NeD 2018

Charm dynamics and its hadronization in AA(pp)

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17th April 2018 - Varadero, Cuba

Outline

✧ Basic scales for heavy flavor physics

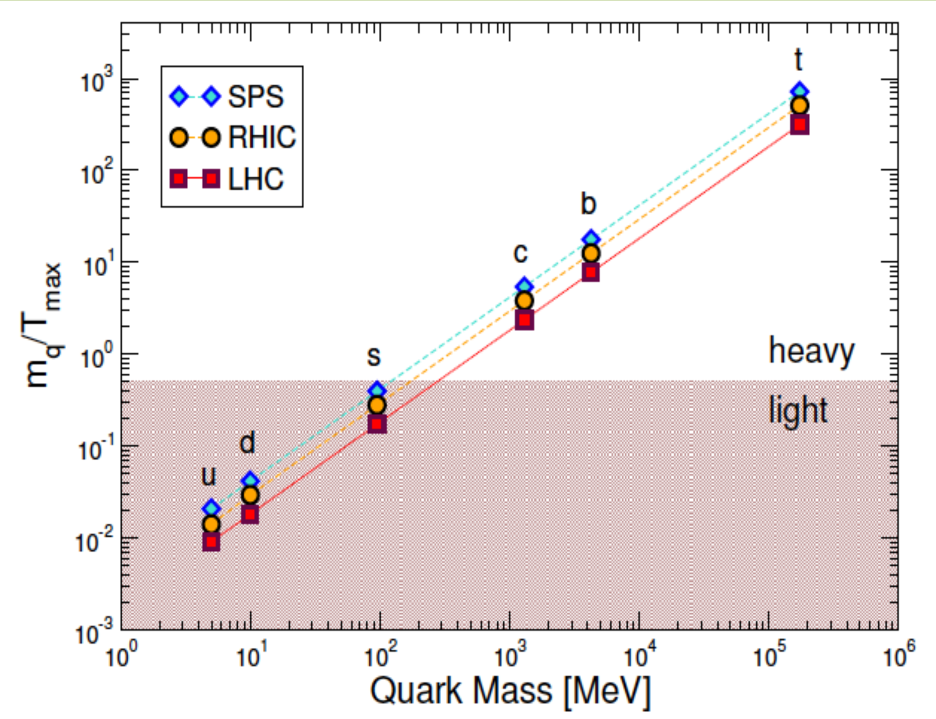
✧ HF dynamical evolution in QGP:

- Boltzmann vs Langevin
- predictions at RHIC and LHC within a Quasi-Particle Model
- Estimating Ds transport coefficient

✧ Hadronization mechanics: Λ_c/D ratio, $R_{AA}(\Lambda_c)$

✧ Impact of electro-magnetic field on HF dynamics

Basic Scales



- $m_{c,b} >> \Lambda_{QCD}$ pQCD initial production
- $m_{c,b} >> T_{RHIC,LHC}$ negligible thermal production
- $\tau_0 \approx 1/2m_Q << \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information
- $m_{HF}>>T$, gT -> $q^2<<m^2$ dynamics reduced to Brownian motion

Link to lattice QCD at finite T

- **Extract the Free Energy of QQ**

  → HQ Potential F=U-TS

  $$q_0^2 \approx \vec{q}^{\,4} / m_Q^2 << \vec{q}^{\,2}$$

  space-like transf. mom. → V(r)

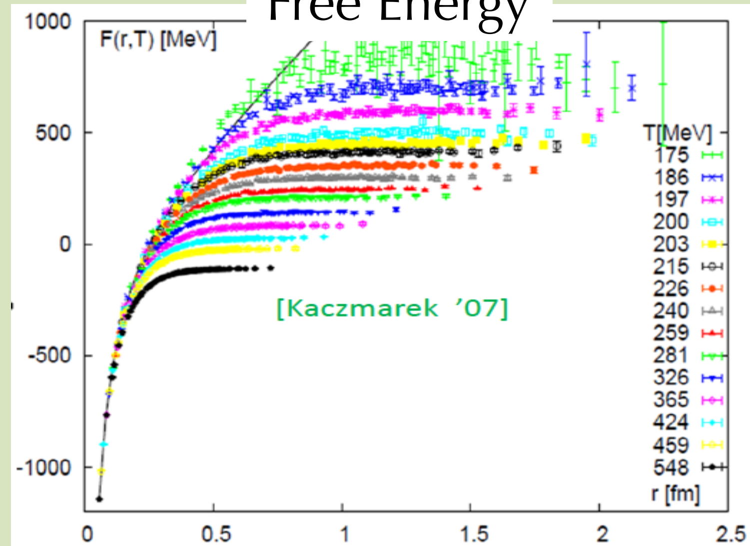
- **Evaluate Diffusion Transp. Coeff.**

  Extract Spectral function ρ_E from color-electric correlator with an initial assumption for ρ_E , then Kubo formula:

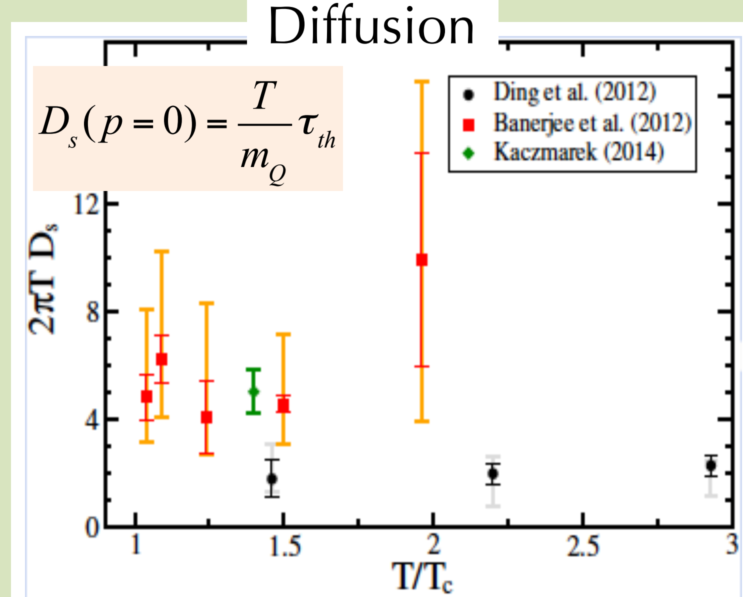
  $$\kappa/T^3 = \lim_{\omega\to 0} \frac{2T\rho_{\rm E}(\omega)}{\omega} \qquad D = \frac{2T^2}{\kappa}$$

  Approximations/limitations:
  quenched QCD, heavy quark vs. charm quark, continuum extrapolation, still systematic large errors …

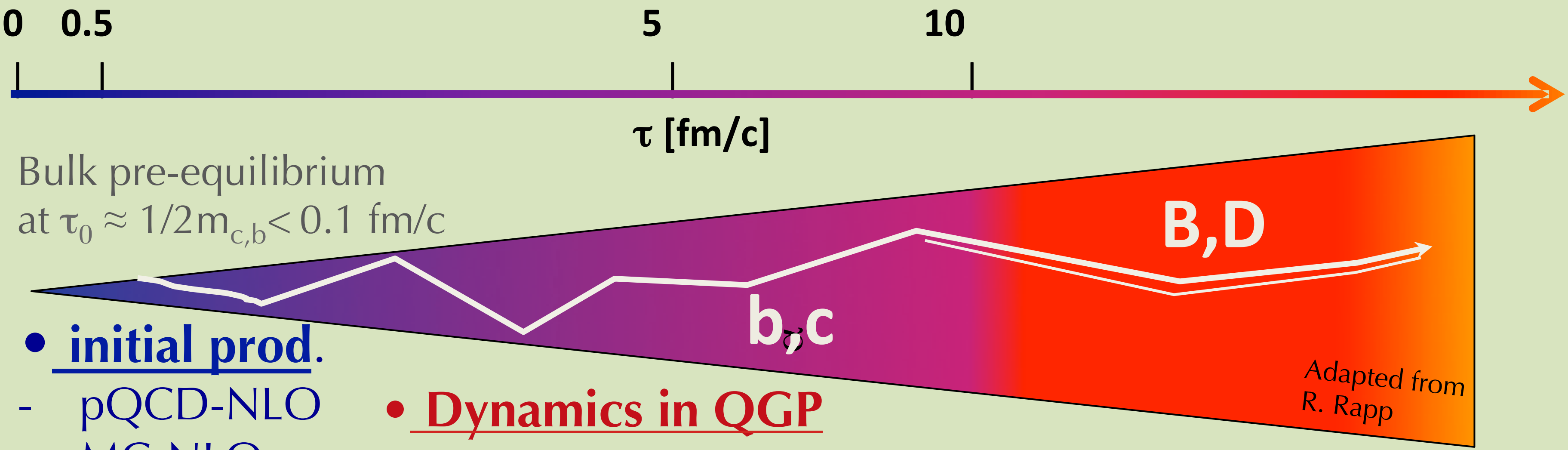
Free Energy



Diffusion



Studying the HF in uRHIC

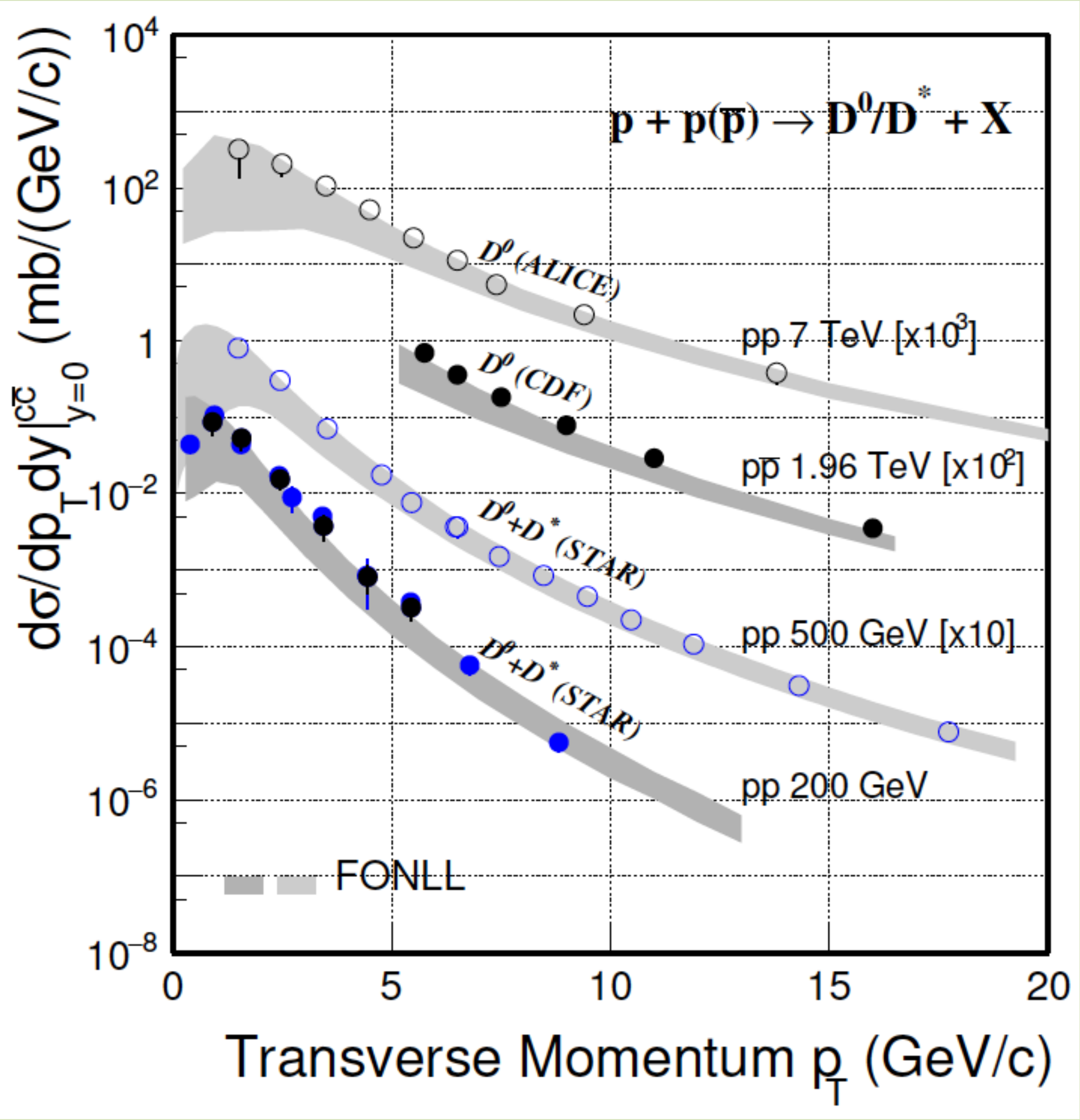


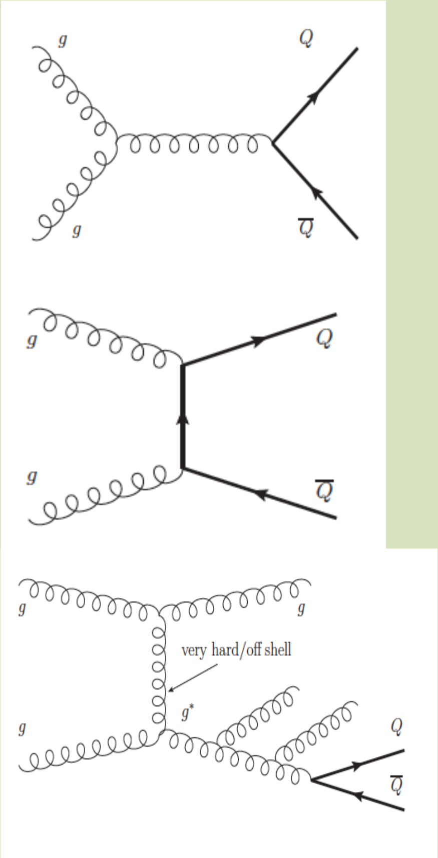
- **initial prod.**
  - pQCD-NLO
  - MC-NLO
  - CNM effect [pp,pA exp.]

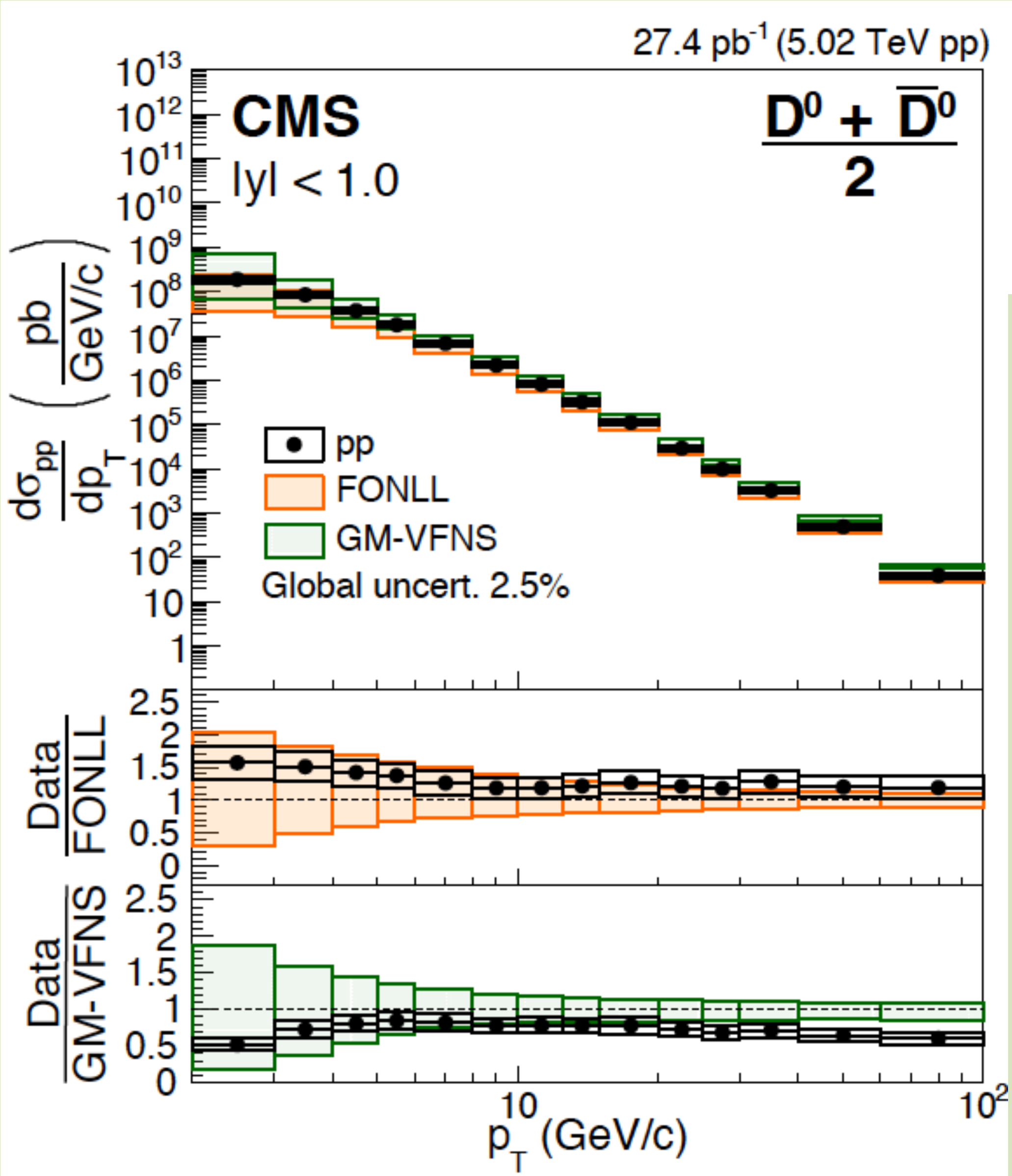
- **Dynamics in QGP**
  - **Transp. coeff. of QCD matter -> thermalization ?!**

- **hadronization**
  - coalescence and/or fragm.
  - hadronic rescattering

Initial Production - $m_Q >> \Lambda_{QCD}$







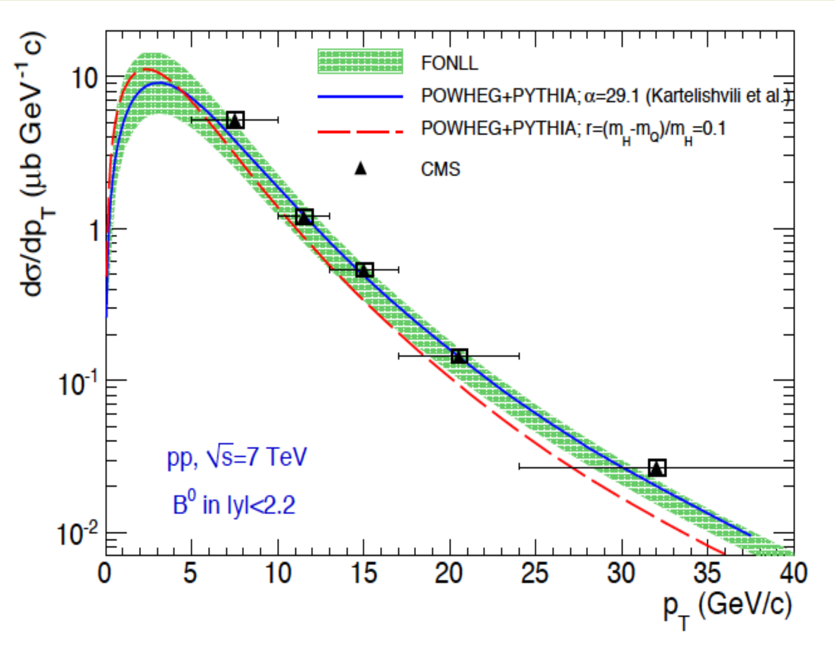
$$\mathrm{d}\sigma^{Q+X} \simeq \sum_{i,j} f_i^A \otimes f_j^B \otimes \mathrm{d}\tilde{\sigma}_{ij\to Q+X}$$

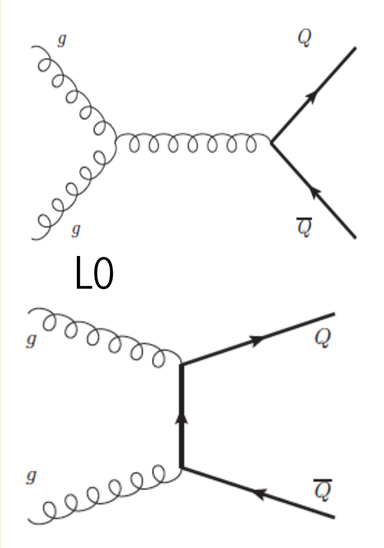
$$\mathrm{d}\sigma^{H} = \mathrm{d}\sigma^{Q} \otimes D_Q^H(z)$$

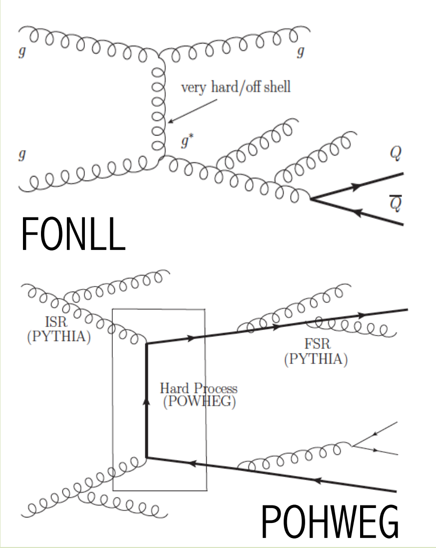
FONNL (Fixed Order NNLO pQCD)

GM-VFNS (General Mass- Variable Fixed Flavor Number Scheme)

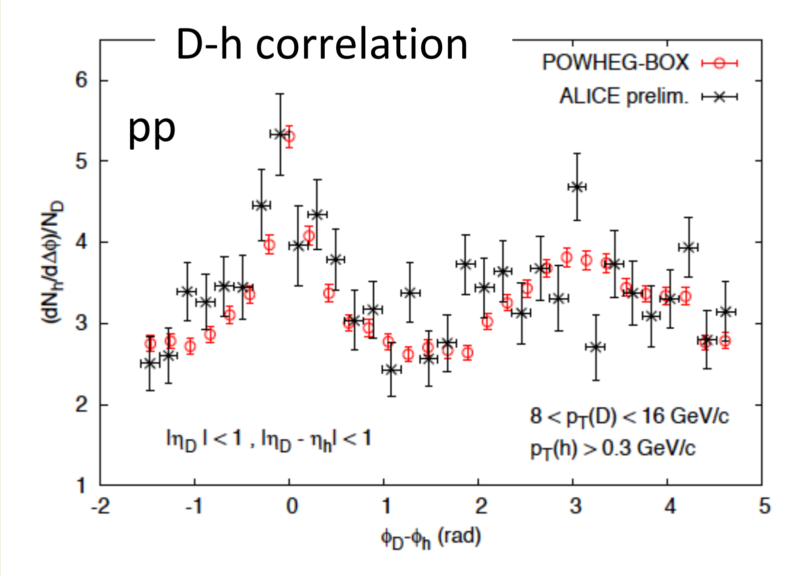
Initial Production - $m_Q >> \Lambda_{QCD}$

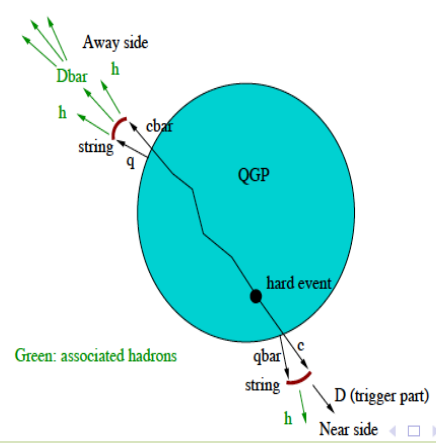




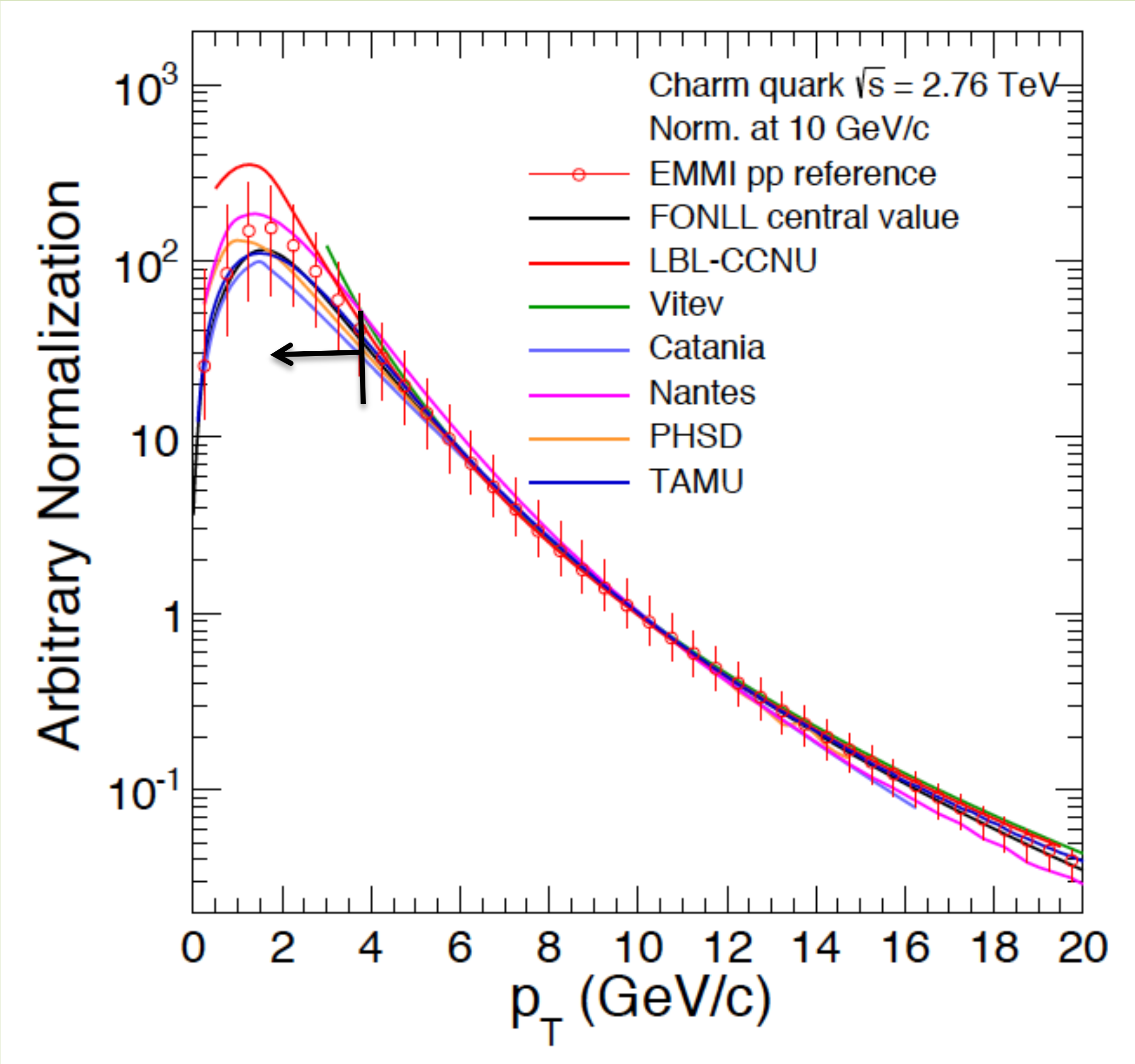


Now we have MonteCarlo (MC) generator at NLO compatible with FONNL, this will be Relevant when accessing triggered angular correlations.





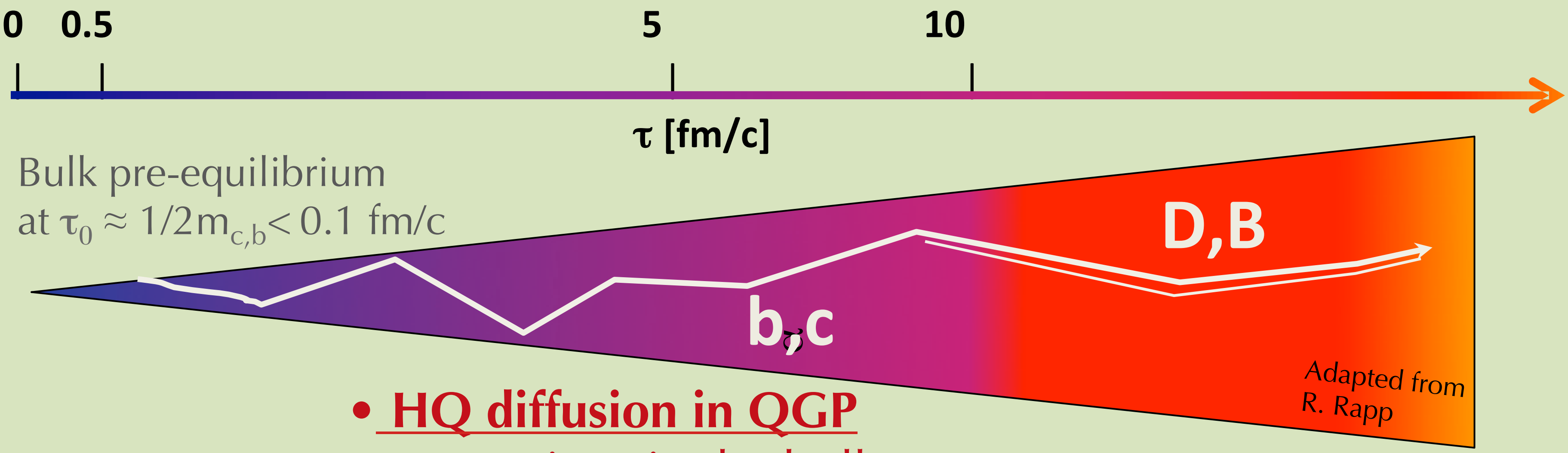
Initial Charm distribution from various groups



EMMI-RRTF Collab., ArXiV:1803.03824

Still to our purpose (R_{AA} at p_T< 4-5 GeV)
The best would be good precision data at low p_T

Studying the HF in uRHIC



- **HQ diffusion in QGP**
  - scatterings in the bulk
  - **transport equation:**
    Langevin – Boltzmann (PHSD)
  - **Transp. Coeff. for HQ**

- **hadronization**
  - coalescence and/or fragm.

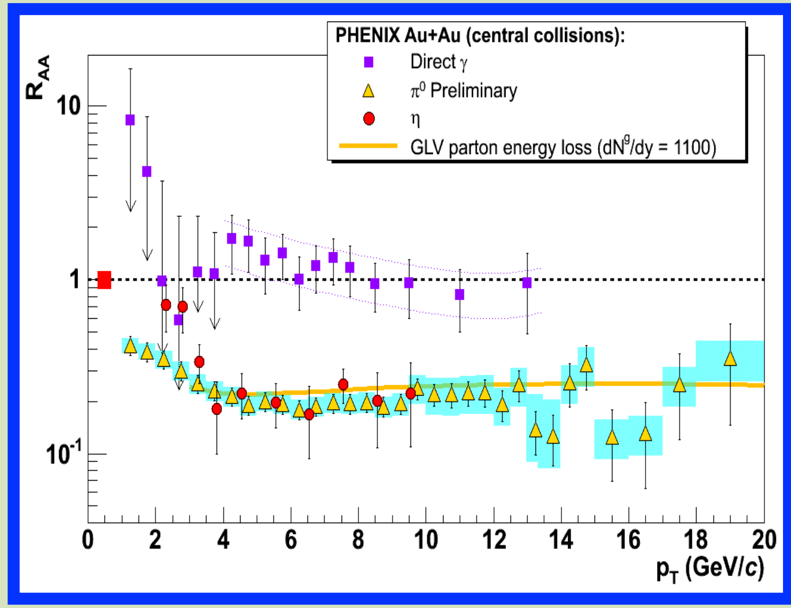
$f_Q(r,\phi_r,p,\phi_p,t)$ -> R_{AA}, v_2, v_3, $dN/d\Delta\phi_{12}$, v_2(soft)-v_2(HF)

Two Main Observables in HIC

❖ Nuclear Modification factor

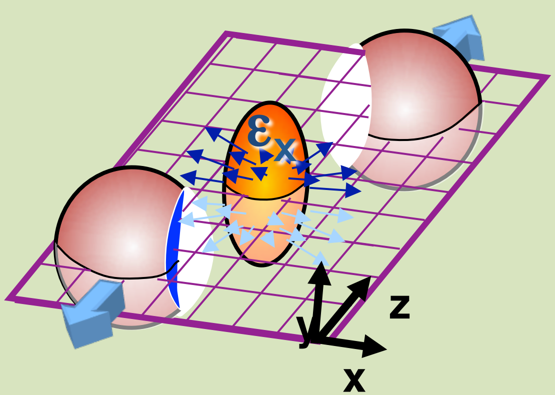
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{NN}/dp_T d\eta}$$

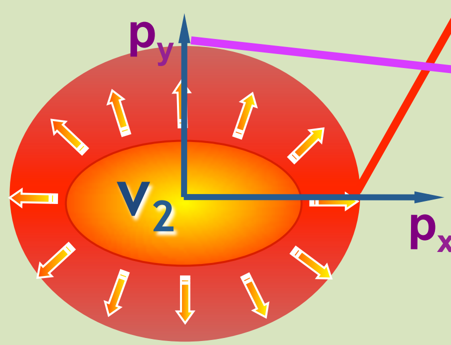
- Modification respect to pp
- Decrease with increasing partonic interaction

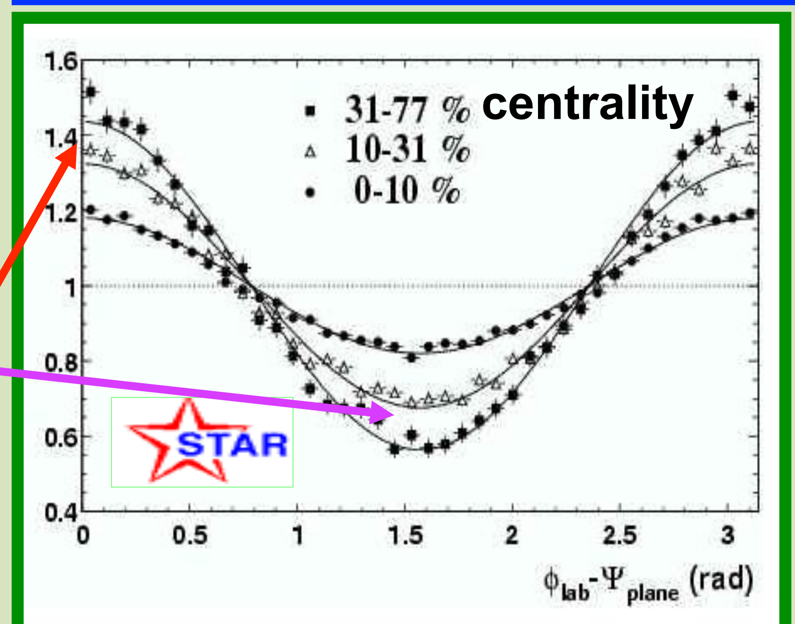


❖ Anisotropy p-space: Elliptic Flow v_2

$$\frac{dN}{p_T dp_T d\varphi} = \frac{dN}{2\pi p_T dp_T}\left[1 + 2v_2\cos(2\varphi) + \ldots\right]$$



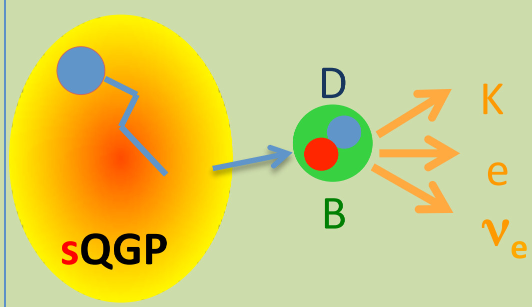




Standard Dynamics of Heavy Quarks in the QGP

Fokker-Planck approach ($T \ll m_Q$) in Hydro/transport bulk

c,b quarks



Brownian Motion

$$\boxed{\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D_p \frac{\partial^2 f_{c,b}}{\partial p^2}}$$

$$\langle \mathrm{p} \rangle = \mathrm{p}_0 \mathrm{e}^{-\gamma t}$$

$$\langle \Delta p^2 \rangle = 3 D_p / \gamma (1 - e^{-2\gamma t})$$

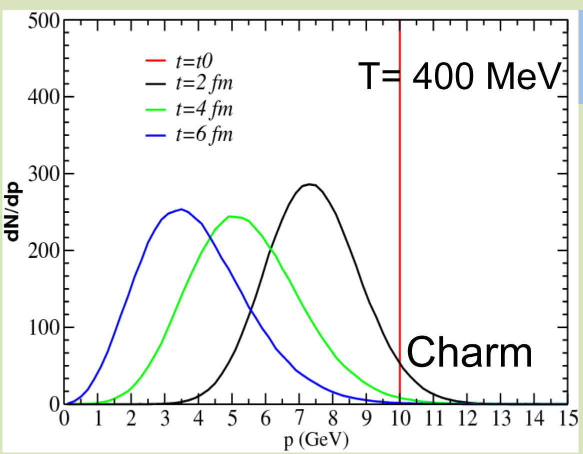
D =ETγ − FDT

$$\gamma = \int d^3k \, |M(k,p)|^2 \, p$$

$$D_p = \frac{1}{2} \int d^3k \, |M(k,p)|^2 \, p^2$$

$|\mathcal{M}|^2$ scatt. matrix from some theory: HTL, pQCD coll.,rad.,T-matrix

- D_s from lQCD

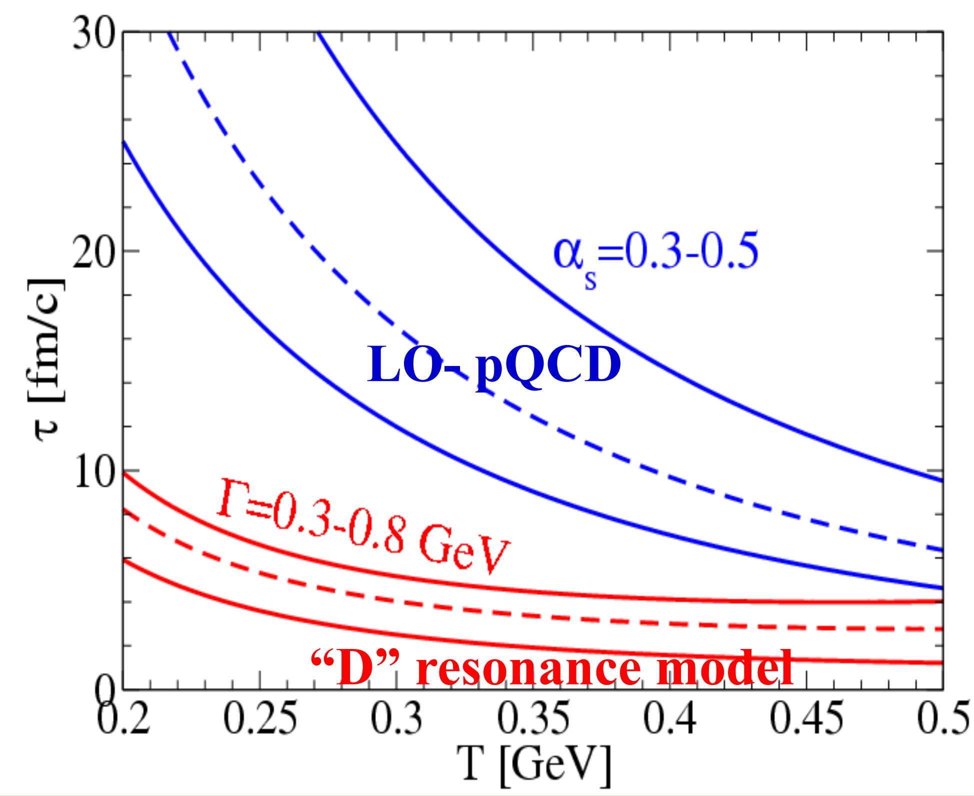


$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta(p - 10GeV)$$

- Evolution in p_T of a single charm at $P_T(t=0)$=10 GeV
- For HIC double folding with $f_{HQ}(r,p,t)$ and $\rho_{Bulk}(r,t)$
- I will also challenge such a scheme…

In 2003-04 …pQCD dynamics for HQ in the QGP!?

Equilibration time



"D" Resonance model used in
Van Hees, Rapp, PRC71(05)
Van Hees, Greco, Rapp, PRC73 (06)

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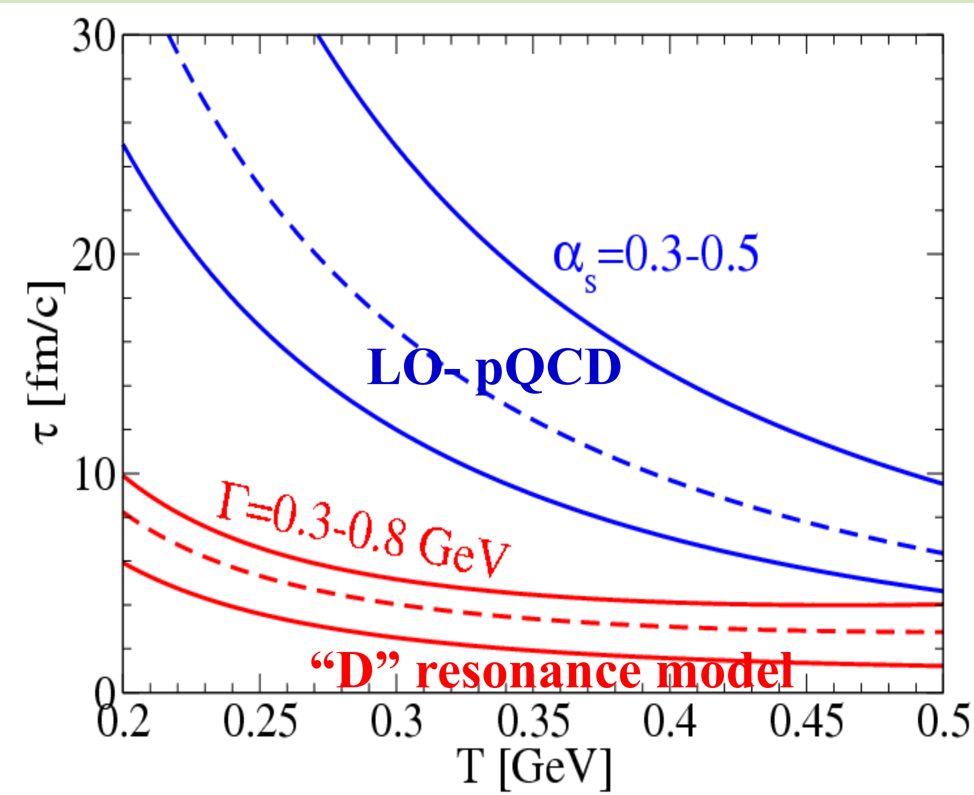

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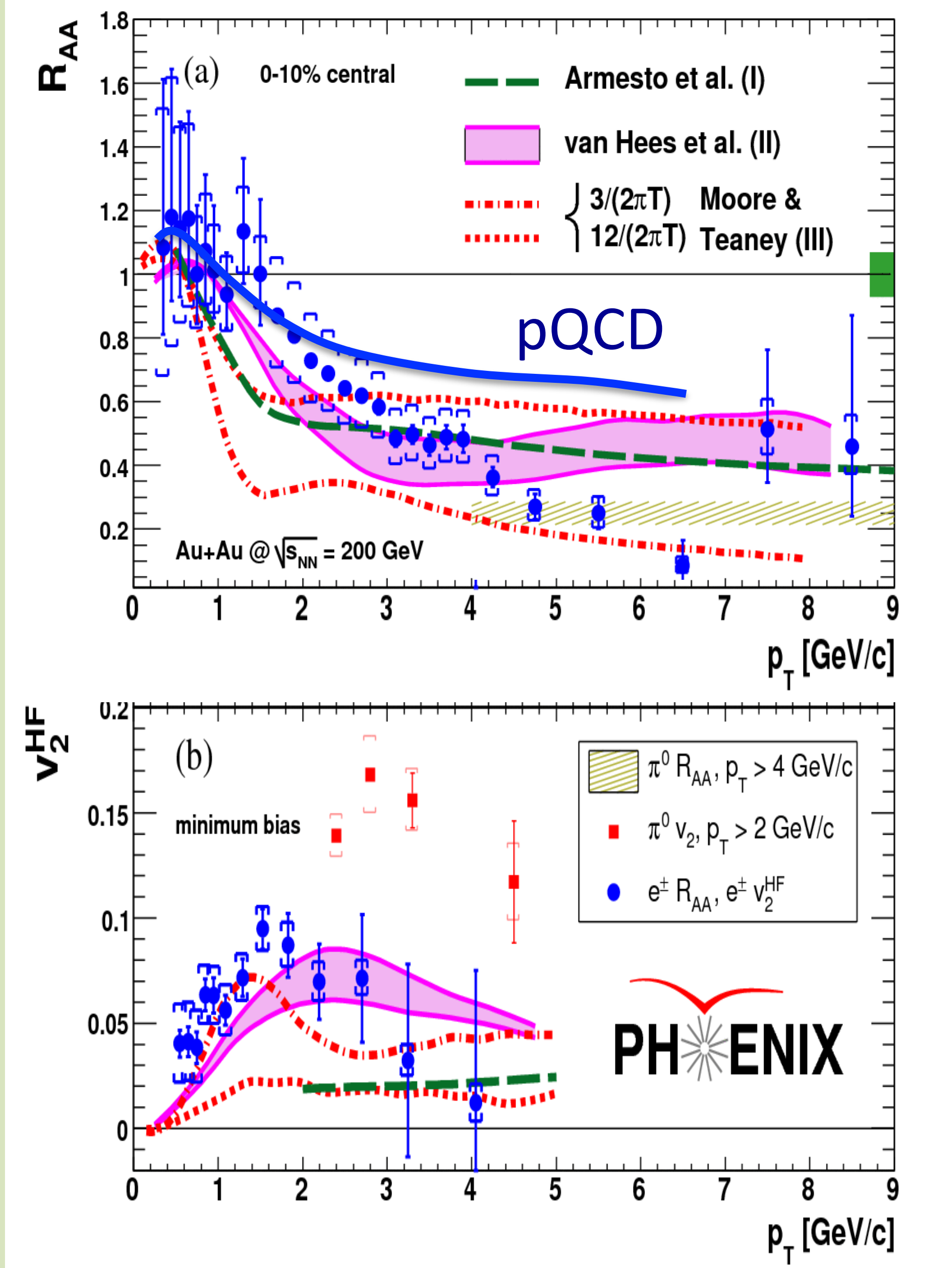
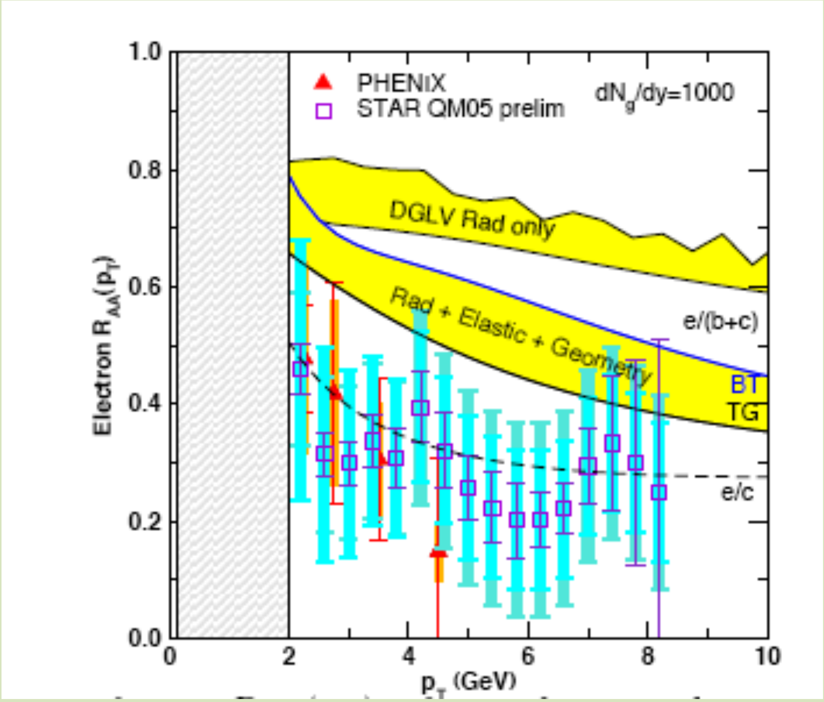


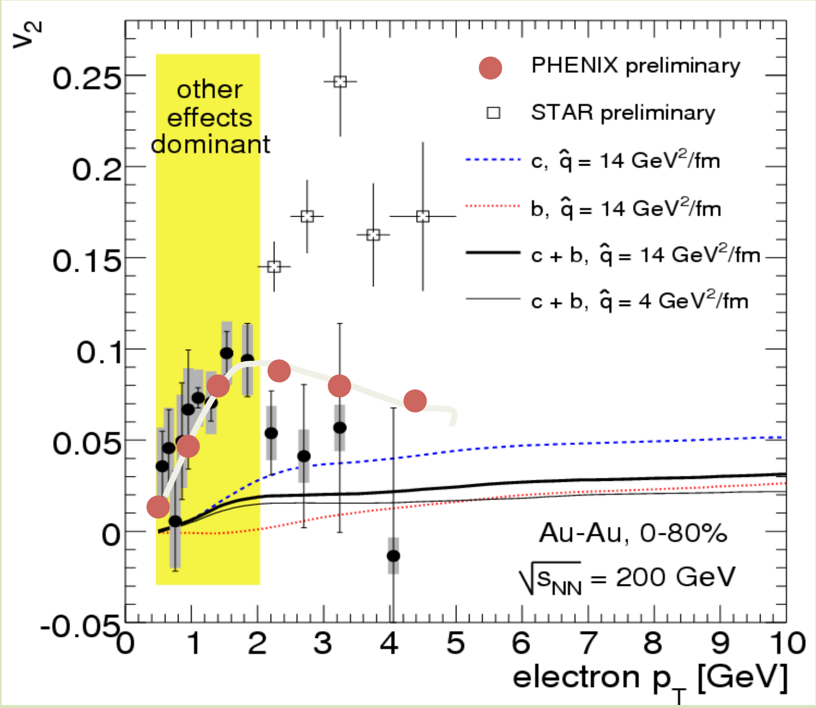
From QM2006 …

Strong suppression

Large elliptic Flow

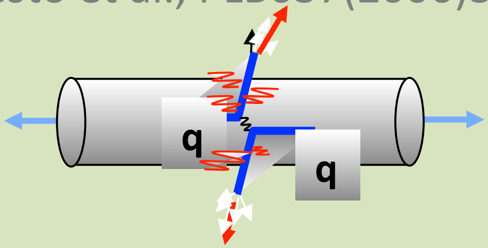


S. Wicks et al. (QM06)



N. Armesto et al., PLB637(2006)362

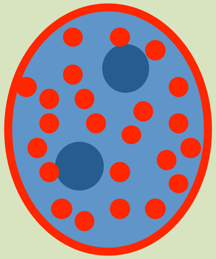
- Radiative energy loss not sufficient
- Charm seems to flow like light quarks



Heavy Quark strongly dragged by interaction with light quarks

pQCD does not work may be the real cross section is a K factor larger?

R_{AA} & v_2 with upscaled pQCD cross section



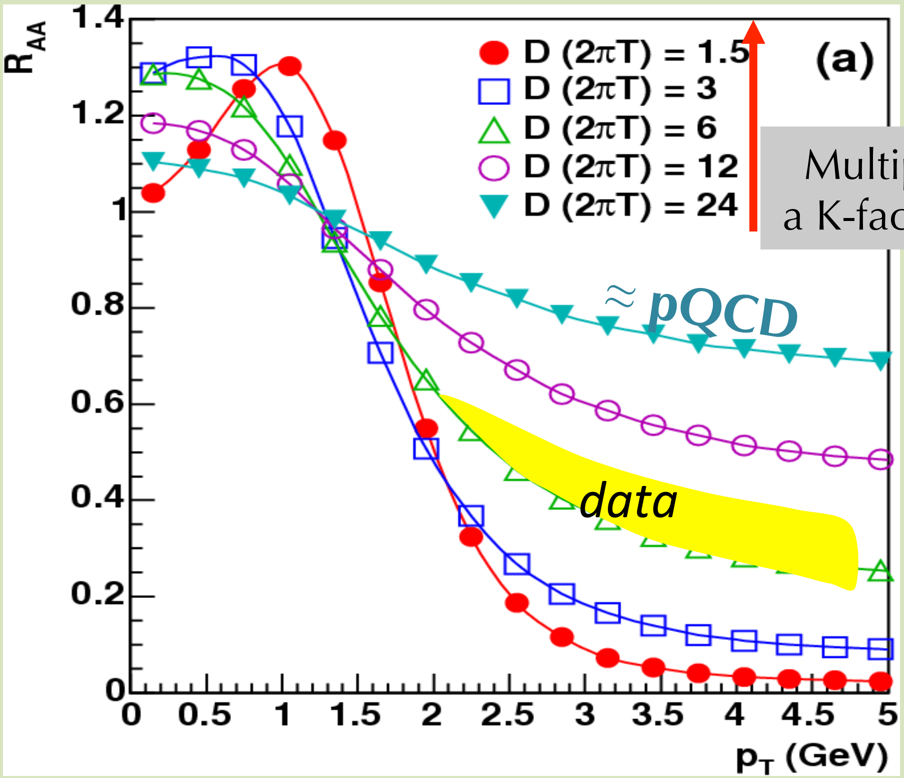
Fokker-Plank for charm interaction in a hydro bulk

Moore & Teaney, PRC71 (**2004**)

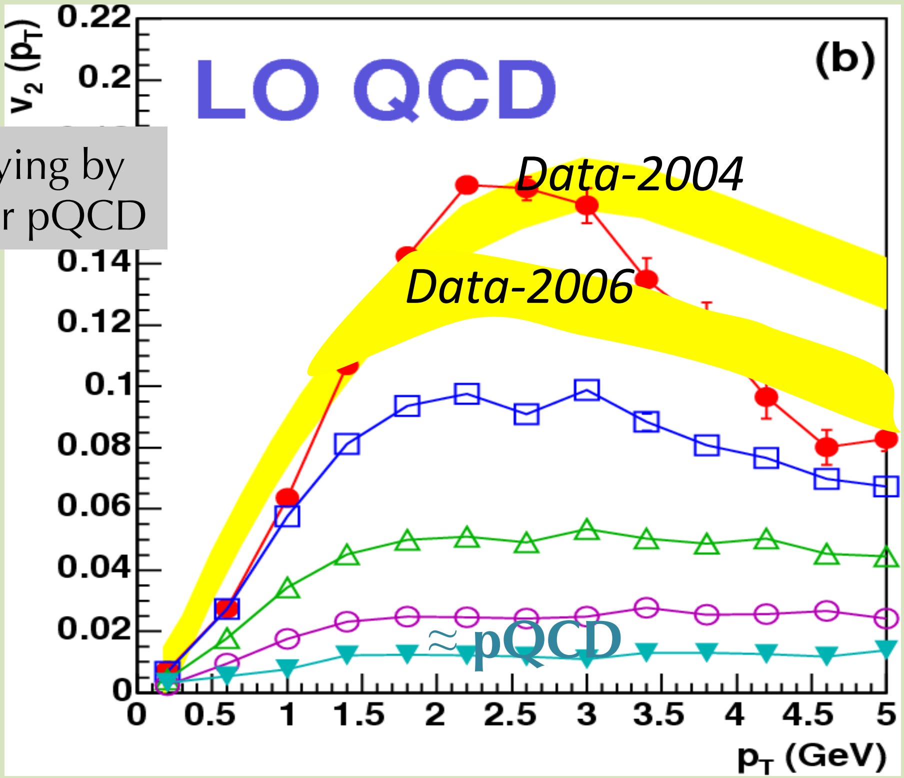
Diffusion coefficient

$$D_p \propto \int d^3k \left| M_{g(q)c \to g(q)c}(k,p) \right|^2 k^2$$

scattering matrix



Multiplying by a K-factor pQCD

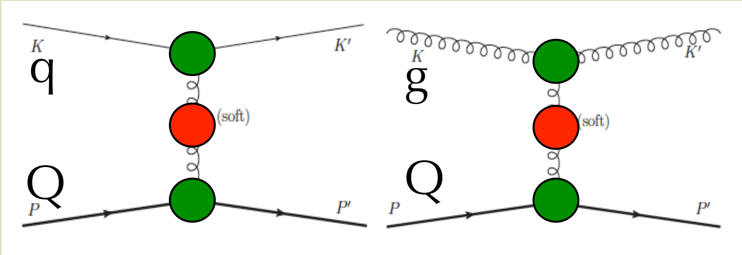


It's not just a matter of pumping up pQCD elastic cross section: too low R_{AA} or too low v_2

How HQ interact with the medium

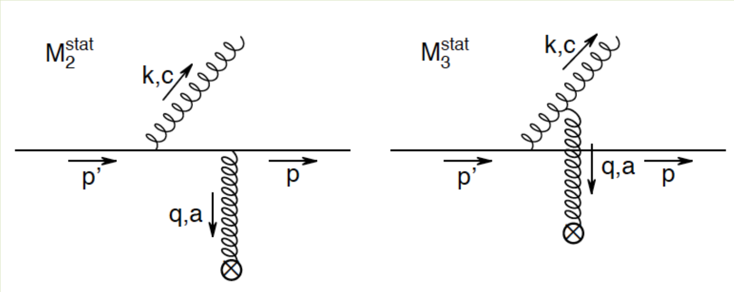
❖ Elastic Collisional Energy Loss

- **pQCD inspired+HTL** (*Torino, Nantes,LBL…*)
  LO diagrams, soft scale resummed in HTL
  Infrared singularity, $gT << g^2$?
- **QuasiParticleModel** (*Catania, Frankfurt-PHSD*)
  LO diagram, $\alpha_s(T)$ from a fit to lQCD-EoS
  main feature increased strength as T -> Tc



❖ Radiative Energy Loss

- **pQCD** (p_T > 10 GeV) (*AMY, DGLV, WHDG,HT, …*)
  some have both collisional and radiative
  both light & heavy but v_2 is often missed



Agreement that:
- $p \approx m_Q$ is dominated by Collisional E_{loss}
- $p >>> m_Q$ radiative dominated
- what is the crossing is model dependent and exp. data are not able to clarify it even if favor collisional up to $p_T \approx$ 5-6 GeV for charm

Some main specific features of:

1) LBL-CCNU-Duke

2) Nantes

3) QPM- Catania

4) PHSD

5) BAMPS,

6)TAMU

7)Torino, HTL

8) CUJET

9) DGLV

10) AdS/CFT

Some main specific features of:

1) **LBL-CCNU-Duke**, pQCD* $K(p_T,T)$ + Bayesian → drag ≈ T

2) **Nantes**, HTL for $|t|<|t^*|$ + modified propagator $1/(t-km_D^2)$ → forward peak

3) **QPM-Catania**, $\alpha_s(T)$ fitted to lQCD thermodynamics ε,p,s

4) **PHSD**, like QPM + off-shell dynamics

5) **BAMPS**, pQCD LO radiative+elastic α_s=0.6

6) **TAMU**, Resonant scattering drive by V(r,T) from lQCD

7) **Torino**, HTL for $|t|<|t^*|$ starting from D_p + FDT

8) **CUJET**, α_s (T) large increase at T→ Tc due to monopoles

9) **DGLV**, α_s(T) opacity expansion base on scattering on yukawa interaction

10) **AdS/CFT**, Drag ≈ T^2 like pQCD but 10-20 time larger (no p dep.)

Shared feature Drag >> pQCD-LO and some have stronger interaction as $T \rightarrow T_c$

Simple QP-Model fitting lQCD

Plumari, Alberico, Greco, Ratti, PRD84 (2011)

$$P(T) = \sum_{i=g,q,\bar{q}} \frac{D_i}{(2\pi)^3} \int_0^\infty d^3k \frac{k^2}{3\omega_i(k)} f_i(k) - B(T)$$

$$\varepsilon(T) = \sum_{i=g,q,\bar{q}} \frac{d_i}{(2\pi)^3} \int_0^\infty d^3k \; \omega_i(k) \; f_i(k) + B(T) + \widetilde{W}_B(T)$$

W_B=0 guarantees
Thermodynamicaly consistency

$$\omega_{q,g} = k^2 + m^2_{q,g}(T)$$

$$m_g^2 = \frac{1}{6}\left(N_c + \frac{1}{2}N_f\right) g^2T^2$$

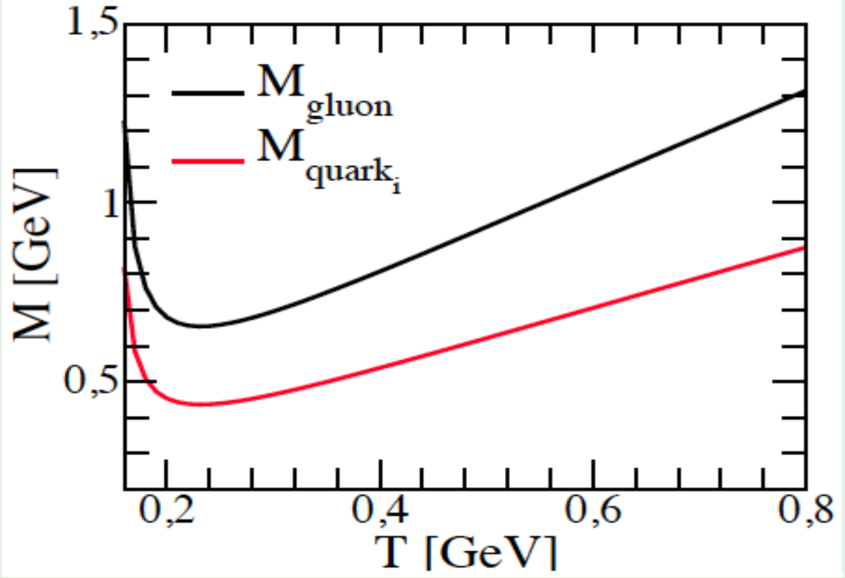
$$m_q^2 = \frac{N_c^2 - 1}{8N_c} g^2T^2($$

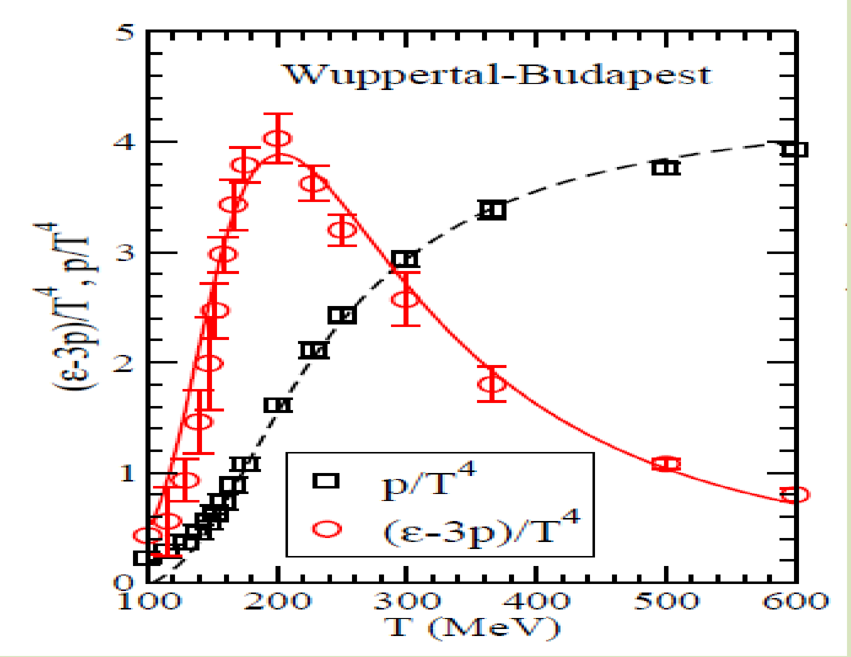
g(T) from a fit to **ε** from lQCD
-> good reproduction of P, e-3P, c_s

$$g^2_{QP}(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

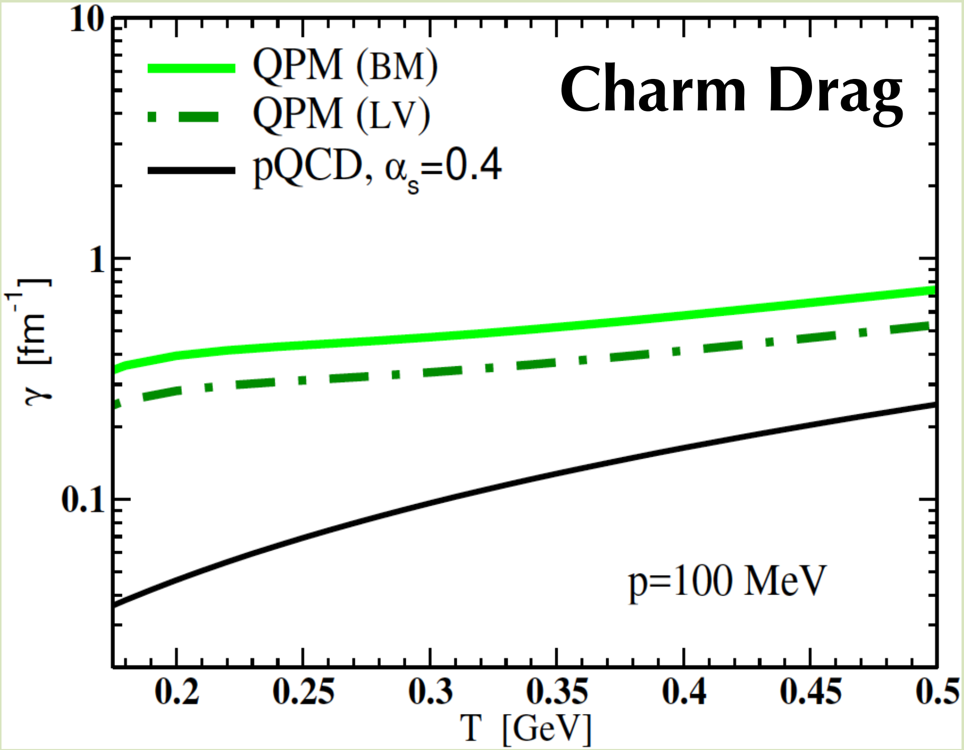
λ=2.6
T_s=0.57 T_c

Larger than pQCD





Drag Transport coefficient in QPM

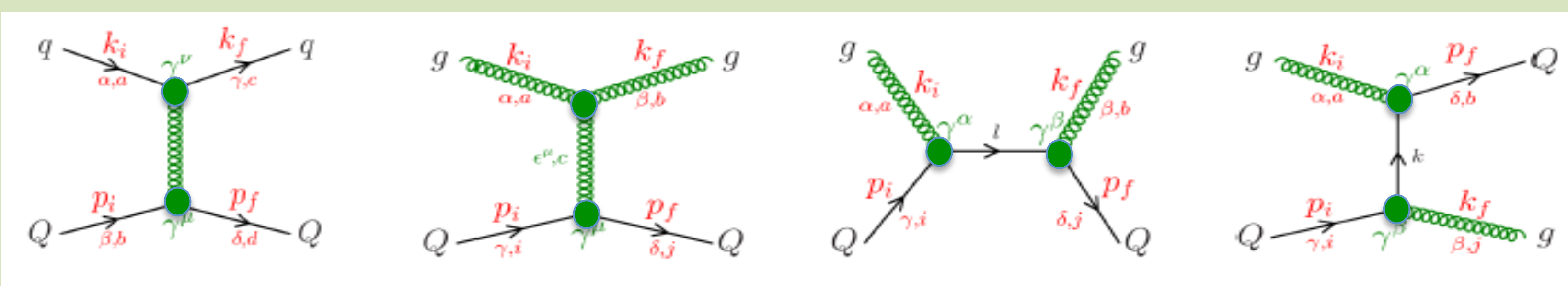


$f(p,t=0)=\delta(p-p_0)$

$\langle p \rangle = p_o\, e^{-\gamma t}$

- ✧ Drag from QPM quite large than pQCD : g(T) enhanced as T-->Tc weak dependence on T
- ✧ pQCD or AdS/CFT γ (T)≈ $1/T^2$

$$\gamma_i = \gamma(p^2)p_i = \frac{1}{2E_p}\int\frac{d^3q}{(2\pi)^3 2E_q}\int\frac{d^3q'}{(2\pi)^3 2E_{q'}}\int\frac{d^3p'}{(2\pi)^3 2E_{p'}}\sum\left|M_{(q,g)+Q\to(q,g)+Q}\right|^2(2\pi)^4\delta^4(p+q-p'-q')f(q)\left[(p-p')_i\right]$$

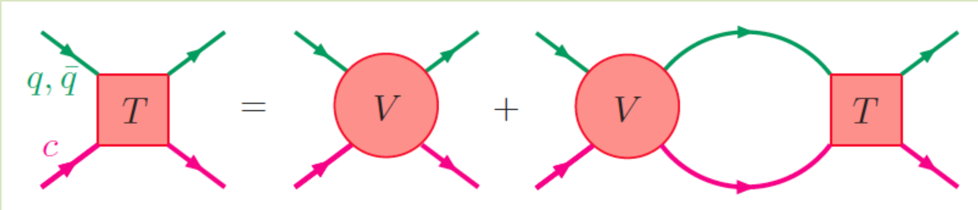


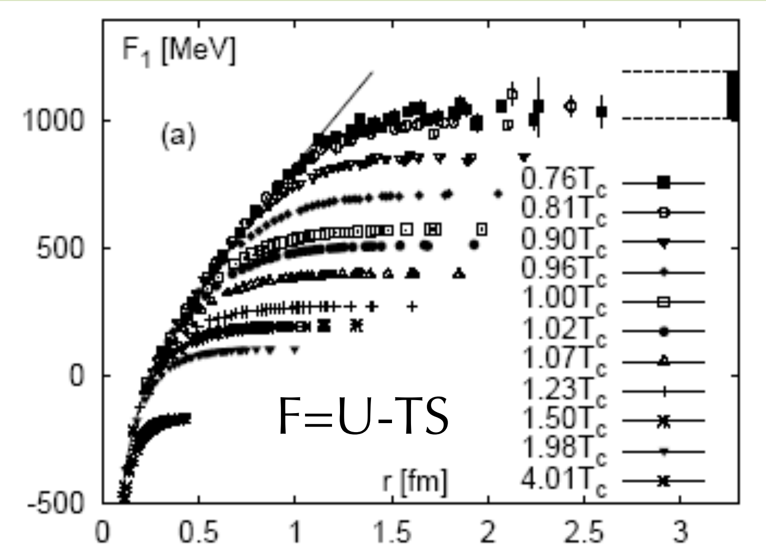
Some other recent theoretical progress

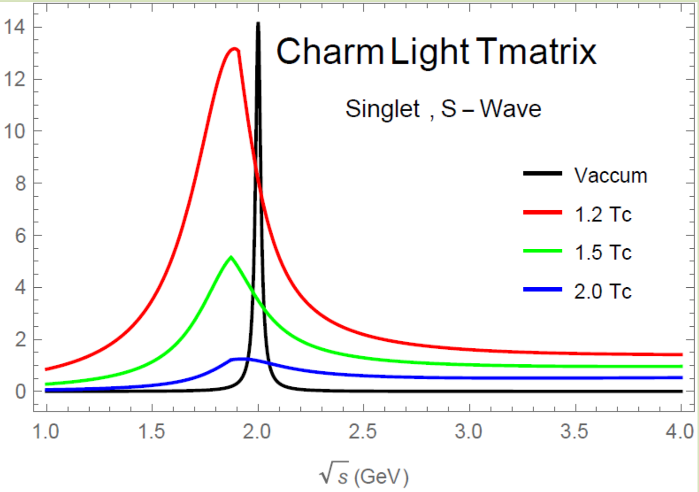
Resonant Elastic scattering with T-matrix

Scattering under a potential derived from lQCD Free-energy:

Like QPM indicates an increasing interaction as T -> T_c







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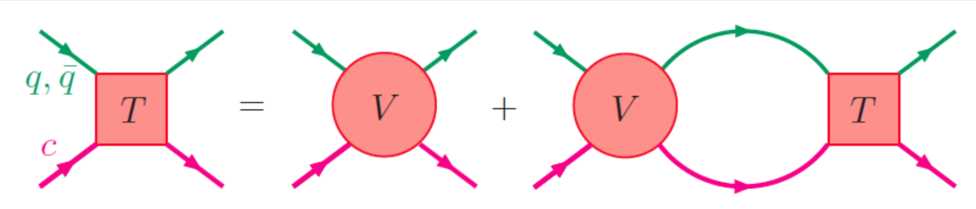
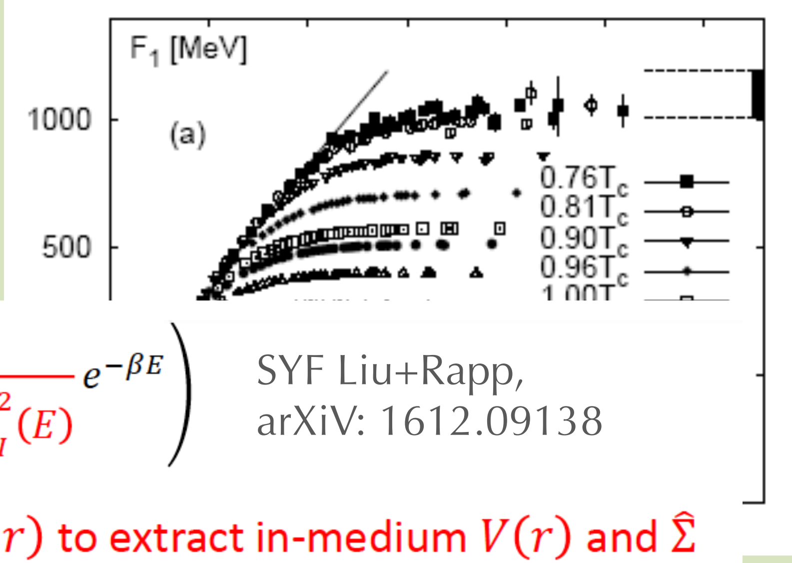


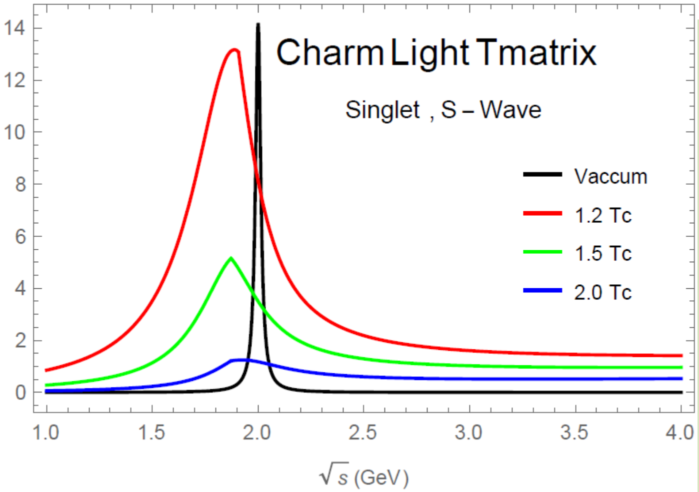


Recent new theoretical development

$$F_{Q\bar{Q}}(T,r) = -T\ln\left(\int_{-\infty}^{\infty} dE \, \frac{-1}{\pi} \frac{(V+\hat{\Sigma})_I(E)}{\left(E-(V+\hat{\Sigma})_R\right)^2 + (V+\hat{\Sigma})_I^2(E)} e^{-\beta E}\right)$$

SYF Liu+Rapp, arXiV: 1612.09138

➢ Compare T-matrix $F_{Q\bar{Q}}(T,r)$ with lattice $F_{Q\bar{Q}}(T,r)$ to extract in-medium $V(r)$ and $\hat{\Sigma}$

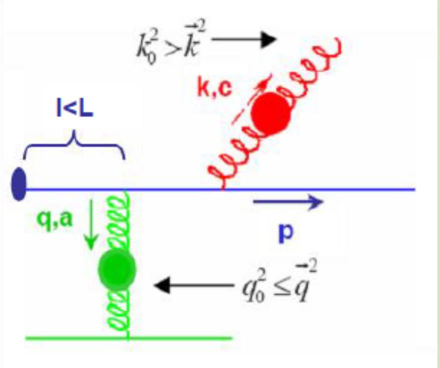


- ➢ A way to solve the issue of V from F=U-TS
- ➢ V keeps long range remnants of confinement
- ➢ Consistent with hadronization by coalescence
- ➢ Scope: *consistency with quarkonium correlator, HQ susceptibilities, EoS, …3-body?*

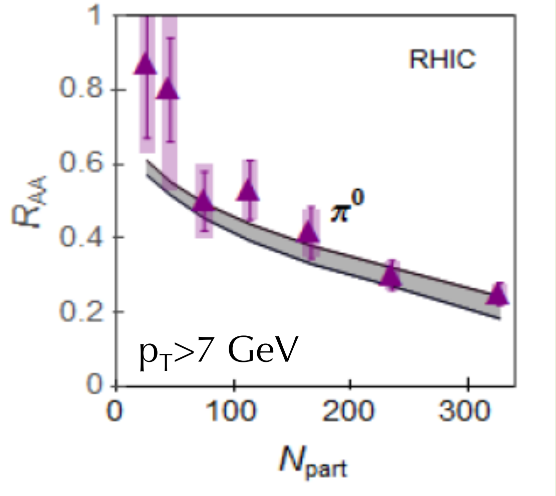
pQCD E_{loss} extension of DGLV

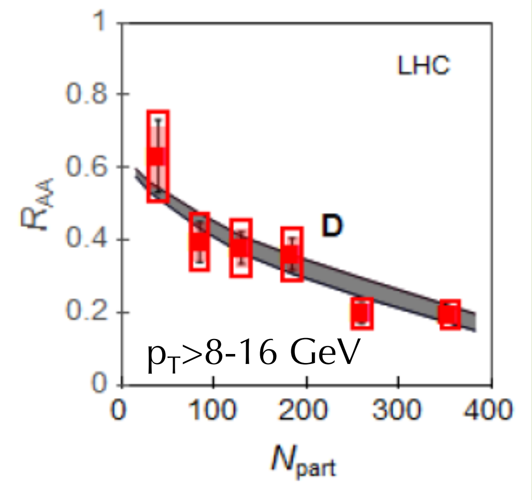
Continous improvement: no static scatterings → coll.+rad., finite size, magnetic and electric mass, α_s running, …both heavy& light,

- Collisional non negliglible (also at p_T>5-10 GeV)
- Explain $R_{AA}(\pi) \approx R_{AA}(D) < R_{AA}(B)$

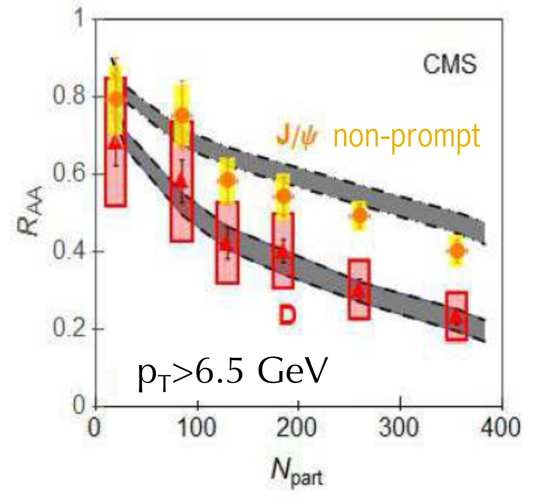


M. Djordjevic et al. PRC80 (2009), PRL101(2008), PLB709 (2012), PLB734 (2014) …





PLB737(2014)

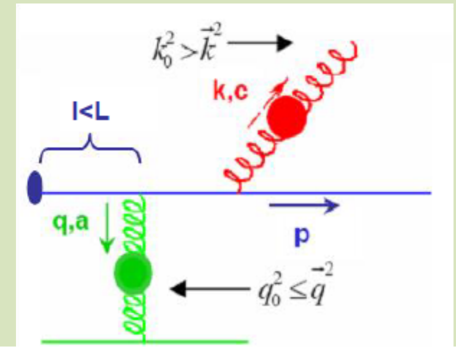


PRC94(2016)

pQCD E_{loss} extension of DGLV

Continous improvement: no static scatterings → coll.+rad., Both heavy& light, finite size magnetic and electric mass, α_s running,…

- Collisional non negliglible (also at p_T>5-10 GeV)
- Explain $R_{AA}(\pi) \approx R_{AA}(D) > R_{AA}(B)$

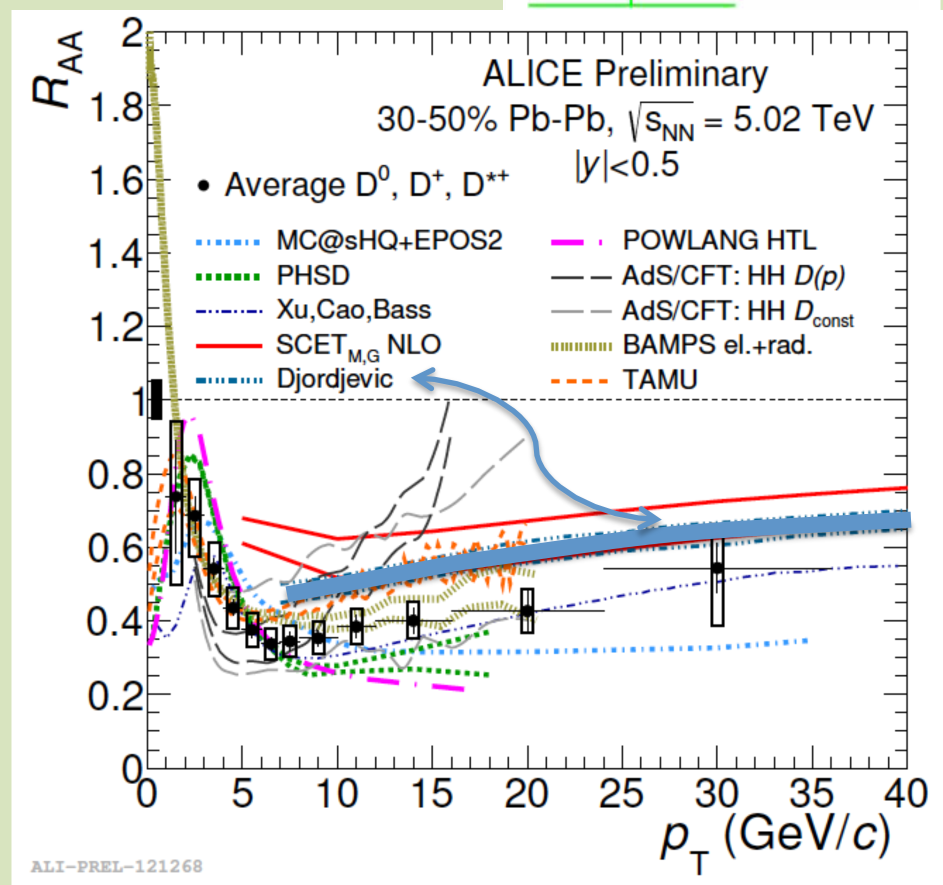


Progress needed:

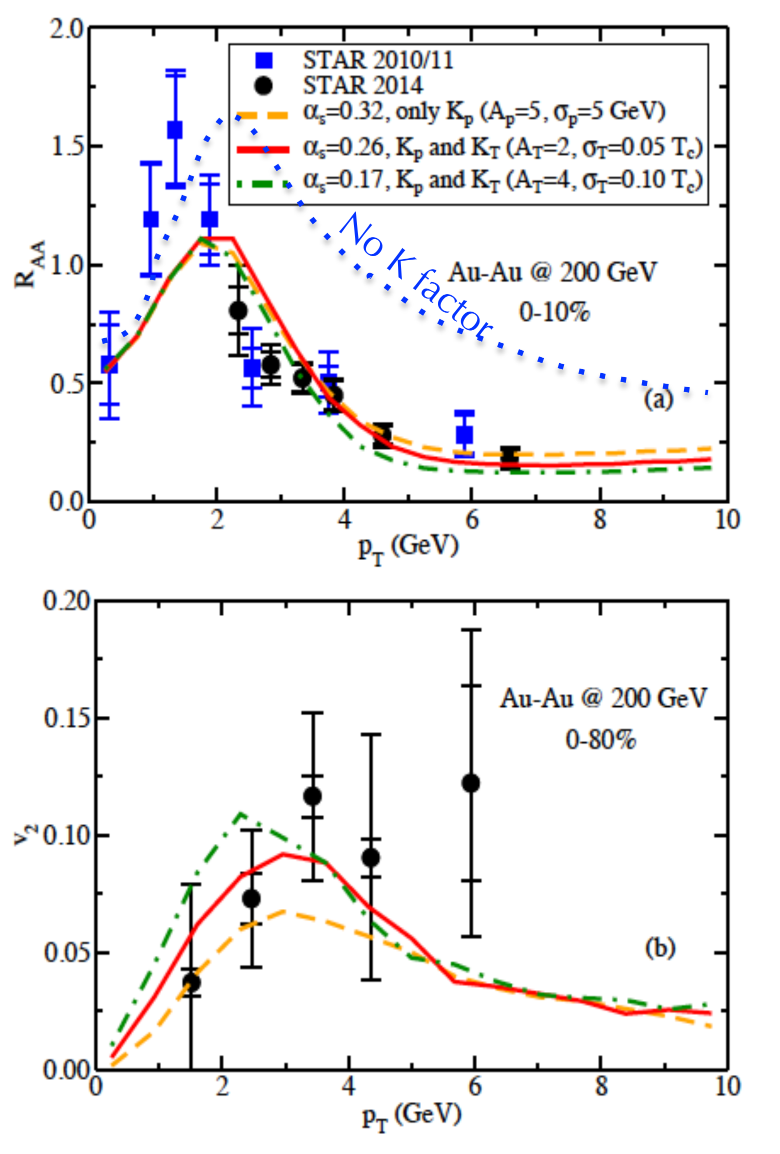
✧ Miss an underlying Hydro well controlled background

✧ Miss prediction for v_2

This step is starting … ERC-Grant $$$$



Linearized Boltzmann Transp.: Coll.+Rad.



S. Cao et al., PRC94(2016)

Main point:

✧ Starting from pQCD a **K-factor is needed** that is T and p depedent:

$$\hat{q} = \hat{q}_{pQCD} \cdot K^2 \left[1 + A_p e^{-\frac{p^2}{2\sigma_p^2}}\right] \left[1 + A_T e^{-\frac{(T-Tc)^2}{2\sigma_T^2}}\right]^2$$

✧ This means non-perturbative dynamics
- that is larger as T -> T_c
- that disappears as p >> m_c

Data led different modeling to a coherent message

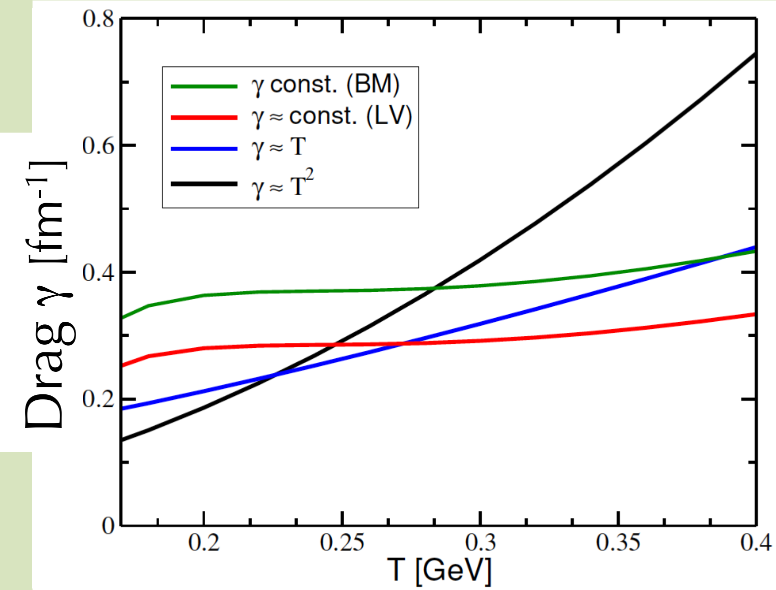
Future: 5 param. Global Bayesan fit [S.Bass talk]

Strong points:

✧ Both heavy and light
✧ Both radiative and collisional
✧ Realistic hydro background

What is the relation between transport coefficients and experimental observables?

Impact of T dep. interaction on $R_{AA} - v_2$

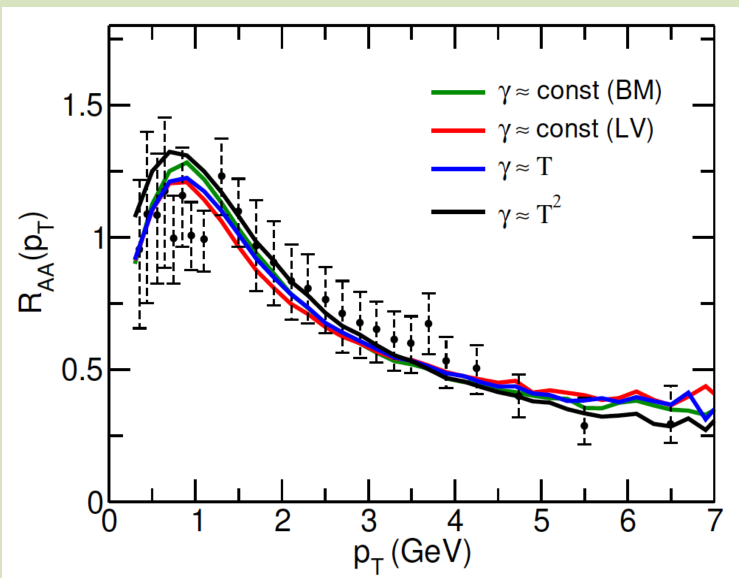


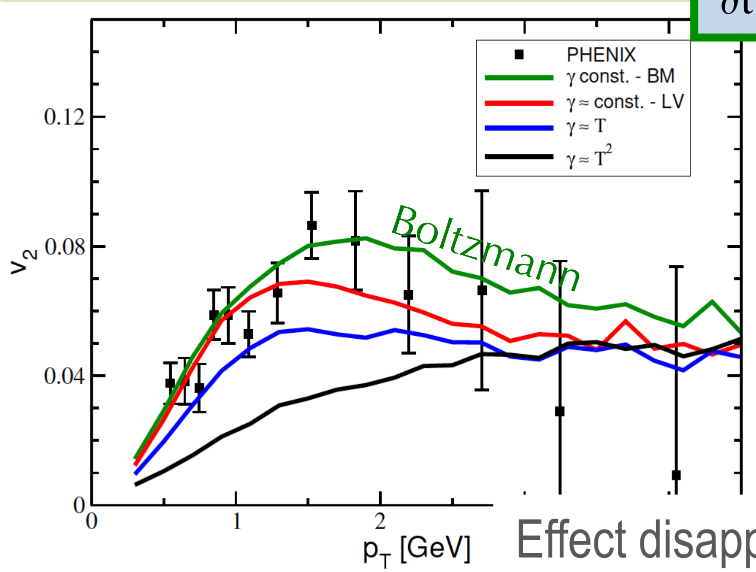
Looking at it beyond the specific modelings

- **$\gamma \approx T^2$** [Ads/CFT, pQCD α_s=const, *Duke*]
- **$\gamma \approx T$** [pQCD strong α_s running] [LBT] [MC@HQ] [T-matrix]
- **$\gamma \approx$ const.** [QPM, PHSD,..] [QPM, PHSD]

γ rescaled to fit $R_{AA}(p_T)$, D from FDT

$$\frac{\partial f_Q}{\partial t} = \gamma \frac{\partial (p f_Q)}{\partial p} + D \frac{\partial^2 f_Q}{\partial p^2}$$





Effect disappears at p_T> 3 GeV
extends for v_3 Caio's talk

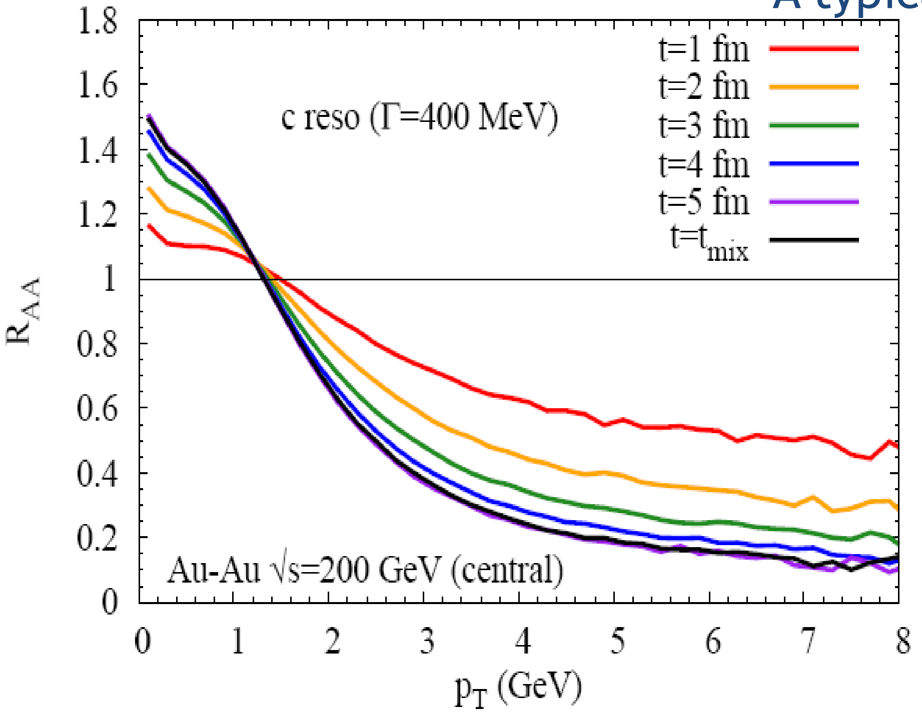
S. Das et al., PLB747 (2015) 260

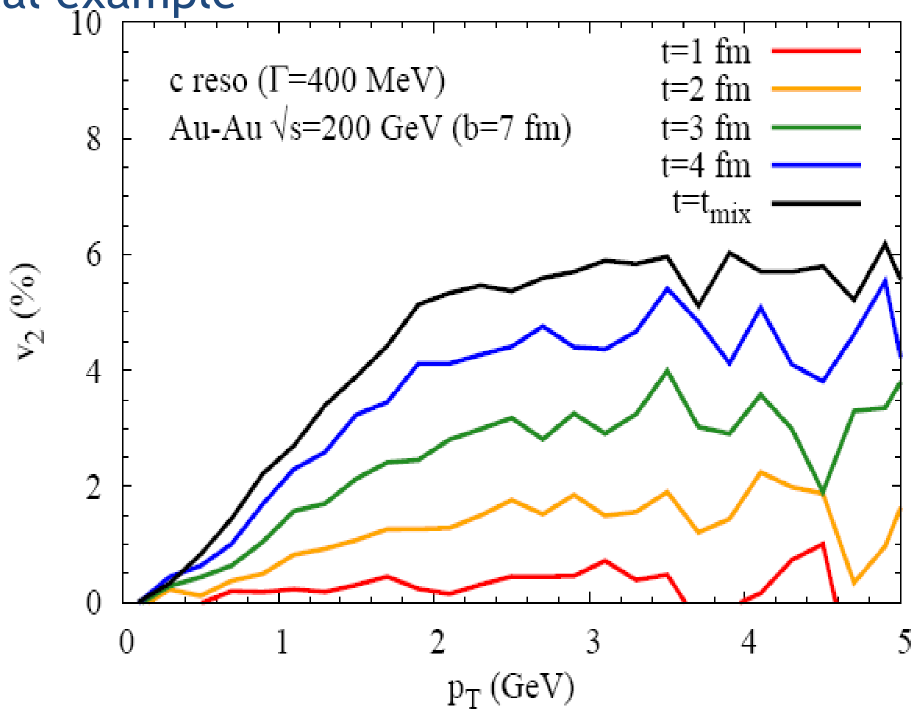
R_{AA} and v_2 correlation

No interaction means R_{AA}=1 and v_2=0. More interaction decrease R_{AA} and increase v_2

R_{AA} can be "generated" faster than v_2

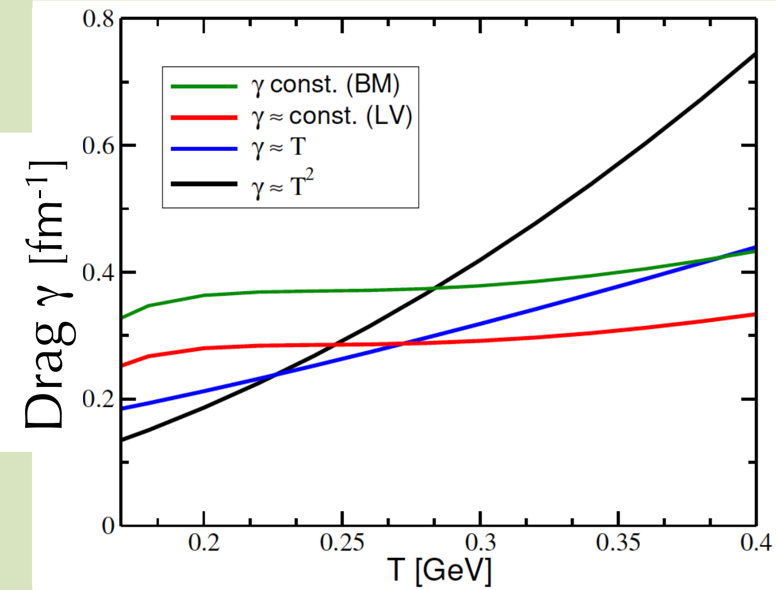
A typical example





The relation between R_{AA} and time is not trivial and depend on how one interact and loose energy with time.

Impact of T dep. interaction on $R_{AA} - v_2$



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- ➢ $\gamma \approx T$ [pQCD strong α_s running] [MC@HQ] [LBT]
- ➢ $\gamma \approx$ **const.** [QPM, PHSD,..] [T-matrix]

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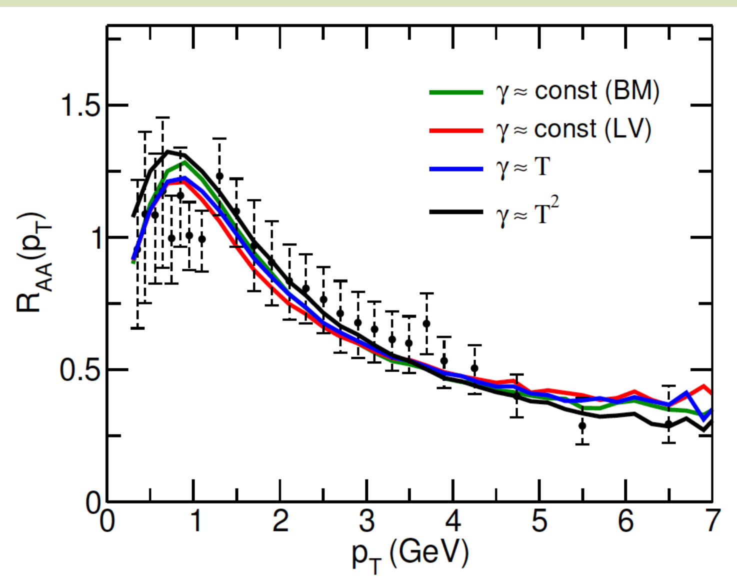
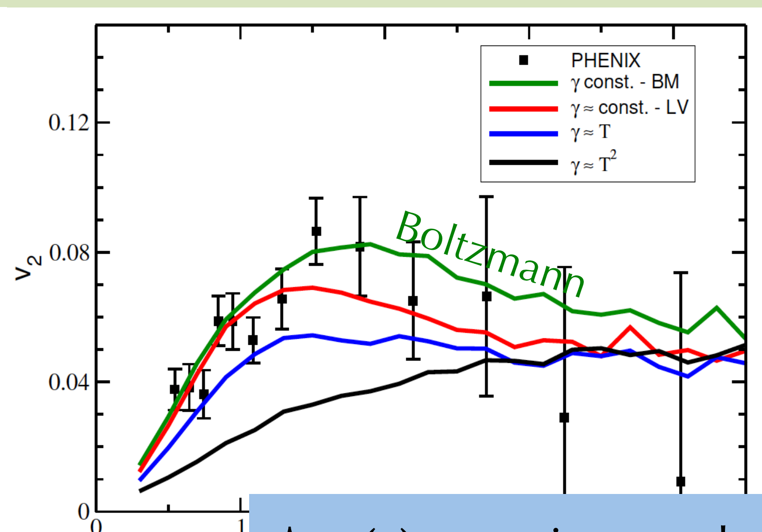
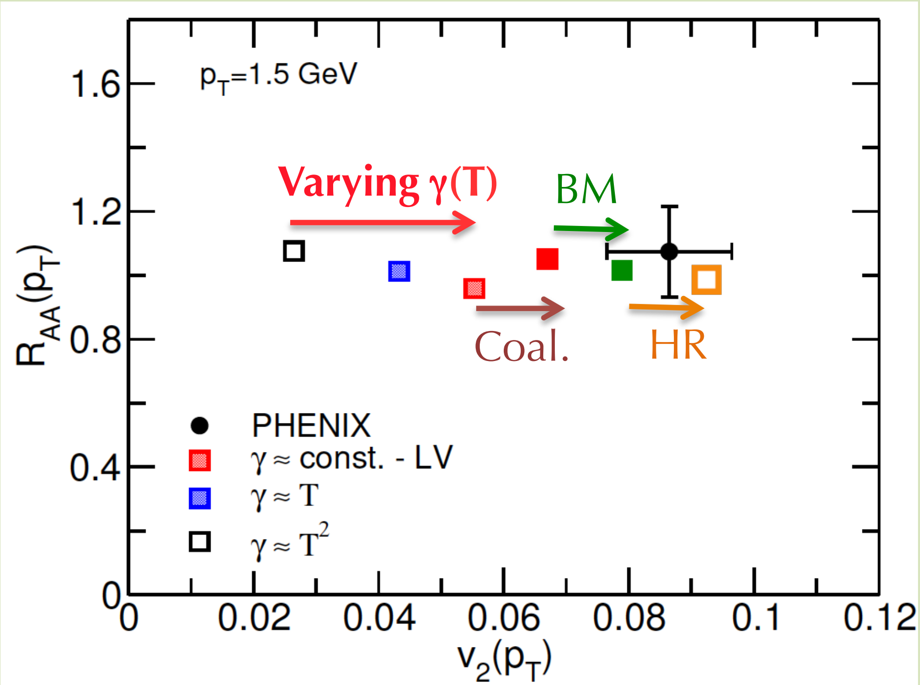




S. Das et al., PLB747 (2015) 260

✧ **γ(T)** more impact than η/s(T) for bulk
factor 2 in v_2 vs 10-20%

$R_{AA} - V_2$



<u>3 main contributions:</u>

- ✧ **γ(T) factor 2 in v_2** vs 10-20% more impact than η/s(T) for bulk
- ✧ 10-25% Boltzmann dynamics
- ✧ 20-30% Hadronization by coalesc.

Still several ingredients to be scrutinized: *initial p_T,w w/o CNM, hydro bulk, hadronization impact,w/o hadronic rescattering…* we are working on this:

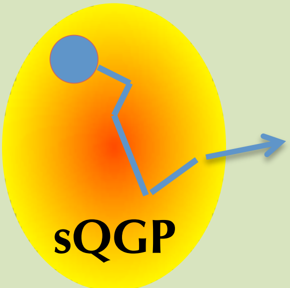
- **EMMI-RRTF@GSI**
- **Jet-HQ**
- **Duke-Frankfurt-Nantes-Catania**

✧ At RHIC solution for R_{AA}-v_2, not clear is sufficient at LHC (still large error bars)

✧ Impact of Hadronic Rescattering 0-20%, but T_c=155-175 MeV would be appropriate to have 155 MeV (lQCD, SHM) and check v_{2D} vs v_{2Ds}

HQ diffusion in the expanding QGP

c,b quarks



Two main approaches:

1) **Langevin approach** ($T \ll m_q$ soft scattering)

[*TAMU, Duke, Nantes, Torino, Catania, …*]

2) **Boltzman kinetic transport** (…Kadanoff-Baym-PHSD)

[*Catania, Nantes, Frankfurt, LBL, CCNU,…*]

background Hydro/transport expanding bulk

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Two main approaches:

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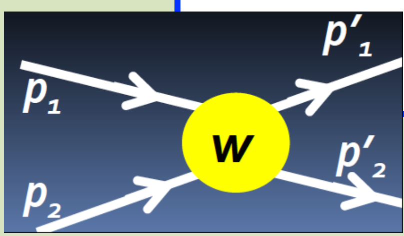
2) **Boltzman kinetic transport** (…Kadanoff-Baym-PHSD)

[Catania, Nantes, Frankfurt, LBL, CCNU,…]

background Hydro/transport expanding bulk

Boltzmann (BM)

$$\frac{Df_Q(p)}{Dt} = C_{22} = \frac{1}{2E_p}\int \frac{d^3q}{(2\pi)^3 2E_q}\int \frac{d^3p'}{(2\pi)^3 2E'_p}\frac{d^3q'}{(2\pi)^3 2E'_q}\left[f'_g(q')f'_Q(p')\left|M_{gQ\to gQ}(p'q'\to pq)\right|^2 - f_g(q)f_Q(p)\left|M_{gQ\to gQ}(pq\to p'q')\right|^2\right](2\pi)^4\delta^4(p+q-p'-q')$$



Small q^2 <<M, M>> gT

Brownian motion

Langevin/Fokker Planck (LV)

$$\gamma = \int d^3k\left|M(k,p)\right|^2 p$$

$$D = \frac{1}{2}\int d^3k\left|M(k,p)\right|^2 p^2$$

$|M|^2$ scatt. matrix from some theory: *HTL, pQCD coll.,rad.,T-matrix..*

Fluct.-Dissip. Th.

D =ETγ

$$\frac{\partial f_Q}{\partial t} = \gamma\frac{\partial(pf_Q)}{\partial p} + D\frac{\partial^2 f_Q}{\partial p^2}$$

<p>≈ $e^{-\gamma T}$

Drag

<Δp²>

Diffusion

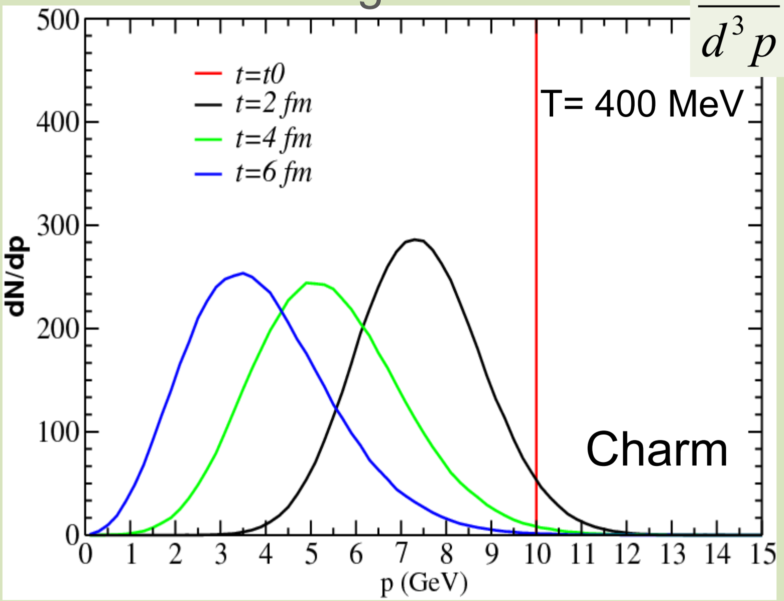
Going more differential

$m_D = gT = 0.83$ GeV

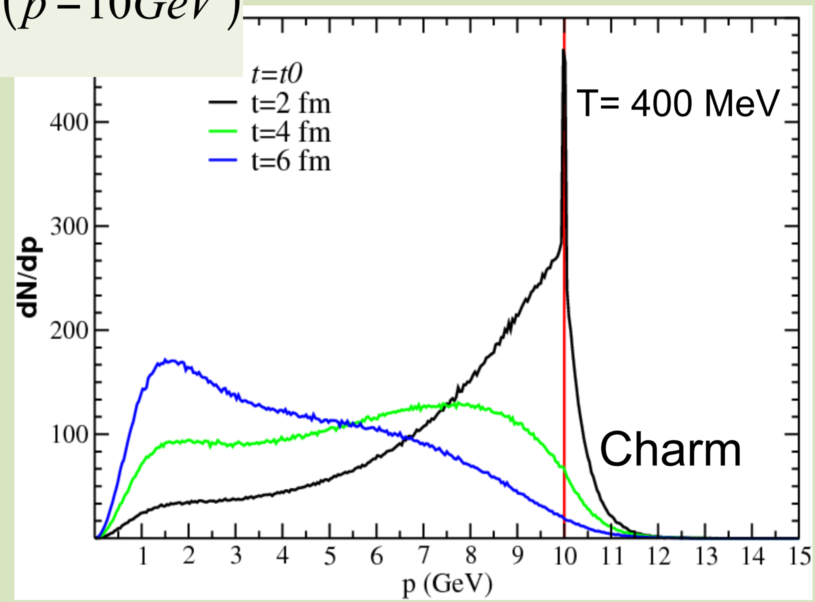
Brick problem

$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta\left(p - 10GeV\right)$$

Langevin



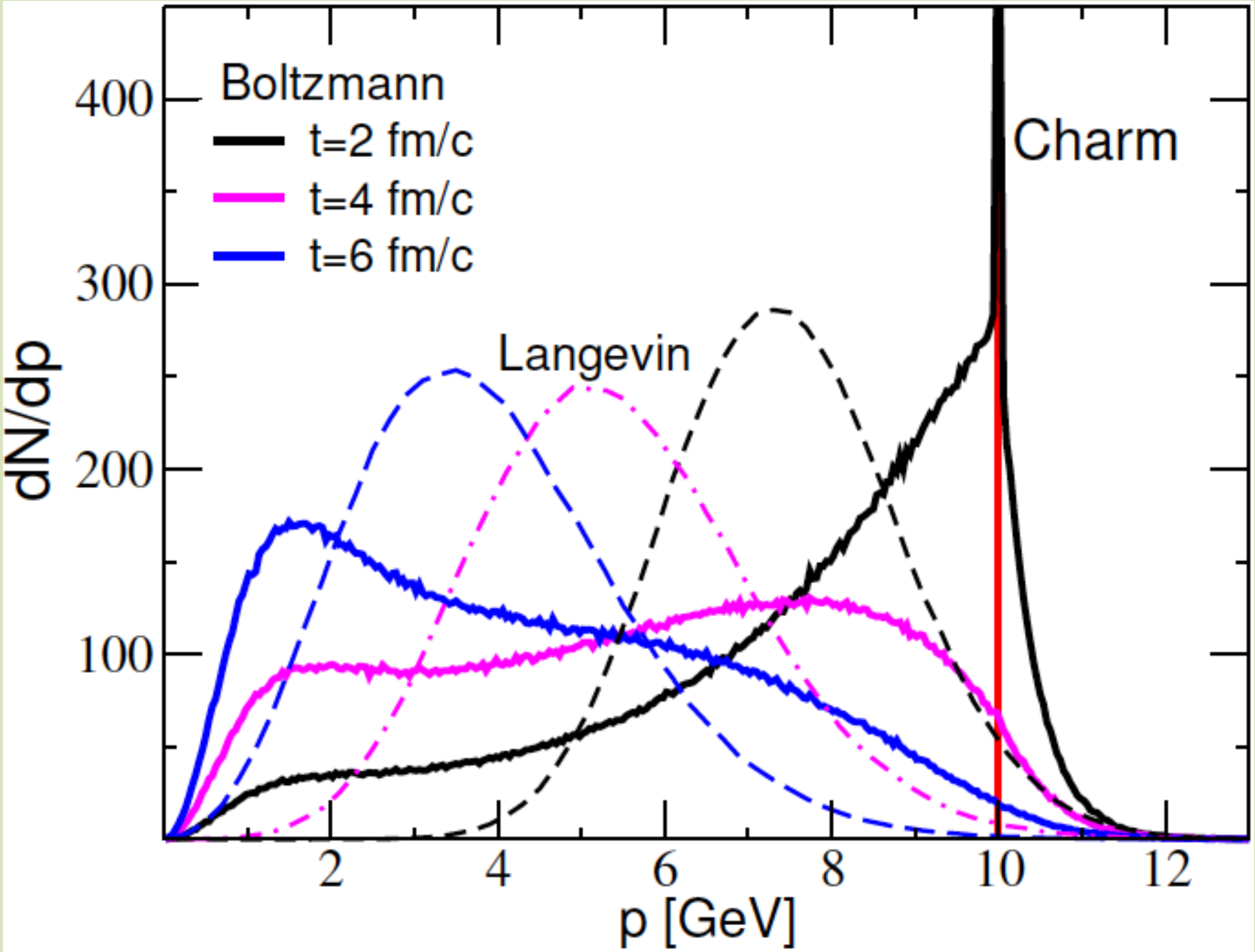
Boltzmann



S.K. Das et al., PRC90 (14) 044901

- ✧ Kinematics of collisions (Boltzmann) can throw particles at very low p soon.
- ✧ The motion of single HQ does not appear to be of Brownian type, on the other hand $M_c/T \approx 3$ -> $M_c/\langle p_{bulk}\rangle \approx 1$ & $p \gg m_Q$
- ✧ Evolution of <p> is nearly identical in BM & LV

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\left(q^2(\theta) + m_D^2\right)^2}$$



Equal evolution of <p> vs time

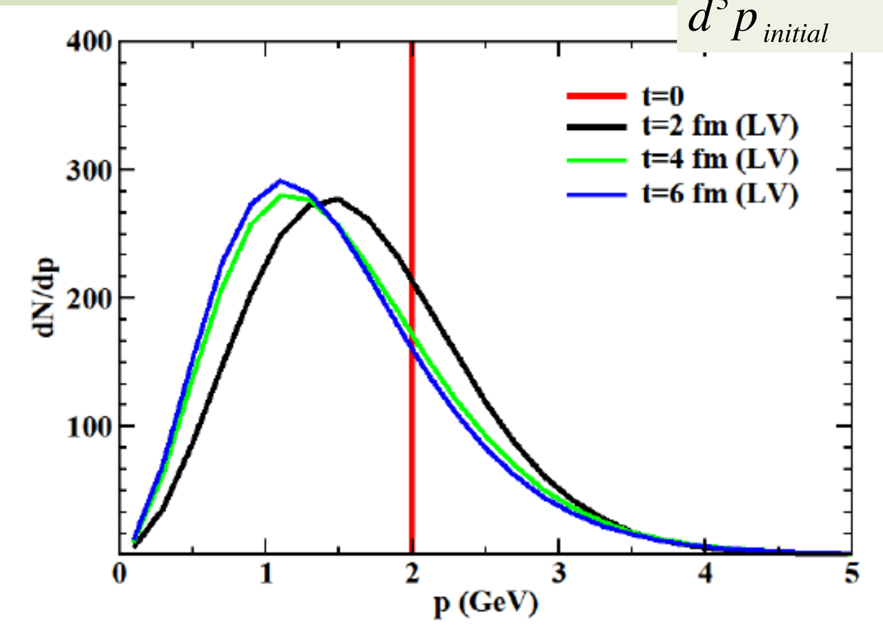
Very different fluctuations around <p>

Going more differential – low p_T

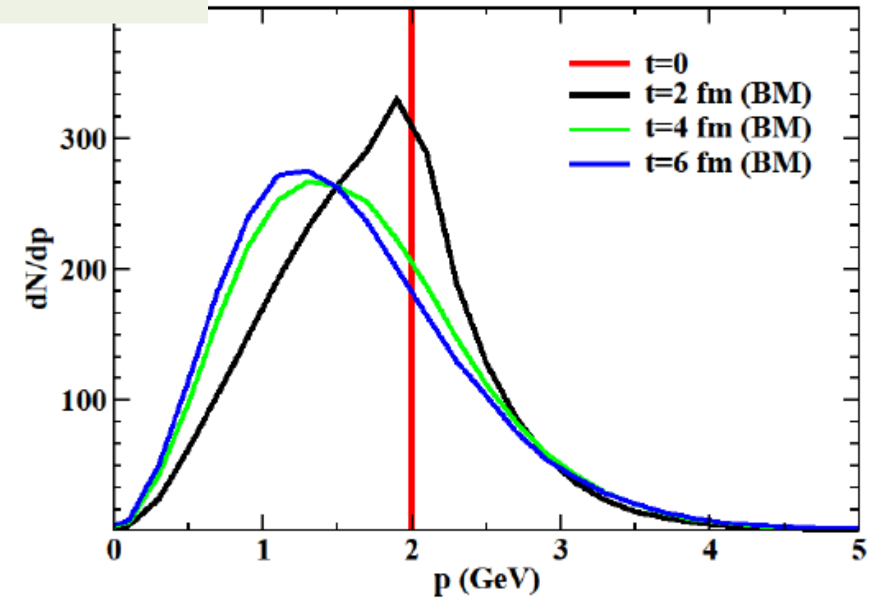
Brick problem

$$\frac{dN}{d^3p_{initial}} = \delta(p - 2GeV)$$

Langevin



Boltzmann

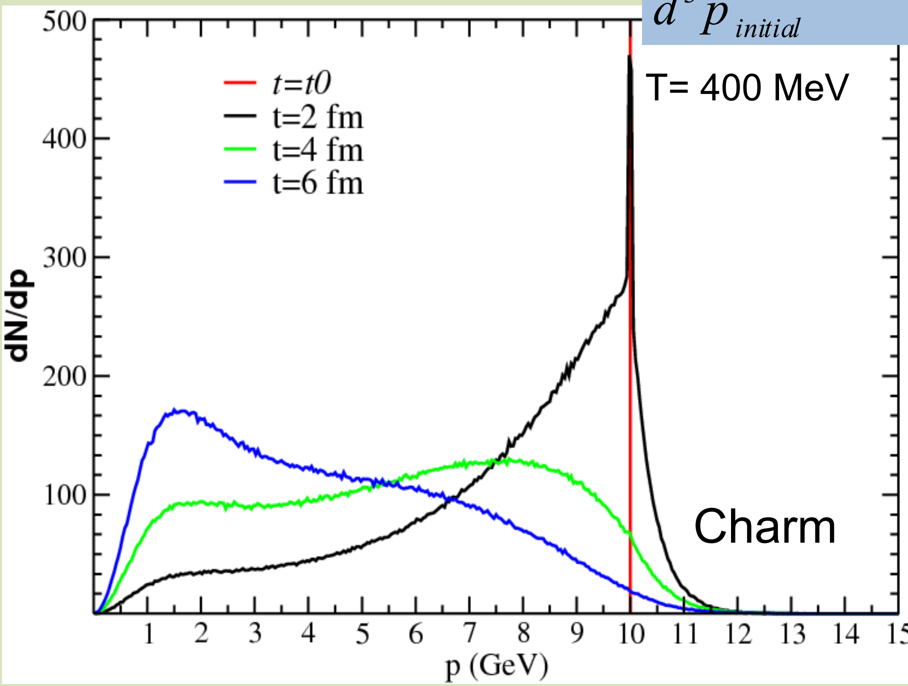


- ✧ Low p_T for charm protected by thermalization
- ✧ Bottom protected by the significantly larger M/T

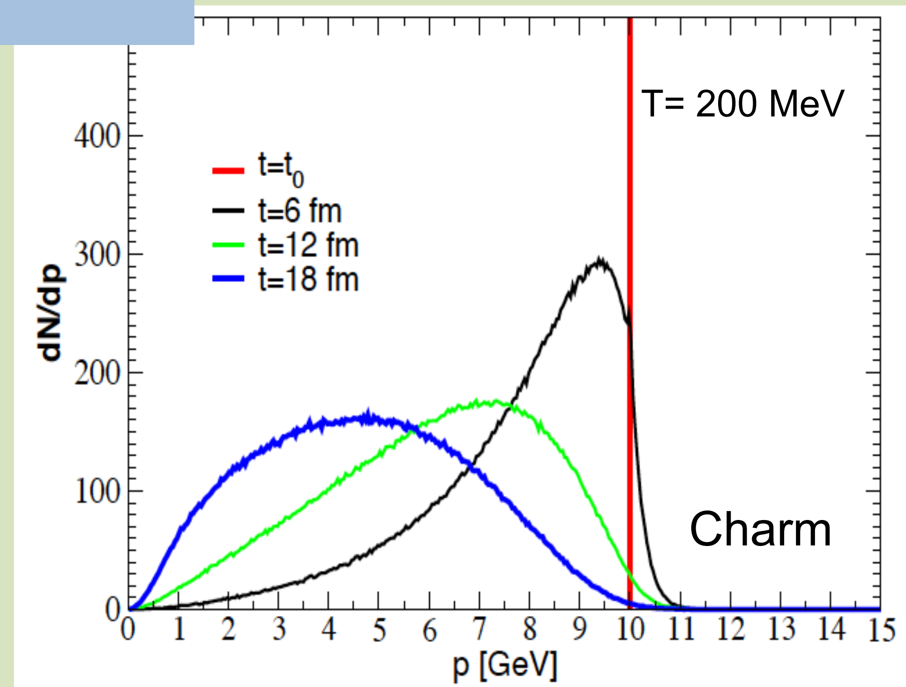
Momentum evolution for charm vs temperature

$$\frac{dN}{d^3p}_{initial} = \delta\left(p - 10GeV\right)$$

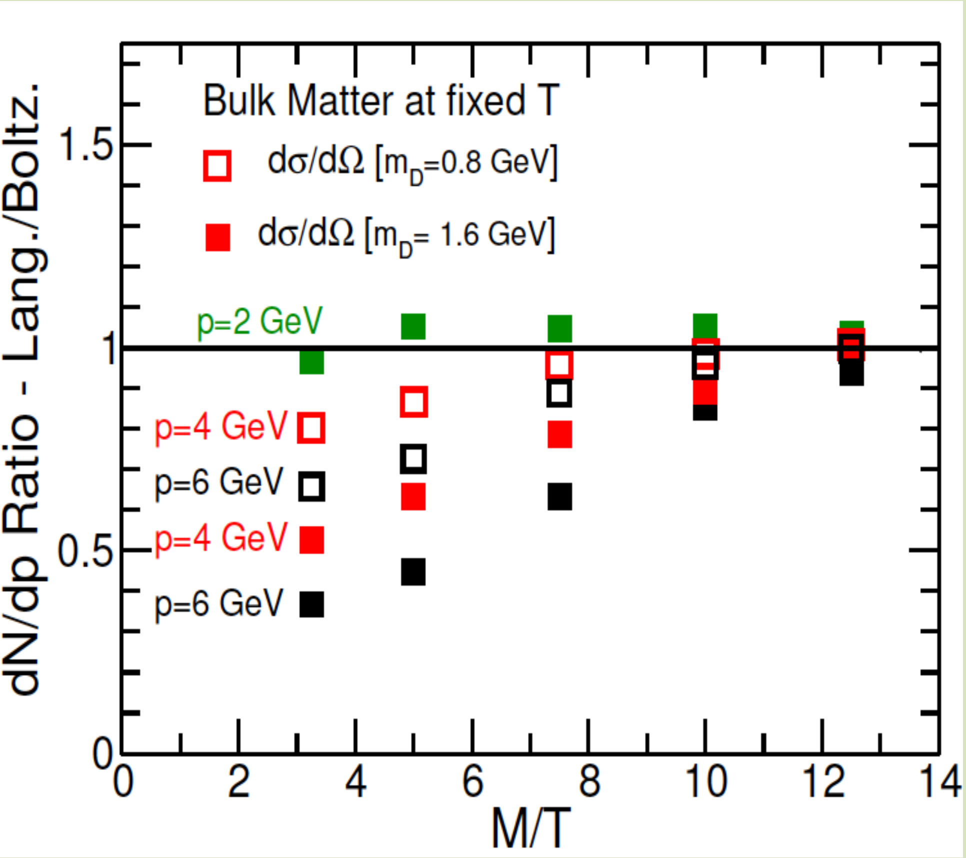
Boltzman



Boltzmann

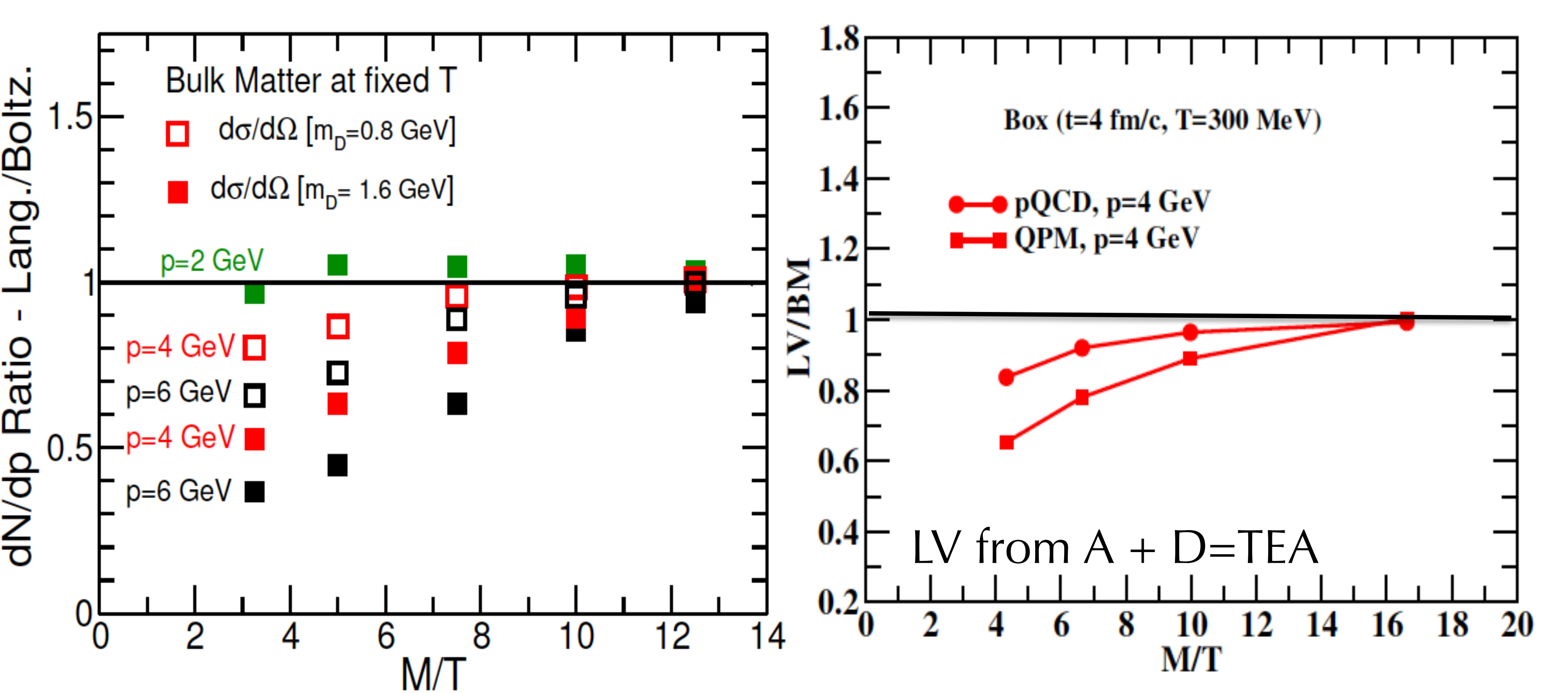


Ratio of p-spectra in a box at fixed T



- ✧ Main impact dσ/dθ:
  - Large difference for isotropic scattering
  - For Nantes $1/(t-0.2*m_D^2)$difference small (if starting from A)
- ✧ M/T ≈ 10 BM similar to LV

Ratio of p-spectra in a box at fixed T

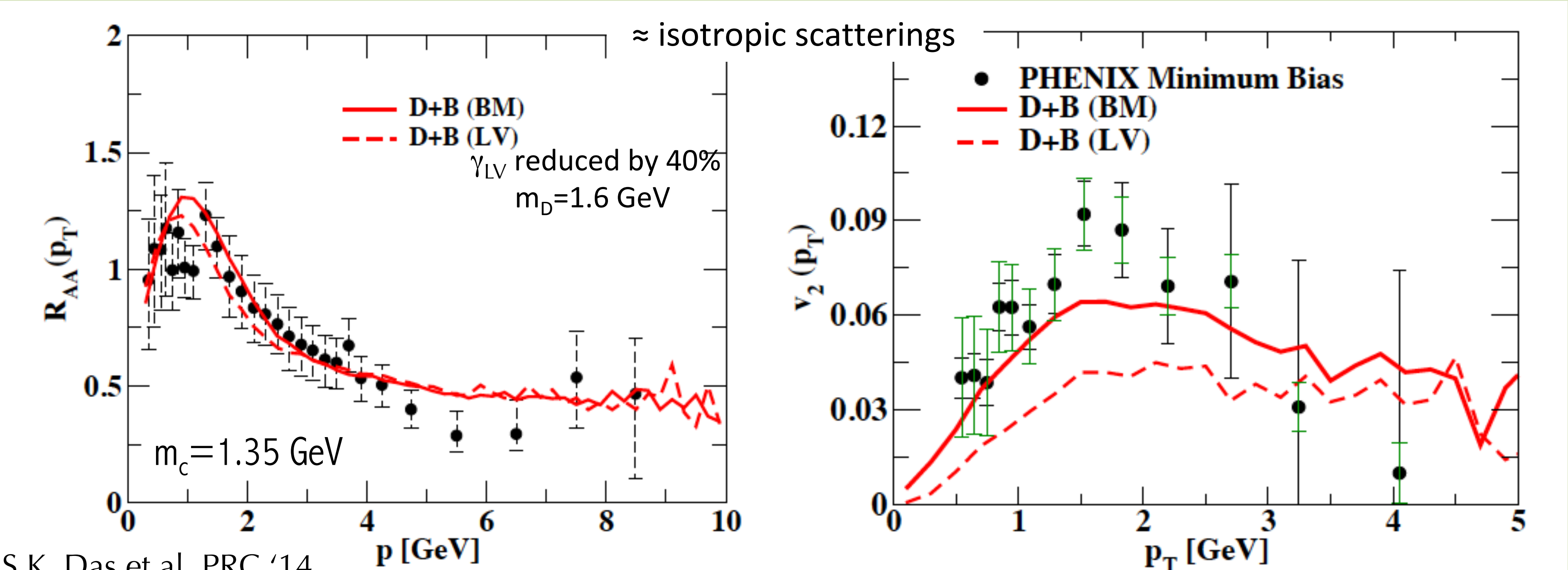


- ✧ Main impact $d\sigma/d\theta$:
  - Large difference for isotropic scattering
  - For Nantes $1/(t-0.2*m_D^2)$difference small (if starting from A)

- ✧ $M/T \approx 10$ BM similar to LV

Are there differences coming from BM vs LV?

Most of the groups start from drag γ or from D_T (not D_L)
This choice is more in line with Boltzmann that not having the FDT issue, *can serve as a guide…*



S.K. Das et al.,PRC '14

BM and LV → $R_{AA}(p_T)$ shaper nearly identical:

- but Drag γ has to be reduced by 15-40% *depending on* m_c & $d\sigma_{gQ}/d\Theta$
- Larger $v_2(p_T)$ ≈ 10-30% again *depending on* m_c & $d\sigma/d\Theta$

Impact of different implementation of FDT

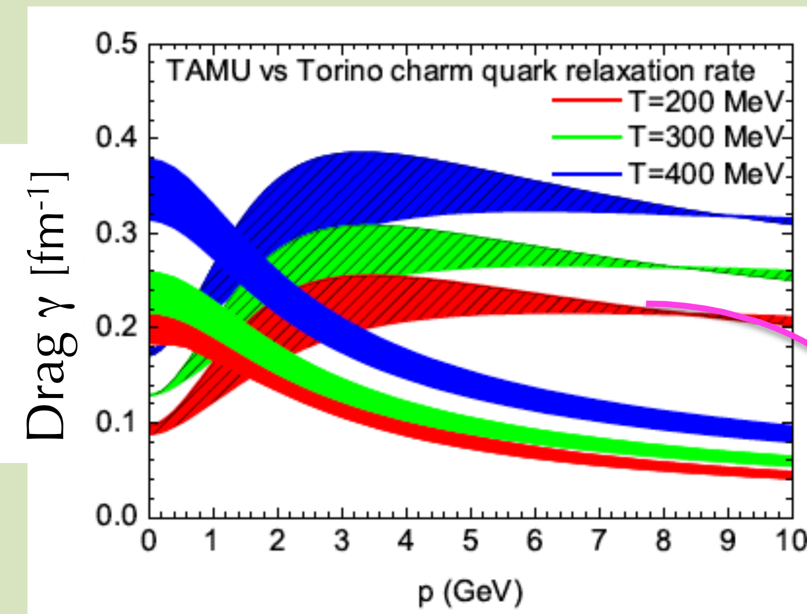
- An essential part of LV is the Fluct.- Dissip. Th.: **D(p) =ETγ(p) (*)**
  D_L , D_T and γ from the scattering matrix that does not fulfill (*)
  [a sign that microscopic dynamics imply more than <p> and <Δp²>]

- Issue less relevant for bottom (M>>gT, T → Brownian motion)

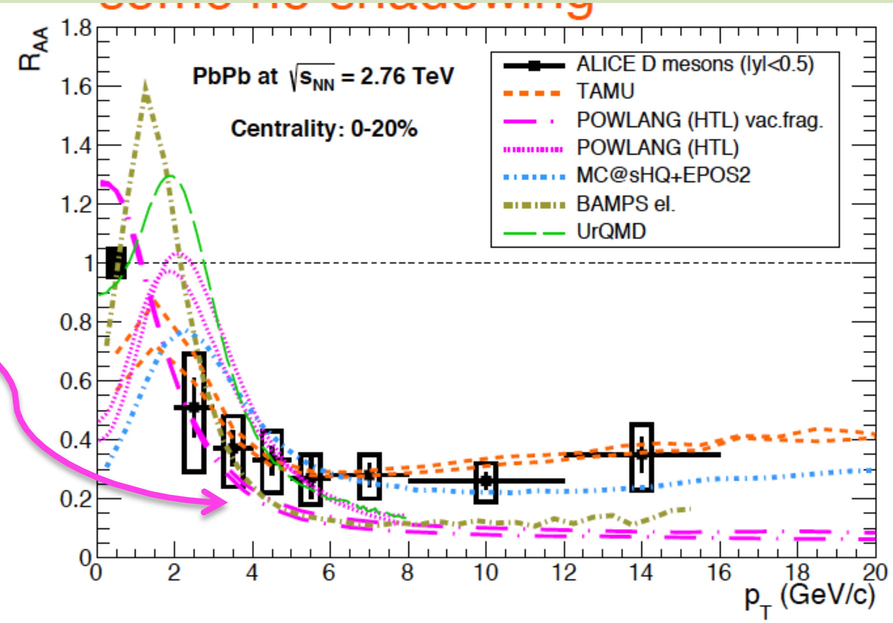
FDT

$$\gamma = \frac{1}{p} D_{\parallel} \frac{1}{T}\frac{\partial E}{\partial p} - \frac{1}{p}\frac{\partial D_{\parallel}}{\partial p} - \frac{2}{p^2}\left(D_{\parallel} - D_{\perp}\right)$$

main difference if one input D_L from M scatt. - matrix



Rapp & Prino, JPG43 (2016)093002



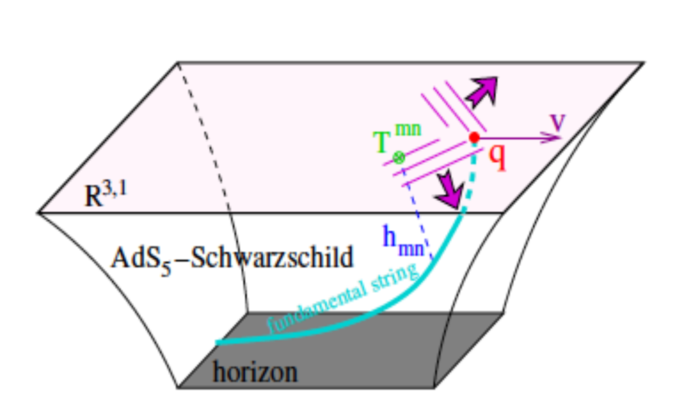
Andronic et al., EPJA (2016) [SAPORE GRAVIS Review]

Issue also in AdS/CFT

$$\gamma = \pi\sqrt{\lambda}\,\frac{1}{2m_Q}\,T_{SYM}^2 \xrightarrow{\text{FDT}} D = \pi\sqrt{\lambda}\left(\frac{E}{m_Q}\right)T_{SYM}^3$$

$$D_T = \pi\sqrt{\lambda}\left(\frac{E}{m_Q}\right)^{1/2} T_{SYM}^3 \qquad D_L = \pi\sqrt{\lambda}\left(\frac{E}{m_Q}\right)^{5/2} T_{SYM}^3$$

$\lambda = g^2_{sym} N_C$ to be gauged to QCD

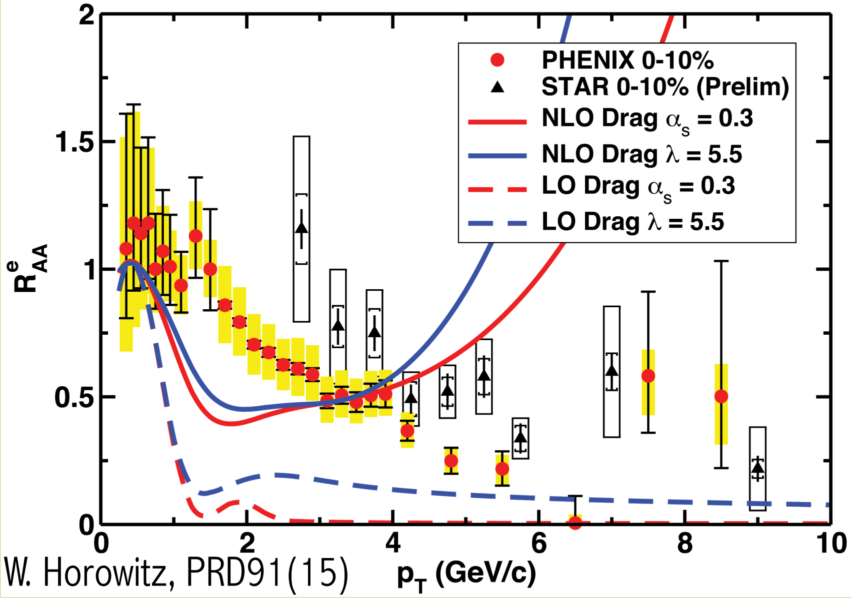


- ✓ No set –up for realistic v_2 prediction
- ✓ T^2 is quite unfavored by the exp.data on v_2

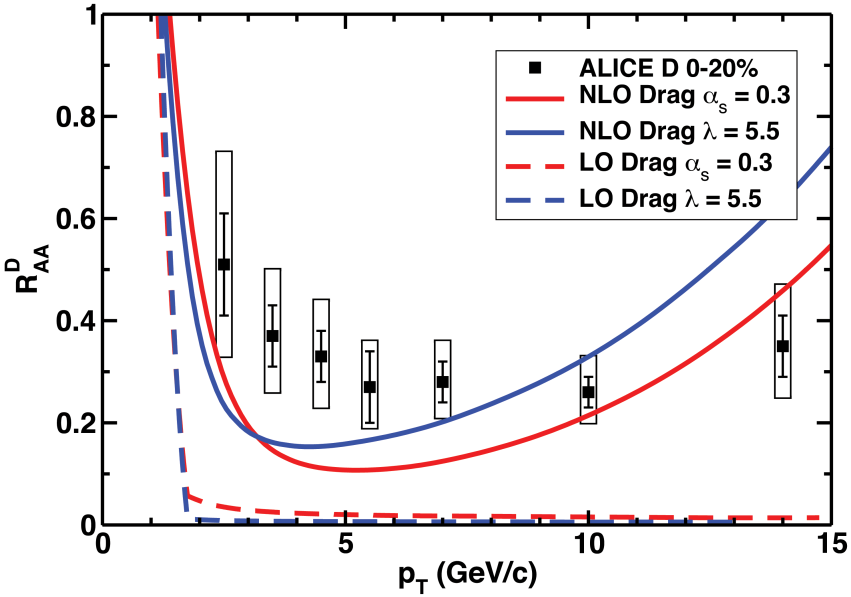
New Result (≠FDT)

$$D = \pi\sqrt{\lambda}\,T_{SYM}^3$$

Horowitz: arXiv:1612.05908 [hep-ph]



W. Horowitz, PRD91(15)



AdS/CFT

$$\gamma = \pi\sqrt{\lambda}\,\frac{1}{2m_Q}\,T_{SYM}^2 \xrightarrow{\text{FDT}} D = \pi\sqrt{\lambda}\left(\frac{E}{m_Q}\right)T_{SYM}^3$$

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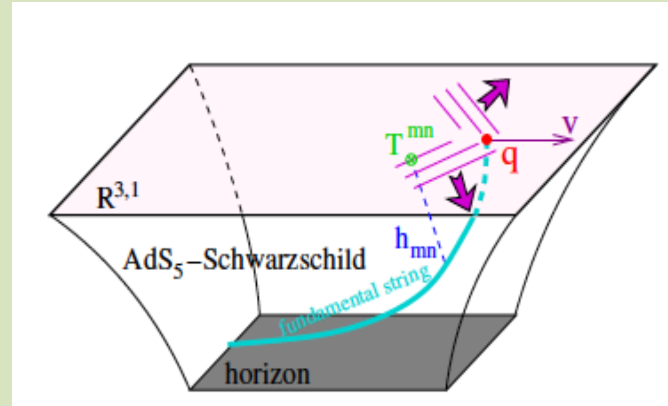

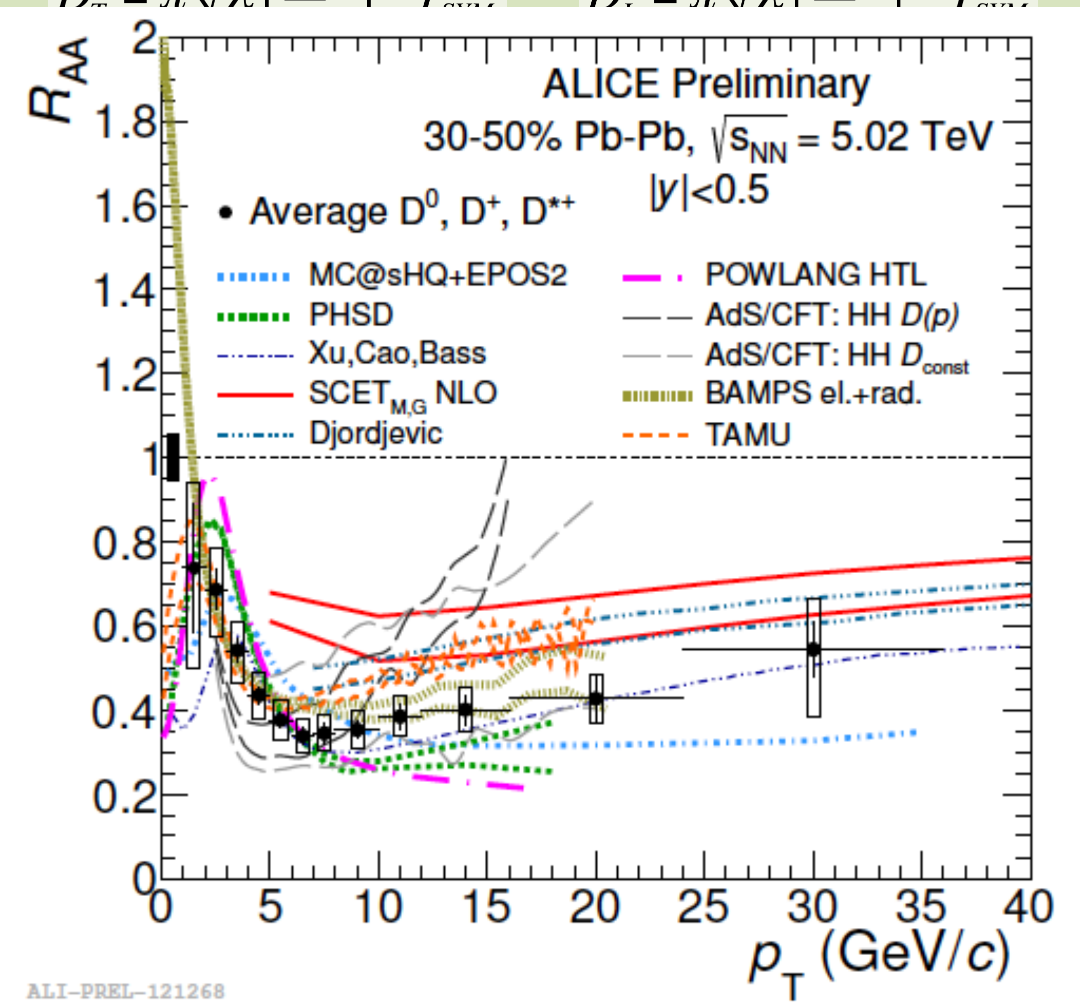

of HQ

New Result (≠FDT)

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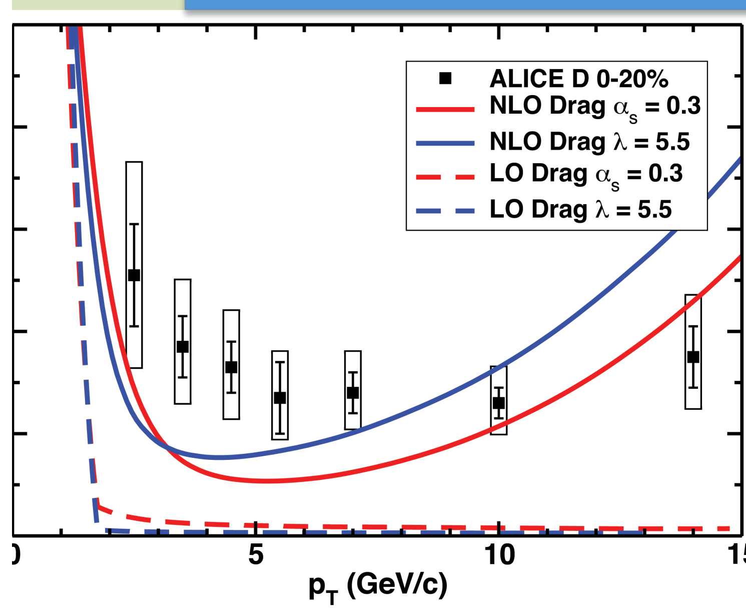
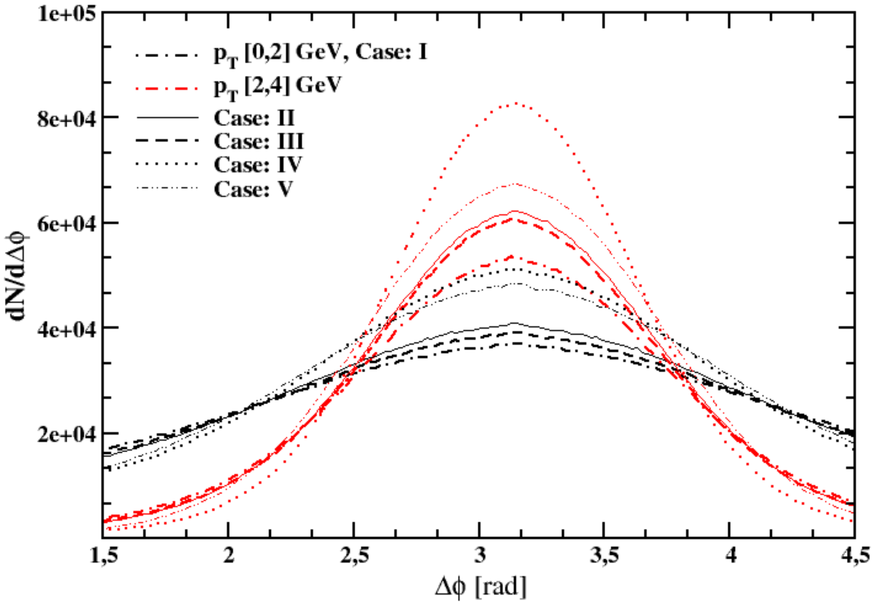
Horowitz: arXiv:1612.05908 [hep-ph]

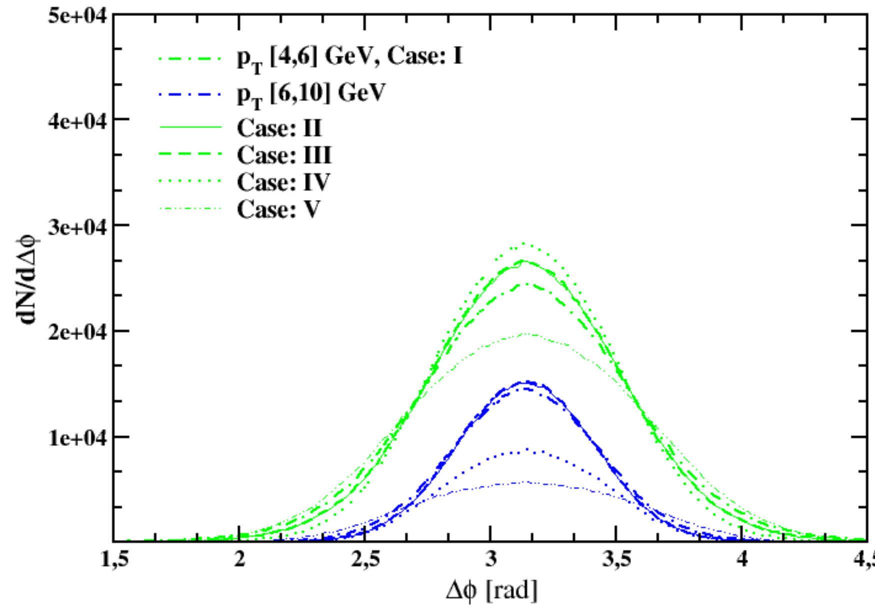


Impact on pairs correlation of the different form of FDT

LHC Pb+Pb at 2.76 ATeV (D-meson)

Fixed $R_{AA}(p_T)$





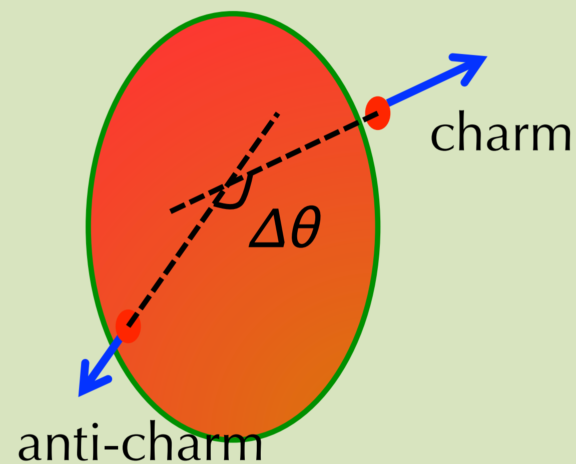
1) A and B_T (from pQCD No FDT, but $B_{||} = B_T$)

2) $B_{||} = B_T$ (pQCD) ; A (FDT) $\qquad A = \dfrac{B_T}{ET} - \dfrac{1}{p}\dfrac{\partial B_T}{\partial p}$

3) A pQCD ; $D = B_{||} = B_T$ (FDT) $\qquad D = AET$ Post-Ito

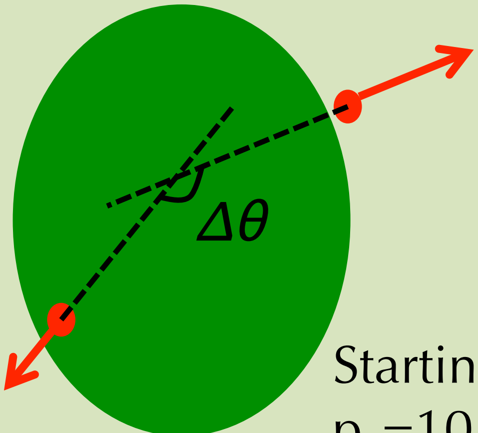
4) B_T and $B_{||}$ (pQCD) ; A FDT $\qquad A = \dfrac{1}{p} B_{\|} \dfrac{1}{T}\dfrac{\partial E}{\partial p} - \dfrac{1}{p}\dfrac{\partial B_{\|}}{\partial p} - \dfrac{(n-1)}{p^2}\left(B_{\|} - B_{\perp}\right)$

5) $B_T = B_{||}$ (pQCD) ; A FDT $\qquad A = \dfrac{B_{\|}}{ET} - \dfrac{1}{p}\dfrac{\partial B_{\|}}{\partial p}$



Boltzmann vs Langevin for angular correlations

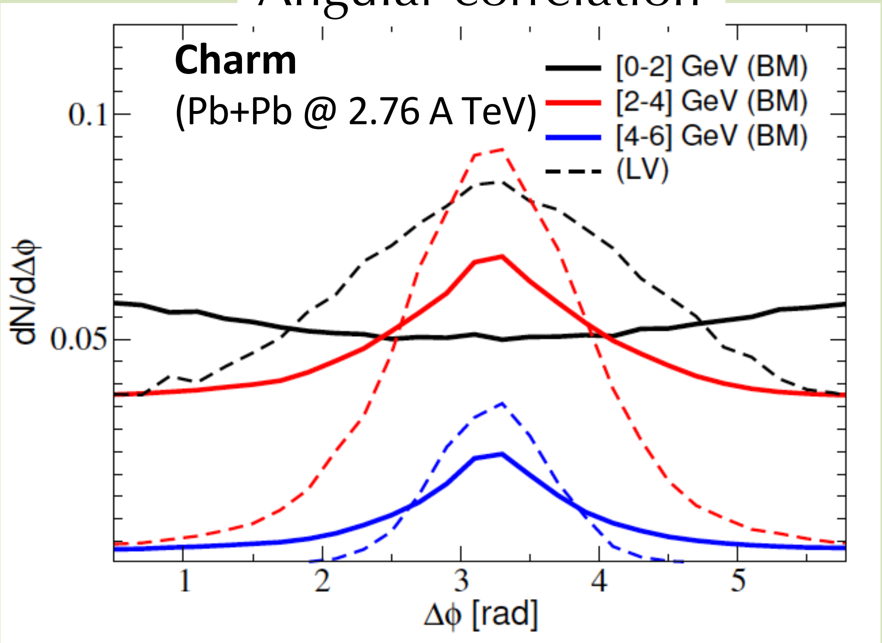
BM vs LV would make a difference for up coming [D-h] + [D-D̲] triggered angular correlations



p_T [0-2]GeV
p_T [2-4]GeV
p_T [6-8]GeV

Starting from back-to-back p_T=10 GeV as trigger only collisional E_{loss}

Angular correlation



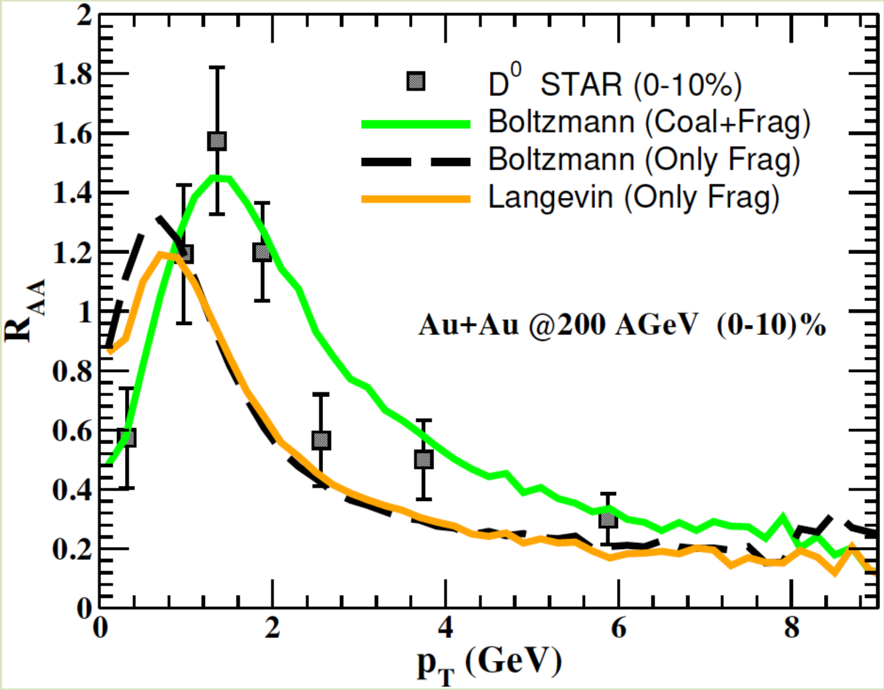
In $dN/d\Delta\phi_{12}$ sizeable differences between BM& LV also for **Bottom**

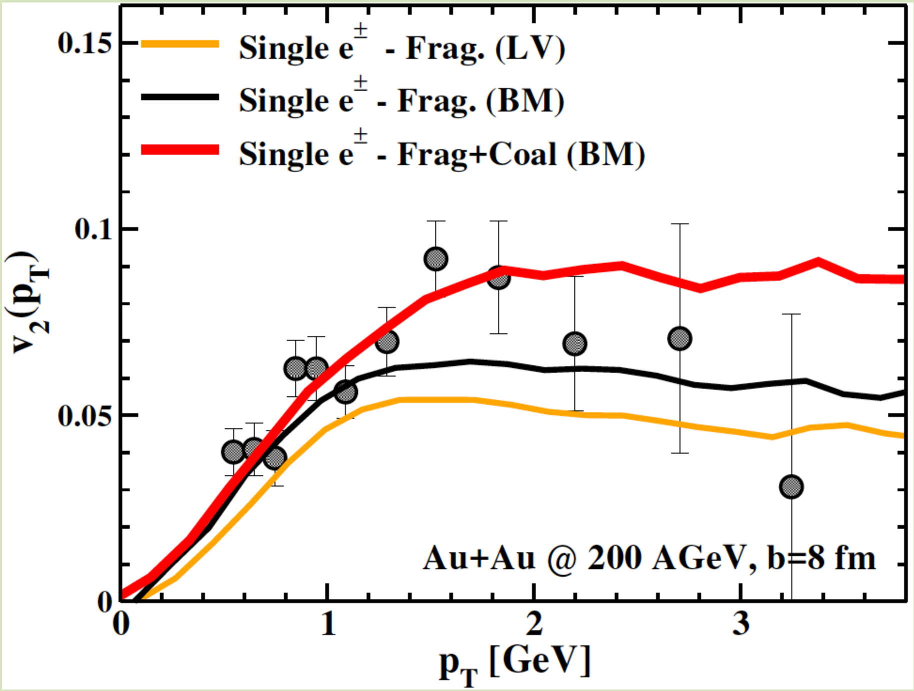
- Boltzmann especially going to $dN/d\Delta\phi_{12}$ and high p_T including both radiative and collisional should be more appropriate
  → Frankfurt, Subatech, LBL- CCNU, Catania, …

What predictions can we do for charm experimental observables with QPM-Catania?

What are the differences coming from BM vs LV?

Most of the groups start from drag γ or from D_T (not D_L)
This choice is more in line with Boltzmann which not having the FDT issue, *can serve as a guide…*

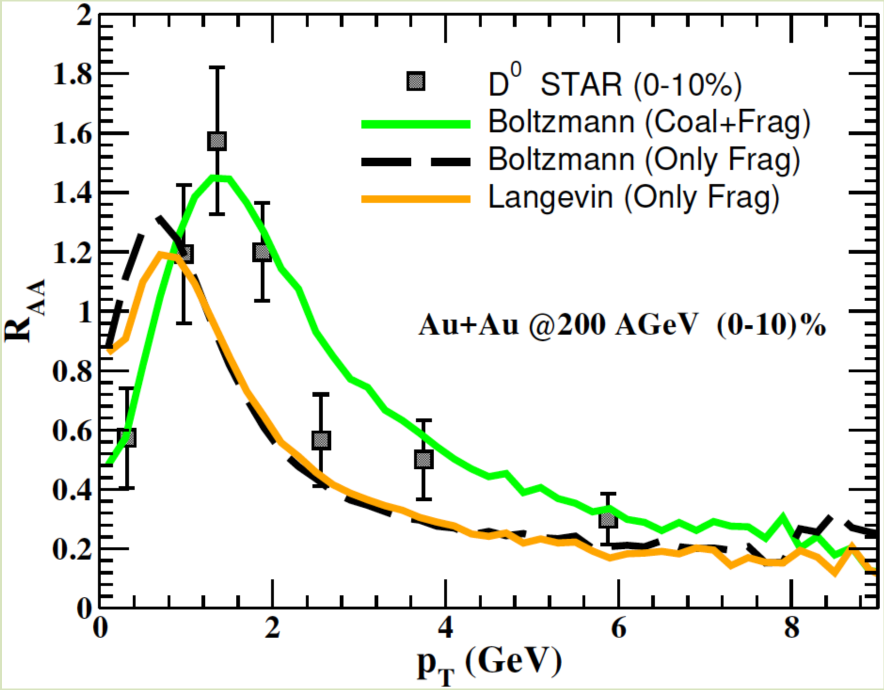


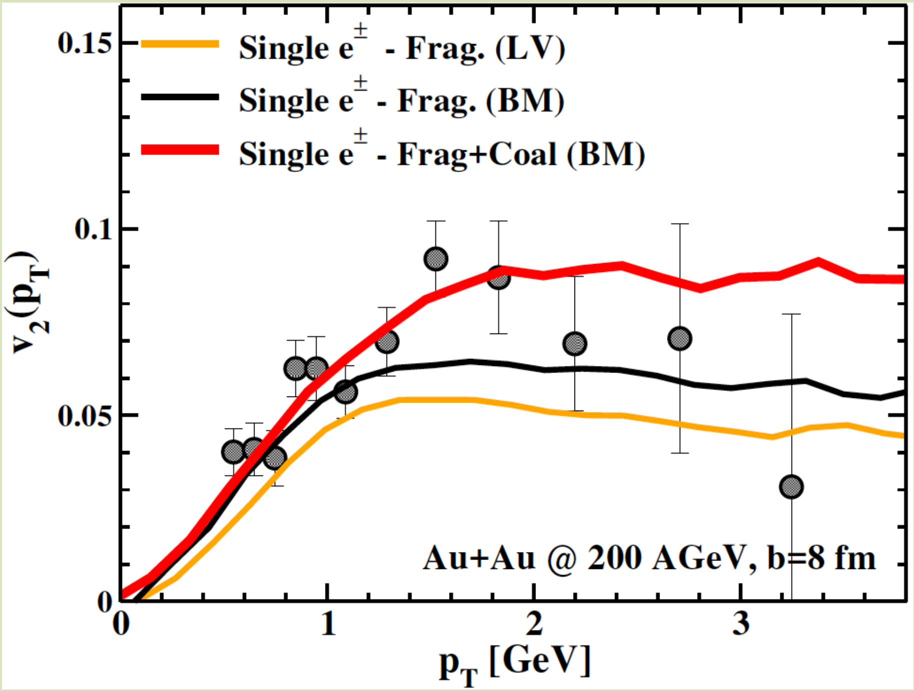


Scardina et al., arXiV: 1707.05452

BM and LV → $R_{AA}(p_T)$ shaper nearly identical:
- but Drag γ **has to be reduced by 35%** *with a QPM model [max. 55%]*
- Larger $v_2(p_T) \approx 15\%$ again *with QPM [max. 30-35%]*

What is the impact of coalescence?

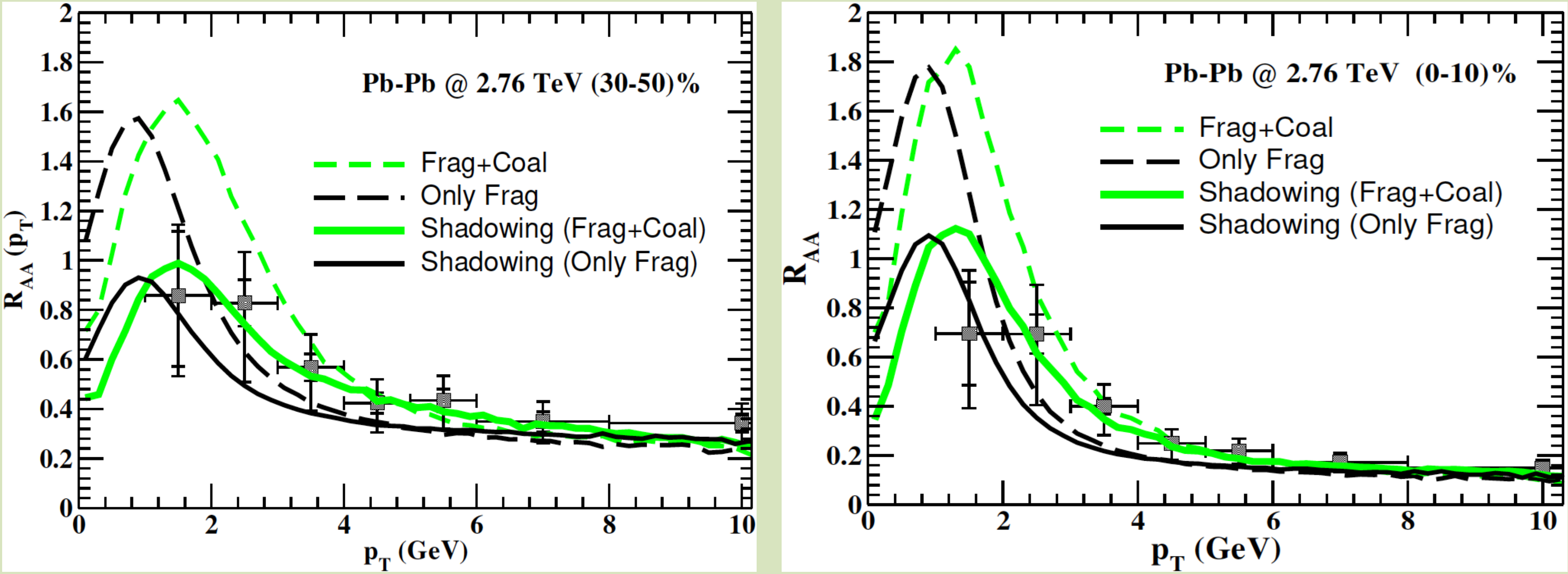




- $R_{AA}(p_T)$ signficant reshaped → exp. data
- *Opposite to energy loss Coalescence brings up both R_{AA} and v_2*

What we predict for LHC?

No change in the HQ interaction,
Only the evolution in the bulk expansion of course

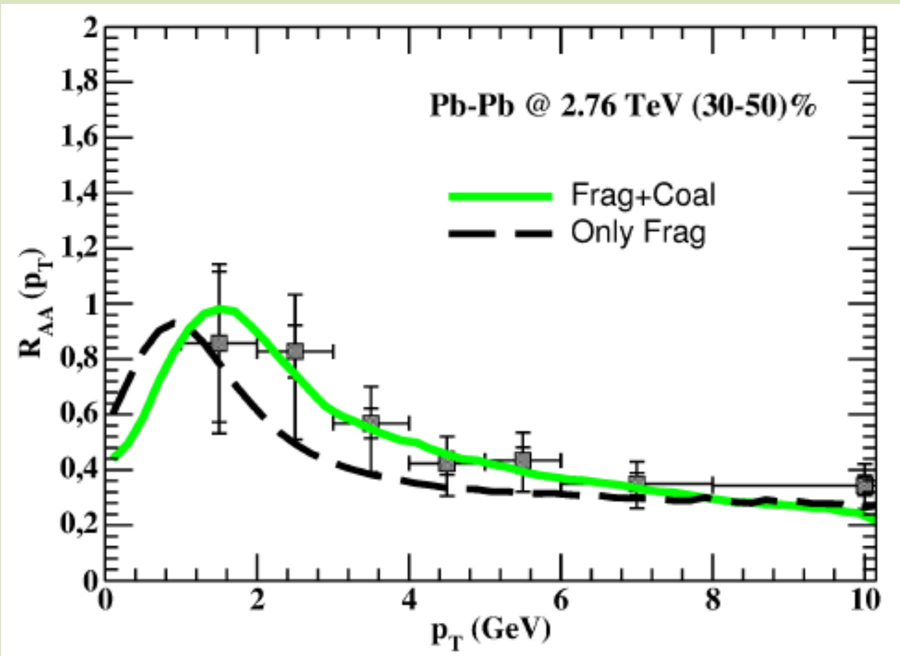


Scardina et al., arXiV: 1707.05452

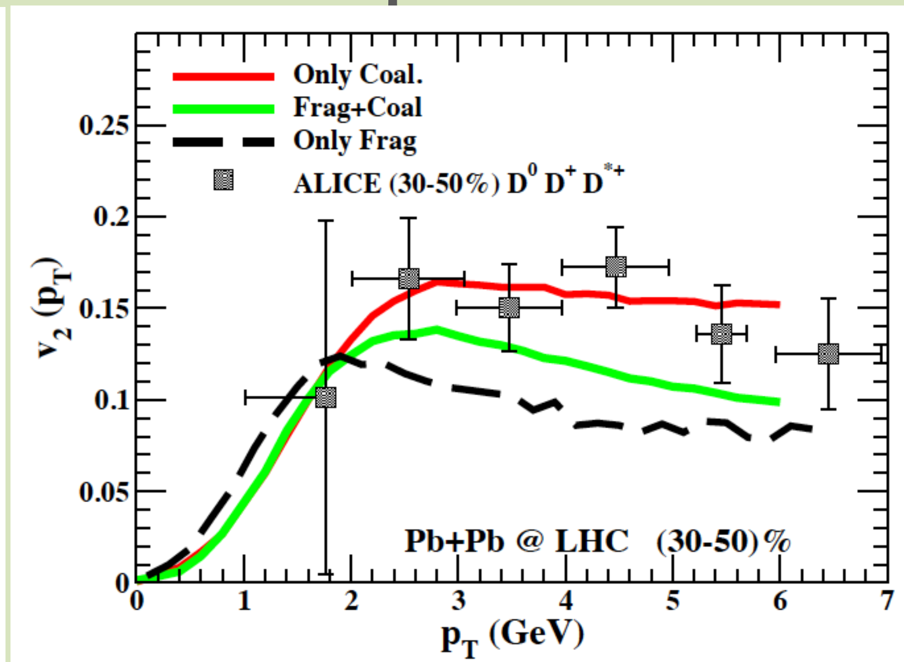
- ✓ Shadowing appear necessary [EPS09, Eskola-Salgado JHEP(2009)]
- ✓ Coalescence still important

What we predict for LHC?

Nuclear Modif. Factor



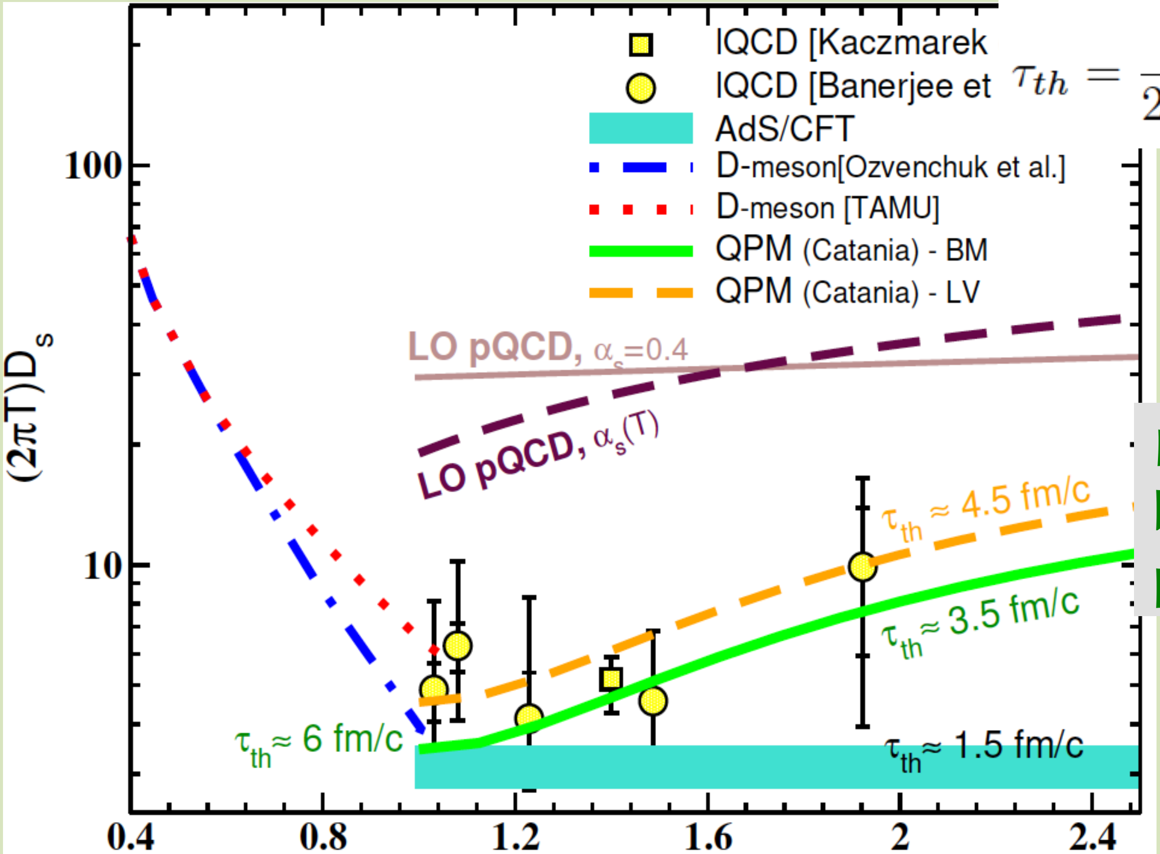
Elliptic flow



Scardina et al., arXiV: 1707.05452

- ✓ Shadowing appear necessary [EPS09, Eskola-Salgado JHEP(2009)]
- ✓ Coalescence still important
- ✓ Reasonable descripttion of v_2
  Hadronic rescattering does not change R_{AA} - increase by 15% v_2

What is the underlying D_s?



Scardina et al., arXiV: 1707.05452

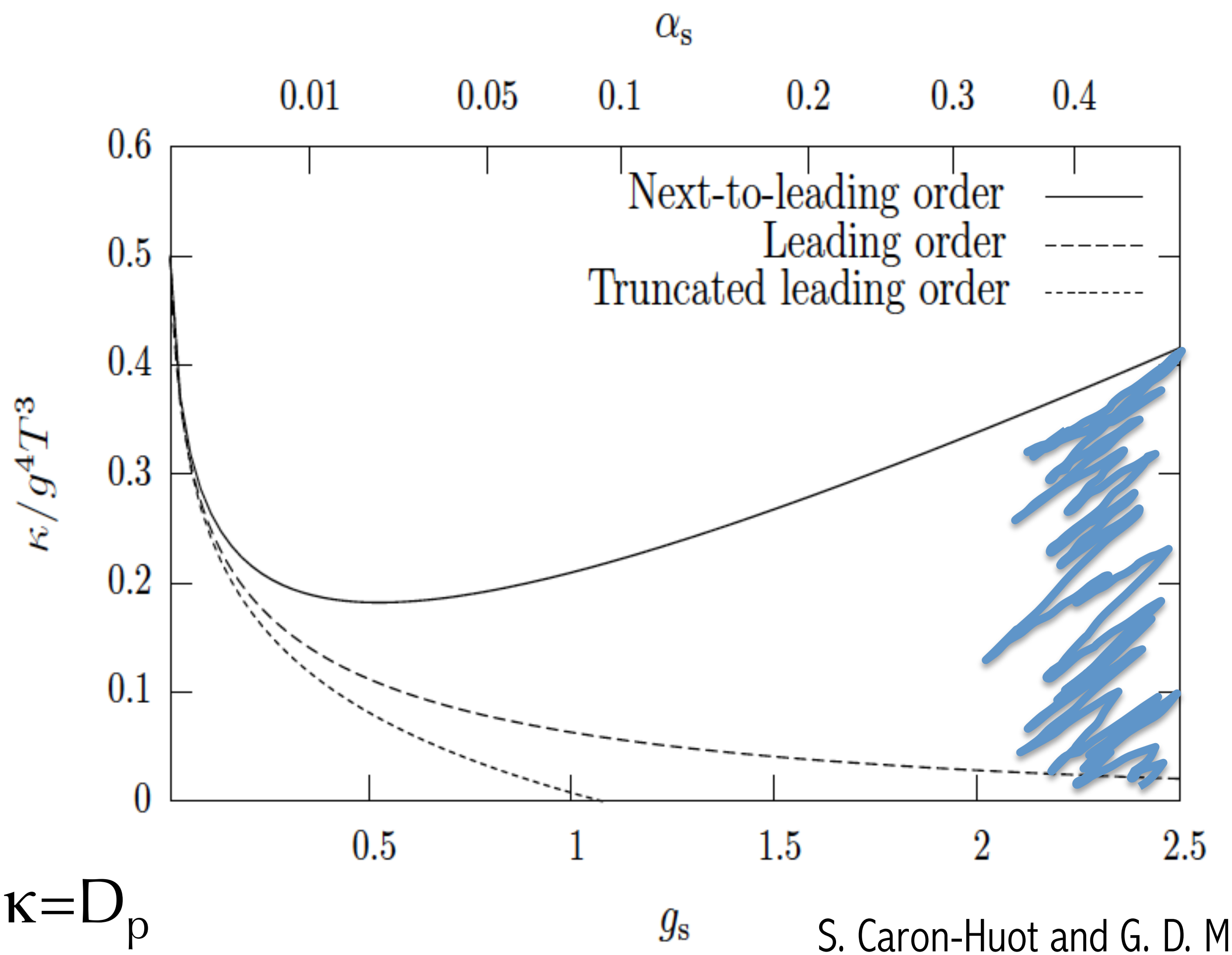
$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8\,\frac{2\pi T D_s}{(T/T_c)^2}\ \text{fm/c}$$

$$D_S = \frac{T}{M\gamma} = \frac{T^2}{D_p}$$

Not a model fit to lQCD data! but the result from the predictions of $R_{AA}(p_T)$ & $v_2(p_T)$

- Another hint that the matter we create in uRHICs is the **Hot QCD matter**!
- We have a probe with $\tau_{therm} \approx \tau_{QGP}$ → easier to pin-down a T dependence of the transport coeff.

From theory itself pQCD does not work



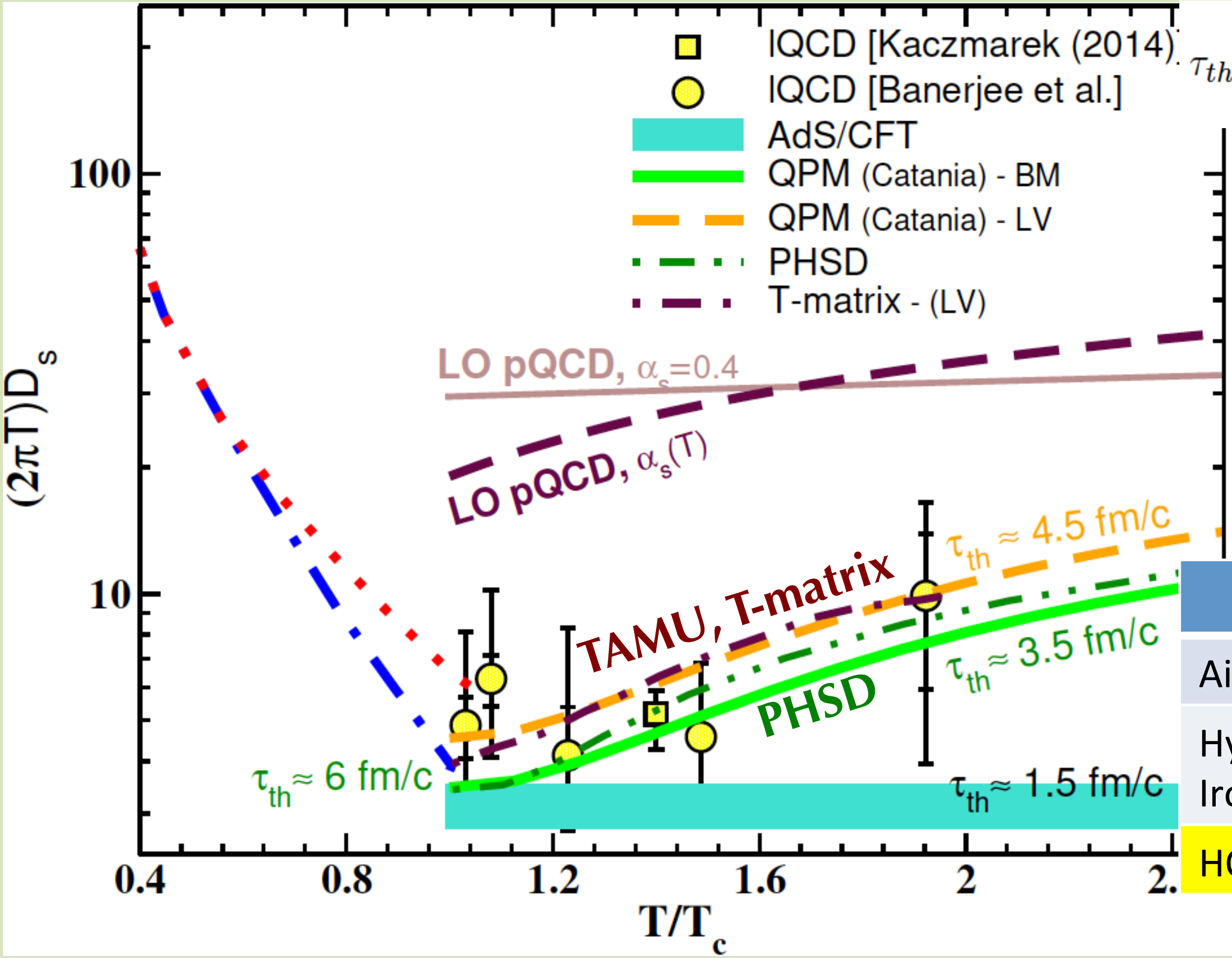
$\kappa = D_p$

S. Caron-Huot and G. D. Moore, JHEP 02 (2008) 081

$$\mathcal{D}_s^{\mathrm{NLO}} = \frac{27}{16\pi\alpha_s^2 T}\left(\left[3+\frac{N_f}{2}\right]\left[\ln\frac{2T}{m_D} - 0.64718\right] + \frac{N_f \ln(2)}{2} + 2.3302\frac{3m_D}{T}\right)^{-1}$$

NLO corrections for transport coefficent dominated by soft sector $p \approx m_D$

What is the underlying D_s?



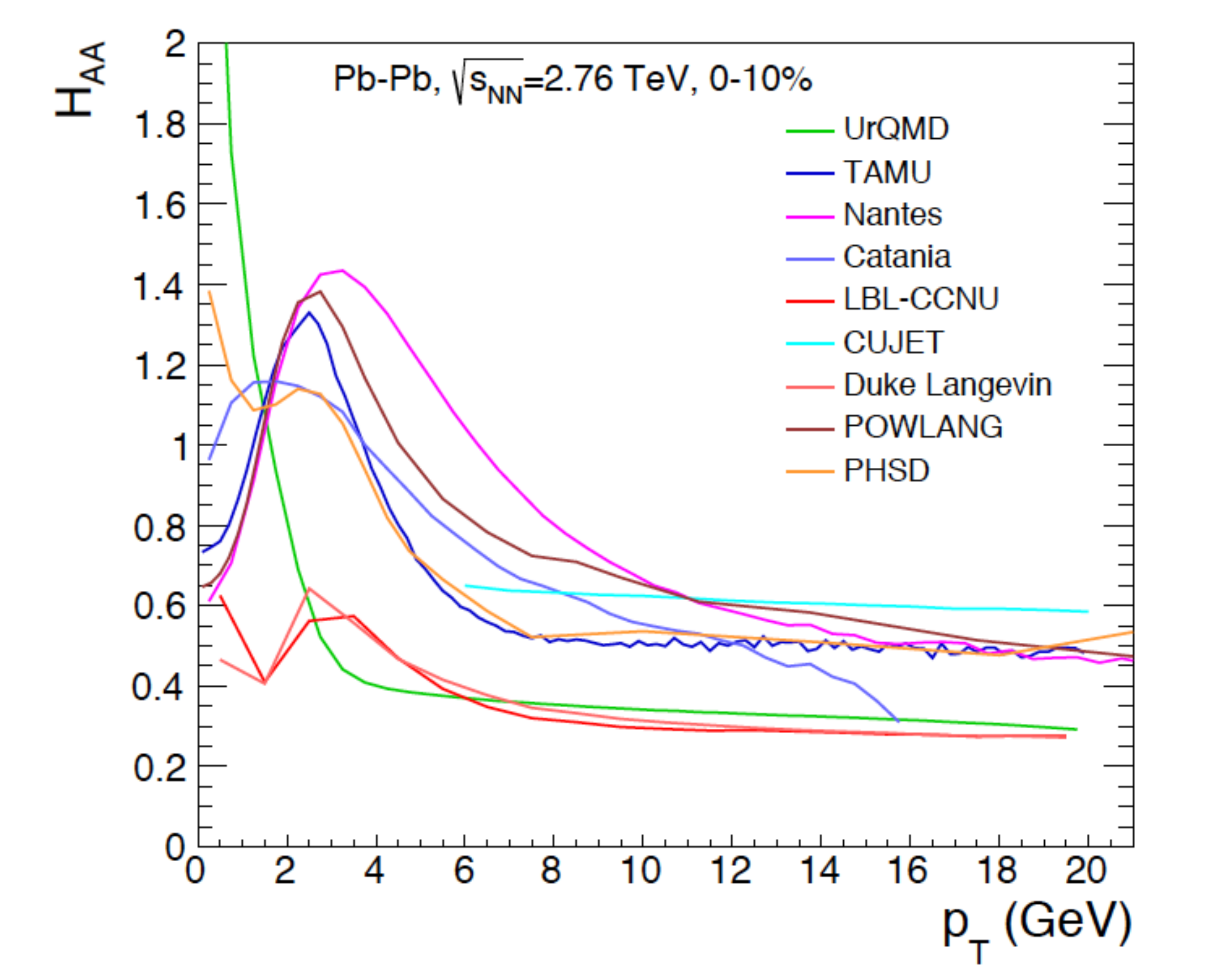
$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8\,\frac{2\pi T D_s}{(T/T_c)^2}\ \mathrm{fm/c}$$

QGP diffuse Charm quarks like a "perfect fluid"

	State	D_s (cm^2/s)
Air in Water	liquid	2.0×10^{-5}
Hydrogen in Iron	solid	1.66×10^{-9}
HQ in QGP	Liquid!	$\approx 300 \times 10^{-5}$

Phenomenological approach in the right ball-park, and now we are starting to extend the analysis to v_3, v_2 - v_3 light-heavy correlations and upcoming angular triggered correlation $dN/d\Delta\phi_{12}$ ....

D meson to final charm spectrum: strong impact of hadronization



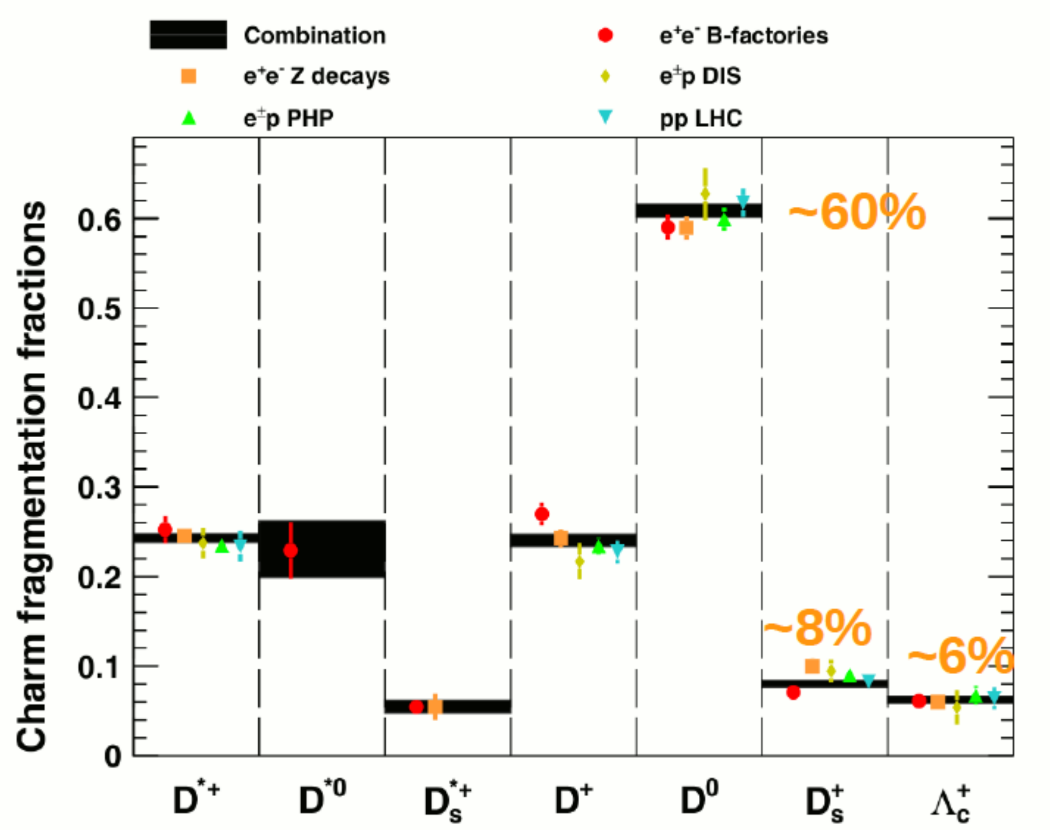
✧ Measurement of Λ_c/D can signficantly provide *bounds and constraints on hadronization by coalescence* and/ or fragmentation

A step back:

- **Do all agree with Coalescence implementation?**

- Impact of coalescence differs among the approaches
- Measurement of Λ_c/D would provide *bounds and constraints on hadronization by coalescence* and/or fragmentation

Λ_c/D in elementary collisions



M. Lisovyi, et al. EPJ C76 (2016) no.7, 397

Fragmentation functions

$$\left(\frac{\Lambda_C}{D^0}\right)_{\substack{e^+e^-\\pp}} \approx 0.1$$

Statistical Hadronization model

$$\left(\frac{\Lambda_C}{D^0}\right)_{\substack{e^+e^-\\pp}} \approx 0.25-0.30$$

A. Andronic et al. PLB571 (2003)
I. Kuznetsova, J. Rafelski, EPJ C51 (2007)
Y. Oh, C.M. Ko, et al., PRC79 (2009)

What happens in a coalescence model?

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i) f_W(x_1, \ldots, x_n; p_1, \ldots, p_n) \delta(p_T - \sum_i p_{iT})$$

distribution function giving R_{AA} and v_2 for D just discussed

Wigner function with the width fixed by radius from quark model

$$f_M(x_1, x_2; p_1, p_2) = A_W \exp\left(-\frac{x_{r1}^2}{\sigma_r^2} - p_{r1}^2 \sigma_r^2\right)$$

C.-W. Hwang, EPJ C23, 585 (2002).

C. Albertus et al., NPA 740, 333 (2004)

$$\langle r^2 \rangle_{D^+} = 0.184\, fm^2 \quad \langle r^2 \rangle_{D_s^+} = 0.124\, fm^2 \quad \langle r^2 \rangle_{\Lambda_c^+} = 0.152\, fm^2$$

$$= \frac{3}{2} \frac{Q_1 m_2^2 + Q_2 m_1^2}{(m_1 + m_2)^2} \sigma_r^2$$

S. Plumari et al,ArXiv:1712.****

What happens in a coalescence model?

In our calculations we take into account main hadronic channels, including the ground states and the first excited states for D and Λ_c

Statistical factor

$$\frac{\left[(2J+1)(2I+1)\right]_{H*}}{\left[(2J+1)(2I+1)\right]_{H}} \left(\frac{m_{H*}}{m_H}\right)^{3/2} e^{-(E_{H*}-E_H)/T}$$

MESONS

- **D^+** *(I=1/2,J=0)*
- **D^0** *(I=1/2,J=0)*
- **D_s^+** *(I=0,J=0)*

Resonances

- **D^{*+}** *(I=1/2,J=1)* → **$D^0\,\pi^+$** *B.R. 68%*
  → **D^+ X** *B.R. 32%*
- **D^{*0}** *(I=1/2,J=1)* → **$D^0\,\pi^0$** *B.R. 62%*
  → **$D^0\,\gamma$** *B.R. 38%*
- **D_s^{*+}** *(I=0,J=1)* → **D_s^+ X** *B.R. 100%*
- **D_{s0}^{*+}** *(I=0,J=0)* → **D_s^+ X** *B.R. 100%*

BARYONS

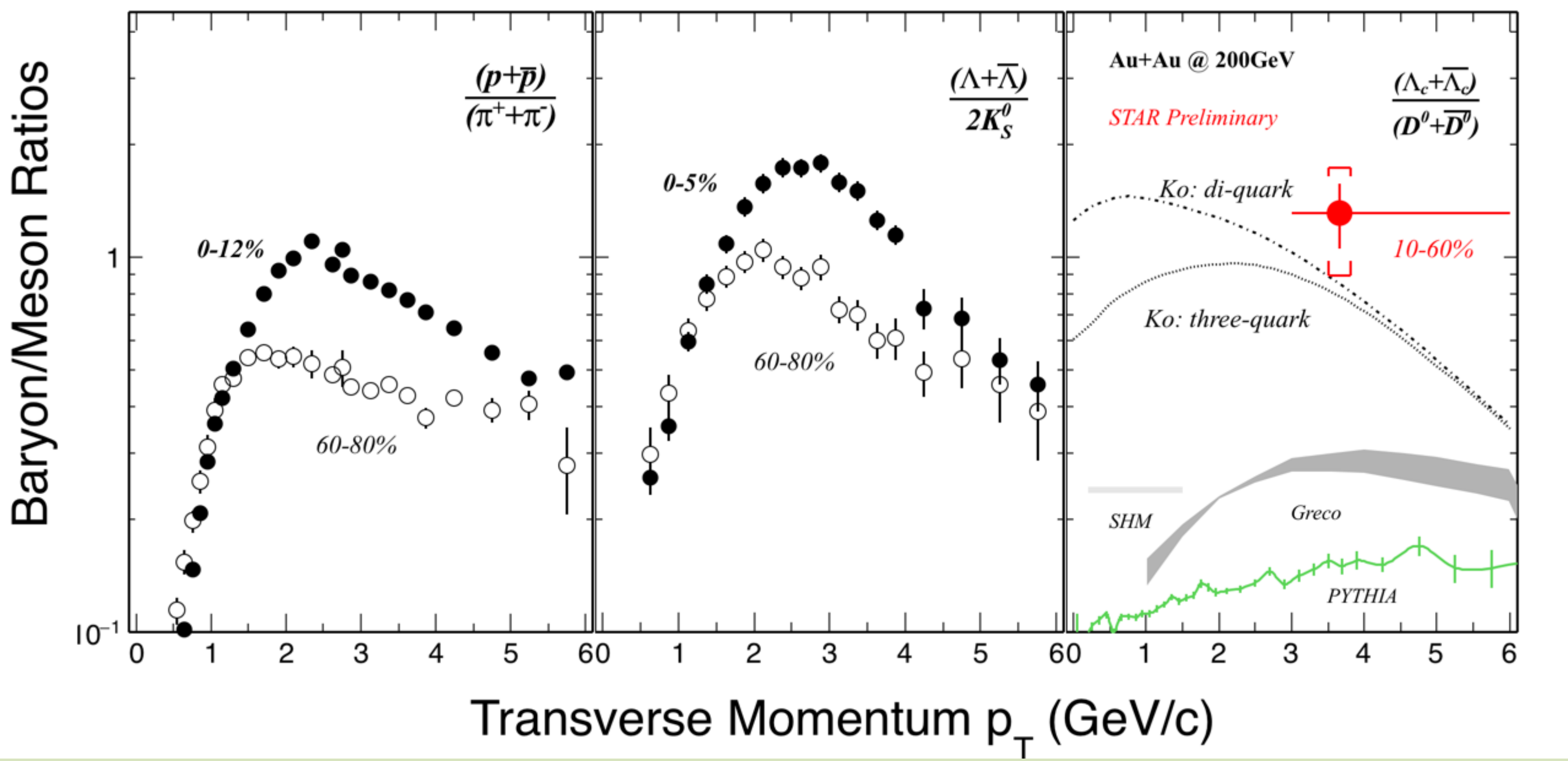
- **Λ_c^+** *(I=0, J=1/2)*

Resonances

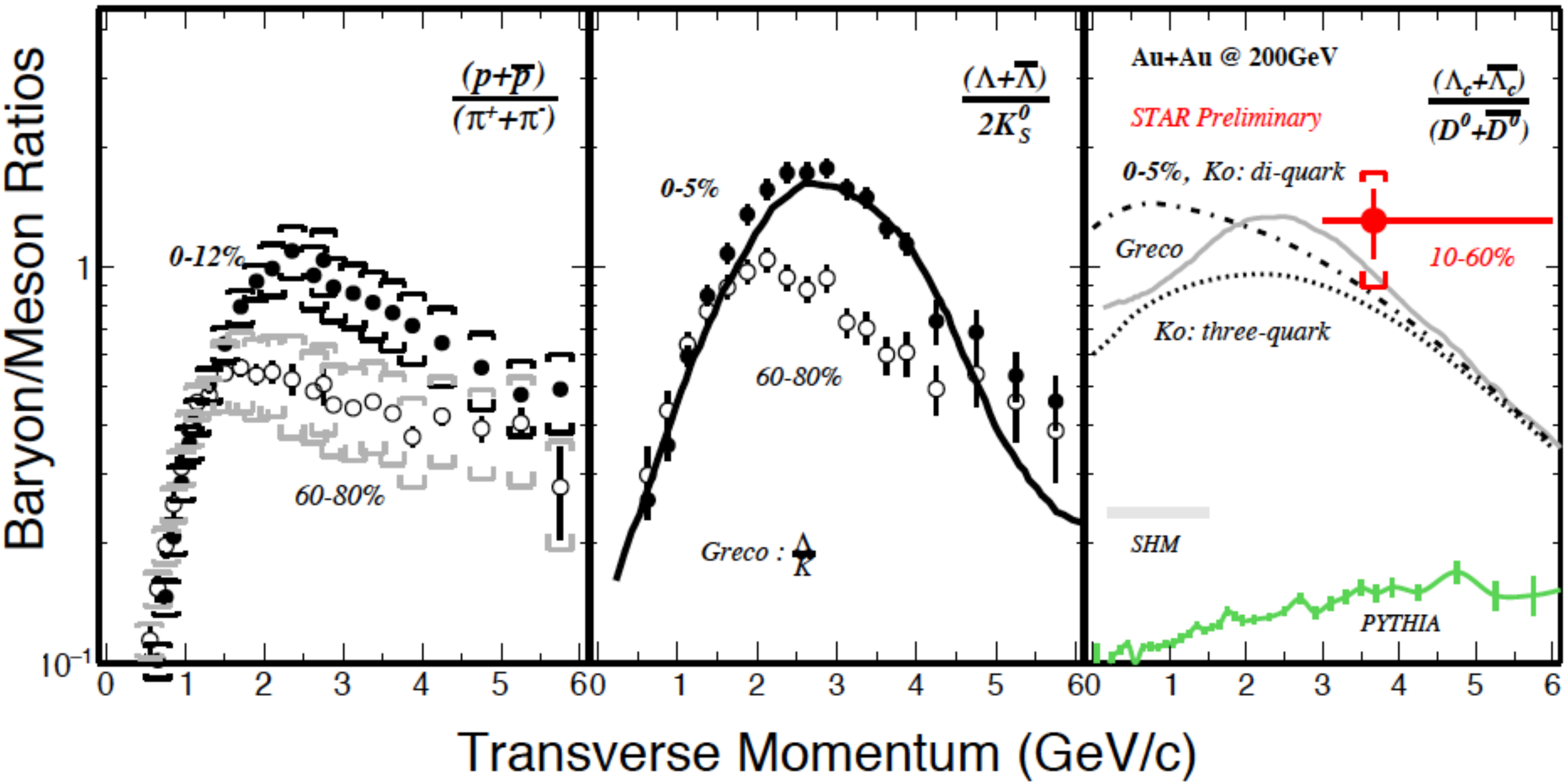
- **$\Lambda_c^+(2595)$** *(I=0,J=1/2)* → **Λ_c^+** *B.R. 100%*
- **$\Lambda_c^+(2625)$** *(I=0,J=3/2)* → **Λ_c^+** *B.R. 100%*
- **$\Sigma_c^+(2455)$** *(I=1,J=1/2)* → **$\Lambda_c^+\pi$** *B.R. 100%*
- **$\Sigma_c^+(2520)$** *(I=1,J=3/2)* → **$\Lambda_c^+\pi$** *B.R. 100%*

What happens in a coalescence model?

Data from STAR Coll., arXiv:1704.04364 [nucl-ex].



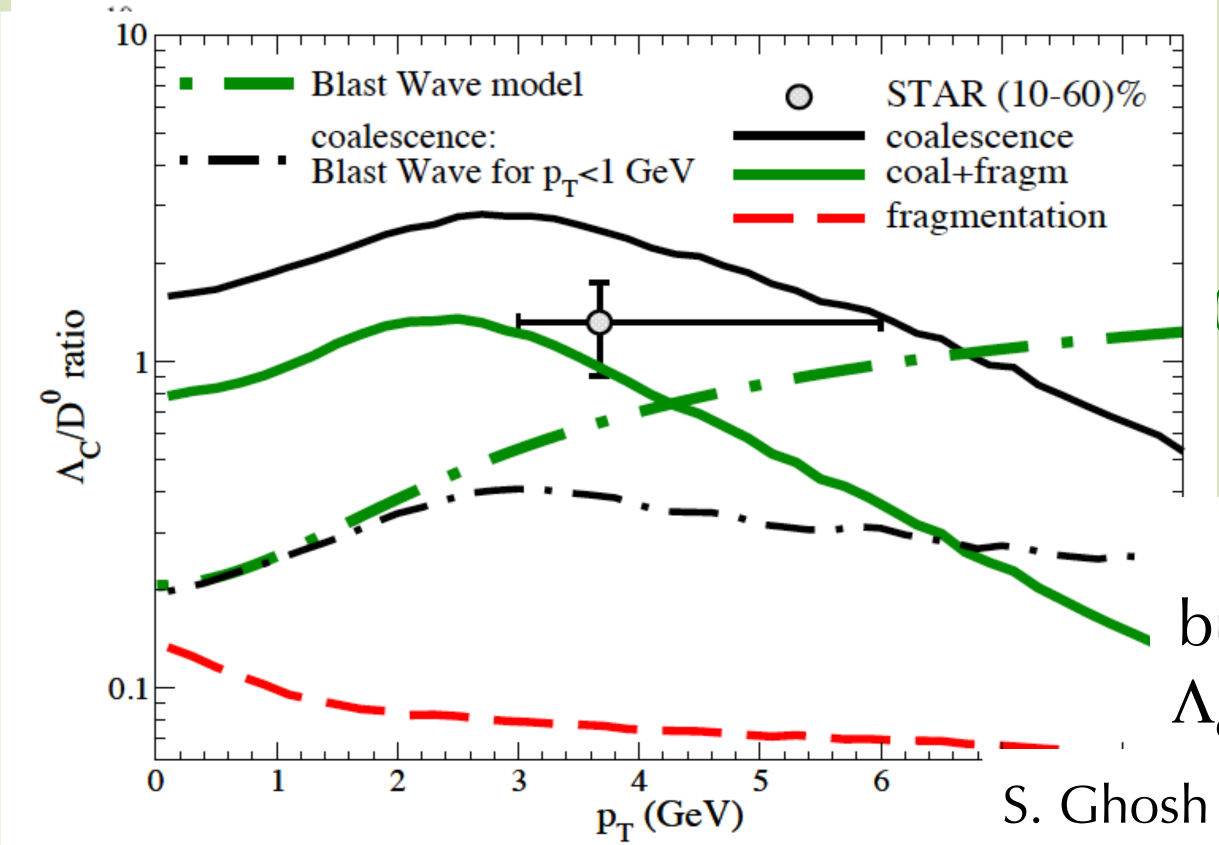
What happens in a coalescence model?



X. Dong and V. Greco, Progress in Particle and Nuclear Physics (2018)

What happens in a coalescence model?

Data from STAR Coll., arXiv:1704.04364 [nucl-ex].



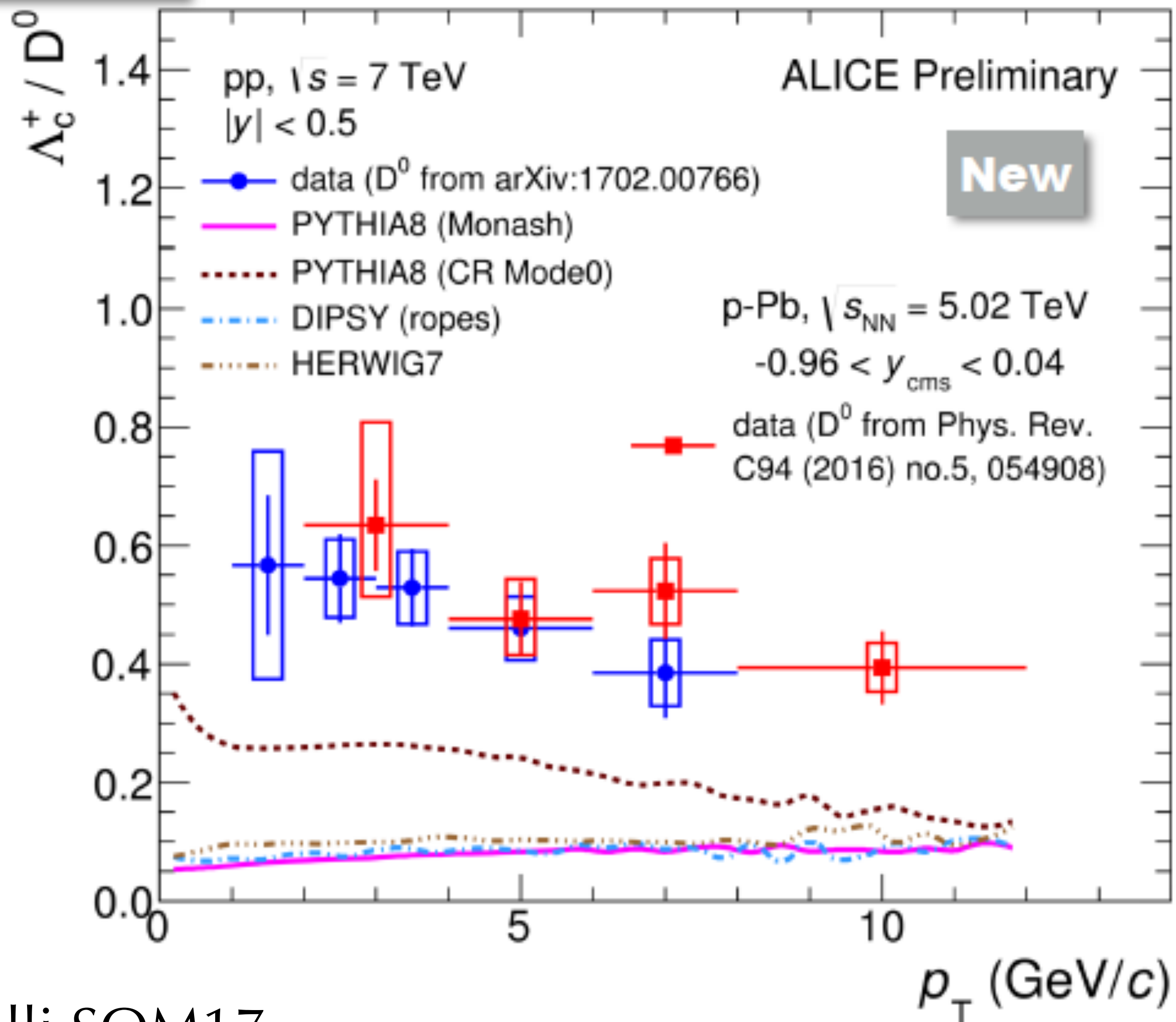
Blast wave model
(statistical hadronization)

Coal. + fragm.
but σ_p of Λ_c fixed to have Λ_c/D like in SHM@low p_T

S. Ghosh et al., PRD90 (2014)054018
& reported by STAR as "*Greco Λ_c/D*"

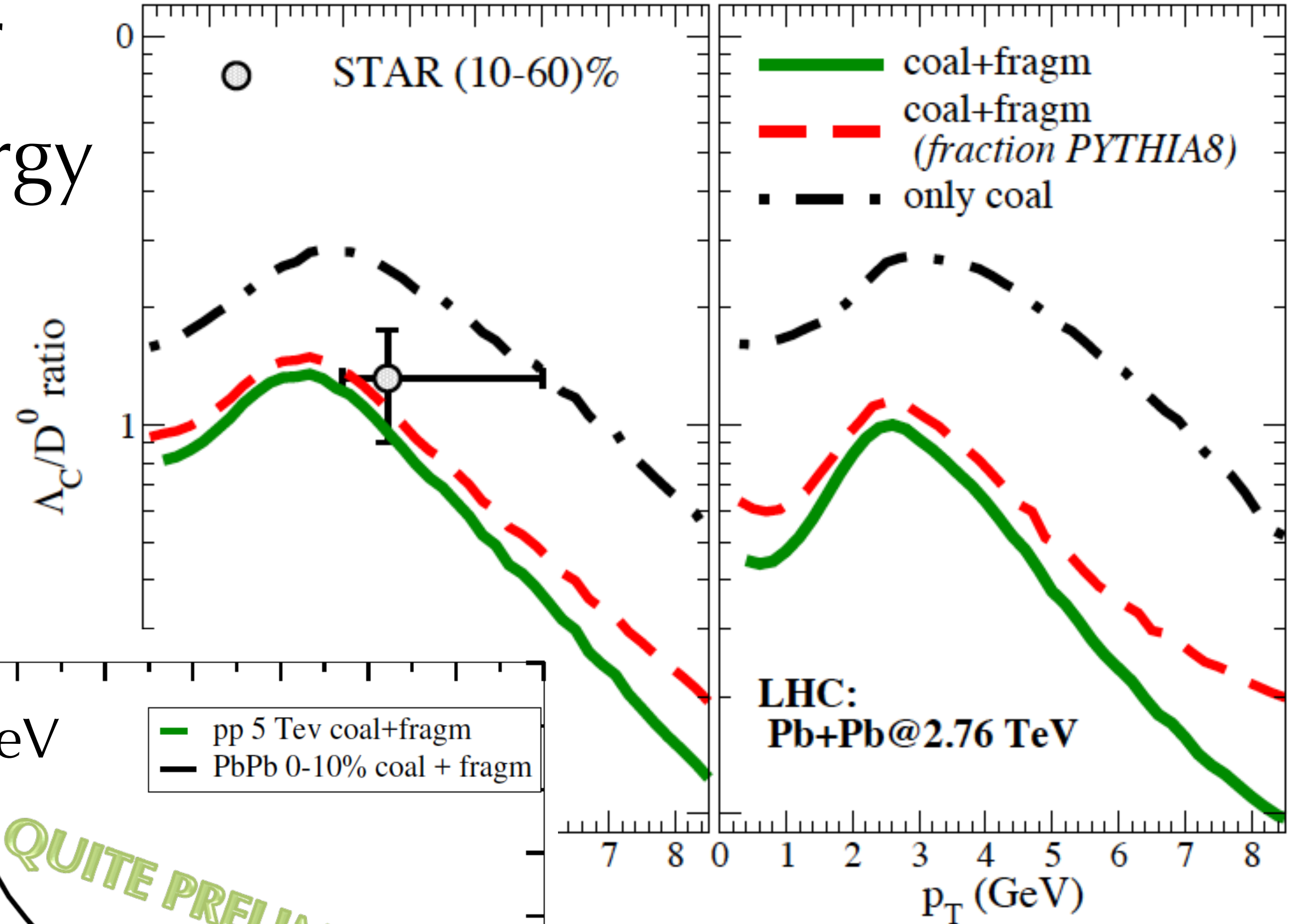
Needed data at low p_T:
For the first time a failure of SHM!?

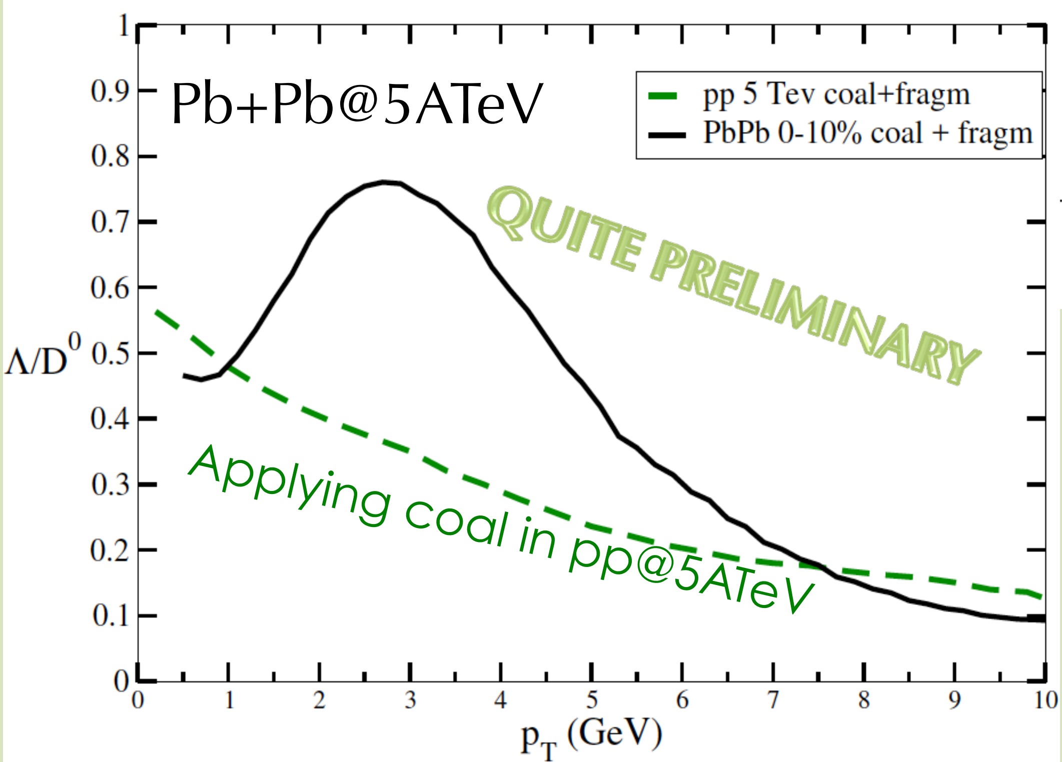
Run I data



A. Grelli,SQM17

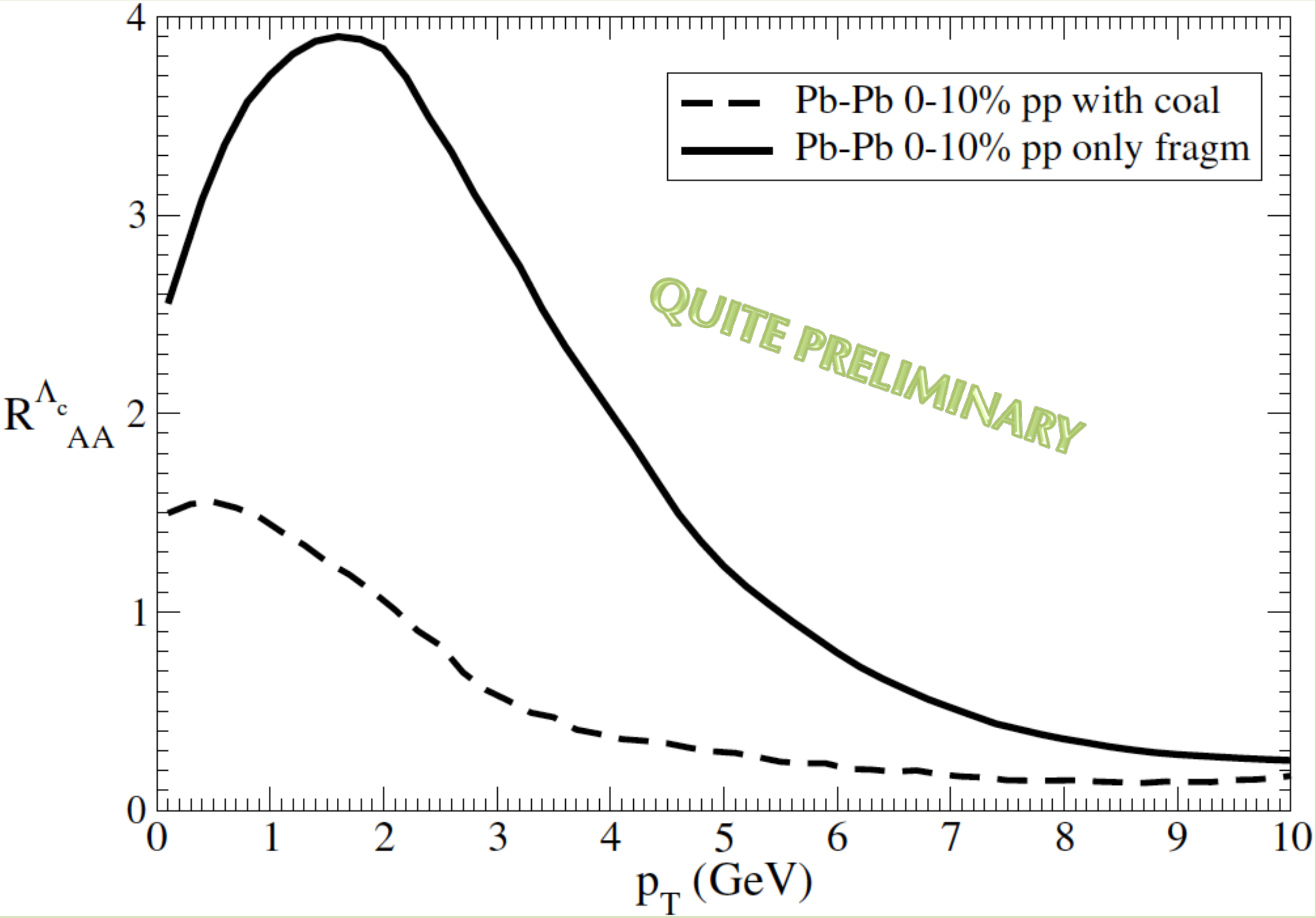
Evolution of Λ_c/D with energy





Fireball for pp from
P.Romatschke, PLB774 (2017)

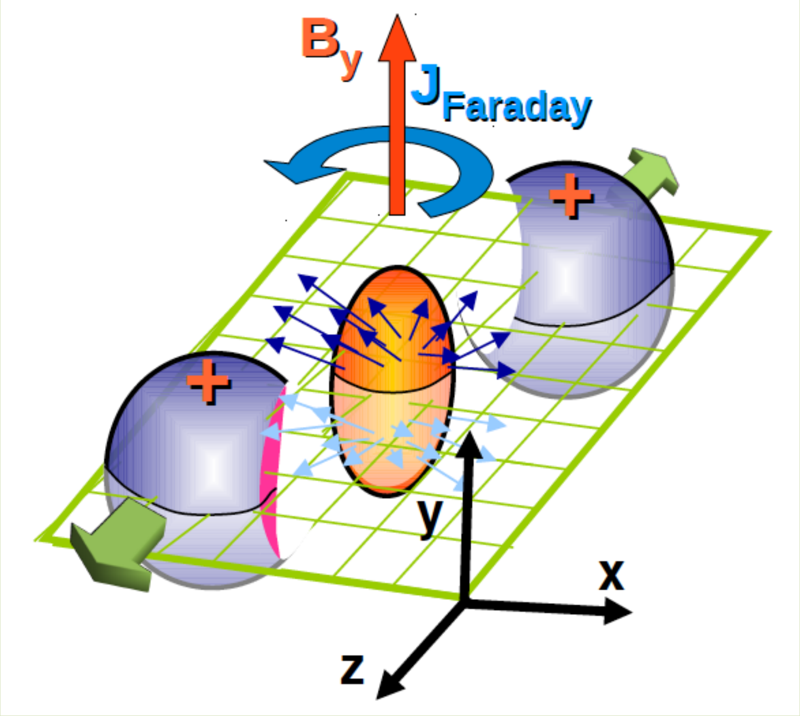
T=0.165 GeV,
β_0=0.4
R_T=2.5 fm
τ=2 fm/c



4
3
2
1
0
$R^{\Lambda_c}_{AA}$
0
1
2
3
4
5
6
7
8
9
10
p_T (GeV)
Pb-Pb 0-10% pp with coal
Pb-Pb 0-10% pp only fragm
QUITE PRELIMINARY

Another plus from $\tau_{th} \approx \tau_{QGP}$

Impact of large Magnetic Field on the Charm dynamics



K Tuchin, Adv.High Energy Phys. 2013 (2013) 490495

K. Hattori, X.-G. Huang, arXiv:1609.00747 [nucl-th]

Strong B field induces:

- Chiral magnetic effect

Impacts on:

- Quarkonia states
- Radiative E_{loss}
- Electromagnetic radiation
- HQ transport coefficient $D_T >> D_{||}$

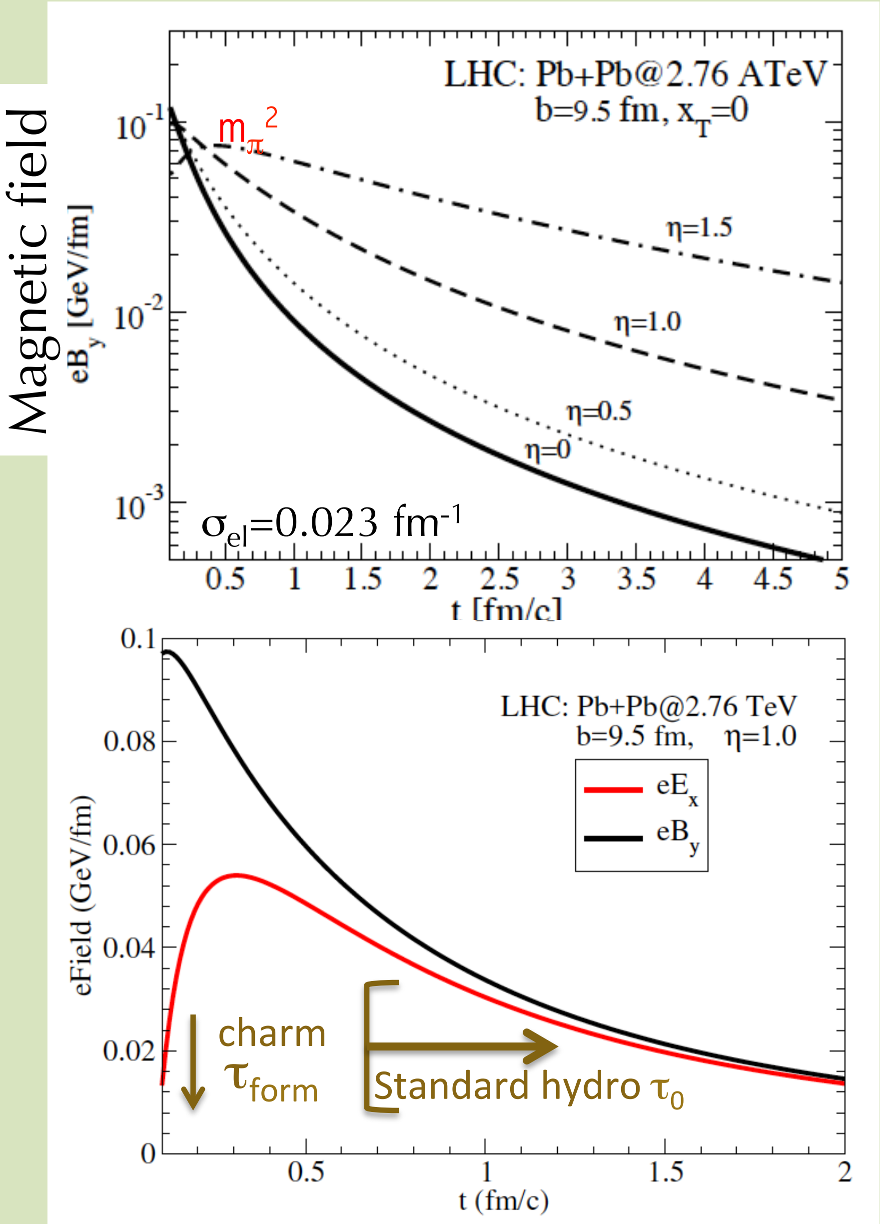
B field strength:

- created on Earth ≈ 10^7 Gauss
- Neutron Star ≈ 10^{13} Gauss
- uRHIC ≈ 10^{19} Gauss ≈ 10 m_π^2

I will discuss the direct effect on HQ dynamics of the e.m. interaction

New

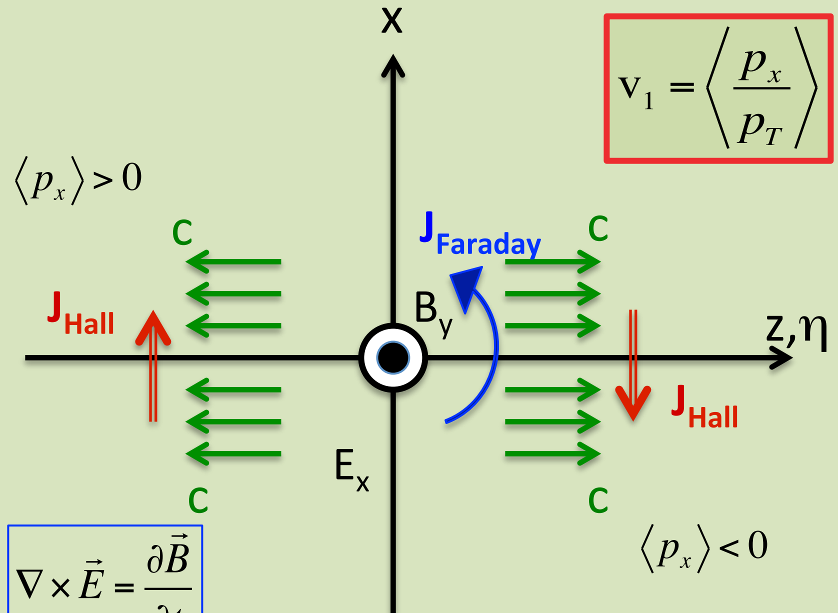
Impact of Magnetic Field on charm



E-B fields like Gursoy et al., PRC89(2014)

$$\mathbf{F}_{ext} = q\mathbf{E}' + \frac{q}{E_p}(\mathbf{p}\times\mathbf{B}')$$

Faraday Hall

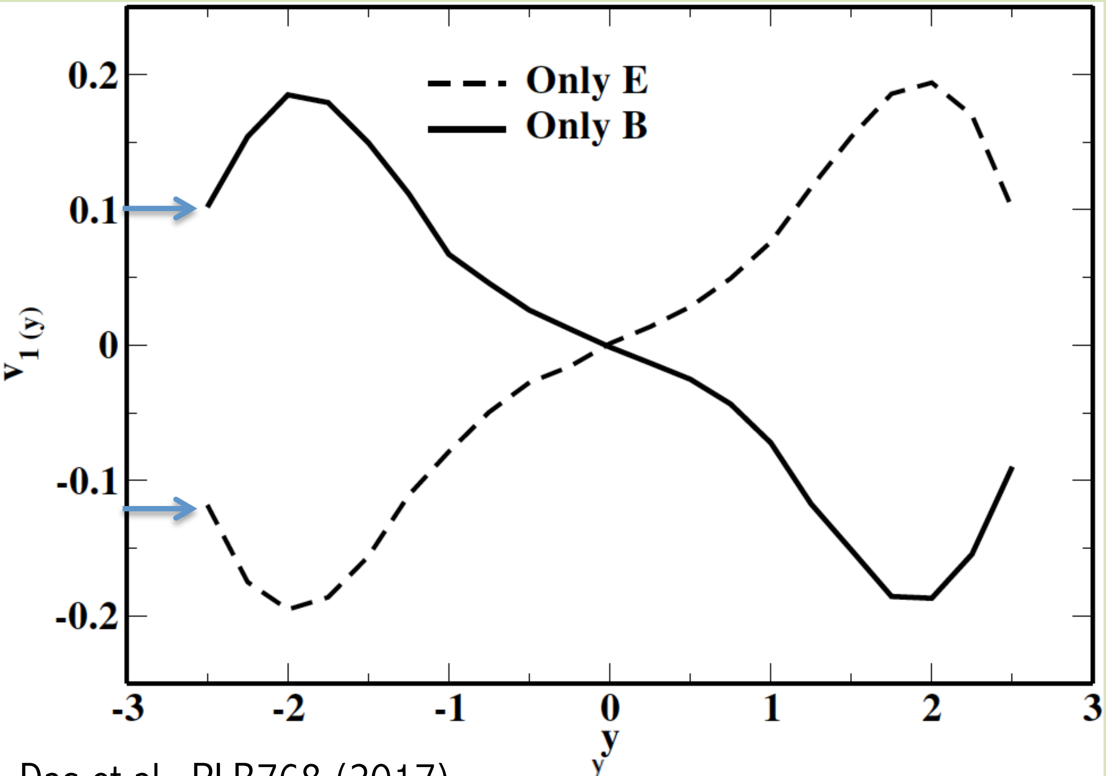


$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

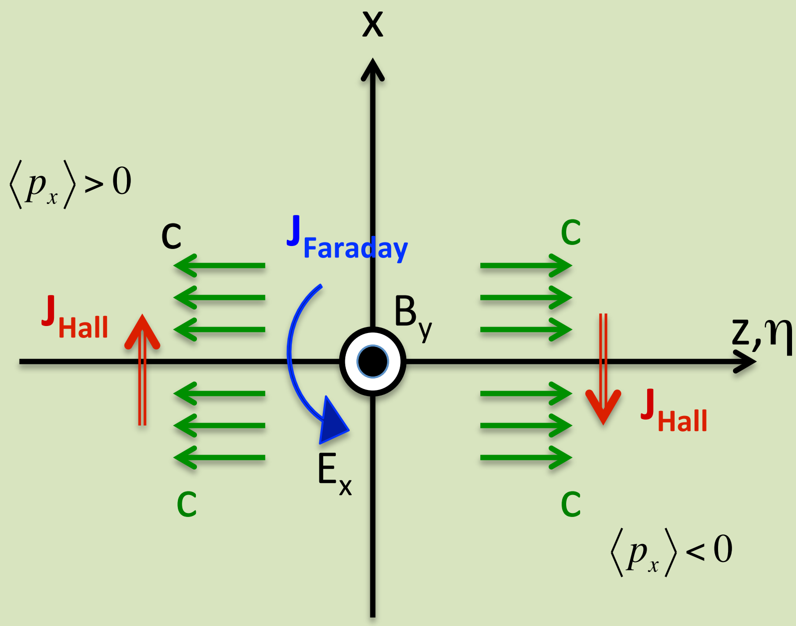
$$\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$$

$$\eta = \frac{1}{2}\ln\left(\frac{t+z}{t-z}\right)$$

Balance between Faraday current and Hall drift



Das et al., PLB768 (2017)

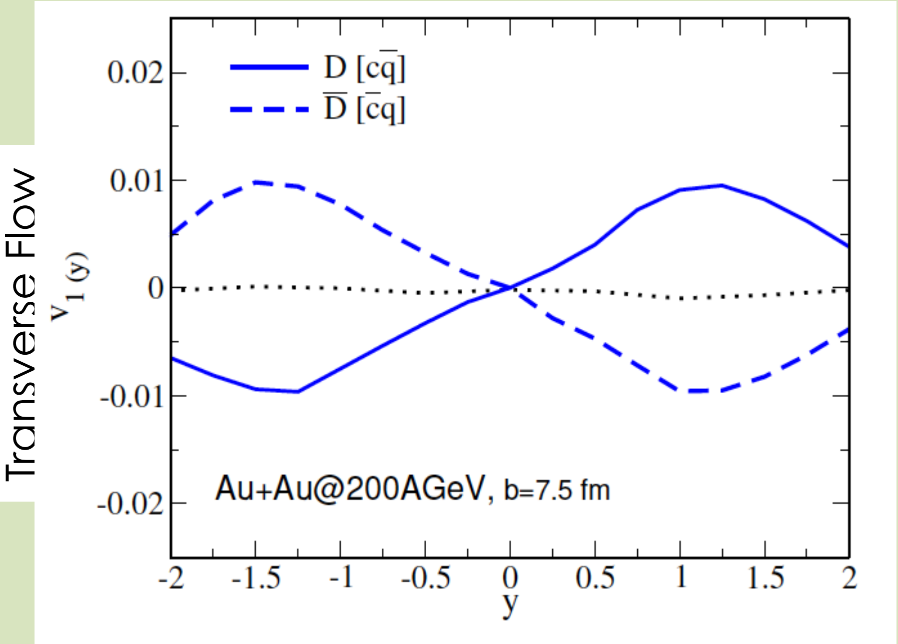


✧ Decreasing magnetic field B_y creates E_X that induces a current in opposite direction w.r.t. to the Magnetic Hall drift: <u>delicate balance!</u>

✧ Larger initial (t<1 fm/c) field important to determine a sizeable v_1 flow

New

Impact of Magnetic Field on charm

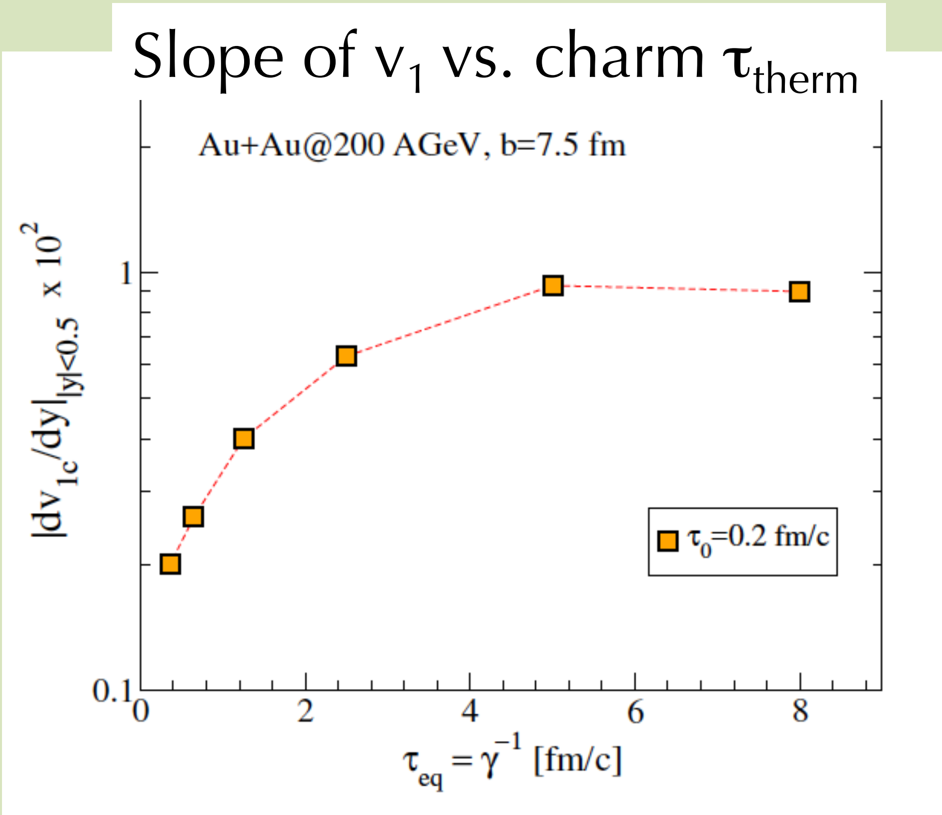


V. Greco, QM2017, NPA (2017)
S. Das et al., PLB768 (2017)

For light quarks predicted $v_1 \approx 10^{-3}$-10^{-4} [Gursoy et al., PRC89 (2014)]

For charm quark we find a sizeable v_1 using the same E-B field evolution

About 40 times larger!



HQ best probe for v_1 from e.m. field:

- $t_{form} \approx 0.1$ fm/c vs q << g at this time
- $\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$
- do not mix with CME [c no chiral]
- do not mix vorticity [Odd- parity]

Conclusions

❖ Open Charm is an excellent probe having:

- potential to link lQCD to phenomenology
- observables ***not easy*** to predict containing information on T dependence of the Hot-QCD interaction in ***non-perturbative regime*** (p_T < 10 GeV)

❖ $\tau_{therm} \approx \tau_{QGP}$ → make it a probe carrying more info:

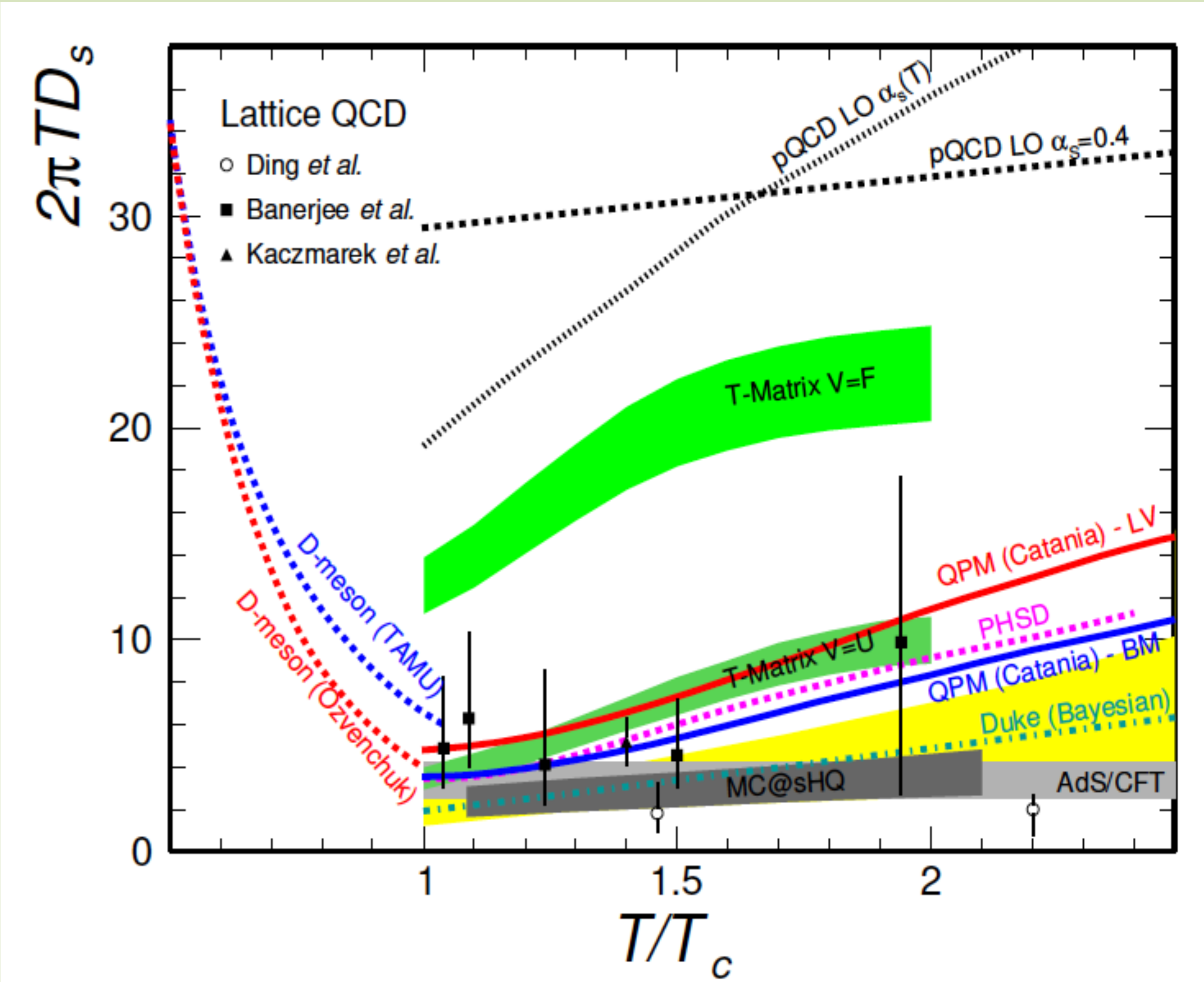
– from R_{AA} ,v_2 → **D_s(T) of Hot QCD medium** within lQCD

*… we are going to have **v_3, v_2(HQ)-v_2(QGP)**, $dN_D/d\Delta\phi_{12}$,*

– **Charm can allow to access the initial strong E-B field**

❖ **Haronization: Λ_c/D ratio in AA &pp? Will SHM fail? $R_{AA}(\Lambda_c) \approx$ 3-4?**

At the moment quite not under control even in pp

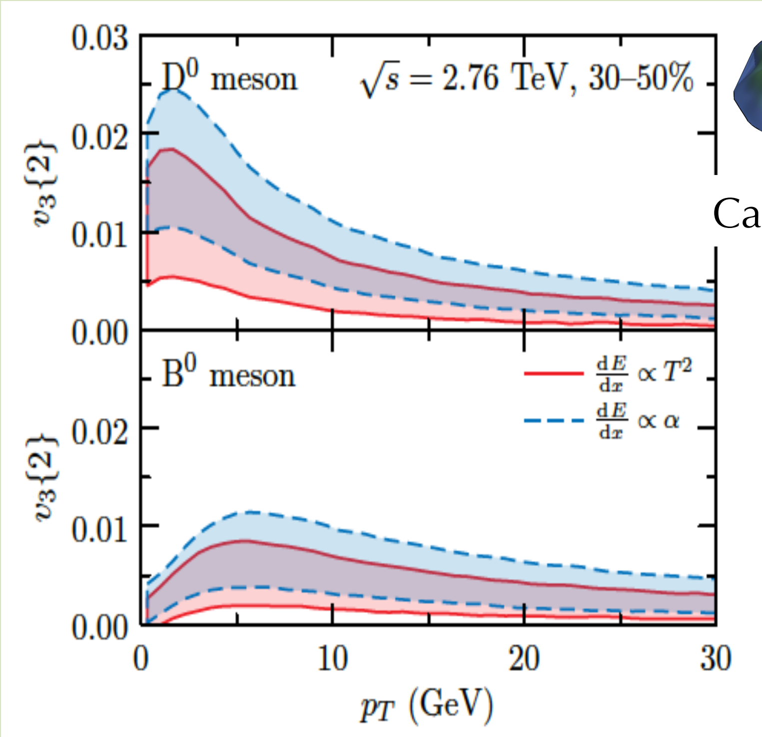


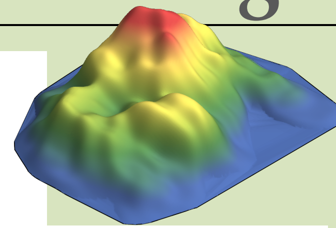
X. Dong and V. Greco, Progress in Particle and Nuclear Physics (2018)

New observable are coming

v3, v_2(bulk)-v_2(charm), …?

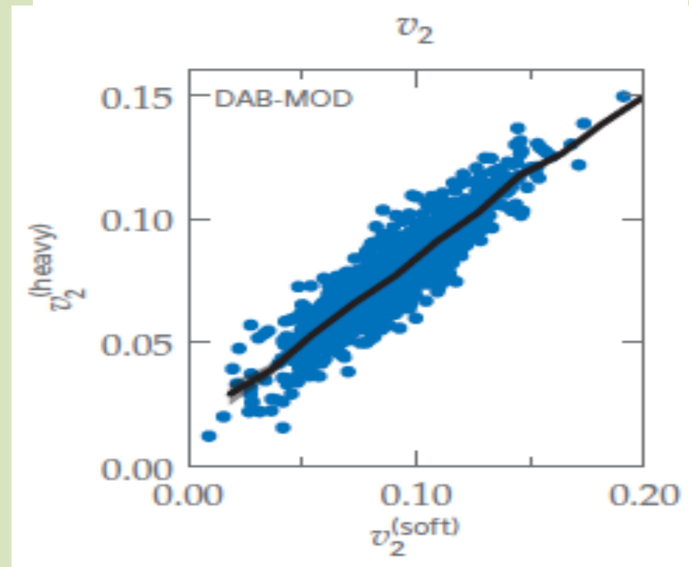
B & D at high p_T: path length but on e-b-e bulk





Caio, Wed 17:30

HF- bulk v_n correlation w ESE



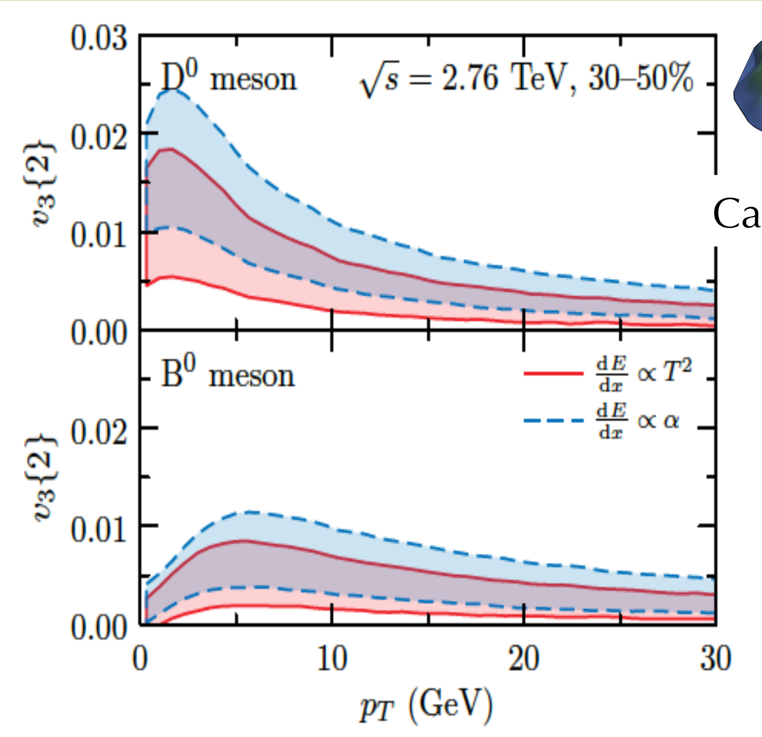
D meson –Pb+Pb@5.02 ATeV,30-40%

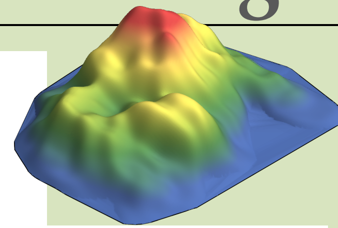
$$\frac{dE}{dx}(T,v) = f(T,v)\,\Gamma_{\text{flow}},$$

Caio-Prado et al.,arXiv:1612.05724

- ✧ R_{AA} of B and D appears to be the same!
- ✧ $V_{2D,B}$ linearly correlated with v_2 bulk – ***for D see ALICE****, A.Barbano - Tue 16:50*
- ✧ V_3 significantly affected by the T dependence of E_{loss}
- ✧ $v_{2,3}\{2\}$, $v_{2,3}\{4\}$, $v_{2,3}\{6\}$, $v_{2,3}\{8\}$ all cumulants are equal → flow

B & D at high p_T: path length but on e-b-e bulk





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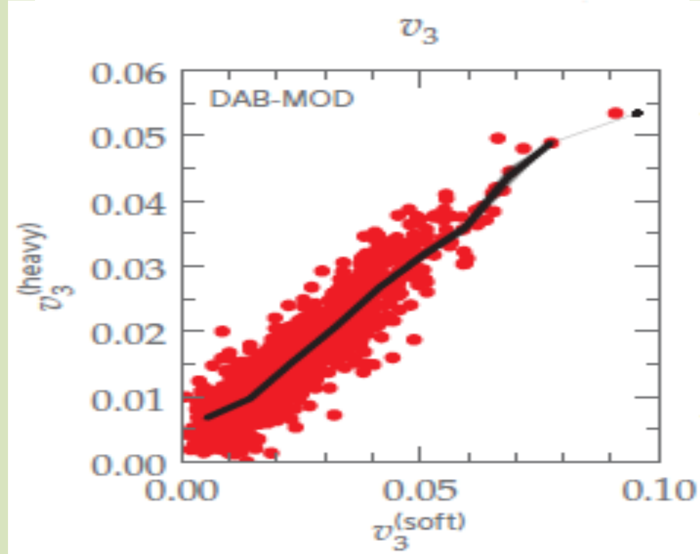

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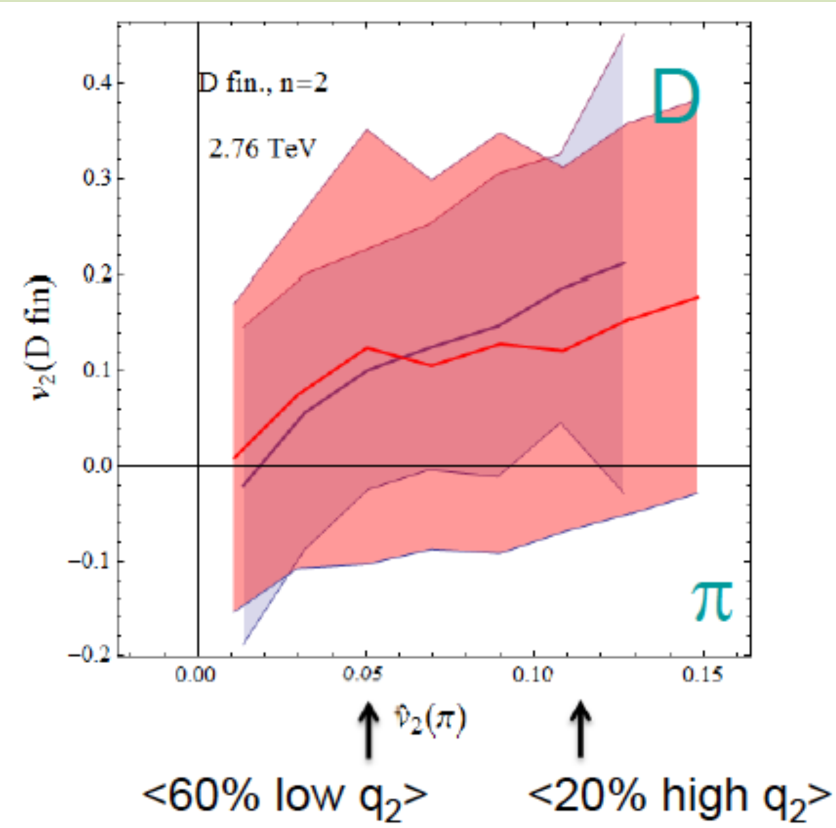
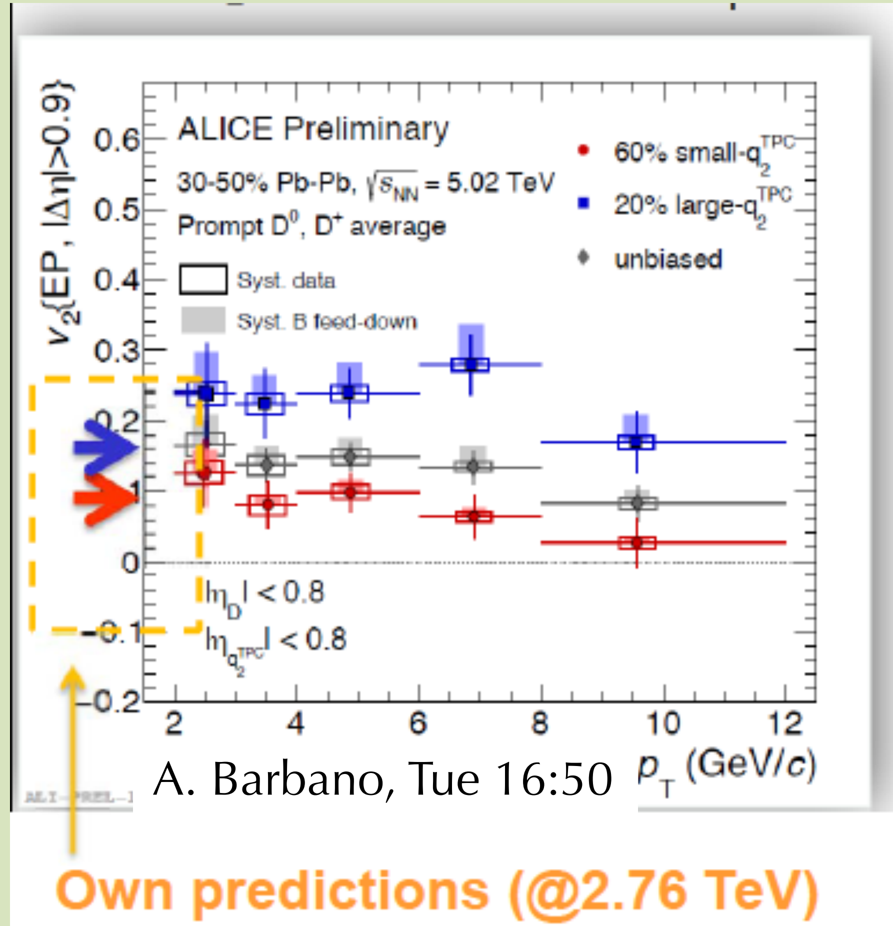
- ✧ R_{AA} of B and D appears to be the same!
- ✧ V_n linearly correlated with v_n bulk – ***for D see ALICE***, *A.Barbano - Tue 16:50*
- ✧ v_3 show a persistence of the correlation with T dependence of E_{loss}
- ✧ $v_{2,3}\{2\}$, $v_{2,3}\{4\}$, $v_{2,3}\{6\}$, $v_{2,3}\{8\}$ all cumulants are equal → flow

How v_2 of D is build-up?

SUBATECH-Nantes [MC@sNLO + EPOS]

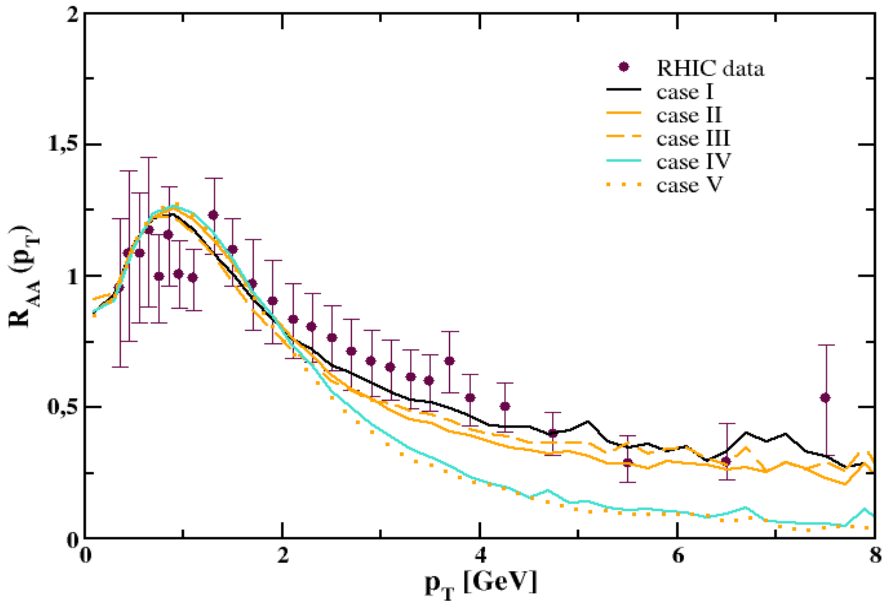


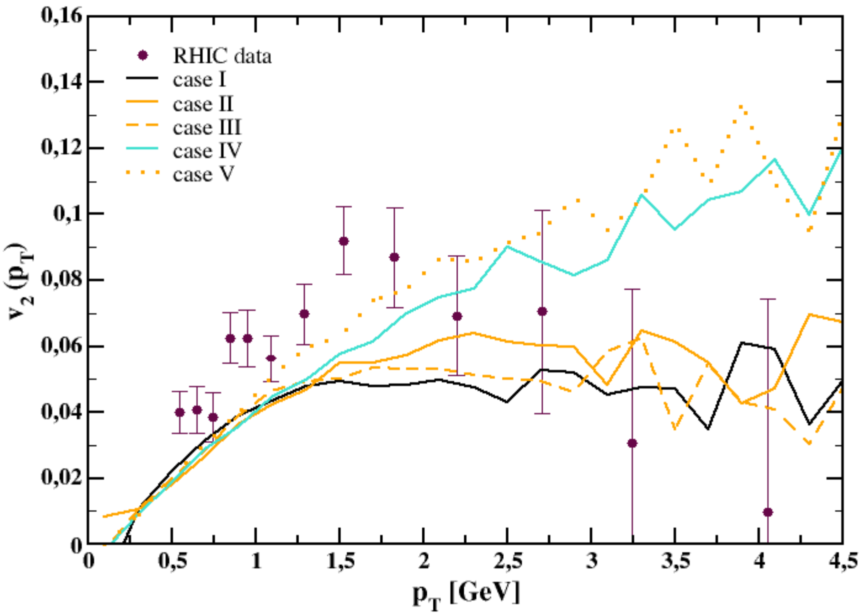


This is just the beginning of a new step forward, how we will learn from it … next QM2018

Gossiaux over night calculation

Impact of FDT implementation for pQCD-LO





1) A and B_T (from pQCD No FDT, but $B_{||} = B_T$)

2) $B_{||} = B_T$ (pQCD) ; A (FDT)

$$A = \frac{B_T}{ET} - \frac{1}{p}\frac{\partial B_T}{\partial p}$$

3) A pQCD ; D= $B_{||} = B_T$ (FDT)

$$D = AET$$

Post-Ito

4) B_T and $B_{||}$ (pQCD) ; A FDT

$$A = \frac{1}{p} B_{\parallel} \frac{1}{T}\frac{\partial E}{\partial p} - \frac{1}{p}\frac{\partial B_{\parallel}}{\partial p} - \frac{(n-1)}{p^2}\left(B_{\parallel} - B_{\perp}\right)$$

5) B_T=$B_{||}$ (pQCD) ; A FDT

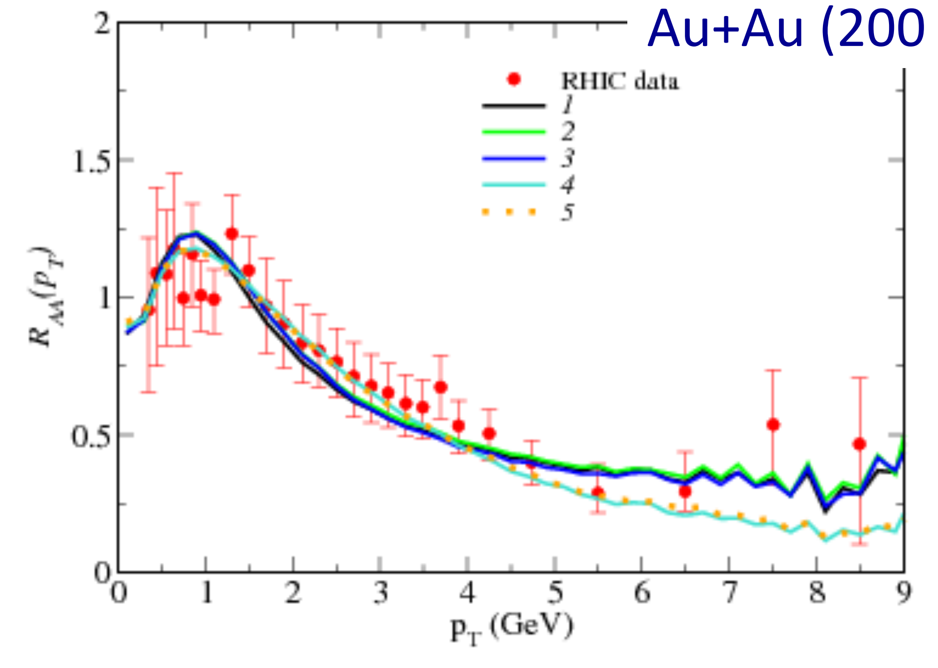
$$A = \frac{B_{\parallel}}{ET} - \frac{1}{p}\frac{\partial B_{\parallel}}{\partial p}$$

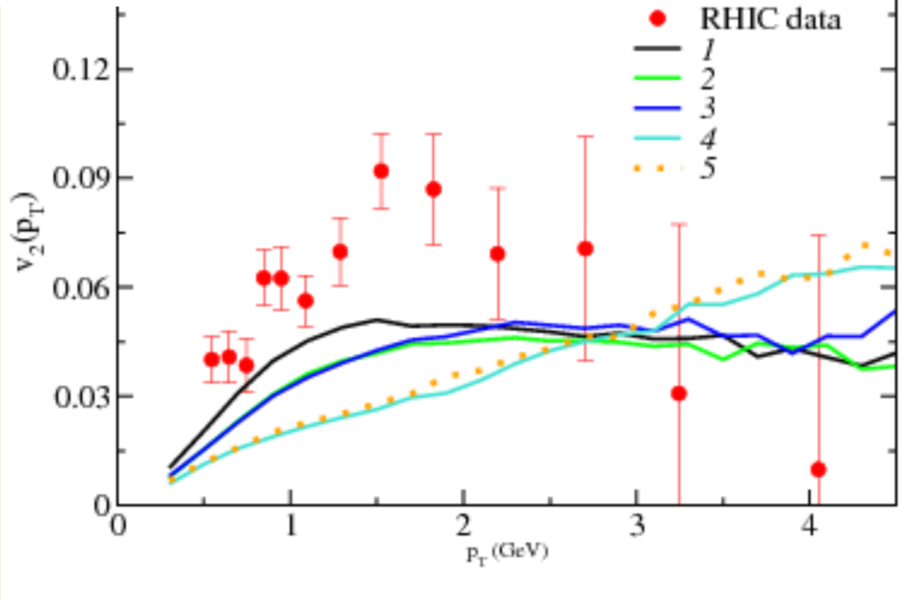
Shape of 1,2,3, similar to Boltzmann dynamics

Impact on R_{AA} and v_2 of the different form of FDT

Rescaling A and B to have the same R_{AA} at $p_T < 4$ GeV

Au+Au (200 GeV) b=8 fm





4) B_T and $B_{||}$ (pQCD) ; A FDT

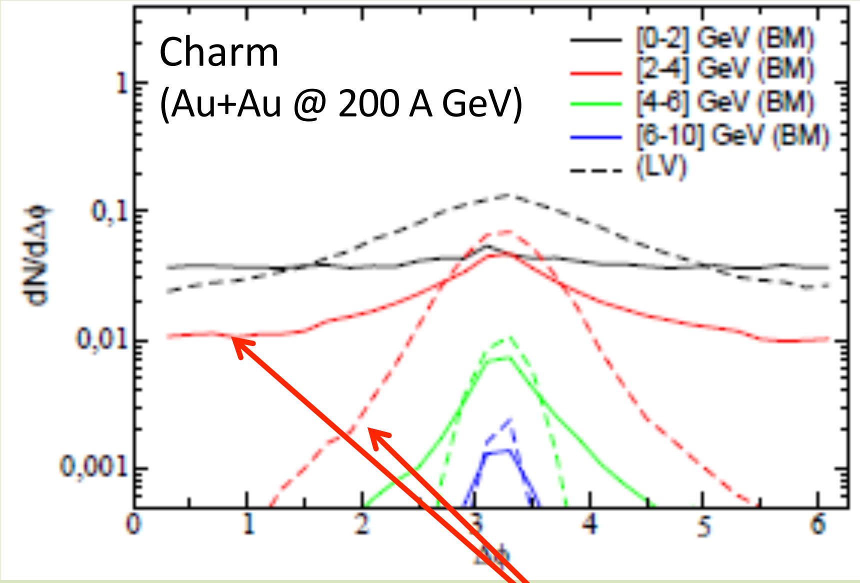
5) B_T=$B_|$ (pQCD) ; A FDT

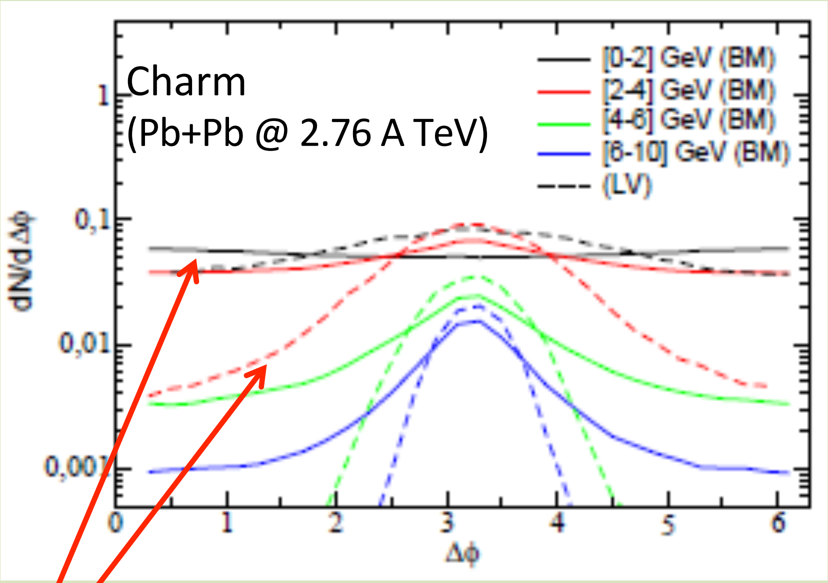
If $B_{||}$ is evaluated from pQCD one has to reduce the drag and the diffusion by 50% but the p_T dependence of R_{AA} and v_2 is quite different

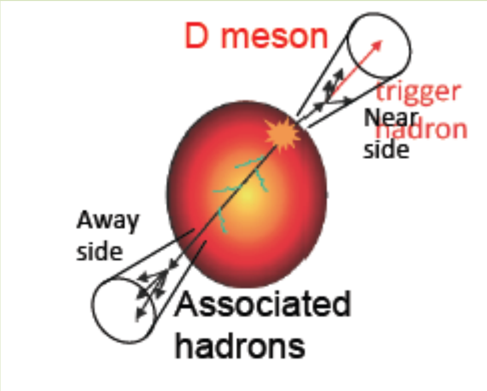
Langevin vs Boltzmann angular correlation

Initially the c-$\bar{c}$ and b-$\bar{b}$ are distributed back to back (LO)

We have <u>fixed the R_{AA}</u> on exp. data for both the two approaches



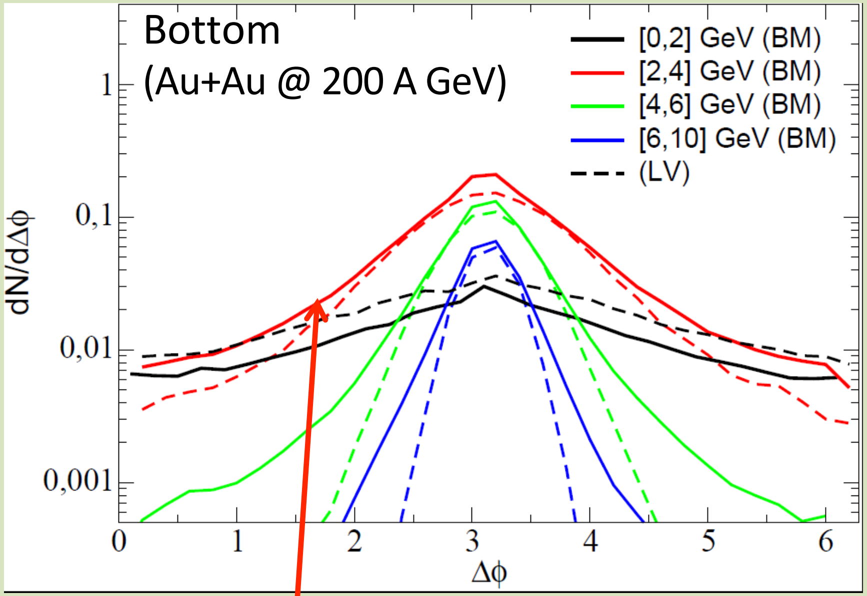


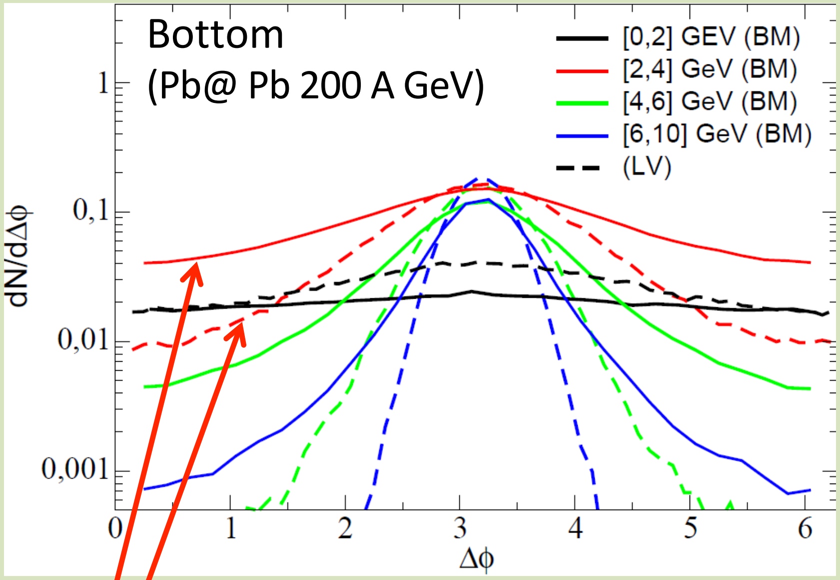


A difference of an
order of magnitude

Langevin vs Boltzmann angular correlation

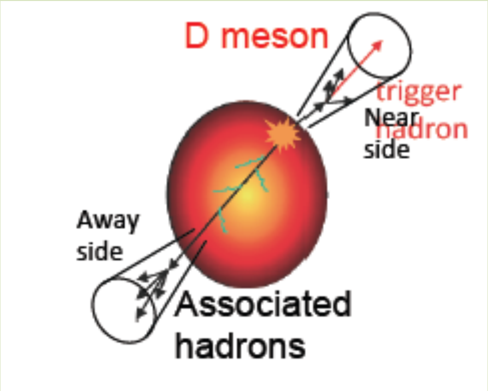
Initially the c-c and b-b are distributed back to back (LO)

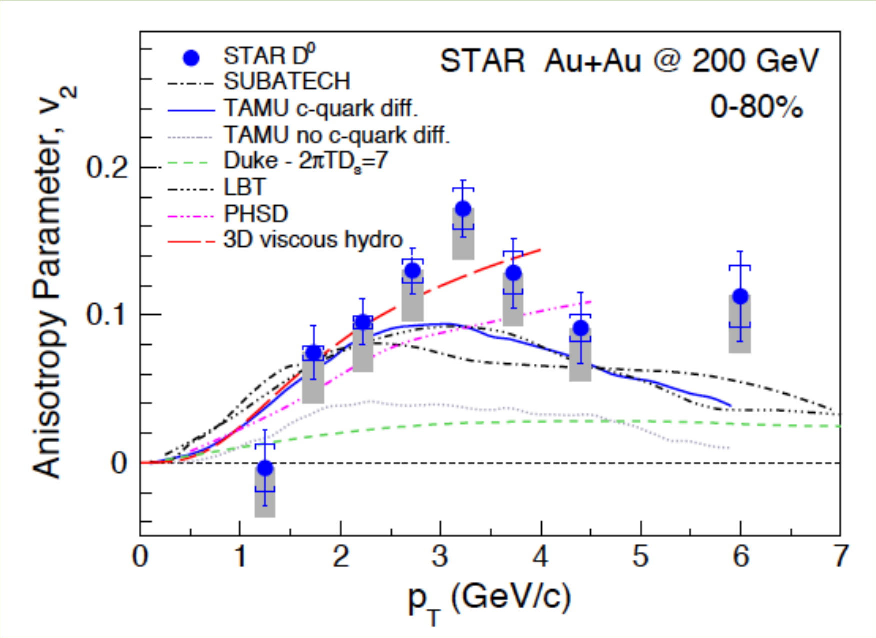


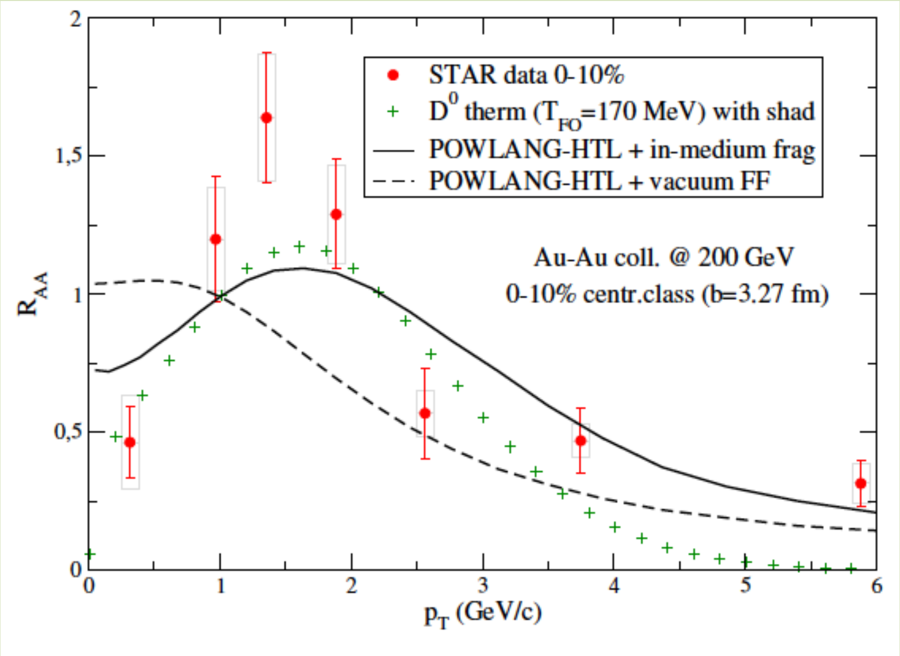


There are not differences at RHIC

Significant differences at LHC

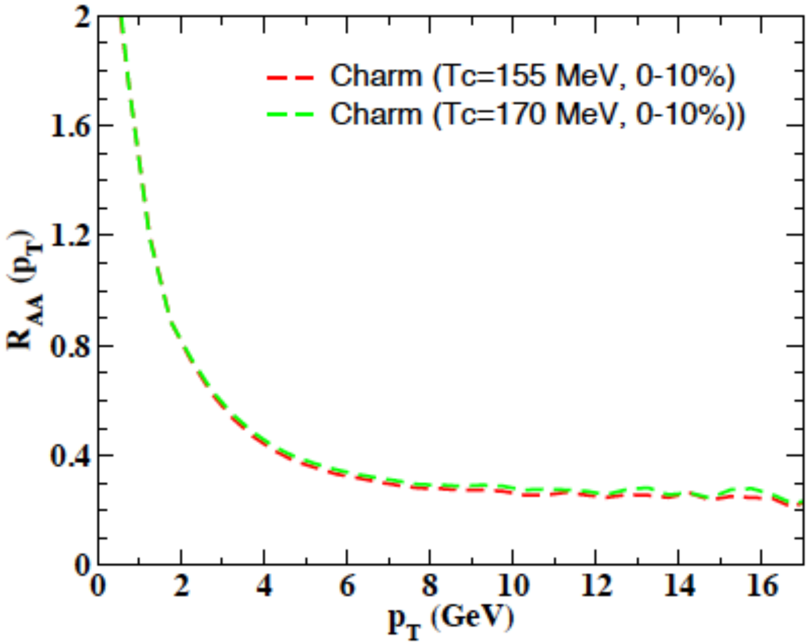


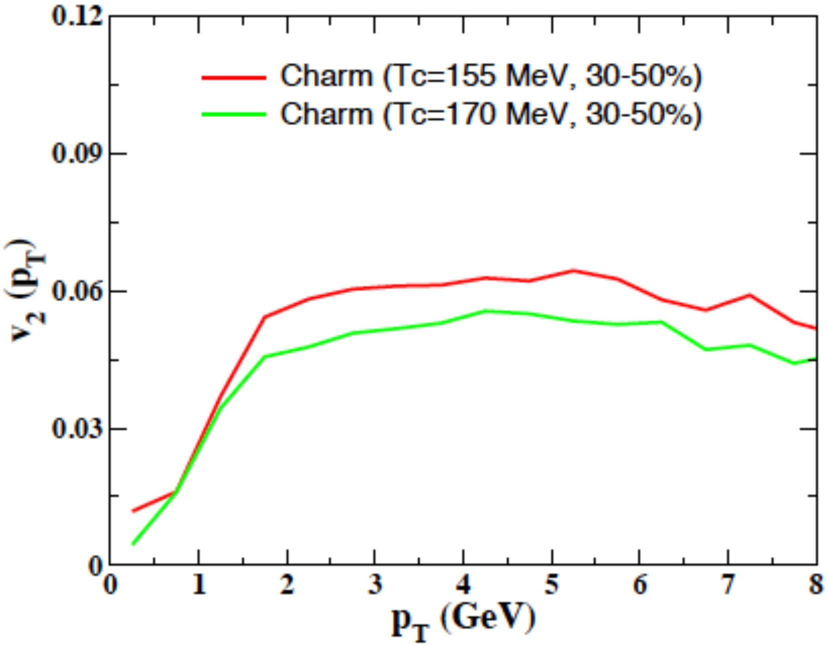




- Centrality bias
- R_{AA} is non-thermal
- We can see that $\gamma \approx T^2$ generates the smallest flow

Impact of different Tc





Two Main approches in LV-FP

Post-point Ito (already assumed that $D_L = D_T = D$)

(1)

$$D[E(p)] = \Gamma(p)E(p)T \ , \tag{23}$$

$$\Gamma(p) = A(p) + \cancel{\frac{1}{E(p)}\frac{\partial D[E(p)]}{\partial E}} \ . \tag{24}$$

One is not able to embed into Lagevin all the information from the Scattering Matrix

A(p) from the Scatt. matrix

(2) $$\Gamma = A = \frac{1}{p}D_L\frac{1}{T}\frac{\partial E}{\partial p} - \frac{1}{p}\frac{\partial D_L}{\partial p} - \frac{(n-1)}{p^2}(D_L - D_T)$$

Both $D_L(p)$ & $D_T(p)$ from the scatt. matrix

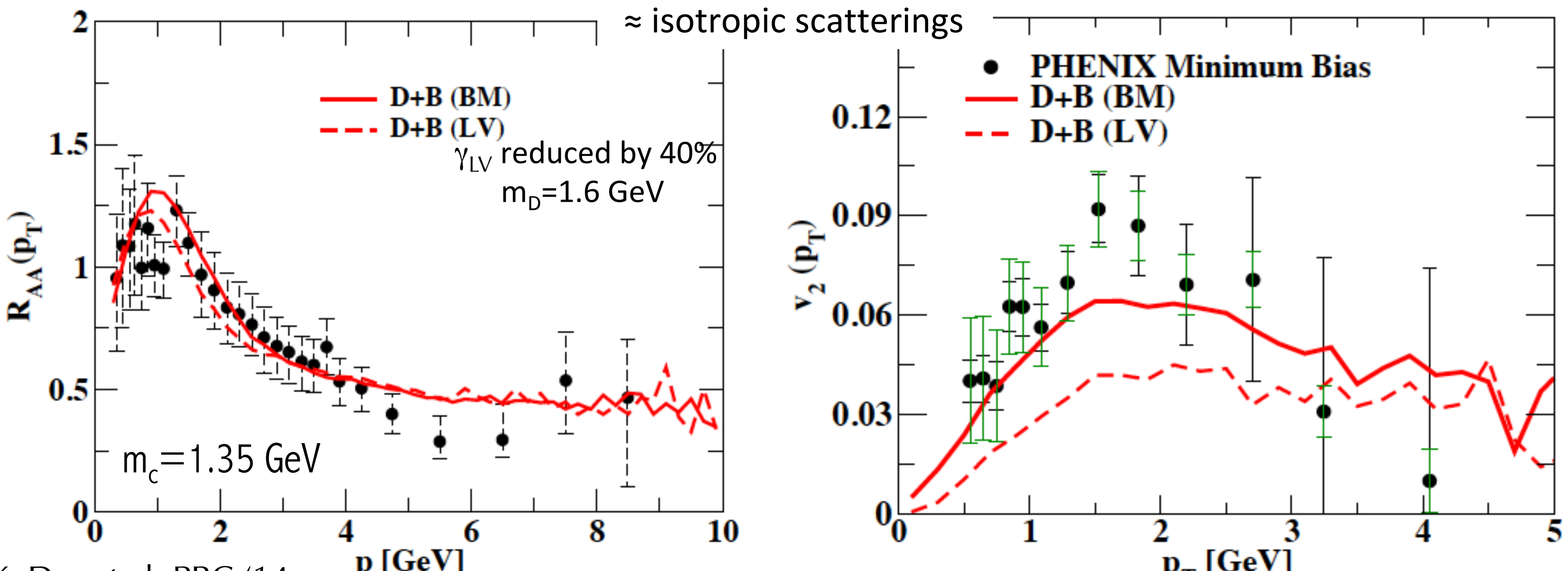
$$\frac{\partial}{\partial t}f(t,\boldsymbol{p}) = \frac{\partial}{\partial p_i}\Big\{\Gamma(p)p_i f(t,\boldsymbol{p}) + D(p)\frac{\partial}{\partial p_i}f(t,$$

$$\mathrm{d}x_j = \frac{p_j}{E}\mathrm{d}t \ ,$$

$$\mathrm{d}p_j = -\Gamma(p,T)p_j\mathrm{d}t + \sqrt{\mathrm{d}t}C_{jk}(\boldsymbol{p}+\xi d\boldsymbol{p},T)\rho_k$$

Are there differences coming from BM vs LV?

Most of the groups start from drag γ or from D_T (not D_L)
This choice is more in line with Boltzmann that not having the FDT issue,
can serve as a guide…



S.K. Das et al.,PRC '14

BM and LV → $R_{AA}(p_T)$ shaper nearly identical:
- but Drag γ has to be reduced by 15-40% *depending on m_c & $d\sigma_{gQ}/d\Theta$*
- Larger $v_2(p_T)$ ≈ 10-30% again *depending on m_c & $d\sigma/d\Theta$*

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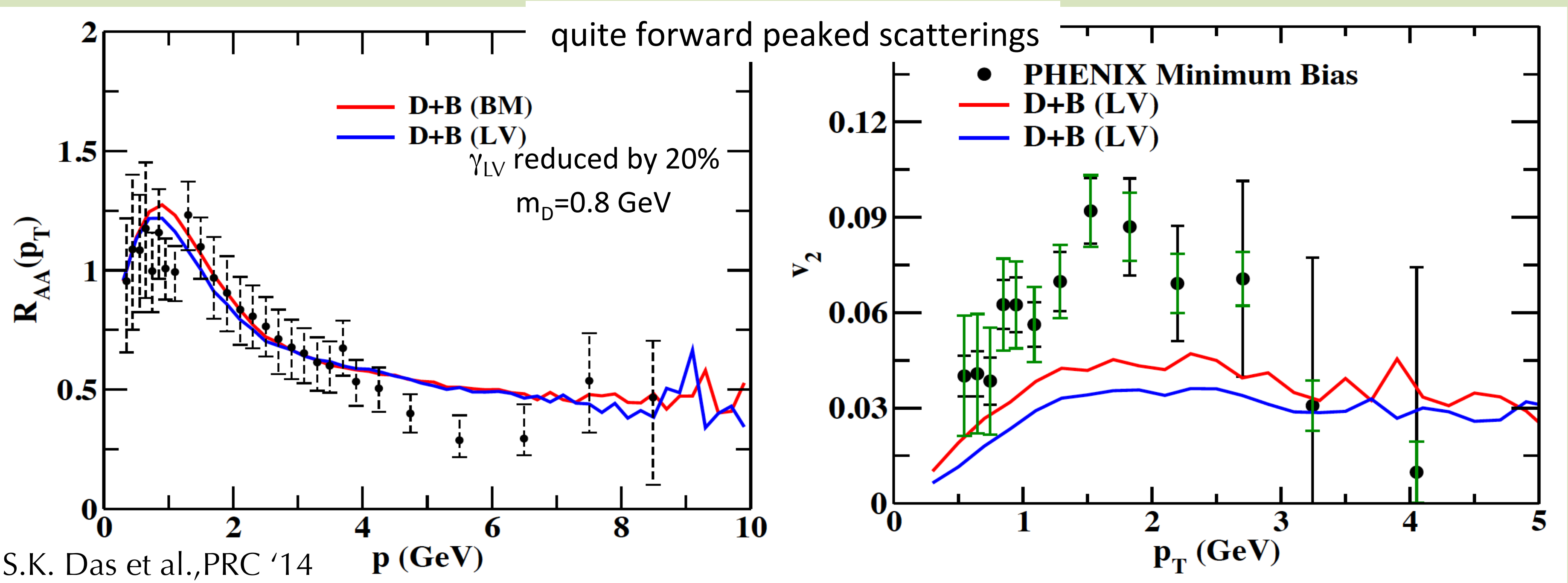

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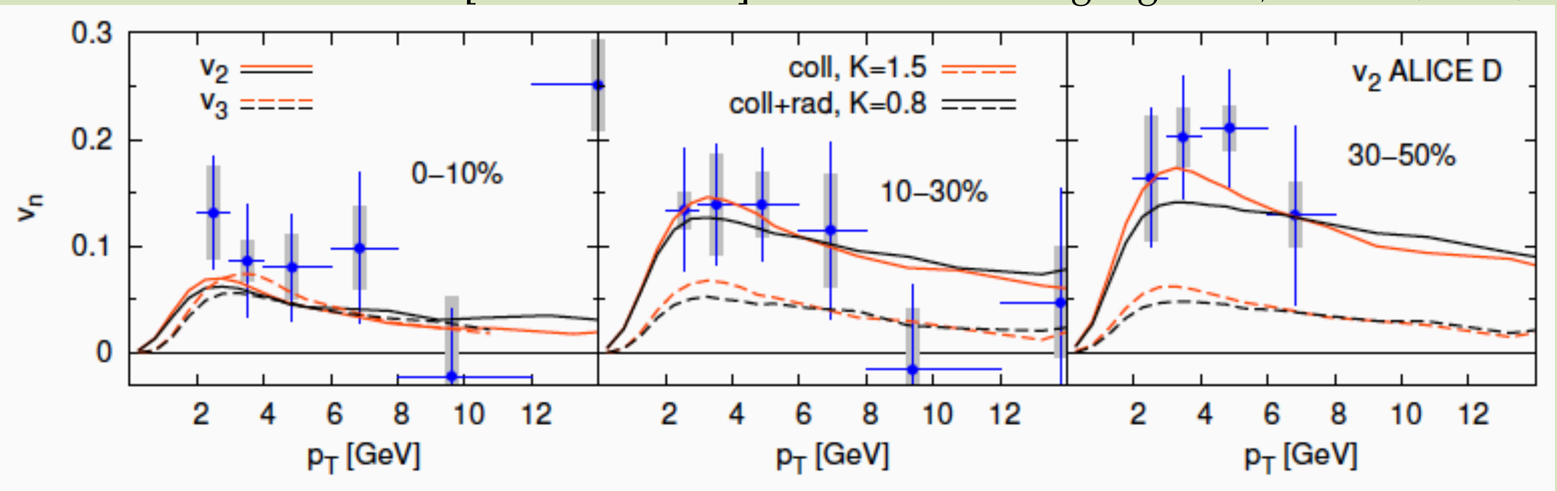
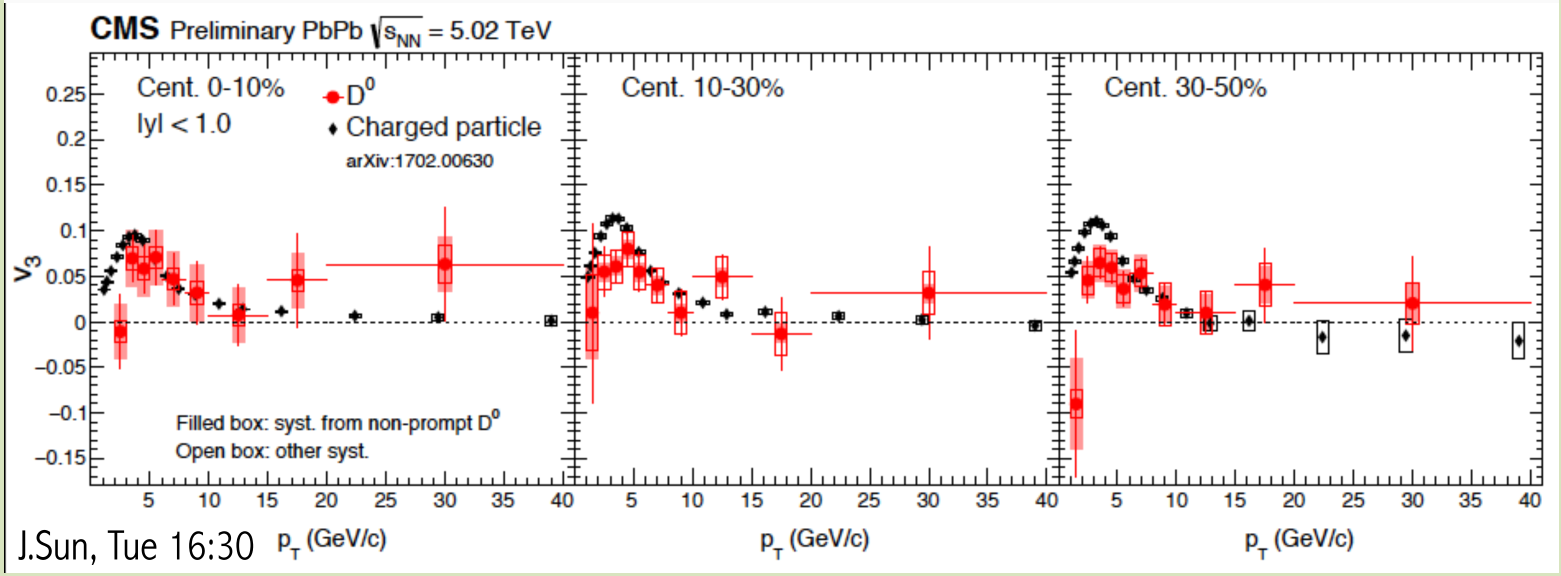
V_3 with e-b-e hydro bulk

SUBATECH-Nantes [MC@sNLO] M. Nahrgang et al., PRC91(2015)





J.Sun, Tue 16:30

Will v_3 constraint more Ds, hadronization, incomplete coupling to medium…?

Linearized Boltzmann: Coll.+Rad.

S. Cao, Tue 18:10

Linearized Boltzmann Transport : Rad.(pQCD) + Coll. E_{loss}

Inelastic Scatt. probability based on the average number of medium-induced gluon

Spectrum of medium-induced gluon (Higher-Twist formalism):

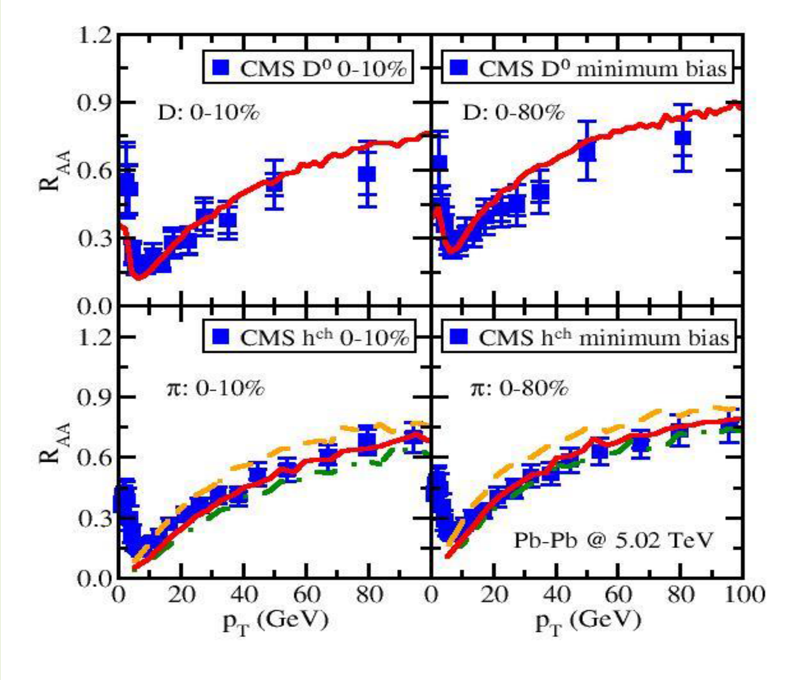
$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4}\hat{q}\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4 \sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

[Guo- Wang (2000), Majumder (2012); Zhang, Wang-Wang (2004)]

Number n of radiated gluons during Δt – Poisson distribution:

$$P(n) = \frac{\langle N_g\rangle^n}{n!}e^{-\langle N_g\rangle} \qquad P_{\text{inel}} = 1 - e^{-\langle N_g\rangle}$$

[S.Cao, Luo, Qin and Wang, arXiv: 1605.06447]



Strong points:

- ✧ Both heavy and light
- ✧ Both radiative and collisional
- ✧ Realistic hydro background

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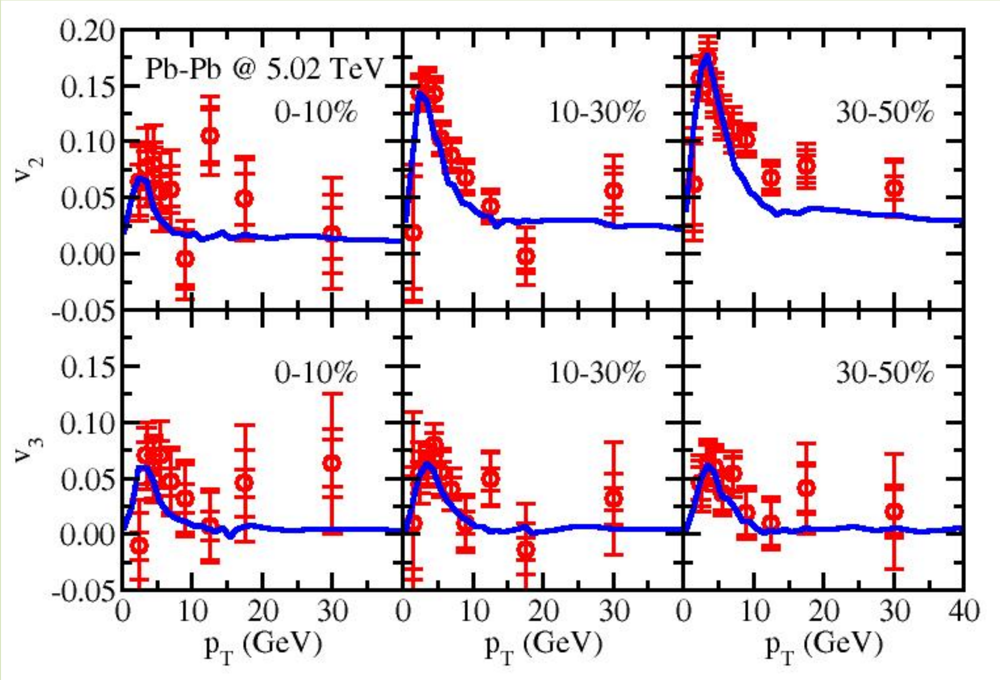

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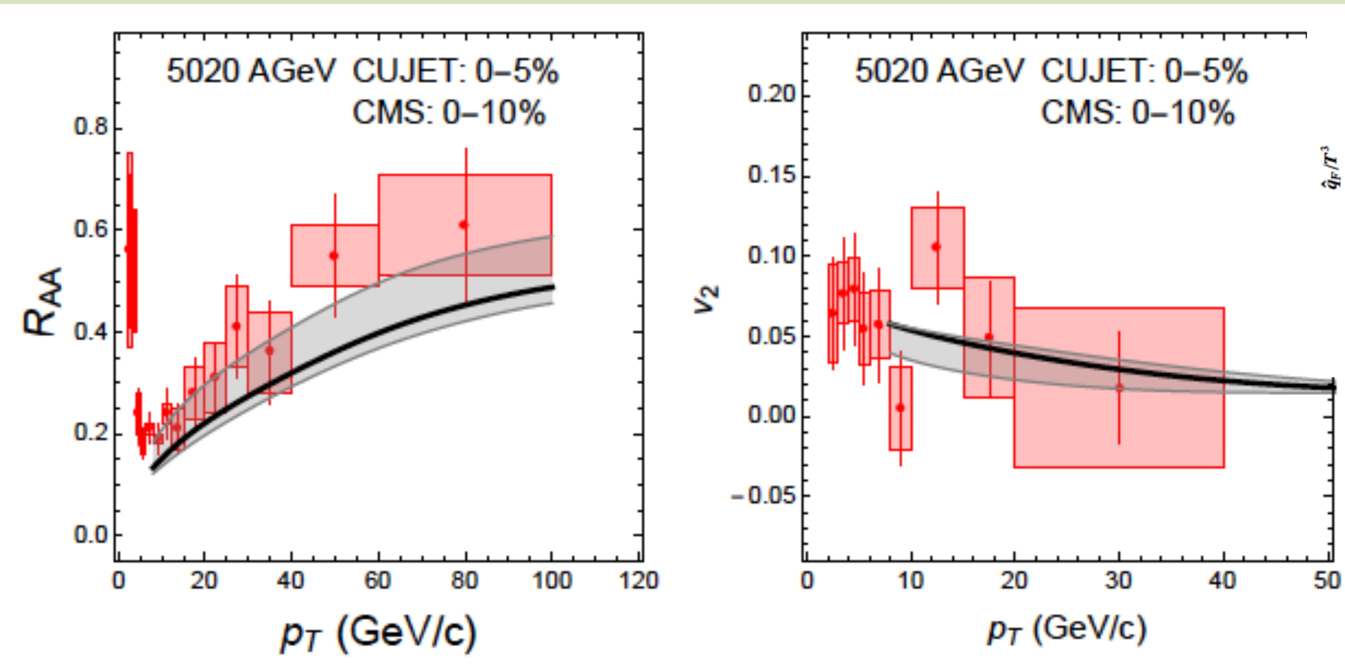
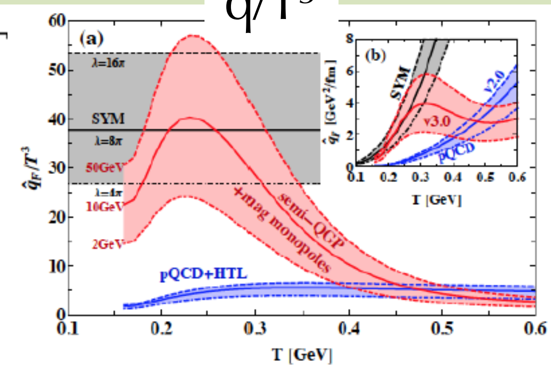
CUJET3.0 on HF [high p_T]

CUJET3.0: a simulation framework based on a microscopic picture of Semi-quark-gluon **monopole plasma**. E_{loss} from DGLV plus magnetic mass effect. Implement **non-pQCD physics near T_C** due to monopoles



q/T^3



First predictions on HF (independent test) with no parameter calibration within error bars nice description of R_{AA} and V_2 at high p_T.

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

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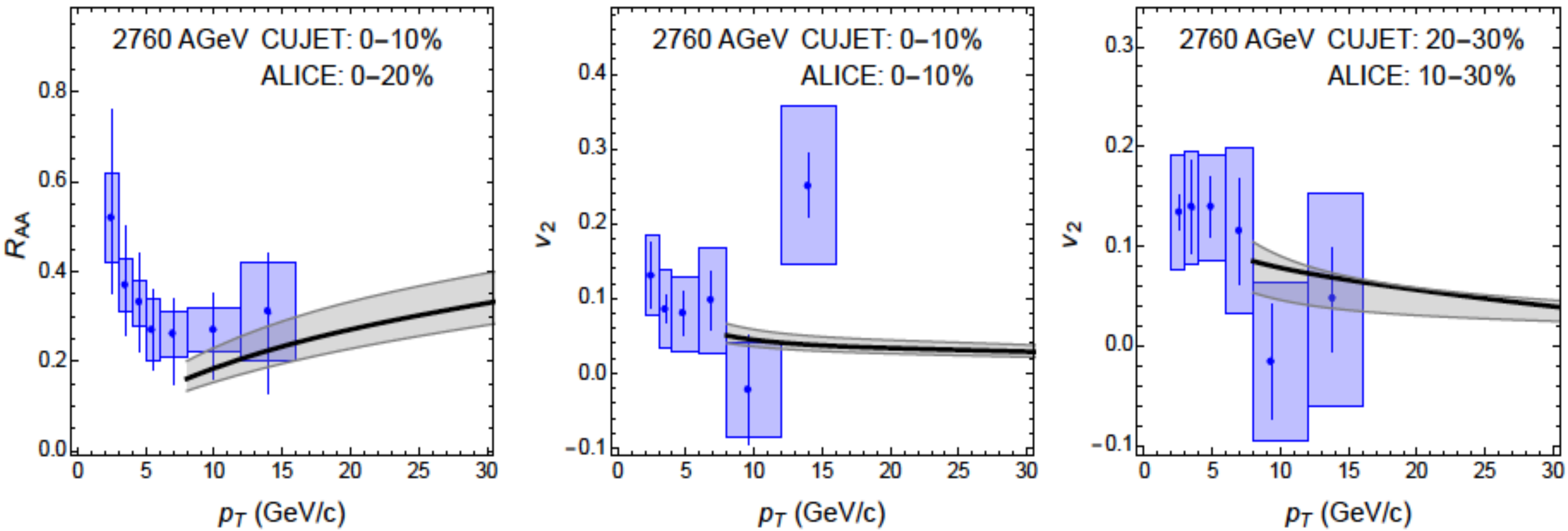

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Open HQ in soft-collinear effective theory

✧ A new **effective theory [power counting in p_T/Q]** derived that describes the propagation of HQ in a background QCD medium – $\mathrm{SCET}_{M,G}$

Z. Kang et al. ArXiv: 1610.02043, JHEP submitted

✧ Role of mass understood in the vacuum and the medium to 1st order in opacity beyond the soft gluon approximation, but reduce to GLV in that limit

Massive splitting function with dead cone

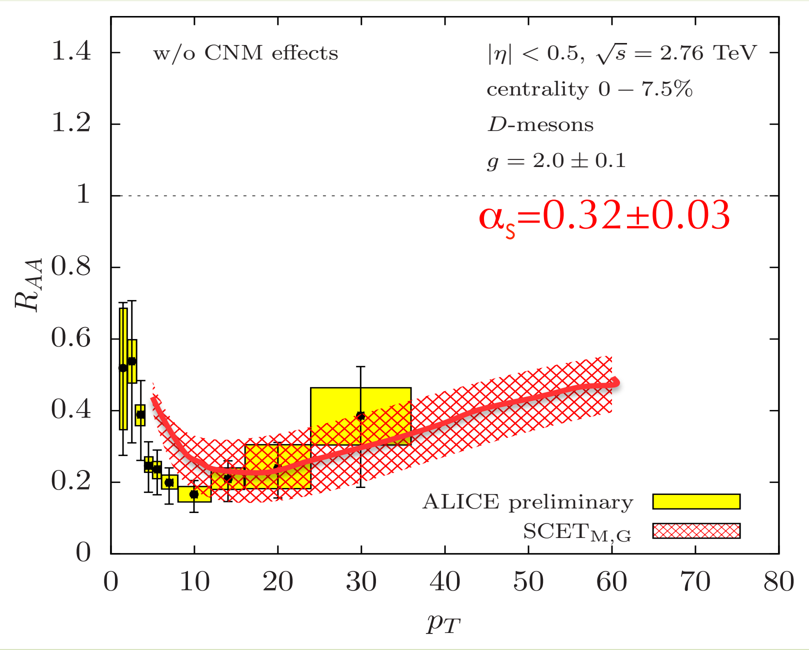
$$\left(\frac{dN}{dx\,d^2k_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2}\frac{1}{k_\perp^2+x^2m^2}\left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{k_\perp^2+x^2m^2}\right]$$

Consistent full NLO calculation

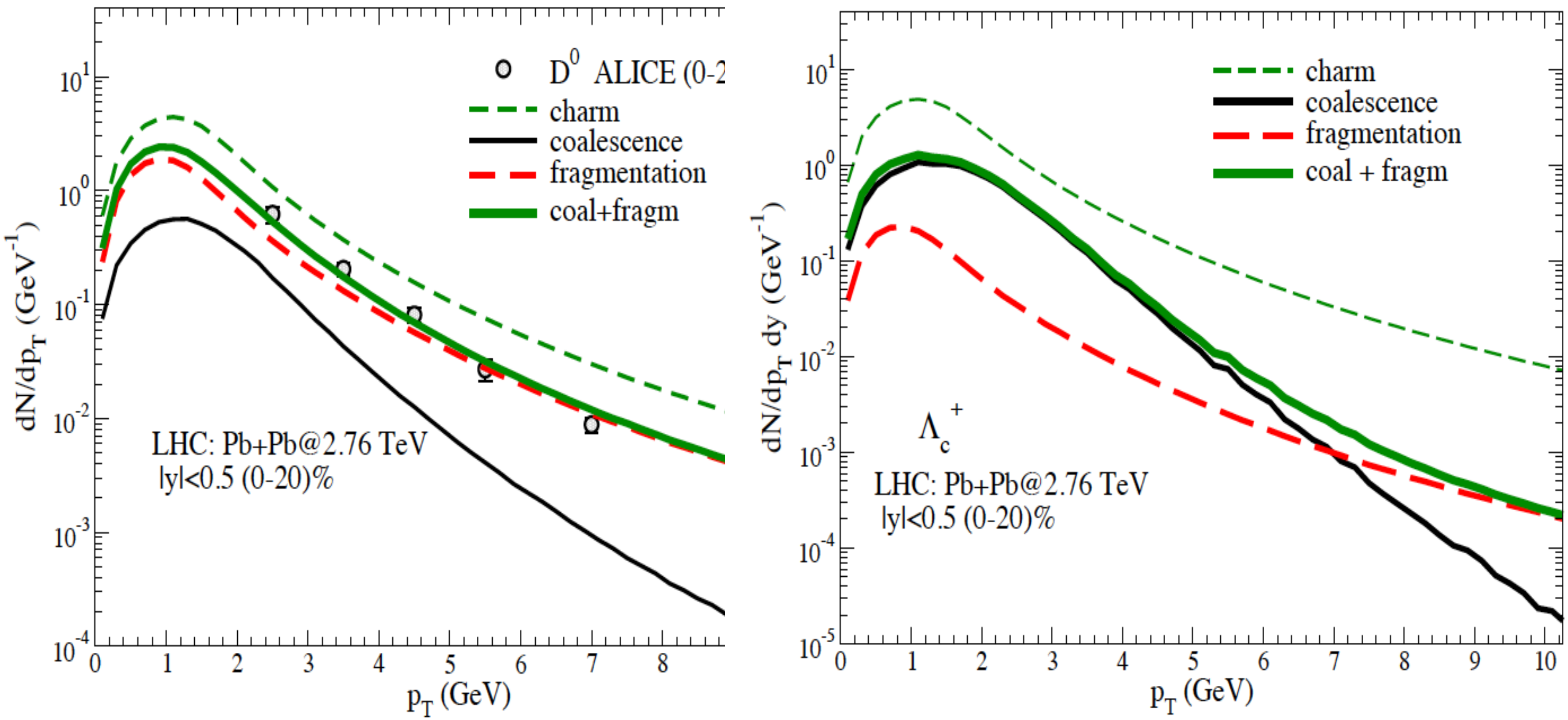
$$d\sigma^H_{\mathrm{PbPb}} = d\sigma^{H,\mathrm{NLO}}_{pp} + d\sigma^{H,\mathrm{med}}_{\mathrm{PbPb}}$$

$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}^{\mathrm{med}}_{i\to jk}\otimes D^H_j \equiv \hat{\sigma}_i^{(0)}\otimes D_i^{H,\mathrm{med}}$$

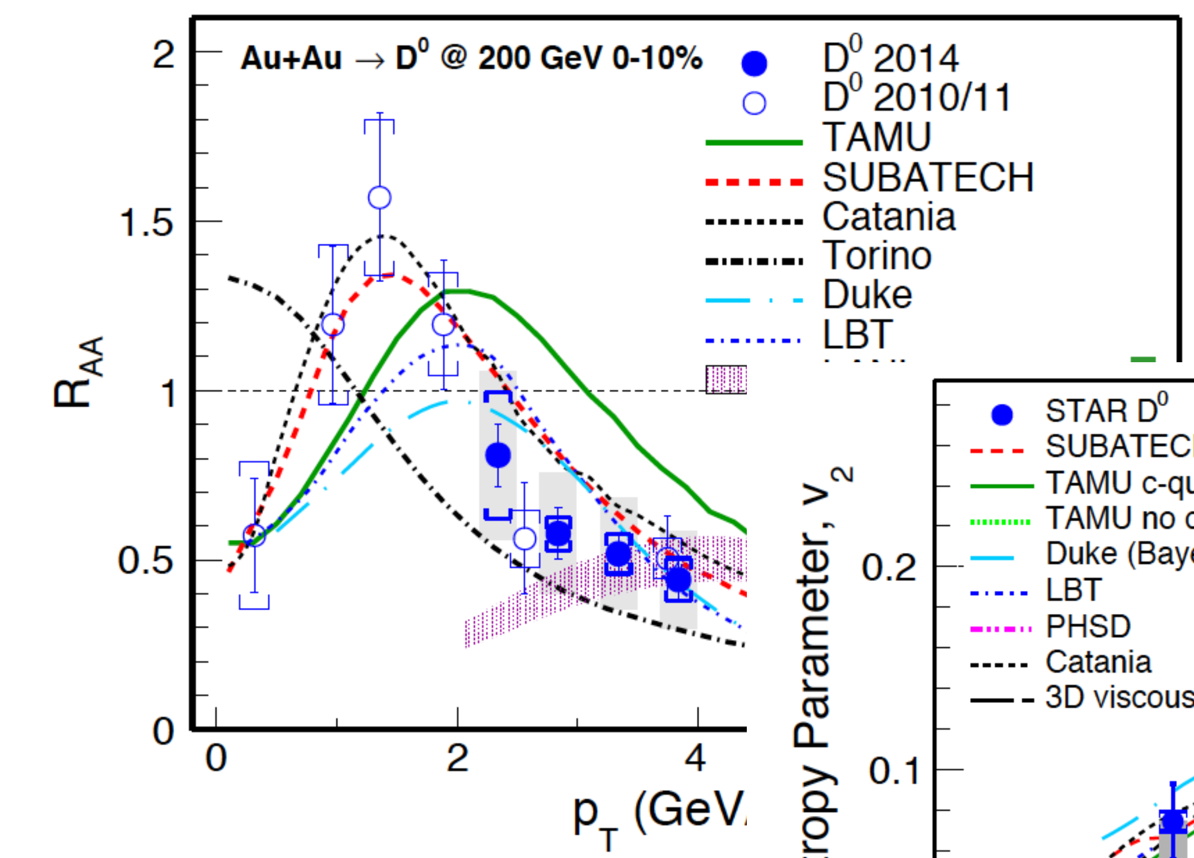
Gluon fragmentation plays an important role in the lower p_T range R. Sharma et al. PRC (2009)



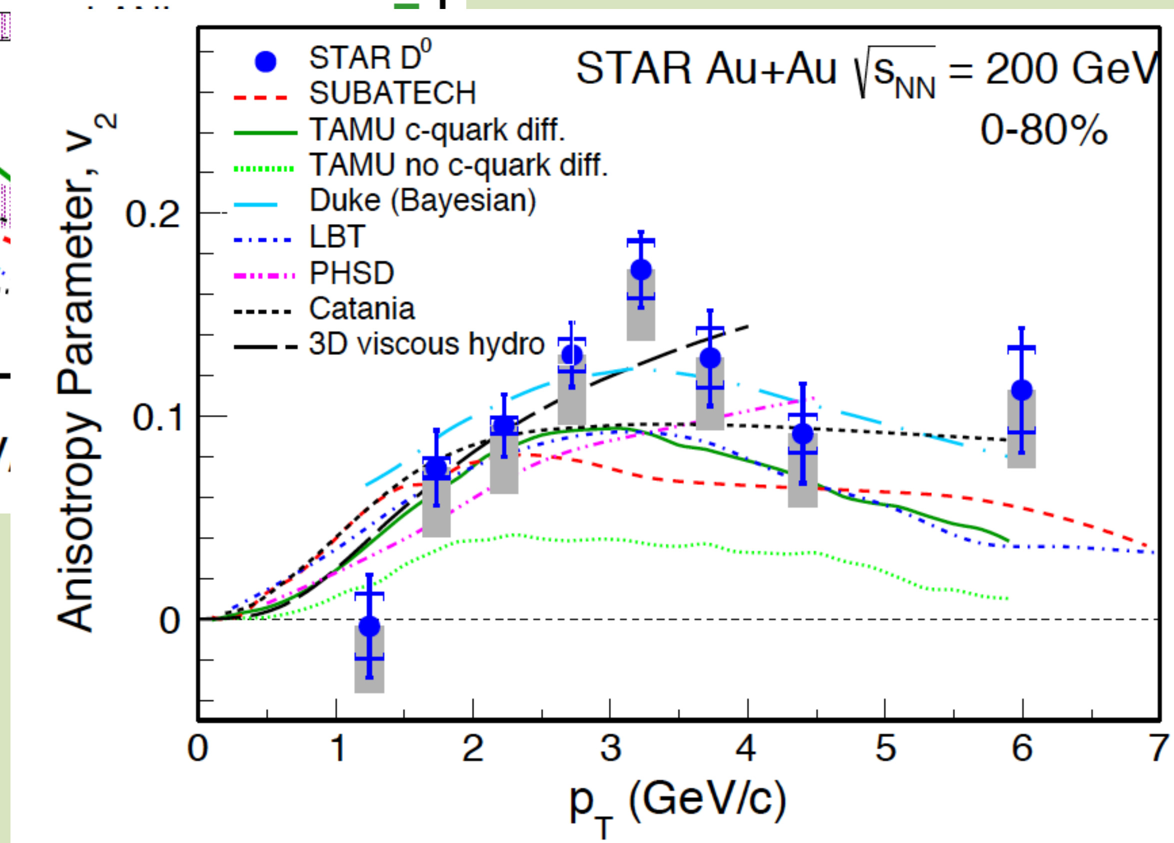
At lower p_T including collisional **Dissociation** of D meson ($\tau_D=\tau_0 * E/m_D$)



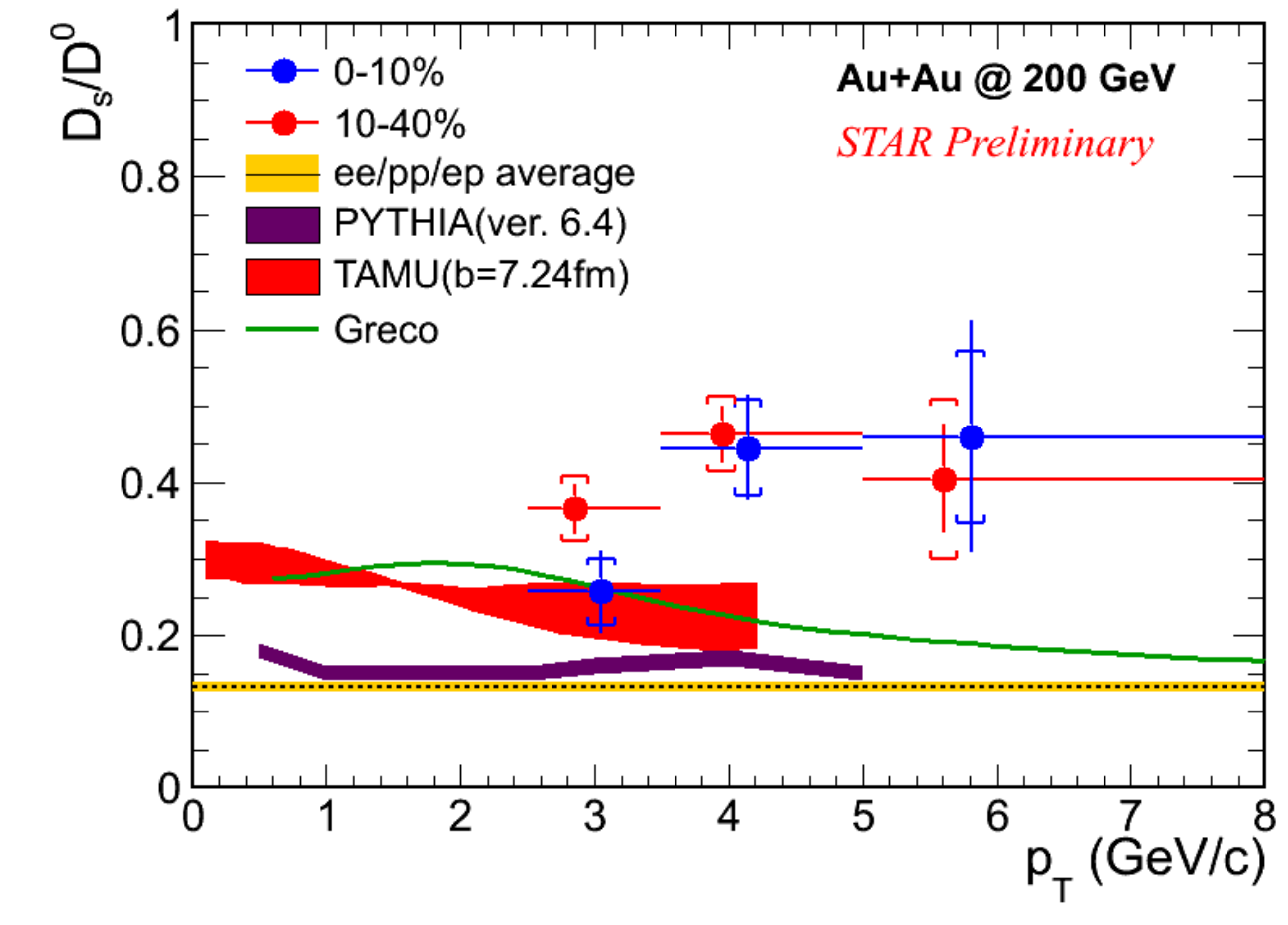
S. Plumari et al,ArXiv:1712.****



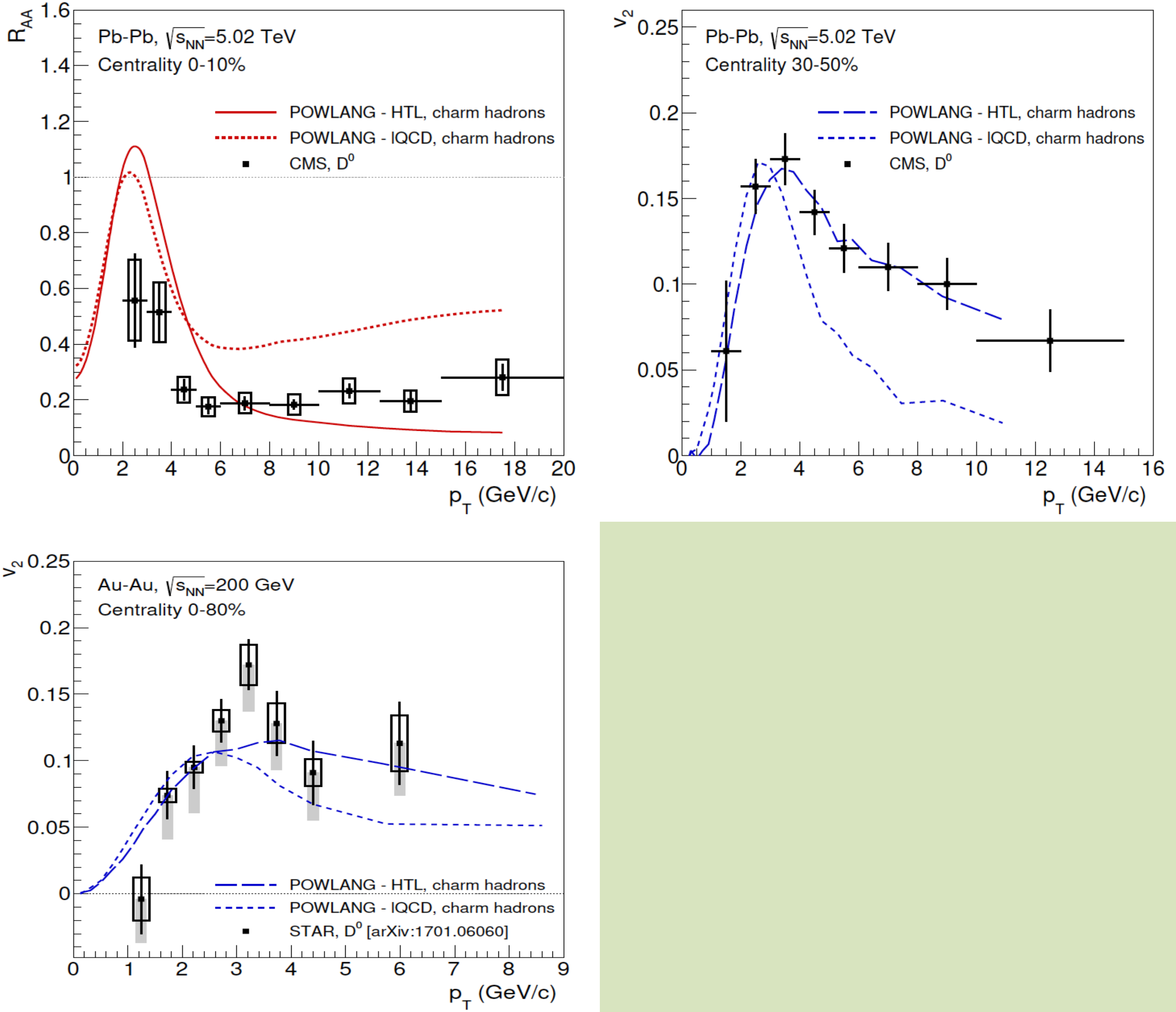
Au+Au → D⁰ @ 200 GeV 0-10%
D⁰ 2014
D⁰ 2010/11
TAMU
SUBATECH
Catania
Torino
Duke
LBT
R_AA
p_T (GeV



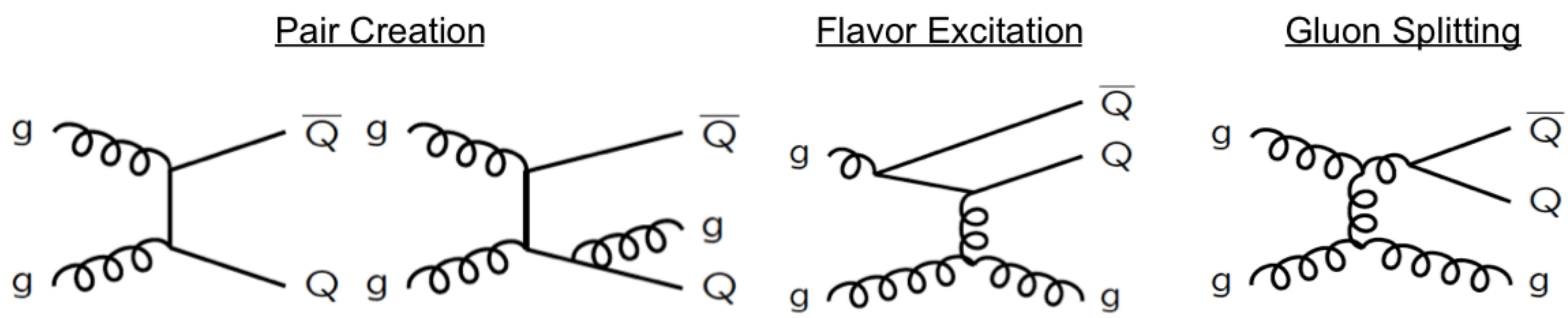
STAR Au+Au √s_NN = 200 GeV
0-80%
STAR D⁰
SUBATECH
TAMU c-quark diff.
TAMU no c-quark diff.
Duke (Bayesian)
LBT
PHSD
Catania
3D viscous hydro
Anisotropy Parameter, v_2
p_T (GeV/c)

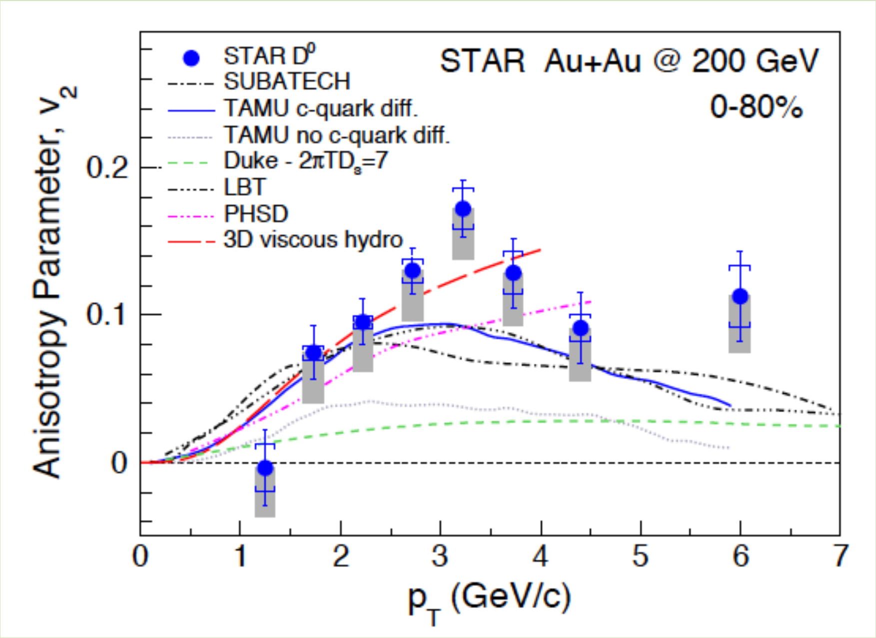


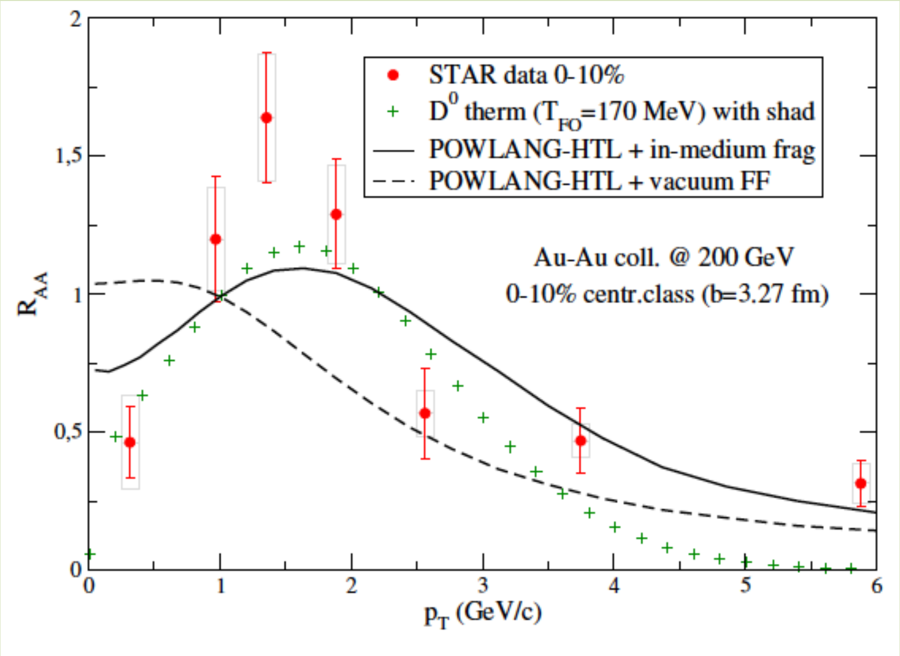
D_s/D^0
0-10%
10-40%
ee/pp/ep average
PYTHIA(ver. 6.4)
TAMU(b=7.24fm)
Greco
Au+Au @ 200 GeV
STAR Preliminary
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
6
7
8
p_T (GeV/c)



Pb-Pb, $\sqrt{s_{NN}}$=5.02 TeV
Centrality 0-10%
POWLANG - HTL, charm hadrons
POWLANG - lQCD, charm hadrons
CMS, D^0
R_{AA}
p_T (GeV/c)
Pb-Pb, $\sqrt{s_{NN}}$=5.02 TeV
Centrality 30-50%
POWLANG - HTL, charm hadrons
POWLANG - lQCD, charm hadrons
CMS, D^0
v_2
p_T (GeV/c)
Au-Au, $\sqrt{s_{NN}}$=200 GeV
Centrality 0-80%
POWLANG - HTL, charm hadrons
POWLANG - lQCD, charm hadrons
STAR, D^0 [arXiv:1701.06060]
v_2
p_T (GeV/c)


Pair Creation
Flavor Excitation
Gluon Splitting
g
$\overline{Q}$
Q





- Centrality bias
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