Searching for New States of Matter

in Baryon-Rich Environment Using Unconventional Signatures

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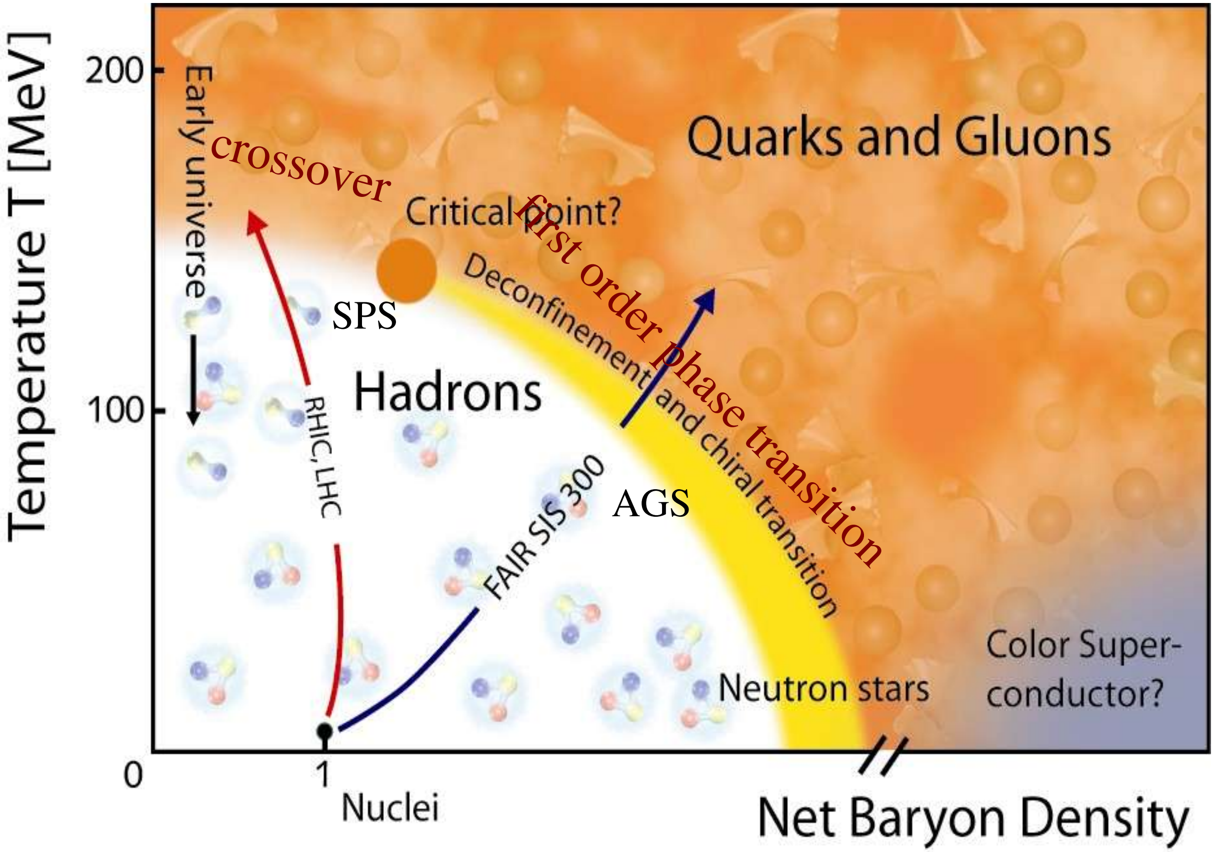
LINC, Protvino 2008

QCD Phase Diagram

Motivation for Heavy Ion collisions:



- **Reproduce matter created at the early cosmological epoch (RHIC, ALICE - hot QGP)**
- **Explore very rich structure of the phase diagram in regions of large µB and moderate T.**

- ***Phase transitions and high-μ_B QGP.***
- ***Critical end-point***

- The early universe cooled slowly down along the vertical axis. It was filled with QGP microseconds after the Big Bang.
- The 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.
- Cold dense quark matter which may occur in neutron stars, is in one of several possible colour superconducting phases.

Interesting Physics
in BARYON-RICH REGION

WHAT ARGUMENTS ?

THEORETICAL:

- **Non-monotonic behaviour close to the end-pont:**
  $T_E \sim 160$ MeV, $\mu_B \sim 360$ MeV
- **Various quark condensates and phase transitions at high μ_B (Rajagopal, Wilczek)**

EXPERIMENTAL:

- ***Exotic events in cosmic-ray experiments***
- **Accelerator results:**

SPS – surprising characteristics at ~10-40 GeV

RHIC – high nuclear transparency, increase of chemical potentials with rapidity, Color Glass Condensate?

What FLUCTUATIONS?

- **CENTAURO – type events**
- **DCC clusters**

$\Rightarrow$ ***Anomalous***

N_{ch}, N_γ/N_{ch} $\Sigma E_\gamma/\Sigma E_h$

- **Strongly penetrating objects**
  - **STRANGELETS**

$\Rightarrow$ ***Anomalous pattern of energy deposit in deep calorimeters***

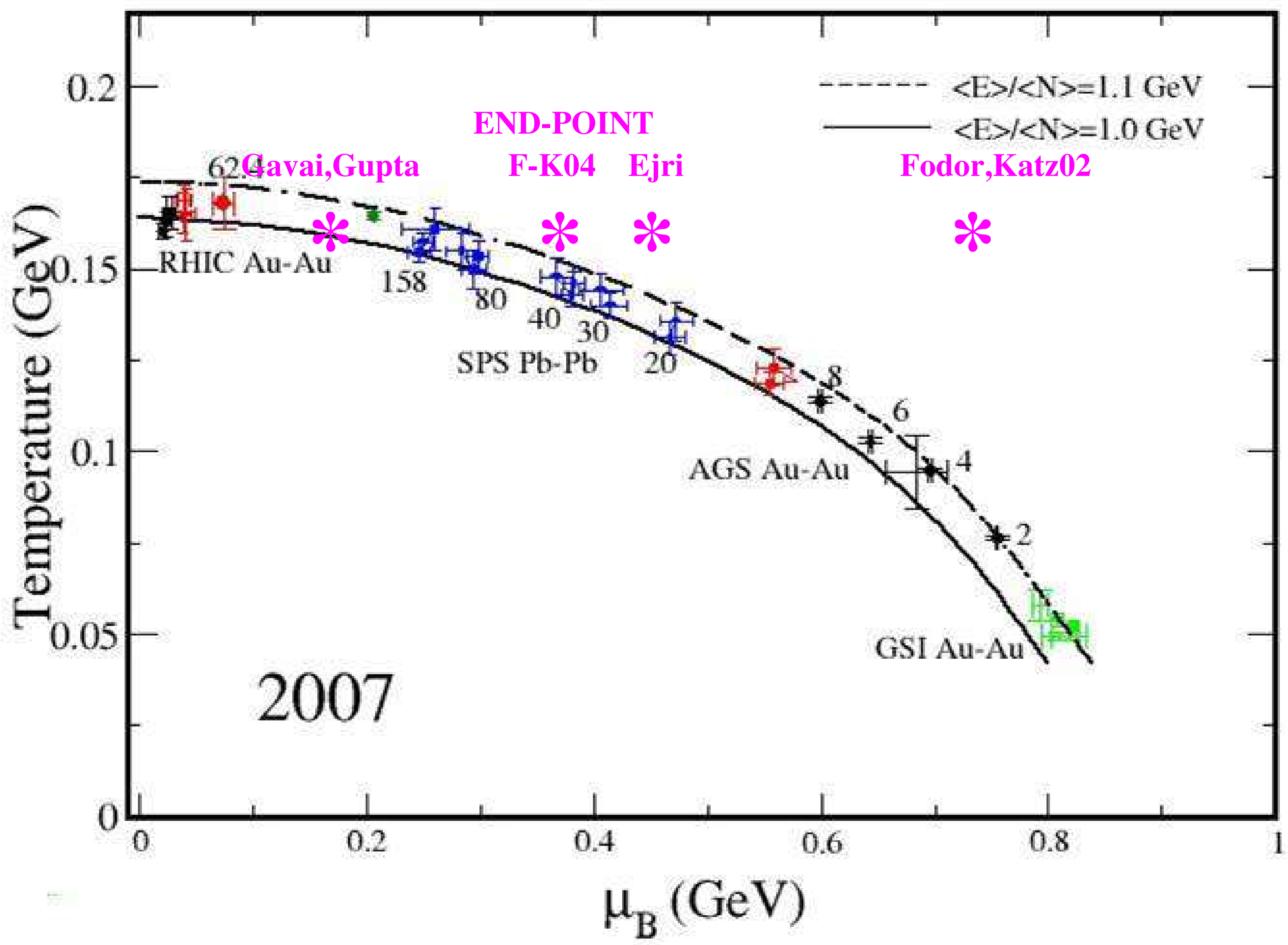
Where and how to explore the high density region?

- In heavy ion collisions at moderate energies (5)**10 – 40 A GeV** the high baryon density and high relative strangeness content is expected
- **In forward rapidity region** (also at much higher energies – LHC, cosmic rays)
- Via **“unconventional signals” - extreme fluctuations** (expected to appear in the vicinity of the critical end-point) and **multi-strangeness degrees of freedom**

Why at moderate energies
and
in forward rapidity region?

Indications from theory
and
TRENDS in ACCELERATOR DATA

Investigations of the **critical end-point** and the **first order phase transition** region needs moderate energies.



μB decreases with beam energy

T – varies between ~50 MeV at SIS and ~160 MeV at SPS.

μB – changes from ~240 MeV at SPS to ~ 820 MeV at SIS

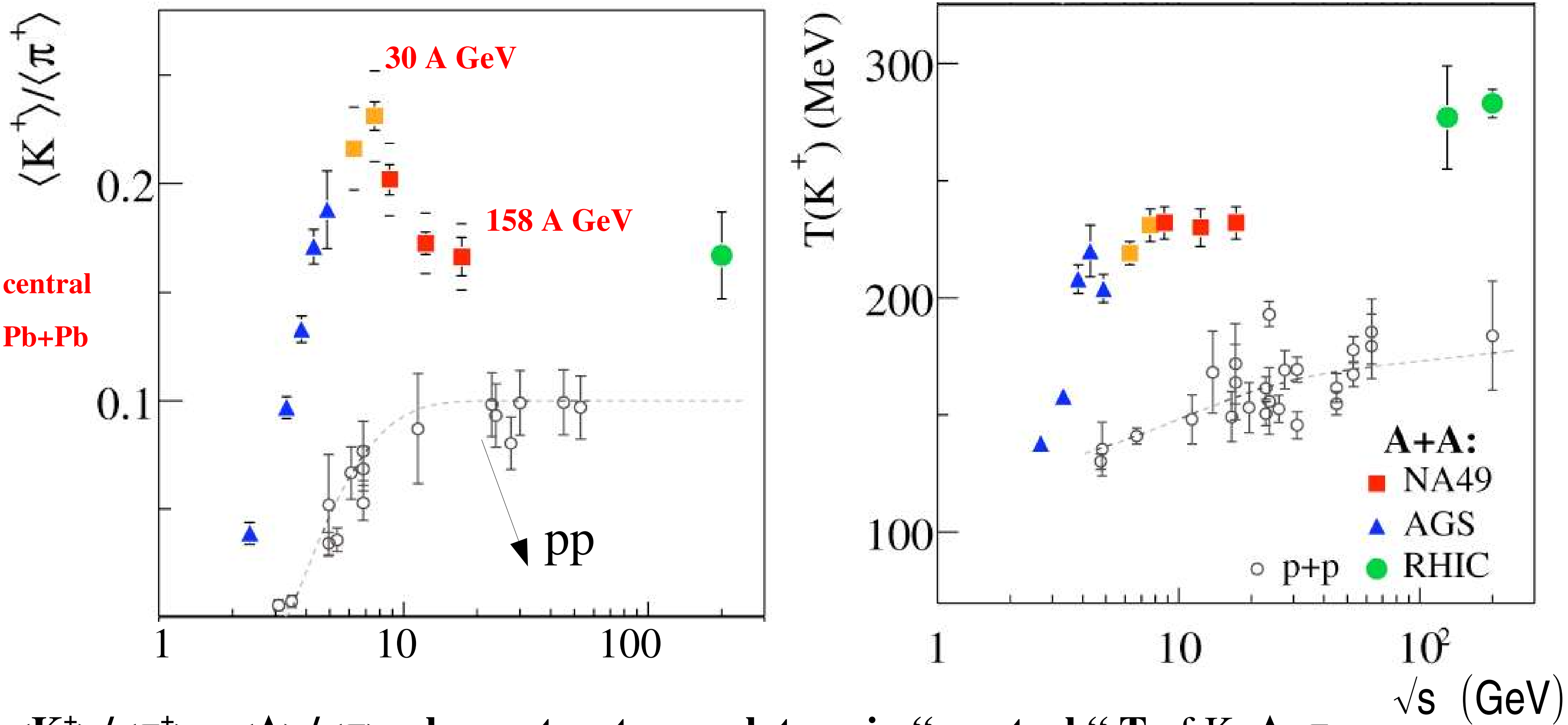
theoretical estimates of an end -point - μB ~170 -750 MeV T ~ 150 -160 MeV

RHIC – midrapidity, other experiments – ***integrated particle yields***

Change of thermal parameters over the full range of beam en. – Becattini et al.,hep-ph/0709.2599

STRANGENESS PRODUCTION - there is something interesting at moderate (~10 – 40 AGeV) energies

AGS **SPS** **RHIC**

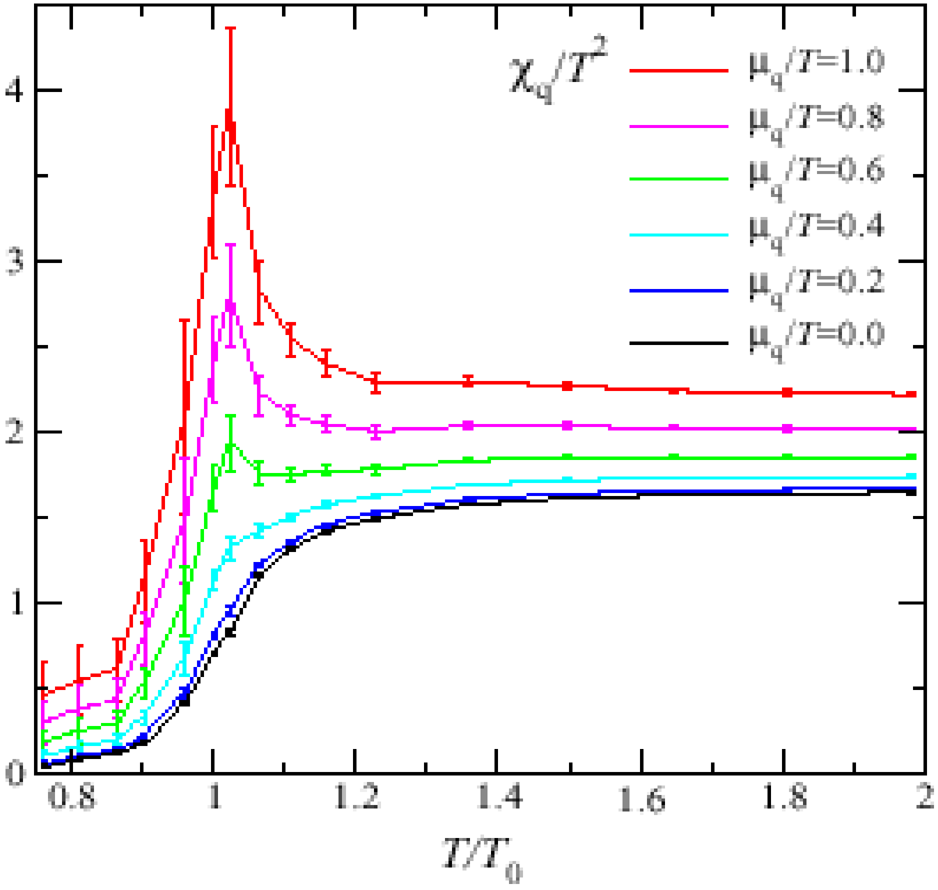


<K^{+}>/<π^{+}> , <Λ>/<π> - **horn structure**, **plateau in "spectral " T** of K, **Λ**, π ,
collapse of p flow (v1, v2), event-by-event fluct. - <K+>/<π+> increases towards 30 AGeV – unexplained by models (UrQMD, HSD, RQMD, Hadron Gas)

max strangeness near 30 A GeV, plateau signals phase coexistence ????

Susceptibilities develop peaks at T ≈ T_c and grow with μ_q

⇨ **Fluctuations** in the quark number density **increase** in the vicinity of T_0

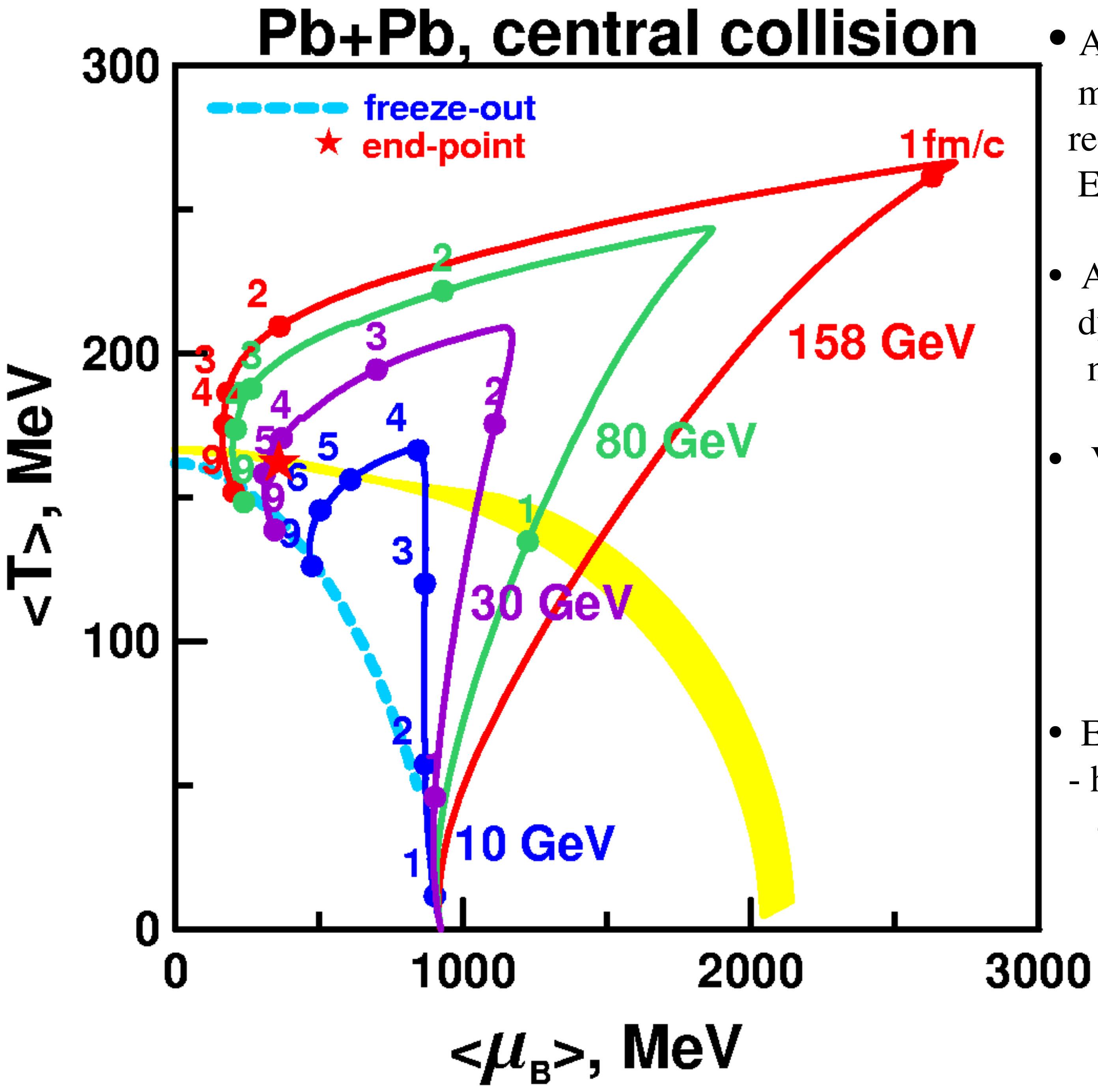


$\chi_q/T^2 = \partial^2(p/T^4)/\partial(\mu_q/T)^2$

maximal baryon number density at T_0 for $\mu_q = T_0$ (μ_B ~ 450 MeV)

Allton et al., hep-lat 0305007 – lattice QCD at small μq

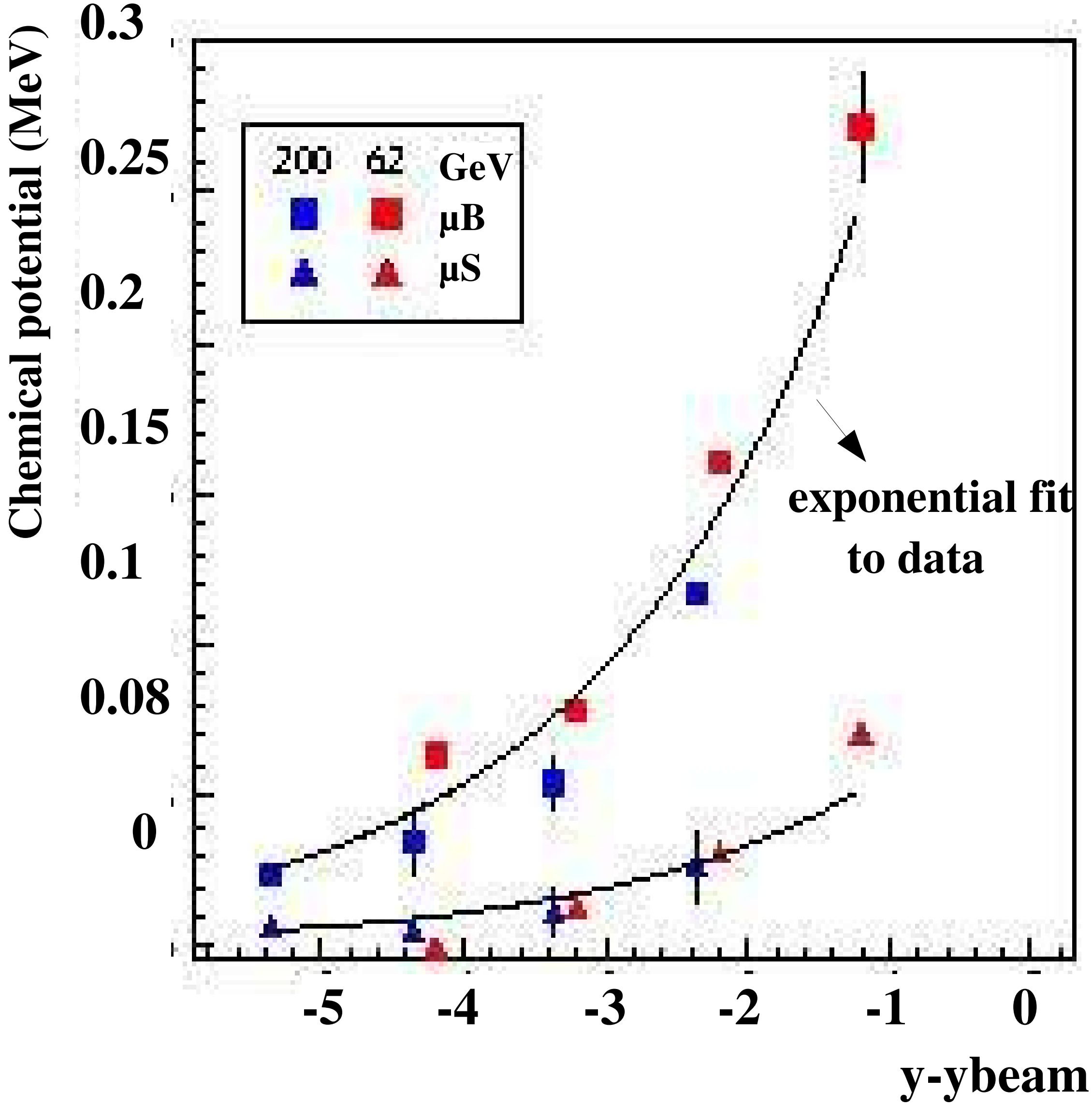
“Trajectories” from 3 fluid hydrodynamics



- At high compression of nuclear matter deconfinement can be reached even at low E ~10–30 AGeV
- At E ~30 A GeV dynamical trajectory passes near the critical endpoint
- Very high values of μ (and <ϱ_B>) are predicted <ϱ_B> ~ **11x ϱ_0 (6x ϱ_0)** at 158 (40) AGeV
- Early phase not equilibrated - high density fluctuations can be expected

Hadron gas EOS:
Ivanov, Russkikh,Toneev
nucl-th/0503088

RHIC - BRAHMS



exponential fit to data

Both chemical potentials:

μ_B and μ_S

- increase with y-ybeam

(towards forward rapidity region)

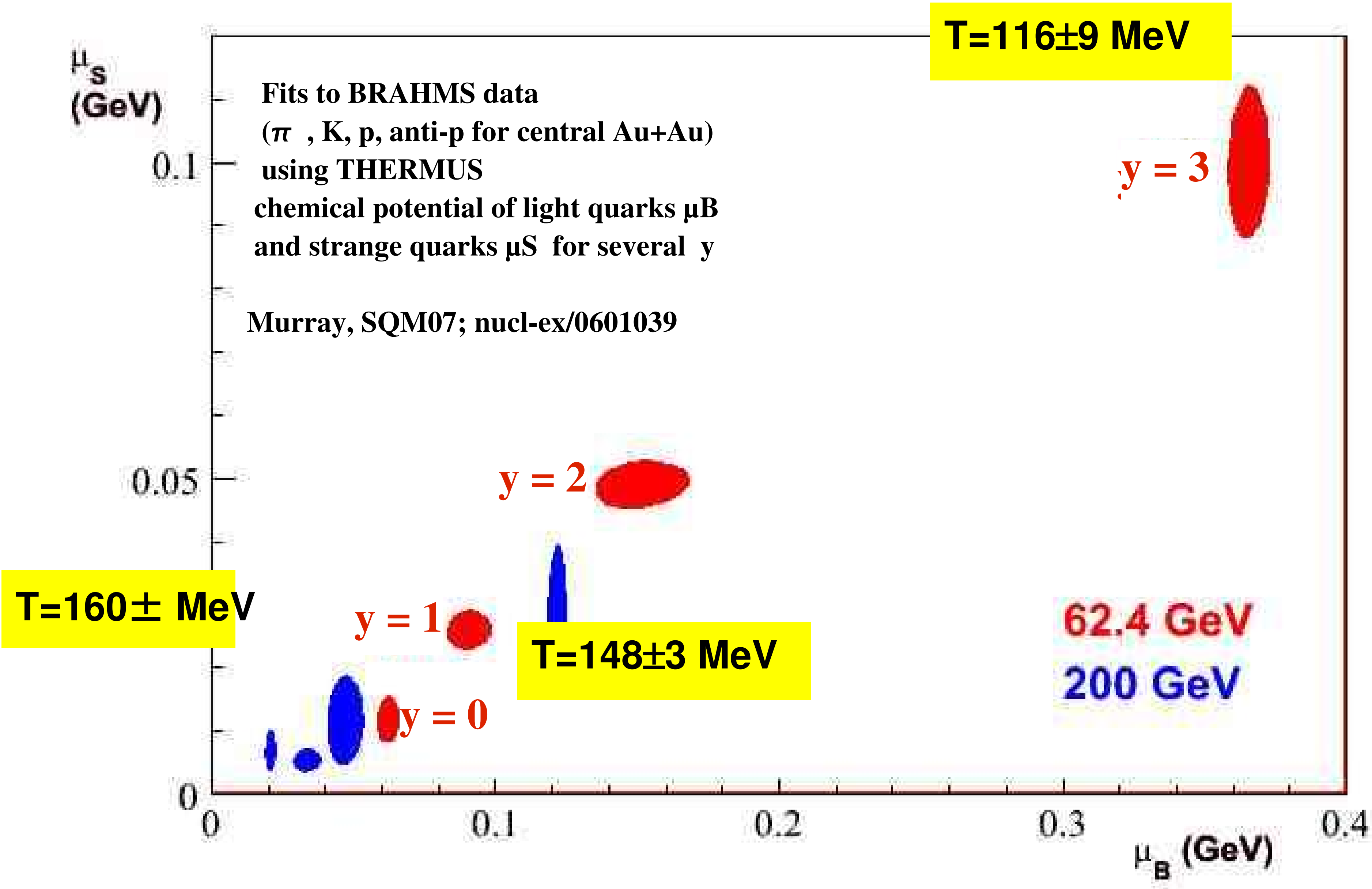
- decrease with energy

(at a fixed rapidity)

fits to BRAHMS data
(π, K, p, anti-p for central Au+Au)
using THERMUS ➔
chemical potential of light quarks μB
and strange quarks μS for different y

Stiles, Murray, nucl-ex/0601039

- linear correlation between μ_S and μ_B : $\mu_S = (0.21 \pm 0.01)\mu_B$
- both potentials increase with y and decrease with energy
- T drops with y and increases with E



T=116±9 MeV

Fits to BRAHMS data
(π , K, p, anti-p for central Au+Au)
using THERMUS
chemical potential of light quarks μB
and strange quarks μS for several y

Murray, SQM07; nucl-ex/0601039

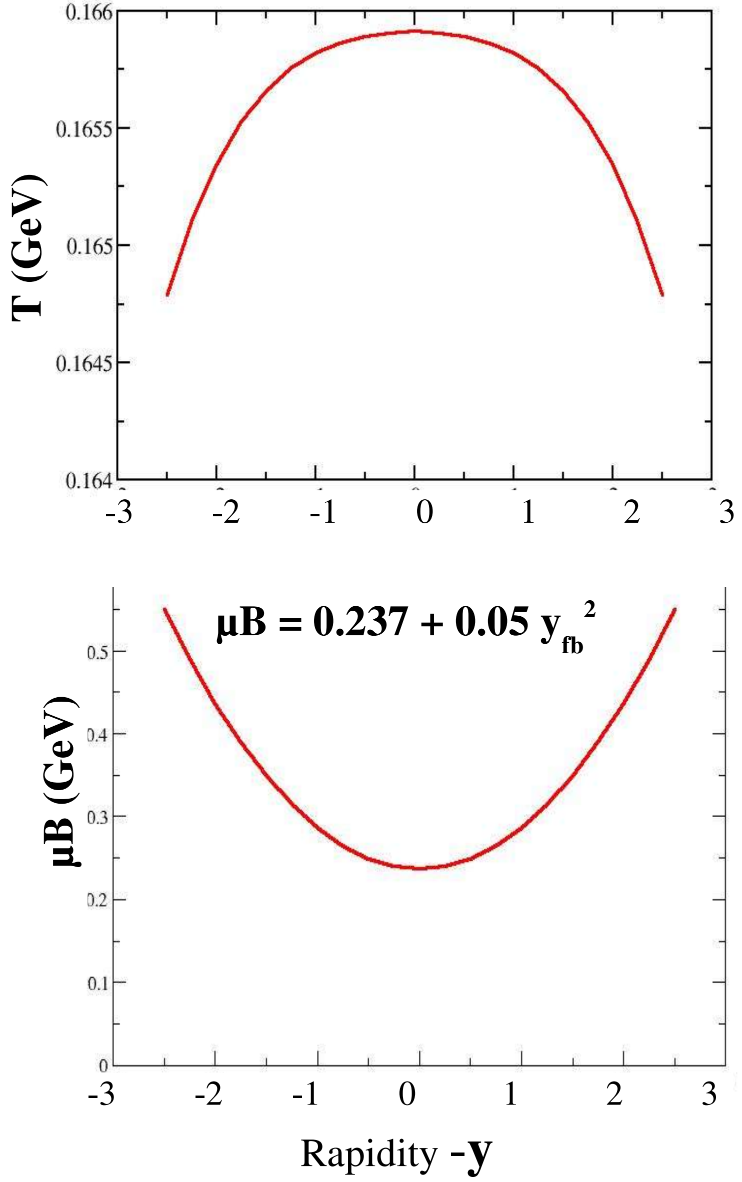
T=160± MeV

T=148±3 MeV

Rapidity dependence of thermal parameters

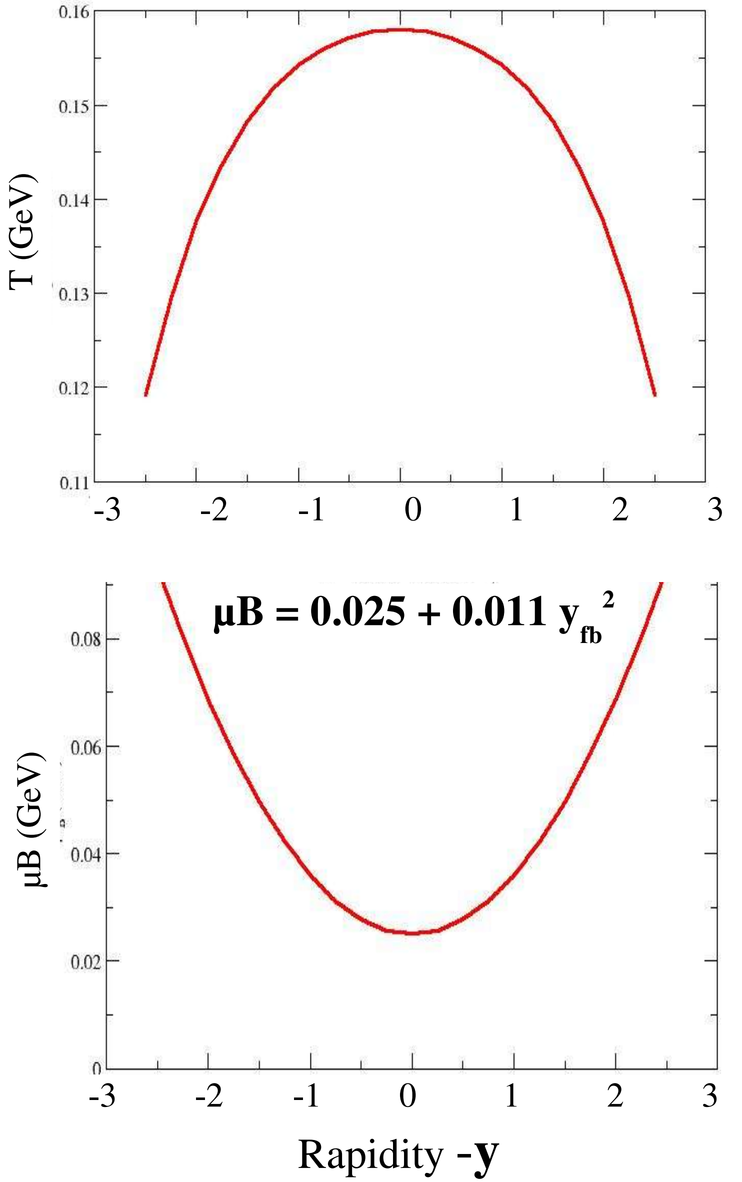
μ_B increases, T decreases with y

RHIC – $\sqrt{s}$ =200 A GeV



$\mu B = 0.237 + 0.05\, y_{fb}^{\;2}$

SPS – E_{lab} = 158 A GeV ; $\sqrt{s_{nn}}$ =17.2 GeV



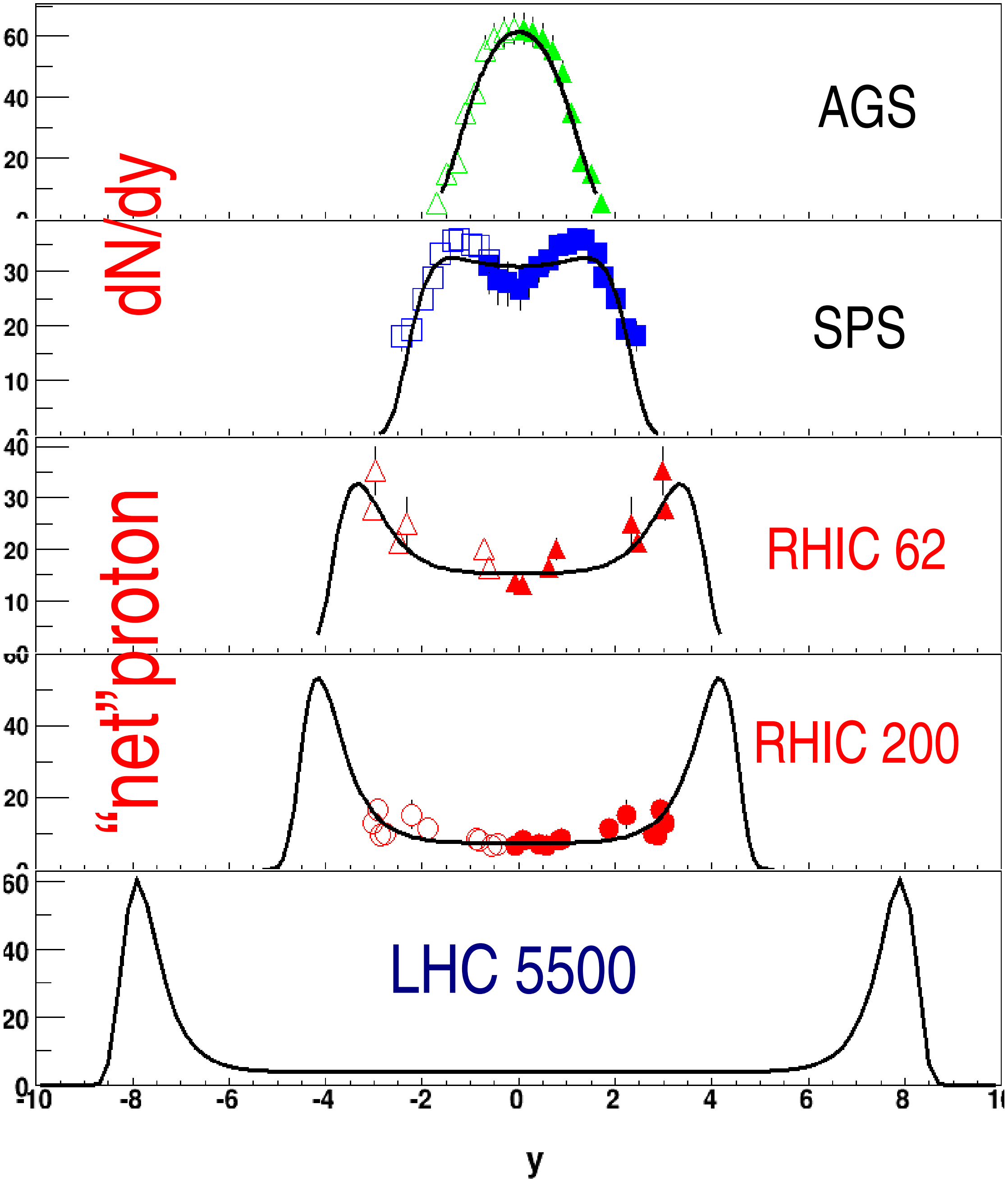
$\mu B = 0.025 + 0.011\, y_{fb}^{\;2}$

Cleymans, SQM07

High nuclear transparency at RHIC

- Peaks of net baryon densities at forward rapidity (fragmentation region)

- Separation of baryon-free from baryon-rich environment increases with energy



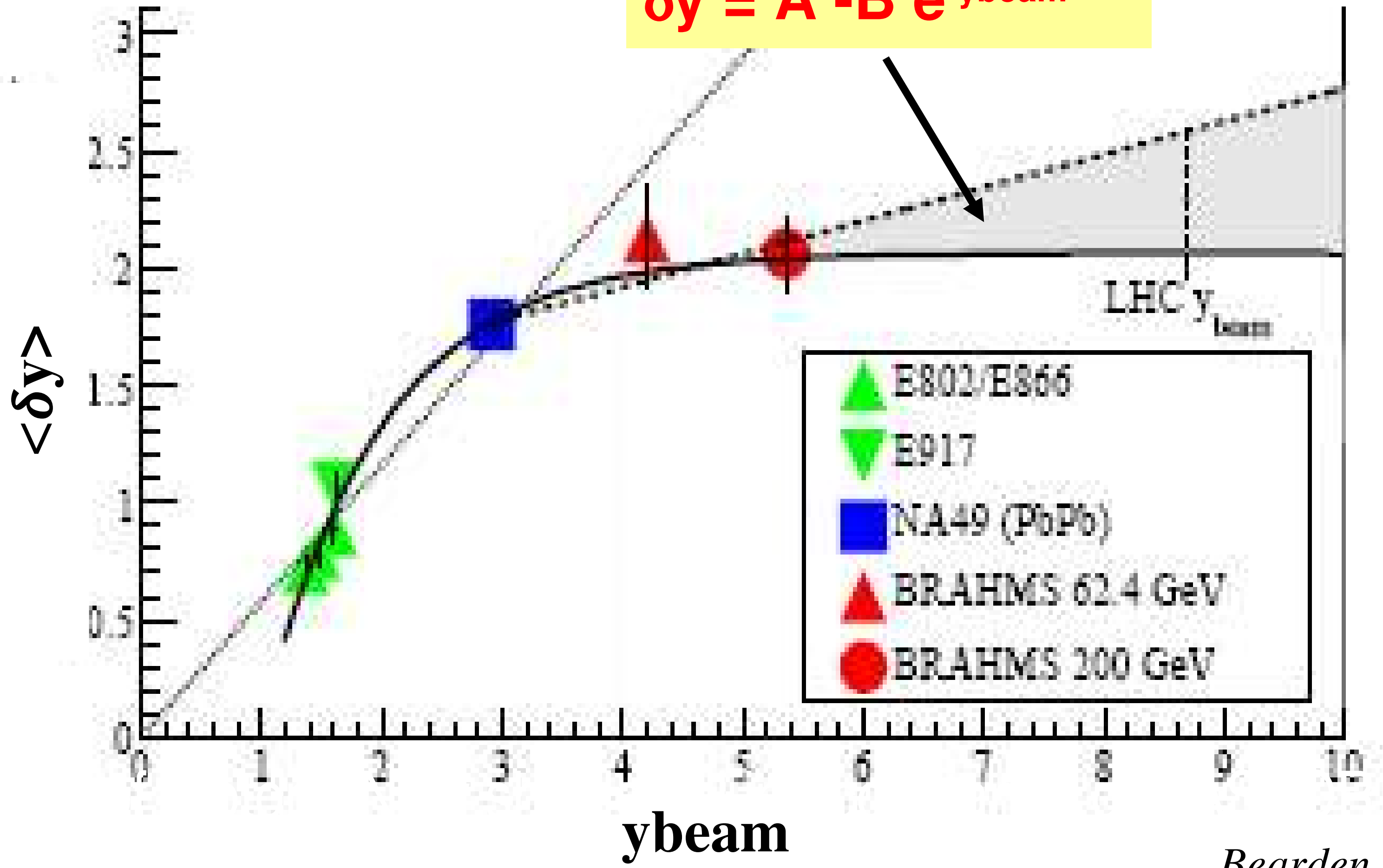
BRAHMS Coll.,Murray, SQM07; hep-ex/07010041

Stopping power quantified by rapidity loss $\langle \delta y \rangle = y_{beam} - \langle y \rangle_{netbaryon}$

BRAHMS

$\delta y = 2.16$ at 62.4 AGeV

$\delta y = 2.0$ at 200 AGeV



$\delta y = A - B\, e^{-ybeam}$

LHC:

$\delta y \sim 2 - 3$

Bearden, BRAHMS Coll., J. Phys.G: Nucl. Part.Phys. 34 (2007)S207

Surprising results of cosmic-ray experiments

(forward rapidity)

- **Experimental observations - Exotic Events**
- **Explanation**
  – Strange Quark Matter fireball model + Strangelets
- **Unconventional signature of New States of Matter**
- **CASTOR (Centauro And Strange Object Research)**
  - detector for CMS at LHC

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**

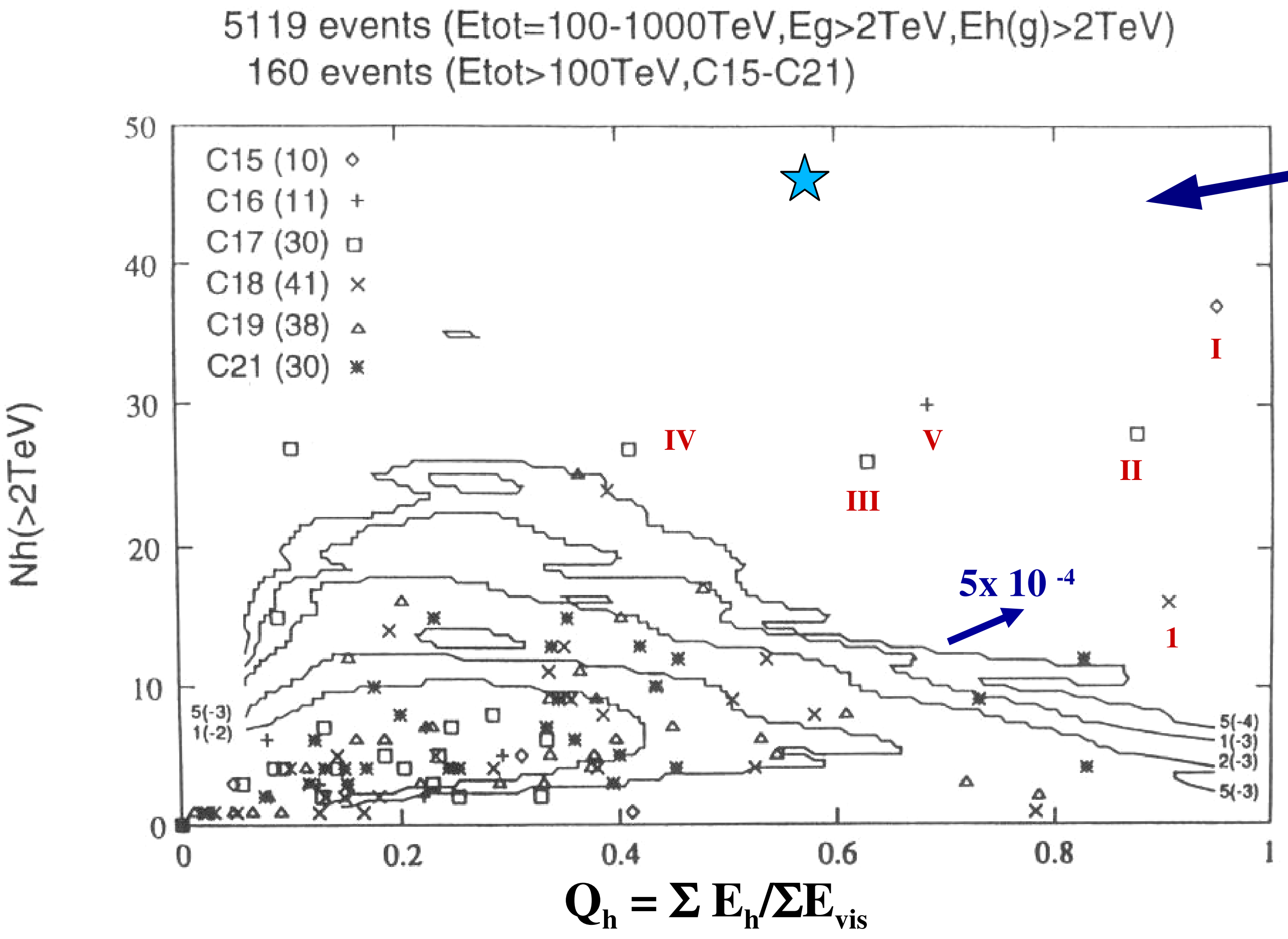
Review:

E.G.-D. Phys. Part. Nucl34(2003)285

STRONGLY PENETRATING COMPONENT:

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

Anomalous hadron dominance confirmed in simulations



Chacaltaya CENTAUROS –

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

20% hadron-rich events at E_{vis} > 100 TeV

Chacaltaya, Pamir, Pami-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

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)

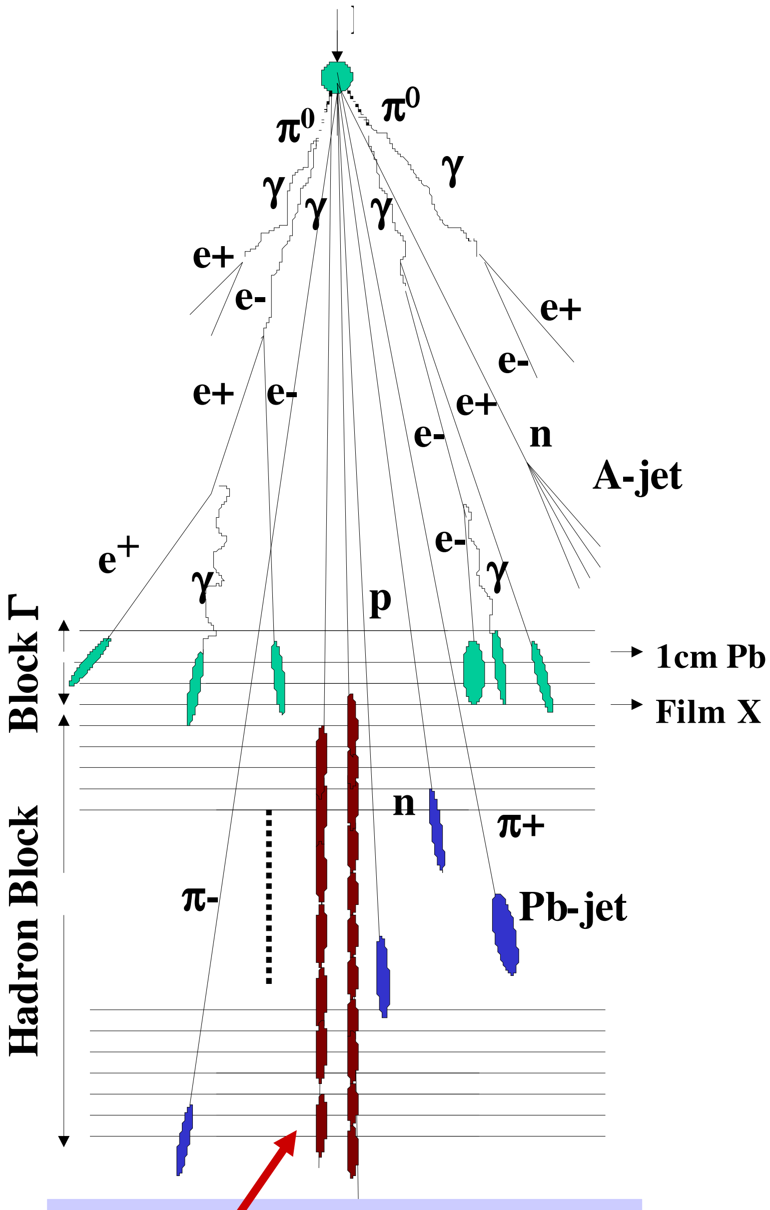
Hadron-rich event

Nh = 55, Nγ = 74, ΣEh = 382 TeV, Σ Eγ=305 TeV

2 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 through the chamber and escaped through the bottom



Strongly penetrating component

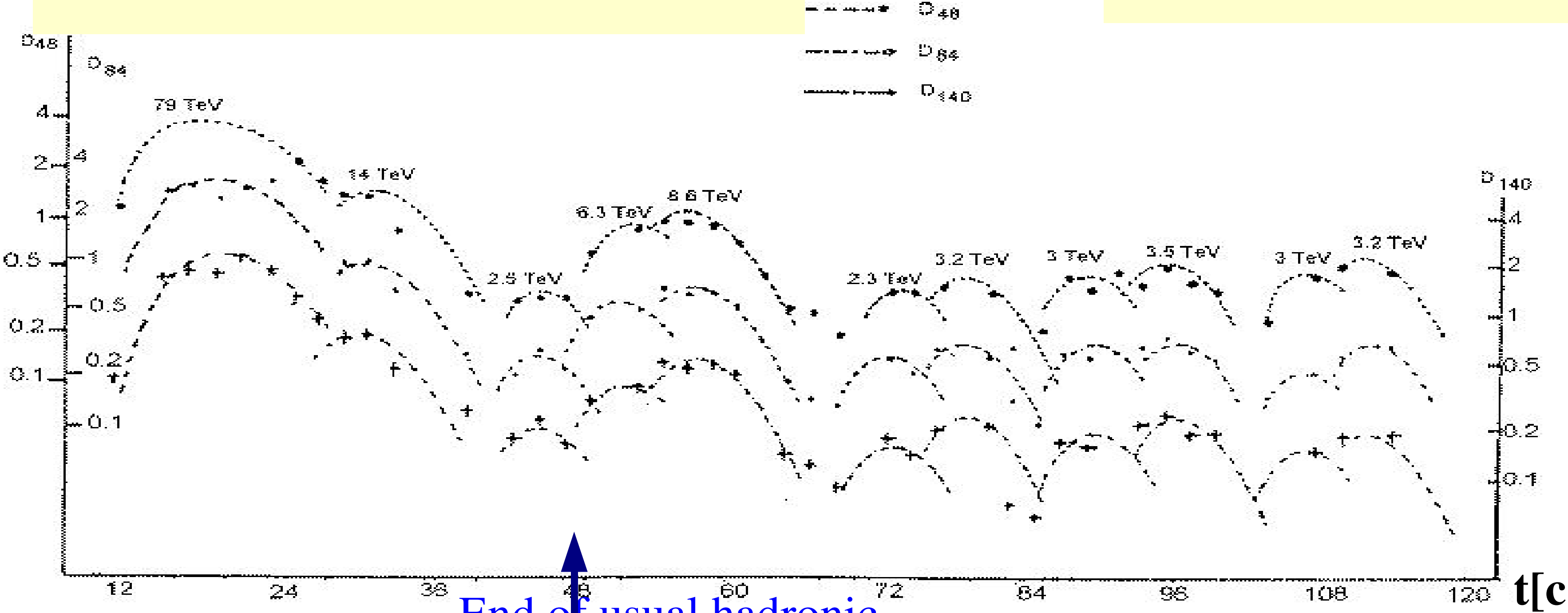
Cracow group, presented by E.G-D., ICRC, Paris, 1981, Vol. 11, p. 104.

STRONGLY PENETRATING CASCADES in Pb CHAMBERS

STRANGELETS???

First observation:
Krakow group,17th ICRC, 1981
2 exotic cascades in Centauro-like event

Confirmation - other events
Arisawa et al.,Nucl. Phys.
B424(1994)241



End of usual hadronic cascade ~1.5 Λ int

60 cm Pb~3.6 Λint

Cascades pass through the chamber practically without attenuation and reveal many-maxima shape with small distances between humps (~ 2 X shorter than at usual hadron cascades)

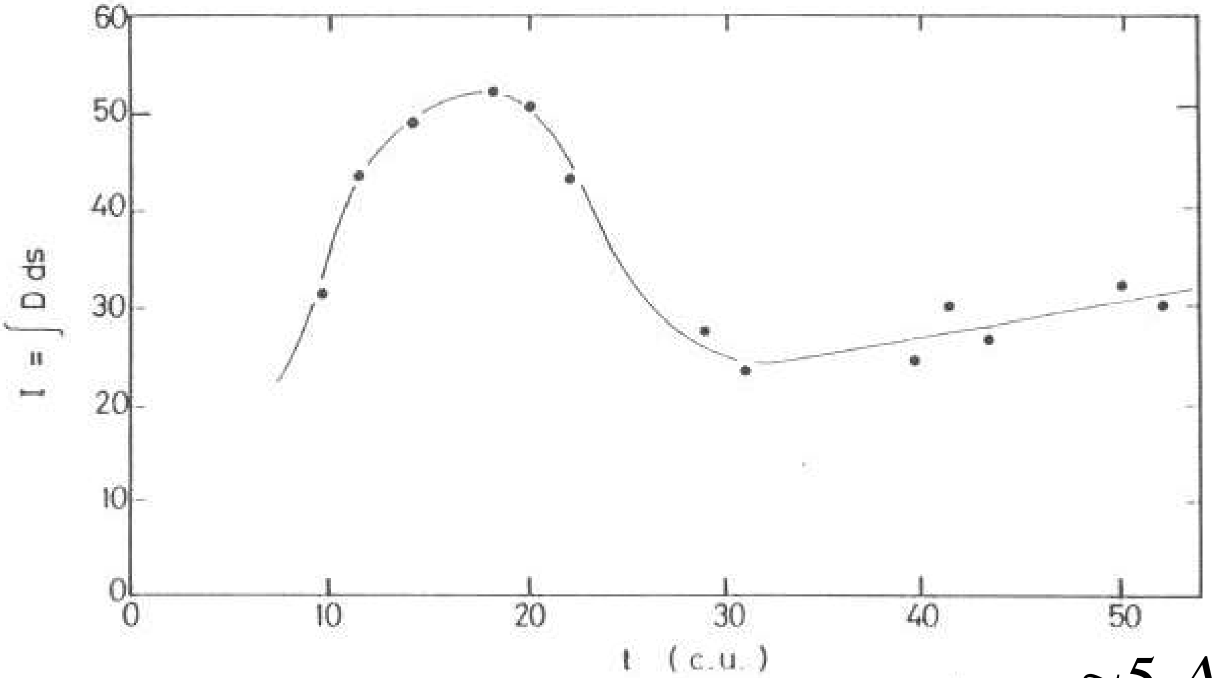
Penetrating halo in the center of family “Татьяна” –

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

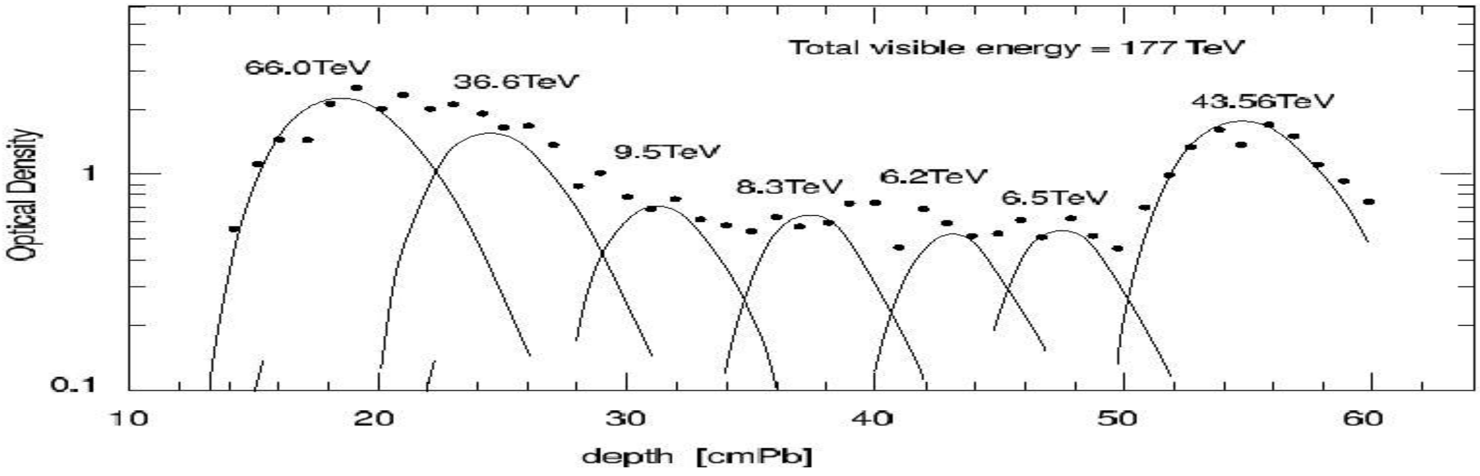
CONFIRMATION

Other examples of exotic cascades in thick Pb chambers:

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



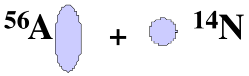
$\sim 5\ \Lambda_{\rm int}$



EXPLANATION
STRANGE QUARK MATTER ??

- Centauros and strongly penetrating component unexplained by fluctuations in “usual” hadronic interactions and /or development of normal hadronic cascades
- A lot of models proposed to explain hadron rich composition in Centauros (Bialas, Bjorken, Karmanov. Morozov, McLerran, Rajagopal, Wilczek, Zelevinsky...)
- Only **STRANGE QUARK MATTER** scenario offers simultaneous explanation of both phenomena

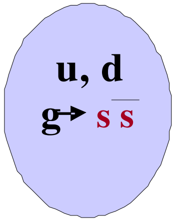
CENTAURO FIREBALL EVOLUTION



CENTRAL COLLISION

at the top of the atmosphere

$E_p \sim 1740$ TeV

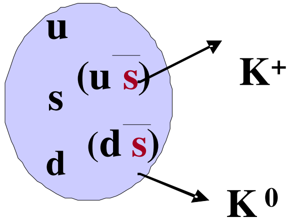


QUARK MATTER FIREBALL

in the baryon-rich fragmentation region

High μ_q suppresses production

of $(u\,\bar{u})$, $(d\,\bar{d})$, favoring g → s $\bar{s}$

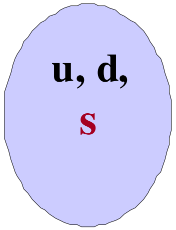


(pre-equilibrium)

KAON EMISSION

K^+, K^0 carry out:

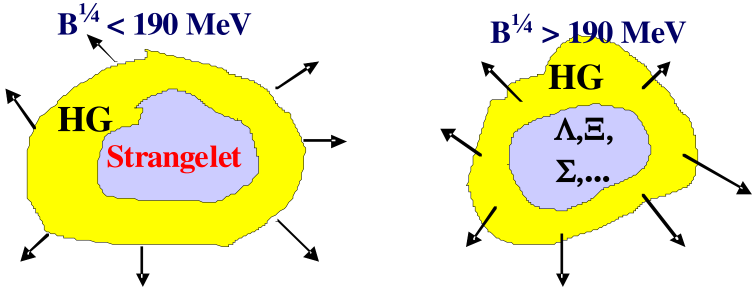
K^0 anti-strangeness, positive charge, entropy



SQM FIREBALL

Stabilizing effects of s quarks

→ long lived state



EXPLOSION

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

Strangeness distillation mechanism

C. Greiner et al., Phys. Rev. D38 (1988)2797

Estimates for Centauro at LHC

- Energy density
  ~ 3 - 25 GeV/fm^3,
- Temperature
  T ~ 130 - 300 MeV
- Baryon chemical potential
  $\mu_b \sim 0.9 - 1.8$ GeV/fm^3

CNGEN

Centauro and Strangelet Generator

A. Panagiotou et al., Phys. Rev. D45 (1992)3134 , E. G.- D. and Panagiotou,

SQM'94; Astroparticle Phys. 2(1994)167

S. Sadovsky et al., Phys. Atom. Nucl. 67 (2004)396

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

Simulation of STRANGELETS

- **UNSTABLE $\Rightarrow$ 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 $\Rightarrow$ 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 neutron decay

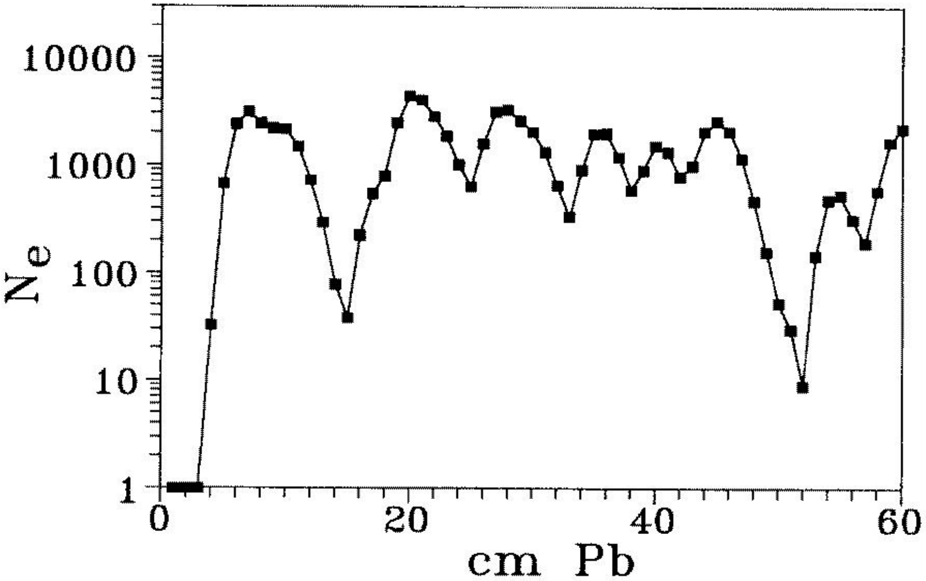
- **STABLE $\Rightarrow$ lifetime long enough to pass through the apparatus without decay**

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

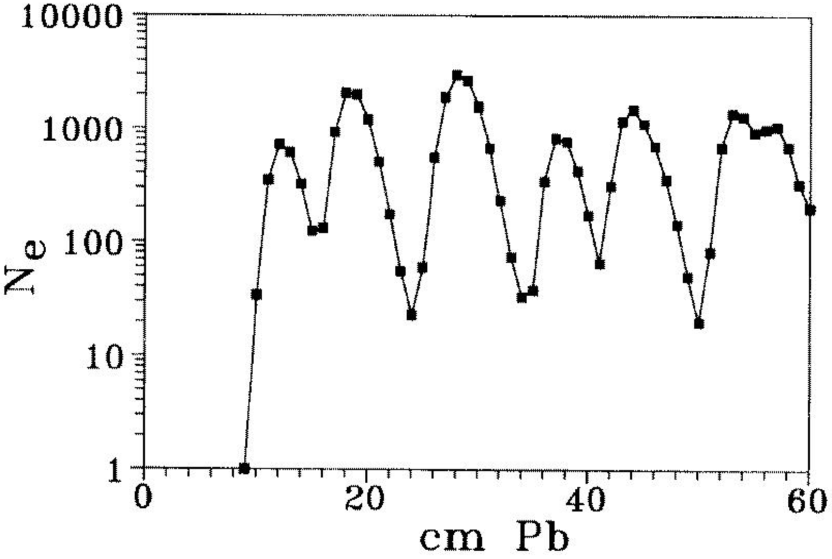
  Long τ_0 in weak radiative (d+$u \leftrightarrow s+u+\gamma$) and leptonic decays (d $\leftrightarrow u+e^-+\upsilon_e$, $s \leftrightarrow u+e^-+\upsilon_e$), caused by flavour changing and 3-body phase space

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

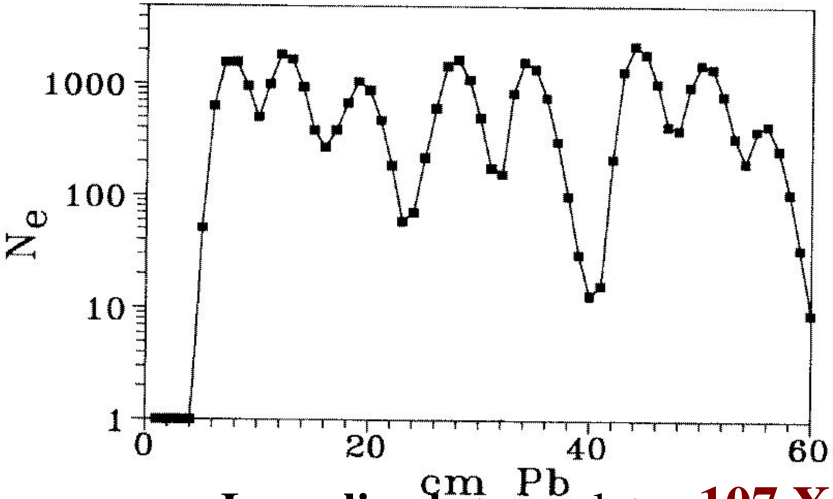
Strangelet passage through the Pb emulsion chamber



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

The strongly penetrating component can be the sign of strangelet passage through the matter

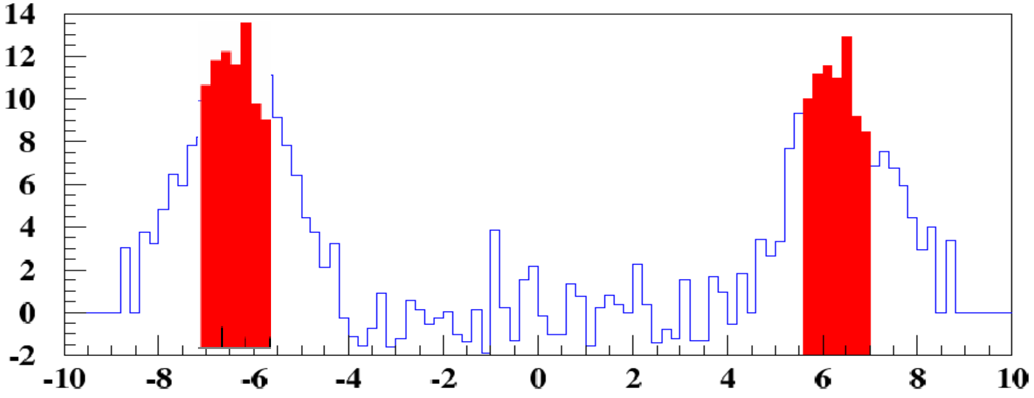
E. G.-D. and Z. Wlodarczyk,
J. Phys., Nucl. Part. Phys. G23 (1997)2057

NEW SIGNATURE of QUARK GLUON PLASMA

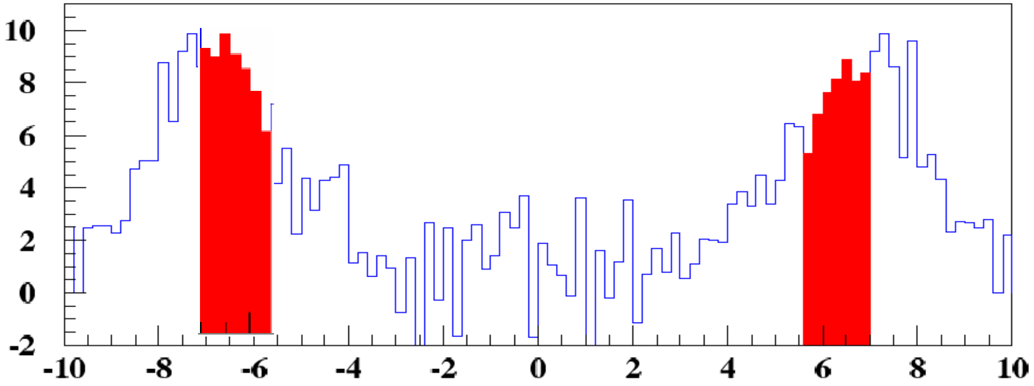
and
the CASTOR detector

EXOTIC EVENTS at the LHC

Net Baryon Number at the LHC
In Red the CASTOR Acceptance



Venus, Average of 50 Pb+Pb central events



Hijing, Average of 50 Pb+Pb central events

Favourable conditions:

Sufficiently high energy

- **CR Centauro:** "Fe+N"

  $E_p \sim 1740$ TeV

  $\sqrt{s_{NN}} \sim 233$ GeV $\sqrt{s_{ToT}} \sim 6.7$ TeV
- **LHC Centauro**: Pb+Pb

  2.75 TeV/n + 2.75 TeV/n

  $\sqrt{s_{NN}} \sim 5.5$ TeV, $\sqrt{s_{TOT}} \sim 1150$ TeV

Baryon-rich environment
at $\sim 5 < \eta < 7$

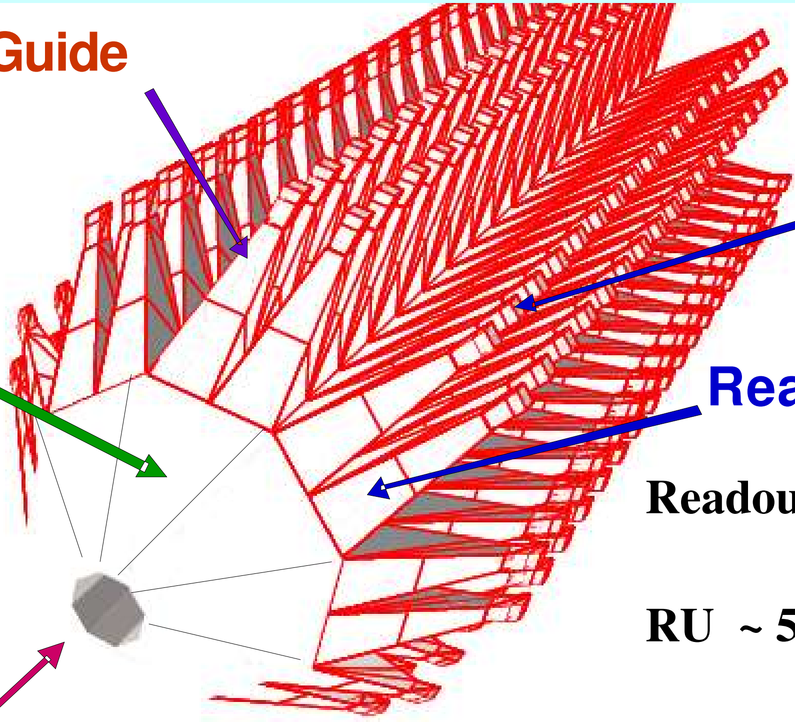
BRAHMS

Peak in the net baryon distribution: $\eta \sim y_{beam} - 2.4 \sim 6.3$

THE CASTOR CALORIMETER

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

- **EM = 2RU (~ 20 X0)** **HAD = 12 RU (~10 Λ_I)**



Air-core Light Guide

PMTs

Active volume

W/Q - plates
Sampling Units

Reading Unit

(16 azimuthal sectors)

Beam

Readout Unit = 5 Sampling Units

EM section:

RU ~ 5x5 mm W ~ 10 X0 ~ .4 Λ_I

H section:

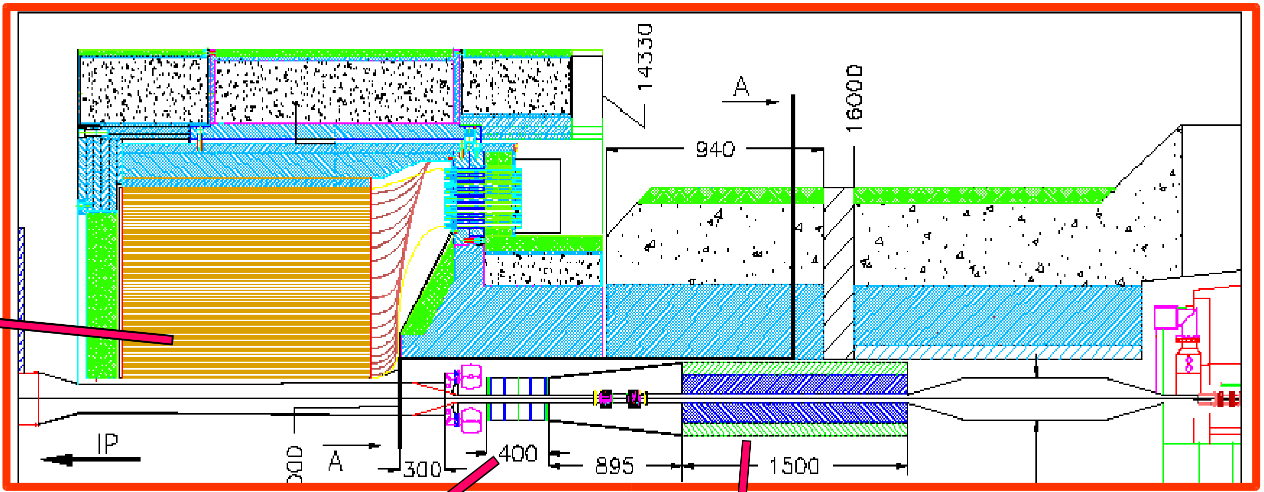
RU ~ 5x10 mm W ~ 20 X0 ~ .79 Λ_I

finer longitudinal segmentation possible in future

CMS - $|\eta| > 3$ (forward rapidity)

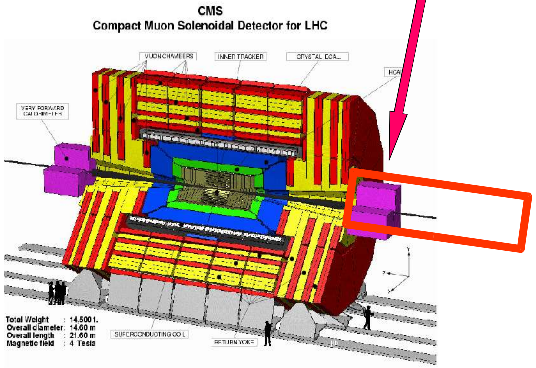
CMS Central region
Tracker, muons

ECAL + HCAL
$3 < |\eta| < 5$



CMS

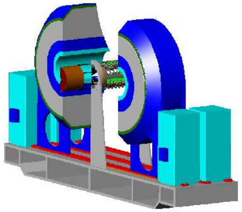
Forward HCAL



$3 \leq |\eta| \leq 5.2$

large total acceptance $\Delta\eta \approx 13$

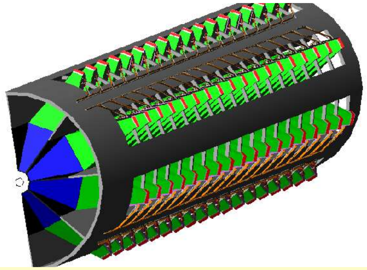
TOTEM



$5.3 \leq \eta \leq 6.7$

z = 14.37 m

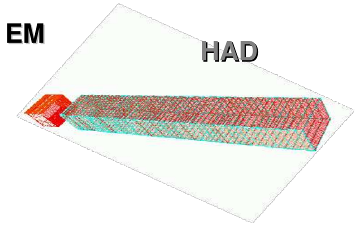
CASTOR



$5.2 \leq \eta \leq 6.6$

z = ± 140 m

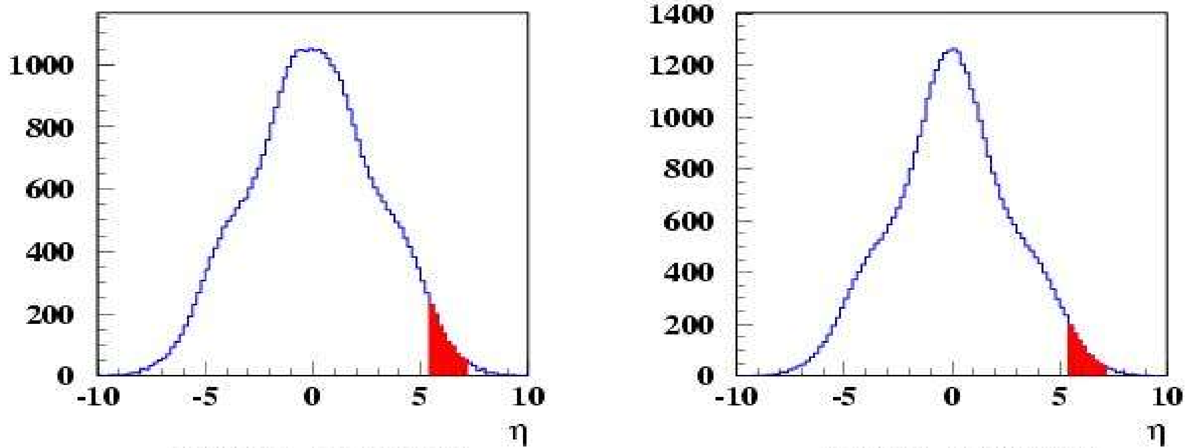
ZDC



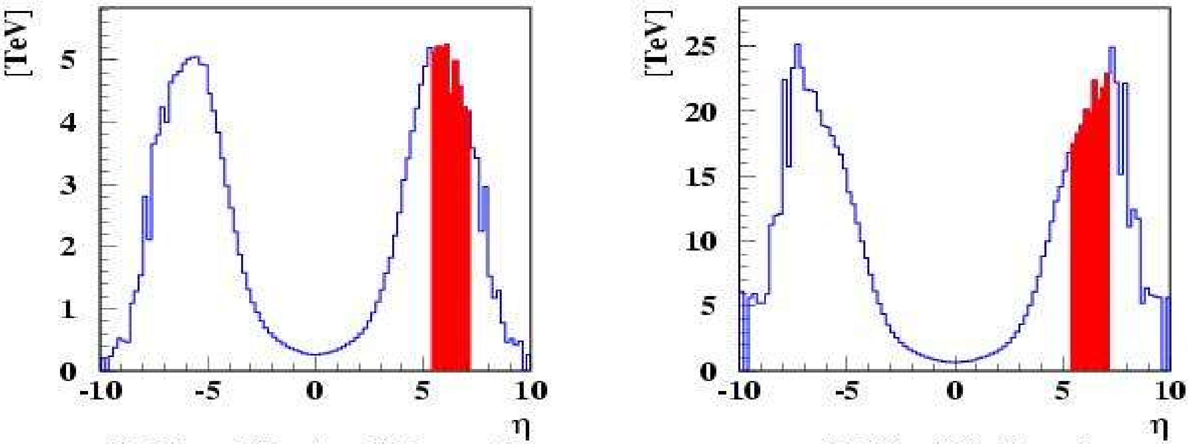
$8.3 \leq |\eta|$

Collider experiments, in opposite to cosmic ray studies, explore mainly the central rapidity region

HIJING Pb+Pb central



dN/dη, Charged   dN/dη, Photons

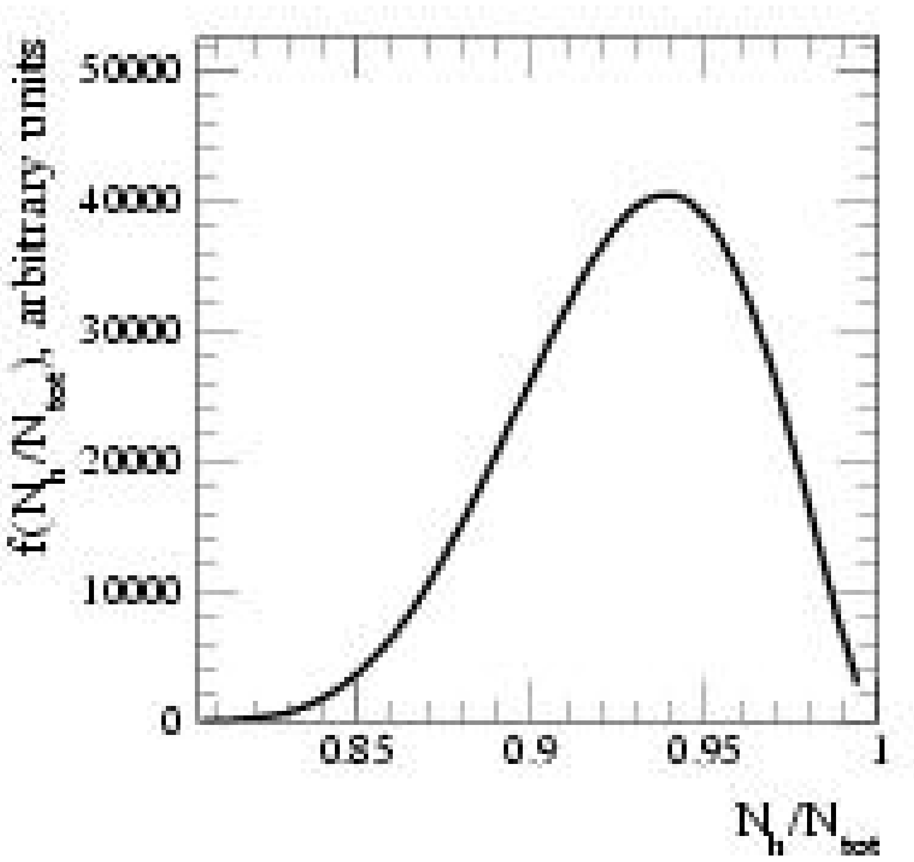


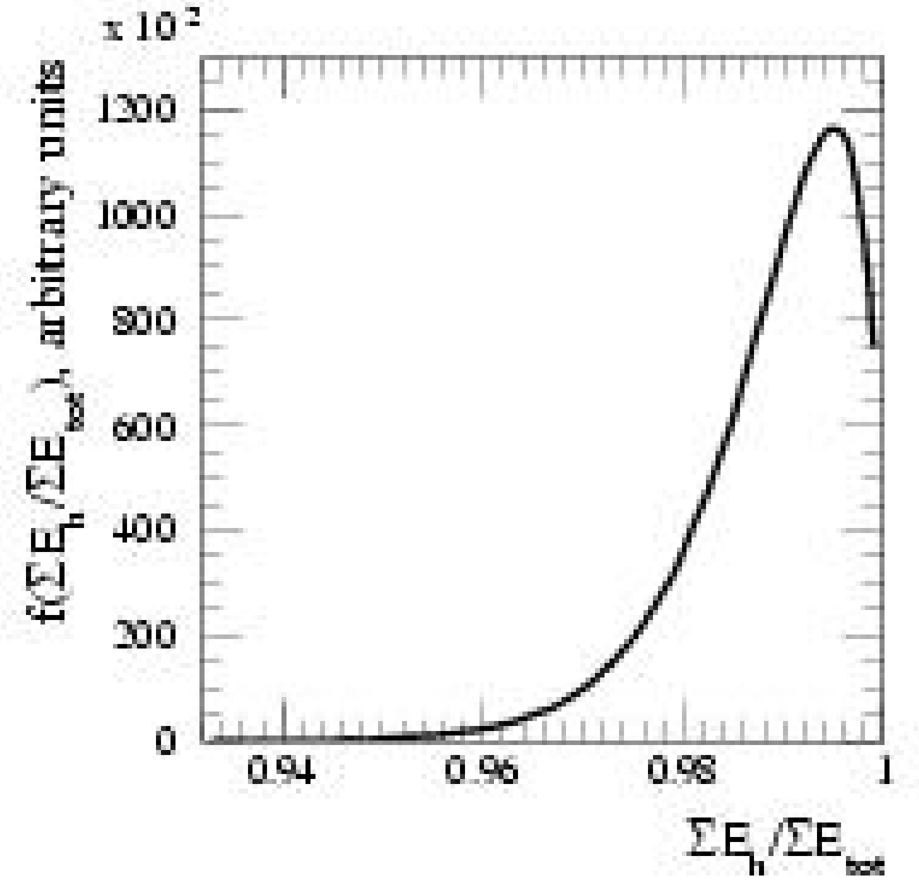
dE/dη, Electro-Magnetic   dE/dη, Hadronic

CASTOR, similarly to cosmic ray detectors, will study the forward high energy flow region :

~ 32% of total energy flow

SIMULATIONS of EXOTIC OBJECTS - CENTAUROS





Anomalous hadron dominance

Nh/Ntot = 0.93

ΣEh/ΣEtot = 0.99

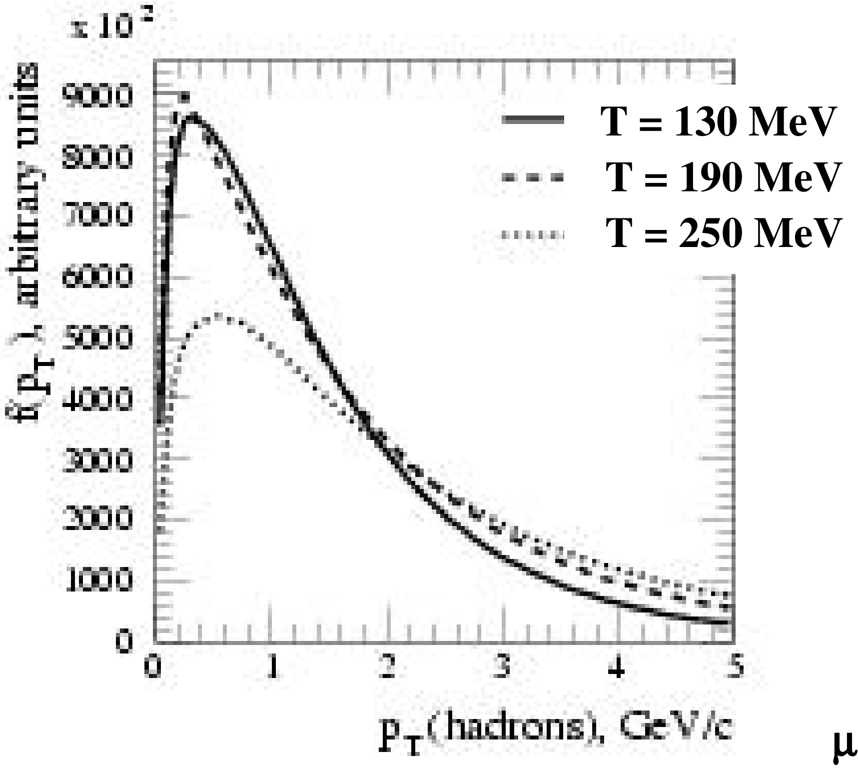
μ_θ = 600 MeV

T = 130 MeV

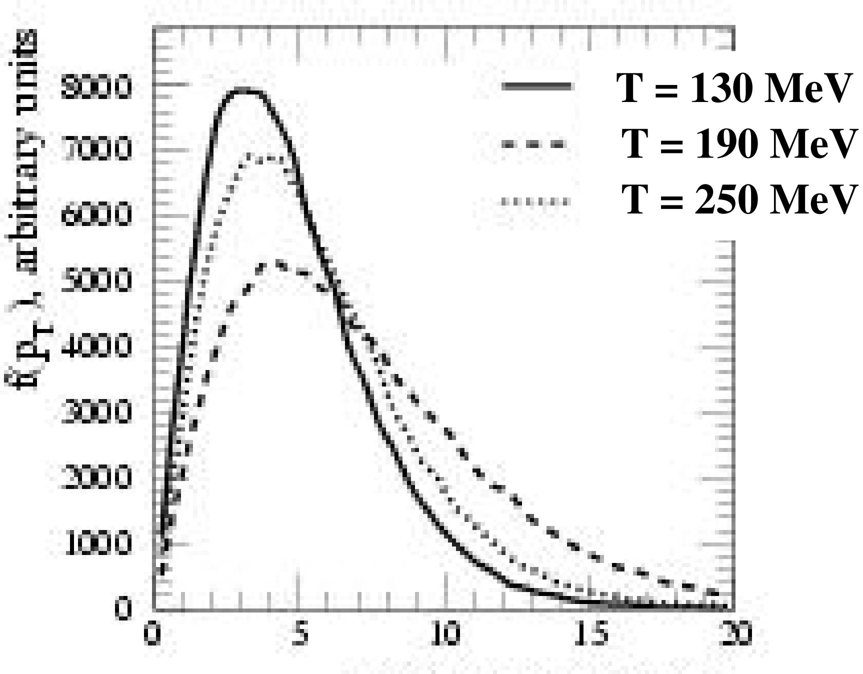
CNGEN generator - S. Sadovsky et al., Ядерная Физика 67(204)414

High transverse momenta

CENTAURO



STRANGELET



μ_q = 600 MeV

p_T(strangelet), GeV/c

CENTAURO

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

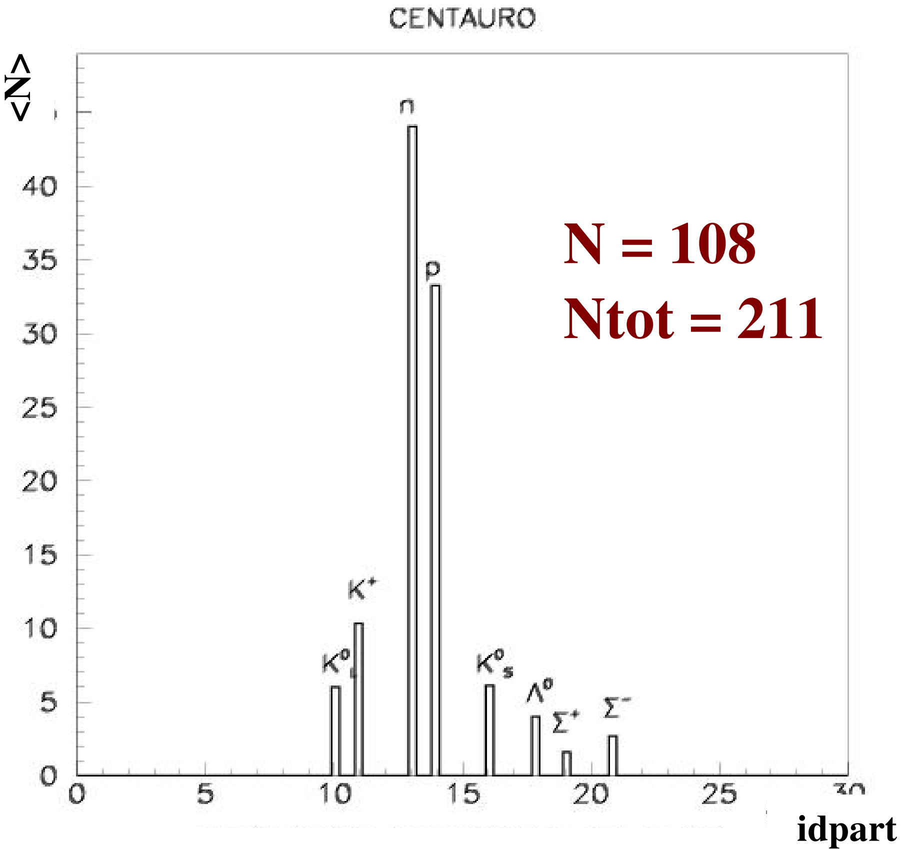
T = 250 MeV, <pT> = 1.75 GeV/c

HIJING

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

S. Sadovsky et al., Ядерная Физика 67(204)414

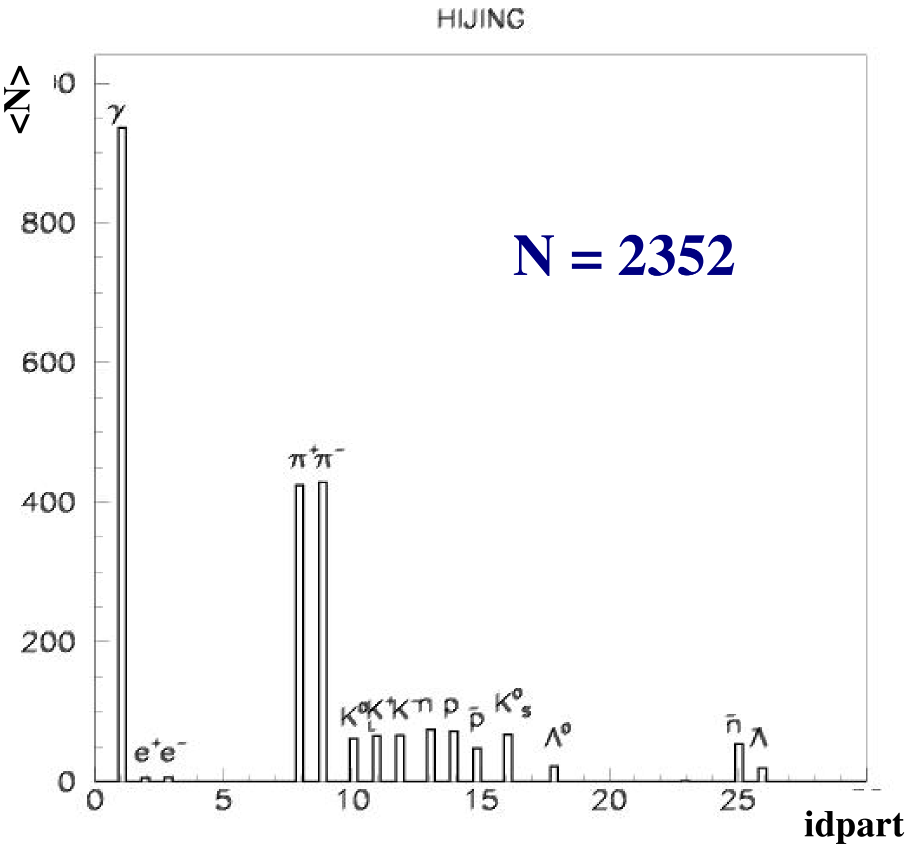
MULTIPLICITY in the CASTOR acceptance



N = 108

Ntot = 211

T = 250 MeV, μ_q= 600MeV, Δy_{stop} = 3.0



N = 2352

$5.2 < \eta < 6.5$

CENTAURO

Low multiplicity
mostly baryons + kaons

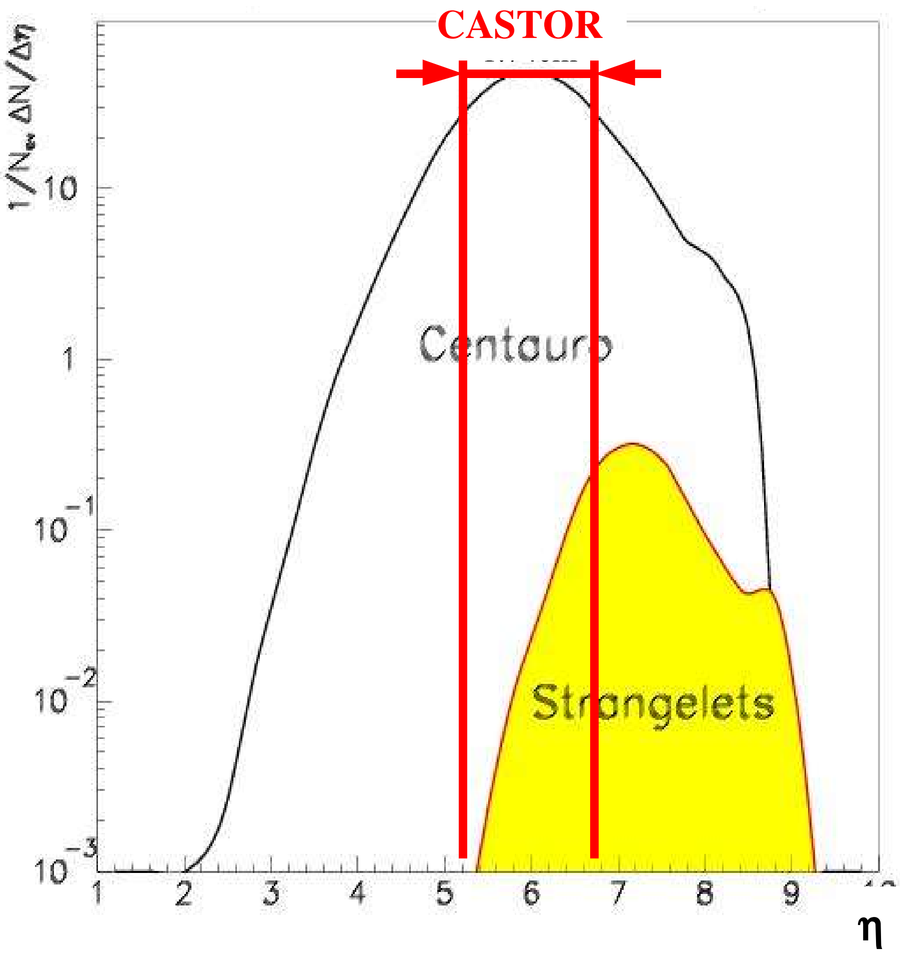
HIJING

High multiplicity
dominated by pions

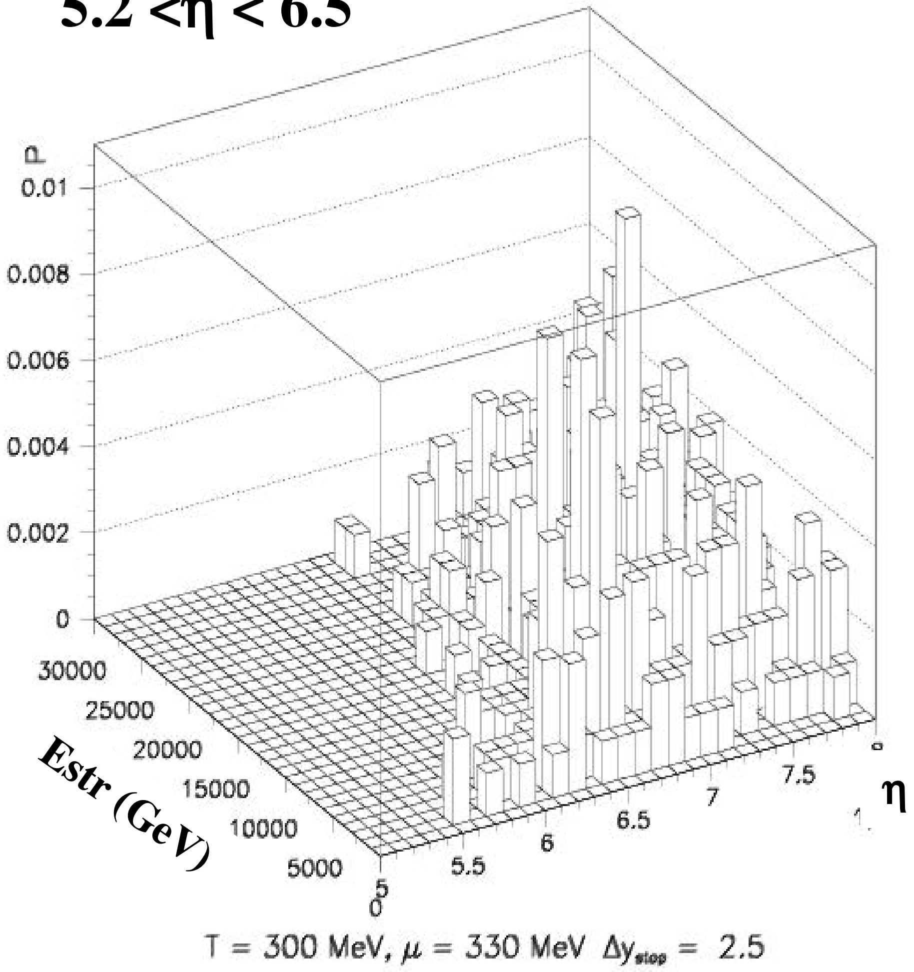
E. G.-D., Acta Phys.Pol. B37 (2006) 153

Probability of CENTAURO and STRANGELET detection

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



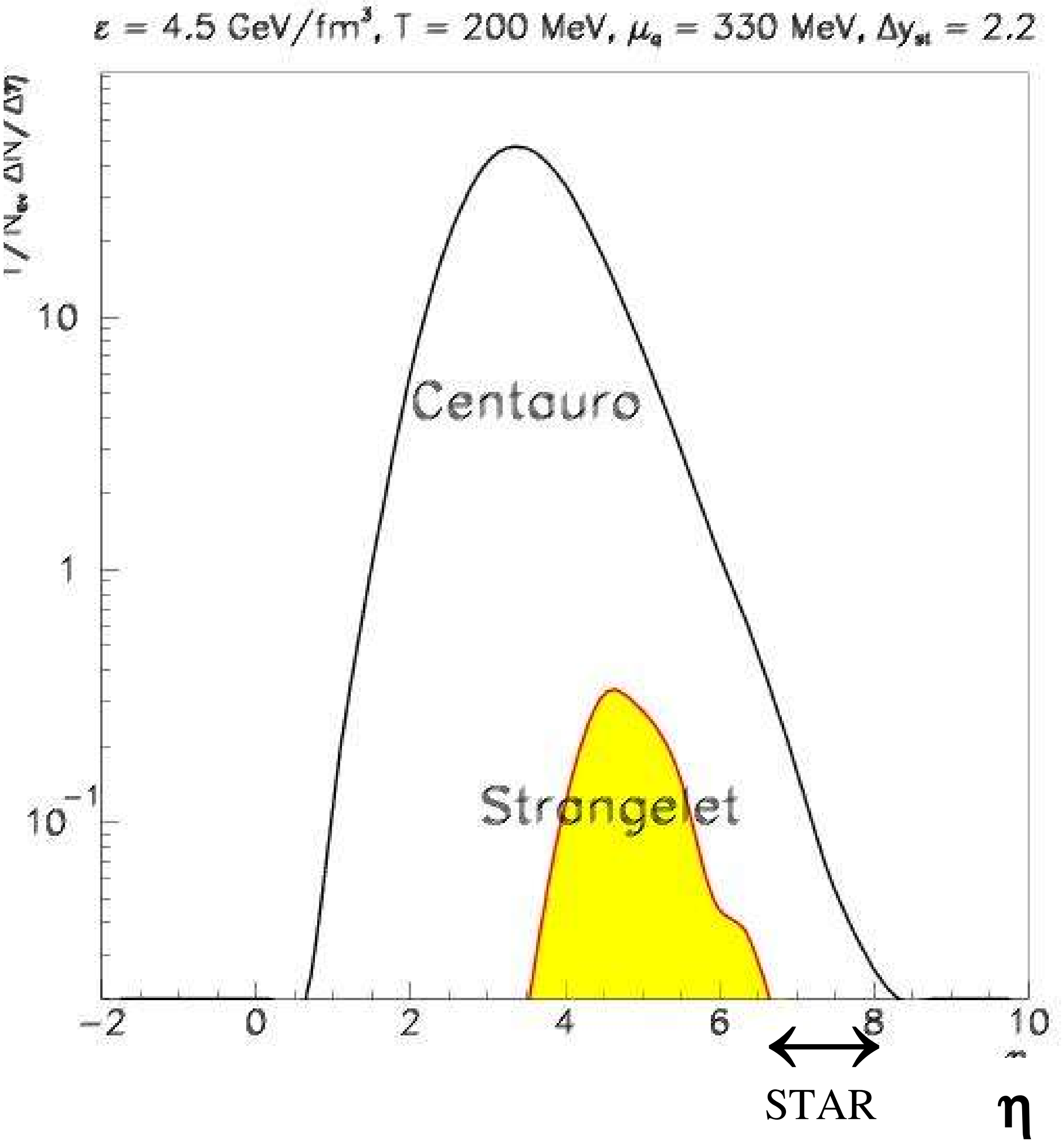
5.2 <η < 6.5



- ~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

By the way...

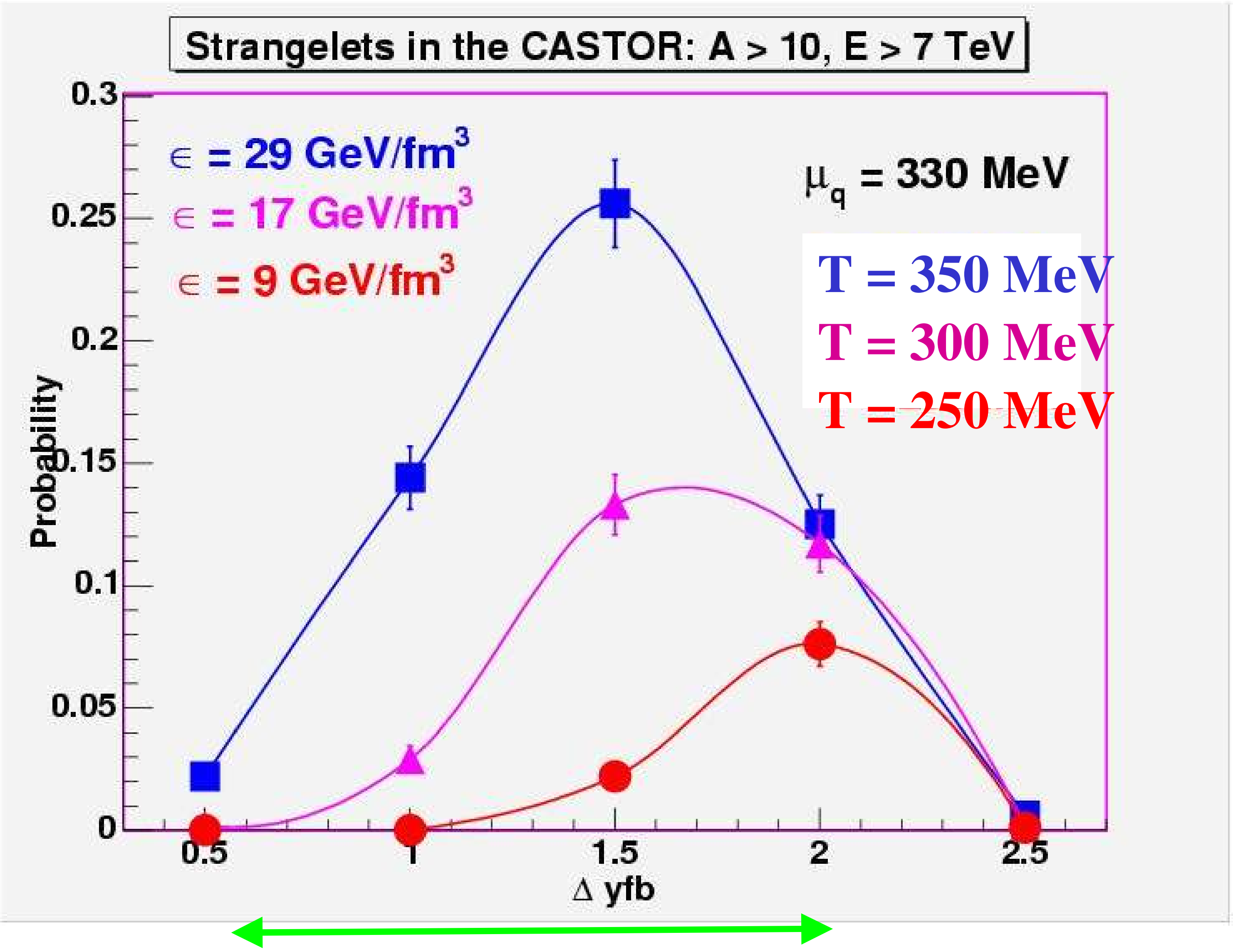


Central Au + Au at RHIC

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 – may be too forward rapidity region for strangelet formation ??

Strangelets from Centauro Decay



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

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

$5.2 < \eta < 6.5$

Expected at LHC:

- **Energy densities up to**

  $\epsilon \sim 30$ GeV/fm^3

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

  HIJING,VENUS

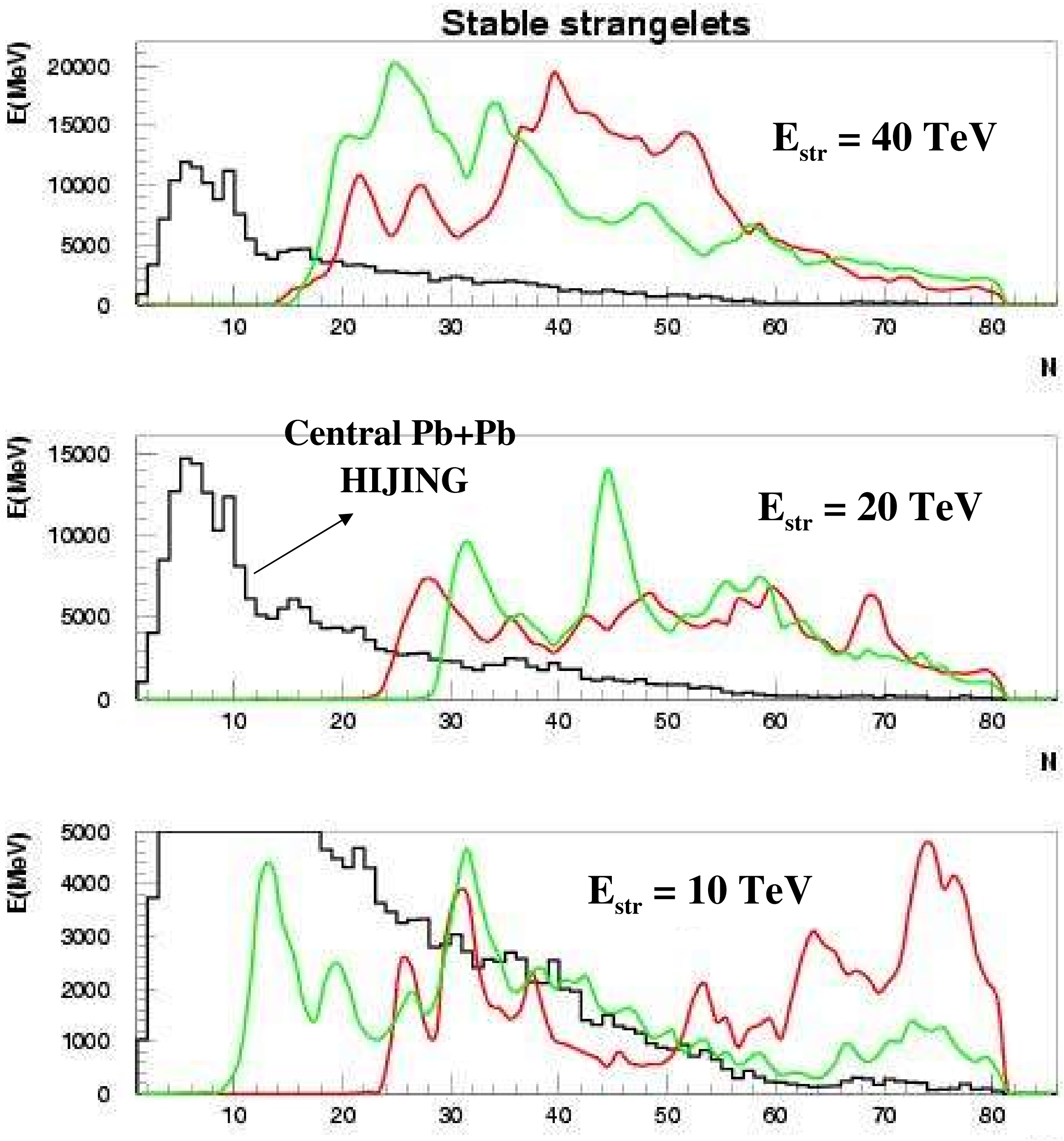
- **$\Delta y_{stop} \sim 2 - 3$**

  BRAHMS at RHIC

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

Passage of strangelets through the calorimeter

GEANT-3.21



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

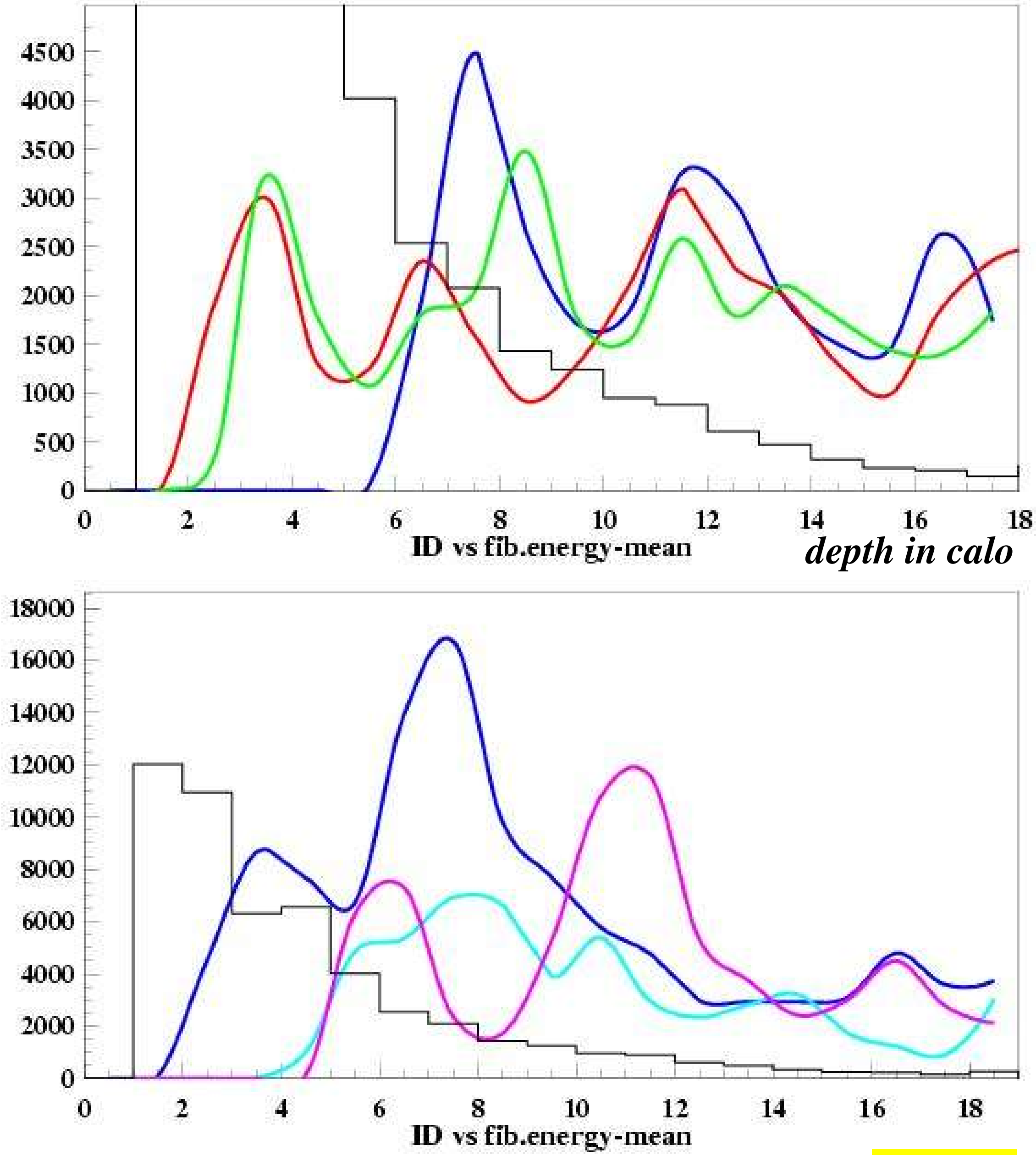
STRANGELET SIGNALS clearly seen ABOVE the BACKGROUND

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)

Stable Strangelets: E = 5-7.5 TeV; E = 12-16 TeV



depth in calo

300 X0

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

Strangelet
simulations in the CMS environment
GEANT4-OSCAR

Geometry:

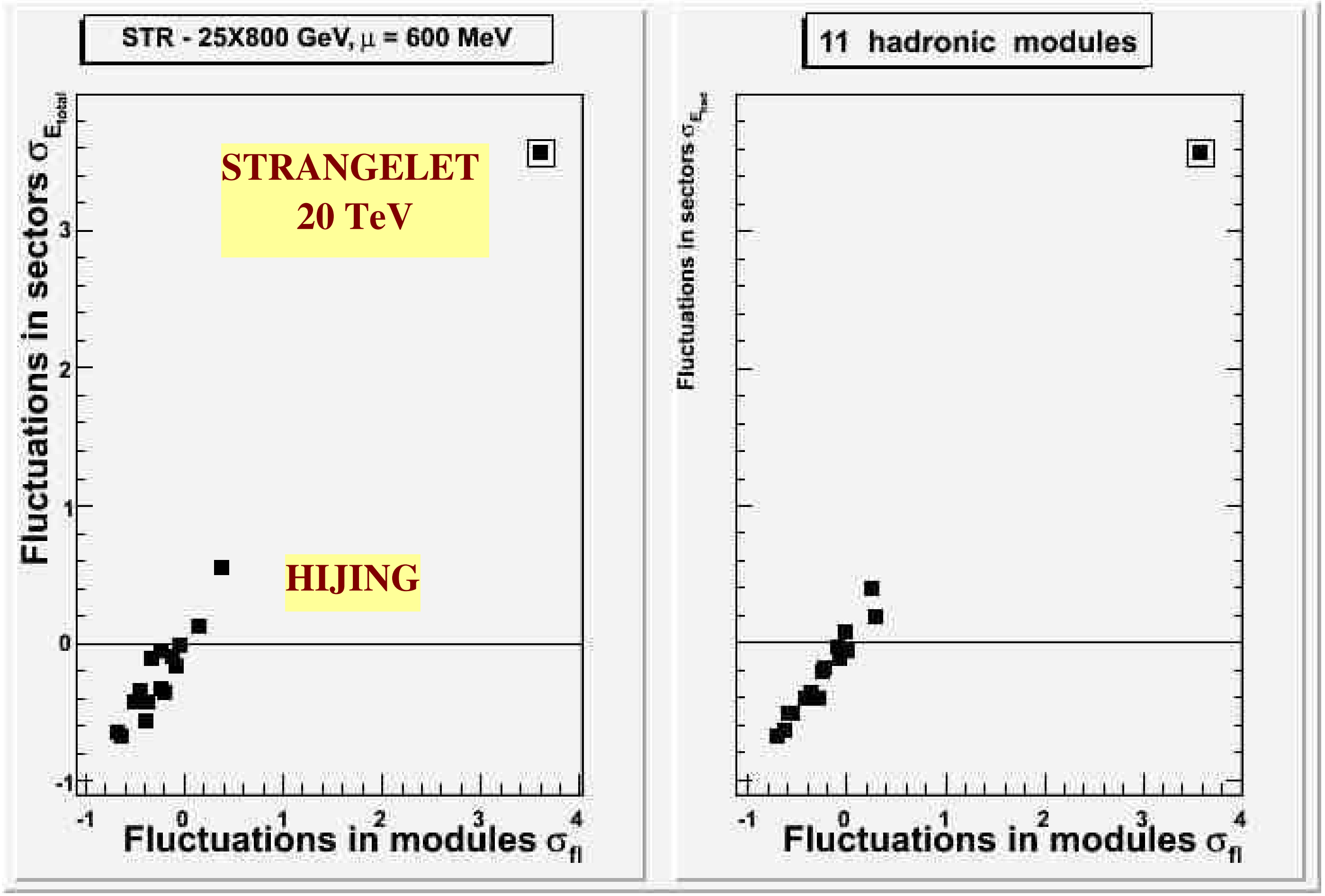
- *one layer: 5 mm W + 2 mm quartz plate ~2.4 X0*
- *7 layers per readout unit*
- *16 (in ϕ) x 18 readout channels*
- *Total depth: ~300 X0, 10.5 Λint*

Hump-structure, seen for the finer longitudinal segmentation becomes wave-like structure, but

EVEN LOW ENERGY (~ 5 TeV)
STRANGELETS CLEARLY SEEN
ABOVE THE BACKGROUND

Extraction of signal from the background at the level ~ 3 σ

for low energy strangelets (E ~ 7 TeV)



EM + H section

H section

Characteristic **many maxima form of the energy deposit** in deep calorimeters with fine longitudinal segmentation and appearance of unexpectedly strong signal close to the end of the calorimeter can be a **signature of strangelets** (despite of their electric charge and lifetime) **and of any strongly penetrating objects**

Panagiotou, CMS Week, 23-09-06,
E. G.-D., P. Katsas, M. Rybczynski,

ENERGY DEPOSITION PATTERN

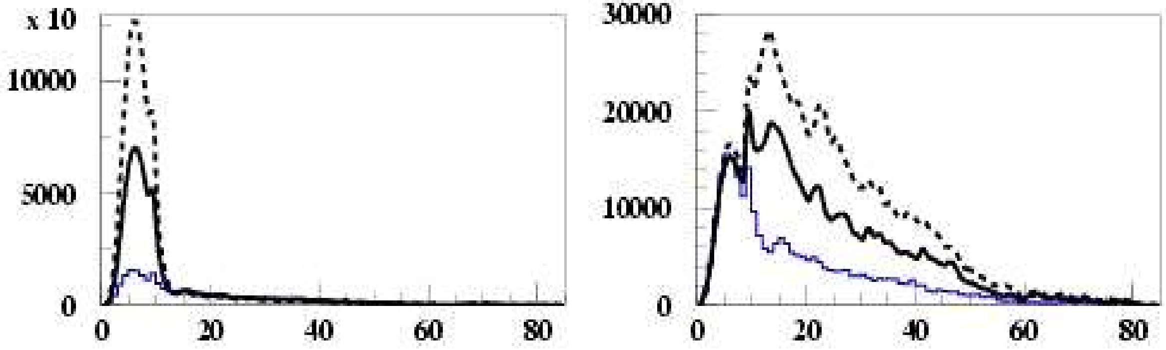
= NEW SIGNATURE of NOVEL STATES of MATTER

Different EXOTIC SPECIES produce characteristic signals

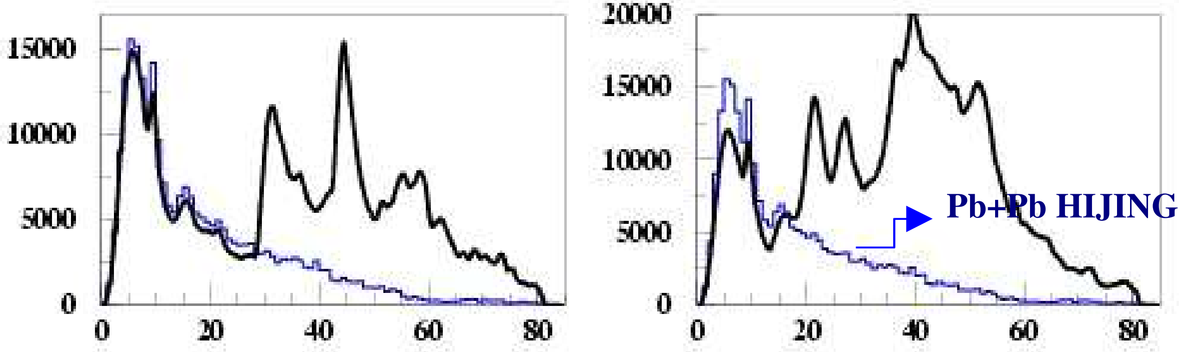
They can be distinguished one from another and from the "usual" events.

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

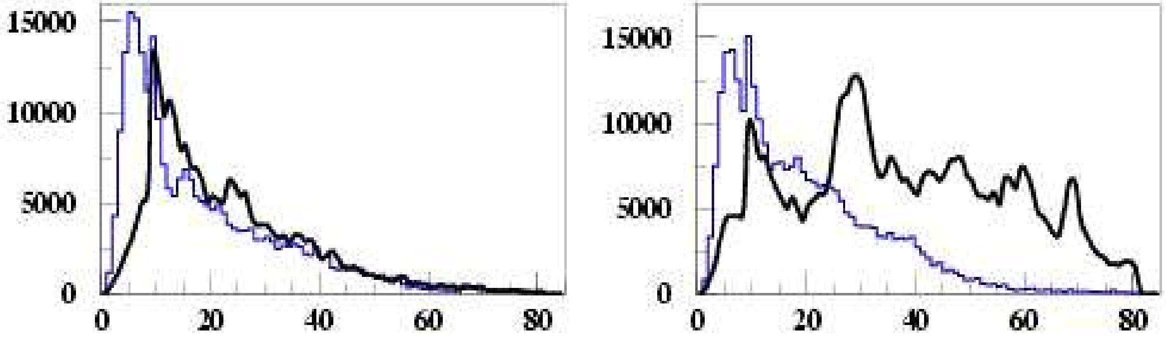
EXOTIC EVENTS (signal + background) in comparison with HIJING



Neutral DCC, 40 and 20 TeV **Charged DCC, 40 and 20 TeV**



STRANGELET, 20 TeV **STRANGELET, 40 TeV**



CENTAURO, 140 TeV **STR+CENT, 106+20TeV**

Sensitivity of the calorimeter to detection of **EXOTIC OBJECTS**

- CASTOR calorimeter – suitable for detection of different exotic objects
- Increase of ability with increasing the depth of the calorimeter and finer longitudinal and azimuthal segmentation
- Possibility of identification of (both long- and short-living) **STRANGELETS** of **Estr > ~ 5-7 TeV и Astr >10.**
- Correlation of $\sigma_{\mathbf{Etot}}$ (asymmetry in energy deposit in azimuthal sectors)

  and $\sigma_{\mathbf{fluct}}$ (fluctuations of the signal amplitude in longitudinal segments) will allow to identify even low energy objects

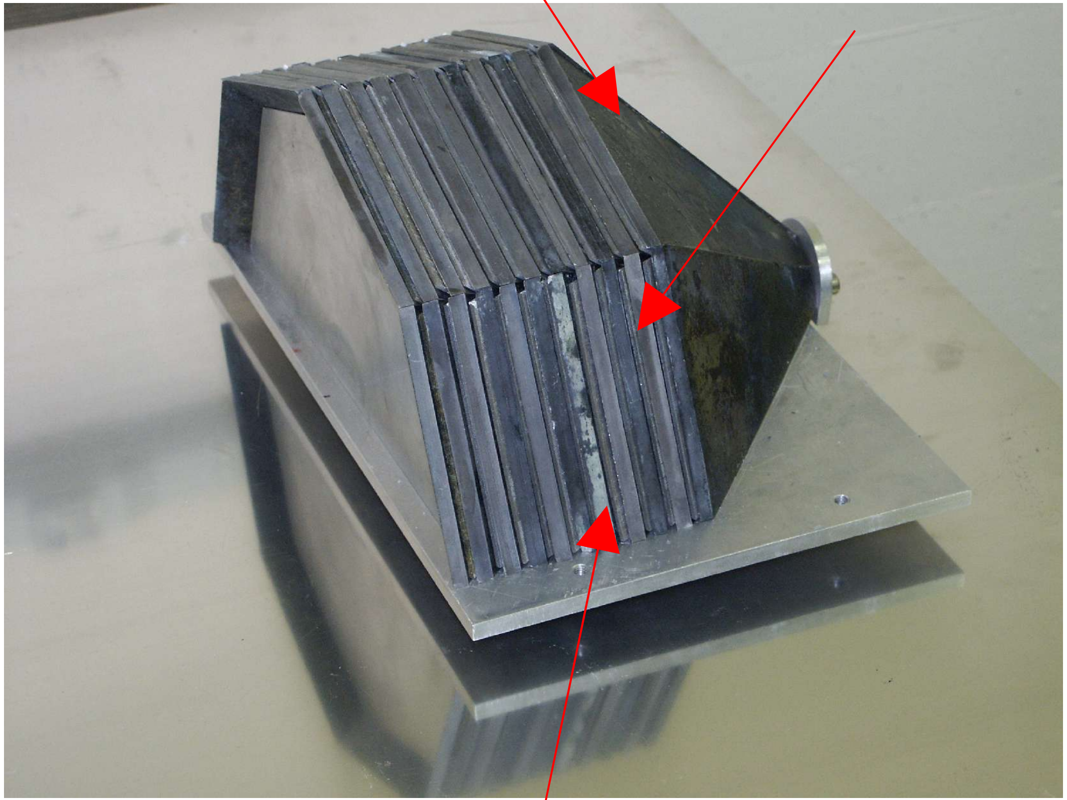
  $\Rightarrow$ extraction of signal from background at the level $> 3\sigma$

EM-PROTOTYPE TEST-2003

5mm **W-plate**

19.1 g/cm^3 ; 2.02 X$_0$ @45^0

3 Q-fiber (Q-plate) planes

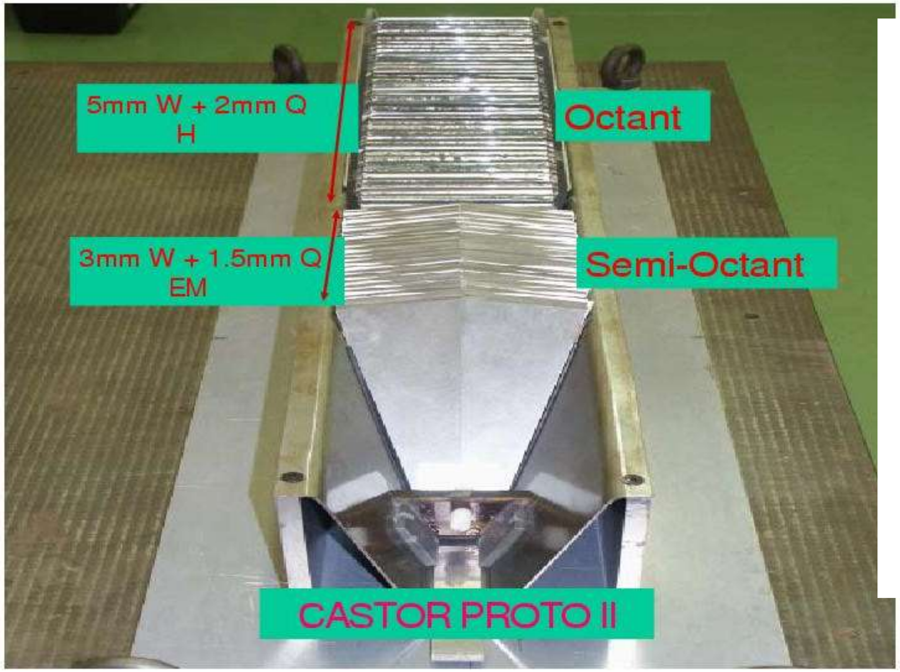


1- Reading unit = 10 (W+Q plates)

~ 23.7 Xo ~0.83   int

to be publl. in Acta Phys Pol, 2008

- **Electron beam (20-200 GeV) at CERN SPS**
- Light production with Q-fibres and Q-plates
- Uniformity of response
- Linearity
- Energy resolution
- Light transmittance with different reflectors



TEST -2004

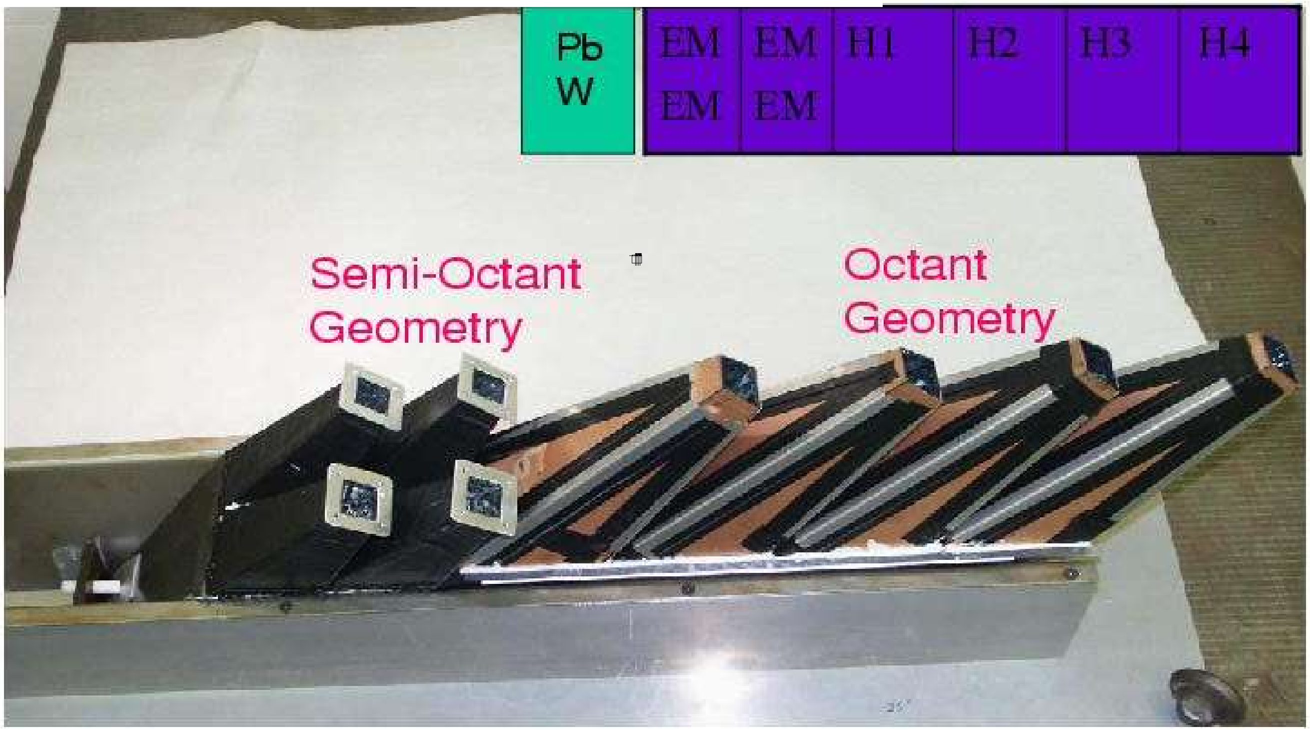
CASTOR PROTOTYPE II

EM = 2EMRU = 27 X

H = 2EMRU+4HRU = 4.3 Λ_I

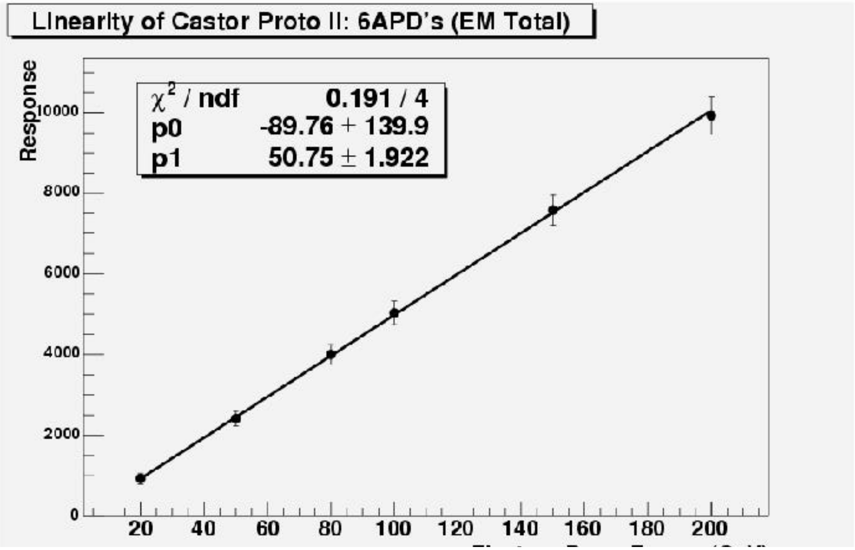
TEST - 2007

ONE TOTAL OCTANT

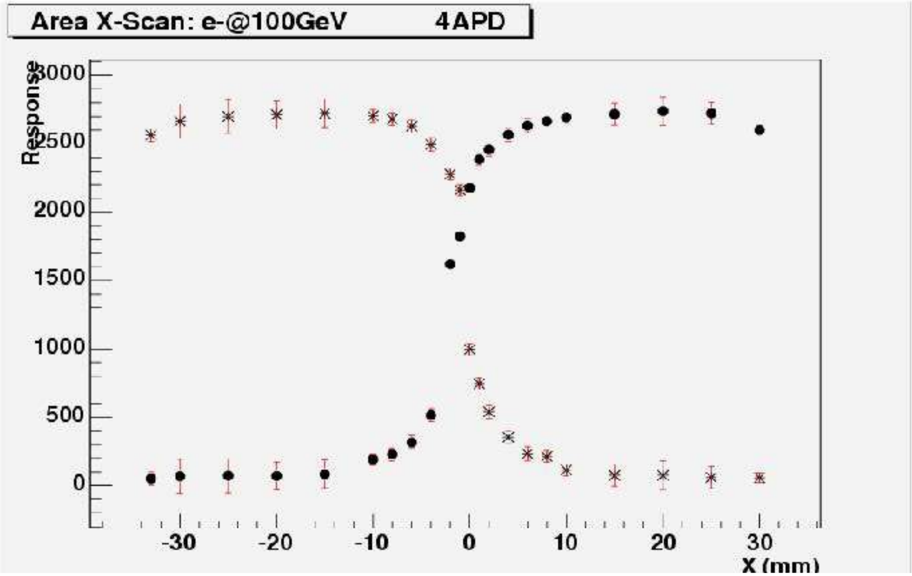


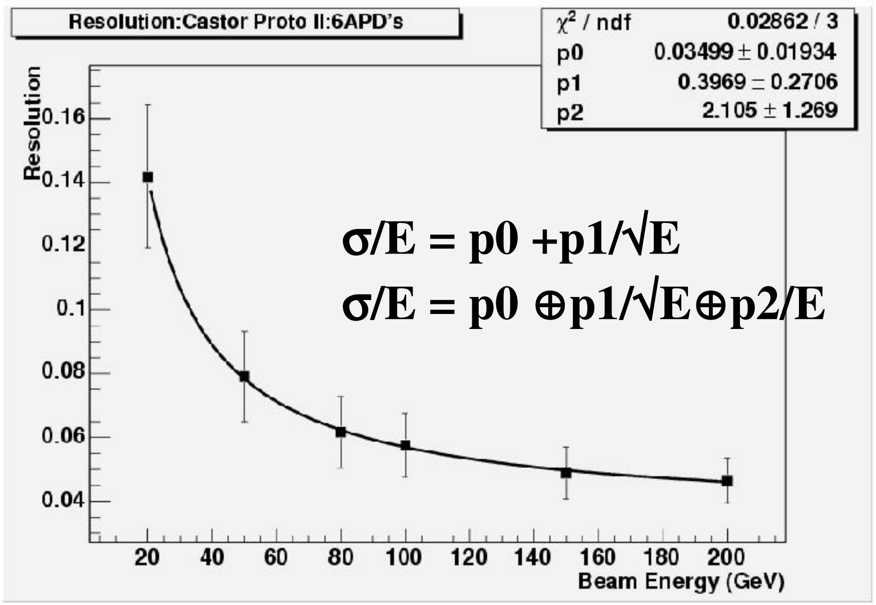
X. Aslanoglou et al.,
EPJ C52:495,2007

PROTOTYPE II



X-SCAN: SECTOR - TO - SECTOR

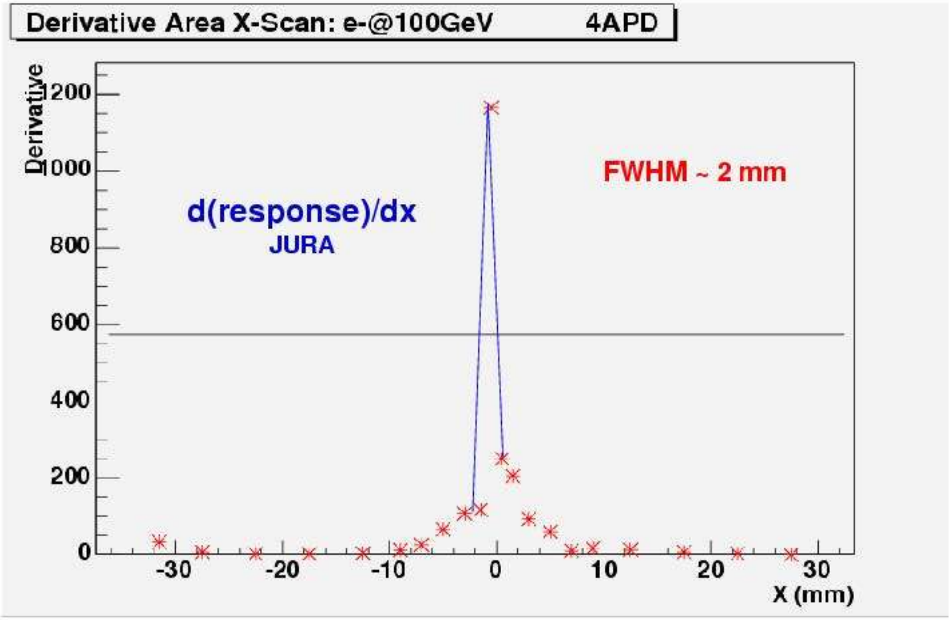




$$\sigma/E = p0 + p1/\sqrt{E}$$

$$\sigma/E = p0 \oplus p1/\sqrt{E} \oplus p2/E$$

EM SHOWER SIZE – Q-PLATE



Results of the beam tests

- **The semi-octant geometry (16 azimuthal sectors) has an efficient light collection**

- **Using quartz plates instead of quartz fibres is a good option**

- **Good linearity**

- **Energy resolution:**

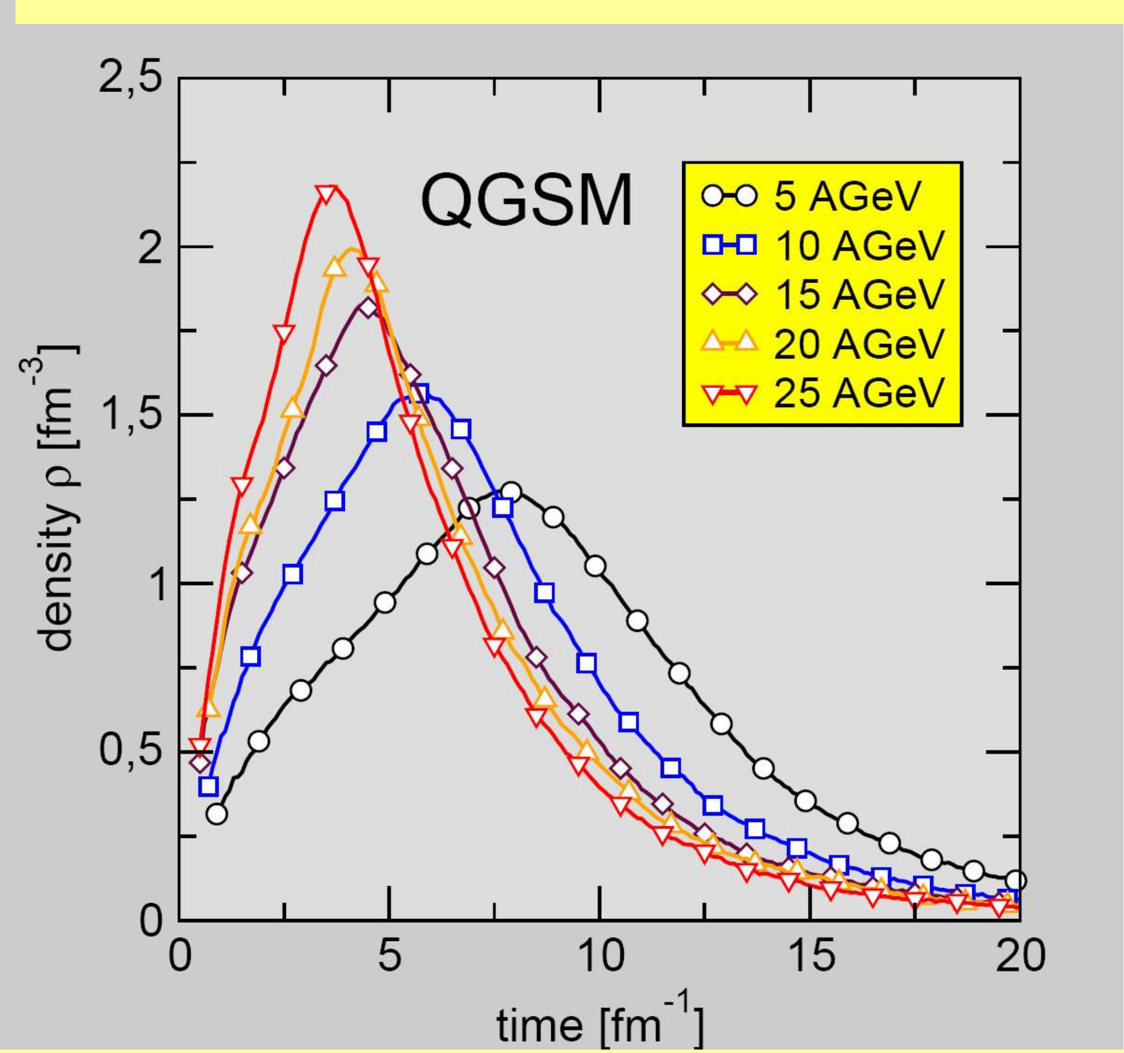
  Constant term: p0 ~ 0
  Stochastic term: p1~ 30-40 %
  Exotic objects produced at LHC with energies ~ TeV will be **measured with sufficient precision** σ/E below ~ 0.5 %

SUMMARY

- The high baryon chemical potential environment is worth a study and it could be reached in AA collisions of both moderate (~10 – 40 A GeV) and high energies, but at forward rapidity
- Extreme fluctuations are expected in a baryon rich environment produced in AA collisions at LHC energies
- Strange Quark Matter fireball model successfully describes both Centauros and strongly penetrating component
- Energy deposition pattern in deep calorimeters is proposed to be a new signature of both long-lived and short-lived strangelets and of QGP formation
- Detector CASTOR for a study of forward rapidity region at the LHC will be sensitive to different novel phenomena

Backup slides

Very high energy densities – comparable to those in the core of neutron starts are predicted to be reached in heavy ion coll. already **at moderate beam energies**



Baryon density in the inner volume of central Au+Au as a function of time, calculated with a transport code (QGSM - Quark Gluon String Model).

Already at beam en. of 5 AGeV density ϱ exceeds a value 1 fm-3, i.e. more than 6x saturation density

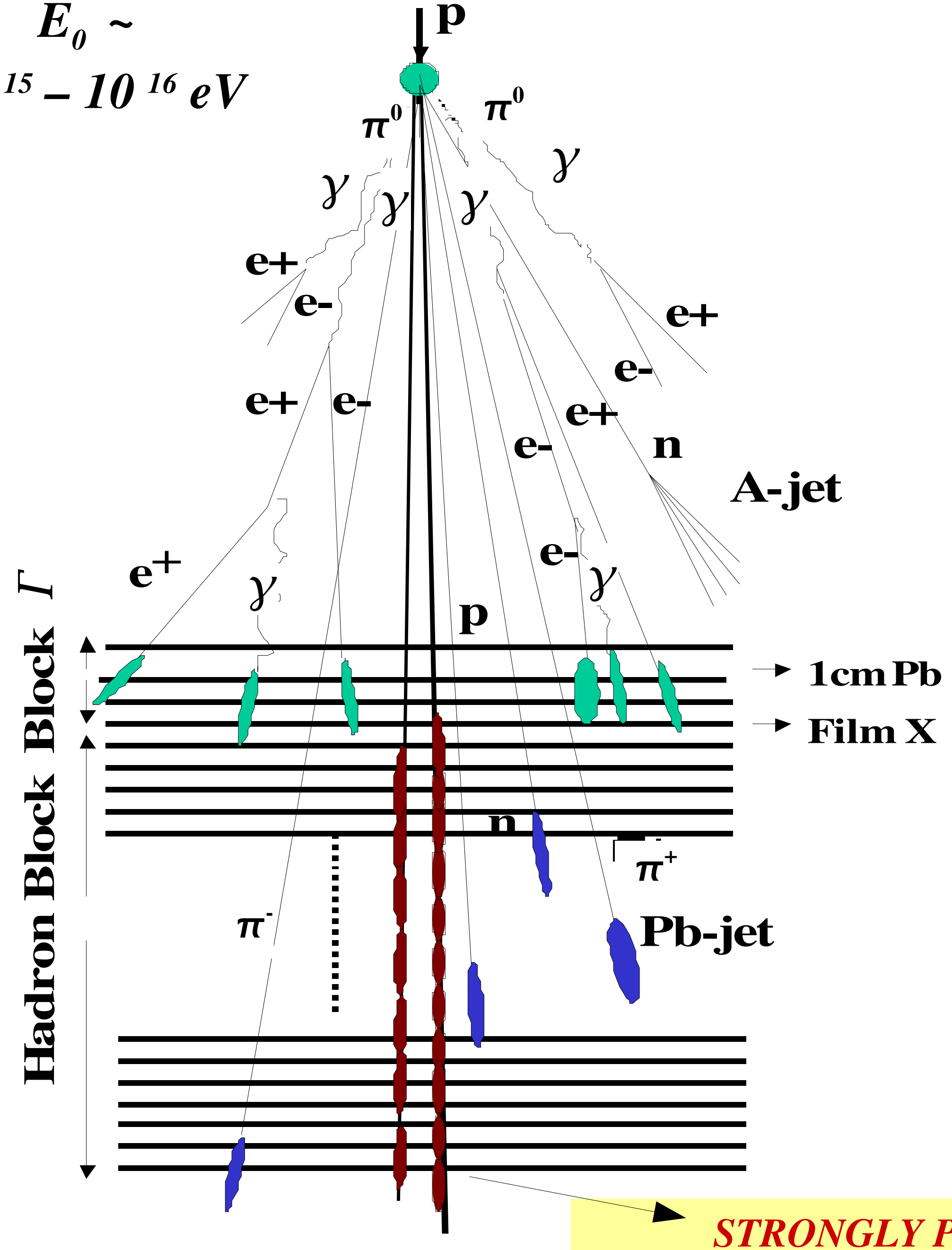
Also -fluid model - very high densities : $<\varrho_B>$ ~ **11x ϱ_0 (6x ϱ_0**) for Pb+Pb at 158 (40) A GeV – *Ivanov, Russkikh, Toneev)*

C. Fuchs, E. Bratkovskaya, W. Cassing

Transport calculations (Cascade, hadrons + resonances + strings) P. Senger, *Florence, 2006*

PHOTON-HADRON FAMILY at mountain cosmic ray experiments

$E_0 \sim 10^{15} – 10^{16}$ eV



TYPICAL EVENT

$\Sigma E_h < 30\,\%\,\Sigma E_{vis}$

$H \sim 100 – 1000$ m

CENTAURO

$\Sigma E_h >> \Sigma E_\gamma$

$N_h > N_\gamma$

$Q_h = \Sigma E_h/\Sigma E_{vis} > 0.5$

STRONGLY REDUCED ELECTROMAGNETIC COMPONENT

STRONGLY PENETRATING COMPONENT

$\Sigma E_{vis} = \Sigma E_h + \Sigma E_\gamma$

CENTAURO I

Estimated point of interaction

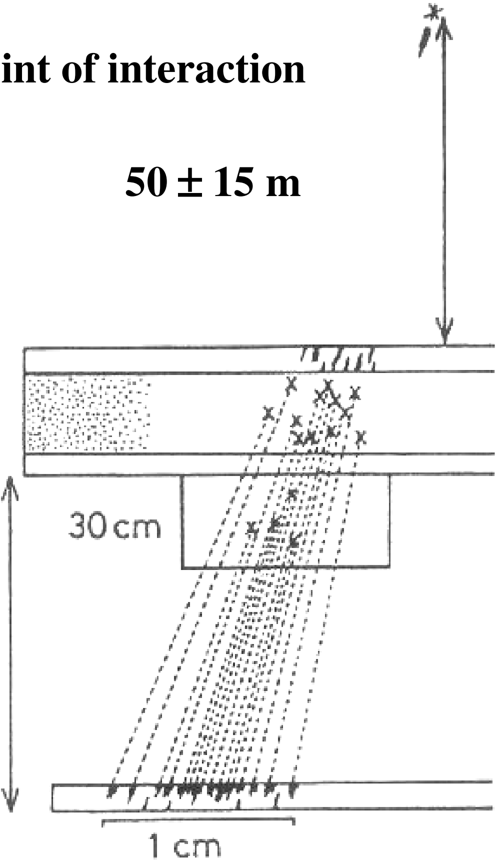
50 ± 15 m

upper chamber
6cm Pb
target layer
23 cm pitch

wooden support

space 158 cm

lower chamber
6 cm Pb



Observed in
Upper chamber… 1 e, γ
6 hadrons
0 (1)

Observed in
Lower chamber…43 hadrons
28
Estimated penetrating
through…22 hadrons

Japan-Brasil Coll., ICRC 1973

Observation:
Energy ~ 231 TeV

upper ch. - 7 cascades
lower ch. - 43 cascades
⇒
Nh = 74, Nγ =0
at interaction point

Remeasurement:
NO cascades
belonging to family
in upper ch.
The EVENT even MORE EXOTIC!!!

Ohsawa, Shibuya, Tamada, Phys. Rev.D70,074028 (2004); Nucl. Phys. Proc. Suppl. 151(2006)227 and 231

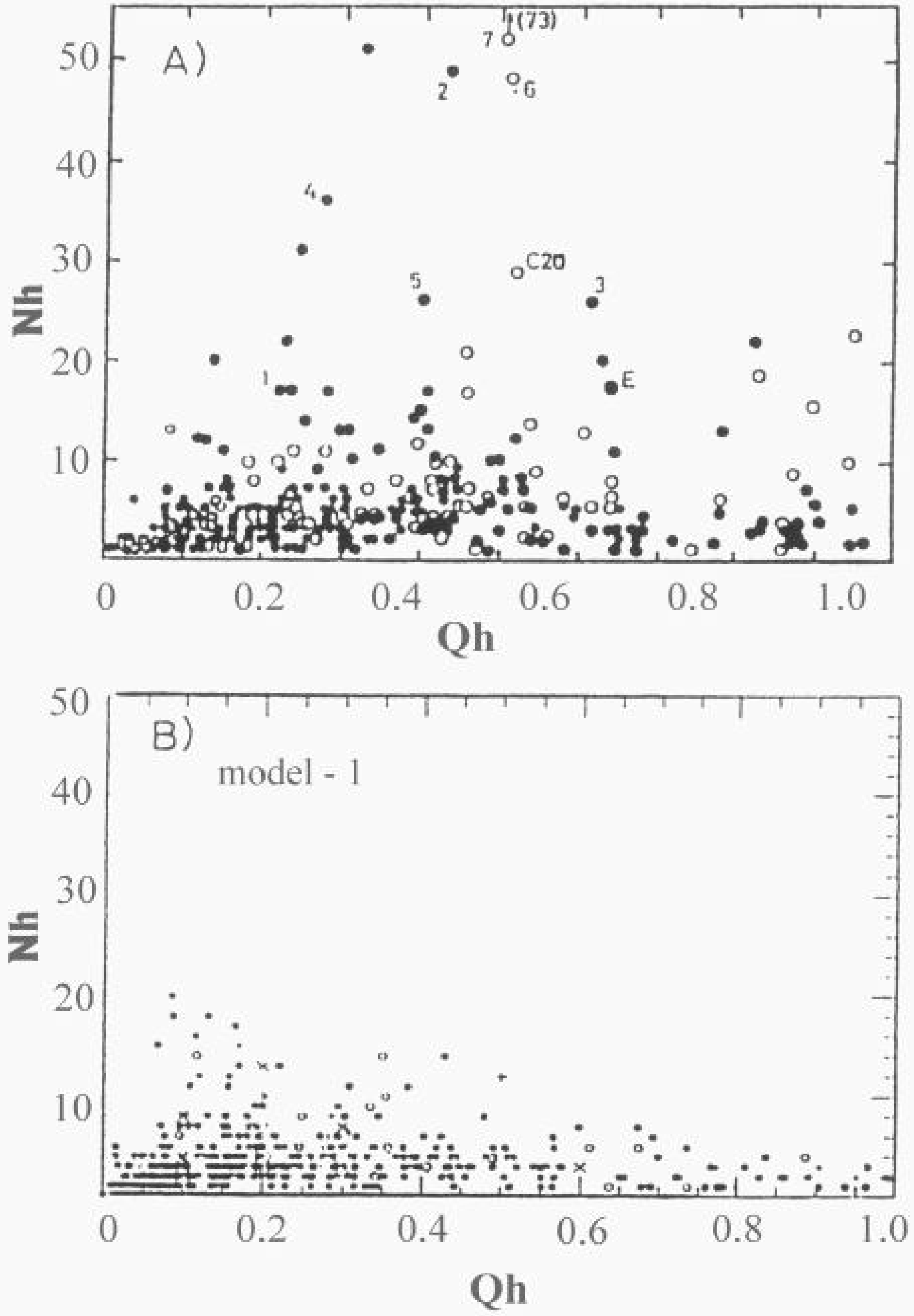
Second „clean" Centauro *Japan-Brasil Coll., ICRC 1997*

$\Sigma E_{vis} \approx 57.4$ TeV, Nh =31, Nγ =0

Probability of clean Centauros:

$P_{eksp} \sim 10^{-3}$ $P_{sim} < \sim 10^{-5}-10^{-6}$

Ohsawa et al., Nucl. Phys. Suppl. B) 74A (1999) 3



- Analysed unbiased sample of 737 events (E > 100 TeV) from Chacaltaya, Pamir and Pamir Joint-Chambers (*Baradzei et al., Nucl. Phys. B370 (1992) 365)*
- 20 % of hadron rich (Centauro-like) families
- None of simulated familes have Qh > 0.75 and Nh > 5

CENTAURO

"OBSERVED"

Multiplicity $N_h = 64 - 90, <75$

$\langle N_\gamma \rangle \sim$ *0*

Energy - *lab* $\langle E \rangle \geq 1740$ TeV

"60+14" c.m. $\sqrt{s} \geq 6760$ GeV

N+N c.m. $\sqrt{s}_{NN} > 233$ GeV

$\langle \eta_{fb} \rangle = 9.9 \pm 0.2$ ~*FRAGMENTATION*

$y_{pr} = 11.0$

$\Delta\eta_{fb} = 1 \pm 0.2$

$\langle p_T \rangle = 1.75 \pm 0.7$ GeV/c

- **STRANGELET**

Mass A ~ 10 – 15
Charge/baryon Z/A ~ 0
Strangeness/baryon fs ~ 1

ESTIMATED

$M_{fb} = 180 \pm 60$ GeV

$V_{fb} = 75 - 100\ \mathrm{fm}^{-3}$

Є$_{fb}$ = 2.4 ± 1 GeV fm^{-3}

ц$_b$ = 1.8 ±0.3 GeV fm^{-3}

$T_{fb} = 130 \pm 6$ MeV

$\langle \rho_b \rangle = 2.7 \pm 1\ \mathrm{fm}^{-3}$

$\langle \rho_s \rangle \sim 0.14 \pm \mathrm{fm}^{-3}$

$N_s - N_{\bar{s}} \sim 14$

$(Z/A)_{fb} \sim 0.4$

N(pion)/N(nukleon) ~ 7 10^{-6}

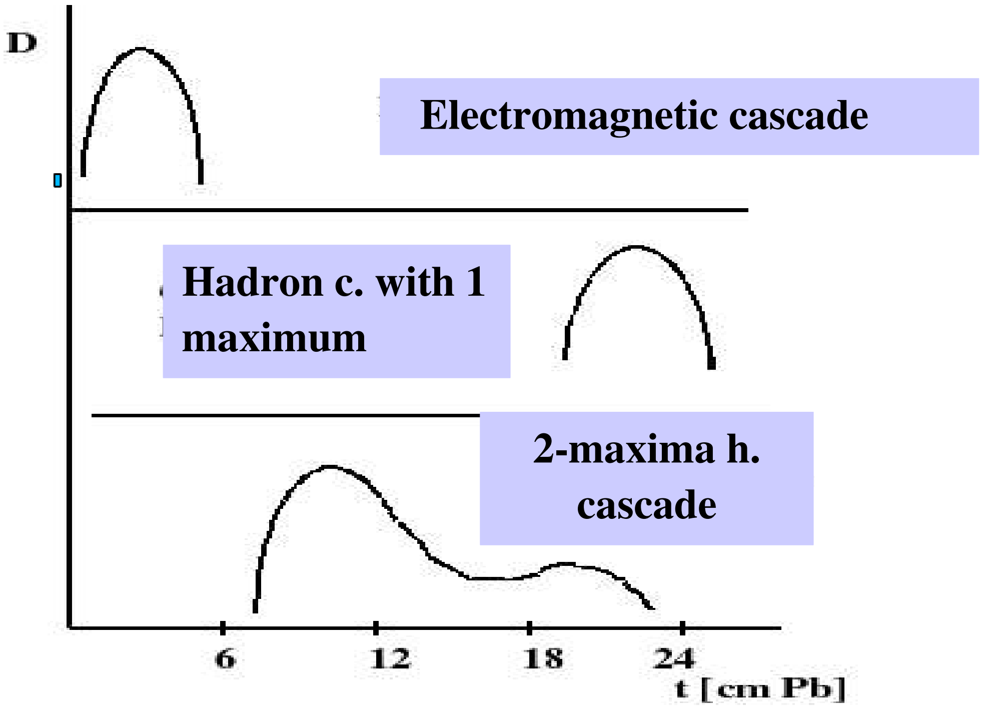
Є$_{fb}$, ц$_b$,T$_{fb}$
sufficient for phase transition

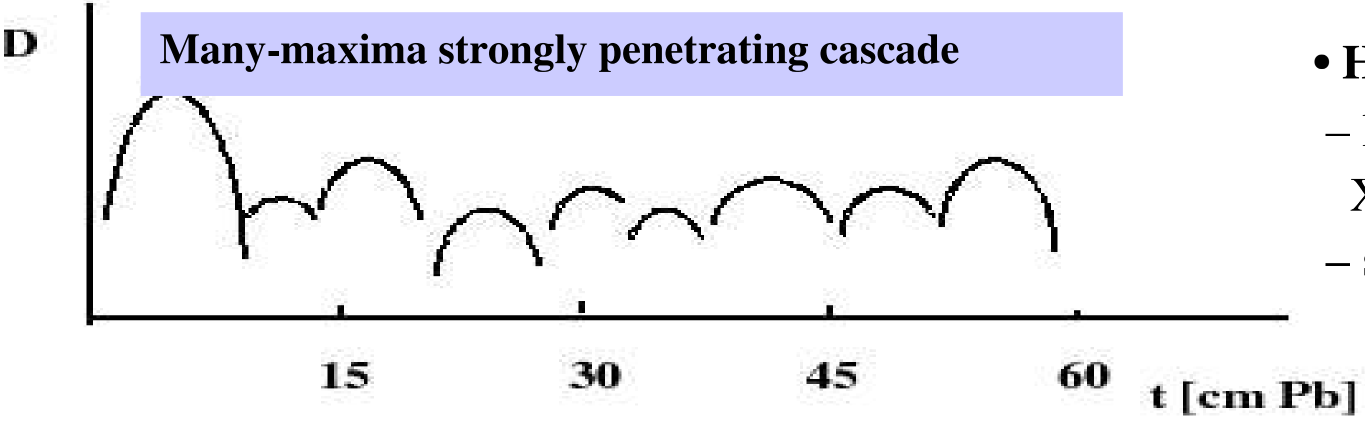
$\langle \rho^{Cfb}_b \rangle \sim 18 \langle \rho^{normal}_b \rangle$

High ц$_b$ ⇒
suppression of pion production

N$_q$ ~exp (-ц$_q$ /T)
+
suppression of u, d production by Pauli blocking

Transition curves of cascades in thick Pb chamber





HADRON -RICH EVENTS

are frequently accompanied by a STRONGLY PENETRATING COMPONENT

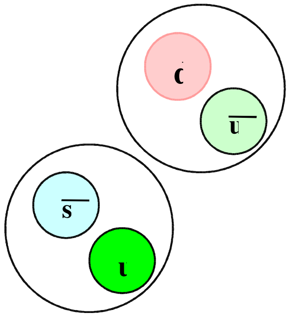
- **Long single cascades**
  - in Centauros, Chirons
- **Penetrating clusters**

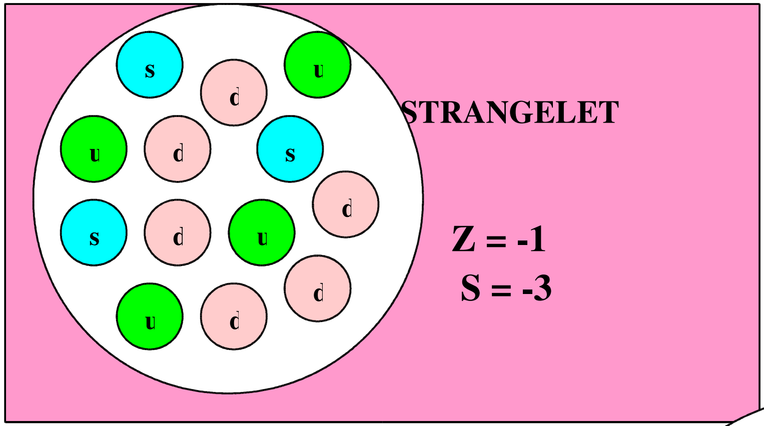
  (several cascades at small distances and with small relative pT ~ 10-20 MeV/c
  - in Chirons
- **Halo**
  - large (mm – cm) dark area at X-ray film
  - superfamiles at $E > 10^{16}$ eV

Strange Quark Matter

Bodmer – Collapsed Nuclei
Witten - SQM
Phys. Rev. D30 (1984)272

Mesons

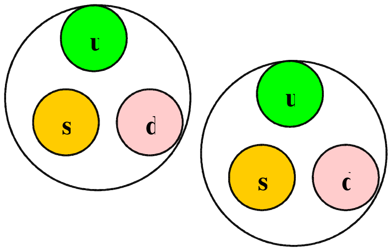




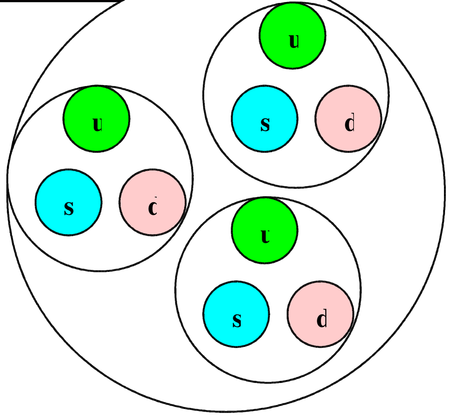
STRANGELET

Z = -1
S = -3

Baryons



Hyper-nuclei



Mass range of SQM
light nuclei – neutron stars

Lightest strangelet -
H dibaryon (*u u d d s s)*
can be looked for at
lower energies (~10-40 GeV)

- Systems with large number (> 3) of quarks are allowed in QCD
- Adding of strange quarks
  ⇒ occupation of lower energetic levels
- Reduction of Coulomb repulsion (low Z/A)
  ⇒ increase of stability

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**

$$r_0 = \left(\frac{3}{4} n \right)^{1/3}$$

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

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

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

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

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
$\alpha_c = 0.3$

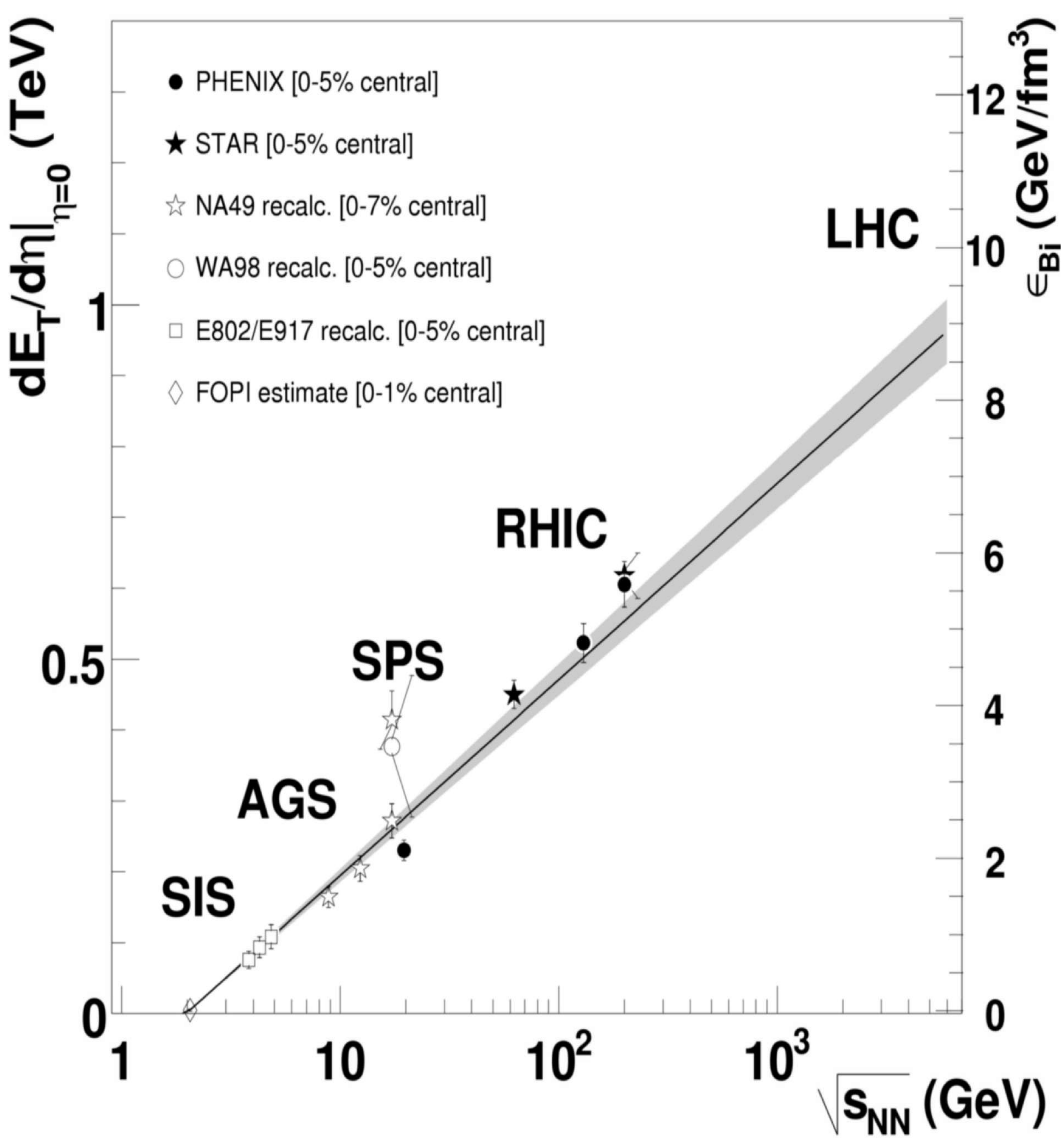
Lower limits of energy densities

- Bjorken estimate at midrapidity
- $\tau = 1$ fm/c
- (indications that $\tau < 1$ fm/c (fast termalization at RHIC)

->

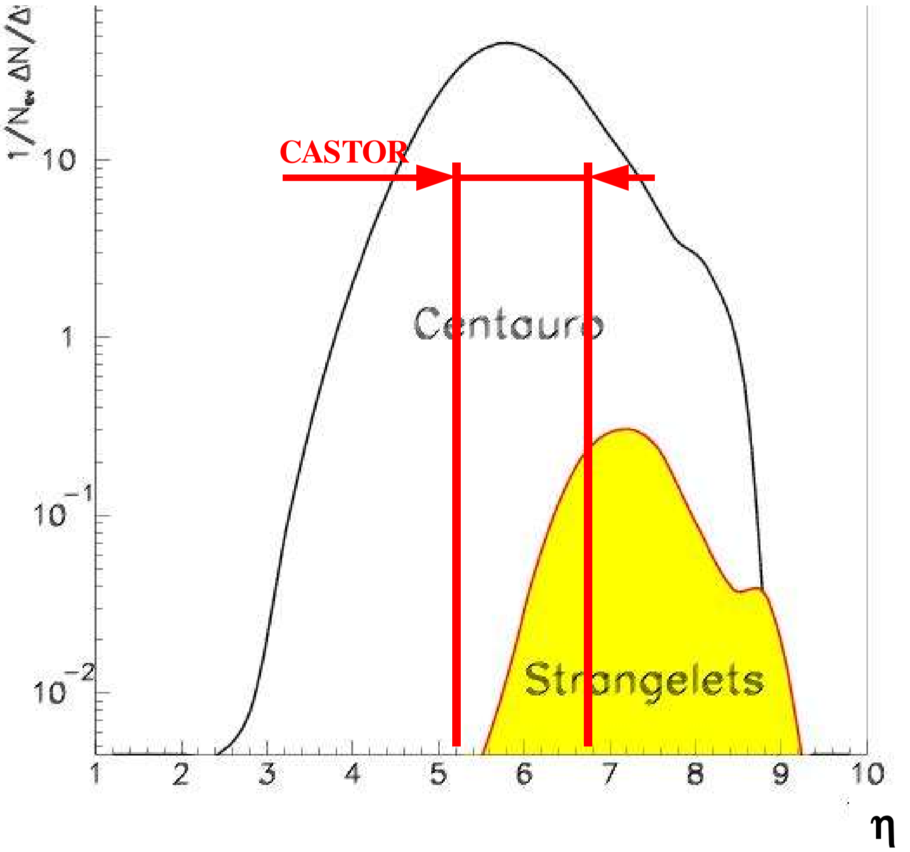
higher energy densities are expected at LHC

D'Enterria, nucl-ex/0611012

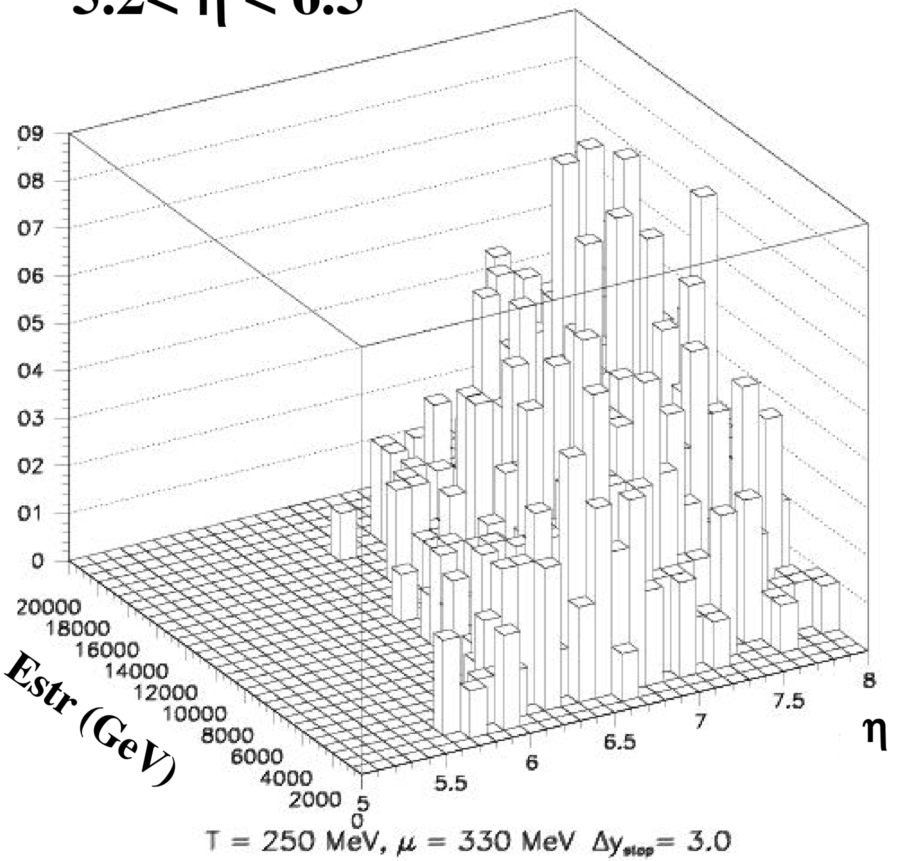


Probability of CENTAURO and STRANGELET detection

ε = 9 GeV/fm^3, T = 250 MeV, μ_q= 330 MeV, Δy_{stop} = 3.0



5.2< η < 6.5

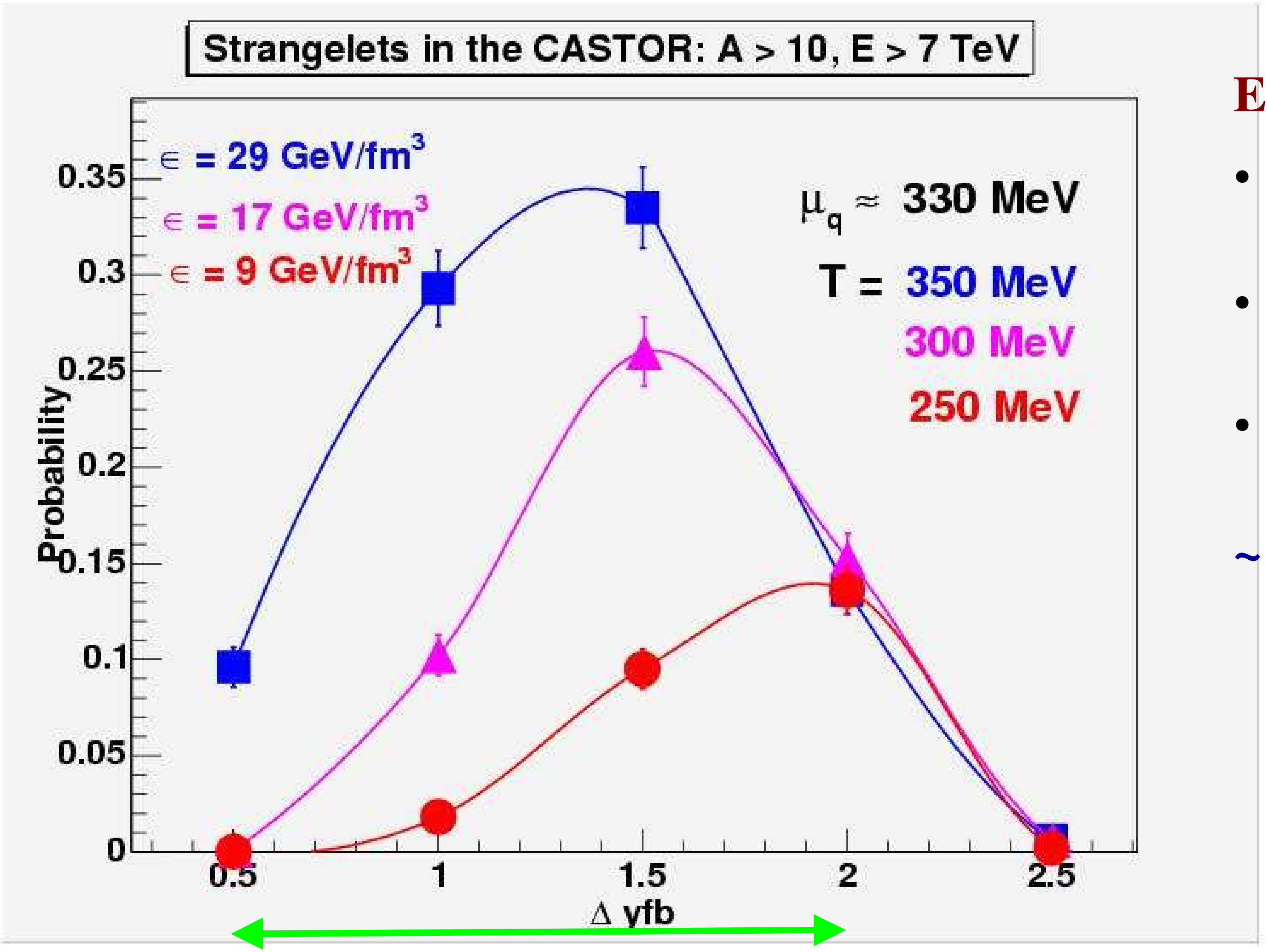


- **~60 % of Centauro fb decay products and ~ 8% of strangelets within the CASTOR acceptance**
- **NOTE: Even very high energy strangelets (E ~ 20 TeV) are produced**

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

Strangelets from Centauro decay

$5.3 < \eta < 6.8$



Δ y stop ~ 2 – 3.5

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

Expected at LHC:

- **Energy densities up to ϵ ~ 30 GeV/fm^3**
- **Δy_{stop} ~2 – 3.5 HIJING, VENUS**
- **Δy_{stop} ~ 2 – 3 BRAHMS-RHIC**

~ several – 34 % strangelets are produced in the decay of Centauro with energies E > 7 TeV, (sufficiently high to be detected)

Investigate viability of different options

Different readout devices:

PMT’S: Hamamtsu R374 (25mm),

Philips XP2978 (25mm)

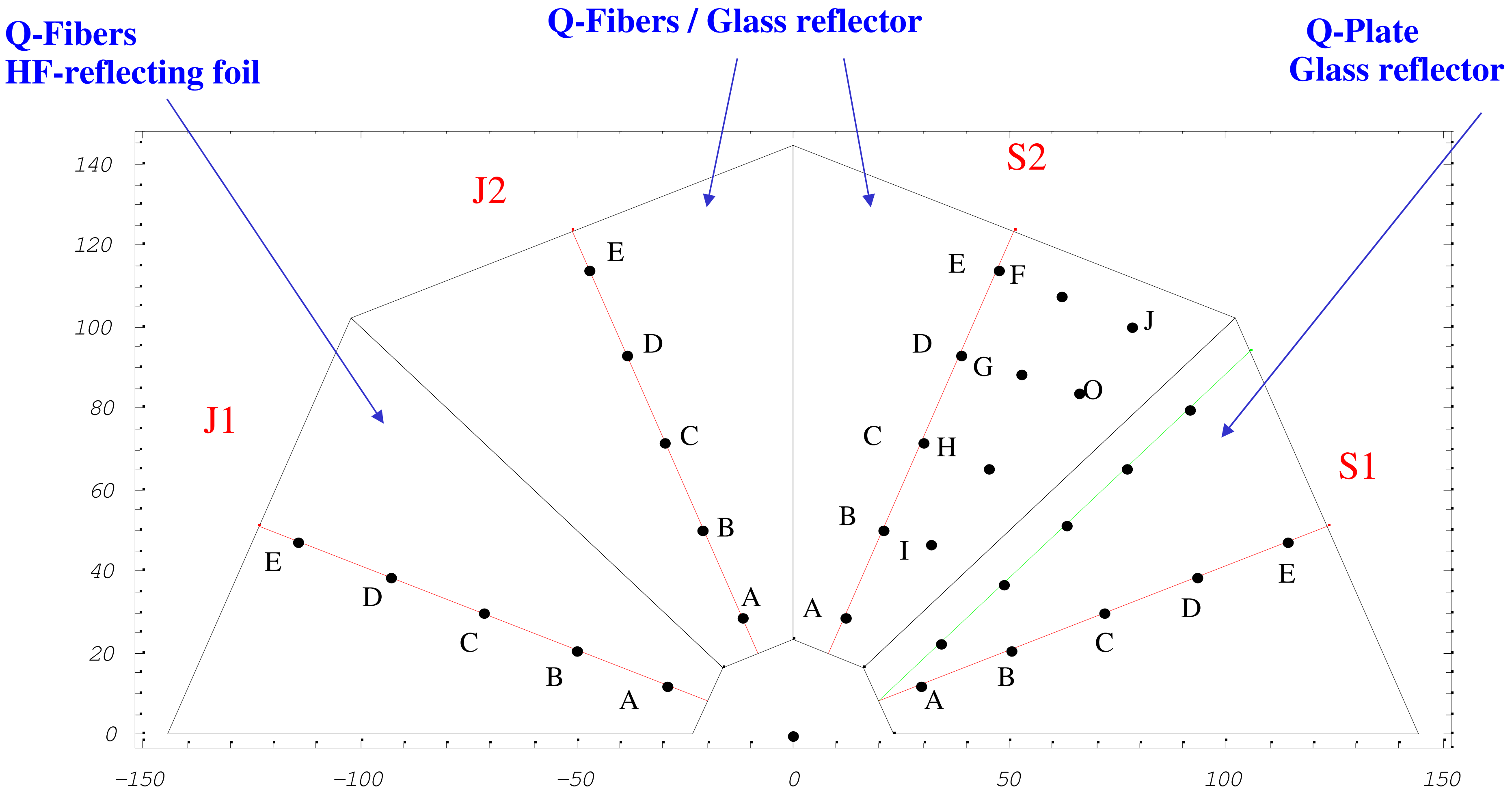
APD’s: Hamamatsu S8148 [2x2 = 1cm^{-2}]

Advanced Photonics DUV (16mm)

Different reflectors:

foil or glass

Quartz fibres or Q-plates ?



Q-Fibers
HF-reflecting foil

Q-Fibers / Glass reflector

Q-Plate
Glass reflector