Physics with ALICE at the Large Hadron Collider

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NIKHEF

for the ALICE collaboration

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Content

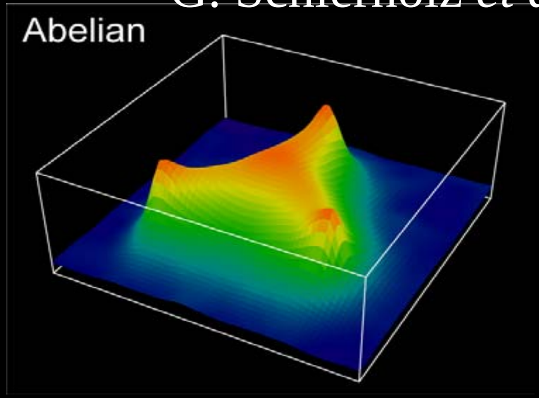
- QCD at high densities and temperatures
- The LHC heavy-ion program and ALICE the dedicated heavy-ion detector
- Probes and Observables (more detailed current status see Jamie Nagle's presentation of the recent RHIC results)

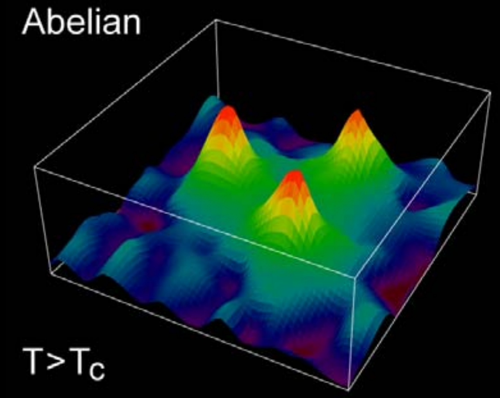
Disclaimer: only cover small part of ALICE physics program and detectors

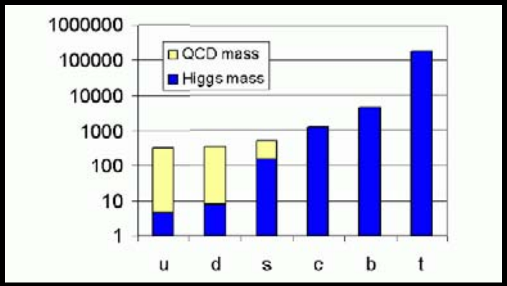
Quantum Chromo Dynamics

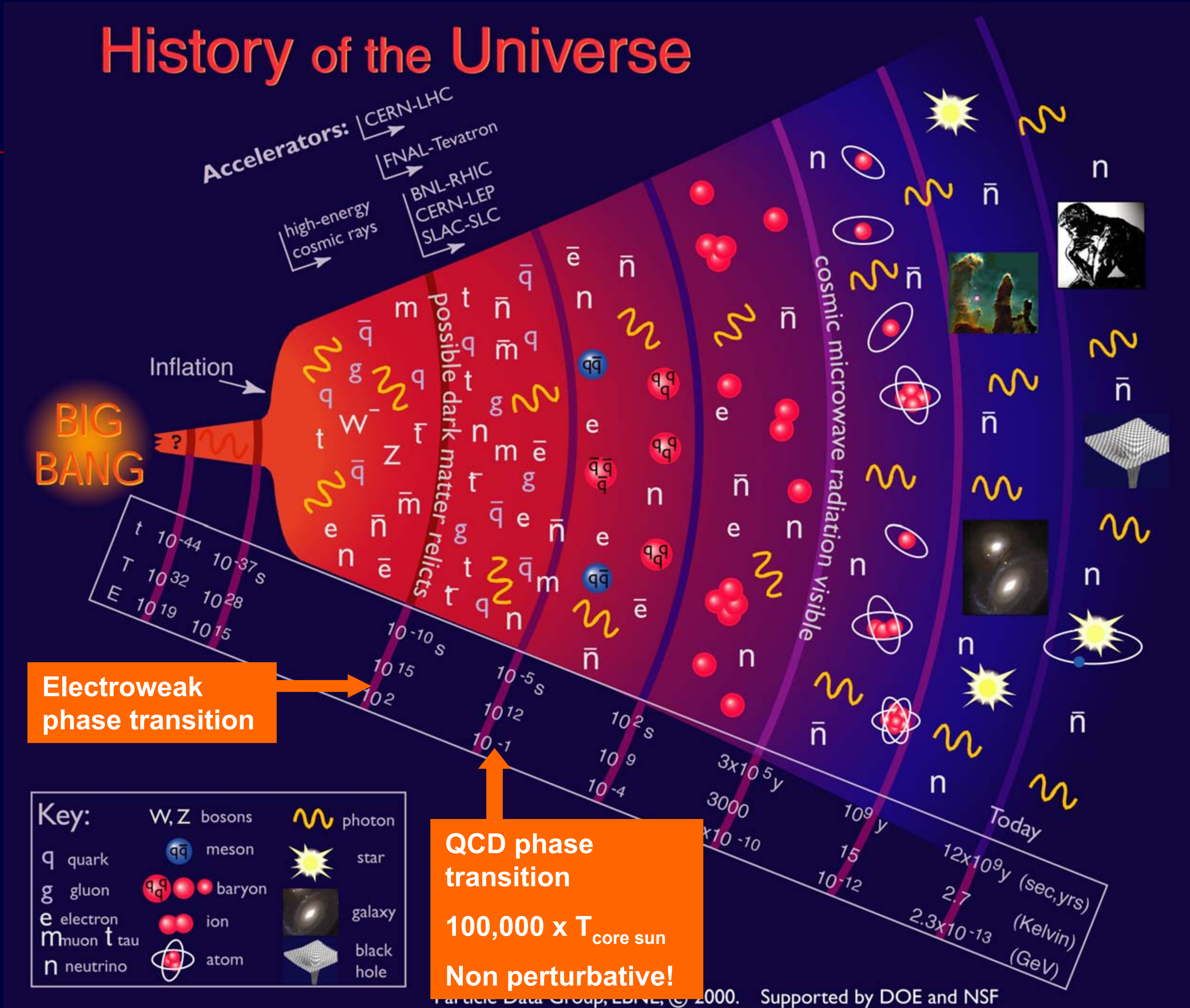
- Theory of the strong interaction
  - Part of the standard model
  - Quarks as constituents, gluons as field quanta
- Confinement
  - Quarks and gluons are not observed as free particles, they are confined in hadrons
- Chiral symmetry breaking
  - Hadrons are much heavier than their constituents

G. Schierholz *et al.*



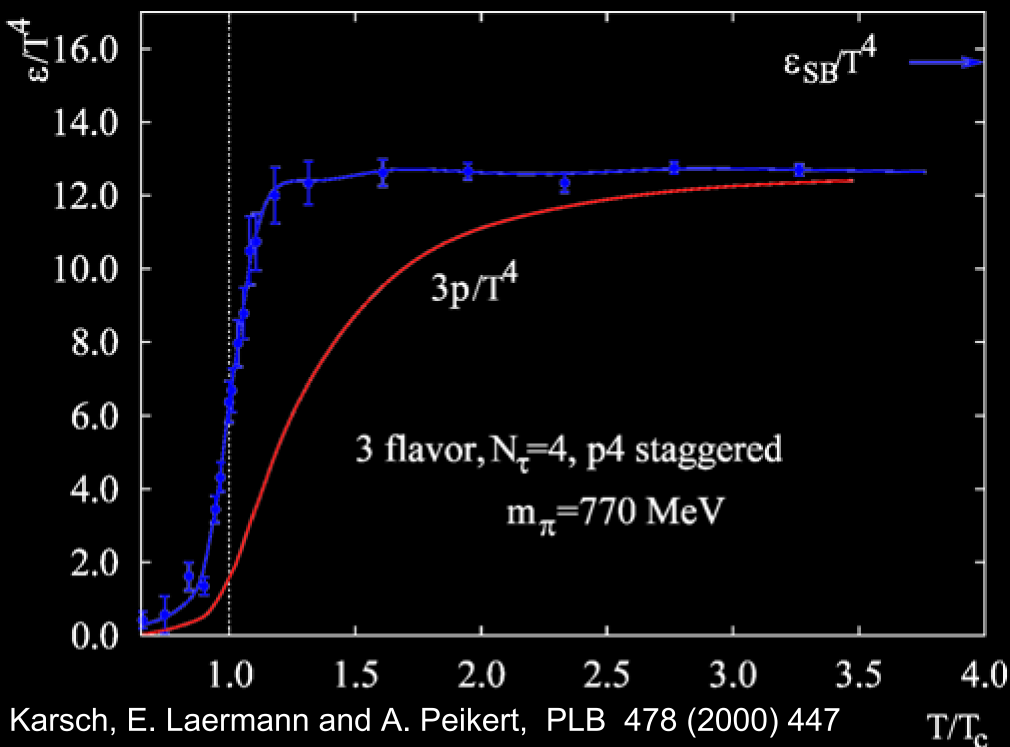





History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$x10^{-10}$
10^{9} y
15
10^{-12}
Today
$12x10^{9}$y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
W, Z bosons
q quark
g gluon
e electron
m muon t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
Electroweak phase transition
QCD phase transition
100,000 x $T_{core\ sun}$
Non perturbative!

Understanding QCD and the early universe

- QGP properties are in principle calculable from the QCD Lagrangian using lattice QCD

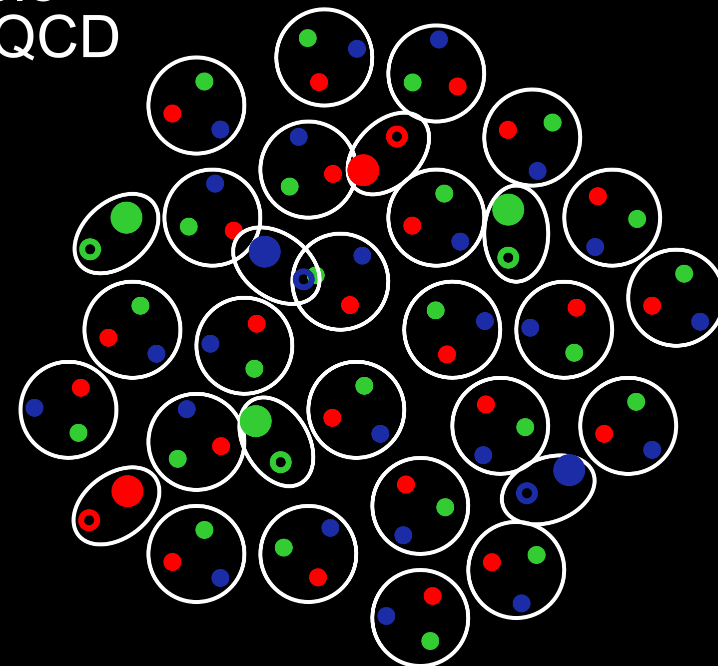


F. Karsch, E. Laermann and A. Peikert, PLB 478 (2000) 447

ε/T^4 ~ # degrees of freedom

- How to make a connection with experiment?

Animation: Mike Lisa



- Heating the matter
- Compressing the matter
  - deconfined matter with color degrees of freedom

Energy density, T and degrees of freedom

$$\frac{\varepsilon}{T^4} = g\,\frac{\pi^2}{30}$$

$$\frac{\varepsilon}{T^4} = 3\cdot\frac{\pi^2}{30}$$

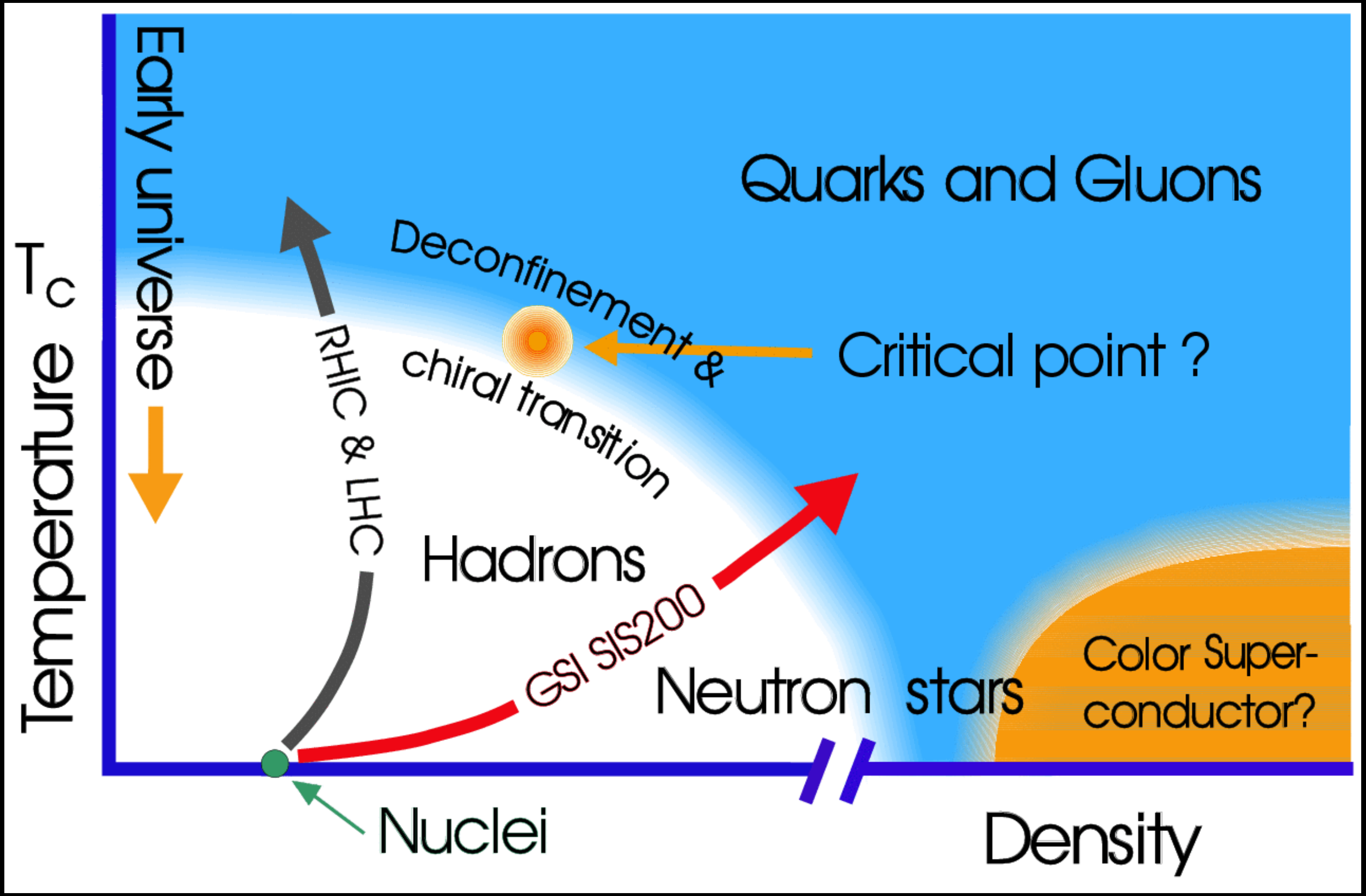
- Energy density for g massless degrees of freedom
- Hadronic matter (T< 170 MeV, π^+,π^- and π^0)

$$\frac{\varepsilon}{T^4} = \left\{2\cdot 8_{gluons} + \frac{7}{8}\cdot 2_{flavors}\cdot 2_{anti}\cdot 2_{spin}\cdot 3_{color}\right\}\cdot\frac{\pi^2}{30}$$

$$\frac{\varepsilon}{T^4} = 37\cdot\frac{\pi^2}{30}$$

- Quark Gluon Plasma (T>170 MeV)

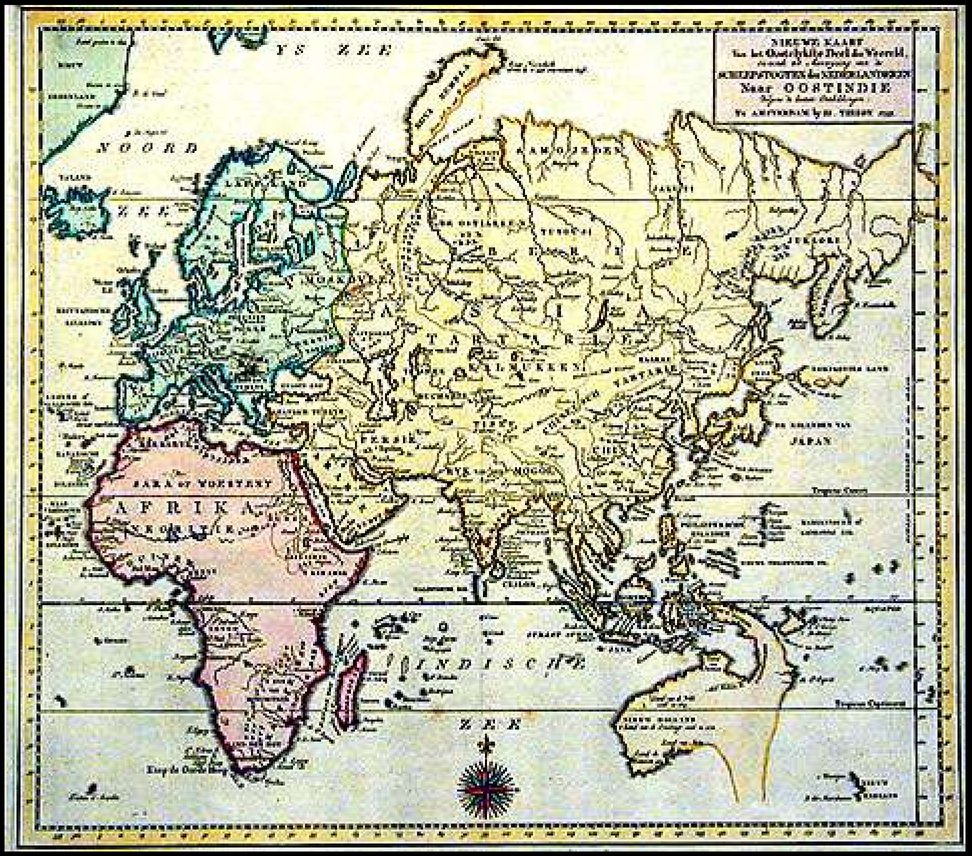
Our current map of the QCD landscape



Based on Krishna Rajagopal and Frank Wilczek: Handbook of QCD

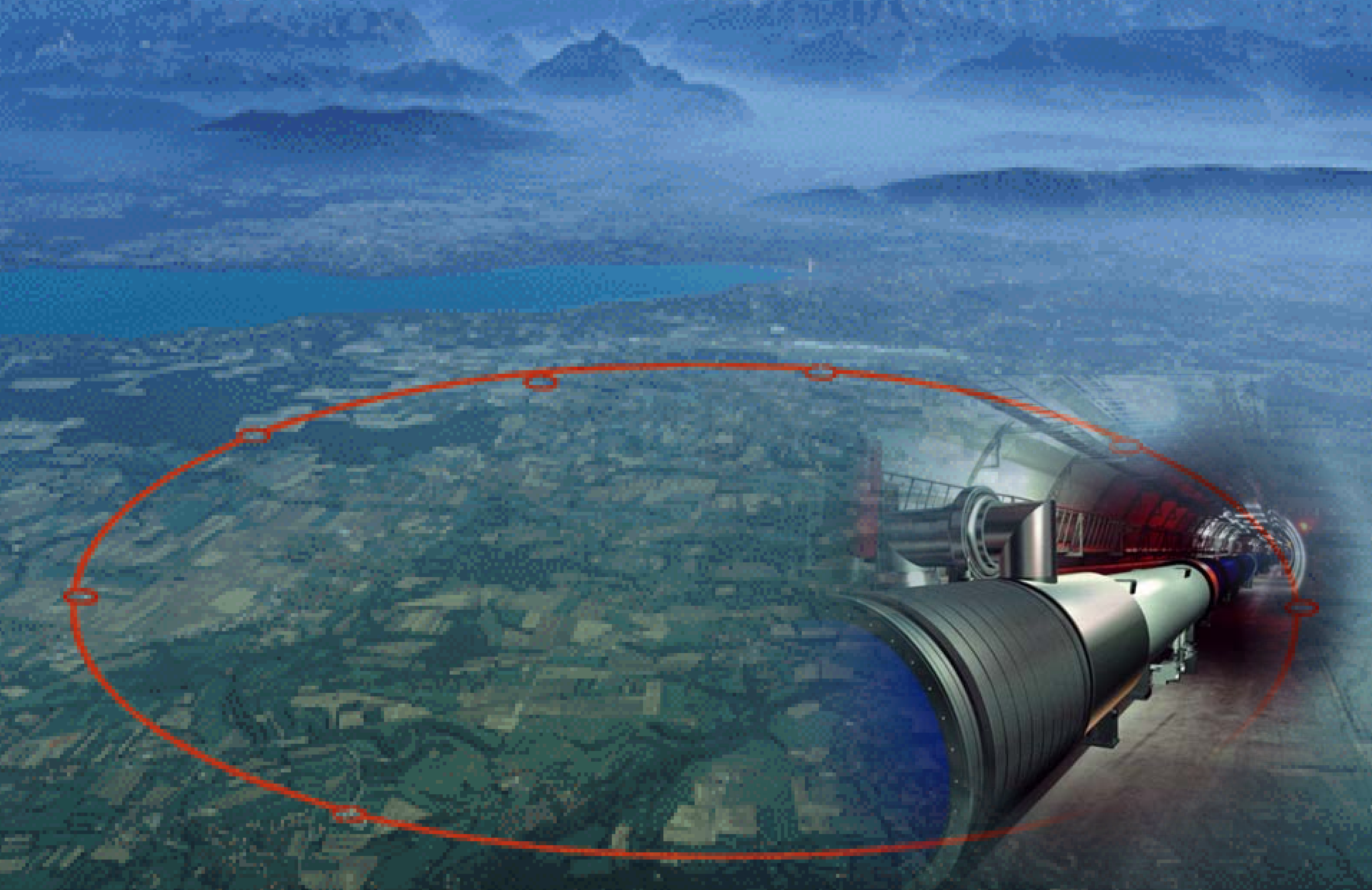
- Theory view of phases in QCD matter
- Accessible in ultra relativistic heavy-ion collisions

Mappamundi 1452

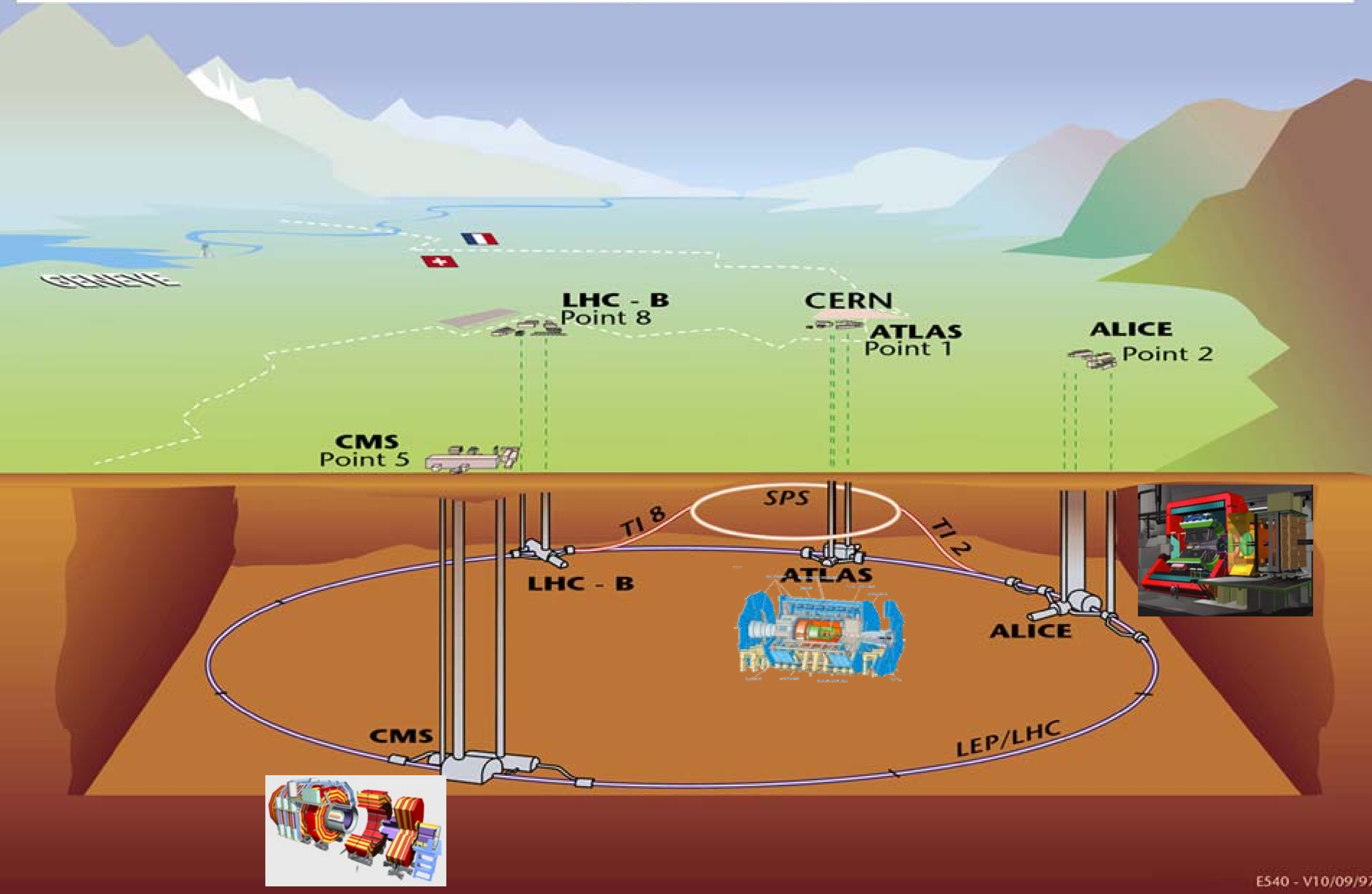


The map anno 2006

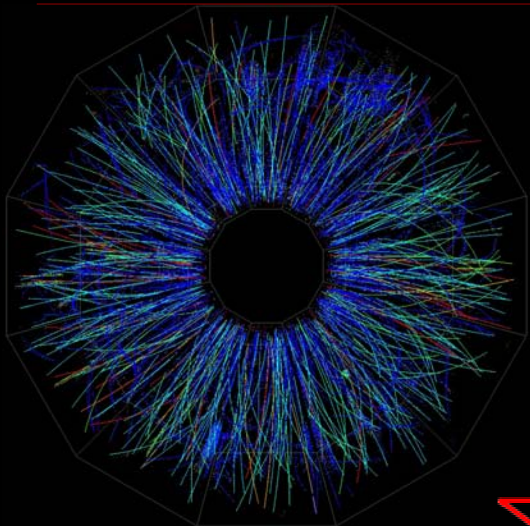
The Large Hadron Collider (LHC)



Overall view of the LHC experiments.

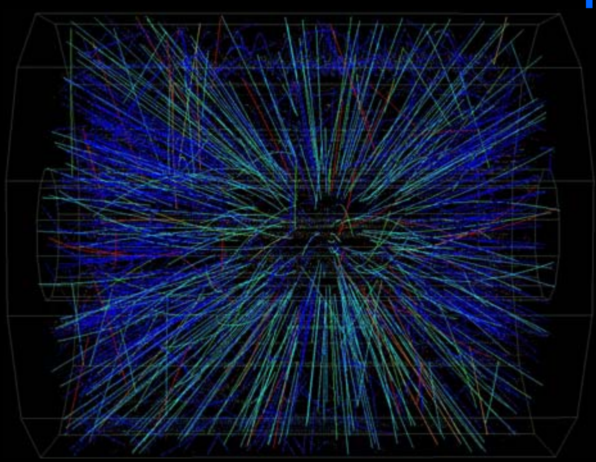


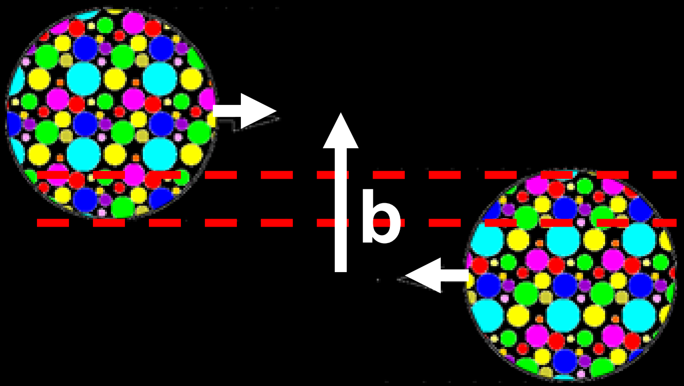
The impact parameter: **b**



Peripheral Event

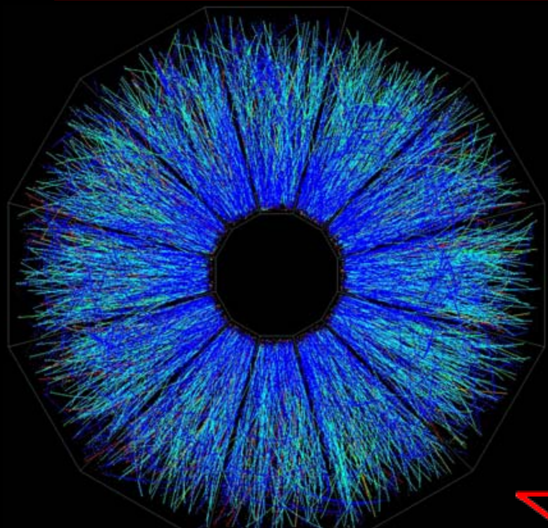
From real-time Level 3 display





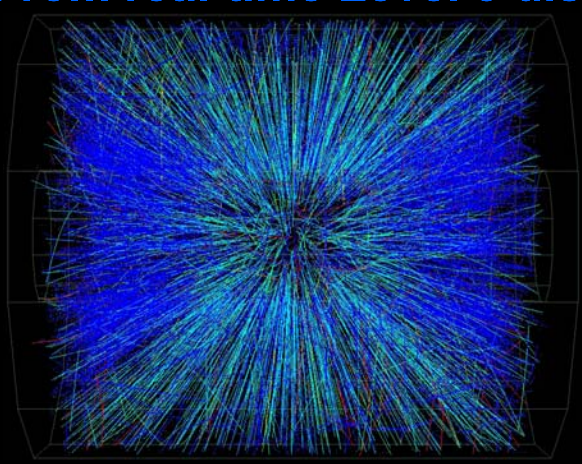
- peripheral collisions, most likely configuration
- “few” particles produced
- many “spectators”
- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions

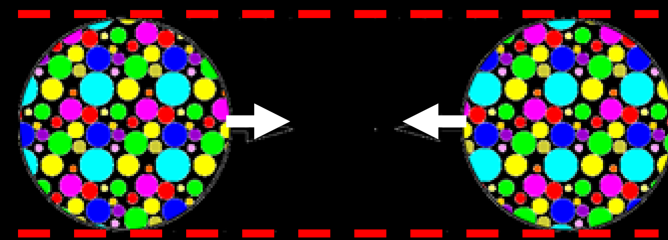
The impact parameter: **b**



Central Event

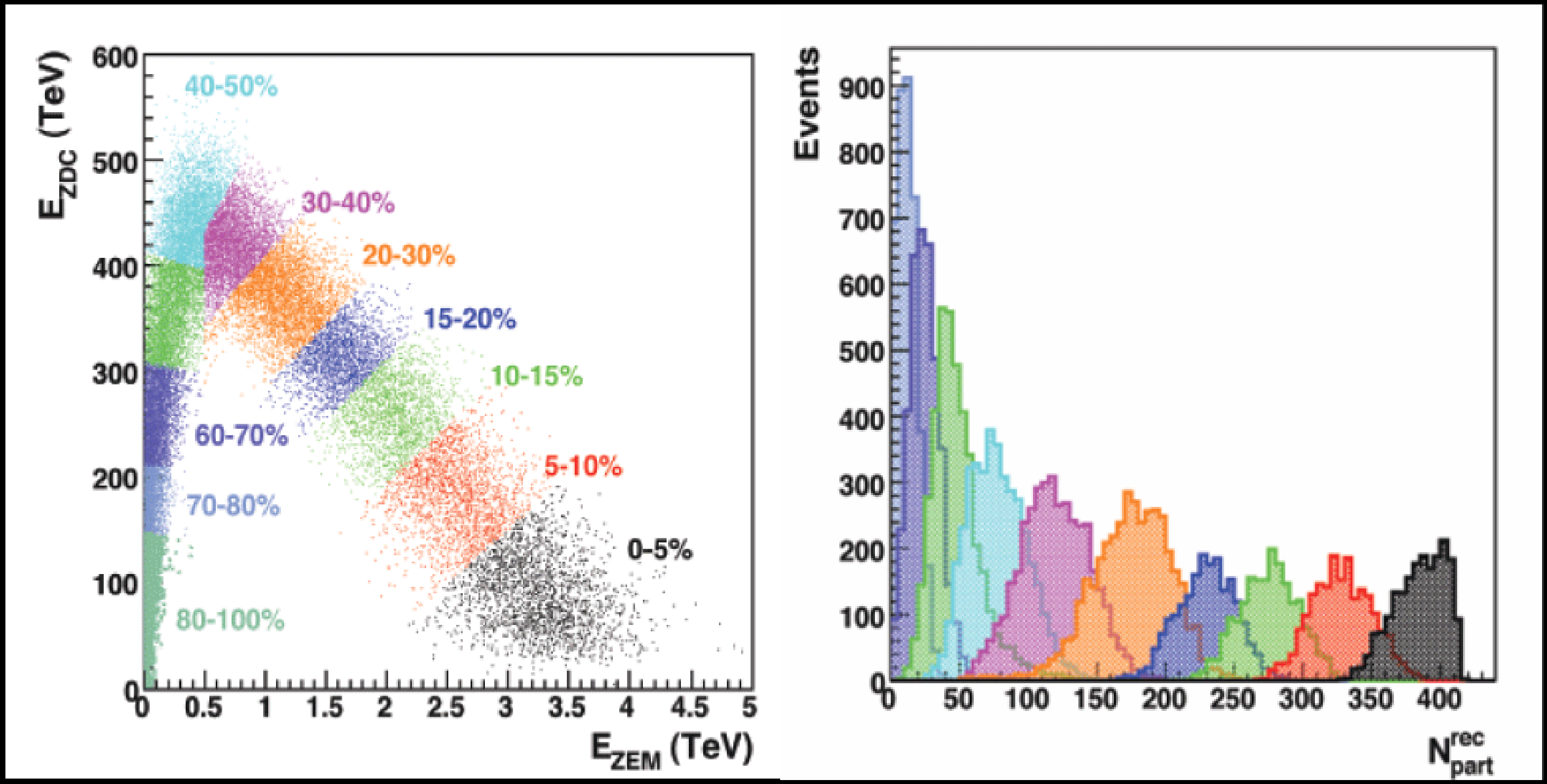
From real-time Level 3 display





- central collisions, small probability
- many particles produced
- no spectators
- impact parameter **b** = 0

Centrality determination in ALICE

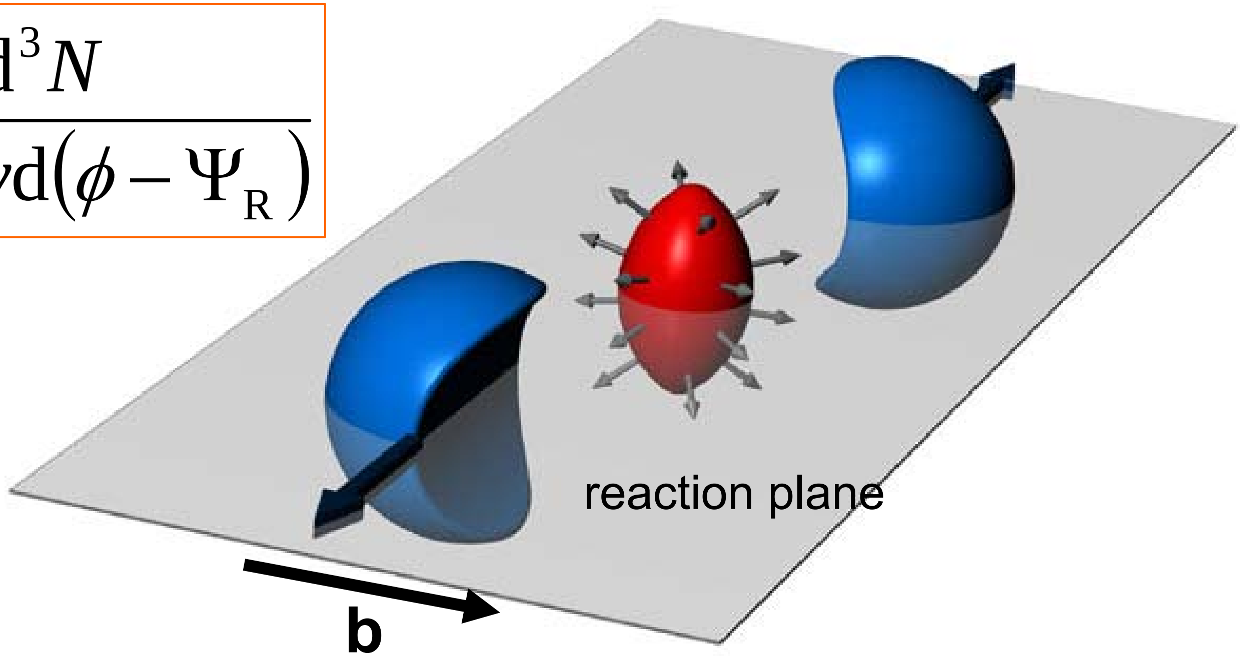


- Allows for a determination of the magnitude of the impact parameter

The reaction plane

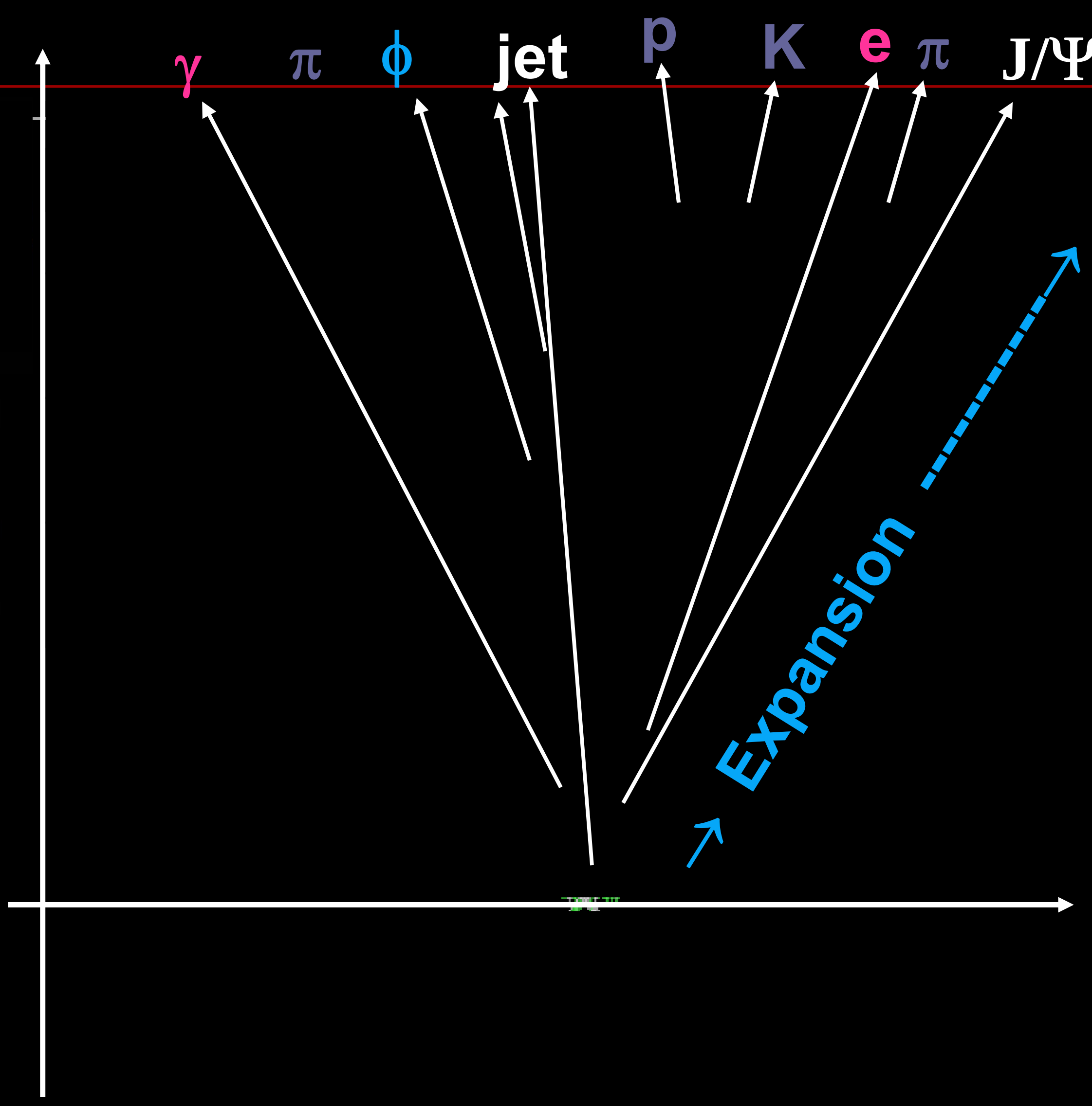
- **The reaction plane**
  - Spanned by the beam direction and the impact parameter **b**

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_t dp_t dy d(\phi - \Psi_R)}$$



The almond shape of the created quark gluon plasma in non-central collisions leads to an azimuthal dependence of the observables sensitive to the medium properties

Schematic Time Evolution



Freeze-out

Hadronization

QGP?

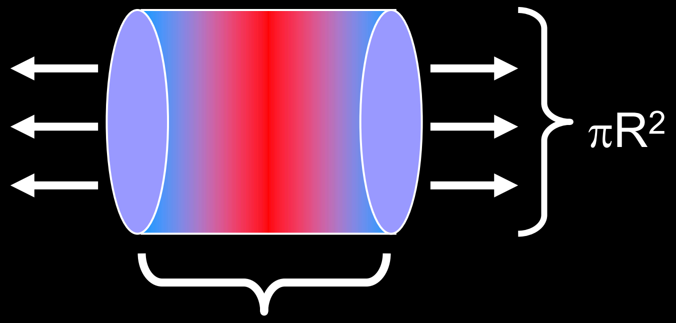
Thermalization?

Hard Scattering

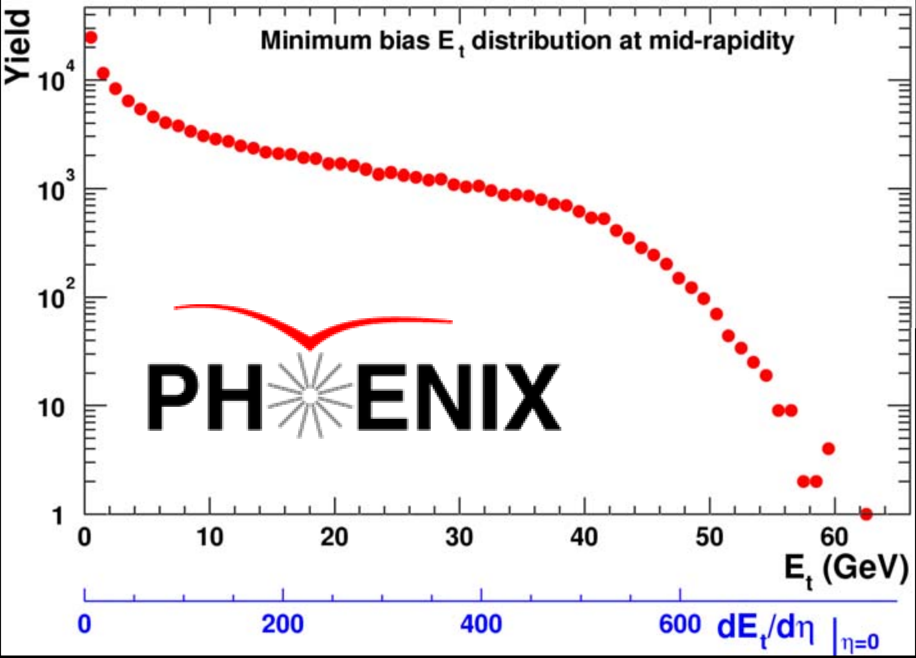
Transverse Energy and Energy Density

- Bjorken energy density estimate

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$



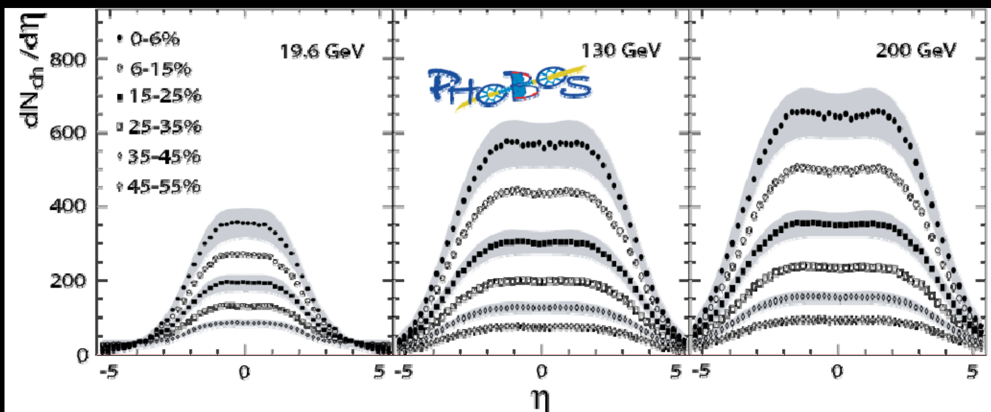
$$\varepsilon_{BJ} = 4.6\, GeV / fm^3$$

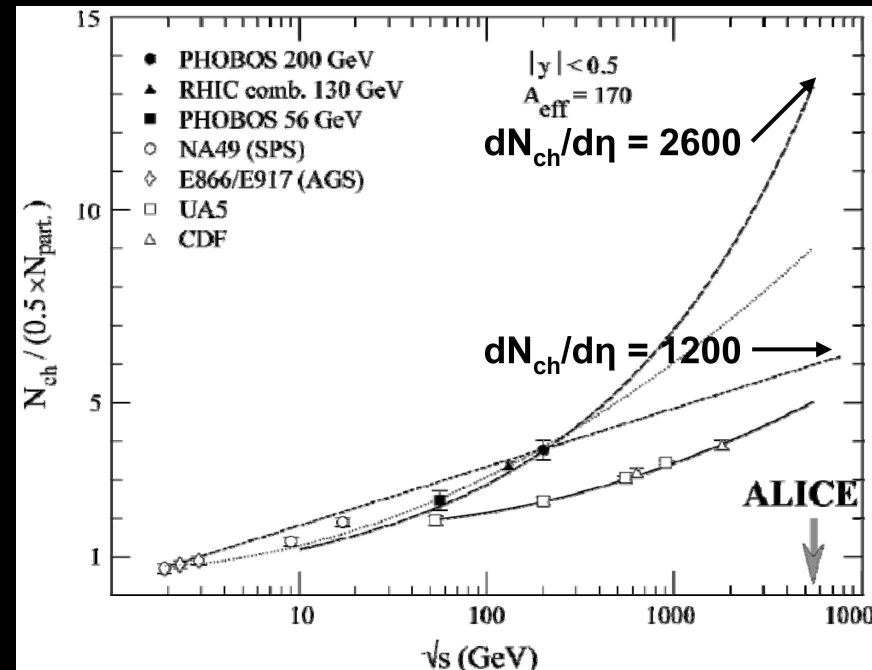


$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2 \text{ GeV (130 GeV)}$$

- Far above the critical energy density

Particle Yields and Energy Density



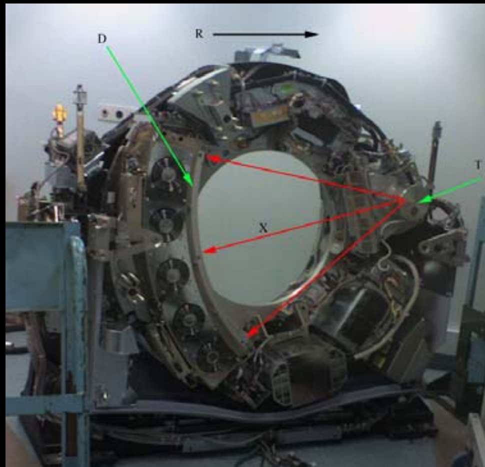


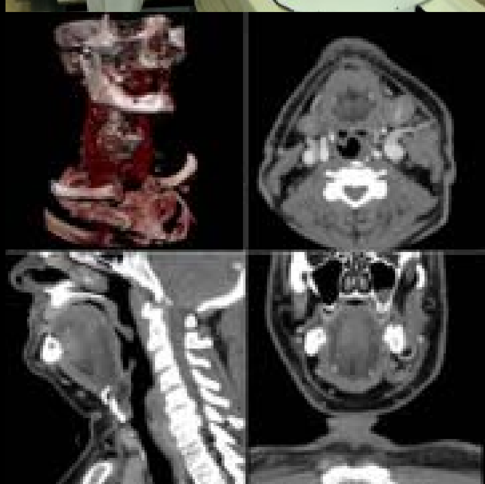
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

$$\frac{dE_T}{dy} = \langle m_T \rangle \frac{3}{2}\frac{dN_{ch}}{dy} \text{ at } y=0; \frac{dN_{ch}}{dy} = \left(1 - \frac{m^2}{\langle m_T \rangle^2}\right)^{-1/2} \frac{dN_{ch}}{d\eta}$$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\langle m_T \rangle \frac{3}{2}\left(1 - \frac{m^2}{\langle m_T \rangle^2}\right)^{-1/2} \frac{dN_{ch}}{d\eta}$$

- Bjorken energy density estimate from charged particle density
- 3-10x increase of ε_{Bj} at the LHC

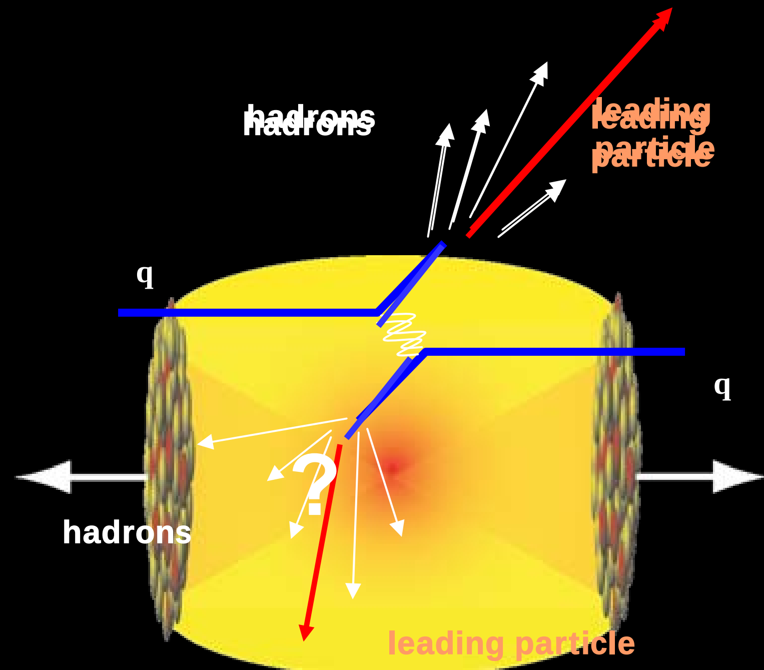




Hard Probes and Gluon Density

- Like to make a snapshot of the early phase of the collision
- Need well calibrated source
- Particles from the source (probes) needs to interact with the medium (in a controlled fashion)

schematic view of jet production



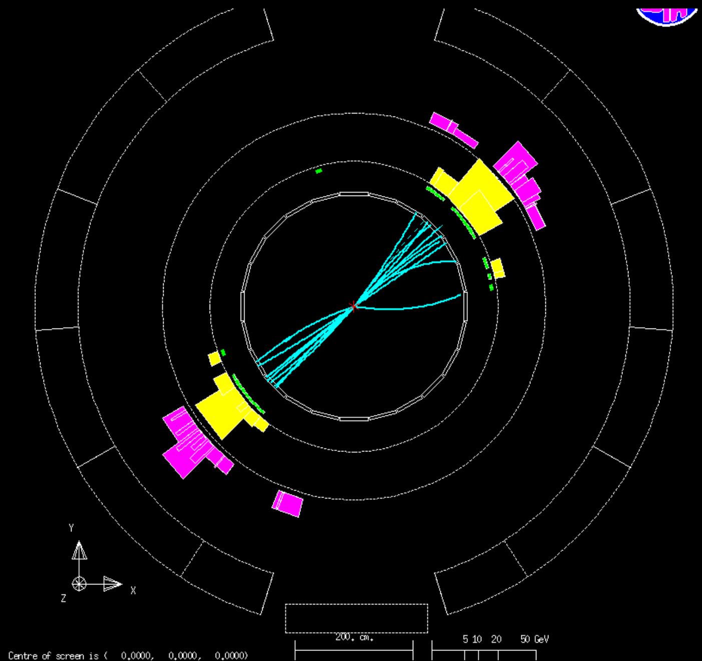
$$\Delta E_{GLV} = C_R \alpha_S^3 \int d\tau \tau \rho_{glue}(\tau, r(\tau)) Log\left(\frac{2E_{jet}}{\mu^2 L}\right)$$

$$\Delta E_{BDMS} = \frac{C_R \alpha_s}{4} \hat{q} L^2 \tilde{v}$$

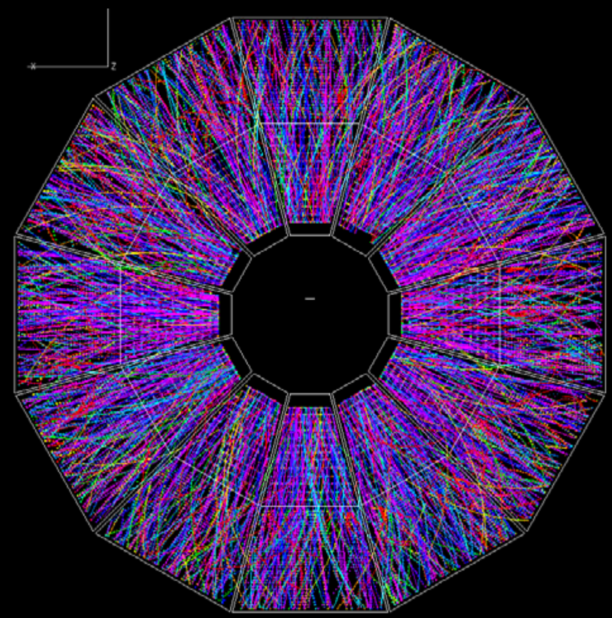
$$\hat{q} = \frac{\mu_{Debye}^2}{\lambda_{glue}} \propto \alpha_S \rho_{glue}$$

Jets in a heavy-ion environment

Jets in e^+e^-



Jets from Au + Au at 200 GeV

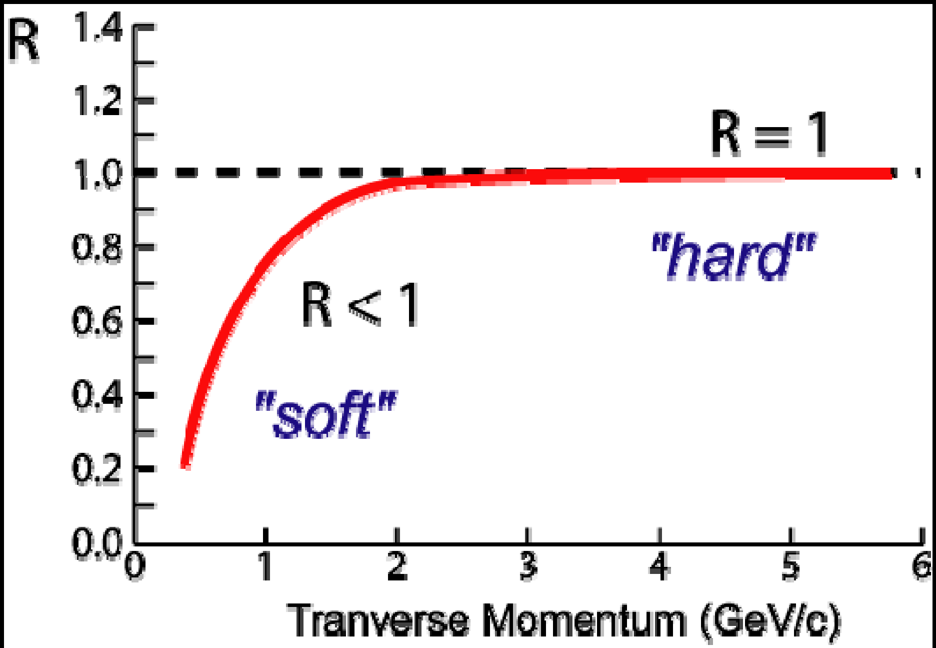


- Heavy ion collisions are a complicated environment to do full jet reconstruction

Construct simple observables

- We measure: Yield(p_t) in AA and nucleon-nucleon
- Create Ratio:

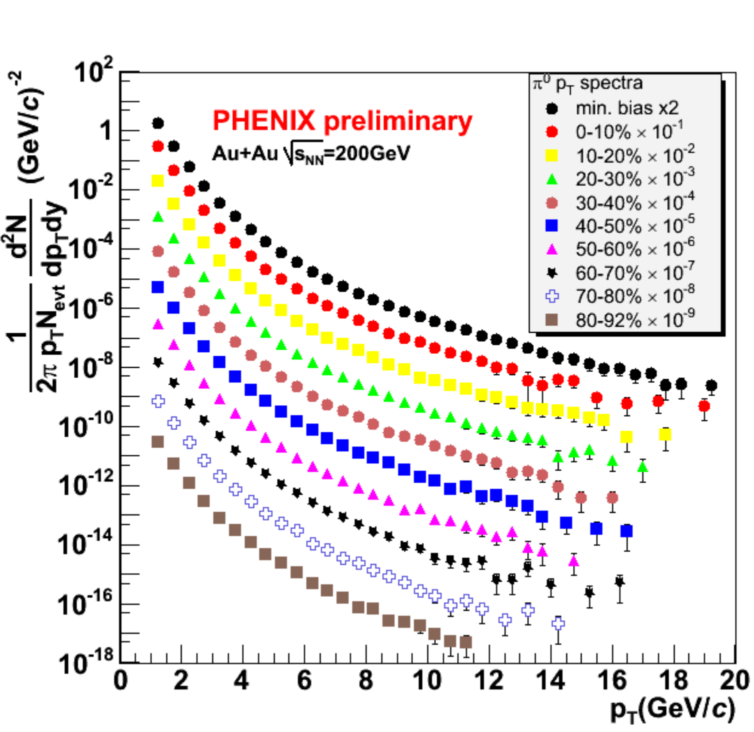
$$R(p_t) = \frac{Yield_{Au+Au} / \langle N_{bin} \rangle}{Yield_{nucleon-nucleon}}$$

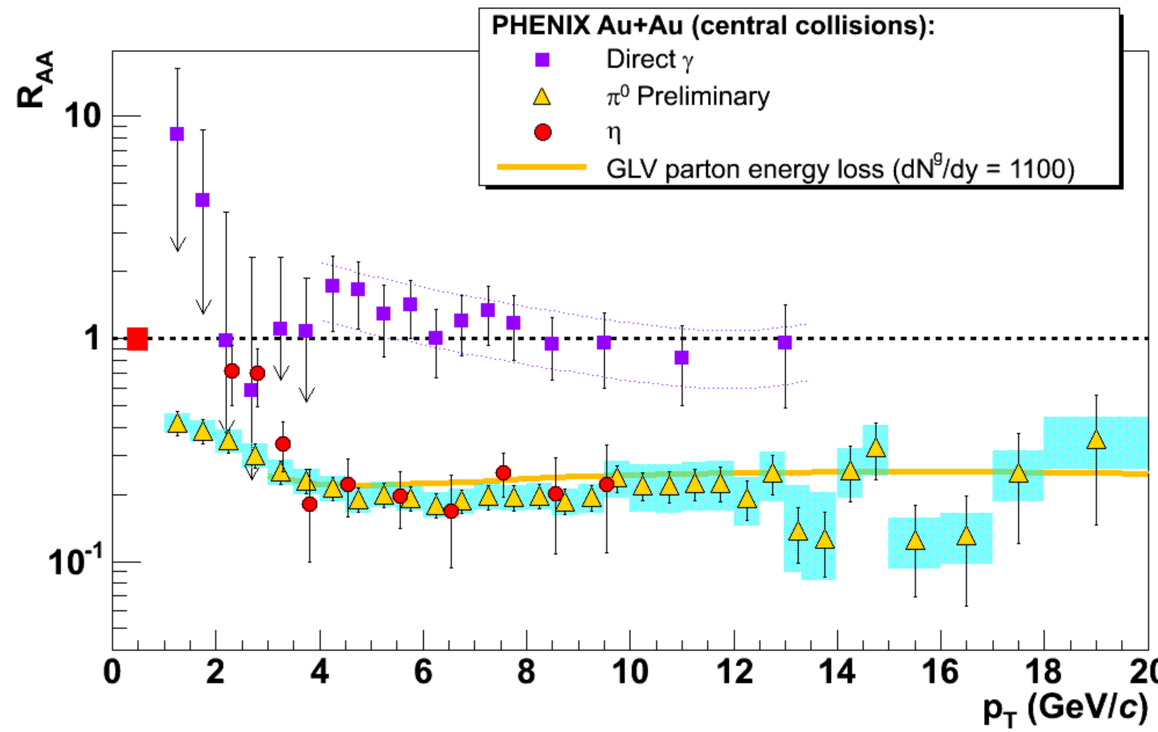


If no “nuclear effects”:
- R < 1 in regime of soft physics
- R = 1 at high-p_t where hard scattering dominates

Suppression:
- R < 1 at high-p_t

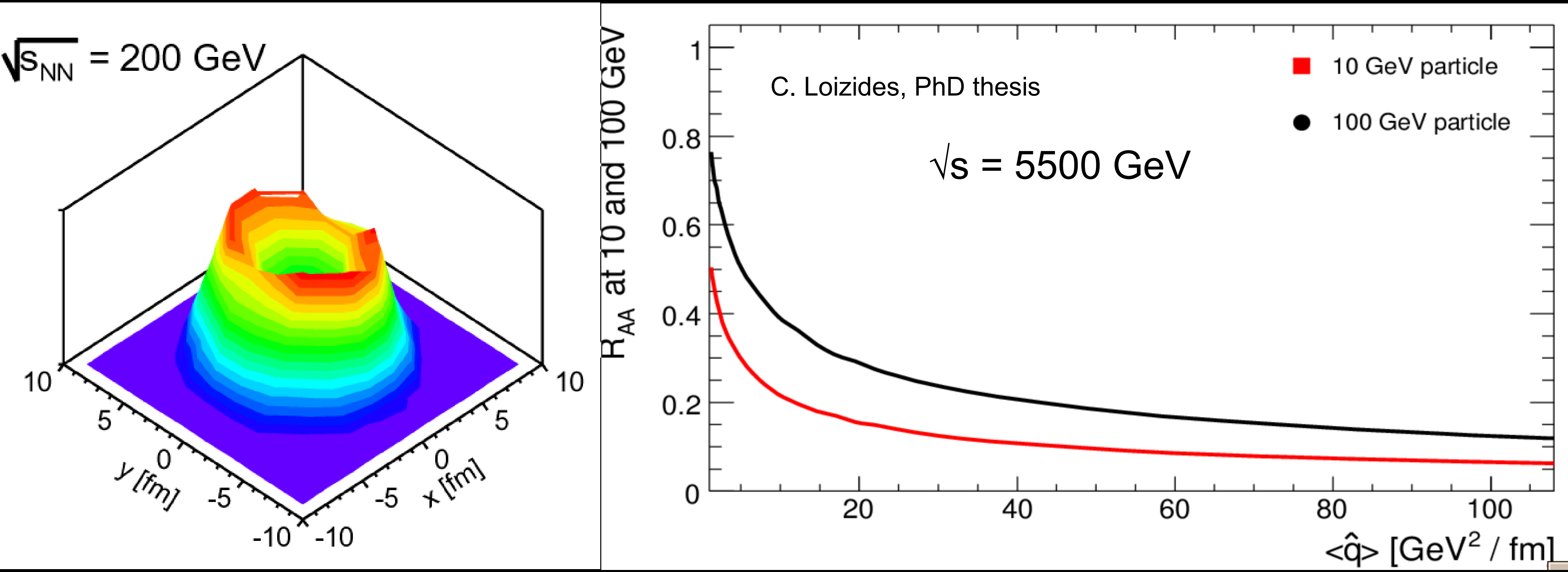
R_{AA} at RHIC





- One of the important RHIC discoveries: strong suppression of high-p_t particles

R_{AA} at RHIC and at the LHC

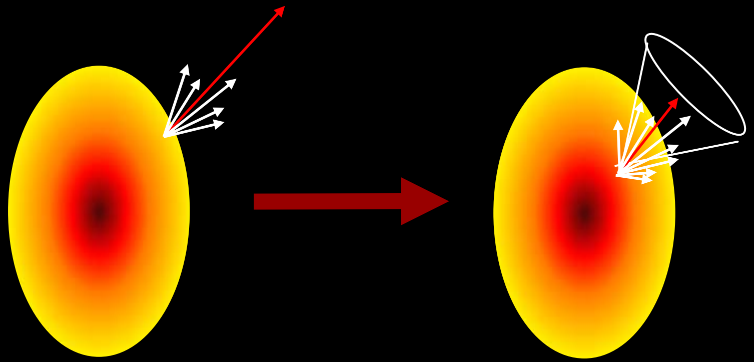


A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C38(2005) 461

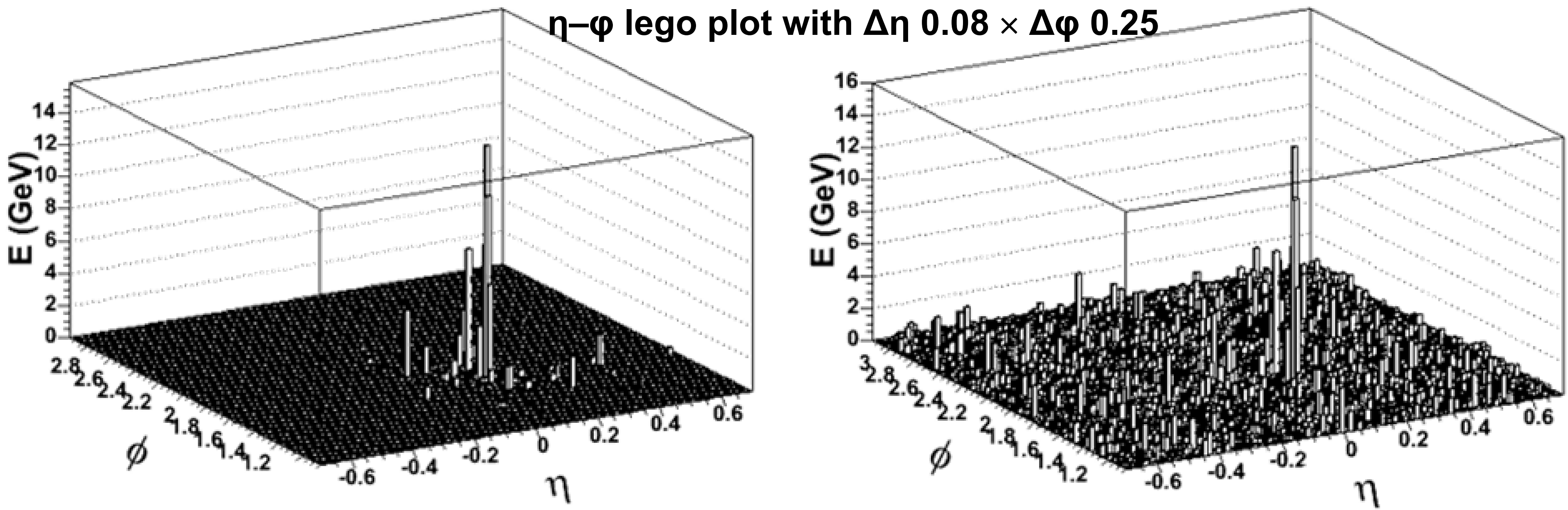
- R_{AA} at RHIC: very strong jet quenching lead to strong surface bias
- R_{AA} at the LHC also rather insensitive to the density of the medium

Less biased jet modifications

- Fully reconstructed jets
  - modification of the leading hadron
  - additional hadrons from gluon radiation
  - transverse heating



η–φ lego plot with Δη 0.08 × Δφ 0.25



Jets at the LHC

- At LHC jet rates are high at energies at which jets can be reconstructed over the large background from the underlying event
- More than 1 jet > 20 GeV per central collision (more than 100 > 2 GeV!)
- Reach to about 200 GeV
- Provides lever arm to measure the energy dependence of the medium induced energy loss

1 month of running	
$E_T >$	N_{jets}
50 GeV	2.0×10^7
100 GeV	1.1×10^6
150 GeV	1.6×10^5
200 GeV	4.0×10^4

penetrading probes: γ-jet and heavy quarks

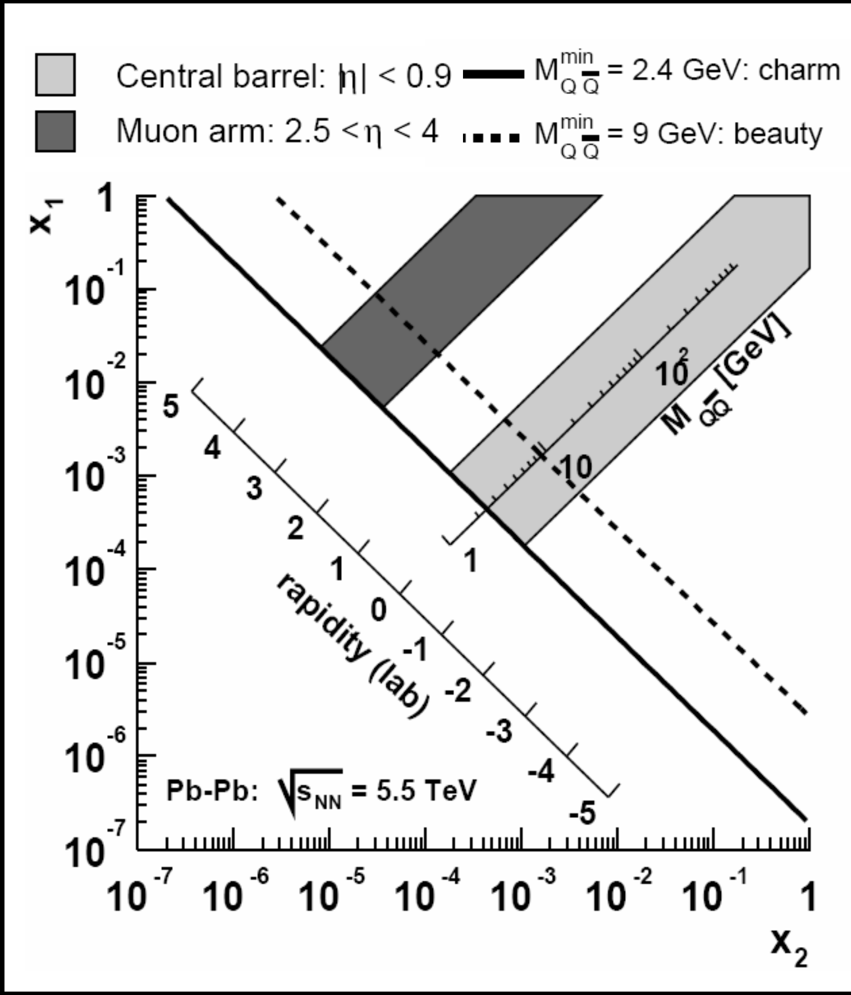
	SPS PbPb Cent	RHIC AuAu Cent	LHC pp	LHC pPb	**LHC PbPb Cent**
N_{cc}/evt	0.2	10	0.2	1	**115**
N_{bb}/evt	-	0.05	0.007	0.03	**5**

- produced early and calculable: $\tau \propto 1/m_C$
- Relatively long lifetime: $\tau_{decay} \gg \tau_{QGP}$
- detailed test of parton energy loss
  - dead cone effect

Probability:

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

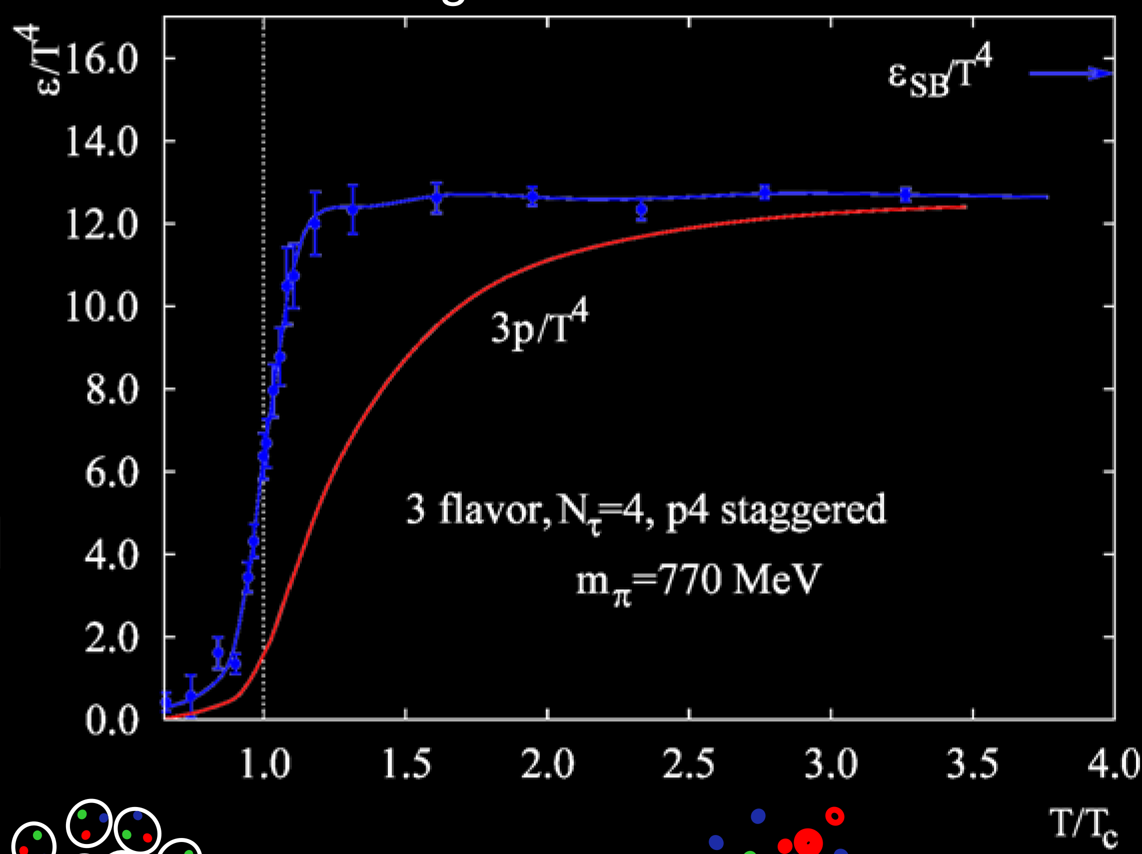
  - In medium dead cone implies less energy loss
- probes small x_{Bj} (10^{-3} – 10^{-5})

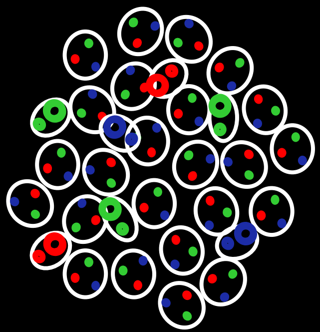


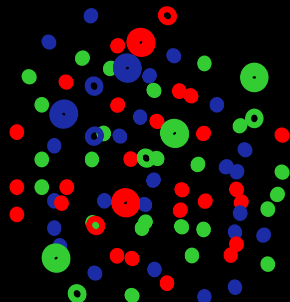
Thermalization and the Equation of State

- Is the created system approximately thermalized and can we make a connection to Lattice QCD calculations and learn about the EoS?

ε/T^4 ~ # degrees of freedom







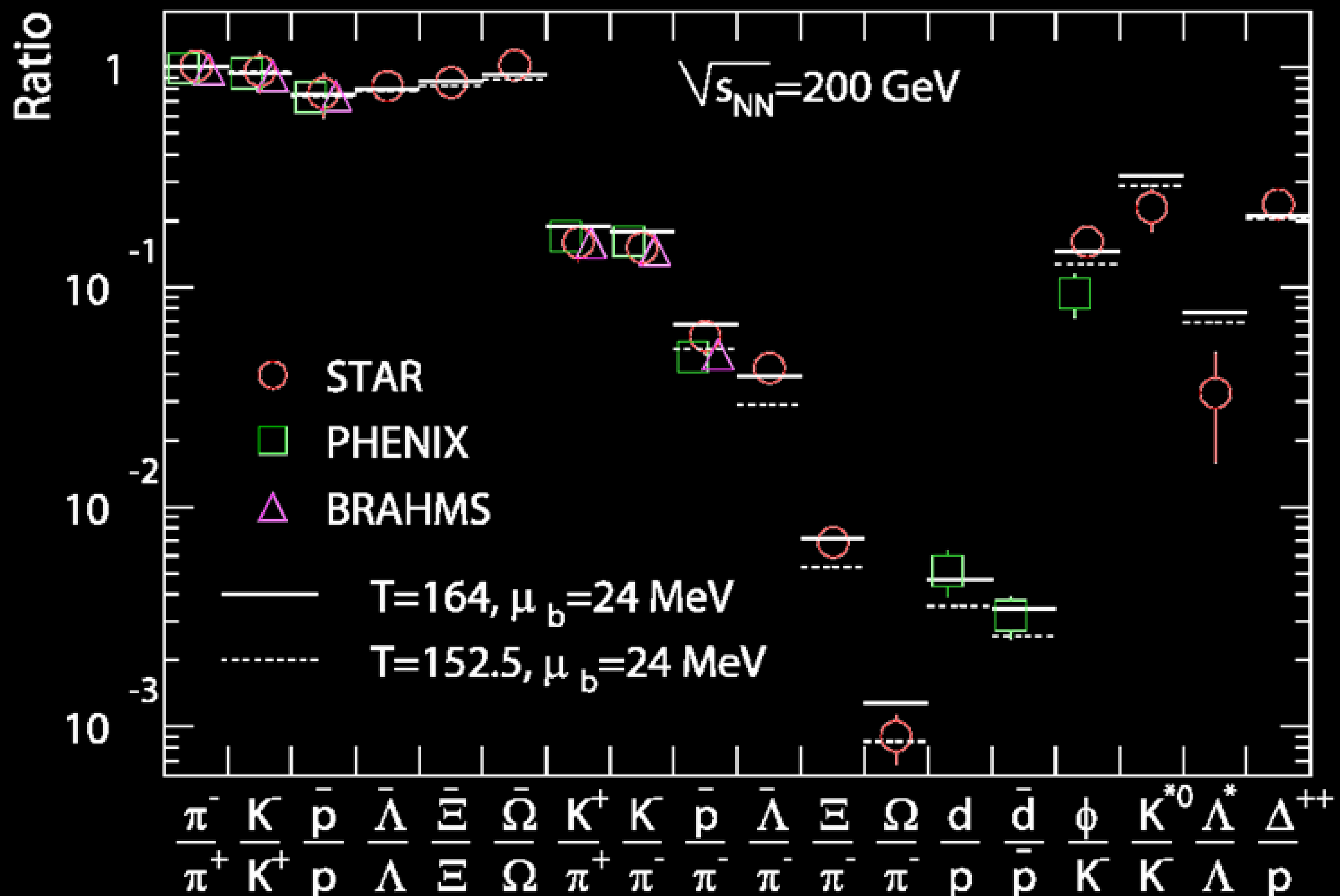
Thermal Model

- Assume chemically equilibrated system at freeze-out (constant T_{ch} and μ)
- Composed of non-interacting hadrons and resonances
- Given T_{ch} and μ 's, particle abundances (n_i's) can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

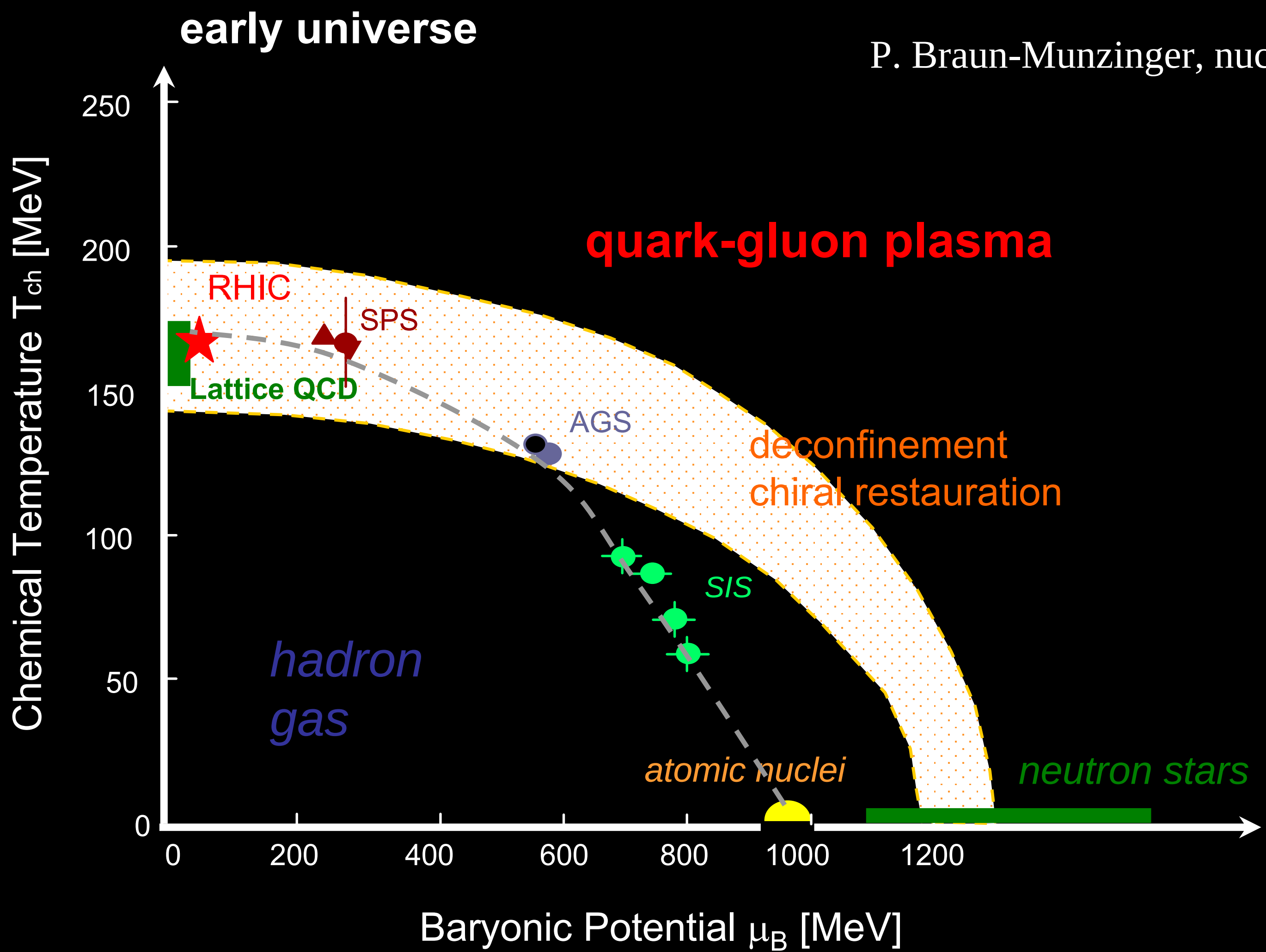
Integrated identified particle yields



- Thermal model fits rather well
- Works rather well in proton-proton collisions as well !?

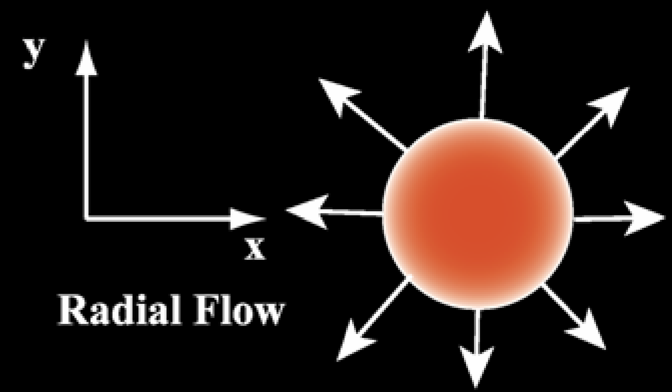
The phase diagram revisited

P. Braun-Munzinger, nucl-ex/0007021



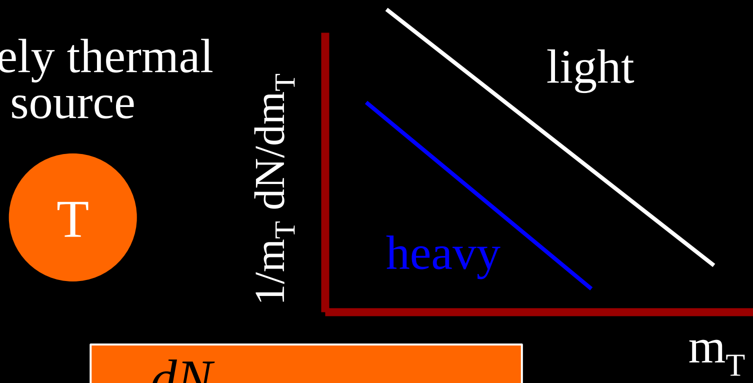
Collective Motion

- Only type of transverse flow in central collision (b=0) is transverse flow.
- Integrates pressure history over complete expansion phase

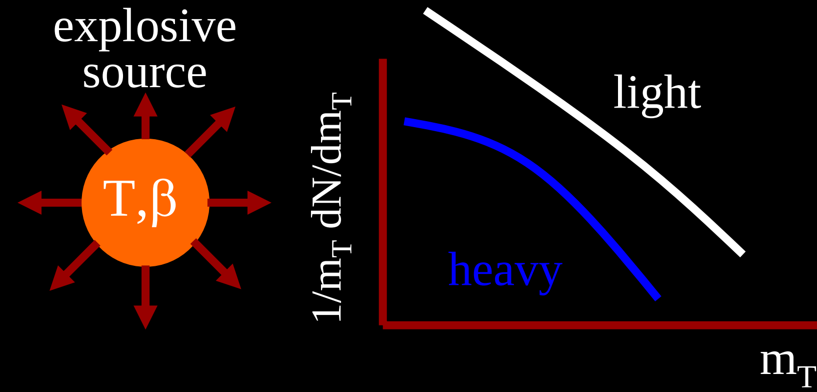


Identified Particle Spectra

purely thermal source

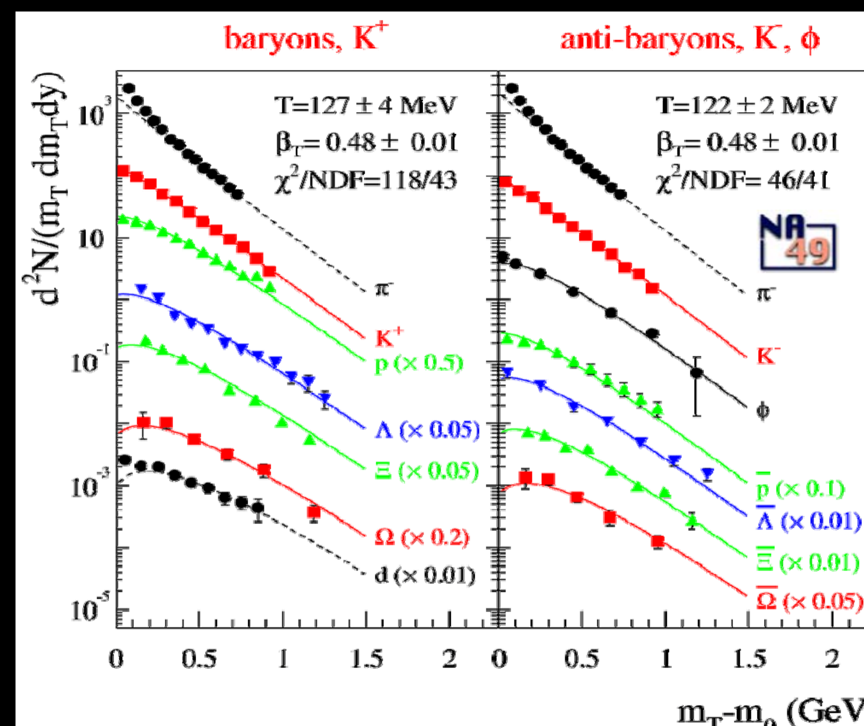


explosive source

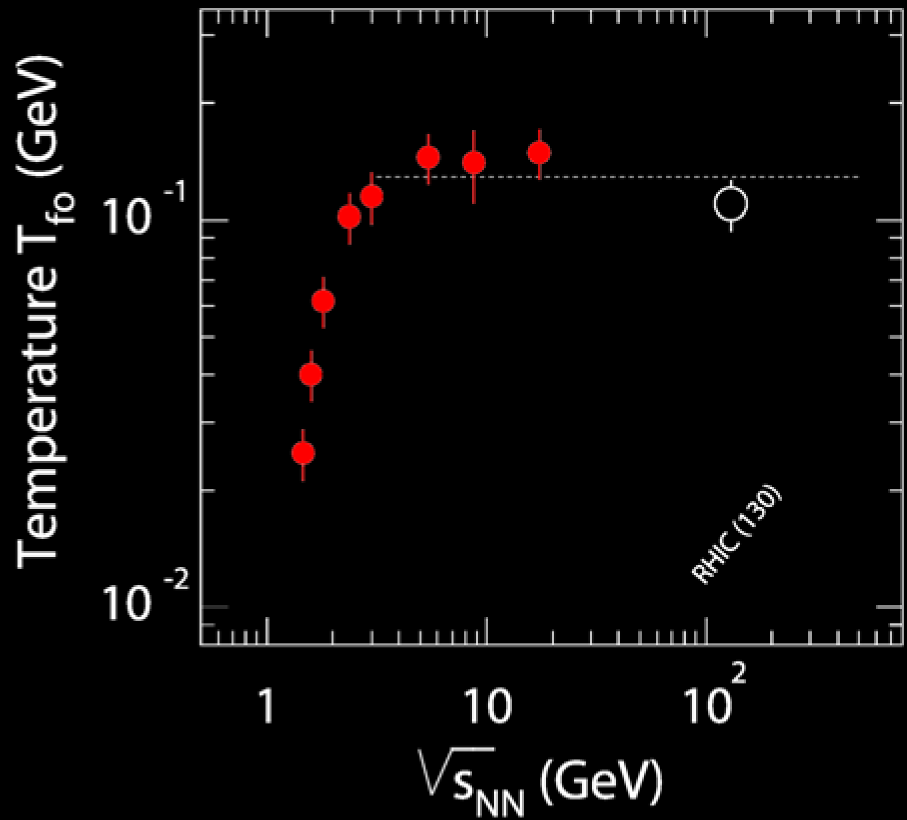


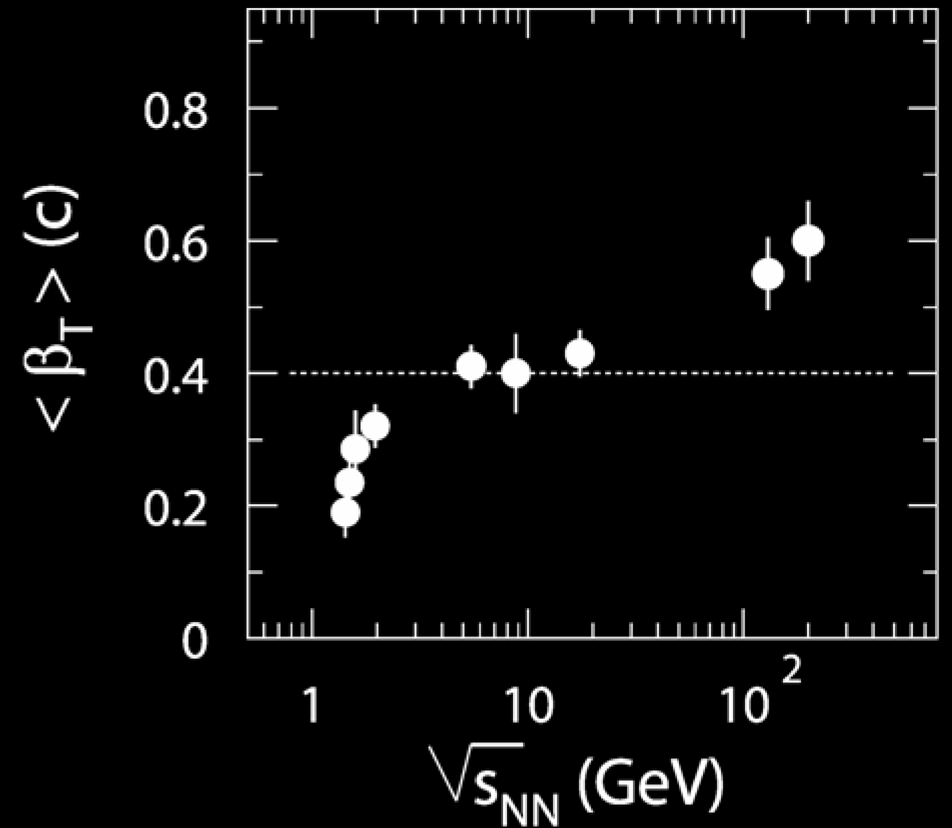
$$\frac{dN}{m_T\, dm_T} \propto m_T\, e^{-m_T/T}$$

- Boosted thermal spectra give a very good description of the particle distributions measured in heavy-ion collisions



Temperature and Flow

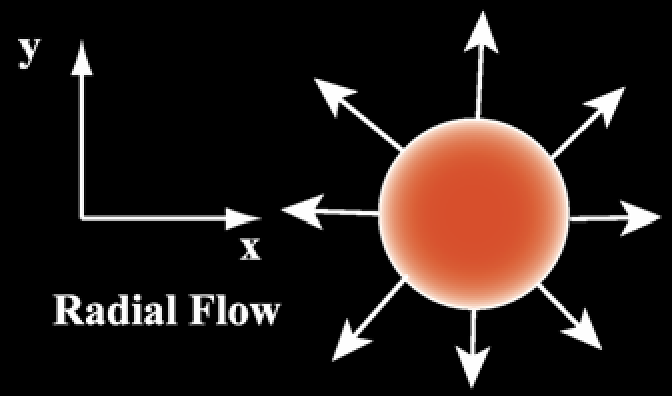




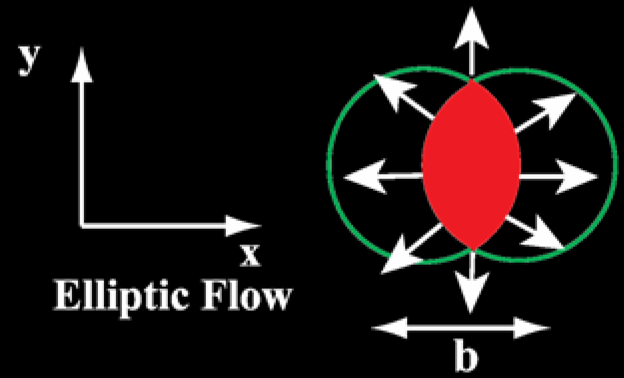
- Strong collective motion, particularly at RHIC energies

Collective Motion

- Only type of transverse flow in central collision (b=0) is transverse flow.
- Integrates pressure history over complete expansion phase



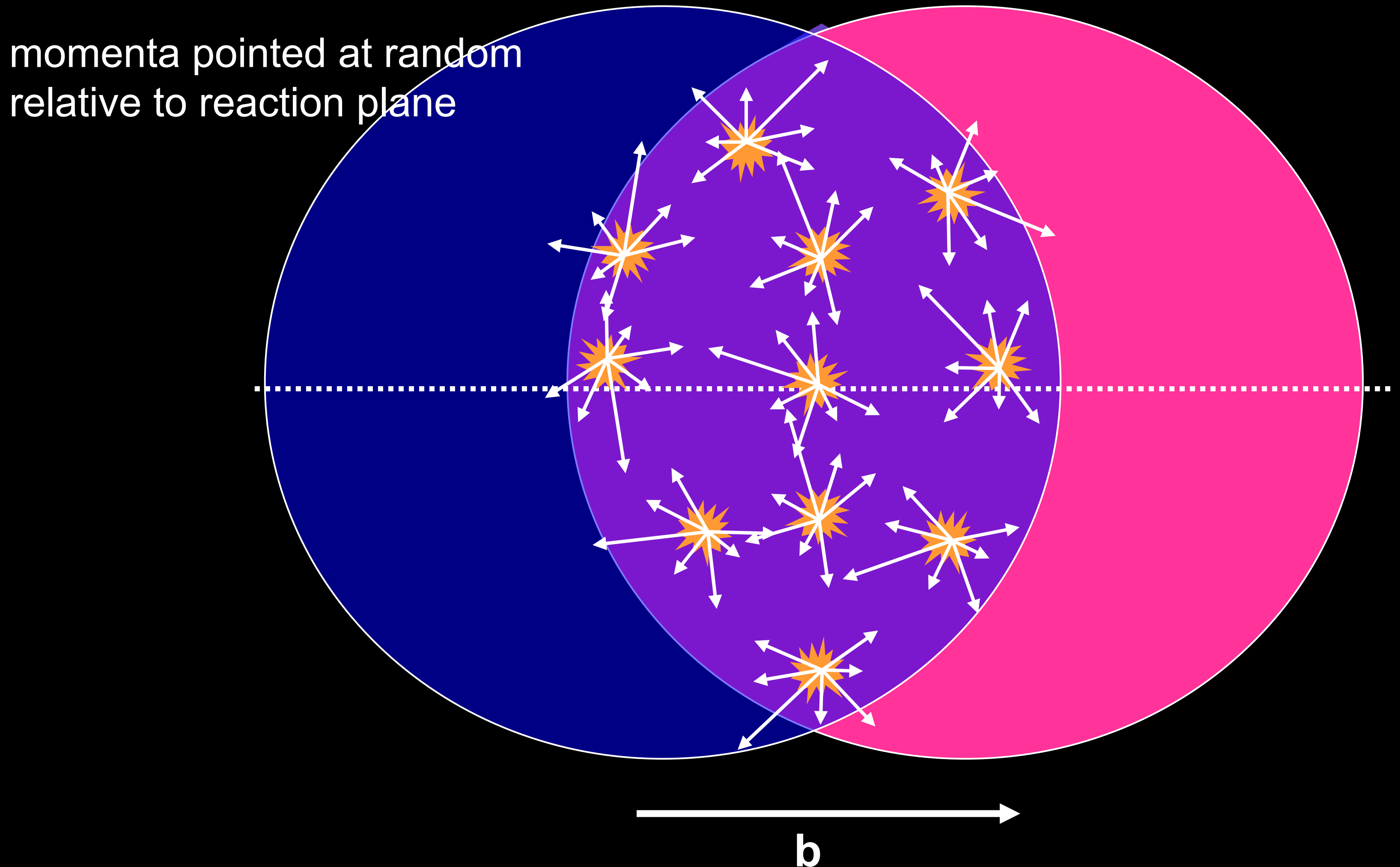
- Elliptic flow, caused by anisotropic initial overlap region (b > 0)
- More weight towards early stage of expansion (the QGP phase)



Forming a system and thermalizing

Animation: Mike Lisa

1) Superposition of independent p+p:

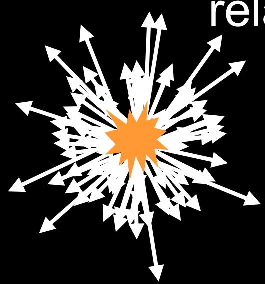


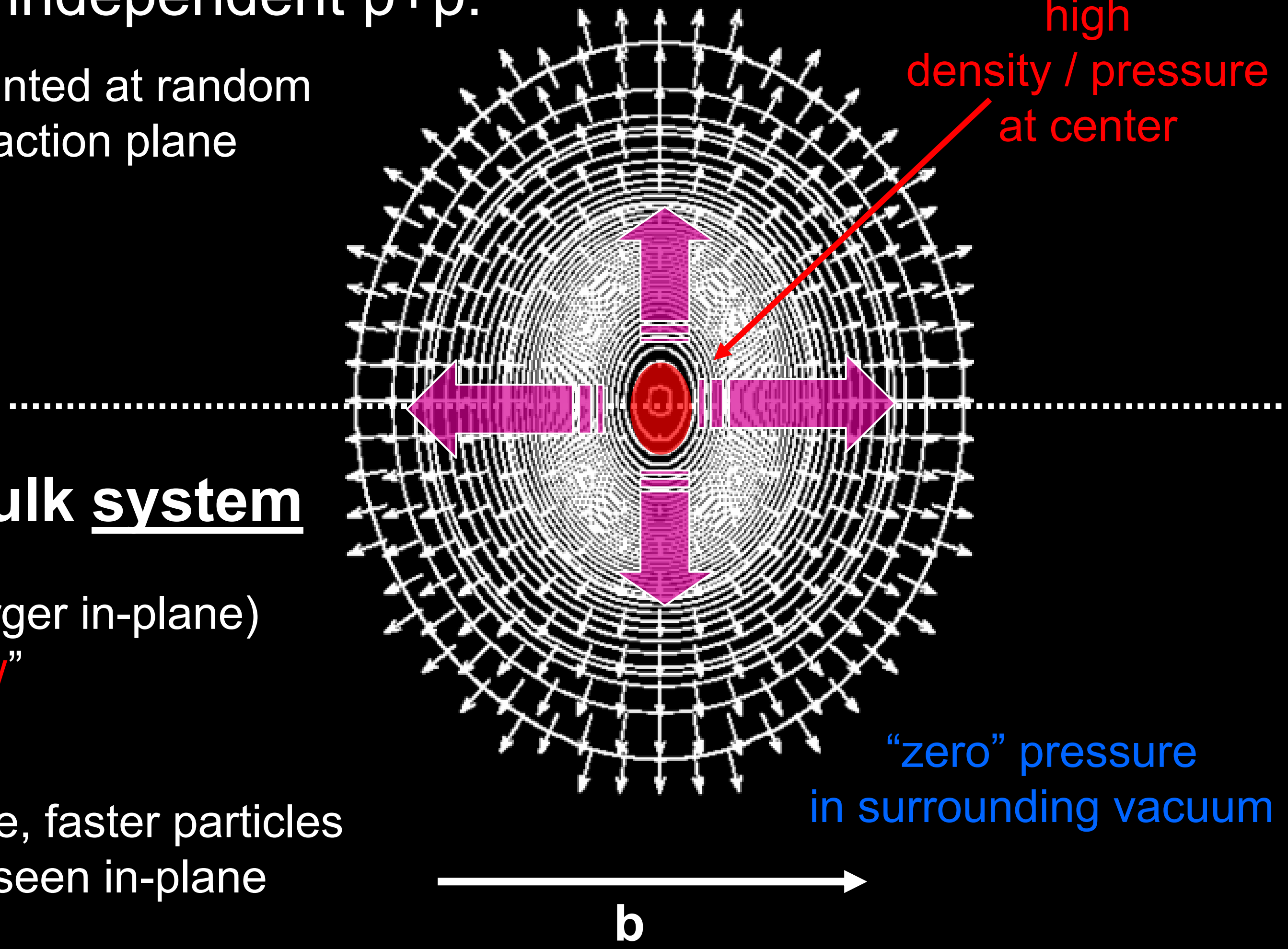
Forming a system and thermalizing

Animation: Mike Lisa

1) Superposition of independent p+p:

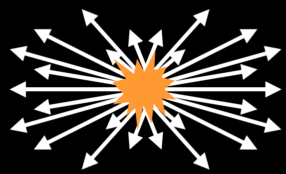
momenta pointed at random
relative to reaction plane





2) Evolution as a **bulk <u>system</u>**

Pressure gradients (larger in-plane)
push bulk "out" → "flow"

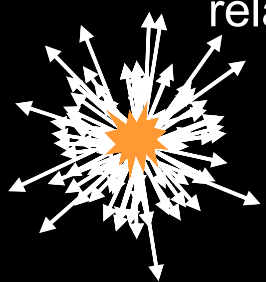


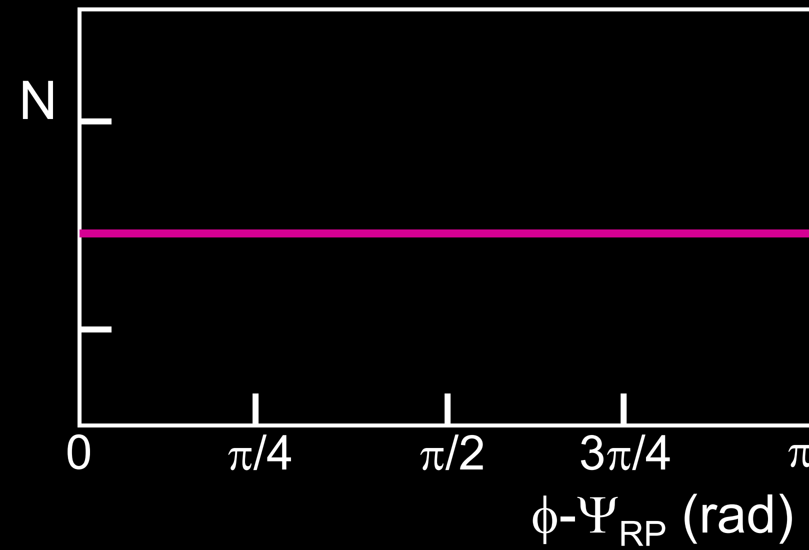
more, faster particles
seen in-plane

How does the system evolve?

1) Superposition of independent p+p:

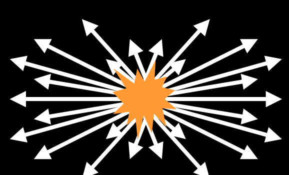
momenta pointed at random relative to reaction plane



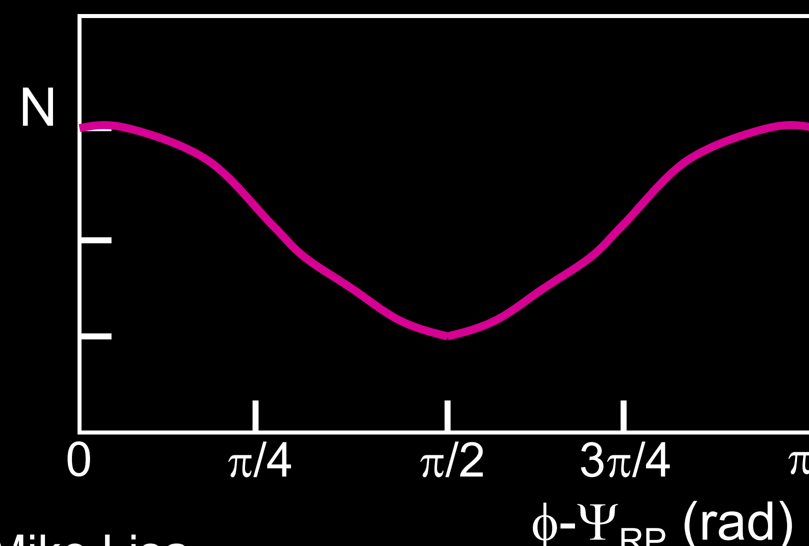


2) Evolution as a **bulk** **<u>system</u>**

Pressure gradients (larger in-plane) push bulk “out” → “flow”

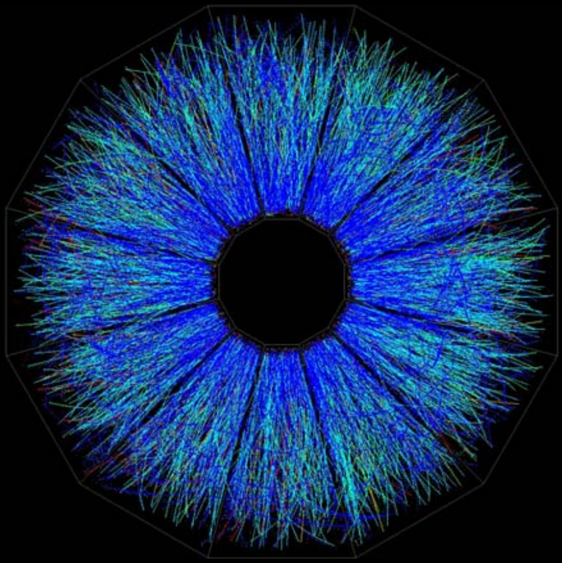


more, faster particles seen in-plane

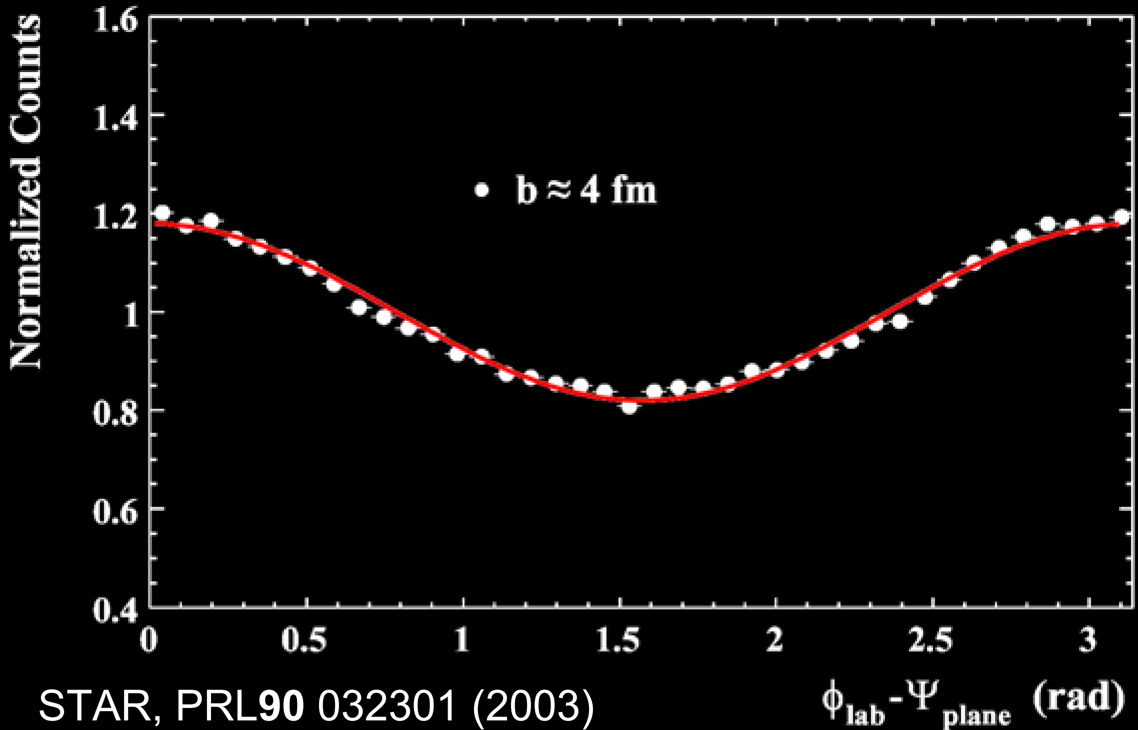


Animation: Mike Lisa

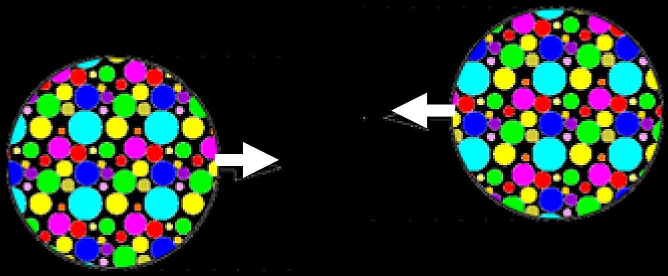
Measurements in STAR at RHIC

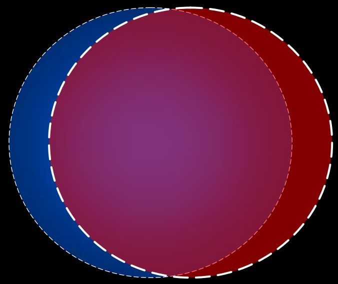


"central" collision



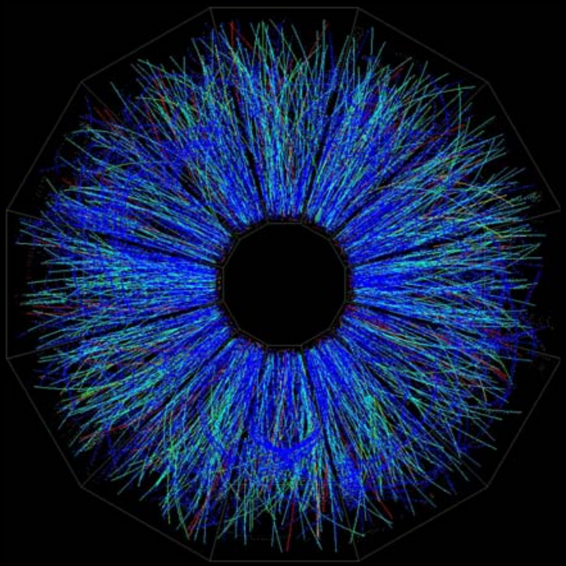
STAR, PRL**90** 032301 (2003)



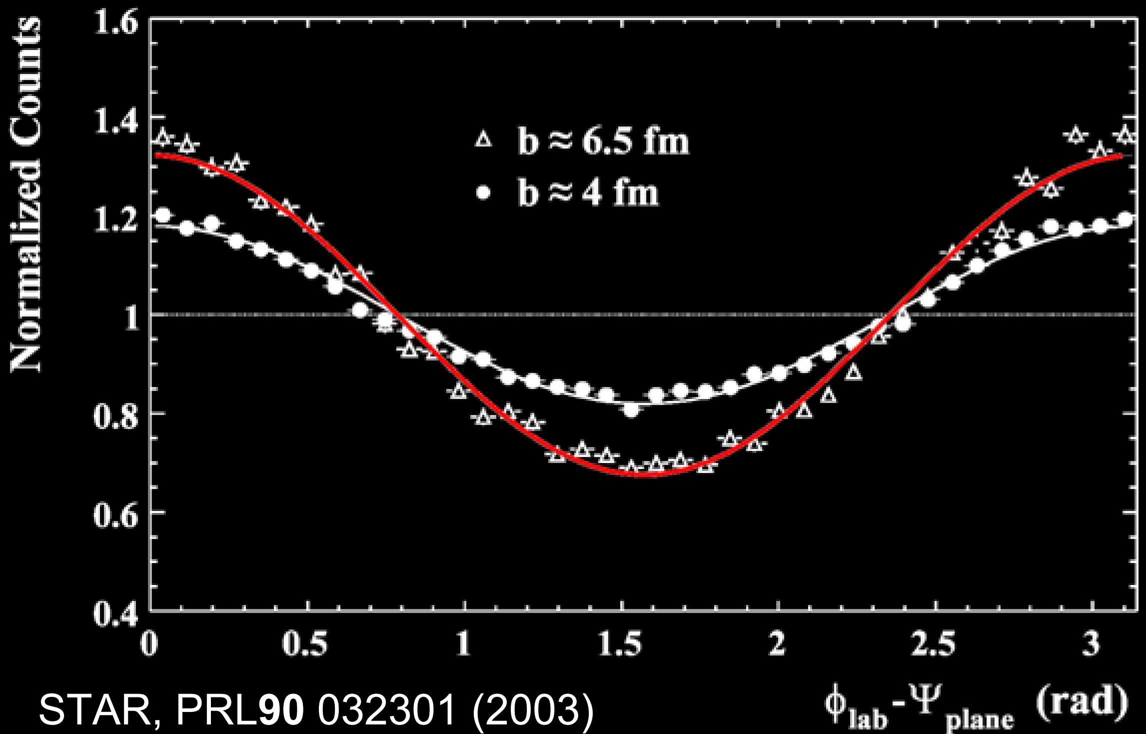


Raimond.Snellings@nikhef.nl

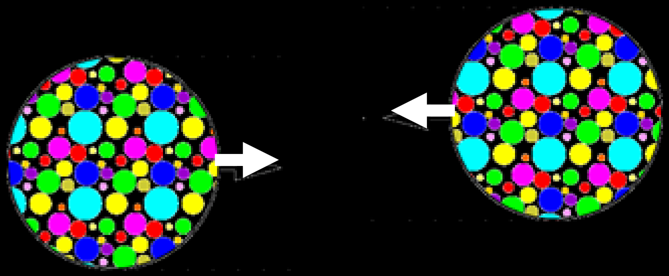
Measurements in STAR at RHIC

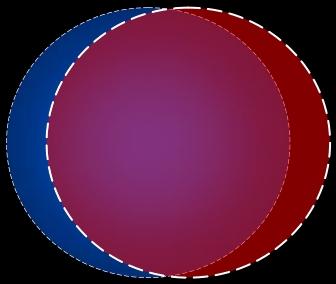


“mid-central” collision

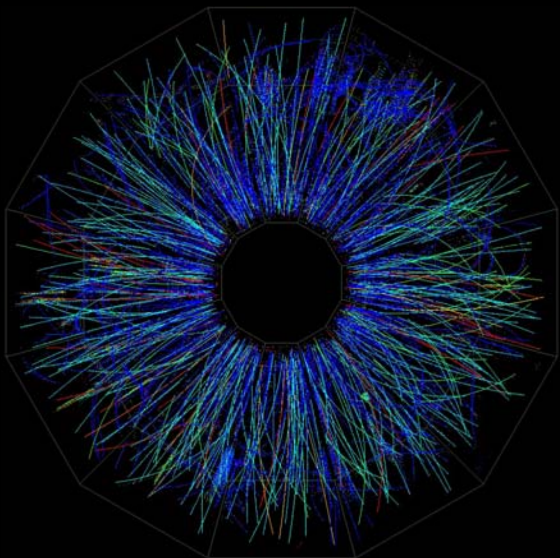


STAR, PRL**90** 032301 (2003)

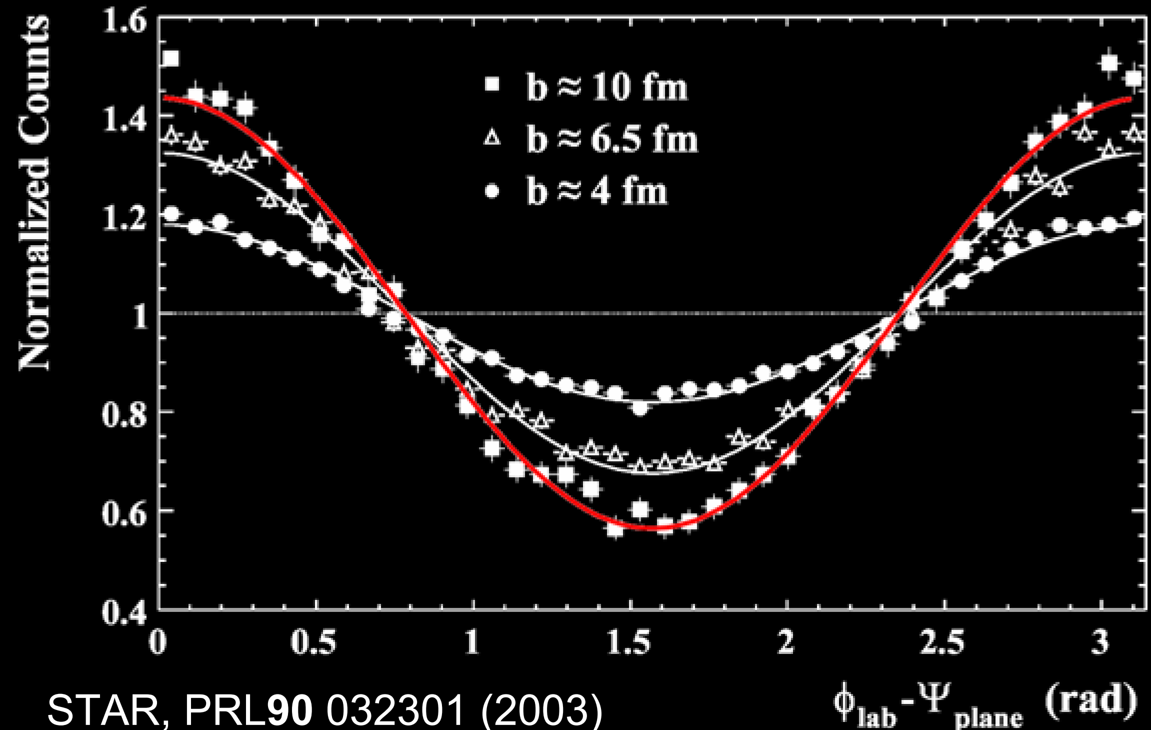




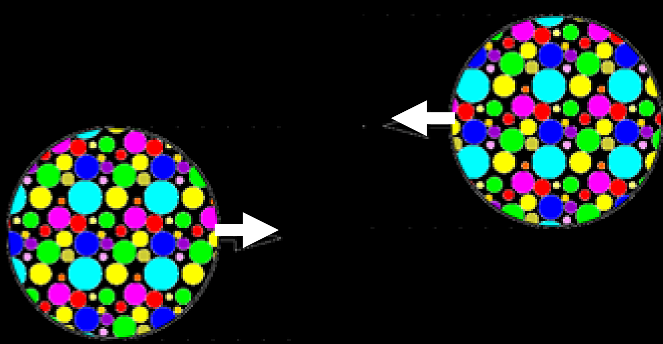
Measurements in STAR at RHIC

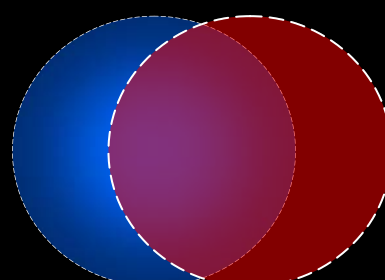


"peripheral" collision



STAR, PRL**90** 032301 (2003)





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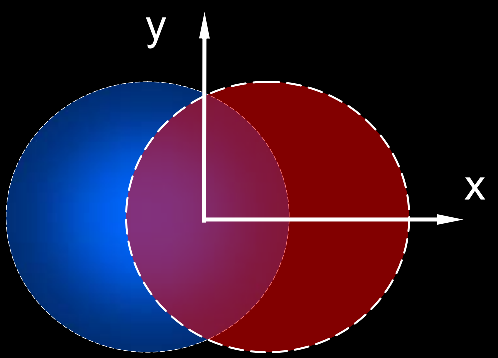
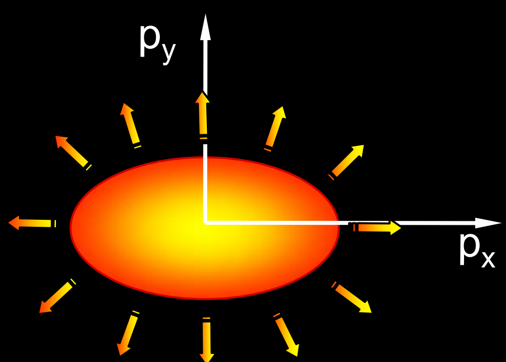
elliptic flow an unique probe!

coordinate space



Momentum space

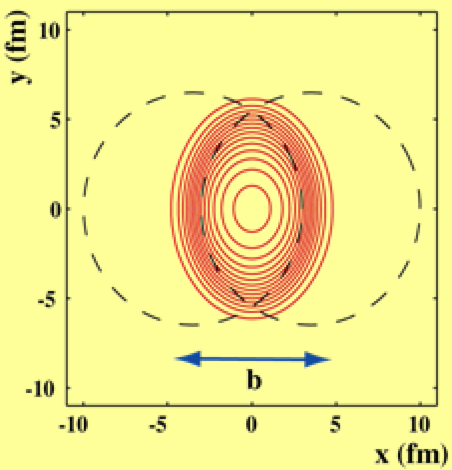


- Non central collisions coordinate space configuration anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric).
- Only interactions among constituents (mean free path small) generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy
- Multiple interactions lead to thermalization -> limiting behavior hydrodynamic flow

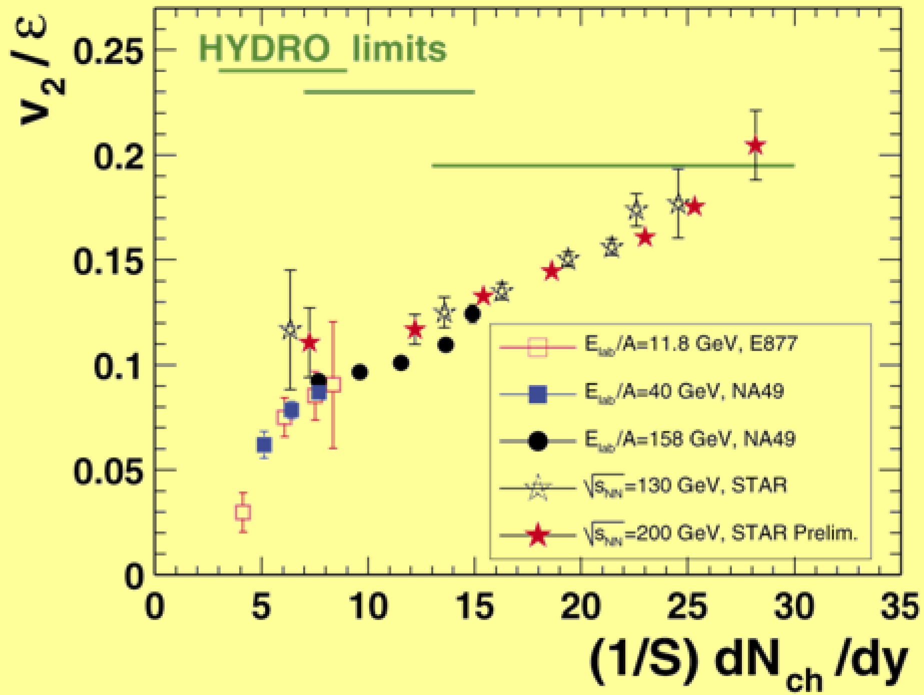
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+2\sum_{n=1}^{\infty} v_n(p_t,y)\cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

$$v_2 = \left\langle \cos 2(\varphi-\Psi_r)\right\rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Energy dependence of flow



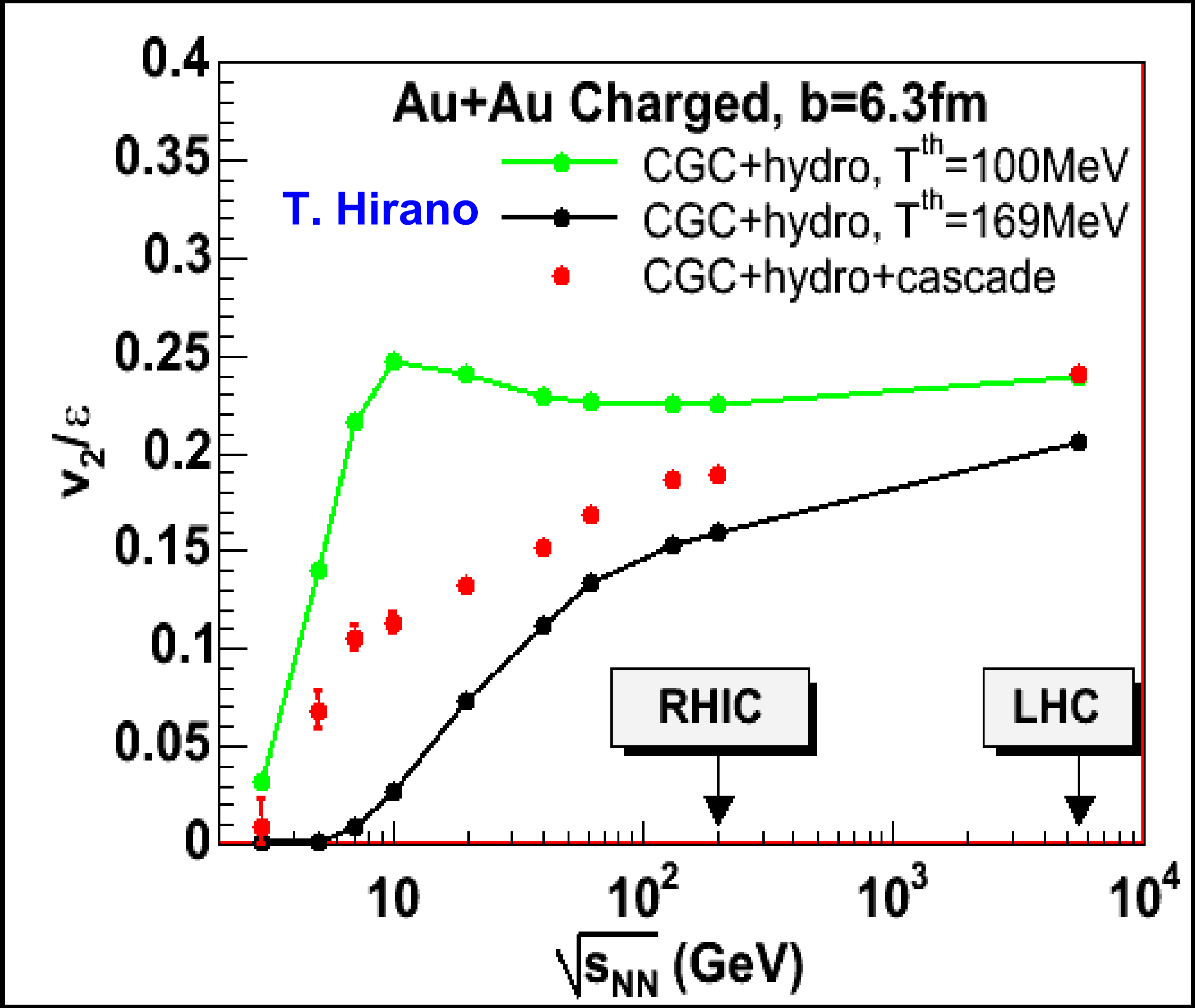
$$\varepsilon \equiv \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



- At RHIC observed flow for the first time consistent with ideal hydrodynamics!!
- Understood in terms of strongly interacting quark gluon plasma with small viscosity – the almost perfect liquid
- Connection to AdS/CFT calculations of viscosity
- See for more details Jamie Nagle's presentation

Elliptic flow at the LHC

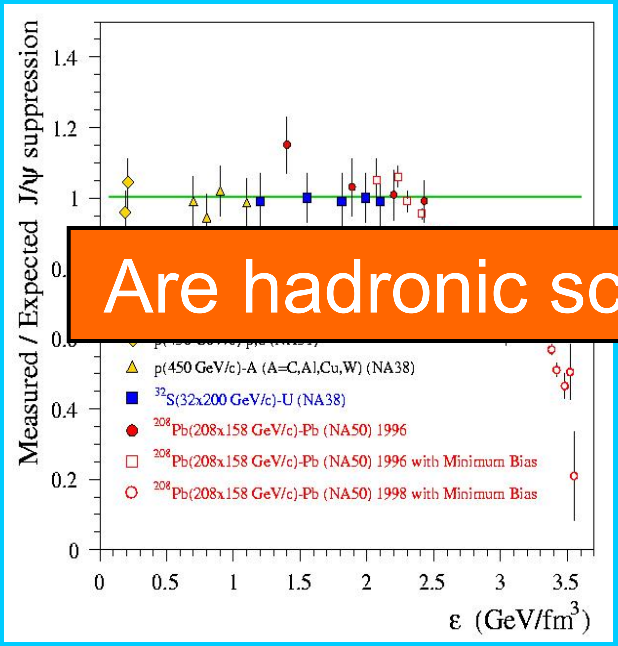
- At RHIC the elliptic flow is completely dominated by the partonic phase!

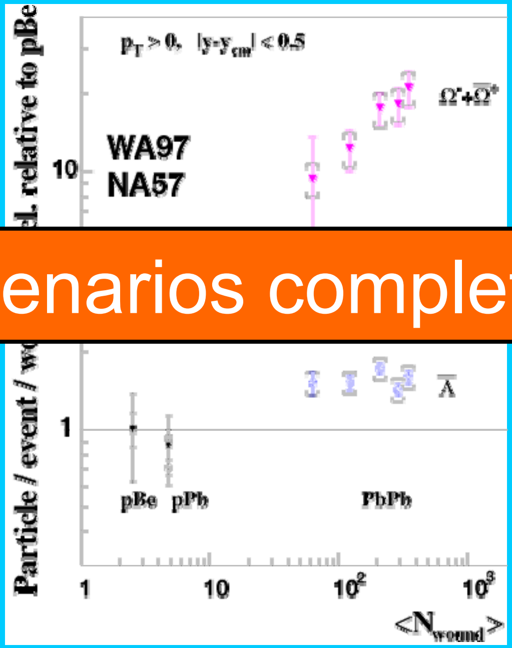


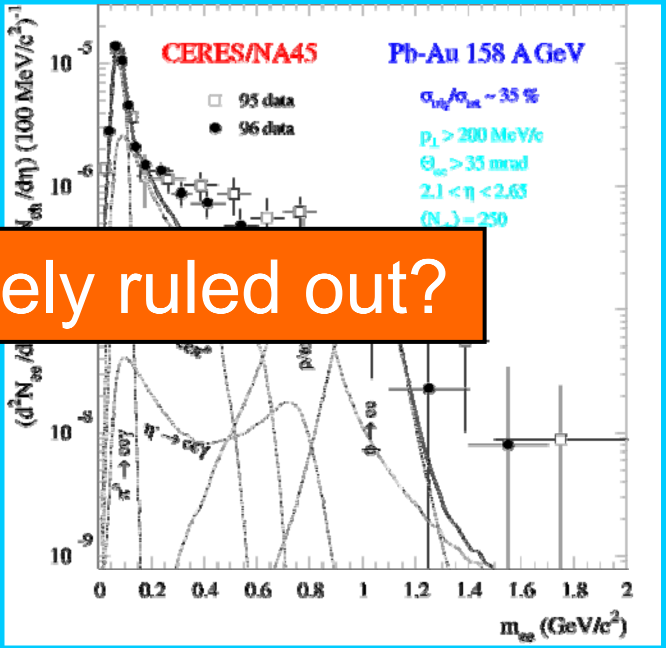
From SPS, RHIC to the LHC

- SPS
  - Observed many of the signatures predicted for QGP formation
  - New state of matter

CERN SPS, a new state of matter







Are hadronic scenarios completely ruled out?

- J/Ψ suppression indication of deconfinement?
  - J/Ψ loosely bound system melts in QGP due to debeye screening
- Strangeness enhancement
  - Mass of strange quark decreases in QGP therefore easier to produce
- Melting of the ρ
  - If ρ decays in QGP medium its mass is modified

From SPS, RHIC to the LHC

- SPS
  - Observed many of the signatures predicted for QGP formation
  - New state of matter
- RHIC
  - Large collective motion, suppression of high transverse momentum particles
  - Discovery of the sQGP (not the QGP we naively expected 10 year ago)?

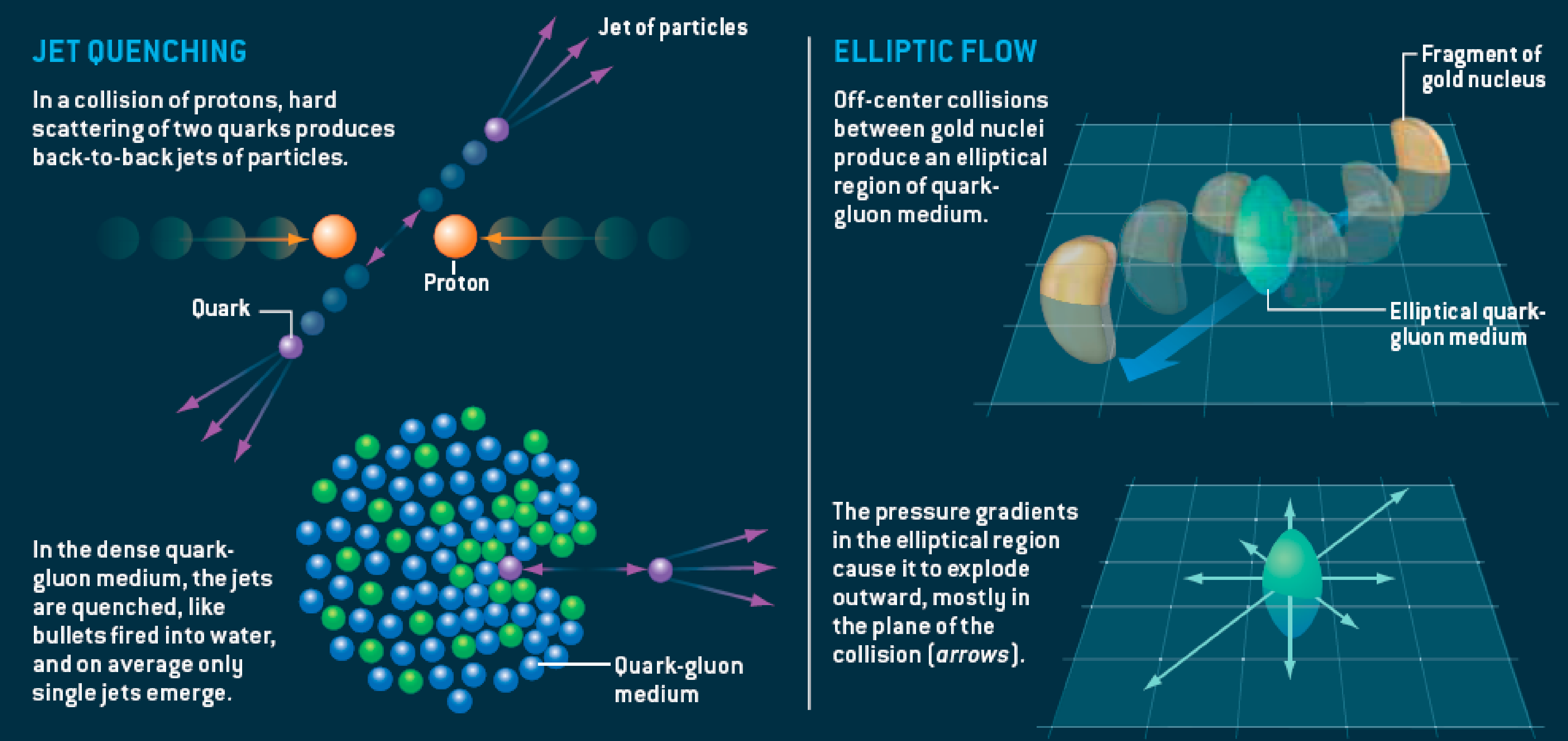
RHIC scientists serve up perfect liquid

The perfect liquid

EVIDENCE FOR A DENSE LIQUID

M. Roirdan and W. Zajc, Scientific American 34A May (2006)

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

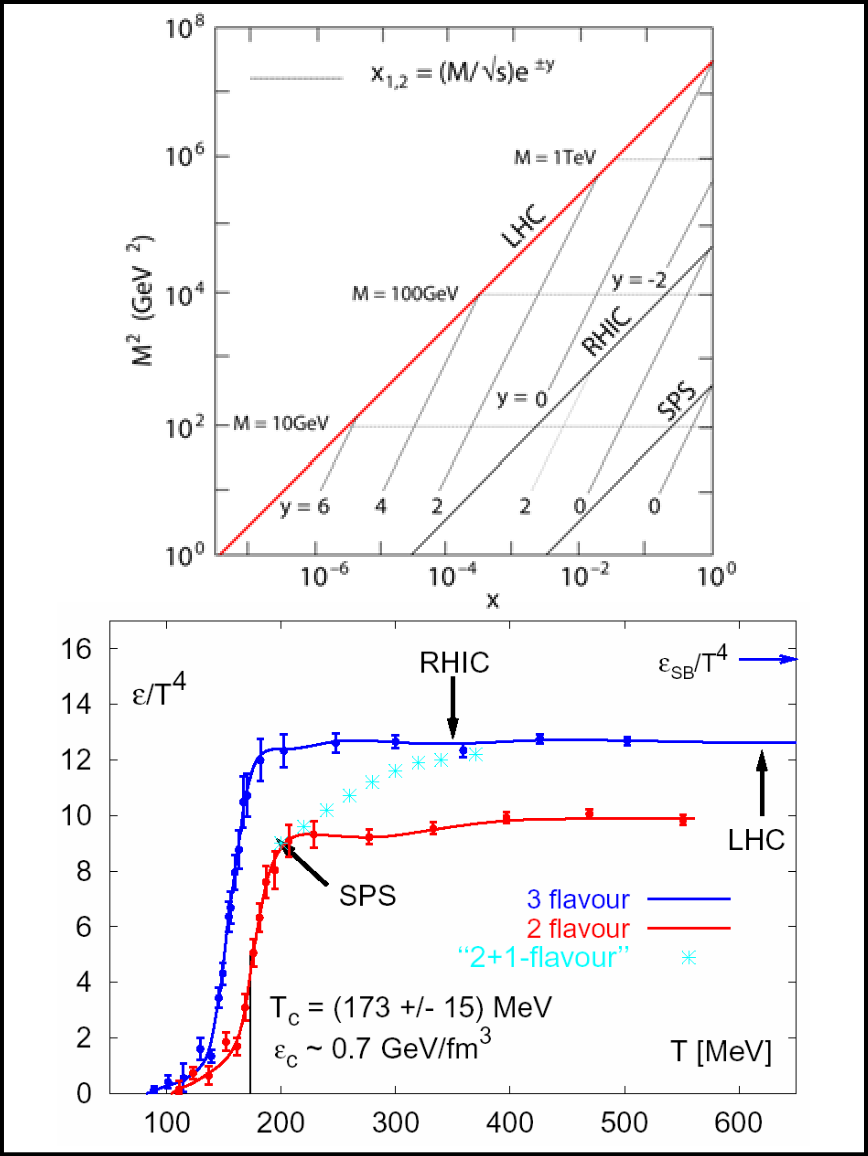


From SPS, RHIC to the LHC

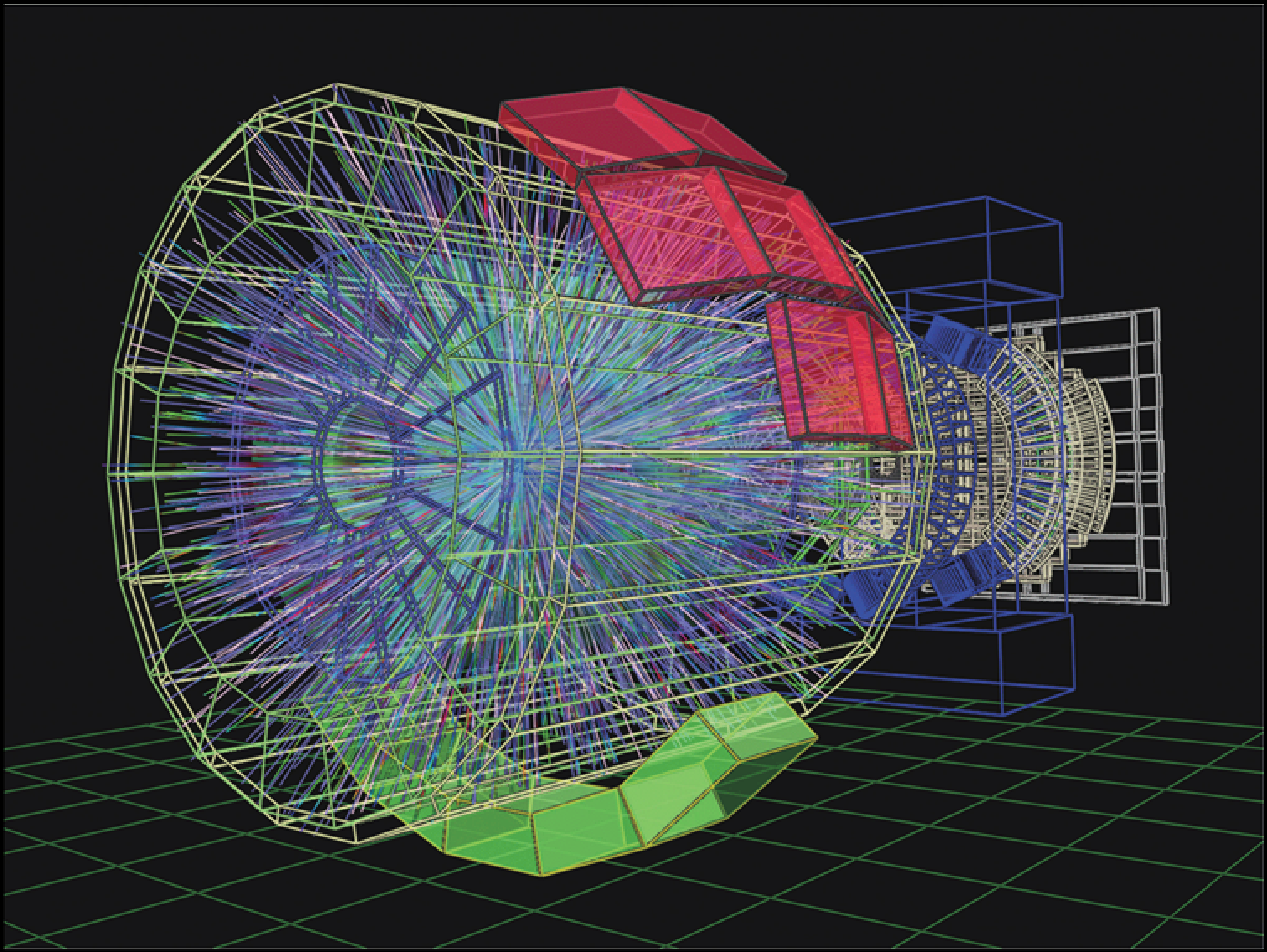
	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	
dN_{ch}/dy	500	850	1500-4000	
τ^0_{QGP} (fm/c)	1	0.2	0.1	
T/T_c	1.1	1.9	3-4	Hotter
ε (GeV/fm^3)	3	5	15-60	Denser
τ_{QGP} (fm/c)	≤2	2-4	≥10	Longer
τ_f (fm/c)	~10	20-30	30-40	
V_f(fm^3)	few 10^3	few 10^4	Few 10^5	Bigger

From SPS, RHIC to the LHC

- Not just super sized, a new regime!
  - high density pdf's (saturized) determine particle production
  - parton dynamics dominate the fireball expansion
- with new tools
  - hard processes contribute significantly to the cross section
  - weakly interacting hard probes become available



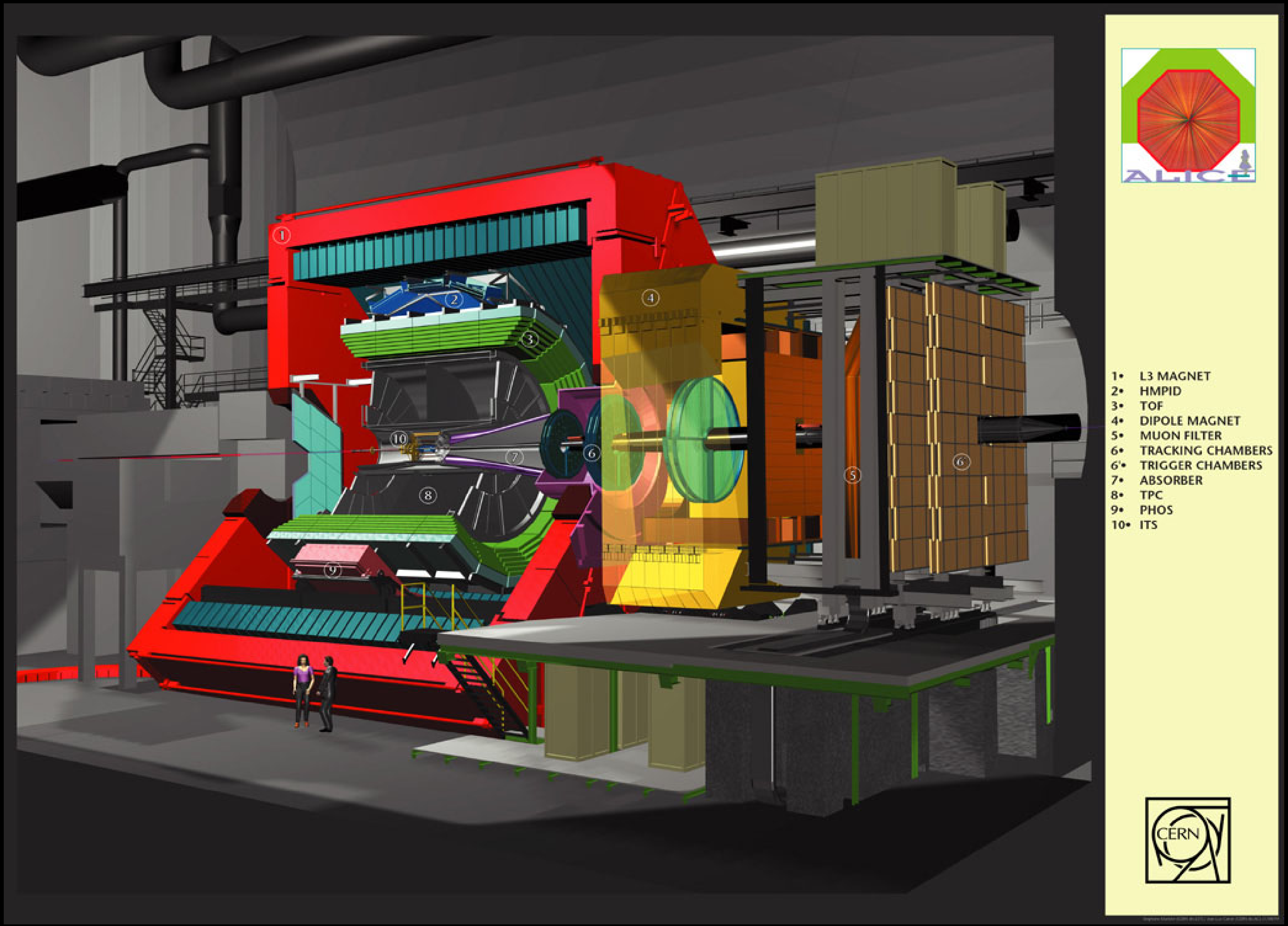
ALICE Event



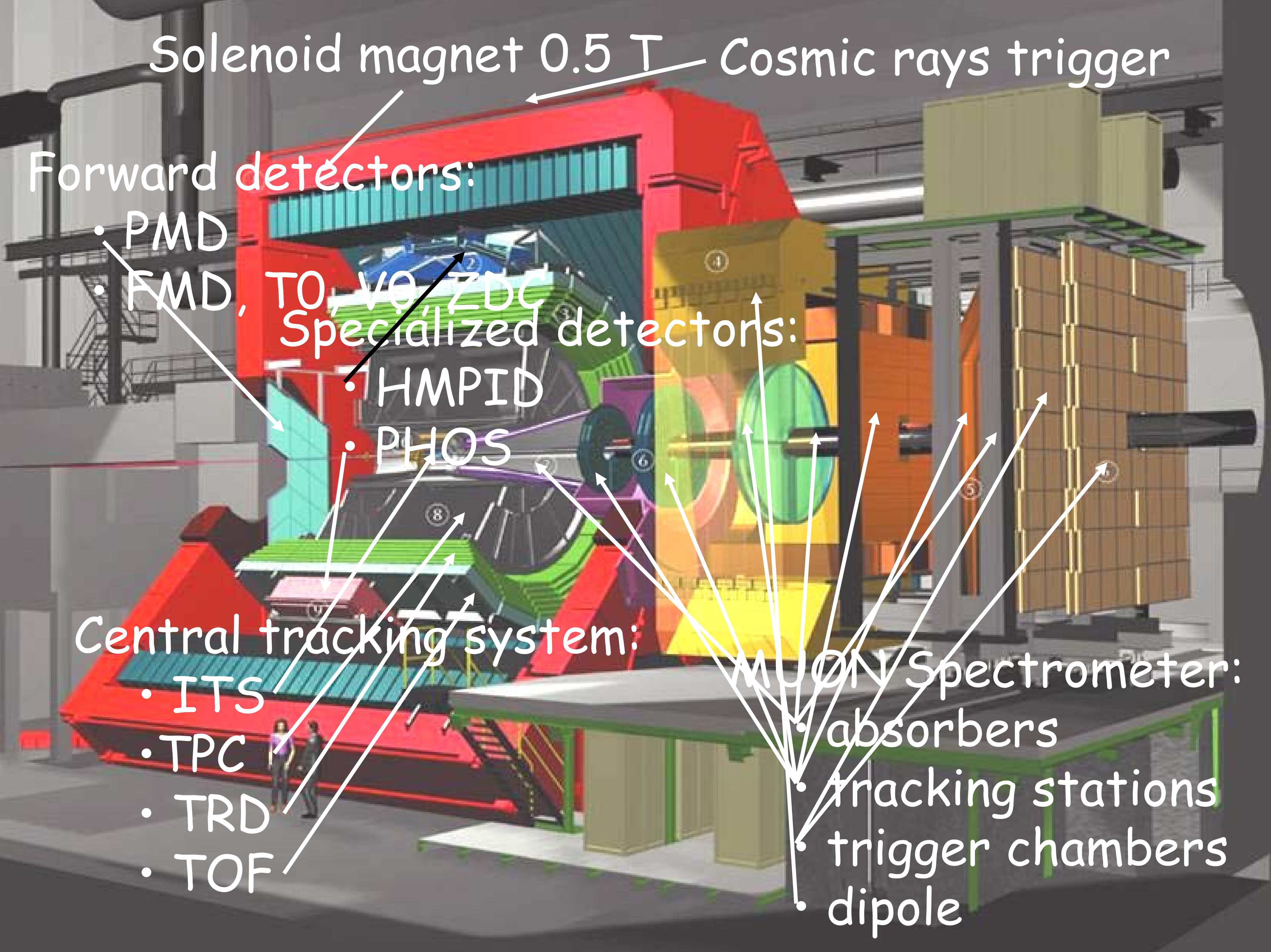
ALICE detector design

- Cover very low-p_t ~ 100 MeV
- Cover high-p_t ~ 100 GeV
- Particle identification over a large momentum range
- Able to handle large multiplicities > 4000 per unit rapidity
- Measure rare probes, charm, bottom, direct-γ, J/Ψ …

The ALICE detector



ALICE Collaboration: ~ 1000 people, 30 countries, ~ 80 Institutes


Solenoid magnet 0.5 T
Cosmic rays trigger
Forward detectors:
• PMD
• FMD, T0, V0, ZDC
Specialized detectors:
• HMPID
• PHOS
Central tracking system:
• ITS
• TPC
• TRD
• TOF
MUON Spectrometer:
• absorbers
• tracking stations
• trigger chambers
• dipole

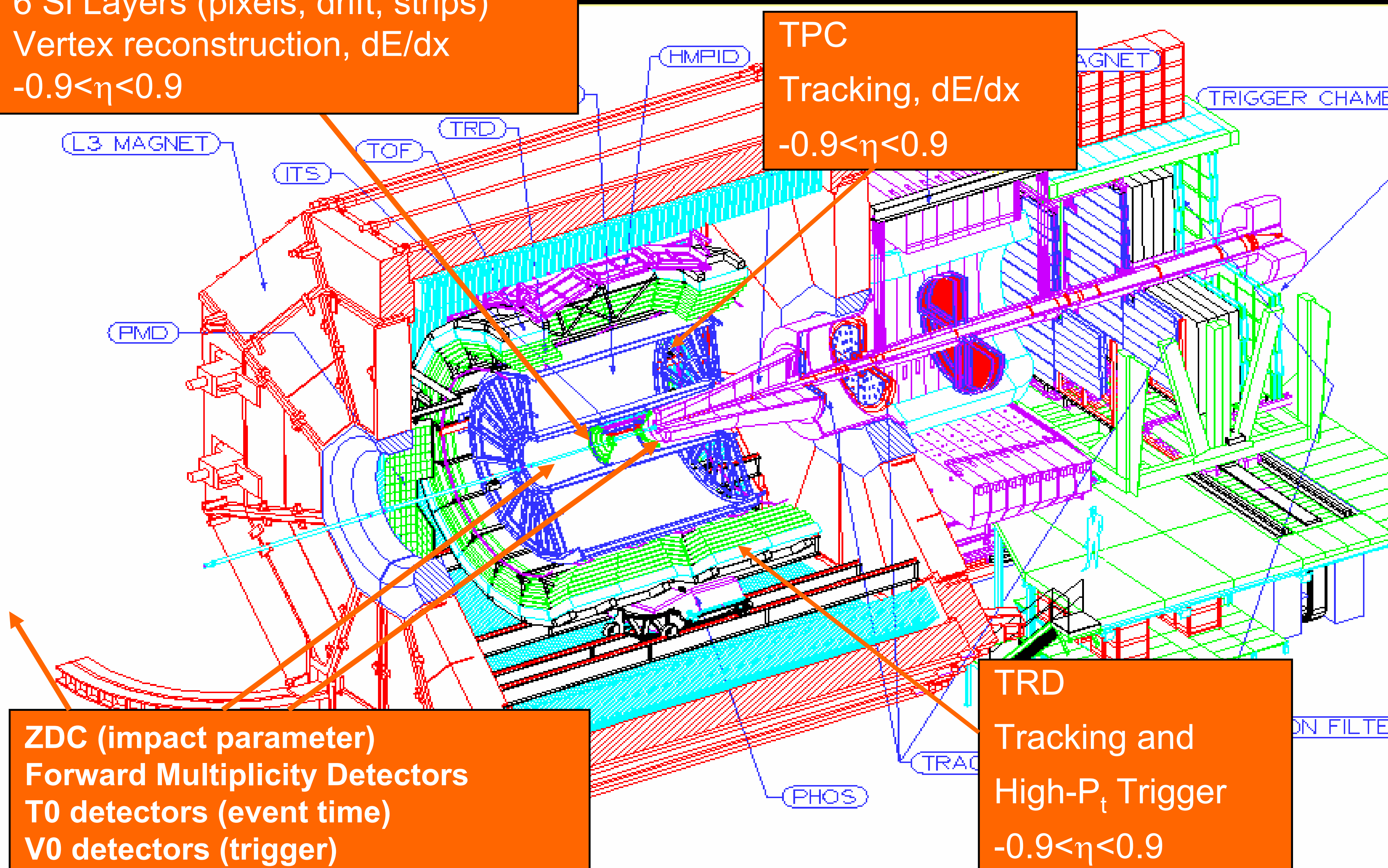
ALICE Tracking and Event Characterization

Inner Tracking System (ITS):
6 Si Layers (pixels, drift, strips)
Vertex reconstruction, dE/dx
$-0.9<\eta<0.9$

TPC

Tracking, dE/dx

$-0.9<\eta<0.9$



TRD

Tracking and

High-P_t Trigger

$-0.9<\eta<0.9$

ZDC (impact parameter)
Forward Multiplicity Detectors
T0 detectors (event time)
V0 detectors (trigger)

ALICE PID

TRD

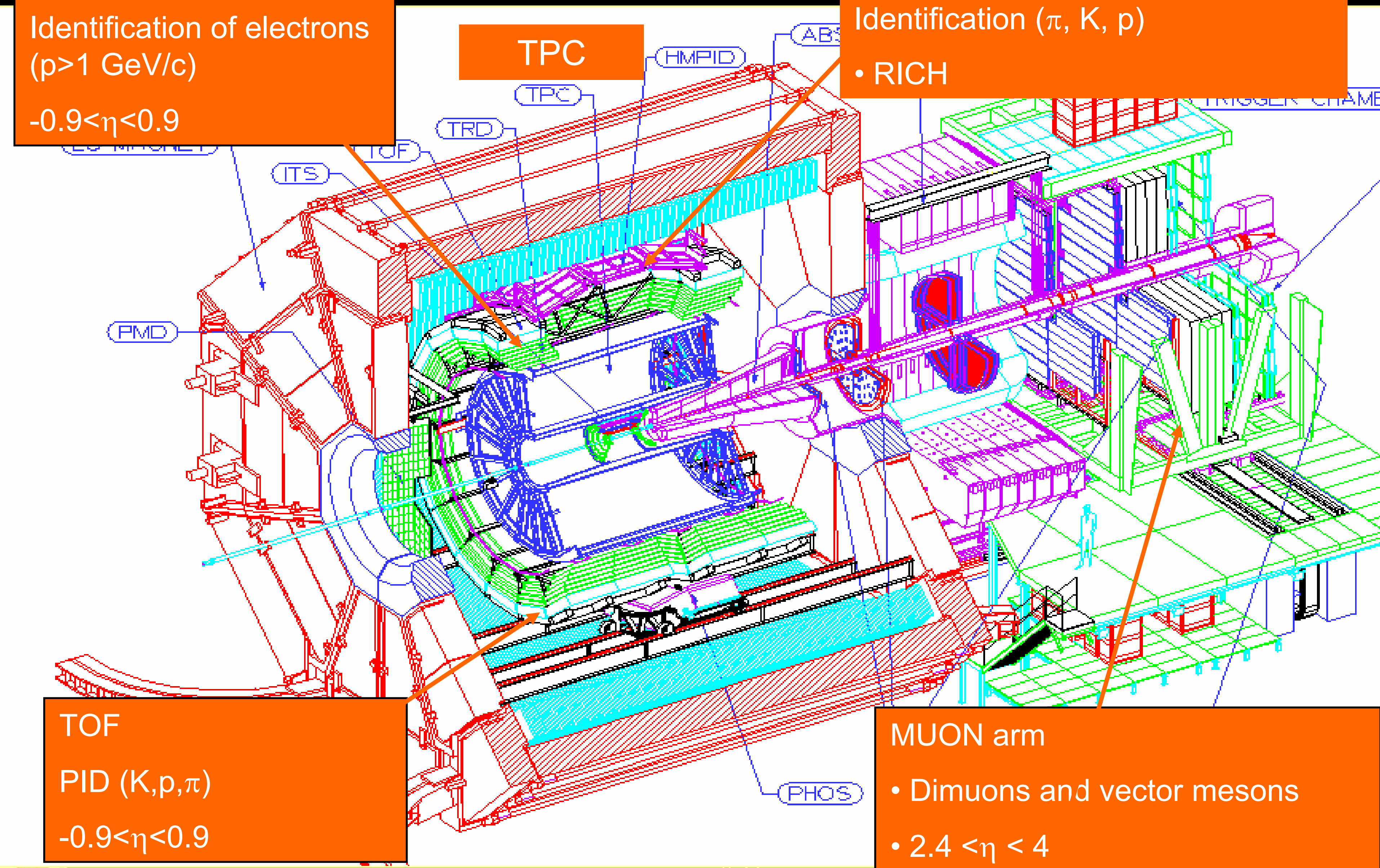
Identification of electrons (p>1 GeV/c)

$-0.9<\eta<0.9$

TPC

HMPID: High Momentum Particle Identification (π, K, p)

- RICH



TOF

PID (K,p,π)

$-0.9<\eta<0.9$

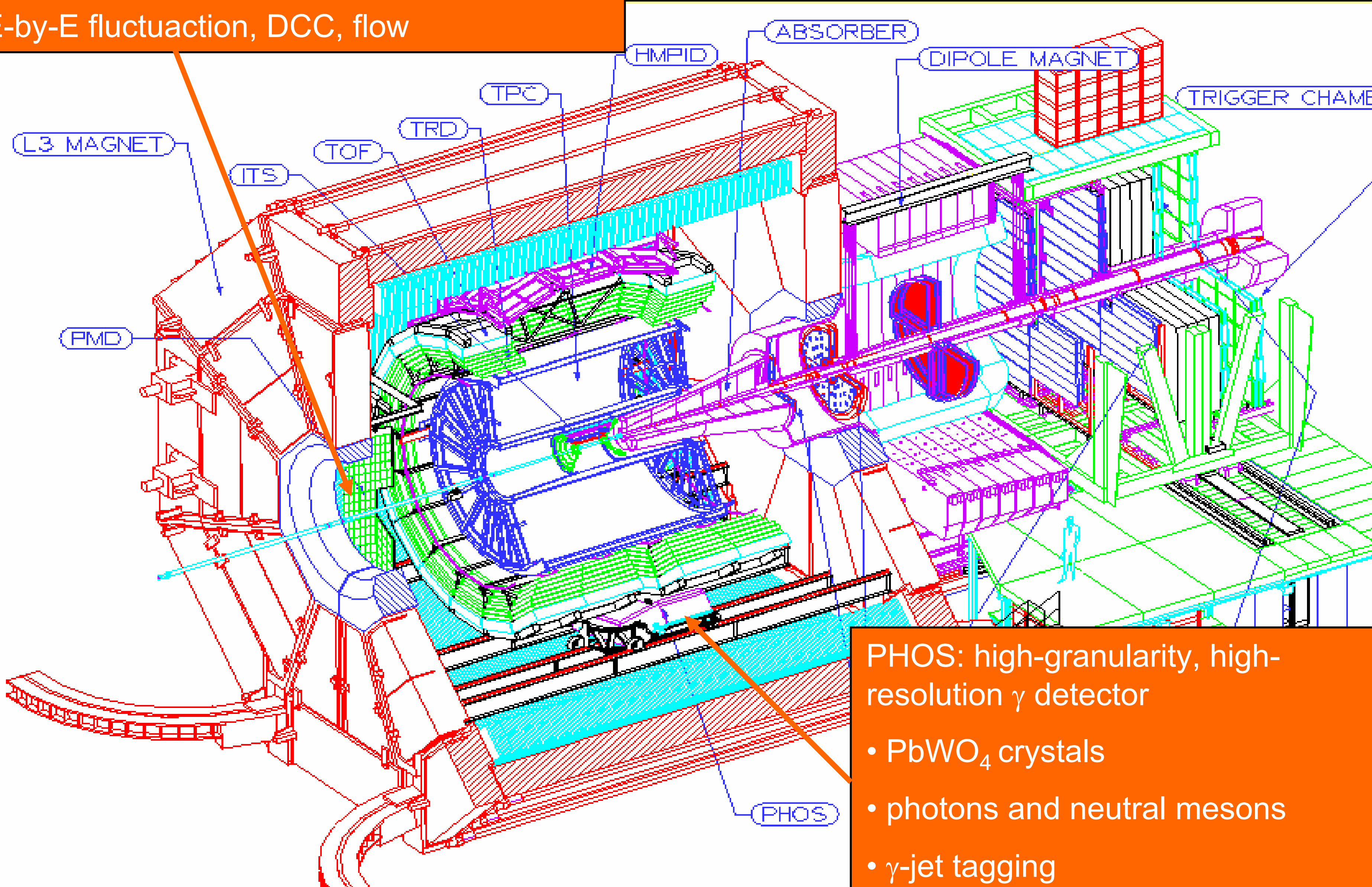
MUON arm

- Dimuons and vector mesons
- $2.4 < \eta < 4$

ALICE Photons

PMD: Photon Multiplicity Detector

- Preshower detector with fine granularity
- Coverage: 2.3< h <3.5, 270 k channels
- E-by-E fluctuaction, DCC, flow



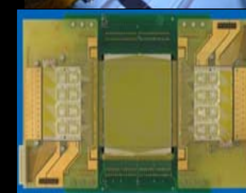
PHOS: high-granularity, high-resolution γ detector

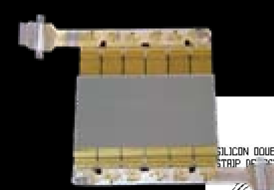
- $PbWO_4$ crystals
- photons and neutral mesons
- γ-jet tagging

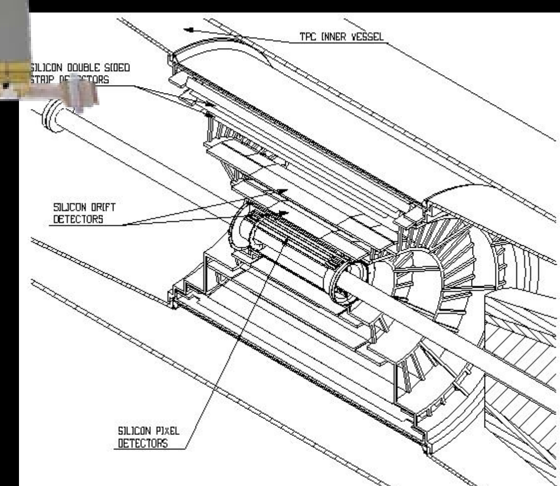
The inner tracking system

low mass: 7 % X_0

6 layers		R	σ rφ	σ Z
Layer 1	pixels	4 cm	12 μm	100 μm
Layer 2	pixels	8 cm	12 μm	100 μm
Layer 3	drift	15 cm	38 μm	28 μm
Layer 4	drift	24 cm	38 μm	28 μm
Layer 5	double sided strip	38 cm	17 μm	800 μm
Layer 6	double sided strip	43 cm	17 μm	800 μm

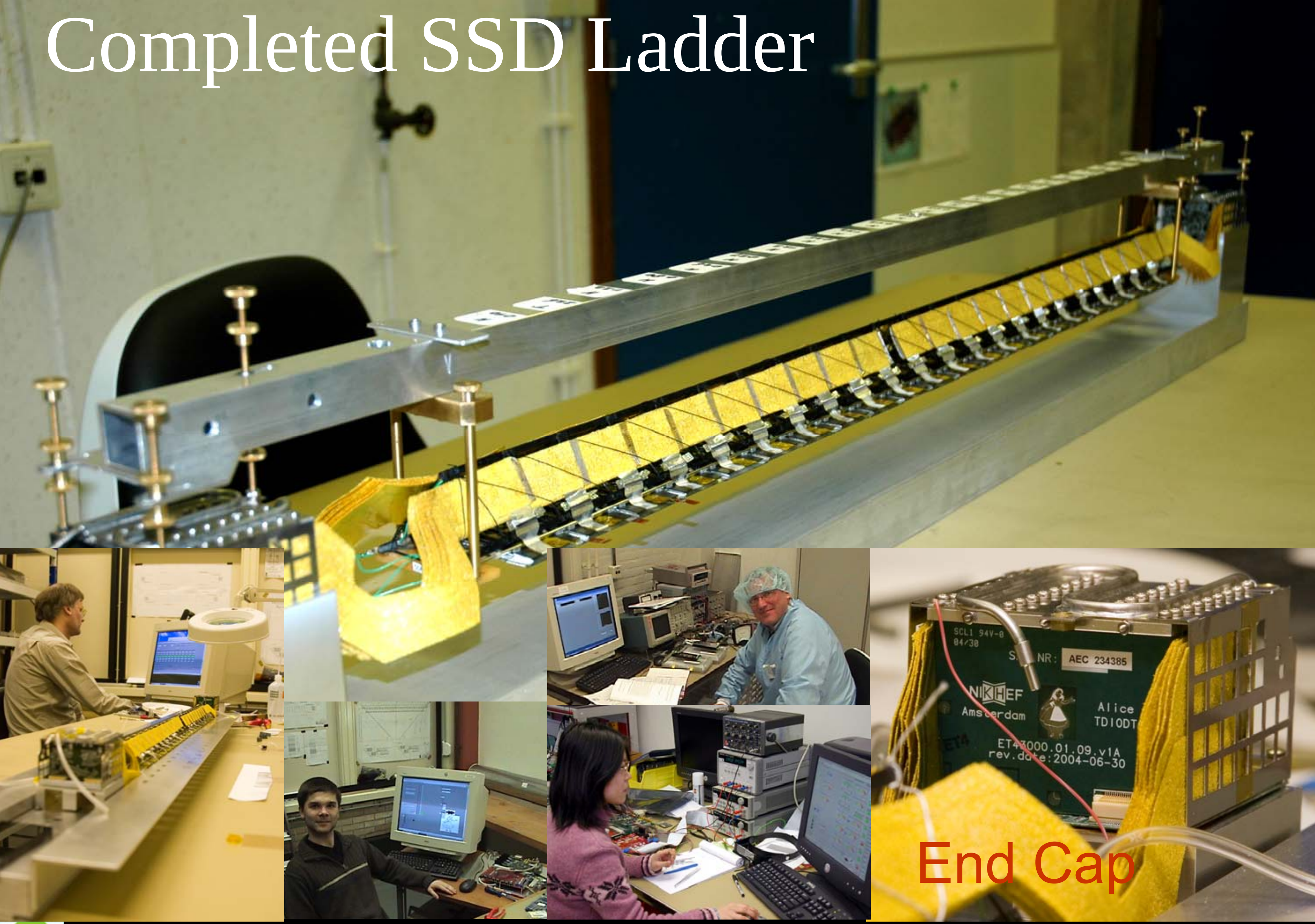




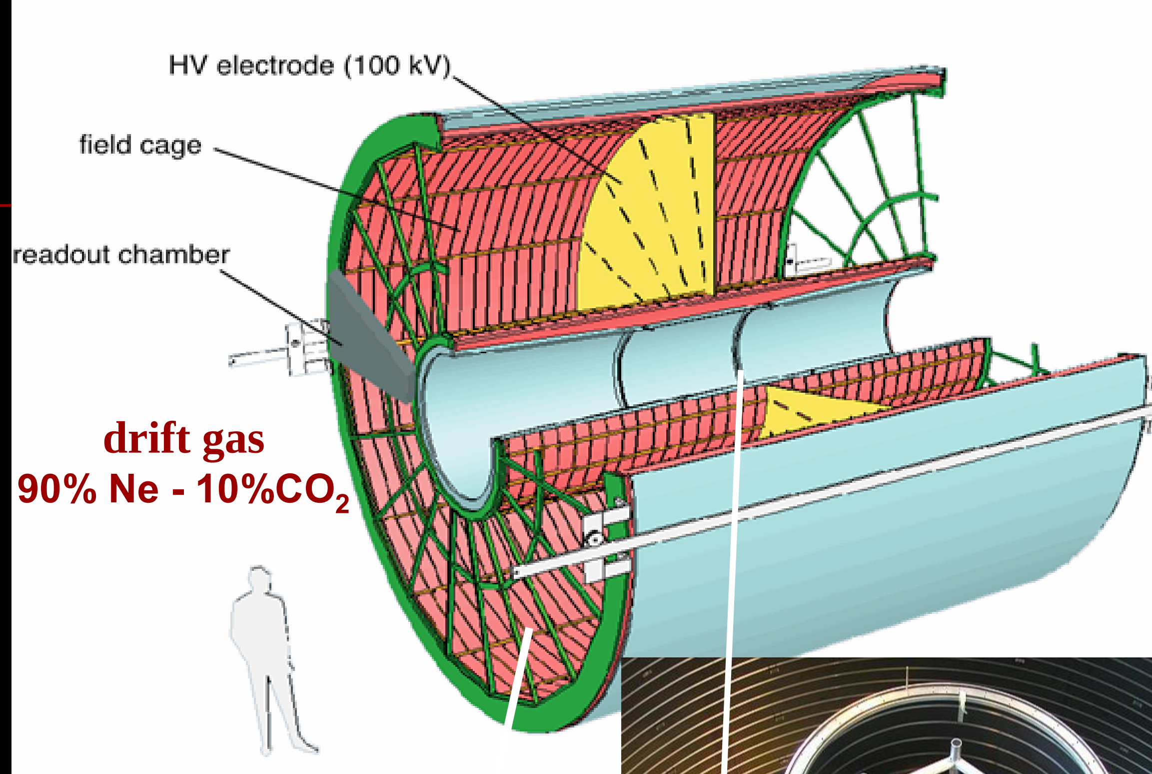


- The ITS is the center of the ALICE tracking system
  - needed to get reasonable momentum resolution at higher p_t
  - needed to reconstruct secondary vertices
  - needed to track low momentum particles

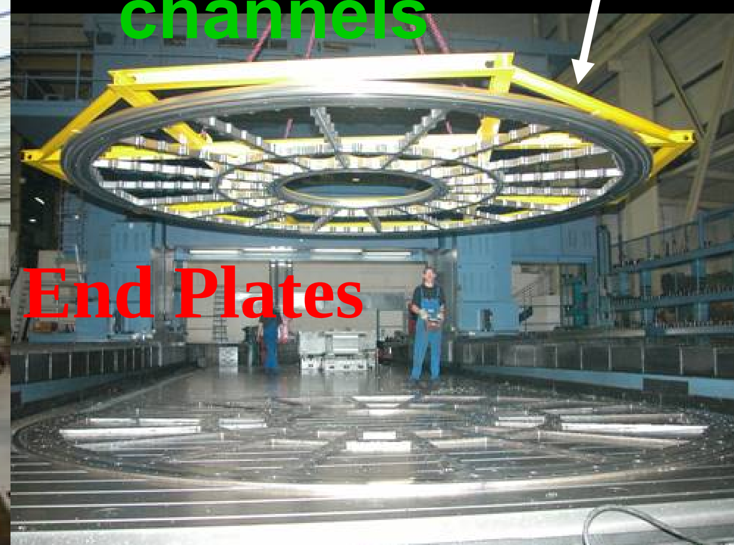
Completed SSD Ladder



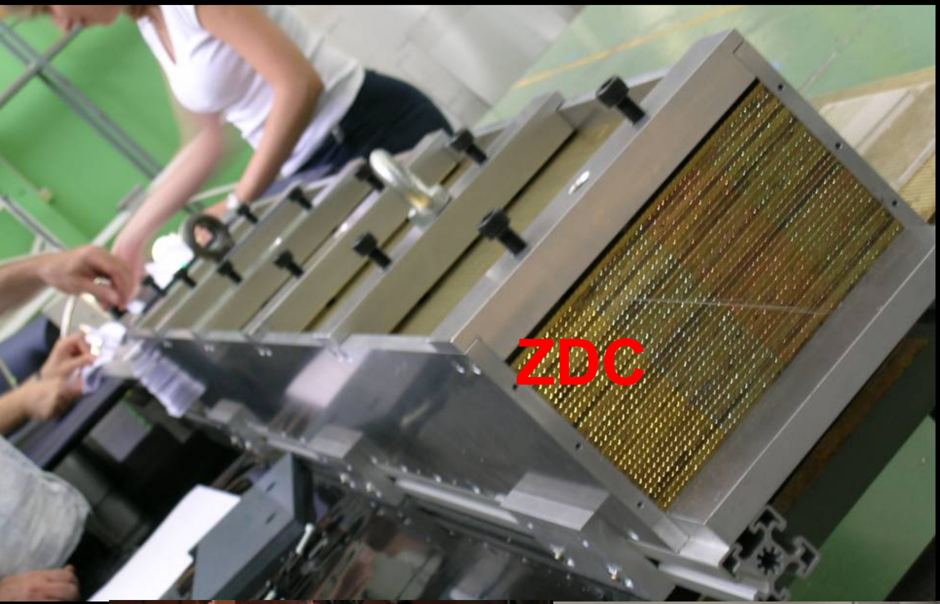
The TPC
largest ever

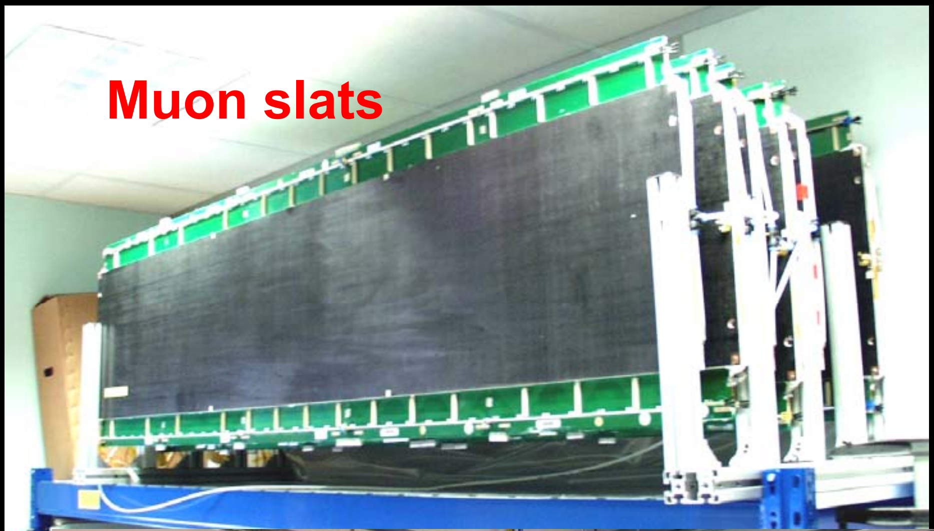


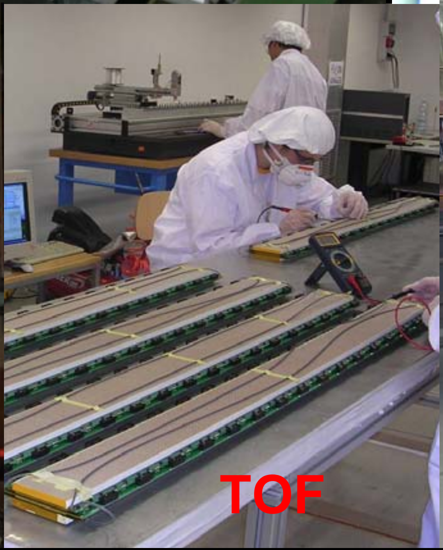
88 m^3, 570k channels



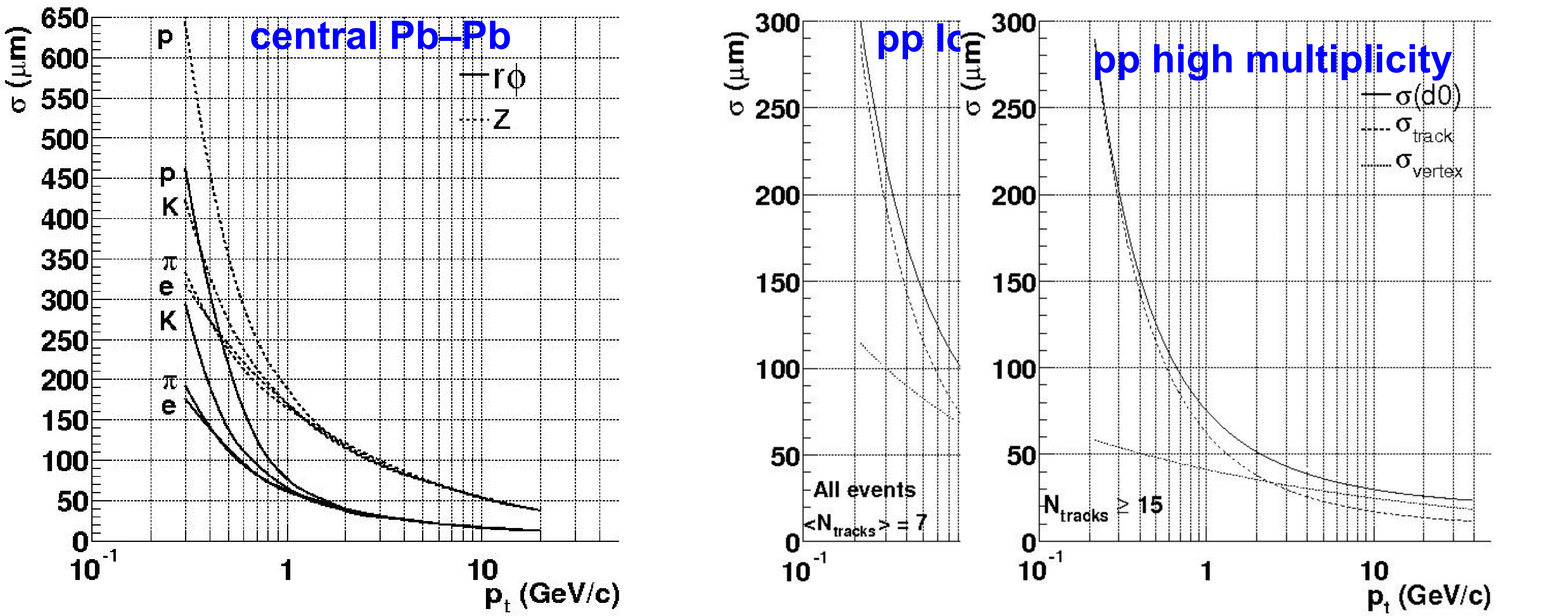
A few other detectors







Impact Parameter Determination

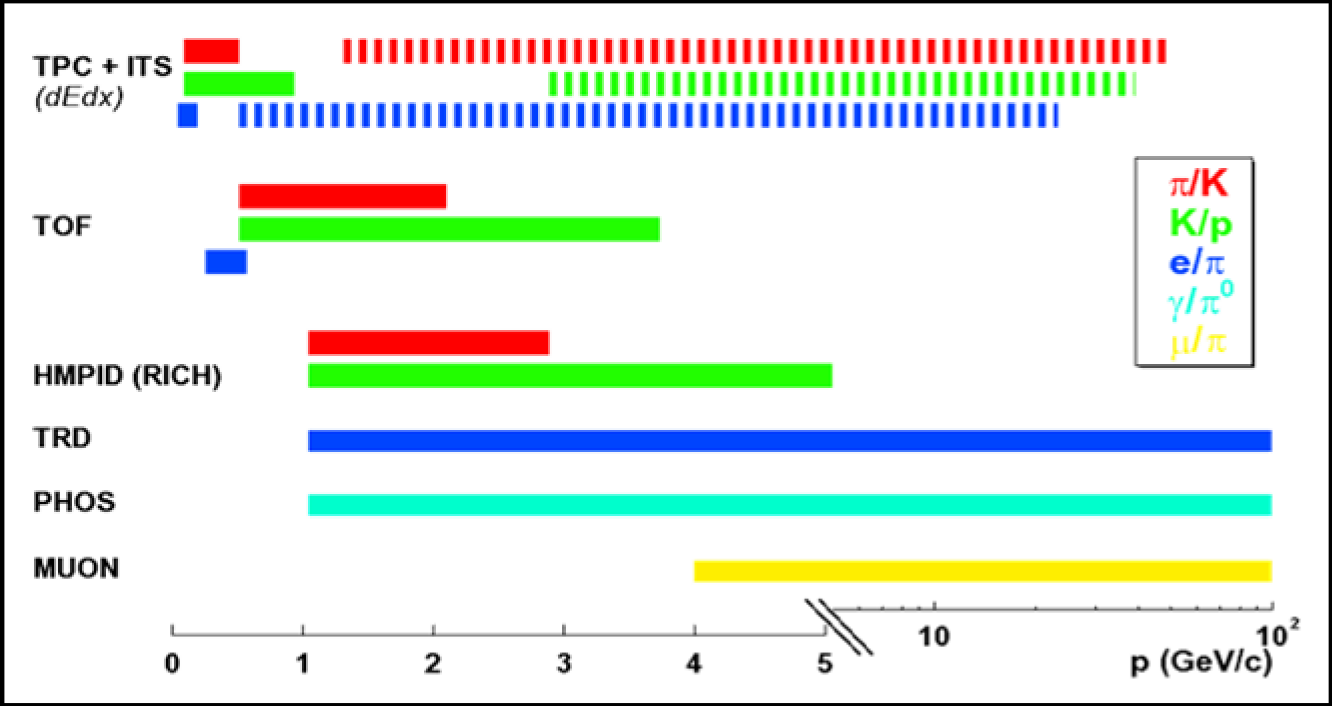


For low-multiplicity events (i.e. pp) the contribution from primary-vertex resolution is not negligible
Full reconstruction with primary tracks has to be used

Impact parameter resolution is crucial for the detection of short-lived particles - charm and beauty mesons and baryons

At least one component has to be better than 100 μm (cτ for D^0 meson is 123 μm)

Particle Identification



stable hadrons (π, K, p): 100 MeV < p < 5 GeV (few 10 GeV)

dE/dx in silicon (ITS) and gas (TPC) + Time-of-Flight (TOF) + Cerenkov (RICH)

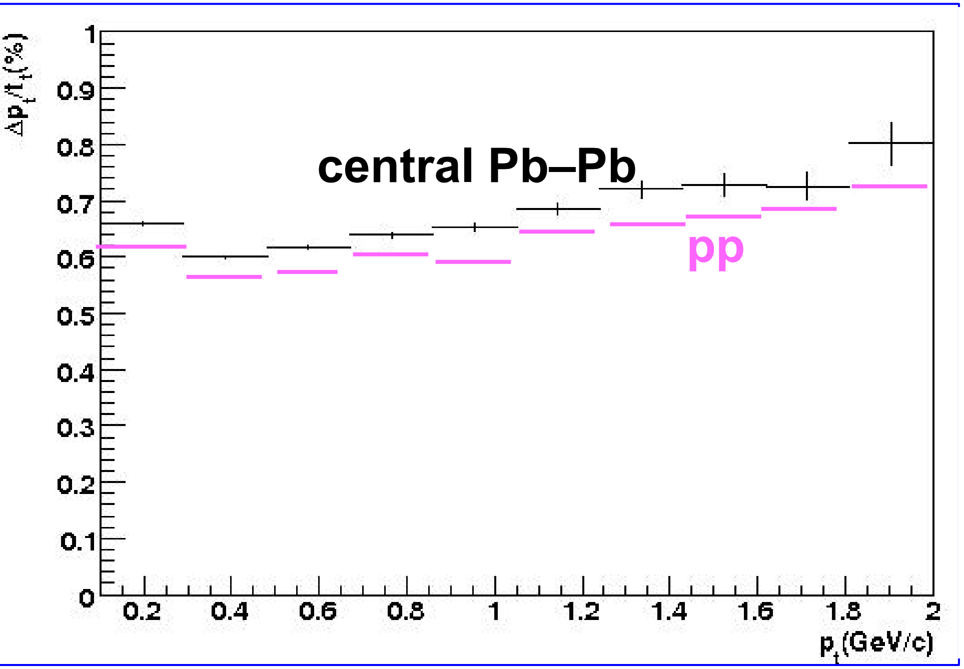
decay topology (K^0, K^+, K^-, Λ)

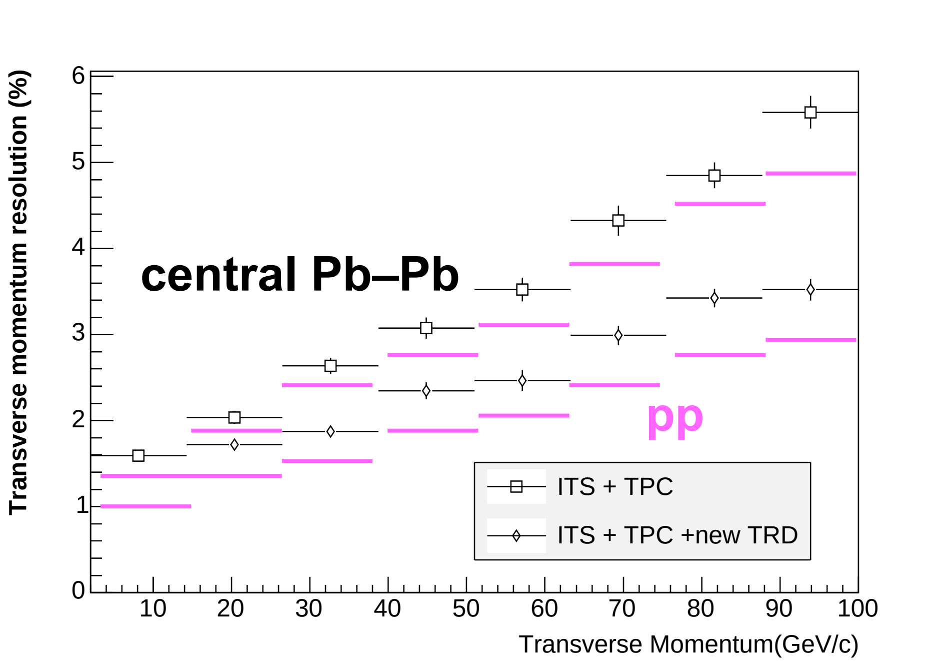
K and Λ decays up to at least 10 GeV

leptons (e, μ), photons, π^0, η

electrons in TRD: p > 1 GeV, muons: p > 5 GeV, π^0 in PHOS: 1 < p < 80 GeV

Momentum resolution





at low momentum dominated by

- **ionization-loss fluctuations**
- **multiple scattering**

at high momentum determined by

- **point measurement precision**
- **and the alignment & calibration**

Summary

- At the LHC we expect to create a QGP which is hotter, denser and longer lived compared to lower energies
- This implies that even commonly available probes are dominated by the QGP partonic phase and thus allow us to constrain the QCD EoS and the transport properties in greater detail
- In addition, rare penetrating probes become much more abundant (large production cross sections for high-p_t jets, γ-jet, charm and beauty ….)
- The heavy-ion program at the LHC and in particular ALICE is in a good position to harvest some of the LHC gold nuggets in the coming years

Physics Performance Report

- Published in two volumes:
  - PPR Vol I: CERN/LHCC 2003-049
    - Published: ALICE coll. (2004) J. Phys. G 30 1517 – 1763
  - PPR Vol II: CERN/LHCC 2005-030 (part 1 – part 2)
    - to be published in J. Phys. G
- Volume I
  - ALICE Physics – theoretical overview
  - LHC experimental conditions
  - ALICE detector
  - Offline computing and Monte Carlo generators
- Volume II
  - Detector performance
  - ALICE physics performance