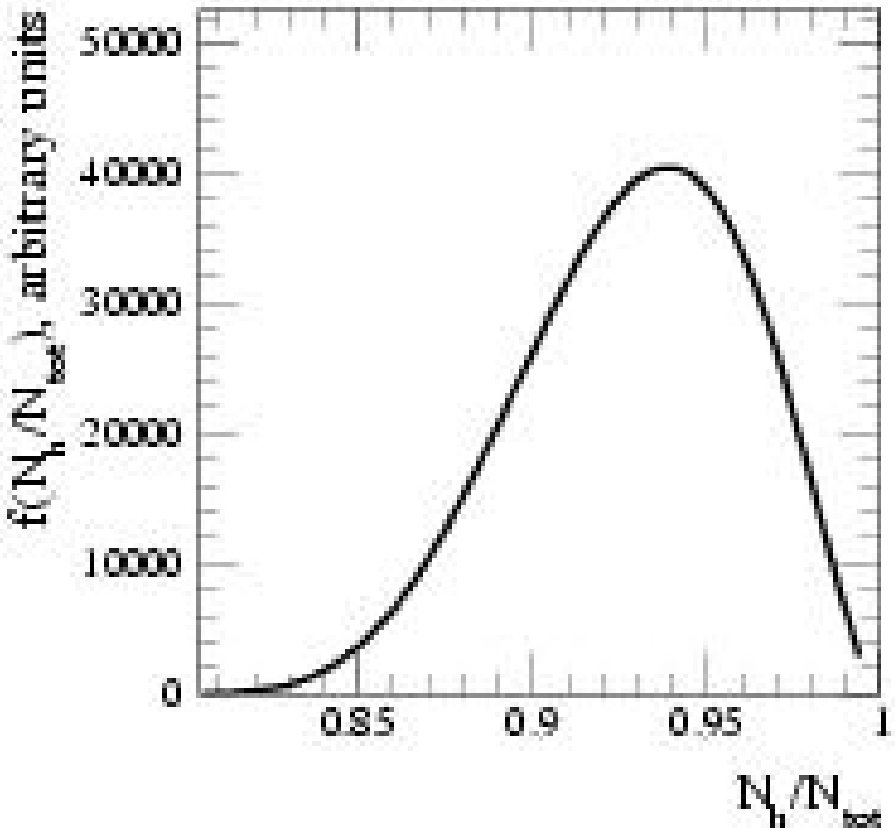
Preliminary suggestions for ALICE

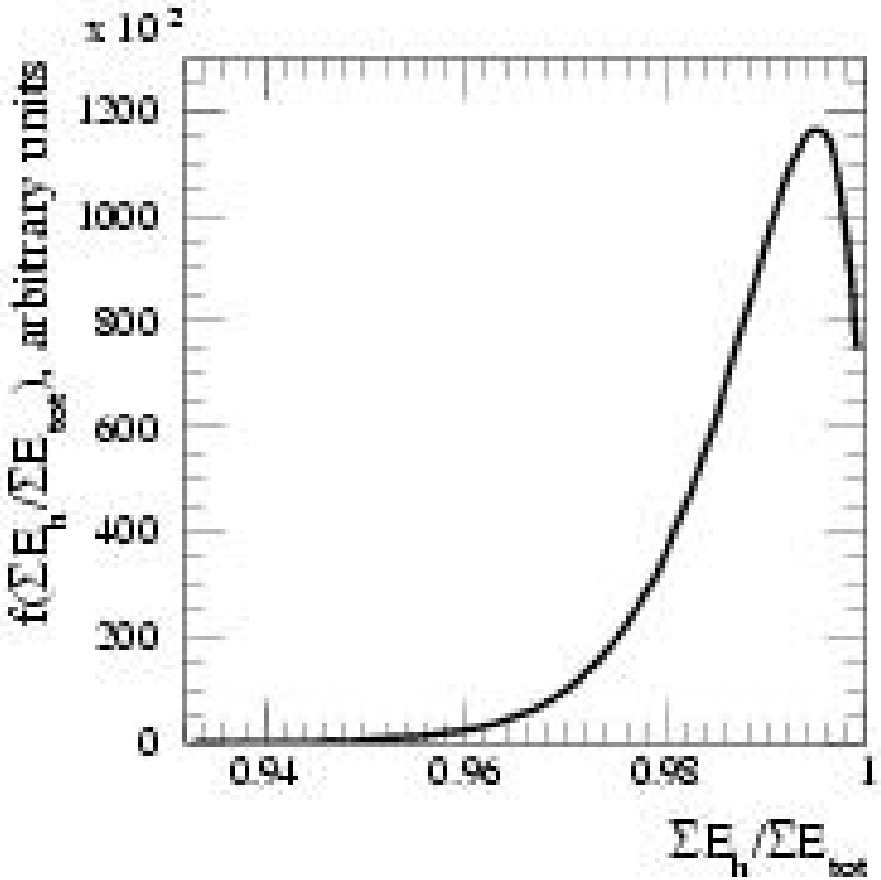
STRANGELETS

- *if produced via strangeness distillation mechanism – detection by characteristic energy deposit in deep calorimeters, e.g. dedicated CASTOR/CMS calorimeter, ALICE ZDCs ??*
- *if produced at midrapidity via coalescence - by decay pattern in central detectors, e.g. ALICE*

GENERATION of EXOTIC OBJECTS

- LHC CENTAUROS in Pb+Pb at √s = 5.5 TeV/n





Anomalous hadron dominance

Nh/Ntot = 0.93

ΣEh/ΣEtot = 0.99

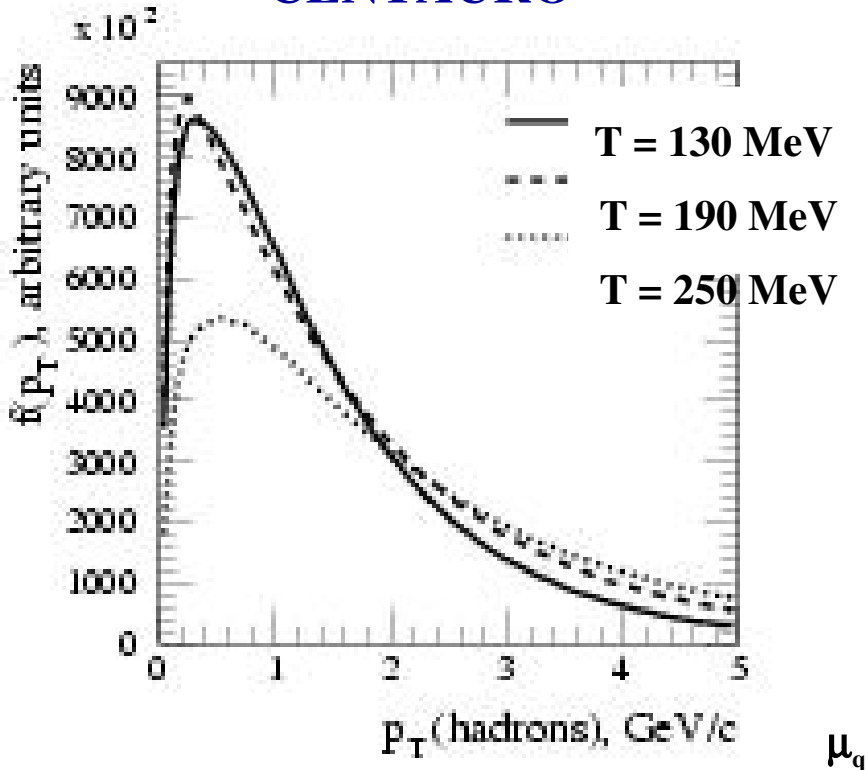
μ = 600 MeV

T = 190 MeV

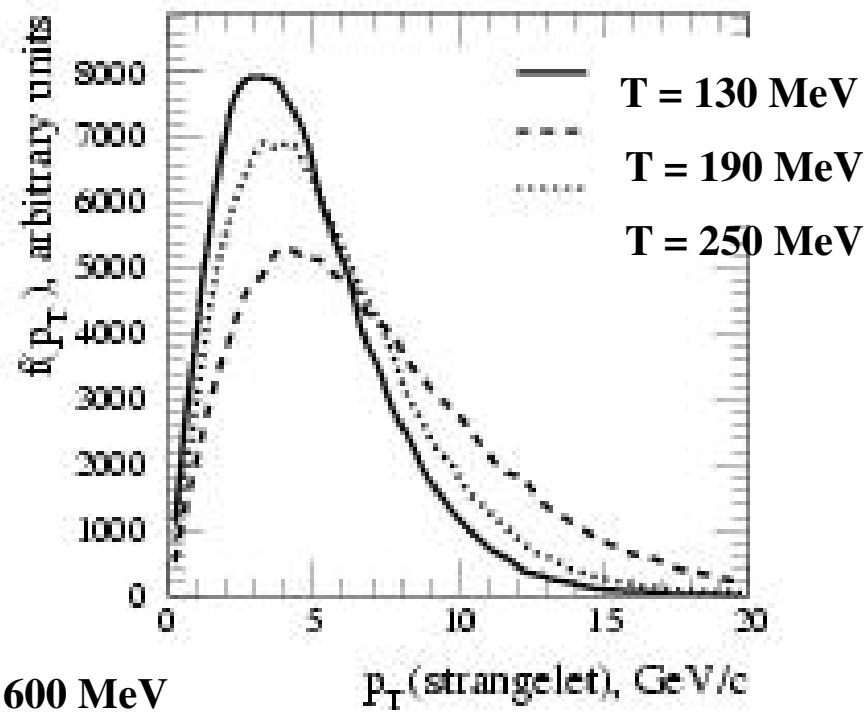
CNGEN – Phys. Atom. Nucl. 67(204)396

High transverse momenta

CENTAURO



STRANGELET



μ_q = 600 MeV

CENTAURO

T = 130 MeV , <pT> = 1.34 GeV/c

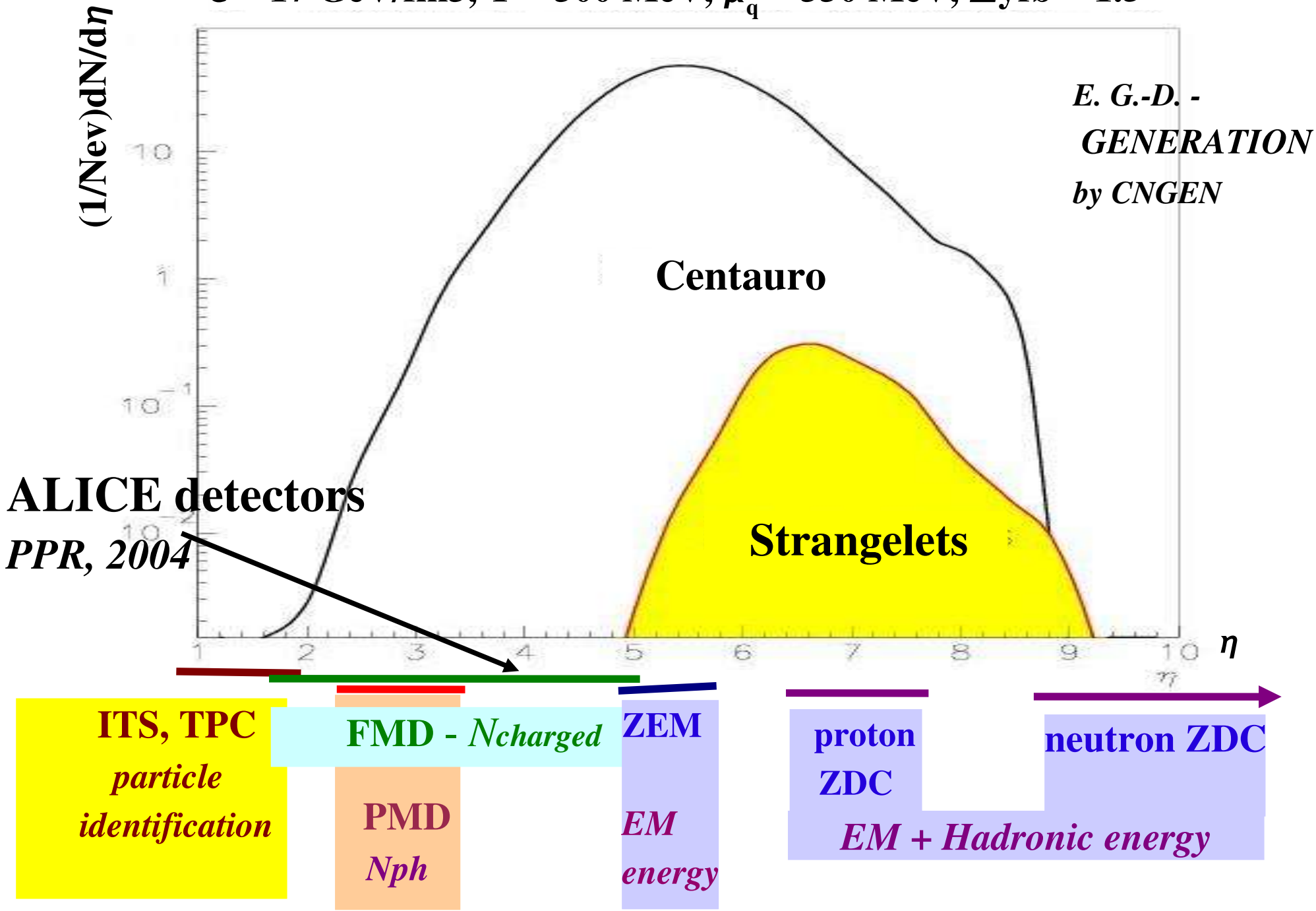
T = 250 MeV, <pT> = 1.75 GeV/c

HIJING

<pT> = 0.44 GeV/c ≈ 3-4 times smaller than in Centauros

CNGEN – Phys. Atom. Nucl. 67(204)396

ε = 17 GeV/fm3, T = 300 MeV, μ_q = 330 MeV, Δyfb = 1.5

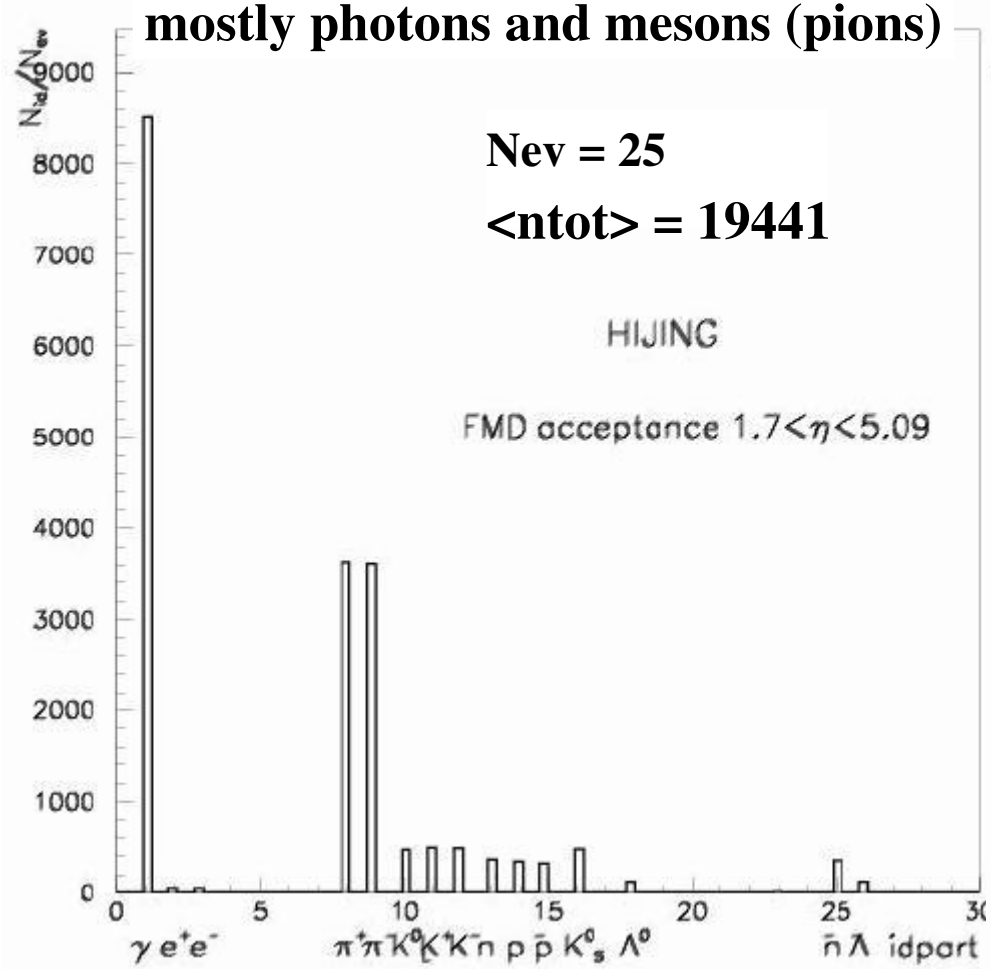


Multiplicity and particle composition in central Pb+Pb within the ALICE FMD acceptance

HIJING

high multiplicity

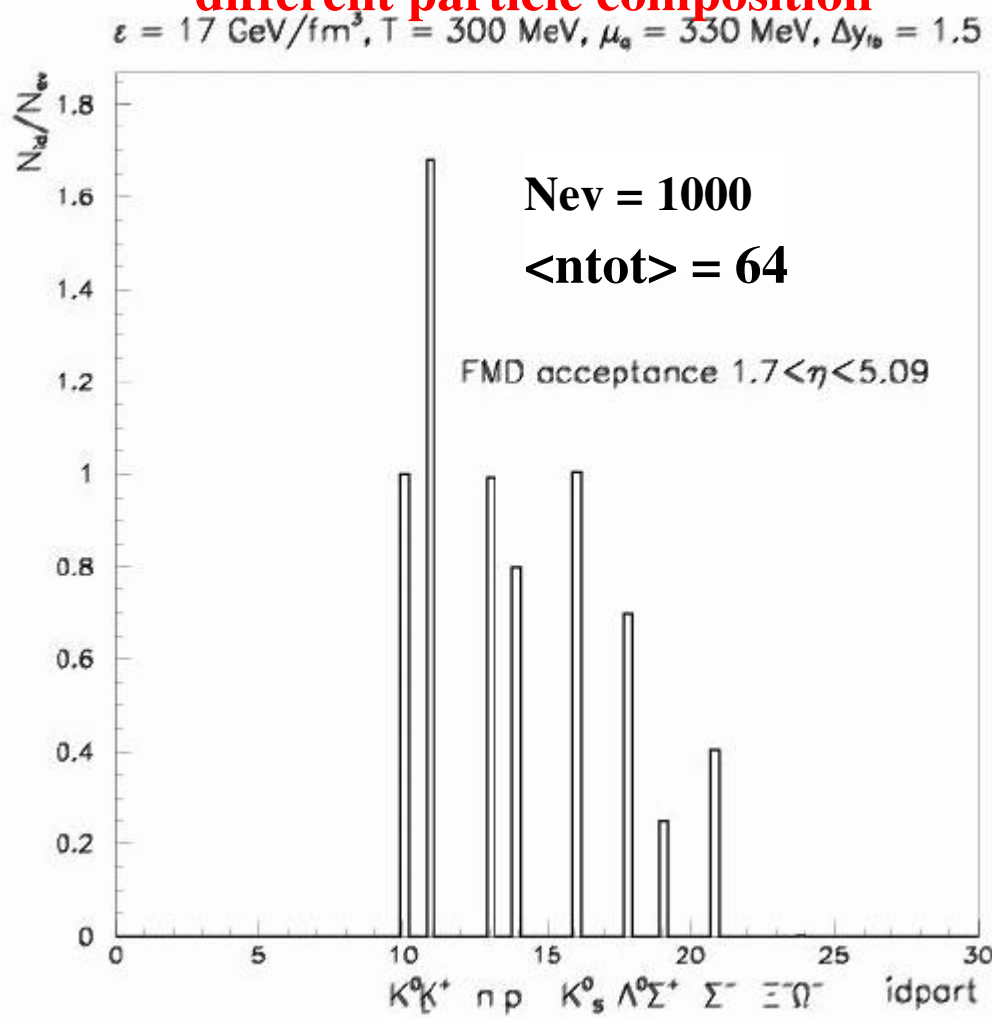
mostly photons and mesons (pions)



CENTAURO

low multiplicity,

different particle composition



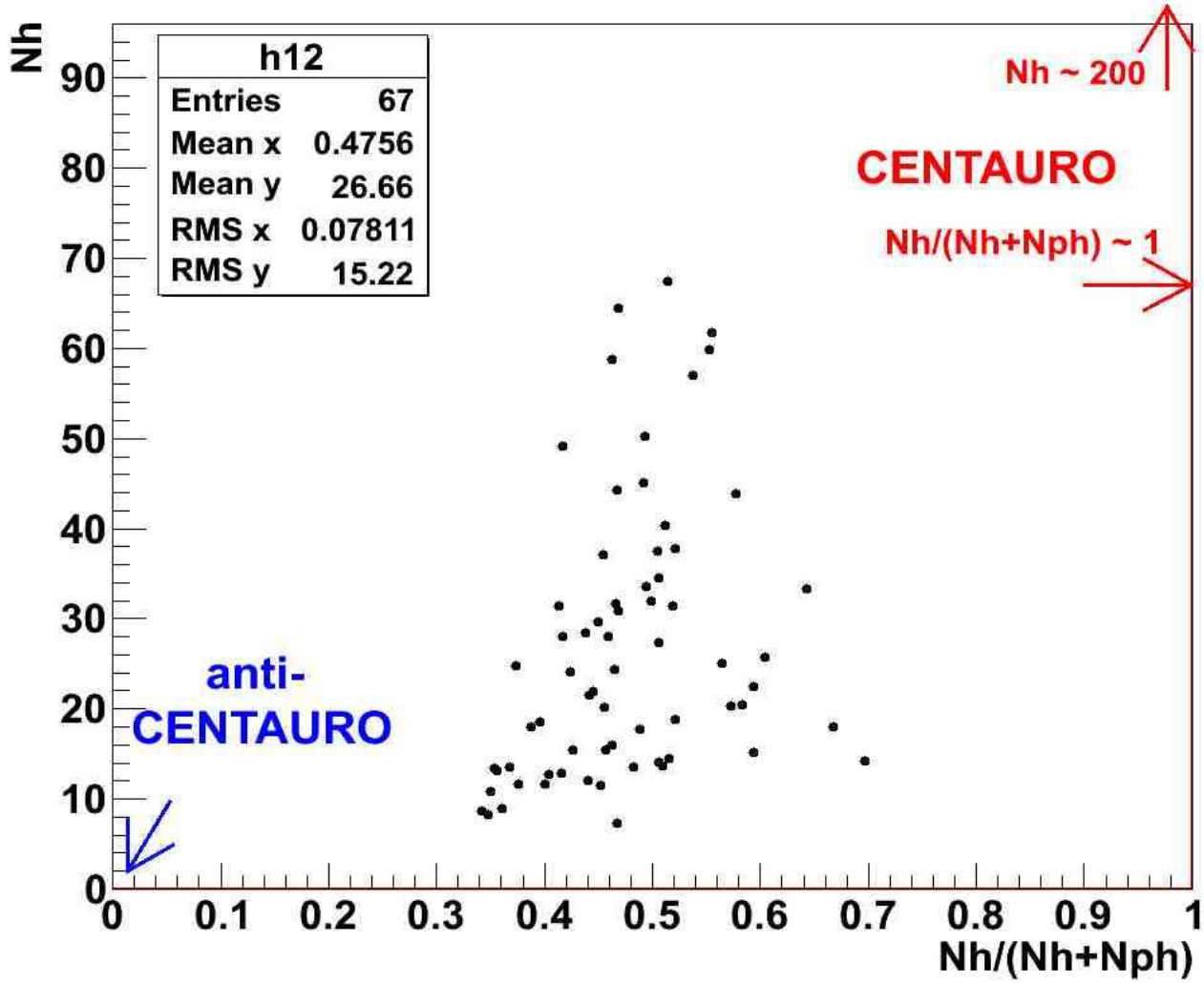
E. G.-D. – generation by CNGEN

no gammas and pions, mostly baryons

Preliminary suggestions

Search for Centauros in ALICE PMD (~ 2.4 < η < 3.6)

Simulations, 67 pp Pythia events with N>60, 7 TeV



CENTAUROS:

- **high N_veto and N_veto/N_pres ≈Nh/Ntot**
- **high Nh and Nh/(Nh+Nph)**

N_veto ≈ Nh (+ Ne)

N_presh ≈ Nh+ Nph (+Ne)

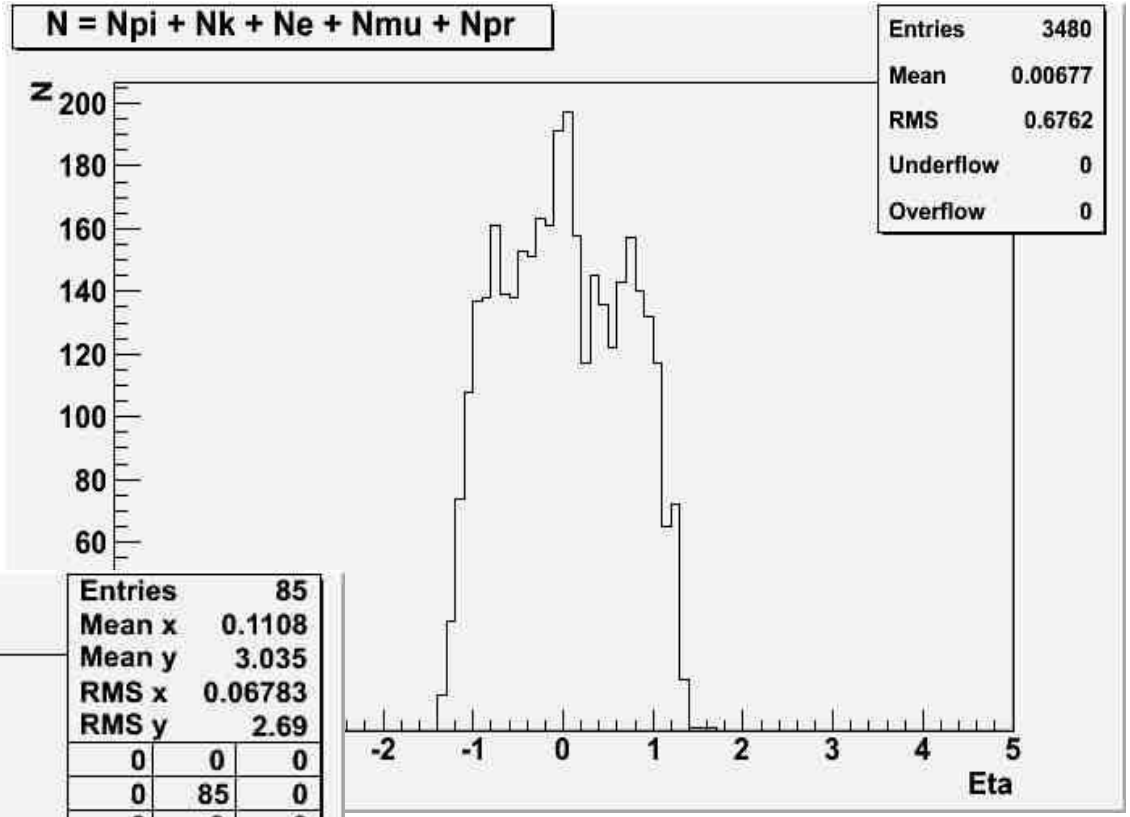
Assumption:

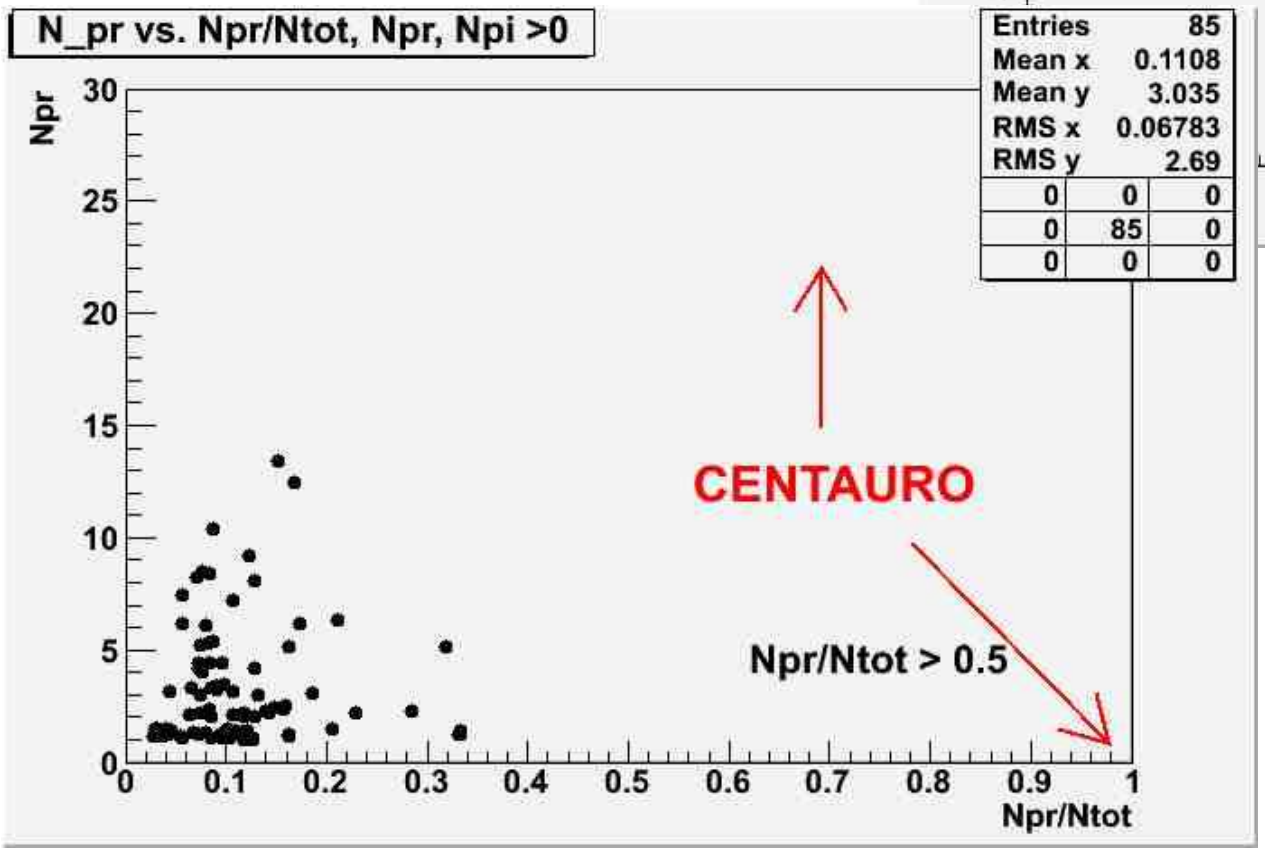
Photons: seen in Preshower and Ncell > 1.

Hadrons: seen in VETO and Ncell =1.

Preliminary suggestions

Finding CENTAUROS in ALICE central detectors possible if Centauros are baryon fireballs





CENTAUROS:

high Npr

and

Npr/Ntot ≈ 1

Npr = p + anti-p

STRANGELETS and exotic di-baryons (MEMOs - $(\Lambda\Lambda)_b$ $(\Xi\Lambda)_b$...)

- **if produced beyond midrapidity, in the high μb environment via strangeness distillation mechanism – unusual shape of strongly penetrating showers – CASTOR/CMS**
- **if produced at midrapidity by coalescence - ALICE**

  ALICE TP, 1995; Coffin et al., 2002 and 1997

- **long-lived** ($\tau > 10^{(-7)}$ s) (6u6d6s) and A = 10, 12, 16; Z = -4, -6, -6)

  - via **dE/dx** (TPC) and/or **time of flight** (TOF)

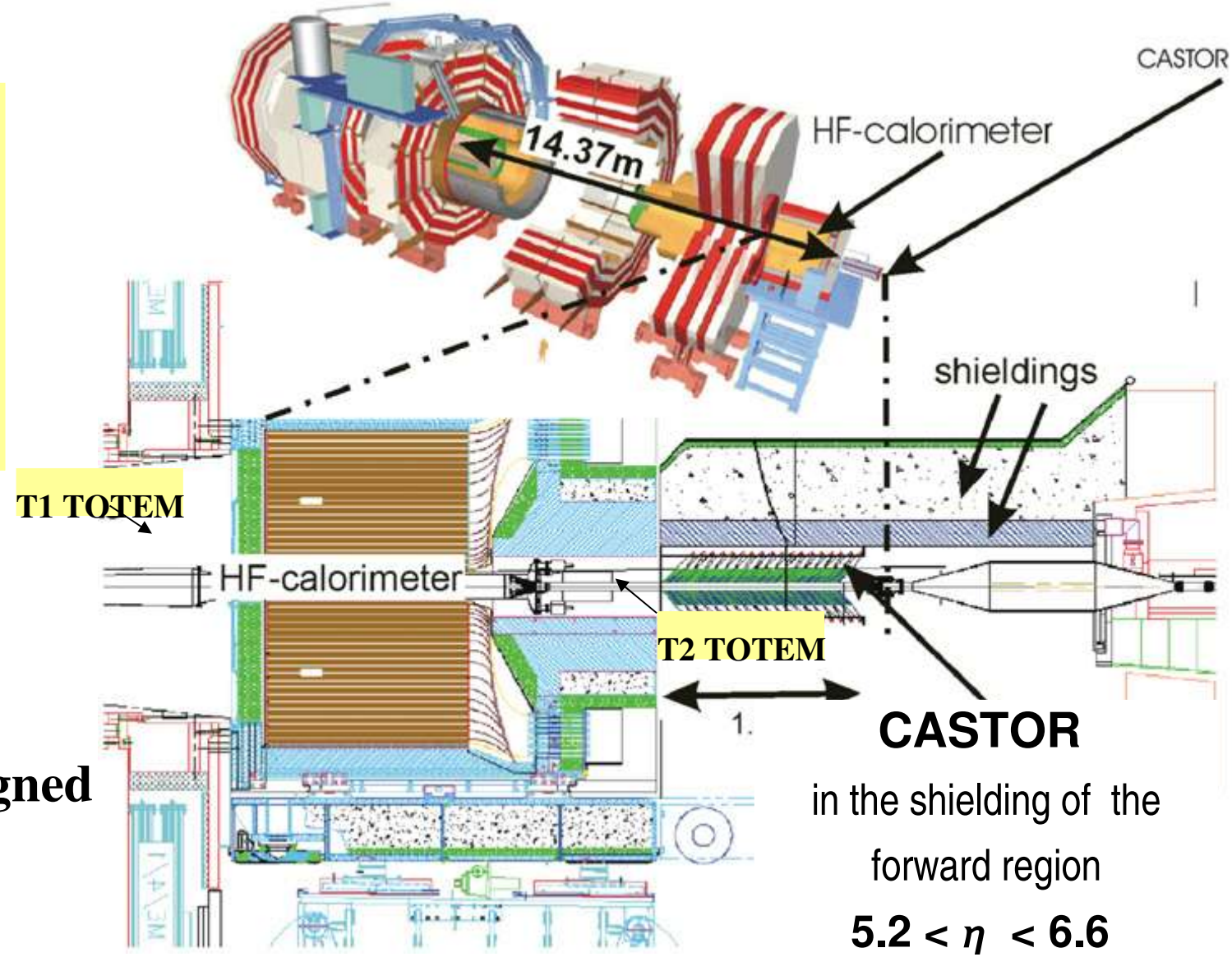
- **short–lived** (weak decay - $\tau \sim 10^{(-8)} - 10^{(-10)}$ s)

  Jaffe - >**H^0** (*2u2d2s*, M ~ 2055-2231 MeV) -> **decay pattern (TPC)**

$$H^0 \rightarrow \Lambda^0 + p + \pi^- \rightarrow p + \pi^- + p + \pi^-$$

CASTOR

Centauro
And
STrange
Object **R**esearch



CASTOR

in the shielding of the forward region

$5.2 < \eta < 6.6$

enlarges the coverage of main CMS detectors

($\eta < 5.2$)

dedicated and designed as ALICE detector but finally integrated in the CMS

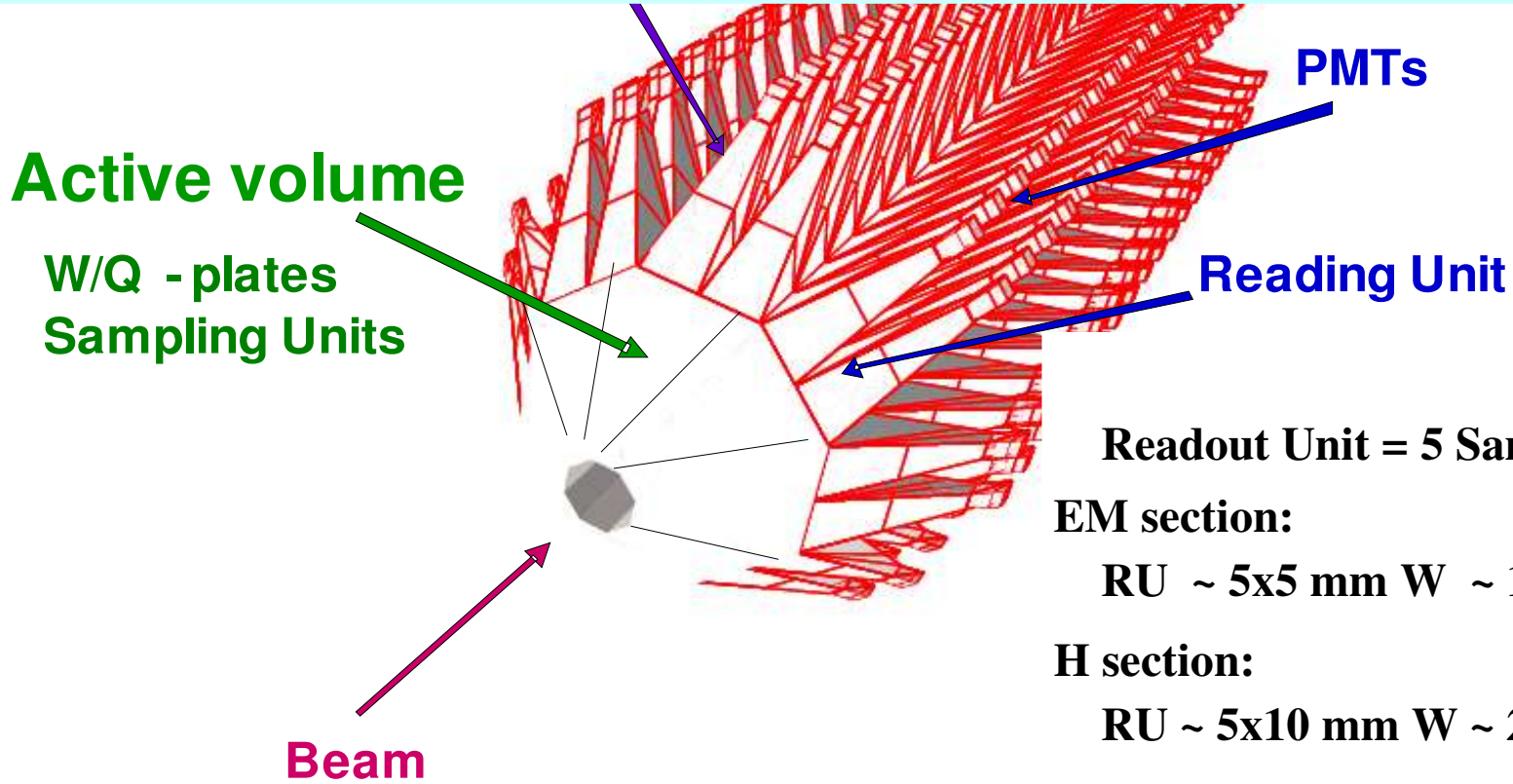
P. Gottlicher, CMS-CASTOR Coll., NIM A, 2010

CASTOR CALORIMETER

- Cherenkov light is generated inside the quartz plates as they are traversed by fast charged particles in the shower (shower core detector) developing in tungsten
- Azimuthal and longitudinal sampling sufficient for a study of structures in longitudinal development of cascades
- High depth for detection of strongly penetrating objects

- **760 mm W ≈ 10.3 λ**

14 longitudinal layers(12H + 2EM)x
16 azimuthal sectors = 224 channels



Readout Unit = 5 Sampling Units

EM section:

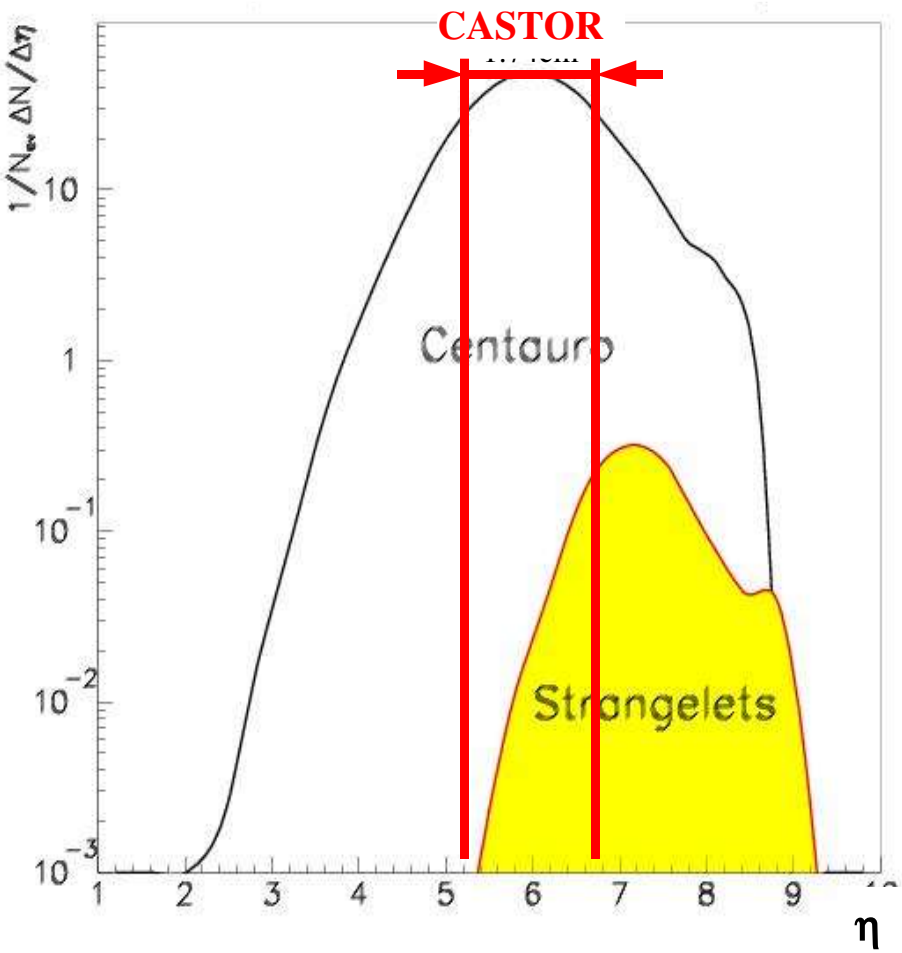
RU ~ 5x5 mm W ~ 10 X0 ~ 0.4 λ_I

H section:

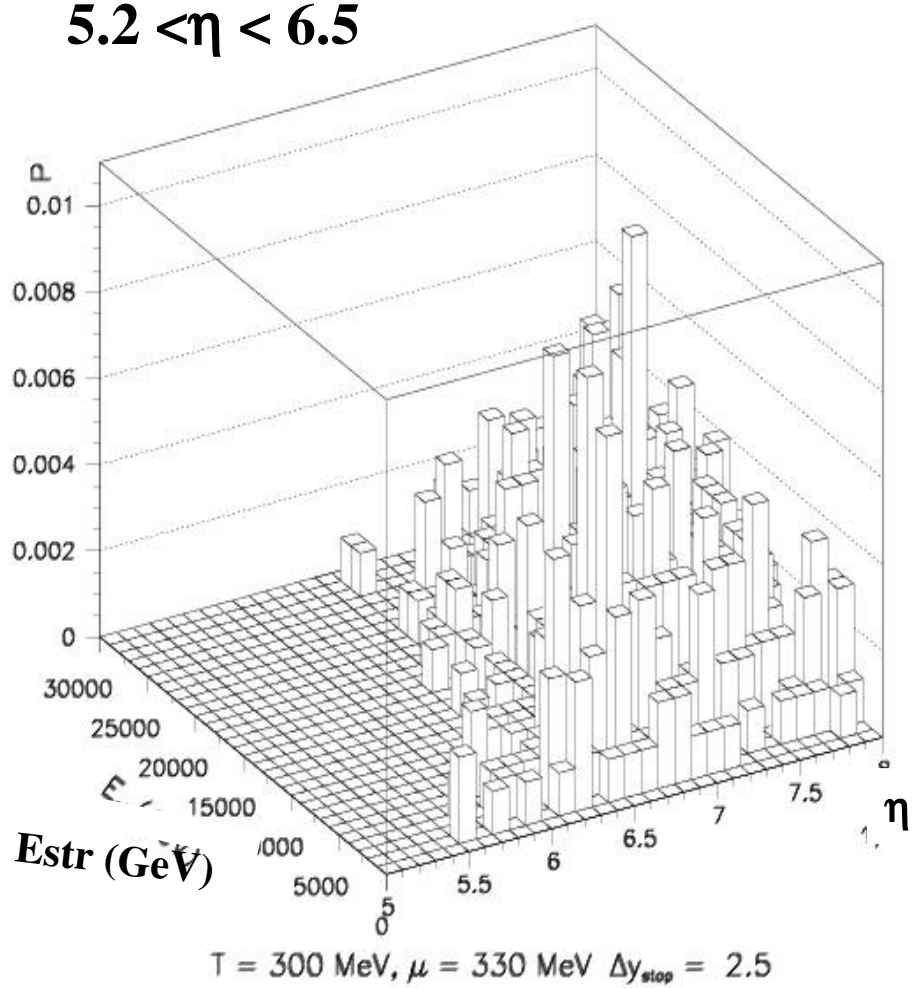
RU ~ 5x10 mm W ~ 20 X0 ~ 0.79 λ_I

Probability of CENTAURO and STRANGELET detection

ε = 17 GeV/fm³, T = 300 MeV, μ_q= 330 MeV, Δy_{stop} = 2.5



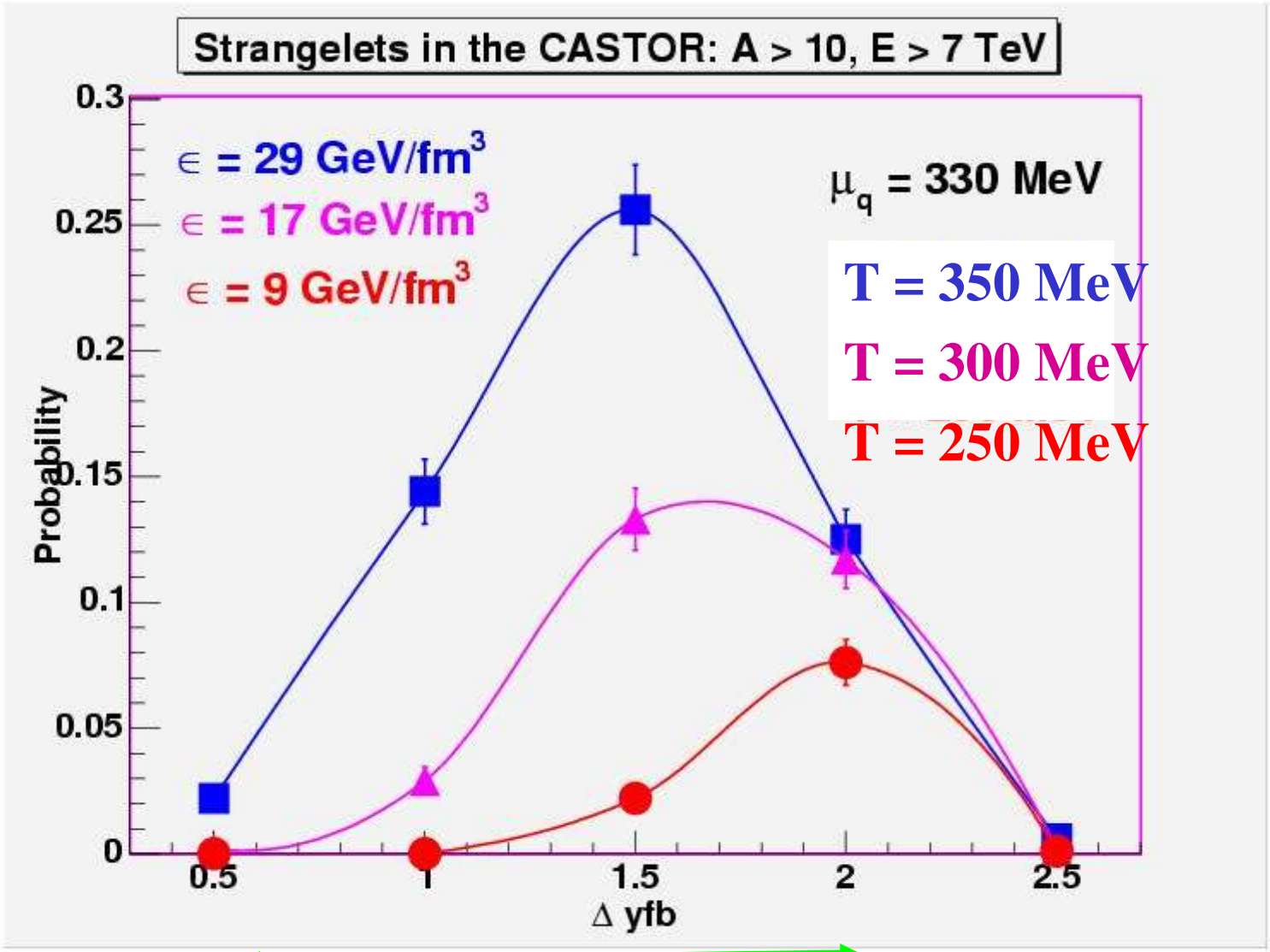
5.2 <η < 6.5



- ~60 % of Centauro fb decay products and substantial part of strangelets within the CASTOR acceptance
- NOTE: Even very high energy strangelets (E ~ 30 TeV) are produced

E. G.-D., Acta Phys.Pol. B37 (2006) 153

Probability of STRANGELET detection



$\Delta y_{stop} \sim 2 - 3.5$

$5.2 < \eta < 6.5$

Expected at LHC:

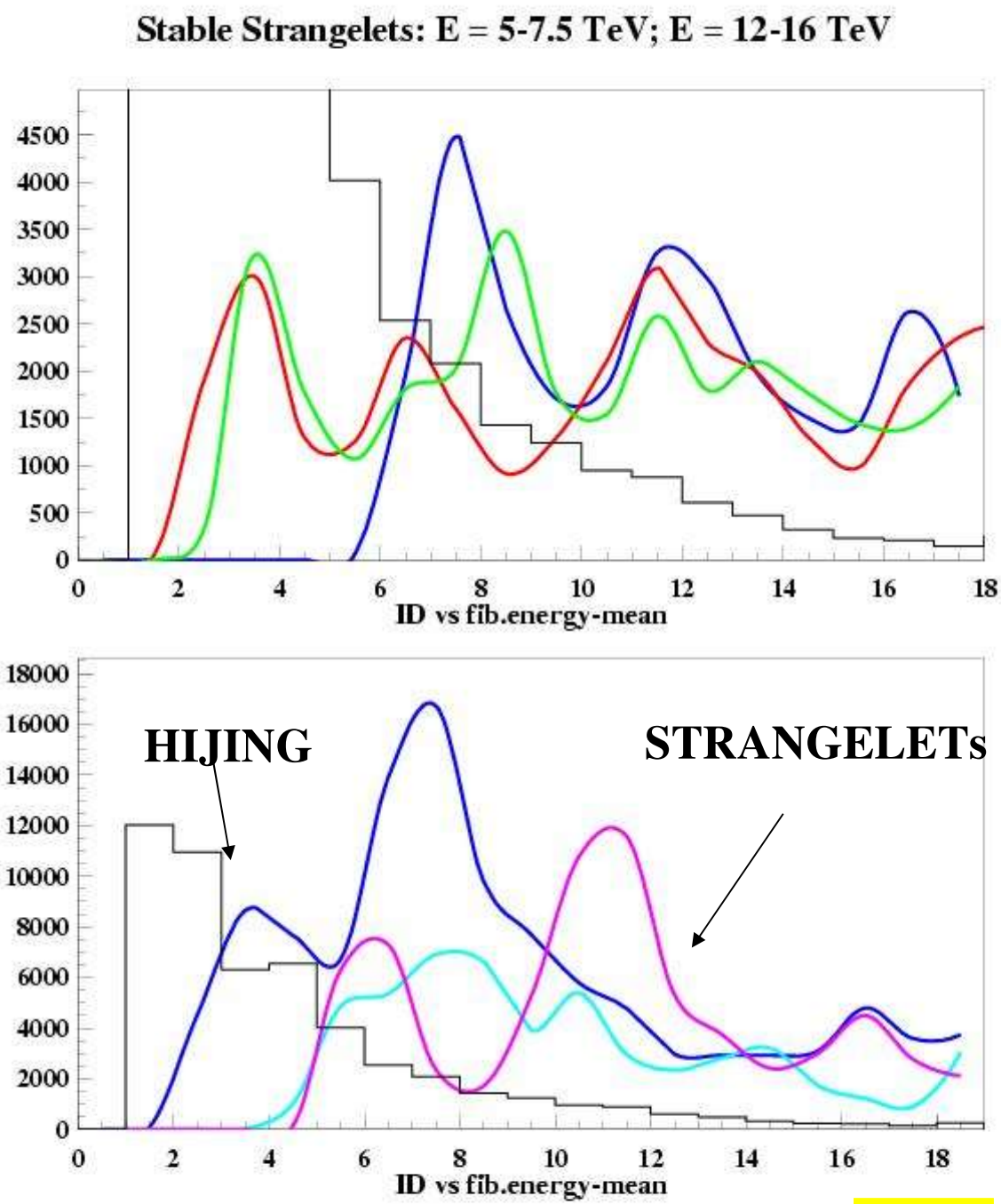
- **Energy densities up to $\epsilon \sim 30$ GeV/fm³**
- **$\Delta y_{stop} \sim 2 - 3.5$**

  HIJING,VENUS
- **$\Delta y_{stop} \sim 2 - 3$**

  BRAHMS at RHIC

→ **several to ~ 25% strangelets with energies E > 7 TeV (sufficiently high to be detected).**

E. G.-D., Acta Phys.Pol. B37 (2006) 153



300 X0

E. G.-D. , Acta Phys. Polonica, 2006
P. Katsas

Strangelet

simulations in the CMS environment

GEANT4-OSCAR

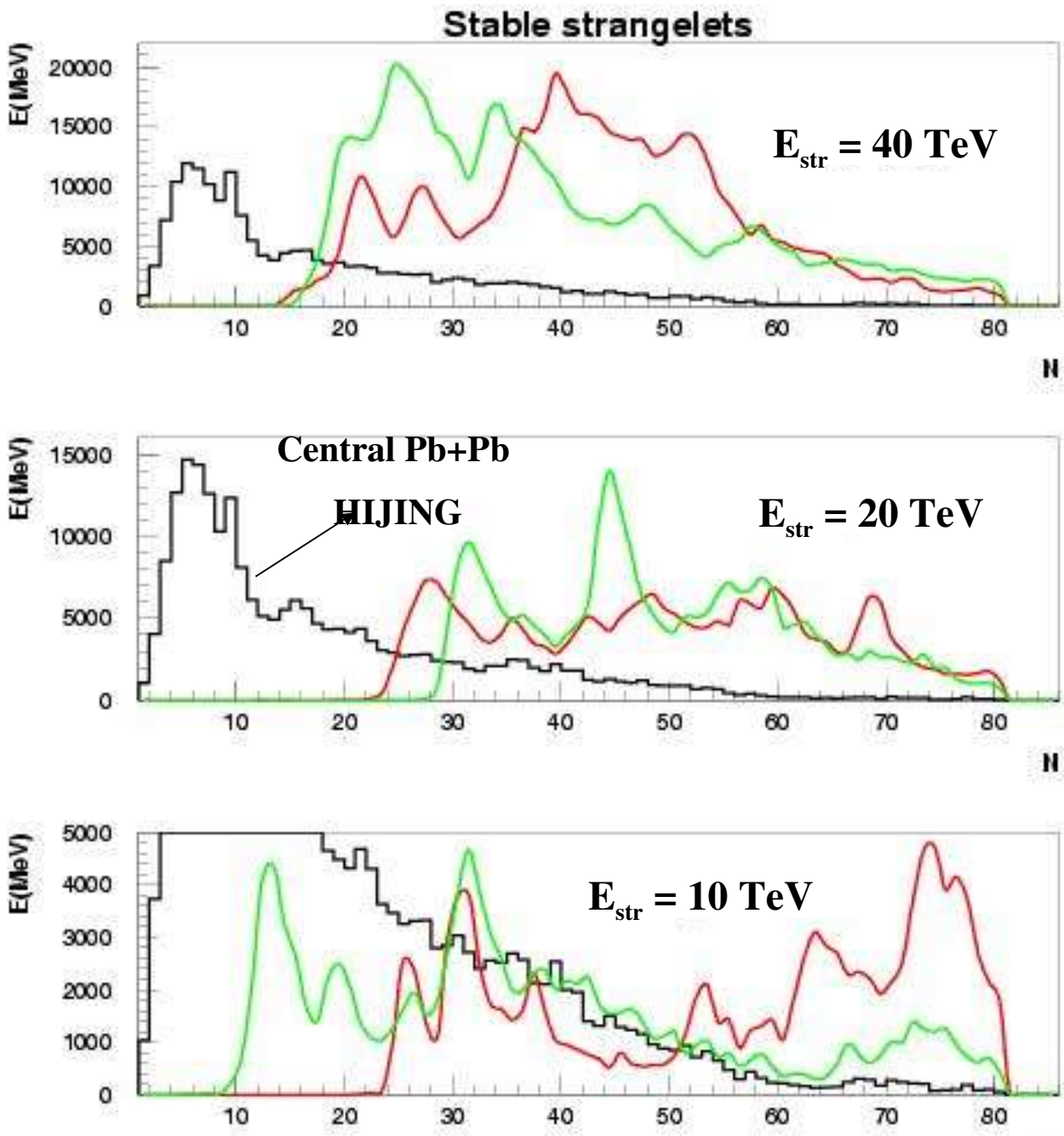
Geometry:

- *1 layer: 5 mm W + 2 mm quartz plate ~2.37 X0*
- *7 layers per readout unit*
- *16 (in ϕ) x 18 readout channels*
- *Total depth: ~300 X0, 10.5 Λint*

EVEN LOW ENERGY (~ 5 TeV)

STRANGELETS MAY BE SEEN

ABOVE THE BACKGROUND !



A. Angelis et al., EPJ direct, C9 (2000) 1.

Passage of strangelets through the calorimeter

GEANT-3.21

STRANGELET SIGNALS clearly seen ABOVE the BACKGROUND

finer sampling -> more apparently seen hump structure

Configuration:

- *1 layer: 5 mm (10 mm) W + quartz fibres*
- *8 (ϕ) x (8 EM + 72 H) segments*

Depth: 760 mm W (effective depth ~300 X0, 11 Λint)

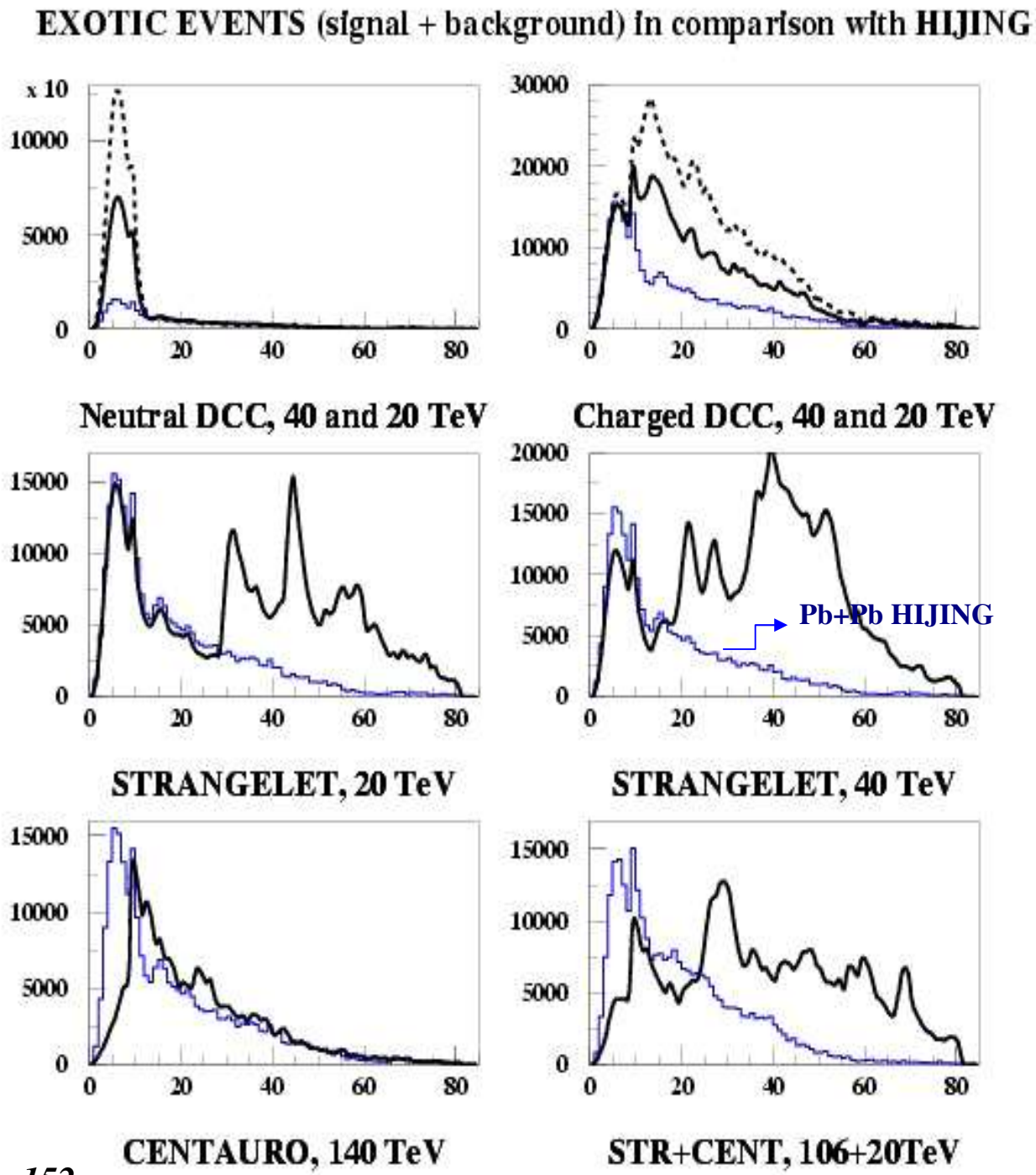
ENERGY DEPOSITION PATTERN

= NEW SIGNATURE of NOVEL STATES of MATTER

Different EXOTIC SPECIES produce characteristic signals

R-hadrons, Monopoles?

They can be distinguished one from another and from the "usual" events.



E. G.-D. „Nuclear Theory"21, Rila , 2002, p.152

STRANGELETS in fragmentation region - ALICE, CMS - ZDCs

- **OBSERVATION: strongly penetrating component in cosmic rays observed in very forward region**

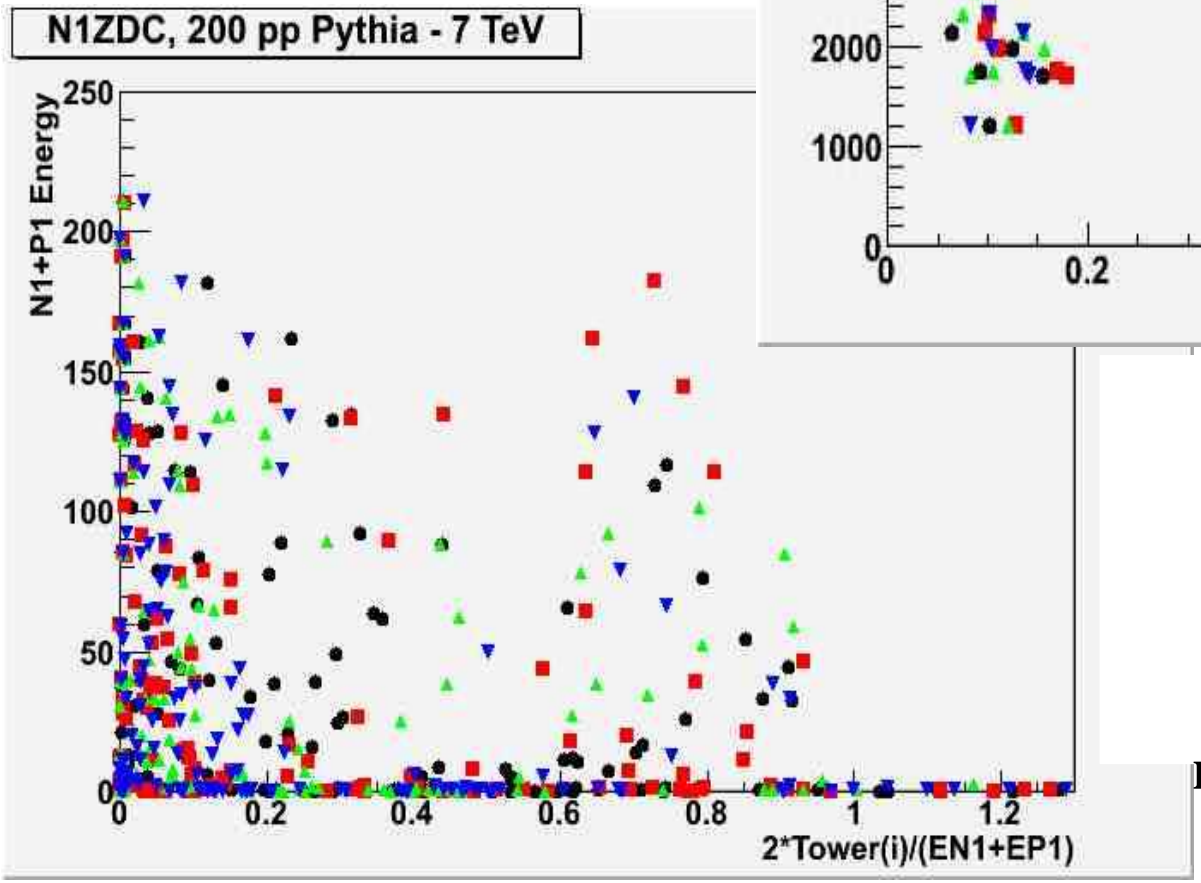
- **IDEA: modified spectator matter – enhancement of strange quarks after absorbing K^- produced in QGP -> low Z/A -> high signal in neutron ZDC** ***Norbeck and Onel, Jamaica 2010***

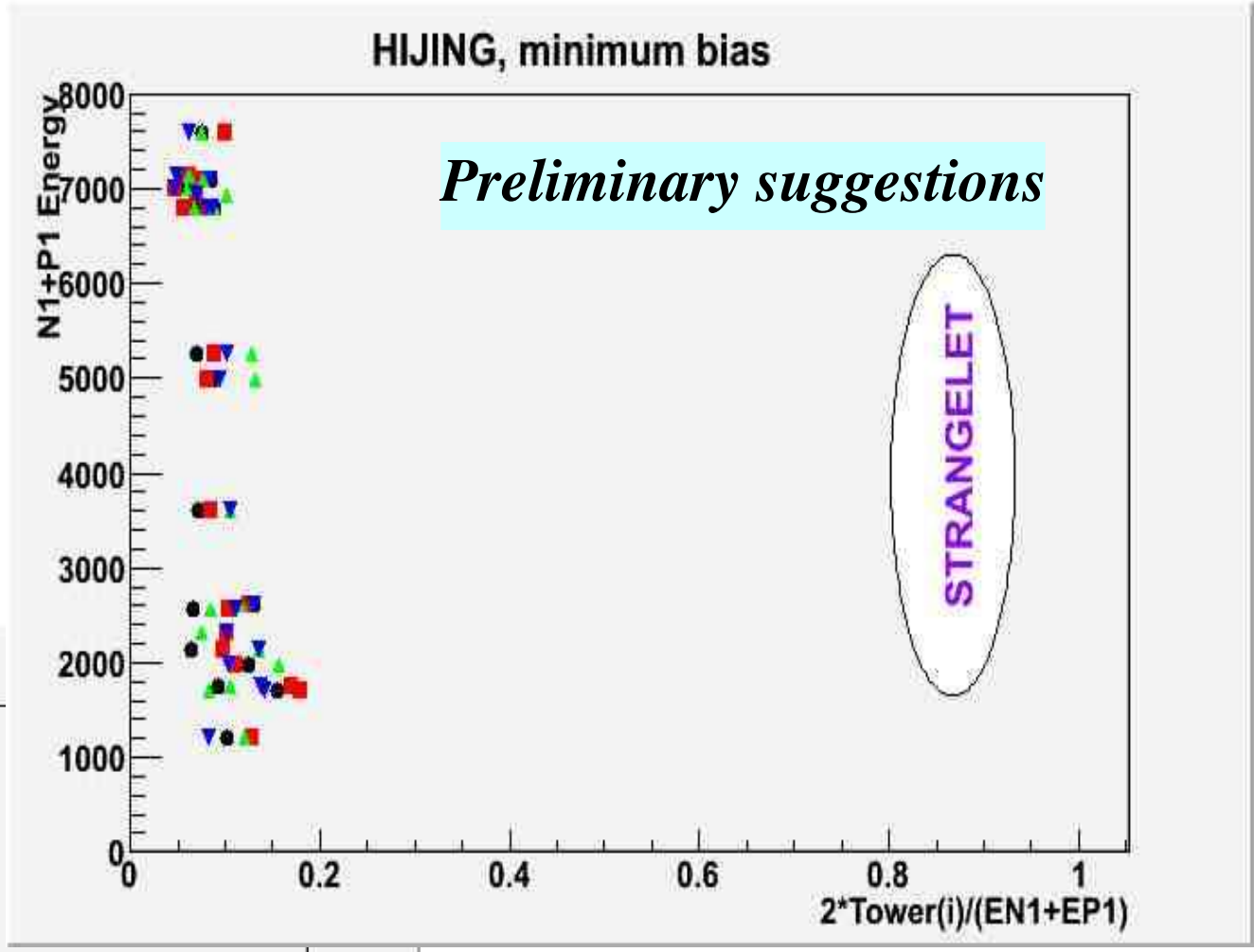
Look at:

- **peripheral nucleus-nucleus collisions**
- **high signal in neutron ZDC** (higher than expected from impact parameter determined by other methods)
- **deviation from expected ratios of signals from proton to neutron ZDCs**
- **unexpectedly high energy fraction in one tower of the neutron (or proton) ALICE ZDC**

ALICE ZDCs better than CMS -> division of ZDC into 4 towers

pp -> there are events in which almost all energy is deposited in one tower





PbPb -> energy uniformly distributed in towers

STRANGELET -> unexpectedly high energy fraction in one tower of the neutron (or proton) ALICE ZDC

Other exotic objects at the LHC

REMARKS

- R-hadrons
- Monopoles
- Cherenkov gluons

➔ **Suggested new signature**

Standard signatures of R – HADRONS at the LHC

- **unstable** (τ~picosecond) -> decays before first sensitive layers of detectors -> recognized by secondary vertex technique **(ATLAS, CMS)**
- **(meta) stable** - τ **long enough** to traverse a (part) detector

➔ **dE/dx** – depends on the mass and the charge -> striking difference between R-hadrons and ordinary particles **(ALICE)**

A. Dobrin, P. Christiansen, arXiv: 0910.0759

➔ **Time of flight** – high mass (~ TeV) and non-relativistic R-h -> longer time to reach outer detectors than that for usual particles (ATLAS, CMS, ALICE)

➔ **Charge exchange –** R–h, as a composite particle can change sub-structure through nuclear interactions in a detector -> charge variation $\Delta Q = 1, 2$ (charge flip) -> changing curvature of the trajectory

NEW suggested signature of R-h – energy deposition pattern in deep calorimeters

Successive hard interactions of heavy R-h (tennis ball among ping-pong balls) -> single cascades strung along R-h trajectory –> shape of transition curve depends on the absorber

- **air – usual -h** $(\lambda/X0) \approx (90/36.66) = 2.45$

  R-h $(\lambda/X0) \approx (47/36.66) = 1.28$

small distances between consecutive interactions $\Delta t \approx 1.3X0$ -> flat transition curve

[Anchordoqui et al.]

- **Pb – usual -h** $(\lambda/X0) \approx (194/6.37) = 30.4$

  R-h $(\lambda/X0) \approx (111/6.37) = 17.4$

$\Delta t \approx 17.4\ X0$ comparable with longitudinal extent of cascade -> possible separation of single cascades -> many-maxima transition curve

- **possibility to observe R-h at LHC in thick longitudinally segmented calorimeters (CASTOR/CMS)**

- **experimental many maxima cascades in Pb: $\Delta t \approx 10.4\ X0$**

How can we search for monopoles at LHC?

1. STANDARD METHODs - abnormally high ionization

combined with

- **trajectories, in solenoidal magnetic fields, dramatically different than for ordinary charged particles –** ***no curvature in r-φ plane***

it needs: a dedicated highly ionizing particle trigger, large pulses in TOF, special reconstruction of monopole candidates

2. suggested NEW SIGNATURE ->

- **monopoles tend to be swept out along the beam pipe**
- **energy gain** $W_m/LB = nx20.6$ GeV $m^{-1}T^{-1}$

-> strong signal in one tower of one ALICE ZDCs or in CMS CASTOR calorimeter

-> characteristic (many-maxima) showers in deep longitudinally segmented calorimeters with heavy absorber

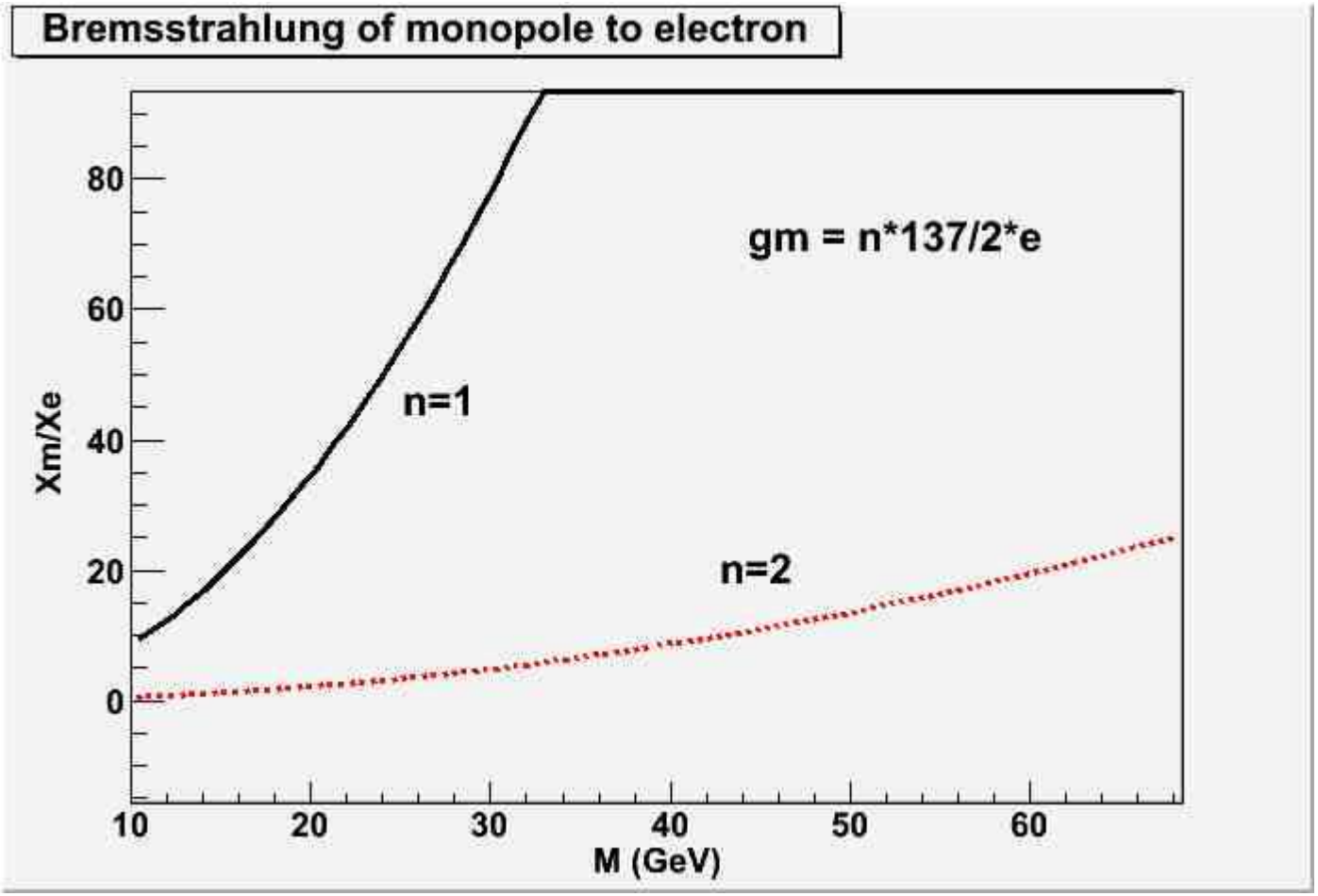
Monopole radiation length $(X0)_{mon}$ is longer than $(X0)_e$ for electrons

E.G.-D. preliminary

Bremsstrahlung energy loss – *Amaldi; Cabrera, Trower* (for $\gamma > 20$)

$$(dE/dx)^{mon}/(dE/dx)^{e} = (X0)_e/(X0)_{mon} = 2(ng/e)^4\,(me/mg)^2$$

Cosmic ray many-maxima showers with distances between humps <ΔX>~20 (X0)e could be produced by low mass monopoles (e.g. n =1, M ~ 15 GeV; n =2 , M ~ 60 GeV)



CHERENKOV GLUONS
– inspired by cosmic ray "ring-like" events

- **First ideas – pre-QCD times** when pions were quanta of radiation –

e. g. *Ivanenko, Gurgenidze, 1949; Czyz, Glashow, 1960*

- **Renaissance – RHIC and LHC era** - *many papers by* ***I. Dremin, e.g.***

Heavy ion collisions at the LHC, Last call for predictions, 2007

Int. J. Mod. Phys. A22: 3087,2007

Cherenkov gluons can be emitted (if n>1) in hadronic collisions at the cone surface at the angle θ_c to the momentum of parton-emitter in the rest system of the infinite medium:

$$\cos\theta_c = 1/(\beta n) \Rightarrow$$ "**Cherenkov rings**

the ring-like two-dimensional distribution of particles must be observed in plane perpendicular to the momentum of the parton

Diagnostic tools of the nuclear medium properties:

jet quenching, elliptic flow, suppression of high pT

Cherenkov gluons are the other diagnostic tool of the partonic properties of matter

Dremin, *arXiv:0910.0099,2009*

Nucl. Phys. A785(2007)365

RHIC

- The refractive index from the distances between the peaks:
  n ≈ 2.5 - 3 (STAR, PHENIX) -> **high density medium – a liquid**
- The density of partons -> $\nu \approx 30$ (per nucleon)
- The energy loss of Cherenkov gluons -> dE/dx ≈1 GeV/fm
- The free path length of gluons ≈ $7 \times 10^{(-13)}$ cm (from the height of the peaks (ring width))

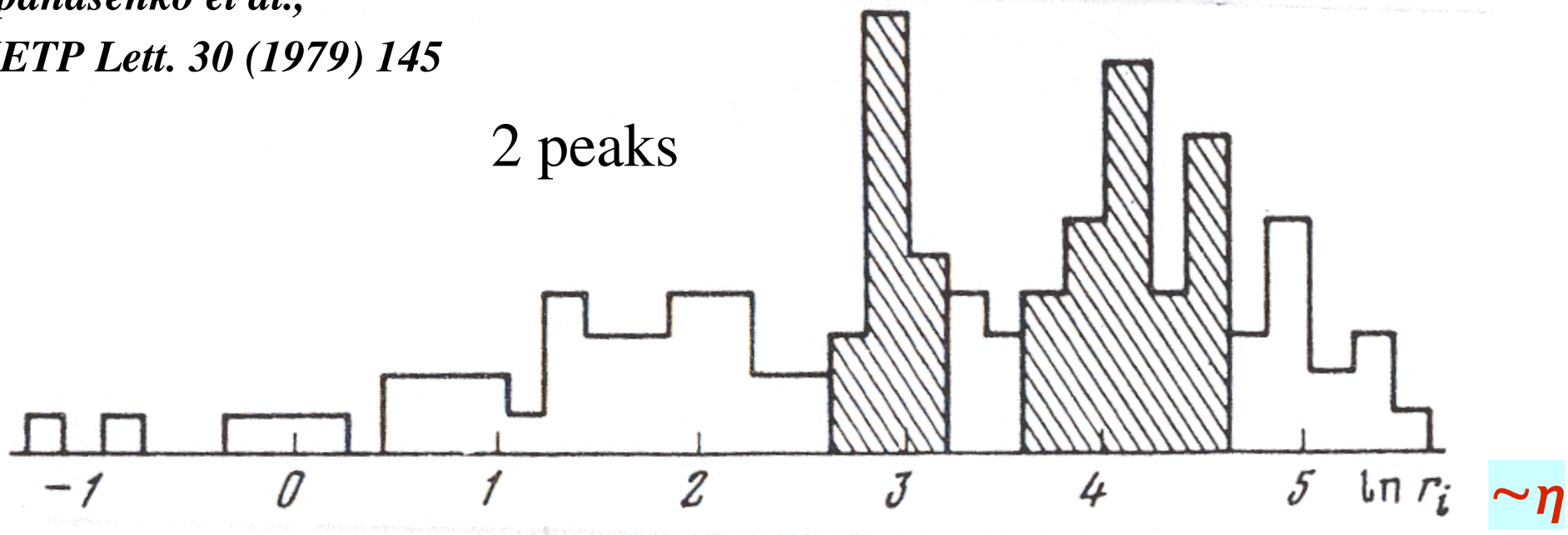
Cosmic Rays (LHC ?)

n ≈ 1 -> more transparent medium – a gas

Stratospheric event at 10^{16} eV

nuclear and X-ray film detector at the balloon

Apanasenko et al.,
JETP Lett. 30 (1979) 145



2 rings with r1 = 1.75 cm and r2 = 5 cm are produced by forward and backward moving (in c.m.s) partons

$\mathrm{tg}\theta = r/H$; $\Delta\eta = -\ln(r1/r2)$; $\mathrm{tg}\,\theta_c/2 \approx \gamma\theta_t$

$\theta_{1t}/\theta_{2t} = r1/r2 = \mathrm{tg}(\theta_{1c}/2)/\mathrm{tg}\,(\theta_{2c}/2) = 0.35$

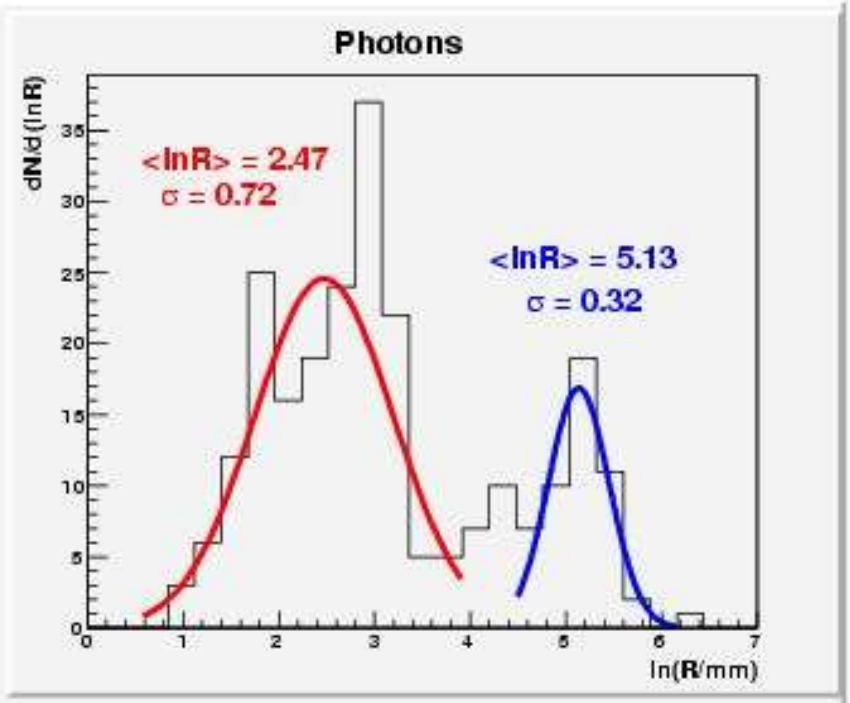
OLD 4 events (~ 1000 TeV)
PAMIR – thick Pb chamber
Krakow group ICRC Paris 1981

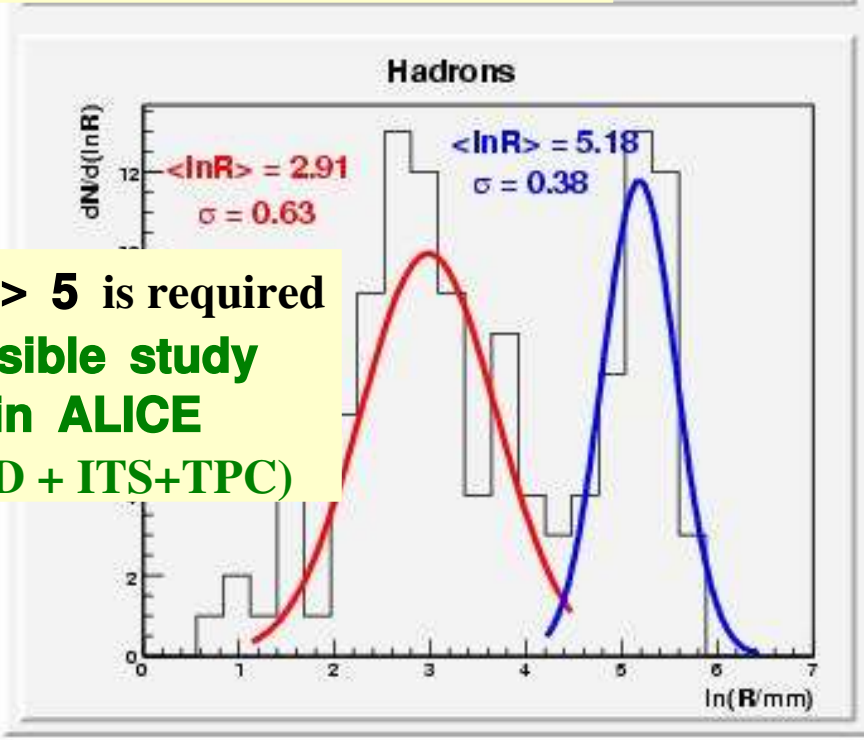
NEW INTERPRETATION ?

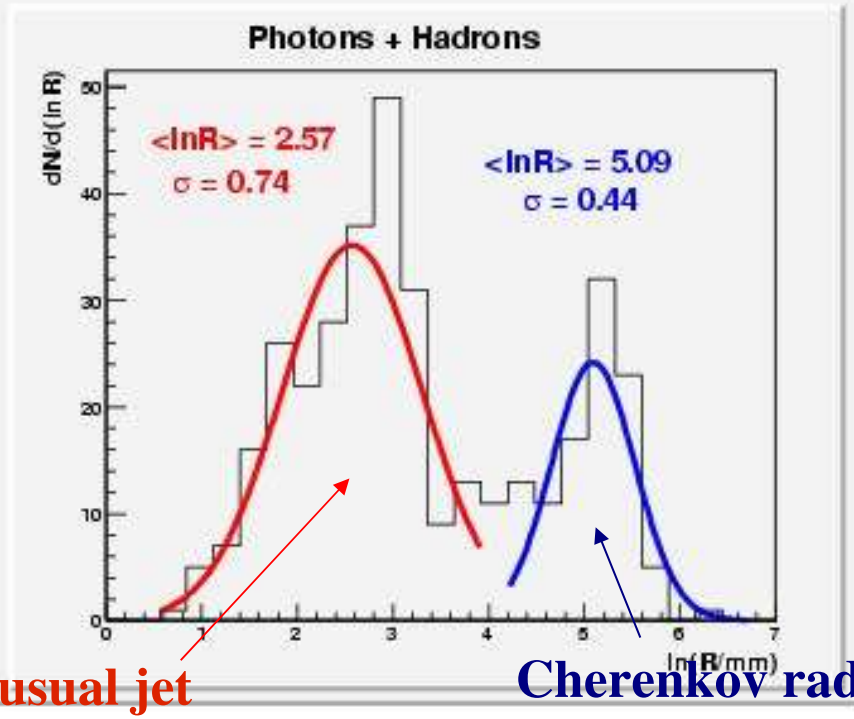
$\langle R_{II} \rangle \approx 16$ cm, H ≈ 100-500 m

-> $\theta_{Ch} \approx (0.09\text{-}0.02)^0$

-> n = $1/\cos\theta_{Ch} \approx 1$







$\Delta\eta$ > 5 is required
possible study in ALICE
(FMD + ITS+TPC)

usual jet fragmentation ??

Cherenkov radiation in medium jet

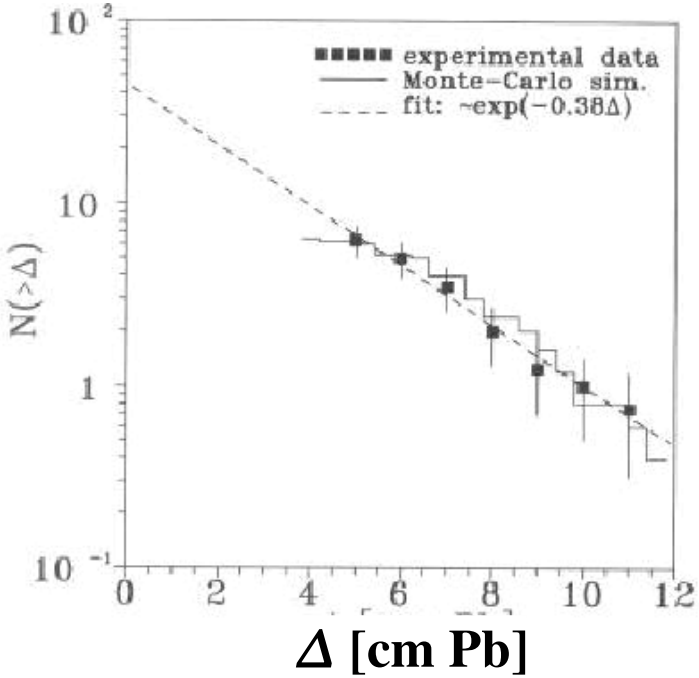
E.G.-D.

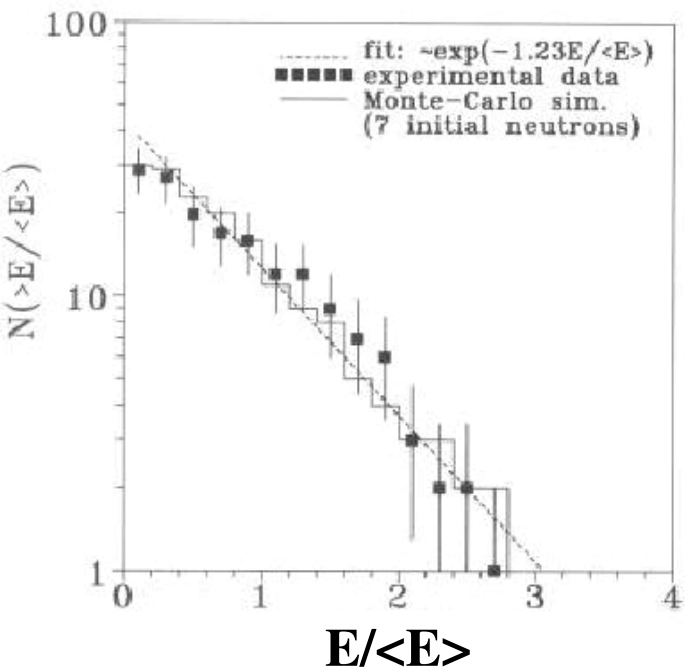
We are waiting for LHC results

and

a solution of cosmic ray puzzles

BACKUP





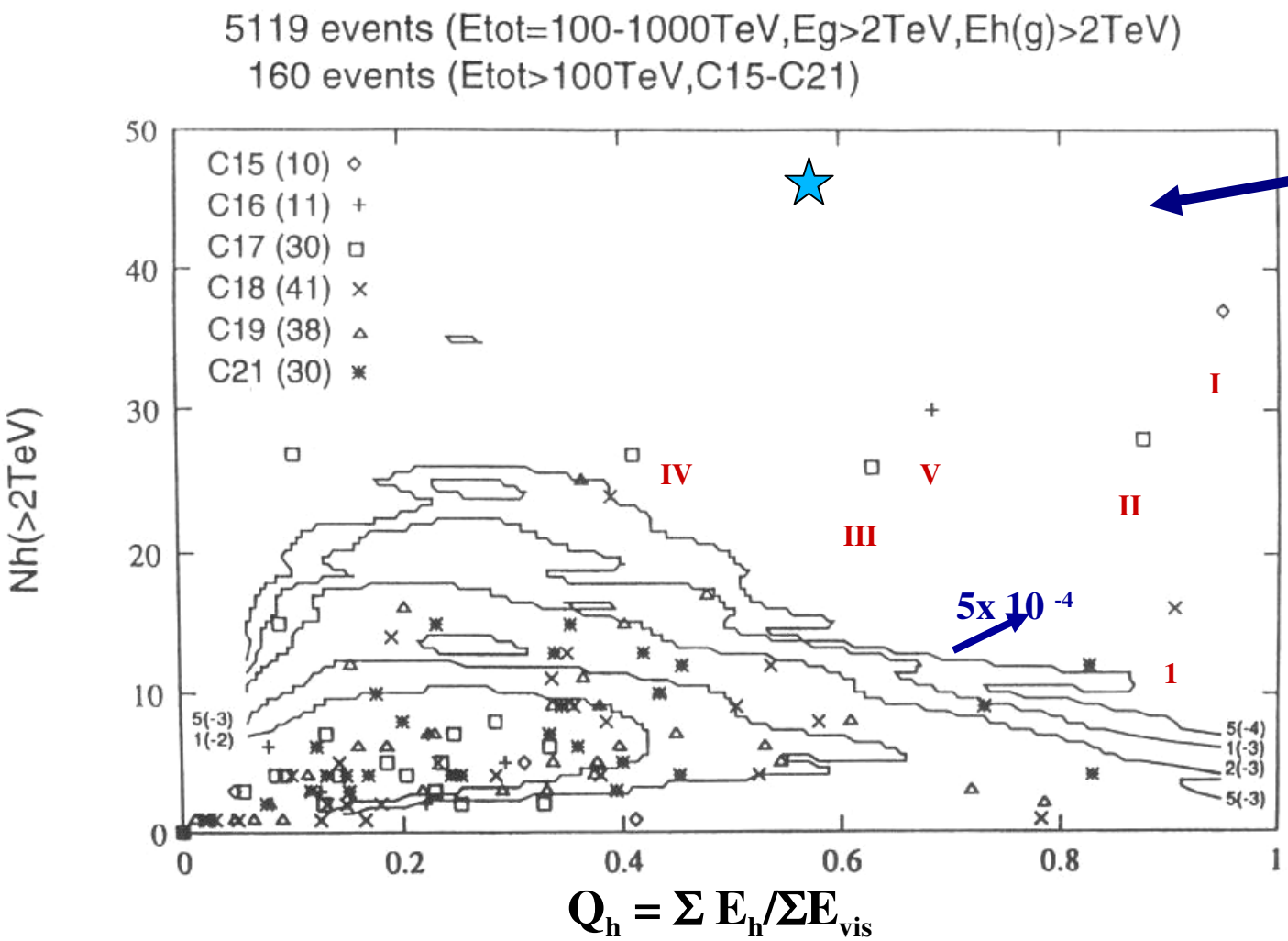
Distances between humps and energy ratios of cascades produced by unstable strangelets (bundle of 7 neutrons) are described by simulations.

- **Long-range many-maxima cascades could be the result of penetration of strangelets through the apparatus**

- **SQM scenario could explain different forms of strongly penetrating component (single cascades, mini-clusters, halo)**

E. G.-D. and Z. Wlodarczyk,
J. Phys., Nucl. Part. Phys. G23 (1997)2057

Anomalous hadron dominance confirmed in simulations



Chacaltaya CENTAUROS –

Ohsawa et al., Nucl. Phys. (Suppl.B) (1999) 3

20% hadron-rich events (among 737) at E_{vis} > 100 TeV

Chacaltaya, Pamir, Pamir-Joint Chambers, Nucl.Phys. B370(1992)365

Also M. Tamada - 4 different models of AA interactions (VENUS, QGSJET, HDMP, UA-5) + CORSIKA code for simulations of development of hadron-electromagnetic cascade in the atmosphere

Is the strongly penetrating component a sign of strangelet passage through the matter?

Simulation of STRANGELETS

- **UNSTABLE ⇒ collimated beam of neutrons (mini-cluster)**

  Main decay channel -> neutron emission in strong interactions (in practice, at interaction point , $\tau_0 \sim 10^{-20}$ s)

- **METASTABLE ⇒ successive evaporation of neutrons in weak decays during their passage through the apparatus**

  Because of flavour changing , ($s+u \leftrightarrow u+d$) process is much slower than strong decay into neutrons

- **STABLE ⇒ lifetime long enough to pass through the apparatus without decay**

  ($\tau_0 > 10^{-10}$ s in cosmic ray expts, and $> 10^{-8}$ s for CASTOR)

  Long τ_0 in weak radiative ($d+u \leftrightarrow s+u+\gamma$) and leptonic decays ($d \leftrightarrow u+e^-+\upsilon_e$, $s \leftrightarrow u+e^-+\upsilon_e$), caused by flavour changing and 3-body phase space

E. G.- D., Z. Włodarczyk, J. Phys. G23(1997)2057

Strangelet interaction in a calorimeter

- **Strangelet is an object with the radius:**

$$R = r_0 A^{1/3}_{str}$$

- **Rescaled radius**

$$r_0 = \{3\pi/[2(1-2\alpha_c/\pi)(\mu^3 + (\mu^2 - m_s^2)^{3/2})]\}^{1/3}$$

- **Mean interaction path in the lead absorber**

$$\lambda_{str\text{-}Pb} = A_{Pb} m_n/[\pi(1.12 A^{1/3}_{Pb} + r_0 A_{str}^{1/3})^2]$$

Passing through the chamber strangelet collides with Pb nuclei:

Spectator part is continuing a passage;

Wounded part produces particles in a standard way.

Particles produced in successive interaction points initiate a development of electromagnetic-nuclear cascades.

Process ends when a strangelet is destroyed.

E. Gładysz, Z. Włodarczyk, J. Phys. G23(1997) 2057

- **Strange quark matter bulk radius**

$$n = (ns + nd + nu)/3 = A/V = A/((4/3)\pi(r_0 A^{1/3})^3)$$

- **is determined by the number density of the *strange mater***

$$n_i = -\partial\Omega_i/\partial\mu_i \qquad i=u,d,s$$

- ***n_i* - calculated from thermodynamical potentials - J. Berger and L. Jaffe, Phys. Rev. C35(1987)213:**

A_{str}	15	15	40
μ [MeV]	300	600	1000
r_0 [fm]	0.86	0.41	0.25
R_{str} [fm]	2.12	1.02	0.85
λ^{coll}_{geo} [cm]	7.9	10.6	11.1

target – W

$\lambda_{coll} \approx 5.7$ **cm**

$\alpha_c = 0.3$

CENTAURO I

Japan-Brasil Coll., ICRC 1973

Estimated point of interaction

upper chamber

6cm Pb

target layer

23 cm pitch

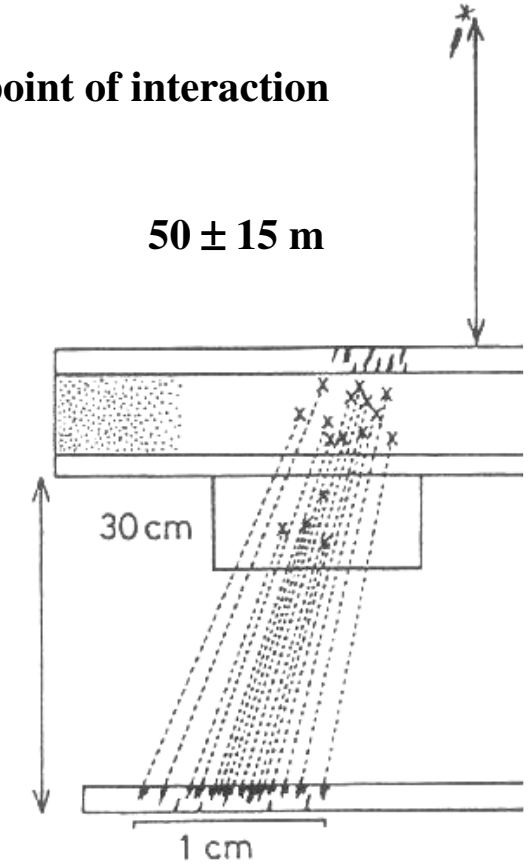
wooden support

space 158 cm

lower chamber

6 cm Pb

50 ± 15 m



Observed in

Upper chamber… 1 e, γ

6 hadrons

0 (1)

Observed in

Lower chamber…43 hadrons

28

Estimated penetrating

through…22 hadrons

Observation:

Energy ~ 231 TeV

upper ch. - 7 cascades

lower ch. - 43 cascades

⇒

Nh = 74, Nγ =0

at interaction point

NEW FINDINGS: Reexamination of Centauro I:

NO CASCADES belonging to the family **in the upper chamber**

EVENT MORE EXOTIC !?

HIJING

high multiplicity

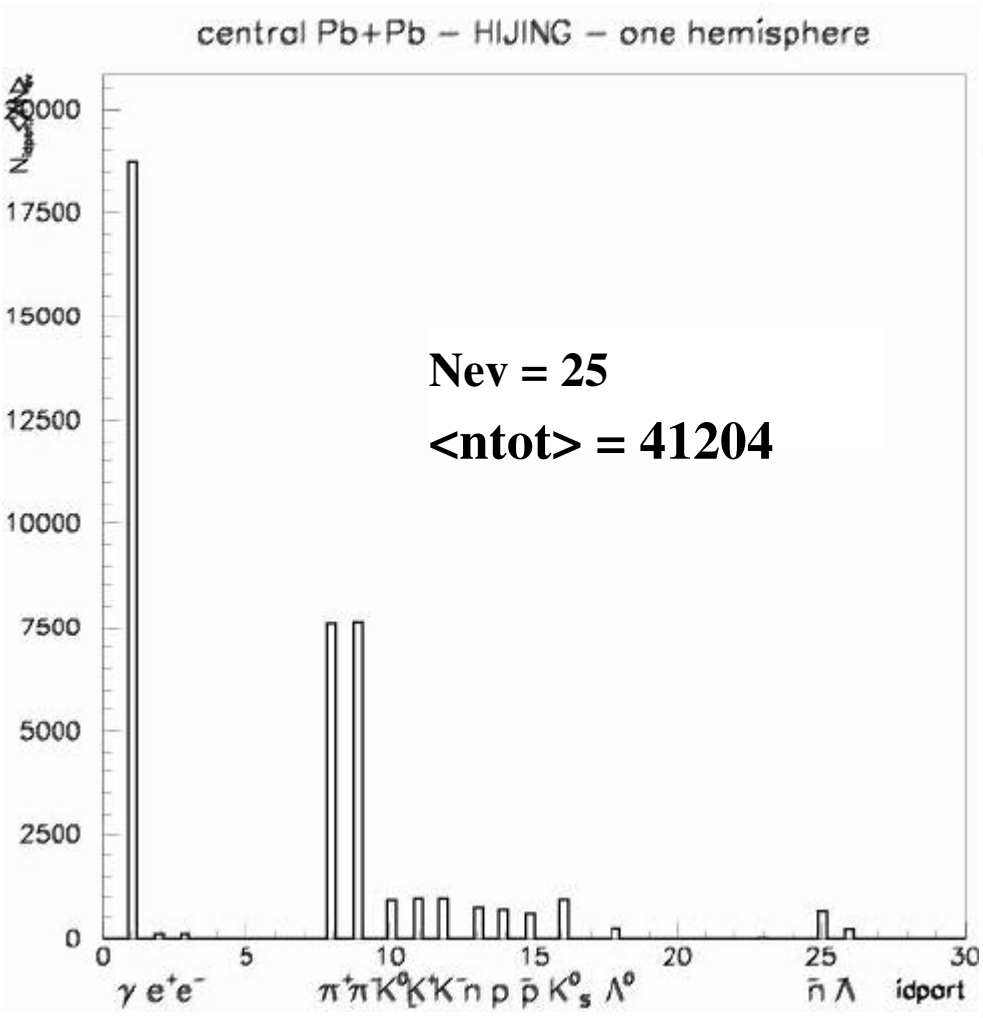
mostly photons and mesons (pions)

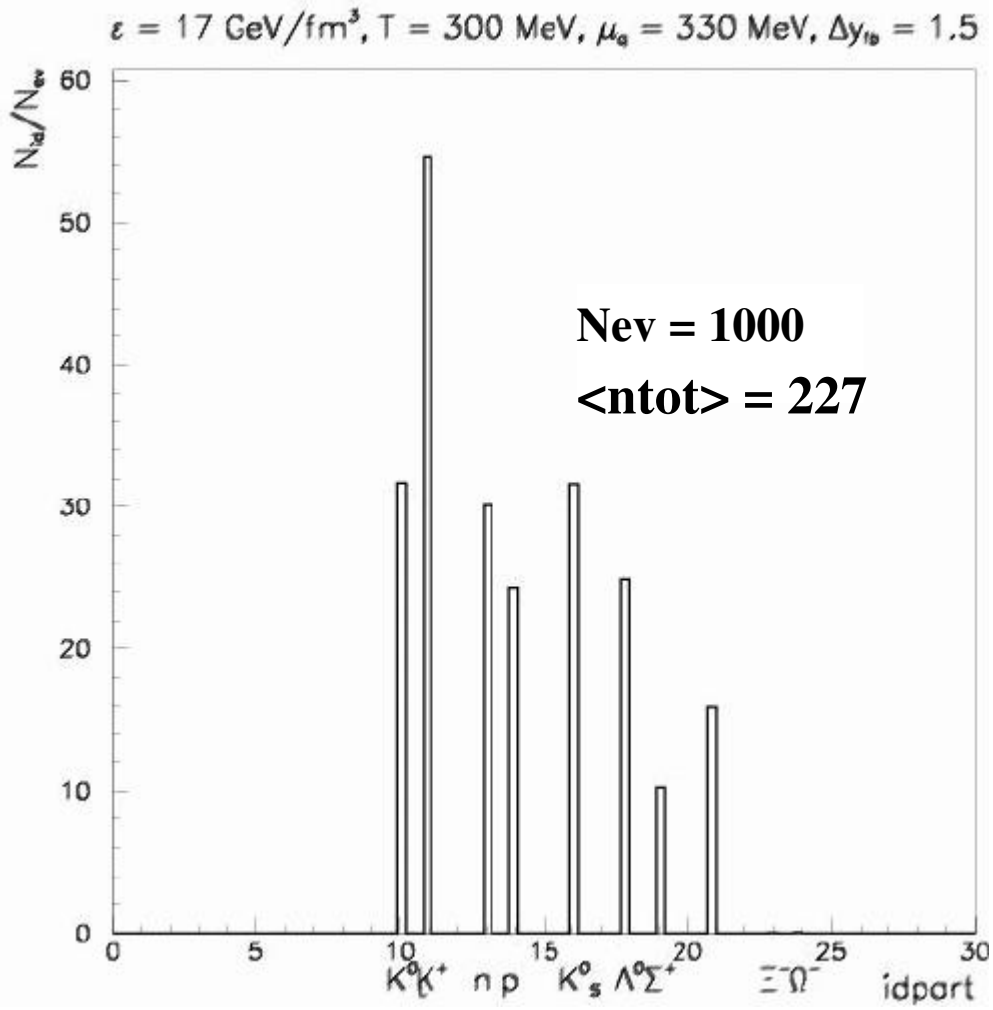
CENTAURO

low multiplicity

different particle composition

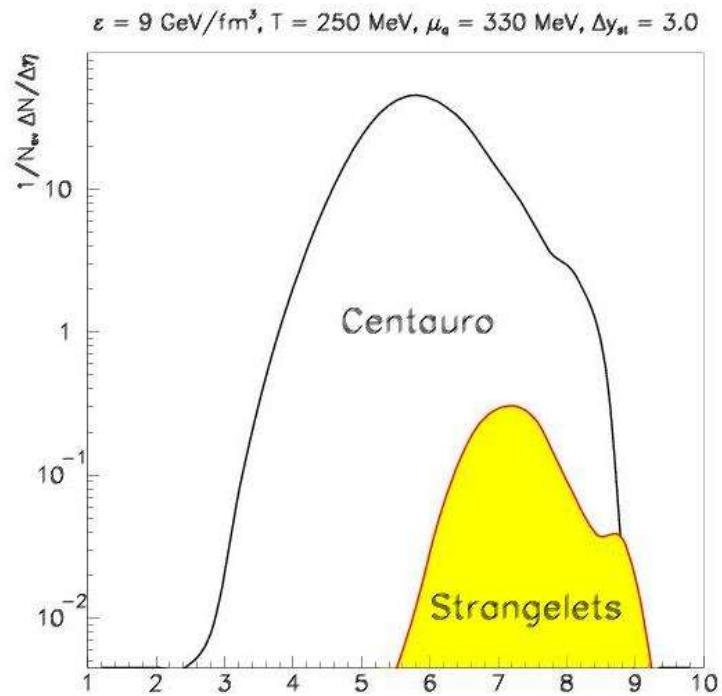
no gammas and pions, mostly baryons





E. G.-D. - generation by CNGEN

Pseudorapidity distributions of Centauro decay products and strangelets depend on fireball characteristics: temperature, baryon chemical potential, stopping



Expected at LHC:

- **Energy densities up to**

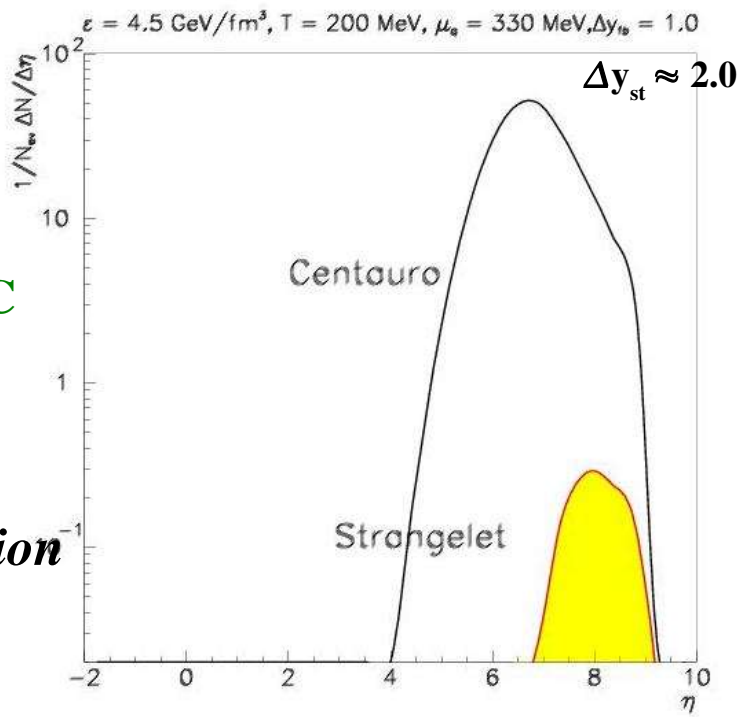
  ε ~ 30 GeV/fm³

- **Δy_{stop} ~ 2 - 3.5**

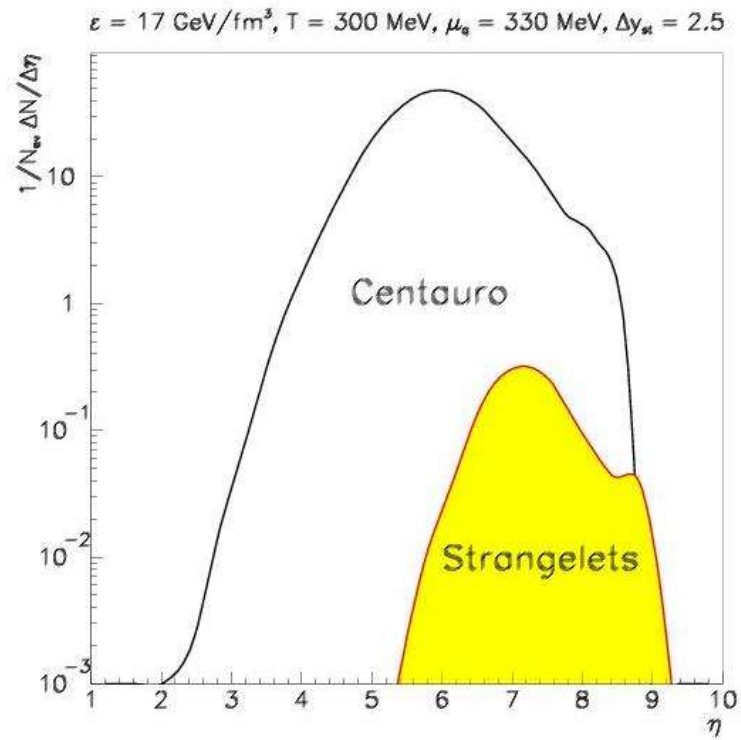
  HIJING,VENUS

- **Δy_{stop} ~ 2 - 3**

  BRAHMS at RHIC



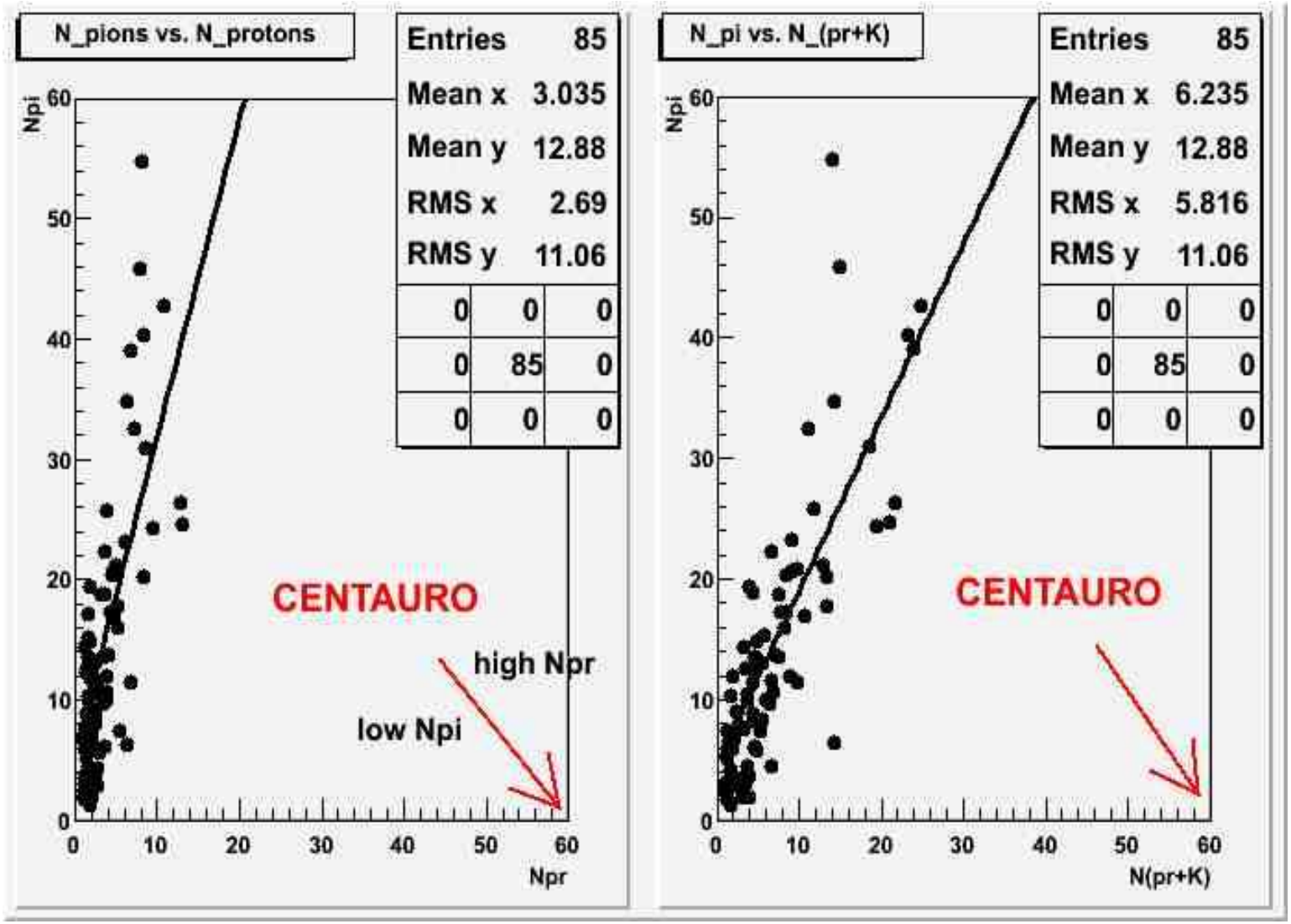
$\Delta y_{st} \approx 2.0$



E. G.-D. - generation by CNGEN

Preliminary suggestions

Search for Centauros in central detectors



CENTAUROS:

N_pions ~ 0

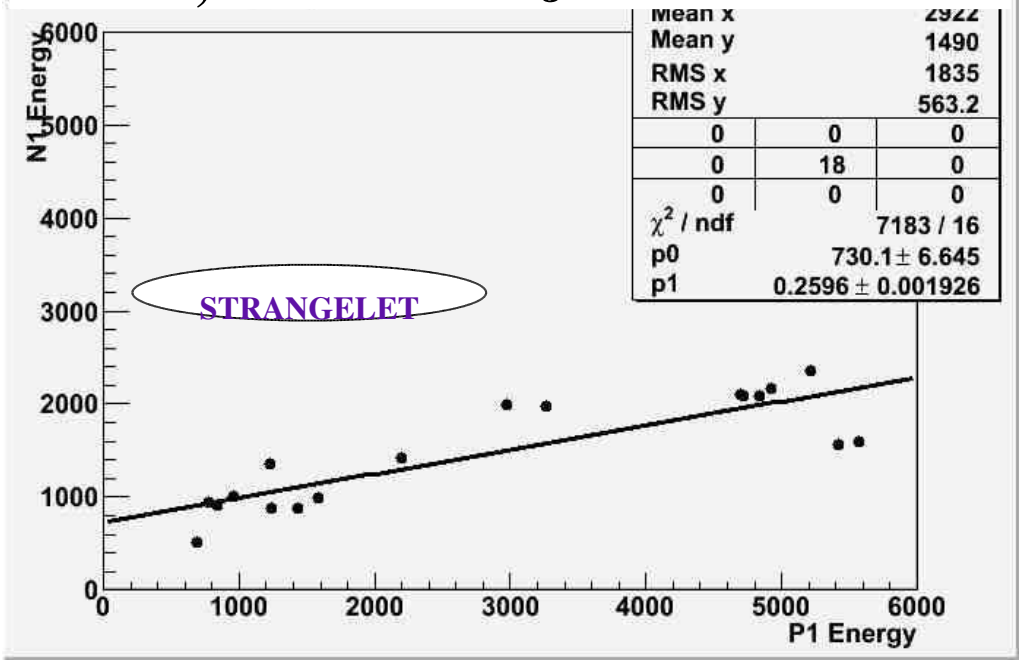
high N_pr
or N_(pr+K)

Search for Strangelets in ALICE

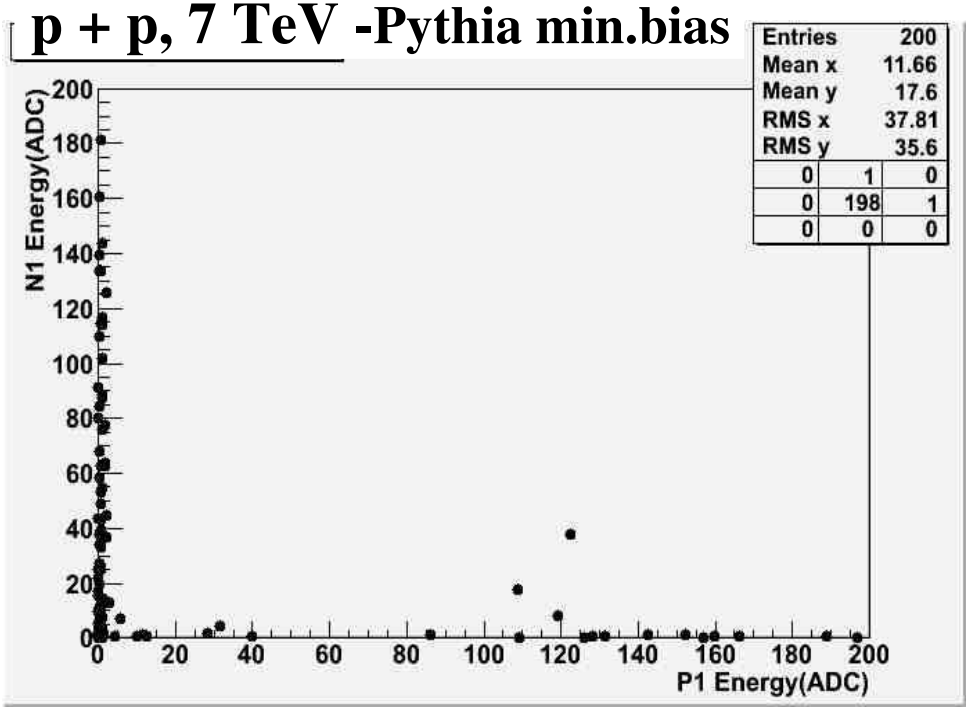
Preliminary suggestions

- **deviation from expected ratios of signals from proton to neutron ZDCs**

Pb+Pb, 5.5 TeV – HIJING min.bias



p + p, 7 TeV -Pythia min.bias

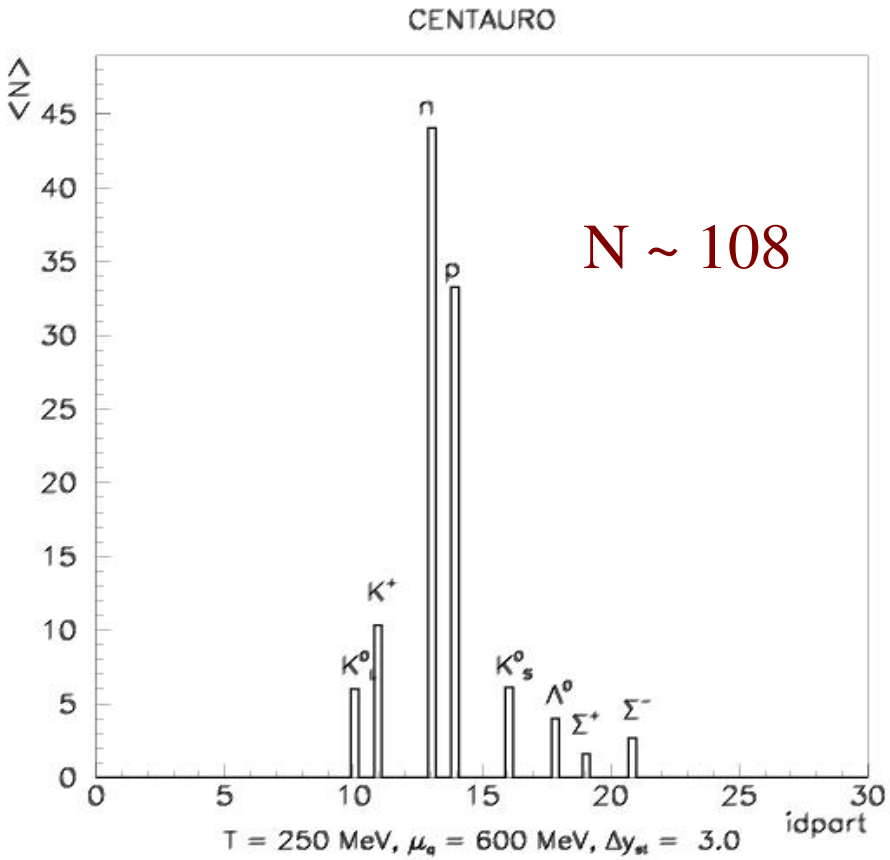


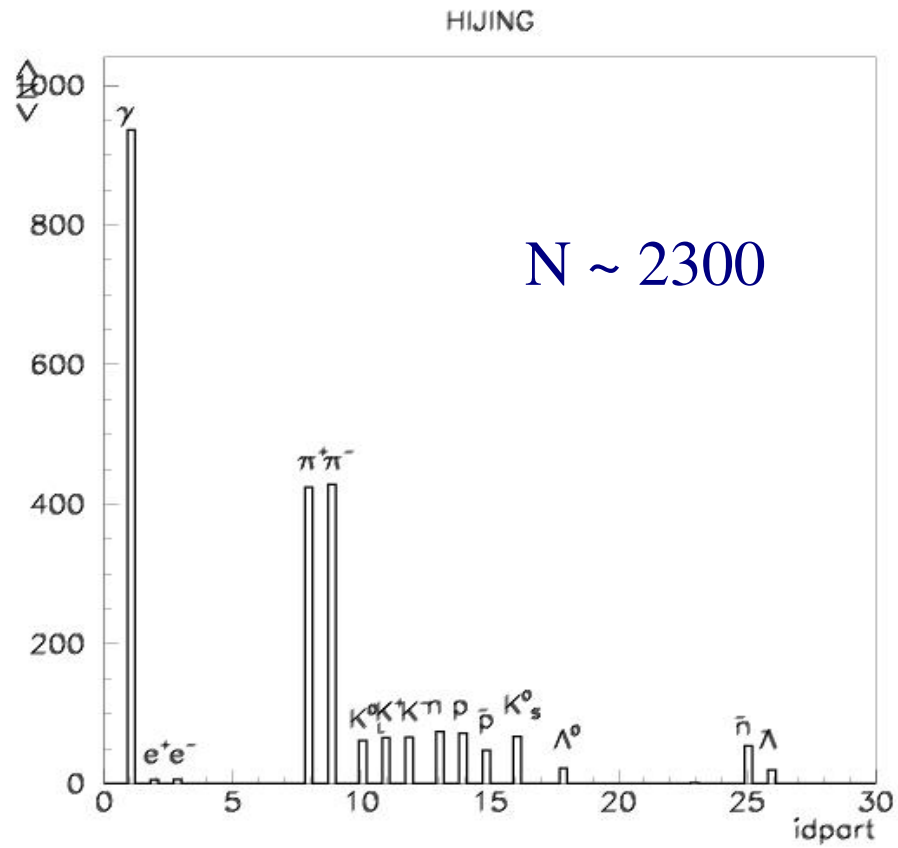
No events with high N1/P1 (or N1~P1~ 0)

There are events in which almost all energy is deposited in N1 or P1 ZDC

for STRANGELETS: unusually high N1/P1 is expected in Pb + Pb

MULTIPLICITY in the CASTOR acceptance (and T2-TOTEM)





CENTAURO $5.2 < \eta < 6.5$ HIJING

Low multiplicity

mostly baryons + kaons

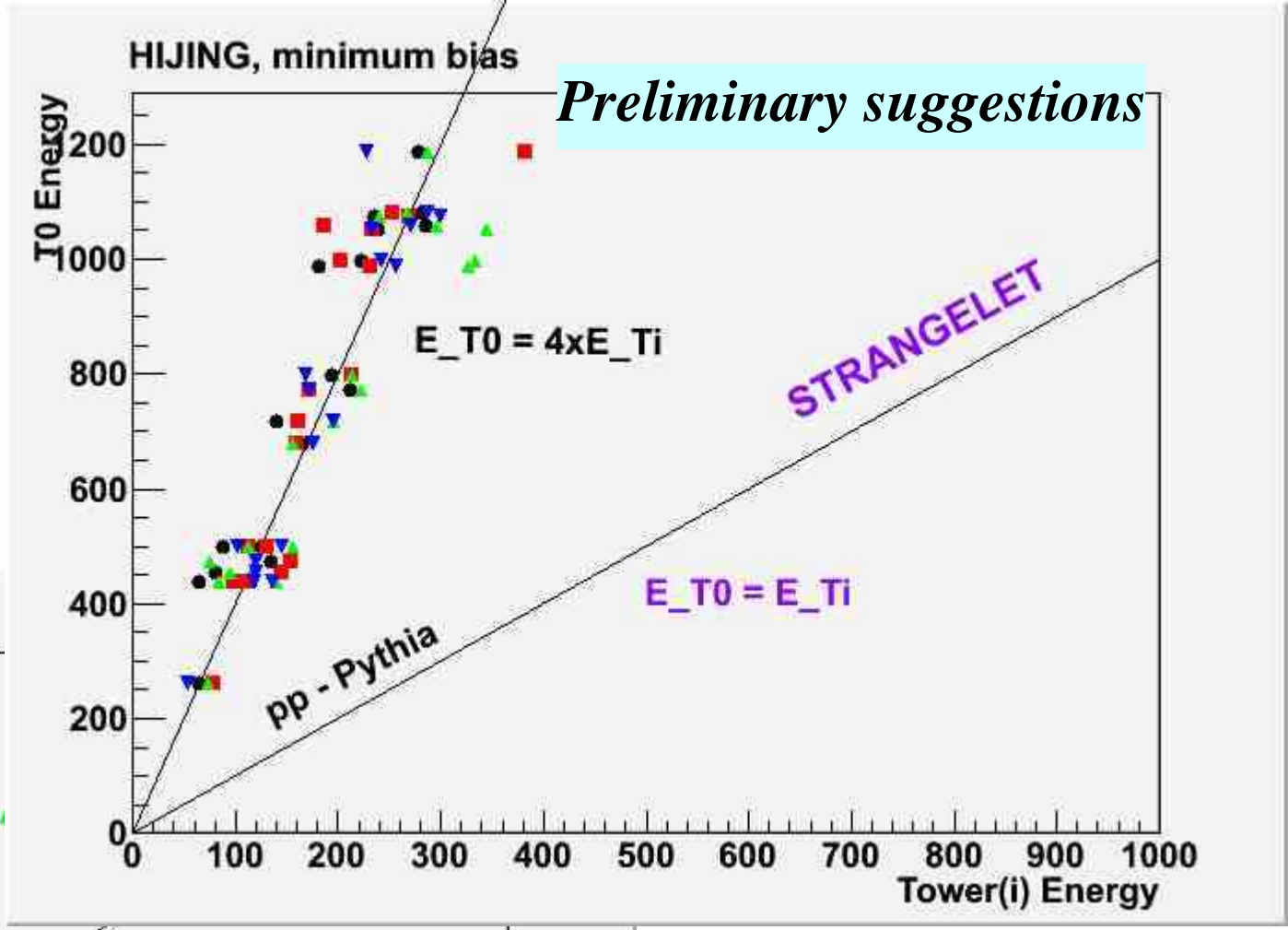
High multiplicity

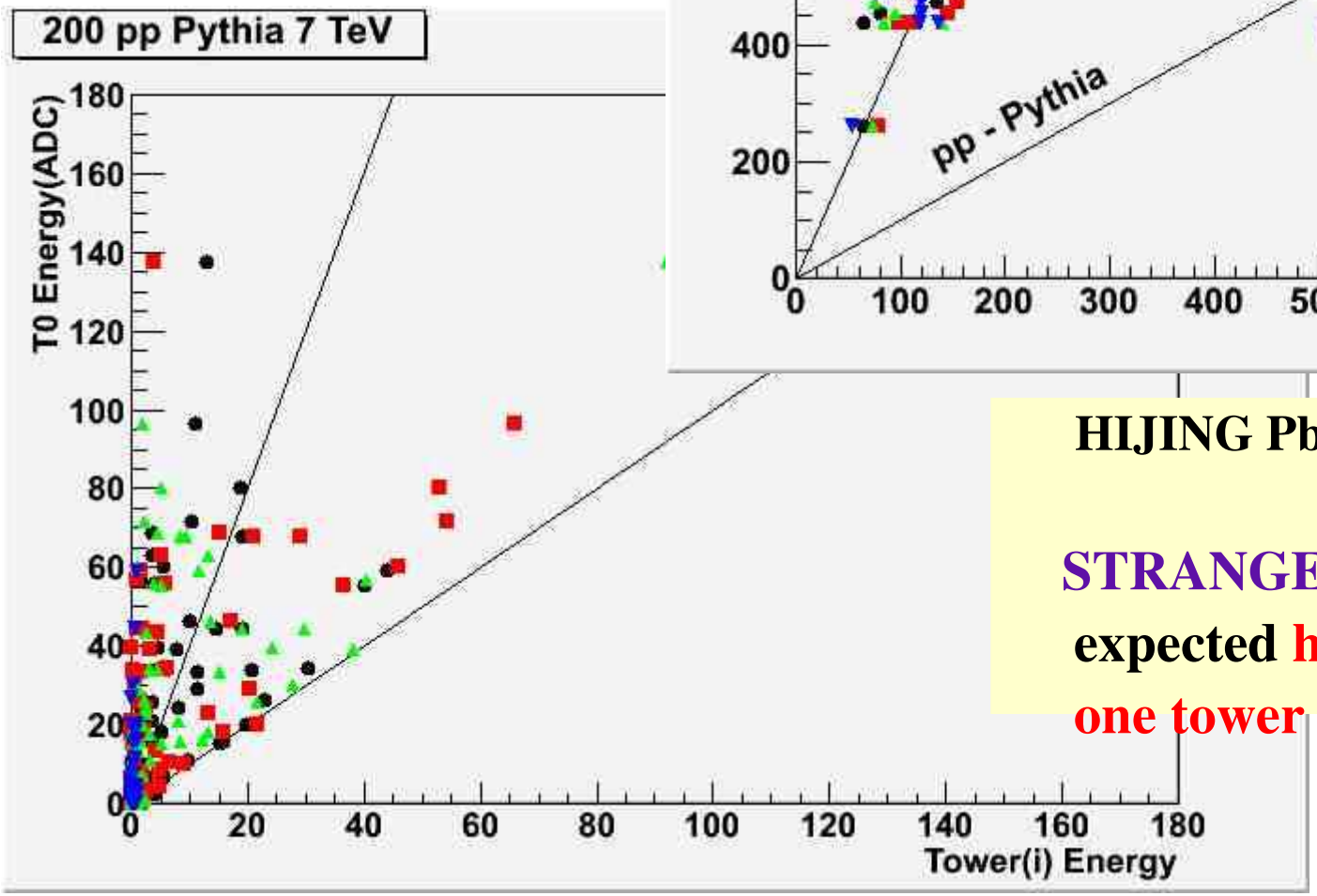
dominated by pions

E. G.-D., Acta Phys.Pol. B37 (2006) 153

ALICE
neutron ZDC

pp -> there are events in which almost all energy is deposited in one tower





HIJING PbPb -> energy uniformly distributed in towers

STRANGELET -> expected high energy fraction in one tower of the ALICE ZDC

R- Hadrons - hypothetical particles

composed by a supersymmeric particle and at least one quark

- Predicted by a few new theories (**split SUSY**, Universal Extra Dimensions)

- Possible when a colored supersymmetric particle (e.g. **gluino** or **squark**)
  has a litefime longer than typical hadronization time scale

- R-bosons are very massive, and R-fermions (e.g. gluino) are at the TeV scale (split SUSY)

- Colored gluino (spin = 1/2, R = -1), supersymmetric partner of gluon (spin = 1, R = 1)

➔ can only decay to other colored particles
➔ R-parity prevents a direct decay to quarks/gluons
➔ the only colored supersymmetric particles (R = -1) are squarks, but being bosons have much higher masses

➔ very **long lifetime of gluino**,
which can decay only through a virtual high-mass squark

➔ opportunity **to observe a SUSY particle directly** in a detector,
instead by reconstructing its decay chain or by momentum imbalance

- The same role can be played by the lightest squark (e.g. *stop)*

$$R = (-1)^{3(B-L) + 2S}$$

- **Known particles R = + 1:**

Fermions:

(anti) quarks: B = (-1/3) 1/3, L = 0, spin S = ½ n

(anti) leptons: B = 0, L = (-1)1, S = 1/2n

Bosons: B = 0, L =0, S = 0, n

- **Supersymmetric particles R = - 1:**

each particle has supersymmetric partner with the same quantum numbers with exception of a spin shifted by 1/2

R – parity conserved in most SUSY models

↓

pair production and stability

of the lightest SUSY particle

Magnetic monopoles – Dirac 1931

$e\,g = n\,\hbar c/2,\ n=0,\pm1,\pm2,\ldots \quad \rightarrow \quad g_D = \hbar c/2e = (137/2)\,e$

- **No predictions for Dirac monopole mass**

  assuming that `classical monopole radius` $r_m = r_e$

  $M_m = n^2 g^2 m_e/e^2 = \cong\ n^2 4700\ m_e \cong n^2 x 2.4\ \mathrm{GeV}$

- **GUT**

  $M_m \approx 10^{16}\text{-}10^{17}\ \mathrm{GeV}$ **of the order of the unification scale**

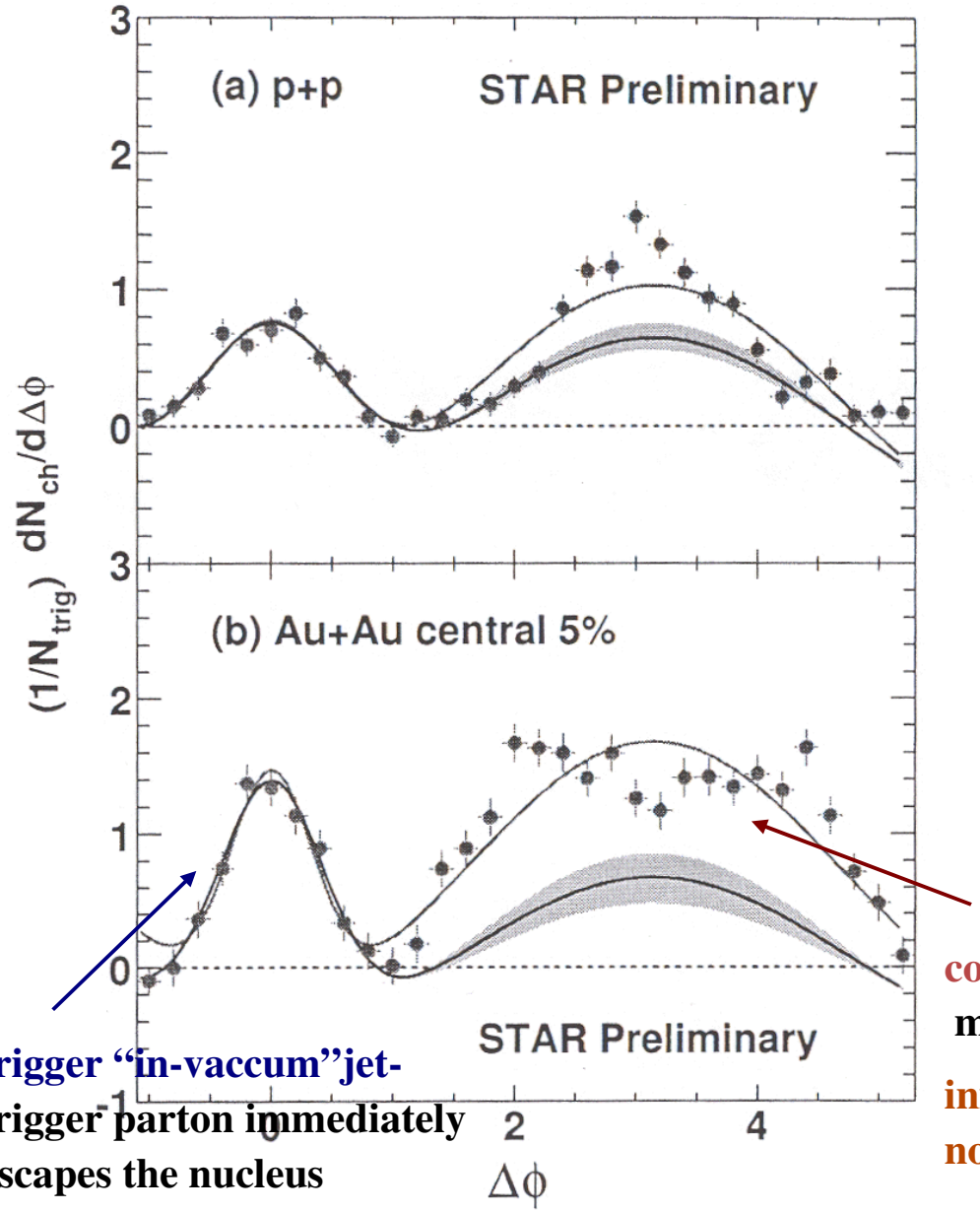
- **New Theories**

  - $M_m \sim 1 - 15\ \mathrm{TeV}$ **Intermediate Mass Monopoles (IMMs)**

  unification scale could be lowered through appearance of extra dimensions

-> monopoles could be produced at LHC energies.

Azimuthal distribution of particles produced by trigger and companion jets



- η -plot is unavailable at RHIC but
- two -bump structure of the azimuthal angle distribution of the hadrons belonging to companion (away-side) jet is seen in AuAu

(it is the projection of the ring on its diameter)

trigger "in-vaccum"jet-
trigger parton immediately escapes the nucleus

companion jet- traversing the whole nucleus is modified by "in-medium" effects:

initiating parton:
normal fragmentation +Cherenkov gluons

Relativistic monopoles

IDEA

lower monopole masses **M**

and/or

higher magnetic charges **ng**

and

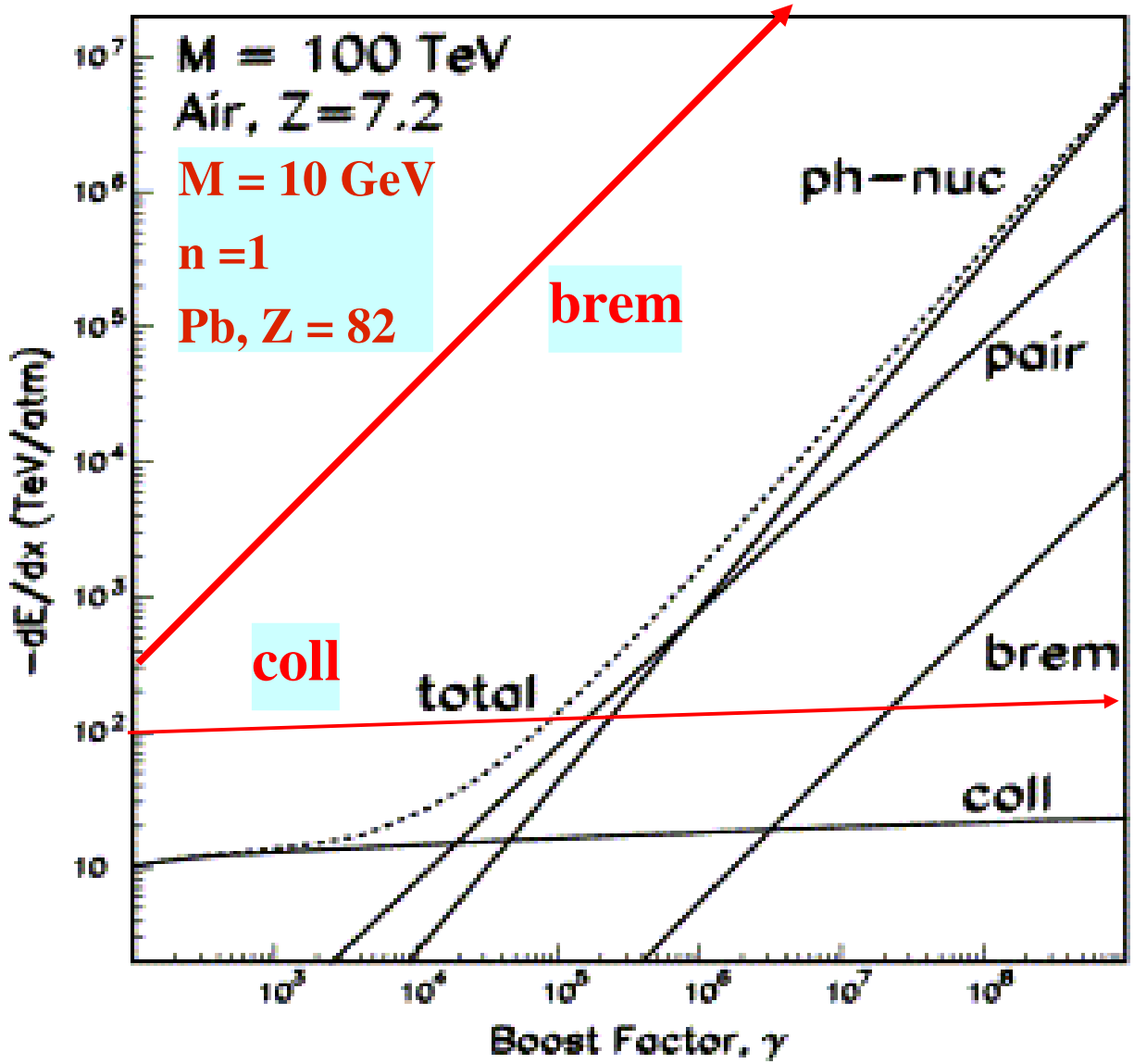
heavier absorber

↓

bremsstrahlung dominates

Wick et al., ***Astr. Phys. 18 (2003) 663***

-> calculations for M = 100 TeV in air



E.G. -> estimation for M = 10 GeV, n=1, Pb

The proposed new method of monopole detection needs:

- **Relativistic monopoles ->**

  - LHC energies enough high to produce relativistic monopoles

  pp – 7 TeV-> M=10,100,1000 GeV; =700,70,7

  *PbPb -2.76 TeV/n*208 = 574 TeV -> M=10,100,1000 GeV;*

  =57000,5700,570

  - Monopoles could gain energy in magnetic fields

- **Bremsstrahlung domination -> monopole energy losses mostly by successively emitted high energy photons**

- **Radiation length several times longer than that for electrons -> separation of electromagnetic showers initiating by monopole radiated photons and developing in the calorimeter absorber**

For high γ bremsstrahlung dominates at some values of monopole mass and charge

- ionization: $(dE/dx)_g^{ioniz} \sim (ng)^2 Z \ln(\gamma)$
- bremsstrahlung: $(dE/dx)_g^{brem} \sim (ng)^4 Z^2 \gamma \ln(\gamma)/M_g$

➔ $\mathbf{(dE/dx)_g^{brem}/(dE/dx)_g^{ioniz} \sim (ng)^2 Z \gamma / M_g}$

Strong bremsstrahlung for high magnetic charges (high n and g), low monopole masses, heavy absorbers (high Z)

Monopole trajectories in a solenoidal field

Lorentz force $F = e(E+\beta x B) + g(B- \beta x E)$

Bauer et al., NIM, A545(2005)503, modified GEANT

⇓

- parabolic trajectory in the beam line (r,Z) plane (for e=0; E =0),
- straight line in the plane (r,ϕ) perpendicular to the magnetic field **no other particle mimic the parabolic trajectory of monopole !**
- monopole is accelerated along an external magnetic field

⇓

➔ light monopole (and heavy with small kinetic energy and pT) tend to be swept out along the beam pipe

➔ **energy gain** $W_m/LB = nx20.6$ GeV $m^{-1}T^{-1}$

(H.Knoepfel, "Magnetic Fields" Wiley - IEEE,2000)

⇓

strong signal in one tower of one ALICE ZDCs

or in CMS CASTOR calorimeter

Bremsstrahlung domination -> monopole energy losses mostly by successively emitted high energy photons

replacing **ze->ng** in formula from *Ahlen, Rev. Mod. Phys. (for γ >>1) gives:*

$$(dE/dx)_{mon}^{brem}/(dE/dx)_{mon}^{ioniz} \sim [(4/3\pi)(ng)^2 Zm_e /(137M_g)][\ln(\lambda M_g 192/m_e(ng)^{1/3}]/L$$

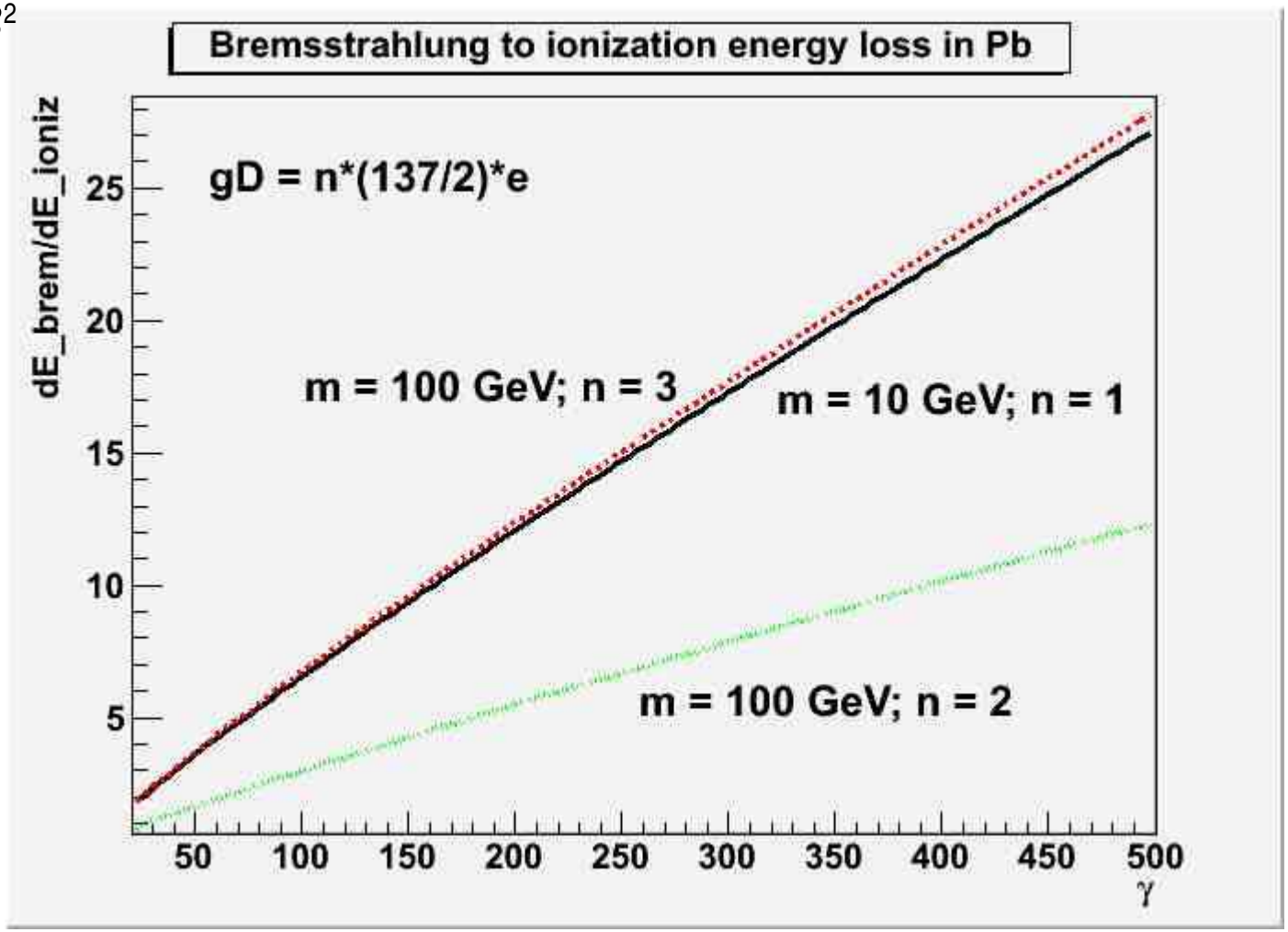
where $L=\ln(2m_e c^2\beta^2\gamma^2/I)-\beta^2$

Strong bremsstrahlung for high charges, low monopole masses, heavy absorbers (high Z)

e.g. for

M<100 GeV/c2, γ>100

bremsstrahlung dominates ionization energy loss



E.G.-D. preliminary

- replacing **ze->ng** in formula from *Ahlen, Rev. Mod. Phys. (for γ >>1) gives*:

$$(dE/dx)^{pair} / (dE/dx)^{brem} \sim M_g / [1000\, m_e (ng)^2]$$

Strong bremsstrahlung for high charges, low monopole masses

M<100 GeV/c2 bremsstrahlung dominates pair production energy losses