

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

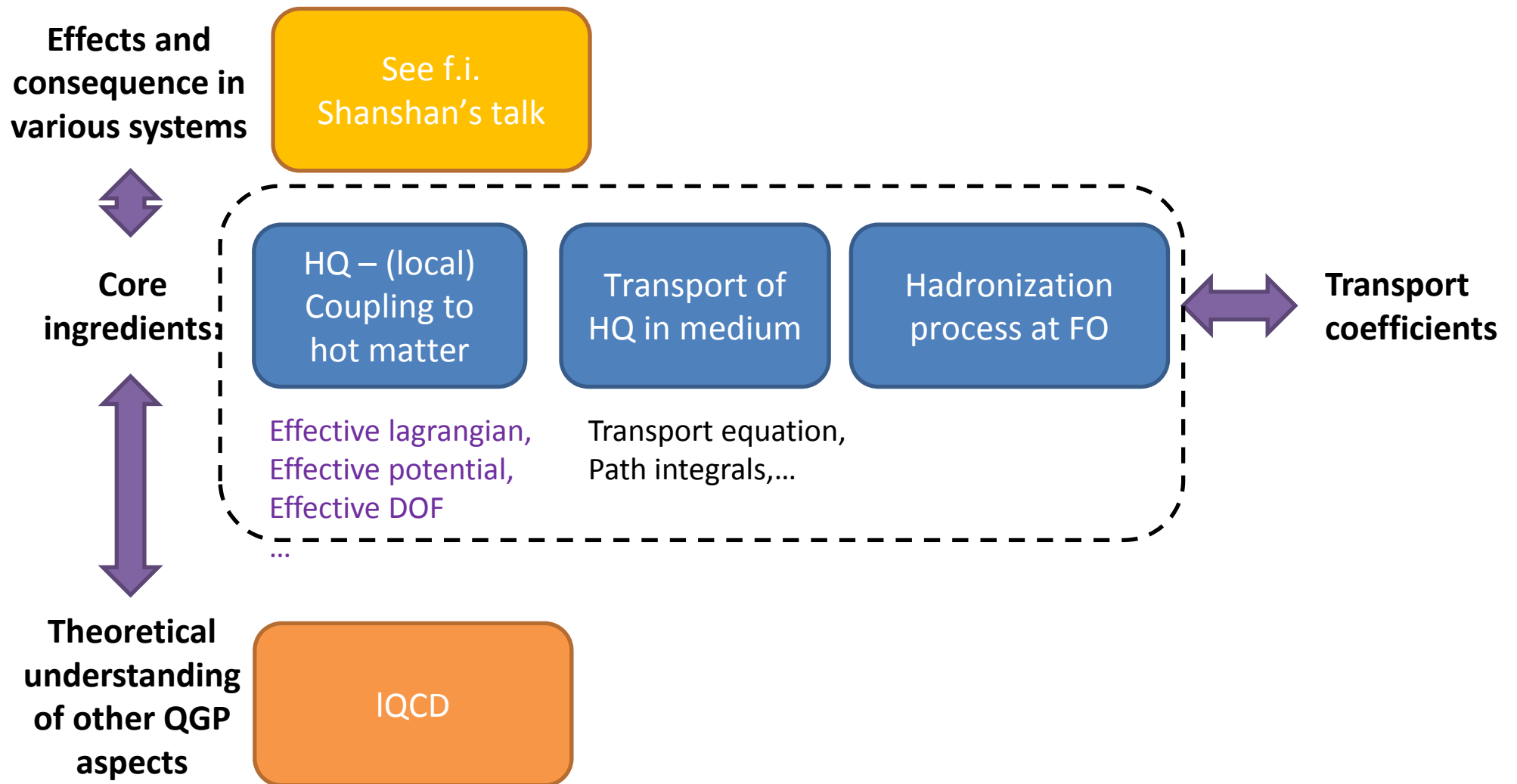
SUBATECH, UMR 6457

Université de Nantes, IMT Atlantique, IN2P3/CNRS

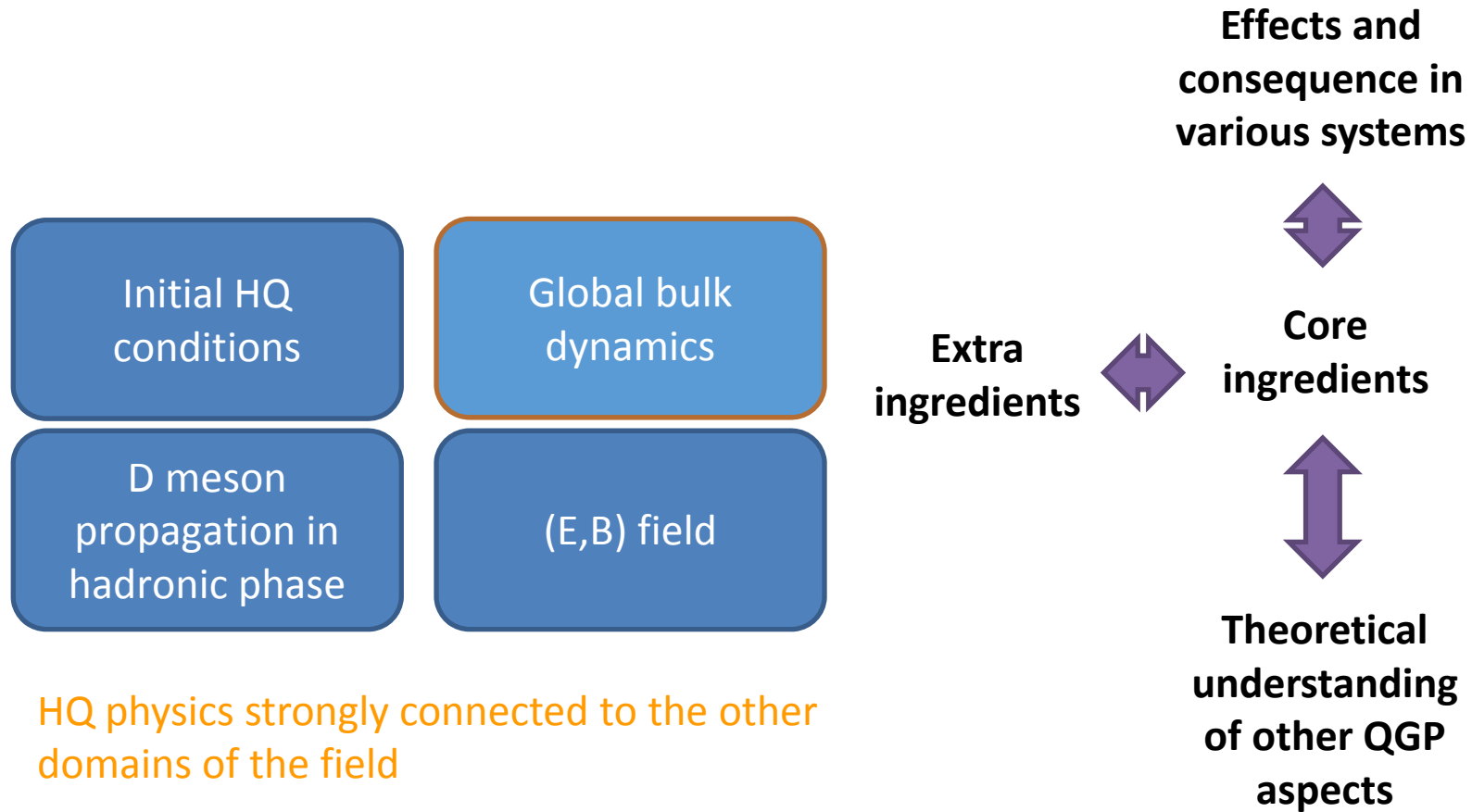
with

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

One model, several components



One model, several components

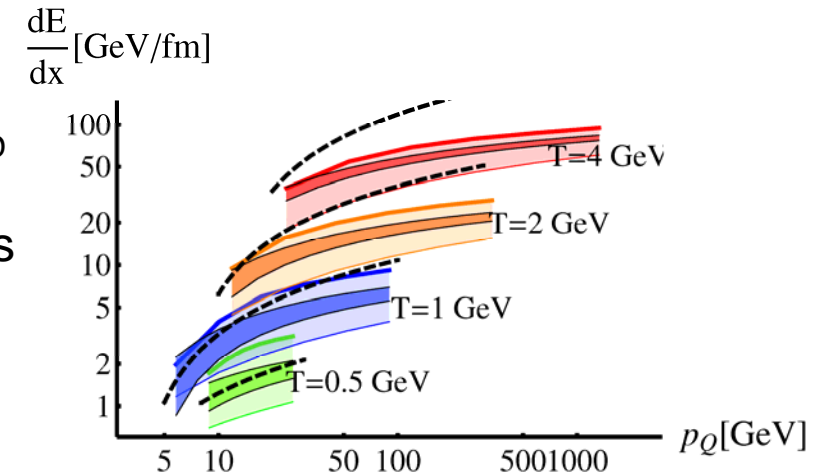


The core energy loss

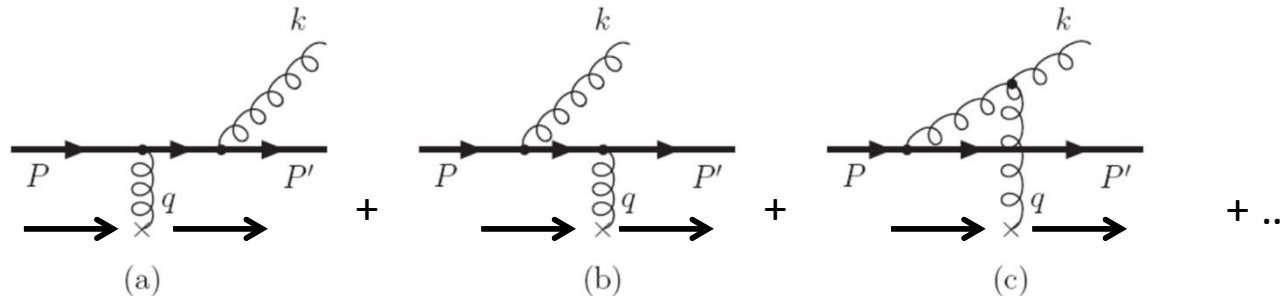
Collisional component

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

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



Radiative component

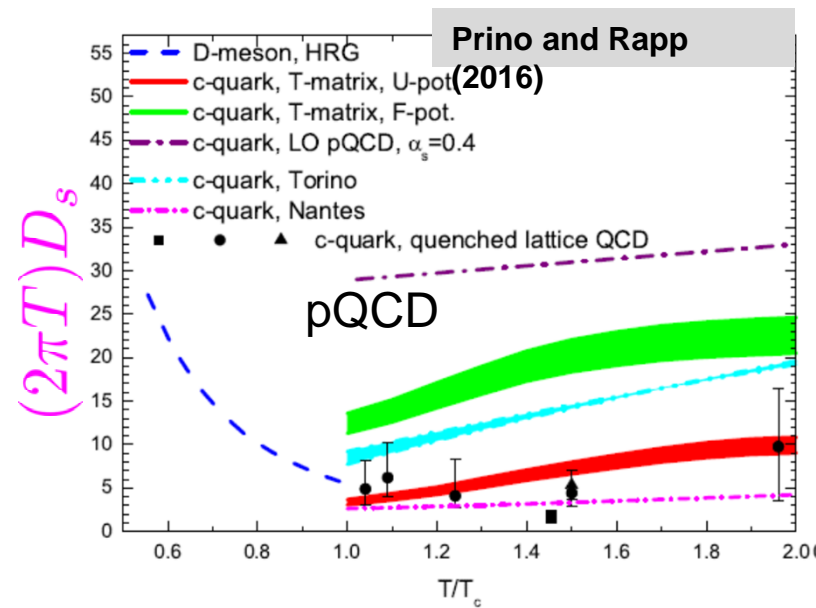


- Extension of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision ($\Delta E_{\text{rad}} \propto E L$):

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

- LPM effect for moderate gluon energy
- One extra K factor affecting the cross sections to be fitted on exp results

The core energy loss



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

- One of the strongest coupling on the « market »

The « extra » ingredients

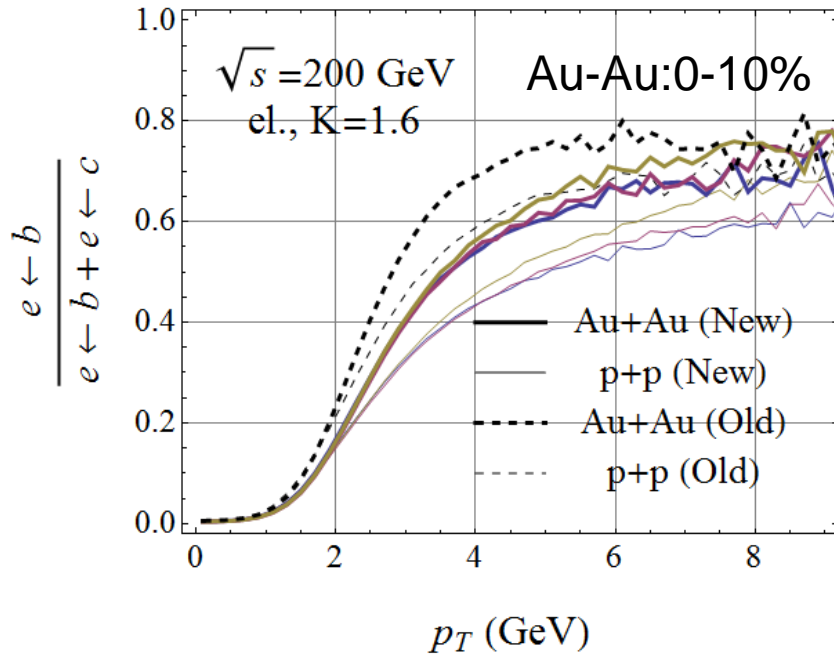
- 2 main « bundles »

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

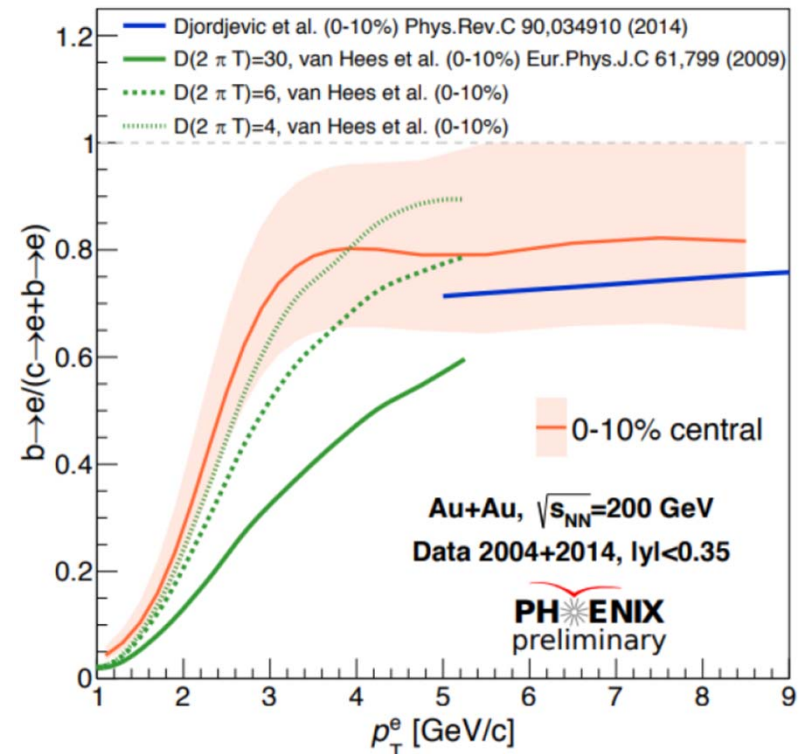
- Same E loss model in the 2 bundles

The « extra » ingredients

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



Talk Timothy Rinn

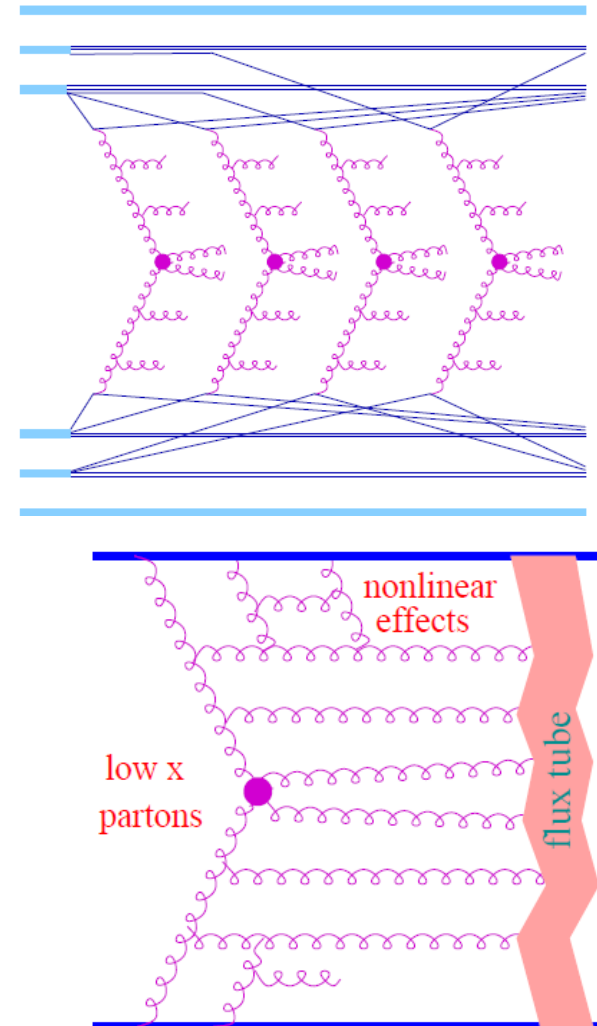


EPOS + Hydro as a background for MC@sHQ

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

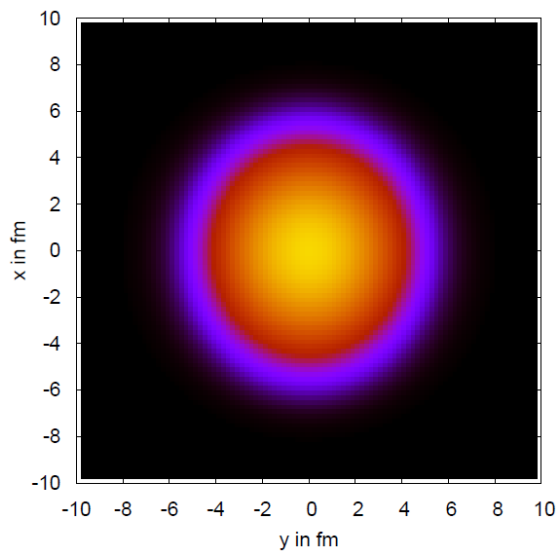


Ref: K. Werner, Iu. Karpenko, M. Bleicher, T. Pierog, and S. Porteboeuf-Houssais Phys. Rev. C 85 (2012), 064907

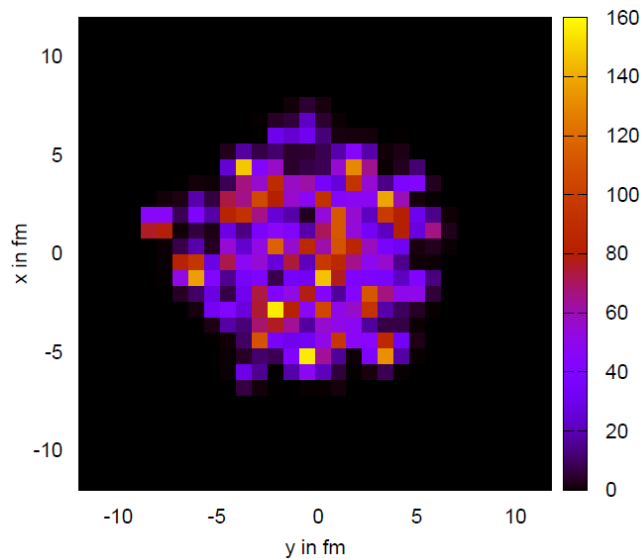
EPOS + hydro as a background for MC@sHQ

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

Initial energy density



Kolb Heinz (used previously)



EPOS

Beware: \neq color scales

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

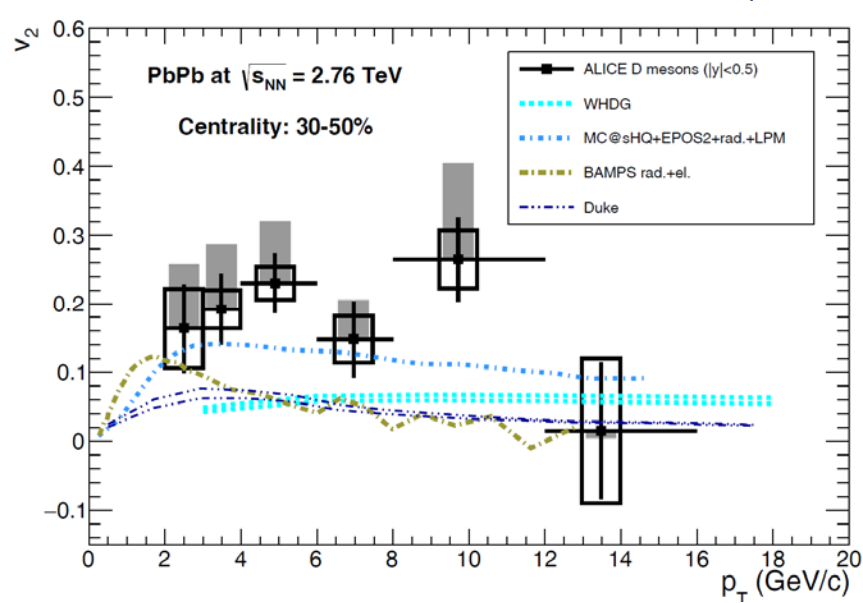
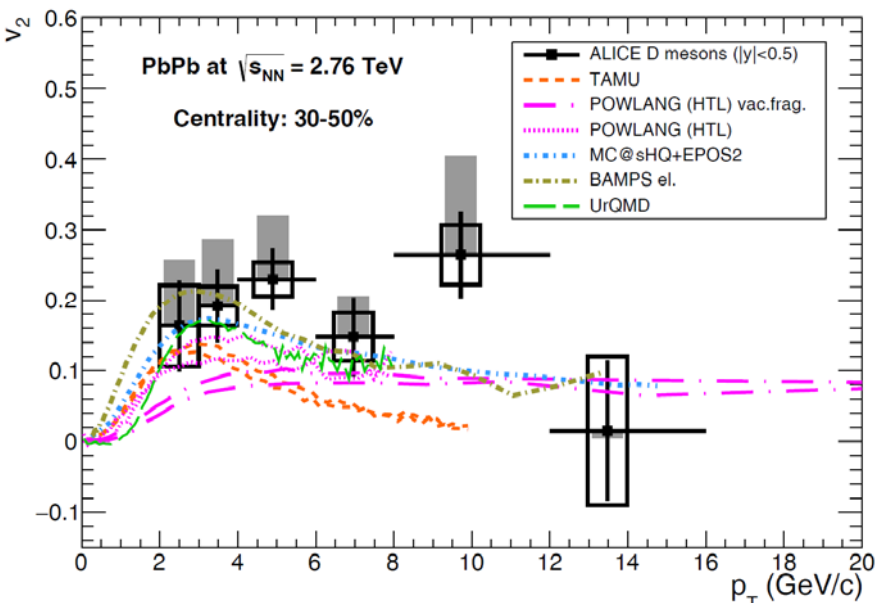
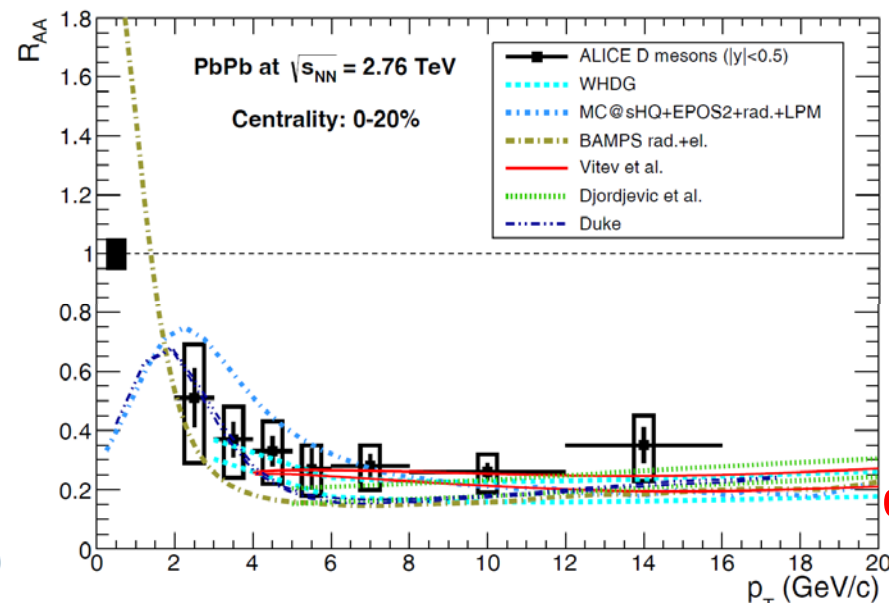
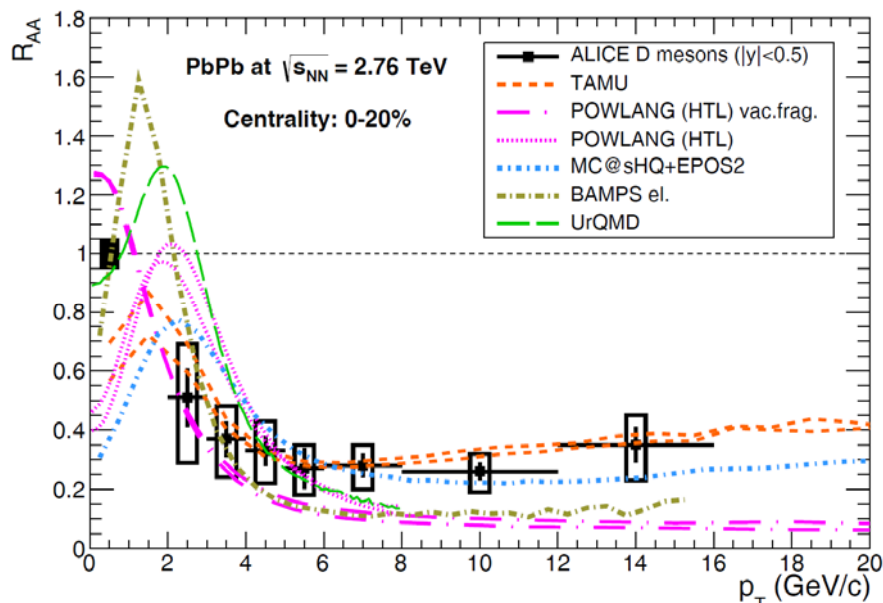
- 1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)
- 2) correlations between HF and light hadrons

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 success...

Bundle 2 @ LHC

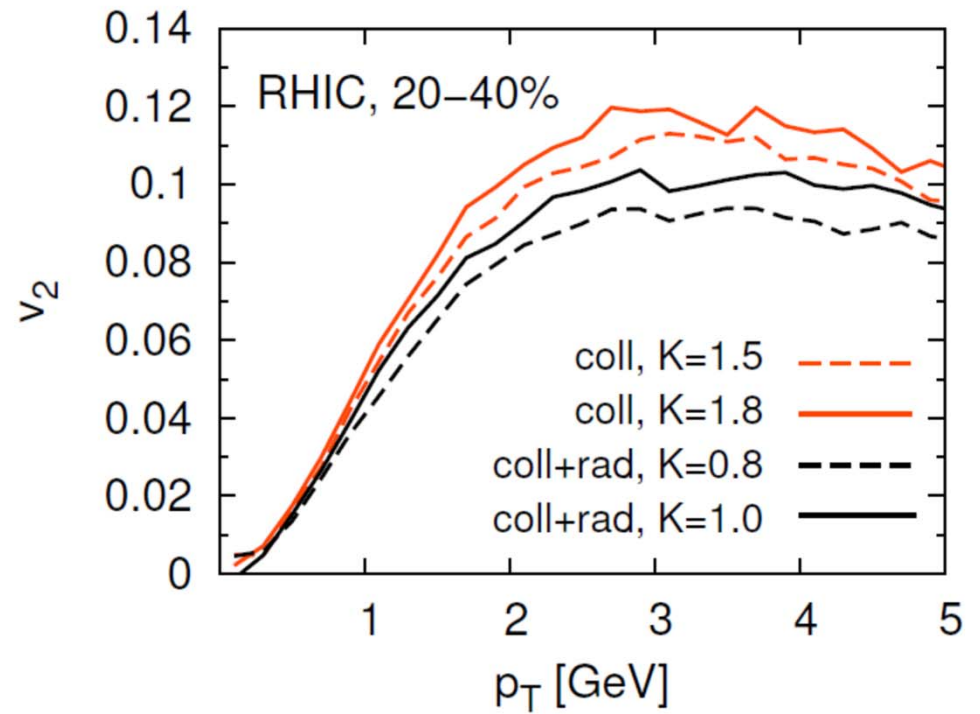
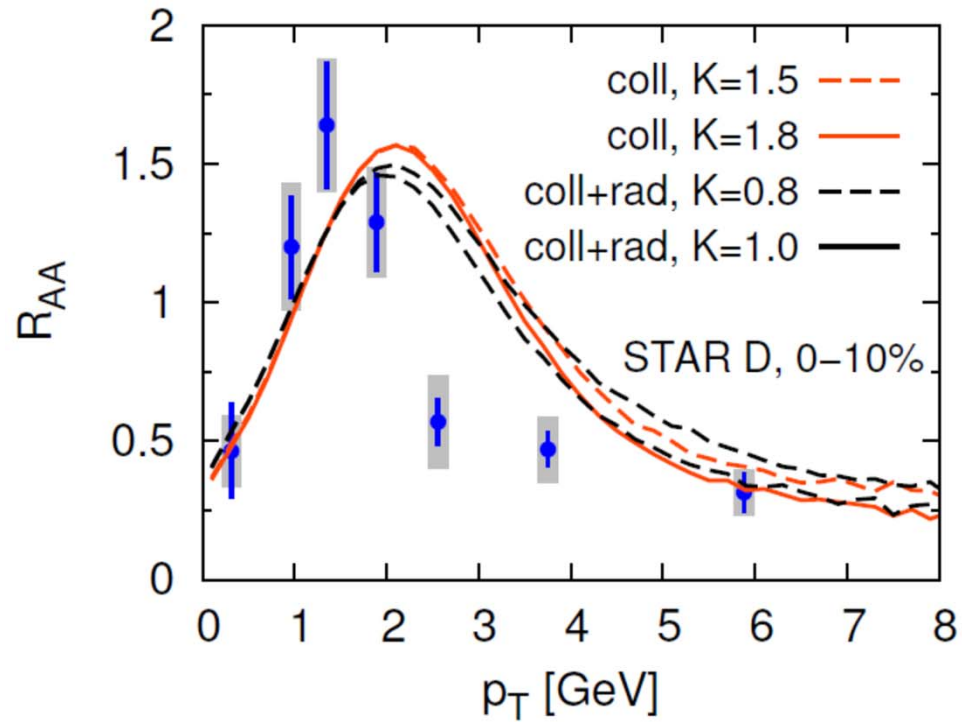
Purely elastic scatterings



Elastic scatterings + radiative energy loss

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 !!!

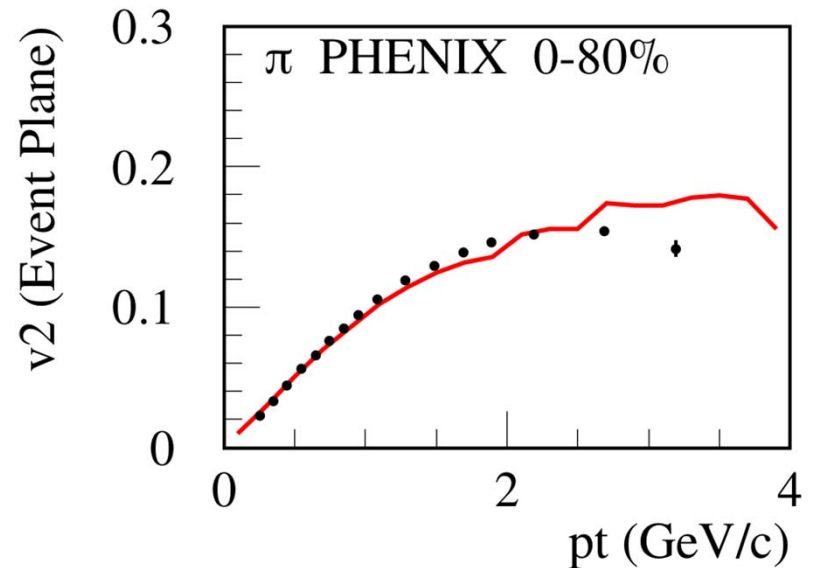
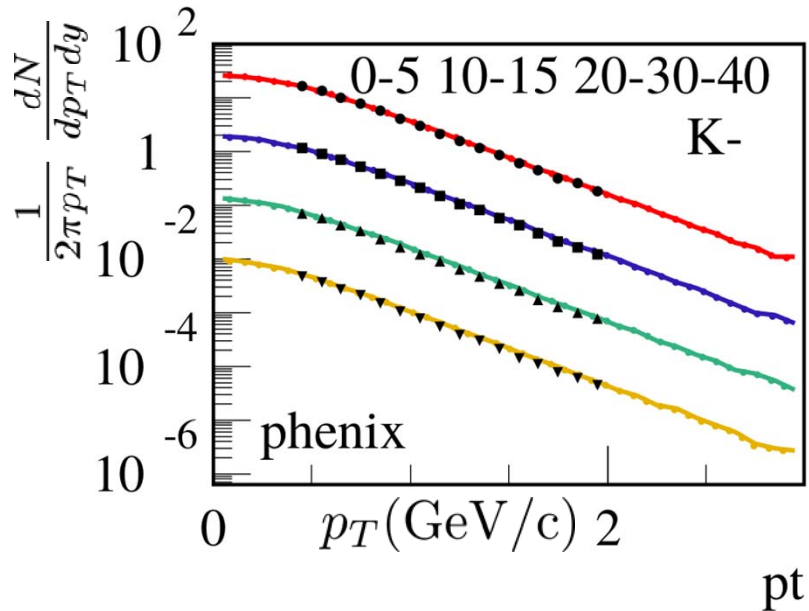
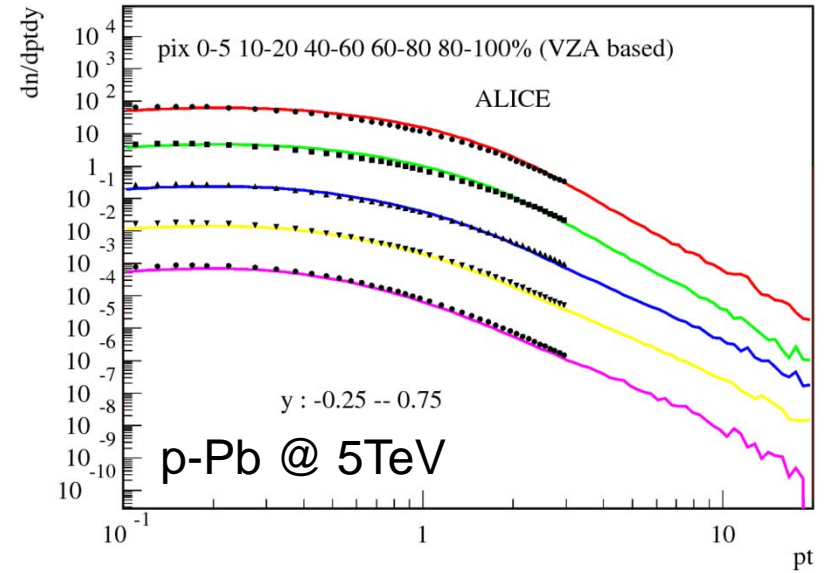
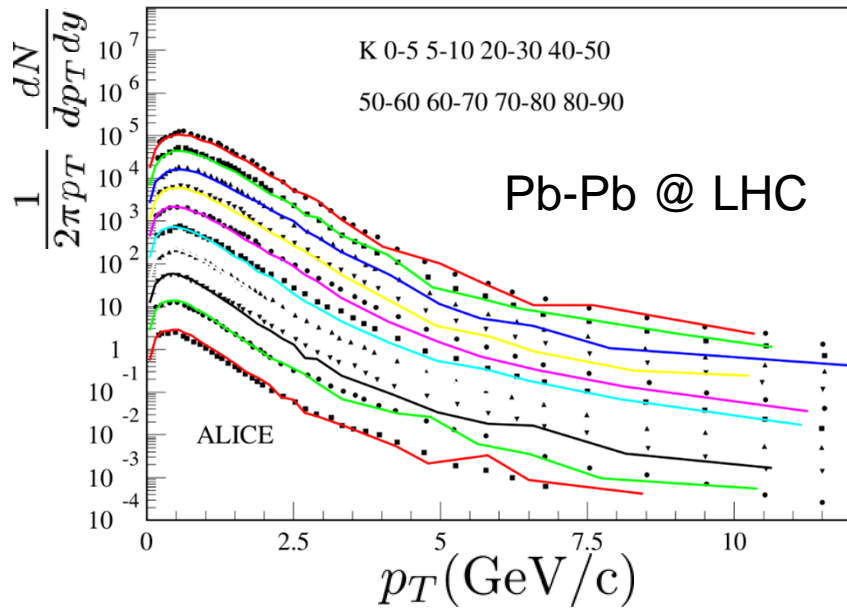
Motivation for the new bundle

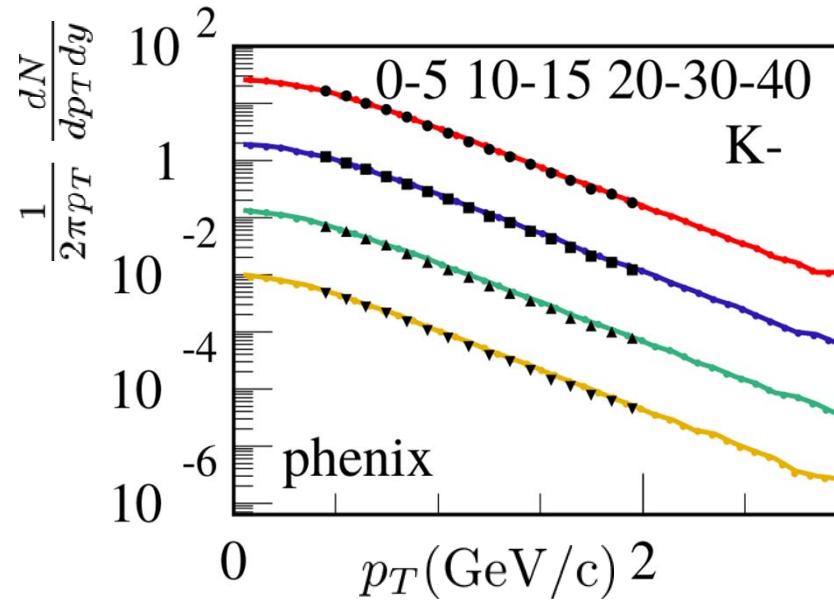
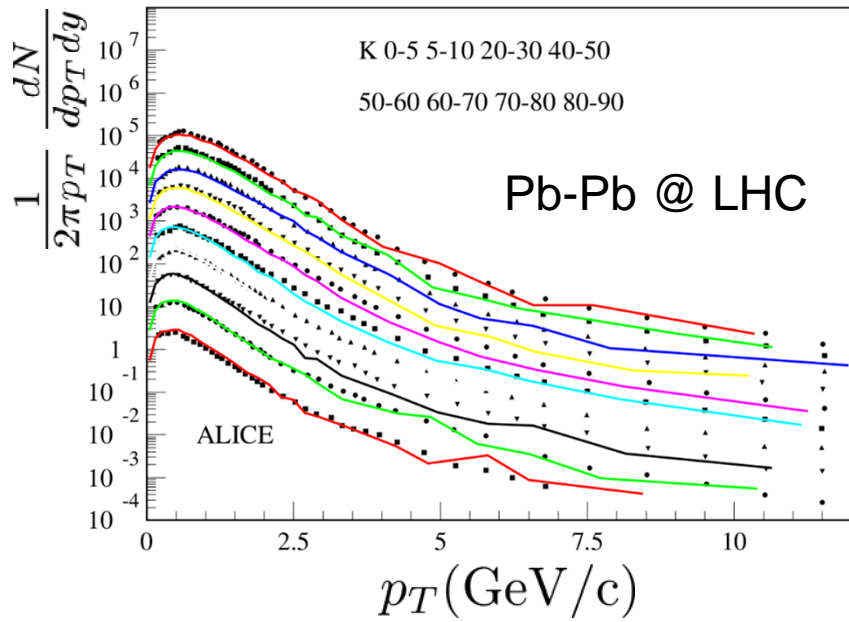
Bundle 3: EPOS(3)-HQ

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

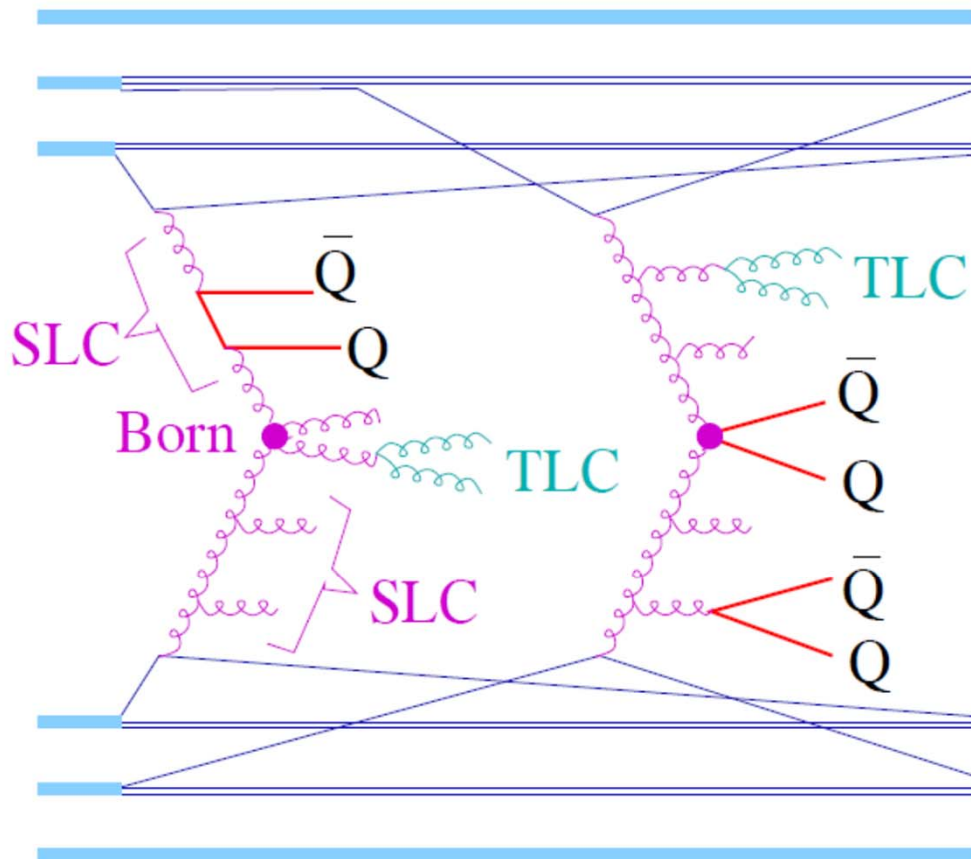
Illustrating EPOS3 vs data for light hadrons





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:

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

Lessons from EMMI RRTF

R. Rapp et al, arXiv: 1803.03824

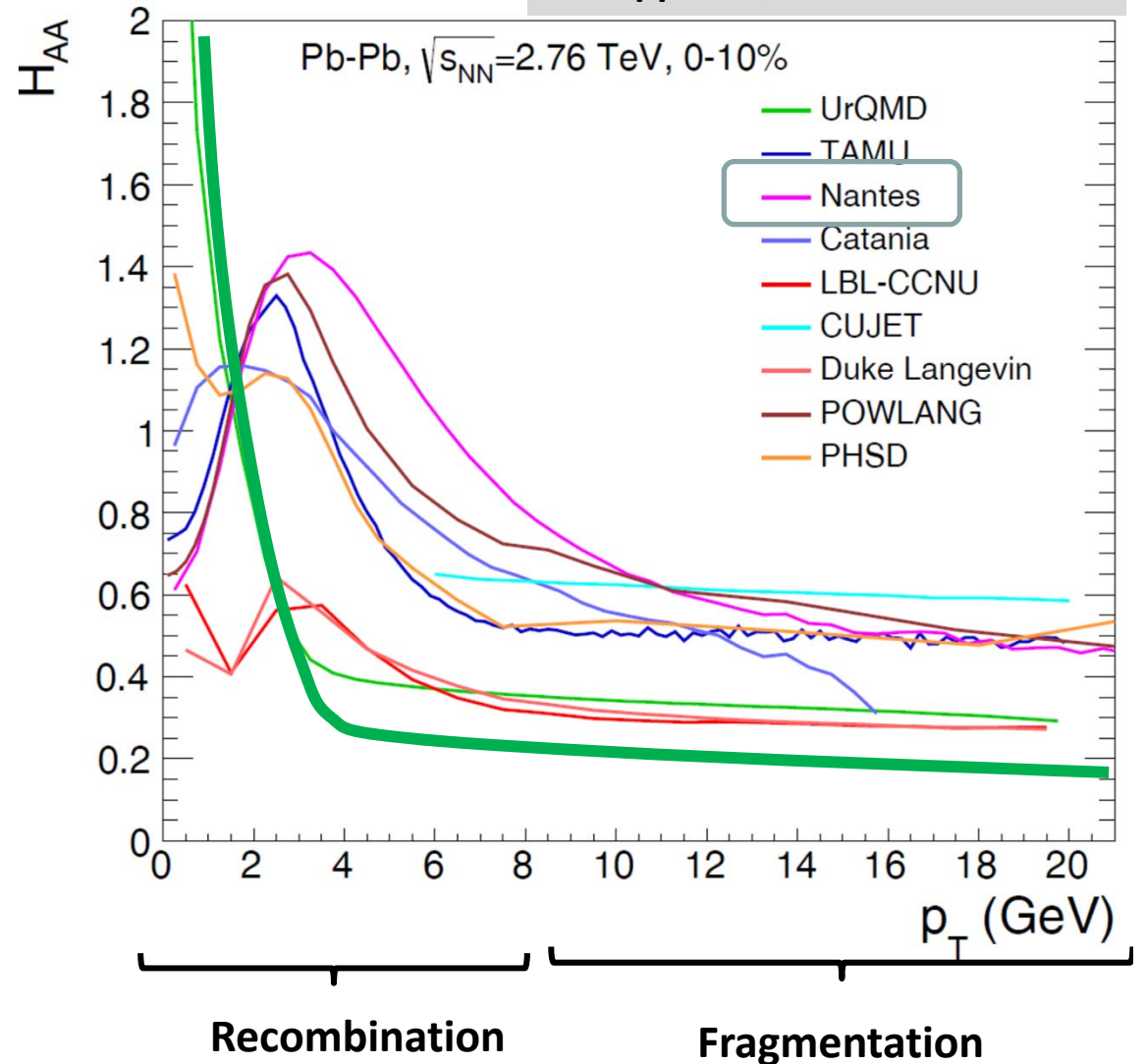
We define and display the H_{AA} quantity

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

...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 coalescence.



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

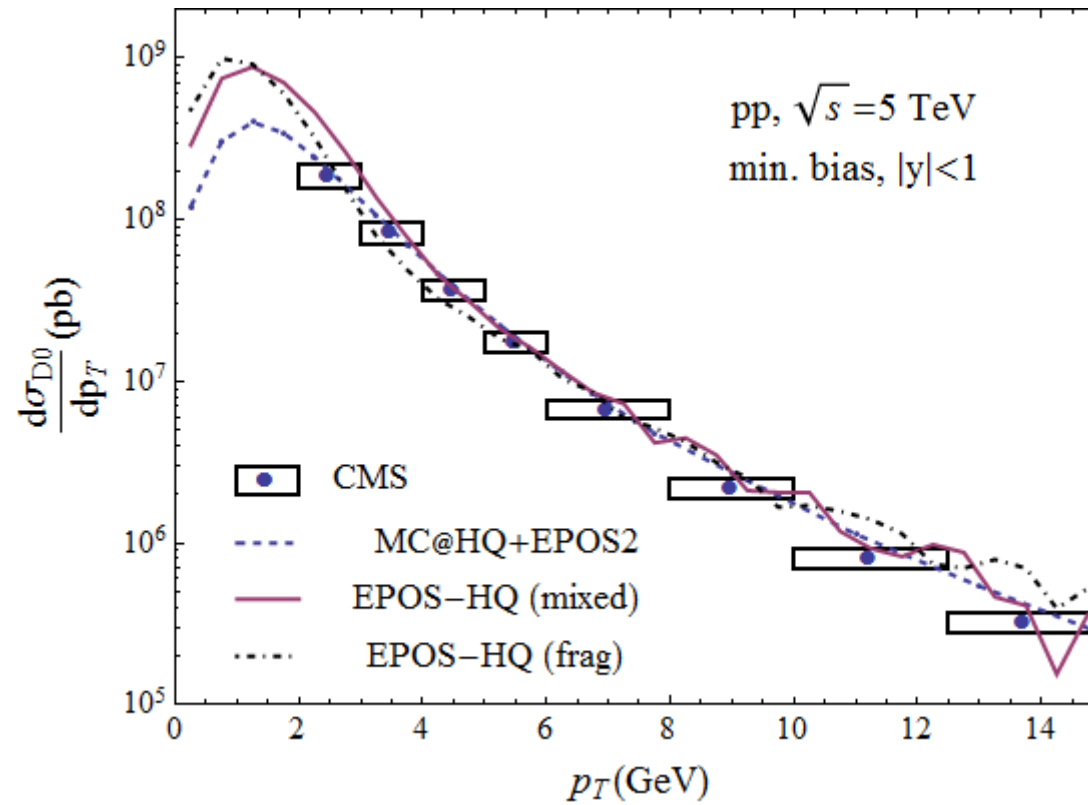
Main questions:

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 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)

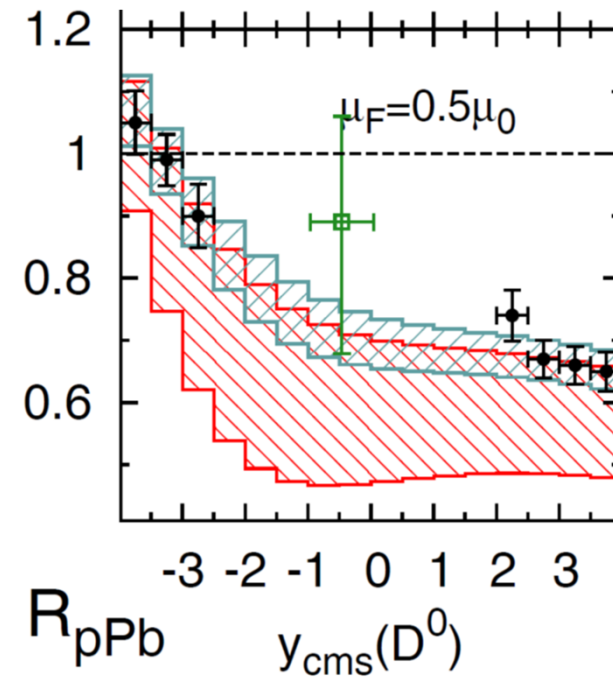
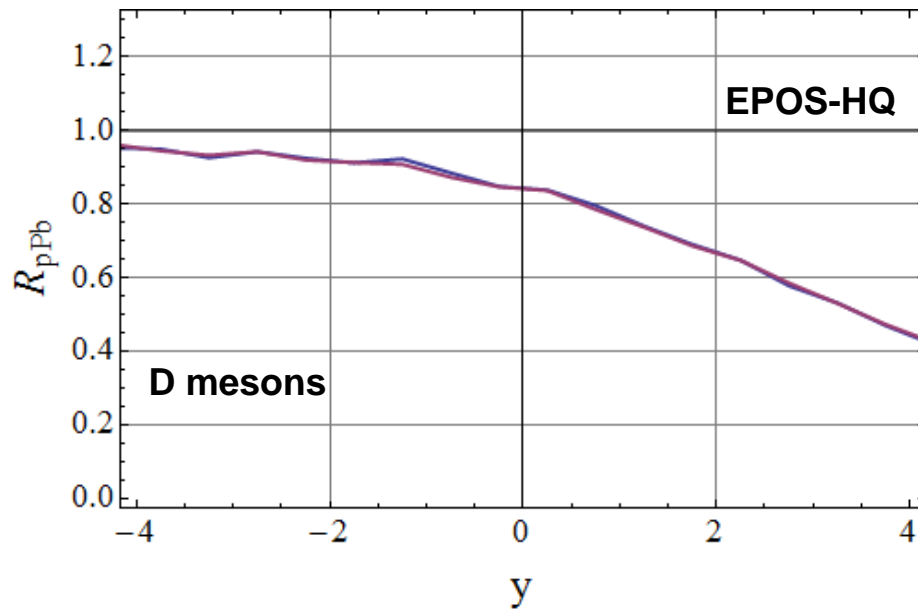
Method : Needs to adjust several components => complicated issue.

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

“pp” @ 5 TeV



“initial state effects” in p-Pb 5 TeV

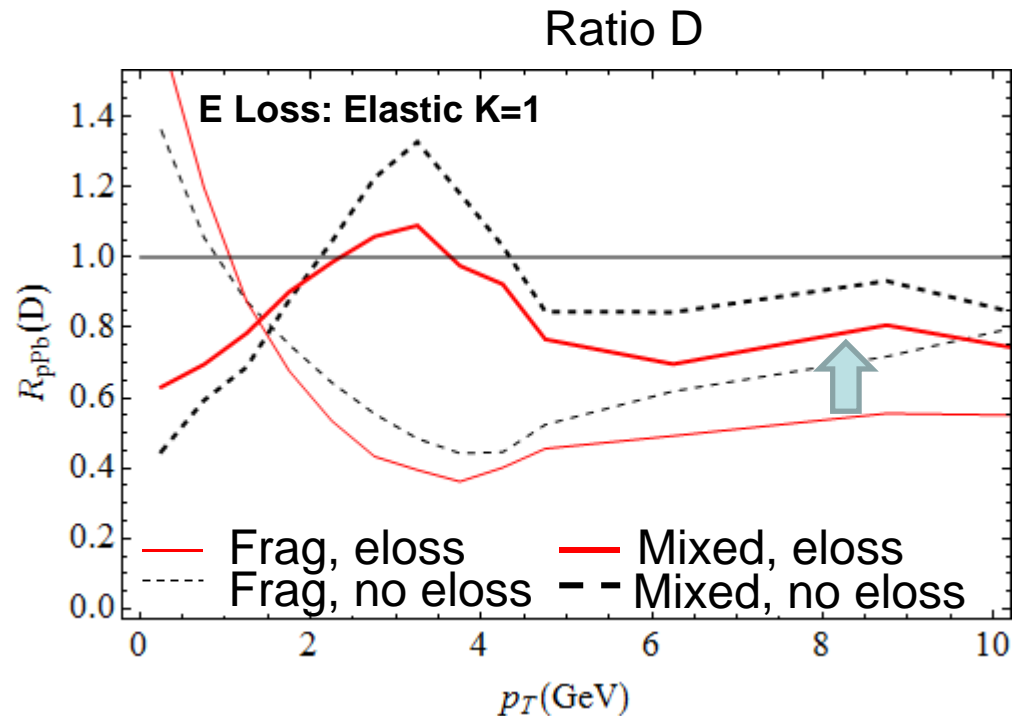
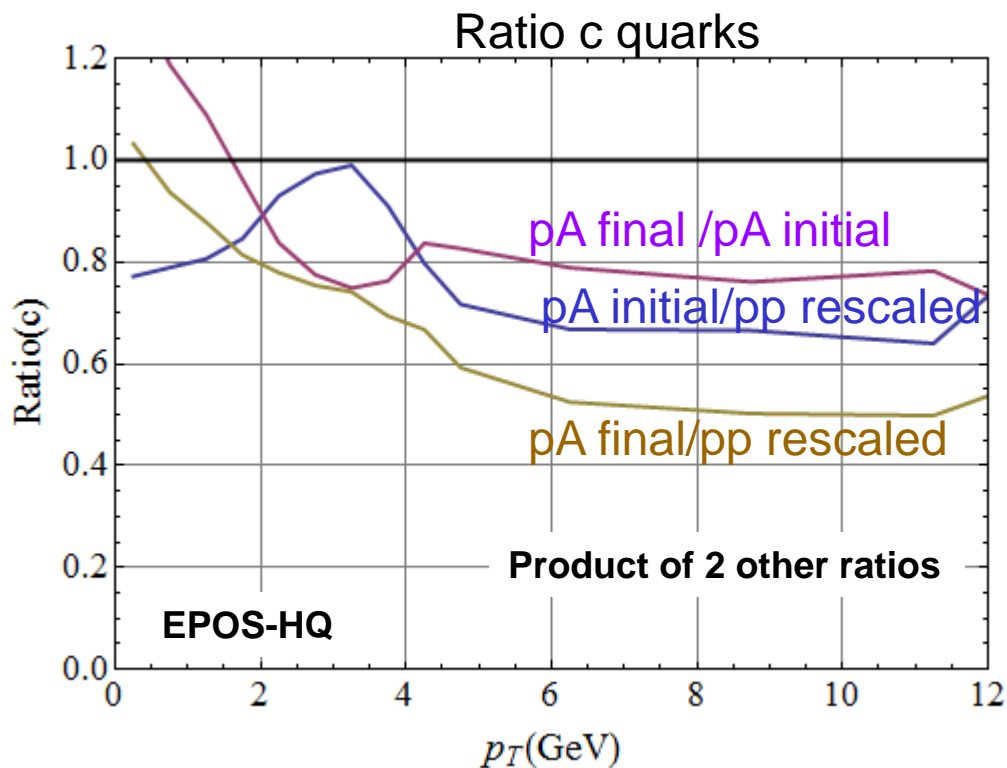


Sensitivity

Saturation	Hadronisation	E Loss
YES	NO	NO

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

“initial state effects” in p-Pb 5 TeV

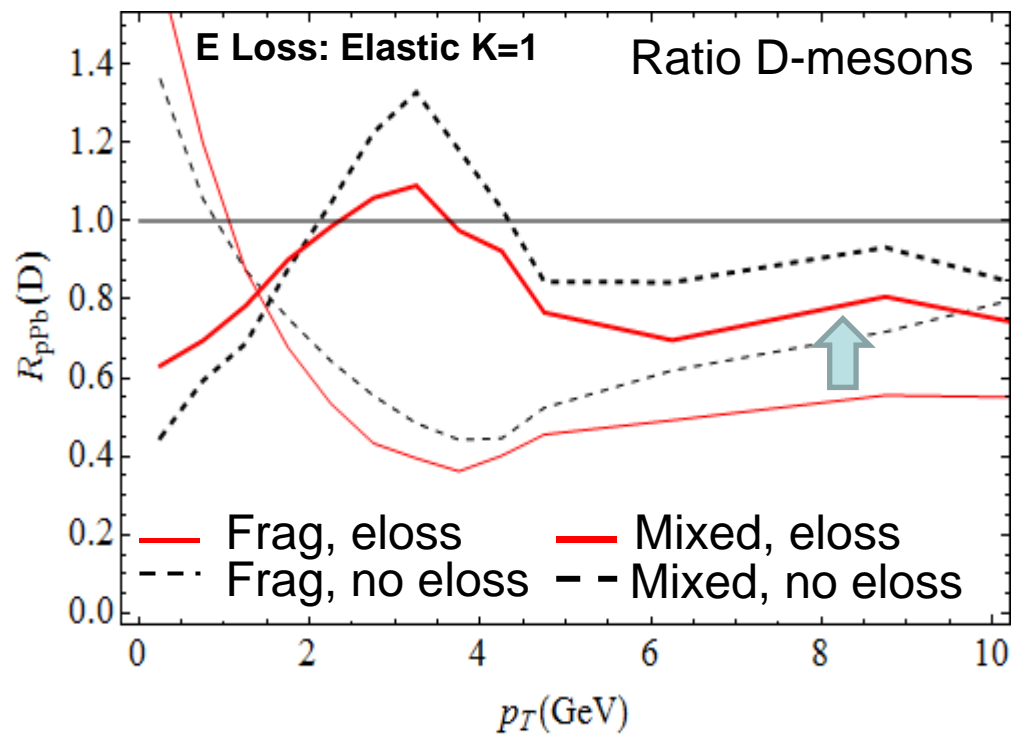
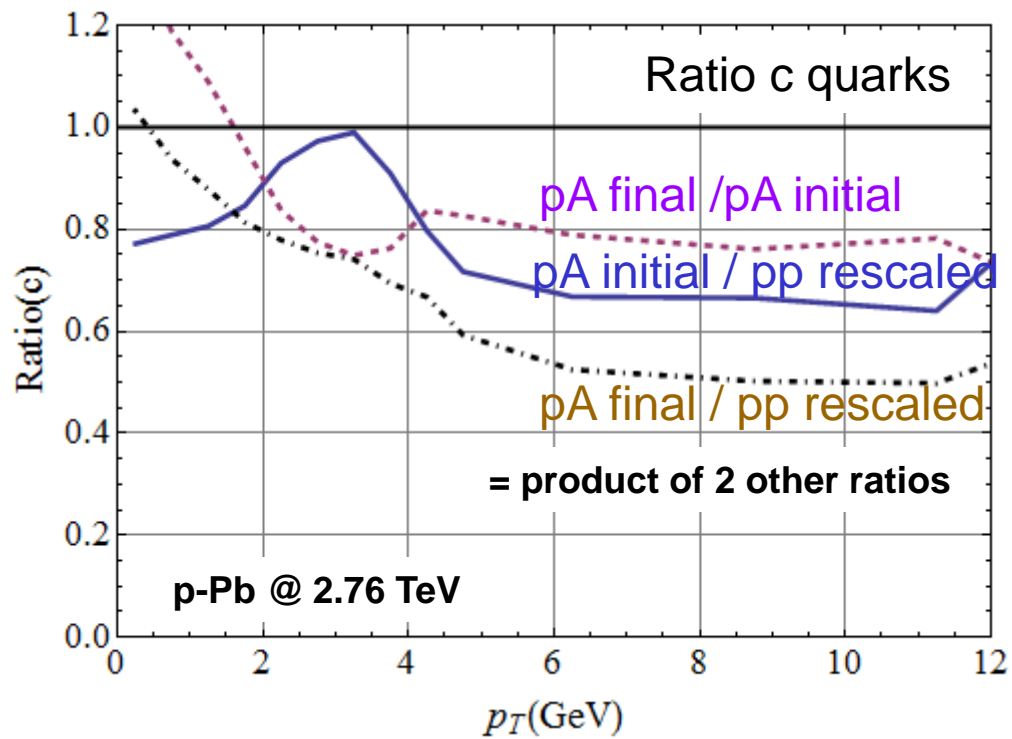


Sensitivity

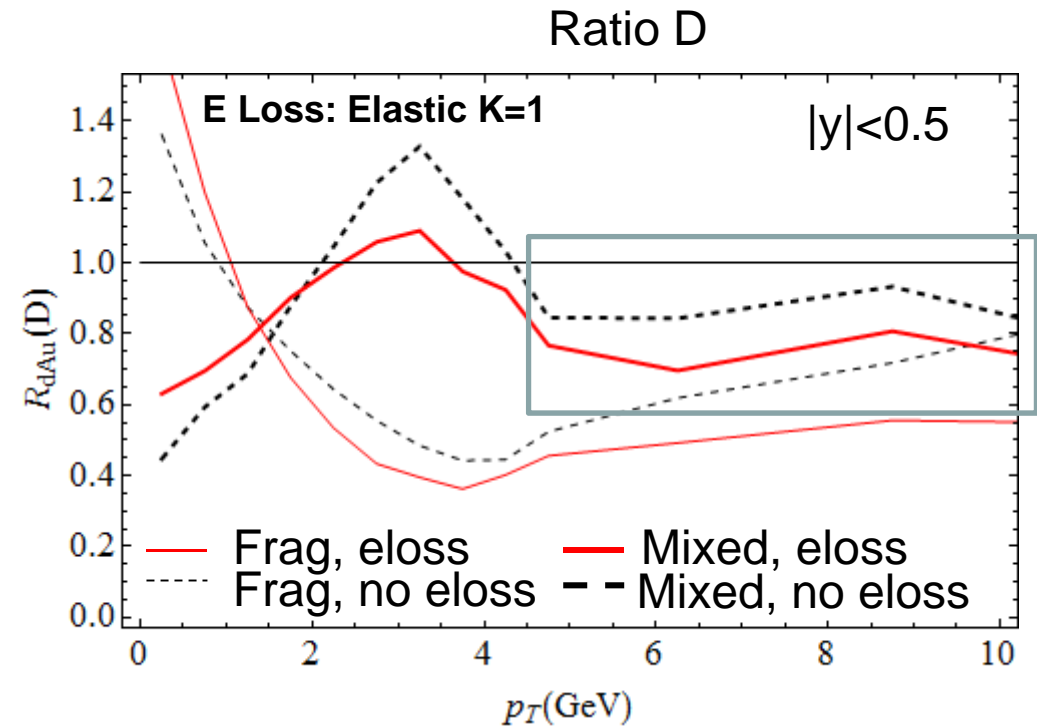
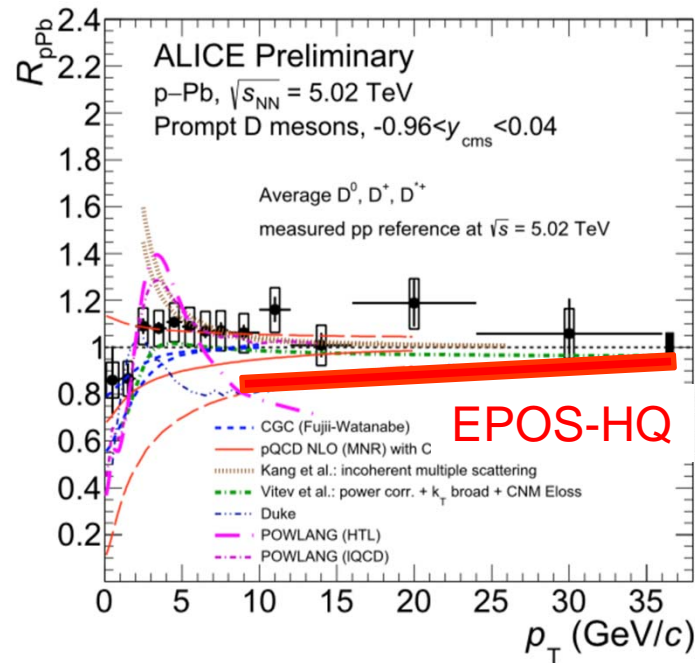
Saturation	Hadronisation	E Loss
YES	YES	YES

Our implementation of the coalescence has consequences up to 10 GeV

... and chemistry ! Complicated !!!



“initial state effects” in p-Pb 5 TeV



Sensitivity

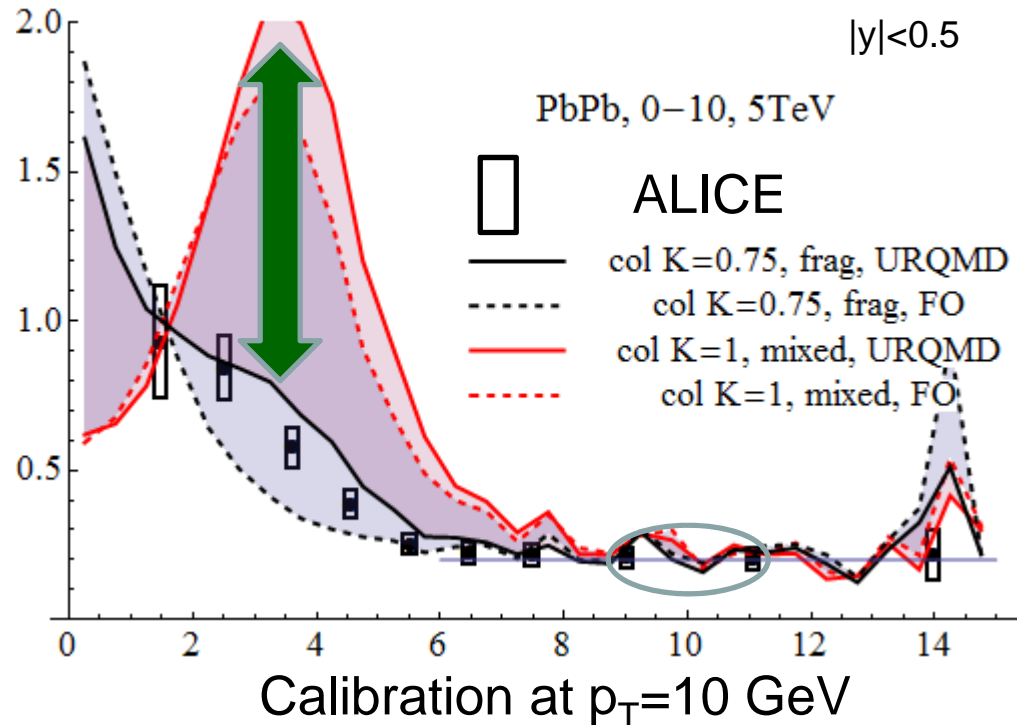
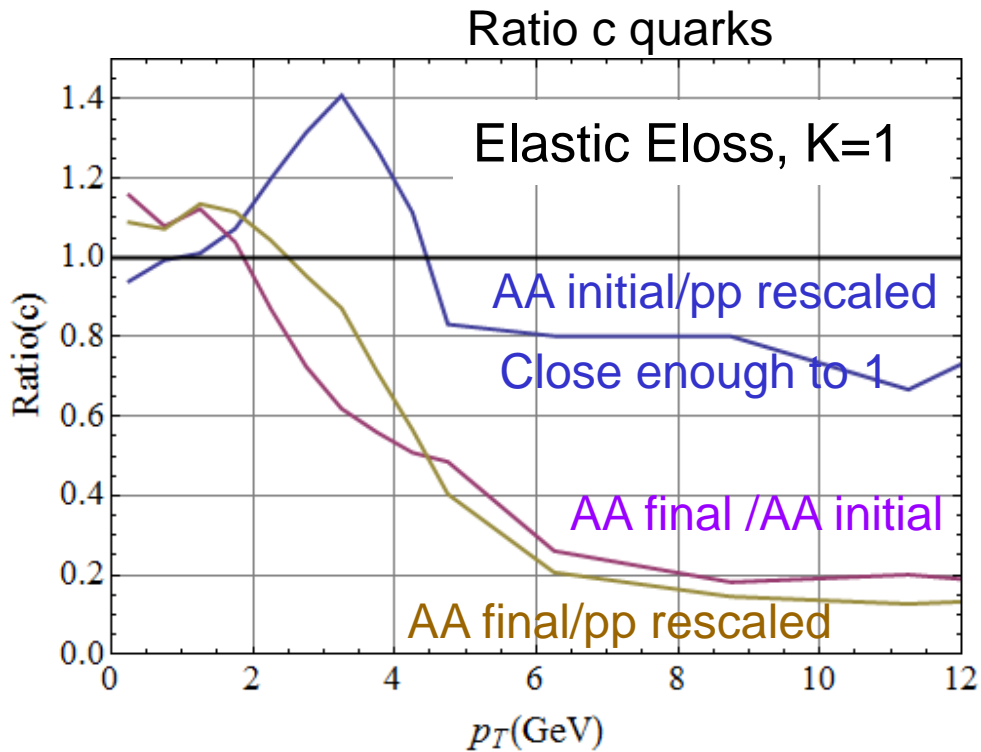
Saturation	Hadronisation	E Loss
YES	YES	YES

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

Also need to compare to LHCb data

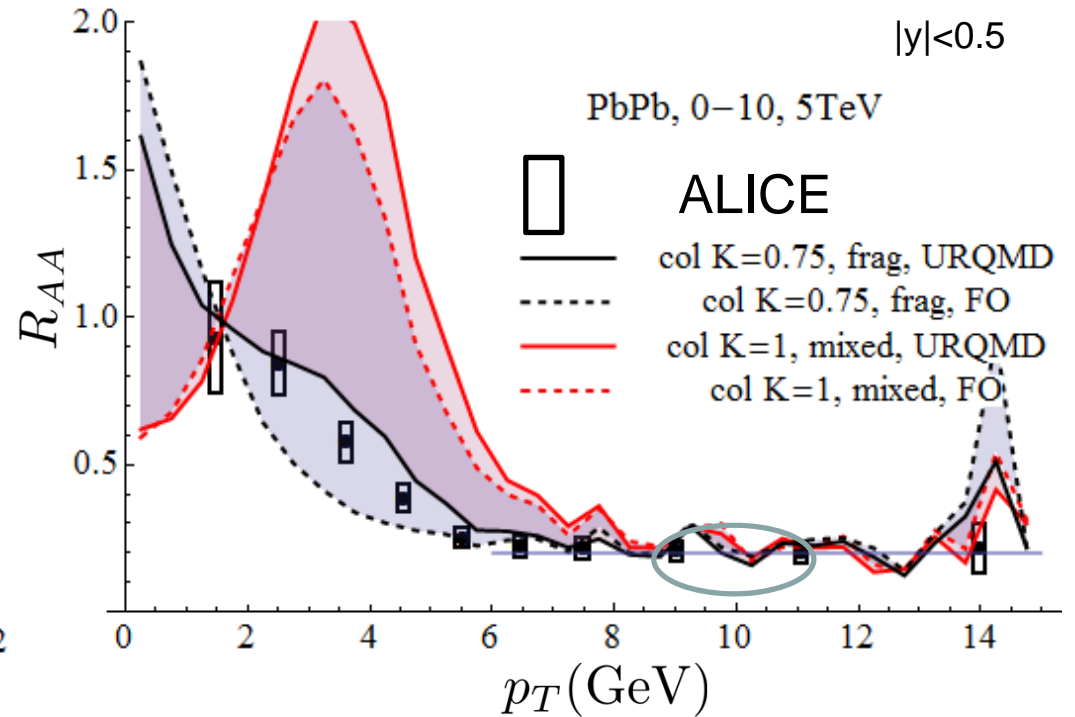
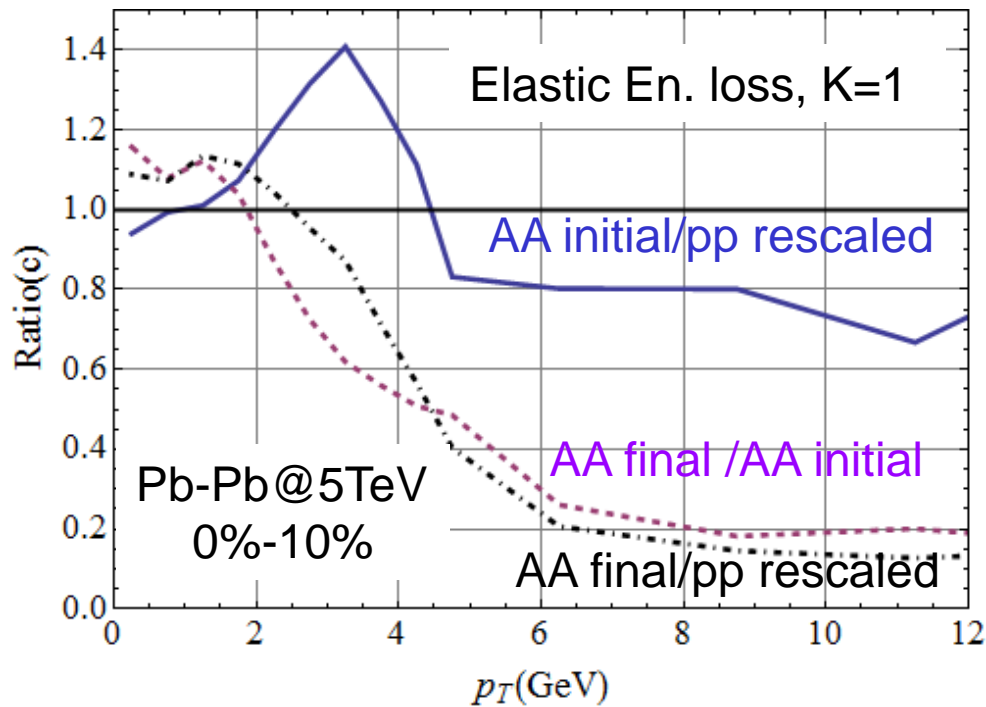
At least one conclusion: pure fragmentation ruled out

D meson production in central Pb-Pb



CNM	Hadro	E Loss	Hadro rescat	Chemistry
YES	Large $p_T < 8\text{GeV}$		Moderate $p_T < 5$ GeV	?

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

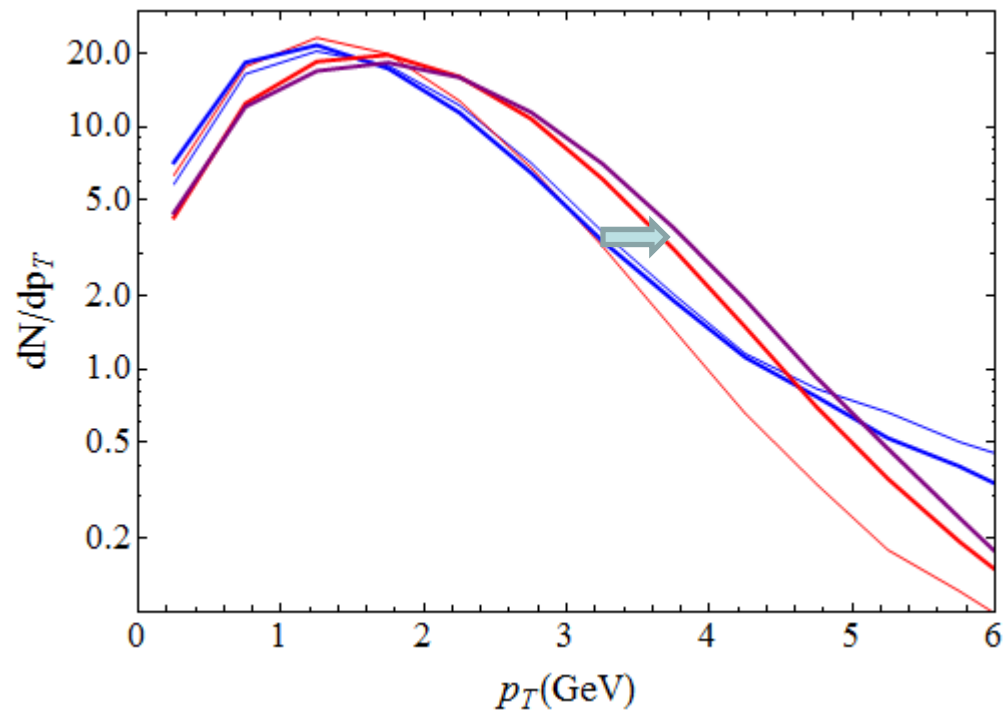


We overshoot unity with our present coalescence model; pure frag does not perform so bad after all !

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):

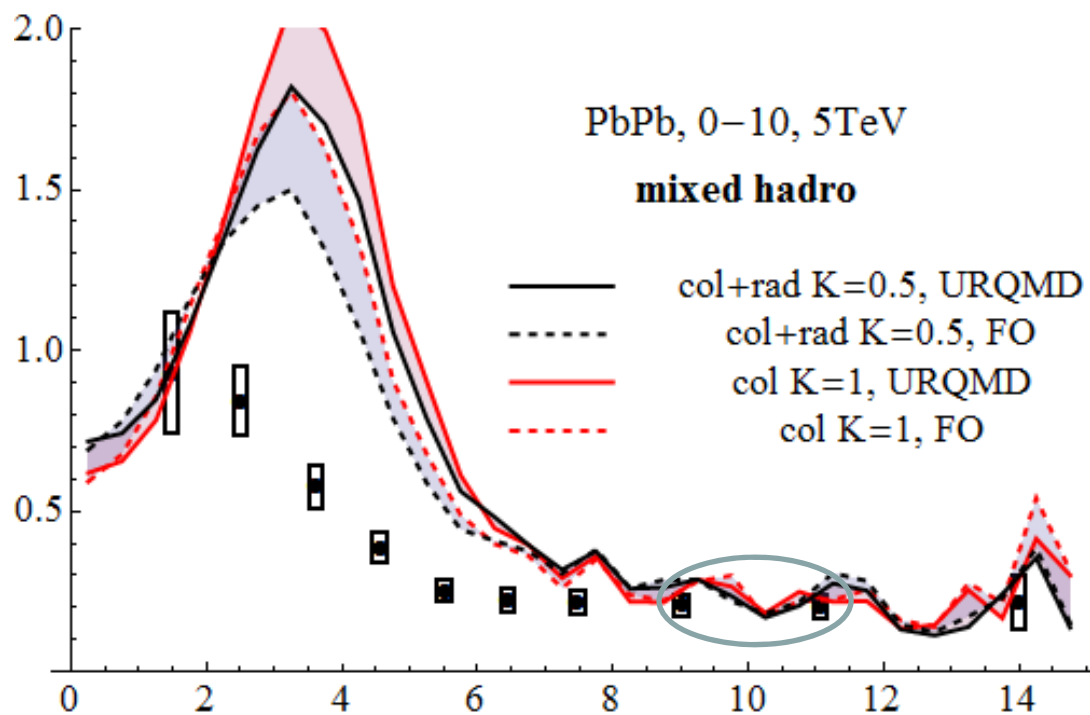
- Some $c \rightarrow \Lambda_c$
- Modify coalescence to gain less momentum at FO (as in RRM)

Need to consider the full chemistry effects

D meson production in central Pb-Pb

Looking at “full” Eloss

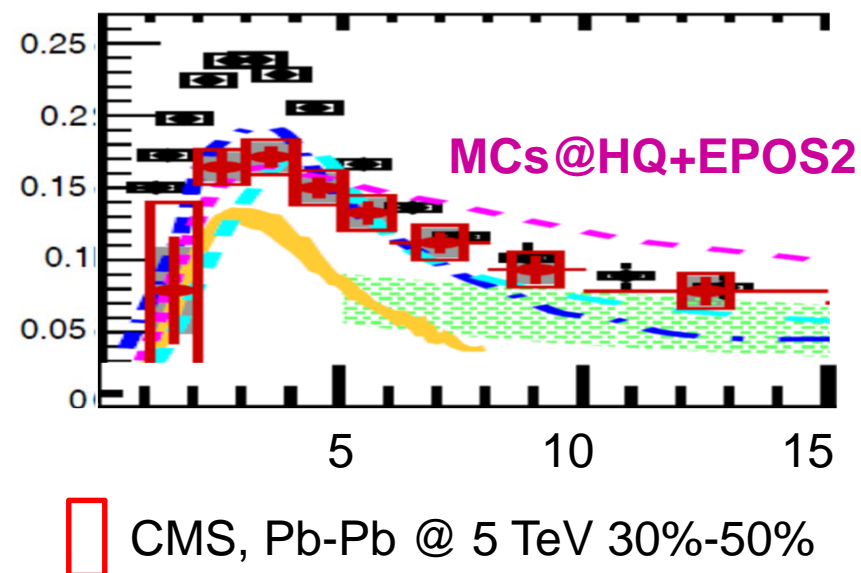
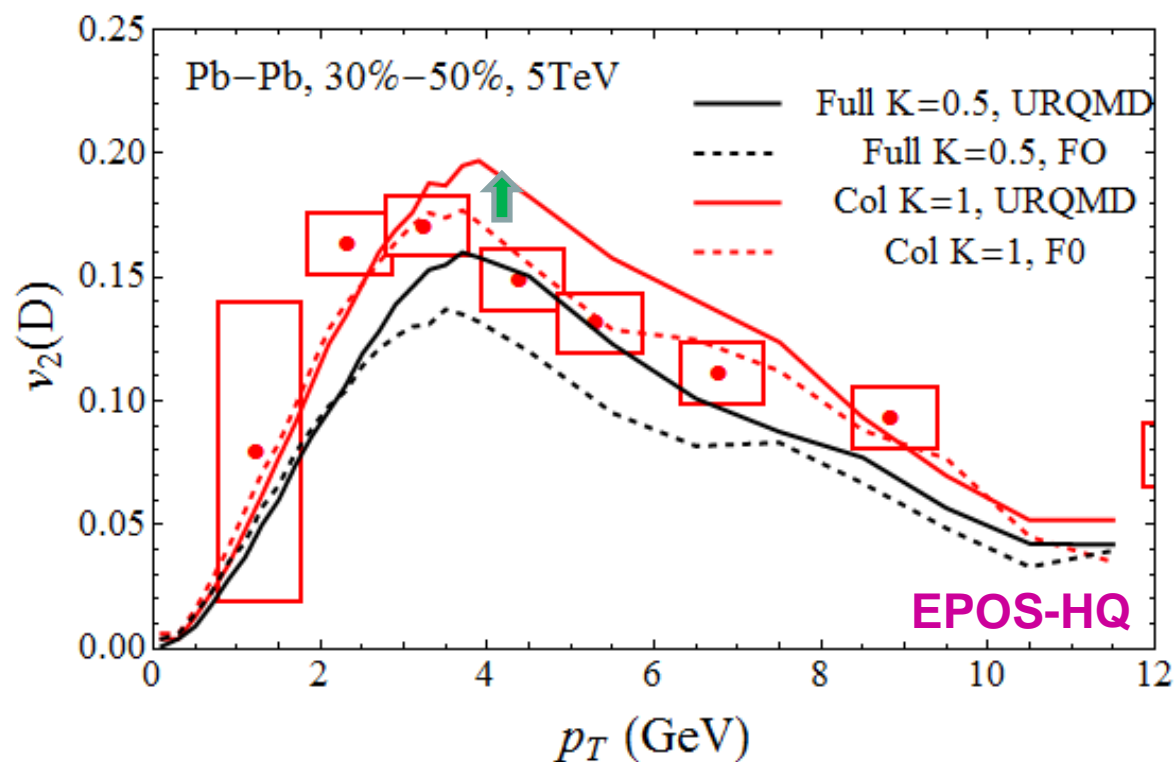
Elastic + Radiative Eloss, $K=0.5$



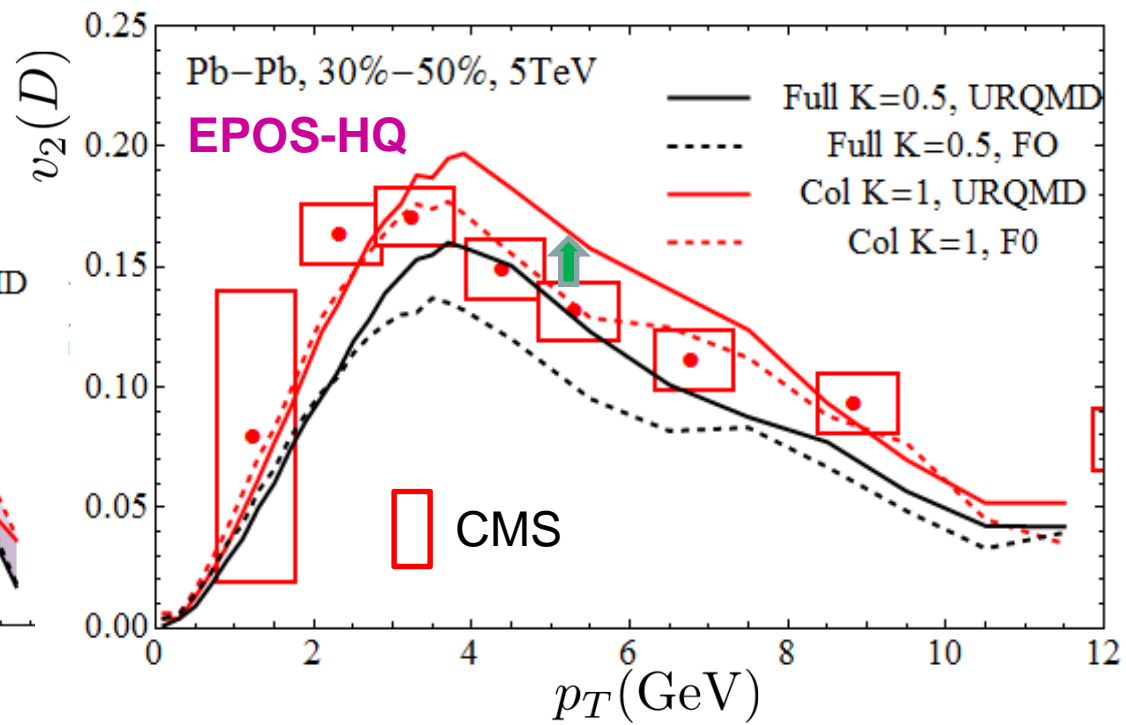
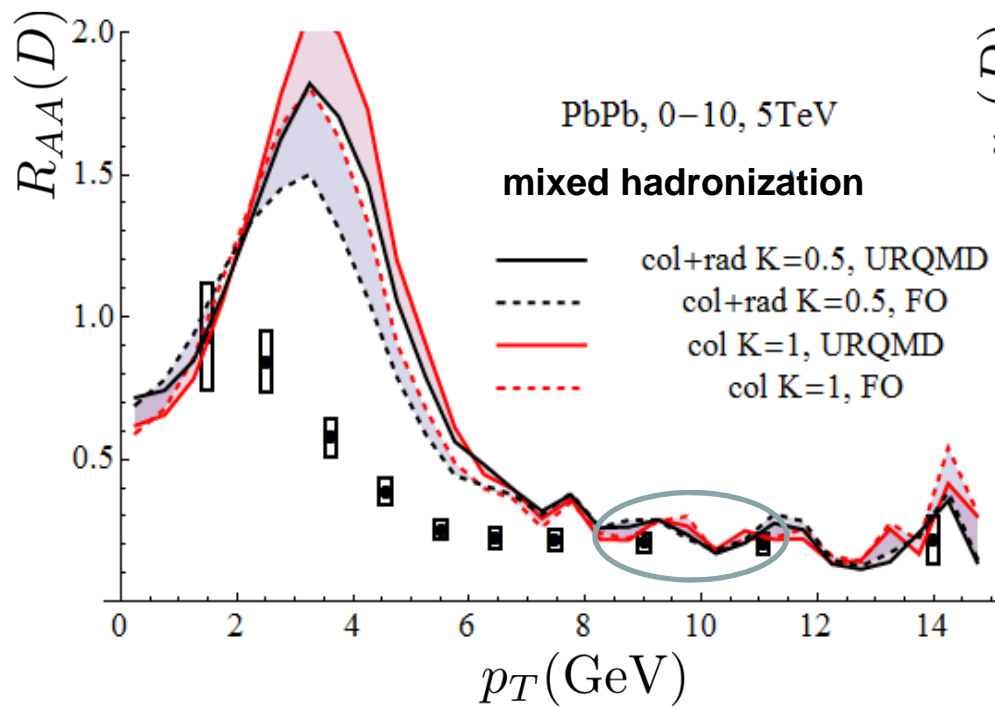
Calibration at $p_T=10$ GeV

CNM	Hadro	E Loss	Hadro rescat
YES	Large $p_T < 8\text{GeV}$	Moderate for $p_T < 20\text{ GeV}$	Moderate $p_T < 5\text{ GeV}$

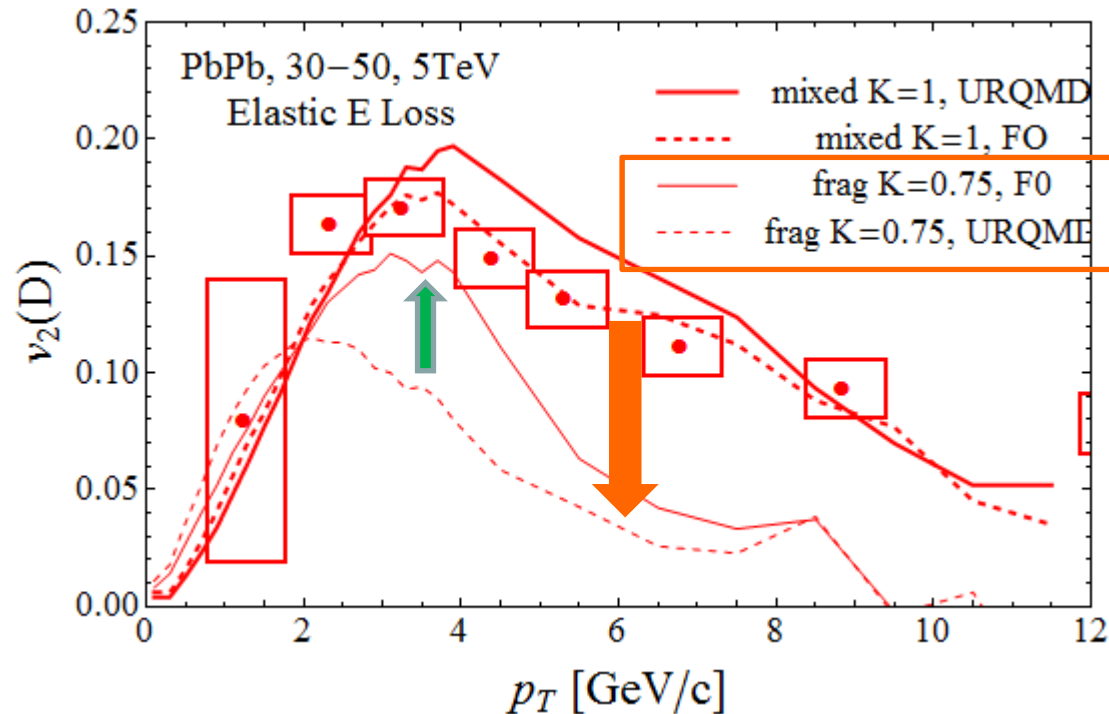
D meson production in semi-central Pb-Pb: flows



- Moderate but significant increase of v_2 from production at FO \rightarrow end of URQMD evolution (\uparrow)
- Better agreement than in previous predictions (especially the decrease at intermediate p_T)

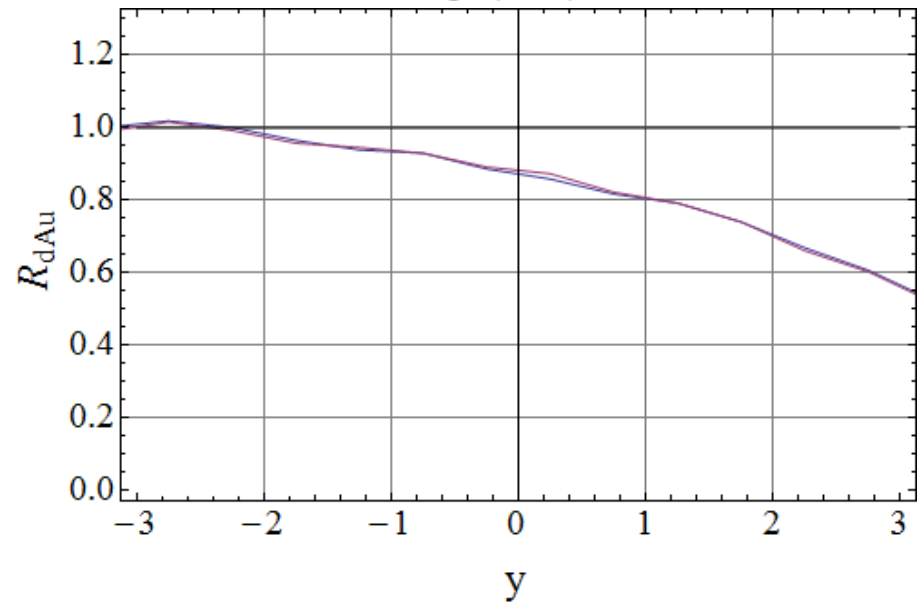
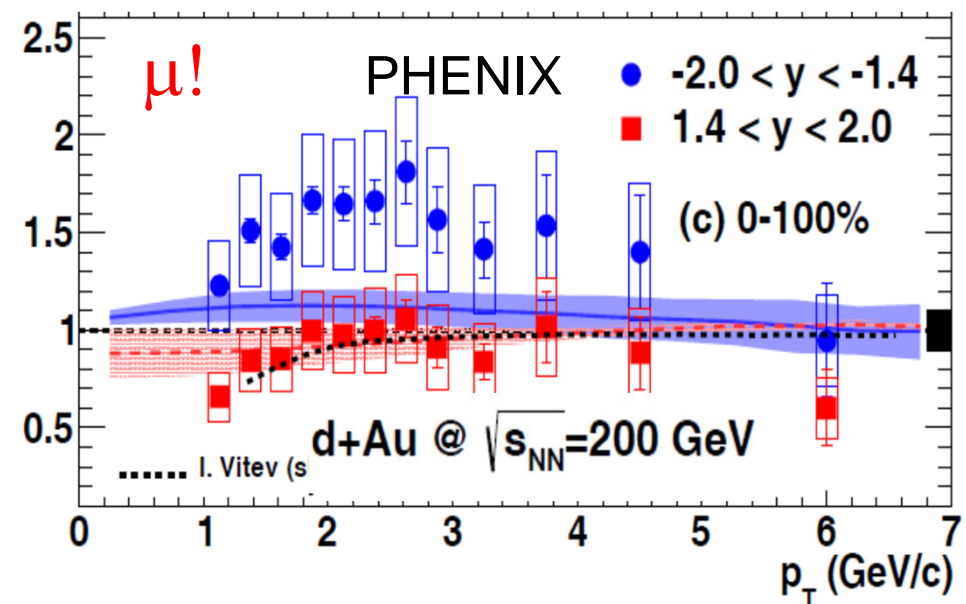
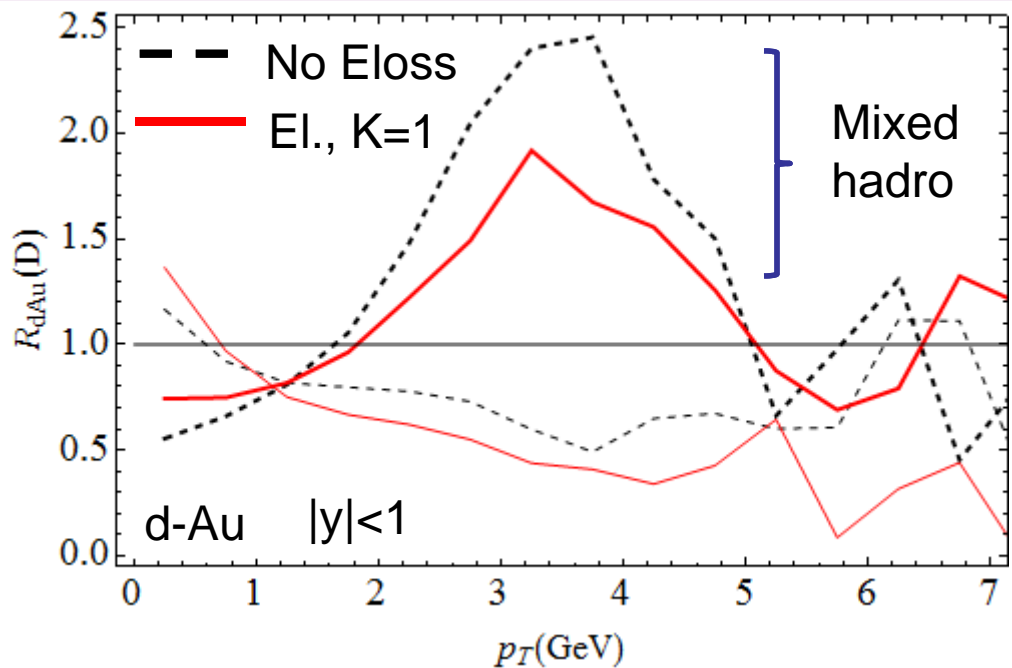


D meson production in semi-central Pb-Pb: flows



- If pure fragmentation is assumed, strong reduction of v_2 at FO (↓ expected), only partially compensated by later evolution 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

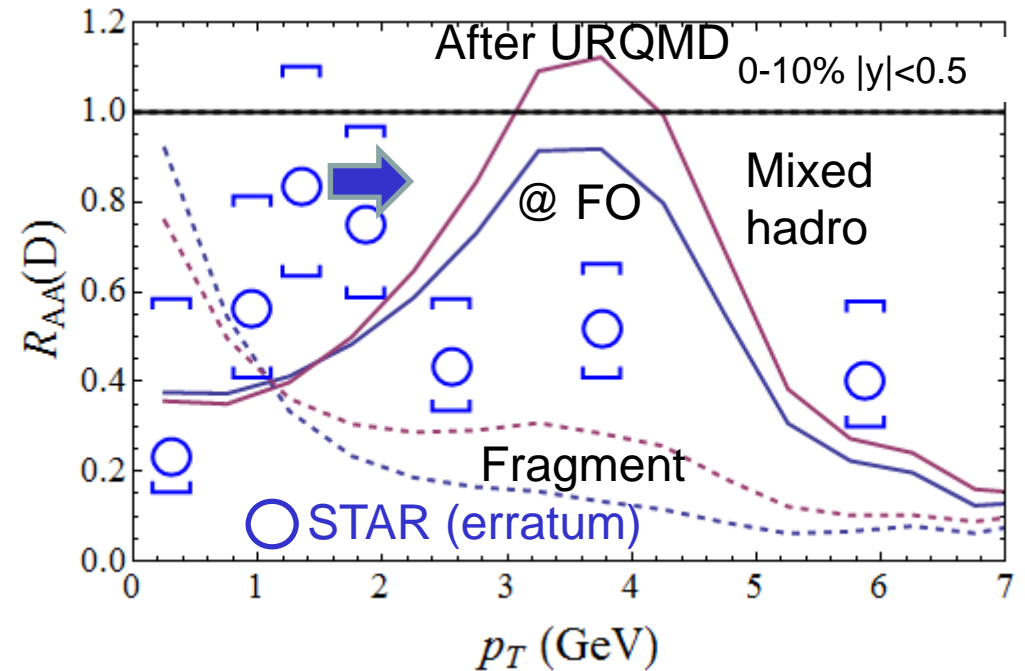
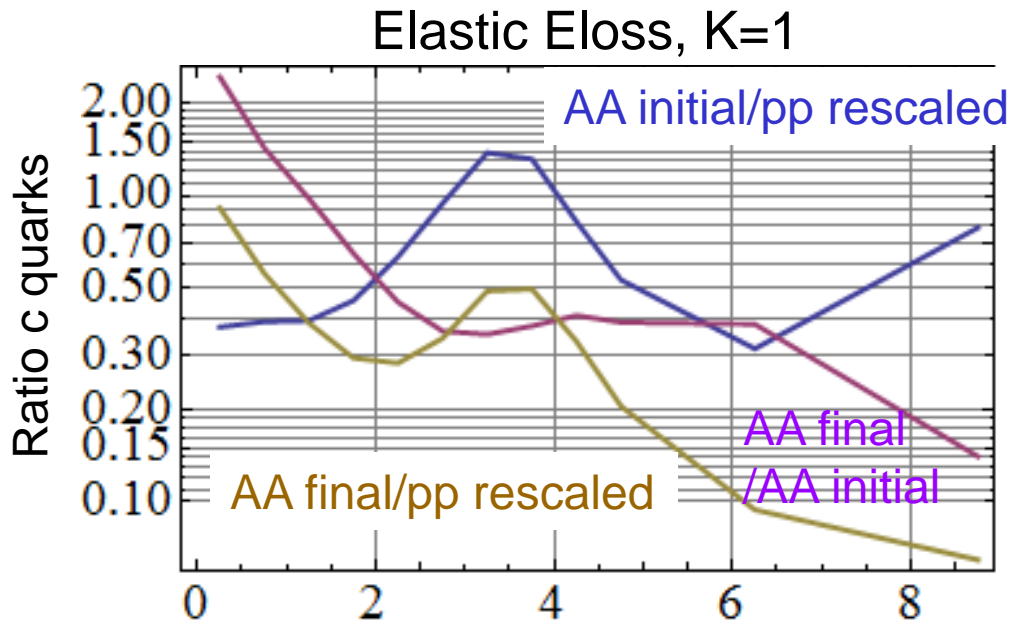


Sensitivity

Saturati on	Hadronisa tion	E Loss	“Chemi stry”
YES	YES	YES	Most probably

← More suppression in the p-going direction

D meson production in central Au-Au @ 200 GeV

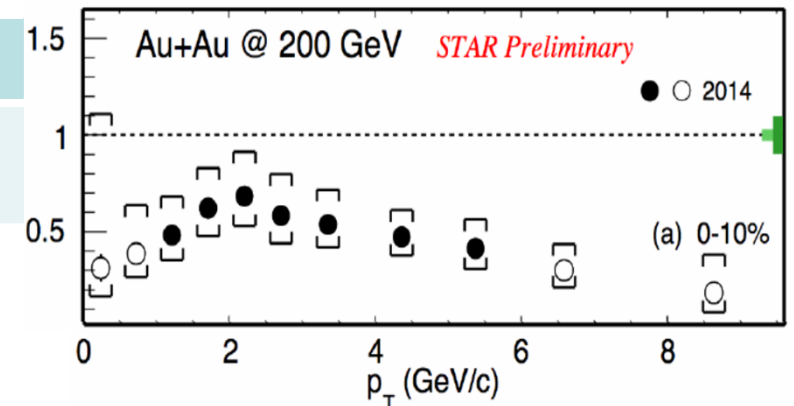


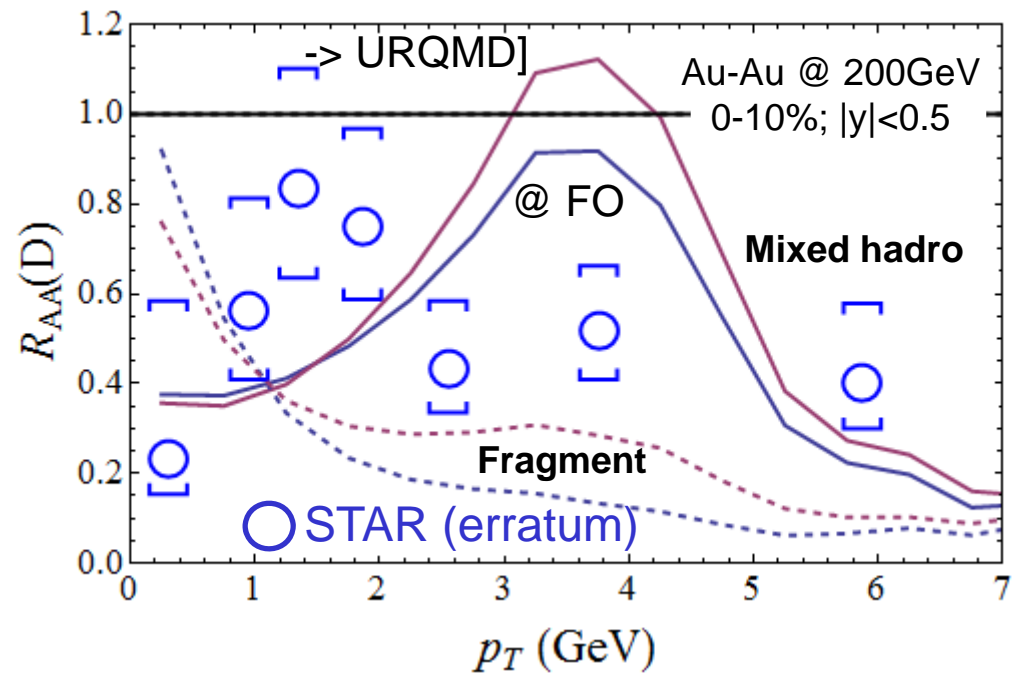
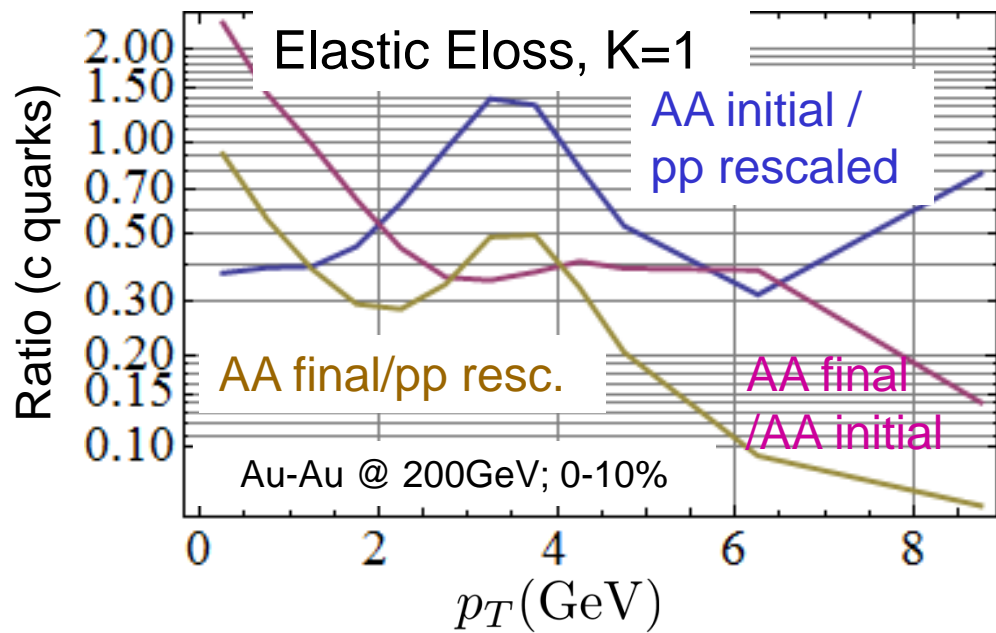
Sensitivity

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

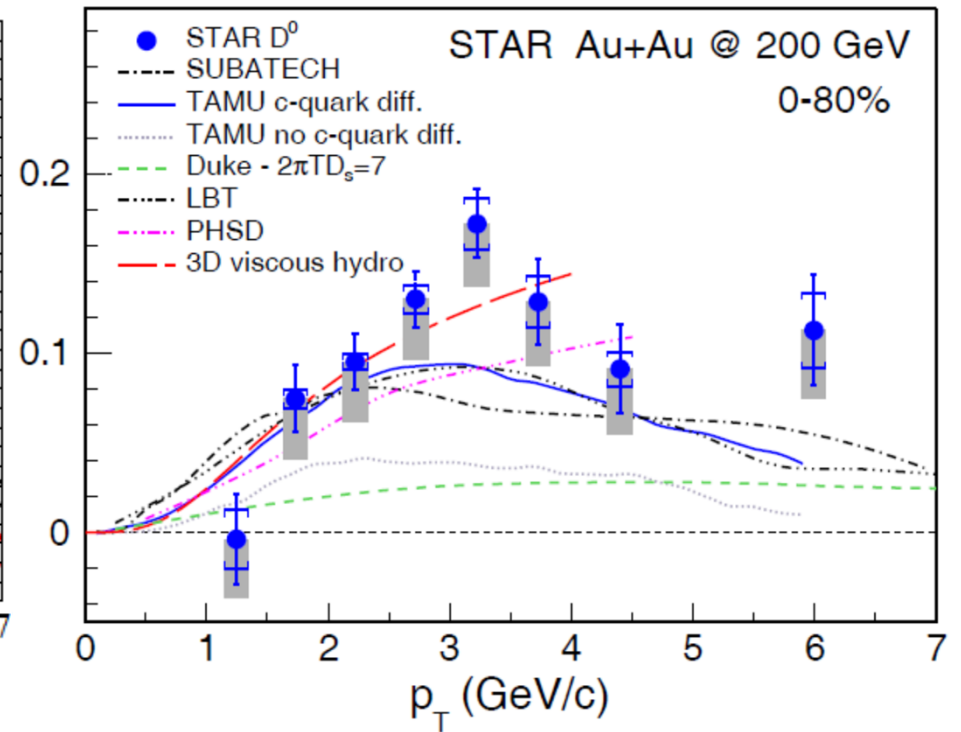
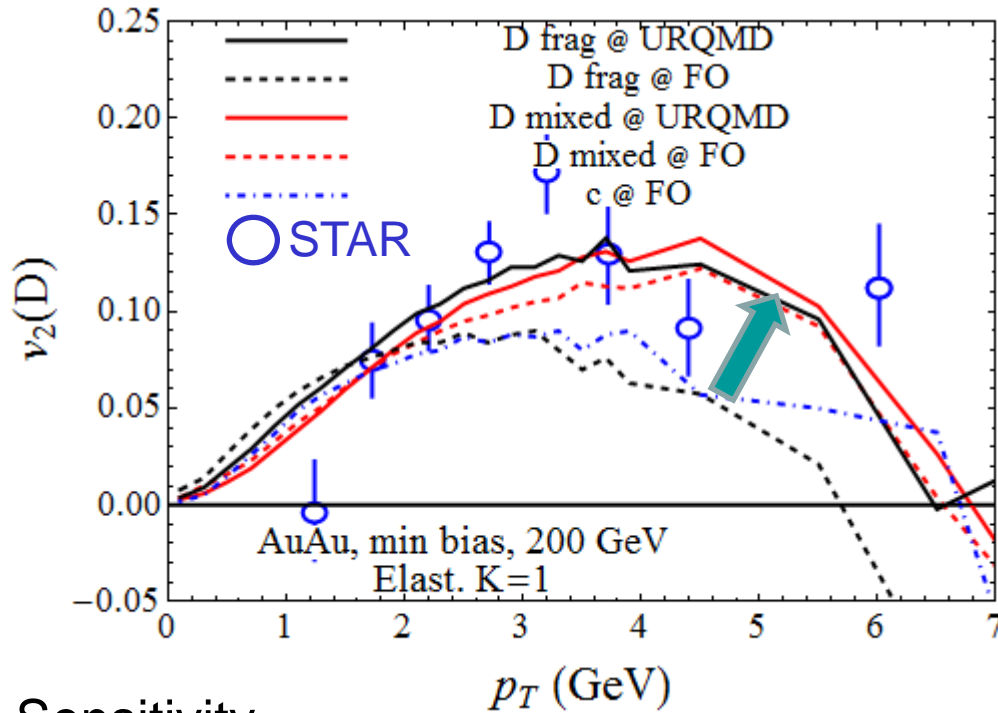
- Same pattern as for LHC, no unity overshooting

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





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

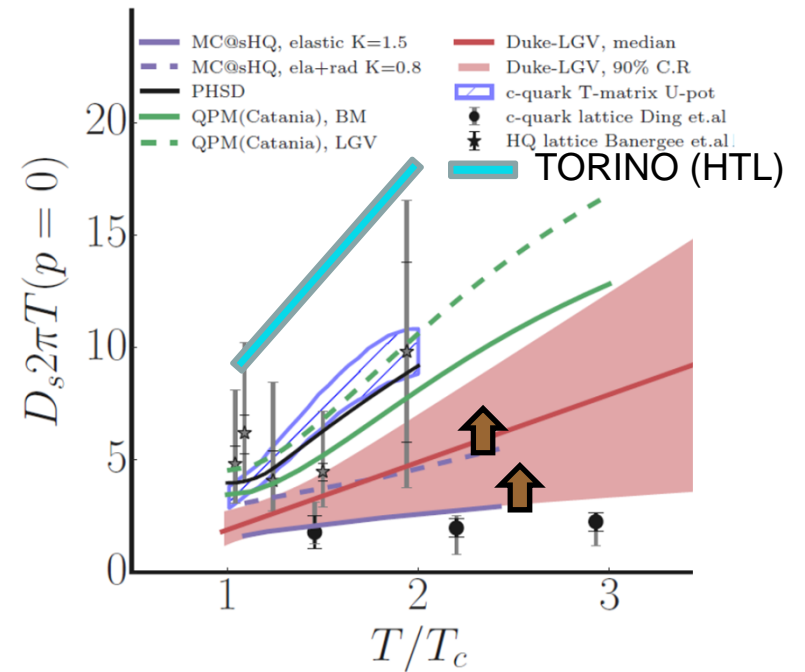
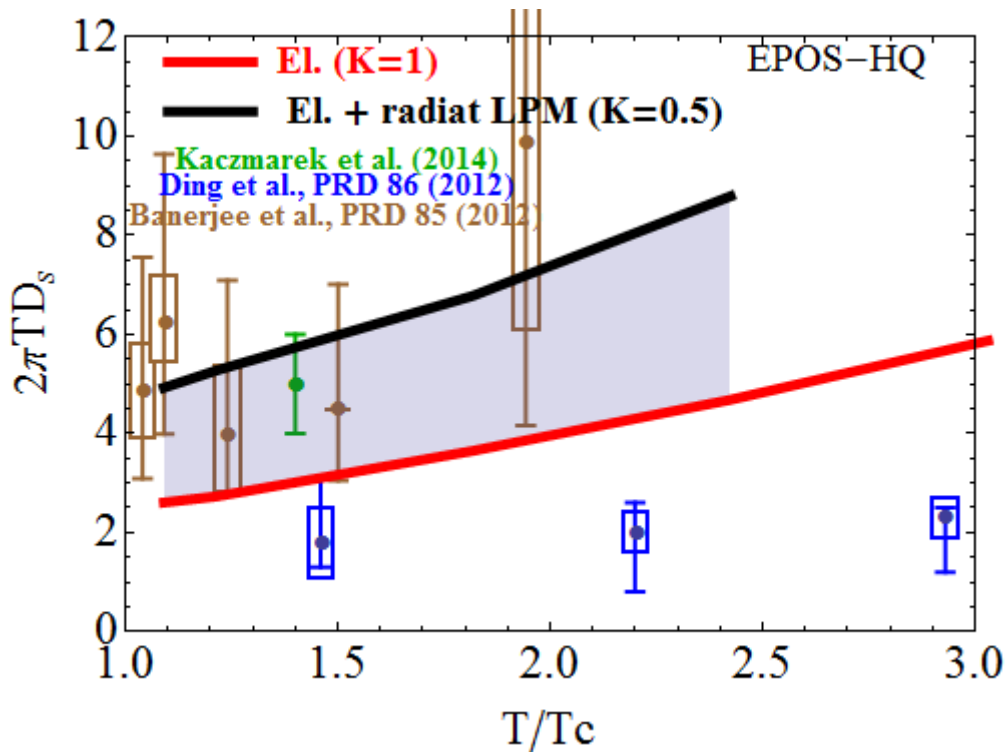


Sensitivity

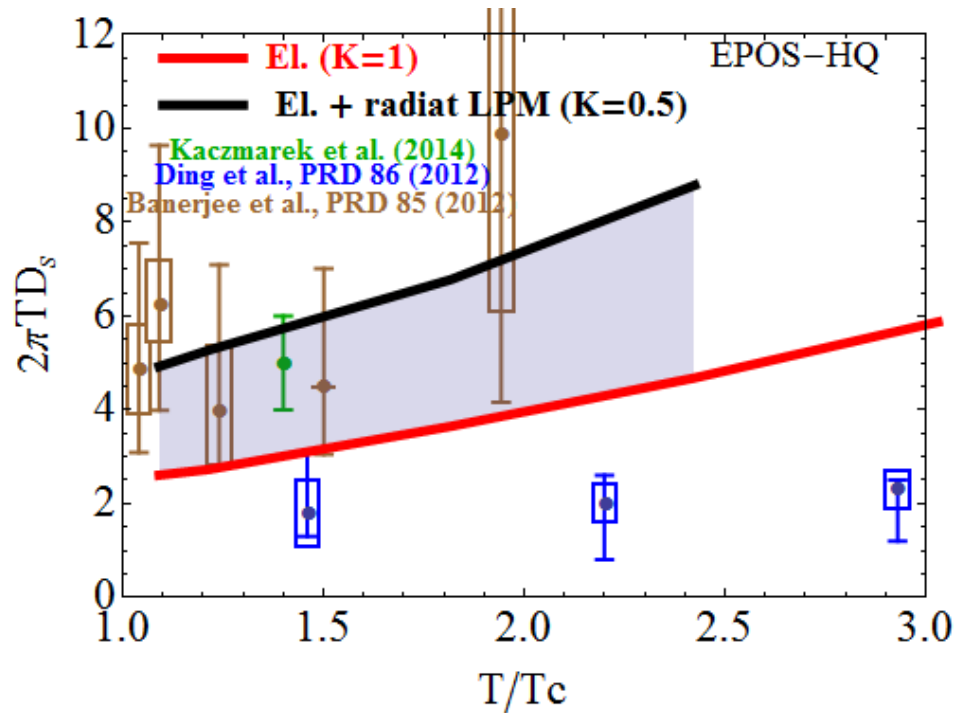
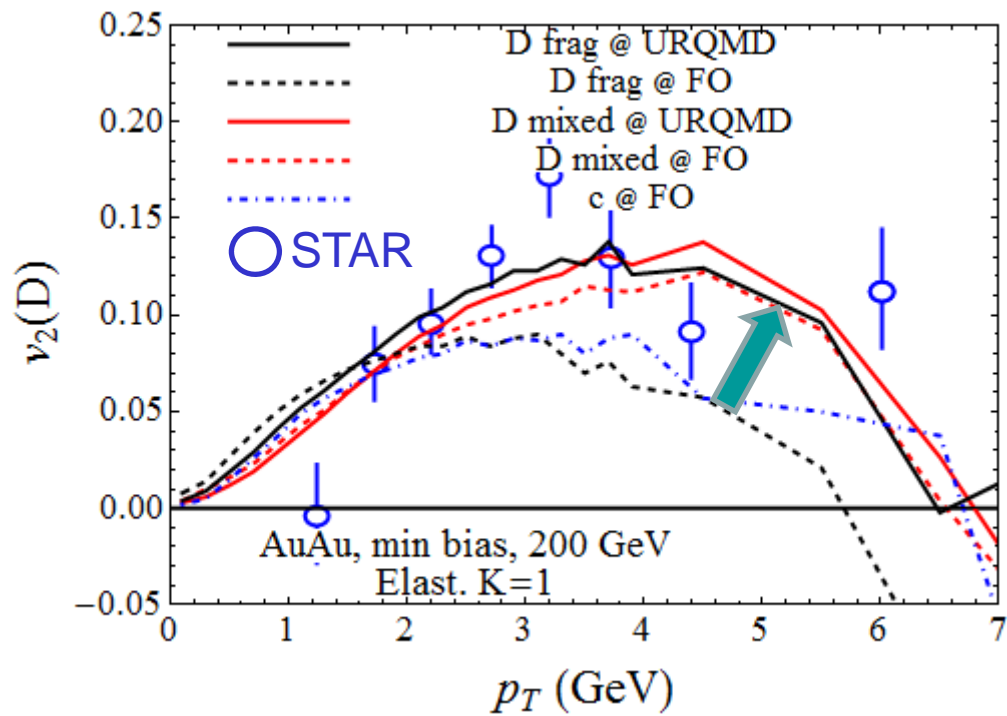
CNM	Hadro	E Loss	Hadro rescat
NO	Large	Moderate	Large for fragmentation

- Strong contribution of hadronic rescattering if $v_2(D)$ 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 T_c**

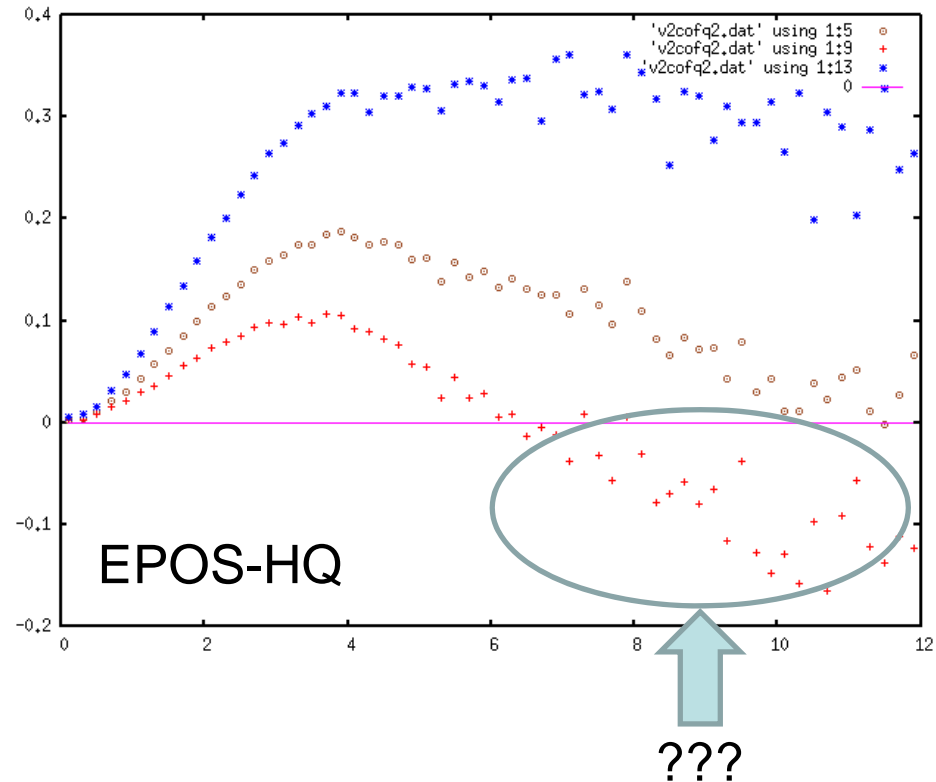
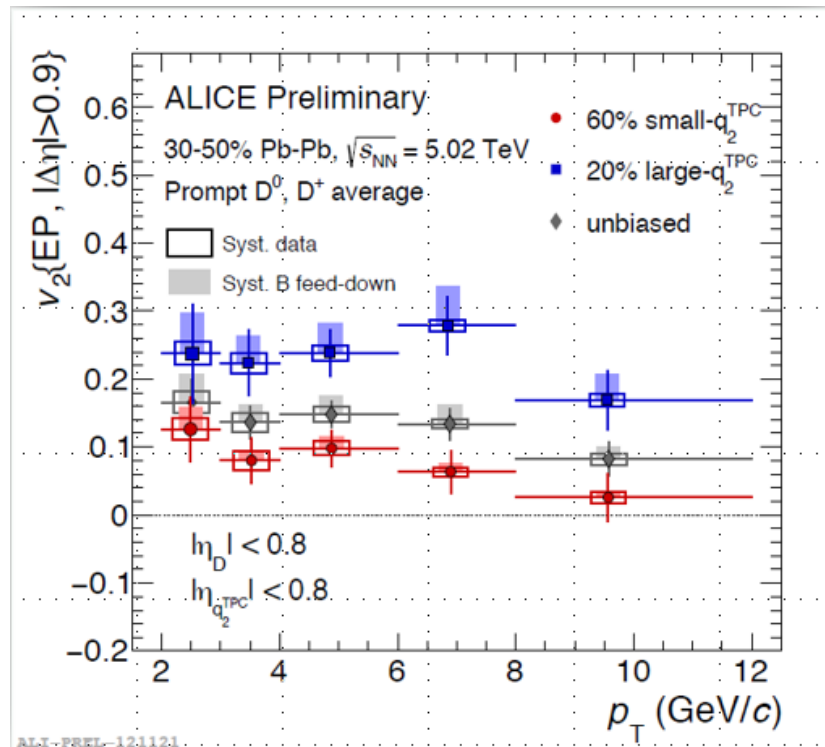
Updated D_s extraction



- 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**



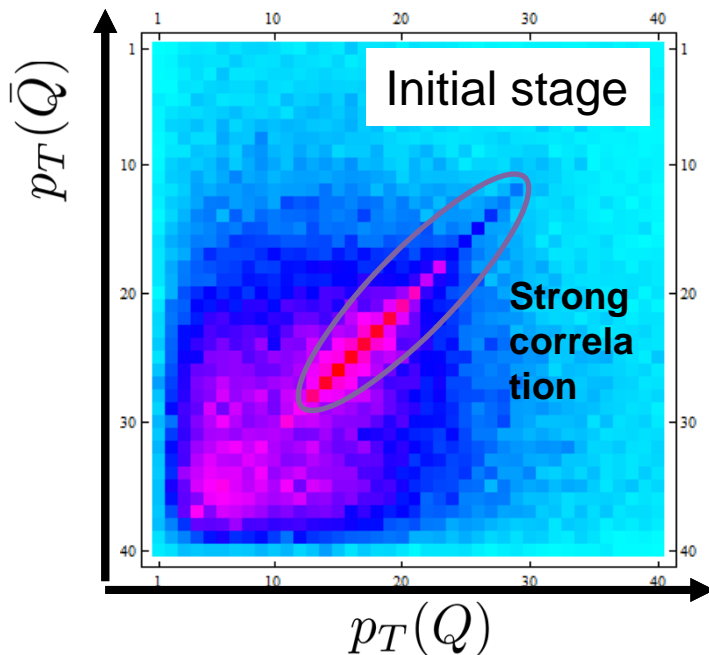
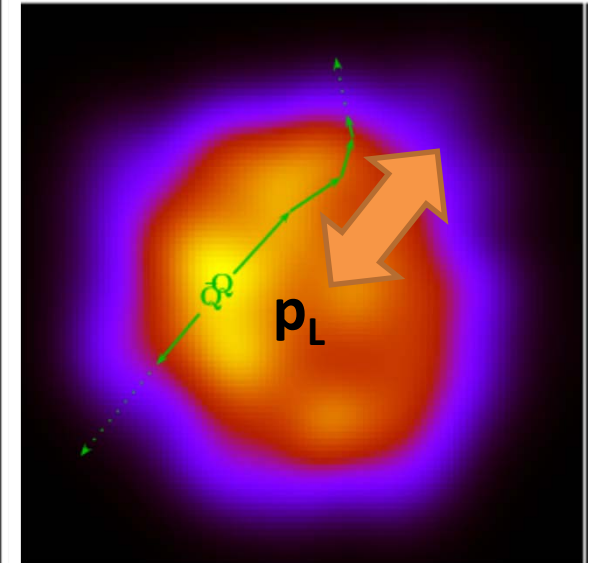
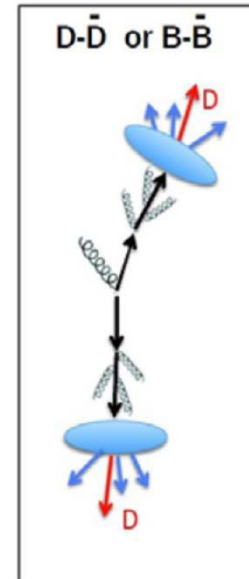
More involved observables: EBE flow



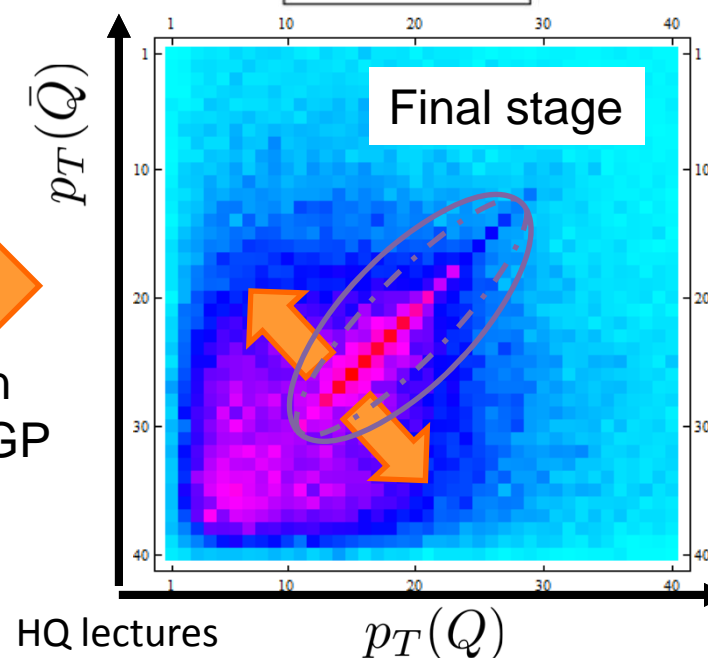
- Trends well reproduced by EPOS-HQ at low p_T
- ... However, inversion of the $v_2(D)$ for “cylindrical events” and large p_T . No physical explanation at this stage.
- Besides this, no big surprise: bulk v_2 is well transferred to c-quarks

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: ...

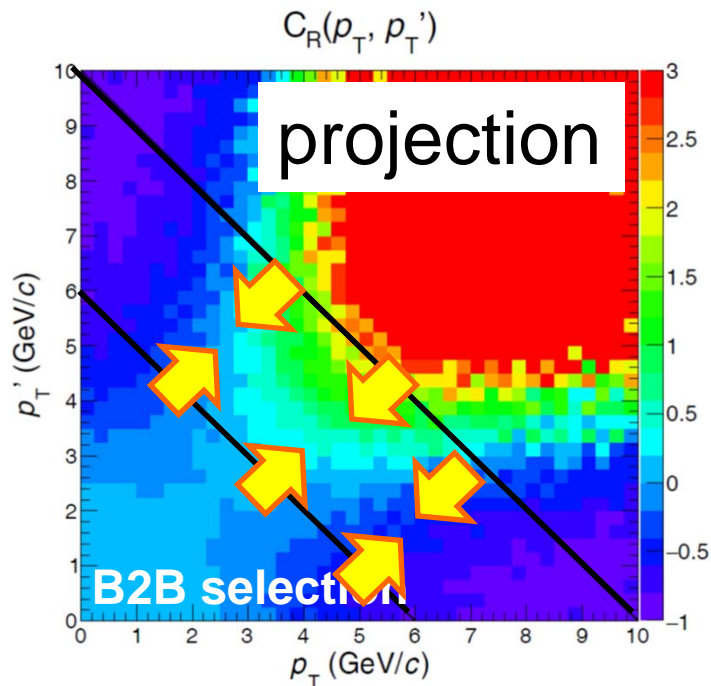


➔ Evolution in hot QGP medium



- decorrelation due to various path lengths + fluctuations: **reduction**

More involved observables: momentum imbalance



Method: we project on a “diagonal band” of fixed $p_T(c)+p_T(cbar)$

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

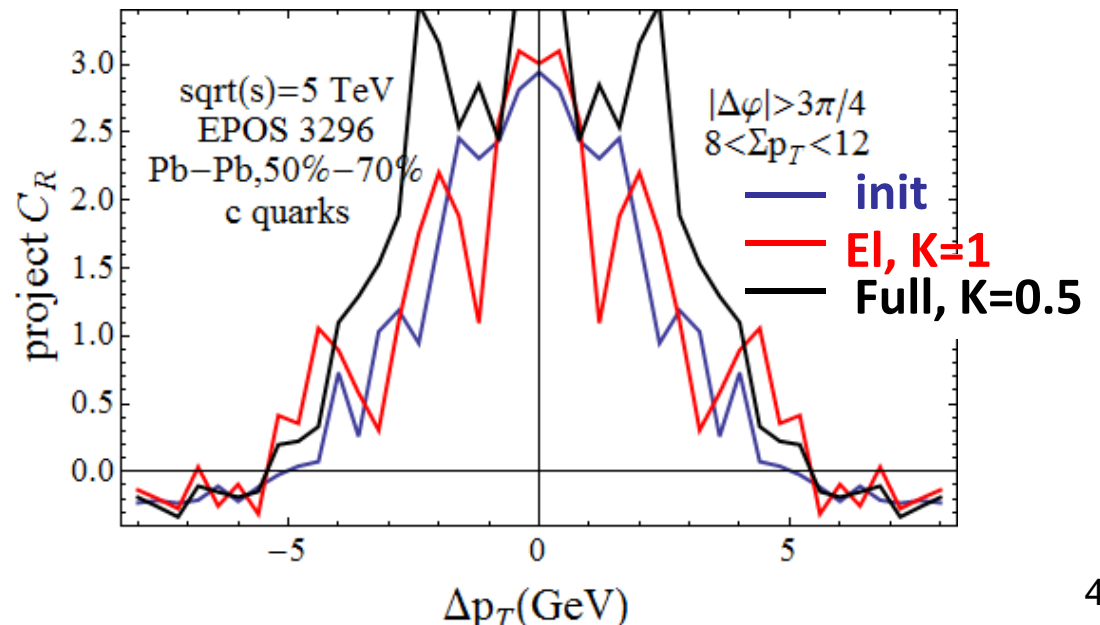
Absolute correlation:

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

- Vanishes if d^2N factorizes ($d^2N(p, p') = dN(p) \times dN(p')$)
- Satisfies $\int C(p_T, p'_T) dp_T dp'_T = 0$

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

- Reveals correlation at finite p_T



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 $p_T < 5 \text{ GeV}/c$ some extra work on the hadronization and HQ production is mandatory

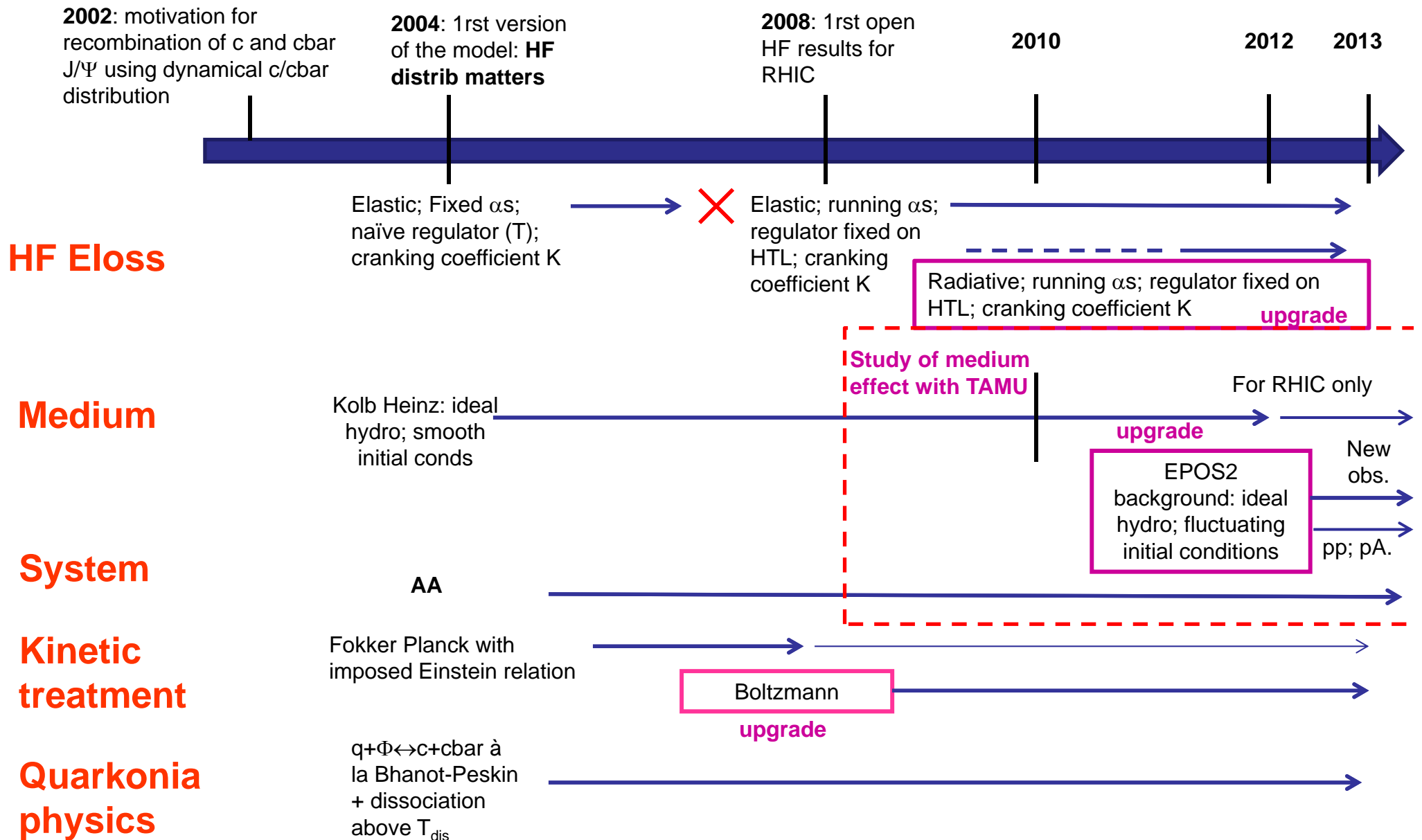
2. Is it possible to **FALSIFY** our ELOSS model, i.e. to show, f.i.:
 - That one needs extra coupling around T_c in order to benefit from extra bulk- v_2
 - That one needs smaller relaxation time at small p (as in the TAMU approach)

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 v_2 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.**

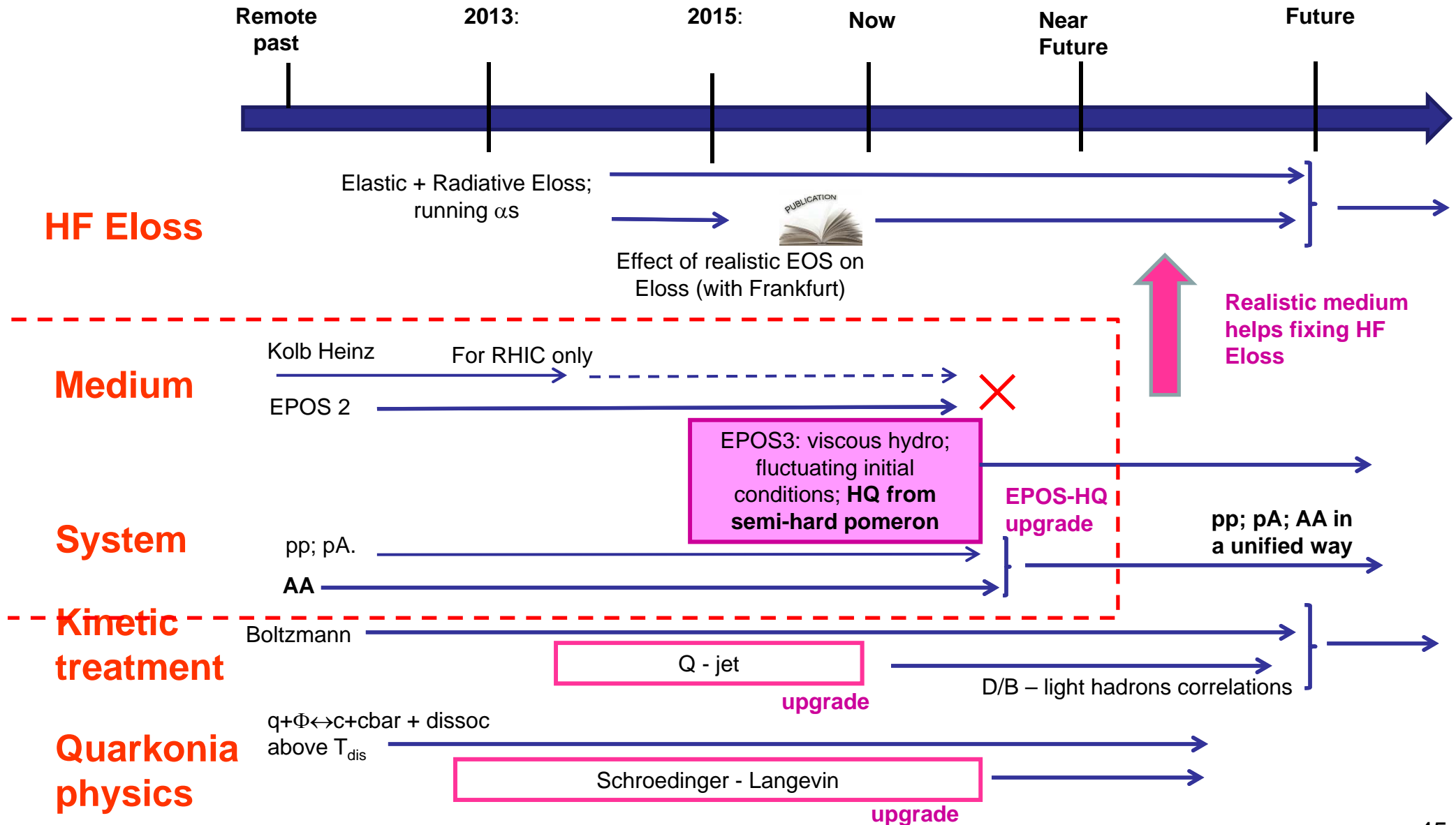
Perspective at short term: more “combinations” relying on collective work

Back Up

Some global view of our model development



Some global view of our model development



Saturation effects in EPOS3

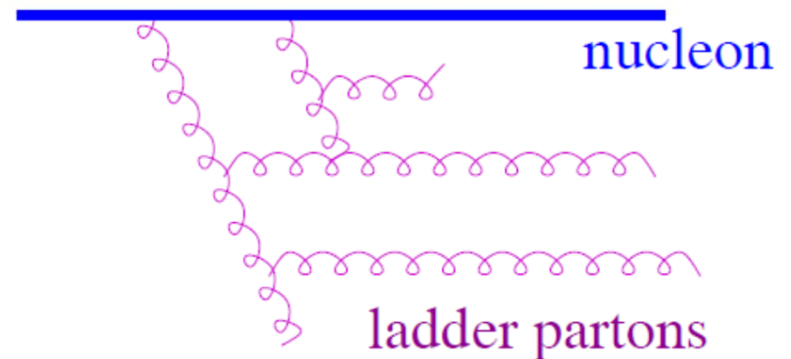
GDRE Meeting September 2017 Athens - Klaus Werner - Subatech - Nantes

Non-linear effects

Computing the expressions G for single Pomeron:
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 (\Rightarrow wrong)

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



Saturation effects in EPOS3

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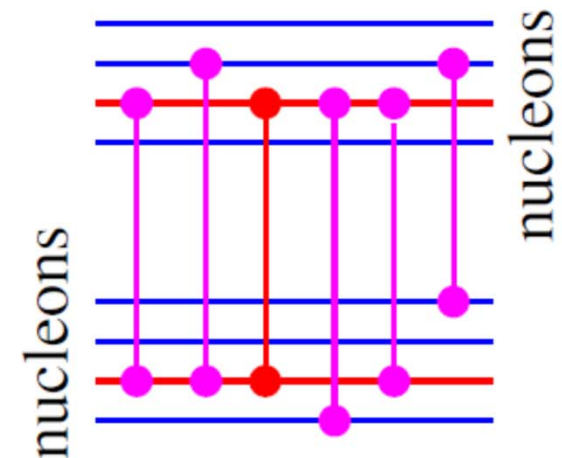
Solution: Instead of a constant Q_0 , use a dynamical **saturation scale for each Pomeron:**

$$Q_s = Q_s(N_{\text{IP}}, s_{\text{IP}})$$

with

N_{IP} = **number of Pomerons connected to a given Pomeron** (whose probability distribution depends on Q_s)

s_{IP} = **energy of considered Pomeron**



Saturation effects in EPOS3

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We get $Q_s(N_{\text{IP}}, s_{\text{IP}})$ 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

$$Q_s \propto \sqrt{N_{\text{IP}}} \times (s_{\text{IP}})^{0.30}$$

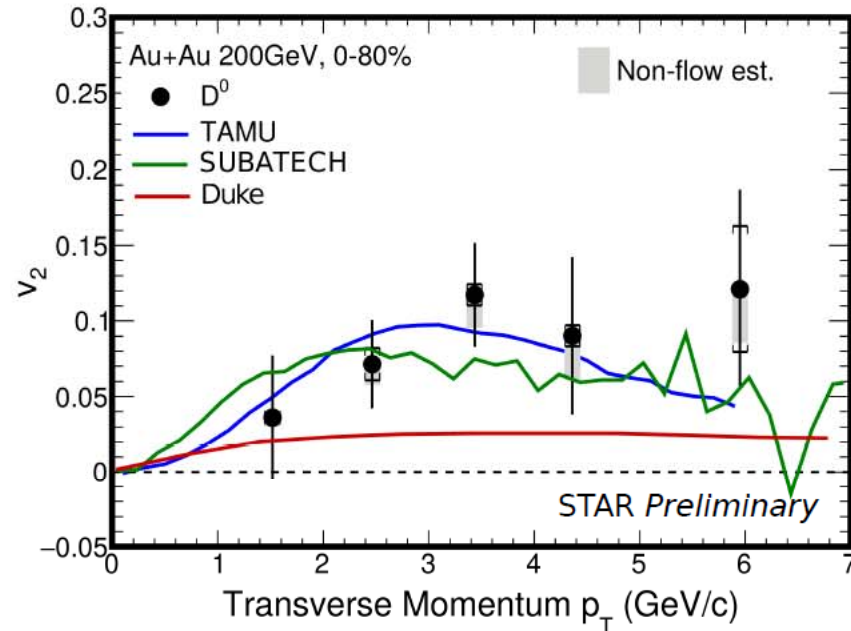
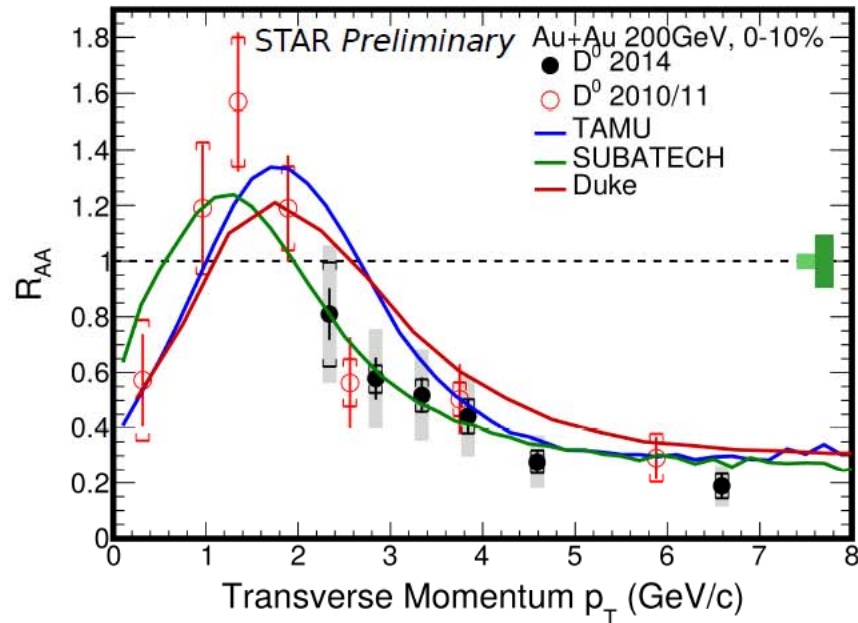
CGC for AA:

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

B2' for RHIC

Comparison to Theory

Sept 2015



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

Subatech: same Eloss model as previously

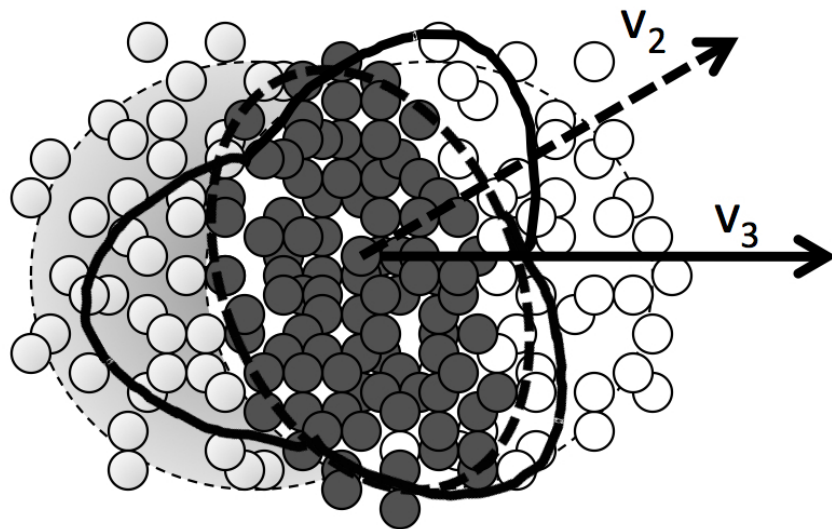
	$D \times 2\pi T$	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

[arXiv:1506.03981 \(2015\)](https://arxiv.org/abs/1506.03981) & private comm.

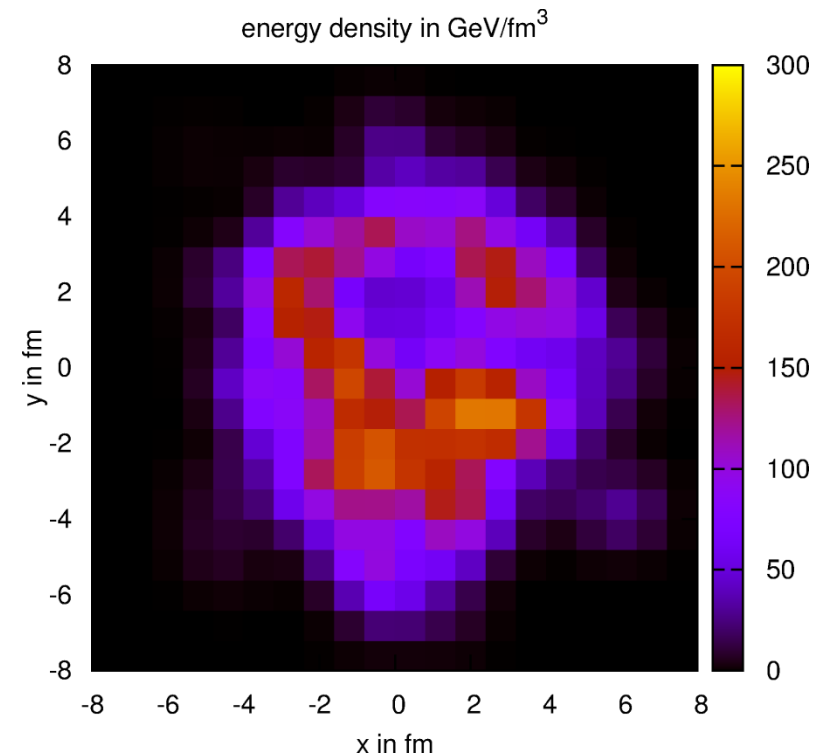


More recent observables: Higher HQ flow components

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



sketch



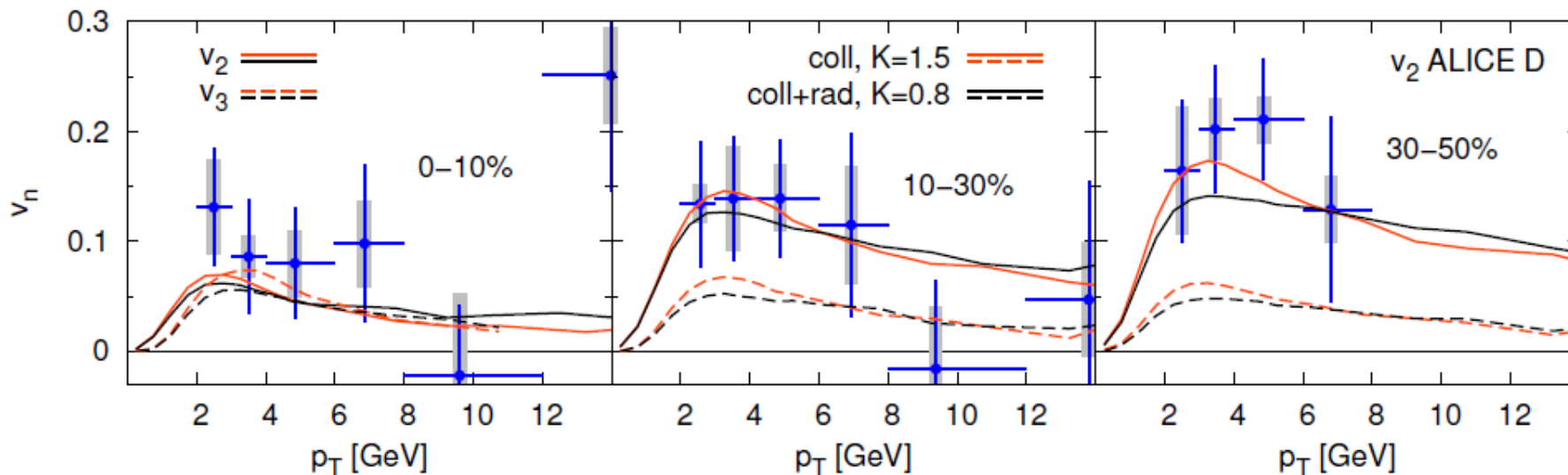
EPOS initial conditions

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

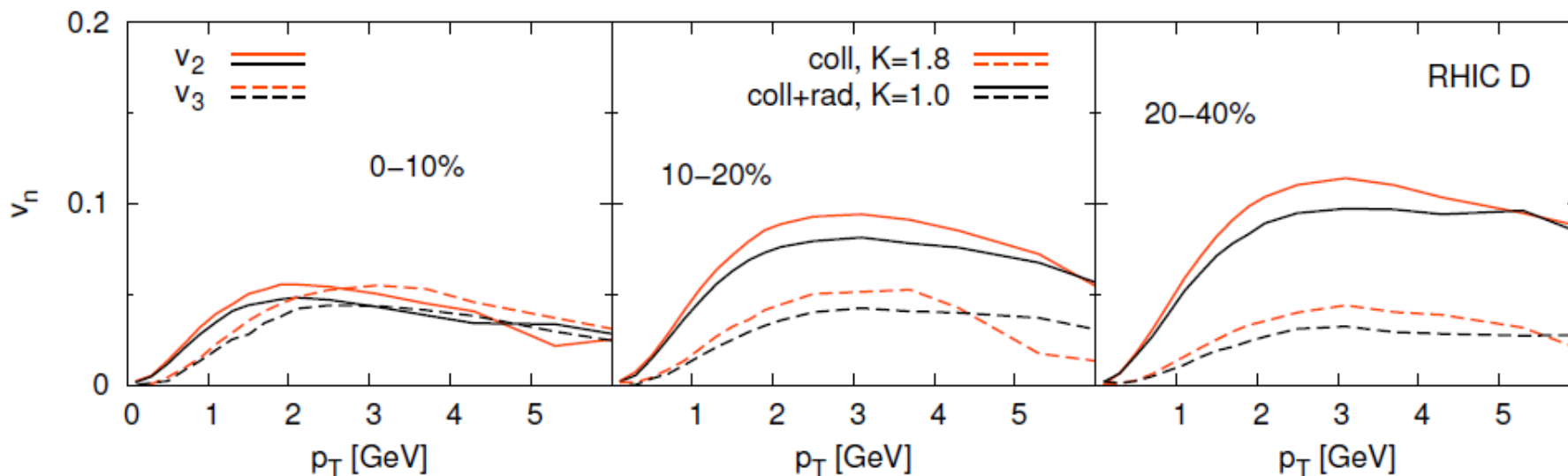
More recent observables: Higher HQ flow components

Nahrgang et al, Phys. Rev. C 91 (2015), 014904

LHC



RHIC

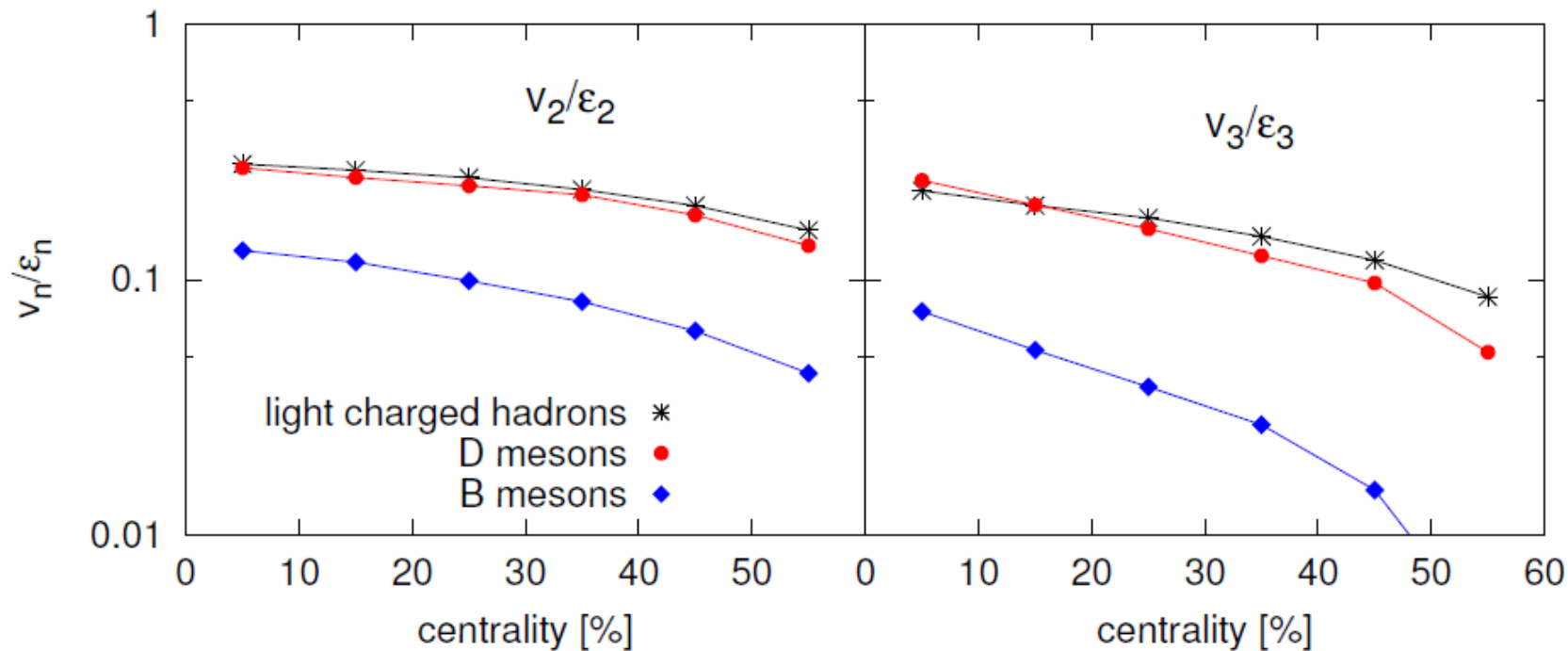


Indeed finite v_3 observed at all centralities, both at RHIC and LHC

More recent observables: Higher HQ flow components

In 1st approximation: $v_n \propto$ eccentricity $\varepsilon_n \Rightarrow$ 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 \Rightarrow 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)