Heavy flavor in heavy-ion collision at RHIC and LHC

MinJung Kweon
Physikalisches Institut, Universität Heidelberg

29 Mar 2010, EMMI Symposium

Motivation to start having interest in heavy quarks in medium

- In terms of heavy quark energy loss in medium
  - 1997 Shuryak suggested (Phys. Rev. C 55, 961 (1997)) that heavy quarks will have large energy loss in QGP $\Rightarrow$ large suppression of heavy mesons.
  - 2001 Dokshitzer and Kharzeev proposed "dead cone" effect in the medium $\Rightarrow$ cause small energy loss for heavy quark

- In terms of quarkonium production in medium
  - T. Matsui and H. Satz (PLB178 (1986) 416) predict J/Ψ suppression in QGP due to Debye colour screening
  - Significant suppression seen in central Pb+Pb at SPS top energy (NA50) matching with QGP expectations

- Without medium
  - Systematics of heavy quark cross section compared to NLO pQCD

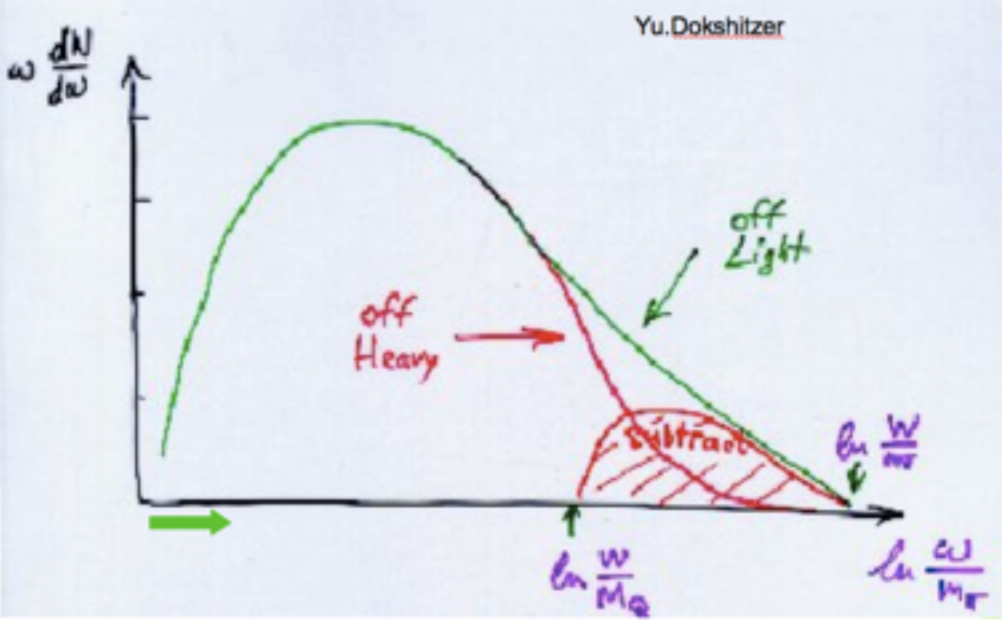
Energy loss for heavy quarks: differ from light?

- In vacuum, characteristic mass-dependent depletion of the gluon radiation at angles $\theta < m_Q/E_Q$: dead cone effect
  - distribution of gluons radiated by a heavy quark

$$dP_{HQ} = dP_0 \cdot \left(1 + \left(\frac{M_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2} \quad \text{,where} \quad \theta \simeq \frac{k_T}{\omega}$$

- In medium, dead cone implies lower energy loss (Dokshitzer and Kharzeev, 2001)
  - angular distribution of gluons induced by the quark propagation in the medium with the size of the dead cone(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

$$\omega \frac{dI}{d\omega}\bigg|_{Heavy\ in\ Medium} = \omega \frac{dI}{d\omega}\bigg|_{Light\ in\ Medium} \cdot \left(1 + \left(\frac{M}{E}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

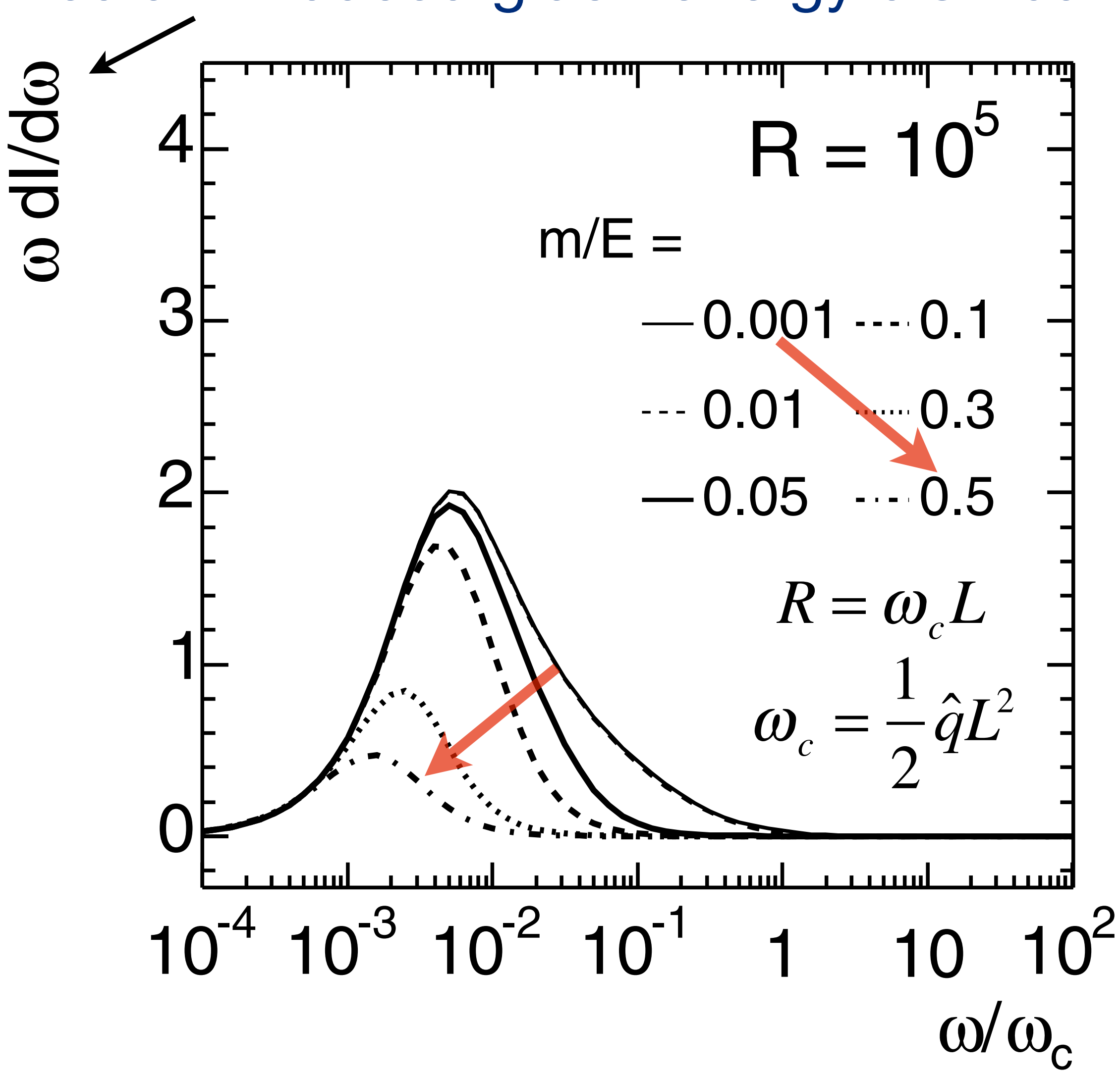


suppress high-energy tail of gluon radiation spectrum

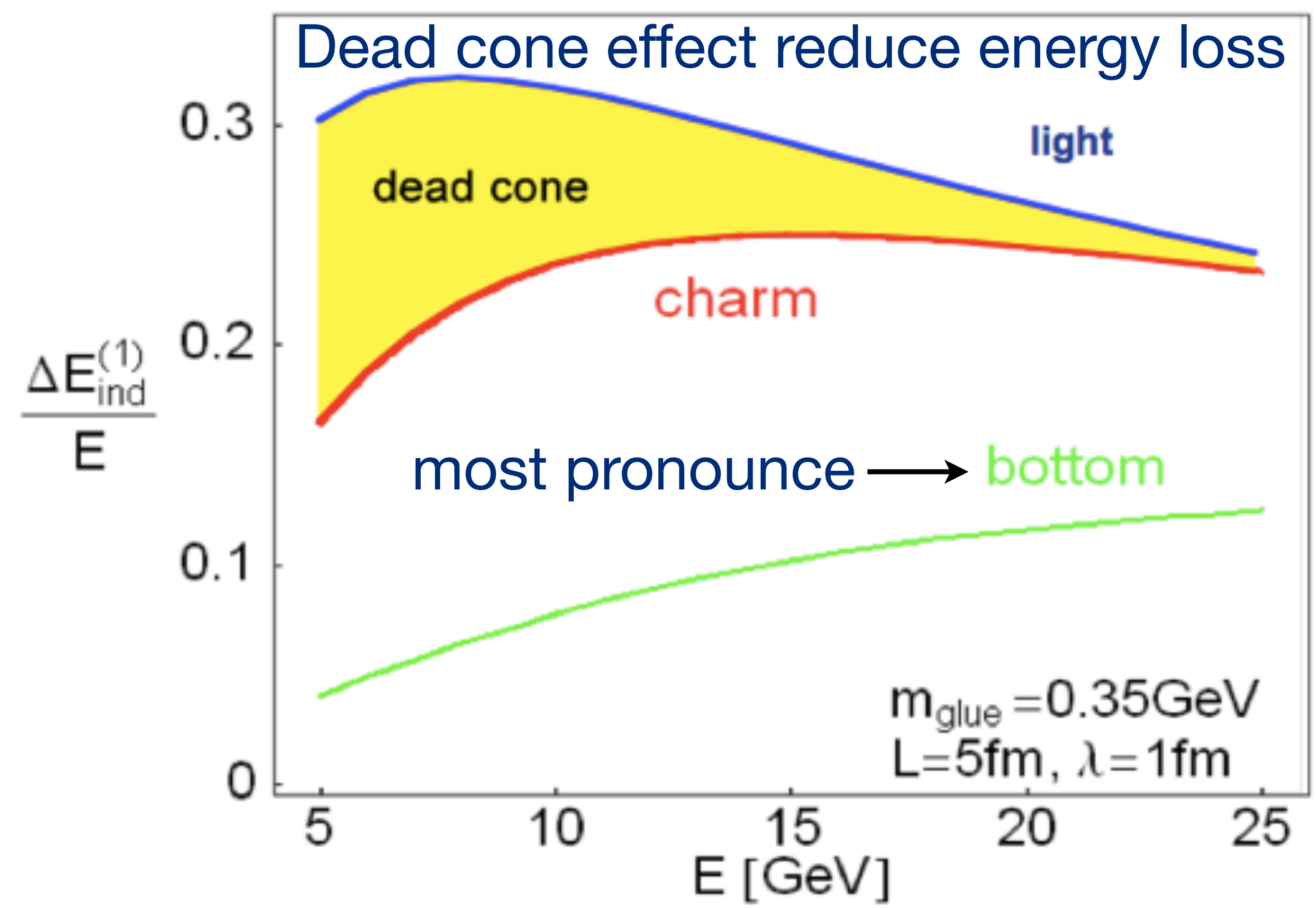
⇒ sizable reduction of energy loss

Dead cone effect in other models

medium induced gluon energy distribution



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

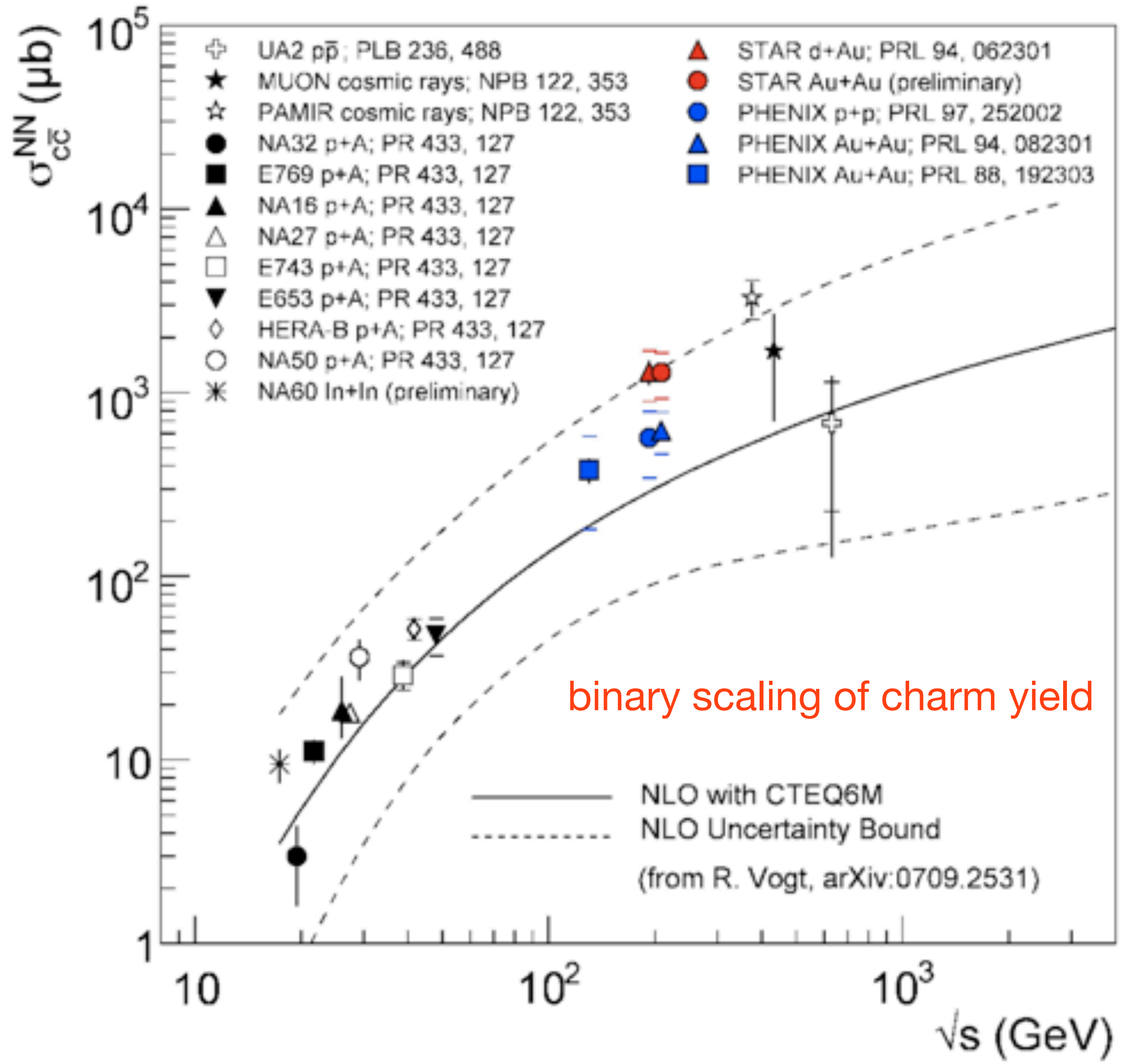


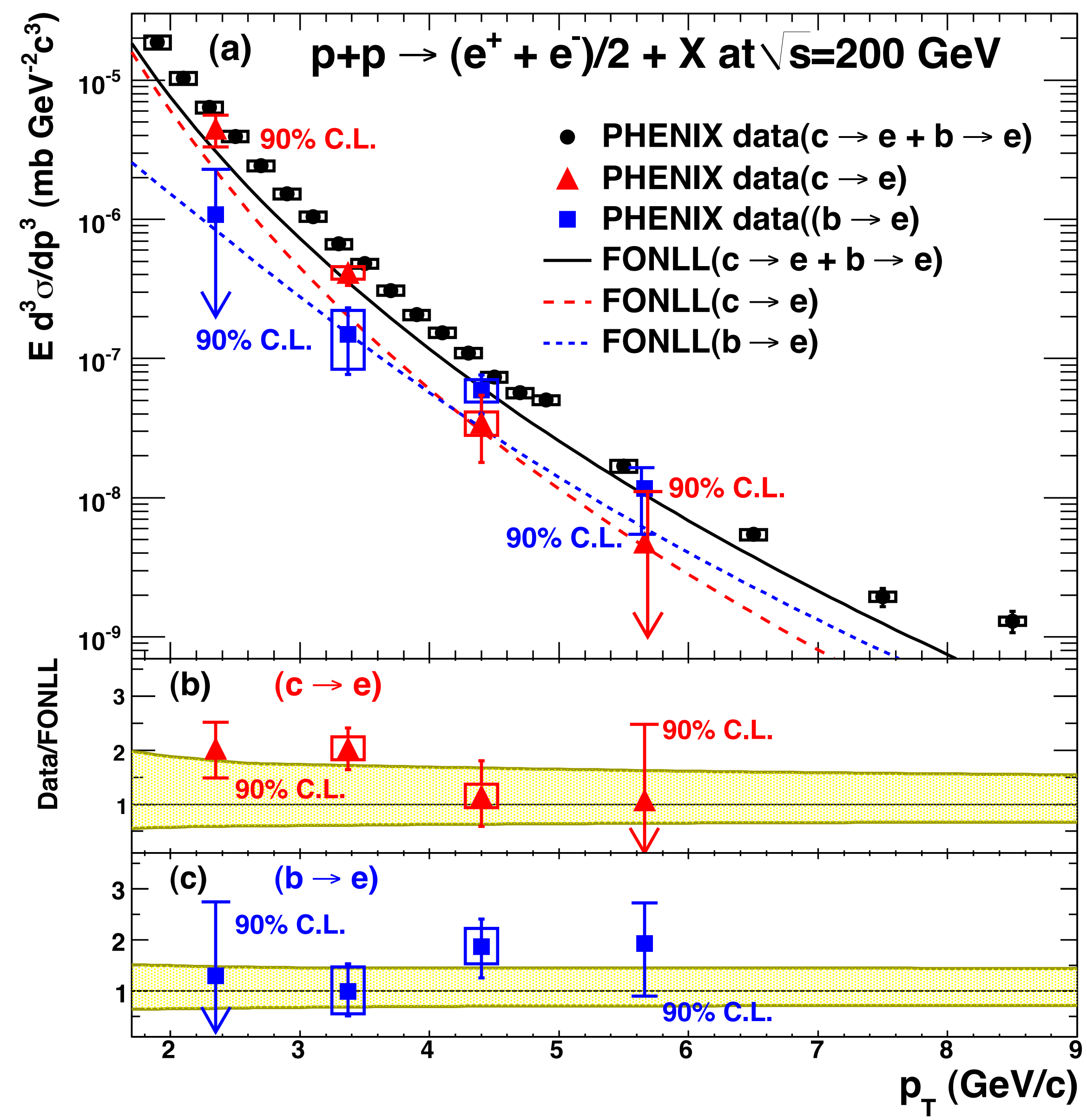
M.Djordjevic J.Phys.G30:S1183-S1188,2004

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291. Salgado, Wiedemann, PRD 68(2003) 014008. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.

Massive calculation confirms this qualitative feature

Systematics of charm and beauty cross section compared to NLO pQCD





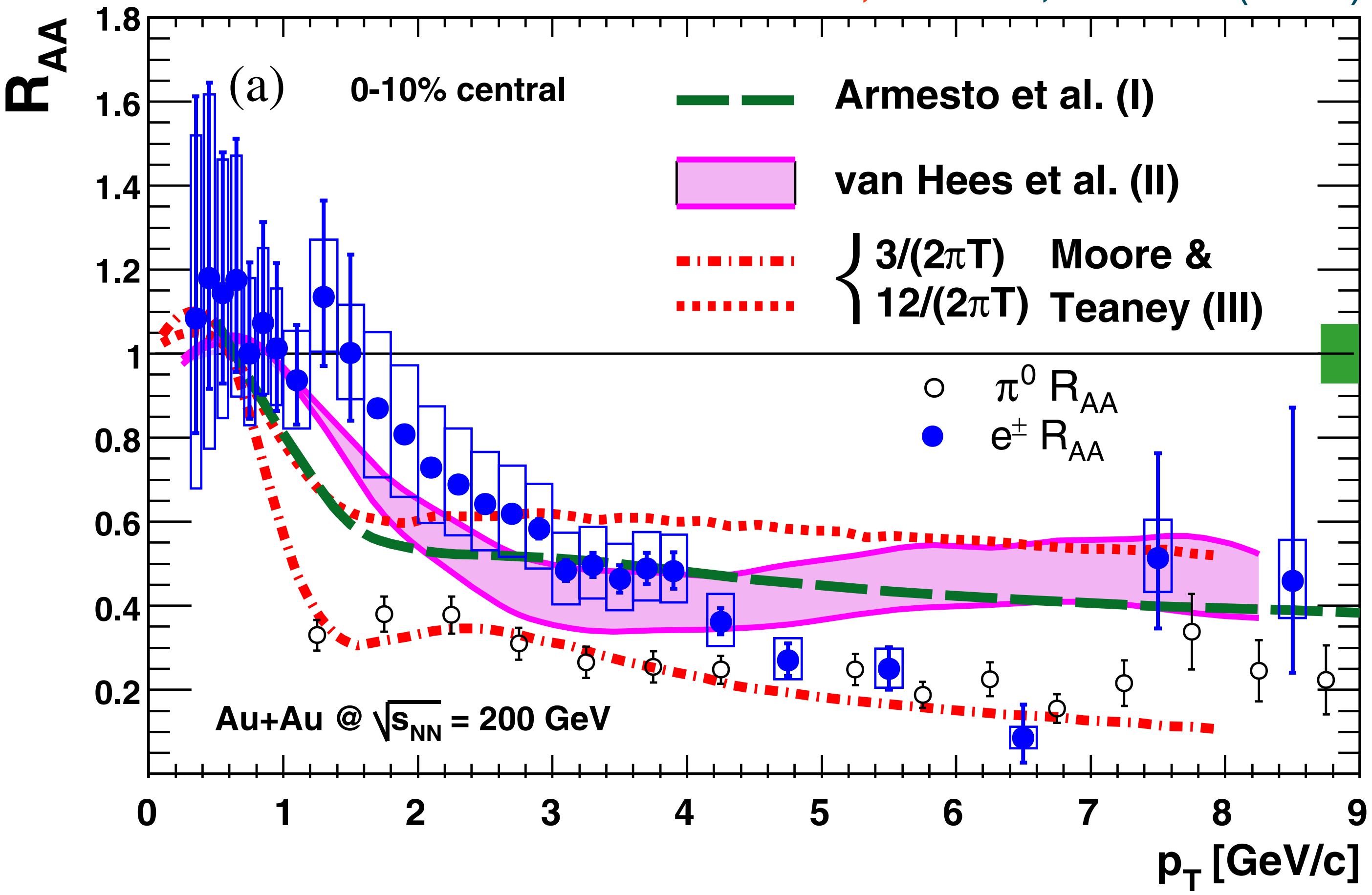
pQCD charm cross section consistent with data
(modulo discrepancy between STAR & PHENIX: STAR ~ 4 x pQCD value, ~2 x PHENIX value)

PHENIX charm and bottom cross section in p+p agrees with pQCD(FONNL) calculation

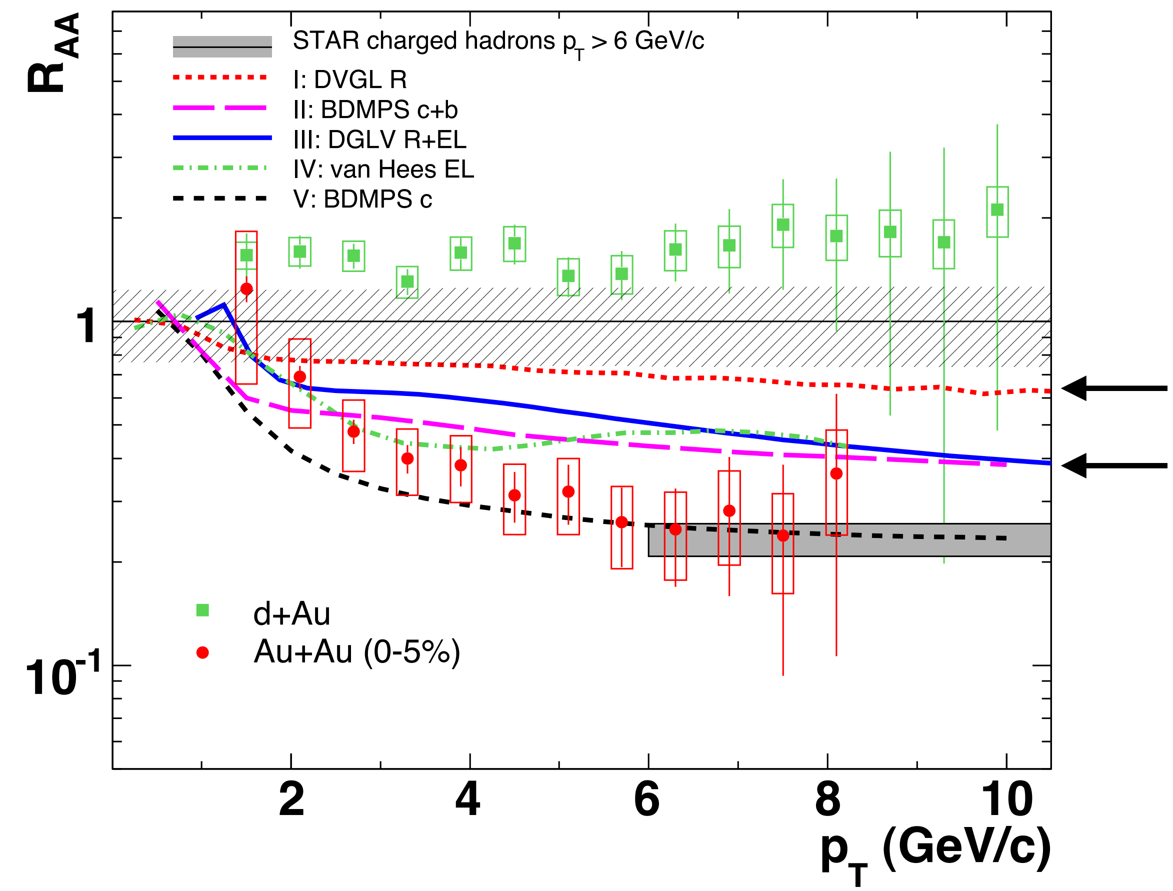
Experimental result of heavy quark energy loss at RHIC

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

PHENIX, PRL 98, 172301 (2007)



STAR, nucl-ex/0607012



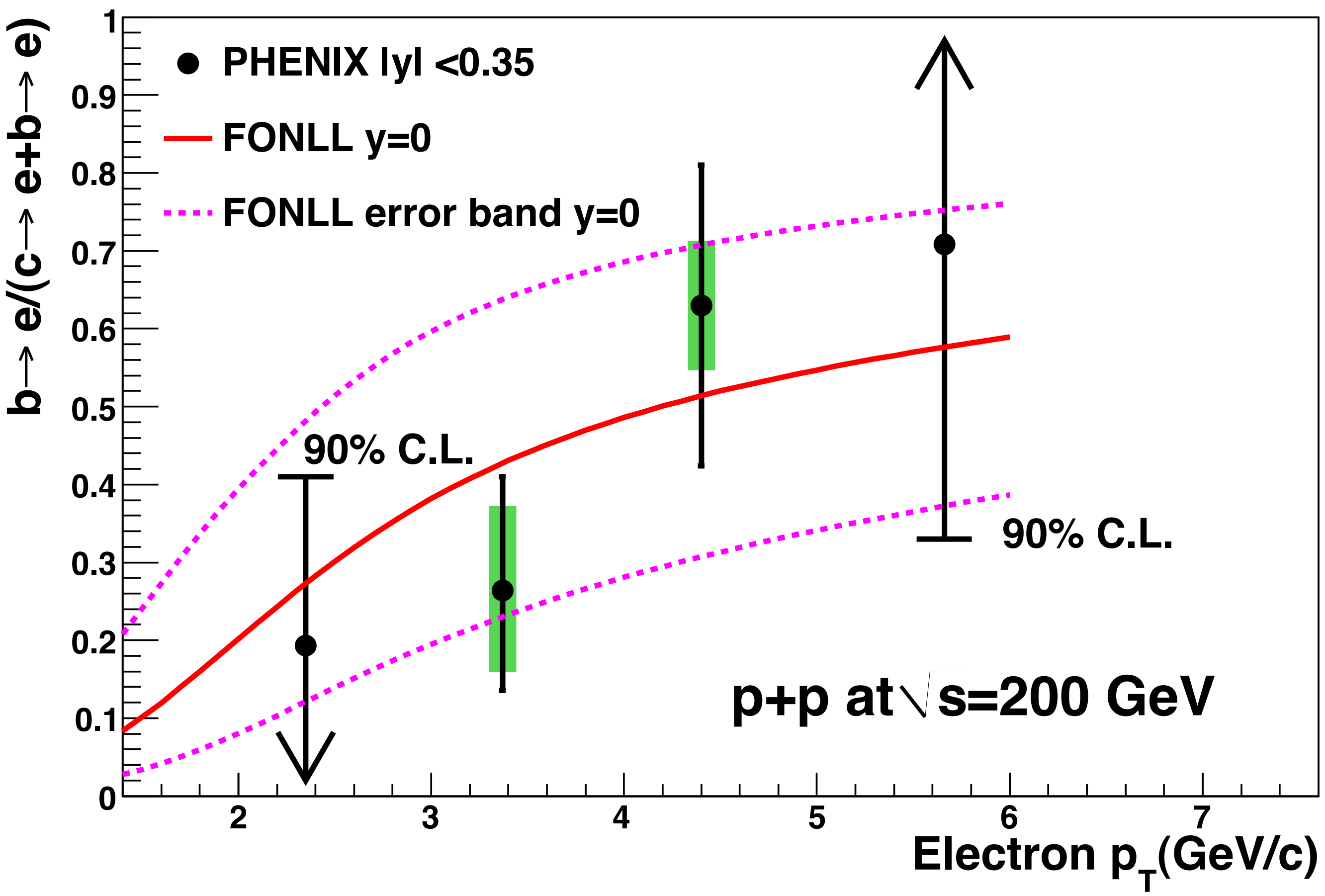
R_{AA} of the heavy-flavour electrons approaches the π^0 value for $p_T > 4$ GeV/c

→ Indicate strong coupling of heavy quarks to the medium (larger than expected)

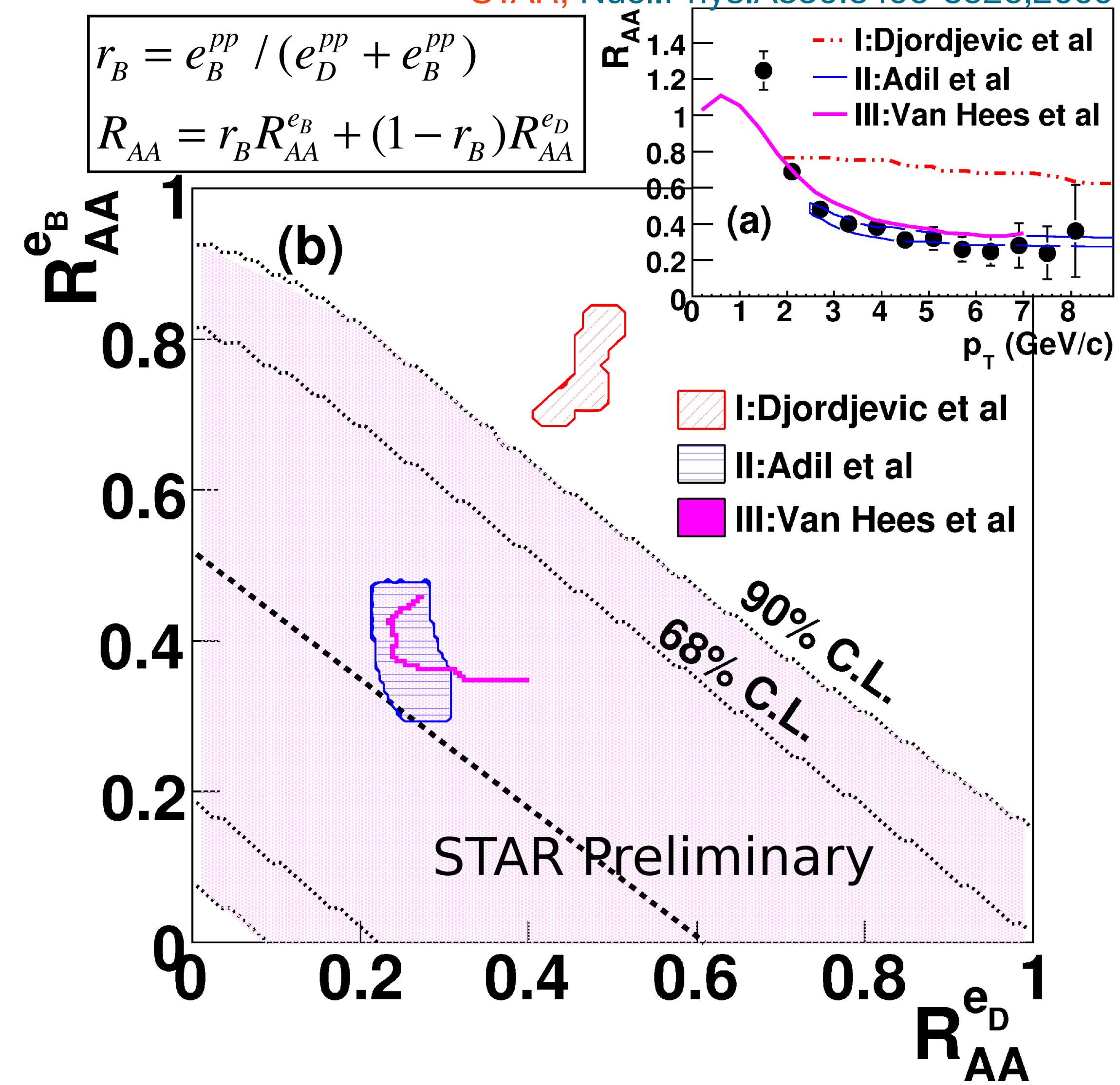
⇒ additional energy loss mechanism required?

Charm to bottom ratio

PHENIX, Phys.Rev.Lett.103:082002,2009



STAR, Nucl.Phys.A830:849c-852c,2009



I: **Djordjevic, Gyulassy, Vogt and Wicks,** Phys. Lett. B 632 (2006) 81; dNg/dy = 1000
II: **Adil and Vitev,** Phys. Lett. B 649 (2007) 139
III: **Hees, Mannarelli, Greco and Rapp**, Phys. Rev. Lett. 100 (2008) 192301

Bottom/charm ratio in p+p agrees with theory expectations(FONLL)

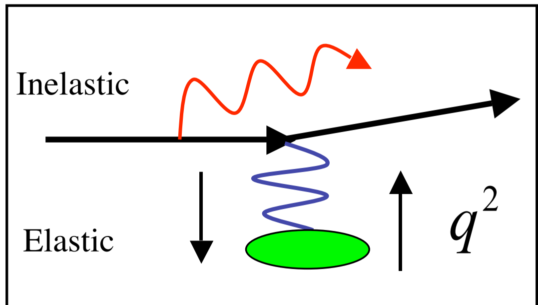
$R^e(B)_{AA} < 1$; B meson is also suppressed

Not prefer model (I) (small b energy loss)

⇒ require additional energy loss mechanism

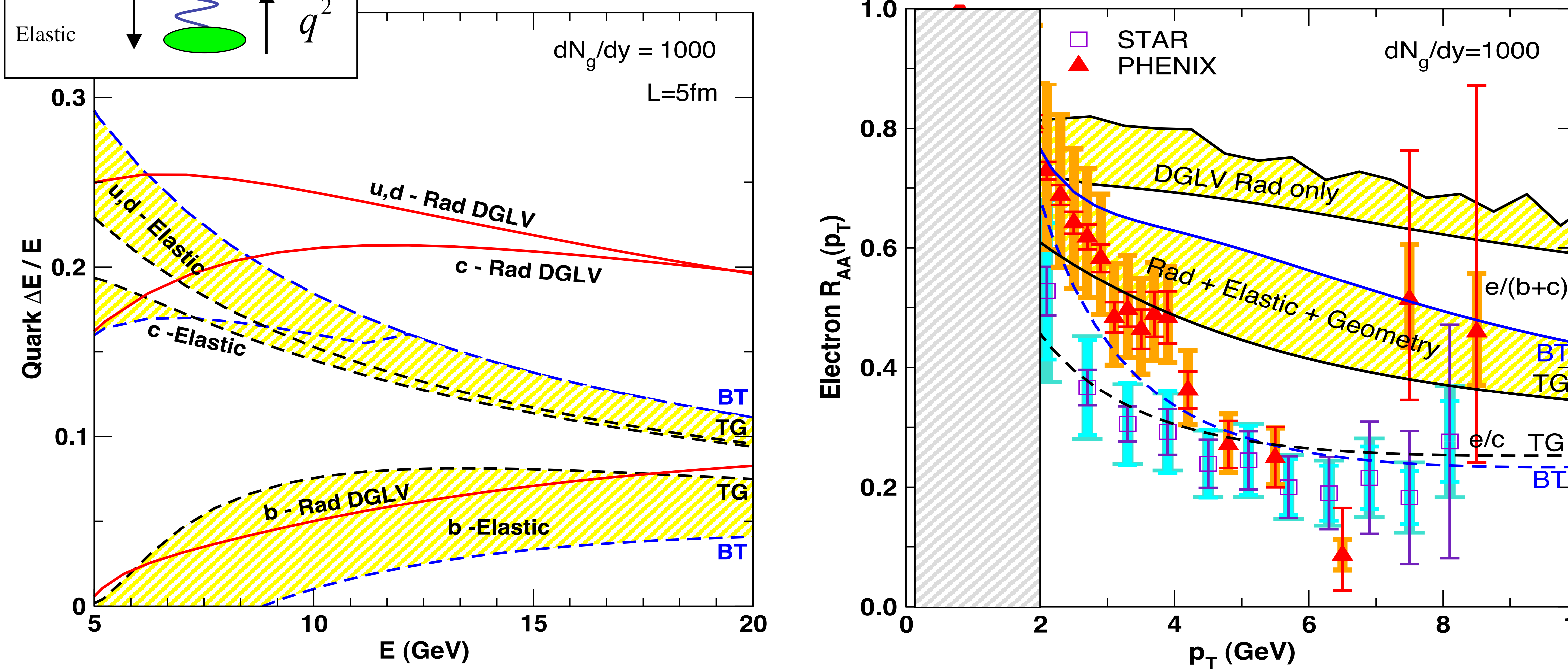
Approaches to describe non-photonic electron $R_{AA}(p_T)$

- Inelastic(radiative) + elastic parton energy losses



Regarded elestic parton energy loss is negligible → valid ?

Simon Wicks, William Horowitz, Magdalena Djordjevic, Miklos Gyulassy, Nucl.Phys.A784:426-442,2007



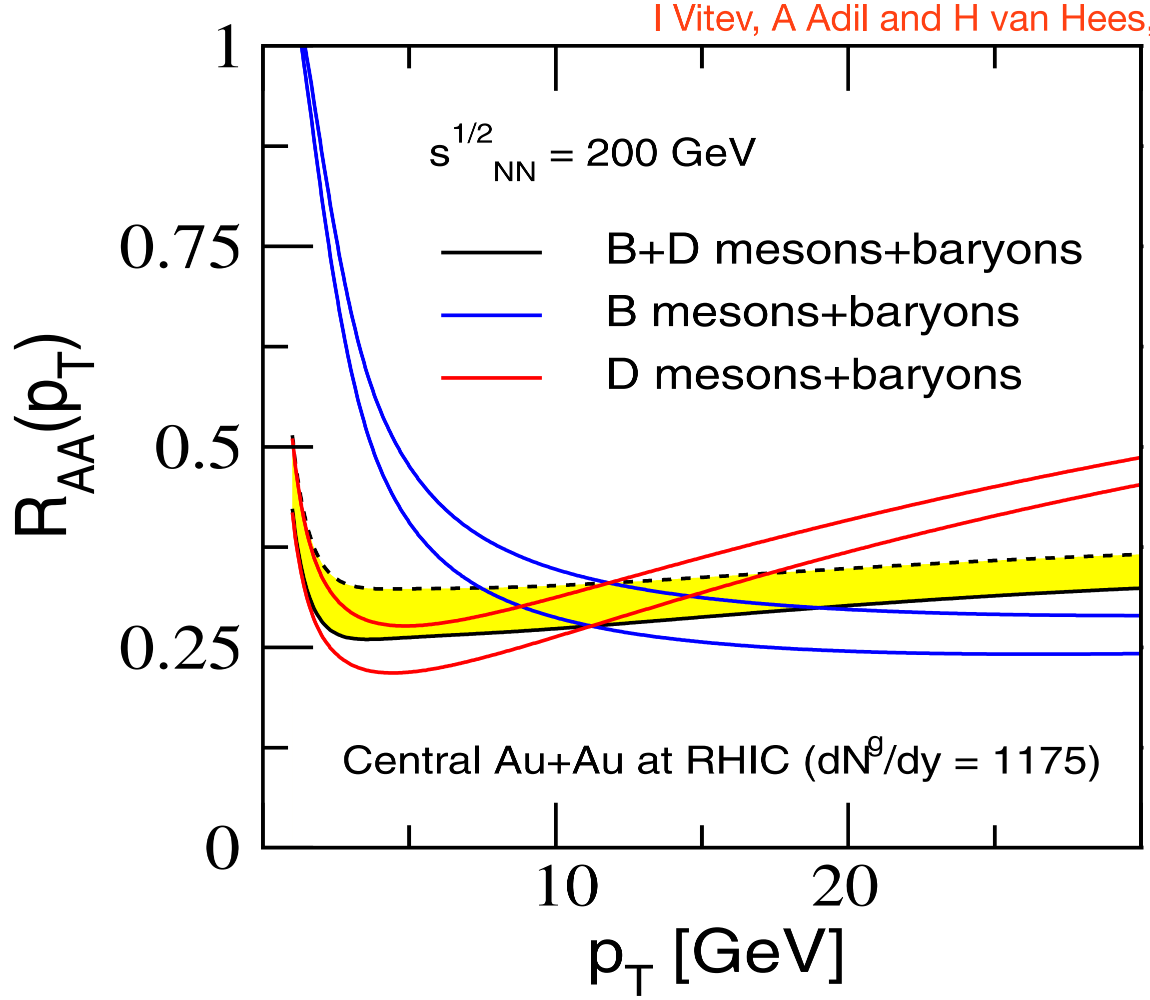
Radiative and elastic energy losses for heavy quarks are comparable
(Mustafa found, here confirms this founding)
→ can reach below R_{AA} ~ 0.5 in spite of keeping dN_g/dy = 1000

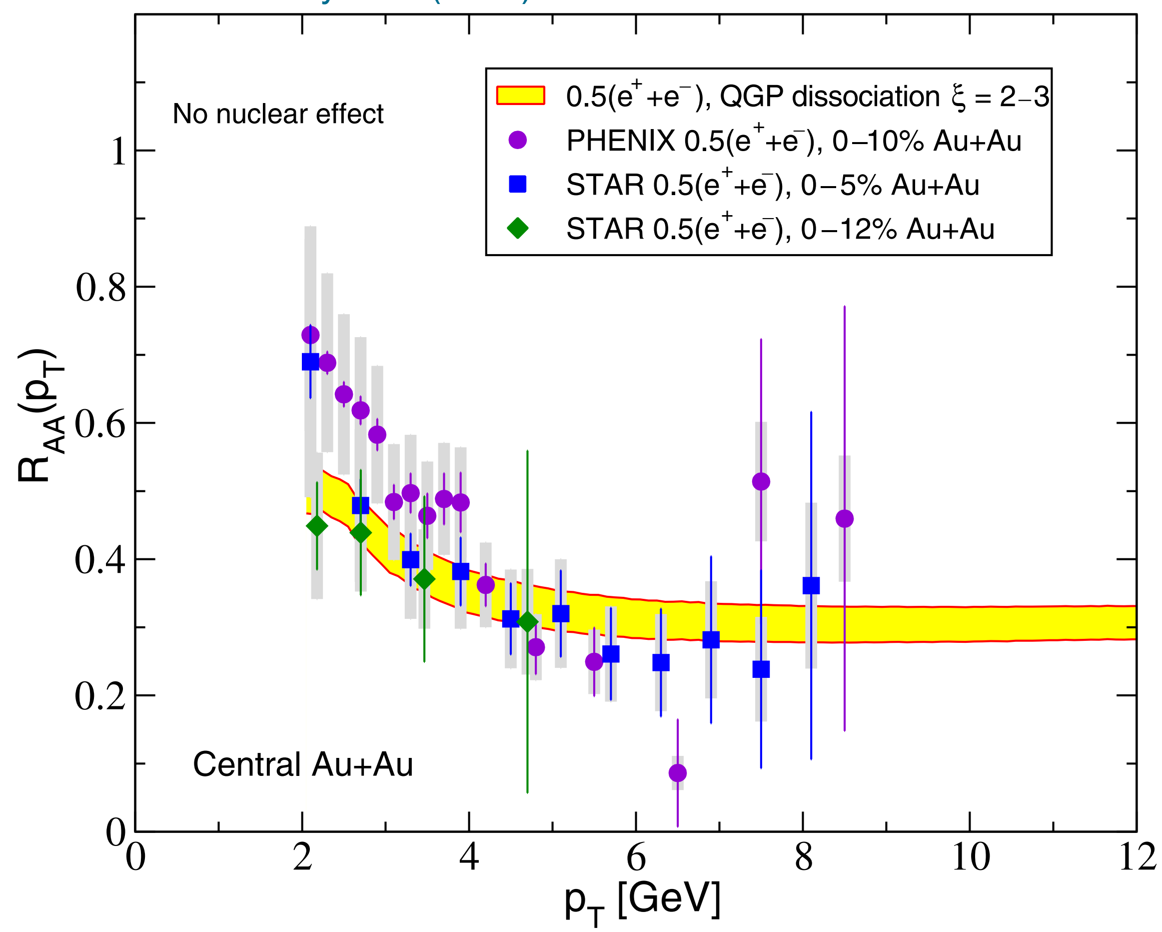
However, current data suggest even the combined radiative+elastic pQCD mechanism is not sufficient (here, assume charm/bottom ratio given by FONNL is accurate)

Approaches to describe non-photonic electron $R_{AA}(p_T)$
- Heavy meson dissociation in QGP

pQCD factorization approach assume hard jet hadronization in vacuum → valid for different species?

I Vitev, A Adil and H van Hees, J. Phys. G: Nucl. Part. Phys. **34** (2007) S769–S773





Shorter D- and B-meson formation time: $\tau_{\text{form}}(p_T = 10\ GeV)$

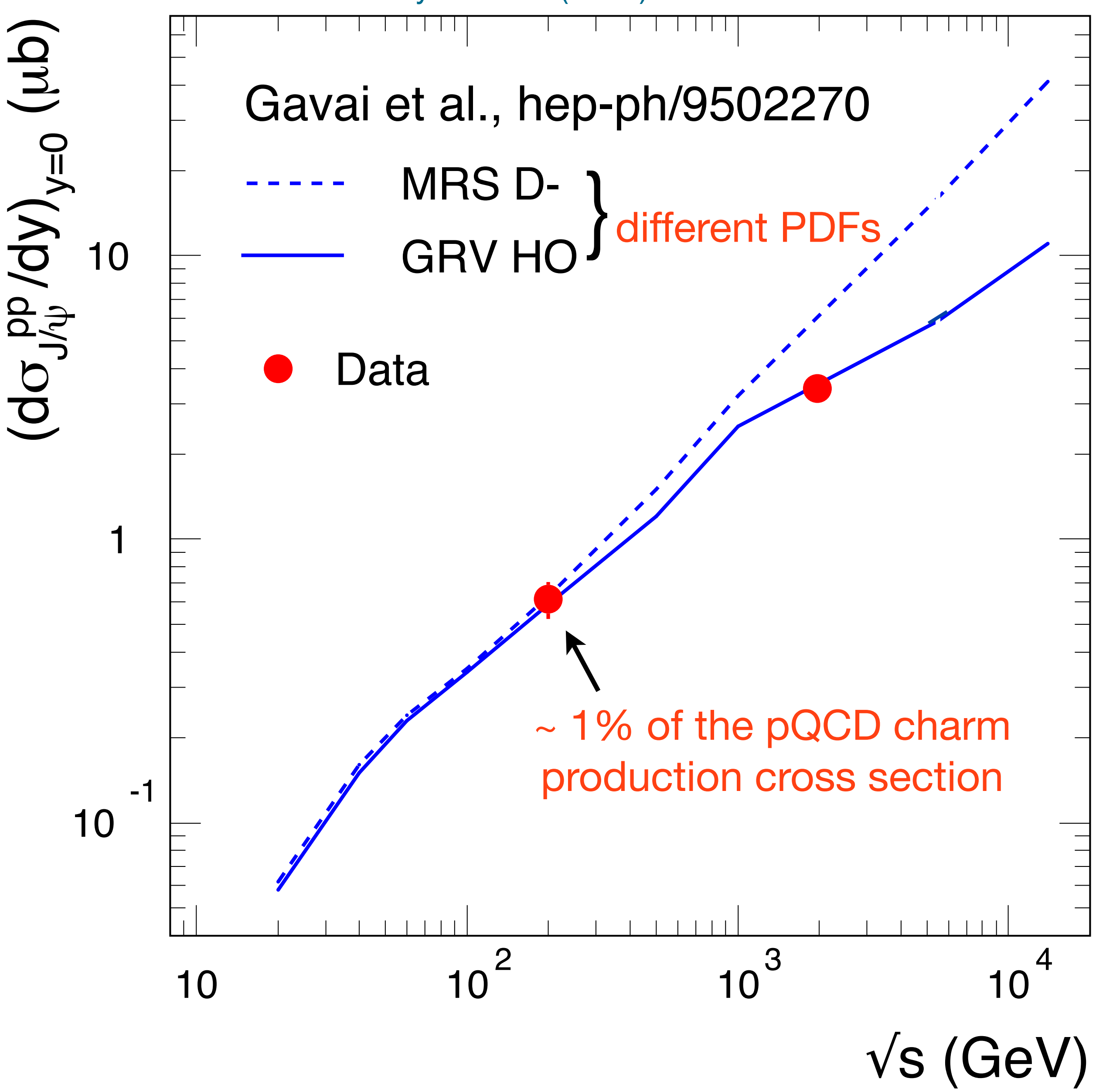
π	D	B	L_{QGP}
20 fm	**1.5 fm**	**0.4 fm**	≤ 6 fm

→ collisional dissociation probability of heavy mesons in the QGP

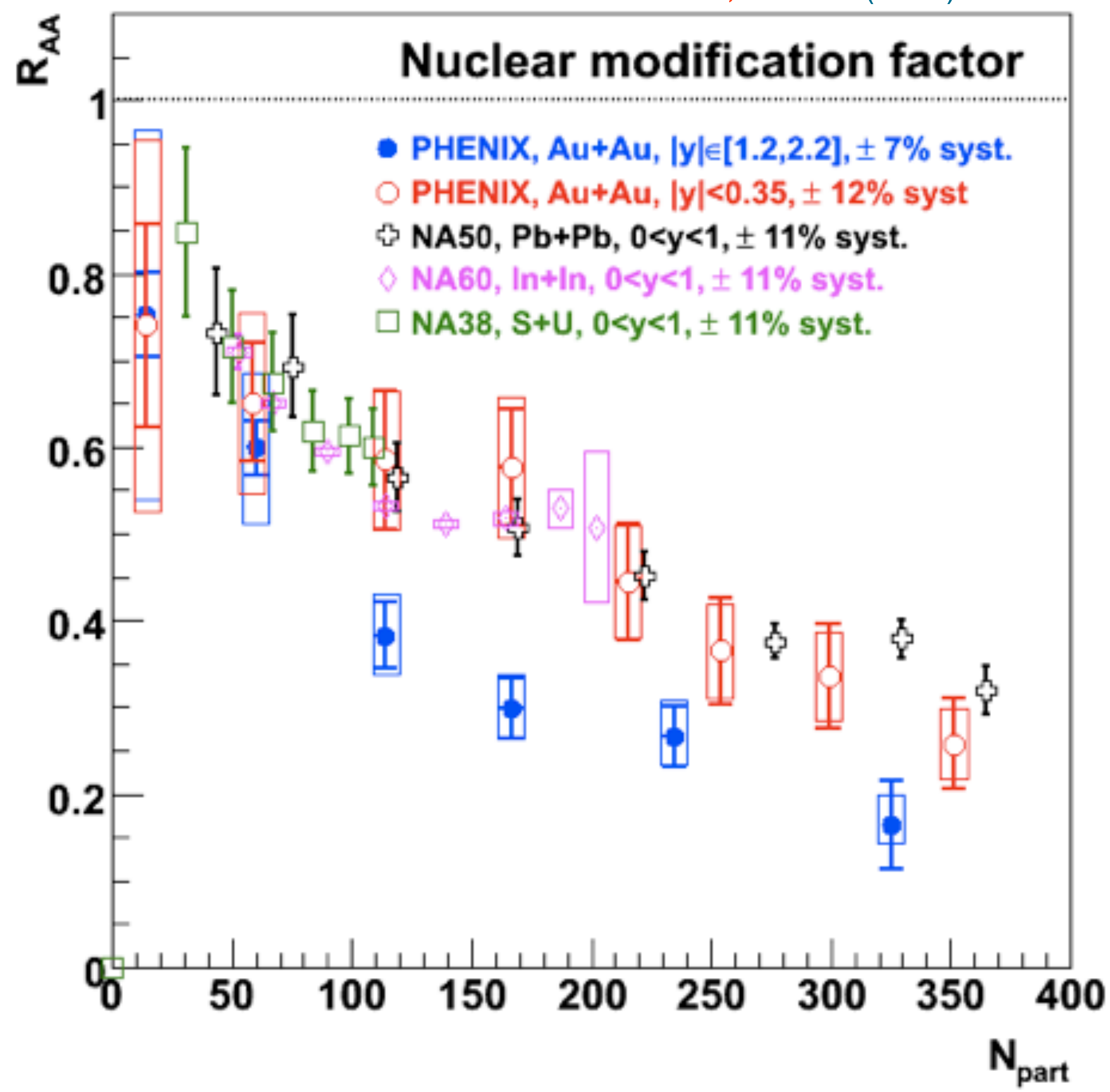
B-meson suppression comparable to D-meson as low as p_T ~10 GeV ($\tau_{\text{B-form}} < \tau_{\text{D-form}}$)
→ R_{AA}, which doesn't neglect large B-meson contribution, describes well the quenching

J/Ψ production at RHIC

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
Nucl. Phys. A 789 (2007) 334

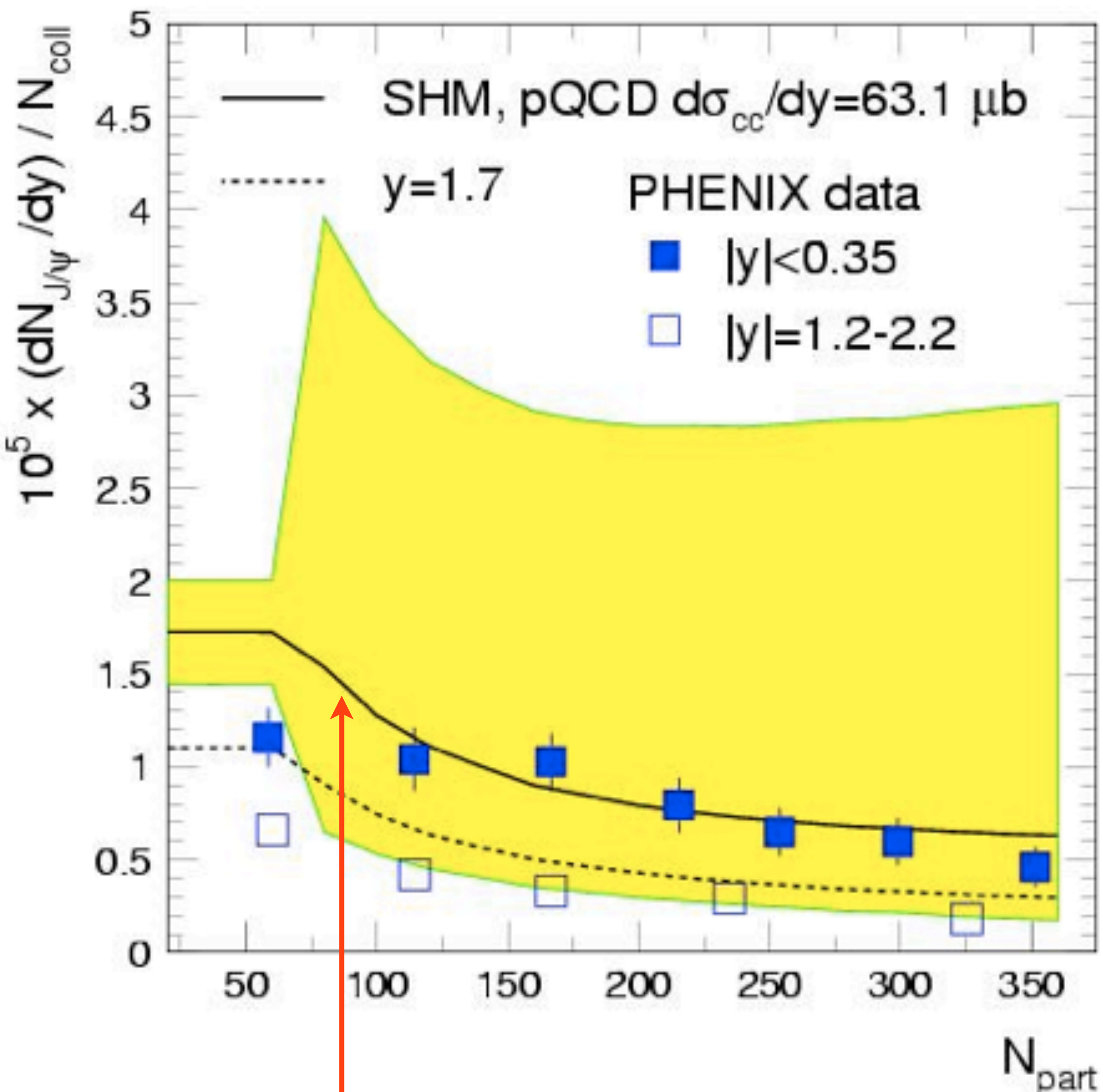


PHENIX, PRL 98 (2007) 232301

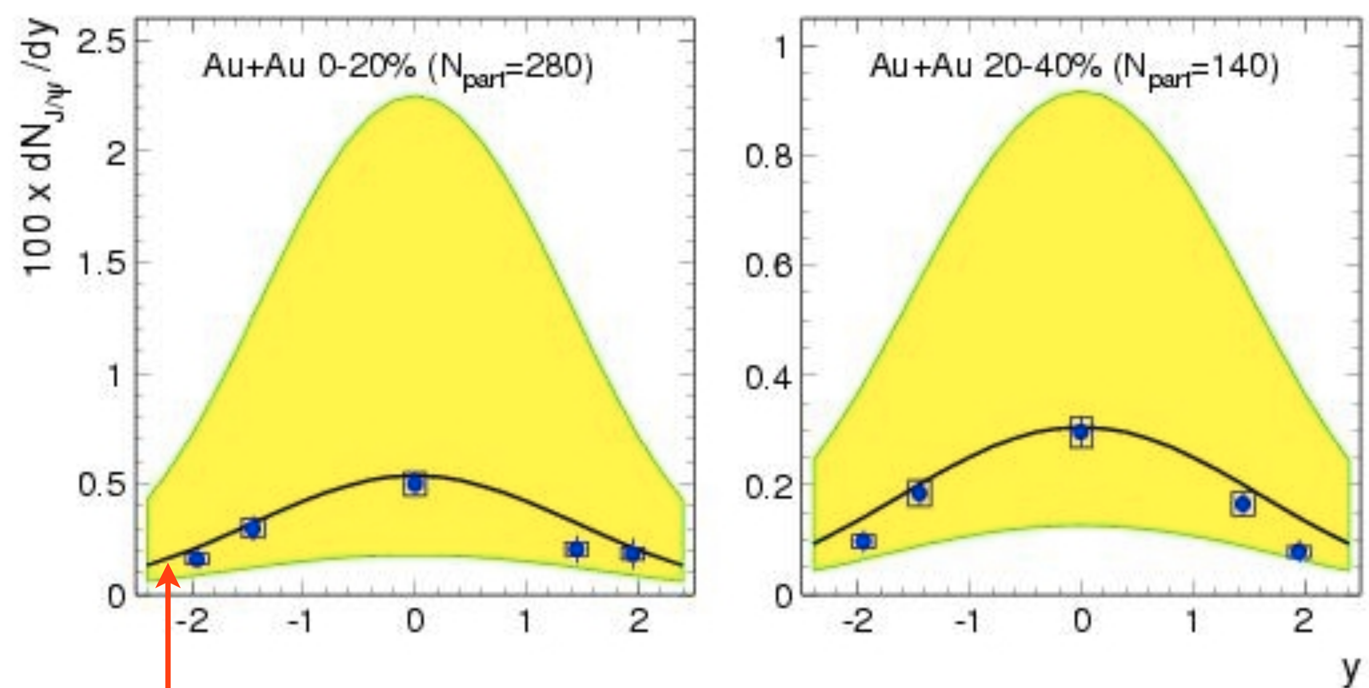


At mid-rapidity, suppression at RHIC very similar to SPS (different system!)
Suppression at forward/backward rapidity stronger (differ from naive expectation!)

Comparison of model prediction to RHIC data



A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
Nucl. Phys. A 789 (2007) 334



p+p open charm cross section FONLL Cacciari et al., PRL 95 (2005) 122001

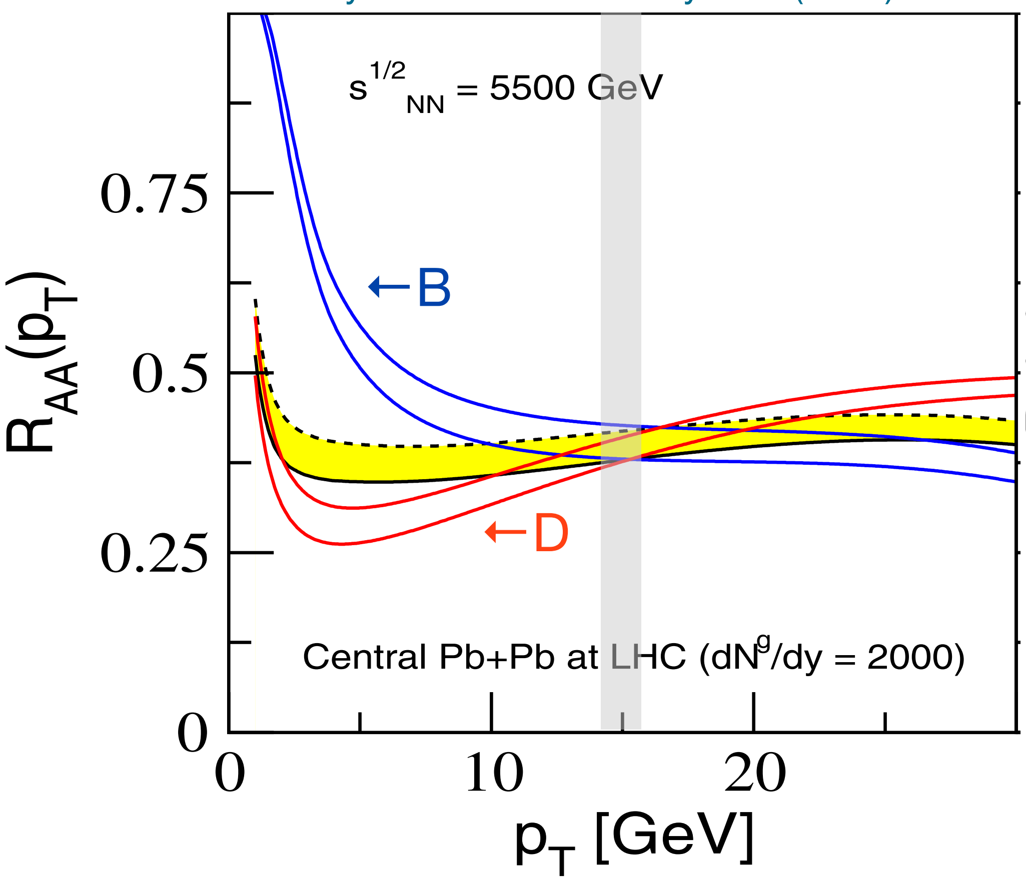
calculation for central value of the pQCD charm production cross section

Good agreement and no free parameters

Open heavy flavour R_{AA} at LHC (I)

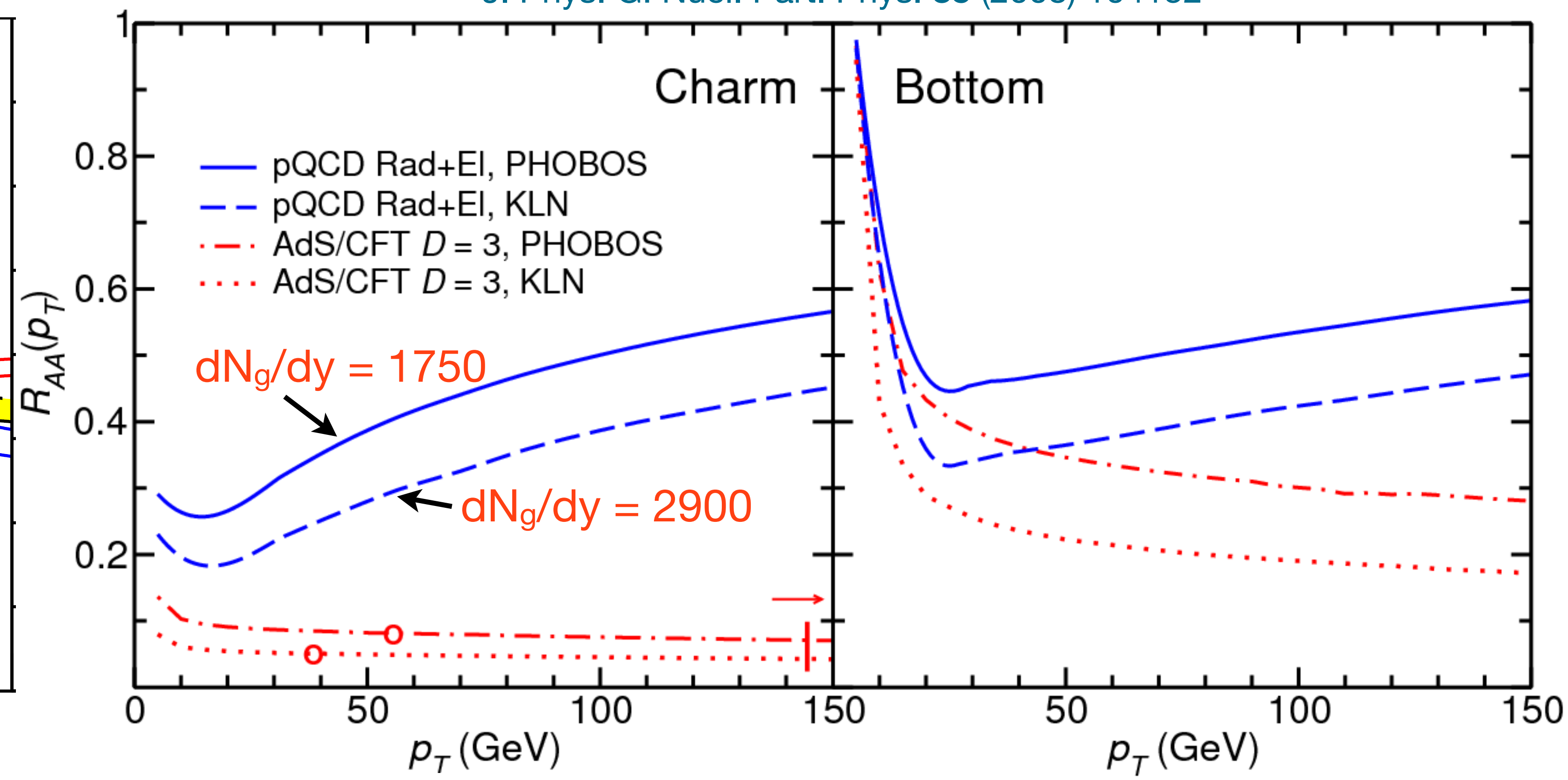
Heavy meson dissociation in QGP

I Vitev, A Adil and H van Hees,
J. Phys. G: Nucl. Part. Phys. **34** (2007) S769



AdS/CFT drag and pQCD

W A Horowitz and M Gyulassy,
J. Phys. G: Nucl. Part. Phys. **35** (2008) 104152

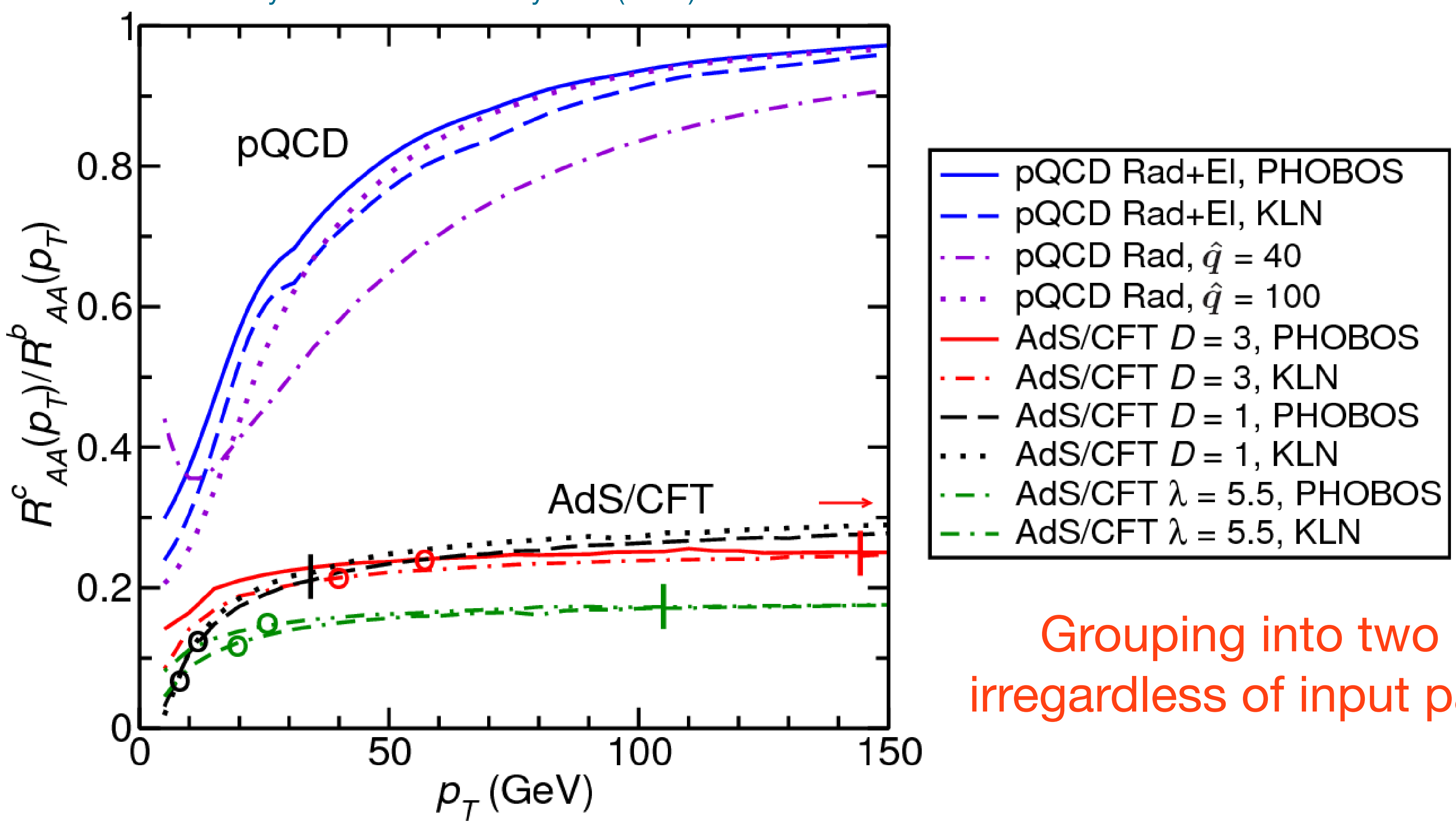


GLV + QGP dissociation shows B-meson suppression comparable to (or larger) D-meson as low as $p_T \sim 15$ GeV

pQCD curves have a significant rise and the AdS curves fall with p_T

Charm-to-Bottom ratio at LHC

W A Horowitz and M Gyulassy,
J. Phys. G: Nucl. Part. Phys. **35** (2008) 104152



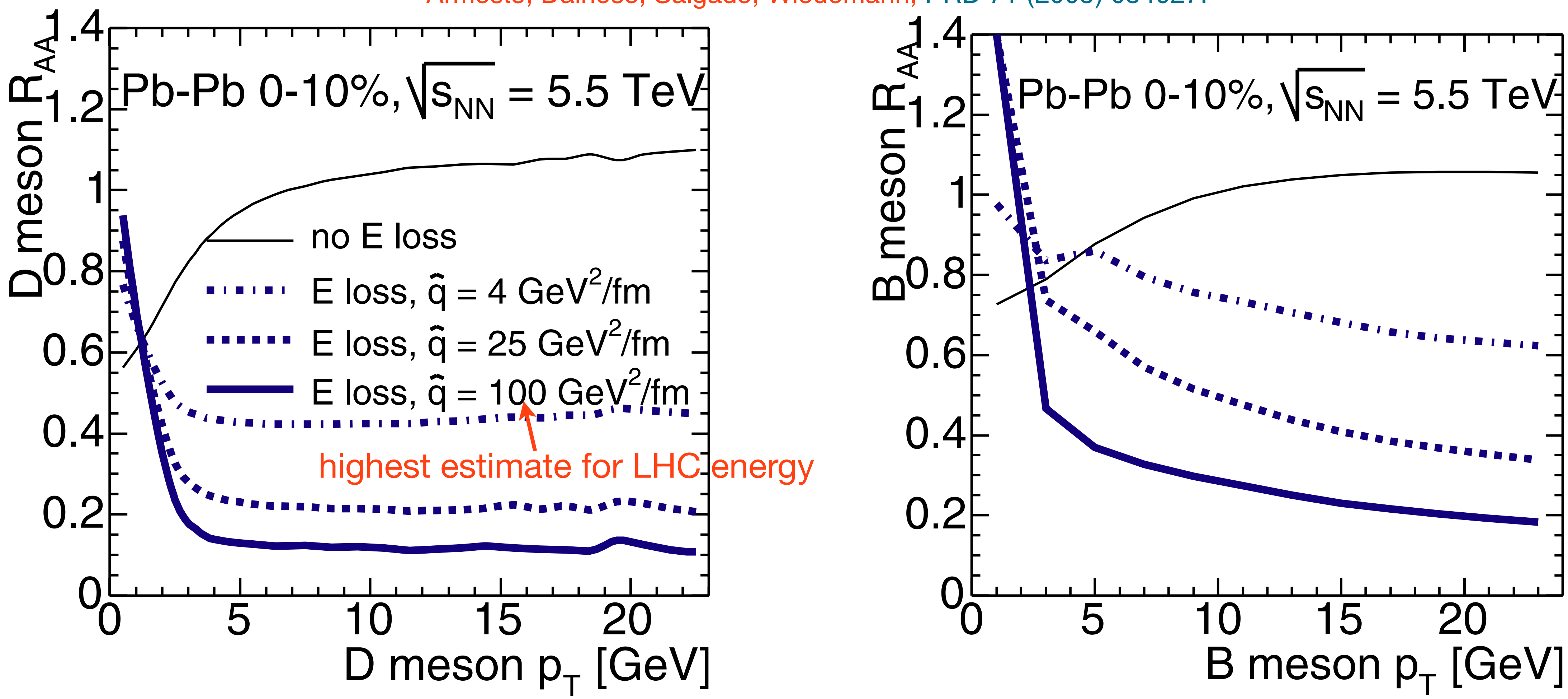
Grouping into two bands, irregardless of input parameters

$R_{AA}{}^c/R_{AA}{}^b$ vs. p_T is remarkably robust observable for finding deviations from different theoretical framework

→ Interesting to measure charm and bottom separately

Open heavy flavour R_{AA} at LHC (II)

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



Baseline: PYTHIA, with EKS98 shadowing, tuned to reproduce c and b p_T distributions from NLO pQCD(MNR) MNR: Mangano, Nason, Ridolfi, NPB 373 (1992) 295.

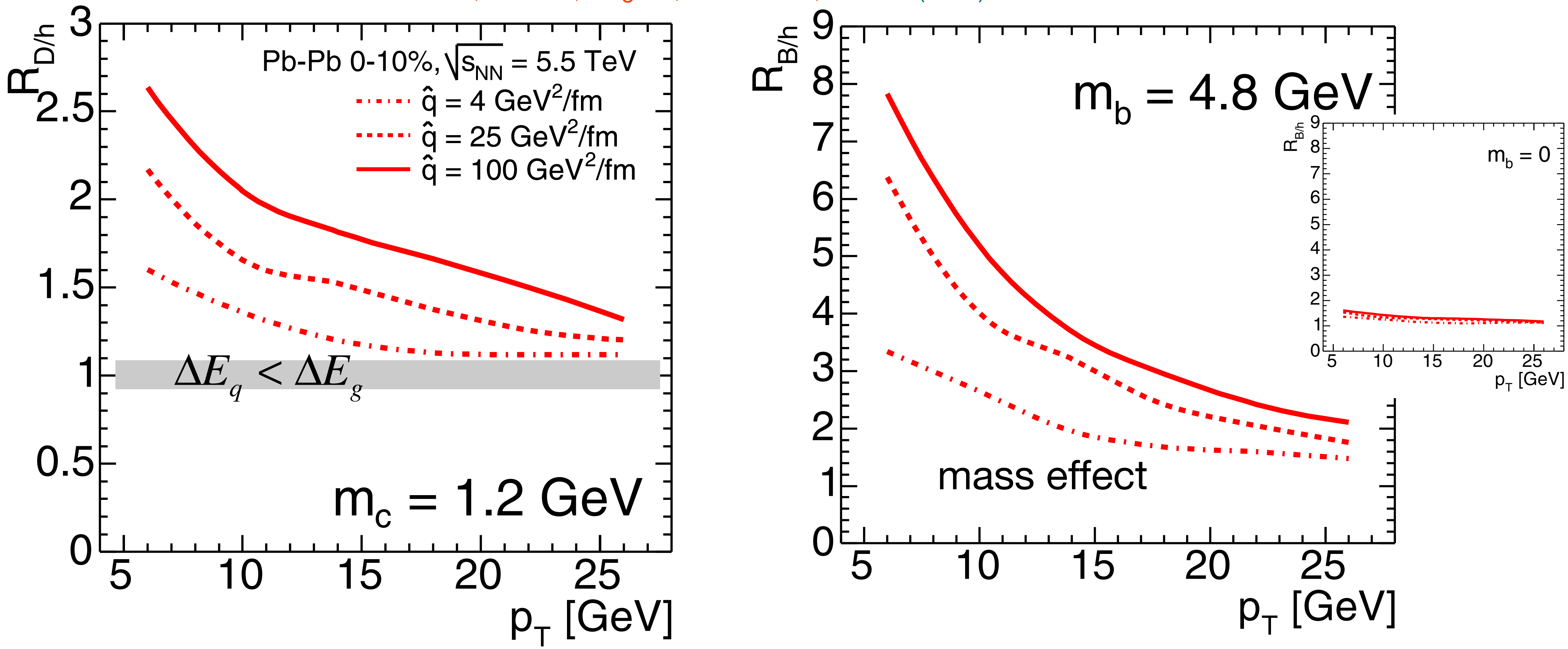
R_{AA} of D meson is less sensitive on varying $\hat{q}$ (higher $\hat{q}$ region), but can give good constraint together with R_{AA} of B meson with precise measurement

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→h, c→D and b→B (Light flavour hadrons come mainly from gluons)

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



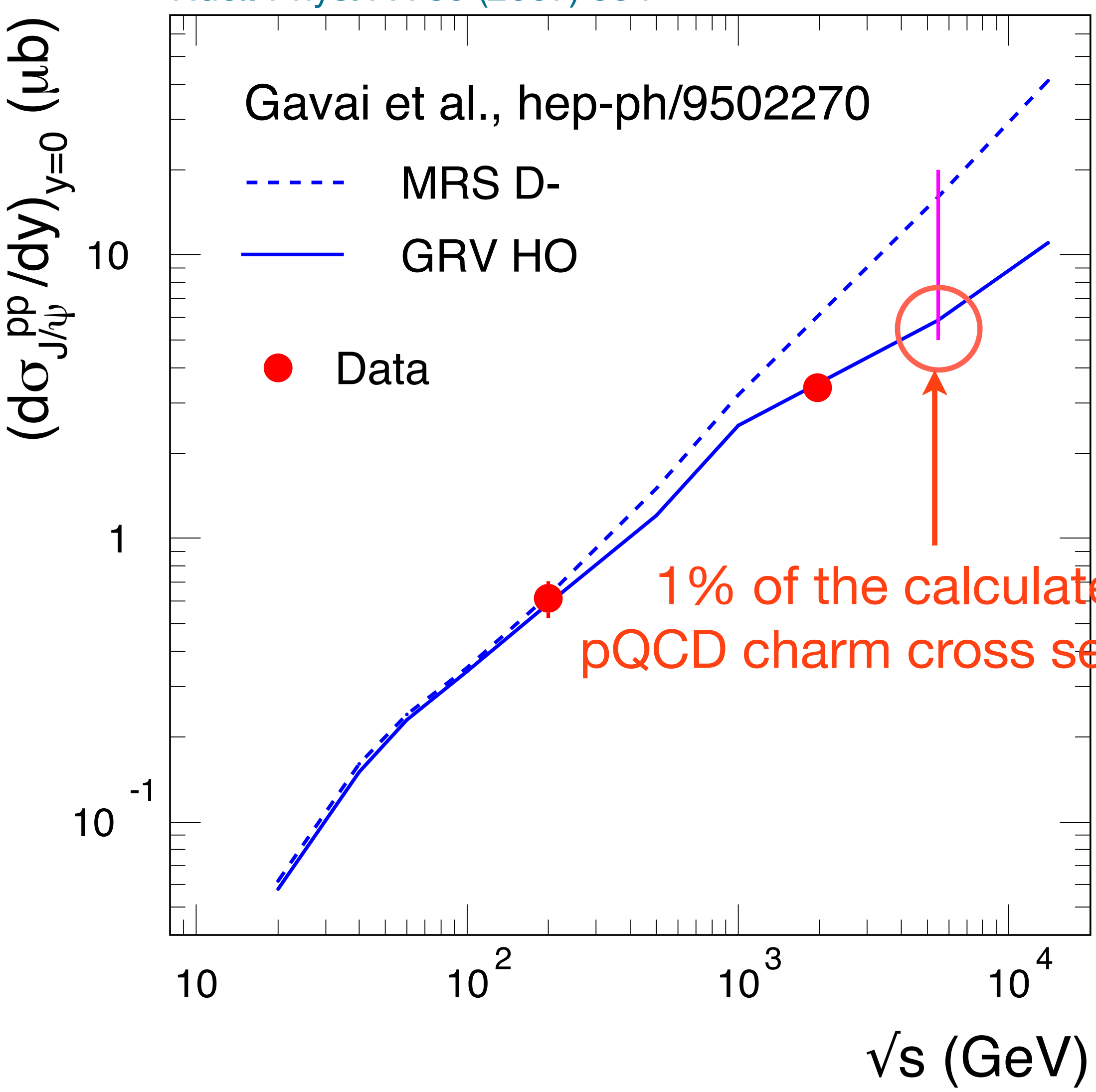
$R_{D/h}$ enhancement probes colour-charge dependence of energy loss

$R_{B/h}$ enhancement probes mass dependence of energy loss

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega),$$
$$C_R = 3(4/3) \;\; for \; g(q)$$

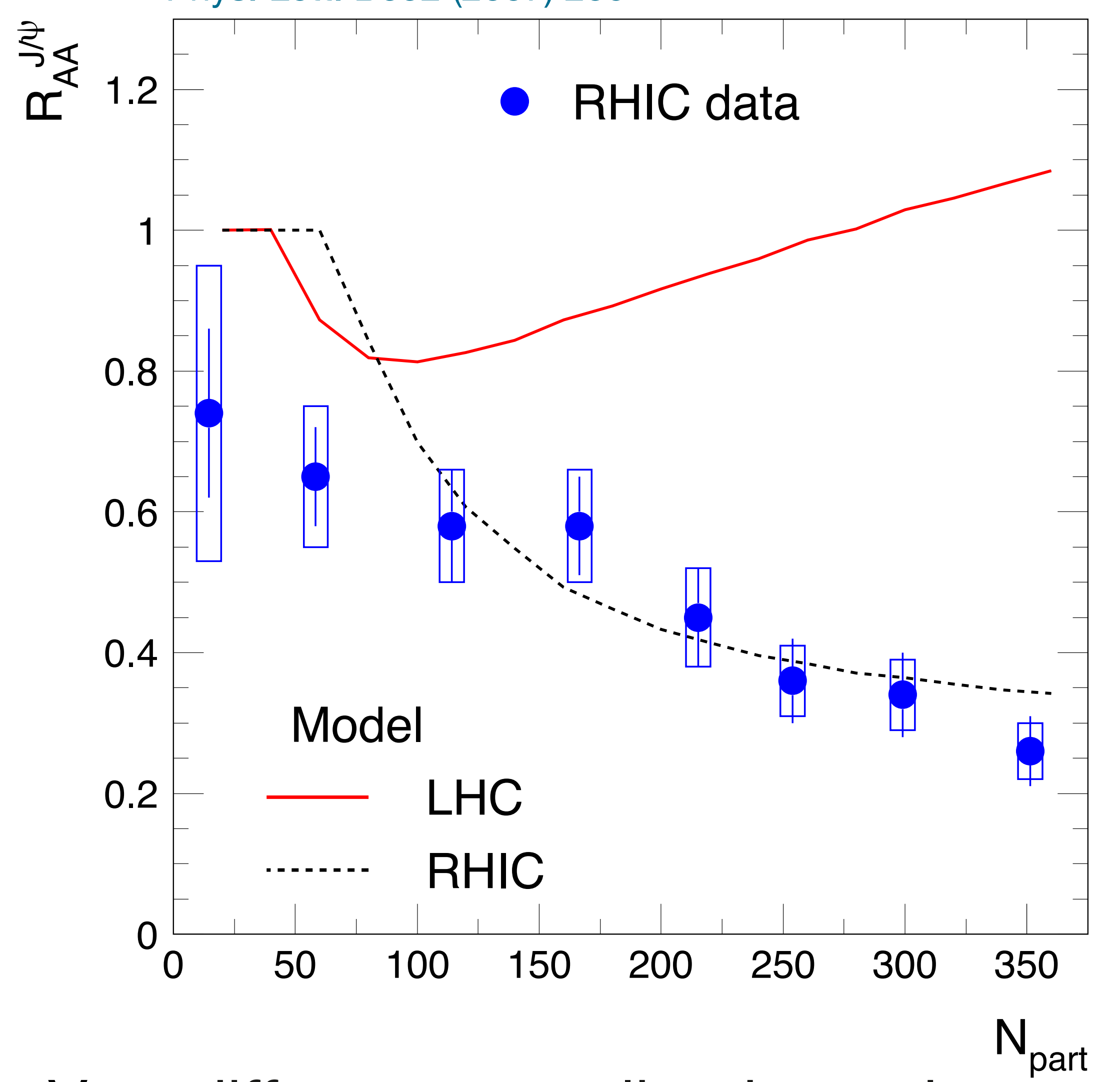
J/Ψ at LHC

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
Nucl. Phys. A 789 (2007) 334



$\sqrt{s_{NN}}$ (GeV)	$d\sigma^{pp}_{c\bar{c}}/dy$ (μb)	$d\sigma^{pp}_{J/\psi}/dy$ (μb)
17.3	$5.7^{+5.7}_{-2.8}$	0.050±0.030
200	$63.7^{+95.6}_{-42.3}$	0.774±0.124
5500	639^{+639}_{-319}	6.4±3.2

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
Phys. Lett. B652 (2007) 259



Very different centrality dependence

"suppression" at RHIC

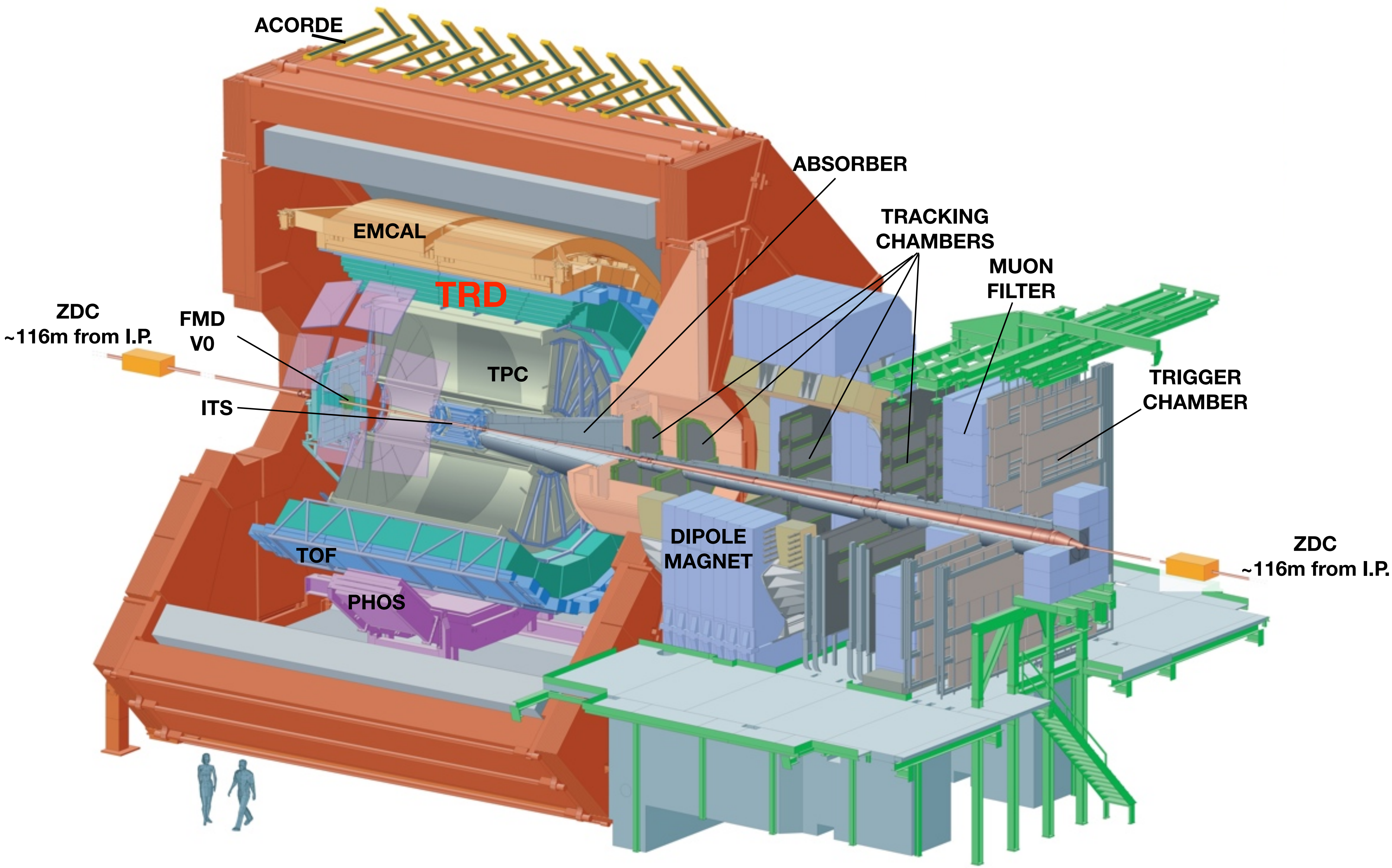
"enhancement" at LHC: $N_{J/\Psi} \sim (N_{cc}^{dir})^2$

Compared to RHIC

σ_{cc} : 10x, Volume: 3x

Centrality dependence → striking finger print of deconfined & thermalized heavy quarks in QGP

A Large Ion Collider Experiment



Collaboration: 31 countries, 109 institutes, > 1000 people

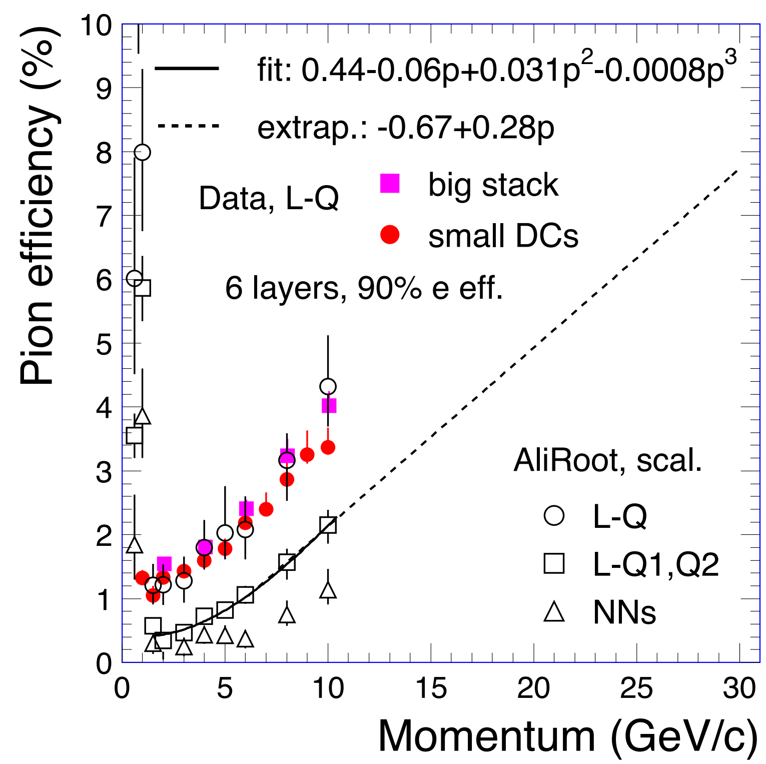
Heavy flavour measurement at ALICE

- Hadronic decays: $D^0 \rightarrow K\pi$, $D^{\pm} \rightarrow K\pi\pi$, $D_s \rightarrow K K^*$, …
- Leptonic decays:
  - $B \rightarrow l$ (e or μ) + anything
  - Invariant mass analysis of lepton pairs: J/Ψ, Ψ', ϒ family, $B \rightarrow J/\Psi$ + anything, $\chi_c \rightarrow J/\Psi$ + anything
- e-D^0 correlations
- B-Jet

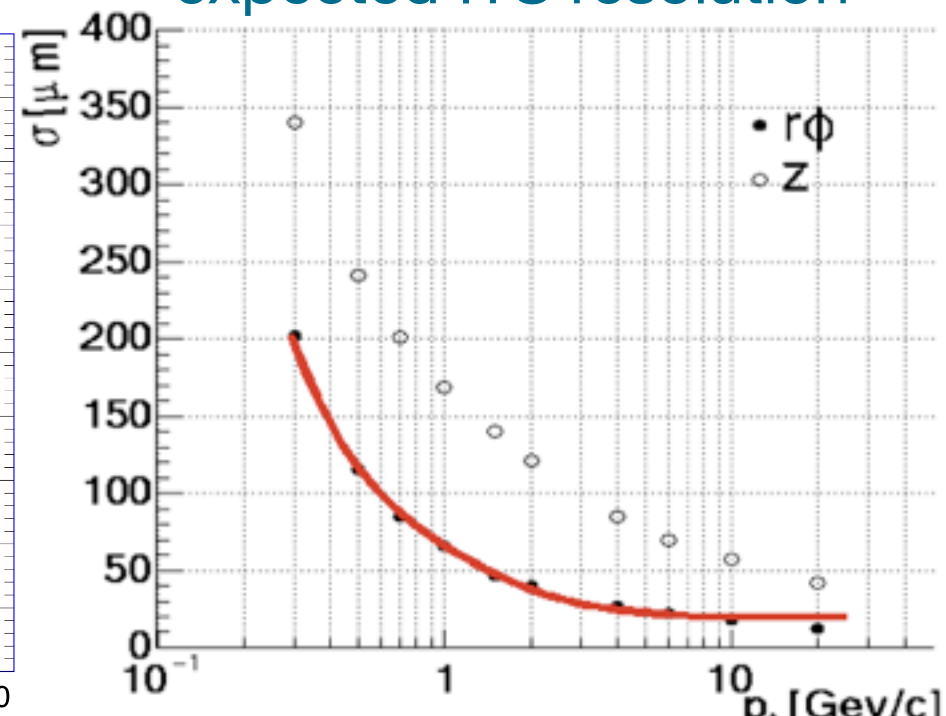
PID of
hadrons, electrons: $-0.9<y<0.9$
muons: $2.5<y<4.0$

In central barrel: vertex cut effective for heavy quark identification

TRD pion rejection



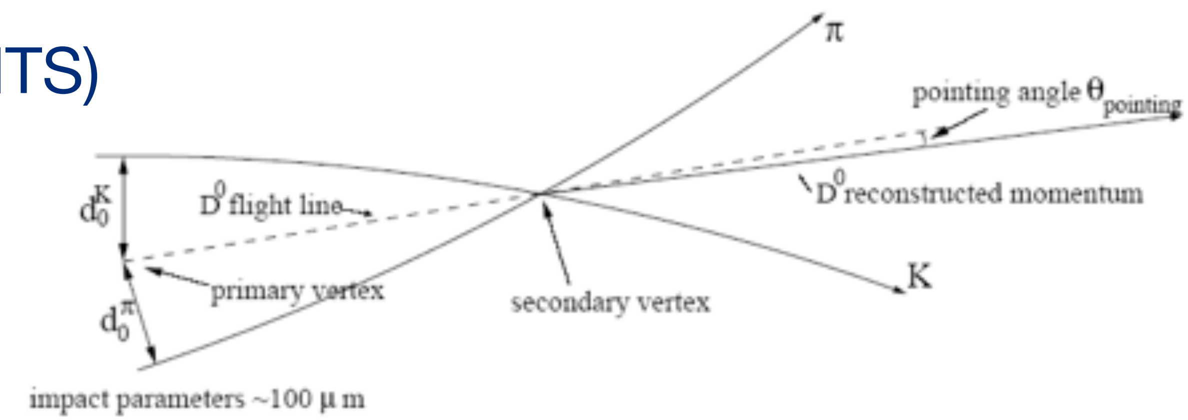
expected ITS resolution

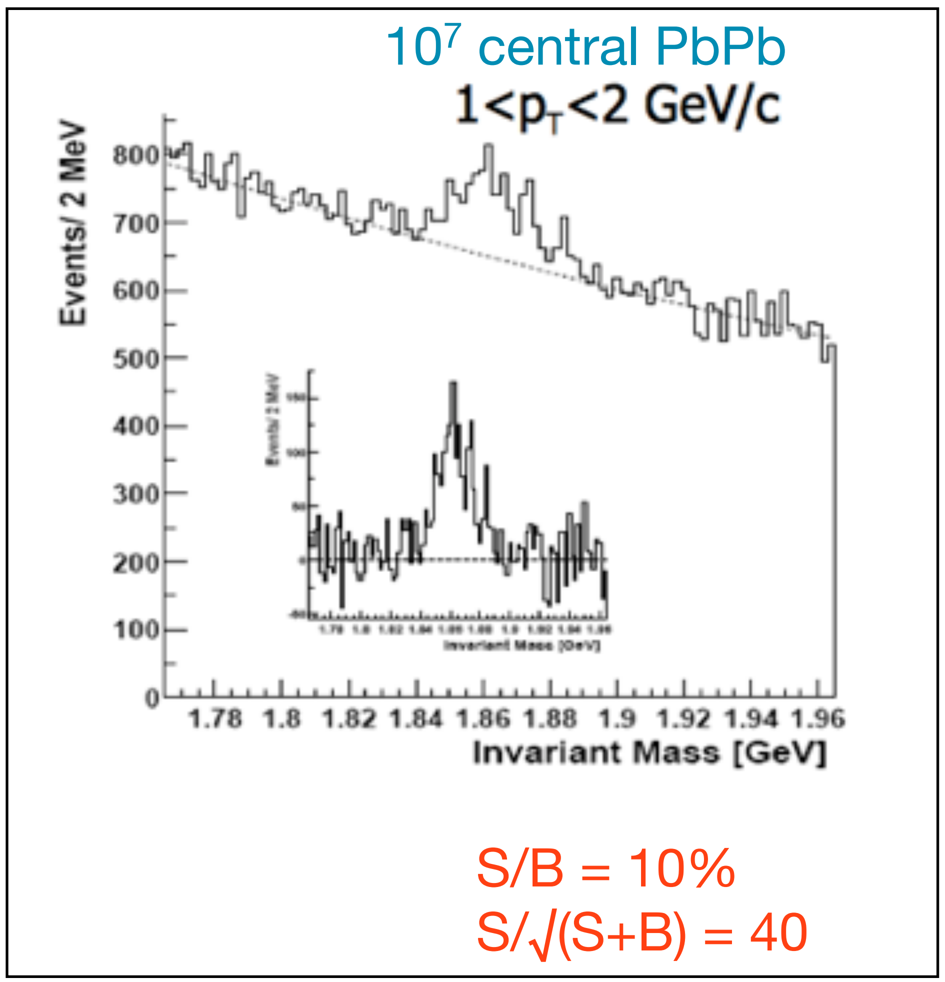


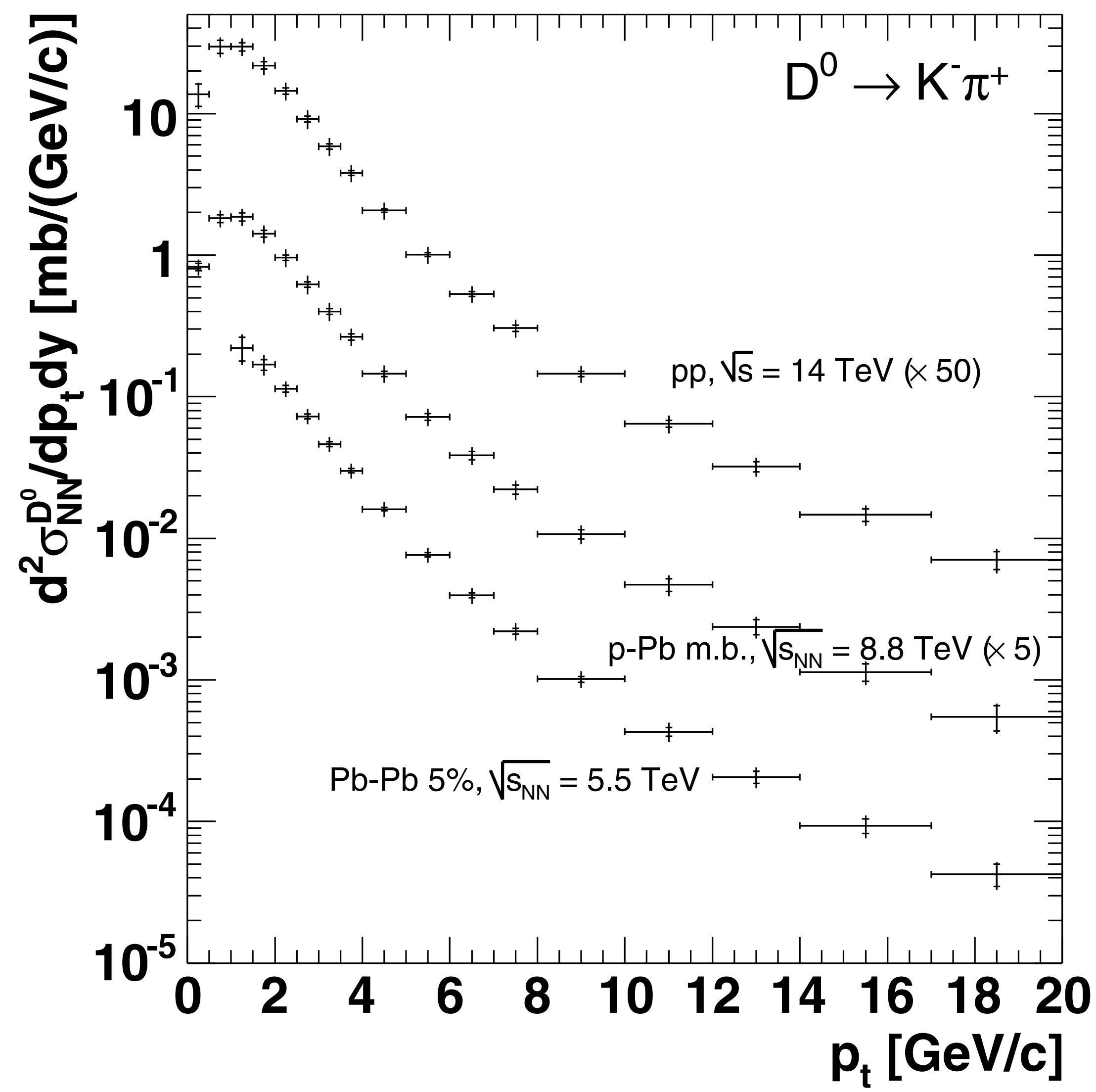
ALICE Physics Performance Report 2, J. Phys. G: Nucl. Part. Phys. 32 (2006) 1295

Open charm from $D^0 \rightarrow K\pi$

- high precision vertexing, better than 100 μm (ITS)
- high precision tracking (ITS+TPC)
- K and/or π identification (TOF)



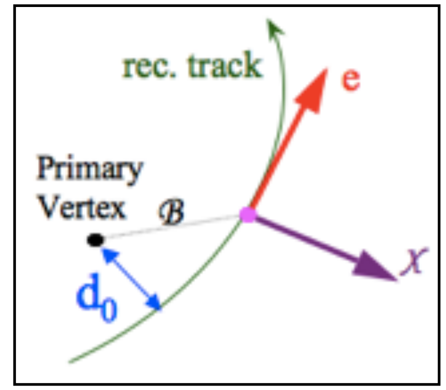


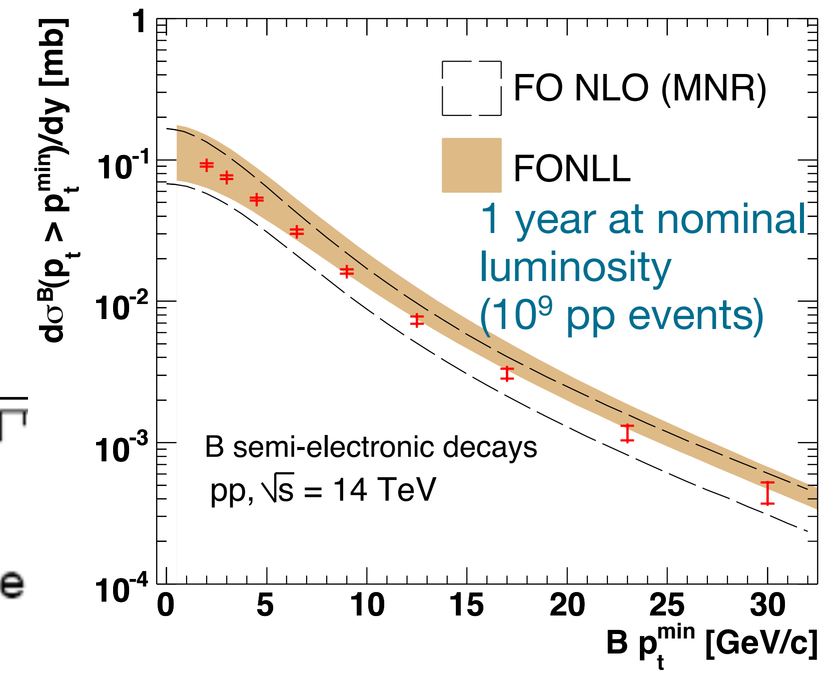


Alice can measure charm from $0 < p_T < 20$ GeV (down to $p_T \sim 0$) with high precision

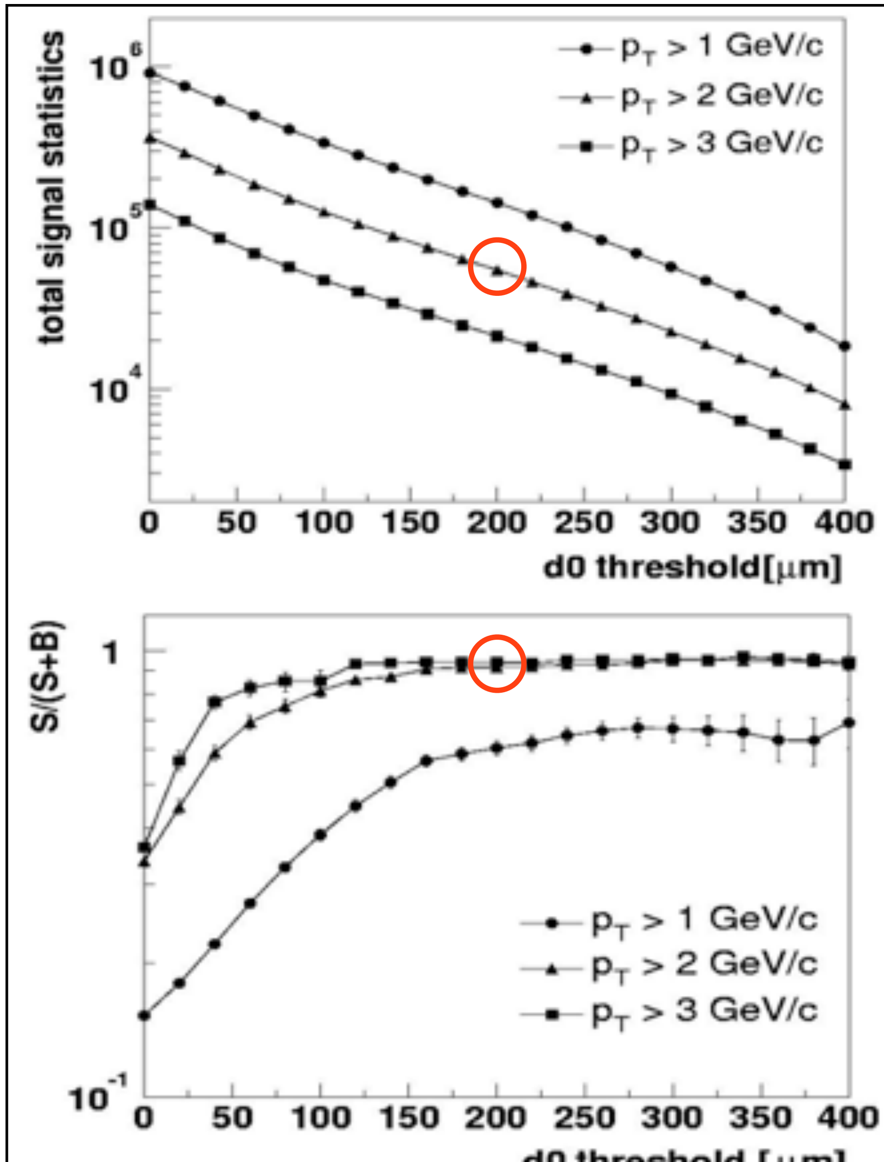
Open beauty from single electrons

- ALICE has excellent electron identification capabilities
- Displaced electrons from B decays can be tagged by an impact parameter cut

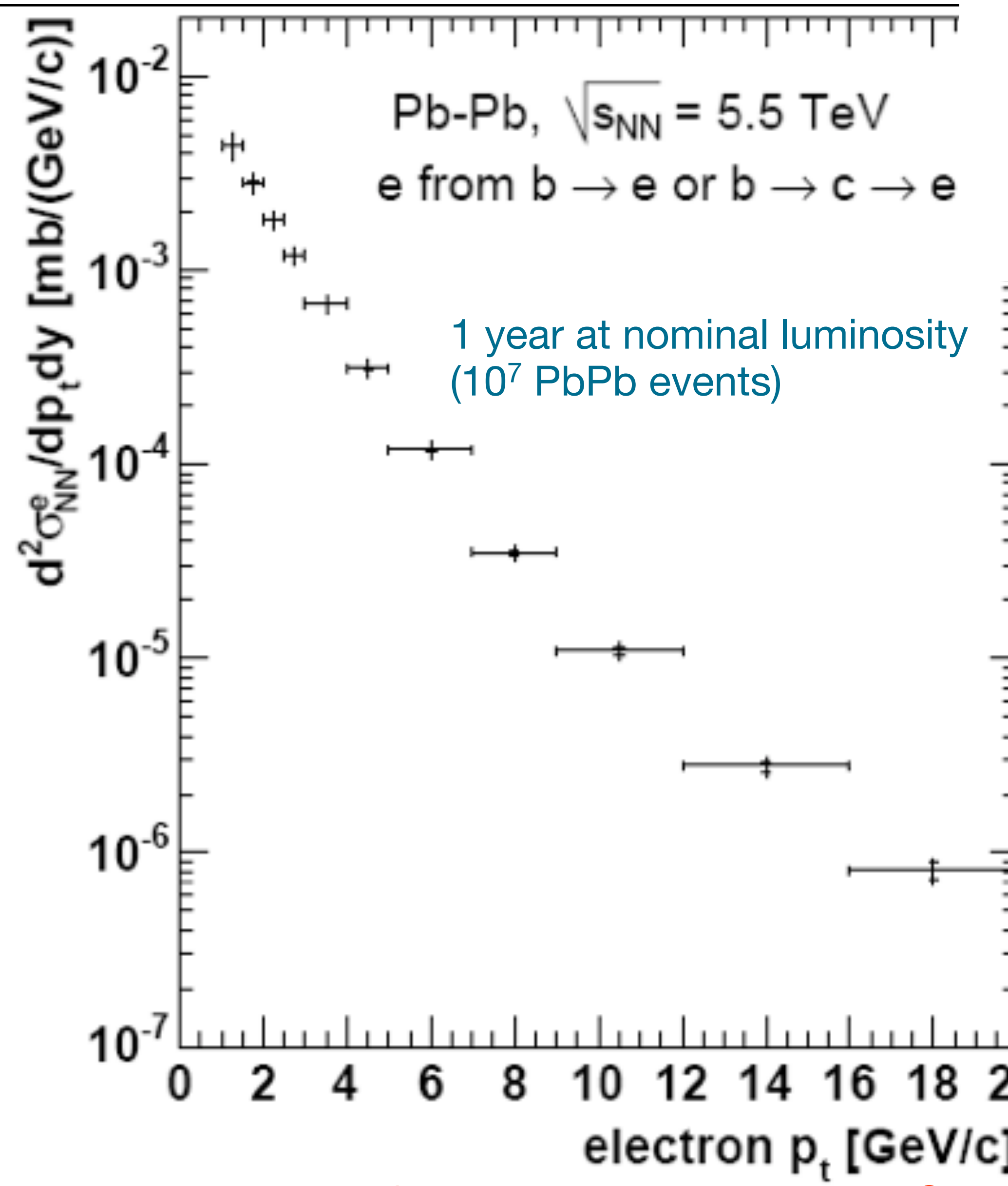




A. Dainese, nucl-ex/0811.3237



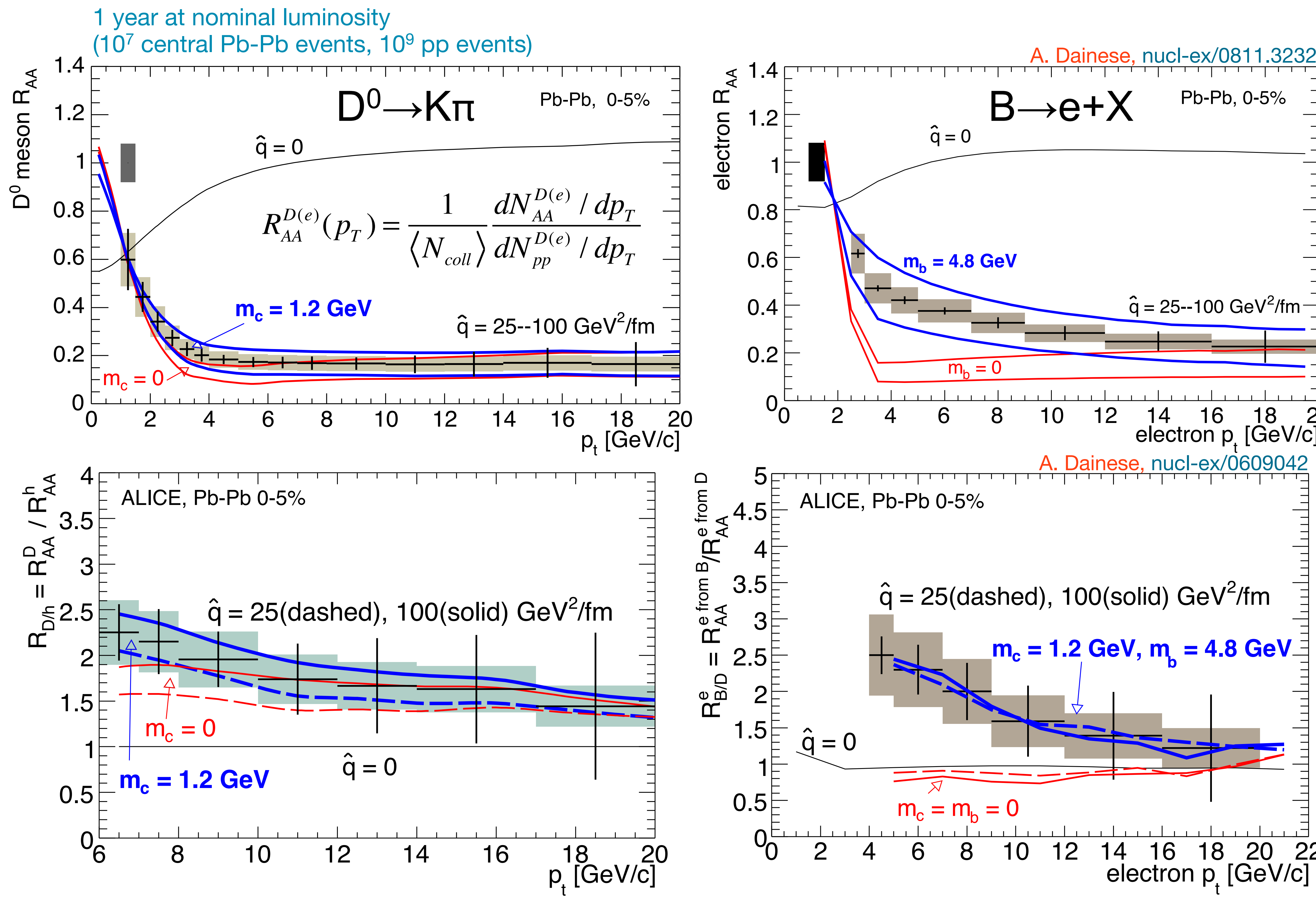
pt > 2 GeV/c & d0 = 200 -600μm:
80 000 electrons with S/(S+B) = 80%



ALICE Physics Performance Report 2,
J. Phys. G: Nucl. Part. Phys. 32 (2006) 1295

Alice can measure beauty (semi-leptonic decays) up to 30(20) GeV/c in p+p (Pb+Pb) events

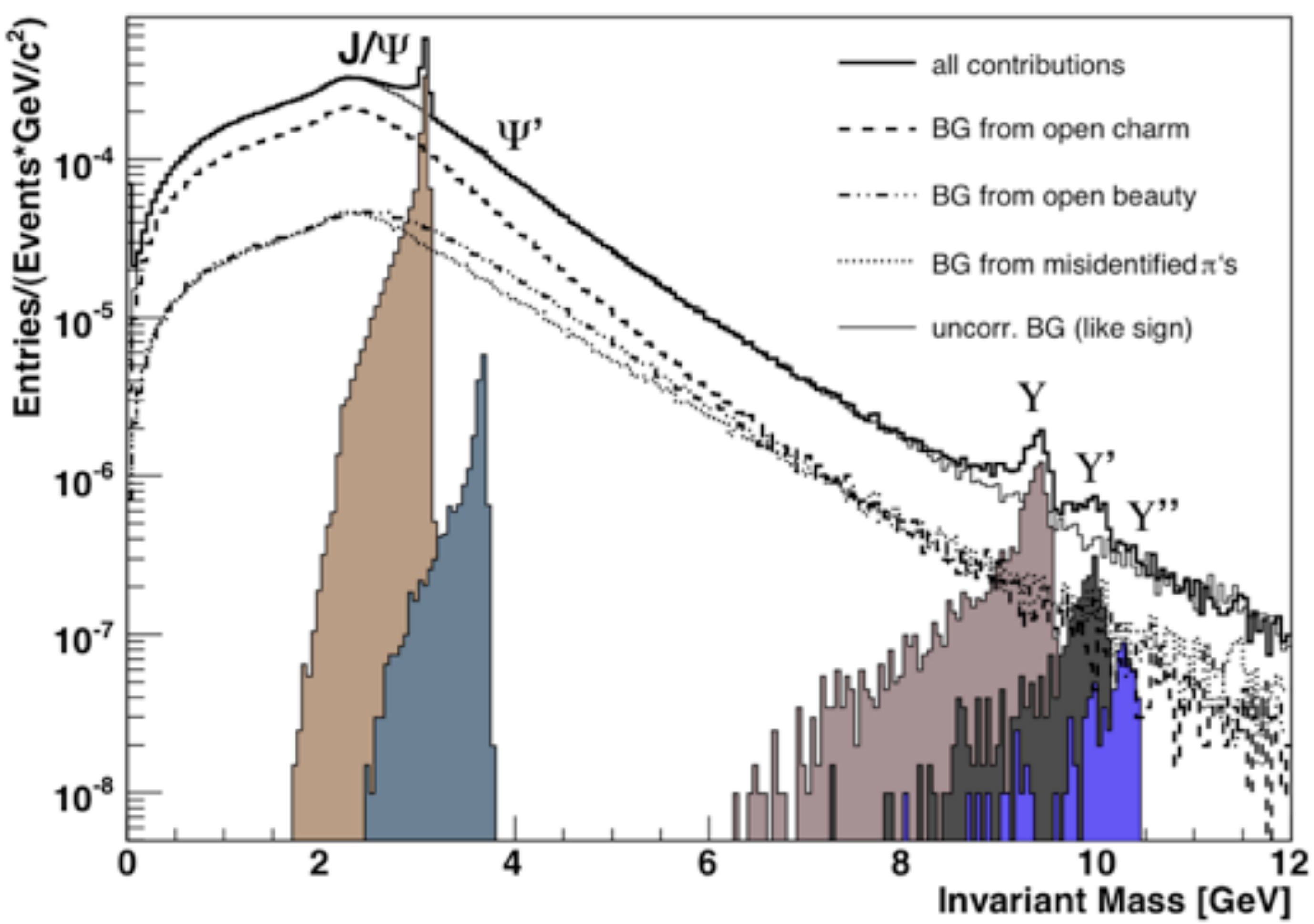
Nuclear modification for open heavy flavour

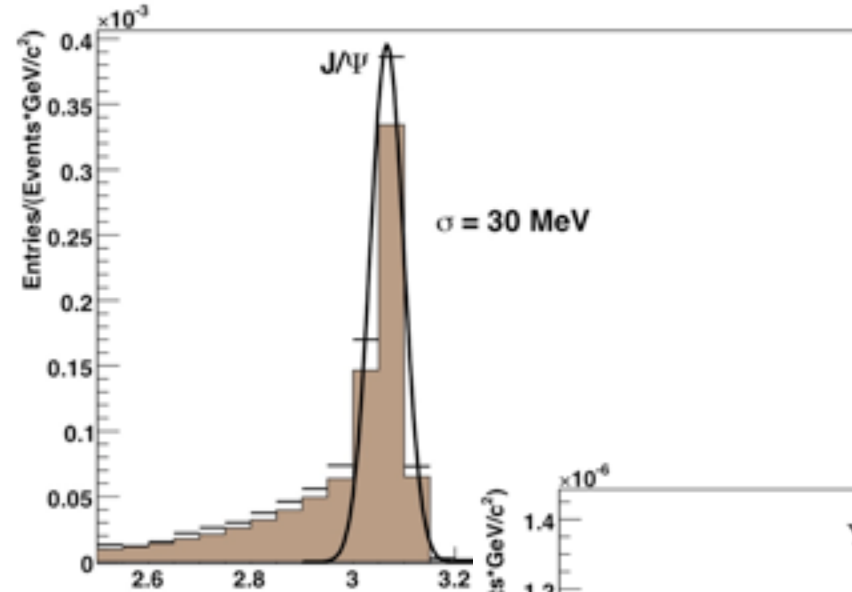


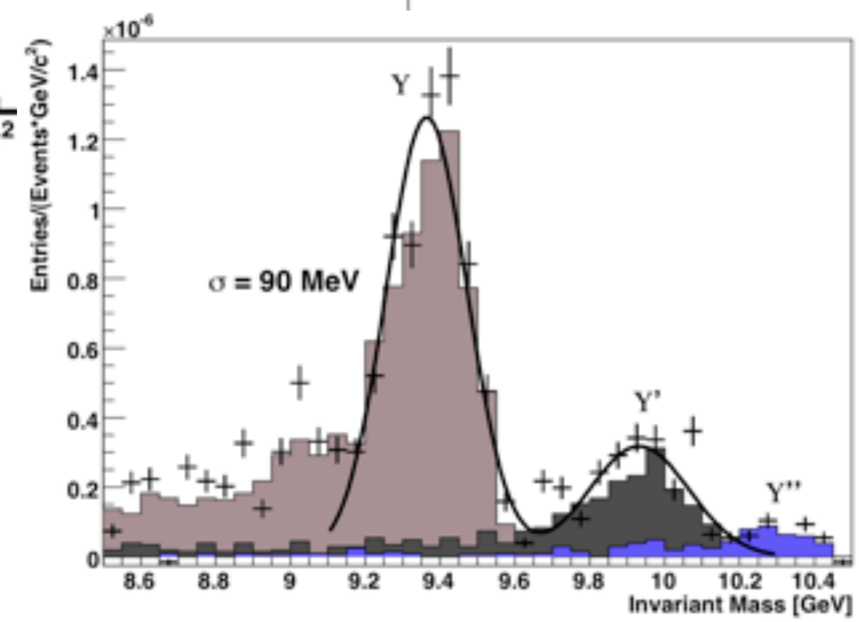
Data of one full luminosity Pb+Pb run (10^6 s) should clarify heavy flavor quenching story

Quarkonium from di-electrons at mid-rapidity

Electron identification with TPC and TRD







2×10^8 central Pb-Pb events, Full TRD W. Sommer et al, nucl-ex/0702045

$p_T^e > 1$ GeV/c

	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$
signal	120.000	900	350
S/B	1.2	1.1	0.35
$S/\sqrt{S+B}$	245	21	8

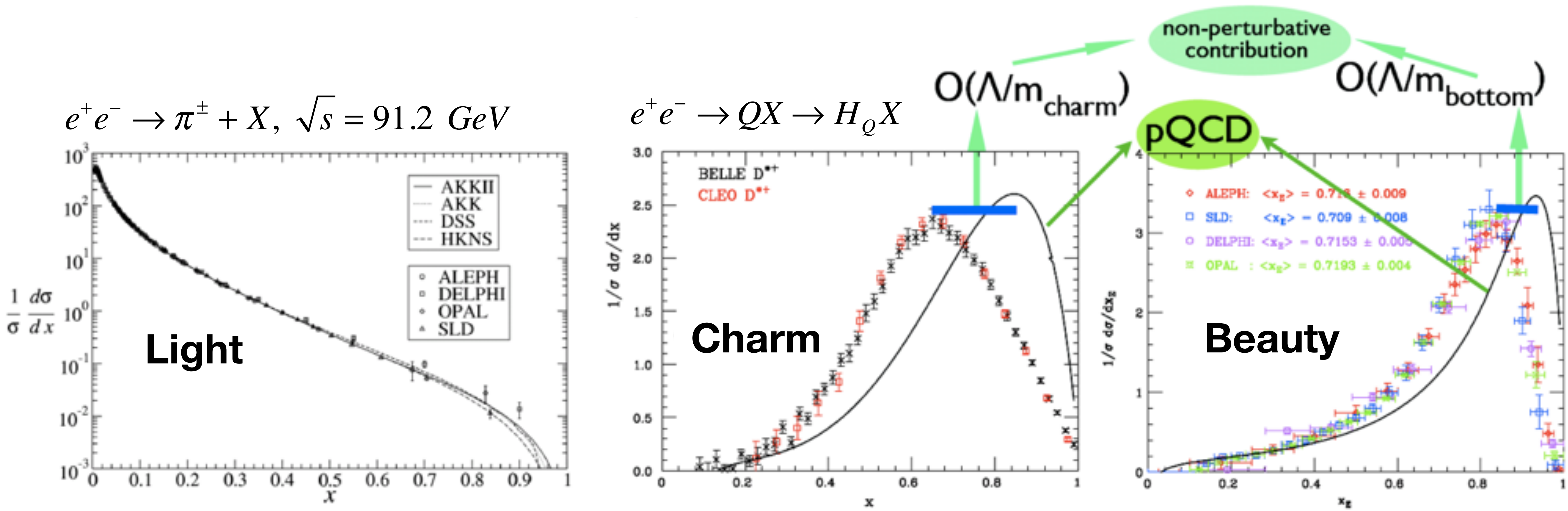
Good mass resolution and signal to background

Estimation by A. Andronic

First run → $\sqrt{s_{NN}}$=2.75 TeV, 7/18 TRD
$\sim$10000 J/ψ, $\sim$70 Υ

Expect with full TRD and trigger ~ 2500 Upsilon per Pb+Pb year

Beauty jet fragmentation function



Heavy quark fragmentation: leading heavy meson carries large momentum fraction

→ More control to extract P(ΔE)? here, P(ΔE): probability to lose energy

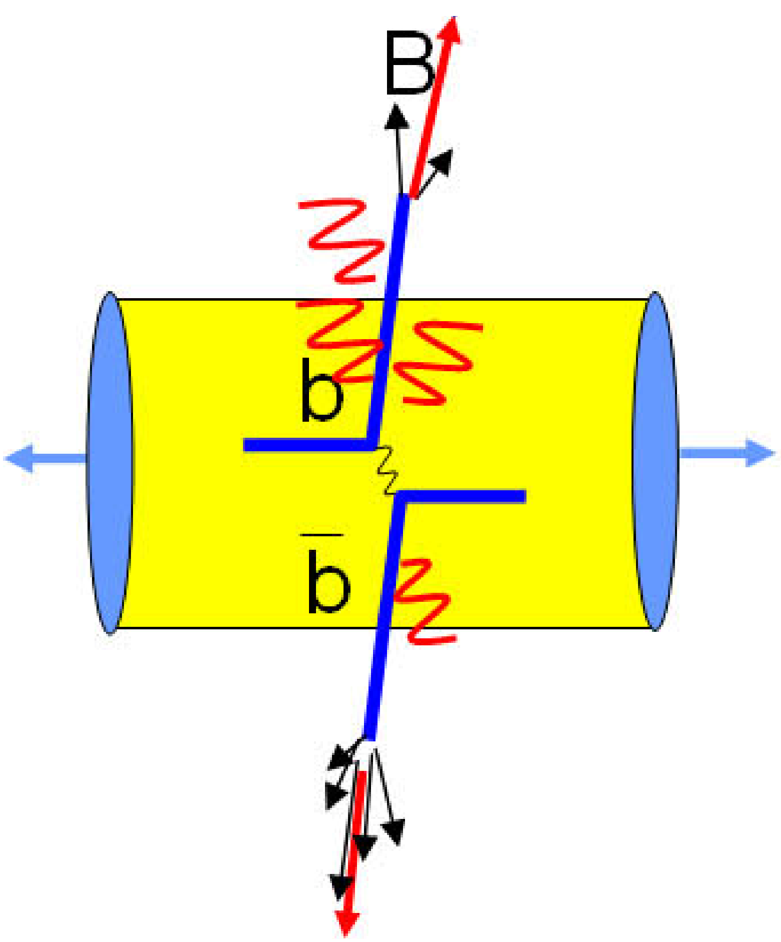
Significant non-perturbative effects seen even in heavy quark fragmentation

→ Interesting to investigate medium modified heavy flavor jet fragmentation function

Beauty, Beauty-Jet measurement at ALICE

Why?

- Measure heavy flavor cross section, also baseline measurement
- Understand heavy flavor production mechanism
- Heavy quark energy loss mechanism in medium
- Medium modified heavy flavor jet fragmentation function

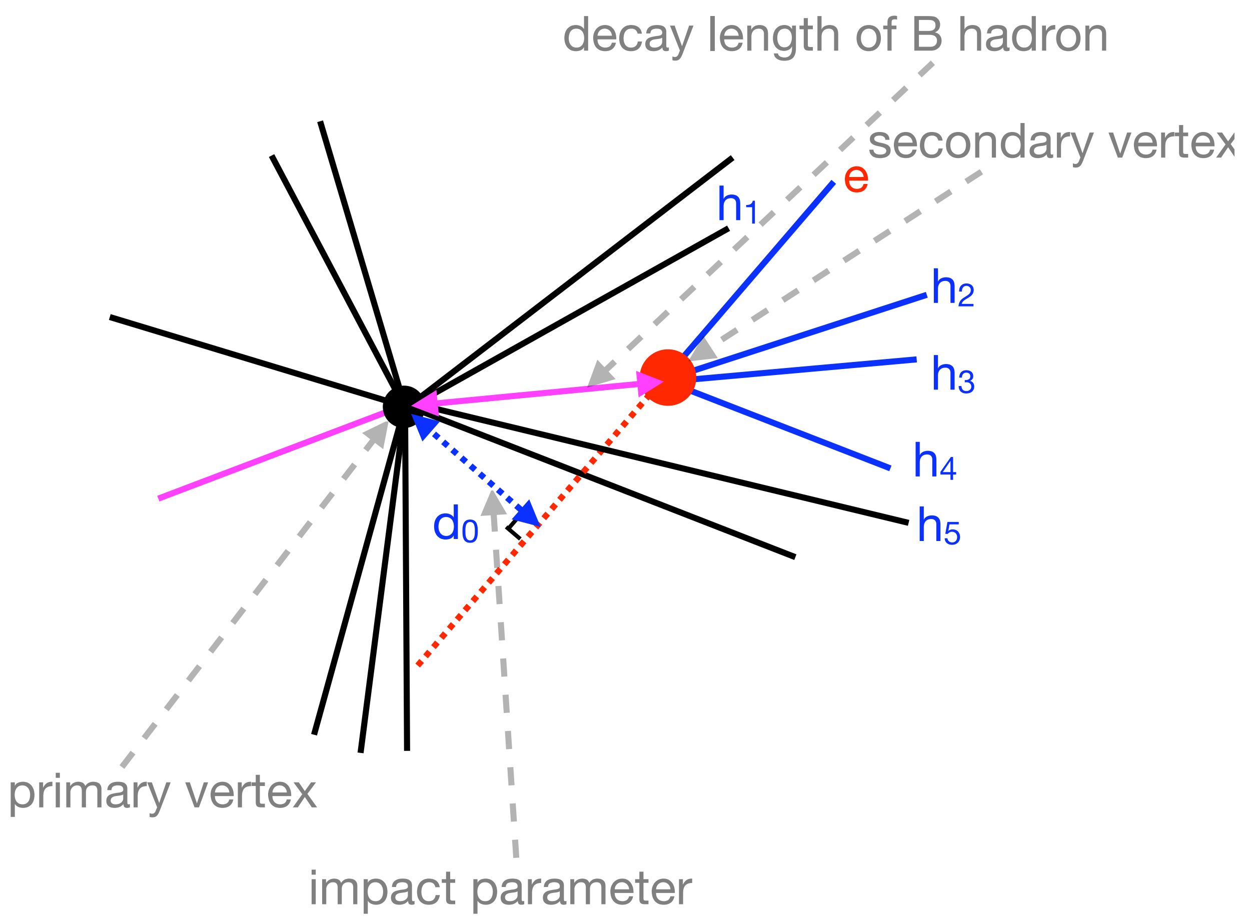


Idea

- Reconstruct jets, tag b-jet by:
  - secondary vertex from charged tracks seeded by beauty electron candidate
  - beauty jet probability considering track impact parameters
  - beauty electron tagging by looking for the evidence of semi-electron decay within a jet

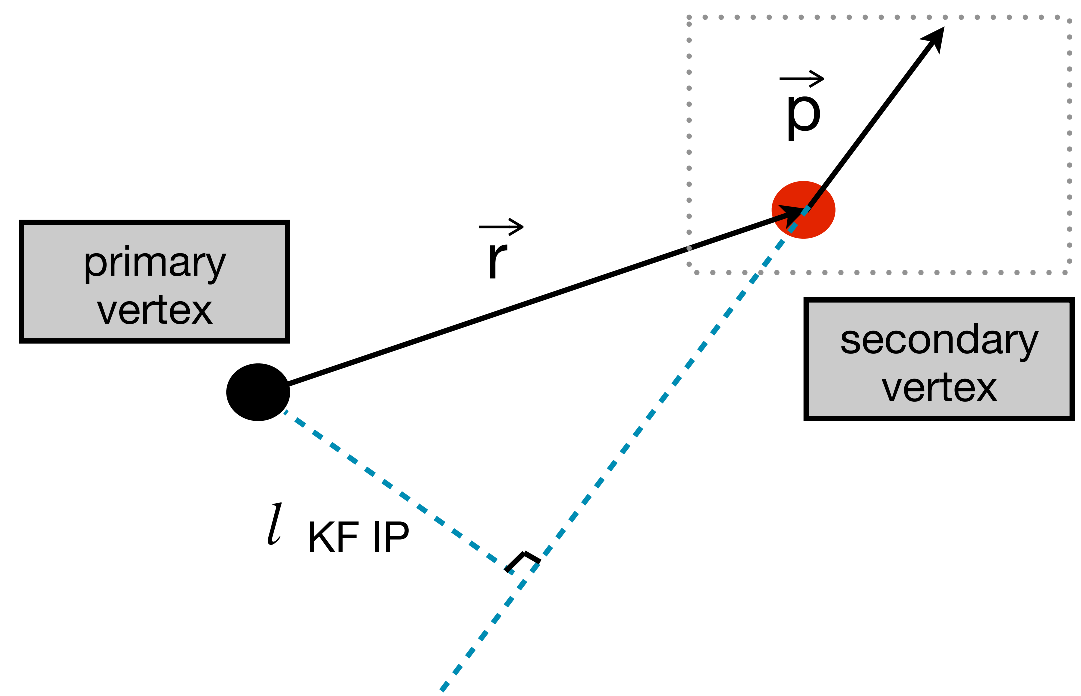
Similar approaches evaluated at CDF which resulted in many important physics publications

Beauty Tagging using secondary vertexing

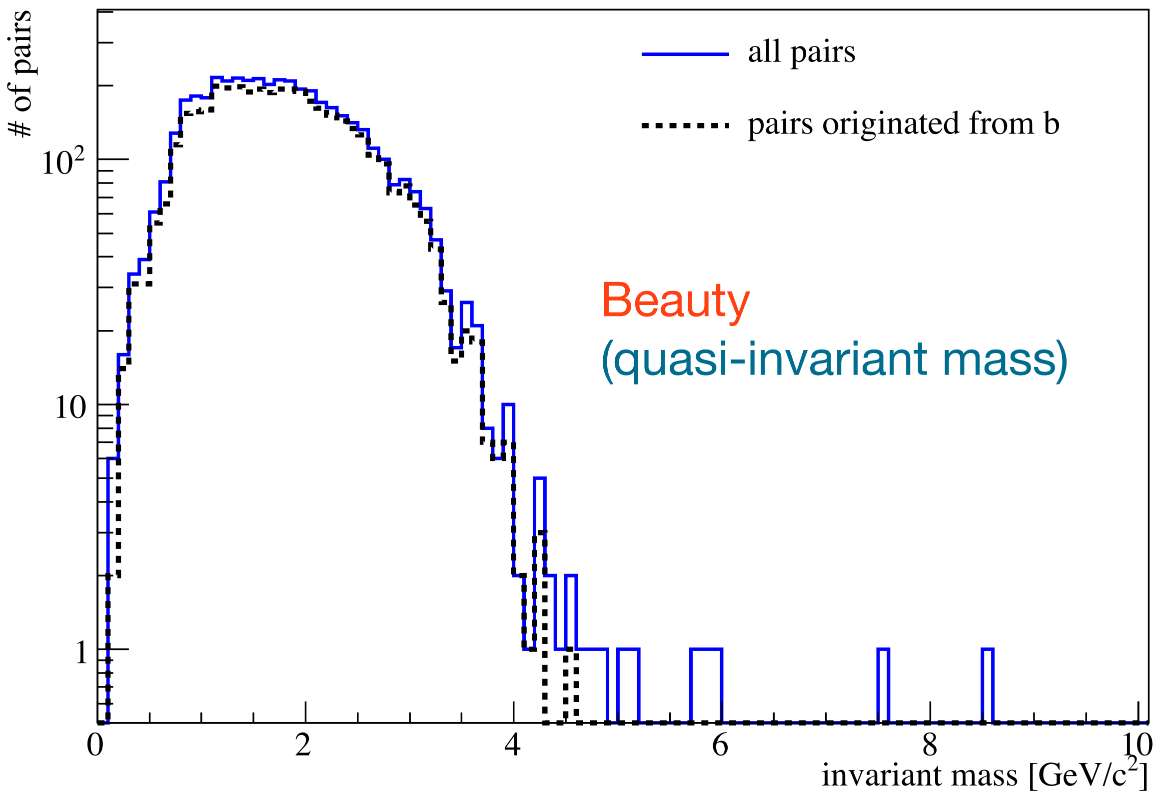


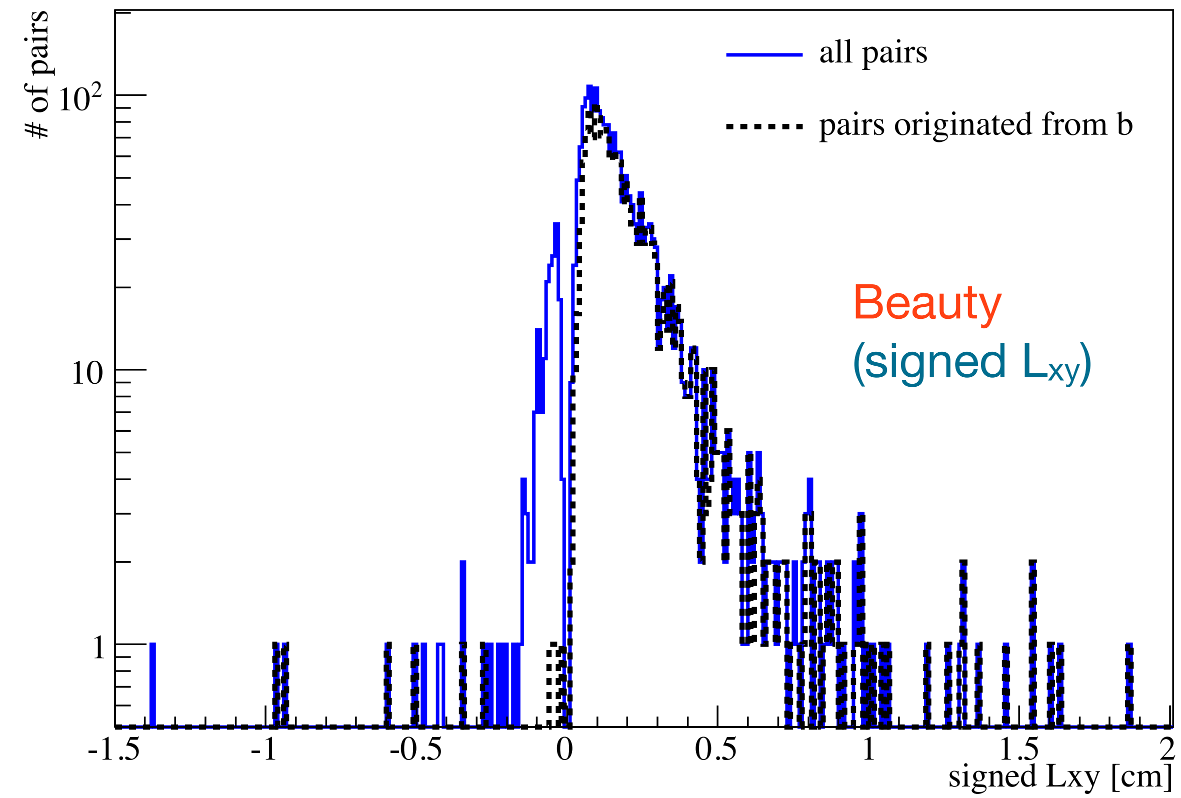
- Secondary vertex reconstruction of beauty decay through electron + hadrons
  - high rate of lepton production from semi-leptonic decay (~11%[b→e] + 10%[b→c→e])
  - long life time (~ 500 μm)
  - large mass (~ 5 GeV/c^2)
  - decay multiplicity

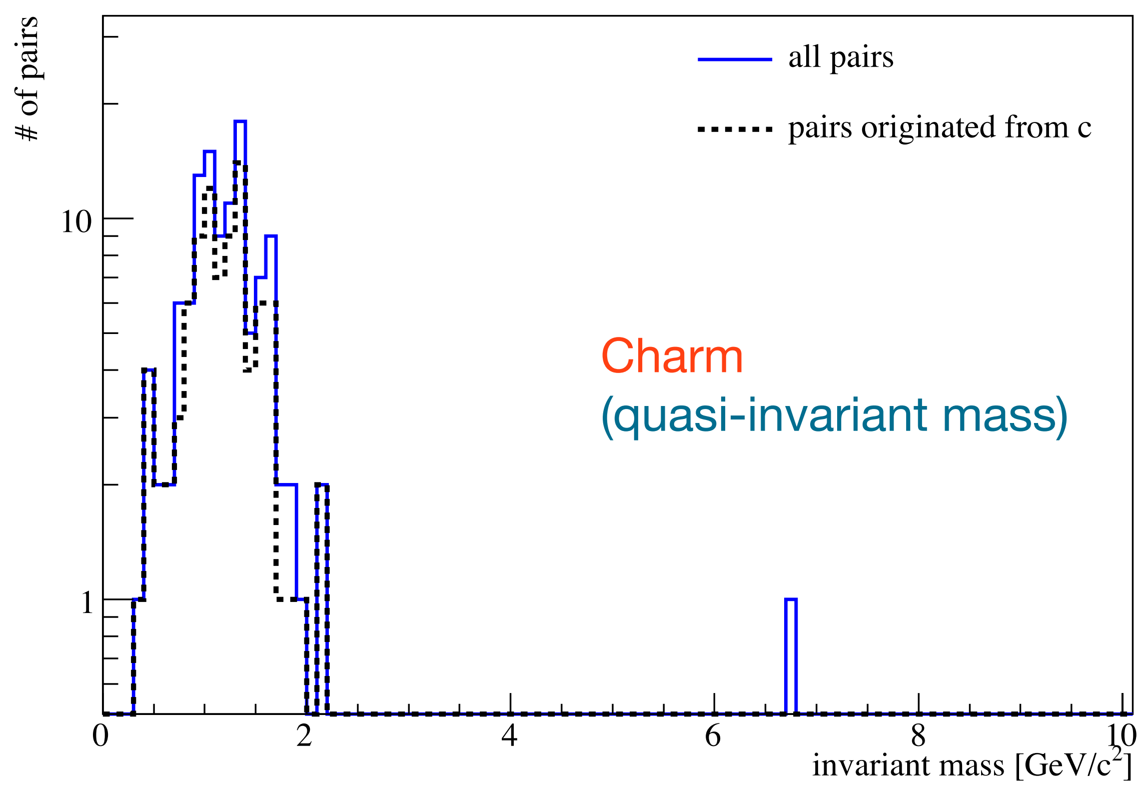
- distinctive variables
  - signed $L_{xy} = \frac{\vec{r}\cdot\vec{p}}{|\vec{r}||\vec{p}|}\vec{r}$
  - invariant mass
  - secondary vertex χ^2/NDF
  - impact parameter of secondary particle ⇒



Distinctive Variables: p+p @$\sqrt{s}$= 7 TeV







b, c→semi-electron decay triggered samples

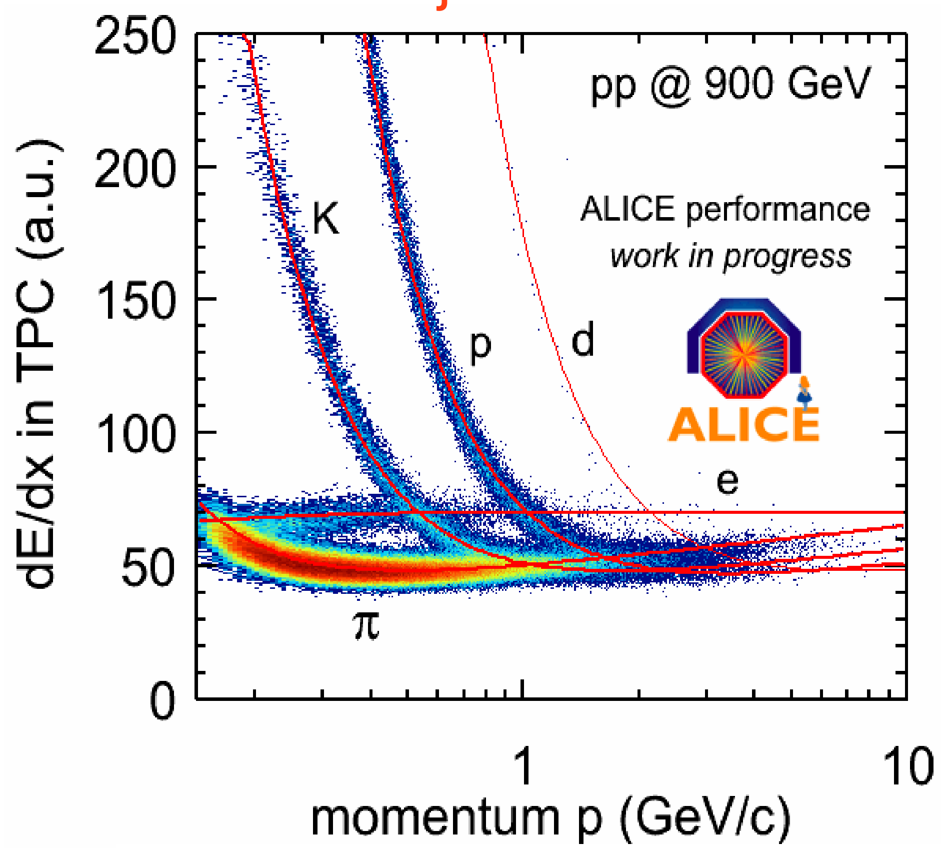
Invariant mass cut is good to suppress charm background

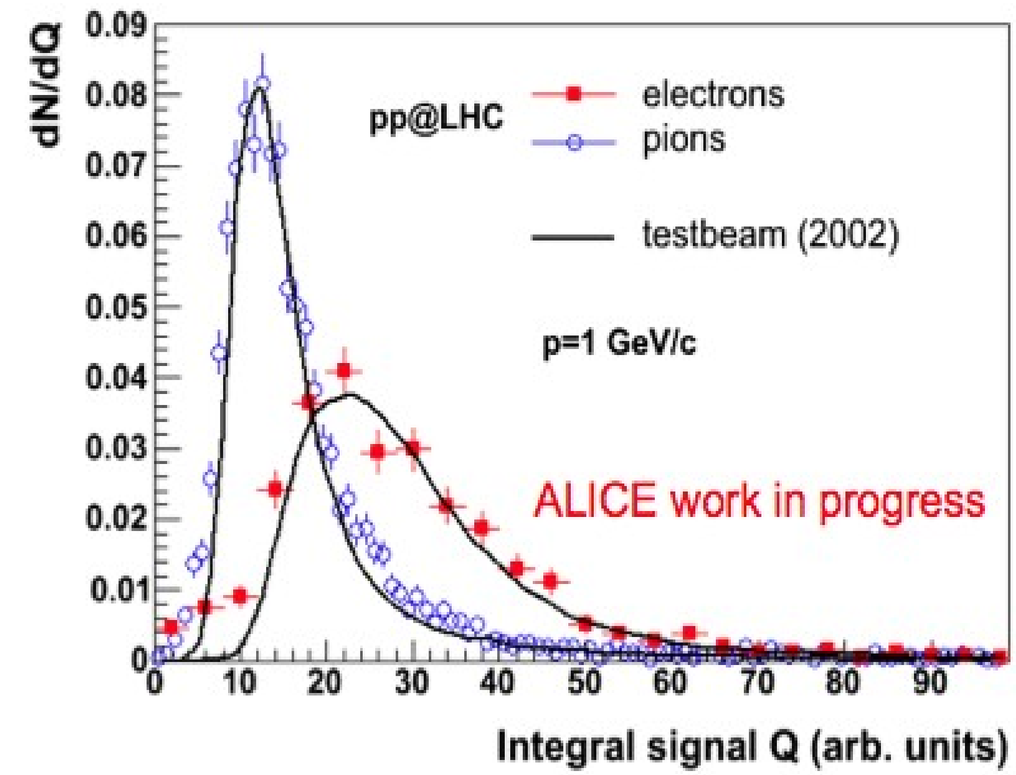
→ Allow to separate beauty from charm

Combined effort with Heavy flavour electron/Jet working group

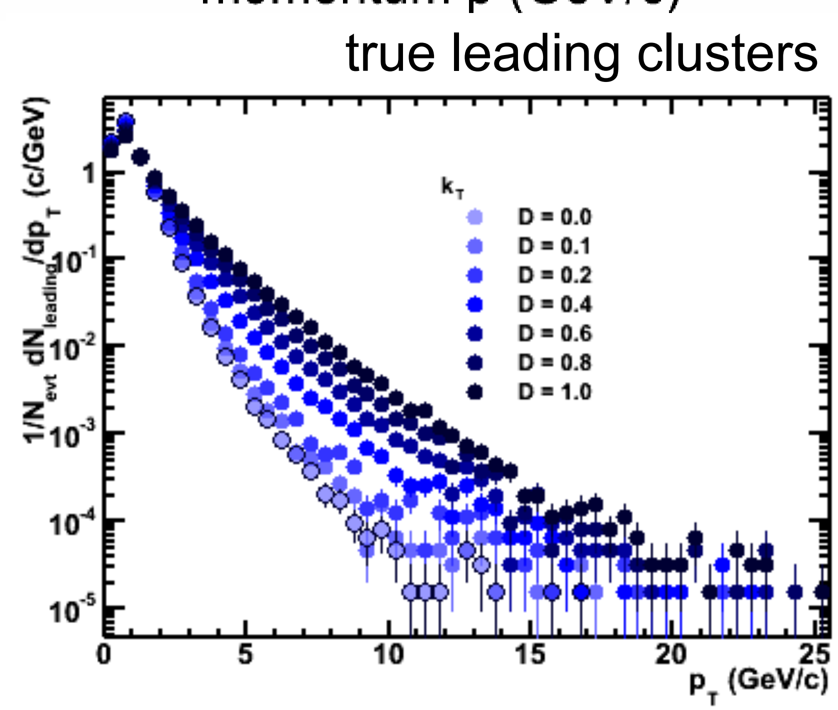
Electron identification and jet reconstruction is crucial for this analysis

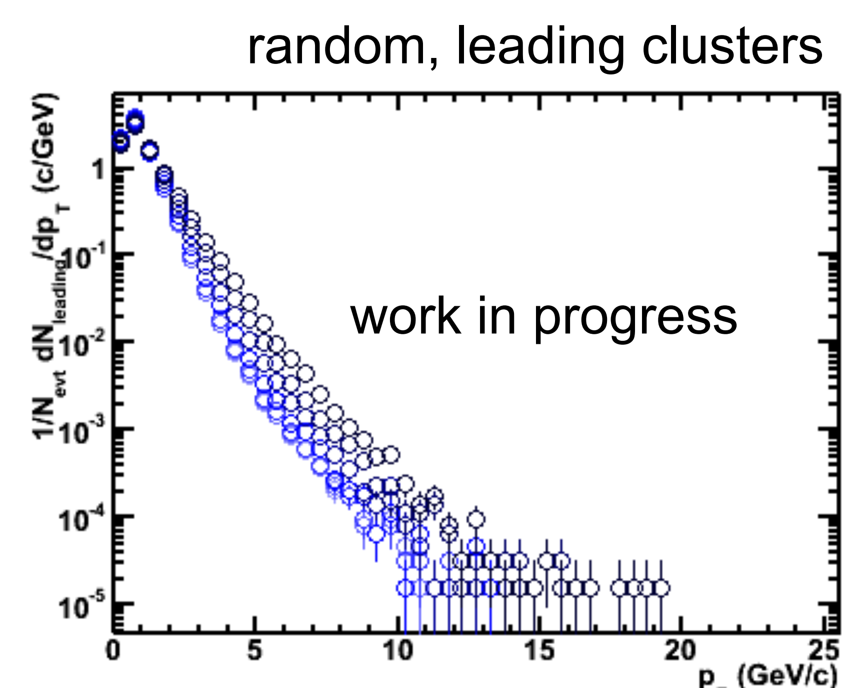
Understanding of PID performance for upcoming high statistics data→





Pseudo-Random Events k_T Jet Finder→





Real Data

Summary

- **At RHIC, Heavy quark suppression is larger than expected,**

  Therefore, various attempts to describe it in theory

- **At LHC, charm and bottom are crucial probe to understand the heavy quark energy loss,**

  More over, separate charm and bottom measurement will allow us to tell heavy quark quenching story

- **In ALICE, there are works ongoing to measure heavy flavour with various channels,**

  Especially, there is work ongoing to tag B, and B jet exclusively

Looking forward high statistics $\sqrt{s}$= 7 TeV RUN !

BACKUP SLIDES

Elastic energy loss

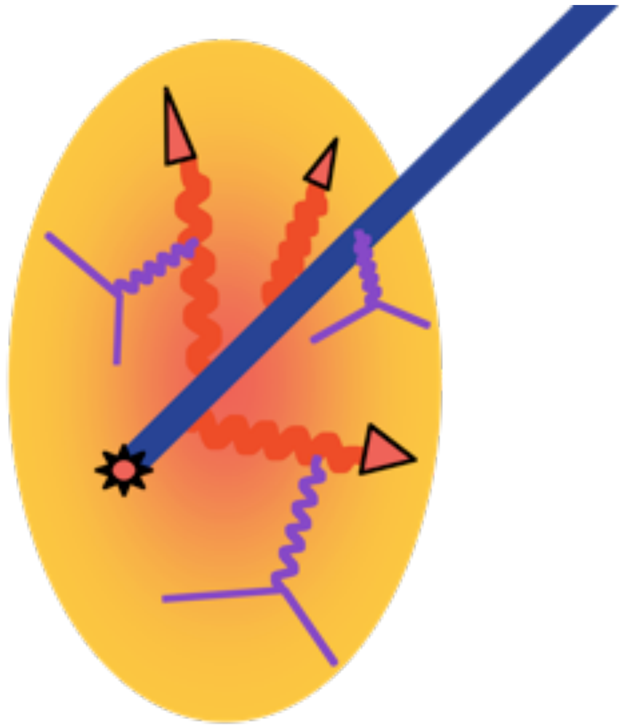
- Bjorken(1984),Thoma&Gyulassy(1991),Braaten& Thoma (1991), Wang, Gyulassy & Plumer (1995), Mustafa et al. (1998), Lin, Vogt & Wang (1998): dEel./dz~0.3- 0.5GeV/fm : negligible!
- Then,allofasudden,,,
Mustafa & Thoma (2003), Dutt-Majumder et al. (2004), Wicks, Horowitz, Djordjevic & Gyulassy (2006), Peshier (2006): it is sizable! (either for heavy quarks only, for c only, for light quarks as well...)
- Yet,atthesametime...
Peigne, Gossiaus, Gousset (2005): yes, elastic energy loos is negeligible, because the parton is formed inside the medium, not at infinity.

Radiative heavy quark energy loss

- Three important medium effects control the radiative energy loss:
    - Ter-Mikayelian effect
    - Transition radiation
    - Energy loss due to the interaction with the medium

Radiative energy loss due to the interaction with the medium

- caused by the multiple interaction of partons in the medium



M. D. and M. Gyulassy, Phys. Lett. B 560, 37 (2003); Nucl. Phys. A 733, 265 (2004);
Generalized GLV (2000) method to compute heavy quark energy loss to all orders in opacity.

B. W. Zhang, E. Wang and X. N. Wang, Phys. Rev. Lett. 93, 072301 (2004);
Generalized ZW (2003) method. Derivation in terms of Modified FF with pQCD (twist expansion approach).

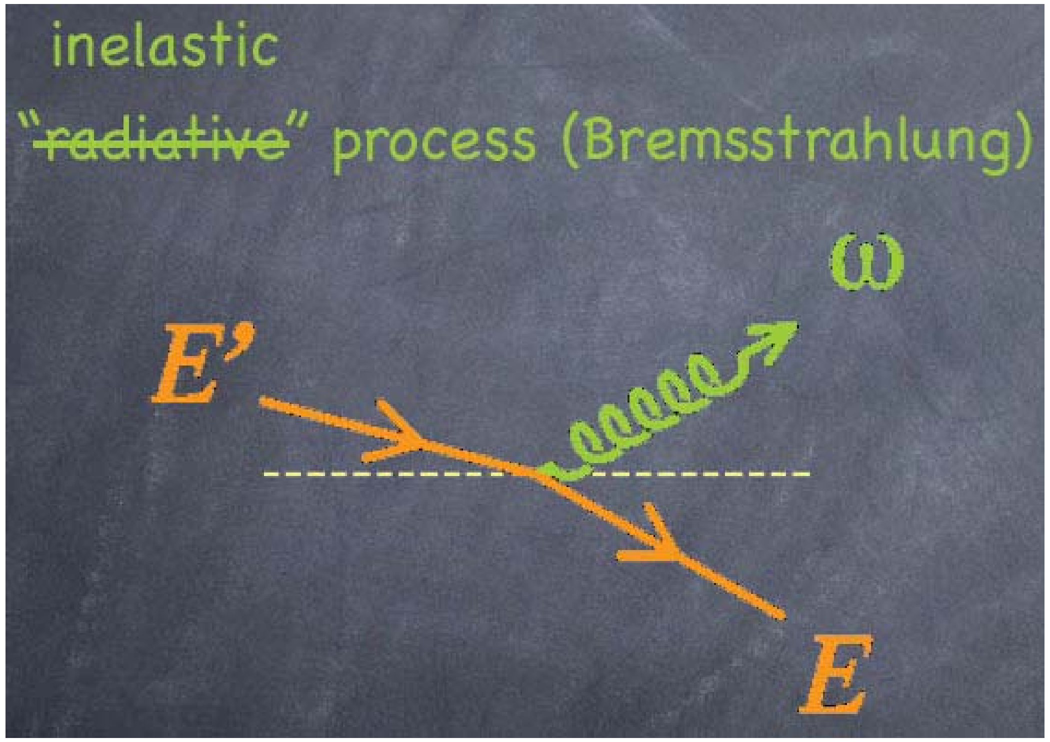
N. Armesto, C. A. Salgado, U. A. Wiedemann, Phys. Rev. D 69, 114003 (2004).
Generalized BDMPS-Z-W (2000) method. Computation based on path integral formalism.

Four theory approaches of energy loss

- Multiple-soft scattering (ASW-BDMPS)
  - Full interference (vacuum-medium + LPM)
  - Approximate scattering potential
- Opacity expansion (GLV/WHDG)
  - Interference terms order-by-order (first order default)
  - Dipole scattering potential $1/q^4$
- Higher Twist
  - Like GLV, but with fragmentation function evolution
- Hard Thermal Loop (AMY)
  - Most realistic medium
  - LPM interference fully treated
  - No interference between vacuum frag and medium

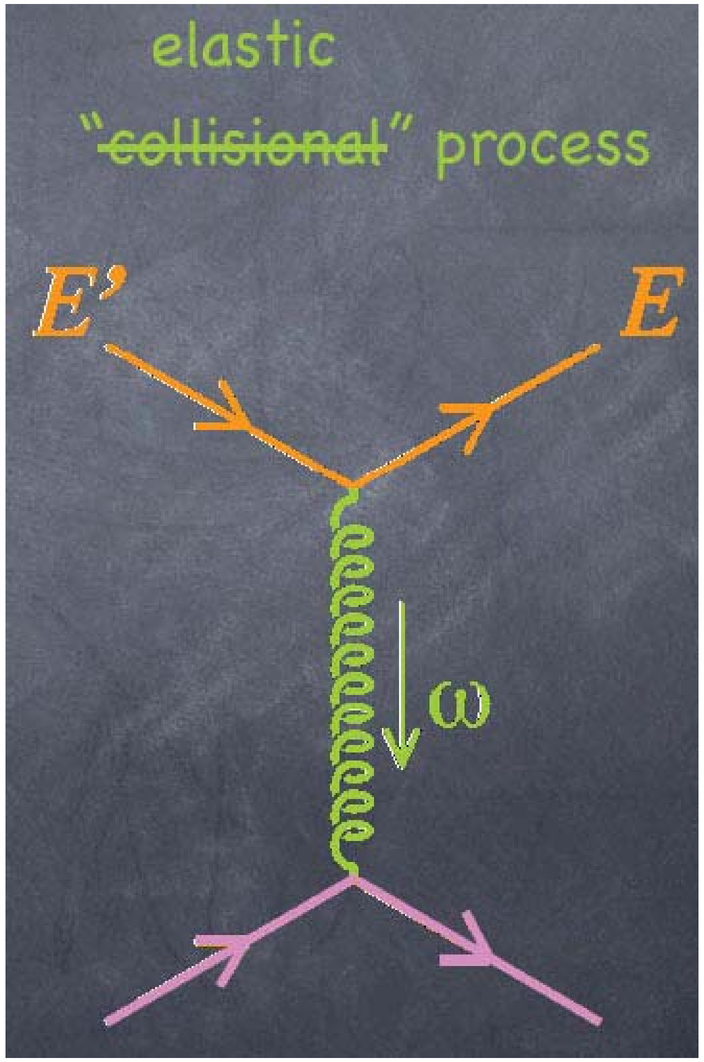
Models of high-p_T parton energy loss

Two different “categories” of models of parton energy loss, depending on the basic underlying process:



Theories and models of radiative energy loss

- **LPM-effect based approaches: BDMPS-Z & AMY**
- **Opacity expansion: GLV; (AS)W**
- **Medium-enhanced higher-twist effects**
- **Medium-modified MLLA**



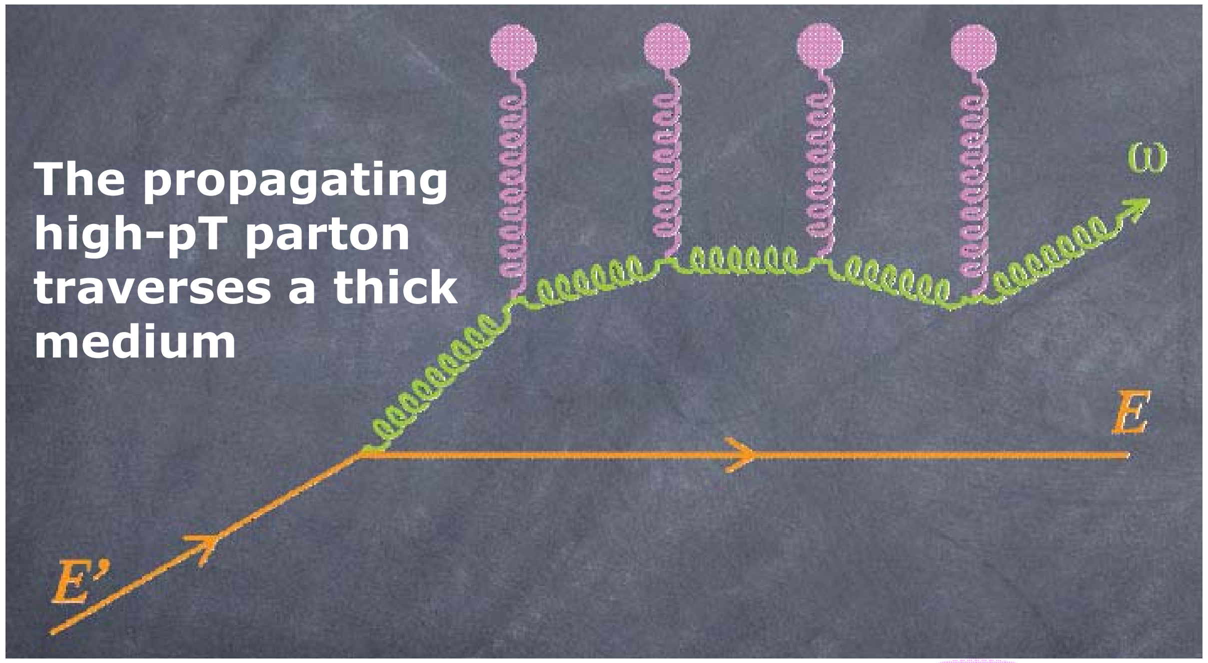
Theories and models of collisional energy loss

- **Regards as negligible!**
- **BUT => it is sizable?**

11

Energy loss by multiple soft scattering

: Models based on the Landau-Pomeranchuk-Migdal effect



It radiates soft gluons, which scatter coherently on independent color charges in the medium, resulting in a medium-modified gluon energy spectrum

Medium properties can be characterized by a single constant : BDMPS, AMY

e.g. transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$ 'average k_T-kick per mean-free-path'

$$\omega \frac{dI_{LPM}}{d\omega dz} = \left(\frac{\lambda}{l_{coherent}} \right) \omega \frac{dI_{\text{Bethe Heitler}}}{d\omega dz} = \sqrt{\frac{\hat{q}}{\omega}} \frac{\alpha_S N_C}{\pi}$$

: Gluon radiation spectrum

$$\Delta E_{med} = \int^{L} dz \int^{\omega_C} d\omega\, \omega \frac{dI_{LPM}}{d\omega dz} \sim \alpha_S \sqrt{\hat{q}\omega_C} L \sim \alpha_S \hat{q} L^2$$

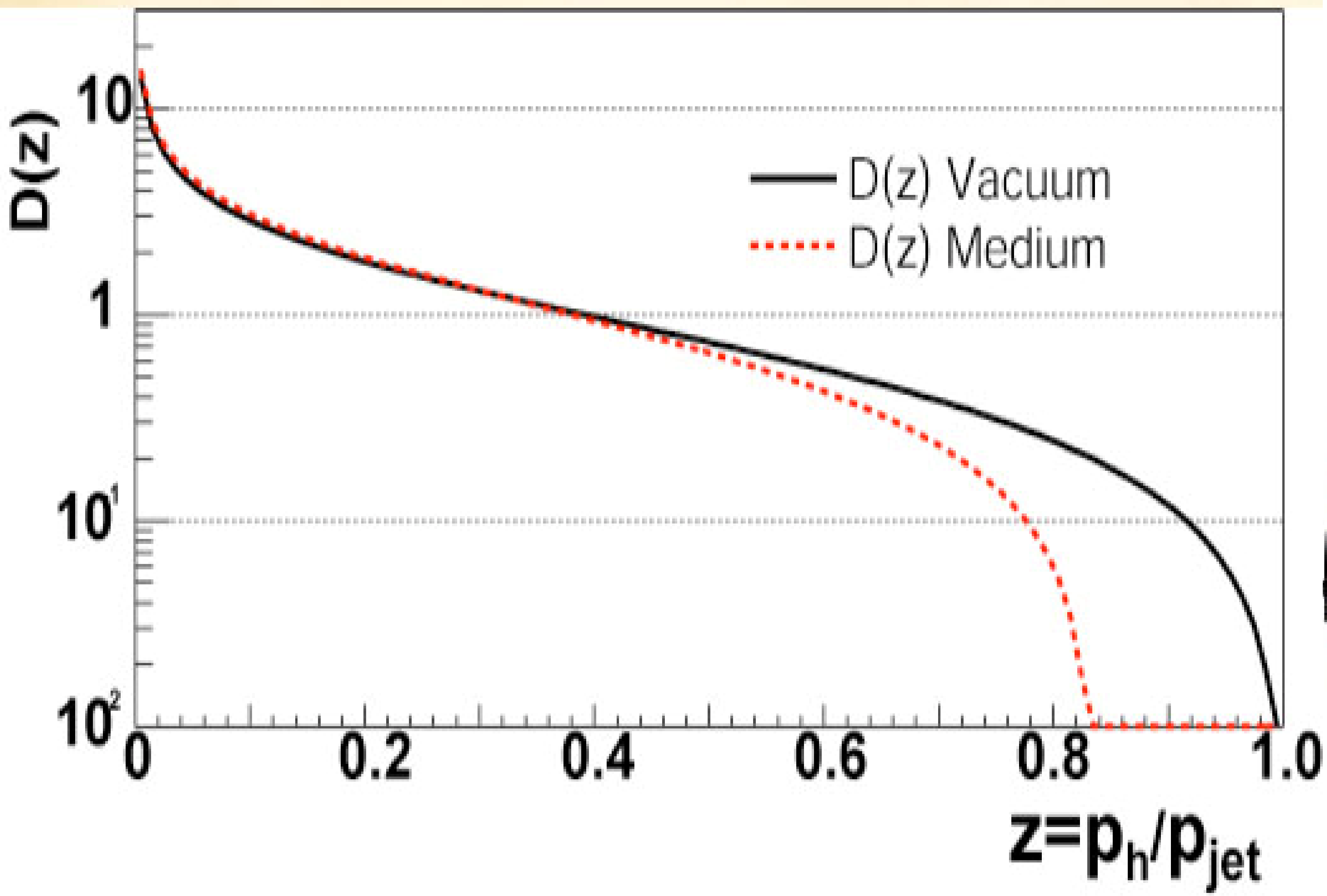
ΔE ∝ L² for a static medium

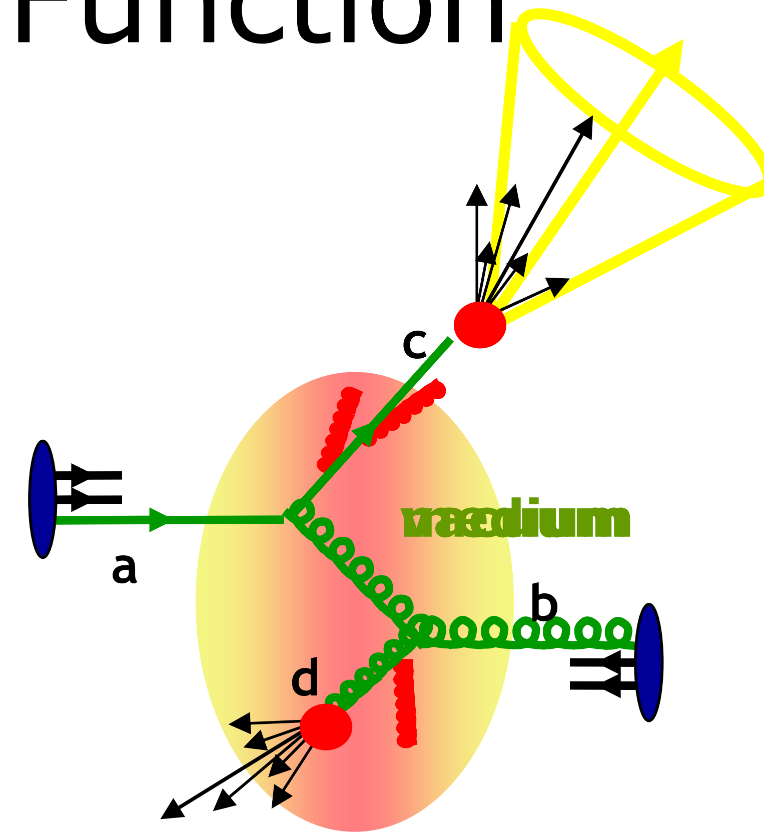
Longitudinal expansion reduces $\Delta E \sim L^2$ to $\Delta E \sim L$

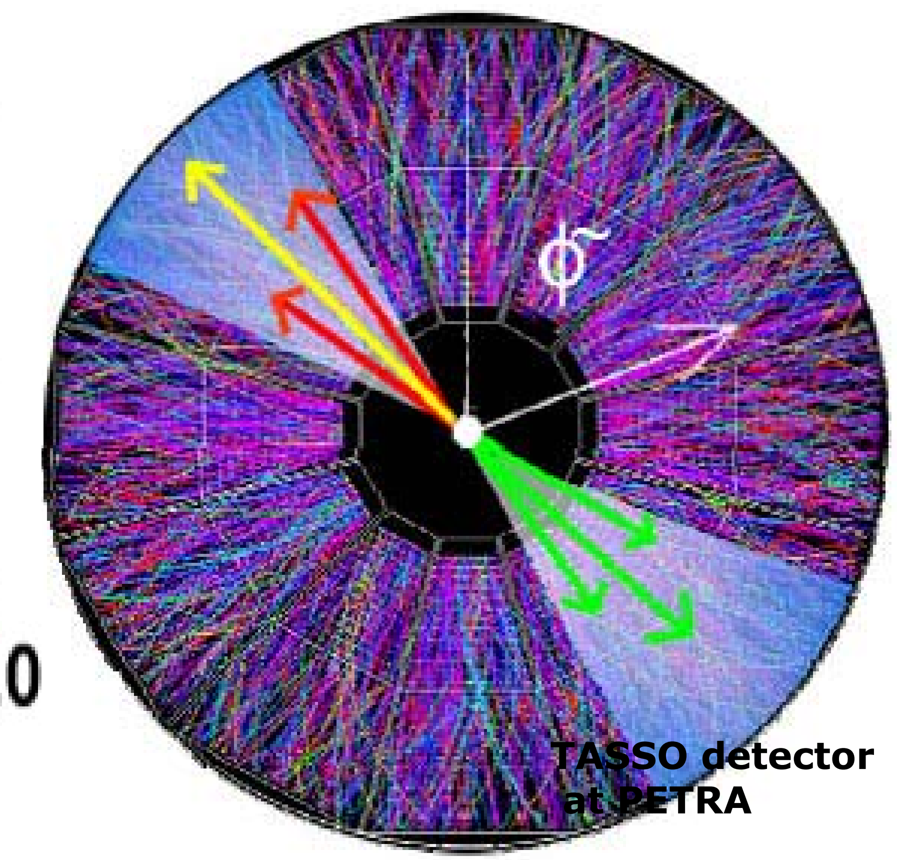
Jets and Fragmentation Function

Gyulassy, Vitev, Wang and Zhang

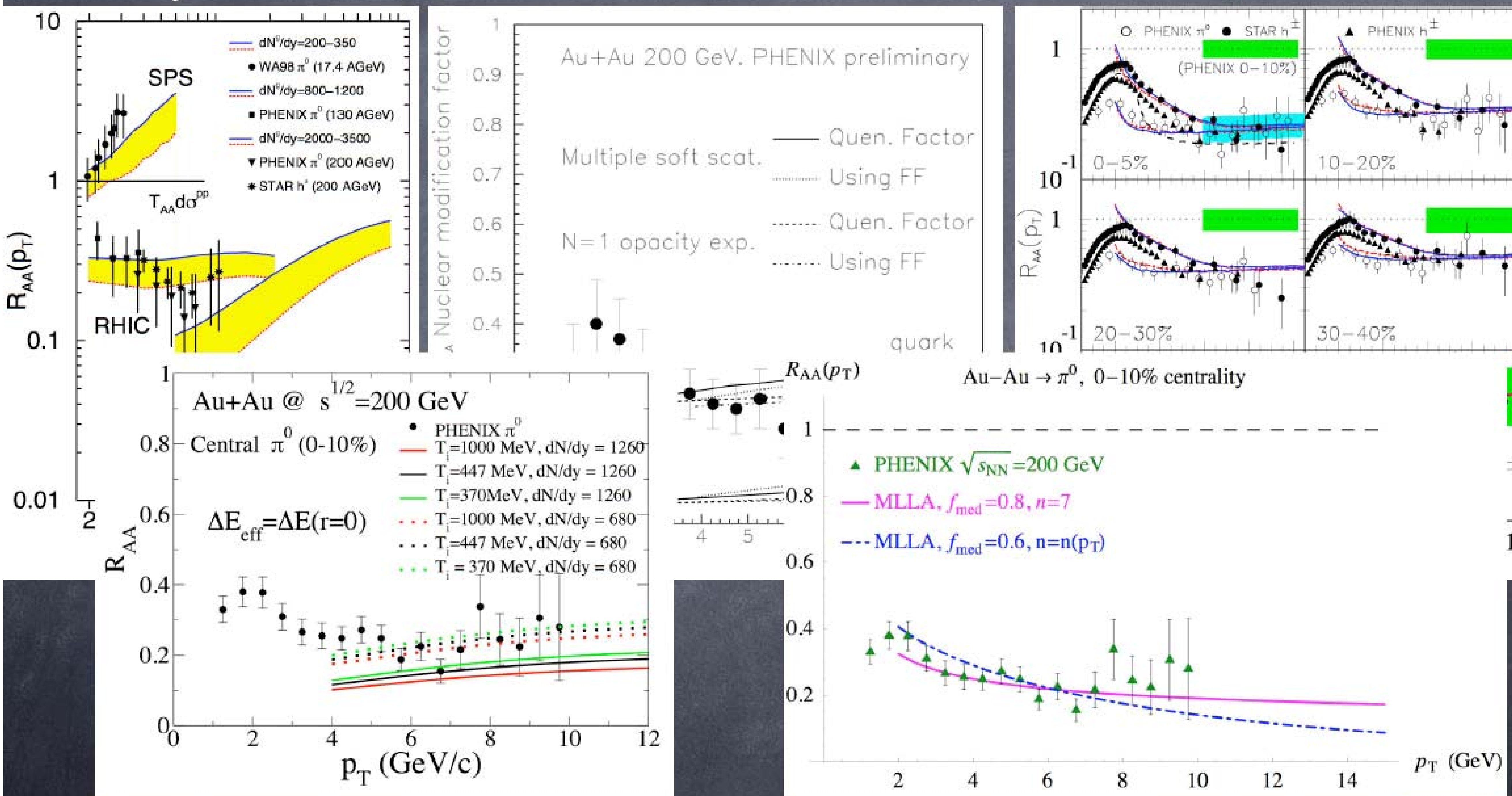
nucl-th/0302077







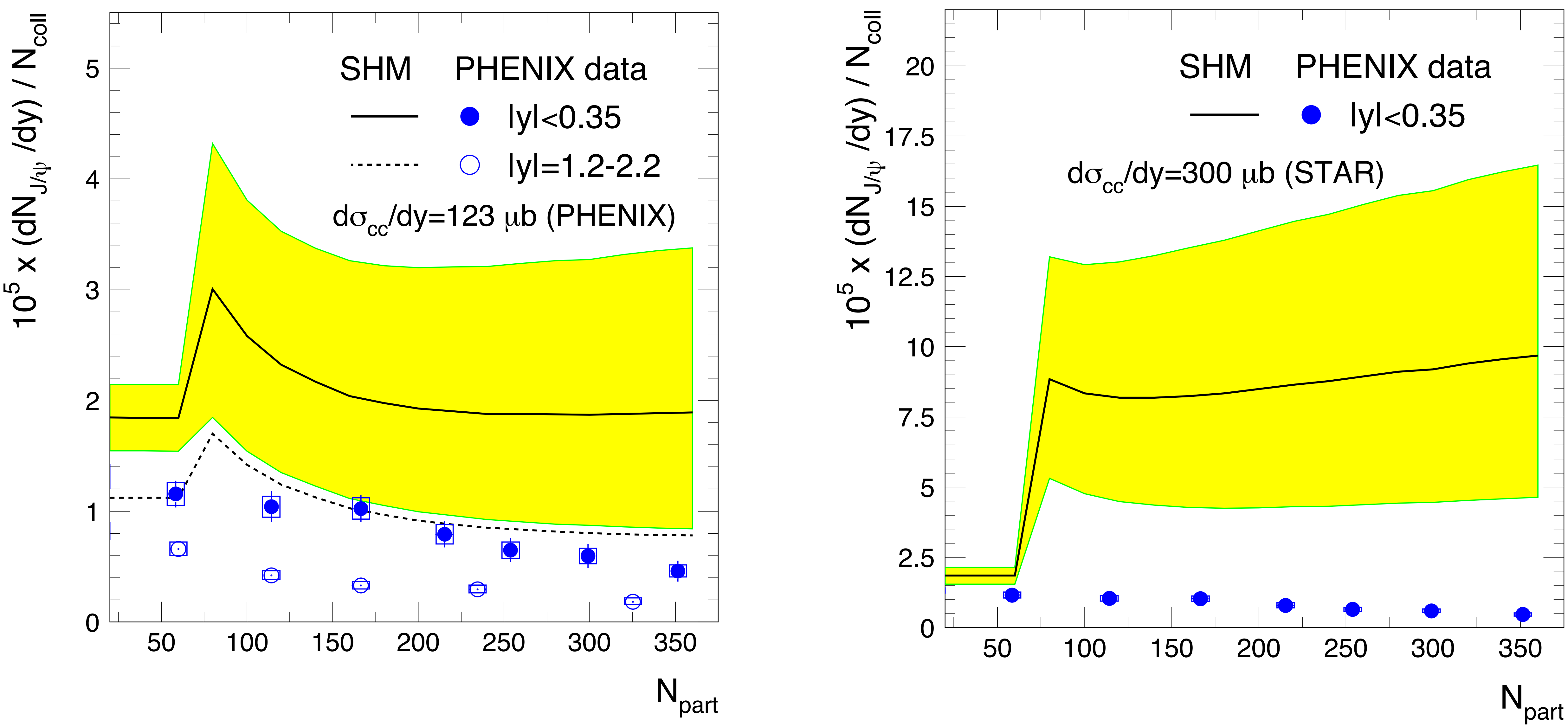
Models of high-p_T parton energy loss reproduce the data remarkably well



35

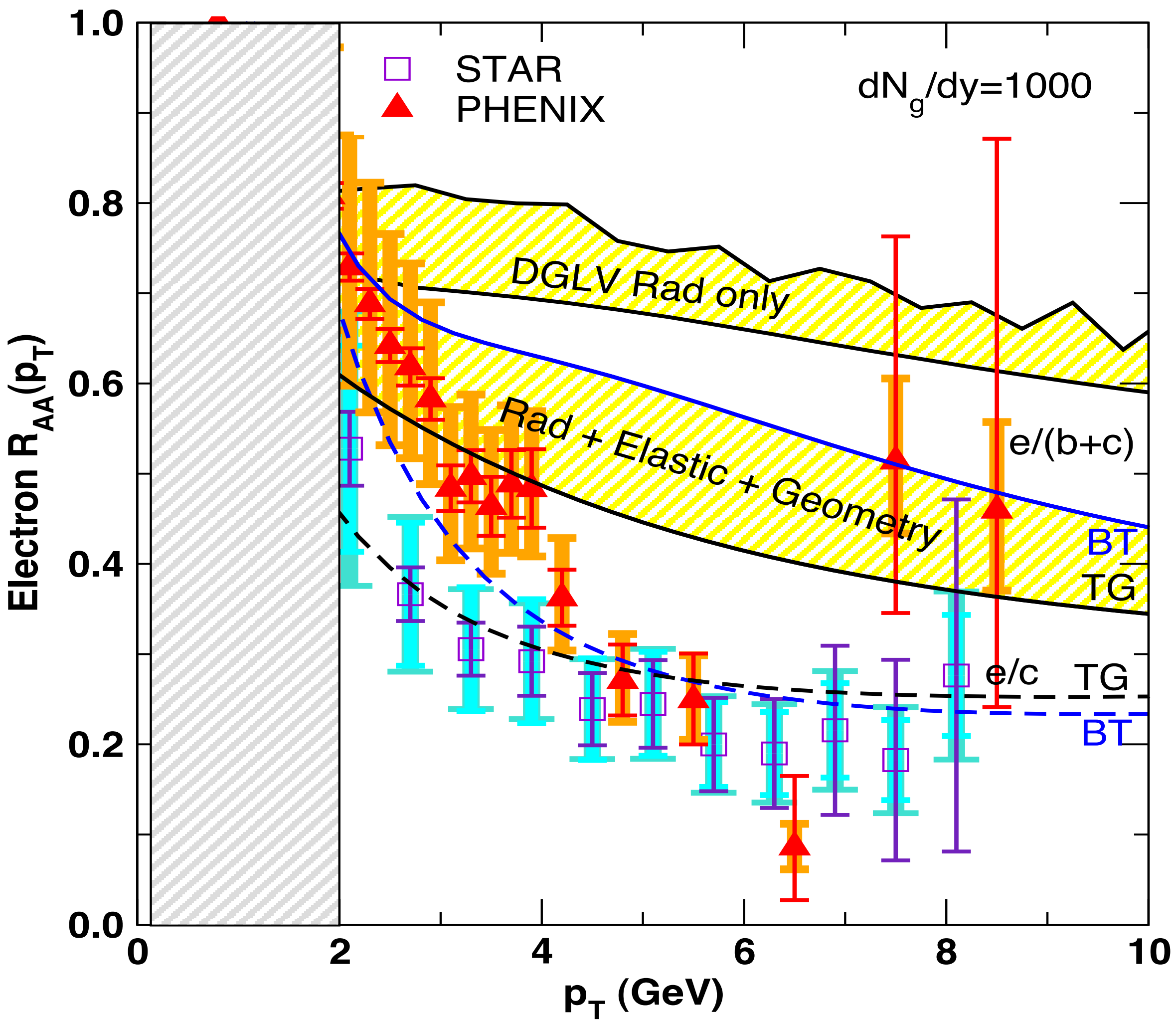
SHM model, considering charm cross section measured by PHENIX and STAR

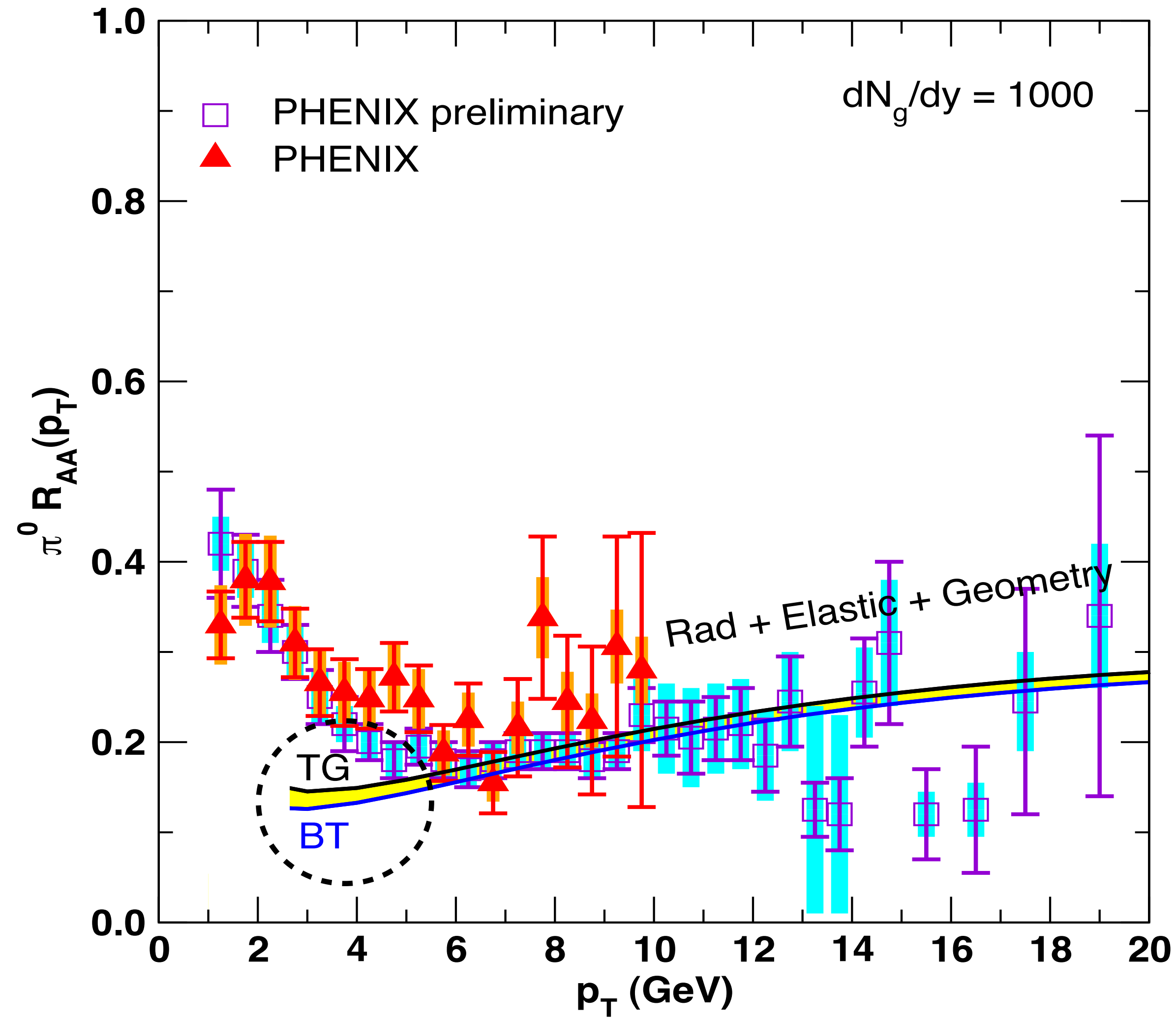
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
Nucl. Phys. A 789 (2007) 334



Approaches to describe non-photonic electron $R_{AA}(p_T)$ at RHIC (I)

Simon Wicks, William Horowitz, Magdalena Djordjevic, Miklos Gyulassy, Nucl.Phys.A784:426-442,2007

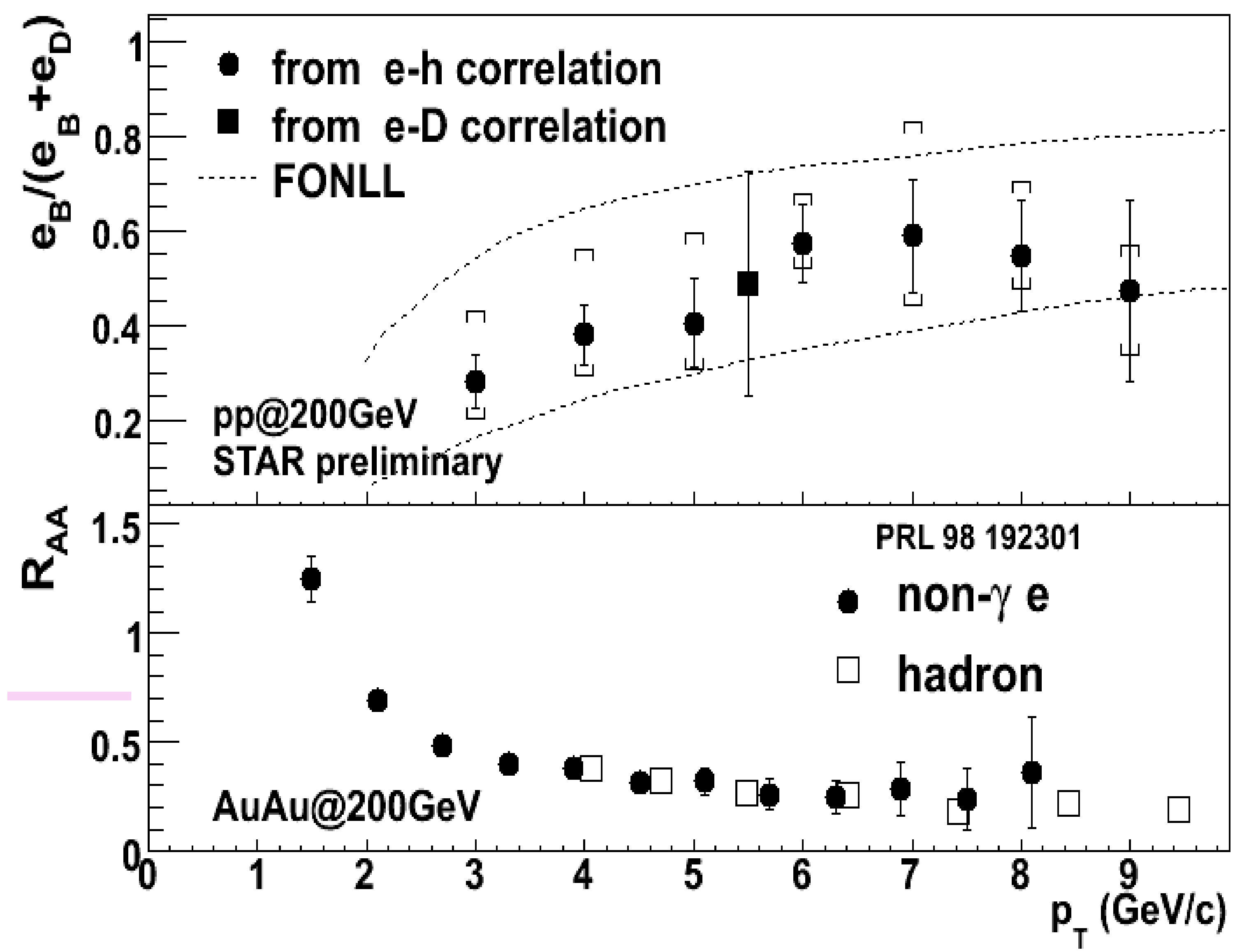


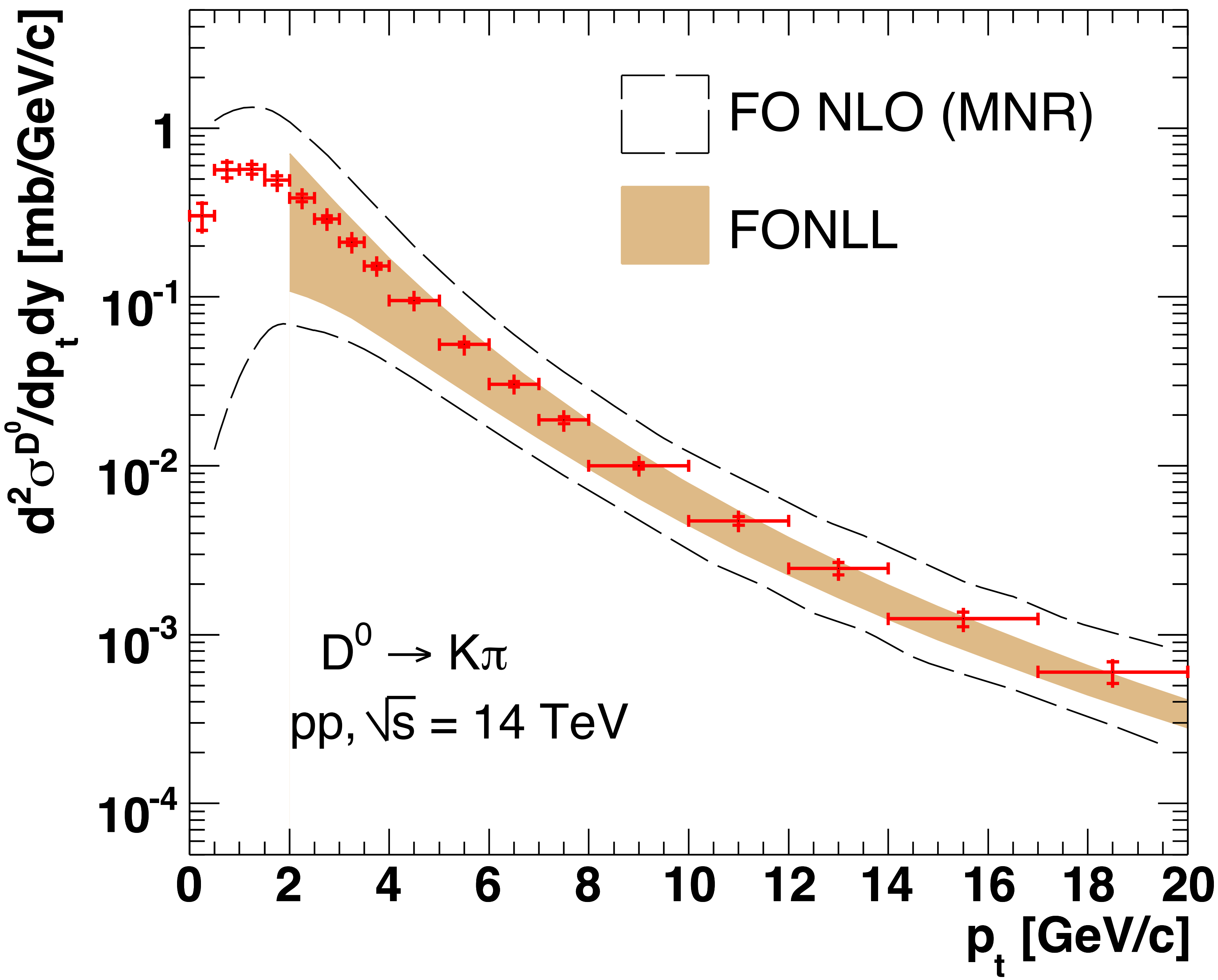


Consistency of the extended jet quenching theory is tested by comparing its prediction to the R_{AA} of the π^0 spectra

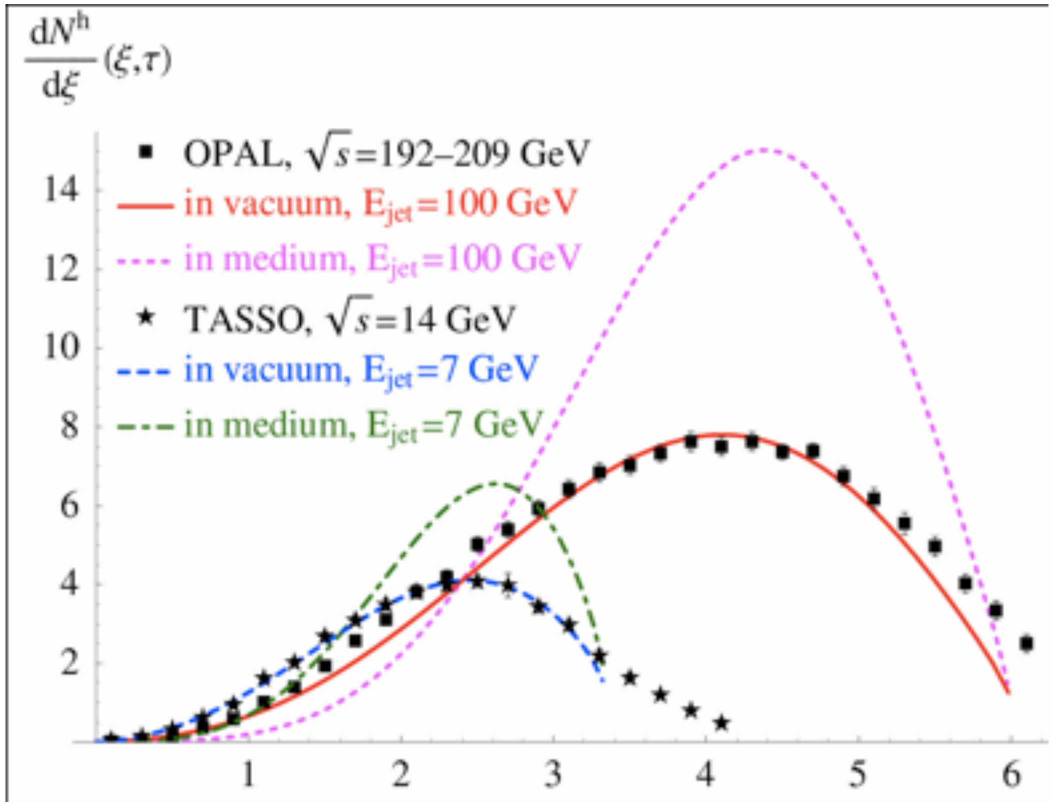
Charm to bottom ratio (STAR data)

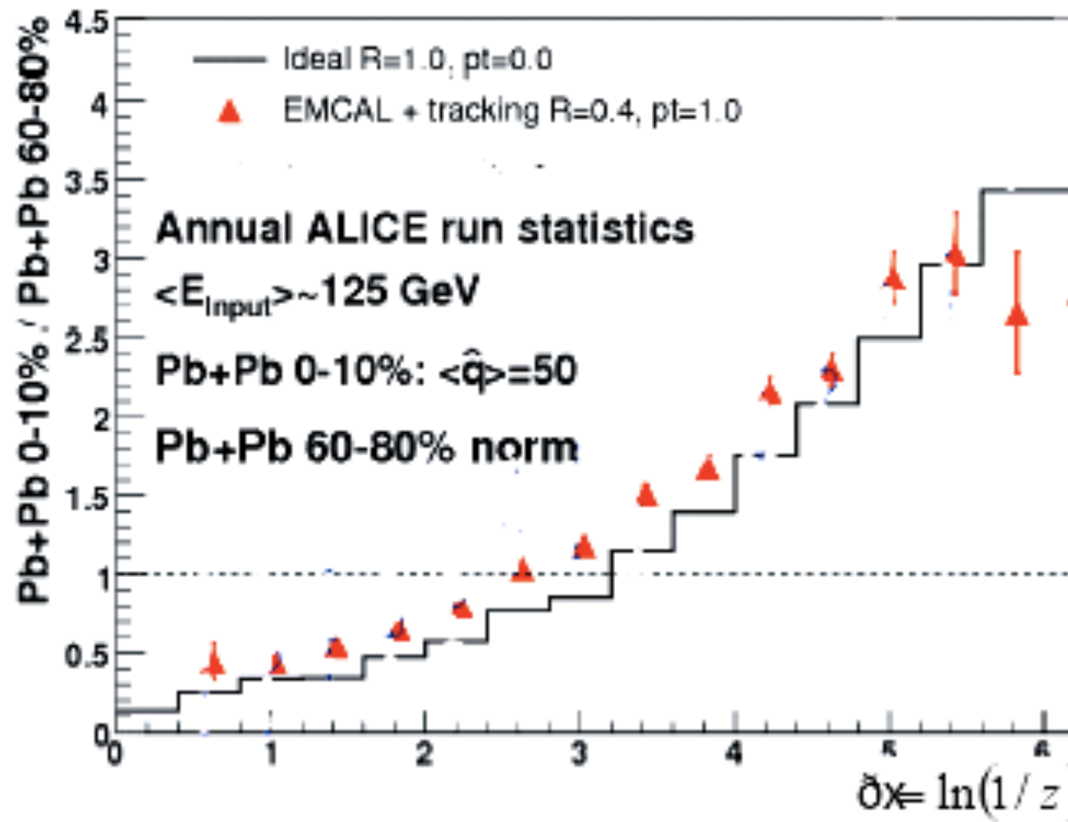
Nucl.Phys.A830:849c-852c,2009

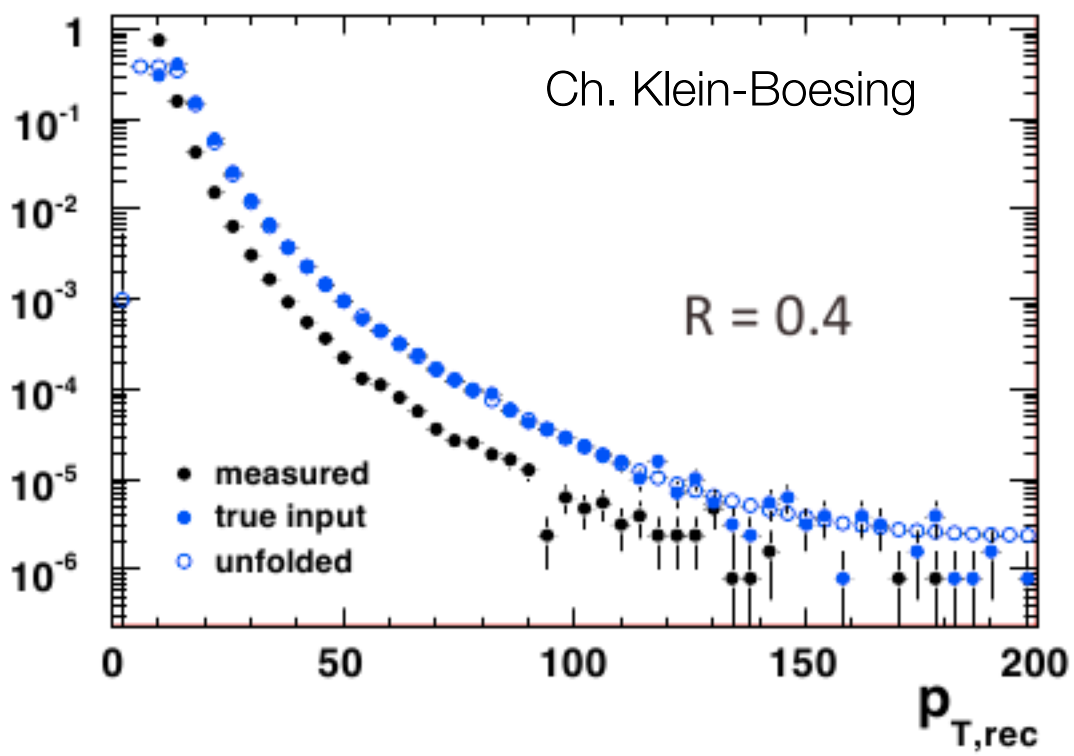



FO NLO (MNR)
FONLL
$D^0 \rightarrow K\pi$
pp, $\sqrt{s}$ = 14 TeV
$d^2\sigma^{D^0}/dp_t dy$ [mb/GeV/c]
p_t [GeV/c]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
12
14
16
18
20

Medium modified fragmentation function measurement







5 10^8 pp events, unfolded for detectors response and cuts

Distinctive Variables - beauty

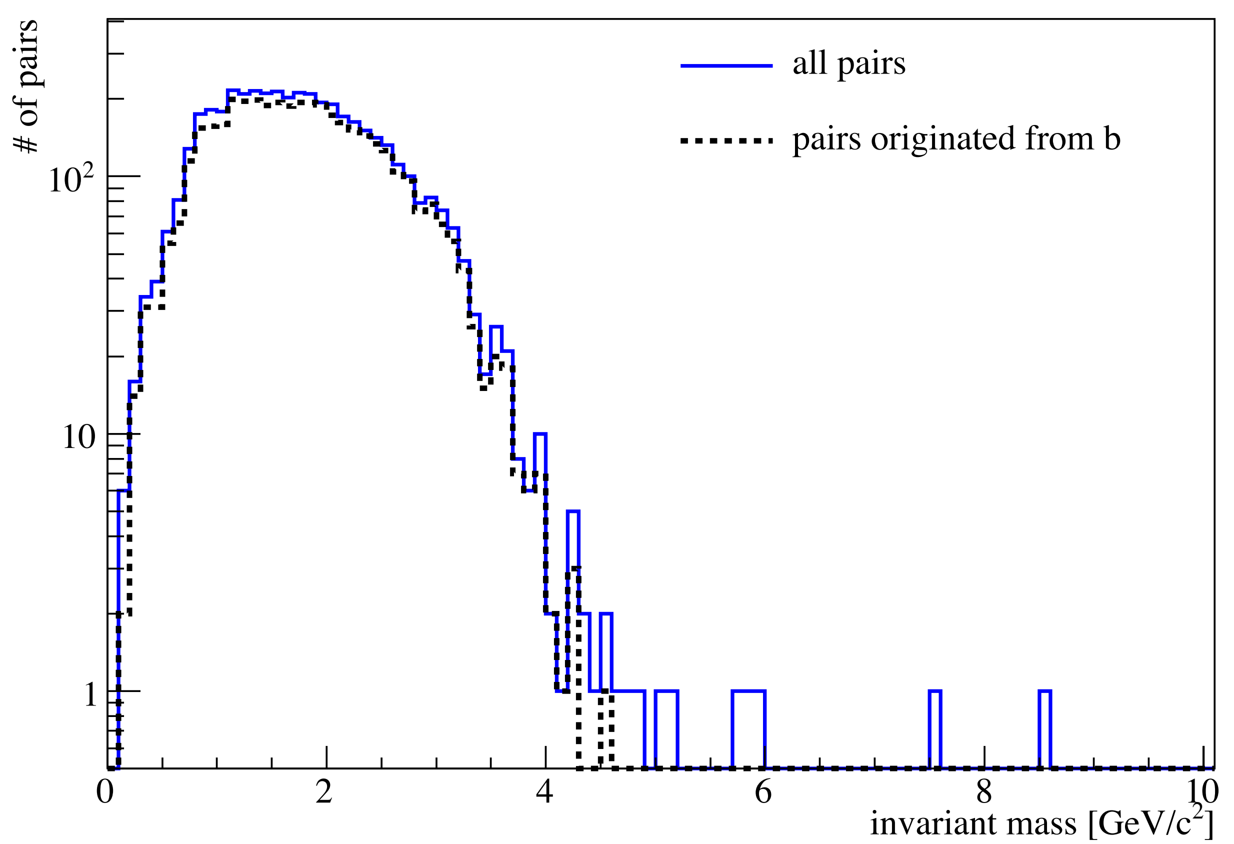
- b electron triggered samples used (7 TeV@pp, ~ 1.8M events)

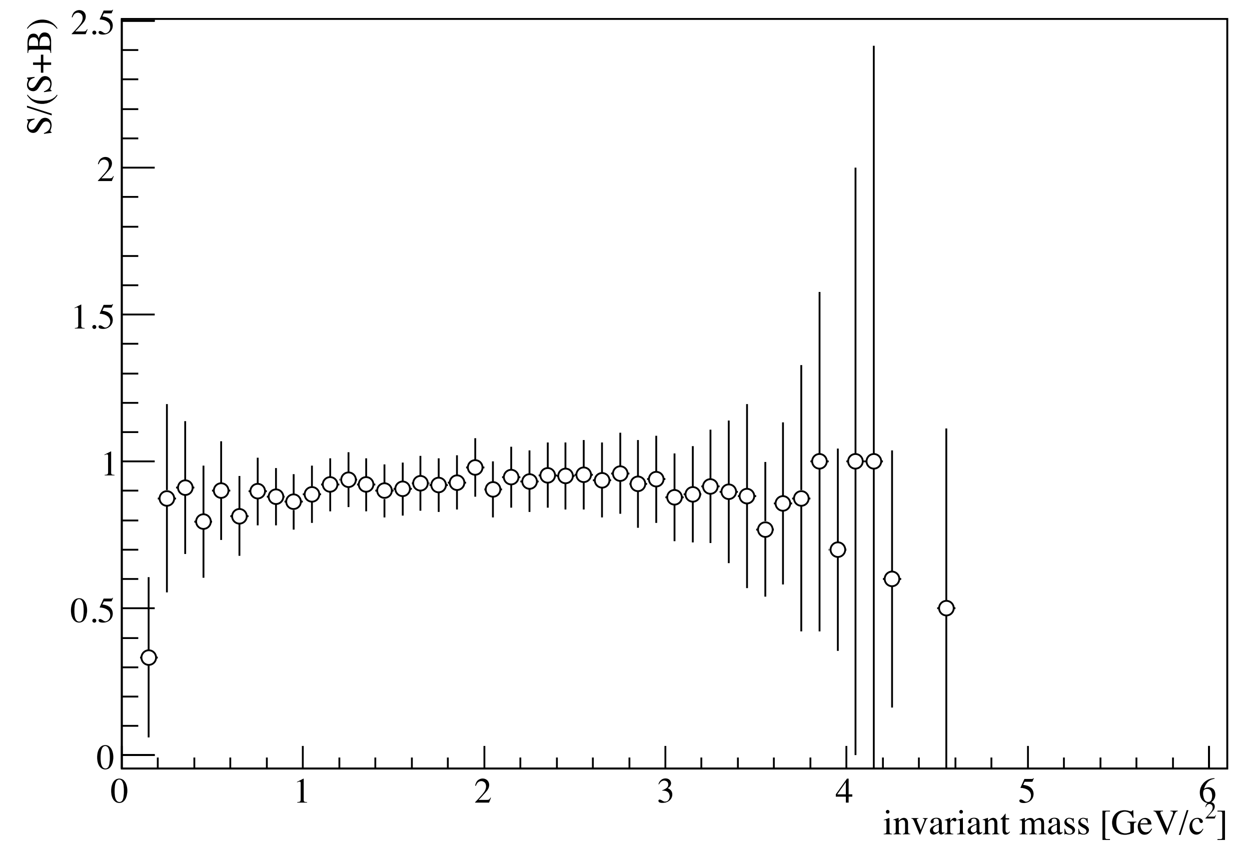
single track cuts

- HFE standard track cuts(ITS pixel layer only for e candidate)
- $p_T > 2.0$ GeV/c,
- DCA for paired tracks(p_T dependent cuts ALICE-INT-2006-015)

pair cuts

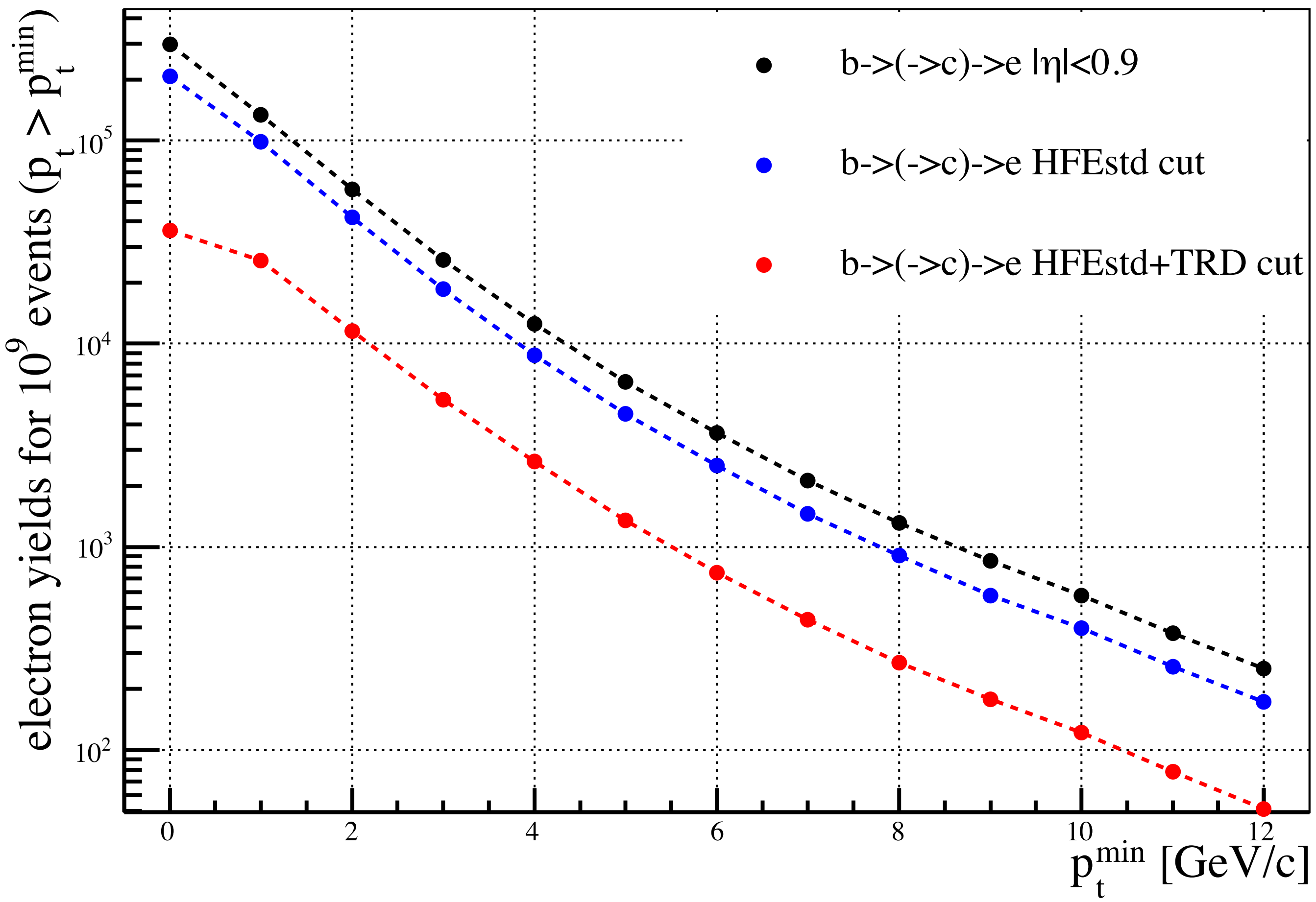
- 700 μm < signed L_{xy} < 1 cm
- 2.0 GeV/c² < invariant mass < 5.2 GeV/c²
- KF secondary vertex χ^2/NDF < 3.0
- opening angle of constructing KF particle < 180°



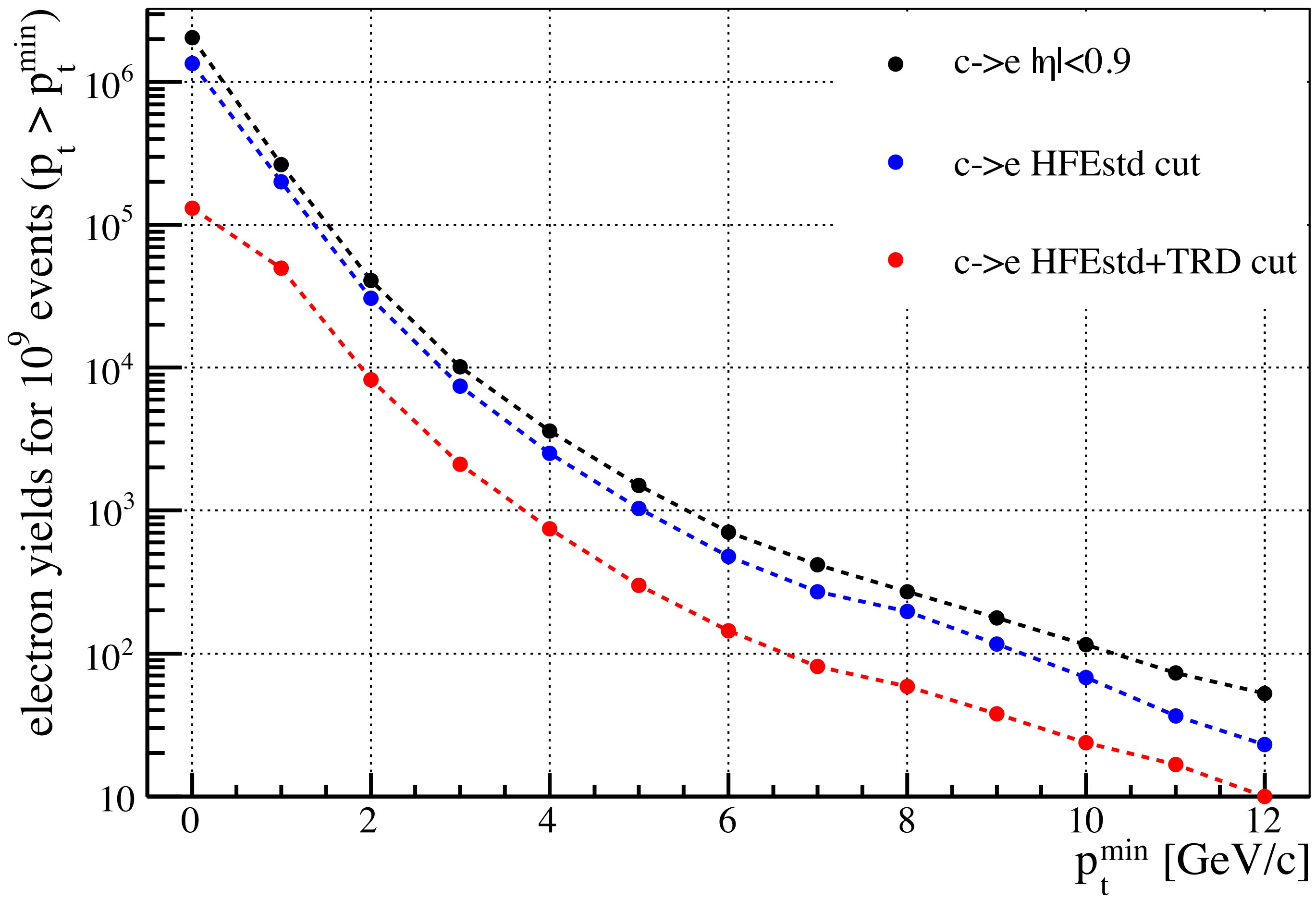


Statistics: pp @ $\sqrt{s} = 7$ TeV

Beauty in pp @ $\sqrt{s}$ = 7 TeV



Charm in pp @ $\sqrt{s}$ = 7 TeV



1 year at nominal luminosity
(10^9 pp events)

With TRD

10^9 pp events leads ~ 47k charm and ~25k beauty electrons at p_t > 1 GeV/c