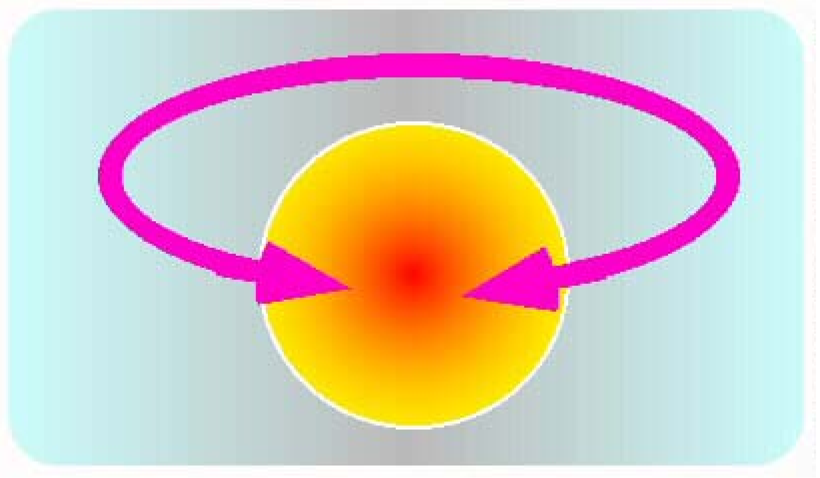
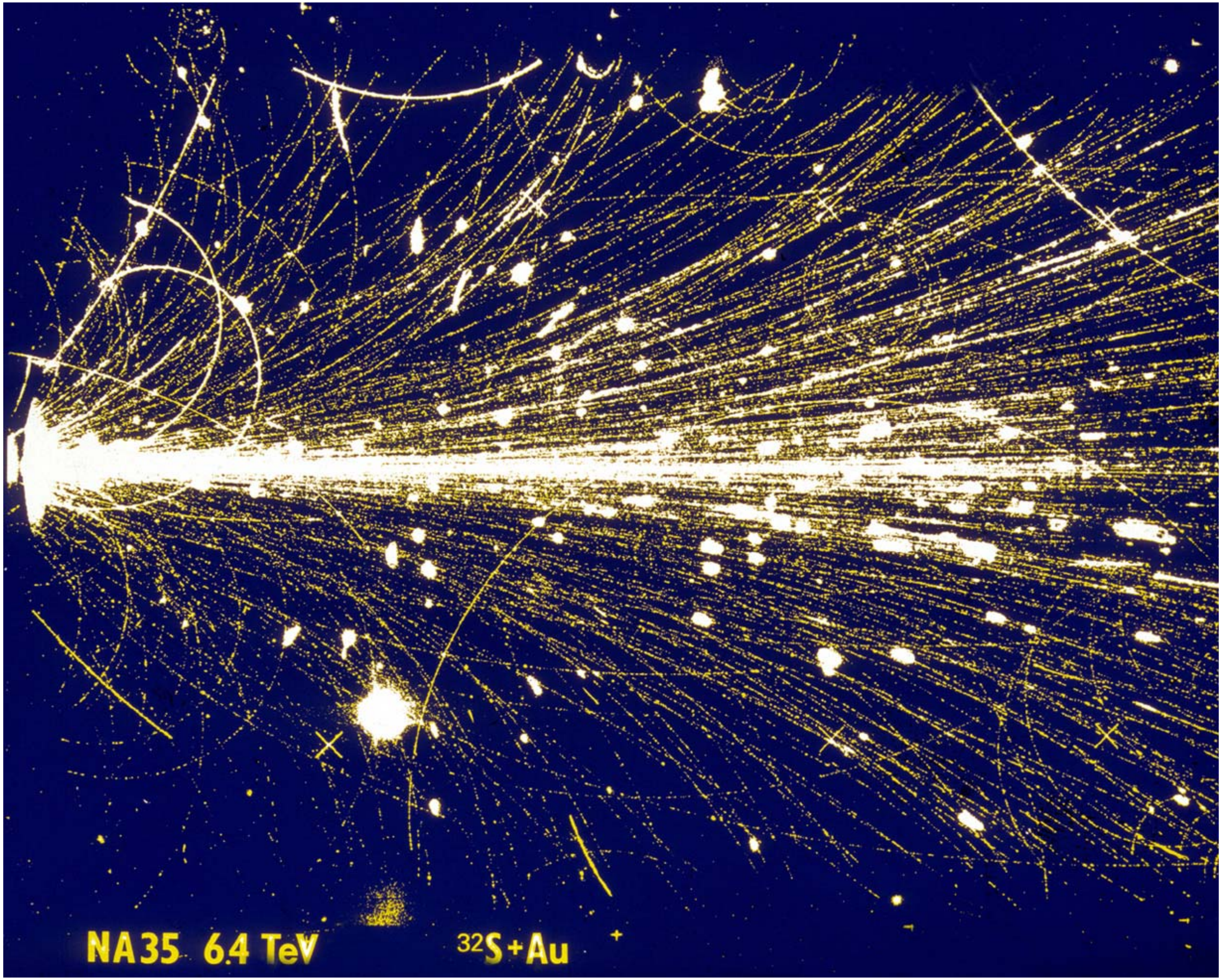
Heavy Ions @ LHC

- **Heavy Ion Physics**
  - (in VERY general terms)
- **Heavy Ion Physics at LHC**
- **LHC Project**
- **ALICE**
  - Collaboration
  - Detector
  - Performance



Pretty Messy …



NA35 streamer chamber picture, ca 1990

Heavy Ion Collisions: What for ?

- **T. D. Lee**

Two outstanding **puzzles** that confront us today:

I) missing symmetries

QCD mass generation via broken chiral symmetry ($m_{u,d} \neq 0$)

II) unseen quarks

confinement

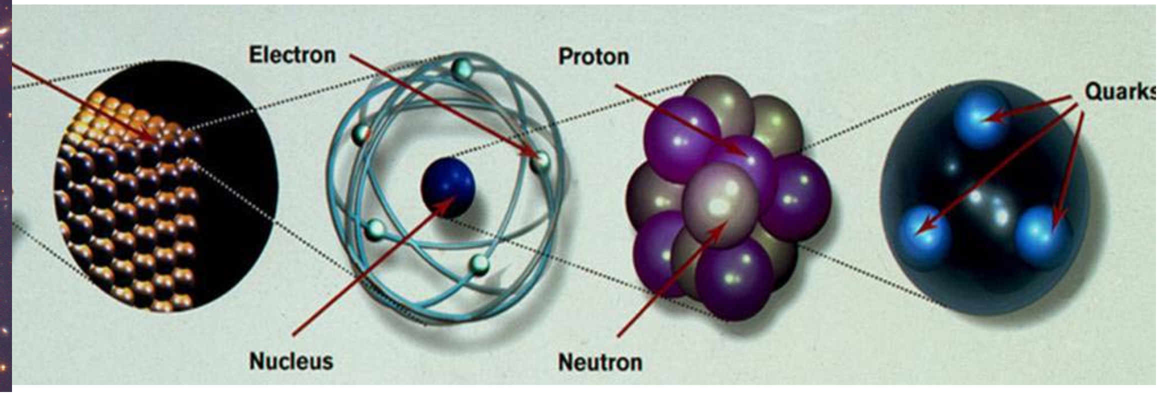
The **resolution** of these puzzles is probably tied to the structure of the vacuum.

… in most high energy physics experiments, the **higher the energy**, the **smaller has been the spatial region** we are able to examine.

In order to study the structure of the **'vaccum'**, we must turn to a **different direction**; we should investigate some **bulk phenomena** by distributing **high energy** over a l**arge volume.**

Rev. Mod. Phys., Vol 47 (1975) 267
Nucl. Phys. A553 (1993) 3c

The Dark Mystery of Matter



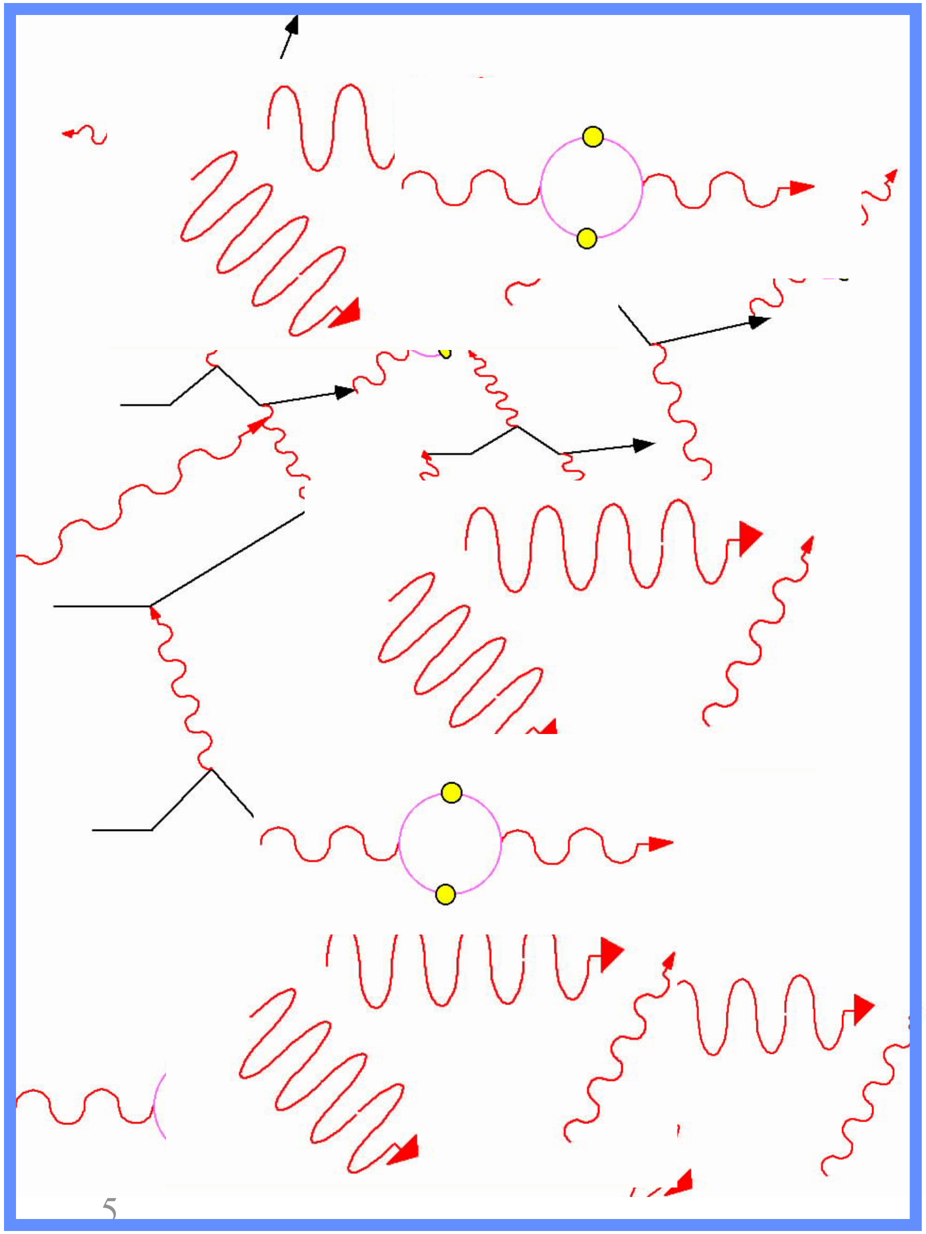
What stuff is the Universe made of ??

- **Elementary Particles** **0.1%**
  - ⇨ 12 matter particles (quarks, leptons)
    - only 4 relevant today (u, d, e, ν)
  - ⇨ 13 force particles (3 massive, 10 massless)
- **Composite Particles (hadrons)** **4%**
  - ⇨ hundreds…
    - only 2 are relevant (p,n), making nuclei
  - ⇨ luminous normal matter (stars, galaxies) **0.05%**
  - ⇨ dark normal matter (gas, planets, ..) **3.95%**
- **Dark Matter** **23%**
  - ⇨ made of unknown particles
- **Dark Energy** **73%**
  - ⇨ vacuum energy
    - of completely unknown origin
  - ⇨ should be infinite or exactly 0

We don't know **how** and **why** for ~ 5%

We don't even know **what** for the other 95%

Vacuum



low resolution

medium resolution

high resolution

large scale

according to I. Pomeranchuk

The book of physics consists of 2 Volumes:

V1: Pumps and Manometers

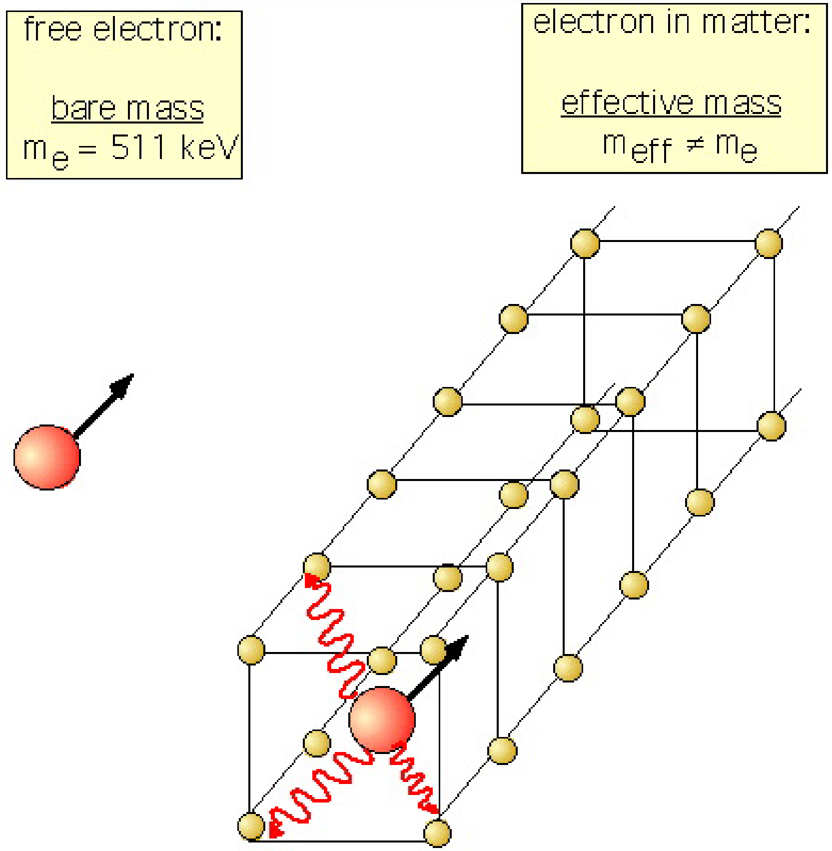
V2: Quantum Field Theory

The Vacuum is filled with the most profound physical content.

<u>Particles influence the vacuum, and the vacuum influences particles.</u>

Quoted by L. Okun, Cern Summer School, August 2001

Effective Masses



- **EW Higgs mechanism**

⇨ symmetry breaking => Higgs VeV
⇨ H coupling to particles => ‘true’ mass
for ‘elementary’ particles u,d,s,c,t,b,W,Z, ….

- **QCD ‘Higgs’ mechanism**

⇨ chiral symmetry breaking
⇨ gluon condensate
$\langle 0|gg|0\rangle \sim 200$ MeV/fm^3
⇨ coupling to partons => ‘effective’ mass
for hadrons (π,K,p,n,….)

- **QCD 'true' mass**

⇨ $m_u \approx 5$ $m_d \approx 10$ $m_s \approx 150$ [MeV]
$m_c \approx 1.5$ $m_b \approx 4.3$ $m_t \approx 170$ [GeV]

⇨ $m_u \approx m_d \approx 0$: Chiral Symmetry

- **QCD 'effective' mass**

⇨ $m_u \approx m_d \approx 300$ MeV ($\approx$ 1/3 m_p)

⇨ $m_s \approx 500$ MeV ($\approx m_K$)

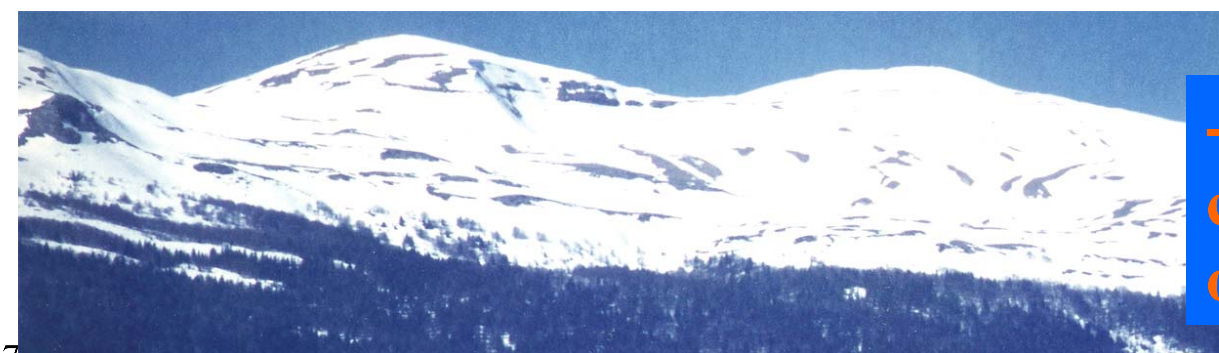
Deconfinement

- A skier (quark?) is confined inside snow patches (hadrons?)

Temperature

- the skier can move further…a new phase develops

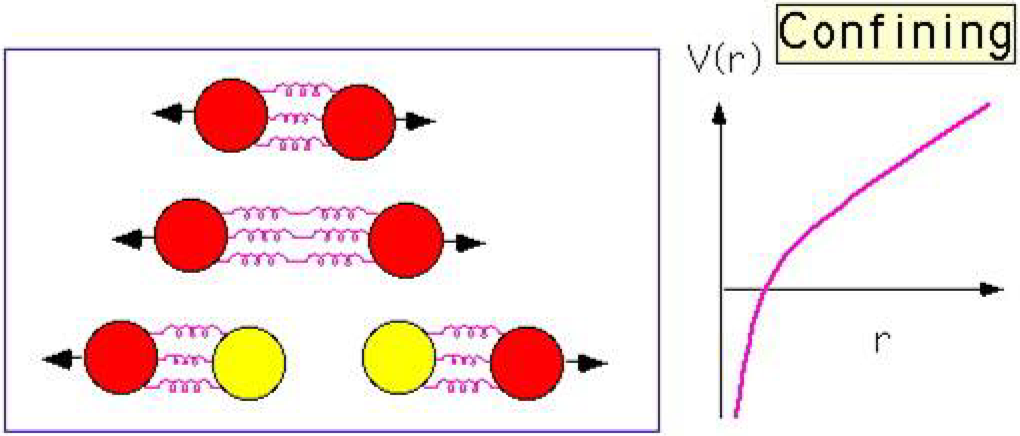
.. goes up

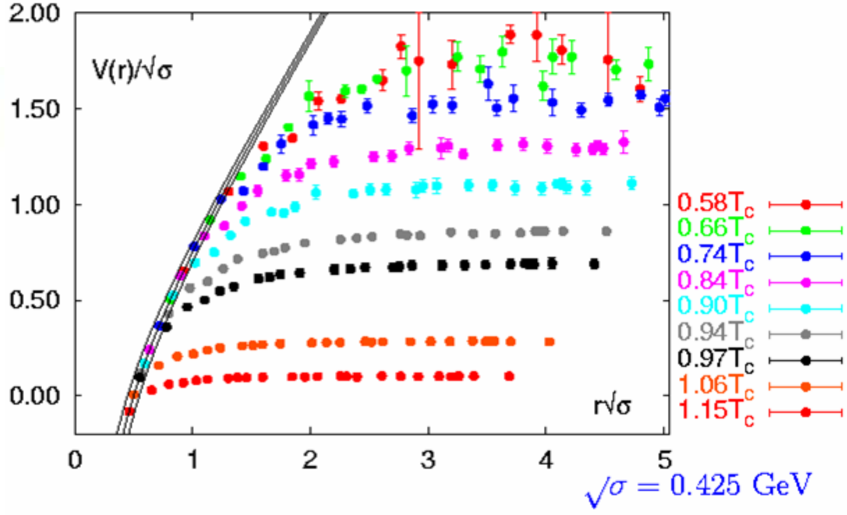


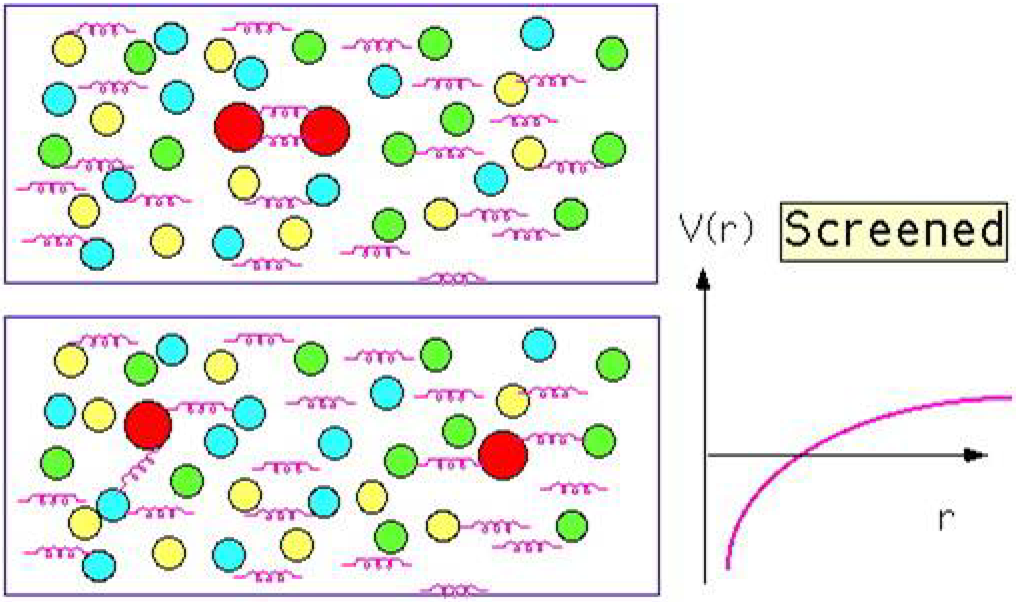
- a skier (quark?) can move freely over long distances...

.. this way

Confinement







● Deconfinement in QGP

⇨ long range QCD potential **screened** by high parton density

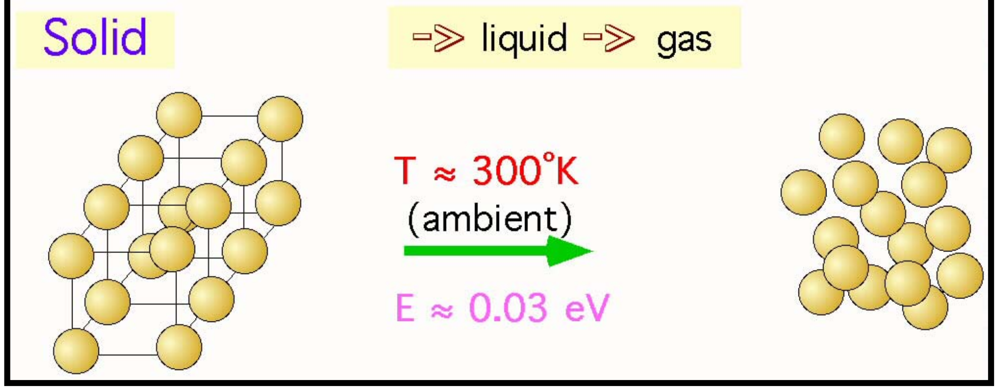
⇨ partons move freely over long distance

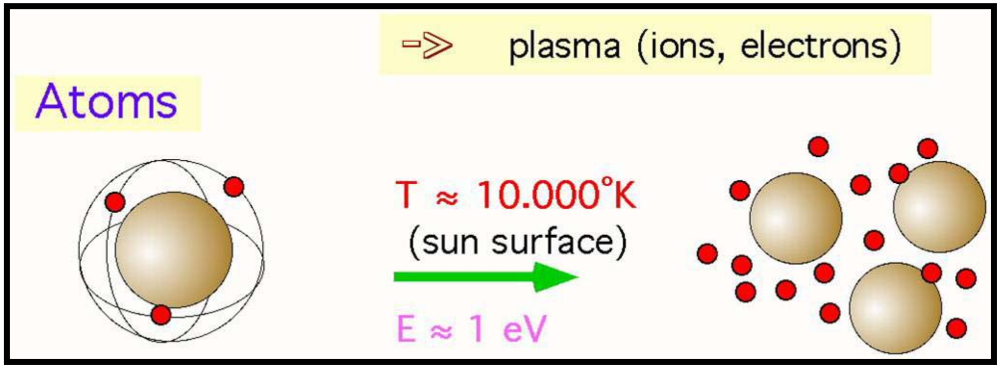
'colour conductor'

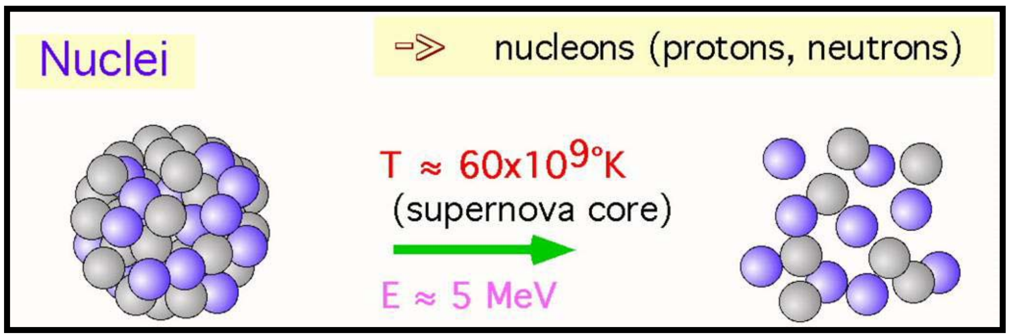
⇨ no bound states possible

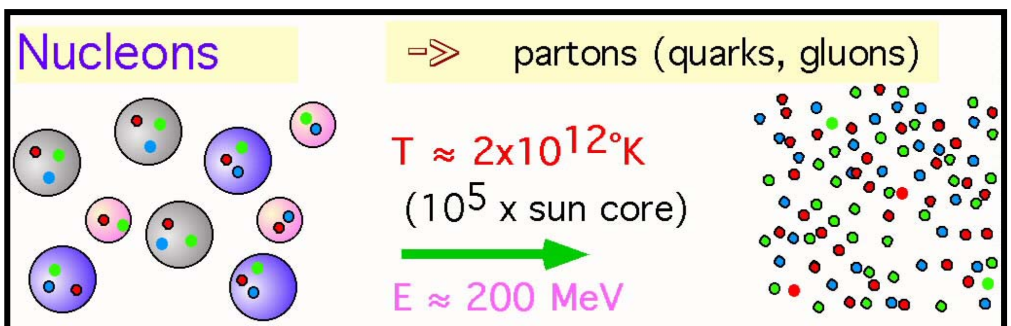
'resonance melting'

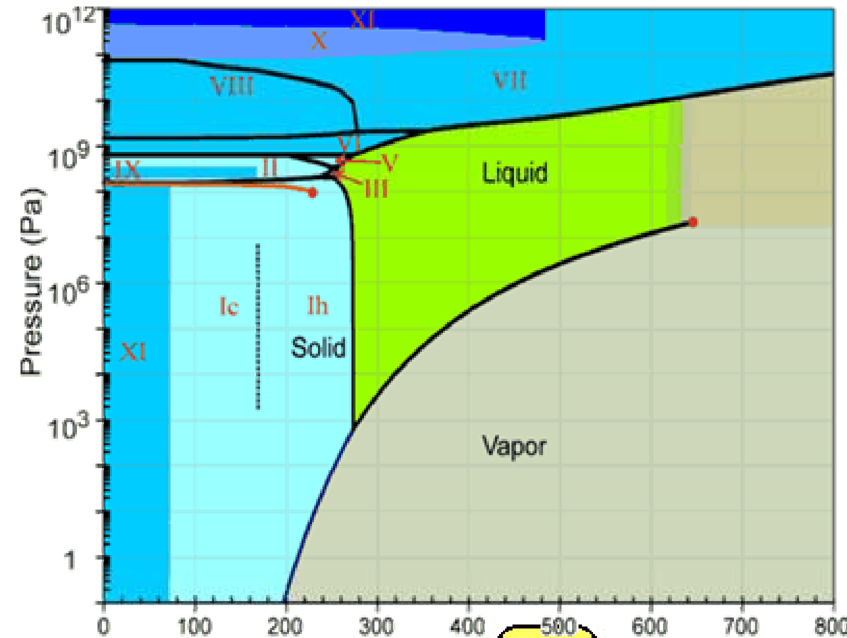
Melting Matter

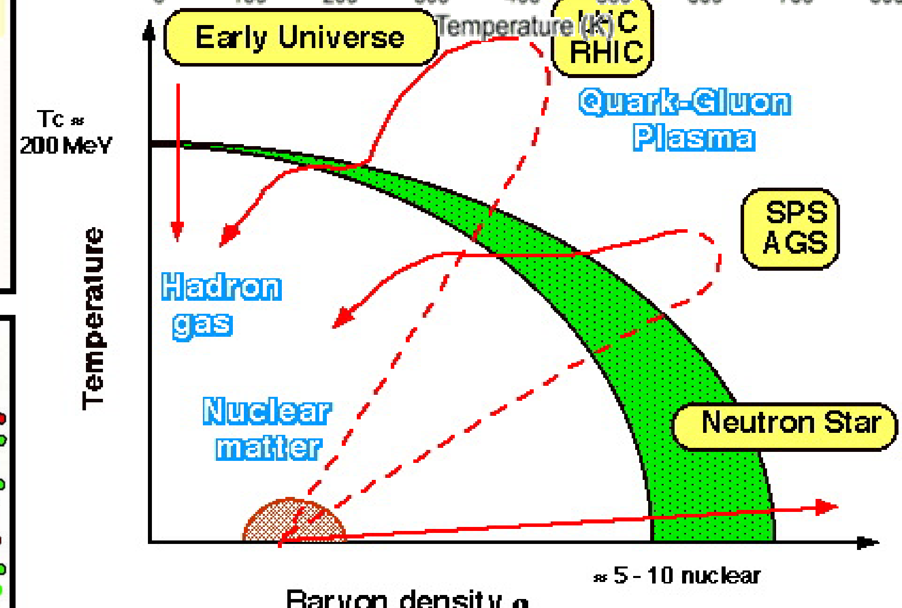




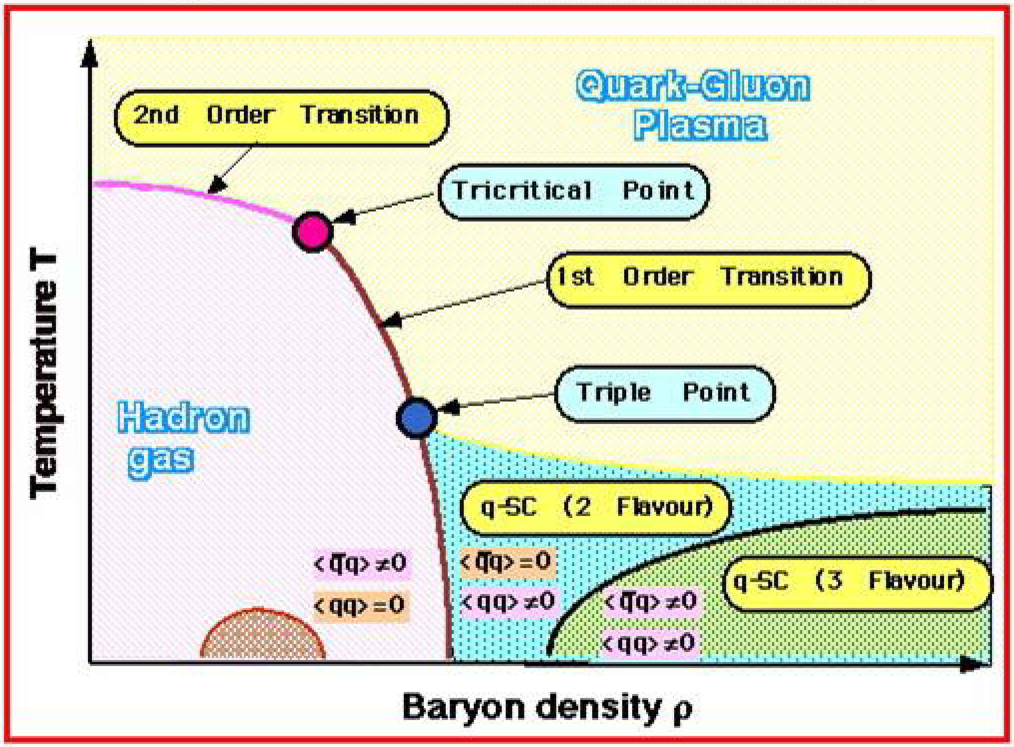








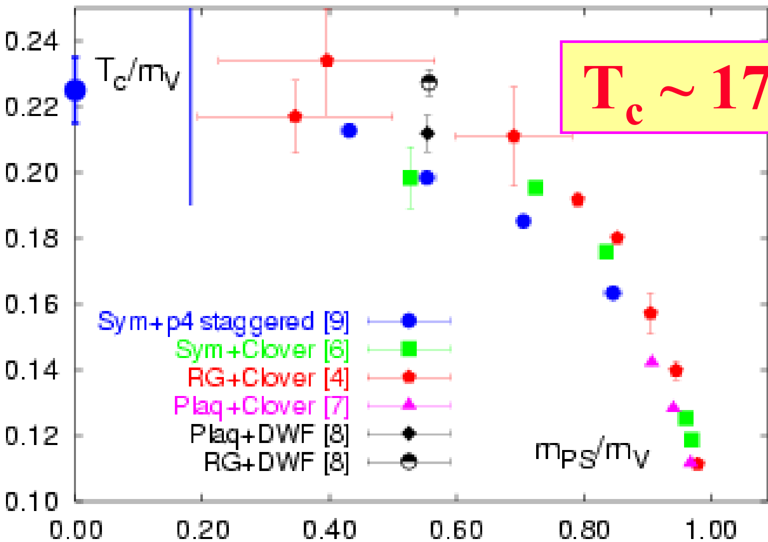
Phase Structure of QCD



- **low T, large ρ: colour superconductor ?**
  - ➩ <qq>≠0: **quark-pair condensation** (Cooper pairs)
  - ➩ a) **2 flavour SC:** chiral symmetry restored
  - ➩ b) **3 flavour SC:** chiral symmetry broken (again)

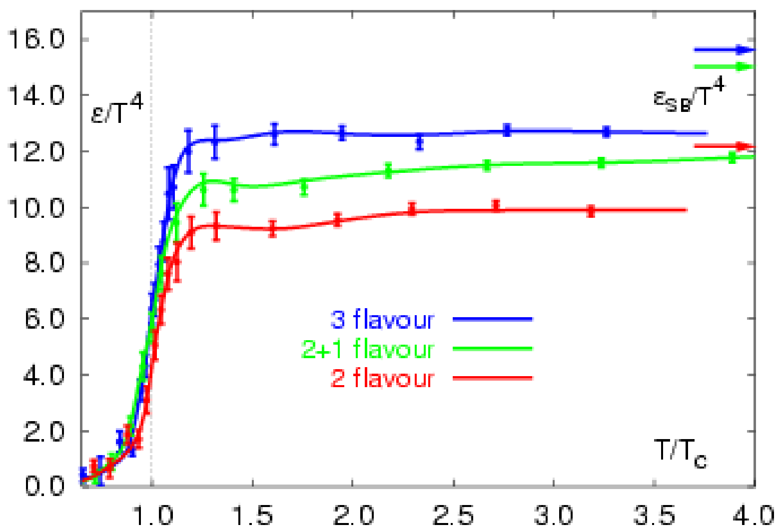
- **medium T, medium ρ: tricritical point ?**
  - ➩ seperates **1st & 2nd order** phase boundaries
  - ➩ leads to **large** event-by-event **fluctuations**

Lattice QCD Results

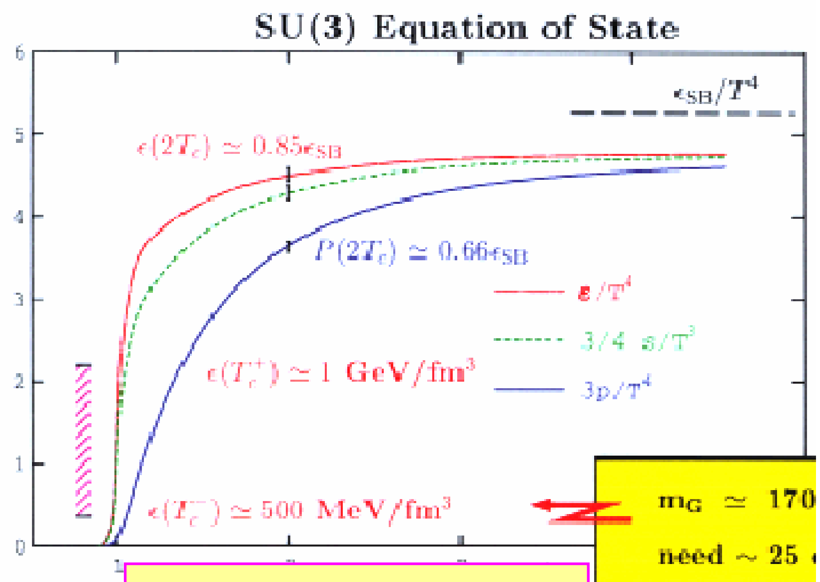


$T_c \sim 175 \pm 8 \pm 8$ MeV

- **recent progress**
  - ⇨ improved actions
  - ⇨ improved symmetries
  - ⇨ larger lattices
- **crit. temperature**
- **energy density**
- **EOS**



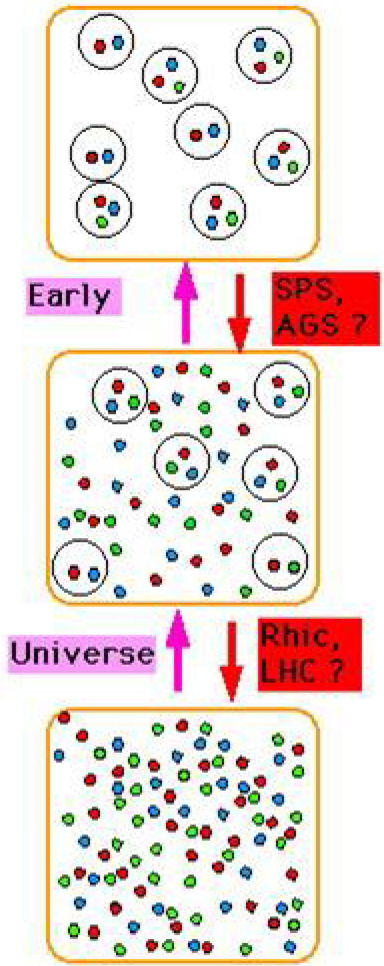
$\varepsilon_c \sim (6 \pm 2)\ T_c^4$



$(\varepsilon - 3P) \neq 0$

The QCD Phase Transition

- **QCD prediction:**
  - ⇨ increase of ε => new phase of matter



hadronic matter

ε(nucleus) ≈ 0.13 GeV/fm³

ε(proton) ≈ 0.5GeV/fm³

q's are confined

q's have large 'effective' mass

$m_u \approx m_d \approx 1/3\ m_p \approx 300$ MeV

$m_s \approx 500$ MeV

phase transition

hadrons & 'vacuum' melt

1st or 2nd order transition ?

latent heat, critical fluctuations

Quark-Gluon-Plasma

ε > 1-2 GeV/fm³

T> 150 MeV

ρ ≈ 5 - 10ρ(nucleus)

q's are deconfined

colour conductivity

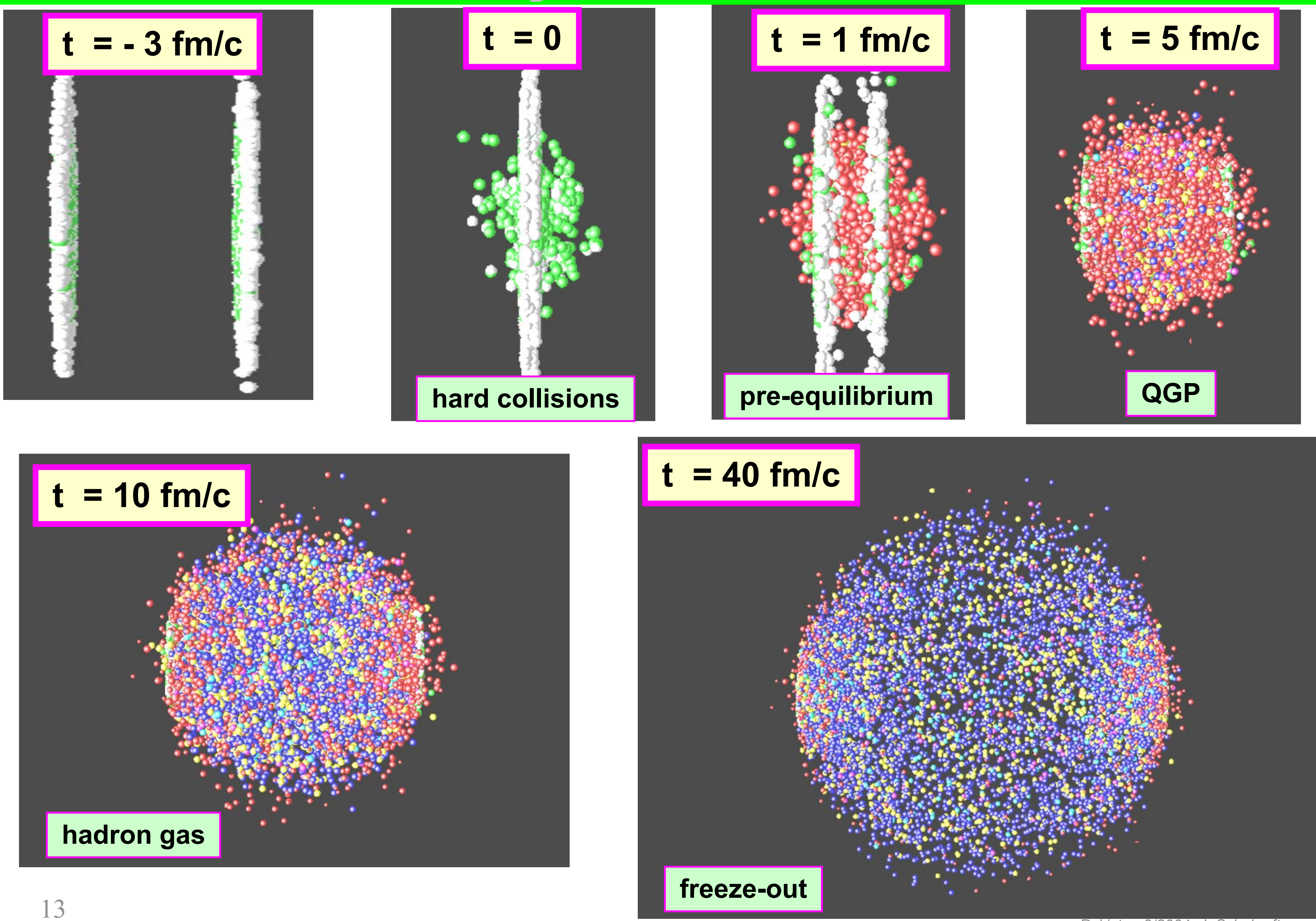
q's have small 'bare' mass

chiral symmetry restored

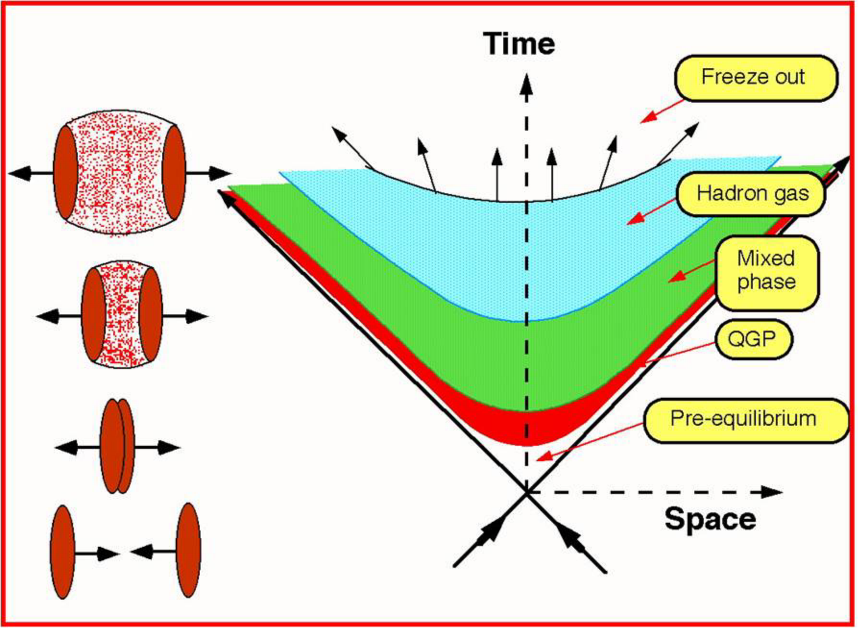
$m_u \approx m_d \approx 5$ MeV

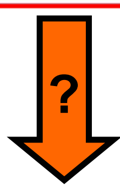
$m_s \approx 150$ MeV

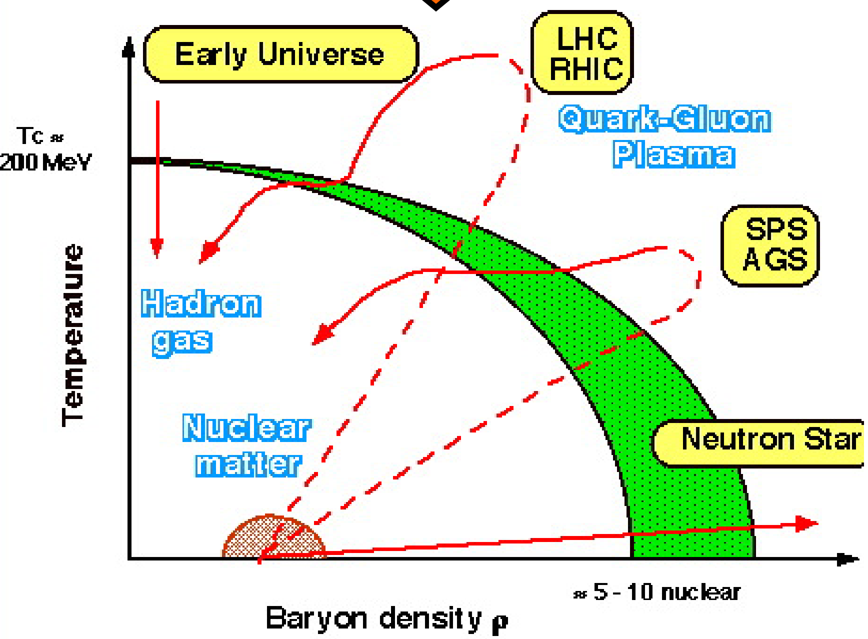
Heavy Ion Collision

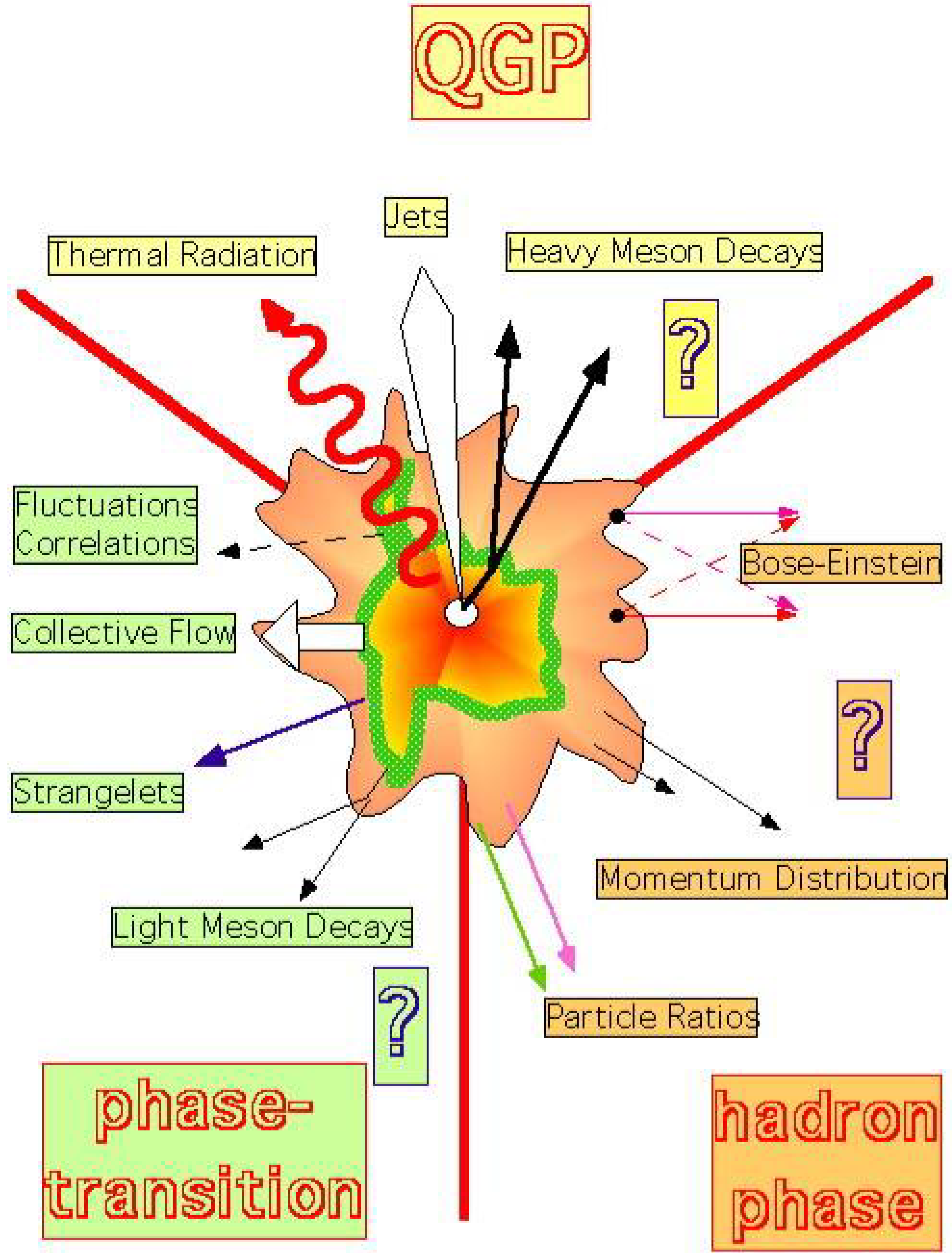


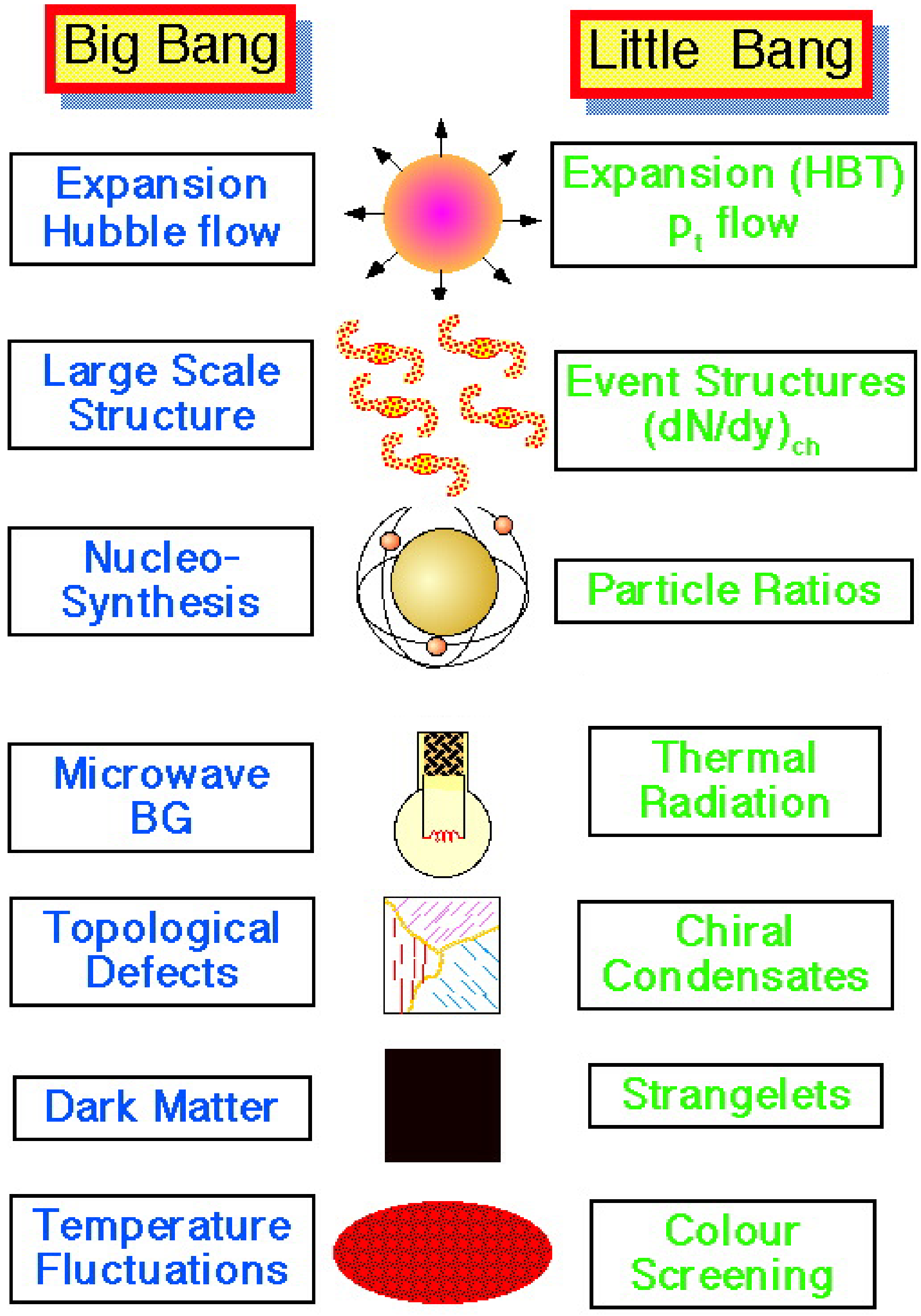
Signals & Observables







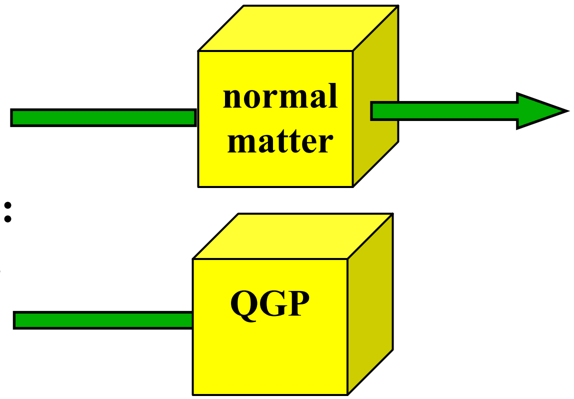


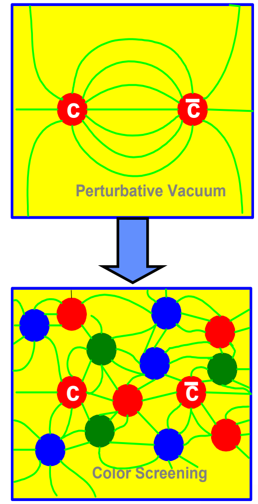


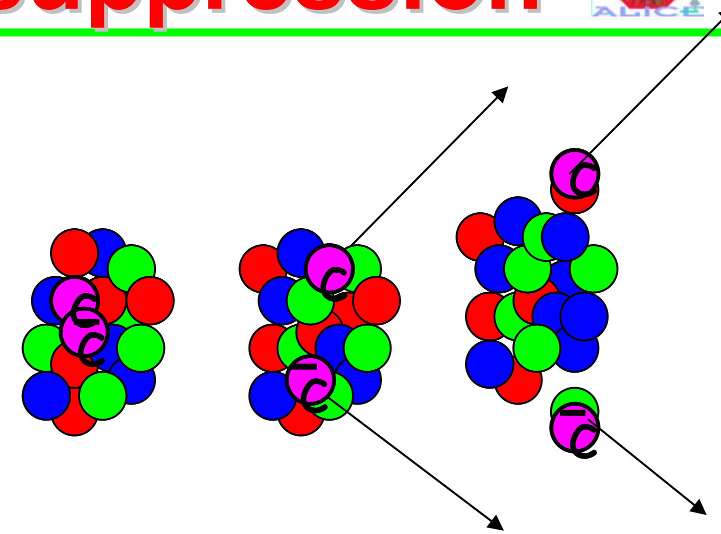
Big Bang
Little Bang
Expansion Hubble flow
Expansion (HBT) p_t flow
Large Scale Structure
Event Structures $(dN/dy)_{ch}$
Nucleo-Synthesis
Particle Ratios
Microwave BG
Thermal Radiation
Topological Defects
Chiral Condensates
Dark Matter
Strangelets
Temperature Fluctuations
Colour Screening

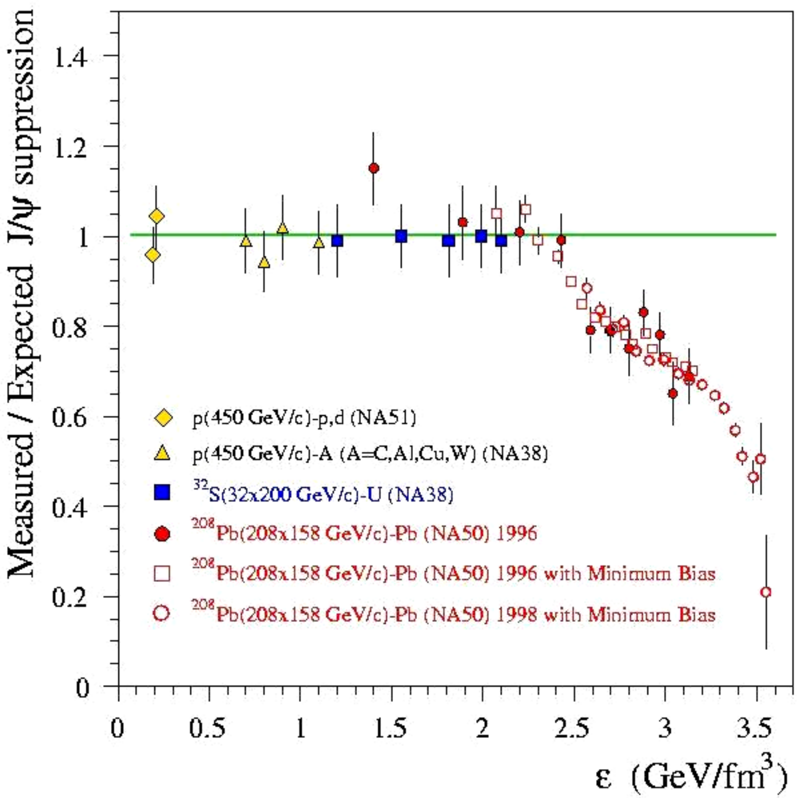
Hard Probes I) J/Psi suppression

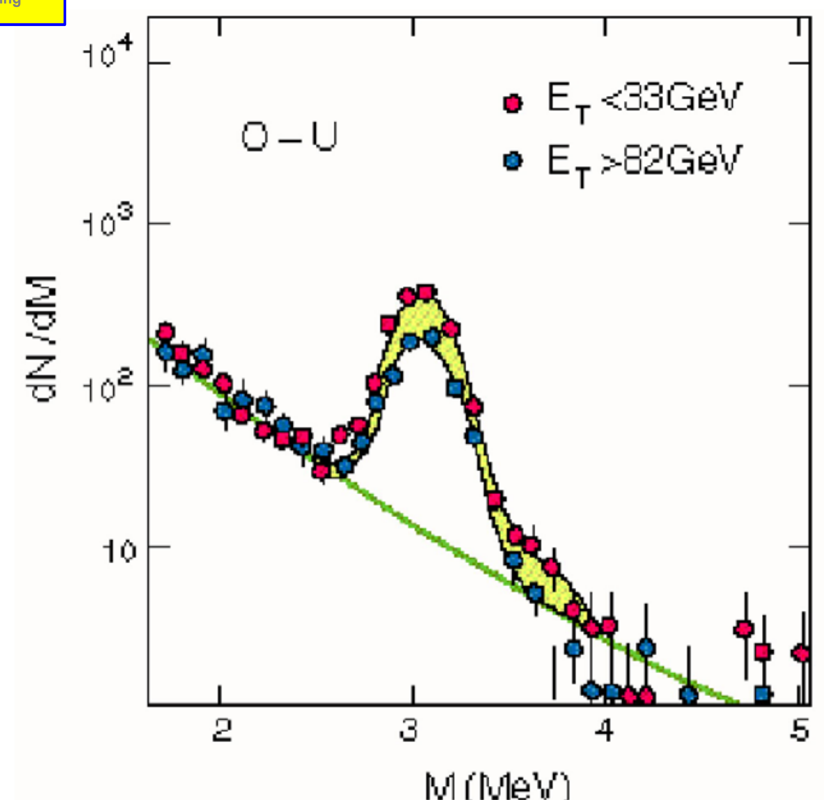
beams of
hard probes:
jets, J/ψ ….





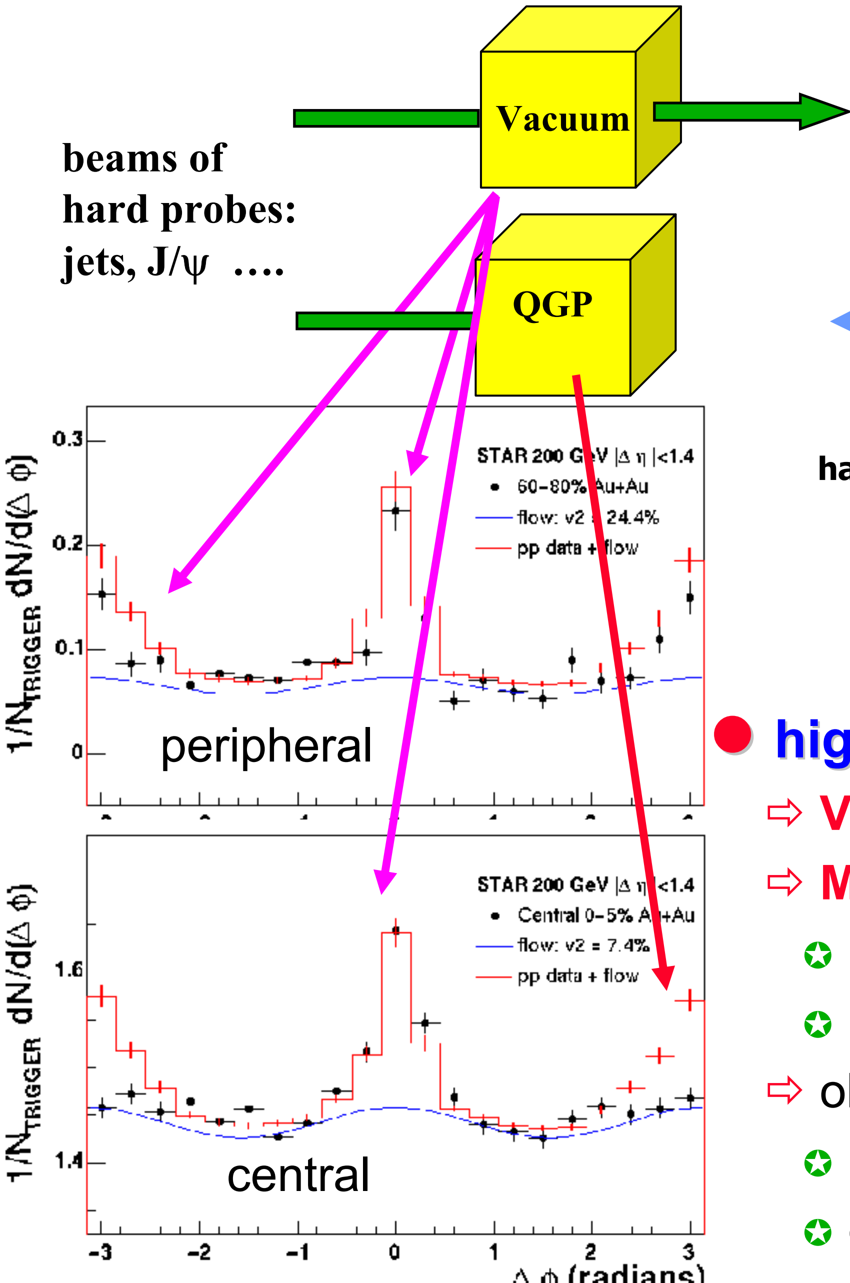


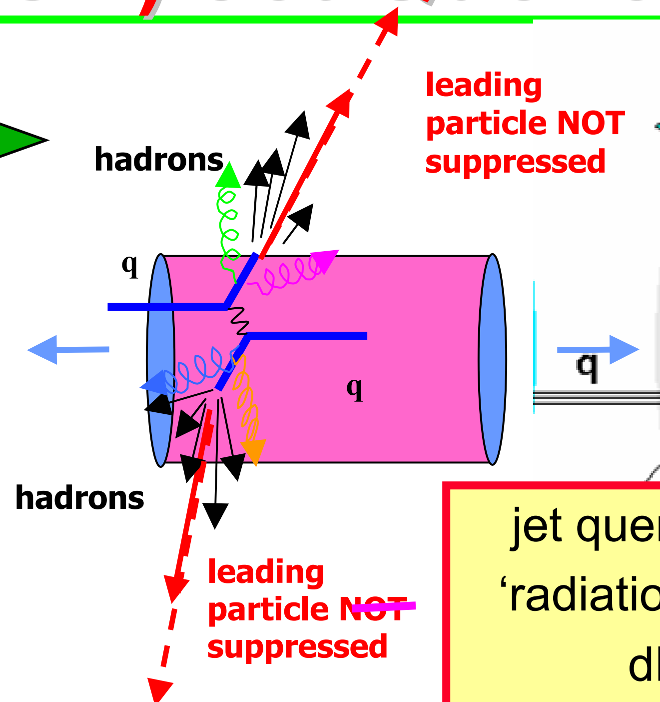


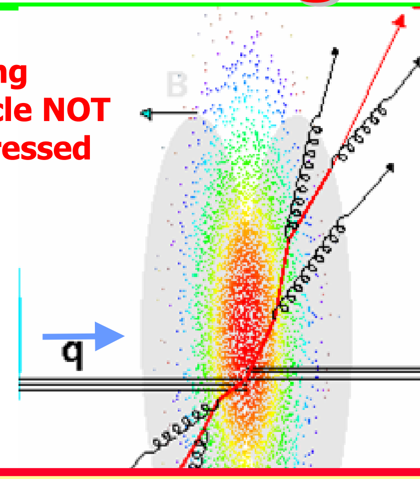


Hard Probes II) Jet Quenching

beams of
hard probes:
jets, J/ψ ….



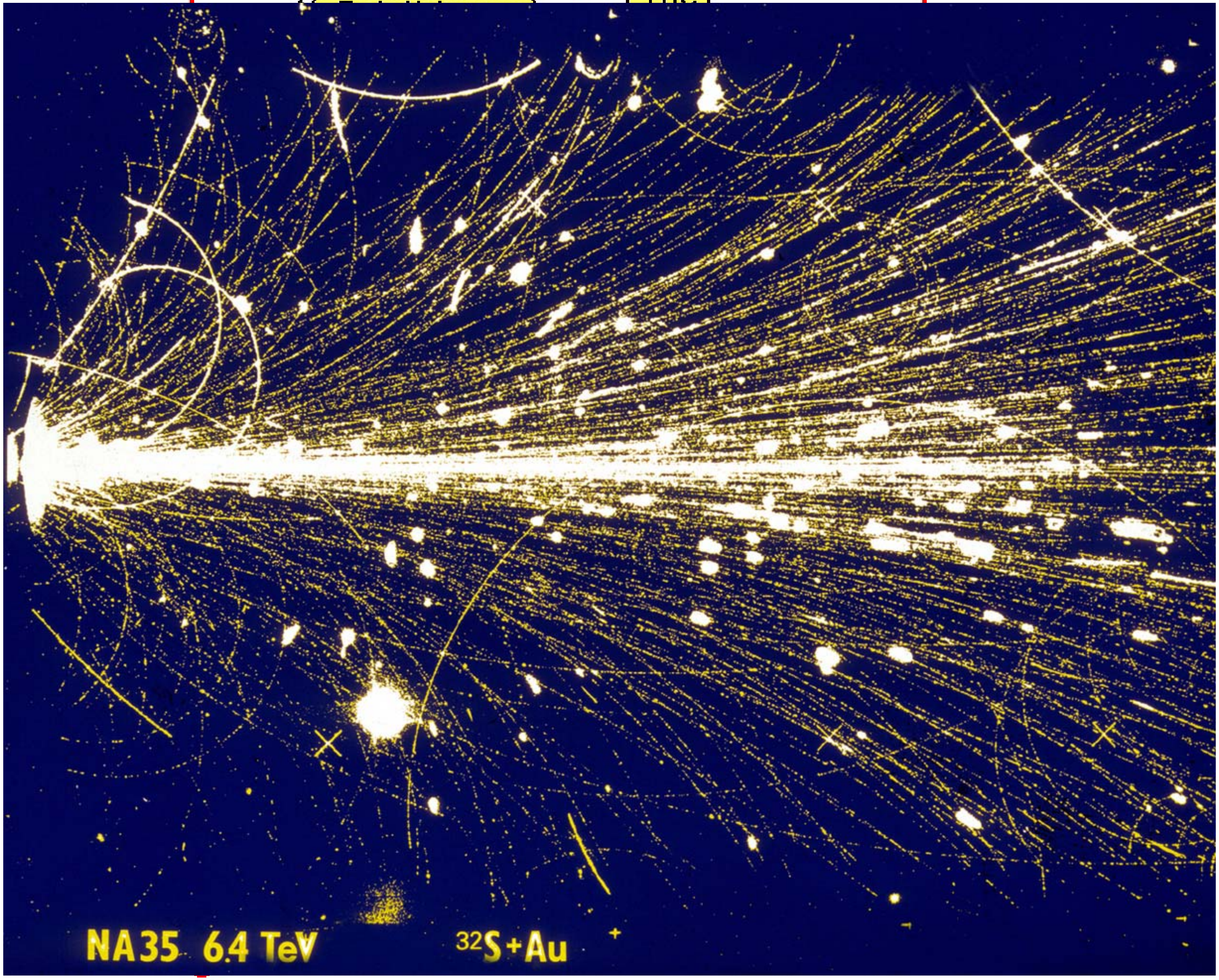




jet quenching measures
'radiation' length of QGP
$dE \sim \mu_D^2 \times L^2$
μ_D = Debye screening mass

- **high p_t partons:**
  - ⇨ **Vacuum**: fragment into hadrons => **JETS**
  - ⇨ **Matter**: additional scattering => more gluon radiation
    - ✪ **normal 'cold' matter:** small effect
    - ✪ **QGP**: strong effect (up to several 10 GeV)
  - ⇨ observables of **'jet quenching'**
    - ✪ leading parton looses energy
    - ✪ energy shows up in soft partons around jet axis

Phase Diagram of Matter



surprises ?

Experimental Facilities

- **AGS** **(1986 - 1998)**
  - Beam: E_{lab} < 15 GeV/N, √s ~ 4 GeV/N
  - Users: 400 Experiments: 4 big, several small

X 5

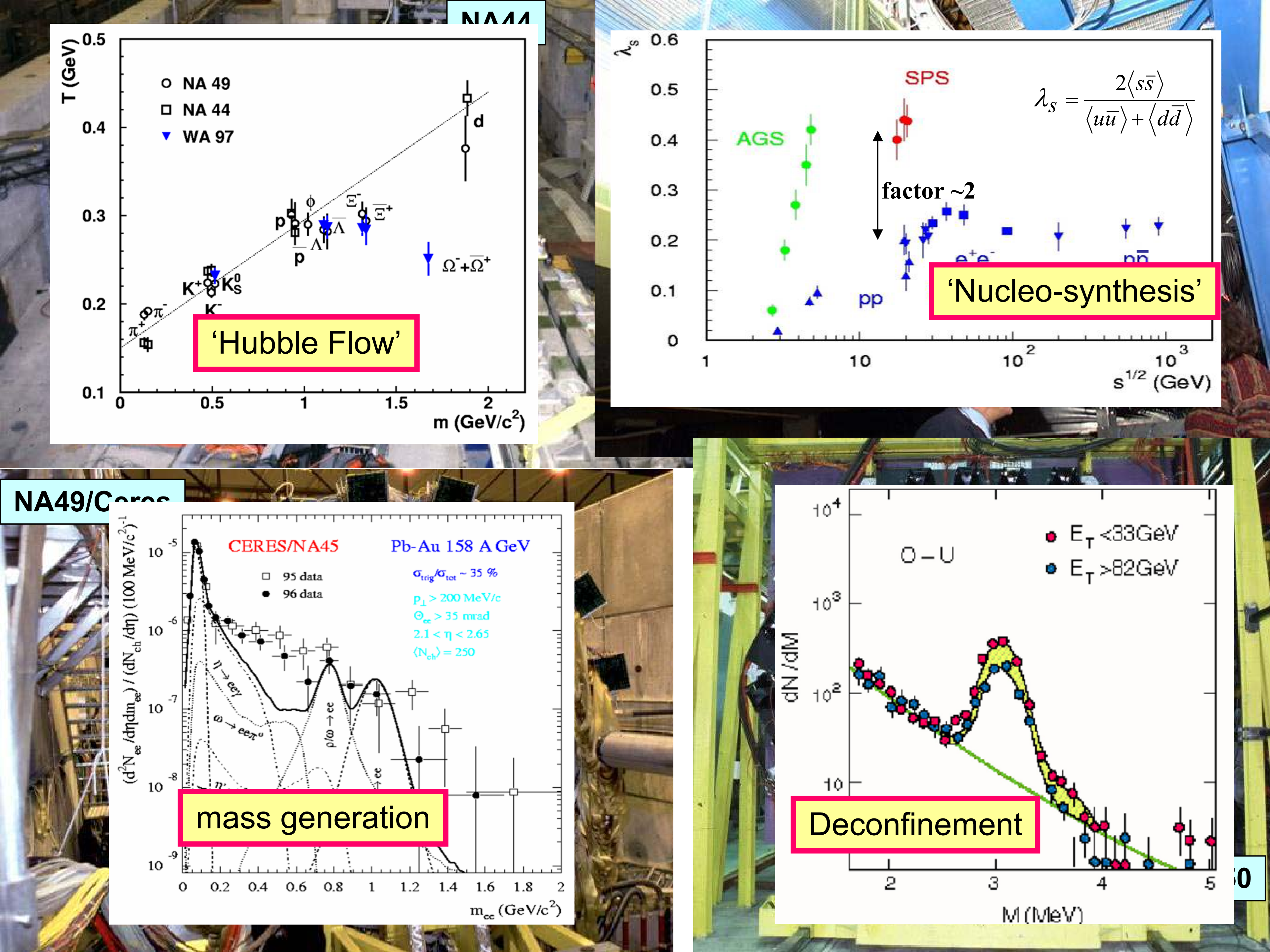
- **SPS** **(1986 - 2003)**
  - Beam: E_{lab} < 200 GeV/N, √s < 20 GeV/N
  - Users: 600 Experiments: 6-7 big, several small

X 10

- **RHIC** **(>2000)**
  - Beam: √s < 200 GeV/N
  - Users: 1000
  - Experiments: 2 big, 2 small

X 30

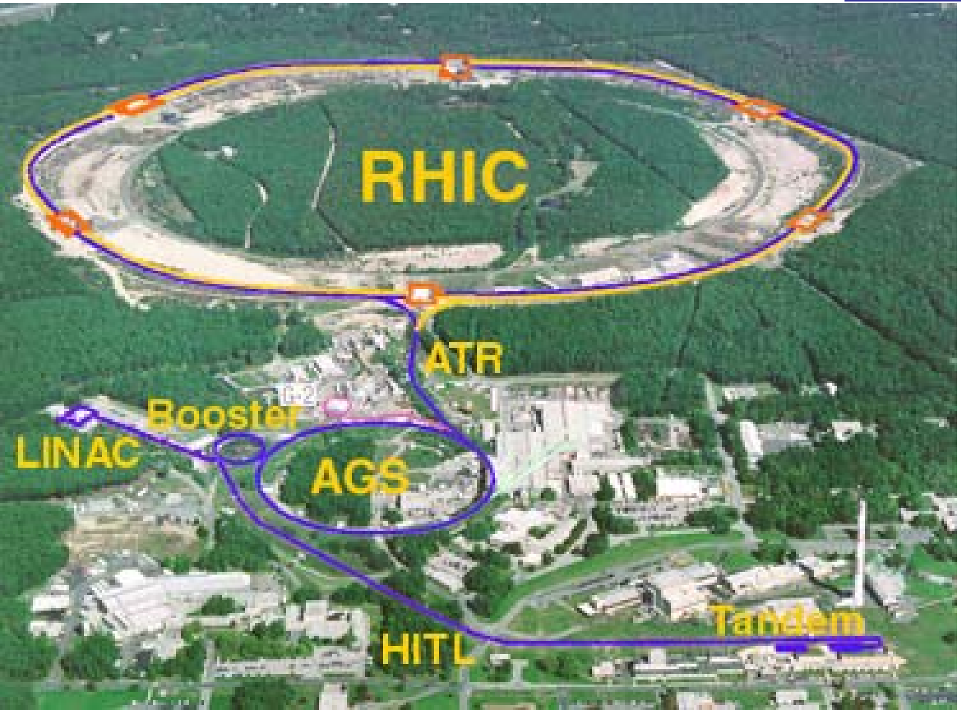
- **LHC** **(>2007)**
  - Beam: √s < 5500 GeV/N
  - Users: 1000
  - Experiments: 1 dedicated HI, 3 pp expts



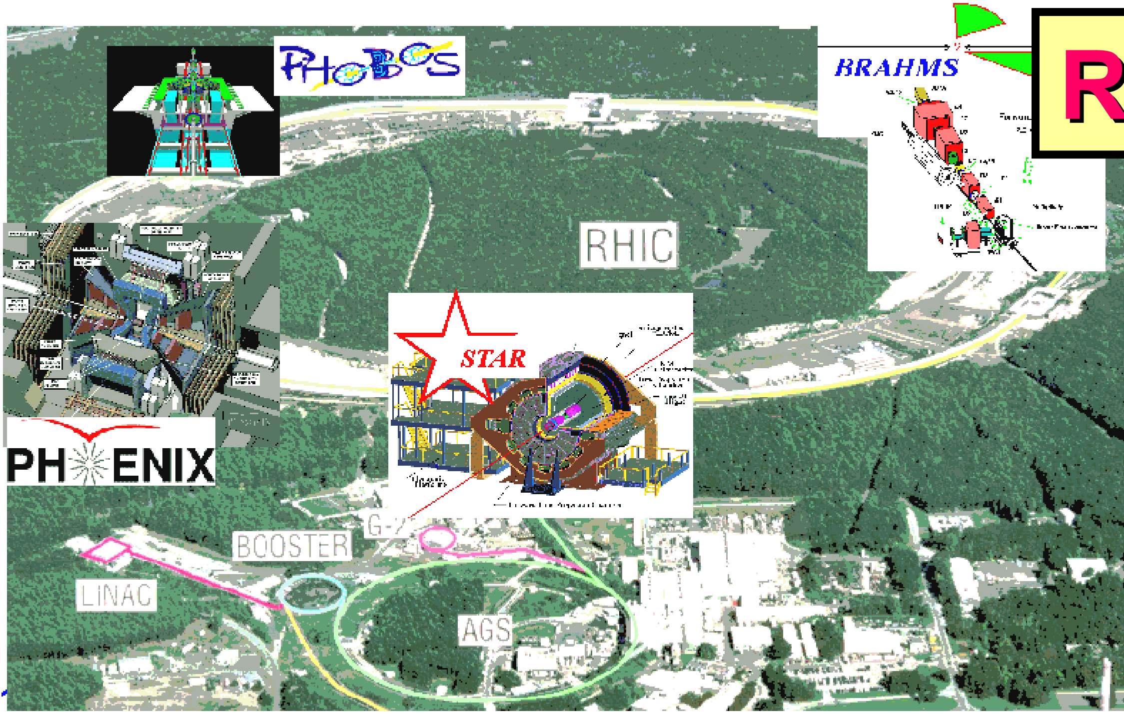
T (GeV)
NA 49
NA 44
WA 97
m (GeV/c²)
'Hubble Flow'
λs
SPS
AGS
factor ~2
pp
s^1/2 (GeV)
'Nucleo-synthesis'
CERES/NA45
Pb-Au 158 A GeV
95 data
96 data
σtrig/σtot ~ 35 %
p⊥ > 200 MeV/c
Θee > 35 mrad
2.1 < η < 2.65
⟨Nch⟩ = 250
m_ee (GeV/c²)
mass generation
O – U
ET <33GeV
ET >82GeV
dN/dM
M (MeV)
Deconfinement

Current hunting ground for Quark Gluon Plasma

The Relativistic Heavy Ion Collider



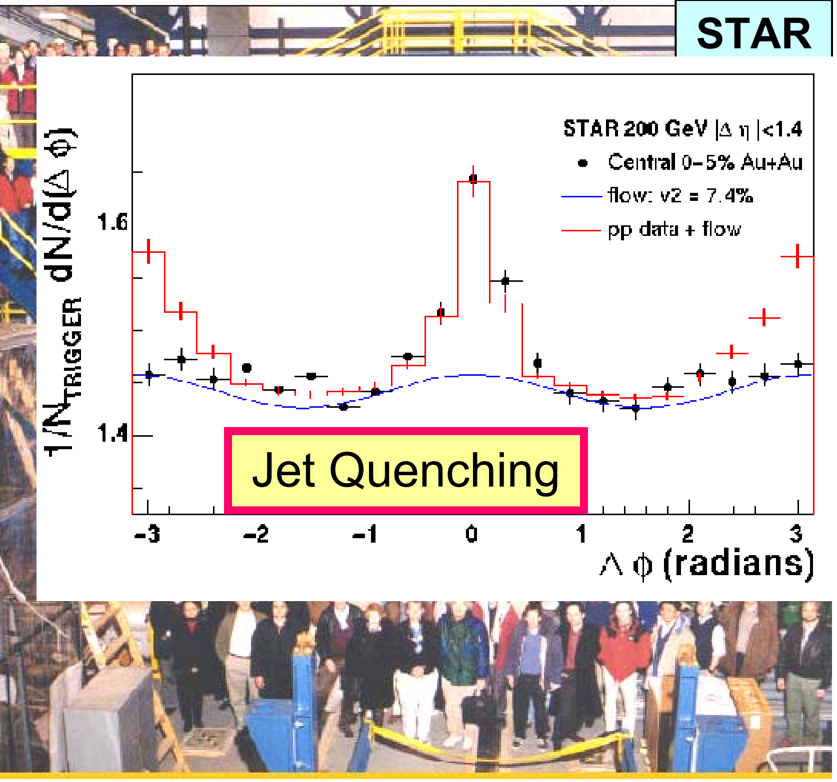
RHIC Experiments

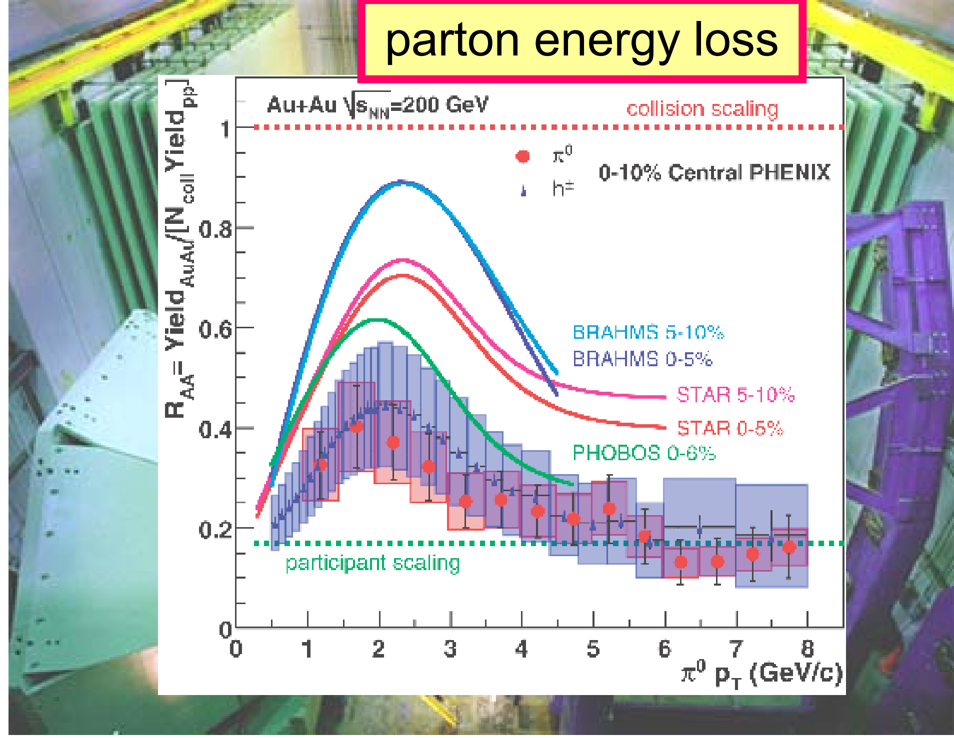


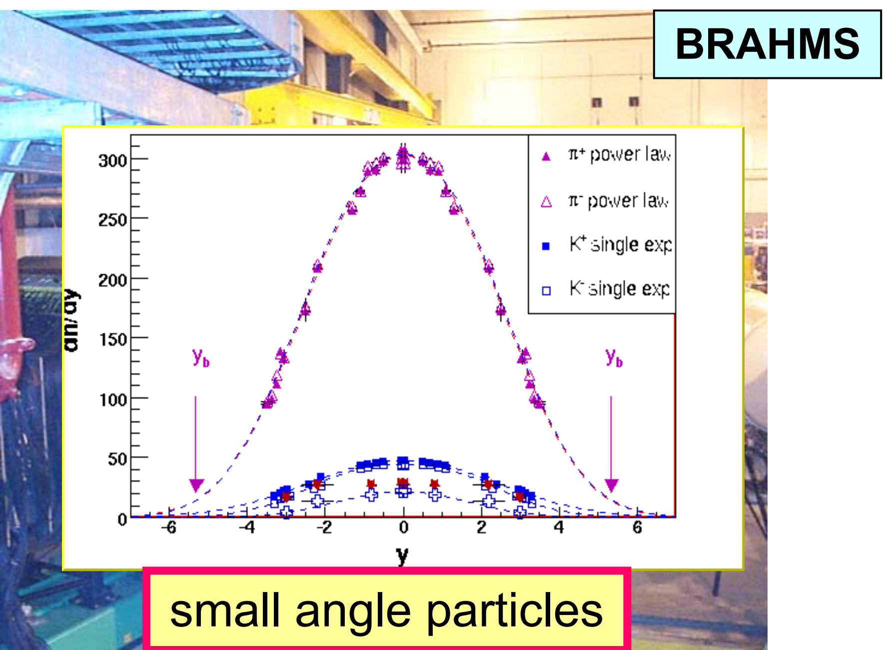
4 Experiments,
~ 1000 people from ~ 100 Institutes
in ~ 20 Countries

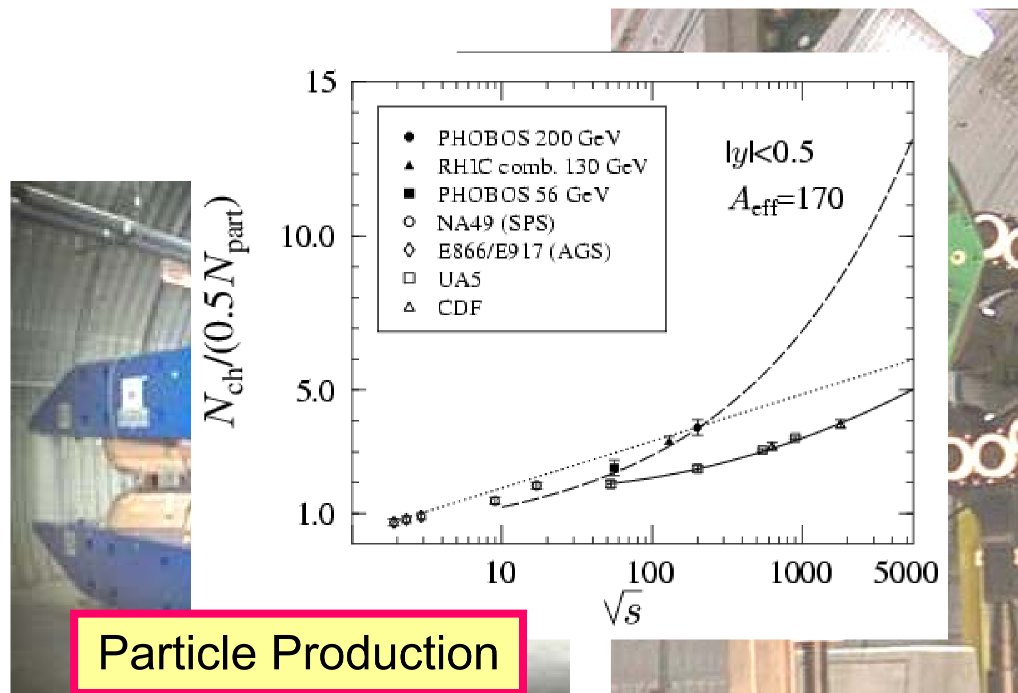
- **STAR**
  - ~ 400 people, ~ 33 Institutes
  - **hadronic probes**
    - particle spectra/ratios, HBT, jets
  - large acceptance TPC, solenoid
- **BRAHMS**
  - ~ 70 people, ~ 12 Institutes
  - **single inclusive hadrons**
    - central and forward region
  - 2 spectrometer arms (tracking+PID)

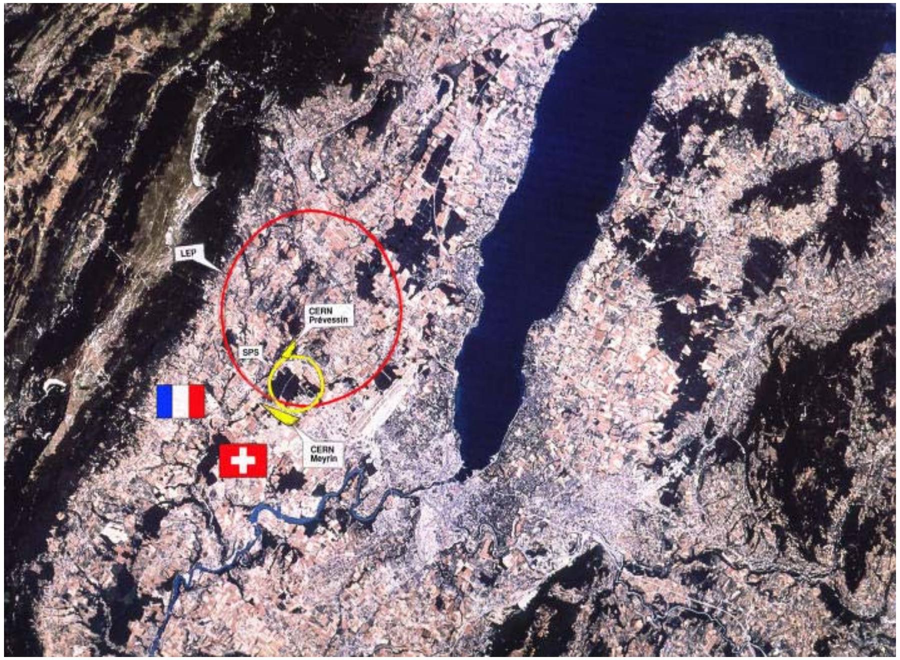
- **PHENIX**
  - ~ 500 people, ~ 50 Institutes
  - **e.m. probes** ()
    - e,μ,γ, small area hadrons
  - several special purpose spectrometer arms
- **PHOBOS**
  - ~ 50 people, ~ 14 Institutes
  - **very low p_t hadrons**
    - down to ~ 20 MeV
  - Silicon telescope + TOF array


STAR
STAR 200 GeV |Δ η |<1.4
Central 0-5% Au+Au
flow: v2 = 7.4%
pp data + flow
1/N_TRIGGER dN/d(Δ φ)
1.6
1.4
-3 -2 -1 0 1 2 3
Δ φ (radians)
Jet Quenching


parton energy loss
Au+Au √s_NN=200 GeV
collision scaling
π0
h±
0-10% Central PHENIX
BRAHMS 5-10%
BRAHMS 0-5%
STAR 5-10%
STAR 0-5%
PHOBOS 0-6%
participant scaling
R_AA= Yield_AuAu/[N_coll Yield_pp]
0 0.2 0.4 0.6 0.8 1
0 1 2 3 4 5 6 7 8
π0 p_T (GeV/c)

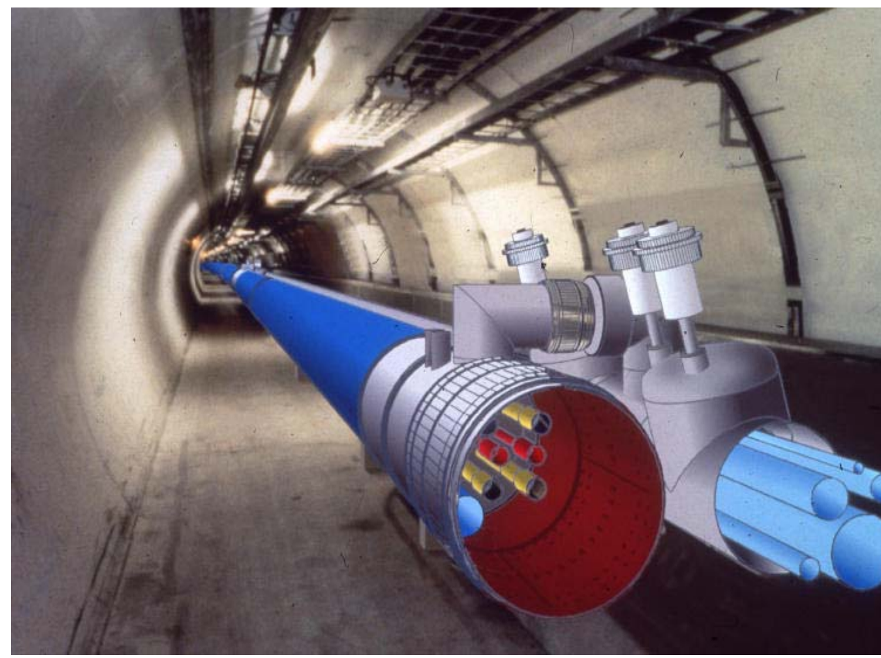

BRAHMS
π+ power law
π- power law
K+ single exp
K- single exp
y_b
y_b
dn/dy
0 50 100 150 200 250 300
-6 -4 -2 0 2 4 6
y
small angle particles


PHOBOS 200 GeV
RHIC comb. 130 GeV
PHOBOS 56 GeV
NA49 (SPS)
E866/E917 (AGS)
UA5
CDF
|y|<0.5
A_eff=170
N_ch/(0.5 N_part)
1.0 5.0 10.0 15
10 100 1000 5000
√s
Particle Production



Future place for studying the Quark Gluon Plasma

The Large Hadron Collider



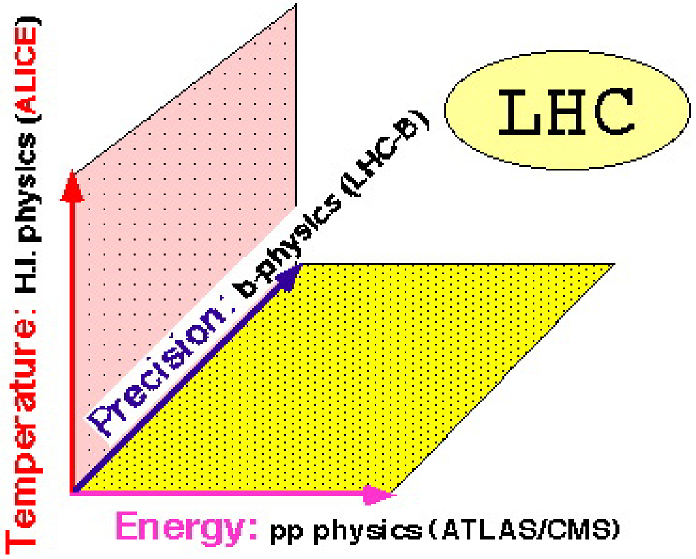
Physics at LHC

Common Questions

- generation of mass
  - elementary particles => Higgs => ATLAS/CMS
  - composite particles => QGP => ALICE
- missing symmetries
  - SuperSymmetry: matter <-> forces => ATLAS/CMS
  - Chiral Symmetry: mass of light quarks => ALICE
  - CP Symmetry: matter <-> antimatter => LHC-B

Different Approaches

- 'Concentrated Energy'
  => (single) high mass particles
- 'Distributed Energy'
  => interaction between matter & vacuum
- 'Borrowed Energy'
  => indirect effects of very high mass particles



Physics@LHC: Caveat

BIG Step ahead: SPS —x 12→ RHIC —x 28→ LHC

- **long distance QCD is difficult to predict**

  > Predictions are notoriously difficult, in particular if they concern the future..

  - Theory well known, not so its consequences or manifestation
  - HEP@LHC: Theory unknown, but each candidate makes precise predictions
- **the fate of 'expectations' at SPS and RHIC**
  - some expectations turned out right:
    - **SPS**: strangeness enhancement — **RHIC:** particle ratios, jet-quenching(?)
  - some turned out wrong:
    - **SPS**: large E-by-E fluctuations — **RHIC:** multiplicity dN/dy
  - a number of unexpected surprises:
    - **SPS**: J/Psi suppression — **RHIC:** elliptic flow, 'HBT-puzzle'
- **lesson when preparing ALICE at LHC**
  - **guided** by theory and expectations, but **stay open minded** !
- **'conventional wisdom'**
  - **soft physics**: smooth extrapolation of SPS/RHIC — necessary, but boring ???
  - **hard physics**: new domain at LHC

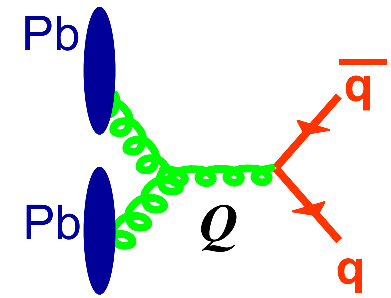
Hard Processes at the LHC

- Main novelty of the LHC: large hard cross section

$$\sigma^{hard} / \sigma^{tot}$$

~2% at SPS
~50% at RHIC
~98% at LHC

K. Kajantie (QM02)



- Hard processes are extremely useful tools
  - ⇨ **happen at t = 0** (initial stage of the collision)
  - ⇨ have **large virtuality Q** and **small "formation time"** $\Delta t \propto 1/Q$
  - ⇨ ***probe matter at very early times (QGP) !!!***

in pp can be calculated by pQCD $\rightarrow$ predicted

$$\alpha_s(Q^2) \propto 1/\ln\left(Q^2/\Lambda^2_{QCD}\right) \qquad \sigma^{hard}_{pp} = O(\alpha_s) + O(\alpha_s^2) + O(\alpha_s^3) + \ldots$$

in absence of nuclear effects:

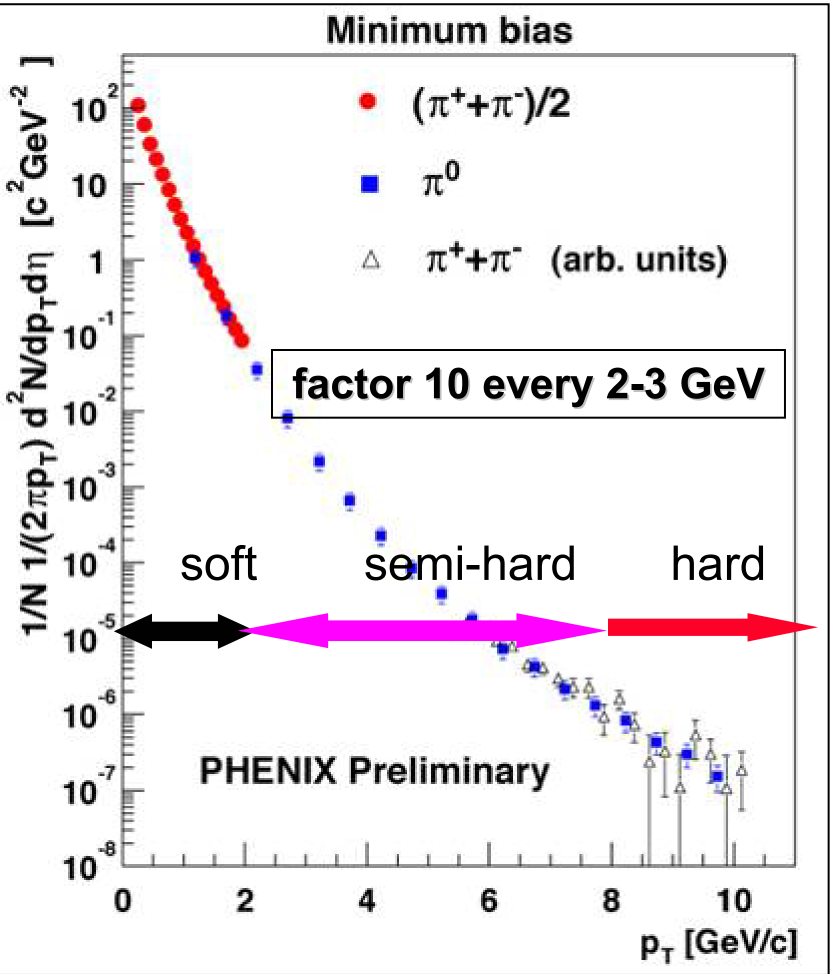
$$N^{hard}_{AA\,(pA)} = N^{hard}_{pp} \times N_{collisions}$$

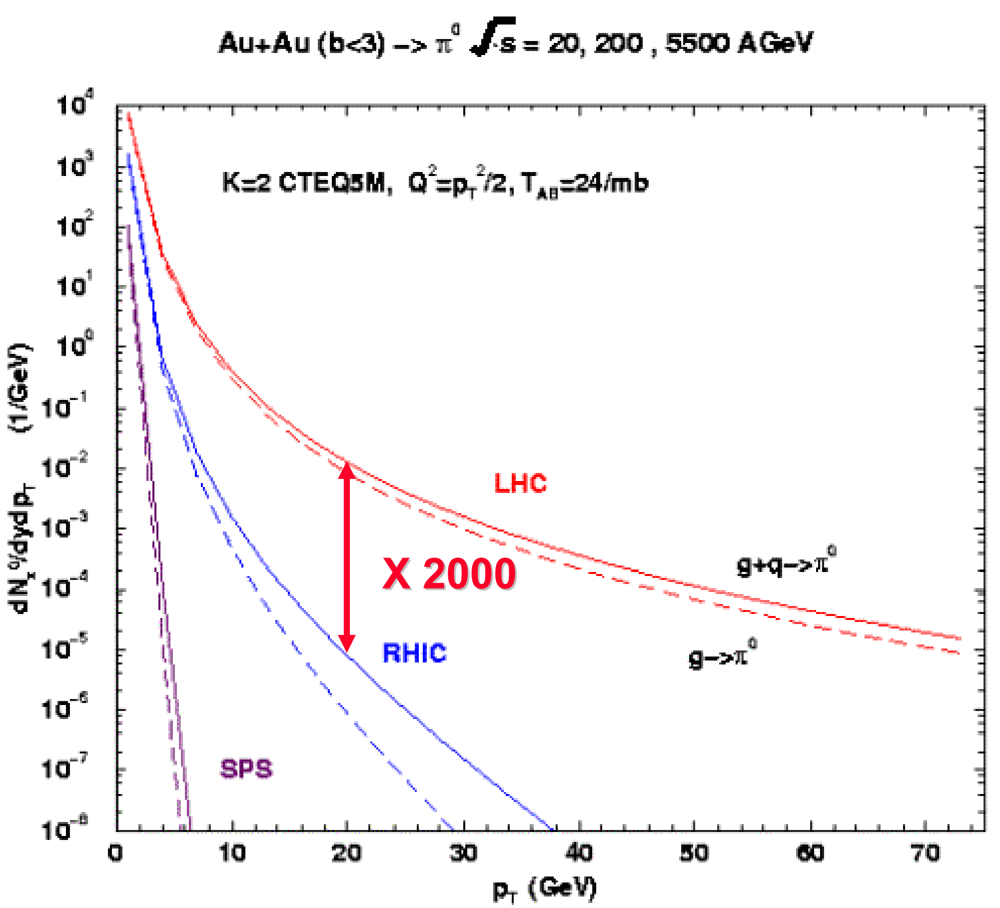
initial production not sensitive to properties of medium formed in the AA collision

Hard Probes @ LHC

● LHC: the full 'spectrum'

- ⇨ **soft** -> **semihard** -> **hard** (>> 20 GeV)
  - ✪ difficult to overcome power law with Luminosity !
- ⇨ high p_t important in order to leave even tails of 'hydrodynamics'

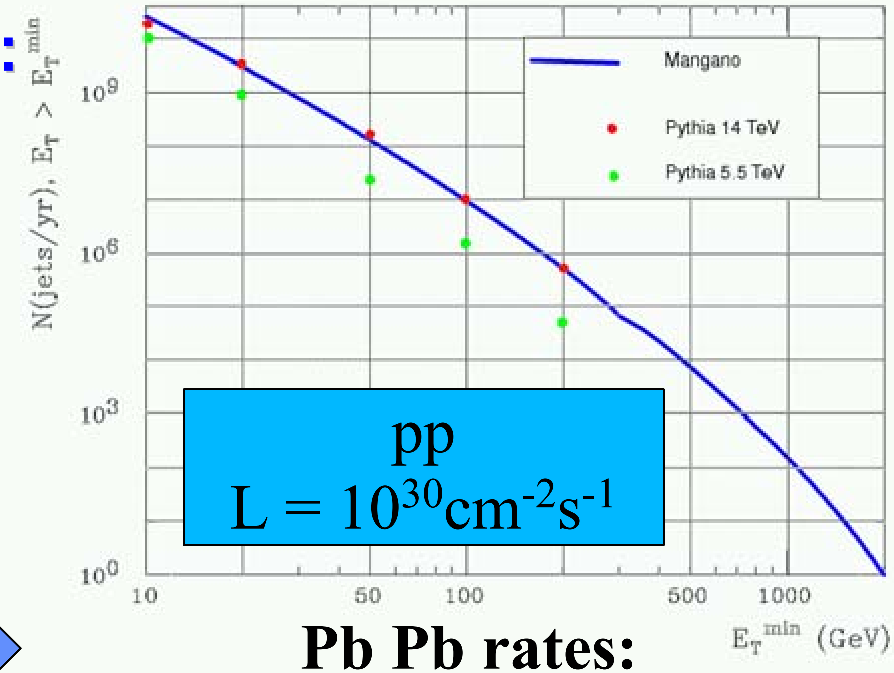




Jets in ALICE $|\eta|<0.9$

- **ideal energy for jet-quenching: around 100 GeV**
  - ⇨ pQCD applicable
  - ⇨ jets measurable above soft background
  - ⇨ energy loss still relatively large effect
    - ✪ $\Delta E/E \sim O(10\%)$, decreasing with E !

Reasonable rate up to E_T ~300 GeV



Pb Pb rates:

p_t jet > (GeV/c)	jets/event	accepted jets/month
5	$3.5\ 10^{2}$	$4.9\ 10^{10}$
50	$7.7\ 10^{-2}$	$1.5\ 10^{7}$
100	$3.5\ 10^{-3}$	$8.1\ 10^{5}$
150	$4.8\ 10^{-4}$	$1.2\ 10^{5}$
200	$1.1\ 10^{-4}$	$2.8\ 10^{4}$

~ 1Hz trigger rate for central PbPb collisions and p_t jet > 100 GeV/c

real jets triggers 0.7/s
false triggers 0.3/s

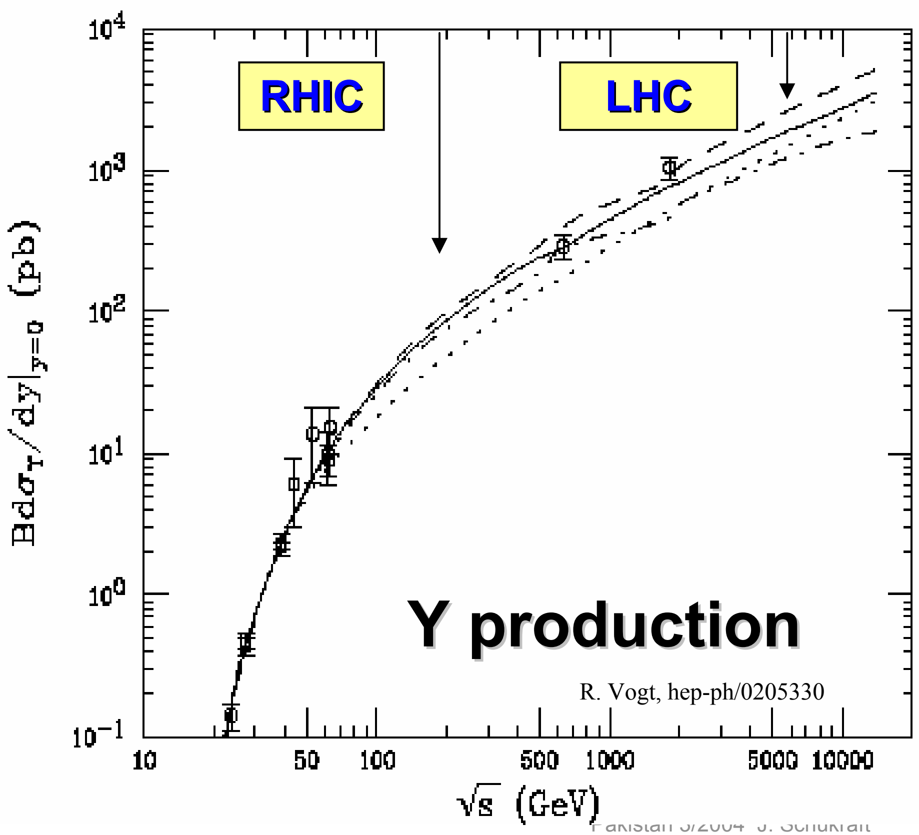
Heavy Quarks & Quarkonia

- **copious heavy quark production**
  - ⇨ **charm** @ LHC ~ **strange** @ SPS
    - hard production => 'tracer' of QGP dynamics (statistical hardonization ?)
    - 2 m_c ~ saturation scale => change in production ?
    - jet-quenching with heavy quarks visible in inclusive spectra ?

N($q\bar{q}$) per central AA (b=0)

	SPS	RHIC	LHC
charm	0.2	10	200
bottom	---	0.05	6

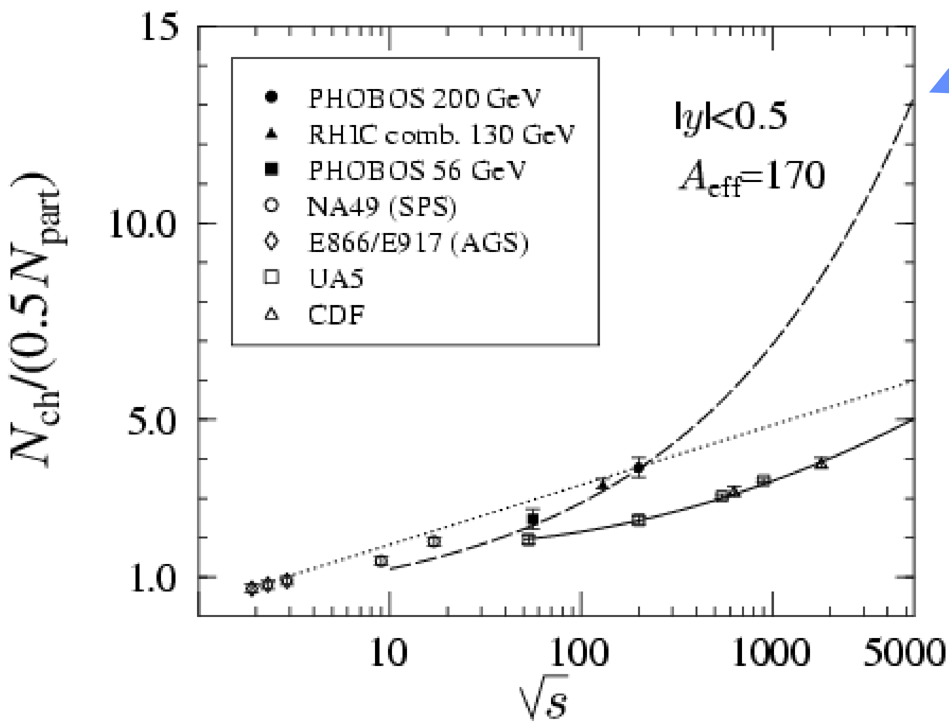
- **Y dσ/dy LHC ~ 20 x RHIC**
  - ⇨ Y will probably need higher Lumi at RHIC
  - ⇨ even at LHC Y'' is difficult

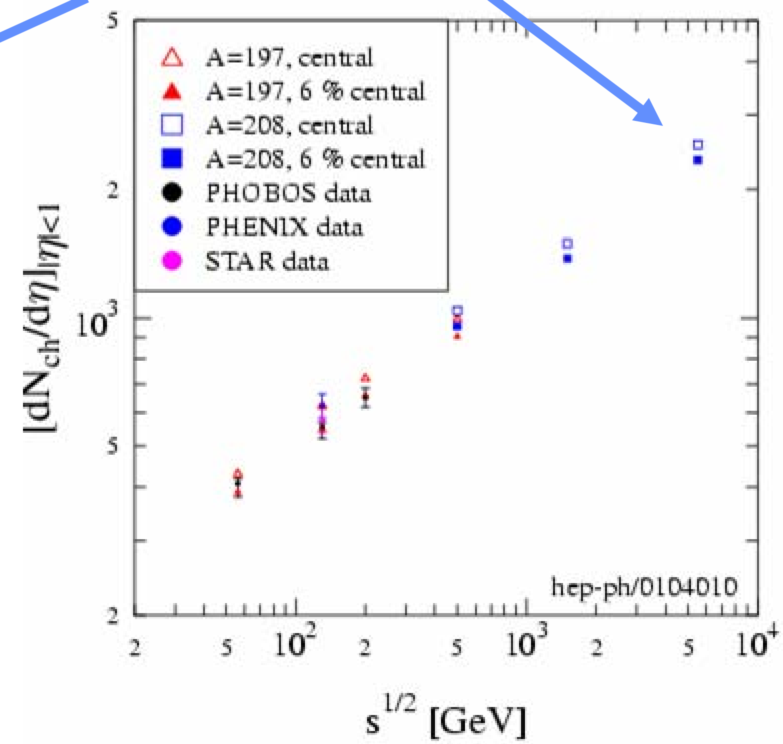


What multiplicity do we expect?

old estimates: dN_{ch}/dy 2000 - 8000,
can we extrapolate from RHIC data ?

$dN_{ch}/d\eta \sim 2500$





(from K.Kajantie, K.Eskola)

Initial Conditions

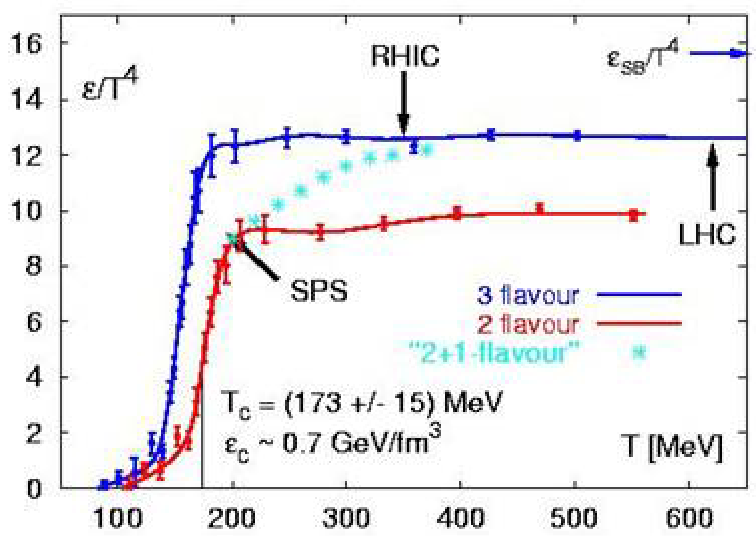
- my pre-RHIC guess (QM2001)
  - ⇨ **still expect conditions to be significantly different**
  - ⇨ **only LHC will give the final answer !**

Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	430	700-1500	2-8 x10^3
ε $(GeV/fm^3)_{\tau 0=1fm}$	2.5	3.5-7.5	15-40
$V_f(fm^3)$	10^3	(?)7x10^3	2x10^4
τ_{QGP} (fm/c)	<1	1.5-4.0	4-10
τ_0 (fm/c)	~1	~0.5	<0.2

Significant gain in ε, V, τ

≈ x 10 SPS -> LHC

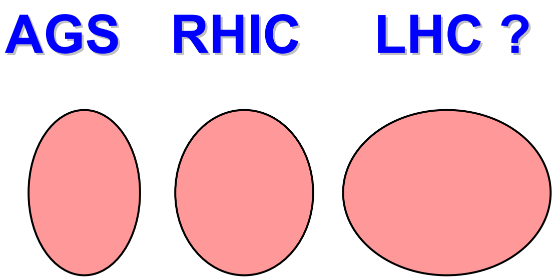
≈ x 3-5 RHIC -> LHC



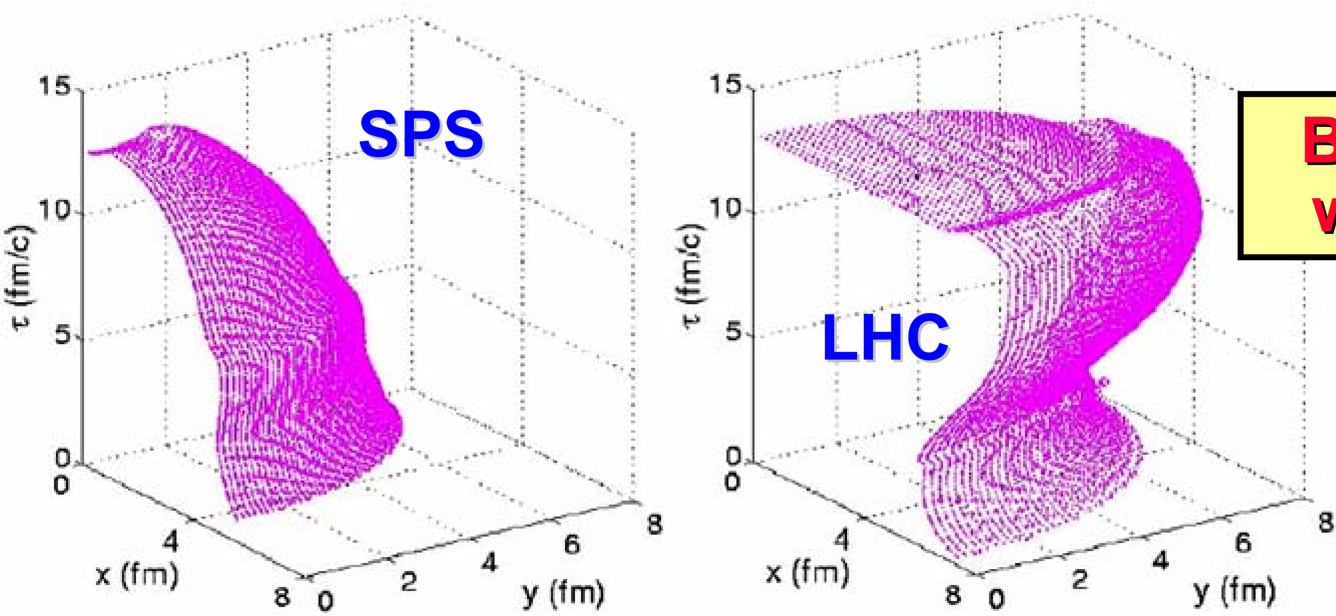
Hotter - Bigger - Longer lived

The Soft Stuff

- **changes in expansion dynamics & freeze-out ARE expected**
  - ⇨ will the measured transverse HBT volume (finally) increase ?
  - ⇨ thermal freeze-out temperature ?
  - ⇨ how will charm fit into particle ratios ?
  - ⇨ will anisotropic flow change shape of freeze-out volume ?
  - ⇨ Event-by-Event fluctuations ?
    - measurement accuracy increases ~ √#particles



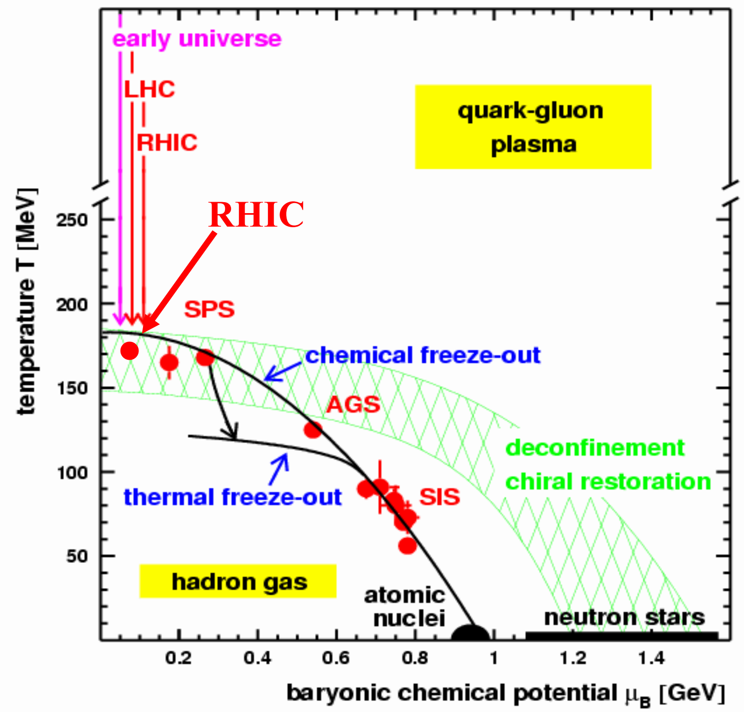
Freeze-out Hyper surface

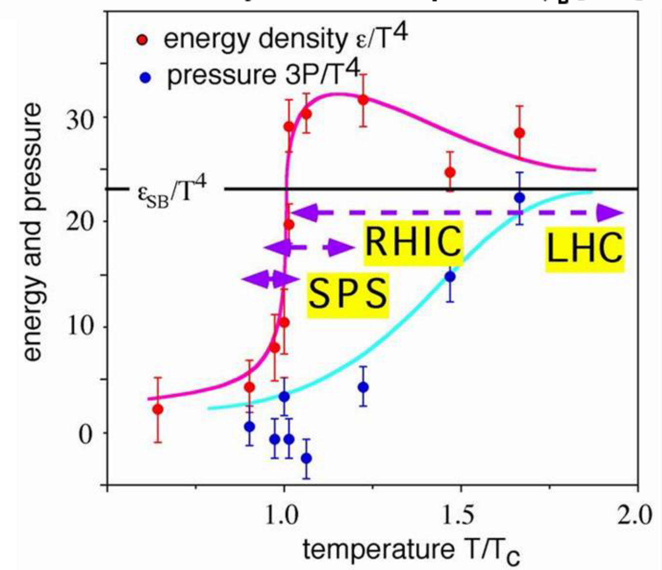


Biggest surprise would be none..

Past-Present-Future

- **AGS/SPS: 1986 – 1994**
  - ⇨ existence & properties of **hadronic phase**
    - ✪ chemical & thermal freeze-out, collective flow,…
- **SPS: 1994 – 2003**
  - ⇨ '**compelling evidence** for **new state of matter** with many **properties** predicted for **QGP**'
    - ✪ J/Psi suppression (deconfinement ?)
    - ✪ low mass lepton pairs (chiral restoration ?)
- **RHIC: 2000 - ?**
  - ⇨ **compelling evidence** -> **establishing** the **QGP** ?
    - ✪ parton flow, parton energy loss
  - ⇨ soft ~ semihard processes; hadron ~ parton phase
- **LHC: 2007 - ??**
  - ⇨ (semi)hard >> soft, parton >> hadron phase
  - ⇨ **precision spectroscopy** of '**ideal** plasma '**QGP**
    - ✪ heavy quarks (c,b), Jets, Y, thermal photons





LHC: will open the **next chapter** in HI physics

significant step over & above existing facilities

THE place to do **frontline research** after 2007

LHC Status

- **the long & winding road to LHC**
  - ⇨ first discussion on HI in LHC: 1990
  - ⇨ LHC approved 1994 /1996
  - ⇨ start-up several times postponed

- **CERN financial problems**
  - ⇨ some 20% cost overrun (~800 MCHF)
  - ⇨ solution:
    - reduce non- LHC program, bank loans, savings, 1 year delay

- **machine well into construction**
  - ⇨ civil engineering almost finished
  - ⇨ many production magnets tested

- **LHC start-up: April 2007**
  - ⇨ first short heavy ion run: end 2007

External Machine Review Committee: 'Tight, but feasible'

LHC Magnets


Main Dipole


MQW
21/8/2002 09:24

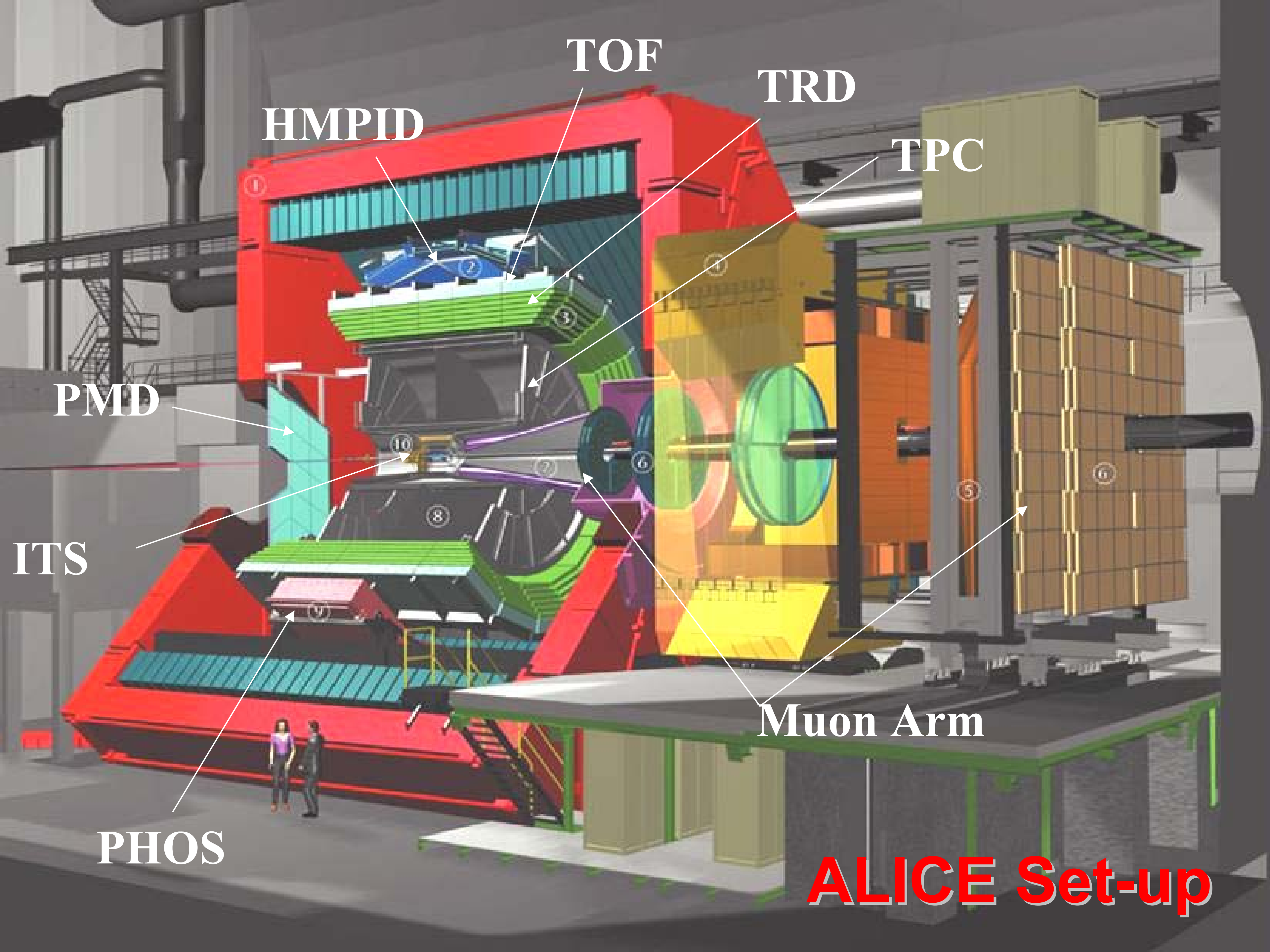

Transfer Lines


Insertion (Japan)

Heavy Ions in LHC

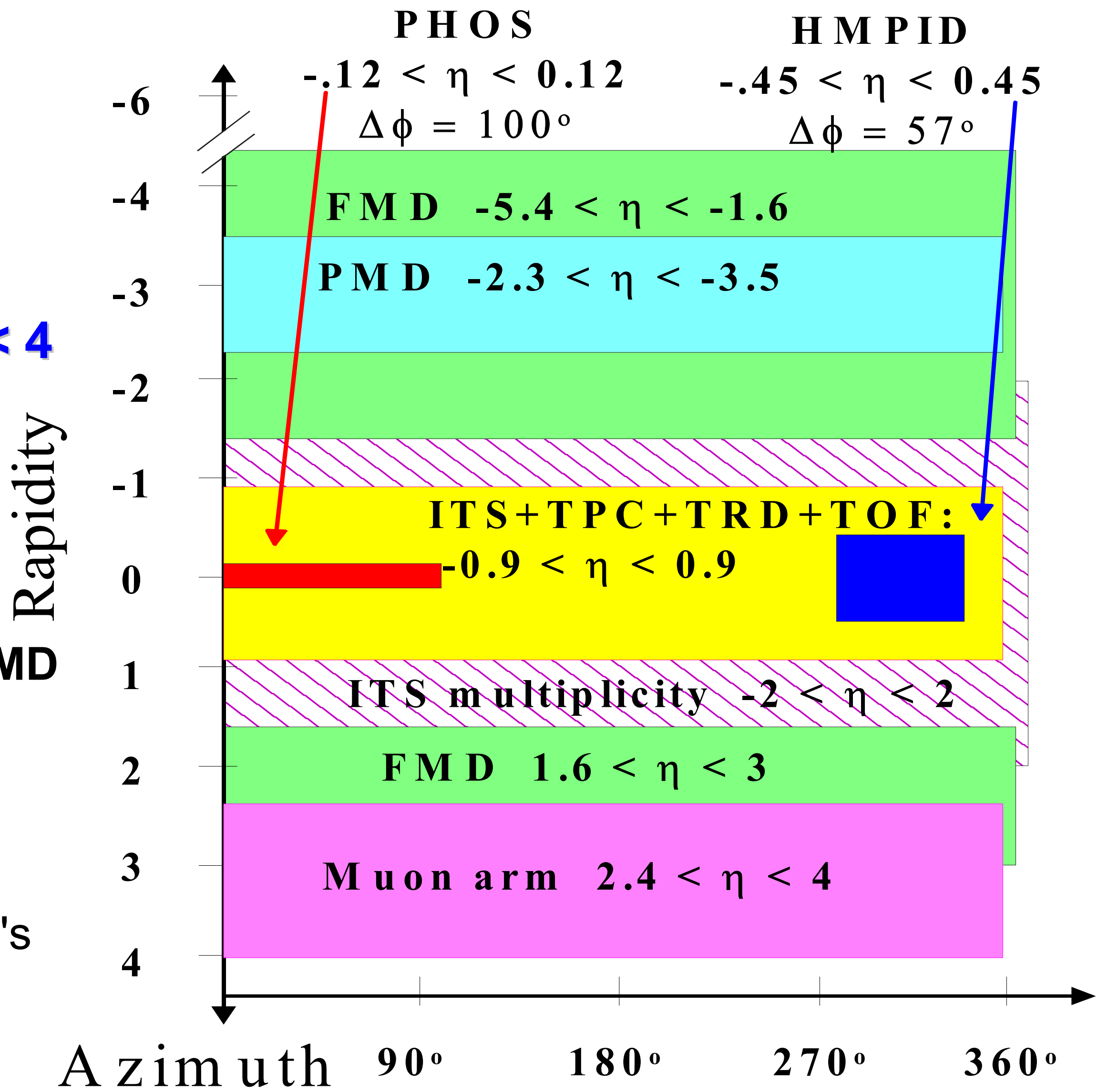
- **energy**
  - E_{beam} = 7 x Z/A [TeV]
  - $\sqrt{s}$ = 5.5 TeV/A (Pb-Pb), 14 TeV (pp)
- **beams**
  - **possible combinations: pp, pA, AA**
    - constant magnetic rigidity/beam ('single magnet')
  - expected heavy ion running
    - **~ 6 weeks heavy ion runs**, typically after pp running (**like at SPS**)
    - initial emphasis on Pb-Pb
    - pp and pA comparison runs
    - intermediate mass ion (eg Ar-Ar) to vary energy density
  - later options: different ion species, lower energy AA and pp
- **luminosity**
  - low L runs:
    - avoid pile-up in TPC
  - high L runs:
    - max rate in muon arm

	Pb-Pb	**Ar-Ar**	**pp**
L [$cm^{-2}s^{-1}$]	**10^{27}**	**3×10^{27} to 10^{29}**	**10^{29} to 3×10^{30}**
Rate [kHz]	**8**	**8 to 250**	**7 to 200**


TOF
TRD
HMPID
TPC
PMD
ITS
Muon Arm
PHOS
ALICE Set-up

ALICE Acceptance

- **central barrel -0.9 < η < 0.9**
  - ⇨ tracking, PID
  - ⇨ single arm **RICH** (HMPID)
  - ⇨ single arm **em. calo** (PHOS)
- **forward muon arm 2.4 < η < 4**
  - ⇨ absorber, dipole magnet tracking & trigger chambers
- **multiplicity -5.4 < η < 3**
  - ⇨ including photon counting in **PMD**
- **trigger & timing dets**
  - ⇨ **Zero Degree Calorimeters**
  - ⇨ **T0:** ring of quartz window PMT's
  - ⇨ **V0:** ring of scint. Paddles



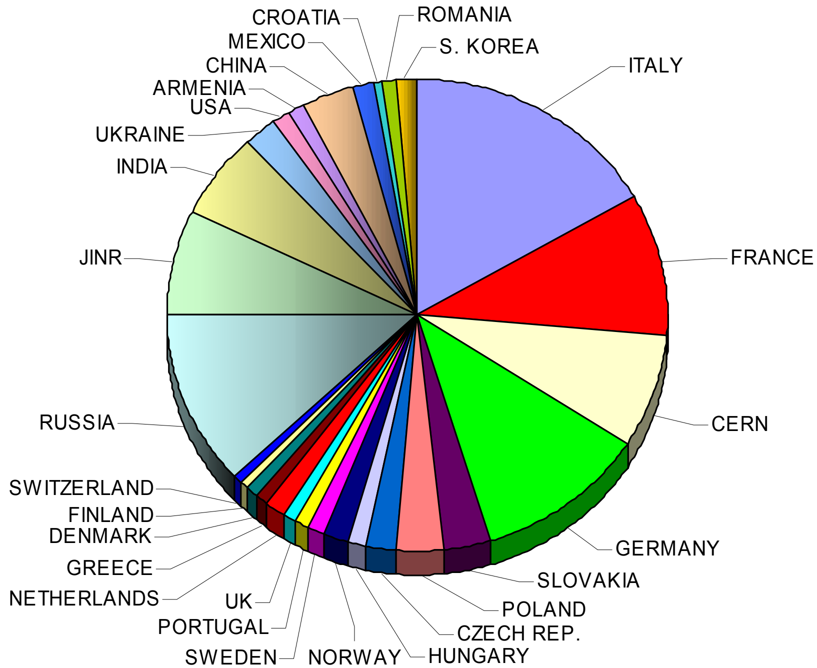
ALICE Collaboration

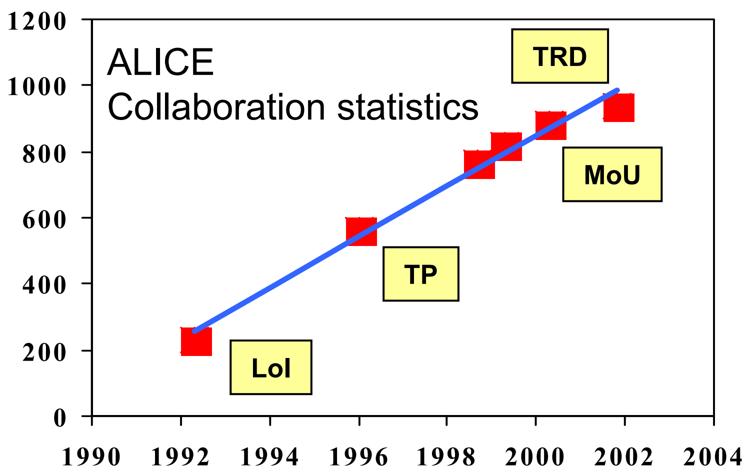
~ 1000 Members

(63% from CERN MS)

~30 Countries

~80 Institutes





ALICE Technical Board

ALICE Design Philosophy

- **General Purpose Heavy Ion Detector**
  - ⇨ **one single dedicated HI expt** at LHC
    - **ATLAS/CMS** have some interest, but **priority is pp** physics
    - AGS/SPS: several (6-8) 'special purpose expts'
    - RHIC: 2 large multipurpose + 2 small special purpose expts
- **cover essentially all known observables of interest**
  - ⇨ **comprehensive** study of **hadrons** at midrapidity
    - large acceptance, excellent tracking and PID
  - ⇨ **state-of-the-art** measurement of direct **photons**
    - excellent resolution & granularity em calo (small but expensive !)
  - ⇨ dedicated & **complementary** systems for **di-electrons and di-muons**
  - ⇨ cover the complete spectrum: **from soft** (10's of MeV) **to hard** (100's of GeV)
    - more recent design feature, still incomplete ...
- **stay open for changes & surprises**
  - ⇨ **high throughput** DAQ system **+** powerful **online intelligence** ('PC farm')
    - flexible & scalable: minimum design prejudice on what will be most interesting

Reality is more difficult..

- **technical and financial constraints lead to compromises**
  - acceptance is limited to about $\Delta y = 2$
  - fragmentation region is not addressed
    - in any case, difficult at LHC (beam rapidity = 9)
  - robust tracking <-> rate capability
    - limited by pile-up in TPC to some 8 kHz in AA
  - no large area calorimeters
    - at least, not yet…

L3 magnet

- still largest magnet
  - ⇨ magnet volume: 12 m long, 12 m high
  - ⇨ 0.5 T solenoidal field


Fresh paint


The ALICE
Magnet:
ready for the experiment to move in!

ALICE R&D

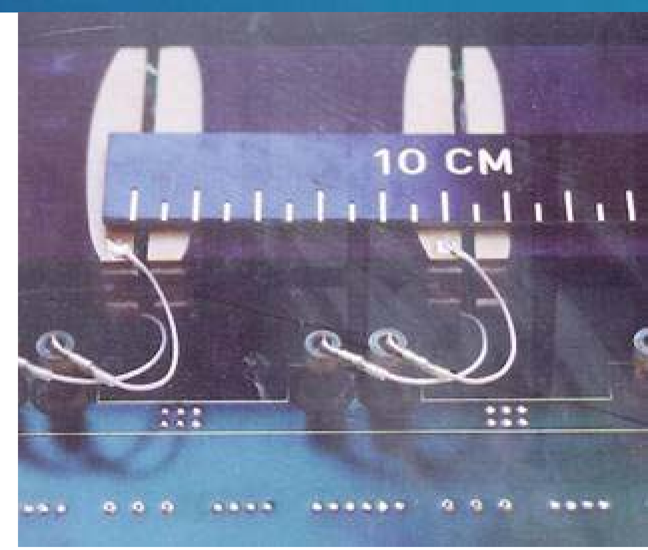
1990-1996: Strong, well organized, well funded R&D activity

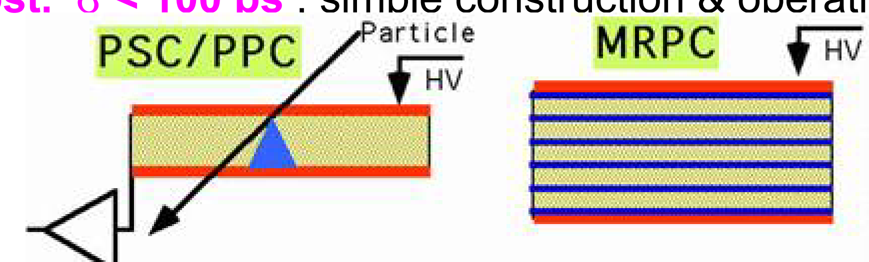
- **Inner Tracking System (ITS)**
  - ⇨ Silicon Pixels (RD19)
  - ⇨ Silicon Drift (INFN/SDI)
  - ⇨ Silicon Strips (double sided)
  - ⇨ low mass, high density interconnects
  - ⇨ low mass support/cooling
- **TPC**
  - ⇨ gas mixtures (RD32)
  - ⇨ new r/o plane structures
  - ⇨ advanced digital electronics
  - ⇨ low mass field cage
- **em calorimeter**
  - ⇨ new scint. crystals (RD18)
- **PID**
  - ⇨ Pestov Spark counters
  - ⇨ Parallel Plate Chambers
  - ⇨ Multigap RPC's (LAA)
  - ⇨ low cost PM's
  - ⇨ solid photocathode RICH (RD26)
- **DAQ & Computing**
  - ⇨ scalable architectures with COTS ?
  - ⇨ high perf. storage media ?
  - ⇨ GRID computing ?
- **misc**
  - ⇨ micro-channel plates
  - ⇨ rad hard quartz fiber calo.
  - ⇨ VLSI electronics

• R&D made effective use of long (frustrating) wait for LHC
• was vital for all LHC experiments to meet LHC challenge !

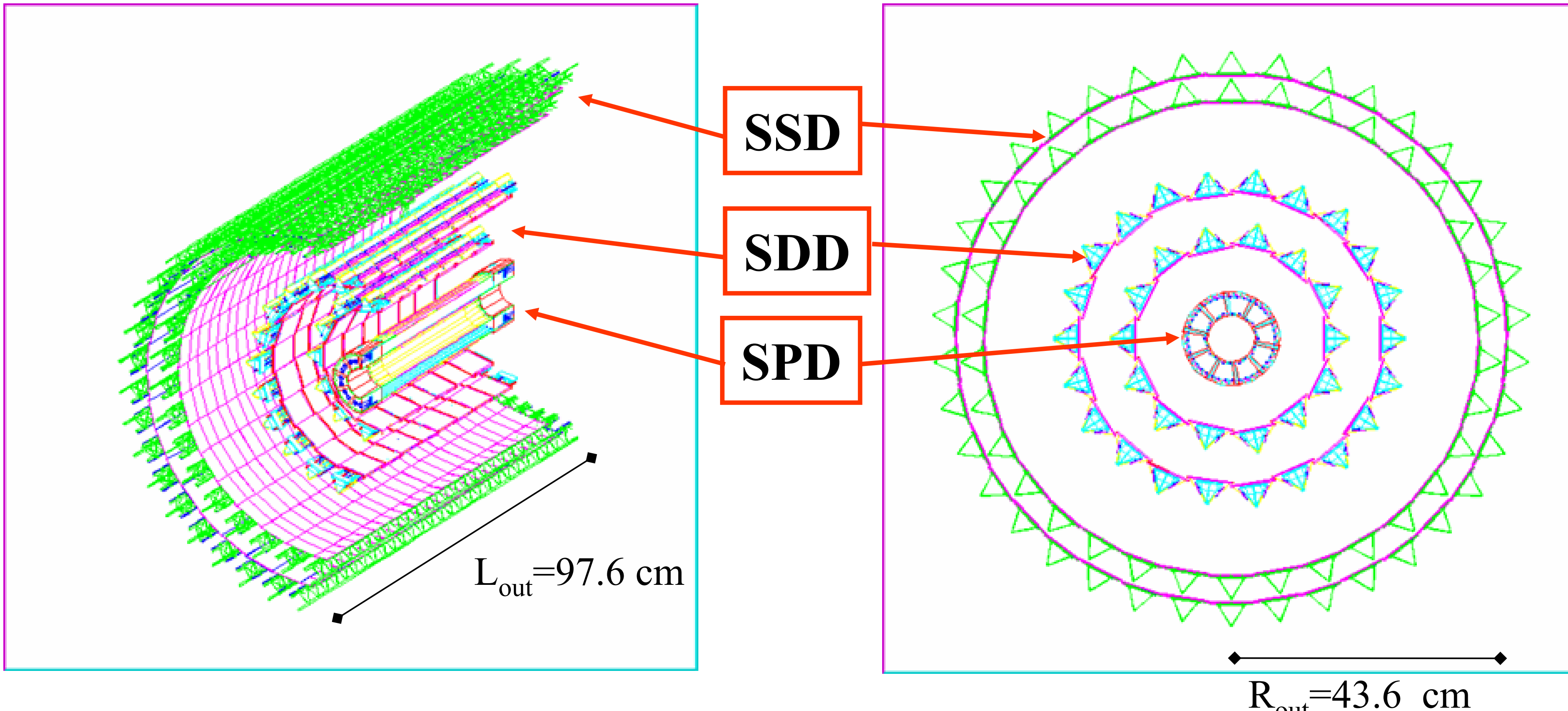
Time of Flight Detectors

- **aim: state-of-the-art TOF at ~1/10 current price !**
  - requirements: area > 150 m^2, channels ~ 150,000, resolution σ < 100 ps
  - existing solution: scintillator + PM, **cost > 120 MSF !**
    - R&D on cheaper fast PM's in Russia failed to deliver
- **gas TOF counters + VLSI FEE**
  - **Pestov Spark Counter** (PSC)
    - 100 μm gap, > 5 kV HV, 12 bar, sophisticated gas
    - σ **< 50 ps,** some 'tails' (?), but only (!) **~ 1/5 cost**
    - technology & materials **VERY challenging**
  - **Parallel Plate Chamber** (PPC)
    - 1.2 mm gap, 1 bar, simple gas & materials
    - **1/10 cost,** but only σ **= 250 ps**
    - **unstable operation, small signal**
  - **Multigap Resistive Plate Chambers** (MRPC)
    - breakthrough end 1998 after > 5 years of R&D !
    - many small gaps (10x250 μm), 1 bar, simple gas & materials
    - **~ 1/10 cost,** σ **< 100 ps** , simple construction & operation,..





Inner Tracking System (ITS)



- **6 Layers, three technologies** **(keep occupancy ~constant ~2% for max mult)**
  - ⇨ **Silicon Pixels** (0.2 m^2, 9.8 Mchannels)
  - ⇨ **Silicon Drift** (1.3 m^2, 133 kchannels)
  - ⇨ **Double-sided Strip Strip** (4.9 m^2, 2.6 Mchannels)

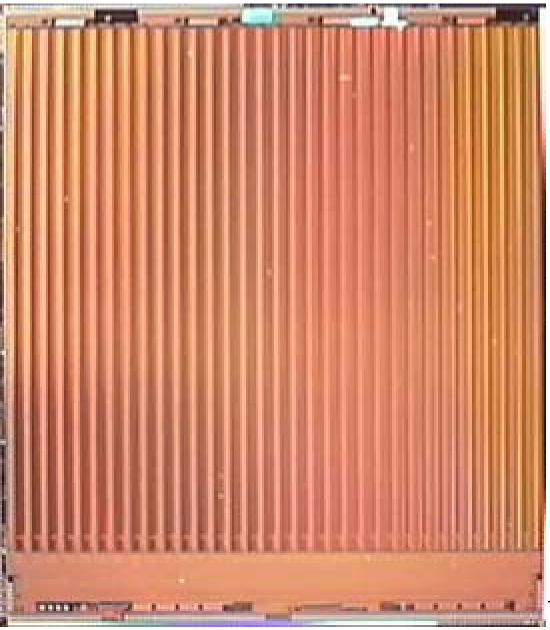
Material Budget: < 1% X_0 per layer !

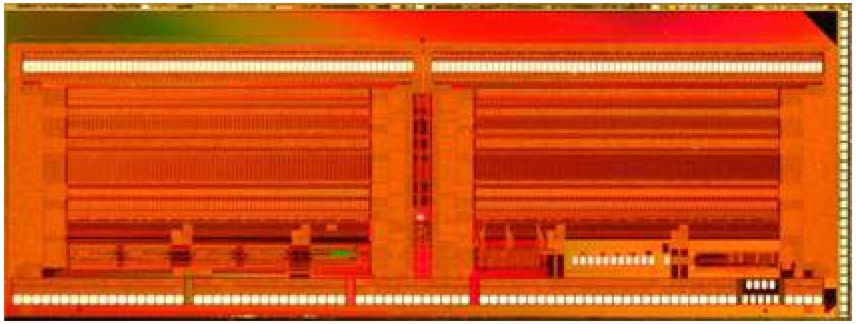
Major technological challenge!

ITS Electronics Developments

(all full-custom designs in rad. tol., 0.25 μm process)

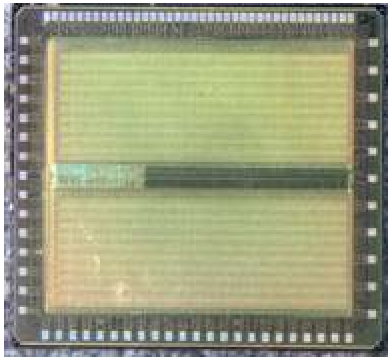
ALICE PIXEL CHIP
50 μm x 425 μm pixels
8192 cells
Area: 12.8 x 13.6 mm^2
13 million transistors
~100 μW/channel

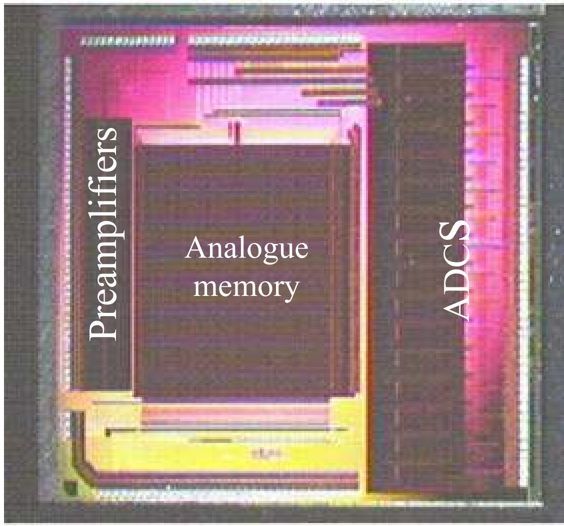




ALICE SSD FEE
HAL25 chip:
128 channels
Preamp+s/h+
serial out

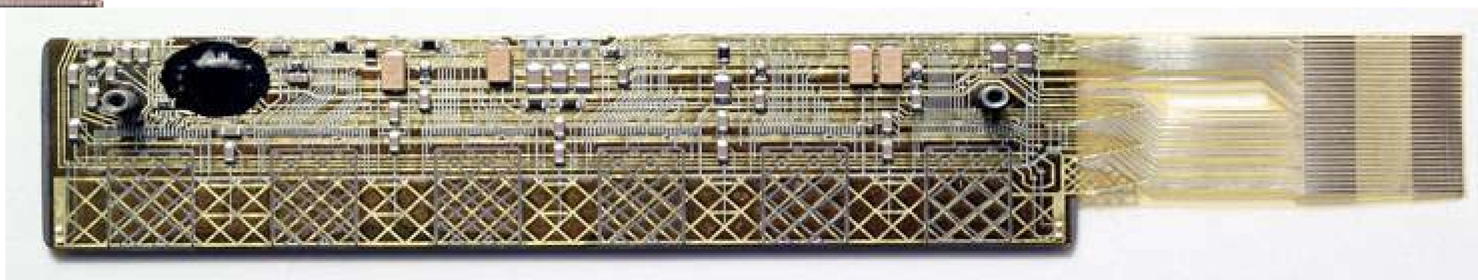
ALICE SDD FEE
Pascal chip:
64 channel preamp+ 256-deep analogue memory+ ADC
Ambra chip:
64 channel derandomizer chip

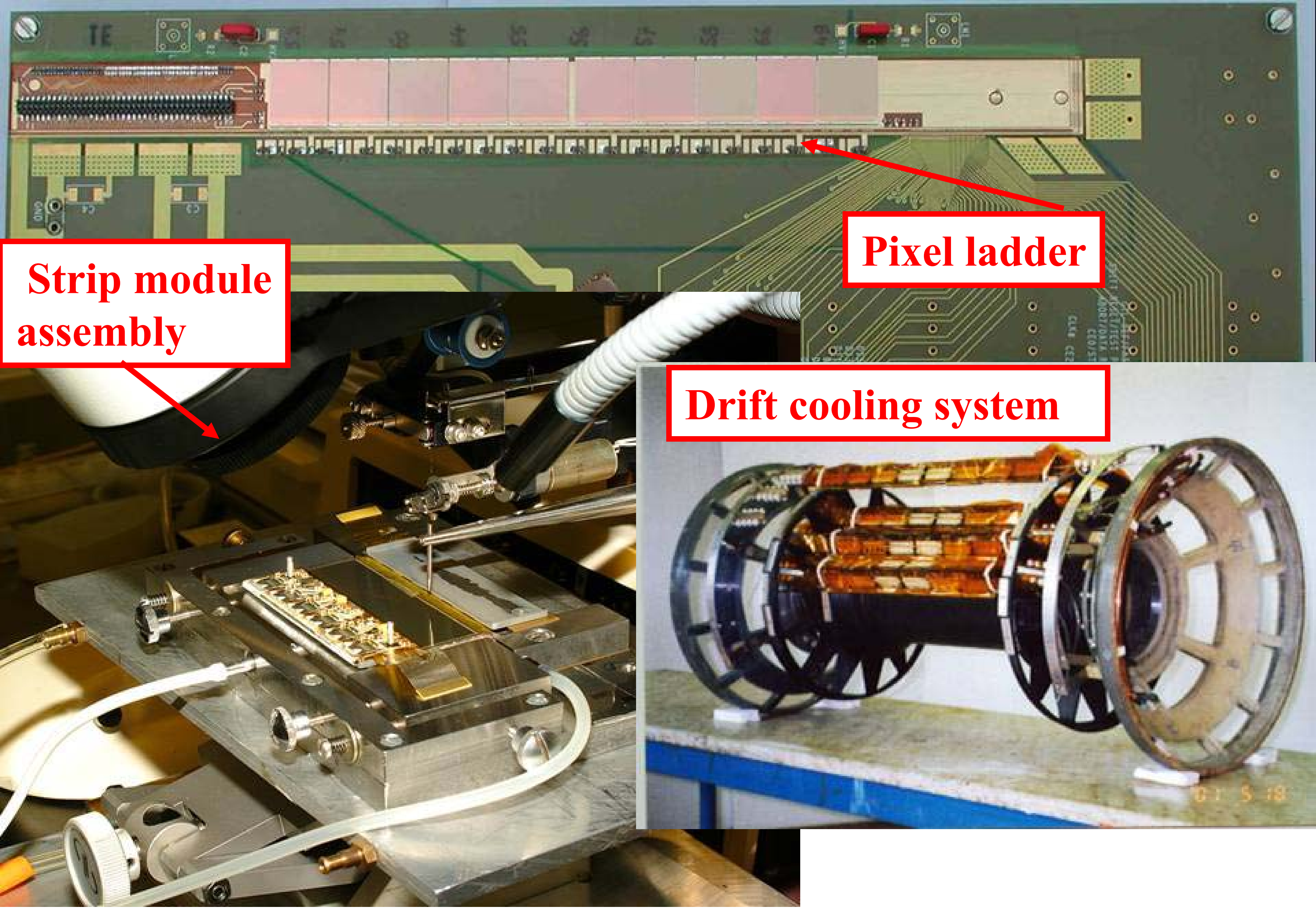




And extreme lightweight interconnection techniques:

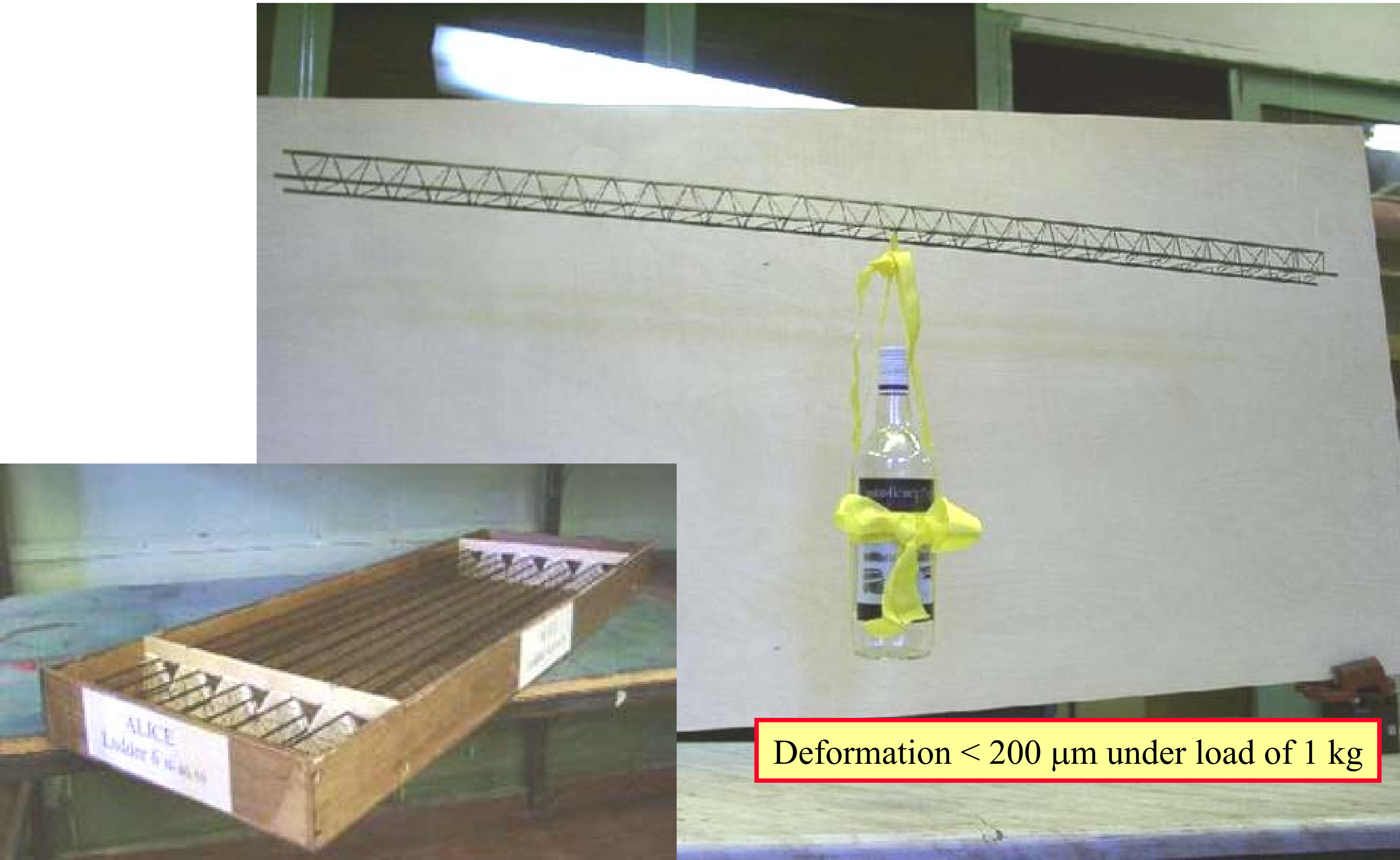
SSD tab-bondable
Al hybrids





System testing and setting up of series production

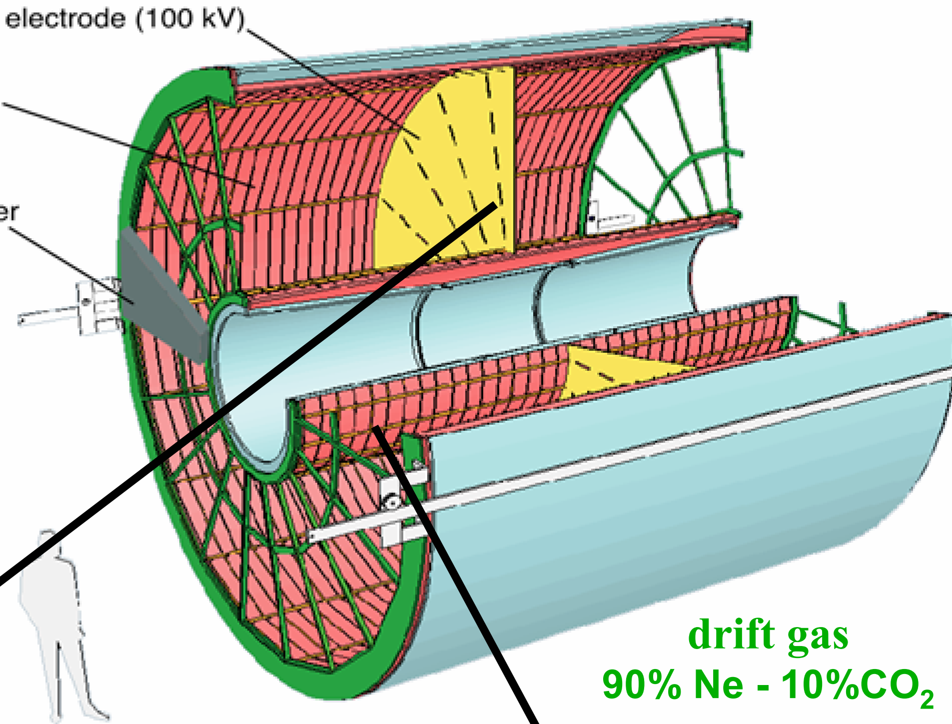
ITS Support Acceptance Test

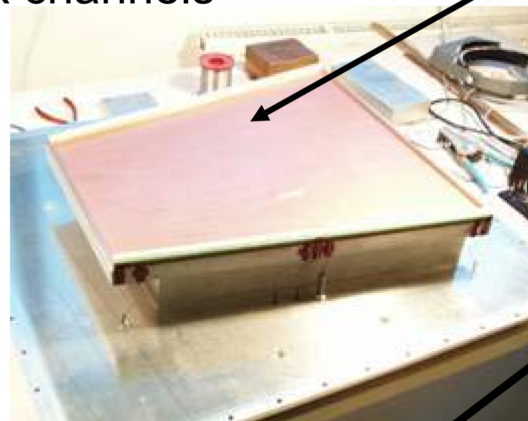


Deformation < 200 μm under load of 1 kg

TPC

- **largest ever**
  - ⇨ 88 m^3, 570 k channels

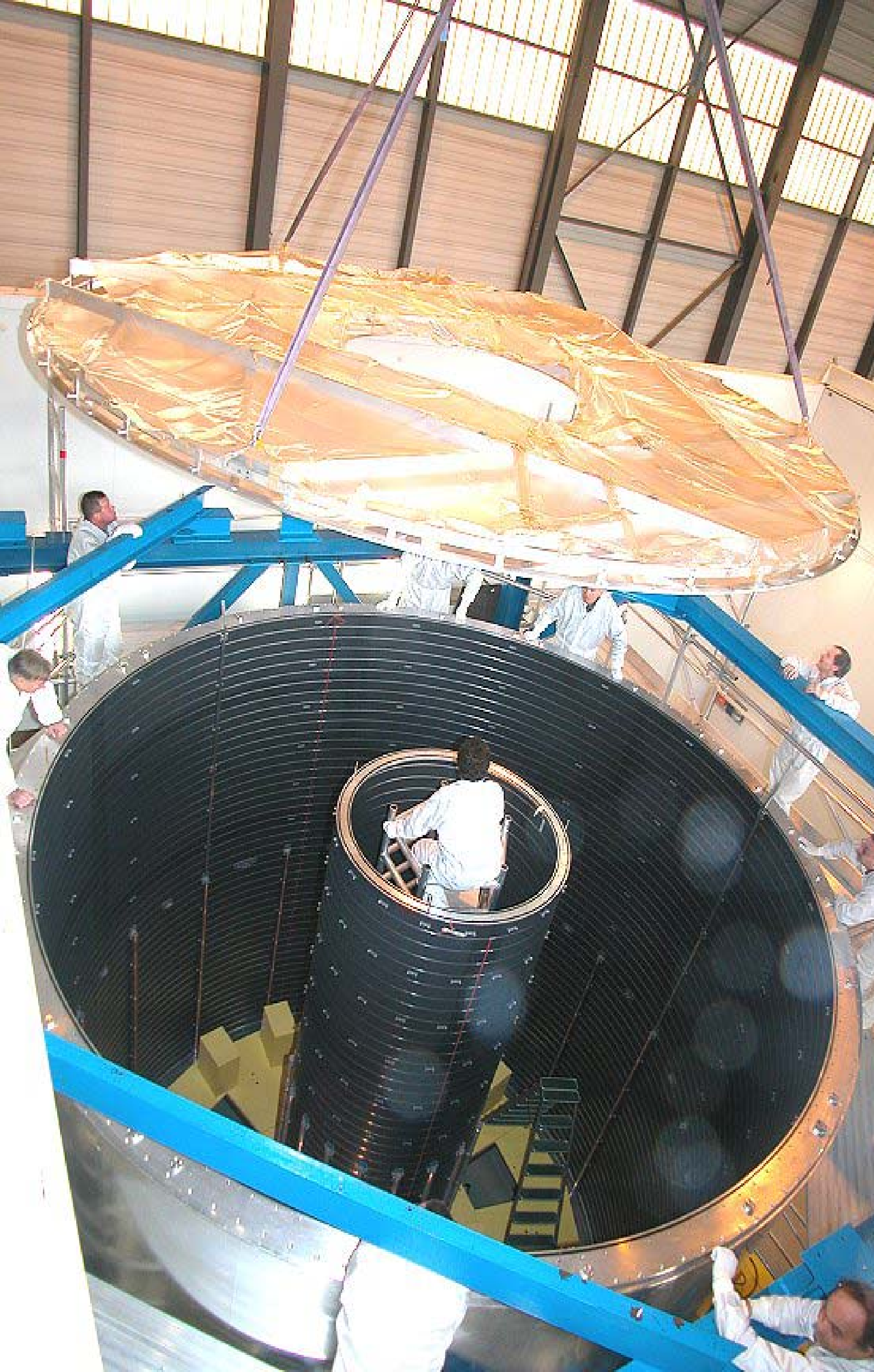
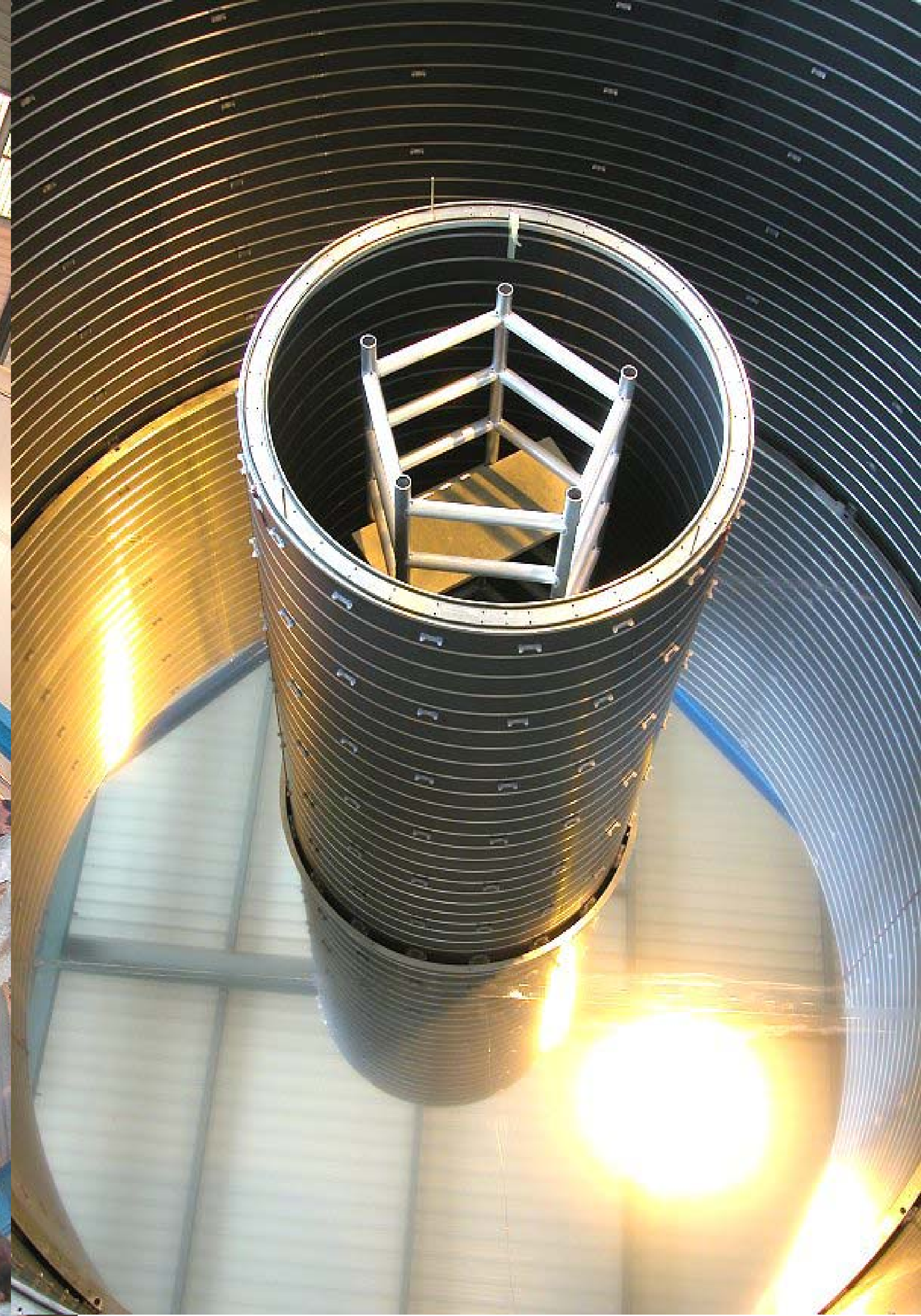


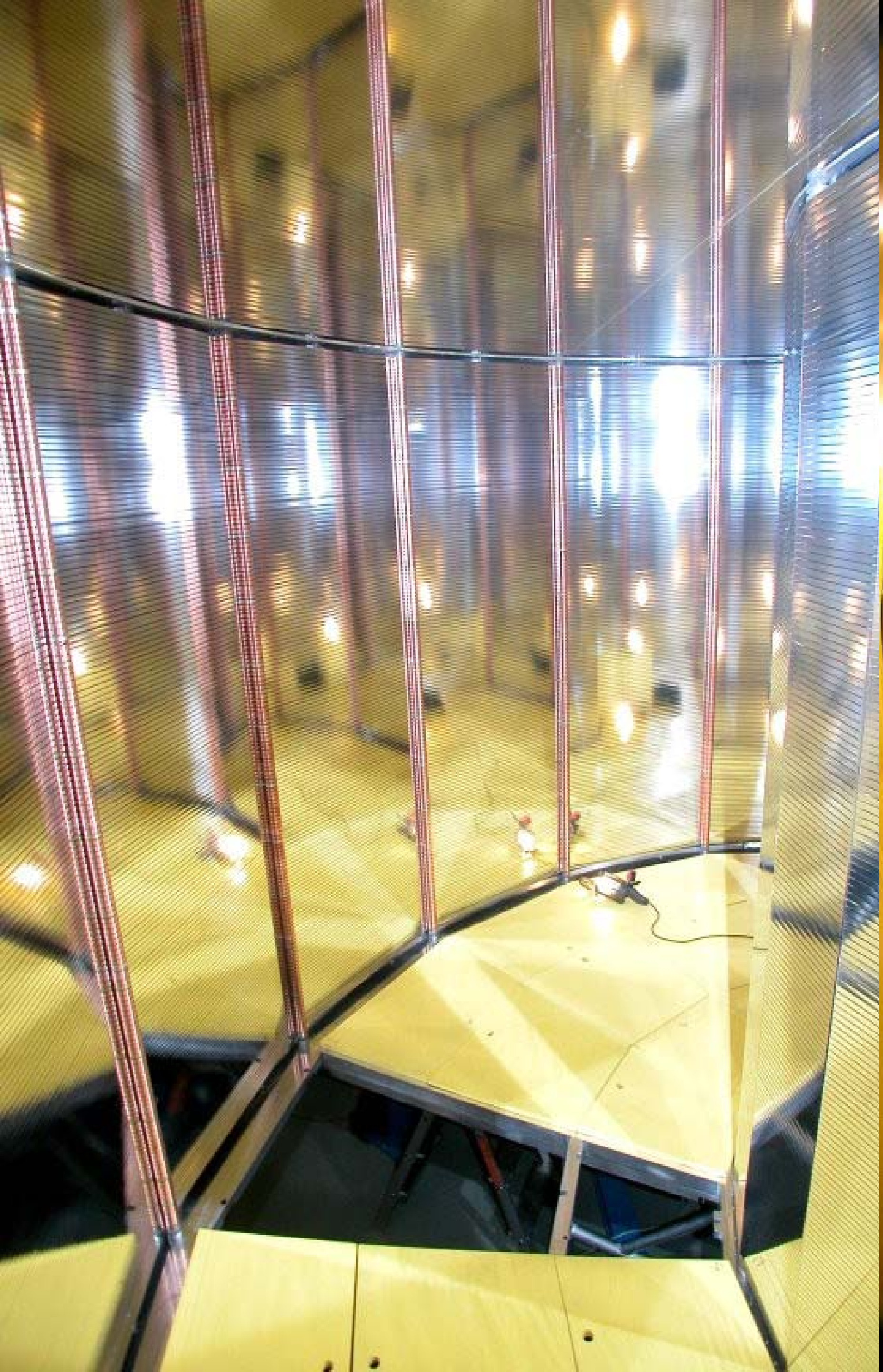


drift gas
90% Ne - 10%CO_2

Central Electrode Prototype
25 μm aluminized Mylar on Al frame

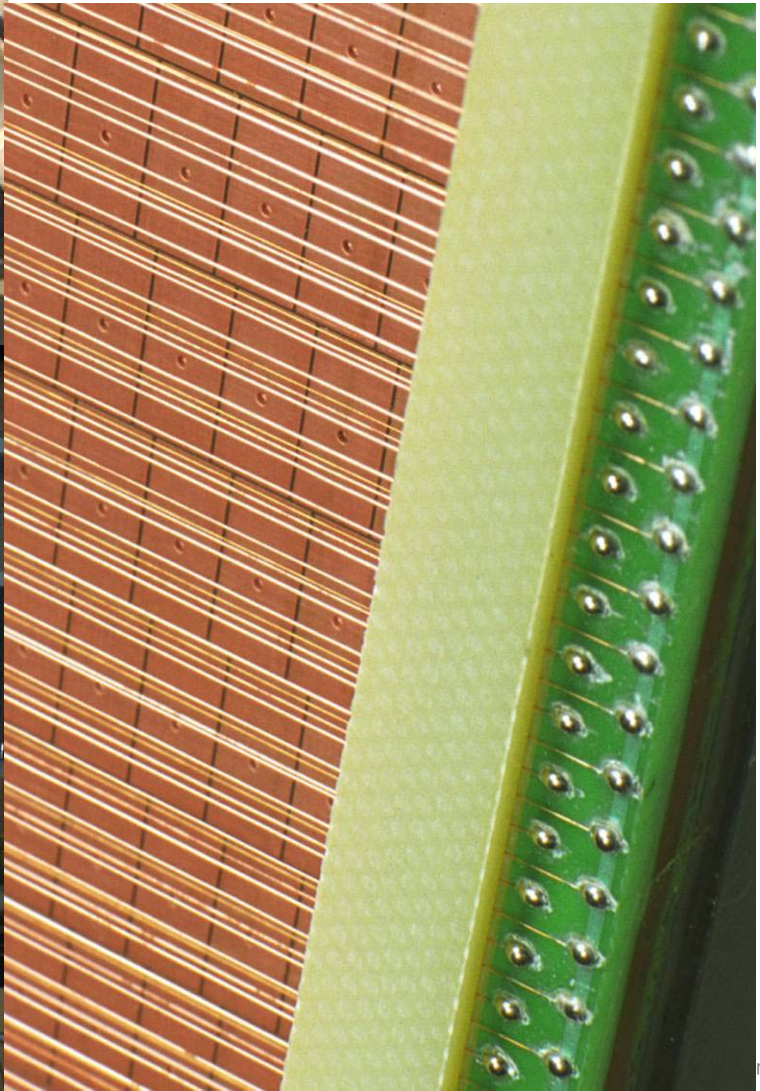
TPC Field Cage

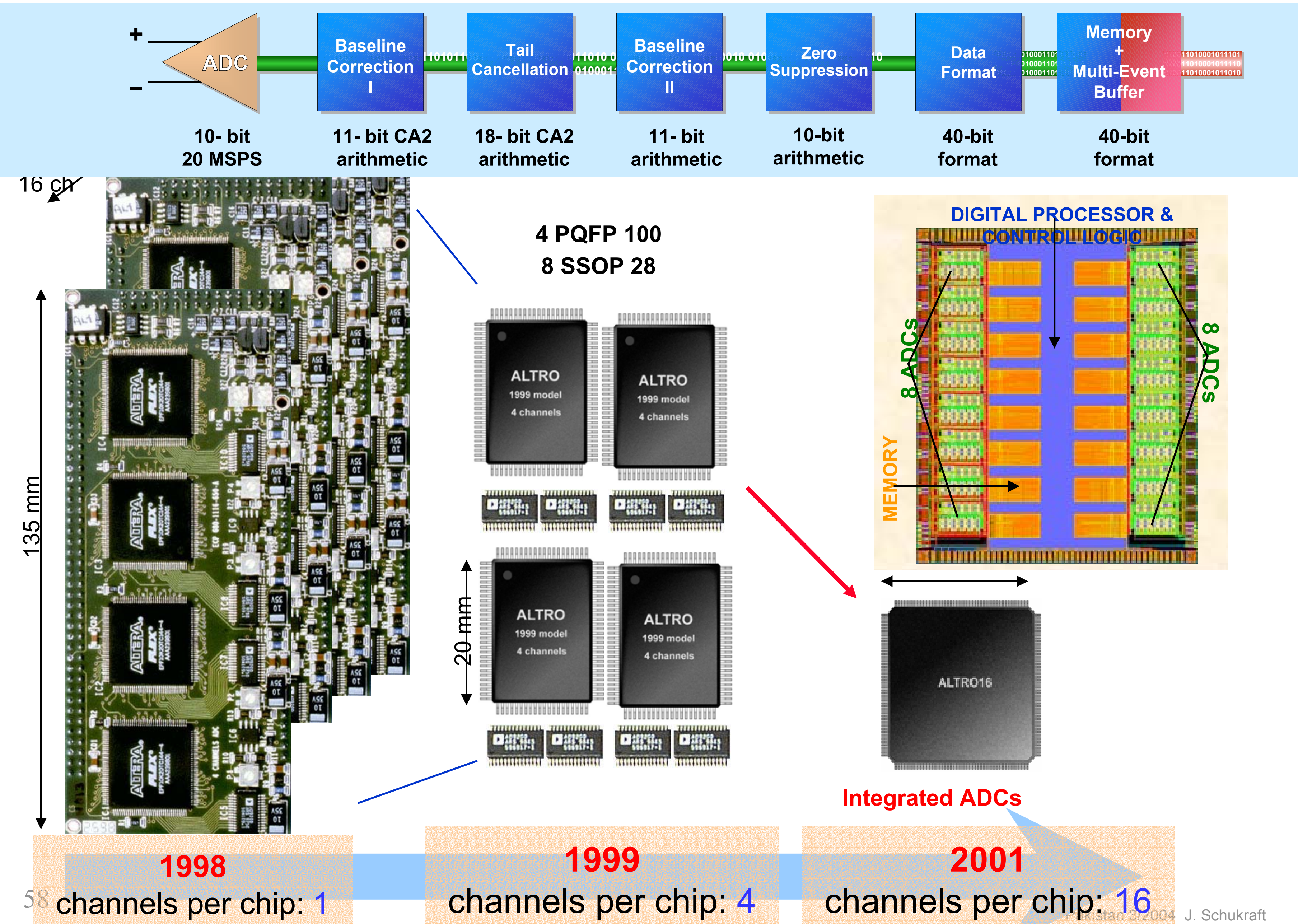



TPC R/O chambers

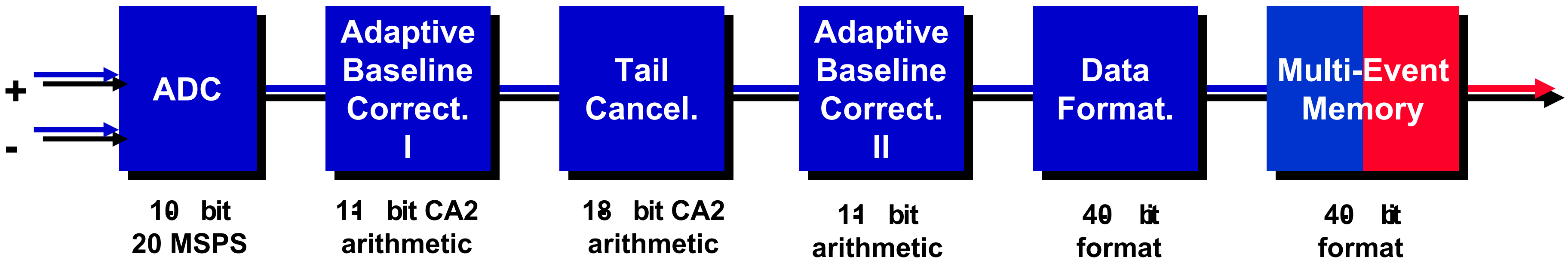
- Chamber production ends spring 2004



ALTRO: Better-Smaller-Cheaper



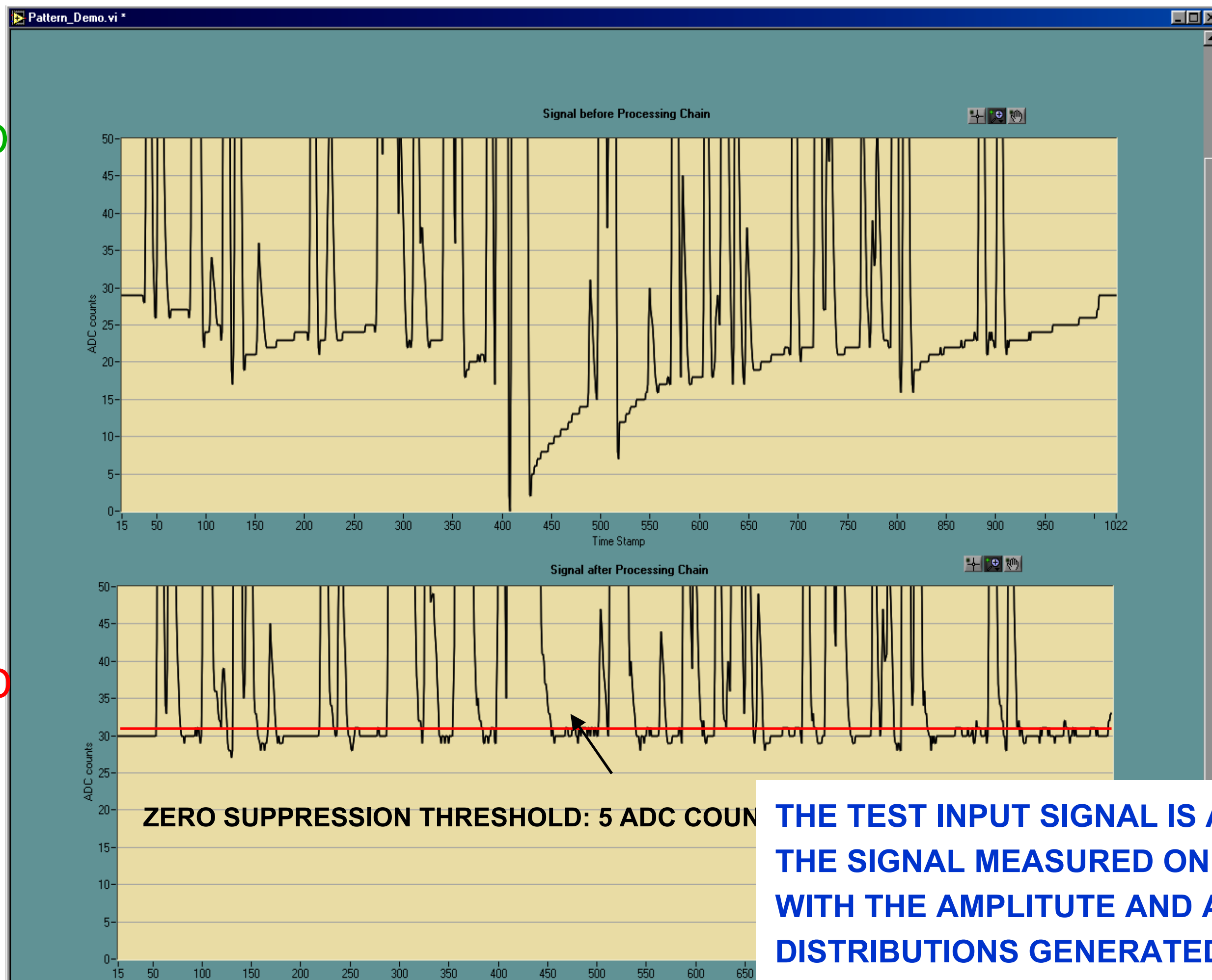
TPC Electronics: ALICE TPCE READOUT CHIP (ALTRO)



ALTRO OUTPUT
FILTER DISABLED

ALTRO test result

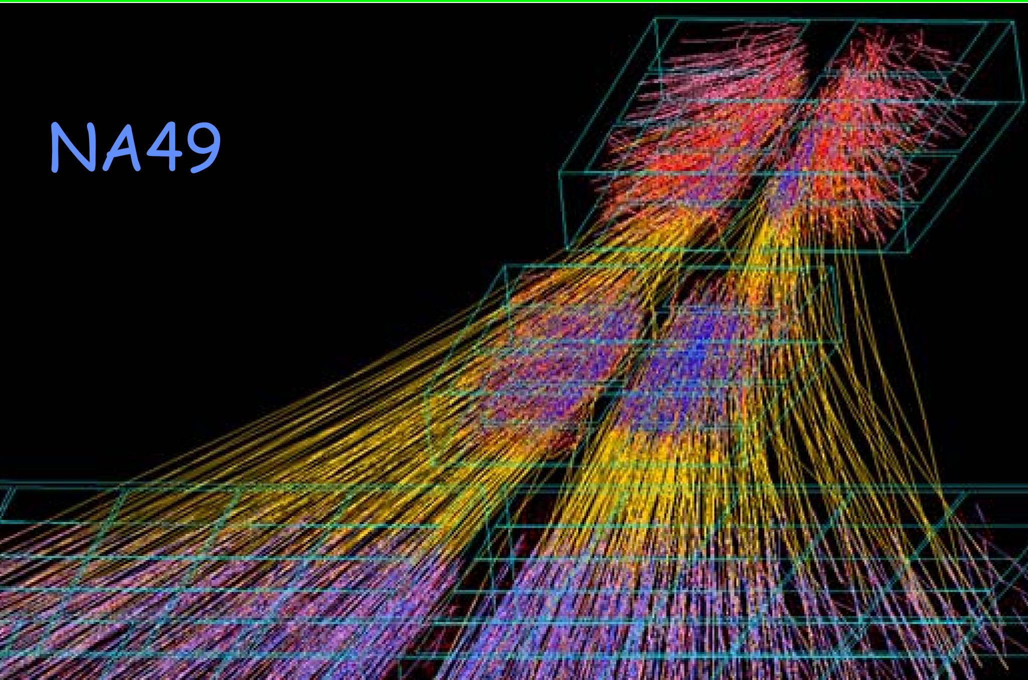
ALTRO OUTPUT
FILTER ENABLED



Taken up in TT Database, lively customer interest ! (both Industry and research labs)

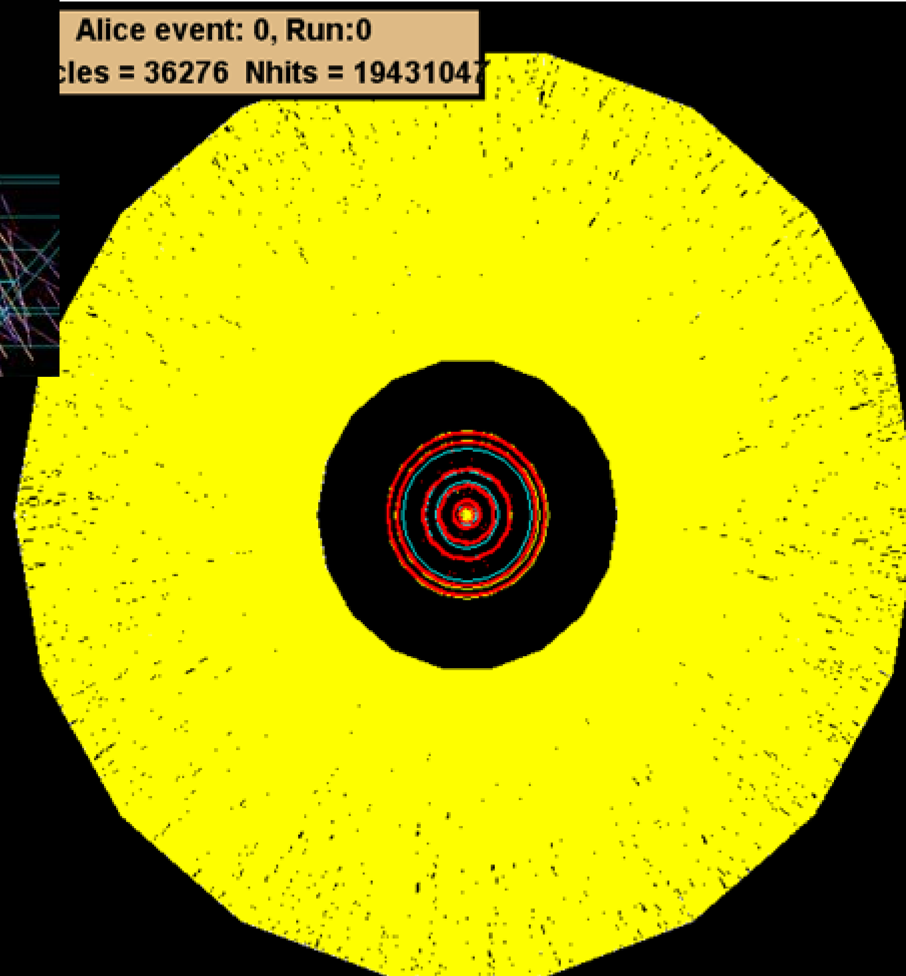
THE TEST INPUT SIGNAL IS A CONVOLUTION OF THE SIGNAL MEASURED ON THE TPC PROTOTYP WITH THE AMPLITUTE AND ARRIVAL TIME DISTRIBUTIONS GENERATED BY ALIROOT

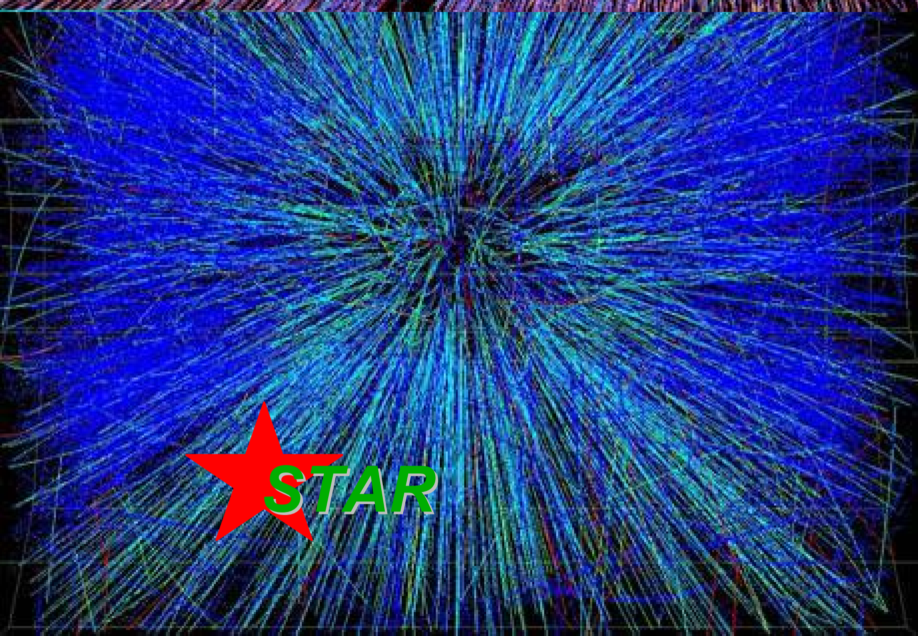
Tracking Challenge



ALICE 'worst case' scenario:

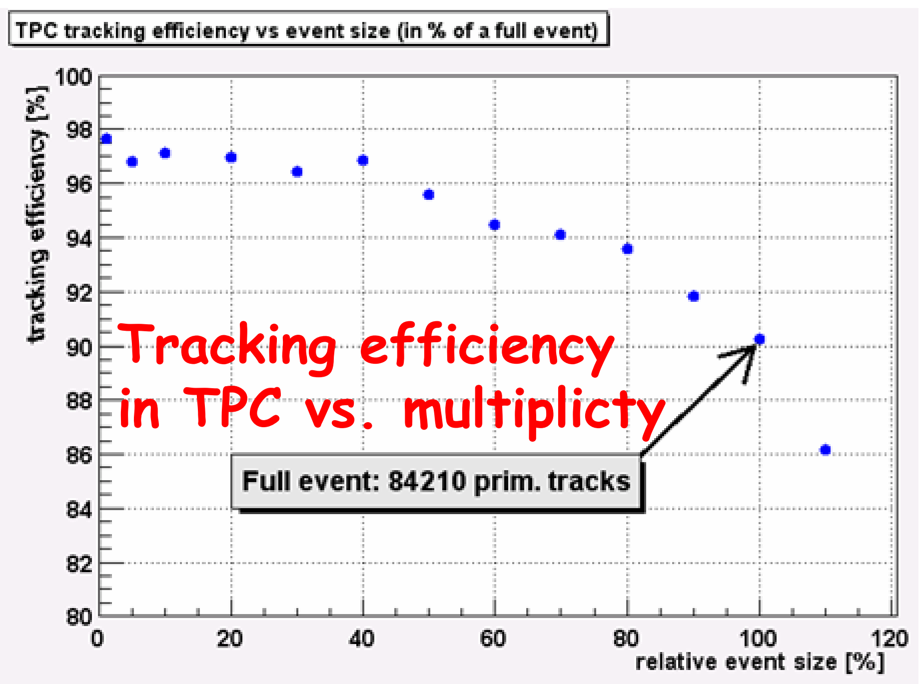
$dN/dy_{ch} = 8000$

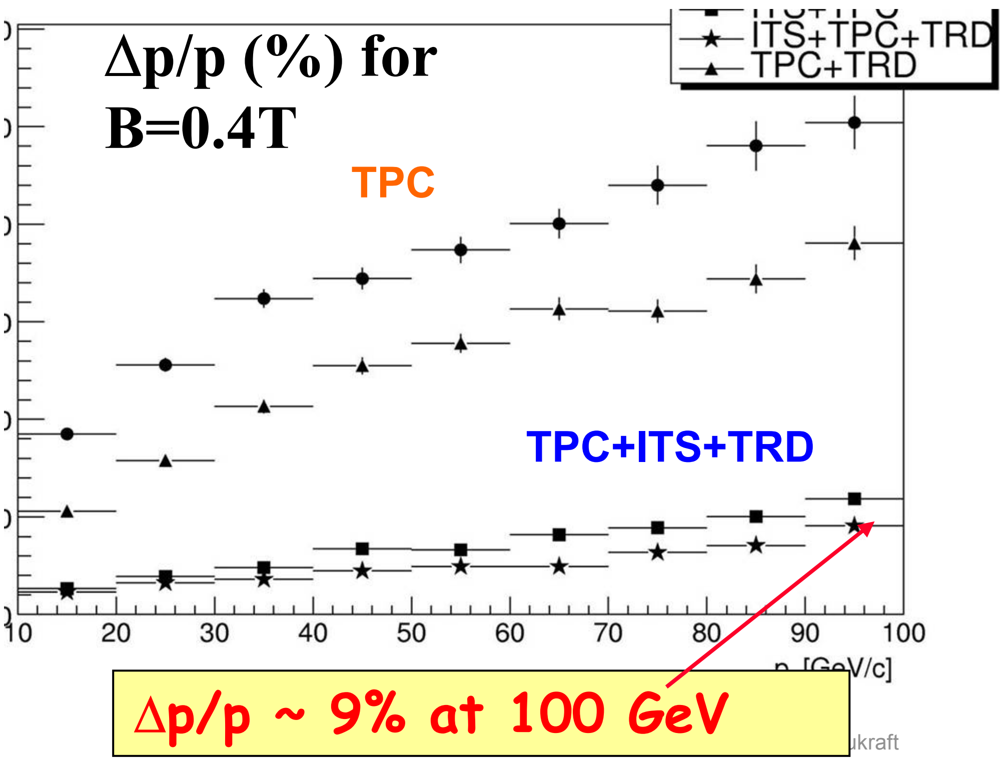




Tracking

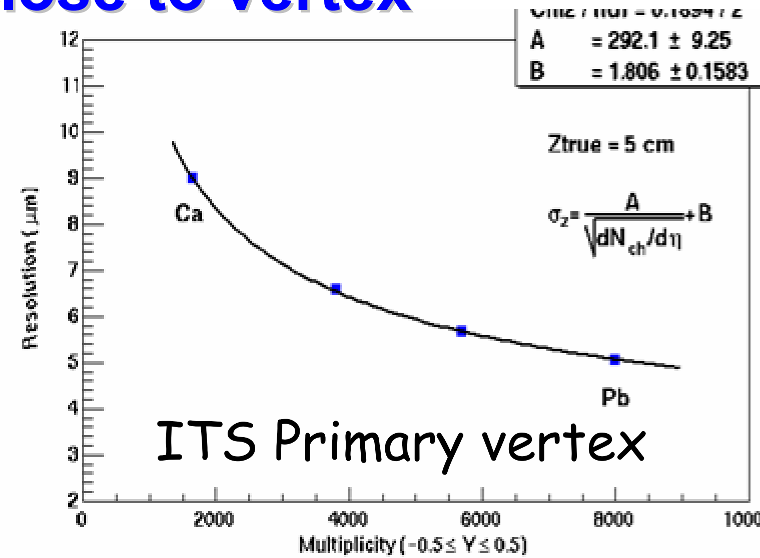
- **robust, redundant tracking from 60 MeV to 100 GeV**
  - ⇨ modest soleniodal field (0.5 T) => easy pattern recognition
  - ⇨ long lever arm => good momentum resolution
  - ⇨ **silicon vertex detector** (ITS) 4 cm < r < 44 cm
    - ✪ stand-alone tracking at low p_t
  - ⇨ **Time Projection Chamber** (TPC) 90 cm < r < 250 cm
  - ⇨ **Transition Radiation Detector** (TRD) 290 cm < r < 370 cm



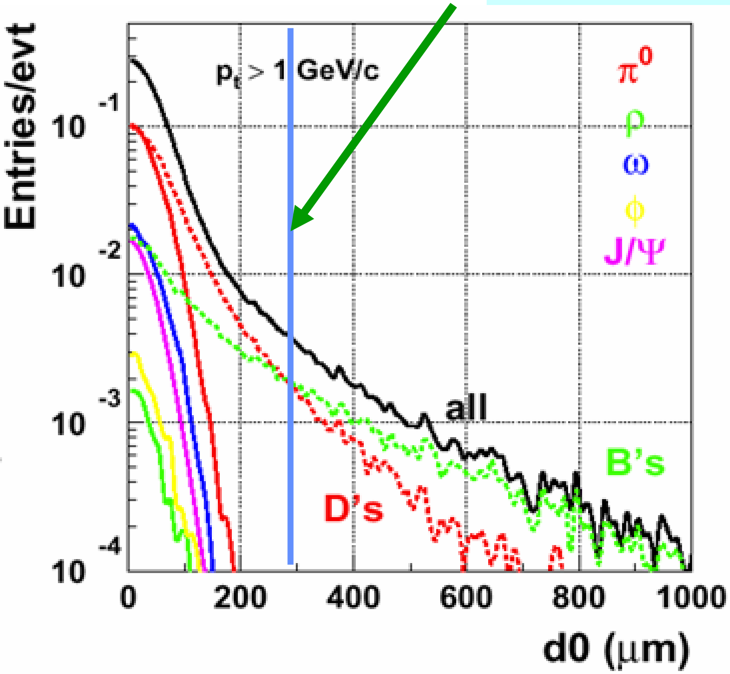


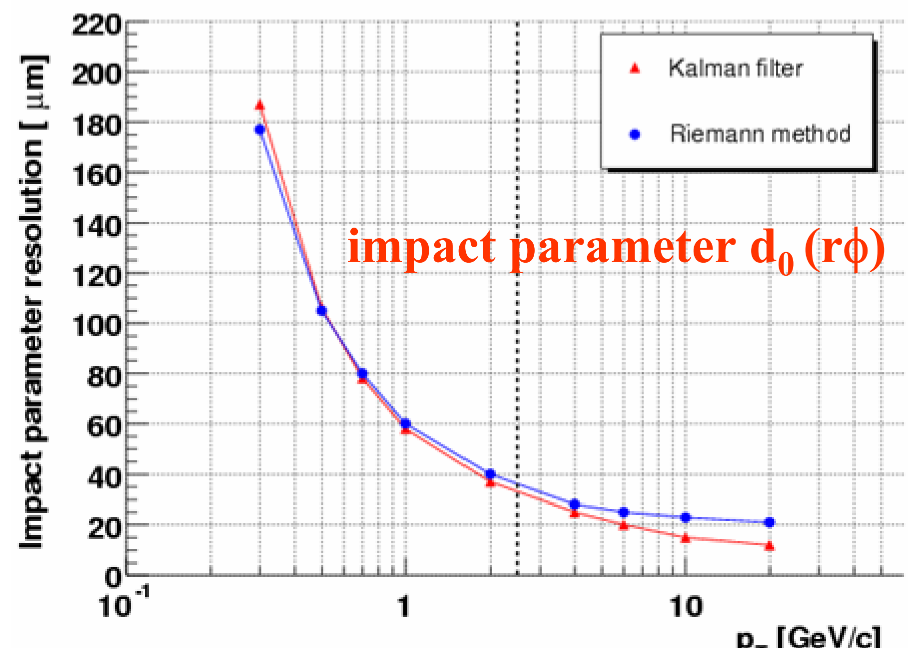
Vertex Finding

- **little material + good resolution + close to vertex**
  - ⇨ primary vertex:
    - 15 μm (rφ) x 5 μm (z)
  - ⇨ secondary vertices:
    - heavy quarks (100's μm)
    - hyperons (cm)



d_0 < cut → resonances
d_0 > cut → D,B mesons





Particle Identification

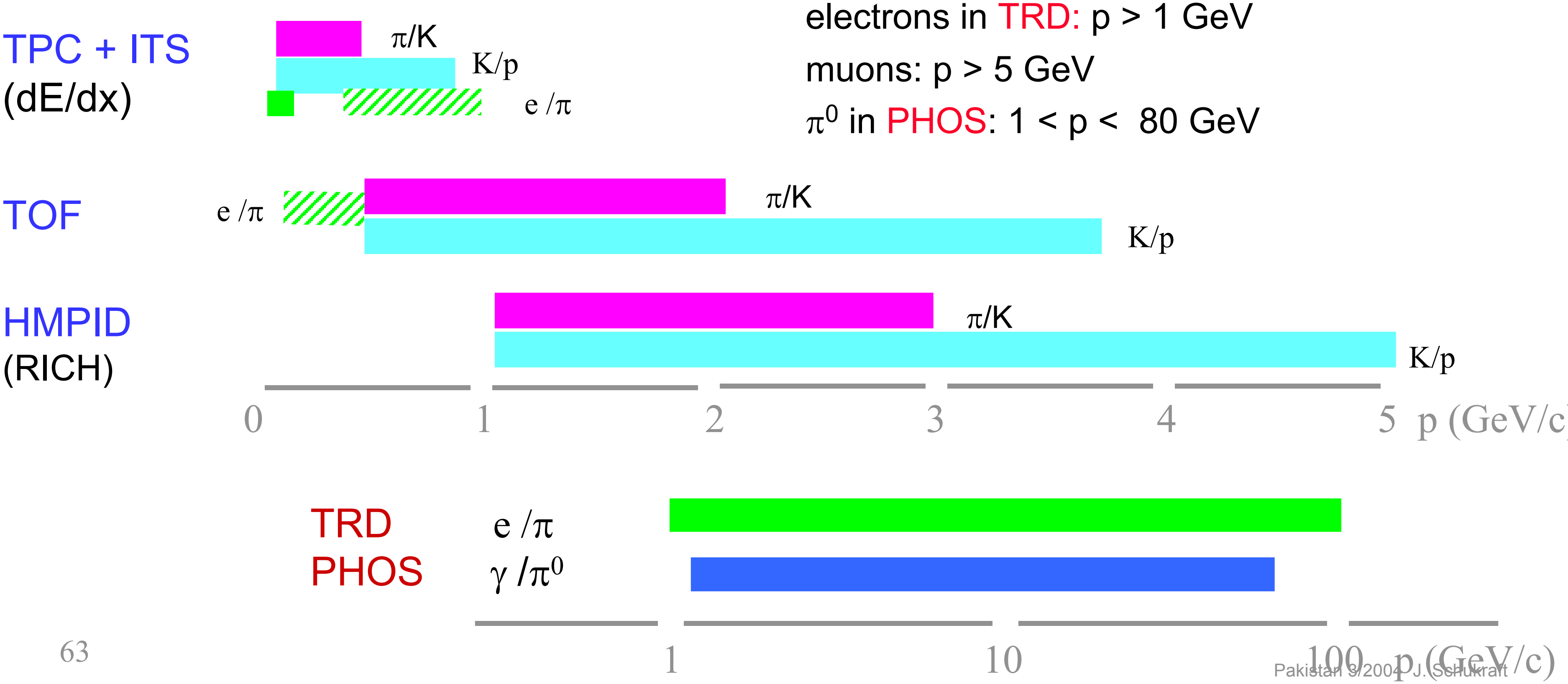
- **stable hadrons (π, K, p): 100 MeV < p < 5 GeV**
  - ⇨ dE/dx in silicon (ITS) and gas (TPC) + Time-of-Flight (TOF) + Cerenkov (RICH)
  - ⇨ dE/dx relativistic rise under study => extend PID to several 10 GeV ??
- **decay topology (K^0, K^+, K^-, Λ)**
  - ⇨ still under study, but expect K and Λ decays up to at least 10 GeV
- **leptons (e, μ), photons, π^0**

Alice uses ~ all known techniques!

electrons in TRD: p > 1 GeV

muons: p > 5 GeV

π^0 in PHOS: 1 < p < 80 GeV



Time Of Flight

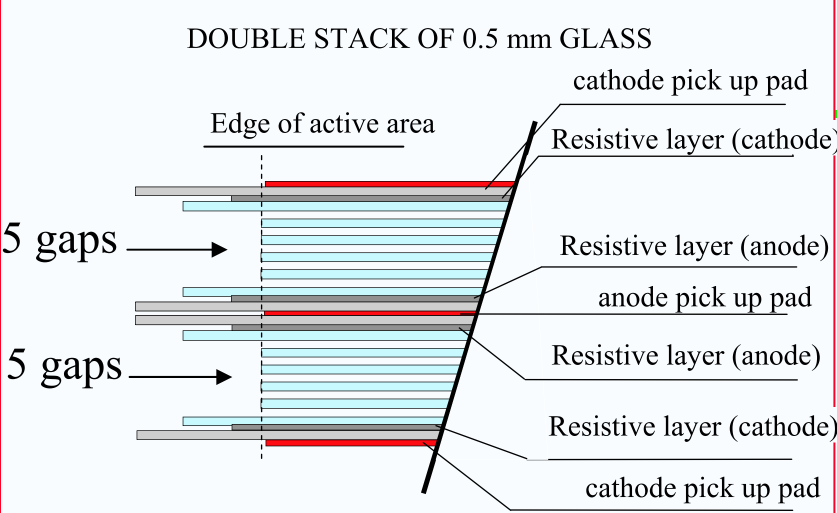
for π, K, p PID

π, K for p <2 GeV/c

p for p <4 GeV/c

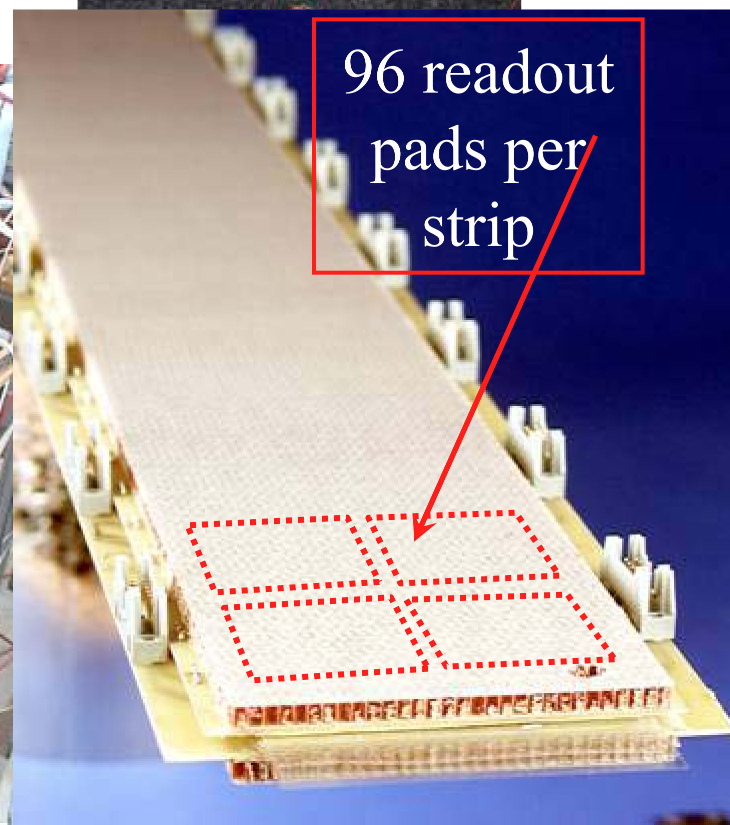
$160\ m^2$, 160 k channels

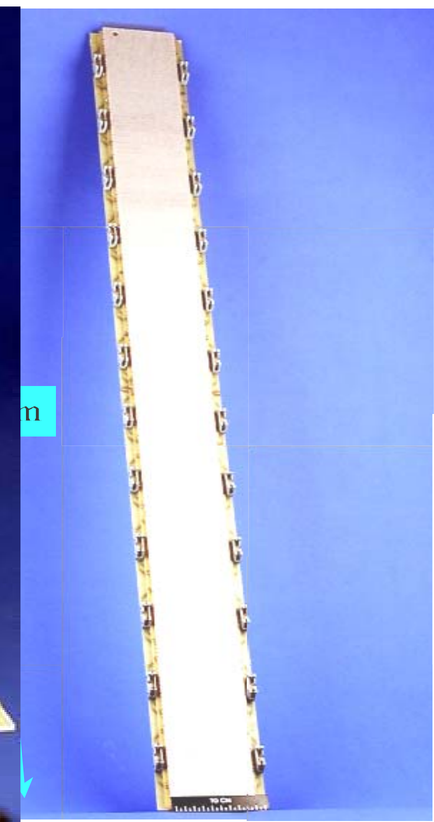
r = 3.7 m, σ < 100 ps



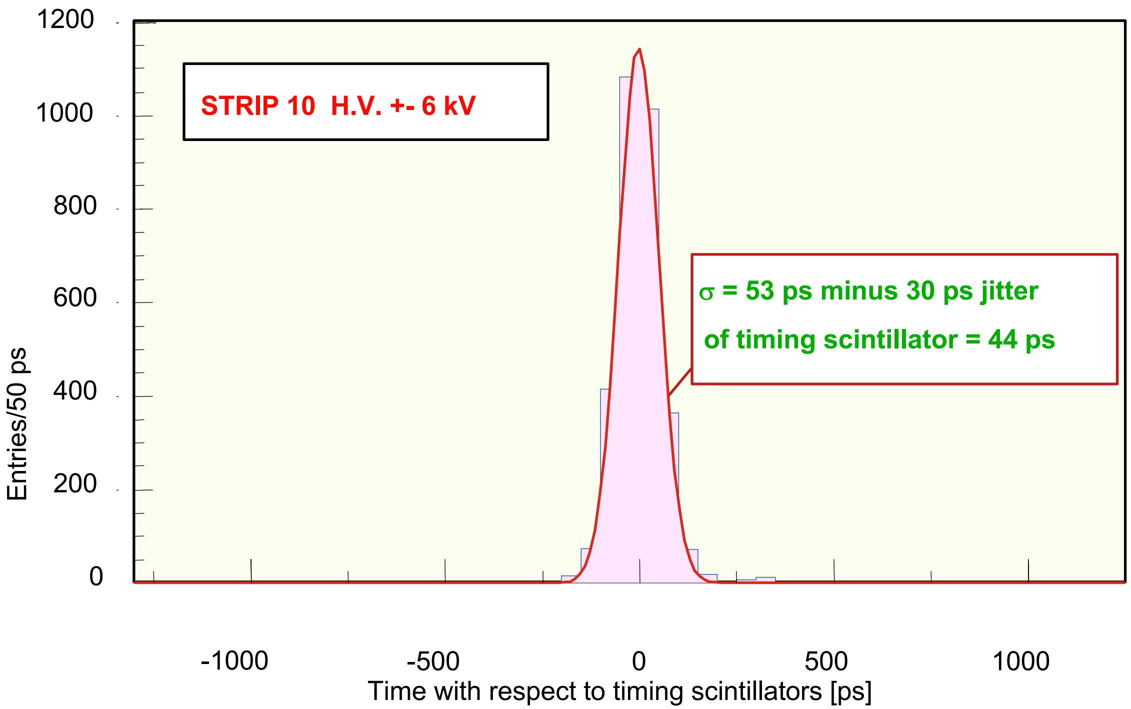
Multigap Resistive Plate Chambers

full size TOF modules under test

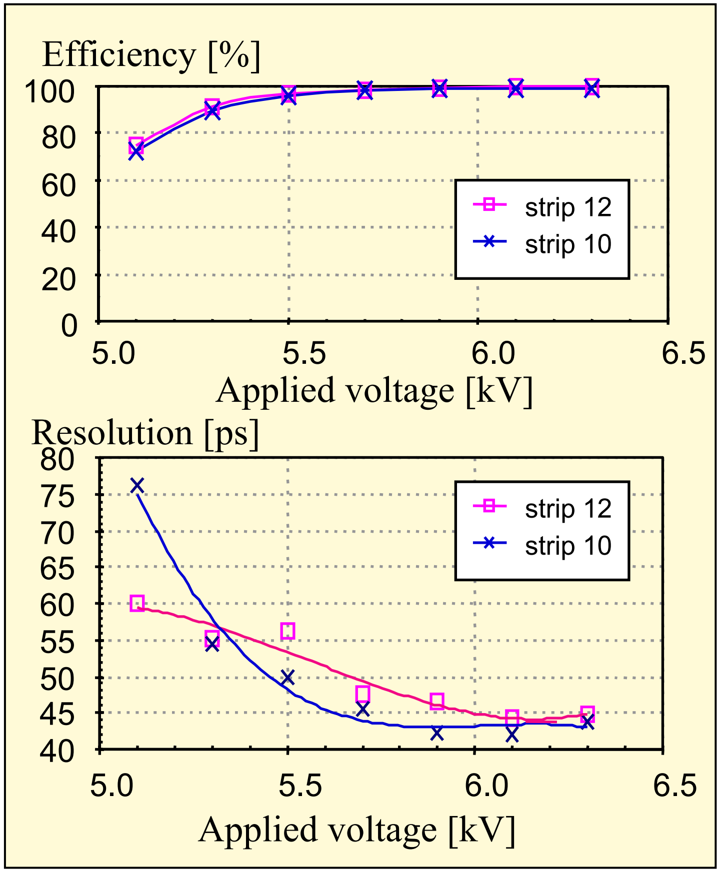




TOF Test Results



Typical time spectrum

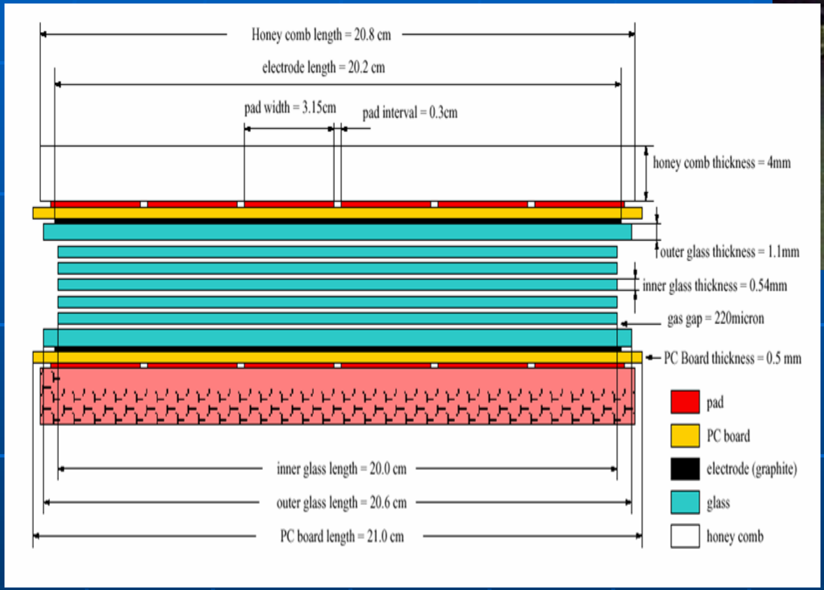


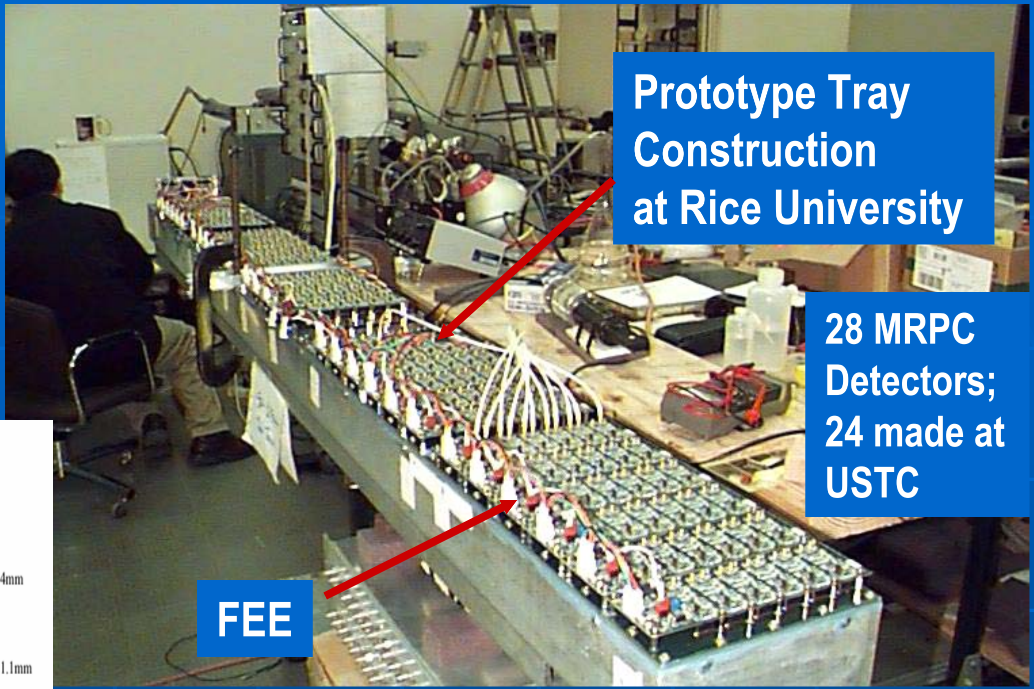
- other expts using ALICE MRPC technology
  - ⇨ **HARP** @ CERN (expt. finished)
  - ⇨ **STAR** @ RHIC (proposal)
  - ⇨ **FOPI** @ GSI (planning)

Typical performance

The STAR Barrel TOF MRPC Prototype

MRPC design developed at CERN, built in China

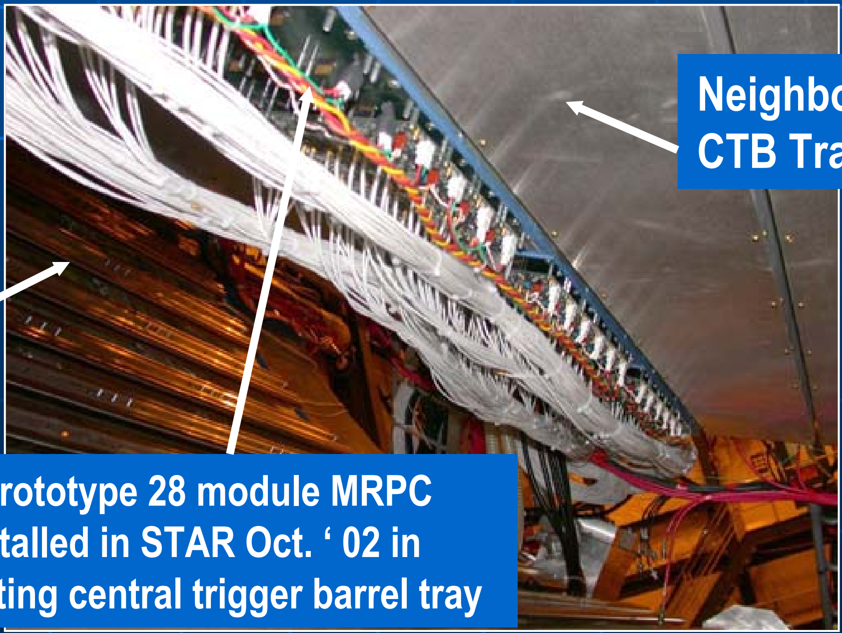




Prototype Tray Construction at Rice University

28 MRPC Detectors; 24 made at USTC

FEE



Neighbor CTB Tray

EMC Rails

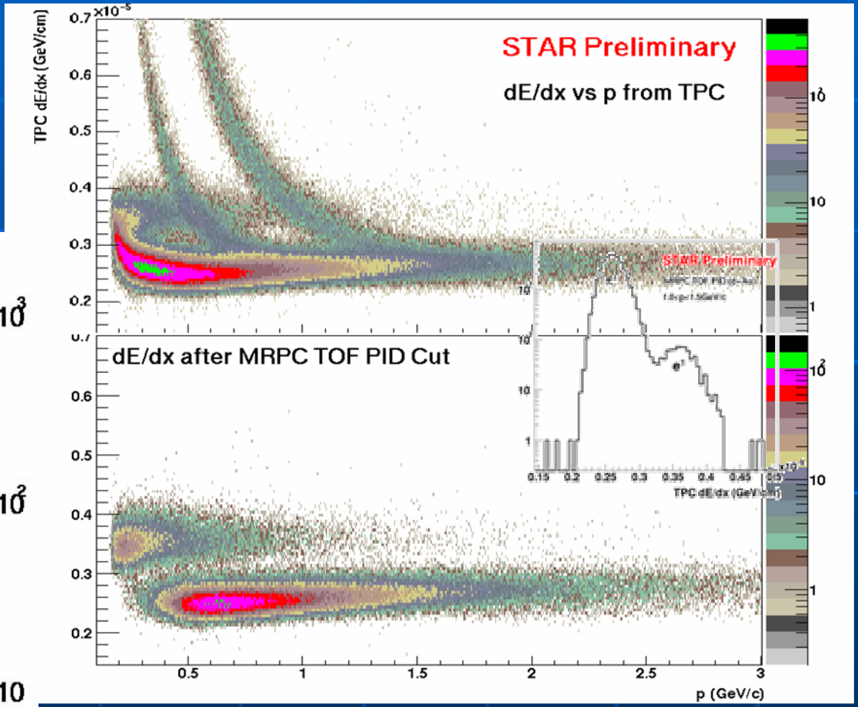
Completed Prototype 28 module MRPC TOF Tray installed in STAR Oct. ‘ 02 in place of existing central trigger barrel tray

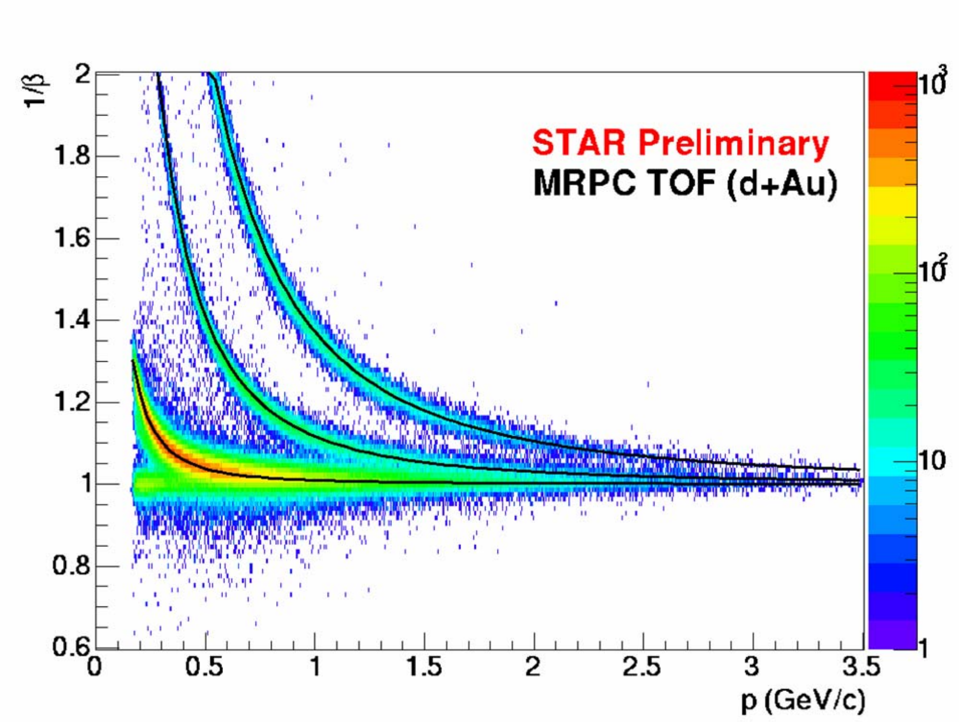
$\sigma \sim$ 50 ps, 2 meter path

Strong team including 6 Chinese Institutions in place

The STAR Barrel TOF MRPC Prototype

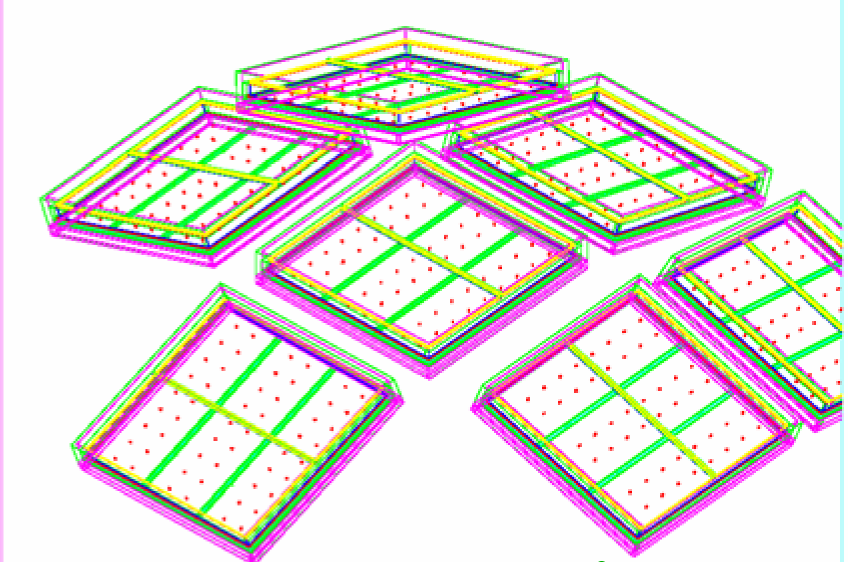
Prototype modules met all performance specs in the STAR environment and produced important physics on PID'd Cronin Effect



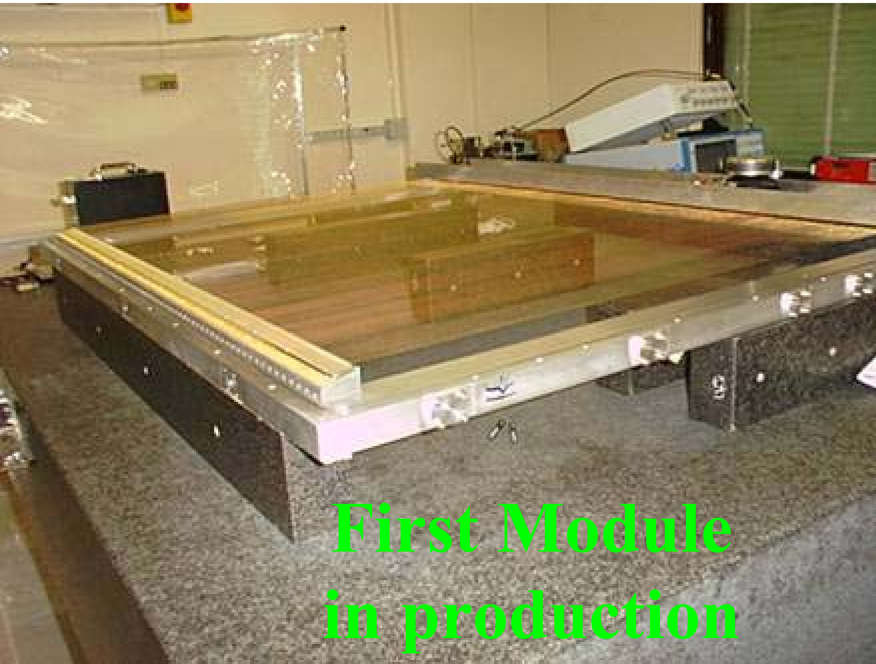


Proposal reviewed and approved by STAR and has been submitted to BNL Management

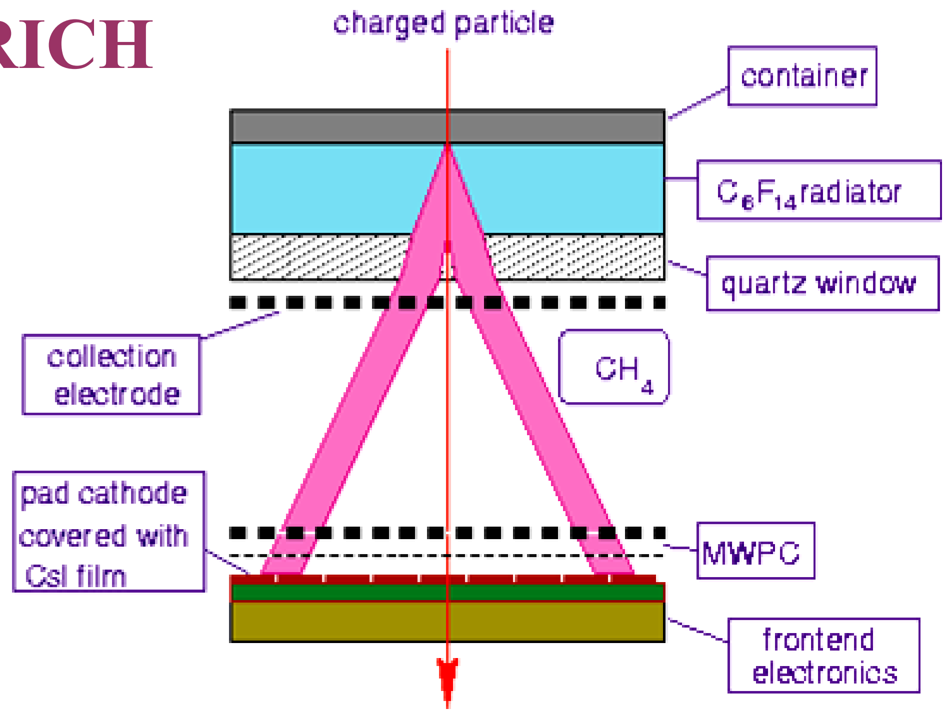
High Momentum Particle Identification



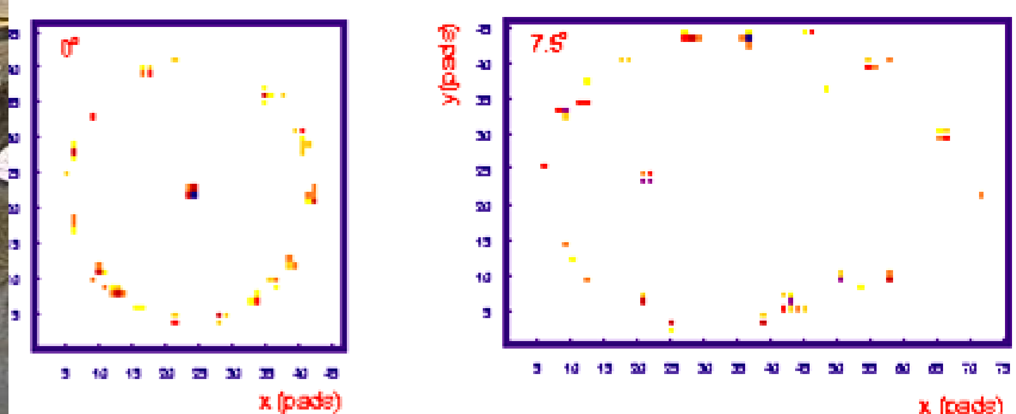
7 modules, each ~1.5 x 1.5 m^2



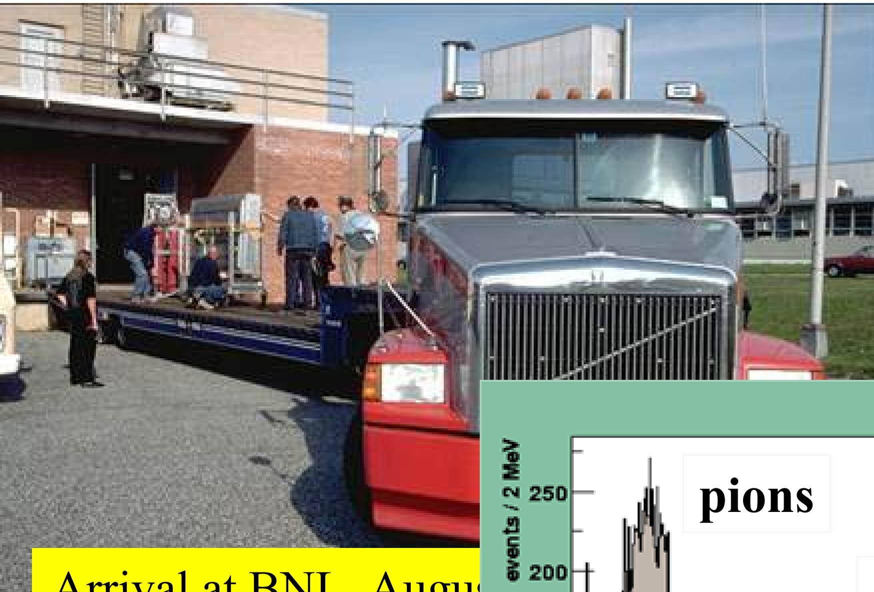
RICH



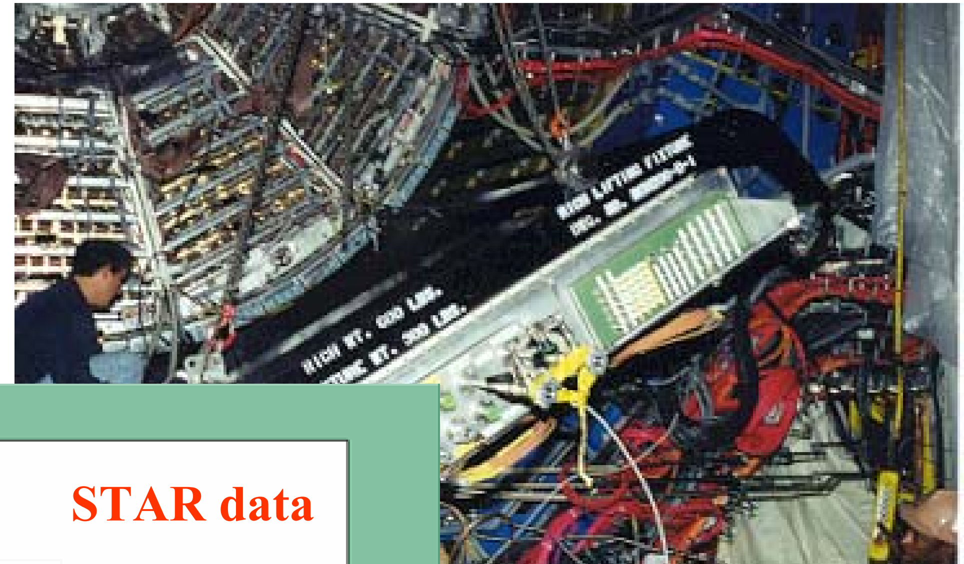
STAR data



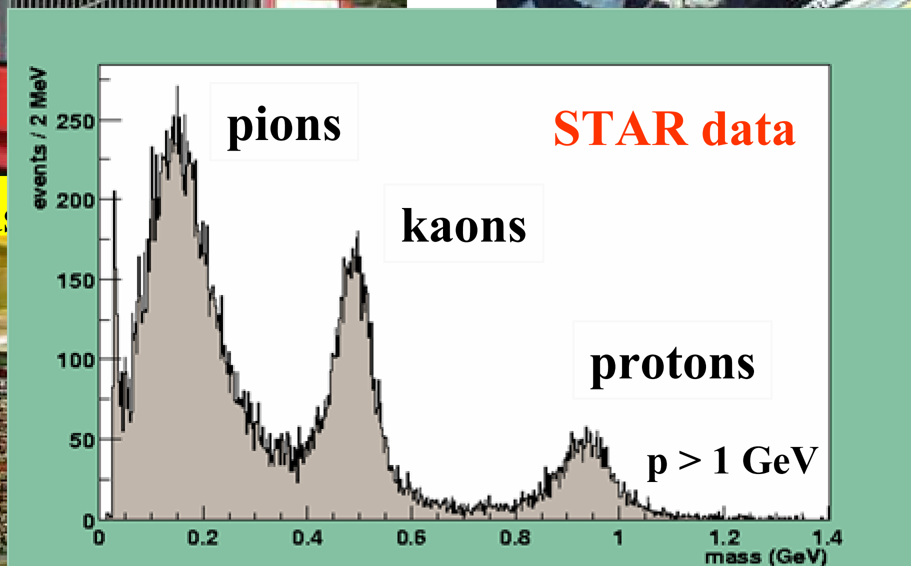
HMPID Proto-2: Excursion to BNL

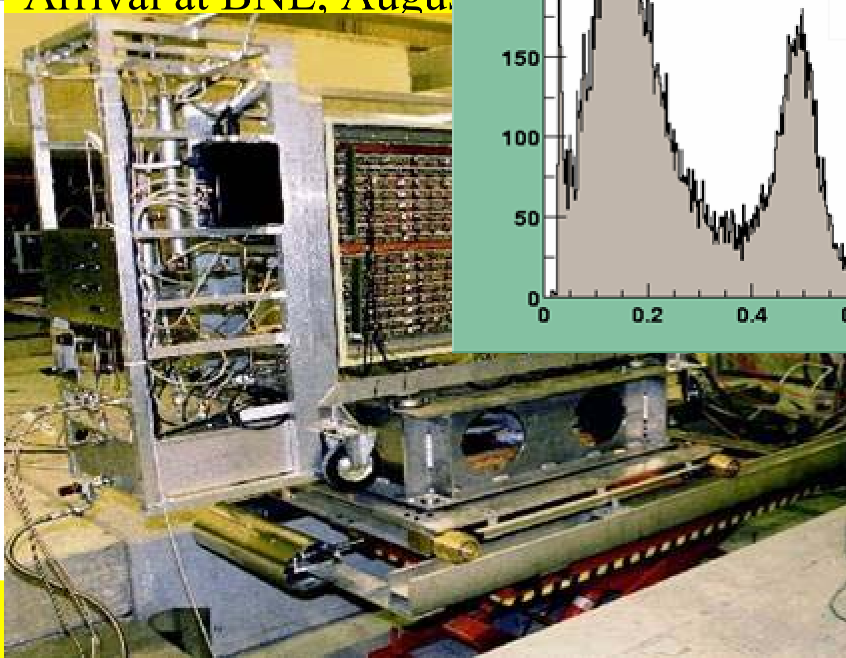


Arrival at BNL, Augus



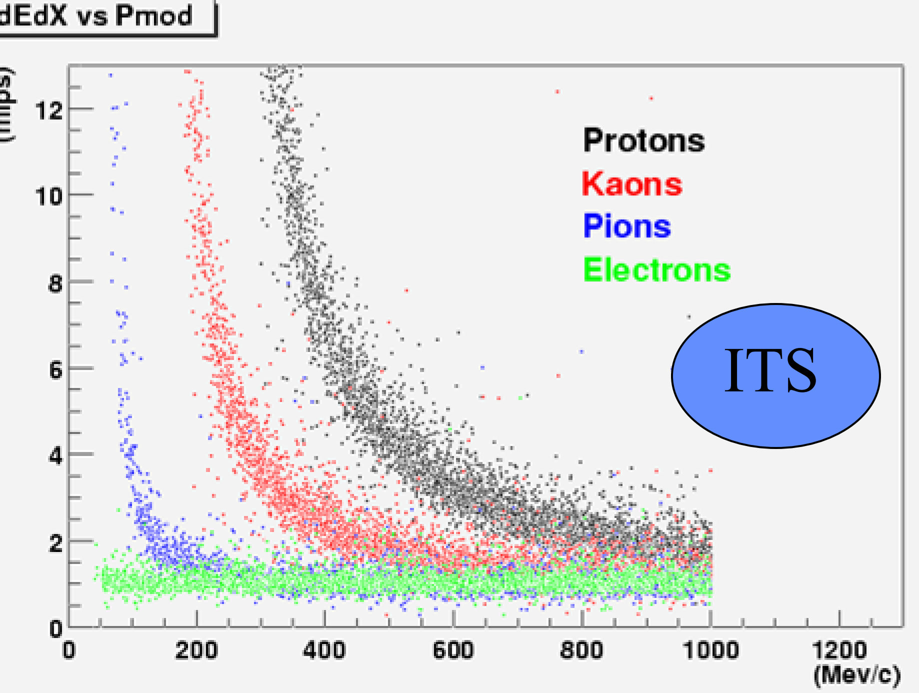
to STAR, November 1999

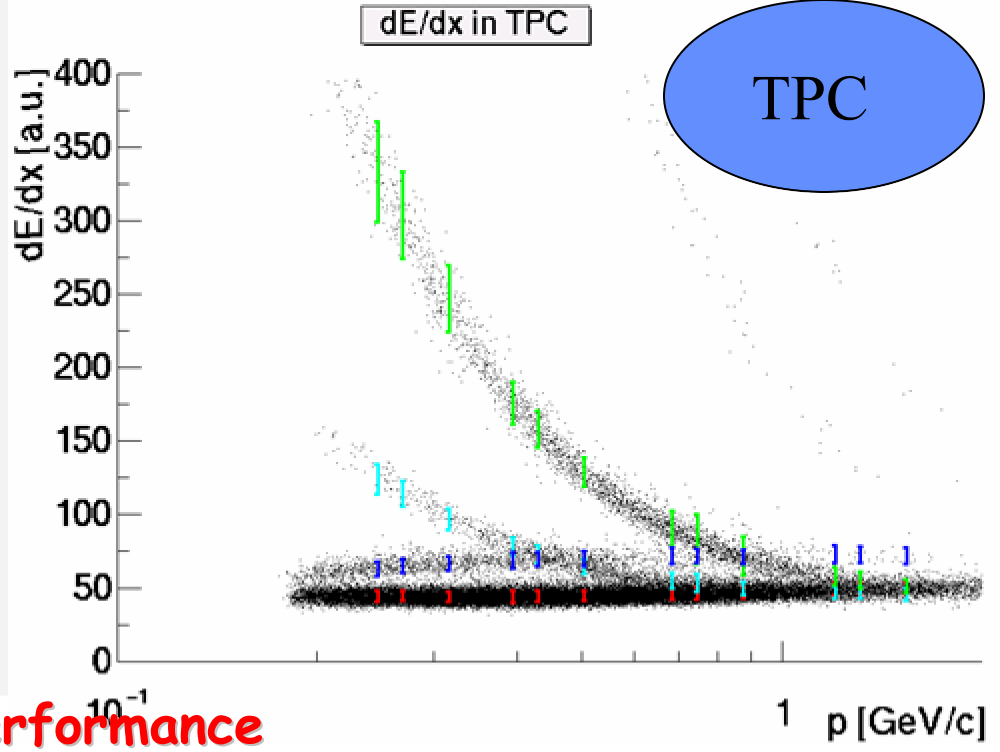


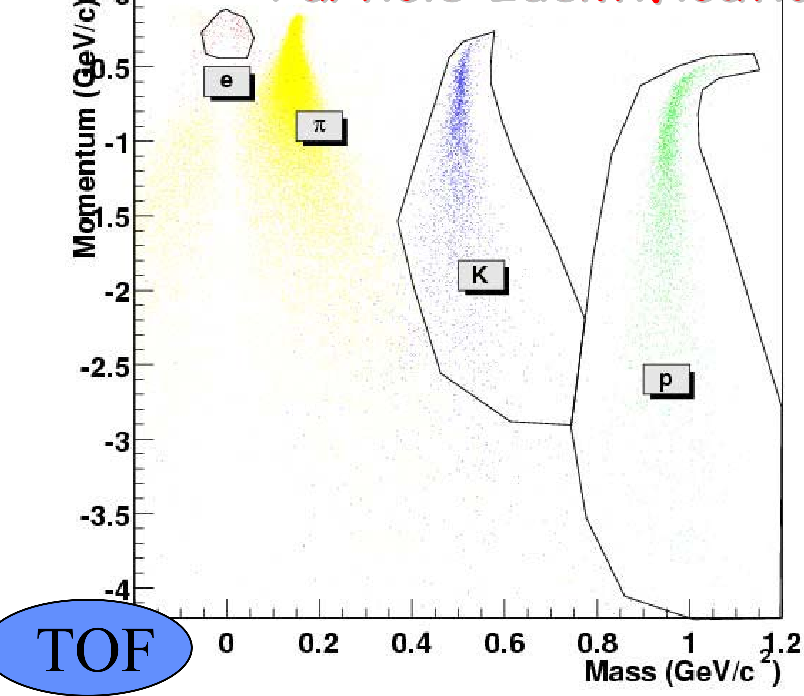


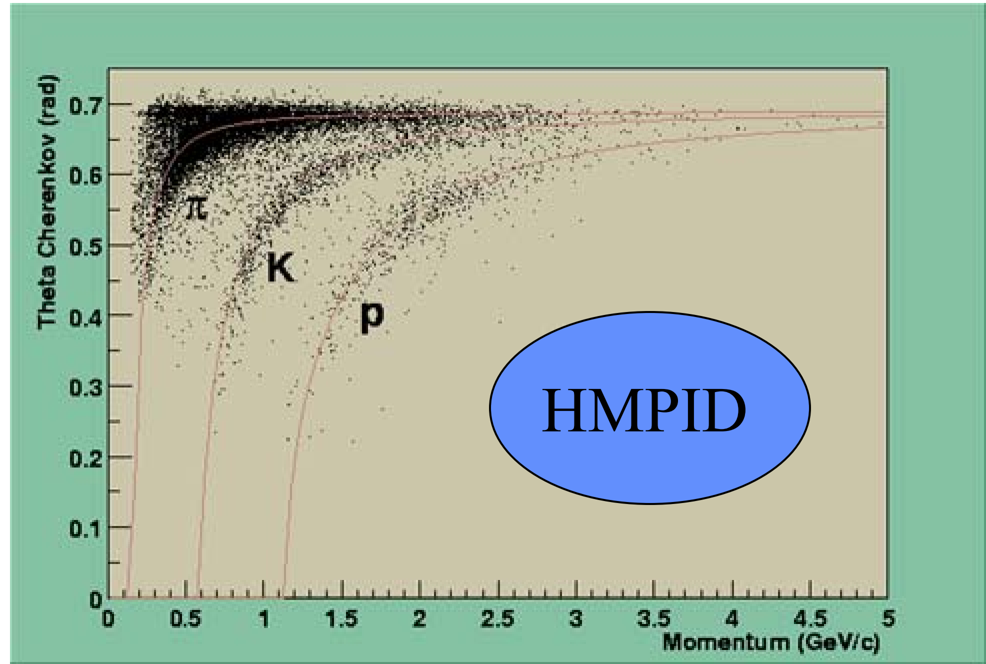
July 2002: Back home again

Particle Identification performance

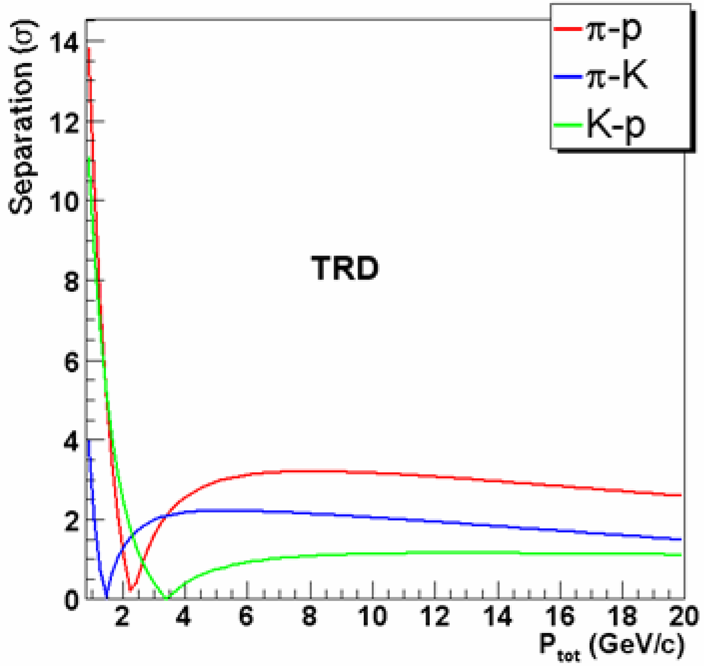




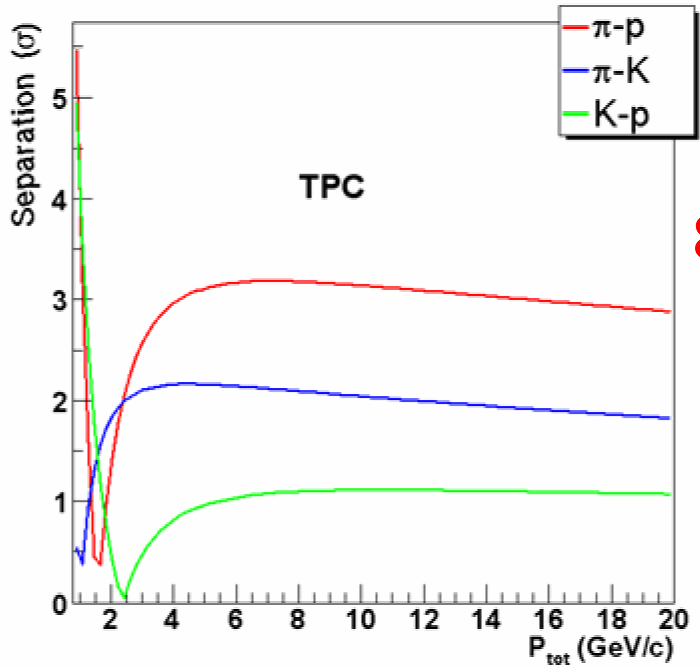




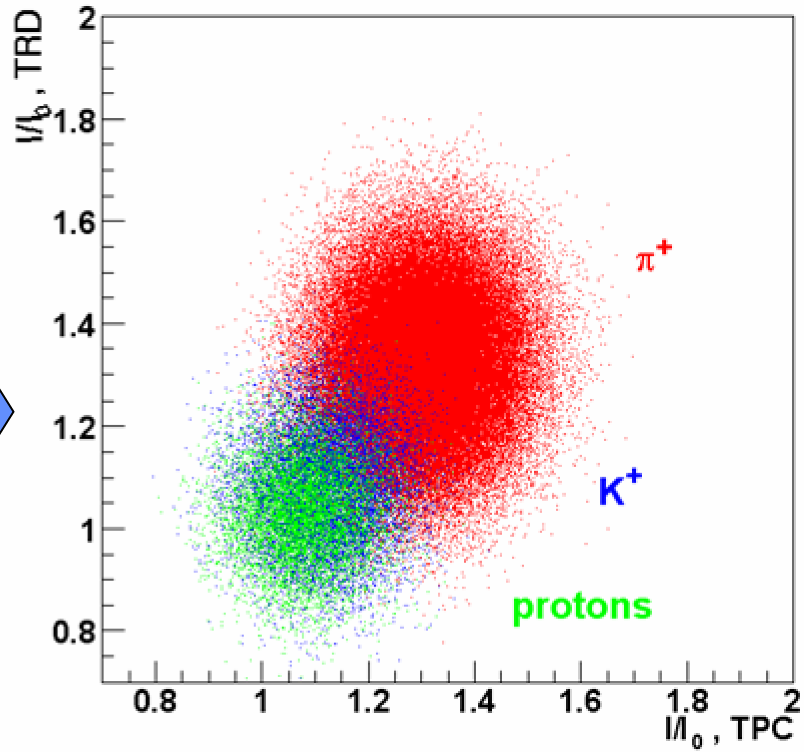
dE/dx relativistic rise ?



- **combine TPC and TRD dE/dx capabilities**
  - ⇨ pion ID up to several 10 GeV ?
  - ⇨ K/p on a statistical basis ?

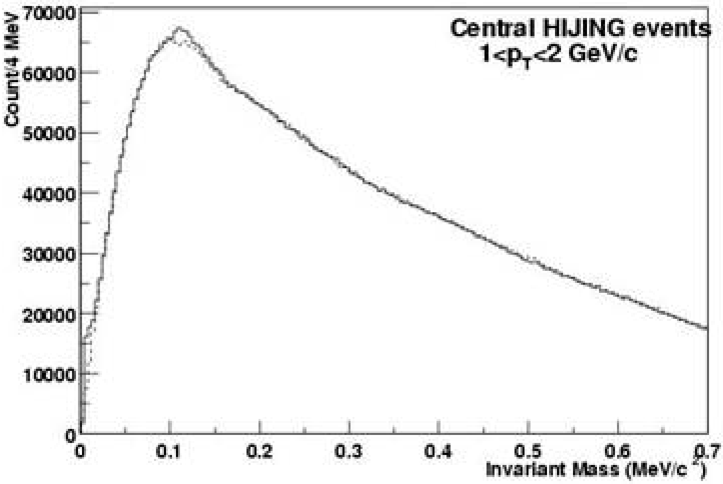


8<p<10 GeV/c

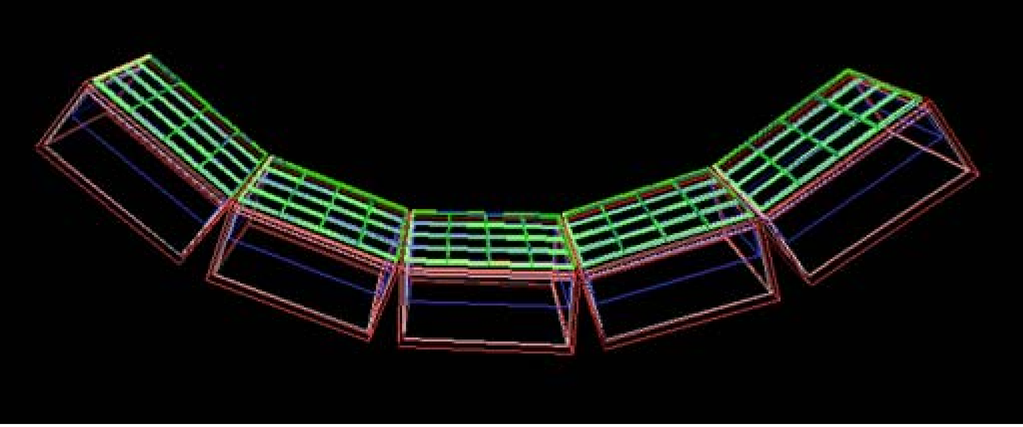


Photons & Leptons

- **Photons**
  - ⇨ LHC: high particle density + large combinatorial background for π^0, η
    - high granularity => dense material + large distance from vertex
    - good resolution => scintillation crystals
  - ⇨ compromise: acceptance (ok for $\eta \to \gamma\gamma$ @ 1GeV)



- **Muons**
  - ⇨ classical muon spectrometer (NA50, Phenix)
    - high performance chambers: ~ 10^6 channels, **very thin**, small dead area
    - goal: $\Delta m/m$ ~ 1% @ 10 GeV (separate Y'')
  - ⇨ challenge: integrate with central barrel !
    - very complex & sophisticated absorbers
- **Electrons** **(later addition to ALICE)**
  - ⇨ combine TPC tracking with e-ID: Transition radiation detector TRD
    - large area (800 m^2) , high granularity (> 10^6 channels)
    - challenge: triggering on high p_t electrons requires on-line tracking in < 6 μs !!!



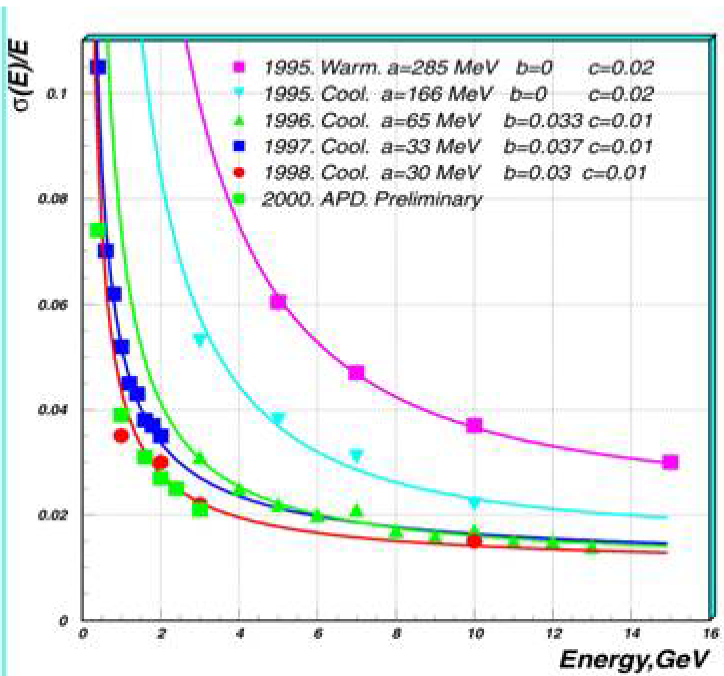
Photon Spectrometer

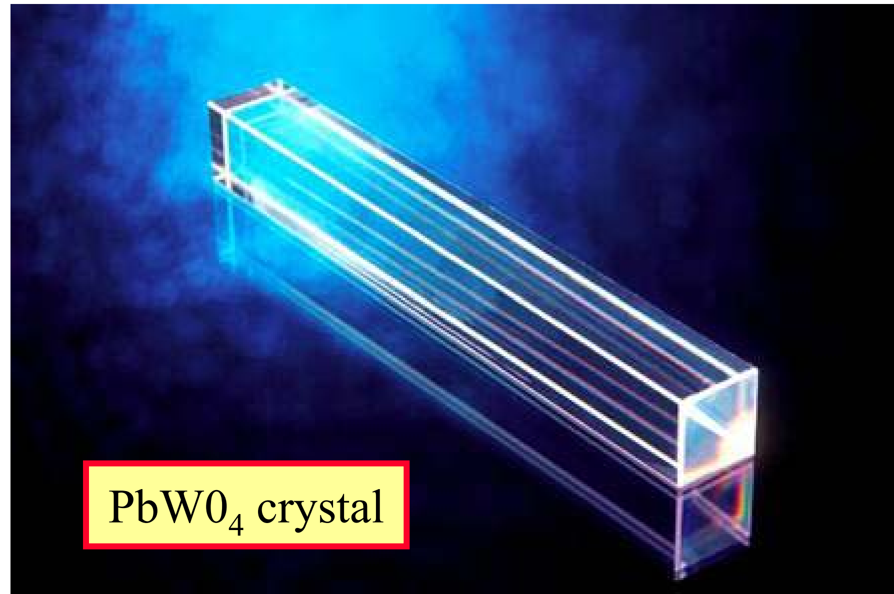
for photons, neutral mesons and γ–jet tagging

- single arm em calorimeter
  - ⇨ **dense, high granularity crystals**
    - ✪ **novel material: $PbW0_4$**
  - ⇨ **~ 18 k channels, ~ 8 m^2**
  - ⇨ **cooled to -25°**

$PbW0_4$: Very dense: $X_0 < 0.9$ cm
Good energy resolution (after 6 years R&D):

stochastic	$2.7\%/E^{1/2}$
noise	$2.5\%/E$
constant	1.3%

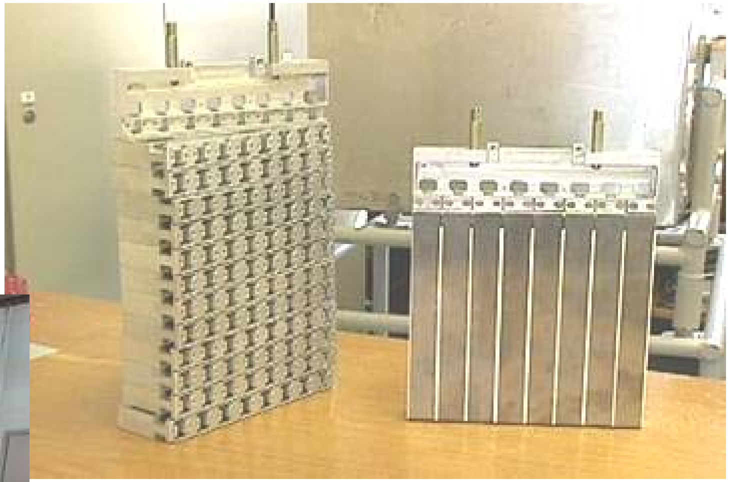




PHOS

- **mass production of crystals ongoing (> 20% available)**
  - ⇨ Apatity, Russia
- **Light Read-out , Electronics**
  - ⇨ APD's (Avalanche Photo Diodes)
  - ⇨ FEE close to production

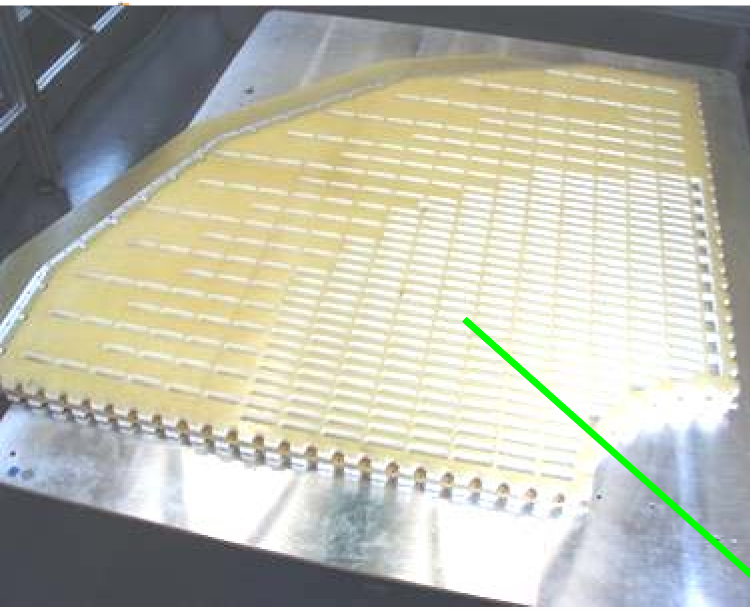
PHOS 256-Channel Prototype



Collaboration:
- Russia + Norway
- China (tbc)
Needs strengthening !

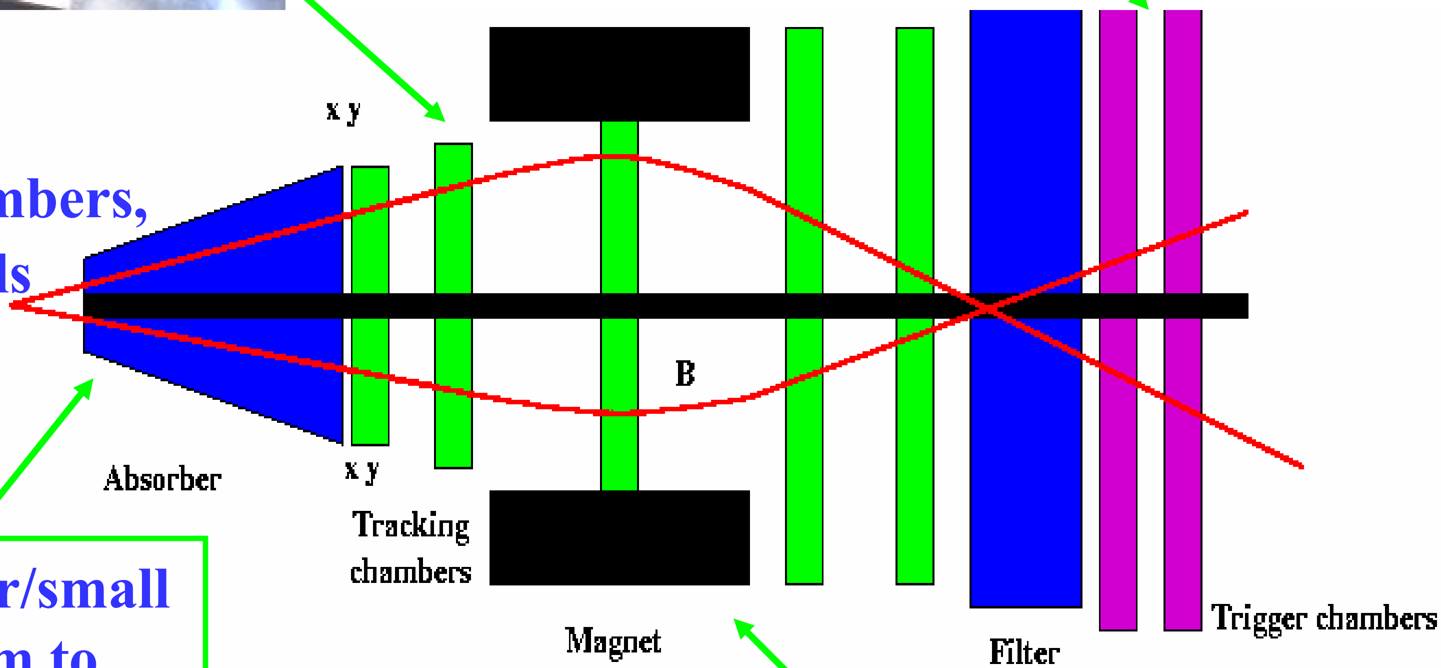
Dimuon Spectrometer

- Study the production of the J/Ψ, Ψ', Υ, Υ' and Υ'' decaying in 2 muons, $2.4 < \eta < 4$
- Resolution of 70 MeV at the J/Ψ and 100 MeV at the Υ



RPC Trigger Chambers

5 stations of high granularity pad tracking chambers, over 800k channels



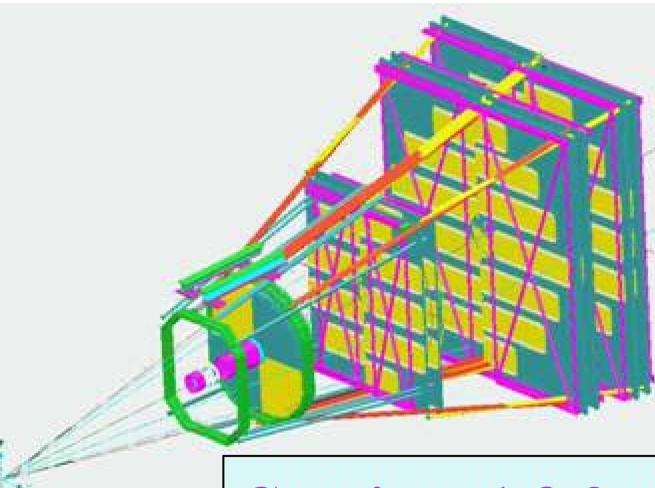
Complex absorber/small angle shield system to minimize background (90 cm from vertex)

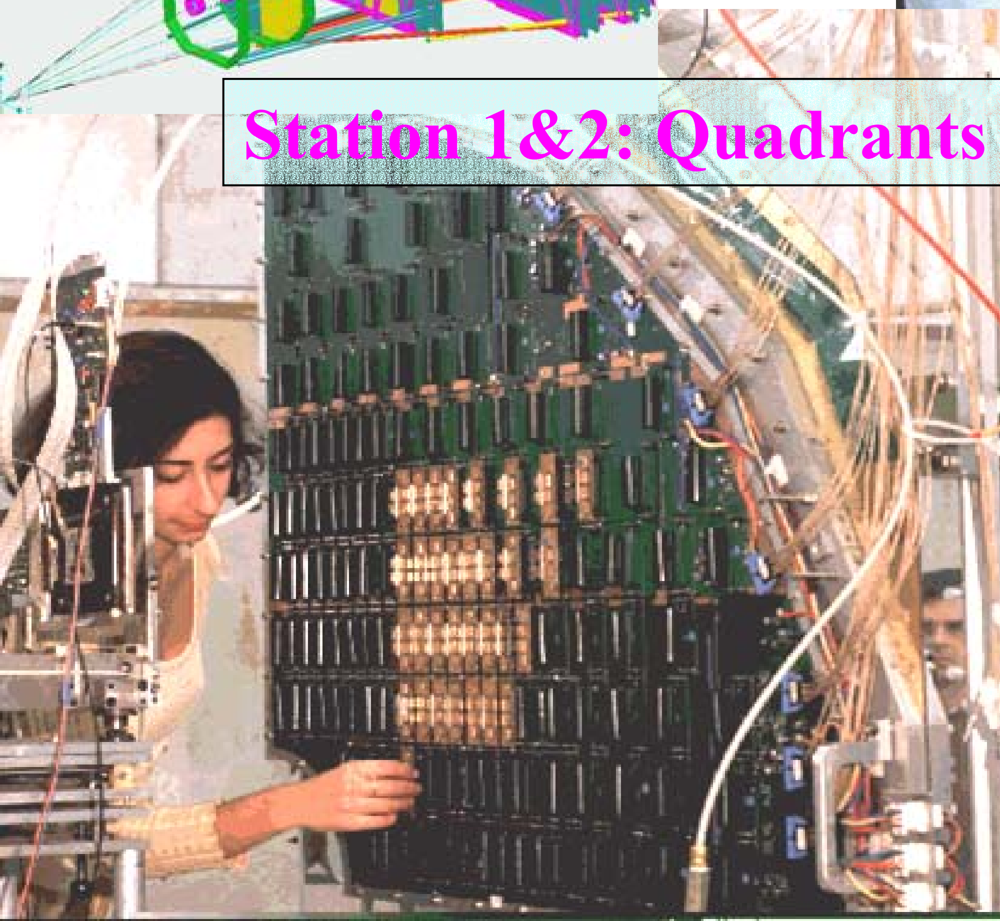
Dipole Magnet: bending power 3Tm

Muon Absorber

ete,

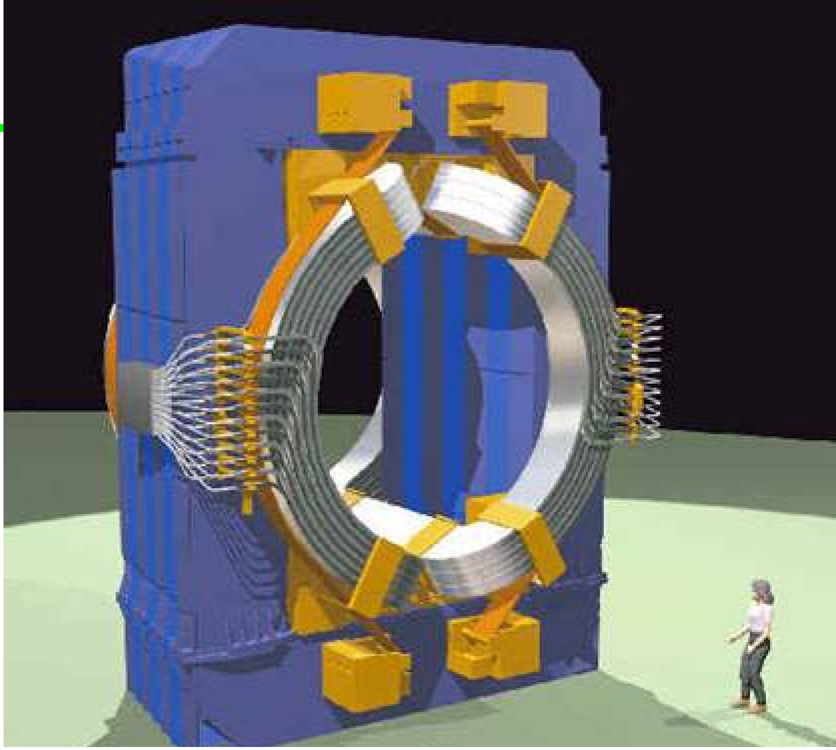
Muon Chambers





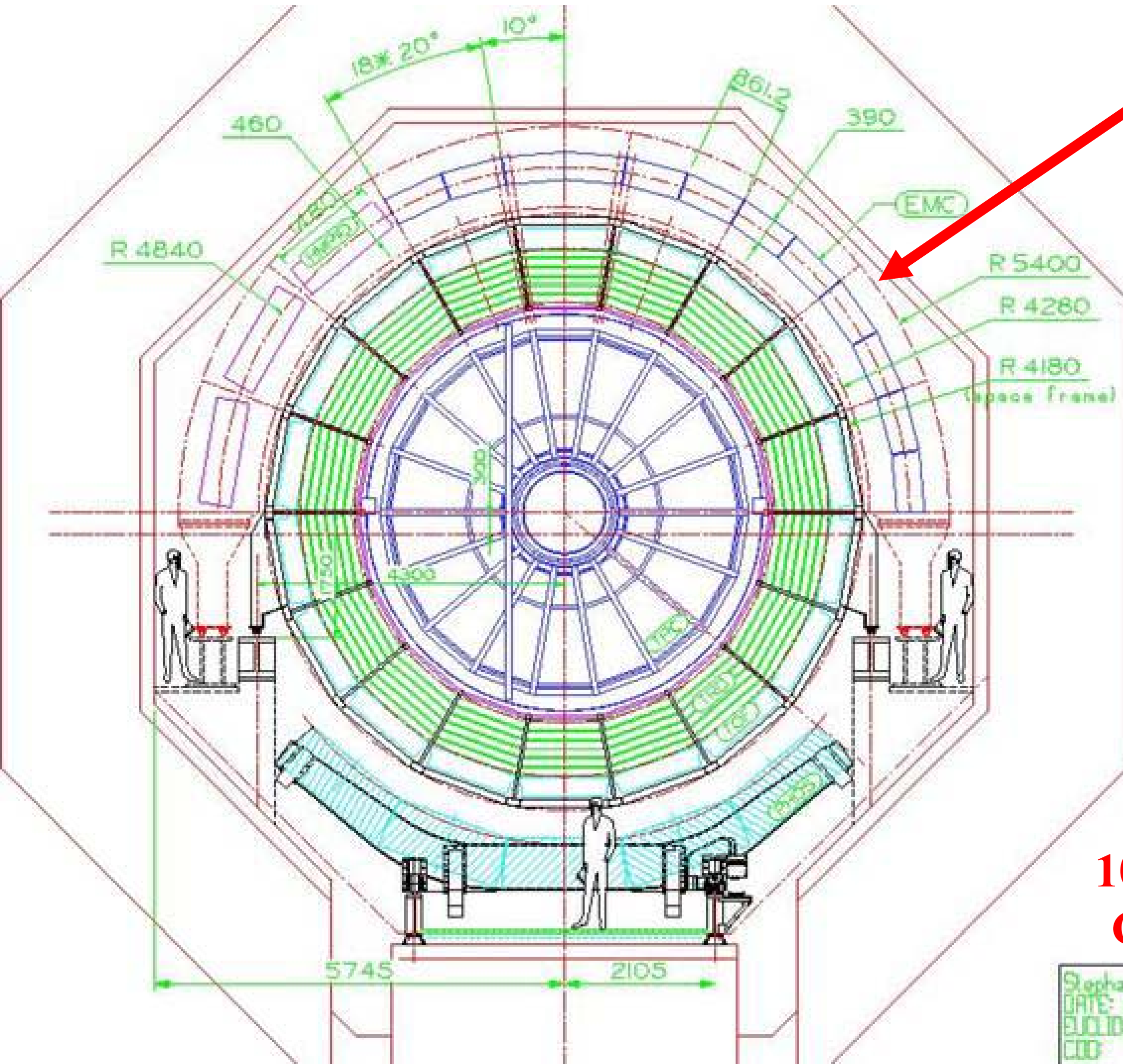
Muon Magnet

- **Dipole Magnet**
  - ⇨ 0.7 T and 3 Tm
  - ⇨ 4 MW power, 800 tons
  - ⇨ World's largest warm dipole



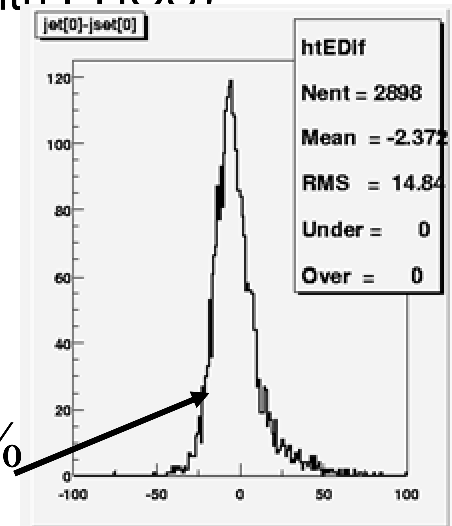
US proposal: large emcal

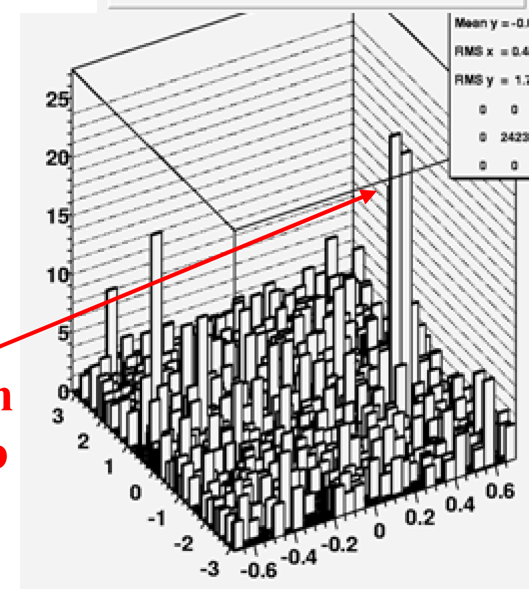
- **large area electromagnetic calorimeter (a la STAR)**
  - ⇨ hadronic energy in TPC + em energy in calorimeter
  - ⇨ trigger on jets, improve energy resolution, γ-jet coincidences (with PHOS)



Proposed EMCAL
$|\eta|<0.7$
$\Delta\phi \sim 120^o$

$\sigma(P_T) \sim 15\%$





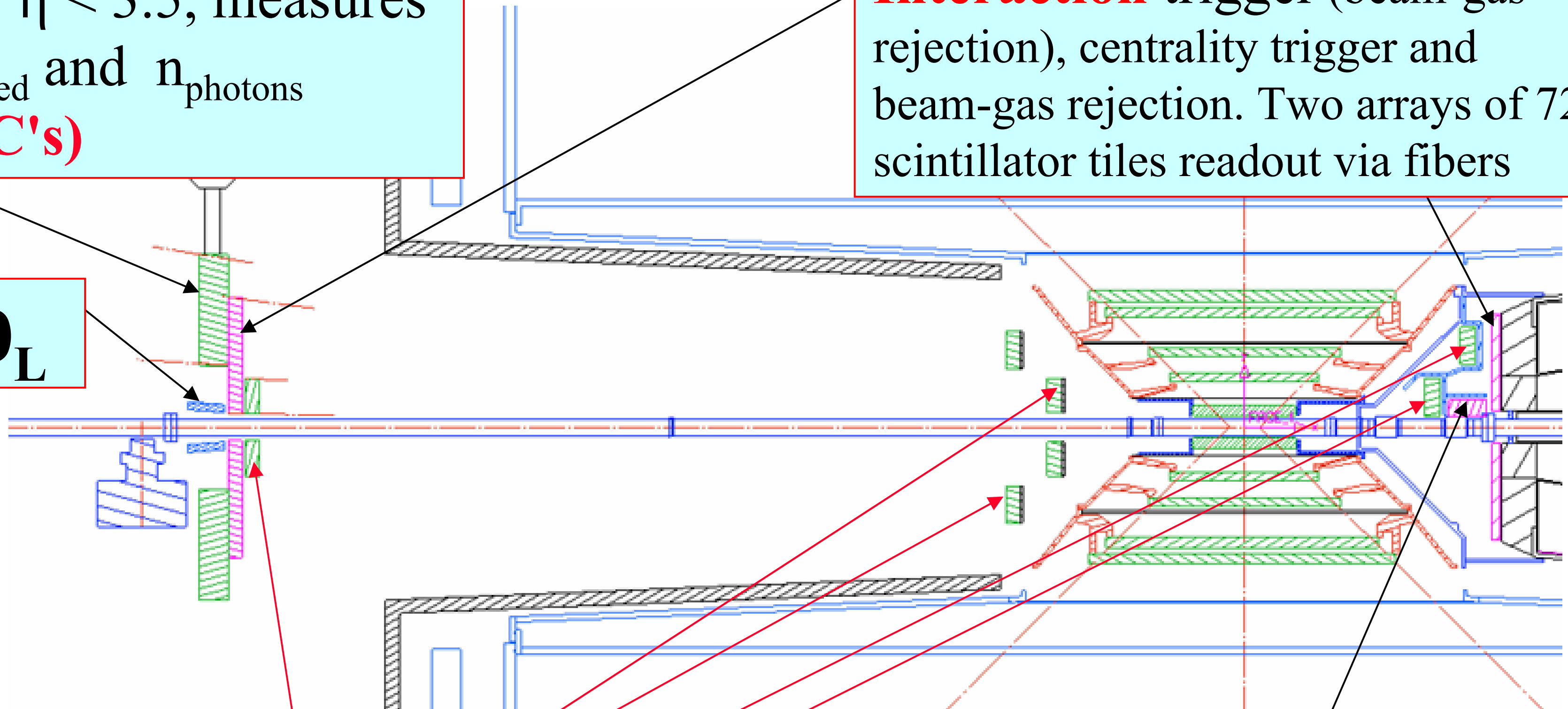
100 GeV Jet in Central PbPb

Forward Detectors

PMD pre-shower detector
$2.3 < \eta < 3.5$, measures $n_{charged}$ and $n_{photons}$
(DCC's)

V0 $1.6 < |\eta| < 3.9$
Interaction trigger (beam-gas rejection), centrality trigger and beam-gas rejection. Two arrays of 72 scintillator tiles readout via fibers

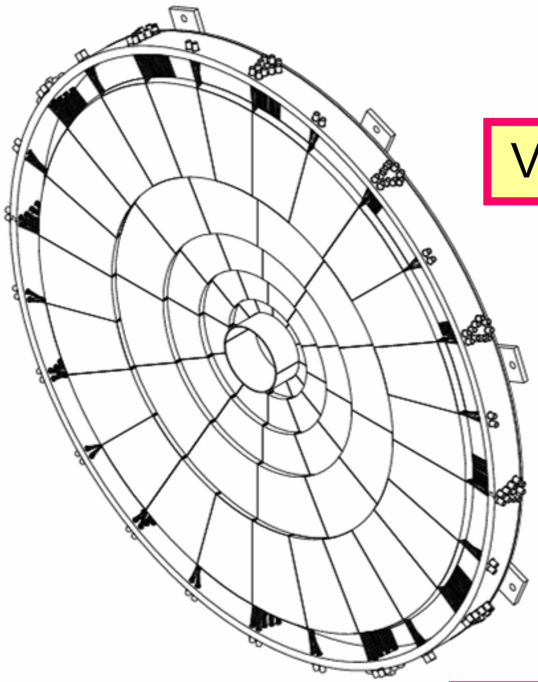
$T0_L$



FMD Measure **Multiplicity** and η dist. over $1.6 < \eta < 3$, $-5.4 < \eta < -1.6$
Silicon pad detector disks (slow readout) with 12k analog channels (occ.>1)

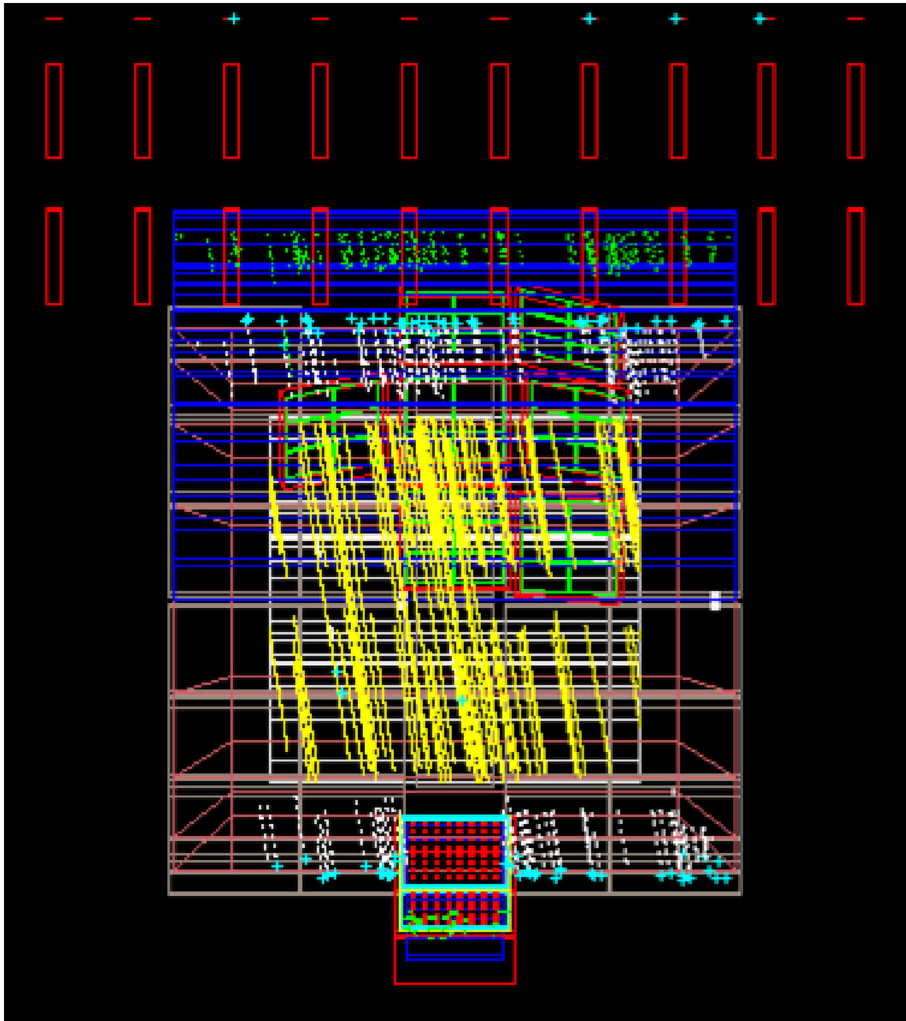
$T0_R$ $2.6 < |\eta| < 3.3$ measure event **Time** (T_0) for the TOF (~ 50 ps time res.) Two arrays of 12 quartz counters. Also backup to V0

Trigger Counters T0/V0/Accorde



V0: Scintillator + PM

Accorde: large area Scintillator + PM trigger on Cosmic rays



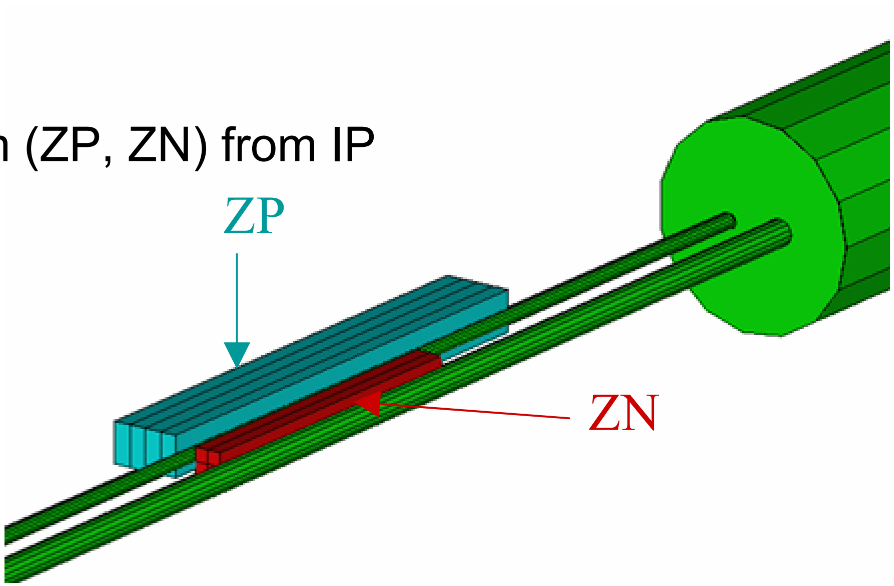
T0: Quartz-C + PM

PMD for STAR (India)

- **Photon Multiplicity Detector**
  - ⇨ searching for non-statistical fluctuations ('Centauro's' from Cosmic rays)
    - high granularity pre-shower detector
    - innovative cell geometry gas detector
- **STAR-PMD design is identical to ALICE-PMD TDR version**
- Installed at STAR, first physics runs in 2003

Zero Degree Calorimeter

- **6 small & dense calorimeters**
  - ⇨ trigger on impact parameter (spectators)
  - ⇨ located between 8m (em calo) and 116 m (ZP, ZN) from IP



	Proton ZDC (ZP)	Neutron ZDC (ZN)	EM ZDC
Dimensions (cm^3)	12x21x150	7x7x100	7x7x21
Absorber	brass	W-alloy	lead
Fibre angle wrt LHC axis	0^{O}	0^{O}	45^{O}
Fibre ∅ (μm)	550	365	550

High Level Trigger (HLT)

- **Task: BE FLEXIBLE !**
  - ⇨ selective R/O (RoI, eg e^+e^- pairs)
  - ⇨ event selection
    - high mass lepton pairs (e, μ)
    - jets (high p_t tracks)
  - ⇨ data compression
    - factor 2 to > 10 with **online tracking** in TPC
- **online PC farm**
  - ⇨ FPGA co-processors in RORC
  - ⇨ ~ 500 - 600 dual CPU PC's
  - ⇨ test clusters running (Heidelberg, Oslo, Bergen)
  - ⇨ FPGA algorithm development

Computing Phase Transition

The Problem:

- **Online: storing up to 1.2 Gbyte/s**
  - ⇨ whole WWW in few hours on tape !
  - ⇨ ~ 10 x RHIC !
- **Offline: 18 MegaSI2000**
  - ⇨ 100,000 PC's in 2000 (500 Mhz)
  - ⇨ ~ 100 x RHIC !!

The Answer:

cheap mass market components

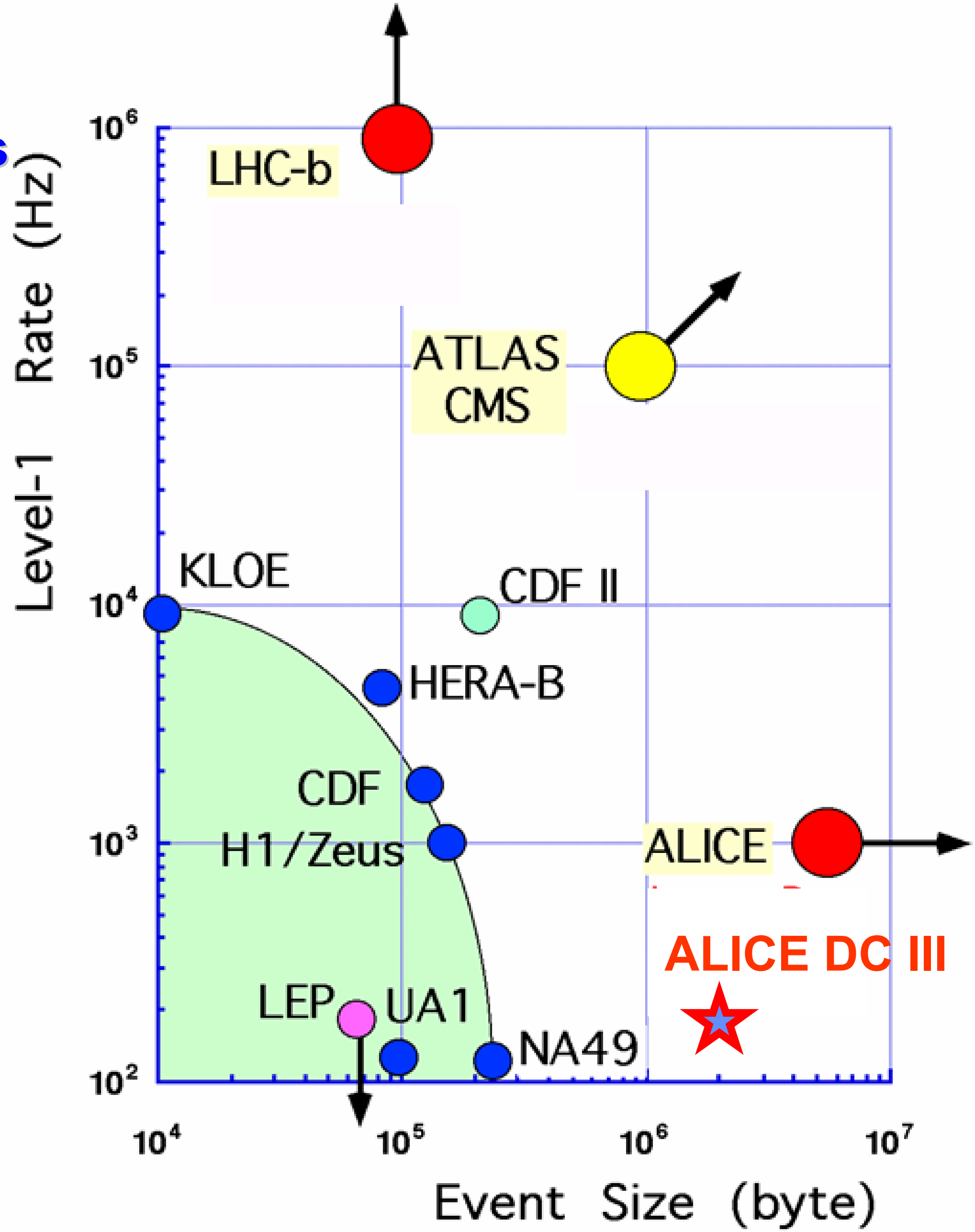
Industry & Moore's law

The Challenge:

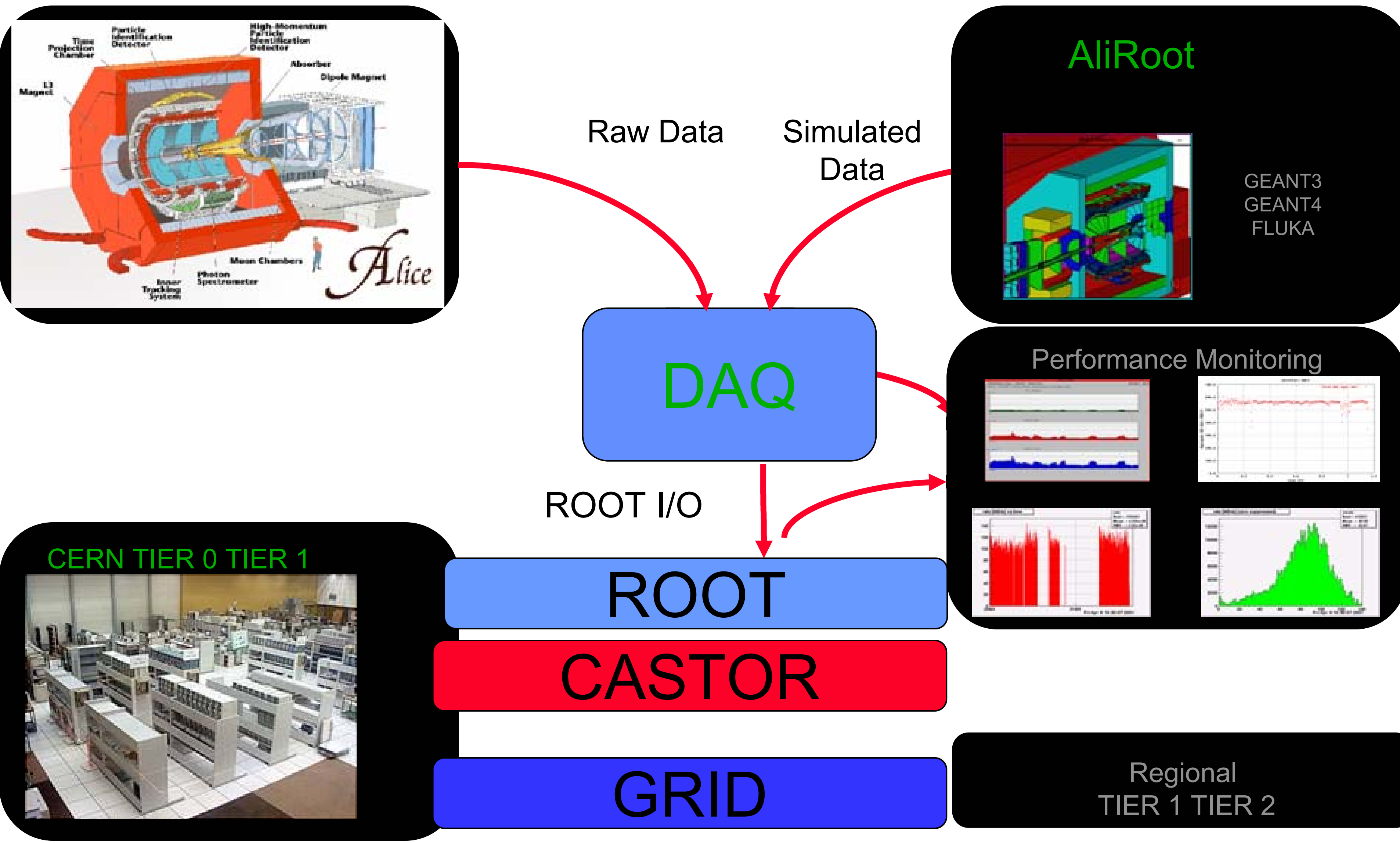
make 10,000 mice do the work of one elephant

new computing paradigm:

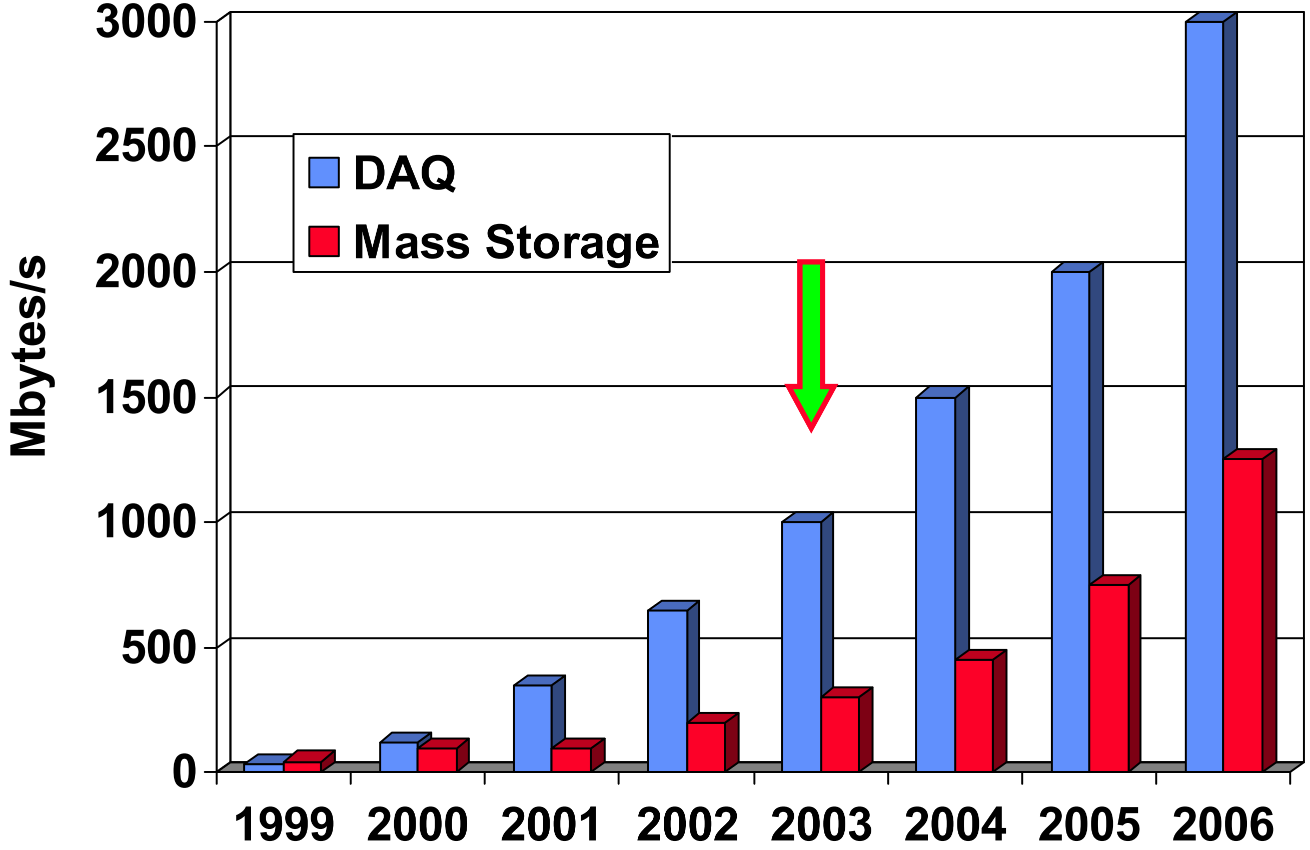
The GRID



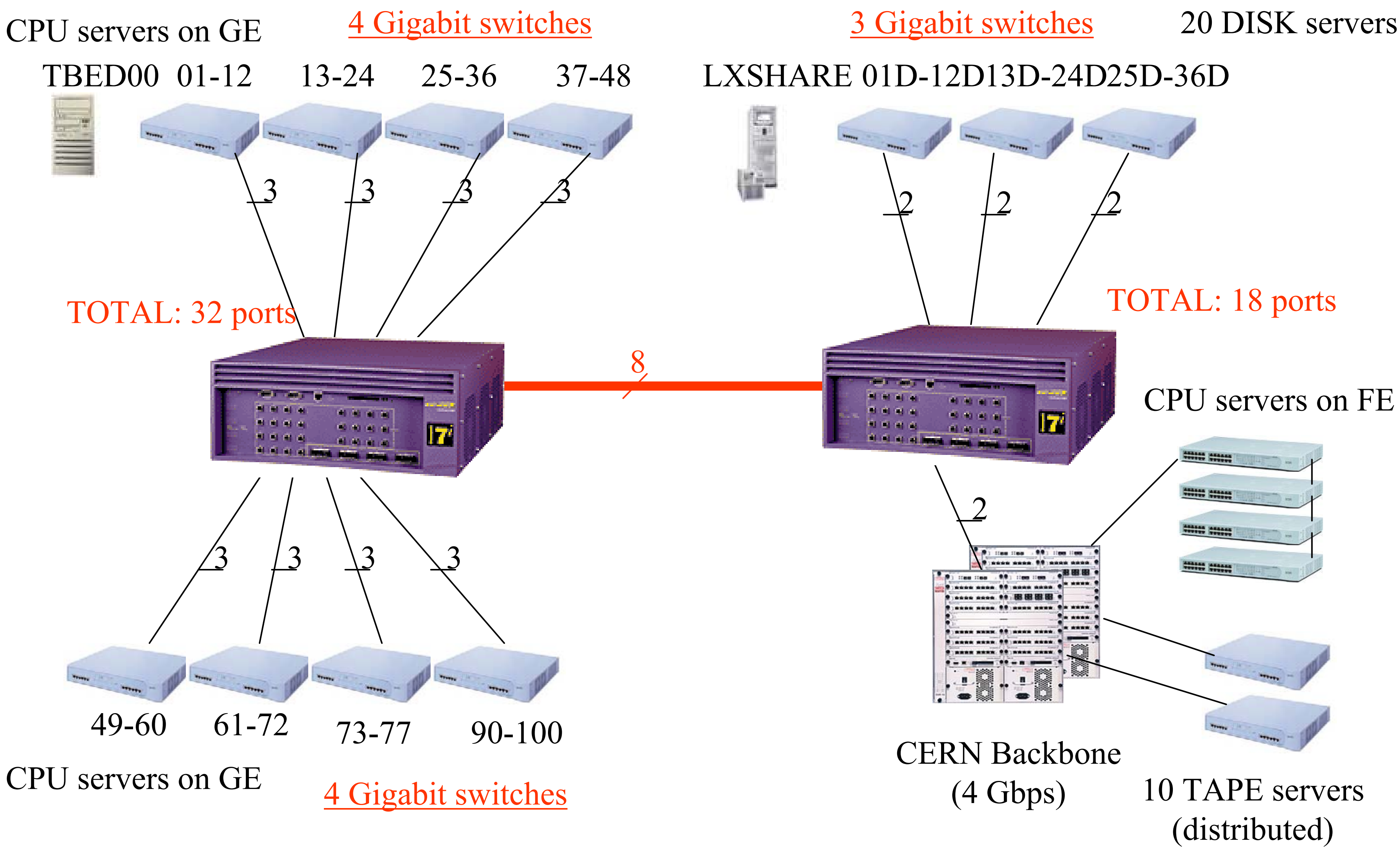
ALICE Data Challenges



ADC Performance Plan:

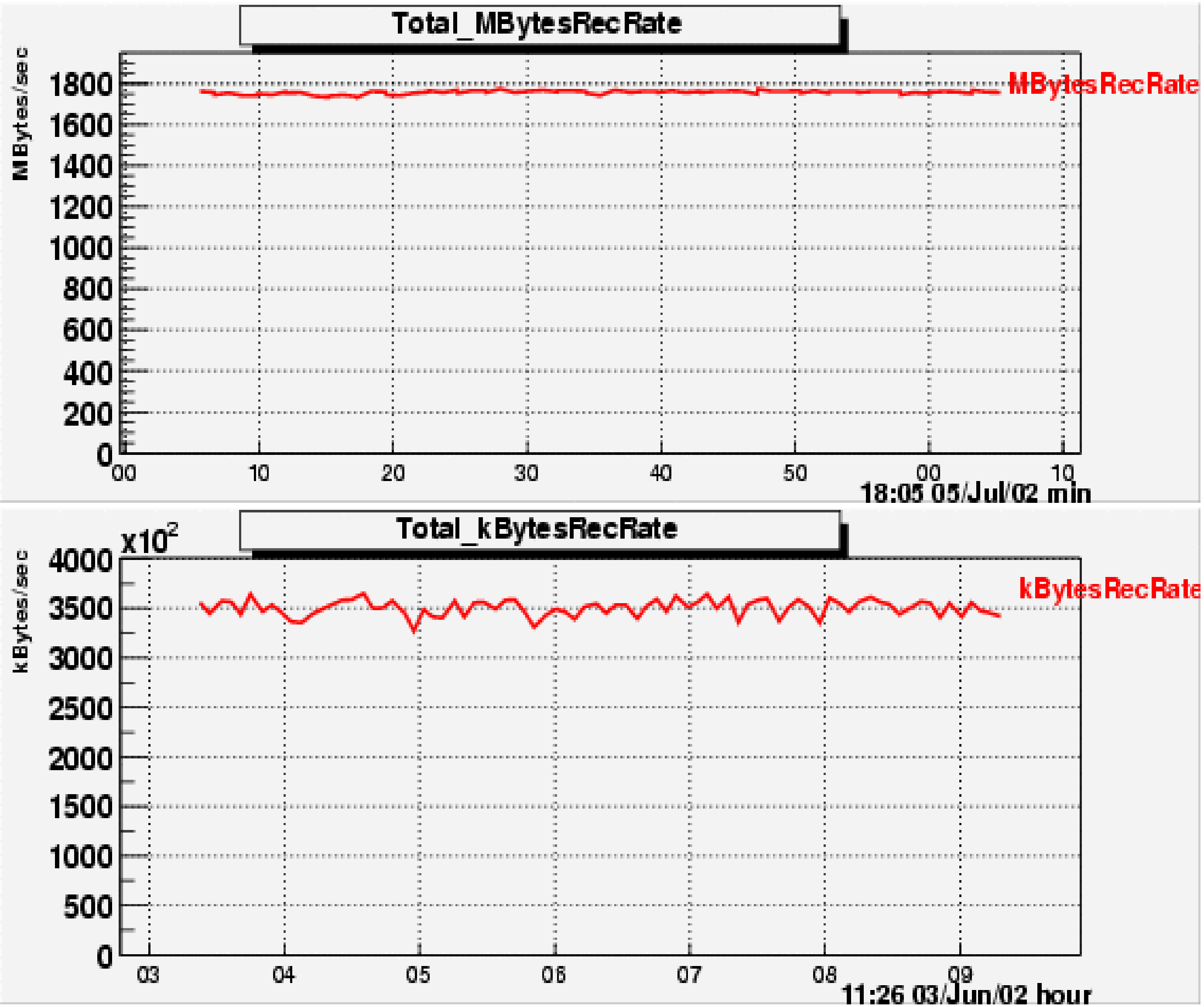


2002: ADC IV Hardware Setup



Total: Up to 192 CPU servers, Up to 36 DISK servers, 10 TAPE servers

ADC IV performances



DATE event-building

1.8 Gbytes/s:

target 1 Gbyte/s

In stable operation

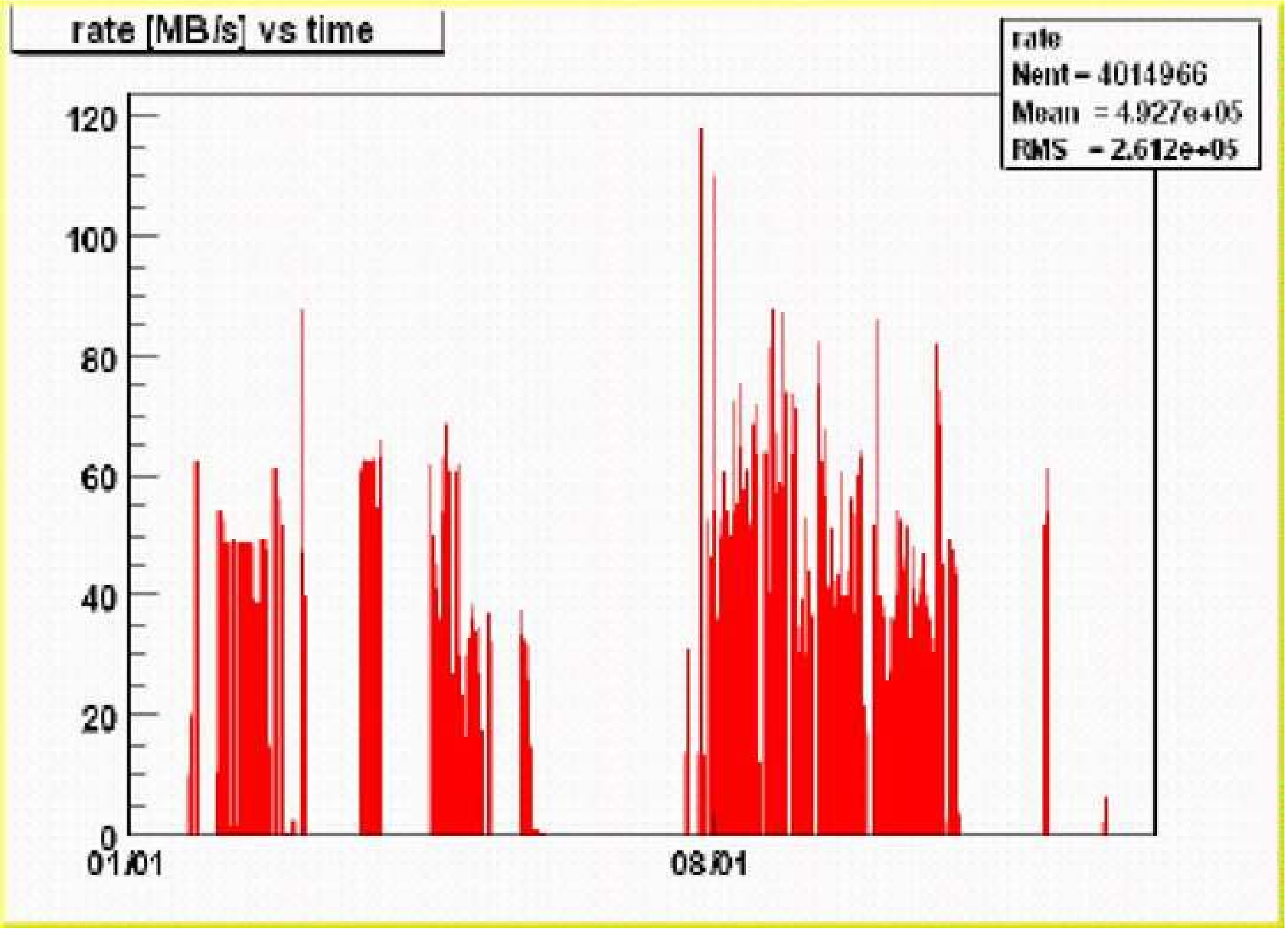
Data recording to disk

350 MBytes/s.

target 300 MBytes/s

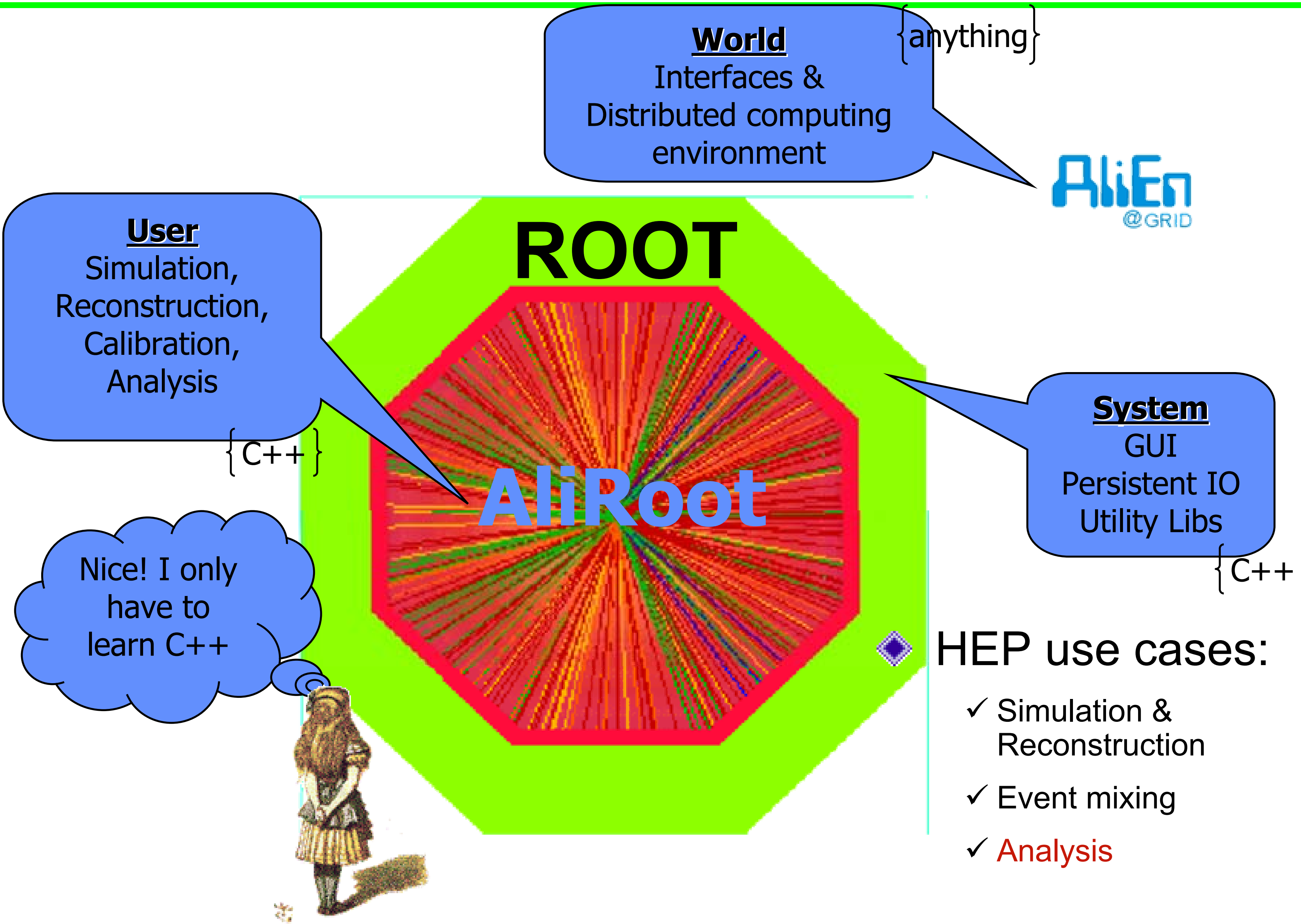
Outperforming the plan, with commodity hardware!

ADC II (2000)



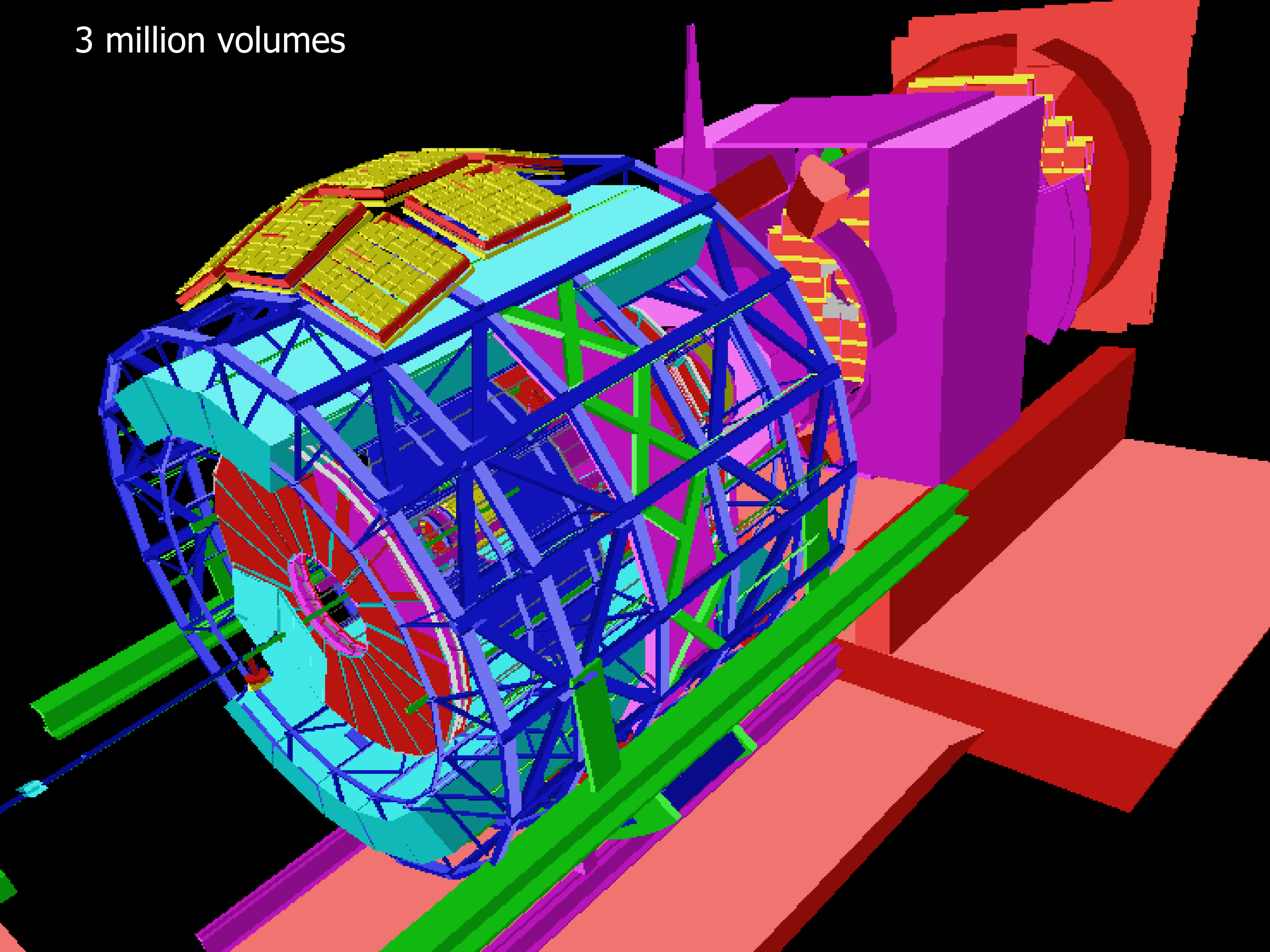
rate [MB/s] vs time
rate
Nent = 4014966
Mean = 4.927e+05
RMS = 2.612e+05
120
100
80
60
40
20
0
01/01
08/01

Offline Framework

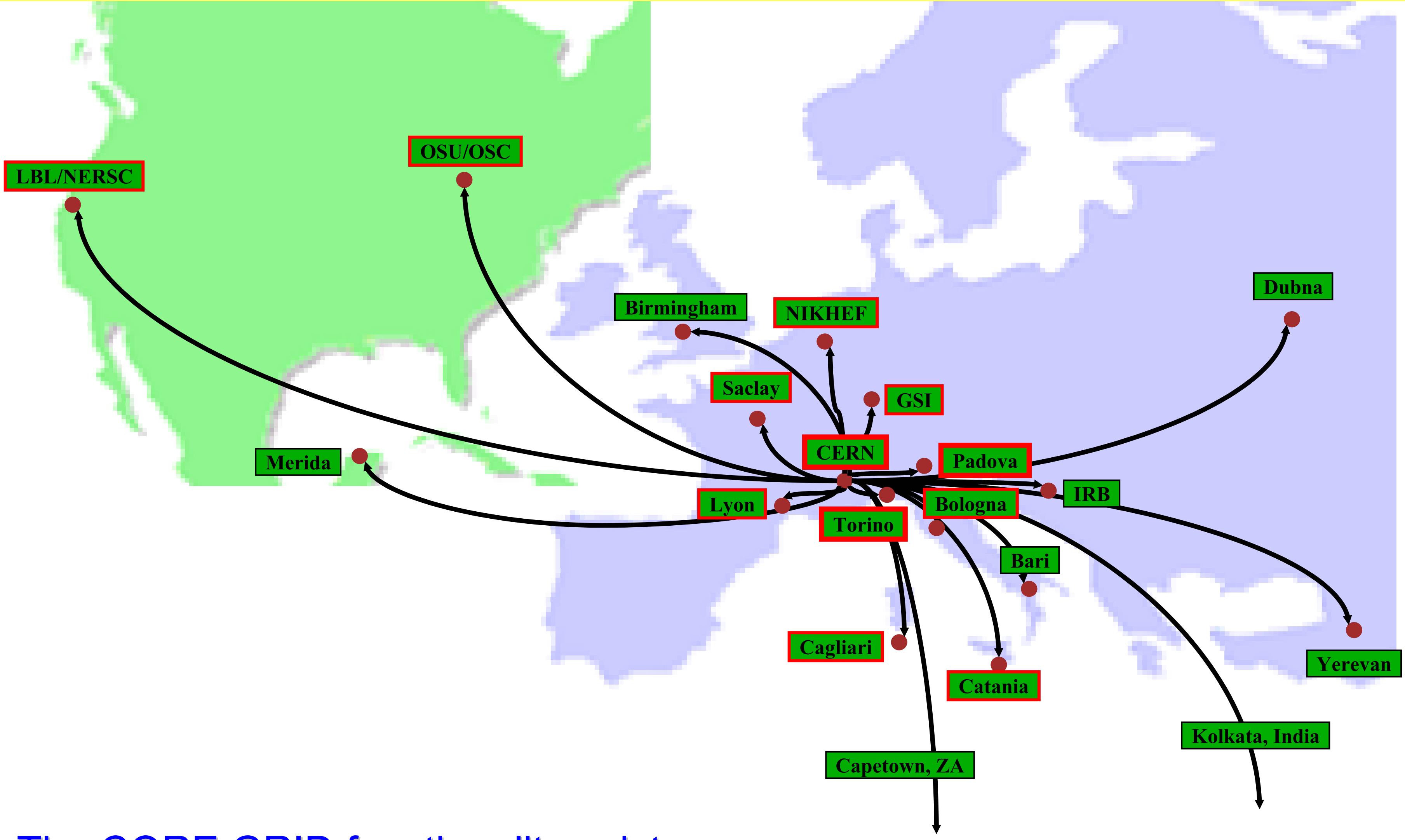


- HEP use cases:
  - ✓ Simulation & Reconstruction
  - ✓ Event mixing
  - ✓ Analysis

3 million volumes

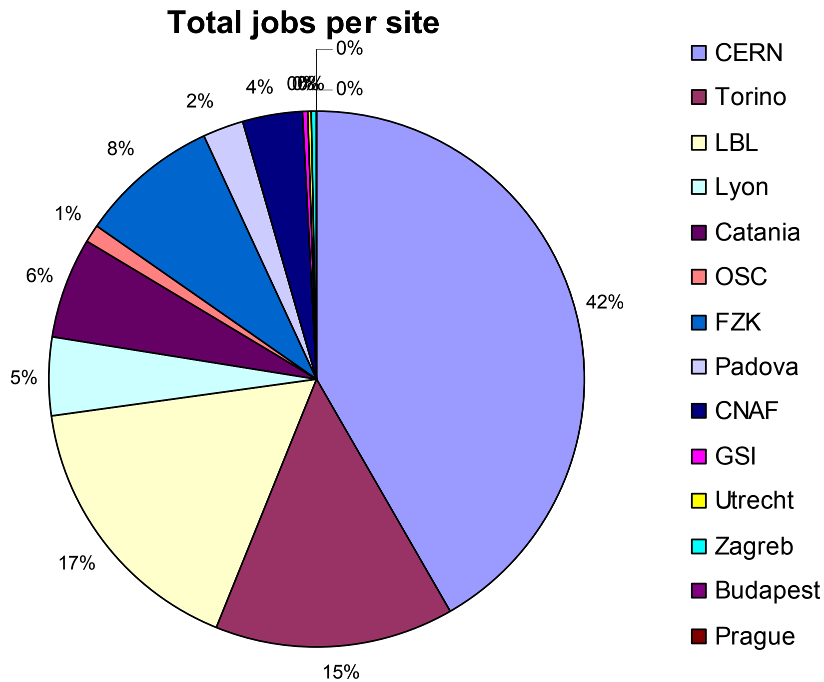


ALICE GRID is there: ALIEN

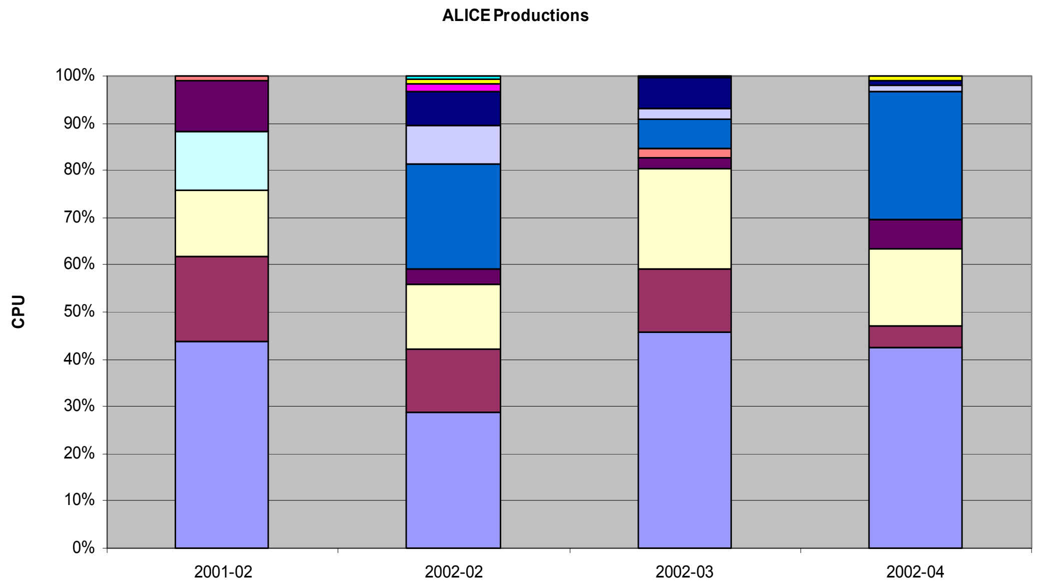


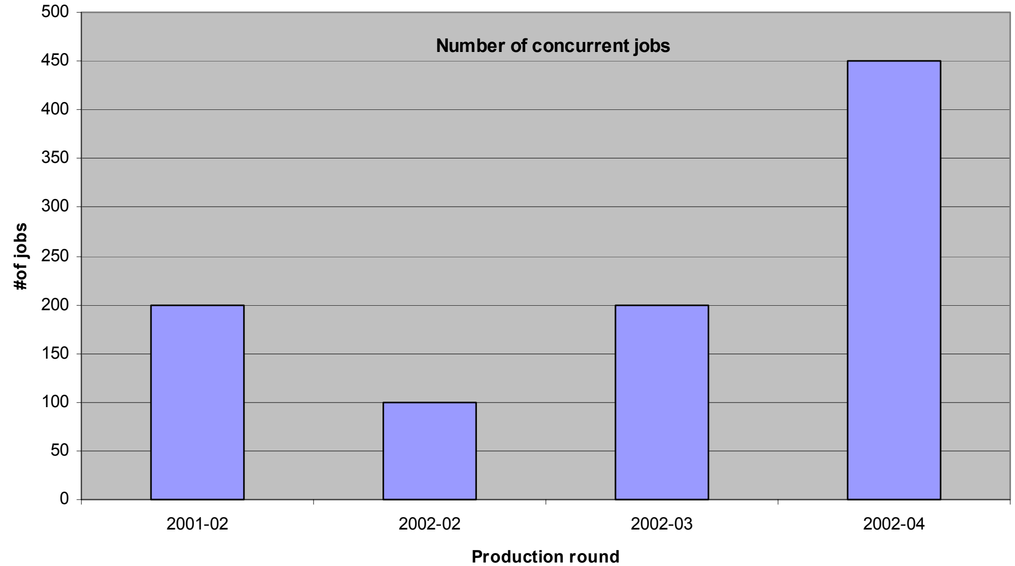
- The CORE GRID functionality exists
- Distributed production in action for the PPR

Production Status



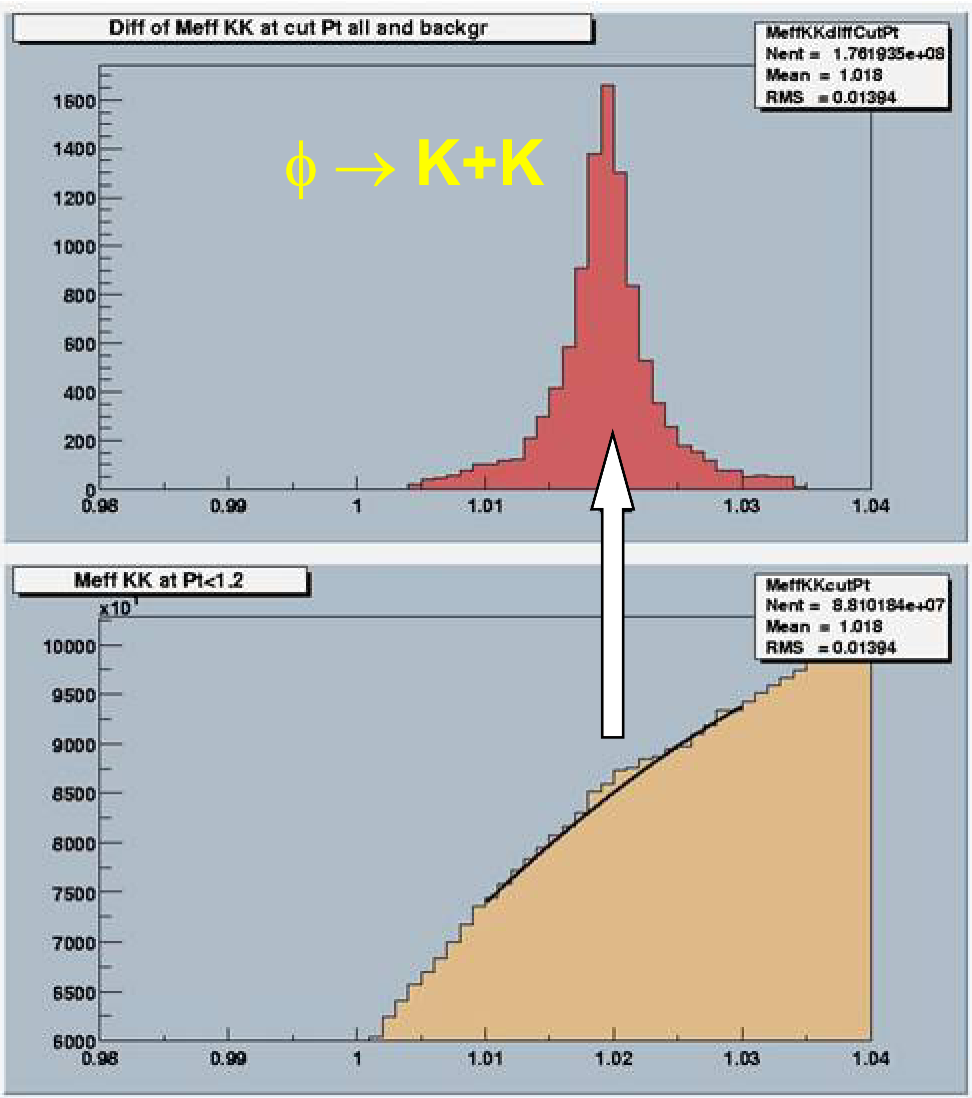
22773 jobs,
~12CPUh/job,
~1GB output/job
up to 450 concurrent jobs
0.5 operators !

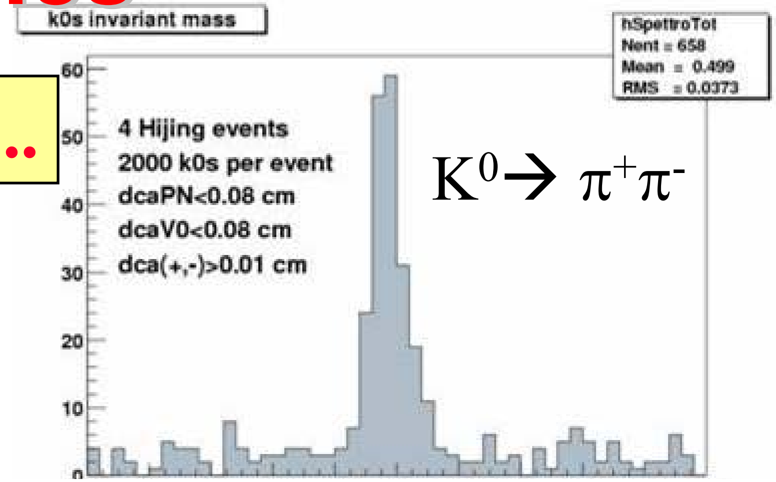


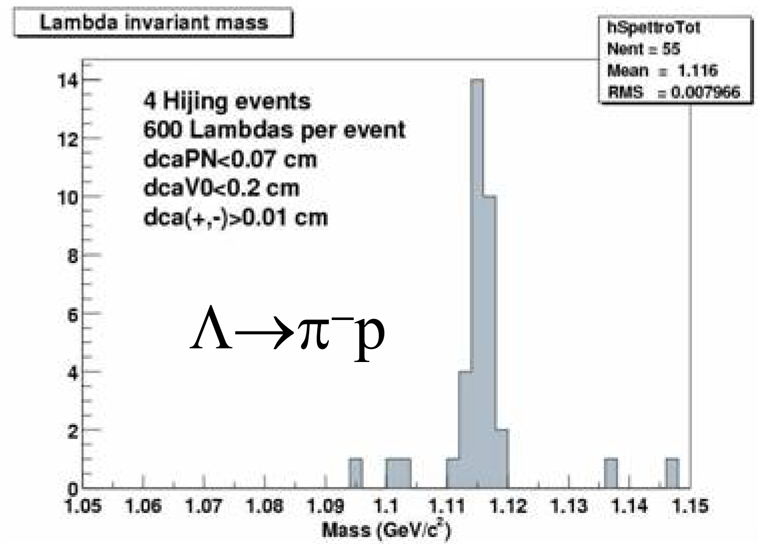


Hadronic Observables

$\pi, \eta, \omega, \phi, p, K, K^*, \Lambda, \Xi, \Omega, D, d, T, \alpha, ..$







Reconstruct (dN/dy~6k):

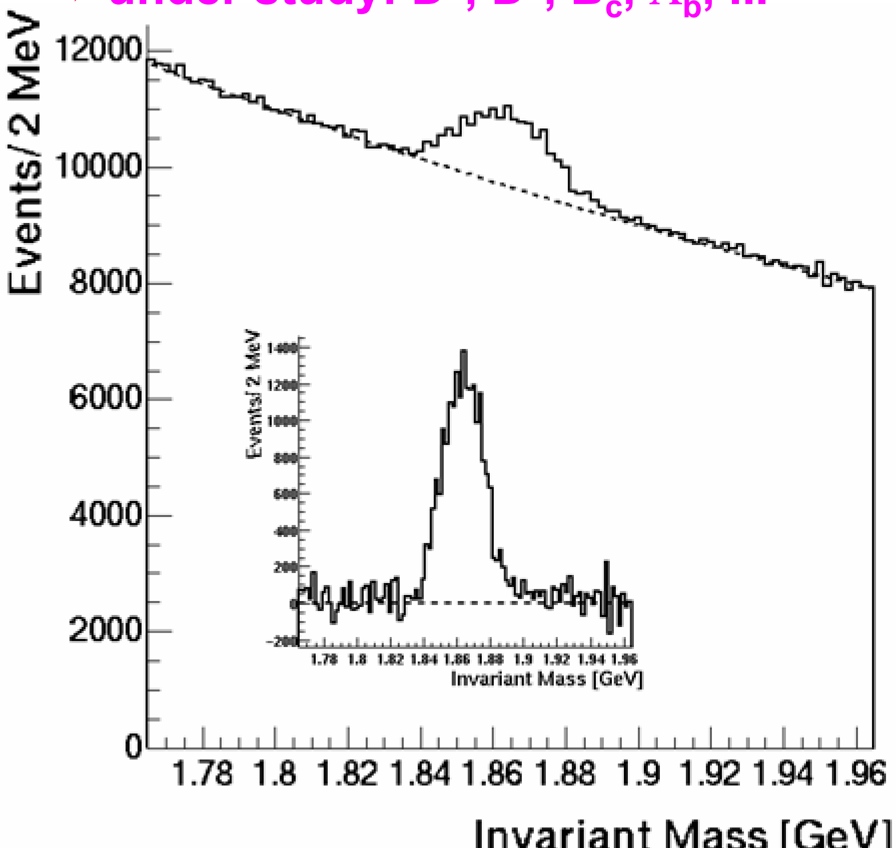
~ 30 K^0/central event

~ 3 Λ/central event

Heavy Quarks

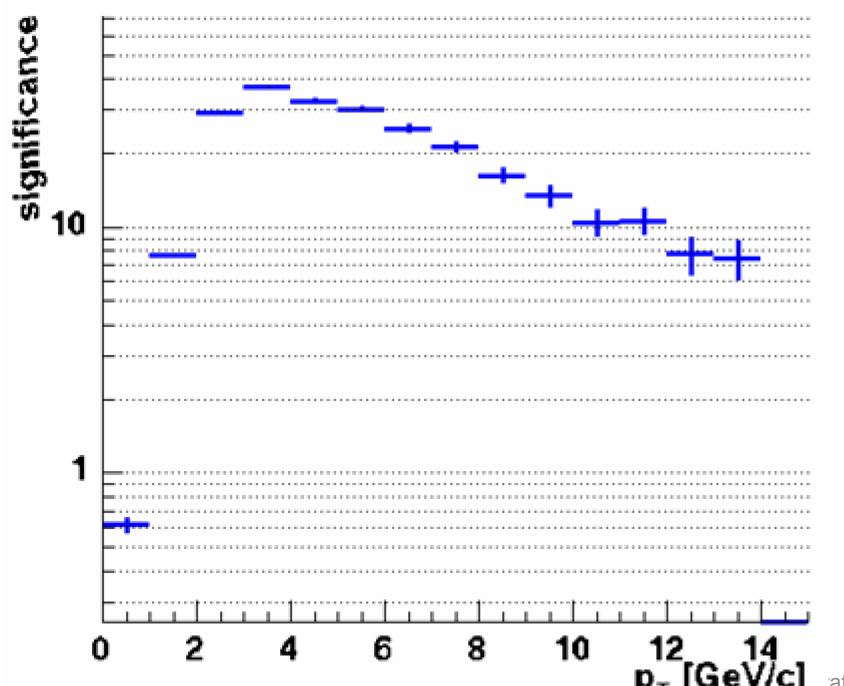
●Hadronic charm: D -> Kπ

- ⇨ uses sec. vertex & PID
- ⇨ acceptance to ~ 0 p_t **=>** σ_{tot}
- ⇨ full kinematic reconstruction
  - ✪ **=> 'quark quenching'**
- ⇨ **under study: D*, D$^{\pm}$, B_c, Λ_b, ...**



ALICE's Heavy Quark Shopping List

probe	channel	acceptance
$J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon''$	e^+e^-	$\|\eta\| < 0.9$
$J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon''$	$\mu^+\mu^-$	$2.5 < \eta < 4$
$c\bar{c}$ & $b\bar{b}$	e^+e^-	$\|\eta\| < 0.9$
$c\bar{c}$ & $b\bar{b}$	$\mu^+\mu^-$	$2.5 < \eta < 4$
D mesons	π,K	$\|\eta\| < 0.9$
B mesons	$B \rightarrow J/\psi \rightarrow e^+e^-$	$\|\eta\| < 0.9$
D & B mesons	single $e^{\pm}$	$\|\eta\| < 0.9$
$c\bar{c}$ & $b\bar{b}$	$e^{\pm}\mu^{\mp}$	$1 < y < 3$

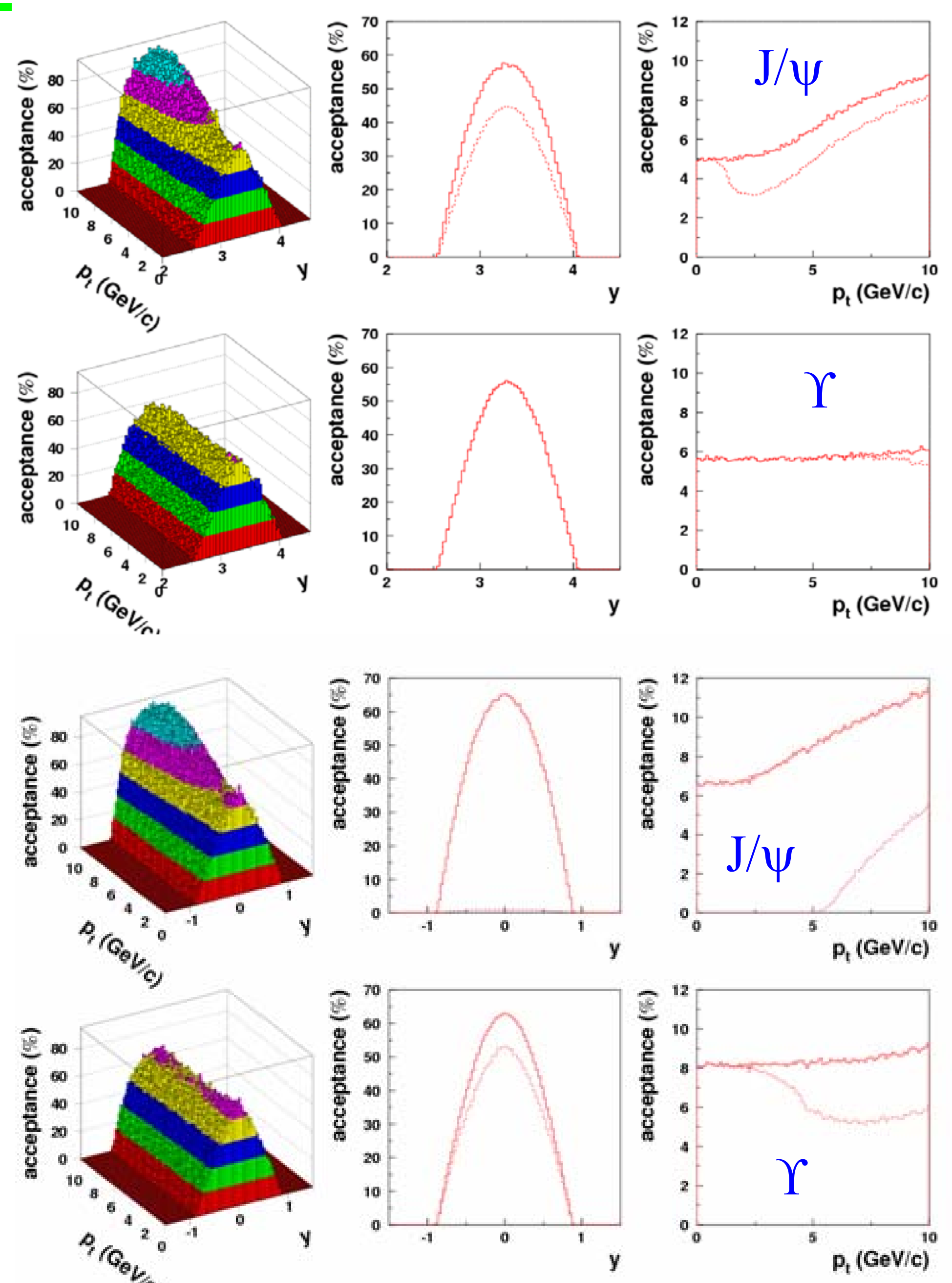


Quarkonia

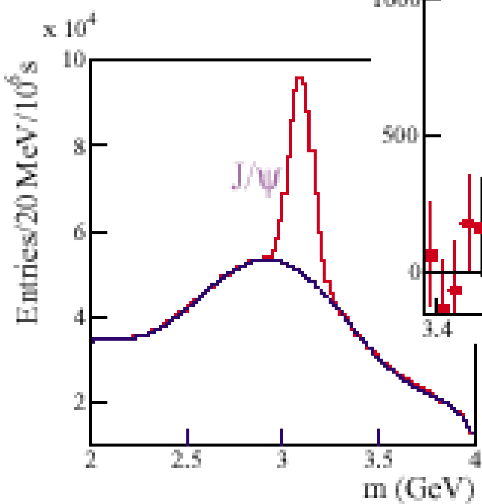
$\mu^+\mu^-$

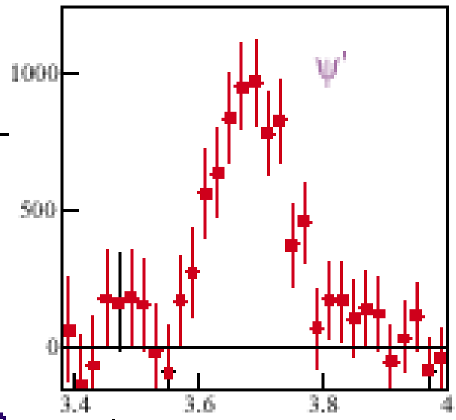
e^+e^-

- **Acceptance**
  - ⇨ down to $p_t = 0$

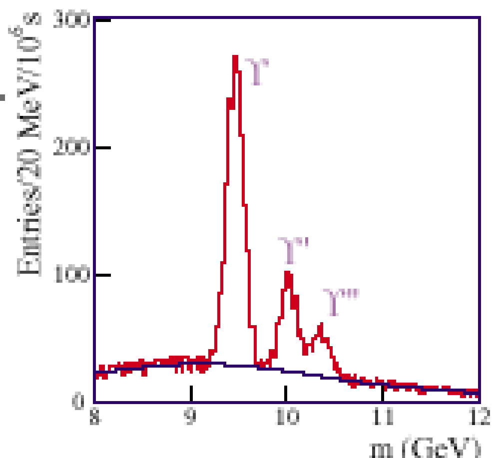


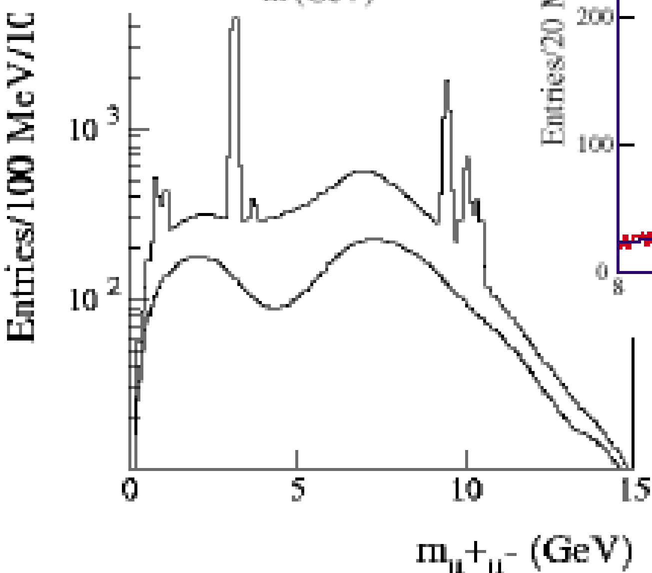
Di-Muons





- $2.5 < \eta < 4$
- from ϕ to Υ''
- high statistics
- low background
- high resolution





- σ_M =94.5 MeV/c² at the ϒ
- Separation of ϒ, ϒ', ϒ''
- Total efficiency ~ 75%
- Expected statistics (significance – 1 yr):

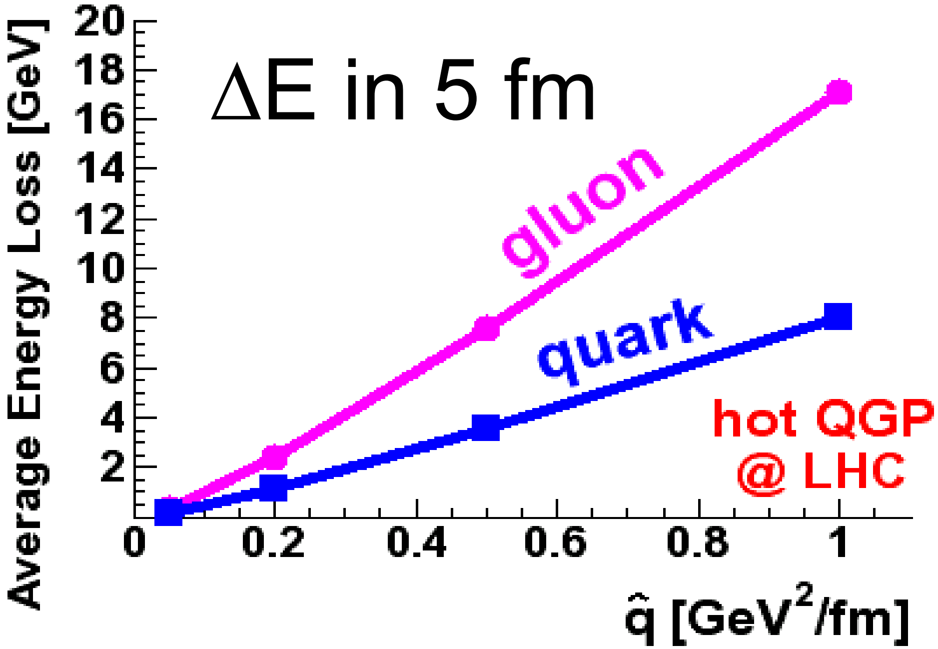
	central	min. bias
J/ψ	310	574
ψ'	12	23
ϒ	39	69
ϒ '	19	35
ϒ "	12	22

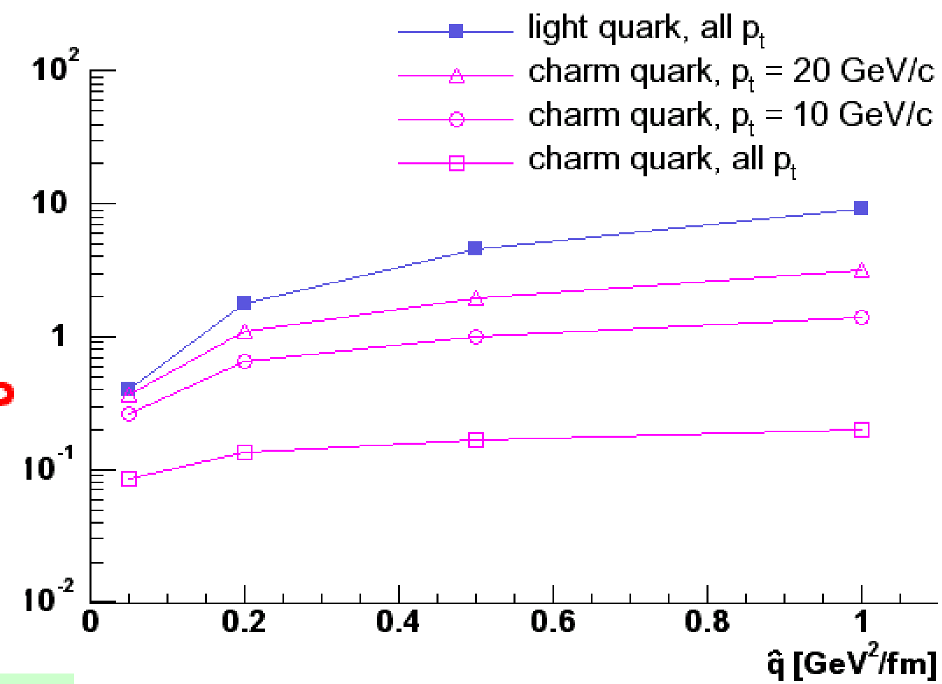
from min. bias events:

~ 8k ϒ and ~700k J/ψ /yr

Energy Loss of Partons

- **jet quenching = medium induced gluon bremsstrahlung**





$$\Delta E \propto \alpha_s \, C_R \, \hat{q} \, L^2 f(m_Q/E)$$

Mass dependent term ('dead cone')

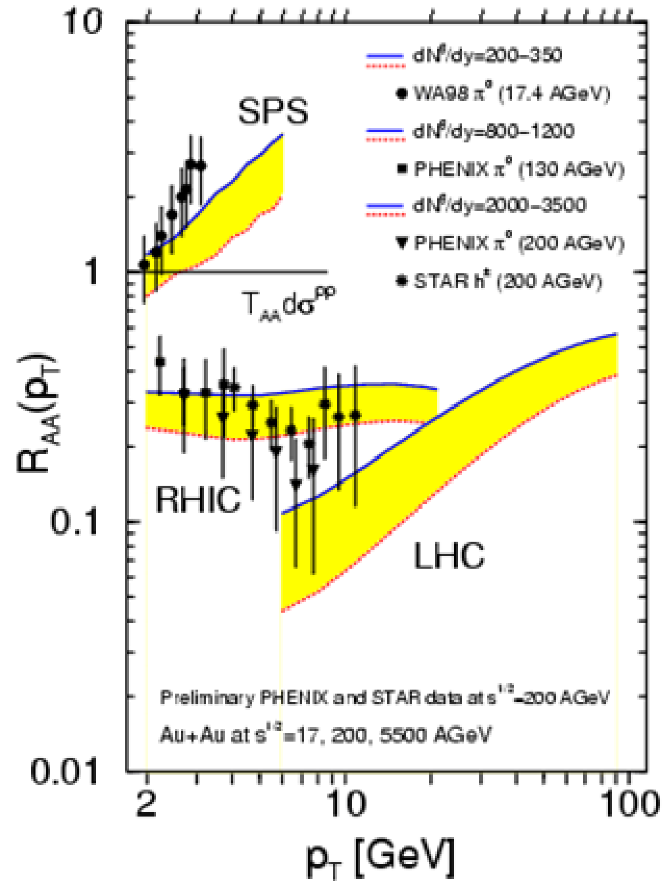
Casimir coupling factor:
4/3 for quarks, 3 for gluons

Medium transport coefficient
$\propto$ gluon density and momenta

Energy Loss of Jets

- **jet quenching = energy loss of leading particle**
  - ⇨ lost energy appears in soft particles => change of jet fragmentation function !
    - total jet-energy does not change ! => calorimeter only is insufficient

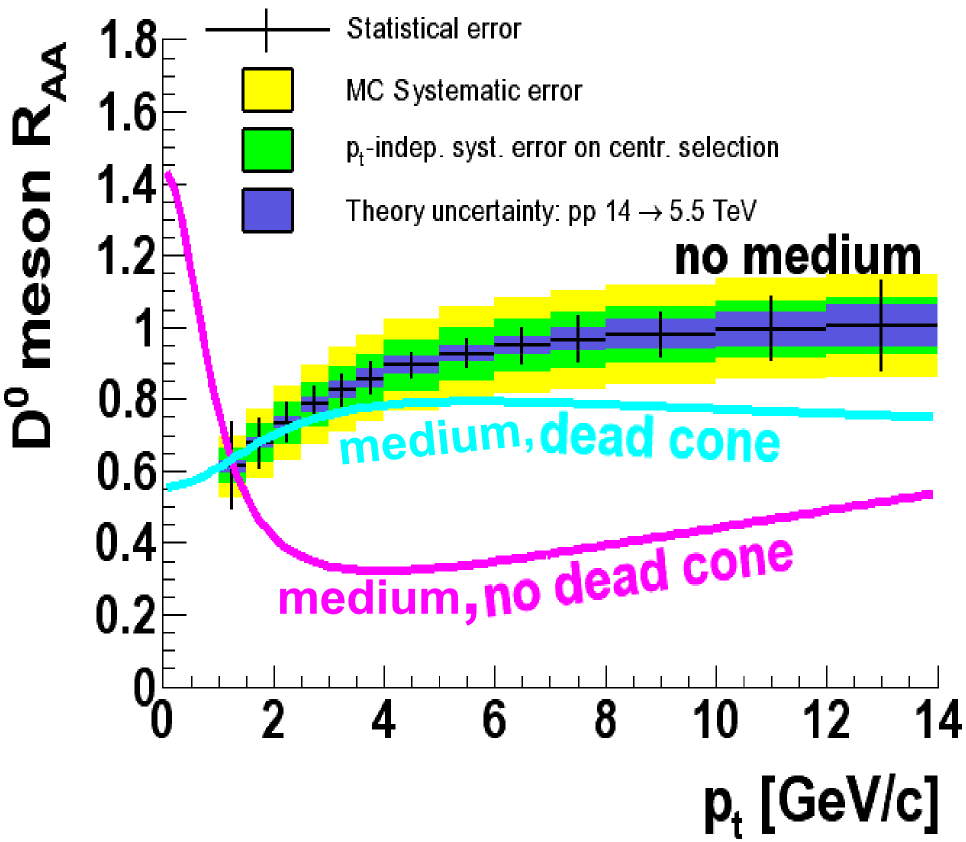
- **ALICE handles on 'jet quenching'**
  - ⇨ leading hadrons (0 - > 50 GeV)
    - inclusive p_t spectra & correlations
    - identified hardons ($\pi^{\pm}$, π^0, η, Λ, $K^{\pm}$)
  - ⇨ leading heavy quarks (0 -> 20 GeV)
    - inclusive b, c, D, B
    - b, c tagging in jets (high p_t electrons in TRD)
  - ⇨ hadron correlations (5 –> 50 GeV)
    - 'same' side, 'opposite' side
  - ⇨ jet **fragmentation function** (40 -> 200 GeV)
    - TPC,TRD,emcal
  - ⇨ jet correlations (-> 50 GeV)
    - γ-jet (PHOS-emcal-TPC)
    - jet1(emcal)-jet2(TPC)



Energy Loss of Charm

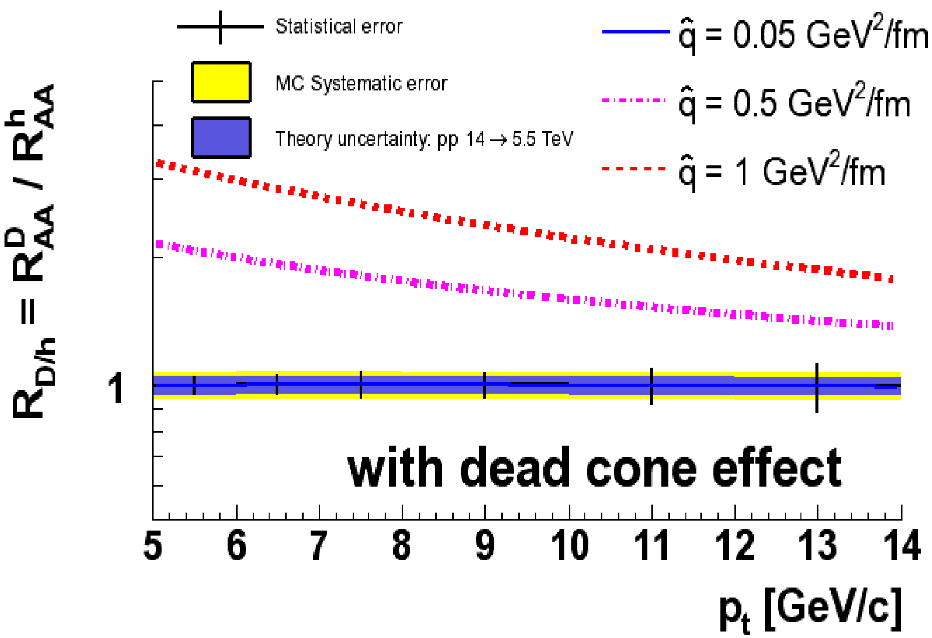
- Charm p_t spectrum in AA relative to pp
  - ⇨ excellent & quantitative tool to investigate QGP properties

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$



D/h ratio:

$R_{D/h} = R^D_{AA} / R^h_{AA}$

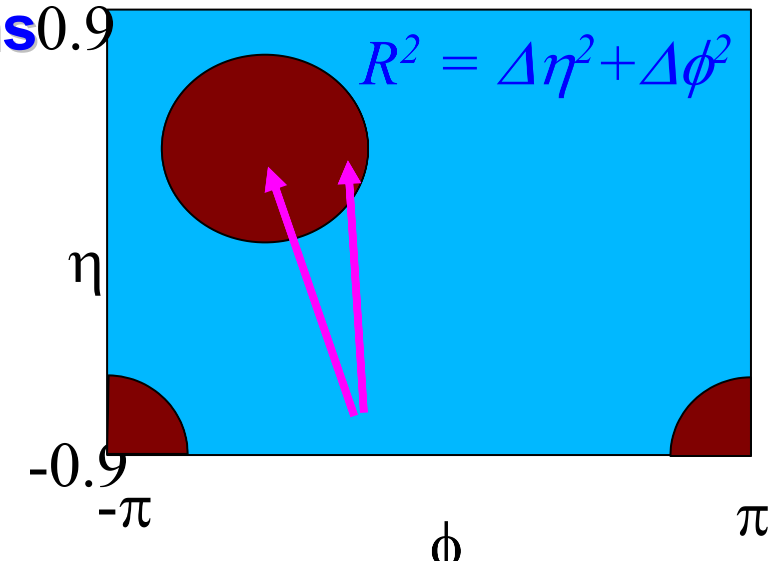


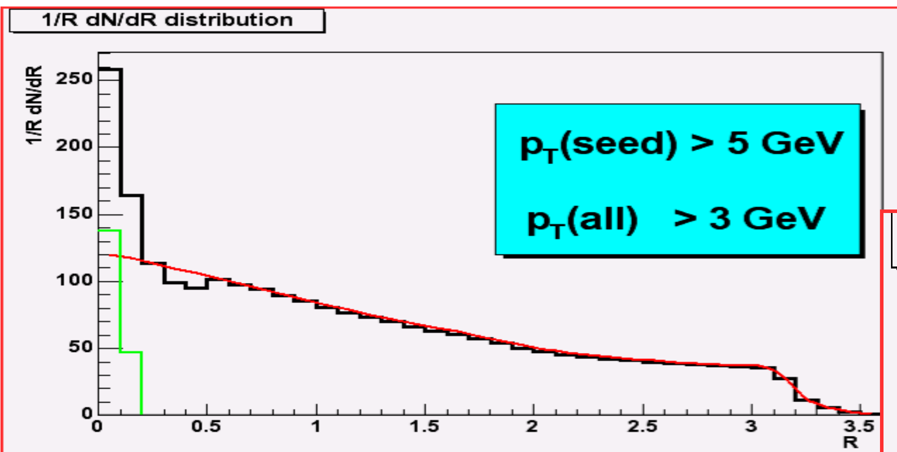
$R_{D/h}$ ~ 2-3 in hot QGP

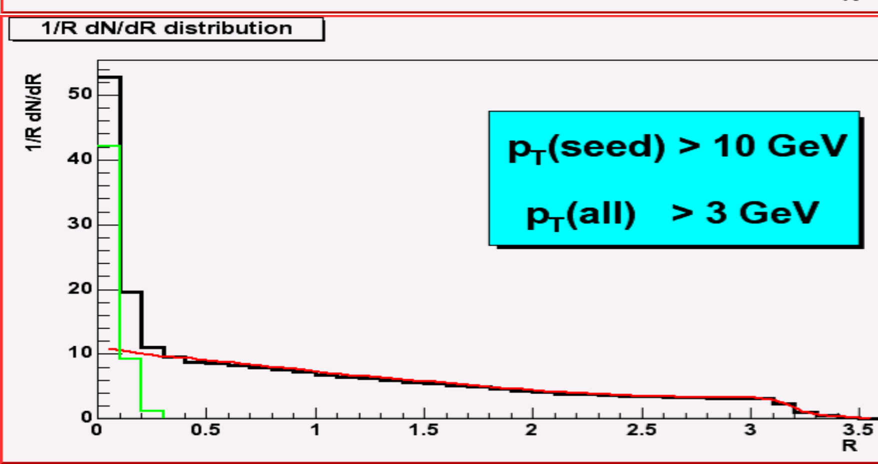
sensitive to medium density

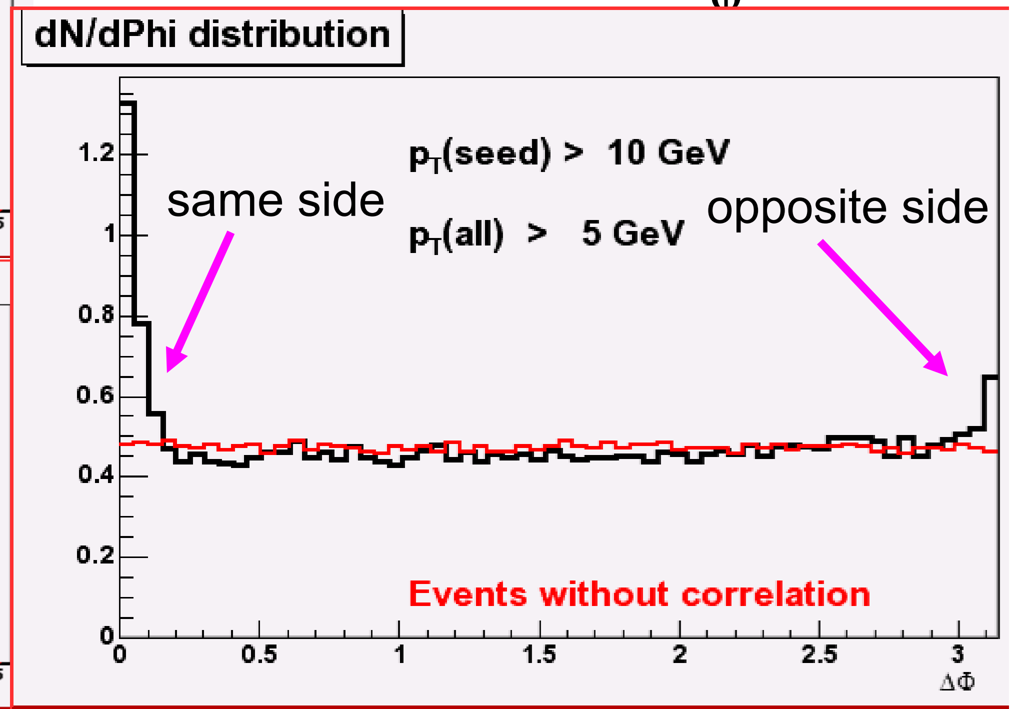
Hadron Correlations

- ‘minijets’ can be seen in correlations
  - ‘opposite side’ jet completely quenched at RHIC
  - should reappear at some high pt at LHC
    - direct measure of energy loss ??



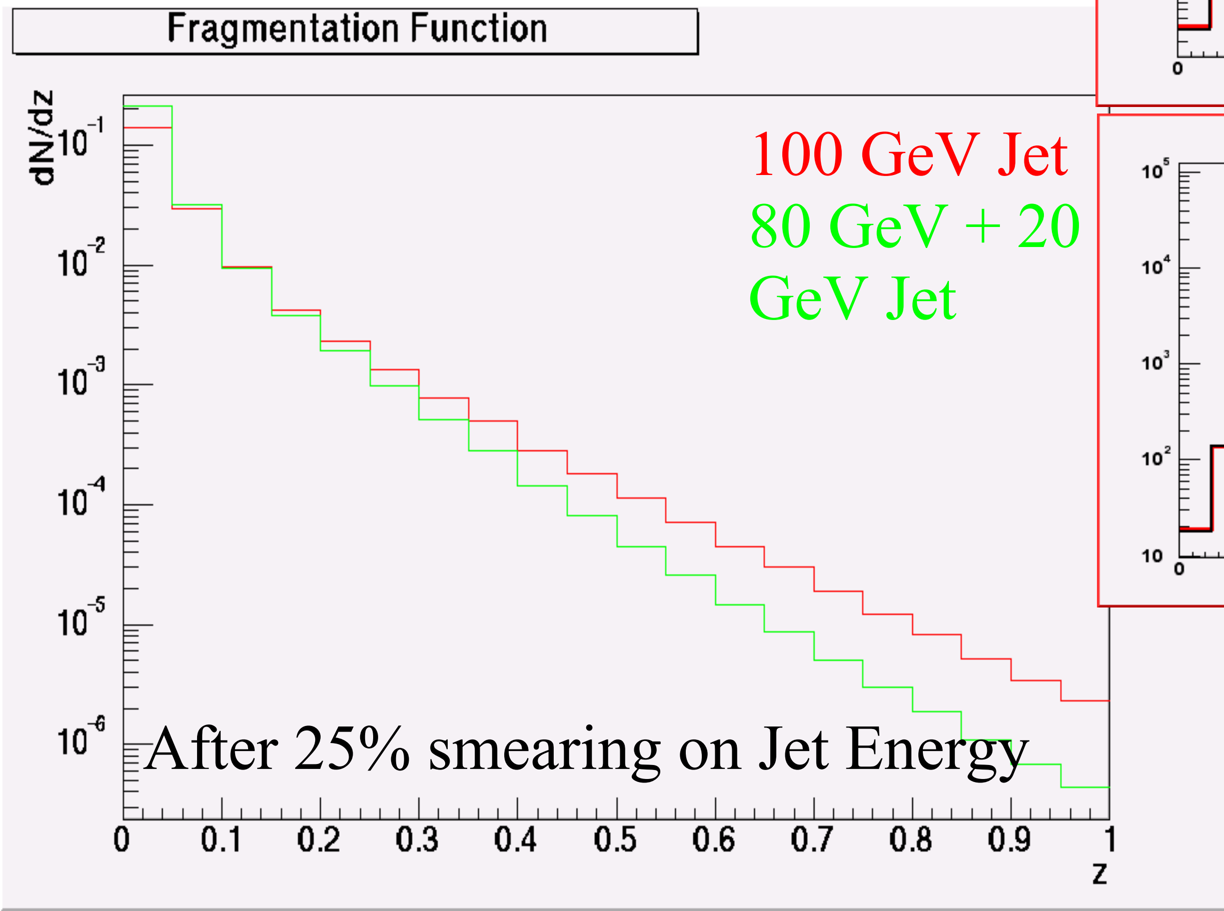


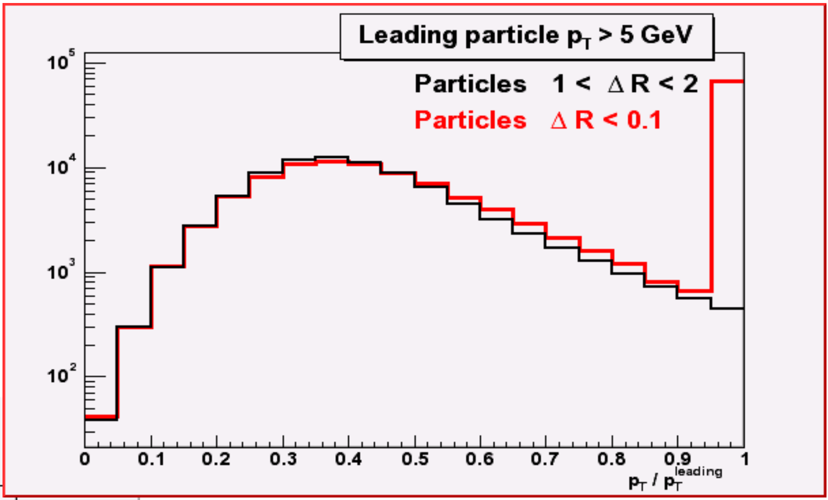


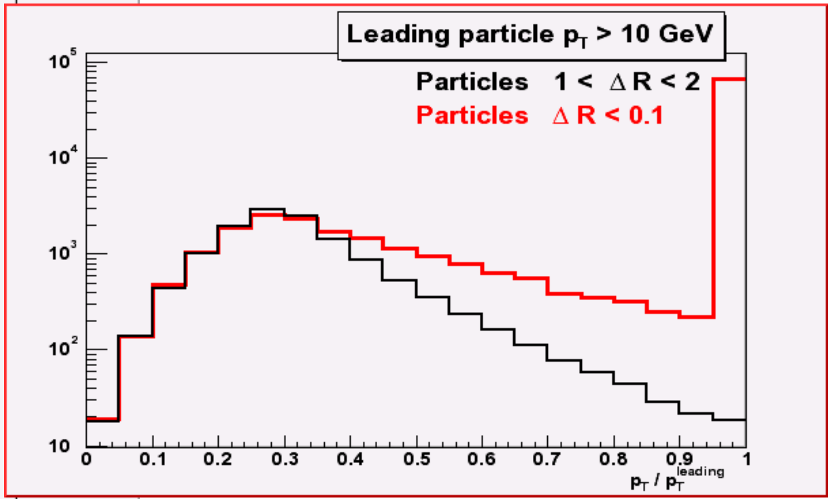


Jet Fragmentation Functions

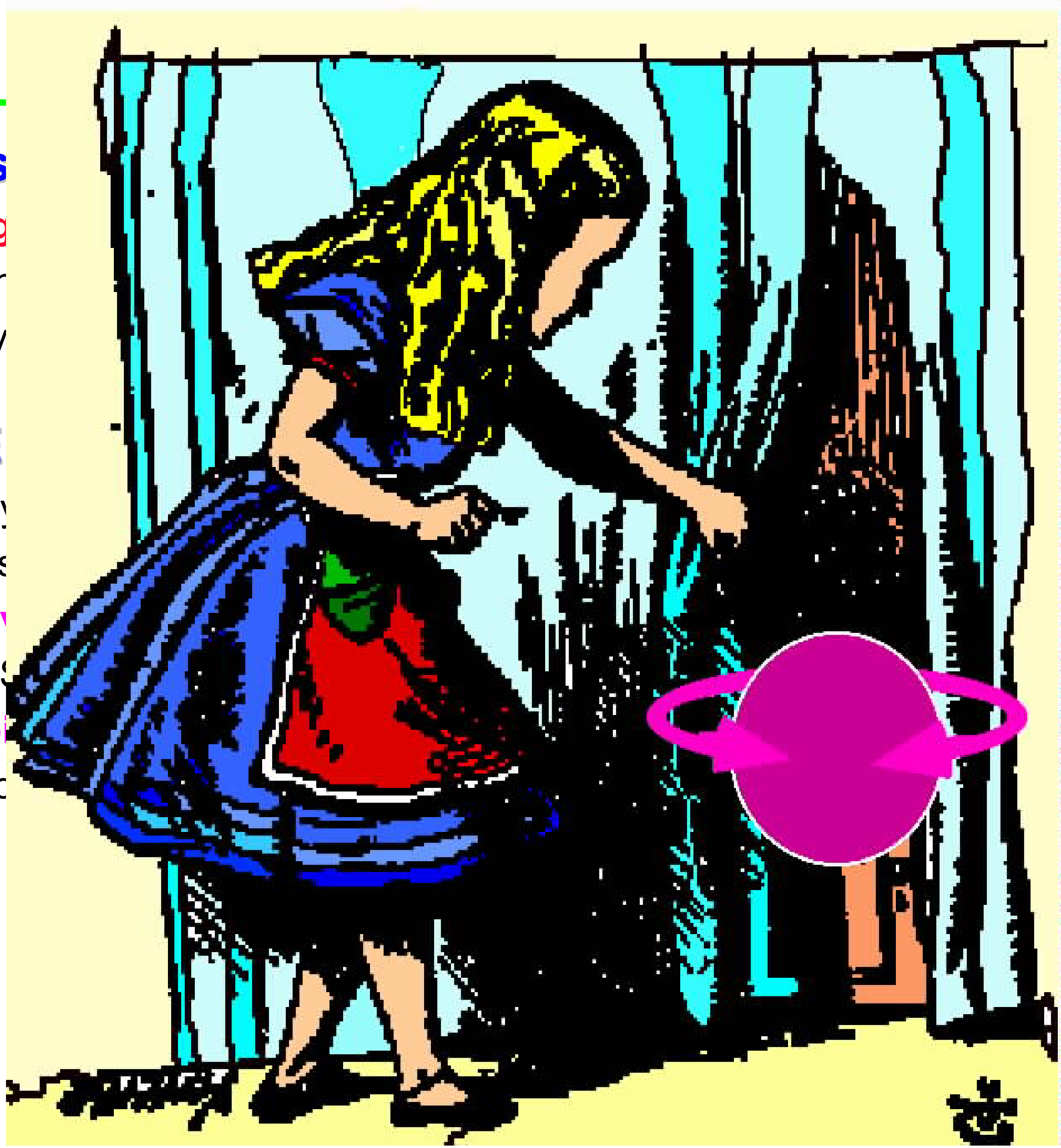
- **Jet spectroscopy:**
  - ⇨ longitudinal fragmentation function
  - ⇨ transverse fragmentation function







- **LHC is** … **ons**
  - very **sig**
  - exceller
  - not only
- **ALICE**
  - first truly
    - addres
  - many **e**
    - SSD, S
  - some **bi**
    - electro



to