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# Cold and hot nuclear matter effects on heavy quarks

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# Contents:

## 1. Introduction:

- Characterizing the medium in HIC through hard probes.
- Collinear factorization.

## 2. Cold nuclear matter effects: initial and final state.

- Collinear factorization: nuclear pdf's.
- Other factorizations.
- Other effects?

## 3. Heavy-ion collisions:

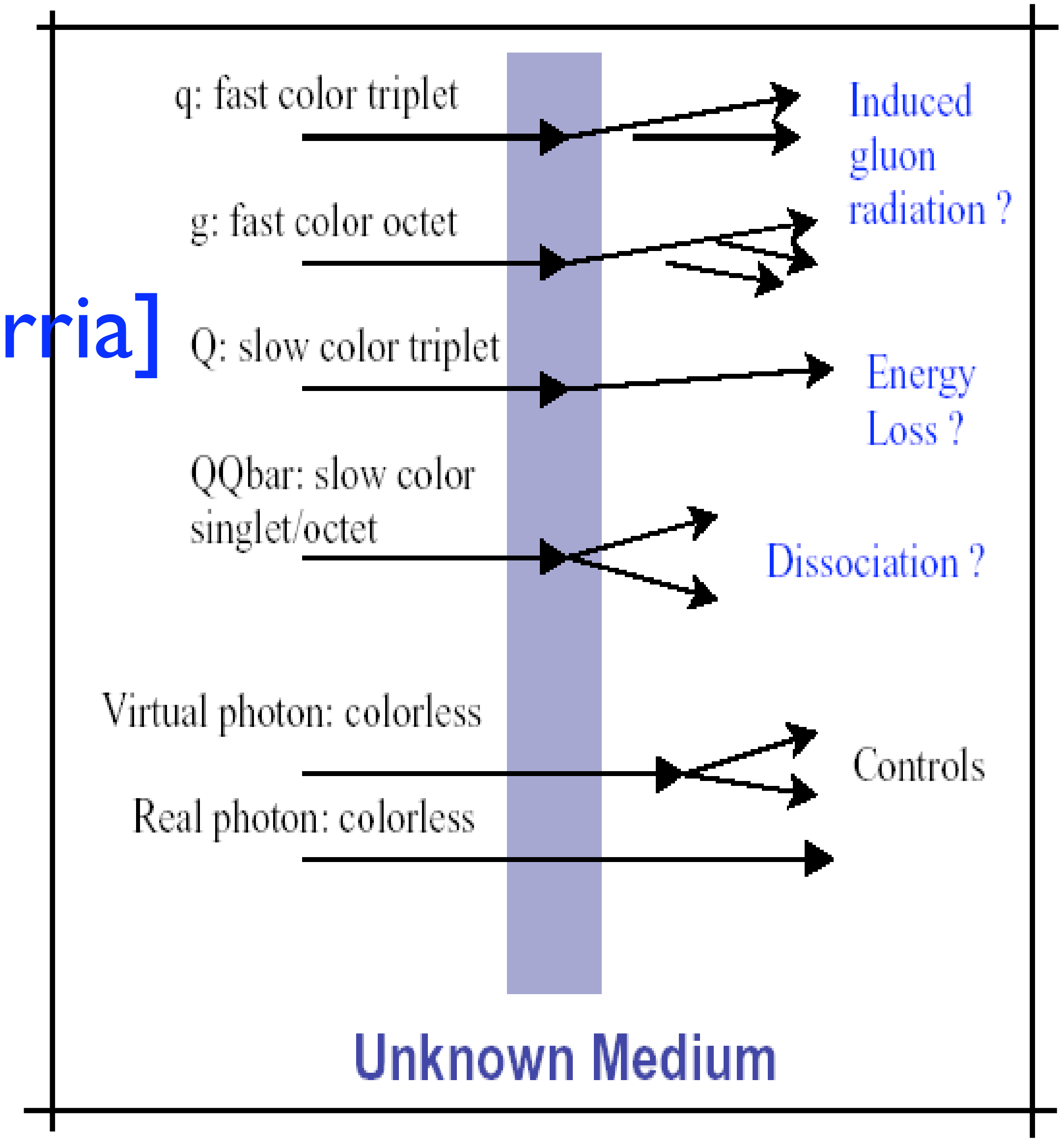
- Mechanisms for energy loss: elastic, radiative, dissociation.
- Comparison with data.

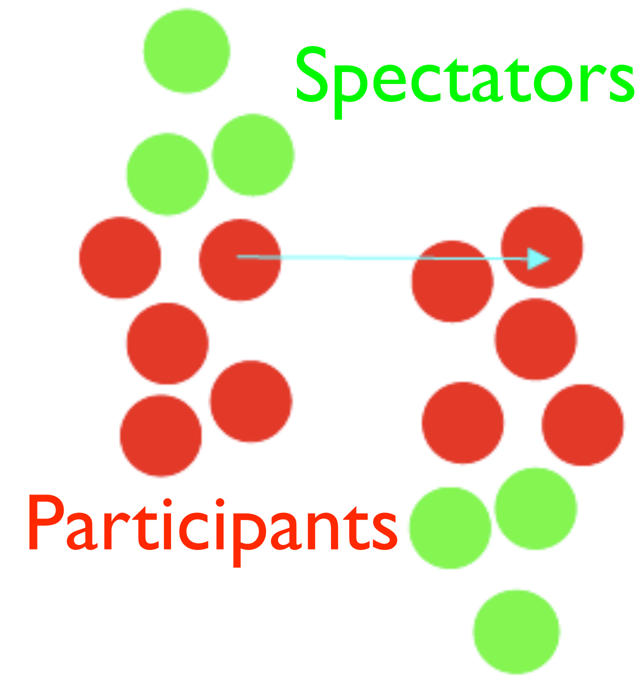
## 4. Summary.

See the talks by J. Aichelin, J. Albacete, A. Andronic, F. Arleo, M. Cacciari, P. Gossiaux, H. van Hees,...

# Characterizing the medium:

[d'Enterria]



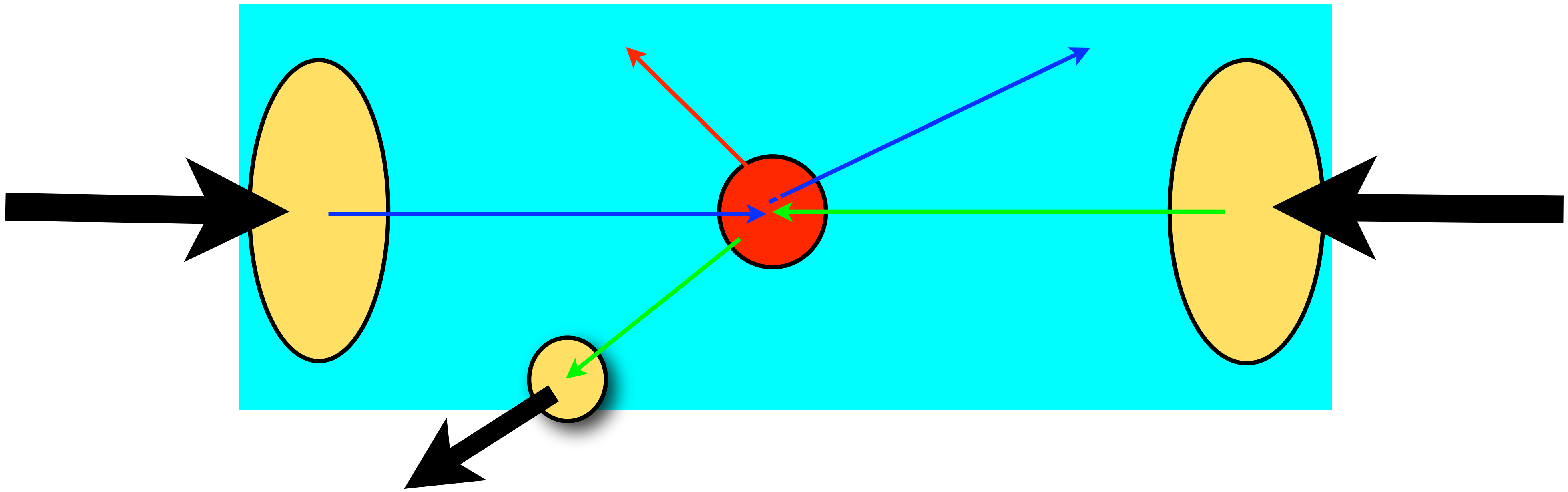

$$R^k_{AB}(y,p_T)=\frac{\frac{dN^k_{AB}}{dydp_T}}{\langle N_{coll}\rangle\frac{dN^k_{pp}}{dydp_T}}$$

• Hard probes are those whose comparison measured/expected (in perturbative QCD) characterizes the (hot) medium: suppression of quarkonium, energy loss of energetic partons. They demand:

  * Control on the denominator: pp.

  * Control on non-medium (cold) effects on the numerator: pA.

# Collinear factorization:



- Assume collinear factorization (for Q,M~$E_{cm}$>>$\Lambda_{QCD}$):

$$d\sigma[A+B\to h+X] \propto \int [dx] f_{i/A}(x_i) \otimes f_{j/B}(x_j) \otimes d\hat{\sigma}[i+j\to k+X](sx_ix_j) \otimes D[k\to h+X](z)$$

cold nuclear matter effects: nPDFs, eloss

cold and hot nuclear matter effects

- pA: check factorization and constrain cold nuclear matter effects: higher-twist terms (Qiu, hep-ph/0305161), different factorization (if any).
- AB: (check factorization and) characterize the medium.

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# npdf's: global fits (I):

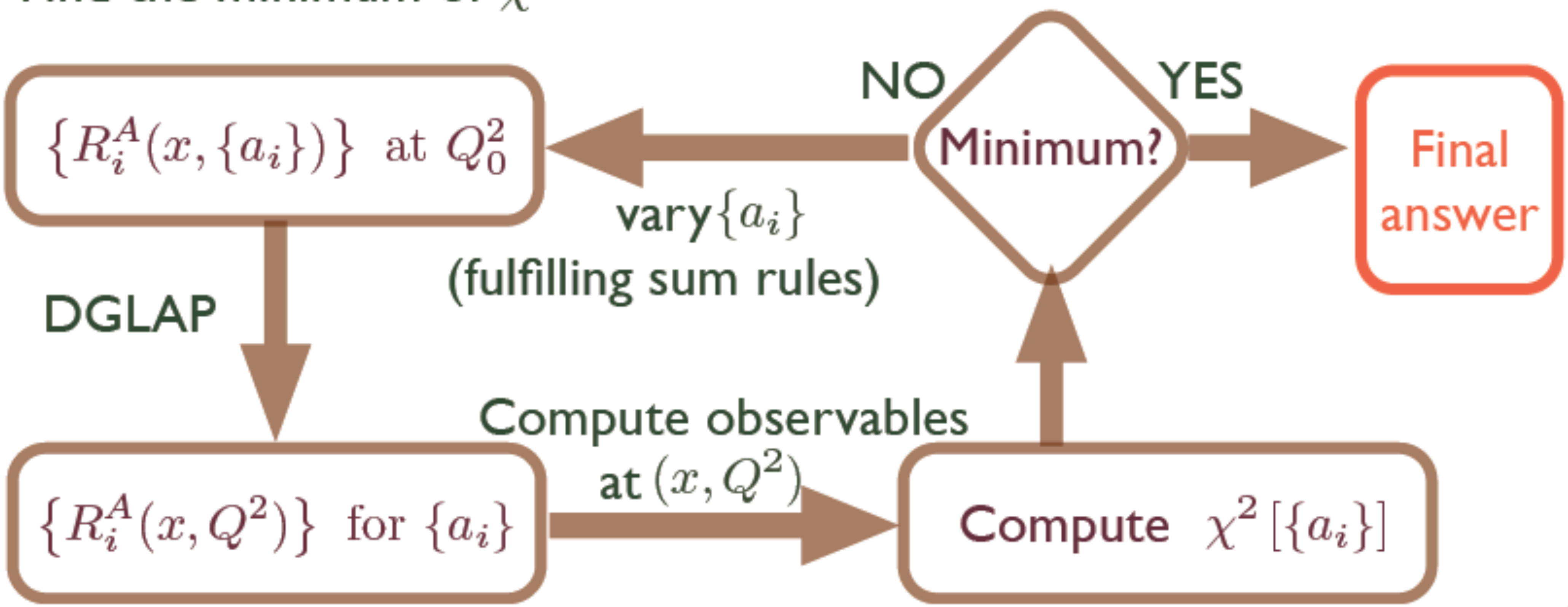
→ Data in EPS09 ($Q^2$, $M^2$>1.69 GeV$^2$; $p_T$>1.7 GeV): 92 from DY (E-772 and 886), 20 from $\pi^0$ ($\eta$=0, PHENIX), rest up to 929 from DIS (E-135, EMC, NMC). ν data under discussion (EPS, CTEQ).

- ⇛ Cross sections computed in collinear factorization
- ⇛ Define

$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

[Salgado]

- ⇛ Using a known set for free protons (CTEQ, MRST....)
- ⇛ and DGLAP evolution of the nuclear and free proton PDFs
- ⇛ Find the minimum of $\chi^2$



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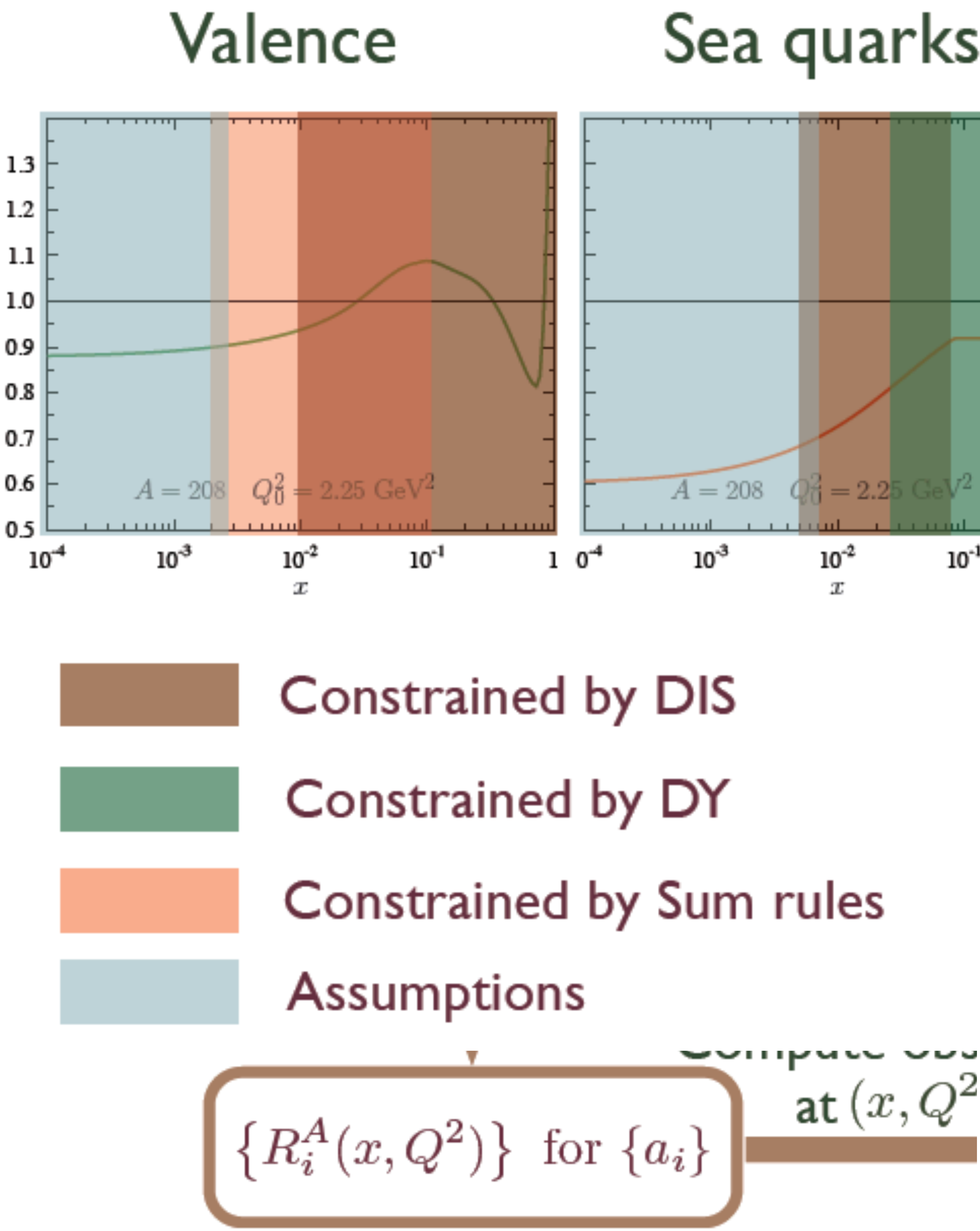


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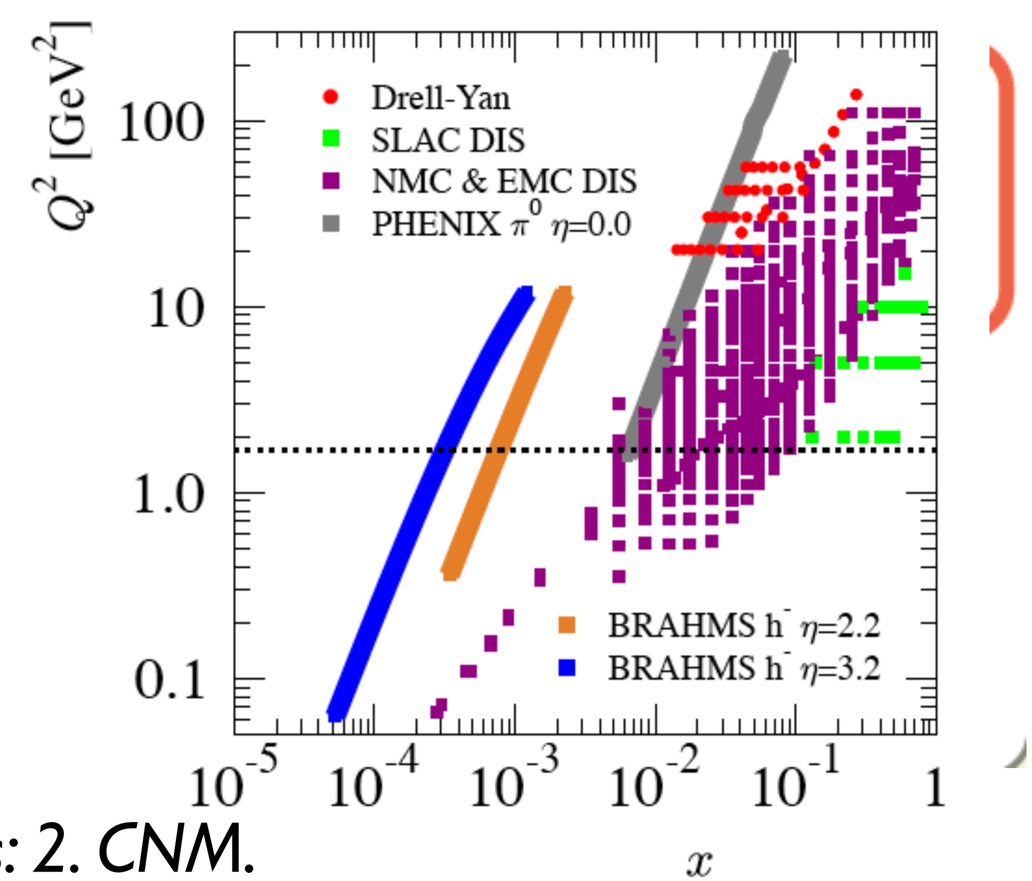

# npdf's: global fits (II):

→ Eskola '94: DGLAP for nuclei.

→ EKS98: first global analysis, LO, DIS+DY.

→ Others non global analysis: Indumathi-Zhu, FGS.

→ nDS (2003): 1st NLO, DIS.

→ HKM, HKN (2001-07): NLO, $\chi^2$ minimization, DIS+DY.

→ EKPS07: LO, error analysis, 1st look at RHIC data.

→ EPS08: LO, BRAHMS forward data (factorization check).

→ EPS09: NLO, $\chi^2$ minimization, error analysis, compatible with $\nu$ data.

→ CTEQ: NLO, $\chi^2$ minimization, $\nu$ data?

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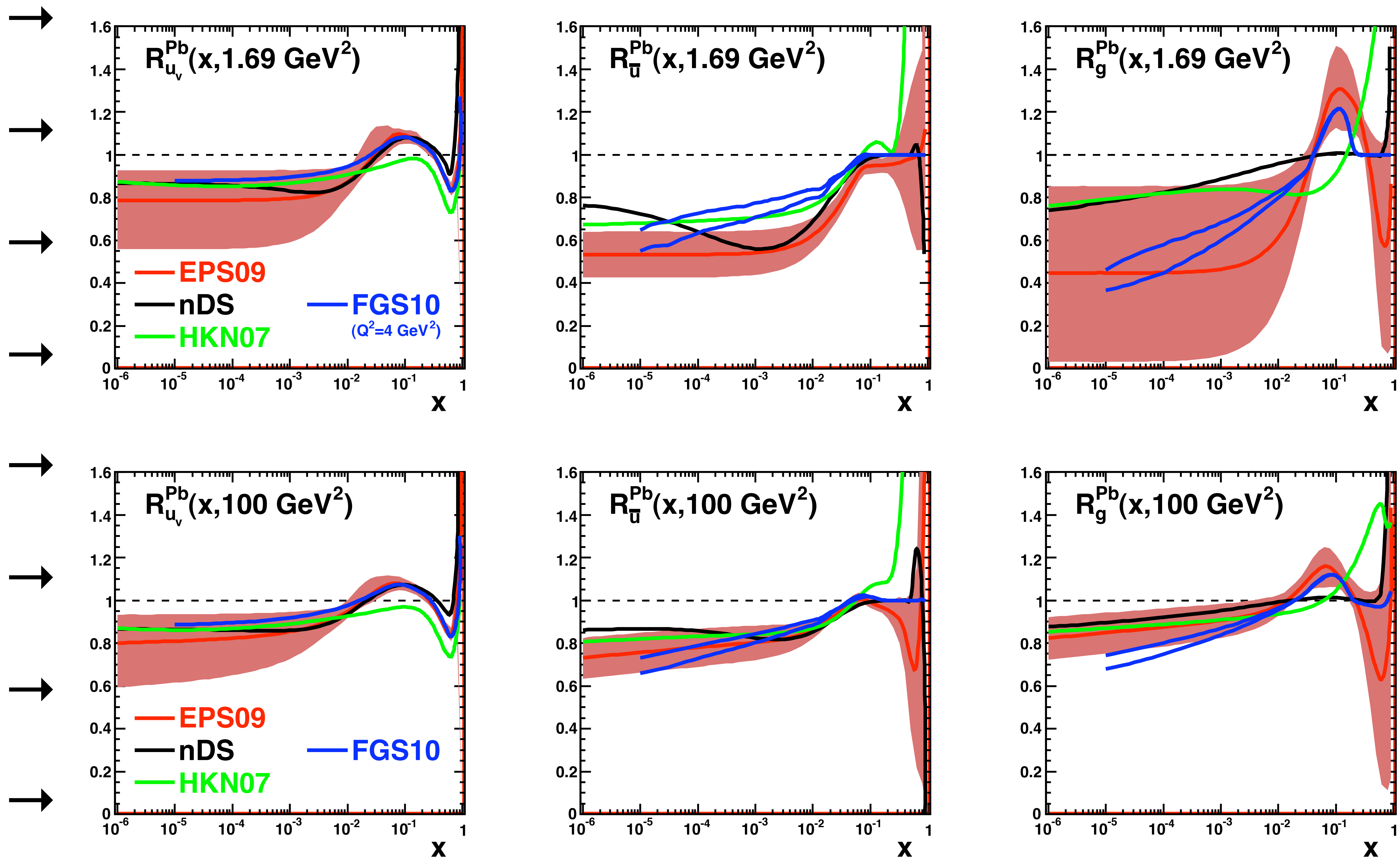


→ CTEQ: NLO, $\chi^2$ minimization, $\nu$ data?

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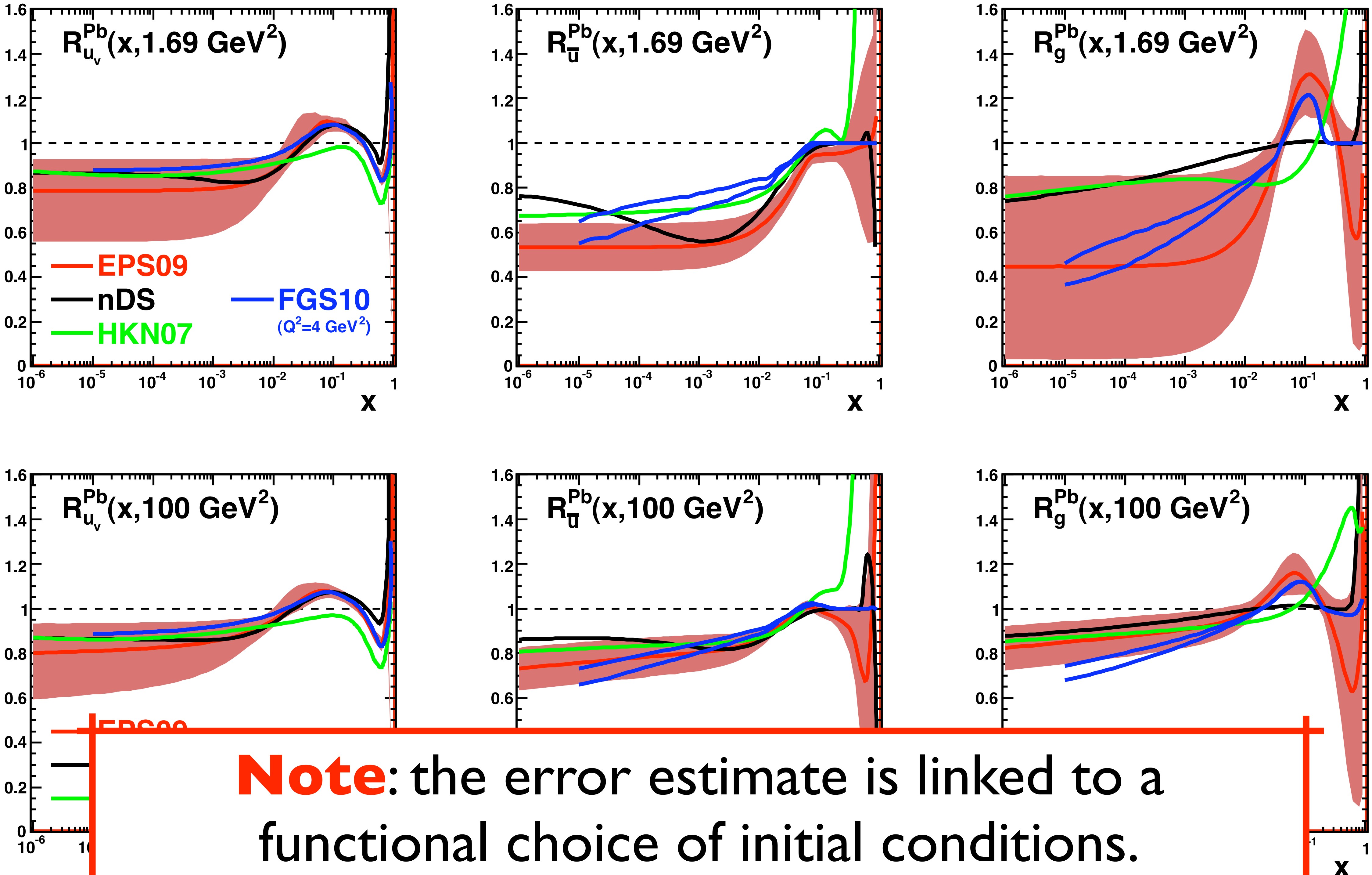
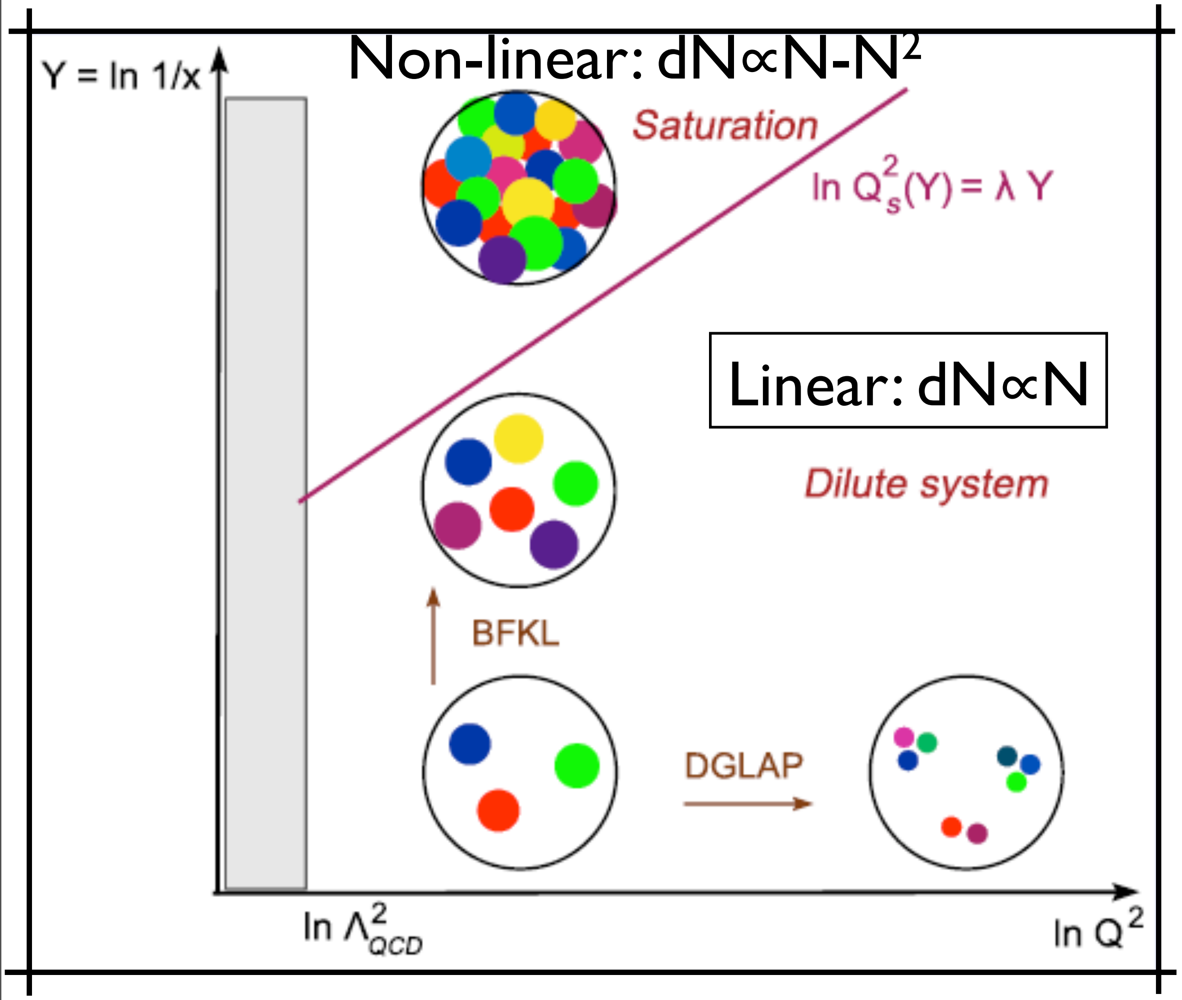



**Note**: the error estimate is linked to a functional choice of initial conditions.

Visit http://lappweb.in2p3.fr/lapth/npdfgenerator/!!

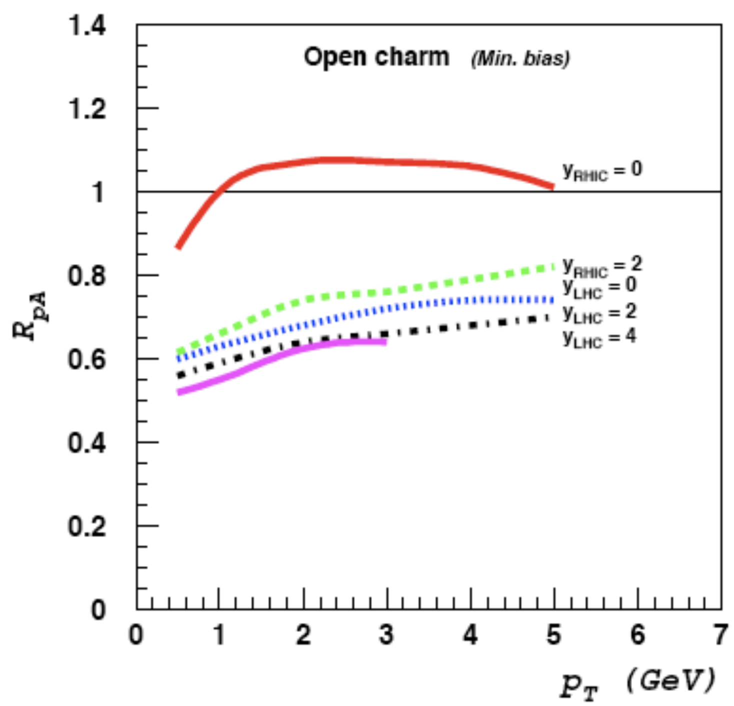
# Other factorizations:

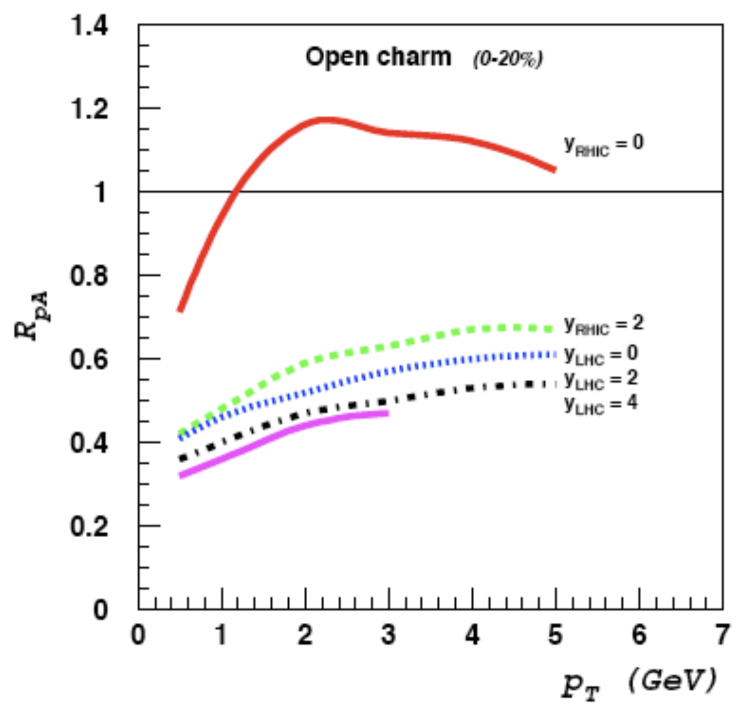



- Heavy quark production is a place to look for high-density effects: factorization may be not collinear (Gelis et al '06), and check saturation models ($Q_s \sim m_c$):

enhanced production at $\eta \sim 0$

(wrt collinear) and increasing suppression with evolution.



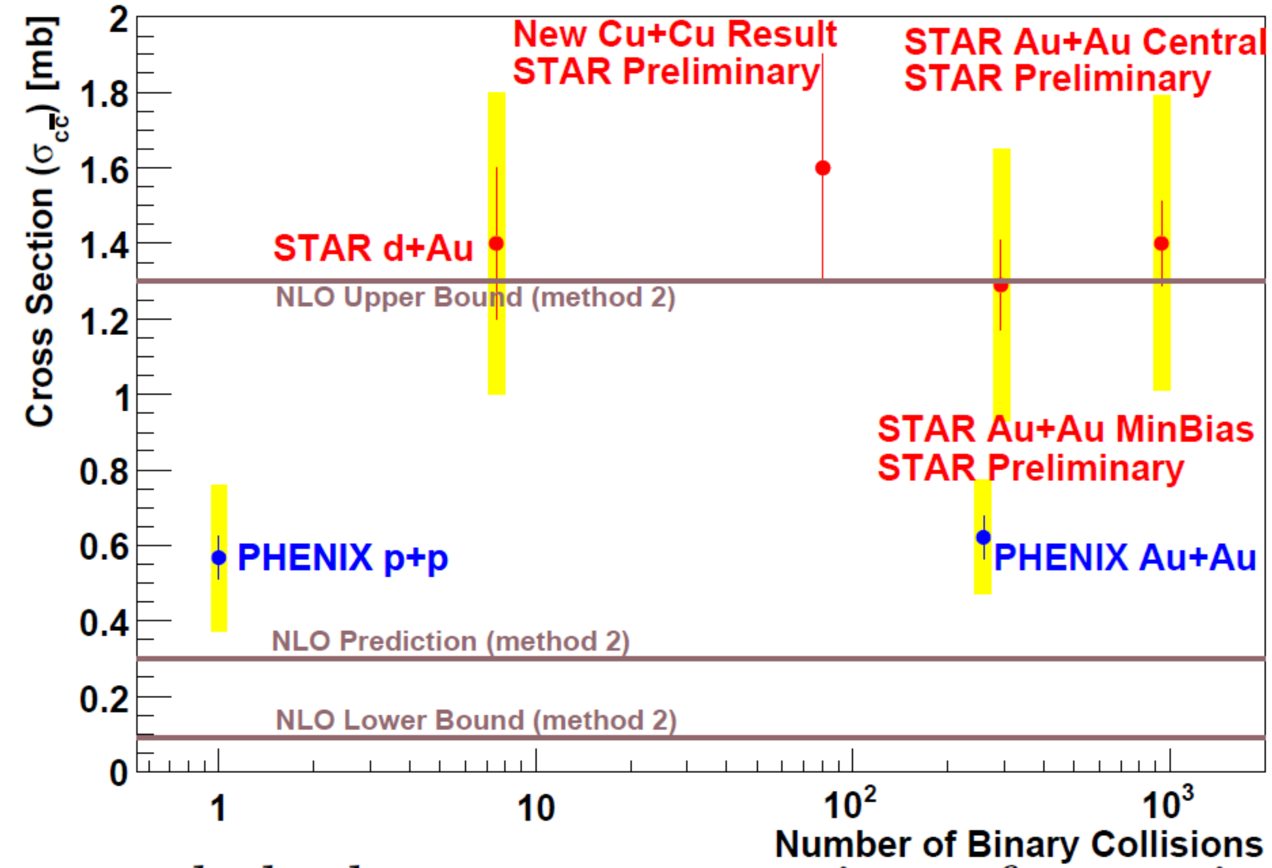

Tuchin '07

# Other effects?

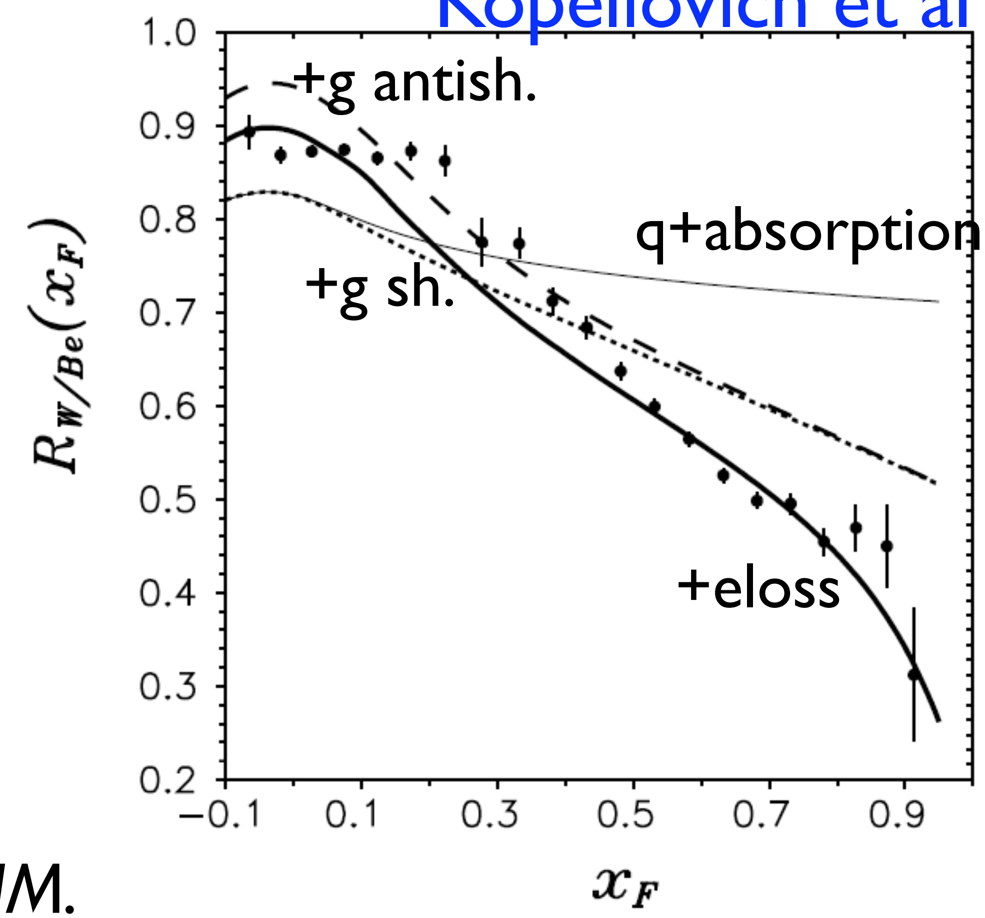
- Rough scaling with the number of binary collisions (R=1) ⇒

nuclear effects on charm at RHIC look < 20 %.

- Pre-RHIC expectations (Boreskov et al '93, Braun et al '97, Kopeliovich et al '01) pointed to larger absorption for QQbar at RHIC than at SPS ☹ and similar nuclear effects for QQbar and open Q production.
- Coherent production, eloss,... also for open Q: ~~factorization~~.
- But indications point to a dominant role of npdf's at midrapidity at RHIC (and LHC).

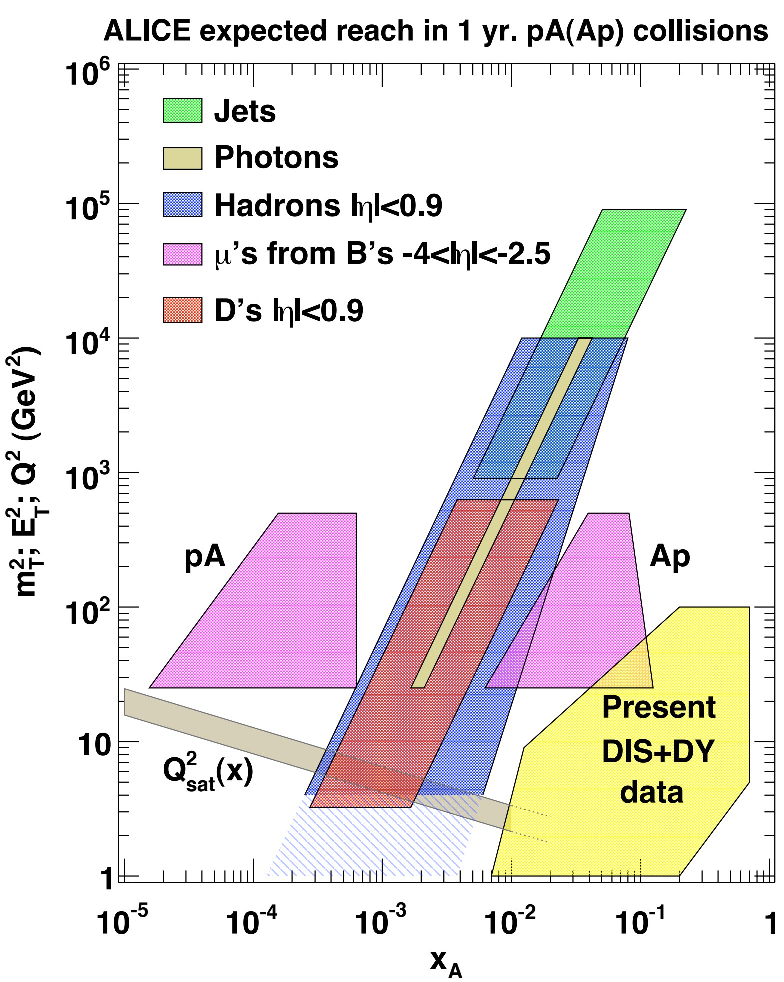


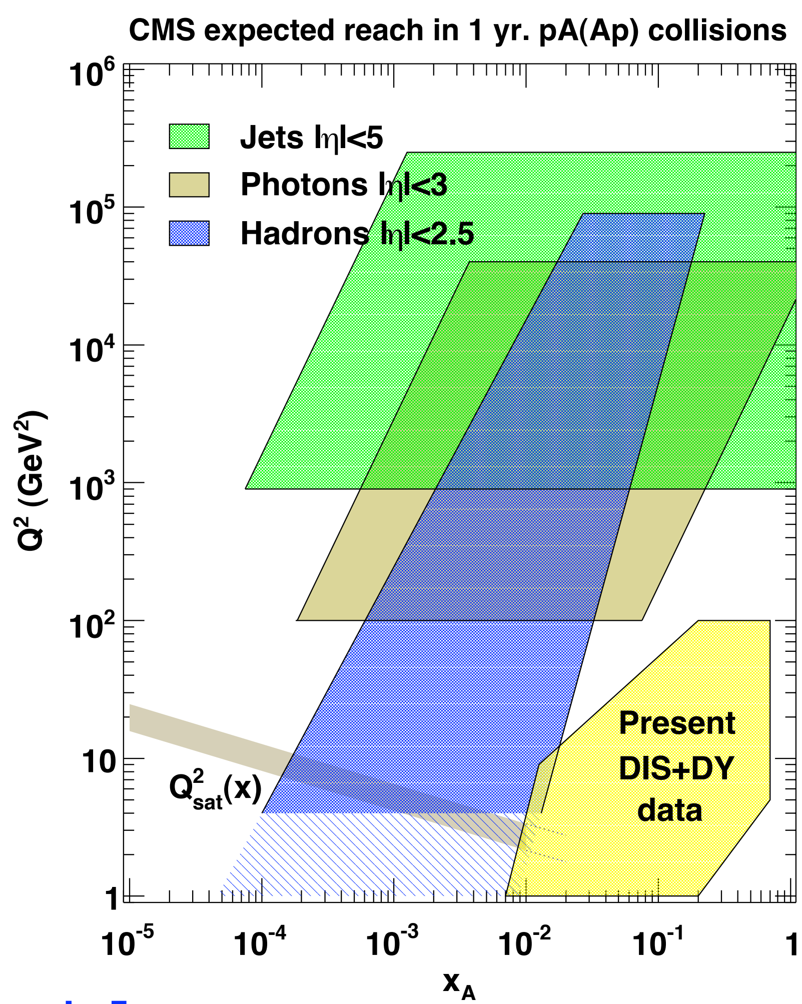

Kopeliovich et al '01



# What to do?

- Information about npdf's and the validity of collinear factorization for heavy quark production on nuclei will come from pA@LHC (some 5 years) and future eA colliders (EIC, LHeC, some 10 years).

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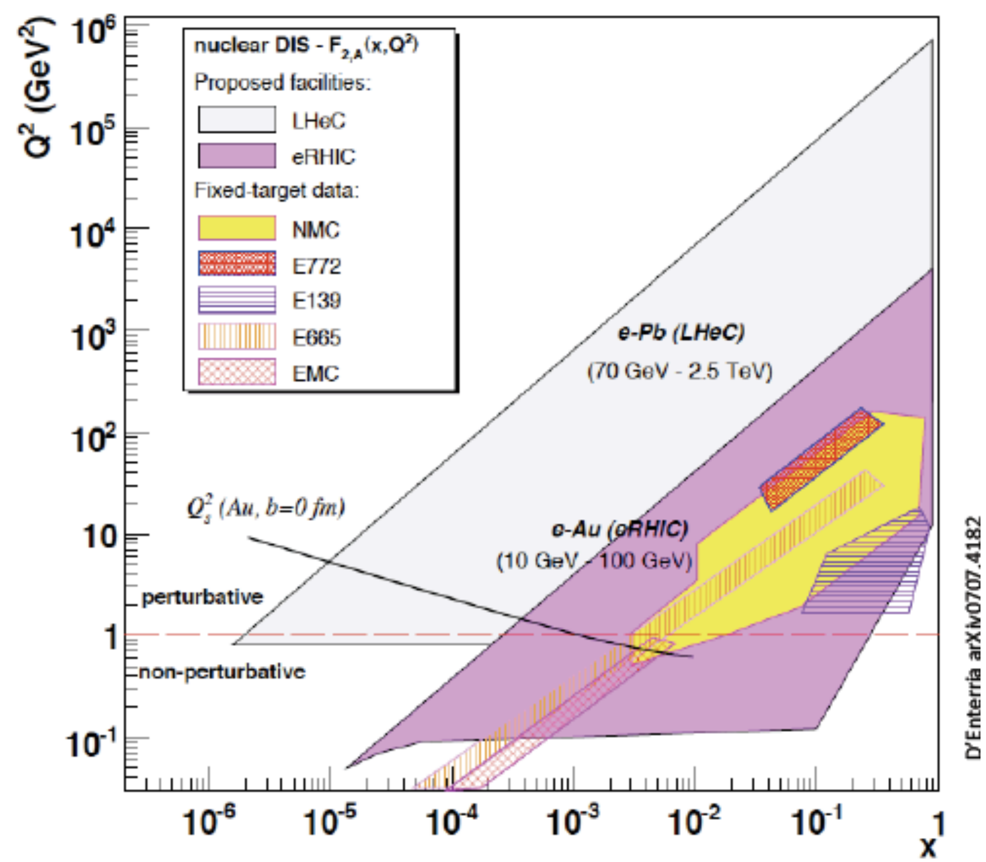


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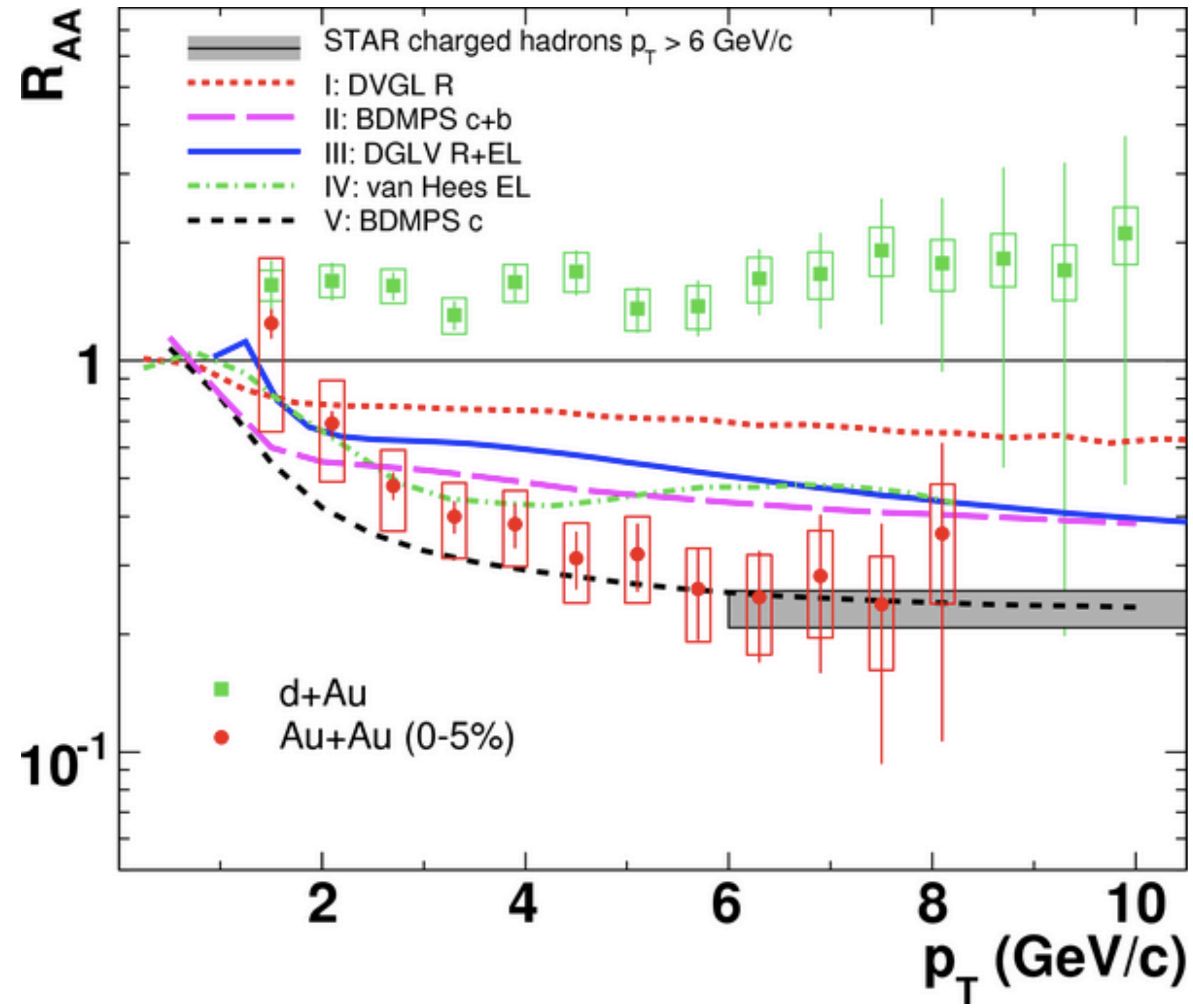
# Mechanisms for eloss:

- In AuAu collisions at RHIC, light hadrons are suppressed a factor ~ 5.

- In AuAu collisions at RHIC, non-photonic electrons appear as suppressed as light hadrons.

- Three main explanations (not mutually exclusive):



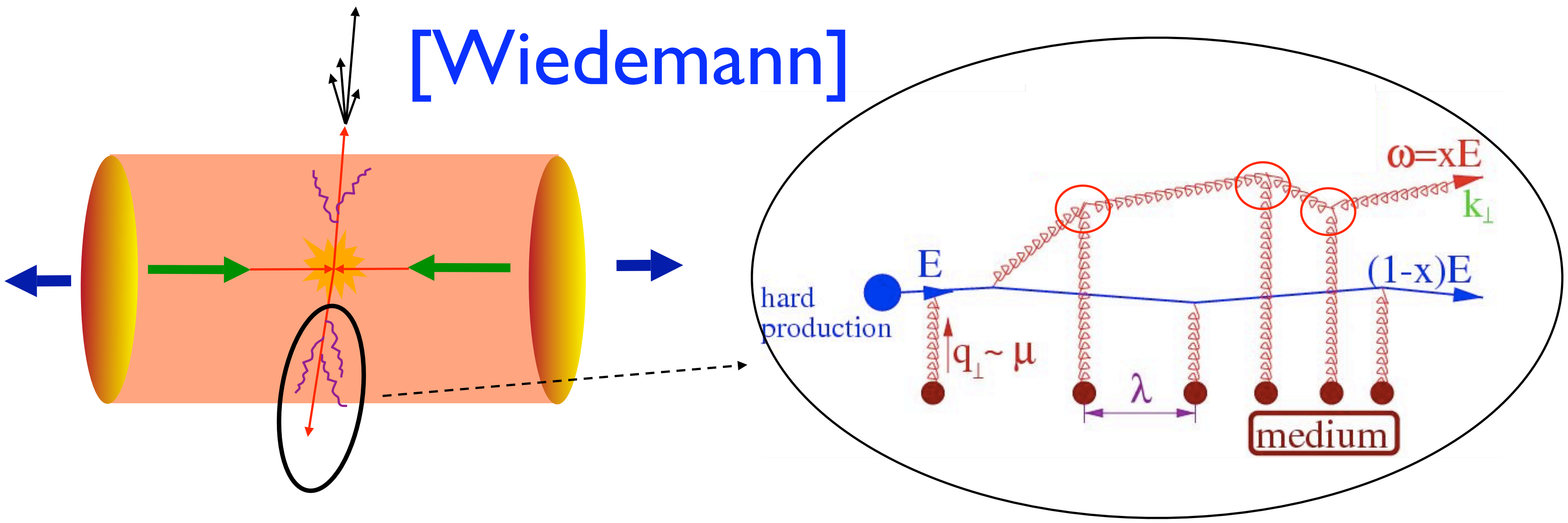

* Radiative energy loss: $E_Q > E_{crit}$: hadronization outside.

* Collisional energy loss: $E_{crit} > E_Q > m_Q L / t_{hadr}$: hadronization outside. [Need not be the case for B's up to large $E_Q$.]

* Meson dissociation/eloss: hadronization inside.

* Others: strong color fields (Topor Pop et al '08, Bautista et al '10),...

# Radiative eloss:




- Medium-modified gluon radiation through interference of production and rescattering.

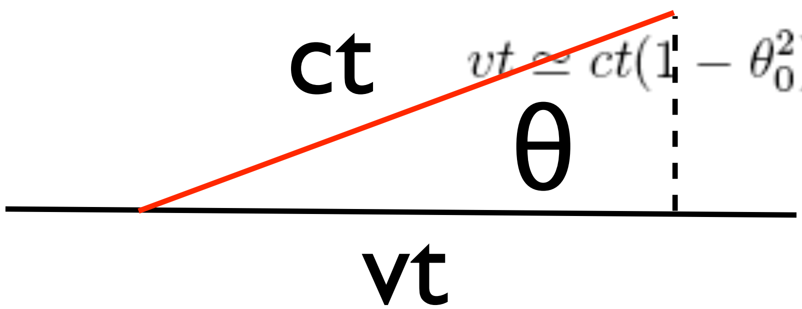
- Two parameters define the medium: density times scattering strength, and length (geometry, dynamical expansion,...). Similarly for other mechanisms.

- Different realizations (DGLV, AMS, AMY, GMW) within a high energy approximation: static or thermal medium, treatment of interference, re-summation of diagrams in different ways.

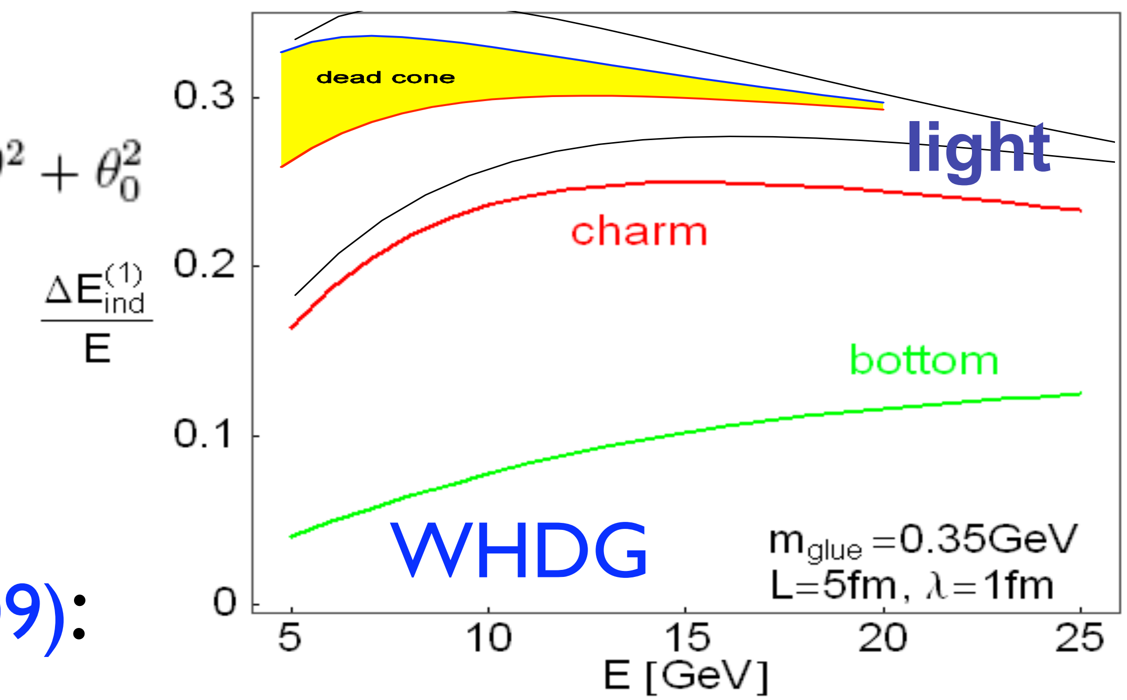
- Extensive comparisons under way (TECHQM), Monte Carlo realizations to go beyond HE approx., correlations,...

# Mass hierarchy:

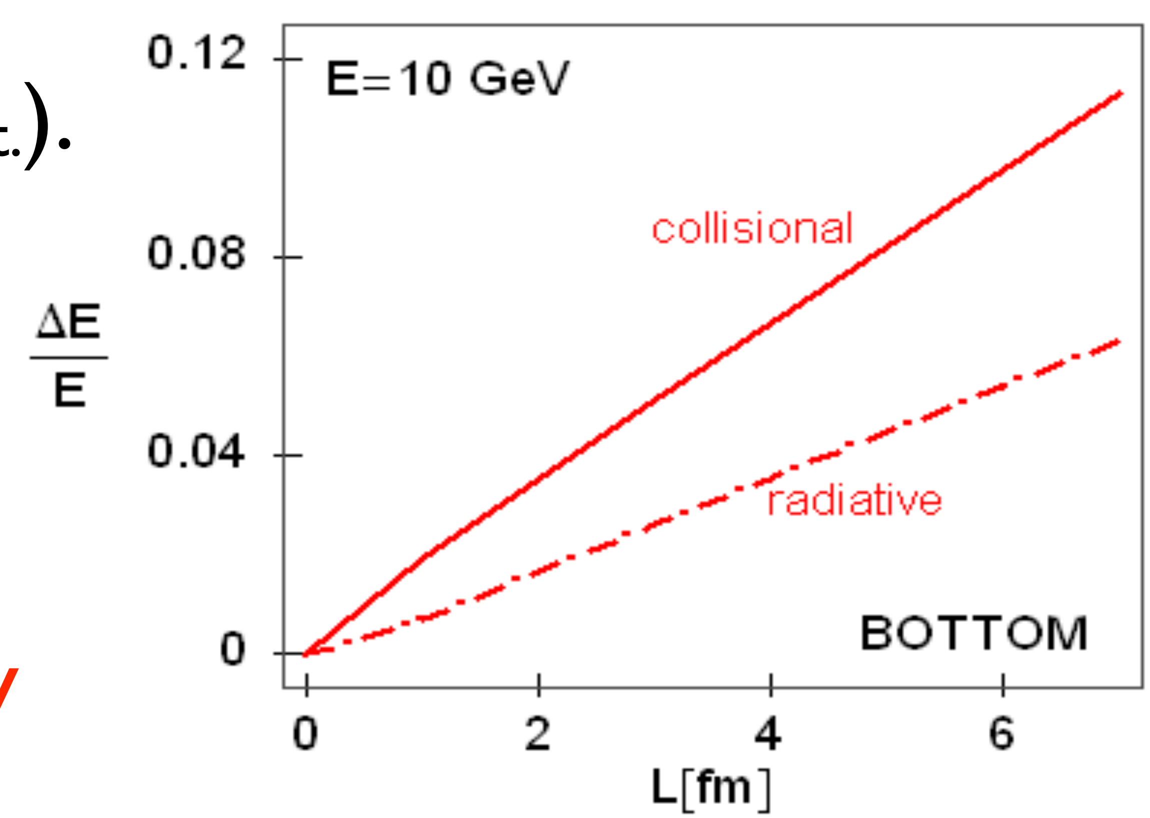
- Radiative eloss: ΔE(g)>ΔE(q)>ΔE(Q), dead cone effect (Dokshitzer-Kharzeev ’01, AMS, DGLV, GMW ‘03). The mass effect is reduced in a thermal medium (Djordjevic ‘08).




$$vt \simeq ct(1-\theta_0^2) \Rightarrow \theta_0^2 = m^2/E^2, \quad \theta^2 \to \theta^2+\theta_0^2$$




- Elastic eloss (Gyulassy-Braaten-Thoma ’90, Mustafa ’05, WHDG ’06, Gossiaxu et al ‘09): relatively more important for heavy (depends on the relation $m_Q/m_{scat.\,cent.}$).

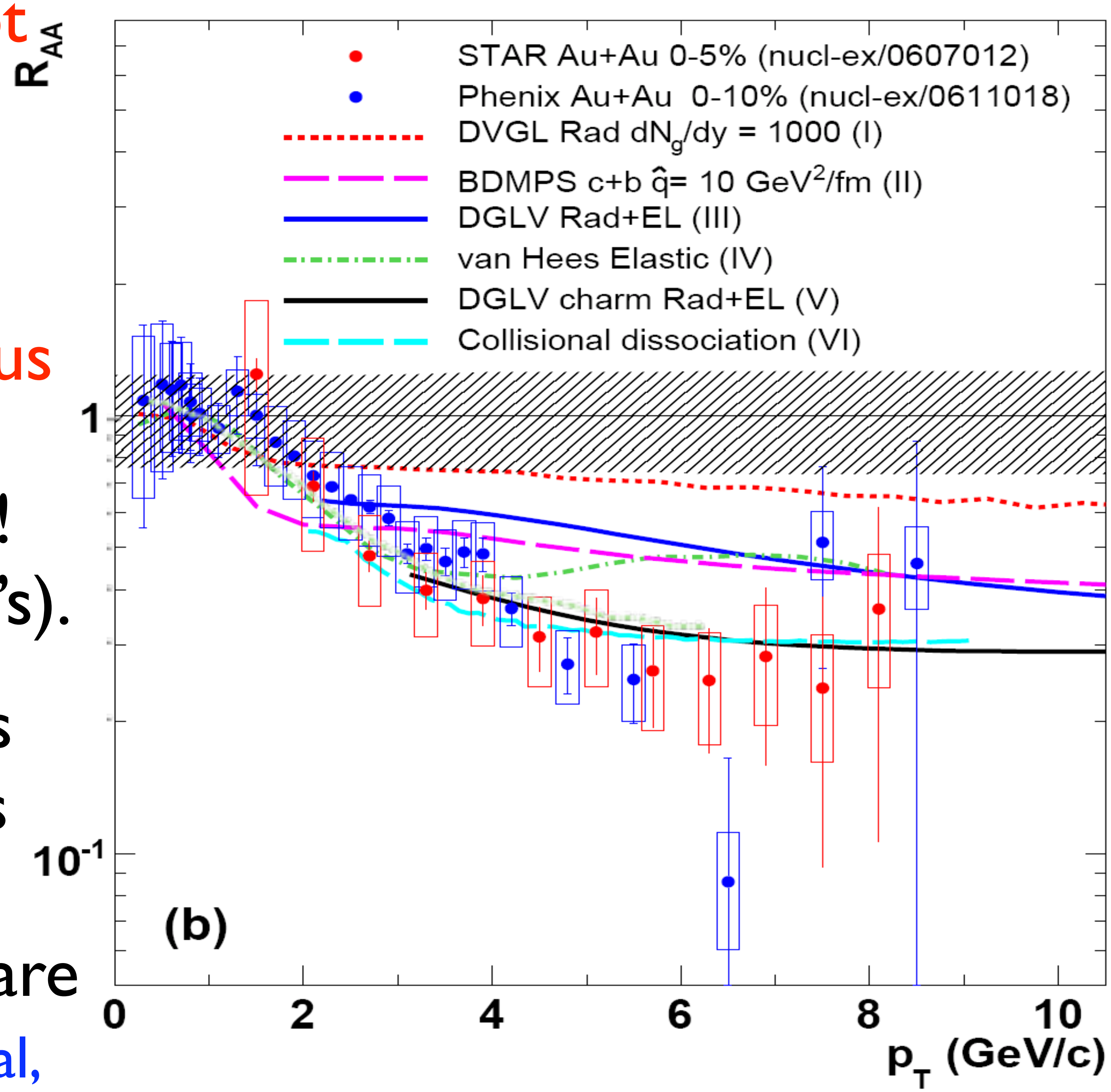



- Meson eloss/dissociation (Adil-Vitev ‘06): more (only) important for heavy.

- Key question: is the medium weakly or strongly coupled (AdS/CFT)?

# Comparison with data (I):

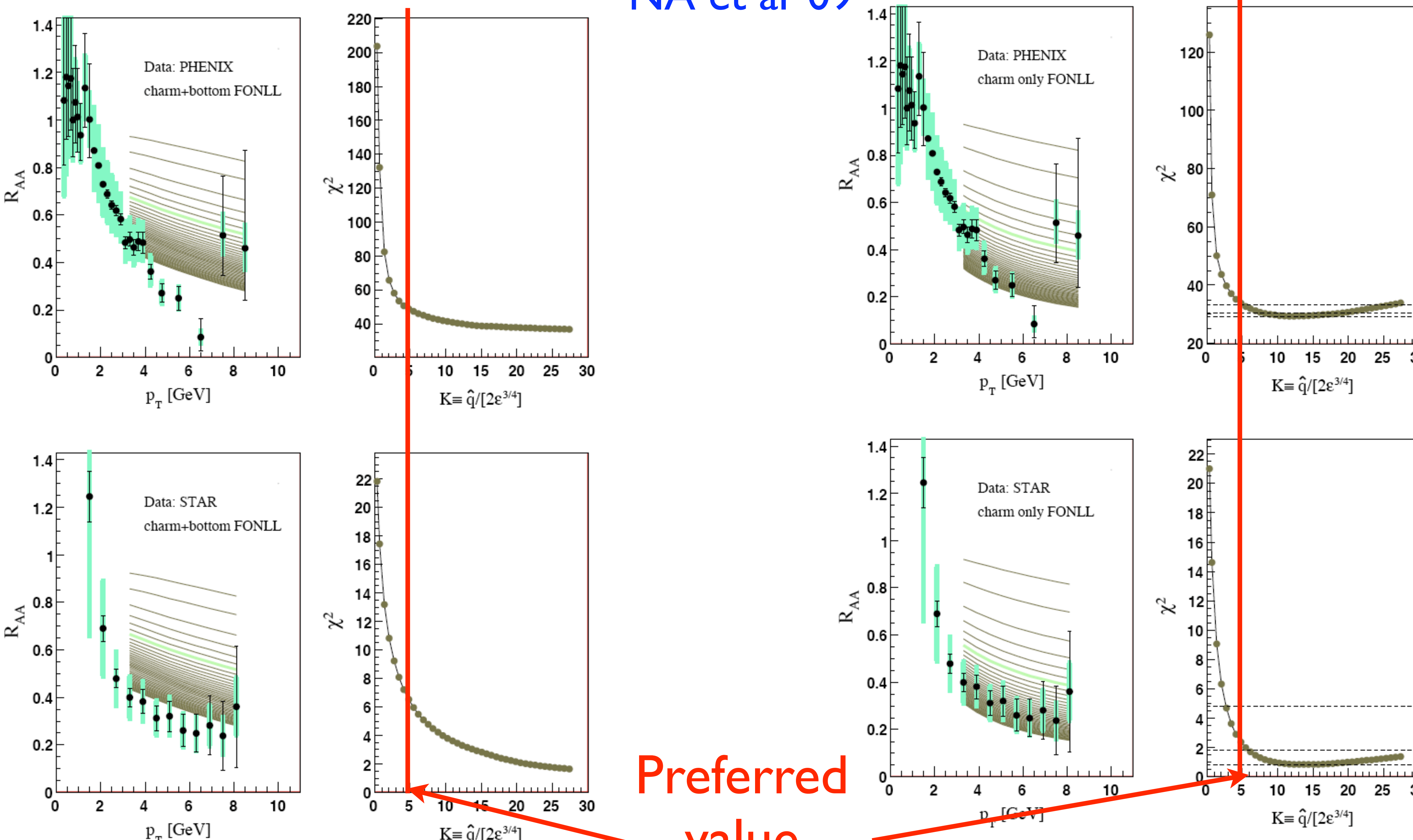
- Radiative eloss tends to overestimate the data, except for pure c composition.
- Elastic+radiative has problems, too.
- Collisional dissociation (plus radiative) looks OK: D's and B's equally suppressed. Fast!!! hadronization (~0.1 fm for B's).




- Note: formulation in terms of transport equations exists for elastic and radiative, the question is whether the σ's are perturbative or non (Rapp et al, Das et al, Greiner et al,...).

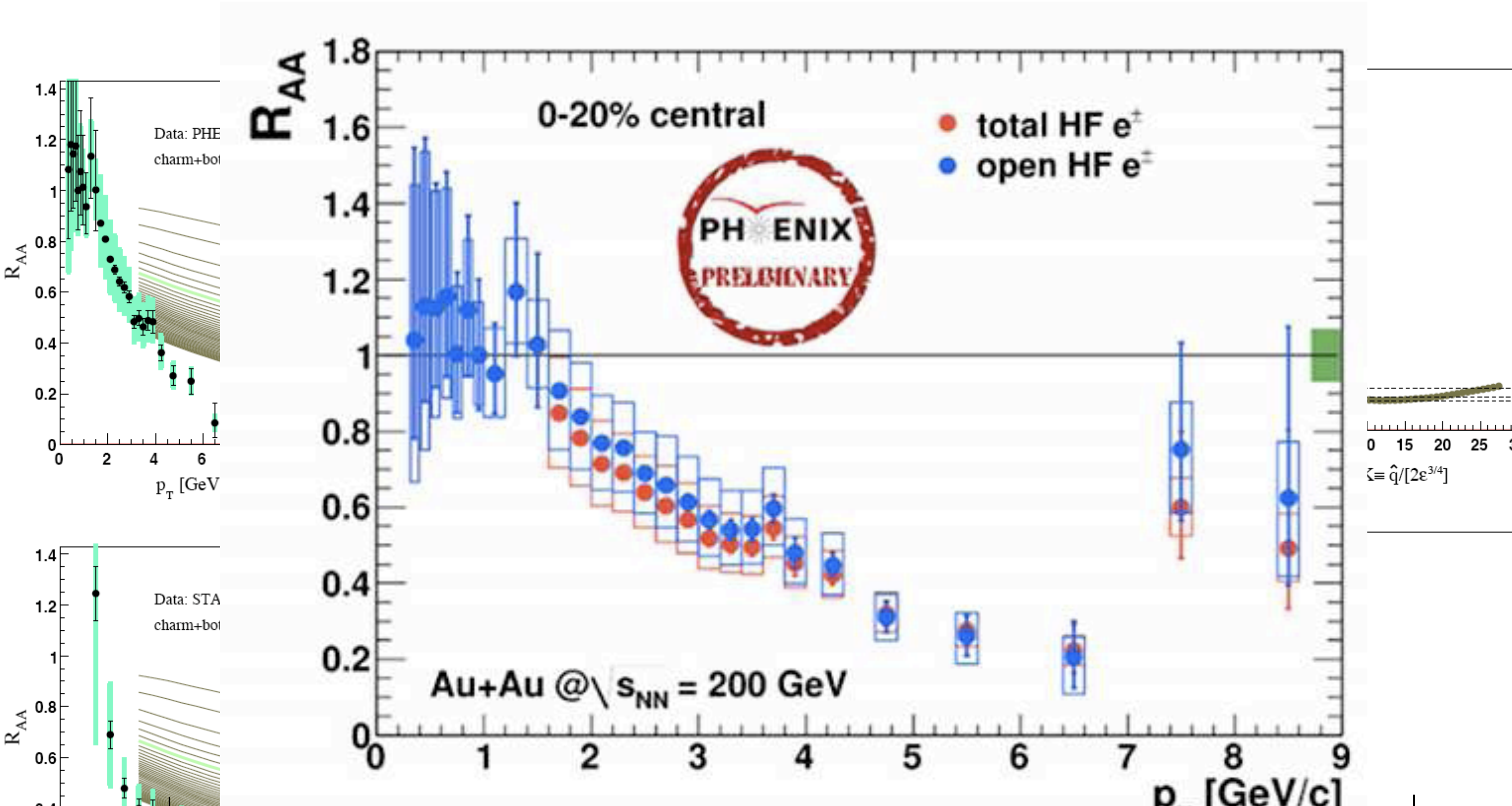
# Comparison with data (II):

NA et al '09



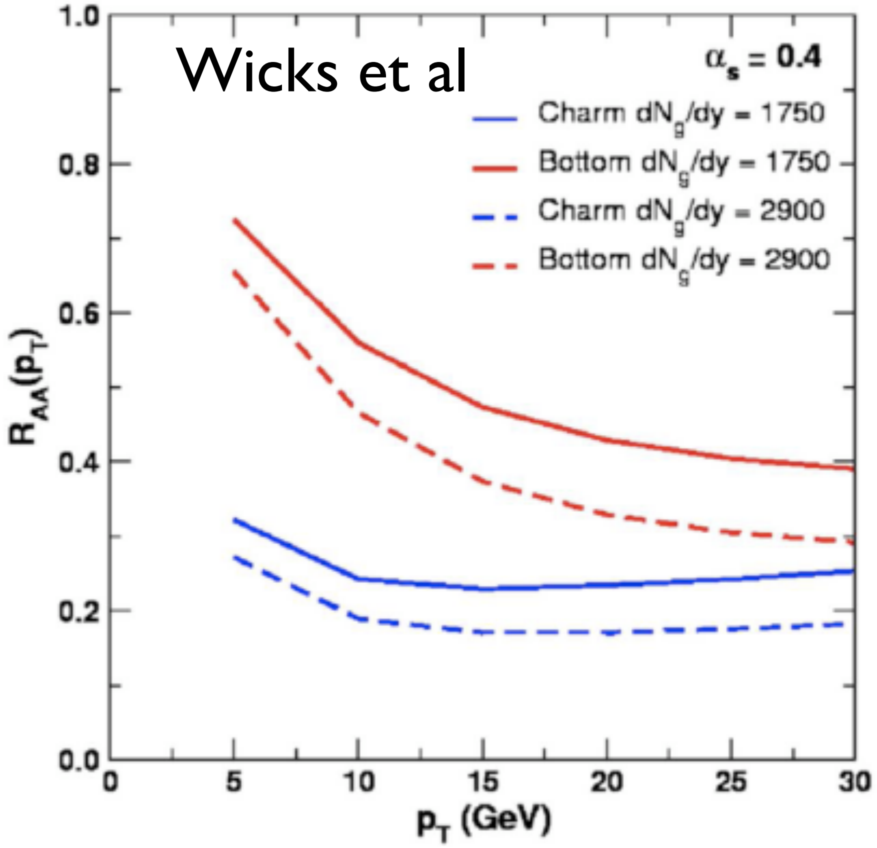

Preferred value for light

# Comparison with data (II):

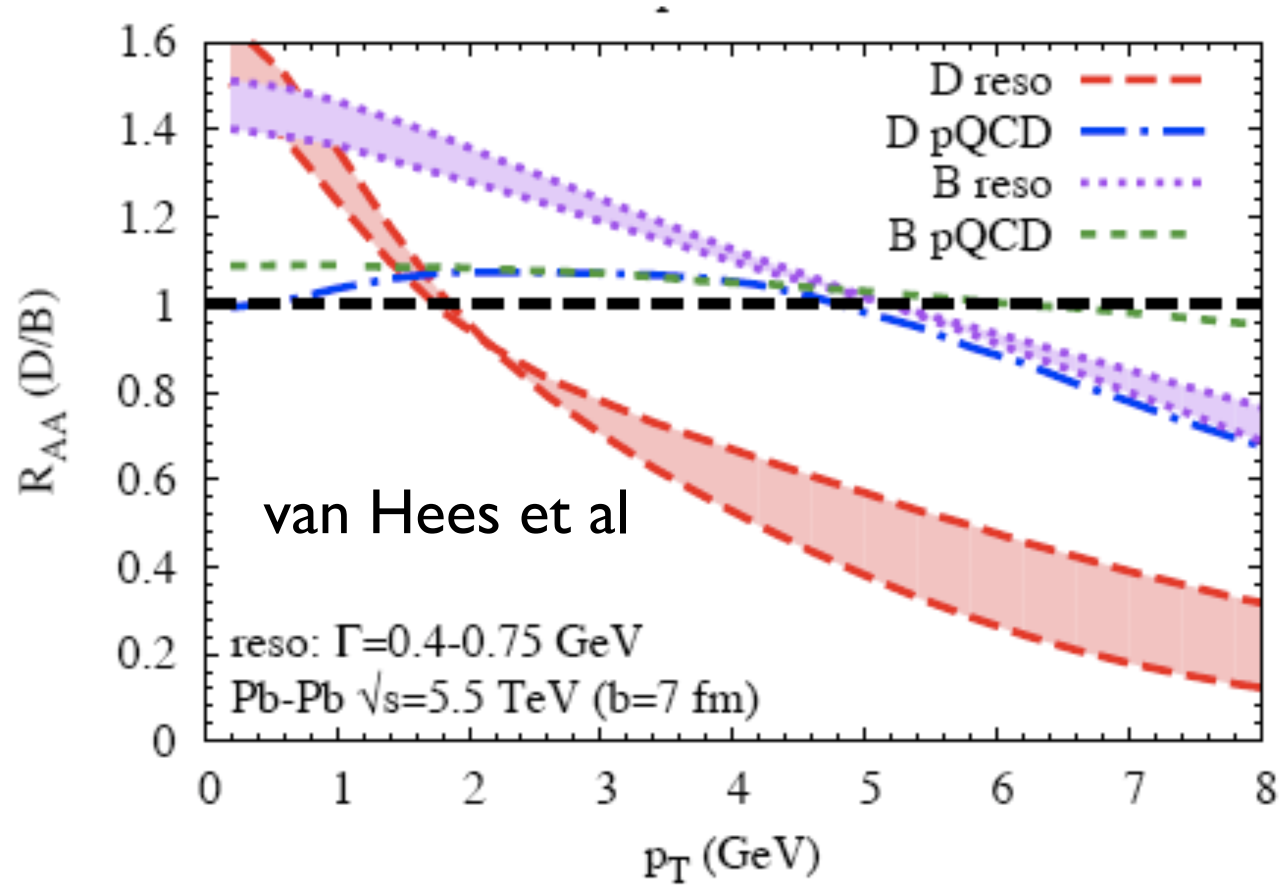


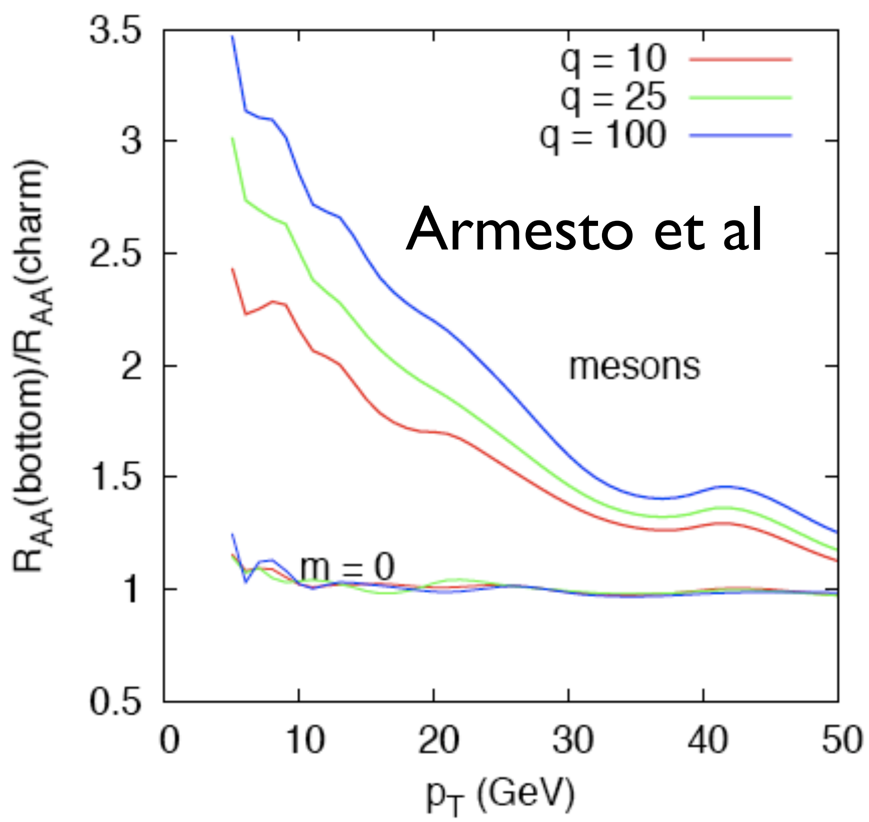

**Note**: no smooth model can explain this; even a small contamination (DY, baryons,... - NA et al '05, Martínez et al '07) may affect the ratio sizeably.

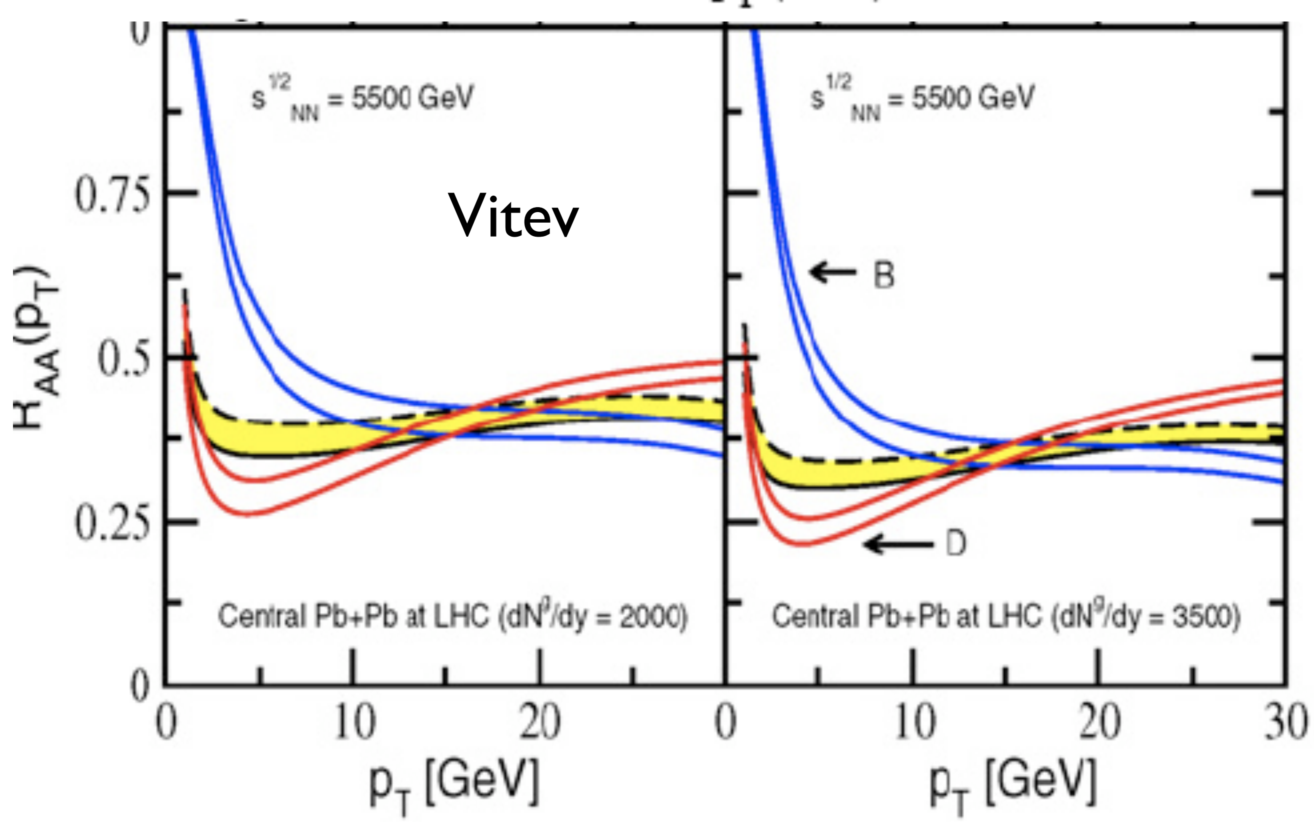
# Predictions for the LHC (I):




JPB35 (2008) 054001; NA '09



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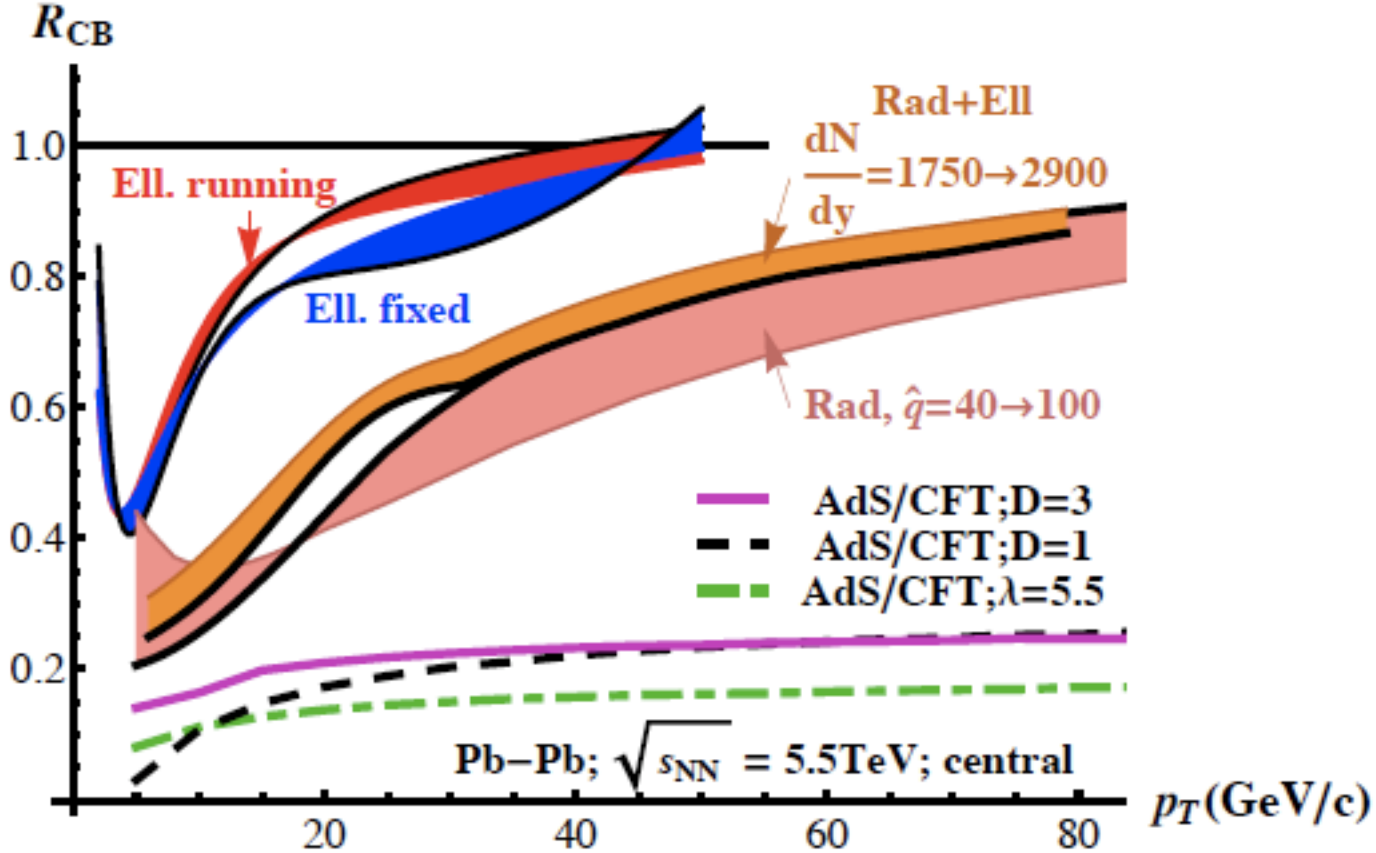
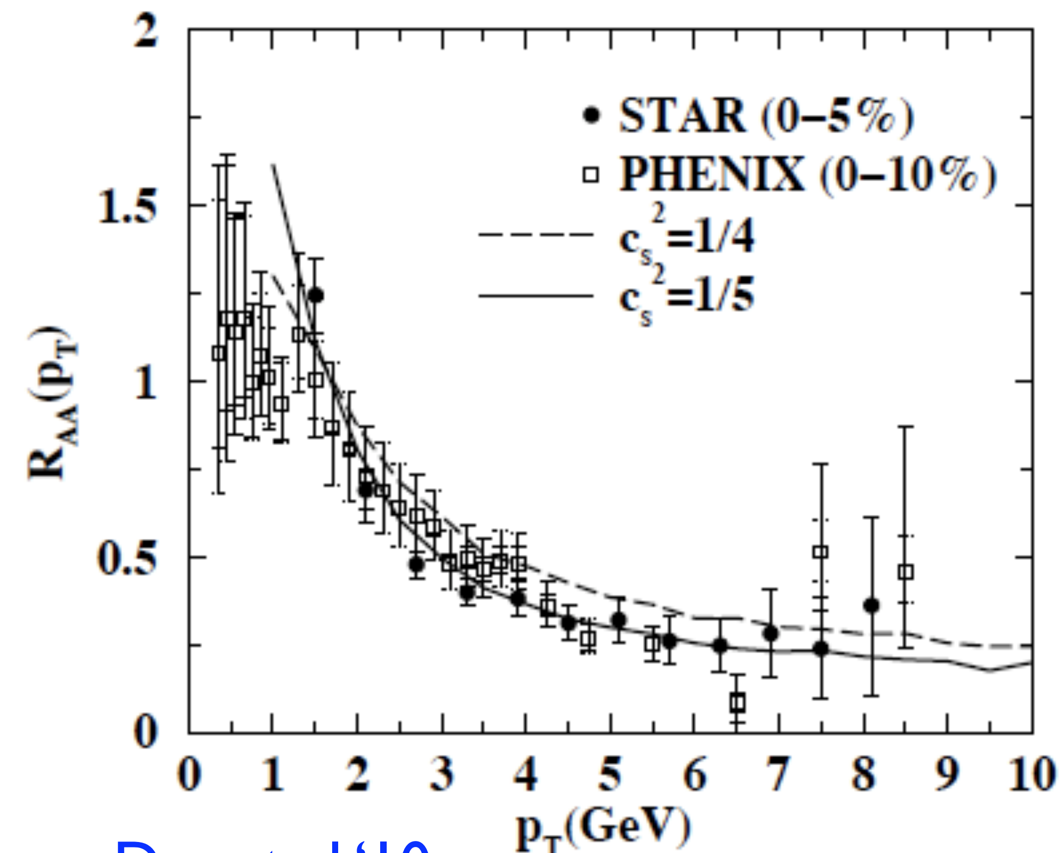
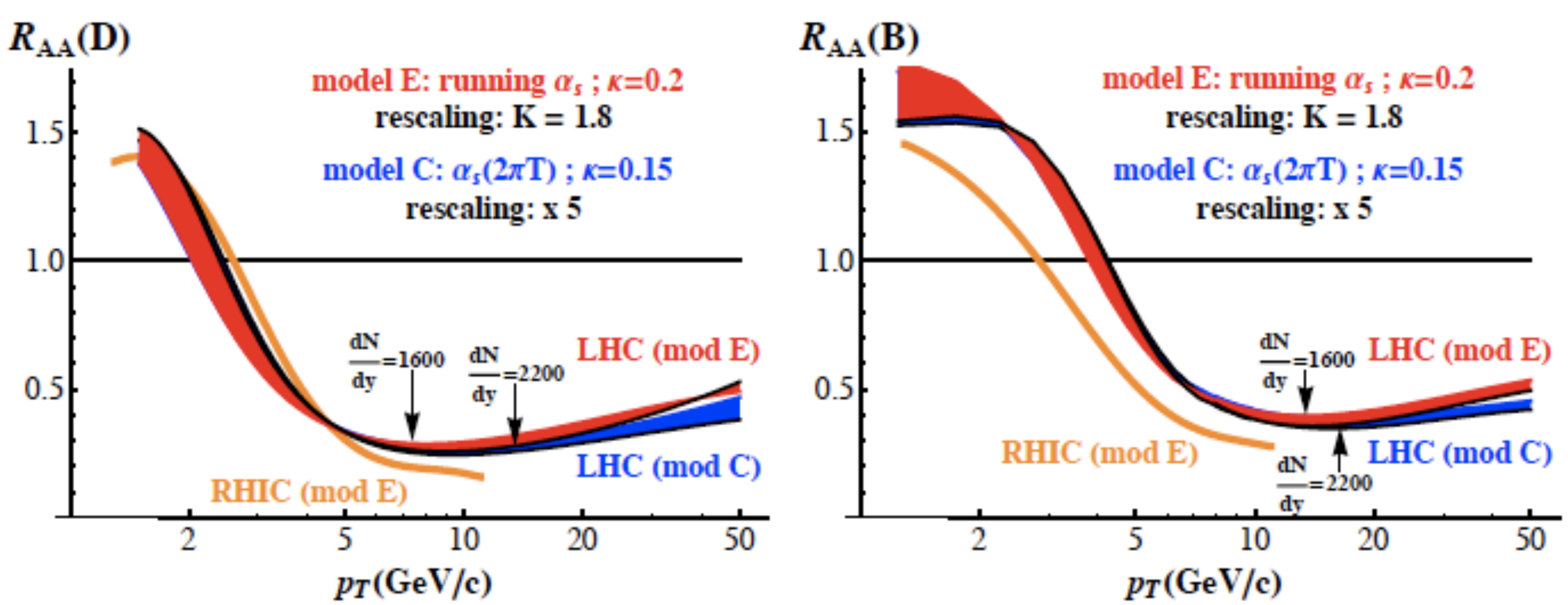
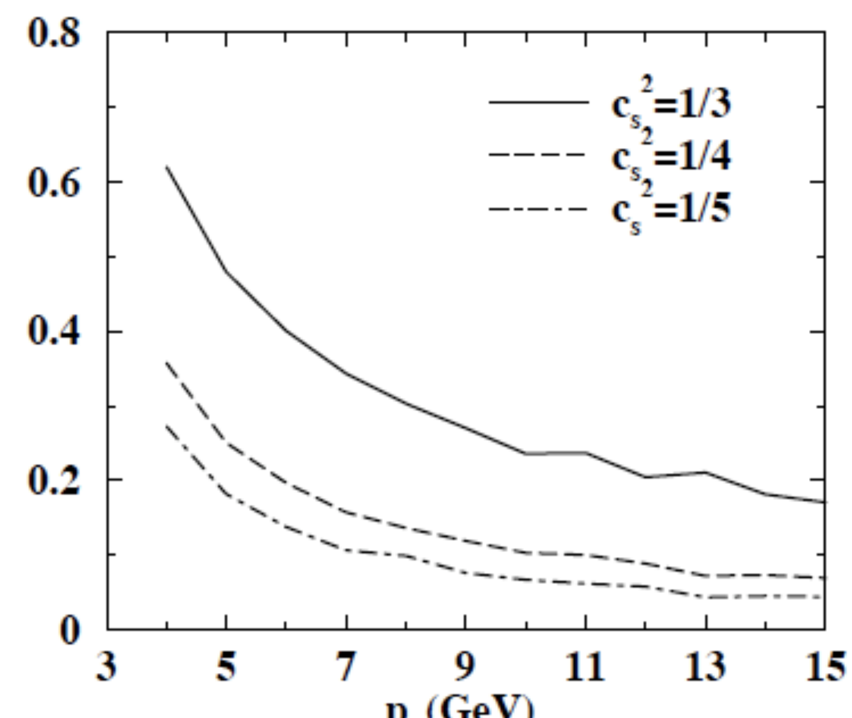



Das et al '10

Gossiaux et al '09



# Predictions for the LHC (II):

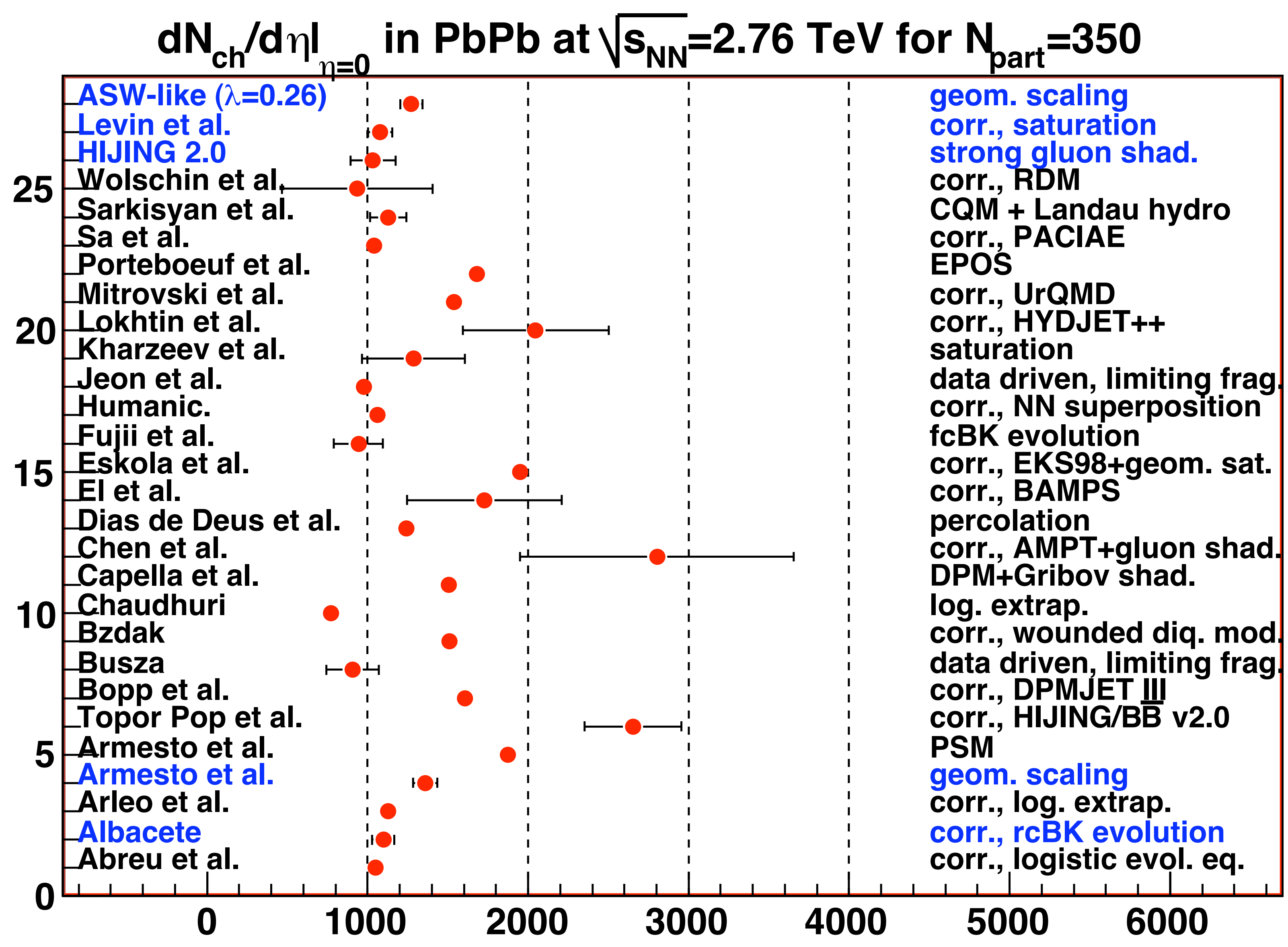
- Sizeable difference between b and c up to $p_T$ ~ 30 GeV in radiative or collisional scenarios.
- Meson dissociation: similar B and D suppression.
- Initial state effects to be controlled.
- Possibility of experimentally separating b and c!
- Differences between perturbative and non perturbative elosses to be settled at not very large $p_T$.
- Large coverage in $p_T$ for muons makes it possible a self-calibration with EW bosons (Dainese et al '08).

# Some remarks:

- Monte Carlo models (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA, Q-HERWIG, MARTINI): none of them includes properly the mass effect at present.

NA, seminar at HIC10 at CERN, 03.09.10

- Density of the medium and dynamical behavior ('length') to be determined by the very first data at LHC on multiplicities and flow.
- Partonic spectra at 2.76 ATeV??!!



# Summary:

- Heavy flavour production in nuclear collisions provides a stringent test of our factorization ideas.

- For its use as a tool to analyse the medium created in HIC, an accurate control of the benchmark is demanded: npdf's.

- Benchmark at RHIC?

- Unsatisfactory situation in HIC at RHIC: data are hard to be reproduced, models are not really consistent with data for light hadrons,...

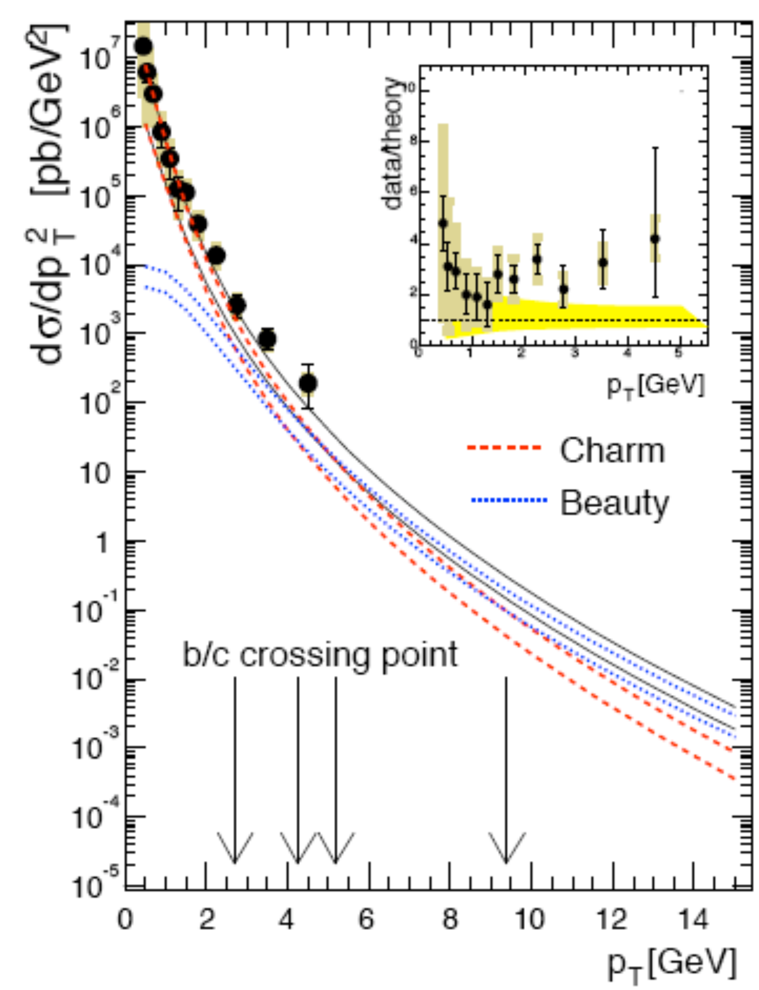
- LHC and RHIC-II offer large possibilities to clarify these issues, through D/B identification.

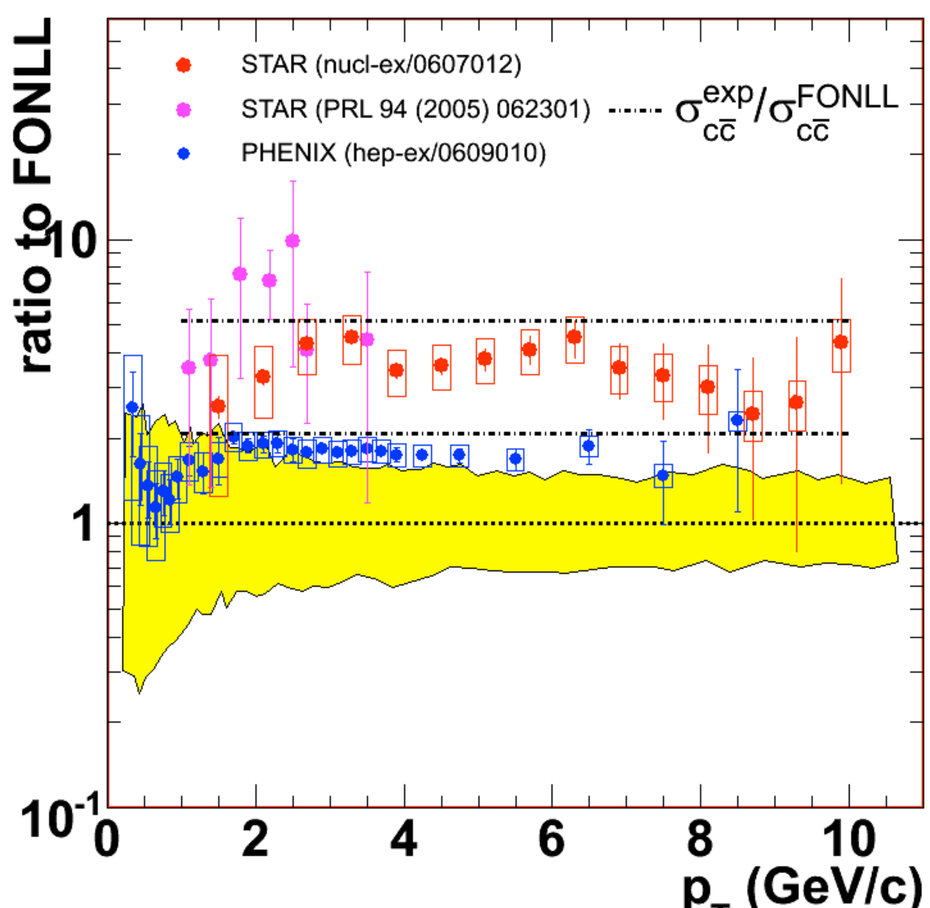
- The fun will begin in 10 days (at long last...): soft data will be most important even for heavy quarks.

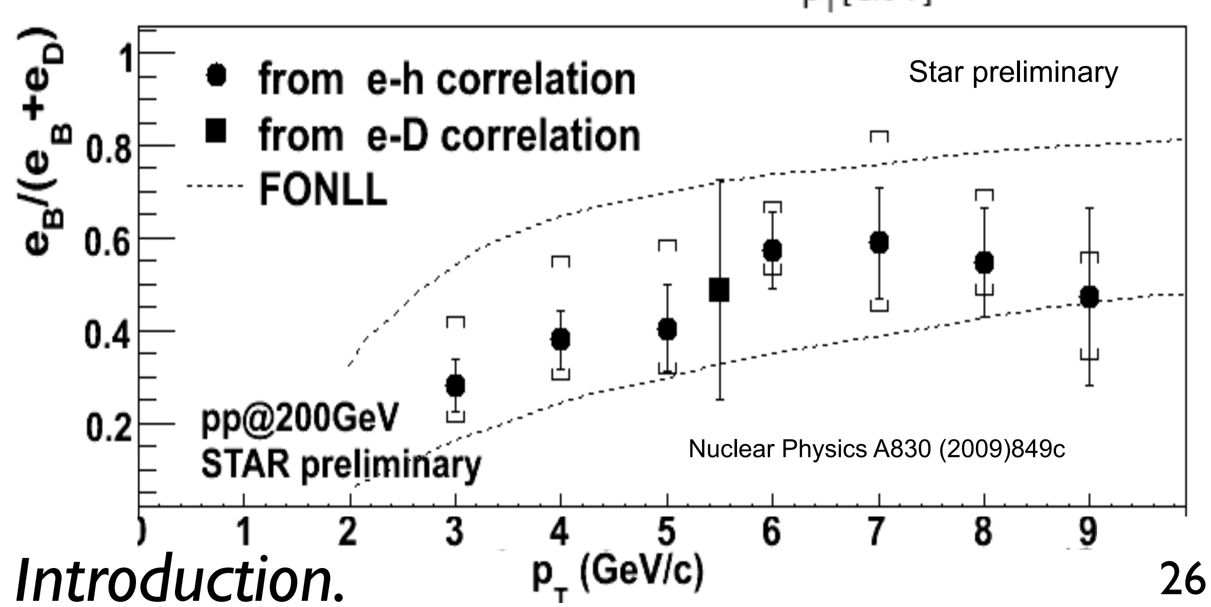
# HQ in pp@RHIC:

- State-of-the-art resummed pQCD (FONLL) which is quite successful in b-production at Tevatron, tends to be low at RHIC.
- b/c ratio looks reasonable, though: most important for energy loss which depends on the mass.
- PHENIX vs. STAR?
- Non-photonic e's: D, B, $\Lambda_c$, DY, QQbar,...

NA et al '06



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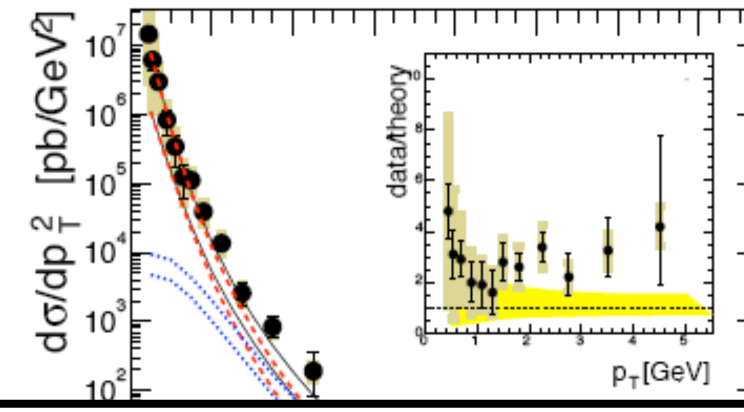
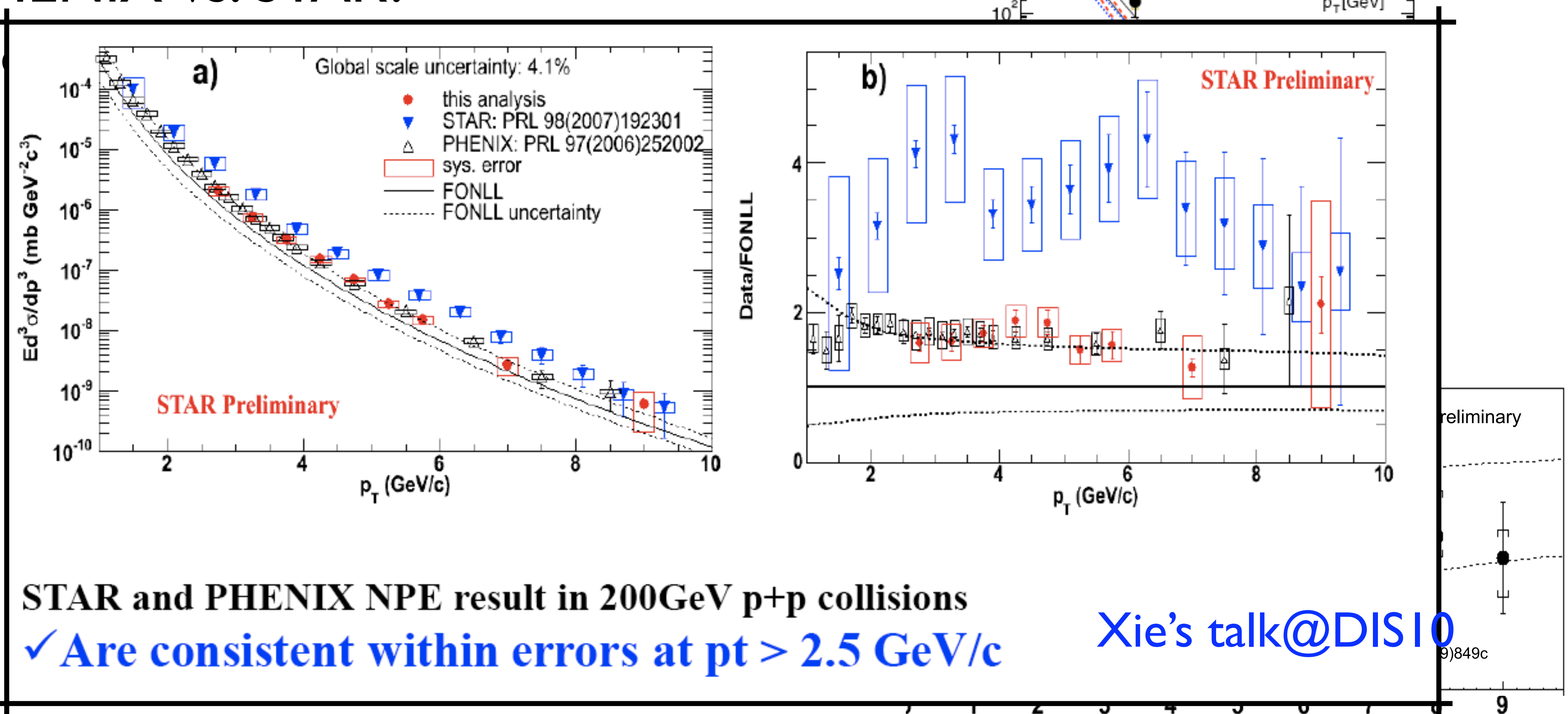
NA et al ‘06




Xie’s talk@DIS10

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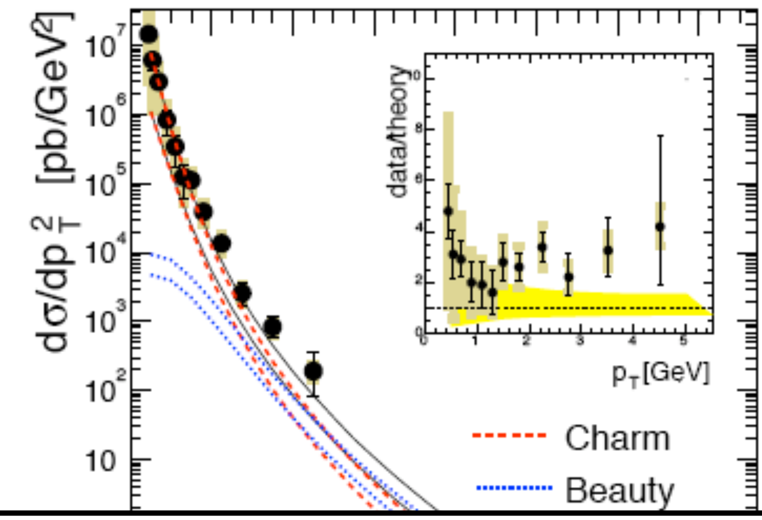


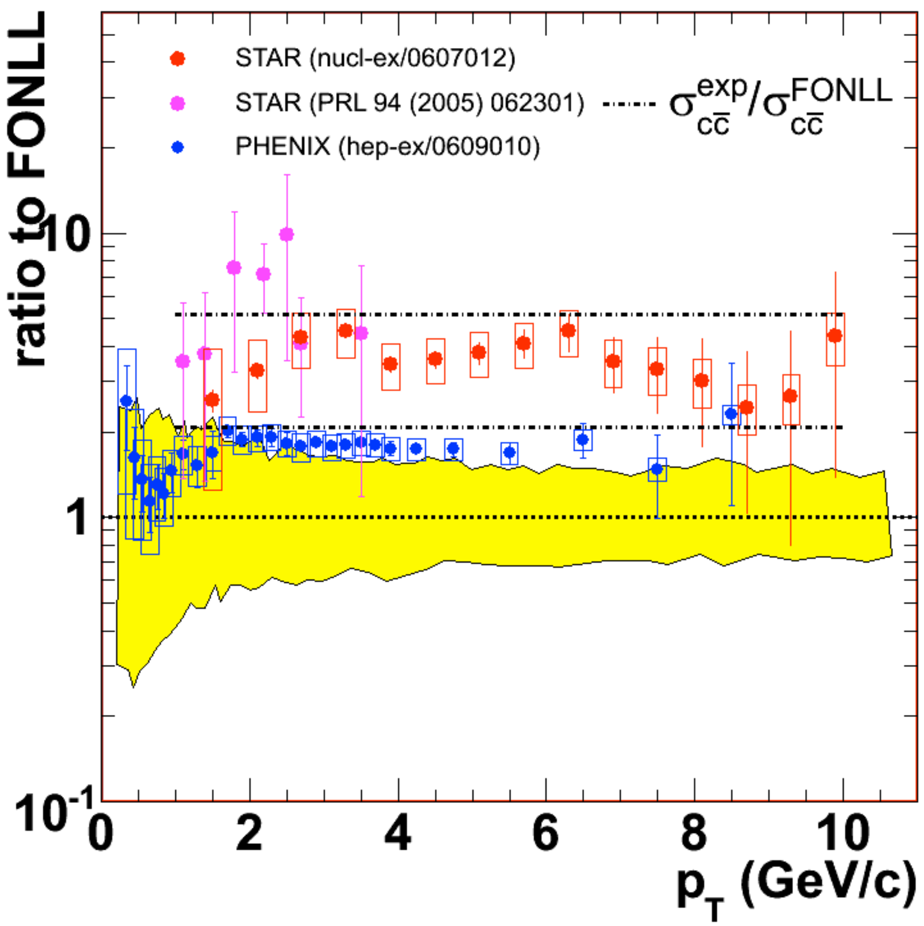


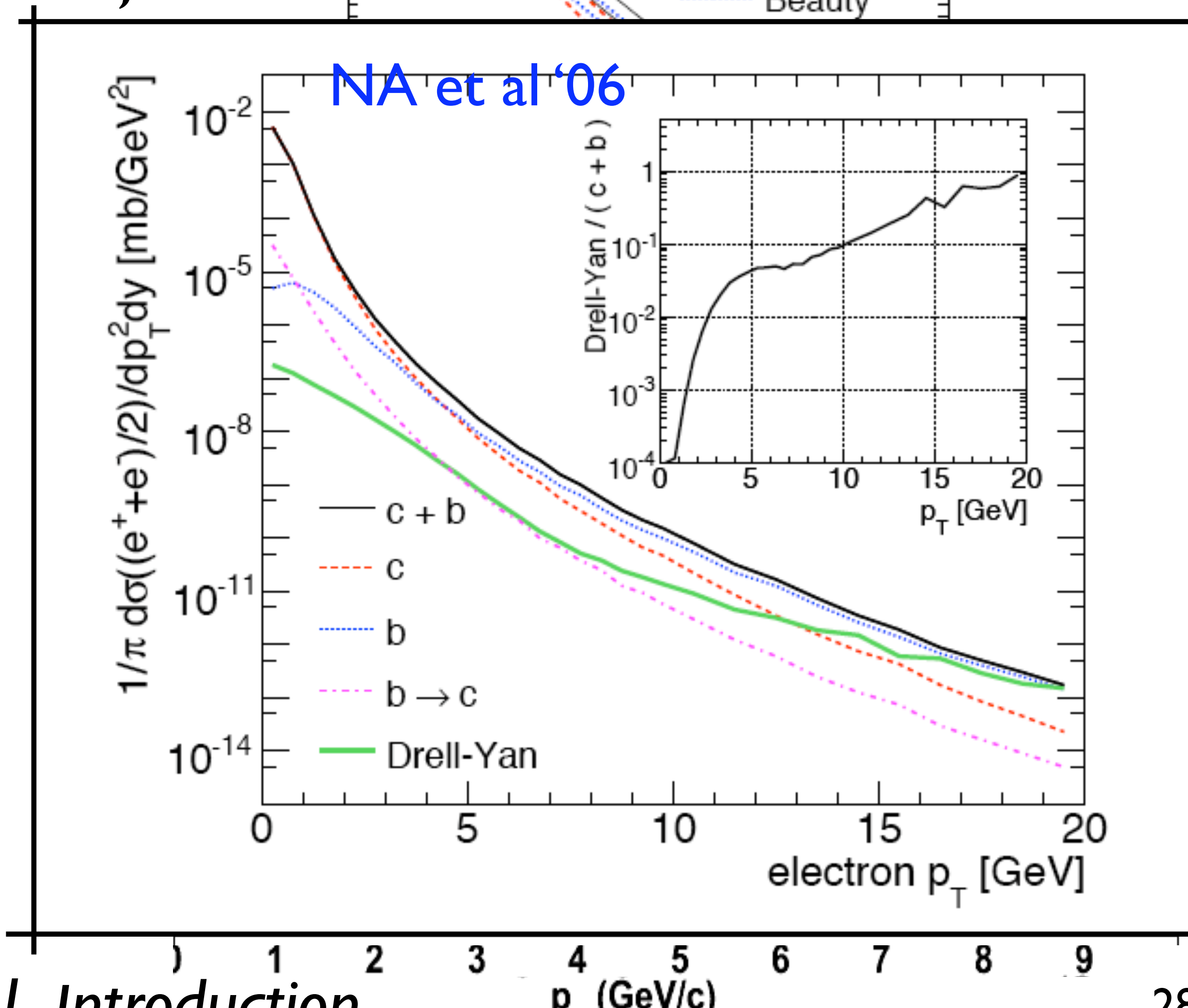

# Radiative eloss: limitations

- The extracted value of qhat depends on medium model: $1 < \hat{q} < 15$ GeV$^2$/fm ⇒ interface with realistic medium

  (TECHQM, JET,...).

- Calculations done in the high-energy approximation: only soft emissions, energy-momentum conservation imposed a posteriori ⇒ Monte Carlo.

- Multiple gluon emission: Quenching Weights, independent (Poissonian) gluon emission: assumption! ⇒ Monte Carlo.

  (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA, Q-HERWIG, MARTINI).

- No role of virtuality in medium emissions; medium and vacuum treated differently ⇒ modified DGLAP evolution.

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  (TECHQI

$$\omega \frac{dI}{d\omega dk_T^2} \quad \text{for} \quad k_T \ll \omega \ll E$$

- Calculatic ion: only soft emissions osed a posterior

$$\omega \frac{dI}{d\omega} = \int_0^{k_T^{2,max}} dk_T^2 \, \omega \frac{dI}{d\omega dk_T^2}, \quad \Delta E = \int_0^E d\omega \, \omega \frac{dI}{d\omega}$$

- Mult nt (Pois lo.

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta \left( \Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[ - \int d\omega \frac{dI}{d\omega} \right]$$

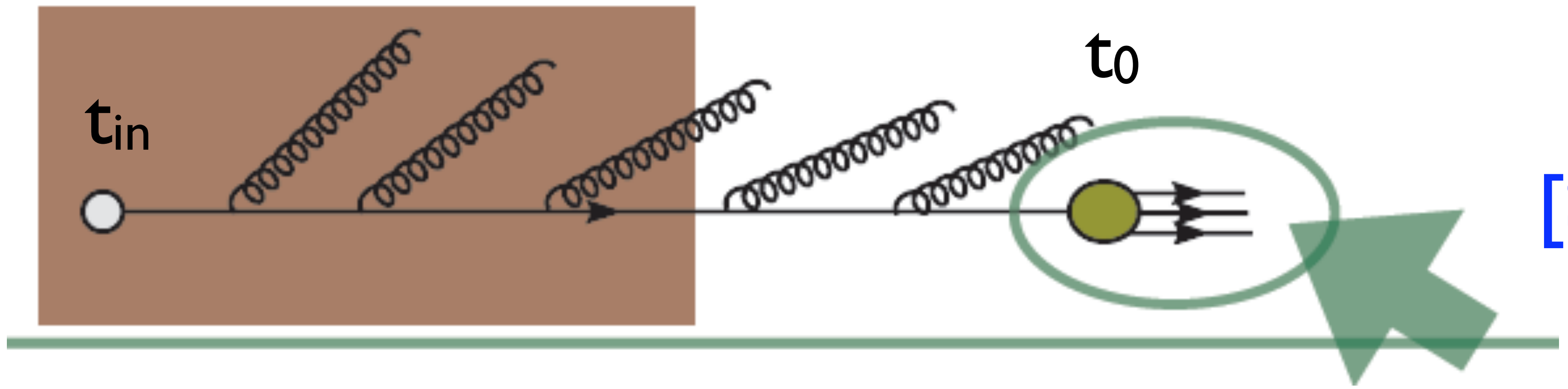
  (P

  M

$$P_{trunc}(\Delta E) = p_0 \delta(\Delta E) + P_{cont}(\Delta E) \Theta(E - \Delta E) + \delta(E - \Delta E) \int_E^{\infty} d\epsilon P(\epsilon)$$

- No role of virtuality in medium emissions; medium and vacuum treated differently ⇒ modified DGLAP evolution.

# Monte Carlo (I):



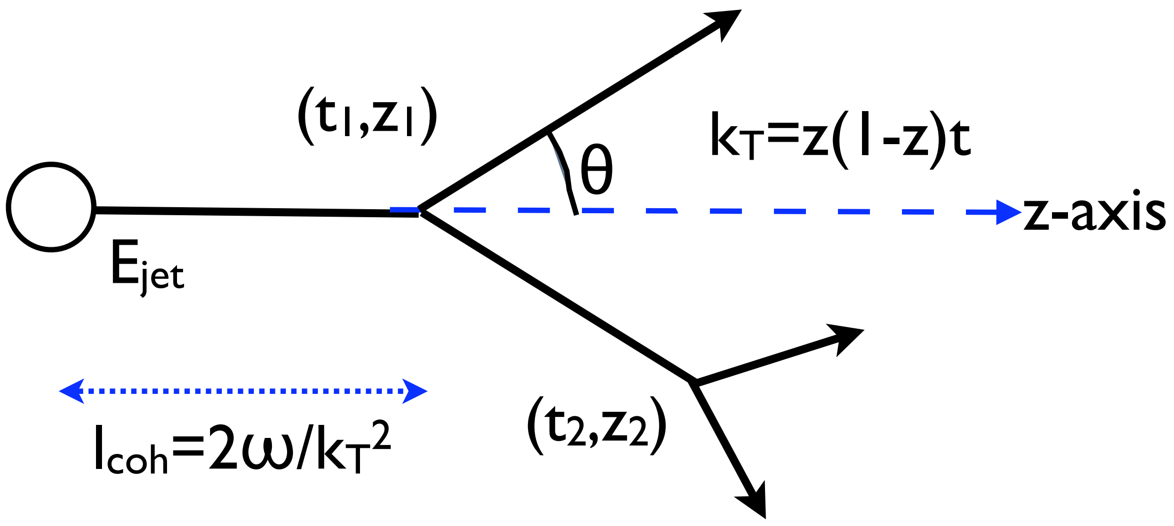

[Salgado]

- **Assumption**: hadronization is not affected by the medium: looks OK at RHIC for pT>7-10 GeV.
- The **splittings are modified:** either radiatively (Q-PYTHIA, Q-HERWIG) or radiative+collisionally (JEWELL, PYQUEN,MARTINI); or the evolution is enlarged due to momentum broadening (YaJEM).

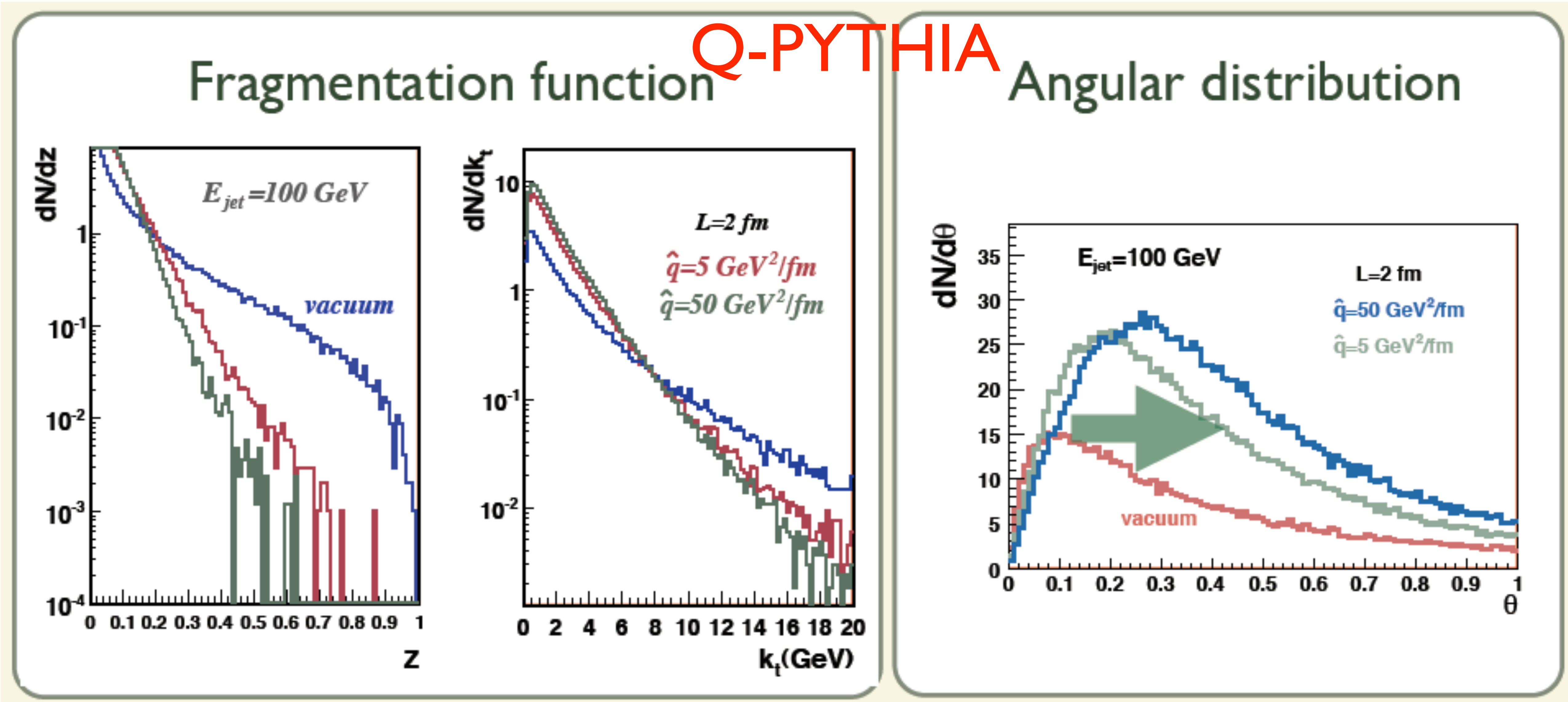
- **Underlying ingredients**: factorization no emission/emission/no emission/... (Sudakov/splitting/Sudakov/...) holds in the medium, and the evolution scale ($t,k_T,\Theta$) can be related with the medium length → both to be proved (Jet Calculus in a medium).

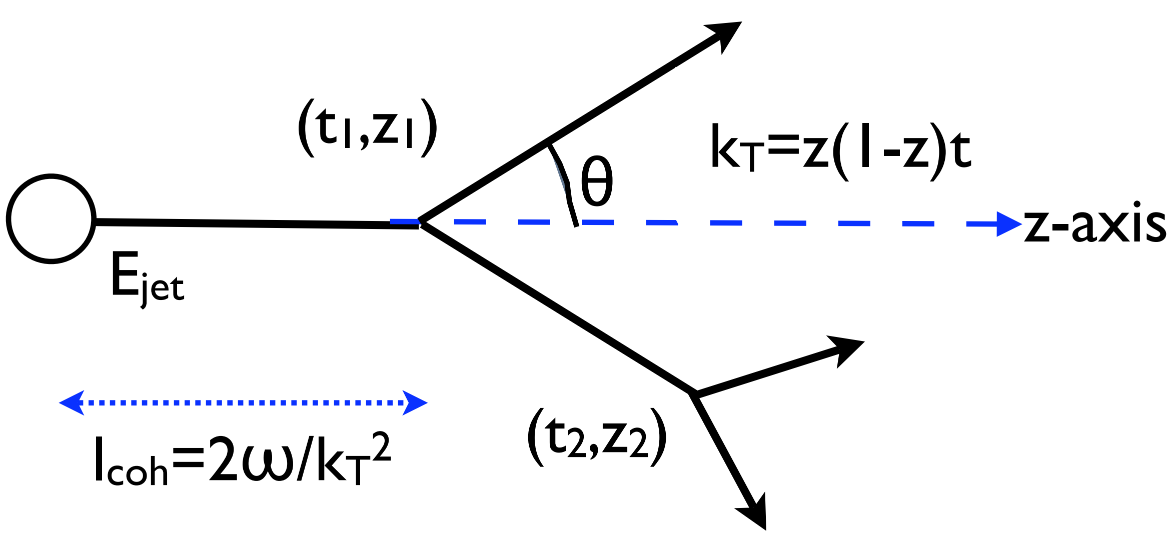
# Monte Carlo (II):

- The MC's generically reproduce the expectations:
  - → Particle spectrum softens (jet quenching).
  - → Emission angle enlarges (jet broadening).
  - → Intra-jet multiplicity enlarges.



# Monte Carlo (II):

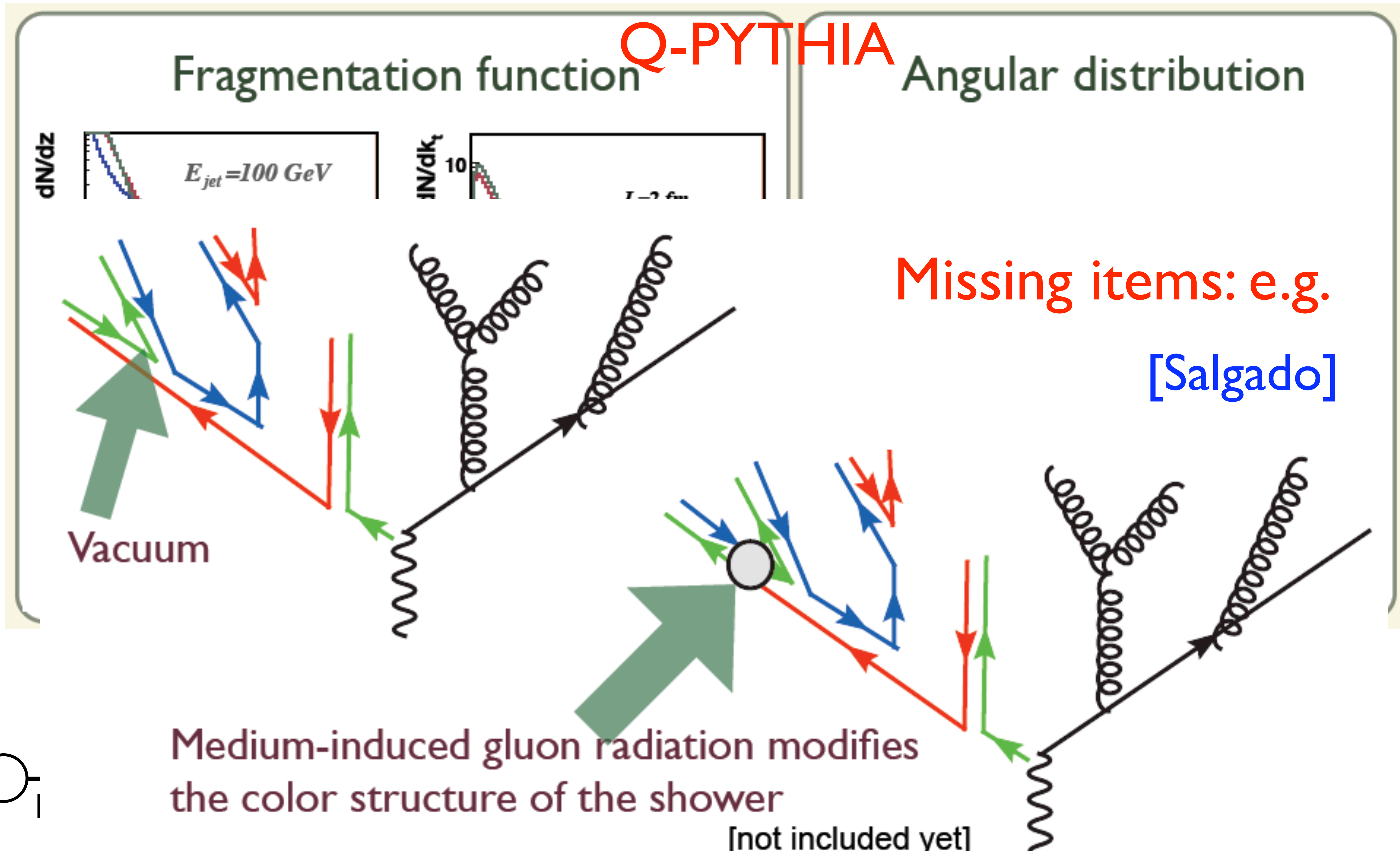



- Intense activity at RHIC and the LHC: jet reconstruction in a large background (small clustering parameters versus out-of-'cone' medium modification).

# Monte Carlo (II):

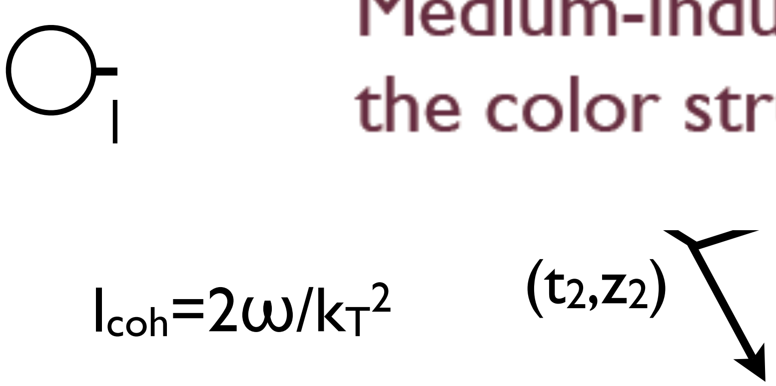
Q-PYTHIA




Missing items: e.g.

[Salgado]

$l_{coh}=2\omega/k_T^2$




parameters versus out-of- cone medium modification).

# More remarks:

- Imagine a gluon loses more energy than a light quark than a heavy quark: still lots of things to consider accurately (partonic spectra, fragmentation,...)...

- Note: the shape of the partonic spectrum is a key ingredient on the shape of $R_{AA}$.

$$\frac{dN^{med}}{dp_T}(p_T) \propto \frac{dN^{vac}}{dp_T}(p_T + \Delta E)$$

$$\propto \frac{1}{(p_T + \Delta E)^n} \quad \text{or} \quad \exp\left[-\beta(p_T + \Delta E)\right]$$

$$\Longrightarrow R_{AA} = \frac{\frac{dN^{med}}{dp_T}}{\frac{dN^{vac}}{dp_T}} \longrightarrow 1 \quad \text{or} \quad \exp\left[-\beta\Delta E\right] \quad \text{for} \quad p_T \to \infty$$