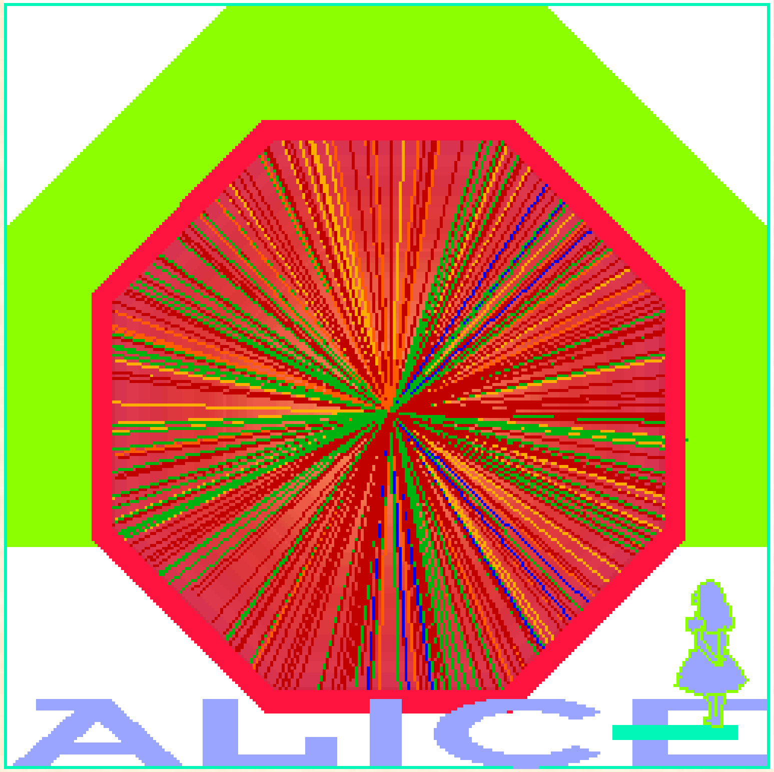
ALICE Experiment @ LHC

A Large Ion Collider Experiment
dedicated to heavy-ion collisions
however, running also pp program



- Physics motivation
- Experimental conditions
- Physics performance

WHY HEAVY IONS AT THE LHC?

... factor ~30 jump in $\sqrt{s}$ ...

J. Schukraft QM2001:
hotter - bigger -longer lived

$\varepsilon_{LHC} > \varepsilon_{RHIC} > \varepsilon_{SPS}$

$V_{f\,LHC} > V_{f\,RHIC} > V_{f\,SPS}$

$\tau_{LHC} > \tau_{RHIC} > \tau_{SPS}$

Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	850	2–8 $\times 10^3$
ε (GeV/fm^3)	2.5	4–5	15–40
V_f(fm^3)	10^3	7×10^3	2×10^4
τ_{QGP} (fm/c)	<1	1.5–4.0	4–10
τ_0 (fm/c)	~1	~0.5	<0.2

LHC Energy

For A-A collisions:

$$E_{cms} = 5500\ A\ \mathrm{GeV}$$

$$E_{lab} = E_{cms}^{\ 2} / (2A\ m_N) = 1.61 \times 10^7\ A\ \mathrm{GeV}$$

for lead ions $E_{lab\ Pb\text{-}Pb} = 3.35 \times 10^9\ \mathrm{GeV} = 3.35 \times 10^{12}\ \mathrm{MeV}$

Further we need **Harald Fritzsch Identity** (definition of Anglo-Saxon pound $£_{AS}$)

$$2 \times 10^{-30}\ £_{AS} = m_e \qquad (= 0.511\ \mathrm{MeV})$$

and some other definitions (gravitational acceleration g,

$$g = 1\ \mathrm{in/tr}^2 \qquad (1\ \mathrm{s} = 19.65\ \mathrm{tr,\ trice})$$

(speed of light c) $\quad c = 6 \times 10^8\ \mathrm{in/tr}$

$$m_e c^2 = 72 \times 10^{-14}\ £_{AS}\ \mathrm{in} \qquad (= 0.511\ \mathrm{MeV})$$

$$1\ \mathrm{MeV} = 1.41 \times 10^{-12}\ £_{AS}\ \mathrm{in}$$

Finally

$$E_{lab\ Pb\text{-}Pb} = 1\ £_{AS} \times 4.7'' \ (= 0.45\ \mathrm{kg} \times 12\ \mathrm{cm})$$

LHC Energy (cont.)

And for pp collisions:

$E_{\text{lab pp(14TeV)}} = 0.15\ £_{AS}$ in $\approx \frac{1}{4}\ £_{AS} \times \frac{1}{2}'' = \frac{1}{8}\ £_{AS} \times 1'' = \ldots$

For those who don't like to be seated on a lead ion (and to fly inside LHC vacuum pipe)

$E_{\text{cms Pb-Pb}} = 5500\ A\ \text{GeV} = 1.14 \times 10^{9}\ \text{MeV}$

(HFI, etc.)

$E_{\text{cms Pb-Pb}} = 10^{-3}\ £_{AS} \times 1.6''$ (= 0.45 g × 4 cm)

Still, macroscopic energy !!! (one can actually hear it)

But the size of ions

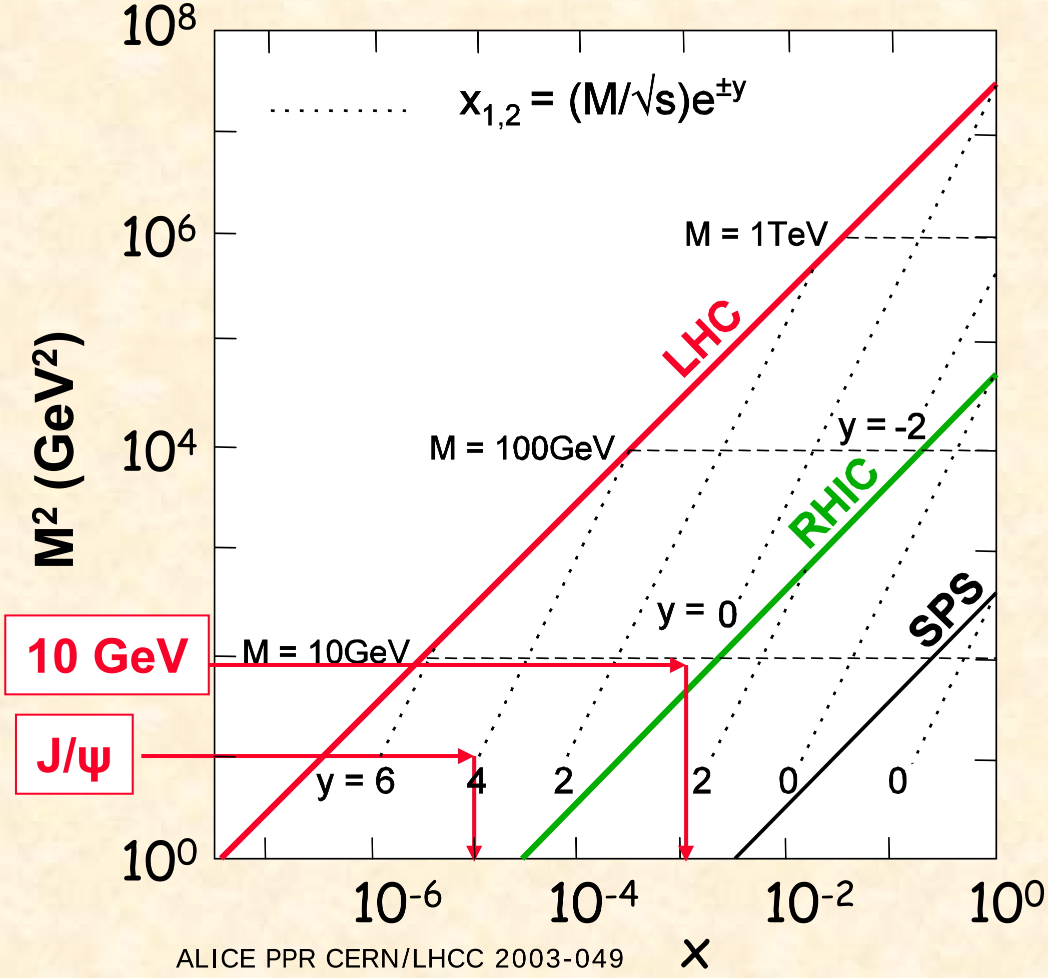
is by factor more than 10^{-12} smaller

Novel aspects

Qualitatively new regime

- **Probe initial partonic state in a novel Bjorken-x range**
  $(10^{-3} – 10^{-5})$:
  - ⇨ **nuclear shadowing,**
  - ⇨ **high-density saturated gluon distribution (CGC)**
  - ⇨ **effectively moves RHIC forward region to mid-rapidity at LHC**

- **Larger saturation scale $(Q_S=0.2A^{1/6}\sqrt{s}^{\delta}= 2.7\ \mathrm{GeV})$ particle production dominated by the saturation region**

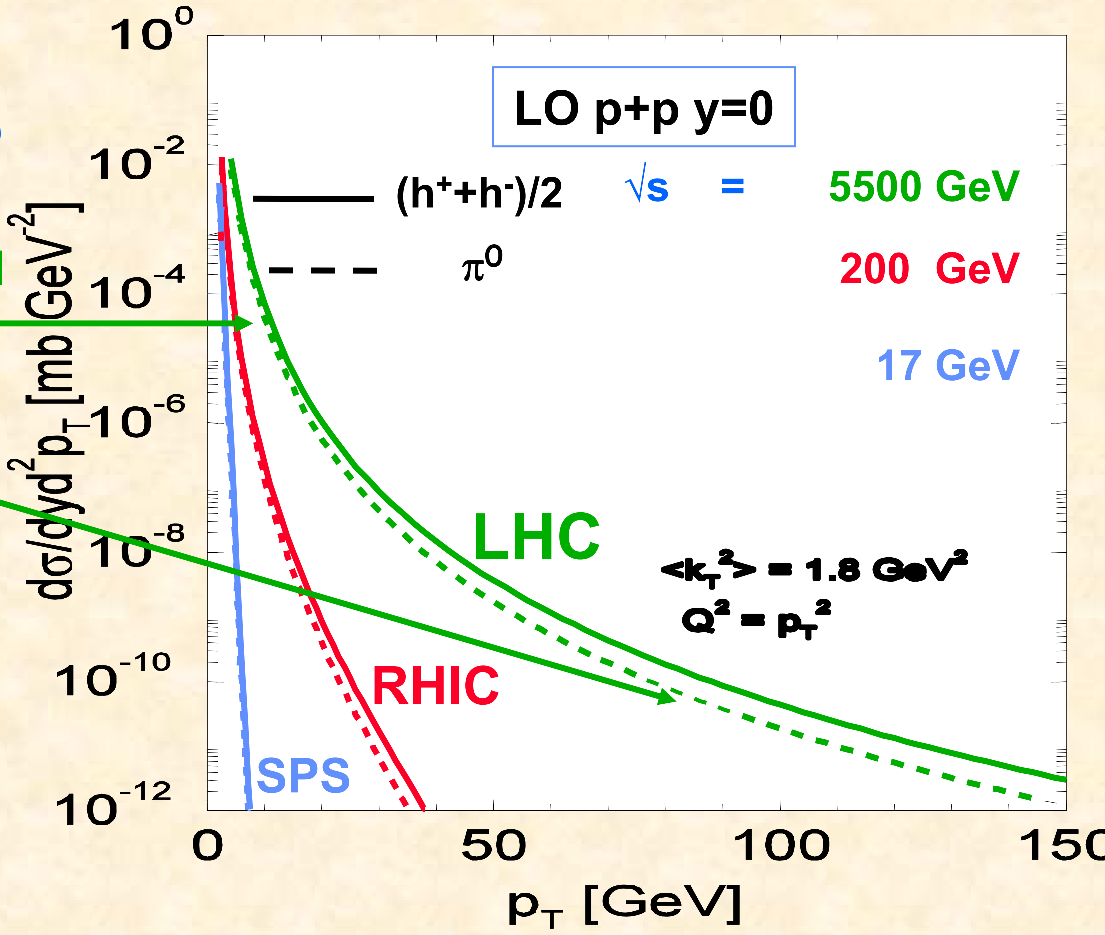


ALICE PPR CERN/LHCC 2003-049

Novel aspects

Qualitatively new regime

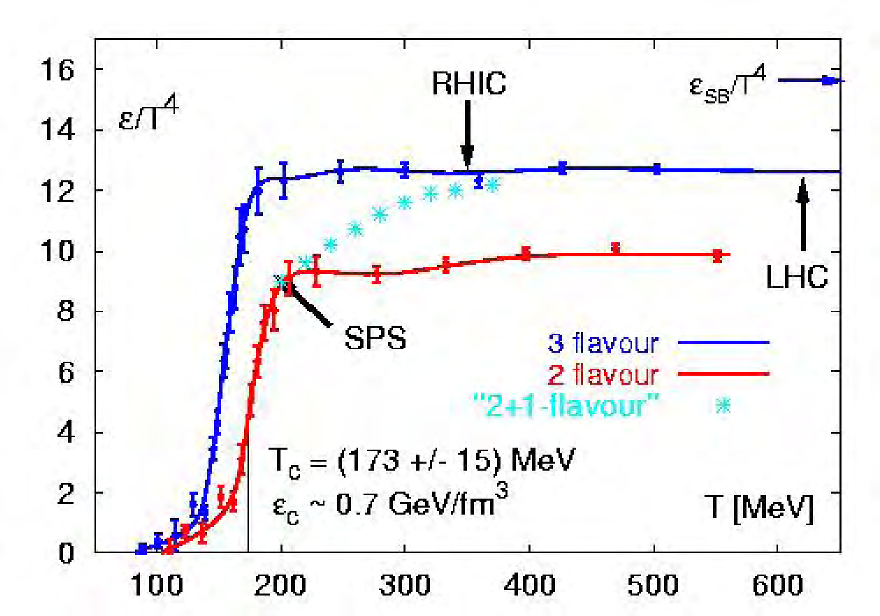
- Hard processes contribute significantly to the total AA cross-section ($\sigma^{hard}/\sigma^{tot}$ = 98%)
  - ⇨ Bulk properties dominated by hard processes
  - ⇨ Very hard probes are abundantly produced
- Weakly interacting probes become accessible (γ, Z^0, $W^\pm$)



Moreover

Qualitative improvements:

- Vanishing net baryon density (μ_B → 0):
  - closer to early Universe, closer to Lattice QCD



(F.Karsch)

- High energy density → maybe approaching the limit of an "ideal" gas of QCD quanta

- Stronger thermal radiation

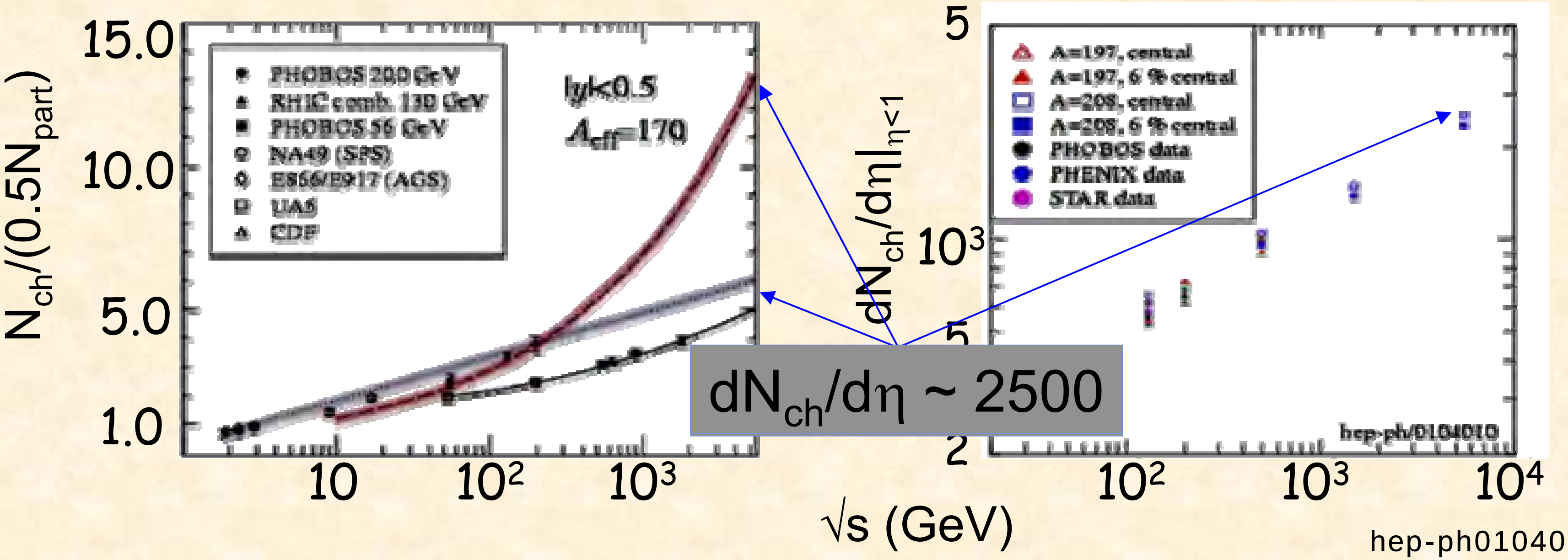
- Hard probes:
  - ✓Heavy flavours
  - ✓Jets and jet quenching

Dominant processes in particle production
SPS: soft
RHIC: soft and semi-hard
LHC: semi-hard and hard

What multiplicity do we expect?

old estimates: dN_{ch}/dy = 2000 – 8000, now we can extrapolate from RHIC data

(from K.Kajantie, K.Eskola)



$dN_{ch}/d\eta \sim 2500$

hep-ph0104010

- **ALICE optimized for dN_{ch}/dy = 4000, checked up to 8000 (reality factor 2)**

but ...

- The major uncertainties in the energy dependence are still there
  - ⇨ only some improvement with the RHIC data!

- Still no safe way to extrapolate
  - ⇨ shadowing/saturation (might decrease charged multiplicity)
  - ⇨ jet quenching (might increase it dramatically)
  - ⇨ A-scaling (importance soft vs. hard changes with energy)

- Simple scaling form RHIC (log–log plot) ~2500

- → safe guess $dN_{ch}/d\eta \sim 1500 - 6000$

Experimental conditions @ LHC

- pp commissioning starts after April 2007
- Agreed initial Heavy-Ion programme at LHC
  - **Initial few years** (1HI 'year' = 10^6 effective s, ~like at SPS)
    - 2 - 3 years Pb-Pb $\mathcal{L} \sim 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
    - 1 year p - Pb 'like' (p, d or α) $\mathcal{L} \sim 10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
    - 1 year light ions (eg Ar-Ar) $\mathcal{L} \sim$ few 10^{27} to $10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

      plus, for ALICE (limited by pileup in TPC):
    - reg. pp run at $\sqrt{s} = 14$ TeV $\mathcal{L} \sim 10^{29}$ and $< 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Later: different options depending on Physics results
- Heavy-ion running is part of LHC initial programme, first run expected by the end of 2008

ALICE Physics goals

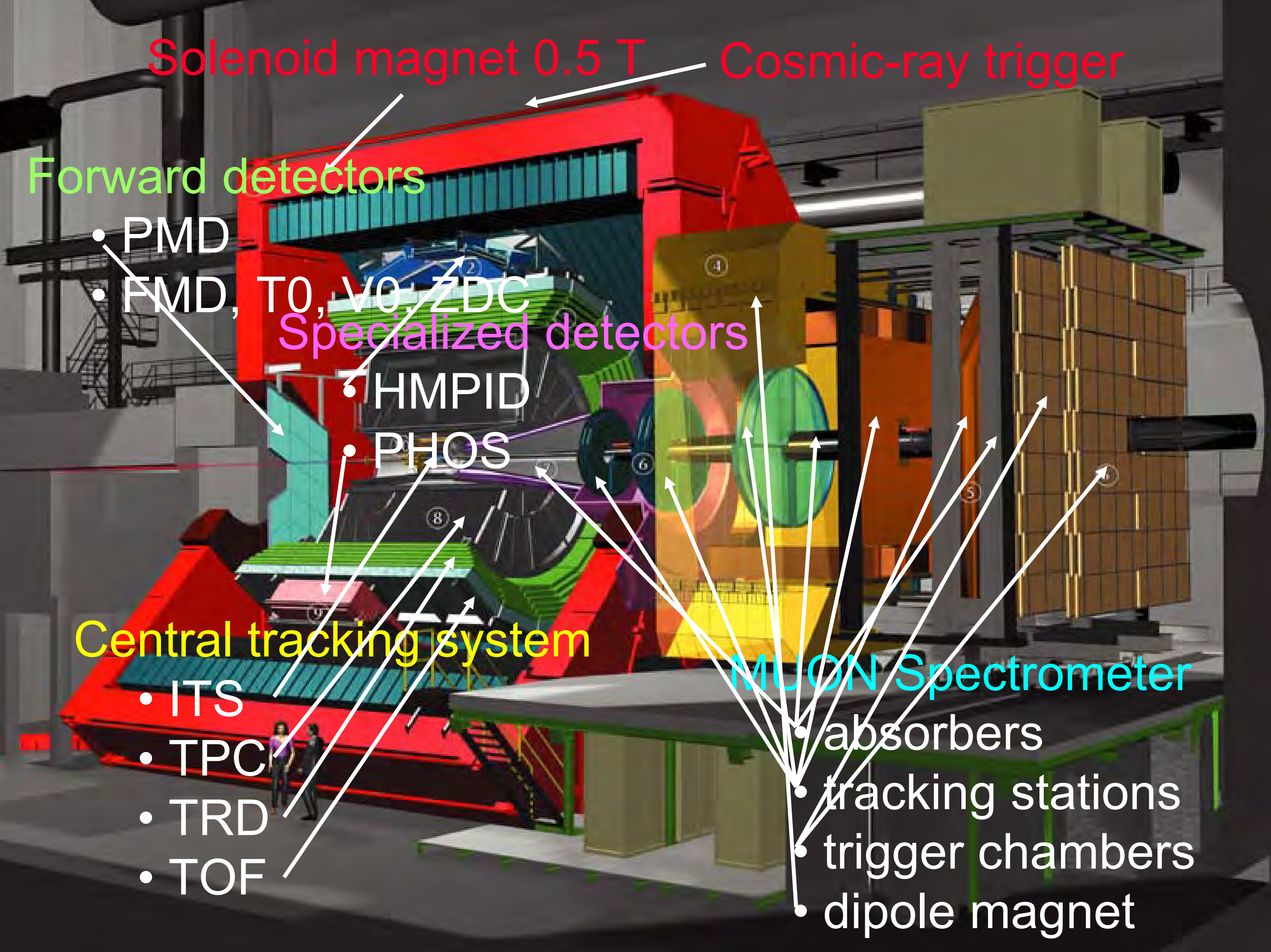
(has to cover in one experiment what at the SPS was covered by 6-7 experiments, and at RHIC by 4!!)

- **Global observables:**
  Multiplicities, η distributions
- **Degrees of freedom as a function of T:** hadron ratios and spectra, dilepton continuum, direct photons
- **Early state manifestation of collective effects:**
  elliptic flow
- **Energy loss of partons in quark gluon plasma:**
  jet quenching, high pt spectra, open charm and open beauty

- **Deconfinement:**
  charmonium and bottonium spectroscopy
- **Chiral symmetry restoration:**
  neutral to charged ratios, res. decays
- **Fluctuation phenomena - critical behavior:**
  event-by-event particle comp. and spectra
- **Geometry of the emitting source:**
  HBT, impact parameter via zero-degree energy flow
- **pp collisions in a new energy domain**

- ➢ Large acceptance
- ➢ Good tracking capabilities
- ➢ Selective triggering
- ➢ Excellent granularity
- ➢ Wide momentum coverage
- ➢ PID of hadrons and leptons
- ➢ Good secondary vertex reconstruction
- ➢ Photon Detection

Use a variety of experimental techniques!



Solenoid magnet 0.5 T

Cosmic-ray trigger

Forward detectors

- PMD
- FMD, T0, V0, ZDC

Specialized detectors

- HMPID
- PHOS

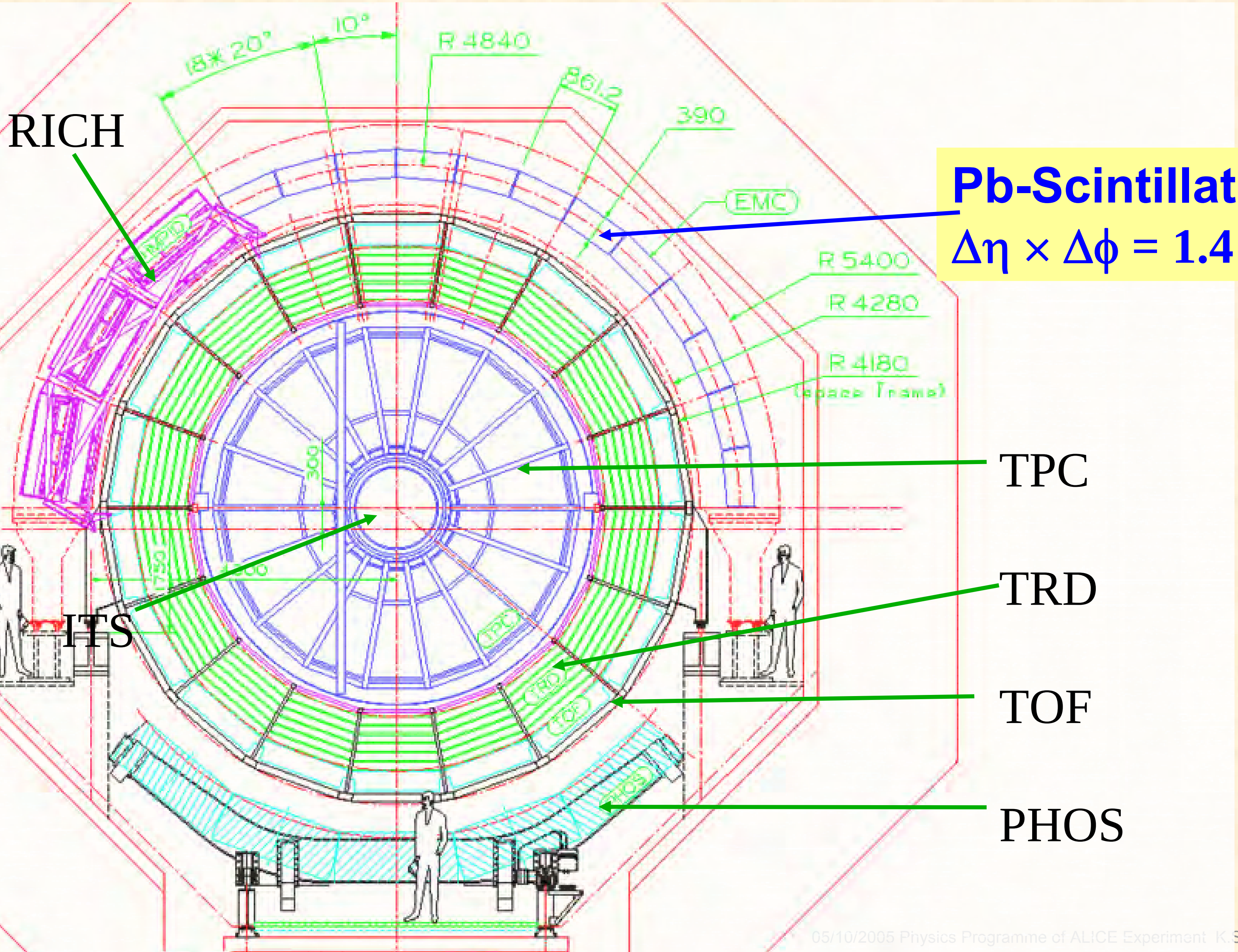
Central tracking system

- ITS
- TPC
- TRD
- TOF

MUON Spectrometer

- absorbers
- tracking stations
- trigger chambers
- dipole magnet

US EMCaL (under discussion)



Pb-Scintillator EMCal
$\Delta\eta \times \Delta\phi = 1.4 \times 120°$

RICH

ITS

TPC

TRD

TOF

PHOS

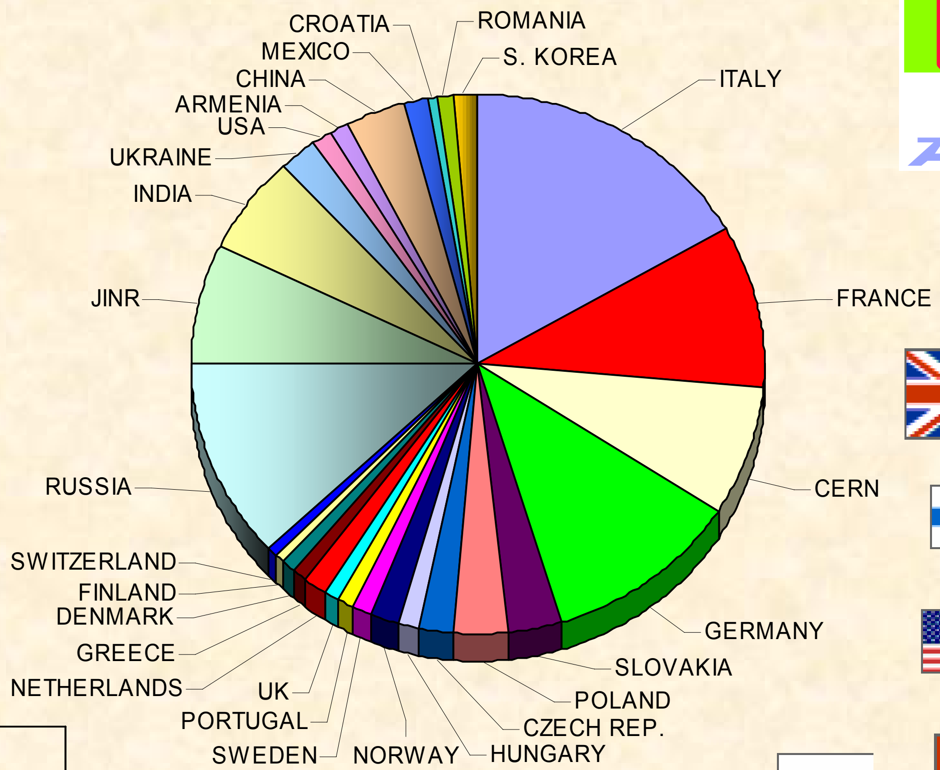
ALICE Collaboration

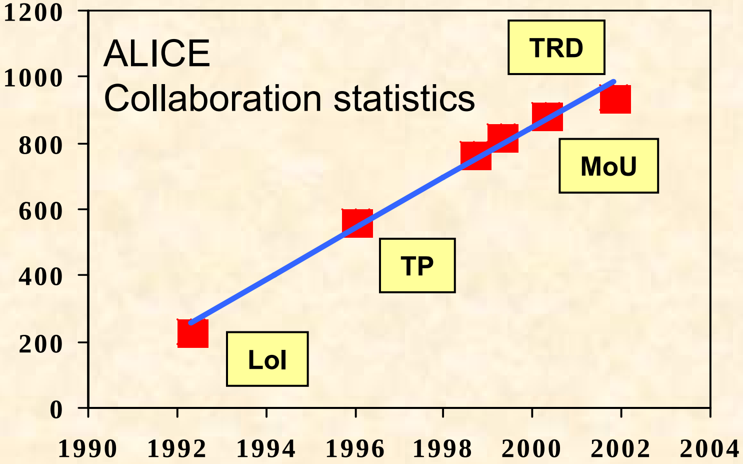
~ 1000 Members

(63% from CERN MS)

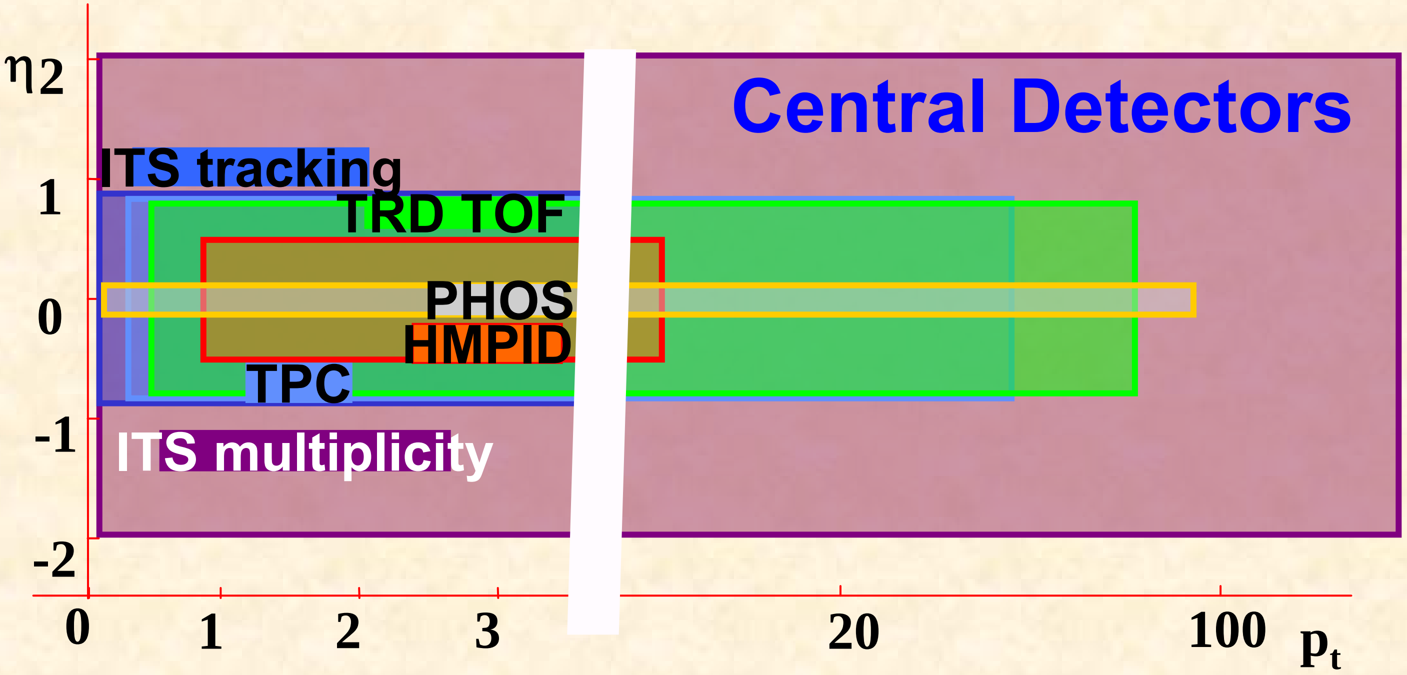
~30 Countries

~80 Institutes





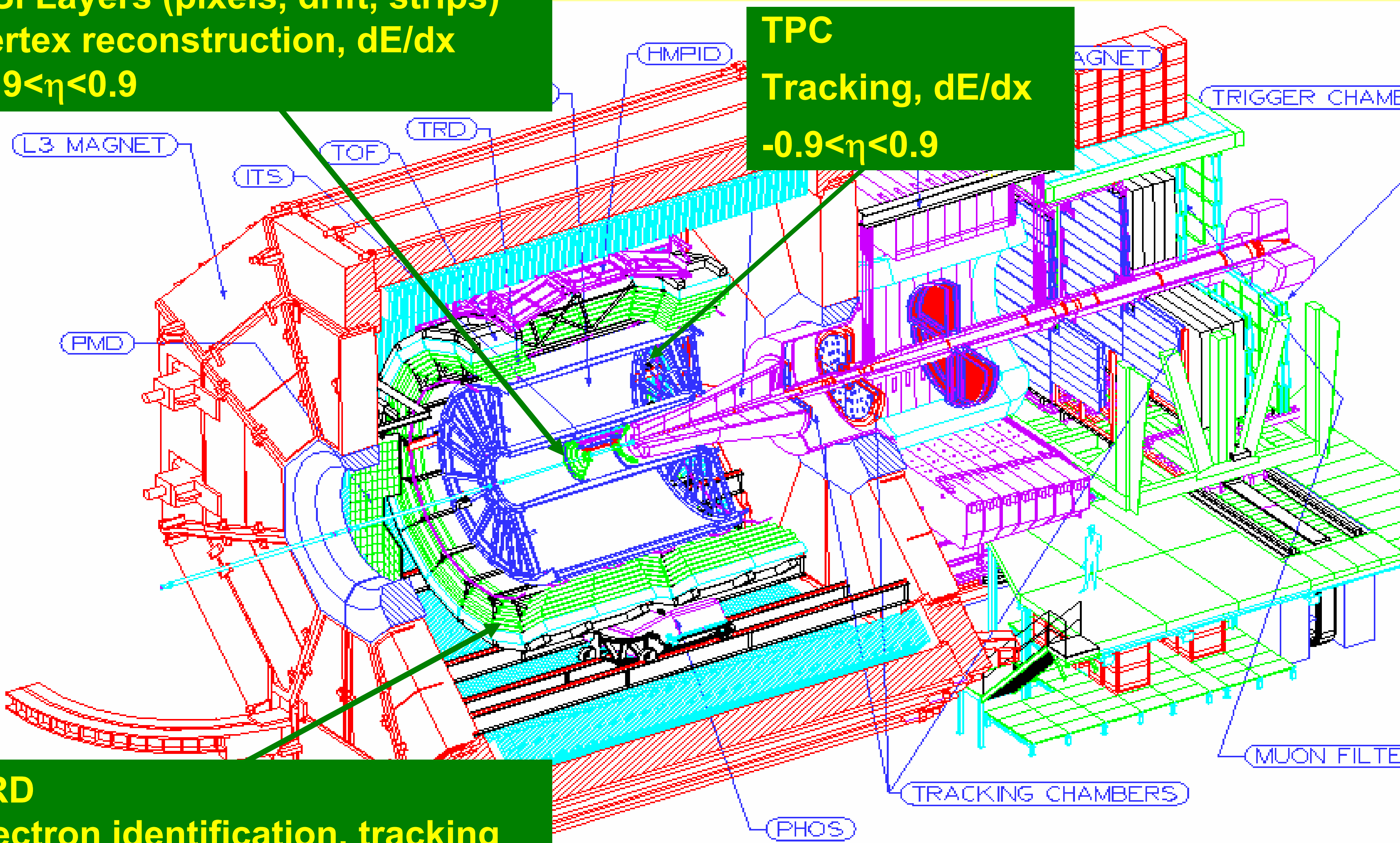
ALICE detector acceptance



Muon arm	$2.4<\eta<4$
Photon Multiplicity Detector	$2.3<\eta<3.5$
Forward Multiplicity Detector	$-5.4<\eta<-1.6$, $1.6<\eta<3$

ALICE LAYOUT: TRACKING

(and event characterization)



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

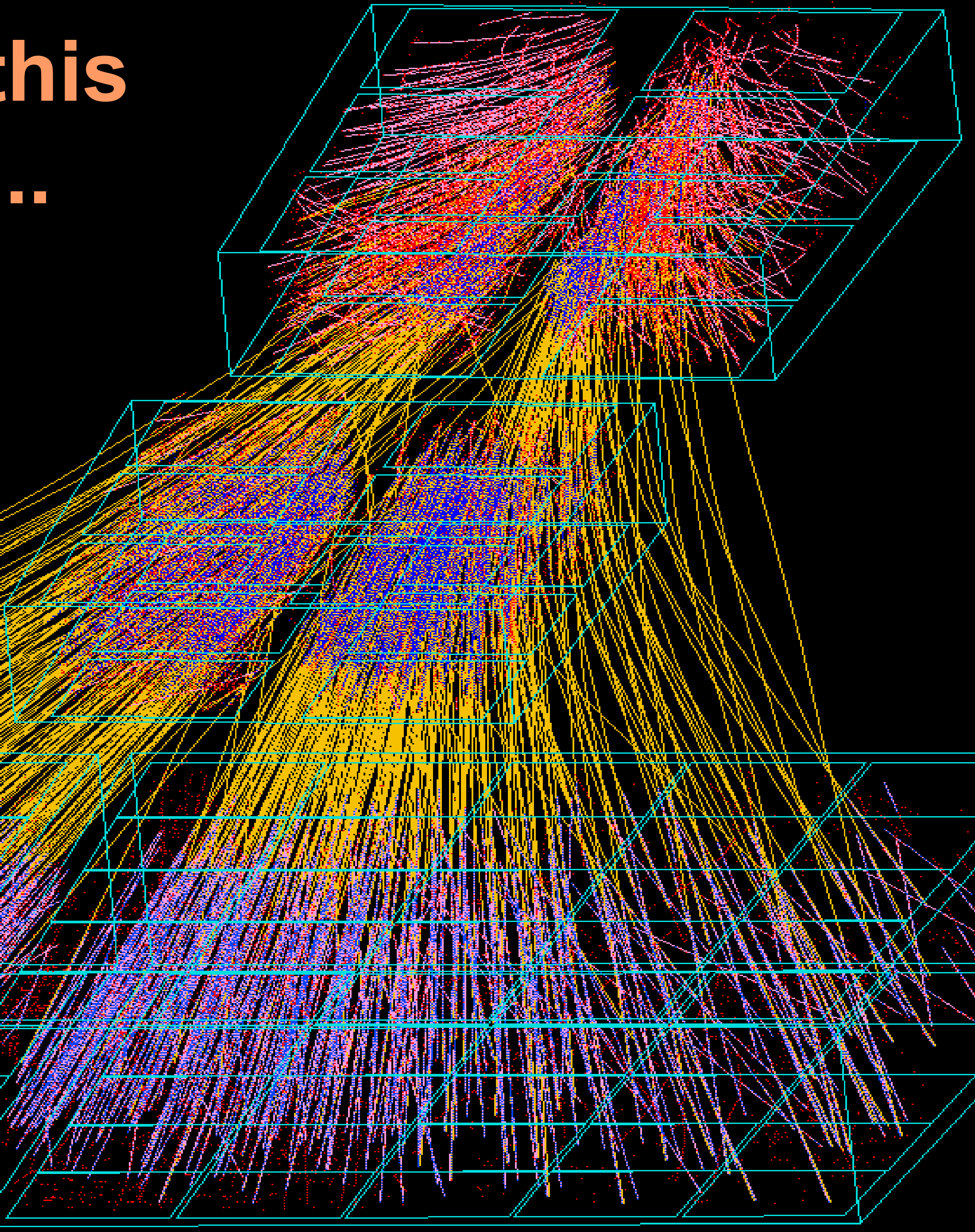
TPC

Tracking, dE/dx

$-0.9<\eta<0.9$

TRD
electron identification, tracking
$-0.9<\eta<0.9$

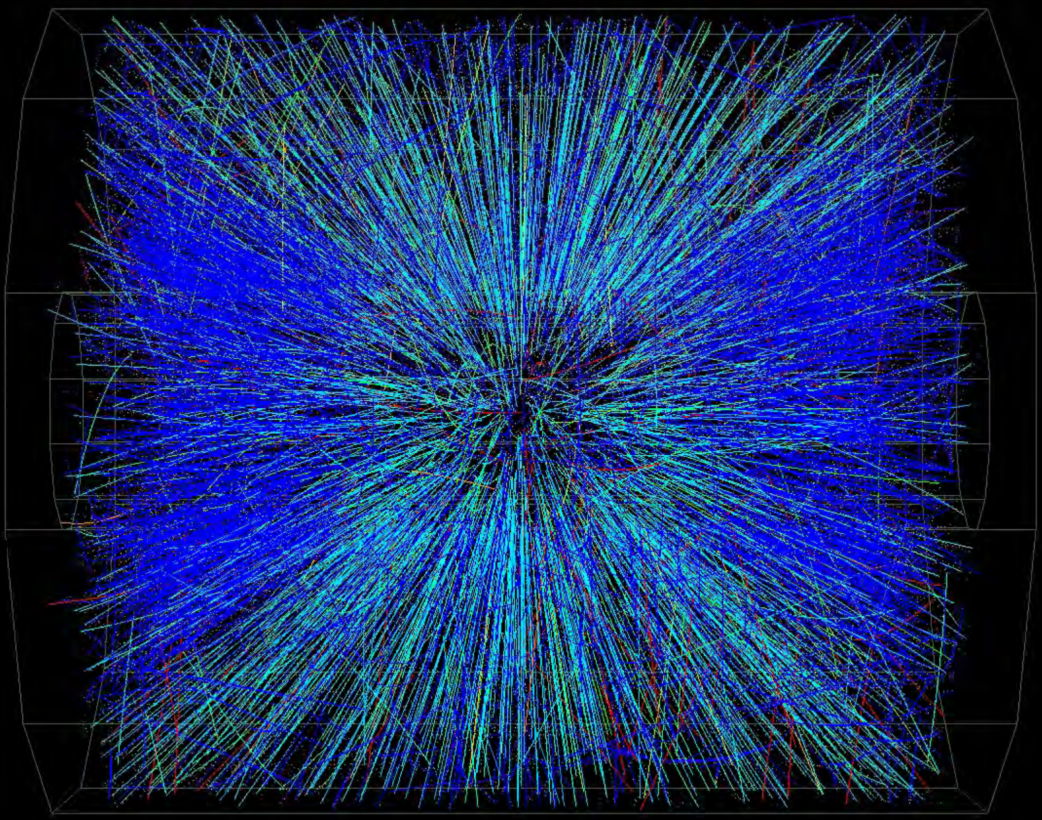
If you thought this was difficult ...

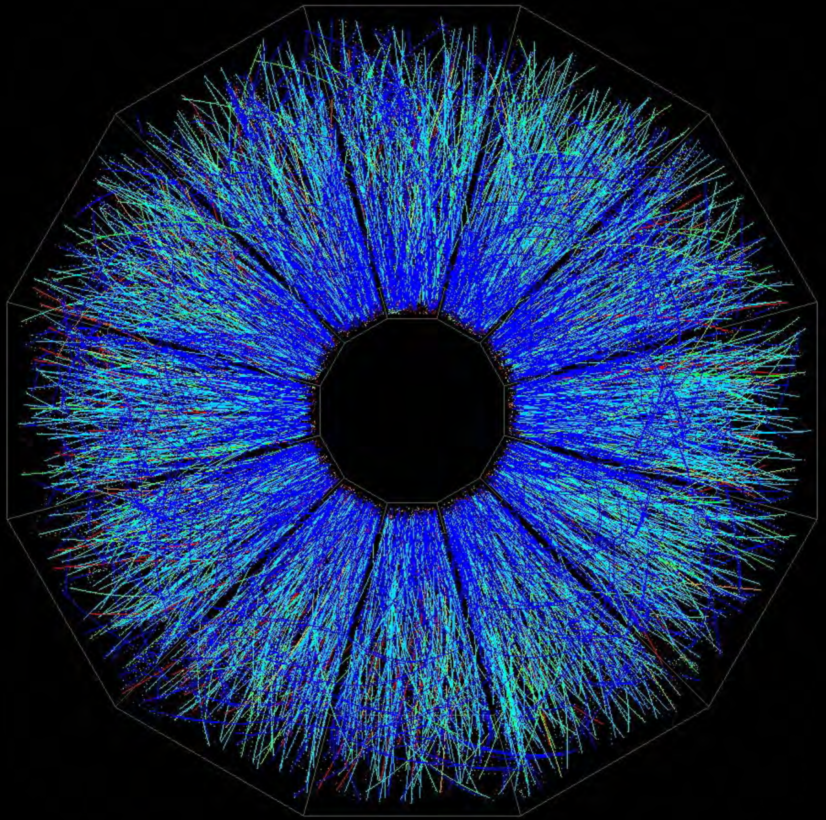


NA49 experiment:

A Pb-Pb event

and this was even more difficult ...



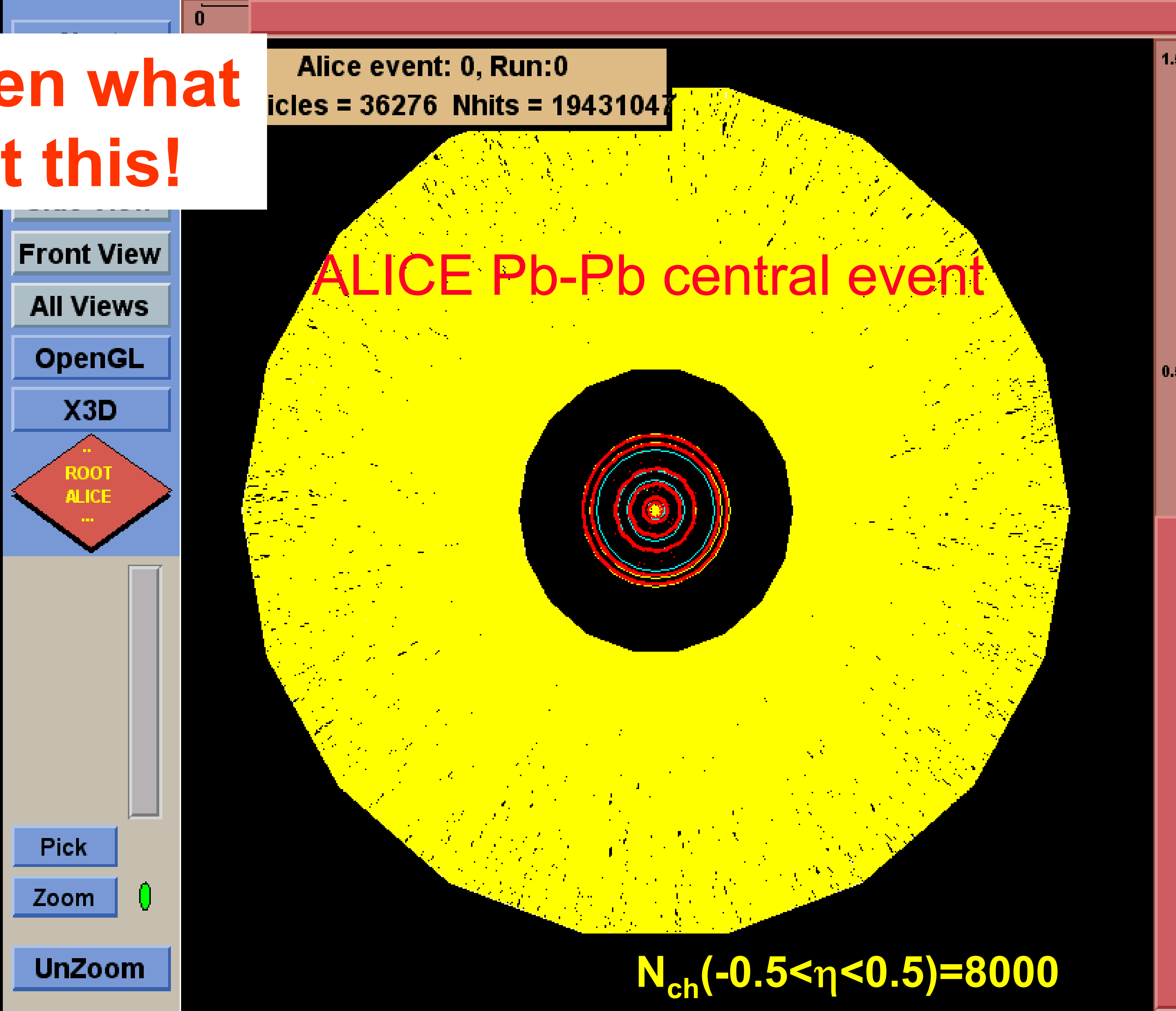


STAR

A central Au-Au event

@ ~130 GeV/nucleon

… then what about this!



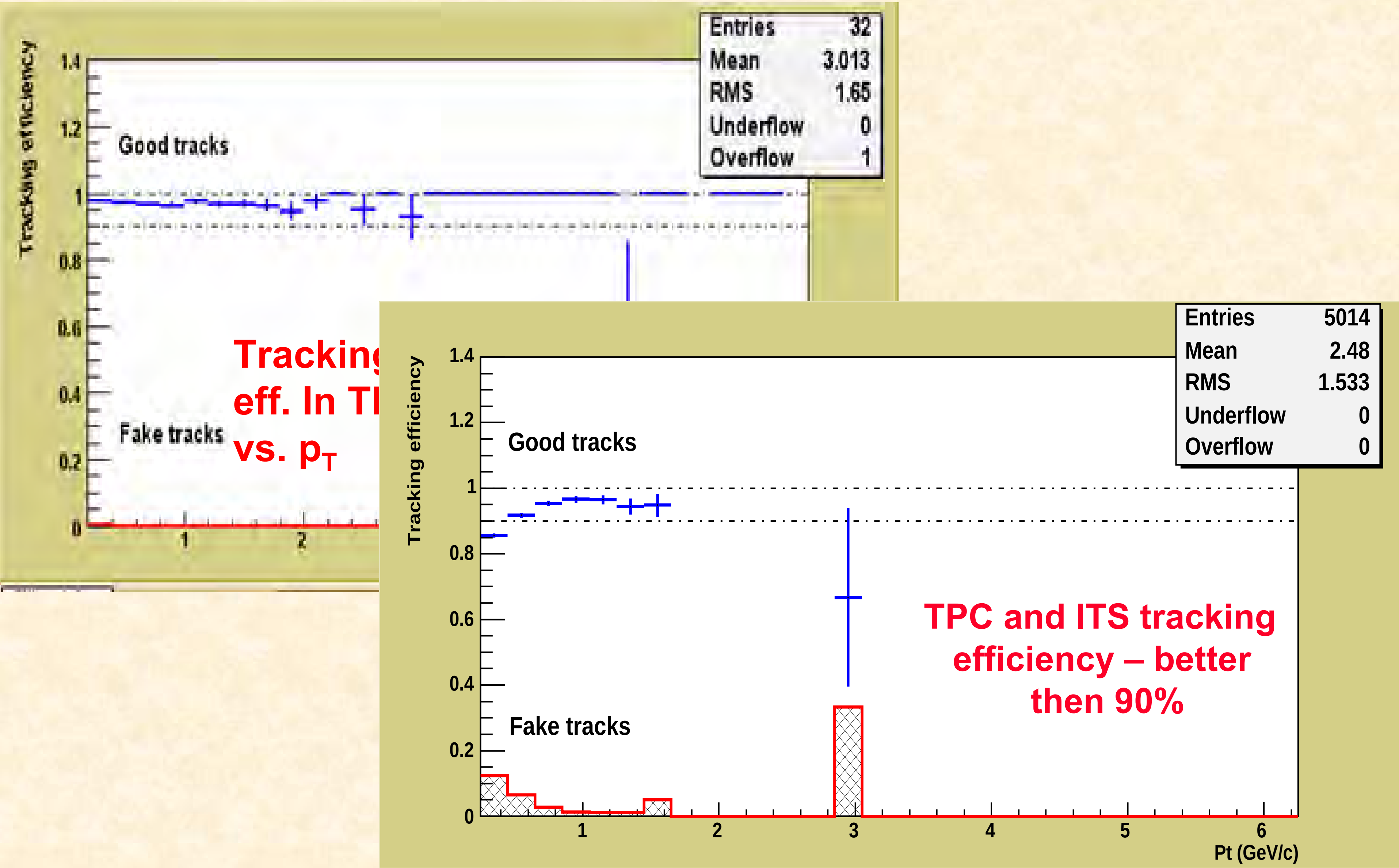
Alice event: 0, Run:0

icles = 36276 Nhits = 19431047

ALICE Pb-Pb central event

$N_{ch}(-0.5<\eta<0.5)=8000$

Tracking performance

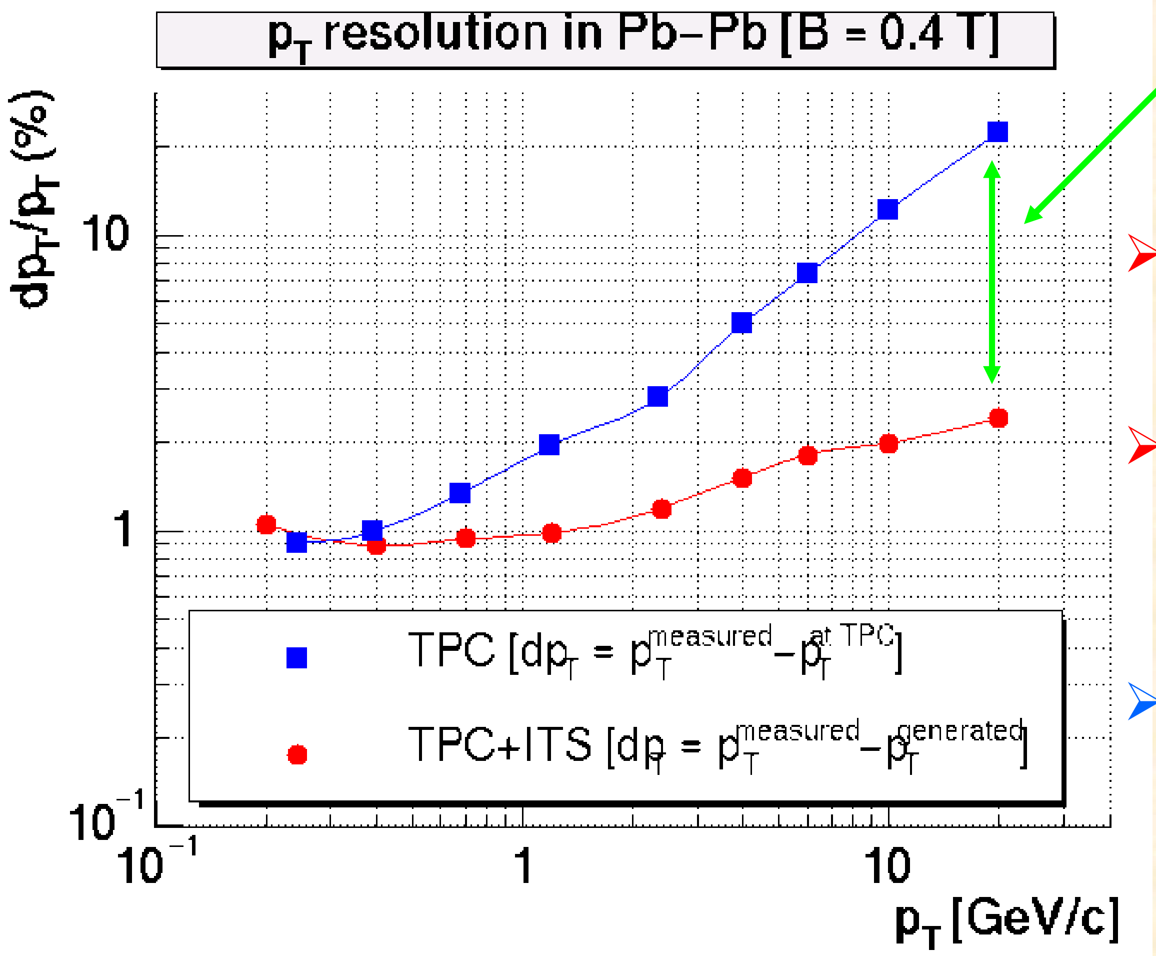


Tracking
eff. In T
vs. p_T

TPC and ITS tracking efficiency – better then 90%

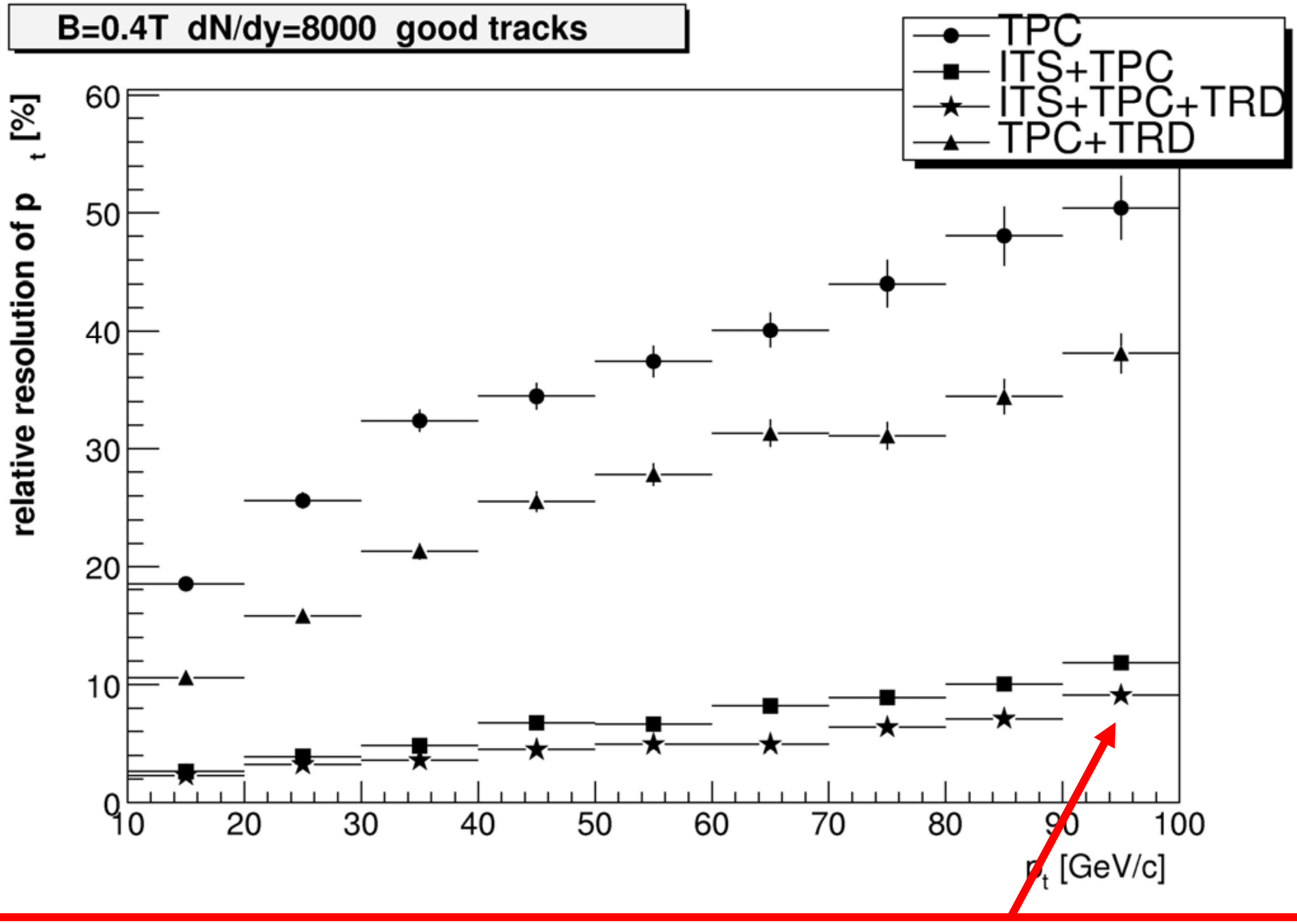
Track reconstruction in TPC-ITS p_T resolution

- The track momentum is measured (mainly) by TPC
- With ITS: resolution improves by a factor ~10 for high p_T



- ➢ Lever arm larger by 1.5 accounts for a factor ~ 2
- ➢ Remaining effect due to high resolution of points measured in ITS
- ➢ More improvement comes including the TRD in the tracking

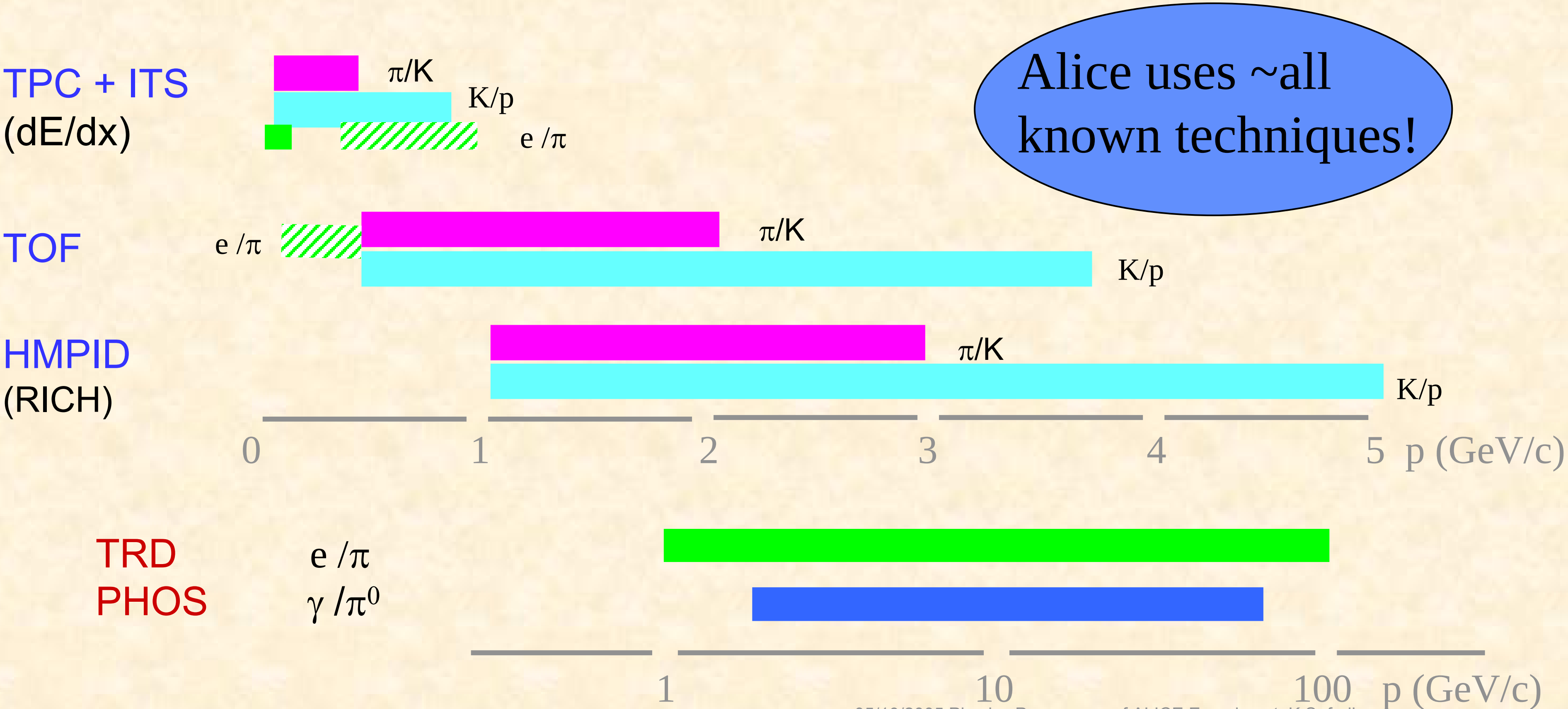
Tracking-II: Momentum resolution



resolution ~ 9% at 100 GeV/c
excellent performance in hard region!

ALICE PID

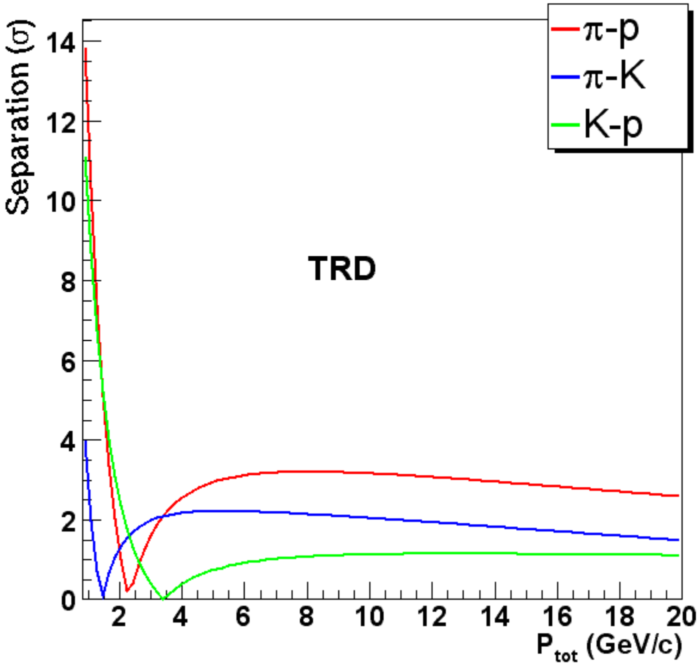
- π, K, p identified in large acceptance (2π * 1.8 units η) via a combination of dE/dx in Si and TPC and TOF from ~100 MeV to 2 (p/K) - 3.5 (K/p) GeV/c
- Electrons identified from 100 MeV/c to 100 GeV/c (with varying efficiency) combining Si+TPC+TOF with a dedicated TRD
- In small acceptance HMPID extends PID to ~5 GeV
- Photons measured with high resolution in PHOS, counting in PMD, and in EMC

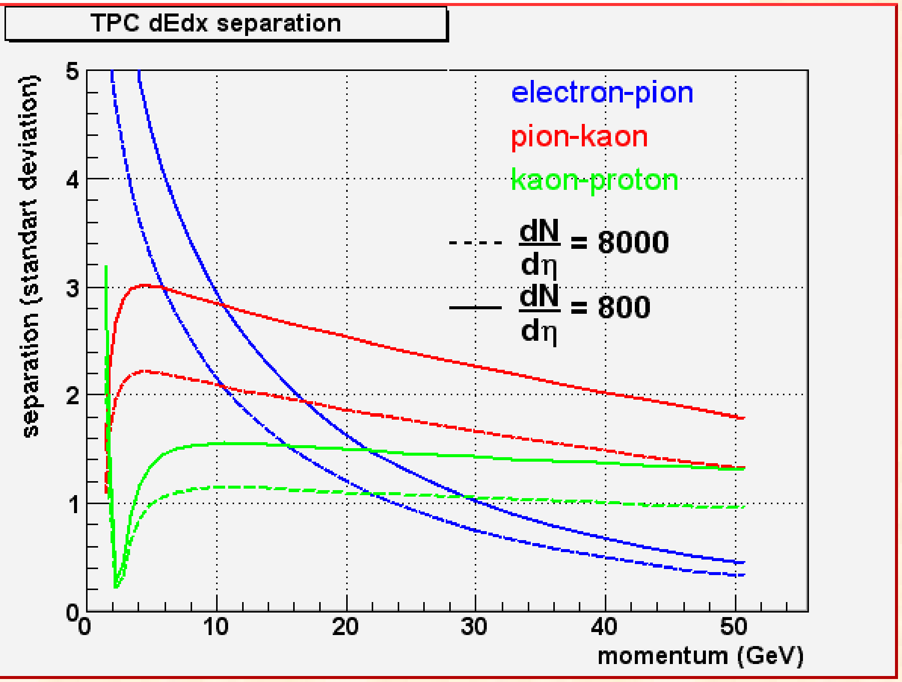


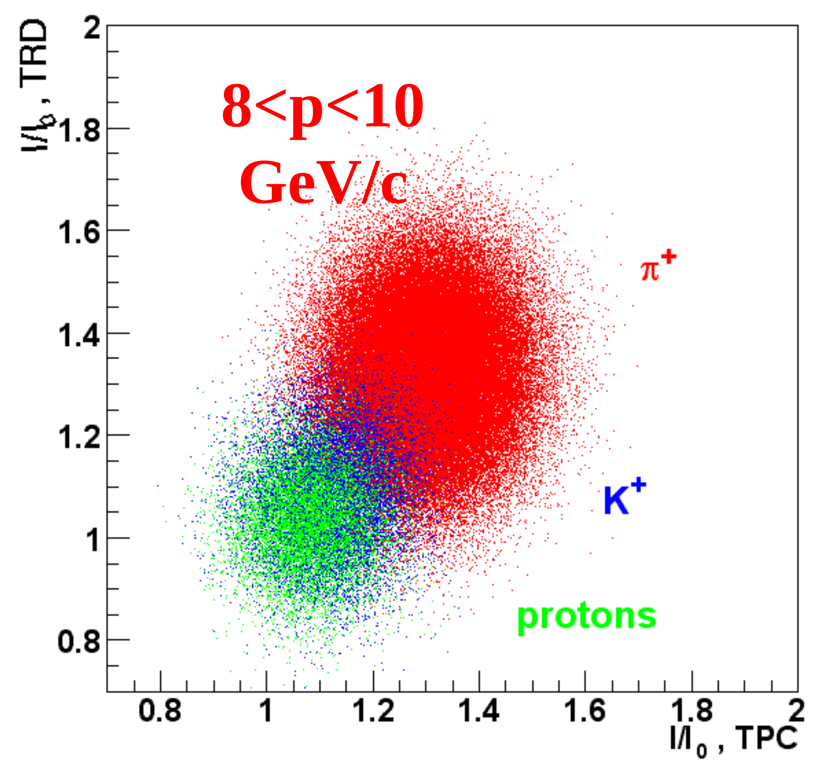
Alice uses ~all known techniques!

Under study: extension of PID to even higher momenta

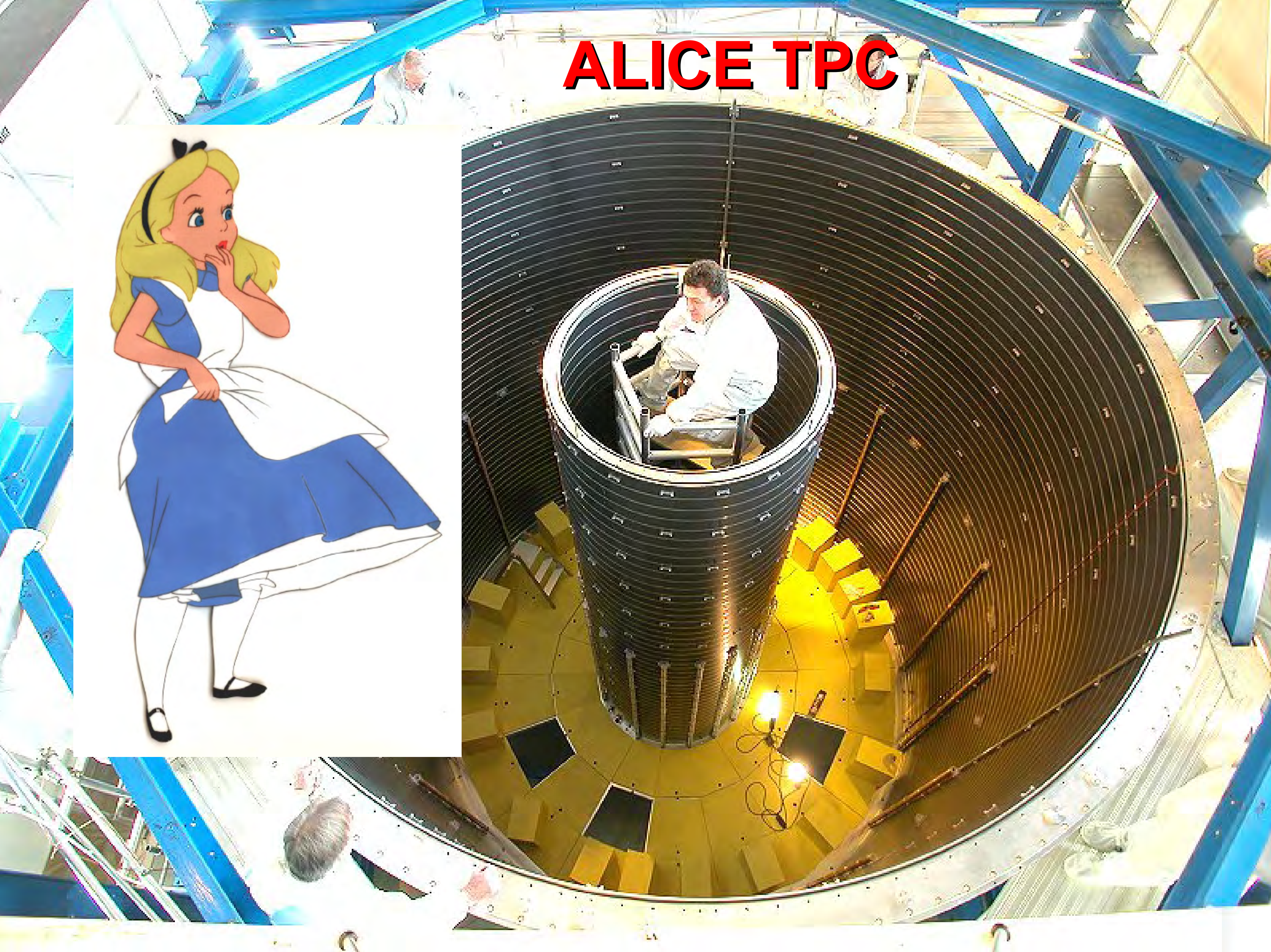
- Combine TPC and TRD dE/dx capabilities (similar number of samples/track) to get statistical ID in the relativistic rise region



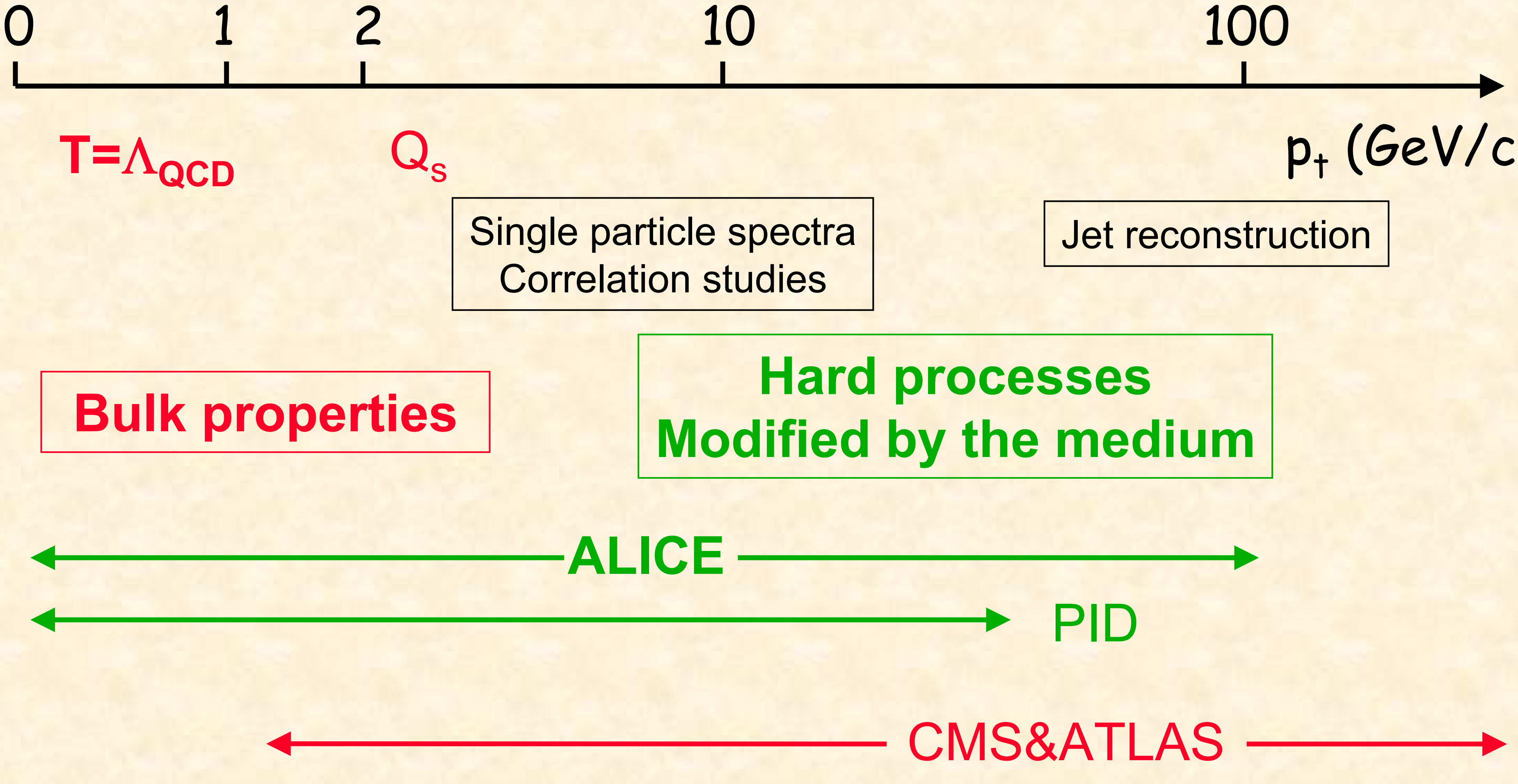




ALICE TPC



LHC Experiments



0 1 2 10 100

$T=\Lambda_{QCD}$

Q_s

p_t (GeV/c)

Single particle spectra
Correlation studies

Jet reconstruction

Bulk properties

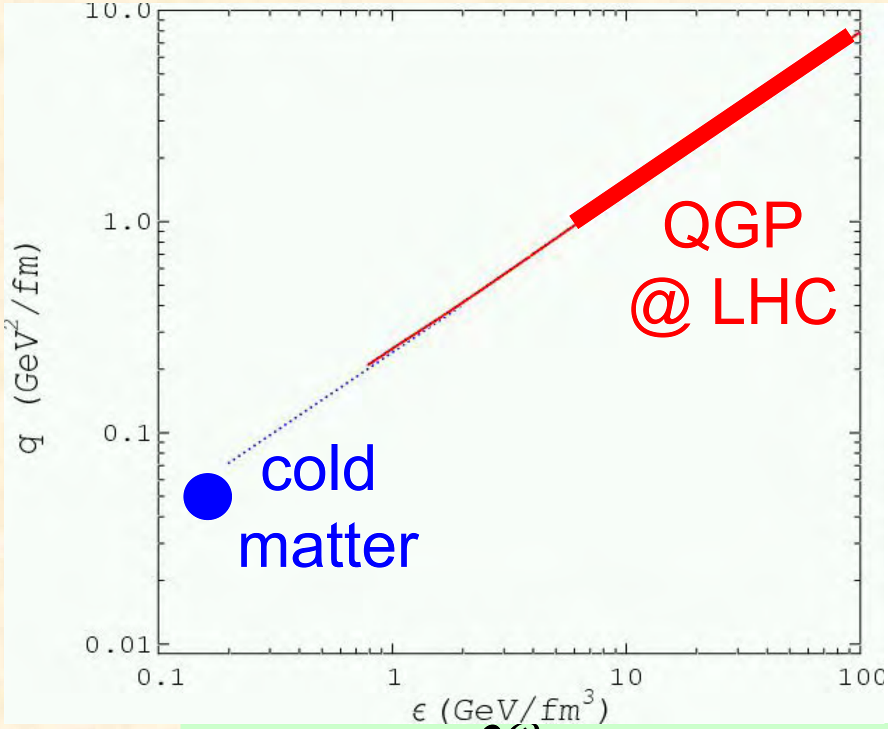
Hard processes
Modified by the medium

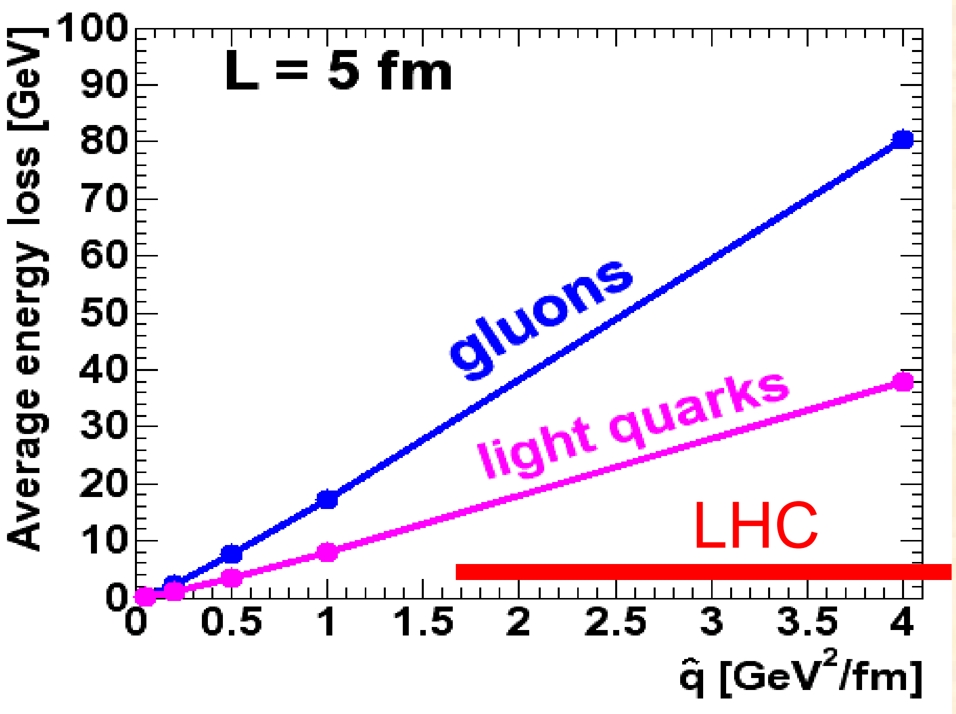
ALICE

PID

CMS&ATLAS

Parton Energy Loss





$$\langle \Delta E \rangle = \int_0^{\omega_c} d\omega\, \omega\, dN / d\omega \propto \alpha_s\, C_R\, \hat{q}\, L^2$$

Casimir coupling factor:
4/3 for quarks
3 for gluons

Medium transport coefficient
$\propto$ gluon density and momenta

R.Baier, Yu.L.Dokshitzer, A.H.Mueller, S.Peigne' and D.Schiff, (BDMPS), Nucl. Phys. **B483** (1997) 291.
C.A.Salgado and U.A.Wiedemann, Phys. Rev. **D68** (2003) 014008 [arXiv:hep-ph/0302184].

Parton Energy Loss

- **Effects:**
  - **Reduction of single inclusive high p_t particles**
    - **Parton specific (stronger for gluons than quarks)**
    - **Flavour specific (stronger for light quarks)**
    - **Measure identified hadrons (π, K, p, Λ, etc.) + partons (charm, beauty) at high p_t**
  - **Suppression of mini-jets**
    - **same-side / away-side correlations**
  - **Change of fragmentation function for hard jets (p_t >> 10 GeV/c)**
    - **Transverse and longitudinal fragmentation function of jets**
    - **Jet broadening → reduction of jet energy, dijets, γ-jet pairs**
- **p+p and p+A measurements crucial**

Heavy Quarks – dead cone

- Heavy quarks **with momenta < 20–30 GeV/*c*** → $v \ll c$
- Gluon radiation is suppressed at angles < m_Q/E_Q

  → "dead-cone" effect

  ⇨ **Due to destructive interference**

  ⇨ **Contributes to the harder fragmentation of heavy quarks**
- **Yu.L.Dokshitzer and D.E.Kharzeev:** *dead cone implies lower energy loss*

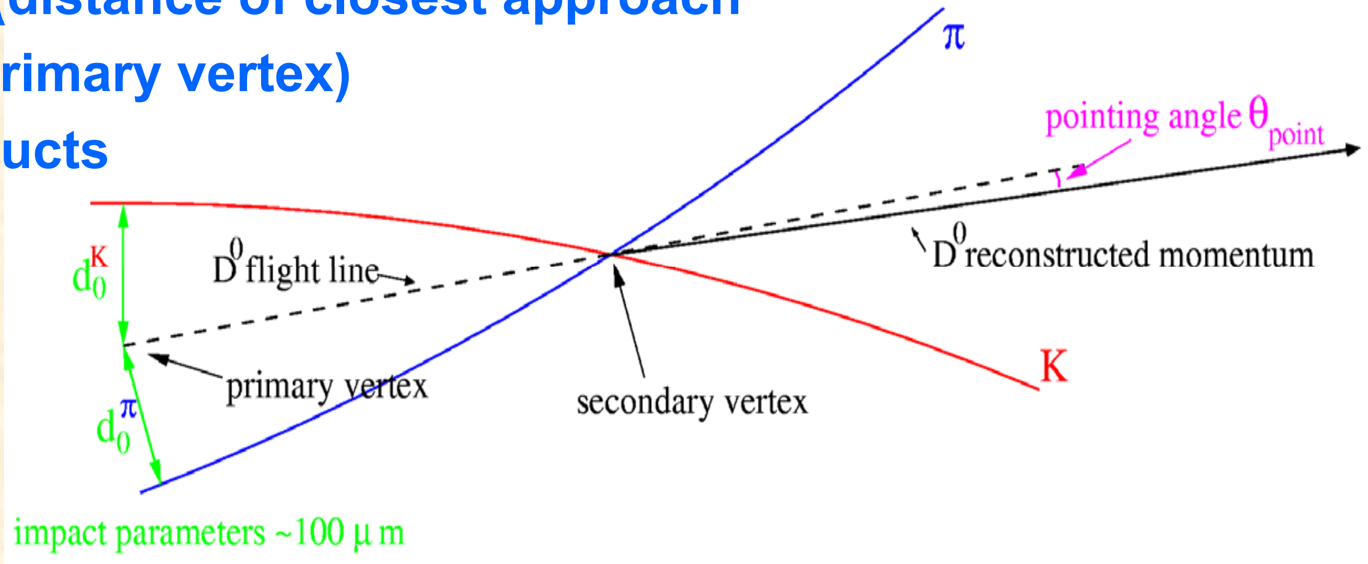
→ **D mesons quenching reduced**

→ **Ratio D/hadrons (or D/π^0) enhanced and sensitive to medium properties**

Yu.L.Dokshitzer and D.E.Kharzeev, Phys. Lett. **B519** (2001) 199 [arXiv:hep-ph/0106202].

Detection strategy for $D^0 \rightarrow K^- \pi^+$

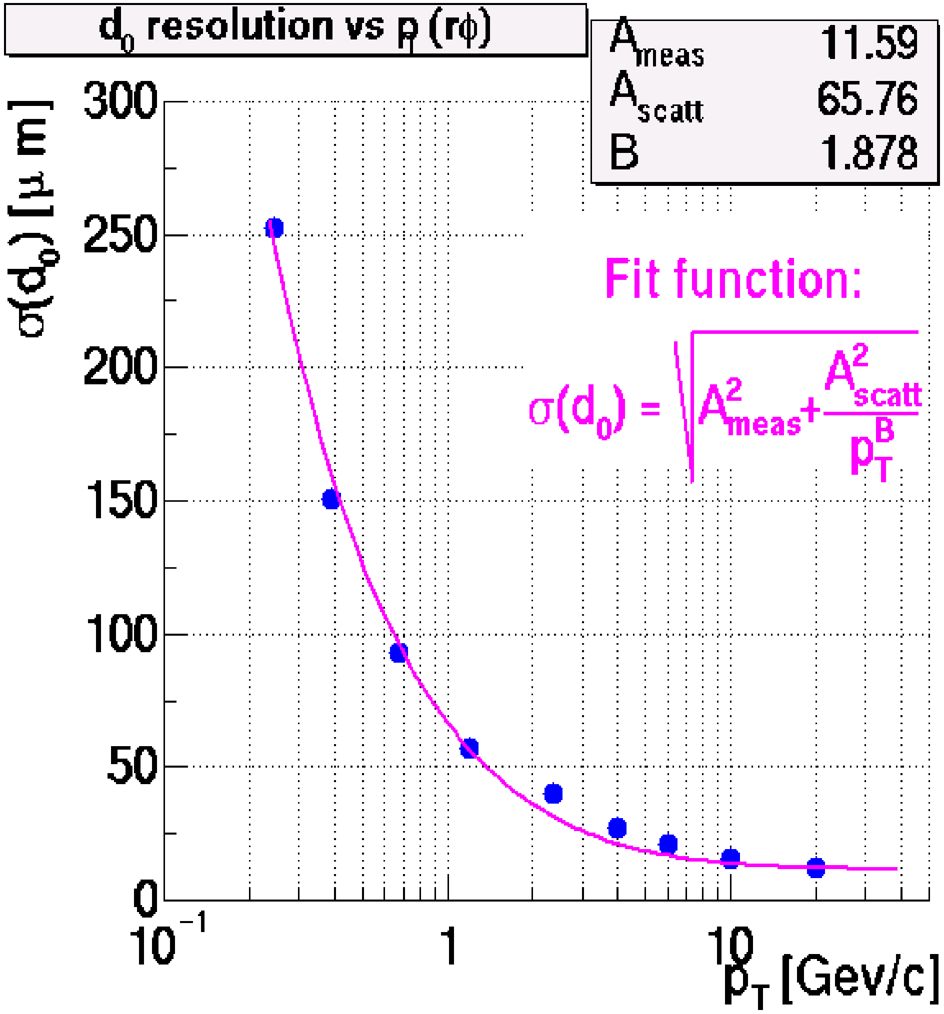
- **Weak decay with mean proper length** $c\tau = 124\ \mu m$
- Impact Parameter **(distance of closest approach of a track to the primary vertex) of the decay products**
  $d_0 \sim 100\ \mu m$

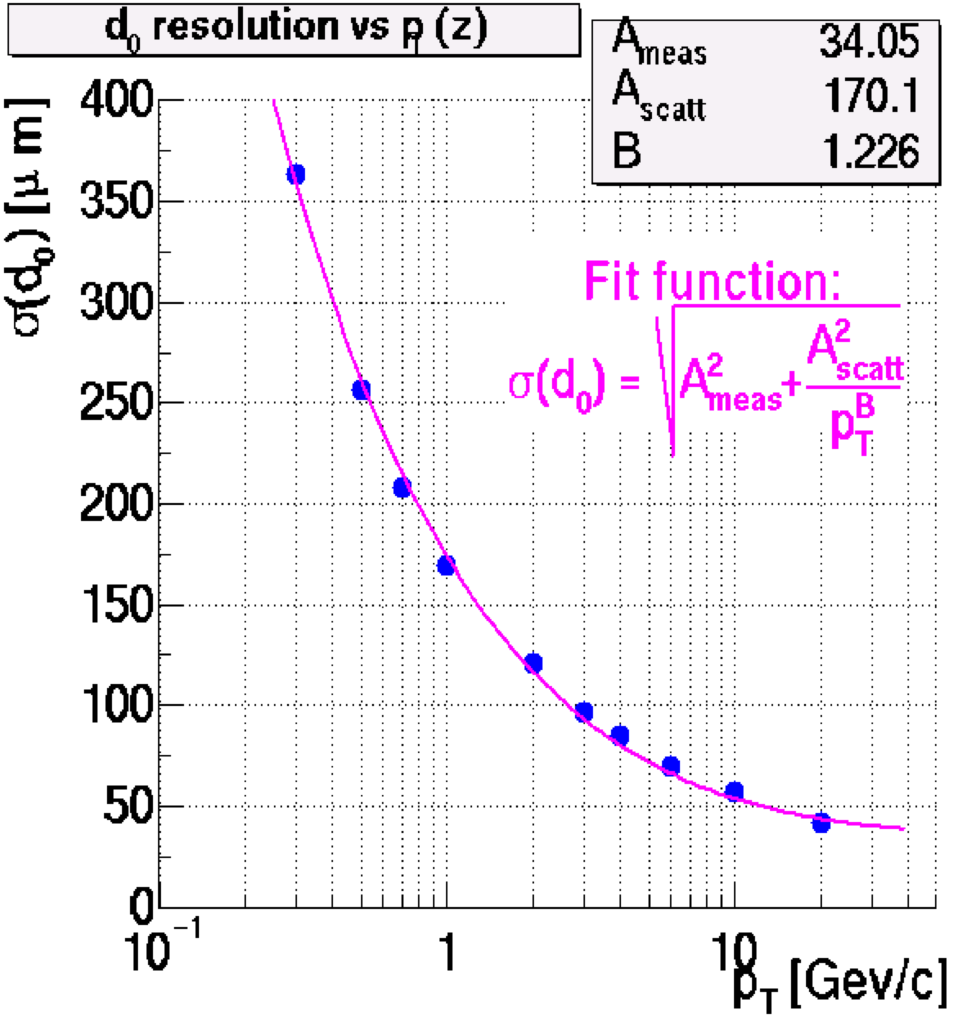


- **STRATEGY:** invariant mass **analysis of fully-reconstructed topologies originating from (displaced)** secondary vertices
  - ⇨ **Measurement of** Impact Parameters
  - ⇨ **Measurement of** Momenta
  - ⇨ Particle identification **to tag the two decay products**

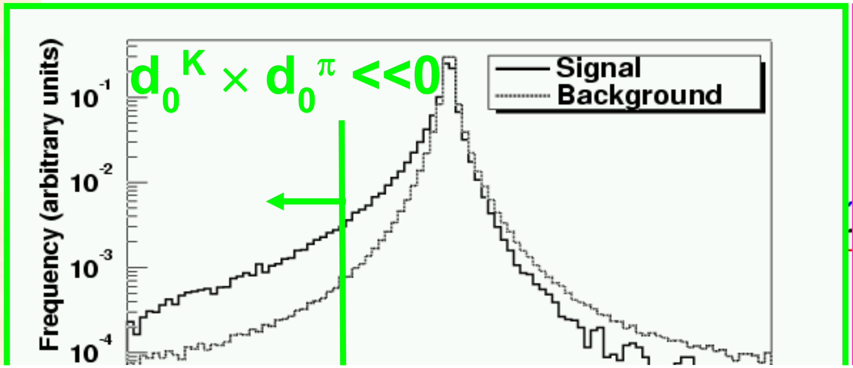
Track reconstruction in TPC-ITS
d_0 measurement

Measurement of impact parameters is *crucial* for secondary vertex reconstruction

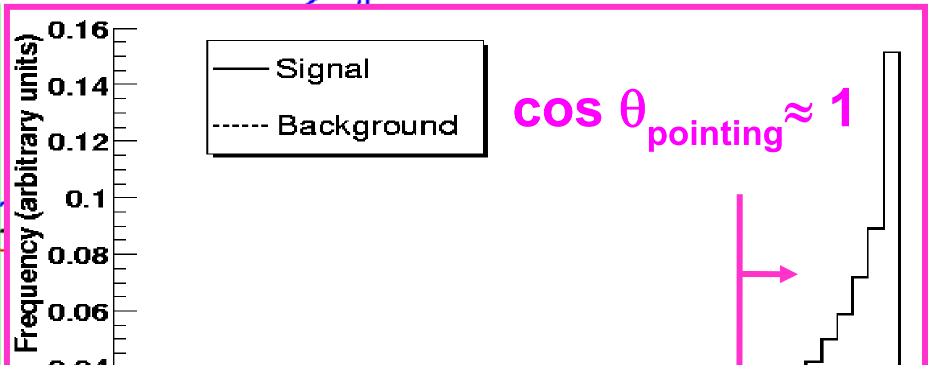




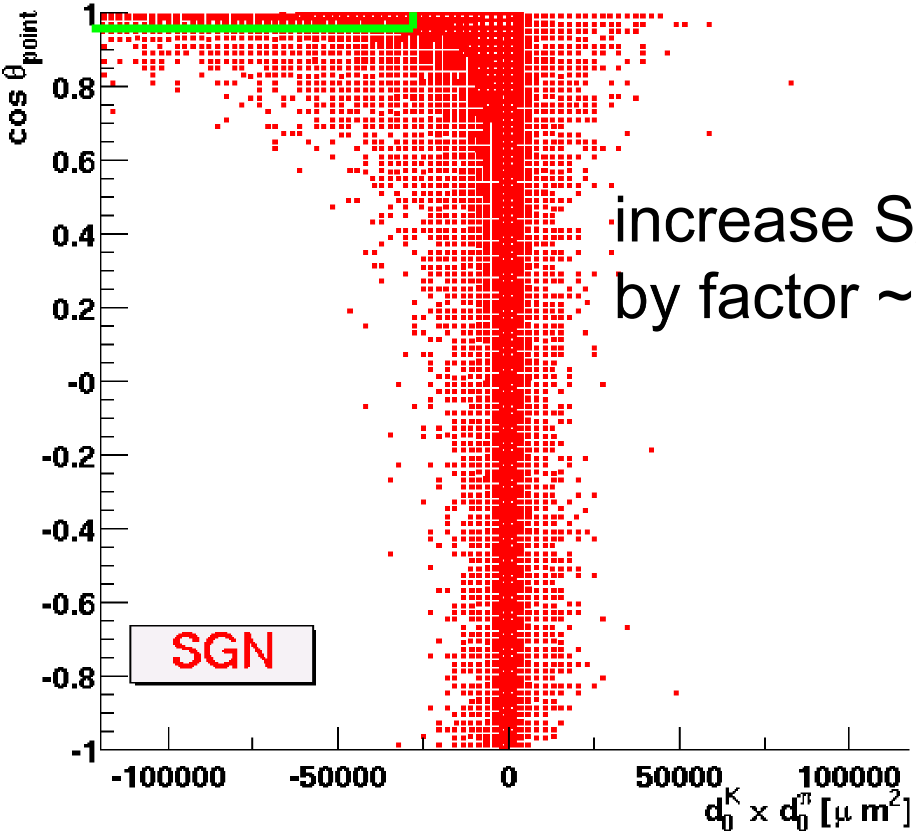
Selection of D^0 candidates

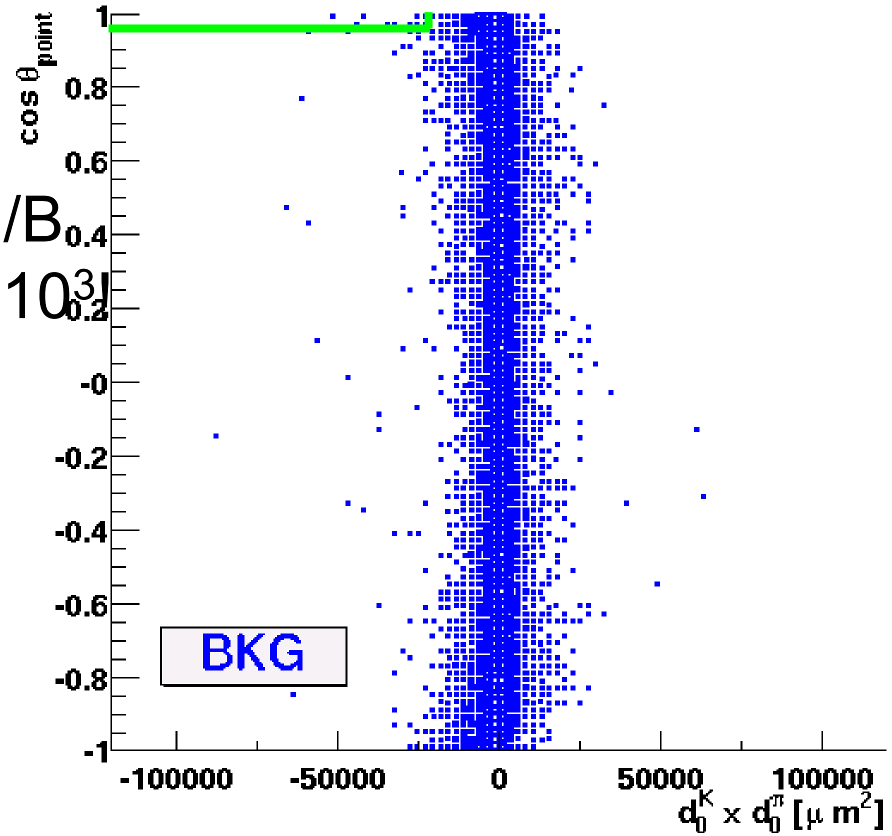


$d_0^K \times d_0^\pi << 0$



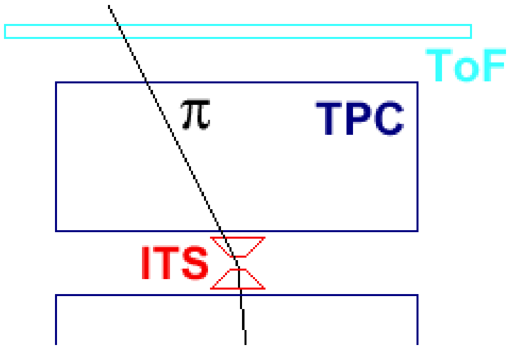
$\cos\theta_{pointing} \approx 1$





increase S/B by factor $\sim 10^3$!

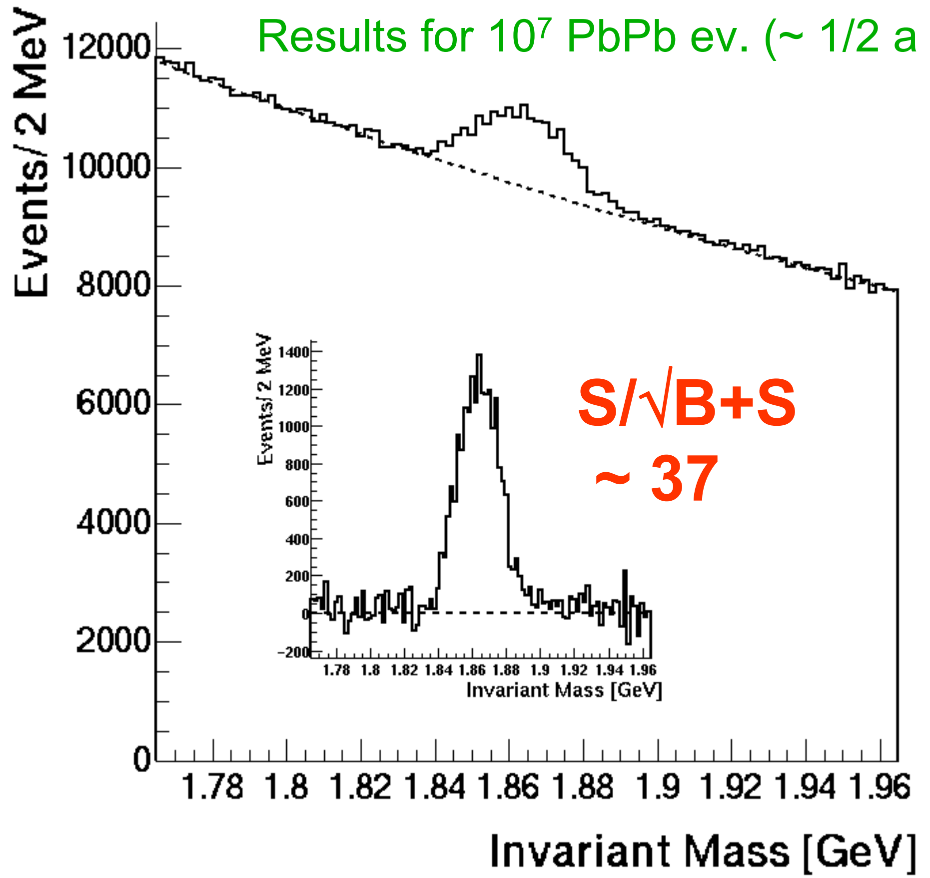
Hadronic charm



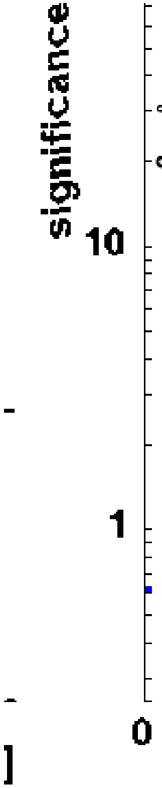
Combine ALICE tracking + secondary vertex finding capabilities (σ_{d0}~60μm@1GeV/c p_T) + large acceptance PID to detect processes as $D^0 \rightarrow K^-\pi^+$

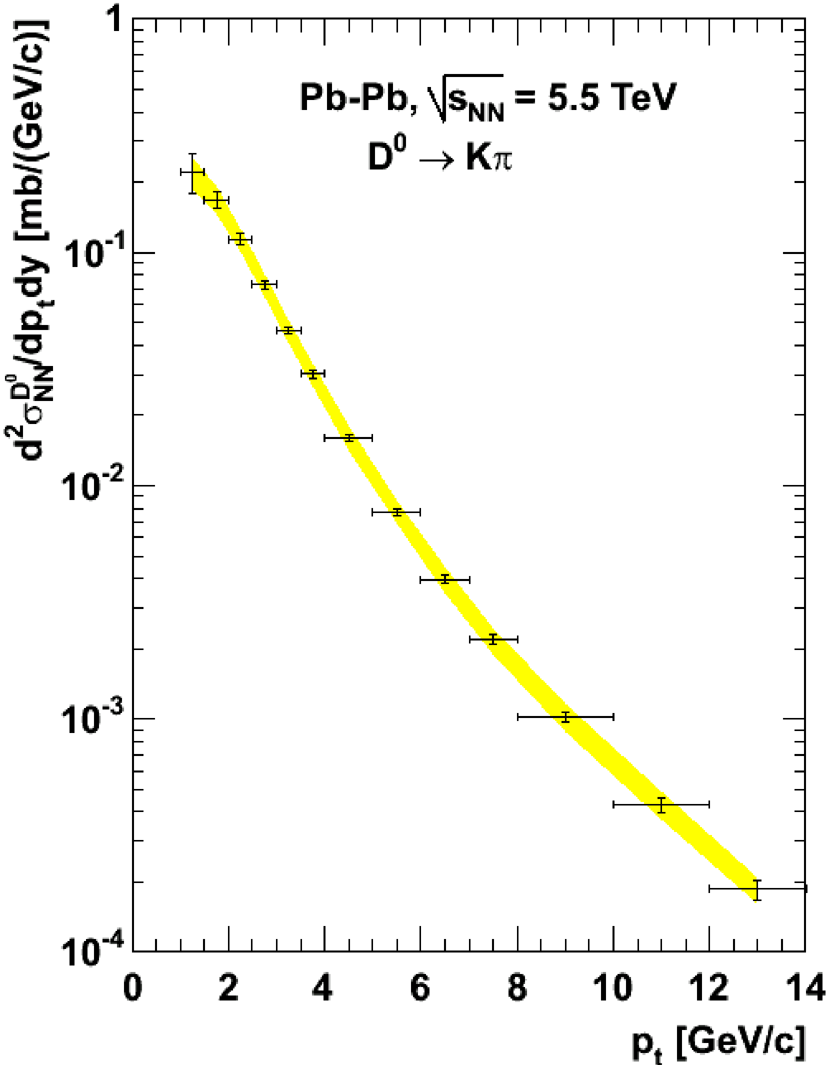
~1 in acceptance / central event ~0.001/centra event accepted after rec. and all cuts

Results for 10^7 PbPb ev. (~ 1/2 a run)



$S/\sqrt{B+S}$
~ 37

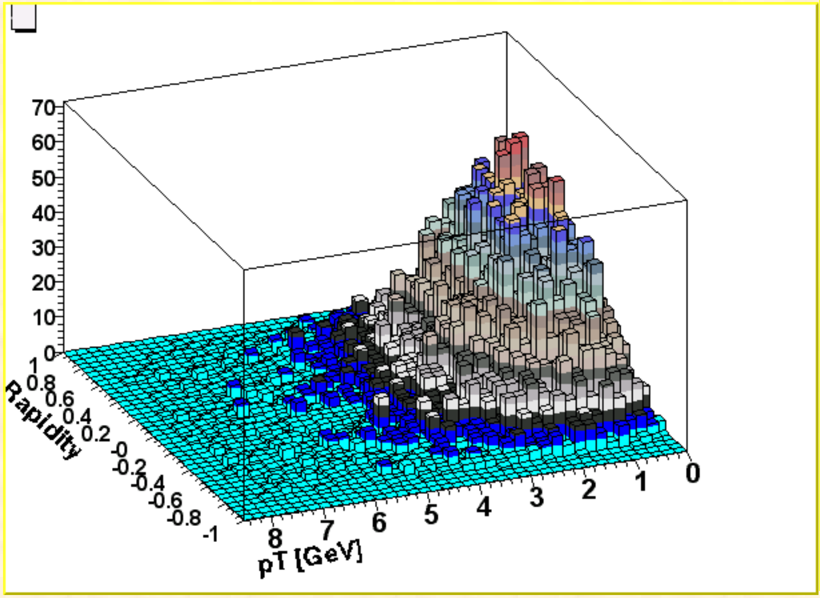


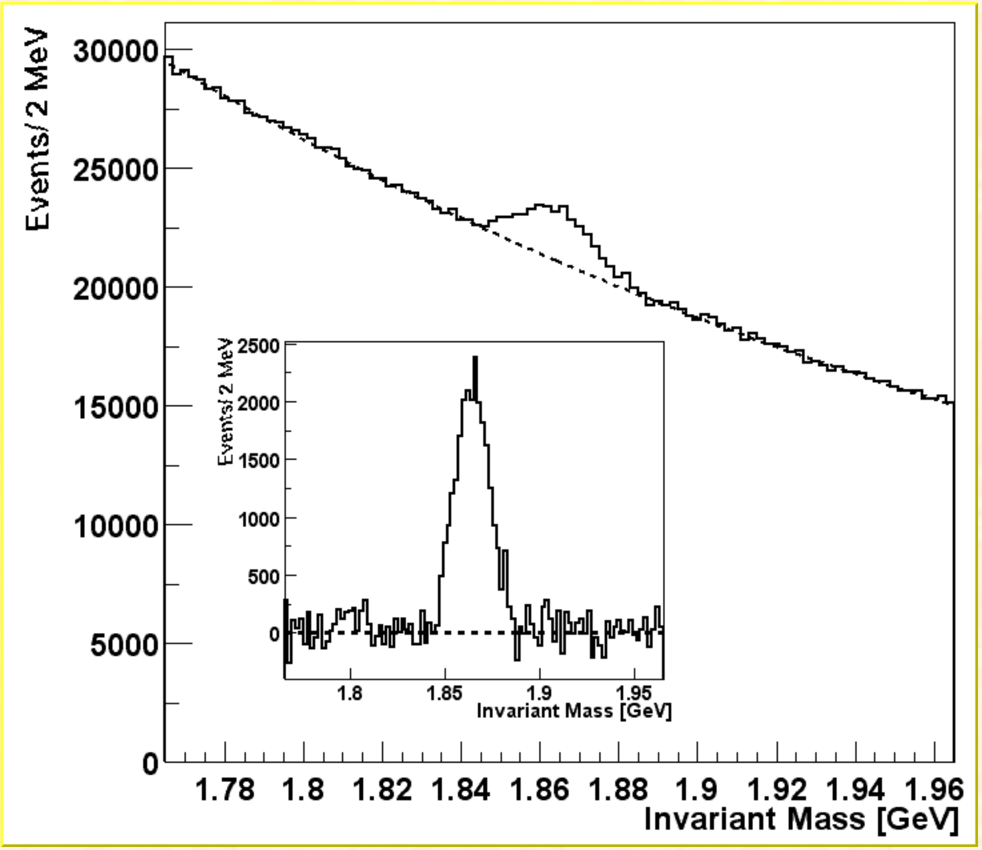


Charm in hadronic decay pp

Similar study for 10^9 pp minimum bias collisions

Acceptance practically down to the $p_t \to 0$ (as for heavy-ion)

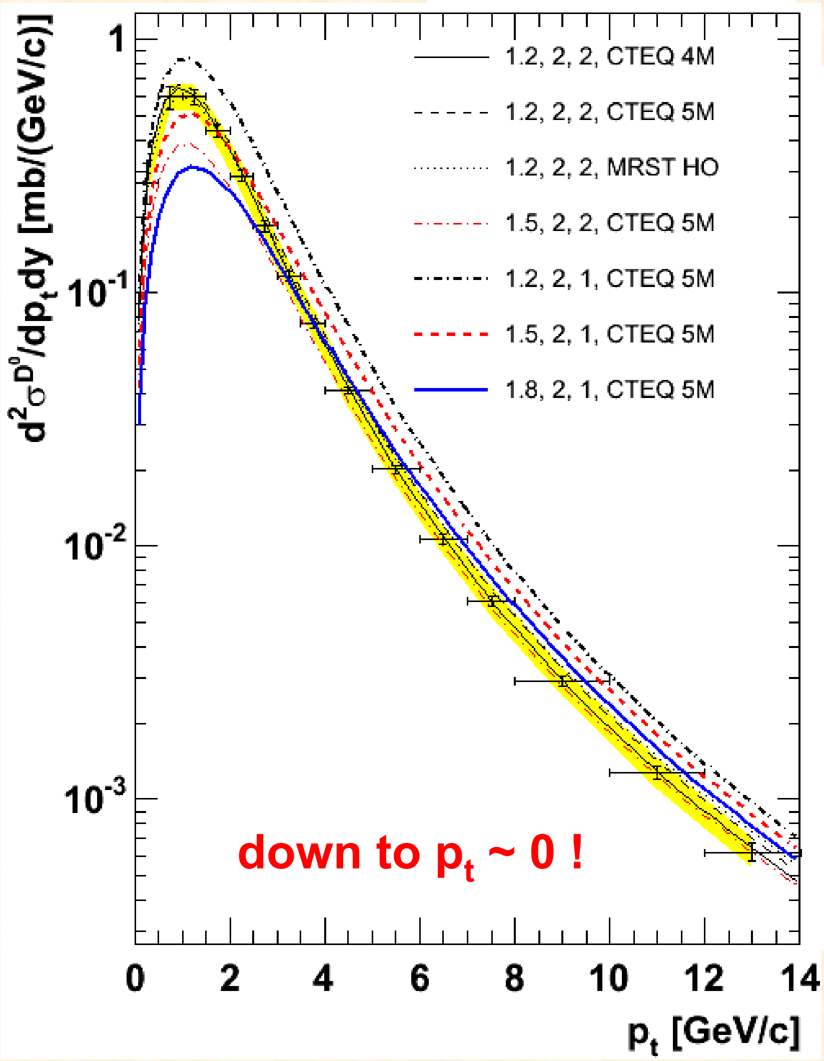




Charm in pp ($D^0 \rightarrow K\pi$) Sensitivity to NLO pQCD params

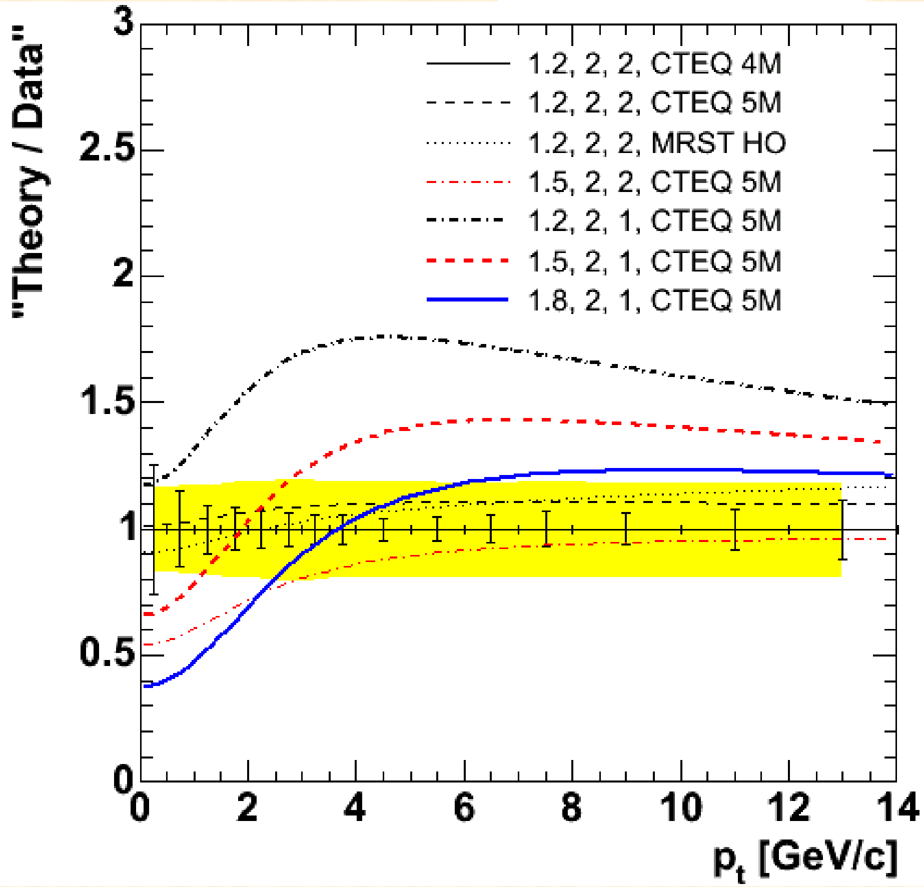
√s = 14 TeV

$$m_c, \frac{\mu_F}{\mu_0}, \frac{\mu_R}{\mu_0}, PDFs$$

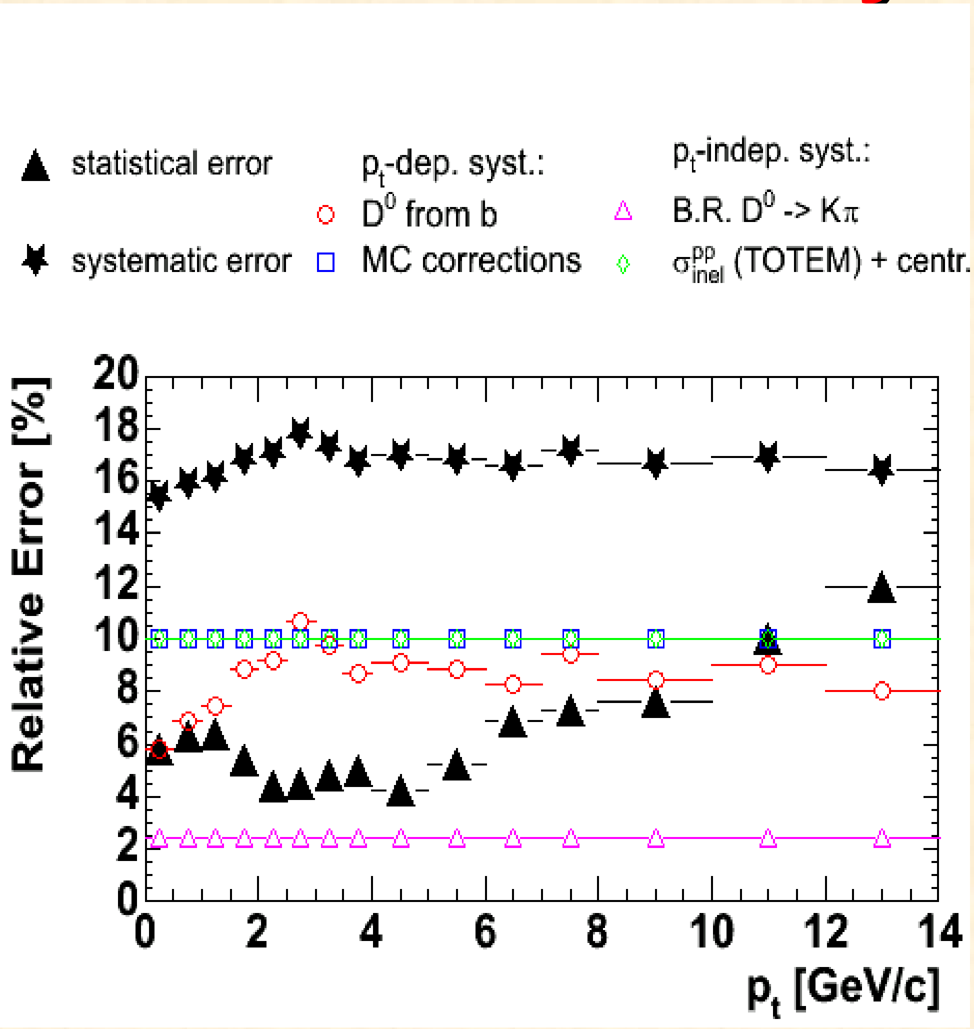


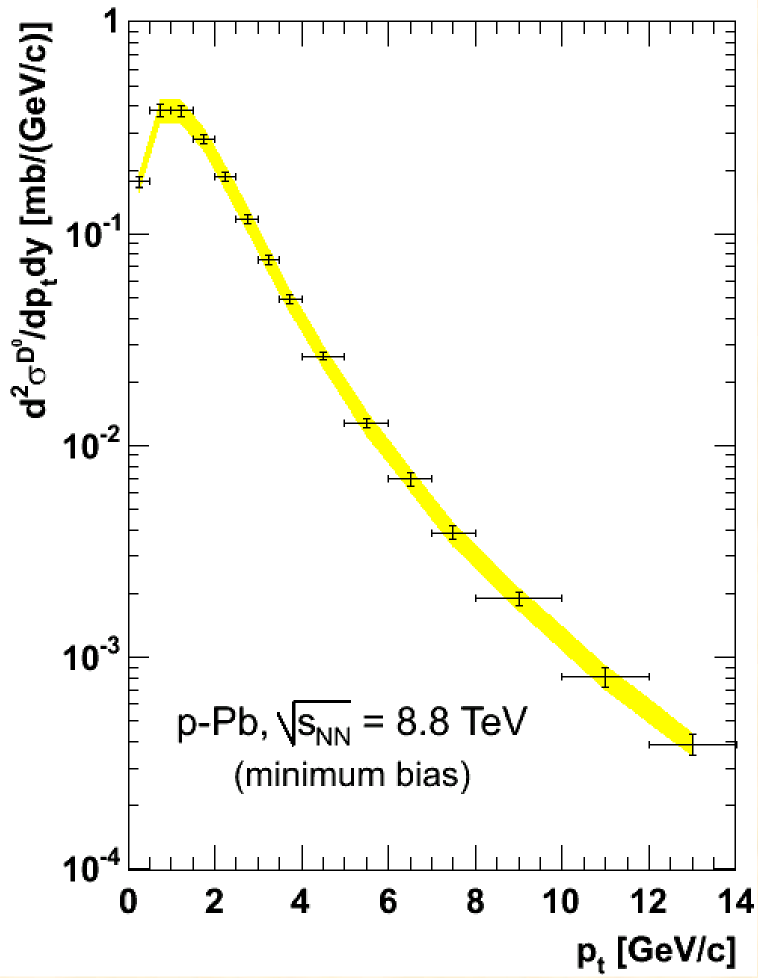
down to p_t ~ 0 !

$$m_c, \frac{\mu_F}{\mu_0}, \frac{\mu_R}{\mu_0}, PDFs$$

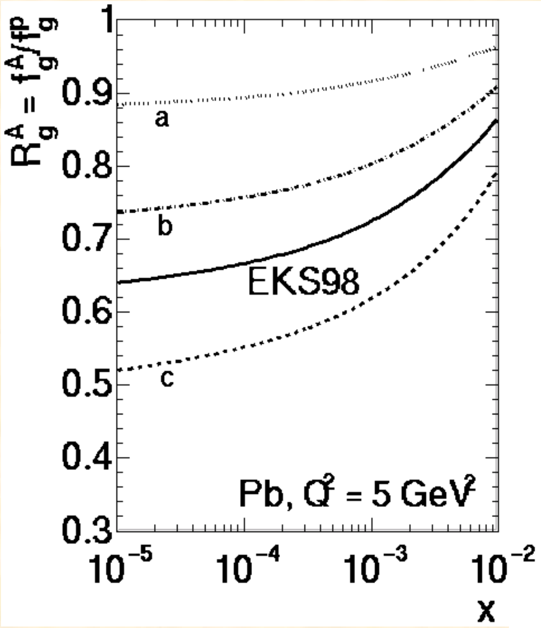


$D^0 \rightarrow K\pi$ in pPb
Statistical and systematic errors

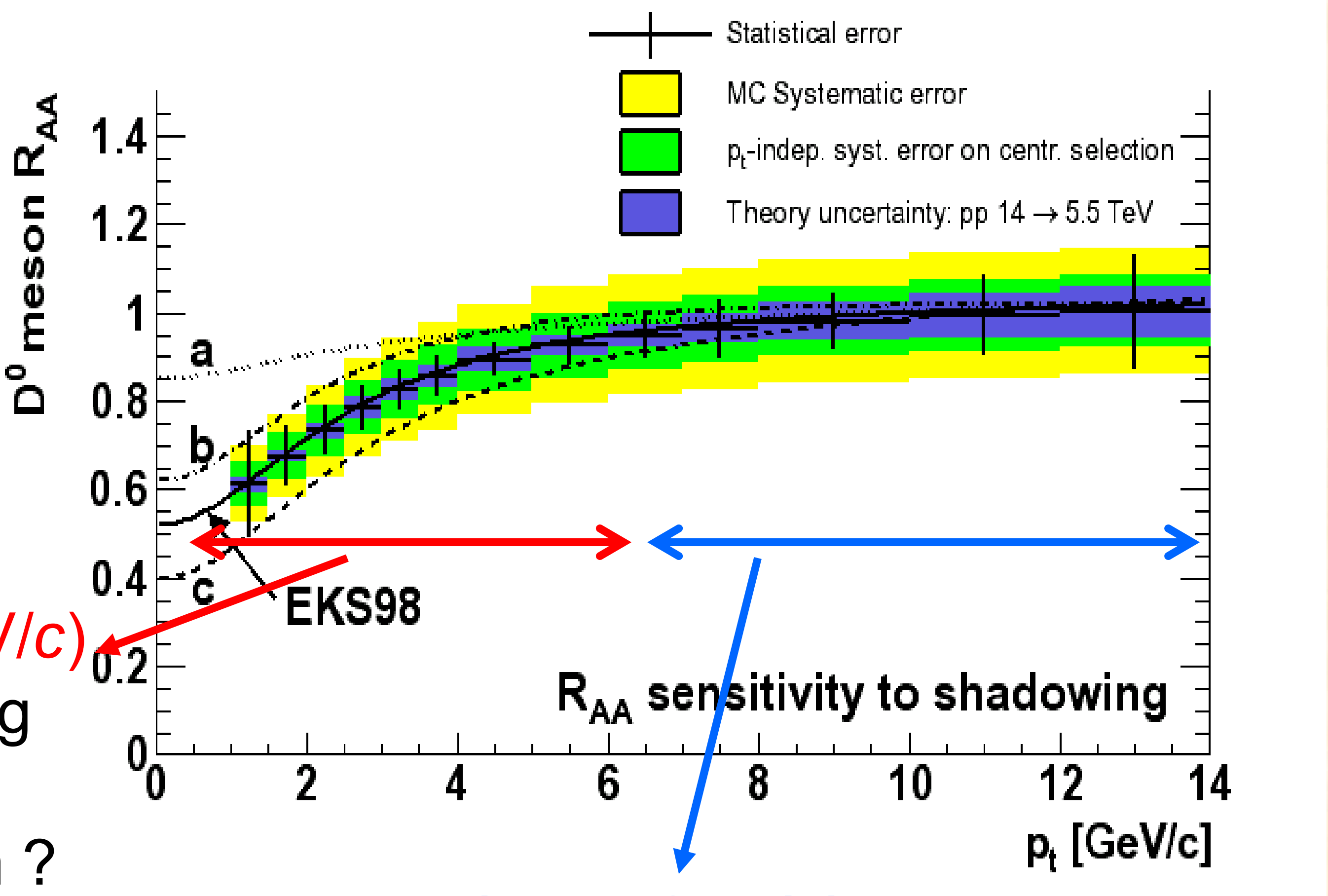




Sensitivity on R_{AA} for D^0 mesons



A.Dainese nucl-ex/0311004



Low p_t (< 6–7 GeV/c)

Nuclear shadowing

+ k_t broadening

+ ? thermal charm ?

‘High’ p_t (6–15 GeV/c)

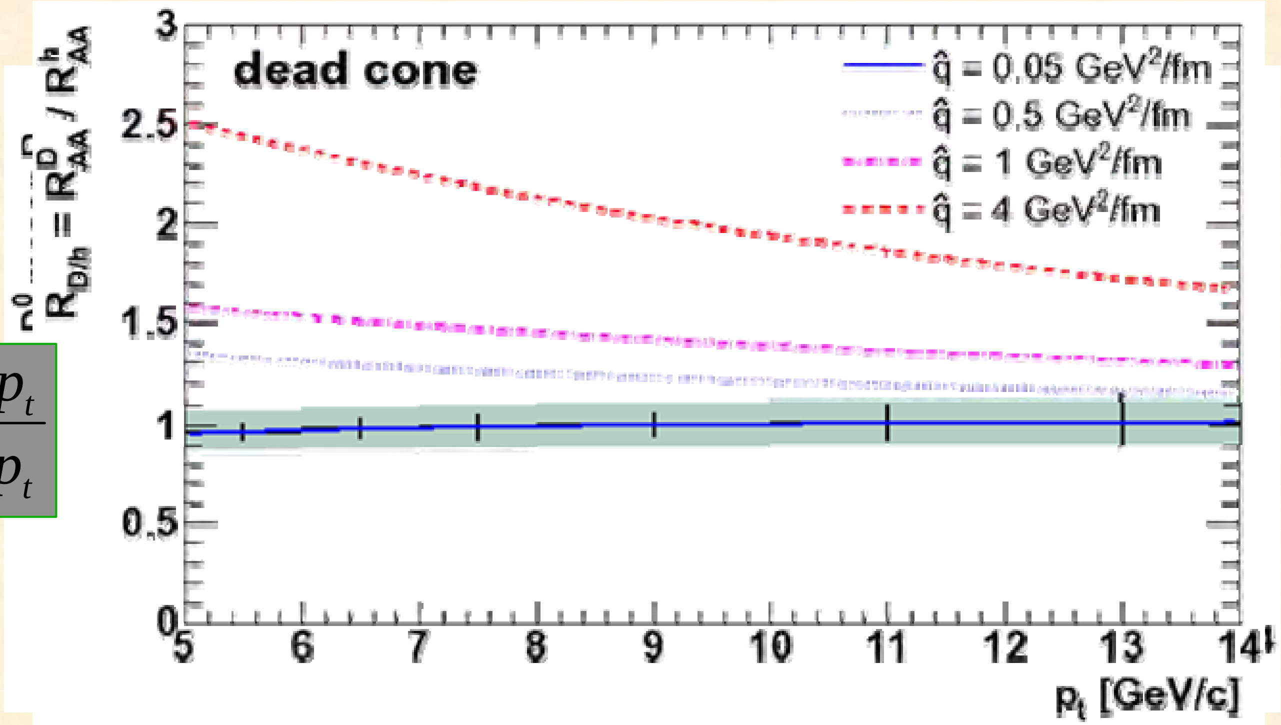
here energy loss can be studied

(it’s the only expected effect)

D quenching ($D^0 \rightarrow K^-\pi^+$)

- **Reduced**

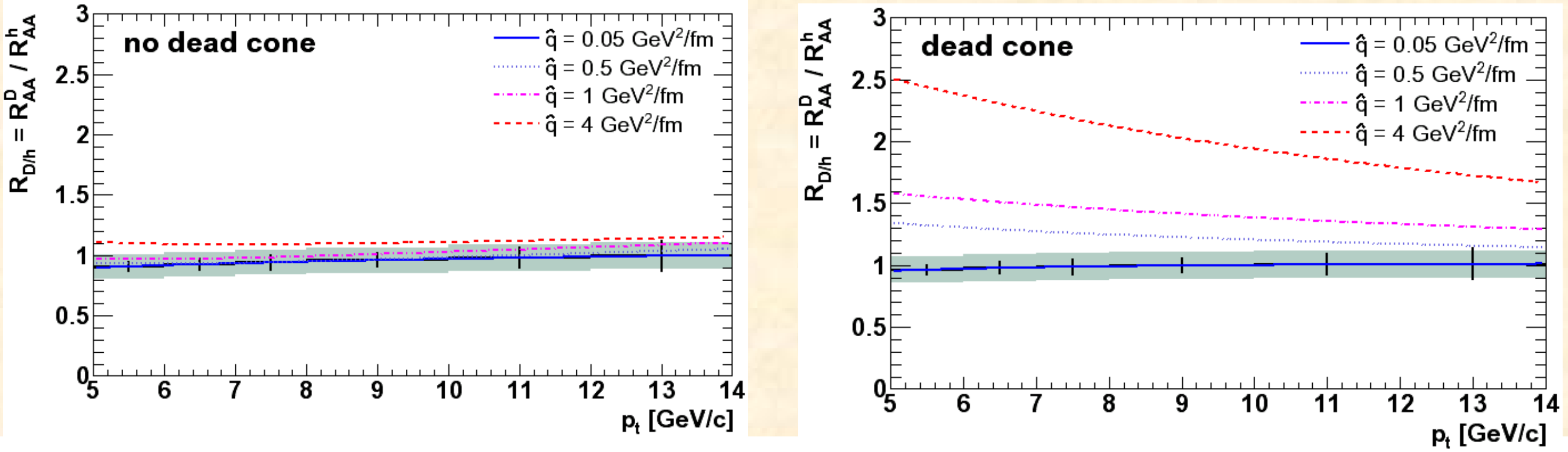
A.Dainese nucl-ex/0311004



$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$

- **Ratio D/hadrons (or D/π^0) enhanced and sensitive to medium properties**

D/hadrons ratio (2)



$p_t^{\text{hadron}} = z\, p_t^{\text{parton}}$ $(p_t^{\text{parton}})' = p_t^{\text{parton}} - \Delta E$

→ $(p_t^{\text{hadron}})' = p_t^{\text{hadron}} - z\, \Delta E$

Energy loss observed in R_{AA} is not ΔE but $z\Delta E$

$z_{c\rightarrow D} \approx 0.8$; $z_{\text{gluon}\rightarrow\text{hadron}} \approx 0.4$ (for p_t>5 GeV/c)

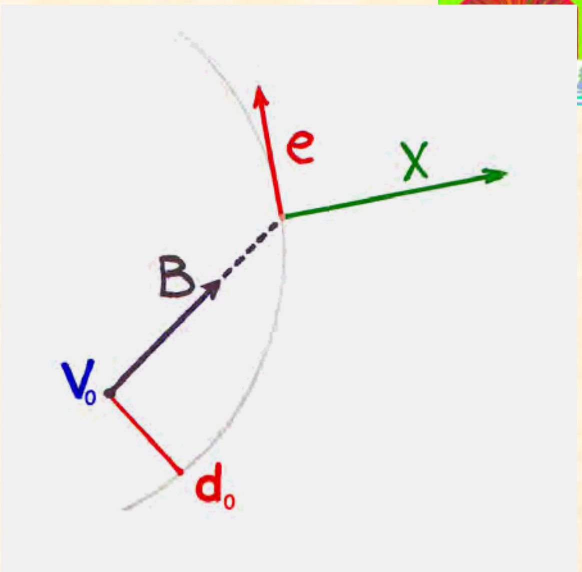
$\Delta E_c = \Delta E_{\text{gluon}}/2.25$ (w/o dead cone)

$$z_{c\rightarrow D}\, \Delta E_c \approx 0.9\, z_{\text{gluon}\rightarrow\text{hadron}}\, \Delta E_{\text{gluon}}$$

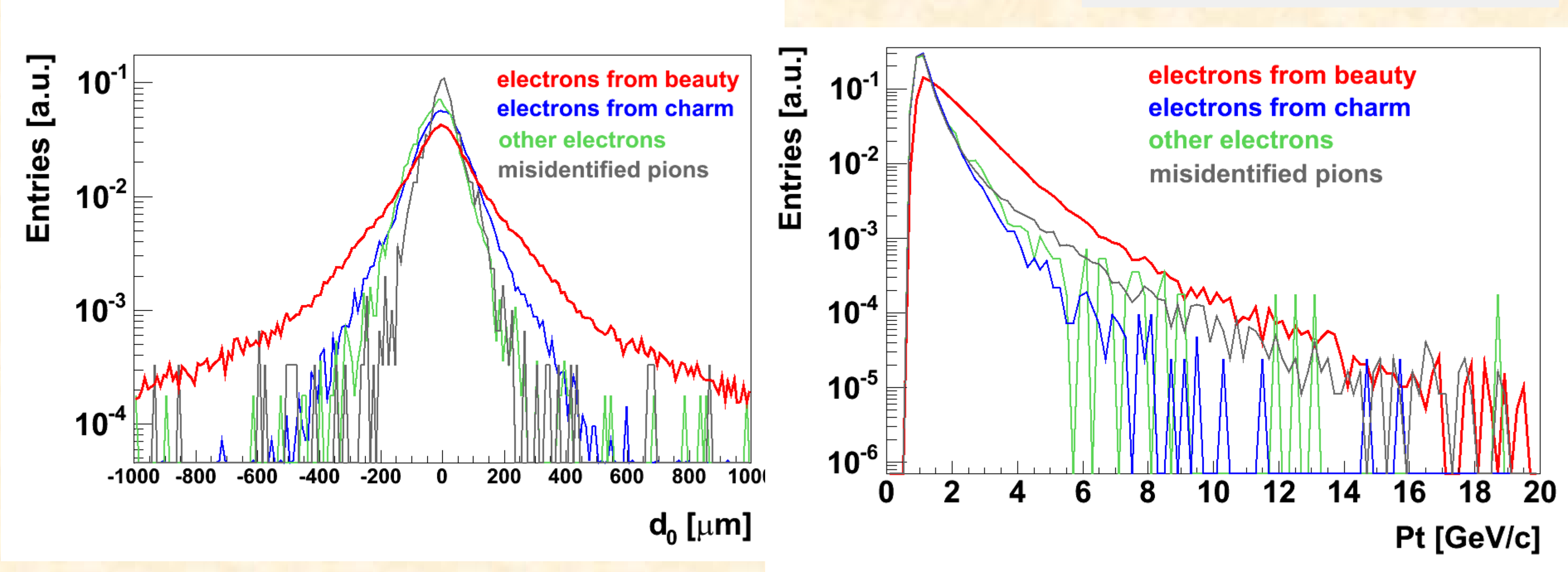
→ Without dead cone, $R_{AA}^D \approx R_{AA}^h$

Beauty: semi-leptonic decays

detection strategy



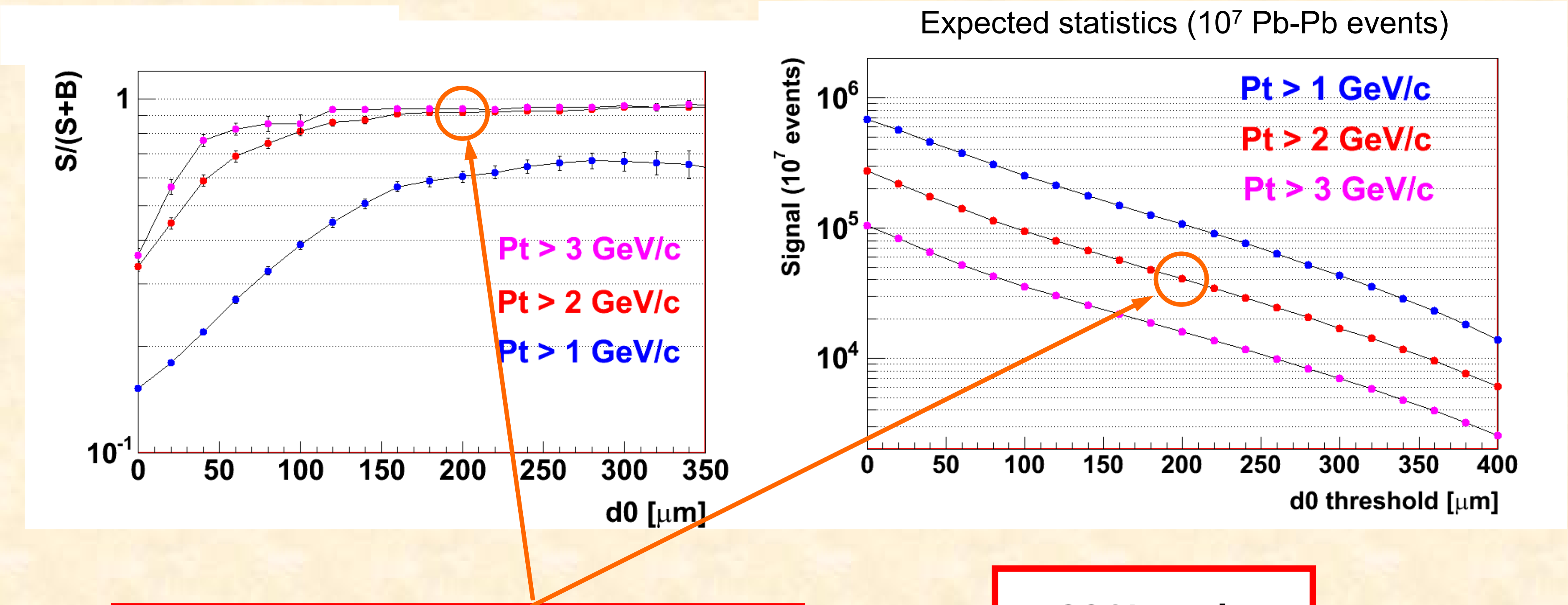
d_0 and p_T distributions for "electrons" from different sources:



Distributions normalized to the same integral in order to compare their shapes

Semi-electronic Beauty detection
simulation results

Signal-to-total ratio and expected statistics in 10^7 Pb-Pb events



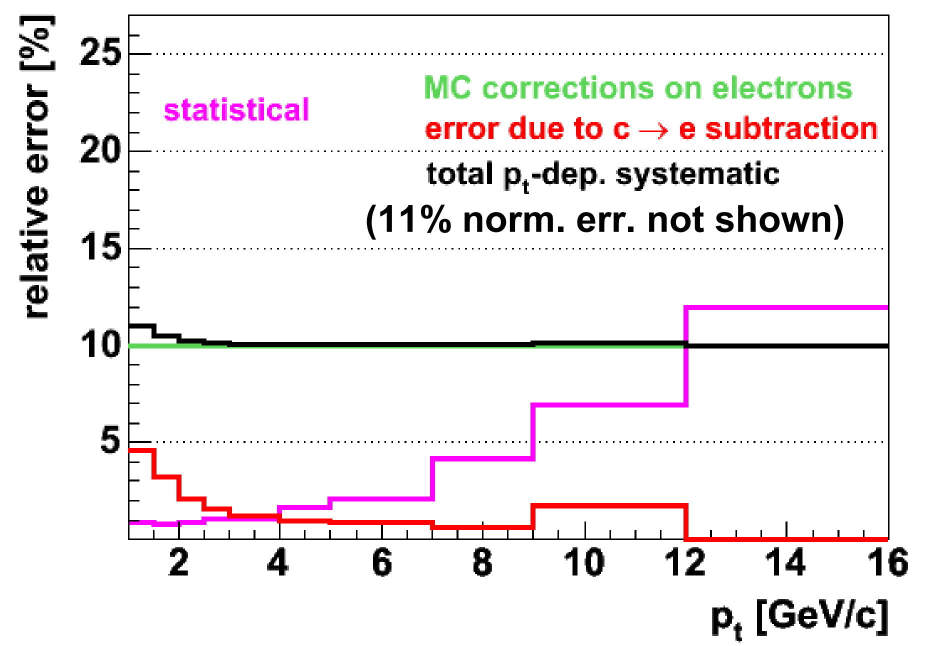
$p_T > 2$ GeV/c , $200 < |d_0| < 600$ μm ⇨

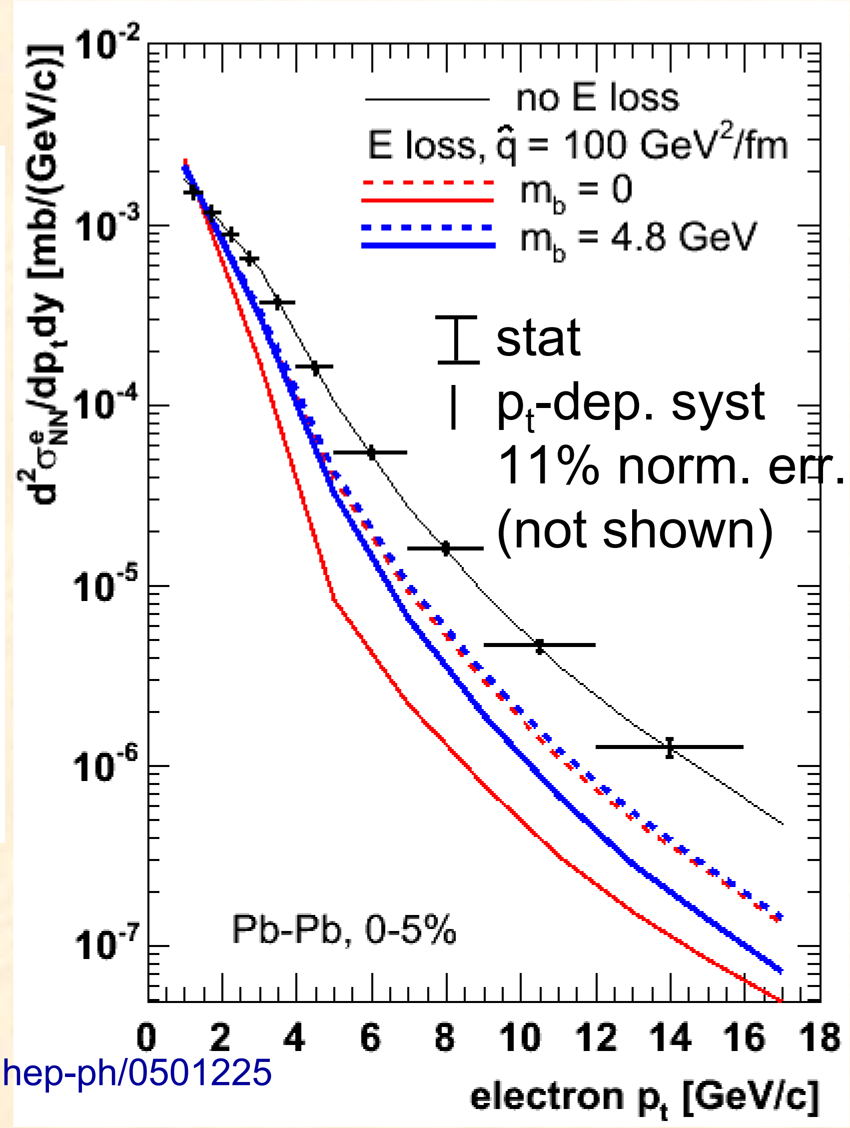
90% purity

40,000 e from B

Estimation of uncertainties on the p_T - differential cross section of beauty electrons

Final B-decay electron p_T distribution





E loss calculations:

N. Amesto, A. Dainese, C.A. Salgado, U.A. Wiedemann, hep-ph/0501225

Extraction of a minimum-p_T-differential cross section for B mesons

Using UA1 MC method (*), also adopted by ALICE μ

The B meson cross section per unit of rapidity at midrapidity with $p_T^B > p_T^{min}$ is obtained from a scaling of the electron-level cross section measured within a given electron phase space Φ^e

$$\frac{d\sigma^B}{dy}(p_T^B > p_T^{\min}) = \sigma^{e,beauty}(\Phi^e)\Big|_{meas} \times \left. \frac{\frac{d\sigma^B}{dy}(p_T^B > p_T^{\min})}{\sigma^B(\Phi^e)} \right|_{MC}$$

The semi-electronic B.R. is included here

$$= \sigma^{e,beauty}(\Phi^e)\Big|_{meas} \times \mathcal{F}_{e\to B}$$

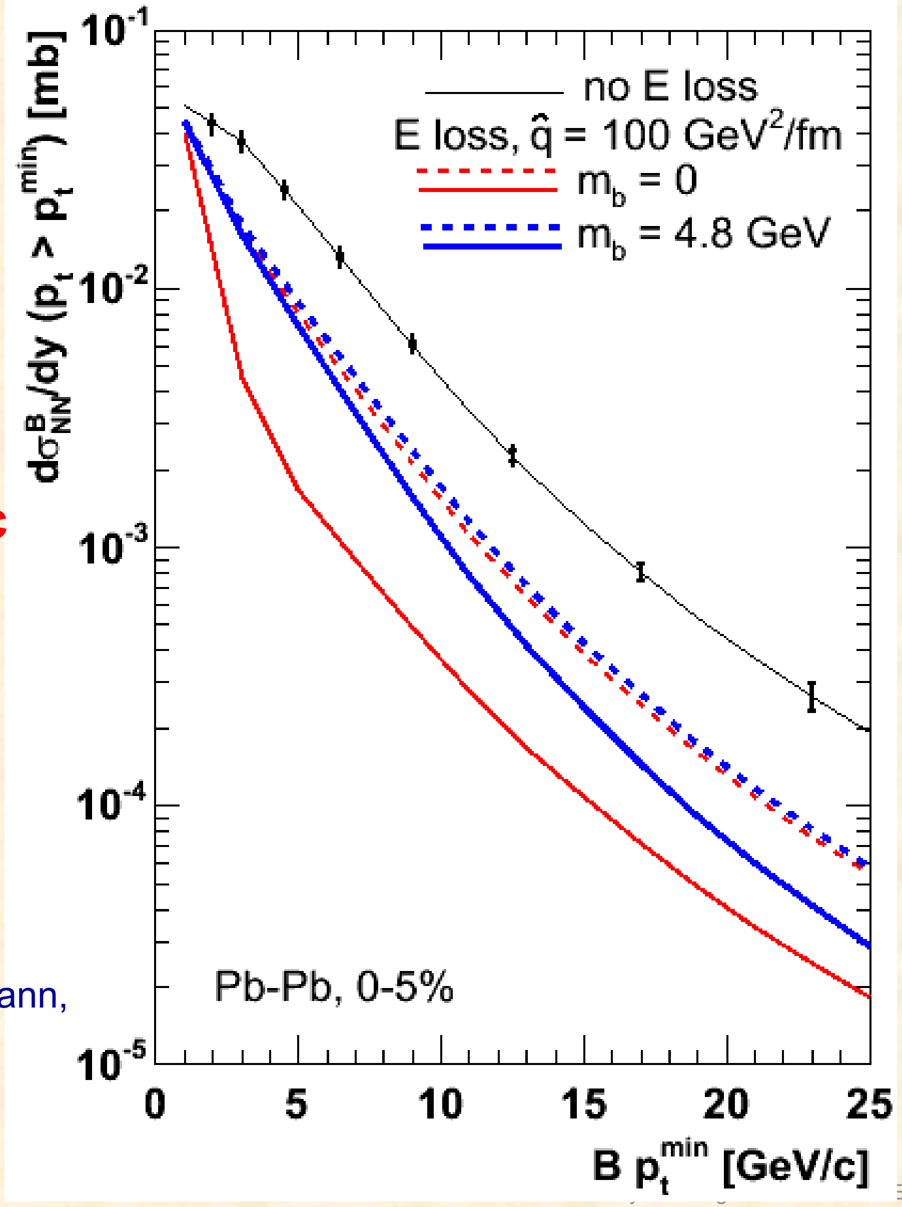
The phase space used is $\Phi^e \equiv \{\Delta p_T, \Delta\eta, \Delta d_0\}$ where Δp_T are the previously used bins, $\Delta\eta$ = [-0.9, 0.9] and Δd_0 = [200,600] μm

(*) C. Albajar et al., UA1 Coll., Phys Lett B213 (1988) 405
C. Albajar et al., UA1 Coll., Phys Lett B256 (1991) 121

Extraction of a minimum-p_T-differential cross section for B mesons

Using electrons in $2 < p_T < 16$ GeV/c

obtain B-meson $2 < p_T^{min} < 23$ GeV/c



⌶ stat

| p_t-dep. syst

11% norm. err.

(not shown)

E loss calculations:

N. Amesto, A. Dainese,

C.A. Salgado, U.A. Wiedemann,

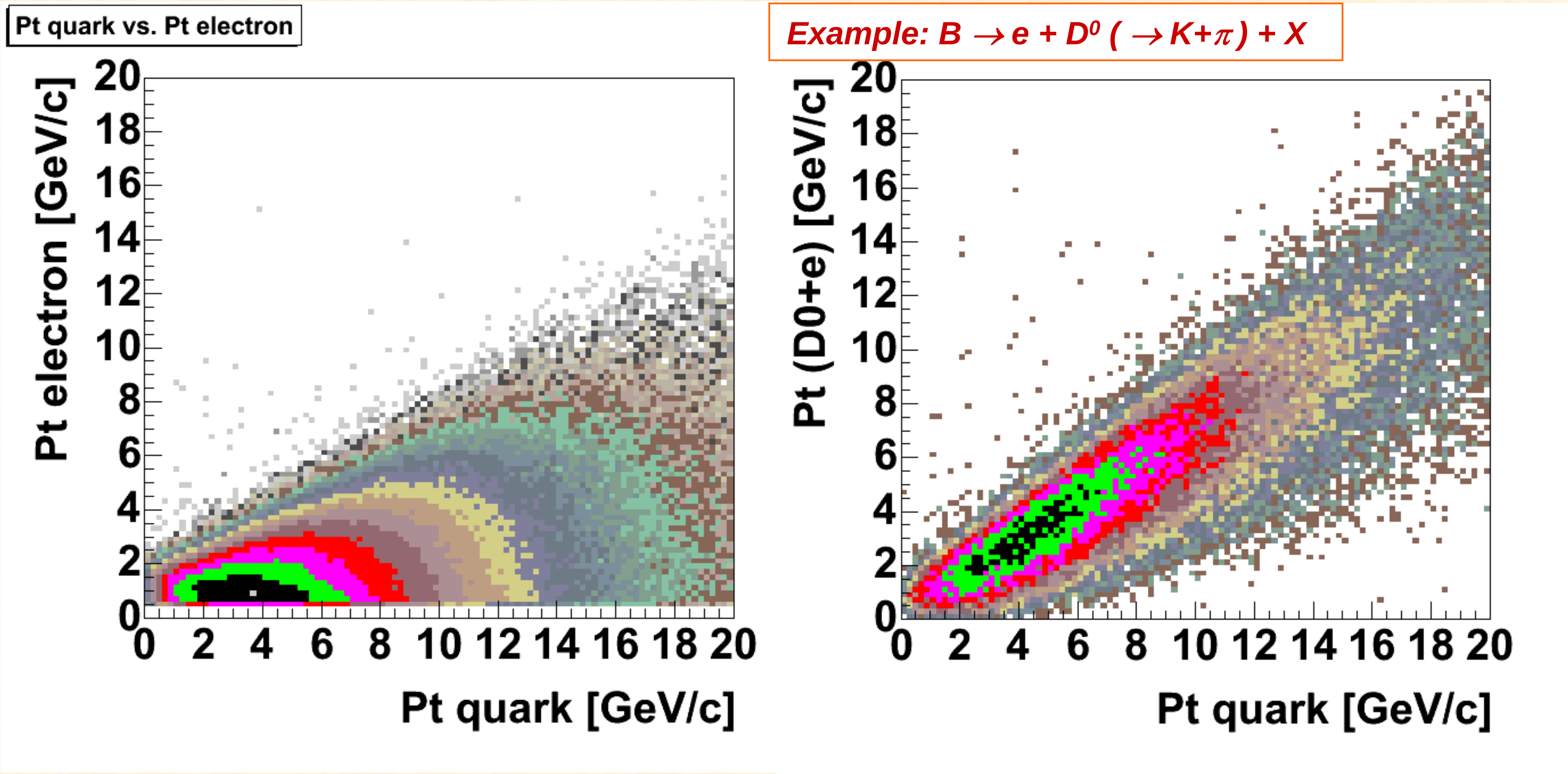
hep-ph/0501225

Semi-electronic Beauty detection + X

p_T quark distribution

Under study B → e X and use
charged particle in X with displaced vertex – b jet tagging

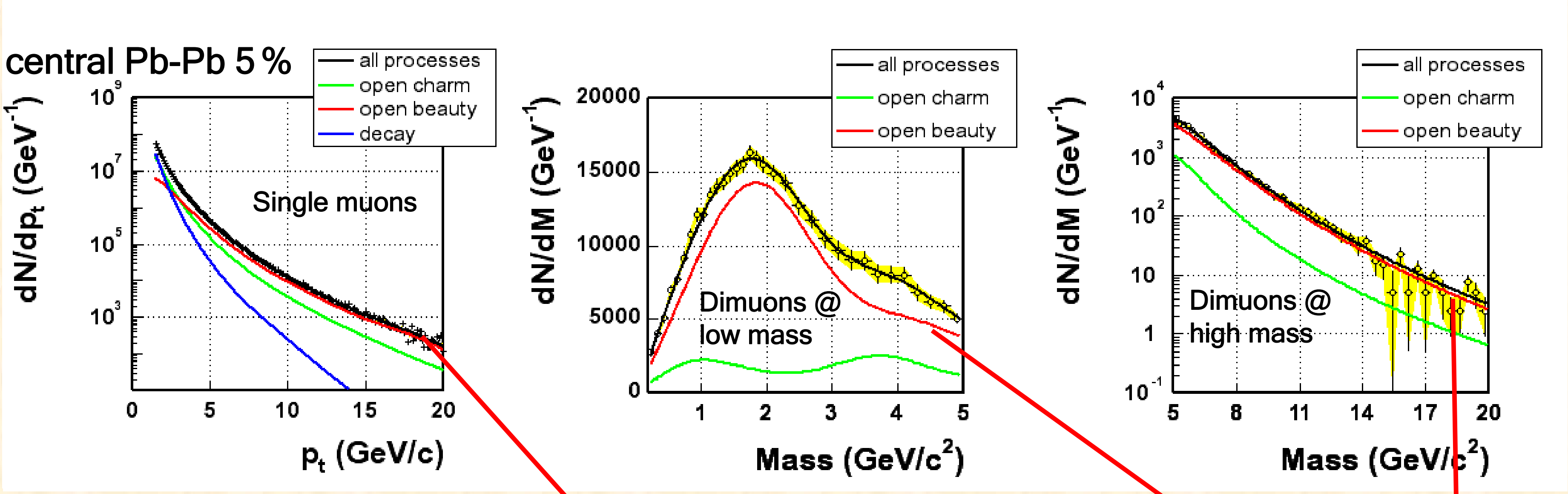
Analysis of the electron p_T distribution useful for beauty production cross section measurement. But, what about the quark p_T distribution?



Beauty from muon raw yields

- Fits with fixed shapes from the Monte Carlo & beauty amplitude as the only free parameter (next: tray c also free)
- Uses 3 different data samples

$\mathcal{L} = 5\times10^{26}\,\mathrm{cm^{-2}s^{-1}}$



(Very) large statistics is expected

M (GeV/c^2)	0 - 5	5 - 20
$N_{\mu\mu}$ from bb	39678 ± 180	6314 ± 71

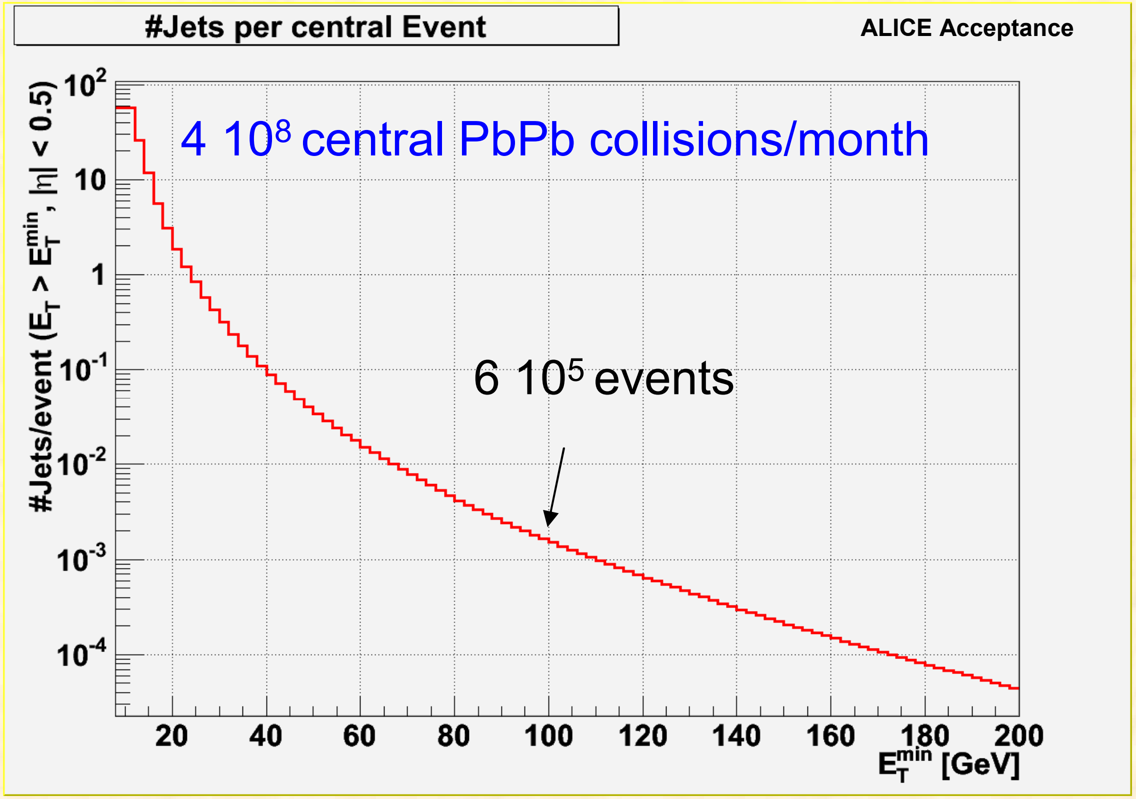
p_t (GeV/c)	1.5 - 2	2 – 2.5	2.5 - 3	3 - 4	4 - 5	5 - 6	6 - 9	9 - 12	12 - 15	15 - 20	20 - 100
N_μ from b	$2.7\ 10^6 \pm 620$	$1.8\ 10^6 \pm 675$	$1.1\ 10^6 \pm 636$	$1.0\ 10^6 \pm 684$	$4\ 10^5 \pm 474$	$1.7\ 10^5 \pm 326$	$1.3\ 10^5 \pm 294$	$2.1\ 10^4 \pm 123$	$5\ 10^3 \pm 60$	$1.8\ 10^3 \pm 38$	474 ± 30

Jet reconstruction

- **Jets are produced copiously**

2 20 100 200 p_t (GeV)

100/event 1/event 100K/year



4 10^8 central PbPb collisions/month

6 10^5 events

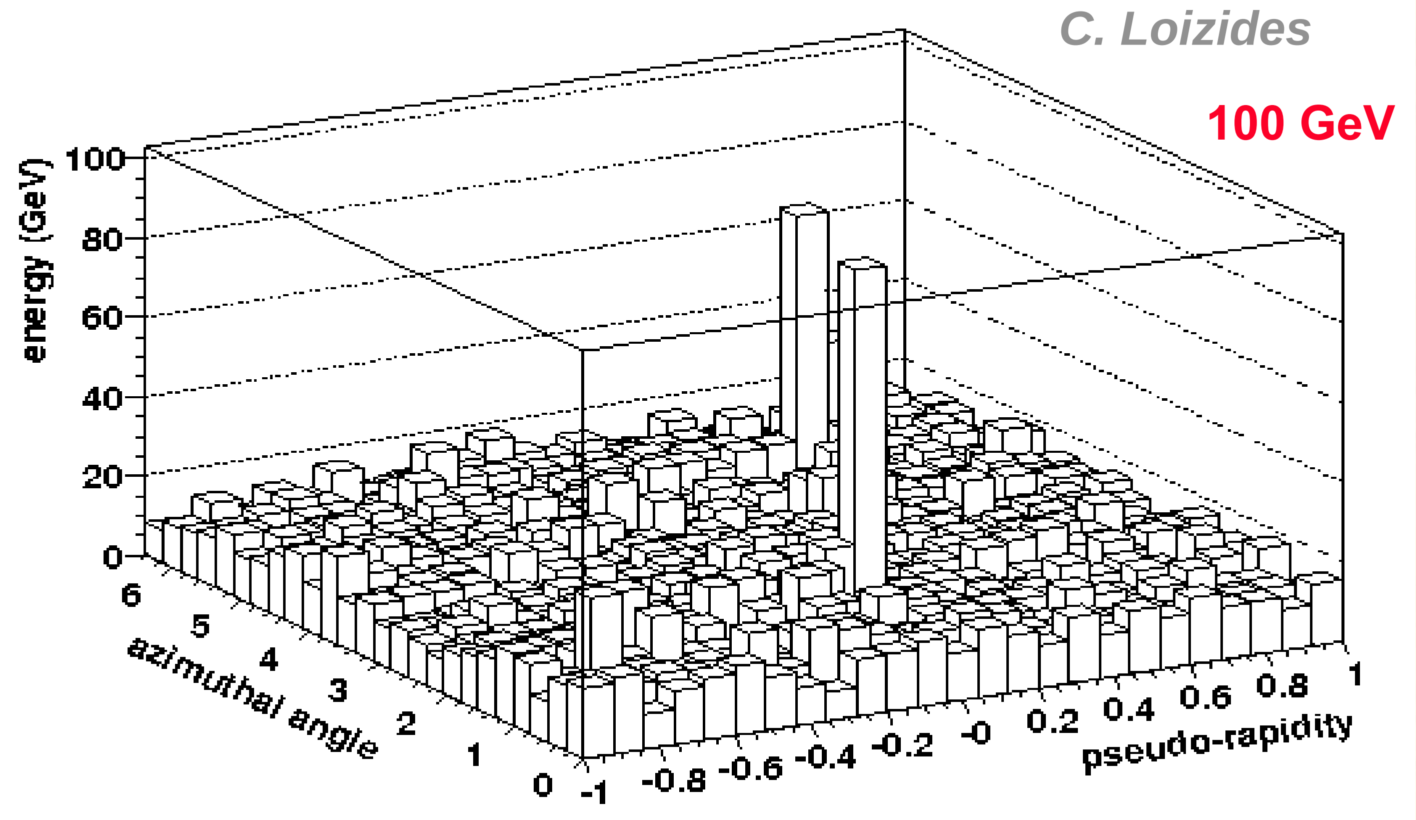
E
d
R

E_T threshold	N_{jets}
50 GeV	**2×10^7**
100 GeV	**6×10^5**
150 GeV	**1.2×10^5**
200 GeV	**2.0×10^4**

50 – 100 GeV jets in Pb–Pb

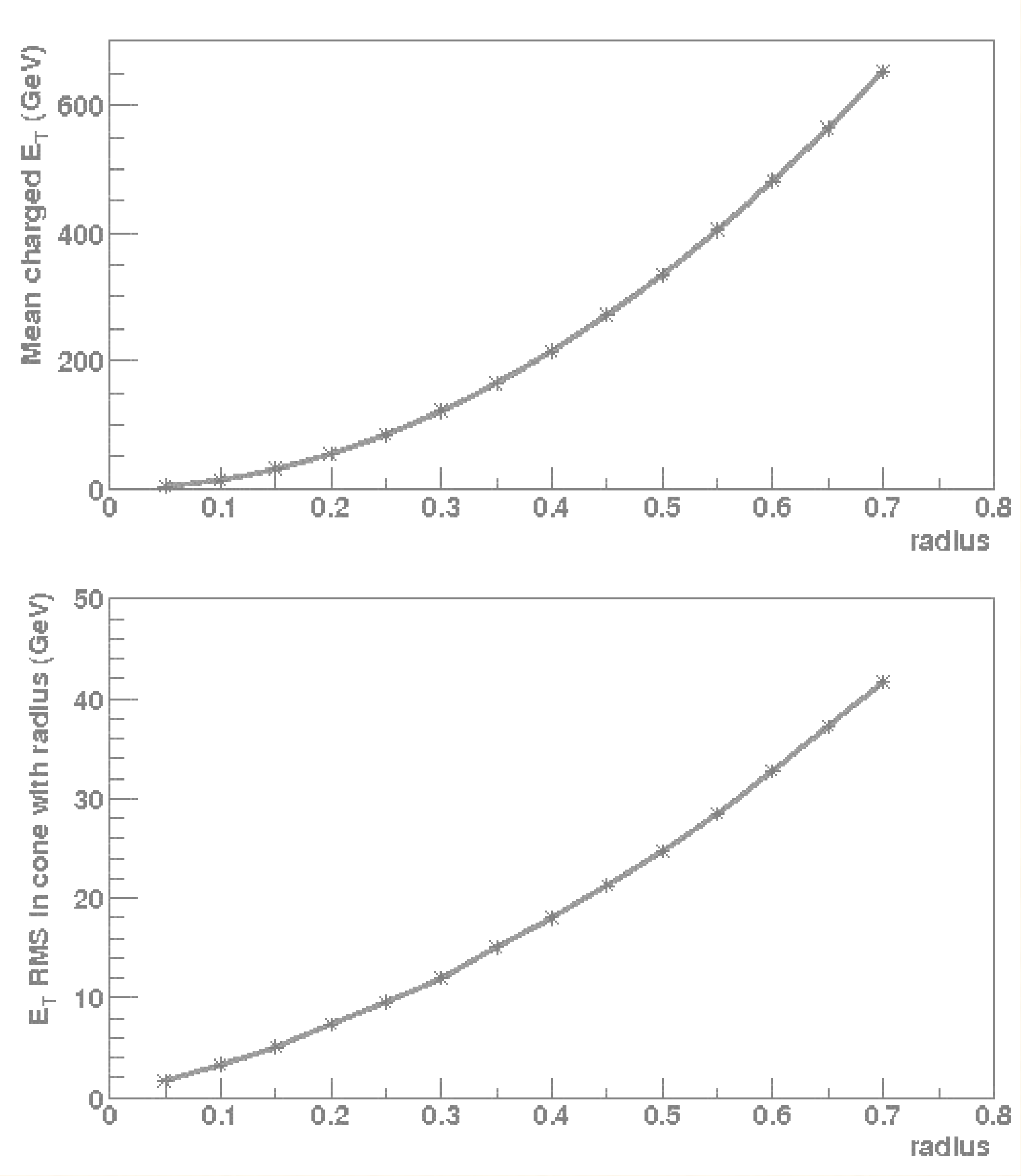
At large enough jet energy – jet clearly visible
But still large fluctuation in underlying energy

η–φ lego plot with Δη 0.08 × Δφ 0.25



Central Pb–Pb event (HIJING simulation) with 100 GeV di-jet (PYTHIA simulation)

Energy fluctuation in UE

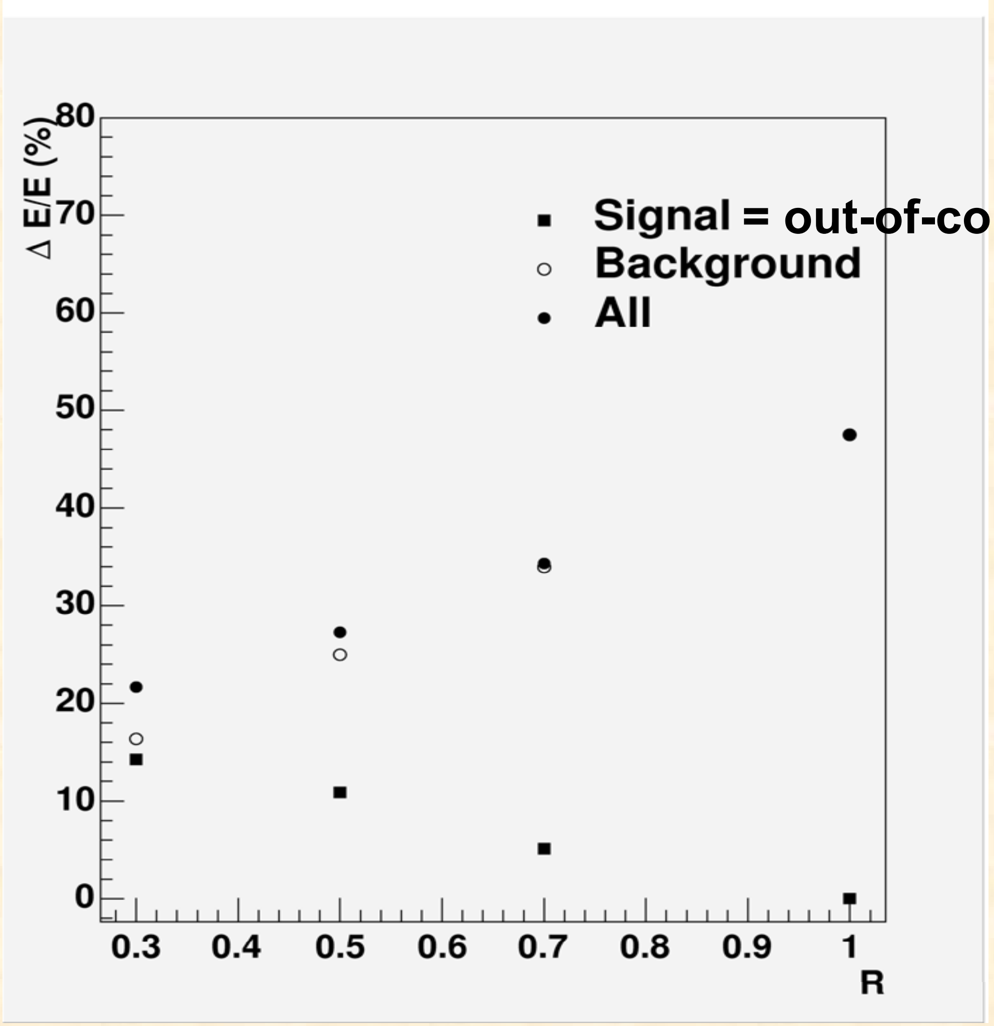


Mean energy in a cone of radius R coming from underlying event

Fluctuation of energy from an underlying event in a cone of radius R

More quantitatively ...

Intrinsic resolution limit for E_T = 100 GeV



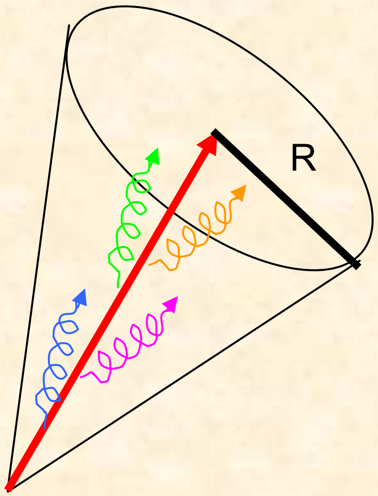
For R < 0.3:

Δ*E*/*E* = 16% from Background
(conservative d*N*/dy = 5000)

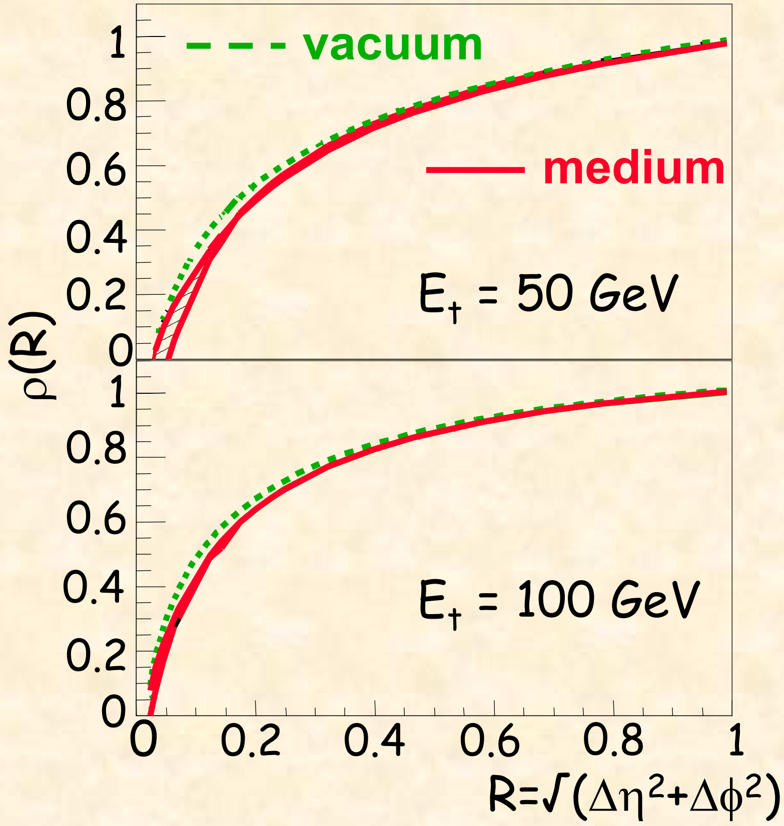
14% from out-of-cone fluctuations

Jet quenching

- **Excellent jet reconstruction… but challenging to measure medium modification of its shape…**



Medium induced redistribution of jet energy occurs inside cone



C.A. Salgado, U.A. Wiedemann hep-ph/0310079

- **E_t=100 GeV (reduced average jet energy fraction inside R):**
  - **Radiated energy ~20%**
  - **R=0.3 $\Delta E/E$=3%**
  - **E_t^{UE} ~ 100 GeV**

Irreducible limits on jet energy resolution

- Small radius of jet cone (R = 0.3)
  - we don't see 30% of energy
  - underlying event fluctuation ~ 15 GeV – 15% for 100 GeV jet

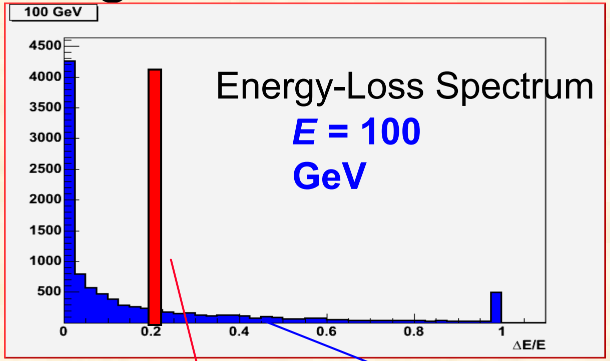
- Larger jet-cone radius (R = 0.7)
  - we don't see 10% of energy
  - underlying event fluctuation ~ 45 GeV – 45% for 100 GeV jet

- We cannot just add non-seen energy outside jet cone
  - as is usually done in pp where jet shape is known
  - that depends on energy distribution which we have to study

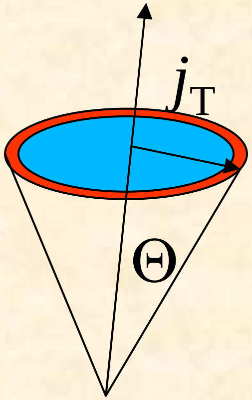
- It's impossible to know jet energy better than 25 – 30% (for 100 GeV jets)
  - we are now at 34 %, pretty close…

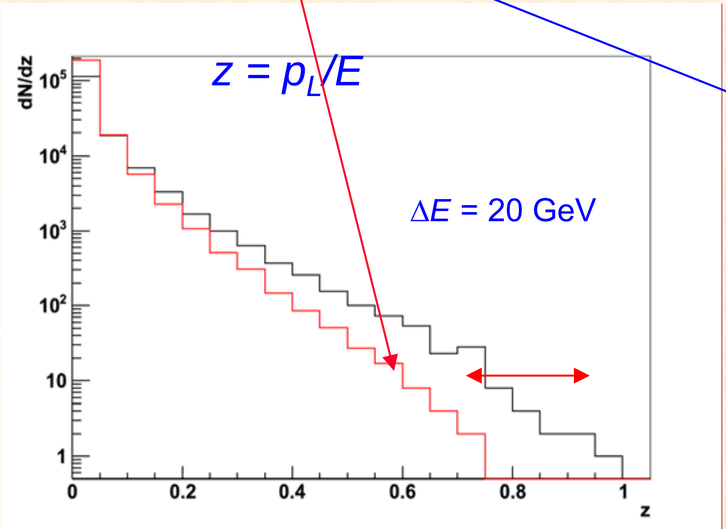
Jet structure observables at the LHC

- **How close can we get to the ideal case**
  - **Measure unquenched parton energy by measuring the jet energy.**
  - **Determine energy loss and transverse heating by measuring the fragmentation function and k_T spectra.**

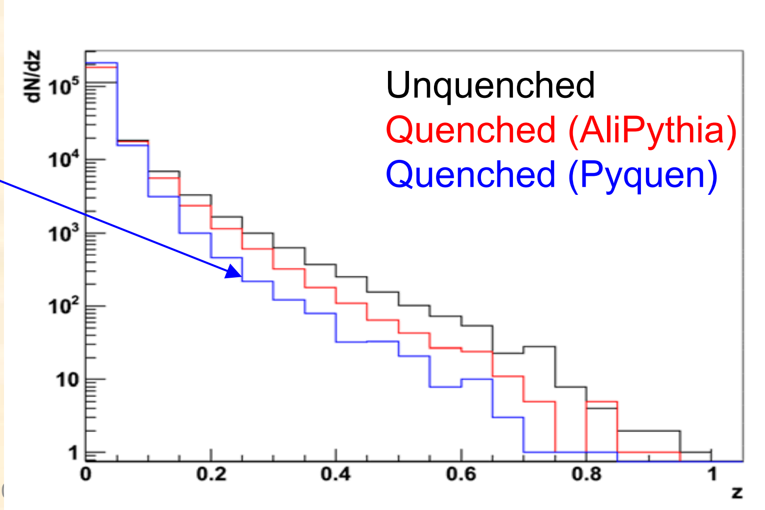

Energy-Loss Spectrum

E = 100 GeV




$z = p_L/E$

Δ*E* = 20 GeV

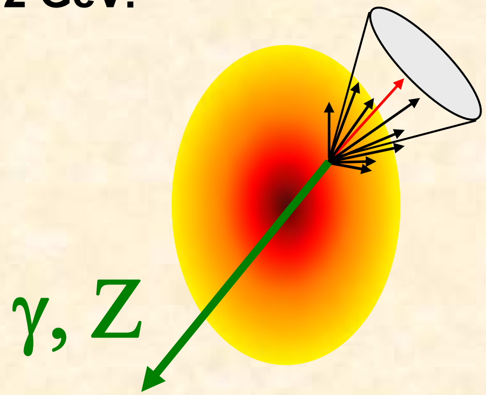

Unquenched

Quenched (AliPythia)

Quenched (Pyquen)

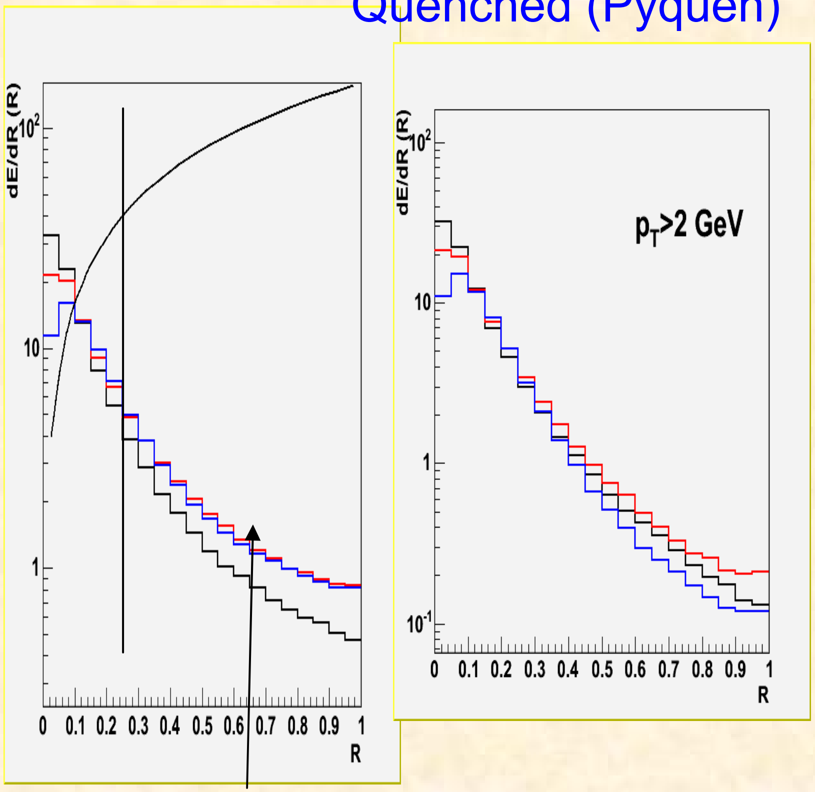
Limit experimental bias ...

- **By measuring the jet profile inclusively.**
  - ⇨ **Low-p_T capabilities are important since for quenched jets sizeable fraction of energy will be carried by particles with p_T < 2 GeV.**



- **Exploit γ-jet correlation**
  - ⇨ **$E_\gamma = E_{jet}$**
  - ⇨ **Caveat: limited statistics**
    - ✪ **$\mathcal{O}(10^3)$ smaller than jet production**
  - ⇨ **Does the decreased systematic error compensate the increased statistical error ?**
  - ⇨ **Certainly important in the intermediate energy region 20 < E_T < 50 GeV.**

Quenched (AliPythia)
Quenched (Pyquen)

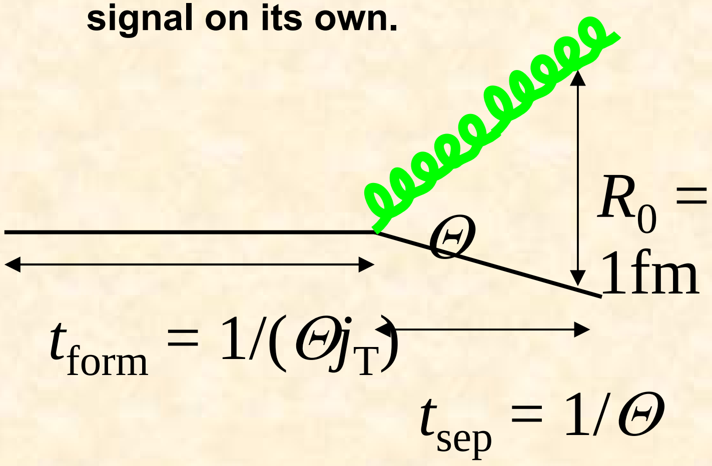


Energy radiated outside core

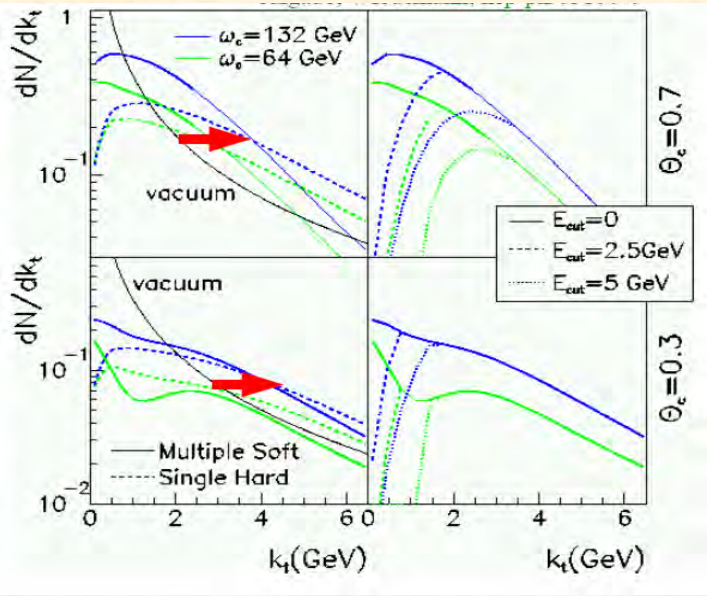
Not visible after p_T-cut.

Jet structure observables: k_T

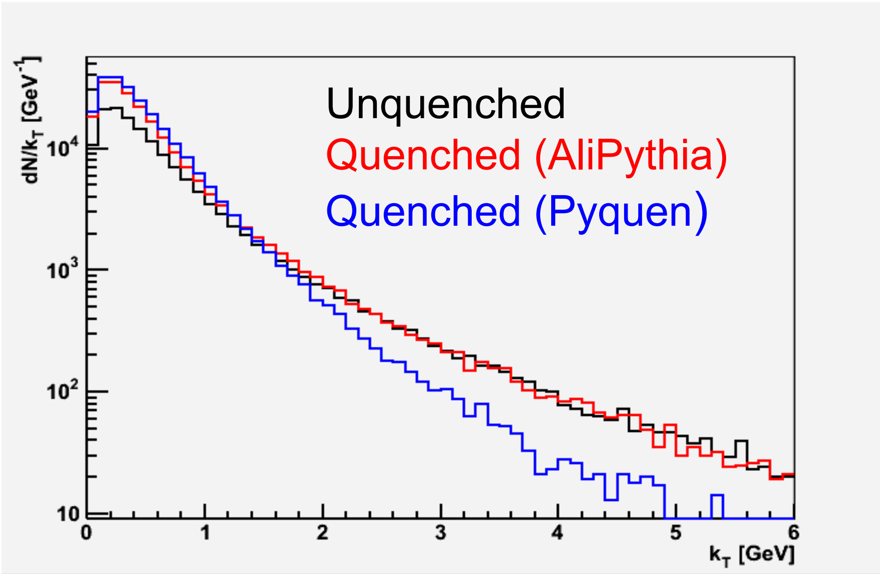
- **Unmodified jets characterized by $<k_T>$ = 600 MeV ~ const(R).**
- **Partonic energy loss alone would lead to no effect or even a decrease of $<k_T>$.**
    - ⇨ **Transverse heating is an important signal on its own.**



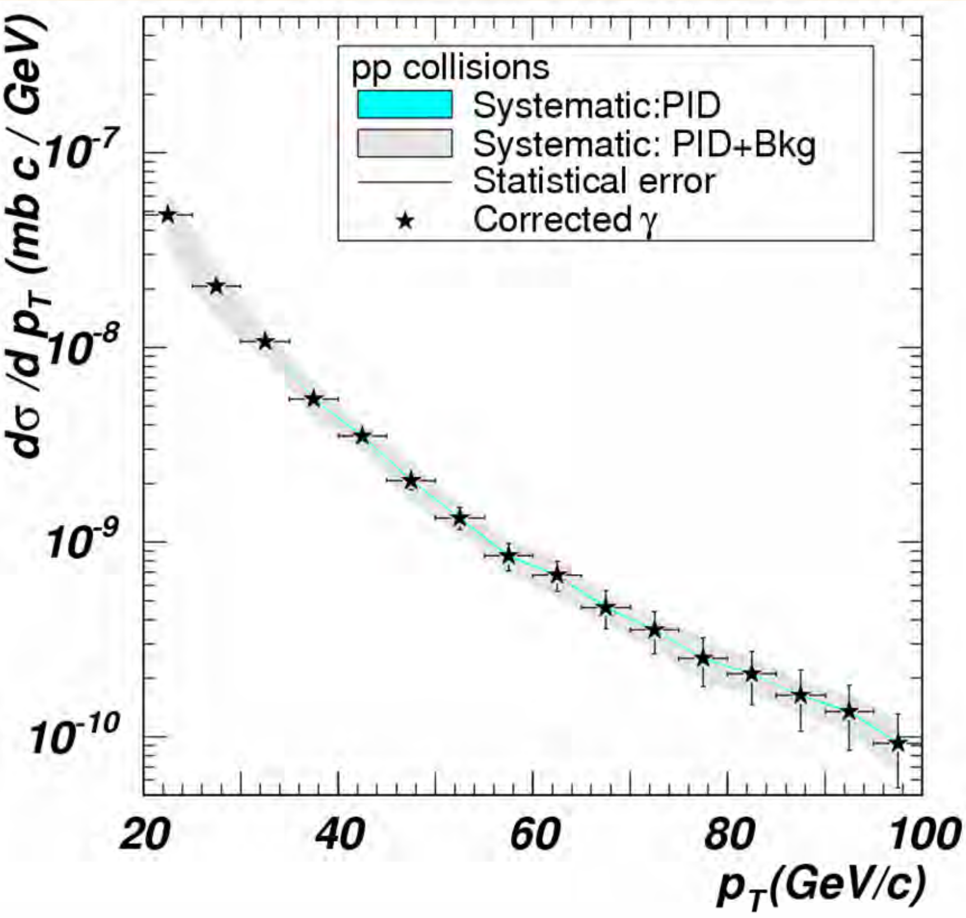
- **Relation between R and formation time of hard final state radiation.**
    - ⇨ **Early emitted final state radiation will also suffer energy loss.**
    - ⇨ **Watch for R – dependence of $<k_T>$!**

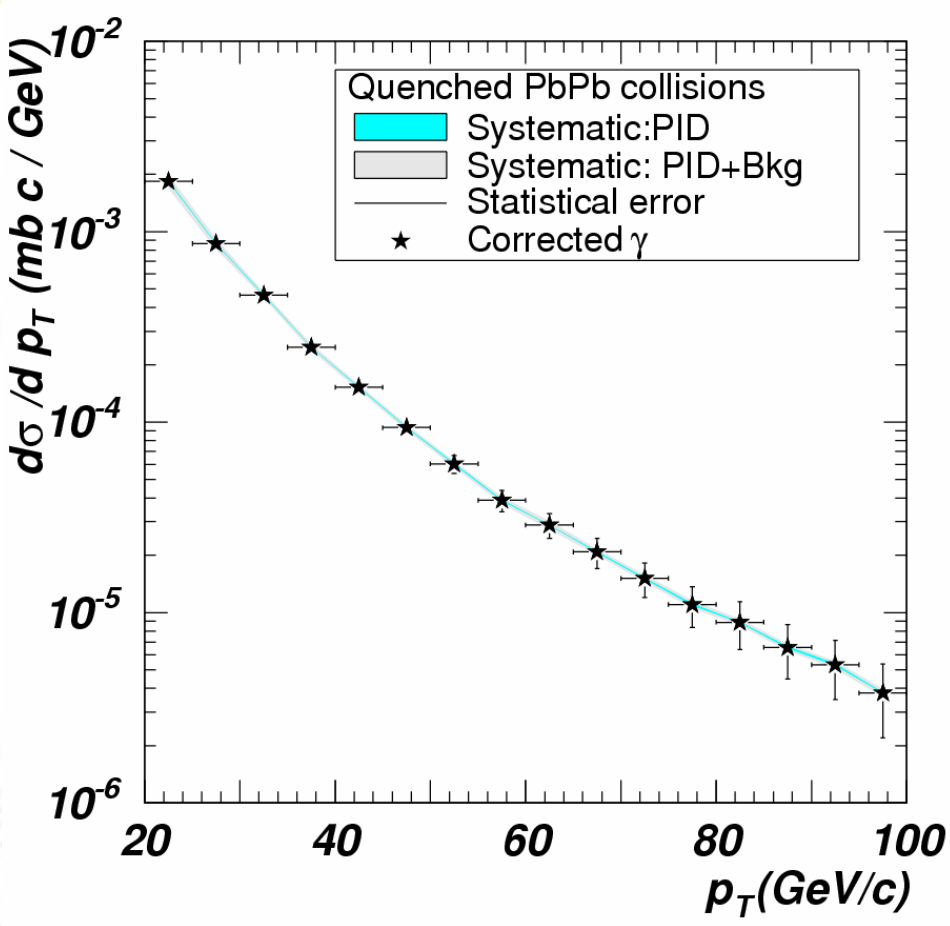


Salgado, Wiedemann, hep-ph/0310079



Prompt γ spectrum (1 year running)

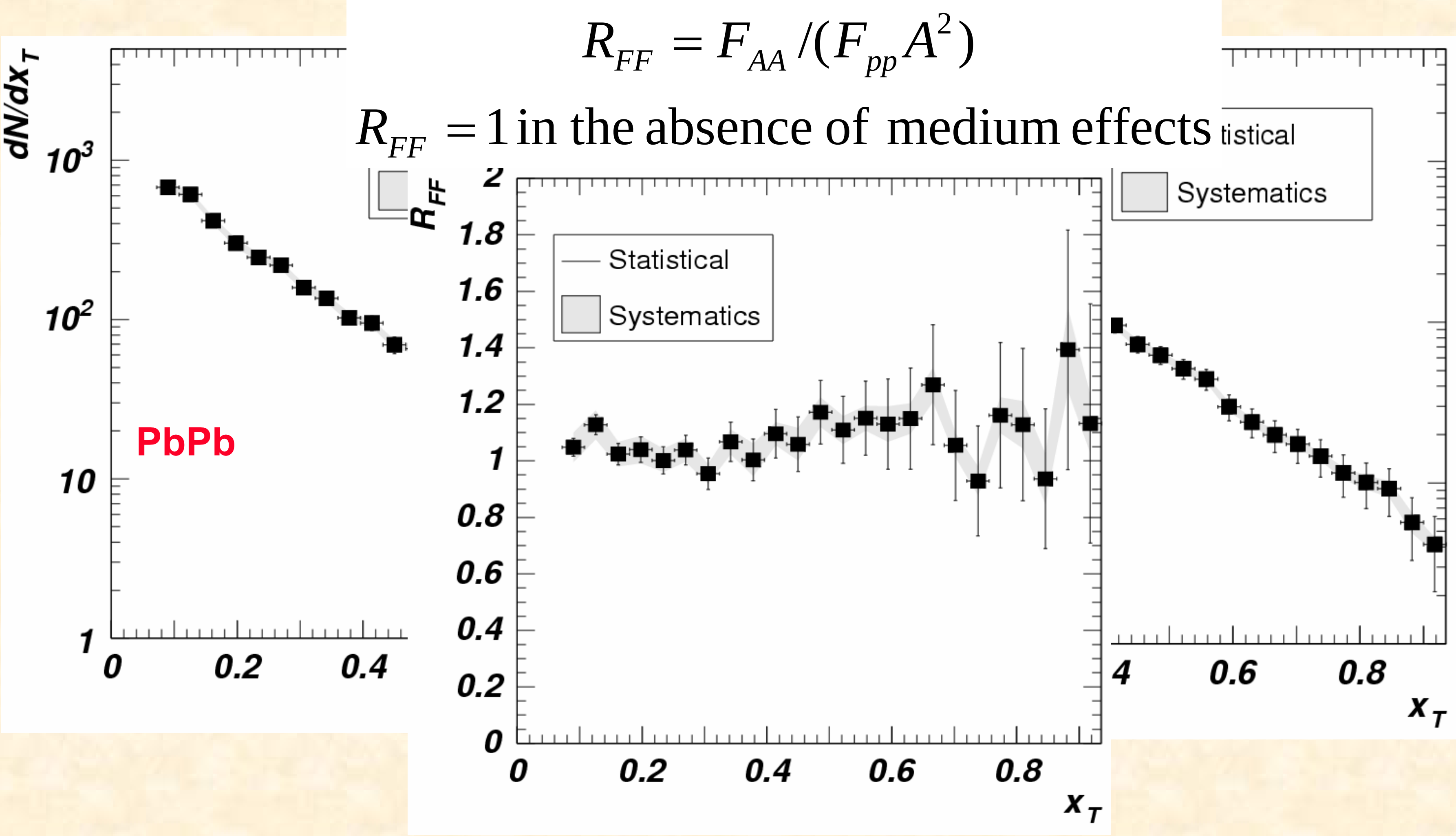




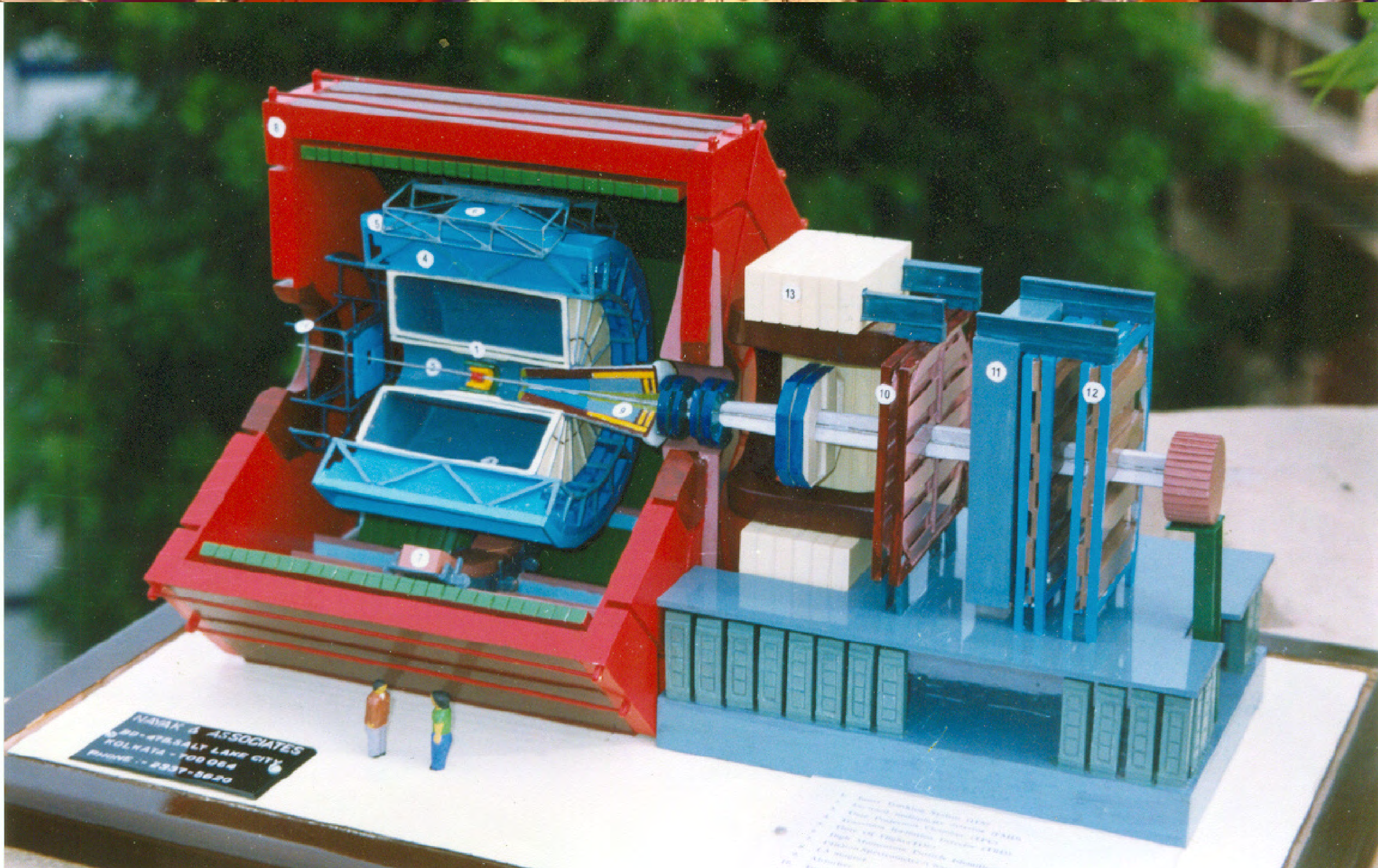
Fragmentation functions: γ jet

$$R_{FF} = F_{AA} / (F_{pp} A^2)$$

$$R_{FF} = 1 \text{ in the absence of medium effects}$$



ALICE already exists



Summary

Looking forward to fill the empty space