Exploring the QCD at LHC with Hard Probes

expect physics highlights with these probes:

- quarkonia (charm- und beauty sector)
- open charm / open beauty
- jets - large reach in p_t/E_t
  - direct reconstruction
  - heavy quarks
  - photon tagging (gluon)

- Debye screening/deconfinement
- norm quarkonia
- quark energy loss in plasma
  'jet tomography'
  for different quark species
  and for gluons

with RHIC results clear that this is where (among others) new physics at LHC will be

at mid rapidty this will be ideally addressed by TRD (electron id; jet trigger) in combination with the other detectors in the ALICE central barrel (TPC, ITS, PHOS/EmCal)

New Physics with ALICE

- ultra-rel. heavy ion program started nearly 20 years ago at AGS & SPS: established that (at least) at top SPS energy and RHIC a new state of matter is created in which partons are the degrees of freedom
  "Quark-Gluon Plasma"
- from RHIC first hints on the properties of this new state of matter task of heavy ion program at LHC: to characterize the QGP

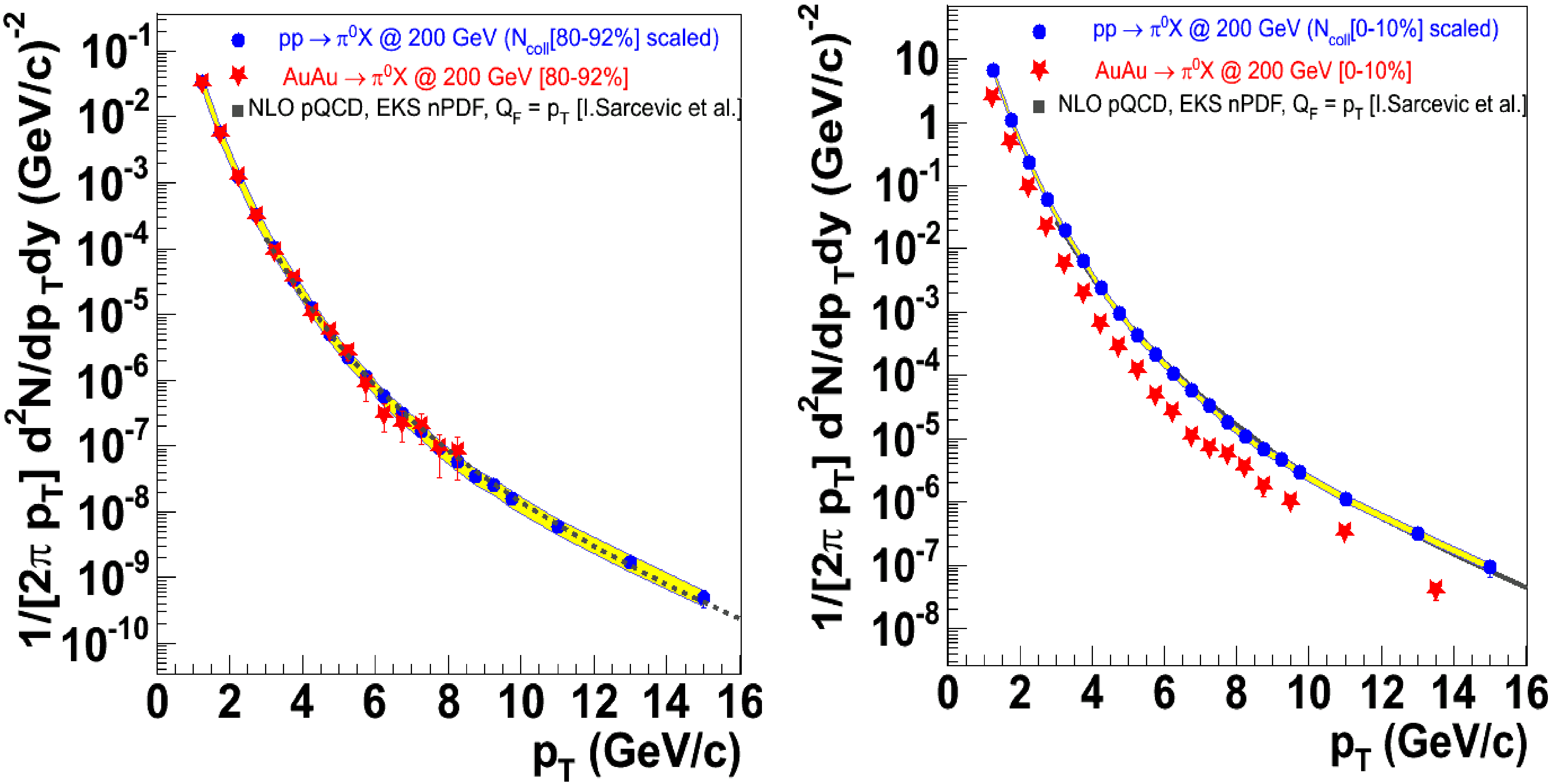
- initial temperature > 600 MeV
  probably about 900 MeV (5 T_c)
- life time of QGP ≈ 10 fm/c
  several 10 k prod. hadrons
  'macroscopic state'
- totally dominated by hard processes → ideal probes

↔

for the first time in 20 years a new accelerator opens totally new energy regime -
huge discovery potential with ALICE in pp and AA

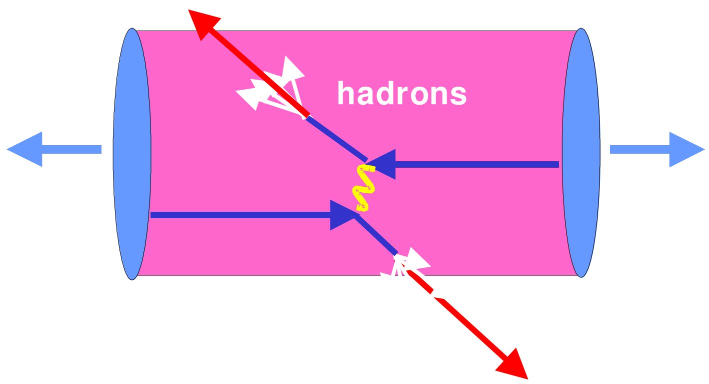
at high p_t: spectra suppressed in AuAu relative to pp

proton data scaled to AuAu with appropriate number of binary collisions

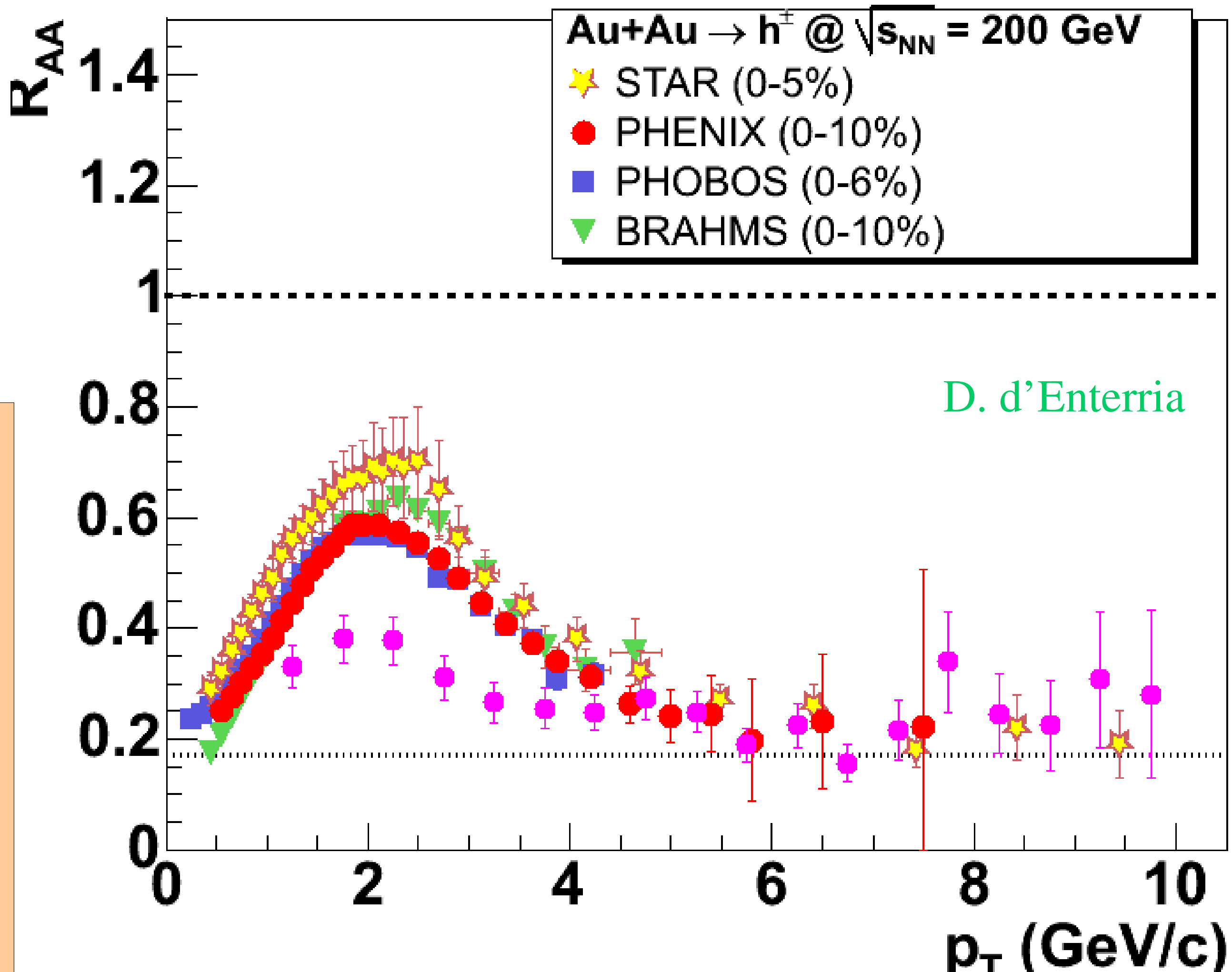


PHENIX PRL 91 (2003) 072305 and 241803

Suppression predicted due to energy loss of partons in hot matter "jet quenching"



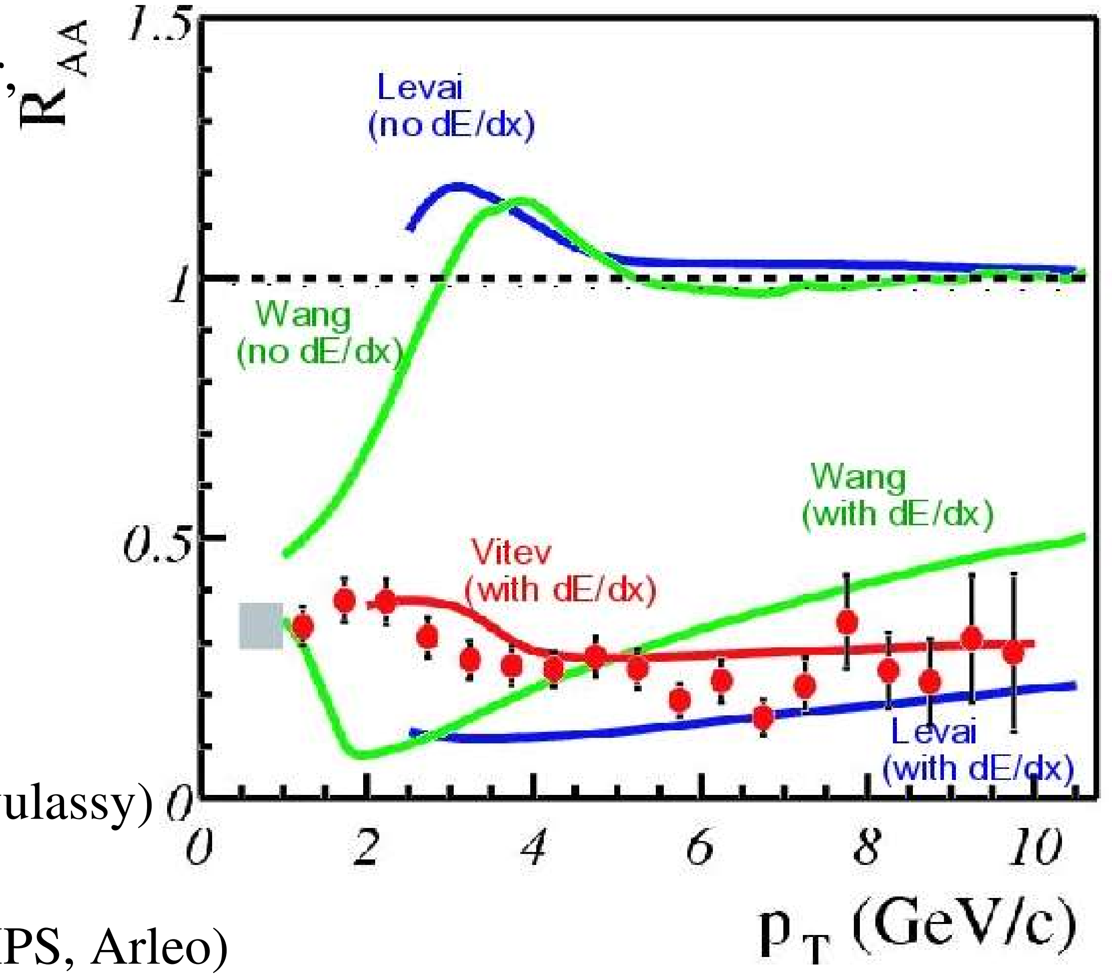
R_{AA}=yield(AuAu)/N_{coll} yield(pp)



- all expts. see large suppression in AuAu
- π^0 lower than $h^{\pm}$
- no suppression in dAu rather
  Cronin enhancement
→ medium effect, not
  incoming partons

Suppression predicted due to energy loss of partons in hot matter "jet quenching"

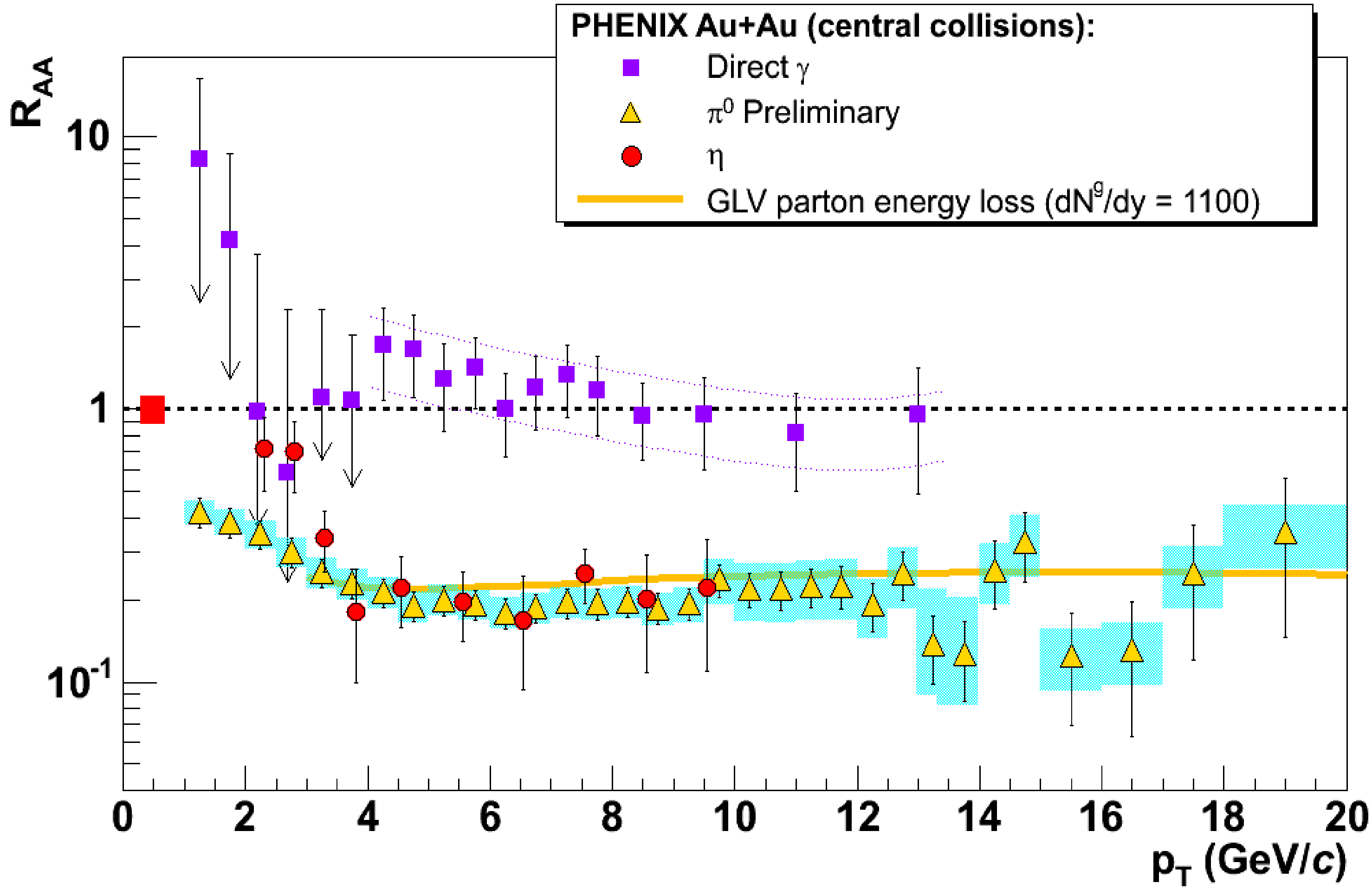
H. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, Nucl. Phys. B483 (1997) 291 and 484 (1997) 265
energy loss of high energy parton traversing color charged medium ->
medium induced gluon radiation in high energy limit
$\Delta E \approx \alpha_s \mu^2 L^2/\lambda \, (1 + O(1/N))$



implemented in models in different ways:
high initial densities dN_g/dy=1100 (Vitev/Gyulassy)
large opacities <n> = $L/\lambda \approx$ 3-4 (Levai et al.)
transport coefficients q_0=3.5 GeV/fm^2 (BDMPS, Arleo)
plasma temperature T = 400 MeV (G. Moore)
medium induced ratiative energy loss
dE/dx(expanding)=0.25 GeV/fm or dE/dx(static source)=14 GeV/fm (S.N.Wang)

RHIC result: jet quenching

R_{AA}=yield(AuAu)/N_{coll} yield(pp)



high gluon density of the plasma induces energy loss of partons

new run 4 data for π^0

Henner Büsching talk DPG 2006

Role of scattering in parton energy loss

inspired by success of soft-color-interaction model for diffractive DIS at HERA
(Ingelman et al., PLB366 (1996) 371, Hoyer at al., PRD71 (2005) 074020)

- soft color interactions between partons after perturbative hard interactions and before hadronization
- color exchange between partons and small momentum transfer

→ describes rapidity gaps, leading baryons, diffractive jets, high p_t J/ψ, ψ', Υ

apply this approach to parton traversing QGP, modelled by medium of space and time dependent high gluon density

- parton from hard scattering scatters with gluons of QGP, successive scatterings can lead to significant energy loss
- independent hadronziation of two ends of string due to QGP
- implemented in PYTHIA

K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, PLB637 (2006) 179

the SCI Jet Quenching Model for QGP

Geometry: N_{part}, N_{coll} etc. from simple Glauber - model

Eskola, Kajantie, Lindfors, Nucl. Phys. B 323 (1989)

EOS: ideal relativistic gluon gas

$$\Rightarrow n = \frac{g}{\pi^2}\zeta(3)T^3 \quad \& \quad \epsilon = \frac{\pi^2 g}{30}T^4$$

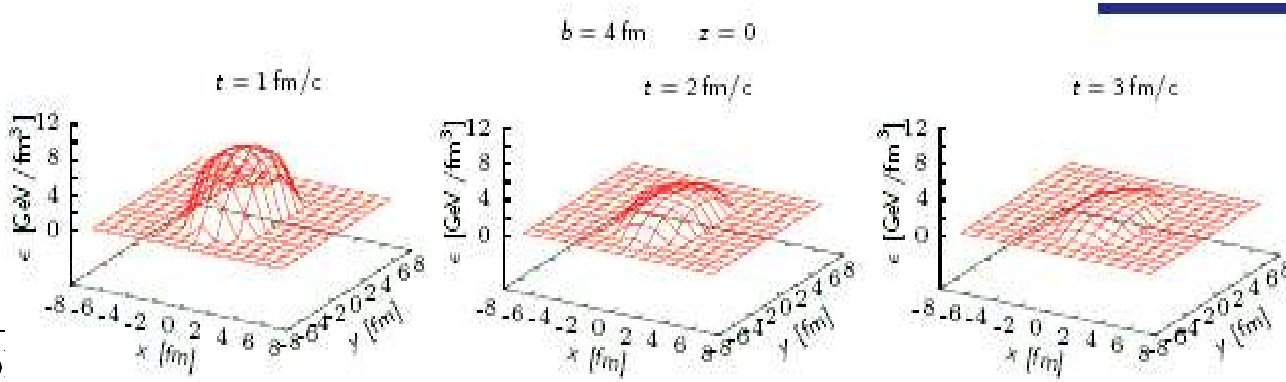
expansion: boost-invariant longitudinal expansion

$$T(\tau) \propto \tau^{-1/3} \quad \Rightarrow \quad n(\tau) \propto \tau^{-1} \quad \& \quad \epsilon(\tau) \propto \tau^{-4/3}$$

$(\tau = \sqrt{t^2 - z^2})$ Bjorken, Phys. Rev. D 27 (1983)

local energy density: $\epsilon(x,y,\tau) \propto N_{\text{part}}(x,y) \cdot \tau^{-4/3}$

jet production: LO pQCD matrix elements (PYTHIA) + distribution in overlap region according to $N_{\text{coll}}(x,y)$



The SCI Jet Quenching Model: Parameters

if parton from hard interaction encounters a QGP gluon within a certain radius it will scatter with probablity 0.5 (0.75) if it is a quark (gluon)

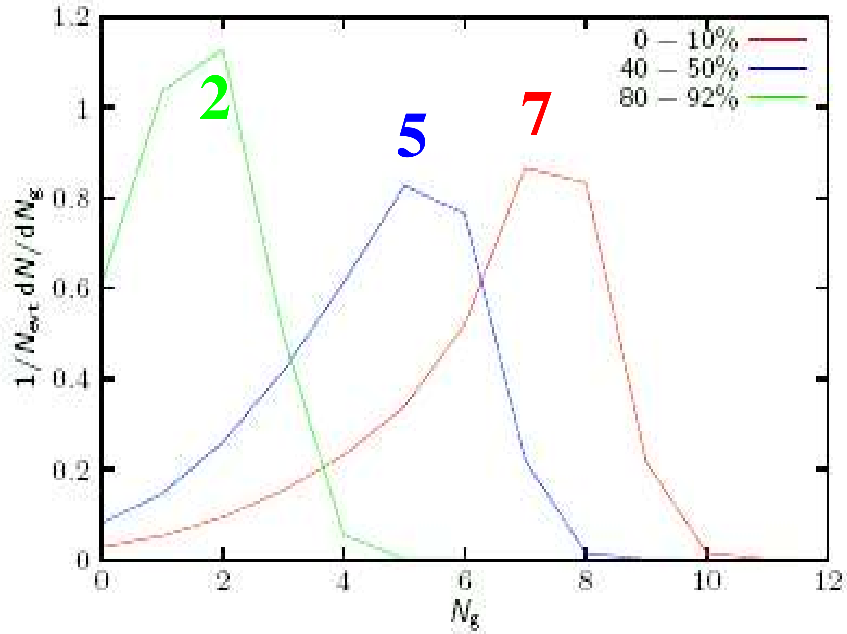
➡ scattering cross section

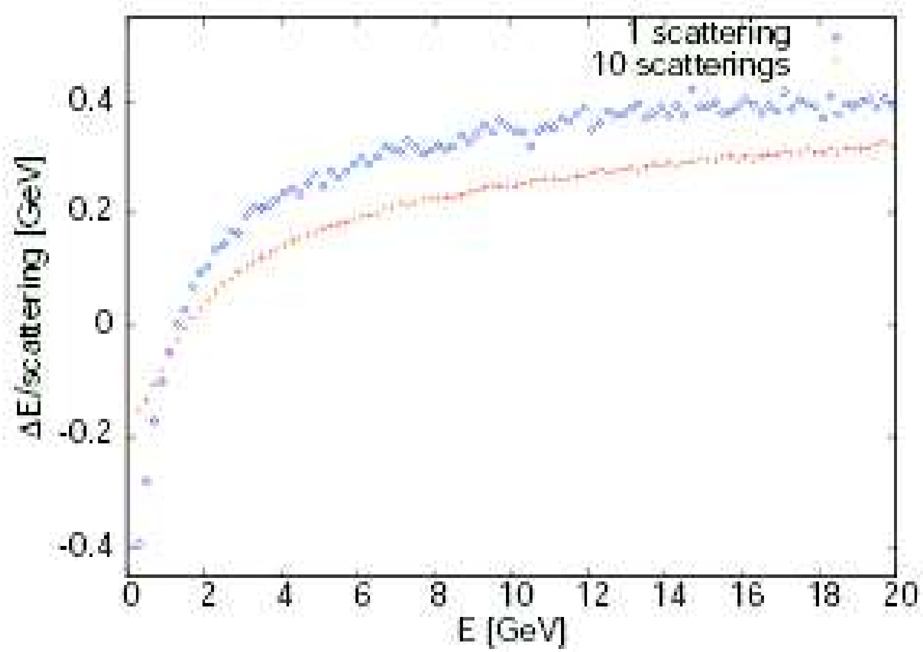
QGP formation time	τ_i	0.2 fm
initial energy density $\epsilon(\tau = 1\,\text{fm})$	ϵ_0	5.5 GeV fm^{-3}
critical temperature	T_c	0.175 GeV
gluon mass	m_g	0.2 GeV
interaction probability	p	0.5
screening radius	R_{scr}	0.3 fm
width of t - distribution	σ_t	0.5 GeV^2
Cronin parameter	α	0.5 GeV^2

➡ σ_{eff} = 1.9 mb

Number of scatterings and energy loss per scattering

scatterings = # gluons encountered × scatt. probability (50/75 %)



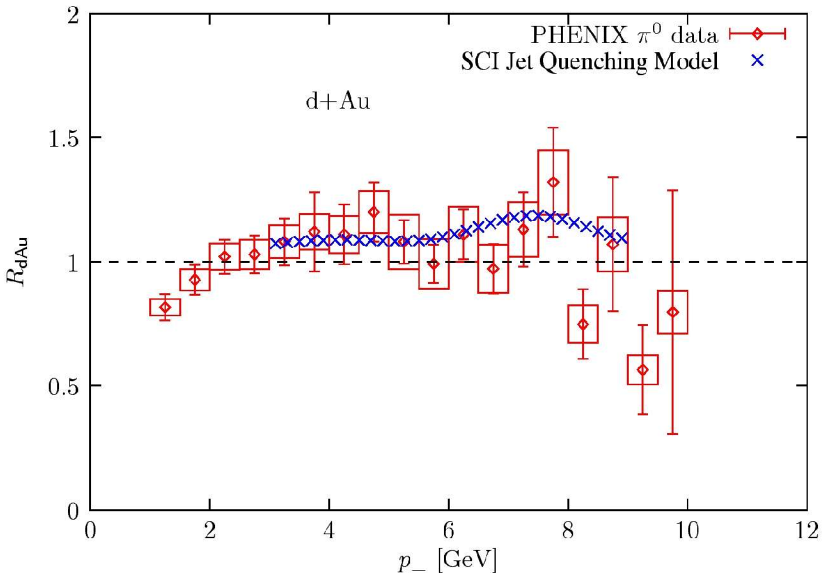


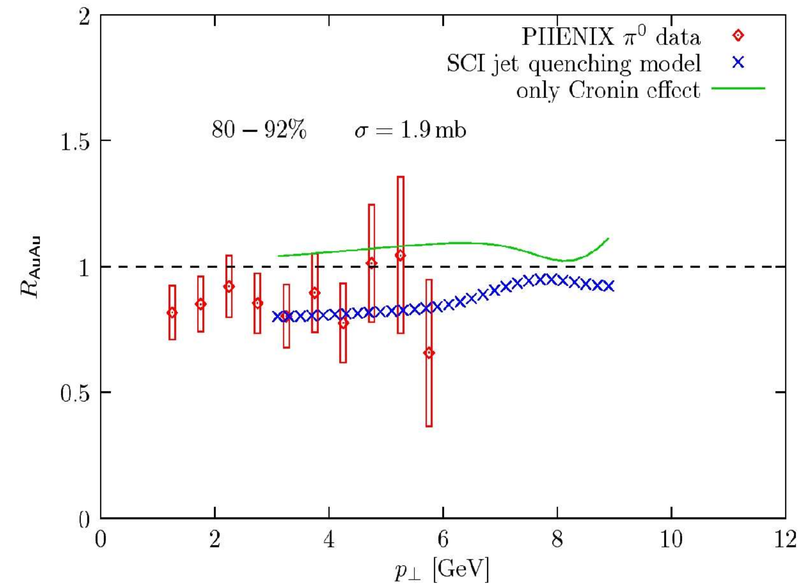
energy loss most efficient for intermediate p_t

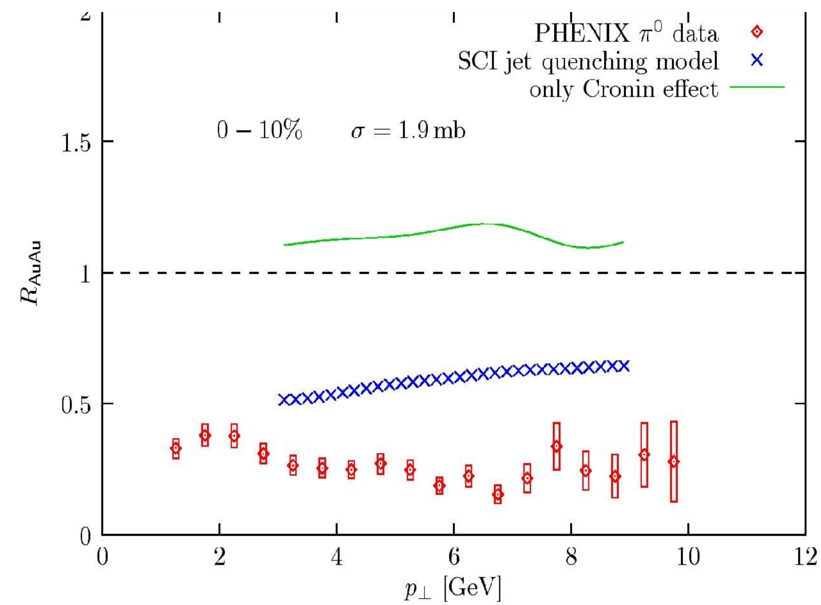
SCI jet quenching model and data as function of centrality

adjust Cronin parameter α

$$\sigma^2_{k_\perp}(x,y,b) = \sigma^2_{k_\perp,0}(x,y,b) + \alpha(\langle N^{(i)}_{\mathrm{scatt}}(x,y,b)\rangle - 1)$$



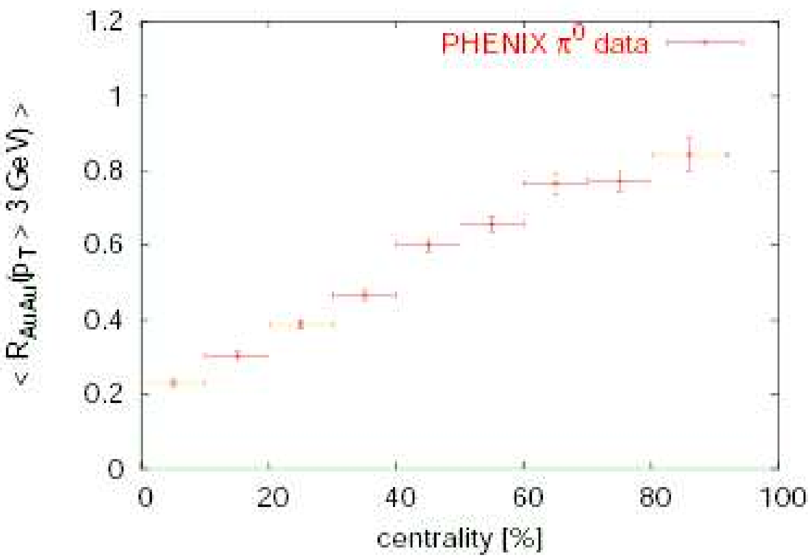


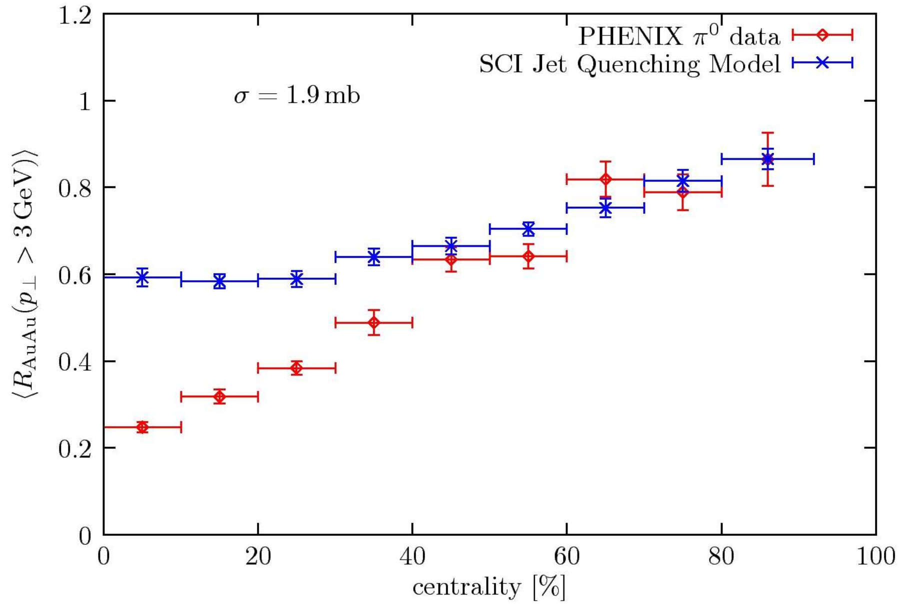


for most central collisions model accounts for half of exp. effect

data: PHENIX, PRL91 (2003) 072301 and 072303

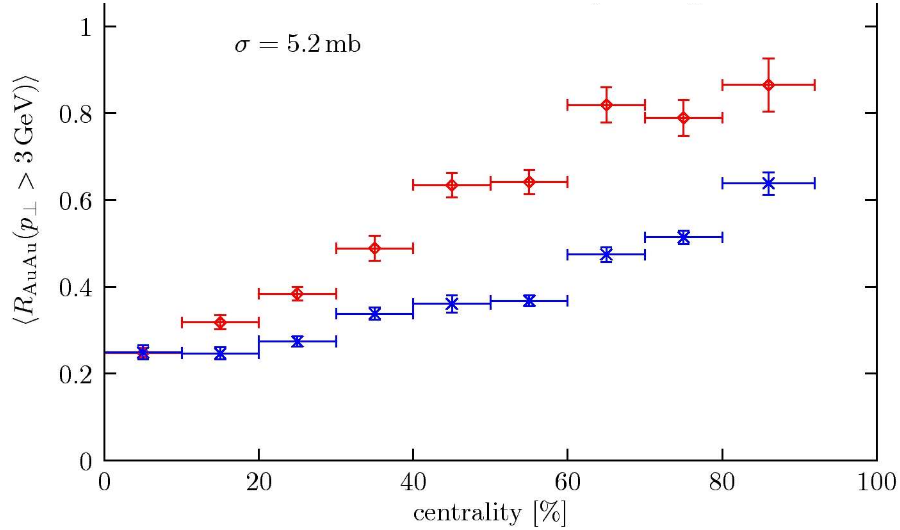
Centrality dependence of jet quenching





nominal cross section

data show linear dependence of R_{AA} as function of fraction of geo. cross section

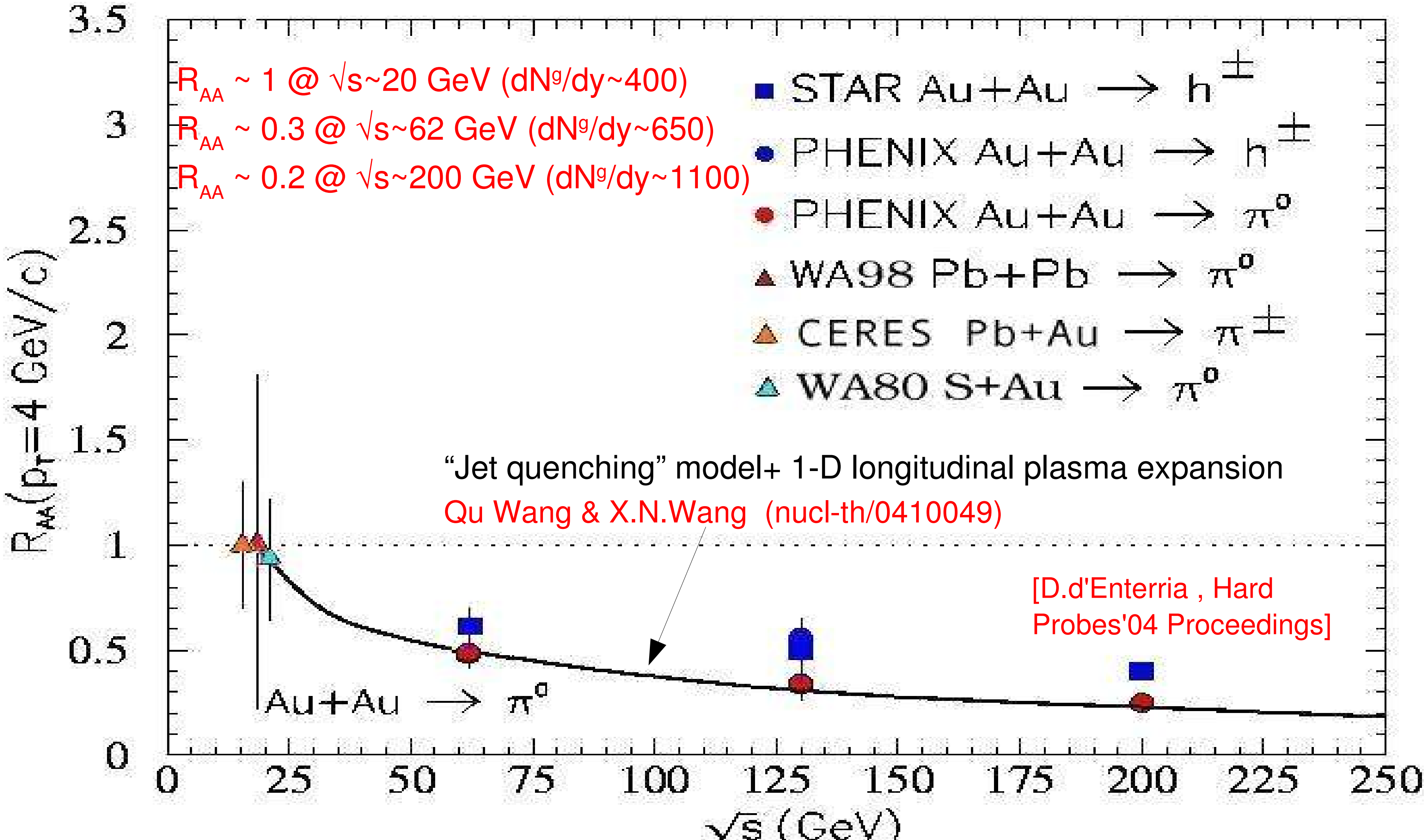


cross section chosen to reproduce most central data

difficult to reproduce in model

R_{AA} at lower beam energies

√s dependence of R_{AA} consistent w/ parton E_{loss} models (ΔE_{loss}~ dN/dy) + Bjorken expansion:

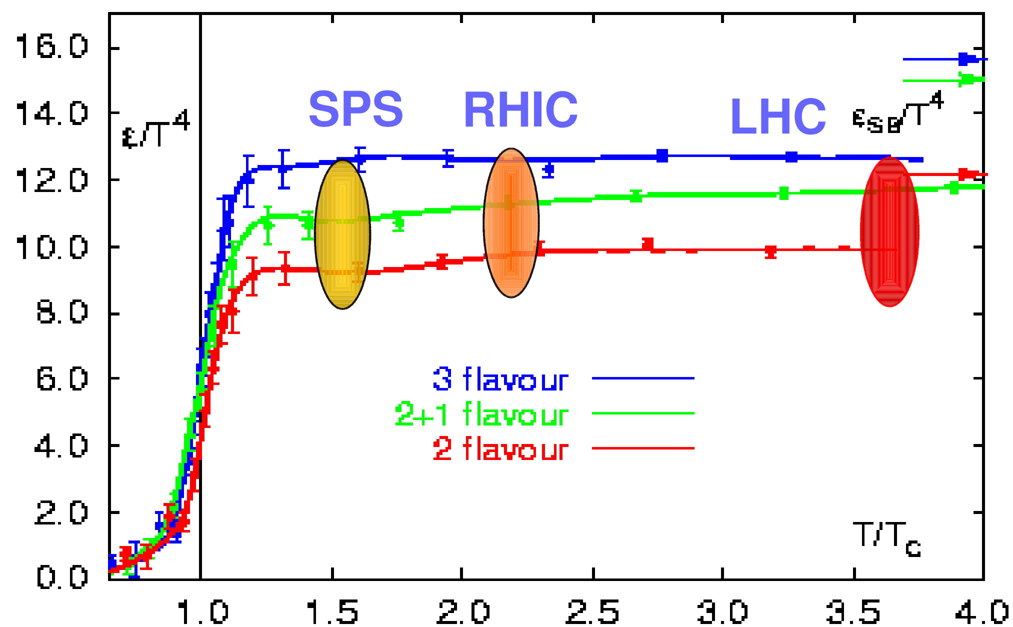


jet quenching indicative of gluon rapidity density

	$\tau_0[fm]$	$T[MeV]$	$\varepsilon[GeV/fm^3]$	$\tau_{tot}[fm]$	dN^g/dy
SPS	**0.8**	**210-240**	**1.5-2.5**	**1.4-2**	**200-350**
RHIC	**0.6**	**380-400**	**14-20**	**6-7**	**800-1200**
LHC	**0.2**	**710-850**	**190-400**	**18-23**	**2000-3500**

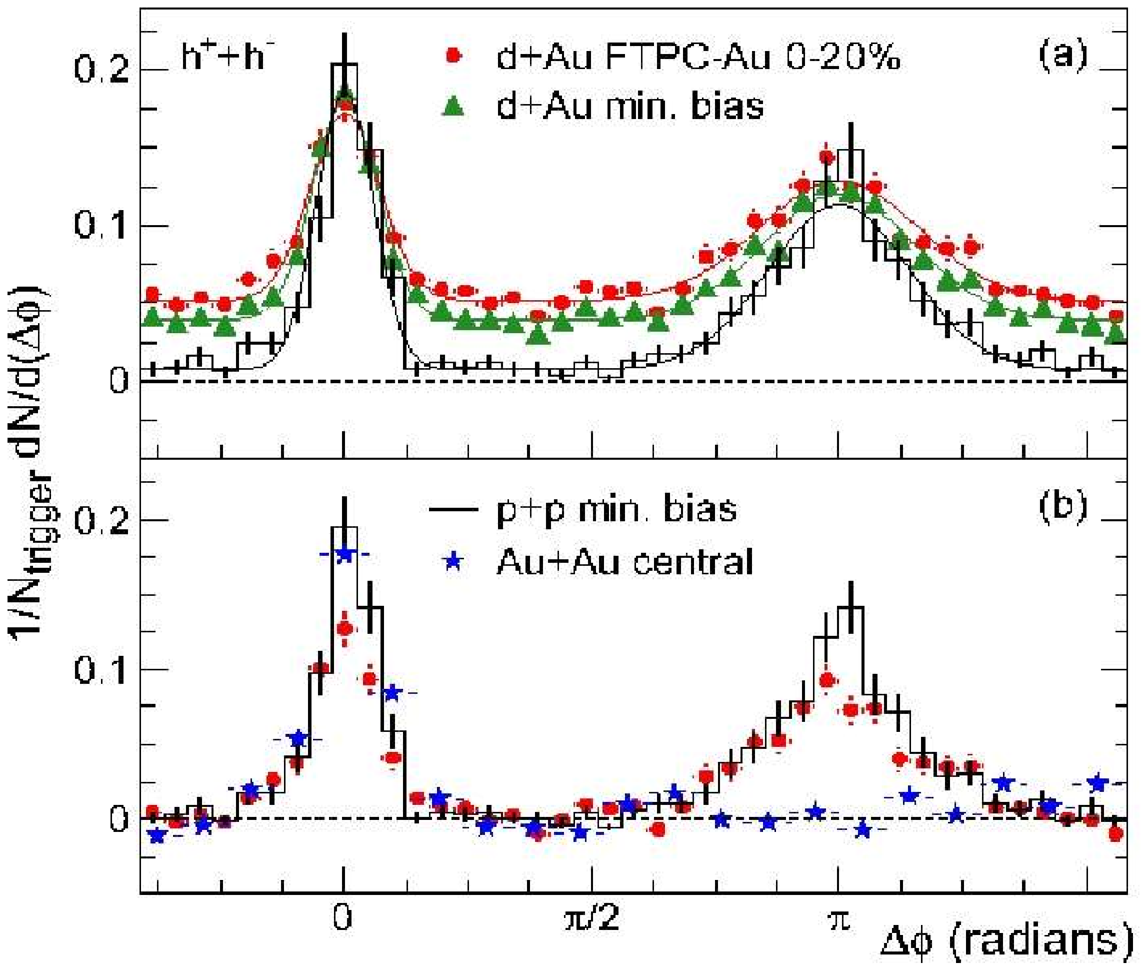
I. Vitev, JPG 30 (2004) S791

- **Consistent estimate with hydrodynamic analysis**



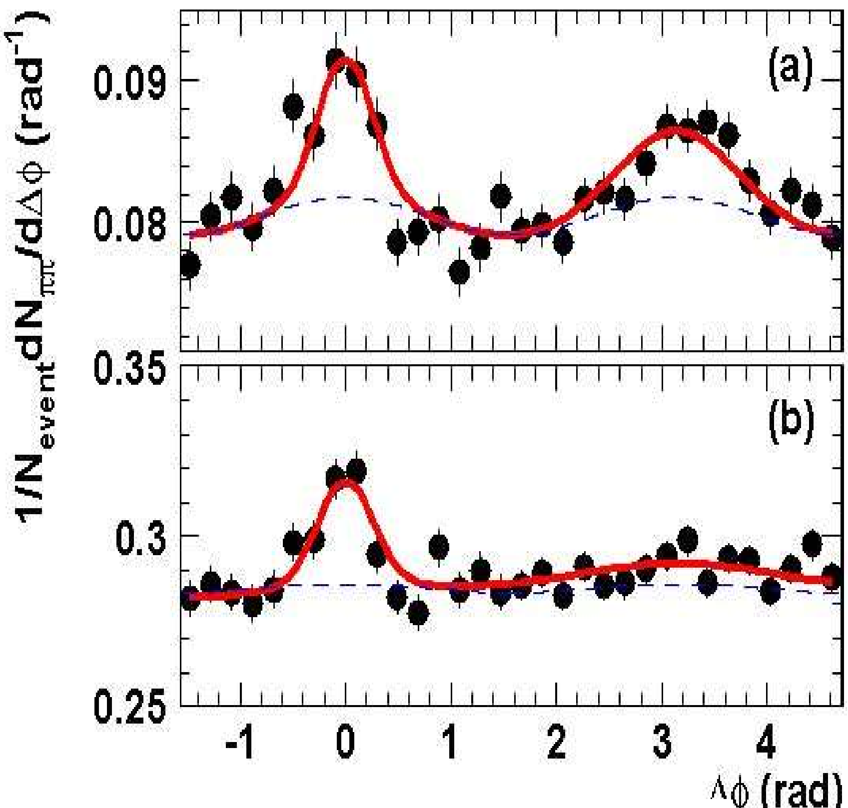
Azimuthal correlations of high p_t particles - disappearance of away-side peak

trigger particle: 4-6 GeV/c correlated with all others with p_t=2-4 GeV/c



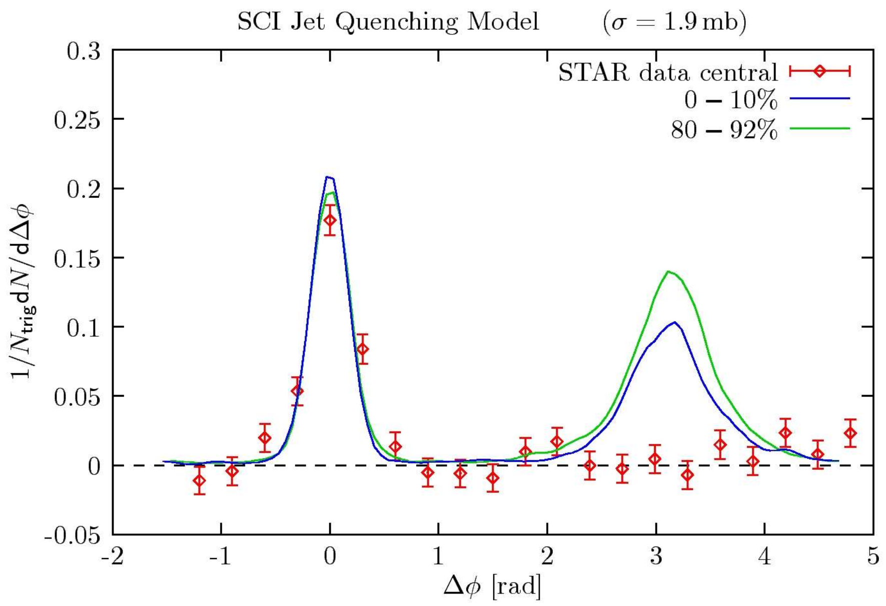
STAR: PRL 91 (2003) 072304

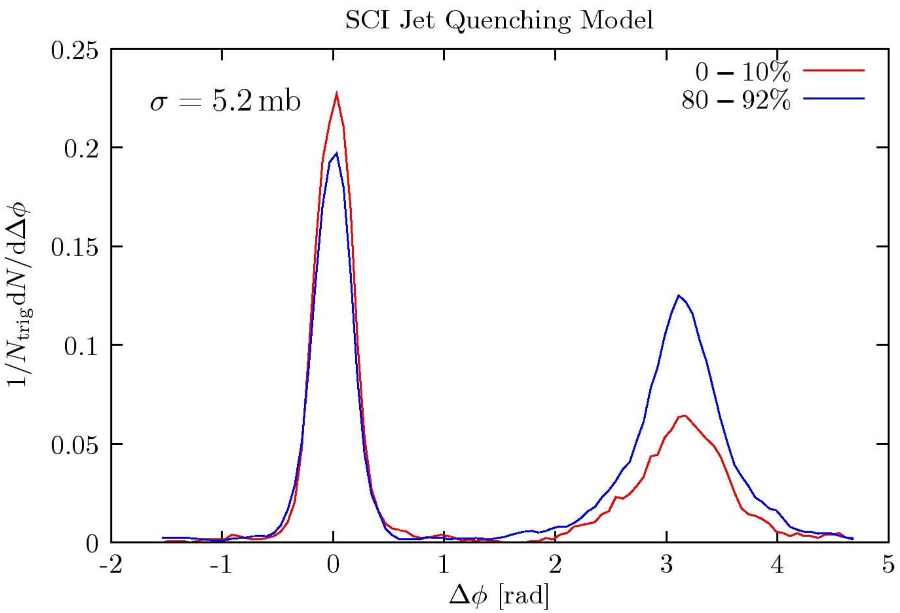
very similar effect seen already at $\sqrt{s}$ = 17.2 GeV



CERES/NA45 PRL92 (2004) 032301

Azimuthal correlations in SCI jet quenching model

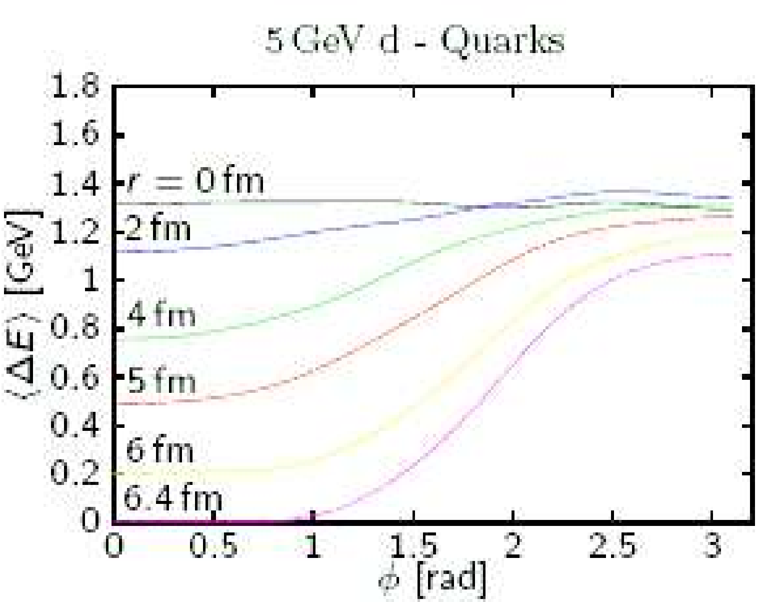


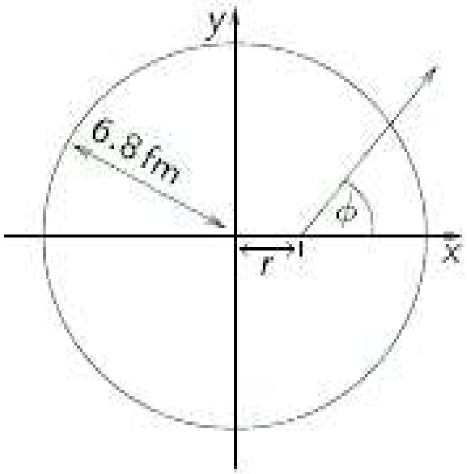


away-side peak is suppressed, but not nearly as much as in data

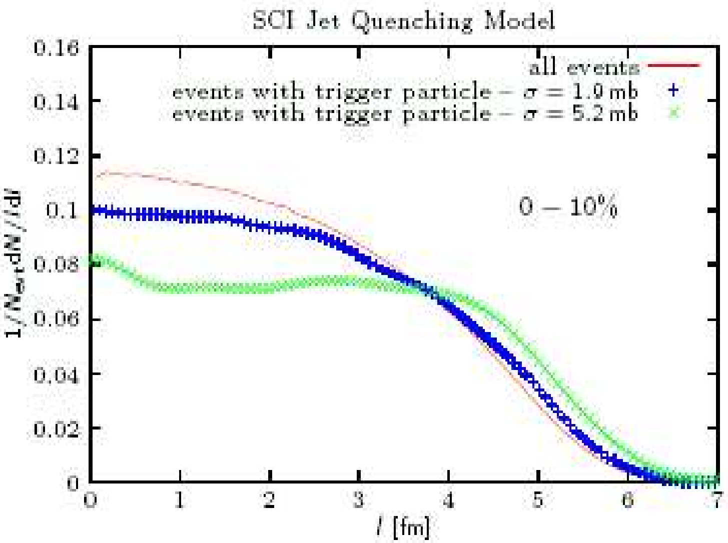
general problem of model: to reproduce this effect need huge cross section of opacity

Complete Suppression of away-side jet generally difficult:

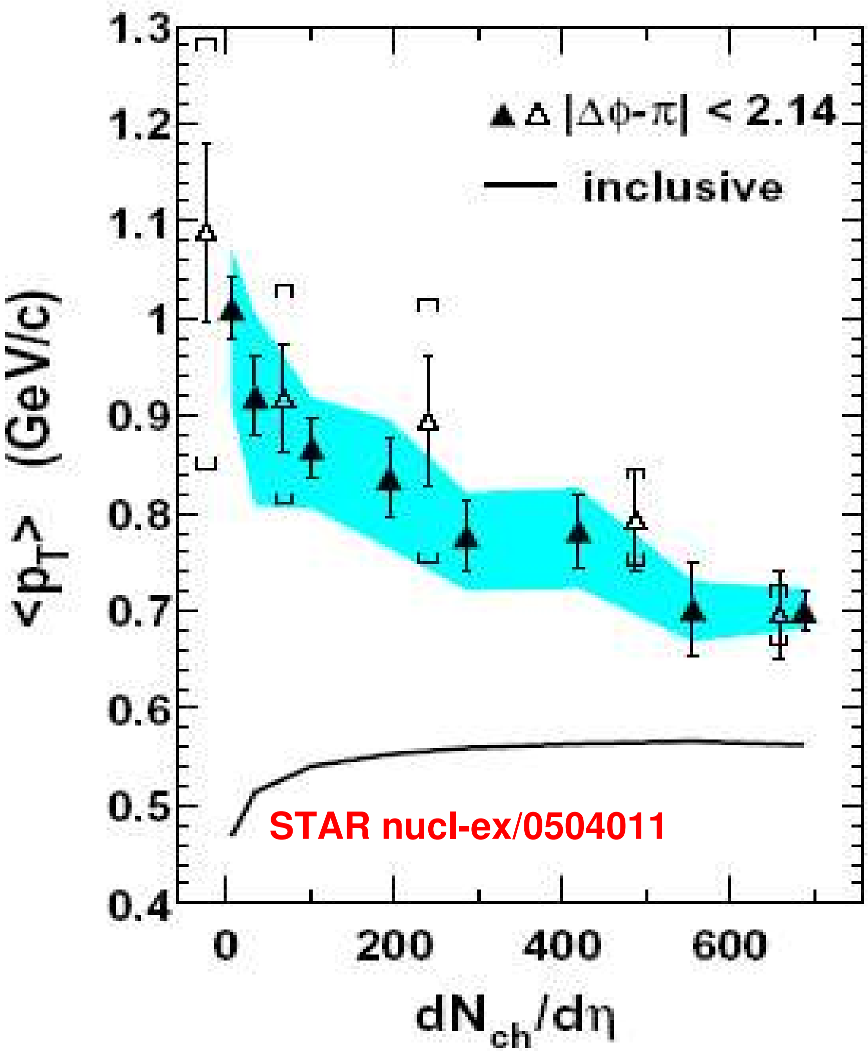




due to rapid expansion surface emission does not help



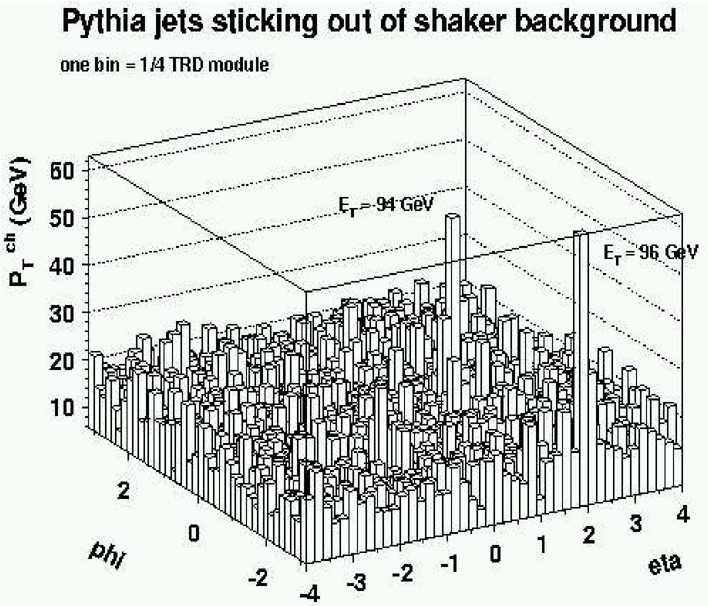
mean p_t in cone opposite to leading trigger particle

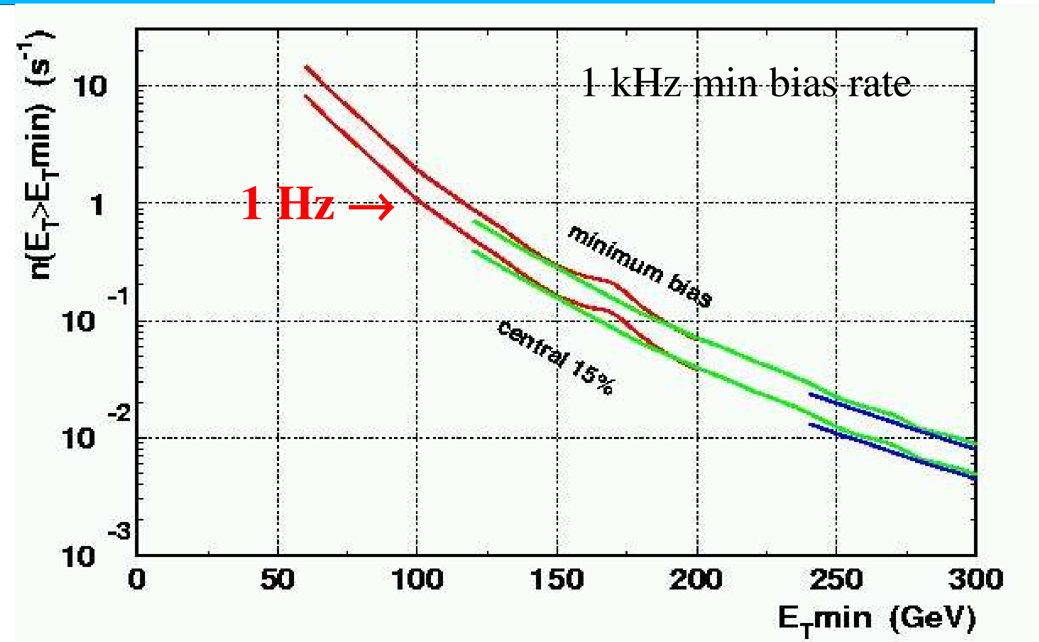


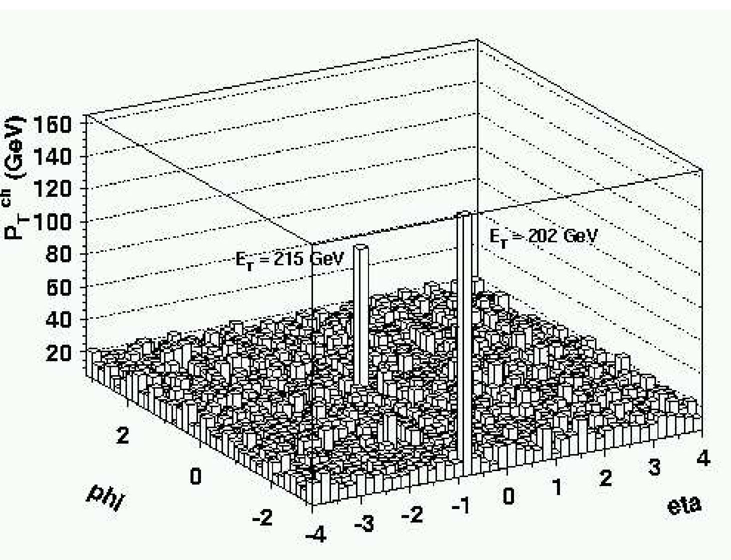
for central collisions mean p_t on opposite side looks nearly thermalized

$\sqrt{s_{NN}}$ = 200 GeV Au+Au results: { Closed symbols ⇔ $4 < p_T^{trig} < 6$ GeV/c; Open symbols ⇔ $6 < p_T^{trig} < 10$ GeV/c } Assoc. particles: $0.15 < p_T < 4$ GeV/c

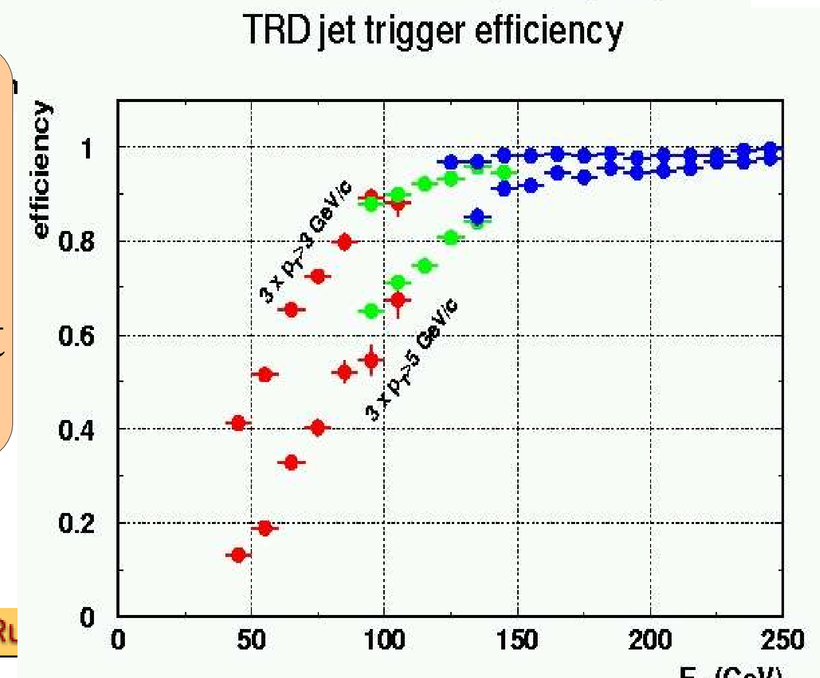
Jets in ALICE: high rates at very high E_t – need and can trigger







go to very high E_t
with trigger
jet – photon coinc.
reconstruct actual jet



Charmonia as QGP signature

- T. Matsui and H. Satz (PLB178 (1986) 416) predict J/ψ suppression in QGP due to Debye screening
- significant suppression seen in central PbPb at top SPS energy (NA50) in line with QGP expectations
- but: at hadronization of QGP J/ψ can form again from deconfined quarks in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \propto N_{cc}^2$
  (P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196)
  - statistical hadronization, charmed hadrons can equilibrate chemically
    similar to production of multi-strange baryons, (BraunMunzinger, Stachel, Wetterich, nucl-th/0311005, Phys. Lett. B596 (2004) 61.)
    typical reaction: $DD_{bar} + \pi\pi\pi \Rightarrow J/\psi + \pi$
  - expect J/ψ suppression at low beam energy (SPS) and enhancement at high energy (LHC)

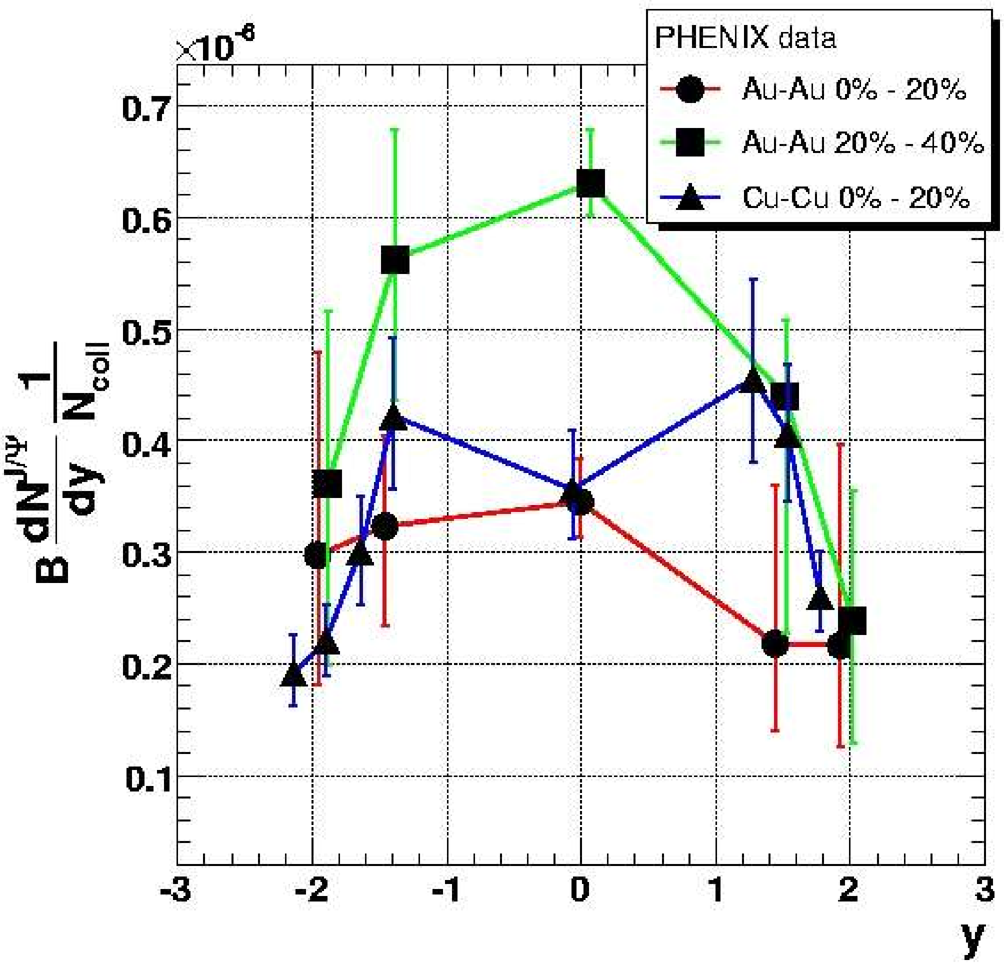
Quarkonia Production through Statistical Hadronization

- Assume: all charm quarks are produced in initial hard scattering number not changed in QGP
- Hadronization at Tc following grand canonical statistical model used for hadrons with light valence quarks (fugacity to fix number of charm quarks, canonical correction factors at low beam energies)

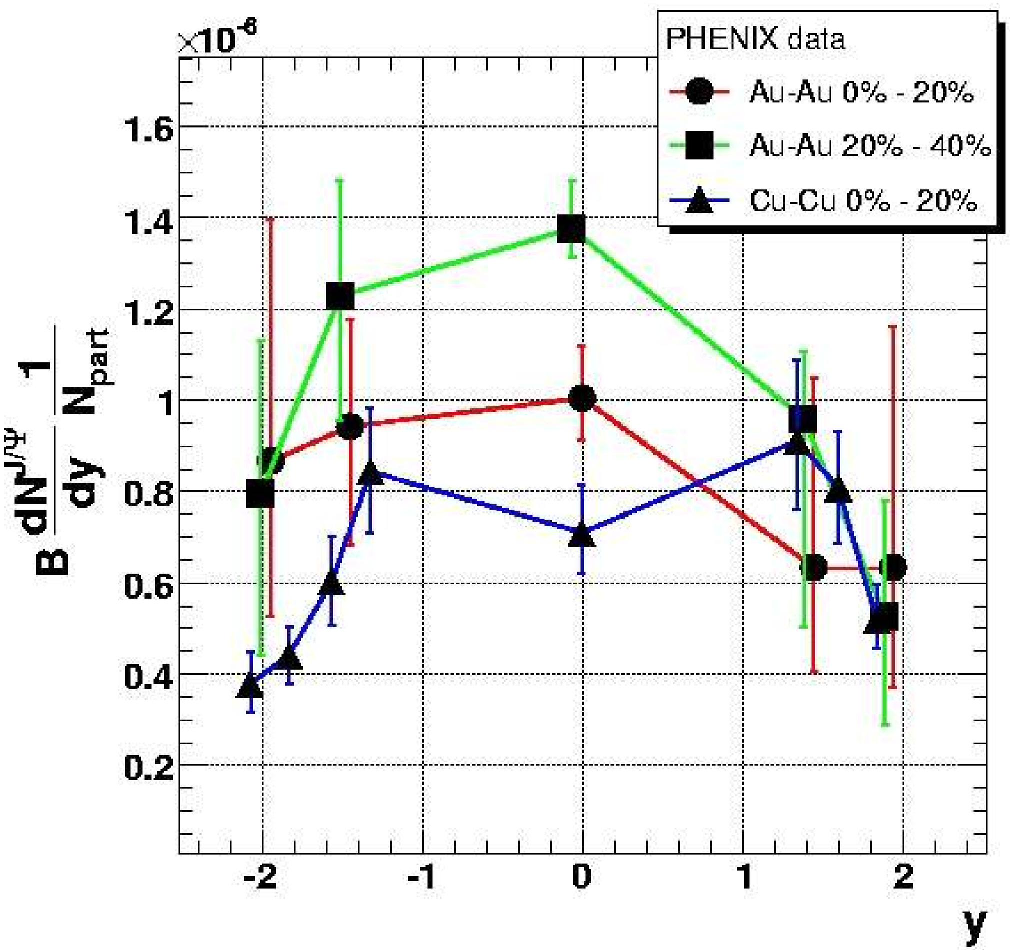
P. Braun-Munzinger, J. Stachel, Phys. Lett. B490 (2000) 196 and Nucl. Phys. A690 (2001) 119
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A715 (2003) 529c and Phys. Lett. B571 (2003) 36
M. Gorenstein et al., hep-ph/0202173; A. Kostyuk et al., Phys. Lett. B531 (2001) 225; R. Rapp and L. Grandchamp, hep-ph/0305143 and 0306077

RHIC data on J/ψ Production

scaling with number of collisions

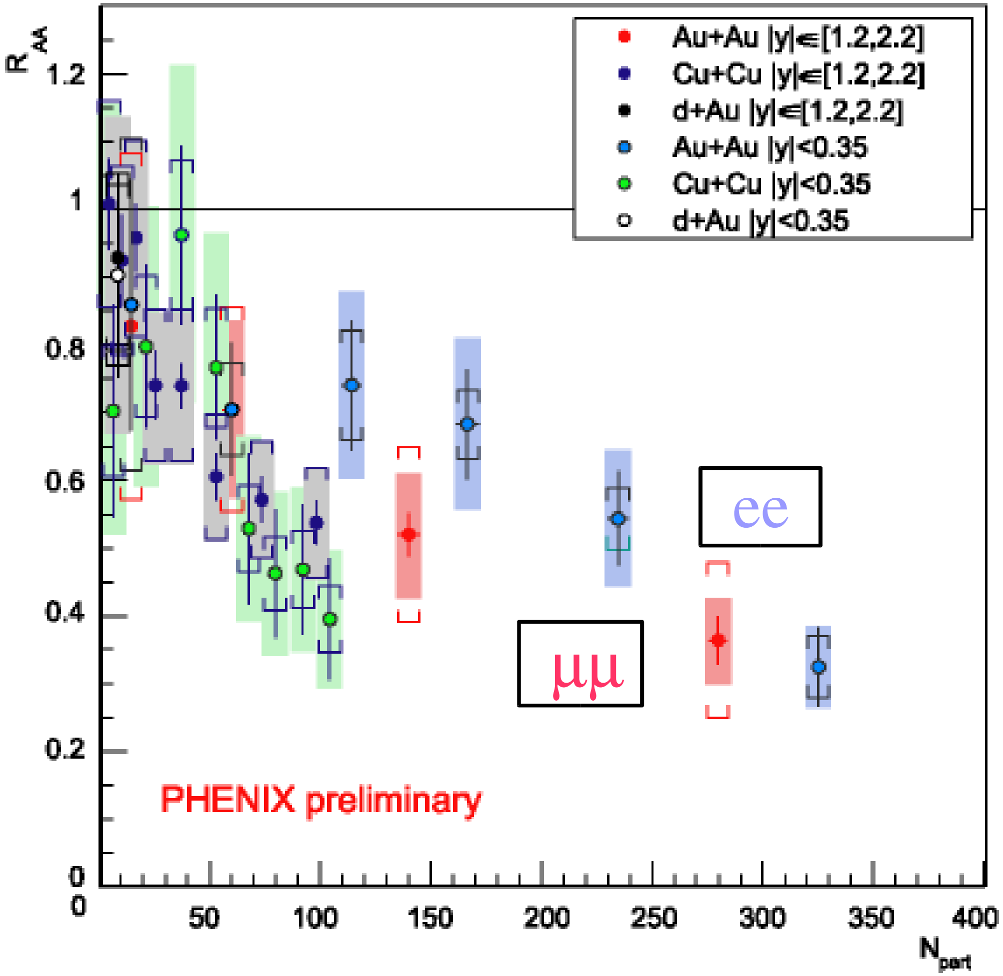


participant scaling

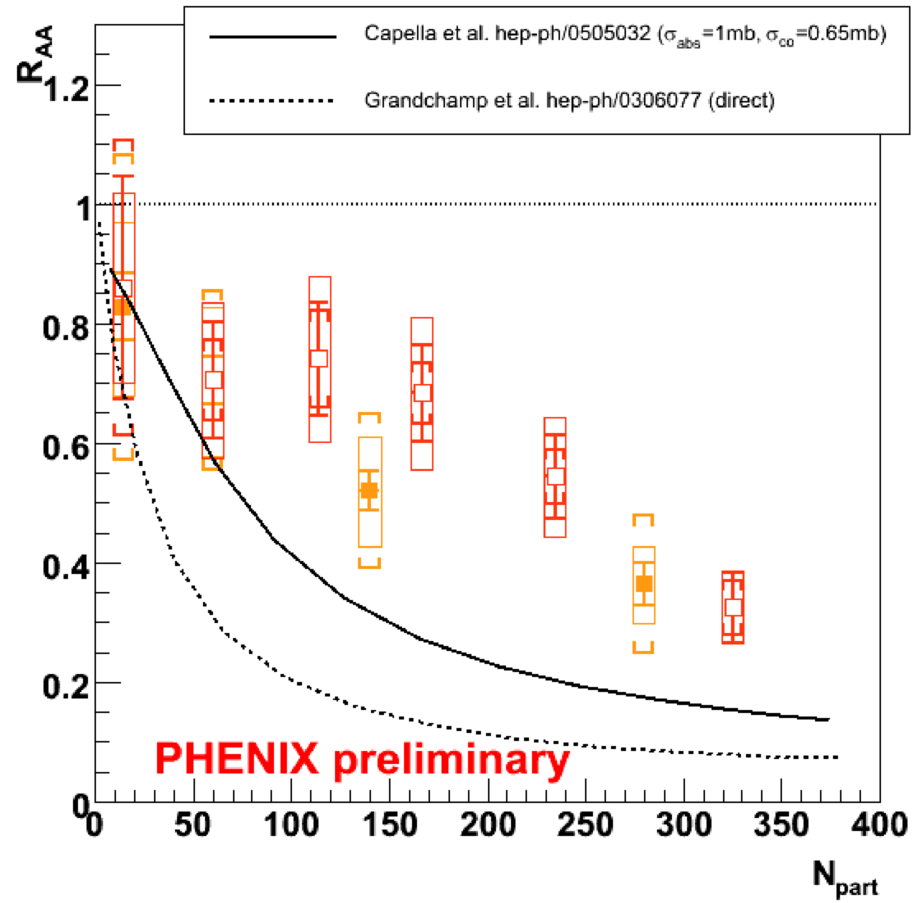


data: Phenix central arms and Phenix muon arms

RHIC results: J/ψ suppression

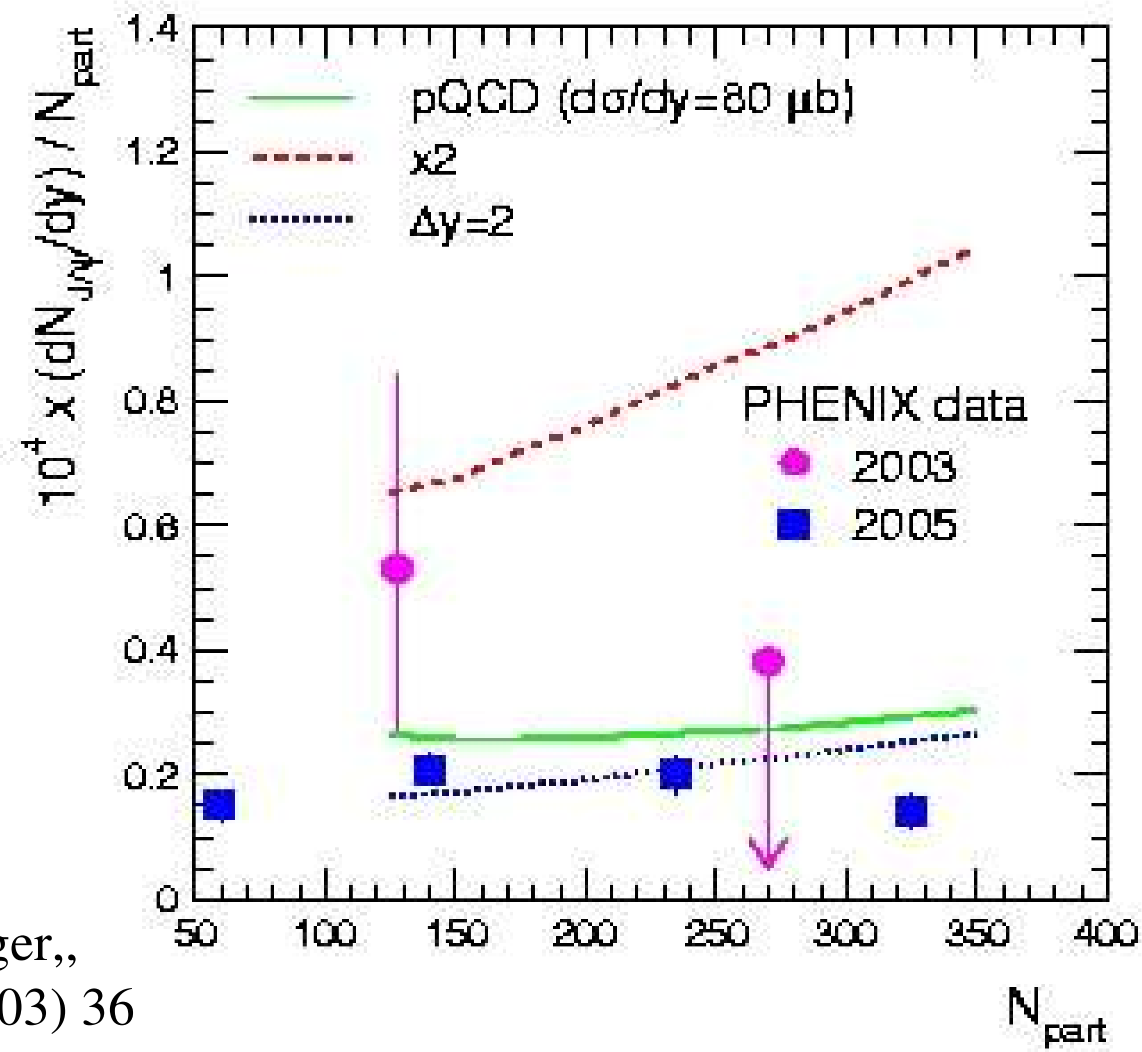


Au+Au y~1.7 |y|< 0.35 order 1000 J/ψ



J/ψ suppressed at RHIC – but not as much as expected from SPS data

Comparison of model predictions to RHIC data

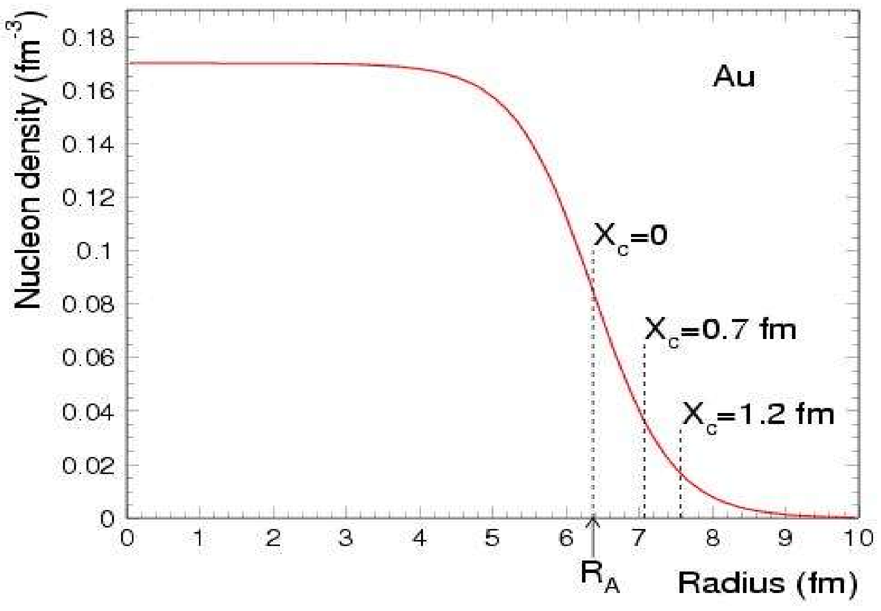


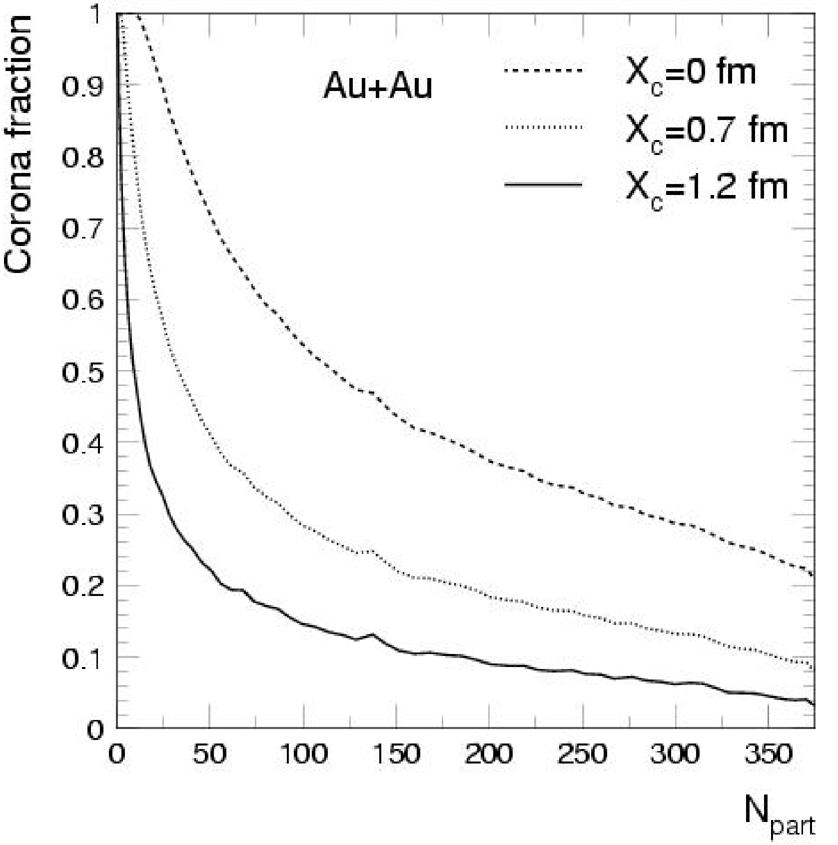
predictions Andronic, Braun-Munzinger,, Redlich, Stachel, Phys. Lett. B571 (2003) 36 using NNLO pQCD results for open charm cross section

New SHM results: take into account the corona effect

relevance recently pointed out by Klaus Werner hep-ph/0603064

Nuclear density distribution:
"core" up to $R_A + X_c$ "corona" outside





$N_{part}(b) = N_{core}(b) + N_{corona}(b)$

fraction of nucleons (participants) in corona: $N_{part}=30 \leftrightarrow 55\%$ $N_{part} = 350 \leftrightarrow 10\%$

Collisions in corona region as in pp, core: medium, e.g. QGP

$$dN_{ch}/d\eta/N_{part}(b) = dN_{ch}/d\eta/N_{core}(b) + dN_{ch}^{pp}/d\eta/N_{corona}(b)$$

does charm quark recombination in QGP play a role?

study ccbar → gg in expanding and cooling QGP

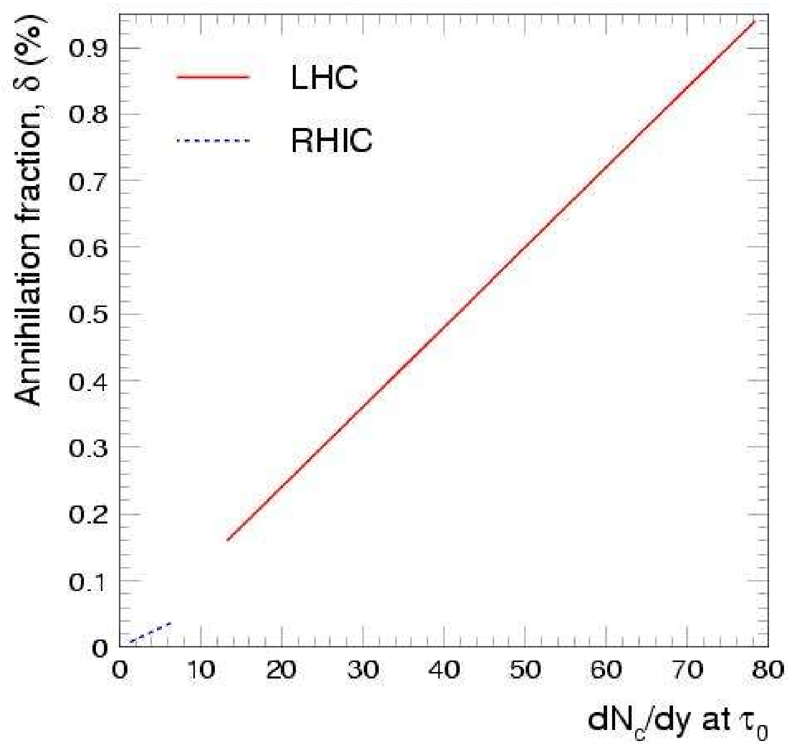
cross section via detailed balance from calculations of gg → ccbar by Glück, Owens, Reya, PRD 17 (1978) 2324

order of 0.1 mb

annihilation rate/volume:

$dr_{cc}/d\tau = n_c^2 < \sigma_{ccbar \to gg}\, v >$

integrate over T evolution until T_c

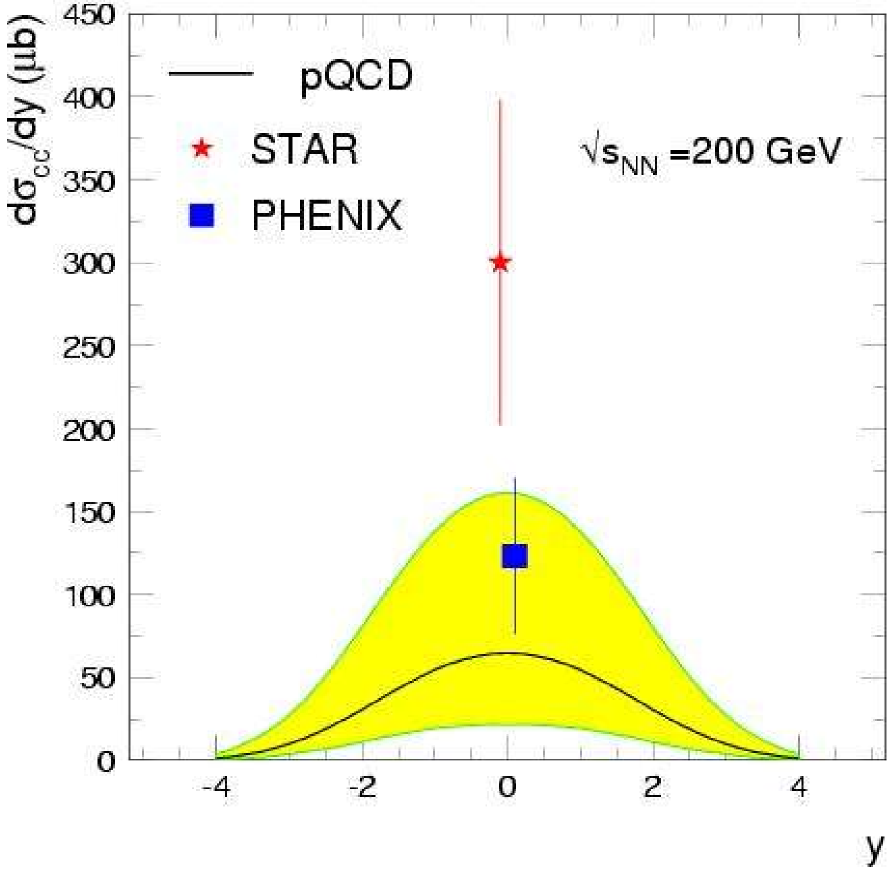


annihilation appears irrelevant even if cross section would be factor 10 bigger

Comparison of charm data with pQCD

pQCD: FONLL Cacciari et al., hep-ph/0502203

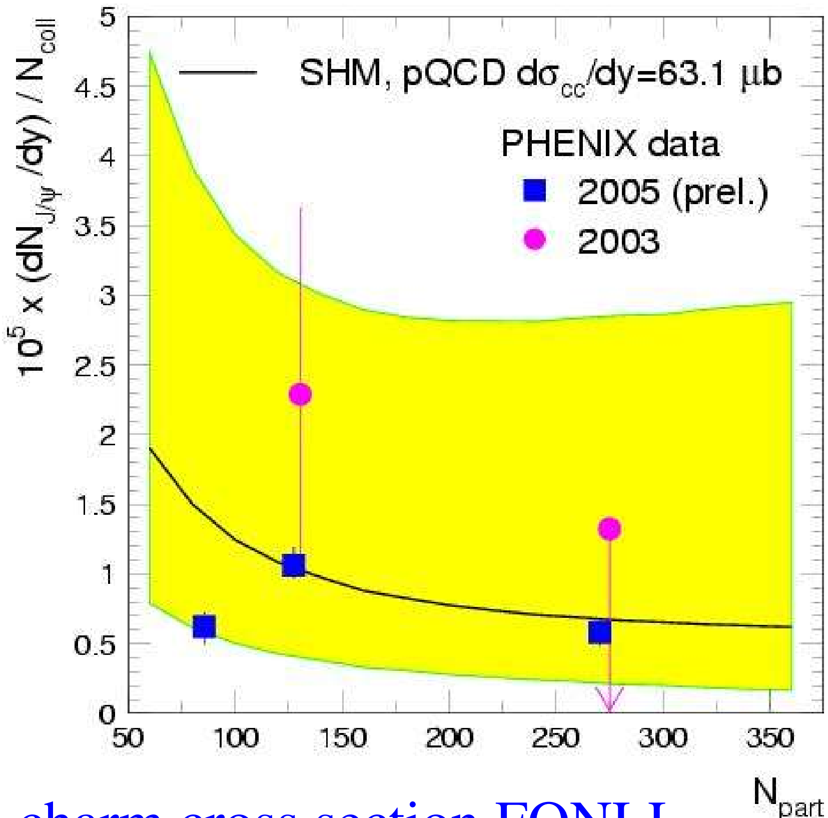
$\sigma_{cc} = 256^{+400}_{-146}\ \mu b$



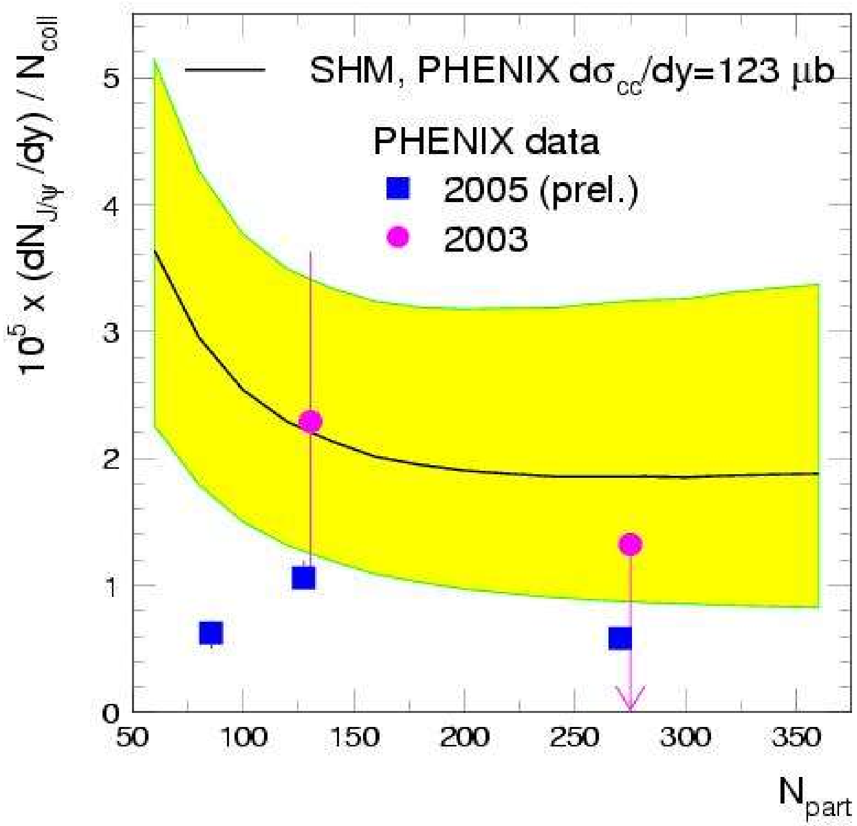
measured PHENIX cross section in upper range of pQCD calc,
STAR factor 2 higher -
need experimental clarification

Statistical charm hadronization and RHIC data

Fall-off of data with centrality very moderate
in line with SHM model (but large uncertainty in σ_{cc})



pp charm cross section FONLL
Cacciari et al., hep-ph/0502203
$\sigma_{cc} = 256^{+400}_{-146}$ μb

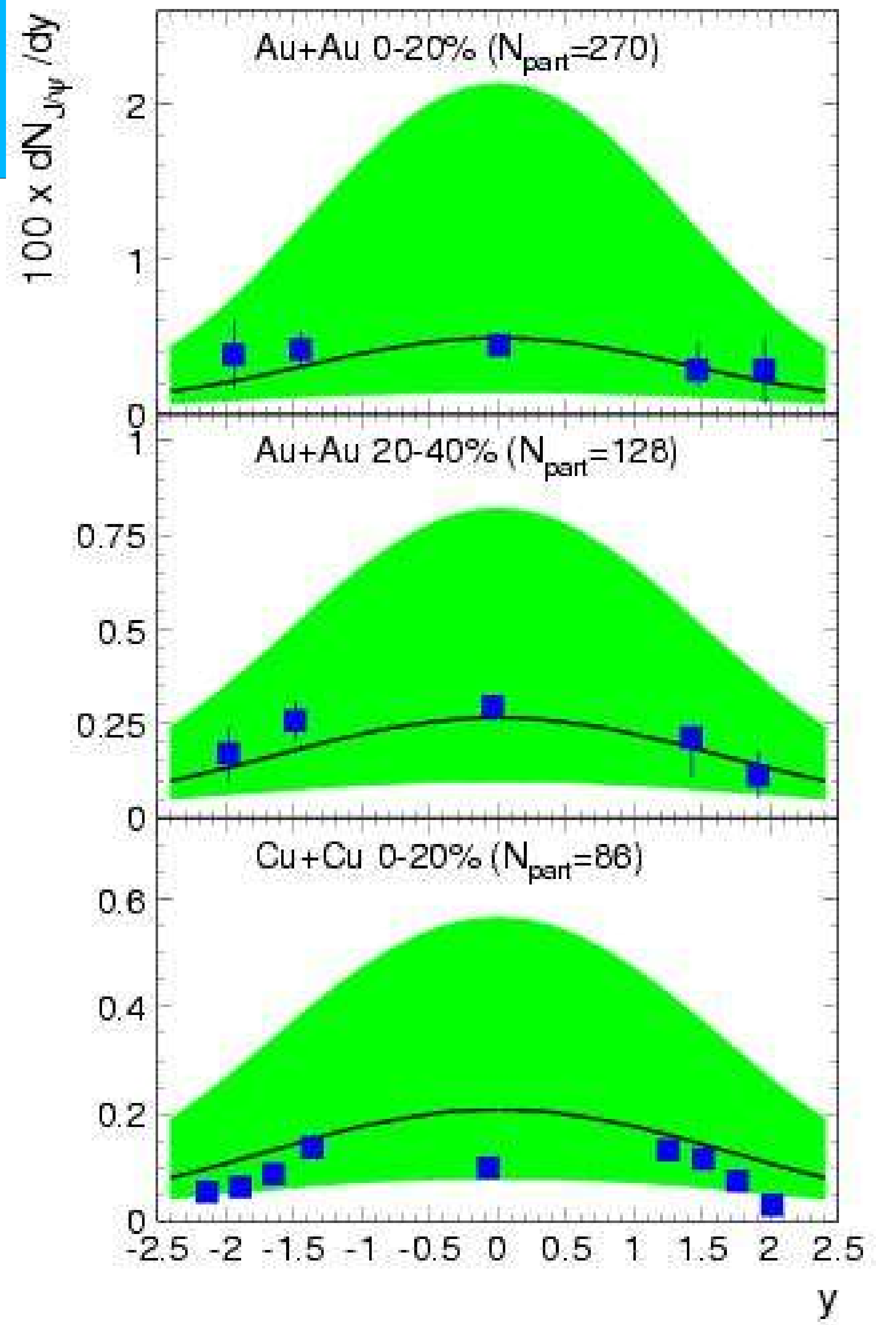


measured PHENIX pp charm
cross section

Statistical charm hadronization and RHIC data vs rapidity

pp charm cross section FONLL
Cacciari et al., hep-ph/0502203
$\sigma_{cc} = 256^{+400}_{-146}$ μb

data very well reproduced

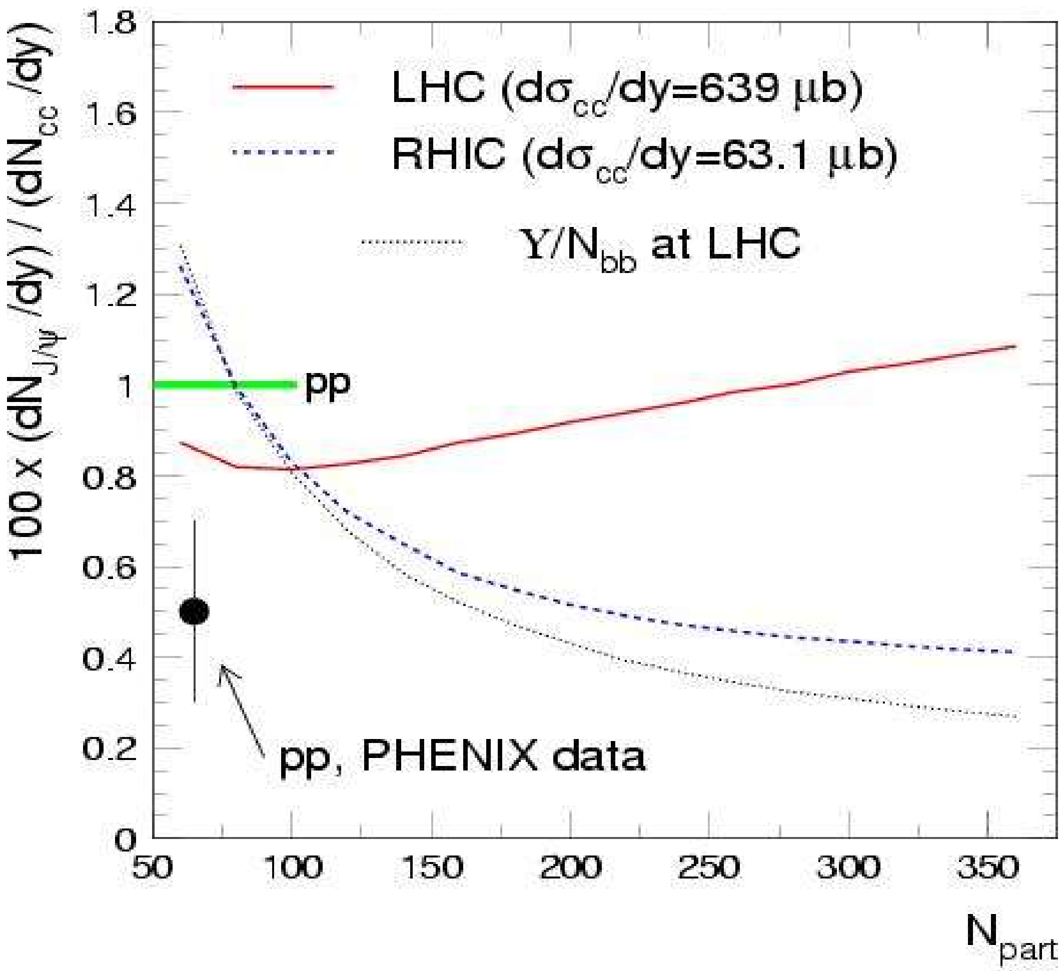


Energy dependence of Quarkonia Production in Statistical Hadronization Model

This predicted centrality dependence is unique for the statistical hadronization model.

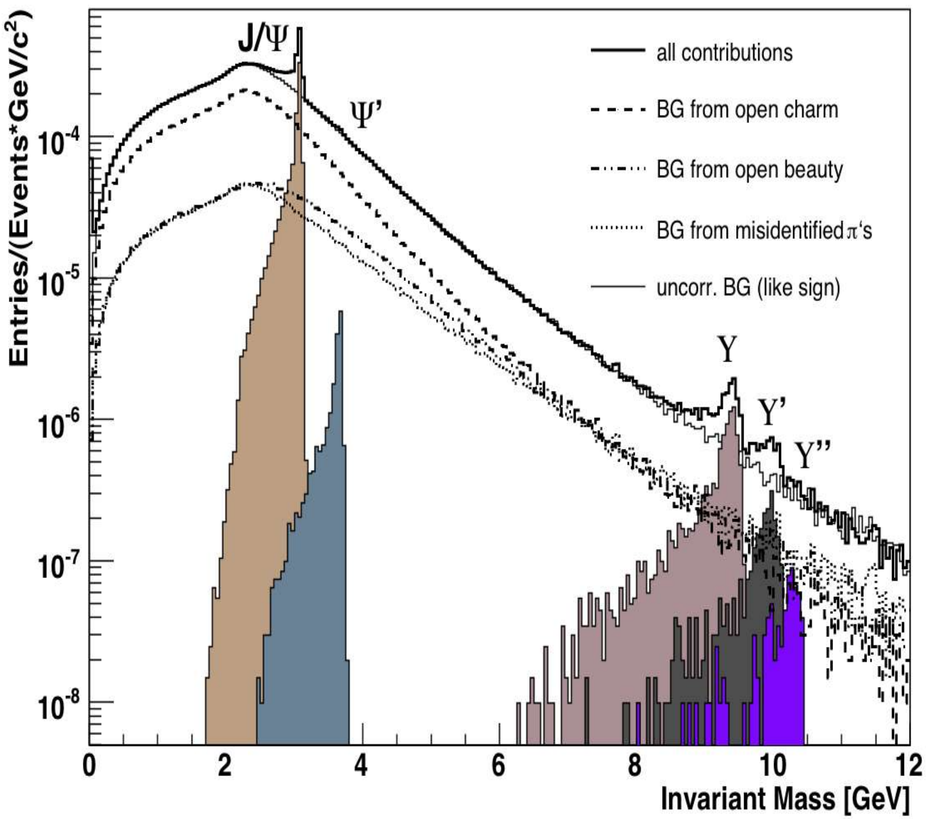
Its observation would not only imply that recombination is at work, but be a fingerprint of **deconfinement.**

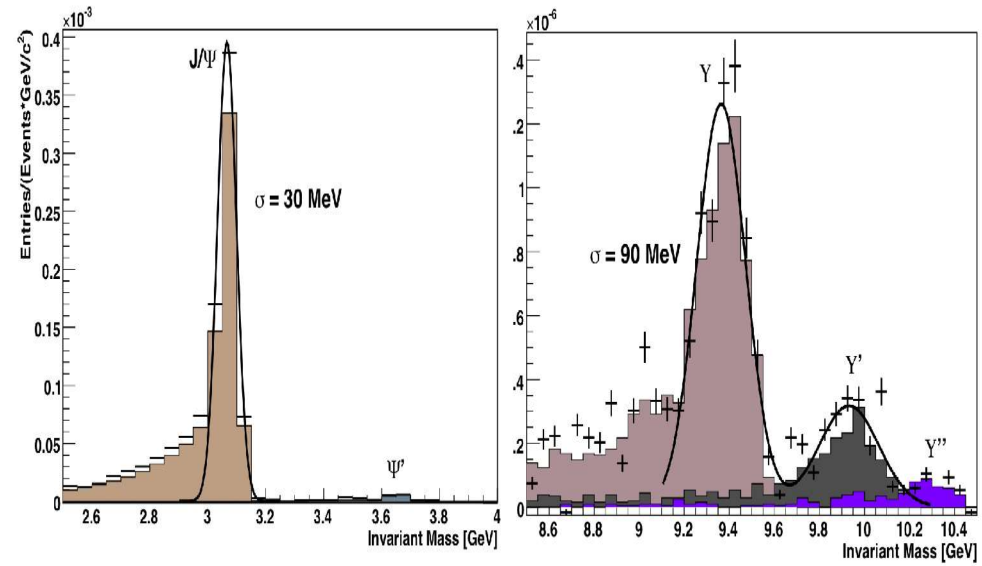
Upsilon at LHC expected to look like J/ψ at RHIC

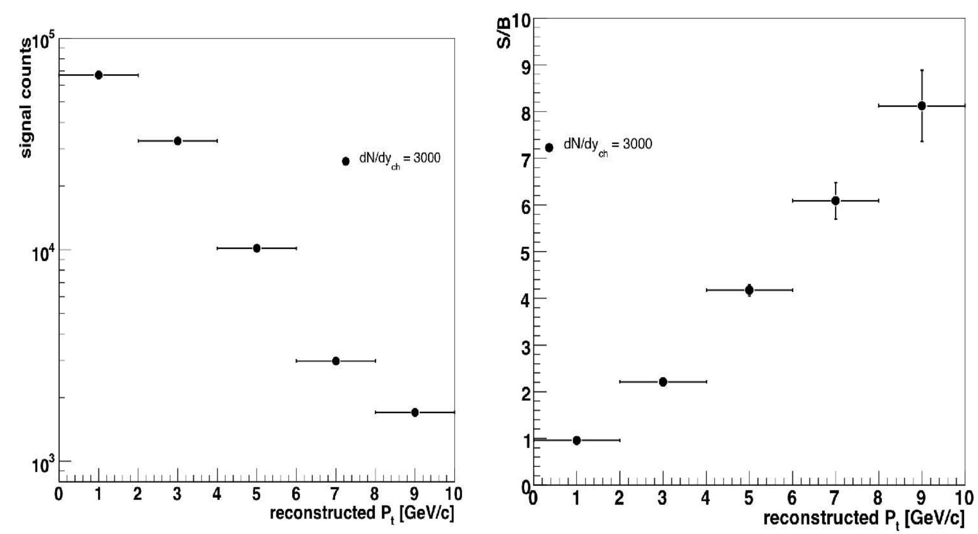


Charmonia in ALICE at mid-rapidity

Electron identification with TPC and TRD



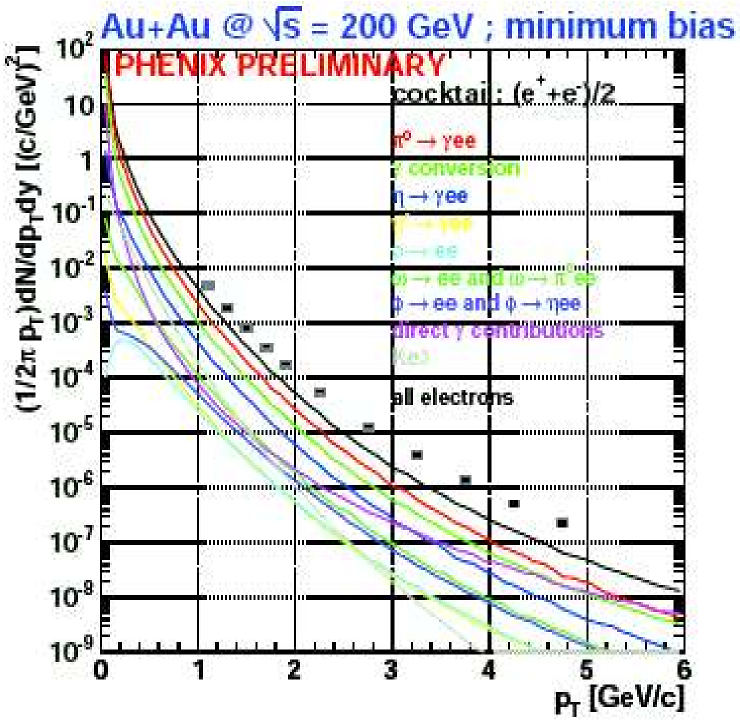


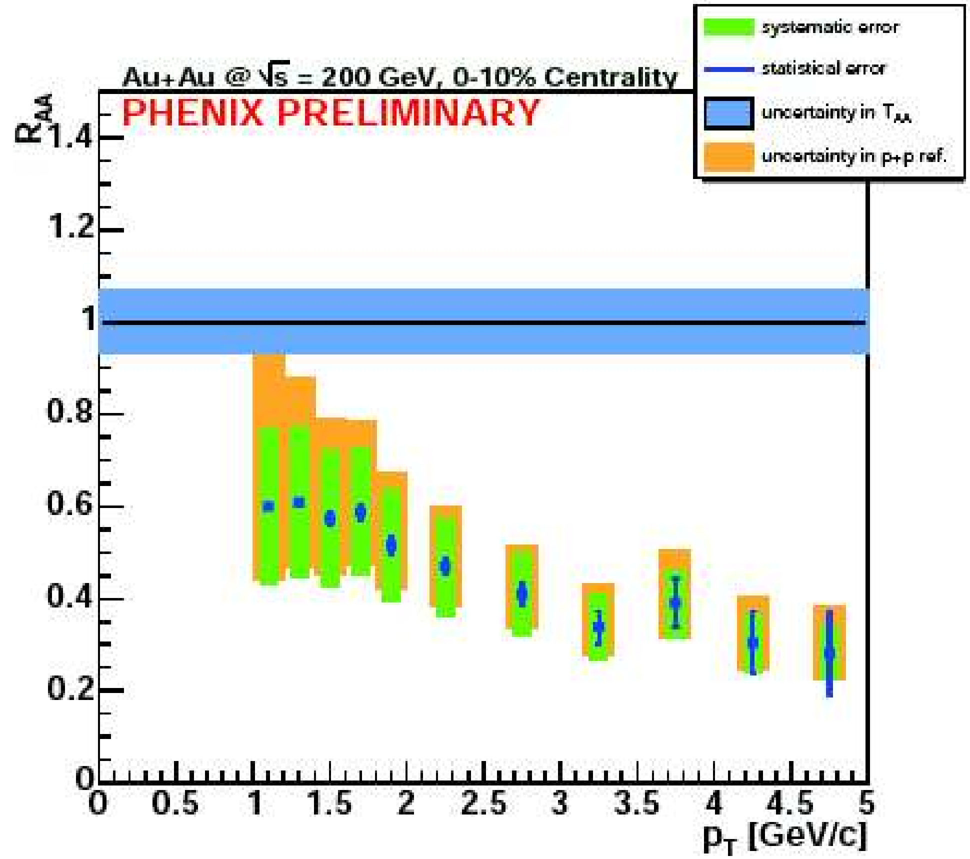


Good mass resolution and signal to background
expect w full TRD and trigger
2500 Upsilon per PbPb year

Simulation: W. Sommer 2 10^8 central Pb Pb coll.

Heavy quark distributions from inclusive electron spectra



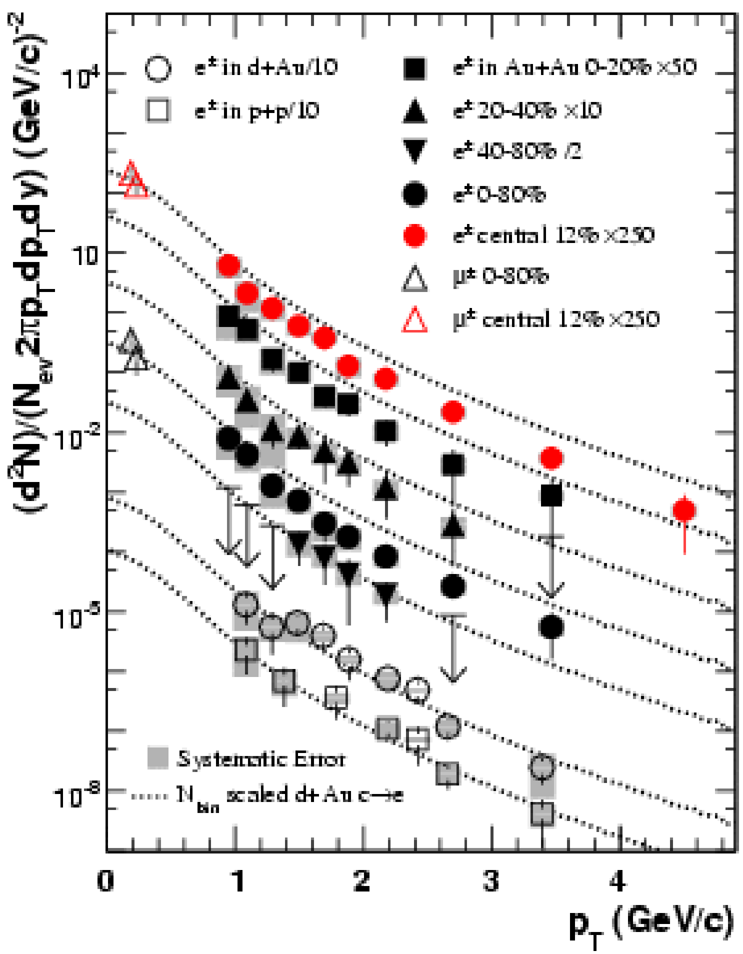


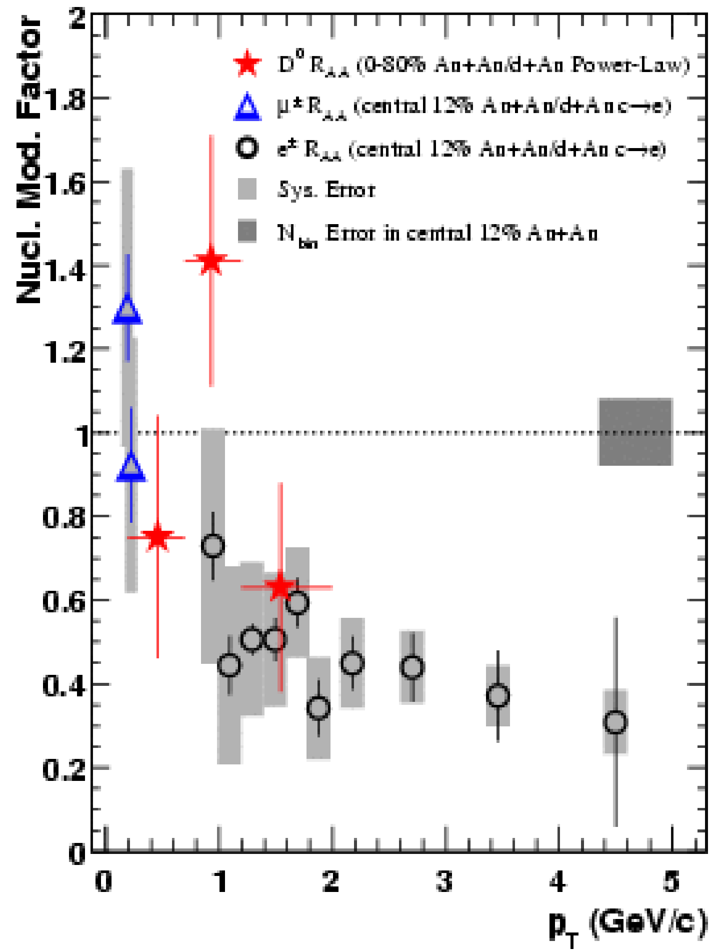
model all contributions from hadron decays and photon conversions using data as input subtraction: leaves D and B semi-leptonic decays

surprize: suppression very similar to pions prediction (Dokshitzer, Kharzeev) less energy loss for heavy quarks (dead cone eff. for radiation)

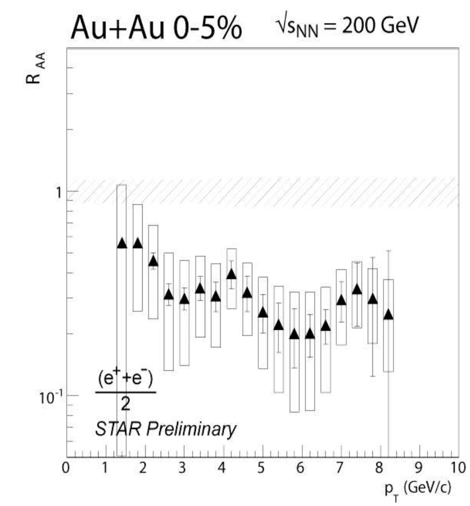
STAR and PHENIX findings agree
– using basically same method

STAR Preliminary



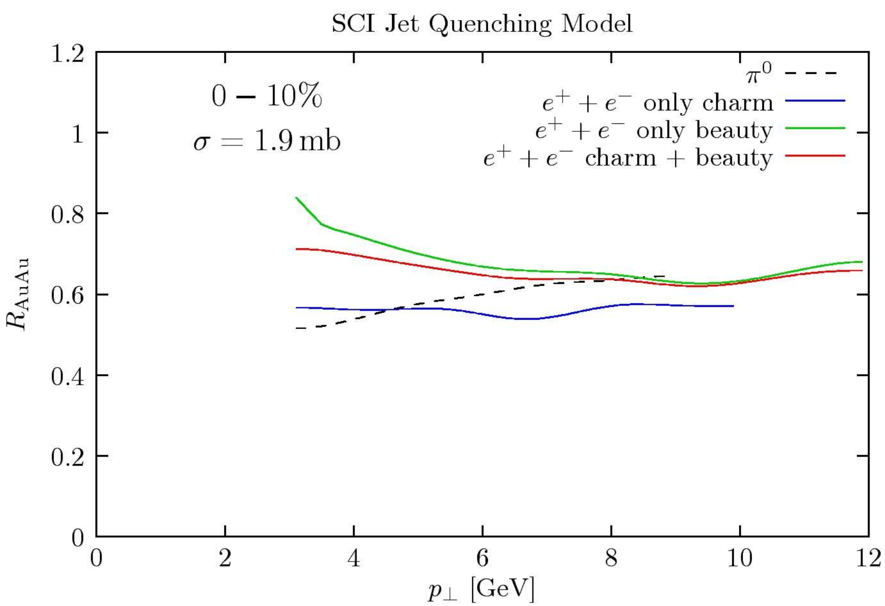


with EMCal even higher pt reach



SCI jet quenching for heavy quarks

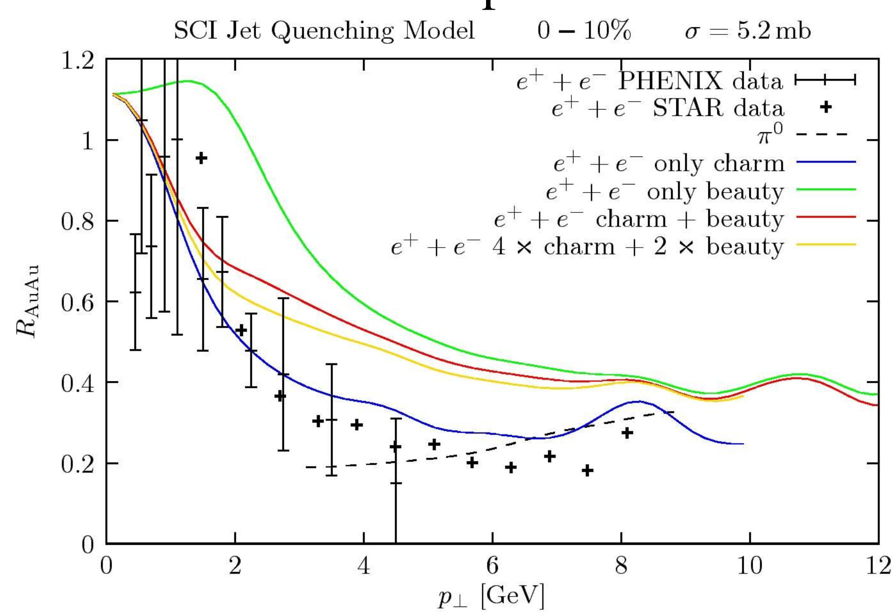
compute in model the measured quantity (K. Zapp)



🡐 standard σ

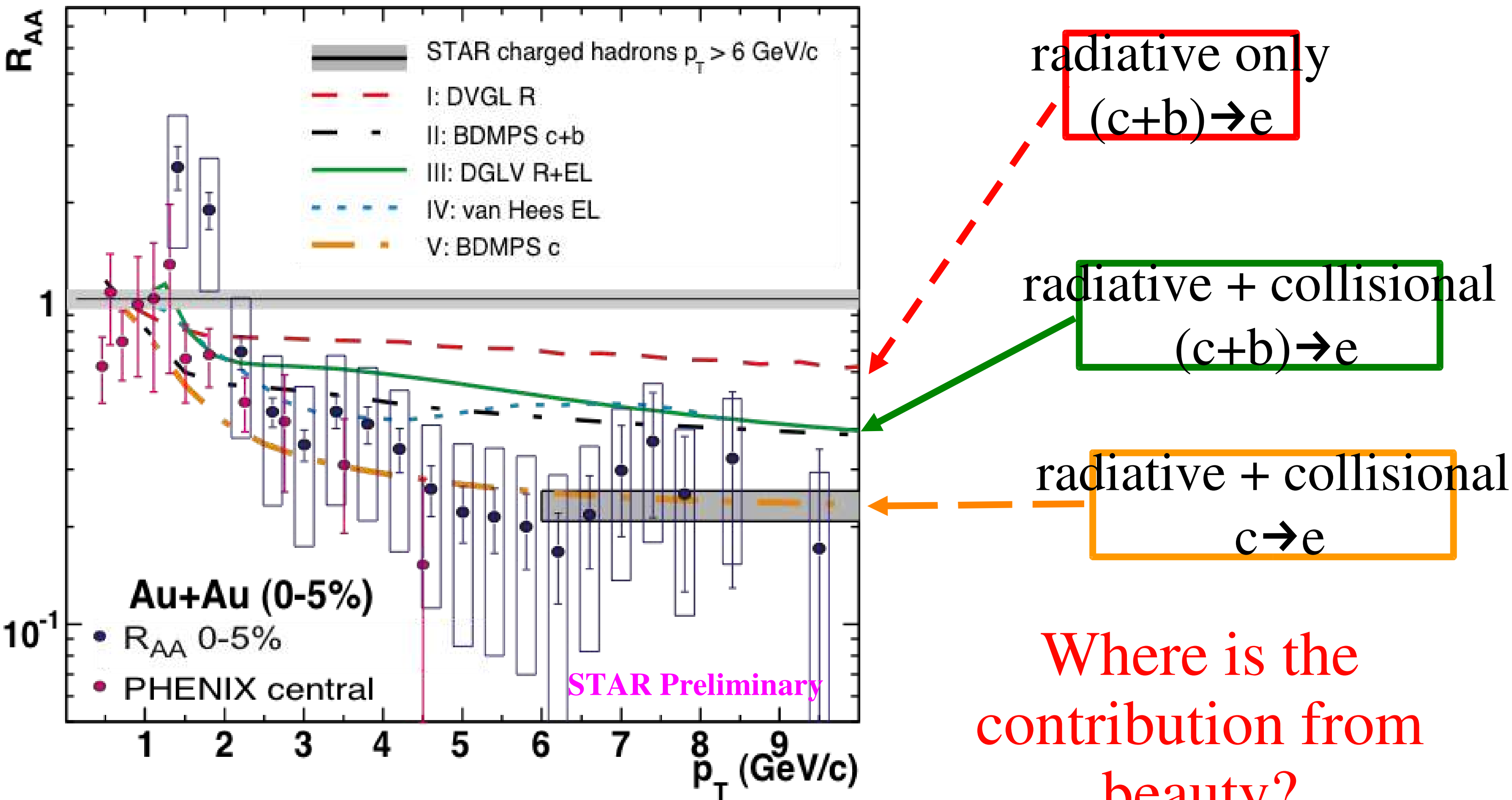
charm contribution indeed suppressed as much as pions but adding beauty data are not reproduced

🡓 σ to match pion data



need improved heavy quark measurements – to come with upgrades

Heavy Quark Energy Loss: theory *vs.* data

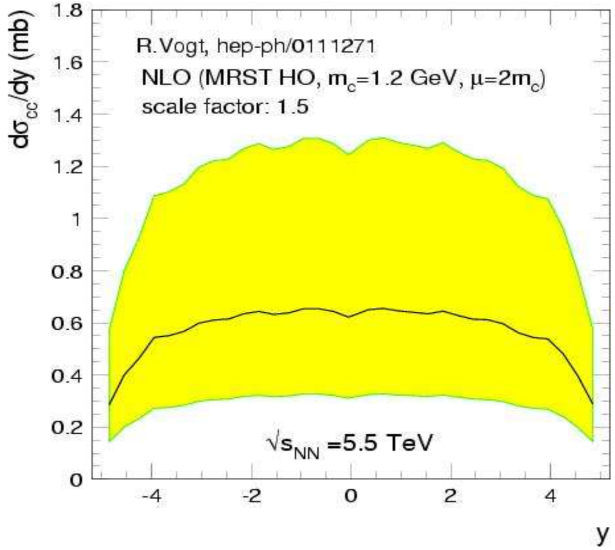


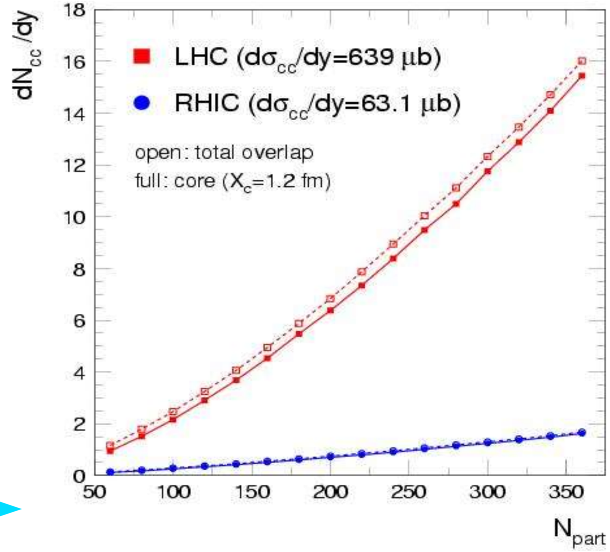
Where is the contribution from beauty?

talk P. Djawotho, STAR, Hard Probes 2006 conference

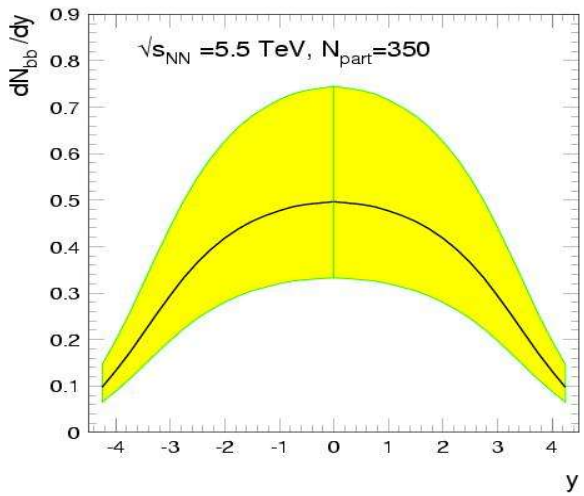
Expectation for charm/beauty production at LHC from pQCD

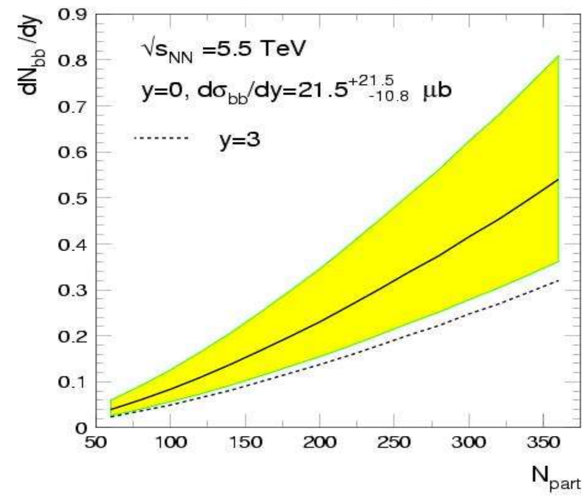
following Cacciari et al., hep-ph/0502203





expect for central PbPb collisions 100 (200) ccbar and 5 (10) bbar over all rapidities





Open/hidden heavy flavor measurements in ALICE

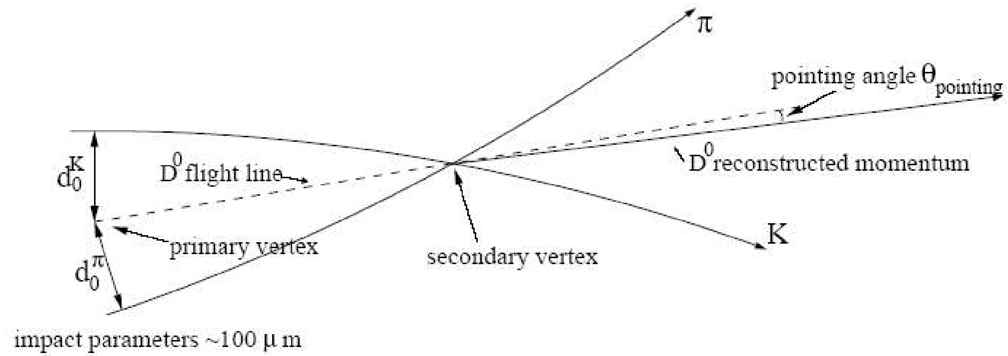
- Hadronic decays: $D^0 \to K\,\pi$, $D^{+-} \to K\,\pi\,\pi$, $D_s \to K\,K^*$, $D_s \to \phi\,\pi$, …
- Leptonic decays:
  - $B \to l$ (e or μ) + anything.
  - Invariant mass analysis of lepton pairs: BB, DD, BD_{same}, J/Ψ, Ψ', Υ family, $B \to J/\Psi$ + anything.
  - $BB \to \mu\,\mu\,\mu$ ($J/\Psi\,\mu$).
  - e-μ correlations.

id. hadrons, electrons: $-0.9 < y < 0.9$ and muons: y=2.5=4.0
in central barrel: vertex cut effective for heavy quark id.

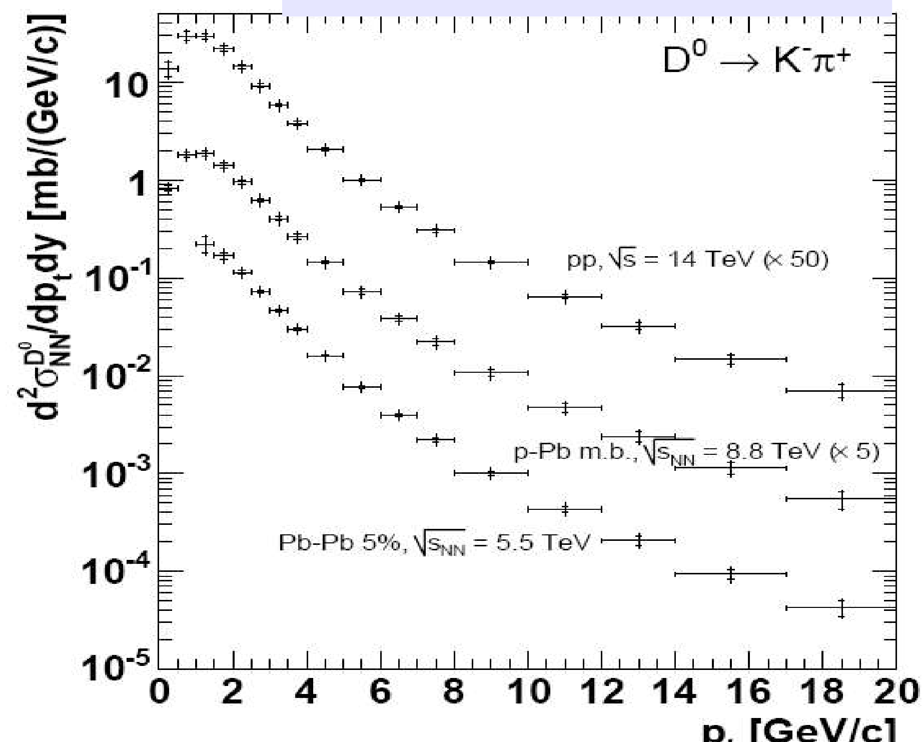
$D^0 \to K\pi$ channel

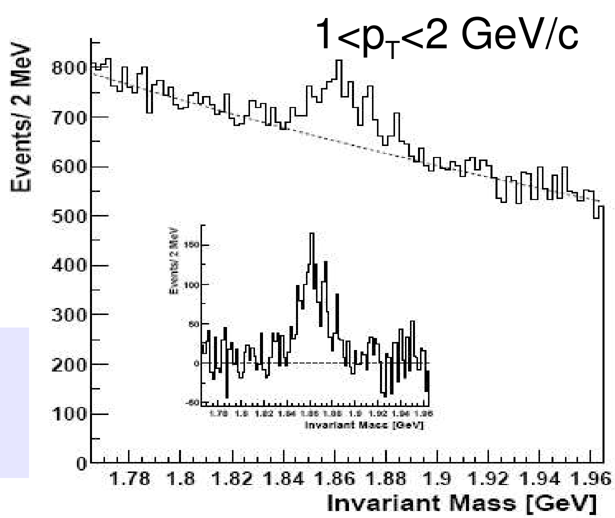
ALICE PPR vol2 JPG 32 (2006) 1295

- High precision vertexing, better than 100 µm (ITS)
- High precision tracking (ITS+TPC)
- K and/or π identification (TOF)



10^9 pp 10^8 pPb 10^7 PbPb



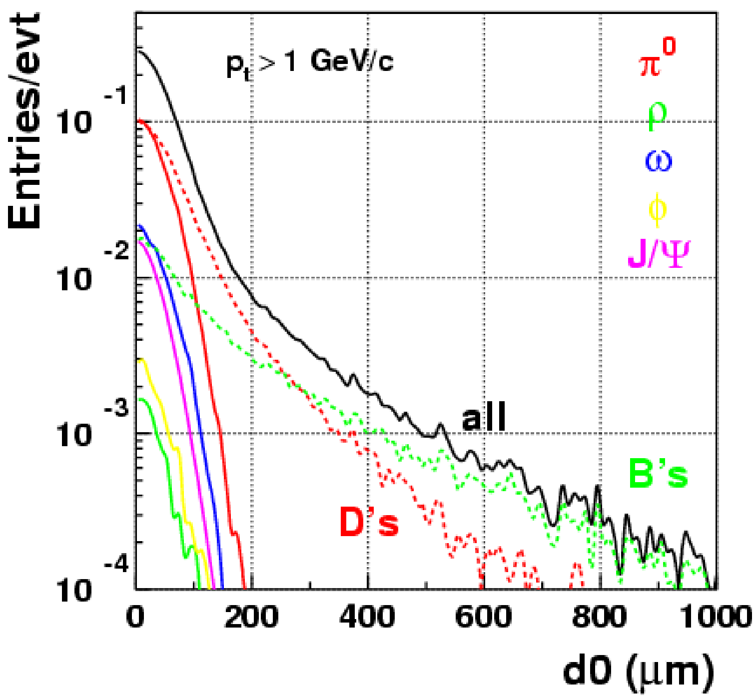


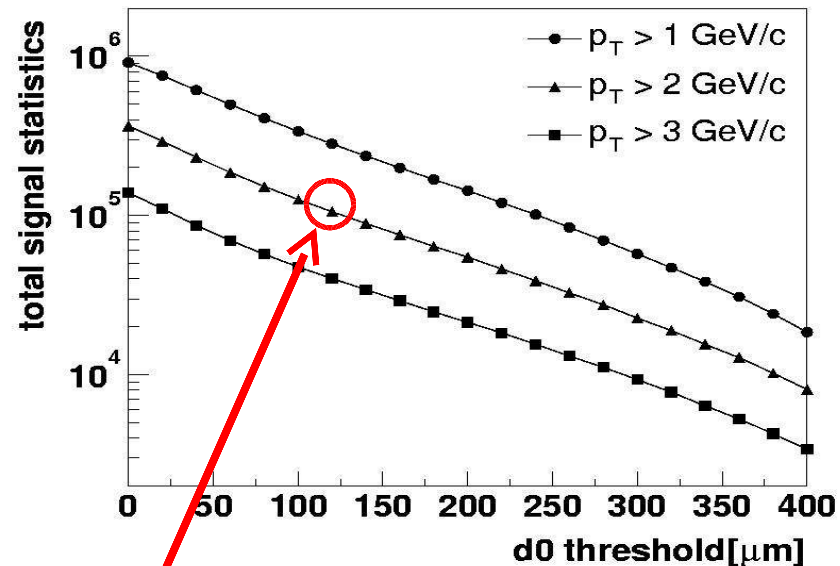
10^7 central PbPb

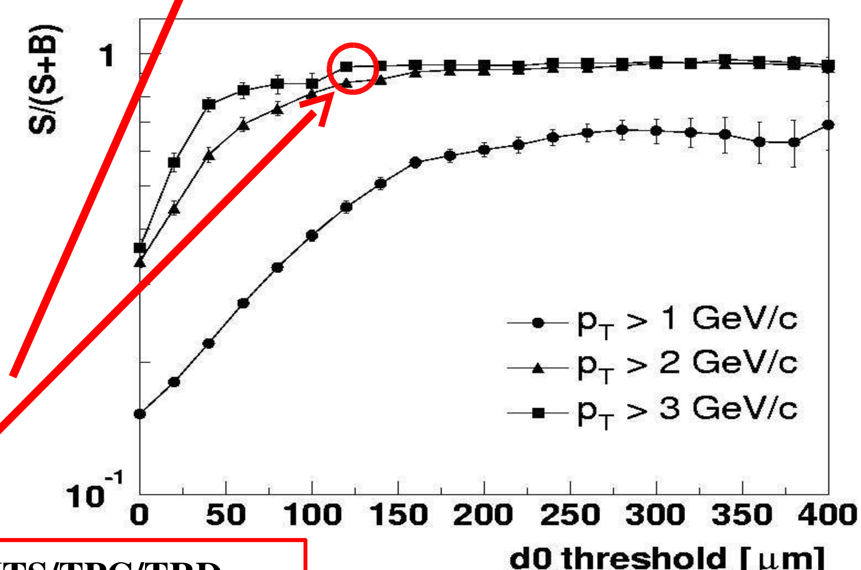
Open heavy flavor measurements in (semi-)leptonic channels in ALICE

- single lepton p_t distributions
  - c & b
- single leptons with displaced vertices
  - c & b

	$D^{\pm}$	D^0	$D_s^{\pm}$	$B^{\pm}$	B^0	B_s^0
cτ (μm)	315	124	140	495	468	462



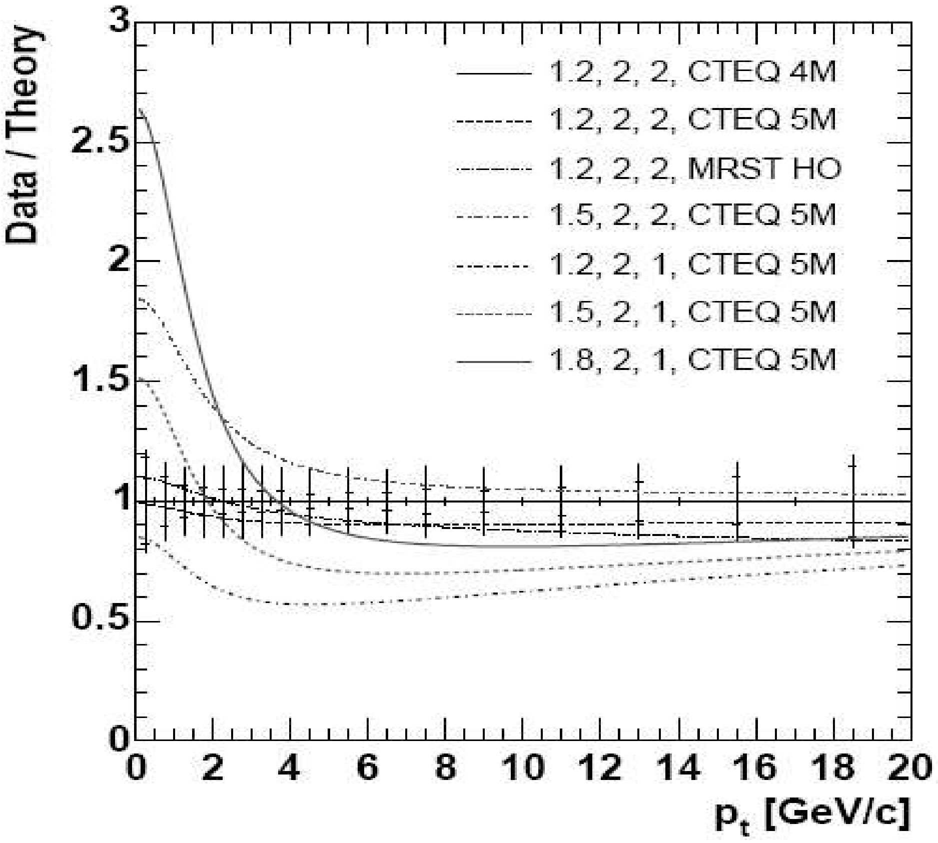




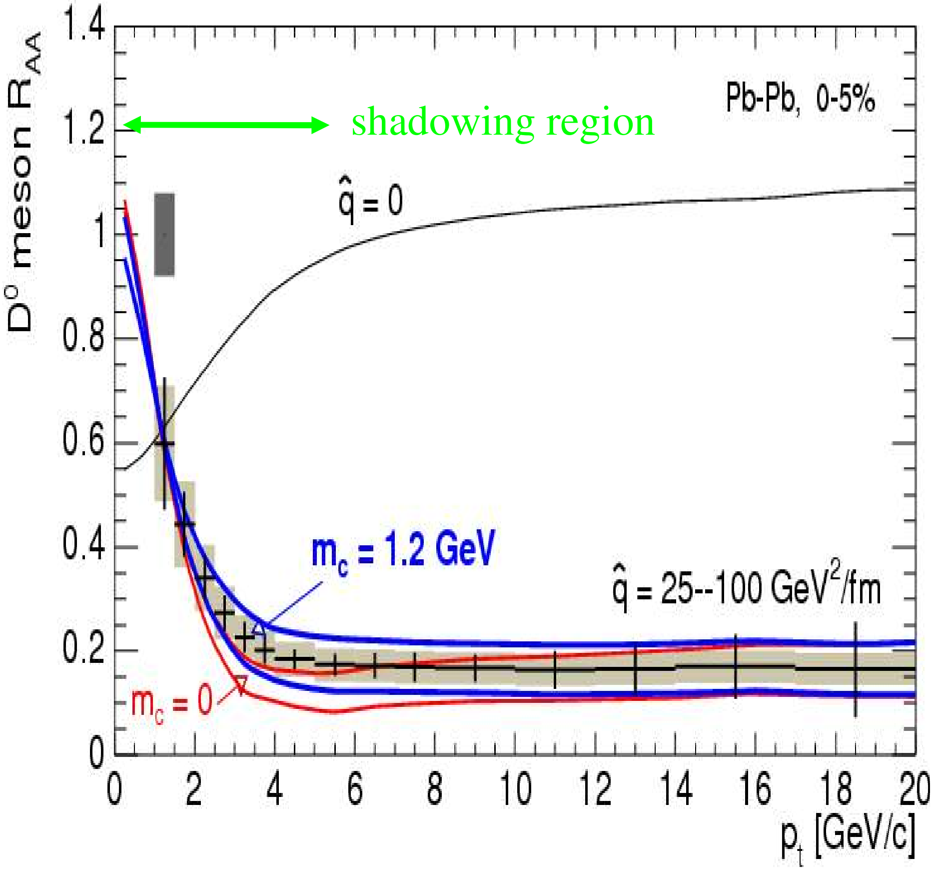
B → e in ALICE ITS/TPC/TRD
p_t > 2 GeV/c & d_0 > 180 μm:
100000 electrons with S/(S+B) = 90%

High Precision charm measurement

pp at 14 TeV
sensitivity to PDF's



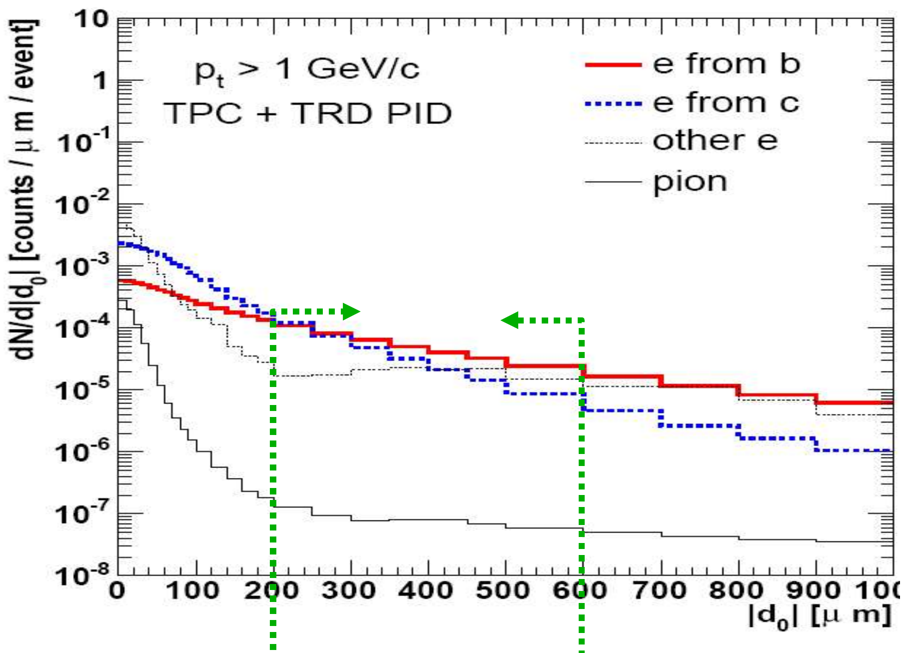
Central PbPb
shadowing + k_T + energy loss

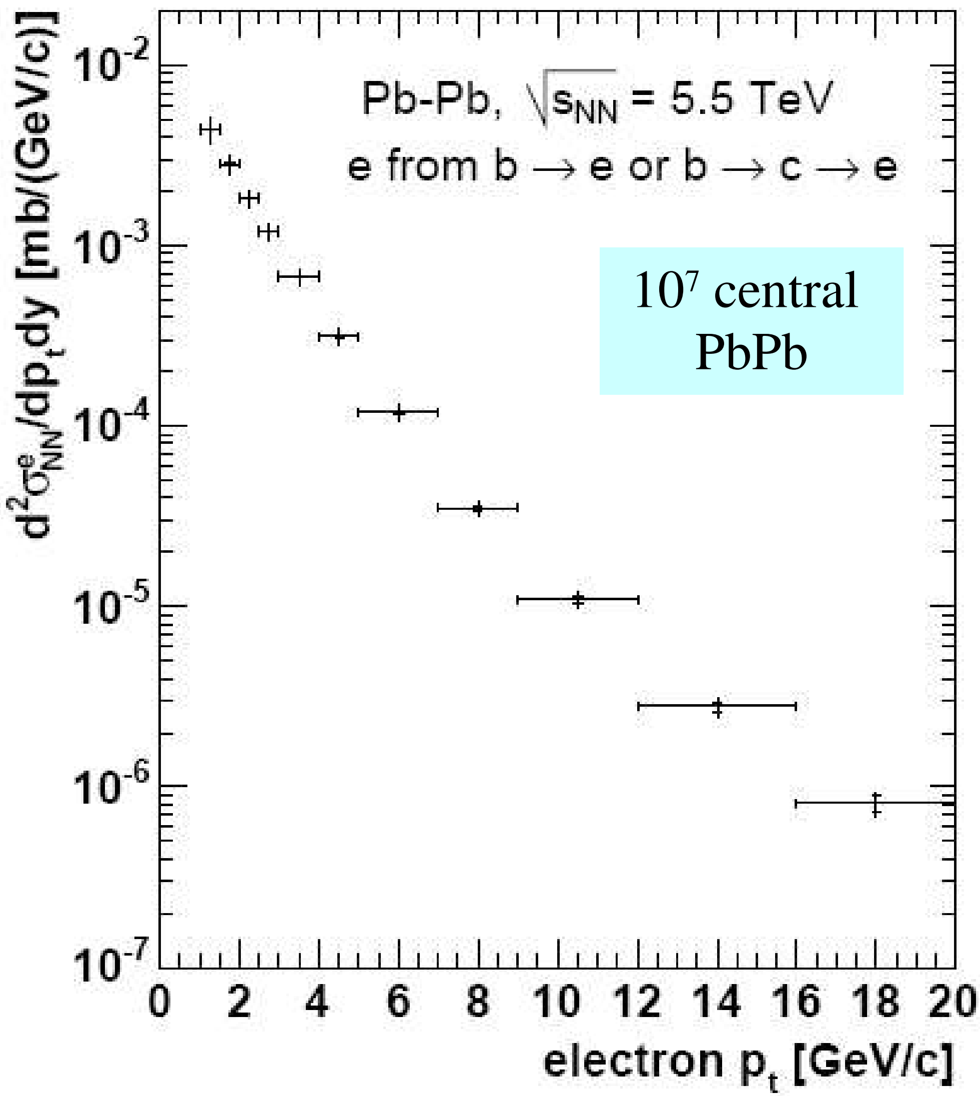


ALICE PPR vol2 JPG 32 (2006) 1295

Open Beauty from single electrons

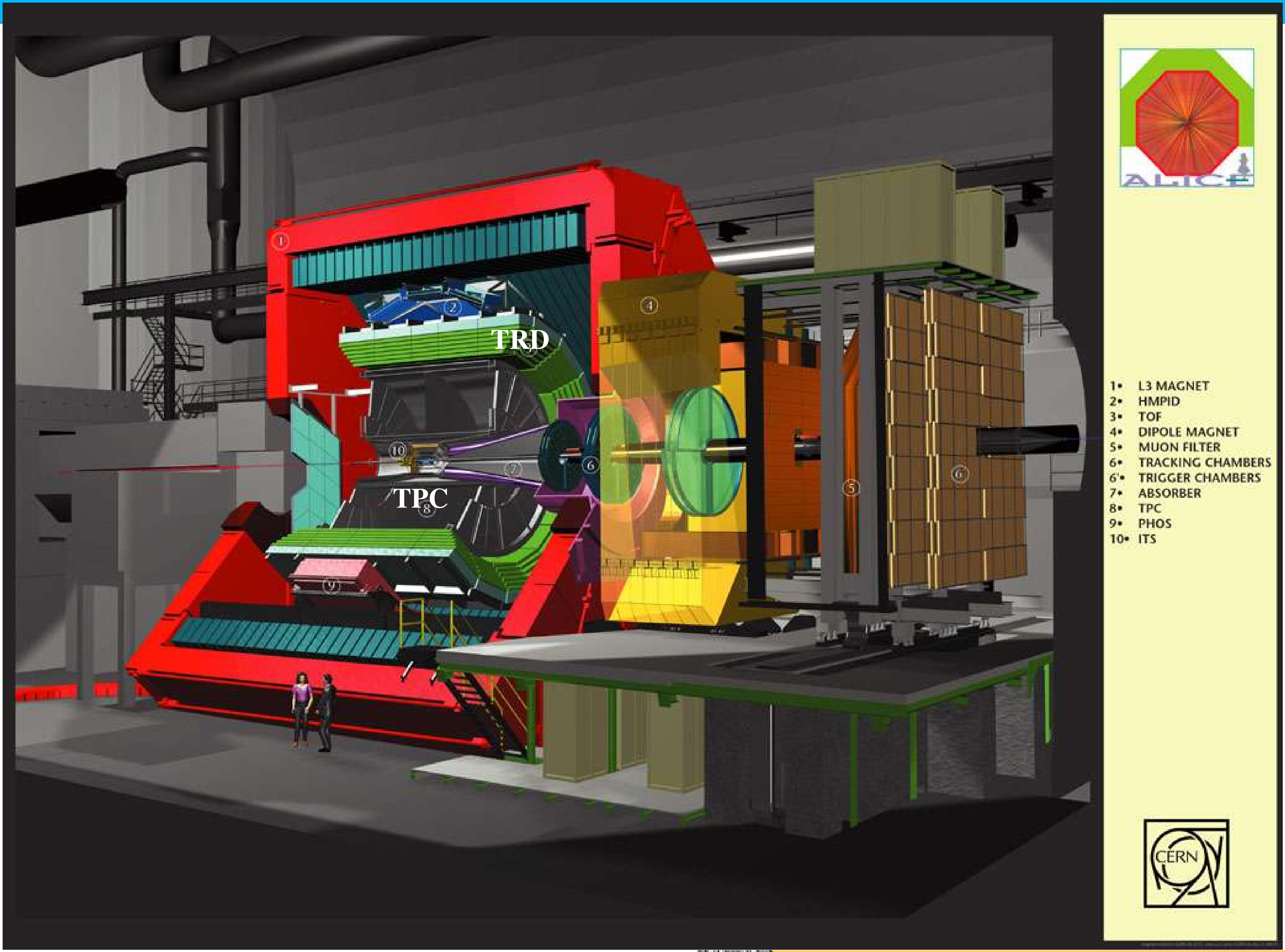
Electron Identification (TRD+TPC)
High precision vertexing (ITS)
Subtraction of the
open charm contribution.





ALICE PPR vol2 JPG 32 (2006) 1295

ALICE - Overview



The TRD (Transition Radiation Detector)

- 18 supermodules
- 6 radial layers
- 5 longitudinal stacks
  - 540 chambers
  - 750m² active area
  - 28m³ of Xe gas

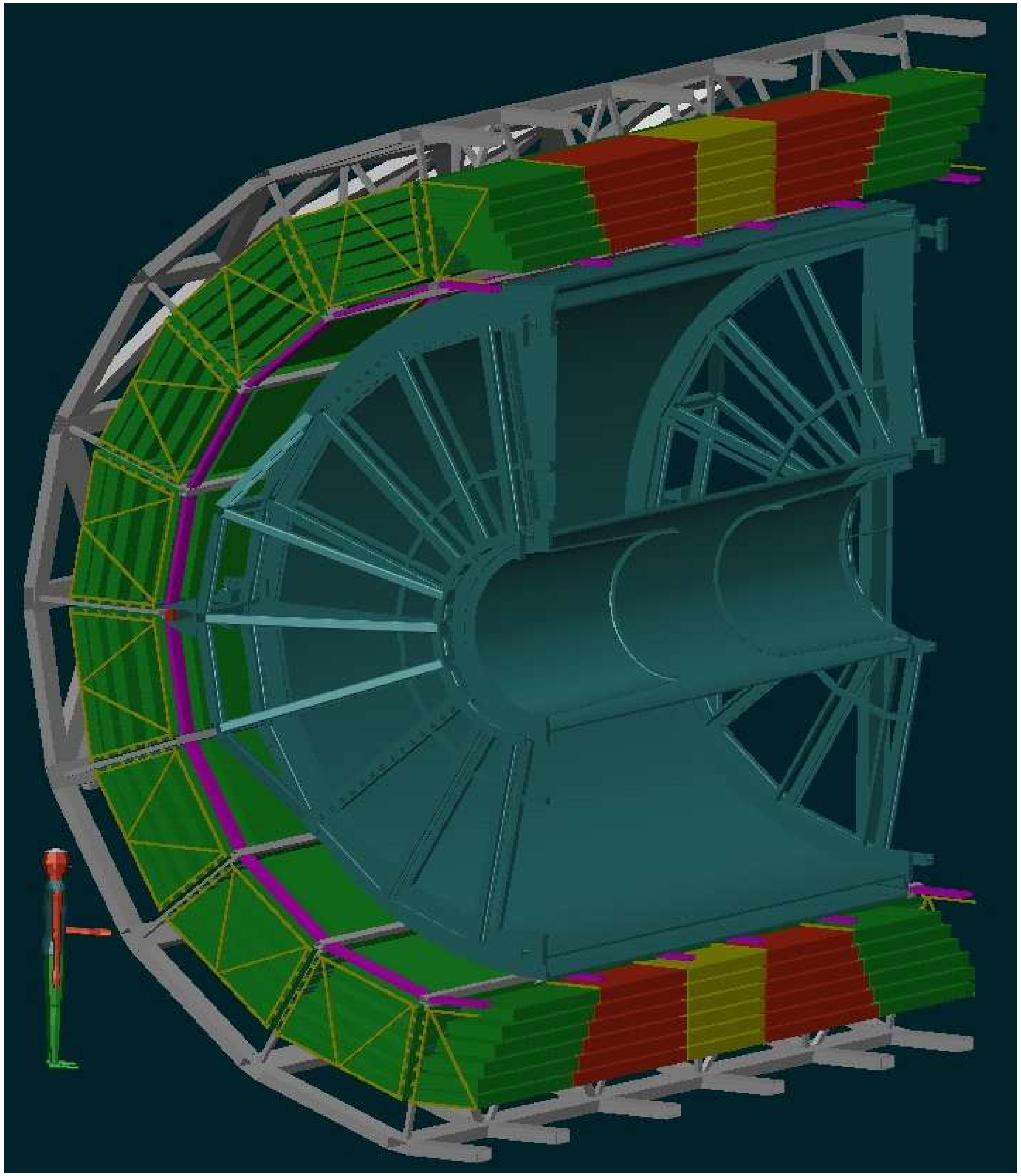
Each chamber:

≈ 1.45 x 1.20m²

≈ 12 cm thick

(incl. radiators and electronics)

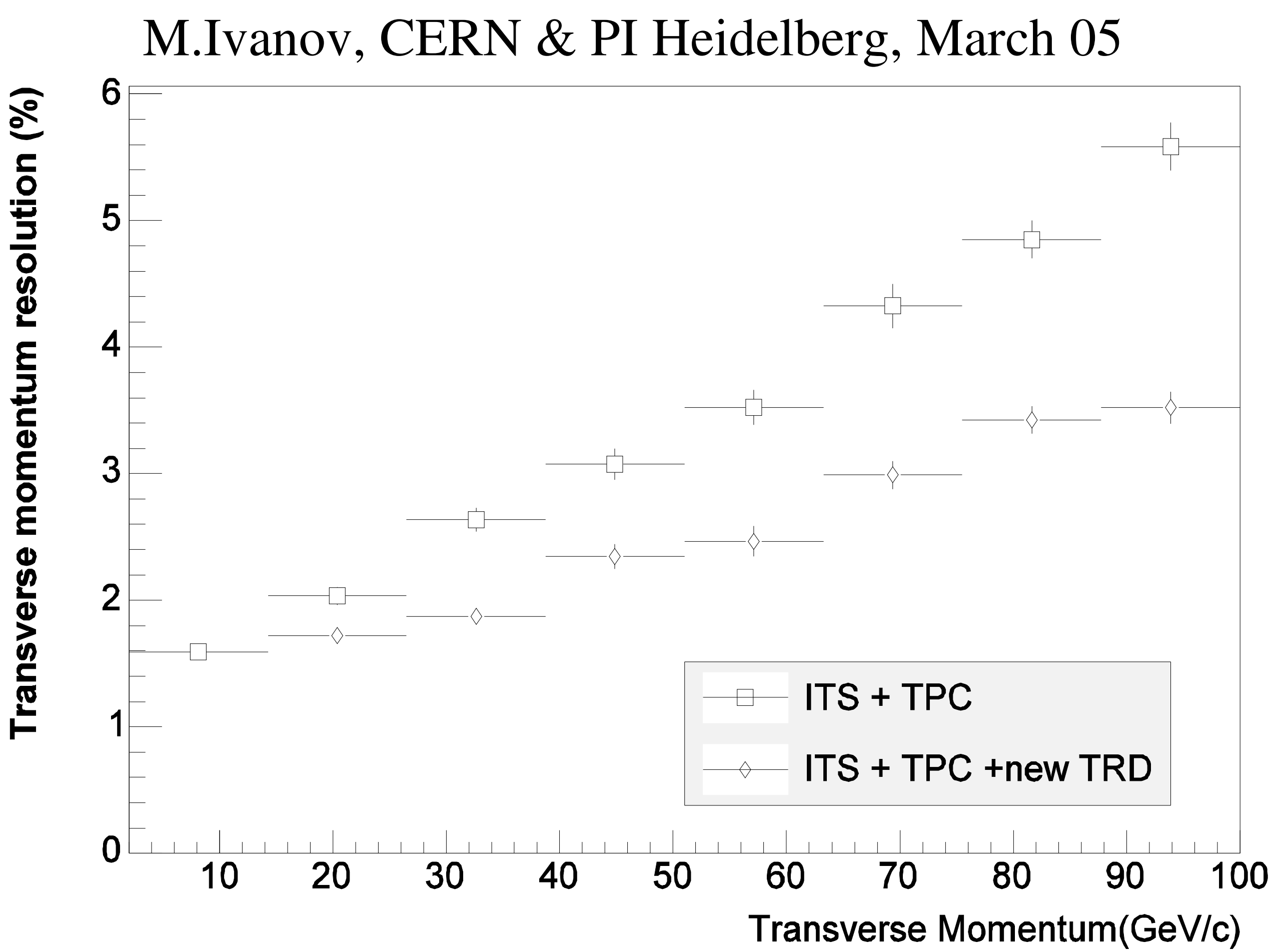
in total 1.16 million read-out ch.



purpose:
electron identification
hard electron pair trigger
jet trigger, high p_t tracking

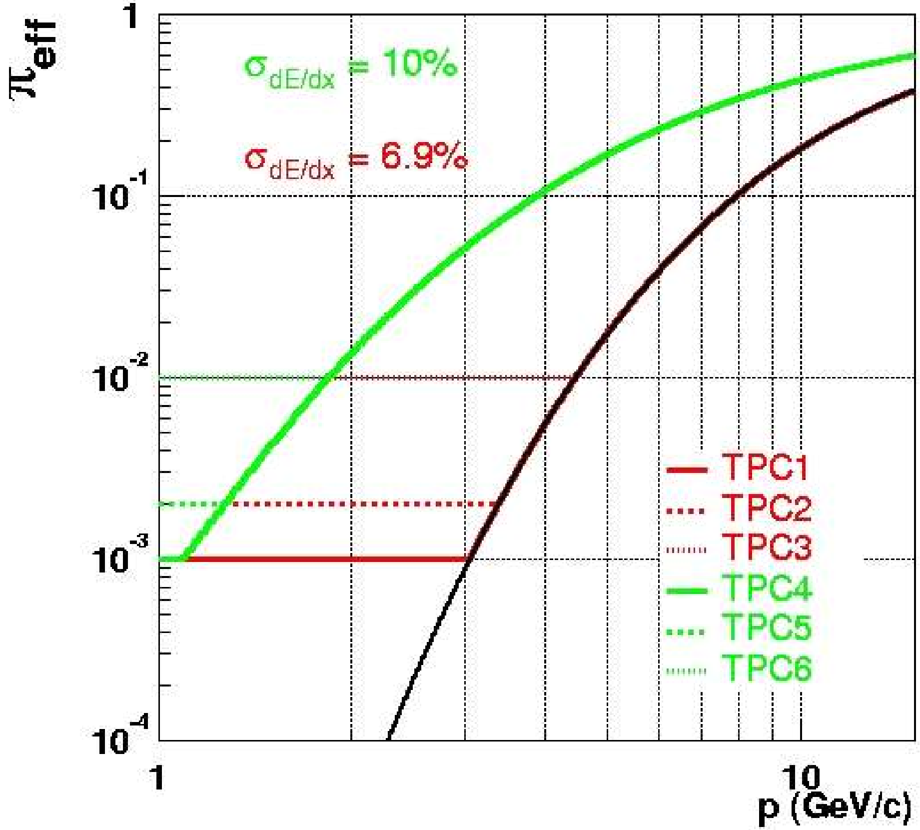
Combined Momentum Resolution in ALICE Central Barrel

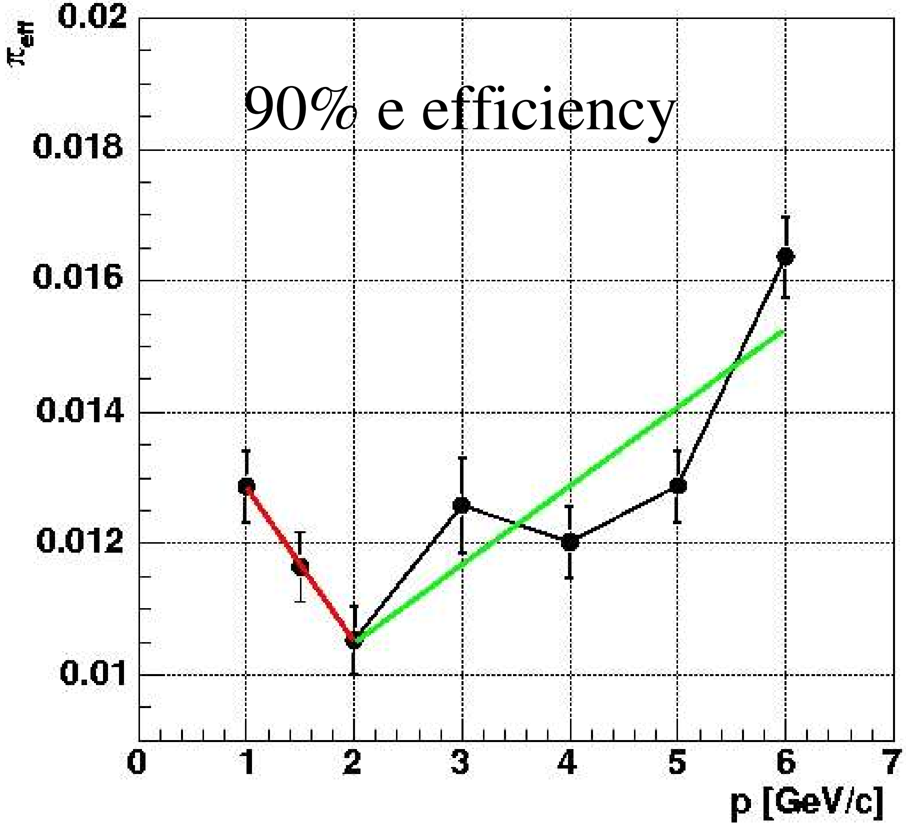
$dN_{ch}/dy \sim 5000$



resolution ~ 3% at 100 GeV/c
excellent performance in hard region!

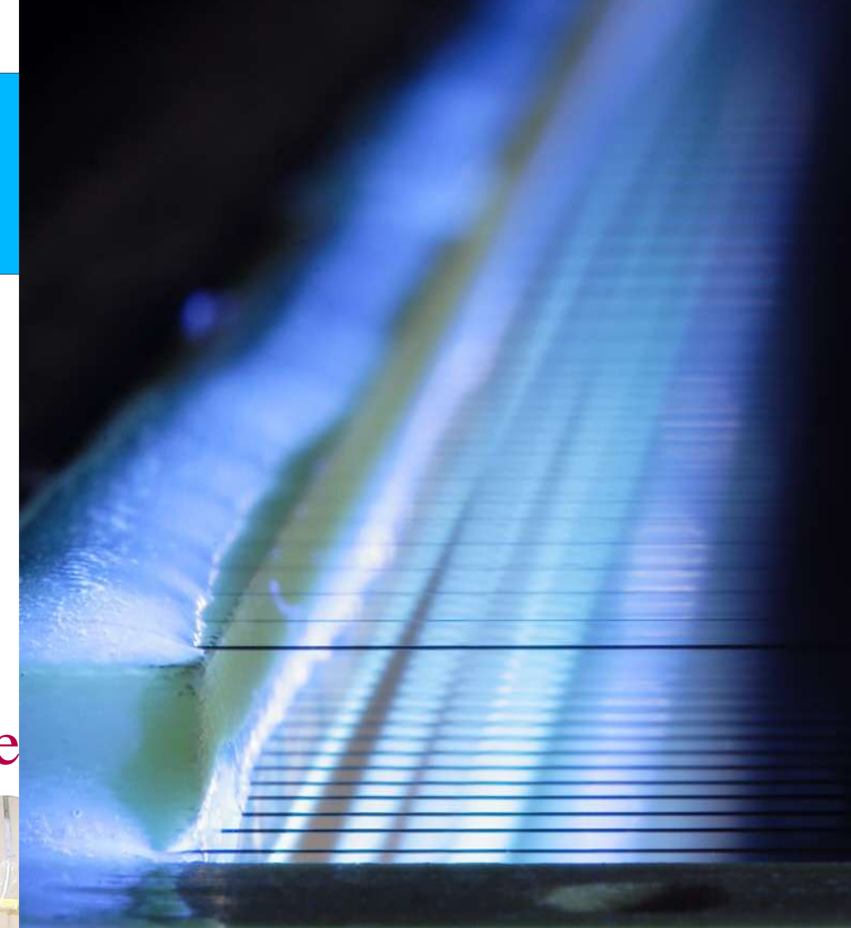
ALICE π rejection via TPC dE/dx and TRD





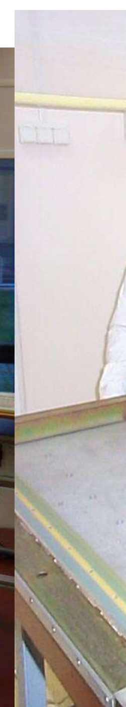
From test beam data: at 2 GeV and 90 % e eff → 10^5 π rejection

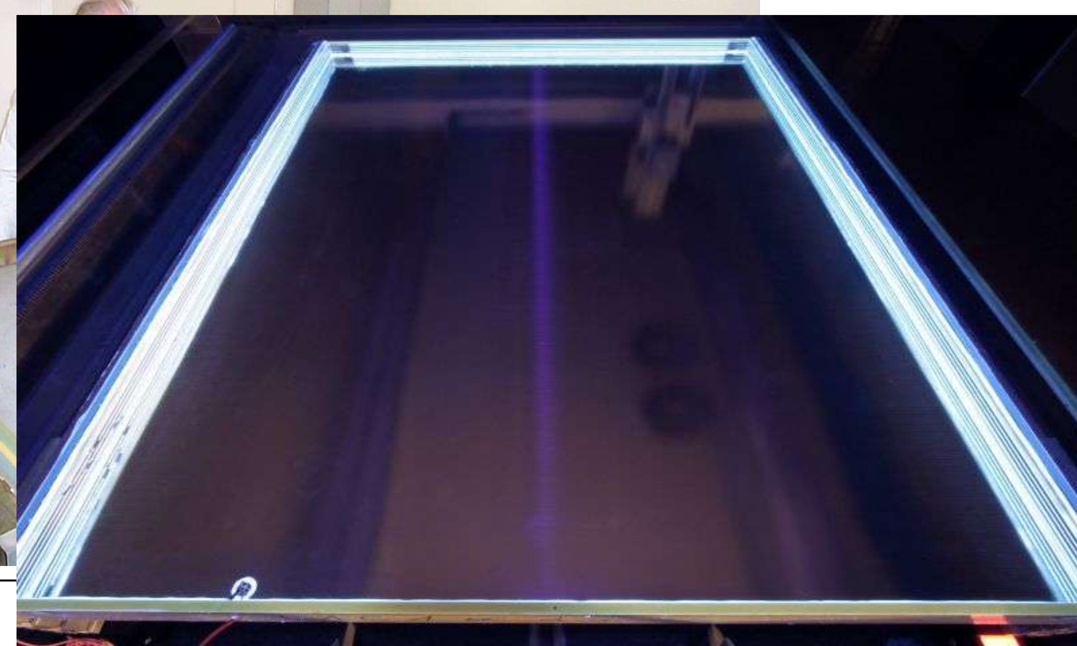
TRD Chamber construction



PI Heidelberg (development of procedure)
JINR Dubna
NIPNE Bucharest
GSI Darmstadt
IKF Frankfurt

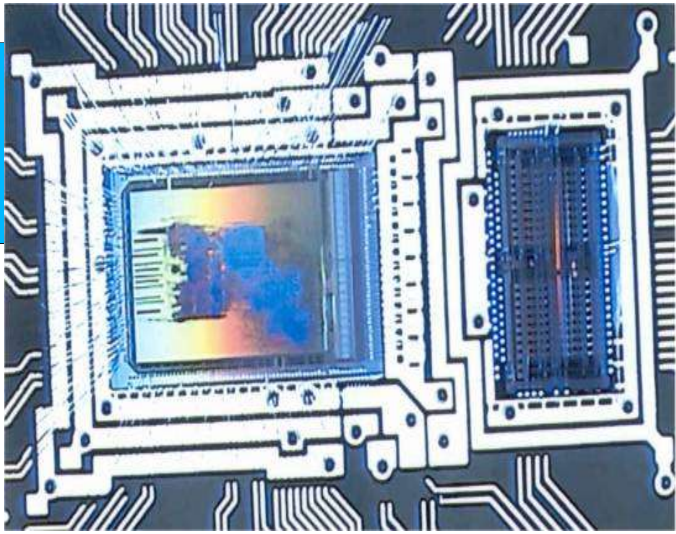
typically 1 chamber each per week on average



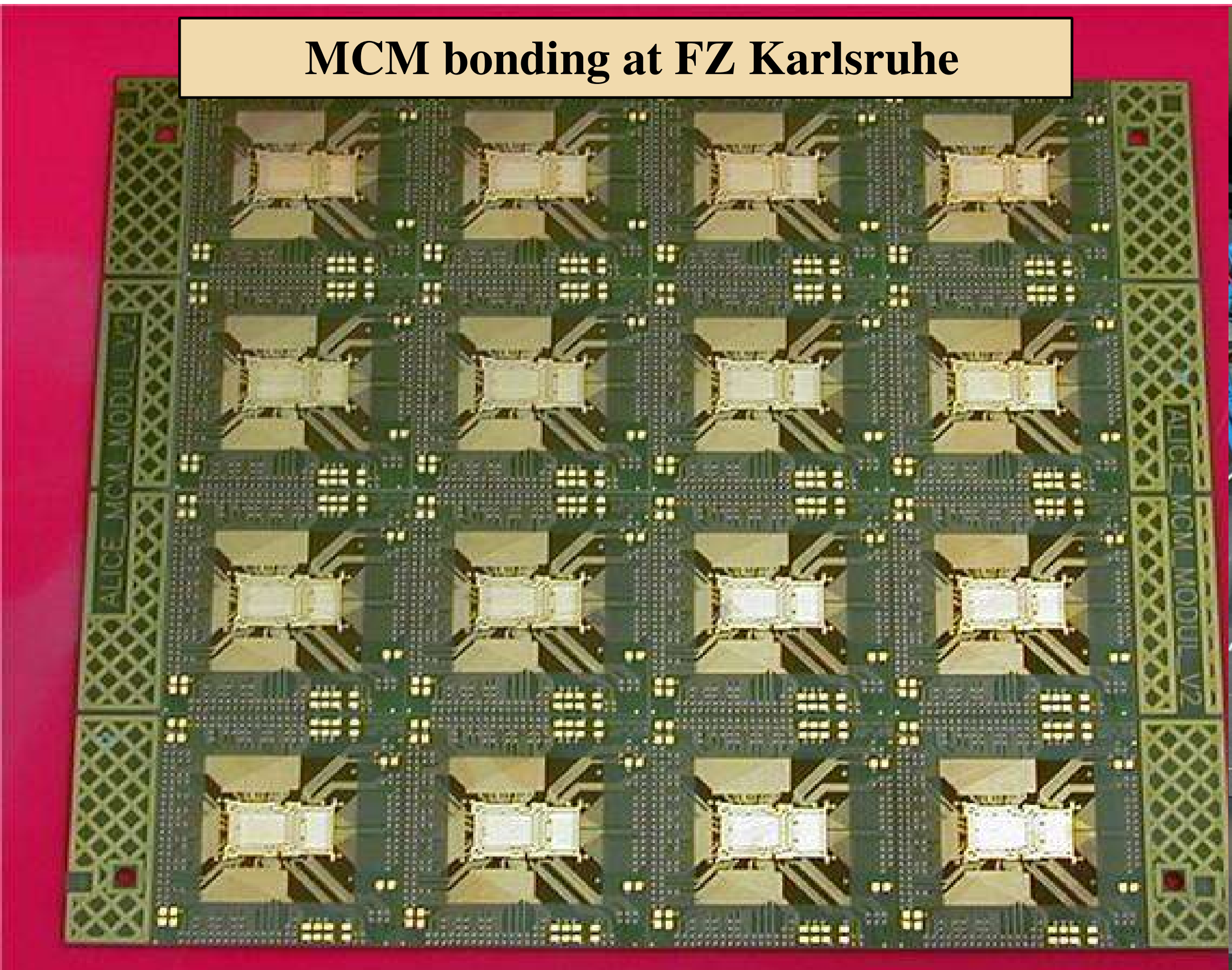


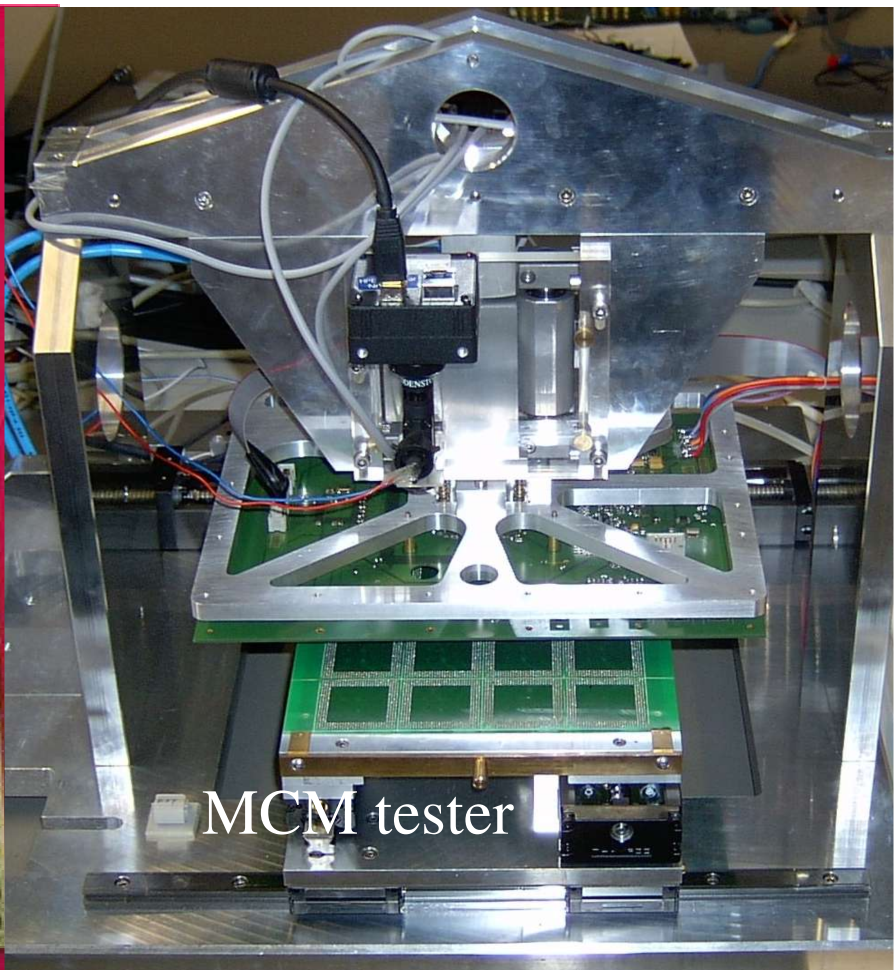
TRD FEE: 2 custom chips on MCMs

PASA and TRAP – developped at PI and KIP in Heidelberg
chips bonded on multi-chip modules

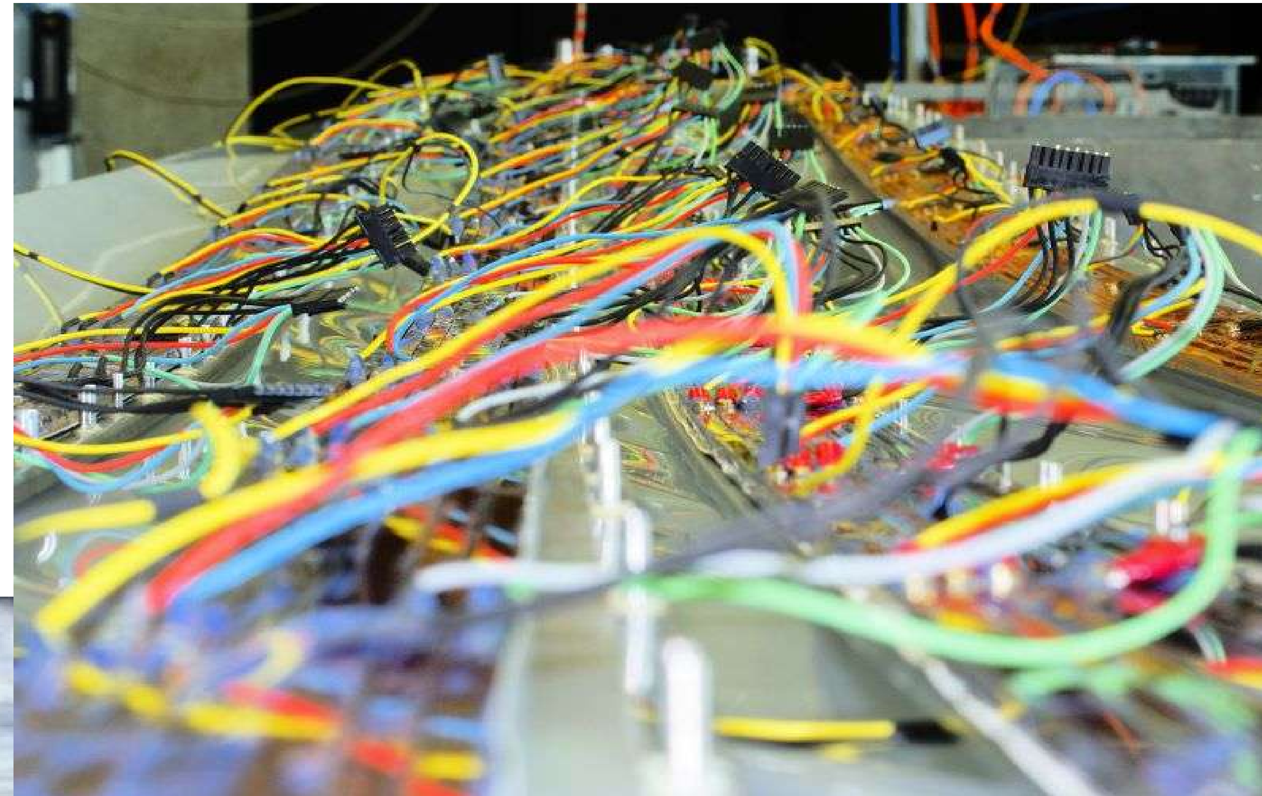


TRAP PASA



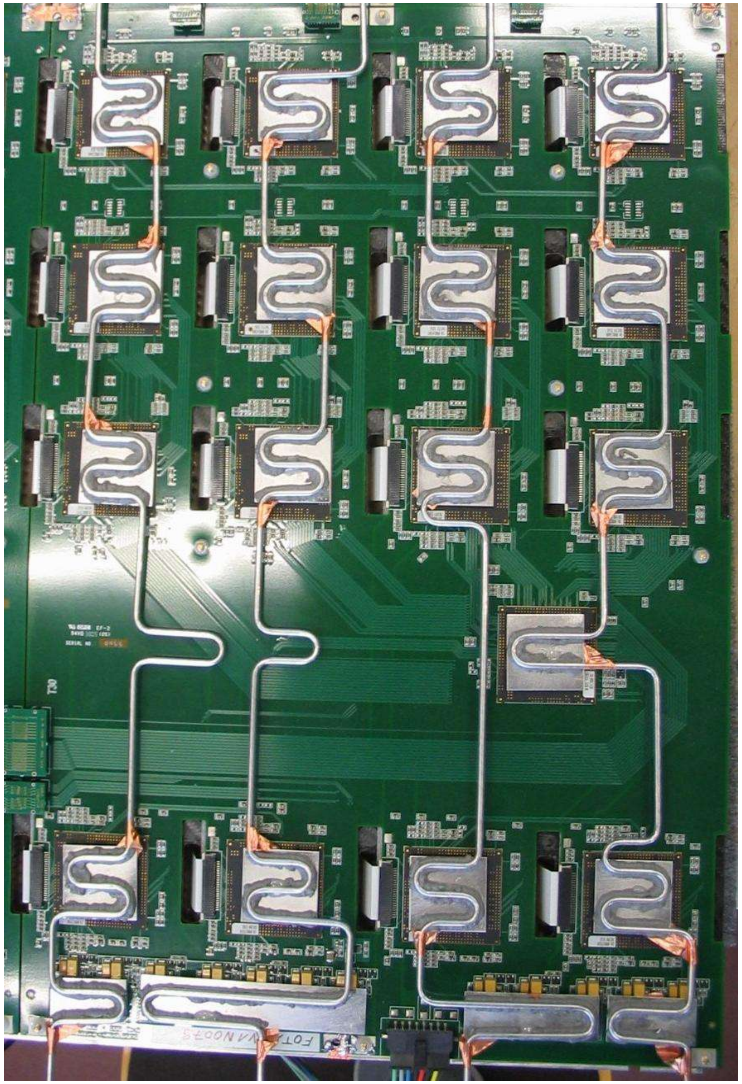


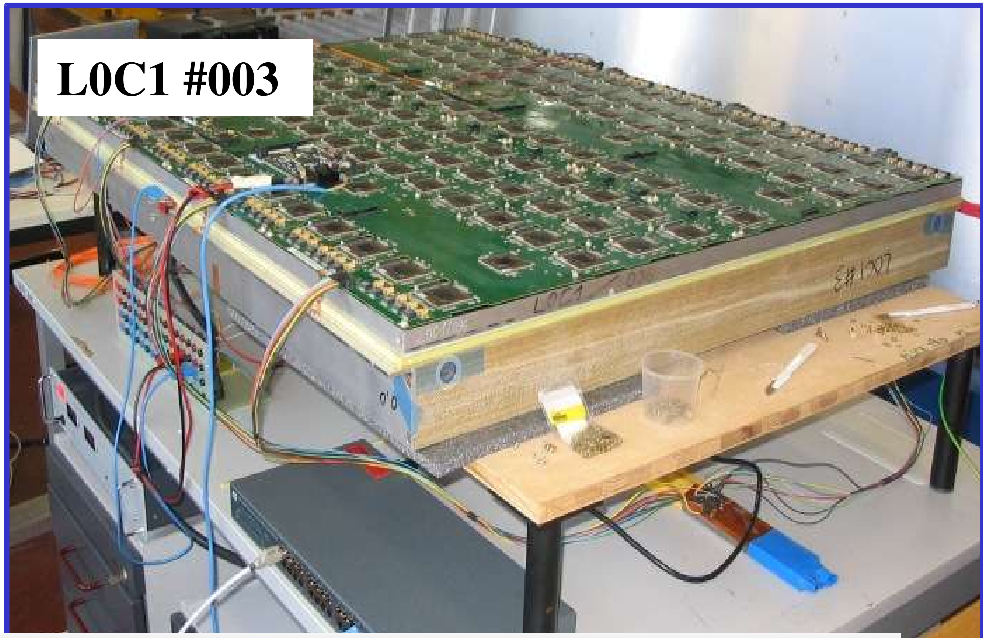
Finally chambers are equipped with electronics - lots of connections - power, water, optical, ethernet (TRD control is 540 node Linux cluster)

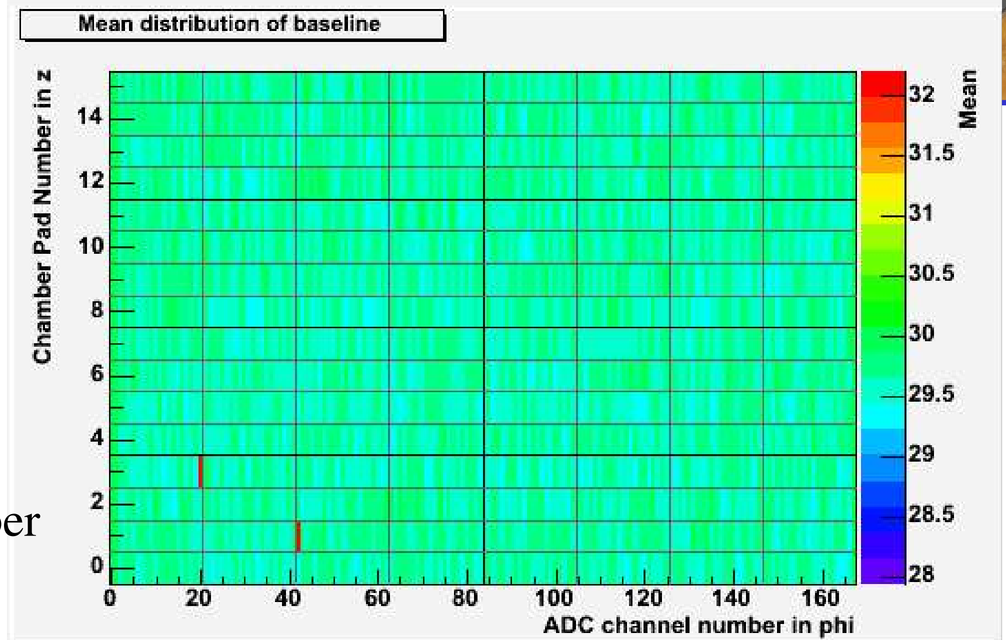


TRD Electronics Integration on Chambers & Noise

Ch. Lippmann, B. Doenigus GSI; K. Oyama, M.J. Kweon. HD

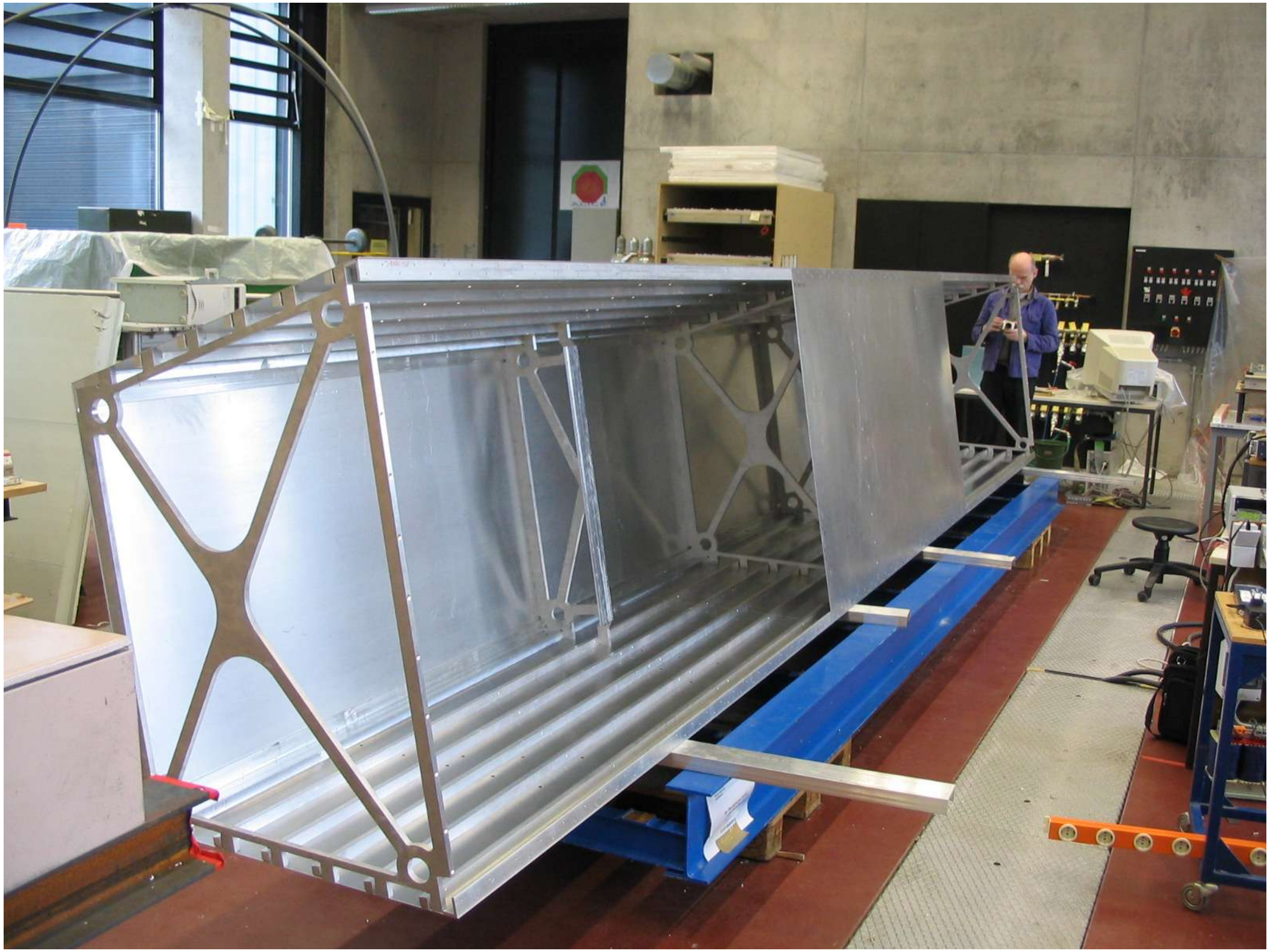






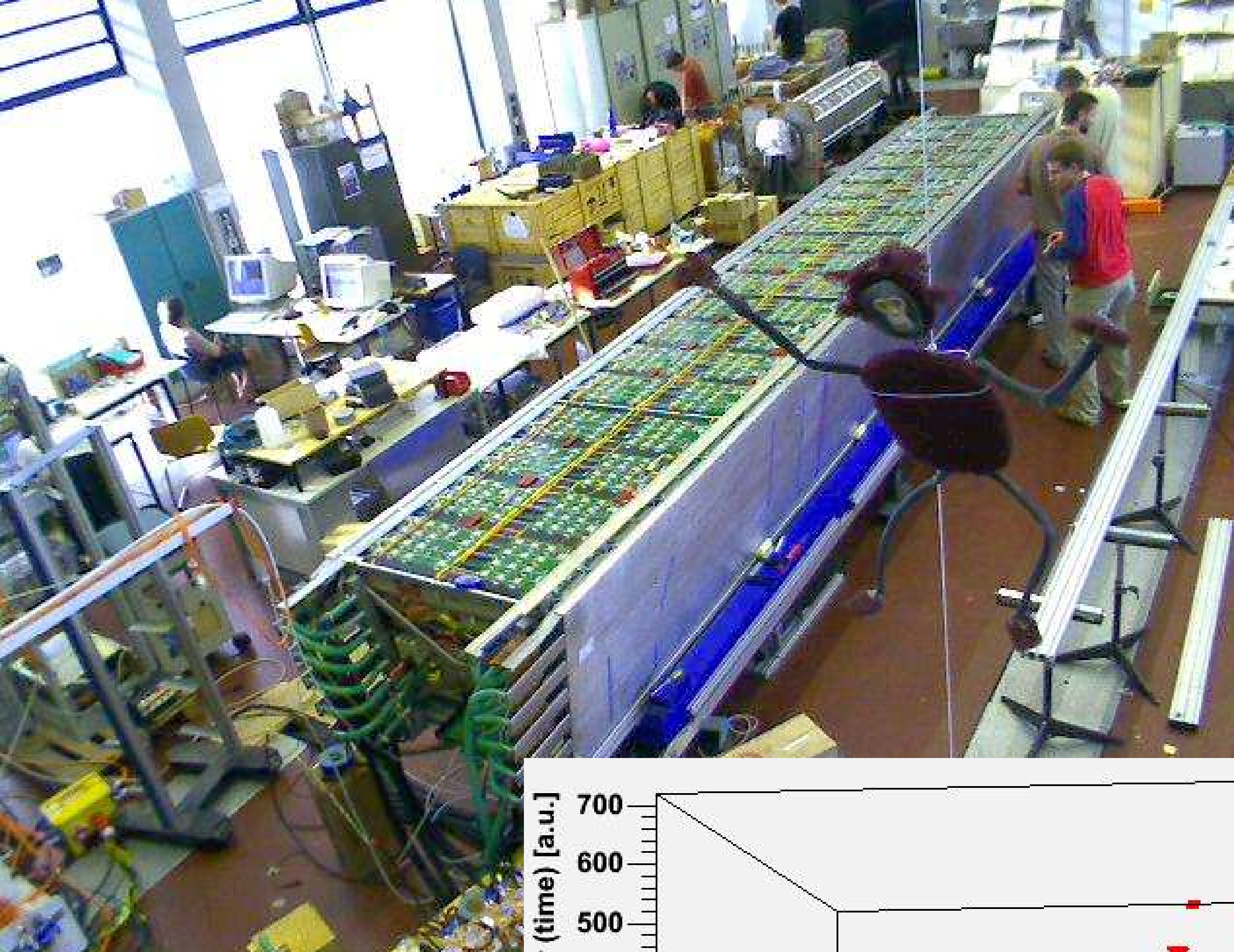
- Noise measurement for fully integrated chamber
  <RMS>= 1.07 LSB~1070 e

TRD Supermodule Full Length Assembly



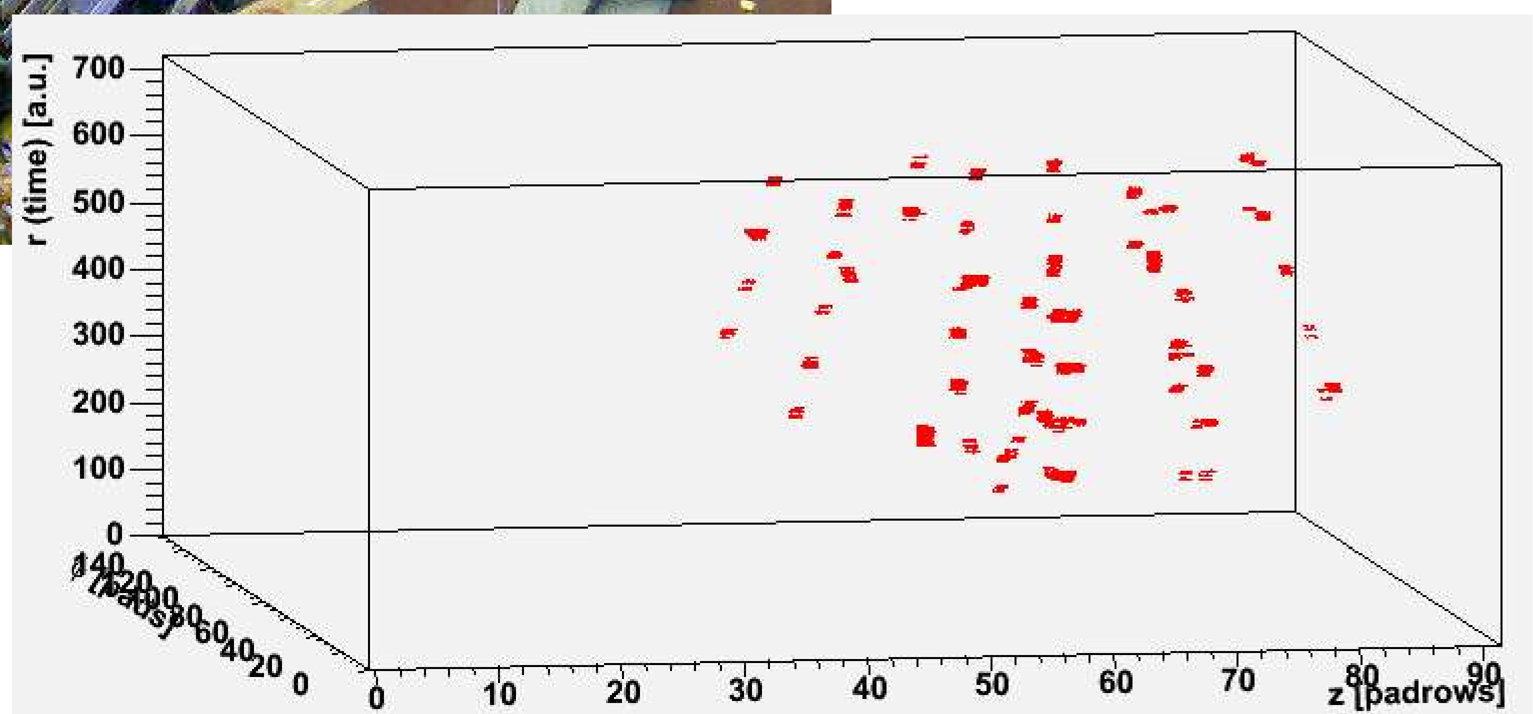
TRD SuperModule Assembly

first layer of completely equipped chambers



First TRD SM completed in Hd on Sept. 22, 2006 arrives at CERN today!

first cosmic ray event



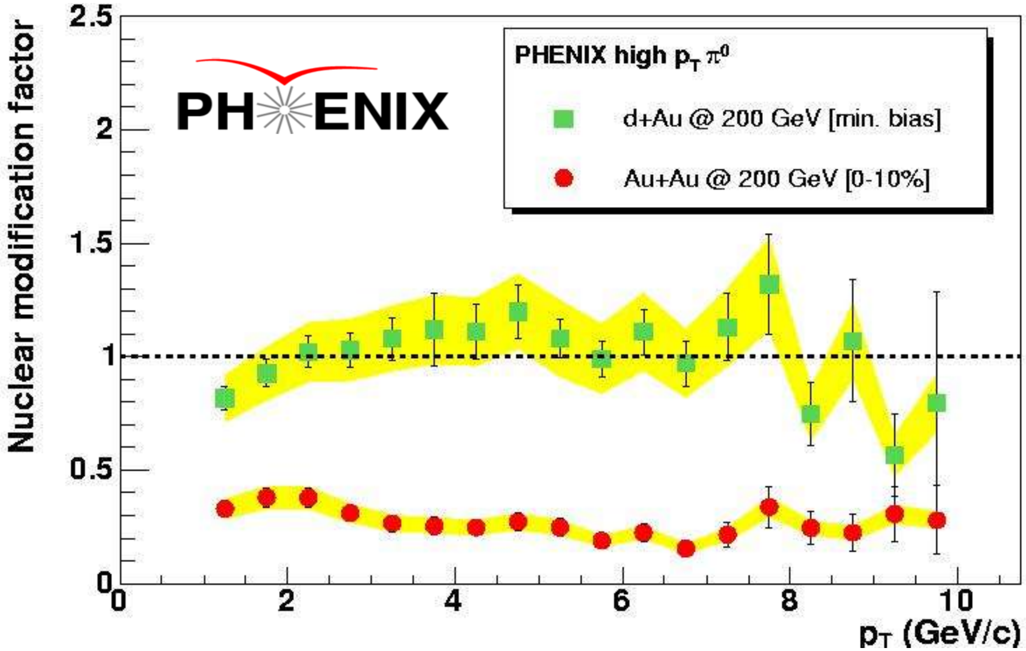
Summary

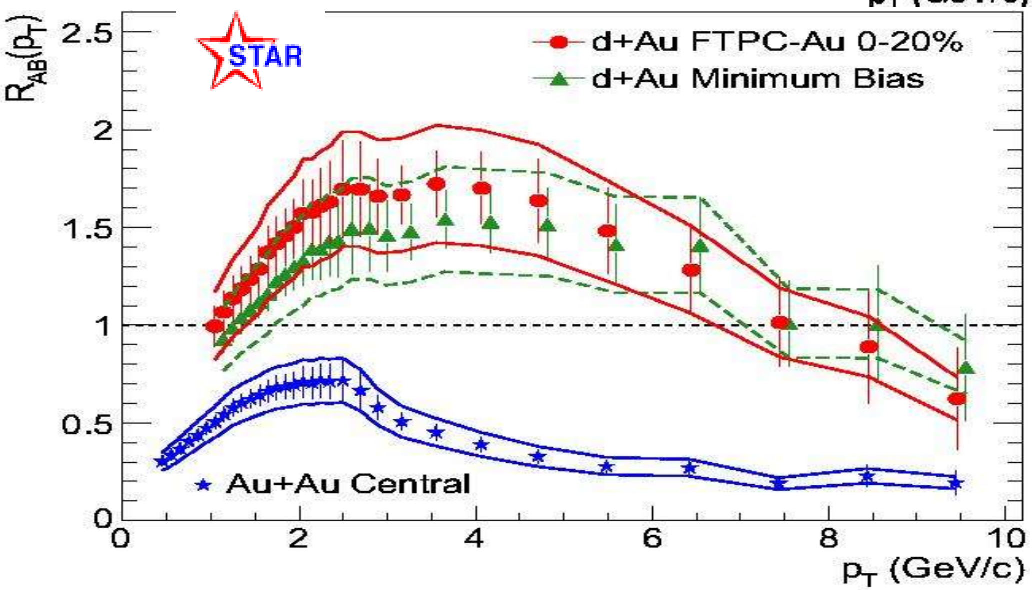
- there are exciting times ahead
- ALICE is dedicated experiment to study all aspects of heavy ion collisions at LHC
- many new aspects of pp collisions as well
- detector is coming together after more than 10 years of hard work and many novel developments

- physics starts with end of 2007

Backup slides

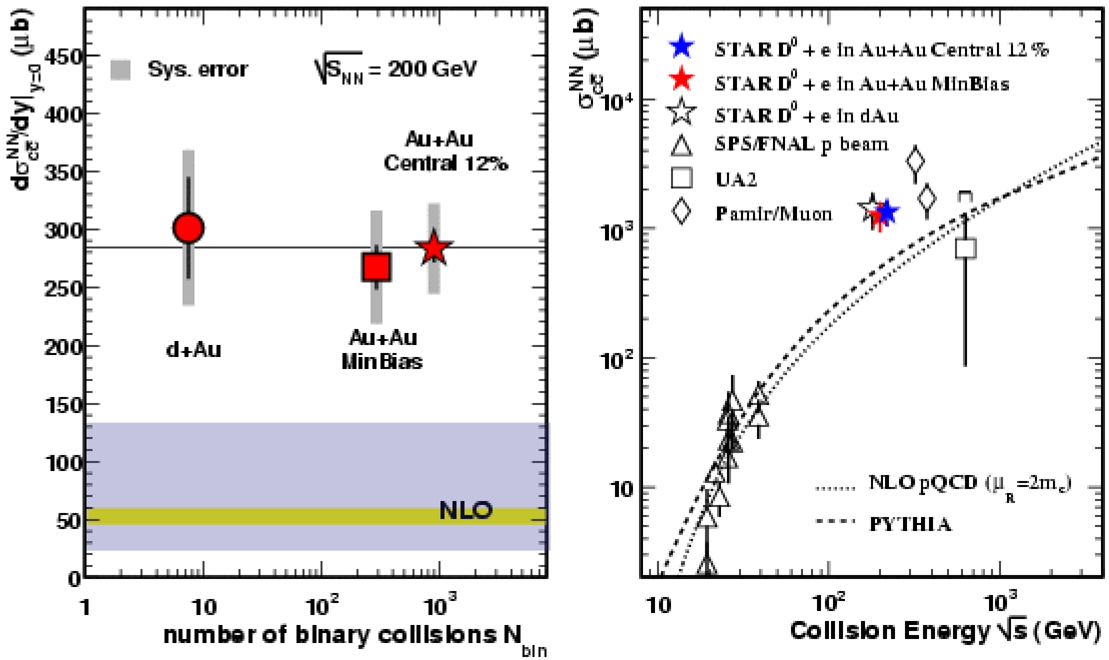
jet production in deuteron - Au collisions





not suppressed but rather enhanced due to initial parton scattering (Cronin effect)

Charm total cross section



∀σ=1.4±0.2±0.4 mb in minimum bias d+Au collisions at $\sqrt{s_{NN}}$=200 GeV

∀σ=1.26±0.09±0.23 mb in minimum bias Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

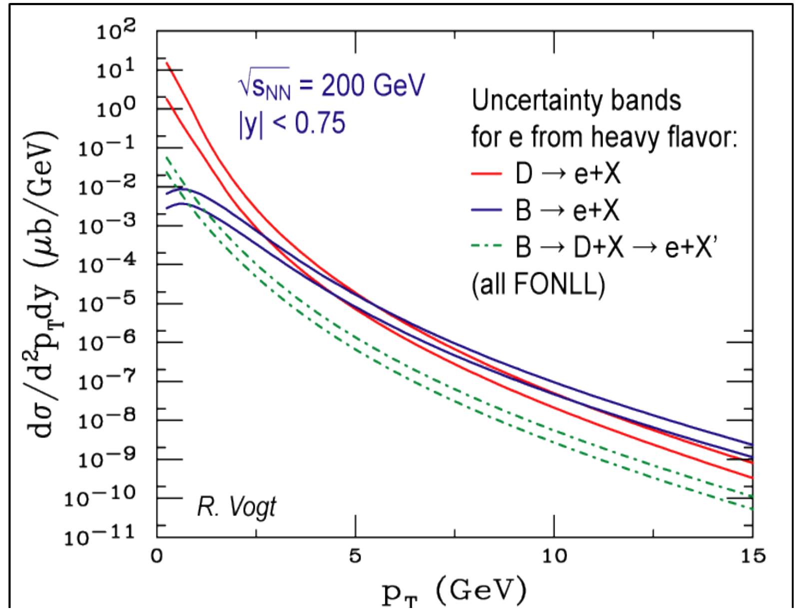
∀σ=1.33±0.06±0.18 mb in 0-12% Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

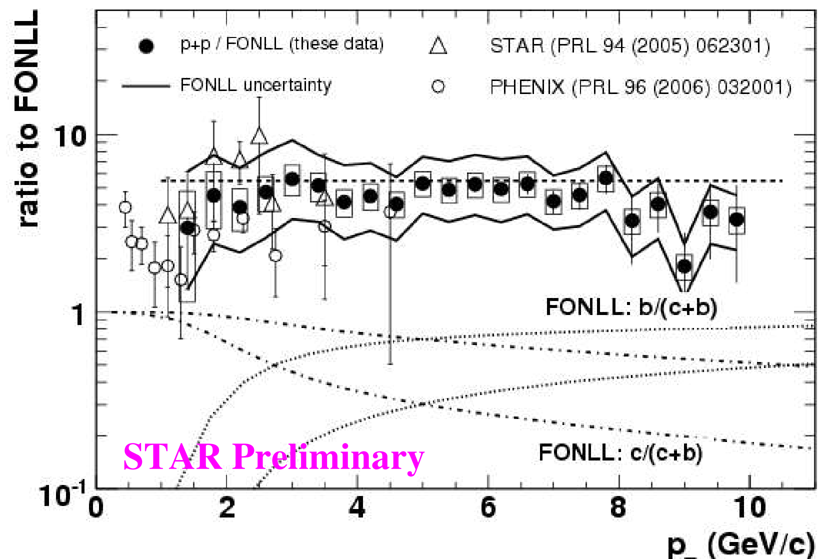
- Charm total cross section obeys N_{bin} scaling from d+Au to Au+Au within error
- Supports conjecture that charm is exclusively produced in initial scattering
- However, the total charm cross section is ~5× larger than NLO (and FONLL) p

talk P. Djawotho, STAR, Hard Probes 2006 conference

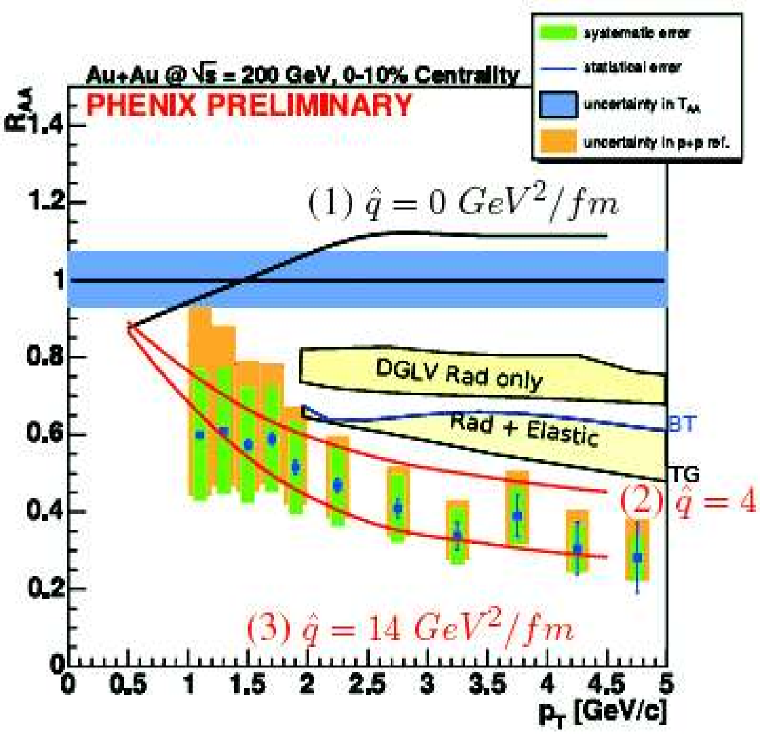
pQCD calculations for p+p *vs.* data

- All suppression predictions use the most recent pQCD calculations as starting point (p+p reference).
- Where does bottom start to dominate?
  - Relative contribution of charm and bottom?
  - Large uncertainty in the crossing point
    - From ~3 to 10 GeV/c
- From shape: significant b contribution at high-p_T?





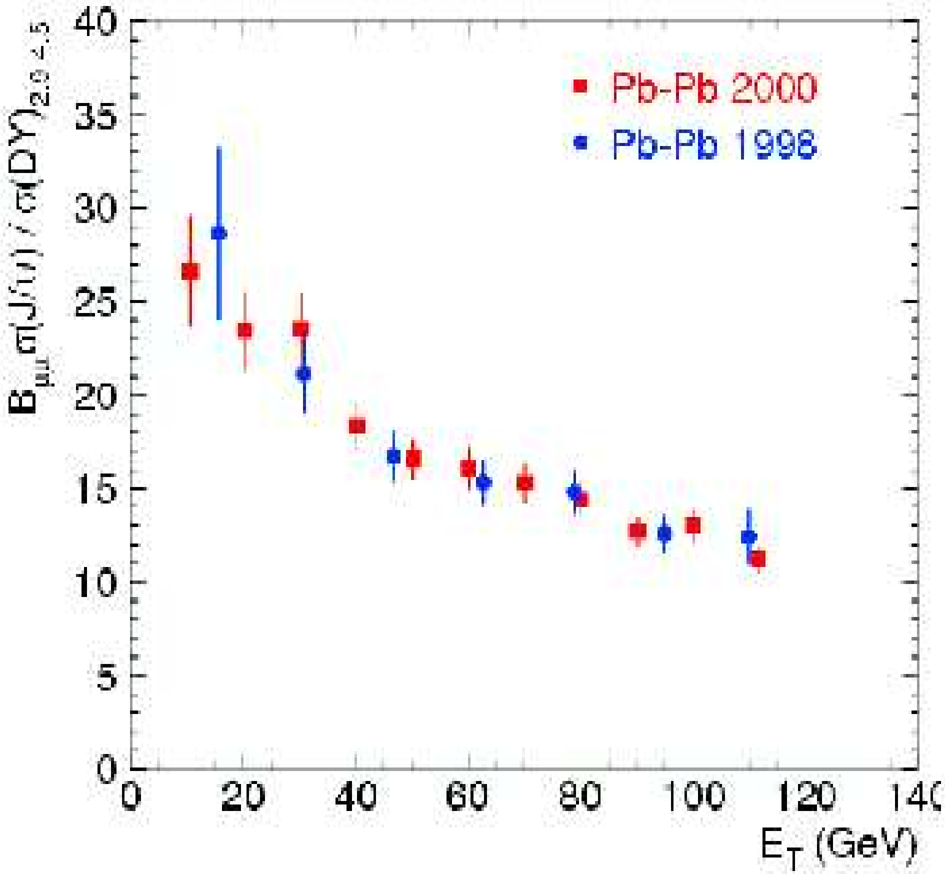
talk P. Djawotho, STAR, Hard Probes 2006 conference

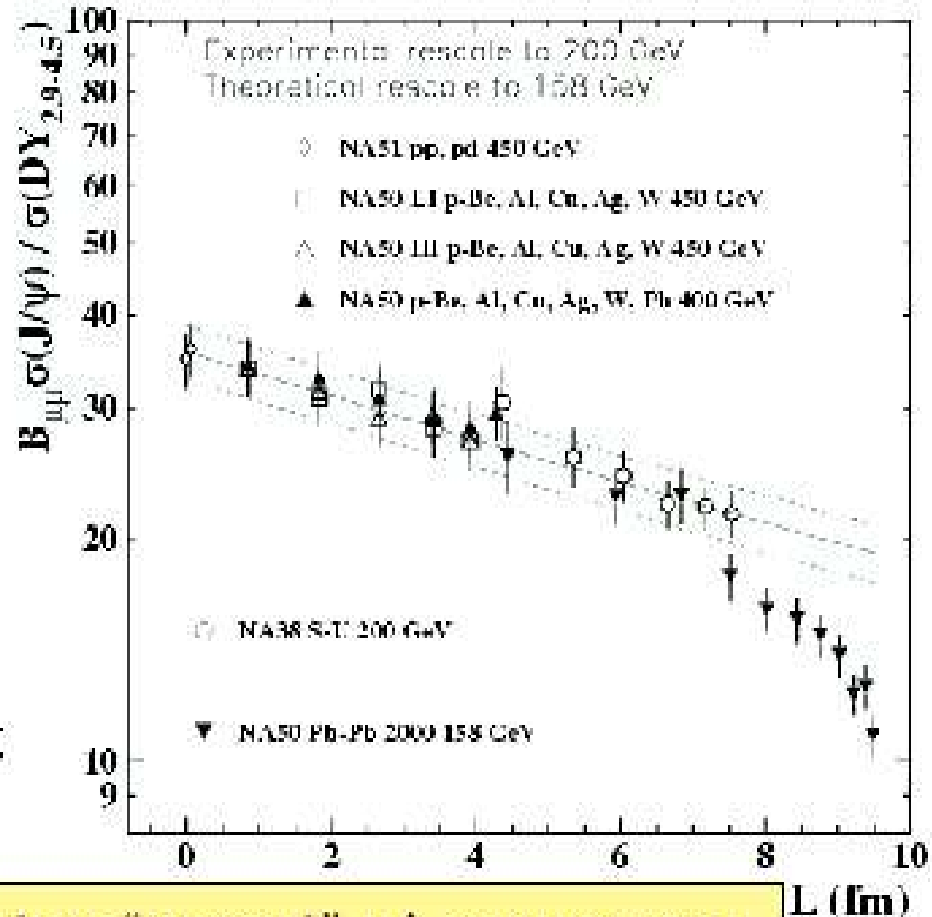


- (1) - (3): N Armesto, et al., PRD 71, 054027 only contains charm contribution
  - $\hat{q} \equiv$ transport coefficient $\propto$ density of scattering centers in medium
- yellow bands: S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy nucl-th/0512076

talk A. Dion, PHENIX, Hard Probes 2006 Conference

Suppression of J/ψ production in Pb + Pb as function of centrality





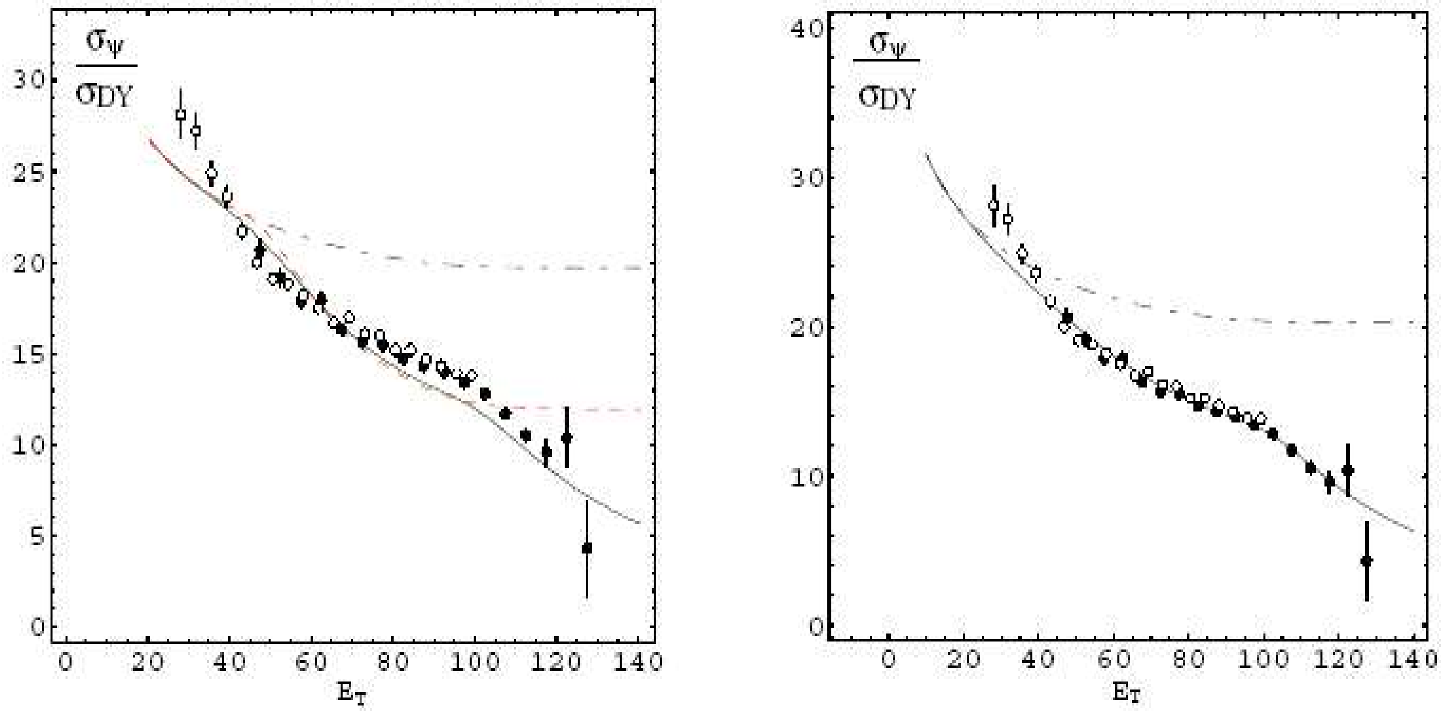
systematically central collision below "normal" pA suppression
consistent with QGP expectations

J/ψ Suppression in QGP

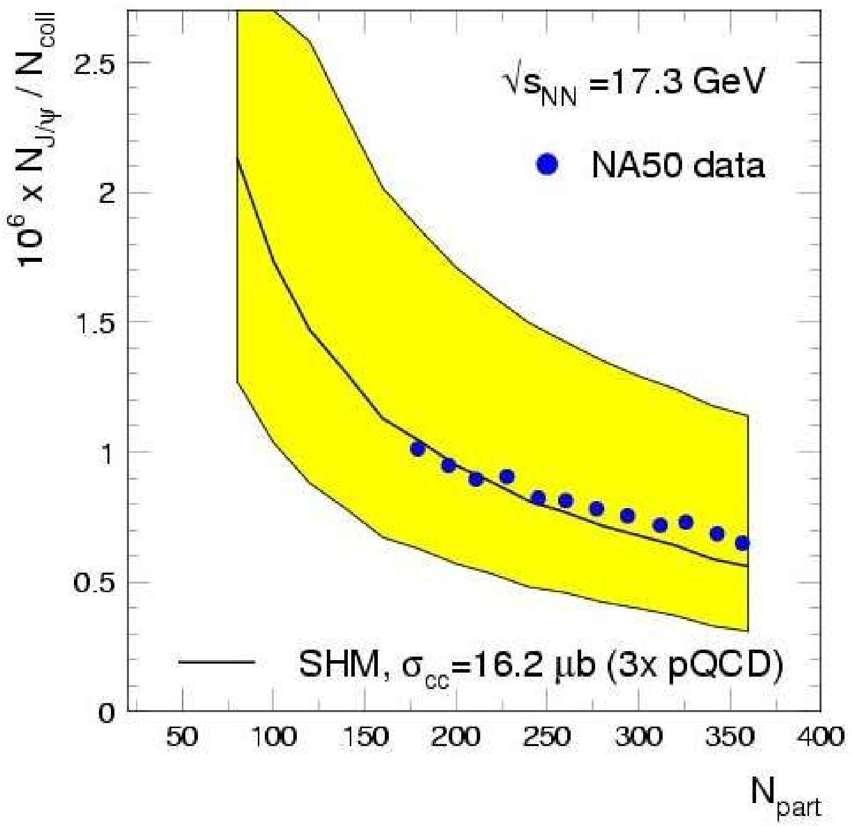
J.P. Blaizot, P.M. Dinh, J.Y. Ollitrault, Phys.Rev.Lett.85(2000)4012

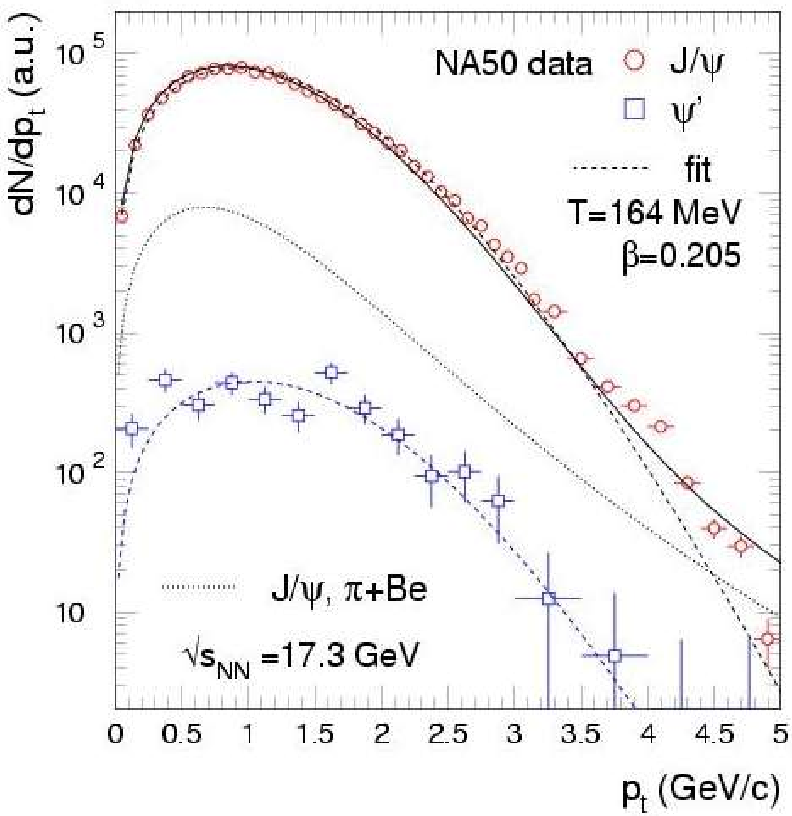
Dissolution in QGP at critical density n_c (dashes)
and with energy density fluctuations (solid)

n_c=3.7/fm^2 n_{c1}=3.3 and n_{c2}=4.2/fm^2



SPS J/ψ data and SHM

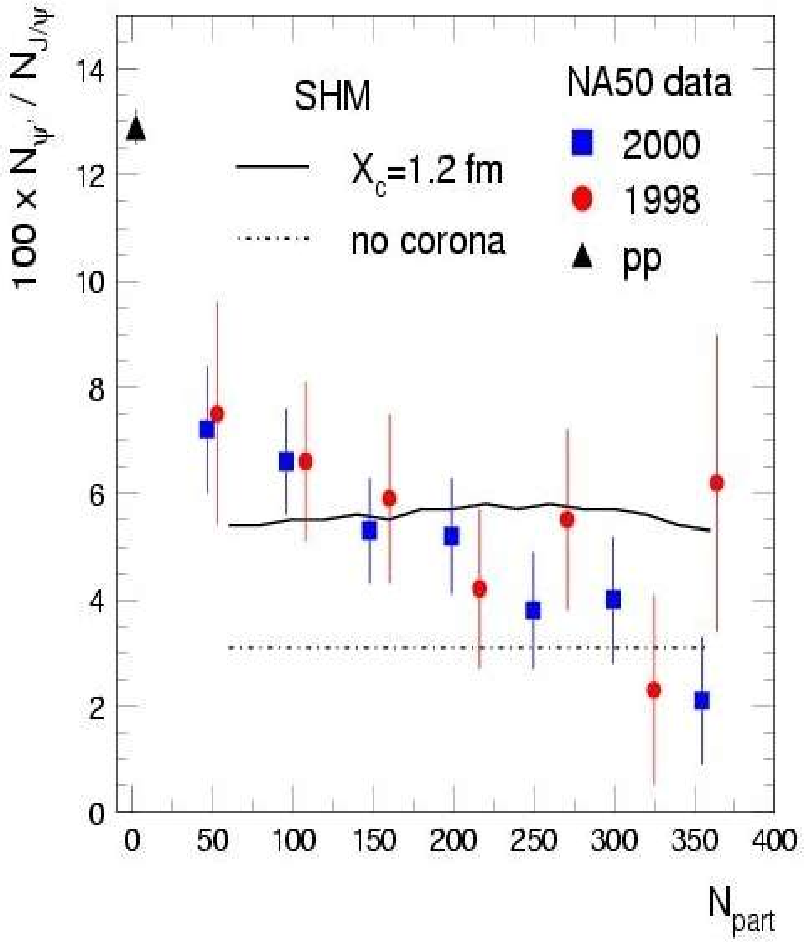




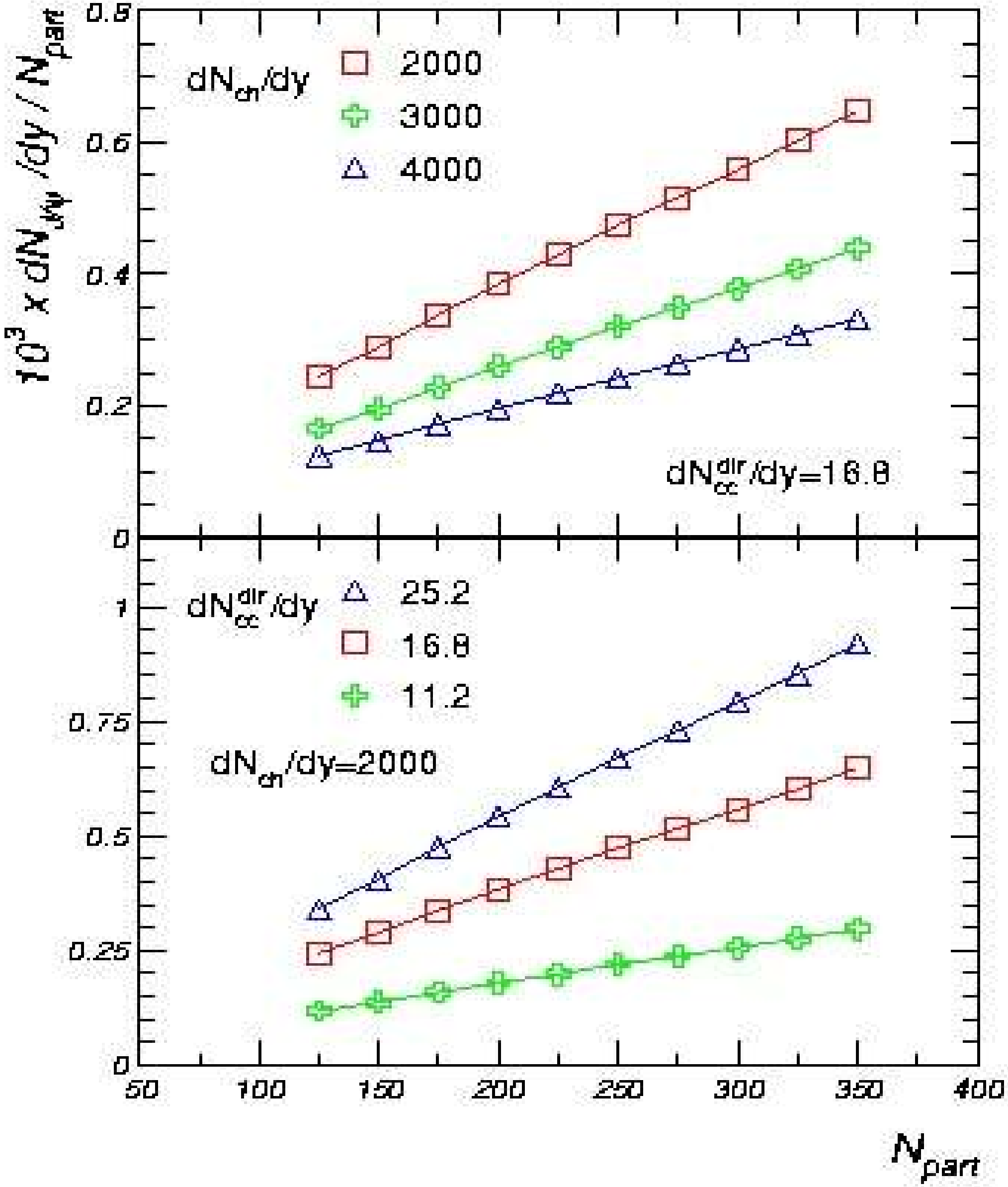
need open charm cross section

spectrum needs flow (in QGP)
T consistent with chem freeze-out

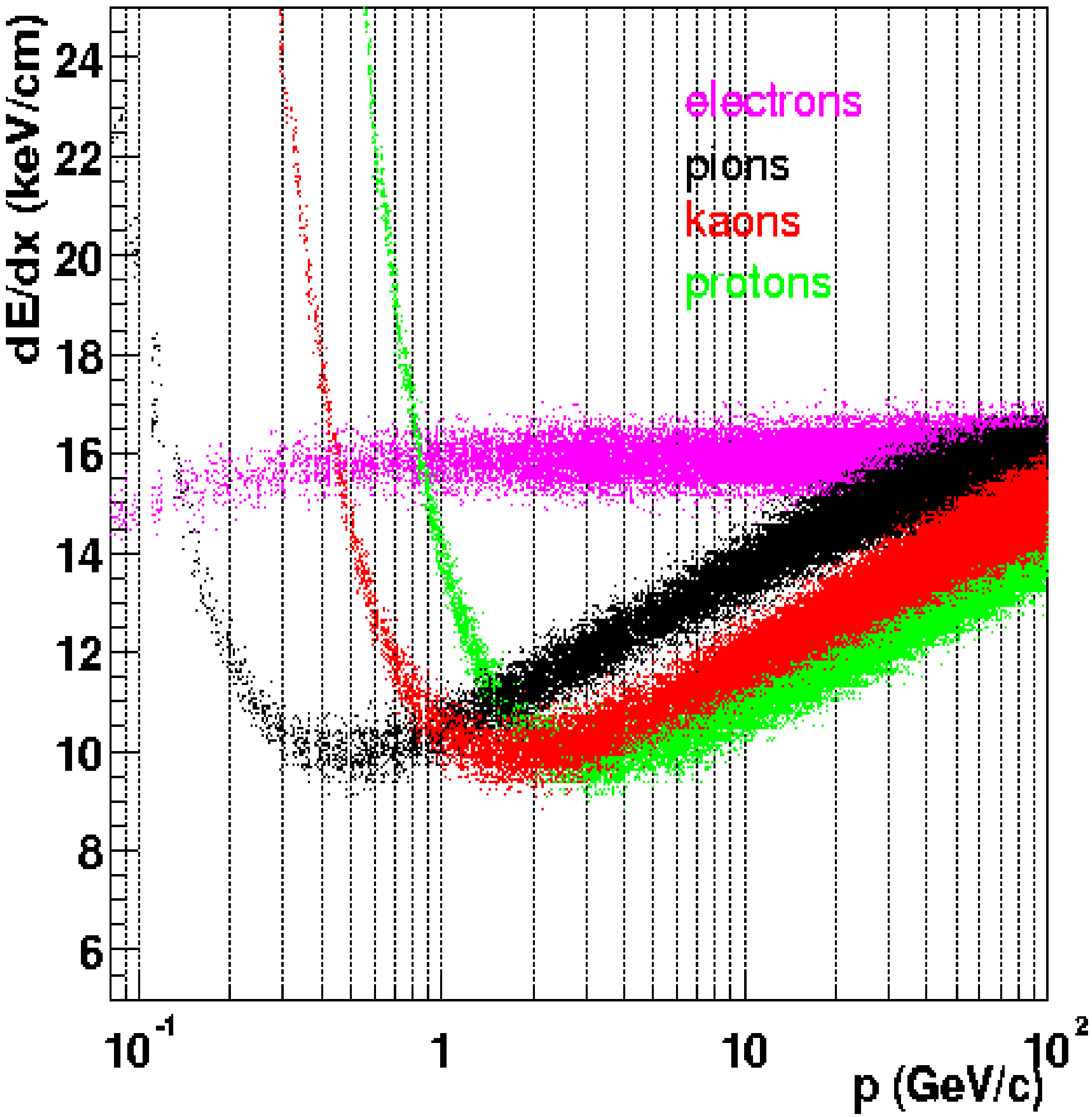
Ratio ψ' to J/ψ and SHM



N_{part} dependence at LHC - SHM prediction



Particle identification by dE/dx - ALICE TPC



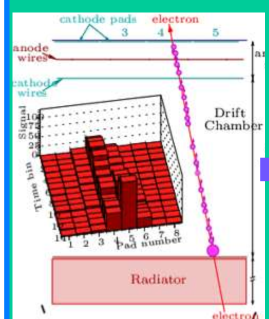
dE/dx resolution 6.9%

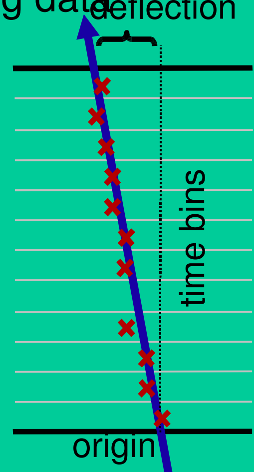
crossings: use TOF to resolve ambiguity

TRD Trigger – tracking on detector

Charge Cluster to Tracklet

- Local tracking units on detector perform linear fits and reject uninteresting data



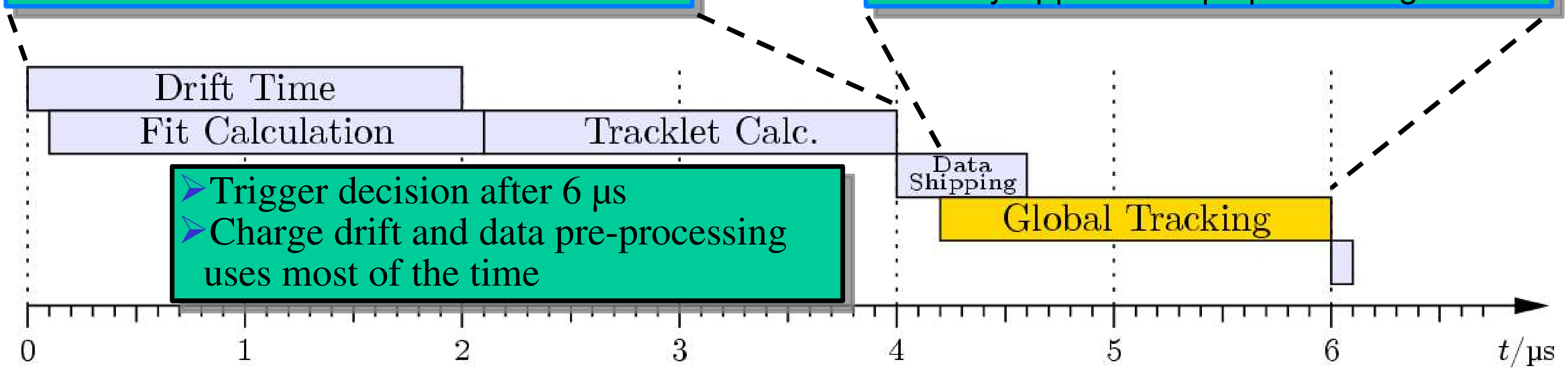


"**Tracklet**" (32-Bit word):

- *y* *position* (origin)
- *slope* (deflection)
- *z* *position* (pad-row number)

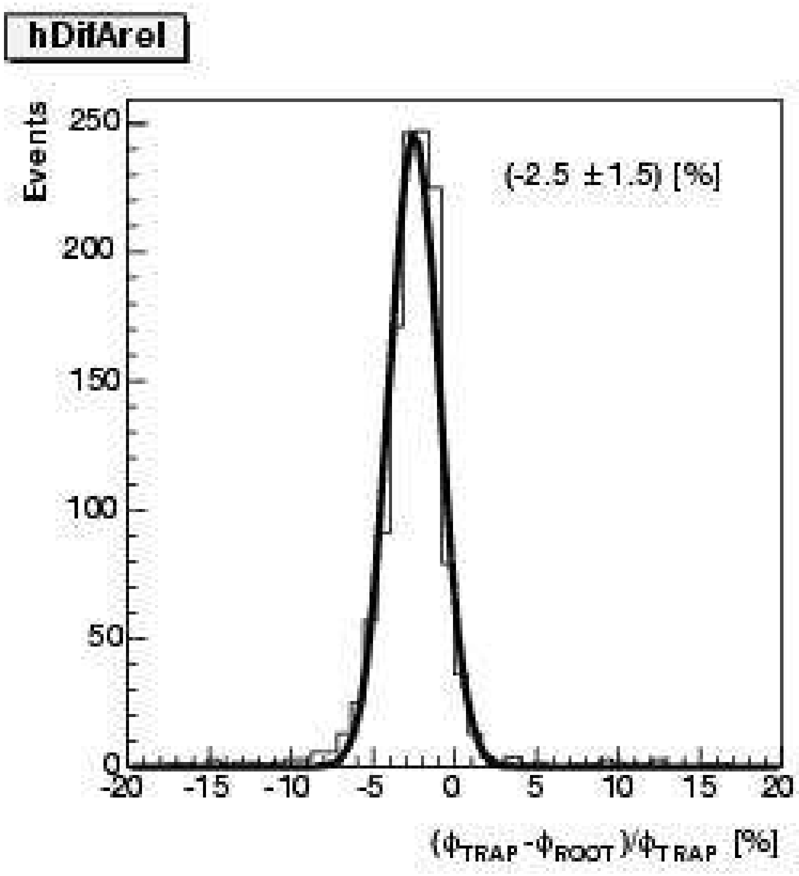
Global Tracking

- Inside GTU (Global Tracking Unit)
- Objective: find high momentum tracks
- Search for tracklets belonging together
- Combine tracklets from all six layers
- Reconstruct p_t, compare to threshold and generate trigger
- Constraint: only approx. 1.5 μs processing time



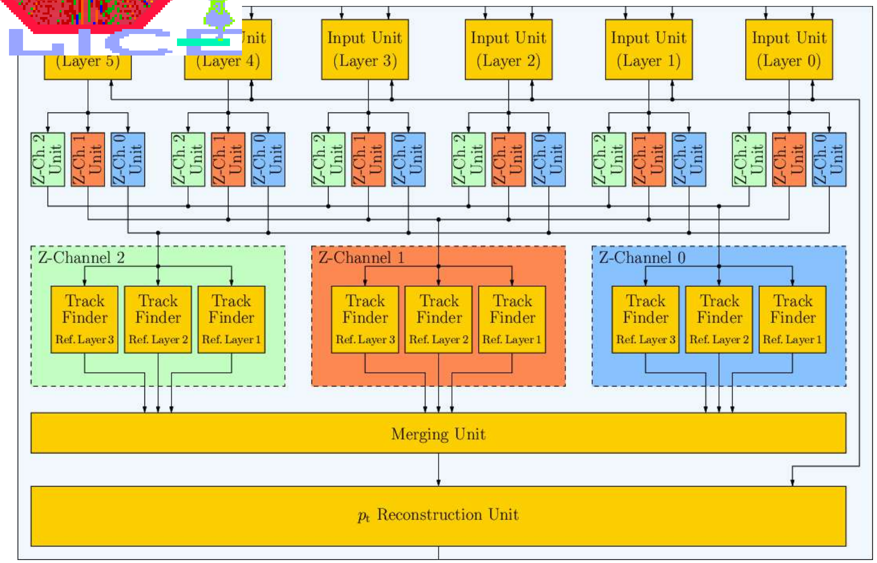
J. DeCuveland, HD

TRAP Performance

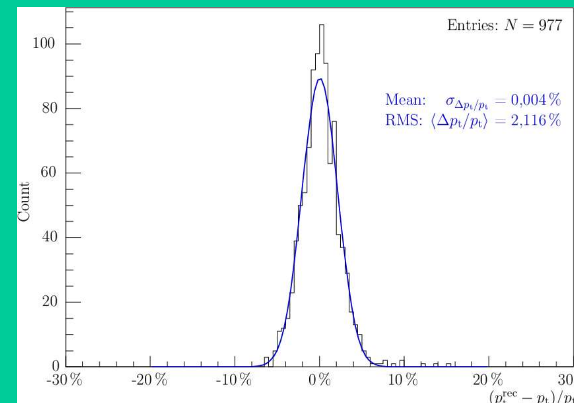


- performs angle reconstruction
- good agreement with offline tracking

TMU Design / Simulation



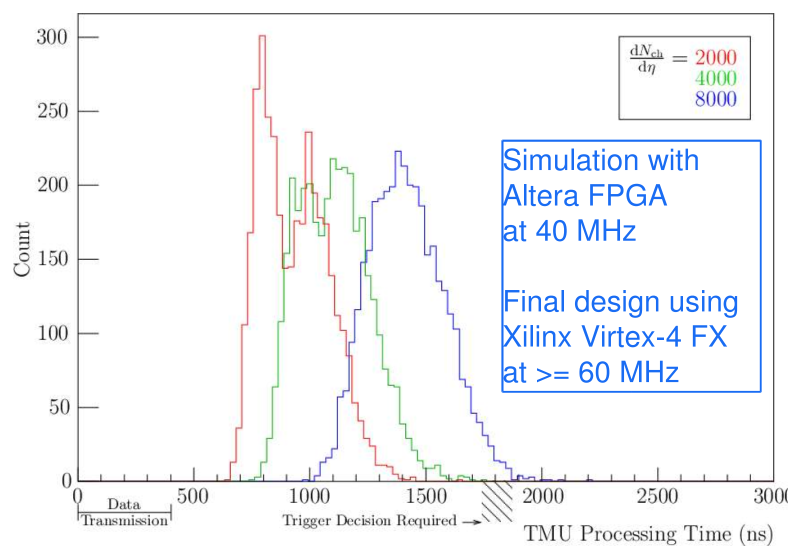
Reconstruction Precision



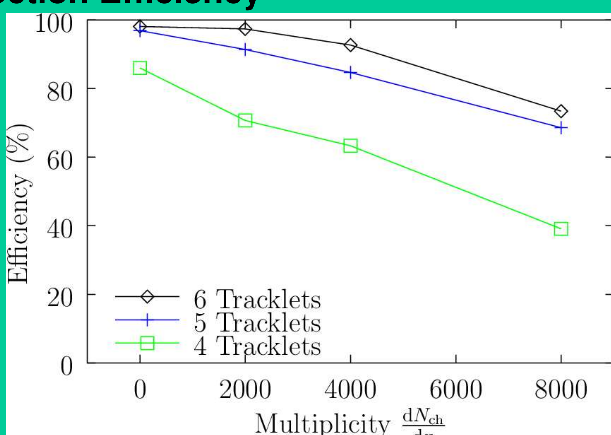
p_t reconstruction precision: 2.1 %

TMU Processing Time

Simulations with AliRoot data, electrons with $p_t > 3$ GeV/c



Detection Efficiency



Results depend on multiplicity density $dN_{ch}/d\eta$ and number of tracklets delivered by detector