Advanced Topics in Particle Physics: LHC Physics

Part III: Heavy-Ion Physics

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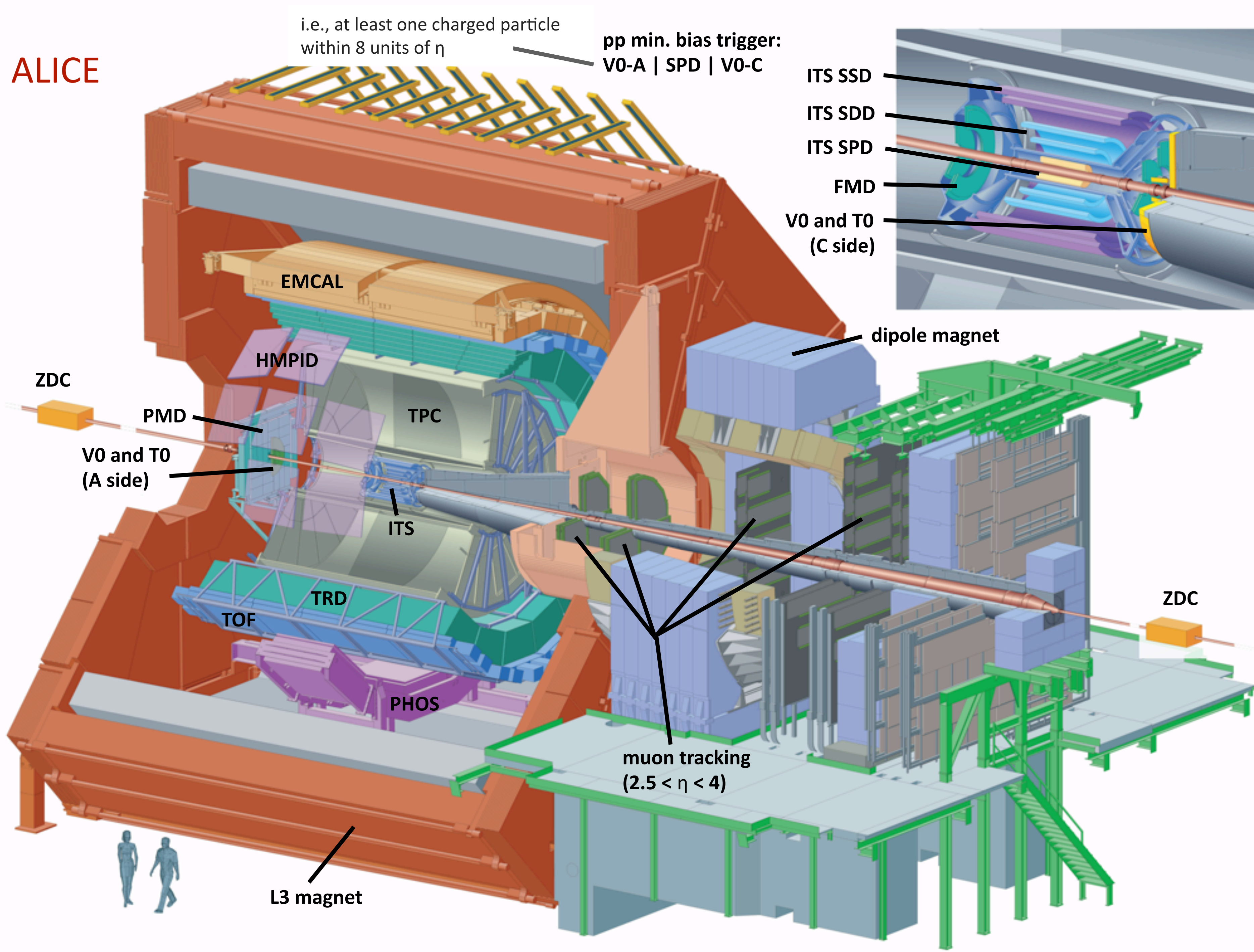
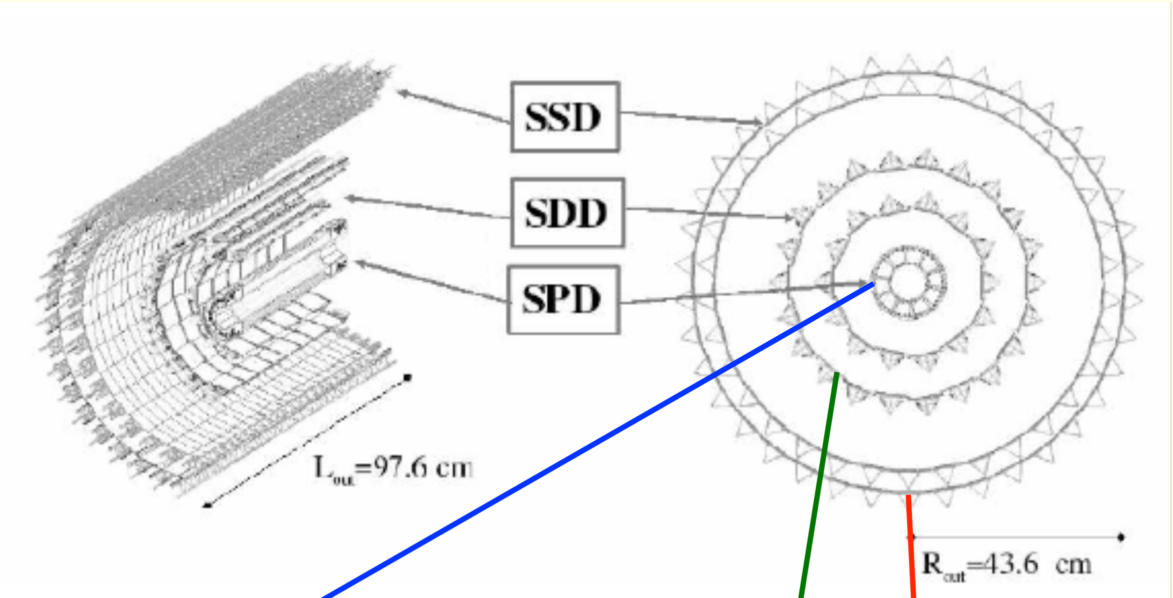
3. The ALICE experiment

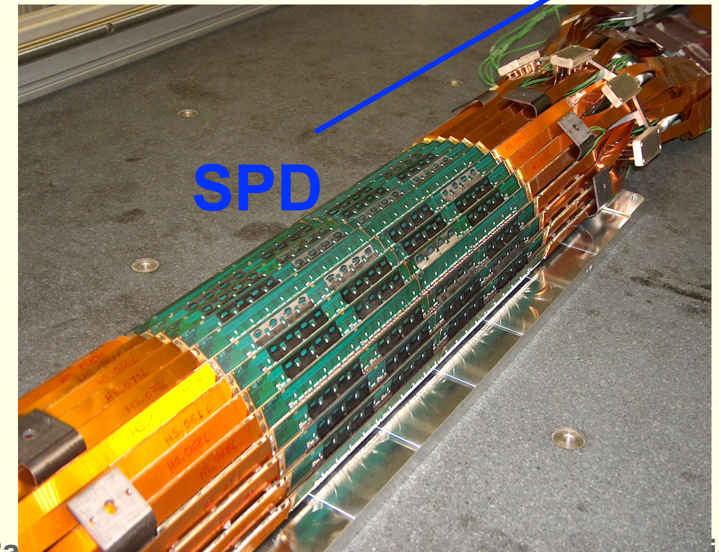


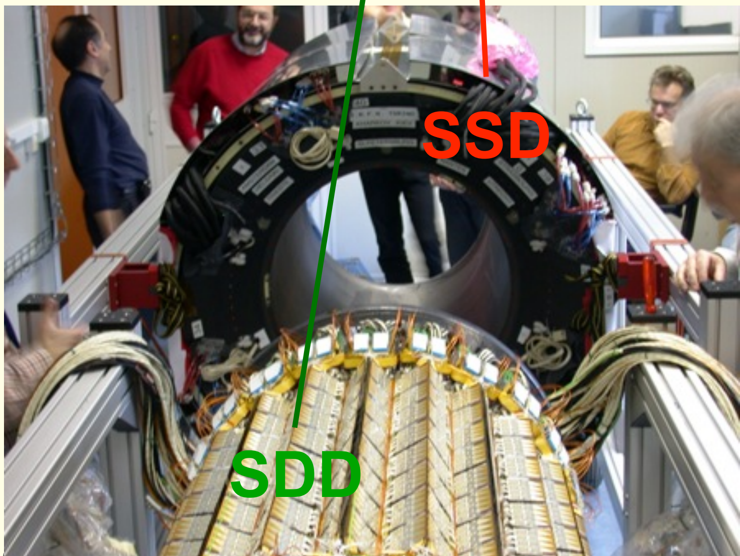
ALICE
i.e., at least one charged particle
within 8 units of η
pp min. bias trigger:
V0-A | SPD | V0-C
ITS SSD
ITS SDD
ITS SPD
FMD
V0 and T0
(C side)
EMCAL
HMPID
ZDC
PMD
TPC
V0 and T0
(A side)
ITS
dipole magnet
TRD
TOF
PHOS
ZDC
muon tracking
(2.5 < η < 4)
L3 magnet

Inner Tracking System (ITS)

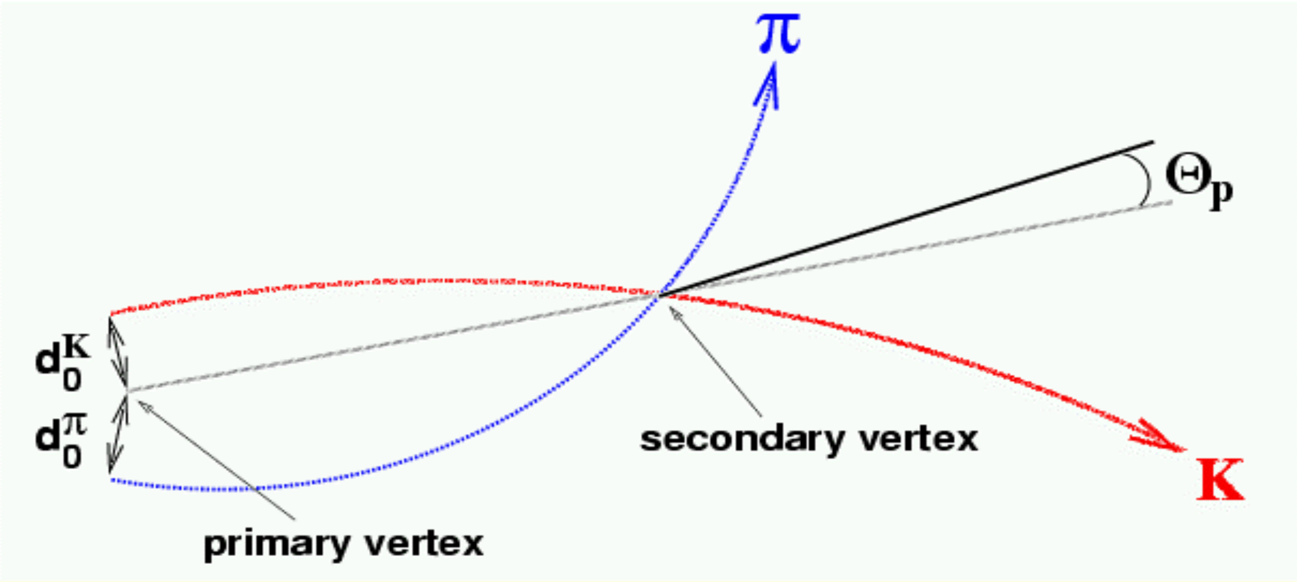
- 6 layers silicon
  - 2 pixel detectors (SPD)
  - 2 drift detectors (SDD)
  - 2 strip detector (SSD)
- Reconstruction of primary vertex ($\sigma < 100\ \mu m$)
- Secondary vertex, e.g., for heavy-quark measurements (see next slide)





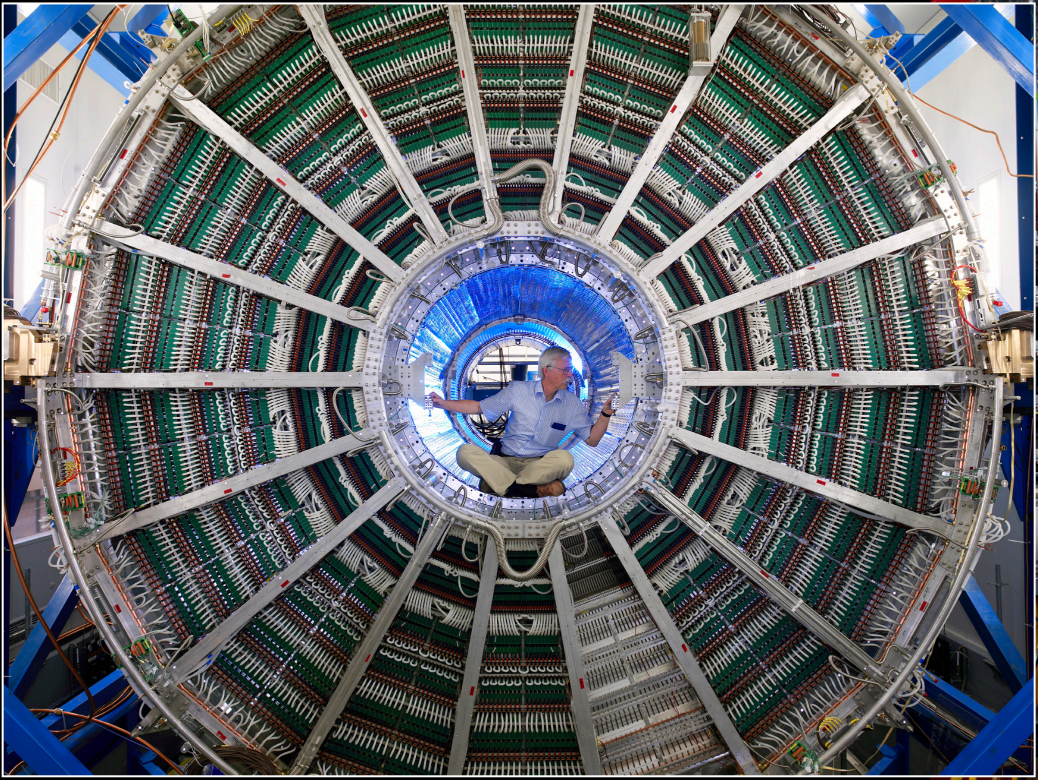


Reconstruction of Particles with c and b Quarks via Displaced Vertices

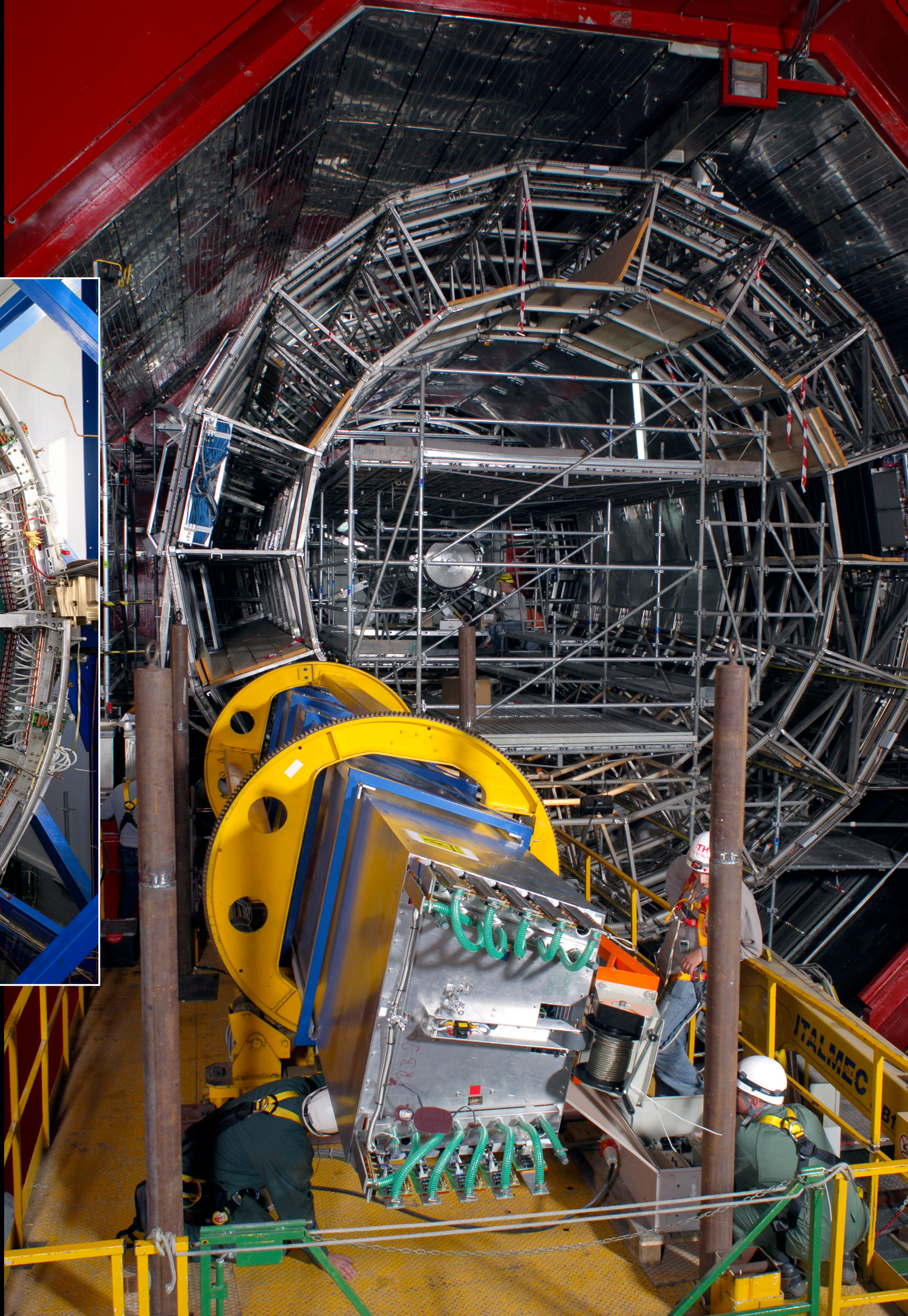


D^0: cτ = 122.9 μm, $D^{+/-}$: cτ = 311.8 μm
B^0: cτ = 455.4 μm, $B^{+/-}$: cτ = 492.0 μm

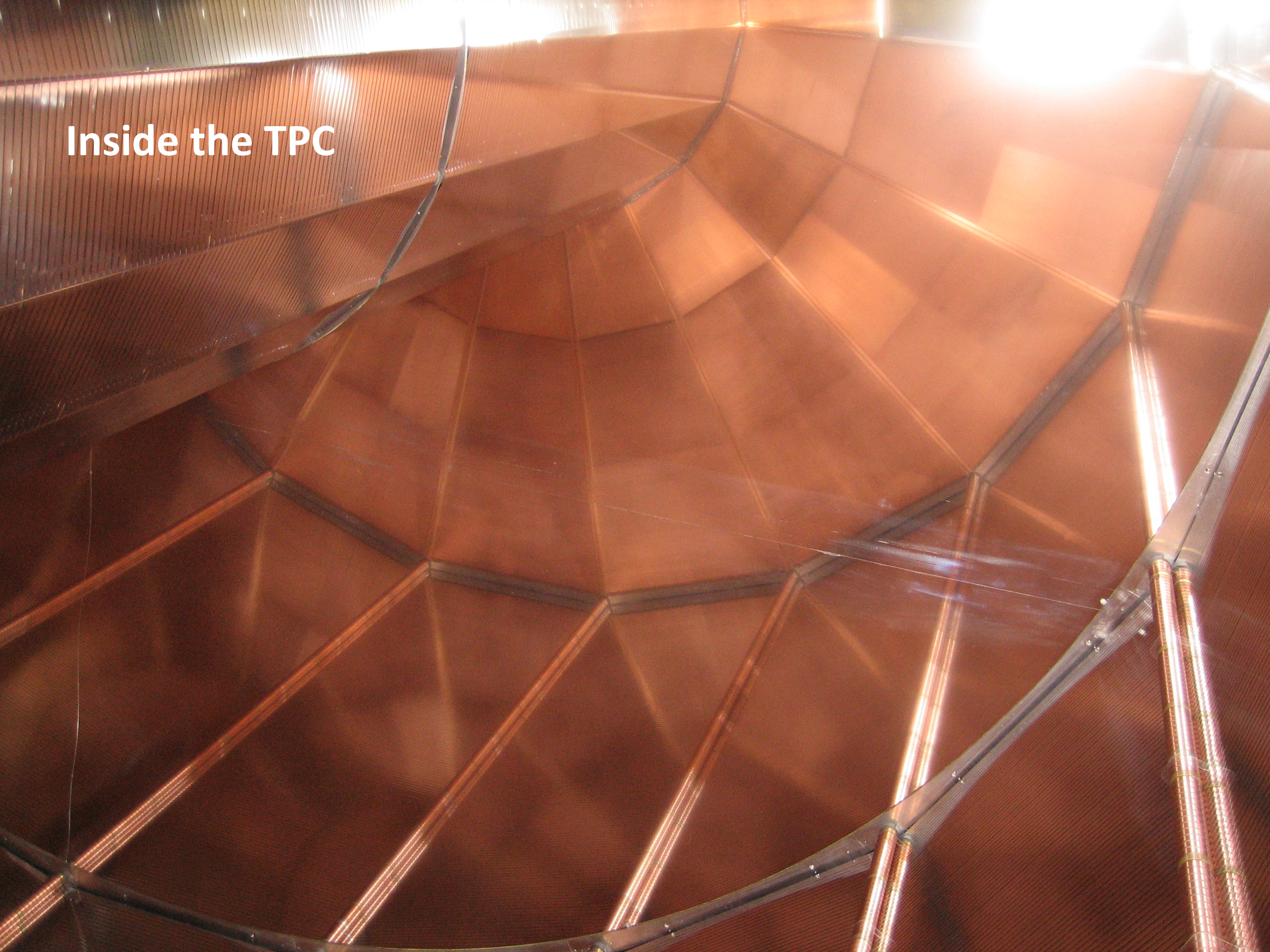
TPC and TRD



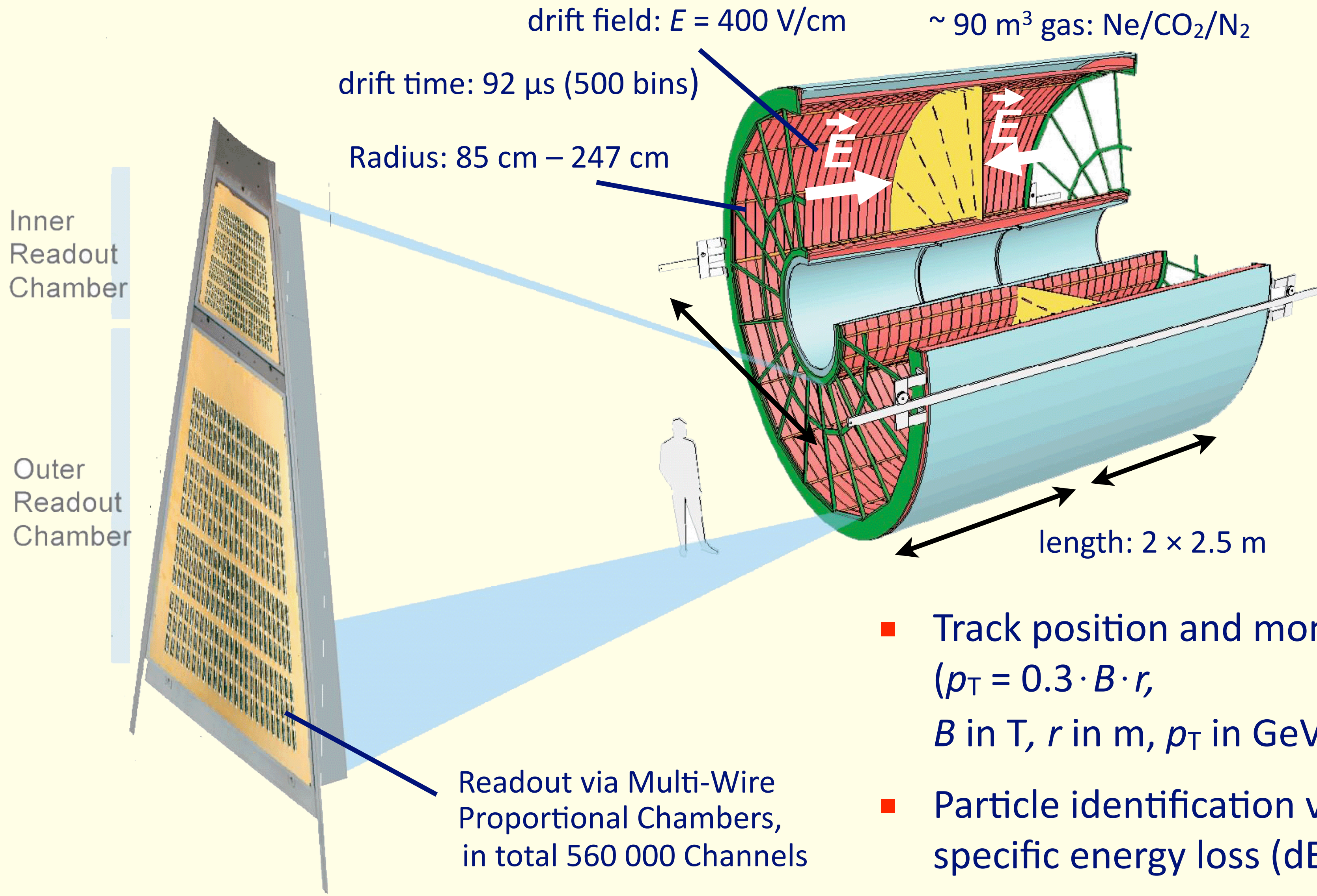
Time Projection Chamber (TPC)



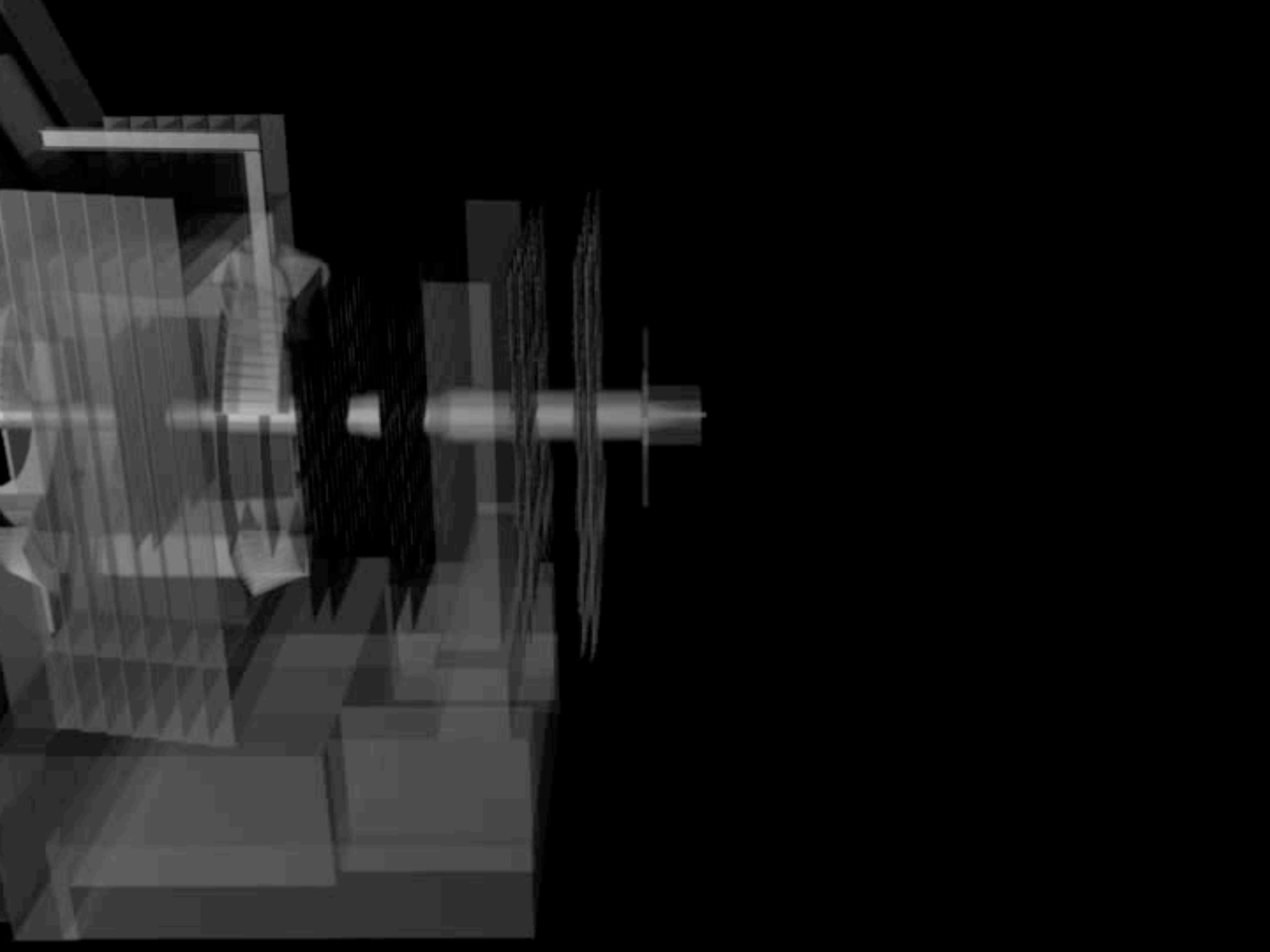
Installation of the
first TRD supermodule
(October 2006)


Inside the TPC

The ALICE-TPC: The World's Largest Time Projection Chamber (TPC)

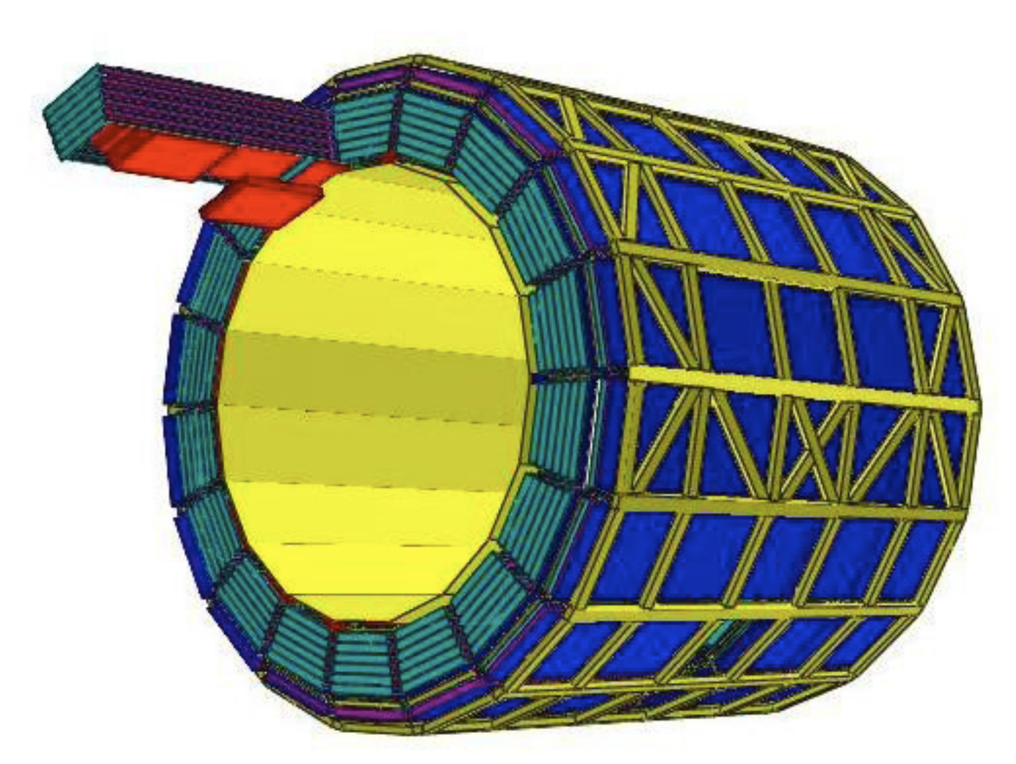


- Track position and momentum ($p_T = 0.3 \cdot B \cdot r$, B in T, r in m, p_T in GeV/c)
- Particle identification via specific energy loss (dE/dx)



The Transition Radiation Detector (TRD)

task: electron id by TR:
J/ψ, $\Upsilon \rightarrow e^+ e^-$
D, B → e + anything (semi-leptonic)
trigger on high p_t electrons



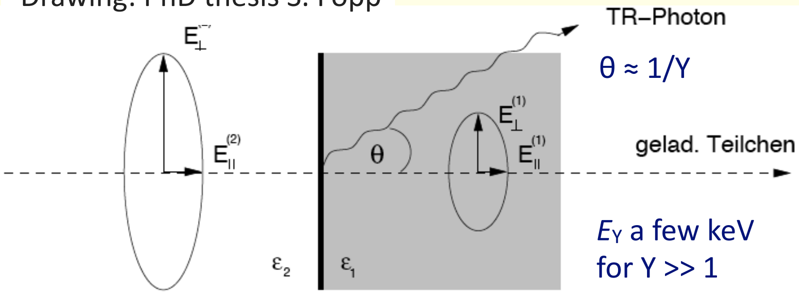
- 540 chambers /18 supermodules
- total area: 694 m^2
- gas volume: 25.8 m^3 (Xe-CO_2, 85:15)
- resolution ($r\phi$): 400 µm
- 1.15 M readout channels

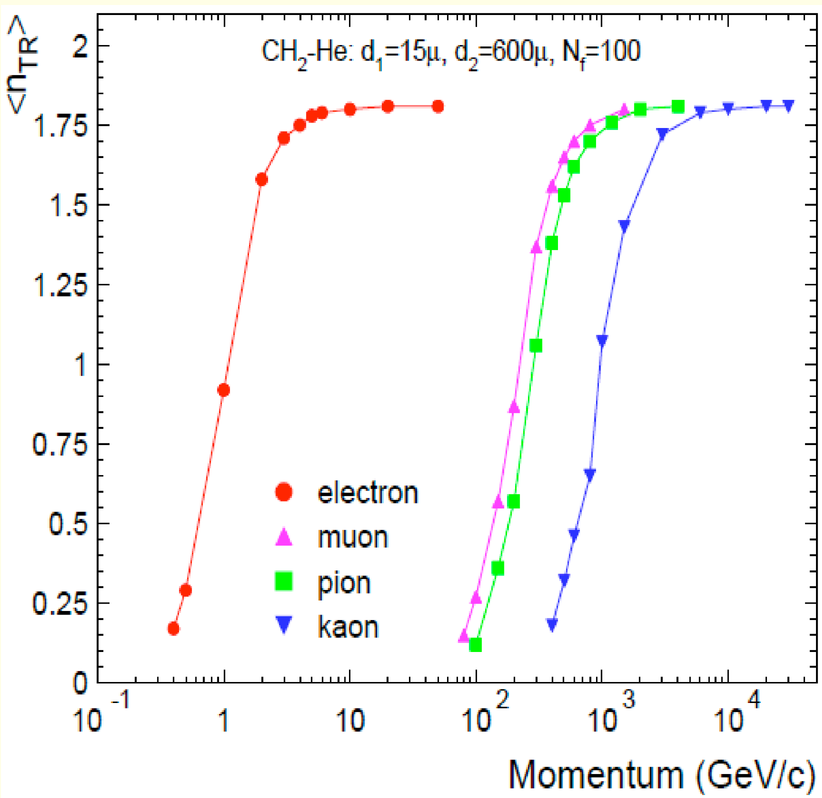
90% funded by Germany: GSI, Univ. DA, HD, FRA, MS, FH Cologne, Worms

Transition Radiation (TR)

A. Andronic, J. Wessel, Transition Radiation Detectors, 2011

Drawing: PhD thesis S. Fopp

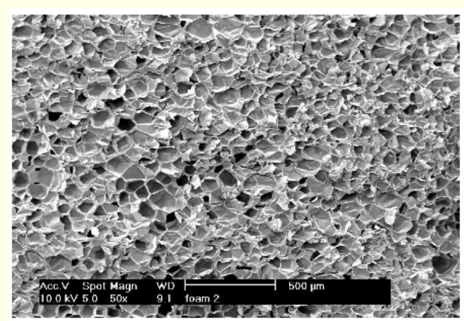




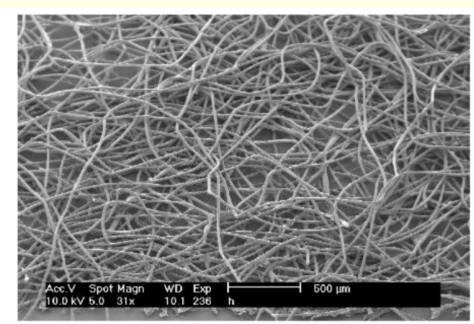
- Charged particles emit transition radiation when they cross boundaries of media with different dielectric constants ε
- Small probability for emission at single surface (~ α = 1/137) ⇒ many boundaries
- Significant TR photon production only for charged particles with Lorentz factor γ > 1000
  ⇒ only electrons emit TR in the relevant momentum range 1 < p < 100 GeV/c

Typical TR radiators:

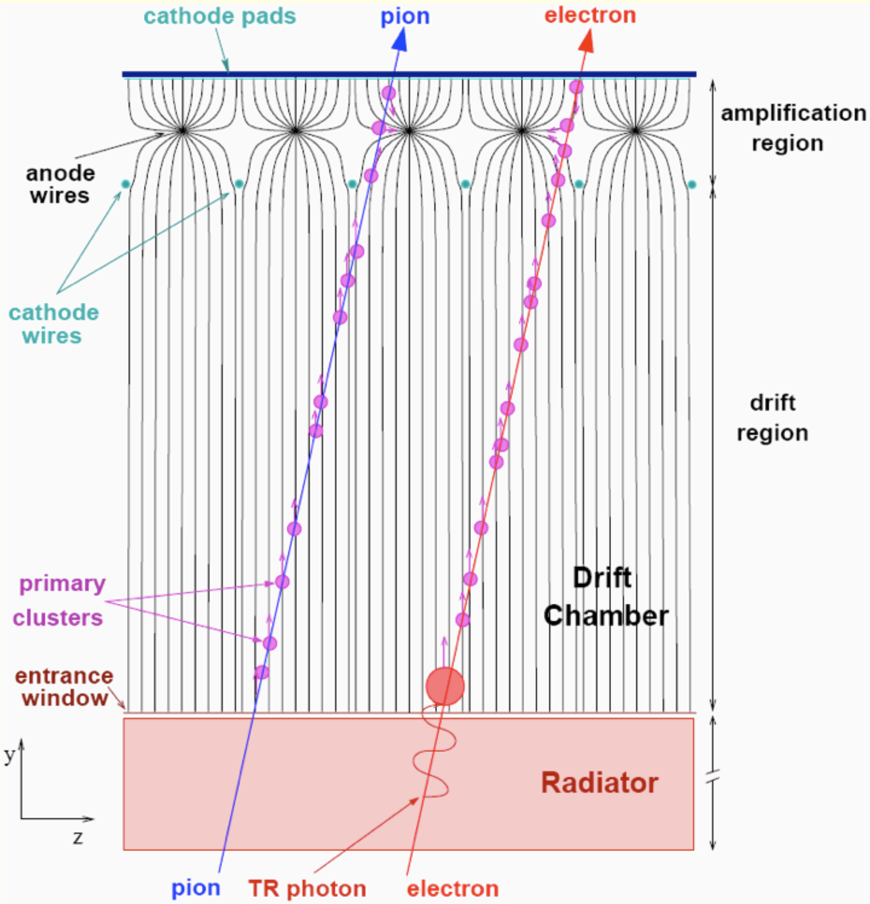
Foams

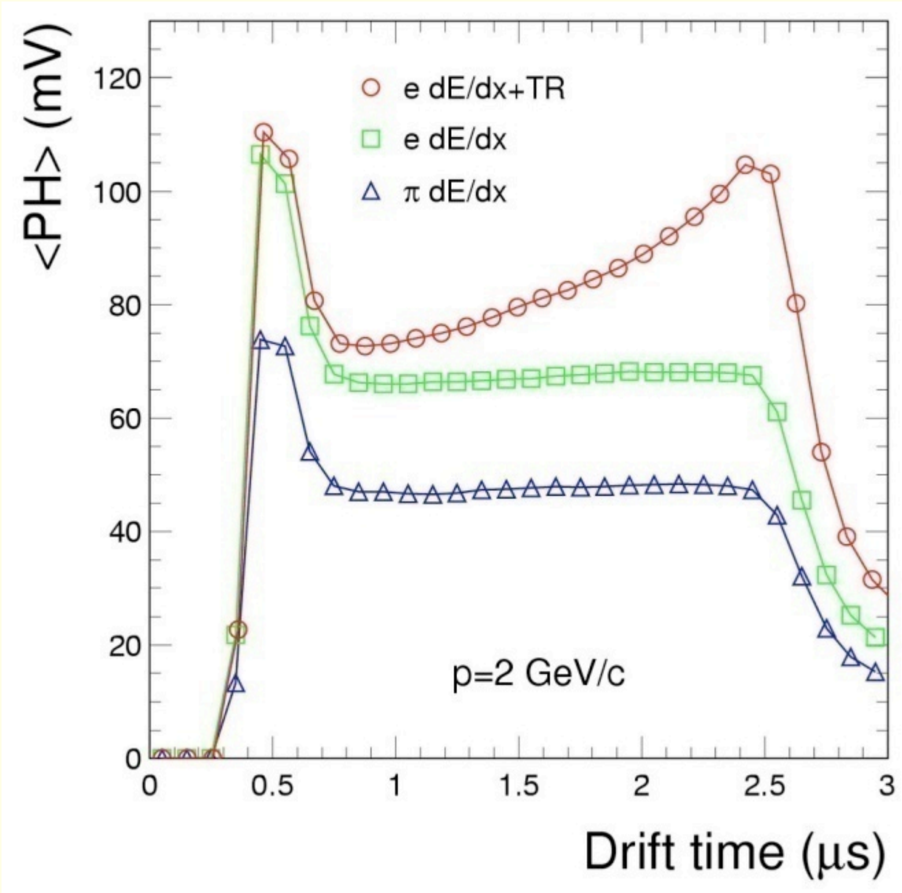


Fibers



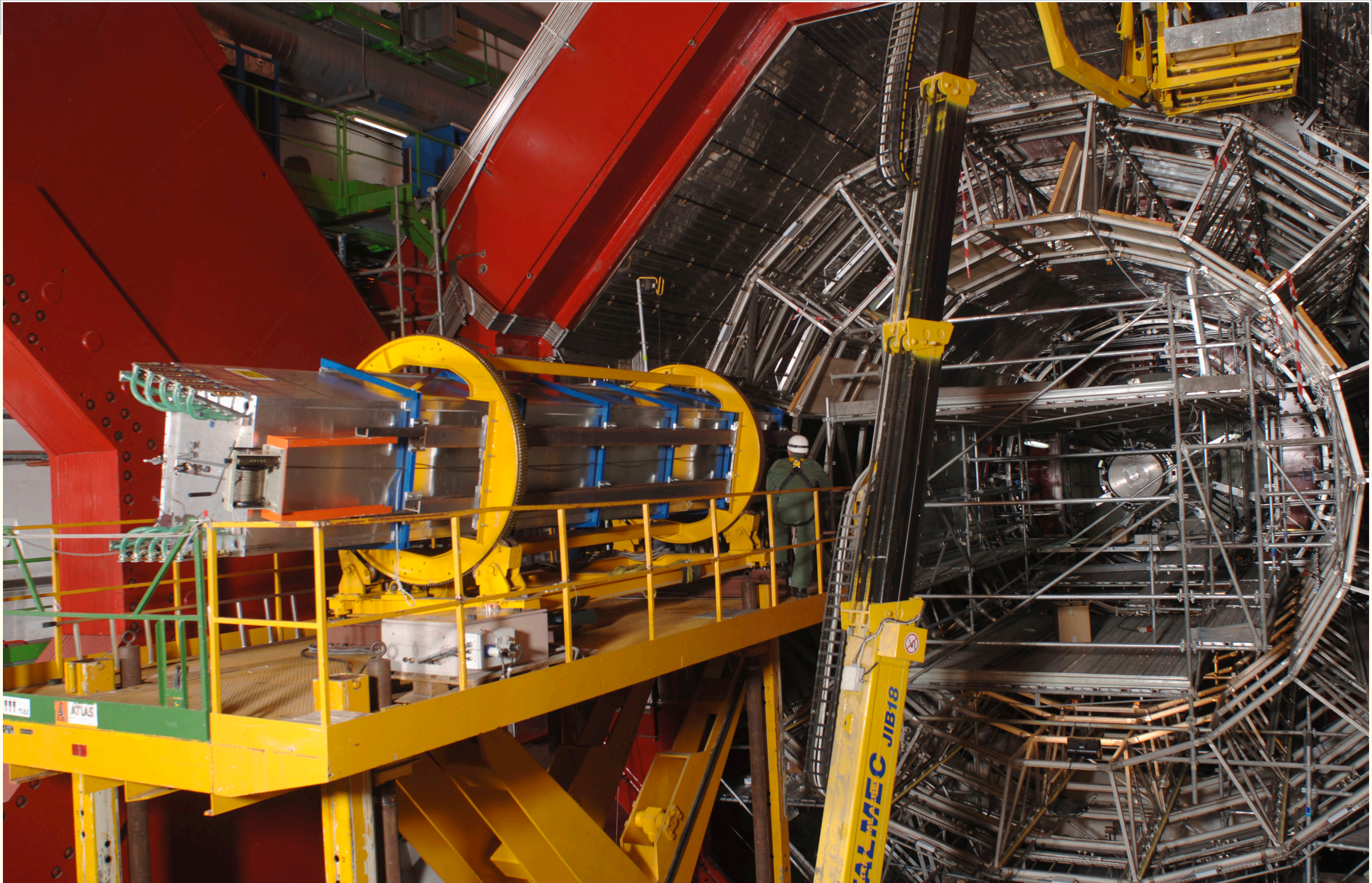
TRD – Signal Generation

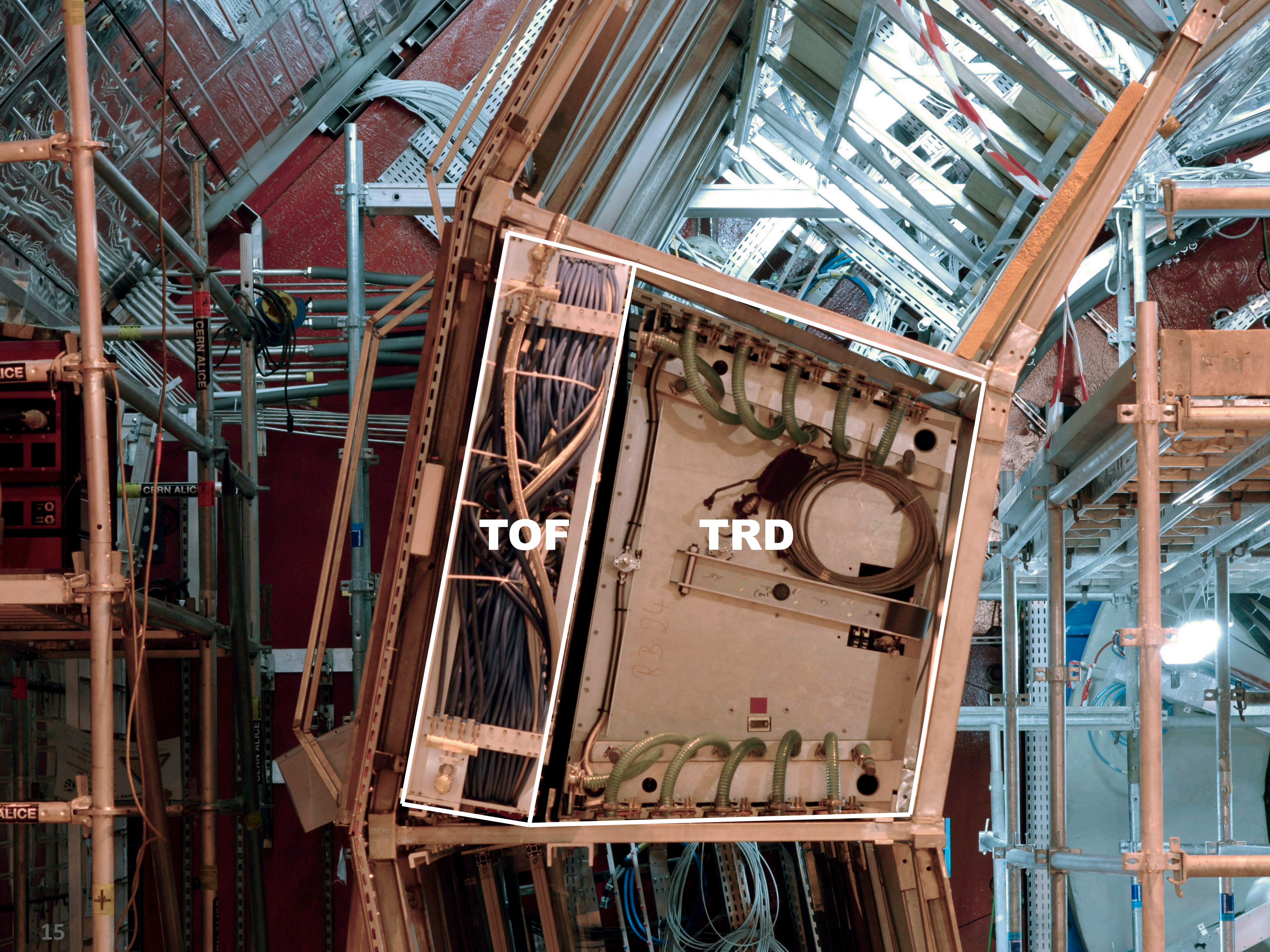




- Charged particles induce a signal in the detector
- Electrons: transition radiation + higher dE/dx
- Goal of Electron ID in ALICE: misidentified pions 1 % or less

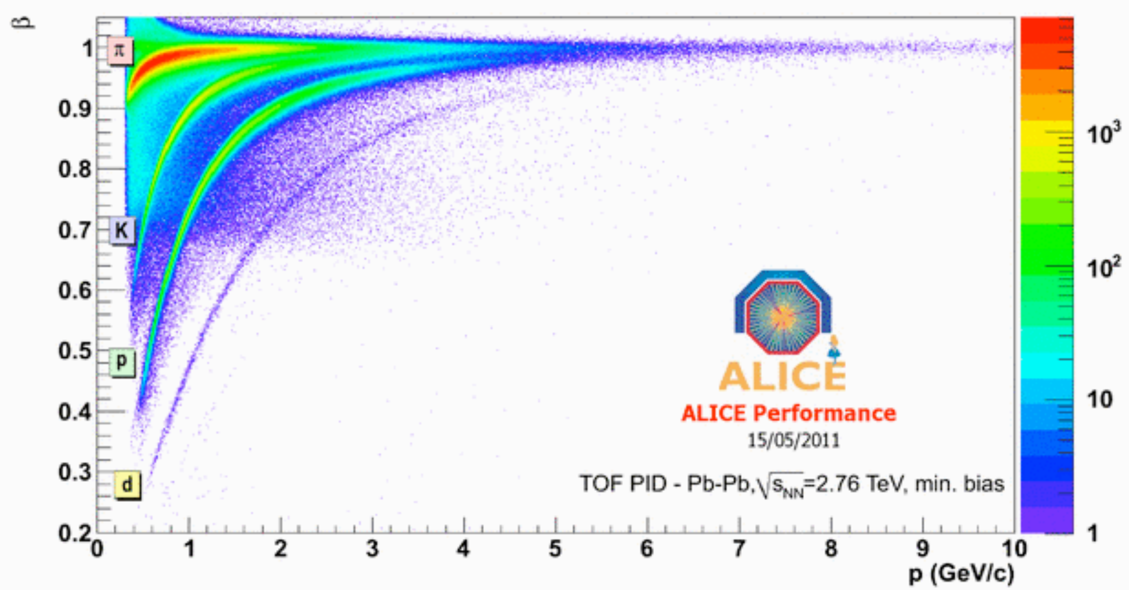
First TRD supermodule in ALICE – Oct 2006

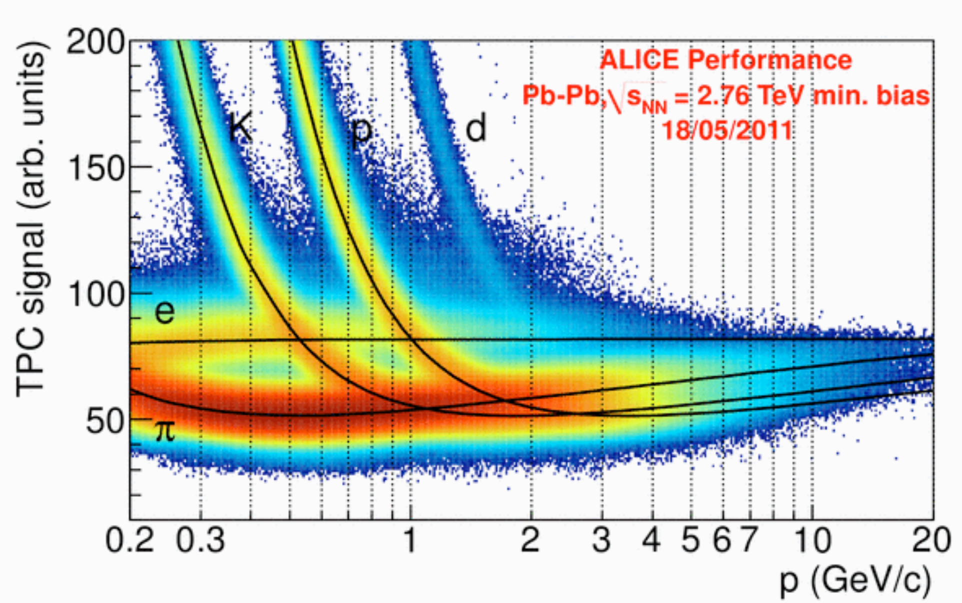


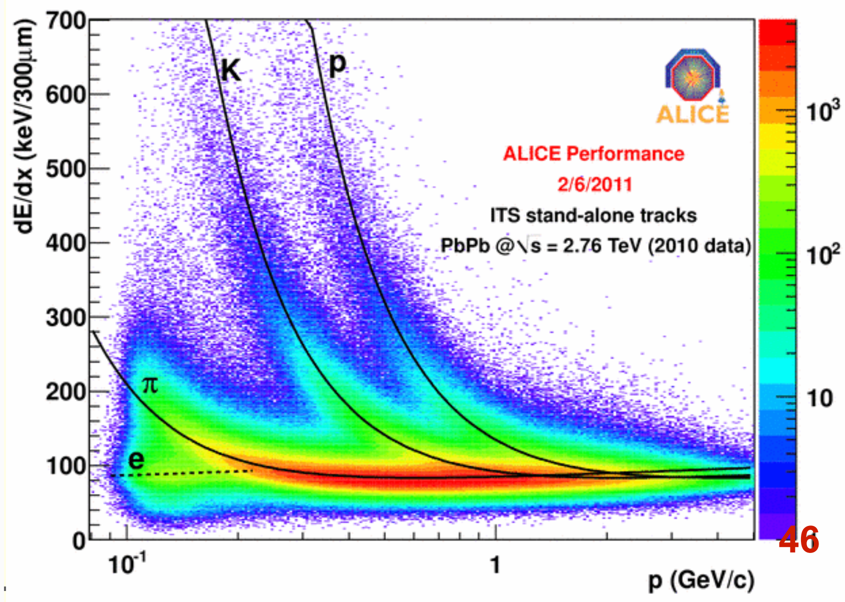

TOF
TRD
CERN ALICE
CERN ALICE

Particle identification via dE/dx and Time-of-Flight

- dE/dx in TPC
  - Up to 159 samples
  - Resolution ~ 5%
- dE/dx in ITS
  - Low momentum reach
- Time of Flight by TOF
  - 3σ separation:
  - π/K up to 2.5 GeV/c
  - p/K up to 4.0 GeV/c







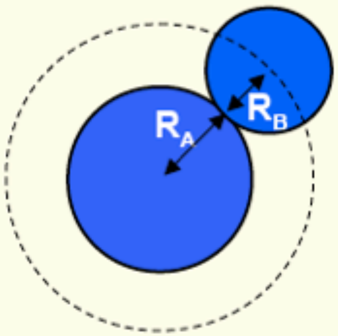
Summary on ALICE: Excellent Momentum Reconstruction and Particle ID Capabilities at Low p_T

- ALICE designed for Heavy-Ion collisions
- Robust tracking over larger p_T range (~0.1 GeV < p_T < 100 GeV)
  - many space points per track
  - low material budget (~ 11.4% X_0 for R < 2.5 m and $|\eta|$ < 0.9)
  - moderate magnetic field (0.5 T)
- Excellent vertexing (6 layers of Si) for charm & beauty
- PID over large p_T range
  - 'Stable' hadrons (π, K, p): 100 MeV < p < (few 10 GeV):
    dE/dx in silicon (ITS) and gas (TPC) + time-of-flight (TOF) + Cherenkov (RICH)
  - Decay topologies: Kinks (K^+, K^-) [e.g., $K \rightarrow \mu + \nu$] and
    invariant mass analysis of decay products (K_S^0, Λ, φ, D, ...):
    Secondary vertex reconstruction
  - Leptons (e, μ), photons, η, π^0:
    Electrons TRD: p > 1 GeV, muons: p > 5 GeV, π^0 in PHOS/EMCal and via conversions

4. Basics of Heavy-Ion Collisions

Ultra-Relativistic Nucleus-Nucleus Collisions: Many Aspects Controlled by Nuclear Geometry

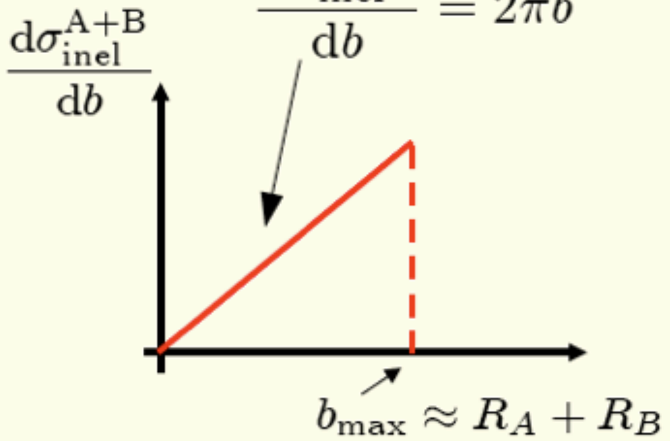
- Ultra-relativistic energies
  - De Broglie wave length much smaller than size of the nucleon
  - Wave character of the nucleon can be neglected for the estimation of the total cross section
- Nucleus-Nucleus collision can be considered as a collision of two black disks



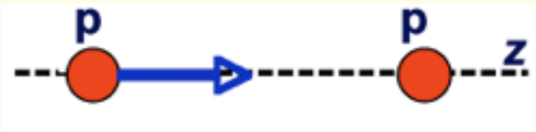
$$R_A \approx r_0 \cdot A^{1/3}, \;\; r_0 = 1,2\,\mathrm{fm}$$

$$\sigma_{\mathrm{inel}}^{\mathrm{A+B}} \approx \sigma_{\mathrm{geo}} \approx \pi r_0^2 (A^{1/3} + B^{1/3})^2$$

$$\frac{d\sigma_{\mathrm{inel}}^{\mathrm{A+B}}}{db} = 2\pi b$$



Stopping in Nucleon-Nucleon Collisions

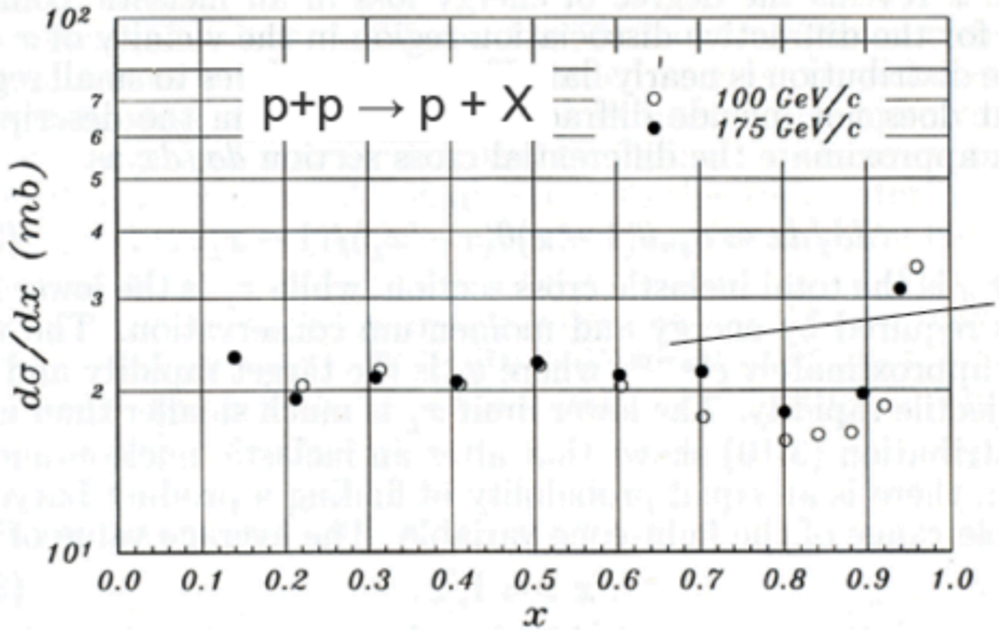


Feynman-x $x_F := \frac{p_z}{p_{z,0}} \approx \frac{E}{E_0} \approx \frac{m_T}{m} e^{y-y_0}$

$E \approx \frac{m_T}{2} e^{y}$

Longitudinal momentum before collisions: $p_{z,0}$

Longitudinal momentum after collisions: p_z



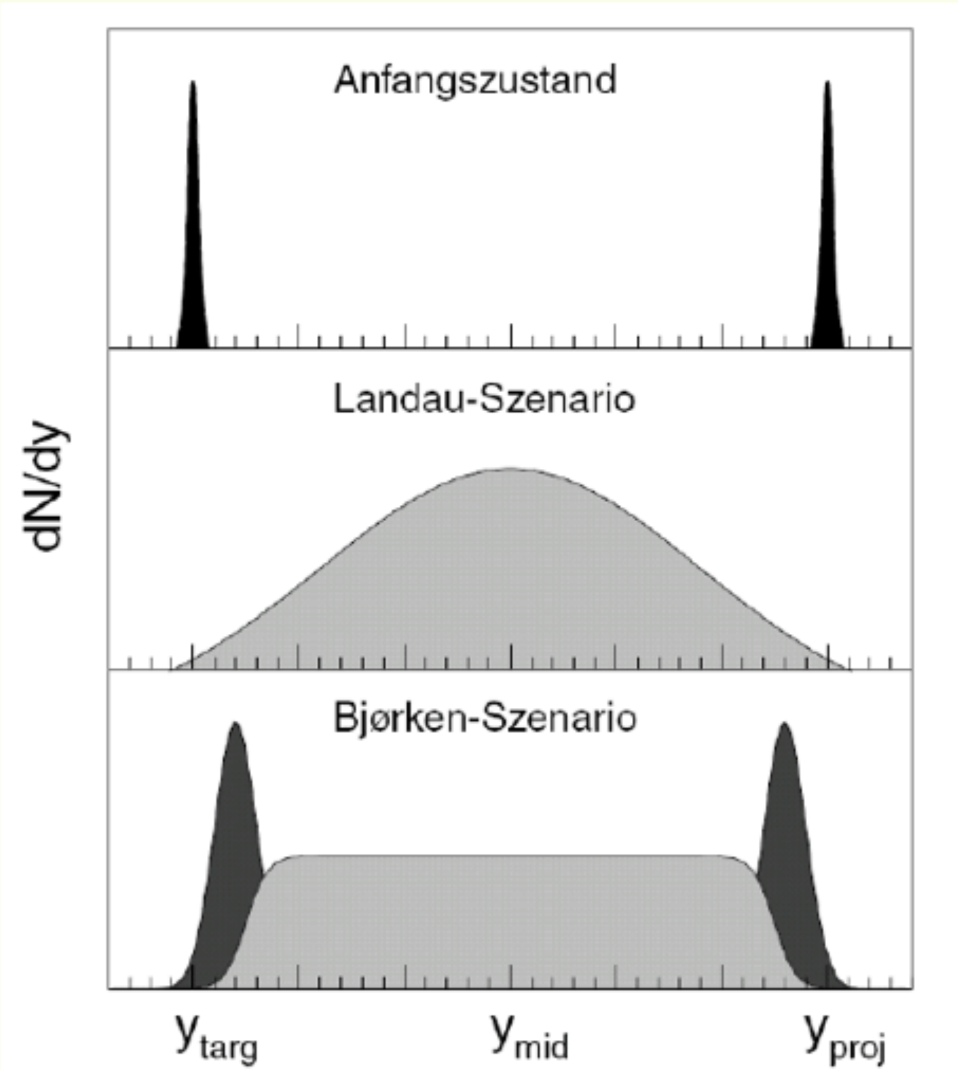
$$\frac{dn_p}{dy} = \underbrace{\frac{dn_p}{dx_F}}_{\approx \text{constant}} \frac{dx_F}{dy} \propto e^{y-y_0}$$

Feynman-x distribution of the leading proton is approximately constant.

$$\langle y \rangle \approx \frac{\int_{-\infty}^{y_0} y\, e^{y-y_0}\, dy}{\int_{-\infty}^{y_0} e^{y-y_0}\, dy} = y_0 - 1$$

On average, a proton loses about one unit of rapidity (Δy ≈ 1) in an inelastic p+p collision (approximately independent of the initial energy)

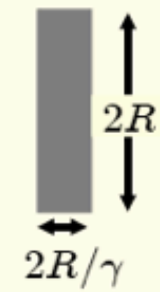
Two Extreme Pictures: Landau and Bjorken Model



- Landau scenario
  - Complete stopping of the nuclei
  - Initial condition for hydrodynamic expansion

$$V_0 = V^{\mathrm{rest}}_{\mathrm{nucleus}} / \gamma_{\mathrm{CMS}}$$

$$\varepsilon_0 = \sqrt{s} / V$$

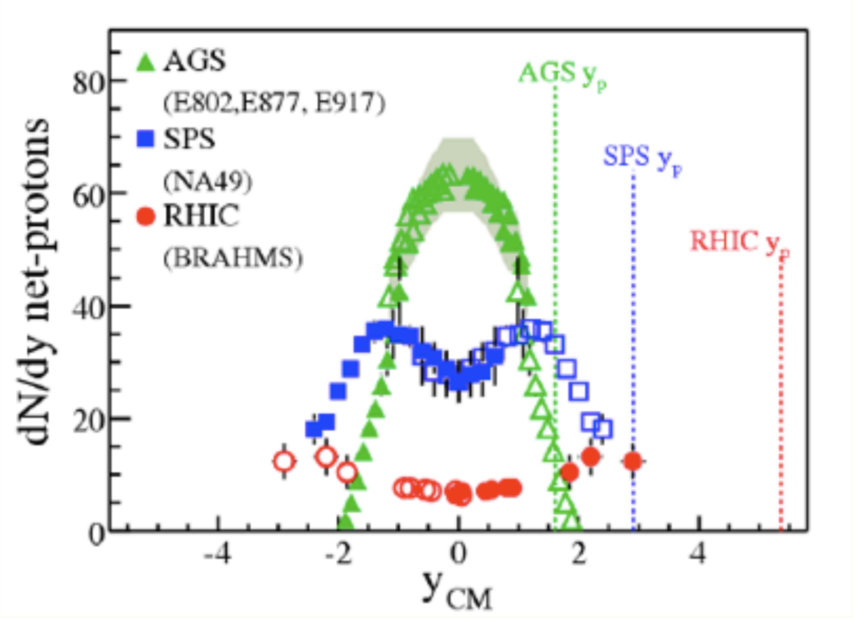


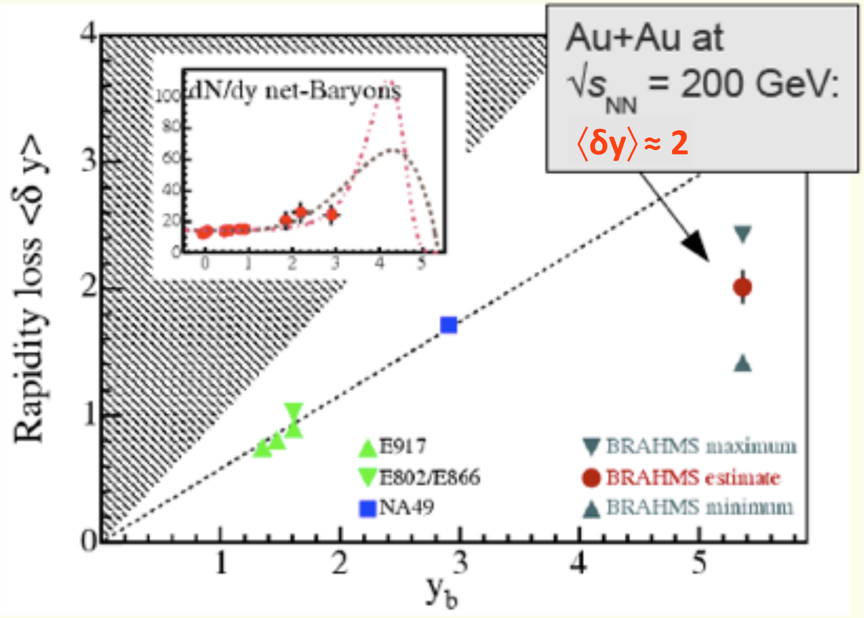
- Bjorken scenario
  - transparency
  - flat rapidity distribution

Complete stopping of the nuclei in central collisions up to $\sqrt{s_{NN}} \sim 5 - 10$ GeV, transparency (baryon-free QGP at central rapidities) for $\sqrt{s_{NN}} > \sim 100$ GeV

Stopping in A+A Collisions

Brahms, PRL 93:102301, 2004





Stopping inferred from rapidity distribution of net-baryons (baryons-antibaryons)

$$\langle \delta y \rangle = y_p - \langle y \rangle \qquad \langle y \rangle = \frac{2}{N_{\mathrm{part}}} \int_0^{y_p} y \frac{dN_{B-\bar{B}}}{dy}\, dy$$

MC generator used to go from the measured net-protons to net-baryons

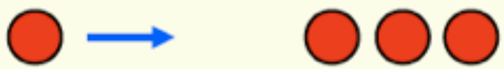
Average energy per net baryon:

$$E = \frac{1}{N_{\mathrm{part}}} \int_{-y_p}^{y_p} \langle m_T \rangle \cosh y \frac{\mathrm{d}N_{B-\bar{B}}}{\mathrm{d}y}\, \mathrm{d}y \approx 27 \pm 6 \mathrm{GeV}$$

Thus, the average energy loss of a nucleon in central Au+Au@200GeV is 73 ± 6 GeV

Particle Multiplicities in p+A Collisions

- Proton-nucleon collision
  - Example:

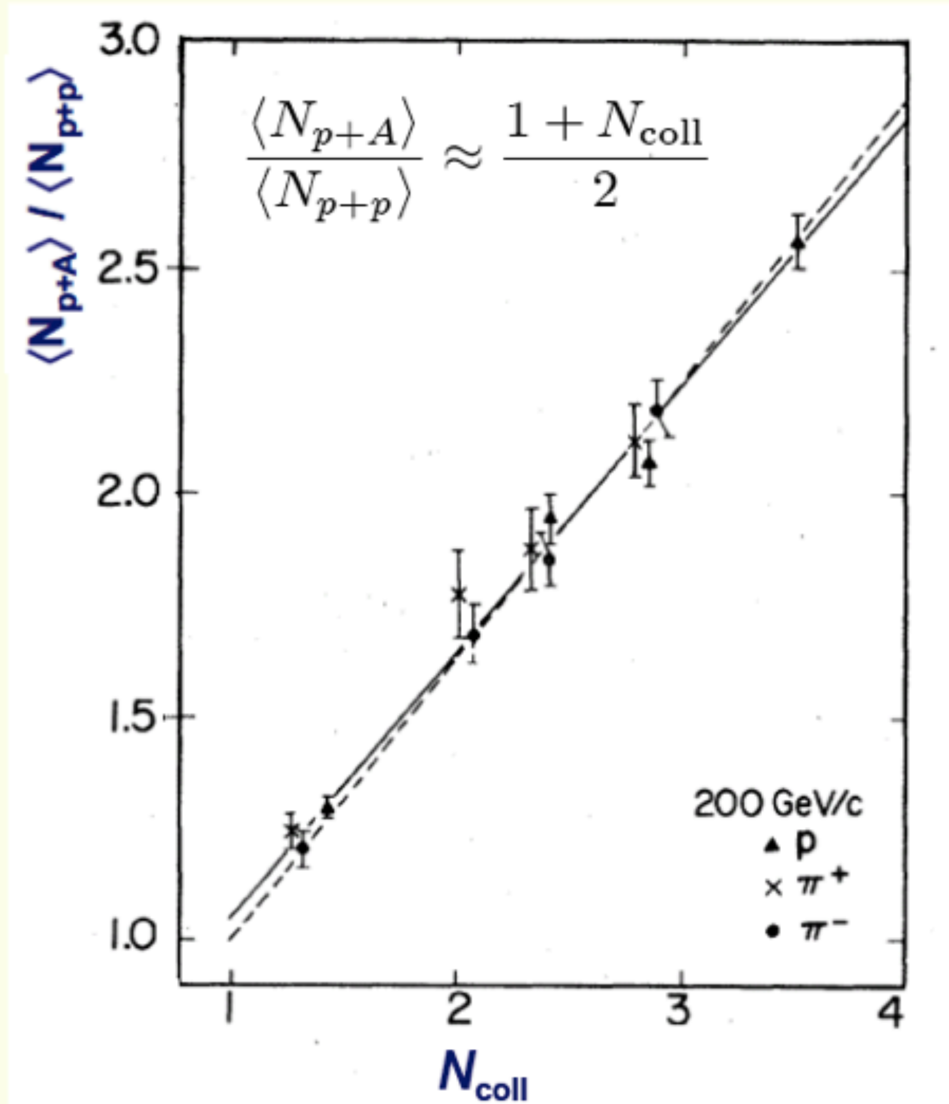


$N_{coll} = 3$, $N_{part} = 4$

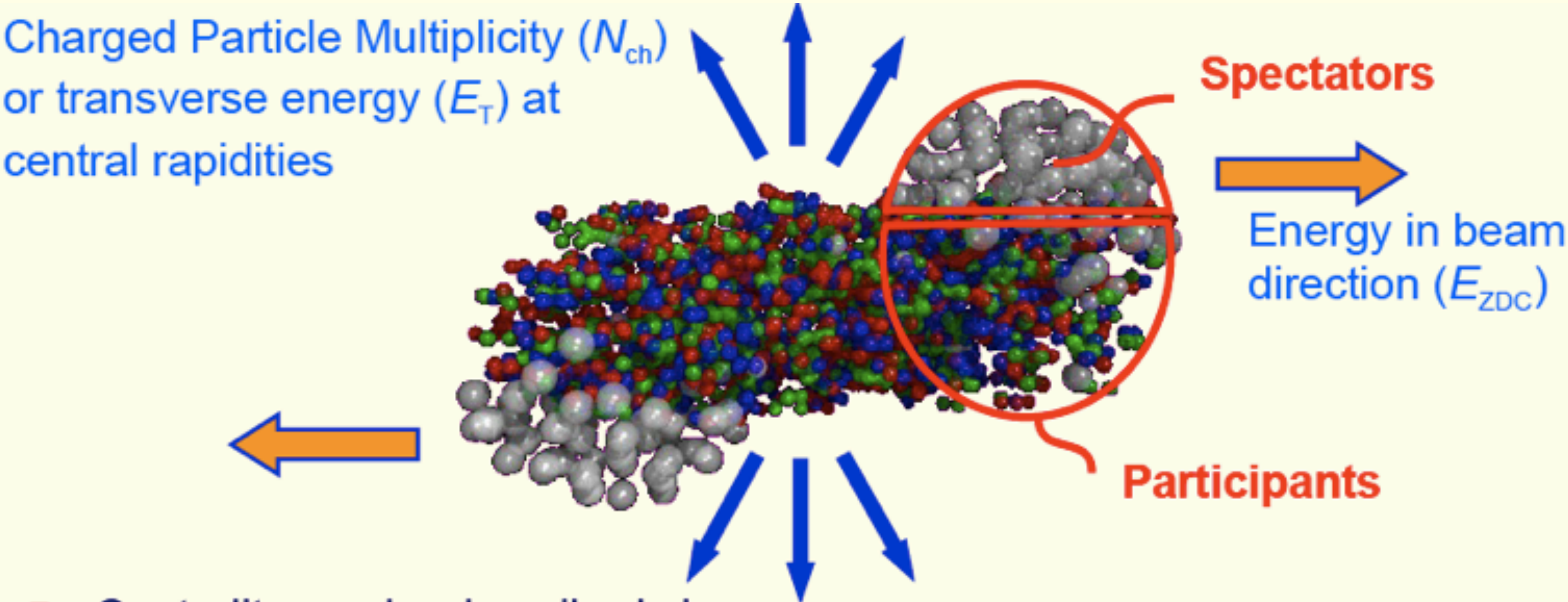
- How do particle multiplicities scale? With N_{part} or N_{coll}?
- Observation: Particle multiplicities scale with N_{part}

$$\langle N_{p+A} \rangle \approx \frac{N_{\text{part}}}{2} \langle N_{p+p} \rangle$$

(Wounded Nucleon Model)

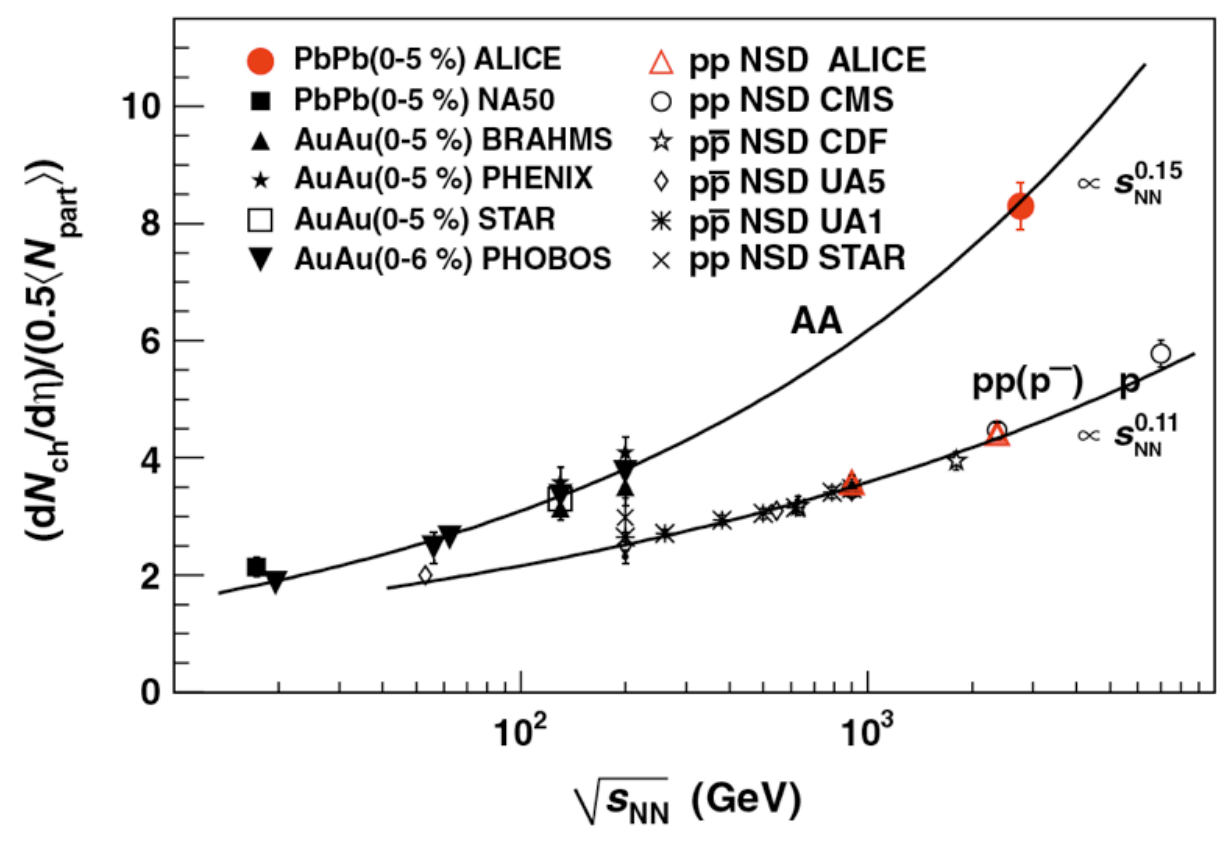


N_{part} and N_{coll} in Nucleus-Nucleus Collisions



- Centrality can be described via
  - N_{coll}: number of inelastic nucleon-nucleon collisions
  - N_{part}: number of nucleons which underwent at least one inelastic nucleon-nucleon collisions
- This simplifies the comparison between theory and experiment and between different experiments
- Typically not directly measured but determined from Glauber calculations

$\sqrt{s_{NN}}$ Dependence of the Charged Particle Multiplicity in p+p and Central A+A Collisions

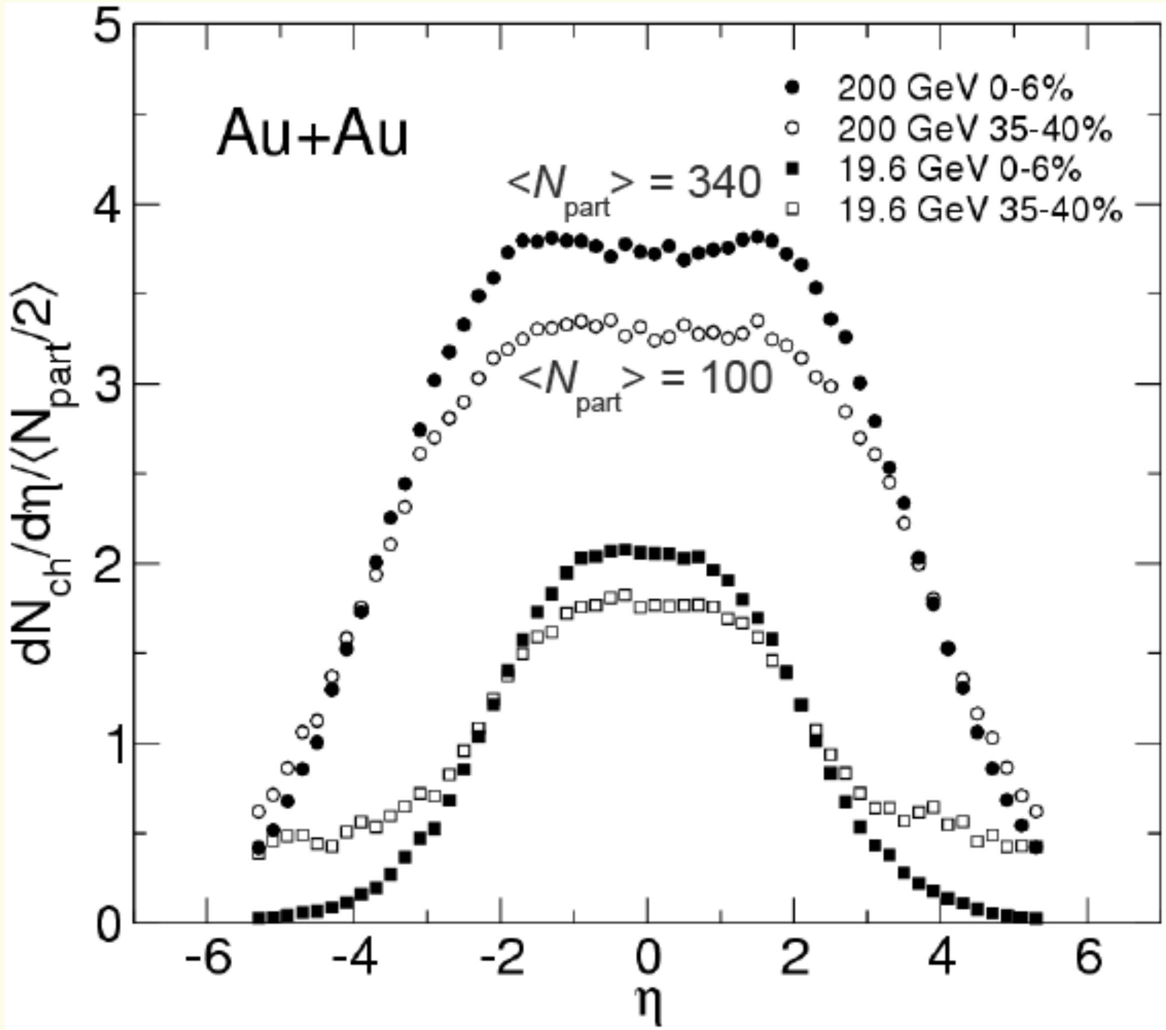


- From $\sqrt{s_{NN}}$ = 200 GeV (Au+Au, RHIC) to $\sqrt{s_{NN}}$ = 2760 GeV (Pb+Pb, LHC) the charged particle multiplicity increases by about a factor 2.2.
- Stronger increase with $\sqrt{s}$ in central A+A than in p+p

Charged Particle Pseudorapidity Distributions in Au+Au Collisions at 19.4 and 200 GeV

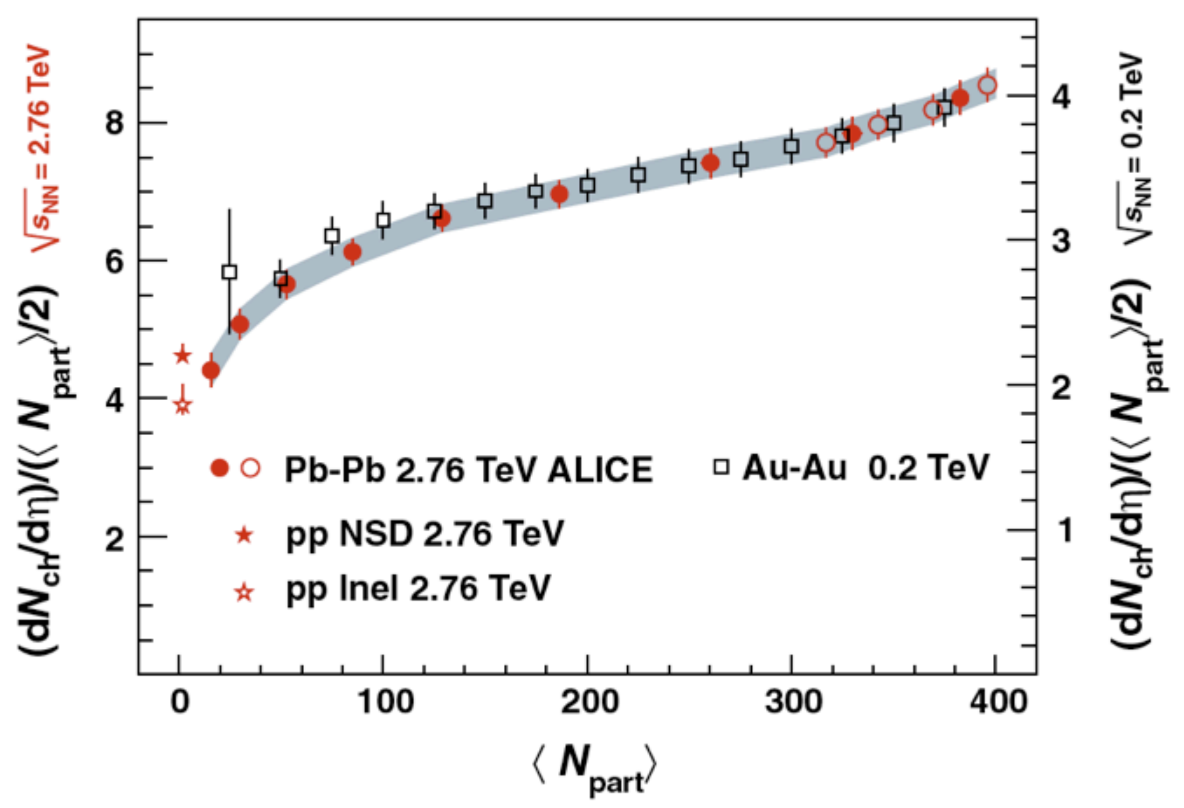
- Multiplicity increases with centrality
- N_{part} scaling only approximately satisfied
- Total charged particles multiplicity in central Au+Au at 200 GeV:

  ≈ 5000



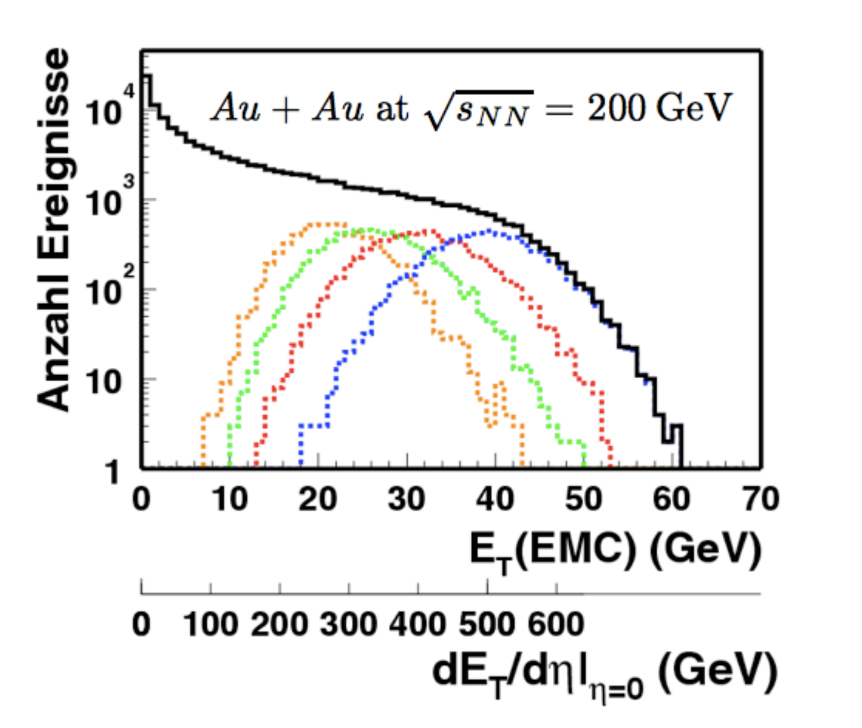
N_{part} Dependence of $dN_{ch}/d\eta$ at RHIC and LHC

ALICE: http://link.aps.org/doi/10.1103/PhysRevLett.106.032301



Same shape of yield/participant at RHIC and LHC

Transverse Energy (I)



- Theoretically defined as

$$E_T = \sum_{i=1}^{N_{\text{particles}}} m_{T,i}, \quad m_{T,i} = \sqrt{m_i^2 + p_{T,i}^2}$$

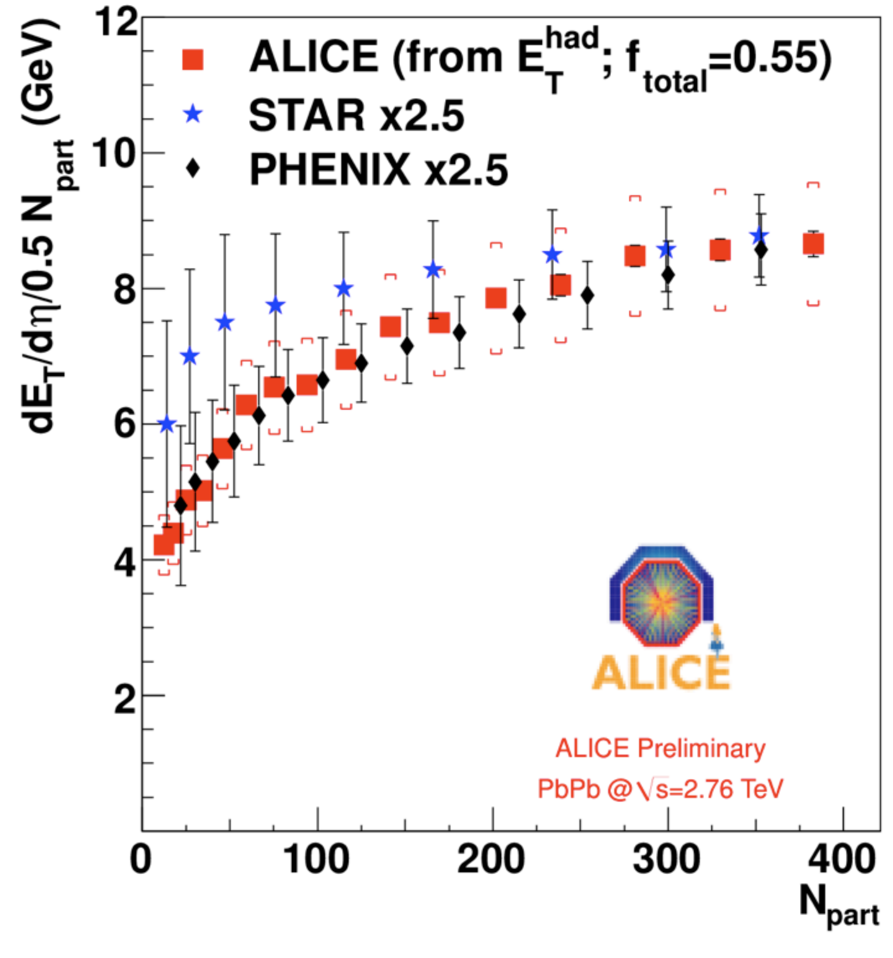
- Often calculated as

$$E_T = \sum_{i=1}^{N_{\text{particles}}} E_i \cdot \sin\vartheta_i$$

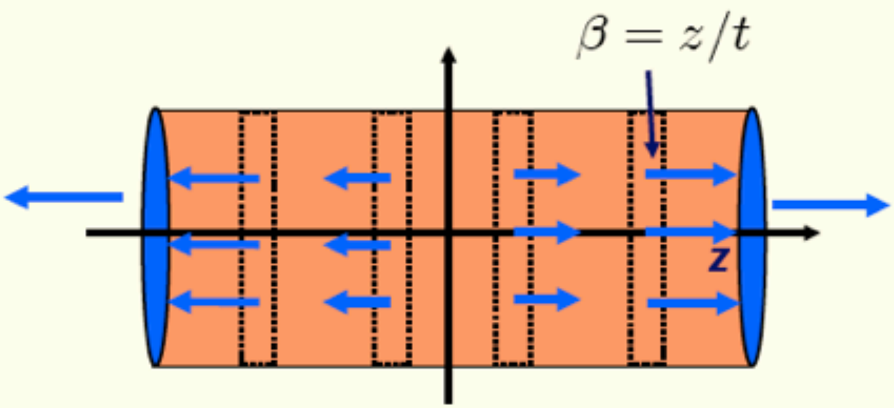
where E_i is by convention taken as the kinetic energy for nucleons and the total energy for all other particles

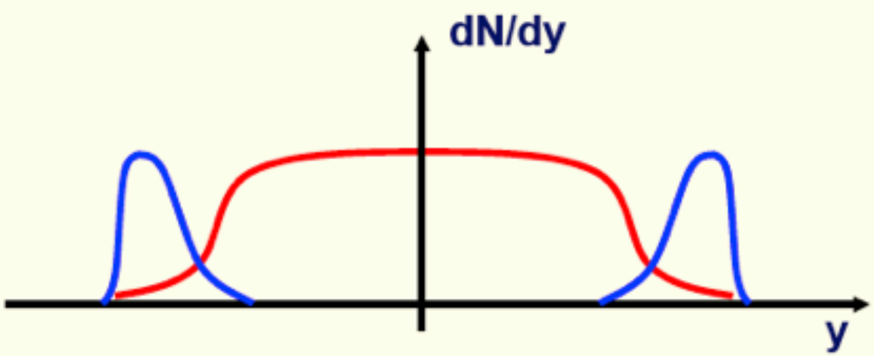
Transverse Energy at RHIC and LHC

- ALICE: Hadronic transverse energy measured with barrel tracking detectors
  - Model dependent correction
  - (f ~ 0.55) to convert into total transverse energy
- From RHIC to LHC
  - Similar centrality dependence
  - 2.5 increase in $dE_T/d\eta/N_{part}$
  - ~2.7 increase in $dE_T/d\eta$
  - Consistent with increase of $\langle p_T \rangle$



Space-Time Evolution: Bjorken Model





Velocity of the local system at position *z* at time *t*:

$$\beta = z/t$$

Proper time τ in this system:

$$\tau = t/\gamma = t\sqrt{1-\beta^2} = \sqrt{t^2 - z^2}$$

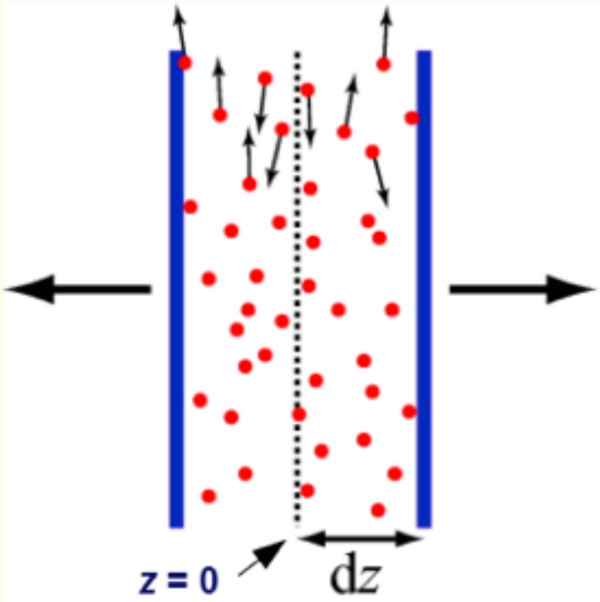
In the Bjorken model all thermodynamic quantities only depend on τ, e.g., the particle density:

$$n(t,z) = n(\tau)$$

This leads to a constant rapidity density of the produced particles (at least at central rapidities):

$$\frac{dN_{ch}}{dy} = \text{const.}$$

Bjorken's Estimate of the Initial Energy Density



J. D. Bjorken,
Phys. Rev. D, 27, 140 (1983) (→ link)

Total energy in central slice [0,dz] at time $\tau = \tau_0$:

$$E = N \cdot \langle m_T \cosh y \rangle |_{y=0} = N \cdot \langle m_T \rangle$$

Energy density:

$$\varepsilon = \frac{\langle m_T \rangle}{A} \frac{\mathrm{d}N}{\mathrm{d}z}\bigg|_{z=0} = \frac{\langle m_T \rangle}{A} \frac{\mathrm{d}N}{\mathrm{d}y}\bigg|_{y=0} \frac{\mathrm{d}y}{\mathrm{d}z}\bigg|_{z=0}$$

transverse area

1D Bjorken flow: relation between *z* position of a slice and rapidity *y*

$$y = \mathrm{atanh}(z/\tau) \Rightarrow \frac{\mathrm{d}y}{\mathrm{d}z}\bigg|_{z=0} = \frac{1}{\tau} \cdot \frac{1}{1 - z^2/\tau^2}\bigg|_{z=0} = \frac{1}{\tau}$$

Bjorken formula for the initial energy density:

$$\varepsilon = \frac{\langle m_T \rangle}{A \cdot \tau_0} \frac{\mathrm{d}N}{\mathrm{d}y}\bigg|_{y=0} = \frac{1}{A \cdot \tau_0} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}\bigg|_{y=0}$$

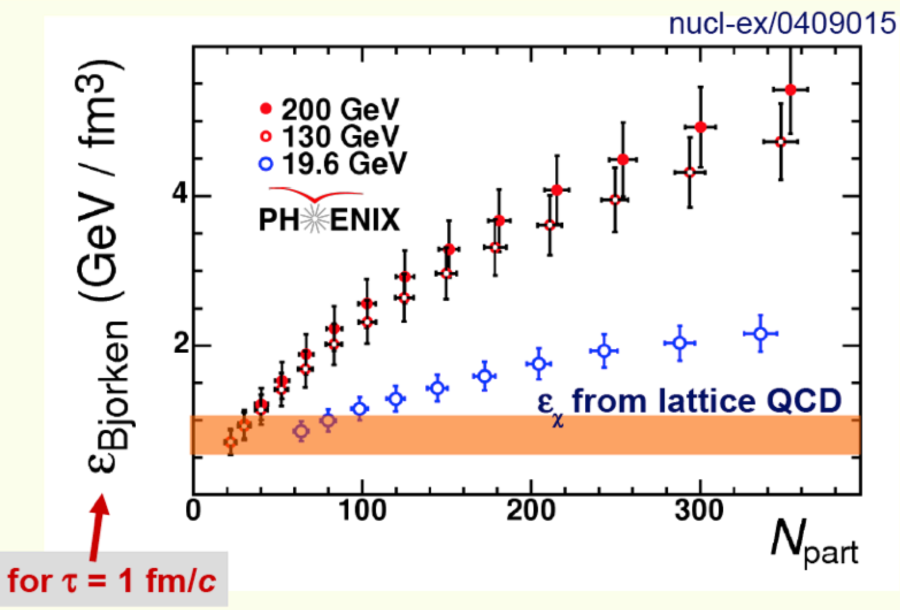
Thermalization time τ_0 = 1 fm/*c* (with large uncertainties)

Energy Densities in Central A+A Collisions at RHIC and LHC

$$\varepsilon_{\text{central}}^{\text{LHC}} = \frac{1}{A \cdot \tau} \frac{dE}{dy} \approx \frac{1}{A \cdot \tau} \frac{dE}{d\eta}, \quad A \approx \pi \cdot R_{Pb}^2 \approx 140 \text{ fm}^2, \; \frac{dE_T}{d\eta} \approx 1600 \text{ GeV}$$

$$\rightarrow \; \varepsilon_{\text{central}}^{\text{LHC}} = 11 \text{ GeV/fm}^3 \text{ for } \tau = 1 \text{ fm}/c$$

$$\rightarrow \varepsilon^{\text{LHC}} \cdot \tau^{\text{LHC}} \approx (2.0 \text{ to } 2.5) \cdot \varepsilon^{\text{RHIC}} \cdot \tau^{\text{RHIC}}$$



$$\rightarrow \varepsilon^{\text{RHIC}} \cdot \tau^{\text{RHIC}} \approx (2.0 \text{ to } 2.5) \cdot \varepsilon^{\text{SPS}} \cdot \tau^{\text{SPS}}$$

In central A+A collisions at SPS, RHIC and LHC energies the estimated initial energy density is above the critical value of about 0.7 GeV/fm^3 for the QGP↔HG transition

Glauber Model: Basic Assumptions

Nobel prize in physics 2005 for
his contributions to quantum optics

Glauber model for nucleus-nucleus collisions

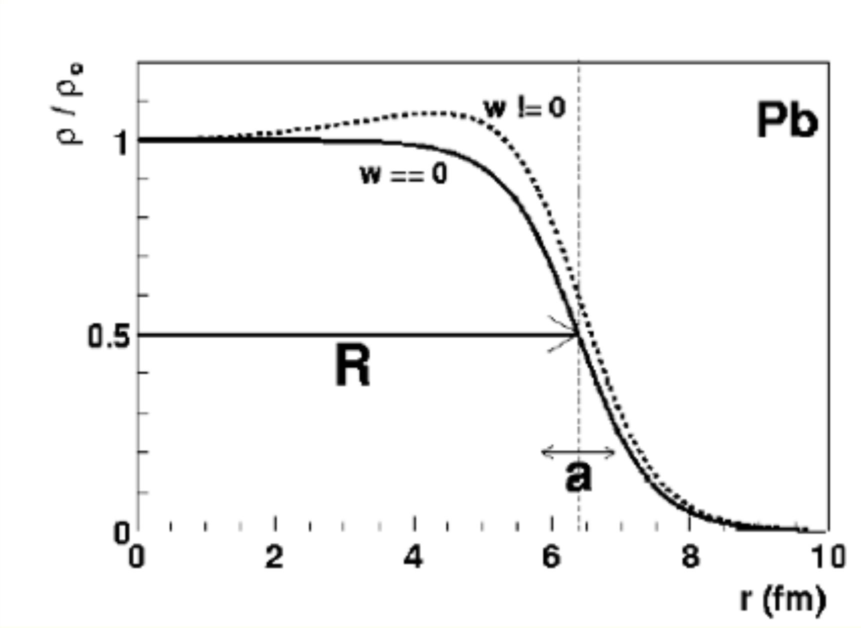
- Nucleons travel on straight trajectories (after a nucleon-nucleon collisions)
- Nucleon-nucleon cross section is independent of the number of collisions a nucleon underwent before
- Input: density profile of the nucleus and inelastic nucleon-nucleon cross section

Review article:
Glauber modeling in high energy nuclear collisions, 2007

Glauber Model: Nuclear Geometry

Woods-Saxon nuclear density profile:

$$\rho(r) = \frac{\rho_0 \left(1 + wr^2/R^2\right)}{1 + \exp((r - R)/a)}$$

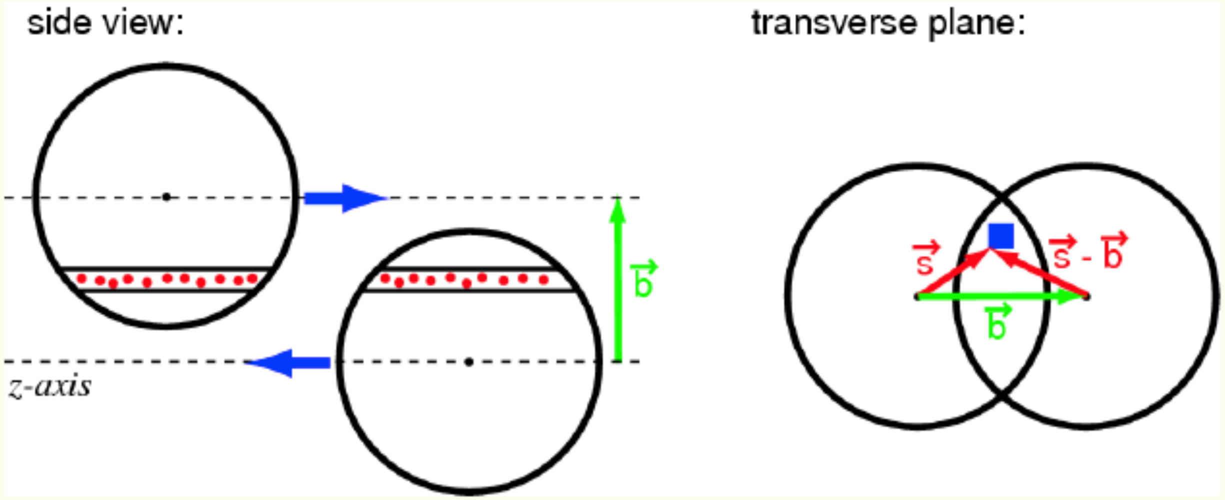


Nucleus	A	R (fm)	a (fm)	w
C	12	2.47	0	0
O	16	2.608	0.513	-0.051
Al	27	3.07	0.519	0
S	32	3.458	0.61	0
Ca	40	3.76	0.586	-0.161
Ni	58	4.309	0.516	-0.1308
Cu	63	4.2	0.596	0
W	186	6.51	0.535	0
Au	**197**	**6.38**	**0.535**	**0**
Pb	208	6.68	0.546	0
U	238	6.68	0.6	0

H. DeVries, C.W. De Jager, C. DeVries, 1987

- Woods-Saxon parameters typically from e^--nucleus scattering (sensitive to charge distribution only)
- Difference between neutron and proton distribution small and typically neglected

Glauber Model:
Number of Nucleon-Nucleon Collisions



Nuclear thickness function:

$$T_\mathrm{A}(\vec{s}) := \int \rho_\mathrm{A}(\vec{s}, z)\,\mathrm{d}z$$

Normalization:

$$\int T_\mathrm{A}(\vec{s})\,\mathrm{d}^2 s = A$$

Nucleon “luminosity” at $\vec{s}$:

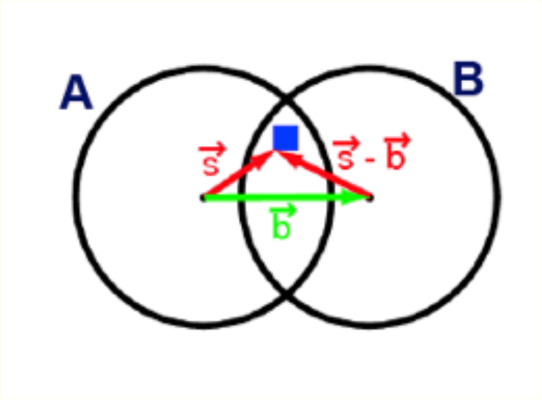
$$\mathrm{d}T_\mathrm{AB}(\vec{s}) = T_\mathrm{A}(\vec{s}) \cdot T_\mathrm{B}(\vec{s} - \vec{b})\,\mathrm{d}^2 s$$

Nuclear overlap function:

$$T_\mathrm{AB}(b) := \int T_\mathrm{A}(\vec{s}) \cdot T_\mathrm{B}(\vec{s} - \vec{b})\,\mathrm{d}^2 s$$

$$\langle N_\mathrm{coll}(b) \rangle = T_\mathrm{AB}(b) \cdot \sigma_\mathrm{inel}^\mathrm{p+p}$$

Glauber Model: Number of Participants



definition:

$$\hat{T}_{\rm B}(\vec{x}) := T_{\rm B}(\vec{x})/B$$

Probability that a “test nucleon” from nucleus A collides with a certain nucleon from nucleus B:

$$p_{\rm int} = \hat{T}_{\rm B}(\vec{s}-\vec{b}) \cdot \sigma_{\rm inel}^{\rm p+p}$$

Probability that a “test nucleon” from nucleus A collides with none of the B nucleons of nucleus B:

$$(1-p_{\rm int})^B = (1-\hat{T}_{\rm B}(\vec{s}-\vec{b}) \cdot \sigma_{\rm inel}^{\rm p+p})^B$$

Probability that a “test nucleon” undergoes at least one inelastic nucleon-nucleon collision:

$$1-(1-\hat{T}_{\rm B}(\vec{s}-\vec{b}) \cdot \sigma_{\rm inel}^{\rm p+p})^B$$

Number of participants in nucleus A:

$$\langle N_{\rm part}^{\rm A}(b)\rangle = A \int \hat{T}_{\rm A}(\vec{s}) \cdot \left(1-(1-\hat{T}_{\rm B}(\vec{s}-\vec{b}) \cdot \sigma_{\rm inel}^{\rm p+p})^B\right) {\rm d}^2 s$$

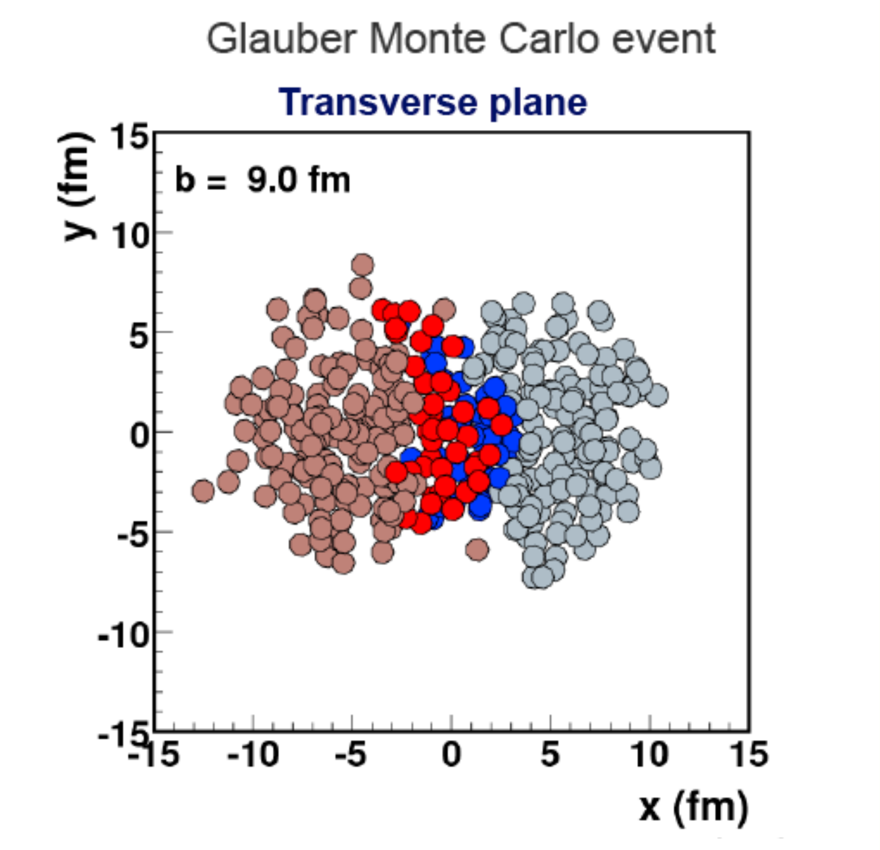
Total mean number of participants for A+B collisions with impact parameter *b*:

$$\langle N_{\rm part}(b)\rangle = \langle N_{\rm part}^{\rm A}(b)\rangle + \langle N_{\rm part}^{\rm B}(b)\rangle$$

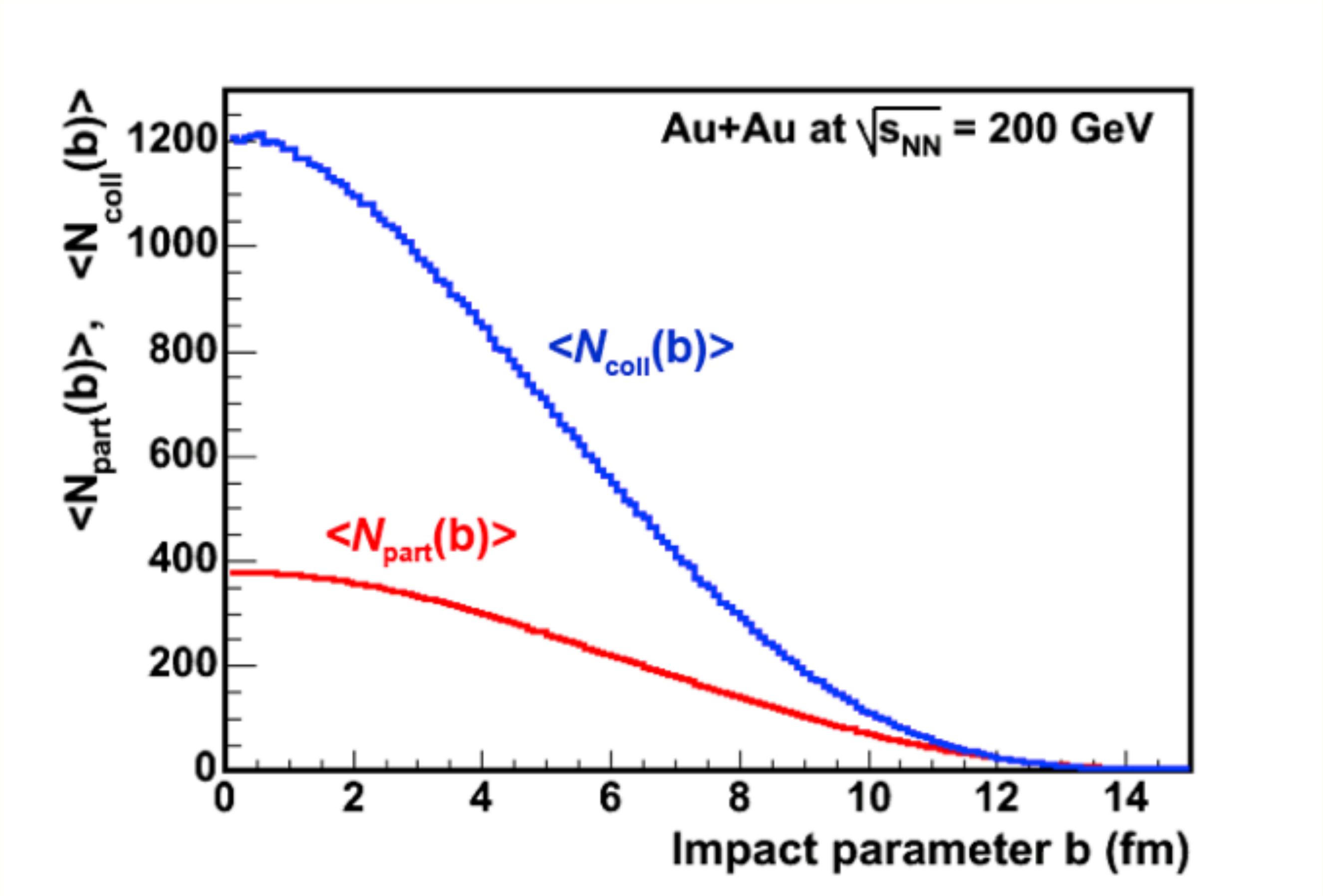
Glauber Model: Monte Carlo Approach

- In practice, most experiments use Glauber Monte Carlo models to determine N_{part} and N_{coll}
- Nucleons distributed according to Woods-Saxon distribution
- Impact parameter randomly drawn from $d\sigma/db = 2\pi b$
- A collision between two nucleons takes place if their distance *d* in the transverse plane satisfied

$$d \leq \sqrt{\sigma_{\mathrm{inel}}^{\mathrm{NN}}/\pi}$$

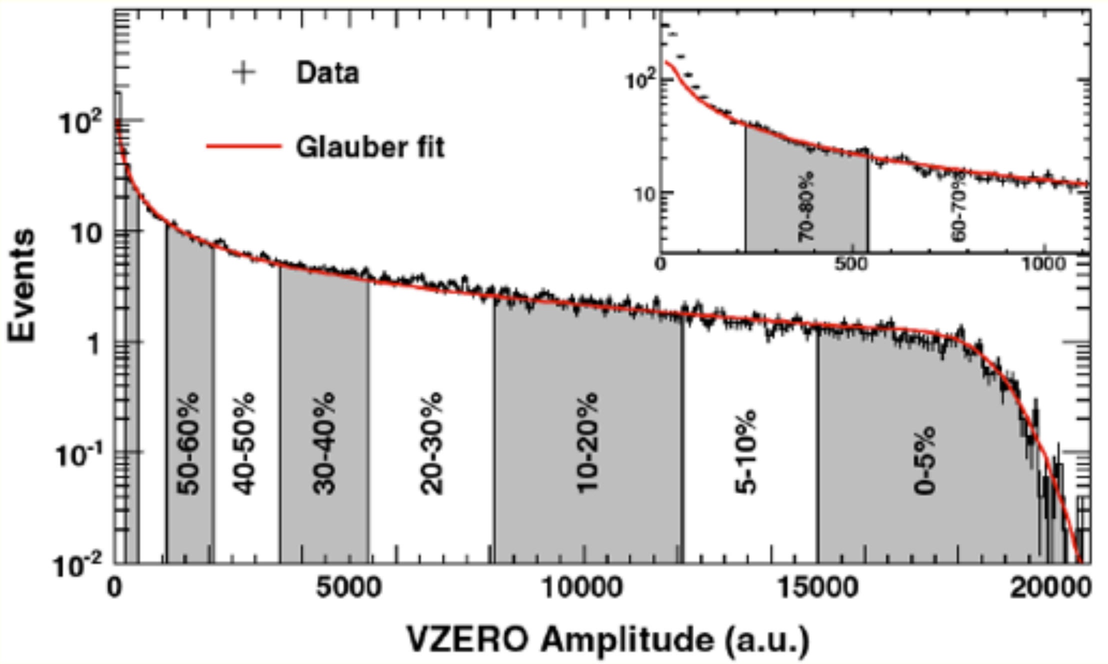


$\langle N_{part}(b) \rangle$ and $\langle N_{coll}(b) \rangle$ from Glauber MC



Approximate relation: $N_{\text{coll}} \propto N_{\text{part}}^{4/3}$

ALICE: <N_{part}> and <N_{coll}> for Experimentally Defined Centrality Classes



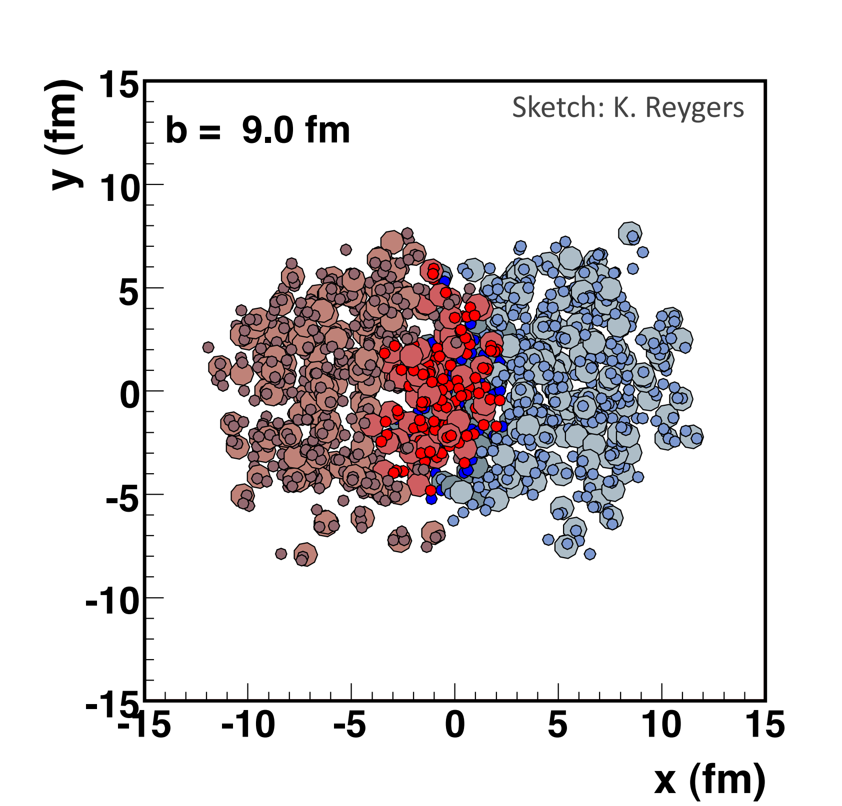
Centrality	$dN_{ch}/d\eta$	$\langle N_{part} \rangle$
0%–5%	1601 ± 60	382.8 ± 3.1
5%–10%	1294 ± 49	329.7 ± 4.6
10%–20%	966 ± 37	260.5 ± 4.4
20%–30%	649 ± 23	186.4 ± 3.9
30%–40%	426 ± 15	128.9 ± 3.3
40%–50%	261 ± 9	85.0 ± 2.6
50%–60%	149 ± 6	52.8 ± 2.0
60%–70%	76 ± 4	30.0 ± 1.3
70%–80%	35 ± 2	15.8 ± 0.6

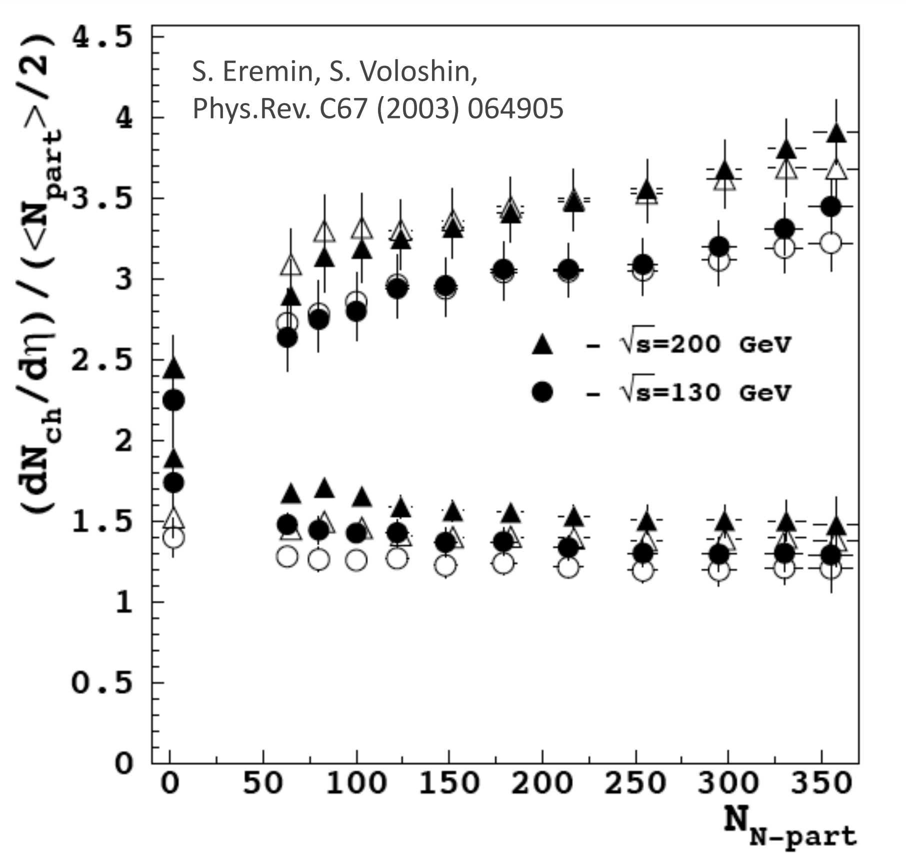
Measured multiplicity distribution described within the Glauber model by assuming a certain centrality dependence for the number of ancestor particles, e.g.

$$N_{\mathrm{ancestors}} = f \cdot N_{\mathrm{part}} + (1 - f) \cdot N_{\mathrm{coll}}$$

Each ancestor than “produces” charged particles according to a Negative Binomial Distribution (NBD). The same centrality cuts as used for real data are then applied to the simulated multiplicity in order to obtain <N_{part}> and <N_{coll}> for a given centrality class.

Constituent Quark Participants





- Particle multiplicity scales linearly with number of quark participants

Basics of Heavy-Ion Collisions: Points to Take Home

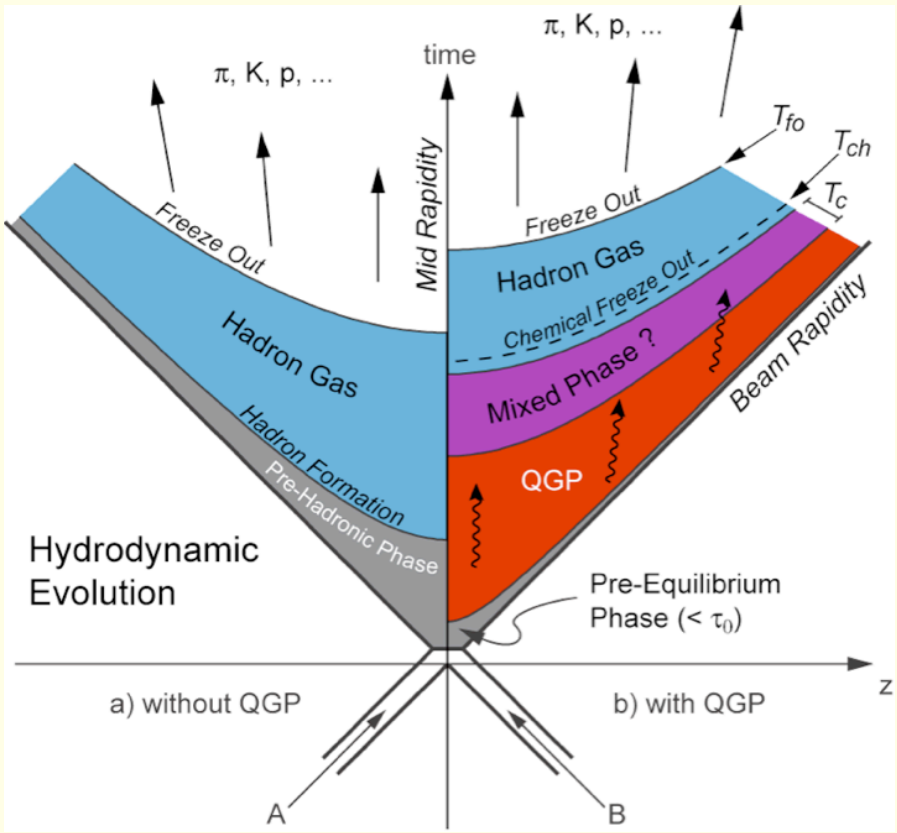
- Stopping: The participating nucleons lose on average two units of rapidity in central Au+Au collisions at RHIC
- Centrality in A+A collisions often characterized by N_{part} and N_{coll} (from Glauber calculations)
- Bjorken's estimate for the initial energy density of the fireball

$$\varepsilon = \frac{1}{A \cdot \tau_0} \left. \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y} \right|_{y=0}$$

- Already in central A+A collisions at CERN SPS energies this estimate yields energy densities above the critical energy density of $\varepsilon_c \approx 0.7$ GeV/fm^3 expected for the QGP transition

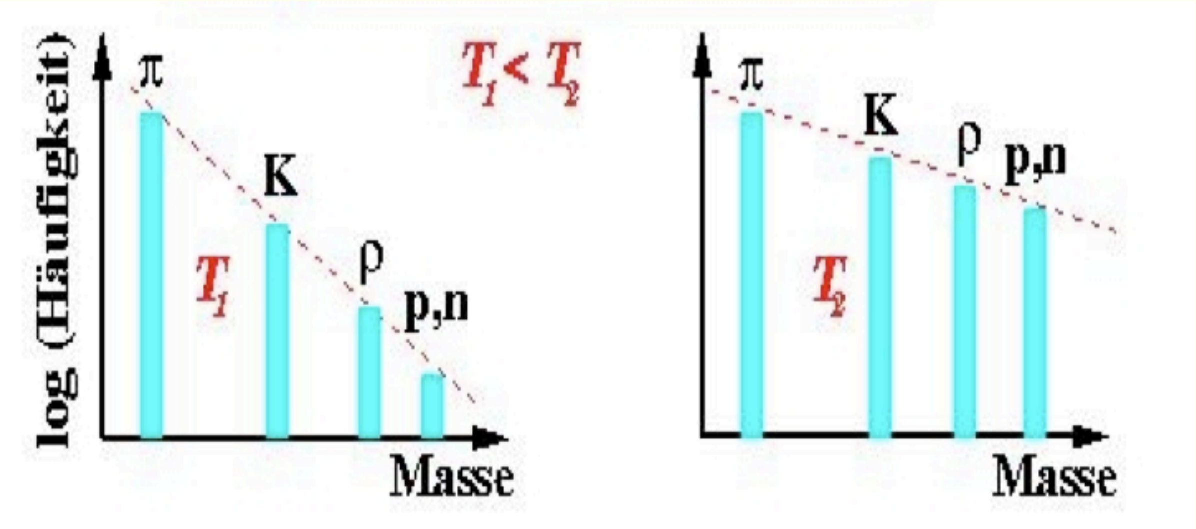
5. Hadron Abundances and the Statistical Model

The Concept of Hadrochemical Freeze-out



- "chemical" or "hadrochemical freeze-out":
  - abundancies of hadrons are frozen in – no more inelastic scattering
  - RHIC: $T_{ch} \approx 160$ - 170 MeV
- "kinetic" or "thermal freeze-out":
  - happens when mean free path becomes large as compared to inter-particle distance
  - Elastic interactions cease and momentum distributions are frozen
  - RHIC: $T_{fo} \approx 110$ - 130 MeV

Chemical Freeze-out Temperatures and Hadron Yields

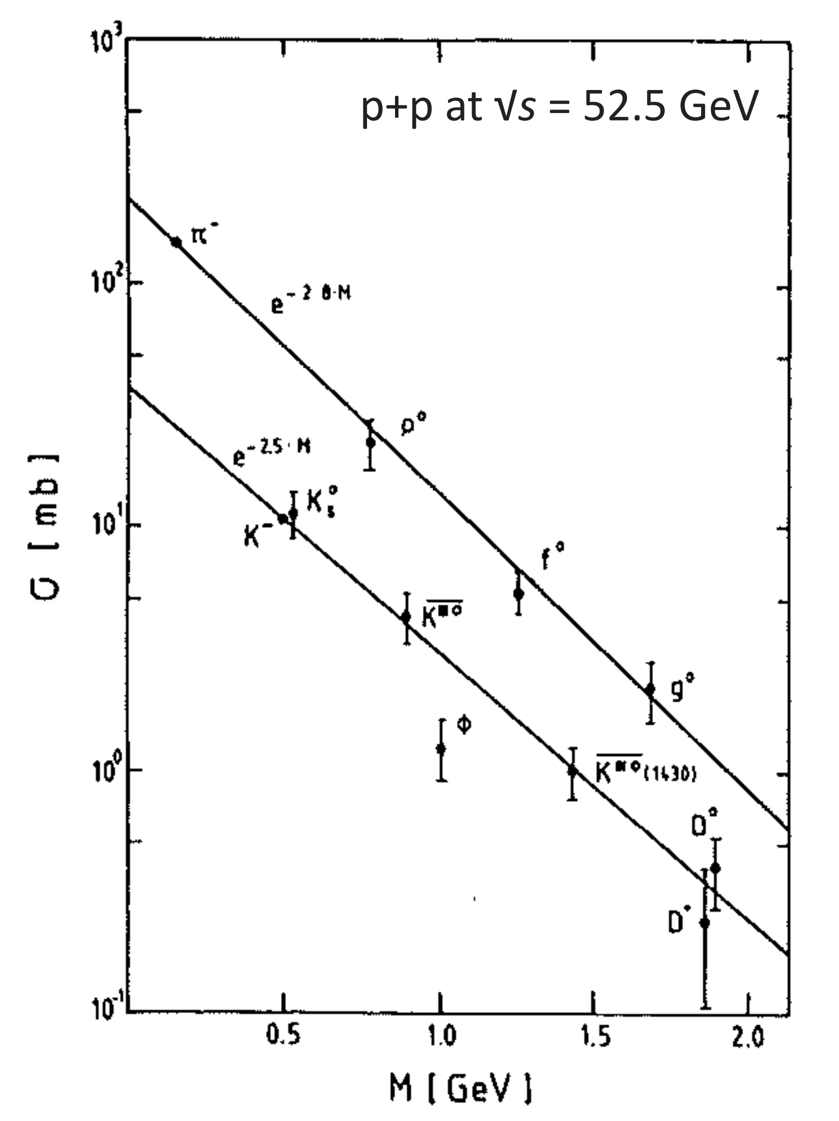


Assume phase space is filled thermally (Boltzmann) at hadronization. Abundance of hadrons then given by:

$$\text{Yield} \propto m^{3/2} \exp(-m/T)$$

I.e., yield determined by temperature (and density) at time of production of hadrons = hadronization

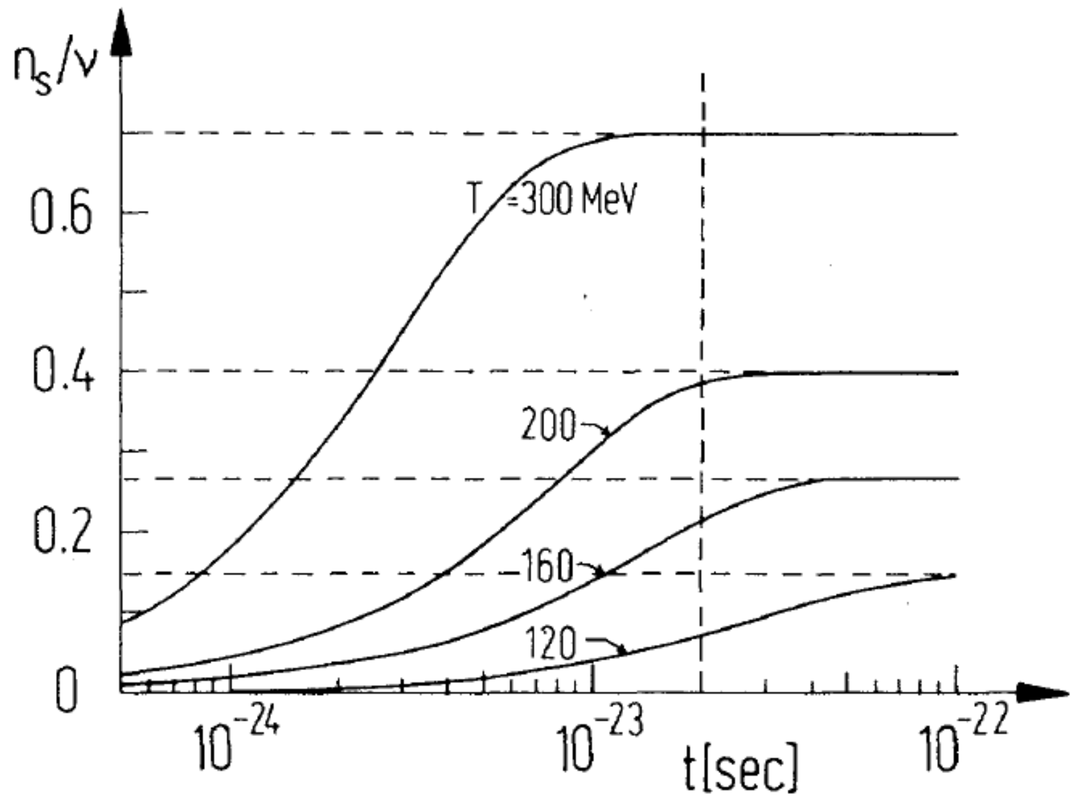
Strangeness Suppression in pp and e^+e^-



- Particle yields fall exponentially with particle mass
- Clear separation between strange and non-strange mesons
- Line that connects strange mesons about a factor 3 below the one for non-strange mesons
  → strangeness suppression
- „double strangeness suppression“ for $\phi = (s\bar{s})$

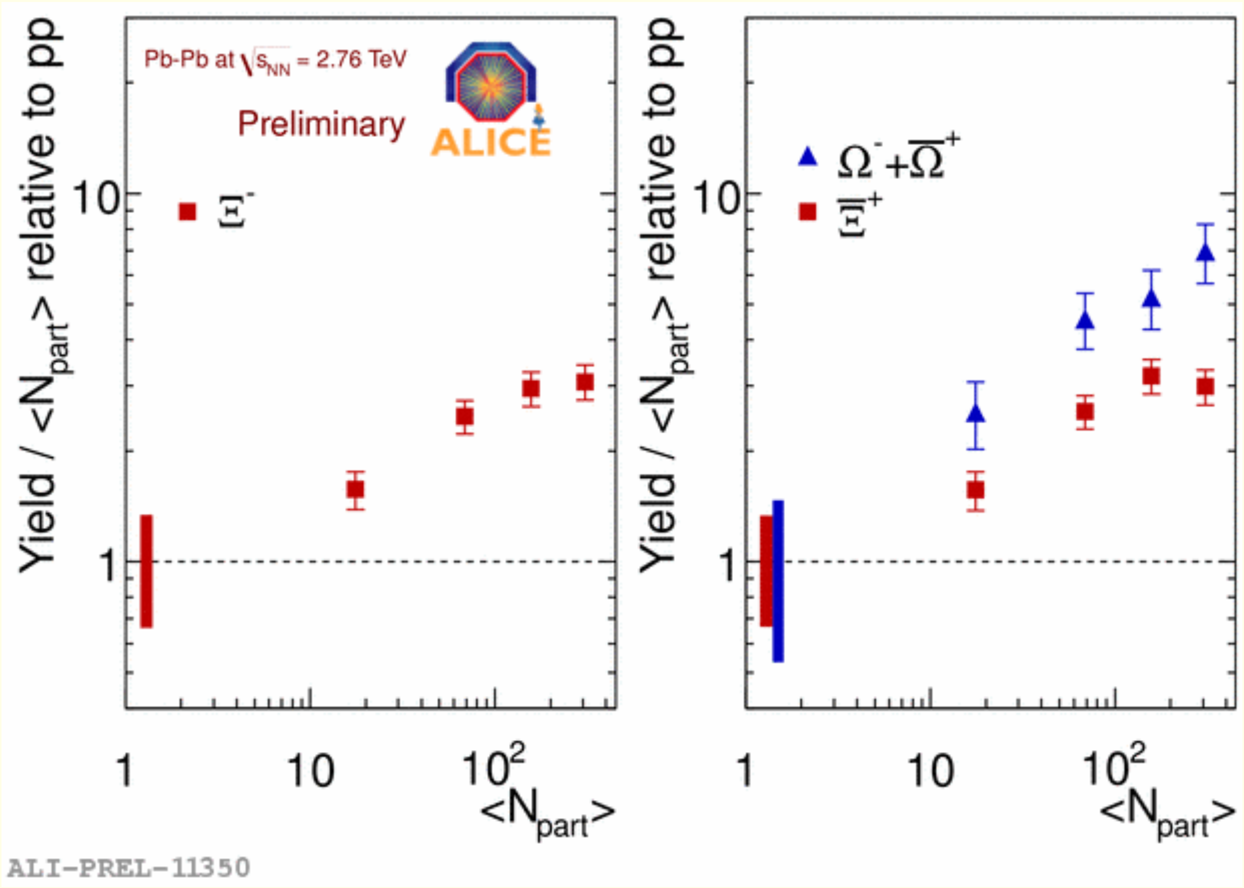
Enhanced Strangeness Production as a QGP Signal in Heavy-Ion Collisions

- In a QGP strangeness gets into equilibrium on a fast time scale
  (J. Rafelski, B. Mueller, Phys. Rev. Lett. 48 (1982) 1066)
- There should be more strangeness in heavy-ion collisions than in elementary collisions if a QGP is formed
- Enhanced production of strange hadrons one of the earliest predicted signature of QGP



Ratio of strange quark to baryon number abundance in a QGP for various temperatures

Strangeness Production in Pb+Pb at 2.76 TeV



- Strangeness production in A+A indeed enhanced with respect to p+p
- Let‘s see if this can be described with statistical particle production ...

Grand canonical ensemble and application to data from high energy heavy ion collisions

Particle densities:

$$n_i = N/V = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp((E_i-\mu_i)/T)\pm 1}$$

For every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

baryon number (B_i), strangeness (S_i), third component of isospin *I* (I_i^3)

Conservation laws constrain *V*, μ_S, μ_{I3}:

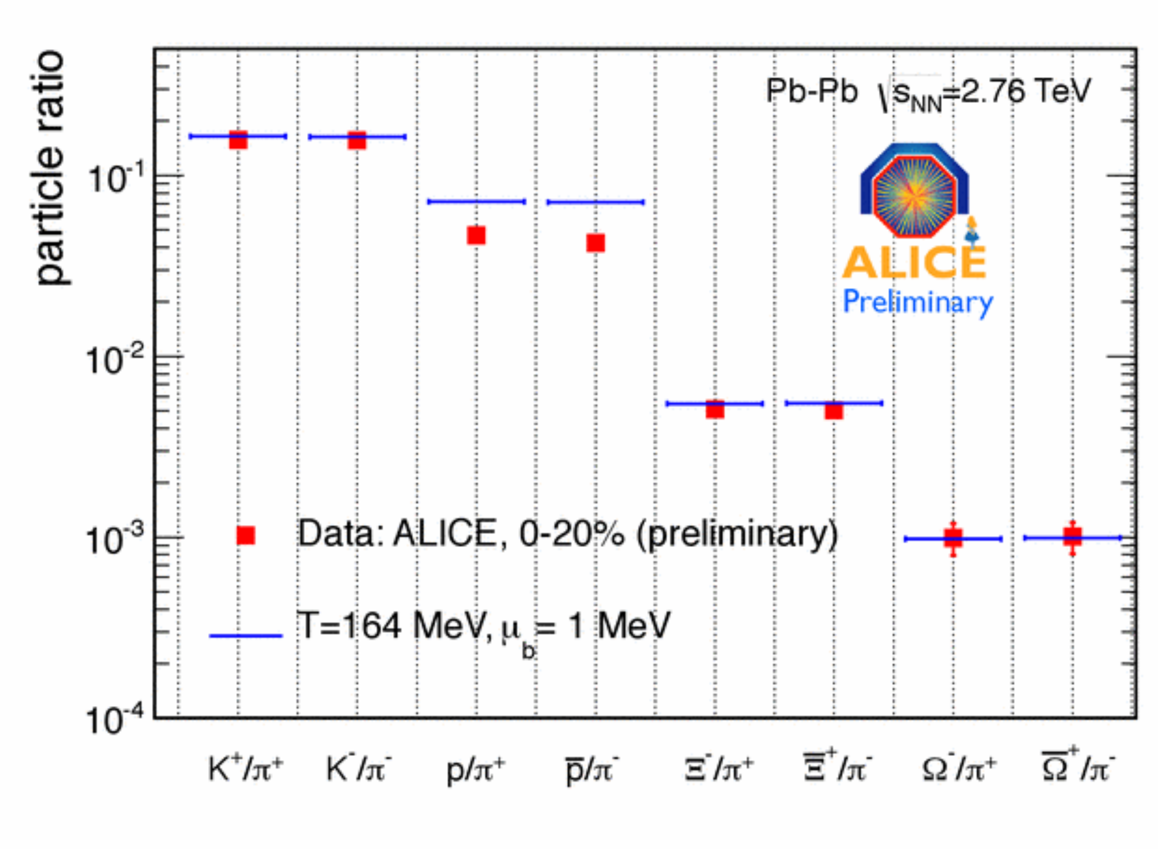
$$V\sum_i n_i B_i = Z + N \quad \rightarrow V$$

$$V\sum_i n_i S_i = 0 \quad \rightarrow \mu_S$$

$$V\sum_i n_i I_i^3 = \frac{Z-N}{2} \quad \rightarrow \mu_{I_3}$$

Fit at each energy provides values for the free parameters *T* and μ_b

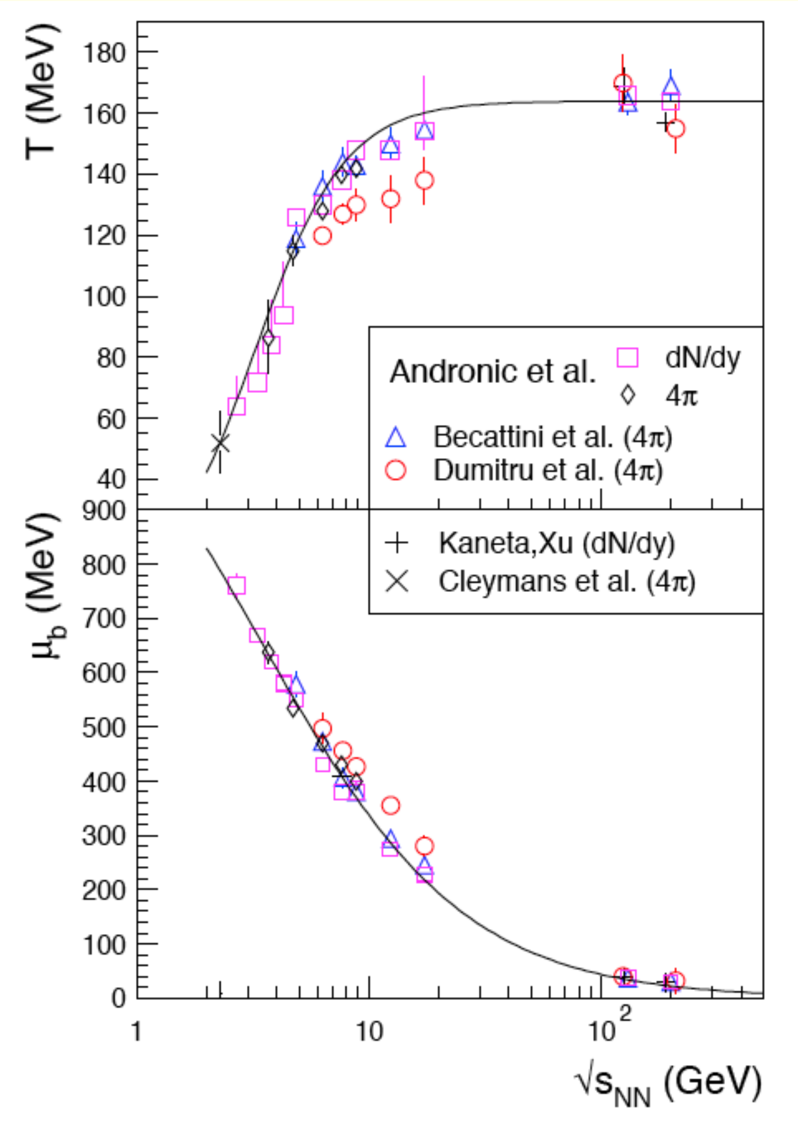
Hadron Abundancies in Pb+Pb Collisions at 2.76 TeV

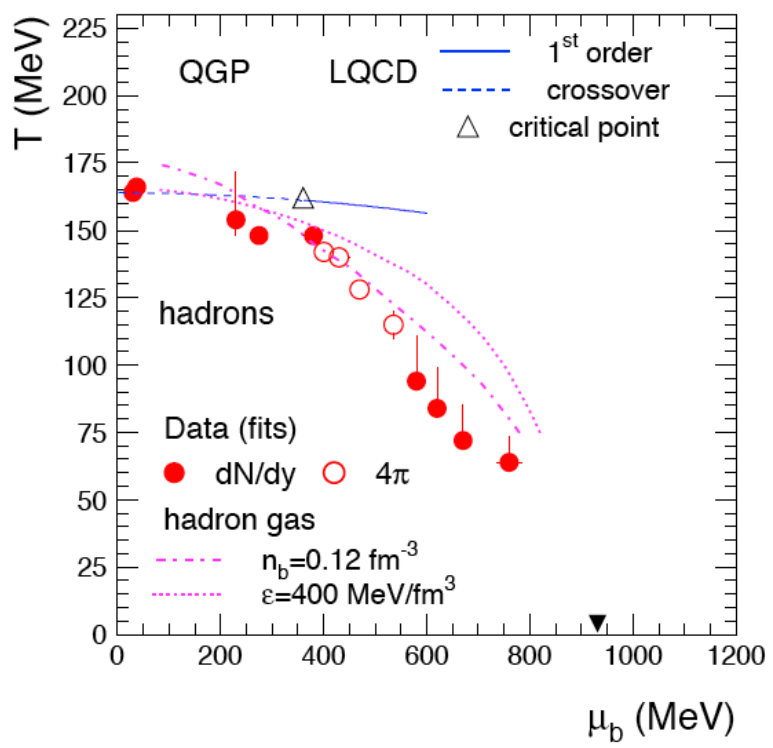


- All yields, except protons, follow thermal model prediction for grand-canonical ensemble and T_{ch} = 164 MeV
- Measured proton/pion ratio below thermal model expectation
- Strange particles perfectly agree with thermal model expectation

T and μ_B vs. $\sqrt{s_{NN}}$

Andronic, Stachel, Braun-Munzinger, arXiv:0911.4931v1





- Freeze-out temperatures saturate at a value $T \approx 160$ MeV
- Chemical equilibrium likely related to rapid density change due to the phase transition