Heavy quark correlations

Workshop on Heavy Flavor Production in High Energy Collisions

Oct. 30 - Nov. 1, 2017, Lawrence Berkeley National Laboratory (USA)

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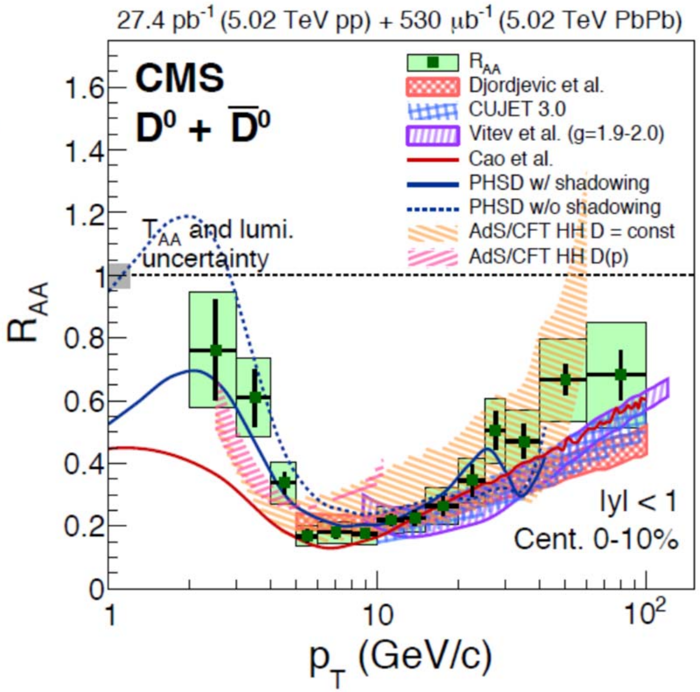
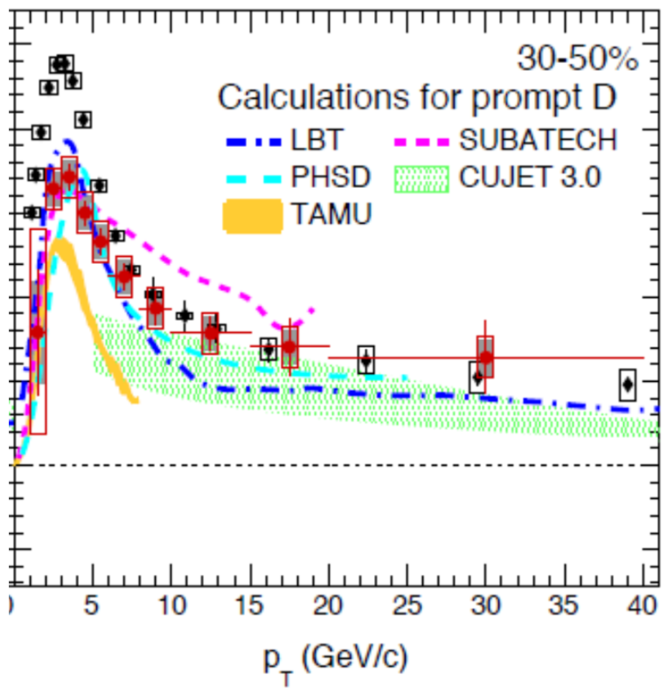
(Short) Motivation

- 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





CMS Talk by Gian Michele Innocenti, 30 Oct

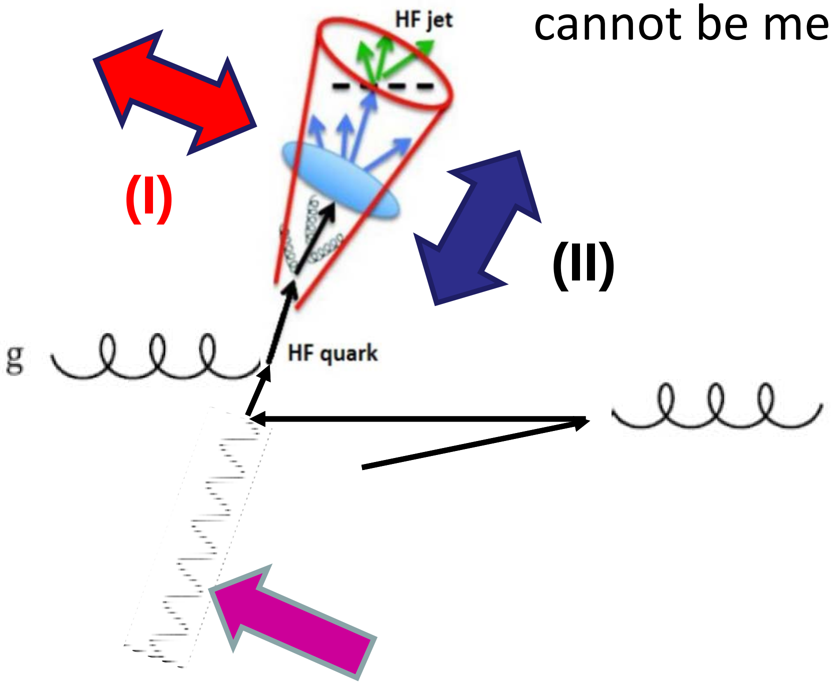
- For the purpose of making the contact with the fundamental theory (see the case presented by R. Rapp), it is desirable to "constrain / pre-sort / rule out" some of the approaches

- Very often, correlations are advocated to be useful in this respect (warning: main viewpoint adopted in this presentation)

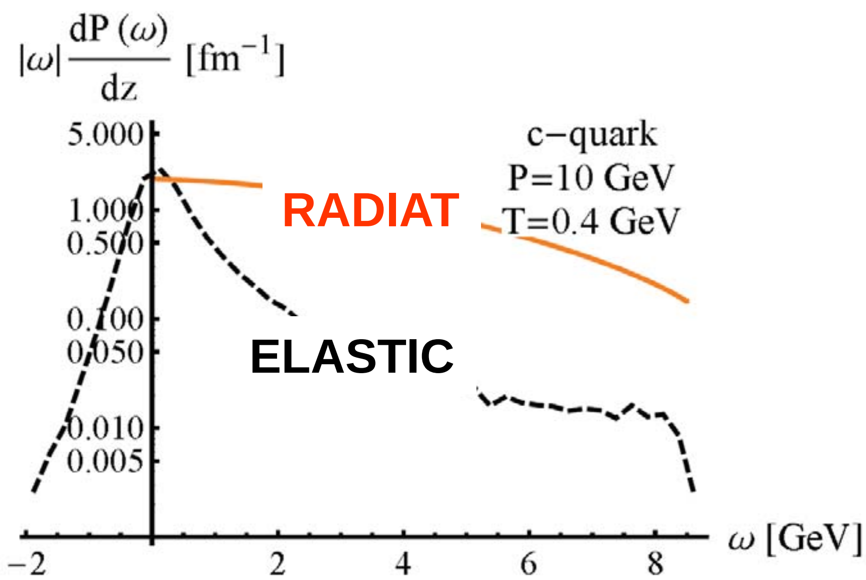
How does it help ? Best HF Correlation ever ?

- 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 RAA or v2



No E loss => perfect probe of initial $\vec{P}_{HQ}$

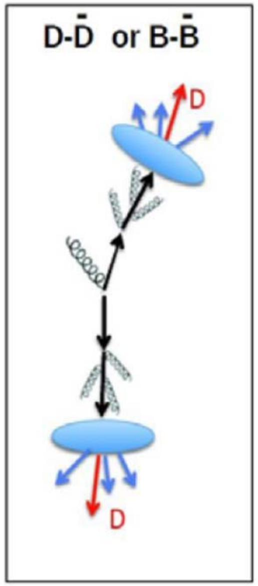


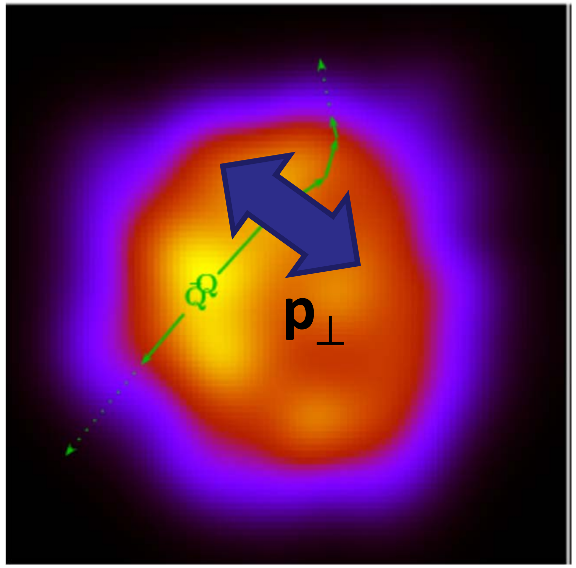
differential probability to loose energy ω per unit time

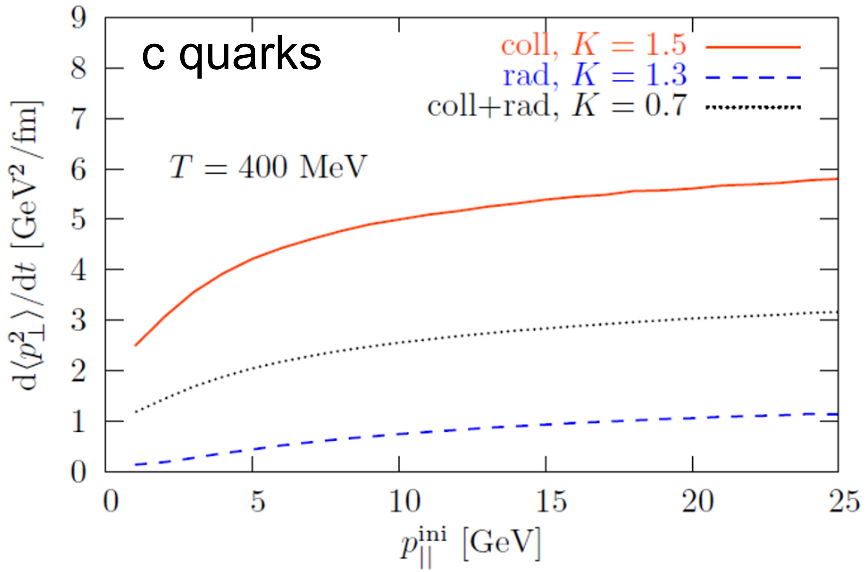
- Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues… RUN3 ? RUN4 ?)

Next best thing: HF-HF correlations

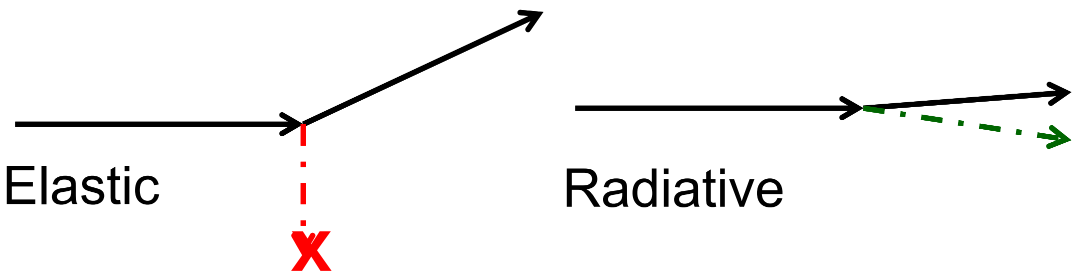
- Back to back D/Dbar or B/Bbar: As compared to γ-D/B: “trigger” itself is affected but symmetry between both particles limitates the various effects.
- Elastic Eloss vs radiative Eloss: **The purely collisional scatterings lead to a larger average $\langle p_\perp^2 \rangle$ then the radiative “corrections”**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







Tuned to reproduce the R_{AA}

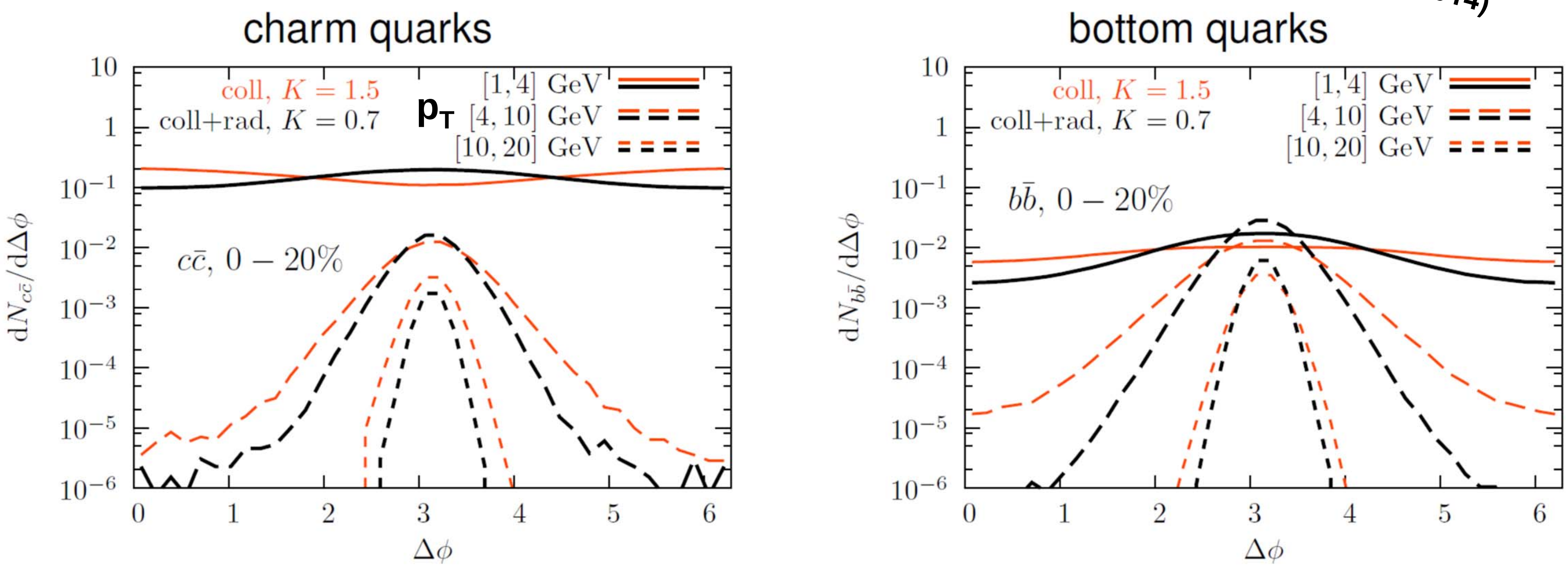


- Expected consequences for azimuthal correlations (probe of B_T: good: **complimentary** to usual RAA and v2)

Next best thing: azimuthal correlations

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

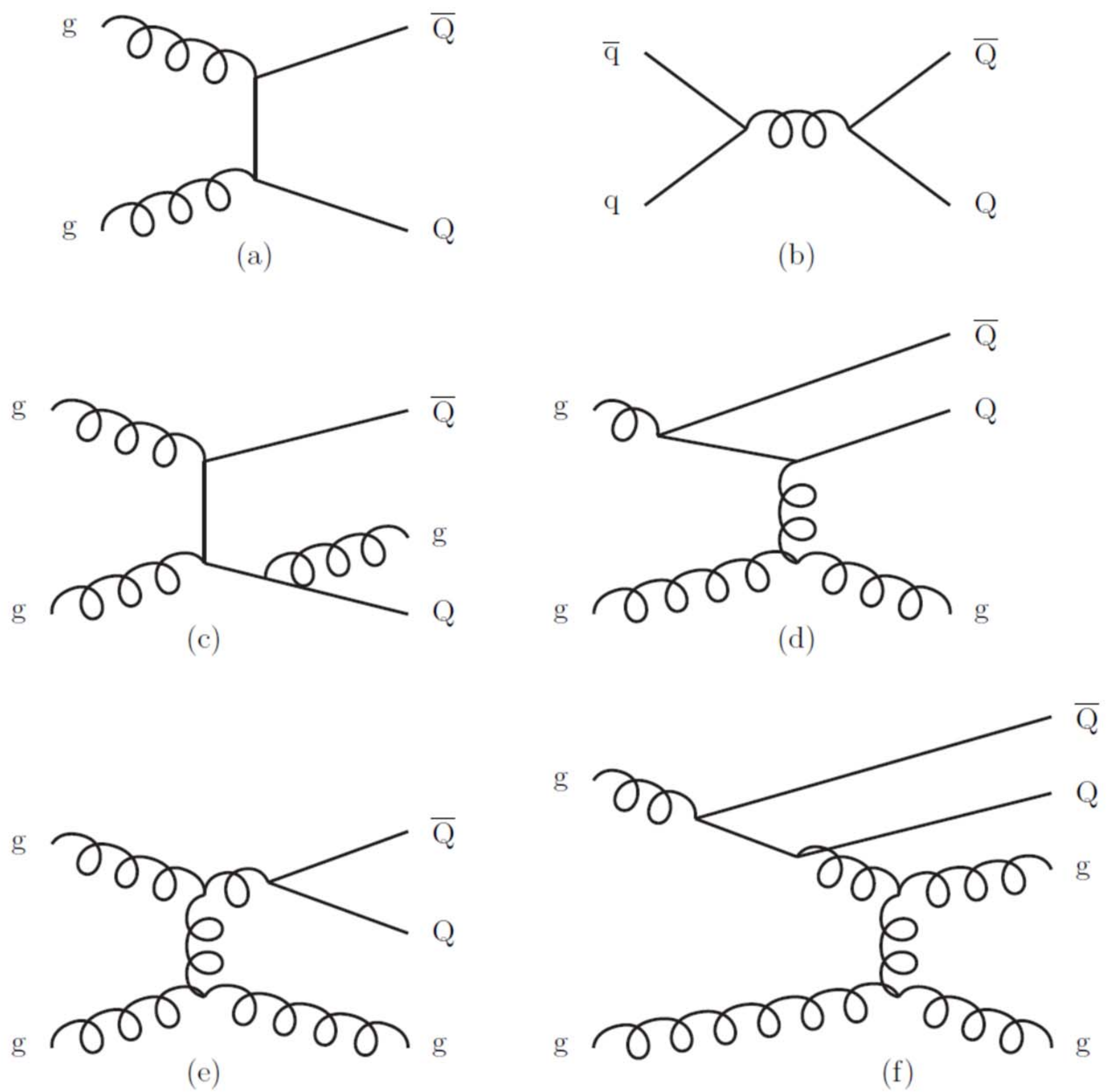
Nahrgang et al. Phys. Rev. C 90, 024907 (2014)



- 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

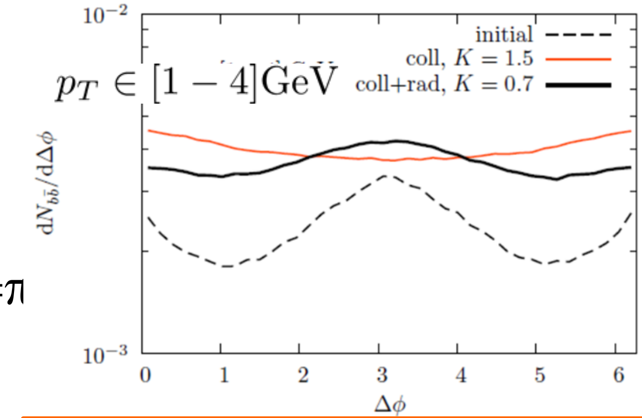
(d): "flavor excitation": no strong azimuthal correlation expected

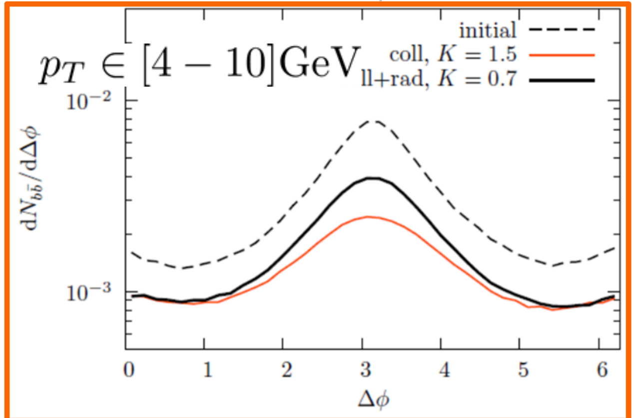
(e): gluon splitting: strong peak around $\Delta\phi=0$

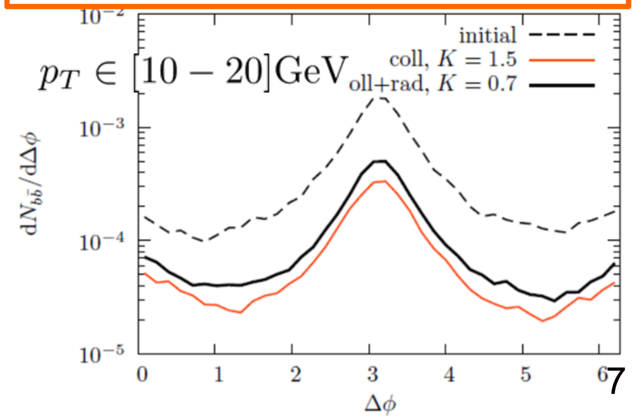
(f): higher order FE; both Q and Qbar in the "remnant" region

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
- Confirmation by other groups (Duke, CCNU-LBL,…)



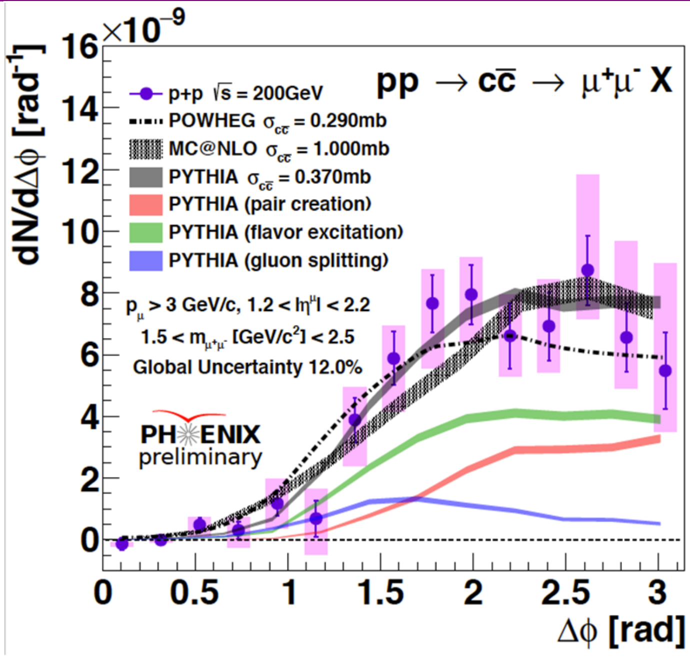




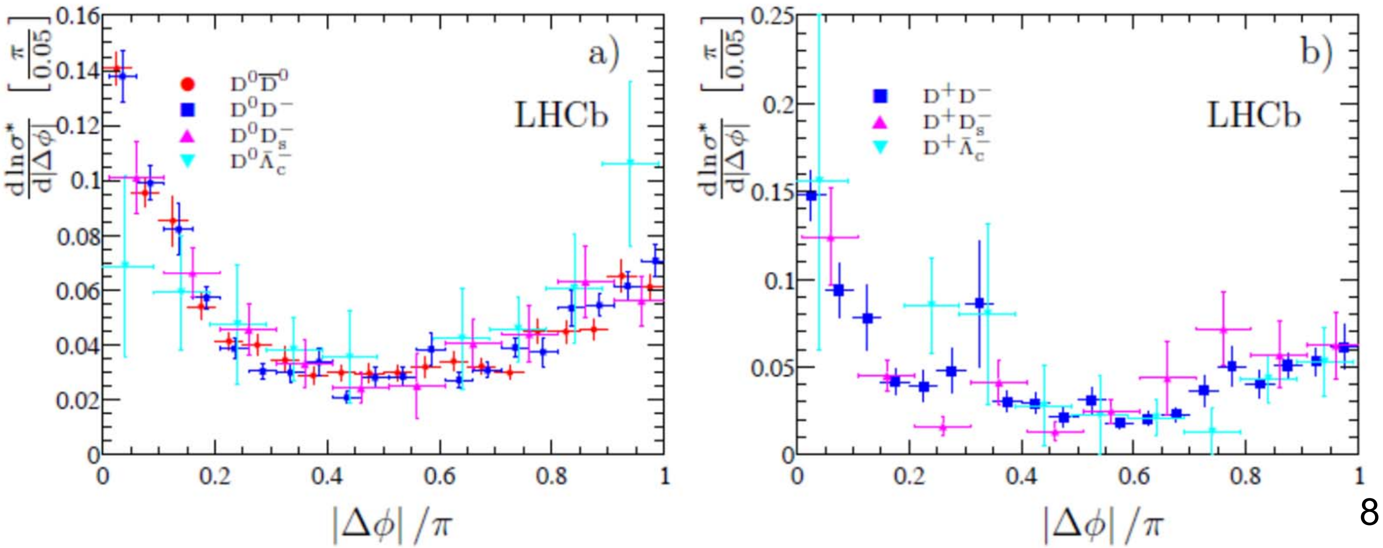
Azimuthal correlations from experimental viewpoint

- 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 ?

PHENIX



LHCb



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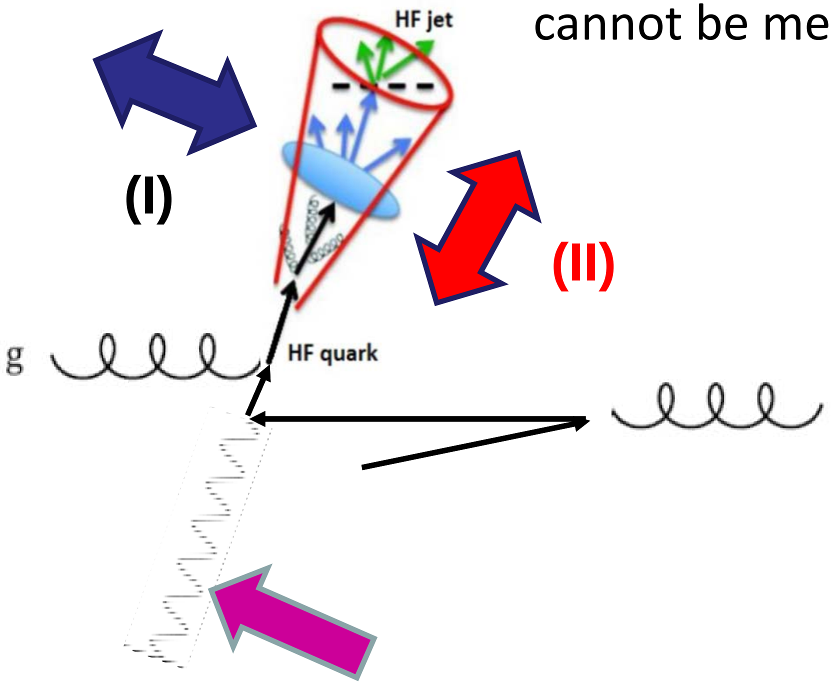
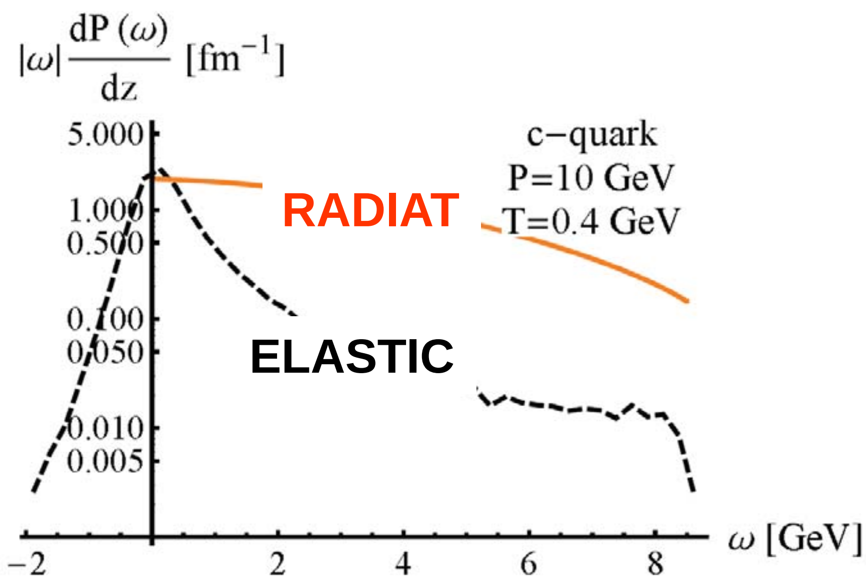


No E loss => perfect probe of initial $\vec{P}_{HQ}$

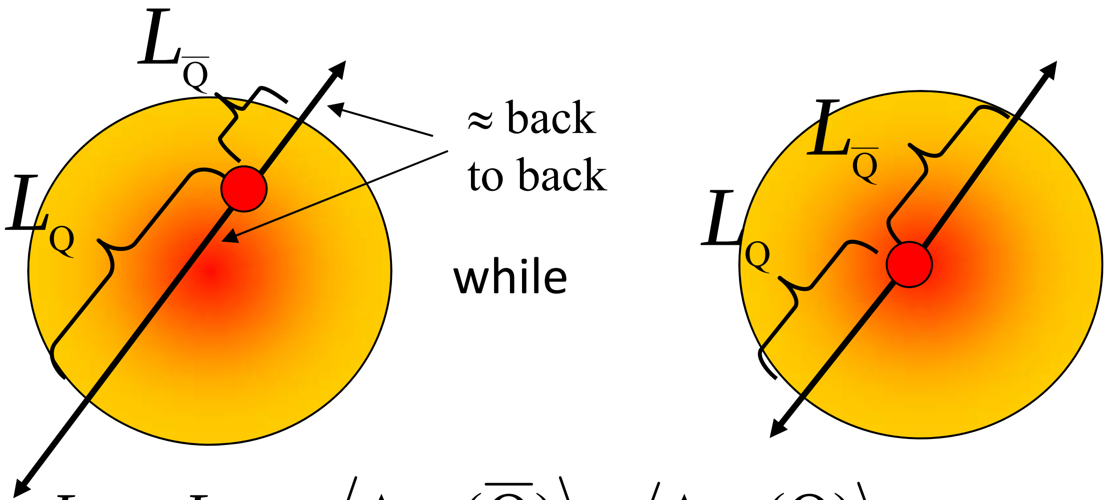


differential probability to loose energy ω per unit time

- Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues… RUN 3 ? RUN 4 ?)

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:

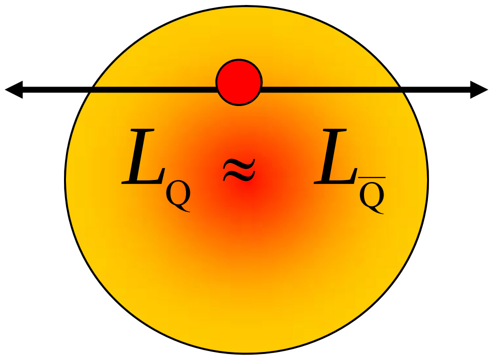


$$L_{\overline{Q}} < L_Q \Rightarrow \left\langle \Delta p_T(\overline{Q}) \right\rangle < \left\langle \Delta p_T(Q) \right\rangle$$

$$L_{\overline{Q}} \approx L_Q \Rightarrow$$
$$\left\langle \Delta p_T(\overline{Q}) \right\rangle \approx \left\langle \Delta p_T(Q) \right\rangle$$

- Reversing the argument: selecting $\left\langle \Delta p_T(\overline{Q}) \right\rangle \approx \left\langle \Delta p_T(Q) \right\rangle$ might bias the data in favor of "central" pairs

Possible caveat:

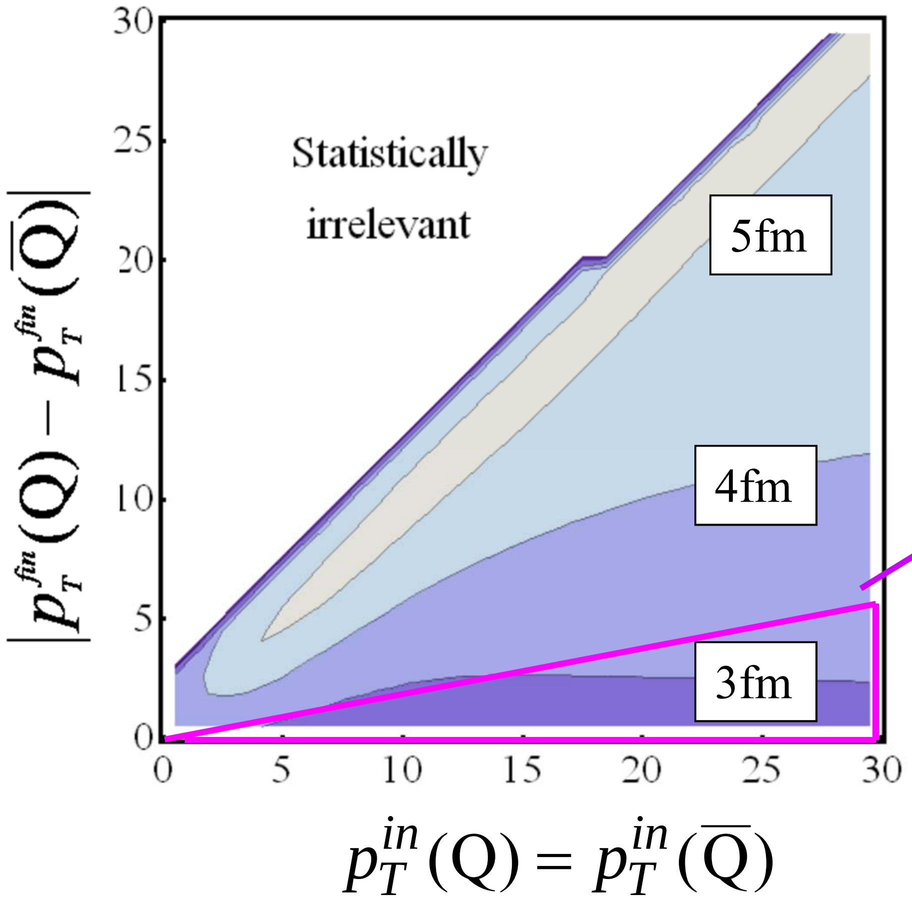


$\Rightarrow$ **Need for a detailed study**

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 $p_T^{in} > 5GeV/c$ and "small" Δp_T^{fin}

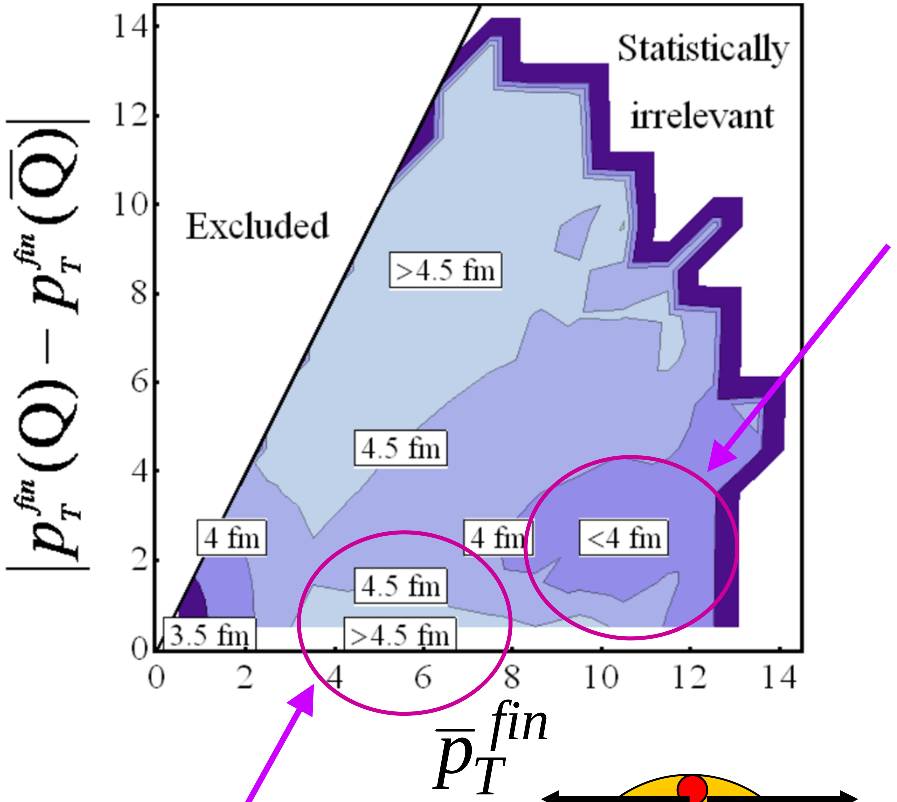
Hope to probe hotter regions of the QGP

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

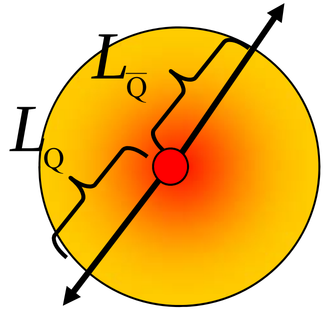
Once upon a time: momentum imbalance for hot core

Best ansatz: $p_T^{in}(\mathrm{Q}) \to \overline{p}_T^{fin} := \dfrac{p_T^{fin}(\mathrm{Q}) + p_T^{fin}(\overline{\mathrm{Q}})}{2}$

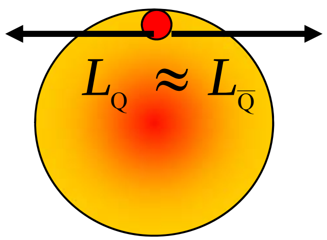
Average transv.-dist. to center as a function of Δp_T^{fin} *for various* $\overline{p}_T^{fin}$



Central production:

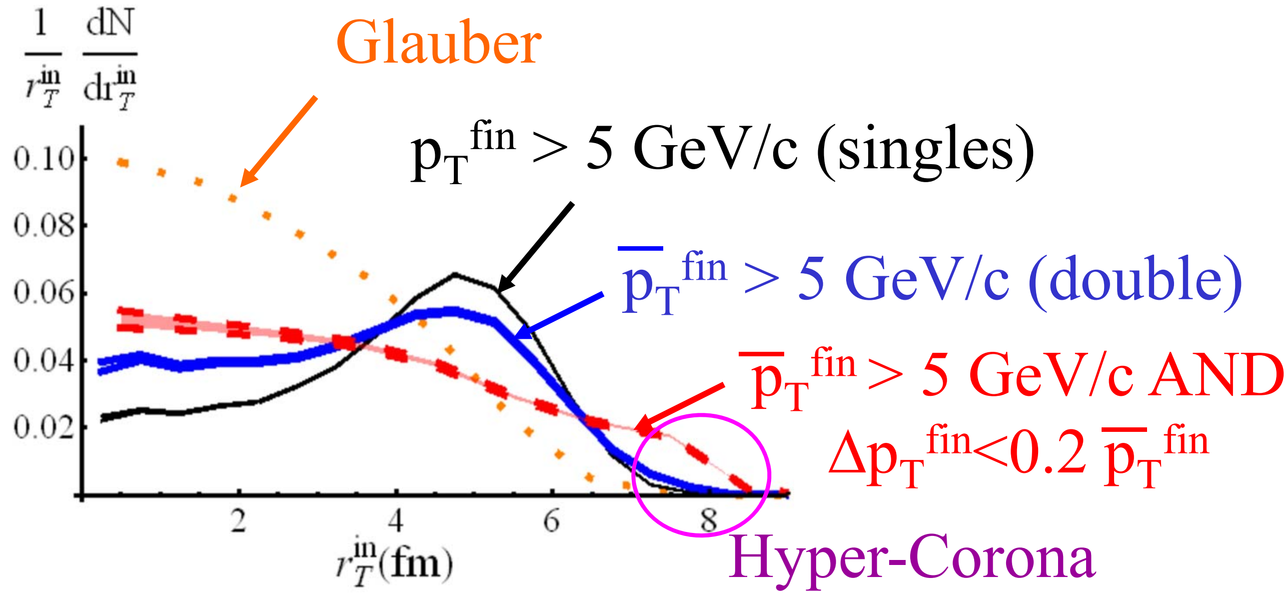


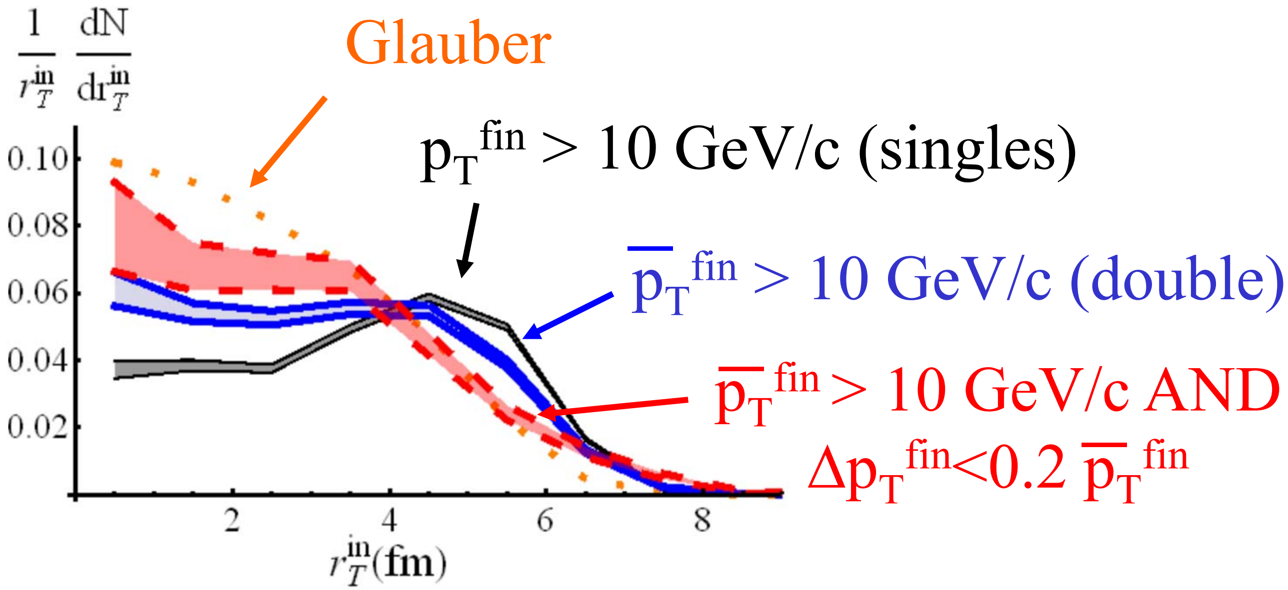
Tangential production



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

momentum imbalance for hot core: back to r_T distributions

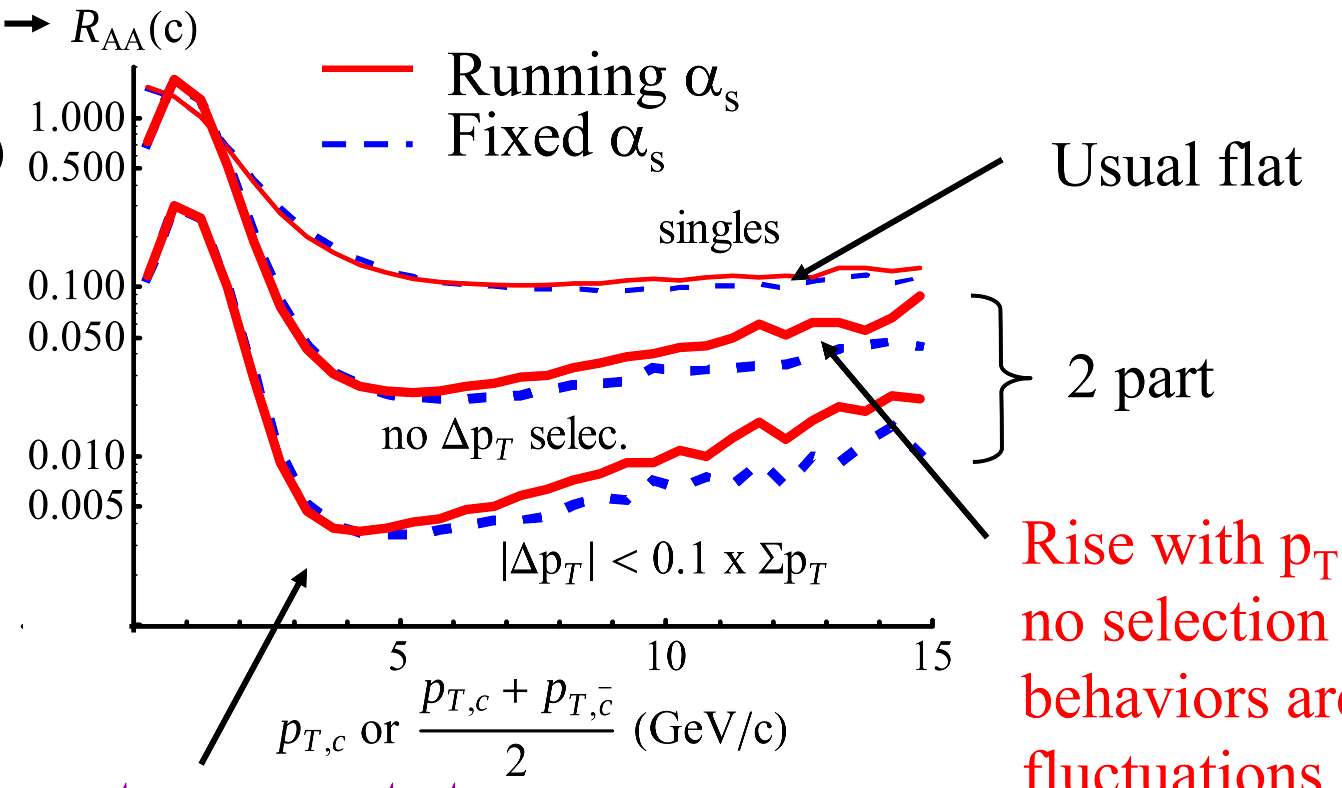




- Final cuts lead to various distributions of initial position
- One nearly recovers the Glauber profile for most severe cut

momentum imbalance: increase R_{AA} sensitivity

Usual ratio: →
Nb(Au+Au)/
Nb_{coll}*Nb(pp)



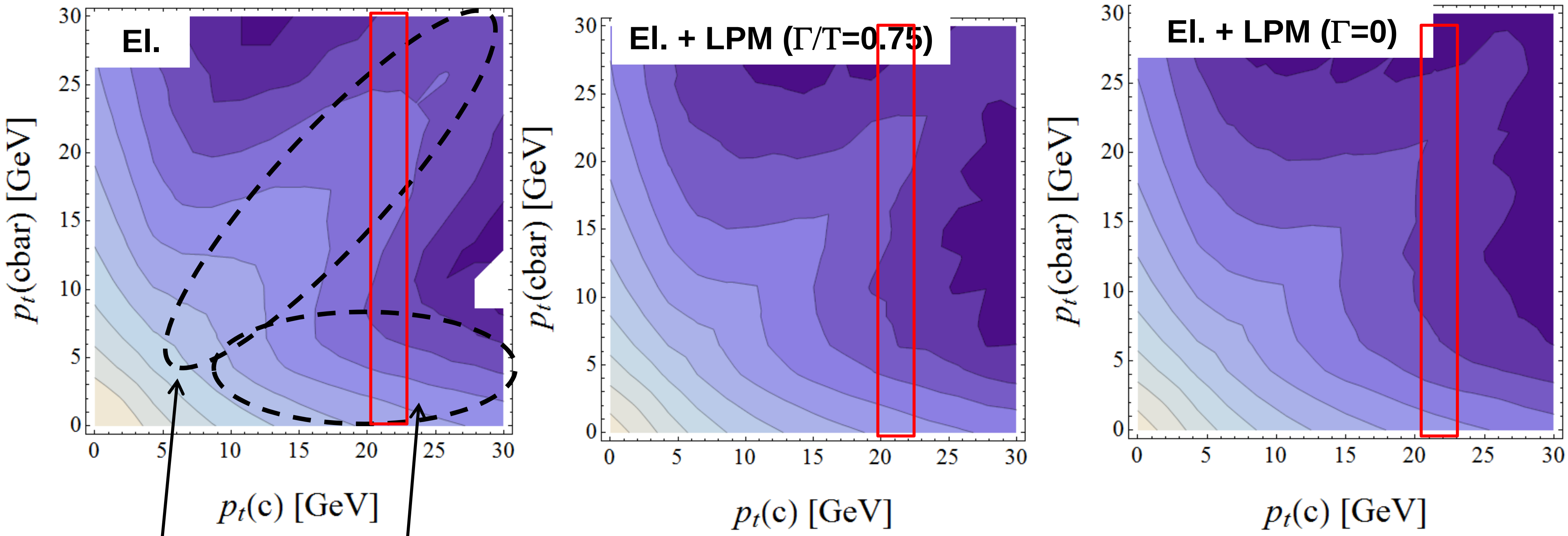
Rise with p_T although no selection ! Different behaviors are due to fluctuations

More and more transparent at large p_T for HQ from center

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

Consequences on the observables: p_t-$p_t$bar correlations

Pb-Pb @ 2.76 TeV; 40-60%. **Toy study: back to back c-cbar**



Background at small p_t

Tagging on 1 high p_T Qbar:

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

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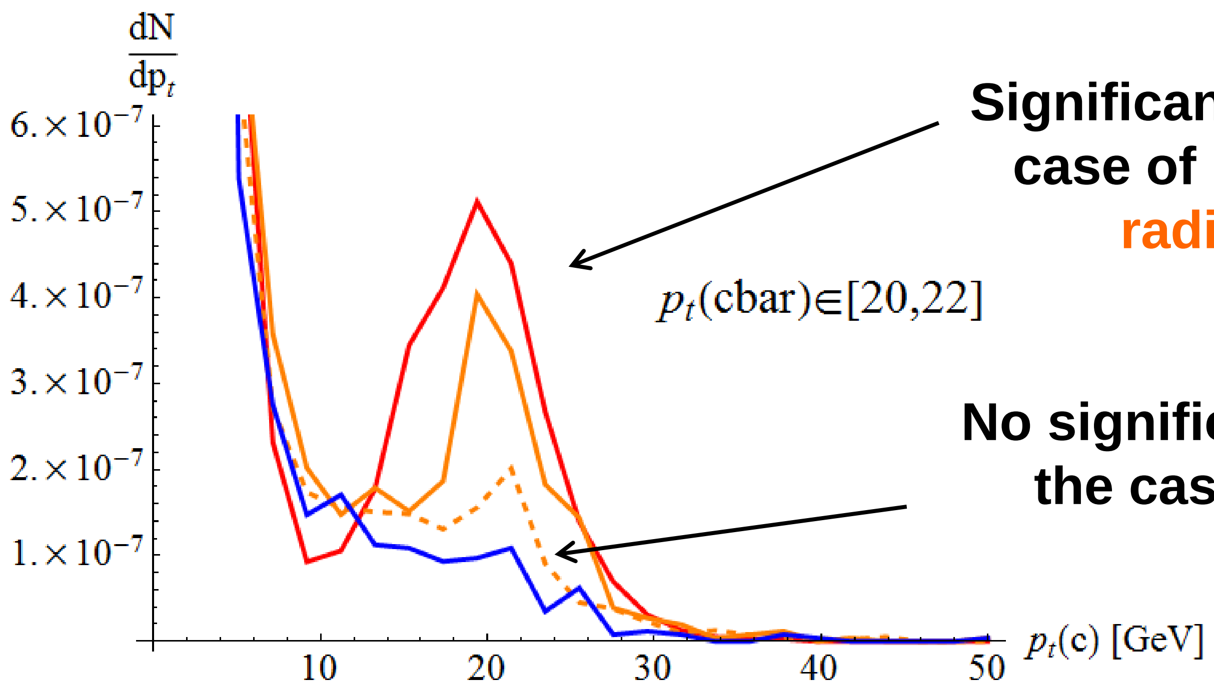


Significant residual correlation for the case of Elastic energy loss or LPM radiative + gluon damping

In the B2B region:

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

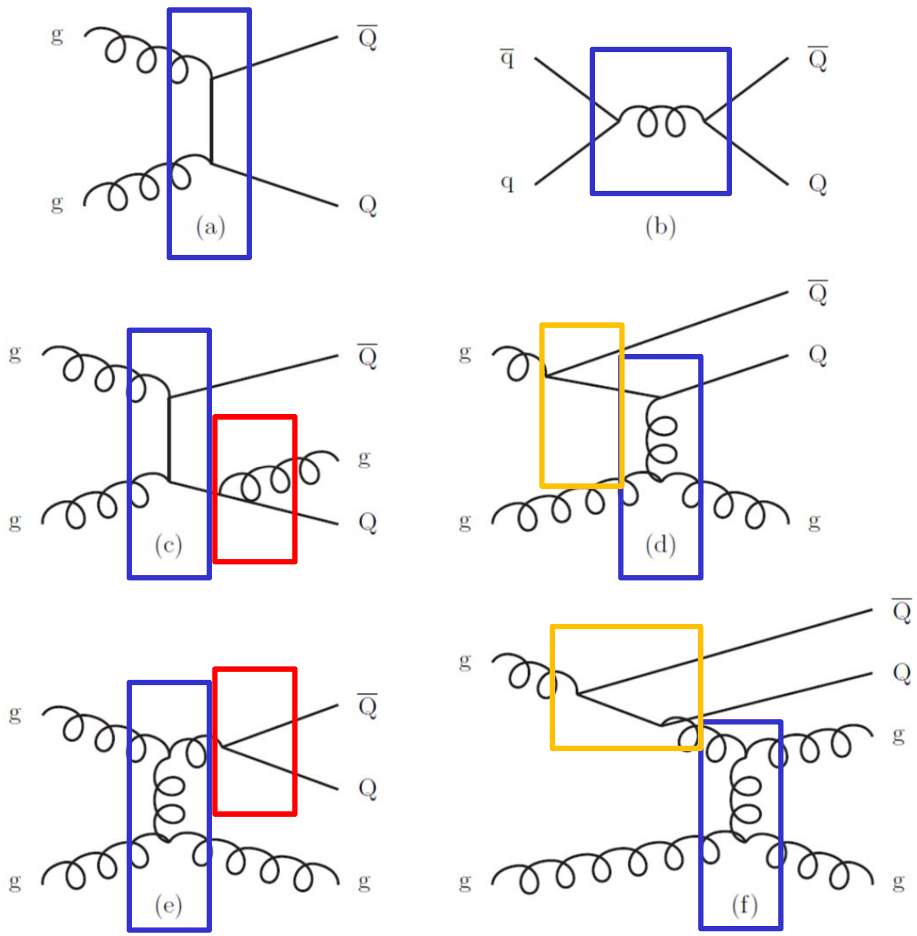
Background at small p_t

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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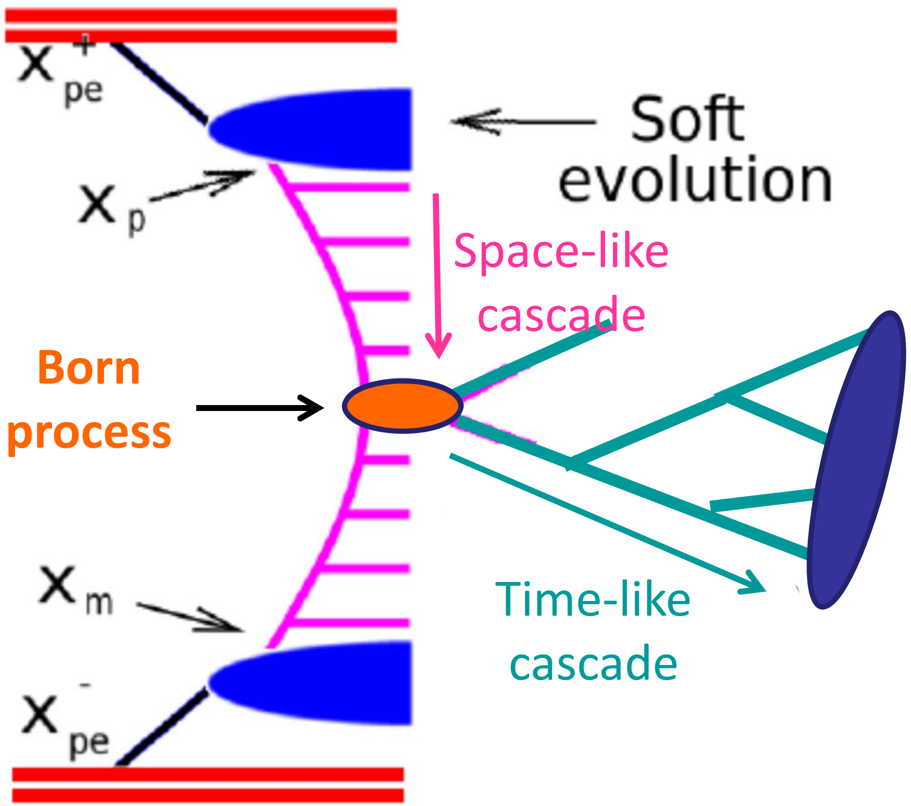

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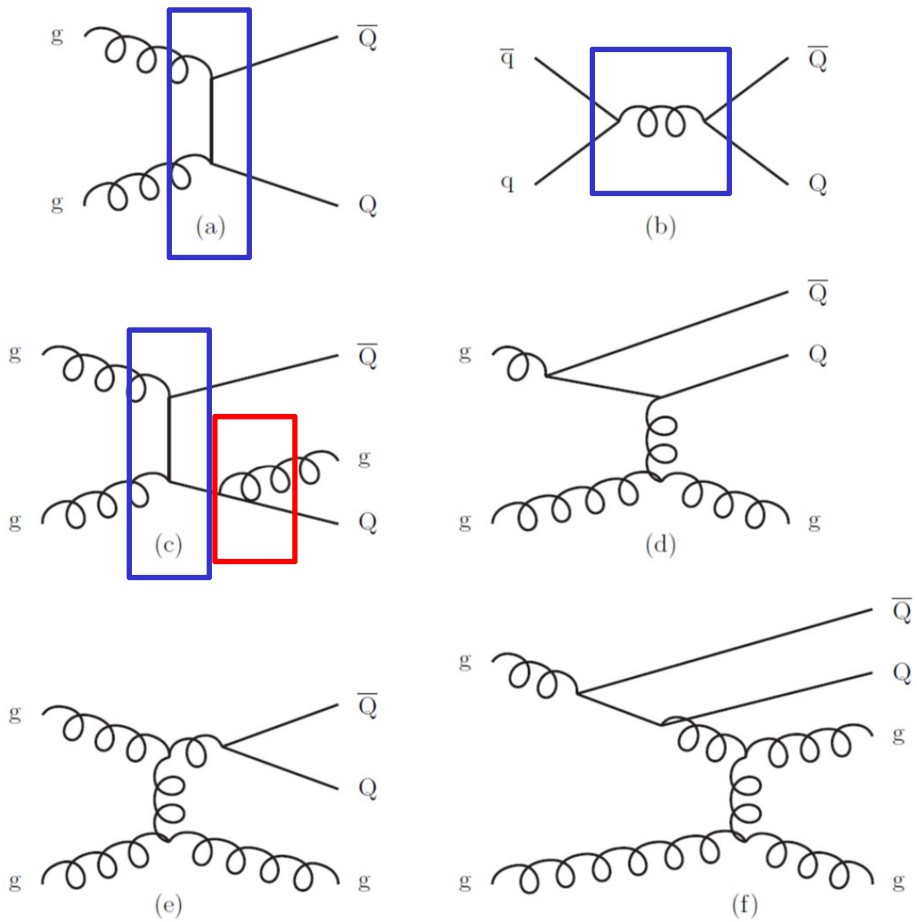

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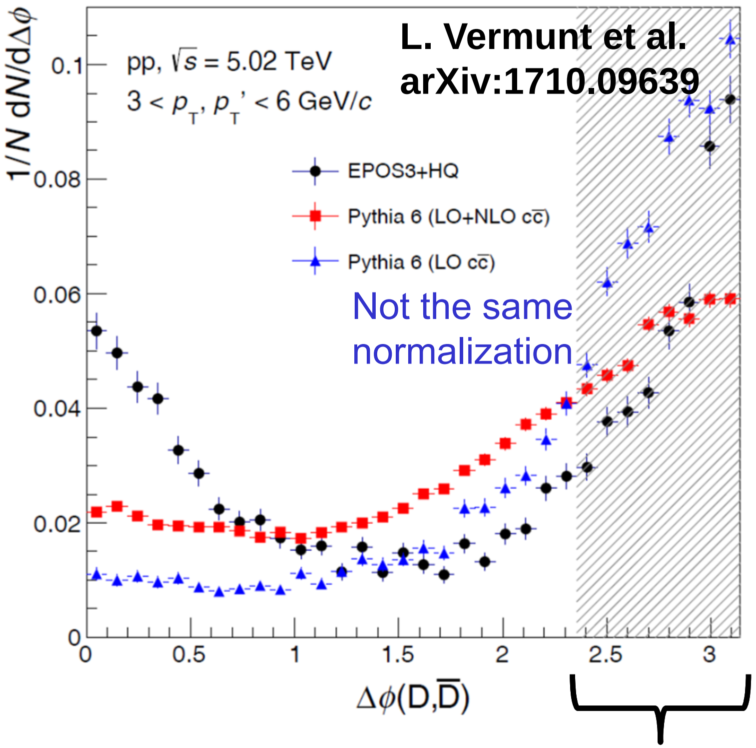
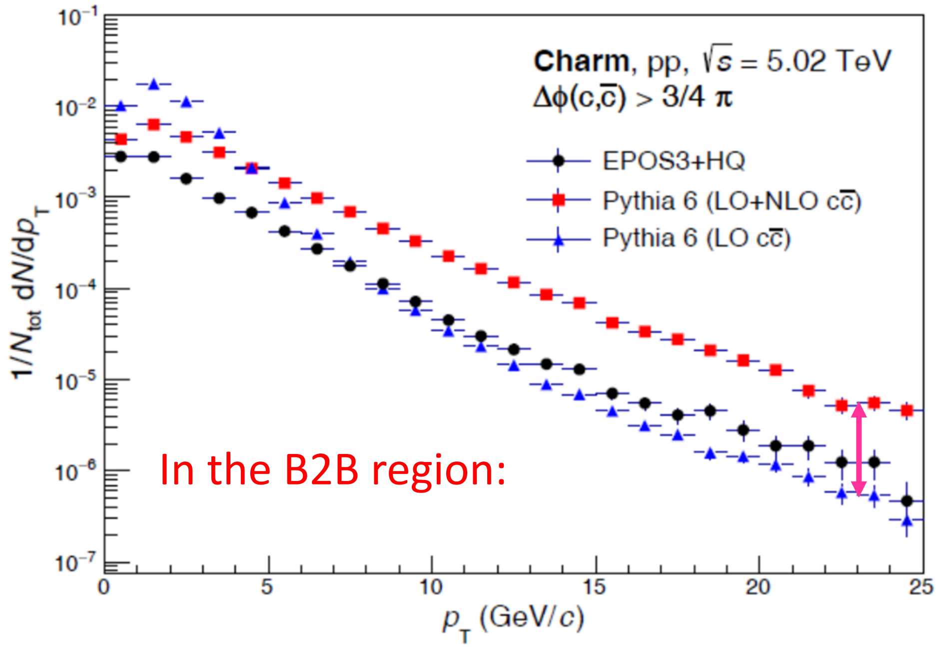
- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.
- In pythia, possibility to restrict to LO ccbar production processes with massive elements (MSEL=1 -> MSEL=4 flag), still switching on the … ISR + FSR … This will be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



B2B selection

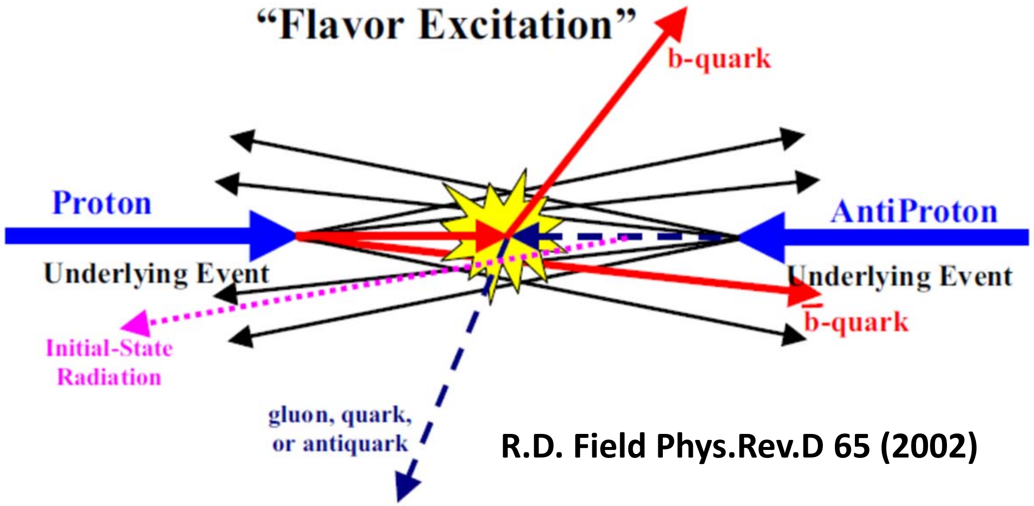


- Good agreement in the normalization for EPOS3 vs PYTHIA « LO » (MSEL=4)
- Large excess PYHTIA « NLO »; shown to be due to flavor excitation like process

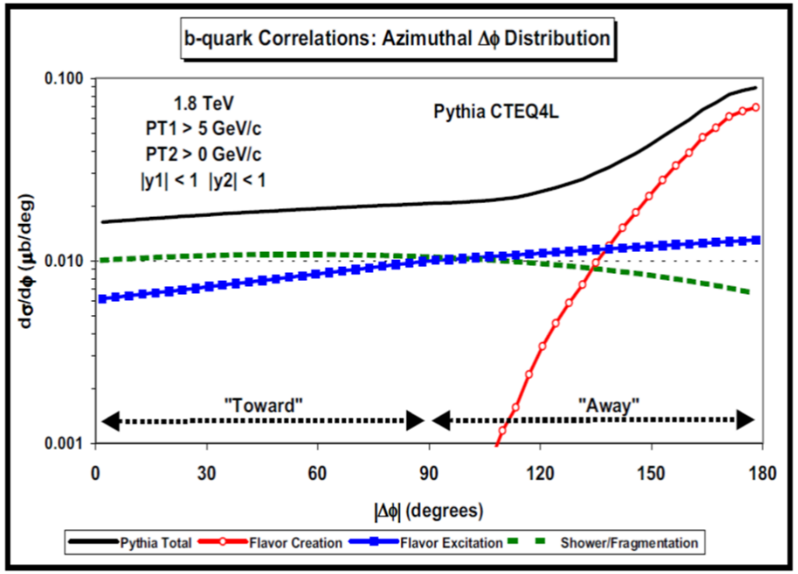
<u>N.B.</u>: Pythia MSEL=4: at least 1 ccbar pair un each event => Normalized according to high-p_T LO charm creation in Pythia MSEL=1

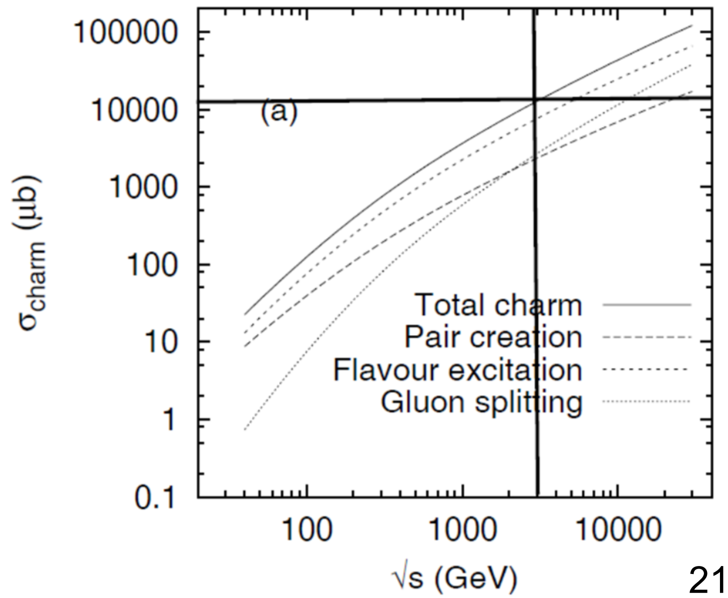
Momentum imbalance: not so naïve approach

➢ Including NLO effects in the charm production:



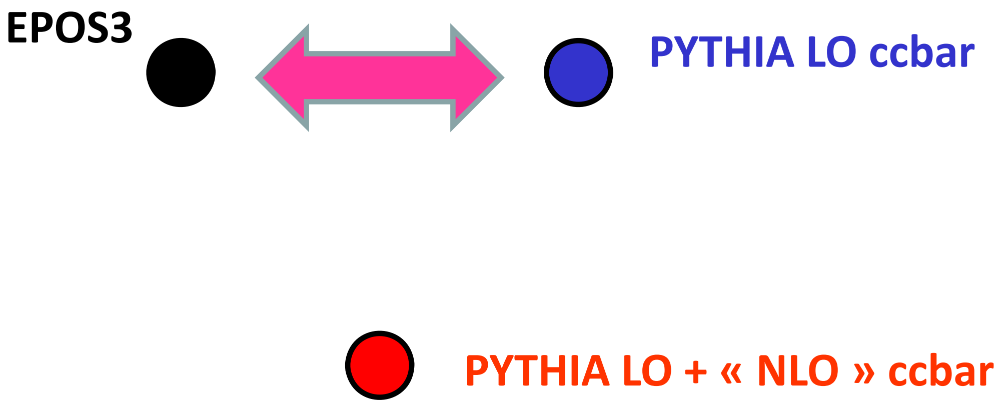
R.D. Field Phys.Rev.D 65 (2002)

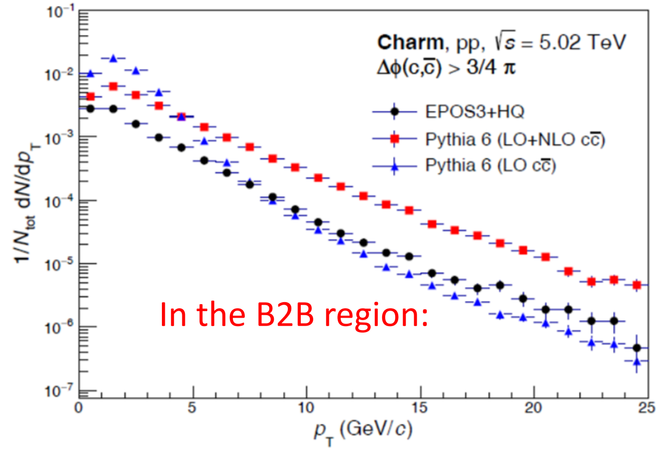




- Flavor excitation: very sensitive to the ccbar in the proton sea, i.e. to the gluon evolution -> large Q^2
- σ_{charm} (Pythia 6,) exceeds measured ALICE value by a factor 3-5. Mostly due to large FEX contribution.
- Similar conclusion of sur-abundant FEX found by CMS (CMS-PAS-HIN-16-005) for beauty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

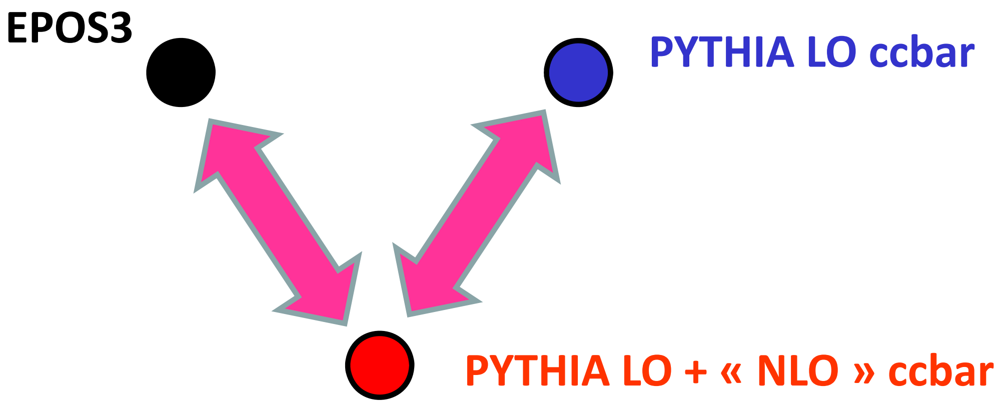
Momentum imbalance: not so naïve approach

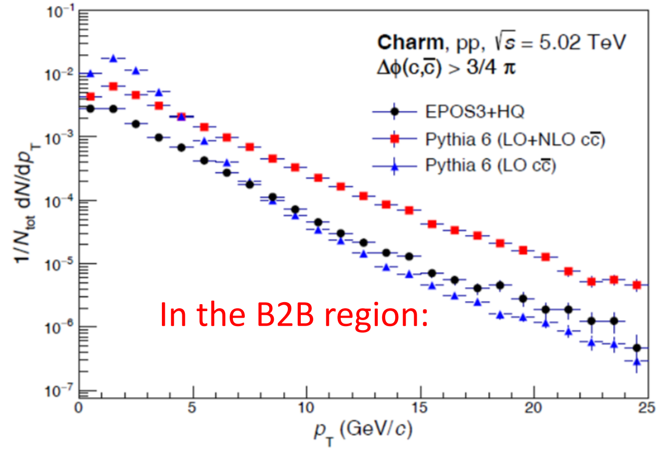




- Same process in the B2B => use the p_T correlations to investigate FSR

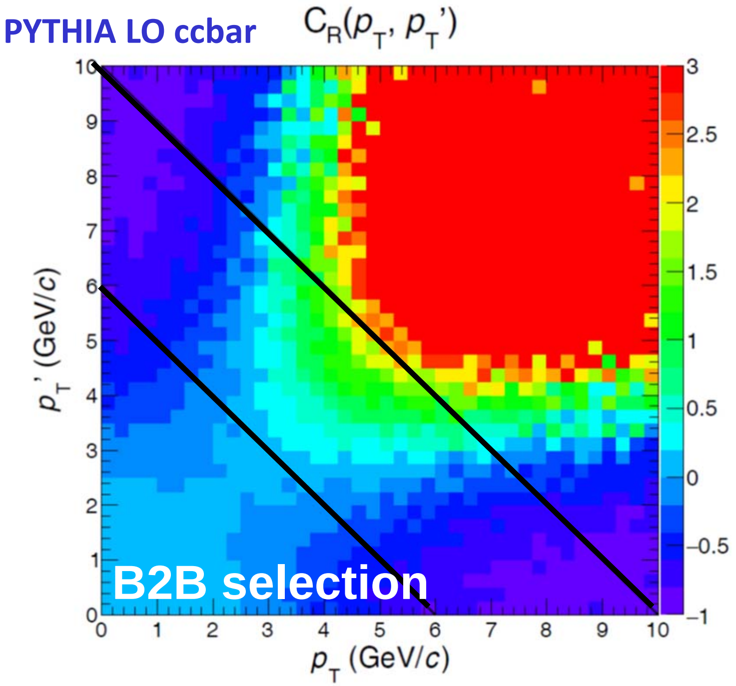
Momentum imbalance: not so naïve approach





- 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



Abolute correlation:

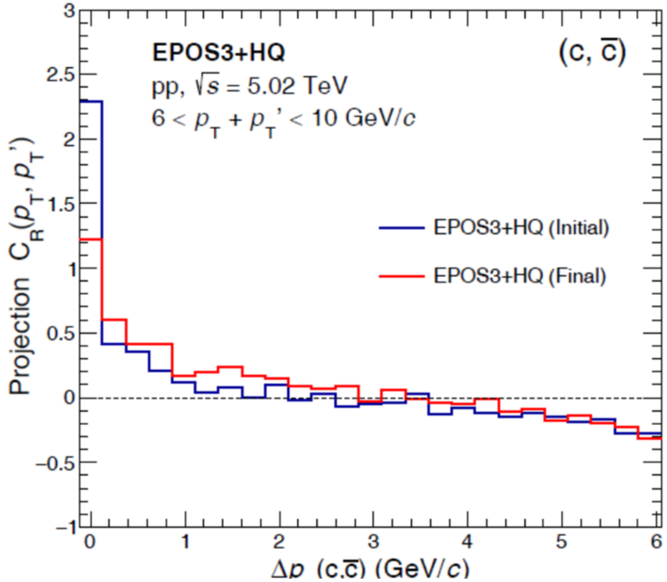
$$C(p_T, p'_T) := \frac{1}{N}\frac{d^2N(p_T, p'_T)}{dp_T dp'_T} - \frac{1}{N}\frac{dN(p_T)}{dp_T} \times \frac{1}{N}\frac{dN(p'_T)}{dp'_T}$$

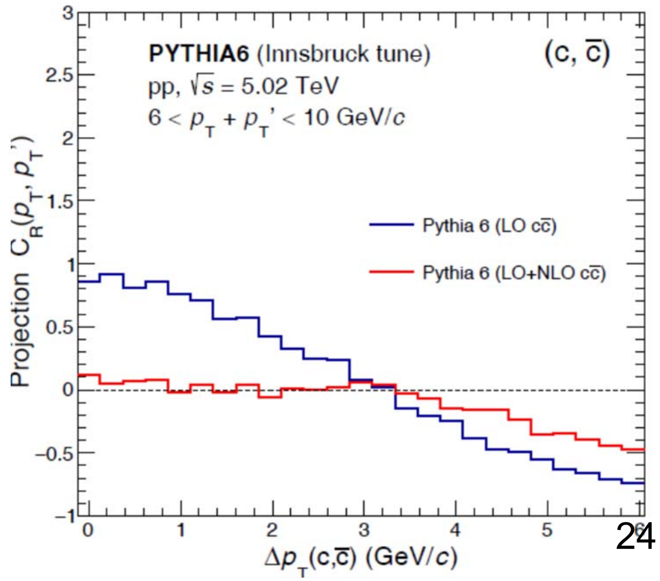
- Vanishes if d^2N factorizes ($d^2N(p,p') = dN(p) \times dN(p')$)
- Satisfies $\int C(p_T, p'_T) dp_T d'_T = 0$

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

- 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

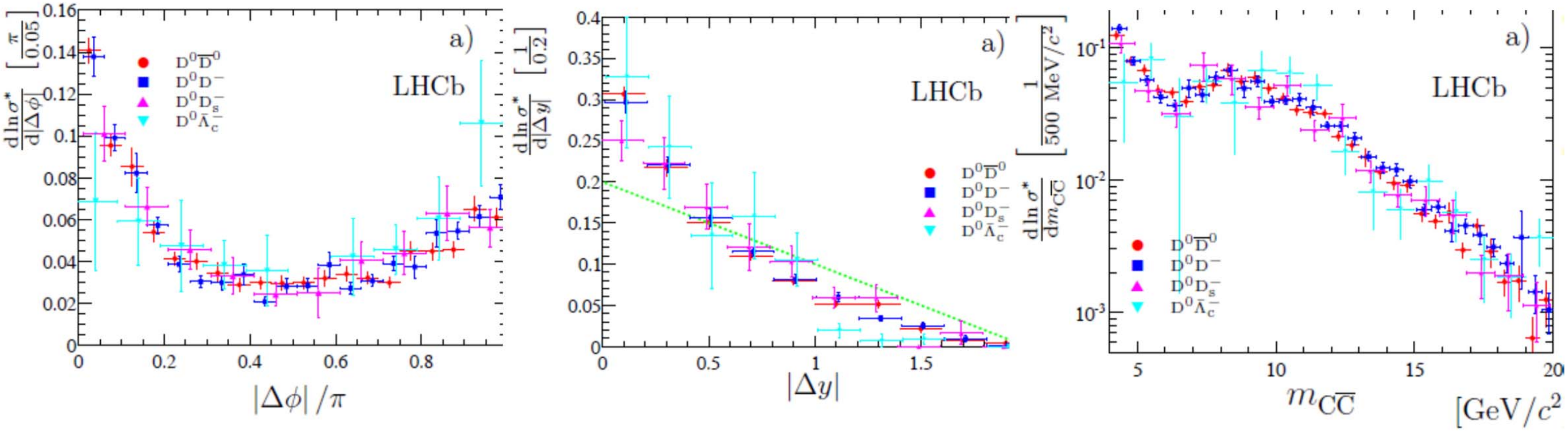




From the experimental viewpoint

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

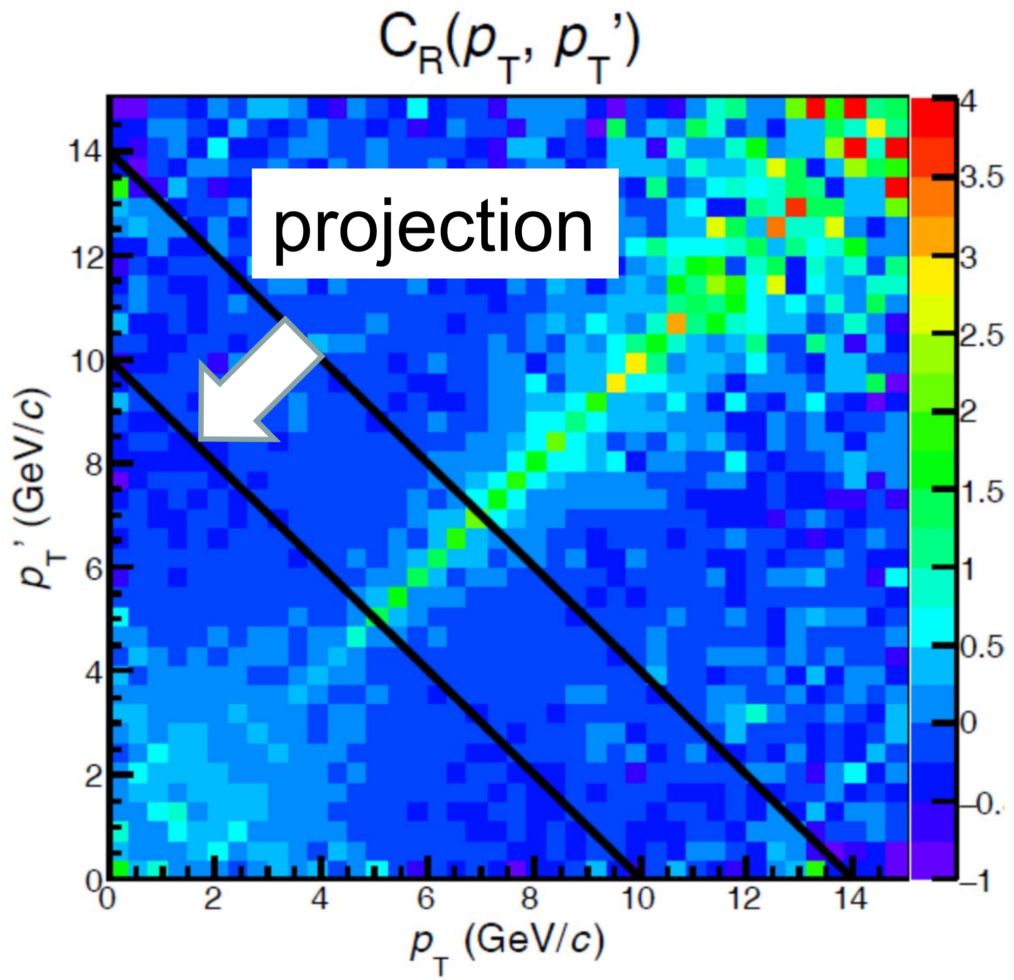
LHCb, J. High Energy Phys. 06, 141 (2012)

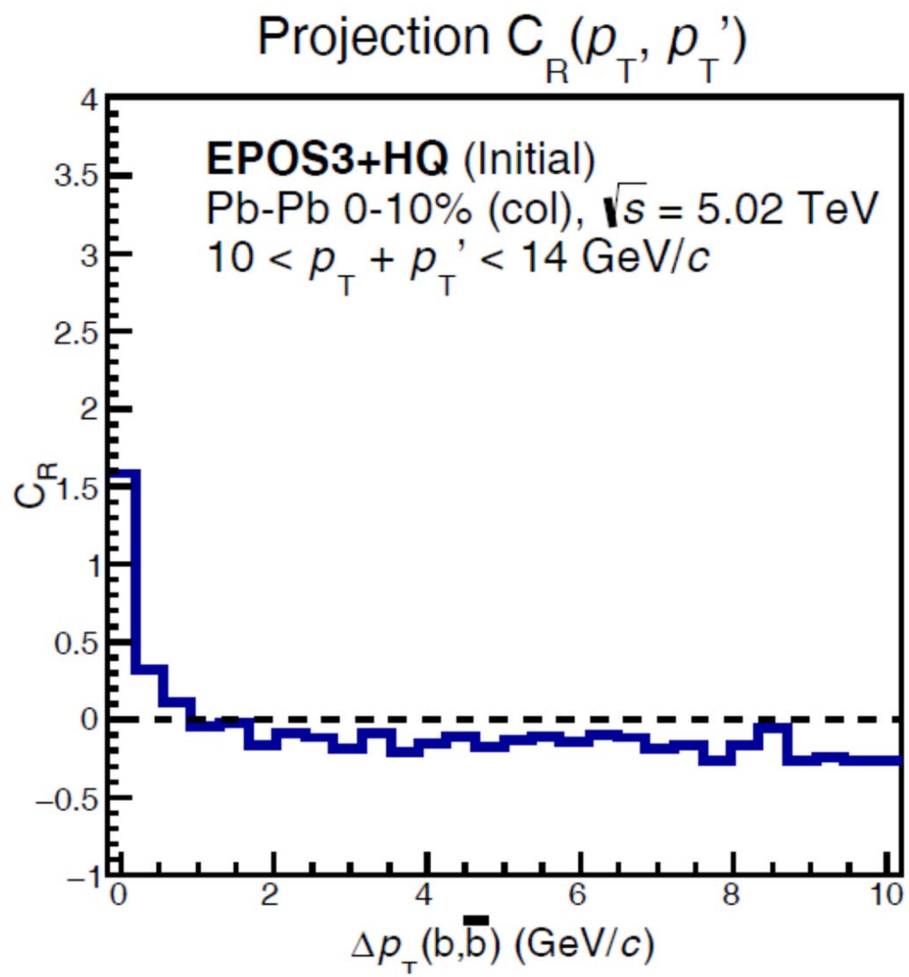


- Under present investigation

Momentum imbalance: b-bar in Pb-Pb

- "Initial" stage (before evolution with the medium)

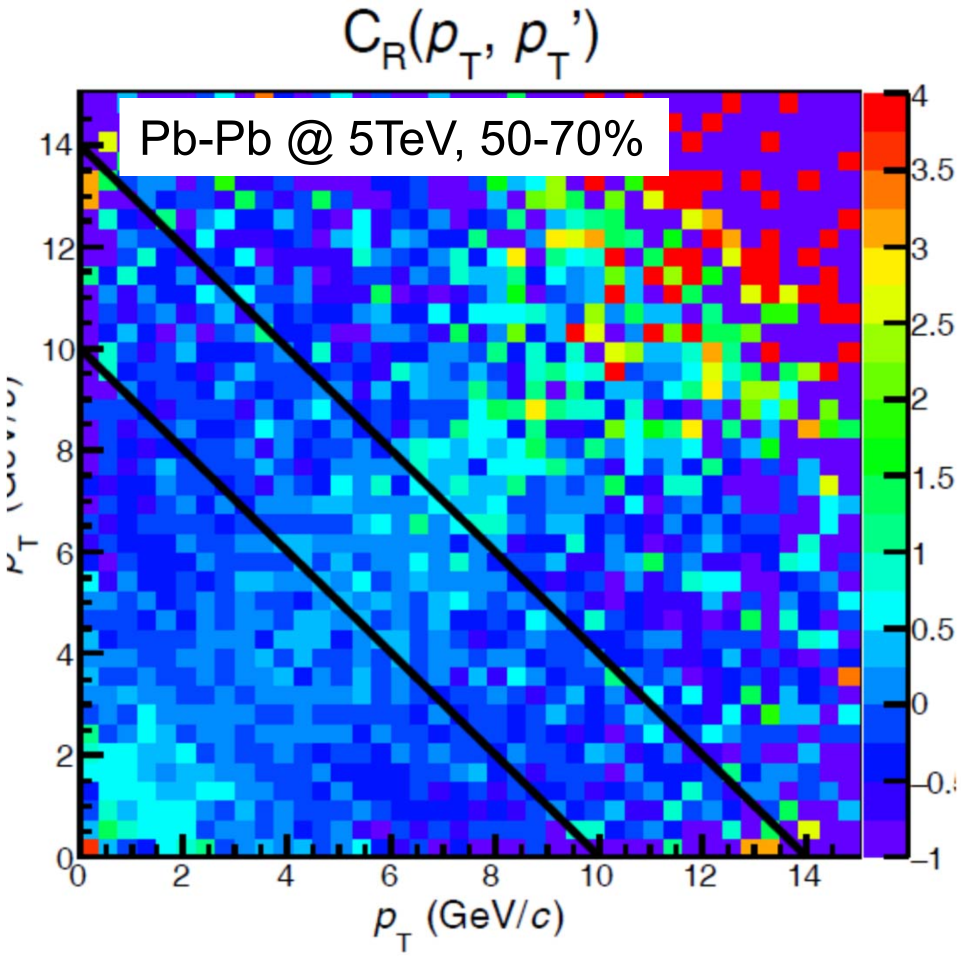




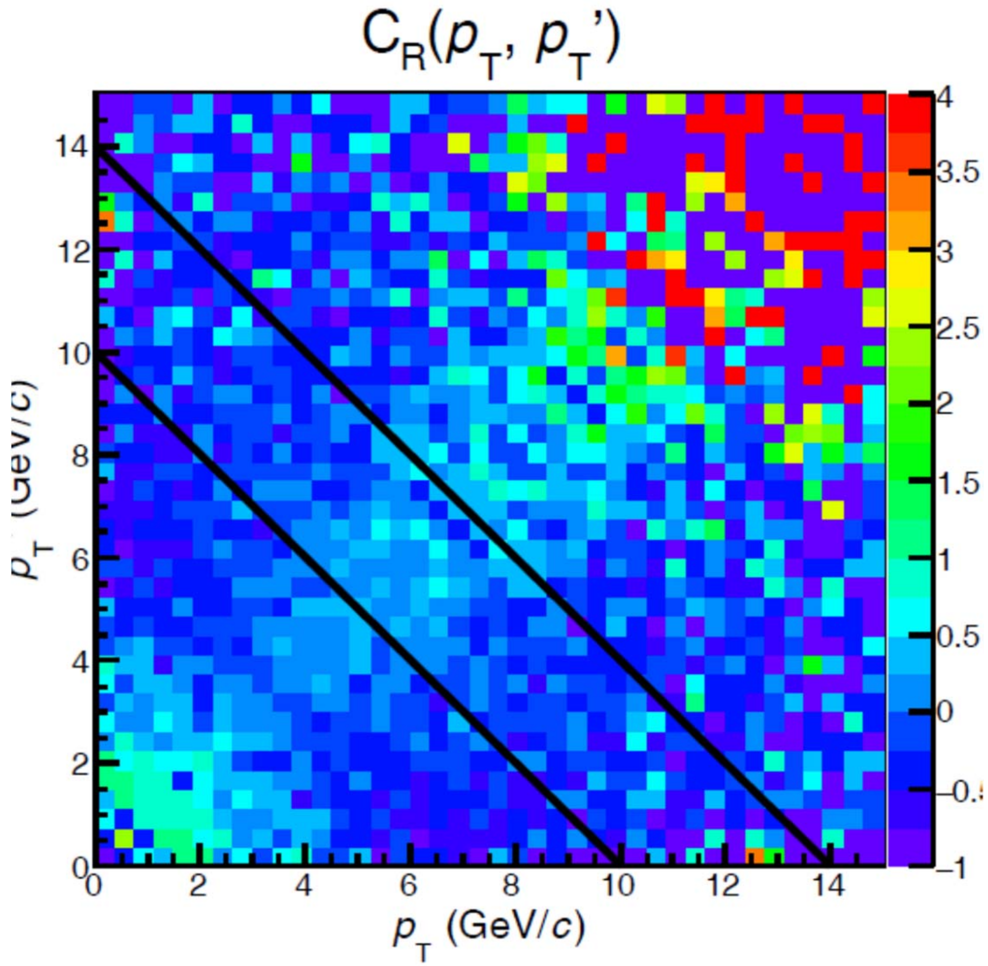
- Very good correlation for high p_T

Momentum imbalance: b-bar in Pb-Pb

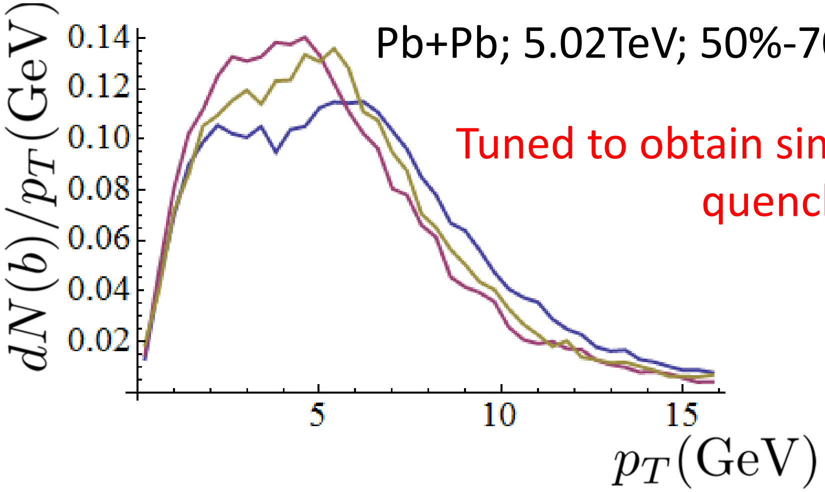
Elastic Energy loss



Elastic + Radiative Energy loss

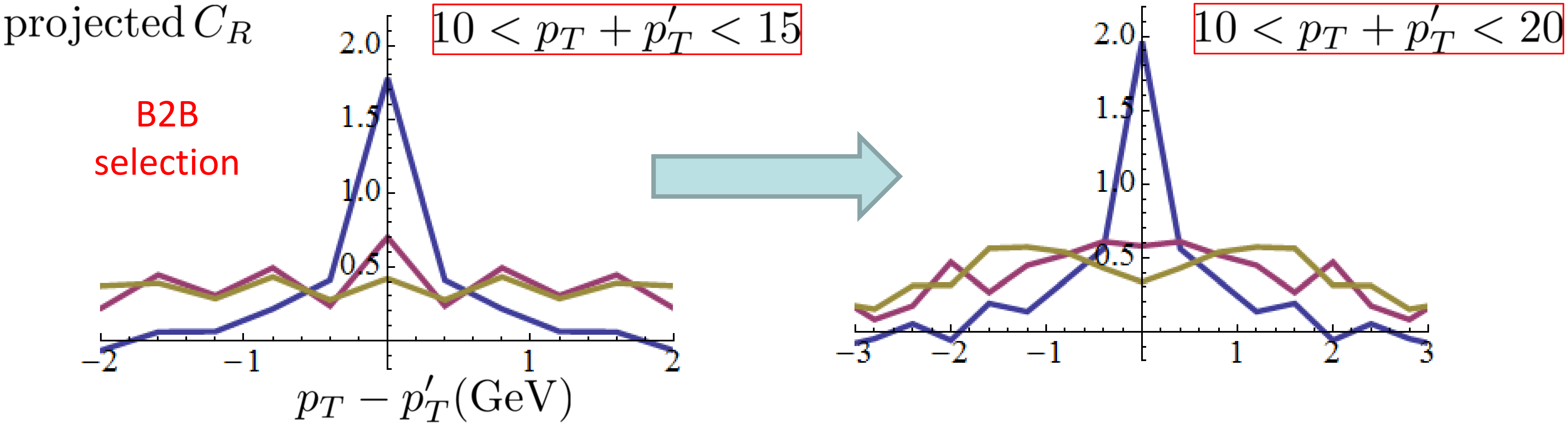


Momentum imbalance: bbar in Pb-Pb



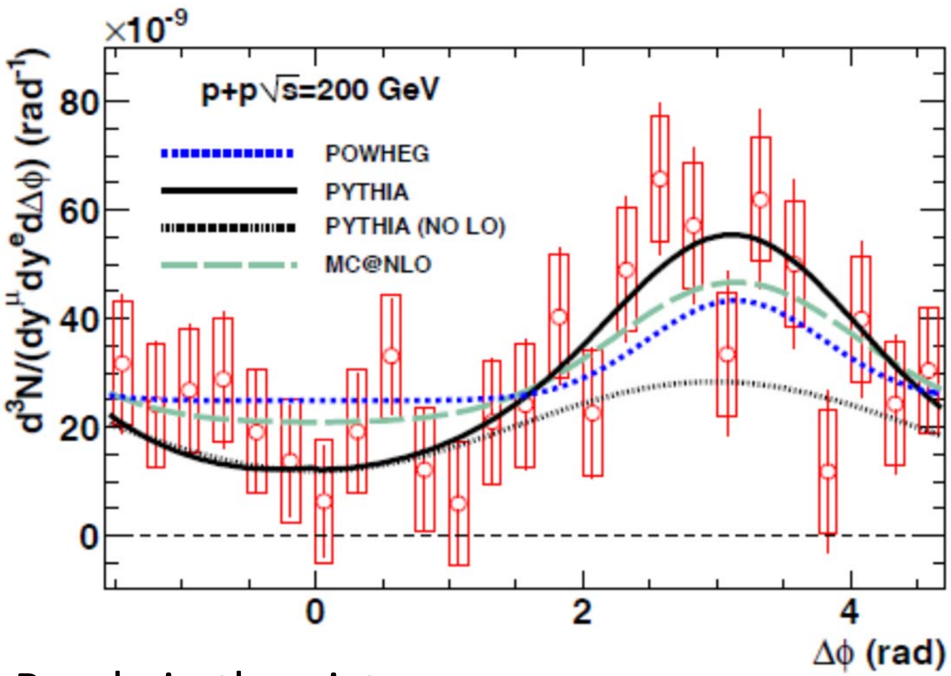
Tuned to obtain similar quenching

- Initial
- Elastic Energy loss
- Elastic + Radiative Energy loss

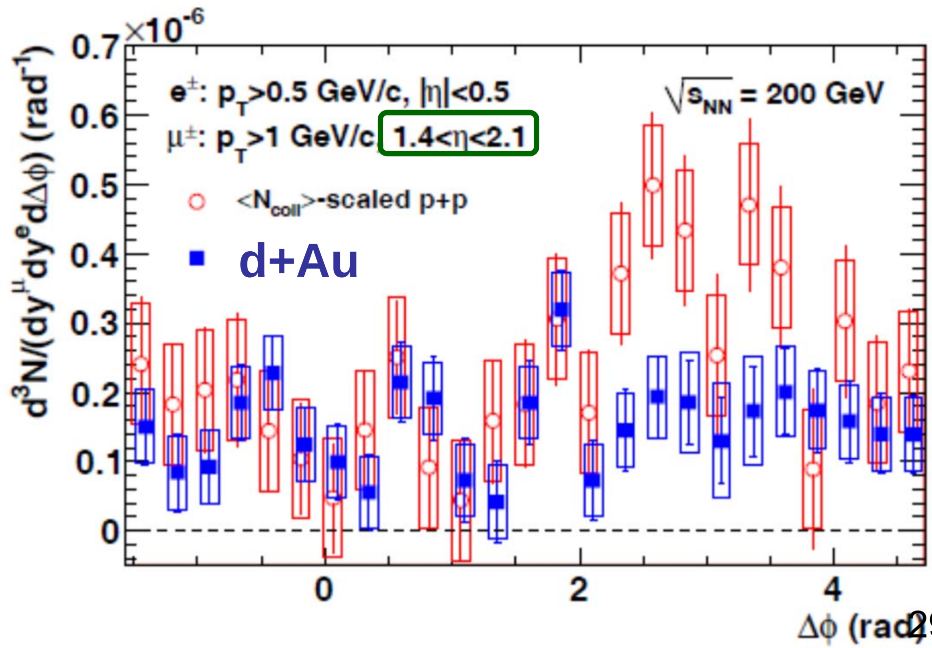


➢ QGP washes away the correlation peak... Possible window to estimate the relative weights of elastic and radiative energy loss for bottom quarks

Next best thing: HF-HF -> e-μ correlations



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

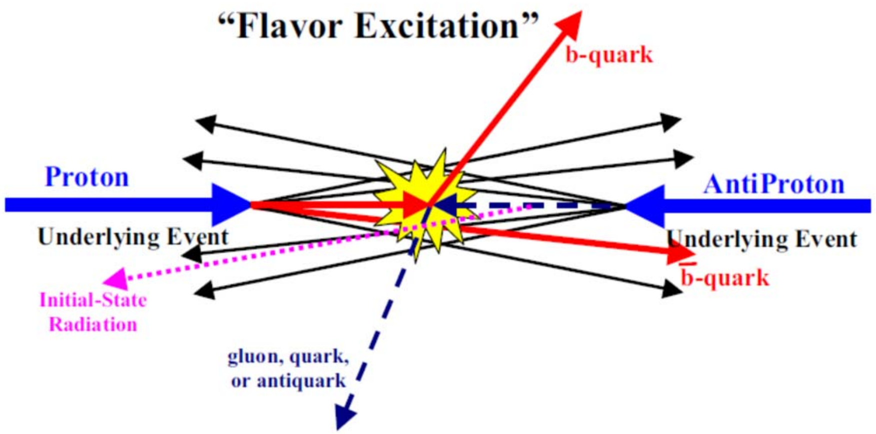


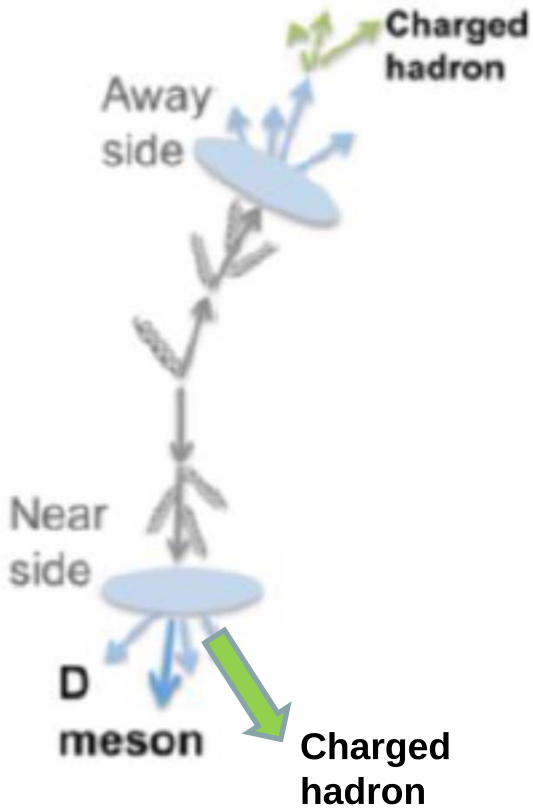
- Puzzle in the picture:
- "Such a suppression could arise due to nuclear PDF shadowing, saturation of the gluon wavefunction in the Au nucleus, or initial/final state energy loss and multiple scattering. »
- Did not seem to have received enough attention from the community

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:

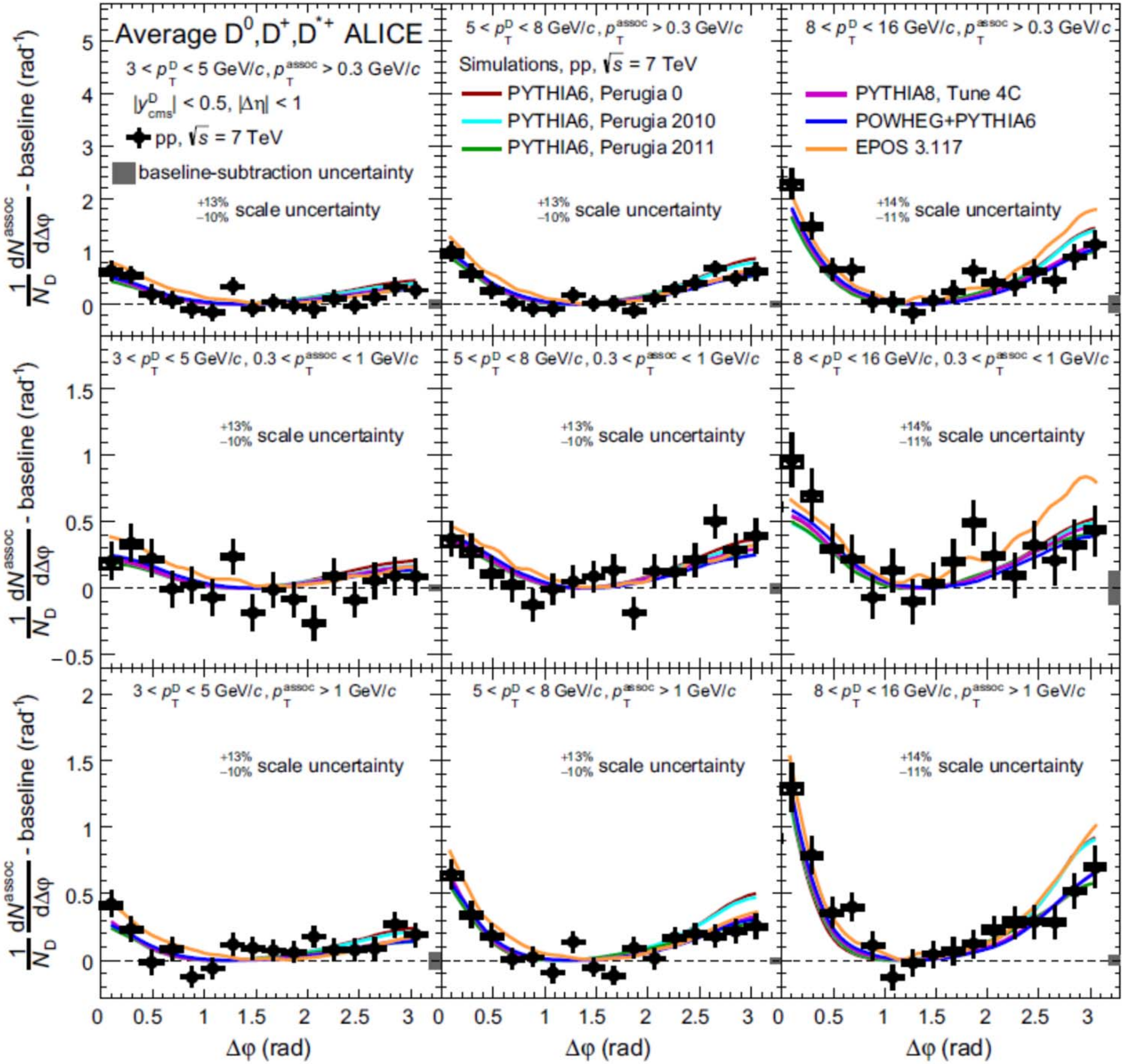




More involved from a theory / modelling view point; requires multi-component models

See f.i. talk by S. CAO

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 Δϕ correlations

Calibration ≈ ok

Some words on e-h / … in AA (at RHIC)

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

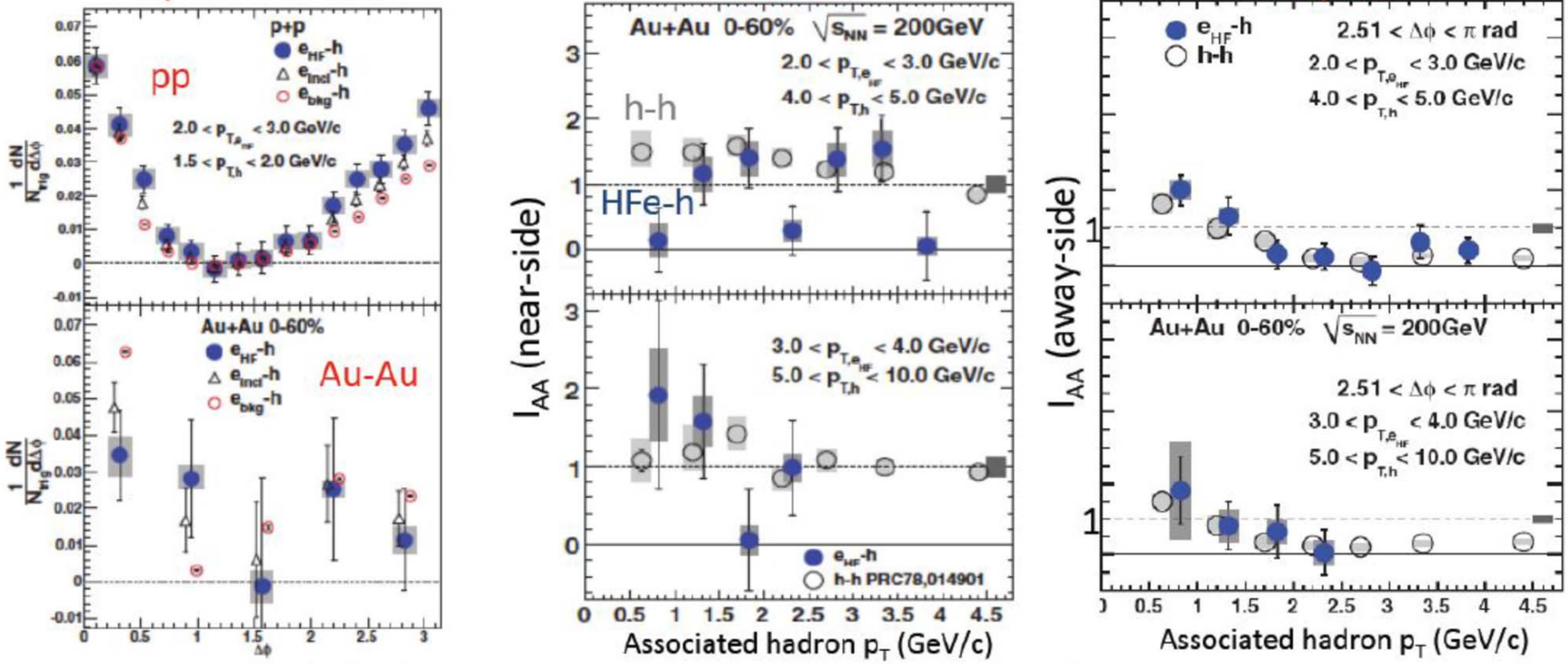
PHENIX Coll.: PRC 83, 044912 (2011)

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

$\Delta\varphi$ distributions

Near side

Away side



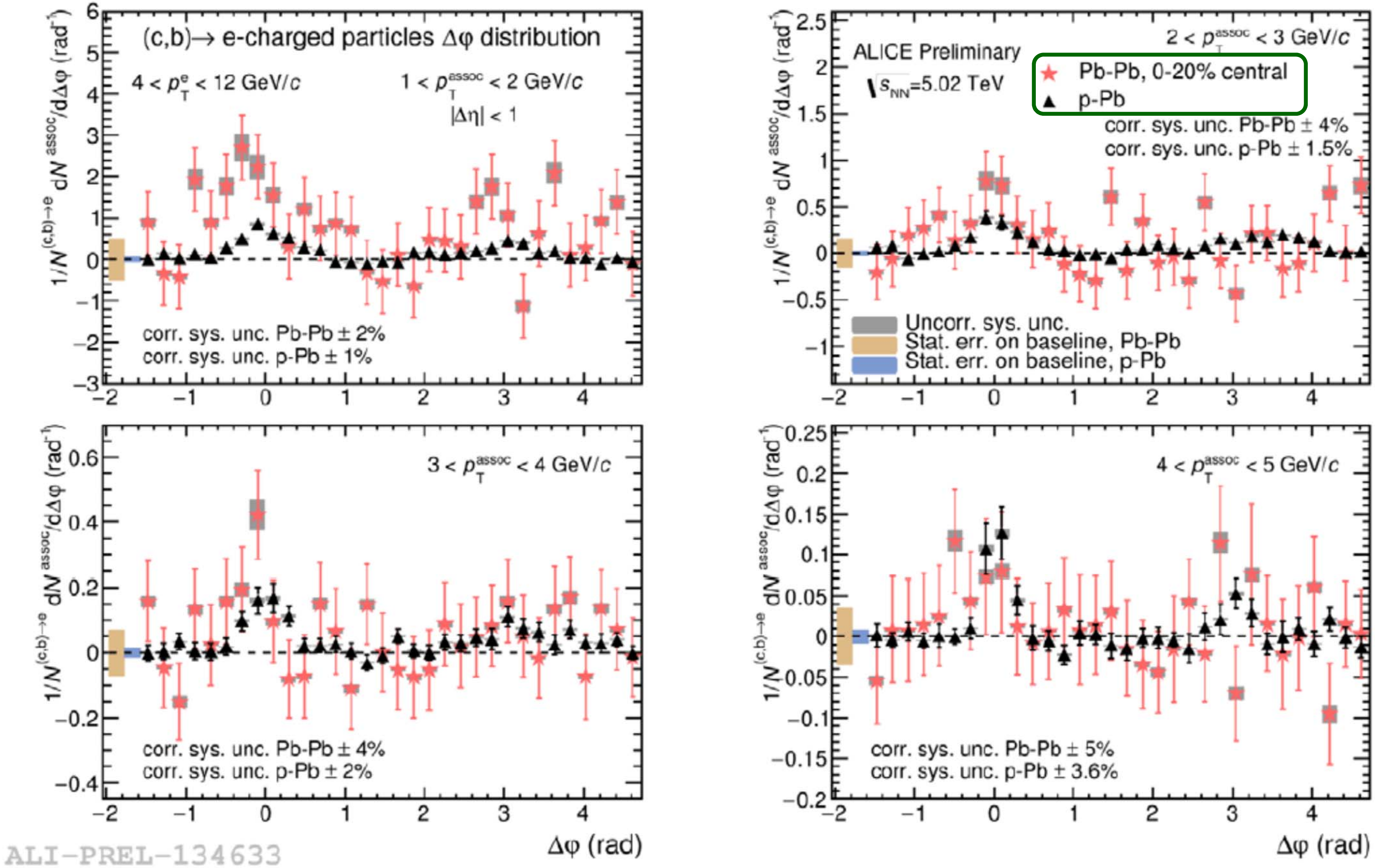
Large uncertainties in Au-Au measurement prevent firm conclusions
Suggest a decreasing I_{AA} trend with hadron p_T in the away side
Similar results than hadron-hadron correlations (a coincidence?)

→ Higher precision with new data

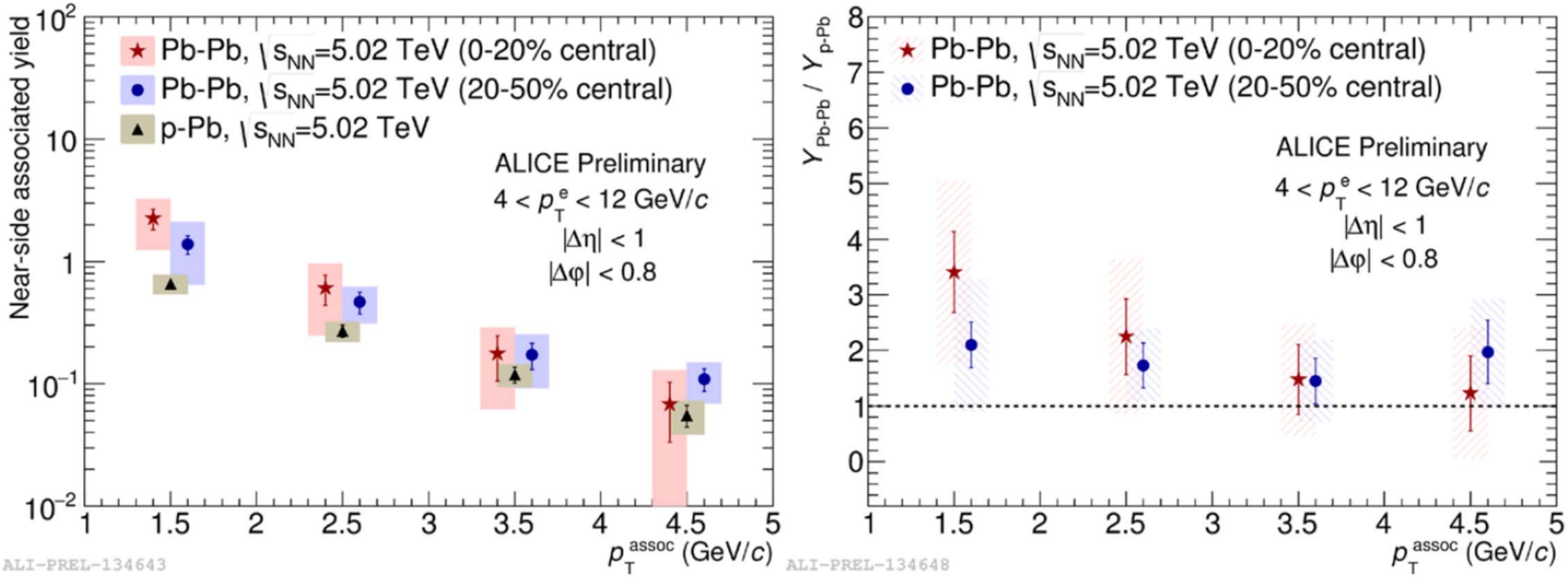
A. Rossi

55

Some words on e-h / … in AA (at LHC)



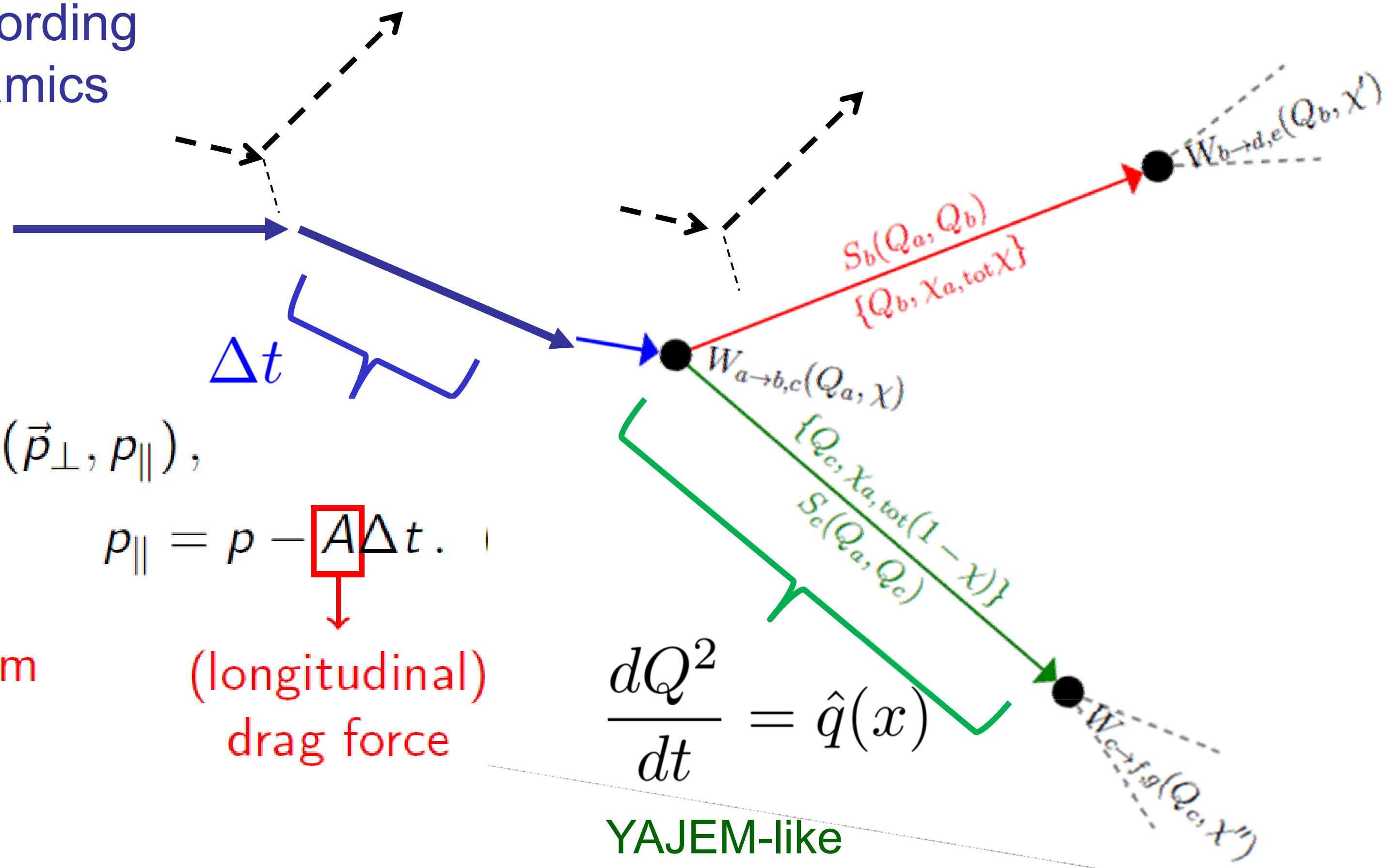
Some words on e-h / … in AA (at LHC)



- 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



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

$$p_\perp = \sqrt{\hat{q}\Delta t}\,, \qquad p_{||} = p - A\Delta t\,.$$

$\hat{q}$ → transverse momentum transfer

A → (longitudinal) drag force

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

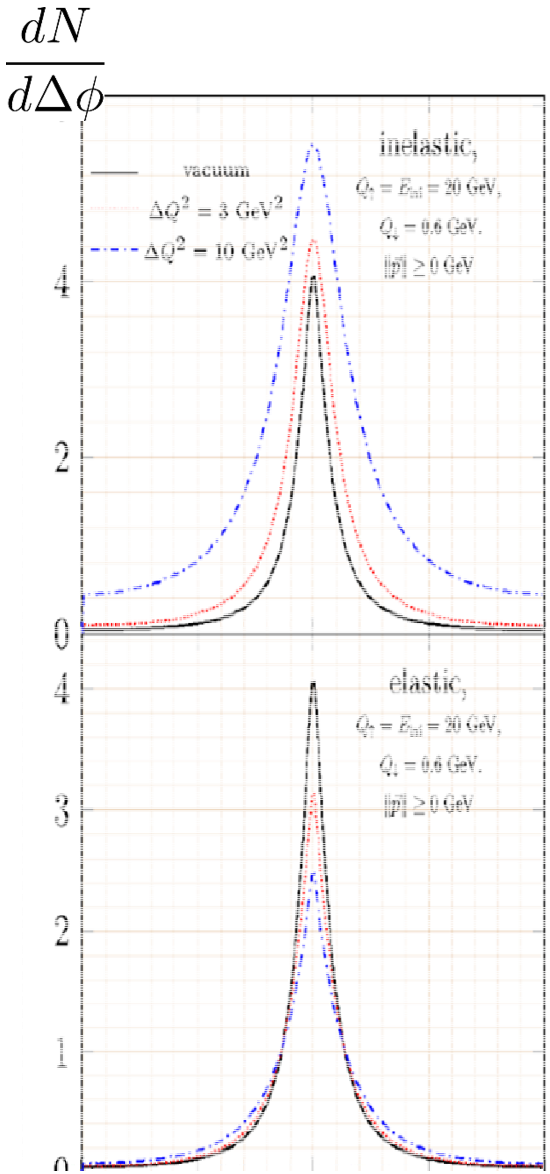
[H. Berrehrah et al. PRC 90, 064906 (2014)]

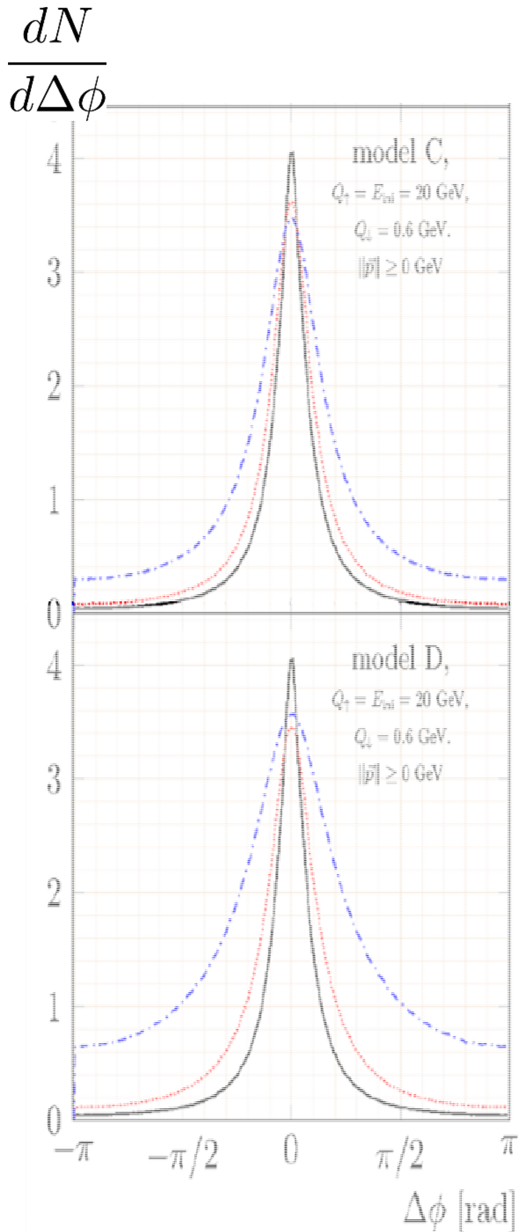
$$\frac{dQ^2}{dt} = \hat{q}(x)$$

YAJEM-like

increase of the virtuality => extra induced radiation.

Near side study with a generic jet – medium model



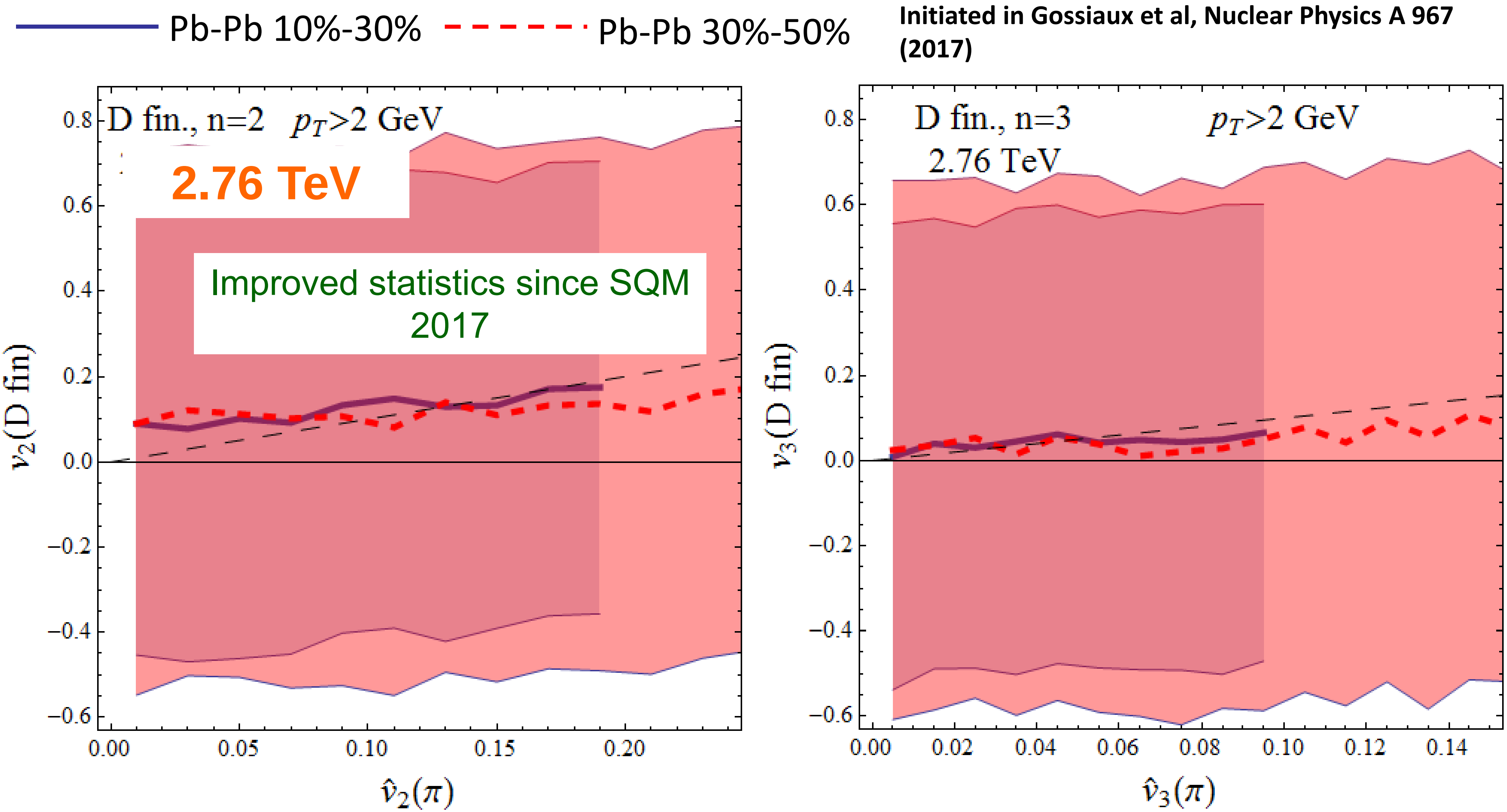


M. Rohrmoser's PhD thesis (2017)

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

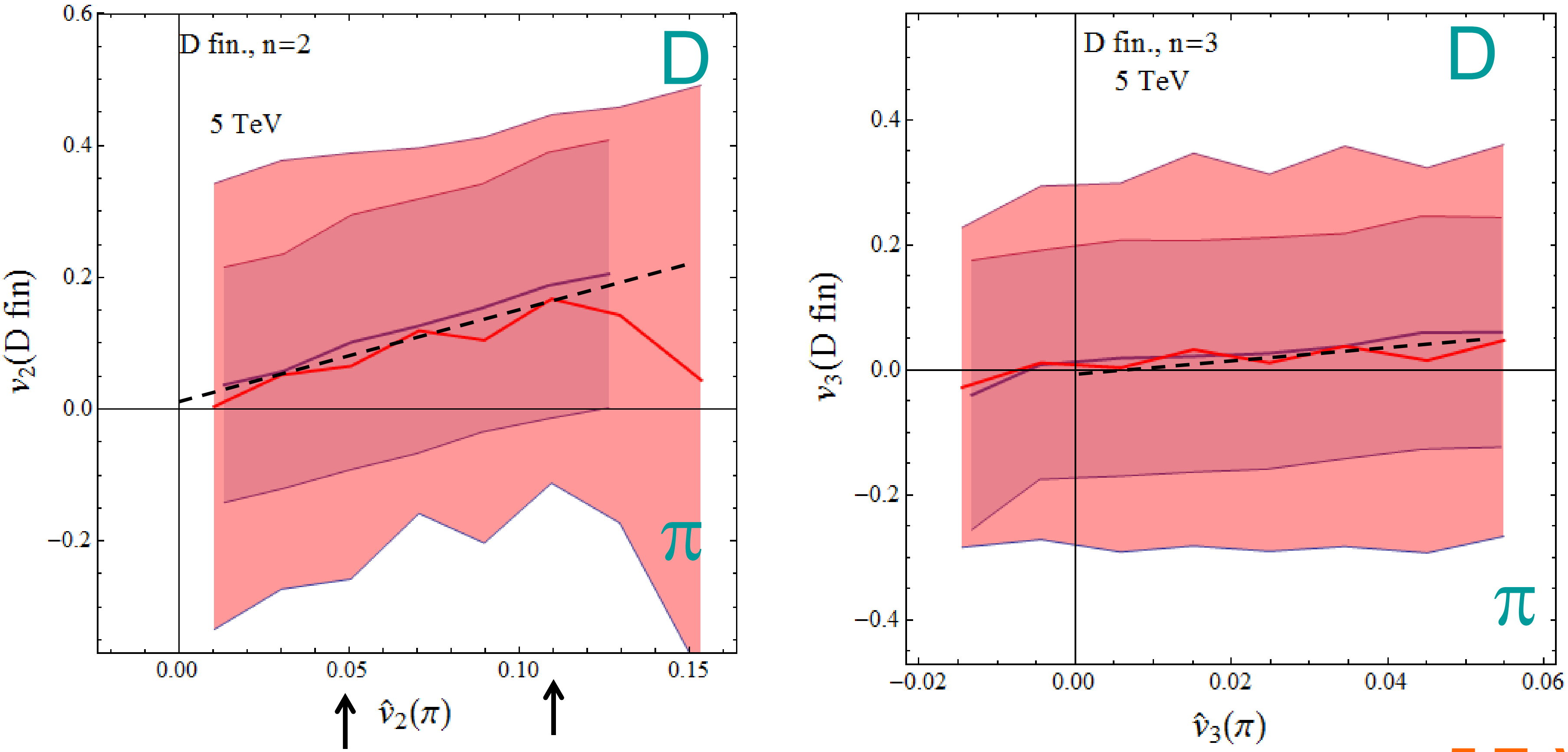
…To be implemented in EPOSHQ with bulk back-reaction

Heavy – light correlations: event shape engineering



- Correlations in EBE, although large fluctuations; sign of saturation for the largest values of v_2(p)

Heavy – light correlations: event shape engineering



<60% low q_2> <20% high q_2>

5 TeV

Good correlation for {π,N} (common freeze out surface), less dependence on the centrality… still large fluctuations

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 !)
- HF – hadrons correlations requires fully fledged models and simulators
- To 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
- By then, the most efficient “constrain” can be obtained by performing systematic multi-domain comparison of the traditional single particle observables…
- Brand new study on momentum imbalance