

The role of correlations in disentangling between heavy-flavor energy-loss Models

Winter Workshop on Nuclear Dynamics

La Guadeloupe (Fr)

P.B. Gossiaux

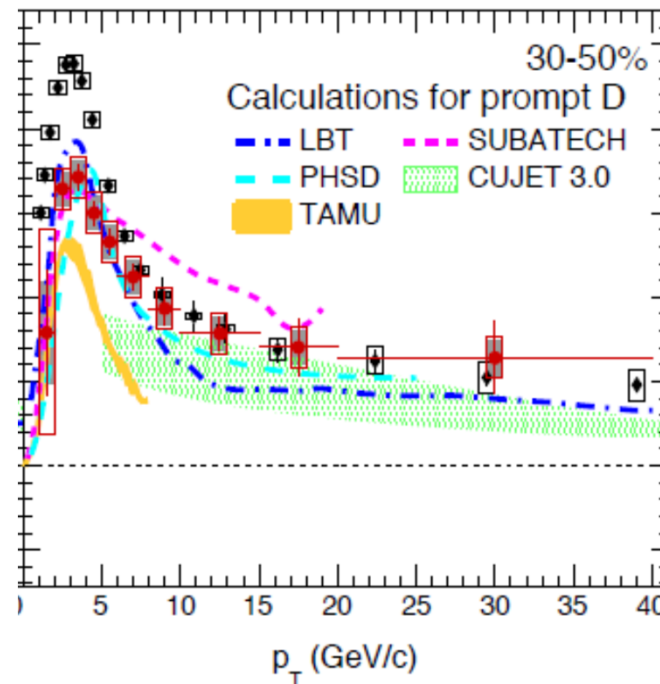
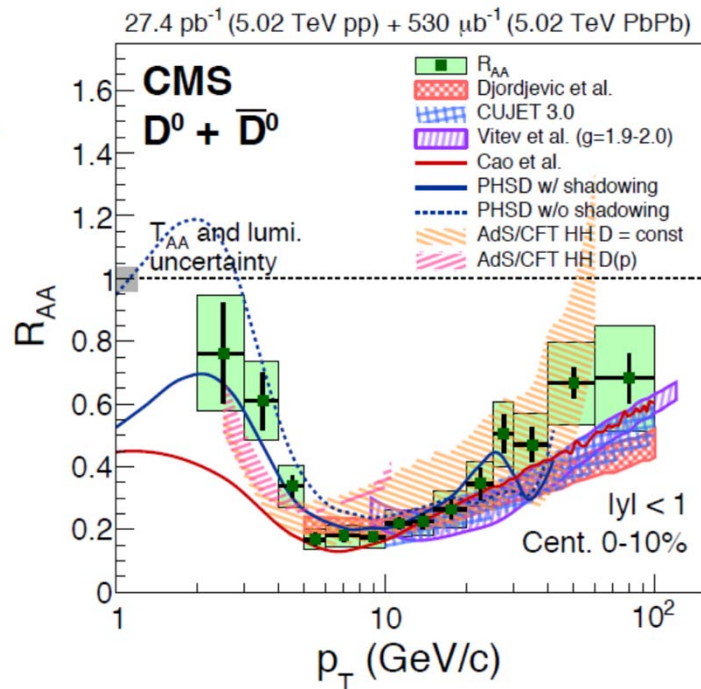
SUBATECH, UMR 6457

Université de Nantes, IMT Atlantique, IN2P3/CNRS

In collaboration with J. Aichelin, B. Guiot, A. Mischke, M. Nahrgang, T. Pierog, L. Vermuunt, K. Werner

(Short) Motivation

- Nowadays, a large variety of models (most of them presented as “effective approaches”) are confronted with the data for the R_{AA} & v_2 single particle observables

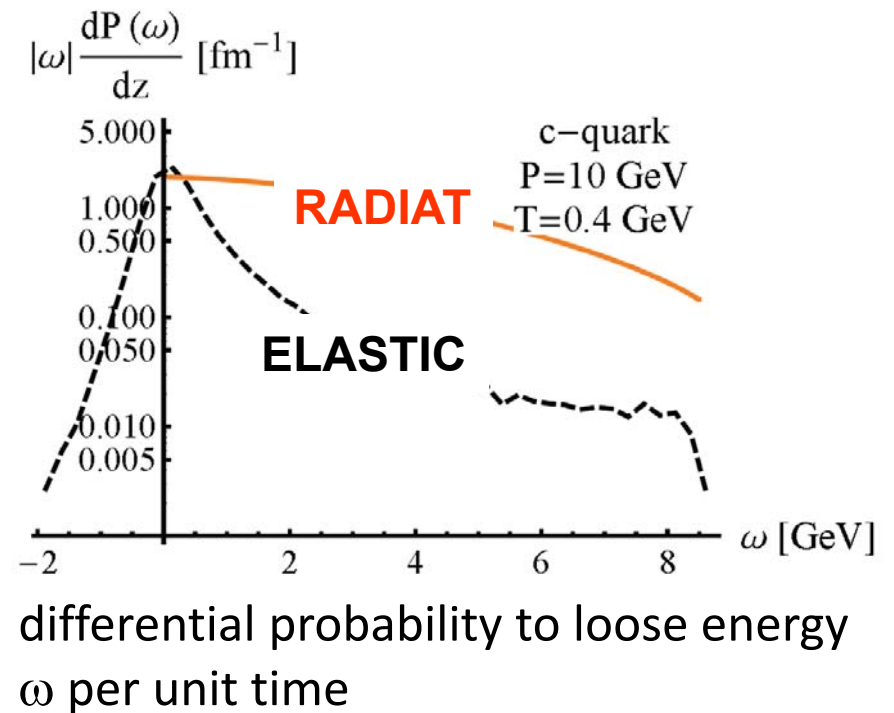
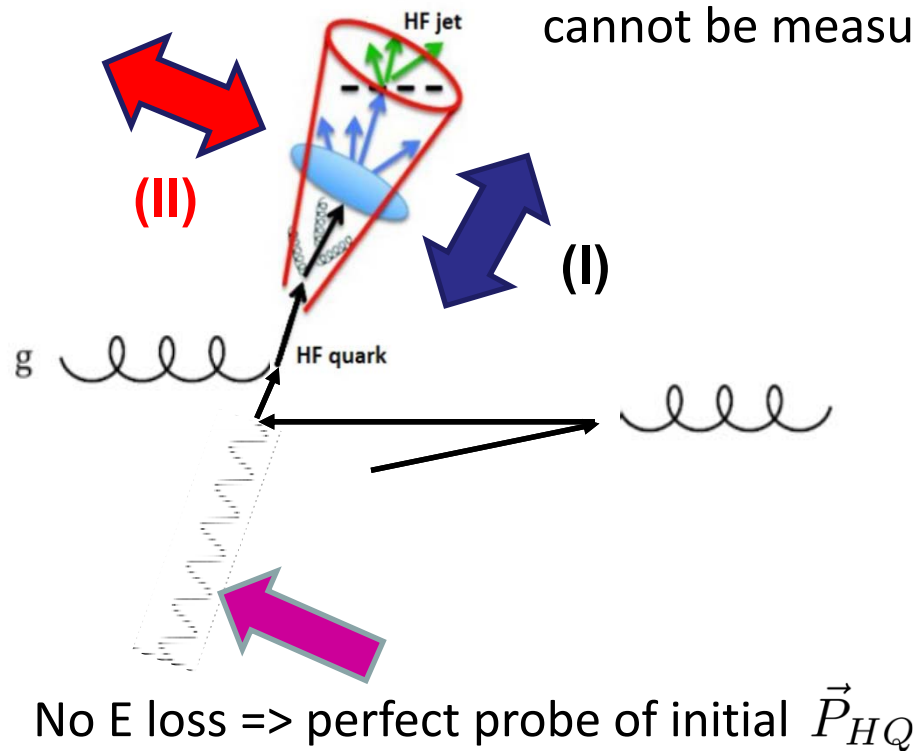


- For the purpose of making the contact with the fundamental theory, it is desirable to “constrain / pre-sort / rule out” some of the approaches
- Very often, correlations are advocated to be useful in this respect (**warning: main viewpoint adopted in this presentation**)

How does it help ? Best HF Correlation ever ?

➤ γ – D/B/c jet /b jet:

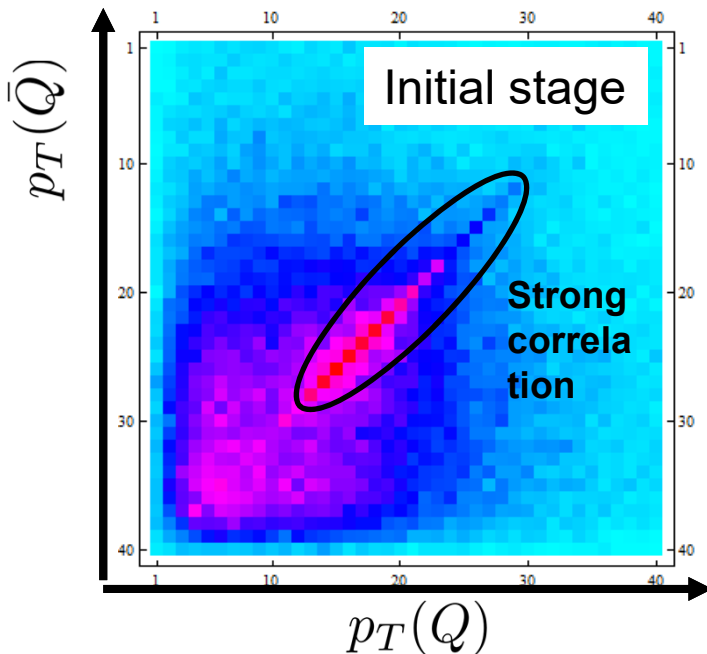
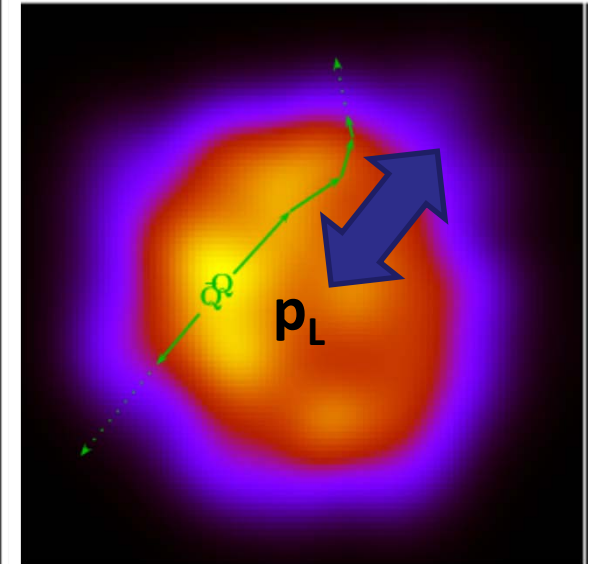
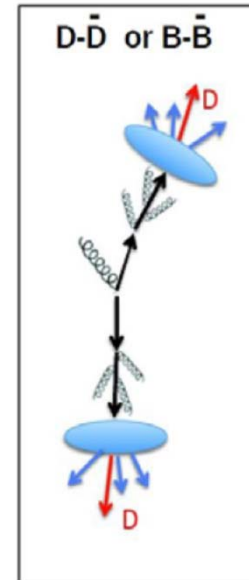
In QGP: **Longitudinal and transverse (qhat) fluctuations** of the HQ, which crucially depend on the Eloss mechanism and cannot be measured in usual observables like R_{AA} or v_2



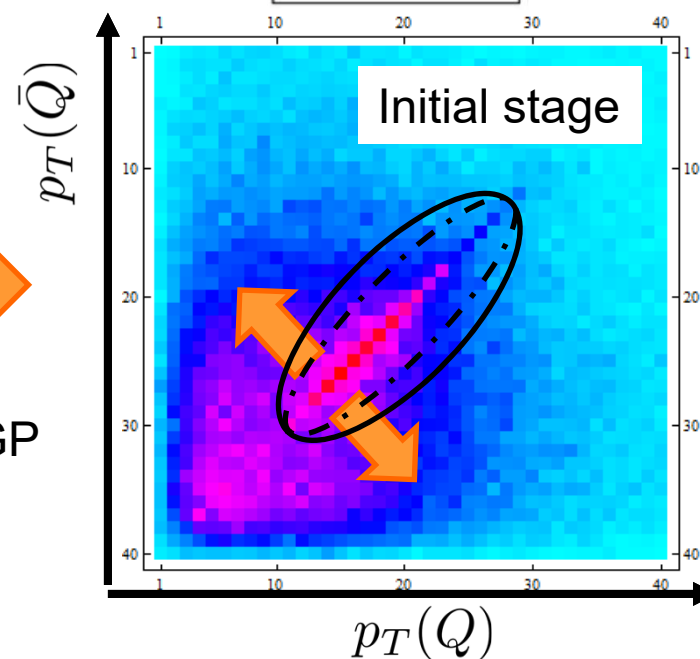
➤ Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues... RUN3 ? RUN4 ?)

Next best thing: HF-HF correlations

- 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: ...



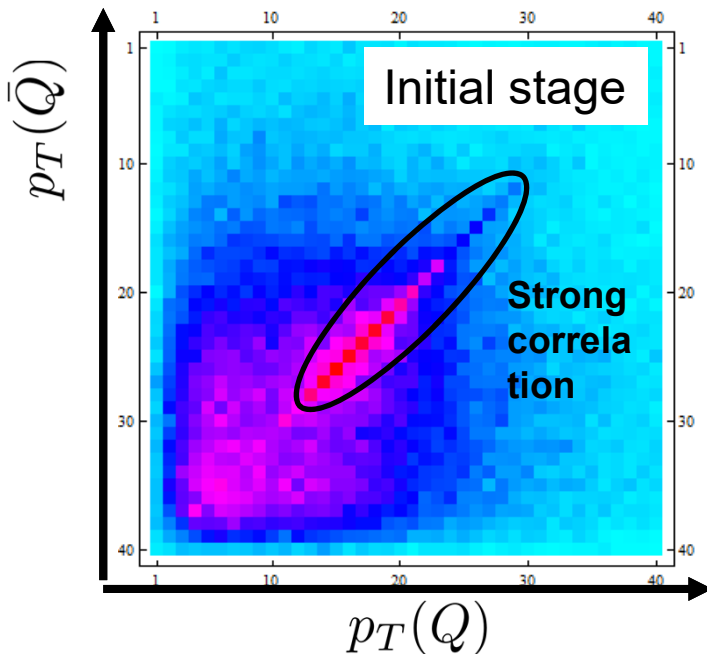
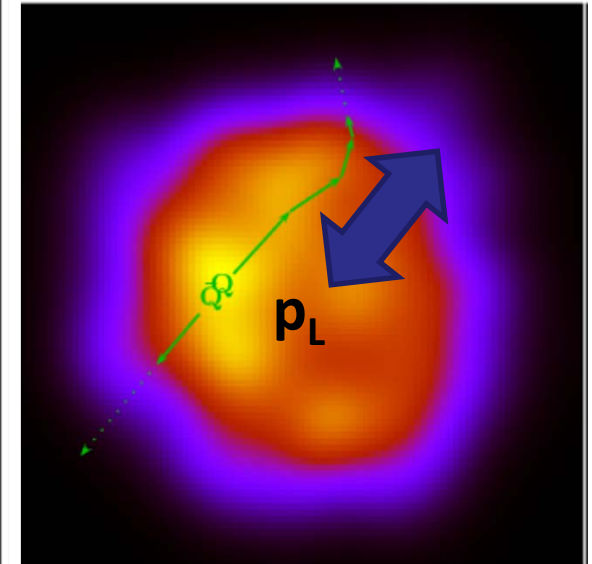
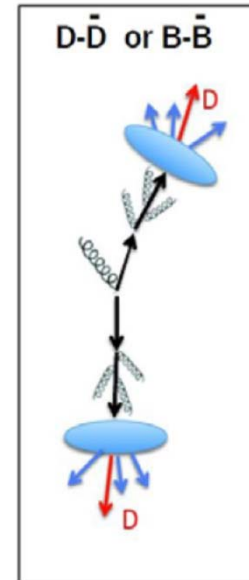
Evolution
in hot QGP
medium



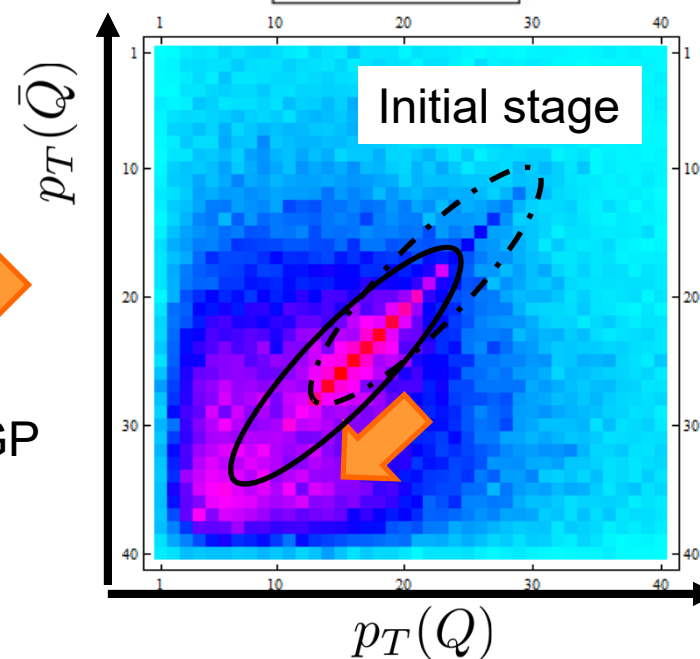
- decorrelation due to various path lengths + fluctuations: **reduction**

Next best thing: HF-HF correlations

- 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:
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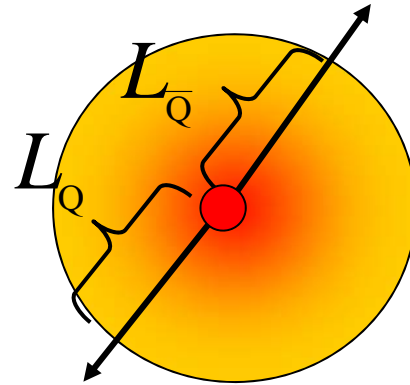
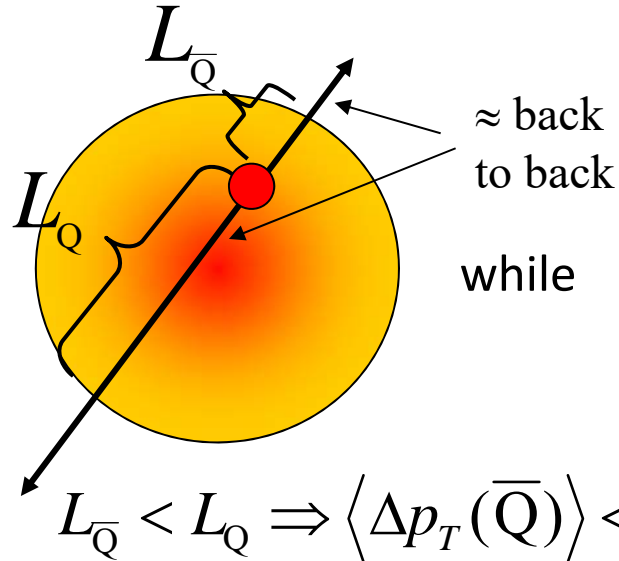
➔ Evolution in hot QGP medium



- feeding from higher p_T (stronger) correlations: **increase**

Once upon a time: momentum imbalance for hot core

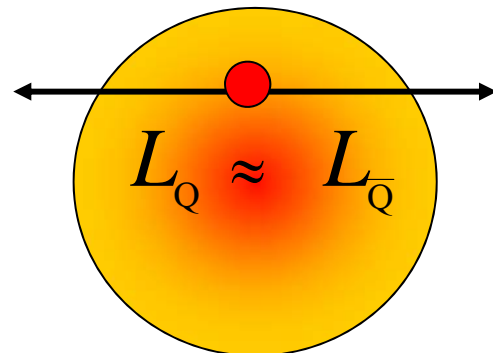
- Challenge: tagging on the “central” Q, i.e. getting closer to the ideal “penetrating probe” concept:



$$L_{\bar{Q}} \approx L_Q \Rightarrow \langle \Delta p_T(\bar{Q}) \rangle \approx \langle \Delta p_T(Q) \rangle$$

- Reversing the argument: selecting $\langle \Delta p_T(\bar{Q}) \rangle \approx \langle \Delta p_T(Q) \rangle$ might bias the data in favor of “central” pairs

Possible caveat:

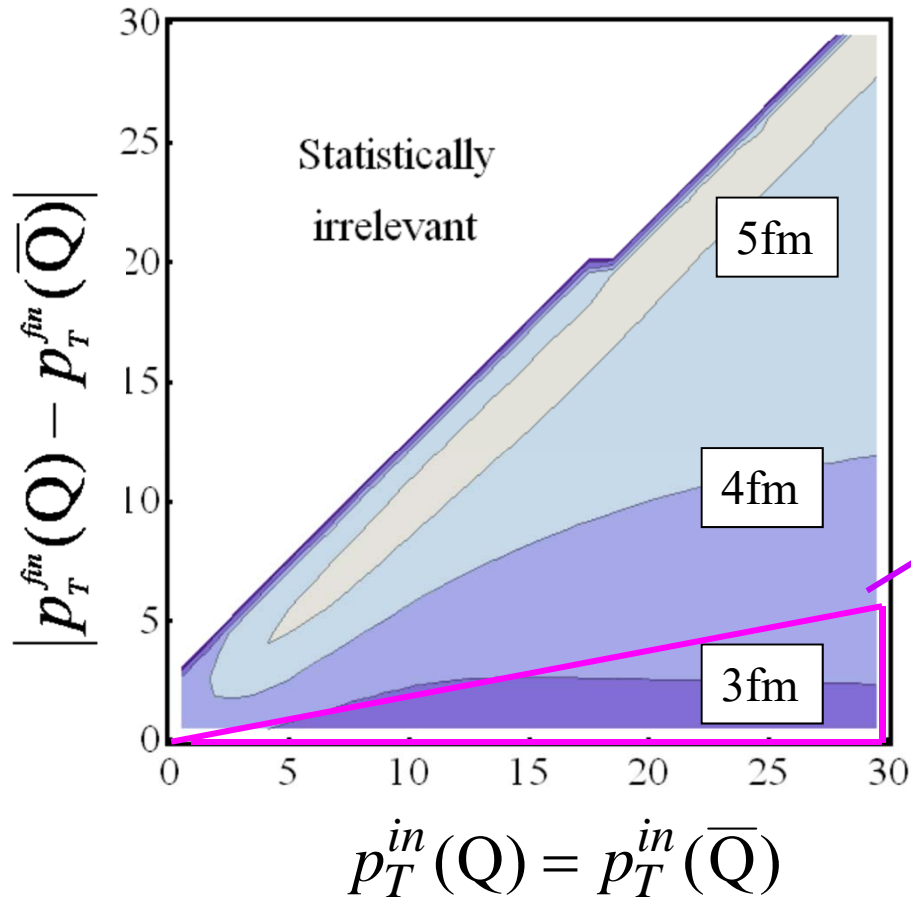


⇒ Need for a detailed study

Gossiaux et al, PHYSICAL REVIEW C 79, 044906 (2009)

Once upon a time: momentum imbalance for hot core

Average transv.-dist. to center as a function of Δp_T^{fin} for various p_T^{in}



Indeed some (favorable) bias for init $p_T^{\text{in}} > 5\text{GeV}/c$ and “small” Δp_T^{fin}

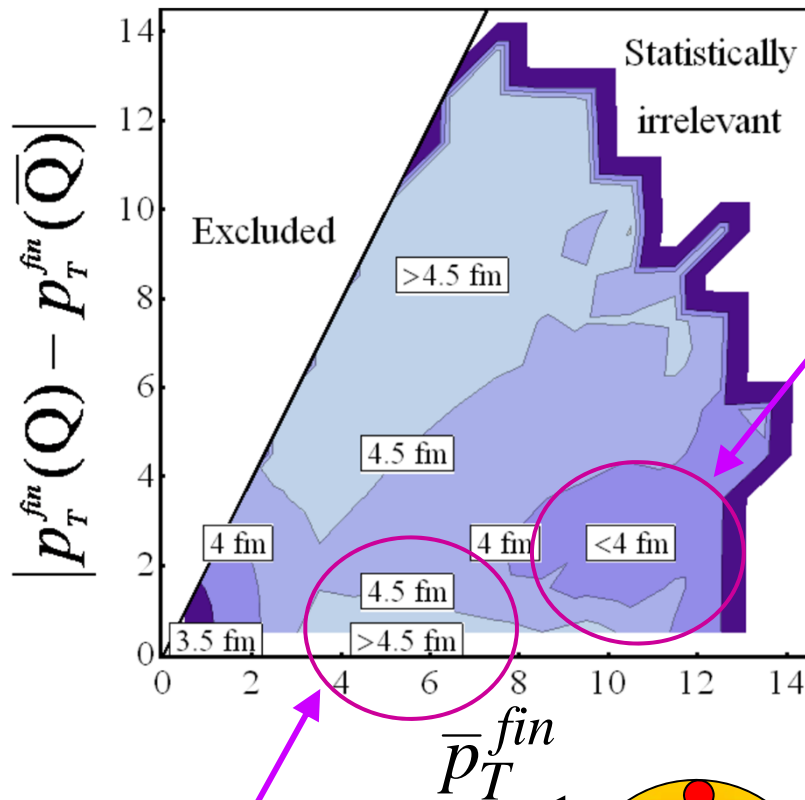
Hope to probe hotter regions of the QGP

However: No access to p_T^{in} !!!

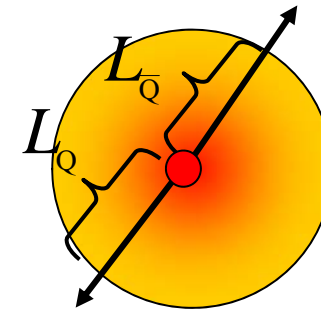
Once upon a time: momentum imbalance for hot core

Best ansatz: $p_T^{in}(Q) \rightarrow \bar{p}_T^{fin} := \frac{p_T^{fin}(Q) + p_T^{fin}(\bar{Q})}{2}$

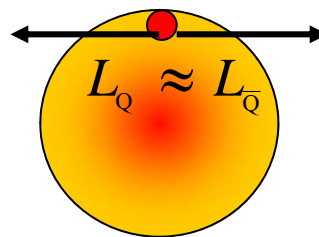
Average transv.-dist. to center as a function of Δp_T^{fin} for various \bar{p}_T^{fin}



Central production:

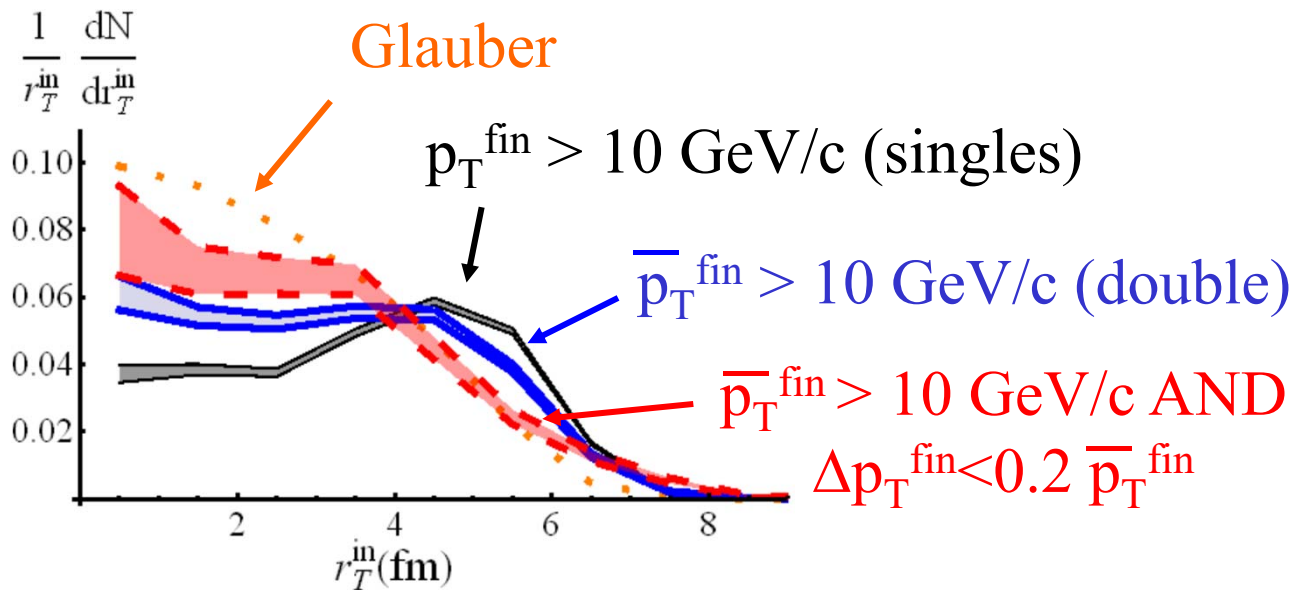
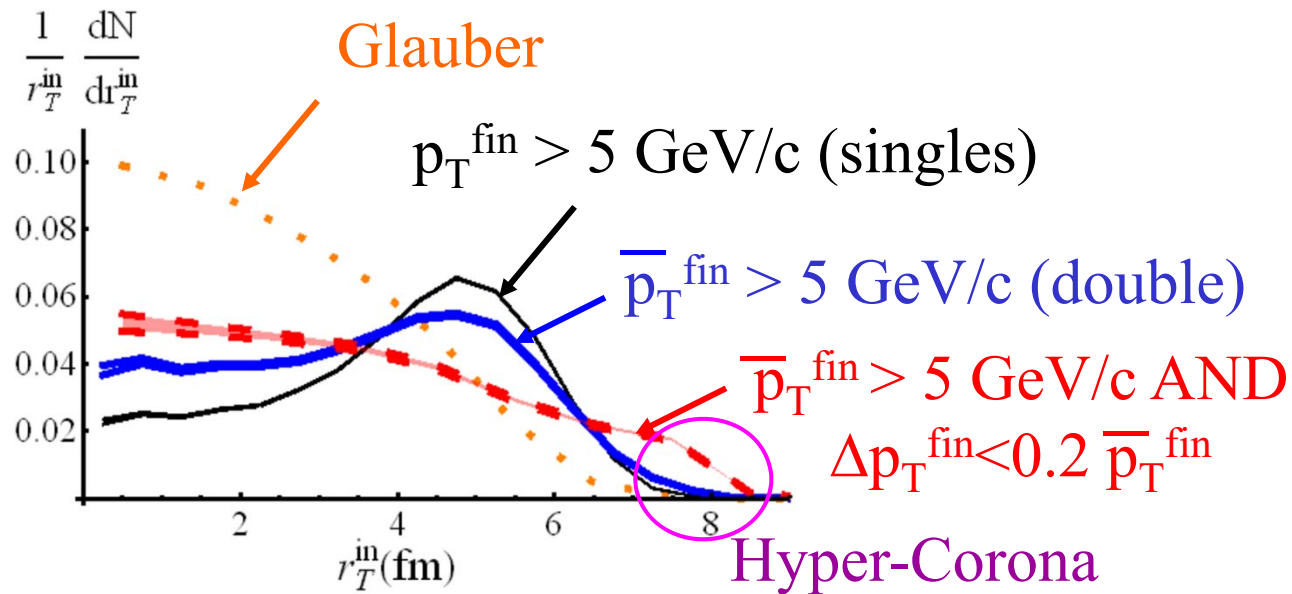


Tangential production



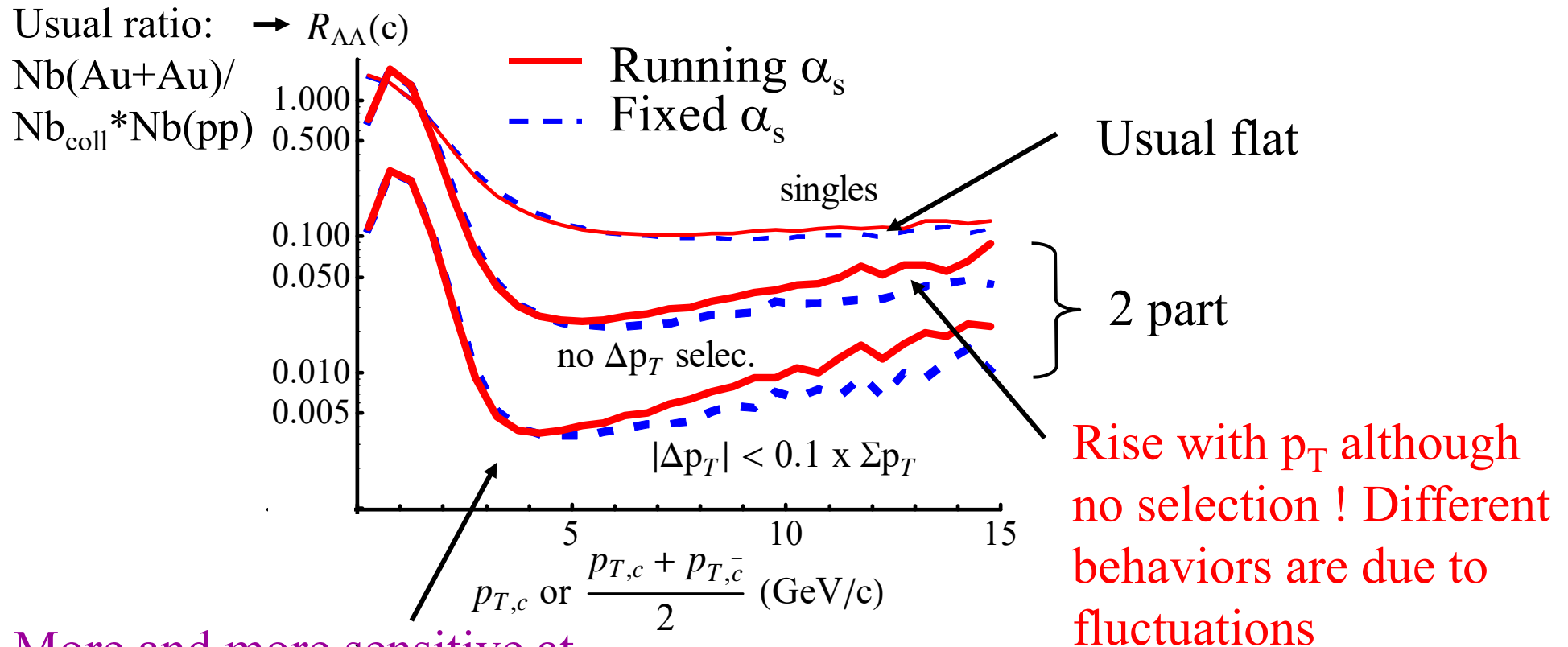
Conclusion: Favorable bias for $\text{av. } p_T^{fin} > 8 \text{ GeV}/c$ and “small” Δp_T^{fin}

momentum imbalance for hot core: back to r_T distributions



- Final cuts lead to various distributions of initial position
- One nearly recovers the Glauber profile for most severe cut

momentum imbalance: increase R_{AA} sensitivity

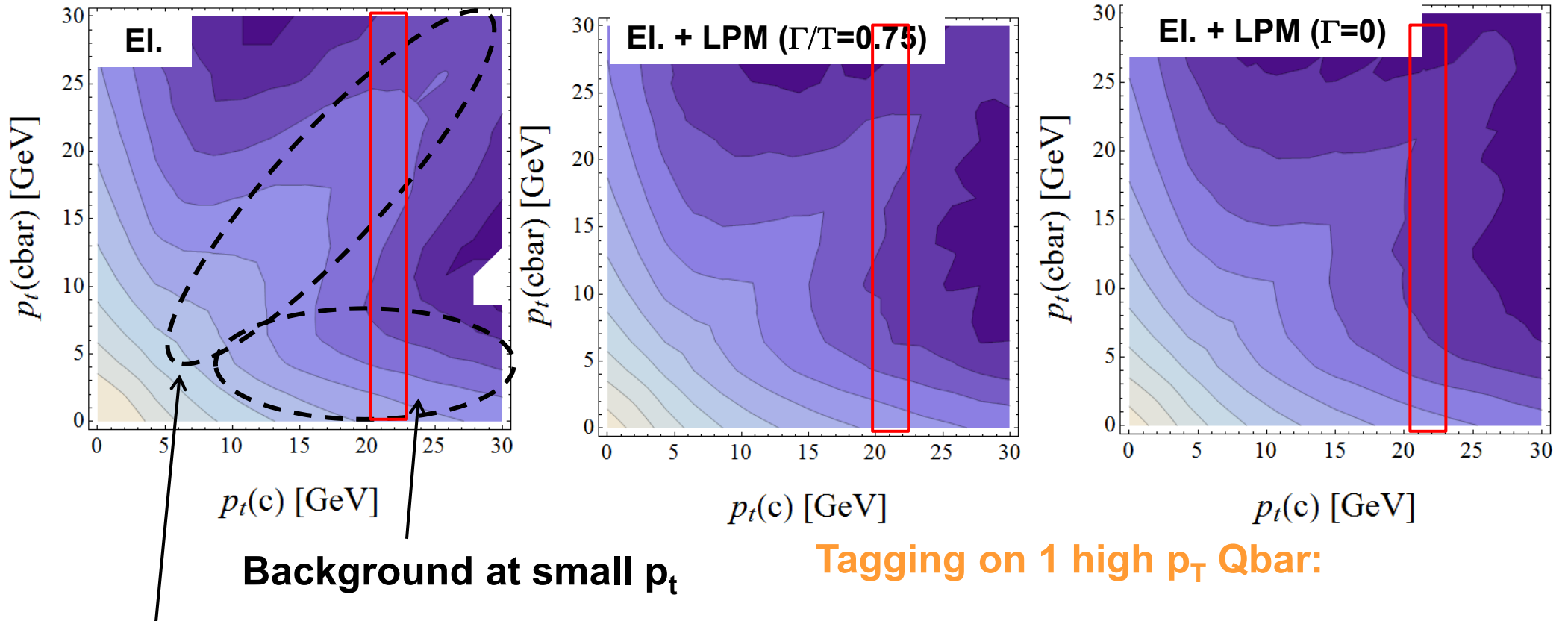


More and more sensitive at large p_T for HQ from center

Close to experimental prediction but not yet (Hadronization, NLO at the time of production, background subtraction,...)

Consequences on the observables: $p_t(c)$ - $p_t(\text{cbar})$ correlations

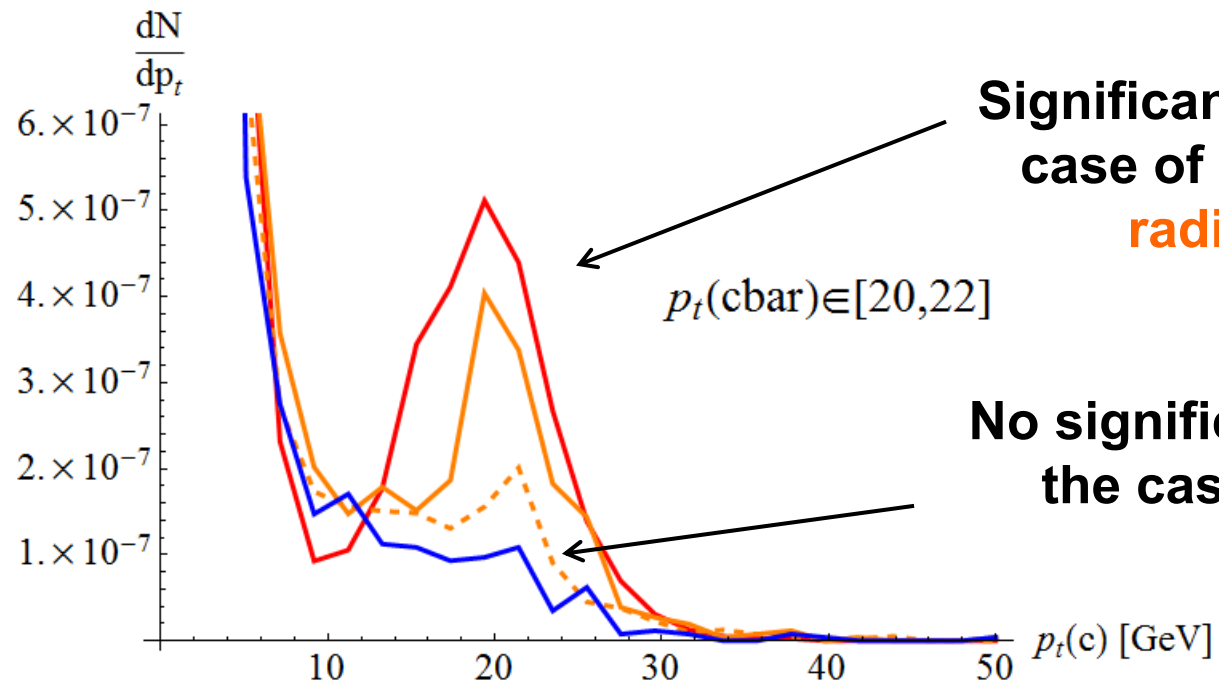
Pb-Pb @ 2.76 TeV; 40-60%. Toy study: back to back c-cbar (no NLO corrections)



Residual correlation after evolution through QGP
(similar path length for most of HQ produced in the core of the reaction)

Consequences on the observables: p_T - p_{Tbar} correlations

Pb-Pb @ 2.76 TeV; 40-60%. Toy study (proof of principle): back to back c-cbar



Significant residual correlation for the case of **Elastic energy loss** or **LPM radiative + gluon damping**

$p_t(\text{cbar}) \in [20, 22]$

In the B2B region:

No significant residual correlation for the case of **radiative GB** or **LPM radiative**

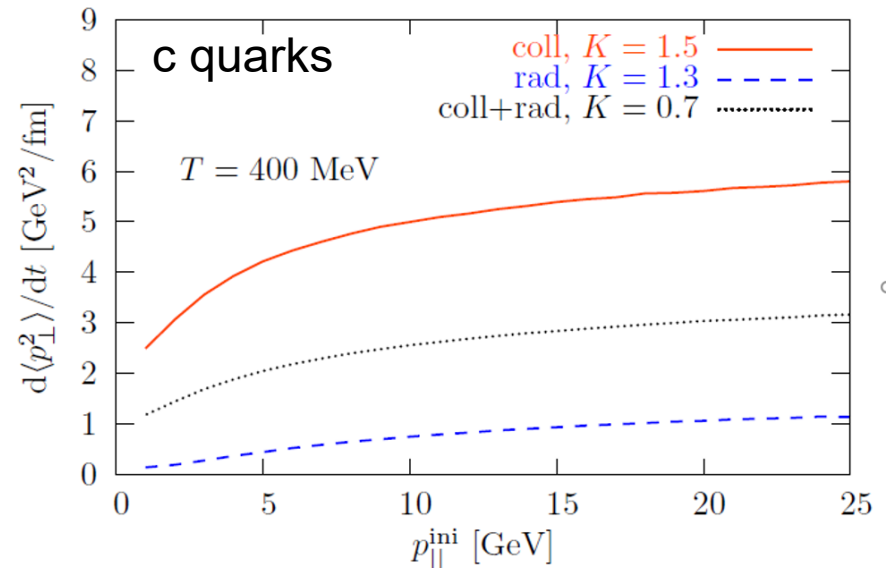
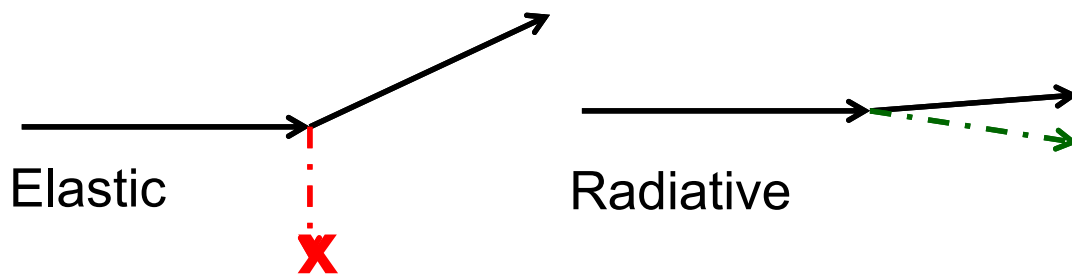
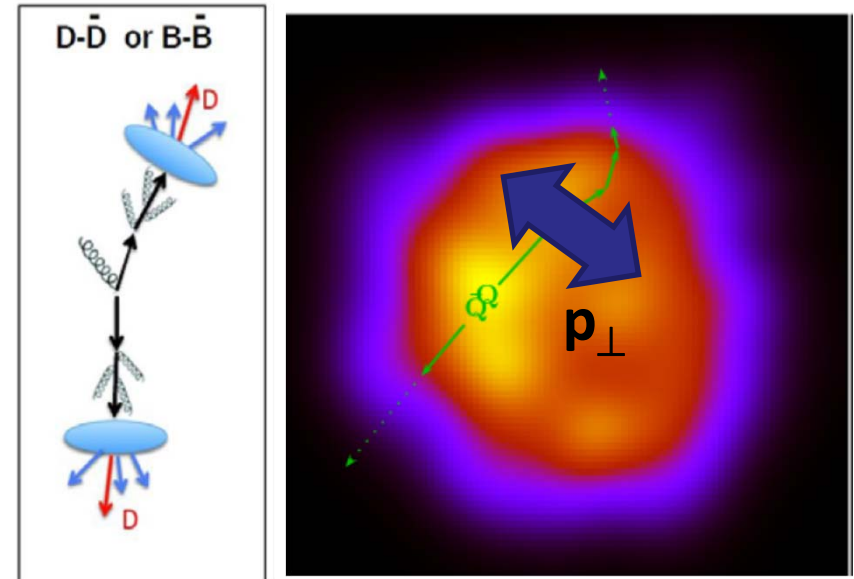
Background at small p_t

WWND 2014
Galveston

How does DGLAP evolution blur momentum imbalance ?

Next best thing: HF-HF correlations

- Back to back D/Dbar or B/Bbar: As compared to γ -D/B: “trigger” itself is affected but symmetry between both particles limitates the various effects.
- Elastic Eloss vs radiative Eloss: **The purely collisional scatterings lead to a larger average $\langle p_{\perp}^2 \rangle$ then the radiative “corrections”** (need for large scattering to be efficient)... although both types can give correct agreement with the data at intermediate p_T .



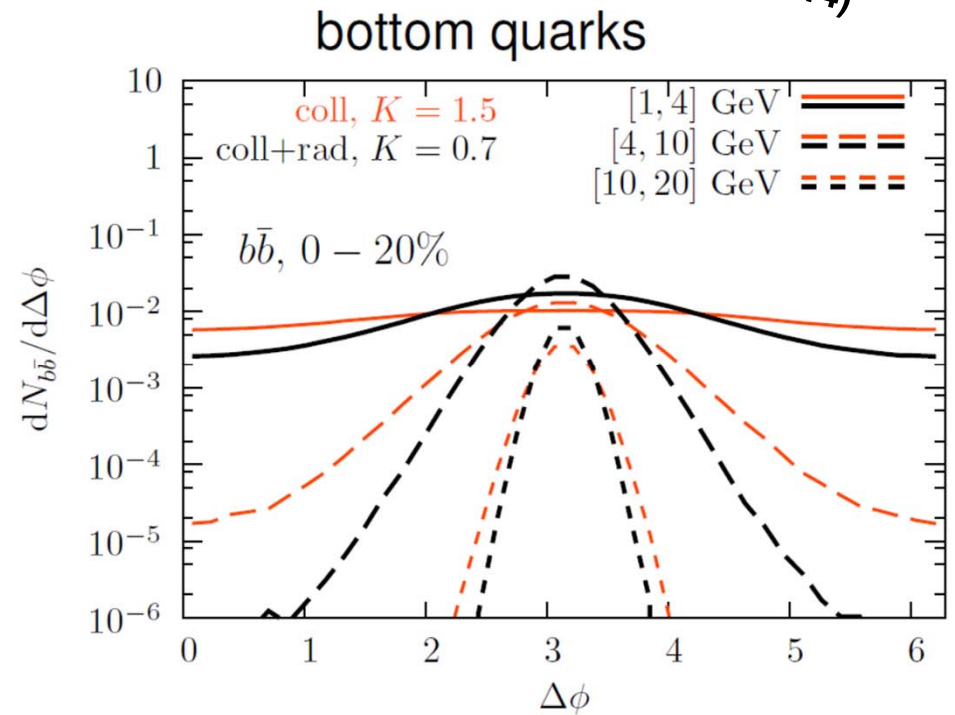
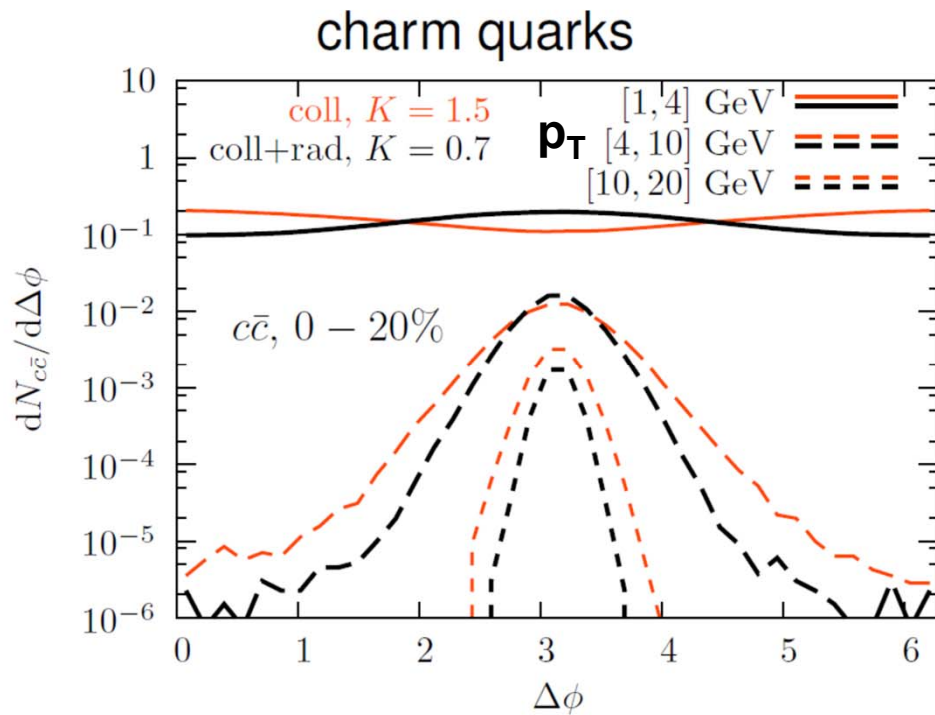
- Expected consequences for azimuthal correlations (probe of B_T : good: **complimentary** to usual RAA and v_2)

Tuned to reproduce the R_{AA}

Next best thing: azimuthal correlations

Nahrgang et al.
Phys. Rev. C 90,
024907 (2014)

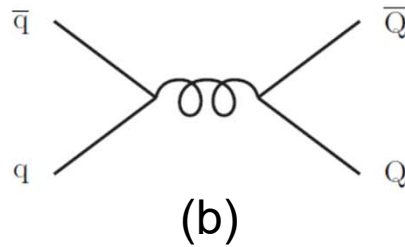
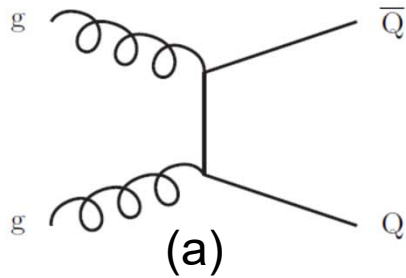
- Assumption of back 2 back emission of initial QQbar (naïve LO...)



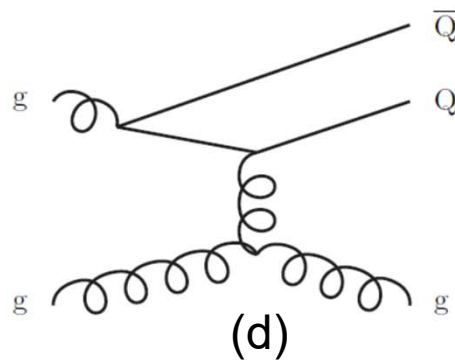
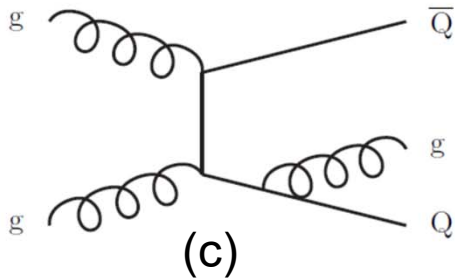
- Indeed, rather large differences found for both b and c, and all kind of p_T cuts (... but good to see there is an effect though,...)
- For the smallest p_T bin and elastic energy loss, we even find an inversion of the correlation (“hot partonic wind” push; v_0 bulk => v_1 correl; underlying event)

Next best thing: azimuthal correlations

➤ ...but higher orders can have a significant impact:



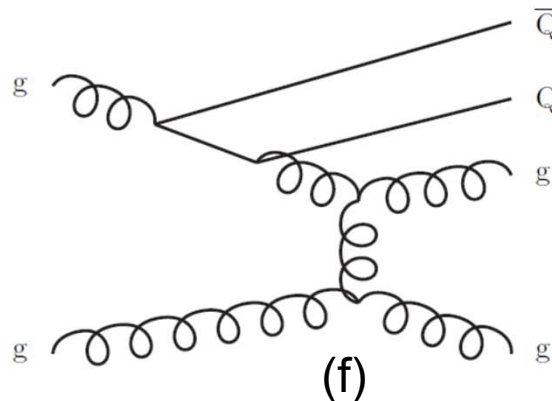
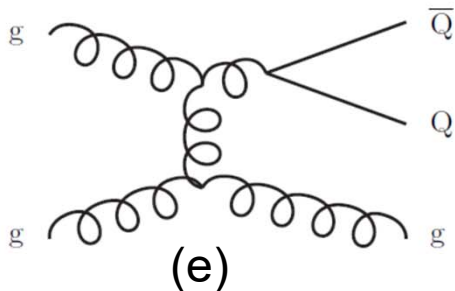
➤ LO; (a): back to back peak



➤ NLO;

(c): “blurring” of B2B peak

(d): “flavor excitation”: no strong azimuthal correlation expected

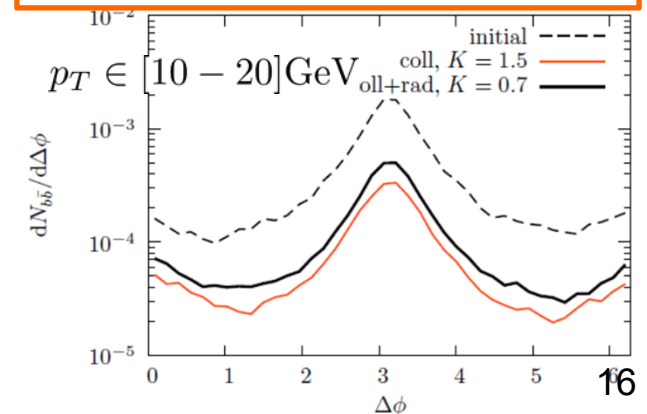
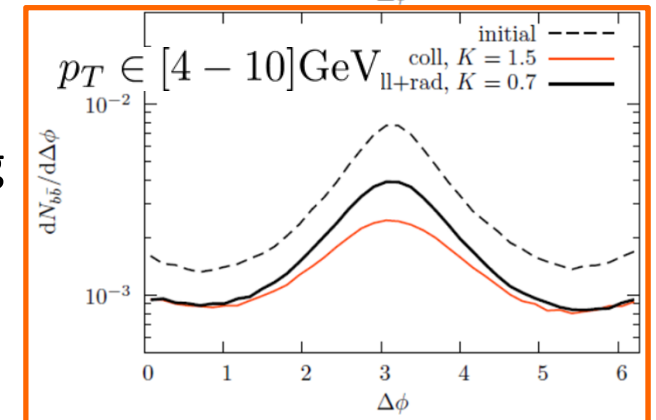
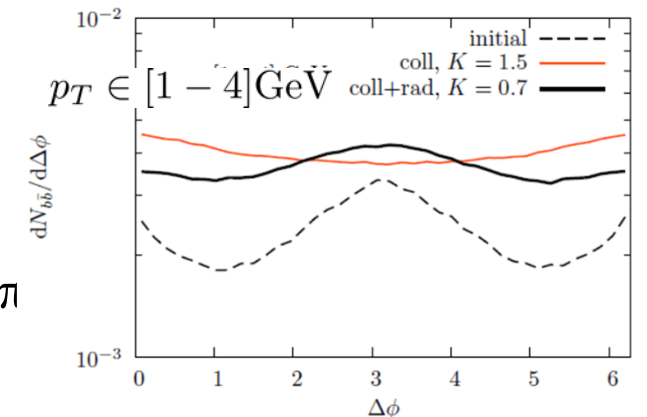


(e): gluon splitting: strong peak around $\Delta\phi=0$

(f): higher order FE; both Q and Qbar in the “remnant” region

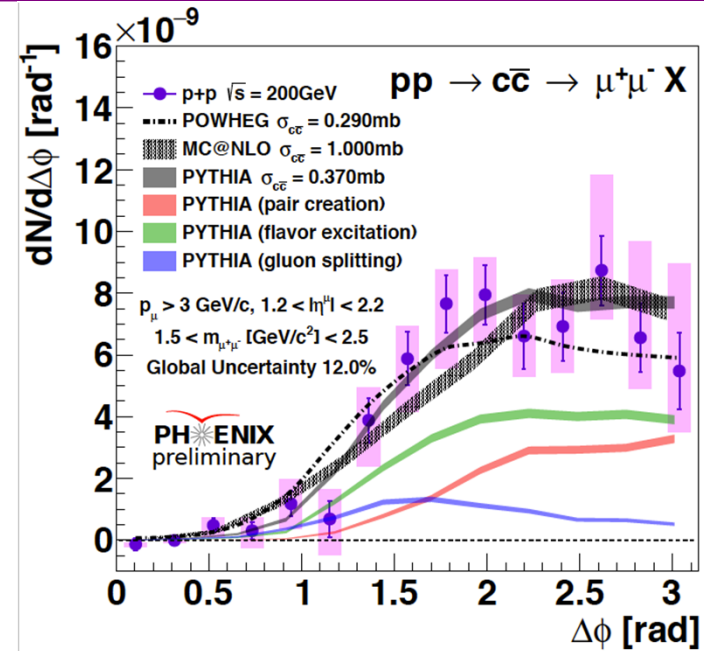
Next best thing: azimuthal correlations

- NLO effect simulated with MC@NLO + HERWIG (parton shower)
- Gluon splitting processes lead to an initial enhancement of the correlations around $\Delta\phi=0$; Strong broadening of the $\Delta\phi=\pi$ peak (“vacuum” radiation is dominant)
- For intermediate p_T : increase of the variances due to Eloss from 0.43 (initial NLO) to 0.51 (+20%) for the purely elastic mechanisms and to 0.47 (+10%) for the interaction including **radiative** corrections.
- Correlations at large p_T seem to be dominated by the initial correlations. **Nothing will be learned on the Eloss mechanisms in this region**
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production
- Study by other groups (Duke, CCNU-LBL,PHSD,...)

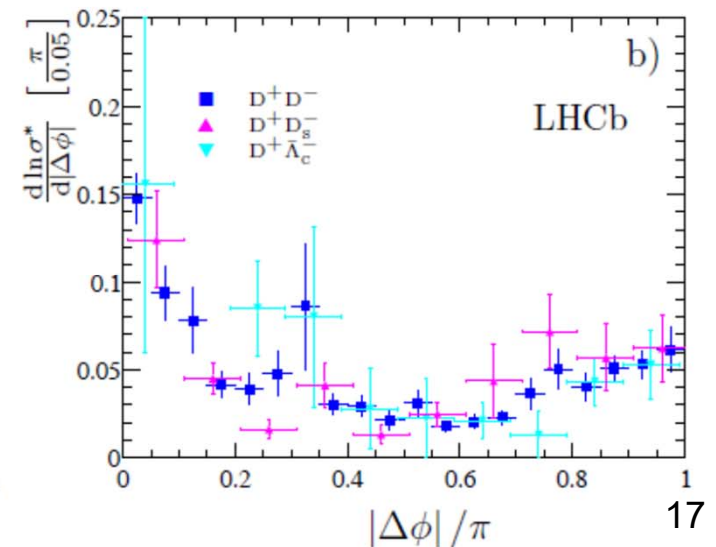
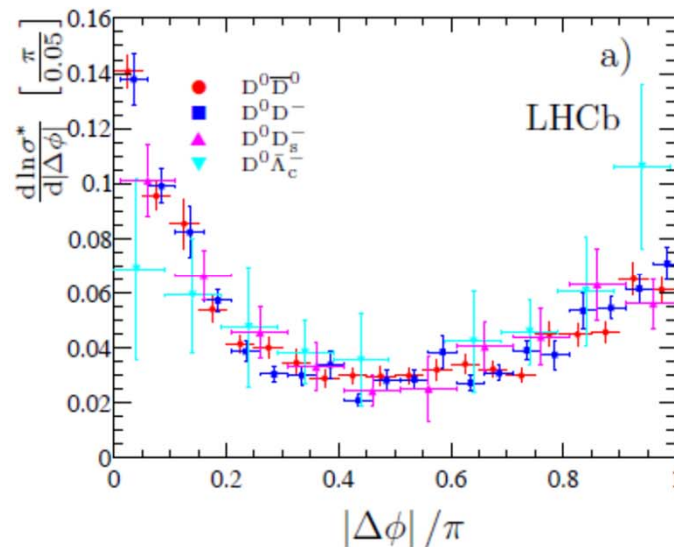


Azimuthal correlations from experimental viewpoint

- Measured in pp both at RHIC and LHC (rising gluon splitting peak)
- Not even sure one could resolve a 10% difference in the width for the pp !!!
- A+A: expected after upgrades ?

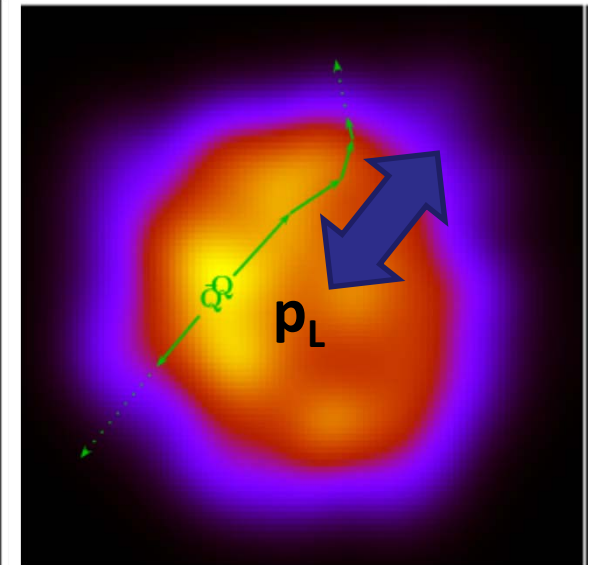
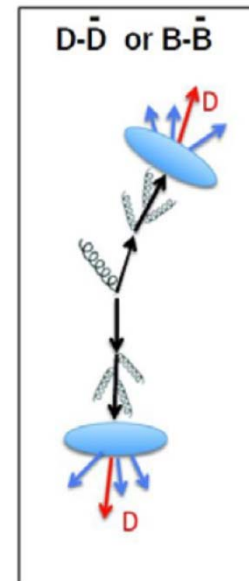


LHCb



Next best thing: HF-HF correlations

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- Large number of c - \bar{c} from various NN collisions => large uncorrelated background
- Competing effects due to energy loss
- Of course: **NLO effect in the production mechanisms makes it not so trivial** (not to speak about exp. Issues... RUN 3 ? RUN 4 ?)



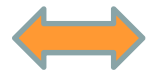
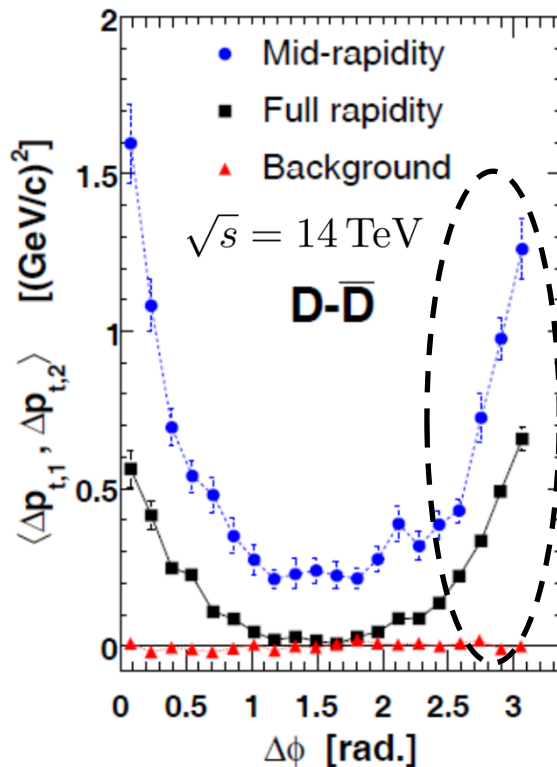
Not so naïve approach: Momentum imbalance in pp

➤ ... including “realistic” initial stage in pp (PYTHIA 6)

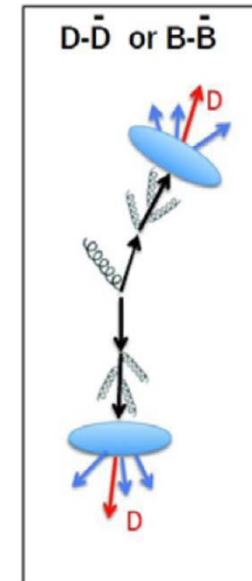
➤ Average auto-correlation:

$$\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle^{(D\bar{D})} = \frac{1}{\sum_{k=1}^{n_{ev}} N_k^D N_k^{\bar{D}}} \cdot \sum_{k=1}^{n_{ev}} \sum_{i=1}^{N_k^D} \sum_{j=1}^{N_k^{\bar{D}}} (p_{ti} - \bar{p}_t^{(D)}) (p_{tj} - \bar{p}_t^{(\bar{D})})$$

G. Tsiledakis et al., Nucl. Phys. A 858 (2011) 86.



In the back-to back region, NLO corrections (FSR) still preserve some degree of correlation



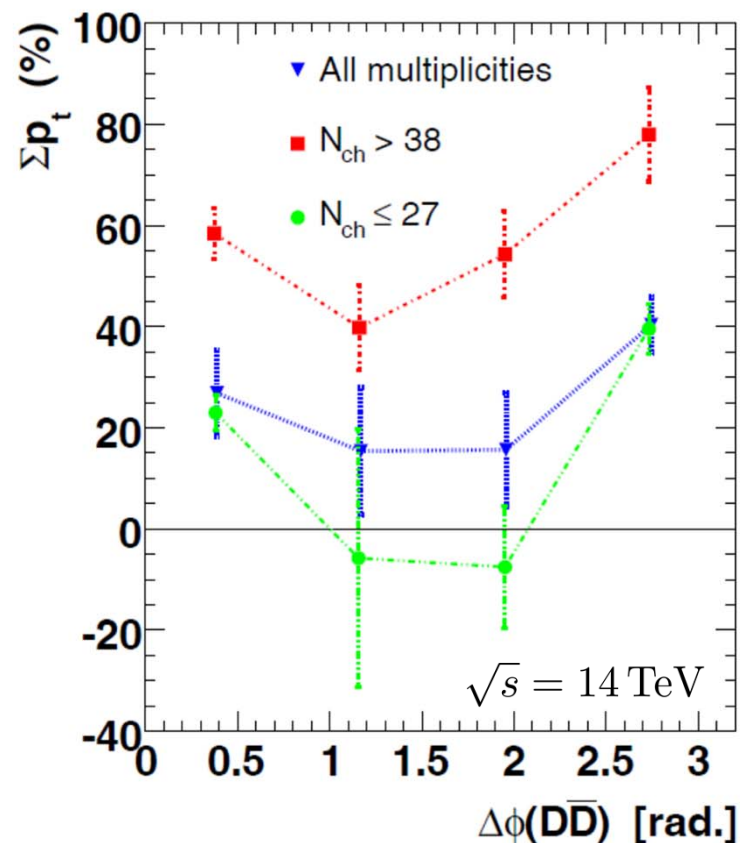
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➤ Average *relative* auto-correlation:

$$\Sigma_{pt} = \text{sgn}(\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle) \frac{\sqrt{|\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle|}}{\bar{p}_t}$$

G. Tsiledakis et al., Nucl. Phys. A 858 (2011) 86.



- Encouraging signs of significant finite (transverse) momentum correlation in pp, i.e. in the initial stage of A-A collisions
- Going beyond average ?
- Lessons from CMS: Pythia has problems to reproduce Q-Qbar azimuthal correlations

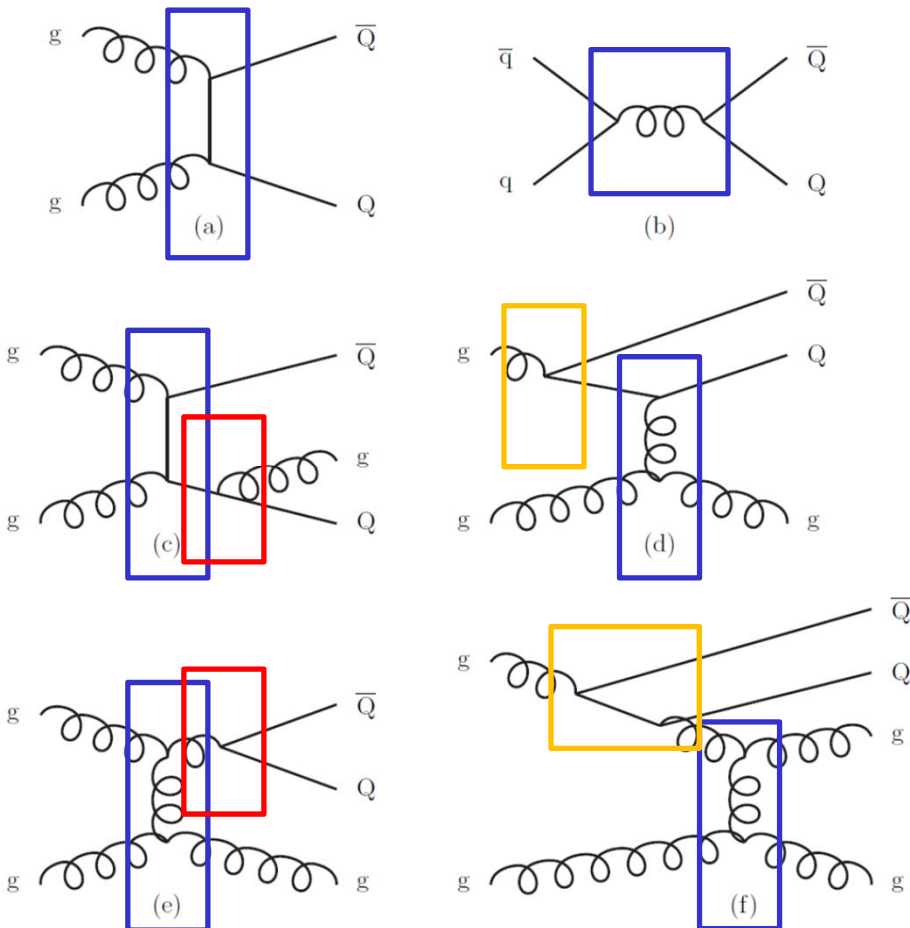
CMS-PASHIN-16-005.

Momentum imbalance: not so naïve approach

- Goal of the study: investigate whether p_T - p'_T correlations survive NLO effects

L. Vermunt et al.
arXiv:1710.09639

- Method for “systematics”: use 2 event generators: PYTHIA (6.4) & EPOS3

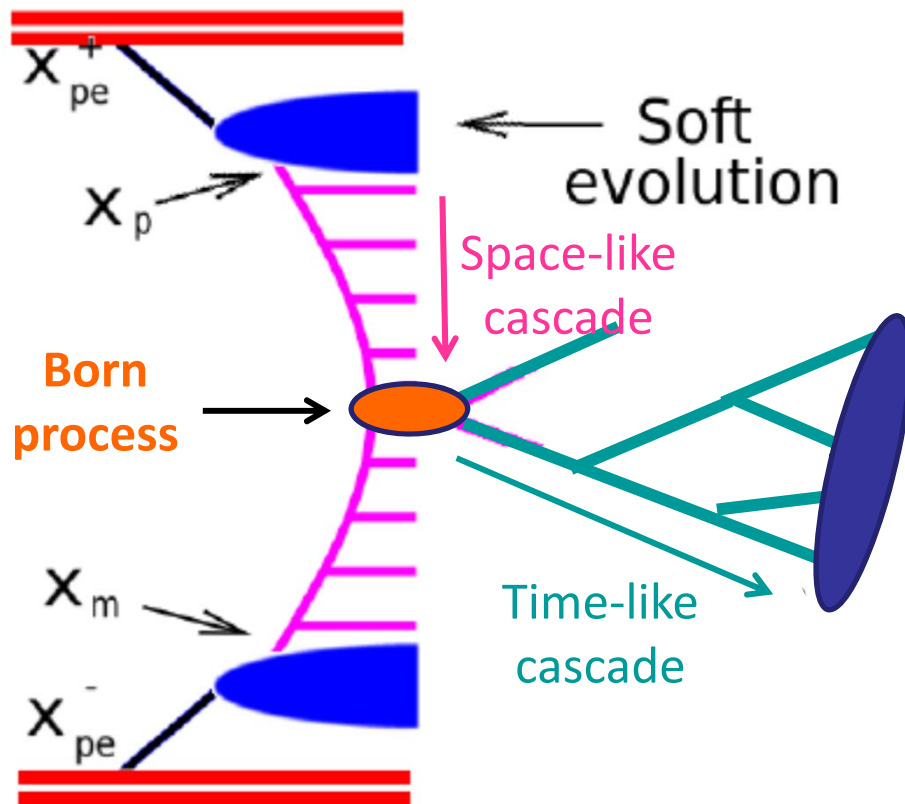


- In pythia, those topologies are generated by coupling LO processes (implying 0,1 or 2 HQ) and ISR + FSR ... This will be referred to as « LO + NLO ccbar » (strictly speaking, no NLO !)

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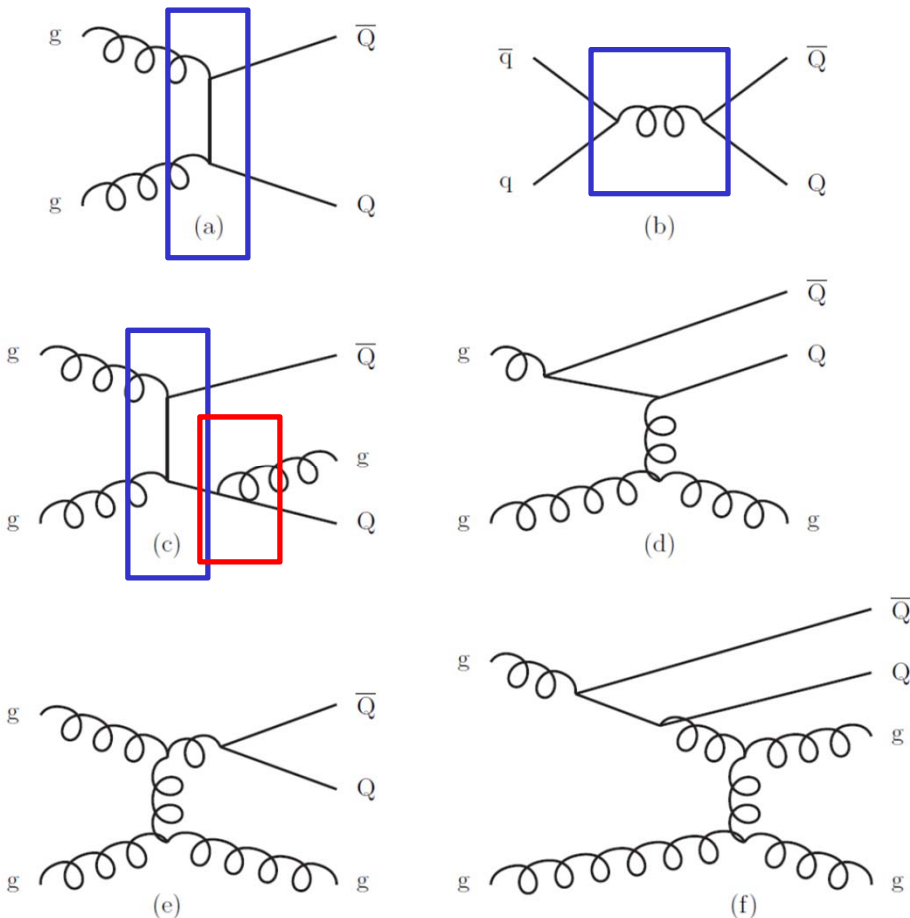
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- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.

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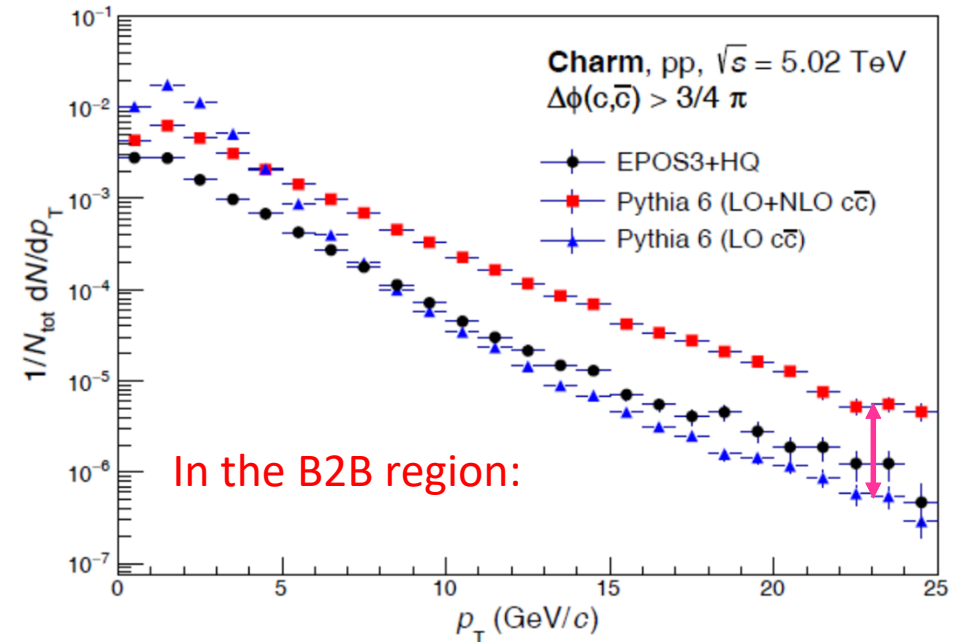
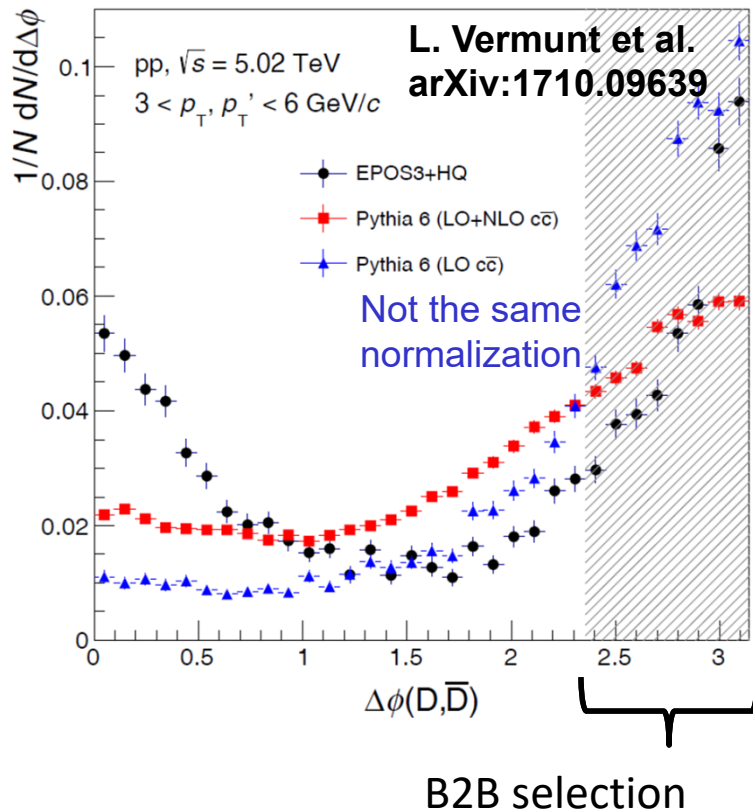
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- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.
- In pythia, possibility to restrict to LO ccbar production processes with massive elements (MSEL=1 -> MSEL=4 flag), still switching on the ... ISR + FSR ... This will be referred to as « LO ccbar »

Momentum imbalance: not so naïve approach

- Including NLO effects in the charm production (N.B. :beauty would be better for our purpose, but very low statistics)

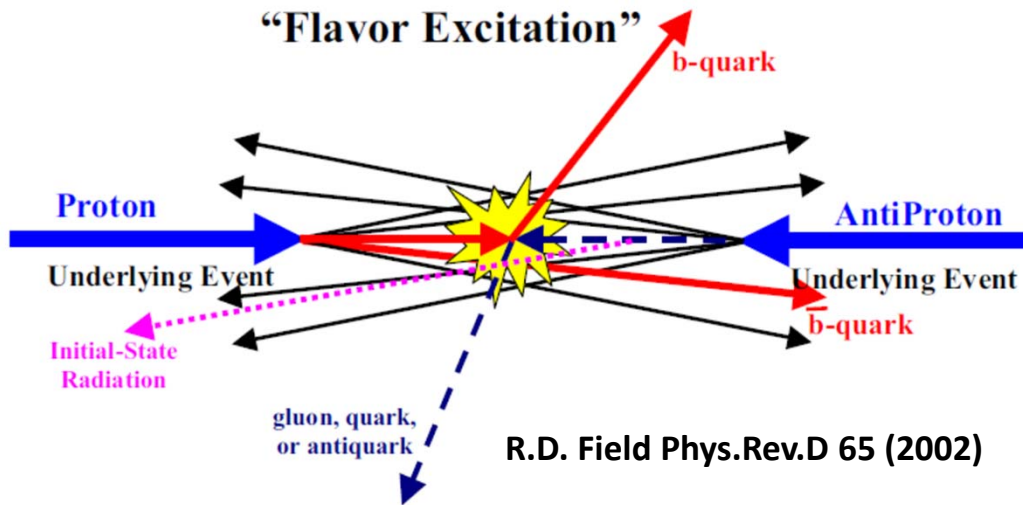


- Good agreement in the normalization for EPOS3 vs PYTHIA « LO » (MSEL=4)
- Large excess PYHTIA « NLO »; shown to be due to **flavor excitation like process**

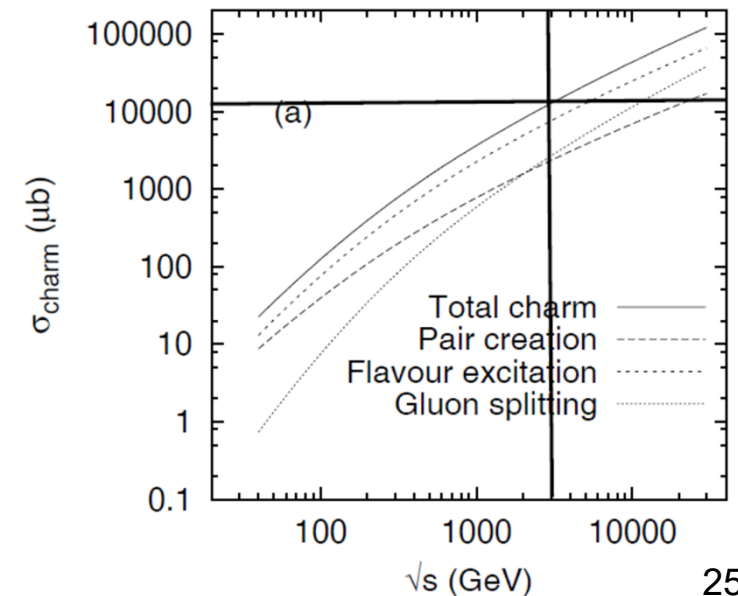
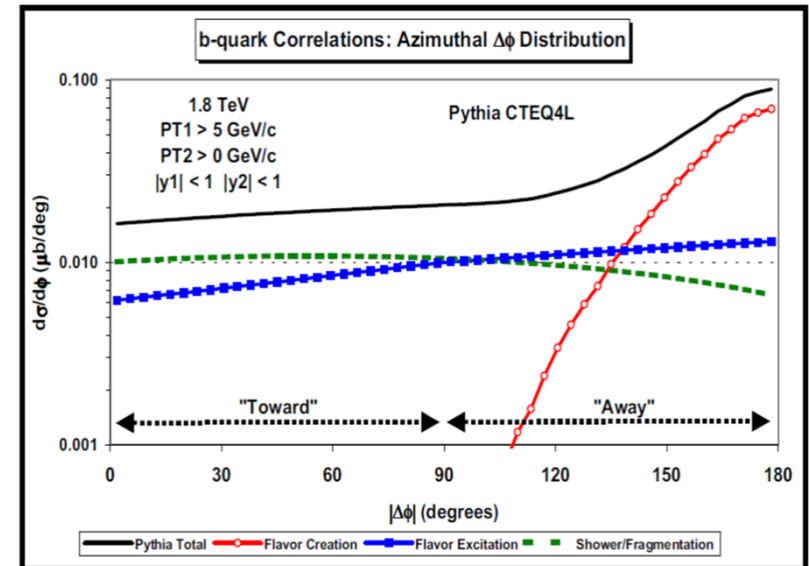
N.B.: Pythia MSEL=4: at least 1 ccbar pair un each event => Normalized according to high- p_T LO charm creation in Pythia MSEL=1

Momentum imbalance: not so naïve approach

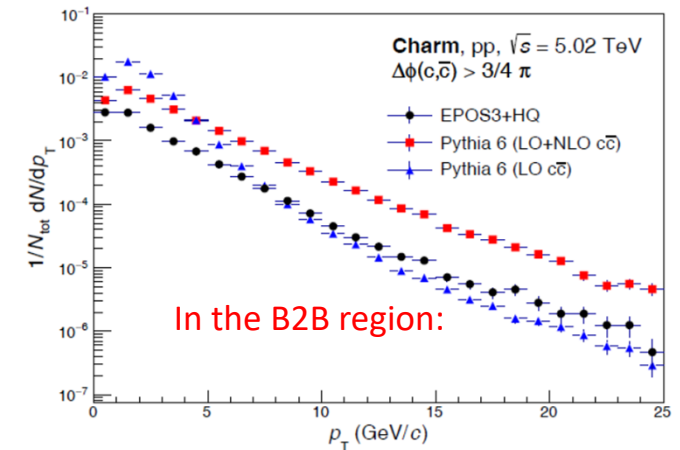
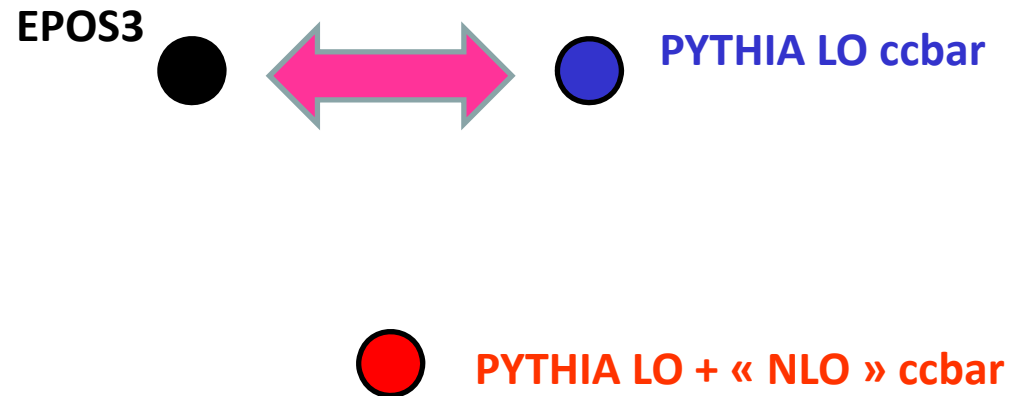
- Including NLO effects in the charm production:



- Flavor excitation: very sensitive to the $c\bar{c}$ in the proton sea, i.e. to the gluon evolution \rightarrow large Q^2
- σ_{charm} (Pythia 6,) exceeds measured ALICE value by a factor 3-5. Mostly due to large FEX contribution.
- Similar conclusion of sur-abundant FEX found by CMS (CMS-PAS-HIN-16-005) for beauty quarks

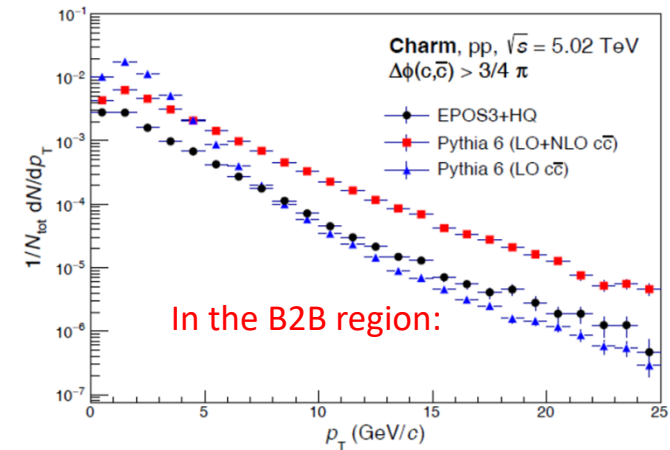
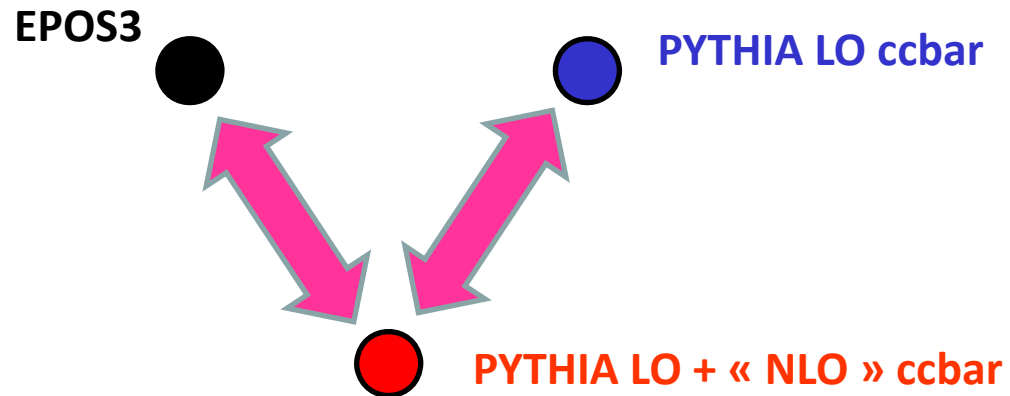


Momentum imbalance: not so naïve approach



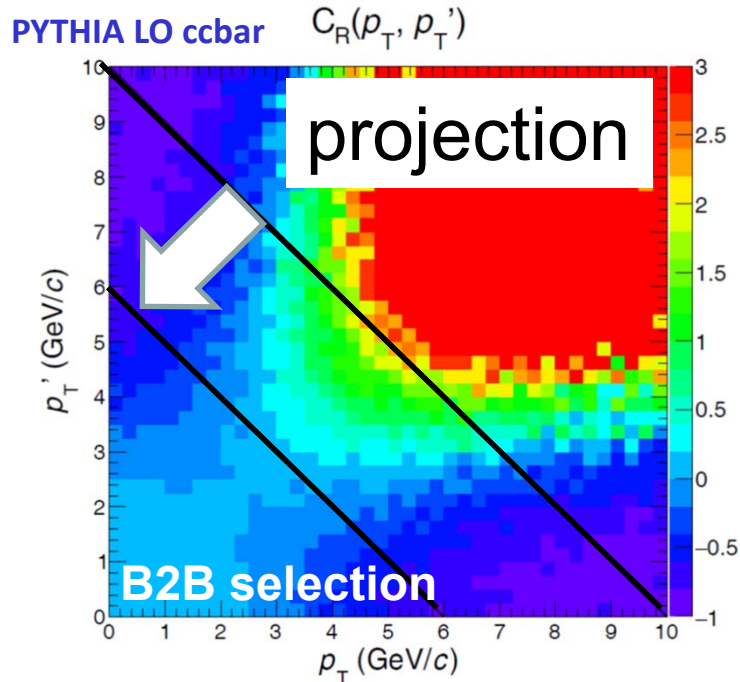
- Same process in the B2B => use the p_T correlations to investigate FSR

Momentum imbalance: not so naïve approach



- Same process in the B2B => use the p_T correlations to investigate FSR
- Use p_T correlations to resolve FEX contribution in the B2B region

Momentum imbalance: not so naïve approach



- Different p_T imbalance for 3 production models in pp
- 2 of them show that NLO effects does not completely destroy the perfect correlation found in LO production
- Similar results for DDbar

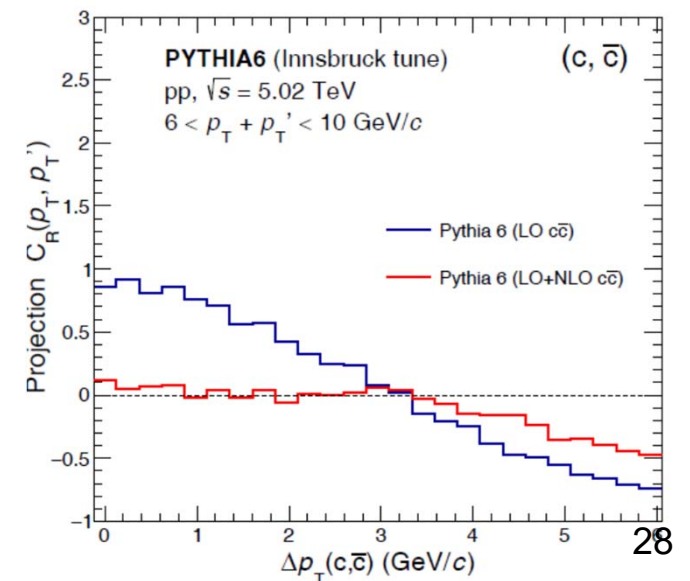
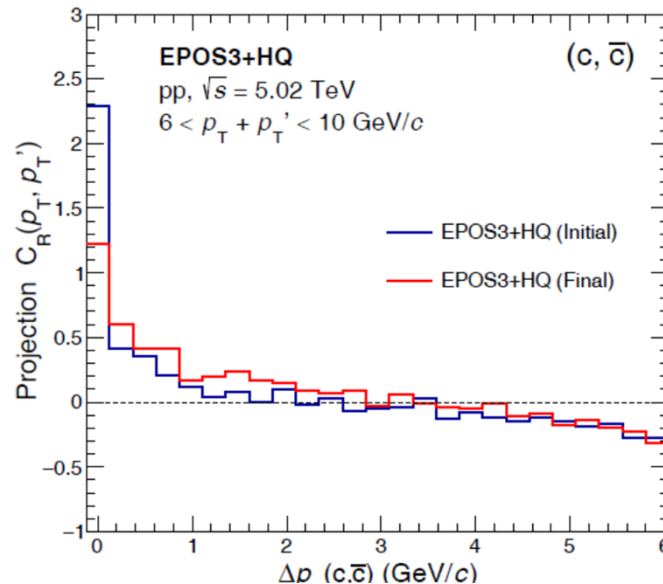
Absolute correlation:

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

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

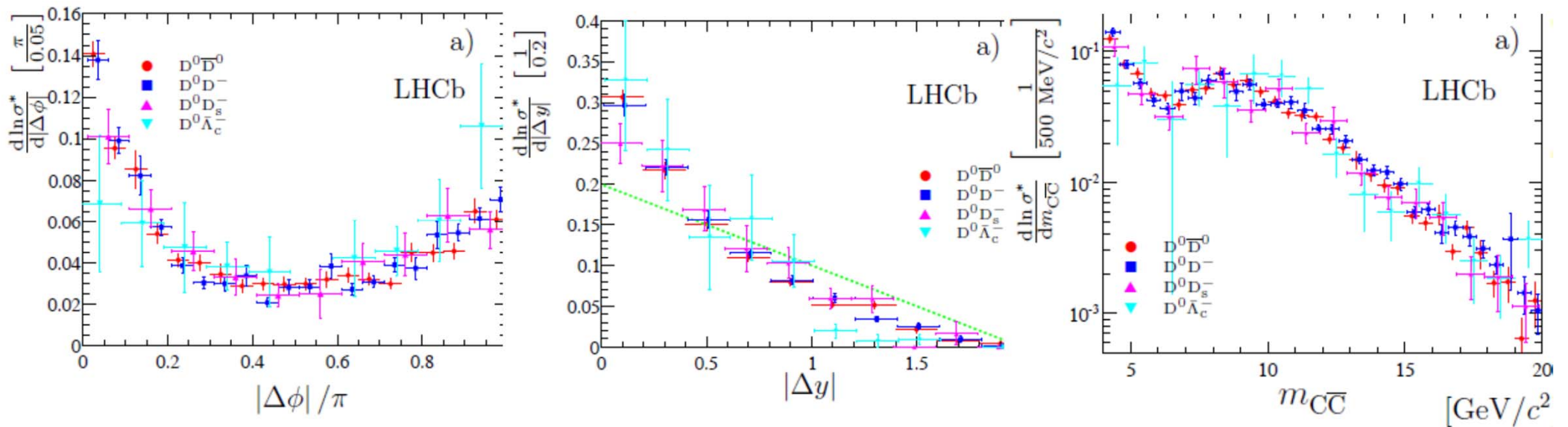
- Reveals correlation at finite p_T



From the experimental viewpoint

- No momentum imbalance so far in pp @ LHC (to my knowledge)...
- But valuable data from LHCb on DD:

LHCb, J. High Energy Phys. 06, 141 (2012)



- Under present investigation

Momentum imbalance in A-A

➤ Some recent works:

➤ J. Uphoff et al. (BAMPS): Phys. Rev. C 89 (2014), 064906

**All including realistic
c-cbar « initial »
production**

Momentum imbalance in A-A

J. Uphoff et al. (BAMPS): Phys. Rev. C 89 (2014), 064906:

- **Collisional Energy loss model** calibrated on $v_2(D)$ meson; lead to acceptable results for R_{AA} as well.

➤ Chosen observable:

$$A_D = \frac{p_{T;1}^D - p_{T;2}^D}{p_{T;1}^D + p_{T;2}^D}$$

Leading D/Dbar Sub- Leading D/Dbar

- Back to back selection

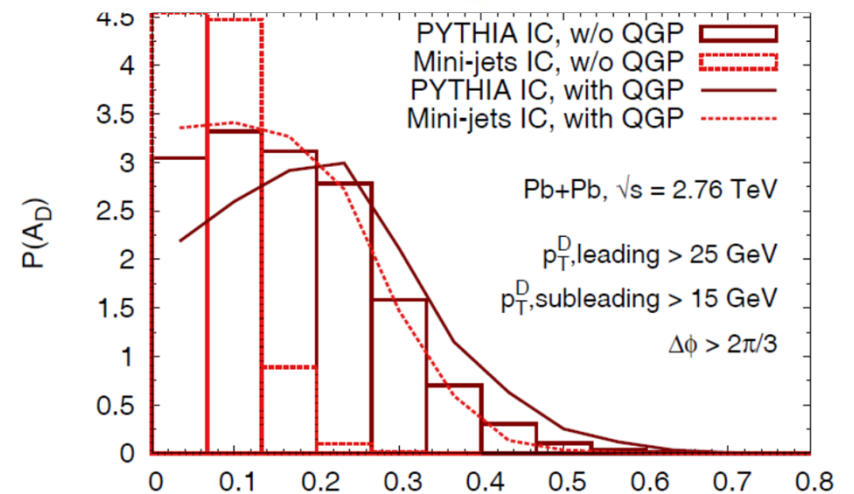
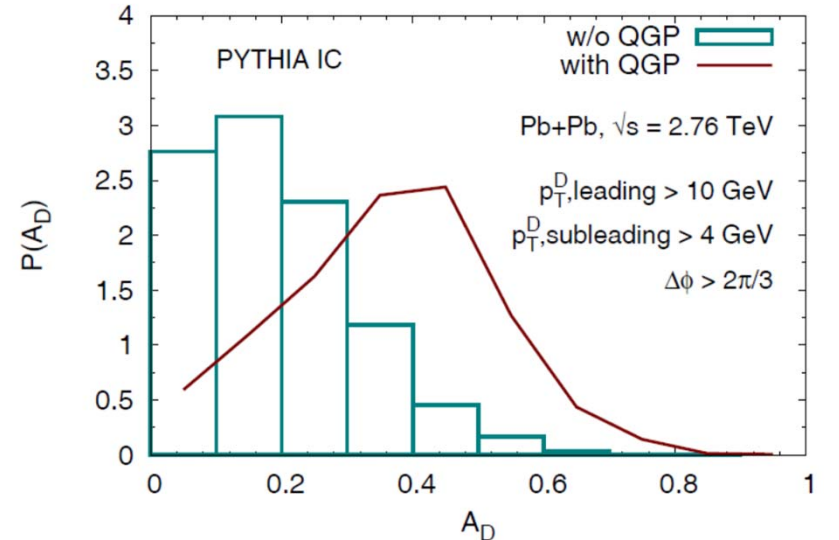
- Two selections for most central Pb-Pb collisions:

- “Intermediate”: $p_{T;1}^D > 10 \text{ GeV}$ and $p_{T;2}^D > 4 \text{ GeV}$
- “High”: $p_{T;1}^D > 25 \text{ GeV}$ and $p_{T;2}^D > 15 \text{ GeV}$

Momentum imbalance in A-A (BAMPS)

- Intermediate p_T selection:
 - Strong momentum imbalance resulting from c-quark interaction with QGP
 - Large fraction of c-cbar pairs stemming from disconnected NN interactions

- High p_T selection (focusing on PYTHIA IC):
 - Large fraction of c-cbar pairs stemming from single NN interactions Strong
 - **Moderate** momentum imbalance resulting from c-quark interaction with QGP (MI dominated by IC, as for azimuthal correlations)



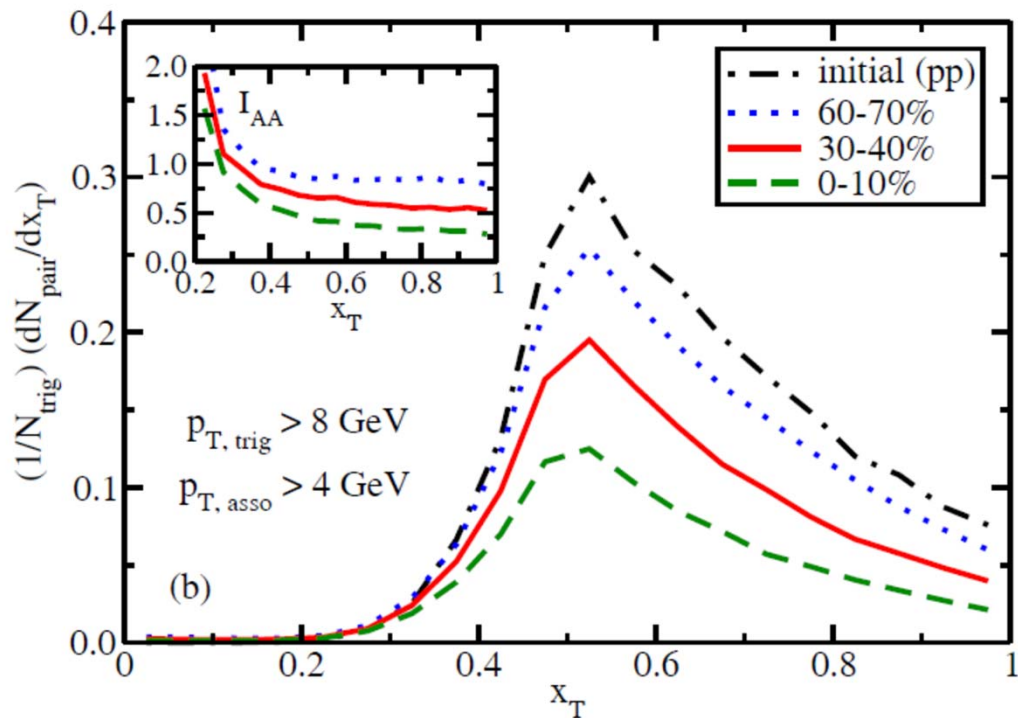
“ Furthermore, it would be intriguing to include also radiative processes for charm quarks and investigate their effects on A_D »

Momentum imbalance in A-A

➤ Some recent works:

All including realistic c-cbar
« initial » production

➤ S. Cao et al.: Phys. Rev. C 92 (2015), 054909 (focused on RHIC energies)



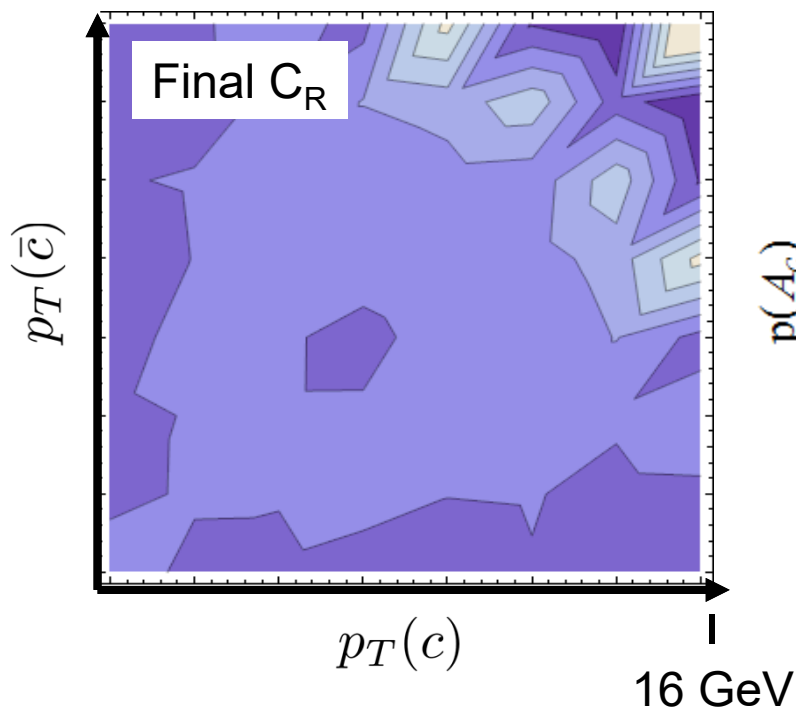
- Observable: $x_T := \frac{p_T^{D(\bar{D}),\text{sublead}}}{p_T^{\bar{D}(D),\text{lead}}}$
- Moderate increase of momentum imbalance from pp → peripheral Au-Au → central Au-Au collisions
- “...momentum imbalances ... value does not strongly depend on the detailed energy loss mechanism as long as the transport coefficient is properly adjusted to describe the D meson RAA. »

➤ T. Song et al. (PHSD): Phys. Rev. C 96 (2017), 014905 (azimuthal correlations)

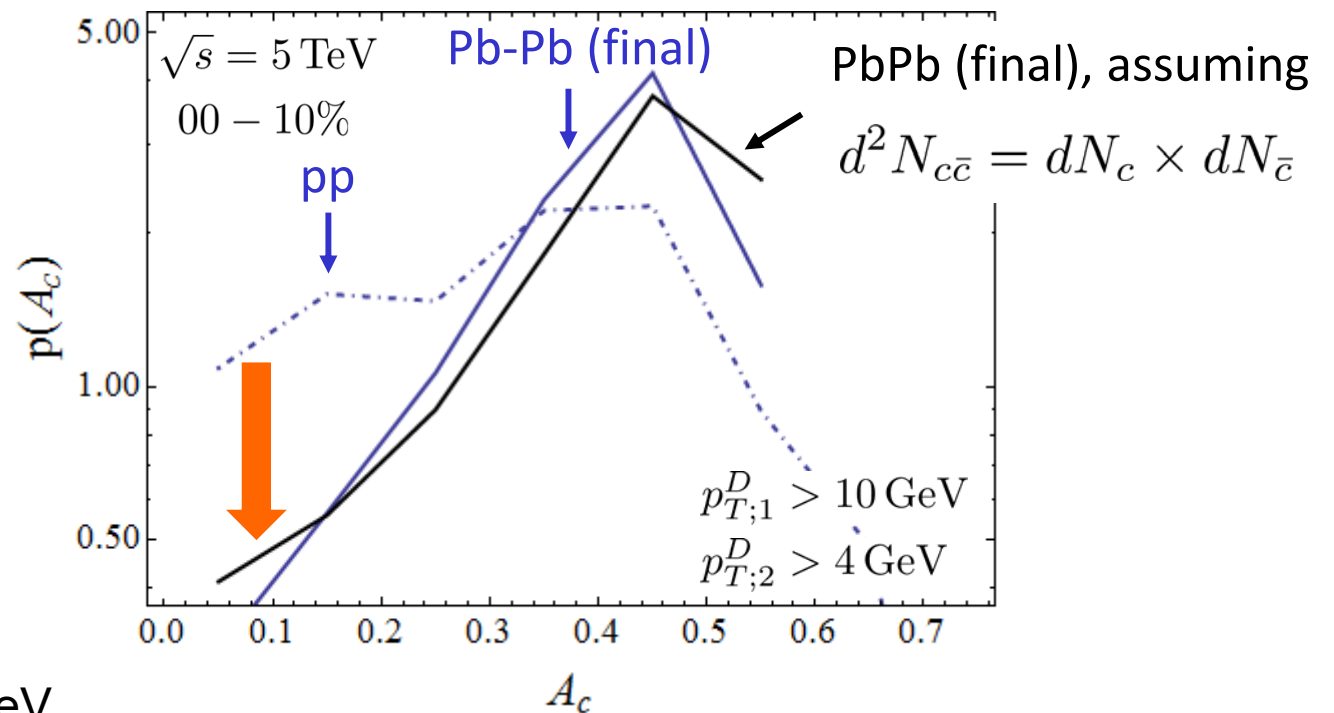
Momentum imbalance in central Pb-Pb (EPOSHQ)



- All HQ produced according to EPOSHQ (V3210)
- Final c-cbar:



Collisional Energy loss (K=1.5)



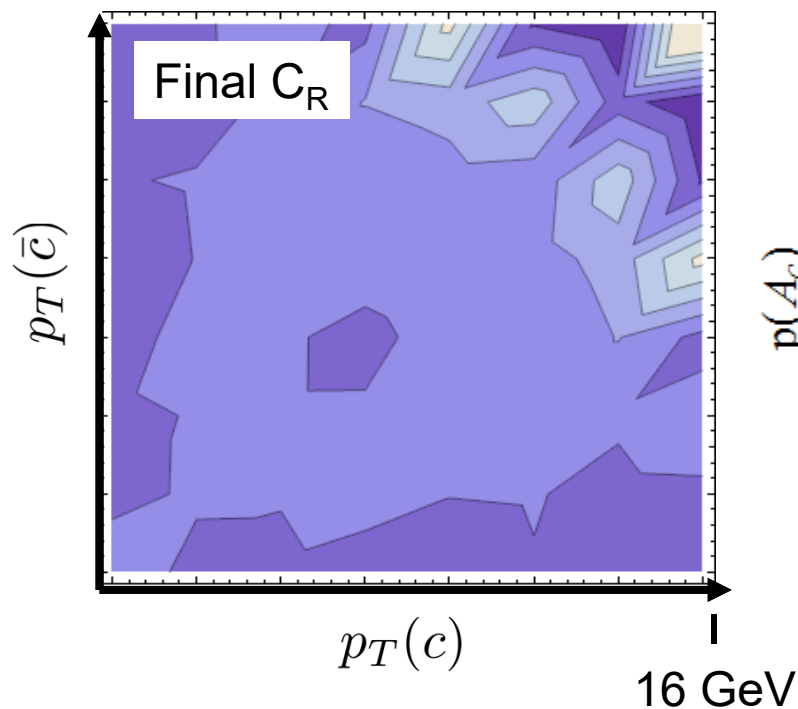
- Very few remaining correlations in the final stage of the collision

- $\approx 100\%$ memory loss of initial correlations

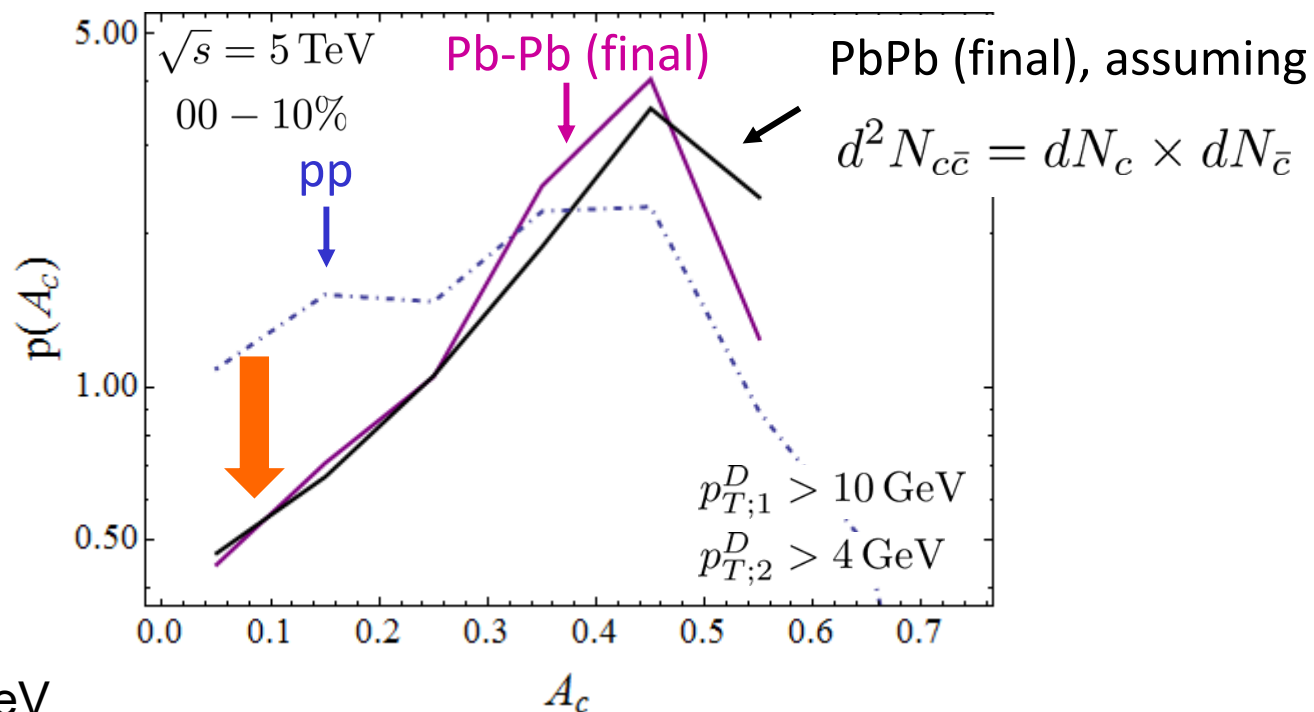
Momentum imbalance in central Pb-Pb (EPOSHQ)



- All HQ produced according to EPOSHQ (V3210)
- Final c-cbar:



Col + Rad Energy loss (K=0.8)



- Very few remaining correlations in the final stage of the collision

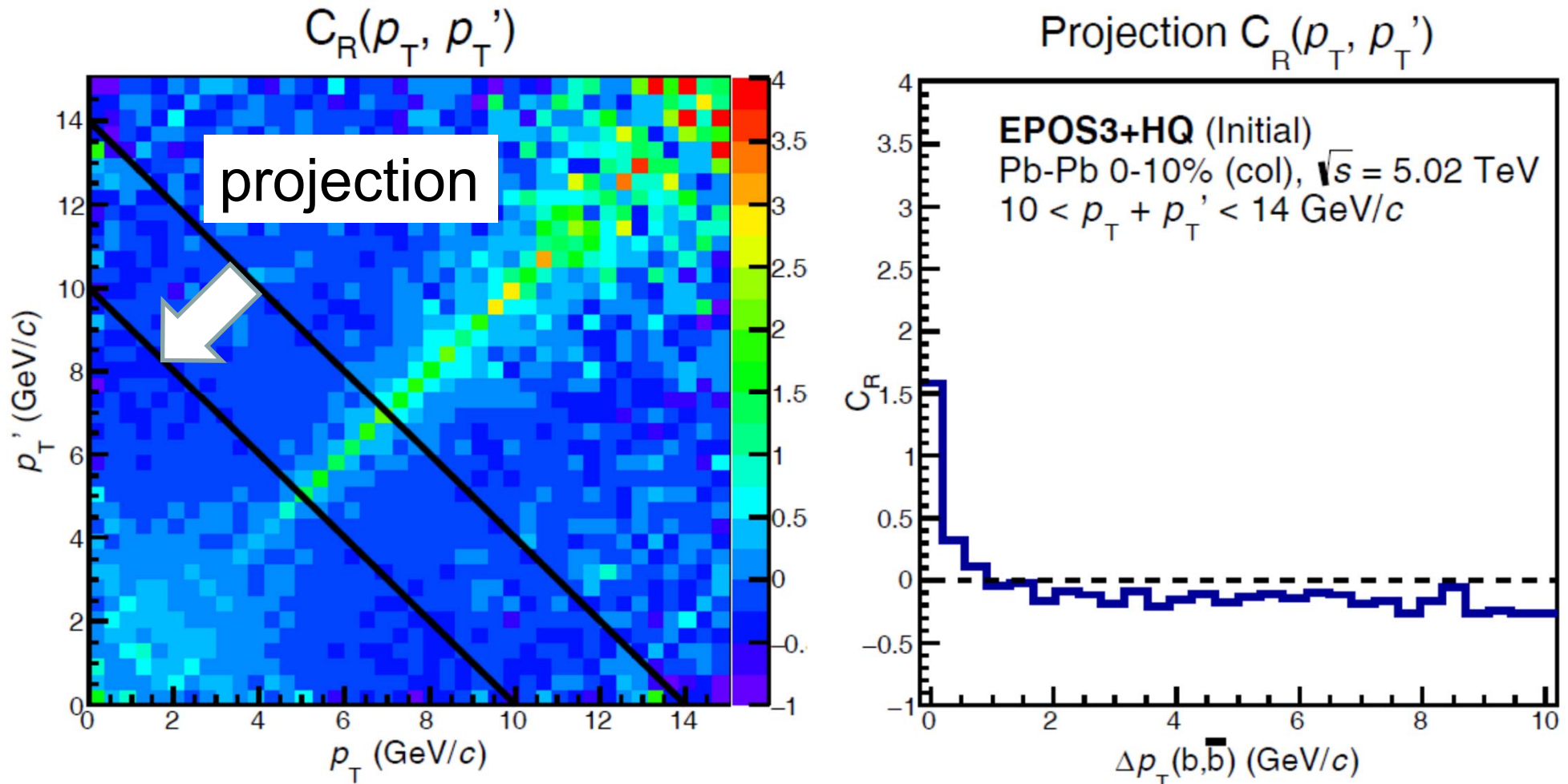
- $\approx 100\%$ memory loss of initial correlations, irrespective of E loss mechanism => no good discrimination (also for beauty)

- Problem with A_D : no clear decorrelation limit

Momentum imbalance: $b\bar{b}$ in Pb-Pb



- “Initial” stage (before evolution with the medium)



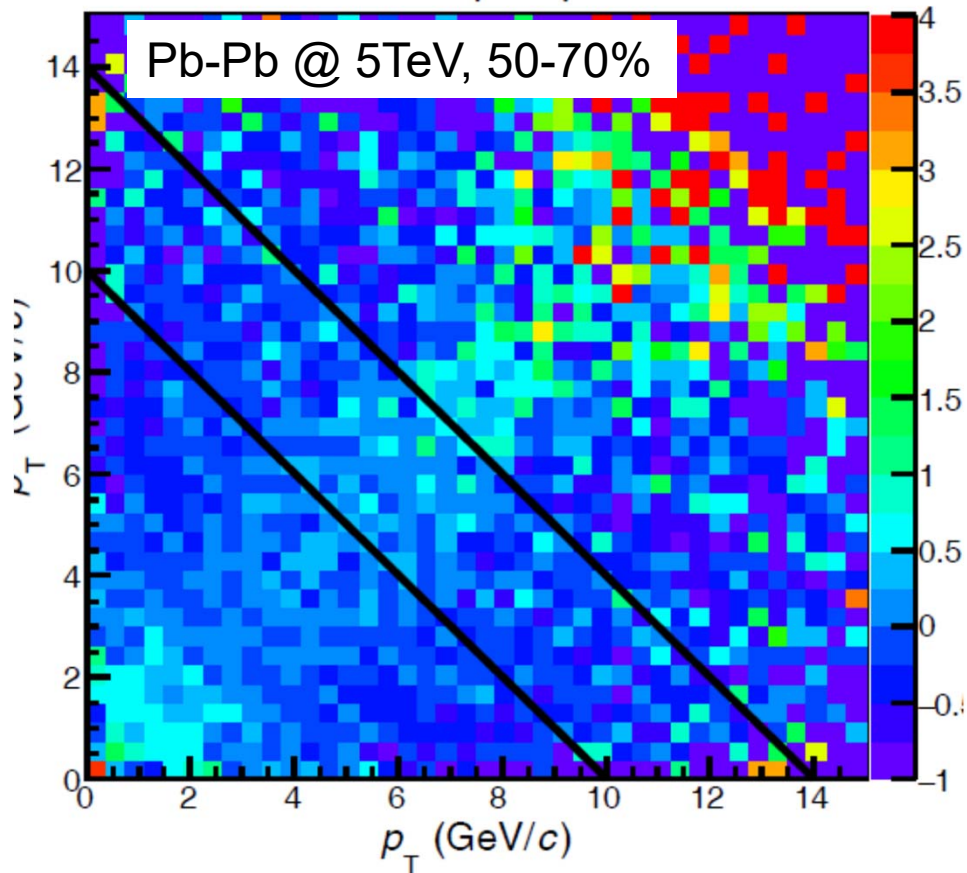
- Very good correlation for intermediate p_T
- Much less uncorrelated background than for $c\bar{c}$.

Momentum imbalance: b-bar in Pb-Pb



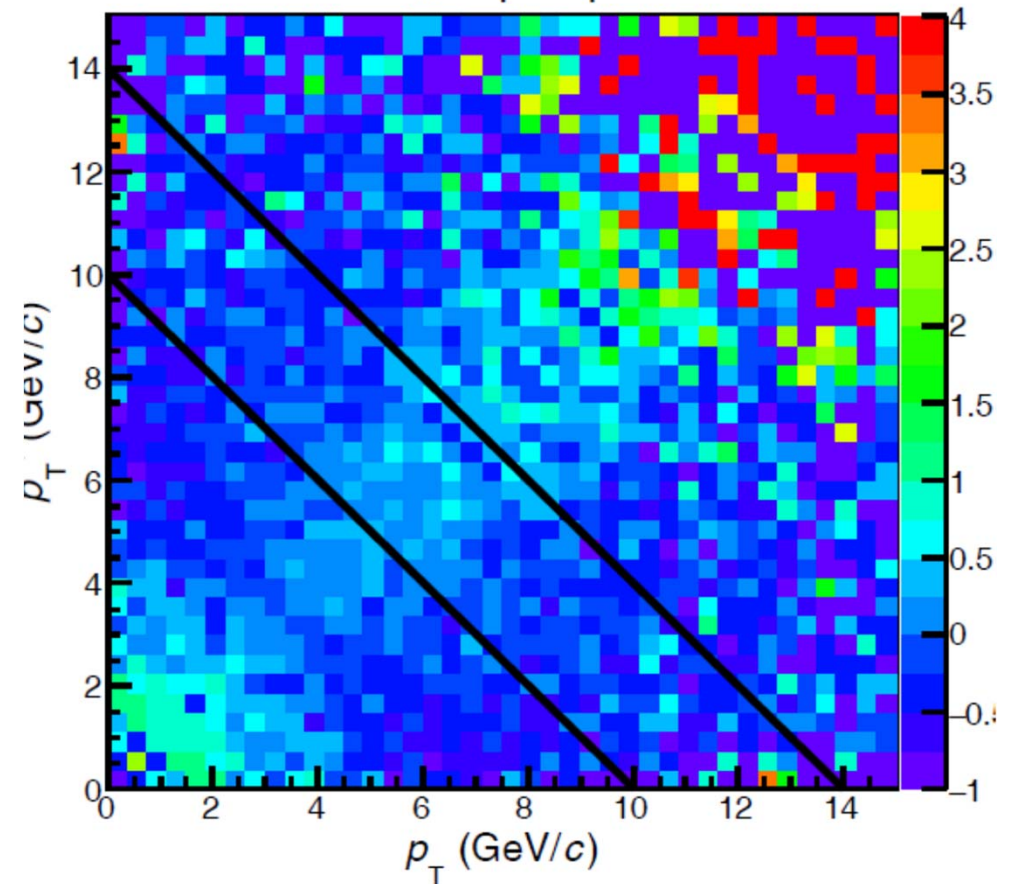
Elastic Energy loss

$$C_R(p_T, p_T')$$

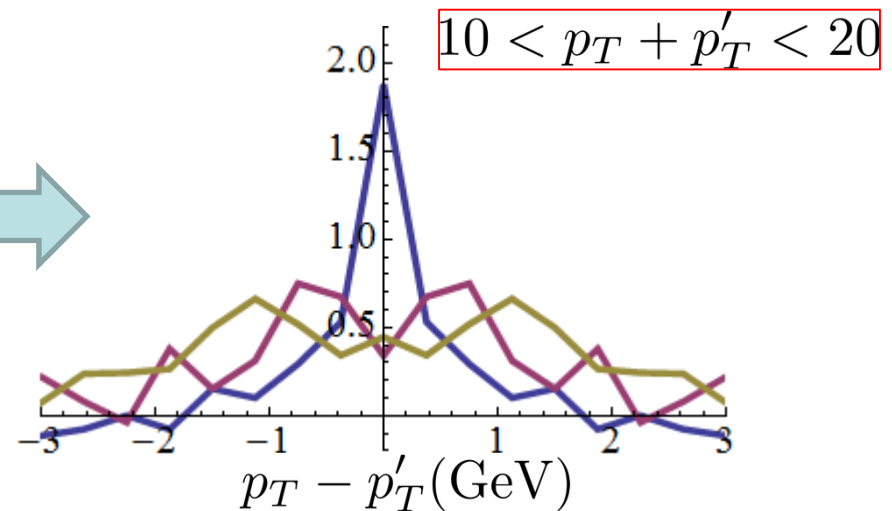
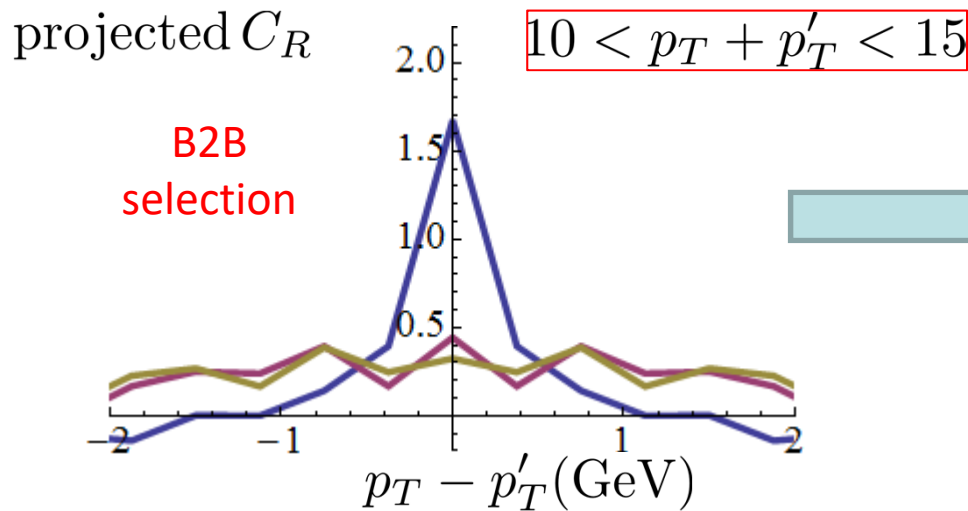
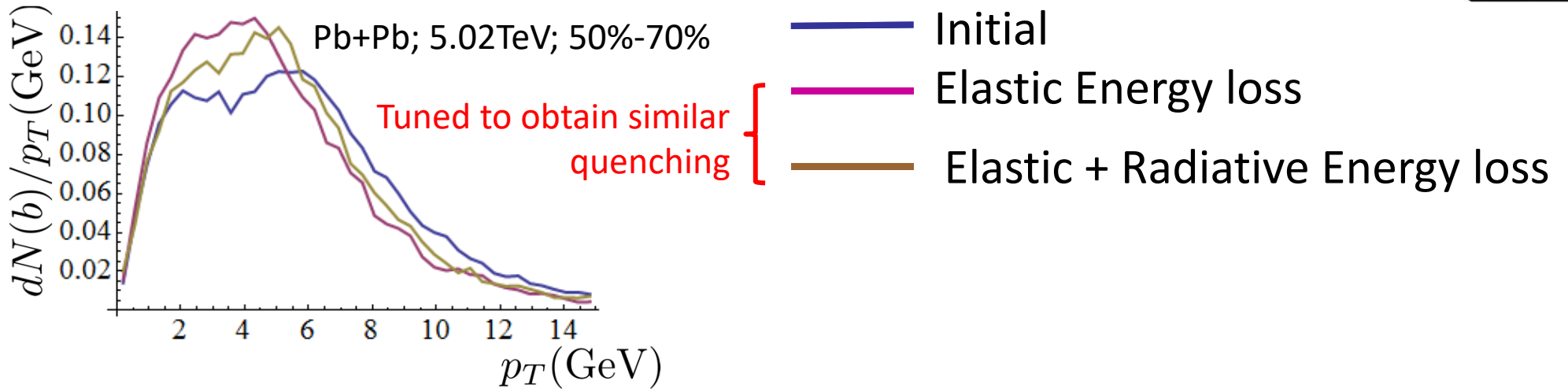


Elastic + Radiative Energy loss

$$C_R(p_T, p_T')$$

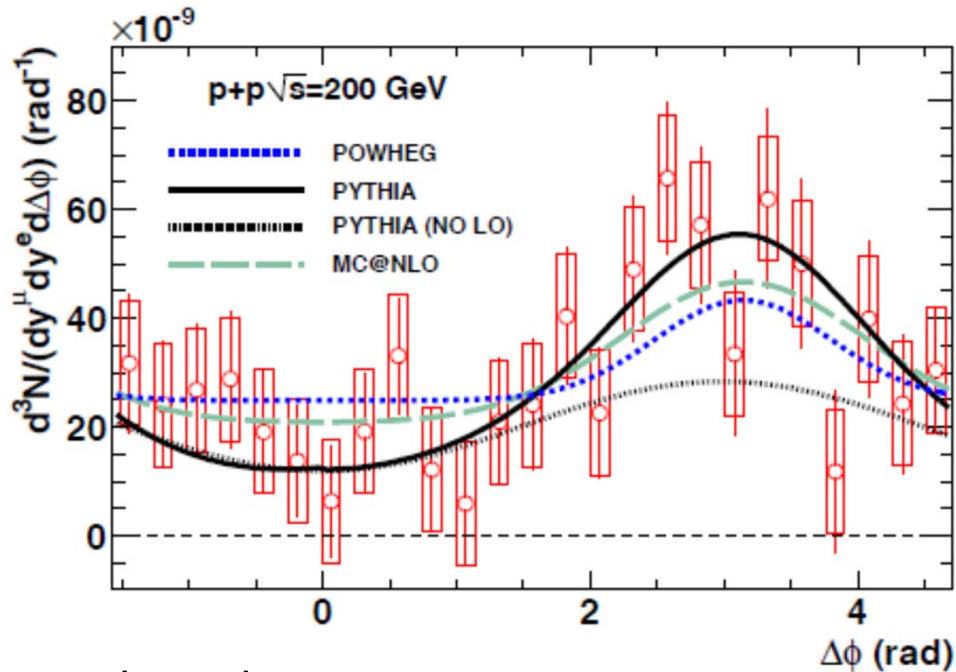


Momentum imbalance: b-bar in Pb-Pb



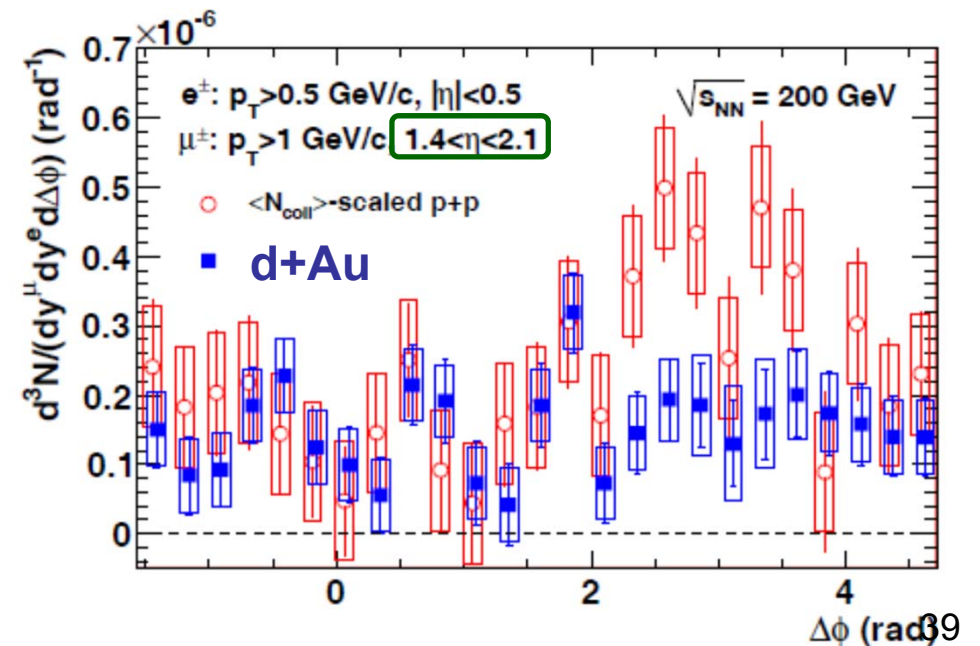
- QGP partly washes away the correlation peak... Possible window to estimate the relative weights of elastic and radiative energy loss for bottom quarks

Next best thing: HF-HF \rightarrow e- μ correlations



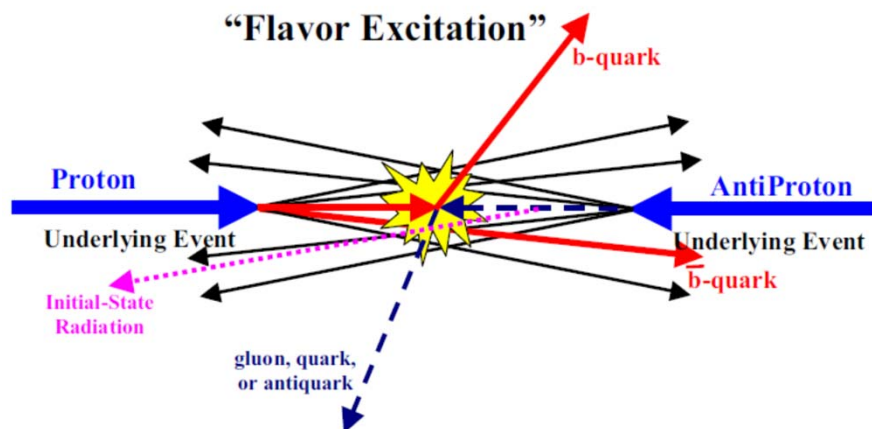
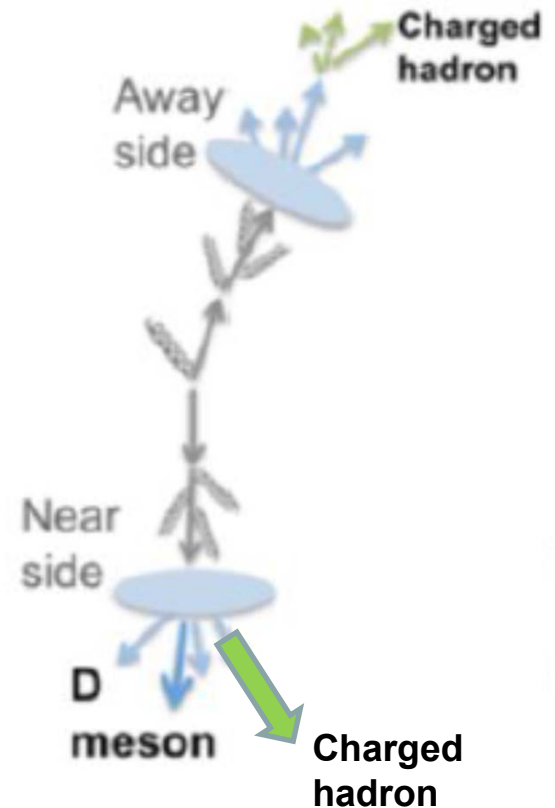
PHENIX: Phys. Rev. C. 89, 034915 (2014)

- Puzzle in the picture:
- “Such a suppression could arise due to nuclear PDF shadowing, saturation of the gluon wavefunction in the Au nucleus, or initial/final state energy loss and multiple scattering. »
- Did not seem to have received enough attention from the community



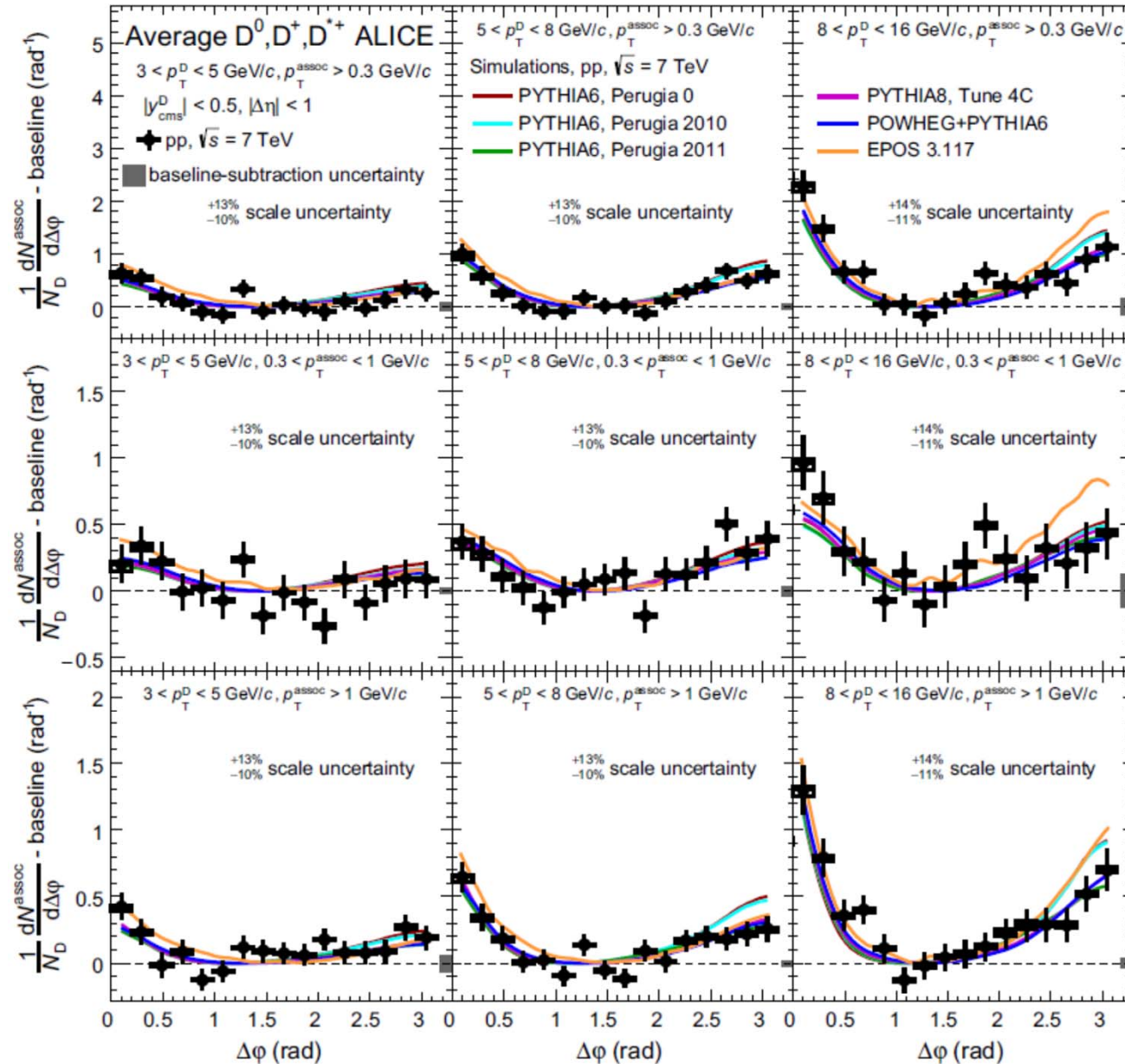
Some words on D/B-h / e-h / ... correlations

- + : less demanding in terms of statistics (already some experimental results at RHIC and at LHC after run 2 @ LHC)
- + : the near side can provide us new information about the “in medium” fragmentation.
- - : Access to QQbar angular correlations is more indirect and “washed out“
- - : More influenced by the “underlying event” than HF-HF correlations : maybe, HF also feel the influence of the bulk
- - : New processes implied in the away side region:



More involved from a theory / modelling view point; requires multi-component models

Some words on D-h ... in pp



ALICE, Eur. Phys. J. C (2017) 77:245

- Qualitative agreement between data and models, within the (large) uncertainties
- EPOS3 predicts larger and wider peaks than the PYTHIA/POWHEG for $\Delta\phi$ correlations

Calibration \approx ok

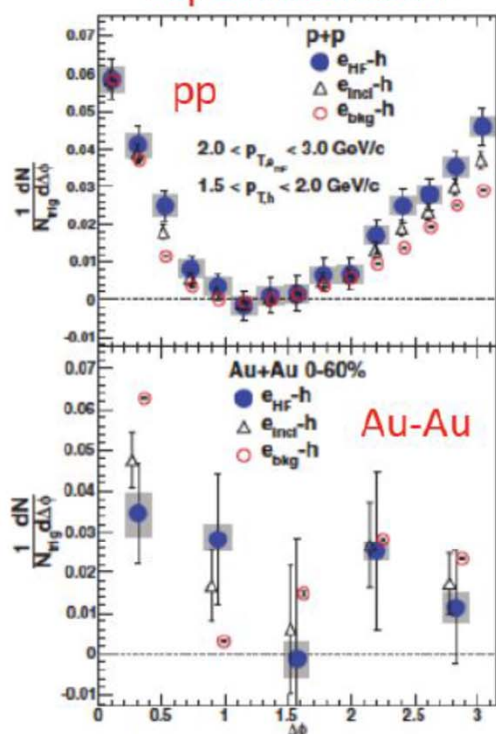
Some words on e-h / ... in AA (at RHIC)

Heavy-flavour electron – charged particle correlations at RHIC, PHENIX

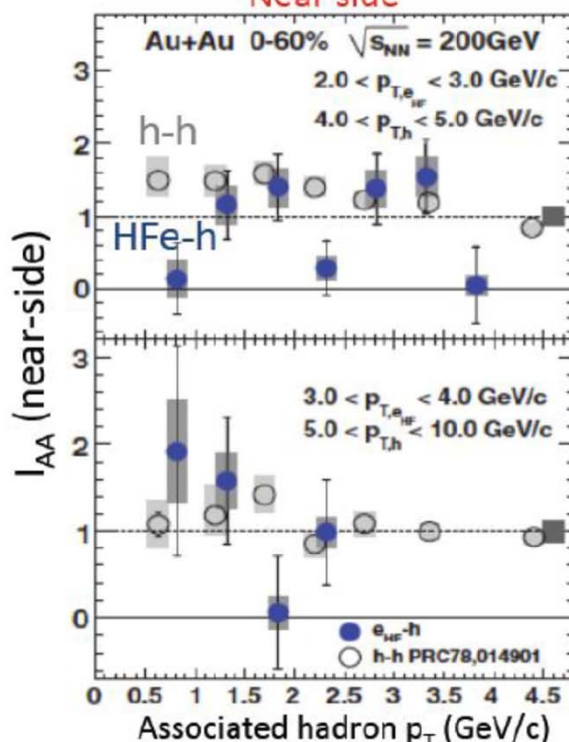
PHENIX Coll.: PRC 83, 044912 (2011)

I_{AA} = ratio of associated yield (Au-Au)/pp

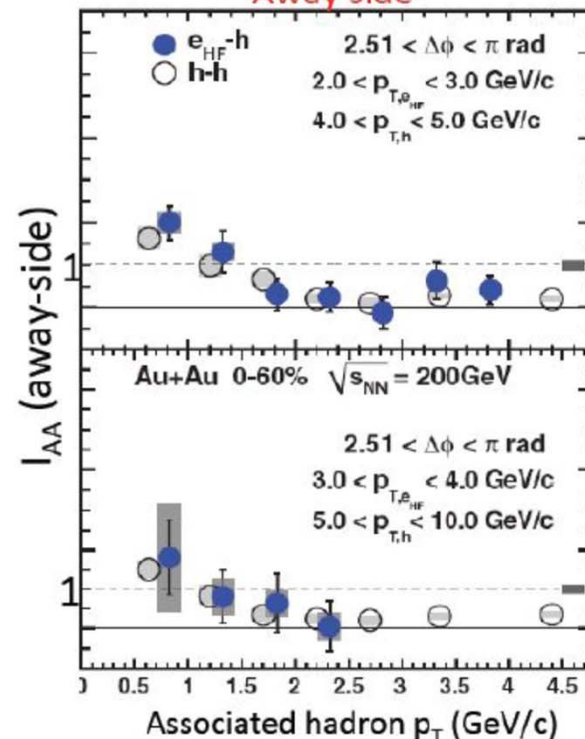
$\Delta\phi$ distributions



Near side



Away side



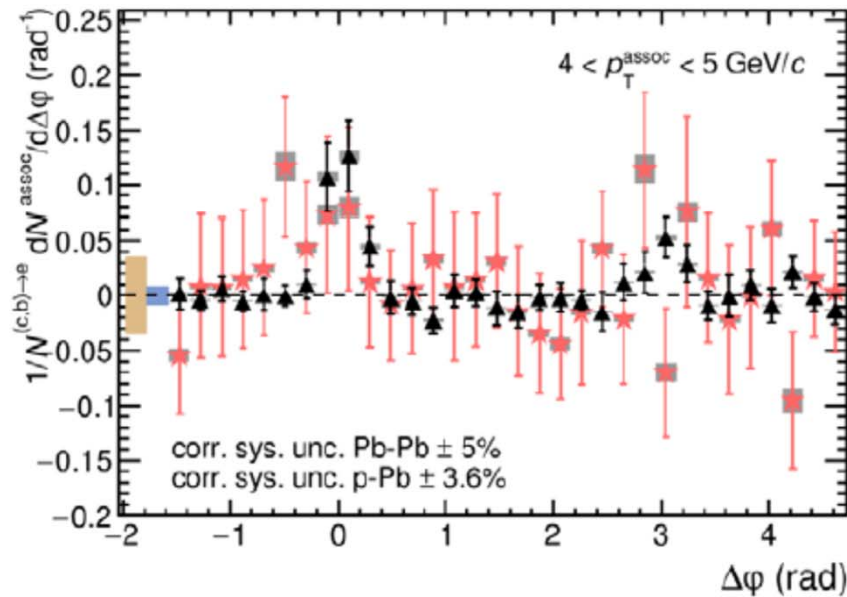
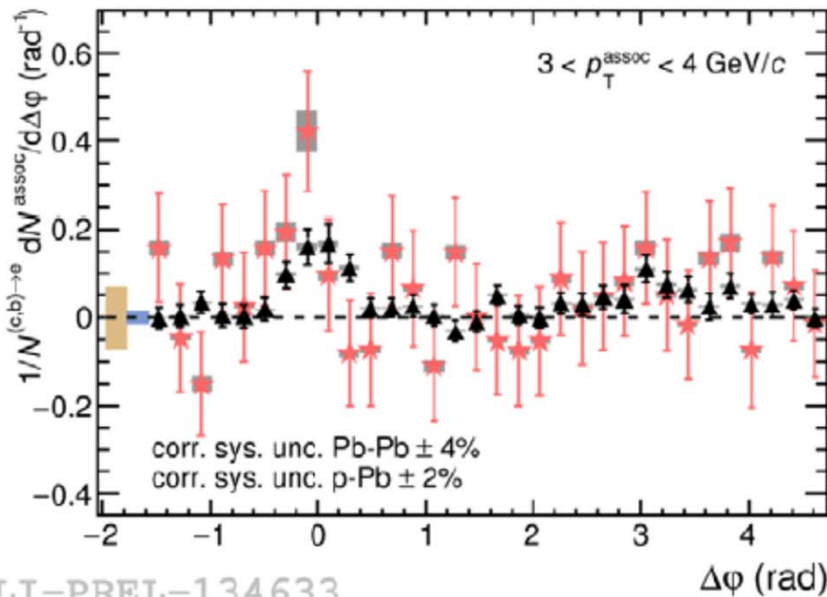
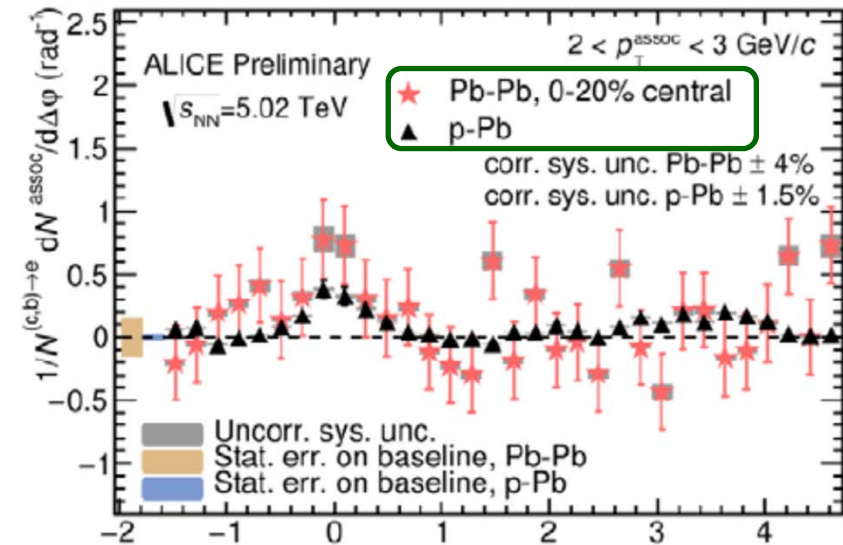
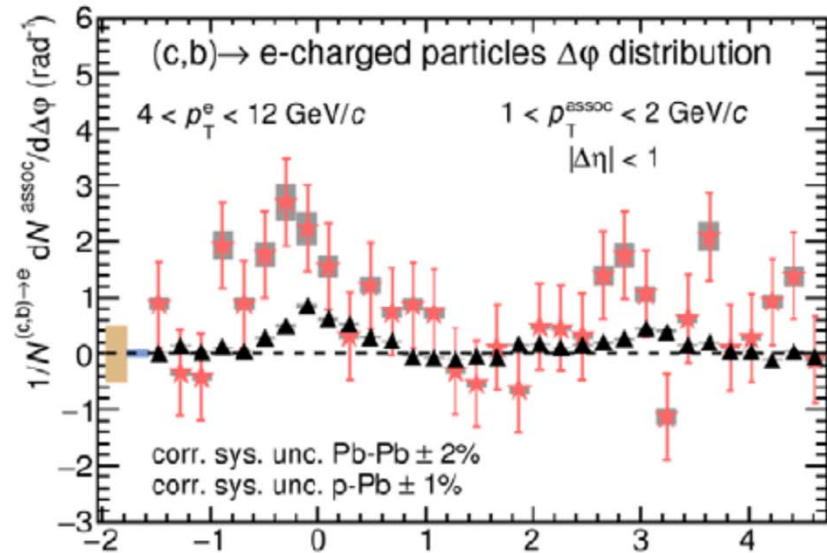
Large uncertainties in Au-Au measurement prevent firm conclusions

Suggest a decreasing I_{AA} trend with hadron p_T in the away side

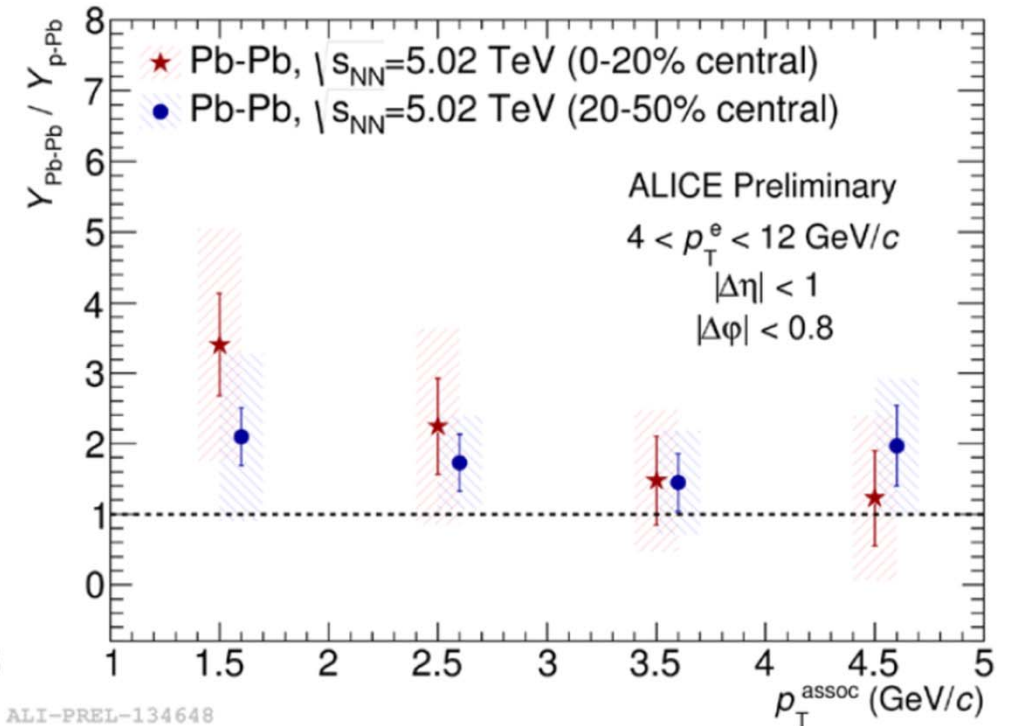
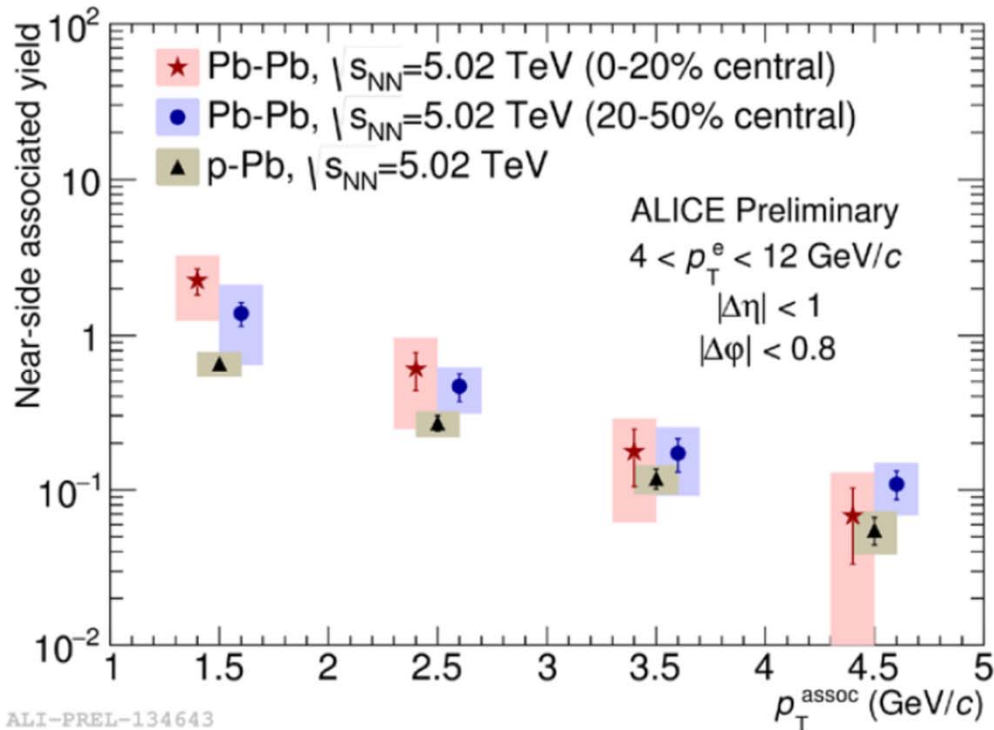
Similar results than hadron-hadron correlations (a coincidence?)

→ Higher precision with new data

Some words on e-h / ... in AA (at LHC)



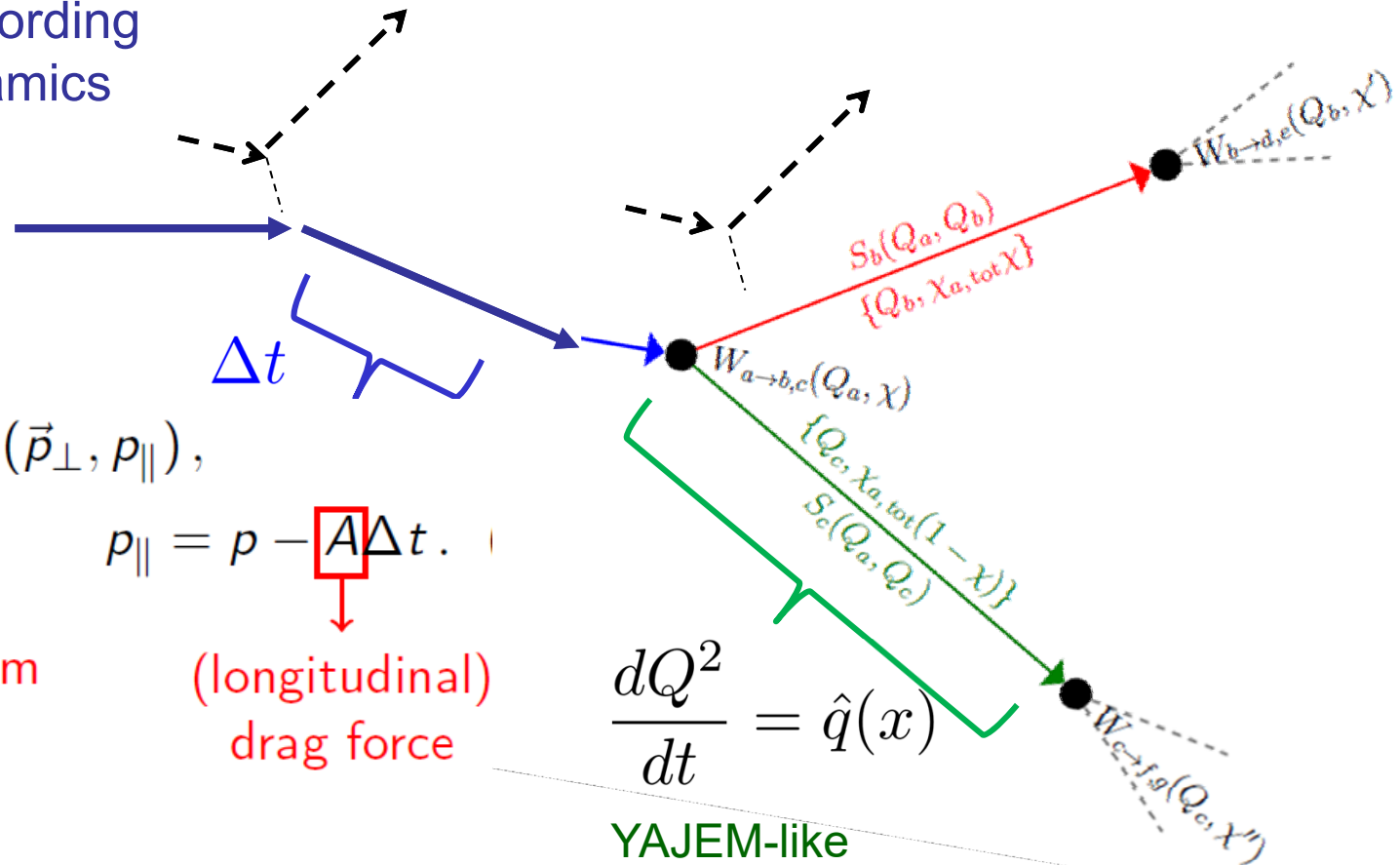
Some words on e-h / ... in AA (at LHC)



- ALICE concludes: “Going lower with p_T^{assoc} , hints of a hierarchy in NS yields: Pb-Pb 0-20% shows an enhancement w.r.t. p-Pb, despite very large total uncertainties” : **priority 1**
- No conclusion for the away side peak after run 2. **priority >1**

Modified DGLAP (Elastic + induced radiation)

Rescattering according to Langevin dynamics



$$\vec{p} = (\vec{0}, p) \mapsto \vec{p}' = (\vec{p}_\perp, p_\parallel),$$

$$p_\perp = \sqrt{\hat{q} \Delta t},$$

$$p_\parallel = p - A \Delta t.$$

transverse momentum transfer

(longitudinal) drag force

$$A = \frac{\hat{q}}{\kappa T}$$

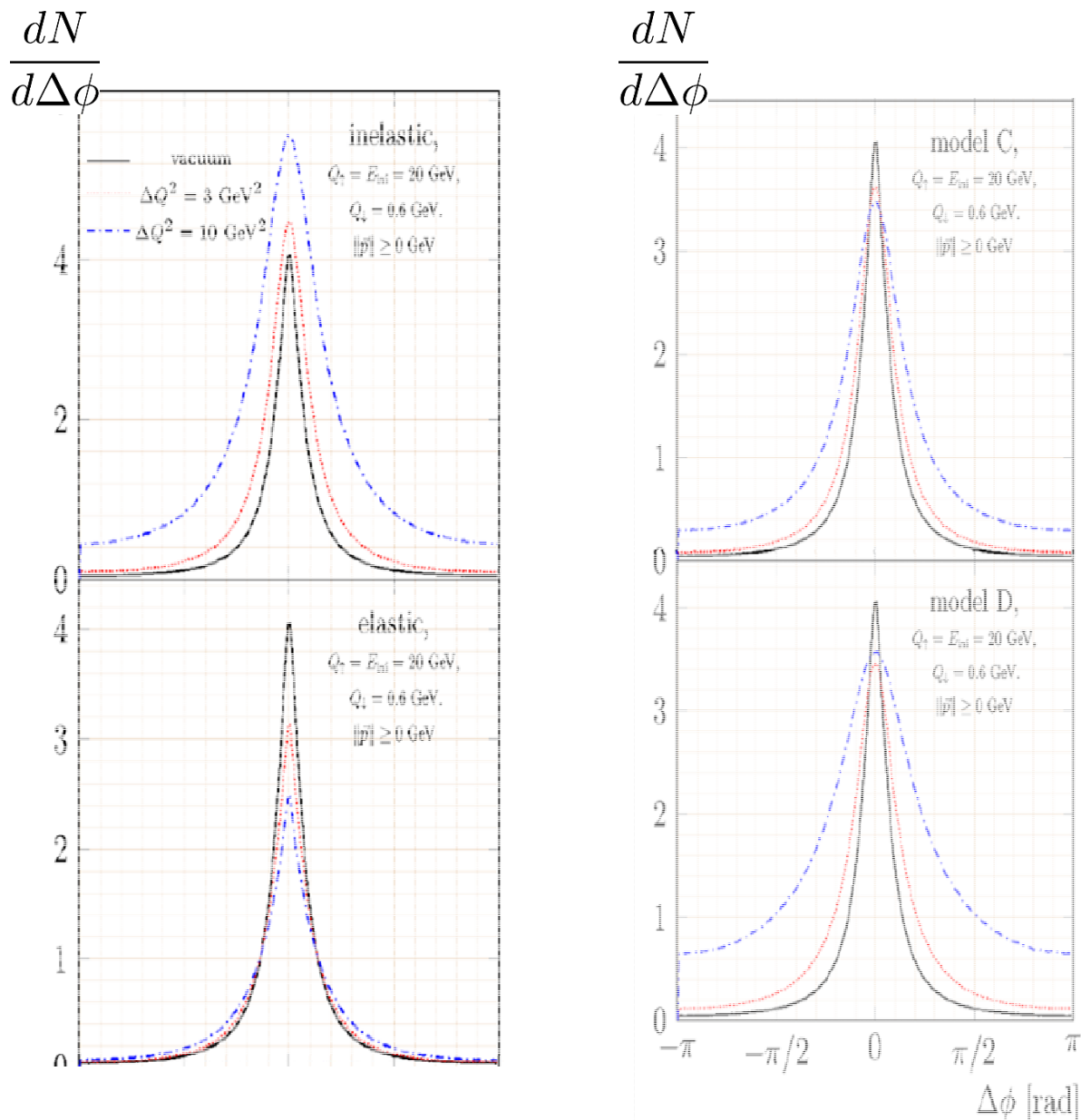
$$\frac{dQ^2}{dt} = \hat{q}(x)$$

YAJEM-like

[H. Berrehrah et al. PRC 90, 064906 (2014)]

increase of the virtuality => extra induced radiation.

Near side study with a generic jet – medium model



M. Rohrmoser's PhD thesis (2017)

Preliminary results in J.Phys. Conf. Ser. 779 (2017), 012032

...To be implemented in EPOSHQ with bulk back-reaction

Conclusions

- HF Correlations are for sure interesting per se and offers a bright future... but:
- One should not expect huge effects ! Up to now, the best effects I am aware of in realistic calculations are of the order of 10 %
- They often imply a much deeper understanding of the production mechanisms (one additional ingredient in the game !)
- **Brand new study on momentum imbalance : avoid central (and even semi-central) collisions in order to discriminate between Eloss mechanisms.**
- Too early to conclude; as a theorist, one has to get ready to deal with the improved precision data in the HF-HF or γ -HF sector
- HF – hadrons correlations requires fully fledged models and simulators
- By then, the most efficient “constrain” can be obtained by performing systematic multi-domain comparison of the traditional single particle observables...