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.
- A good p+p baseline calculation is needed to understand A+A

Single Inclusive Production

Single inclusive (only!, no pairs, no correlations) calculation of heavy flavor quark, hadron and semileptonic decay distribution calculated in Fixed Order Next-to-Leading Log (FONLL) approach (Cacciari and Nason, applied to RHIC w/RV)

Schematically:

$$E\frac{d^3\sigma(e)}{d^3p} = E_Q\frac{d^3\sigma(Q)}{d^3p_Q} \otimes D(Q \to H_Q) \otimes f(H_Q \to e)$$

Fragmentation into heavy flavor hadrons described by FONLL-appropriate fragmentation functions, $D(Q \rightarrow H_Q)$, extracted from e^+e^-

Full FONLL distribution includes resummed terms (RS) order $\alpha_s(\log(p_T/m))^k$ (leading log (LL)) and $\alpha_s^2(\log(p_T/m))^k$ (NLL) to improve $p_T >> m$ region

Subtracts fixed-order (FO) terms, retains only logarithmic mass dependence, “massless” limit of FO calculation (FOM0), employs same renormalization scheme, interpolates between FO and RS regions for same number of light flavors with $G(m,p_T)$

$$\text{FONLL} = \text{FO} + (\text{RS} - \text{FOM0})\, G(m,p_T)$$

Cross section is smaller than at fixed order ($n_f = 3$) since heavy flavor is treated as light ($n_f = 4$ for charm, not 3) so α_s smaller in this approach

Theoretical Uncertainties

Theoretical uncertainty can be large, especially for charm, two approaches:

FONLL standard fiducial uncertainty, fixed range of mass and scales, ecompasses true value:

- Fixed central scales: $\mu_F = \mu_R = m$, vary mass;
  $1.3 < m_c < 1.7$ GeV, $4.5 < m_b < 5$ GeV
- For central masses, $m_c = 1.5$ GeV and $m_b = 4.75$ GeV, independent variation of scales within factor of two:
  $(\mu_F/m, \mu_R/m) = (1,1), (2,2), (0.5,0.5), (1,0.5), (0.5,1), (1,2), (2,1)$

Fit scales to charm and bottom total cross section data to reduce uncertainty:

- Take lattice value for m_c, 1.27 GeV, and 1S value for m_b, 4.65 GeV with 3σ mass uncertainty
- Independent variation of scales within 1σ of central result:
  $(\mu_F/m,\mu_R/m) = (C,C), (H,H), (L,L), (C,L), (L,C), (C,H), (H,C)$
  where C = central value of fit, $L = C - 1\sigma$, $H = C + 1\sigma$

Upper and lower limits on cross section comes from mass and scale variation relative to the central cross section added in quadrature

Fitting charm cross section reduces theoretical uncertainties

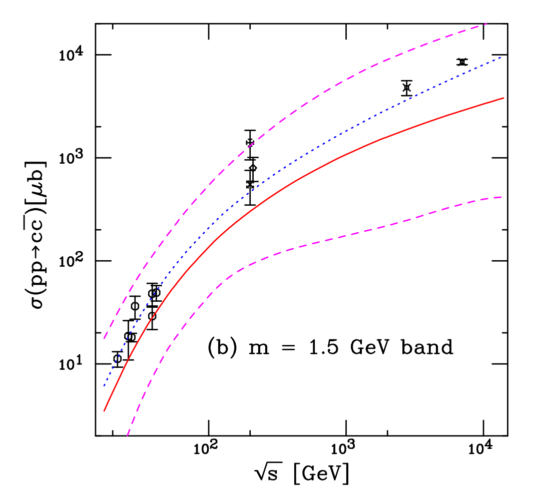
Fit subset of total charm cross section data to obtain best fit values of μ_F/m, μ_R/m

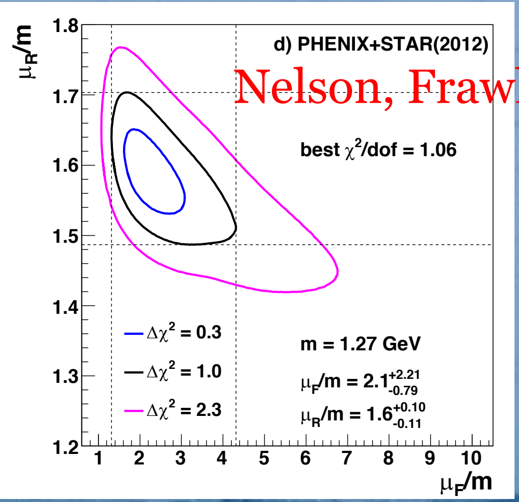
$\Delta\chi^2 = 1$ gives uncertainty on scale parameters, $\Delta\chi^2 = 2.3$ gives one standard deviation on total cross section

LHC results agree well with fit results although not included

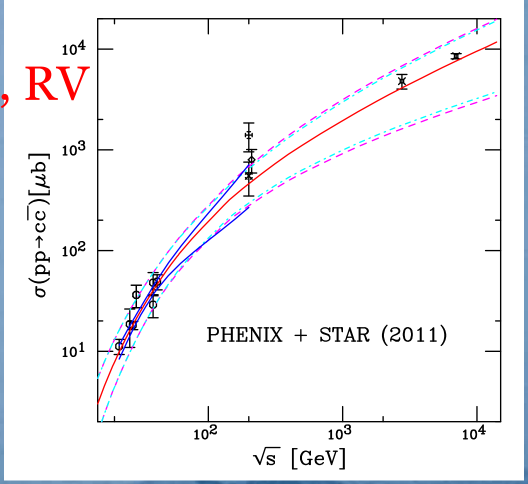
No full NNLO cross section, likely to result in large corrections

Uncertainties may impact predictions for hot matter





Nelson, Frawley, RV



Exclusive heavy flavor pair production

Exclusive production needed to calculate correlations, single inclusive calculations like FONLL and ZM-GFN can't be used to study pair correlations

POWHEG-hvq (Frixione, Nason and Ridolfi):

- Positive weight Monte Carlo
- Leading log resummation
- Can be run either standalone for NLO events or interfaced with shower Monte Carlo like HERWIG or PYTHIA for hadronization and decay

HVQMNR (Mangano, Nason, Ridolfi):

- Negative weight Monte Carlo
- Incomplete cancelation of divergences for heavy quark pairs at low p_T
- No resummed terms
- Peterson function is default fragmentation scheme

Calculations of azimuthal distributions in this work use HVQMNR

Comparing FONLL and HVQMNR single inclusive distributions

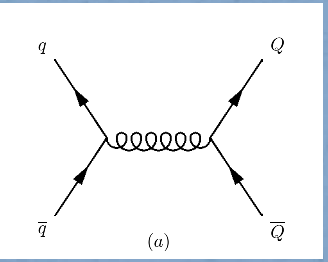
- Use HVQMNR code to look at pair results; start with single quark p_T distribution and compare to FONLL
- Compare effect of fragmentation functions, k_T smearing to bare quark result
- Low p_T region emphasized to highlight small differences; fragmentation effect larger than k_T smearing

Aside on LO event generators

Leading order pair production

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

quark-antiquark



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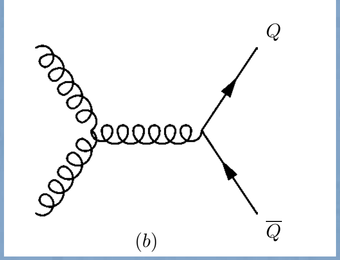

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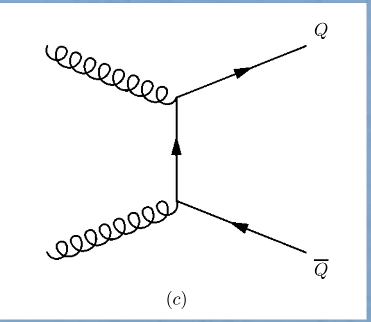
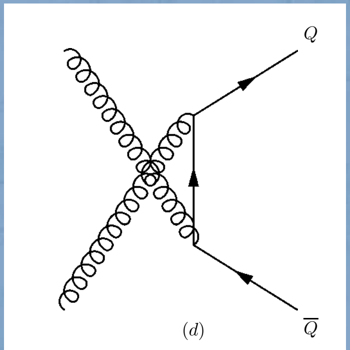


(c)



(d)

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

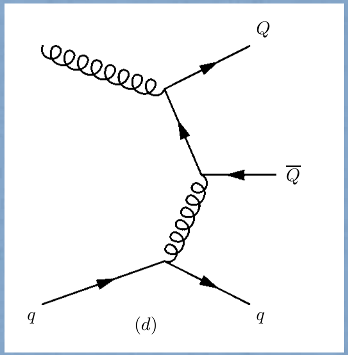
LO event generators calculate different diagrams without proper weights and will not lead to a correct cross section

Some example diagrams

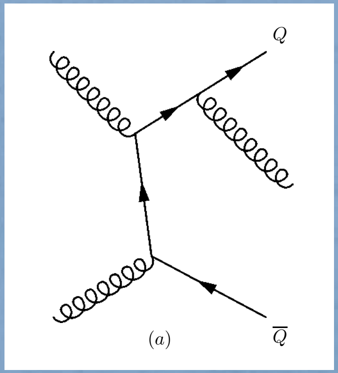
Only some diagrams shown, real and virtual corrections included

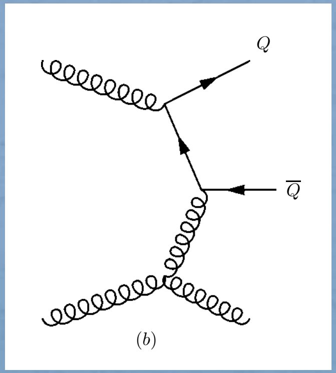
Different diagrams can lead to different azimuthal correlation but no new mechanism

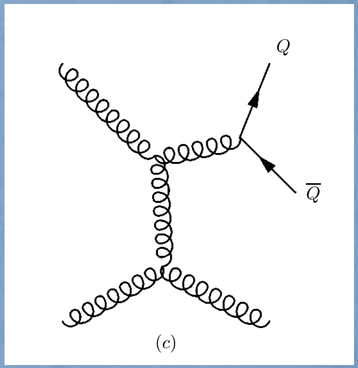
quark-gluon,
new at NLO



gluon-gluon







Real gluon
emission

"flavor excitation"

"gluon splitting"

Fragmentation & k_T broadening

Fragmentation in FONLL and HVQMNR

- FONLL uses different fragmetations 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

$$D(z) = z(1-z)^e$$

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

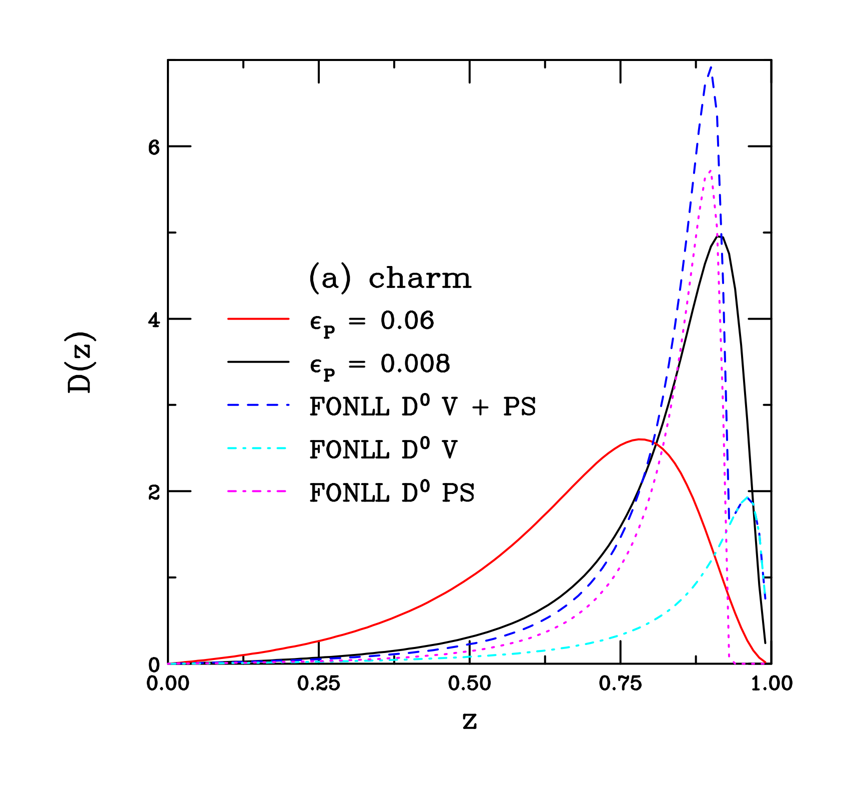
- HVQMNR uses Peterson function for fragmentation with variable parameter, ε_P

$$D(z) = z(1-z)^2/[(1-z)^2 + z\varepsilon_P]^2$$

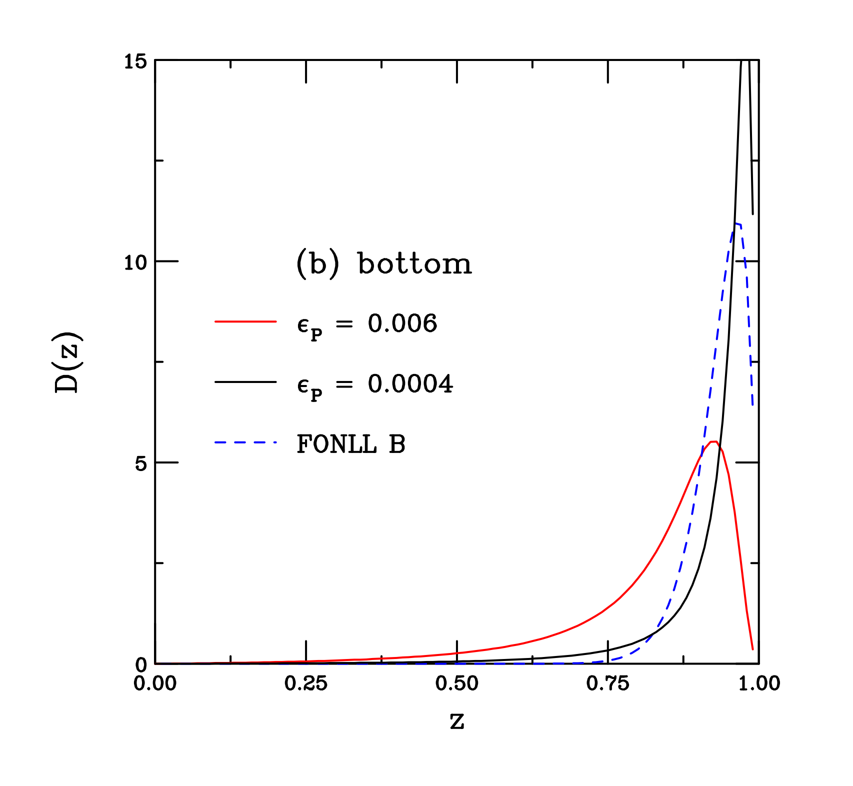
- Standard values for ε_P, 0.06 for c and 0.006 for b are too large for hadroproduction, $\langle z \rangle = 0.67$ & 0.82 respectively
- To match the FONLL result including k_T broadening, ε_P has to be reduced to 0.008 and 0.0004 for c and b respectively, giving $\langle z \rangle =$ 0.822 and 0.930

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:

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

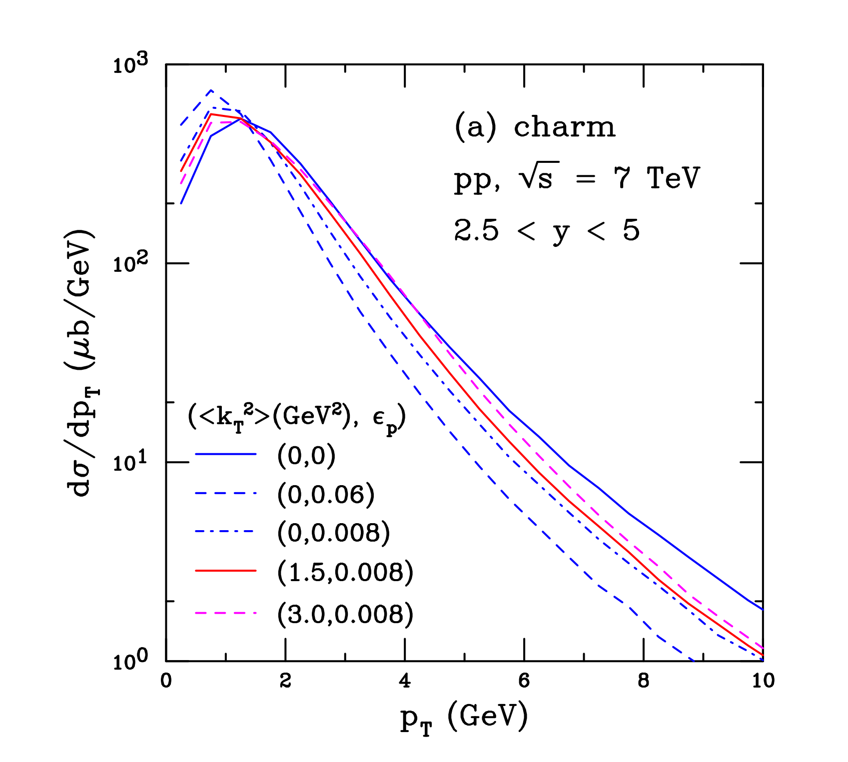
- Gaussian factors are applied to each heavy quark in the final state in HVQMNR, should be equivalent to application to initial-state partons as long as $\langle k_T^2 \rangle \sim 2\text{-}3$ GeV^2
- Energy dependence assumed:

$$k_T^2 = 1 + (1/n) \ln(\sqrt{s}/ (20 \text{ GeV})) \ \text{GeV}^2$$

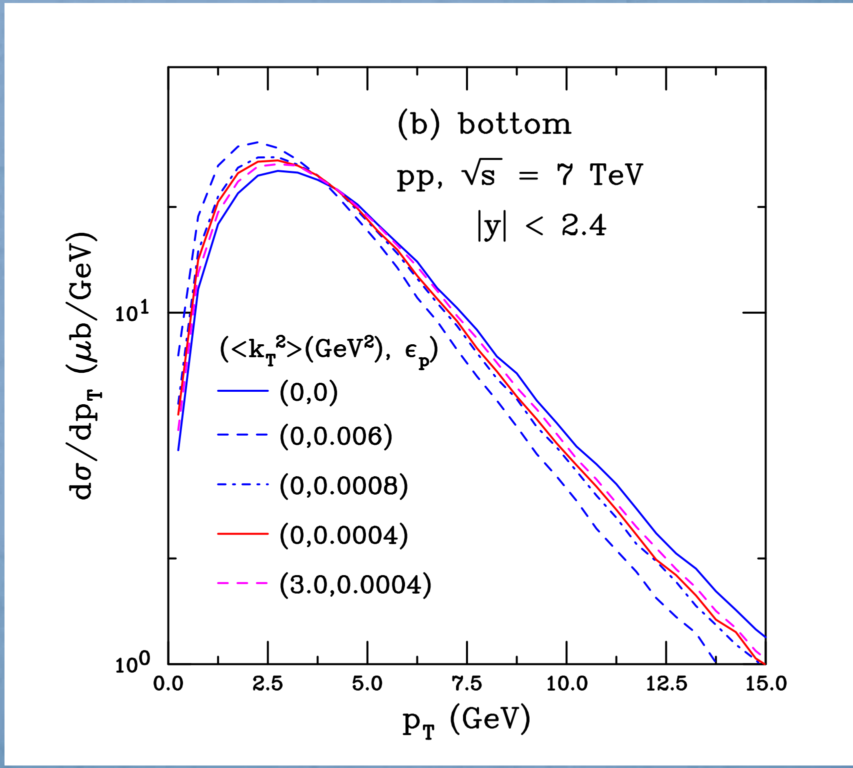
- We take n = 12 for c and 3 for b (from J/ψ and Υ respectively)

Effects of fragmentation and k_T broadening on single inclusive distributions

Charm



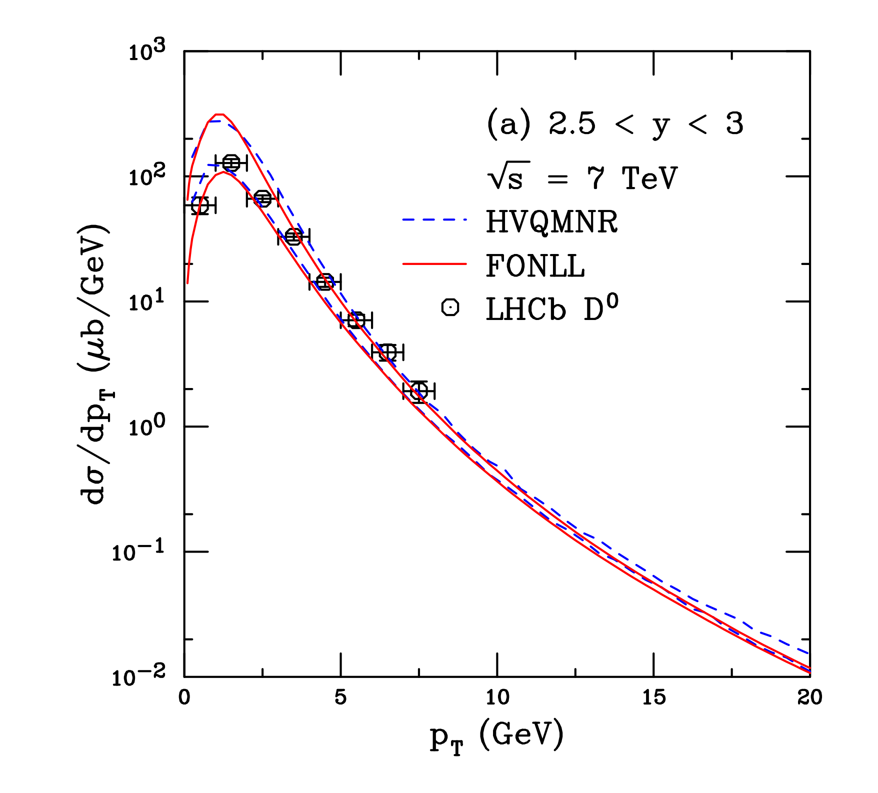
Bottom

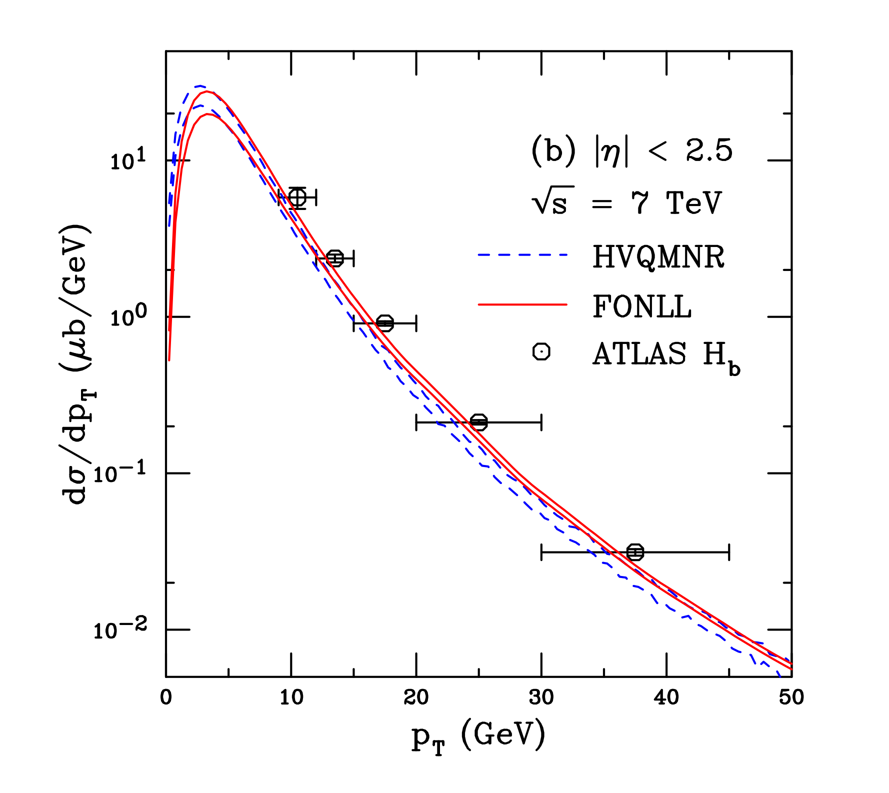


Uncertainty bands on single heavy flavor distributions: FONLL vs. HQMNR

D⁰ compared to LHCb

B mesons from ATLAS





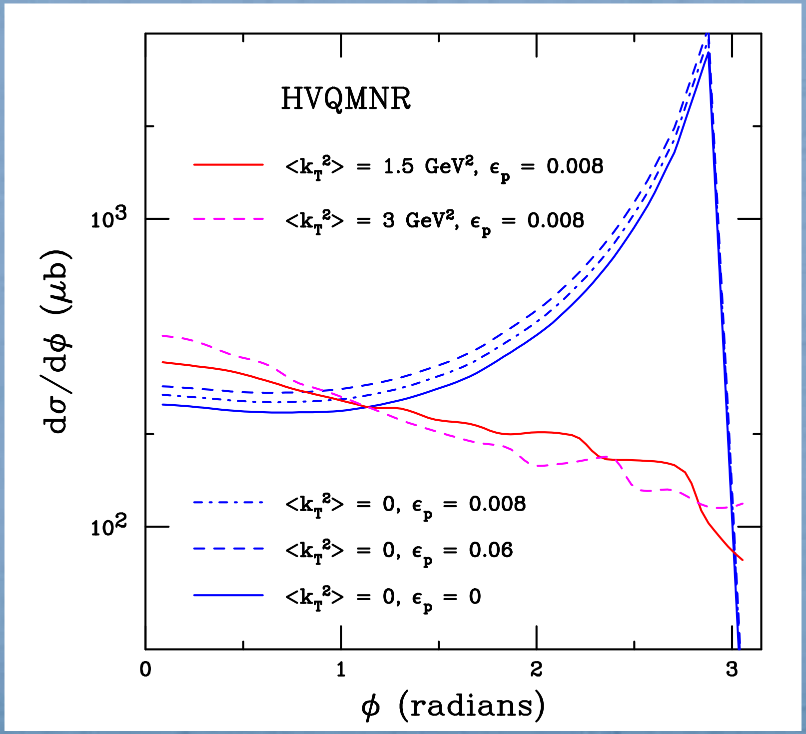
Azimuthal angle correlations

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→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



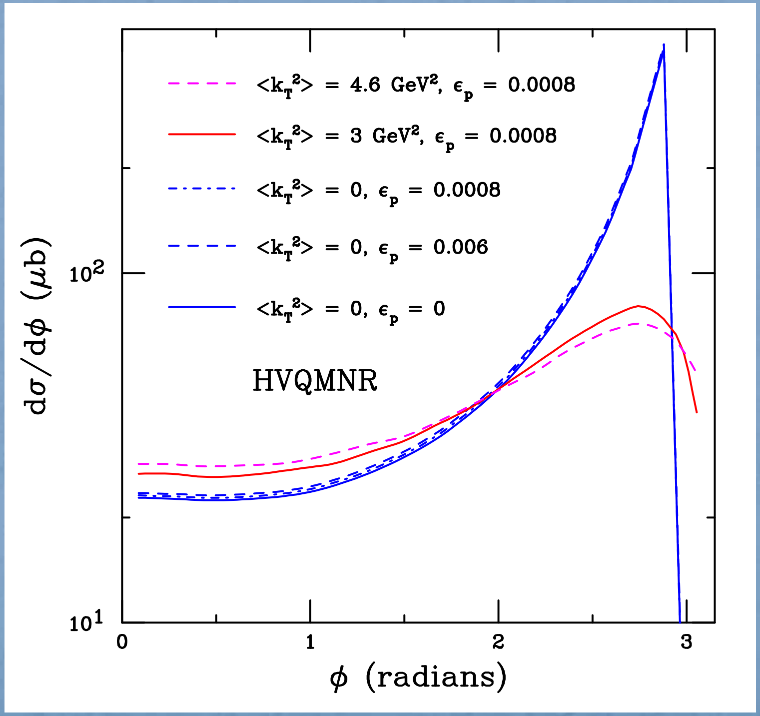
LHCb acceptance, $2.5 < y < 5$

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→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

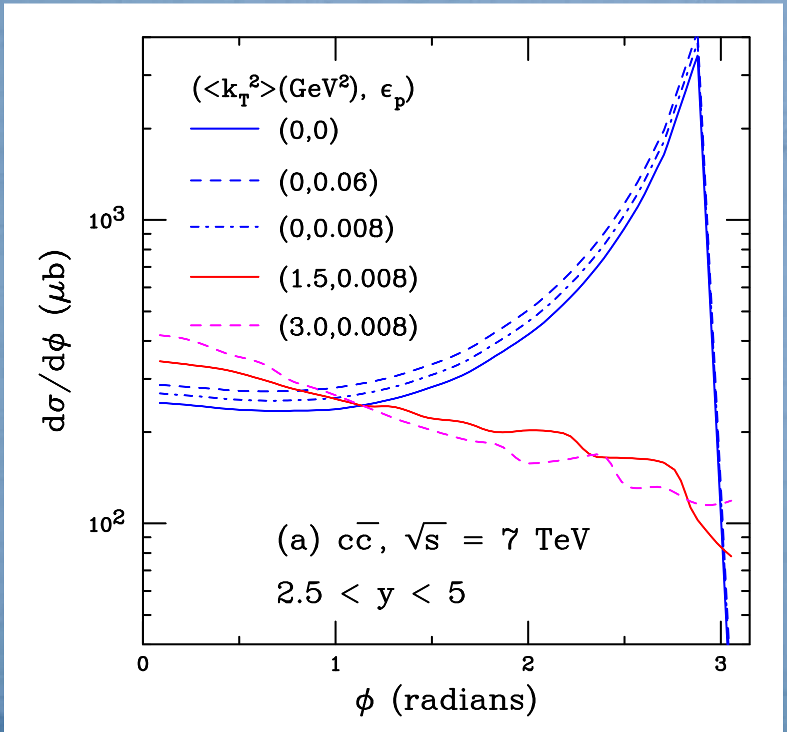


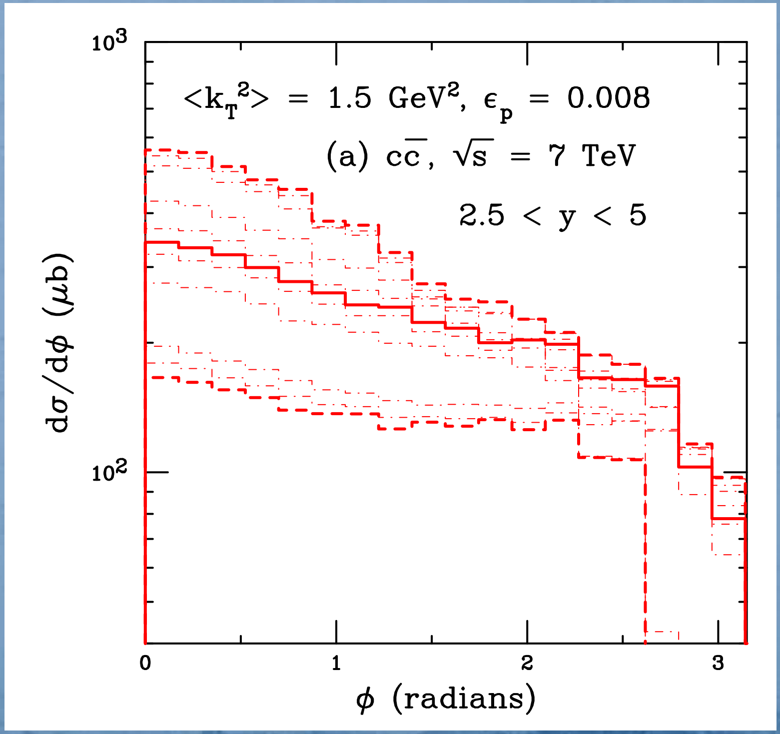
Azimuthal correlation dependence on k_T and ε_P: charm

Fragmentation has small but non-negligible effect on ϕ distribution; large ε_P increases $d\sigma/d\phi$ at angles near zero

k_T broadening has significant effect on distribution at low p_T, no back-to-back peak, only at zero degrees

Factorization/renormalization scale uncertainty is large but shape essentially fixed, band widest at small angles

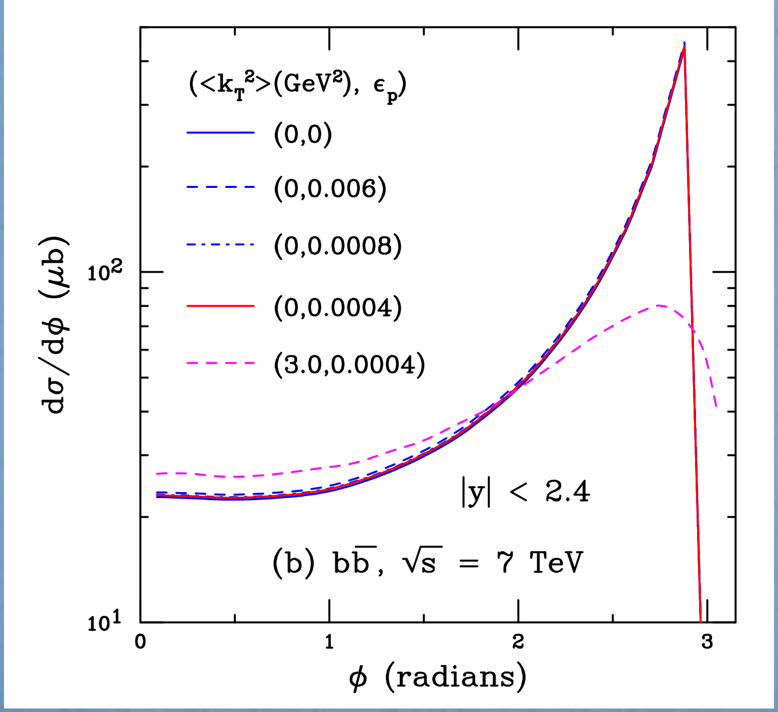


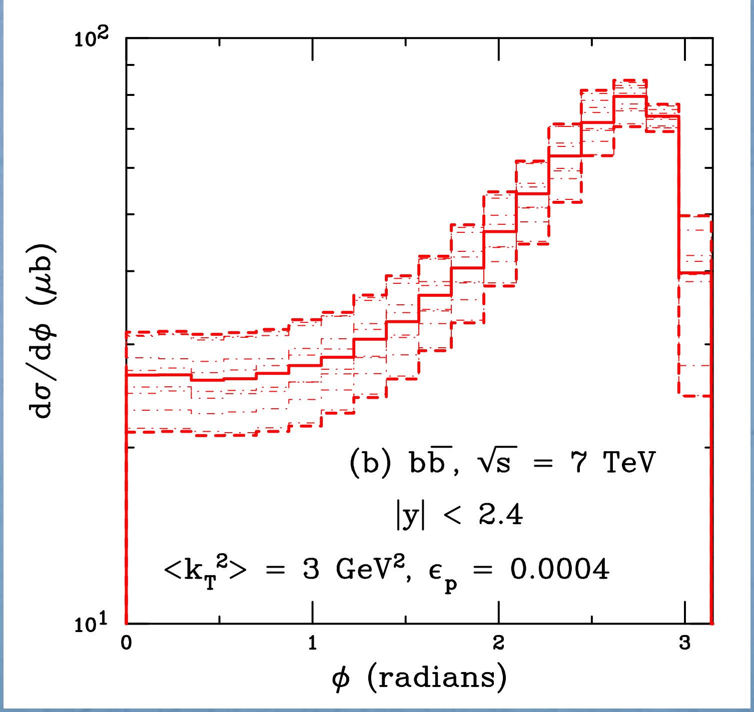


Azimuthal correlation dependence on k_T and ε_P: bottom

Effect of fragmentation on bottom pair $d\sigma/d\phi$ is negligible; k_T broadening changes shape, smears back-to-back peak without eliminating it

Factorization/renormalization scale uncertainty does not show any significant change in shape, band is considerably narrower than for charm pairs





Charm azimuthal correlations with p_T cuts

Results are shown for different p_T cuts on the c quarks in correlation for LHCb acceptance: 2.5 < y < 5, correlation changes from flat to peaked at 0 with higher p_T

Peak develops at $\phi = 0$ if both quarks moving same direction, means light parton balances the pair; the higher the quark p_T, the stronger the 0 degree peak

Demonstrates relative importance of different diagrams even if mechanism fixed

Top to bottom:

$p_T < 10$ GeV

$p_T > 10$ GeV

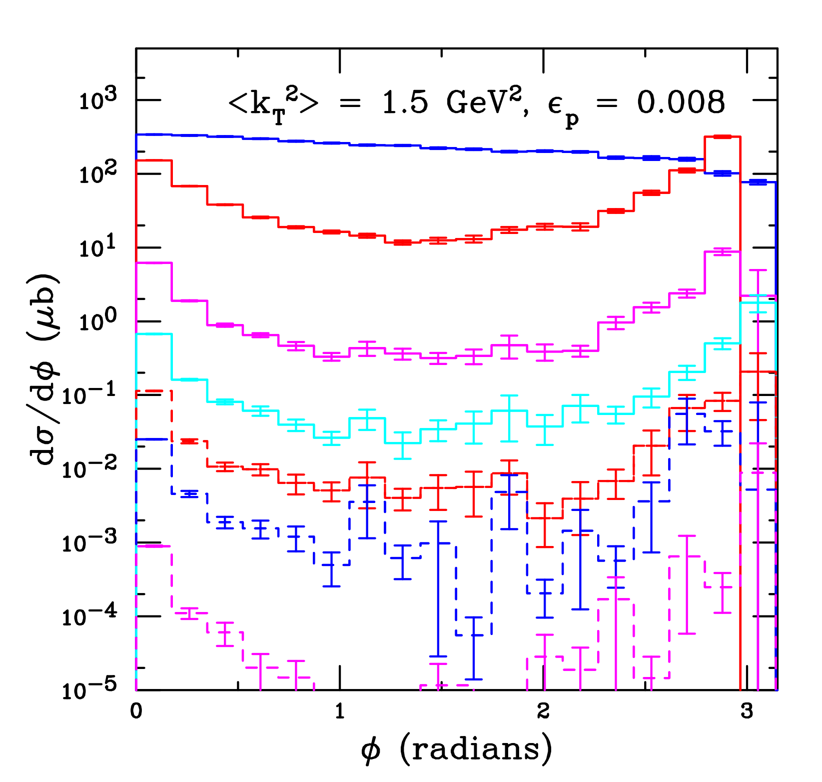
$p_T > 20$ GeV

$p_T > 30$ GeV

$p_T > 40$ GeV

$p_T > 50$ GeV

$p_T > 75$ GeV



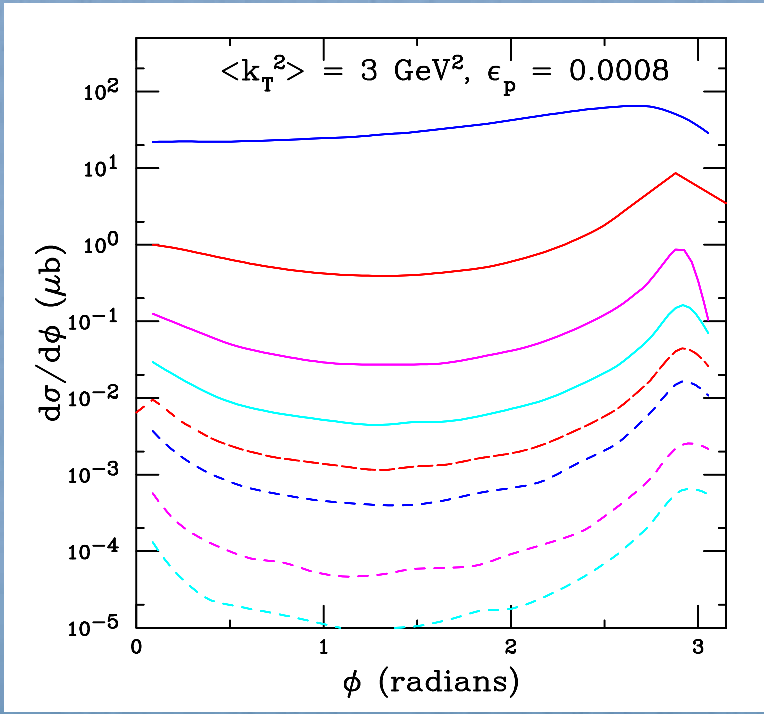
Steeply falling c quark p_T distribution gives large fluctuations for higher p_T cuts; N.B. all distributions but $p_T < 10$ GeV multiplied by 1000 to appear on plot; Peak at 0 degrees gets stronger with higher p_T; Uncertainties added to plot illustrates poor statistics at high p_T

Bottom azimuthal correlations with p_T cuts

Results are shown for different p_T cuts on the b quarks in correlation

Increasing the p_T of the quarks in the pair changes the shape of the azimuthal separation – different p_T cuts explore different diagram topologies

Peak develops at $\phi = 0$ if both quarks moving same direction, means light parton balances the pair; the higher the quark p_T, the stronger the 0 degree peak



Top to bottom:

$p_T < 10$ GeV

$p_T > 10$ GeV

$p_T > 20$ GeV

$p_T > 30$ GeV

$p_T > 40$ GeV

$p_T > 50$ GeV

$p_T > 75$ GeV

$p_T > 100$ GeV

Turn on of k_T effects

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

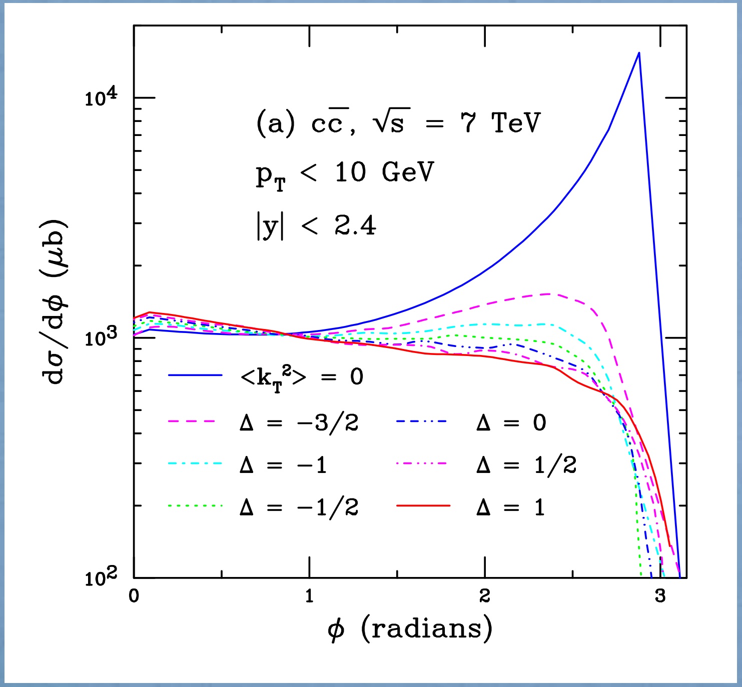
$$\langle k_T^2 \rangle = 1 + (\Delta/n) \ln(\sqrt{s}/ (20 \text{ GeV})) \text{ GeV}^2$$

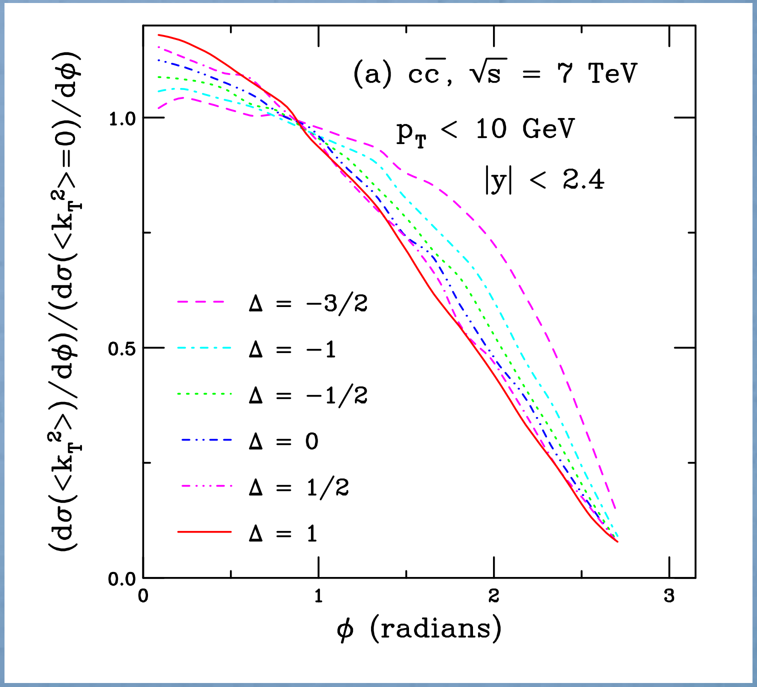
- Δ = -3/2, -1, -1/2, 0, 1/2, 1 for c; -1/2, 0, 1/2, 1 for b (need smaller range for b because $\langle k_T^2 \rangle$ must be positive
- Checked central and forward rapidity regions but results only shown for central – forward is similar enough to make no difference with respect to shape

Charm pairs, $p_T < 10$ GeV

Sharp contrast between $<k_T^2> = 0$ 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 $\phi \sim 1$

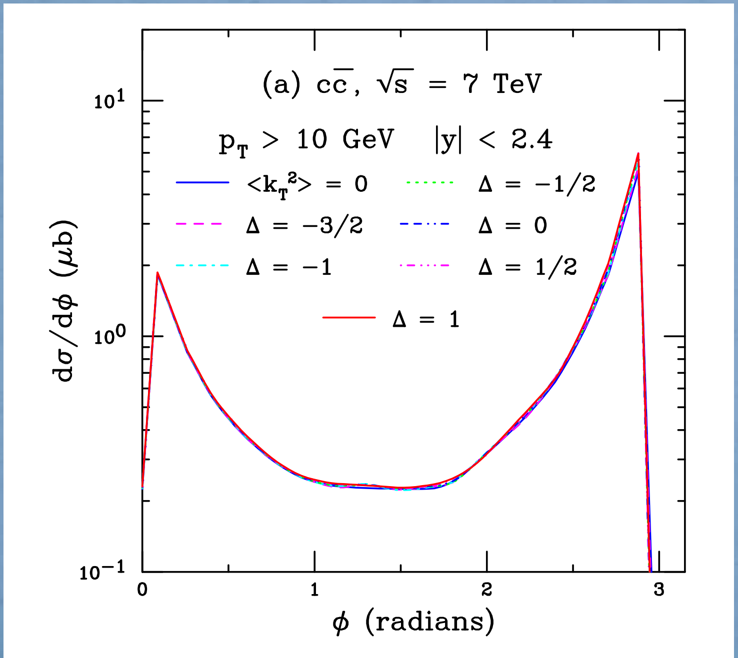


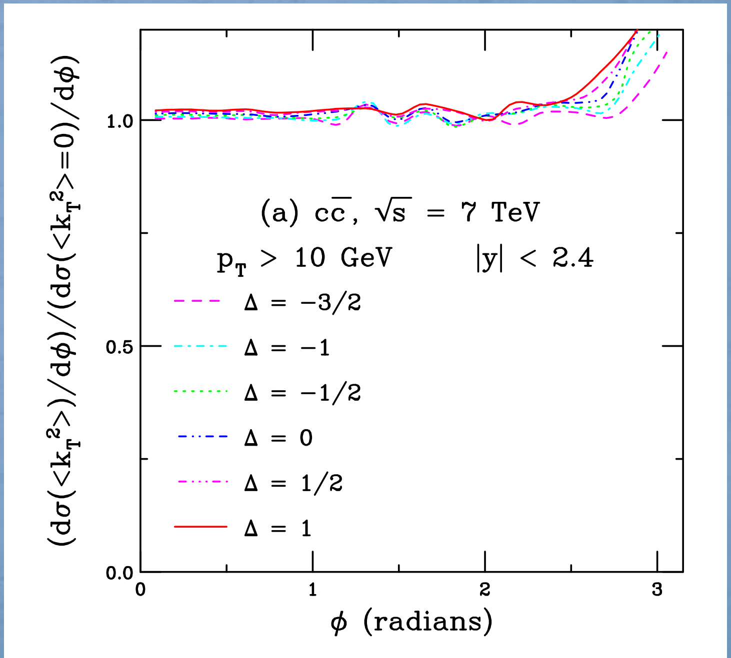


Charm pairs, p_T > 10 GeV

Azimuthal distribution is completely insensitive to value of Δ

Ratio shows some small change for ϕ > 2.5 but only few percent effect because p_T >> m_c already for 10 GeV

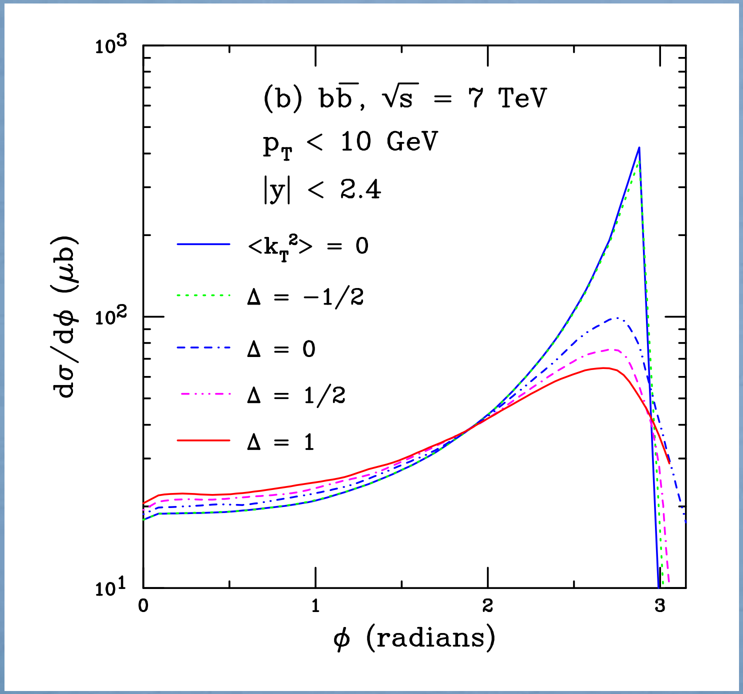


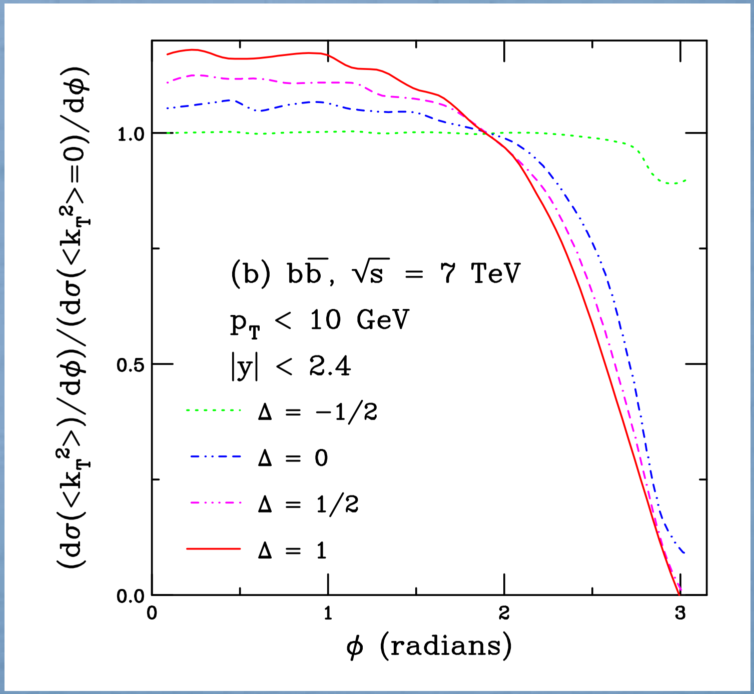


Bottom pairs, p_T < 10 GeV

Distribution in ϕ with Δ = -1/2 is almost identical to that with $<k_T^2>$ 0 since in this case $<k_T^2>$ = 0.002 GeV^2

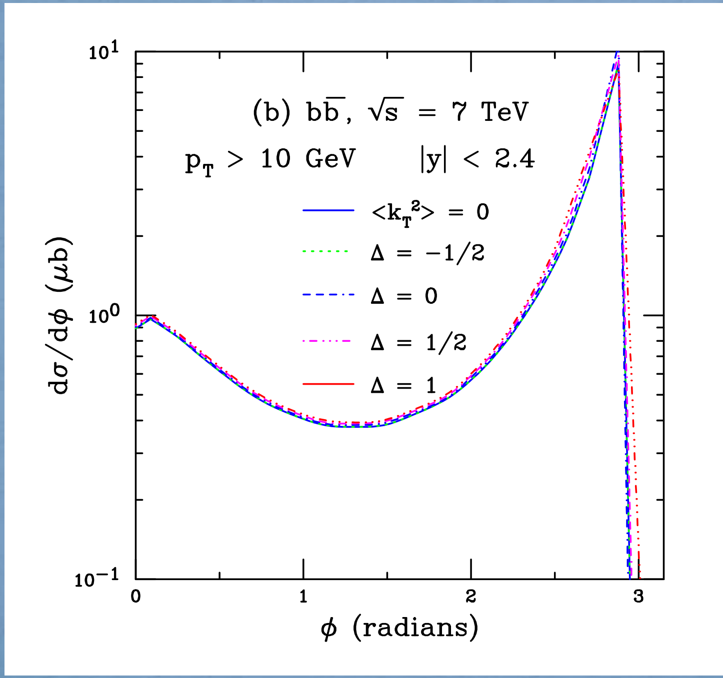
Larger values of Δ show reduce the peak at larger ϕ, ratio pivots now at ϕ ~ 2

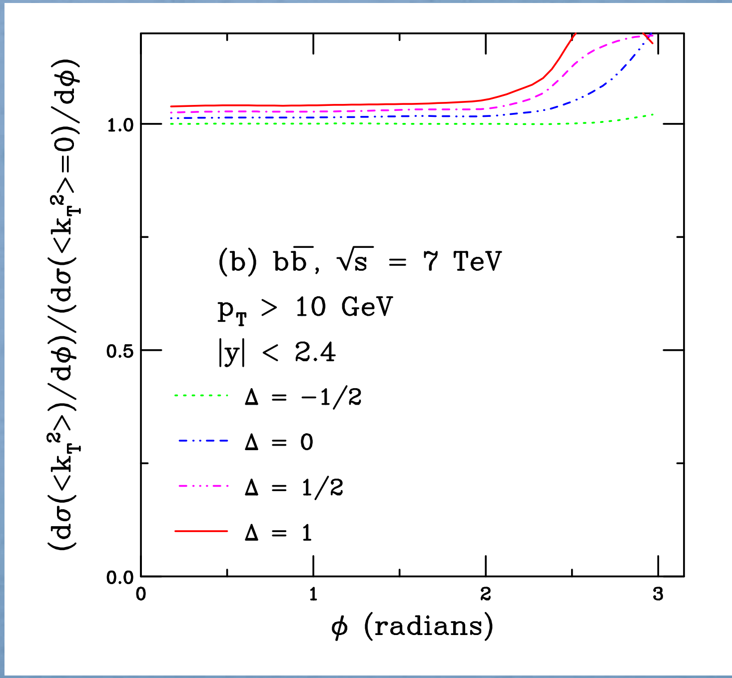




Bottom pairs, $p_T > 10$ GeV

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



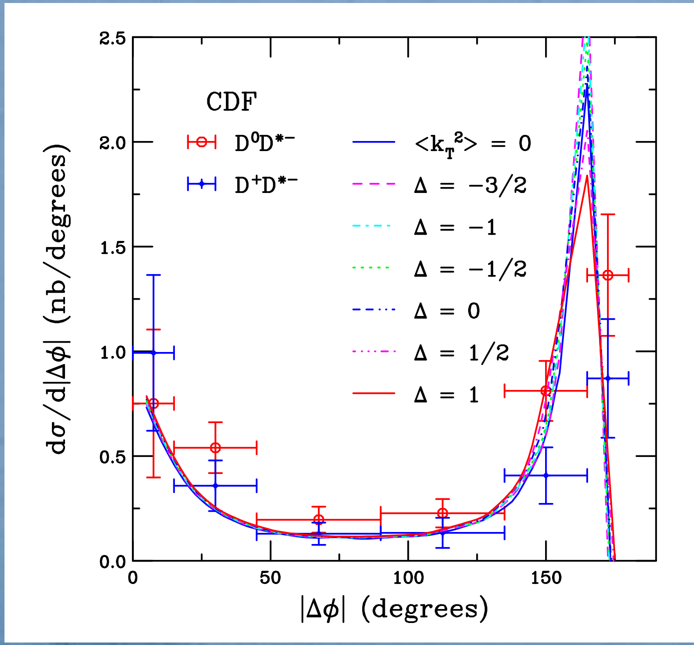


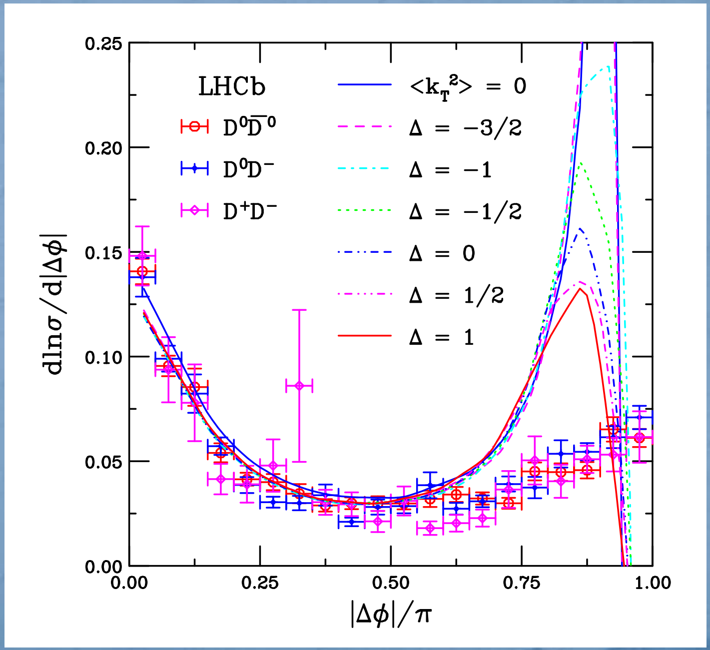
Comparison to Data

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, ~ 2.5 - 4



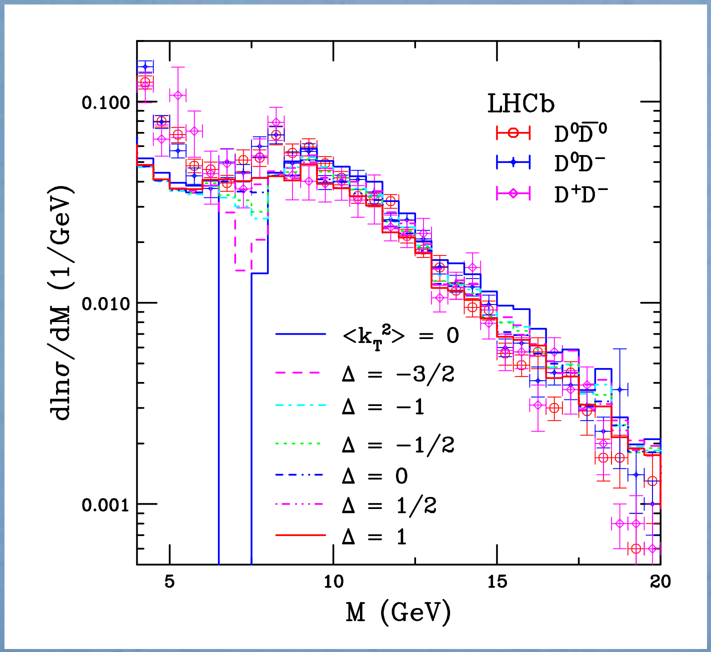


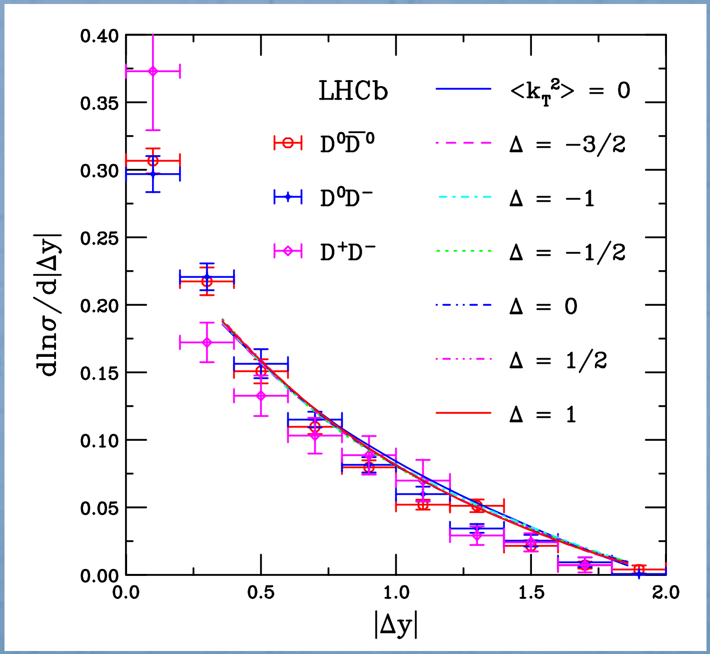
LHCb charm pair mass and Δy distributions

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

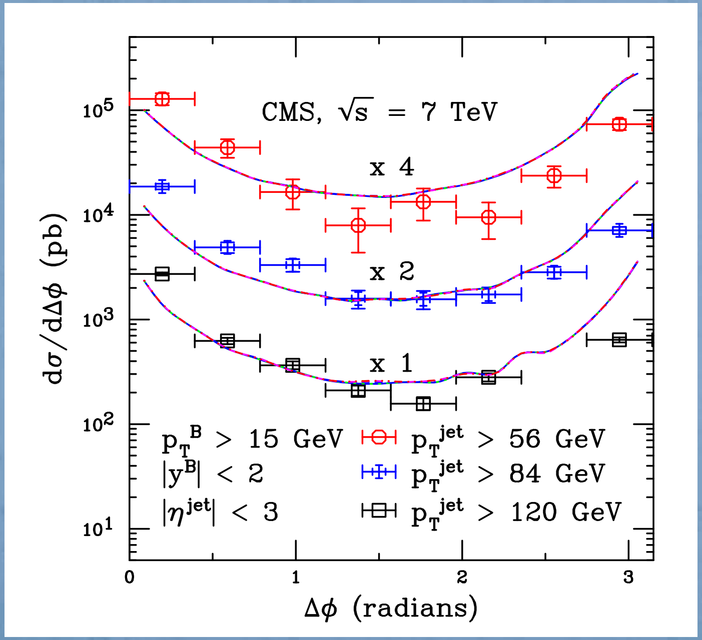


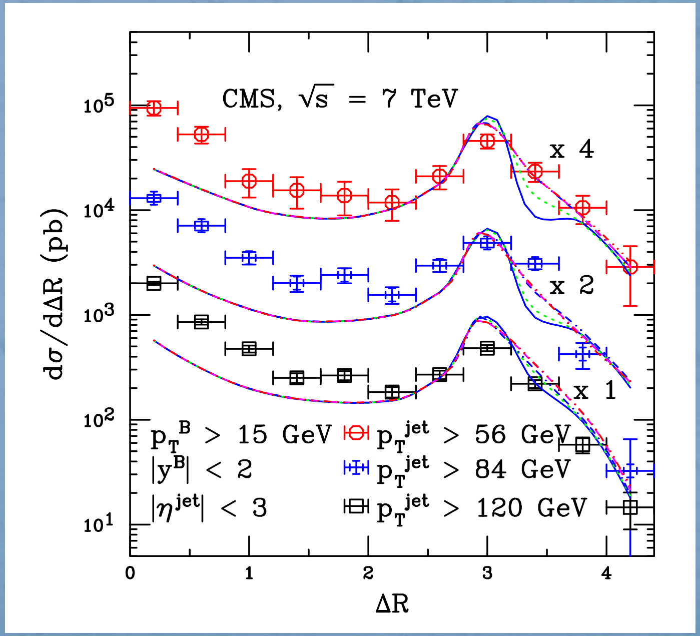


CMS B—b-jet correlations

$\Delta\phi$ distributions agree well with calculations, ΔR distributions with Δ = 1 are in good agreement with calculations for $\Delta R > 2$ $[(\Delta R)^2 = (\Delta\phi)^2 + (\Delta\eta)^2]$

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





LHCb bottom pair correlations

LHCb measured bottom pair correlations through J/ψ pairs at 7 and 8 TeV; four tranverse momentum cuts, $p_T > 2, 3, 5$ and 7 GeV

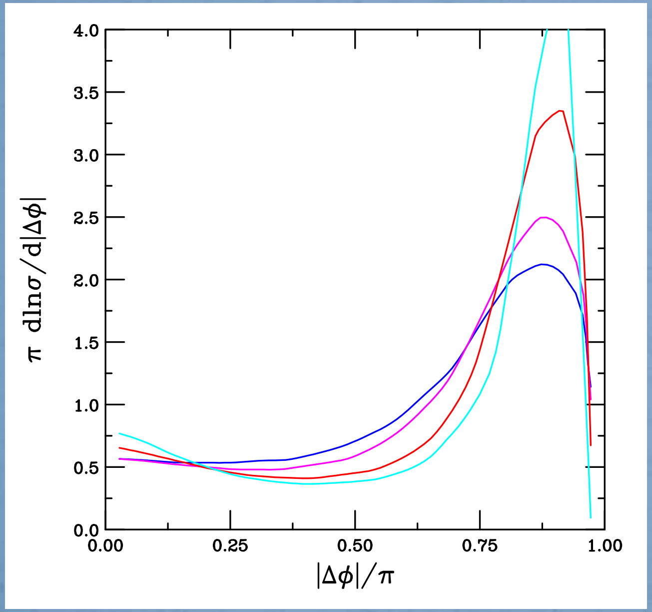
Comparison is not straightforward so no attempt to directly compare with data; calculate bottom pair production, no $B \rightarrow J/\psi$ included, so p_T cuts are on bottom hadrons, however $|\Delta\phi|$ and $|\Delta\eta|$ distributions should be effectively equivalent to those of the correlations between b hadrons (estimated by vector from primary vertex to J/ψ decay vertex)

Results are shown for $\Delta = 1$, for Δy ($\Delta\eta$ for LHCb) and y of pair the result is independent of Δ

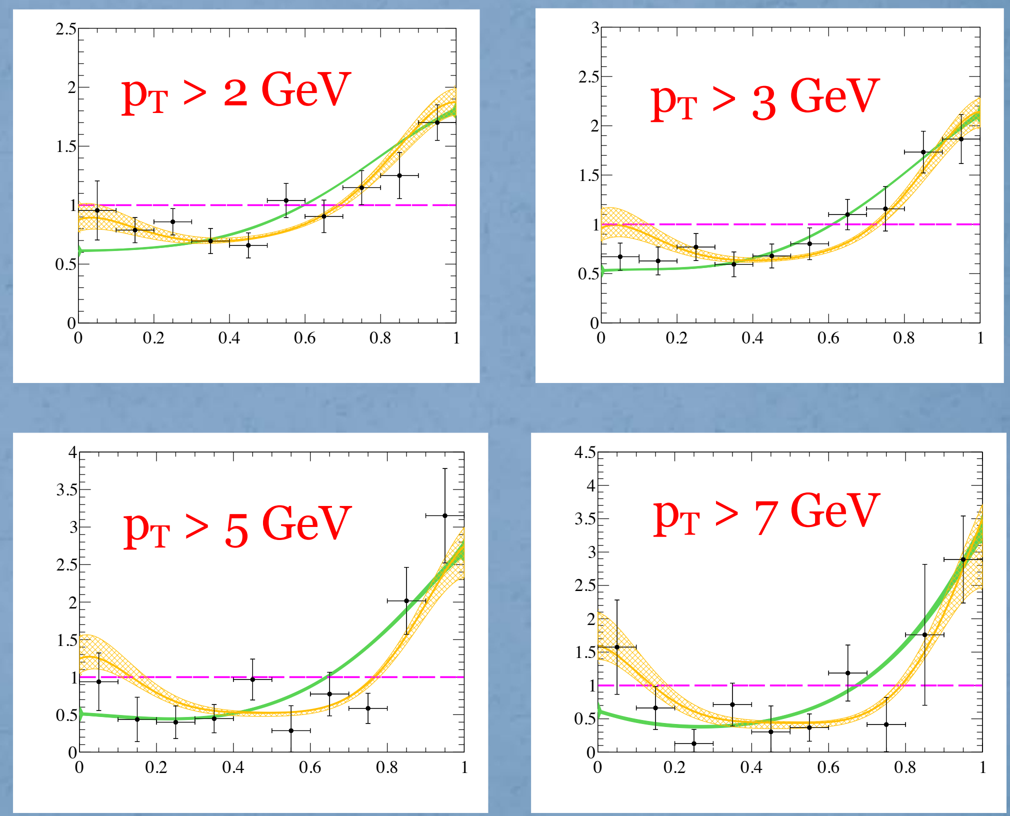
LHCb results compared to POWHEG, PYTHIA and uncorrelated b pairs

Azimuthal correlations

Blue: $p_T > 2$ GeV
Magenta: $p_T > 3$ GeV
Red: $p_T > 5$ GeV
Cyan: $p_T > 7$ GeV



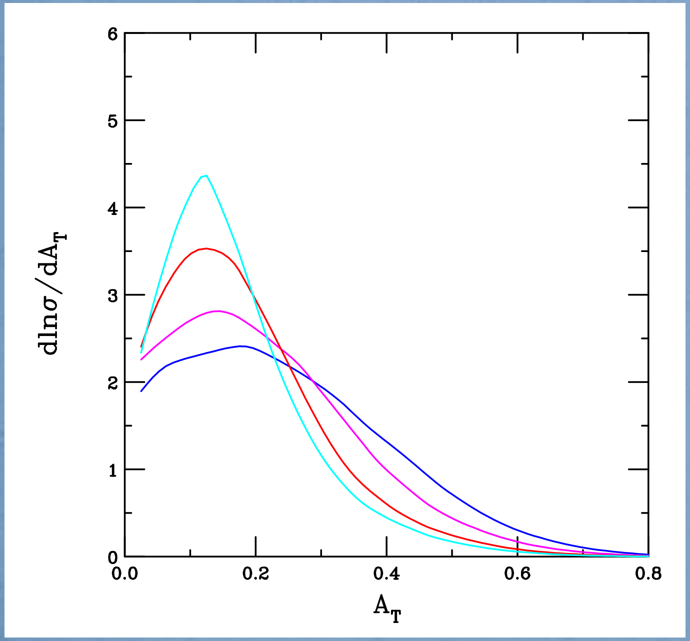
LHCb $\pi/\sigma\ d\sigma/d|\Delta\phi|$ vs $|\Delta\phi|/\pi$



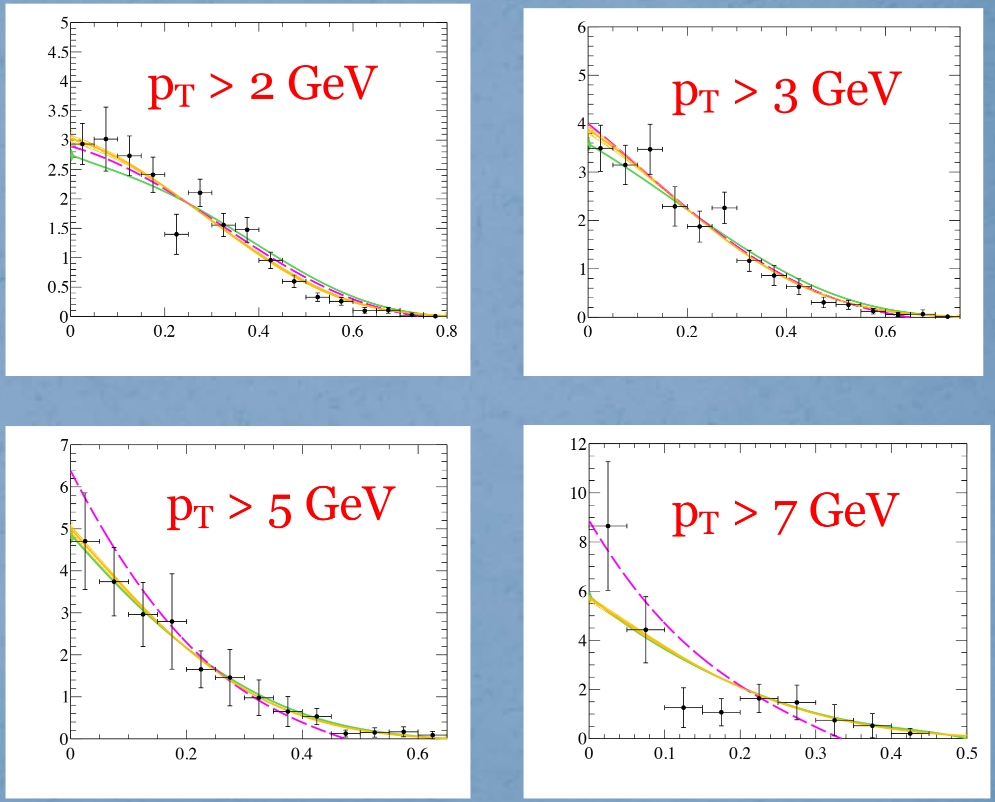
PYTHIA (orange); POWHEG (green); magenta (uncorrelated)

p_T asymmetry ($A_T = |(p_{T1} - p_{T2})/(p_{T1} + p_{T2})|$)

Blue: $p_T > 2$ GeV
Magenta: $p_T > 3$ GeV
Red: $p_T > 5$ GeV
Cyan: $p_T > 7$ GeV



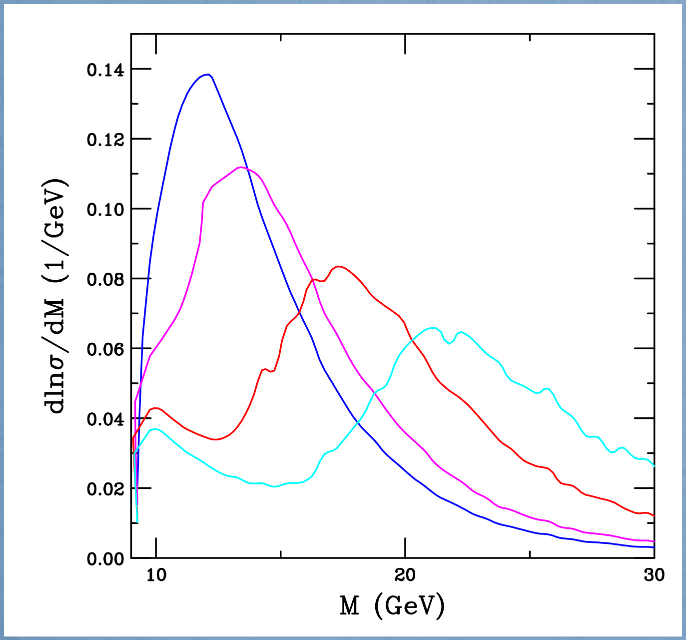
LHCb $1/\sigma\ d\sigma/dA_T$ vs A_T



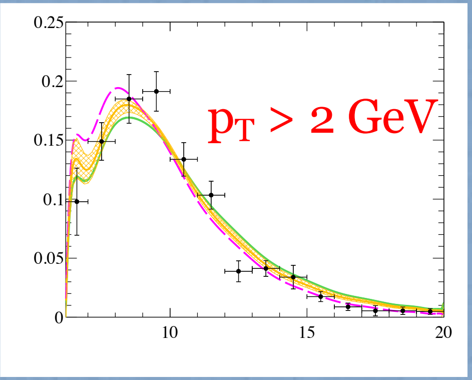
PYTHIA (orange); POWHEG (green); magenta (uncorrelated)

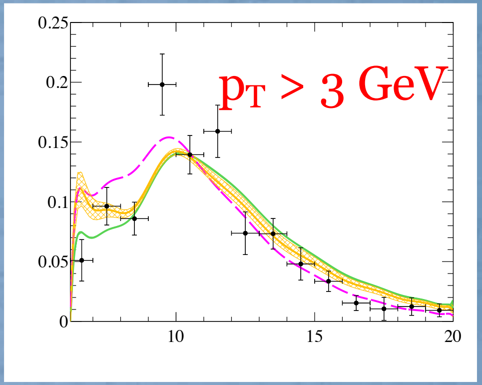
Pair mass

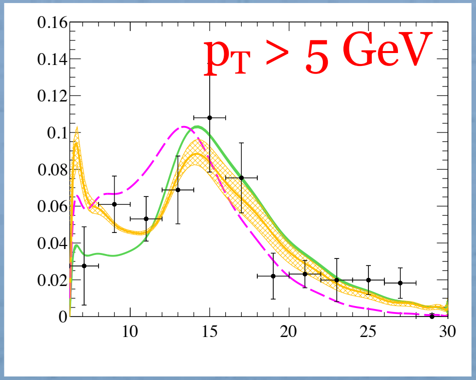
Blue: $p_T > 2$ GeV
Magenta: $p_T > 3$ GeV
Red: $p_T > 5$ GeV
Cyan: $p_T > 7$ GeV

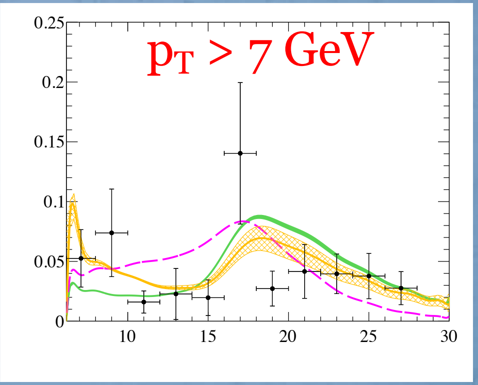


LHCb $1/\sigma\ d\sigma/dM$ vs M (GeV)





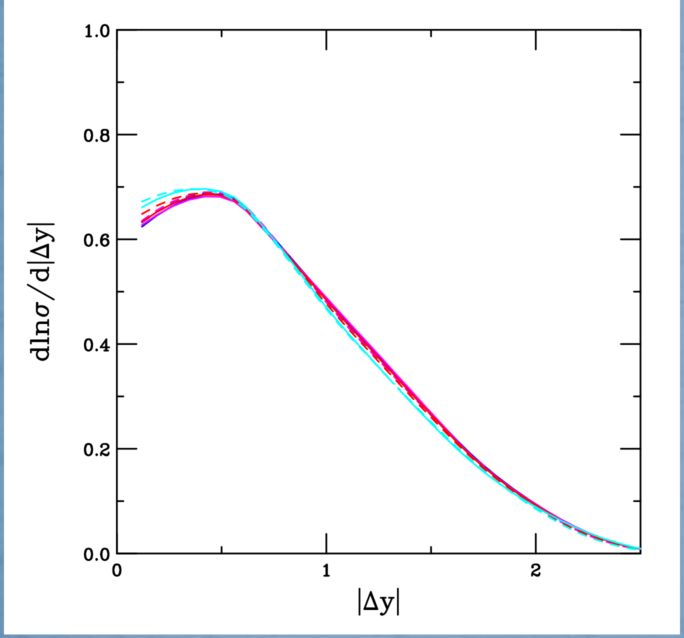




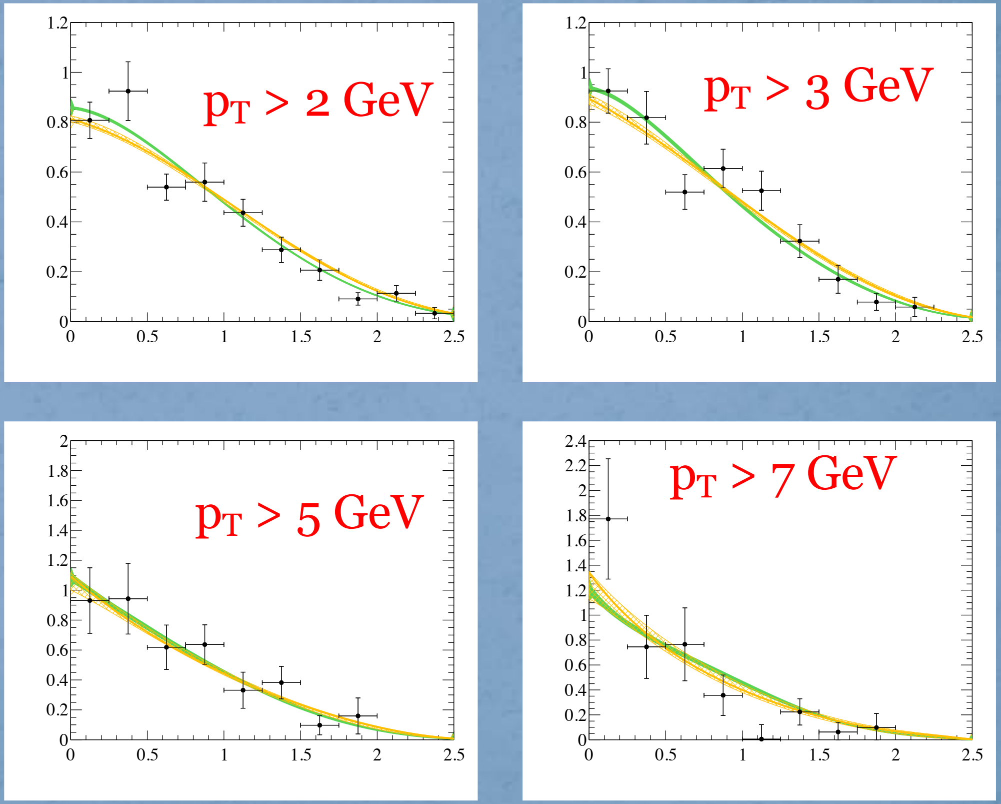
PYTHIA (orange); POWHEG (green); magenta (uncorrelated)

Rapidity difference

Blue: $p_T > 2$ GeV
Magenta: $p_T > 3$ GeV
Red: $p_T > 5$ GeV
Cyan: $p_T > 7$ GeV



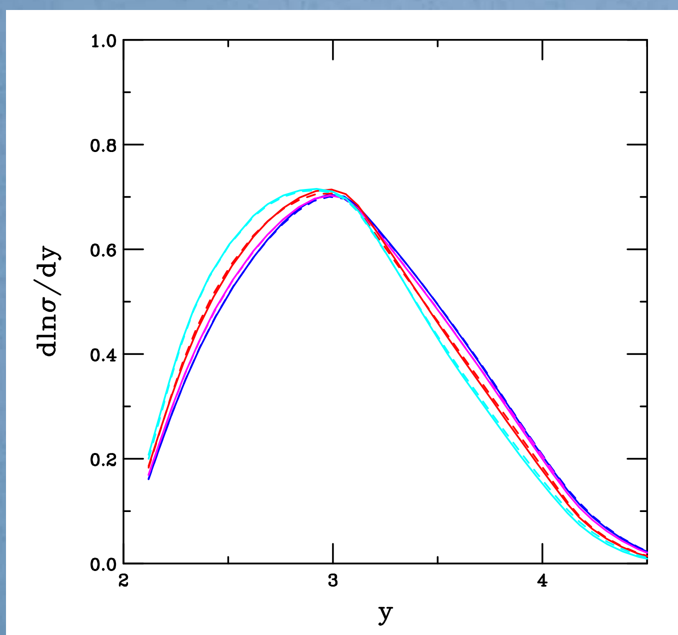
LHCb $1/\sigma \; d\sigma/d|\Delta\eta|$ vs $|\Delta\eta|$



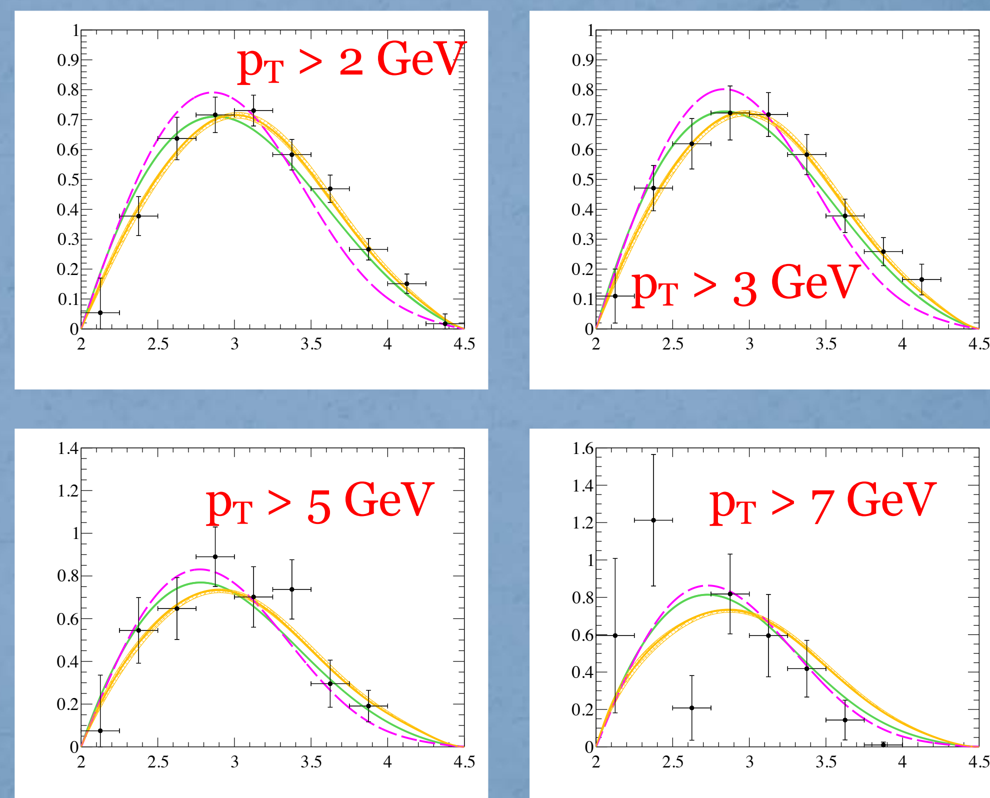
PYTHIA (orange); POWHEG (green); magenta (uncorrelated)

Rapidity of pair

Blue: $p_T > 2$ GeV
Magenta: $p_T > 3$ GeV
Red: $p_T > 5$ GeV
Cyan: $p_T > 7$ GeV



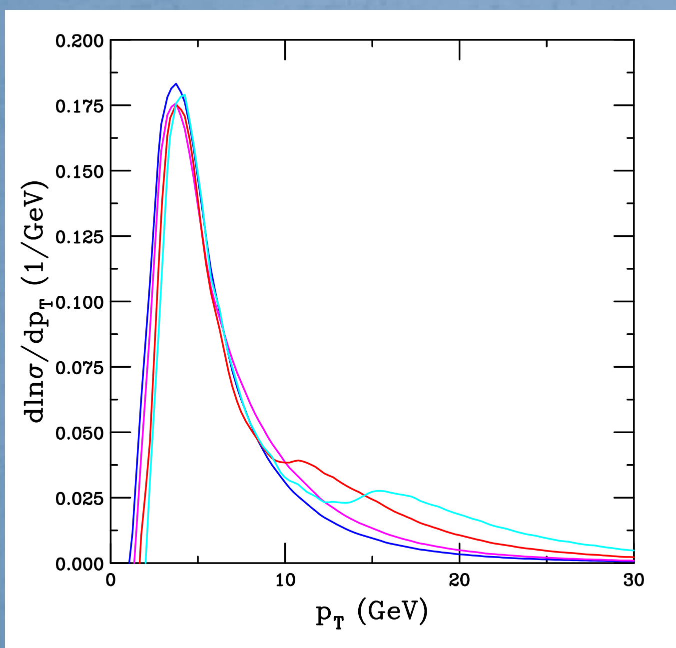
LHCb 1/σ dσ/dy vs y



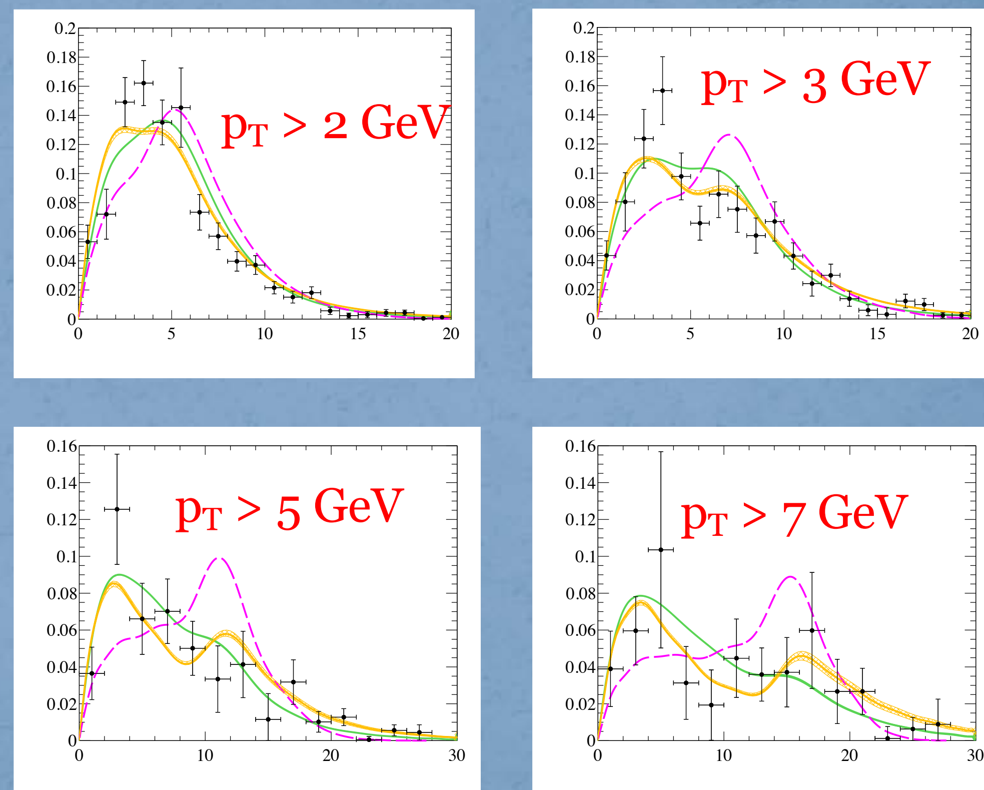
PYTHIA (orange); POWHEG (green); magenta (uncorrelated)

Pair p_T

Blue: $p_T > 2$ GeV
Magenta: $p_T > 3$ GeV
Red: $p_T > 5$ GeV
Cyan: $p_T > 7$ GeV



LHCb $1/\sigma\ \ d\sigma/dp_T$ vs p_T (GeV)



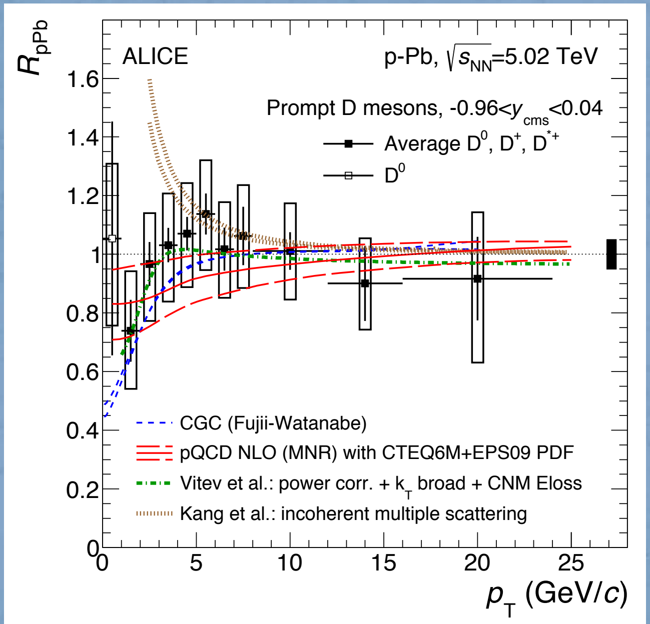
PYTHIA (orange); POWHEG (green); magenta (uncorrelated)

Comments on cold nuclear matter

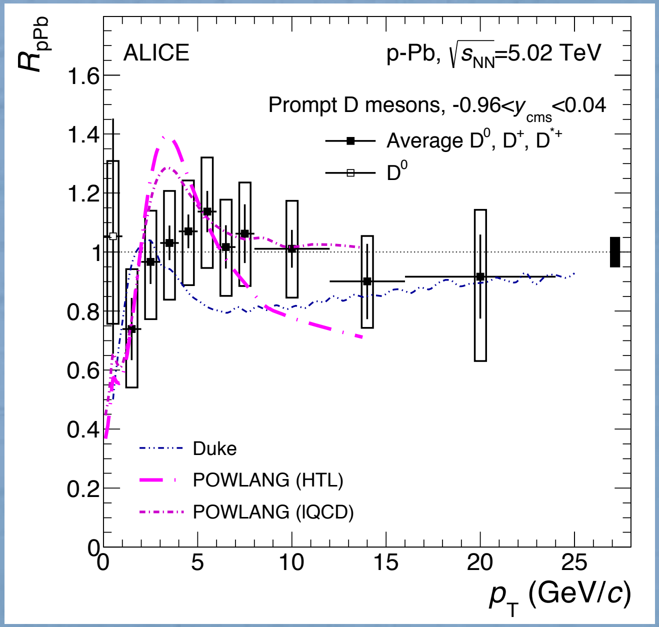
ALICE D mesons in Medium

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

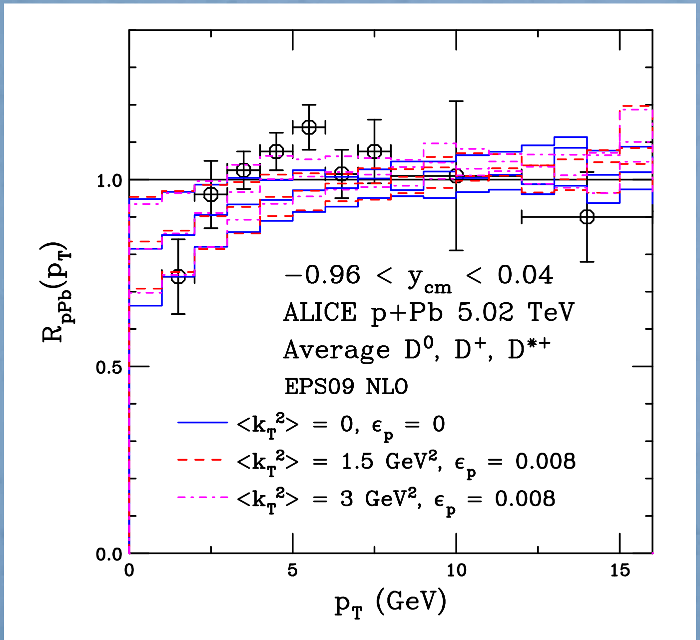


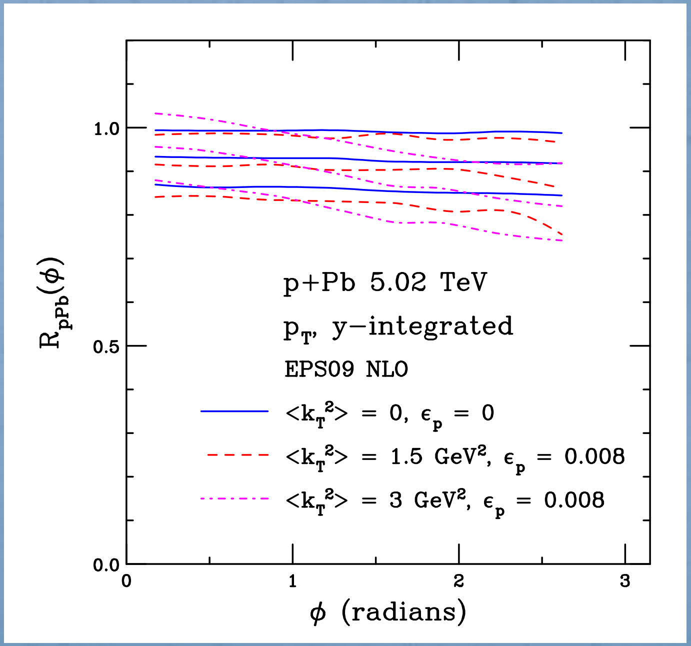
arXiv: 1605.07569

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