

Heavy Flavor Azimuthal Correlations in Cold Nuclear Matter

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Outline:

- Single inclusive heavy flavors
 - fragmentation
 - k_T broadening
- Heavy flavor pairs
 - Comparison with collider data
- Cold nuclear matter effects

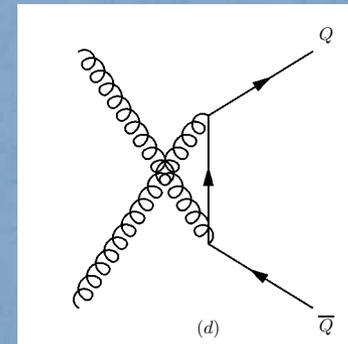
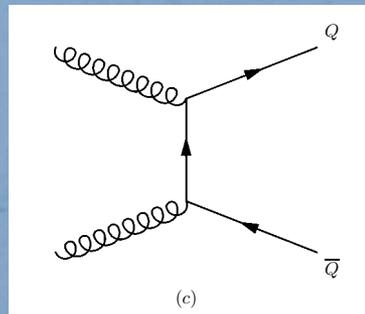
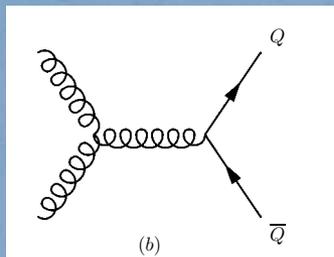
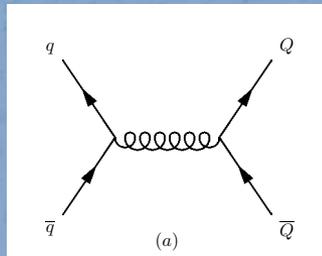
Motivation

- Correlations are more complex observables of heavy flavor production
- Naïve expectation is that pairs are produced back-to-back but next-to-leading order contributions change correlation, result is also strongly dependent on any k_T broadening
- Correlation measurements can probe event topologies by applying appropriate cuts
- In heavy-ion collisions, correlations may be modified or softened by interactions with the medium through energy loss, transport, etc.
- Thus a good p+p baseline calculation is needed to understand Au+Au

Leading order pair production

At LO, heavy quark and antiquark will always be back-to-back in azimuth

quark-antiquark



gluon-gluon

Next-to-leading order contributions to pair production

In addition to quark-antiquark and gluon-gluon contributions present at LO, quark-gluon contributions are now added

Contributions sorted by initial state, not diagram topology at NLO

LO event generators like PYTHIA and HERWIG sort diagrams according to topology, put labels on diagrams to distinguish, like flavor creation, flavor excitation and gluon splitting

These are not different production mechanisms, they all contribute according to weights determined by color factors

Total cross sections obtained by summing contributions from all diagrams and squaring amplitudes

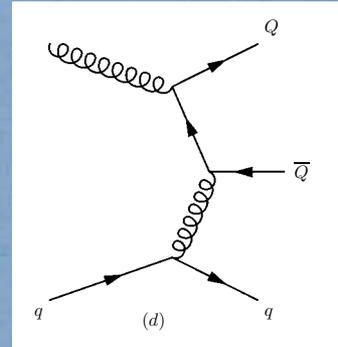
LO event generators calculate different diagrams without proper weights and will not lead to a correct cross section

Some example diagrams

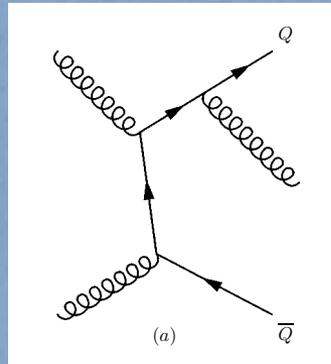
Only some diagrams shown, real and virtual corrections included

Different diagrams can lead to different azimuthal correlation but no new mechanism

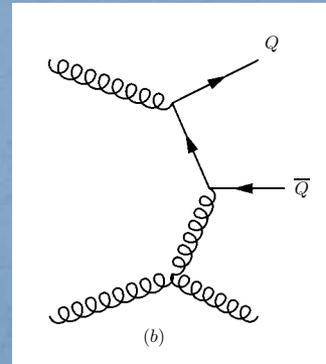
quark-gluon,
new at NLO



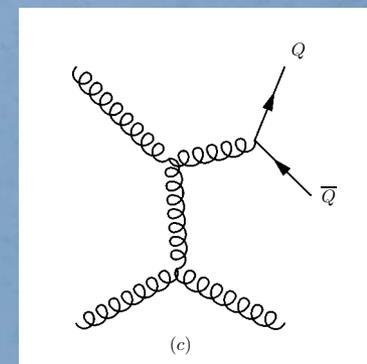
gluon-gluon



Real gluon
emission



“flavor excitation”



“gluon splitting”

Comparing FONLL and HVQMNR single inclusive distributions

- Use HVQMNR code to look at pair results; start with single quark p_T distribution and compare to FONLL
- Compare effect of fragmentation functions, k_T smearing to bare quark result
- Low p_T region emphasized to highlight small differences; fragmentation effect larger than k_T smearing

Fragmentation in FONLL and HVQMNR

- FONLL uses different fragmentations for charm and bottom, based on calculations of Mellin moments compared to e^+e^- data
 - c quarks: combination of pseudoscalar and vector fragmentation channels for ground state and excited D mesons respectively, $\langle z \rangle = 0.822$ for total
 - b quarks: polynomial

$$D(z) = z(1-z)^{\varepsilon}$$

$$\varepsilon = 27.5 \text{ for } m_b = 4.65 \text{ GeV}, \langle z \rangle = 0.934$$

- HVQMNR uses Peterson function for fragmentation with variable parameter, ε_p

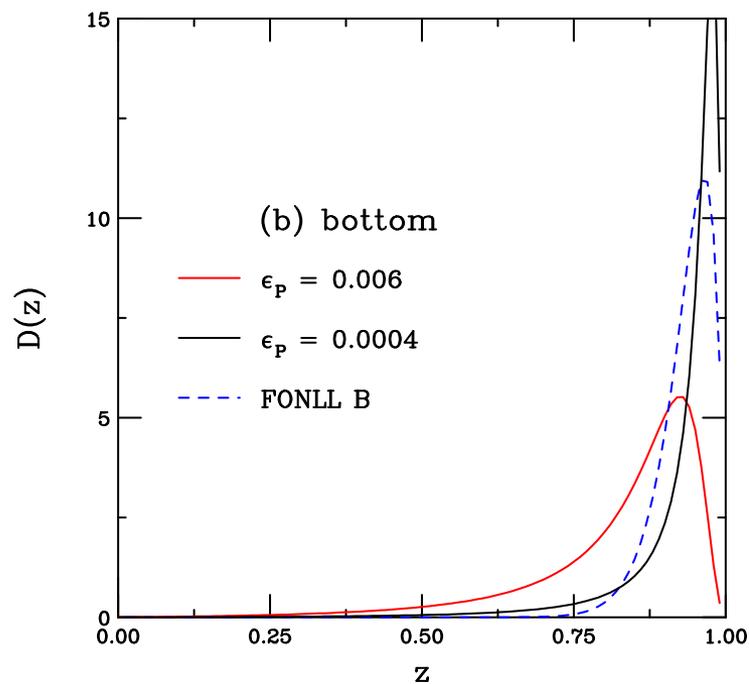
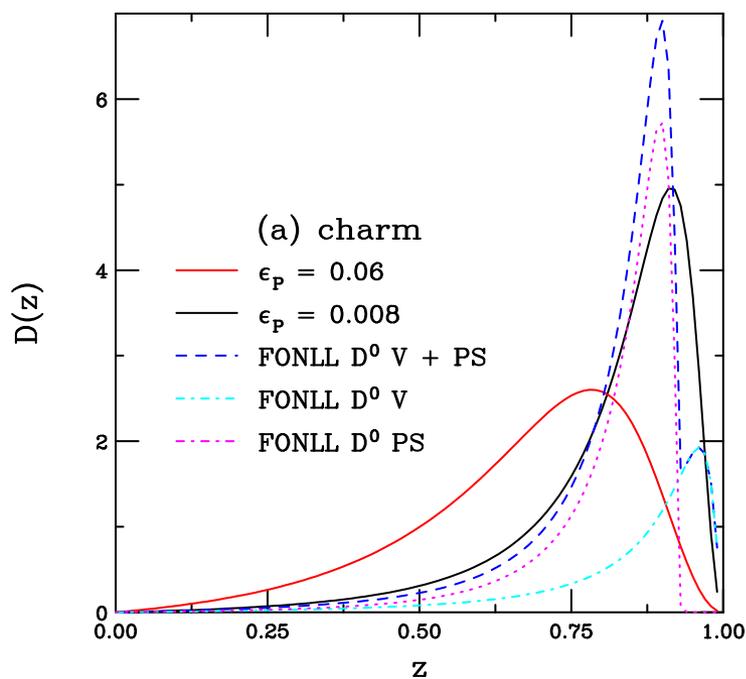
$$\square \quad D(z) = z(1-z)^2 / [(1-z)^2 + z\varepsilon_p]^2$$

- Standard values for ε_p , 0.06 for c and 0.006 for b are too large for hadroproduction, $\langle z \rangle = 0.67$ & 0.82 respectively
- To match the FONLL result including k_T broadening, ε_p has to be reduced to 0.008 and 0.0004 for c and b respectively, giving $\langle z \rangle = 0.822$ and 0.930

Fragmentation: HVQMNR vs FONLL

Charm fragmentation

Bottom fragmentation



k_T broadening in FONLL and HVQMNR

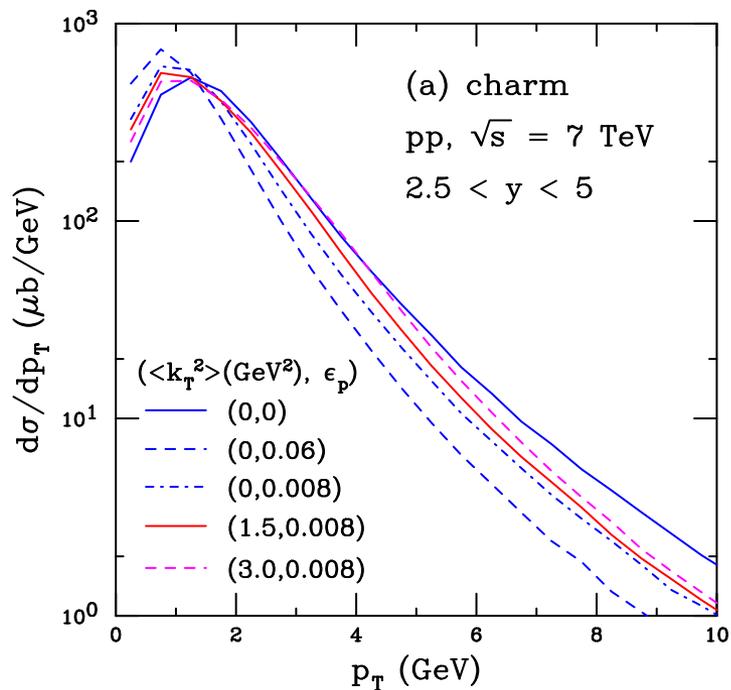
- FONLL does not include any broadening, only fragmentation
- HVQMNR combines broadening with fragmentation, based on p_T distributions at fixed-target energies: including fragmentation with default Peterson function parameters reduced $\langle p_T \rangle$ so much that a rather large k_T broadening had to be included to make up difference
- Precedent from Drell-Yan, k_T broadening included to make low p_T distribution finite and to take the place of full resummation:

$$g(k_T) = (1/\pi \langle k_T^2 \rangle) \exp(-k_T^2 / \langle k_T^2 \rangle)$$

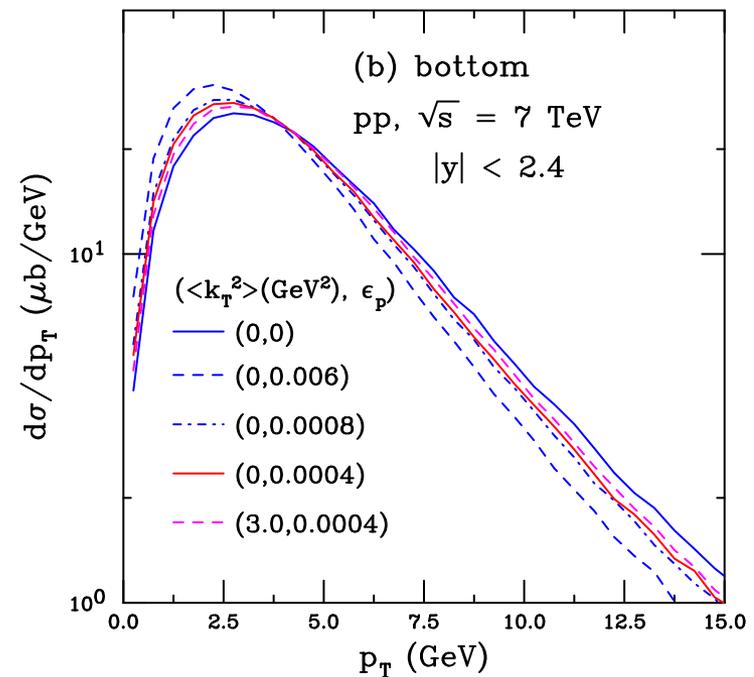
- Gaussian factors are applied to each heavy quark in the final state in HVQMNR, should be equivalent to application to initial-state partons as long as $\langle k_T^2 \rangle \sim 2-3 \text{ GeV}^2$
- Energy dependence assumed:
$$k_T^2 = 1 + (1/n) \ln(\sqrt{s} / (20 \text{ GeV})) \text{ GeV}^2$$
- We take $n = 12$ for c and 3 for b (from J/ψ and Y respectively)

Effects of fragmentation and k_T broadening on single inclusive distributions

Charm



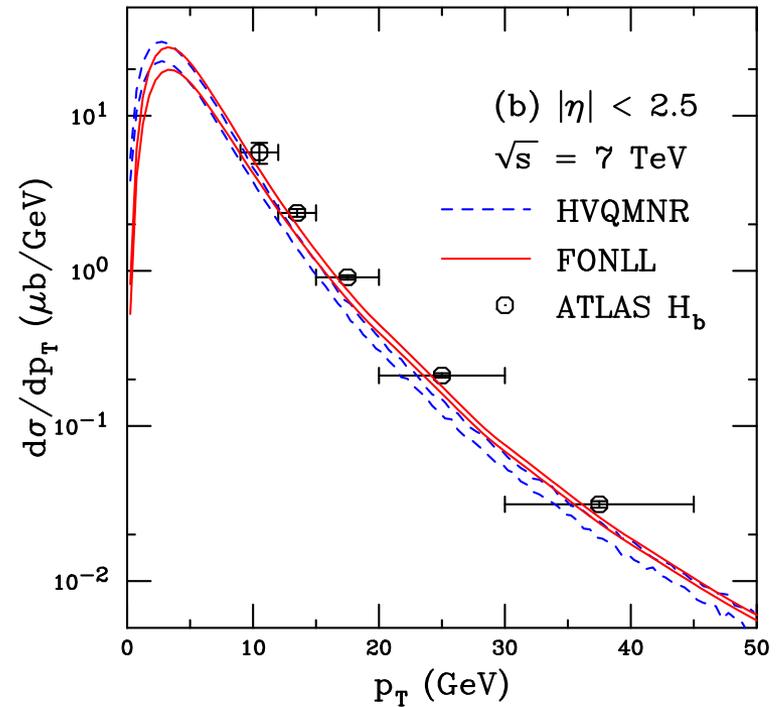
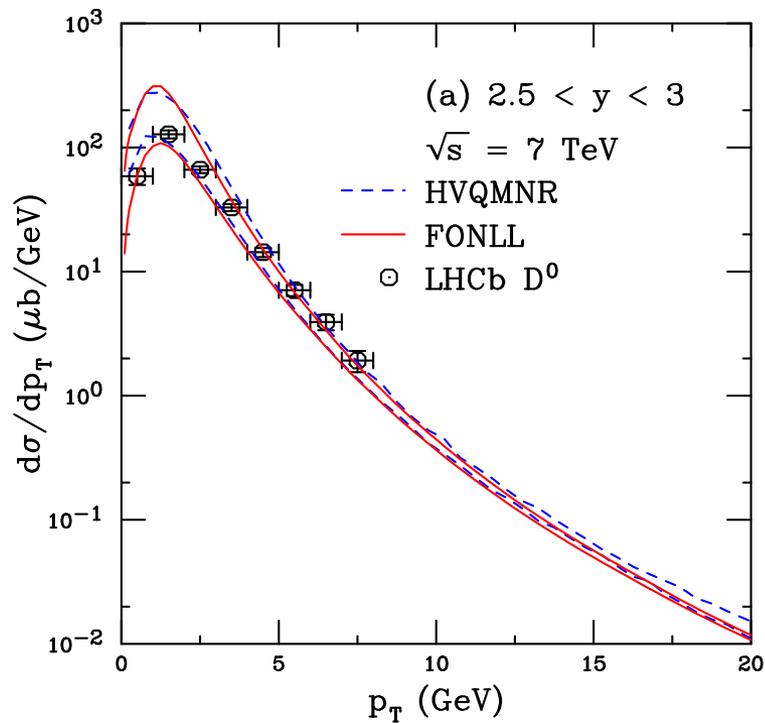
Bottom



Uncertainty bands on single heavy flavor distributions: FONLL vs. HQMNR

D⁰ compared to LHCb

B mesons from ATLAS

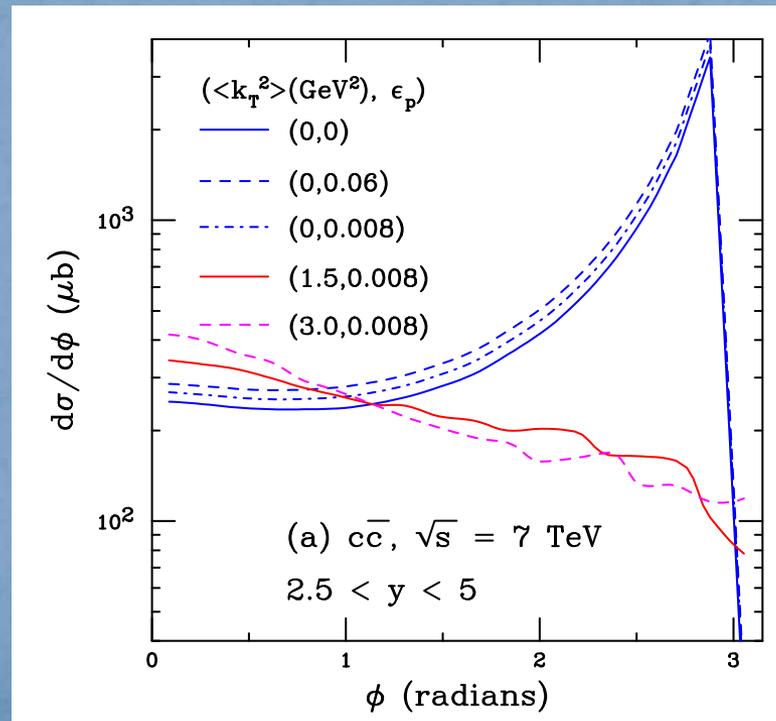


c quark pair production

All results without k_T broadening give strong peak near $\phi = \pi$, integrated over all p_T

No delta function because correlated c quark pair production is $2 \rightarrow 3$ process, light parton (q or g) is also in final state so correlation is no longer exact back-to-back

k_T broadening alone can reduce and change peak at π to peak at zero, fragmentation has almost no effect

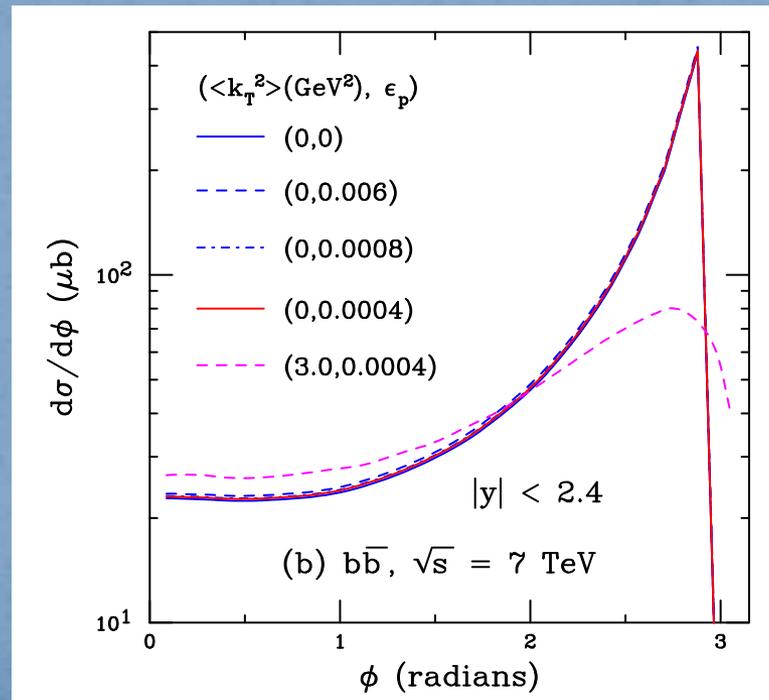


b quark pair production

All results without k_T broadening give strong peak near $\phi = \pi$, integrated over all p_T

No delta function because correlated b quark pair production is $2 \rightarrow 3$ process, light parton (q or g) is also in final state so correlation is no longer exact back-to-back

k_T broadening required to reduce peak, fragmentation has almost no effect



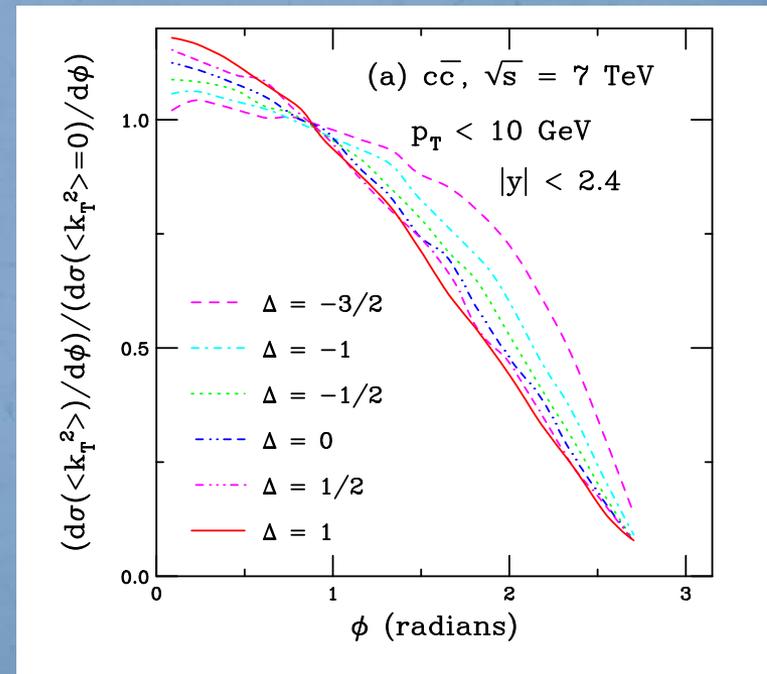
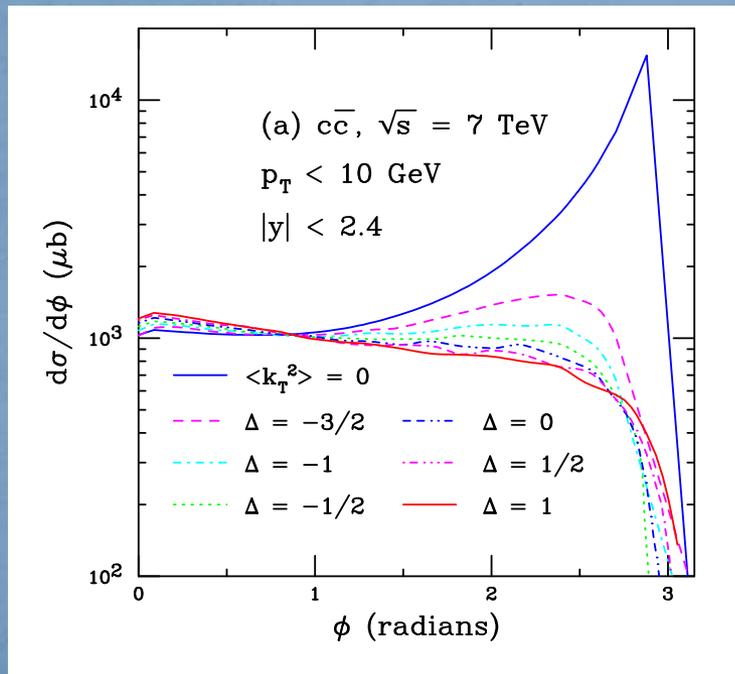
Strength of k_T broadening for different p_T cuts

- Chose semi-arbitrary cut of 10 GeV and looked at azimuthal correlations for p_T above and below this cut for charm and bottom production
- Varied average k_T^2 from 0 to nominal value
$$\langle k_T^2 \rangle = 1 + (\Delta/n) \ln(\sqrt{s} / (20 \text{ GeV})) \text{ GeV}^2$$
- $\Delta = -3/2, -1, -1/2, 0, 1/2, 1$ for c; $-1/2, 0, 1/2, 1$ for b (need smaller range for b because $\langle k_T^2 \rangle$ must be positive)
- Checked central and forward rapidity regions but results only shown for central – forward is similar enough to make no difference with respect to shape

Charm pairs, $p_T < 10$ GeV

Sharp contrast between $\langle k_T^2 \rangle = 0$ and $\Delta = -3/2$: even with this value of Δ the back-to-back peak is washed out and the correlation becomes rather flat in ϕ

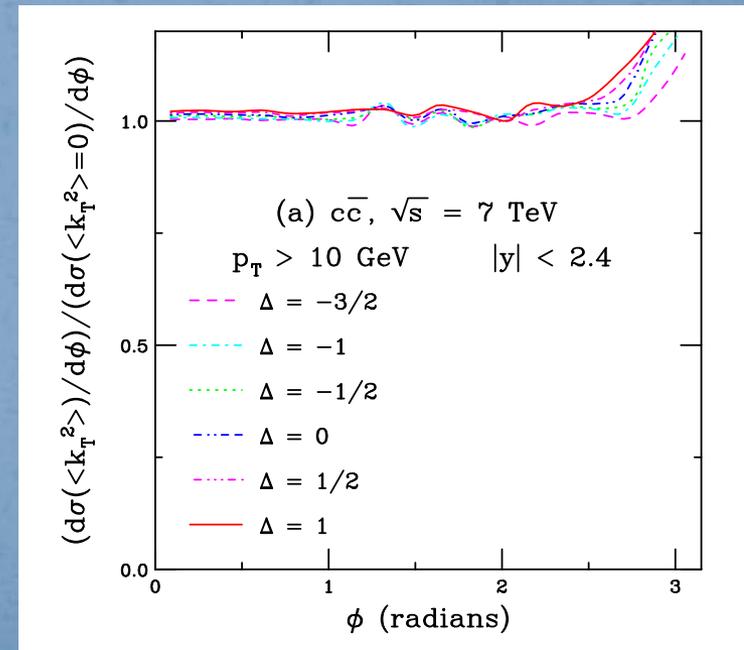
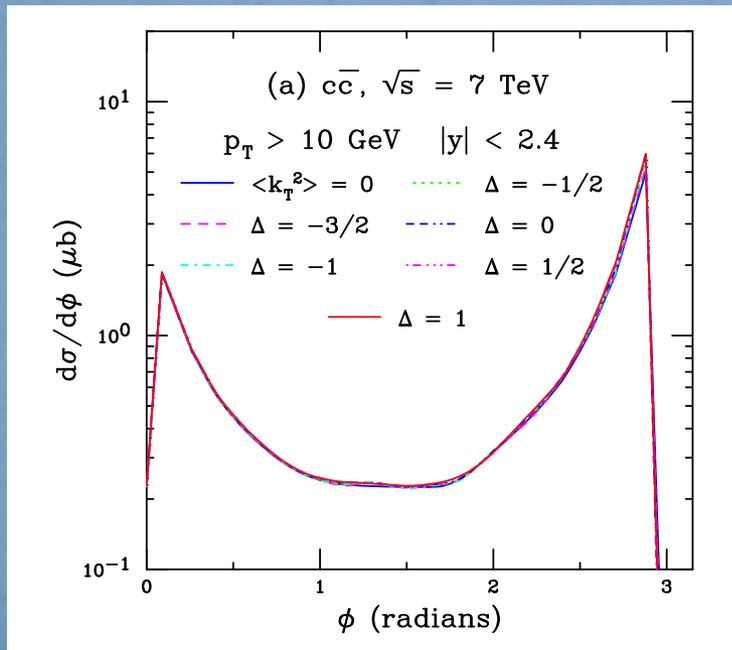
The ratio shows a gradual change with increasing Δ , with a pivot around $\phi \sim 1$



Charm pairs, $p_T > 10 \text{ GeV}$

Azimuthal distribution is completely insensitive to value of Δ

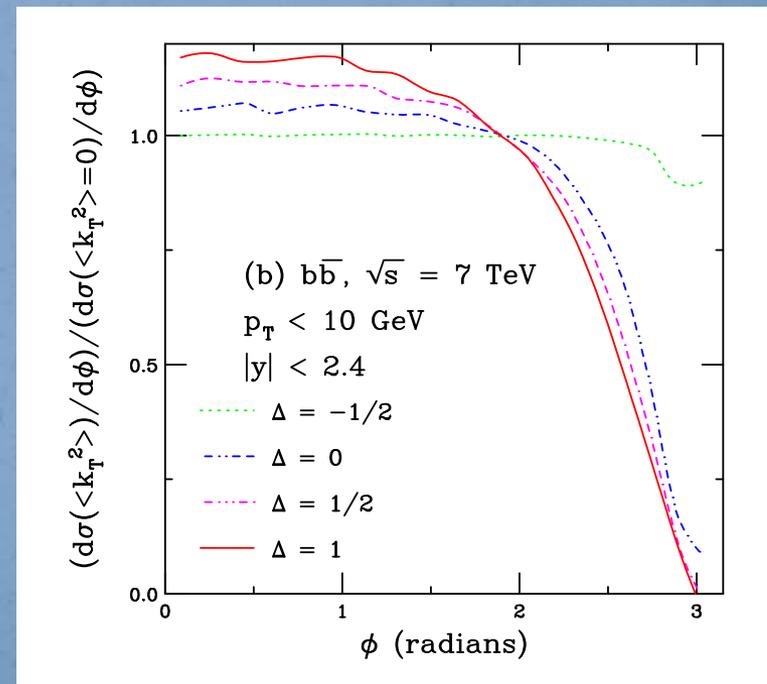
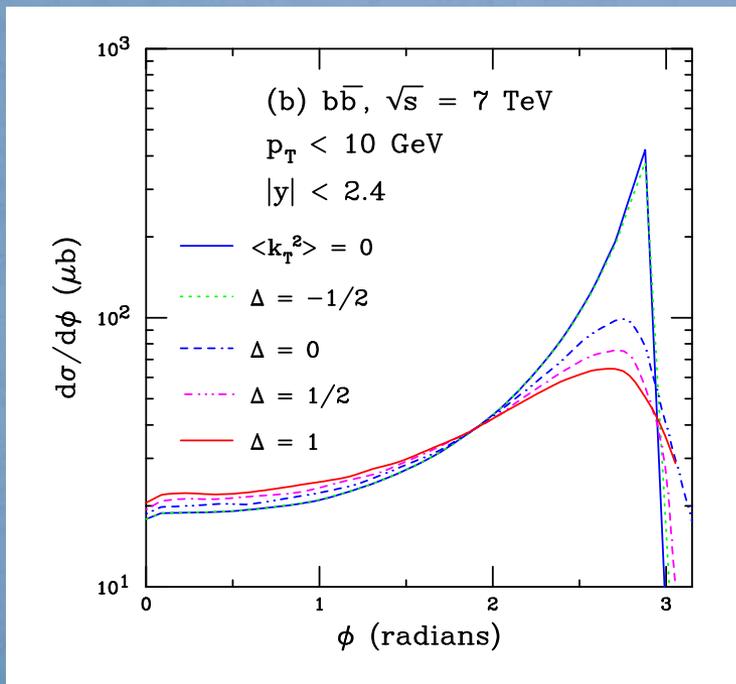
Ratio shows some small change for $\phi > 2.5$ but only few percent effect because $p_T \gg m_c$ already for 10 GeV



Bottom pairs, $p_T < 10$ GeV

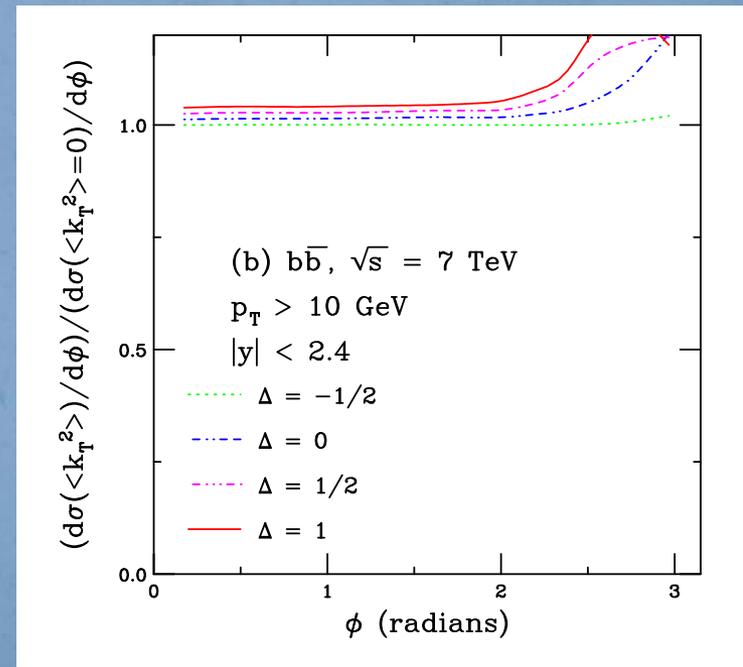
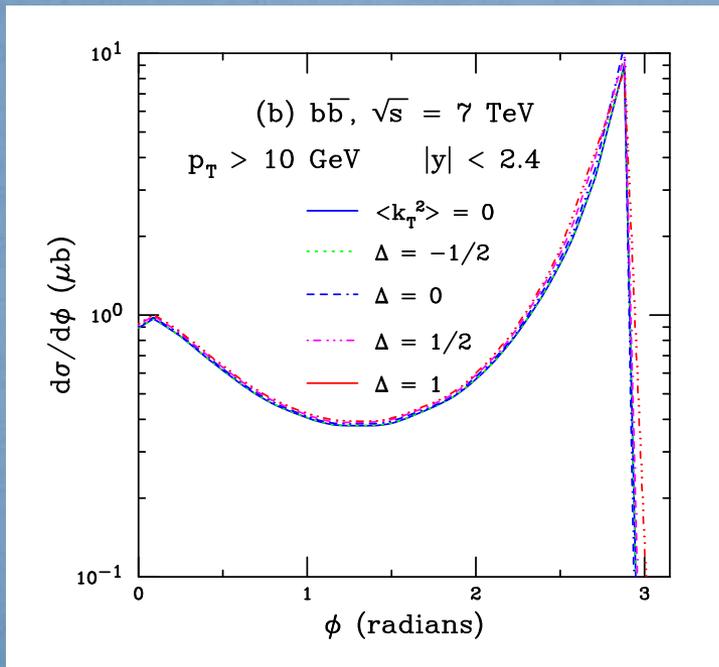
Distribution in ϕ with $\Delta = -1/2$ is almost identical to that with $\langle k_T^2 \rangle = 0$ since in this case $\langle k_T^2 \rangle = 0.002$ GeV²

Larger values of Δ show reduce the peak at larger ϕ , ratio pivots now at $\phi \sim 2$



Bottom pairs, $p_T > 10$ GeV

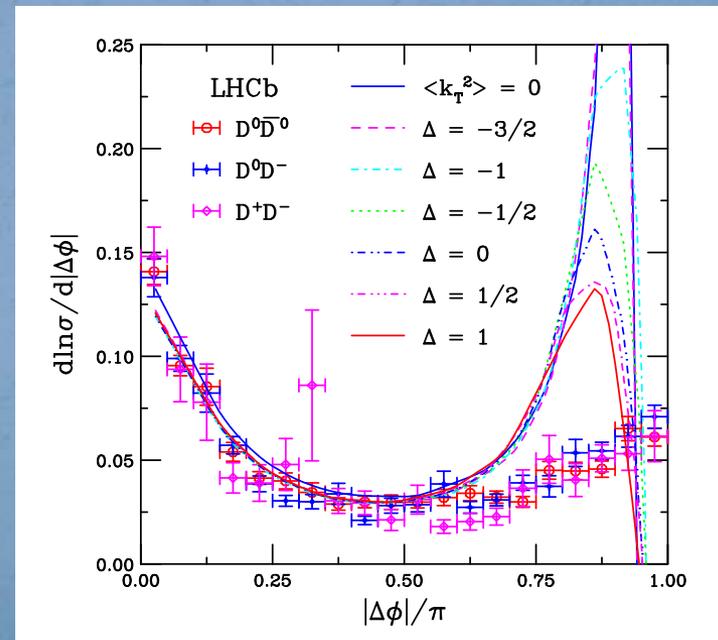
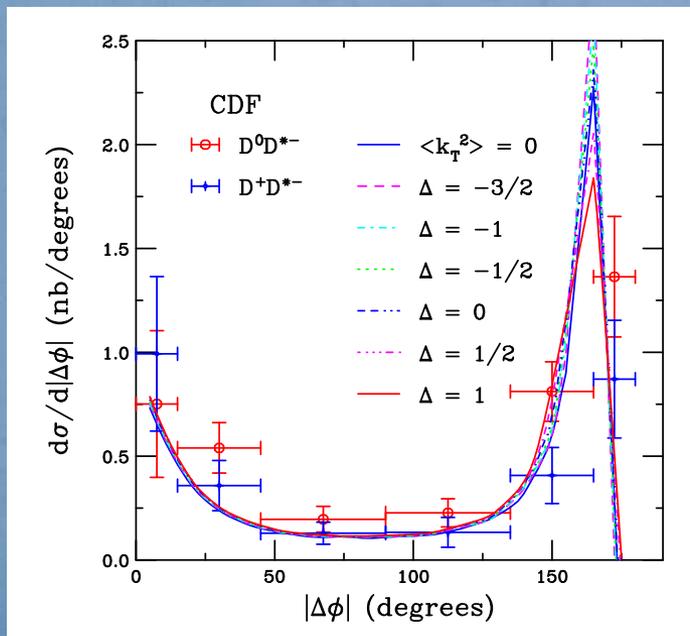
Similar trends seen for bottom as for charm but there is still some effectively negligible but still visible dependence on Δ at small ϕ , Likely because $p_T \sim 2m_b$ in this case



Charm azimuthal distributions compared to data from CDF and LHCb

With minimum p_T of 5.5 GeV for D^0 , D^{*-} and 7 GeV for D^+ , very small dependence on Δ shown in CDF data

Minimum p_T of 3 GeV for LHCb charm-anticharm shows very modest dependence on Δ , in these cases p_T/m_c smaller, $\sim 2.5 - 4$

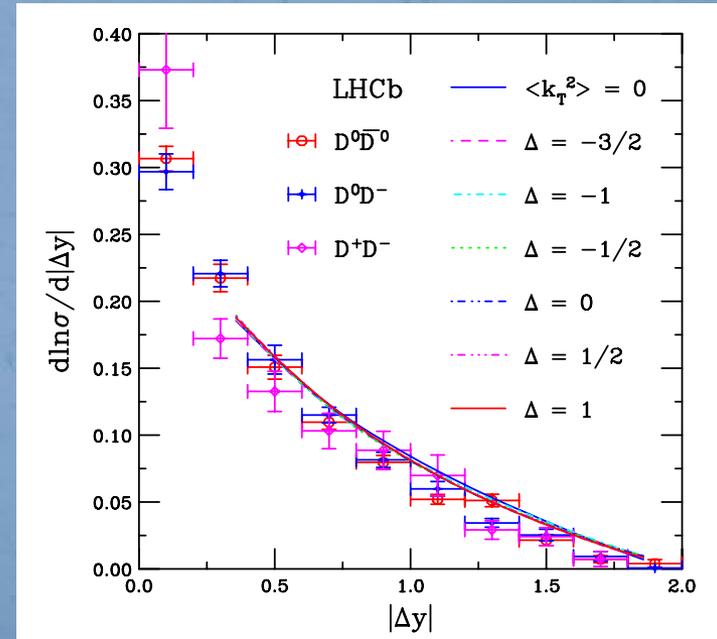
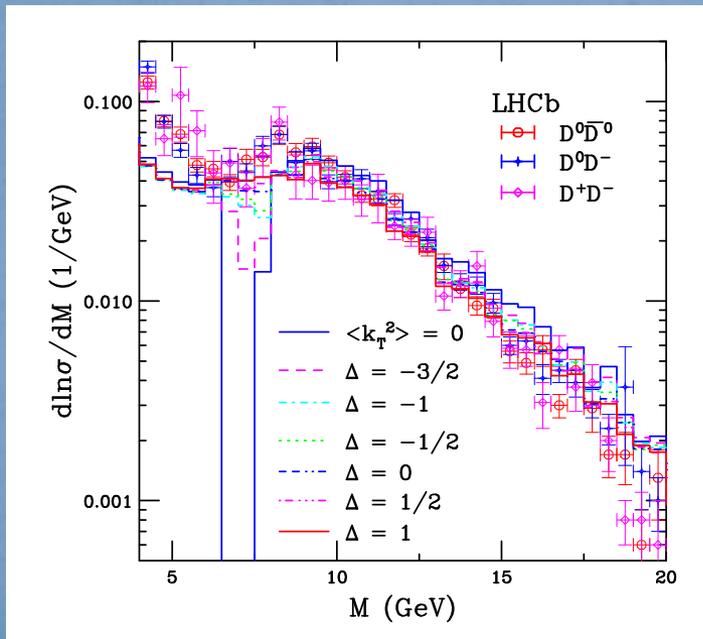


LHCb charm pair mass and Δy distributions

Charm pair mass distributions agree well with data, tend to favor $\Delta = 1$ over $\langle k_T^2 \rangle = 0$, smaller values of Δ

Δy distribution also agrees well

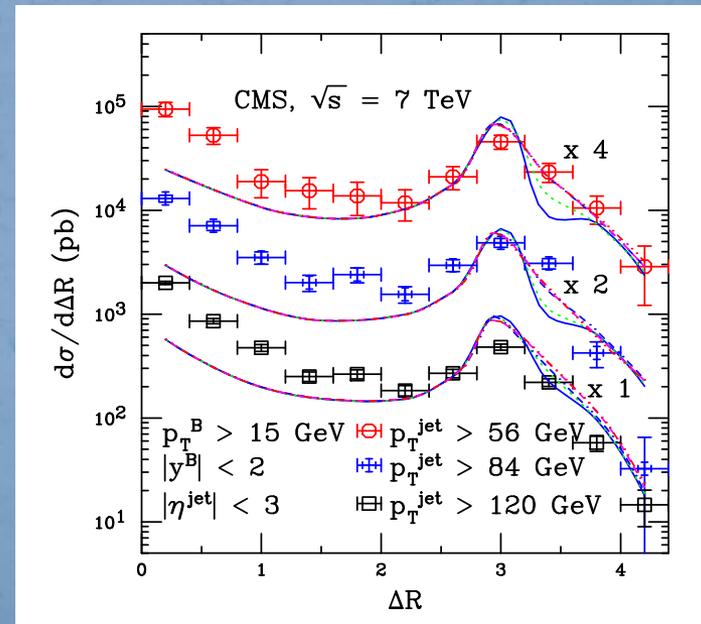
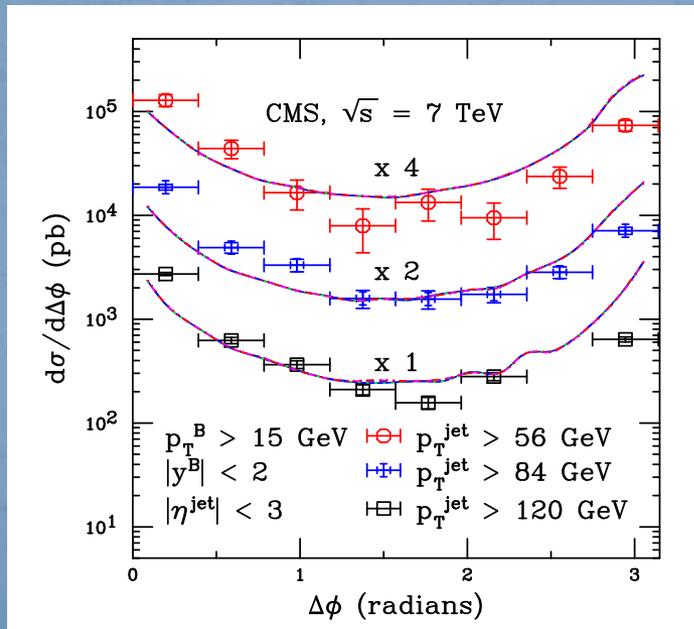
Double charm data consistent with double parton scattering, not from same pair



CMS B—b-jet correlations

$\Delta\phi$ distributions agree well with calculations, ΔR distributions with $\Delta\eta = 1$ are in good agreement with calculations for $\Delta R > 2$

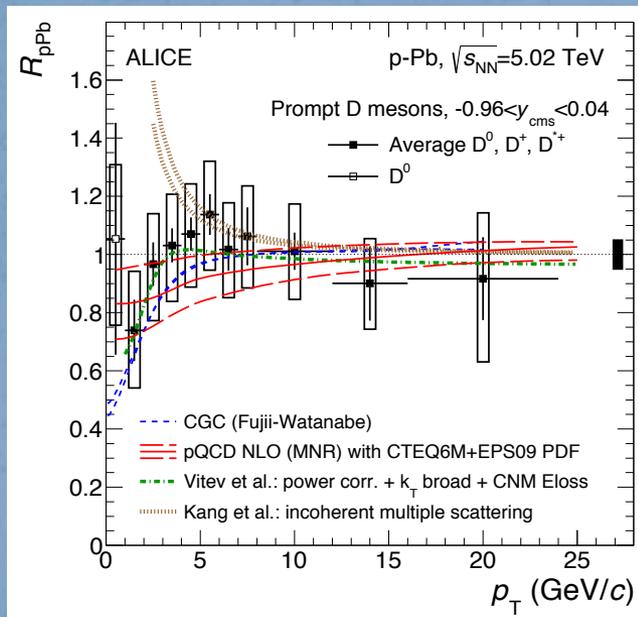
Given that ΔR near zero is supposed to be dominated by "gluon splitting", perhaps discrepancy is due to the $\Delta\eta$ contribution to ΔR



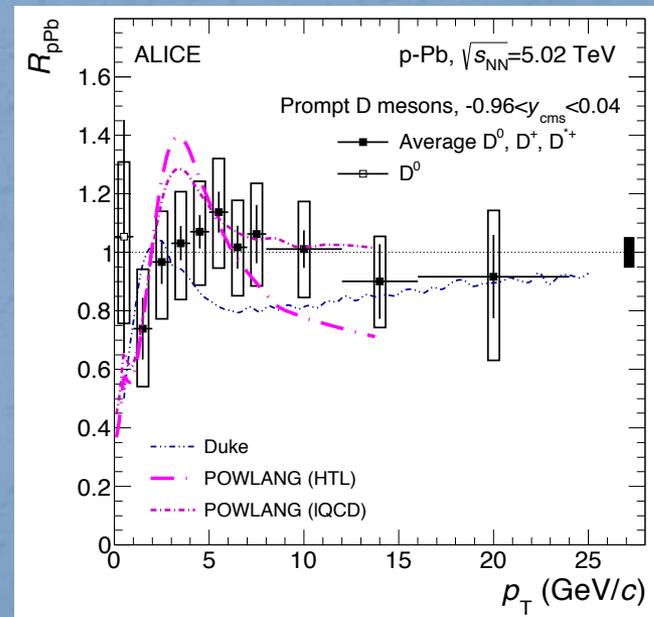
ALICE D mesons in Medium

Most cold matter only calculations do a better job of describing the combined ALICE D meson data than do the hot matter calculations

Cold nuclear matter



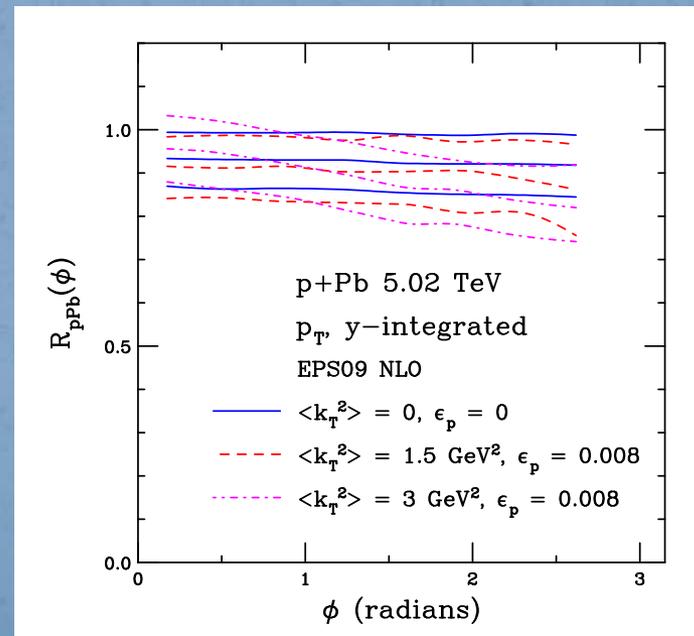
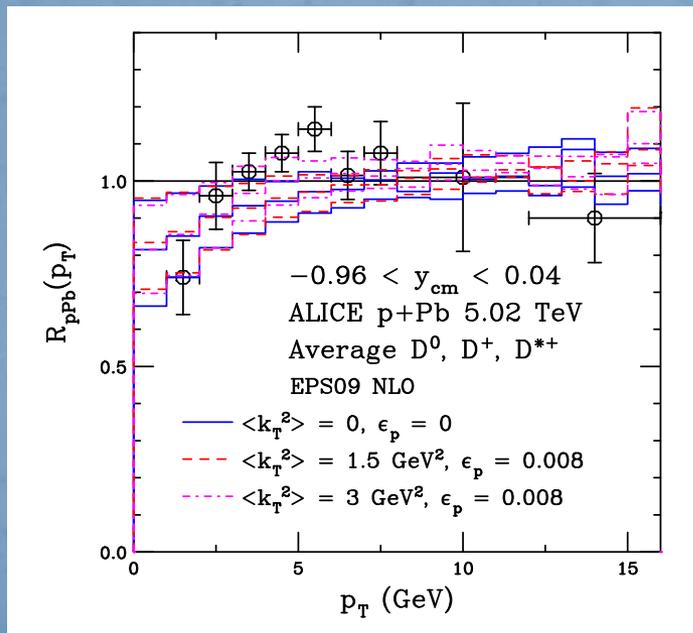
Hot QGP medium



Small effects due to k_T broadening

In cold nuclear matter, R_{pPb} does not change significantly unless broadening is increased in the nucleus but effect is still small

Azimuthal R_{pPb} is effectively flat unless broadening larger in nuclear matter



Summary

- Adding k_T broadening with suitably modified fragmentation to HVQMNR gives good agreement with FONLL and single inclusive p_T data
- Good agreement found with p+p data on azimuthal correlations and other pair data
- In cold nuclear matter, R_{pPb} agrees with data in all cases: range is broad and data do not distinguish but little effect seen in azimuthal distributions