Light Quark Observables
(an experimental overview)

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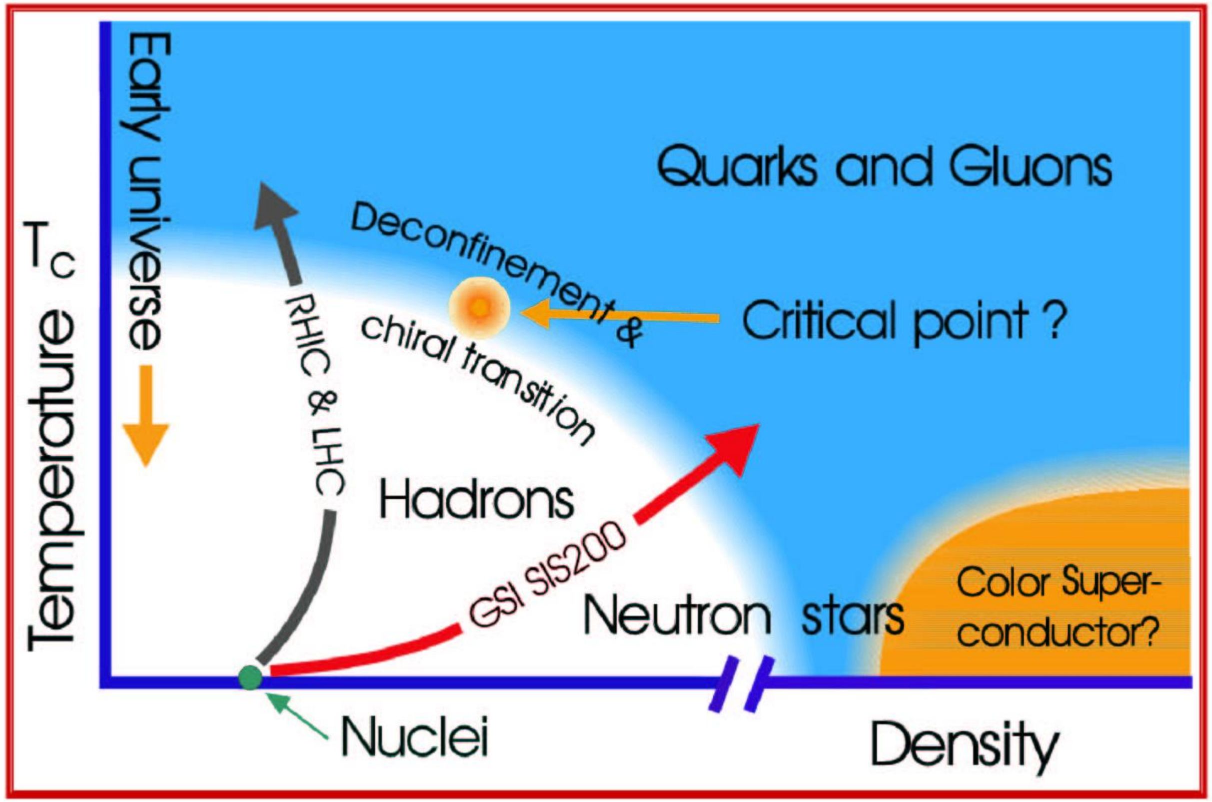
Overview of Topics

- Lecture 1: The Mission
  - Based on lattice QCD and thermodynamics
- Lecture 1: Methods of Light Flavor Particle Identification
  - dE/dx, time of flight, Cerenkov radiation, V0 reconstruction
- Lecture 2: Spectra and Yields
  - Yields: statistical hadronization models, resonances, flavor dependence, momentum dependencies
  - Spectra: fit functions, radial flow, collectivity
- Lecture 3: Anisotropic Flow and the Initial State
  - v2 and higher harmonics, initial state and collective models, state variables
- Lecture 3: Fluctuations and Correlations
  - Higher moments, criticality, hadronization models
- Lecture 3: What have we learned, where do we go ?

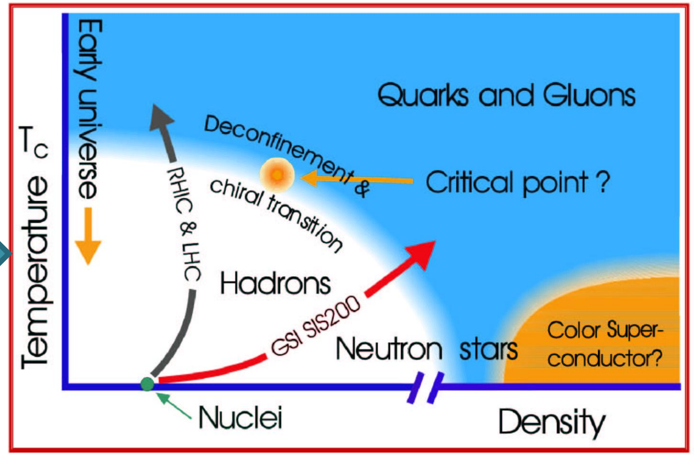
Lecture 1, Part 1: Mission

What is our mission ?



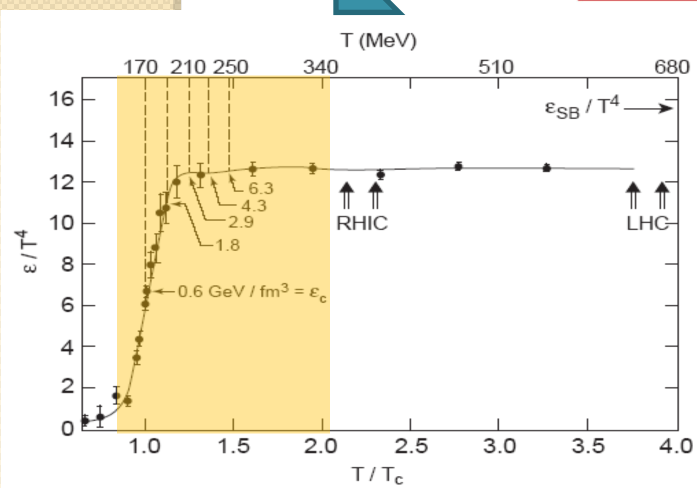
- Establish the existence of a phase (state) of deconfined and chirally symmetric matter. Determine state variables
- Establish the mechanism of *re*confinement

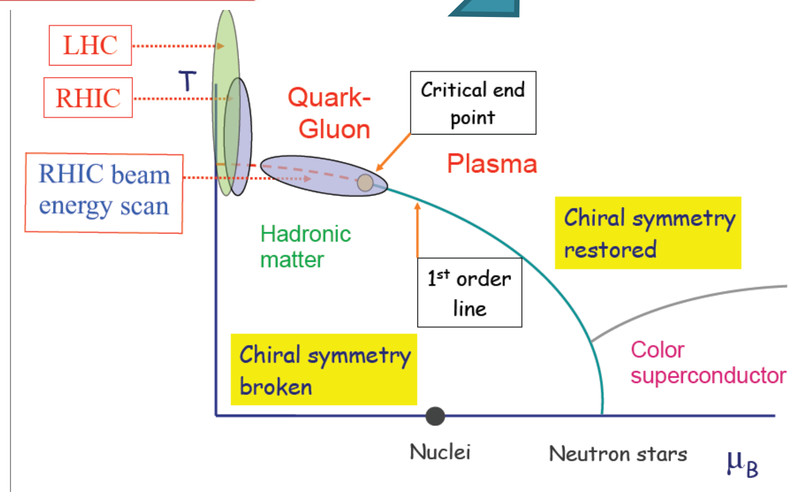
LHC, RHIC and the QCD phase diagram



T

μ





LHC established state variables in long lifetime deconfined state

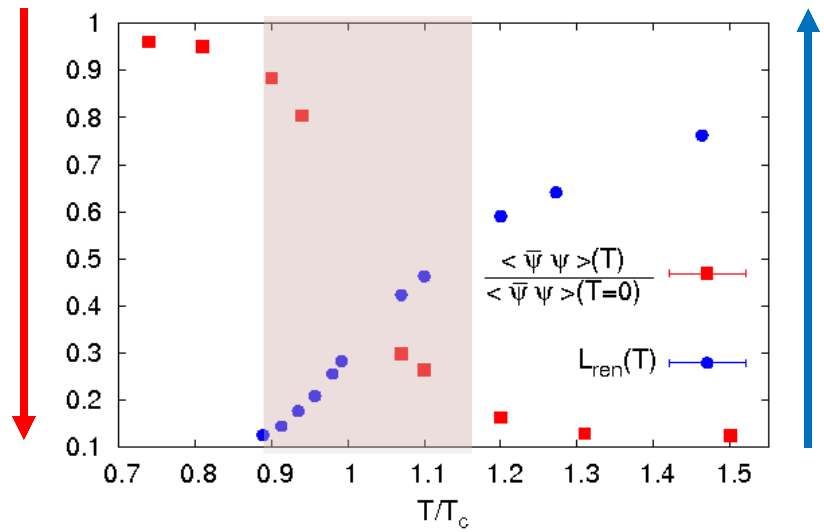
RHIC maps out region at lower energies and higher chemical potential

Lattice QCD: two phase transitions

Chiral symmetry restoration
Massive hadrons in the hadron gas are massless partons in the plasma. Mass breaks chiral symmetry, needs to be restored in the plasma

Deconfinement
The quarks and gluons deconfine because energy or parton density gets too high
(best visualized in the bag model).

Quark condensate:
Measure of chiral symmetry restoration

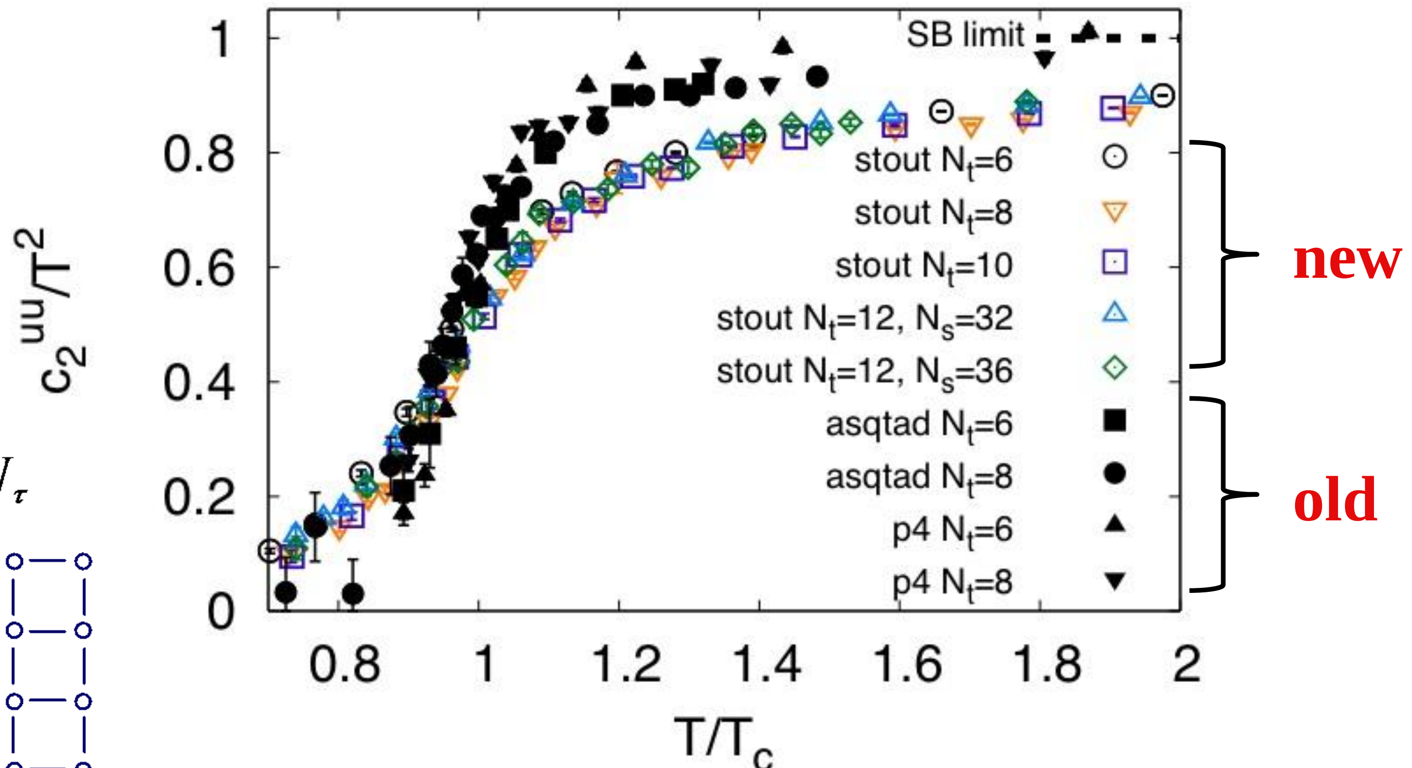


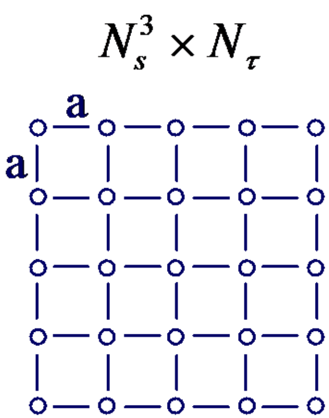
Polyakov loop:
Measure of deconfinement

Mechanism of hadronization ? : How do hadrons obtain their mass ?
Not a question of Higgs fields, but rather of dynamic masses through gluon fields (quasi-particles, constituent quarks, gluon clusters, color-neutral bound states through recombination ?)

Evolution in lattice QCD

the phase transition turns into a crossover due to finer lattice spacing and smaller quark masses = a longer mixed phase ?





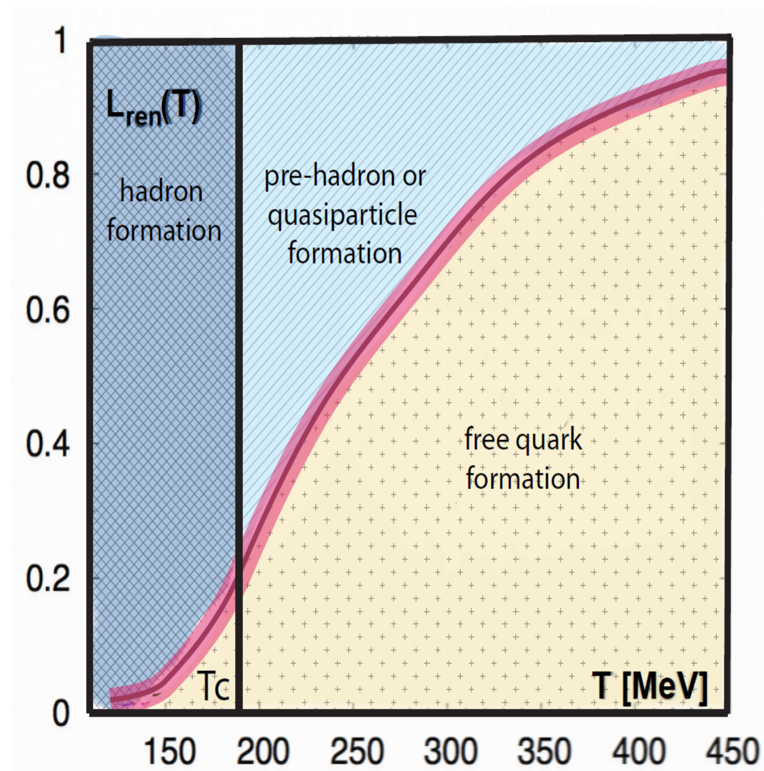
The main transition parameters:

T_c ~ 154 MeV ε_c ~ 1 GeV/fm^3

A smooth cross-over

Can we map out (experimentally) and understand (theoretically) *the transition from QCD degrees of freedom to hadronic degrees of freedom through the QCD crossover region*. The emphasis is on *understanding the formation of matter on a microscopic level*. The main tools are flavor specific identified particles and the detectors that enable PID.

Can we determine *the state variables of a deconfined, yet collective, state that existed only microseconds after the Big Bang* and forms the basis of matter formation in the universe. The emphasis is *on establishing its magnitude of collectivity and its unique properties as a state between the hadron gas phase and the weak coupling limit of asymptotic freedom.*



Bellwied et al., PLB 691 (2010) 208

What do we have to check ?

- If there was a transition to a different phase, then this phase could only last very shortly ($\tau \sim 10$ fm/c = 10^{-23} s). The only evidence we have to check is the collision debris.

- We use: *Light quark observables* (up, down, strange & charged hadrons (= 98% light quark particles))

- Check the make-up of the debris:
  - which particles have been formed and how many ?
  - are they emitted statistically (Boltzmann distribution) ?
  - what are their kinematics (momentum, angular distributions) ?
  - are they correlated in coordinate or momentum space ?
  - do they move collectively ?
  - do some of them 'melt' ?

Signatures of the QGP phase (historical)

For more detail see for example: J. Harris and B. Müller, Annu, Rev. Nucl. Part. Sci. 1996 46:71-107 (http://arjournals.annualreviews.org/doi/pdf/10.1146/annurev.nucl.46.1.71)

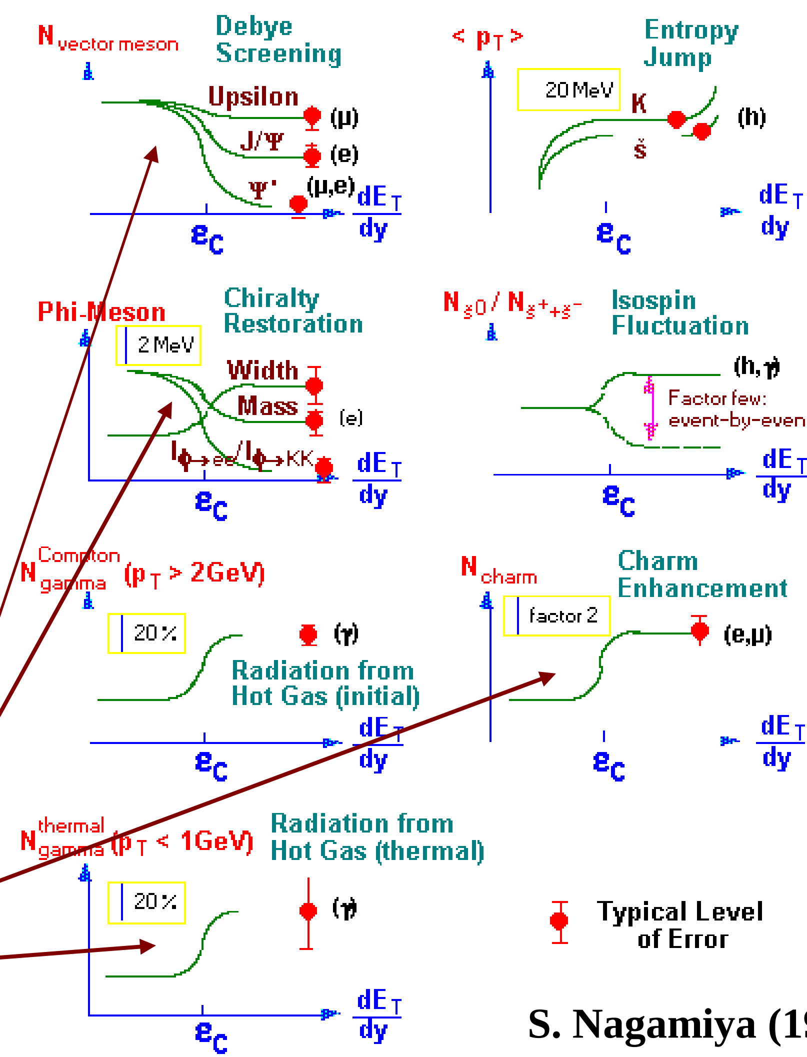
Phase transitions are signaled thermodynamically by a ‘step function’ when plotting temperature vs. entropy (i.e. # of degrees of freedom).

The temperature (or energy) is used to increase the number of degrees of freedom rather than heat the existing form of matter.

In the simplest approximation the number of degrees of freedom should scale with the particle multiplicity.

some signatures drop

some signatures rise



S. Nagamiya (1986)

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Assessing the Initial Energy Density: Calorimetry

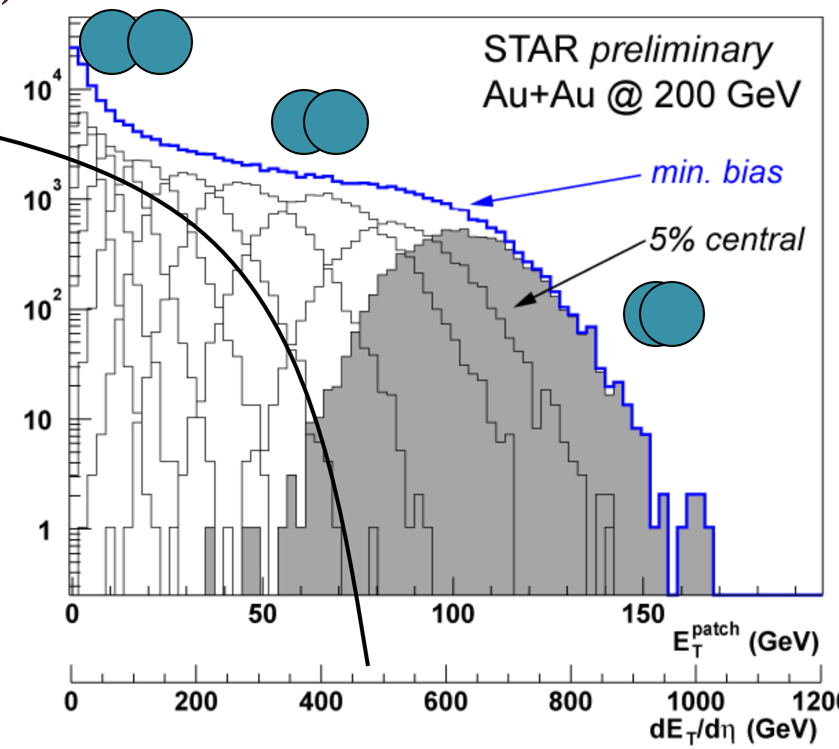
Bjorken-Formula for Energy Density:

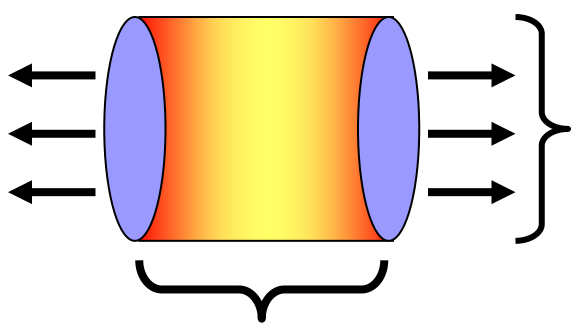
PRD 27, 140 (1983) – watch out for typo (factor 2)

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

~6.5 fm

Time it takes to thermalize system ($\tau_0 \sim$ 1 fm/c)





πR^2

$$dz = \tau_0 dy$$

Note: τ_0 (RHIC) < τ_0 (SPS)
commonly use 1 fm/c in both cases

Central Au+Au (Pb+Pb) Collisions:
17 GeV: $\varepsilon_{BJ} \approx$ 3.2 GeV/fm^3
130 GeV: $\varepsilon_{BJ} \approx$ 4.6 GeV/fm^3
200 GeV: $\varepsilon_{BJ} \approx$ 5.0 GeV/fm^3

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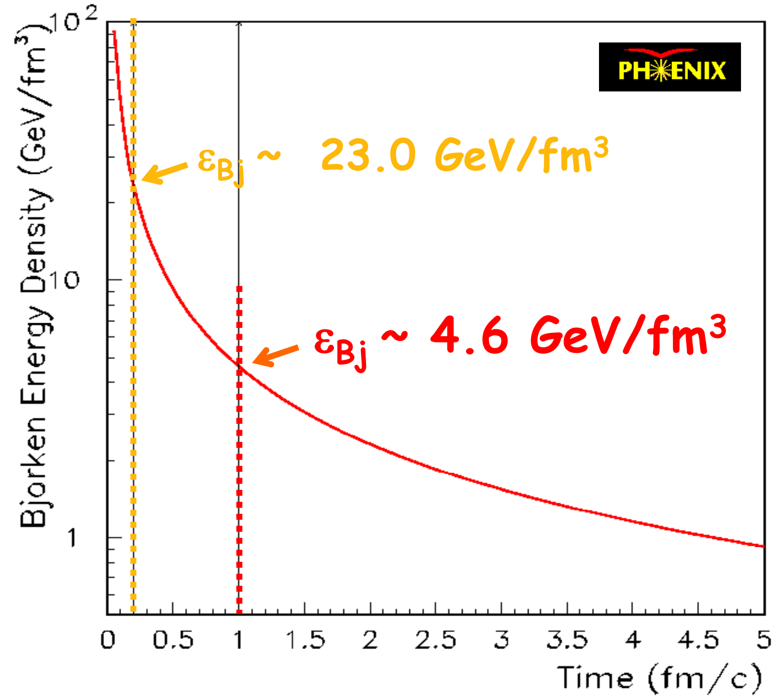
The Problem with ε_{BJ}

- ε_{BJ} is not necessarily a "thermalized" energy density: no direct relation to lattice value, requires boost invariance
- τ_0 is model dependent: usually 1fm/c taken for SPS 0.2 – 0.6 fm/c at RHIC ?
- system performs work p ·dV ⇒ from simple thermodynamics roughly factor 2

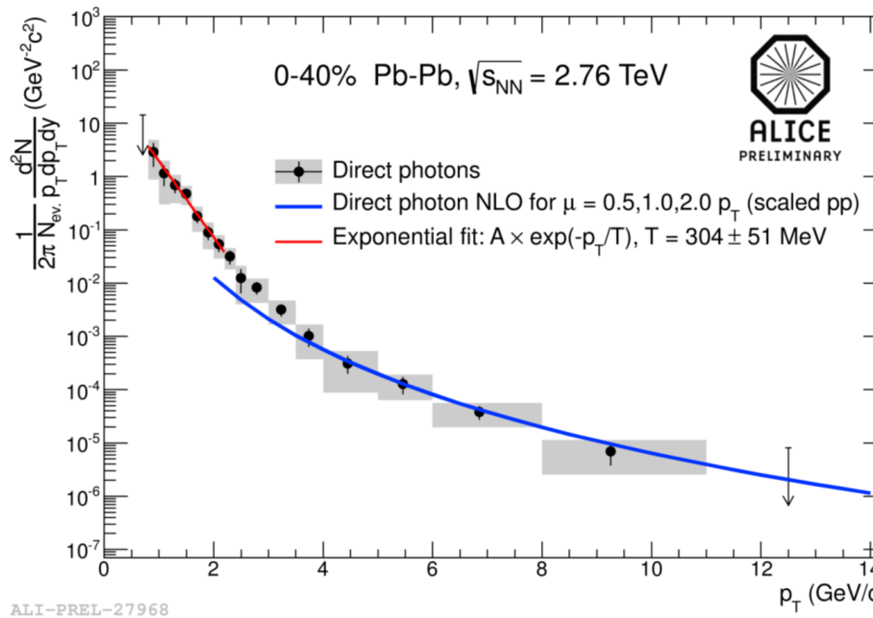


Bottomline: For 200 A GeV central Au+Au collisions (RHIC):

- From Bjorken estimates via E_T and N_{ch}: $\varepsilon > 5$ GeV/fm³
- From energy loss of high-p_T particles: $\varepsilon \approx 15$ GeV/fm³
- From hydromodels with thermalization: $\varepsilon_{center} \approx 25$ GeV/fm³

How about the temperature ?

Measure the spectrum of thermal photons (non-interacting) emitted from the source. The spectrum will display the average temperature over the full lifetime of the partonic source. Determining the initial temperature requires modeling.



ALICE: ***T*** **= 304±51 MeV**
5.5 Trillion Kelvin !!
Modeled $T_{initial}$ > 500 MeV

(PHENIX: ***T*** **= 221±19±19 MeV)**
Modeled $T_{initial}$ ~ 350 MeV

WIRED magazine:
Feeling hot hot hot !!
CERN breaks man-made heat record

http://www.guinnessworldrecords.com/world-records/10000/highest-man-made-temperature

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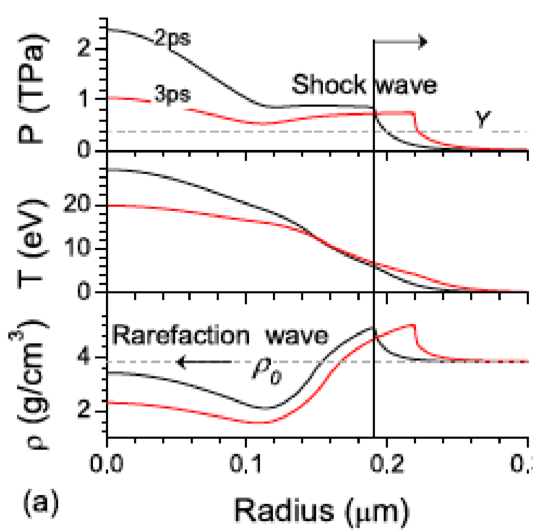
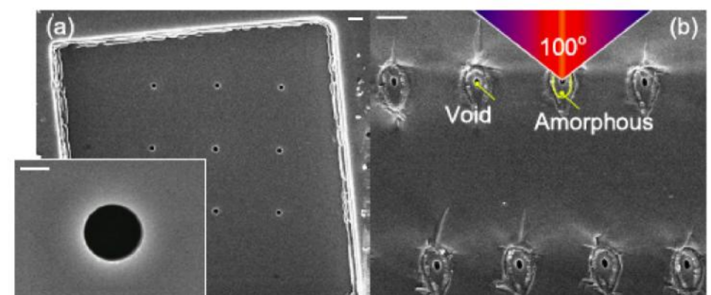
PRL 96, 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal: Evidence of Multimegabar Pressures

S. Juodkazis,[1] K. Nishimura,[1] S. Tanaka,[1] H. Misawa,[1] E. G. Gamaly,[2] B. Luther-Davies,[2] L. Hallo,[3] P. Nicolai,[3] and V. T. Tikhonchuk[3]

Extremely high pressures (~10 TPa) and temperatures (5×10^5 K) have been produced using a single laser pulse (100 nJ, 800 nm, 200 fs) focused inside a sapphire crystal. The laser pulse creates an intensity over 10^{14} W/cm^2 converting material within the absorbing volume of ~0.2 μm^3 into plasma in a few fs. A pressure of ~10 TPa, far exceeding the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by plasma hydrodynamics. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.





	microexplosions	femtoexplosions
√s	0.1 μJ	1 μJ
ε	10^{17} J/m^3	5 GeV/fm^3 = 10^{36} J/m^3
T	10^6 K	200 MeV = 10^{12} K
rate	10^{18} K/s	10^{35} K/s

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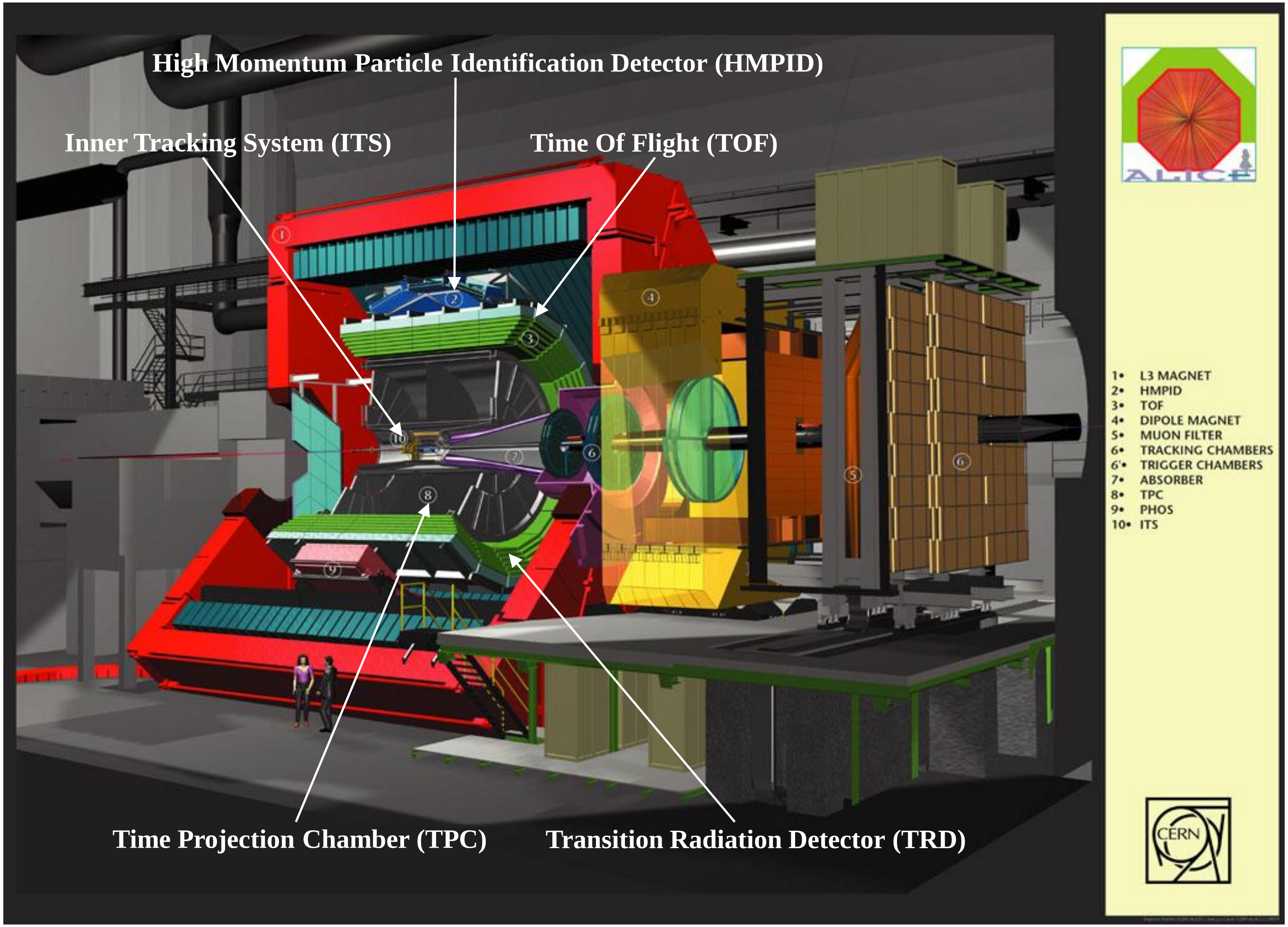
PID signatures of a phase crossover

- In simple yields
  - Strangeness enhancement due to simplified production process
- In p_T-dependent yields
  - Parton specific hadronization mechanism
- In spectral shapes
  - Collective radial flow described by partonic hydrodynamics
- In multiplicity fluctuations
  - Flavor specific freeze-out properties
- In di-hadron correlations
  - Parton correlated production mechanism
- In anisotropic flow
  - Quark number scaling

In general: do the dynamics scale with mass or quark number ?

Lecture 1, Part 2: Technology

Layout of the ALICE detector

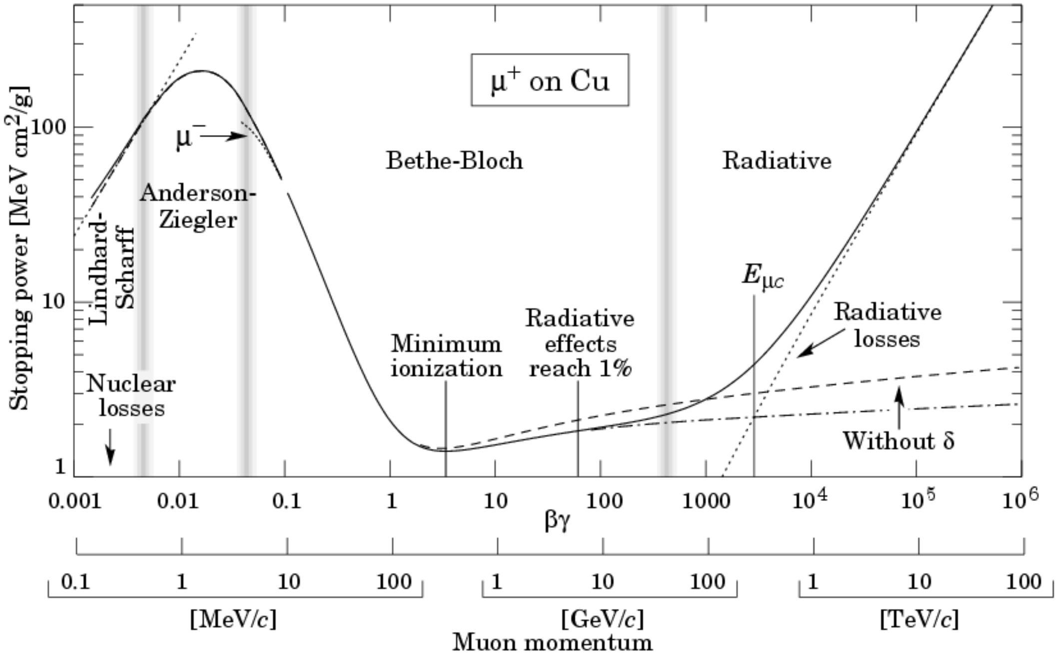


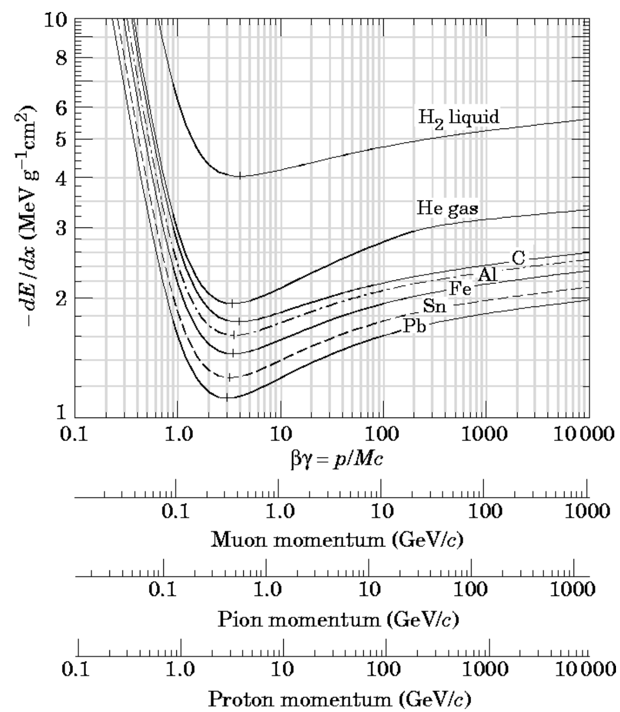
What do we measure in a collider experiment ?

- particles come from the vertex. They have to traverse certain detectors but should not change their properties when traversing the inner detectors
- DETECT but don't DEFLECT !!!
- inner detectors have to be very thin (low radiation length): easy with gas (TPC), challenge with solid state materials (Silicon).
- Measurements: - momentum and charge via high resolution tracking in ITS and TPC in magnetic field
  - PID via dE/dx in ITS and TPC and time of flight in TOF and Cerenkov light in HMPID
  - PID of decay particles via impact parameter from ITS and TPC
- particles should stop in the outermost detector
- Outer detector has to be thick and of high radiation length (e.g. Pb/Scint calorimeter (EMCal))
- Measurements: - deposited energy for event and specific particles
  - e/h separation via shower profile
  - photon via shower profile

Bethe: The principle of particle identification through energy loss

Hans Bethe (1906-2005)



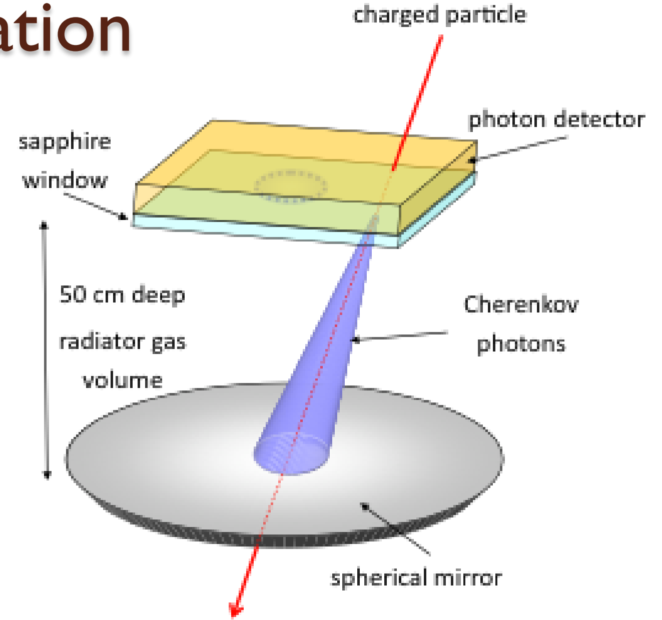


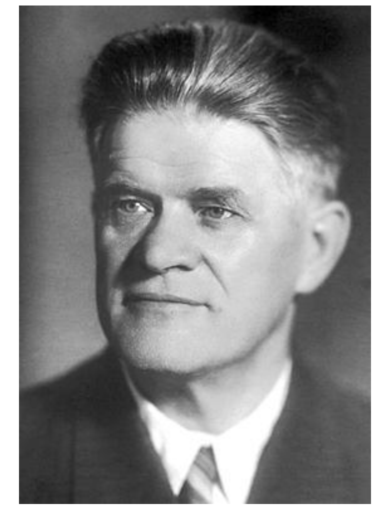
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

K	$4\pi N_A r_e^2 m_e c^2$
Z	Atomic number of absorber
A	Atomic mass of absorber
m_e	Mass of an electron
r_e	Classical radius of an electron
I	Mean excitation energy
T_{max}	Maximum Kinetic energy which can be imparted to a free electron in one collision

Cerenkov: The principle of particle identification through radiation

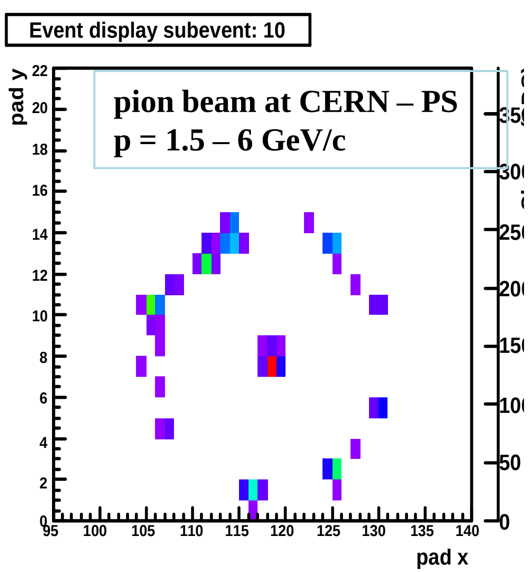
Cerenkov radiation:
Charged particles moving with v > c in local medium

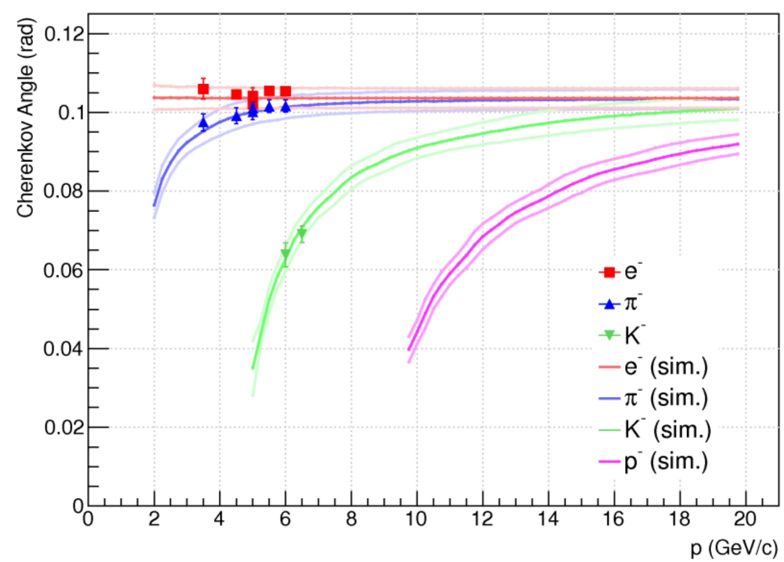




Pavel Cerenkov (1904-1990)

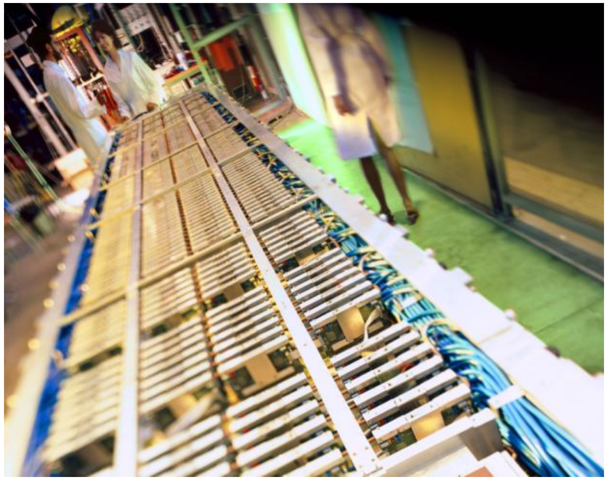
Radiator gas determines: wavelength, ring radius (Cerenkov angle), number of photons

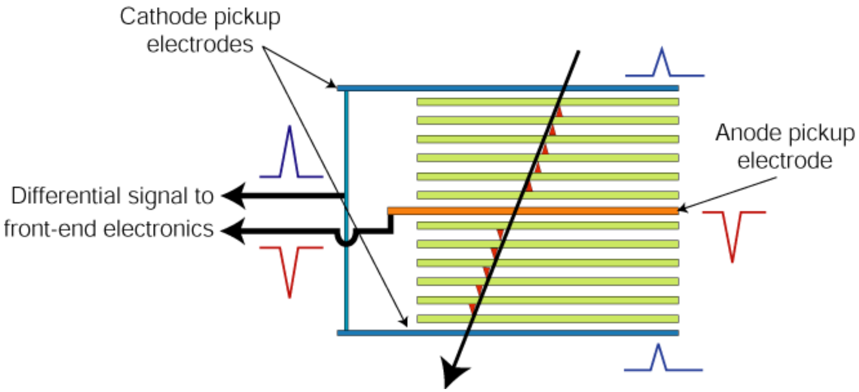




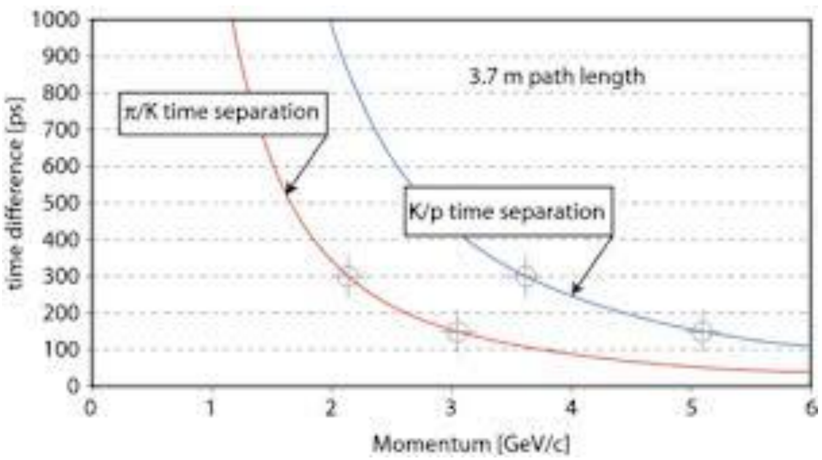
Time of Flight (TOF) detector (example; ALICE)

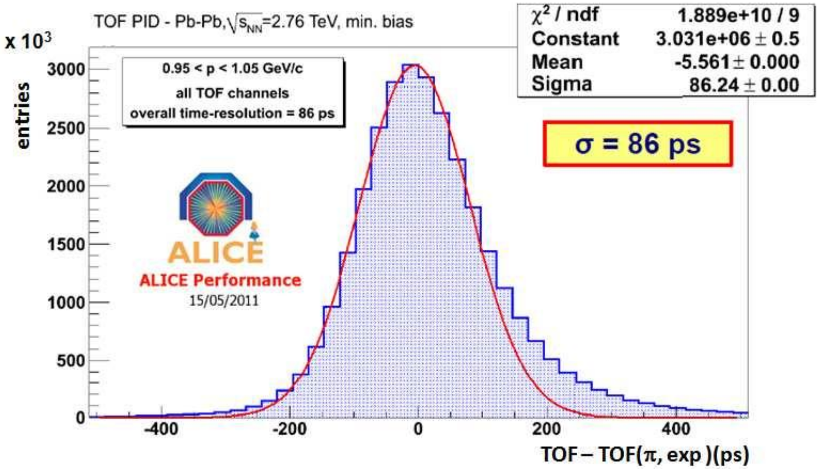
Based on MRPC: Multi Resistive Plate Chamber



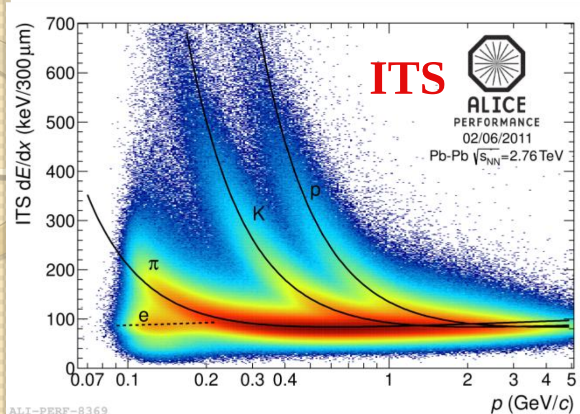


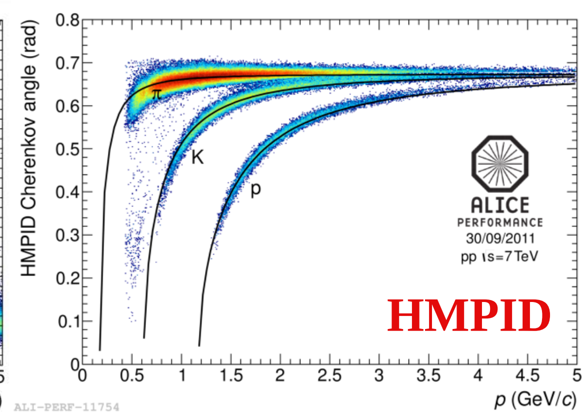
Measure the time of flight from primary vertex to detector: ~4 m = 13 ns (assuming c)

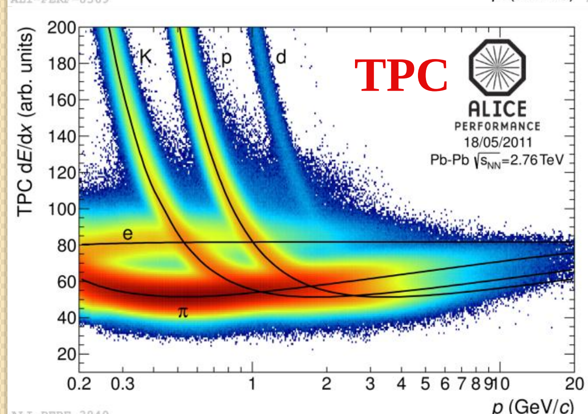


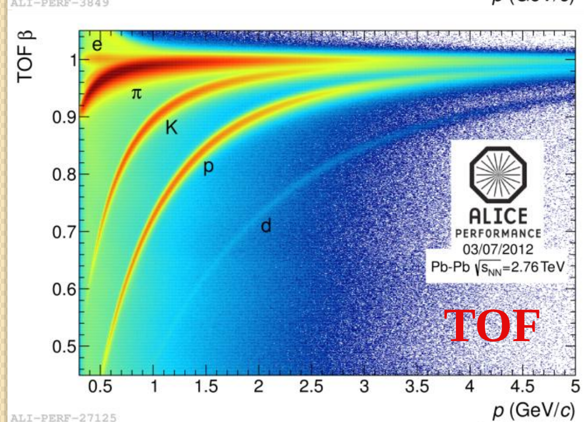


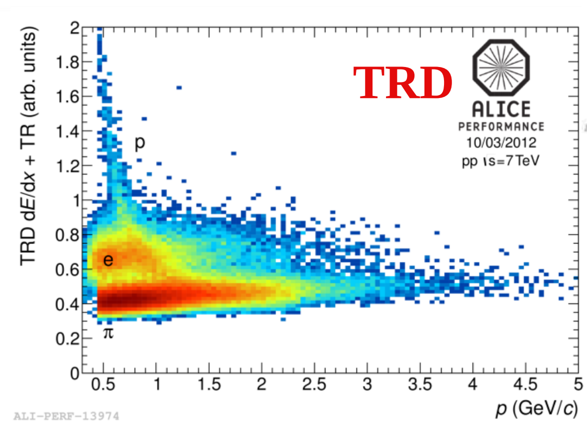
ALICE: five independent PID detectors

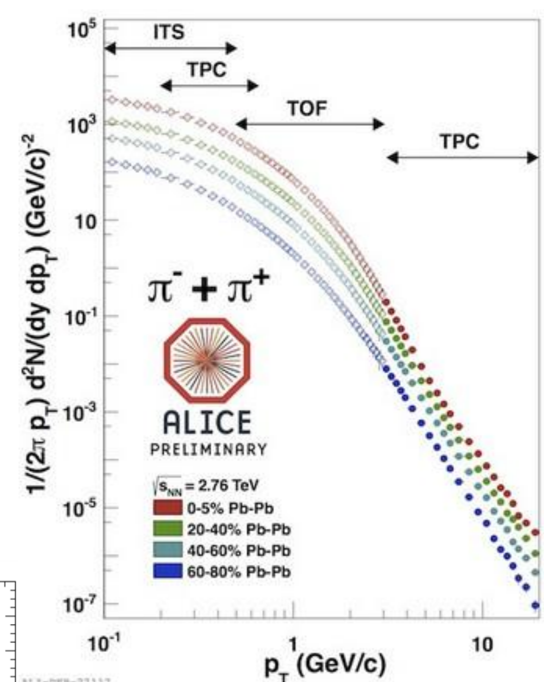












Bayesian PID with a single detector

Probability to be a particle of *i*-type
(*i = e, μ, π, K, p, …*),
if the PID signal in the detector is *s*:

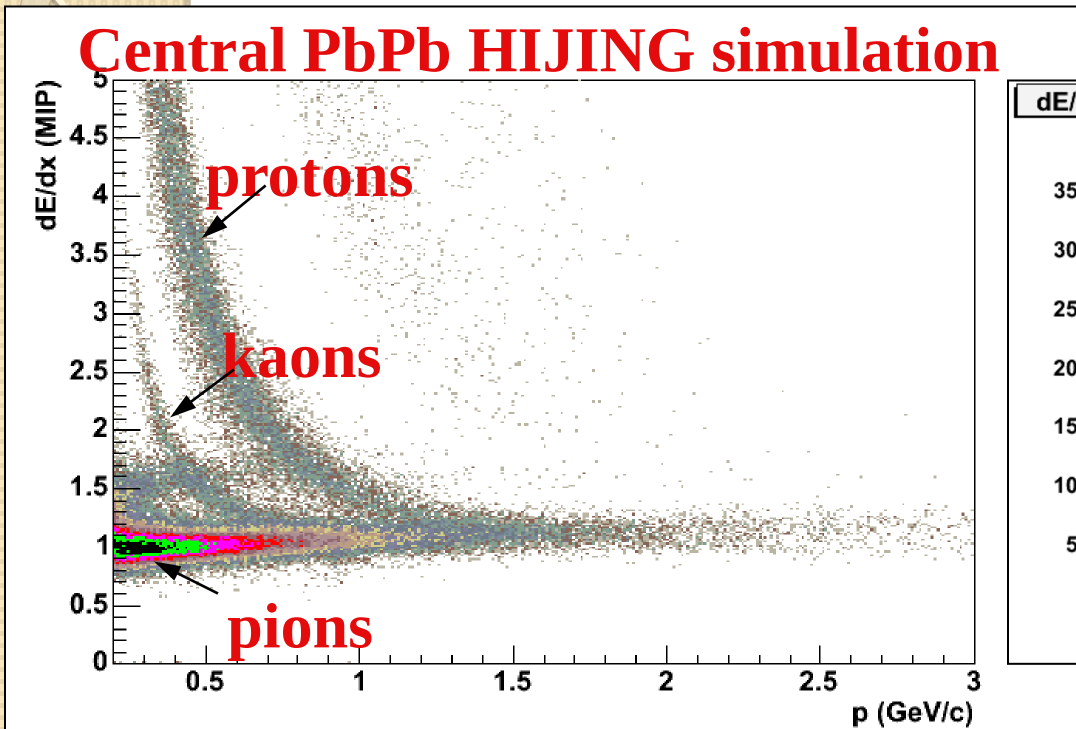
$$w(i \mid s) = \frac{C_i r(s|i)}{\sum_{k=e,\mu,\pi,\ldots} C_k r(s \mid k)}$$

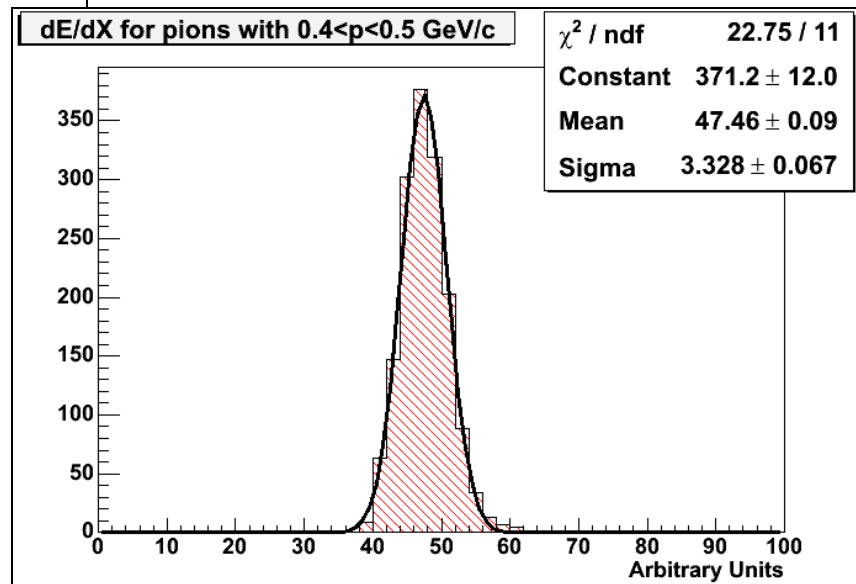
Thomas Bayes (1701-1761)

- **C_i - *a priori* probabilities to be a particle of the *i*-type.**
  "Particle concentrations", that depend on the track selection.
- **$r(s|i)$ – conditional probability density functions to get the signal *s*, if a particle of *i*-type hits the detector.**
  "Detector response functions", that depend on properties of the detector.

The "particle concentrations" and the "detector response functions" can be extracted from the data.

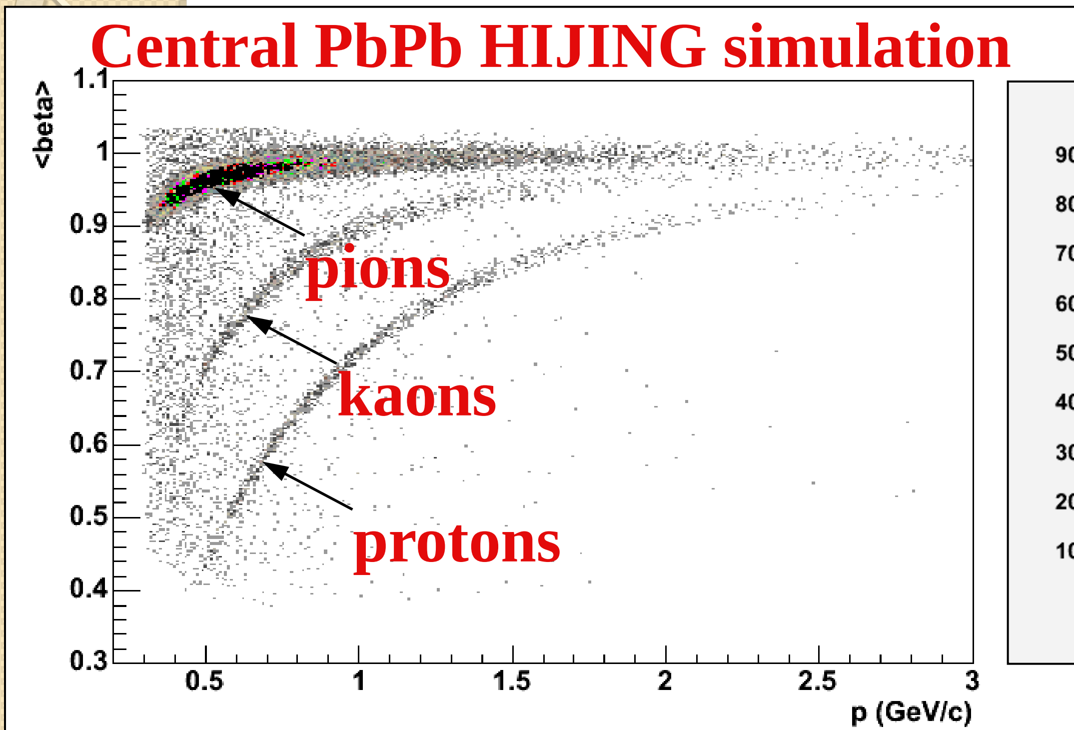
Example: TPC response function

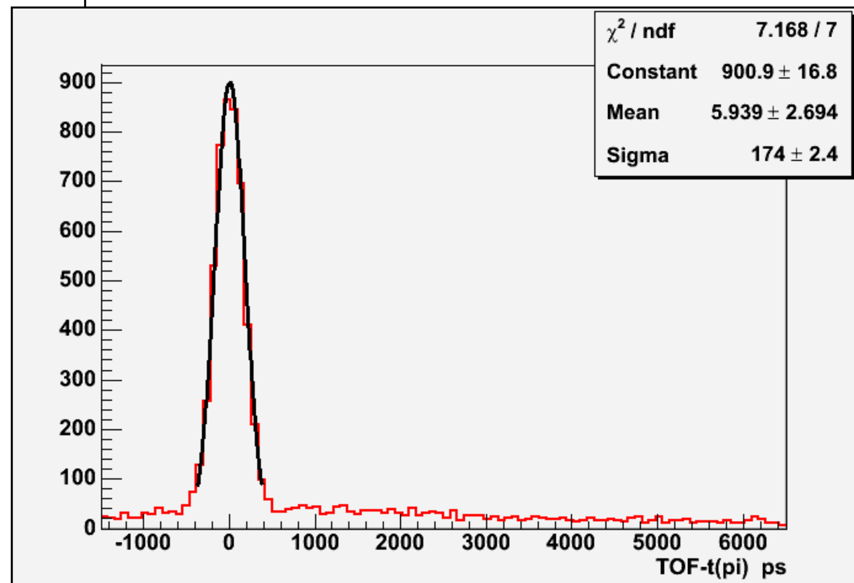




For each momentum ***p*** the function ***r(s|i)*** is a Gaussian with centroid ***<dE/dx>*** given by the Bethe-Bloch formula and sigma σ ***= 0.08<dE/dx>***

Example: TOF response function



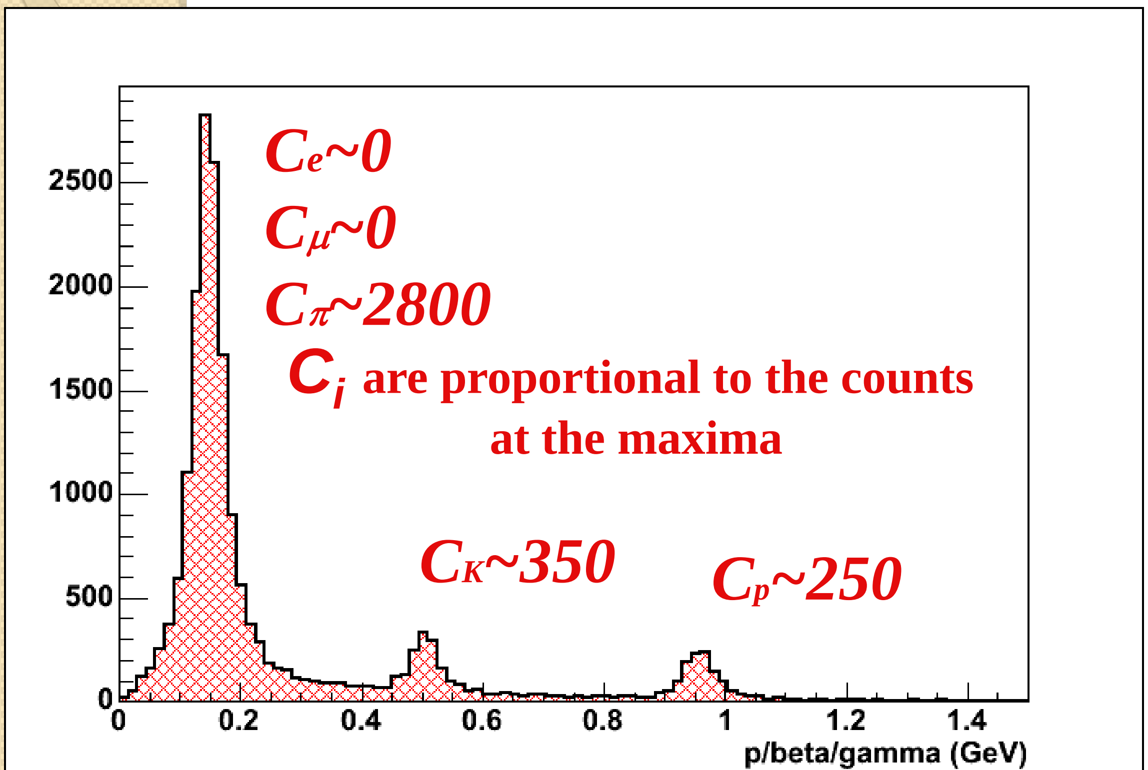


For each momentum *p* the function *r(s|i)* is a Gaussian with centroid at *0* and σ given by the distribution of $(TOF\text{-}t_{\pi})$,

t_{π} – time calculated by the tracking for the pion mass hypothesis.

Example: particle concentrations

<u>Obtaining the *a-priori* probabilities</u>



Selection ITS & TPC & TOF
Central PbPb HIJING events

- *p* – track momentum measured by the tracking
- *beta=L/TOF/c*

  L – track length measured by the tracking

The "particle concentrations" depend on the event and track selection !

PID combined for several detectors

Probability to be a particle of i-type ($i = e, \mu, \pi, K, p, \ldots$), if we observe a vector $S = \{s_{ITS}, s_{TPC}, s_{TOF}, \ldots\}$ of PID signals:

$$W(i\,|\,S) = \frac{C_i R(S|i)}{\sum_{k=e,\mu,\pi,\ldots} C_k R(S\,|\,i)}$$

C_i are the same as in the single detector case (or even something reasonably arbitrary like $C_e \sim 0.1$, $C_\mu \sim 0.1$, $C_\pi \sim 7$, $C_K \sim 1$, …)

$$R(S\,|\,i) \approx \prod_{d=ITS,TPC,\ldots} r_d(s_d\,|\,i)$$ **are the combined response functions.**

The functions $R(S|i)$ are not necessarily "formulas" (can be "procedures"). Some other effects (like mis-measurements) can be accounted for.

The Bayesian Way

- Particle Identification in ALICE uses the "Bayesian method". It consists of three parts:
  - "Calibration part":performed by the calibration software. Obtaining the single detector response functions.
  - "Constant part": performed by the reconstruction software. Calculating (for each track) the values of detector response functions, combining them and writing the result to the Event Summary Data (ESD).
  - "Variable part": performed by the analysis software. Estimating (for a subset of tracks selected for a particular analysis) the concentrations of particles of each type, calculating the final PID weights by means of Bayes' formula using these particle concentrations and the combined response stored in the ESD.

Reconstruction of decaying particles (V0 Reconstruction)

We can distinguish between strong and weak decays

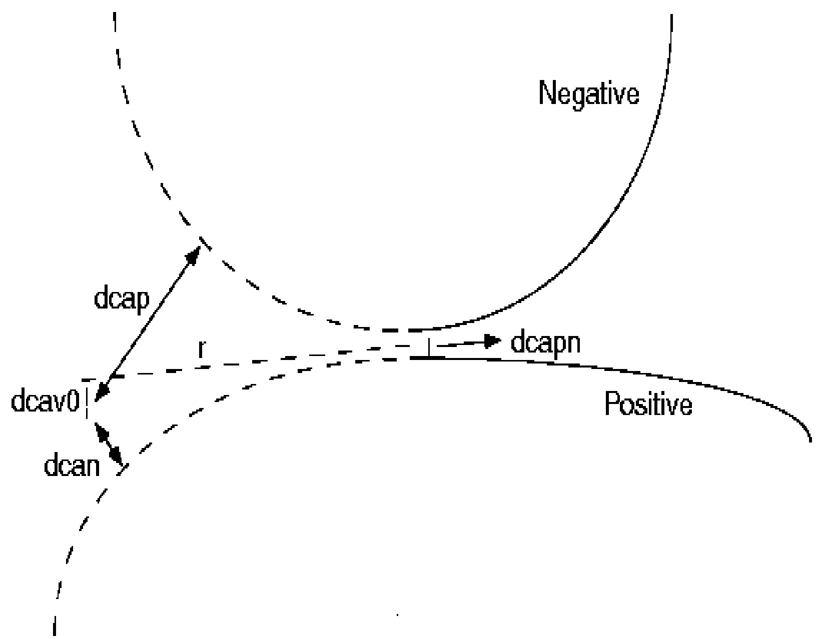
- Strong decays: decay via strong interaction, preserve all quantum numbers ($t \sim 10^{-23}$s ~ few fm/c)

- Weak decays: decay via weak interactions, violate certain quantum number conservation (specifically strangeness), e.g. $\Lambda \rightarrow p + \pi^-$ ($t \sim 10^{-10}$s ~ few cm/c)

- Decaying particles are generally called V0 since a neutral particle decays into two charged particles. Since the neutral track is invisible in the detector, the traces look like a "V".

Geometric cuts in V0 Reconstruction

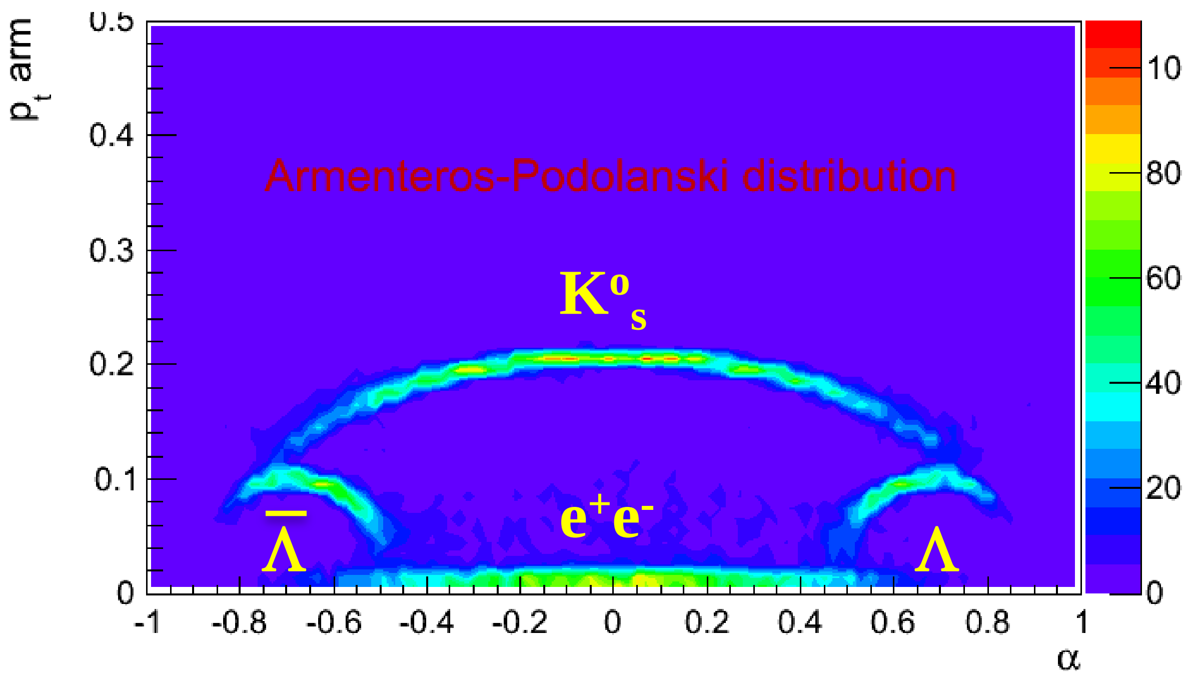
- If decay is strong then simply connect all charged particles from the primary vertex to reconstruct the invariant mass
- If decay is weak then use geometric and kinematic cuts.



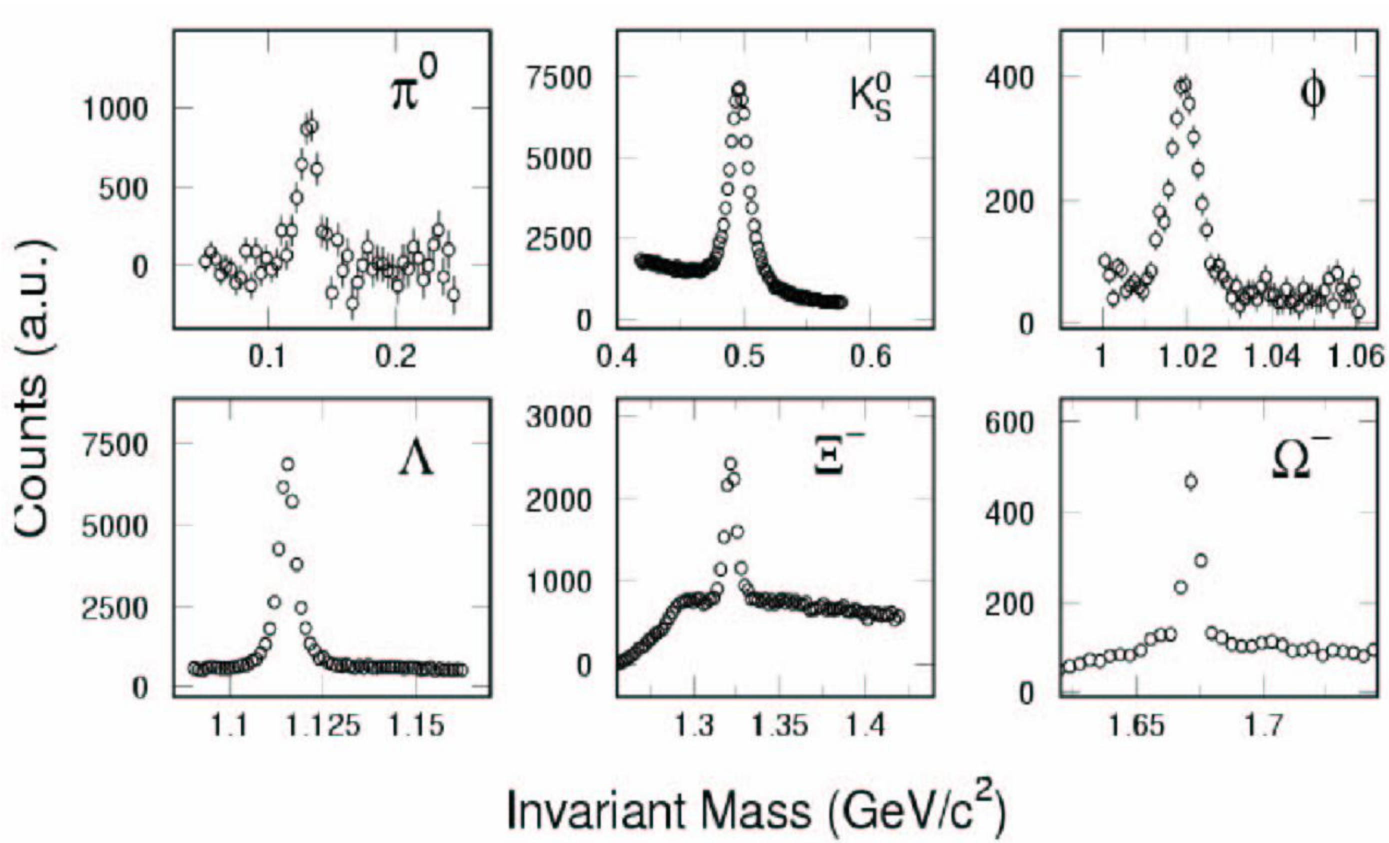
particle	Quark content	mass	Lifetime (ct)
Proton (p)	uud	938 MeV	stable
Lambda (Λ)	uds	1115 MeV	7.89 cm
Xi (Ξ)	uss	1321 MeV	4.91 cm
Omega (Ω)	sss	1672 MeV	2.46 cm

Kinematic cuts in V0 Reconstruction

- Kinematic cuts have to be used with caution since they might introduce biases
- One very successful cut is based on the Armenteros-Podolanski plot: a 2d plot of transverse momentum pT of the oppositely charged decay products with respect to the versus the longitudinal momentum asymmetry: $\alpha = \frac{p_l^+ - p_l^-}{p_l^+ + p_l^-}$



The final product (Example: STAR) for strong decays and weak decays



Reconstruct particles in full azimuthal acceptance of STAR!

$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 = m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right).$$
$$= 2p_{T1}p_{T2}(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)).$$

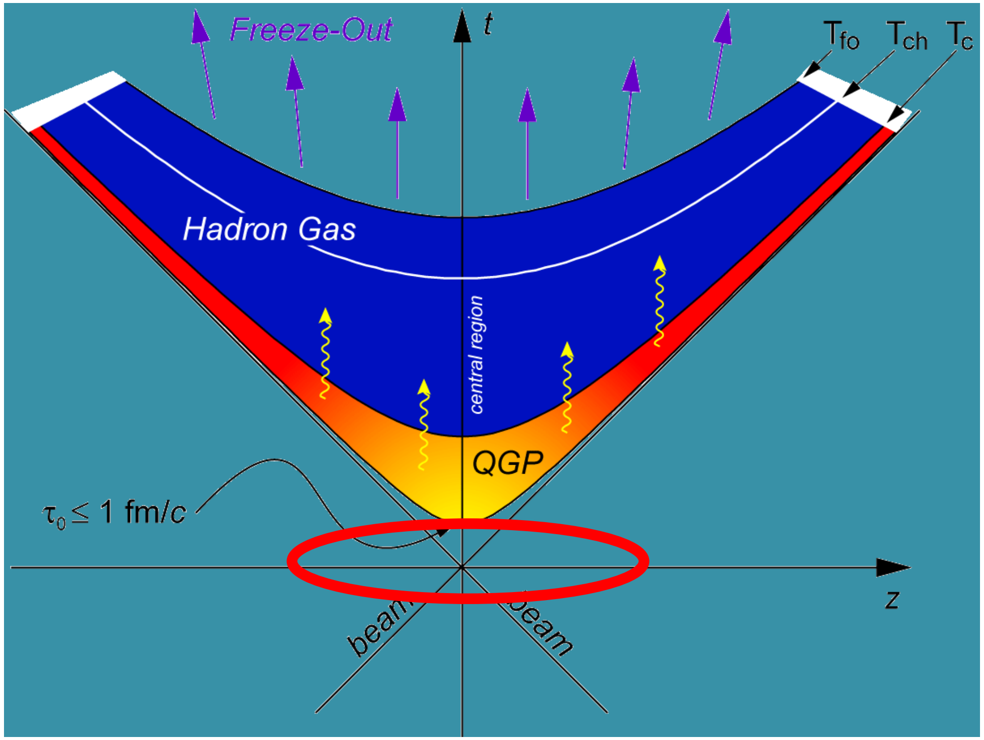
Summary: lecture 1

Requirements for deconfined matter formation
(based on lattice QCD calculations) are met at RHIC and LHC:

Initial energy density:
$\varepsilon \geq 10$ GeV/fm^3
(model dependent)

Initial Temperature:
T_{RHIC} ~ 350 MeV
T_{LHC} > 500 MeV

Gluon density @ RHIC:
dN/dy ~ 800-1200



Experimental tools are in place
to study the new phase and *re*confinement