Probing the High Energy Frontier at the LHC

Part III: Heavy-Ion Physics with ALICE

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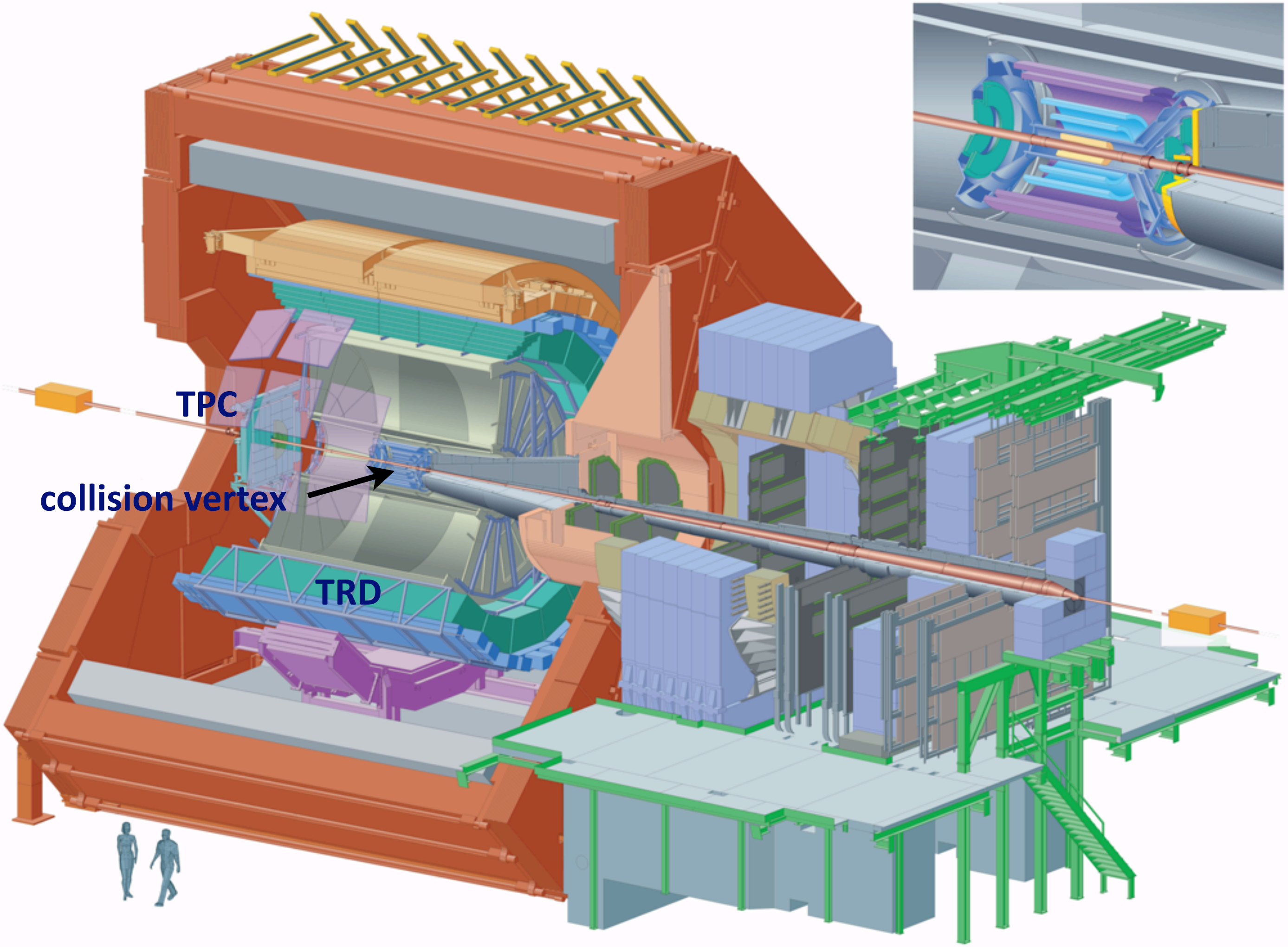
1. The Alice Experiment

The ALICE Experiment: Overview



- 18 detector systems
- ~ 10 000 t
- > 1000 collaborators
- p+p up to 14 000 GeV
- Pb+Pb up to 5500 GeV
- First p+p collision: Nov. 23, 2009
- Pb+Pb: fall 2010

Focus of the german groups (including Heidelberg):
Time Projection Chamber (TPC) and the Transition Radiation Detector (TRD)

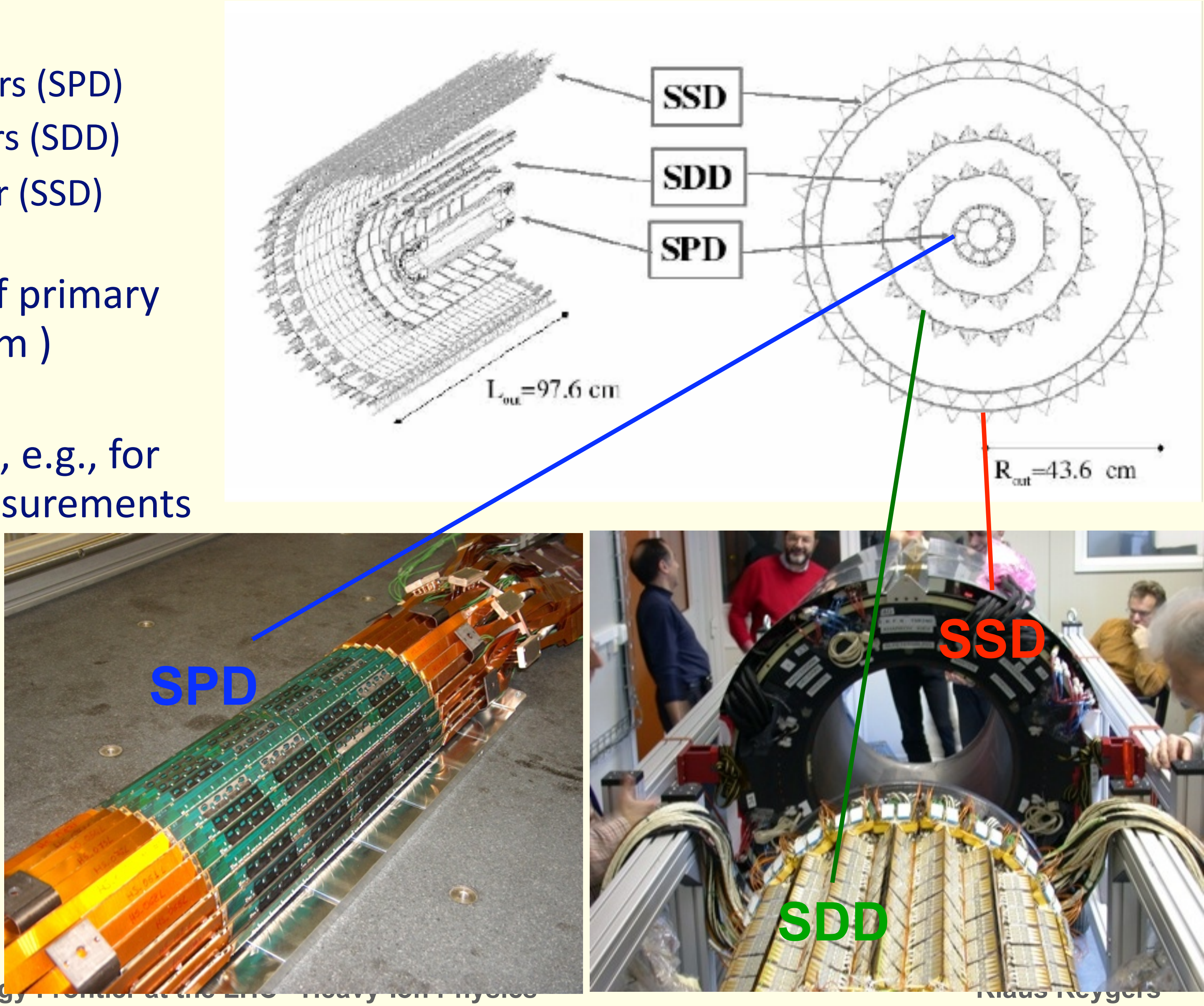
BMBF Forschungsschwerpunkt ALICE Experiment 201

Inner Tracking System (ITS)

- 6 layers silicon
  - 2 pixel detectors (SPD)
  - 2 drift detectors (SDD)
  - 2 strip detector (SSD)

- Reconstruction of primary vertex (σ < 100 μm)

- Secondary vertex, e.g., for heavy-quark measurements

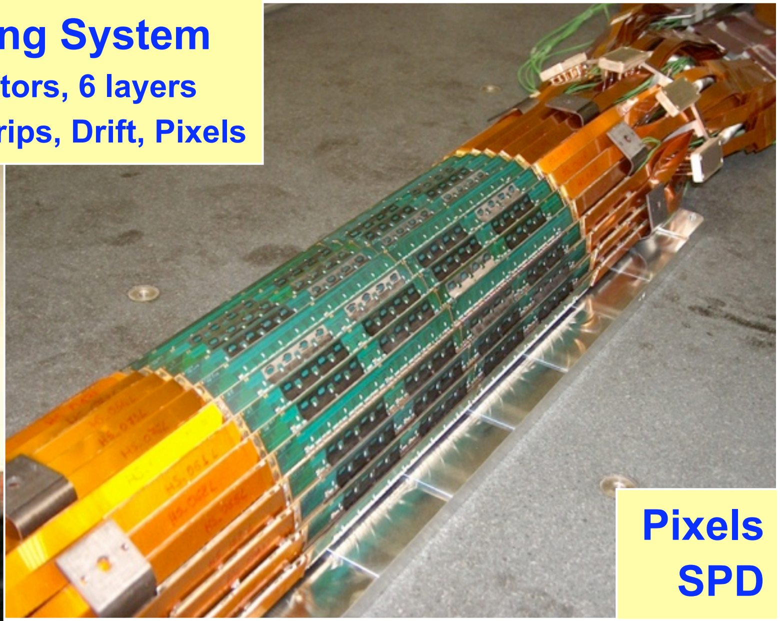


3 x 2 Layers Silicon Technology

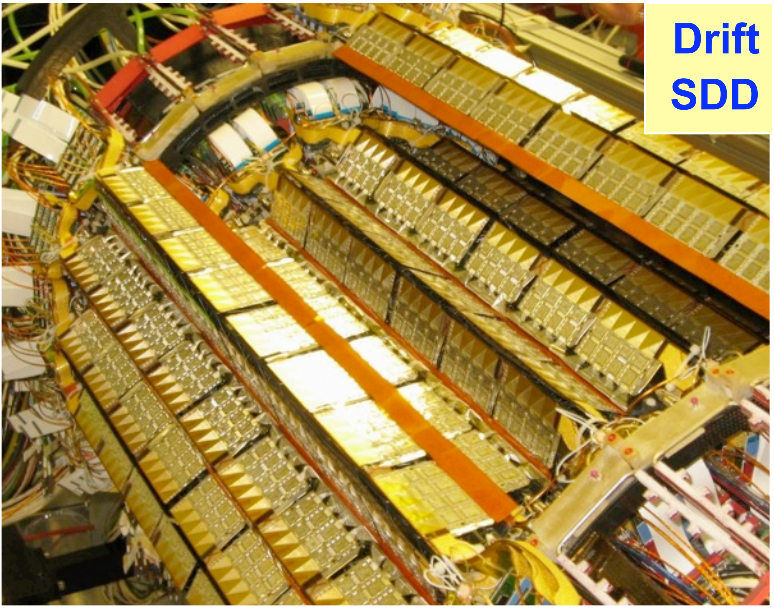
Strips
SSD

Inner Tracking System

~ 10 m^2 Si detectors, 6 layers
double sided Strips, Drift, Pixels

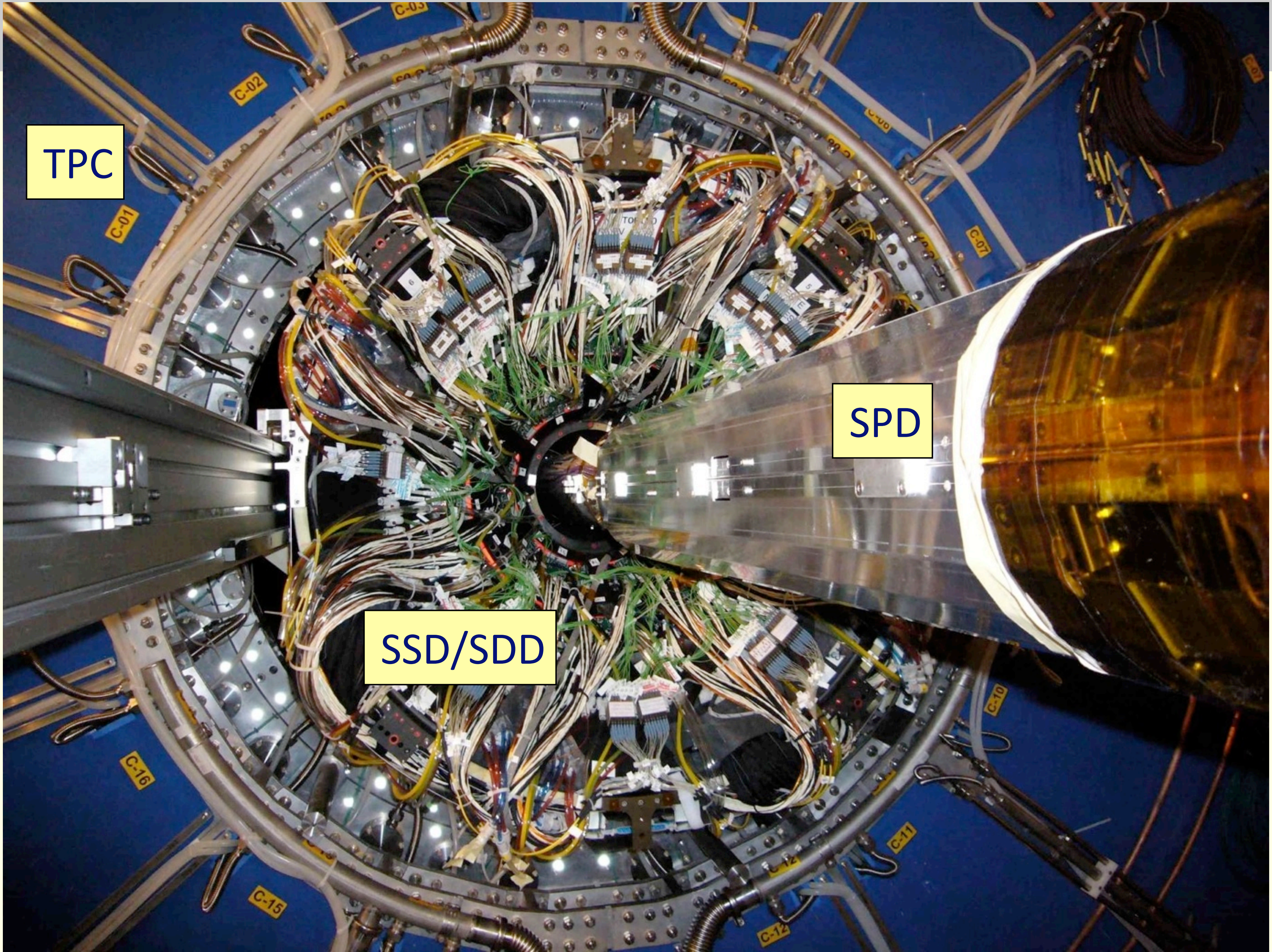


Pixels
SPD

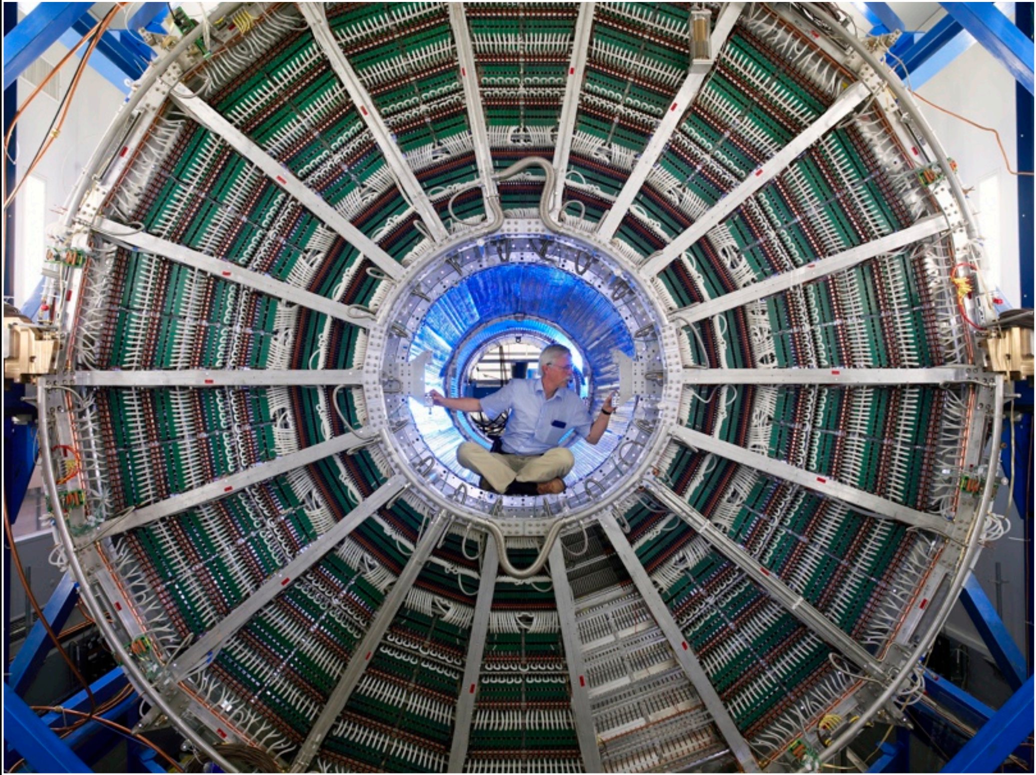


Drift
SDD

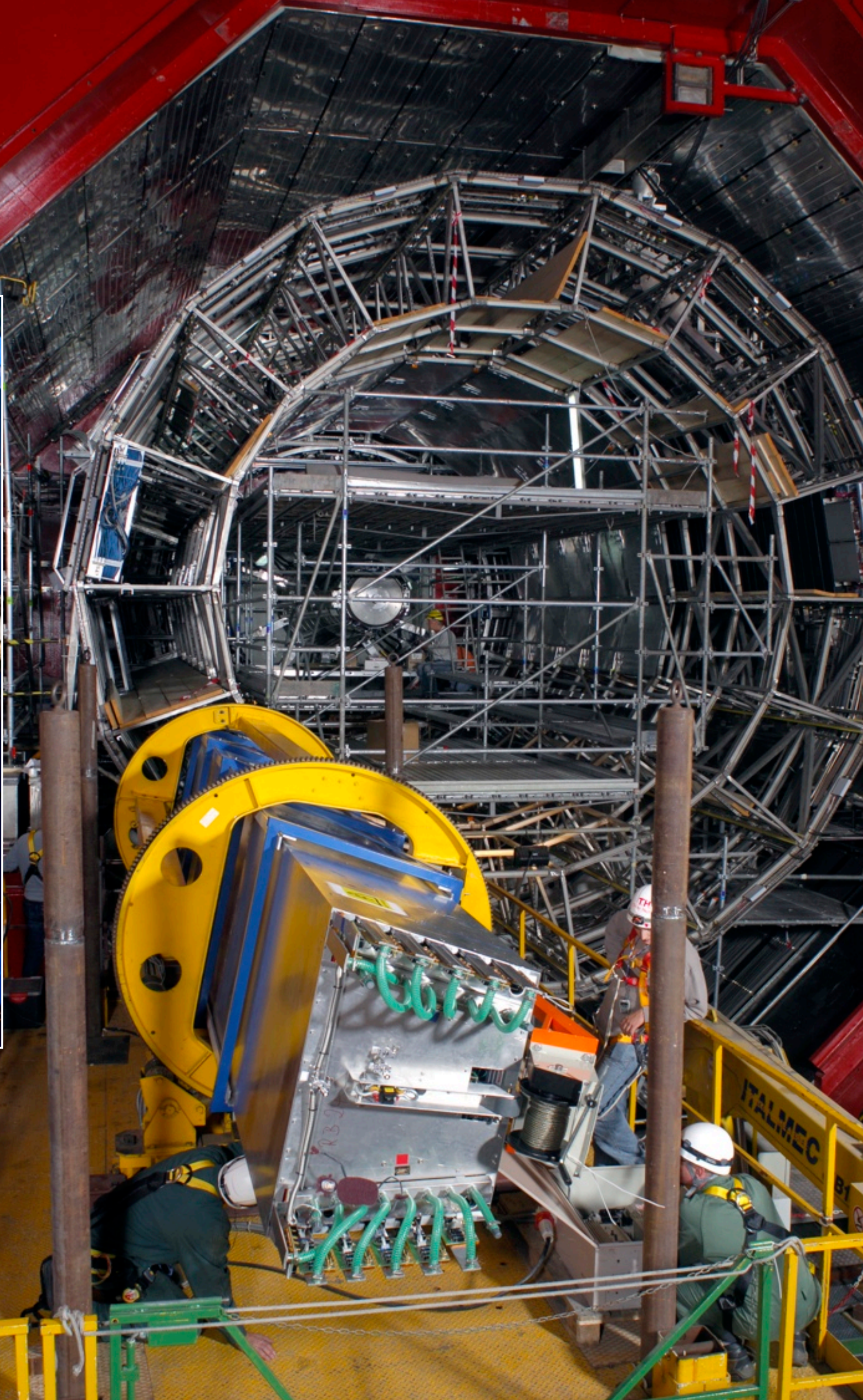
ITS - Sliding the SSD/SDD over the SPD



TPC and TRD

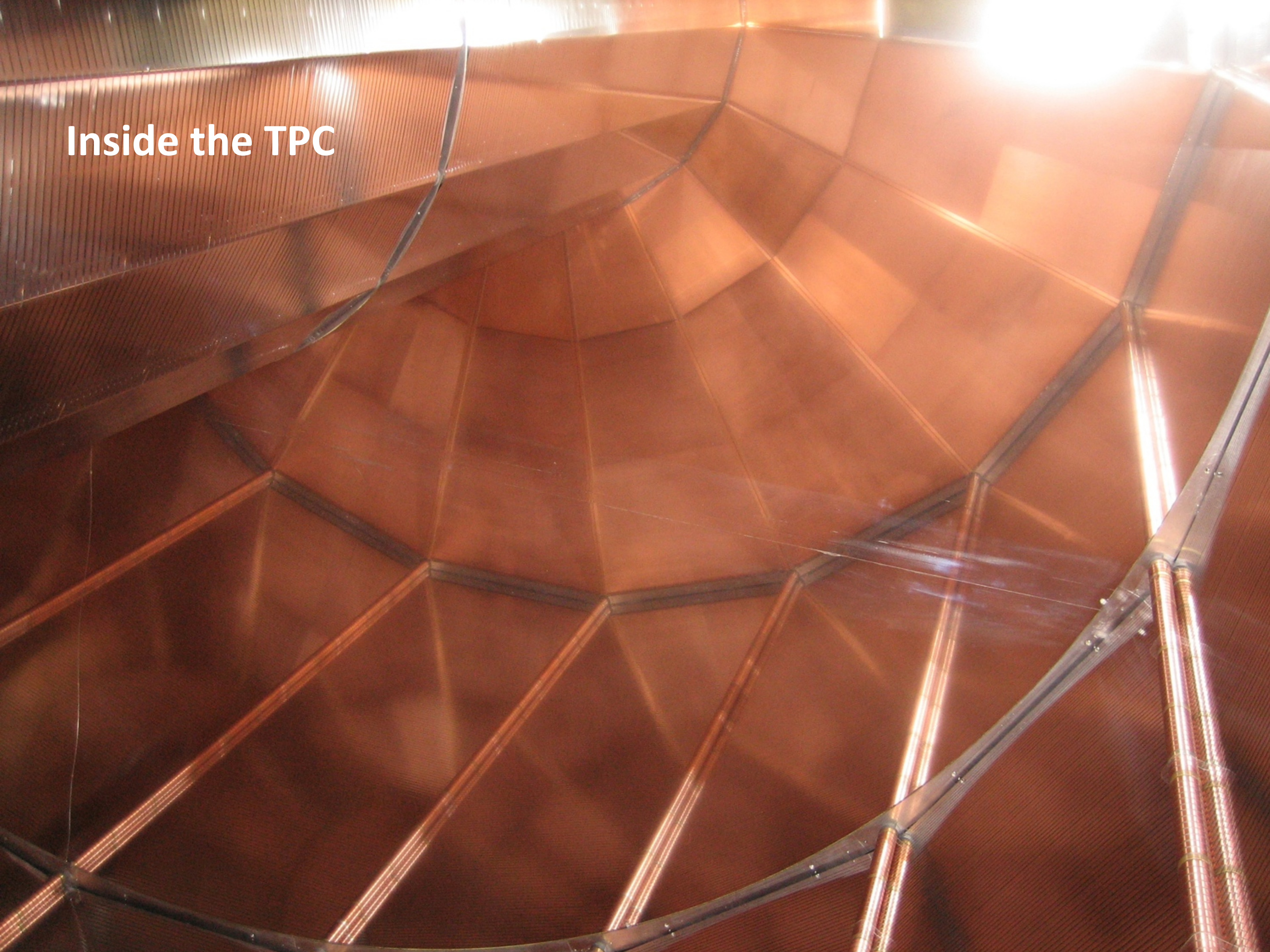


Time Projection Chamber (TPC)

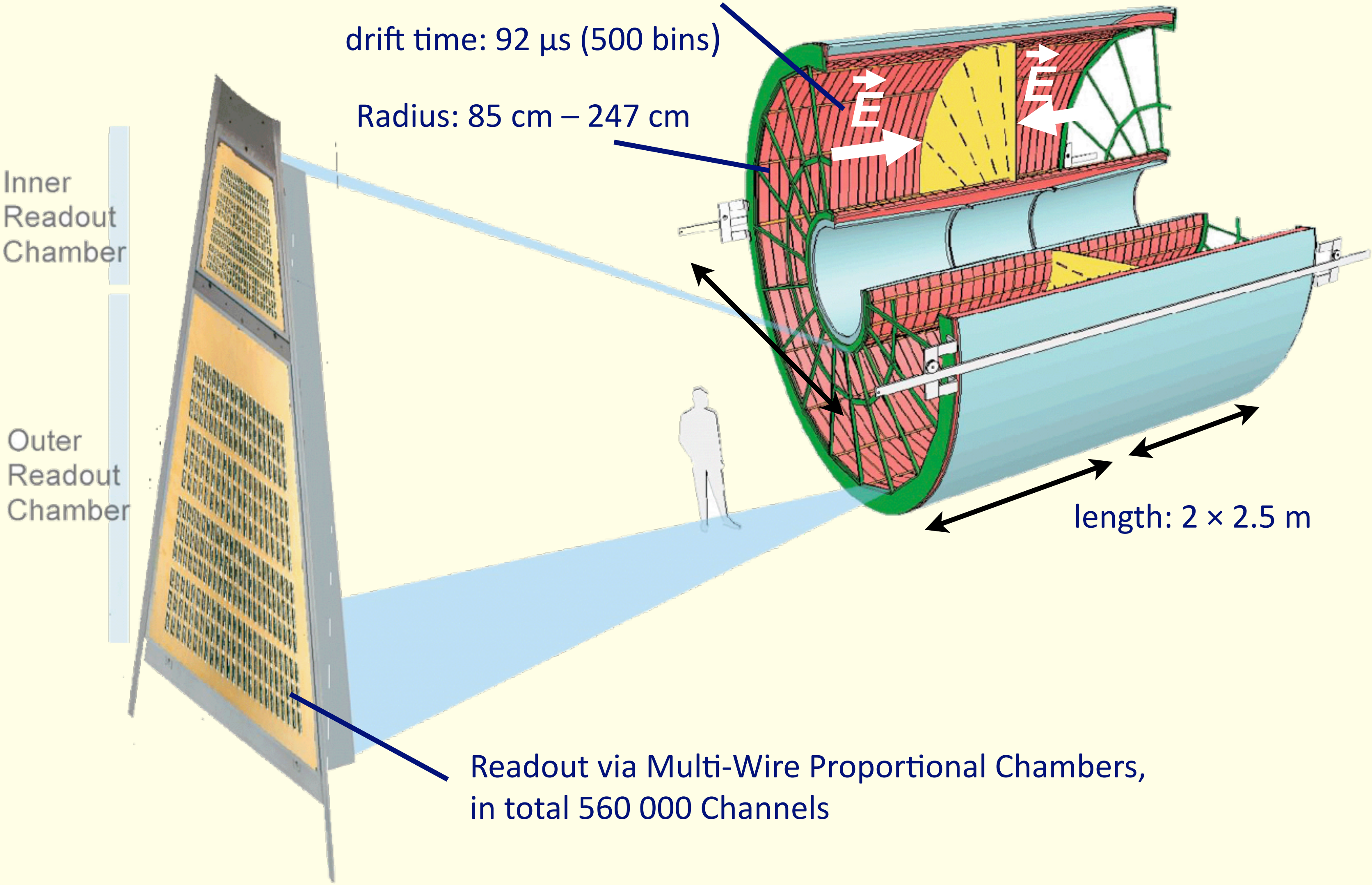


Installation of the
first TRD supermodule
(October 2006)

Inside the TPC



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



drift field: E = 400 V/cm

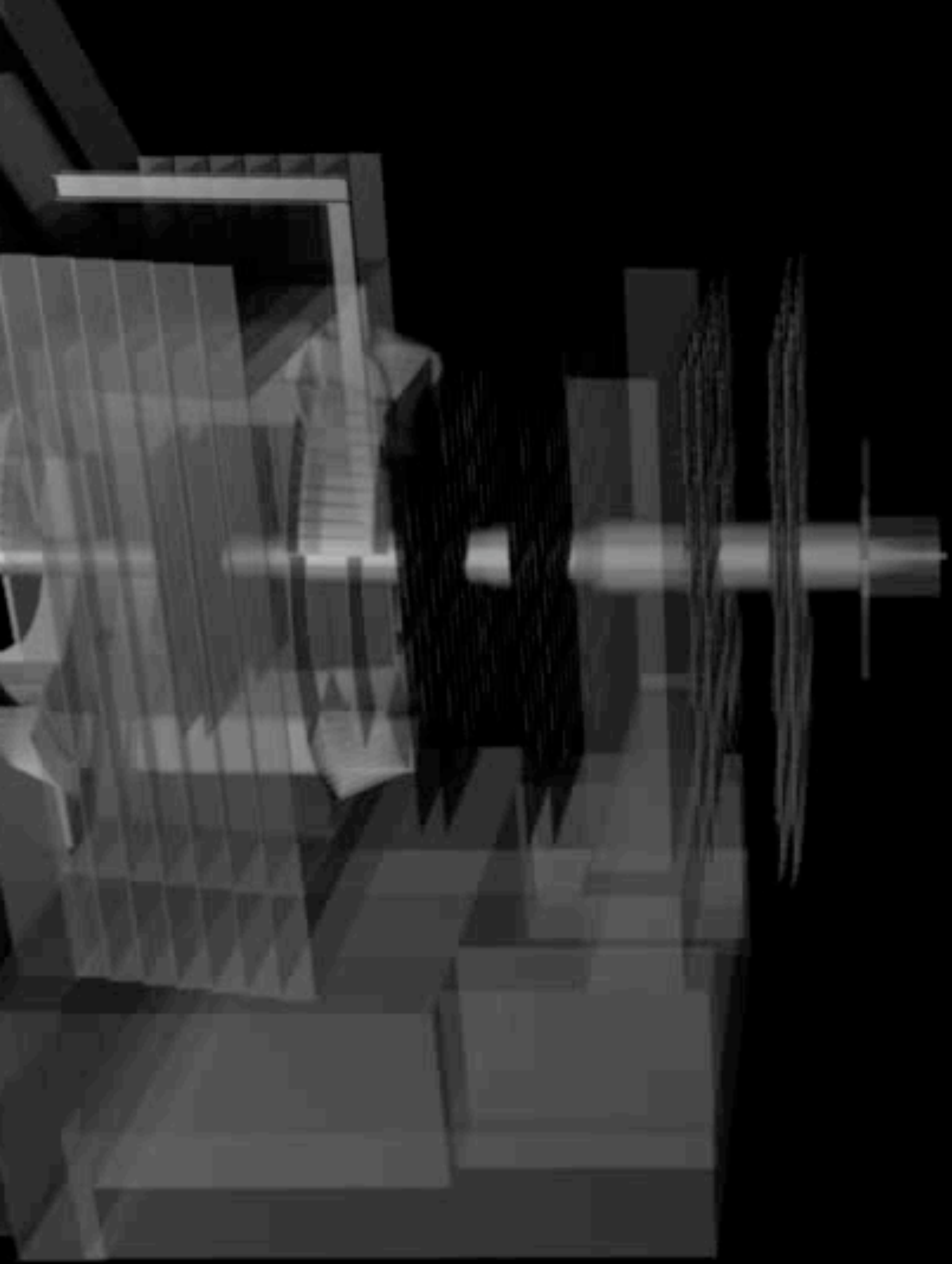
~ 90 m^3 gas: $Ne/CO_2/N_2$

drift time: 92 µs (500 bins)

Radius: 85 cm – 247 cm

length: 2 × 2.5 m

Readout via Multi-Wire Proportional Chambers,
in total 560 000 Channels



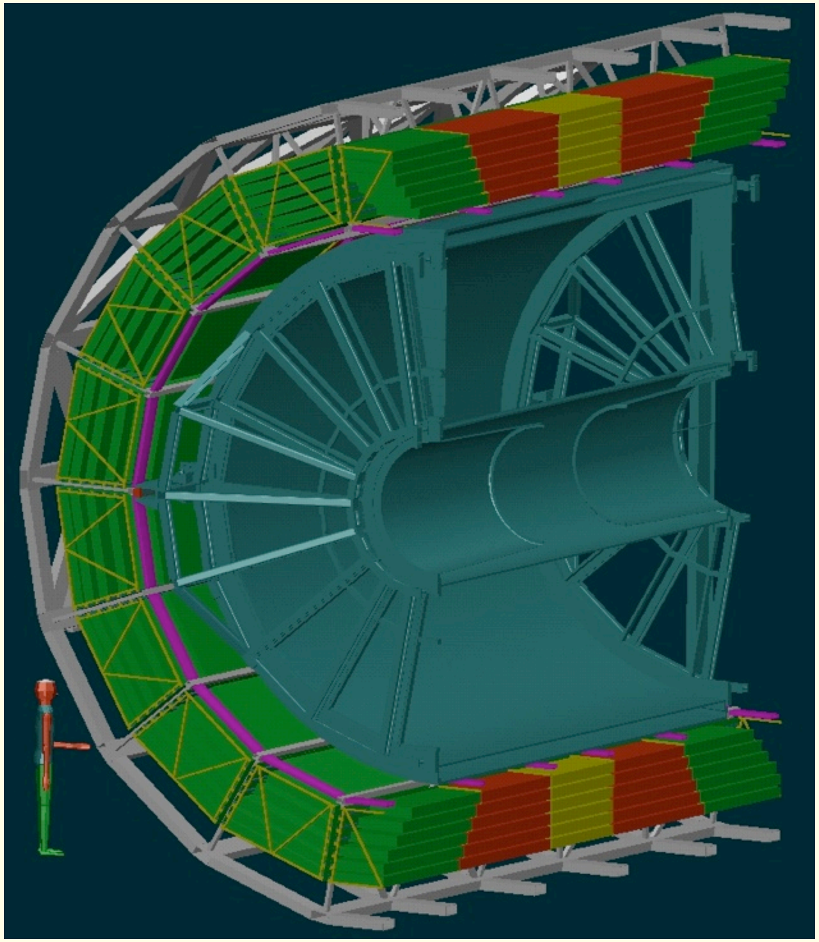
The Transition Radiation Detector (TRD)

task: electron id by TR

J/ψ, $\Upsilon \rightarrow e^+ e^-$

D, B → e + anything (semi-leptonic)

trigger on high p_t electrons

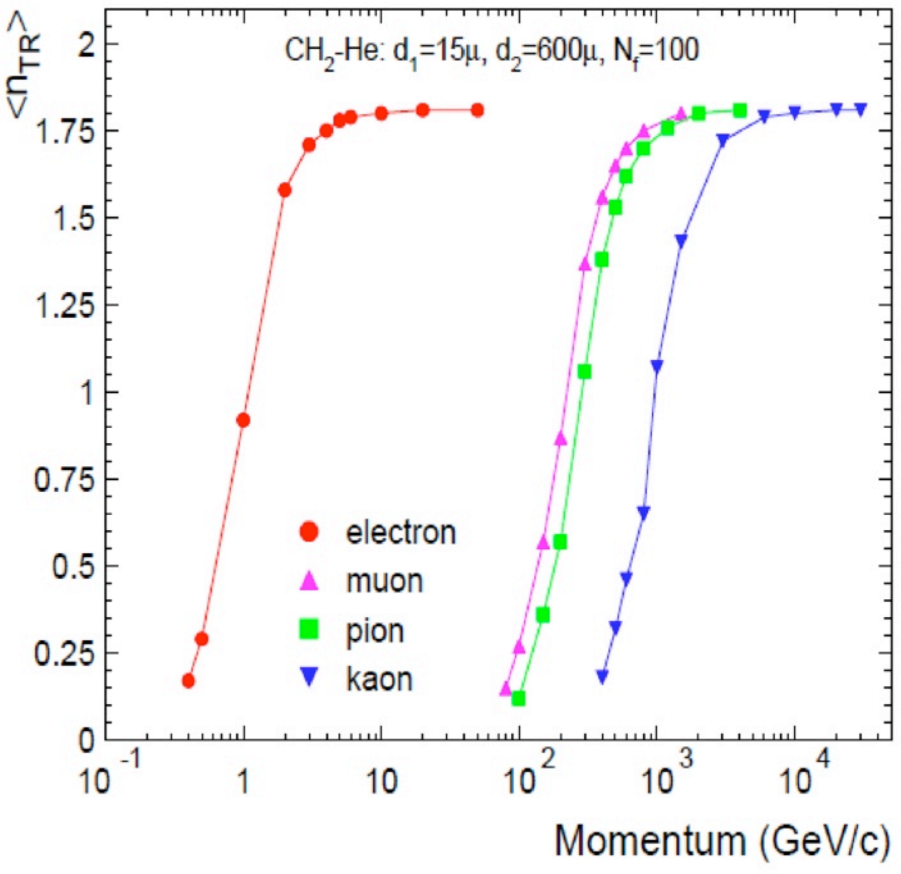


- 540 chambers /18 supermodules
- total area: 694 m^2
- gas volume: 25.8 m^3 (Xe-CO_2)
- resolution ($r\phi$): 400 µm
- trigger: 275 000 CPUs, 6.5µs /event

- chamber production finished
- 7 supermodules in 2009
- completion 2010

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

Transition Radiation (TR)

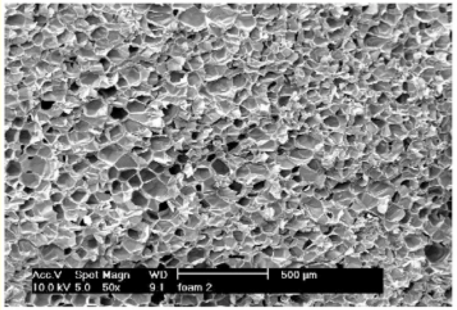


- Charged particles emit transition radiation when cross boundaries of media with different ε
- Small probability
  ⇒ many boundaries
- Here: Lorentz factor γ > 1000
  ⇒ only electrons emit TR

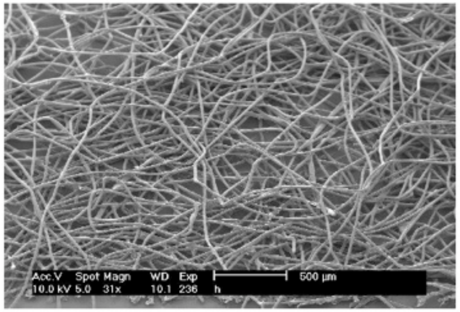
  ⇒ identify electrons !

Typical TR radiators:

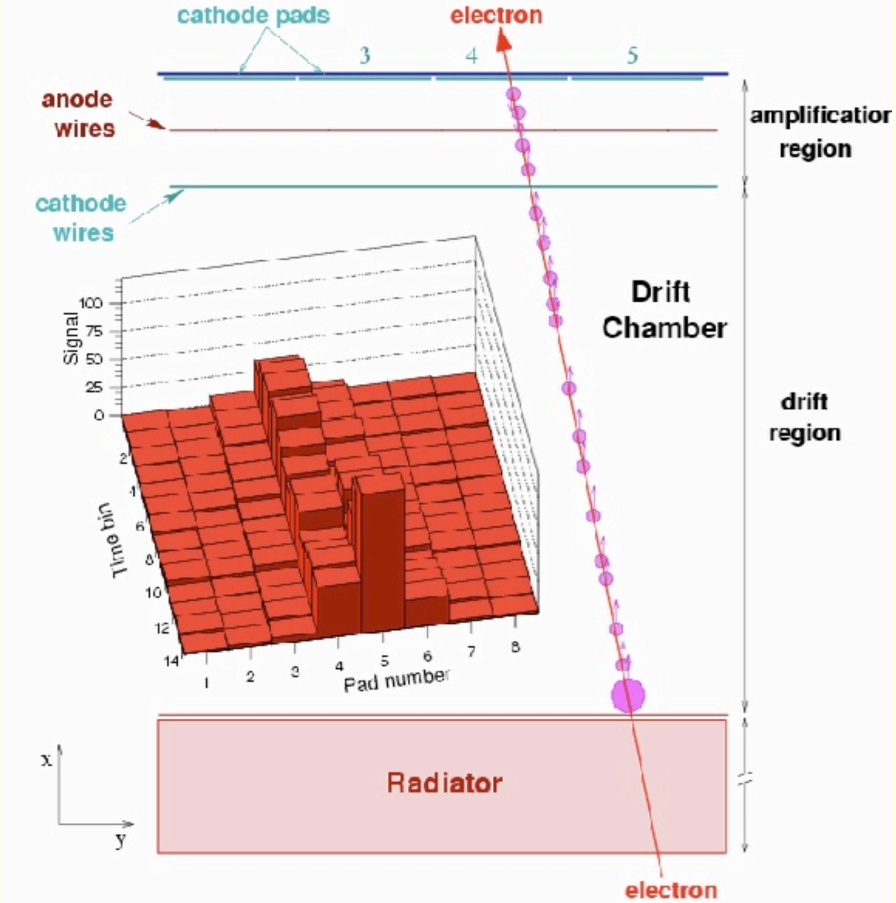
Foams

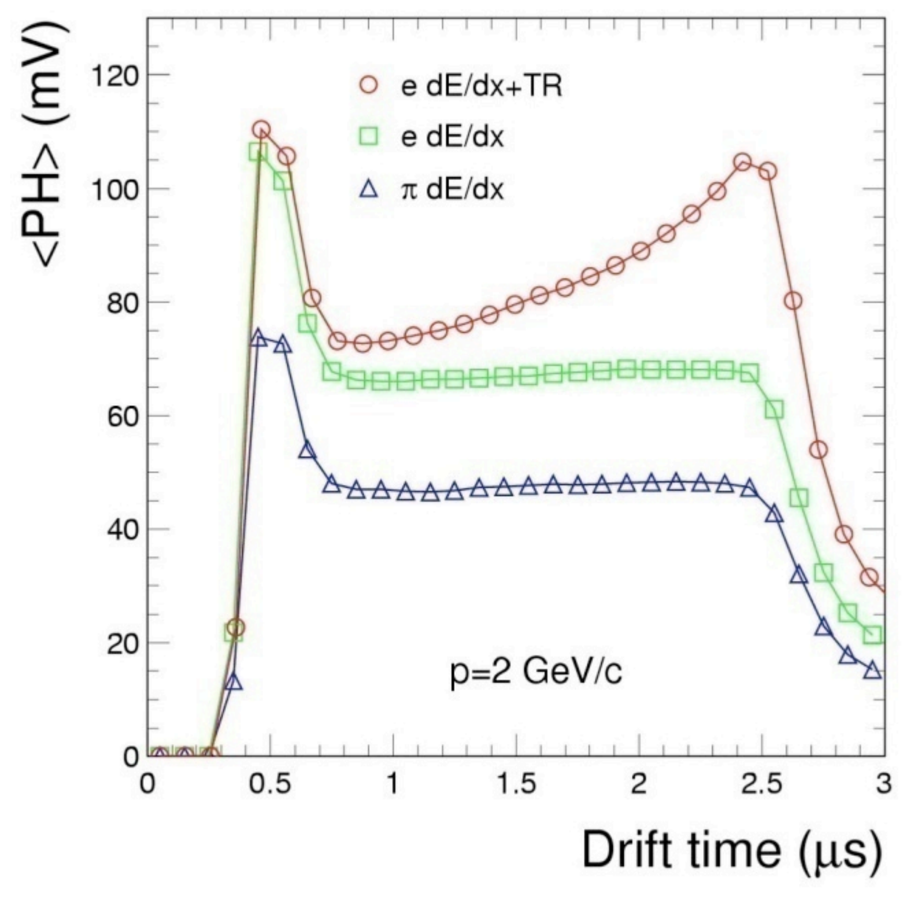


Fibers



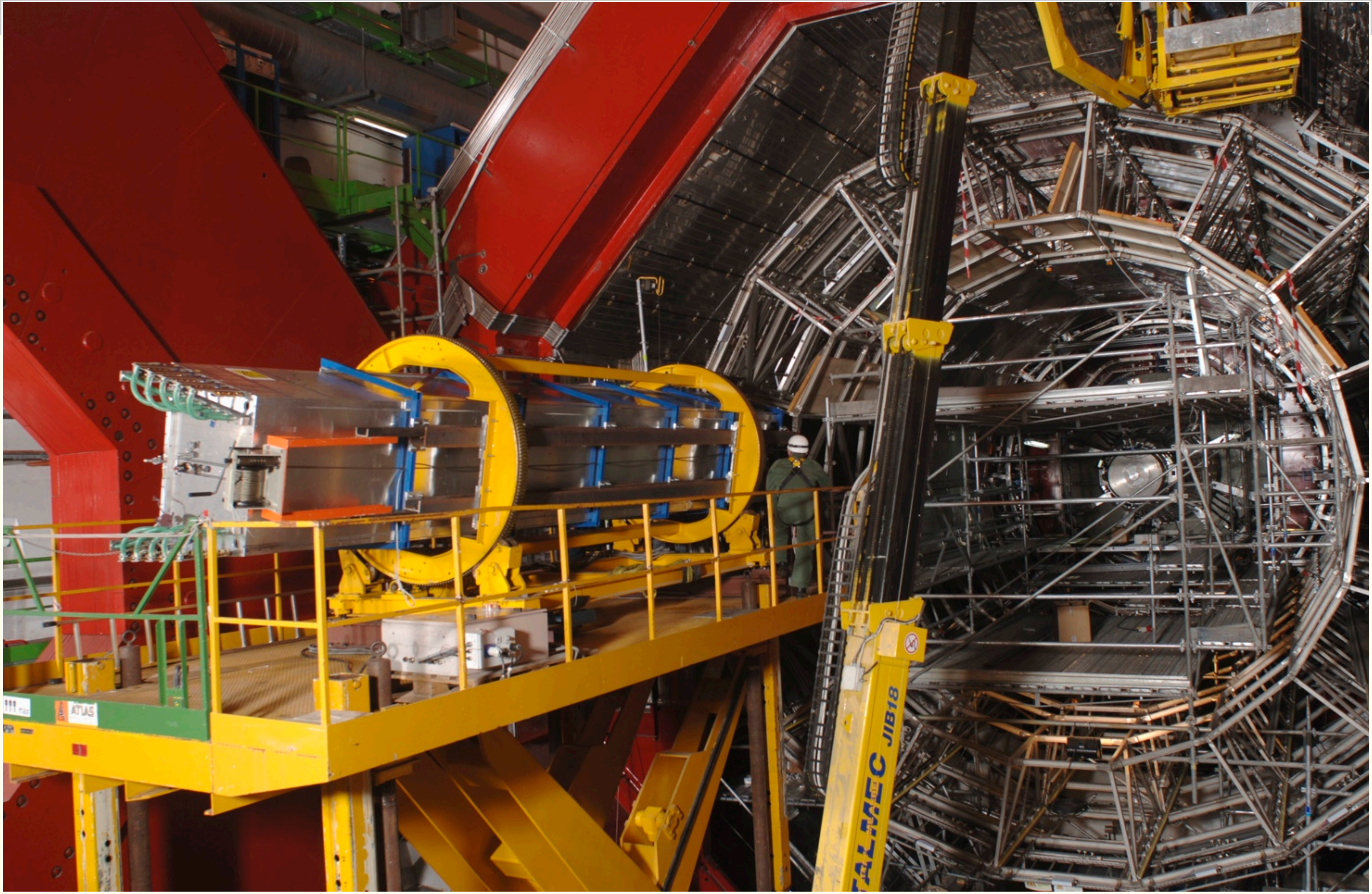
TRD – Signal Generation

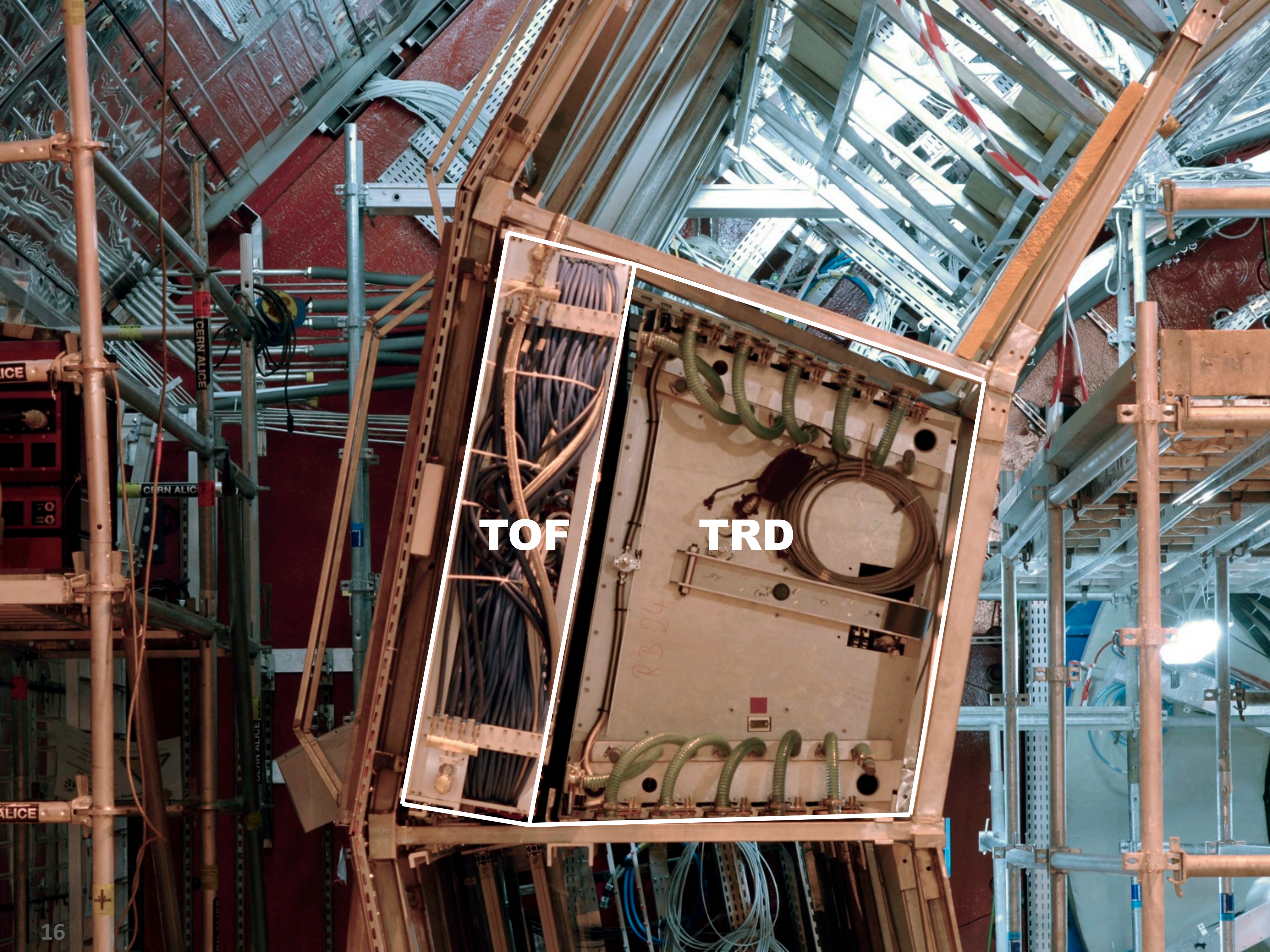




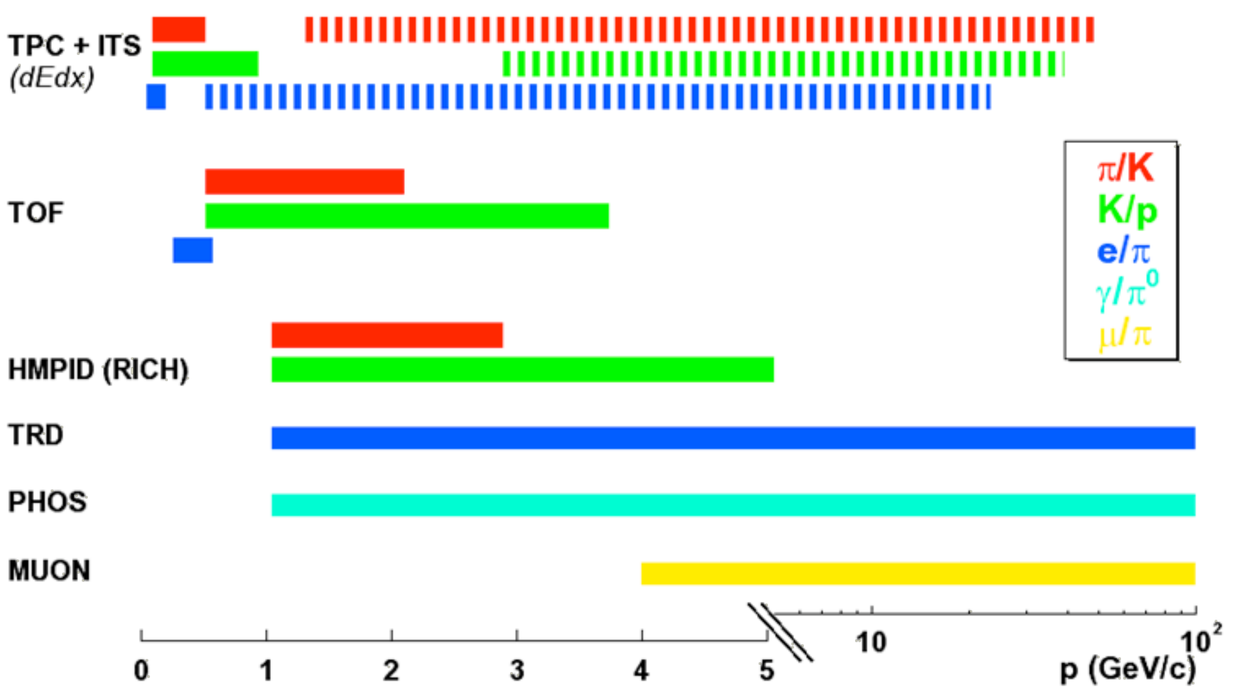
- Charged particles induce a signal in the detector
- Only electrons produce transition radiation
- Electron ID, misidentified pions 1 % or less

First TRD supermodule in ALICE – Oct 2006




TOF
TRD

Particle Identification in ALICE



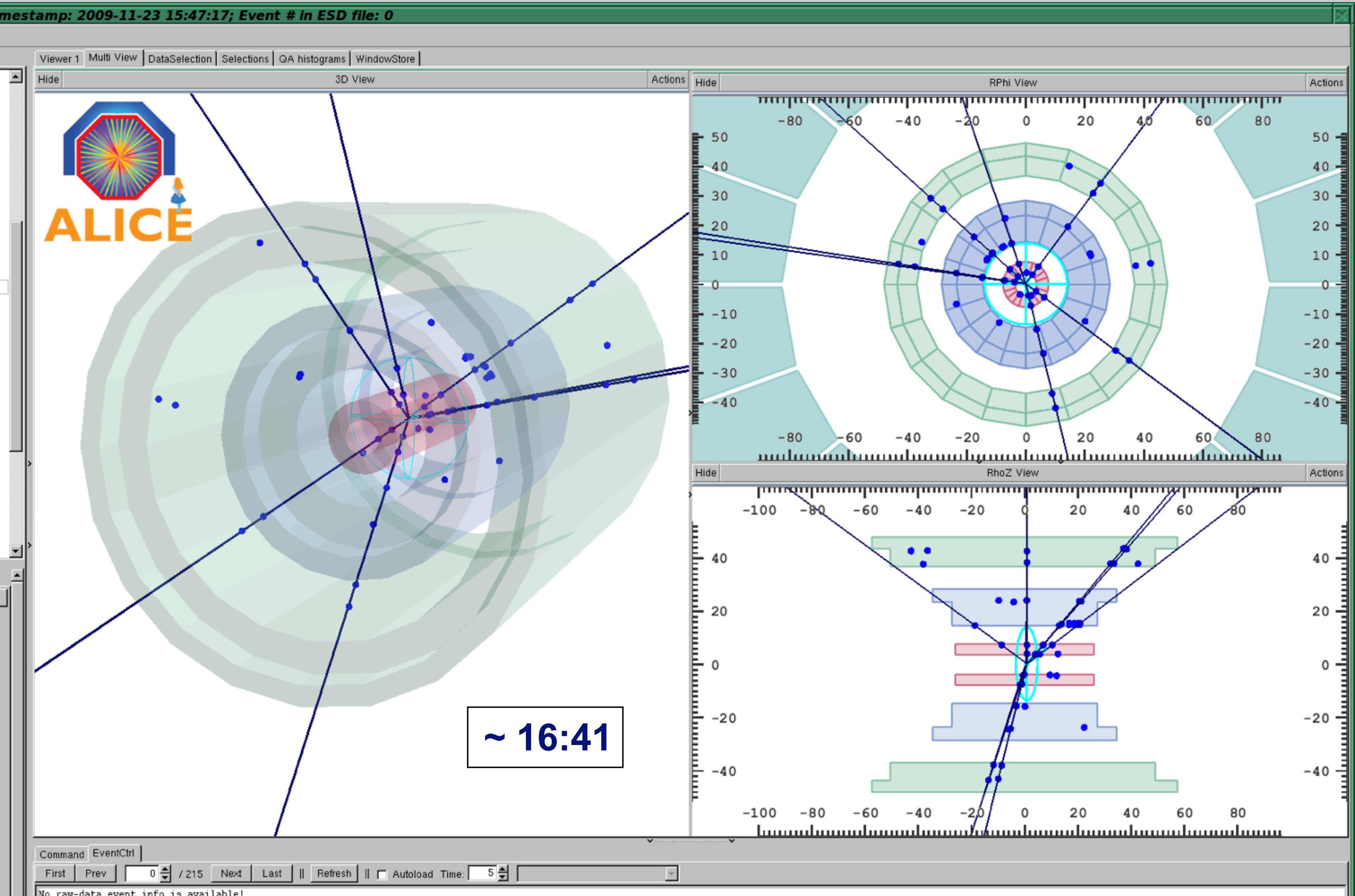
Alice has excellent momentum reconstruction and particle ID capabilities at low transverse momenta

- ‘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) + Cherenkov (RICH)
- Decay topologies (K_S^0, K^+, K^-, Λ, ϕ, D)
  - Secondary vertex reconstruction (+ invariant mass analyses)
- Leptons (e, μ), photons, η, π^0
  - Electrons TRD: p > 1 GeV, muons: p > 5 GeV, π^0 in PHOS: 1 < p < 80 GeV

Some Anxious Minutes Waiting for Collisions..

November 23, 2009, ~ 16:35

The first ‘event’ pops up in the Alice Control Room



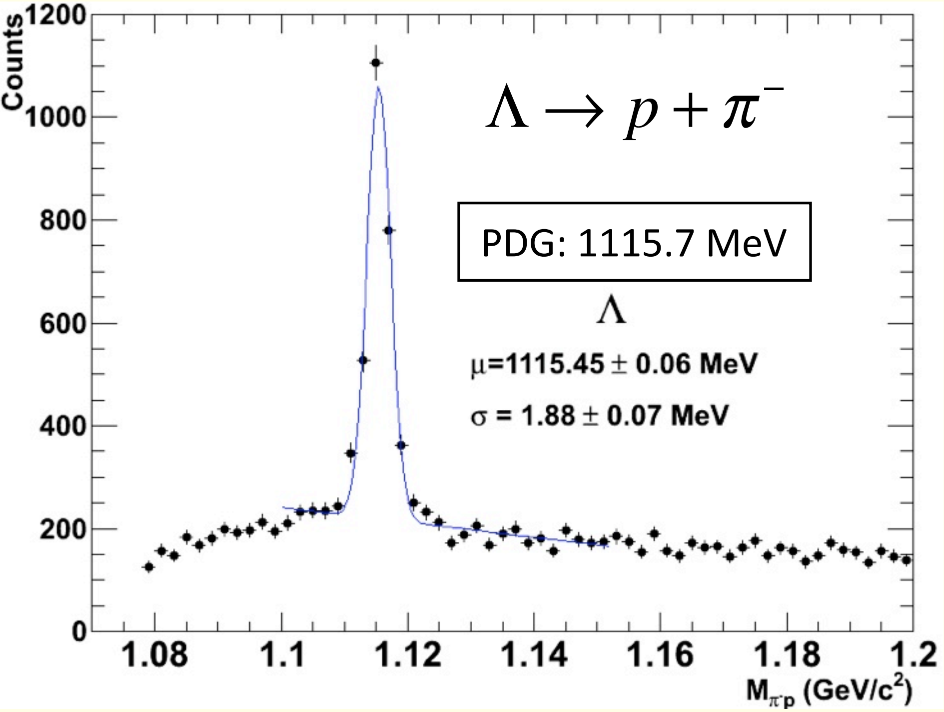
mestamp: 2009-11-23 15:47:17; Event # in ESD file: 0

No raw-data event info is available!

~ 16:41

Relief and Excitement ...

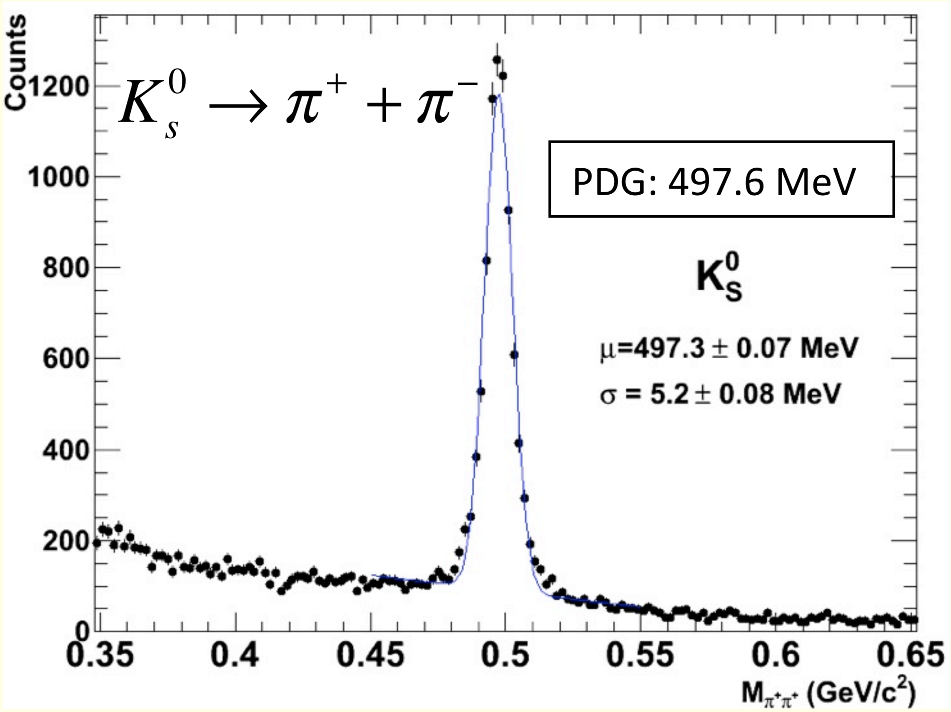
First Checks: Invariant Mass Peaks



$\Lambda \rightarrow p + \pi^-$

PDG: 1115.7 MeV

Λ: $c\tau$ = 7.89 cm



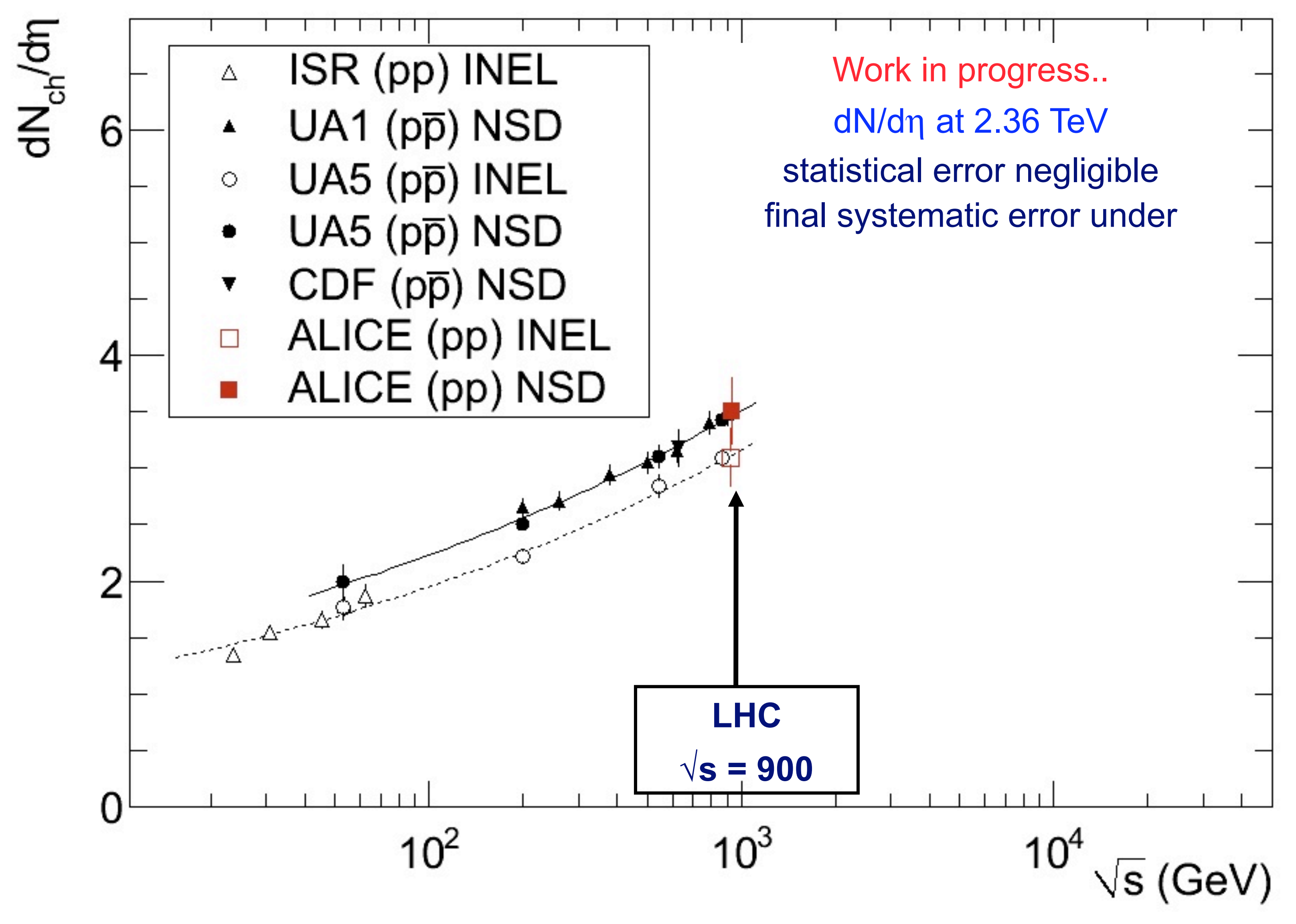
$K_s^0 \rightarrow \pi^+ + \pi^-$

PDG: 497.6 MeV

K_s^0: $c\tau$ = 2.6842 cm

Reconstruction of known particles helps constrain the Momentum Calibration

The First Paper with LHC Data: Multiplicity Measurement at √s = 900 GeV



Work in progress..

dN/dη at 2.36 TeV

statistical error negligible

final systematic error under

LHC

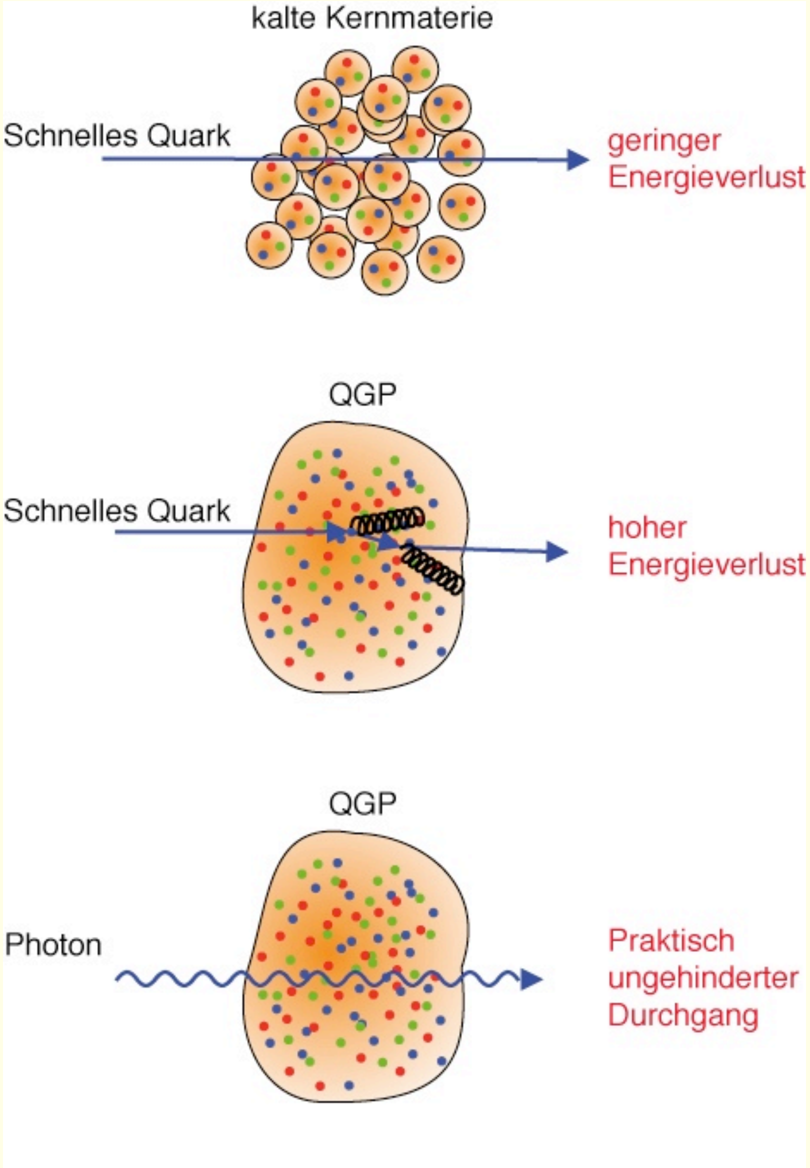
√s = 900

Points to Take Home

- ALICE is the only dedicates Heavy-Ion Experiment at the LHC
- Excellent momentum reconstruction and particle ID capabilities, especially at low p_T (B_nominal = 0.5 T)
- Very good reconstruction of secondary vertices and electron identification: Physics with heavy quarks

2. Hard Scattering and Jet Quenching

Jet Quenching: Basic Idea



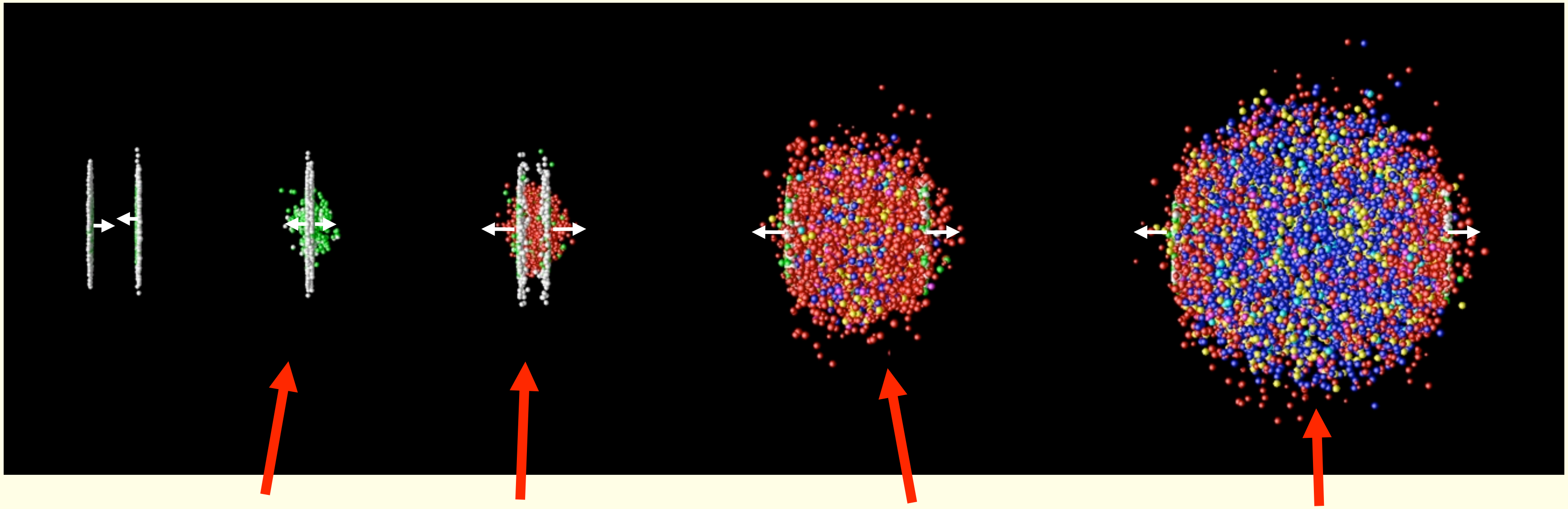
Expectation:
Simple scaling from
p+p to d+Au

Expectation:
Pion suppression in A+A

Expectation:
Simple scaling
from p+p to A+A
for direct photons

Jets as Auto-Generated Probes of the QGP

time →



Early hard parton-parton scatterings ($Q^2 >> \Lambda^2_{QCD}$)

Thermalized medium (QGP!?) ($T_0 > T_c$, $T_c \approx$ 150–200 MeV)

Transition QGP → hadron gas

Freeze-out

- Thermalization of the deconfined quark-gluon matter expected at $\tau_0 < \sim 1$ fm/c
- Hard probes (jets, high-p_T direct photons, c- and b-quarks) produced in early hard parton scatterings prior to QGP ⇒ ideal QGP probes

What Can We Hope to Learn from Jet Quenching?

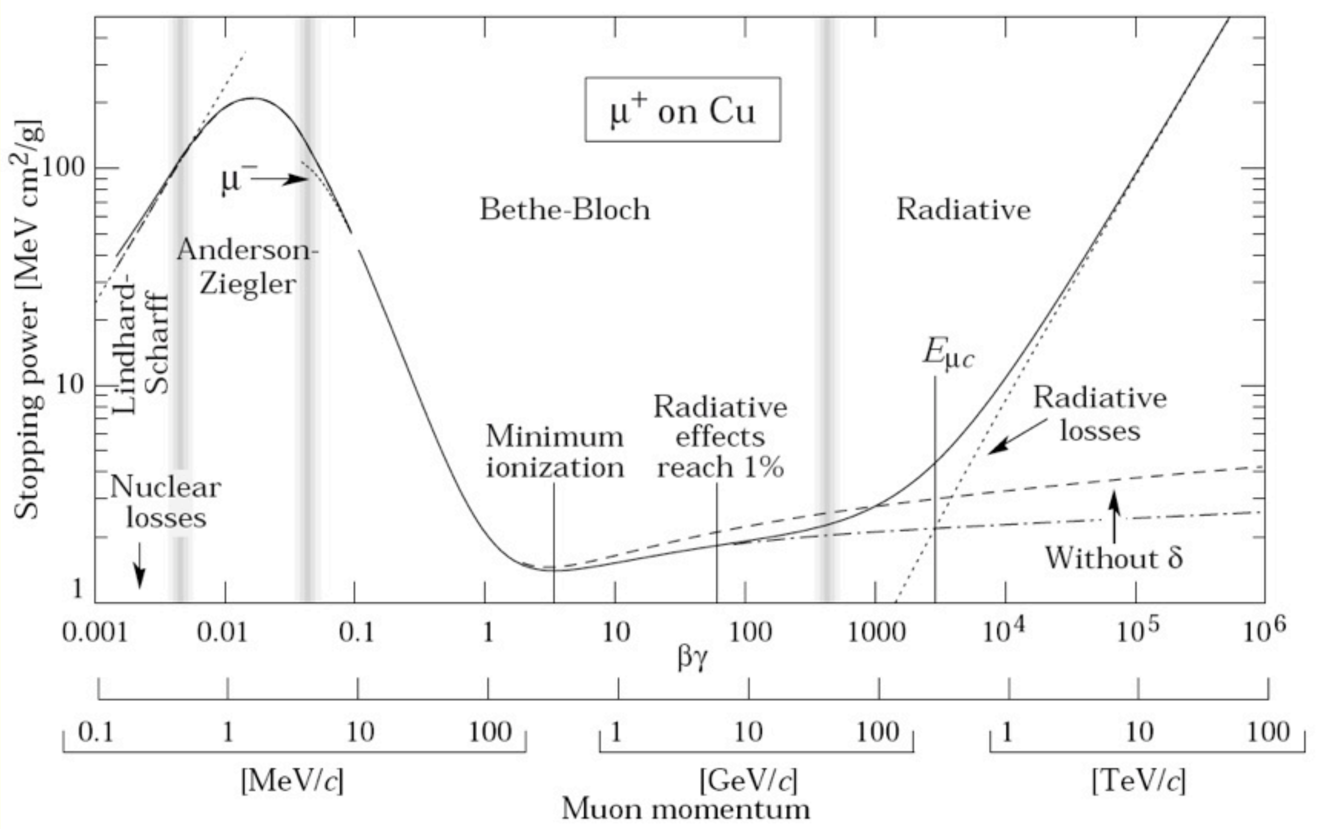
- Objectives of heavy-ion physics:
  - Learn something about QCD in the regime of high temperatures and densities (QCD thermodynamics)
  - Study the deconfinement transition at T_c = 150 - 200 MeV predicted by lattice QCD calculations

- Observables related to Jet Quenching may help to
  - characterize the new state of matter above T_c
  - understand the mechanism of parton energy loss

- Basic logic

$$\text{QGP} \quad \underset{\cancel{\Longleftarrow}}{\Longrightarrow} \quad \text{Suppression of hadrons at high } p_T$$

Analogy:
Energy loss of Charged Particles in Normal Matter



- μ^+ on Cu: Radiational energy loss („bremsstrahlung") starts to dominate over collisional energy loss („Bethe-Bloch formula") for p >> 100 GeV/c
- For energetic quarks and gluons in QCD matter, radiative energy loss via induced gluon emission is/was expected to be the dominant process

Parton Energy Loss – Expected Properties

Radiative energy loss dominant (?):

$$\mathrm{d}E_{\mathrm{rad}} / \mathrm{d}x \gg \mathrm{d}E_{\mathrm{coll}} / \mathrm{d}x$$

Medium parameter $\hat{q} = \frac{\mu^2}{\lambda}$

μ^2 : **Typical momentum transfer from the medium to the parton**

λ : **Mean free path**

Nucl.Phys.B483:291-320,1997

$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

Energy loss ΔE in a static medium of length L for $E \to \infty$ (BDMPS results)

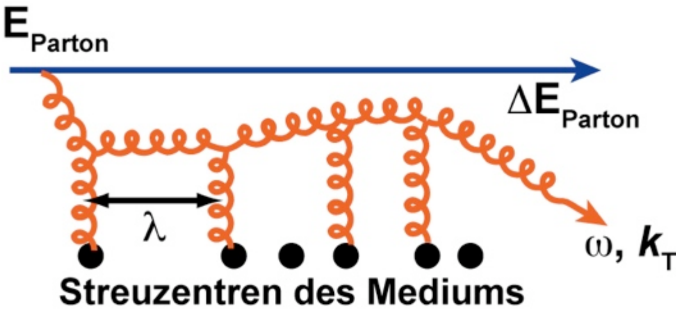
Energy loss for gluon jets larger than for quark jets

$$C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

L^2 dependence:

Non-abelian nature of

QCD + quantenm. interference



The discovery phase (ca. 2000 - 2003)

How Can We Study Jet Quenching?

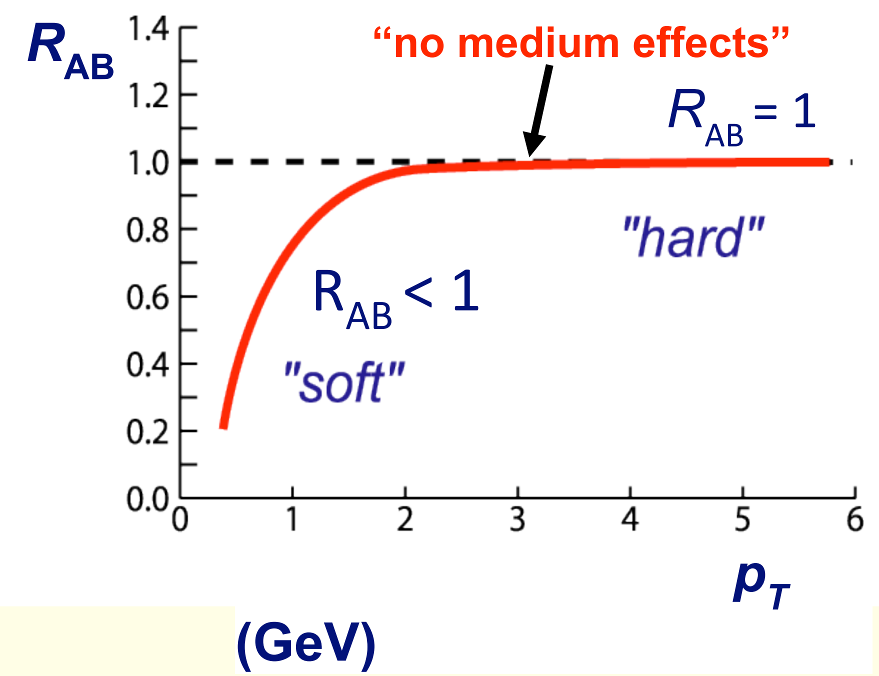
- Measurement of particle multiplicities at high p_T
- Measurement of two-particle angular correlations
- Jet reconstruction on an event-by-event basis
  - Challenging in central nucleus-nucleus collisions at RHIC due to large particle multiplicity from the underlying event
  - Situation improves significantly for Pb+Pb at the LHC due to the increased cross section for jet production

Nuclear Modification Factor

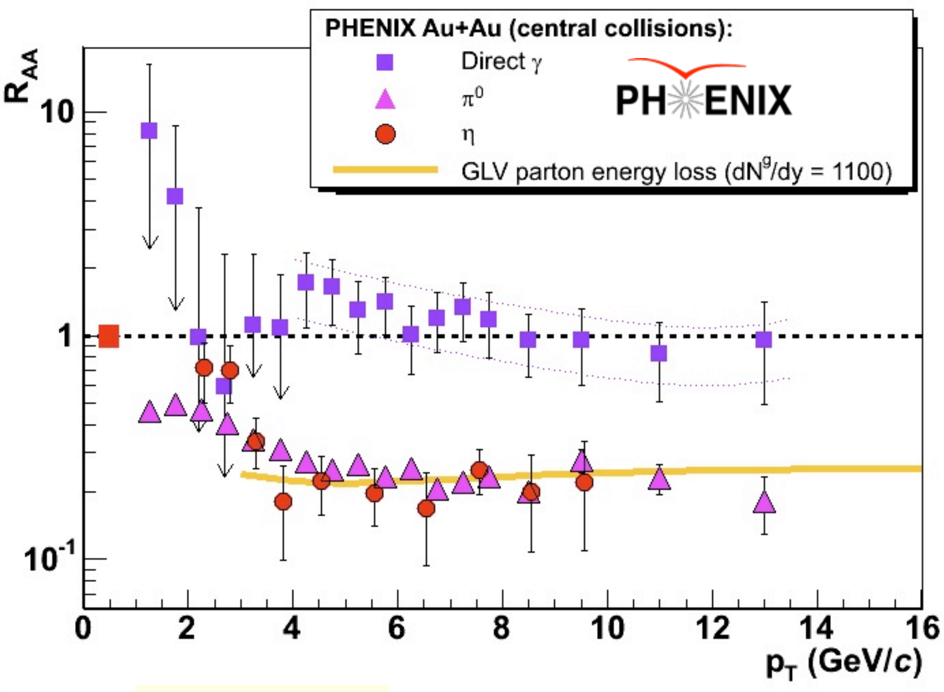
$$R_{AB}(p_\mathrm{T}) = \frac{\mathrm{d}^2 N / \mathrm{d}p_\mathrm{T}\mathrm{d}y\big|_{A+B}}{\langle N_\mathrm{coll}\rangle \times \mathrm{d}^2 N / \mathrm{d}p_\mathrm{T}\mathrm{d}y\big|_{p+p}} = \frac{\mathrm{d}^2 N / \mathrm{d}p_\mathrm{T}\mathrm{d}y\big|_{A+B}}{\langle T_\mathrm{AB}\rangle \times \mathrm{d}^2 \sigma / \mathrm{d}p_\mathrm{T}\mathrm{d}y\big|_{p+p}}$$

$$\langle T_\mathrm{AB}\rangle = \langle N_\mathrm{coll}\rangle / \sigma_\mathrm{inel}^\mathrm{NN}$$

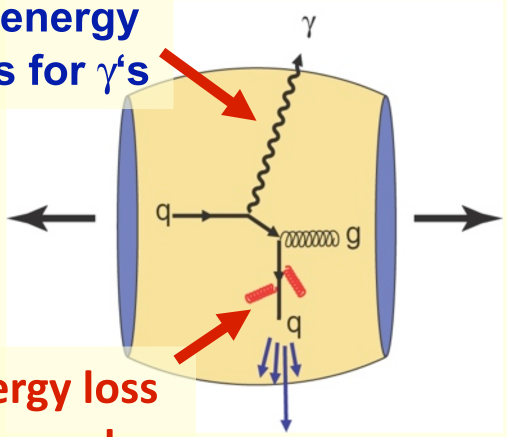
- T_AB is the effective nucleon or parton luminosity per A+A collision
- In practice: $\langle N_\mathrm{coll}\rangle$ from Glauber Monte Carlo calculation
- In the absence of nuclear effects: $R_\mathrm{AB} = 1$ at high p_T ($p_\mathrm{T} > 2$ GeV/c)
- This follows implicitly from the factorization theorem



Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (I)



No energy loss for γ's



energy loss for q and g

$$R_{AB} = \frac{dN/dp_T\big|_{A+B}}{\langle T_{AB}\rangle \times d\sigma_{\mathrm{inv}}/dp_T\big|_{p+p}},$$

$$\text{where } \langle T_{AB}\rangle = \langle N_{\mathrm{coll}}\rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

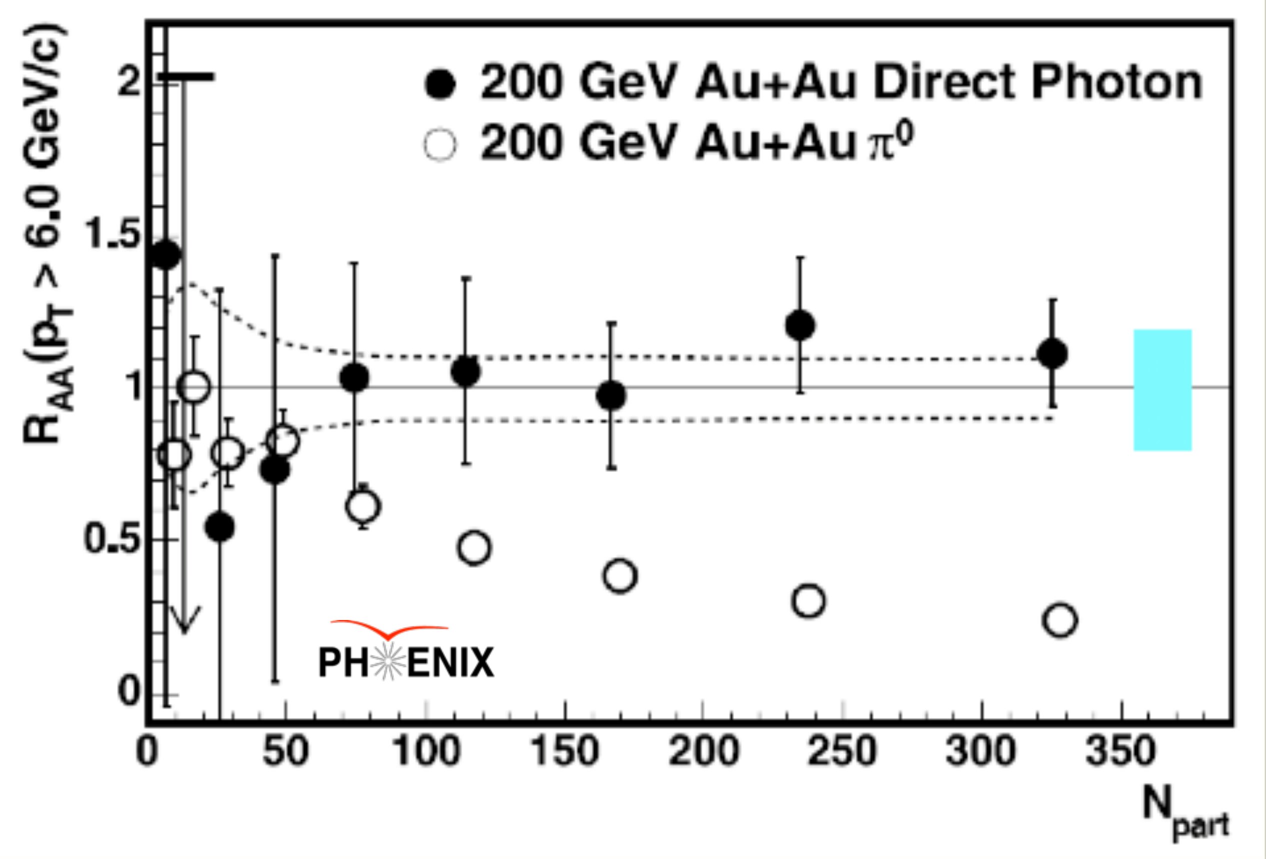
- Hadrons are suppressed, direct photons are not
- No suppression in d+Au (not shown here)
- Evidence for parton energy loss

PHENIX: Phys.Rev.Lett.88:022301, 2002
PHENIX: Phys.Rev.Lett.91:072301, 2003
PHENIX: Phys.Rev.Lett.94:232301, 2005

STAR: Phys.Rev.Lett.89:202301,2002
STAR: Phys.Rev.Lett.90:082302,2003
STAR: Phys.Rev.Lett.91:172302,2003

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (II)

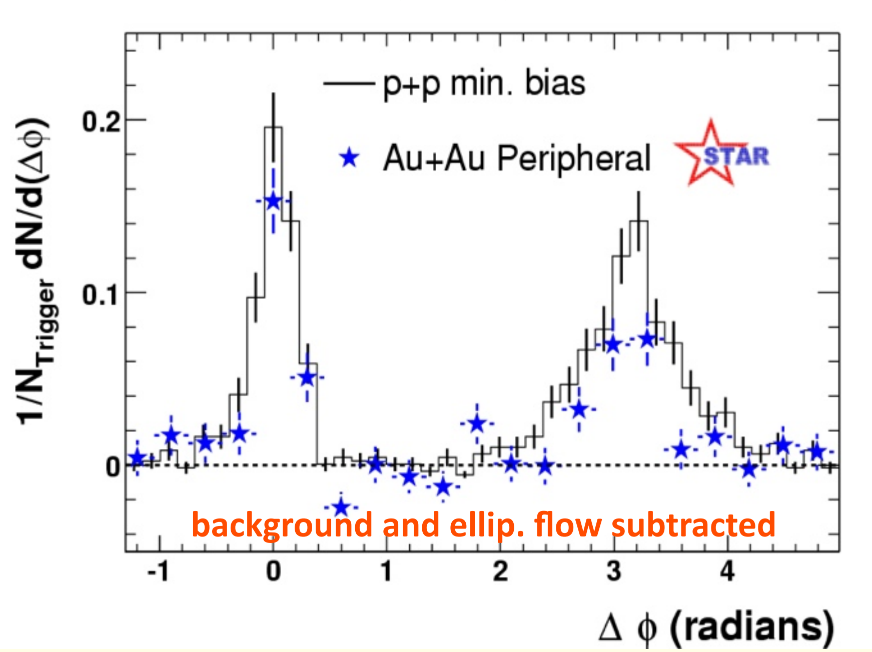
Centrality Dependence of the π^0 and direct γ R_{AA}:



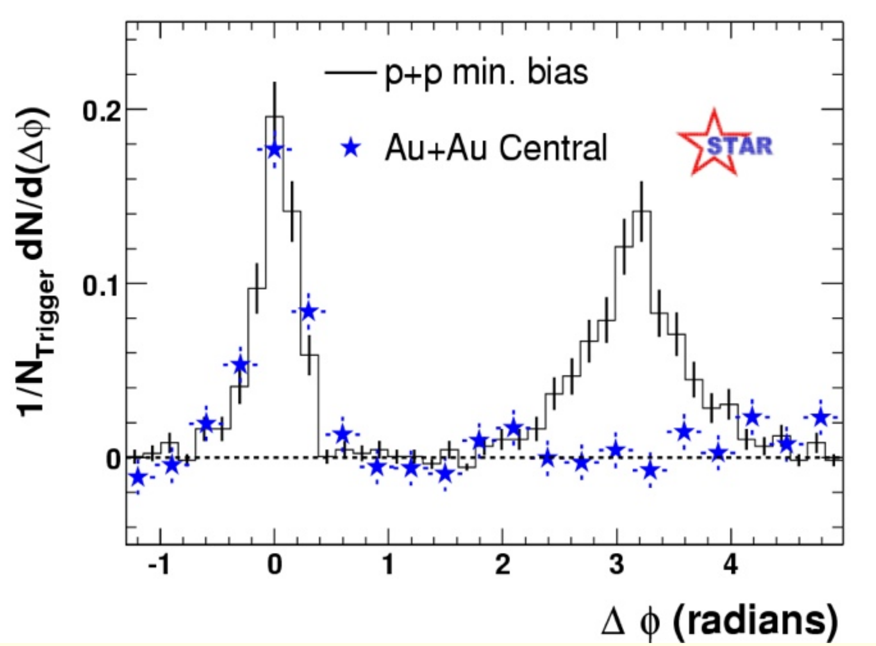
Direct photons follow T_{AB} scaling as expected for a hard probe not affected by the medium

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (III)

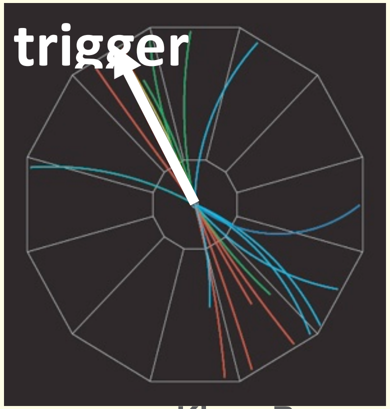
Au+Au peripheral



Au+Au central



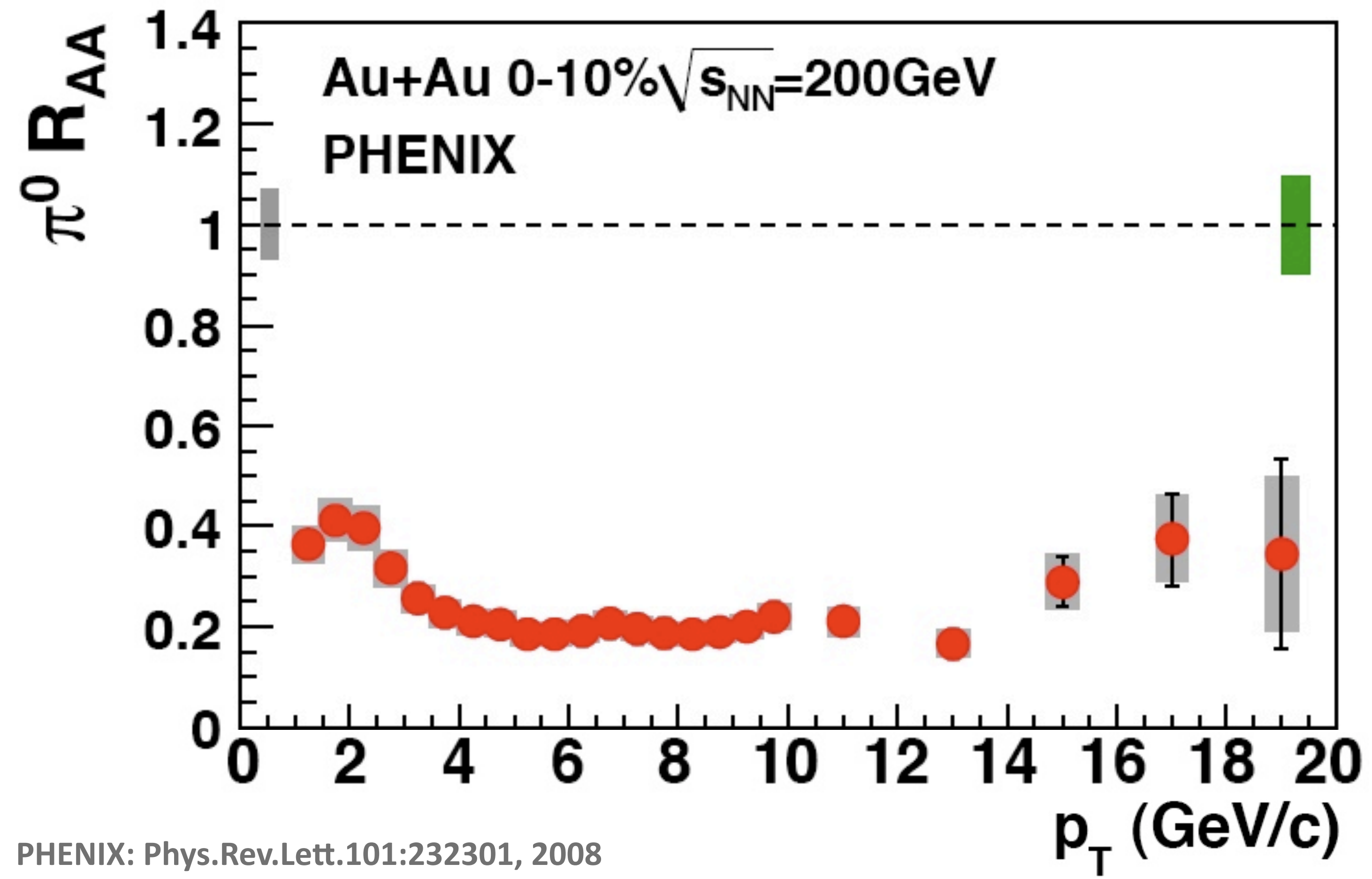
Trigger particle: p_T > 4 GeV/c
Associated particle: p_T > 2 GeV/c



- No jet correlation around 180° in central Au+Au
- Consistent with jet quenching picture

Further Experimental Results Related to Jet Quenching

R_{AA} with Higher Statistics (2004 Run at RHIC)



PHENIX: Phys.Rev.Lett.101:232301, 2008

R_{AA} approximately constant up p_T = 20 GeV/c

Simple Interpretation of the Constant R_{AA}

π^0 spectrum without energy loss: $\dfrac{\mathrm{d}N}{\mathrm{d}p_T} \propto p_{\mathrm{T}}^{-n+1}$

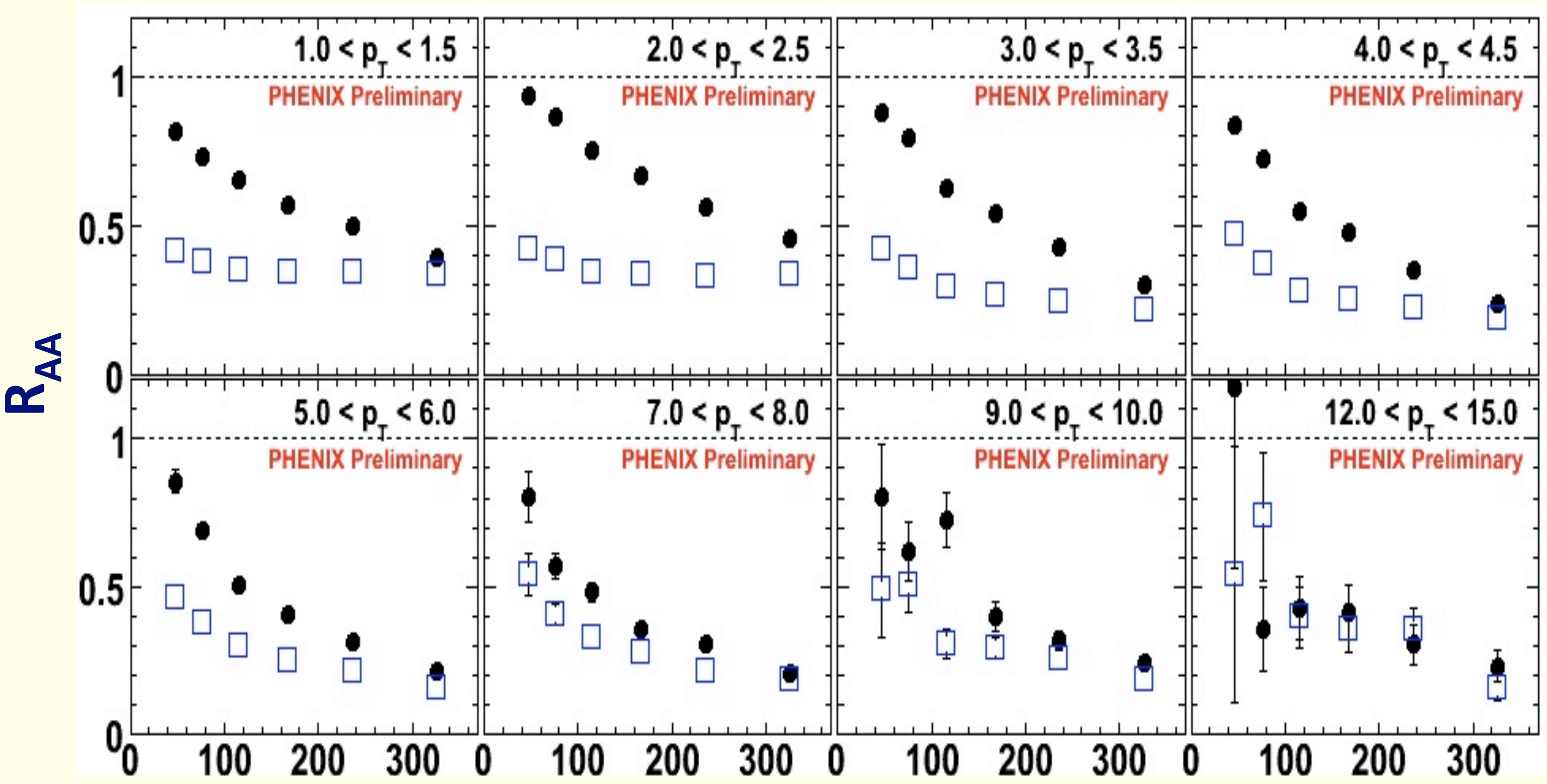
π^0 spectra at RHIC energy ($\sqrt{s_{\mathrm{NN}}}$ = 200 GeV) described with $n \approx 8$

Constant fractional energy loss: $S_{\mathrm{Loss}} := \dfrac{-\Delta p_T}{p_T}$, i.e., $p_T' = (1 - S_{\mathrm{Loss}})\, p_T$

This leads to: $R_{AA} = (1 - S_{\mathrm{loss}})^{n-2} \;\Rightarrow\; S_{\mathrm{loss}} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$

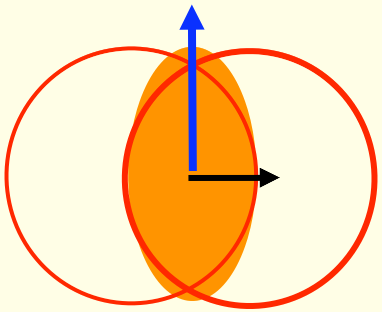
In this simplistic view the constant $R_{\mathrm{AA}} \approx 0.25$ implies a constant fractional energy loss of about 20% in central Au+Au at 200 GeV

Path Length Dependence:
π^0 R_{AA} as a Function of the Angle w.r.t. the Reaction Plane



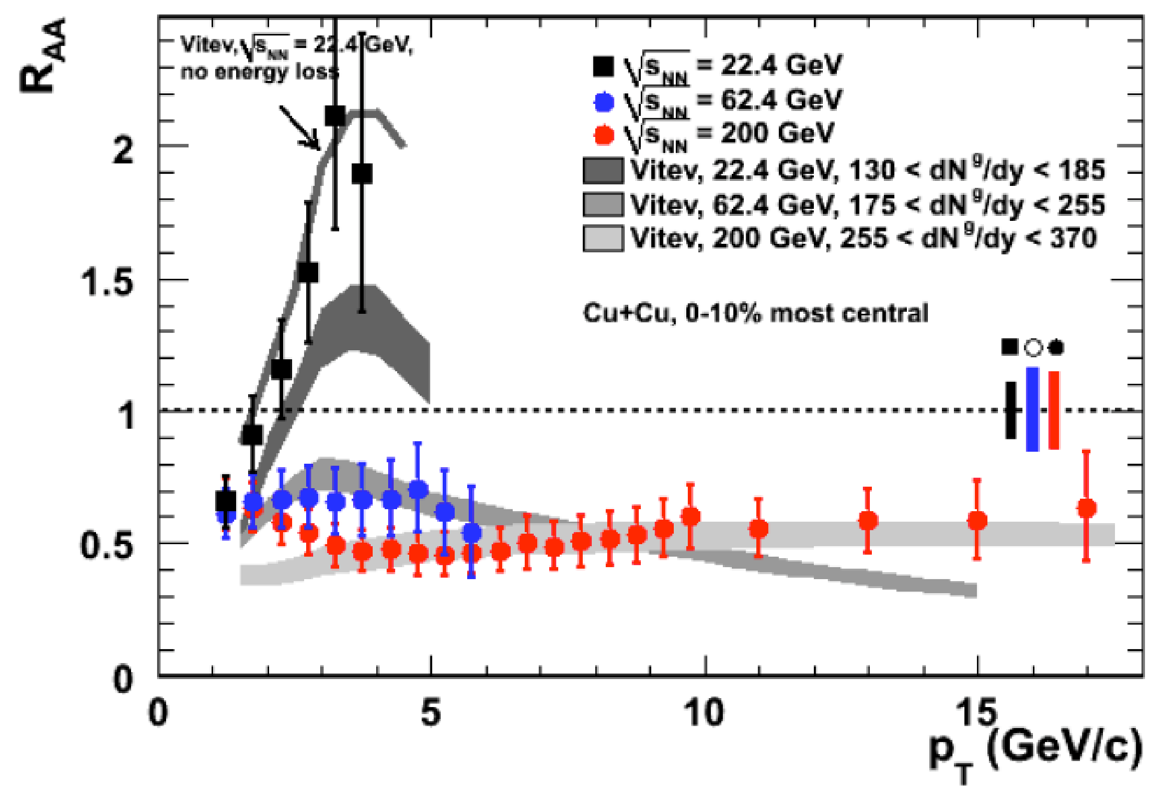
● **in-plane**

□ **out-of-**



- Longer path length for out-of-plane jets
- Hence, stronger suppression for out-of-plane jets in qualitative agreement with parton energy loss

Dependence on the Size of the Nucleus: $\sqrt{s_{NN}}$ Dependence of the π^0 R_{AA} for Cu+Cu (A = 63)



Phenix, Physical Review Letters 101,162301 (2008)

62.4 and 200 GeV

π^0 production less suppressed than in Au+Au

22.4 GeV

- No suppression
- Enhancement consistent with a calculation that describes Cronin effect in p+A

Same conclusion as for heavier nuclei:
Parton energy loss starts to prevail over Cronin enhancement between $\sqrt{s_{NN}}$ = 22.4 GeV and 62.4 GeV

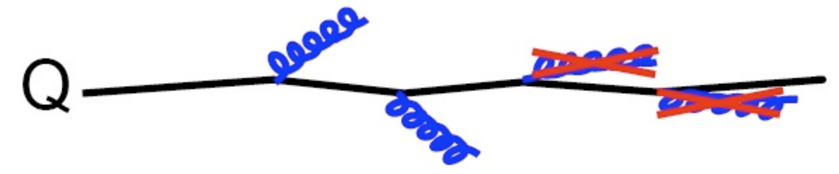
Hierarchy Expected for Different Types of Partons

$$\Delta E_{\mathrm{Gluon}} > \Delta E_{\mathrm{Quark},\,m=0} > \Delta E_{\mathrm{Quark},\,m\neq 0}$$

larger color factor
for gluons:

$$C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

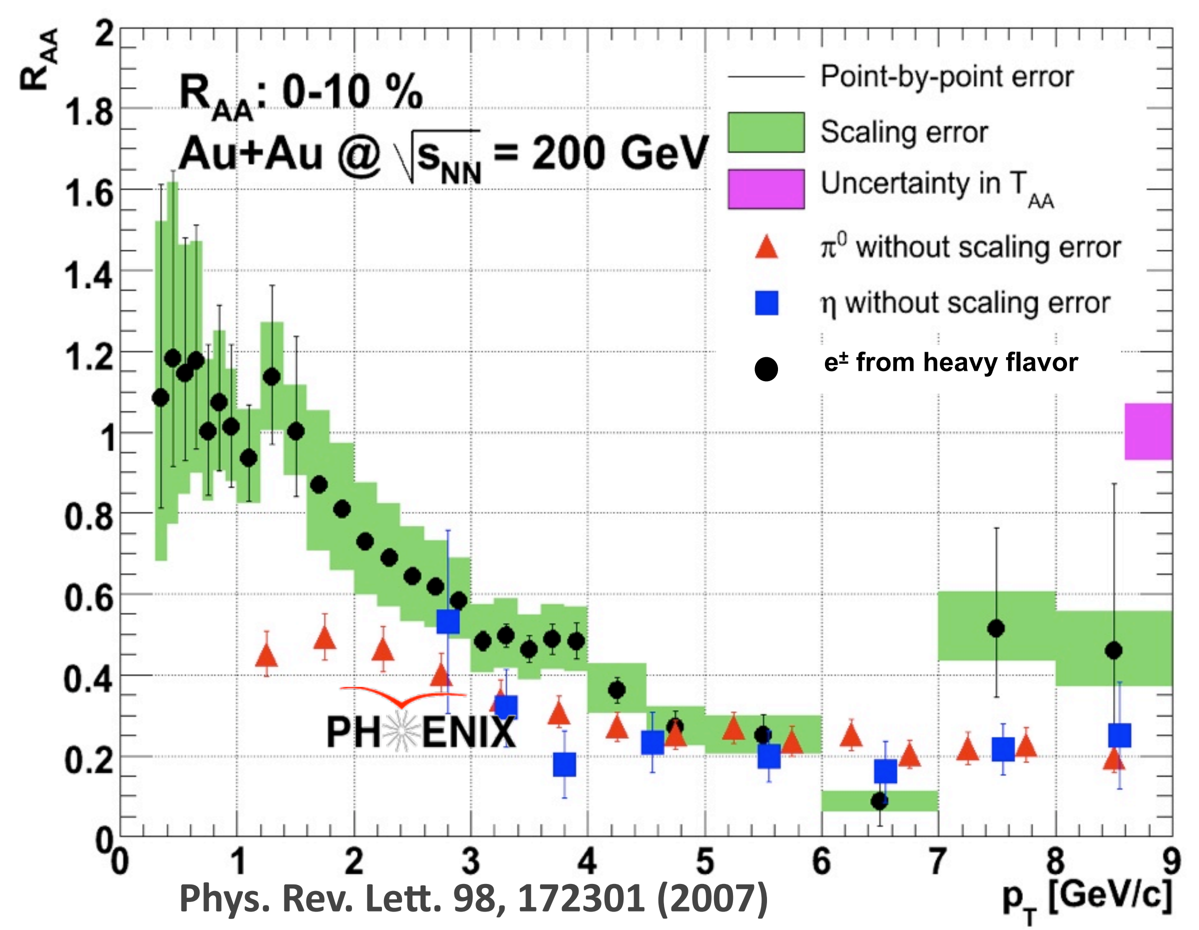
Dead cone effect:
Heavy quarks (c, b) are
slower and radiate fewer gluons



$$\omega \left.\frac{dI}{dw}\right|_{\mathrm{HEAVY}} = \frac{\omega \left.\frac{dI}{dw}\right|_{\mathrm{LIGHT}}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

Dokshitzer & Kharzeev, PLB 519(2001)199

R_{AA} for Electrons from Semileptonic Decays of c- and b-Quark Decays



Phys. Rev. Lett. 98, 172301 (2007)

example: charmed mesons

$$D^+ = c\bar{d},\ D^0 = c\bar{u},$$

$$\bar{D}^0 = \bar{c}u,\ \ D^- = \bar{c}d$$

D^+ branching ratio in e^+:

$$D^+ \rightarrow e^+ + \text{anything}$$

$$(\text{BR} \ \approx\ 16\%)$$

examples:

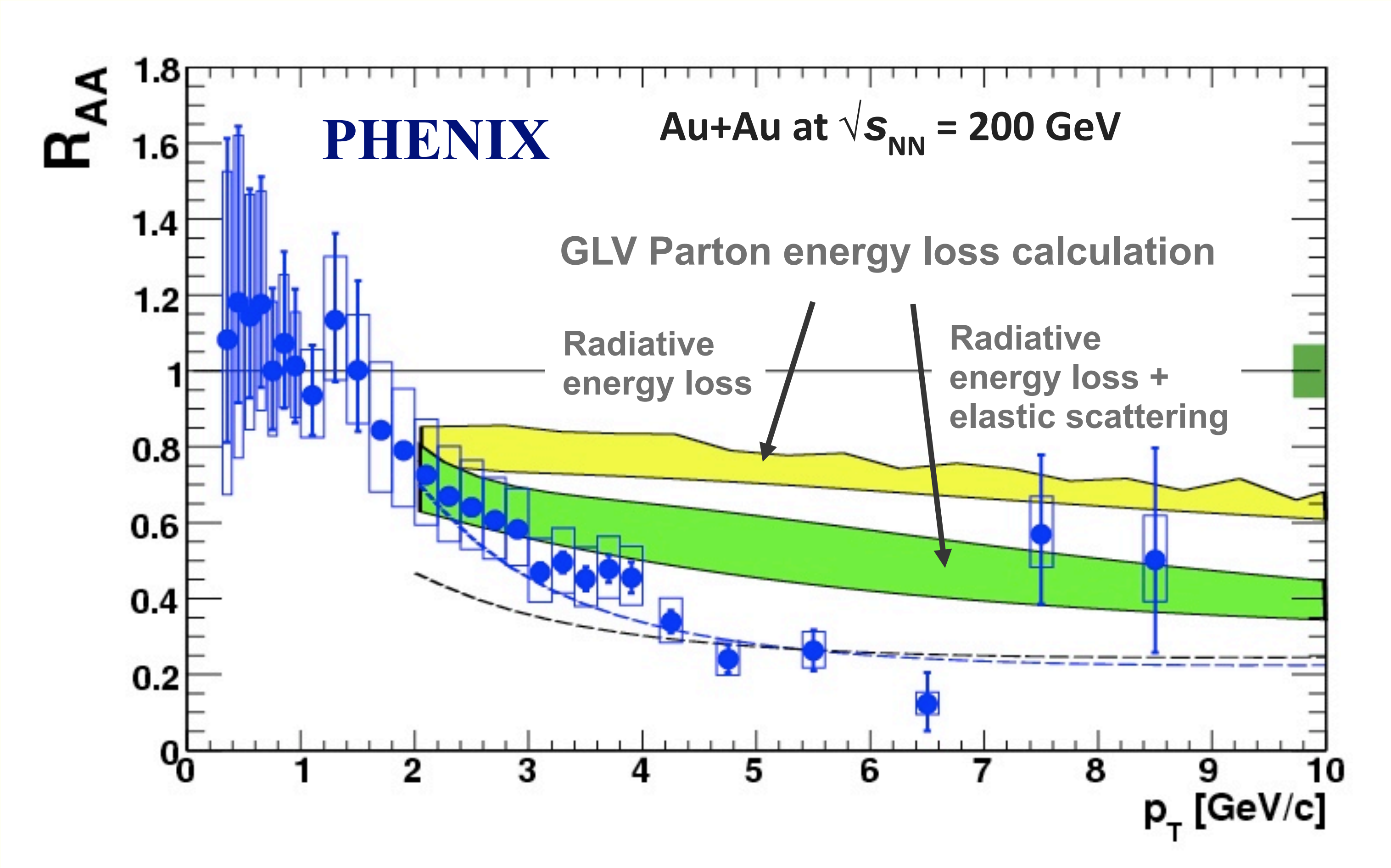
$$D^+ \rightarrow \bar{K} + e^+ + \nu_e$$

$$D^0 \rightarrow K^- + e^+ + \nu_e$$

e^+ and e^- from c and b decays as strongly suppressed as pions:

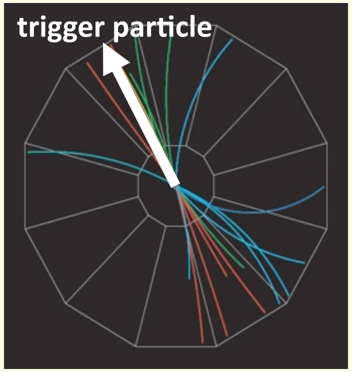
$$\Delta E_{\text{Gluon}} > \Delta E_{\text{Quark},m=0} > \Delta E_{\text{Quark},m\neq 0}$$ not observed!

R_{AA} for Electrons from Heavy Quarks: Not Understood with Current Energy Loss Models

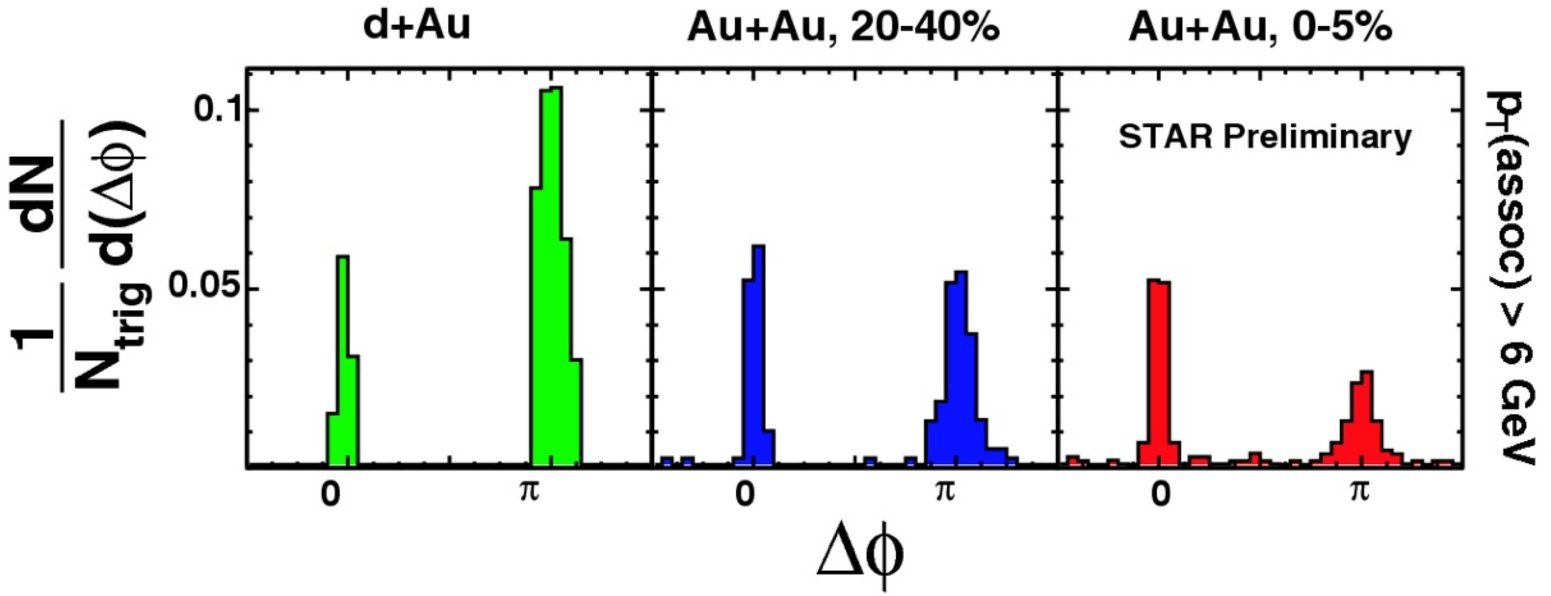


- Radiative energy loss not sufficient to describe excess electron R_{AA}
- Including elastic scattering improves the situation only slightly

Further Results from Two-Particle Correlations: Away-Side Jets Visible Again For Higher Jet p_T



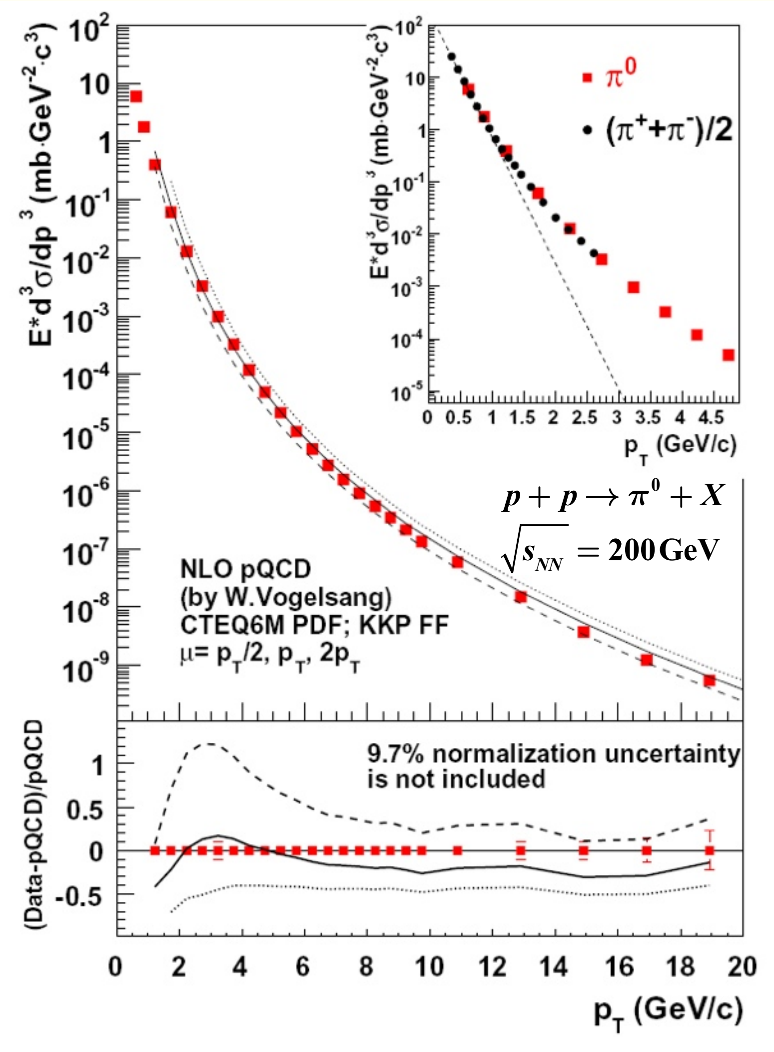
- Charged hadron correlation
- Trigger particle: $p_T > 8$ GeV/c
- Associated particle: $p_T > 6$ GeV/c

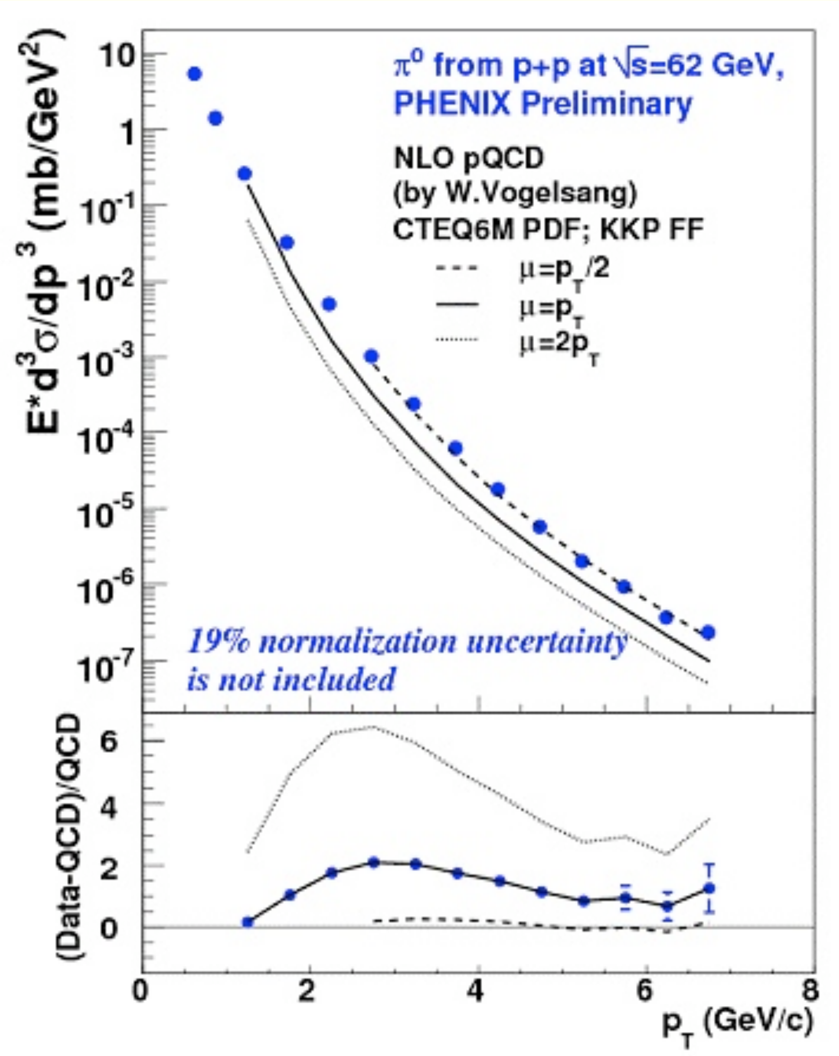


For higher jet energies the correlation at Δϕ = 180° in central Au+Au is not fully suppressed anymore

Brief Overview of Jet Quenching Models

Jet Quenching Models are Based on perturbative QCD





Agreement with pQCD in p+p shows that high-p_T pions are a calibrated probe of the medium created in A+A collisions

Jet Quenching Models (I)

- Currently four major theoretical parton energy loss schemes: (HT, BDMPS-Z-ASW, AMY, GLV)
- Schemes make different approximations and model the medium differently
- All schemes based on pQCD factorization approach
- The final hadronization is always assumed to occur in the vacuum (after some energy loss)

medium modified fragmentation function

vacuum fragmentation function

For example:

$$D^{\mathrm{med}}_{h/q}(x,Q^2) = \int_0^1 d\varepsilon \, P(\varepsilon) \, D_{h/q}\left(\frac{x}{1-\varepsilon},Q^2\right) \frac{1}{1-\varepsilon}$$

energy loss probability

Jet Quenching Models (II)

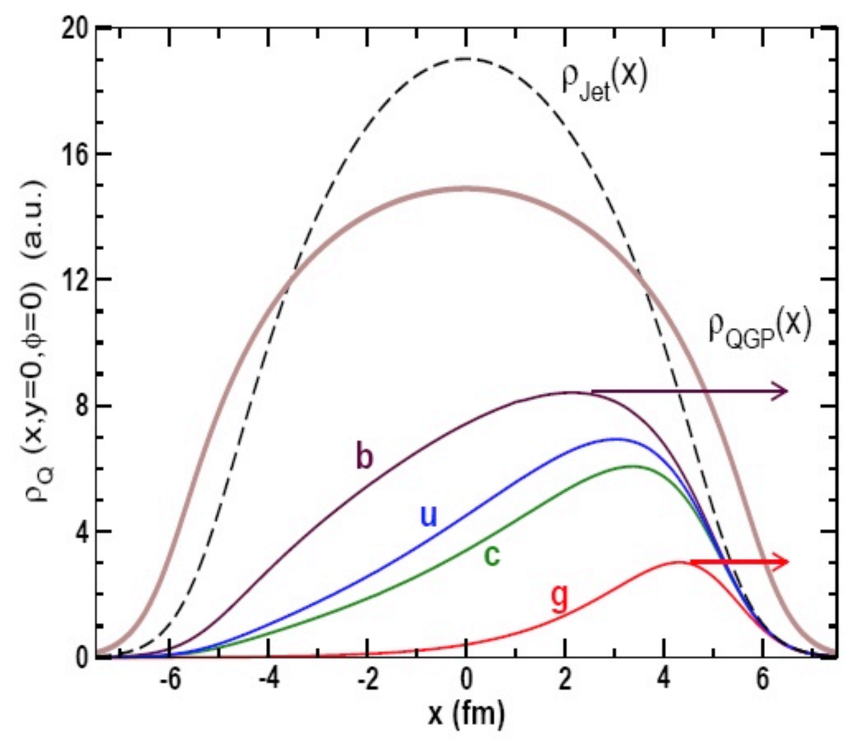
- All schemes can essentially be reduced to 1-parameter models (parameter e.g. fixed by fitting the pion $R_{AA}(p_T)$)
- No scheme describes all of the observed high-p_T observables (R_{AA} for light and heavy quarks, R_{AA} vs. reaction plane, R_{AA} for different particle species, two-particle correlations)
- Large differences (up to a factor 4) between extracted medium parameters like $\hat{q}$
- So far: „Advantage Data“

Future Jet Quenching Measurements

Problems with Relying on Hadron Spectra

- Energy loss bias
  - Hadrons biased to jets that lose the least energy
  - Geometry („surface bias“)
  - Radiation fluctuations
- Averaging
  - Hadron measurements average over jet energies
  - Indirect measurement of jet quenching
- Solutions
  - Direct γ - hadron correlation
  - Full jet reconstruction

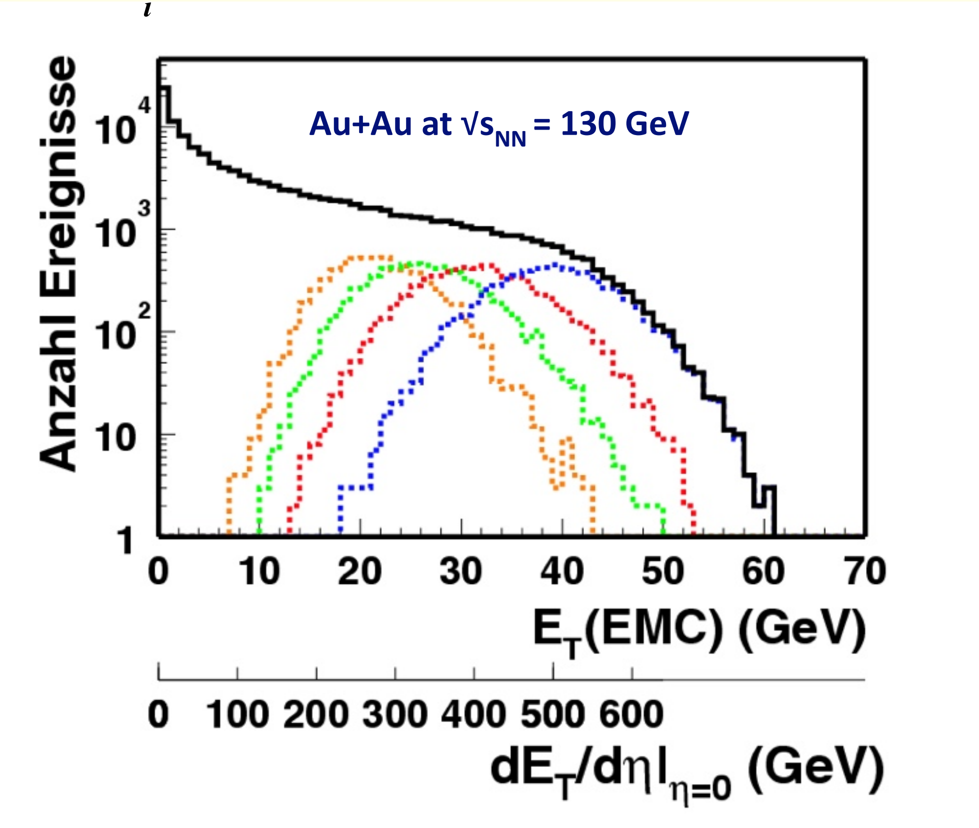
Surface bias:
Surviving jets biased towards the surface of the overlap region:
Difficult to probe the hot core of the QGP



Wicks, Horowitz, Djordjevic Gyulassy, Nucl. Phys. A784, 426-442

Why is Jet Reconstruction Difficult in Central Au+Au Collisions at RHIC ?

$$E_T = \sum_i E_i \sin\vartheta_i, \quad dE_T / d\eta \approx \langle m_T \rangle \cdot dN_{ch} / d\eta$$



Central Au+Au collision at $\sqrt{s_{NN}}$ = 130 GeV:

$$\left.\frac{dE_T}{d\eta}\right|_{\eta=0} \approx 500\ \text{GeV}$$

Consider jet cone with radius *R*:

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.4$$

Total transverse energy in this cone:

$$E_T^{\text{cone}} = \frac{d^2 E_T}{d\eta d\varphi} \cdot \pi R^2$$

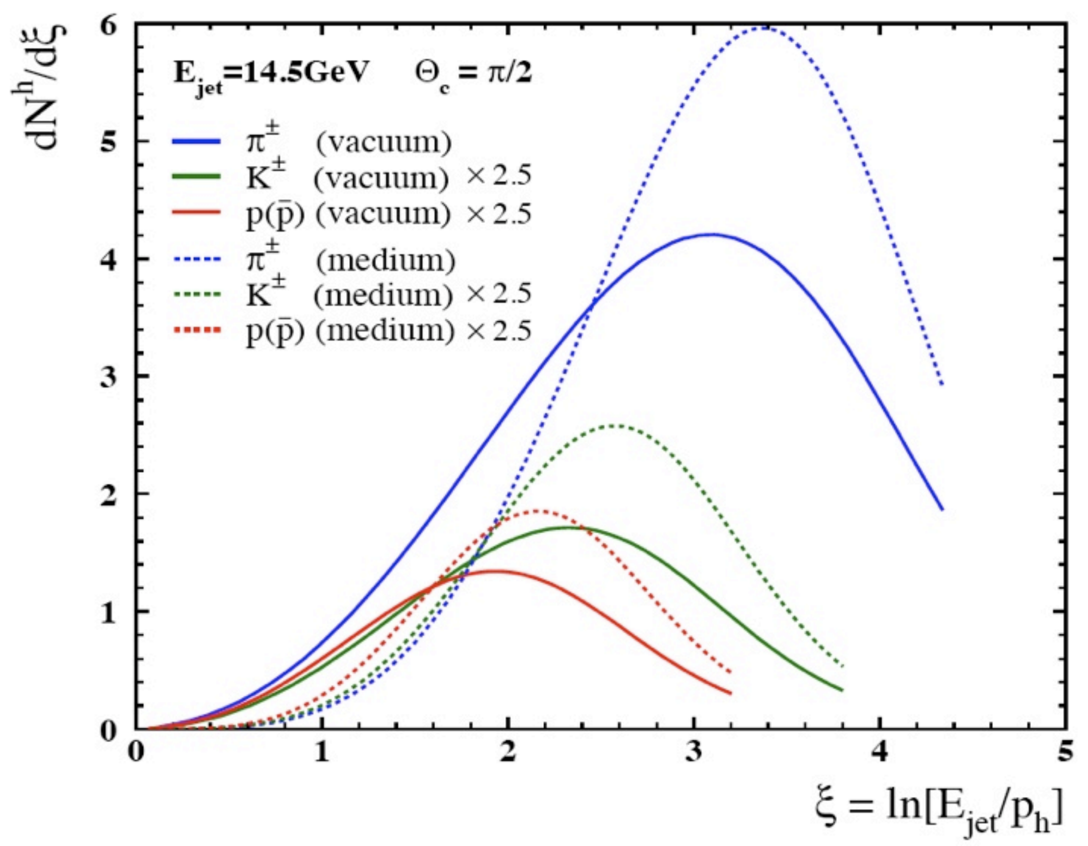
$$= \frac{1}{2\pi} \frac{dE_T}{d\eta} \cdot \pi R^2 \approx 40\ \text{GeV}$$

- Background energy large compared to jet energy in A+A at RHIC.
- Increased jet cross section helps at LHC energies

How Can One Study Parton Energy Loss with Reconstructed Jets at the LHC?

- Measure Jet R_{AA} for different cone radii R
- Study medium induced modification of lateral jet profile
- Study modification of the fragmentation function

Medium-Modified Fragmentation Functions



Sapeta, Wiedemann, Eur.Phys.J.C55:293-302,2008.

- Reconstruction of the full jet energy allows to measure fragmentation function
- Parton energy loss will shift particles to low *z*
  (and thus higher ξ)
- Moreover, the medium is expected to change the particle composition of the jet, e.g., the K/π ratio
- Promising measurement for Alice due to its excellent low p_T particle ID

Points to Take Home

- RHIC results have established jet quenching as an experimental fact
- Heavy quarks are as strongly suppressed as light quarks which is not fully understood in current jet quenching models
- The ultimate goal, the consistent characterization of the medium, is not yet possible since different models yield different results
- RHIC experiments are currently working on full jet reconstruction
- Increased jet cross section makes full jet reconstruction easer at LHC energies