Heavy Ion Physics at the LHC

Santa Fe, October 23rd, 2005

Heavy Quarks in view of the LHC

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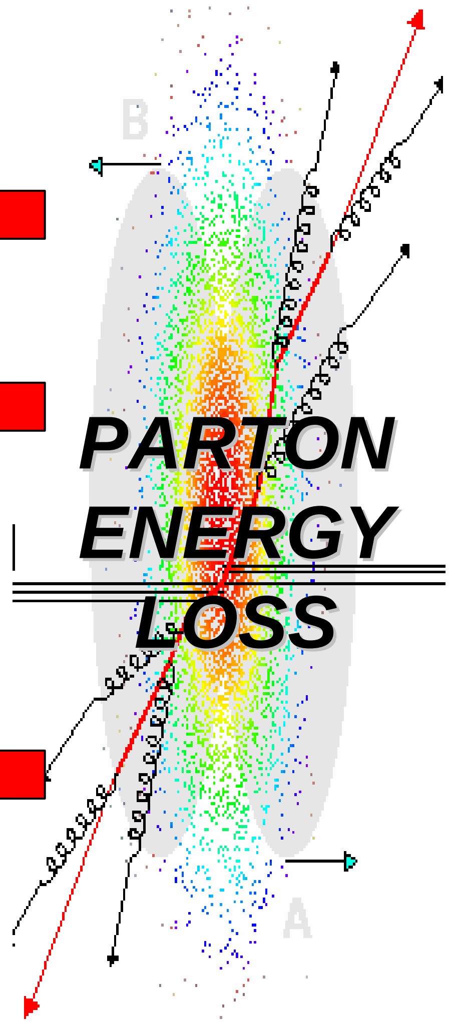
Layout

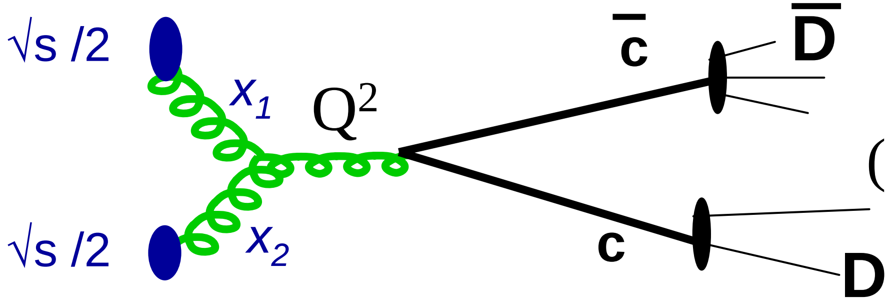
- High-p_T (heavy-flavour) particle production in hadronic collisions –from pp to AA– in factorized QCD
  - pp baseline: pQCD calculations
  - nuclear effects, in initial and final state
- What have we learnt at Tevatron and RHIC?
- What will be new at the LHC?
- What do we expect?

  ⇒ What should we measure?



Heavy-flavour production: pp

proton-proton collisions: factorized pQCD approach



$(x_1 x_2 s \sim Q^2 \sim M^2_{c\bar{c}})$

$$\frac{d\sigma^D}{dp_T^D}(\mu_F,\mu_R) = $$

$$= PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T^c} \otimes D_{c\to D}(z = p_D / p_c)$$

$\mu^2_{F,R} \sim Q^2$

PDF:

- Q^2 evolution calculated in pQCD
- initial condition from data (HERA)

FF:

- non-perturbative
- phenomenolgy

+ fit to the data (e^+e^-)

calculable as perturbative series of strong coupling $\alpha_s(\mu_R)$

$pp \to Q\bar{Q}$: pQCD calculations vs data

- Calculation of partonic cross section $\hat{\sigma}$
  - standard: Fixed Order (NLO) Massive (e.g. MNR code)

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + O(\alpha_s^4) \qquad B(m) = \beta(m) + \gamma(m)\log(\mu/m)$$

  - state-of-the-art: Fixed Order Next-to-Leading Log (FONLL) $\mu \approx p_T$

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + G(m,p_T)\left[\alpha_s^2 \sum_{i=2}^{\infty} a_i\,[\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i\,[\alpha_s \log(\mu/m)]^i\right]$$

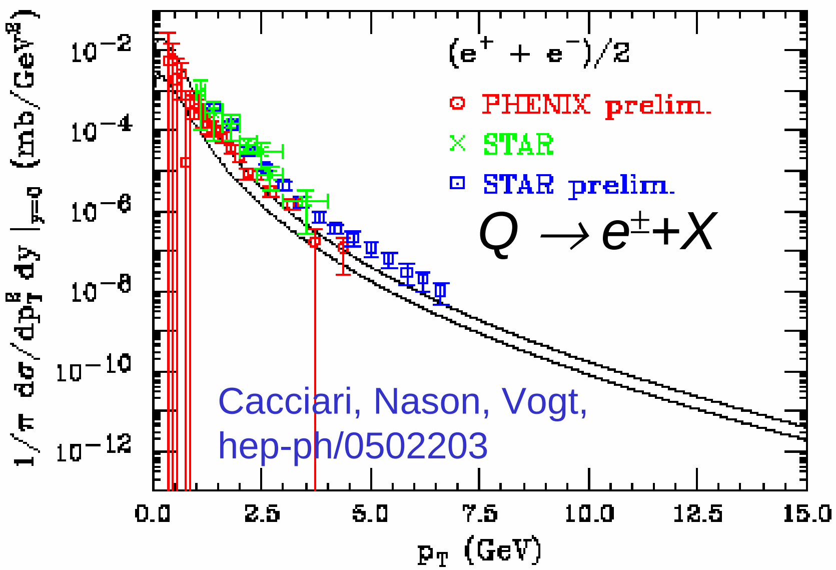
$\to$ more accurate at high p_T

B production at Tevatron (1.96 TeV) is well described by FONLL

Charm production slightly underpredicted at Tevatron (1.96 TeV)

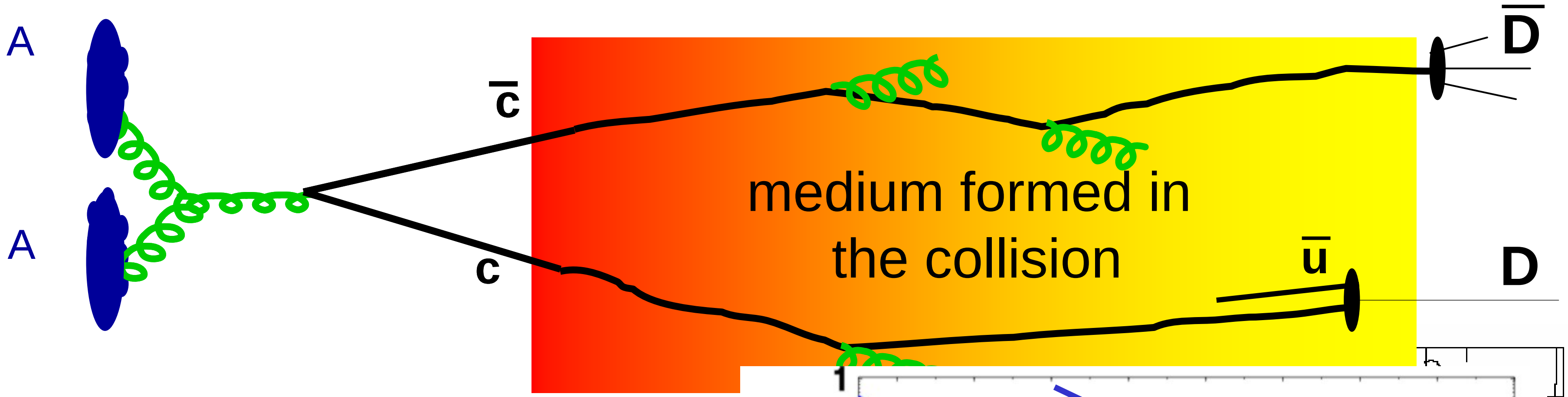
& at RHIC (200 GeV)

Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033



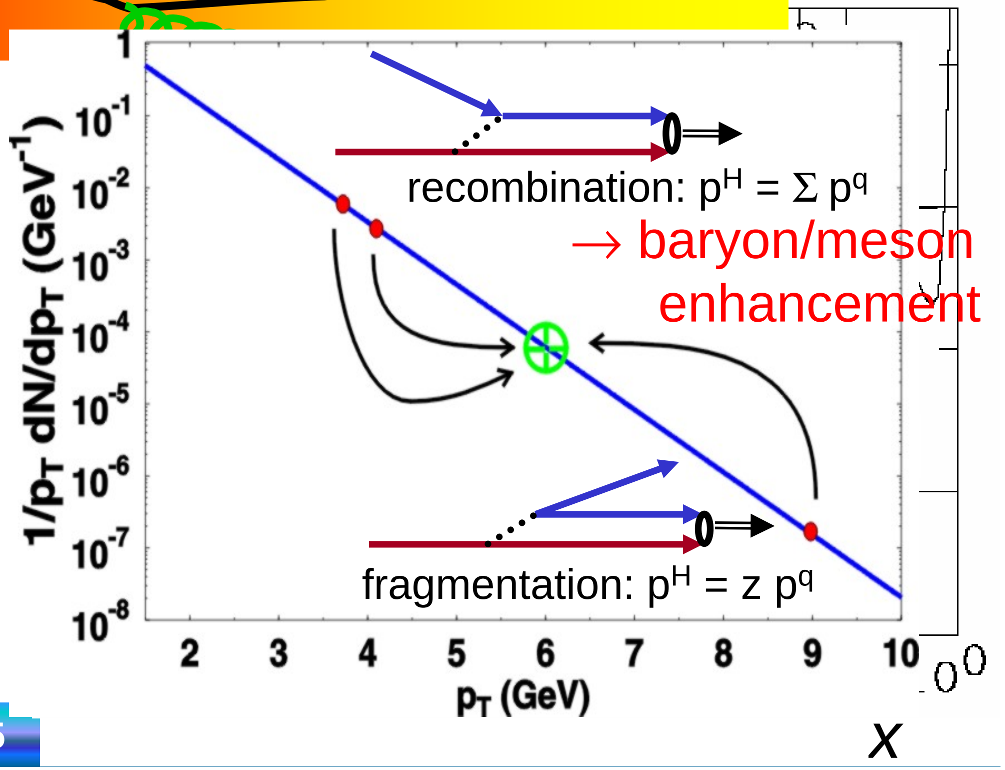
Heavy-flavour production: AA

Binary scaling for hard yields: $\mathrm{d}N^{D}_{AA} / \mathrm{d}p^{D}_{T} = \mathrm{d}N^{D}_{pp} / \mathrm{d}p^{D}_{T} \times N_{coll}$

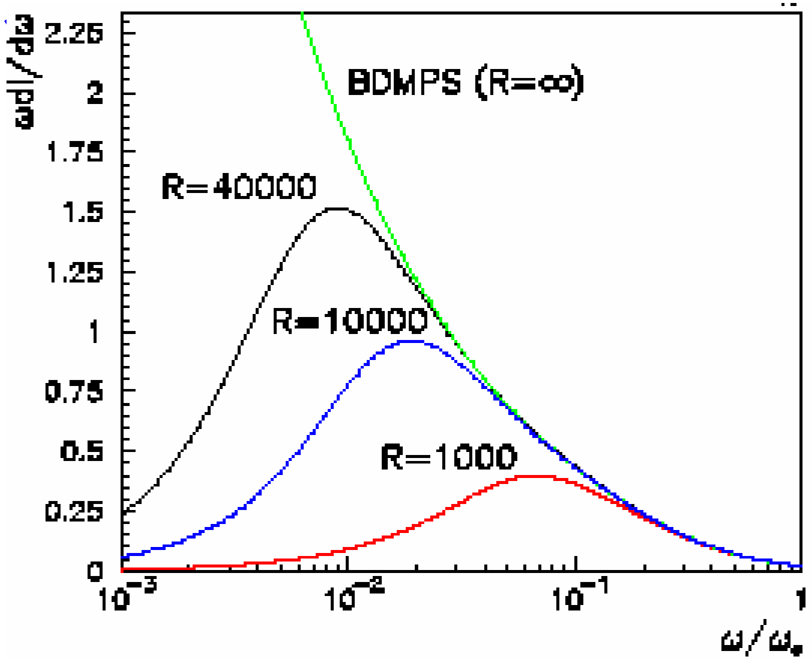


Binary scaling is “broken” by:

- ***initial-state effects:***
  - PDF (anti)shadowing
  - k_T broadening (‘Cronin’)
- ***final-state effects***
  - energy loss? [next slide]
  - in-medium hadronization (recombination?)



Calculating Parton Energy Loss



BDMPS-Z formalism

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

(BDMPS case)

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \begin{cases} \sqrt{\omega_c / \omega} & \text{for } \omega < \omega_c \\ (\omega_c / \omega)^2 & \text{for } \omega \geq \omega_c \end{cases}$$

C_R Casimir coupling factor: 4/3 for q, 3 for g

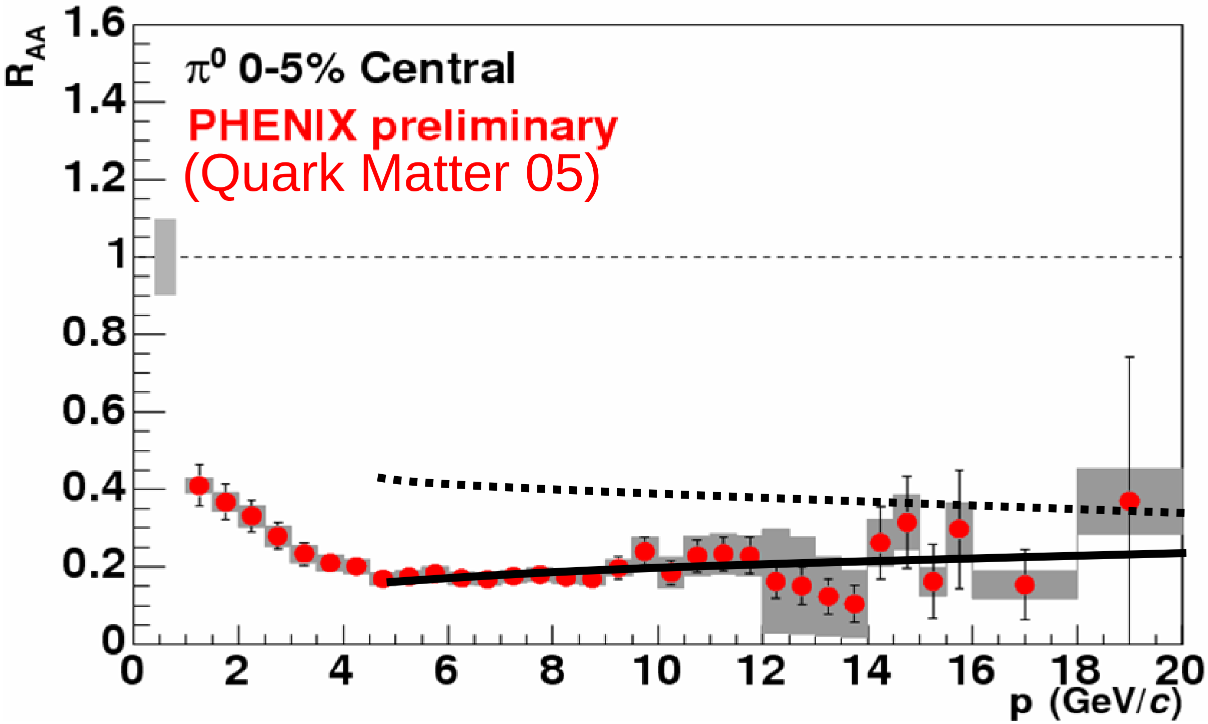
$\omega_c = \hat{q} L^2 / 2$ sets the scale of the radiated energy

$R = \omega_c L$ related to constraint $k_T < \omega$, controls shape at $\omega << \omega_c$

Baier, Dokshitzer, Mueller, Peigne‘, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

Model vs RHIC "light" data

- Model: pQCD + E loss probability + detailed collision geometry
- Density ($\hat{q}$) "tuned" to match R_{AA} in central Au-Au at 200 GeV

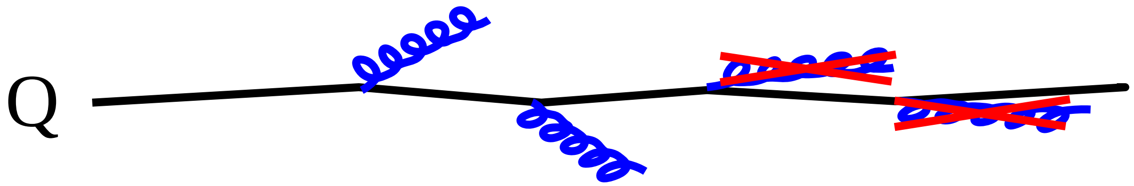


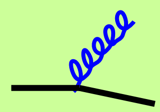
➡ matches p_T-indepence of suppression at high p_T

Lower E loss for heavy quarks ?

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

  → **"dead cone" effect**



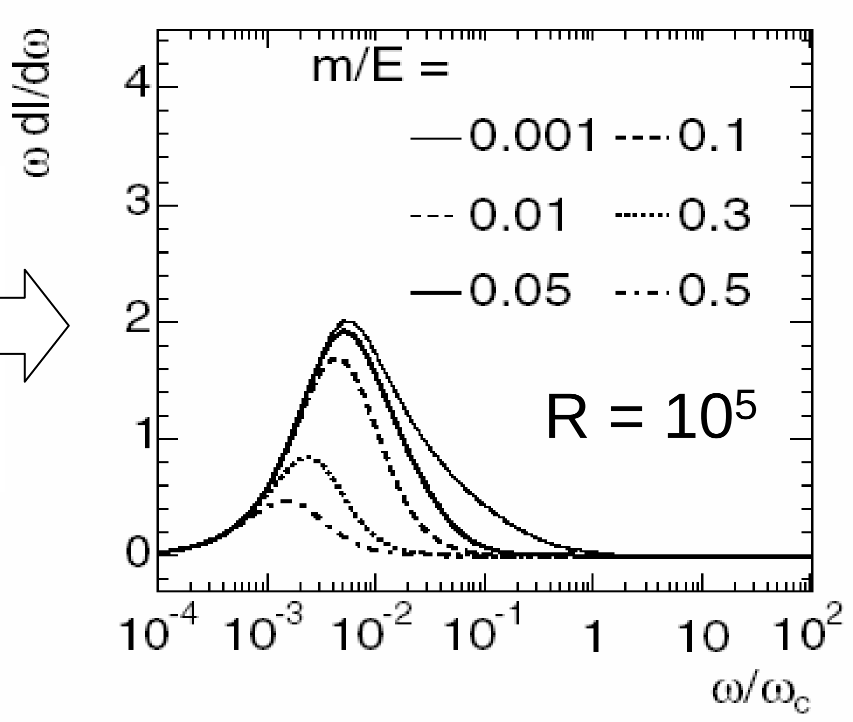


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppress high-ω tail

Detailed massive calculation confirms this qualitative feature

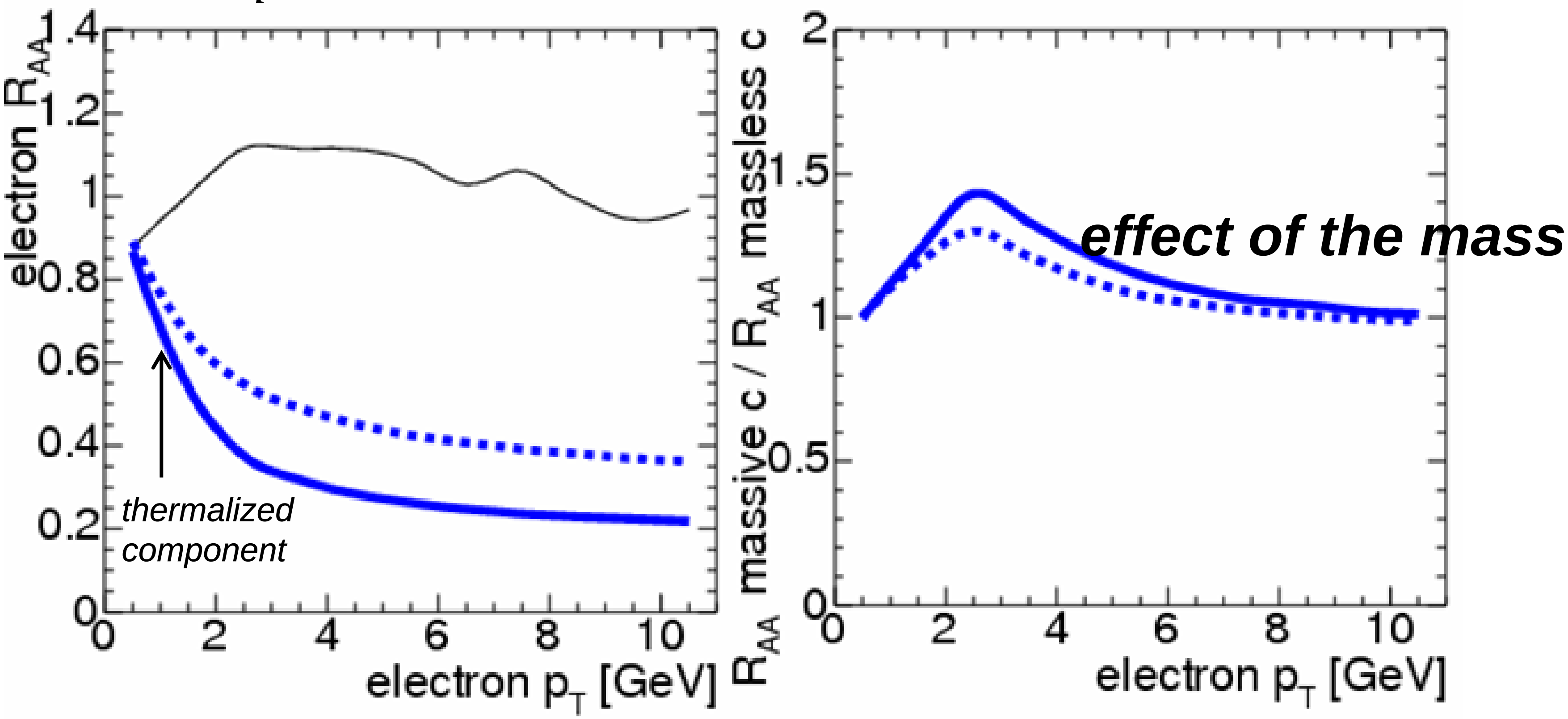
(Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003)



Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Charm R_{AA} at RHIC

$\hat{q} = 4 \div 14\,\mathrm{GeV}^2/\mathrm{fm}$ (extracted from light-hadron data)

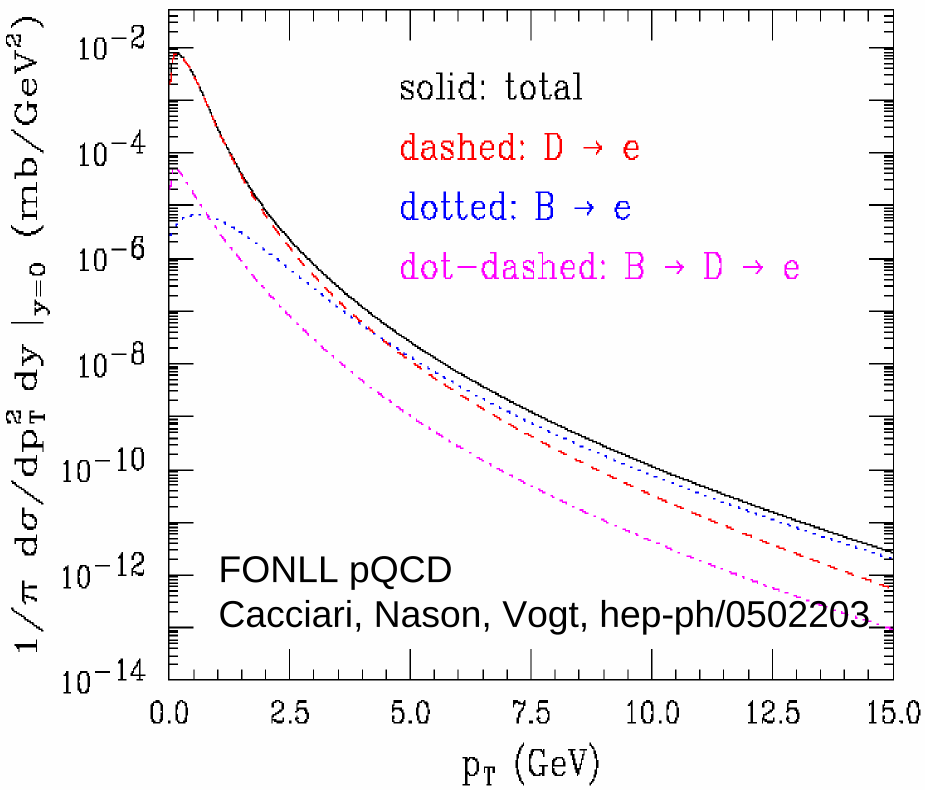


Small effect of mass for charm (~50% for D, ~30% for e) at low p_T [large uncertainties!]
Basically no effect in "safe" p_T-region

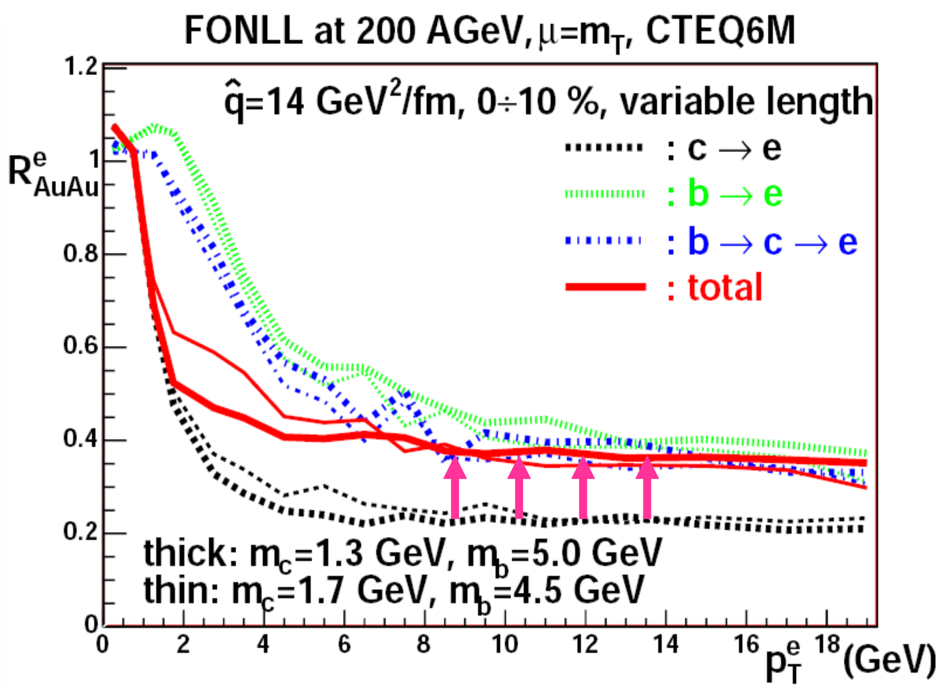
Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.

c + b (?) decay $e^{\pm}$ R_{AA} at RHIC

FONLL:
Electron spectrum may be
~50% charm + ~50% beauty
for $3 < p_T < 8$ GeV

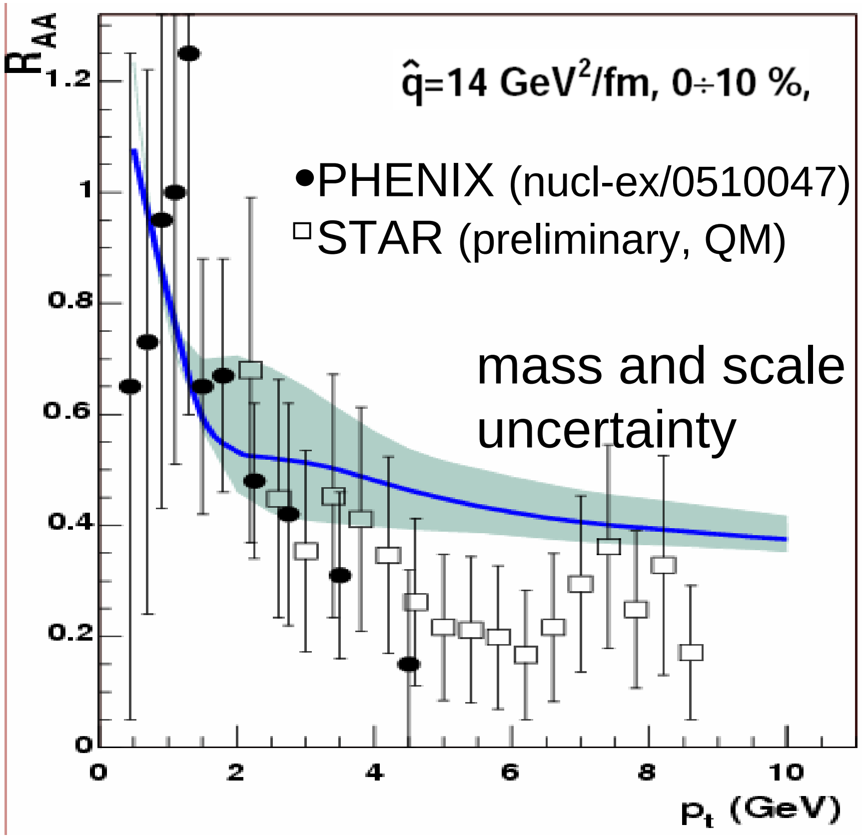


Due to larger mass of b quark electron R_{AA} incresed to ~0.4
(mass uncertainty also studied)

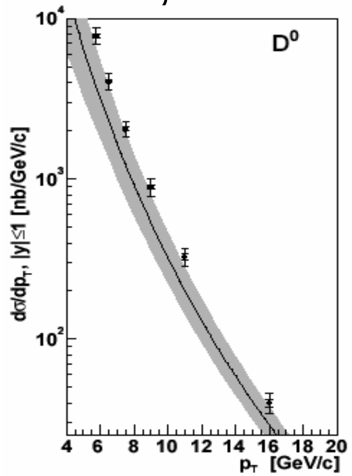


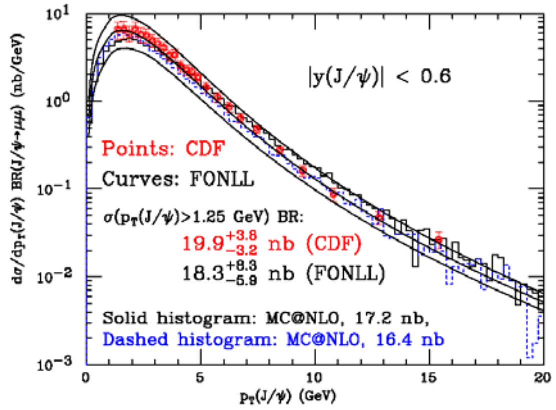
Armesto, Cacciari, Dainese, Salgado, Wiedemann, in preparation,
Armesto @ Quark Matter 05

Heavy-flavour data in Au-Au 200 GeV



Reminder: FONLL@Tevatron:
D production underpredicted
B, instead, is OK





***R_{AA}* down to 0.3 for *p_T* > 4 GeV/c! Heavy-quark quenching.**
Similar to that of light! Small room for mass effect …

Data lower than energy loss calculations, but charm fraction may be higher than predicted by FONLL

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027 + w/Cacciari, in preparation

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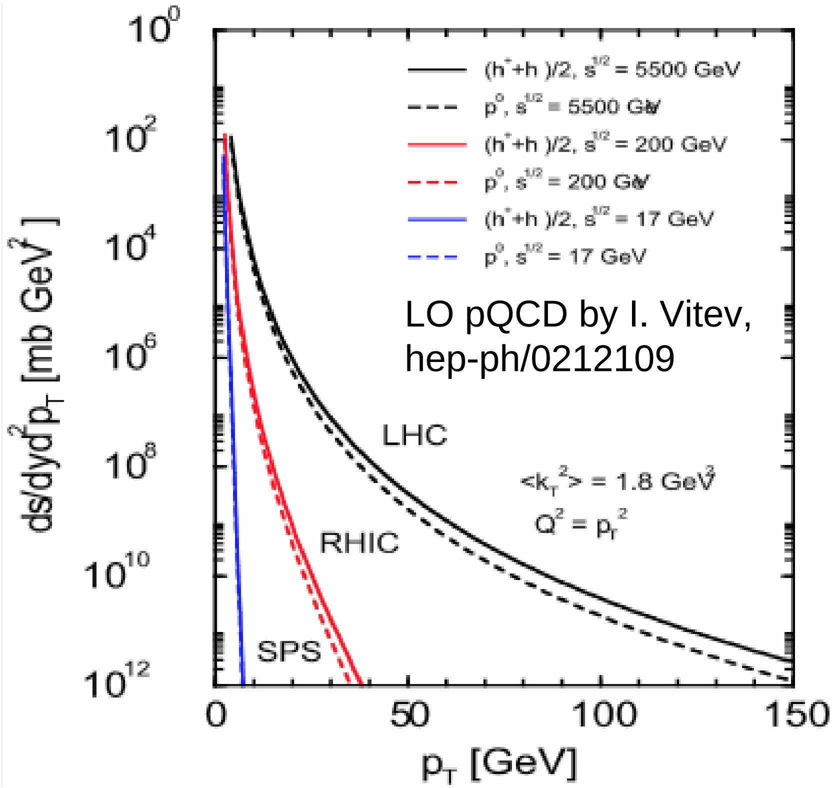
⇨ **What should we measure?**

Novelties at LHC (1): Hard Probes

- LHC: large hard cross sections!
- Our set of "tools" (probes) becomes richer

quantitatively:



qualitatively:

- **heavy quarks**

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

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

- γ + jet correlations
- Z^0 + jet correlations

Heavy-quark production at the LHC

- pp: Important test of pQCD in a new energy domain
- Remember the "15-years saga of b production at Tevatron"*

- Baseline predictions: NLO (MNR code) in pp + binary scaling (shadowing included for PDFs in the Pb)
- ALICE baseline for charm / beauty:

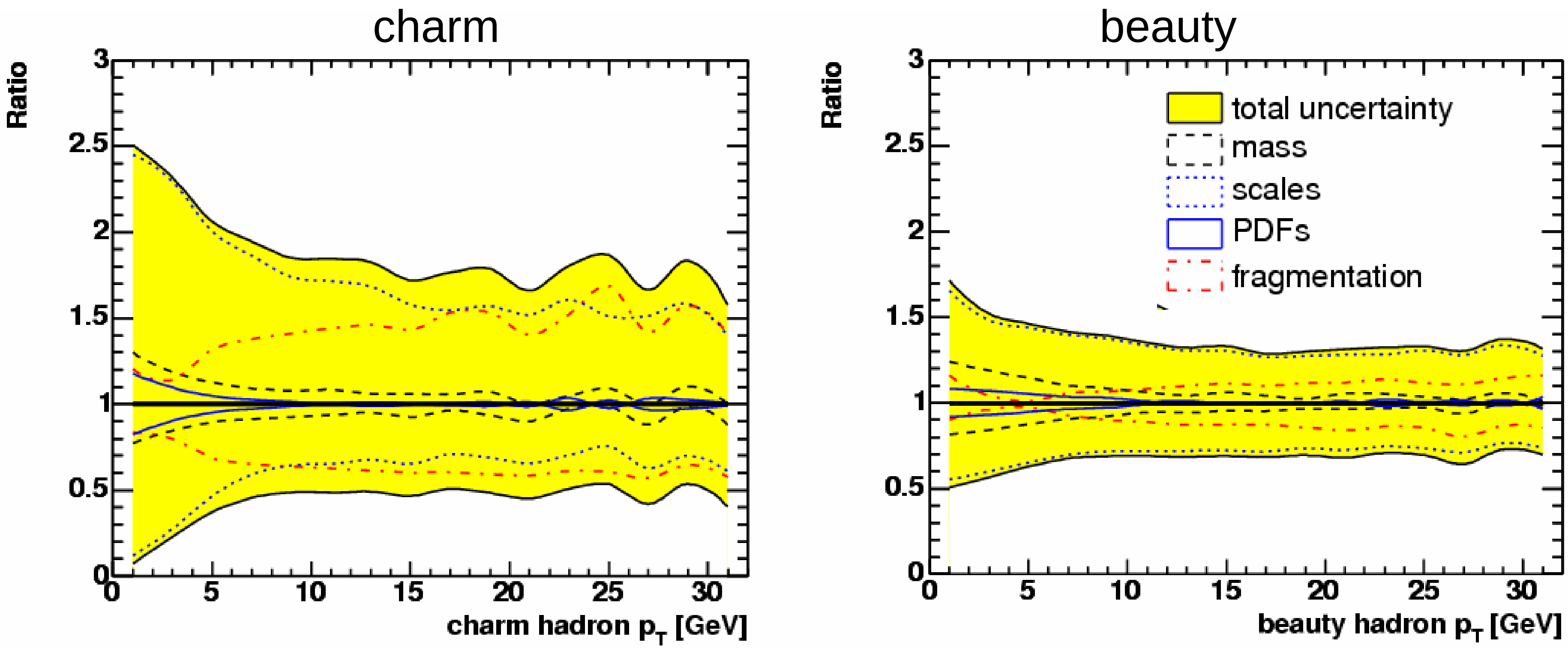
system : $\sqrt{s_{NN}}$:	Pb-Pb (0-5% centr.) 5.5 TeV	p-Pb (min. bias) 8.8 TeV	pp 14 TeV
$\sigma_{NN}^{Q\overline{Q}}$ [mb]	**4.3 / 0.2**	**7.2 / 0.3**	**11.2 / 0.5**
$N_{tot}^{Q\overline{Q}}$	**115 / 4.6**	**0.8 / 0.03**	**0.16 / 0.007**
$C_{shadowing}^{EKS98}$	**0.65 / 0.80**	**0.84 / 0.90**	**--**

Theoretical uncertainty of a factor 2—3 (next slide)

* M.Mangano
MNR code: Mangano, Nason, Ridolfi, NPB373 (1992) 295.

Theoretical Uncertainties
(HERA-LHC Workshop)

Evaluation of theoretical uncertainties



$1.3 < m_c < 1.8$ GeV $\quad 0.5 < \mu_{F,R} / m_T < 2 \quad 0.002 < \varepsilon_c < 0.11$

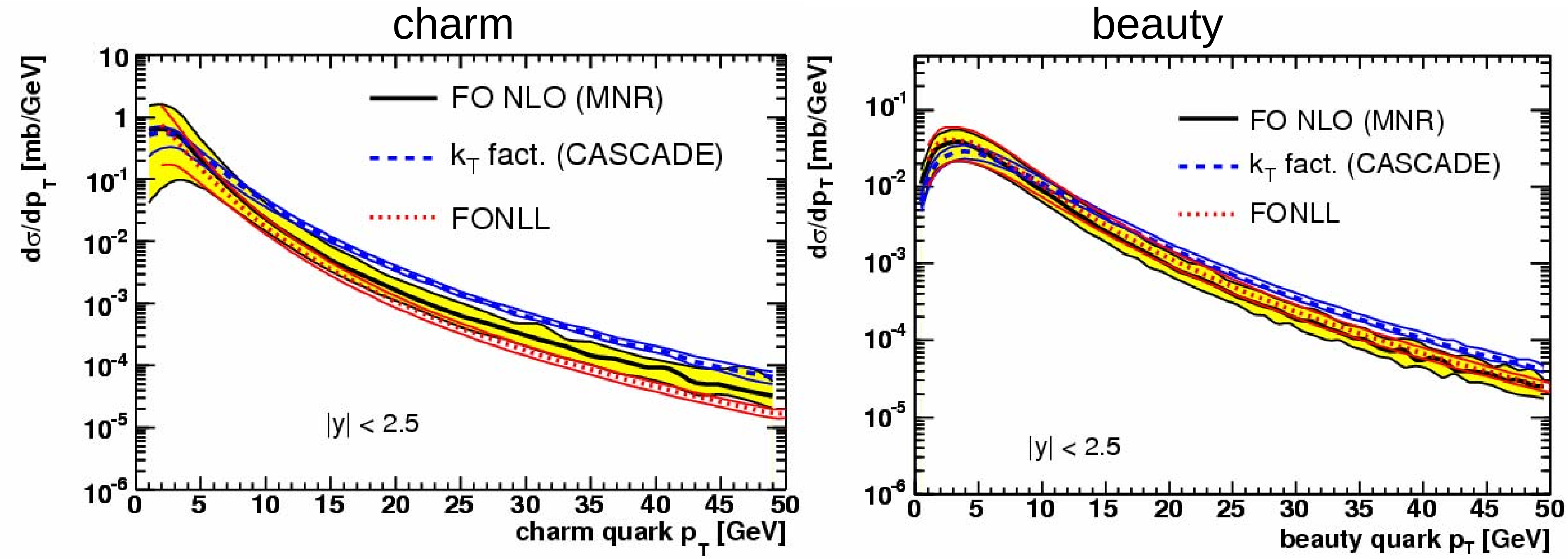
$4.5 < m_b < 5.0$ GeV $\quad 0.5 < \mu_F / \mu_R < 2 \quad 0.0002 < \varepsilon_b < 0.004$

PDFs : CTEQ4, CTEQ5, CTEQ6, MRST2001

MNR code: Mangano, Nason, Ridolfi, NPB373 (1992) 295.

Model Comparisons
(HERA-LHC Workshop)

Compare predictions by several different models

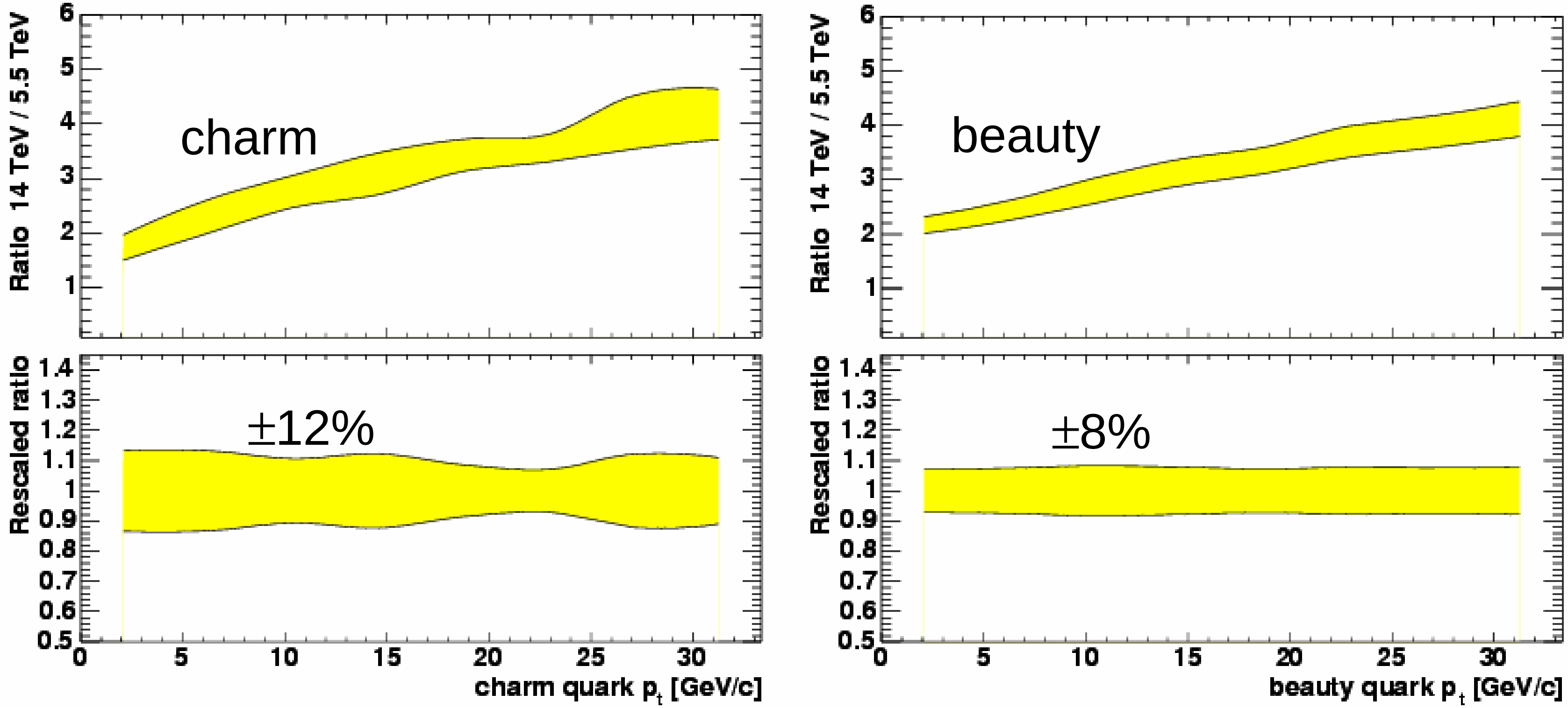


⇒ Good agreement between collinear factorization based calculations: FO NLO and FONLL

⇒ k_T factorization (CASCADE) higher at large p_T

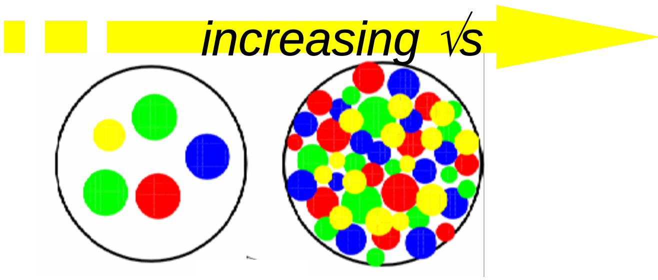
Energy extrapolation via pQCD?

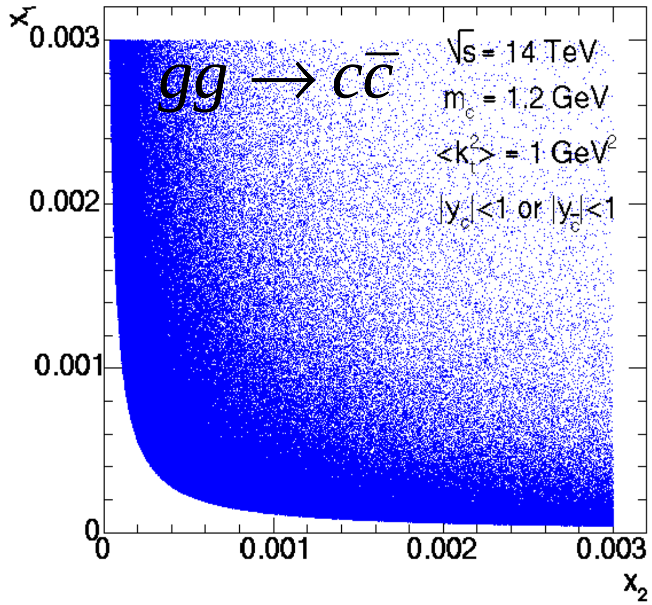
- Different systems (pp, p-Pb, Pb-Pb) will have different $\sqrt{s}$ values
- Results in pp at 14 TeV will have to extrapolated to 5.5 TeV (Pb-Pb energy) to compute, e.g., nuclear modification factors R_{AA}
- pQCD: “there ratio of results at 14 TeV/5.5 TeV has ‘small’ uncertainty”



Novelties at LHC (2): Small x

- Probe unexplored small-*x* region with HQs at low p_T and/or forward *y*
  - down to $x \sim 10^{-4}$ with charm already at $y=0$

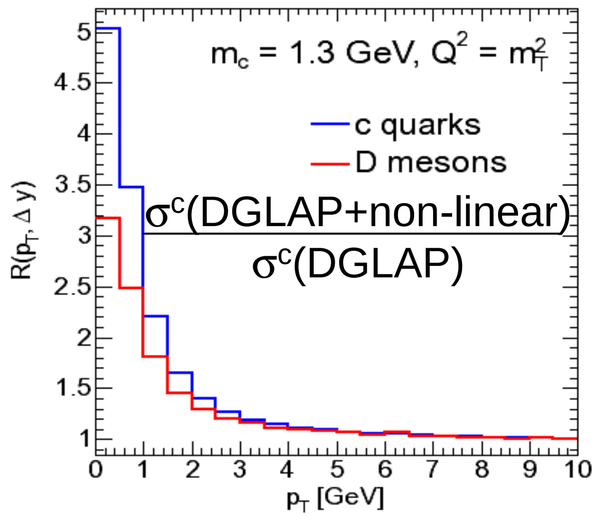




- Window on the rich phenomenology of high-density PDFs:

  gluon saturation / recombination effects

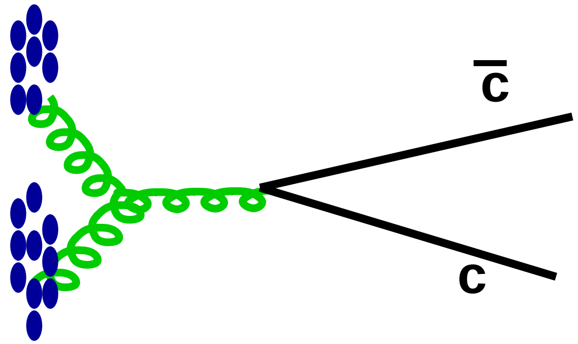
- Possible effect: enhancement of charm production at **low p_T** w.r.t. to standard DGLAP-based predictions, even in pp!

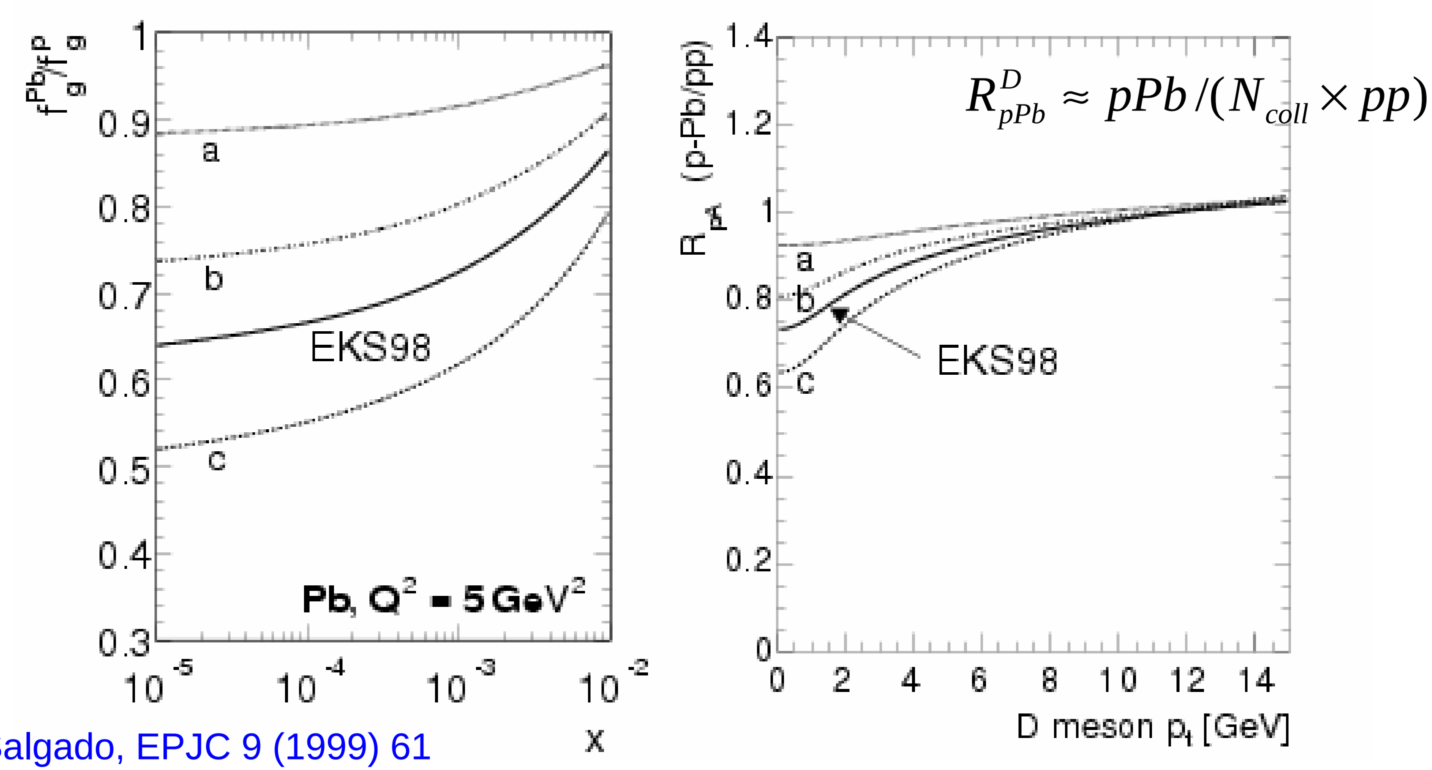


Eskola, Kolhinen, Vogt, PLB582 (2004) 157
Gotsmann, Levin, Maor, Naftali, hep-ph/0504040

Probing nuclear initial state PDFs with HQs

- **Shadowing in pA (AA)**
- CGC in pA (AA)
- Double parton scattering in pA





Eskola, Kolhinen, Salgado, EPJC 9 (1999) 61

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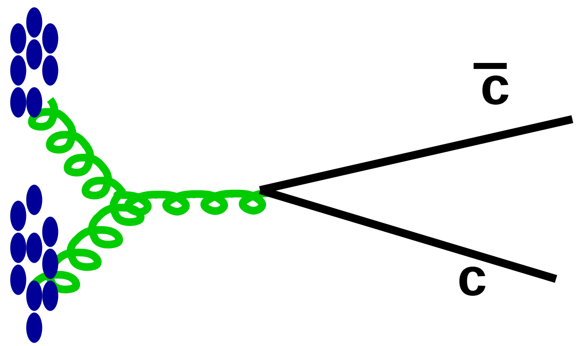
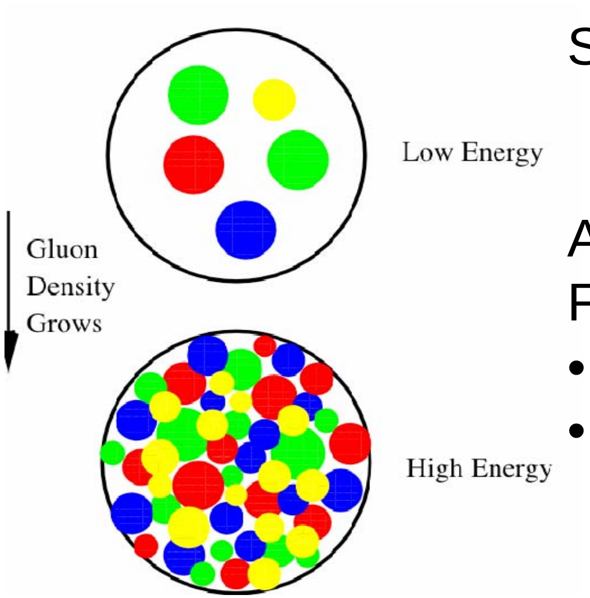




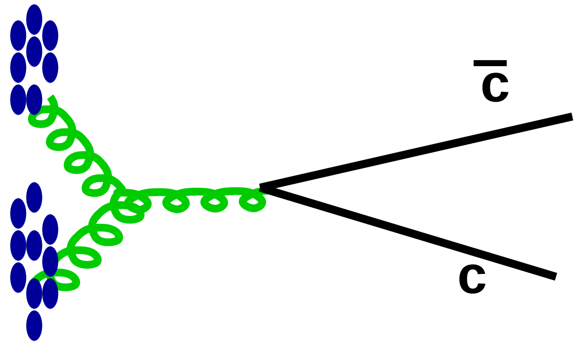
Saturation scale $Q_s^2(x) \sim xg(x)A/R_A^2 \sim xg(x)A^{1/3}$

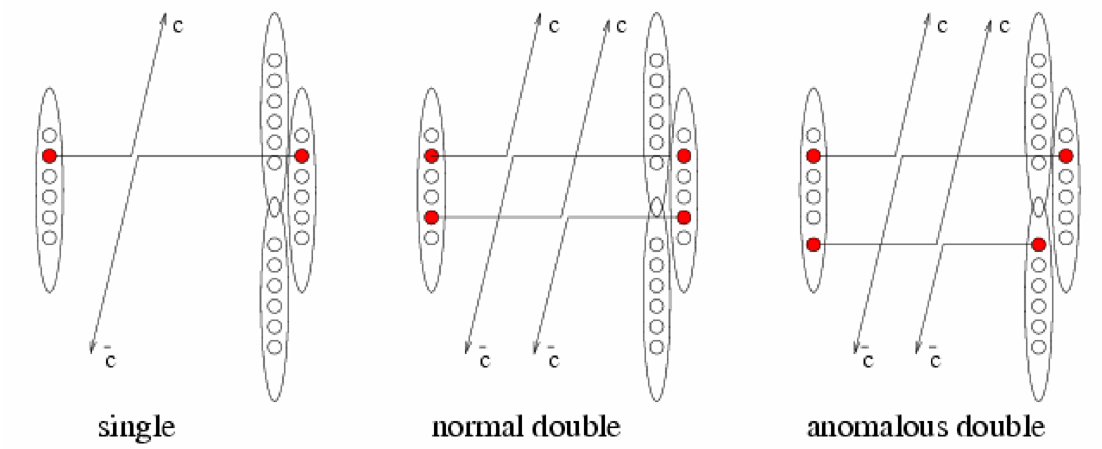
At LHC for $x \sim 10^{-4}$, $Q_s \sim 1.5\text{-}2$ GeV > m_c
For $m_{T,c} \sim Q_s$, charm prod. CGC-dominated:
- scales with $\sqrt{N_{part}}$ in pA (not N_{coll})
- harder p_T spectra, since typical $k_T \sim Q_s \sim 1.5$ GeV, while in standard factorization $k_T \sim \Lambda_{QCD} \sim 0.2$ GeV

Kharzeev, Tuchin, NPA 735 (2004) 248

Probing nuclear initial state PDFs with HQs

- Shadowing in pA (AA)
- CGC in pA (AA)
- **Double parton scattering in pA**





probe “many-body” PDFs

normal and anomalous: different A dep.

predicted rate: $c\bar{c}c\bar{c}/c\bar{c}$ ~ 10% (Treleani et al.)

signature: events with “tagged” DD (can use D^0+e^+ or e^+e^+) and ch. conj.
NB: there is a “background” from normal $b\bar{b}$ events, but is can be estimated from measured single inclusive b cross section

Cattaruzza, Del Fabbro, Treleani, PRD 70 (2004) 034022

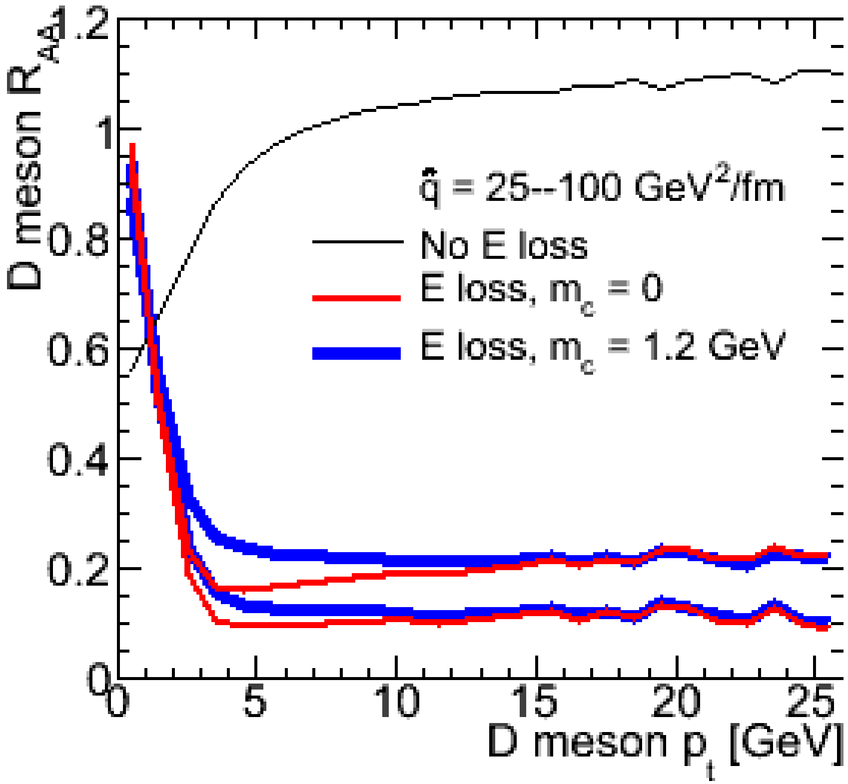
Heavy Quark Energy Loss at LHC

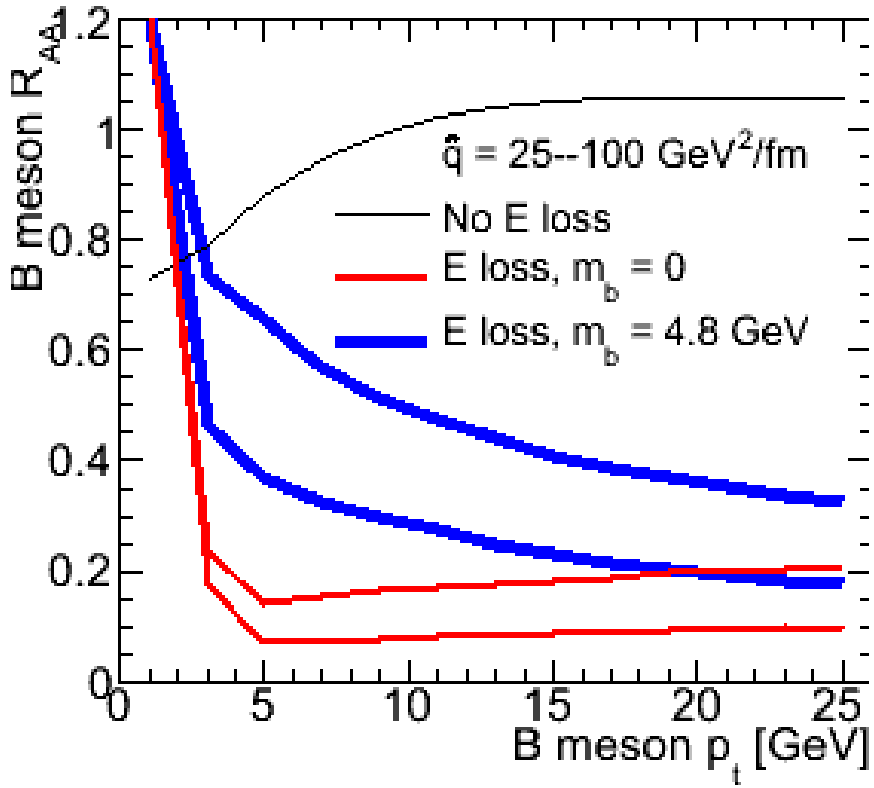
- ~100 $c\bar{c}$ pairs and ~5 $b\bar{b}$ pairs per central Pb-Pb collision
- Experiments will measure with good precision R_{AA} for D and B, and for their decay leptons

What can we learn from a comparative quenching study of massive and massless probes at the LHC?

Heavy Flavour R_{AA} at LHC

- Baseline: PYTHIA, with EKS98 shadowing, tuned to reproduce c and b p_T distributions from NLO pQCD (MNR)
- (m/E)-dep. E loss with $\hat{q}_{LHC} \approx 7^* \times \hat{q}_{RHIC} = 25 \div 100 \,\mathrm{GeV}^2/\mathrm{fm}$





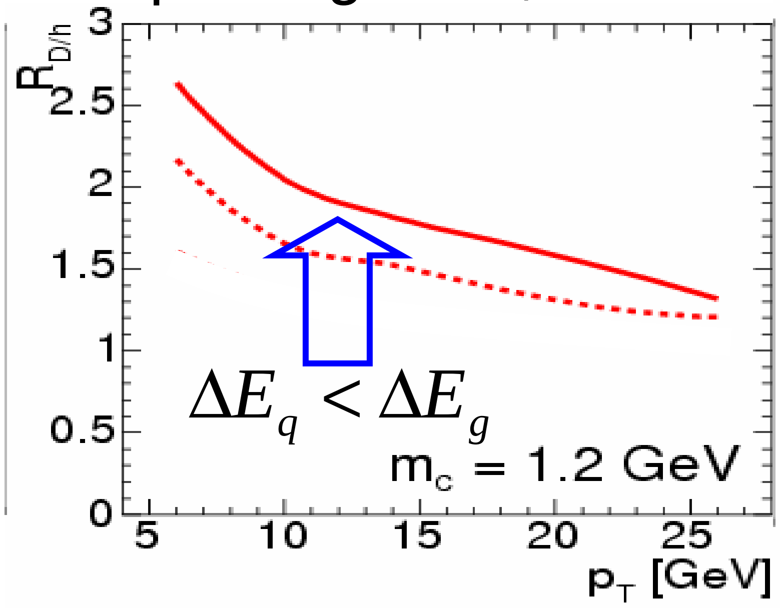
Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.
MNR: Mangano, Nason, Ridolfi, NPB 373 (1992) 295.

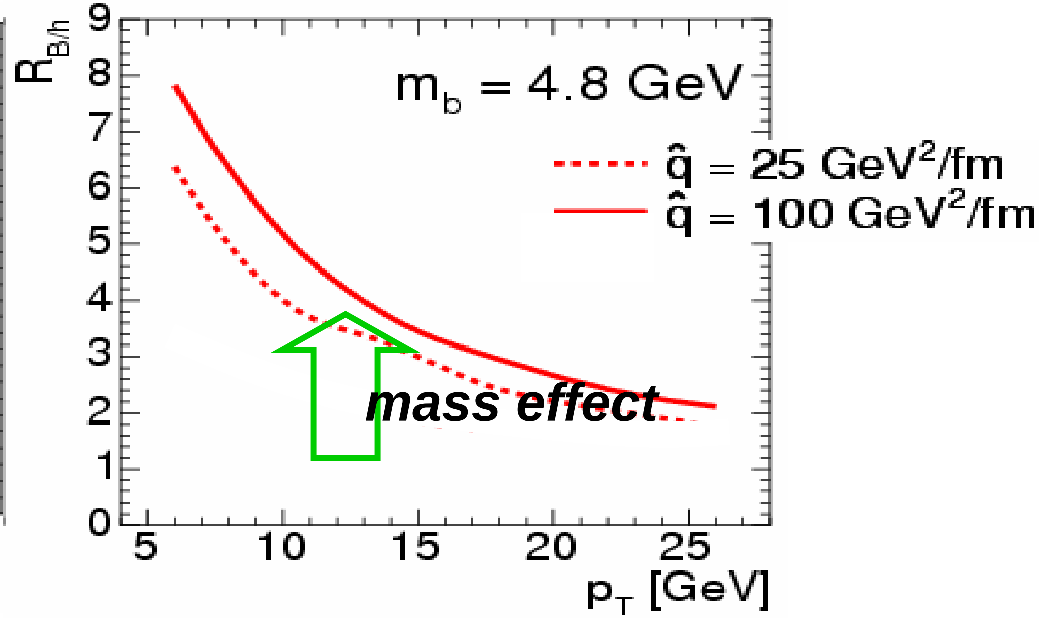
* EKRT Saturation model:
Eskola, Kajantie, Ruuskanen, Tuominen, NPB 570 (2000) 379.

Color-charge and mass dep. of E loss with Heavy-to-Light ratios at LHC

Heavy-to-light ratios: $R_{D(B)/h}(p_t) = R_{AA}^{D(B)}(p_t) / R_{AA}^{h}(p_t)$

Compare $g \to h$, $c \to D$ and $b \to B$





For $10 < p_T < 20$ GeV, charm behaves like a m=0 quark, light-flv hadrons come mainly from gluons

<u>$R_{D/h}$ enhancement probes color-charge dep. of E loss</u>

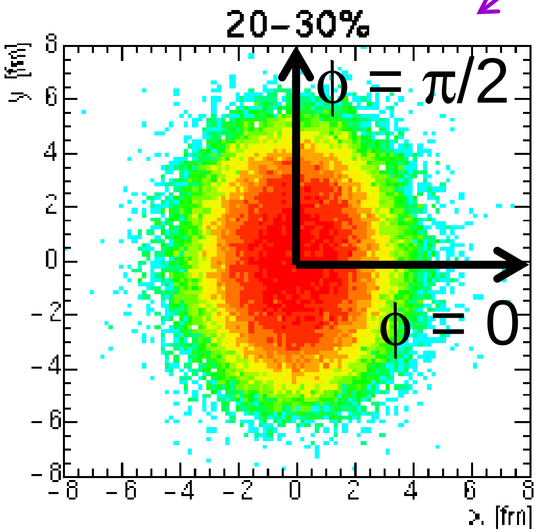
<u>$R_{B/h}$ enhancement probes mass dep. of E loss</u>

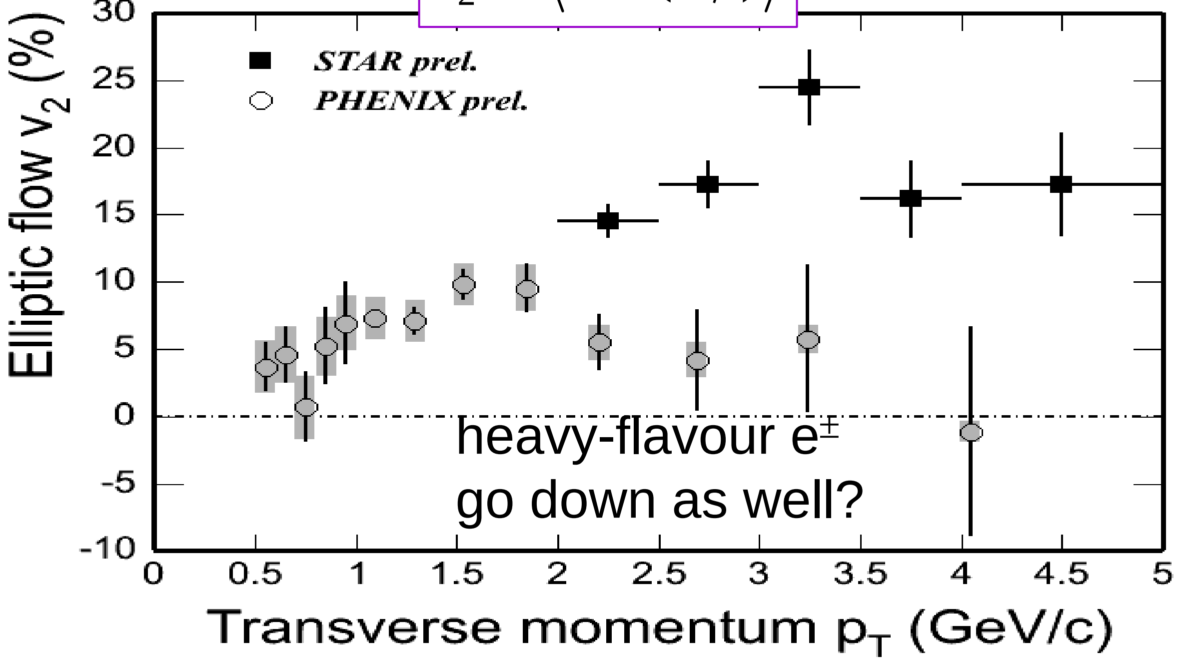
Armesto, Dainese, Salgado, Wiedemann, PRD71 (2005) 054027

Azimuthal asymmetry (v_2)

- The azimuthal asymmetry --v_2 or $R_{AA}(\phi)$-- of D and B mesons in *non-central* collisions tests:
  - at low/moderate p_T: recombination scenario, v_2 of c/b quarks, hence degree of thermalization of medium
  - at higher p_T: path-length dependence of E loss (almond-shaped medium => $v_2 \sim 0.05$--0.10)

$$v_2 = \langle \cos(2\phi) \rangle$$





Conclusions

- The (open) heavy-flavour era of heavy-ion physics has begun
- Observation of heavy-quarks quenching at RHIC !

- The LHC will be a `hard probes and heavy quarks machine' and quenching studies will play a central role

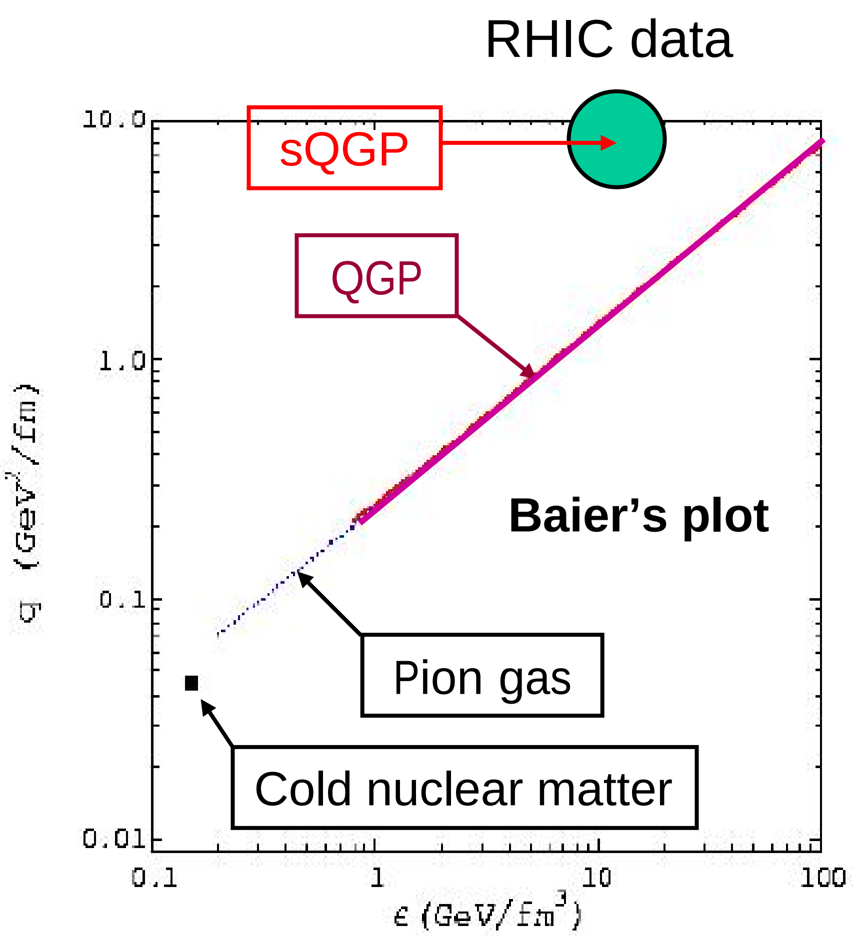
Promising observables at the LHC:

- R_{AA} of D and B mesons
- Heavy-to-light ratios as probes of E loss...
  - ... color-charge dependence ($R_{D/h}$)
  - ... parton-mass dependence ($R_{B/h}$)
- Azimuthal anysotropy for D, B mesons (or their decay leptons): interplay between reco/flow and E loss

+ study of dense QCD initial-state phenomenology

EXTRA SLIDES

B.Muller's QM Theory Summary



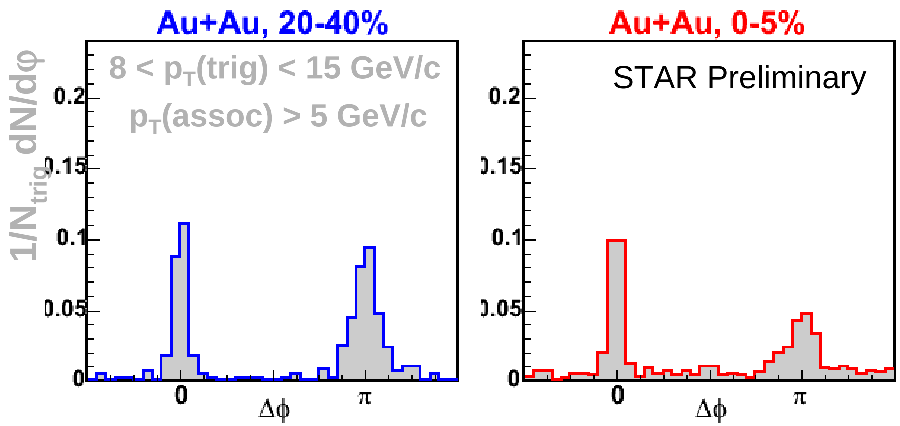
Density of scatterings

Range of color force

$$\hat{q} = \rho\sigma\left\langle k_T^2 \right\rangle = \frac{\mu^2}{\lambda}$$

$$= 5 - 15\ \mathrm{GeV}^2/\mathrm{fm}$$

Emergence of away-side jet will make determination of q^ easier.



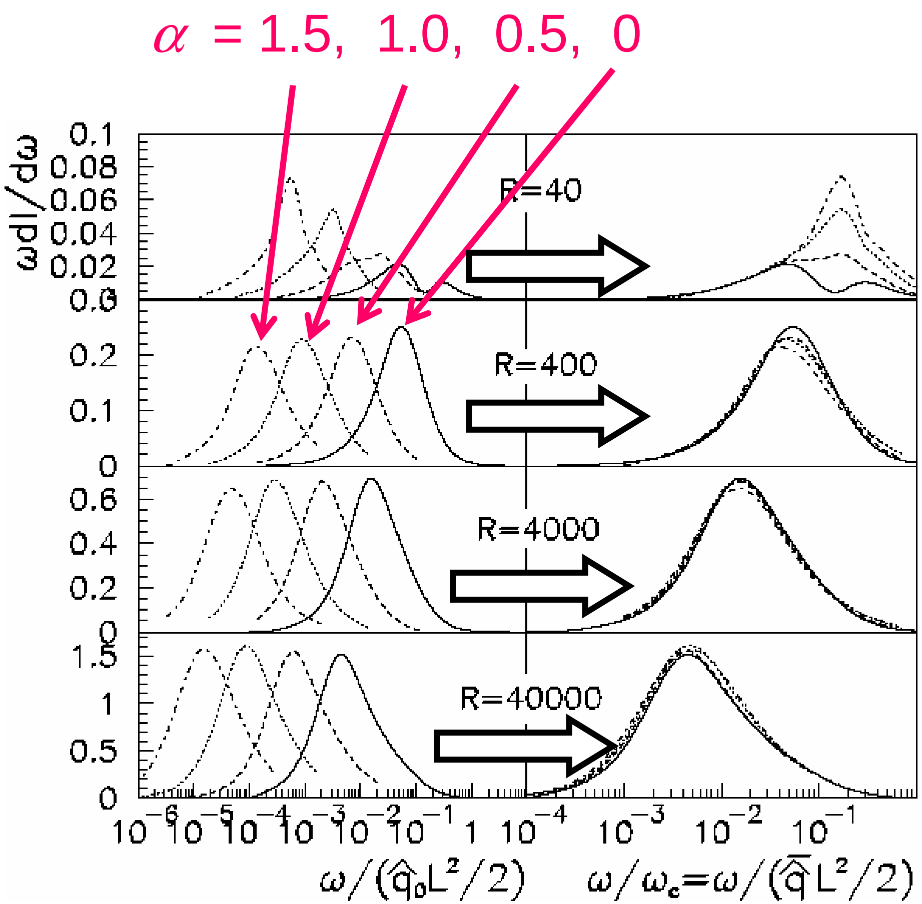
Medium Expansion

- The density of scattering centers is time-dependent:

$$\hat{q}(\tau) = \hat{q}_0 \times \left(\frac{\tau_0}{\tau} \right)^{\alpha}$$

- Dynamical scaling law:
  same spectrum obtained for equivalent static trasport coefficient

$$\bar{\hat{q}} = \frac{2}{L^2} \int_{\tau_0}^{\tau_0 + L} d\tau (\tau - \tau_0) \hat{q}(\tau)$$

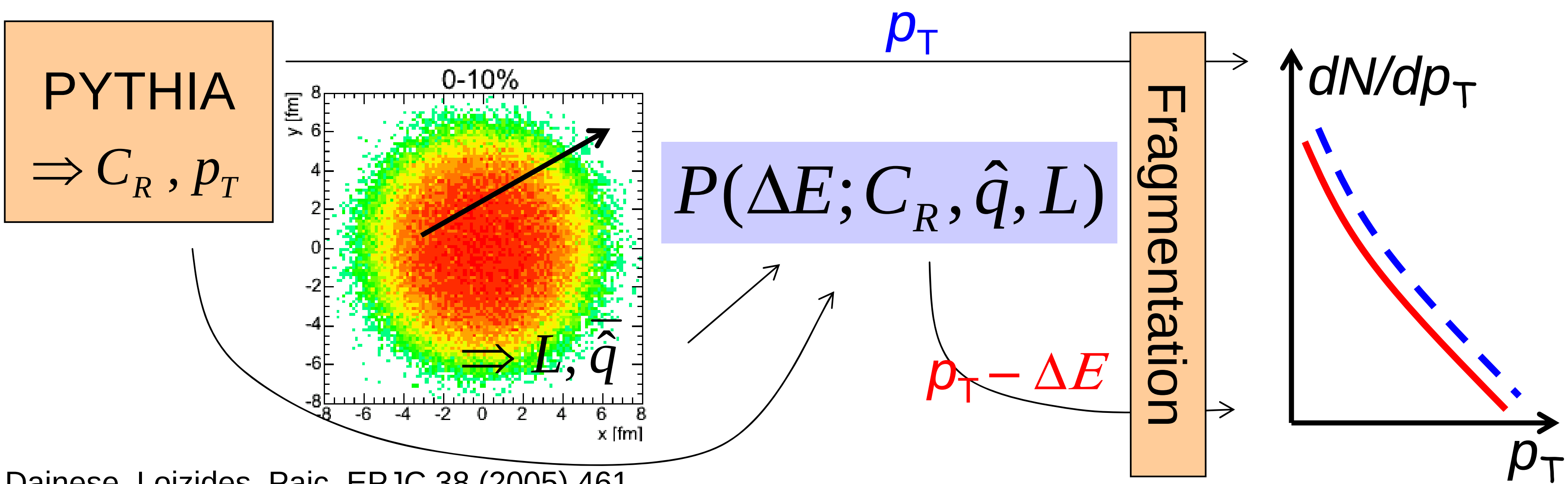


- **Calculations for a static medium apply to expanding systems**

Salgado and Wiedemann, PRL 89 (2002) 092303

Application: Parton Quenching Model

- QW + Glauber-based medium geometry and density profile + PYTHIA for parton generation and fragmentation
- The procedure in short:
  1) generate parton (q or g) with PYTHIA (or back-to-back pair)
  2) calculate its L and average $\overline{\hat{q}}$ along the path $[\hat{q}(\vec{s}) \propto T_A T_B(\vec{s})]$
  3) use quenching weights to get energy loss
  4) quench parton and then hadronize it (independent fragm.)



Dainese, Loizides, Paic, EPJC 38 (2005) 461.

Calculating Parton Energy Loss

$$\langle \Delta E \rangle \approx \int_0^{\omega_c} \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s\, C_R\, \omega_c \propto \alpha_s\, C_R\, \hat{q}\, L^2$$

$$\langle \Delta E \rangle \propto \hat{q} \propto$$ gluons volume-density and interaction cross section

➡ **Probe the medium**

Finite parton energy (qualitatively)

- If $E < \omega_c$ (e.g. small p_T parton with large L):

$$\langle \Delta E \rangle \approx \int_0^{E} \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s\, C_R \sqrt{E\omega_c} \propto \alpha_s\, C_R \sqrt{E}\sqrt{\hat{q}}\, L$$

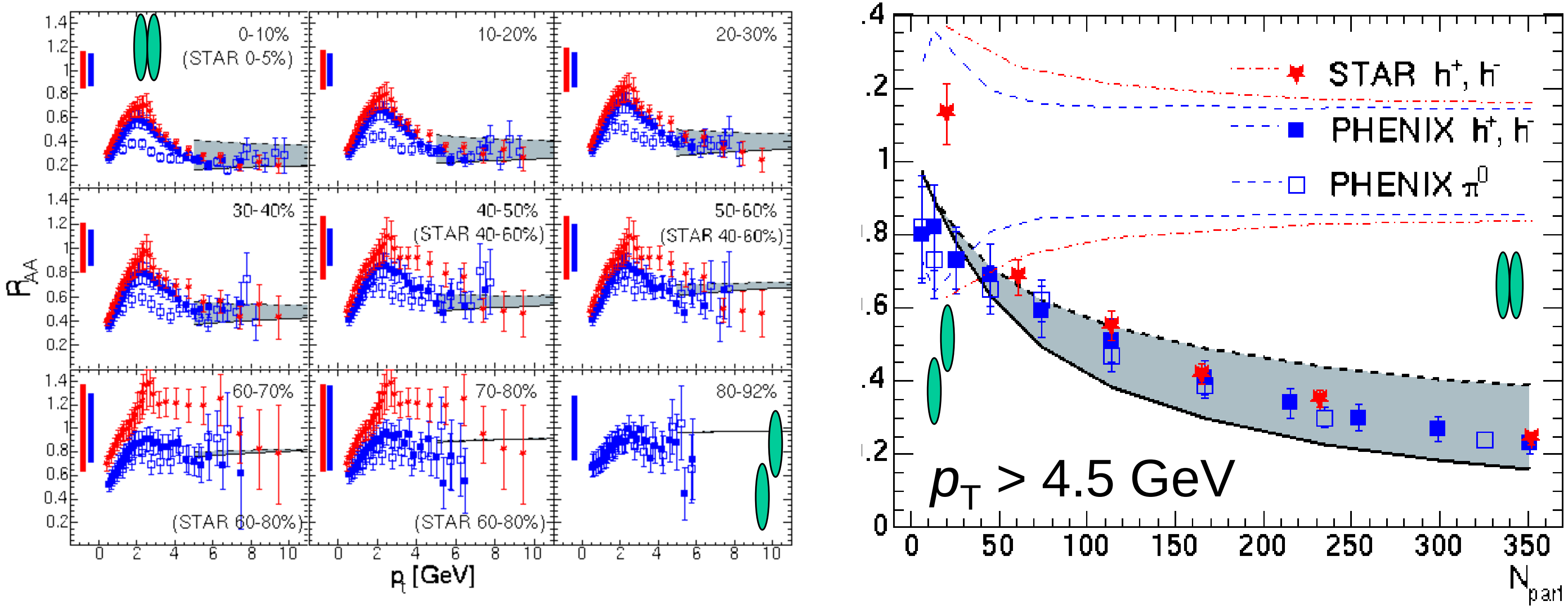
  - **dependence on parton energy**
  - $\hat{q} \to \hat{q}^{1/2}$ **: smaller sensitivity to density**
  - $L^2 \to L$

Model vs RHIC data

Centrality dependence of R_{AA}

- Centrality evolution according to Glauber-model collision geometry

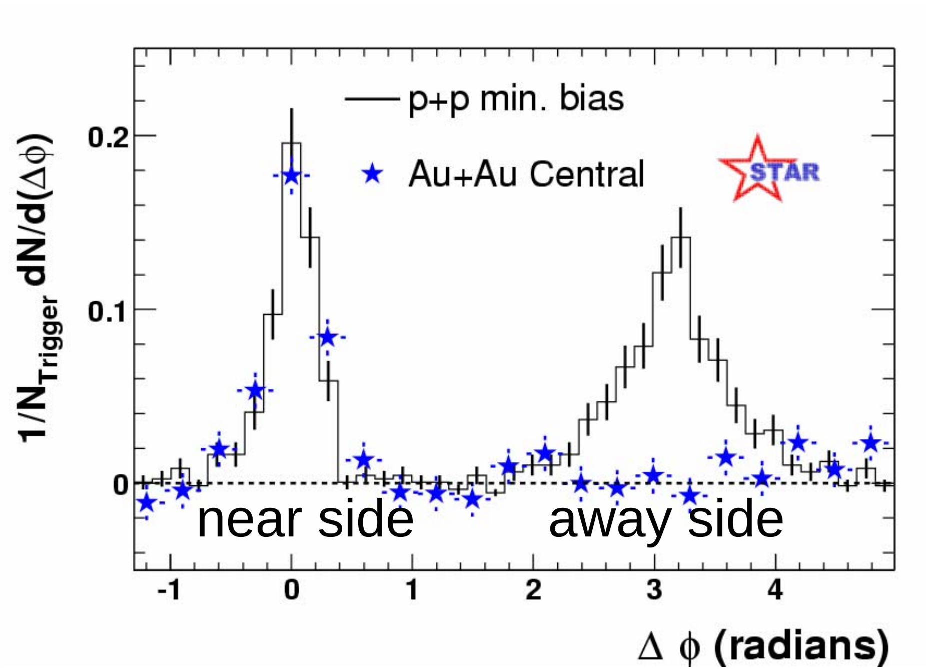
$$\hat{q}(\vec{s};b) = k \times T_A T_B(\vec{s};b)$$



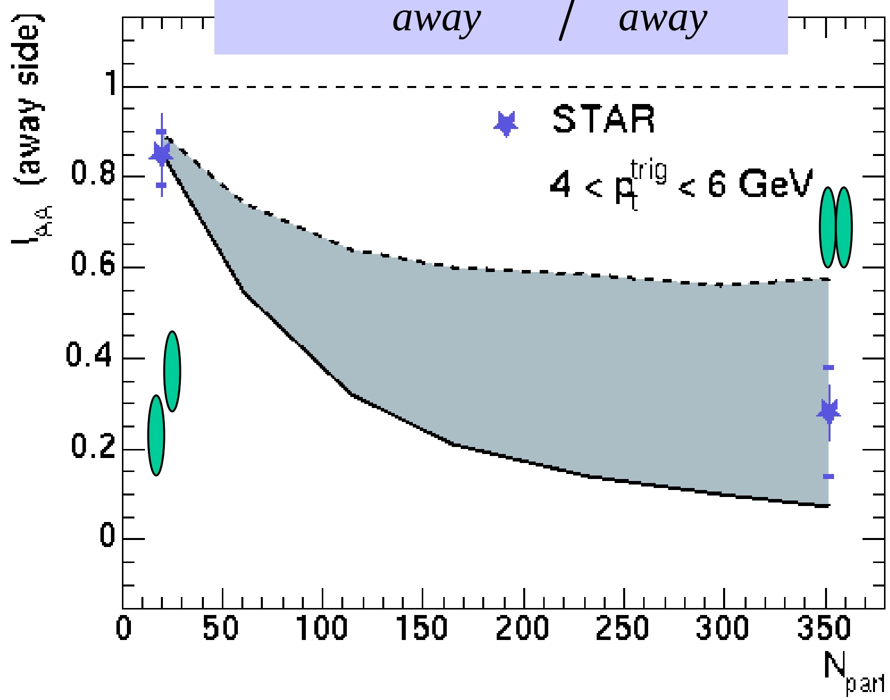
Dainese, Loizides, Paic, EPJC 38 (2005) 461.

Model vs RHIC data

Disappearence of the away-side jet



$$I_{AA} = \int_{away} AA \Big/ \int_{away} pp$$

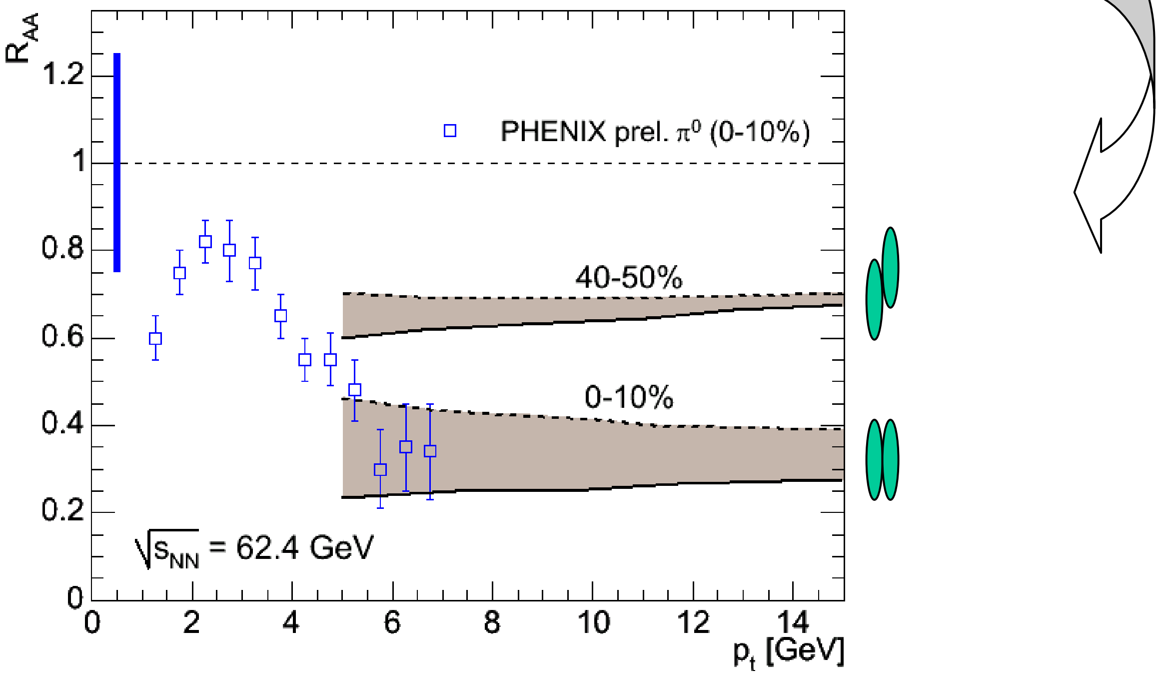


STAR Coll., PRL 90 (2003) 082302.
STAR Coll., nucl-ex/0501016.

Extrapolation in c.m.s. energy

Intermediate RHIC energy √s = 62 GeV

- Extrapolation in √s: assuming $\hat{q} \propto N_{gluons}/\text{volume} \propto (\sqrt{s})^{0.6}$ (EKRT saturation model)
- First test: $\hat{q}_{62\,\mathrm{GeV}} \approx \hat{q}_{200\,\mathrm{GeV}} / 2 \approx 7\,\mathrm{GeV}^2/\mathrm{fm}$



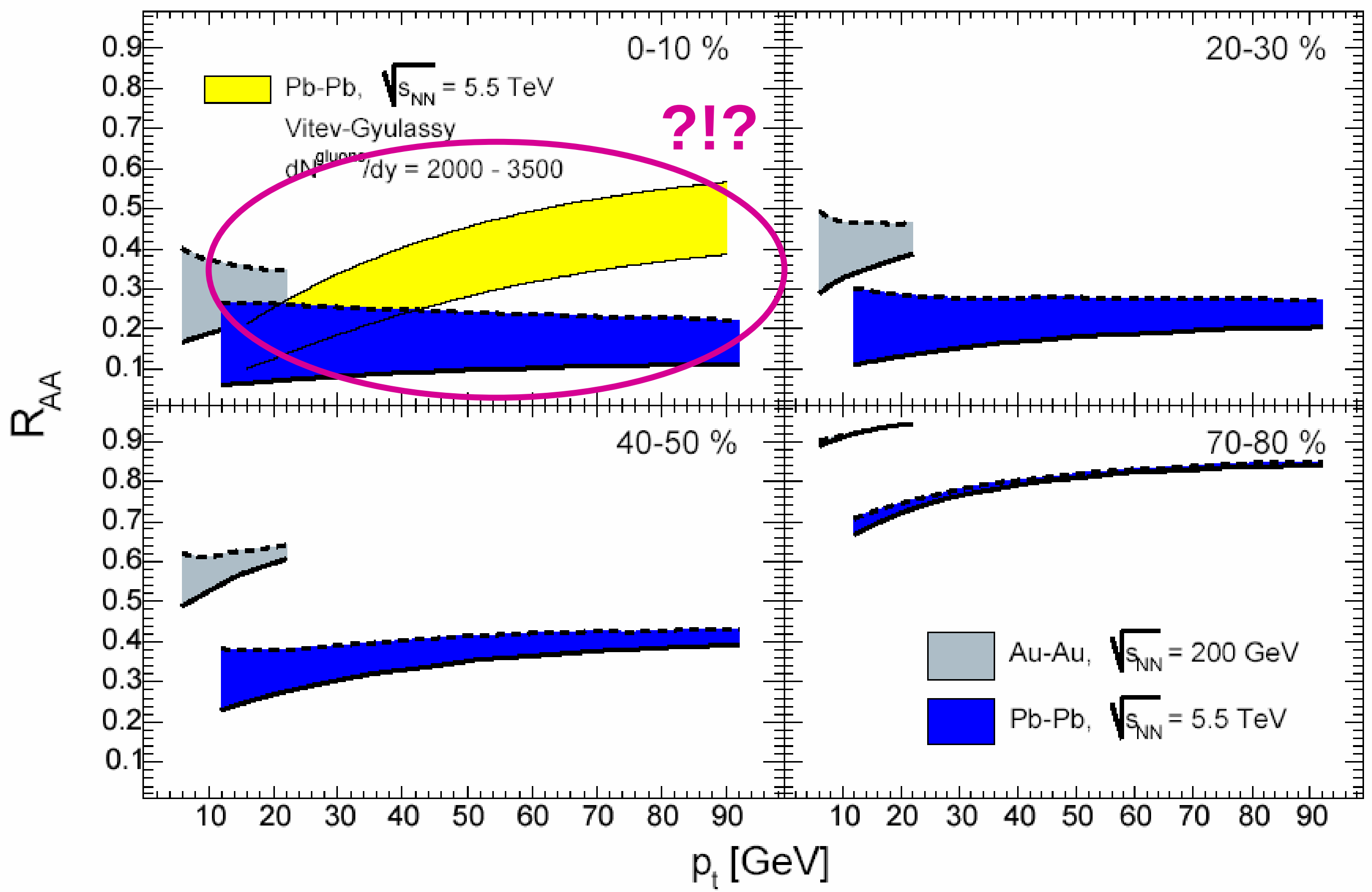
➡ energy extrapolation works reasonably well

EKRT: Eskola, Kajantie, Ruuskanen, Tuominen, NPB 570 (2000) 379.
PHENIX Coll., JPG 31 (2005) S473.

Model prediction for LHC

- Extrapolation to LHC according to saturation model gives:

$$\hat{q}_{5.5\,\mathrm{TeV}} \le 7 \times \hat{q}_{200\,\mathrm{GeV}} \approx 100\,\mathrm{GeV}^2/\mathrm{fm}$$

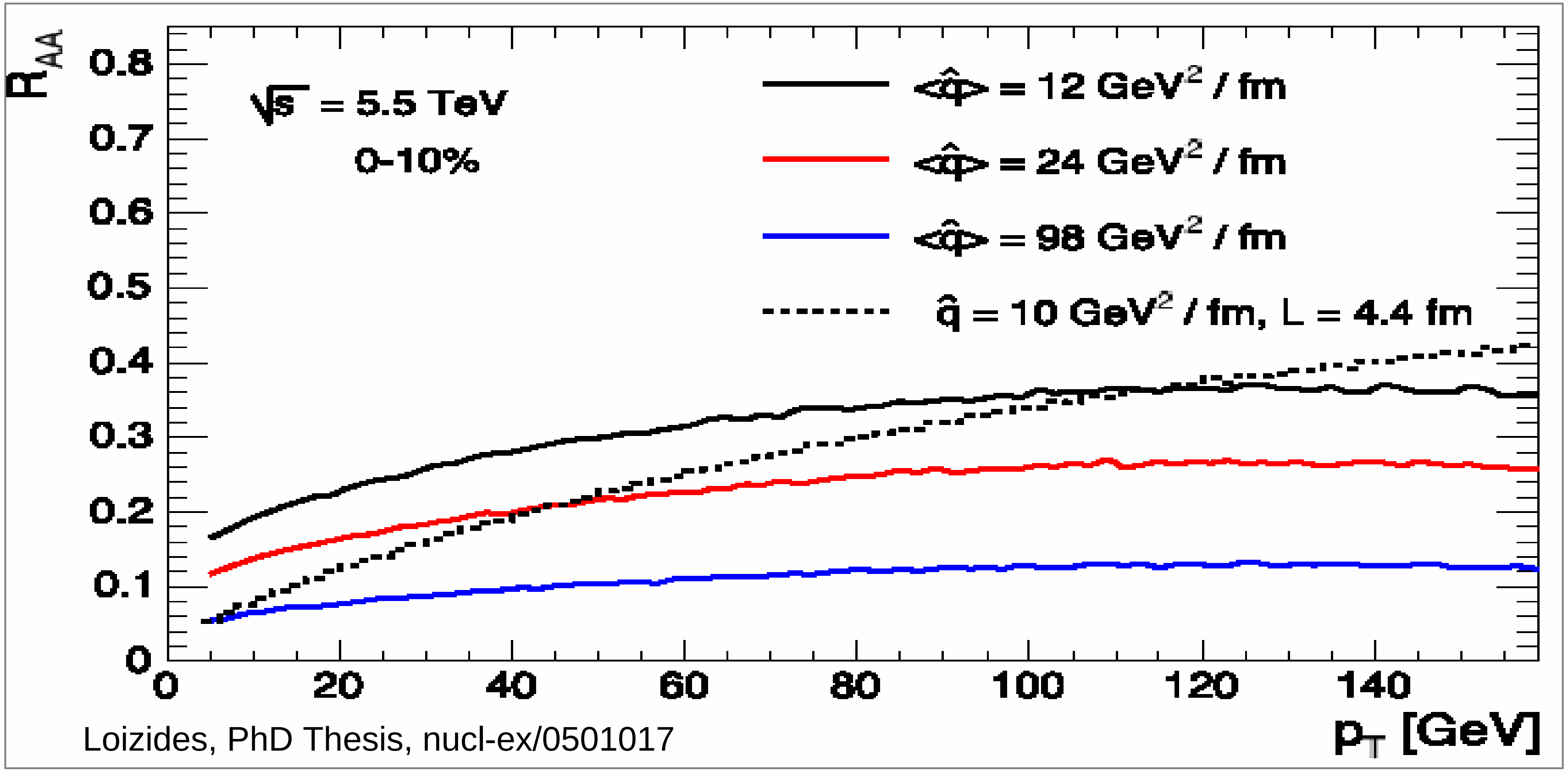


$$R_{AA}^{5.5\,\mathrm{TeV}} \approx \frac{R_{AA}^{200\,\mathrm{GeV}}}{2}$$

indep. of p_T

Dainese, Loizides, Paic, EPJC 38 (2005) 461.
Vitev and Gyulassy, PRL 89 (2002) 252301.

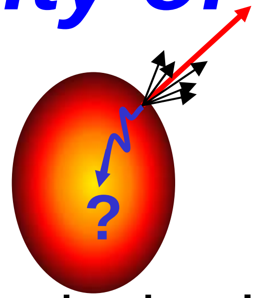
Why R_{AA} is flat $\leftrightarrow$ Surface effect



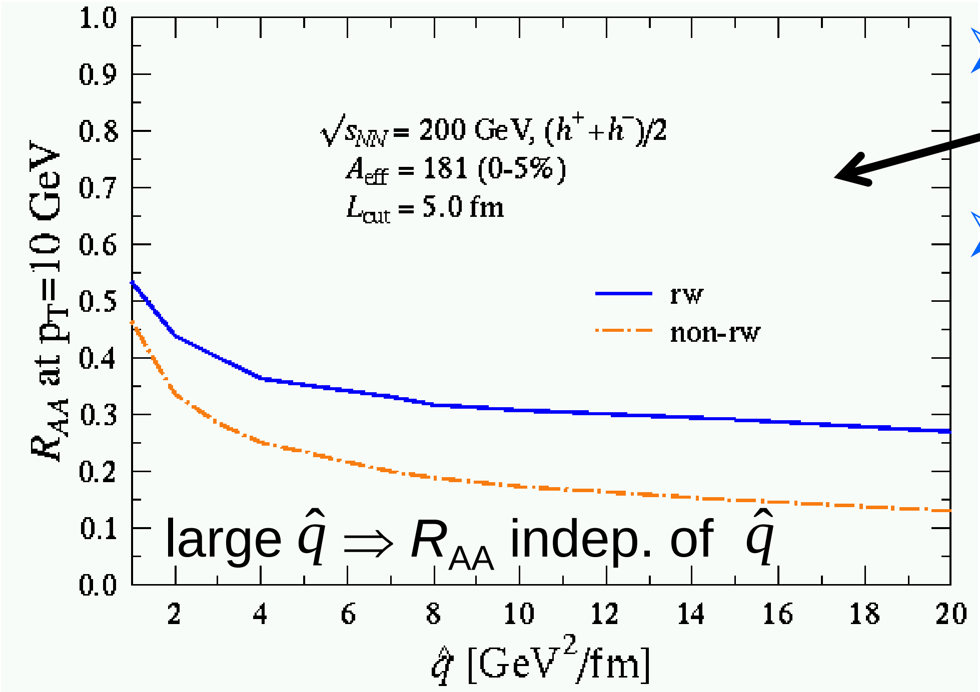
Loizides, PhD Thesis, nucl-ex/0501017

- Long path lengths exploited only by high energy partons
  - effectively, $\langle \Delta E \rangle \propto E^{\alpha}$, with $0.5 < \alpha < 1$
  - R_{AA} doesn't increase at high p_T
  - Exercise: $L \equiv \langle L \rangle \Rightarrow$ R_{AA} increases with p_T

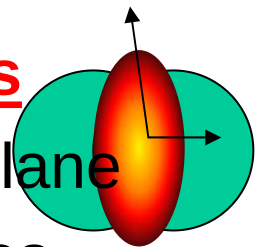
Open points (1): limited sensitivity of R_{AA}



- Strong suppression requires very large density
- Surface emission scenario
- R_{AA} determined by geometry rather than by density itself



- Limited sensitivity to $\hat{q}$
- Need more differential observables:
  - **massive partons**
  - R_{AA} vs reaction plane
  - study of jet shapes
  - …



Eskola, Honkanen, Salgado, Wiedemann, NPA 747 (2005) 511.

Open points (2): the opacity problem

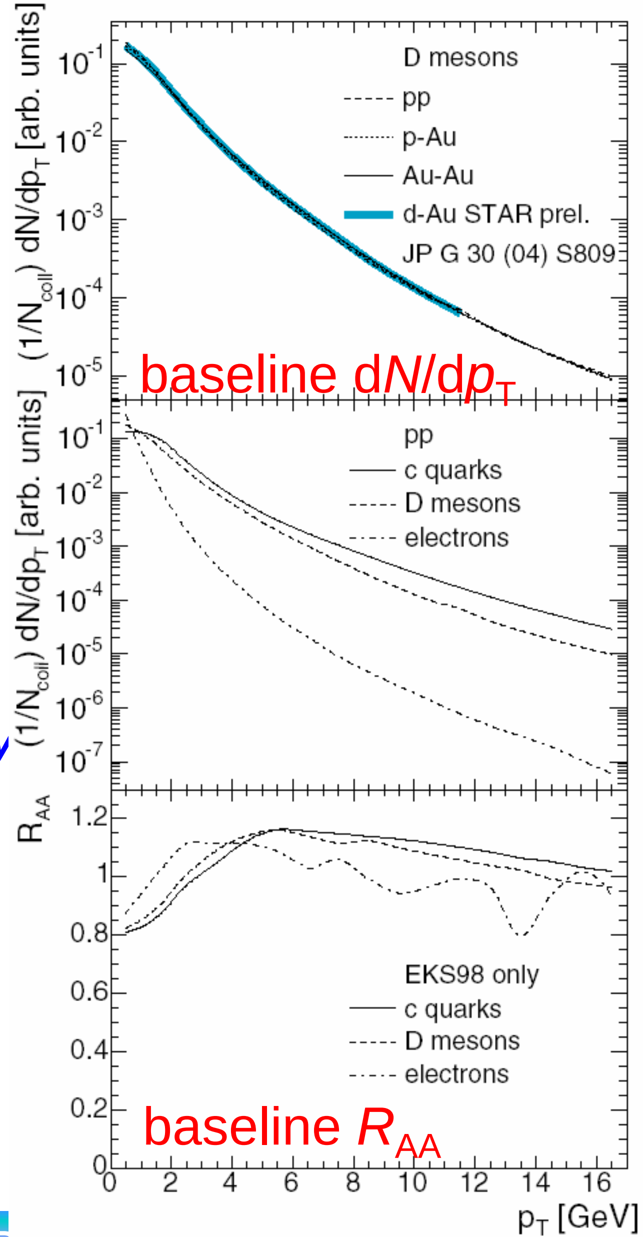
- Can we really *probe* the medium?
- Need to relate extracted $\hat{q}$ to an energy density ε
- QCD estimate for ideal QGP: $\hat{q}(\tau) \approx 2 \times \varepsilon^{3/4}(\tau)$ (Baier)
- A recent analysis* of RHIC data, similar to that presented, extracts energy density ×5 larger than that estimated from produced transverse energy dE_T/dy (Bjorken estimate)
- **Opacity problem: the interaction of the hard parton with the medium is much stronger than expected**

Baier, NPA 715 (2003) 209.
* Eskola, Honkanen, Salgado, Wiedemann, NPA 747 (2005) 511.

Charm Energy Loss at RHIC

- Compute R_{AA} for c, D, e (from D)
- Baseline: *PYTHIA*, with *EKS98 shadowing*, tuned to match p_T-shape of D cross section measured in d-Au by STAR
- c-quark *E* loss as for light-flv hadrons, but using (m_c/E_c)-dependent QW
- $\hat{q}$ extracted from $\pi^0, h^\pm$ R_{AA} (central)
- *Thermalize charms that lose all energy*

  $dN/dm_T \propto m_T \exp(-m_T/T)$, T = 300 MeV
- Use a range in $\hat{q}$ to visualize limited sensitivity of R_{AA} to $\hat{q}$ itself



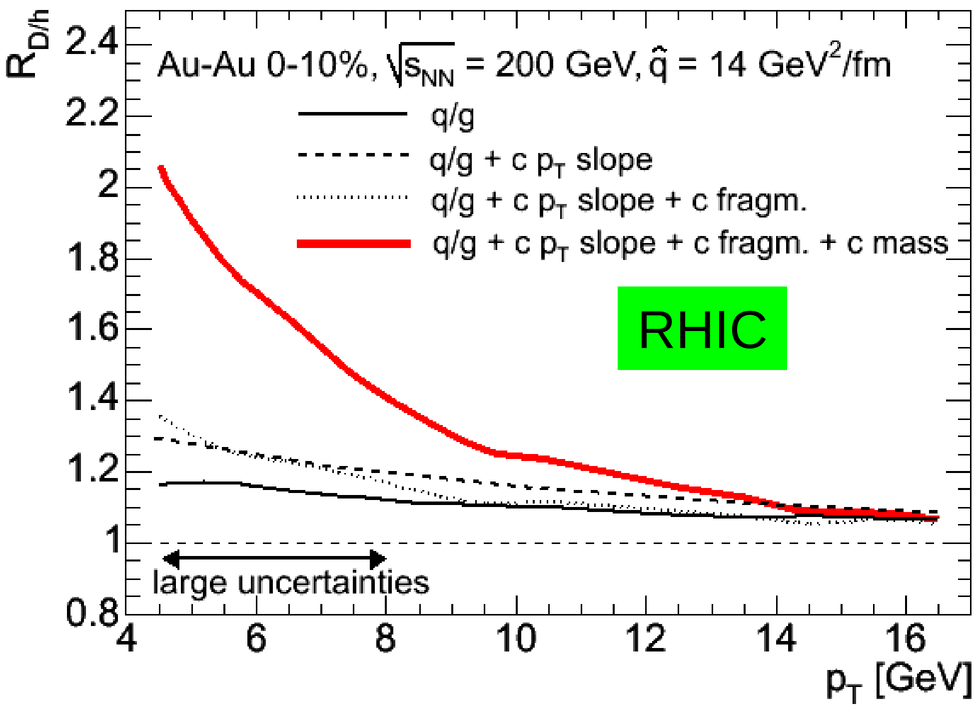
Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.
EKS: Eskola, Kolhinen, Salgado, EPJC 9 (1999) 61.

The heavy-to-light ratio:

$$R_{D/h}(p_T) \equiv \frac{R_{AA}^{D}(p_T)}{R_{AA}^{h}(p_T)}$$

What enters the game:

1) (c) quark vs gluon (Casimir factor) $\rightarrow$ $R_{D/h} > 1$
2) harder charm p_T distribution: $\rightarrow$ $R_{D/h}$ up
3) harder charm fragm. $\rightarrow$ $R_{D/h}$ down
4) mass effects $\rightarrow$ $R_{D/h}$ up



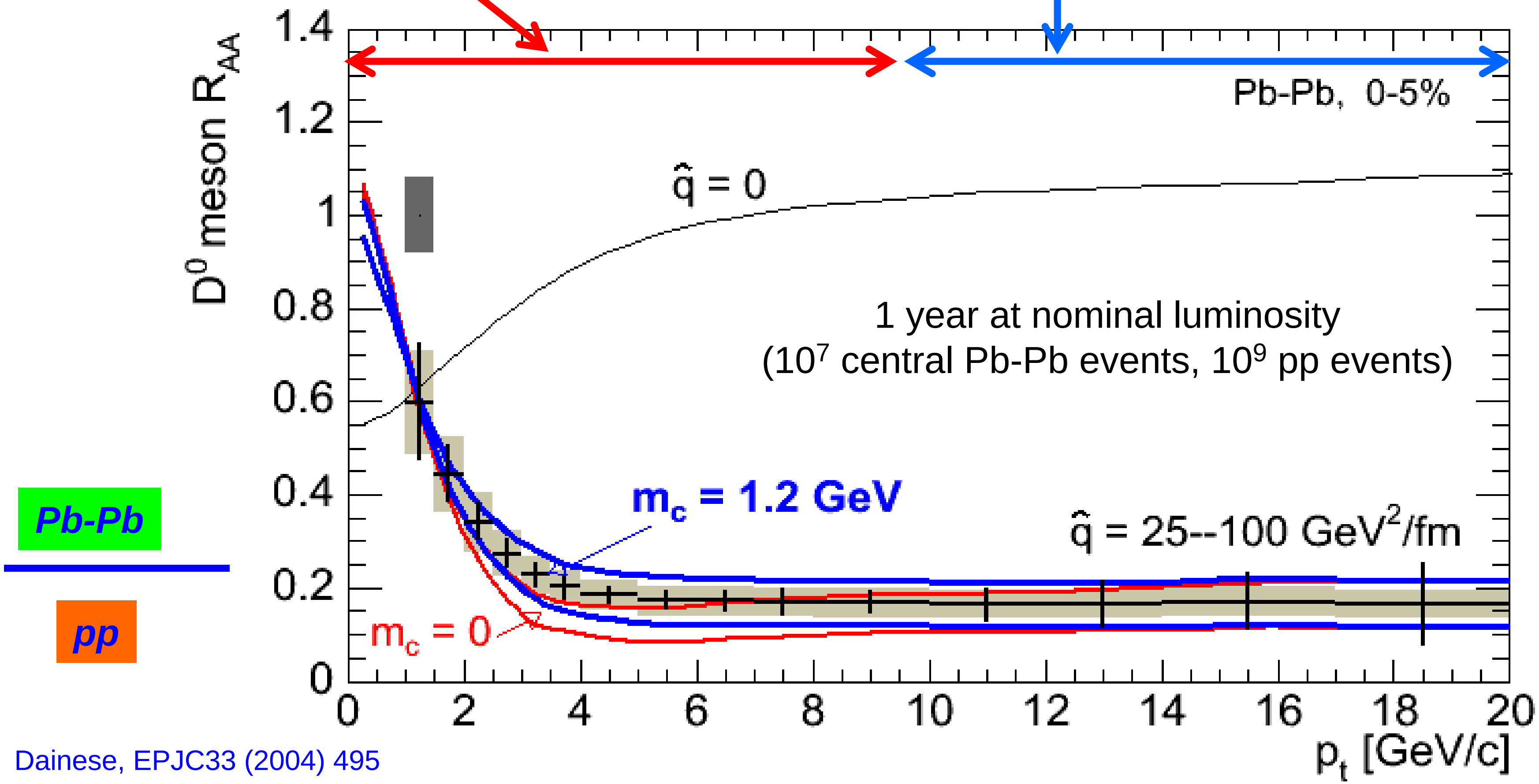
1) dominates > 12-13 GeV
2) and 3) ~ compensate
4) dominates below 12 GeV

Warning: significant non-pert. effects (e.g. reco) below 6-7 GeV

$R_{AA}(p_t)$ of D mesons in ALICE

Low p_t (< 8–10 GeV/c)
Nuclear shadowing, recombination?

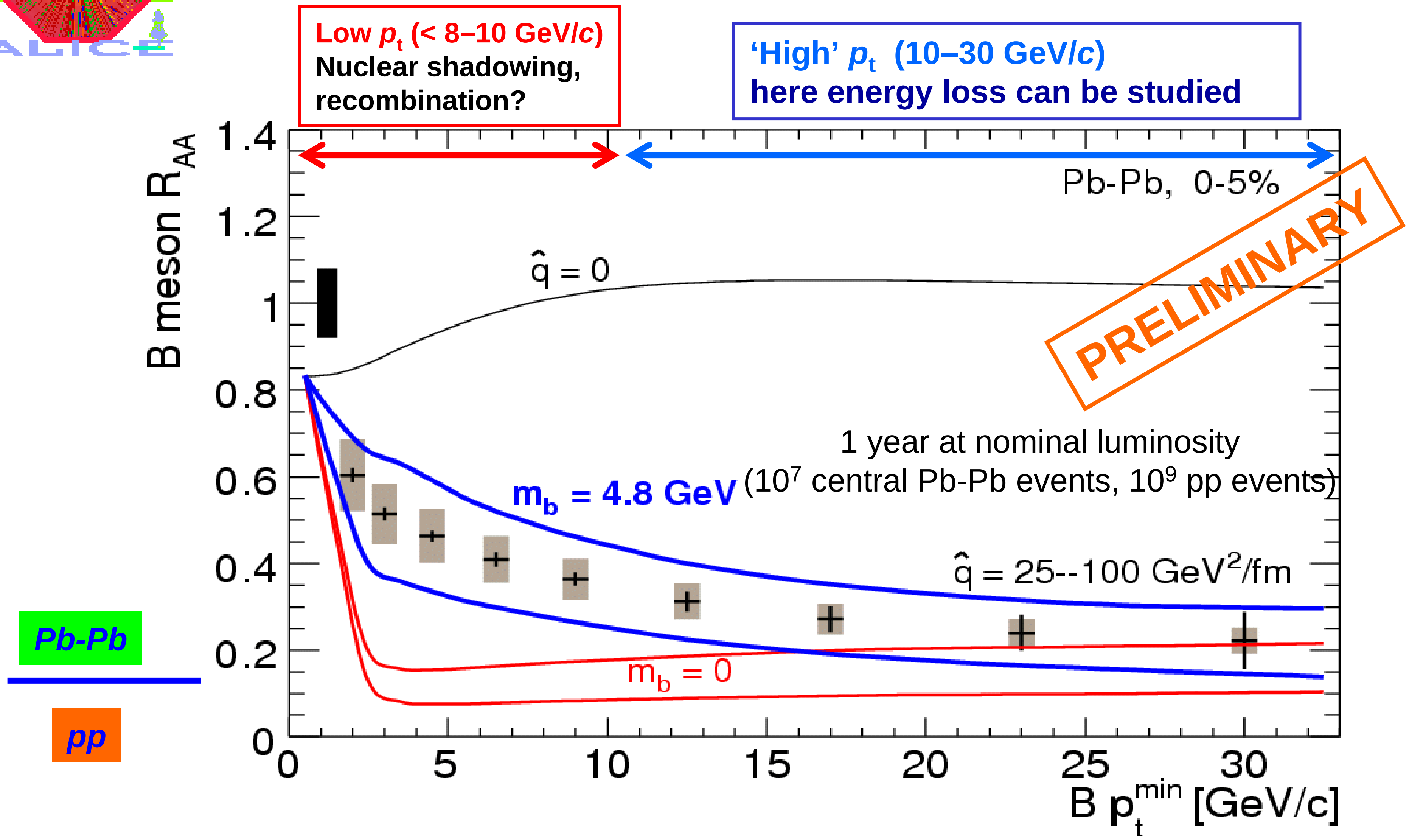
'High' p_t (10–20 GeV/c)
here energy loss can be studied (it's the only expected effect)



Dainese, EPJC33 (2004) 495

E loss calc: Armesto, Dainese, Salgado Wiedemann, PRD71 (2005) 054027

$R_{AA}(p_t^{min})$ of B mesons in ALICE



E loss calc: Armesto, Dainese, Salgado Wiedemann, PRD71 (2005) 054027