Studying charm production and quenching with ALICE

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Physics at LHC

13-17 July 2004 . Vienna . Austria

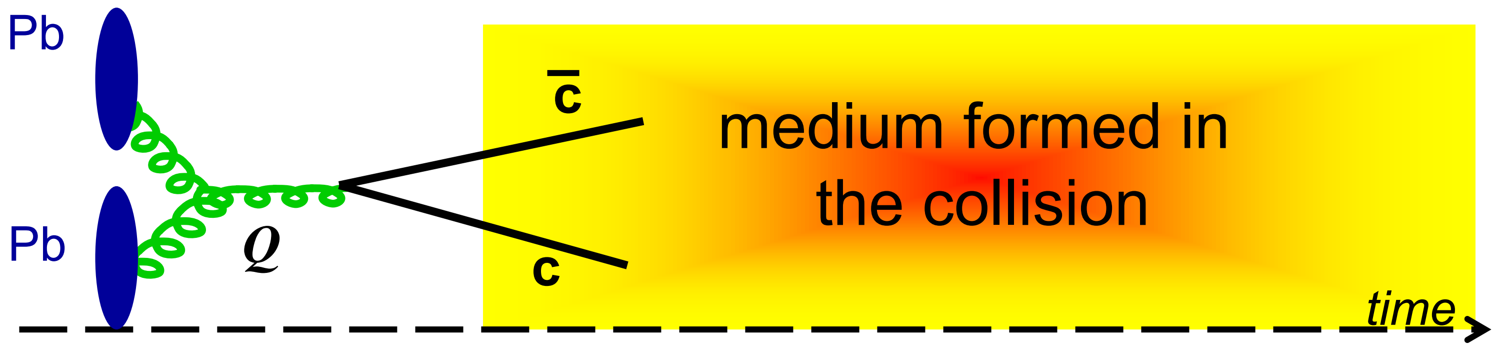
Outline

- Hard probes in heavy-ion collisions
- Parton energy loss (for heavy quarks)
- Exclusive charm reconstruction via $D^0 \rightarrow K\pi$ in ALICE
- Sensitivity to charm energy loss
- Conclusions

Hard Processes in AA at the LHC

- Main novelty of the LHC: **large hard cross section**
- **Hard processes are extremely useful tools**
  - **large virtuality Q → happen at $t = 0$**
    → small "formation time" $\Delta t \sim 1/Q$

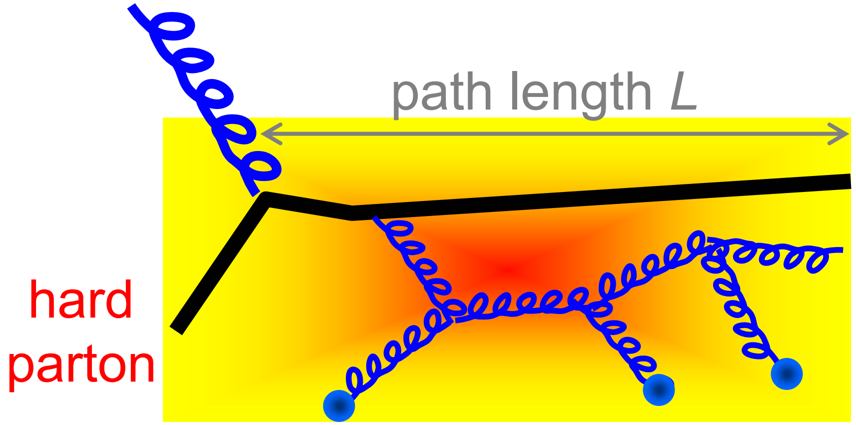
(for charm: $\Delta t < 1/2m_c \sim 0.1$ fm/c << $\tau_{QGP} \sim 5$–10 fm/c)



- Initial yields and p_t distributions in AA can be predicted using pp measurements + pQCD + collision geometry + "known" nuclear effects
- **Interactions with the medium can induce deviations from such predictions**

Parton Energy Loss

- Due to medium-induced gluon emission



QCD process: gluon-gluon interference effects

$\Rightarrow \Delta E \propto L^2$

- Average energy loss (BDMPS model):

$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

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].

Lower Loss for Heavy Quarks?

- **Heavy quarks** with momenta < 20–30 GeV/c $\rightarrow$ $v \ll c$
- **In vacuum, gluons radiation suppressed at $\Theta < m_Q/E_Q$**

  → **"dead cone" effect**
- ***Dead cone implies lower energy loss*** (Dokshitzer-Kharzeev, 2001)
- ***Recent detailed calculation confirms this qualitative feature*** (Armesto-Salgado-Wiedemann, 2003) see talk by N.Armesto

⇒ **D mesons quenching reduced (?)**

⇒ **Ratio D/charged (or D/π^0) enhanced (?) and sensitive to medium properties**

Yu.L.Dokshitzer, V.A.Khoze and S.I.Troyan, J. Phys. **G17** (1991) 1602.
Yu.L.Dokshitzer and D.E.Kharzeev, Phys. Lett. **B519** (2001) 199 [arXiv:hep-ph/0106202].
N.Armesto, C.A.Salgado and U.A.Wiedemann, arXiv:hep-ph/0312106.

Experimental study of energy loss

- **Compare p_t distributions of leading particles in pp and nucleus-nucleus collisions** (+ p-nucleus as a control)

Nuclear modification factor:
see talk by J. Harris

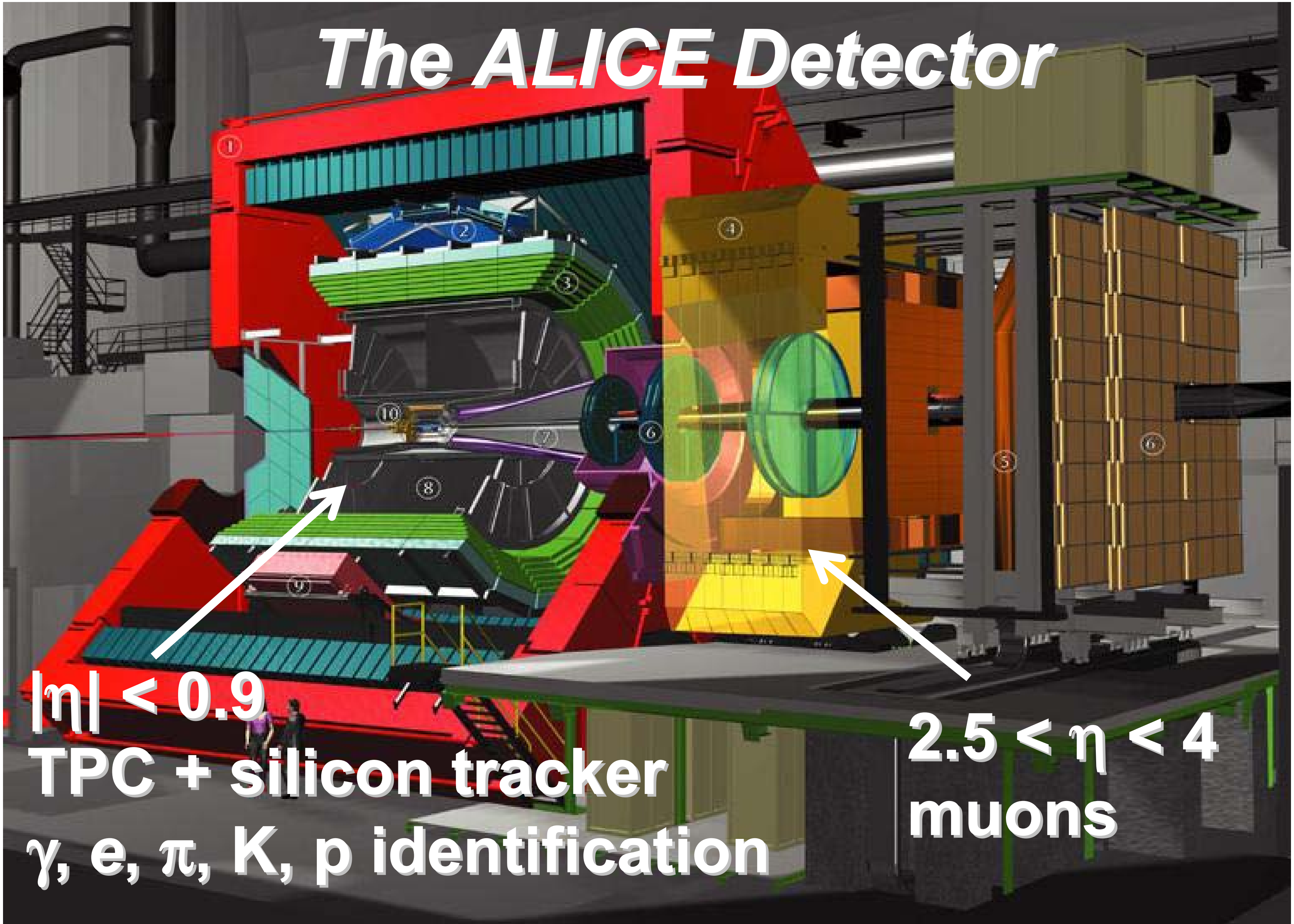
$$R_{AA}(p_t) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$

→ Important step forward at the LHC:

Compare quenching of **massless** and **massive probes**

- **Study jets:**
  - **jets via particle correlations** (RHIC tells us they can tell a lot!) (see talk by A. Morsch)
  - **jets via calorimetry** (CMS/ATLAS speciality see talks by B. Wyslouch and L. Rosselet)

The ALICE Detector

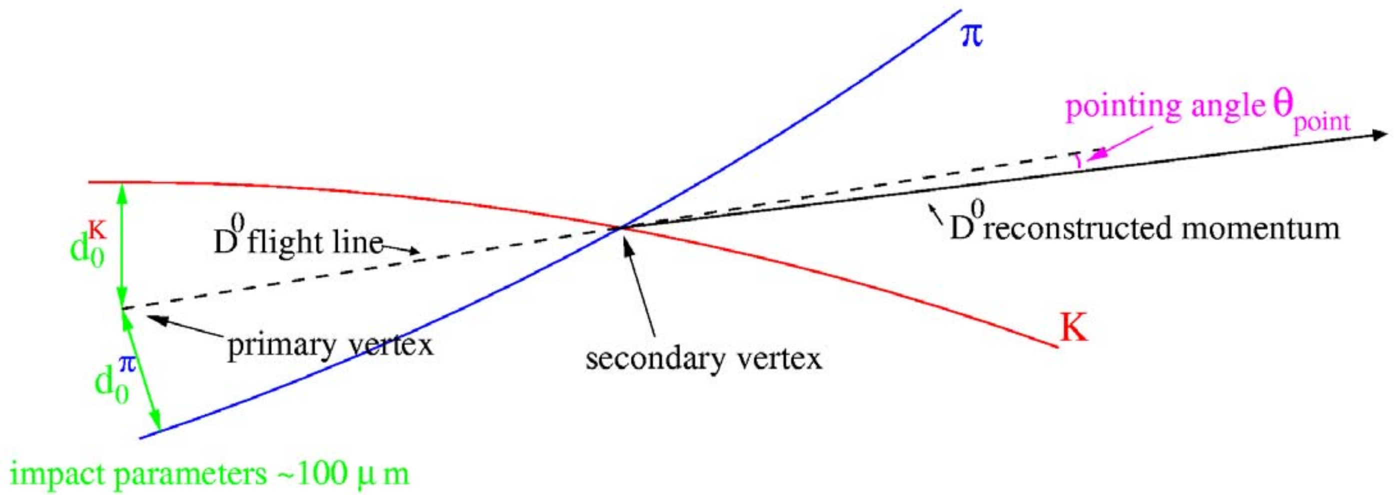


|η| < 0.9
TPC + silicon tracker
γ, e, π, K, p identification

2.5 < η < 4
muons

Exclusive charm in ALICE: $D^0 \to K^-\pi^+$

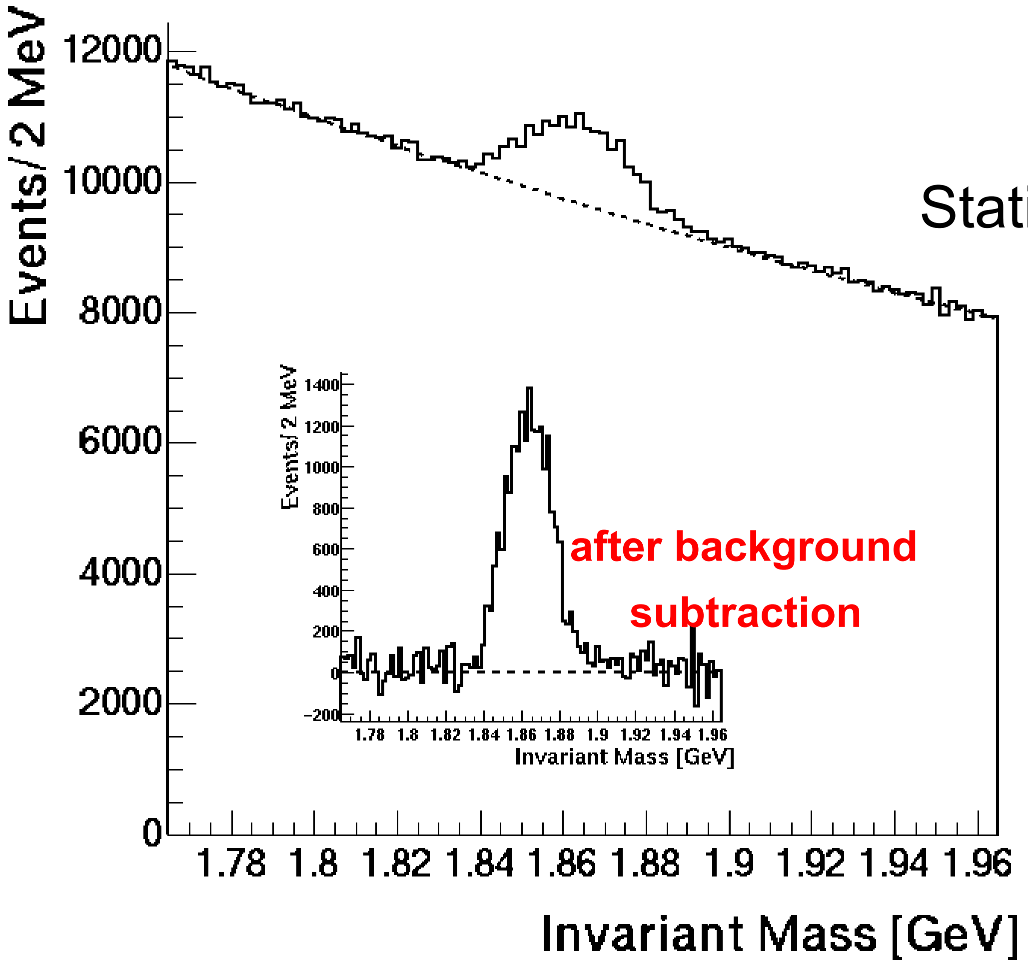
- **Exclusive reconstruction → direct measurement of the p_t distribution → ideal tool to study R_{AA}**
- Large combinatorial background **(dN_{ch}/dy=6000 in central Pb-Pb!)**
- Main selection: displaced-vertex selection
  - pair of opposite-charge tracks with **large impact parameters**
  - **good pointing** of reconstructed D^0 momentum to the primary vertex



→ **Invariant mass analysis to "count" D^0**

Results. Example: Pb-Pb p_t-integrated

(K,π) Invariant Mass distribution (p_t –integrated)
(corresponding to **10^7 central Pb-Pb events ~ 1 month run**)



$$S / B \approx 10\%$$

Statistical Significance of the Signal:

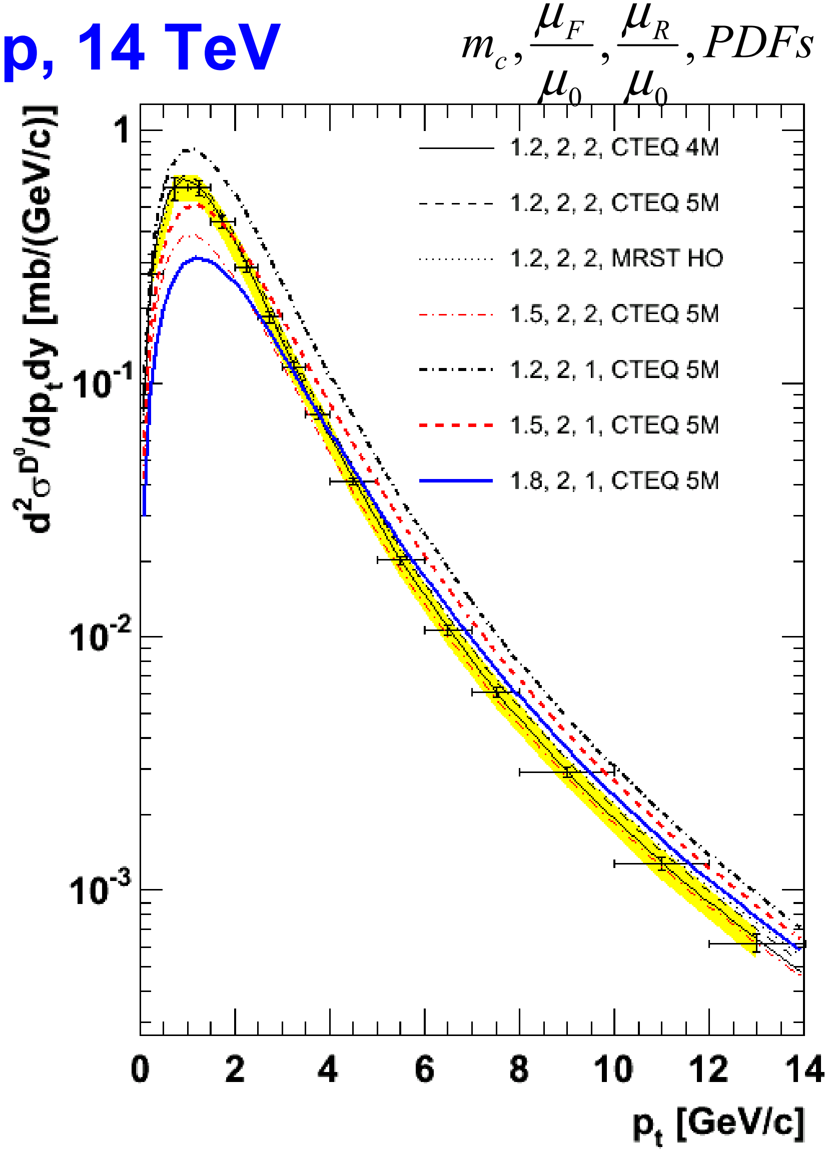
$$S / \sqrt{S + B} \approx 40$$

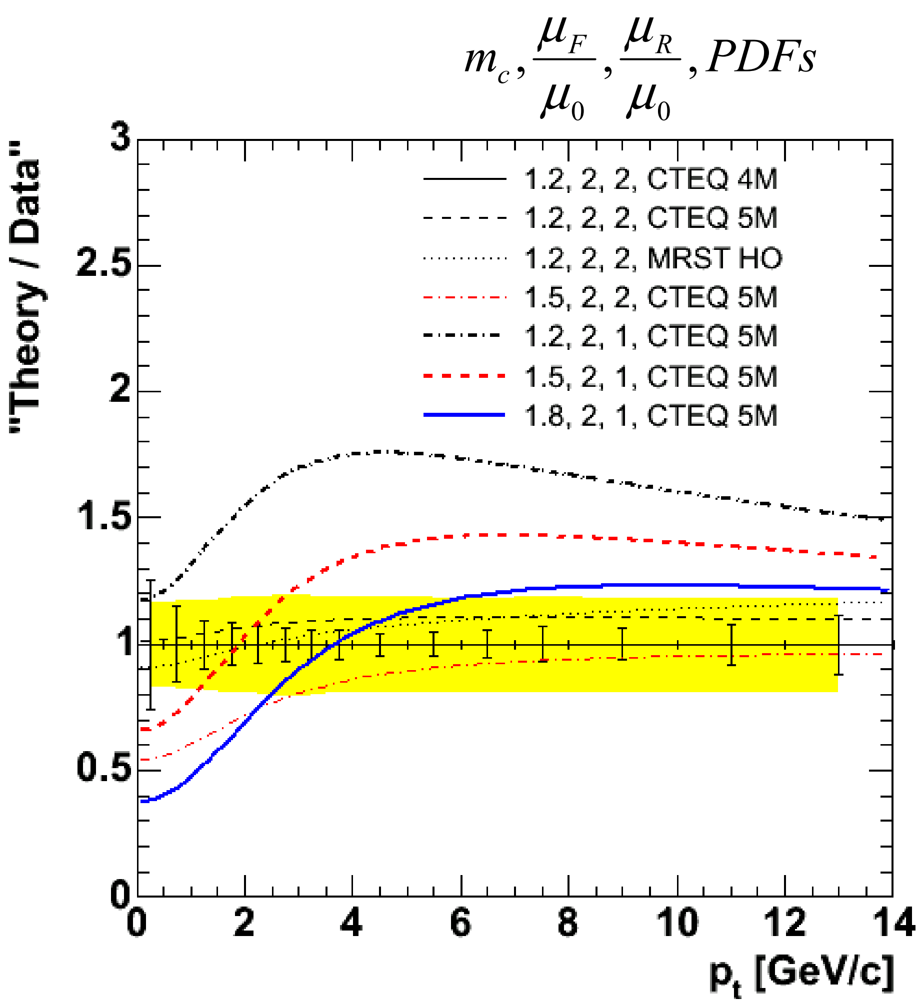
analysis for **Pb-Pb** and **pp** done in bins of p_t and main errors estimated

Details on selection strategy in: N.Carrer, A.D. and R.Turrisi, J. Phys. **G29** (2003) 575.
A.D. PhD thesis (2003), arXiv:nucl-ex/0311004.

Sensitivity to NLO pQCD parameters

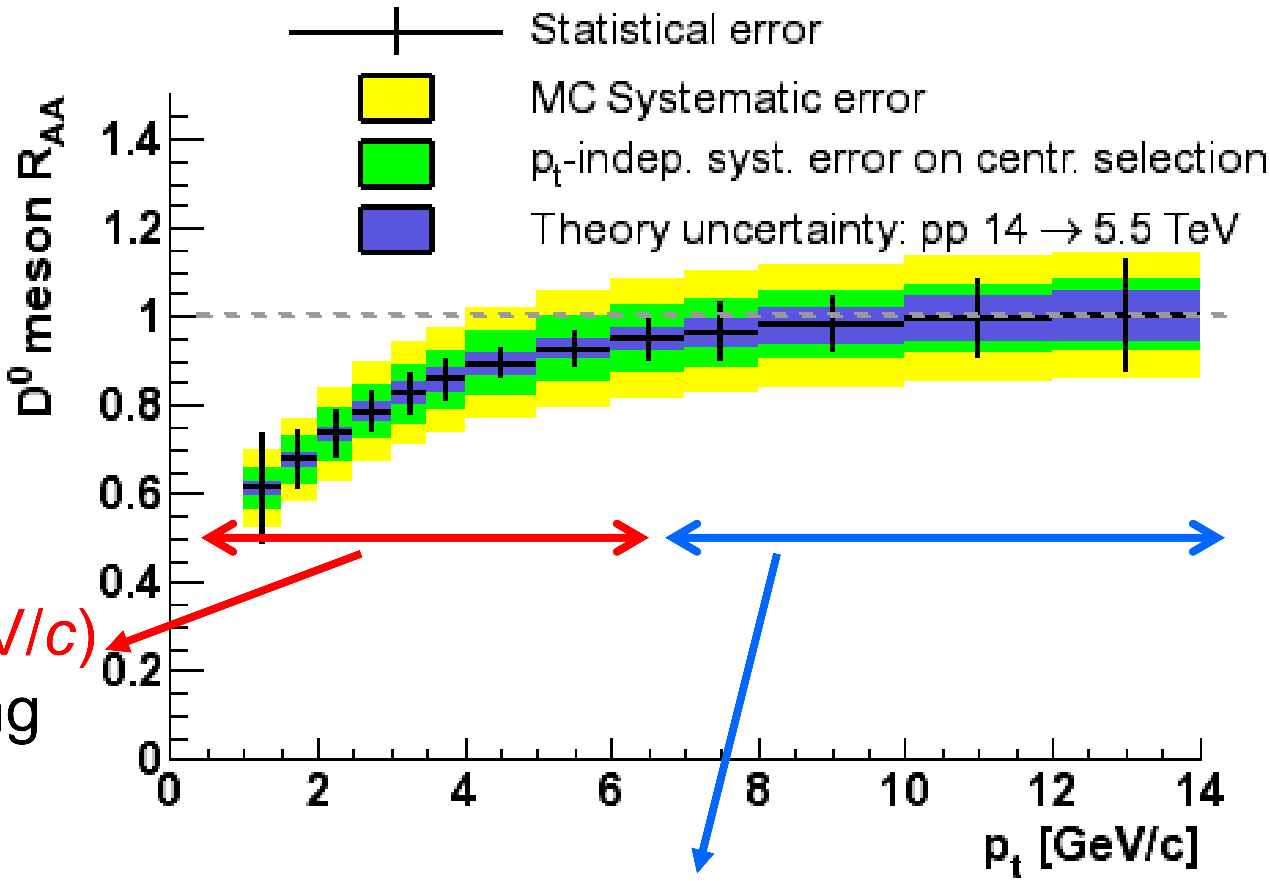
pp, 14 TeV





MNR Program: M.L.Mangano, P.Nason and G.Ridolfi, Nucl. Phys. **B373** (1992) 295.

Sensitivity on R_{AA} for D^0 *mesons*

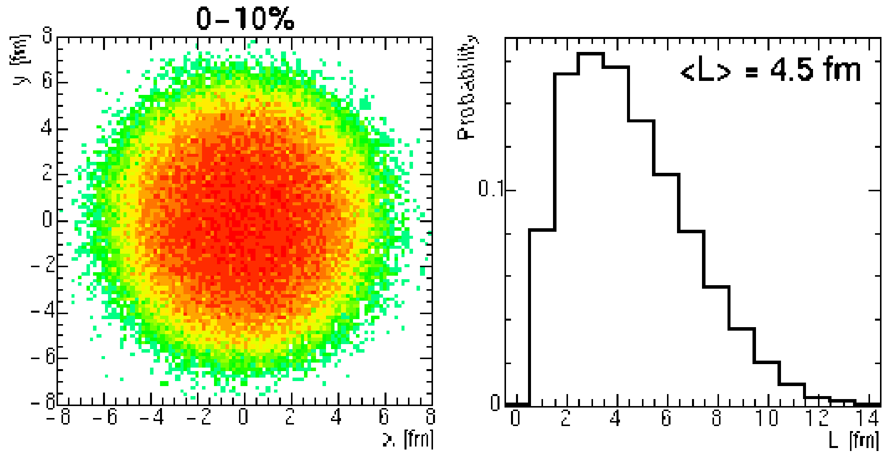


Low p_t (< 6–7 GeV/c)
Nuclear shadowing

'High' p_t (6–15 GeV/c)
here energy loss can be studied
(it's the only expected effect)

Energy-loss simulation

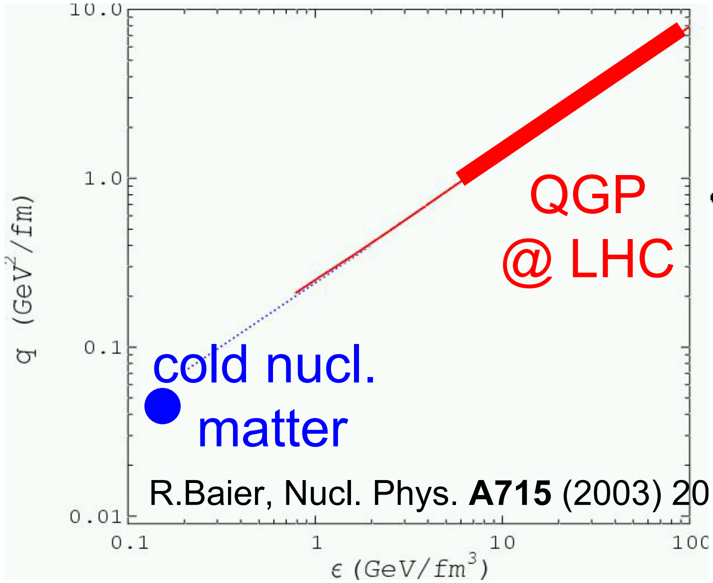
- Energy loss simulated using ***BDMPS quenching weights*** calculated for massive quarks
- With ***realistic path lengths*** of partons in the dense medium (Glaber model)



- ***How to estimate the medium density (transport coefficient $\hat{q}$) for central Pb-Pb collisions at LHC?***
  - two approaches explored:
    - QCD theory estimate
    - model extrapolation based on RHIC data

C.A.Salgado and U.A.Wiedemann, Phys. Rev. **D68** (2003) 014008 [arXiv:hep-ph/0302184].
N.Armesto, A.D., C.A.Salgado and U.A.Wiedemann, in preparation.

Approach A: estimate from QCD



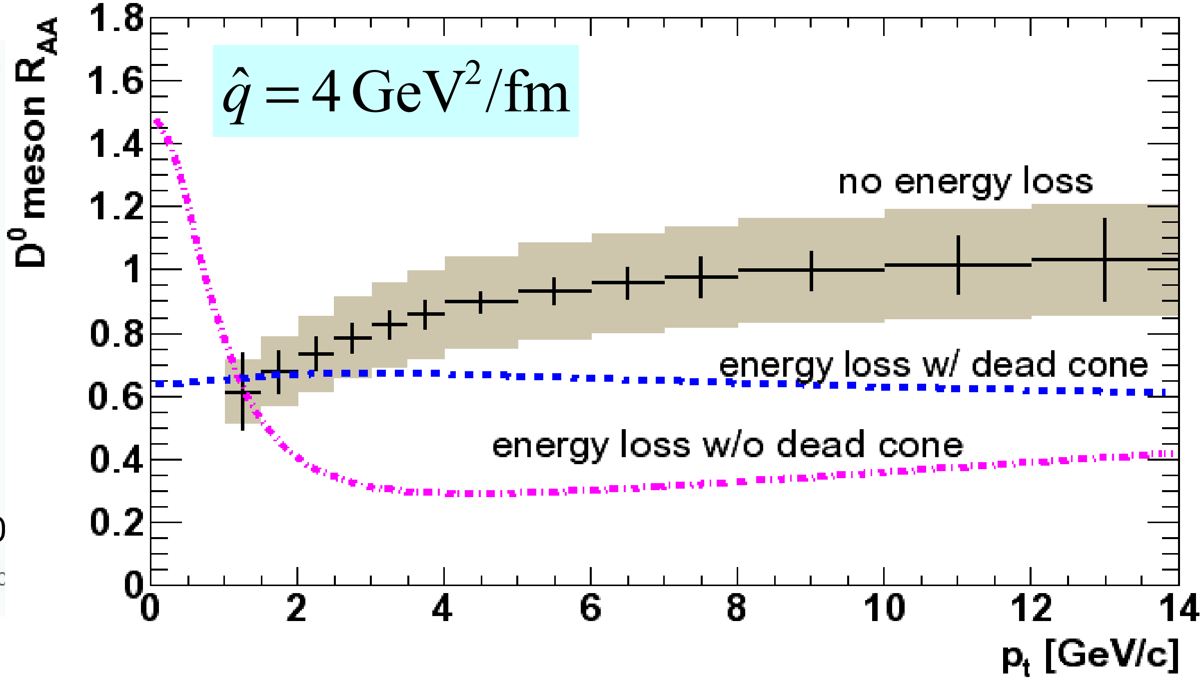
$$\varepsilon \sim 10-100\,\mathrm{GeV/fm^3}$$

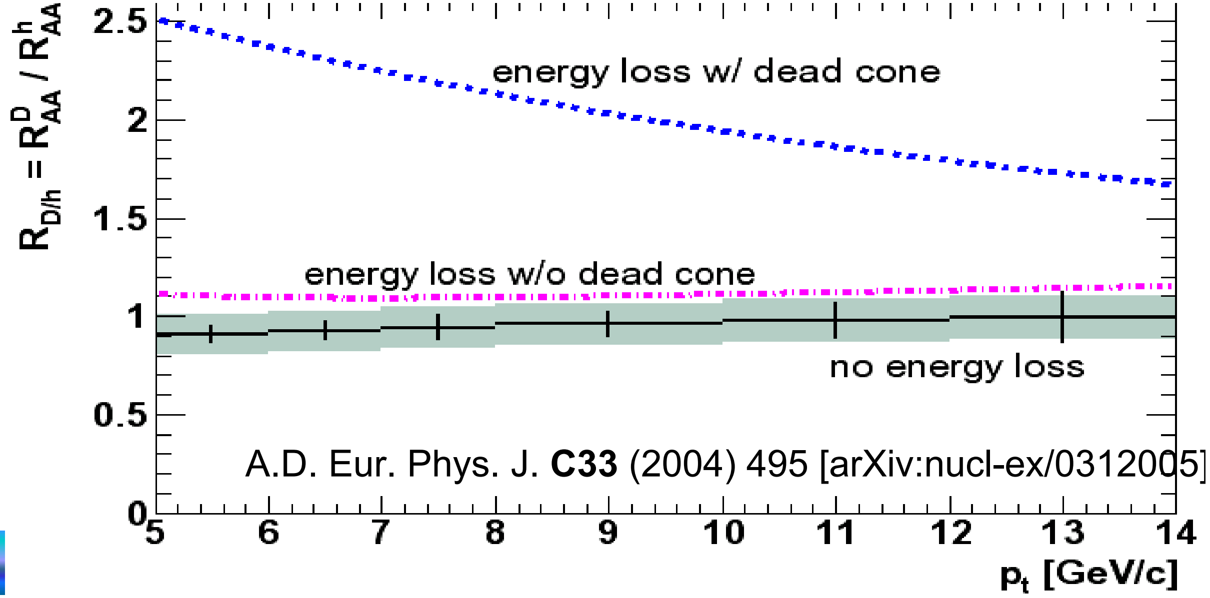
$$\Downarrow$$

$$\hat{q} \sim 1-10\,\mathrm{GeV^2/fm}$$

chosen $\hat{q} = 4\,\mathrm{GeV^2/fm}$

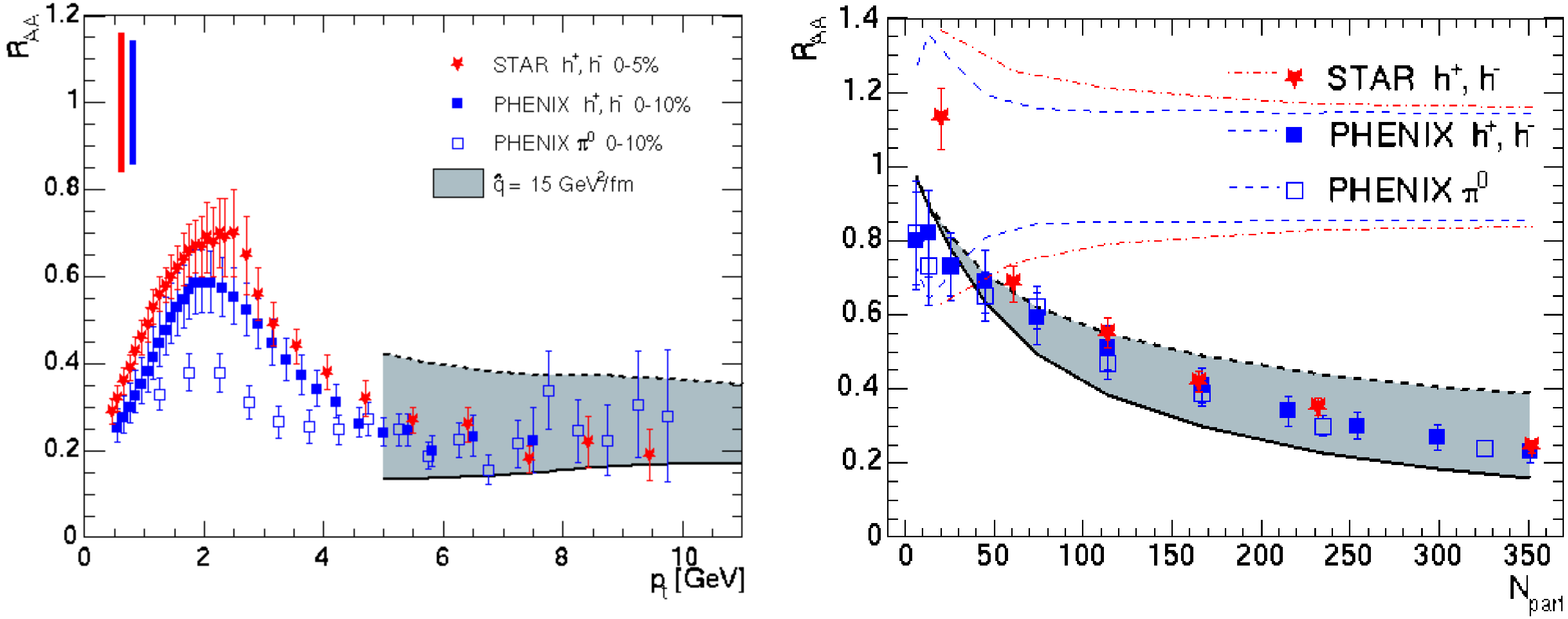
which gives $R_{AA}^{h} \approx 0.25$





Approach B: from RHIC to LHC …

- Transport coefficient as high as $\hat{q} \approx 15\ \mathrm{GeV}^2/\mathrm{fm}$ needed to match leading-particle suppression at RHIC (200 GeV)

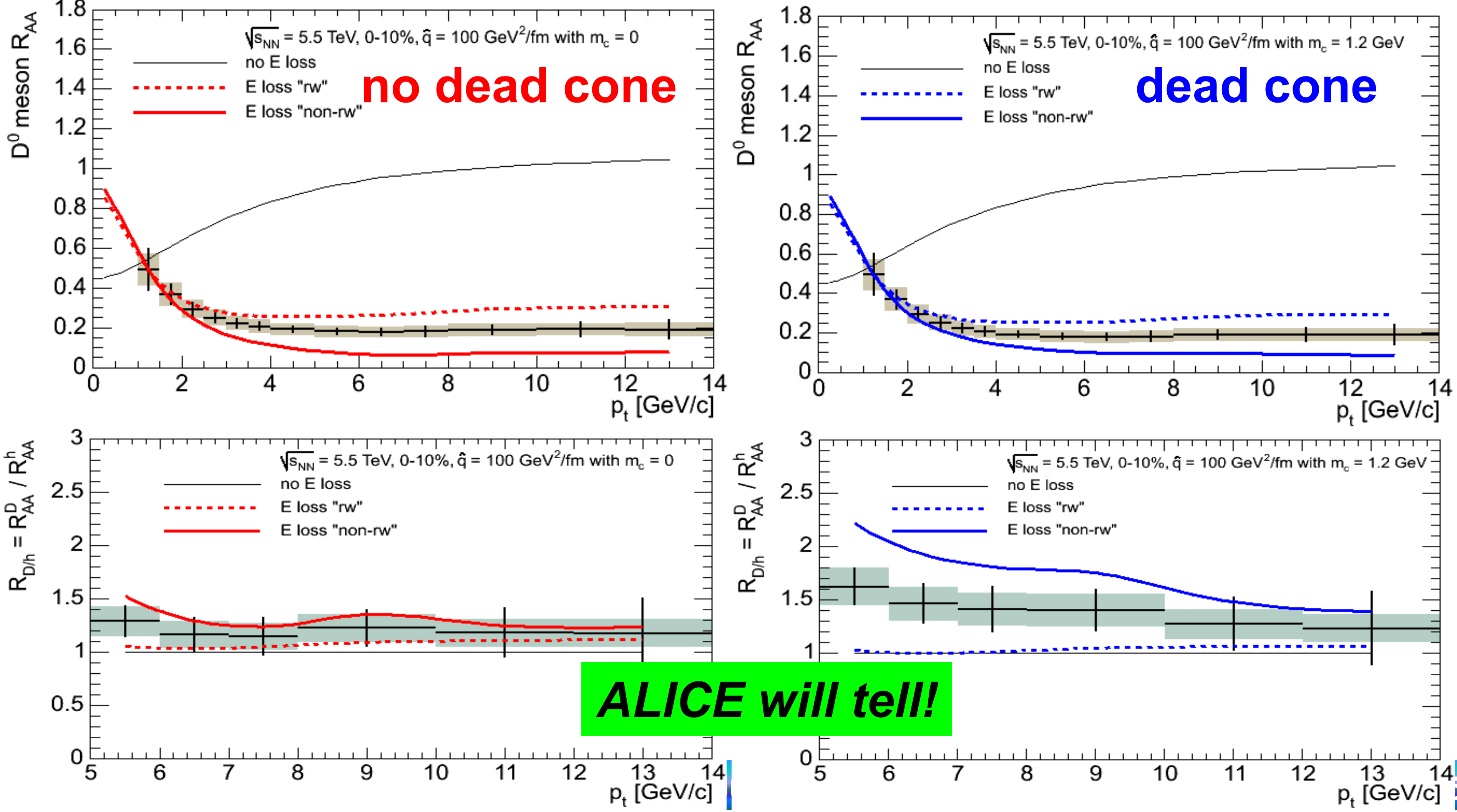


- Extrapolation to LHC gives: $\hat{q}_{LHC} \approx 7\, \hat{q}_{RHIC} \approx 100\ \mathrm{GeV}^2/\mathrm{fm}$

A.D., C.Loizides and G.Paic, arXiv:hep-ph/0406201.
K.J.Eskola, H.Honkanen, C.A.Salgado and U.A.Wiedemann, arXiv:hep-ph/0406319.

... energy loss saturated

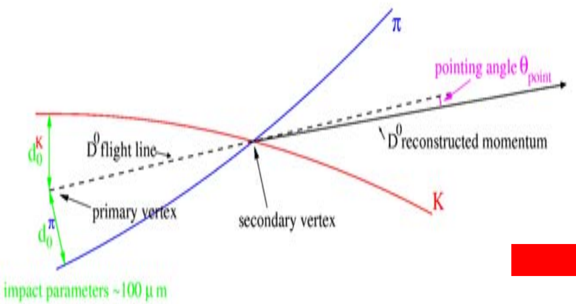
- Most of the partons are absorbed, only those from the surface of the fireball can escape the medium

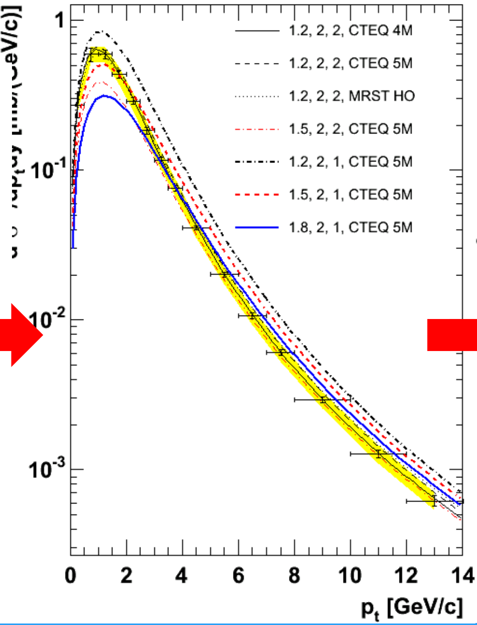


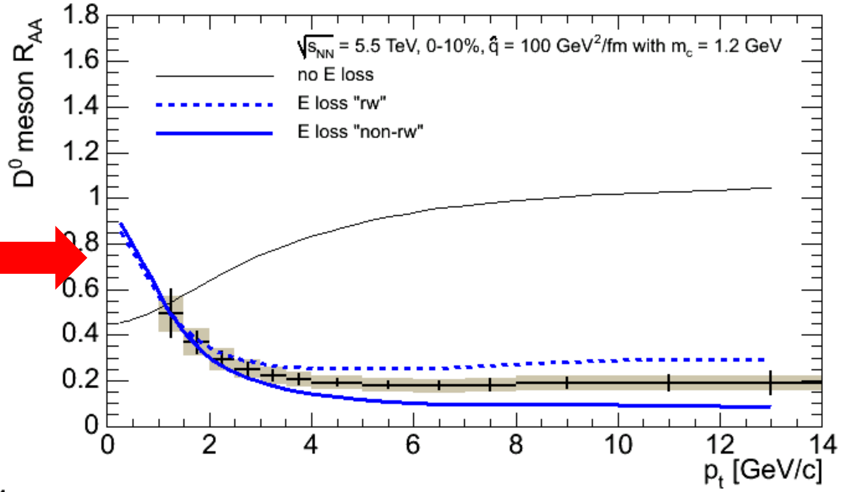
ALICE will tell!

Summary

- **LHC**: study properties for deconfined QCD matter via hard probes and their quenching
- **ALICE**: good potential in the heavy quark sector
- Outstanding example: **ALICE can exclusively reconstruct D^0 mesons in Pb-Pb collisions with dN_{ch}/dy = 6000!**
  - measure charm production in $0 < p_t < 15$ GeV/c (at least)
  - **study the mass and flavour dependence of QCD energy loss**







BACK-UP SLIDES

Go for deep deconfinement at LHC

Next step in the "quest for QGP" …

- **LHC**: factor 30 jump in $\sqrt{s}$ w.r.t. RHIC

➡ much larger initial temperature

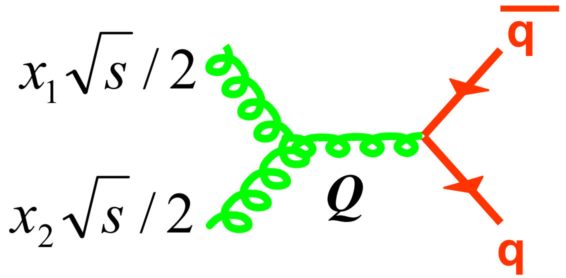
	SPS 17 GeV	*RHIC* 200 GeV	***LHC*** **5.5 TeV**
initial T	~ 200 MeV	~ 300 MeV	**> 600 MeV**
volume	10^3 fm^3	10^4 fm^3	**10^5 fm^3**
life-time	< 2 fm/*c*	2-4 fm/*c*	**> 10 fm/*c***

➡ study of **hotter, bigger, longer-living** 'drops' of QGP

'Deep de-confinement' → closer to 'ideal' QGP
→ easier comp. with theory (lattice)

Initial-state effects: Shadowing

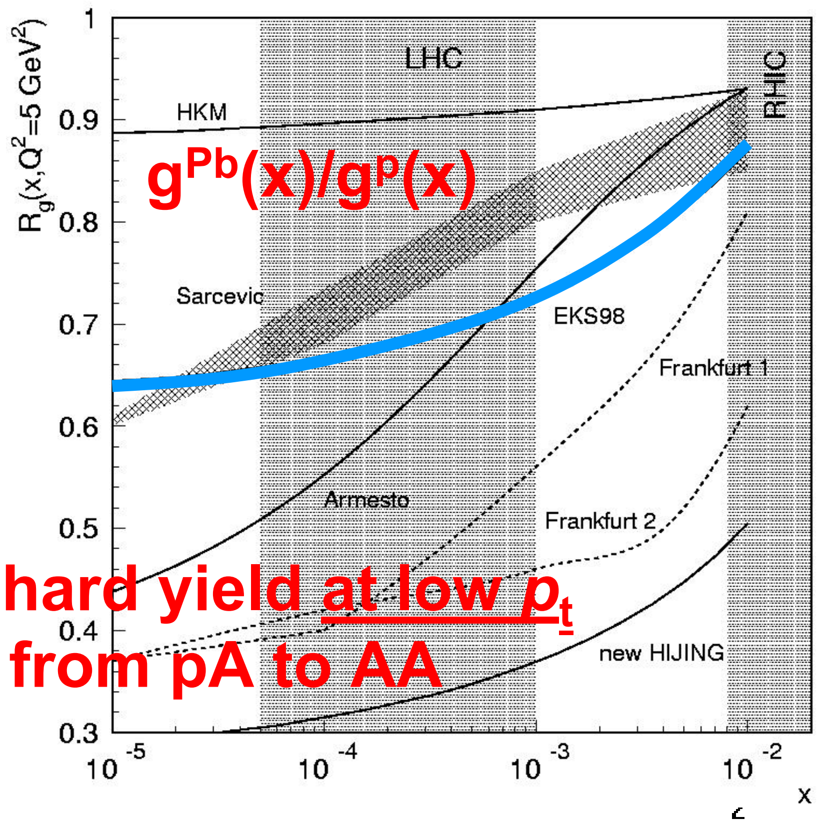
- Bjorken-x: fraction of the momentum of the proton ($\sqrt{s}/2$) carried by the parton entering the hard scattering



$$x \approx Q/\sqrt{s} = M_{q\bar{q}}/\sqrt{s}$$

- At the LHC $x \sim 10^{-3} - 10^{-4}$
- Pb ion @ LHC ~ 10^5-10^6 partons (mainly gluons)

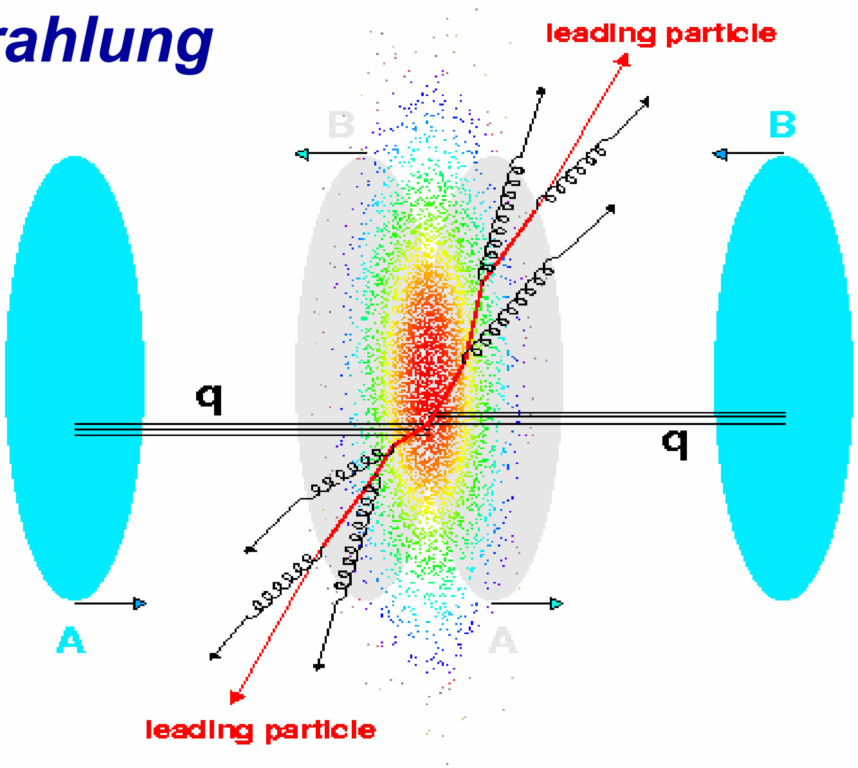
"they are so close that they fuse"



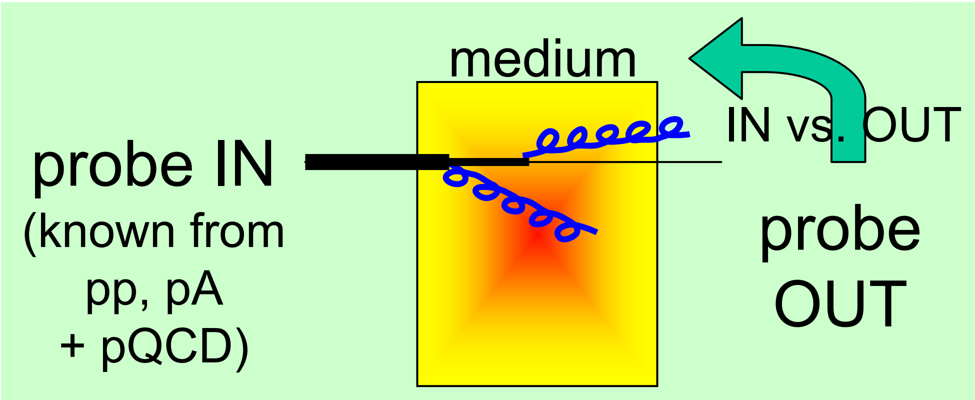
Shadowing:
- **reduces initial hard yield at low p_t**
- **scales trivially from pA to AA**

Hard partons probe the medium

- **Partons travel ~ 5 fm in the high colour-density medium**
- **Energy loss by *gluon bremsstrahlung***
  - modifies momentum distributions
  - jet shapes
  - …
  - **depends on medium properties**



PROBE

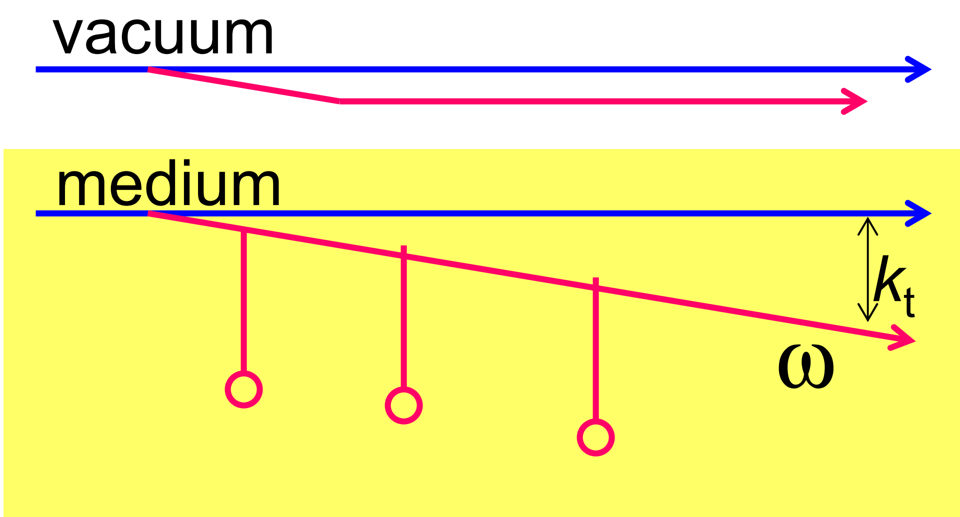


BDMPS model

$$\hat{q} = \langle q^2 \rangle_{medium} / \lambda$$

$$\omega_c = 1/2\, \hat{q}\, L^2$$

$$\omega \frac{dI}{d\omega} = \frac{2\alpha_s C_R}{\pi} \sqrt{\frac{\omega_c}{2\omega}}$$



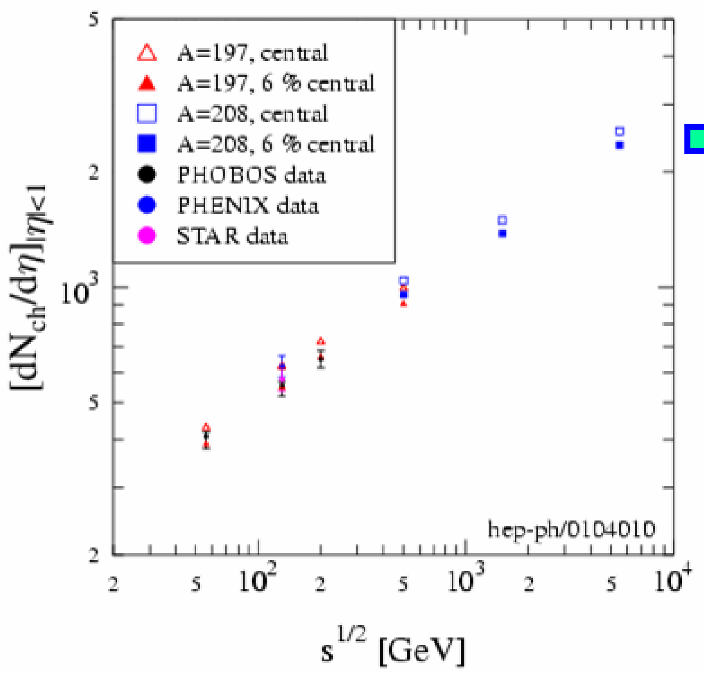
$$\langle \Delta E \rangle \approx \int_0^{\omega_c} d\omega\, \omega \frac{dI}{d\omega} = \frac{2\sqrt{2}\alpha_s C_R}{\pi} \omega_c = \frac{\sqrt{2}\alpha_s C_R}{\pi} \hat{q}\, L^2$$

Background multiplicity in Pb-Pb

- What is the background to hadronic D decays?

  combinatorial background given by pairs of uncorrelated tracks with large impact parameter

$$B \propto \left(dN_{ch}/dy\right)^2$$



$$dN_{ch}/dy \approx 2500$$

in central Pb-Pb at LHC

Simulations performed using

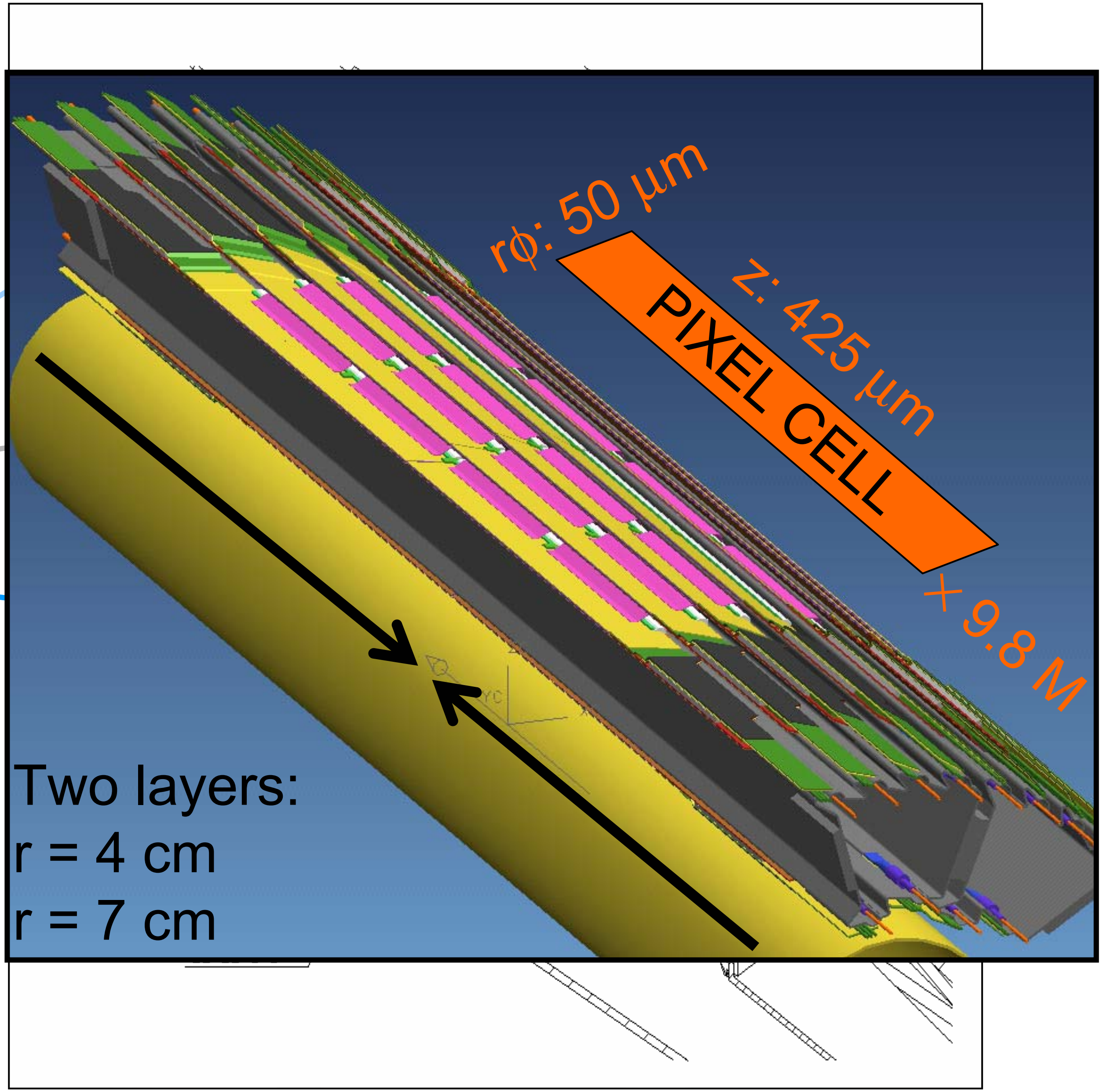
$$dN_{ch}/dy \approx 6000$$

huge combinatorial background!

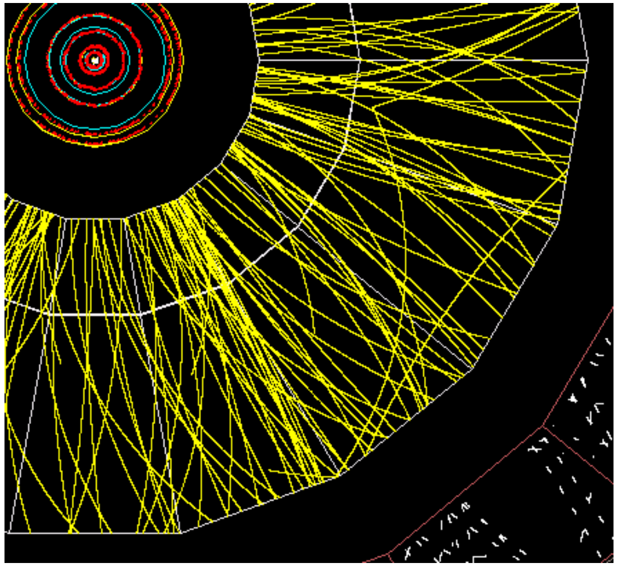
need excellent detector response and good selection strategy

ALICE Barrel

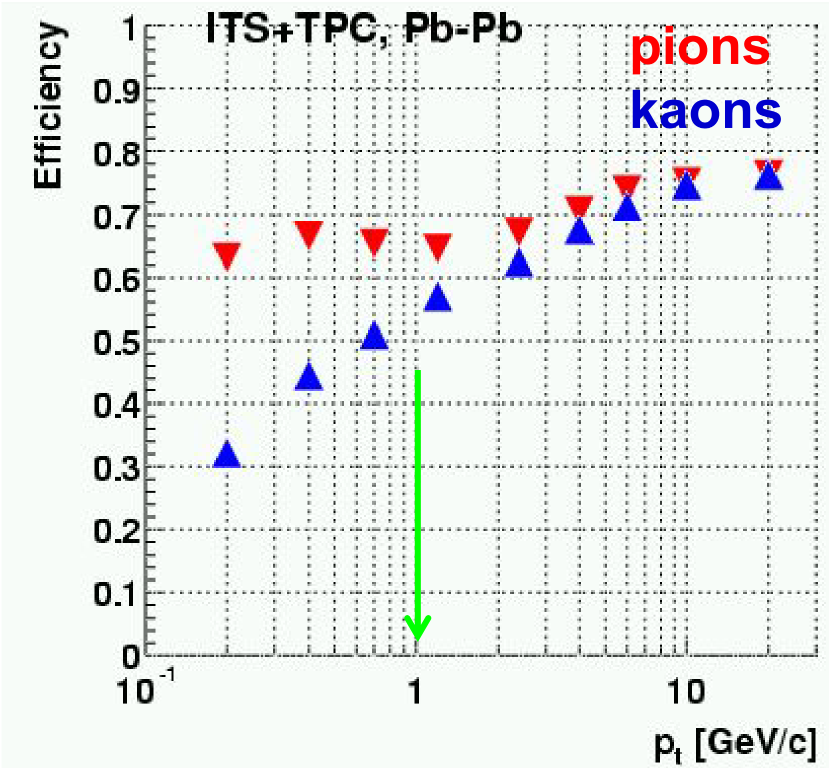
$|\eta|<0.9$:
B = 0.4 T
TOF
TPC
ITS with:
- Si pixels
- Si drifts
- Si strips



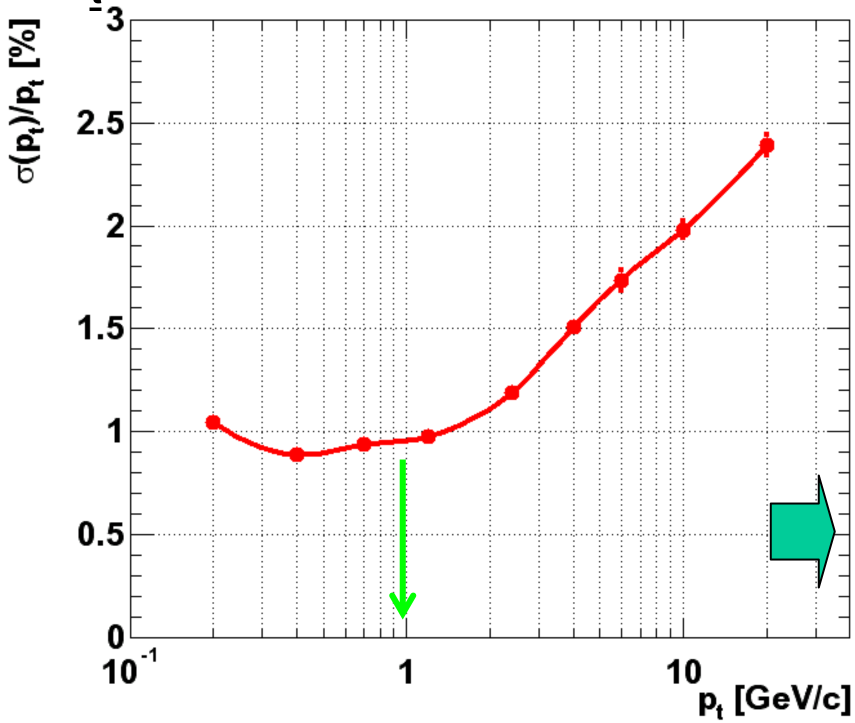
Tracking



Tracking efficiency ~70% with dN_{ch}/dy=6000



p_t resolution = 1% at 1 GeV/*c*

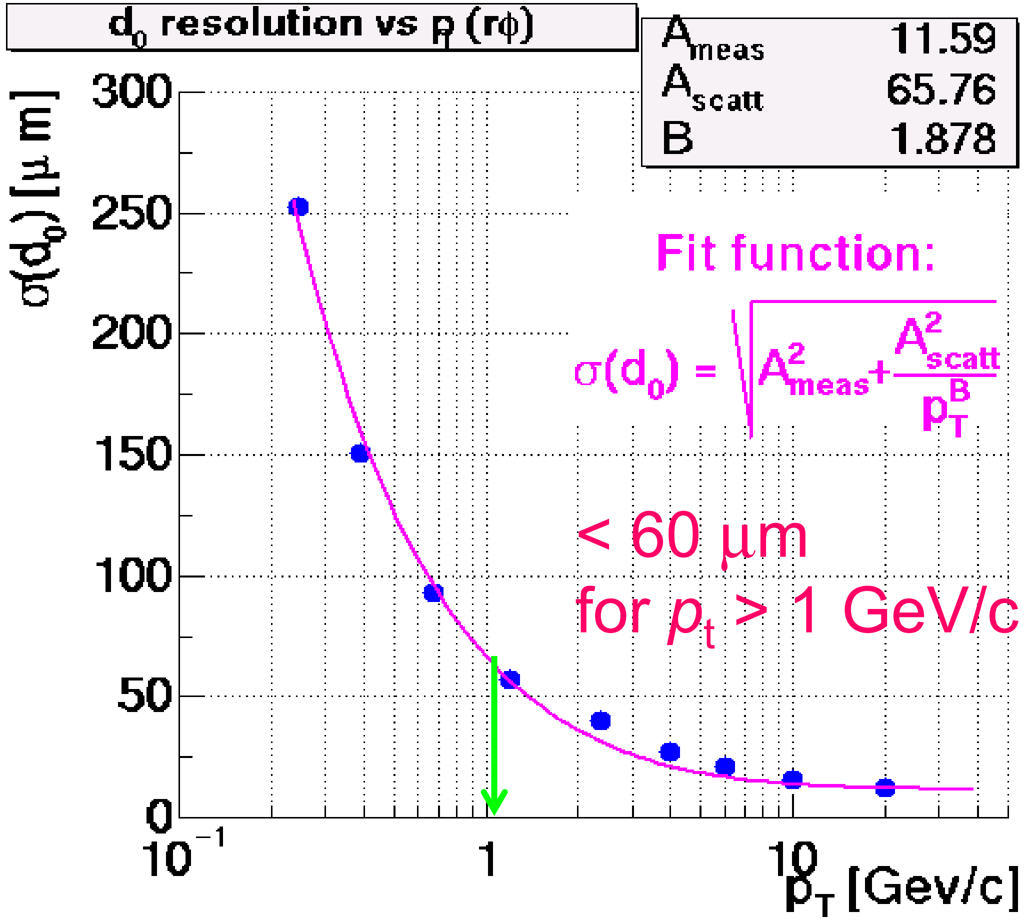


D^0 invariant mass resolution:

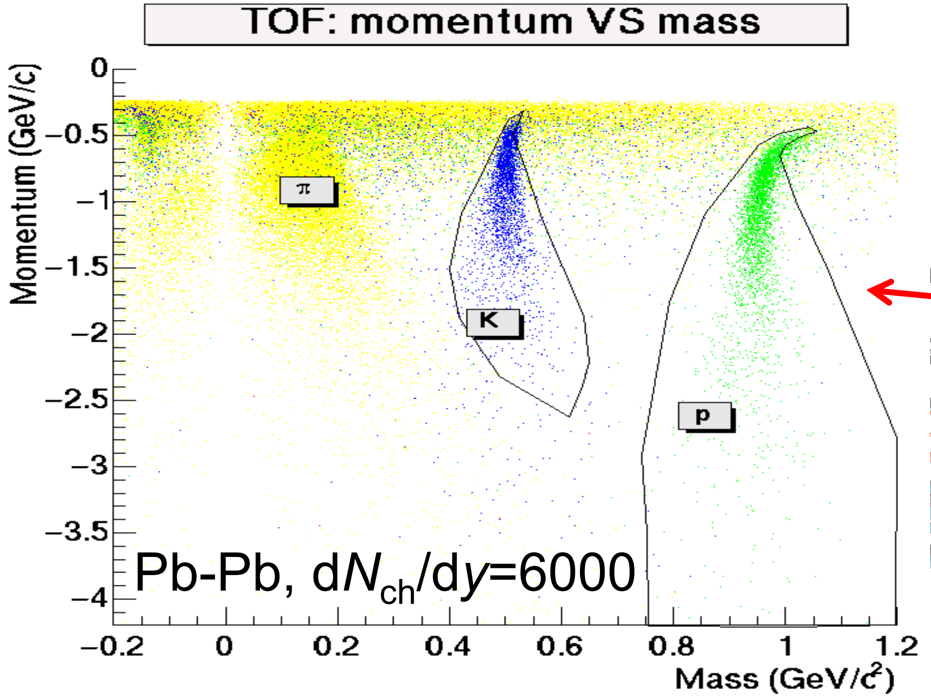
$$\frac{\sigma(M)}{M} = \frac{1}{\sqrt{2}} \frac{\sigma(p)}{p} \approx 0.7\%, \;\; \sigma(M) \approx 13\,\mathrm{MeV}$$

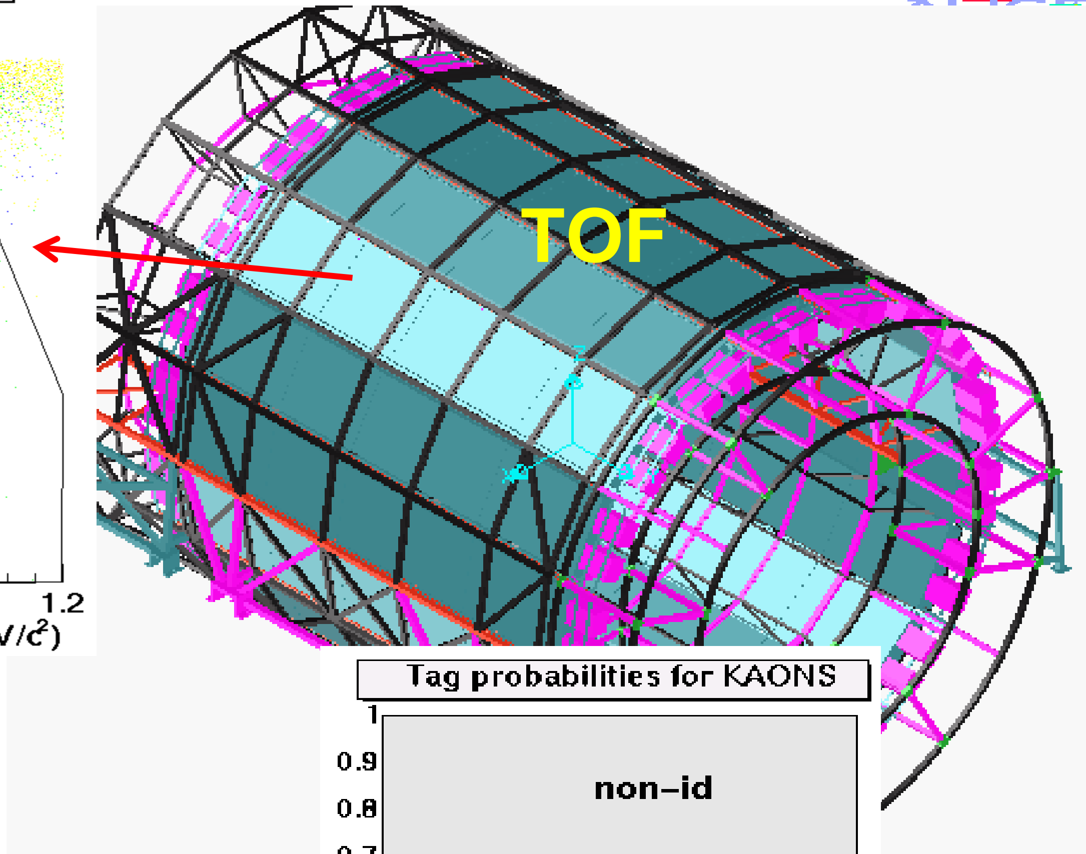
Impact parameter resolution

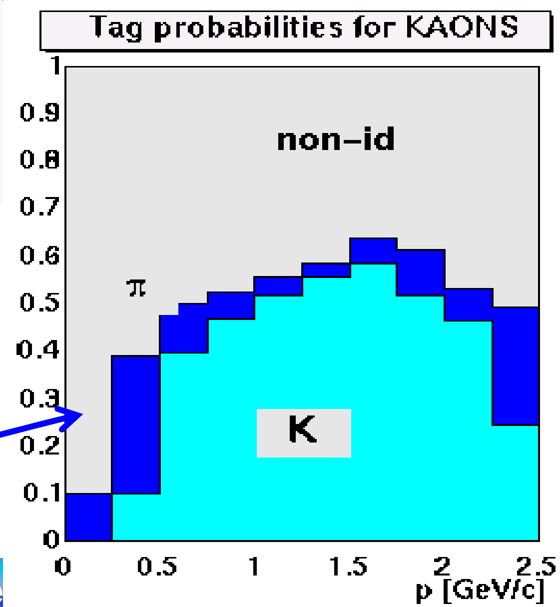
- Crucial for heavy-quark ID
- Systematic study of resolution was carried out



TOF PID







Optimization for hadronic charm decays was studied:
minimize probability to tag K as π

$D^0 \rightarrow K^-\pi^+$: *Signal and background*

- **Signal:**
  - charm cross section from NLO pQCD (MNR program), average of results given by MRS98 and CTEQ5M PDFs (with EKS98 in Pb-Pb)

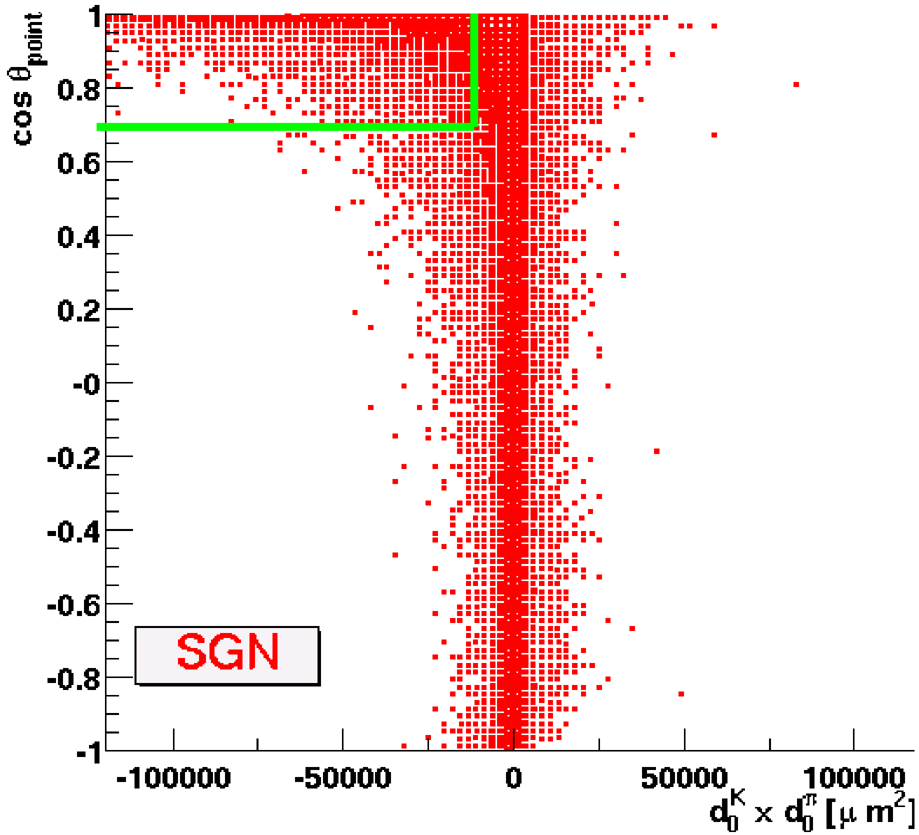
system	$\sigma_{NN}^{c\bar{c}}$ [mb]	shadowing	$N_{tot}^{c\bar{c}}$	$dN(D^0 \rightarrow K\pi)/dy$
pp 14 TeV	11.2	1	0.16	0.0007
Pb-Pb 5.5 TeV (5% cent)	6.6	0.65	115	0.5

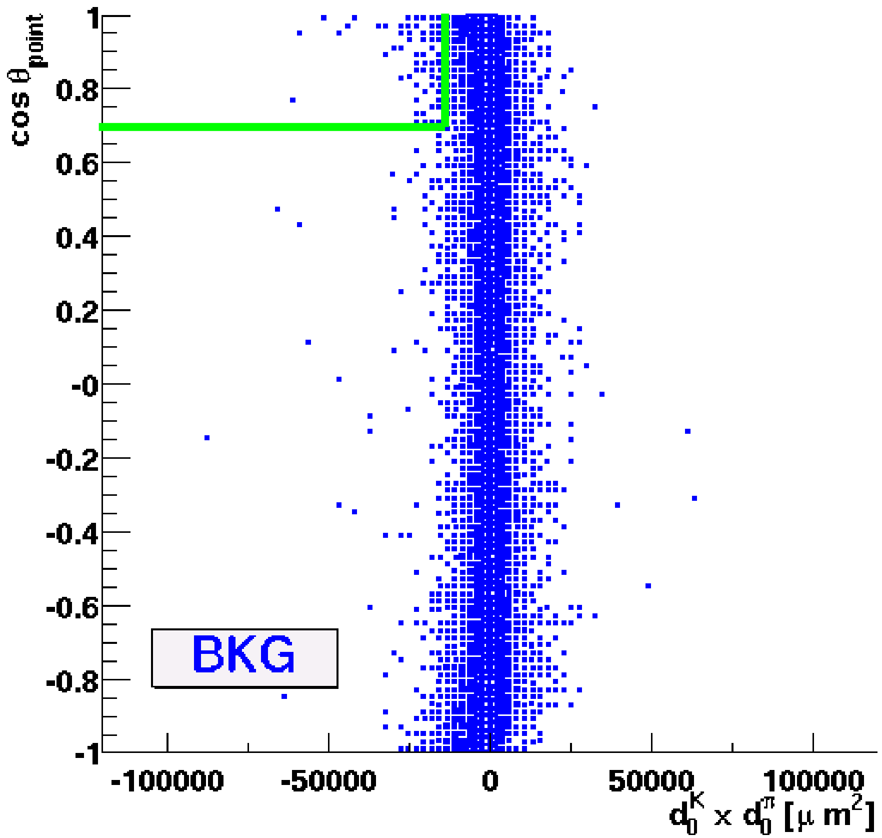
  - signal generated using PYTHIA, tuned to reproduce p_t distr. given by NLO pQCD
  - contribution from $b \rightarrow B \rightarrow D^0$ (~5%) also included
- **Background:**
  - Pb-Pb: HIJING (**dN_{ch}/dy=6000 ! we expect ~2500 !**); pp: PYTHIA;

MNR Program: M.L.Mangano, P.Nason and G.Ridolfi, Nucl. Phys. **B373** (1992) 295.

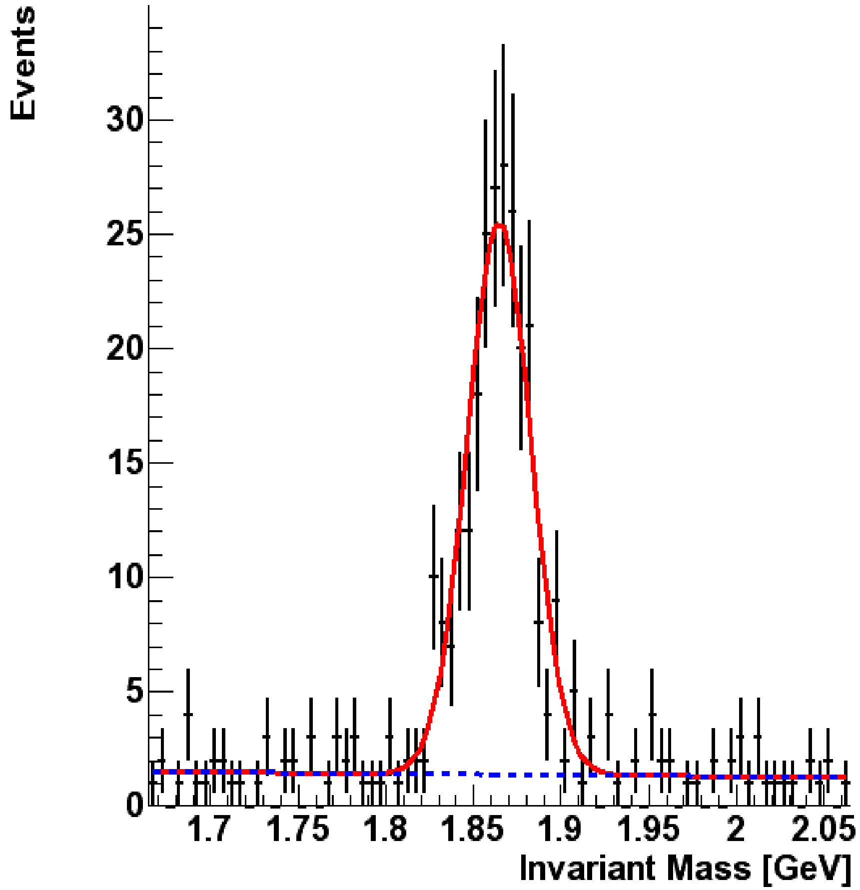
$D^0 \to K^- \pi^+$: *Selection of D^0 candidates*

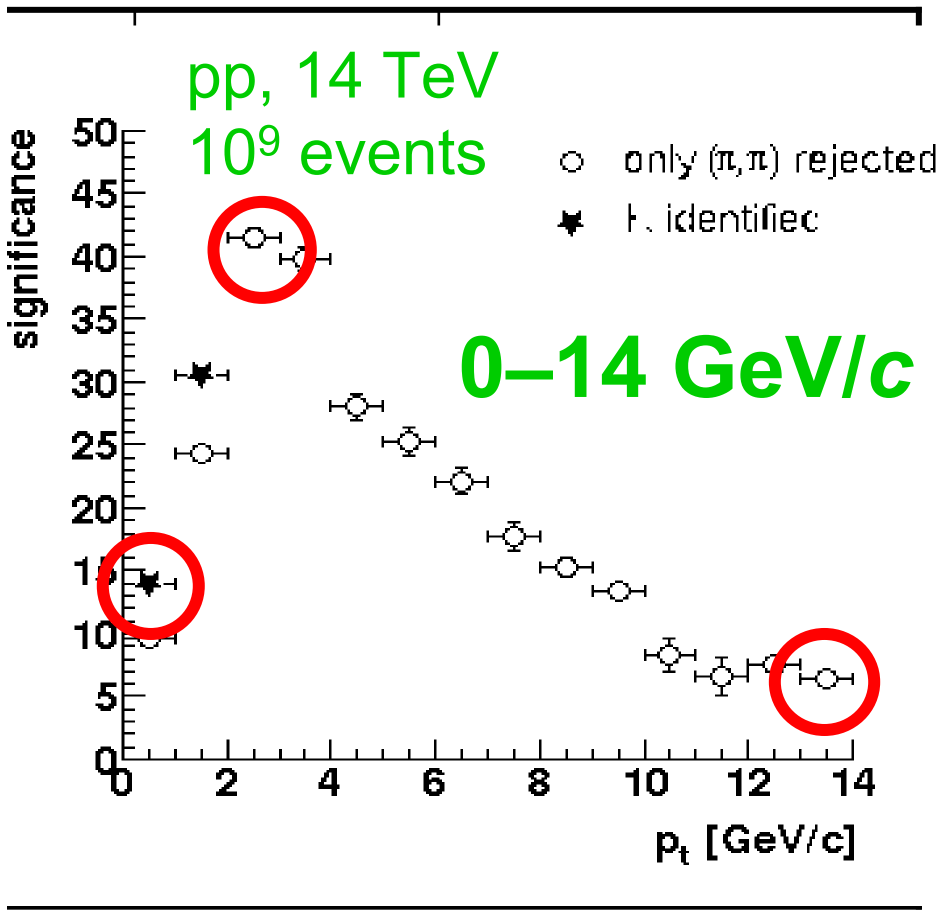
- **Main selection: displaced-vertex selection**
  - pair of tracks with **large impact parameters**
  - **good pointing** of reconstructed D^0 momentum to the primary vertex





$D^0 \rightarrow K^-\pi^+$: *Results*

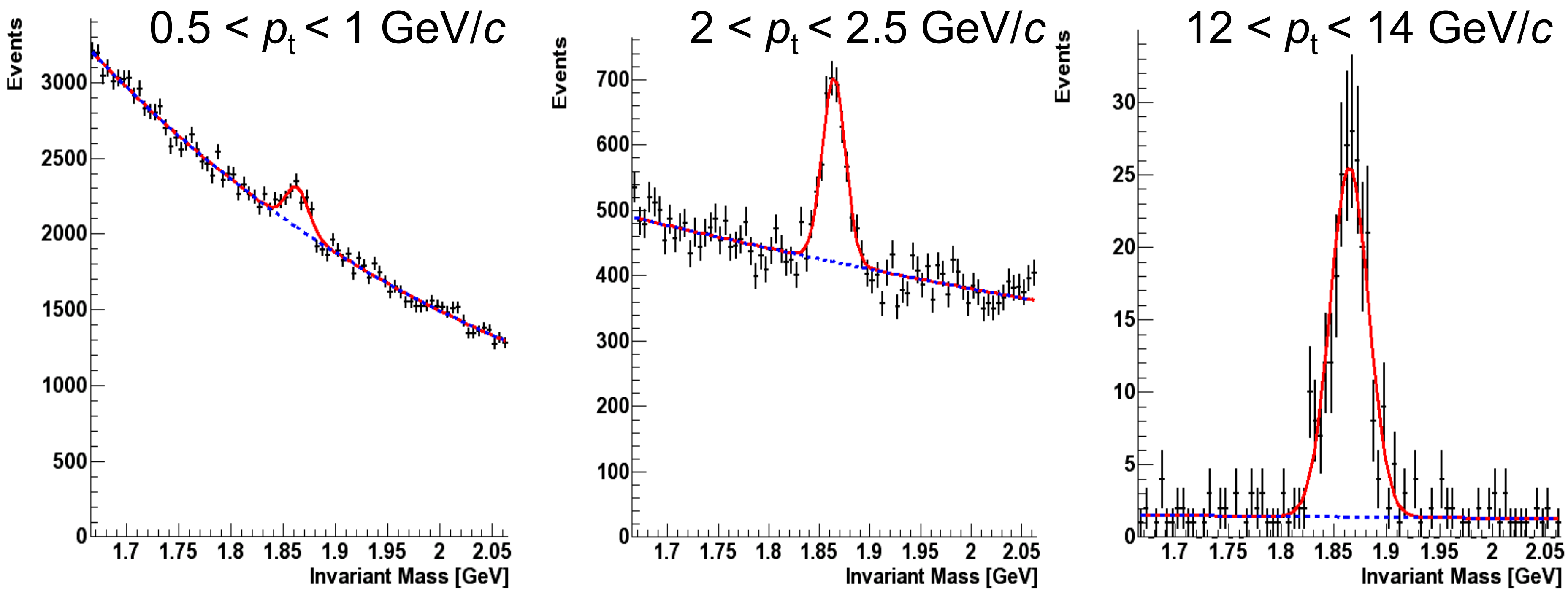




Note: with dN_{ch}/dy = 3000, S/B larger by $\times$4 and significance larger by $\times$2

$D^0 \to K^-\pi^+$: *Results*

S/B initial (M±3σ)	S/evt final (M±1σ)	S/B final (M±1σ)	Significance $S/\sqrt{S+B}$ (M±1σ)
$2 \cdot 10^{-3}$	$1.9 \cdot 10^{-5}$	11 %	44 (for 10^9 evts, ~9 months at 10^{30} $cm^{-2}s^{-1}$)



What if multiplicity in Pb-Pb is lower?

- We used $dN_{ch}/dy = 6000$, which is a pessimistic estimate
- Recent analyses of RHIC results seem to suggest as a more realistic value $dN_{ch}/dy = 3000$ (or less)
- Charm production cross section:
  - estimate from NLO pQCD (only primary production, no collective effects)
  - average of theoretical uncertainties (choice of: m_c, μ_F, μ_R, PDF)

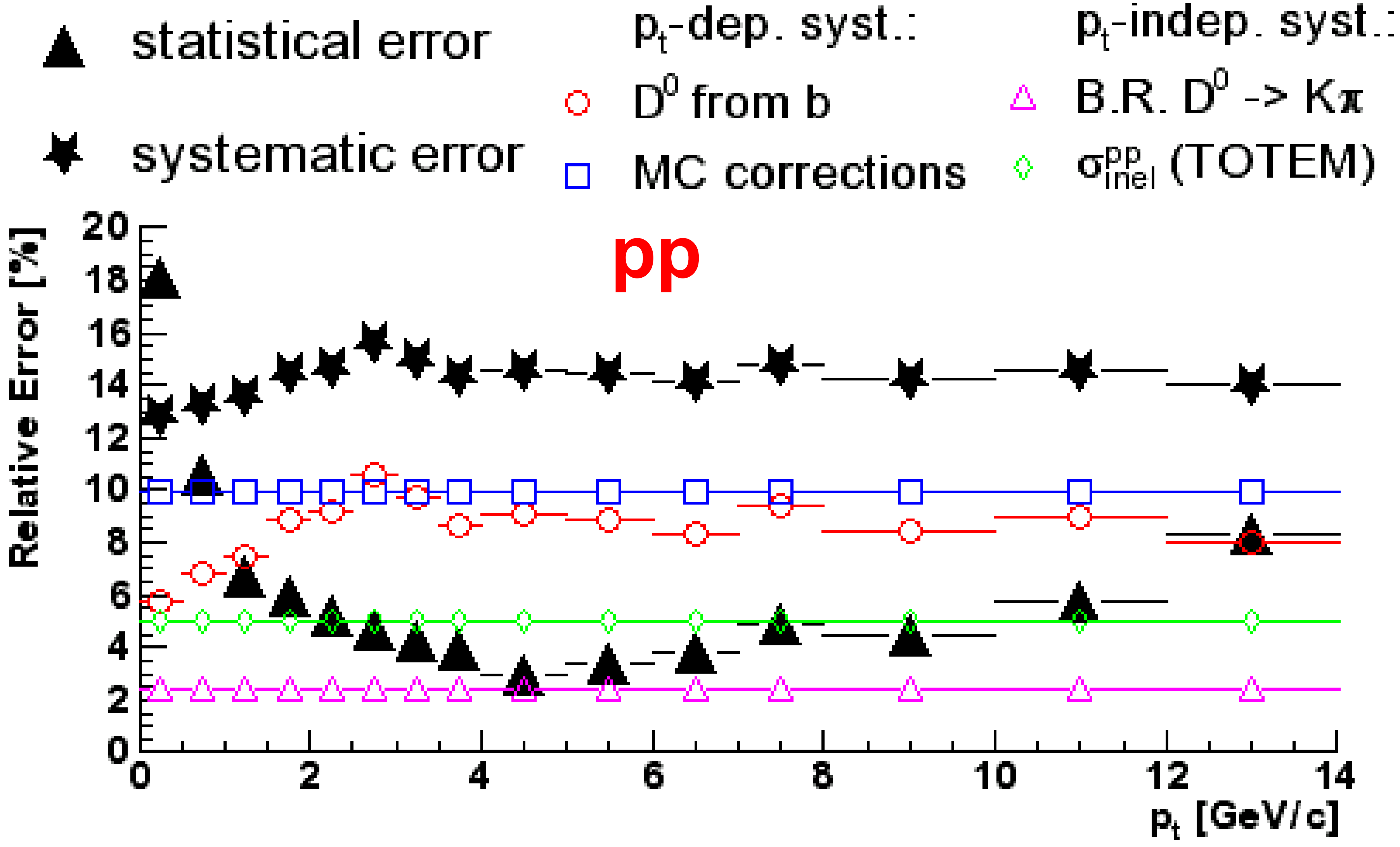
- BKG proportional to $(dN_{ch}/dy)^2$
- We can scale the results to the case of $dN_{ch}/dy = 3000$:

S/B = 44 %

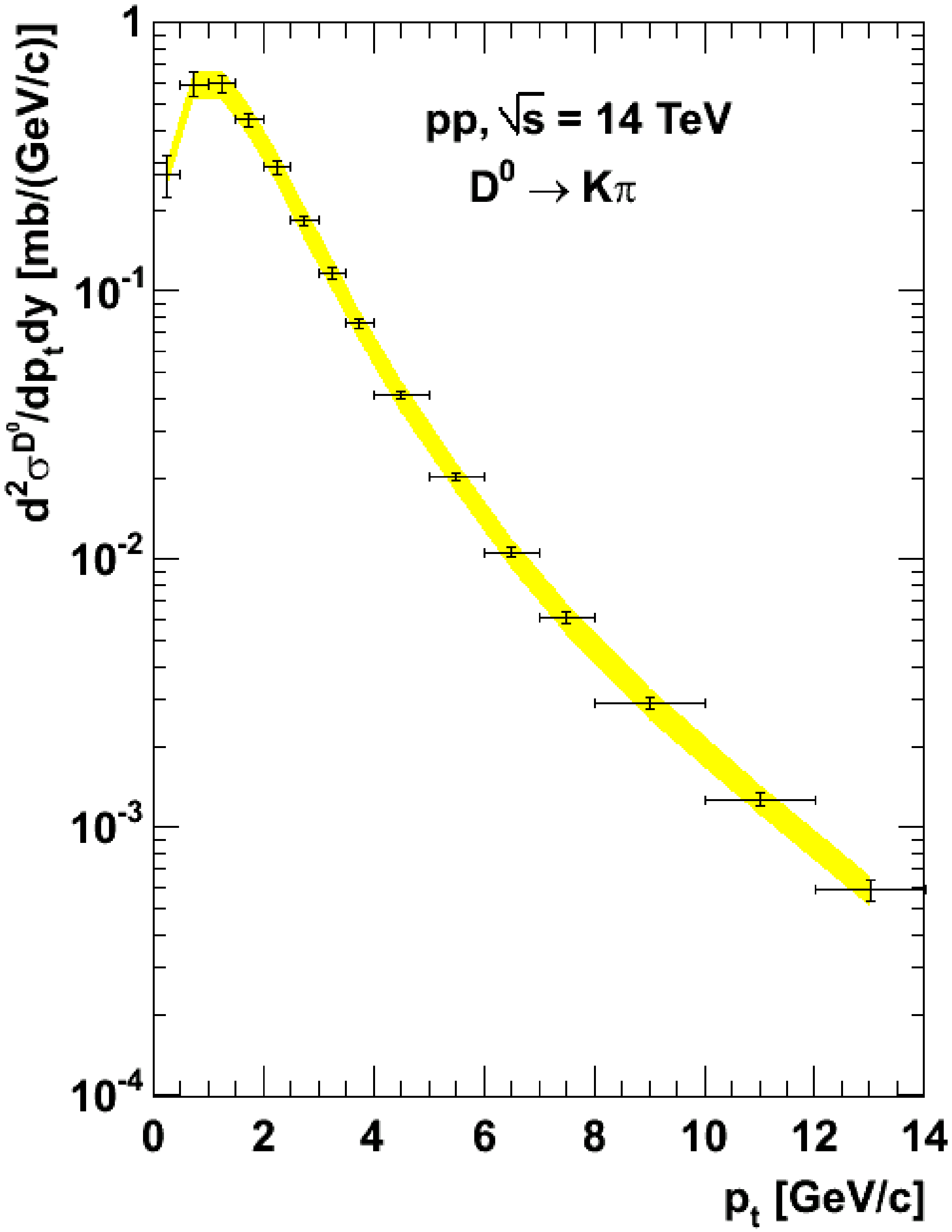
SGNC = 74

(this only from scaling, obviously better with retuning of cuts)

Estimate of the errors



$D^0 \rightarrow K^-\pi^+$: $d^2\sigma(D^0)/dp_t dy$ and $d\sigma(D^0)/dy$



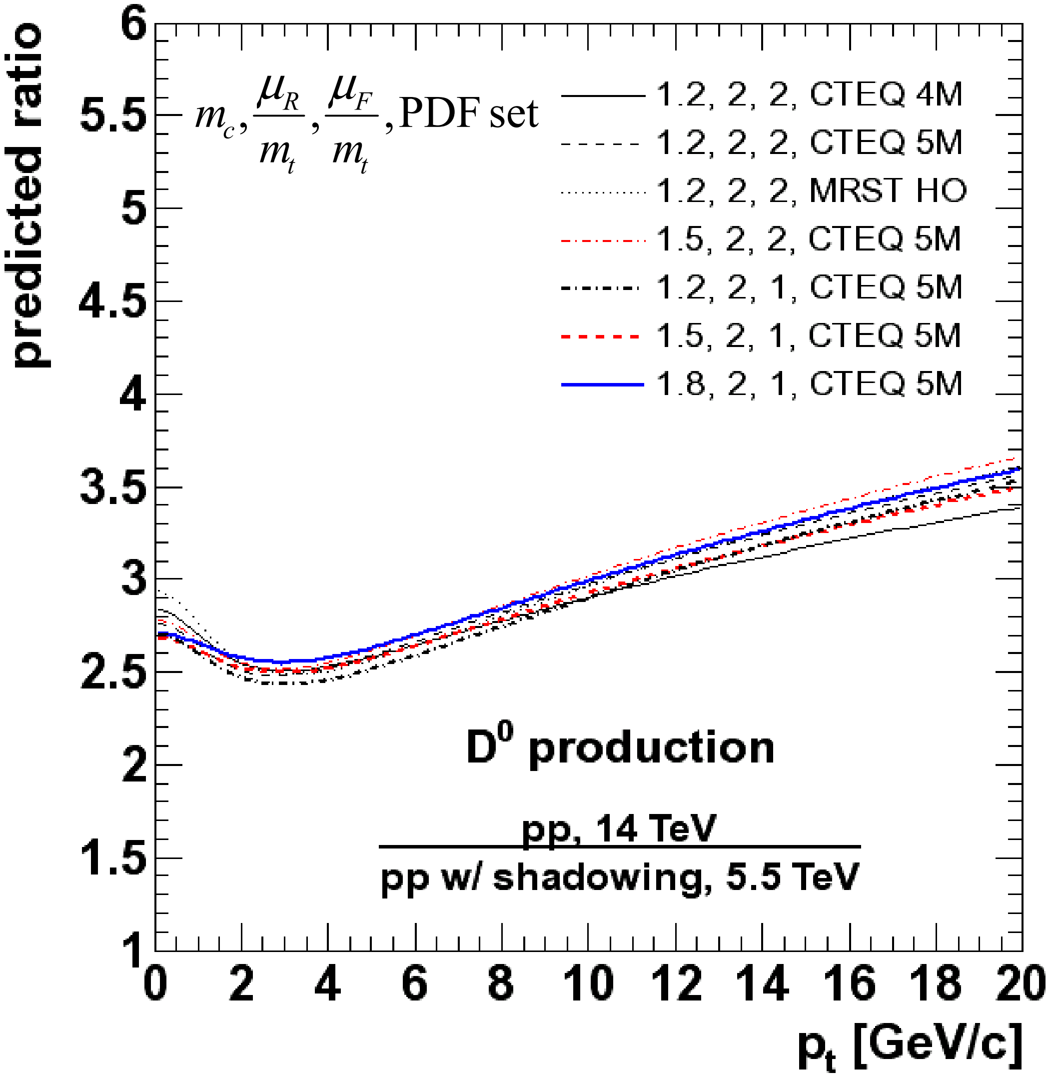
inner bars: statistical
outer bars: systematic

$d\sigma(D^0)/dy$ for $|y| < 1$ and $p_t > 0$

statistical error	= **3 %**
systematic error	= **14 %**
from b	= 8 %
MC correction	= 10%
B.R.	= 2.4 %
σ^{inel}	= 5 %

Interpolation pp 14 → 5.5 TeV

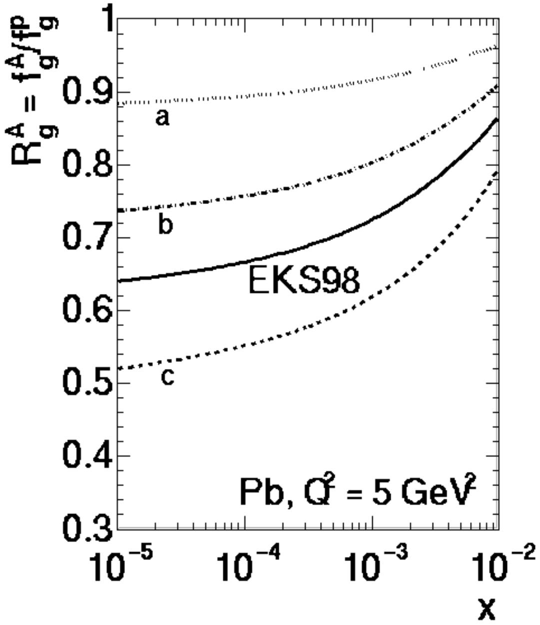
Necessary to compare Pb-Pb and pp by R_{AA}

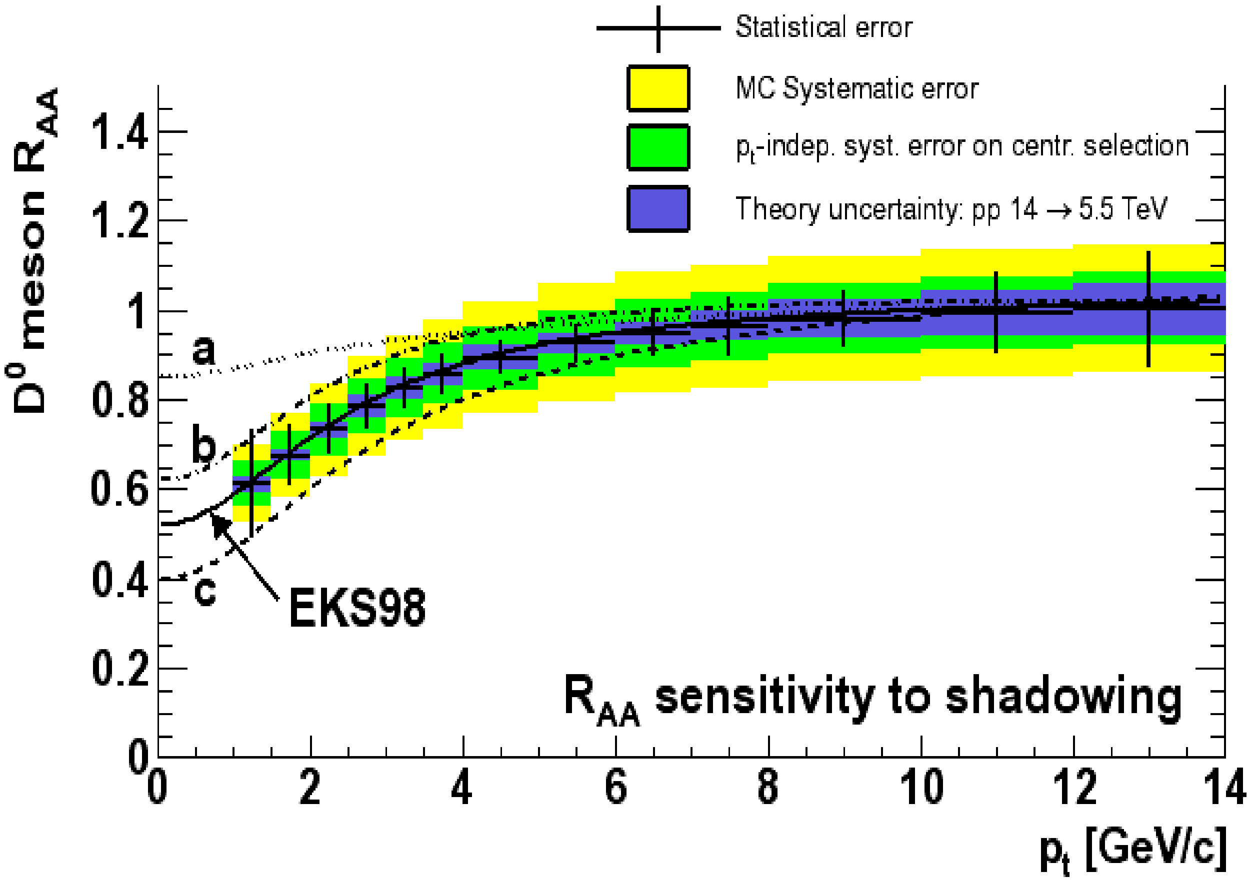


In pQCD calculations the ratio of the differential cross sections at 14 and 5.5 TeV is independent of the input parameters within 10% up to 20 GeV/c

pQCD can be safely used to extrapolate pp @ 14 TeV to 5.5 TeV

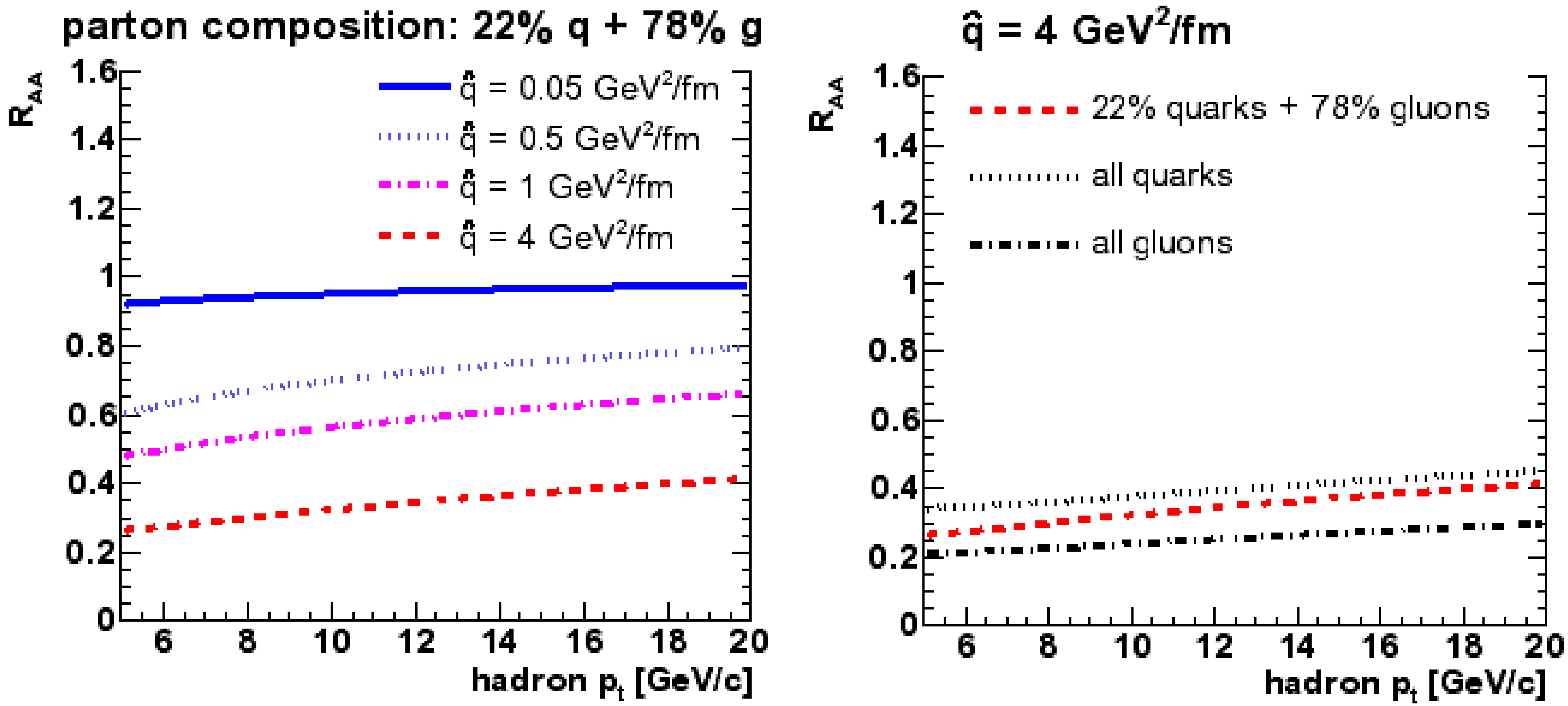
Effect of shadowing



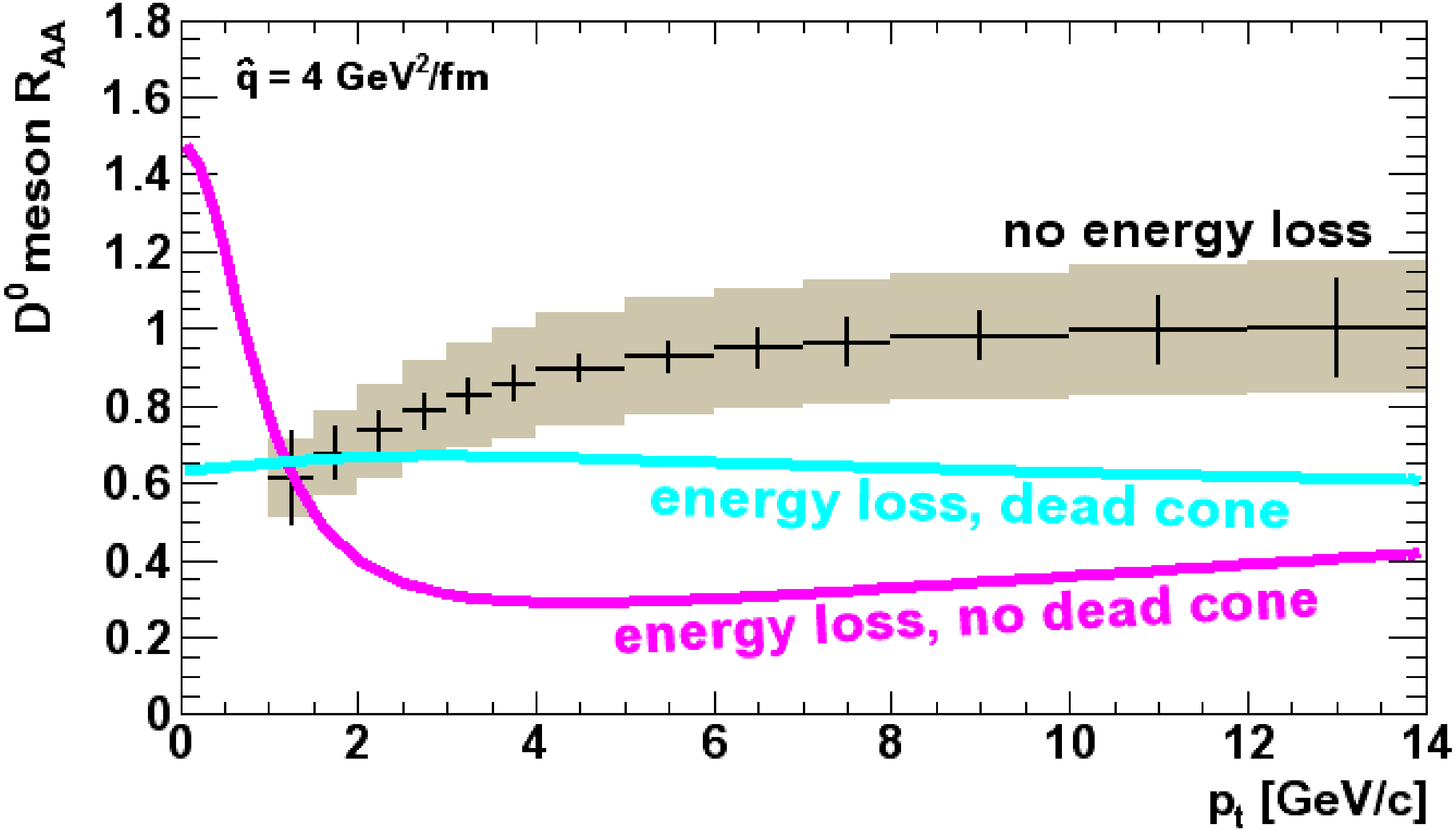


Transport coefficient choice

- Require for LHC suppression of hadrons as observed at RHIC: R_{AA} ~ 0.2-0.3 for $4<p_t<10$ GeV/c



R_{AA} with Quenching



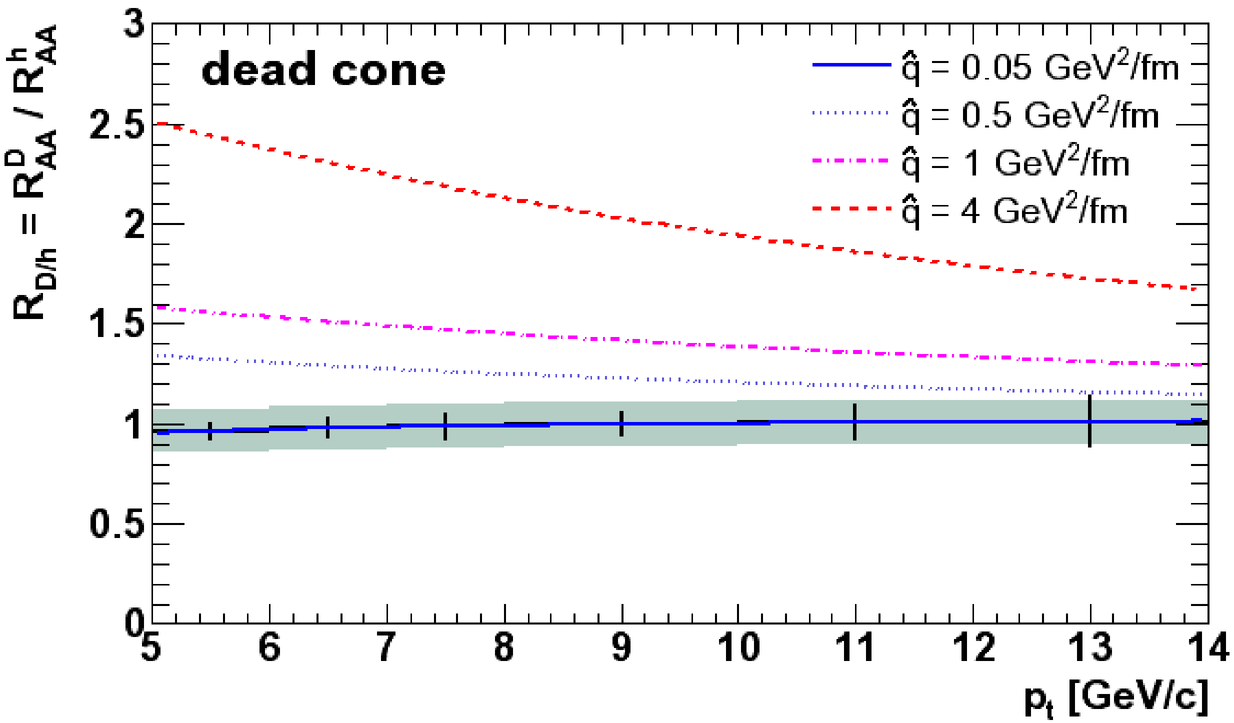
R_{AA} ~ 0.4–0.5
increasing at high p_t

R_{AA} ~ 0.7–0.8
decreasing at high p_t

A.D. Eur. Phys. J. **C33** (2004) 495 [arXiv:nucl-ex/0312005].

D/hadrons ratio (1)

- Ratio expected to be enhanced because:
  - **D comes from (c) quark, while π, K, p come mainly (~80% in PYTHIA) from gluons, which lose ×2 more energy w.r.t. quarks**
  - **dead cone for heavy quarks**



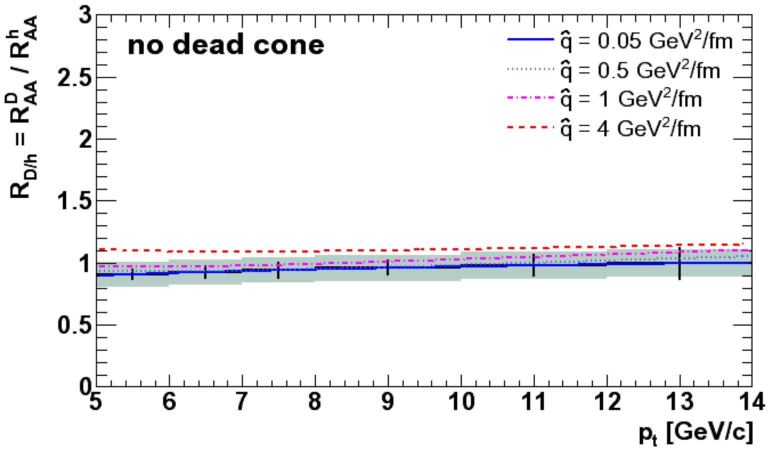
D/h ratio:

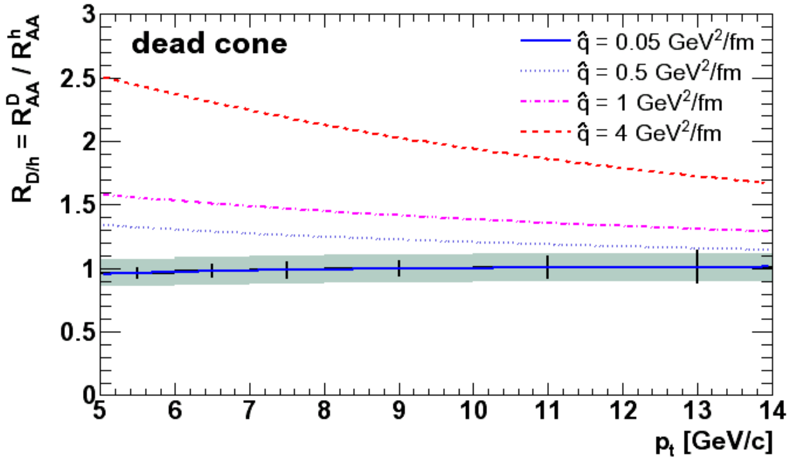
$$R_{D/h} = R_{AA}{}^D / R_{AA}{}^h$$

$R_{D/h}$ ~ 2–3 in hot QGP

sensitive to medium density

D/hadrons ratio (2)





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

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

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

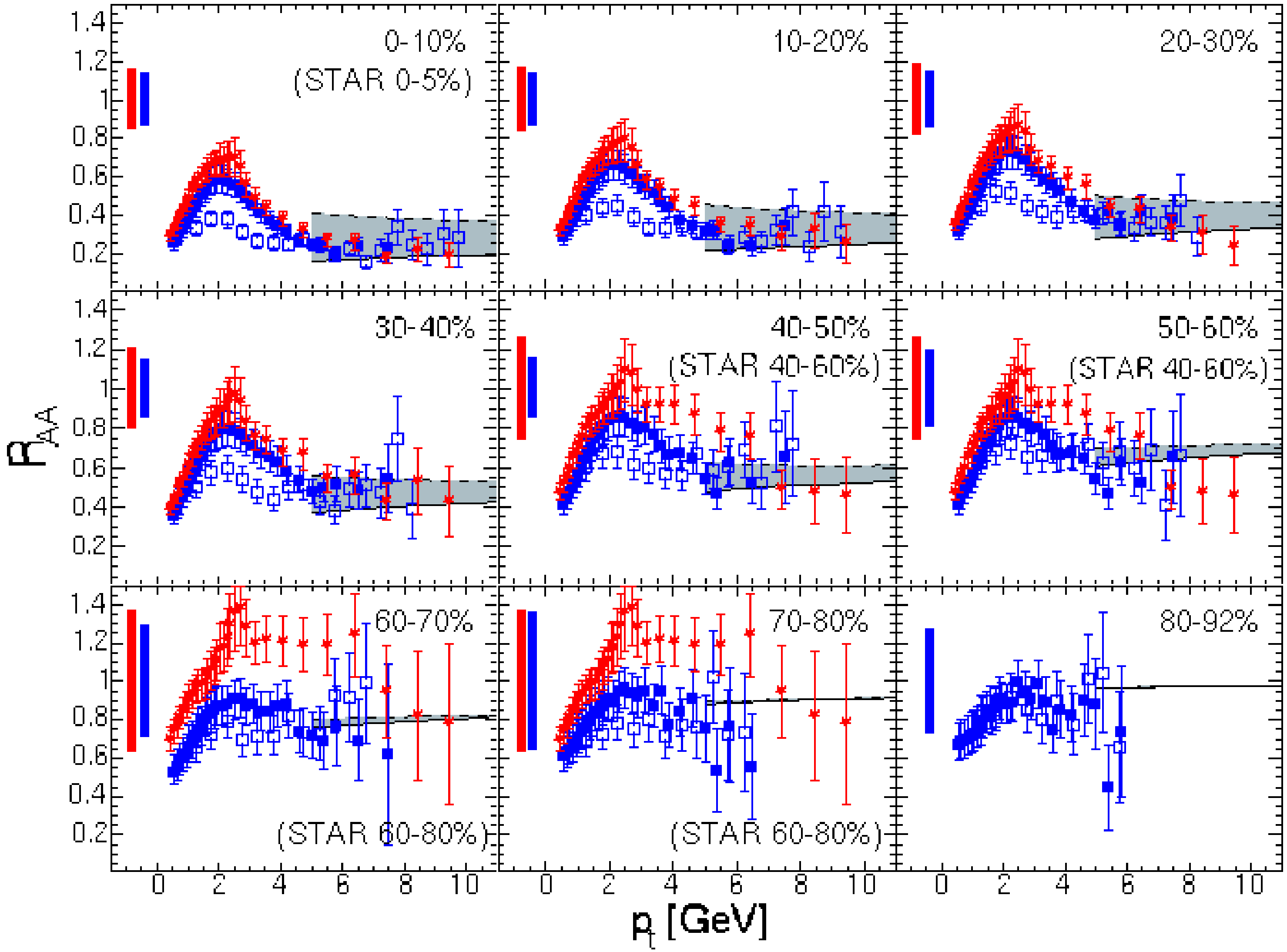
$z_{c\to D} \approx 0.8$; $z_{gluon\to hadron} \approx 0.4$ (for $p_t > 5$ GeV/c)

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

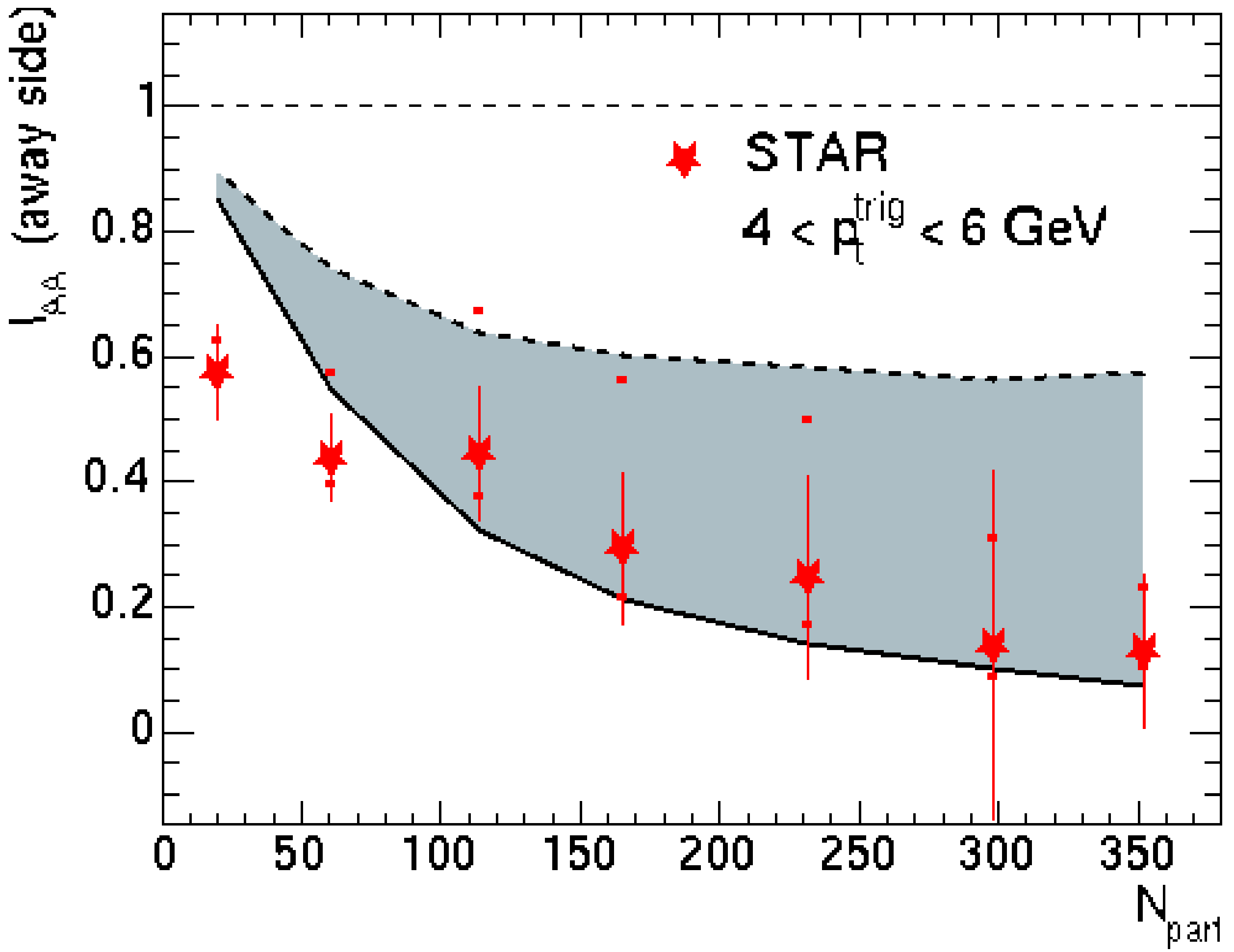
$$z_{c\to D}\,\Delta E_c \approx 0.9\, z_{gluon\to hadron}\,\Delta E_{gluon}$$

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

PQM: R_{AA} all centralities

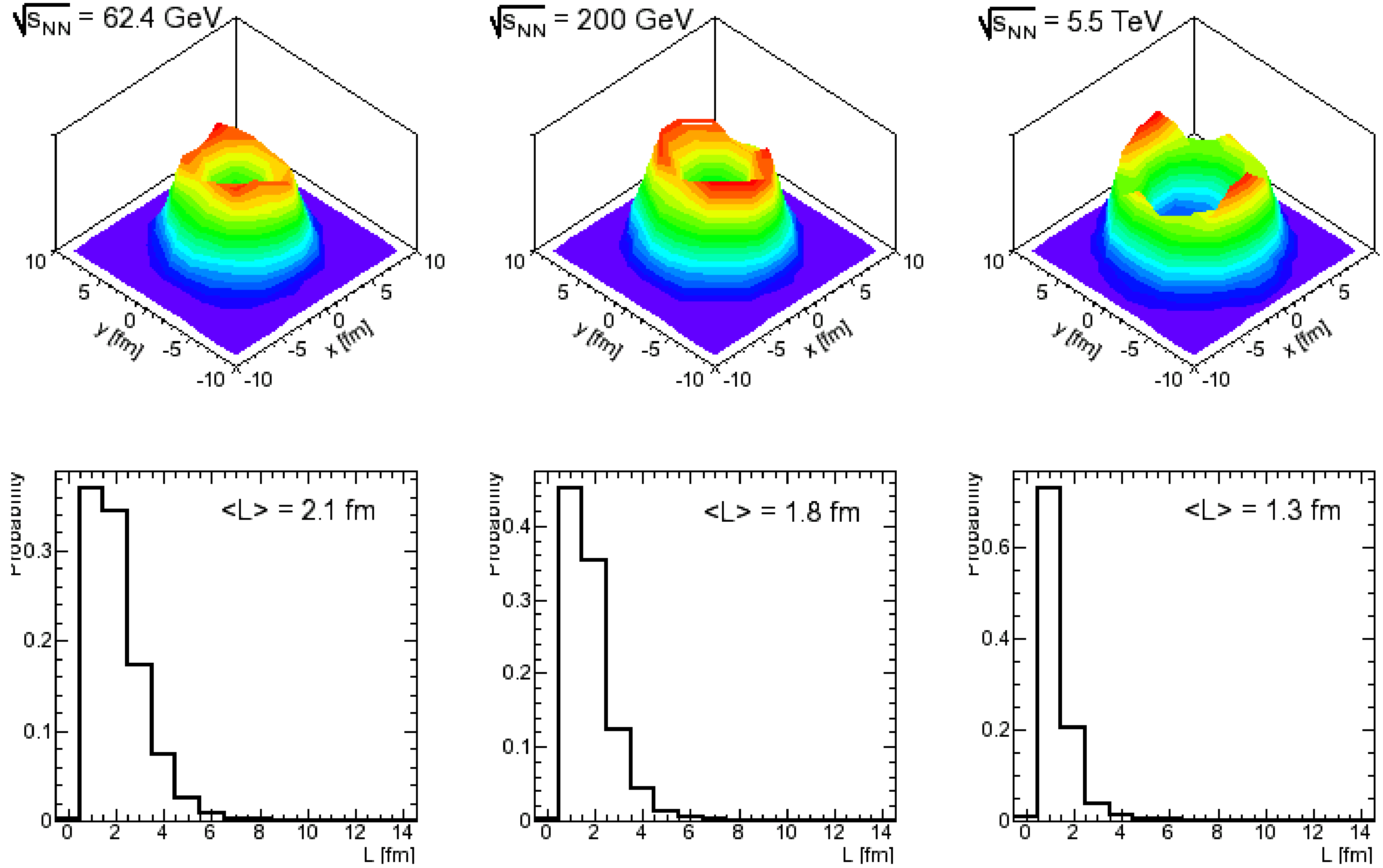


PQM: I_{AA}

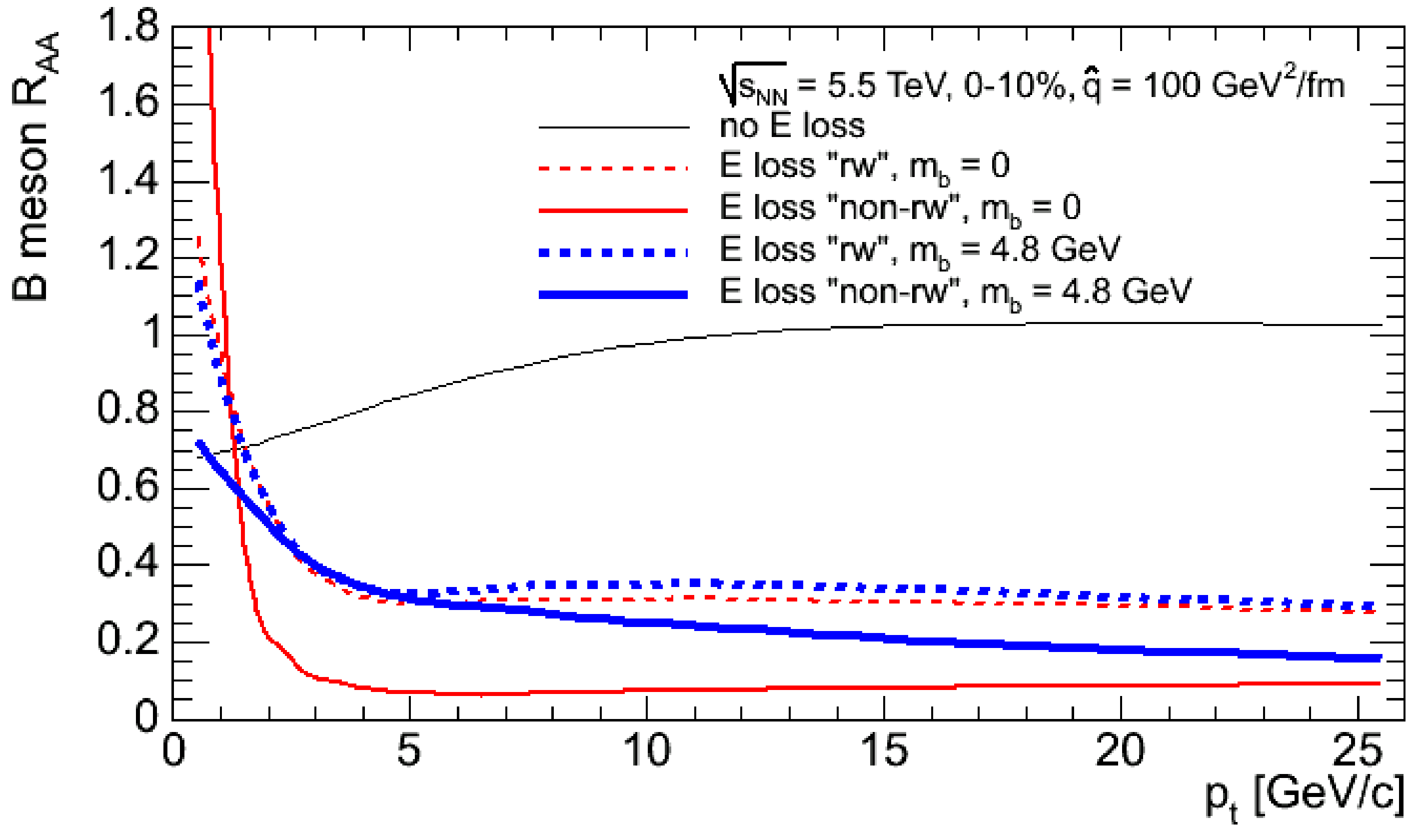


I_{AA} (away side)
STAR
$4 < p_t^{trig} < 6$ GeV
N_{part}
0
50
100
150
200
250
300
350
0.2
0.4
0.6
0.8
1

PQM: surface effect

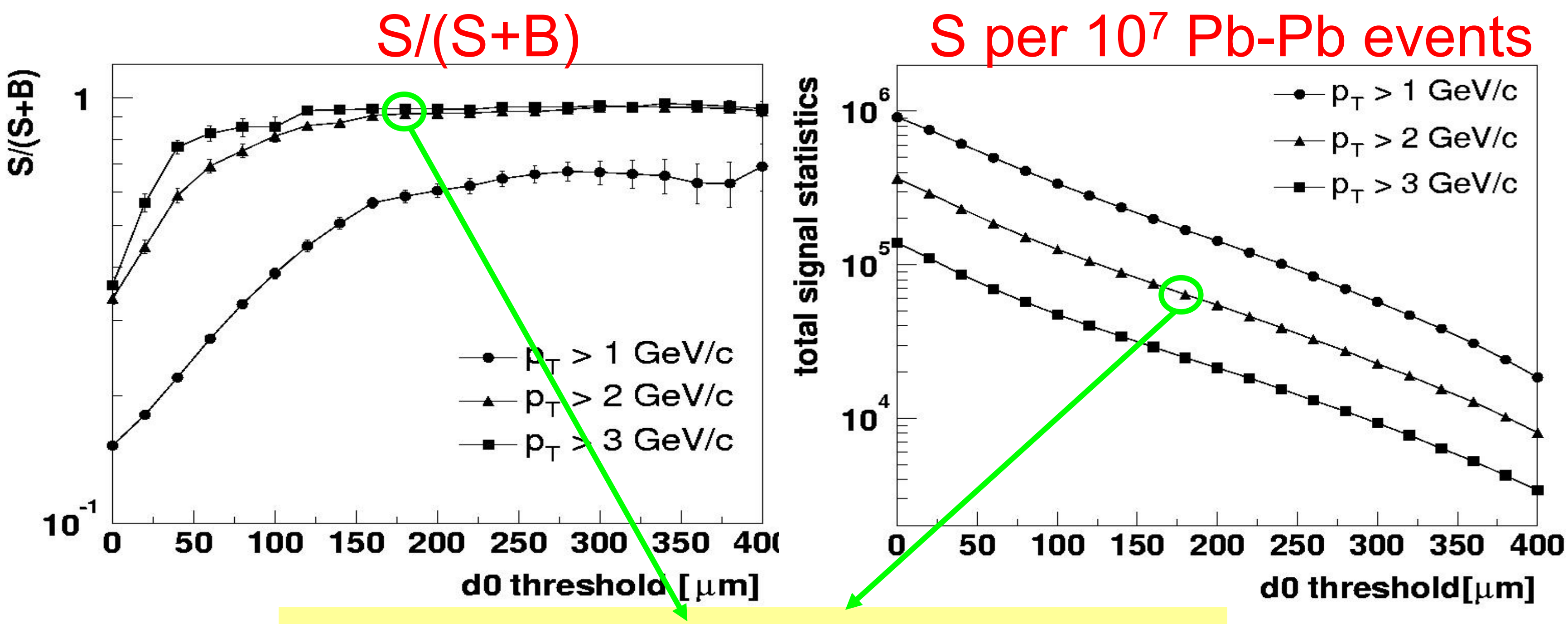


B mesons R_{AA} at LHC



Open Beauty in electron channel

- Inclusive B $\rightarrow e^{\pm}$ + X:
  - electron ID + cut on its p_t & on its impact parameter d0



p_t > 2 GeV/c, d_0 > 180 μm:
50,000 electrons with S/(S+B) = 90 %