1954-2004

LHC heavy ion physics

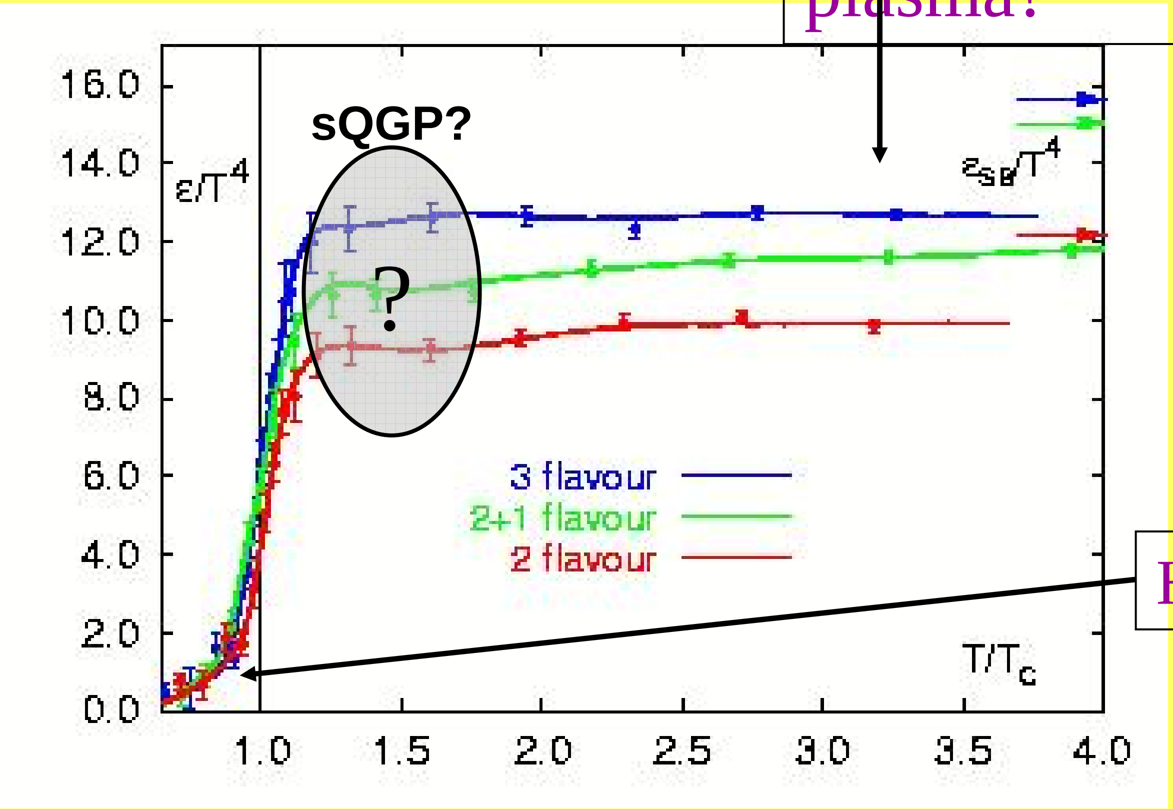
Guy Paić
Instituto de Ciencias Nucleares
UNAM
Mexico

outline

- LHC parameters
- new quality expected at the LHC
- intermediate p_t range
- parton energy loss at RHIC and LHC
- charm parton energy loss
- quarkonia suppression

Present knowledge

$$\varepsilon = \frac{\pi^2}{30} g_{\mathrm{DOF}} T^4$$



QGP = quark-gluon plasma?

QCD equation of state from lattice QCD

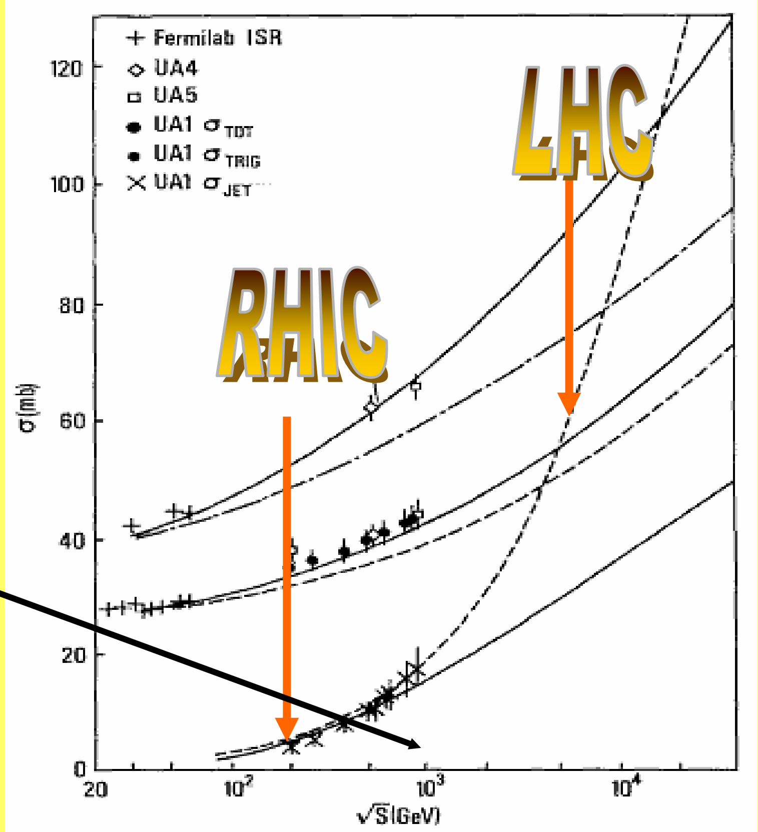
Hadron gas

$$\langle \bar{\psi}\psi \rangle_0$$

We are entering the minijet era

The dominant part of the minijet Xsection comes from from semihard processes between partons (mostly gluons) carrying very small longitudinal momentum fractions $x \leq 0.1$ and $p_T \geq 2$ GeV/c

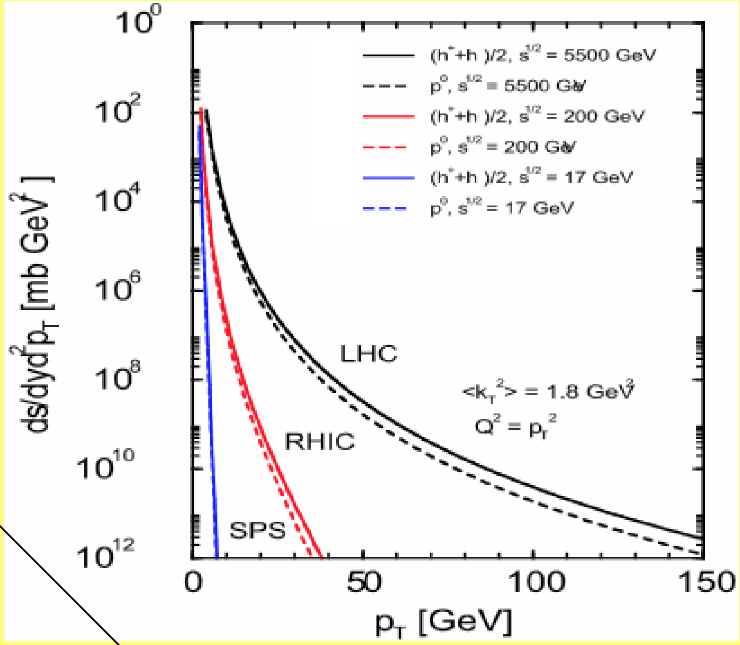
Minijet X-section



From Capella et al.: Phys. Letters PRL 38(1987)2015

What's new at the LHC ?

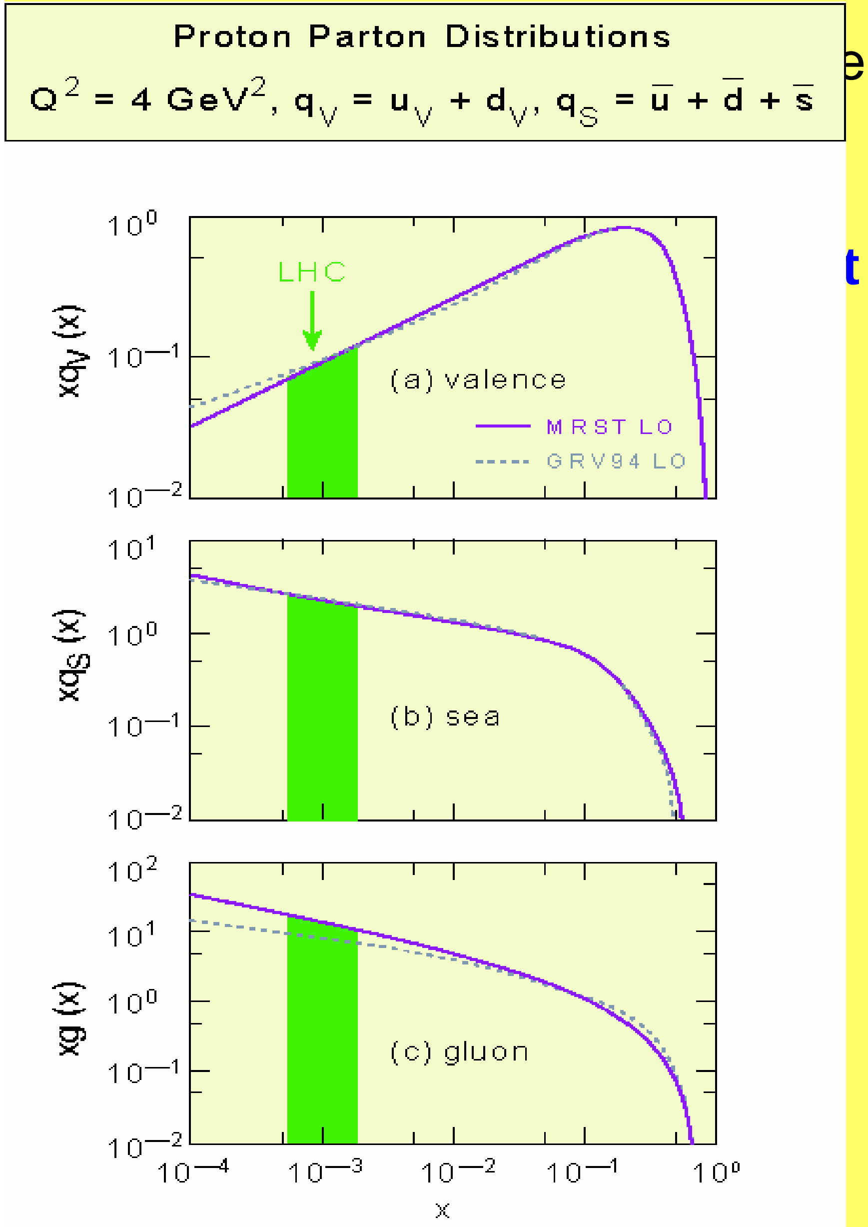
- Higher energy density ε_0 at earlier time τ_0: "sQGP" → QGP ?
- Jet physics can be probed to $p_T > 100$ GeV.
- *b, c* quarks are plentiful, good probes.
- Different $x_{bjorken}$ ranges

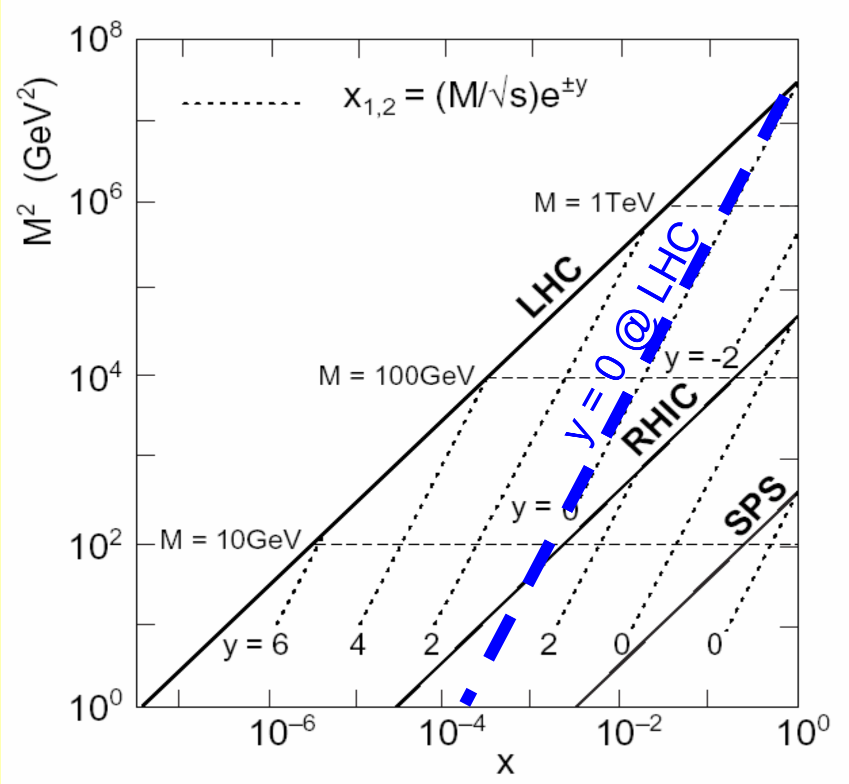


$$\sigma_{LHC}^{c\bar{c}} \approx 10 \times \sigma_{RHIC}^{c\bar{c}}$$

$$\sigma_{LHC}^{b\bar{b}} \approx 100 \times \sigma_{RHIC}^{b\bar{b}}$$

Testing new parts of the PDF Small x





Window on the rich phenomenology of high-density PDFs

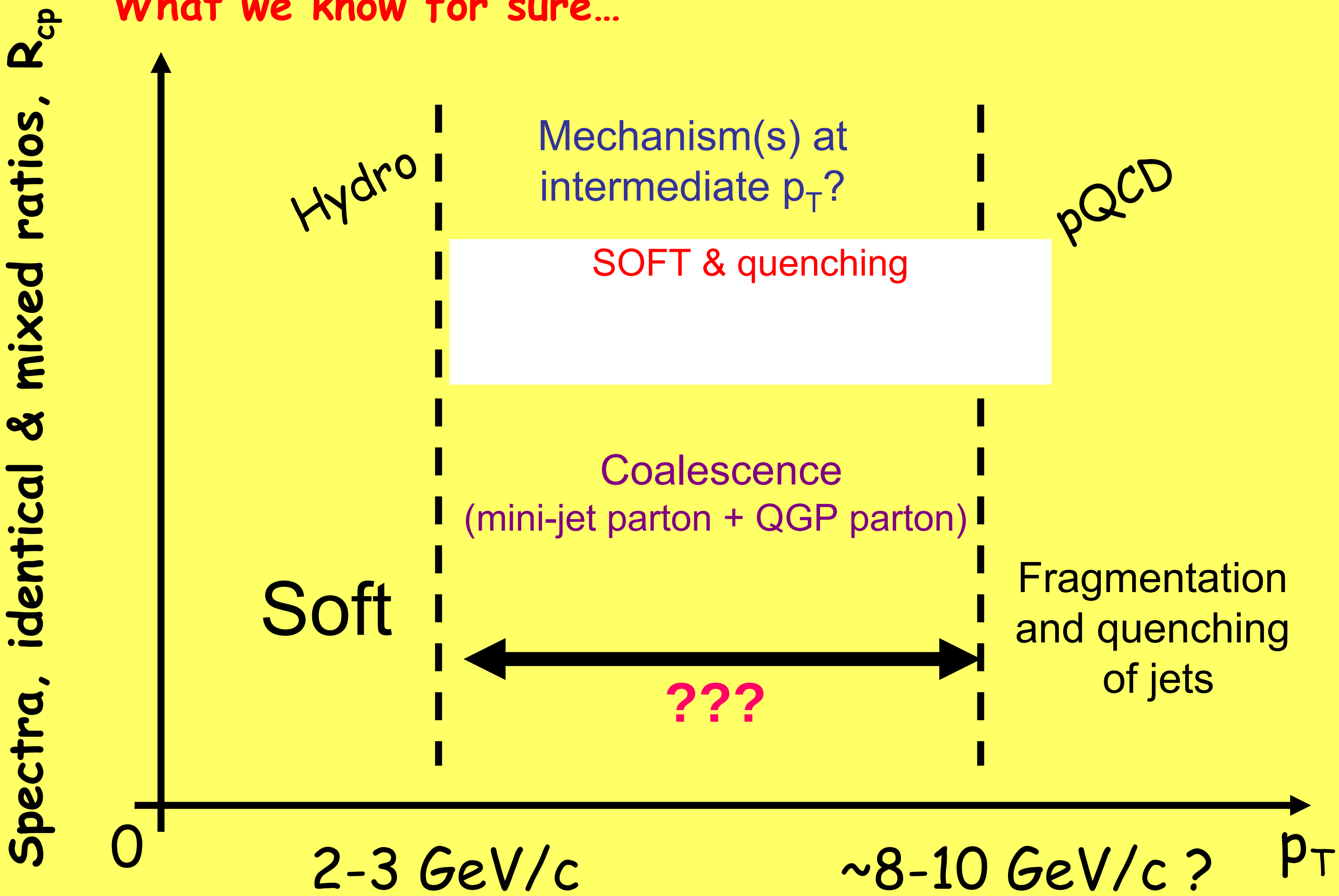
- shadowing / saturation effects / Color Glass

Attempts at sorting the phenomena

- Before we had the so called hard (scarce) probes and the soft (plentiful) probes
- Now the nomenclature has been enriched by an intermediate range

Particle production vs P_T

What we know for sure…



Spectra, identical & mixed ratios, R_{cp}

Hydro

Soft

Mechanism(s) at intermediate p_T?

SOFT & quenching

Coalescence (mini-jet parton + QGP parton)

???

pQCD

Fragmentation and quenching of jets

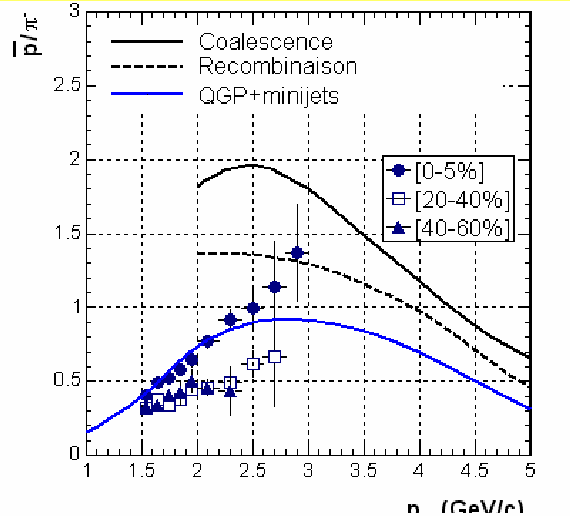
0

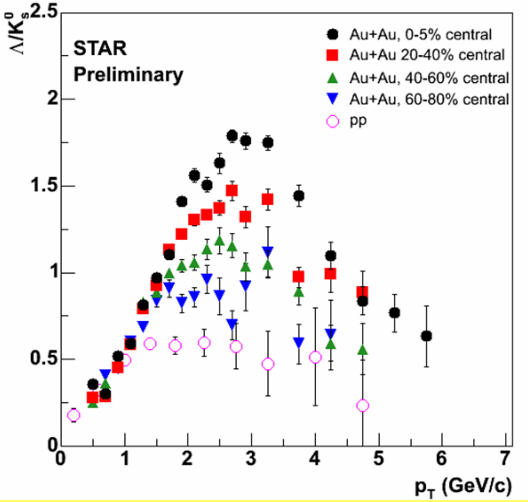
2-3 GeV/c

~8-10 GeV/c ?

p_T

puzzles $\bar{p}/\pi^-$





RHIC data seem to follow the turn over. However where is the turnover ?and what is the underlying physics

Unclear at RHIC and even more so at LHC

Reco : Phys. Rev. C**68** 044902 (2003)

Coal : Phys. Rev. C**68** 034904 (2003)

Hydro: Phys. Rev. C**67**, 044903 (2003)

S+Q: 130 GeV data - Phys. Rev. C**65**, 041902

Recombination+Fragmentation Model

basic assumptions:

- at low p_t, the quarks and antiquark spectrum is thermal and they recombine into hadrons locally "at an instant":

$$q\bar{q} \rightarrow M \qquad qqq \rightarrow B$$

  - ➢ features of the parton spectrum are shifted to higher p_t in the hadron spectrum

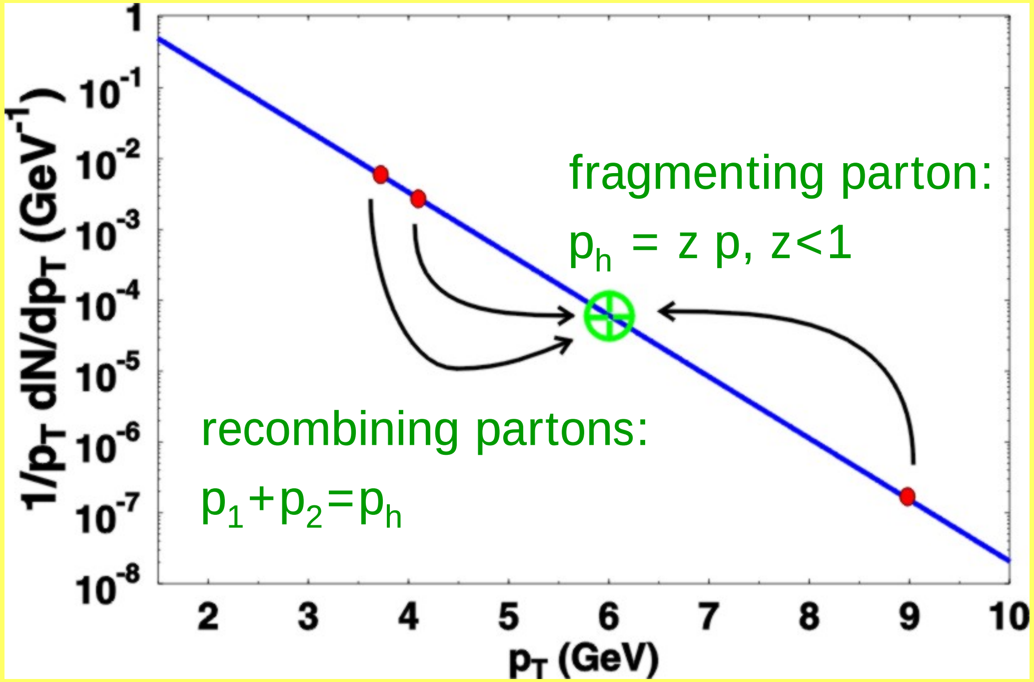
- at high p_t, the parton spectrum is given by a pQCD power law, partons suffer jet energy loss and hadrons are formed via fragmentation of quarks and gluons

Recombination: Pro’s & Con’s

Pro’s:

- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

➢ understand behavior of protons!



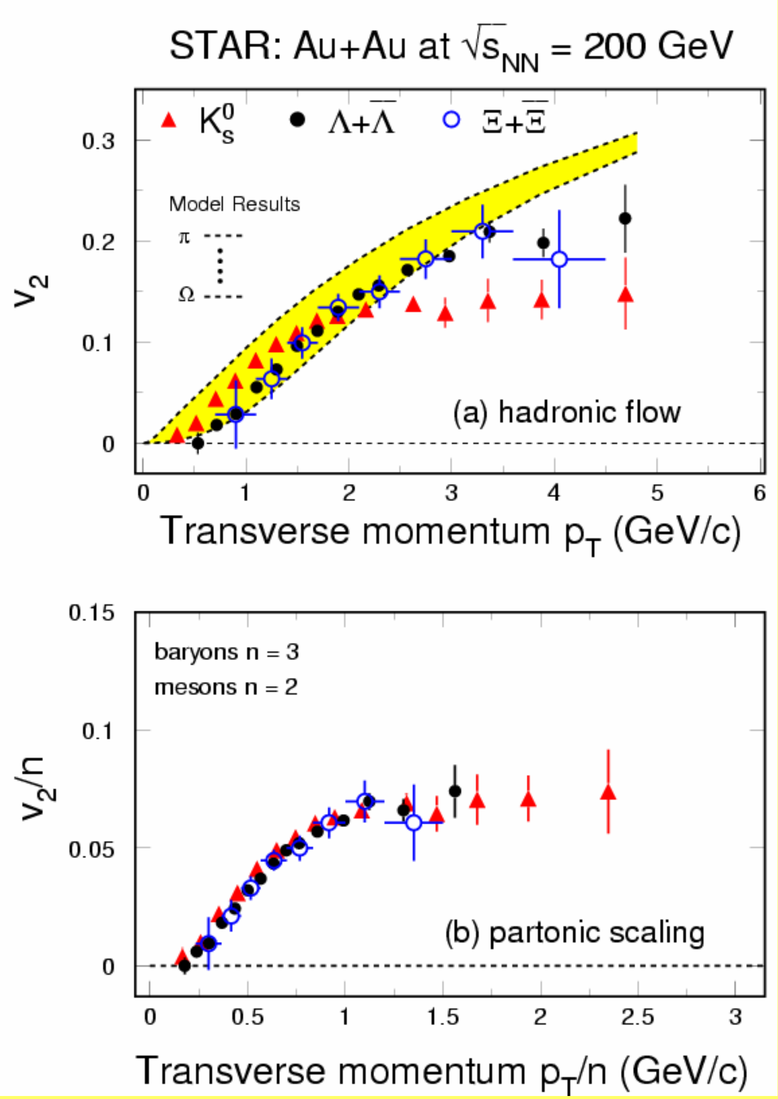
Con’s:

- recombination violates entropy conservation
- gluons at hadronization need to be converted

Quark coalescence / recombination

- Evidence of quark coalescence?
  - –Particle dependence of elliptic flow.

    Constituent quark scaling.

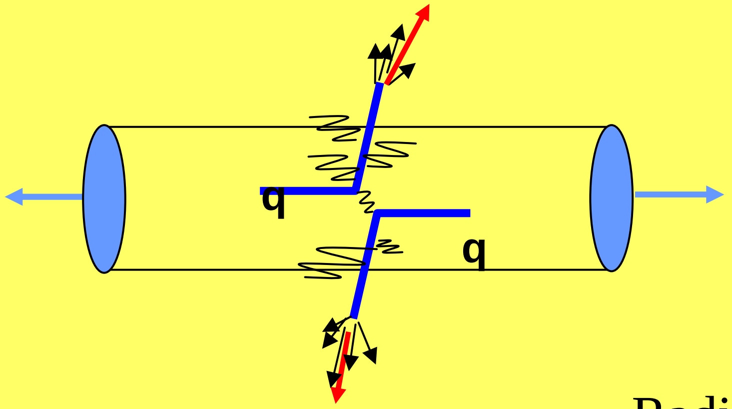


- **Is this a consistent picture?**
- **Can it also explain …**
  - – Anomalous B/M ratio?
  - – Particle dependence of hadron suppression?

Consequences for ALICE physics

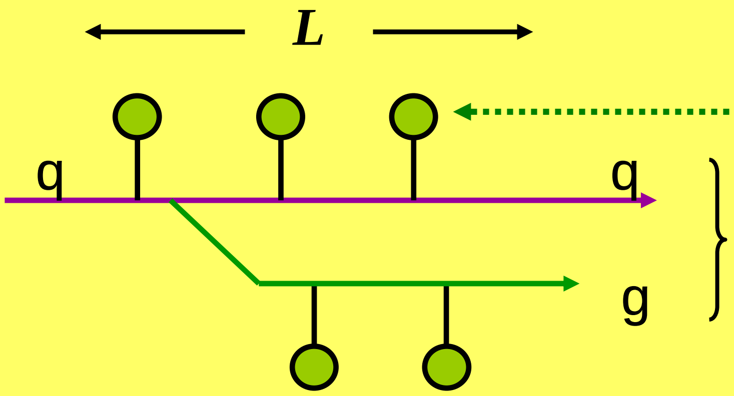
- Necessity : enlarge the PID range as much as possible
- Use lambda detection as far as possible in pt
- Use to the utmost the relativistic rise of ionization in TPC
- Think about new PID detctors.

Jet Quenching



High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss: $dE/dx \sim \rho L \left\langle {k_T}^2 \right\rangle$



Scattering centers = color charges

medium modifed jet

Can be described as medium effect on parton fragmentation:

$$D_{p\to h}(z,Q^2) \to \tilde{D}_{p\to h}(z,Q^2) \approx D_{p\to h}\left(\frac{z}{1-\Delta E/E},Q^2\right)$$

Energy loss in QCD

Density of scattering centers

Scattering “power” of QCD medium:

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho\sigma \left\langle k_\mathrm{T}^2 \right\rangle = \lambda_\mathrm{F}^{-1} \left\langle k_\mathrm{T}^2 \right\rangle$$

Property of medium
(range of color force)

For power law parton spectrum ($\sim p_\mathrm{T}^{-\nu}$) energy loss leads to an effective momentum shift for fast partons (BDMS):

$$\Delta p_T \approx -\alpha_s \sqrt{\pi \hat{q} L^2 p_T / \nu}$$

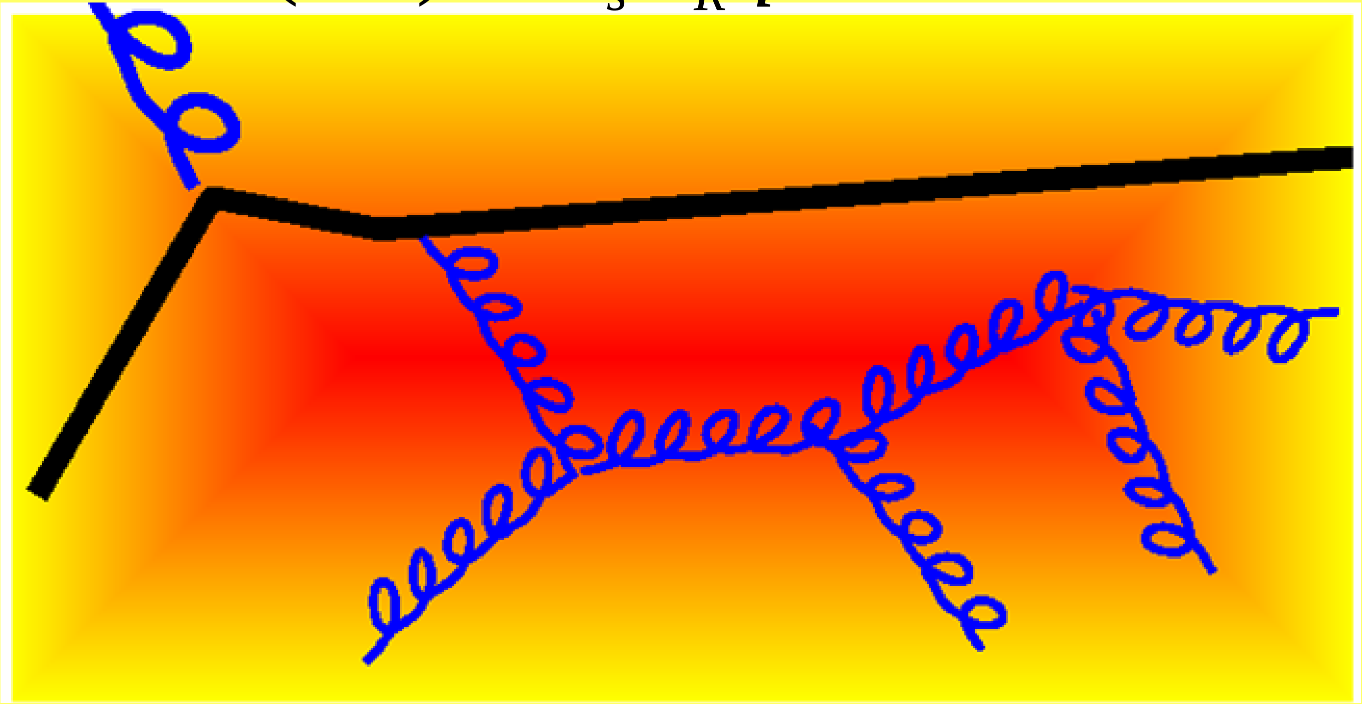
With expansion:

$$\hat{q} \quad \Rightarrow \quad \hat{q}_\mathrm{eff} = \frac{2}{L^2} \int_{\tau_0}^{\tau_0+L} d\tau (\tau - \tau_0) \hat{q}(r_\tau, \tau)$$

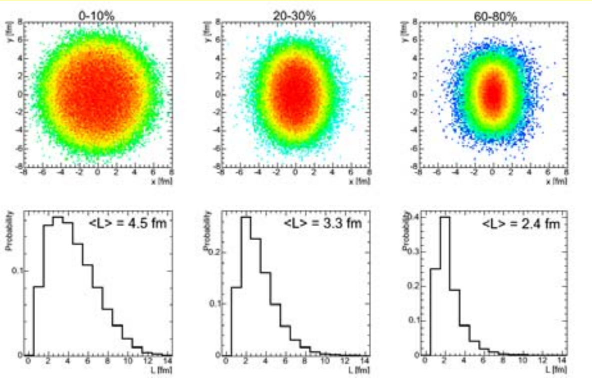
Due to the medium induced gluon radiation of hard parton travelling a distance *L*

Transport coefficient: $\widehat{q} = \langle \widehat{q}_t^2 \rangle_{medium} / \lambda$

Average energy loss BDMPS: $(\Delta E) \propto \alpha_s C_R \widehat{q} L^2$



Importance of the parameter L & $\hat{q}$



Due to the phase space the surface emission is the most probable close to the surface! $\hat{q}$

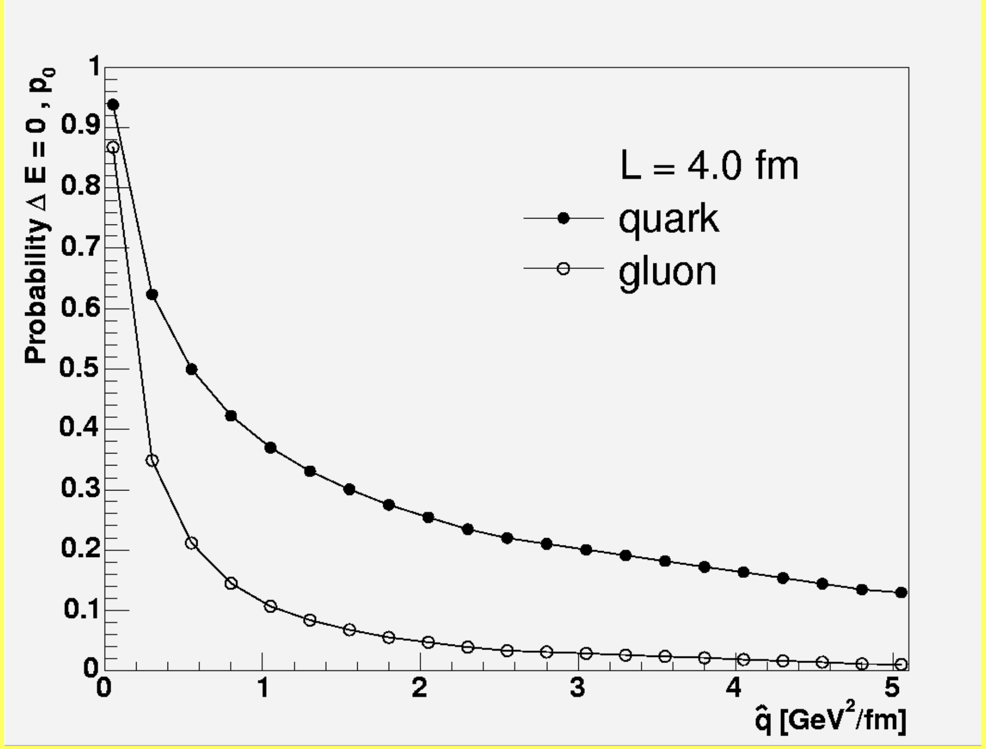
There is nothing we can do about that!!

- Specific energy loss $\hat{q}$ function of the density profile!

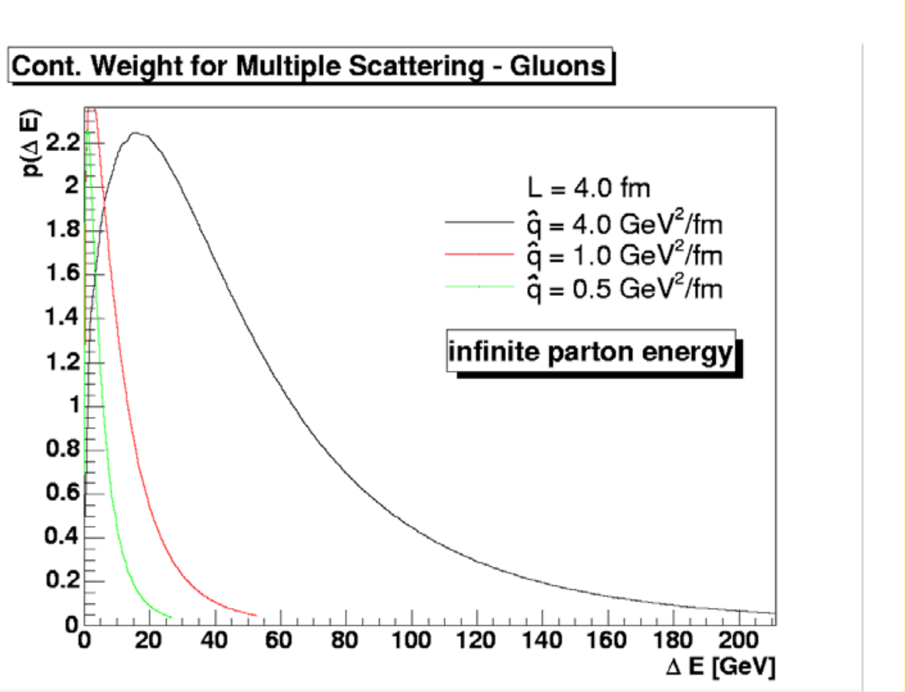
Results from a toy MC model based on the work of Wiedemann and Salgado:

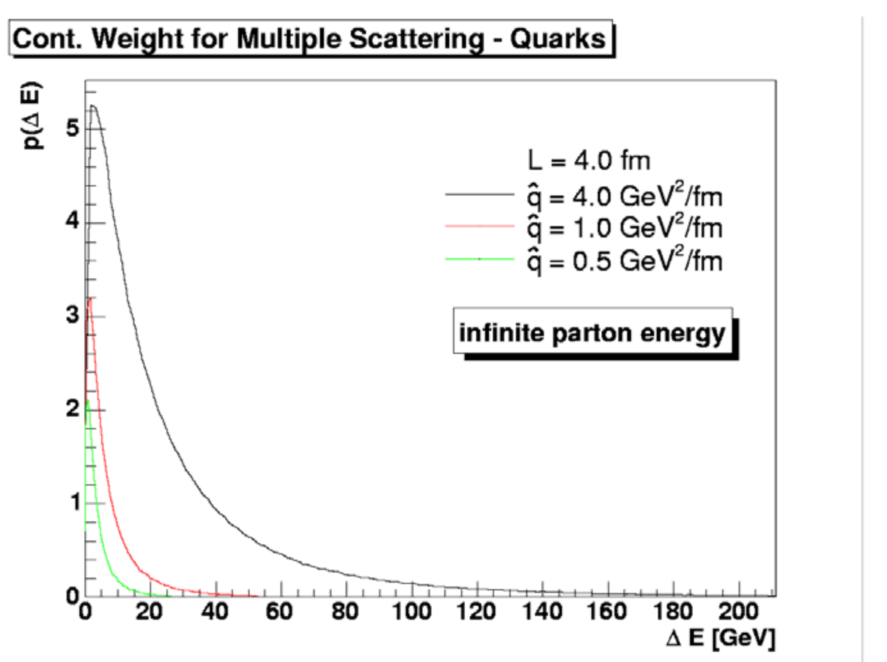
A.Dainese,C. Loizides, G.P: arXiv:Hep-ph/0406201

Probability of no energy loss for a constant length



Energy loss difference between quarks and gluons





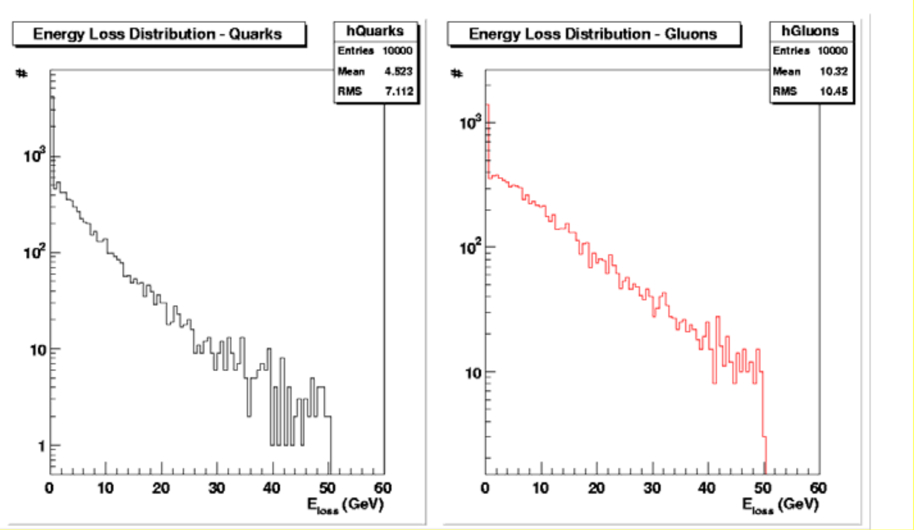
Two ways to go to finite parton energies

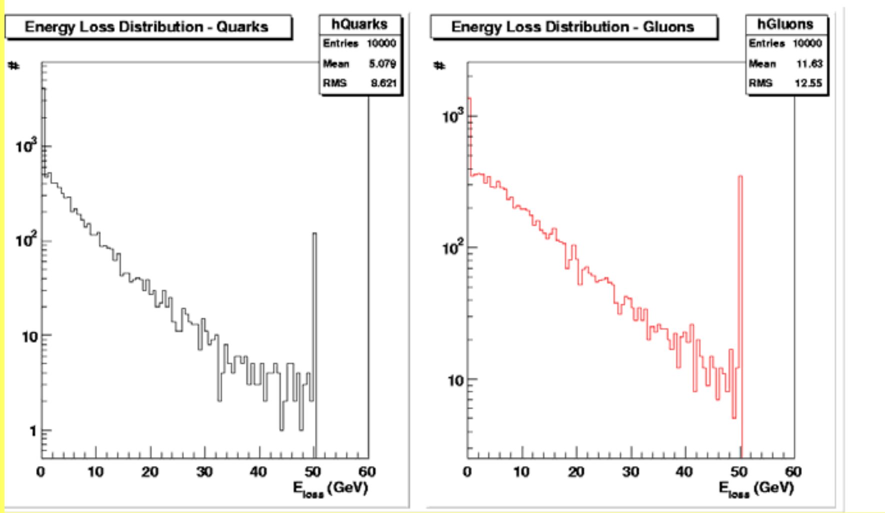
Reweighted: truncate $P(\Delta E) @ \Delta E = E$

And renormalize to 1 using $\int_0^E d\varepsilon P(\varepsilon)$

Non reweighted: add $\delta - function \therefore \delta(\Delta E - E)\int_E^\infty d\varepsilon P(\varepsilon)$

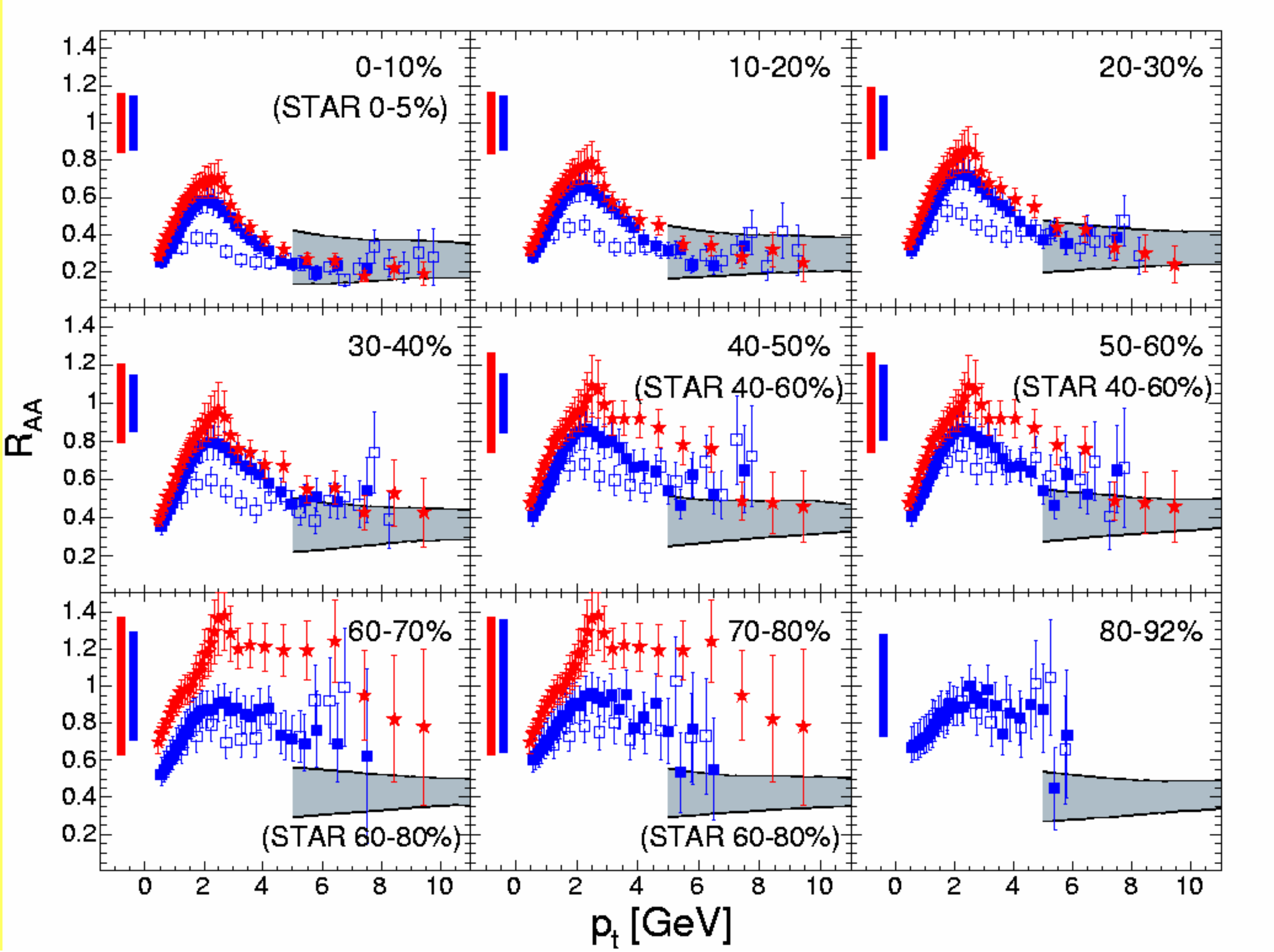
$E = 50 GeV, \hat{q} = 1 GeV^2 / fm, L = 4 fm$





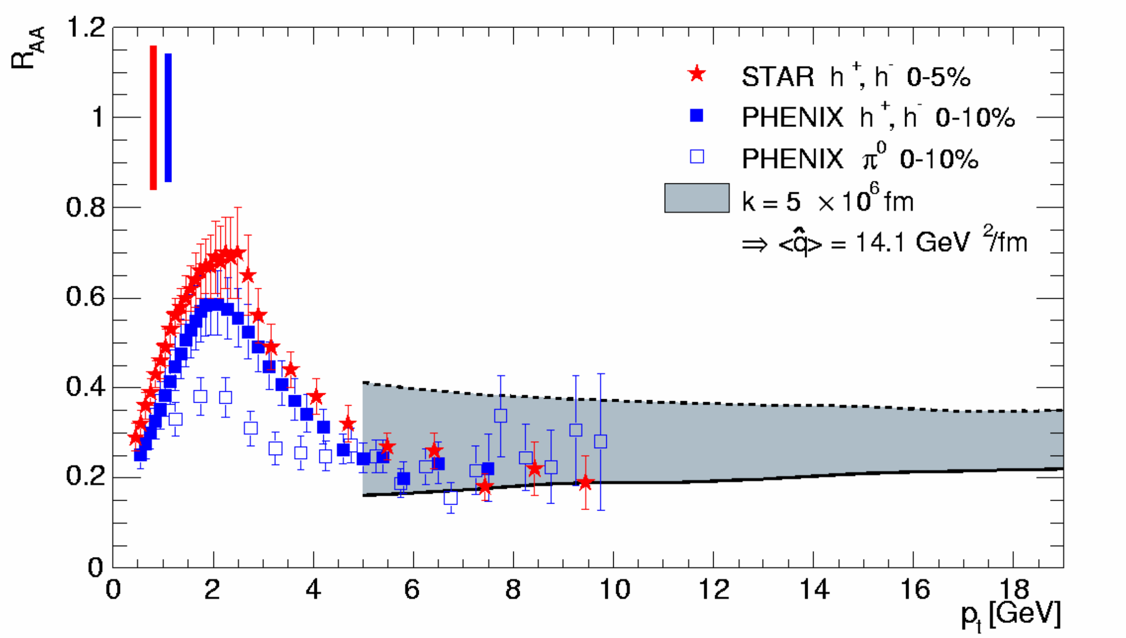
WITH A constant transport coefficient one cannot describe the centrality dependence at RHIC (STAR)

$R_{AA}(p_t)$ at $\sqrt{s_{NN}}$ = 200 GeV (Au–Au) for $\widehat{q}$ = 15GeV^2/fm



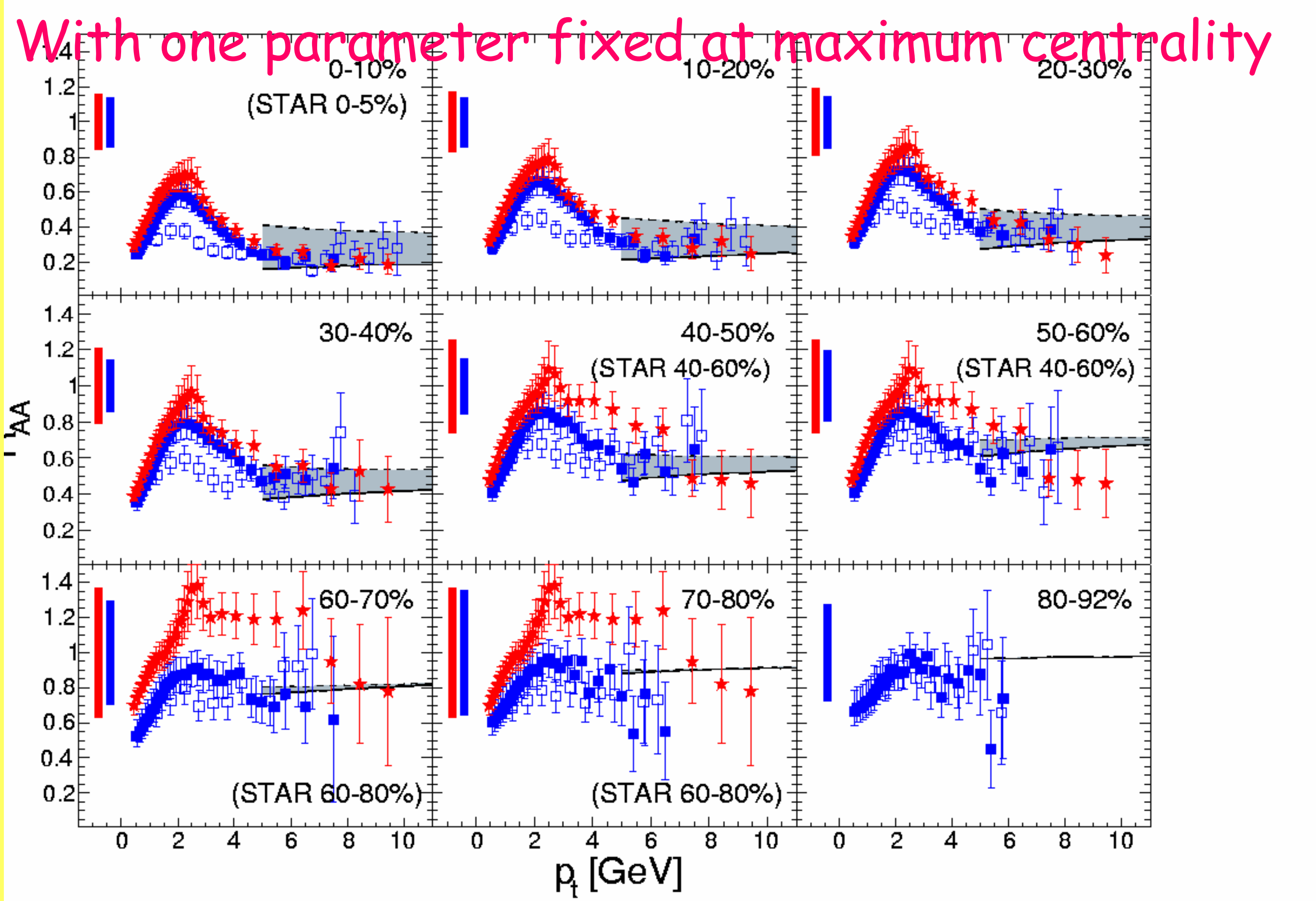
Parton by parton approach in the PQM

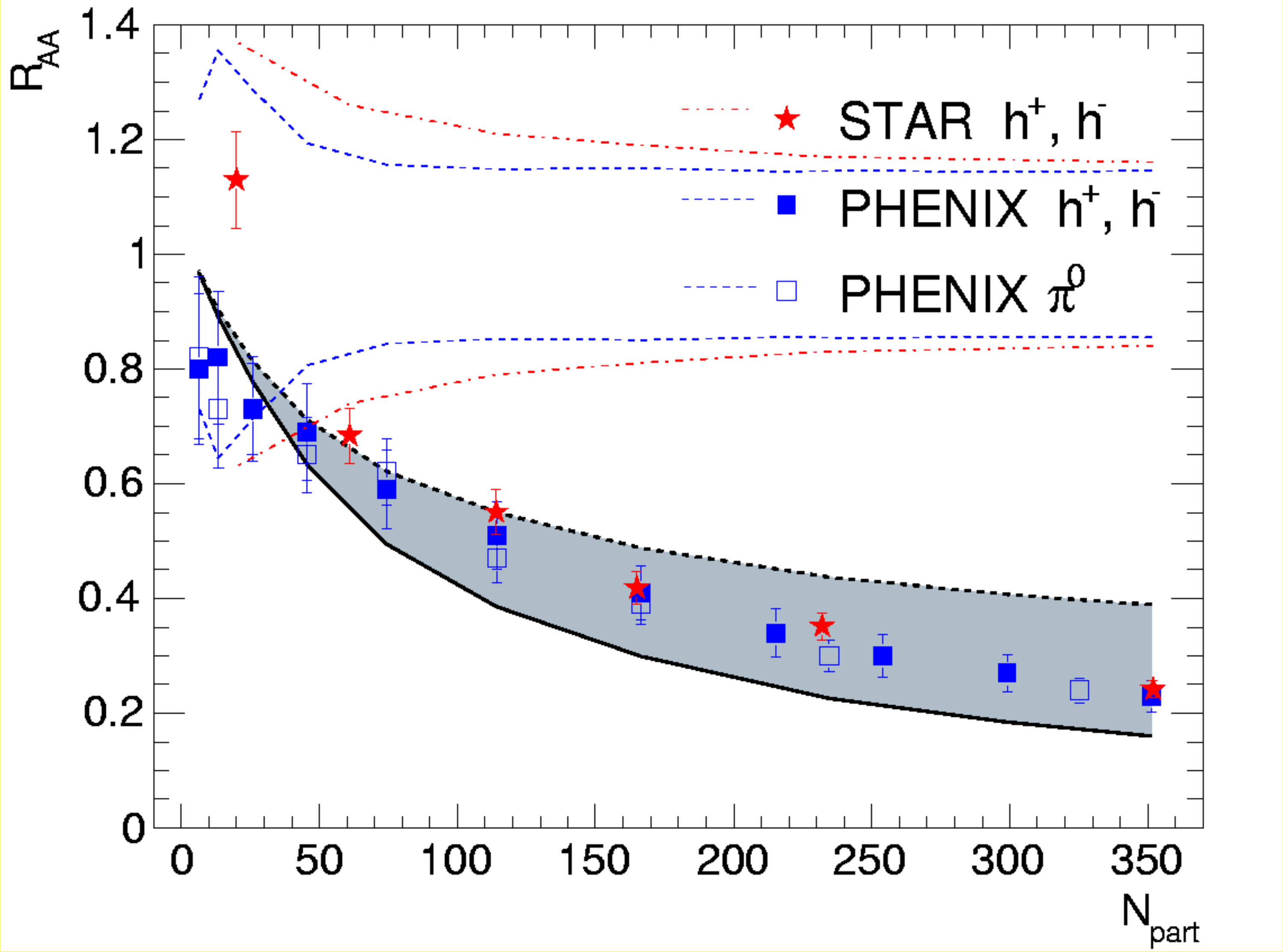
- Define "local" transport coefficient for every parton $\widehat{q}(\xi;b) = k \times T_A T_B(x_0 + \xi u_y;b)$
- Using $I_n \equiv \int^{\infty} \xi^n \widehat{q}(\xi;b)d\xi$ n=0,1



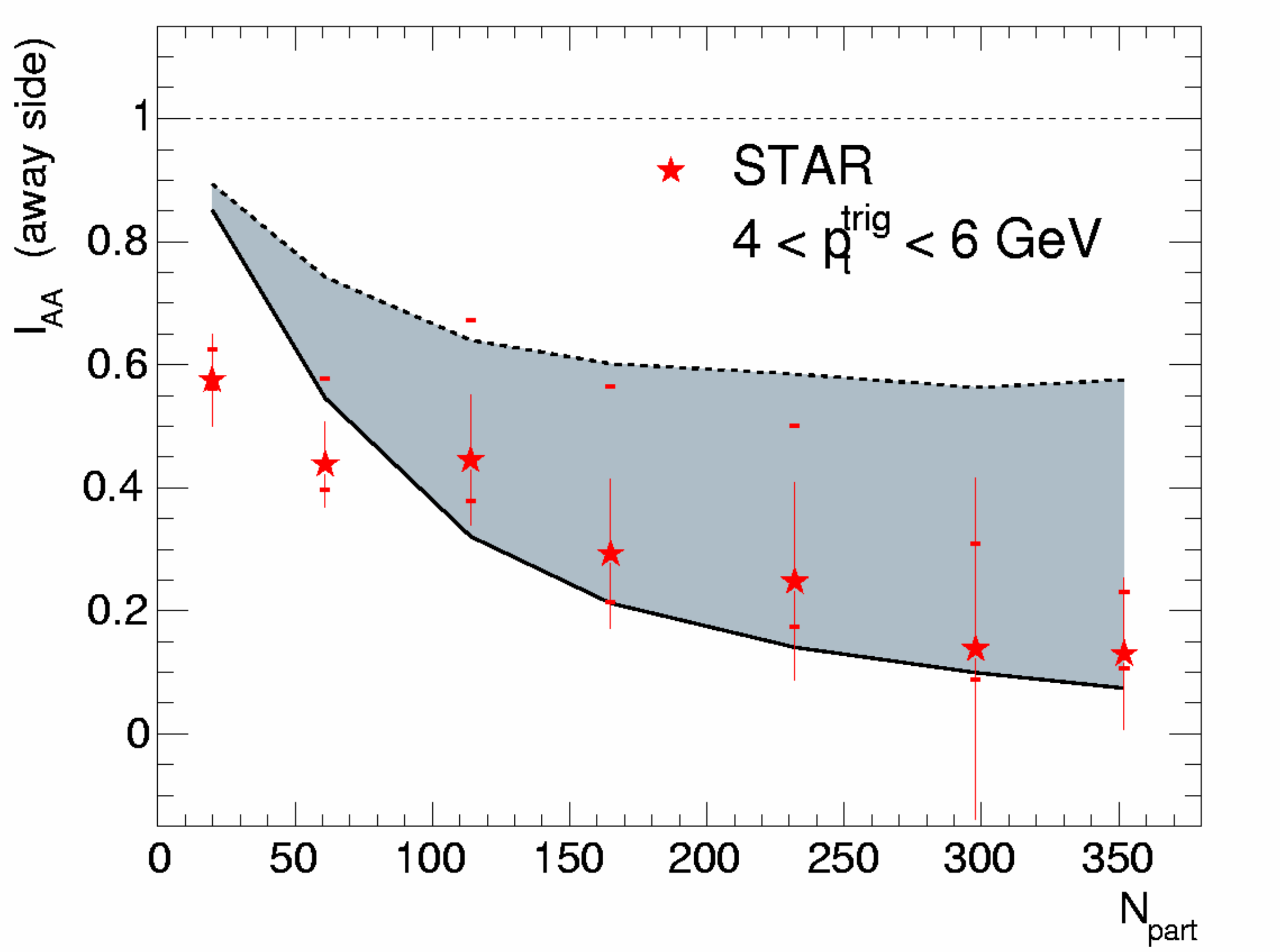
Using the parton by parton approach the centrality is well described

With one parameter fixed at maximum centrality

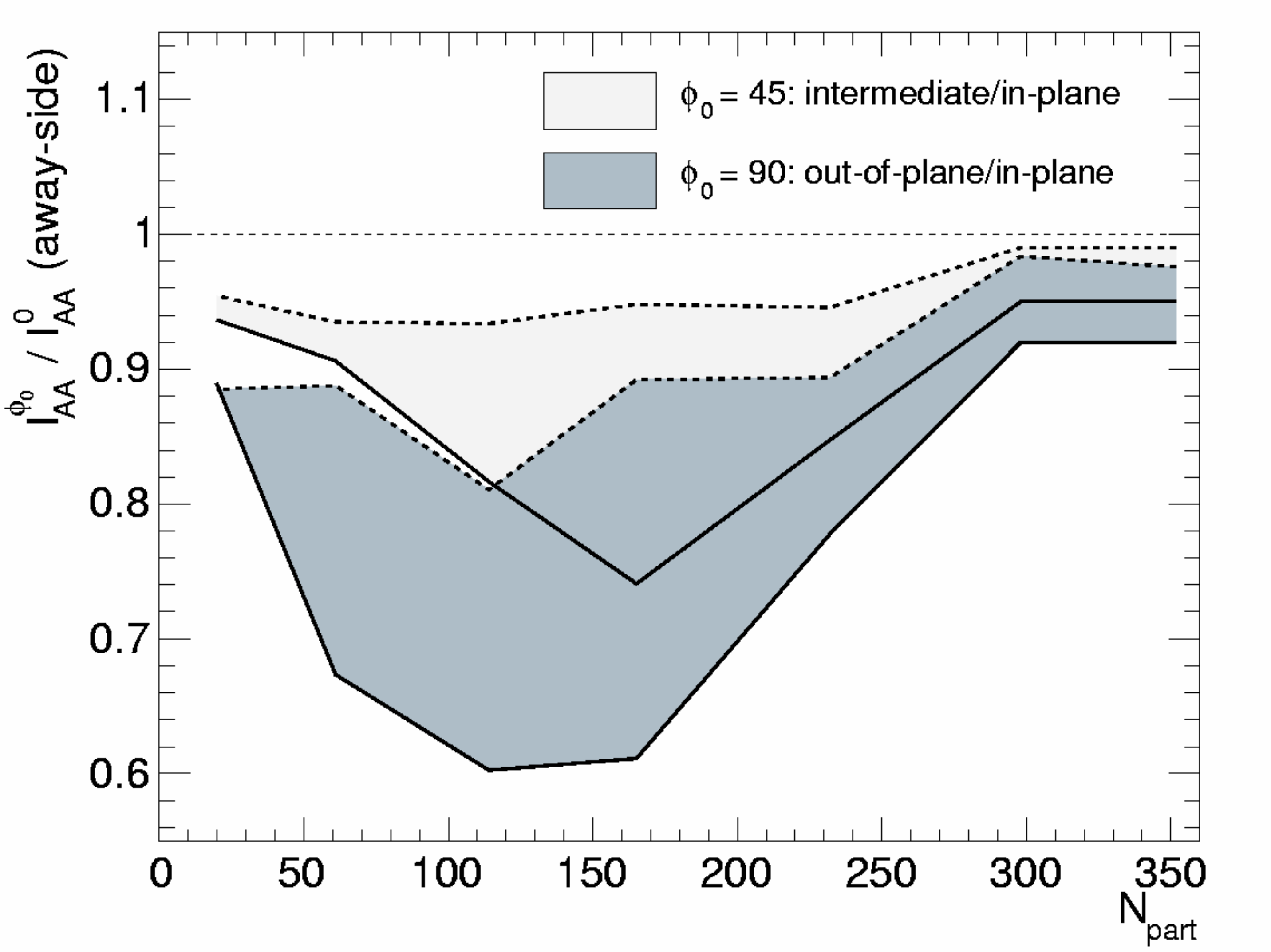



R_{AA}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
N_{part}
STAR h^+, h^-
PHENIX h^+, h^-
PHENIX π^0

The turning off awayside jets also described



More predictions for RHIC:azimuthal dependence



Extrapolaton to different energies

Ansatz:

$\hat{q} \propto n^g_{\rm initial}$ and $n^{\rm g} \propto {\rm A}^{0.383} \left(\sqrt{s_{\rm NN}}\right)^{0.574}$ (saturation model)

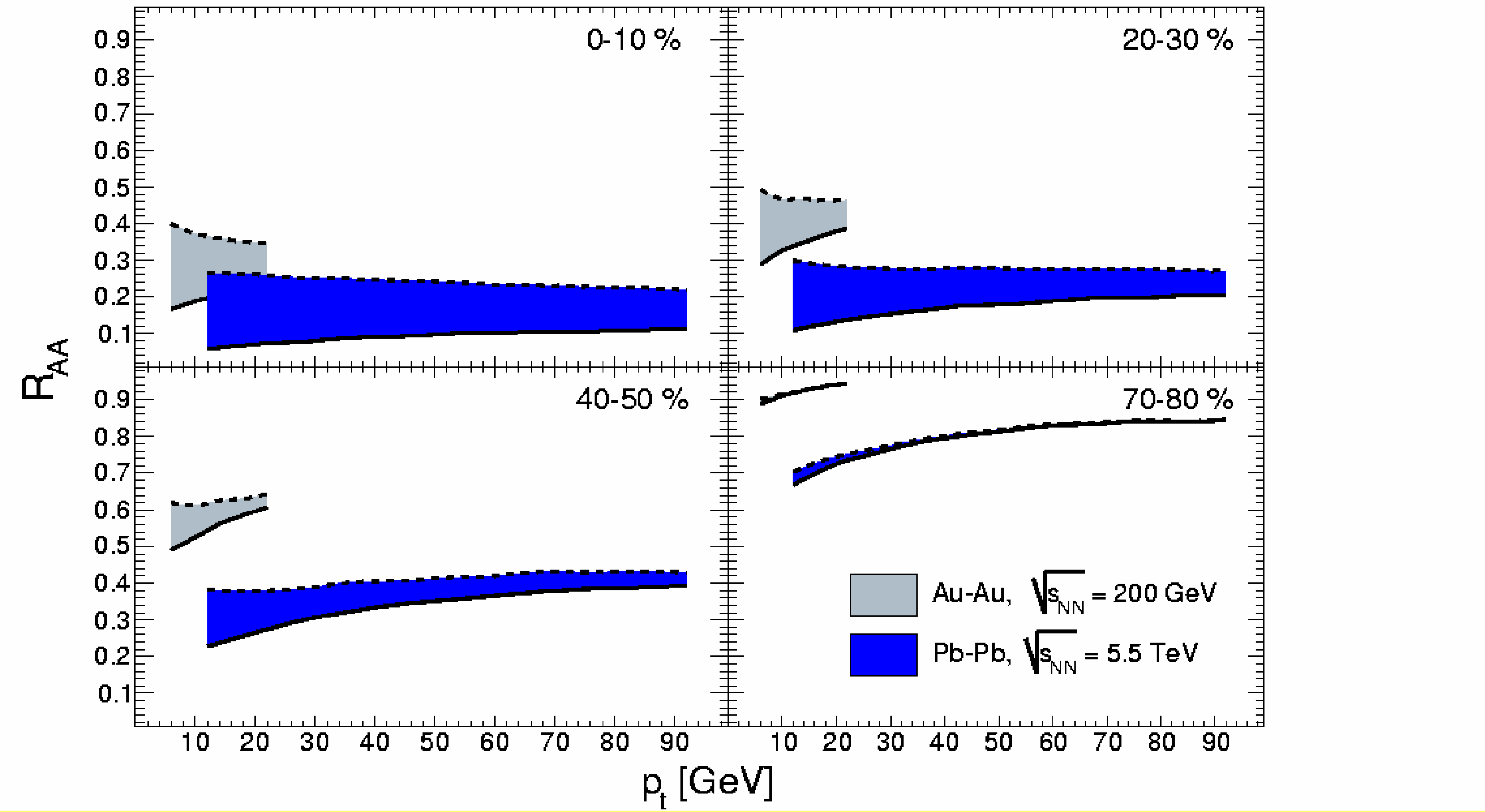
- $n^{\rm g}_{\rm Au-Au,\,62.4\,GeV} \simeq 0.5 \times n^{\rm g}_{\rm Au-Au,\,200\,GeV}$

$$\langle \hat{q} \rangle_{\rm Au-Au,\,62.4\,GeV} \simeq 7\ {\rm GeV}^2/{\rm fm}$$

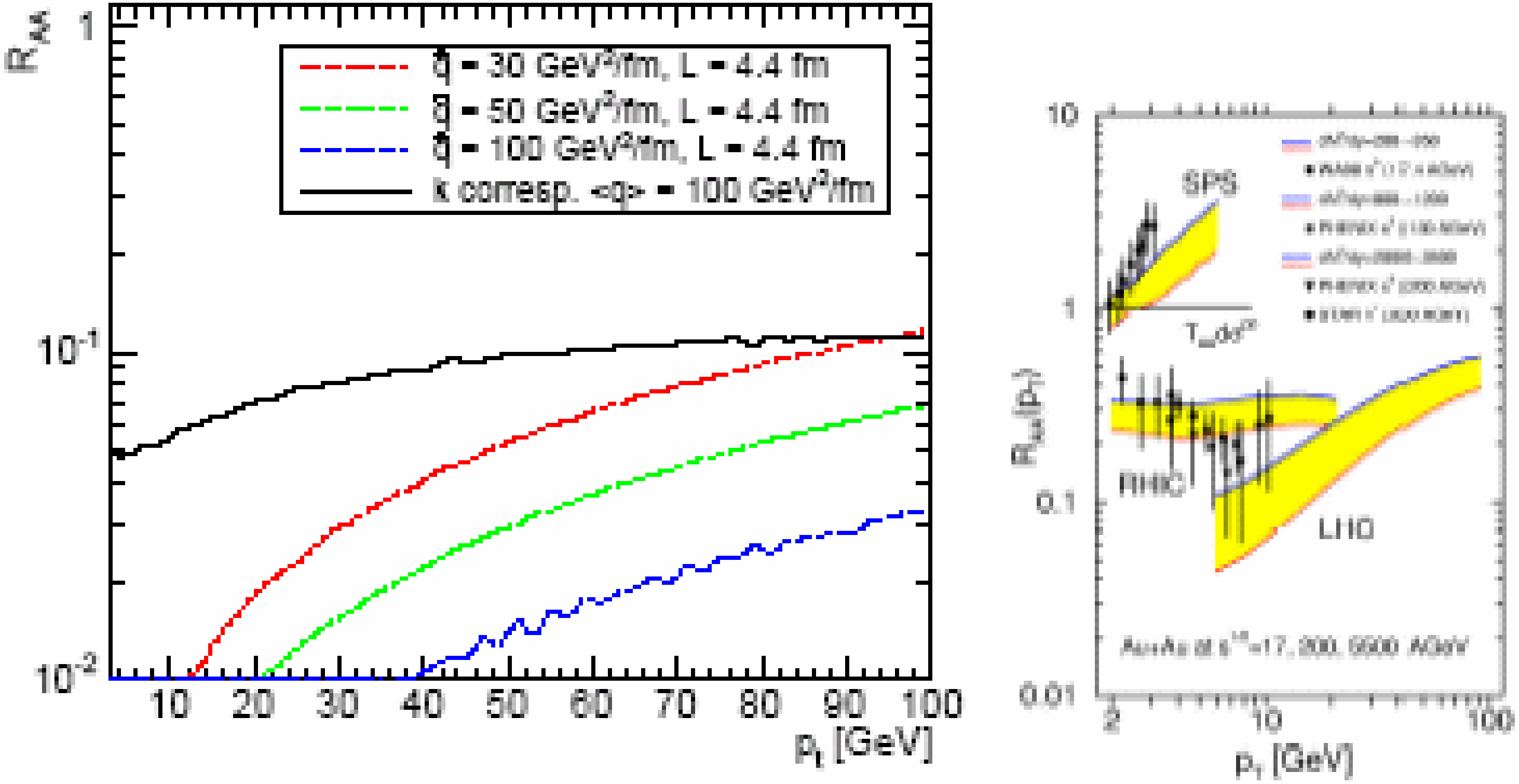
- $n^{\rm g}_{\rm Pb-Pb,\,5.5\,TeV} \simeq 7 \times n^{\rm g}_{\rm Au-Au,\,200\,GeV}$

$$\langle \hat{q} \rangle_{\rm Pb-Pb,\,5.5\,TeV} \simeq 100\ {\rm GeV}^2/{\rm fm}.$$

Case of the LHC



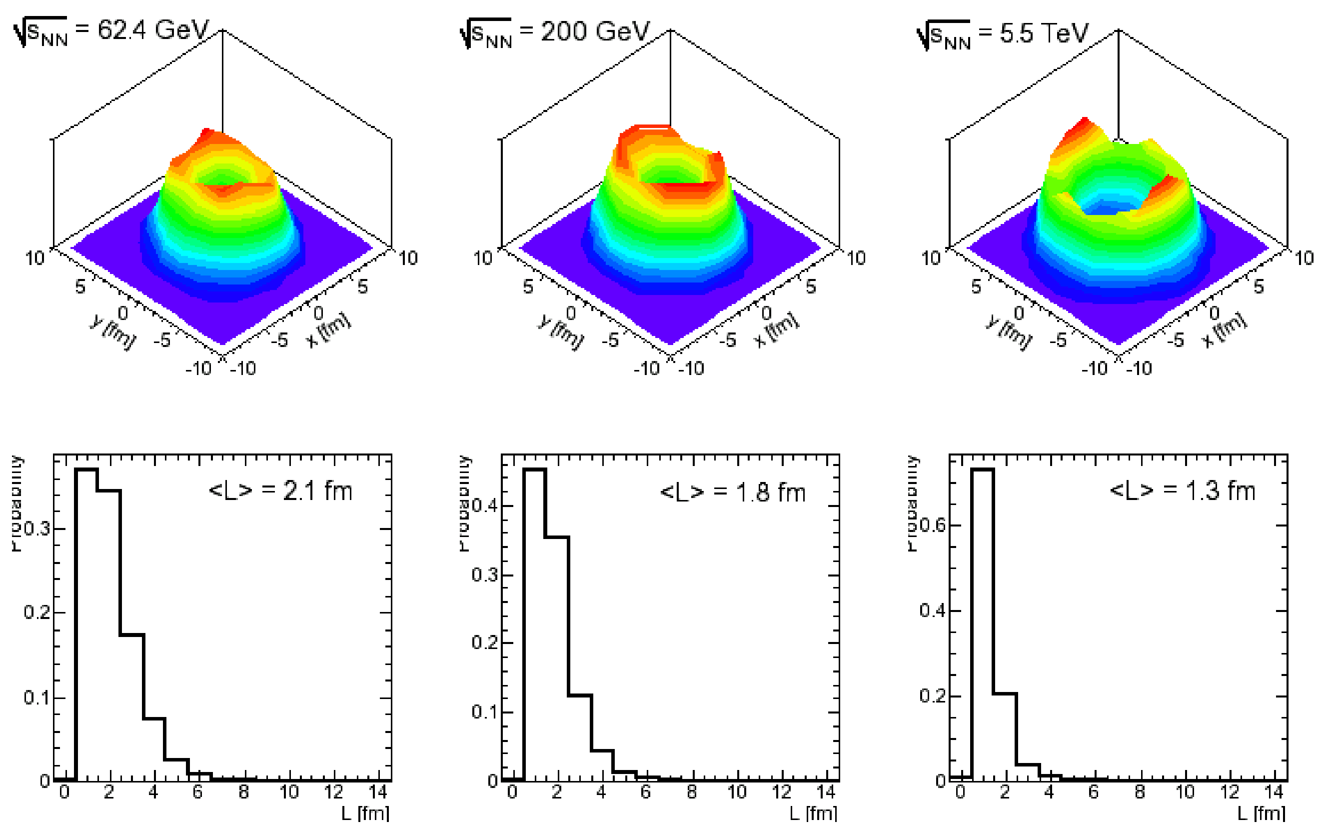
All models do not predict the same for LHC



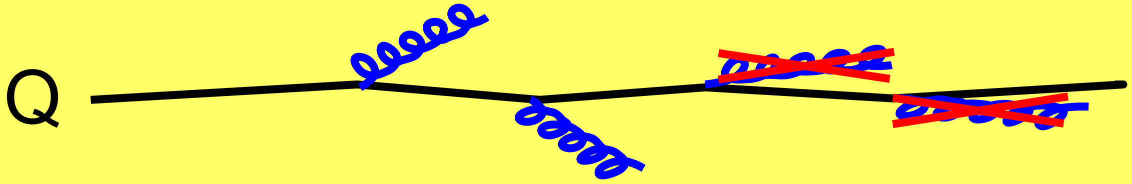
left: PQM non-reweighted, right: Vitev hep-ph/0209161

Corona effect

Emission of hard hadrons is predominantly from a thin surface layer. But “jets” still originate from throughout the volume:



Lower E loss for heavy quarks?



- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

  → **"dead cone" effect**
- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001)
- Detailed calculation confirms this qualitative feature, although effect is small and uncertainties significant (Armesto-Salgado-Wiedemann, 2003)

⇨ Exploit abundant massive probes at LHC & study the effect by measuring the nuclear modification factor for D and B

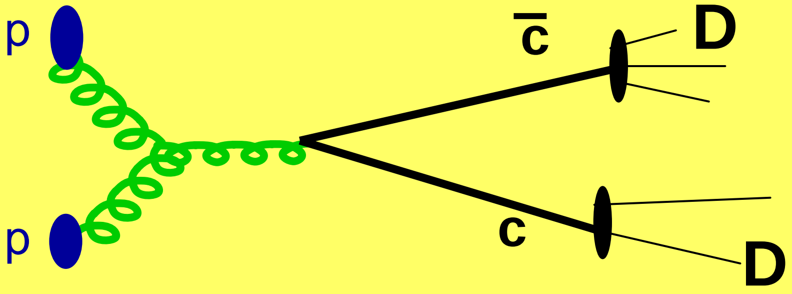
$$R_{AA}^{D,B}(p_t) = \frac{1}{N_{coll}} \times \frac{dN_{AA}^{D,B}/dp_t}{dN_{pp}^{D,B}/dp_t}$$

Yu.L.Dokshitzer and D.E.Kharzeev, Phys. Lett. **B519** (2001) 199 [hep-ph/0106202].
N.Armesto, C.A.Salgado and U.A.Wiedemann, Phys. Rev. **D69** (2004) 114003 [hep-ph/0312106].

Heavy-flavour production

pp collisions: pQCD factorization

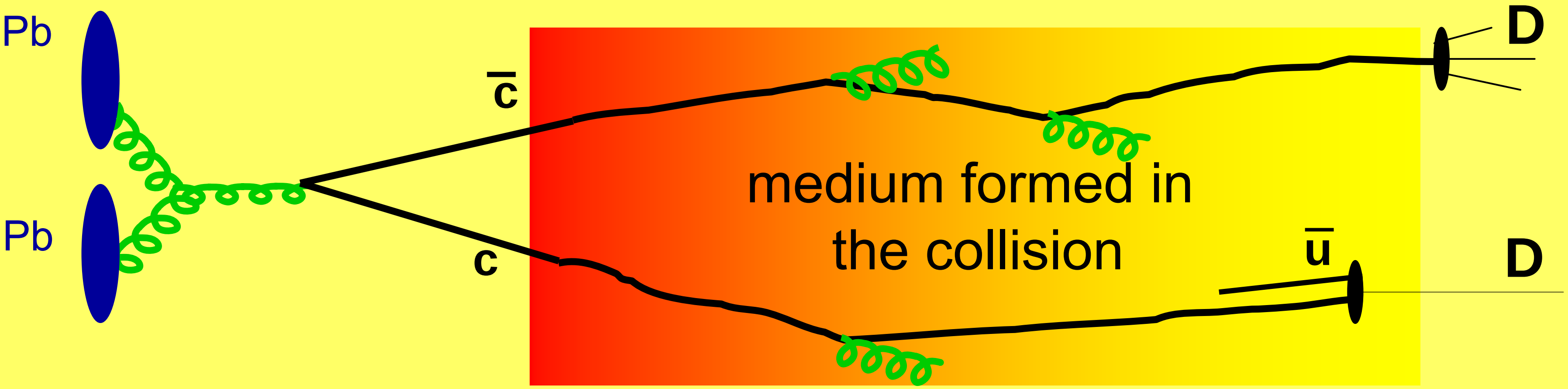
$$\mathrm{d}\sigma^{D} = \mathrm{PDFs} \otimes \mathrm{d}\hat{\sigma}^{c} \otimes \mathrm{Fragm.}$$



(pA) AA: binary scaling for hard yields

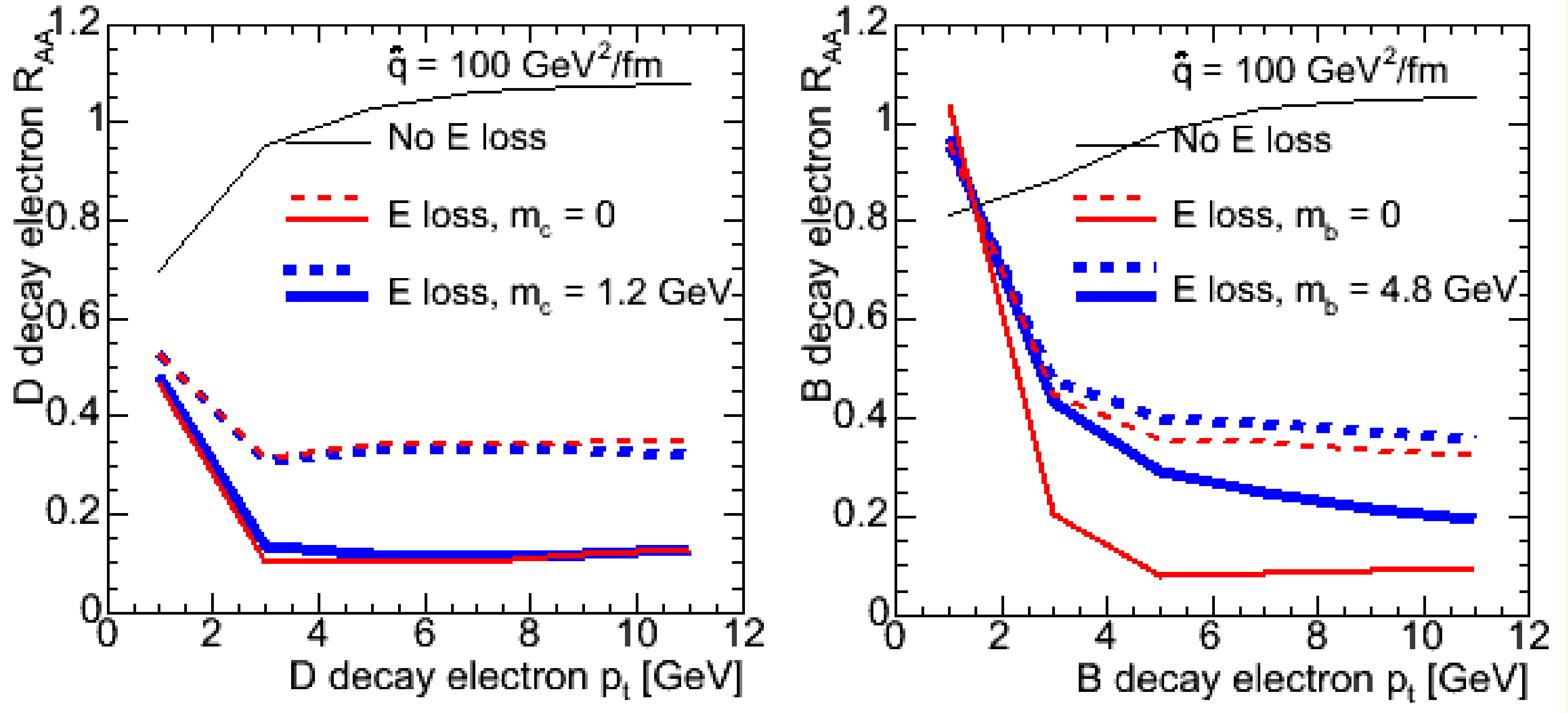
$$\mathrm{d}N^{D}_{AA} = \mathrm{d}N^{D}_{pp} \times N_{coll}$$

"broken" by initial-state effects (shadowing, …)
and final-state effects (energy loss, coalescence, …)



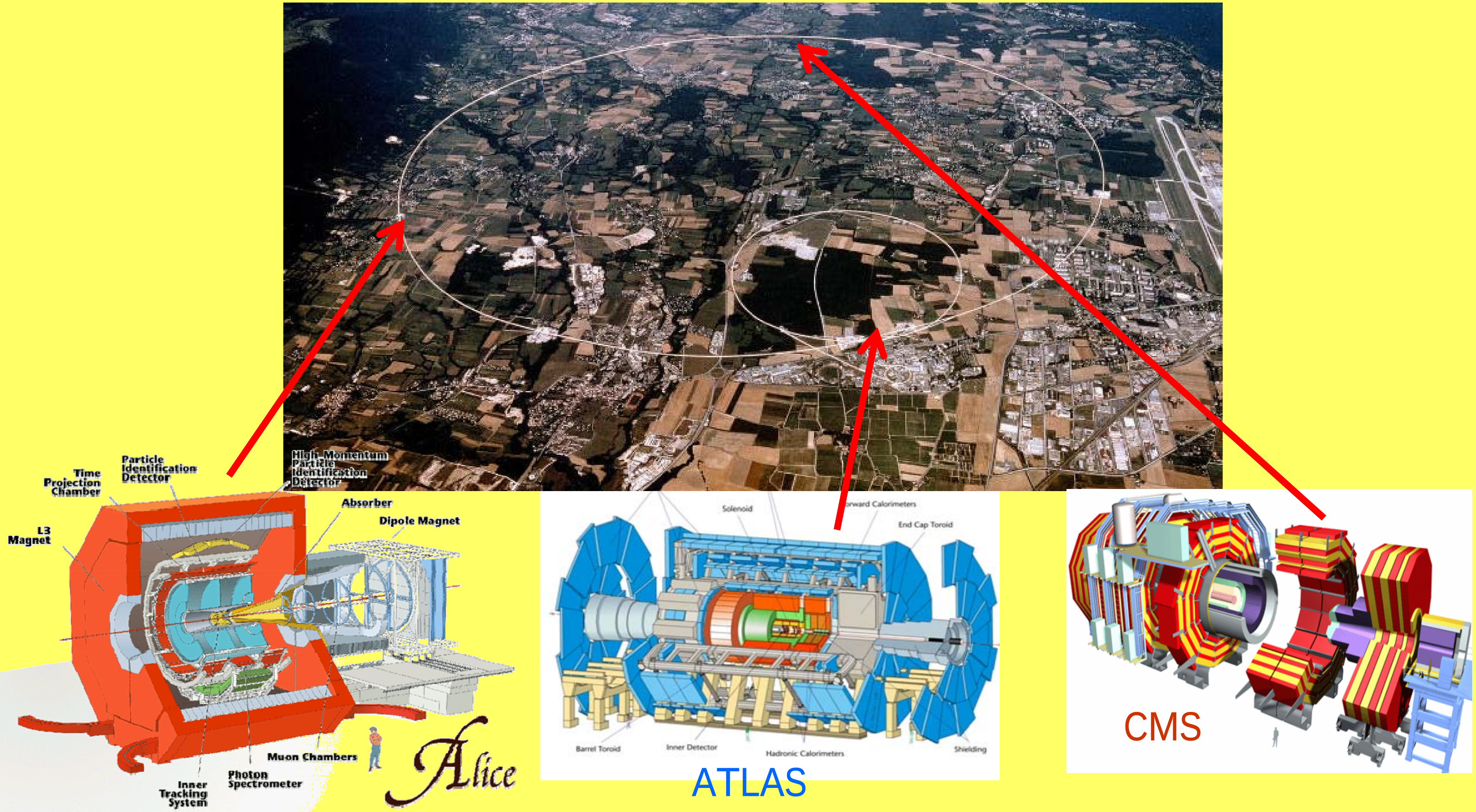
Estimates of R_{AA} for D and B

- Ingredients: *BDMPS quenching weights for heavy quarks + Glauber-based medium geometry + LHC medium density extrapolated on the basis of hadron suppression at RHIC*



RHIC analysis: A.Dainese., C.Loizides and G.Paic, hep-ph/0406201.
N.Armesto, A.D., C.A.Salgado and U.A.Wiedemann, *in preparation*.

Experimental study of heavy flavours in HIC at the LHC



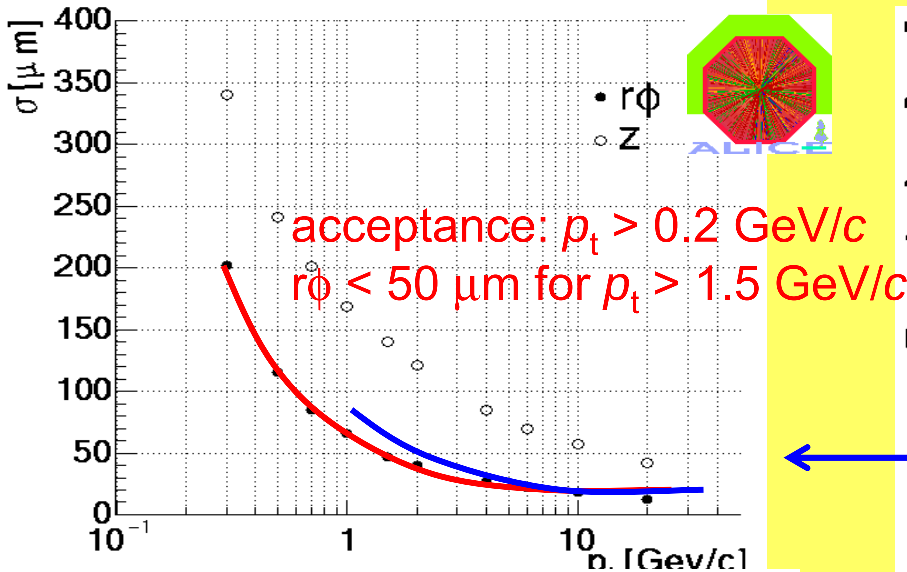
The dedicated HI experiment

HI Letter of intent

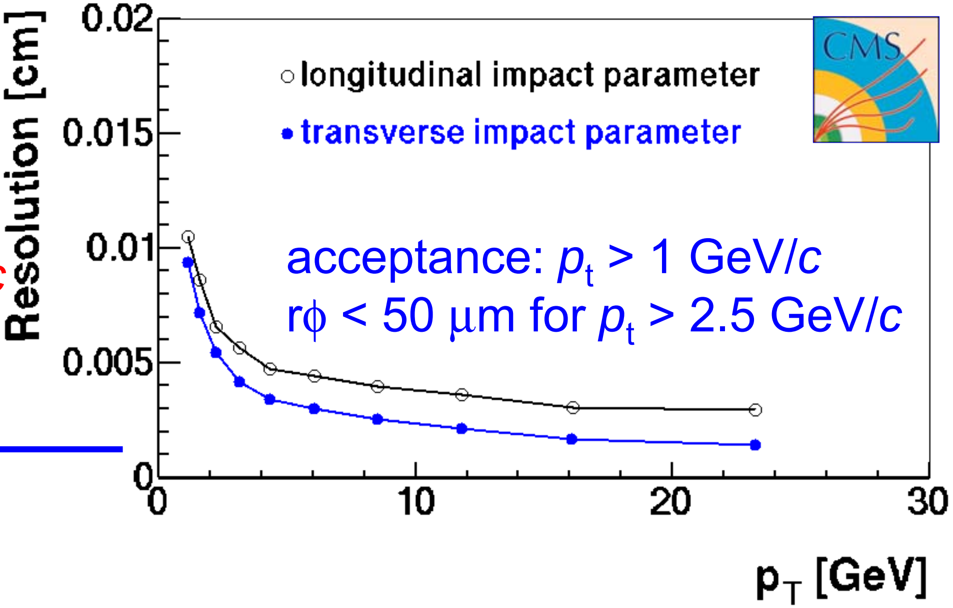
Strong HI program

Tracking & Vertexing

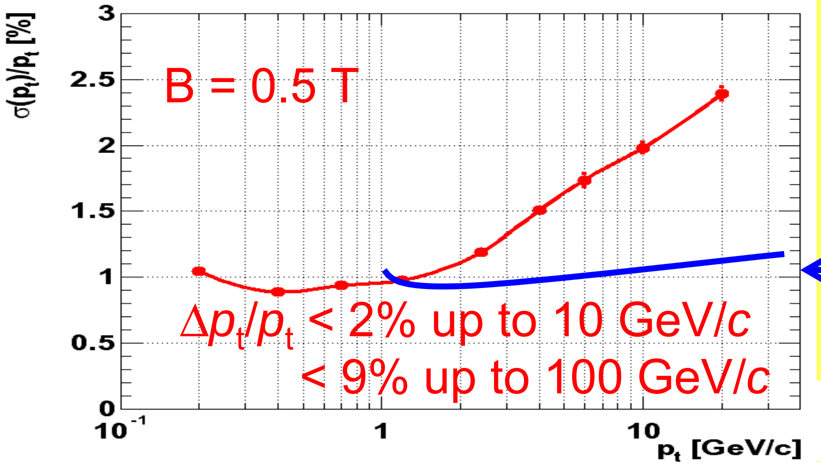
- D mesons $c\tau \sim 100$–$300\ \mu\mathrm{m}$, B mesons $c\tau \sim 500\ \mu\mathrm{m}$
- Secondary vertex capabilities! → **Impact param. resolution!**



acceptance: $p_t > 0.2$ GeV/c
rϕ < 50 μm for $p_t > 1.5$ GeV/c

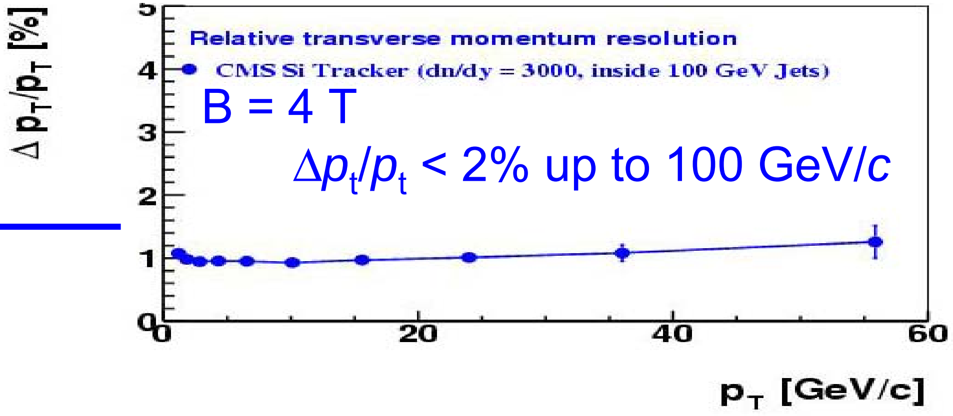


acceptance: $p_t > 1$ GeV/c
rϕ < 50 μm for $p_t > 2.5$ GeV/c



B = 0.5 T

$\Delta p_t/p_t < 2\%$ up to 10 GeV/c
$< 9\%$ up to 100 GeV/c



B = 4 T
$\Delta p_t/p_t < 2\%$ up to 100 GeV/c

Lepton and Hadron ID

- D and B: large B.R. to leptons: ~10% e + ~10% μ
  - ALICE:
    - electrons: Transition Rad. + dE/dx in $|\eta| < 0.9$ and $p_t > 1$ GeV/c
    - muons: $2.5 < \eta < 4$ and $p_t > 1$ GeV/c (use p_z to punch through abs.!)
  - CMS (ATLAS):
    - muons: $|\eta| < 2.4$ (3) and $p_t > 3.5$ (4) GeV/c
    - electrons in EM cal? (no heavy-ion studies yet)

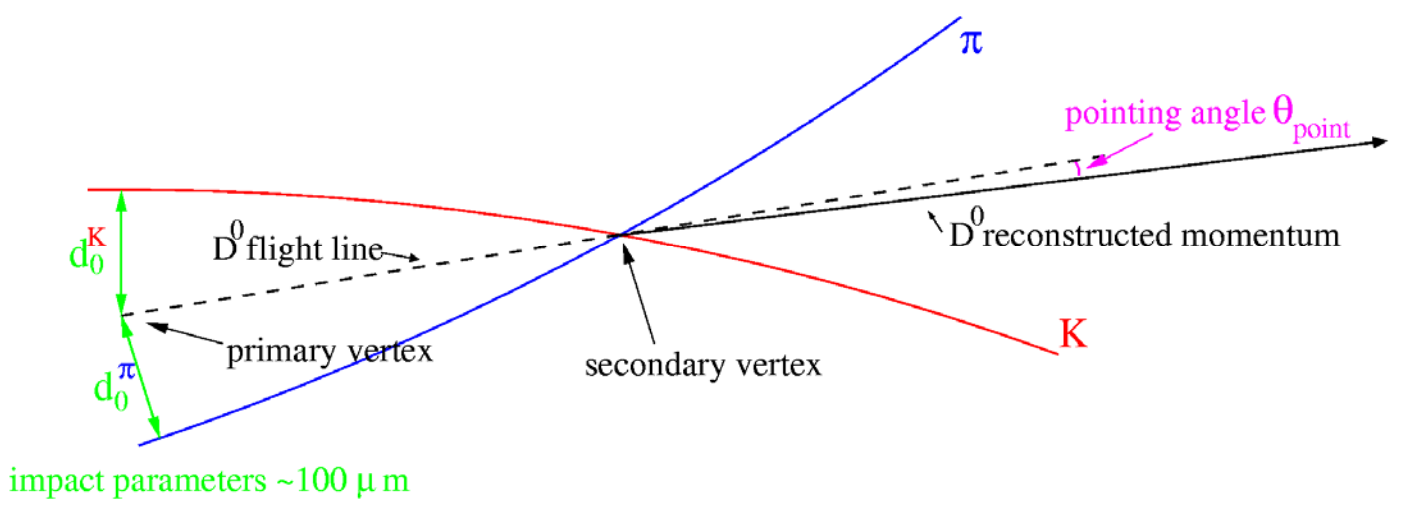
- With leptons, difficult to measure D(B) p_t distr. and go to low p_t (loose p_t correlation)

  → Exclusive hadronic decay channels (charm)

  → Need PID (kaons!) to reject huge combin. background in AA
- ALICE hadron ID: large TPC + high-res TOF + RICH

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

- **Ideal tool to study R_{AA} and low p_t effects**
- 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**
  - ne

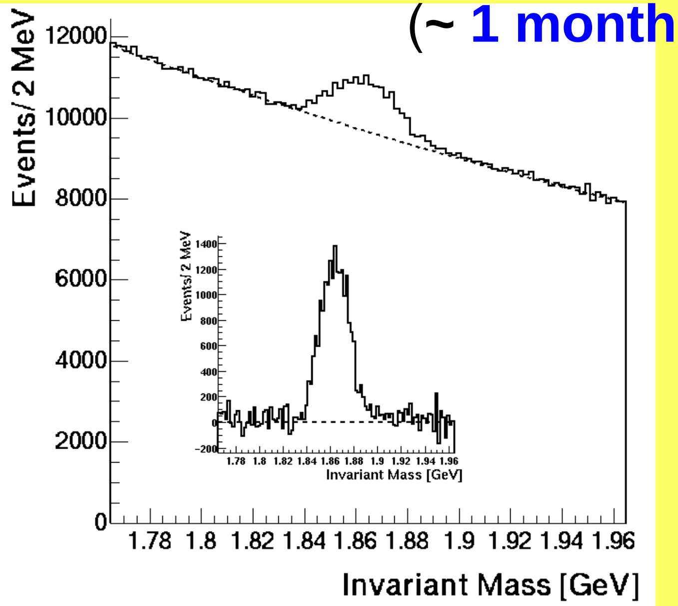


Invariant mass analysis to "count" D^0

D^0 Results

(K,π) Invariant Mass distribution (p_t –integrated) in Pb-Pb

(~ **1 month run**)



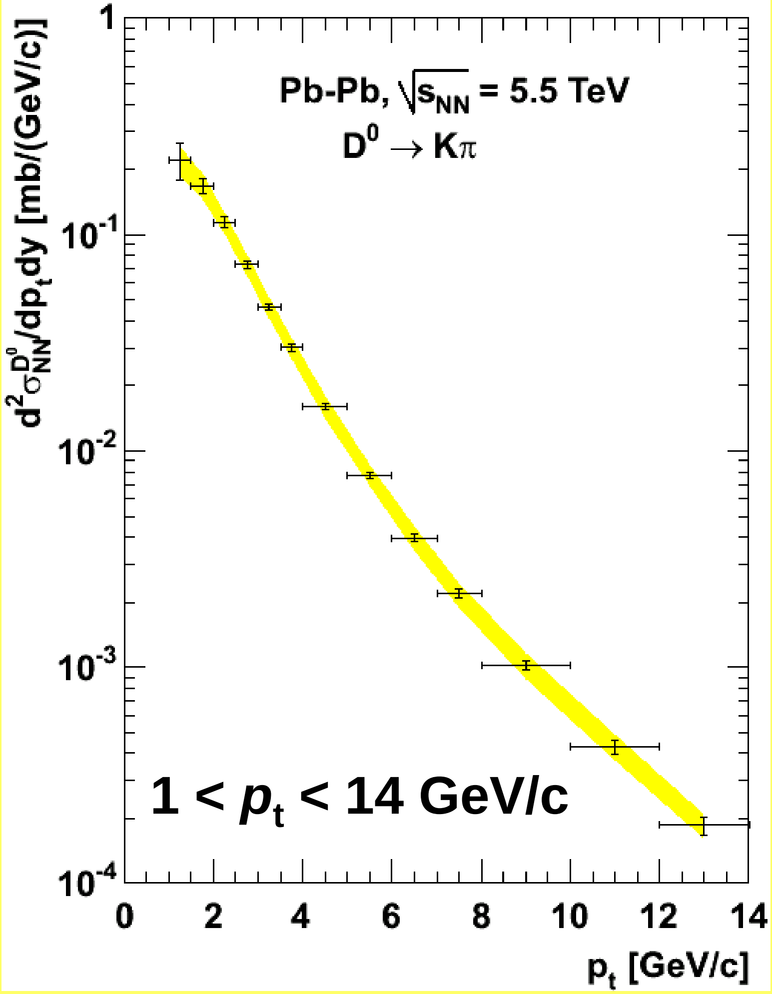
$$S / B \approx 10\%$$

Statistical significance:

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

N.Carrer, A.Dainese and R.Turrisi, J. Phys. **G29** (2003) 575.
A.D. PhD thesis (2003), nucl-ex/0311004.

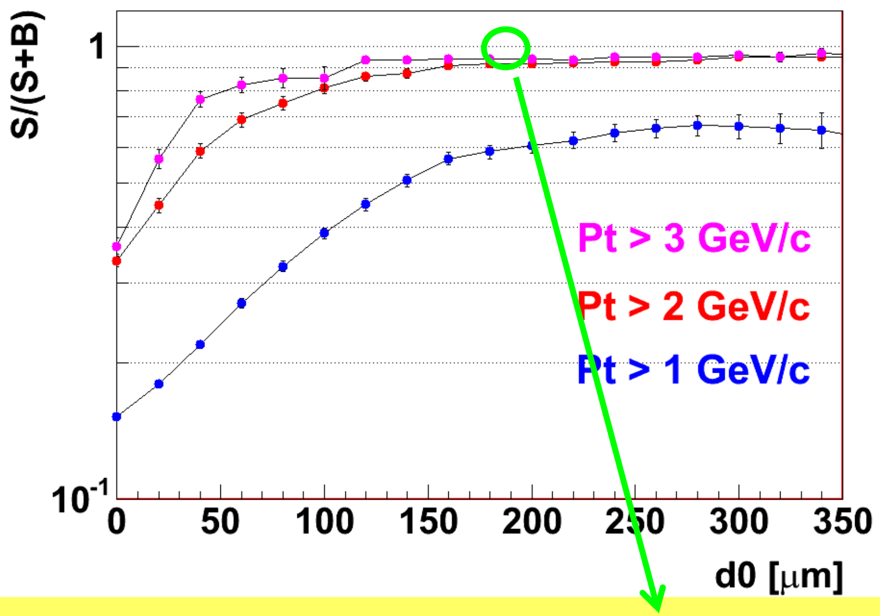
Stat. I and syst. 🟨 errors on D p_t distr. estimated for pp and Pb-Pb



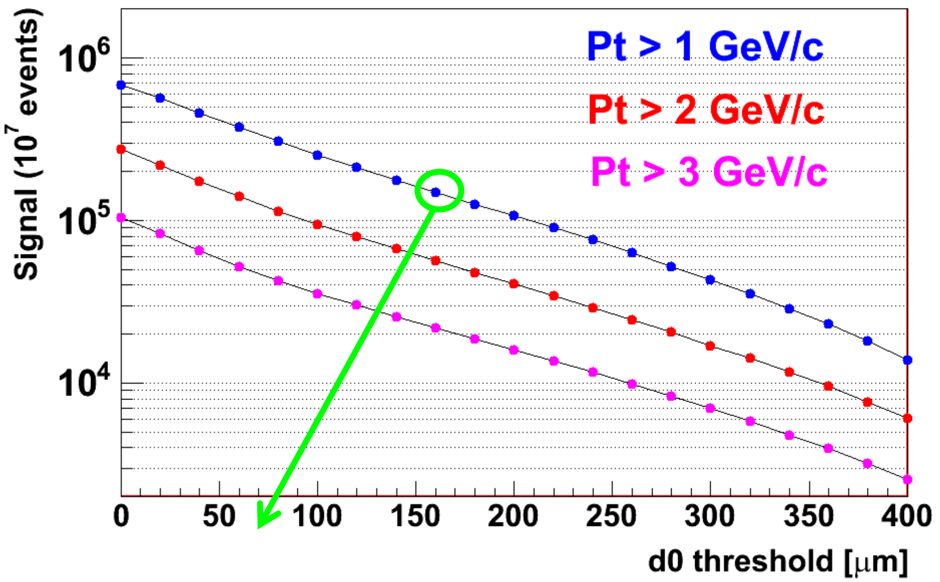
Open Beauty with Electrons

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

S/(S+B)



S per 10^7 Pb-Pb events

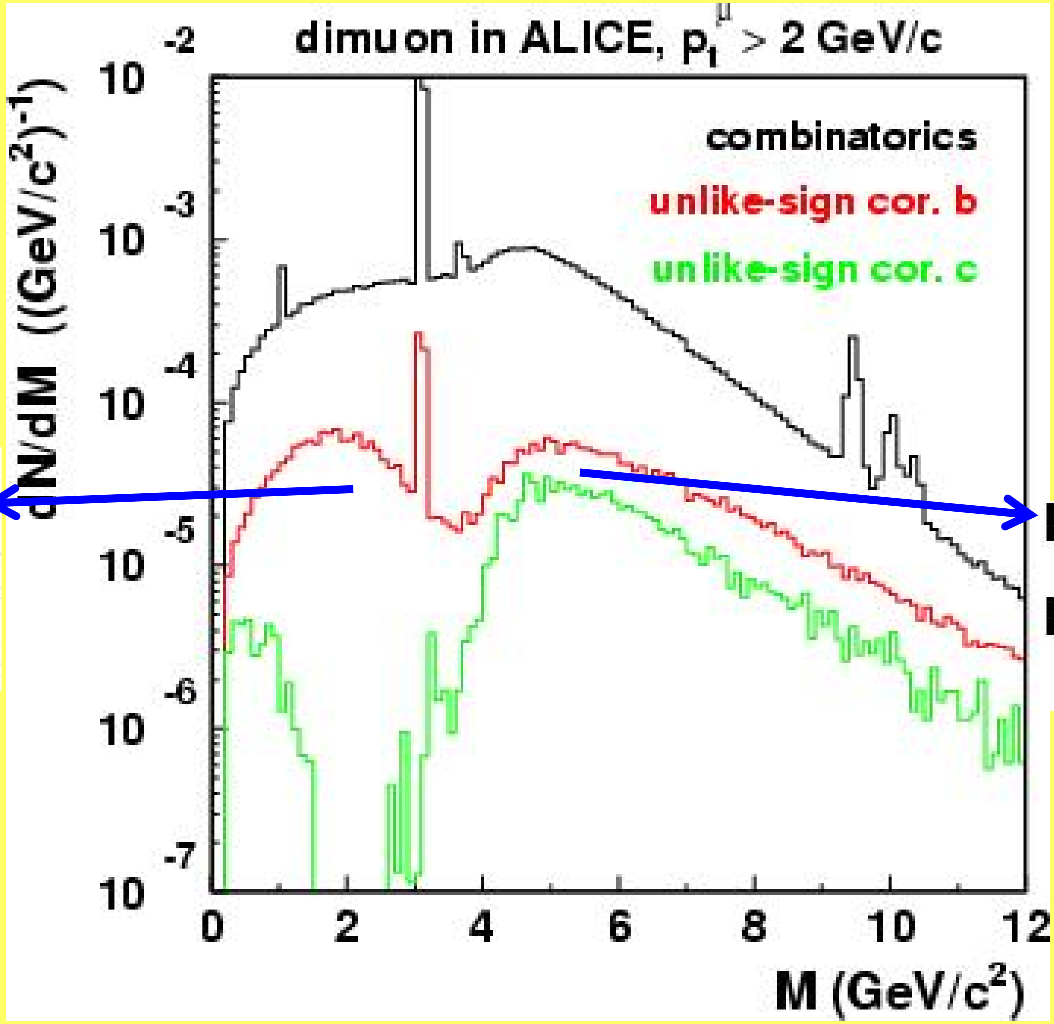


p_t > 2 GeV/c, d0 > 180 μm:
50,000 electrons with S/(S+B) = 90 %

M.Lunardon and R.Turrisi

Open Beauty with Muons (1)

- Single muon cut $p_t > 2$ GeV/c
- Dimuon combinatorial bkgd subtracted with evt-mixing



BB–diff:

$\bar{B}^o \rightarrow l^- + X$

$B^o \rightarrow l^+ + X$

B–chain:

$B^+ \rightarrow \bar{D}^o \, l^+ \, \nu_l$

$\hookrightarrow l^- + X$

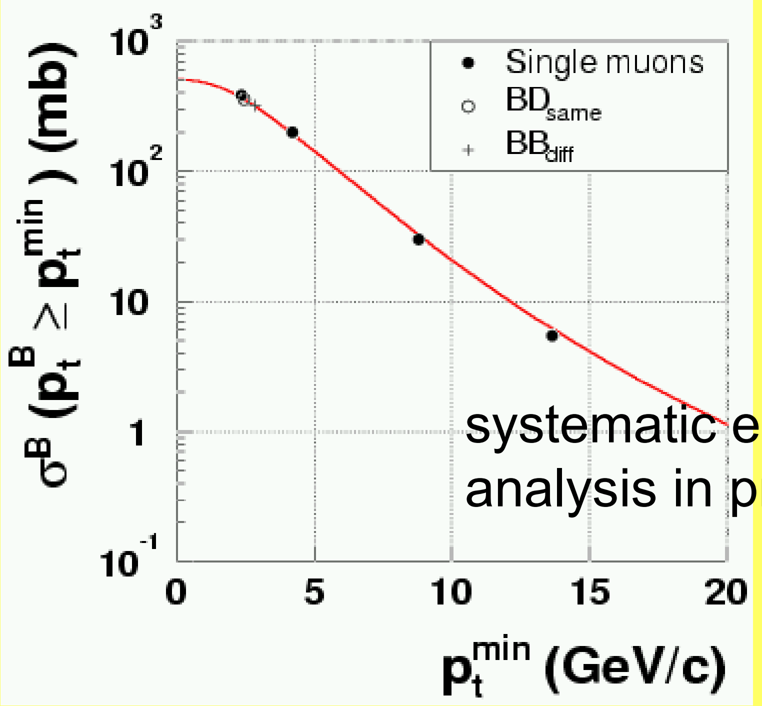
Open Beauty with Muons (2)

- Combined fit of low-mass, high-mass dimuons and single muons with shapes from MC to extract muons from B

- Use MC to extract

$$\sigma^{B} \;\; vs \;\; p_t^{\min}$$

down to ~2 GeV/*c*!

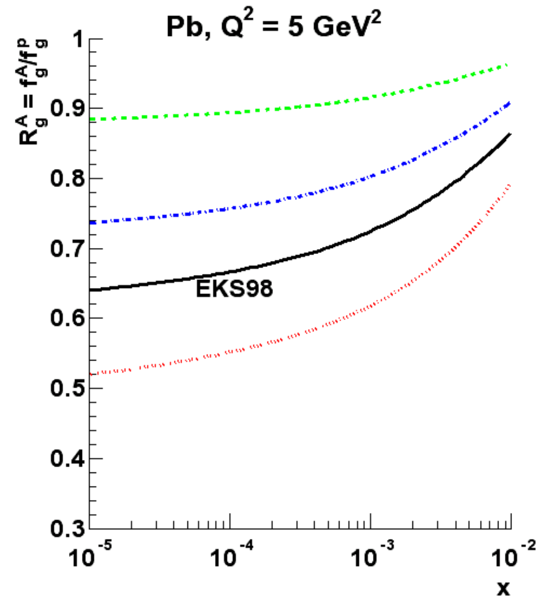


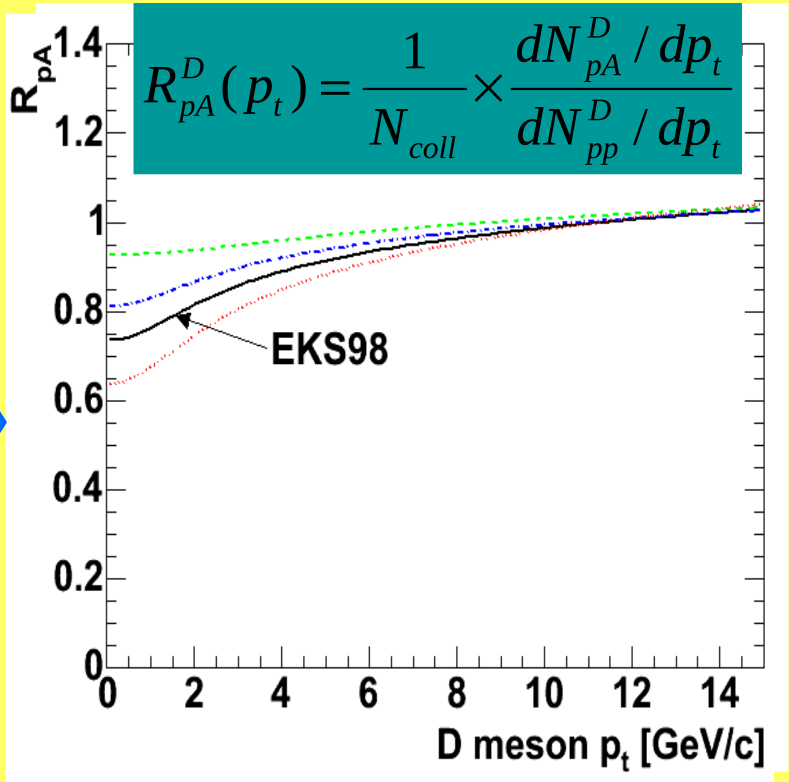
systematic error analysis in progress

R.Guernane

Nuclear Shadowing and Charm

- Bulk at the LHC: $x \sim 10^{-3}$-10^{-4}
- Pb nucleus ~ 10^5-10^6 partons (mainly gluons)
  - ‘they are so close that they fuse’
- Shadowing: suppression of low-x PDFs
- Reduces charm yield at low p_t
- Look at low-p_t D in pPb!

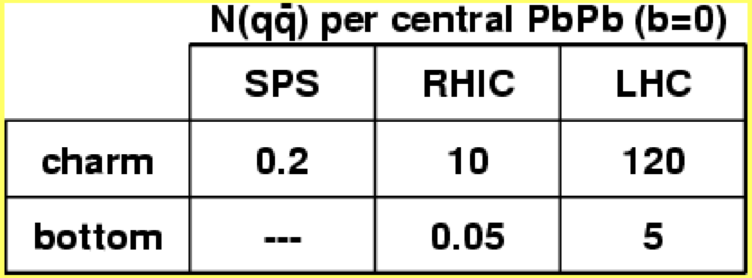




$$R^D_{pA}(p_t) = \frac{1}{N_{coll}} \times \frac{dN^D_{pA}/dp_t}{dN^D_{pp}/dp_t}$$

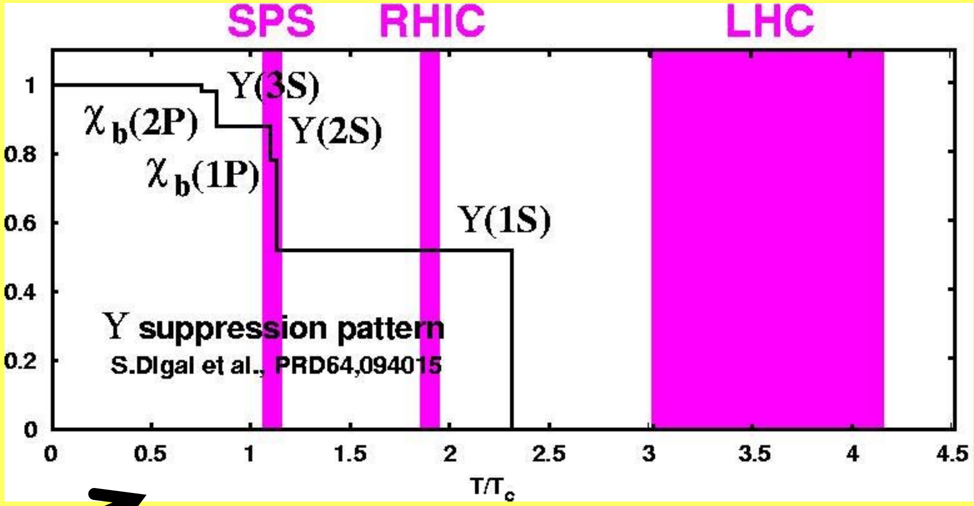
Quarkonia

Specificities of heavy flavor production in heavy ion collisions @ LHC



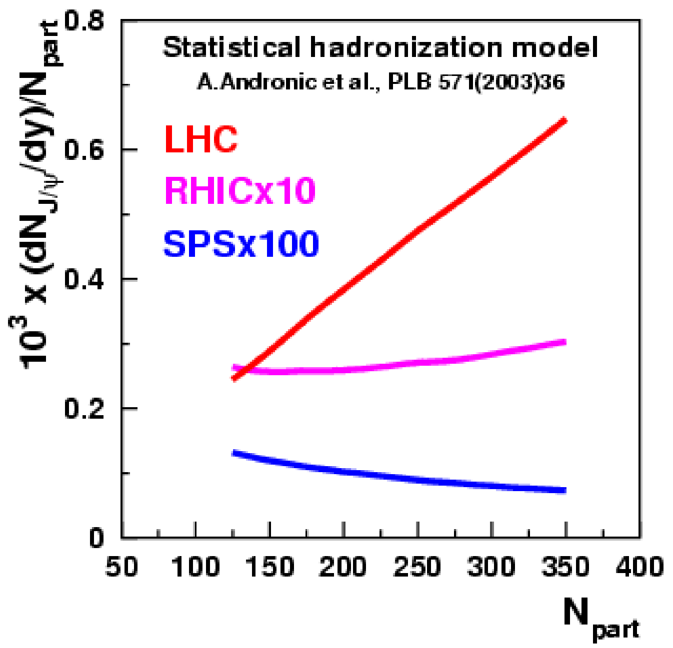
N($q\bar{q}$) per central PbPb (b=0)

	SPS	RHIC	LHC
charm	0.2	10	120
bottom	---	0.05	5



- large primary production
- melting of Υ(1*S*) by color screening
- large secondary production of charmonia

thermal production, kinetic recombination, statistical hadronization, DD annihilation, B hadron decay



rich program & complex background

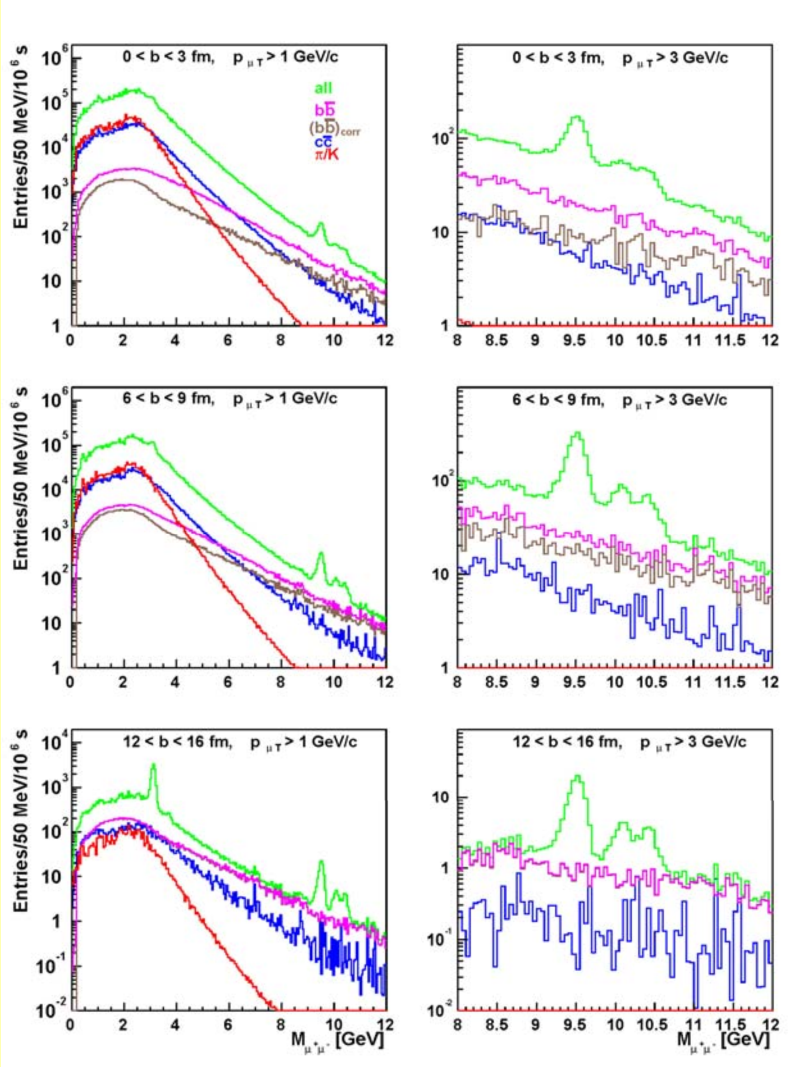
simultaneous measurements of hidden & open heavy flavors is a must

Shopping list

- **quarkonia :**
- **resonances ρ, ω, ϕ, J/ψ, ψ', Υ, Υ', Υ''**
  - **versus Pt**
  - **versus centrality**
  - **versus reaction plane**
  - **versus system-size**
- **open heavy flavors**
  - **single muon pt distributions**
  - **unlike-sign dimuon @ high mass**
  - **unlike-sign dimuon @ low mass**
  - **like-sign dimuon**
  - **electron-muon coincidences**
  - **tri-muons in pp collisions**

Centrality dependence of quarkonium yield

Low p_t^μ
trigger selection
+ sharp p_t^μ cut
p_t^μ > 1 GeV/c



Pb – Pb collisions

High p_t^μ
trigger selection
+ sharp p_t^μ cut
p_t^μ > 3 GeV/c

***S. Grigoryan**, 2003*

B. Forestier

V. Barret

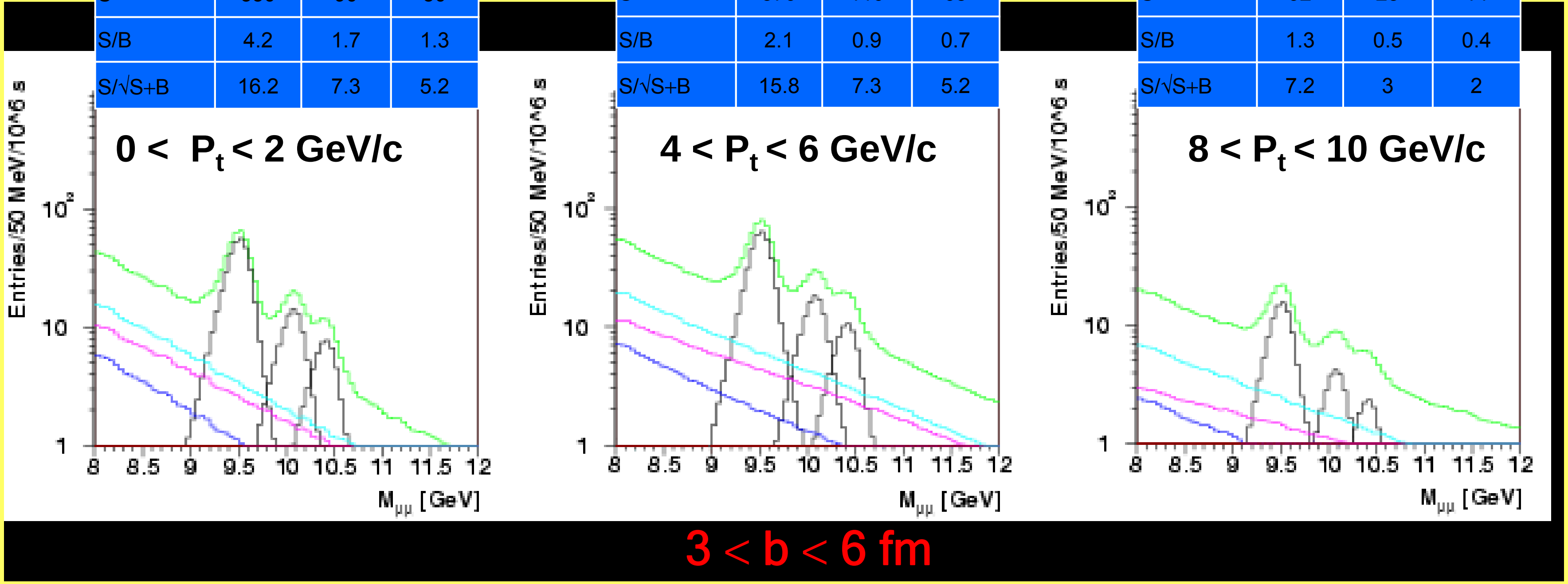
P. Dupieux

P_t dependence of quarkonium yield

	Υ	Υ(2S)	Υ(3S)
S	330	90	50
S/B	4.2	1.7	1.3
S/√S+B	16.2	7.3	5.2

	Υ	Υ(2S)	Υ(3S)
S	370	110	65
S/B	2.1	0.9	0.7
S/√S+B	15.8	7.3	5.2

	Υ	Υ(2S)	Υ(3S)
S	92	25	14
S/B	1.3	0.5	0.4
S/√S+B	7.2	3	2



$3 < b < 6$ fm

Semi-central Pb-Pb collisions

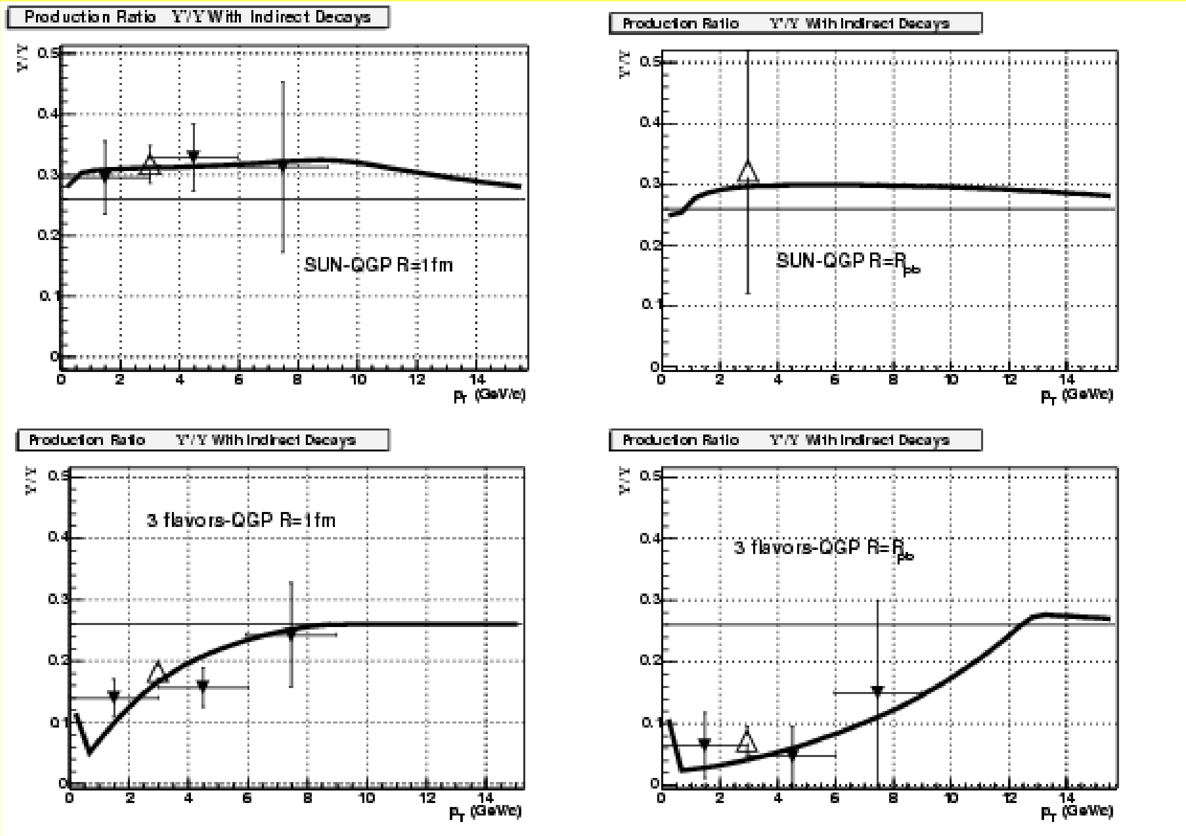
1 month of data taking

***A. De Falco*, 2004**

Υ'/Υ ratio versus P_t

J.P.Blaizot and J.Y.Ollitrault, Phys. Lett. B 199 (1987) 499; F.Karsch and H.Satz, Z. Phys. C 51 (1991) 209; J.F.Gunion and R.Vogt, Nucl. Phys. B 492 (1997) 301

- **Melting depends on**
  - **resonance formation time, dissociation temperature & P_t**
  - **QGP temperature, lifetime & size**
- **Ratio is flat in pp (CDF data)**
- **Any deviation from the pp (pA) value is a clear evidence for the QGP (nuclear effects cancel-out)**
- **The P_t dependence of the ratio exhibits sensitivity to the QGP characteristics**



- **full & realistic simulation**
- **error bars = 1 month of central Pb-Pb (10%)**

E. Dumonteil, PhD Thesis (2004)

Conclusion

- Importance of the whole pt range at LHC
- Dominance of hard processes with soft particles!
- Importance of particle identification
- A rich new frontier for the field!