First results of EPOS-HQ model for open heavy flavor production in AA at RHIC and LHC

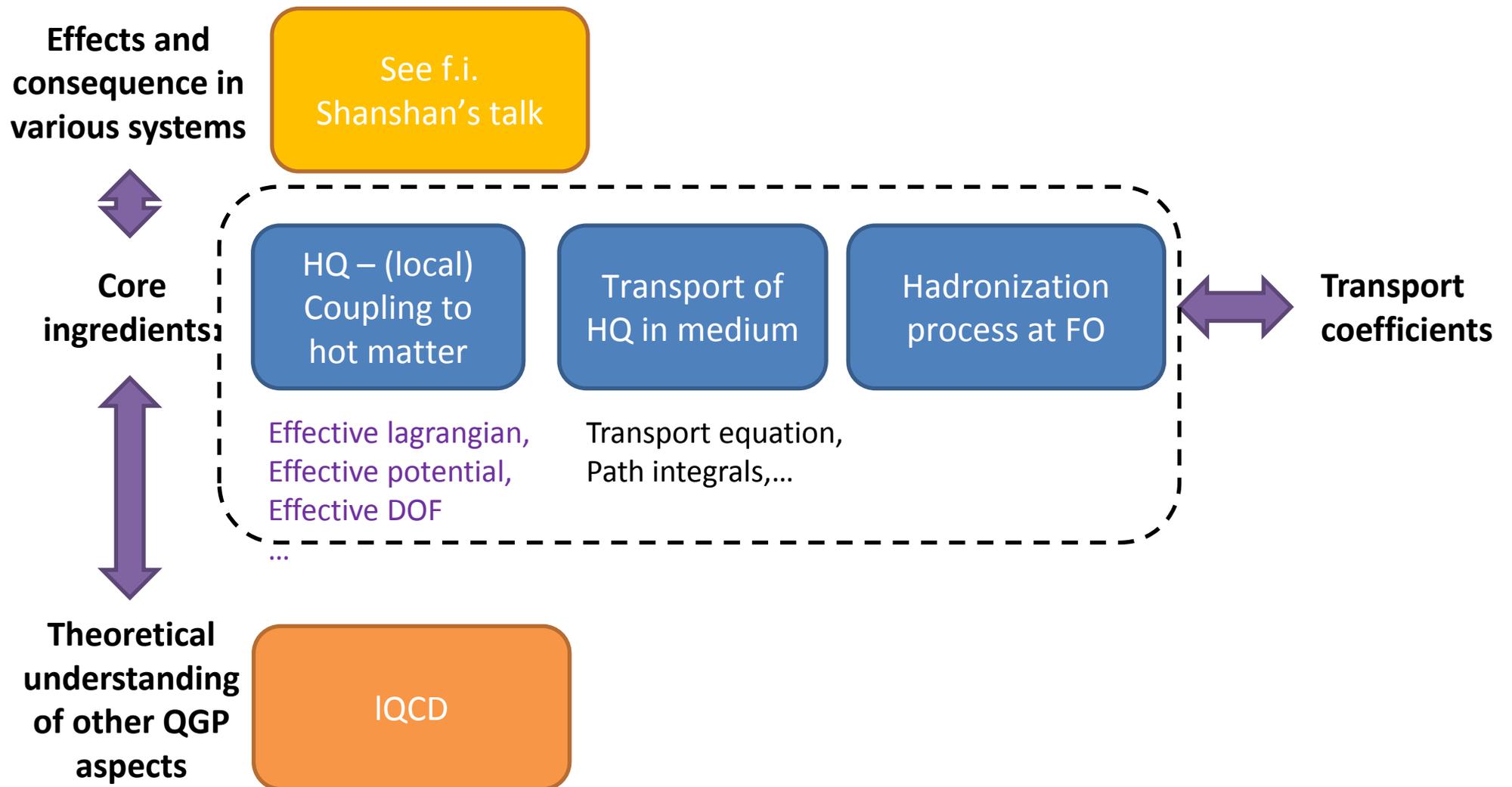Hard Probes 2018

Aix Les Bains (France)

P.B. Gossiaux

SUBATECH, UMR 6457
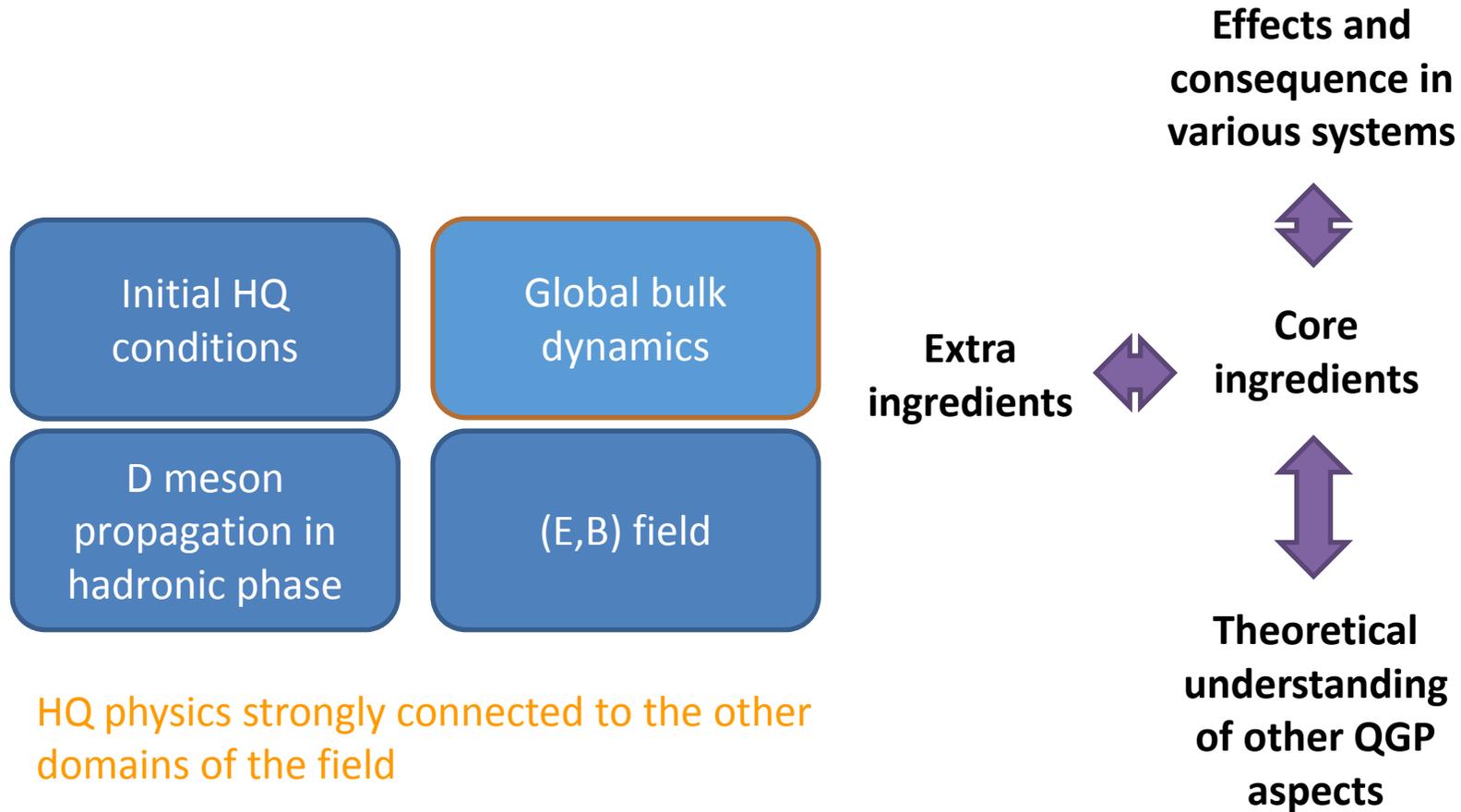Université de Nantes, IMT Atlantique, IN2P3/CNRS

with

J. Aichelin, B. Guiot, I Karpenko, A. Mischke, M. Nahrgang, V. Ozvenchuk, T. Pierrog, L. Vermunt & K. Werner

One model, several components

Effects and consequence in various systems

See f.i. Shanshan's talk

Core ingredients:

HQ – (local) Coupling to hot matter

Transport of HQ in medium

Hadronization process at FO

Transport coefficients

Effective lagrangian, Effective potential, Effective DOF …

Transport equation, Path integrals,…

Theoretical understanding of other QGP aspects

lQCD

One model, several components

HQ physics strongly connected to the other domains of the field
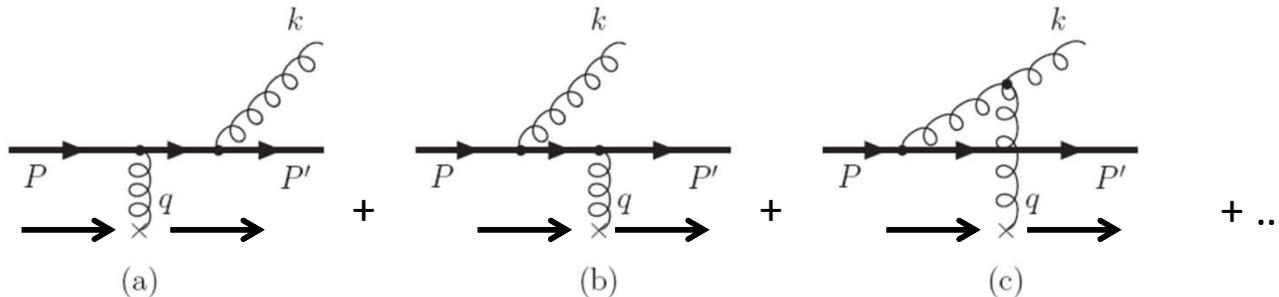
The core energy loss

Colisional component

- One-gluon exchange model: reduced IR regulator $\lambda\, m^2_D$ in the hard propagator, fixed on HTL Energy loss
- Running coupling $\alpha_{eff}\,(t)$ and self consistent Debye mass

$$m_{Dself}^2\,(T) = (1+n_f/6)\ 4\pi\alpha_{eff}(m_{Dself}^2)T^2$$
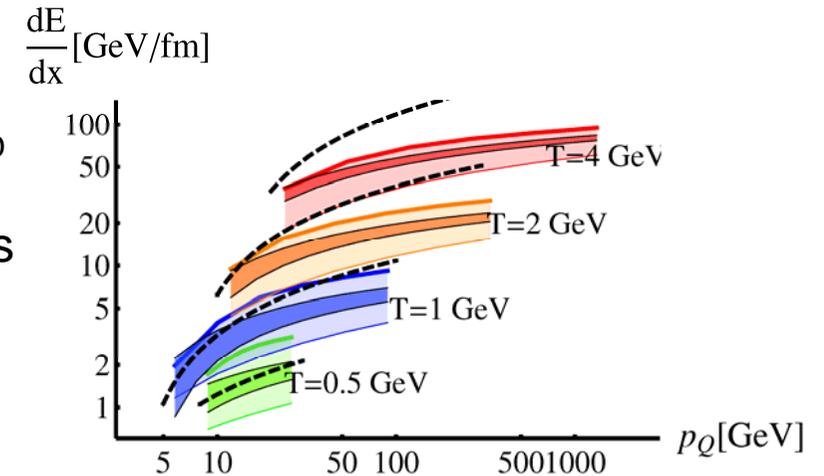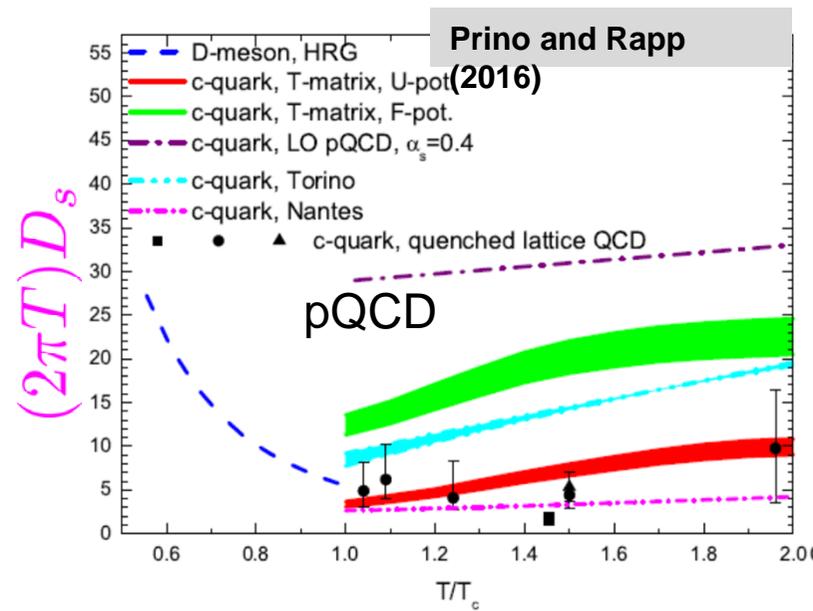

Radiative component

- Extention of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision ($\Delta E_{rad}\ \alpha\ E\ L$):

$$P_g(x, \mathbf{k}_\perp, \mathbf{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2 + xm_Q^2} - \frac{\mathbf{k}_\perp - \mathbf{q}_\perp}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + xm_Q^2}\right)^2$$

- LPM effect for moderate gluon energy

- One extra K factor affecting the cross sections to be fitted on exp results

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The core energy loss

Prino and Rapp (2016)

$$\tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{m_Q}{2\pi T^2}$$

- One of the strongest coupling on the « market »

The « extra » ingredients

- 2 main « bundles »

| Ingredient	B1 (2008)	B2 ⇔ MC@$_s$HQ+EPOS2 (2013)
hydro	Kolb Heinz	vHLLE (0 viscosity)
Init cond (soft)	Glauber	EPOS
Init state fluctuations	No	Yes
hadronization	Covar. Inst. Coal + frag	Same
HQ production	FONLL (p) + Glauber (space)	FONLL (p) + EPOS (space): position of NN interactions
CNM	No shadowing, initial k_T broad.	EPS09
Hadronic interaction	None	None

- Same E loss model in the 2 bundles

The « extra » ingredients

- B1: used for RHIC only, latest used to « predict » the e<-b fraction in Au-Au
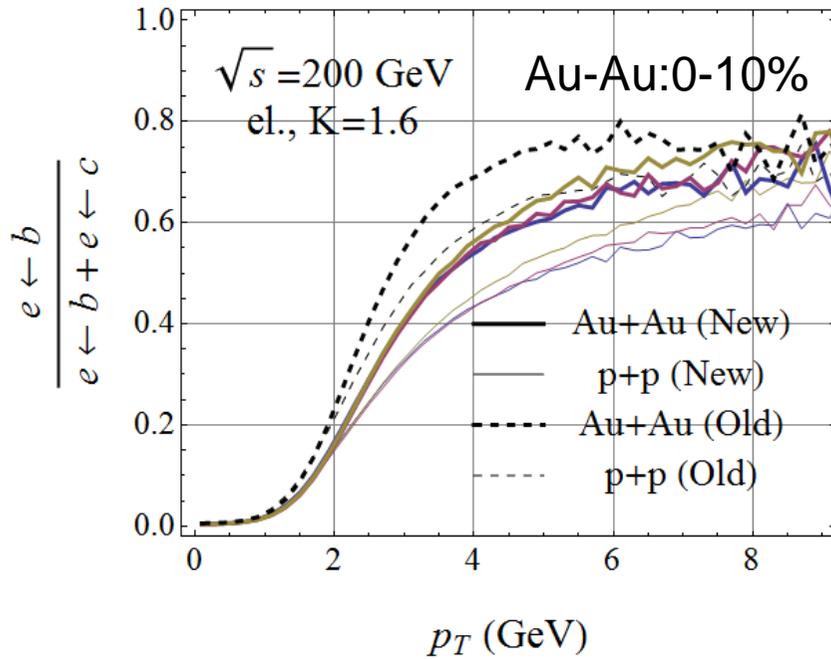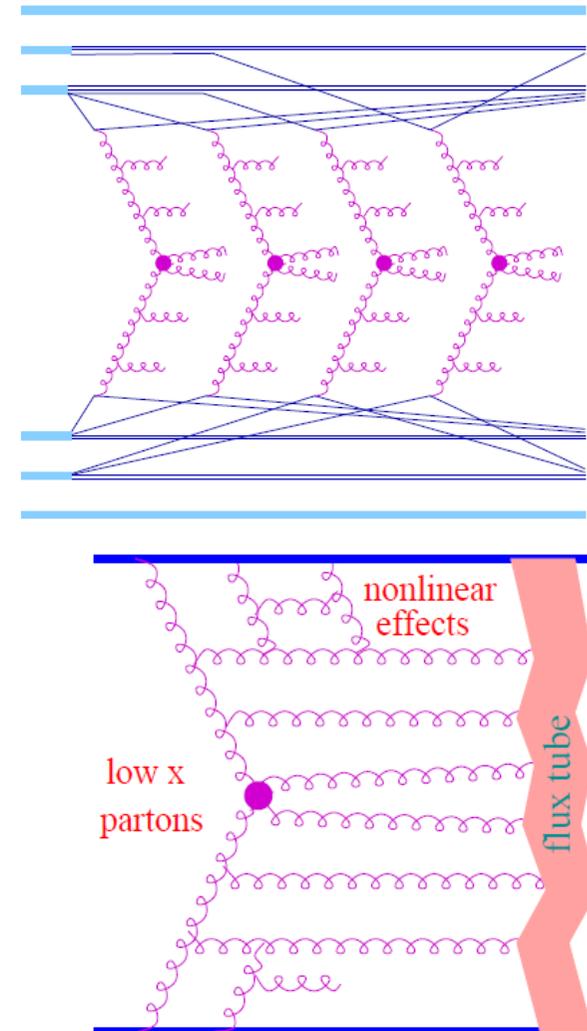

Talk Timothy Rinn
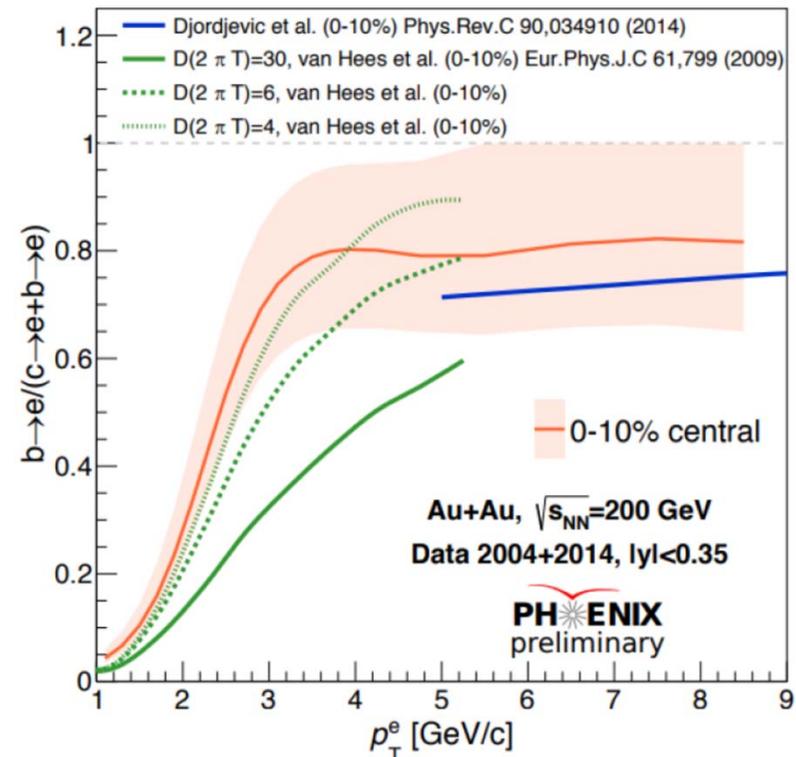
EPOS + Hydro as a background for MC@sHQ

EPOS + Hydro : state of the art framework that encompass pp, pA and AA collisions

EPOS (initial conditions):

- Model based on Gribov-Regge multiple pomeron interactions

- Particle production (including HQ) in cut (semi-hard) pomerons, seen as partons ladder

- Soft particles form a flux tube (string, with its own dynamics, incl. string breaking)… lots of them in A-A

- Slow string segments, far from the surface, are mapped to fluid dynamic fields (-> hydro -> Freeze out)
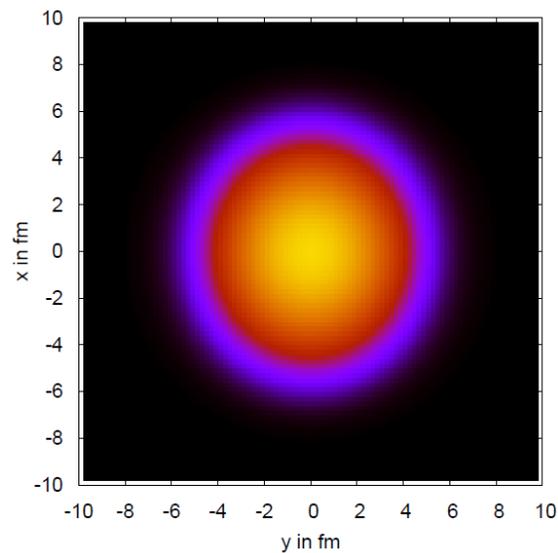
- Hard particles -> jets

Ref: K. Werner, Iu. Karpenko, M. Bleicher, T. Pierog, and S. Porteboeuf-Houssais Phys. Rev. C 85 (2012), 064907
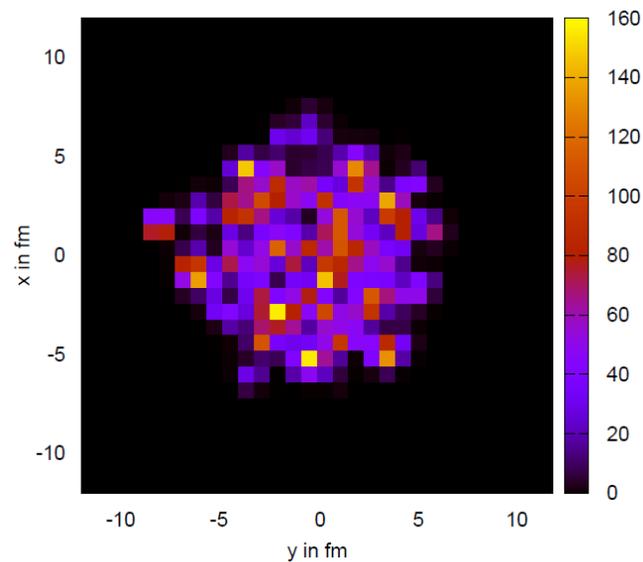

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EPOS + hydro as a background for MC@sHQ

EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density

Beware: ≠ color scales

Kolb Heinz (used previously)   EPOS

More realistic hydro and initial conditions => original HQ studies such as:

 1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)

2) correlations between HF and light hadrons

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Bundle 2

- B2: mainly used for LHC predictions (see f.i. Sapore Gravis Report Eur. Phys. J. C (2016) 76:107), with good agreement up to p_T= 20 GeV (ok, not designed for high p_T)

- Although EI + Rad sounds the most natural, we also try pure « Elastic » energy loss, sometimes with better sucess…

Bundle 2 @ LHC
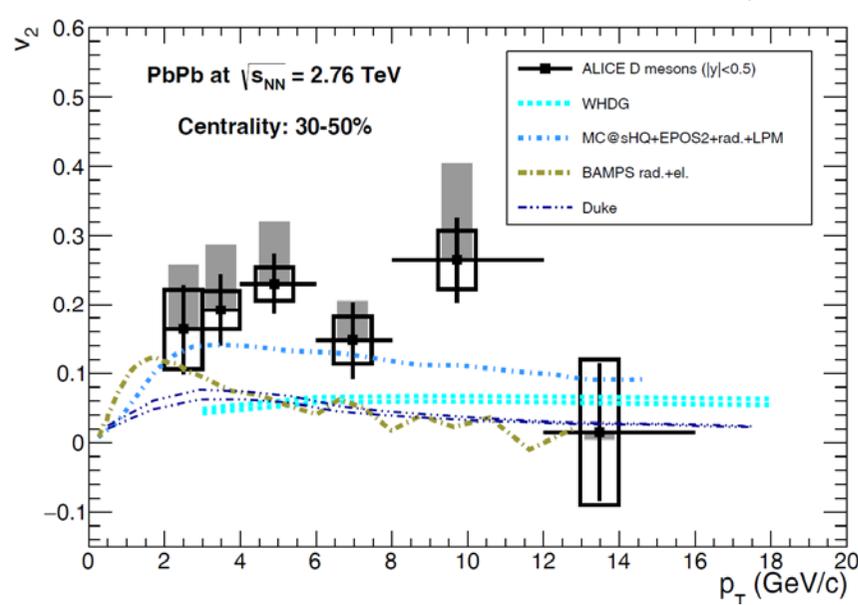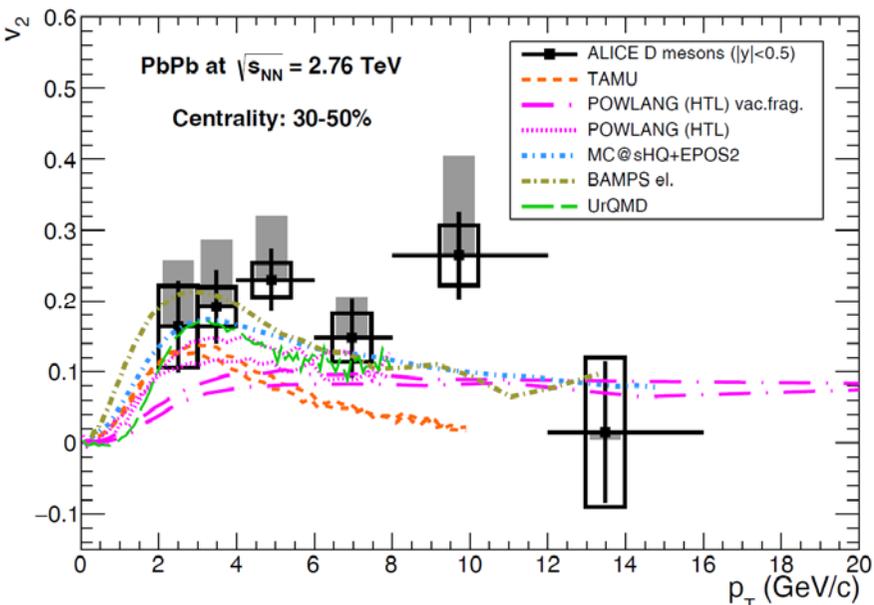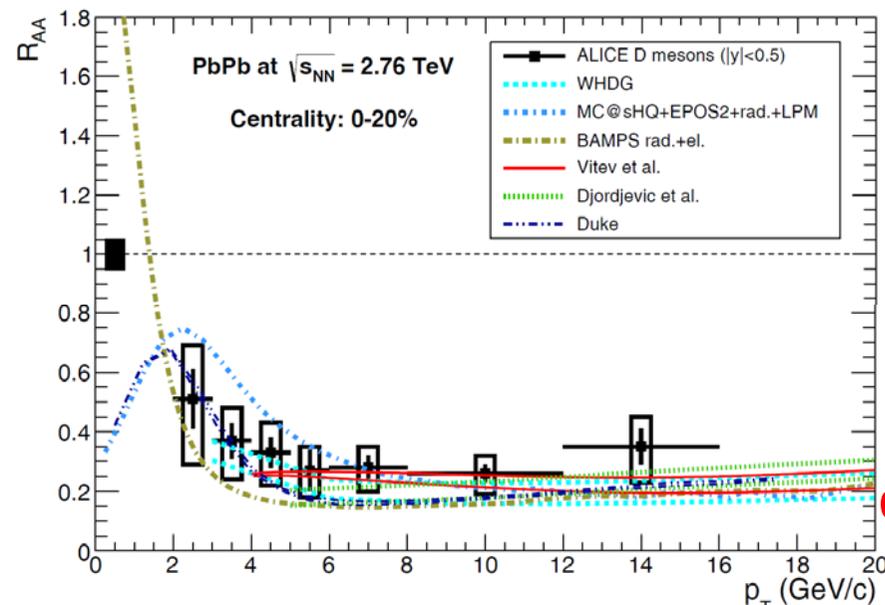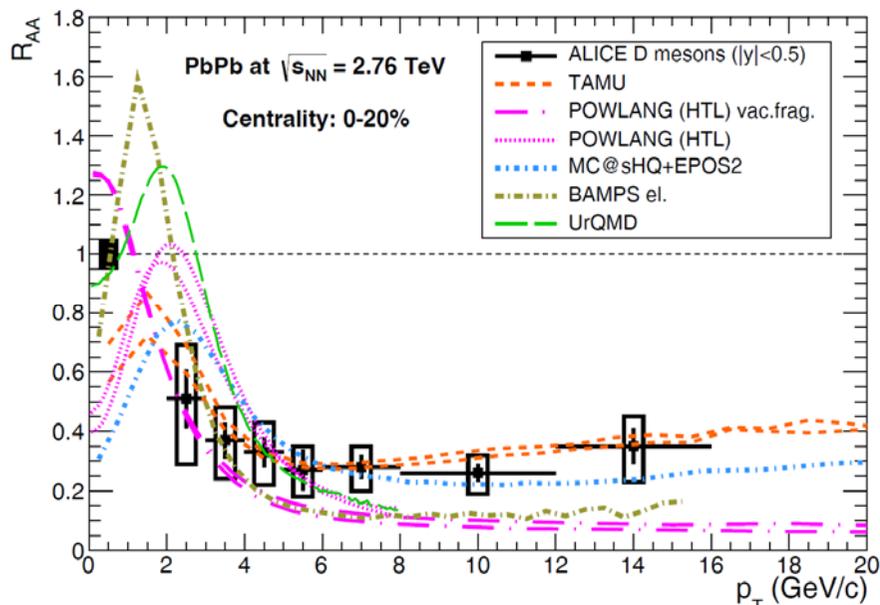
Bundle 2 @ RHIC

Nahrgang et al, QM 2014
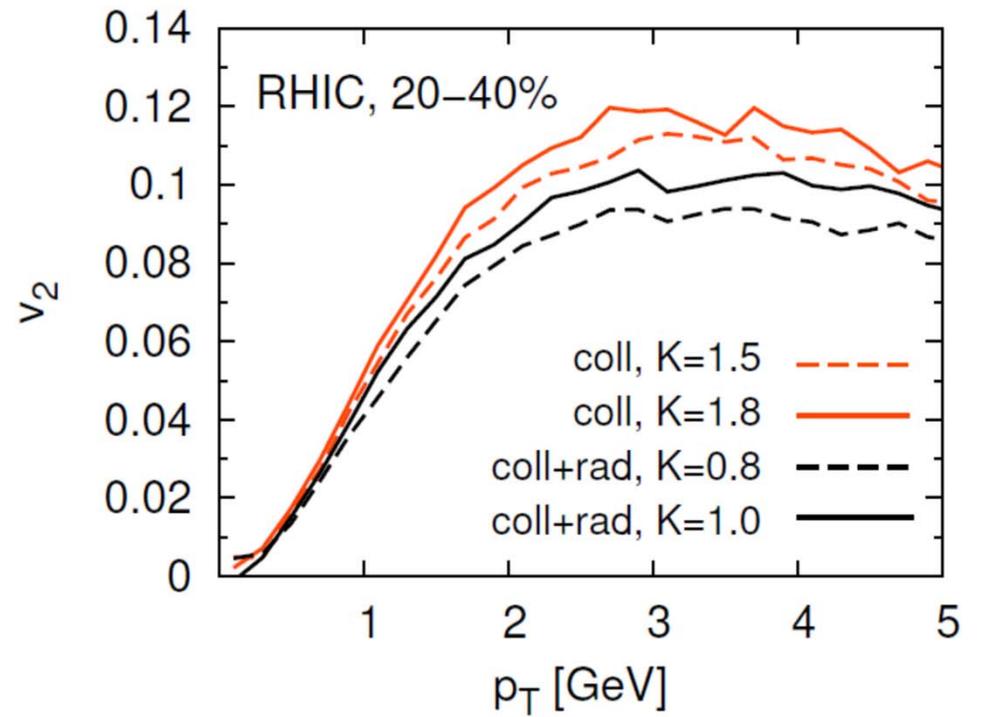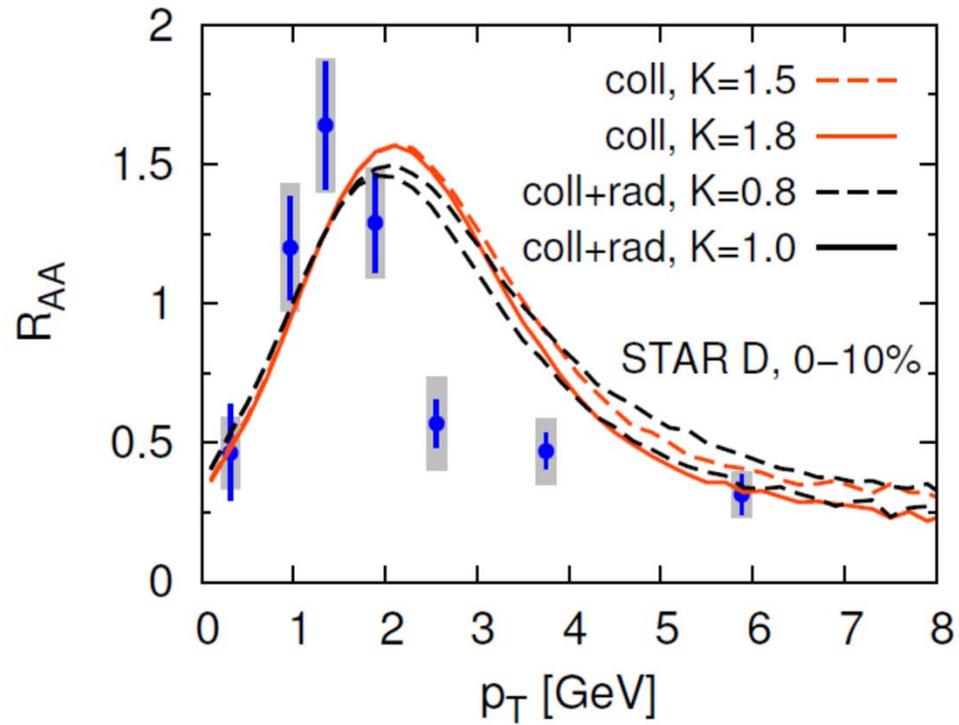
- Obvious tension with the data. Extra radial flow ?

Summary

	RHIC	LHC
B1	"ok"	Not applied
B2	disagree	"ok"
B2' (viscous hydro) while building B3	"ok"	Not applied

Not satisfactory !!!

Motivation for the new bundle

Bundle 3: EPOS(3)-HQ

Ingredient	B1	B2 (MC@$_s$HQ+EPOS2)	B3 (EPOS-HQ)
hydro	Kolb Heinz	vHLLE (0 viscosity)	Viscous vHLLE
Init cond (soft)	Glauber	EPOS	EPOS
Init state fluctuations	No	Yes	Yes
hadronization	Covar. Inst. Coal + frag	Same	Same
HQ production	FONLL (p) + Glauber (space)	FONLL (p) + EPOS (space): position of NN interactions	EPOS3
CNM	No shadowing, initial k_T broad.	EPS09	EPOS3
Hadronic interaction	None	None	URQMD

No modification of the ELOSS model

Illustrating EPOS3 vs data for light hadrons
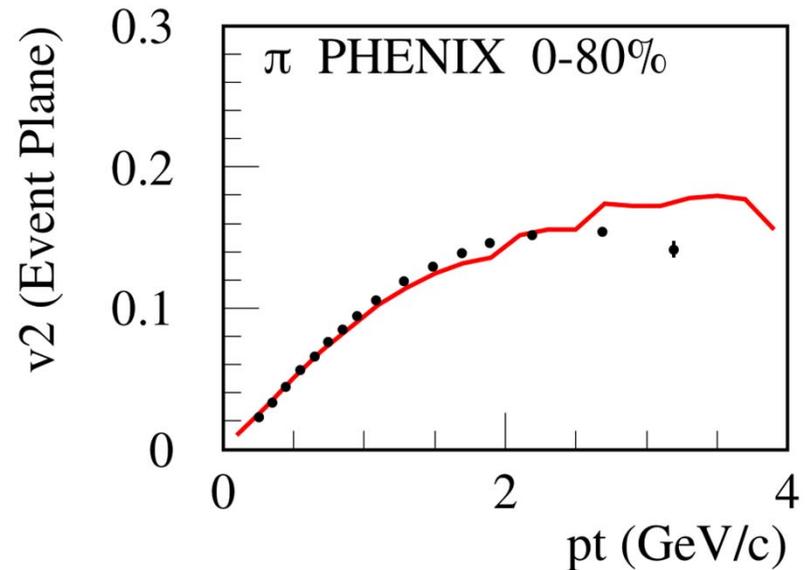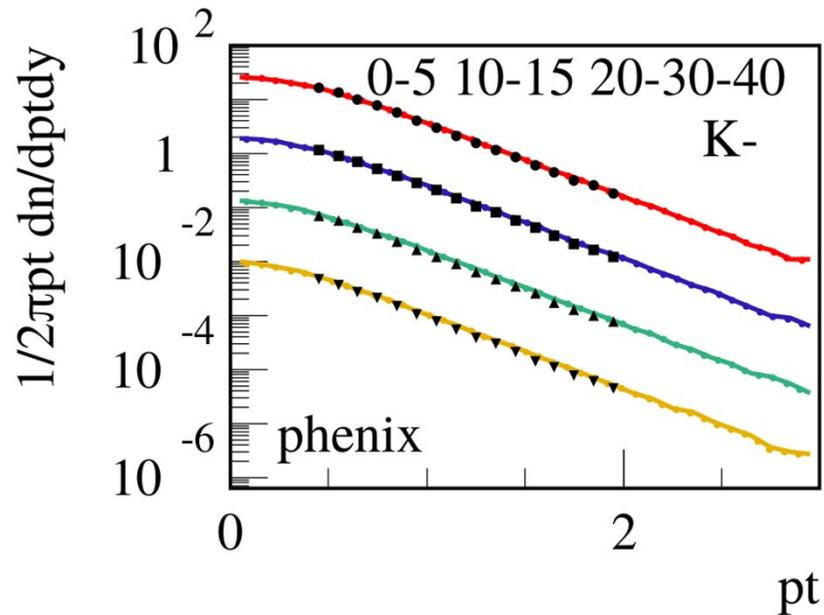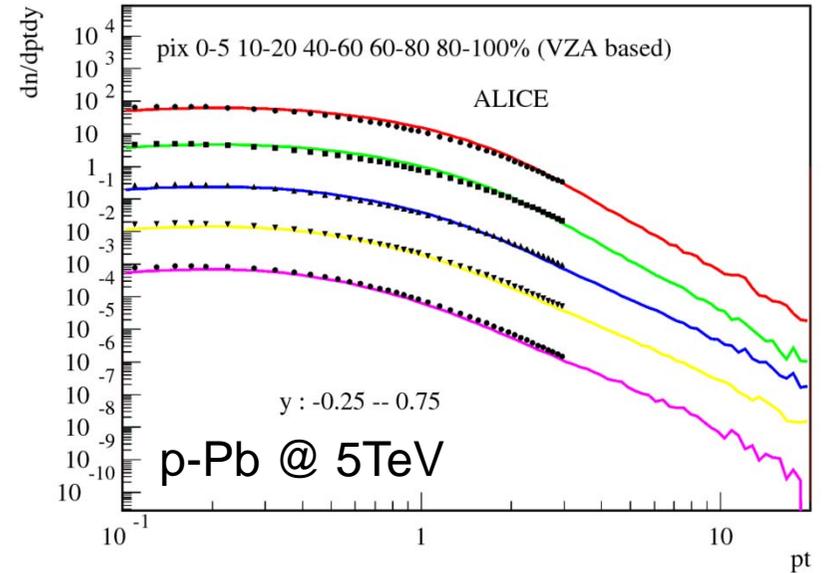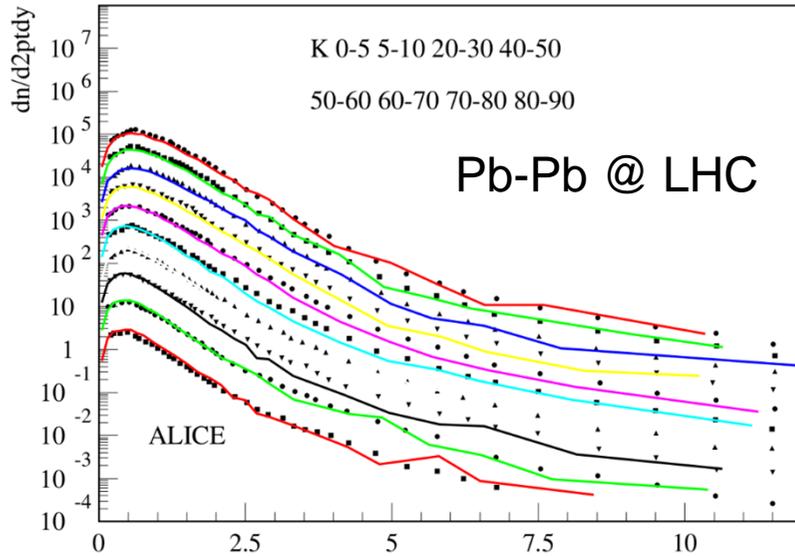
HQ production in EPOS3

(B. Guiot PhD thesis)
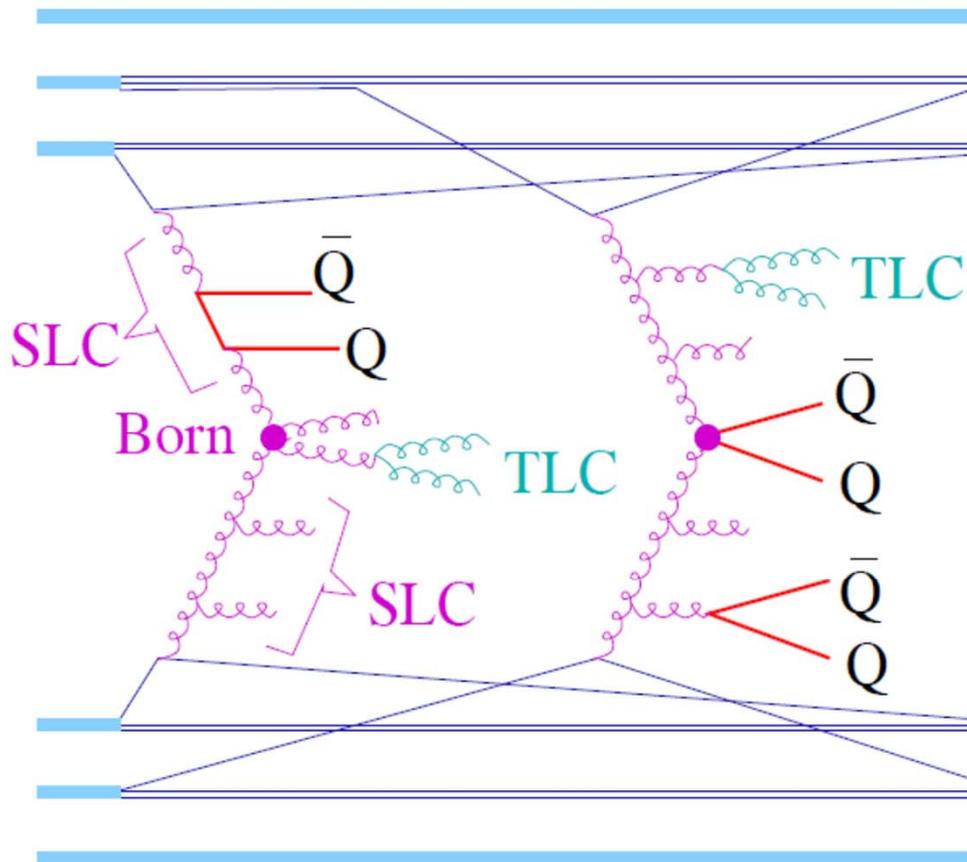
as light quark production

In any of the ladders

- ☐ **during SLC** (space-like cascade)
- ☐ **during TLC** (time-like cascade)
- ☐ **in Born**

but m_Q non-zero

$(m_c = 1.3, \; m_b = 4.2)$

non-zero m_Q affects matrix elements and kinematics in parton splitting processes

Saturation effects taken into account by introducing a regulator in the DGLAP integrals:

$$Q_s = Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$$

(Diagram labels: $\bar{Q}$, Q, SLC, Born, TLC, $\bar{Q}$, Q, SLC, TLC, $\bar{Q}$, Q, $\bar{Q}$, Q)

Lessons from EMMI RRTF

We define and display the H_{AA} quantity

$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ final}}{dp_T}}$$

...which exhibits at best the specific effects of hadronization :

Significant uncertainties !

Nantes approach is the one leading to the stronger « extra push » from the bulk at coalesence.

R. Rapp et al, arXiv: 1803.03824

Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV, 0-10%

UrQMD
TAMU
Nantes
Catania
LBL-CCNU
CUJET
Duke Langevin
POWLANG
PHSD

p_T (GeV)

Recombination   Fragmentation
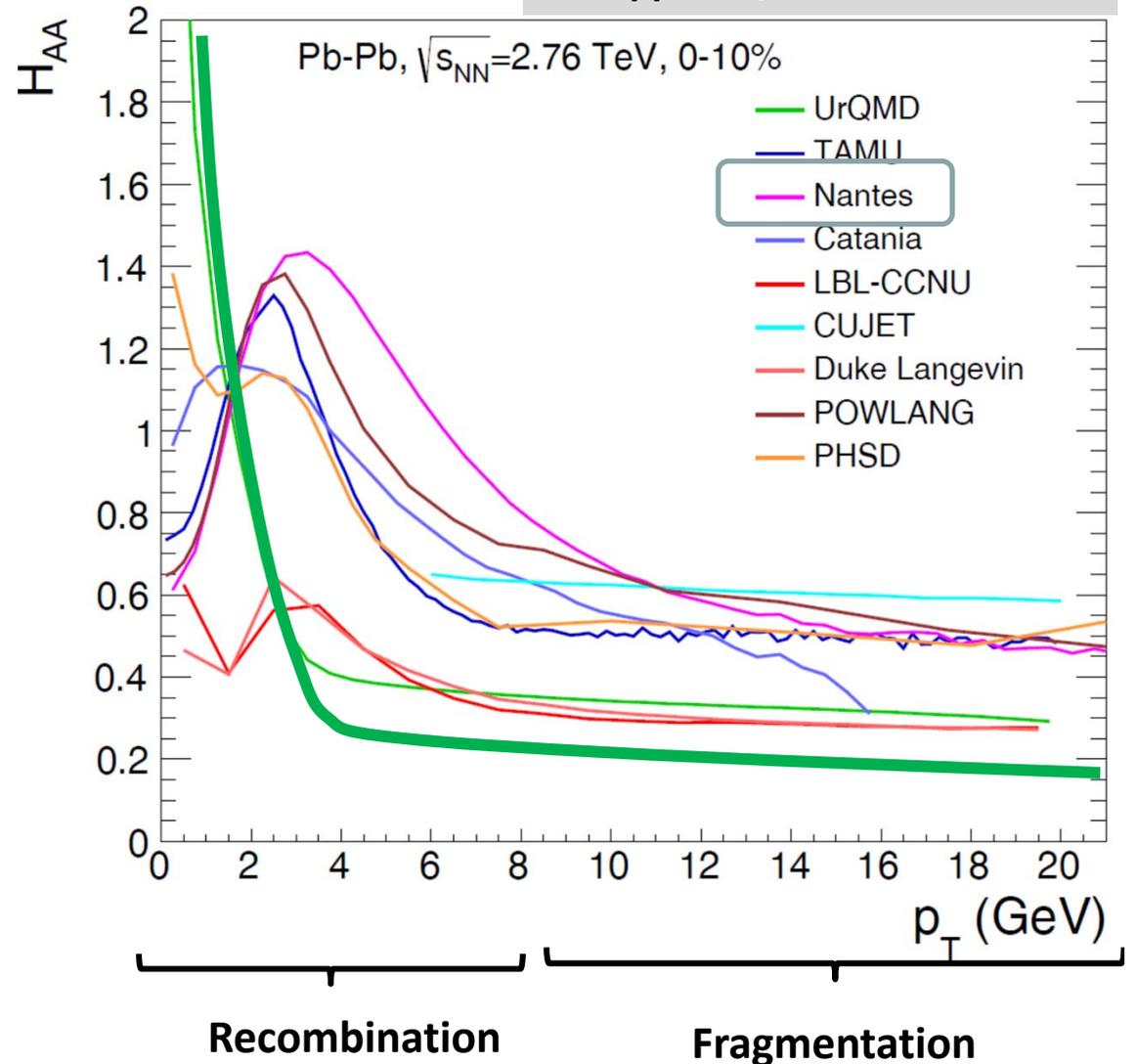
Same interaction for all of them !!!

EPOS-HQ (B3)

Ingredient	B1	B2 (MC@$_s$HQ+EPOS2)	B3 (EPOS-HQ)
hydro	Kolb Heinz	vHLLE (0 viscosity)	Viscous vHLLE
Init cond (soft)	Glauber	EPOS	EPOS
Init state fluctuations	No	Yes	Yes
hadronization	Covar. Inst. Coal + frag	Same	Same*
HQ production	FONLL (p) + Glauber (space)	FONLL (p) + EPOS (space): position of NN interactions	EPOS3
CNM	No shadowing, initial k_T broad.	EPS09	EPOS3
Hadronic interaction	None	None	URQMD

* At least up to this conference

**No modification of the ELOSS model**

Motivation

Main questions:

1. Is it possible to describe both RHIC and LHC data with the same « bundle » of extra ingredients ?

2. Is it possible to **FALSIFY** our ELOSS model, i.e. to show, f.i.:

- That one needs extra coupling around Tc in order to benefit from extra bulk-v_2

- That one needs smaller relaxation time at small p (as in the TAMU approach)

Method : Needs to adjust several components => complicated issue.

Benefit: Once this is done, one obtains a consistent formulation.

"initial state effects" in p-Pb 5 TeV

EPOS-HQ

D mesons

R_{pPb}

$\mu_F = 0.5\mu_0$

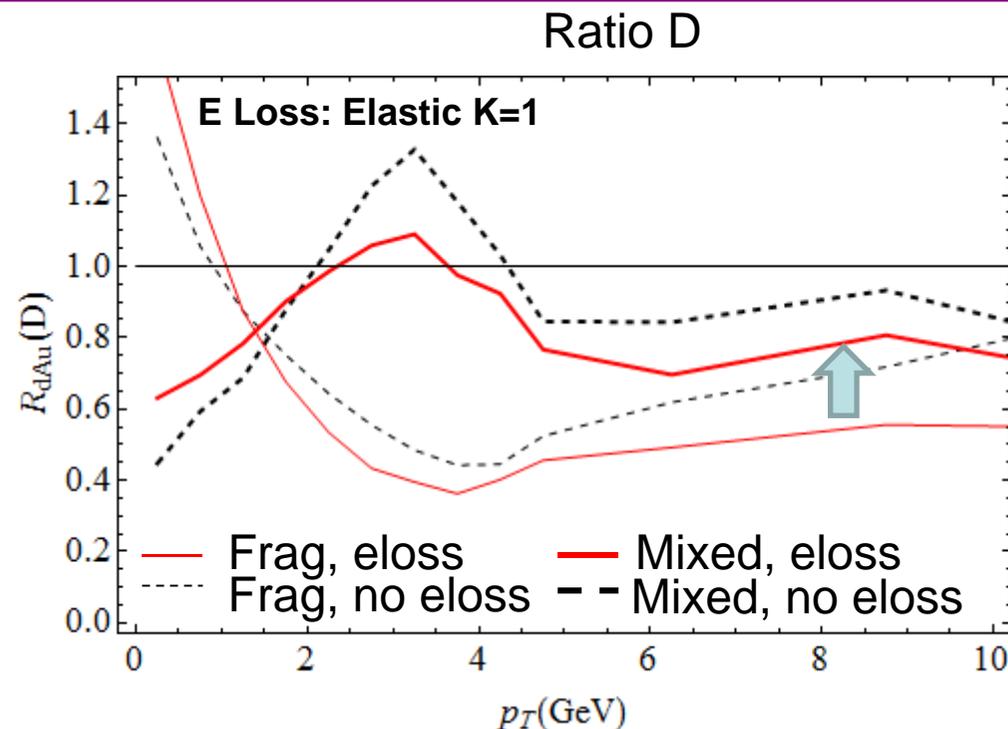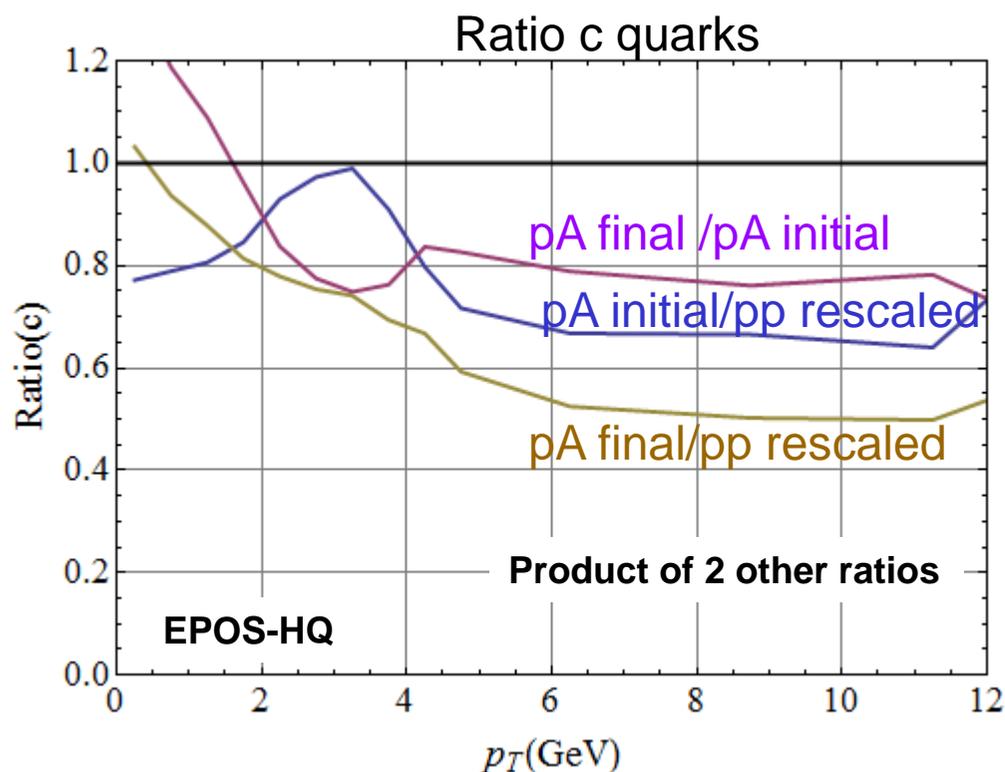R_{pPb} $y_{cms}(D^0)$
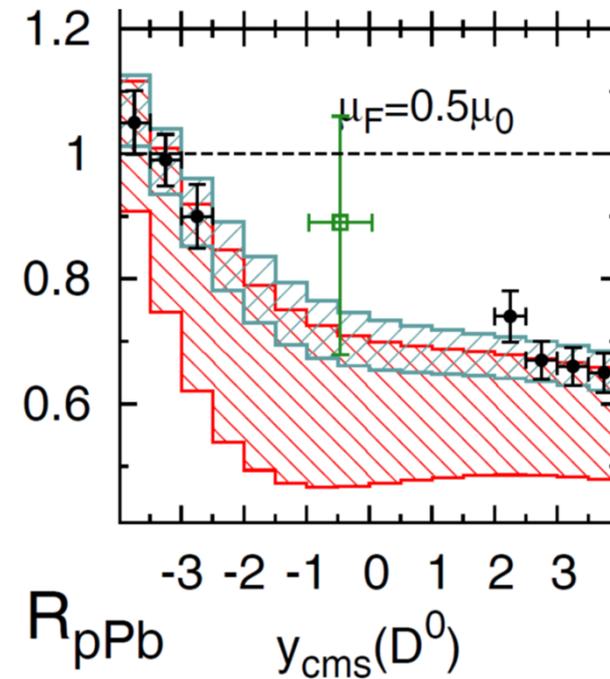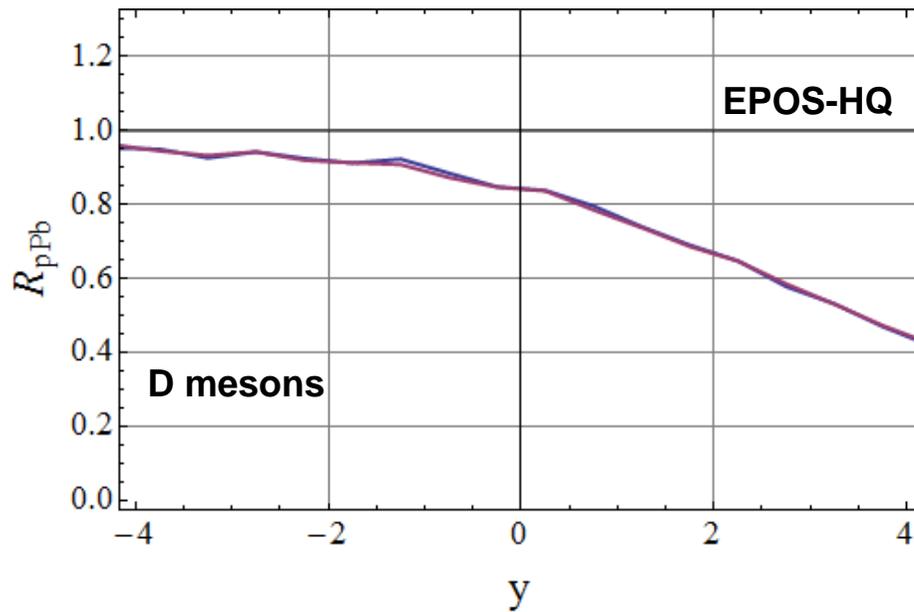
Sensitivity

Saturation	Hadronisation	E Loss
YES	NO	NO

Fair agreement btwn EPOS-HQ (in fact EPOS3) and experimental data

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"initial state effects" in p-Pb 5 TeV

Ratio c quarks

pA final /pA initial

pA initial/pp rescaled

pA final/pp rescaled

Product of 2 other ratios

EPOS-HQ

Ratio(c)

p_T(GeV)

Ratio D

E Loss: Elastic K=1

$R_{dAu}(D)$

p_T(GeV)

| Frag, eloss | Mixed, eloss |
| Frag, no eloss | Mixed, no eloss |

Sensitivity

Saturation	Hadronisation	E Loss
YES	YES	YES

… and chemistry ! Complicated !!!

Our implementation of the coalescence has consequences up to 10 GeV

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"initial state effects" in p-Pb 5 TeV

Ratio D

EPOS-HQ

E Loss: Elastic K=1

|y|<0.5

Frag, eloss — Mixed, eloss
Frag, no eloss — — Mixed, no eloss

Sensitivity

Saturation	Hadronisation	E Loss
YES	YES	YES
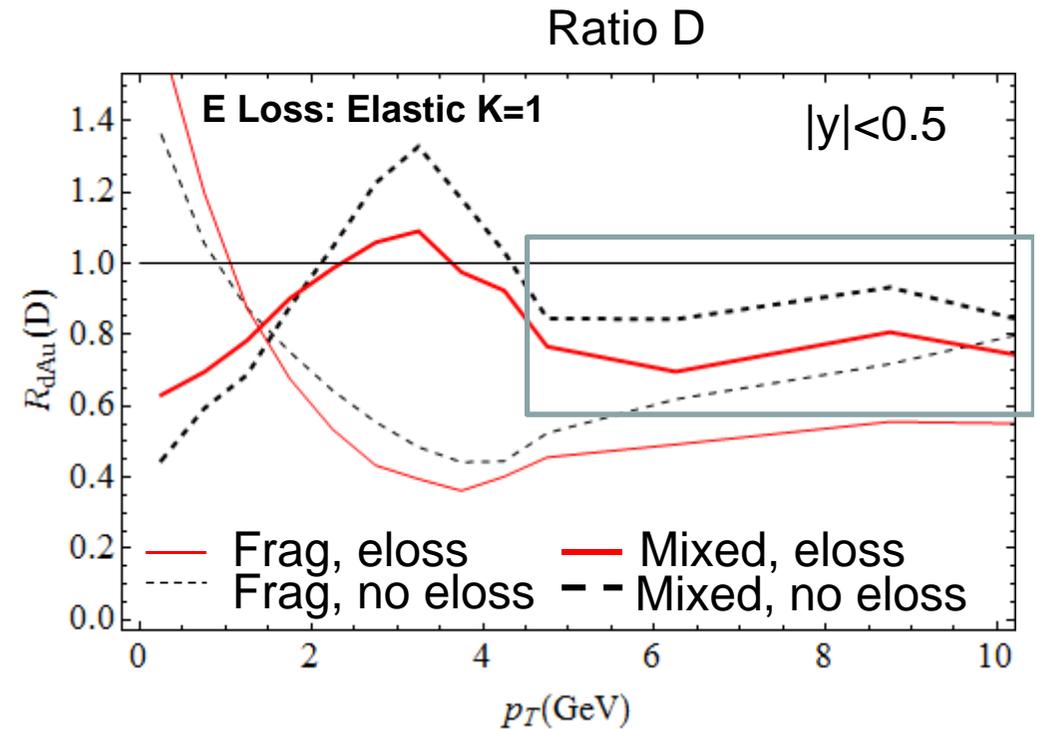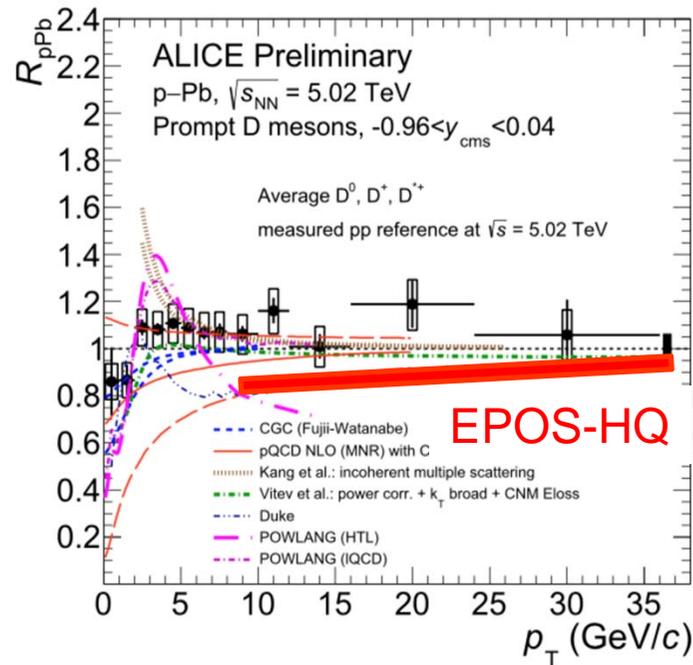
At least one conclusion: pure fragmentation ruled out

Need to improve our implementation of CNM effects for p_T > 5 GeV

Also need to compare to LHCb data

D meson production in central Pb-Pb

Ratio c quarks

Elastic Eloss, K=1

AA initial/pp rescaled

Close enough to 1

AA final /AA initial

AA final/pp rescaled

PbPb, 0−10, 5TeV $|y|<0.5$

ALICE

- col K=0.75, frag, URQMD
- col K=0.75, frag, FO
- col K=1, mixed, URQMD
- col K=1, mixed, FO

Calibration at p_T=10 GeV
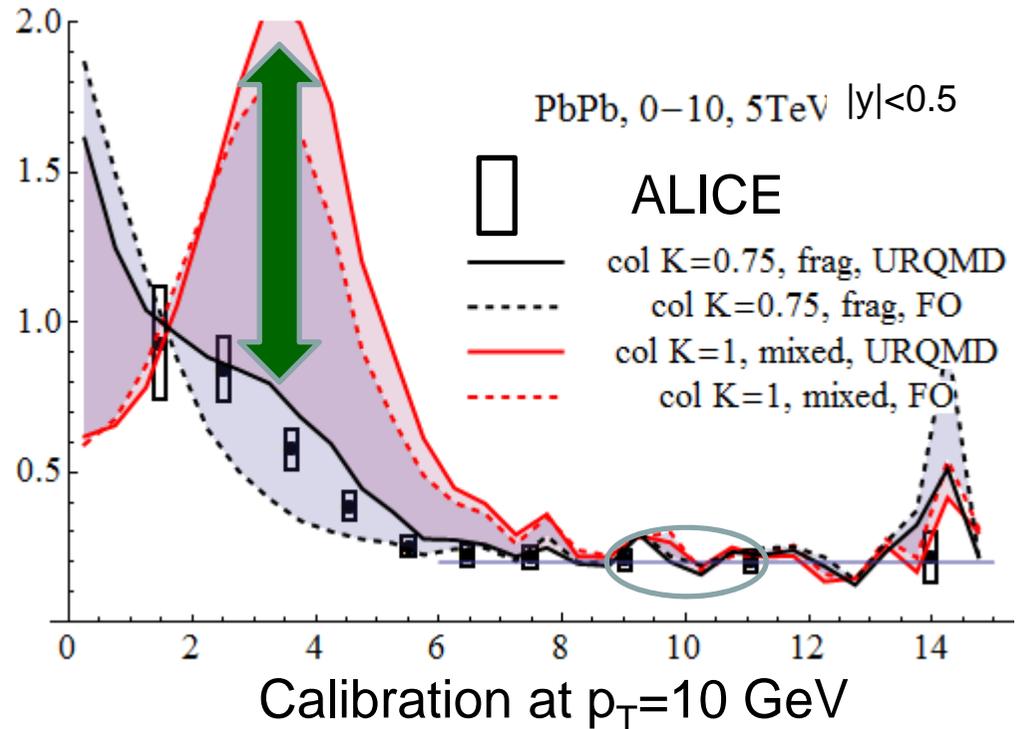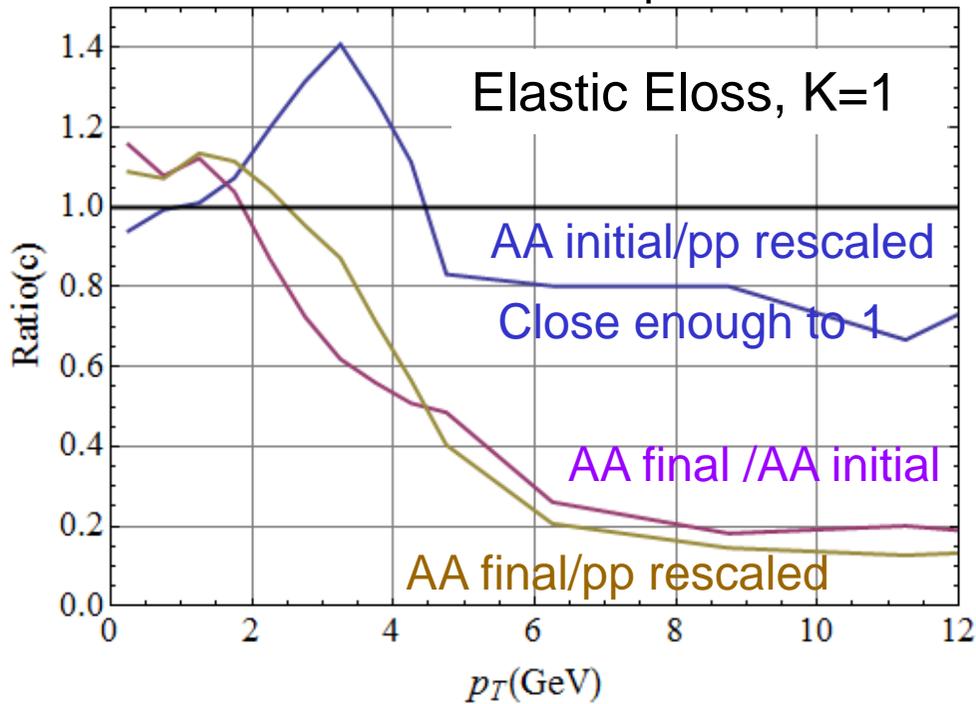
CNM	Hadro	E Loss	Hadro rescat	Chemistry
YES	Large p_T < 8GeV		Moderate p_T < 5 GeV	?

We overshoot unity with our present coalescence model; pure frag does not perform so bad after all !

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D meson production in central Pb-Pb

Looking at spectra

Elastic Eloss, K=1
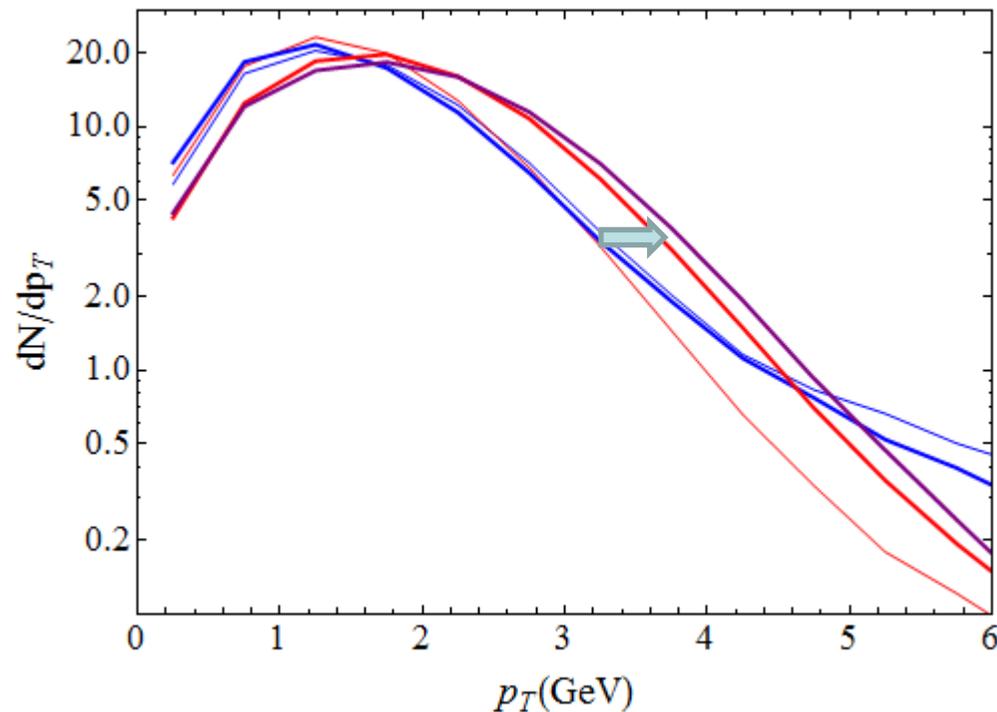
— c in pp (resc)

— D in pp (resc)

— Final c

— D @ FO (mixed hadro)

— D after URQMD

Need to understand why no such problem in previous MC@sHQ + EPOS2
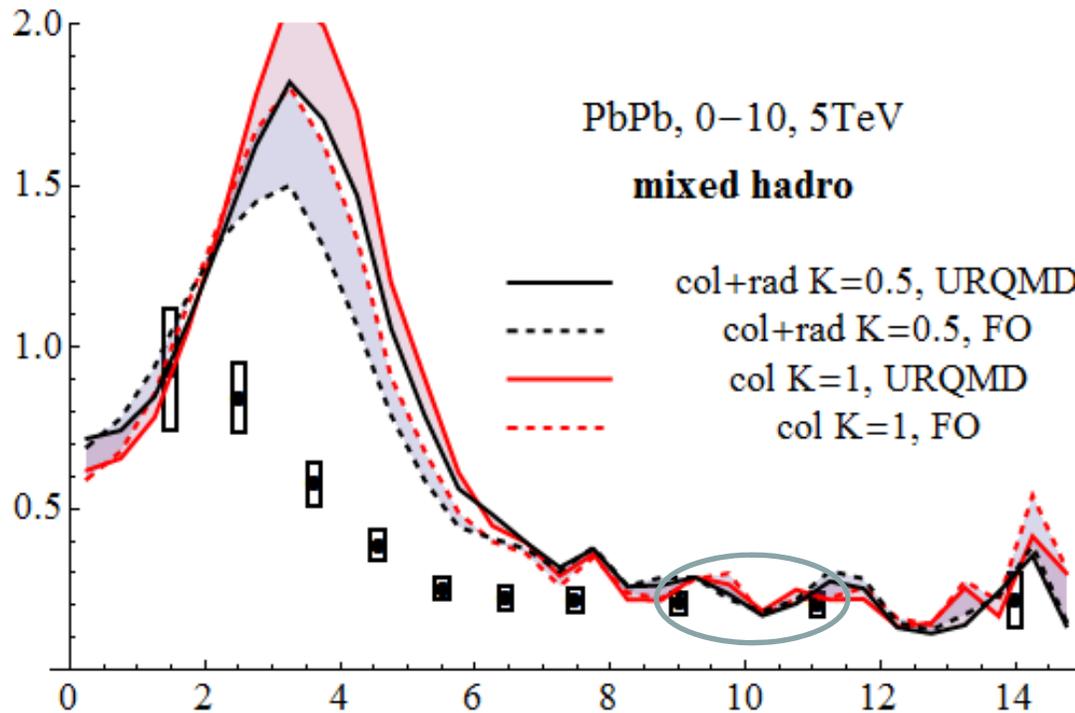
Possible ways out (without changing Eloss mechanism):
- Some c -> Λ_c
- Modify coalescence to gain less momentum at FO (as in RRM)

Need to consider the full chemistry effects

D meson production in central Pb-Pb
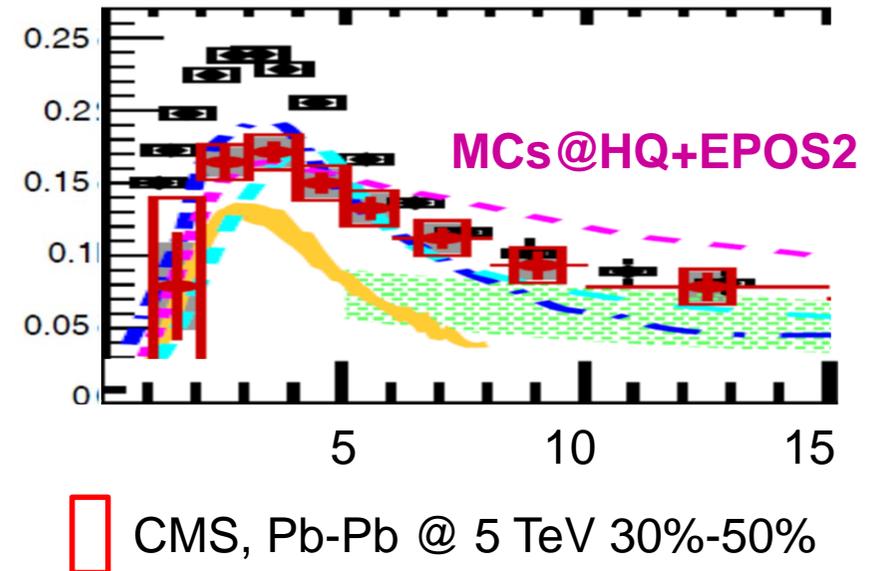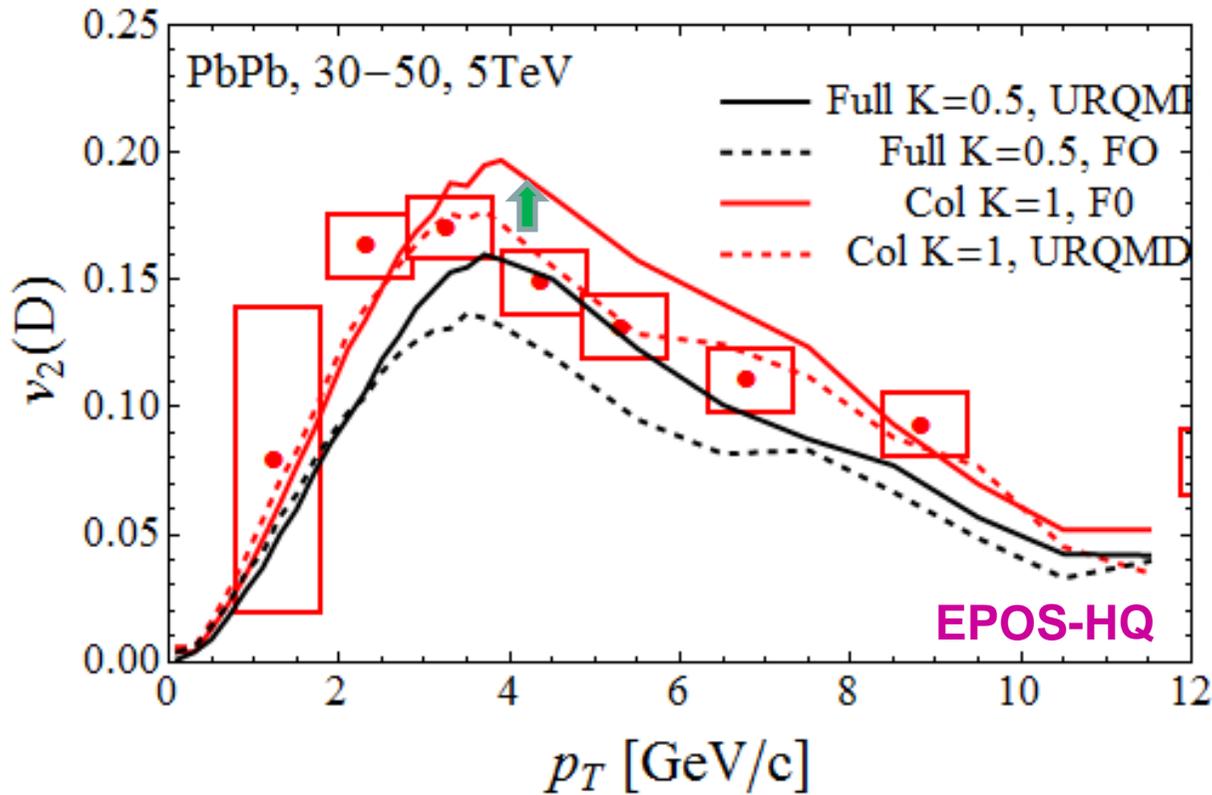
Looking at "full" Eloss

Elastic + Radiative Eloss, K=0.5

Calibration at p_T=10 GeV

CNM	Hadro	E Loss	Hadro rescat
YES	Large p_T < 8GeV	Moderate for p_T<20 GeV	Moderate p_T < 5 GeV

D meson production in semi-central Pb-Pb: flows

PbPb, 30−50, 5TeV

Full K=0.5, URQMD
Full K=0.5, FO
Col K=1, F0
Col K=1, URQMD

$v_2(D)$

p_T [GeV/c]

EPOS-HQ

MCs@HQ+EPOS2

CMS, Pb-Pb @ 5 TeV 30%-50%

- Moderate but significant increase of v_2 from production at FO -> end of URQMD evolution ( )

- Better agreement than in previous predictions (especially the decrease at intermediate p_T)

D meson production in semi-central Pb-Pb: flows
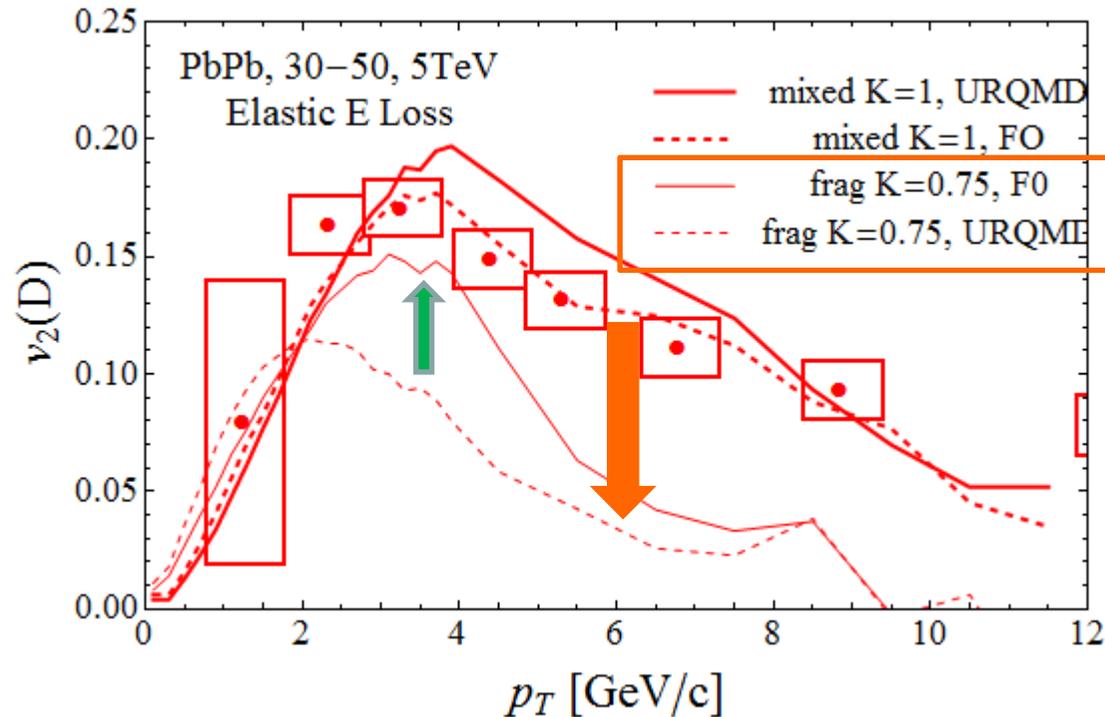
- If pure fragmentation is assumed, strong reduction of v_2 at FO (expected), only partially compensated by later evolultion in URQMD ( ) .

- From the view point of our model, we would need some hadronization model that is able to "transfer" bulk v_2 -> c without extra p_T

"initial state effects" in d-Au 200 GeV
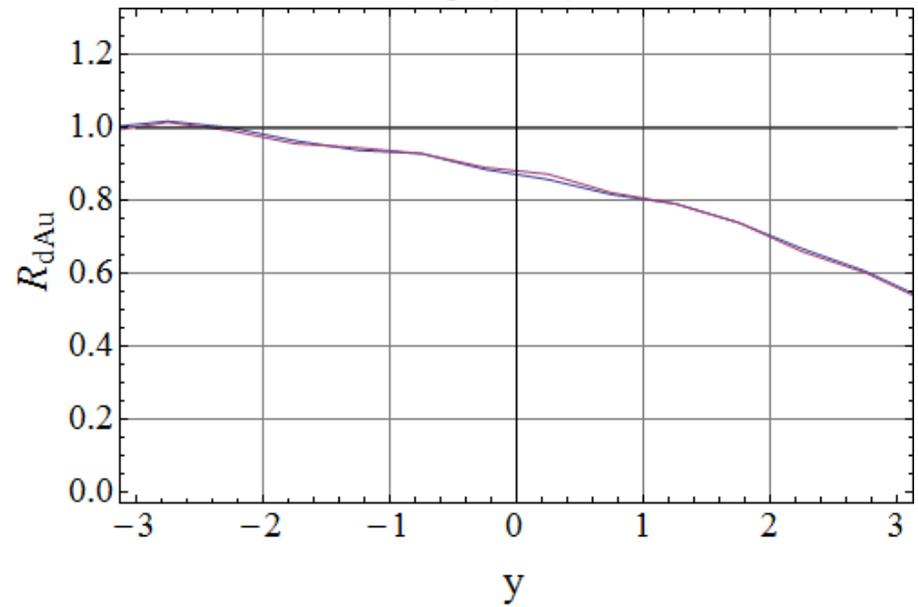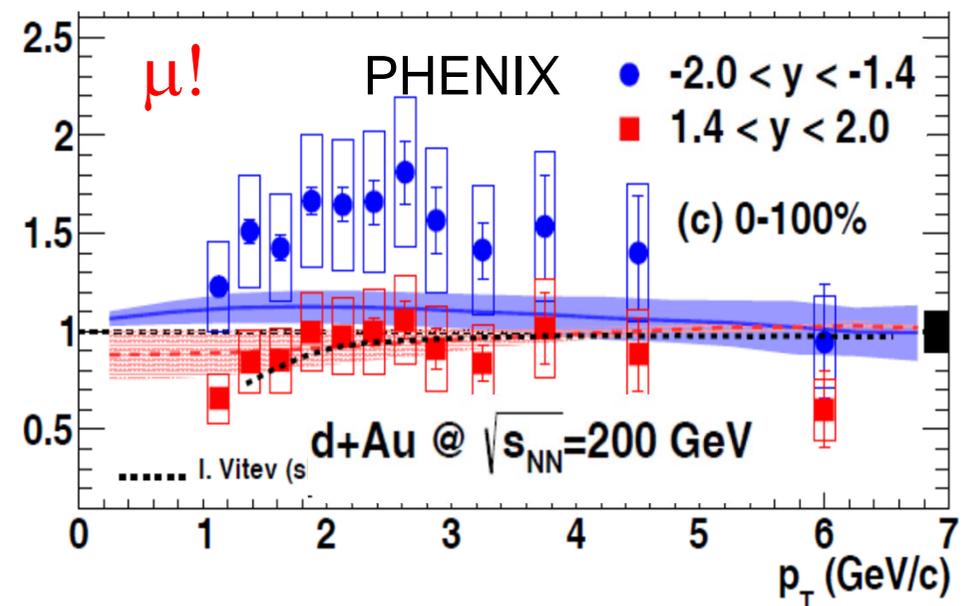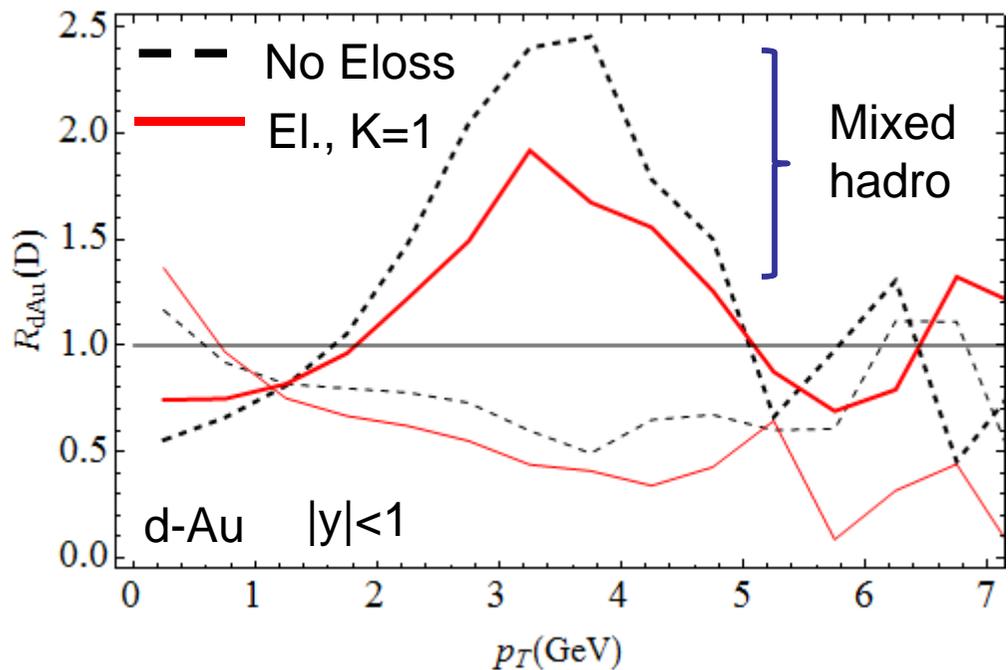
Sensitivity

Saturation	Hadronisation	E Loss	"Chemistry"
YES	YES	YES	Most probably

← More suppression in the p-going direction

D meson production in central Au-Au @ 200 GeV

Elastic Eloss, K=1

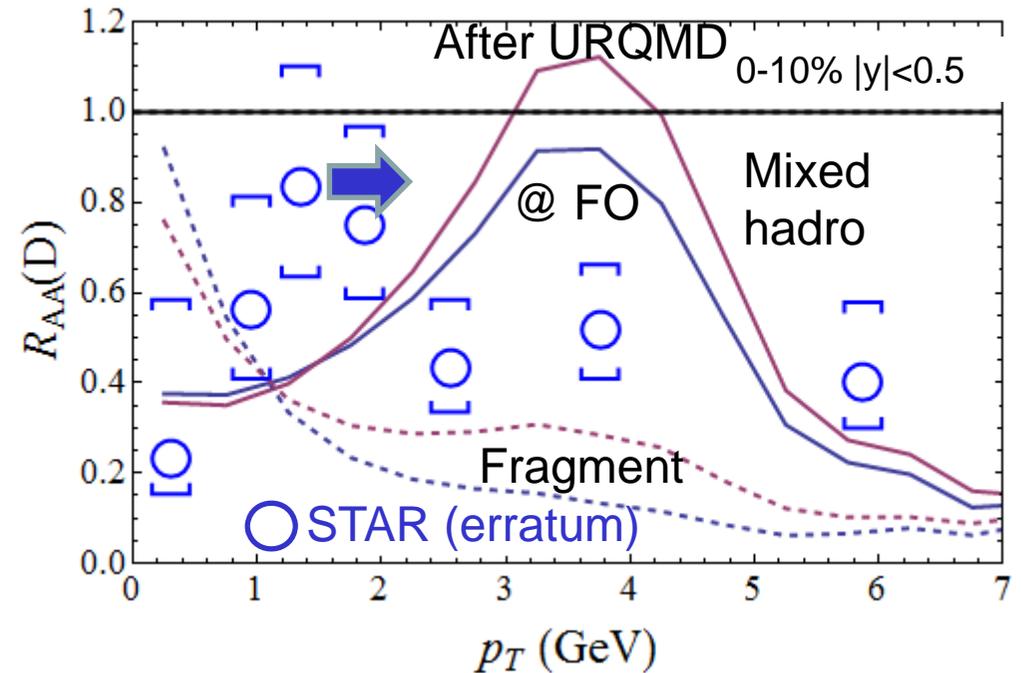AA initial/pp rescaled

Ratio c quarks

AA final/pp rescaled

AA final /AA initial

After URQMD

0-10% |y|<0.5

Mixed hadro

@ FO

Fragment

○ STAR (erratum)

$R_{AA}(D)$

p_T (GeV)
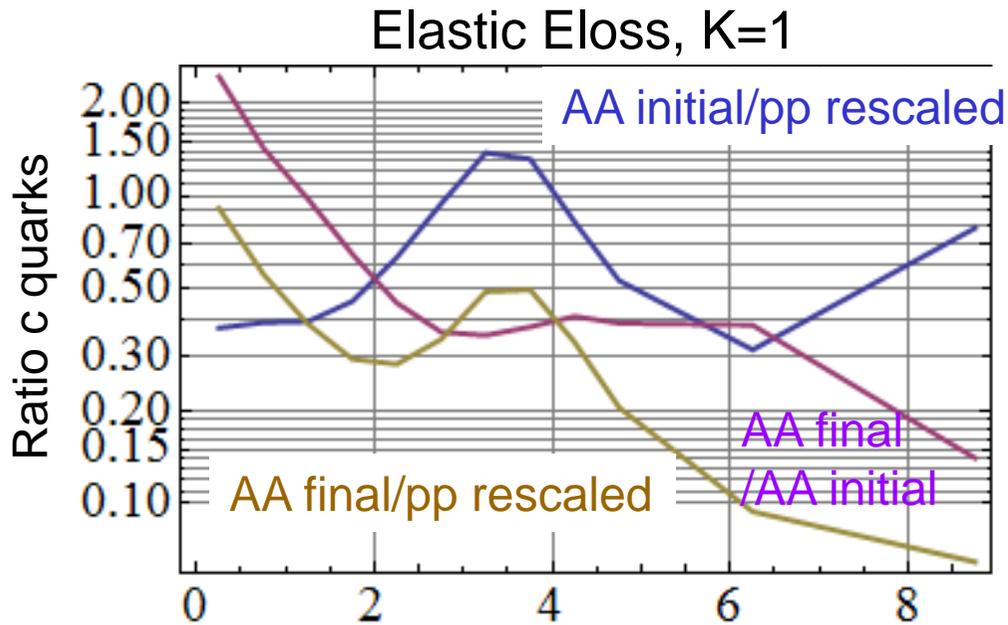
Sensitivity

CNM	Hadro	E Loss	Hadro rescat
YES	LARGE @ small p_T	small	Moderate (p_T < 5 GeV)

Au+Au @ 200 GeV   *STAR Preliminary*

● ○ 2014

(a) 0-10%

p_T (GeV/c)

- Same pattern as for LHC, no unity overshooting

- Radial flow bump at too large p_T, needs to be cured as for LHC

29
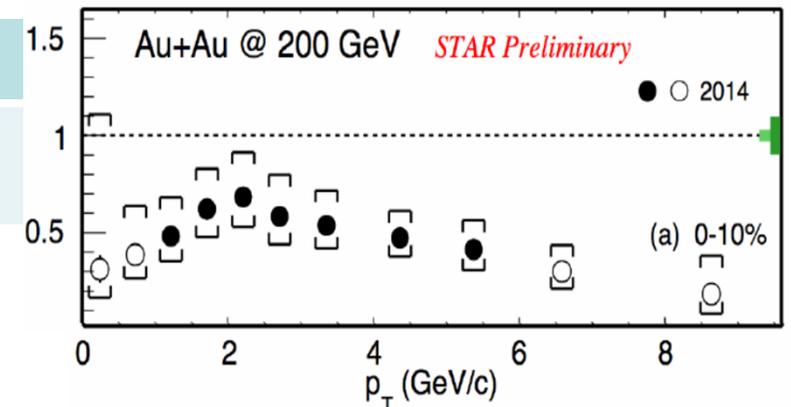
D meson production in min. bias Au-Au 200 GeV
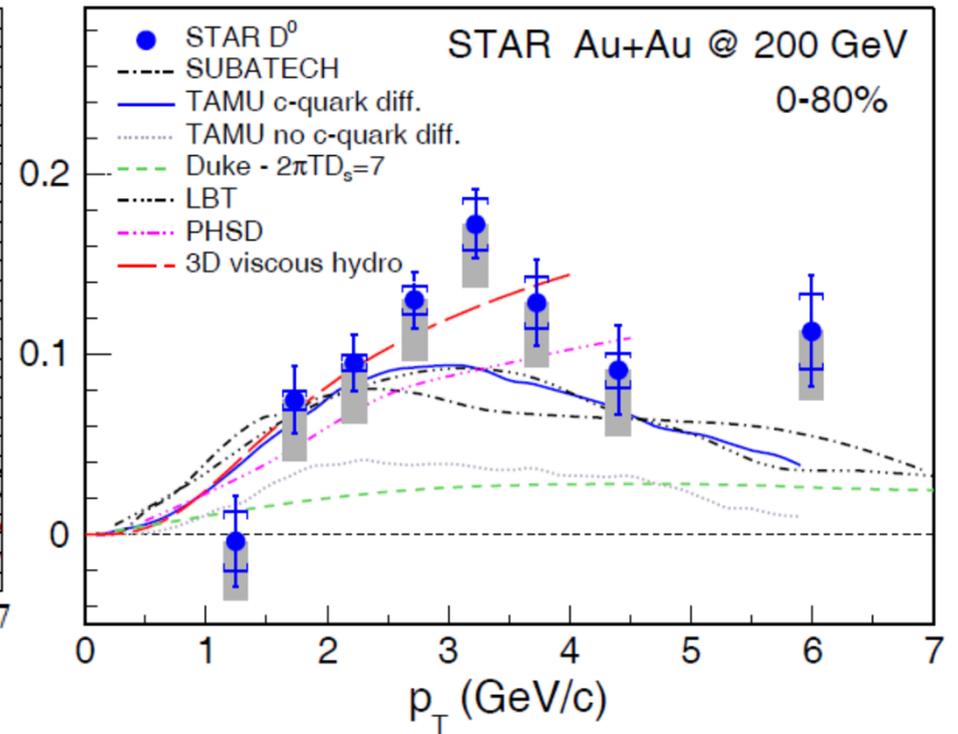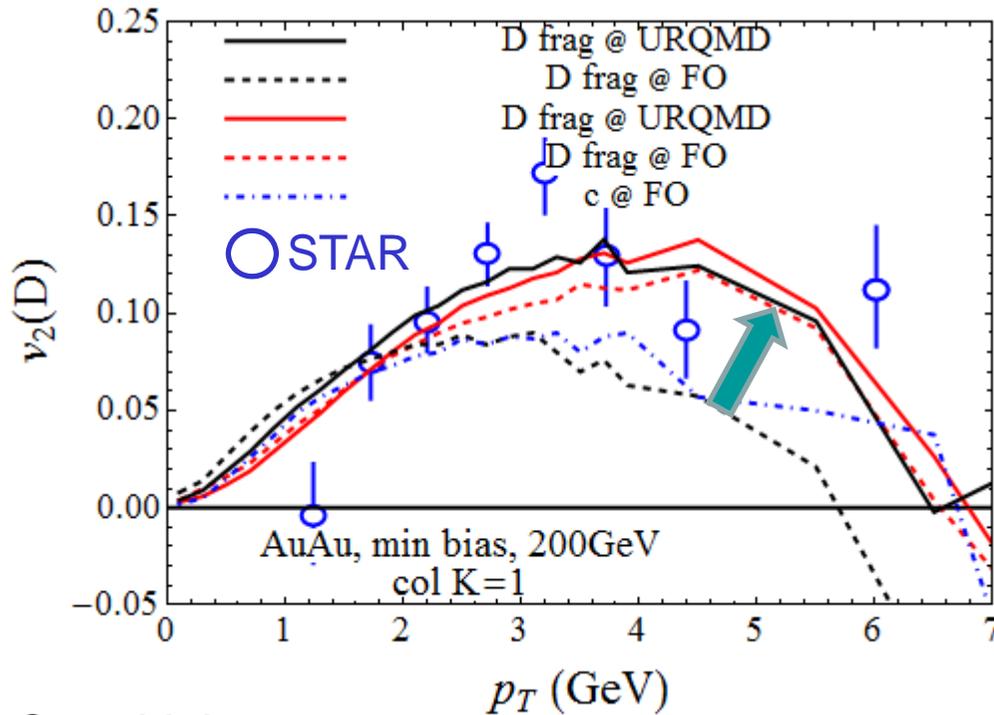
Sensitivity

CNM	Hadro	E Loss	Hadro rescat
NO	Large	Moderate	Large for fragmentation

- Strong contribution of hadronic rescattering if v2(D) is not saturated at freeze out
- No sign of strong disagreement with our Energy Loss model @ RHIC…
- … In particular no need to introduce some extra coupling around Tc

Updated D$_s$ extraction
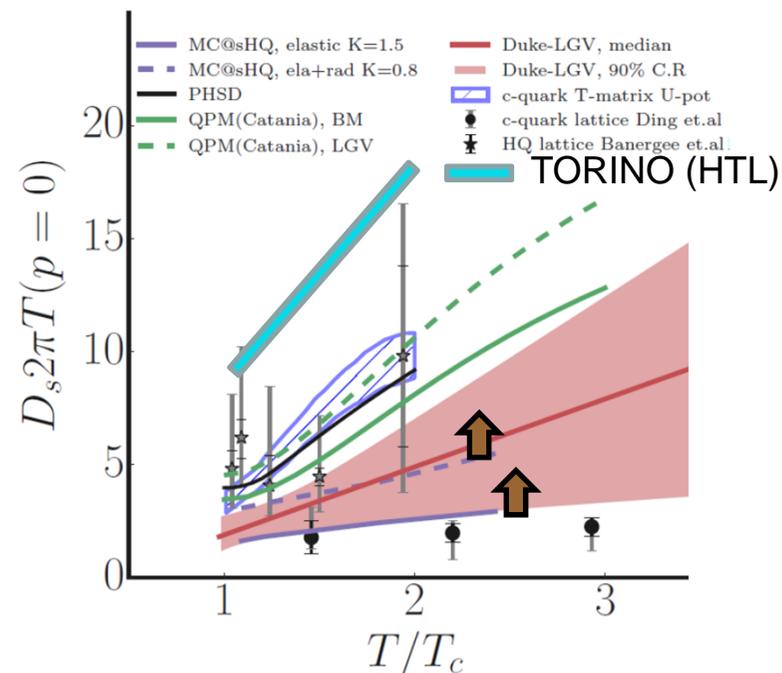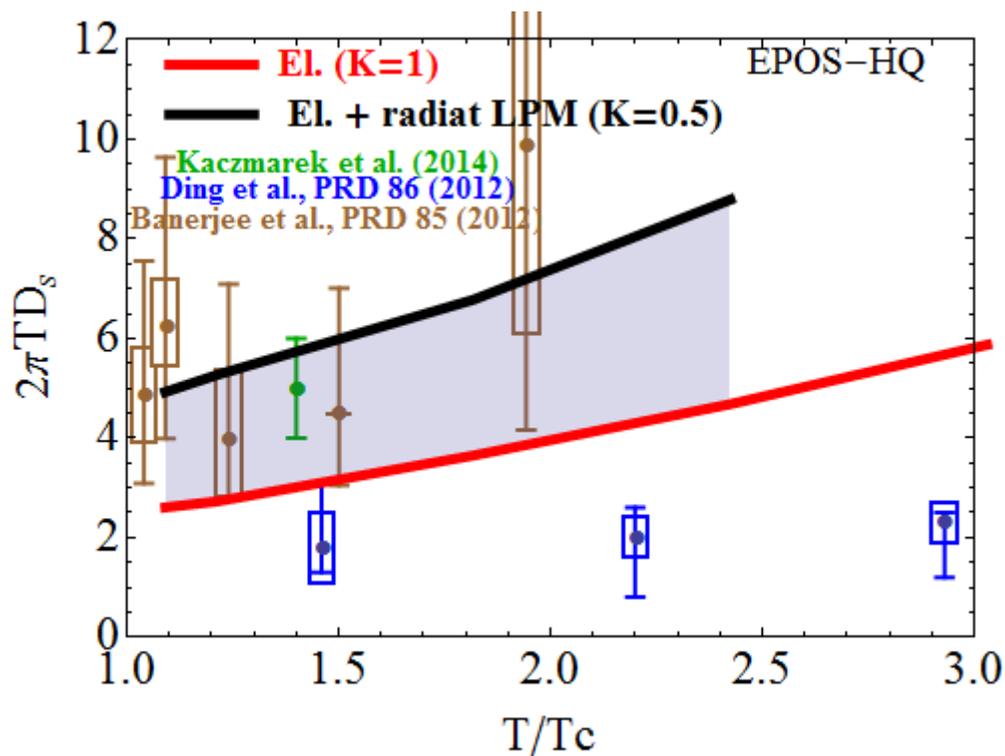
- Despite uncertainties affecting the low p$_T$ regime, transport coefficients can be extracted (comparison with exp. data at p$_T$ = 10 GeV/c)
- … increase by $\approx$30% of the associated D$_s$.
- Bring us (a bit) towards the "bulk" of the D$_s$ from other models

More involved observables: EBE flow

ALICE Preliminary
30-50% Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt D^0, D^+ average

- 60% small-q_2^{TPC}
- 20% large-q_2^{TPC}
- unbiased

Syst. data
Syst. B feed-down

$|\eta_D| < 0.8$
$|\eta_{q_2^{TPC}}| < 0.8$

ALI-PREL-121121

EPOS-HQ

???
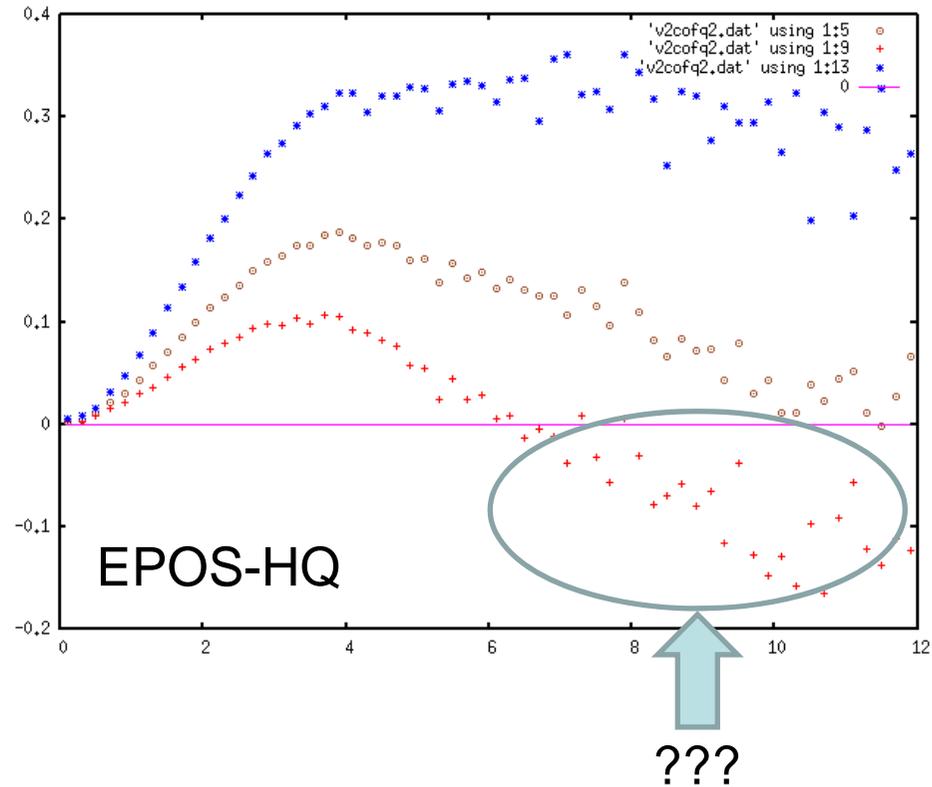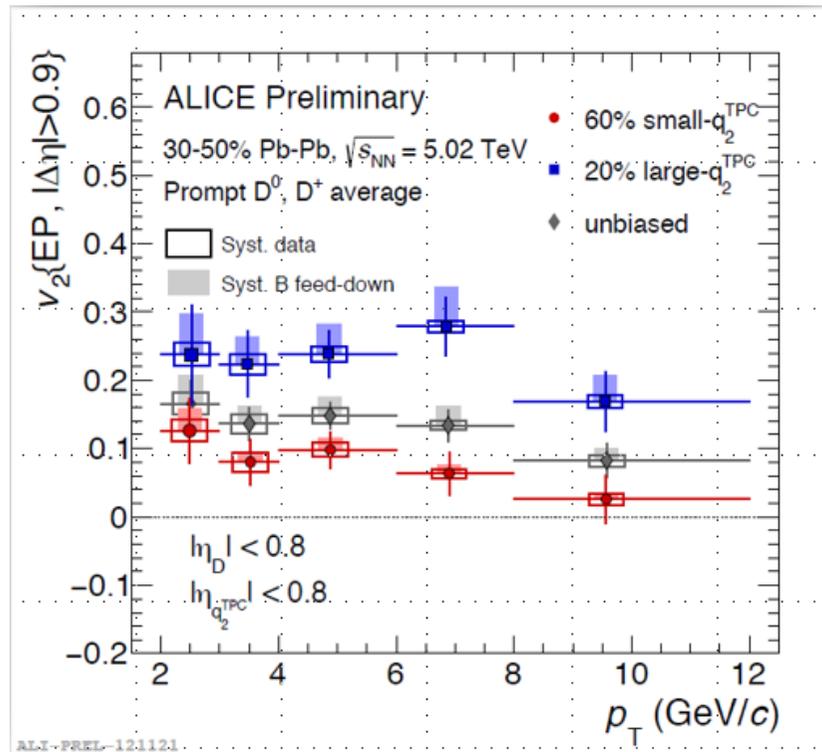
- Trends well reproduced by EPOS-HQ at low p_T

- … However, inversion of the v_2(D) for "cylindrical events" and large p_T. No physical explanation at this stage.

- Besides this, no big surprise: bulk v_2 is well transferred to c-quarks

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More involved observables: momentum imbalance

➤ Back to back D/Dbar or B/Bbar: As compared to γ-D/B: "triggering" itself is affected but symmetry between both particles could limitate the various effects:

➤ Large number of c-cbar from various NN collisions => large uncorrelated background

➤ Competing effects due to energy loss: …

D-$\bar{\text{D}}$ or B-$\bar{\text{B}}$

p_L

Initial stage

Strong correlation

$p_T(\bar{Q})$

$p_T(Q)$
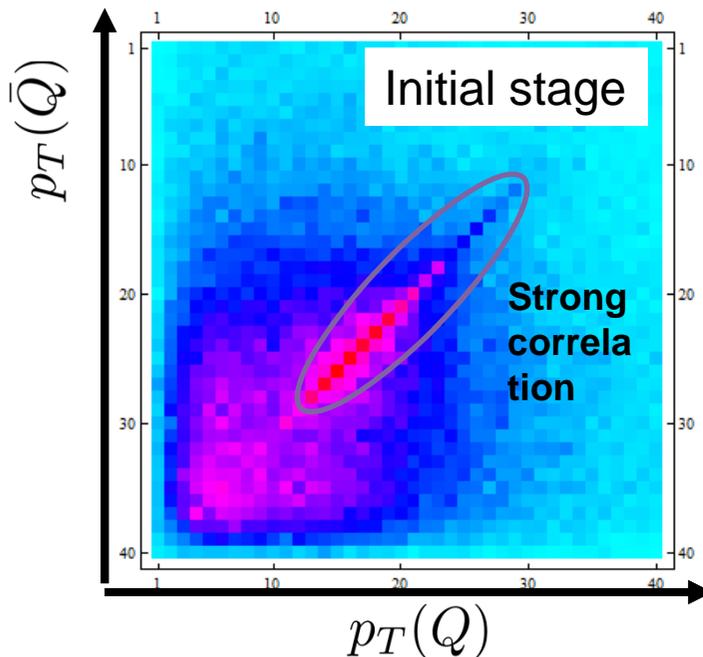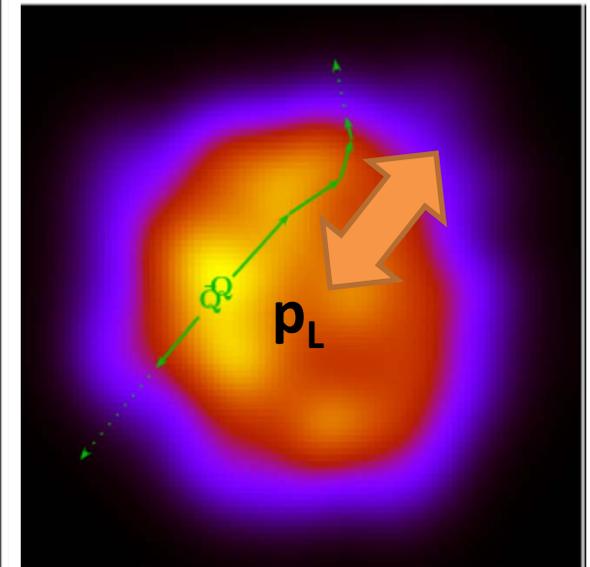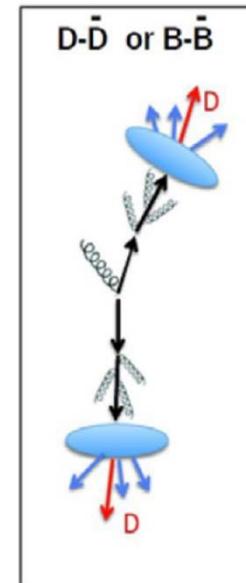
Evolution in hot QGP medium

Final stage

$p_T(\bar{Q})$

$p_T(Q)$
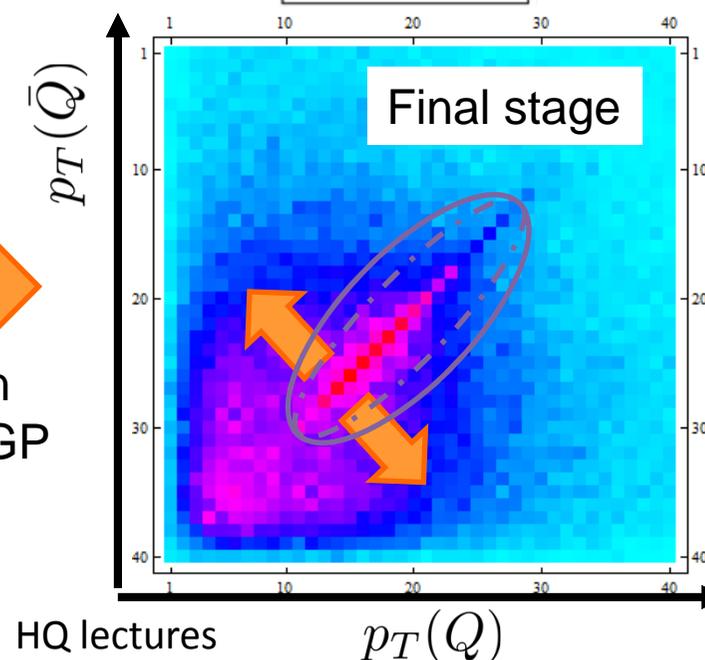
➤ decorrelation due to various path lengths + fluctuations: reduction

More involved observables: momentum imbalance

$C_R(p_T, p_T')$

projection

B2B selection
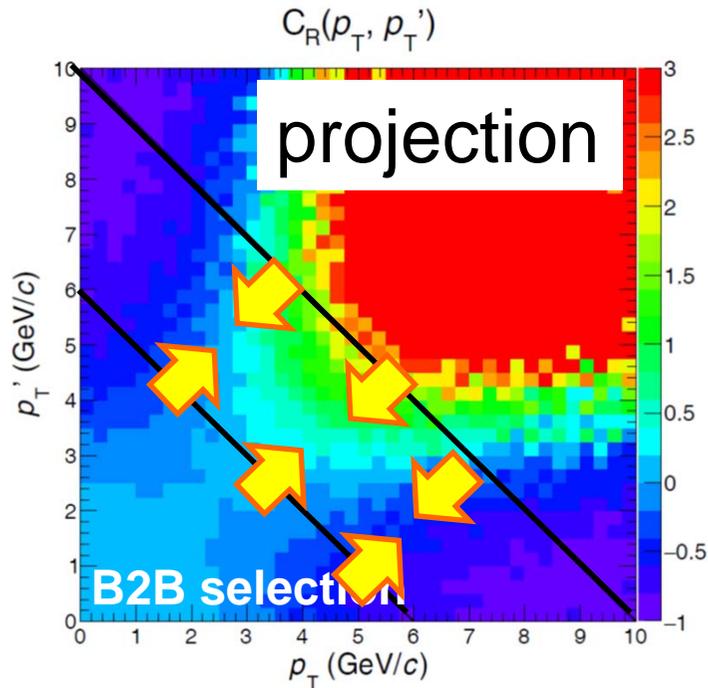
Method: we project on a "diagonal band" of fixed $p_T(c)+p_T(\bar{c})$

Larger decorrelation found for "full" el + rad model, due to larger longitudinal fluctuations

Abolute correlation:

$$C(p_T, p_T') := \frac{1}{N}\frac{d^2 N(p_T, p_T')}{dp_T dp_T'} - \frac{1}{N}\frac{dN(p_T)}{dp_T} \times \frac{1}{N}\frac{dN(p_T')}{dp_T'}$$

- Vanishes if d²N factorizes (d²N(p,p') = dN(p) x dN(p'))

- Satisfies $\int C(p_T, p_T') dp_T d_T' = 0$

Relative correlation: $C_R(p_T, p_T') := \dfrac{C(p_T, p_T')}{\frac{1}{N}\frac{dN(p_T)}{dp_T} \times \frac{1}{N}\frac{dN(p_T')}{dp_T'}}$

- Reveals correlation at finite p_T

sqrt(s)=5 TeV
EPOS 3296
Pb−Pb,50%−70%
c quarks

$|\Delta\varphi|>3\pi/4$
$8<\Sigma p_T<12$

init
El, K=1
Full, K=0.5
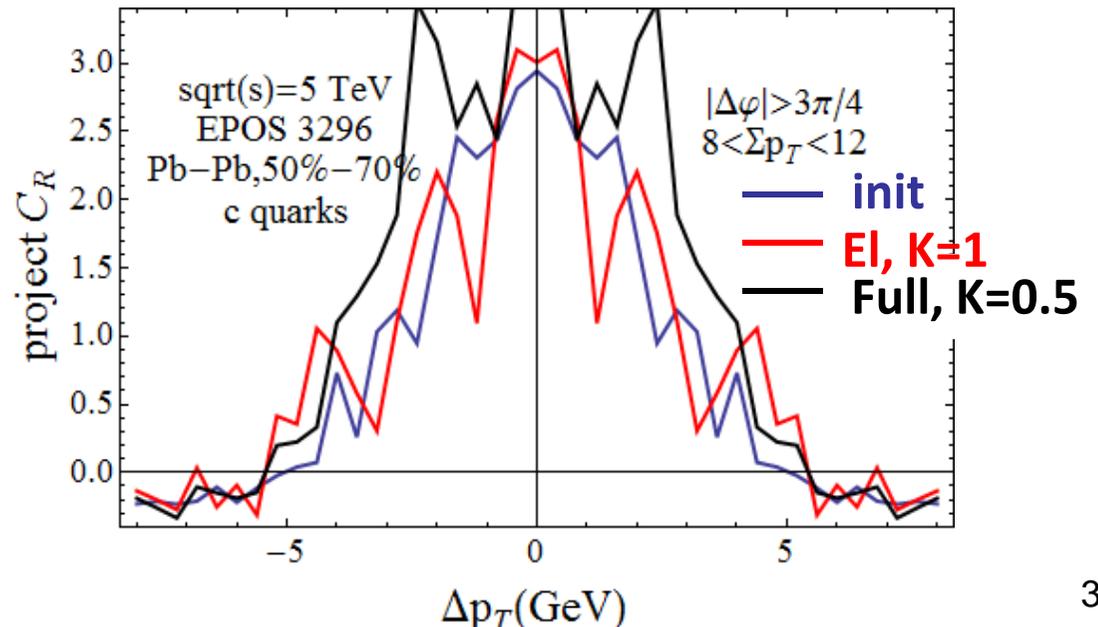
Conclusions and perspectives

1. Is it possible to describe both RHIC and LHC data with the same « bundle » of extra ingredients ?

Not at this stage; remaining issues at pT<5GeV/c some extra work on the hadronization and HQ production is mandatory

2. Is it possible to **FALSIFY** our ELOSS model, i.e. to show, f.i.:

- That one needs extra coupling around T_c in order to benefit from extra bulk-v_2

- That one needs smaller relaxation time at small p (as in the TAMU approach)

On the one side we fail to reproduce the low p_T R_{AA} but on the other side it is not proven that satisfactory agreement cannot be reached at the price of modifying some extra ingredient; besides, satisfactory agreement for the v2 and with the R_{AA} at intermediate p_T (for both RHIC and LHC) with D_s in agreement with IQCD => Conclusion still pending as for the falsification.

Perspective at short term: more "combinations" relying on collective work

Back Up

Some global view of our model development

2002: motivation for recombination of c and cbar J/Ψ using dynamical c/cbar distribution

2004: 1rst version of the model: **HF distrib matters**

2008: 1rst open HF results for RHIC

2010   **2012**   **2013**

HF Eloss

Elastic; Fixed αs; naïve regulator (T); cranking coefficient K

Elastic; running αs; regulator fixed on HTL; cranking coefficient K

Radiative; running αs; regulator fixed on HTL; cranking coefficient K   **upgrade**

Study of medium effect with TAMU

Medium

Kolb Heinz: ideal hydro; smooth initial conds

upgrade   For RHIC only

EPOS2 background: ideal hydro; fluctuating initial conditions

New obs.

pp; pA.

System

AA

Kinetic treatment

Fokker Planck with imposed Einstein relation

Boltzmann

upgrade

Quarkonia physics

q+$\Phi\leftrightarrow$c+cbar à la Bhanot-Peskin + dissociation above T_{dis}

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Some global view of our model development

Remote past   **2013:**   **2015:**   **Now**   **Near Future**   **Future**

HF Eloss

Elastic + Radiative Eloss; running αs

PUBLICATION

Effect of realistic EOS on Eloss (with Frankfurt)

Realistic medium helps fixing HF Eloss

Medium

Kolb Heinz   For RHIC only

EPOS 2

EPOS3: viscous hydro; fluctuating initial conditions; **HQ from semi-hard pomeron**

EPOS-HQ upgrade

System

pp; pA.

AA

pp; pA; AA in a unified way

Kinetic treatment

Boltzmann

Q - jet

upgrade

D/B – light hadrons correlations

Quarkonia physics

q+Φ↔c+cbar + dissoc above T_{dis}

Schroedinger - Langevin

upgrade

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Saturation effects in EPOS3

Non-linear effects

Computing the expressions G for single Pomerons: A cutoff Q_0 is needed (for the DGLAP integrals).

Taking Q_0 constant leads to a power law increase of cross sections vs energy (=> wrong)

because non-linear effects like gluon fusion are not taken into account
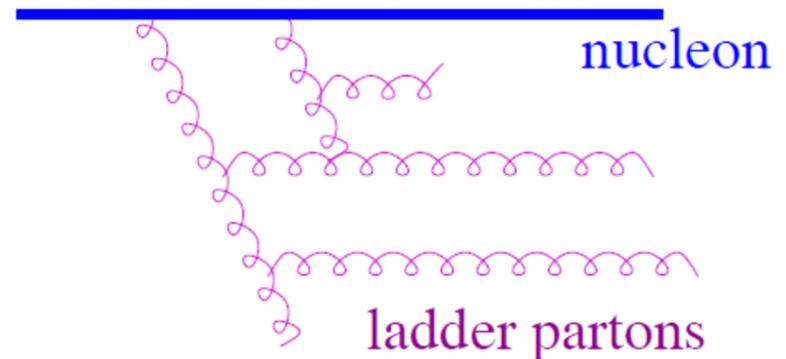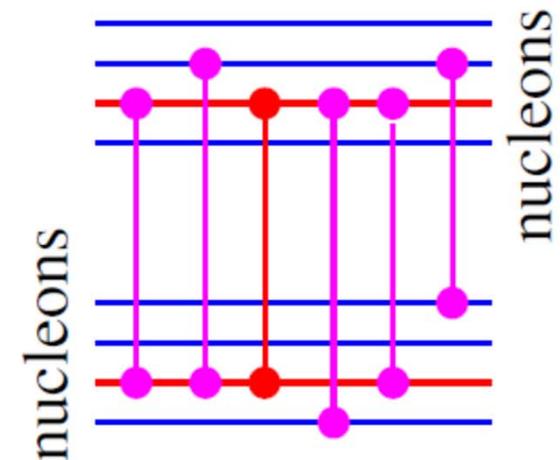
nucleon

ladder partons

Saturation effects in EPOS3

Solution: Instead of a constant Q_0, use a dynamical saturation scale for each Pomeron:

$$Q_s = Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$$

with

$N_{\mathbb{P}}$ = number of Pomerons connected to a given Pomeron (whose probability distribution depends on Q_s)

$s_{\mathbb{P}}$ = energy of considered Pomeron

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Saturation effects in EPOS3

We get $Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$ from fitting

- [ ] the energy dependence of elementary quantities $(\sigma_{\text{tot}}, \sigma_{\text{el}}, \sigma_{\text{SD}}, dn^{\text{ch}}/d\eta(0))$ for pp

- [ ] the multiplicity dependence of dn^{π}/dp_t at large p_t for pp at 7 TeV

We find

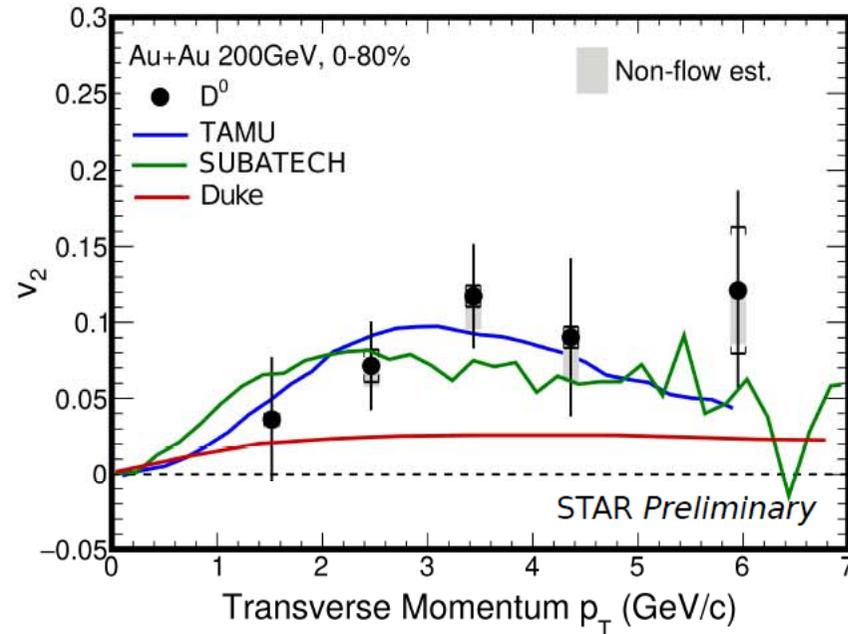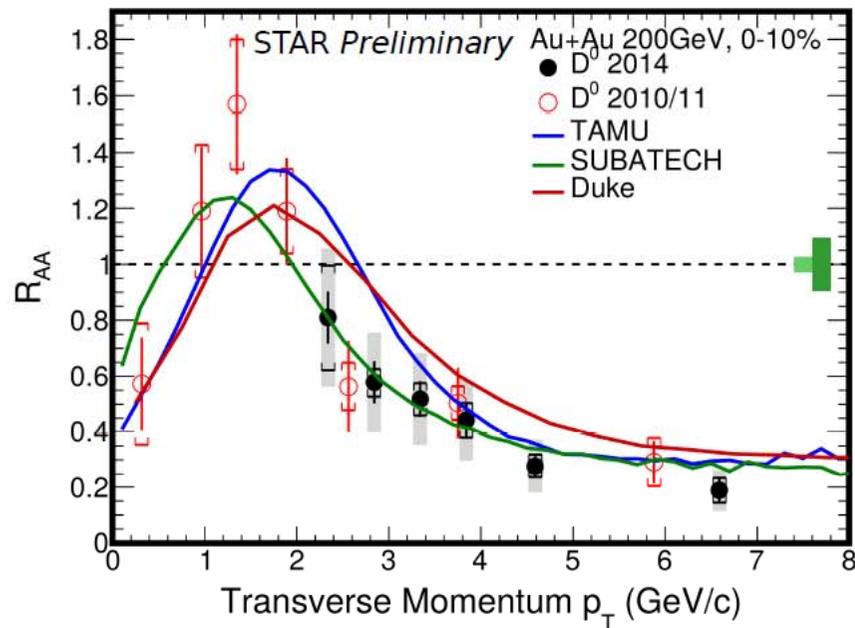$$Q_s \propto \sqrt{N_{\mathbb{P}}} \times (s_{\mathbb{P}})^{0.30}$$

CGC for AA:

$$Q_s \propto N_{\text{part}} \times (1/x)^{0.30}$$

McLerran, Venugopalan, Phys. Rev. D 49, 2233 (1994)

B2' for RHIC

Comparison to Theory

Sept 2015

NEW

- Data favors models with charm diffusion
  - → charm exhibits collectivity with the medium

Subatech: same Eloss model as
previously

	D × 2πT	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

arXiv:1506.03981 (2015) & private comm.

STAR ☆

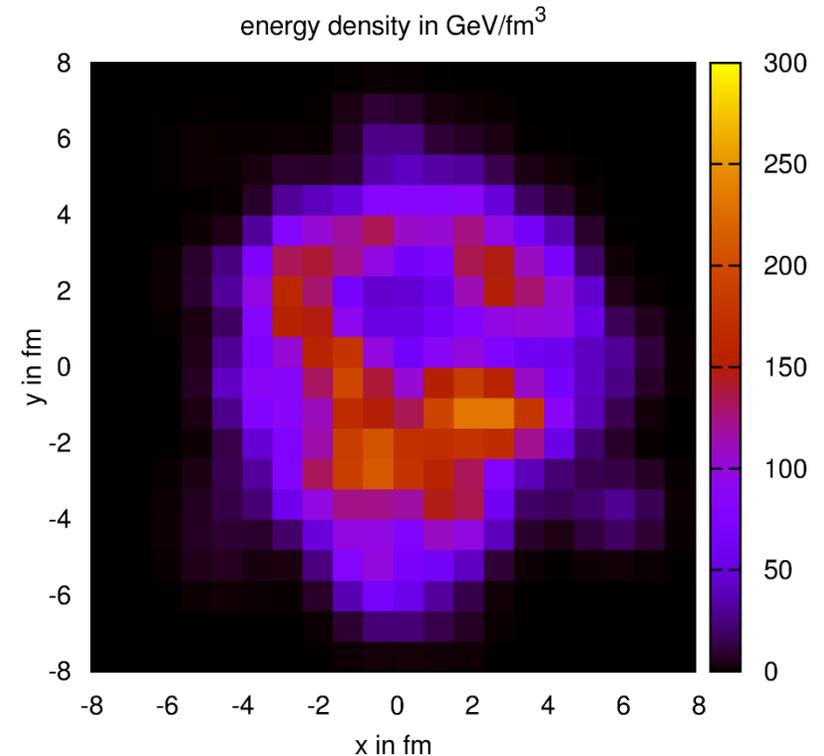Mustafa Mustafa - QM15 - Kobe, Japan

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More recent observables: Higher HQ flow components

Fluctuations in the Initial energy-density profile => odd components of the flow:
v_3, v_5, … (seen indeed in the light particle spectra)
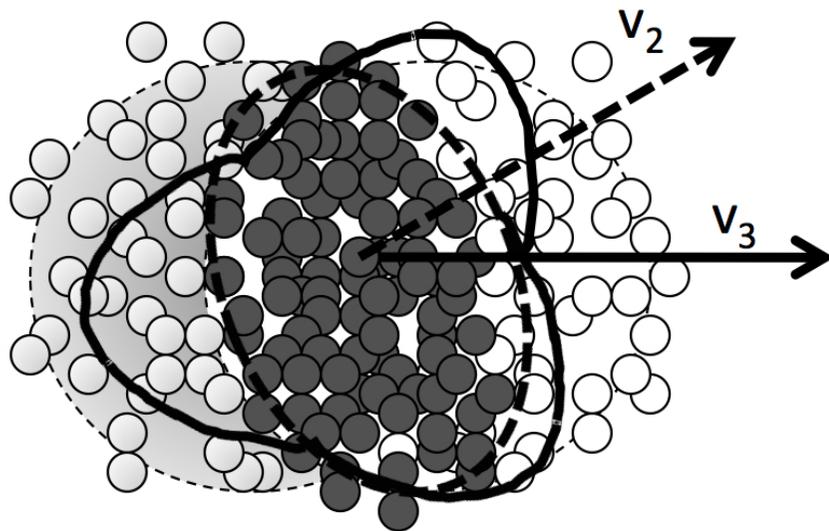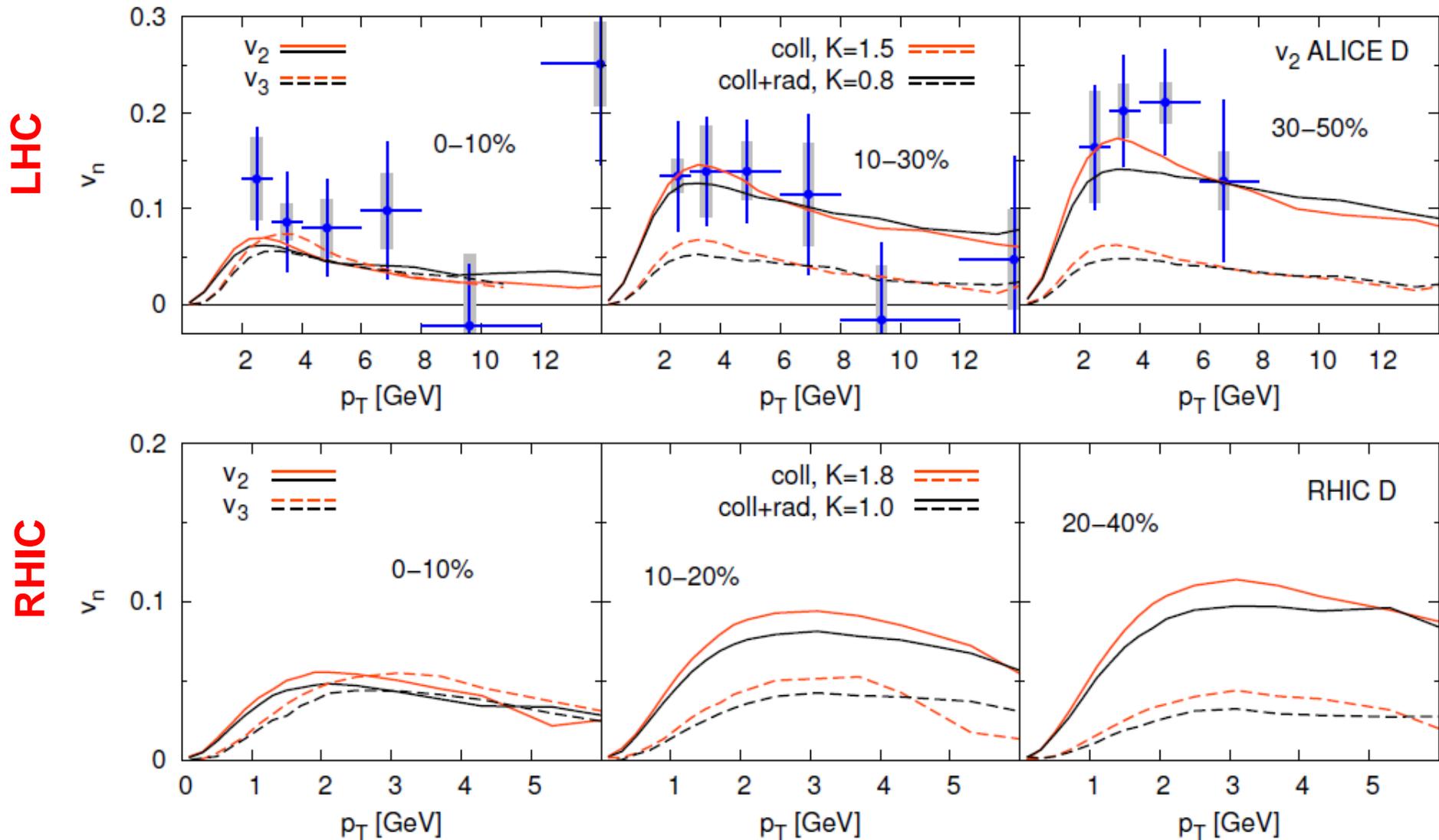
sketch

EPOS initial conditions

As heavy quarks couple to the expending QGP, same trend should be observed

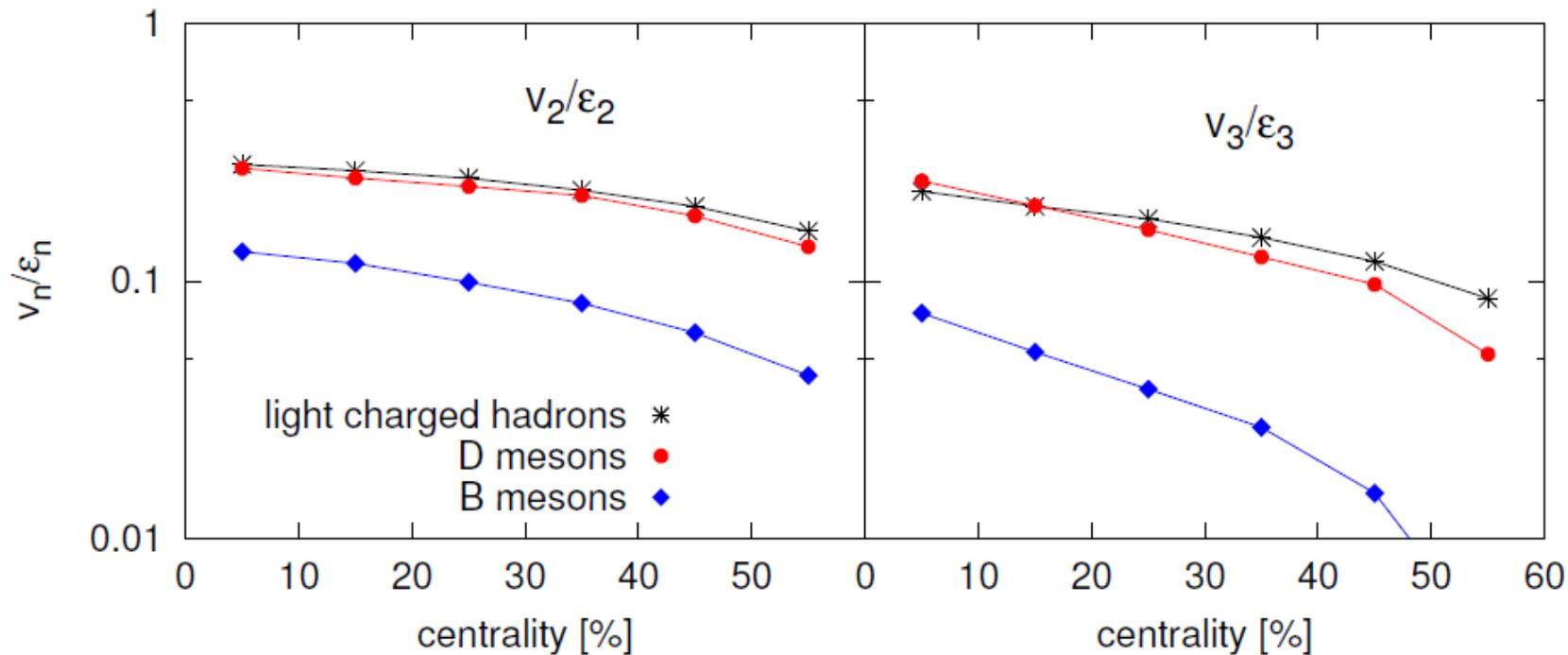# More recent observables: Higher HQ flow components

Indeed finite v3 observed at all centralities, both at RHIC and LHC

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More recent observables: Higher HQ flow components

In 1^{rst} approximation: $v_n \; \alpha$ eccentricity ε_n => look at the ratio for less trivial effects

LHC

More detailed analysis reveals that HQ benefit less and less from the flow of the bulk at large centrality, especially for higher harmonics.

Possible inertia effect: HQ need a longer time to develop their flow => earlier freeze out at larger centrality prevents the v_n to develop fully.

This may offer a different perspective on the probing of the system evolution (ESE)