Heavy flavour production in pp and AA collisions at the LHC

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work done in collaboration with:
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Outline

- Heavy quark production in pQCD: problems and theoretical tools
- Our approach: a Montecarlo setup with a **pQCD event generator** (POWHEG, within the POWHEG-BOX set-up) followed by an implementation of **Langevin diffusion** of heavy quarks in QGP.
- Further refinements (especially in the pp sector) with respect to version of QM2011.
- Predictions for pp collisions at LHC: $\sqrt{s}$=7 TeV and $\sqrt{s}$=2.76 TeV
- Predictions for Pb-Pb collisions at LHC: $\sqrt{s}$=2.76 TeV/n

Heavy flavour production in pQCD

The large mass M of c and b quarks makes possible a pQCD calculation of $Q\overline{Q}$ production:

- it sets a minimal "off-shellness" of the intermediate propagators (diagrams don't explode);
- it sets a hard scale for the evaluation of $\alpha s(\mu)$ (fastening of the convergence of the perturbative series);
- it prevents collinear singularities (suppression of emission of small-angle gluon, the so-called dead cone effect)

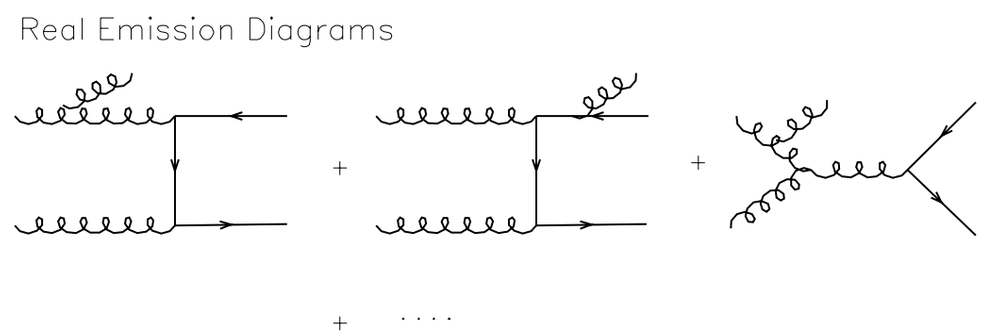
Both the total cross section $\sigma^{tot}_{Q\overline{Q}}$ and the invariant single-particle spectrum $E(d\sigma_Q/d^3p)$ are well-defined quantities which can be calculated in pQCD.

Factorization scheme (large Q^2):

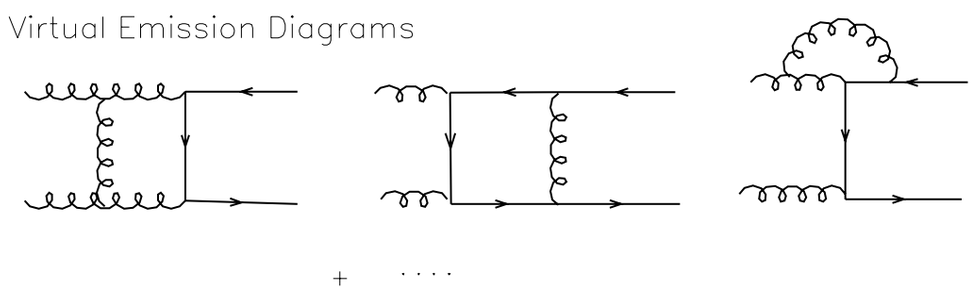
pQCD partonic cross section

$$\int G_{a/A}(x_a)G_{b/B}(x_b)\hat{\sigma}_{ab\to c\overline{c}}(\hat{s}=x_a x_b s)\,D_{D/c}(z) = \sigma_{AB\to DX}$$

Next to Leading Order (NLO) processes



- Real emission $|\mathcal{M}_{\rm real}|^2 \sim \mathcal{O}(\alpha_s^3)$



- Virtual corrections $2{\rm Re}\mathcal{M}_0\mathcal{M}^*_{\rm virt} \sim \mathcal{O}(\alpha_s^3)$

- Calculation at NLO accuracy gives the $\mathcal{O}(\alpha_s^3)$ result for $\sigma^{tot}_{Q\overline{Q}}$ and $E(d\sigma_Q/d^3p)$
- It has being implemented for many years in several numerical codes (as MNR and others) and Montecarlo event generators (as MC@NLO, POWHEG, etc)
- However... ***large terms of collinear origin*** $\sim \alpha_s \ln(p_T/M)$ **can become large for** ***(p_T>>m)***
- Different schemes for ***resummation*** of these logs are possible

Some examples of pQCD tools for heavy flavour studies

- Fixed-order codes: MNR (calculation) or MC@NLO, POWHEG (MC generators).
- FONLL: fixed-order (NLO) calculation of hard processes + next-to-leading log resummation (with implementation also of non-perturbative input to model fragmentation and decays.
- alternative schemes, e.g. GM-VFNS

Montecarlo codes provide the advantage to save maximum information about the event (i.e. correlations in azimuth or rapidity between $Q\overline{Q}$)

POWHEG is a code interfaced to Shower Monte Carlo programs (like HERWIG, PYTHIA) that describe at the Leading Log accuracy how initial and final states partons evolve according to DGLAP.

Our approach: a multi-step simulation of heavy quark production in pp and AA

- Initial generation of QQ pairs with POWHEG (pQCD@NLO), with the addition *a posteriori* of an intrinsic k_T kick; added Parton Shower (PYTHIA)

- for AA collisions: EPS09 nuclear corrections to parton distributions (both at NLO accuracy) have been implemented
- Heavy quark position are distributed in the transverse plane according to nuclear geometry (Glauber); Cronin effect (k_T broadening) included.
- Langevin evolution in the QGP: at each step $u^\mu(x)$ and $T(x)$ are given by hydro codes, and used to evaluate transport coefficients of the expanding fluid and to update position and 4-momentum of the heavy quark.

- At T_c HQ are made hadronize. Fragmentation is performed by sampling hadron species from experimental branching-fractions, and by sampling momentum from appropriate parametrizations of fragmentation functions.
- Finally, heavy quark hadrons are made decay into electrons, by using the PYTHIA decayer with branching-ratios from Particle Data Group review.

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Relativistic Langevin equation

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}}$$

with the properties of the noise encoded in

$$\langle \xi^i(\boldsymbol{p}_t)\xi^j(\boldsymbol{p}_{t'})\rangle = b^{ij}(\boldsymbol{p}_t)\frac{\delta_{tt'}}{\Delta t} \qquad b^{ij}(\boldsymbol{p}) \equiv \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

Transport coefficients to be calculated (**HTL pQCD**):

- momentum diffusion $\kappa_T \equiv \frac{1}{2}\frac{\langle \Delta p_T^2\rangle}{\Delta t}$ and $\kappa_L \equiv \frac{\langle \Delta p_L^2\rangle}{\Delta t}$

- friction term (dependent on the discretization scheme!):

$$\eta_D{}^{\text{Ito}}(p) = \frac{\kappa_L(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial \kappa_L(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_L(p)-\kappa_T(p)}{v^2}\right]$$

fixed in order to insure approach to equilibrium (Einstein relation):

Langevin ⇔ Fokker Planck with steady solution exp(−Ep/T)

Hydrodynamics

The fields $u^\mu(x)$ and $T(x)$ are taken from the output of two longitudinally boost-invariant ("Hubble-law" longitudinal expansion $v_z = z/t$) hydro codes [1,2]:

$$x^\mu = (\tau \cosh\eta, \boldsymbol{r}_\perp, \tau \sinh\eta) \quad \text{with} \quad \tau \equiv \sqrt{t^2 - z^2}$$

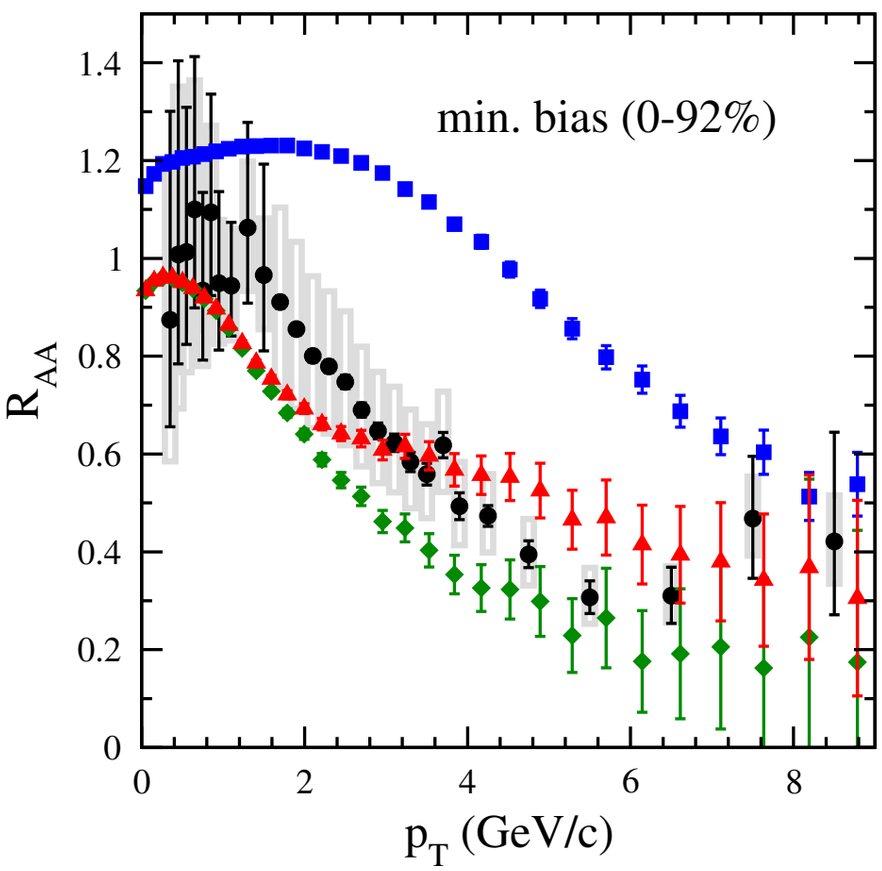
$$u^\mu = \bar{\gamma}_\perp (\cosh\eta, \bar{\boldsymbol{v}}_\perp, \sinh\eta) \quad \text{with} \quad \bar{\gamma} \equiv \frac{1}{\sqrt{1 - \bar{\boldsymbol{v}}_\perp^2}}$$

- $u^{\mu(x)}$ used to perform the update each time in the fluid rest-frame
- $T(x)$ allows to fix at each step the value of the transport coefficients.

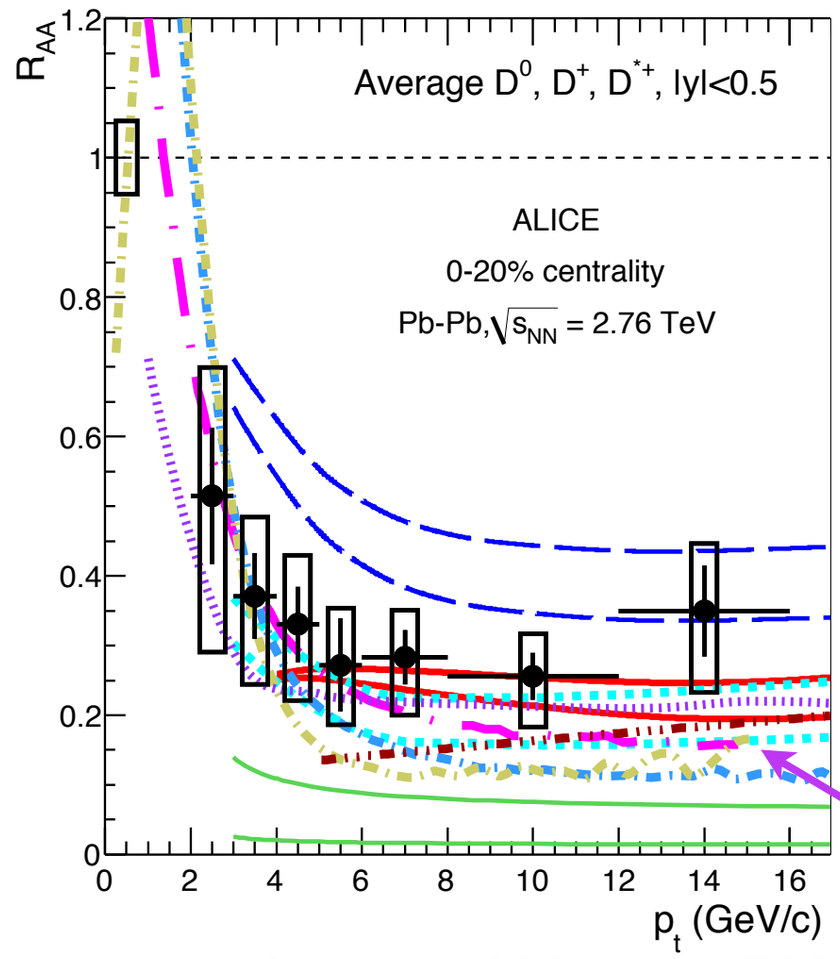
[1] P.F. Kolb, J. Sollfrank and U. Heinz, Phys. Rev. C 62 (2000) 054909
[2] P. Romatschke and U. Romatschke, Phys. Rev. Lett. 99 (2007) 172301

First results (released at QM2011)

PHENIX HFE



ALICE D mesons



HTL2

<u>but...</u>

- missing Parton Shower evolution (ISR and FSR)
- obsolete FF (Peterson)
- output files have poor information for more refined analysis (i.e. rapidity or angular correlations)
- needed study of systematic uncertainties

Fragmentation Functions

Functional forms from Braaten et al. arXiv:hep-ph/9409316
with different functional forms for pseudoscalar and vector mesons:

$$D_{Q\to P}(z) = N\frac{rz(1-z)^2}{(1-(1-r)z)^6}\Big[6-18(1-2r)z+(21-74r+68r^2)z^2 -2(1-r)(6-19r+18r^2)z^3+3(1-r)^2(1-2r+2r^2)z^4\Big] , \quad (31)$$

$$D_{Q\to V}(z) = 3N\frac{rz(1-z)^2}{(1-(1-r)z)^6}\Big[2-2(3-2r)z+3(3-2r+4r^2)z^2 -2(1-r)(4-r+2r^2)z^3+(1-r)^2(3-2r+2r^2)z^4\Big] . \quad (32)$$

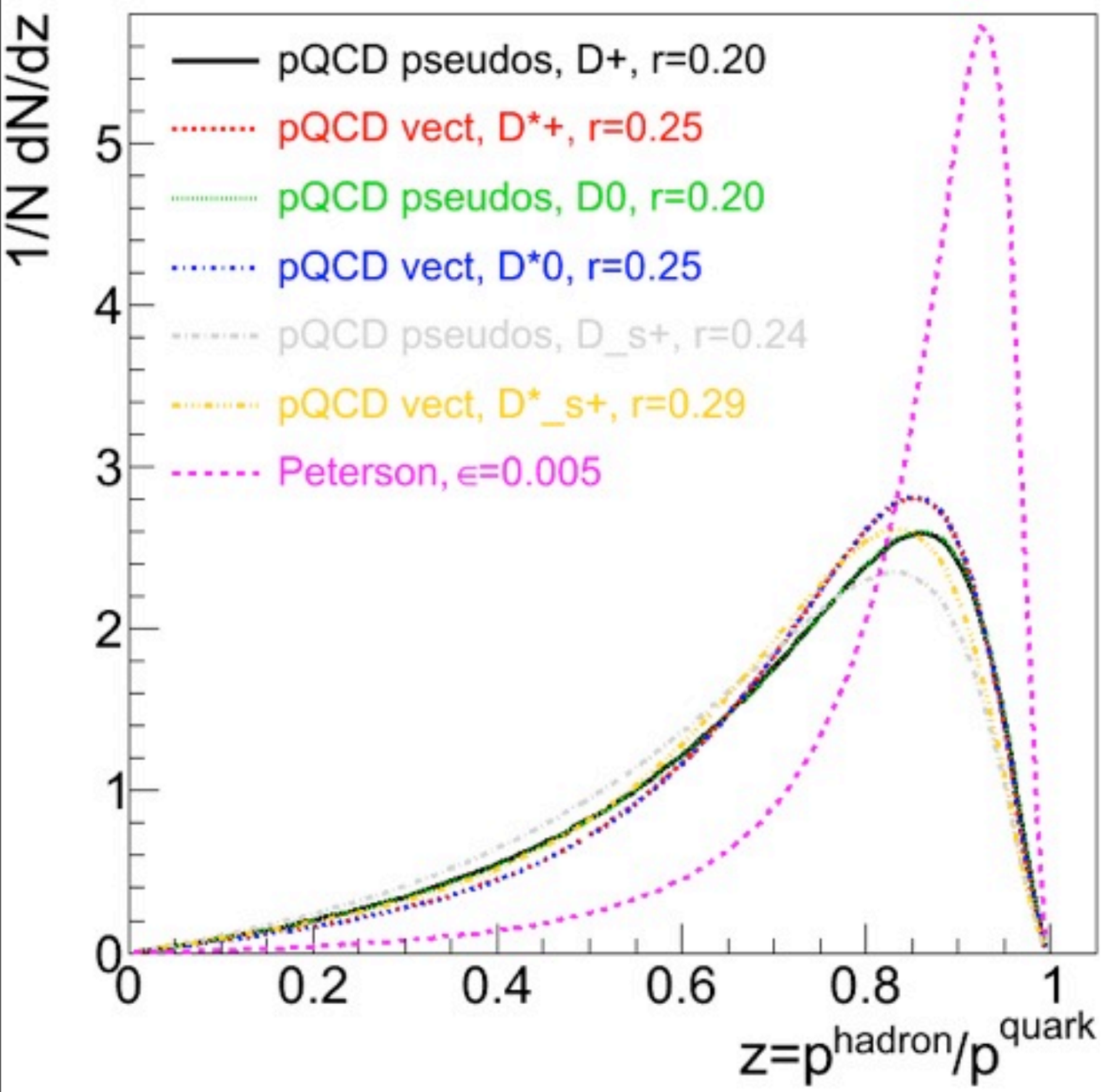
$z=p_H / p_Q$

One parameter: r (but different authors adopt different values)

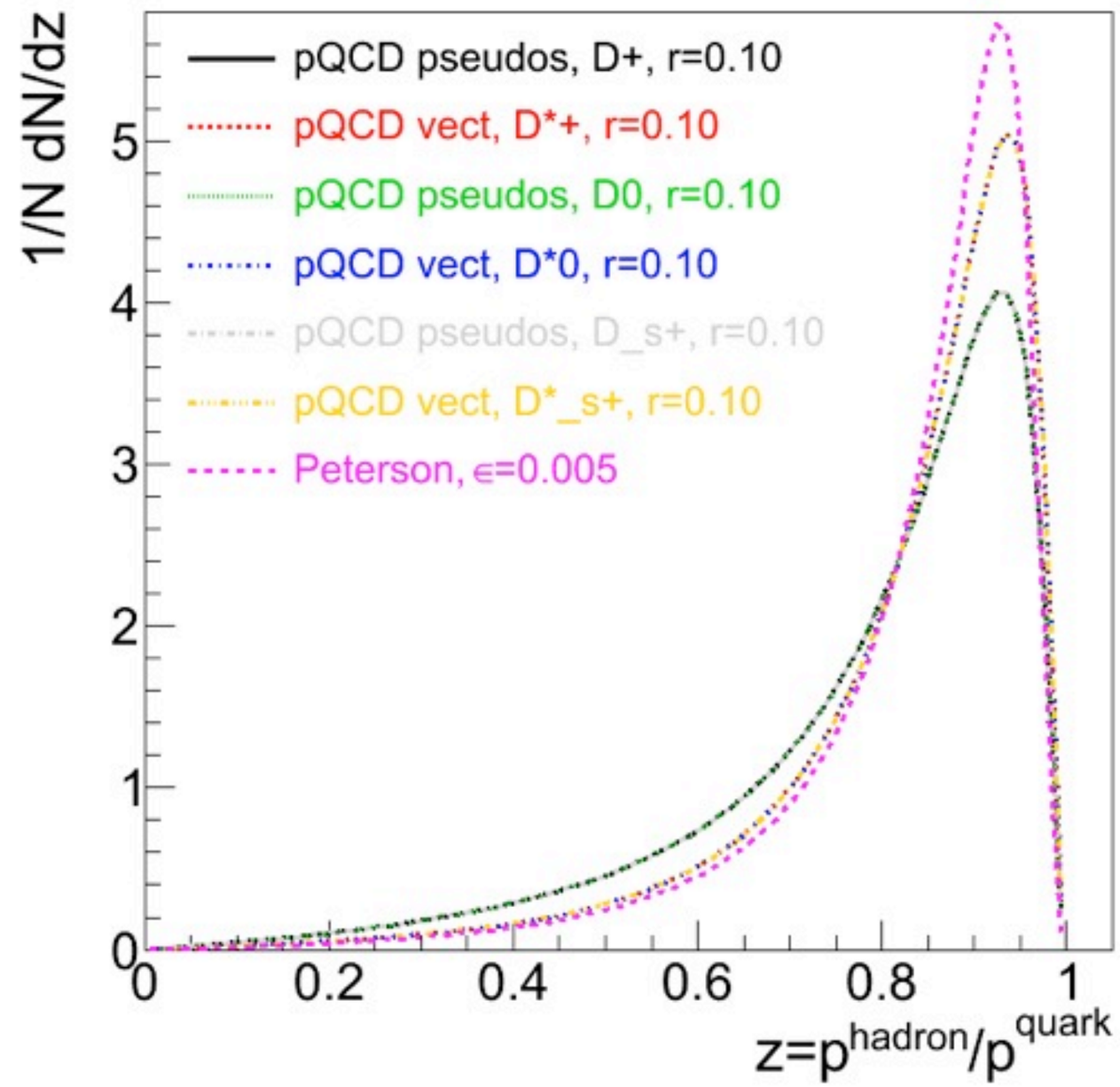
- in **Braaten et al**: **$r=(m_H-m_Q)/m_H$** corresponding to the contribution of light quark to hadron mass (e.g. with **m_Q=1.5 GeV, r=0.2 for D^0 and D^+**)
- In **FONLL** (arXiv:hep-ph/0502203 and arXiv:hep-ph/0306212): **r=0.1 for m_c=1.5 GeV (fitted on D* ALEPH data)**

Which is the effect on syst.uncertainty of calculations?

Comparison between different FF (charm)

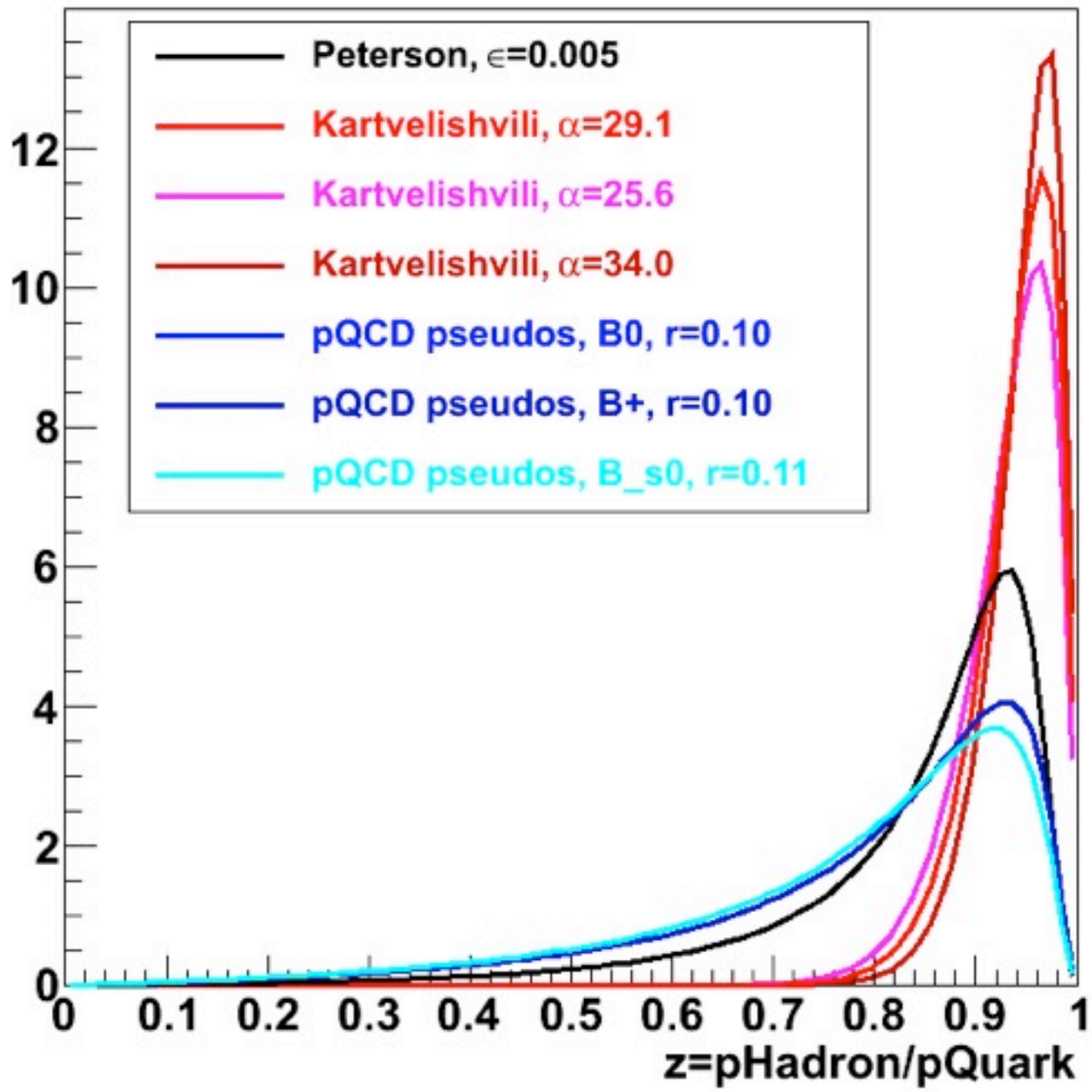


Braaten et al.



FONLL

Comparison between different FF (bottom)



Kartelishvili et al: FONLL

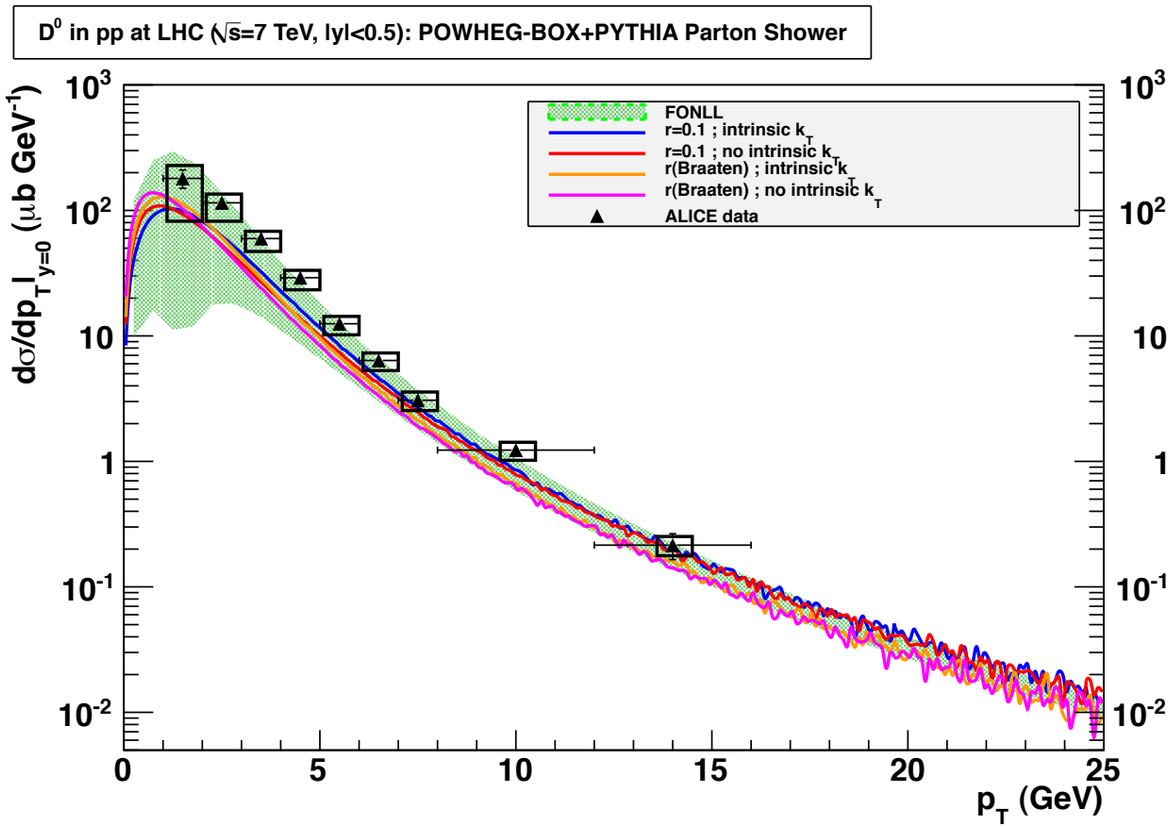
pQCD: Braaten et al

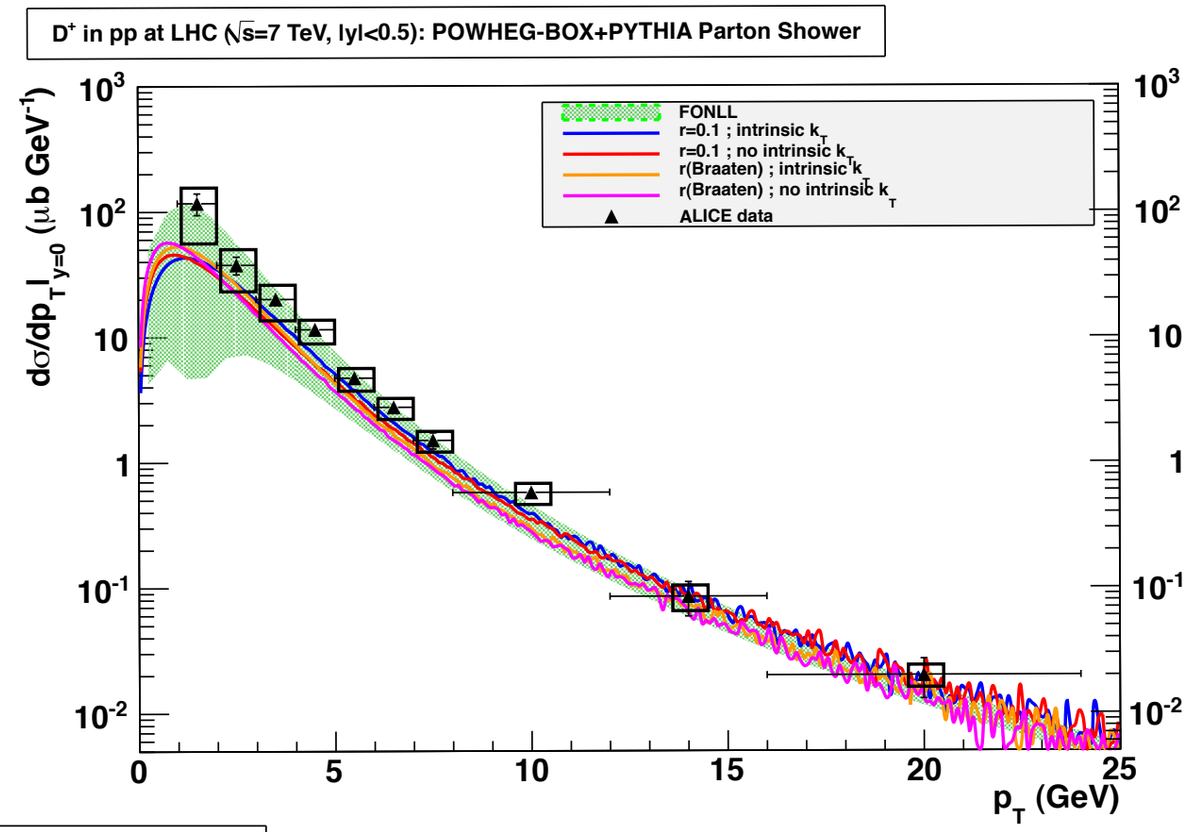
Some predictions for pp collisions at the LHC

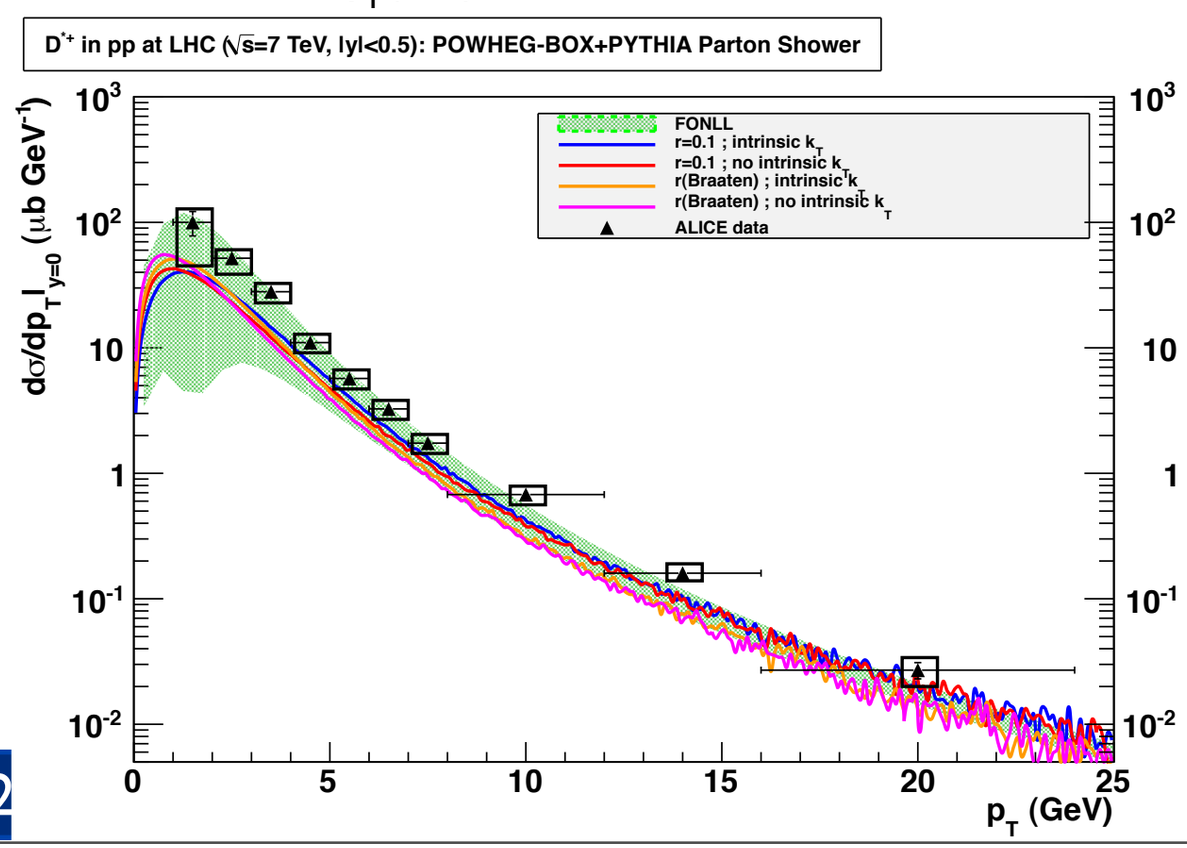
p_T differential cross-sections

- prompt D, D* mesons - ALICE $|y|<0.5$
- B mesons - CMS $|y| < 2.2 - 2.4$

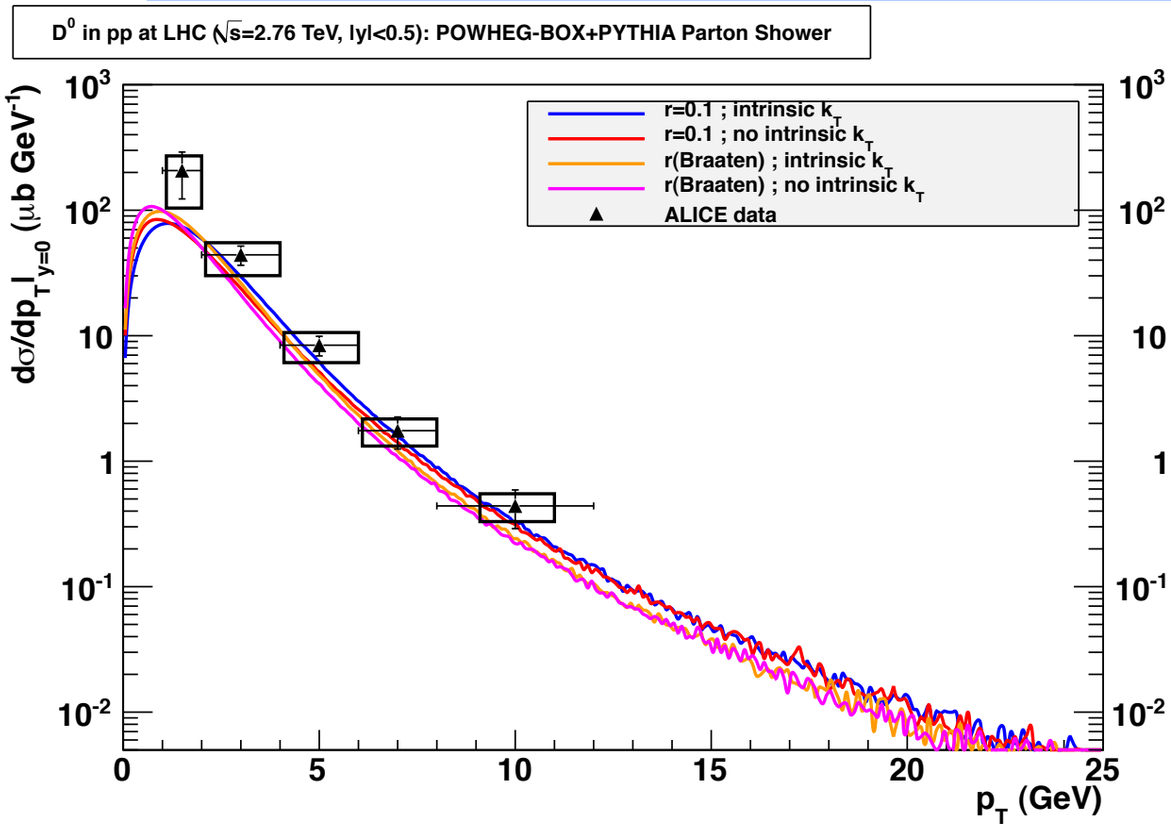
p_T spectra of D mesons in ALICE: $\sqrt{s}$ = 7 TeV

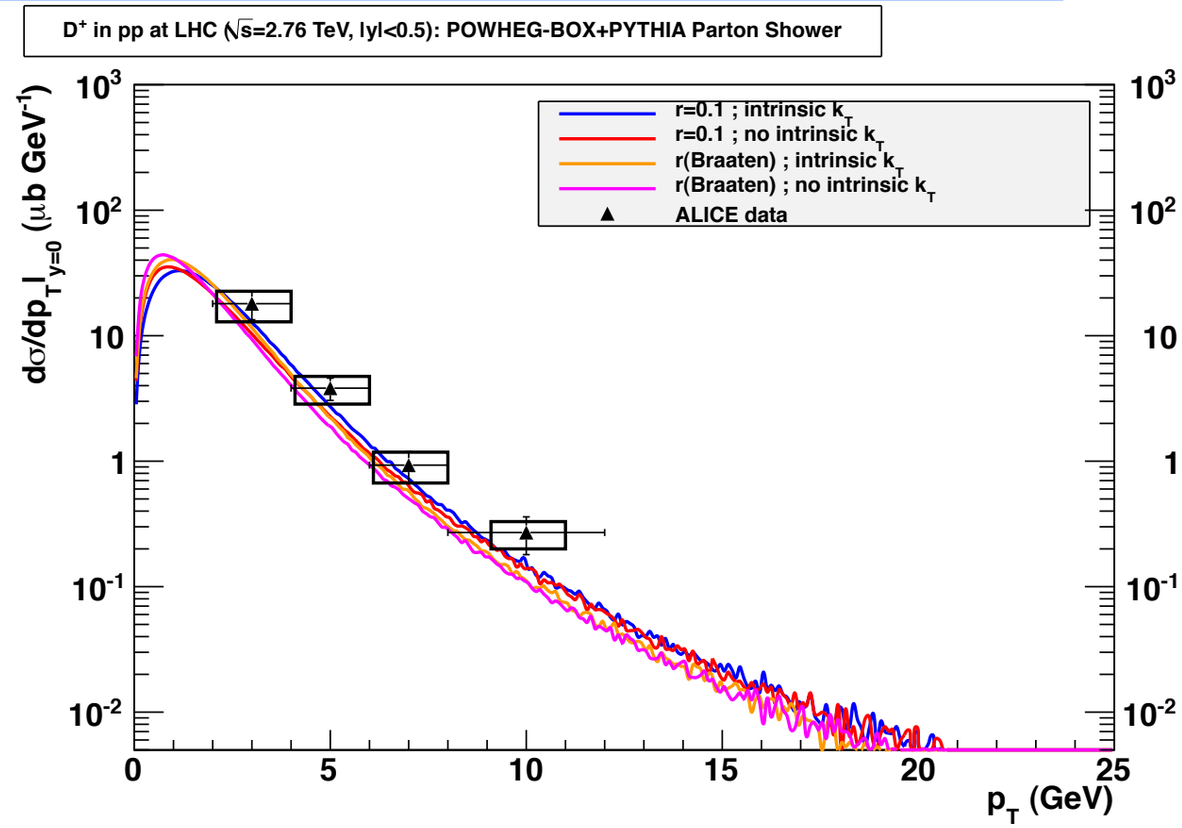


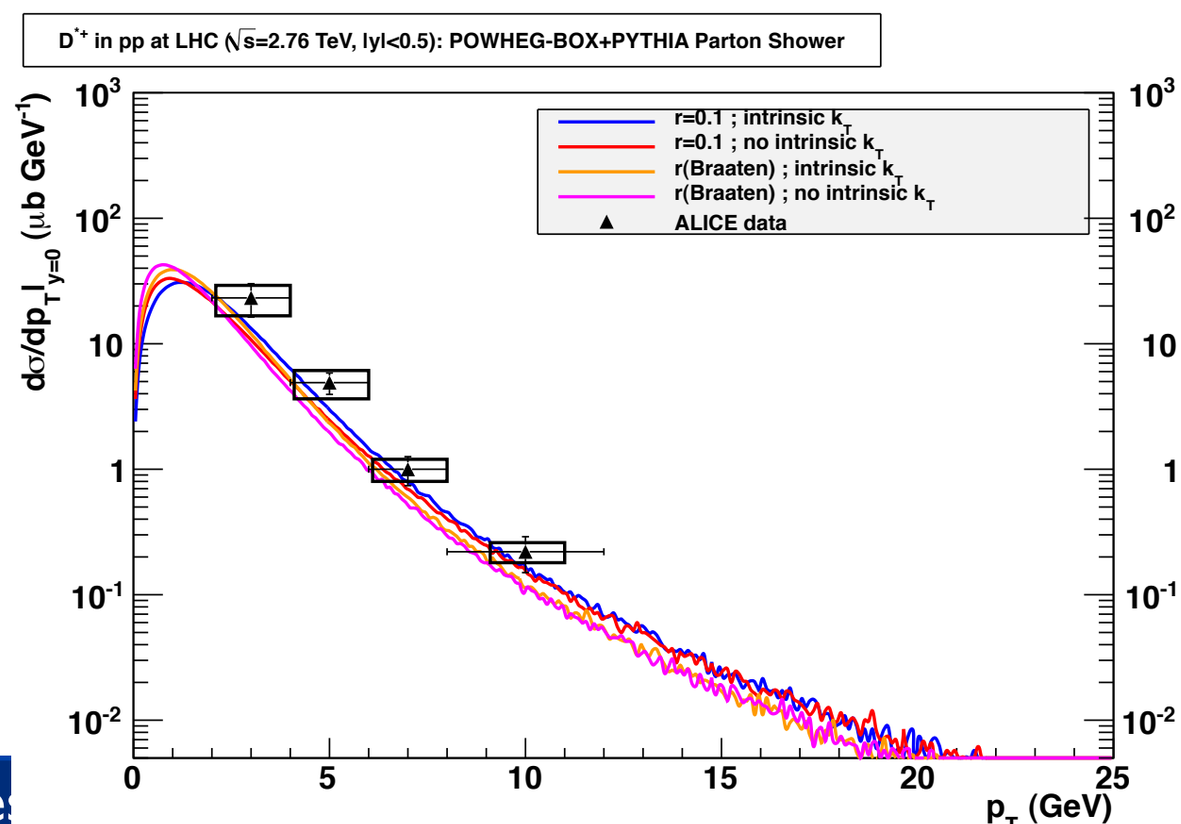




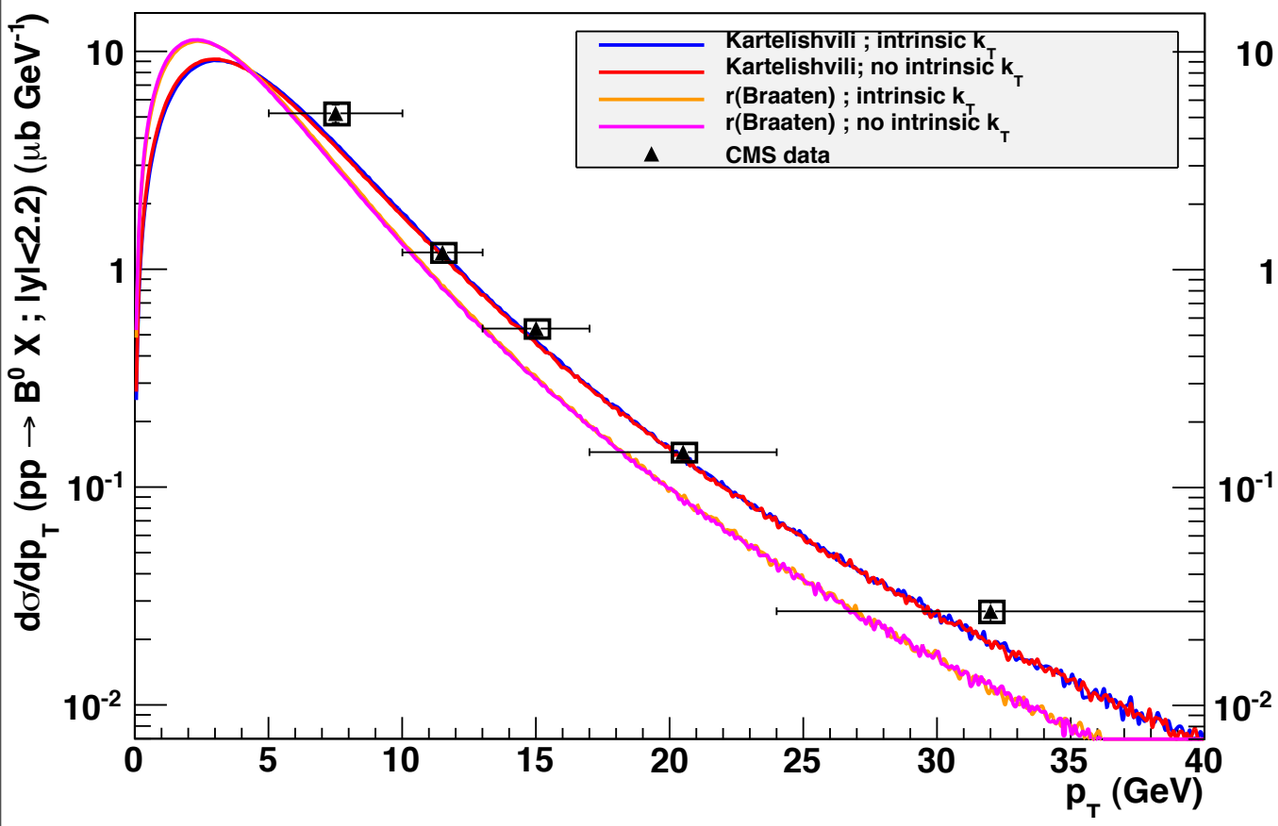
p_T spectra of D mesons in ALICE: $\sqrt{s}$ = 2.76 TeV

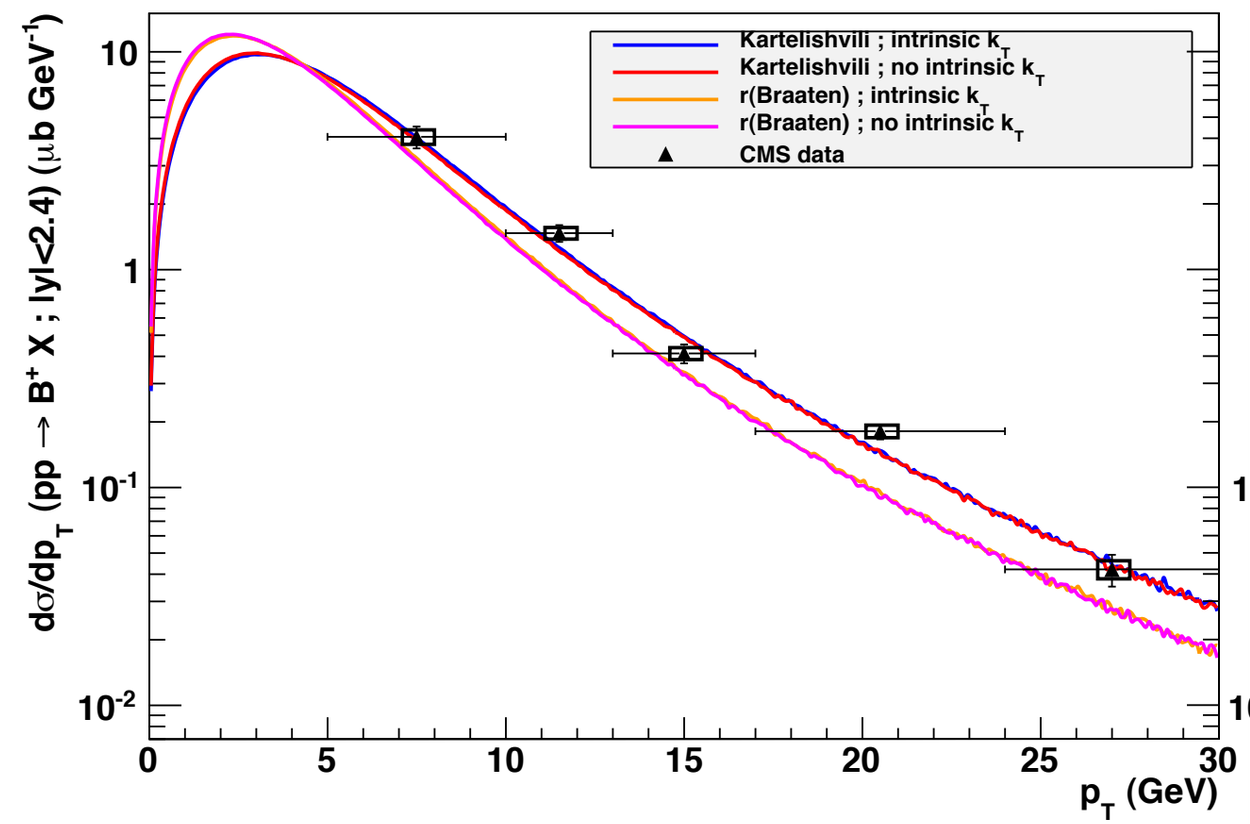


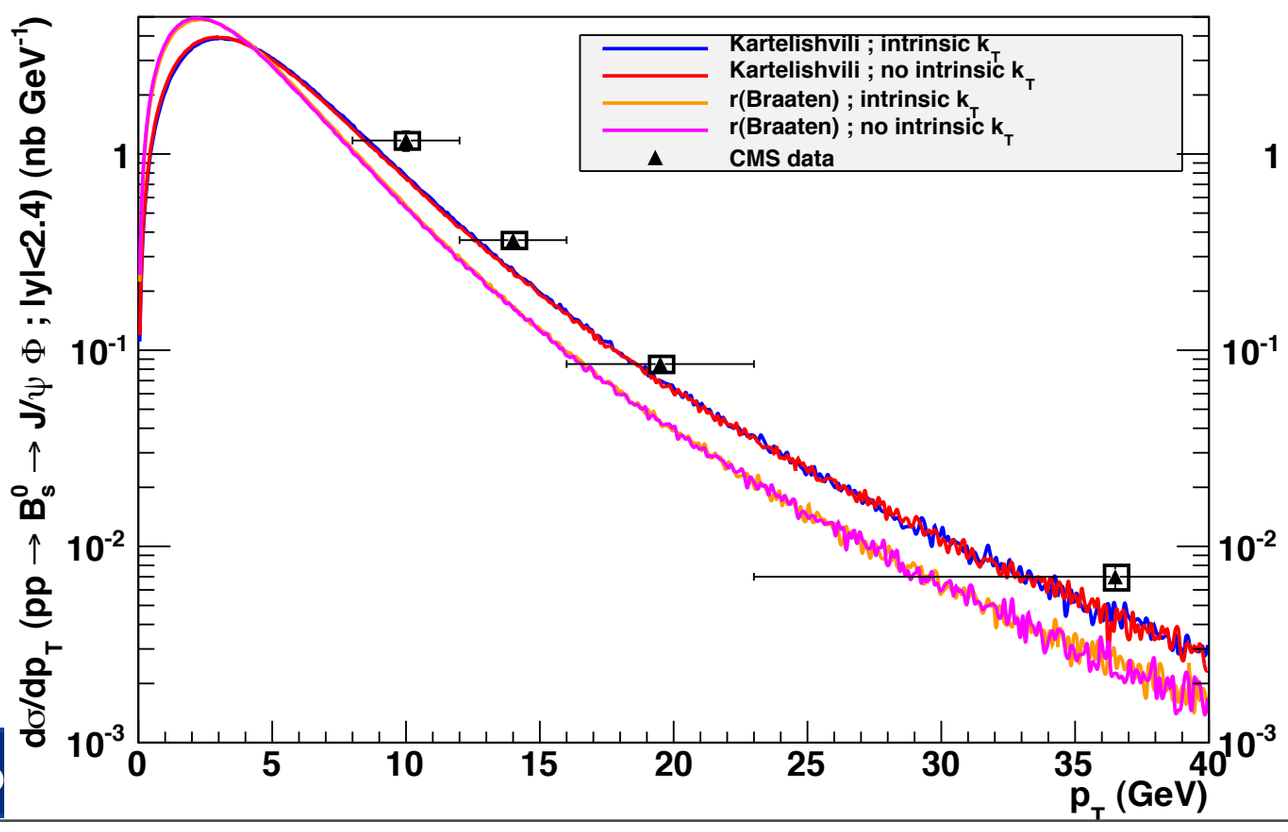




p_T spectra of B mesons in CMS $\sqrt{s}$ = 7 TeV







Predictions for PbPb collisions at the LHC: $\sqrt{s}$ = 2.76 TeV/nucleon

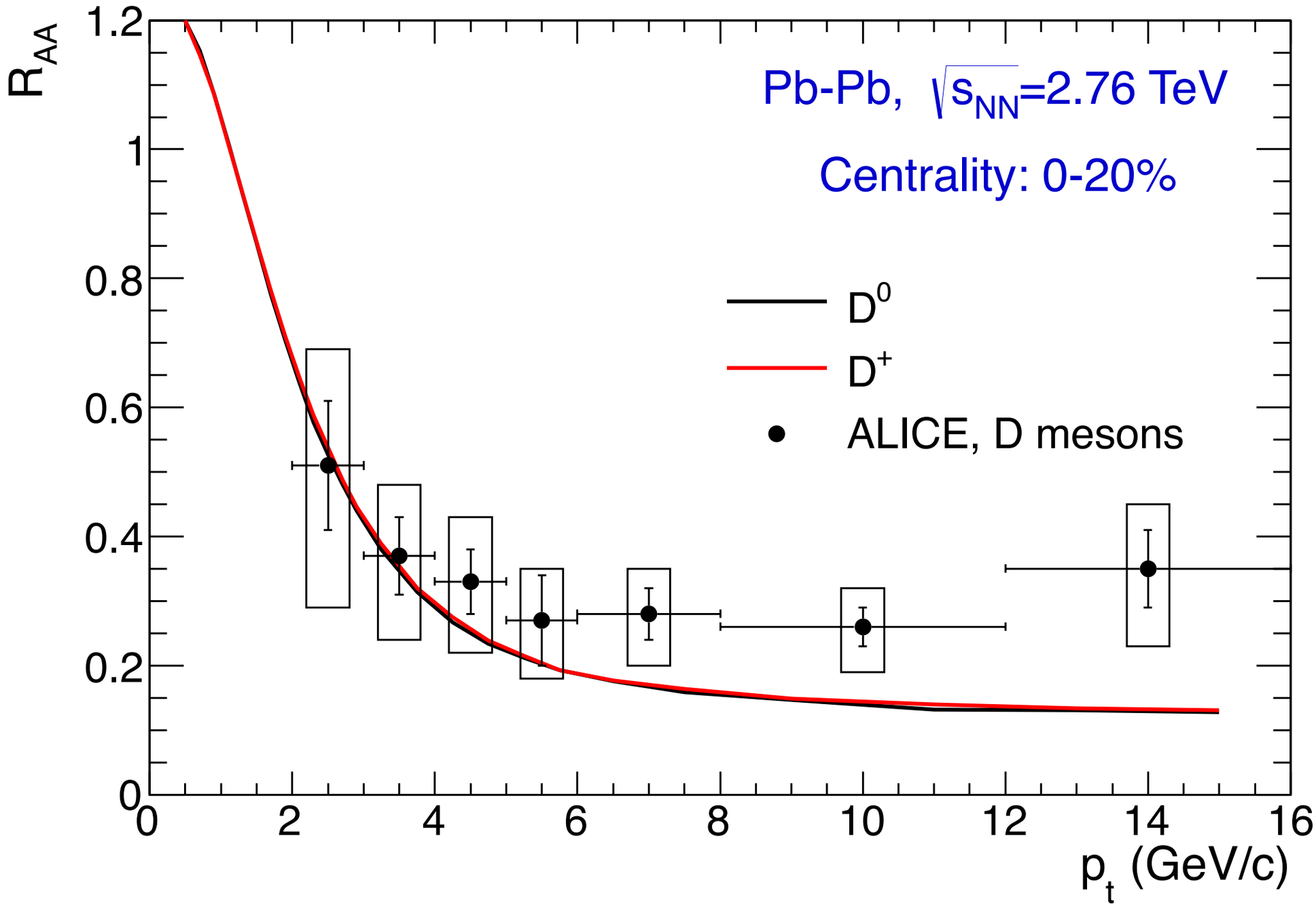
Nuclear modification factors R_{AA}

- R_{AA} D, D* mesons in ALICE |y|<0.5
  centr. (0-20)%

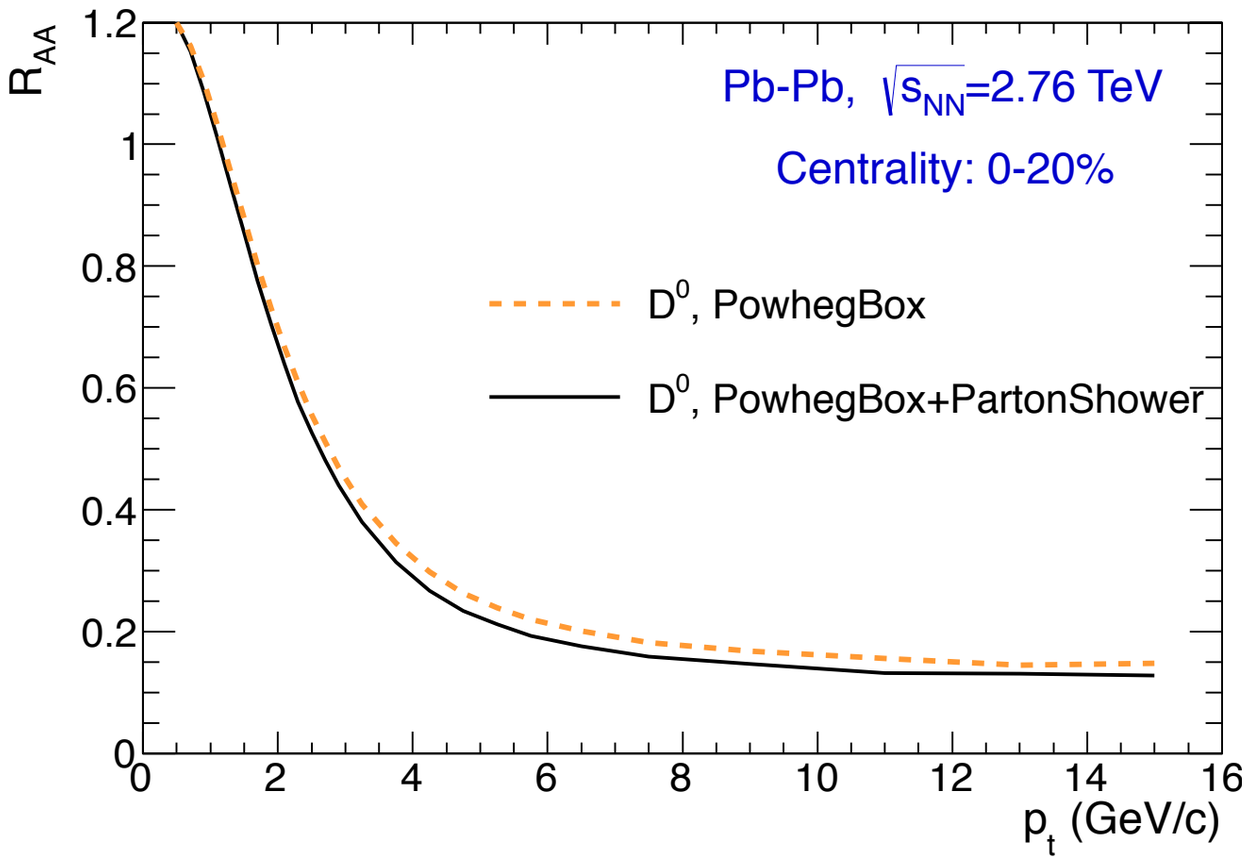
Elliptic flow v_2

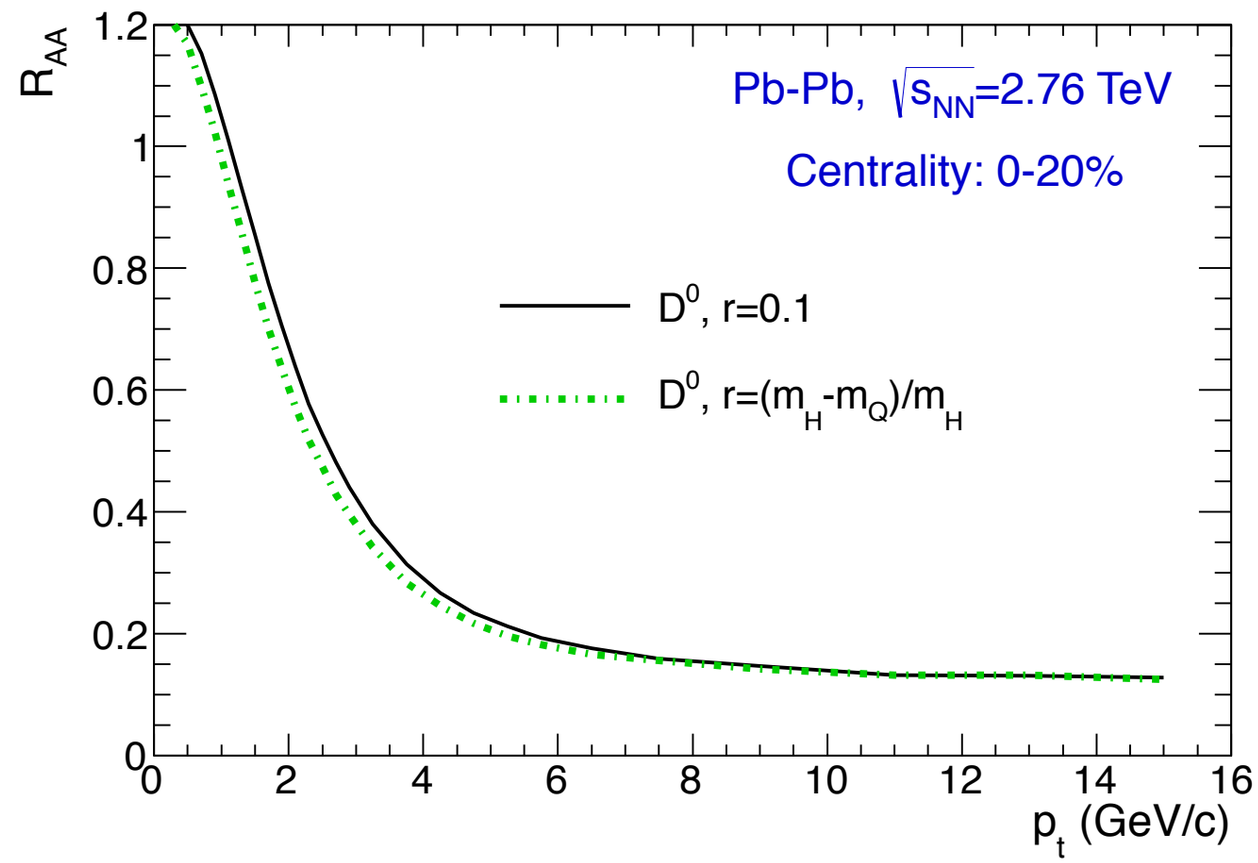
- v_2 of D mesons in ALICE |y|<0.5, centr. (30-50)%

R_{AA} of D mesons in ALICE



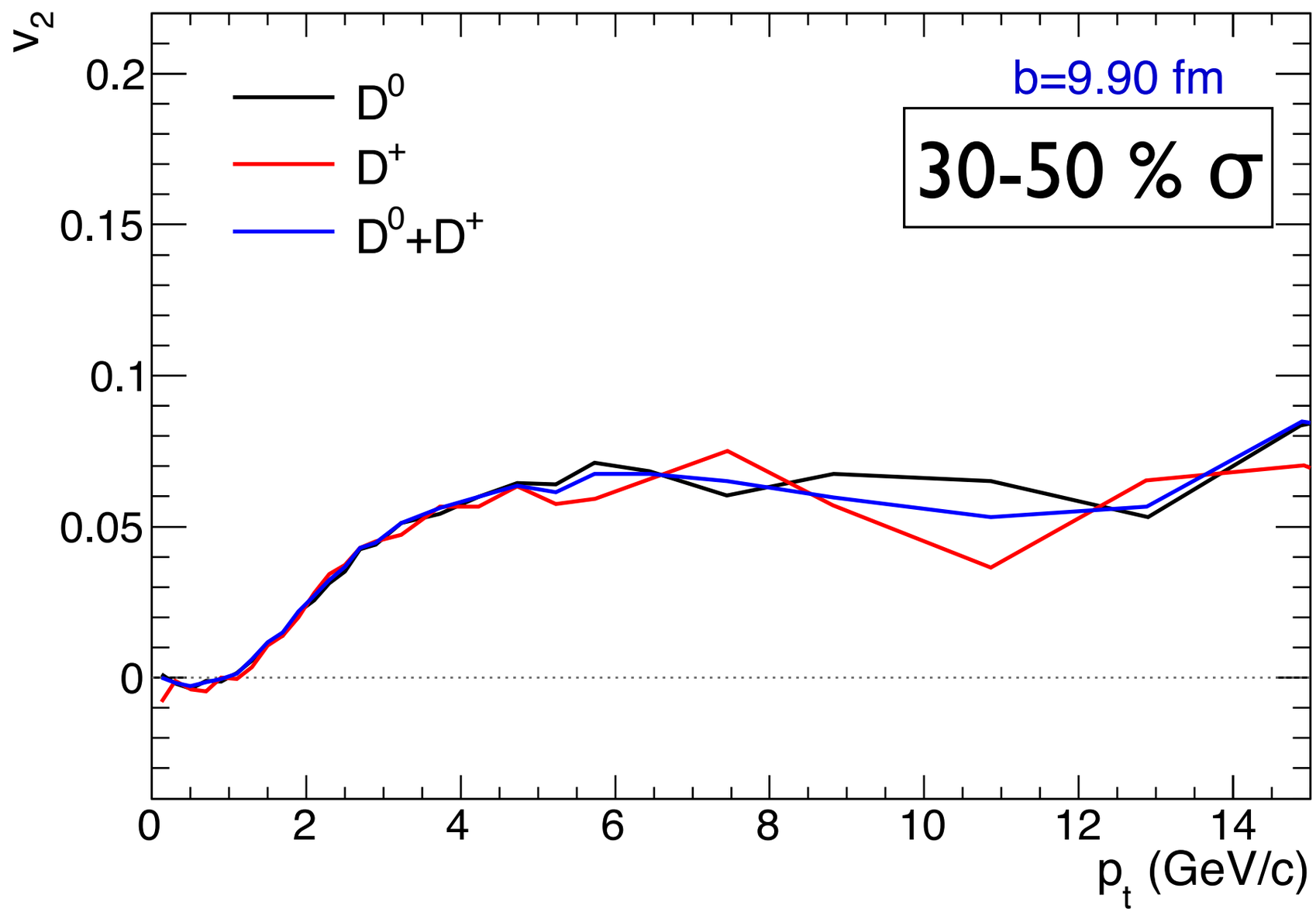
R_{AA} of D mesons in ALICE: systematics



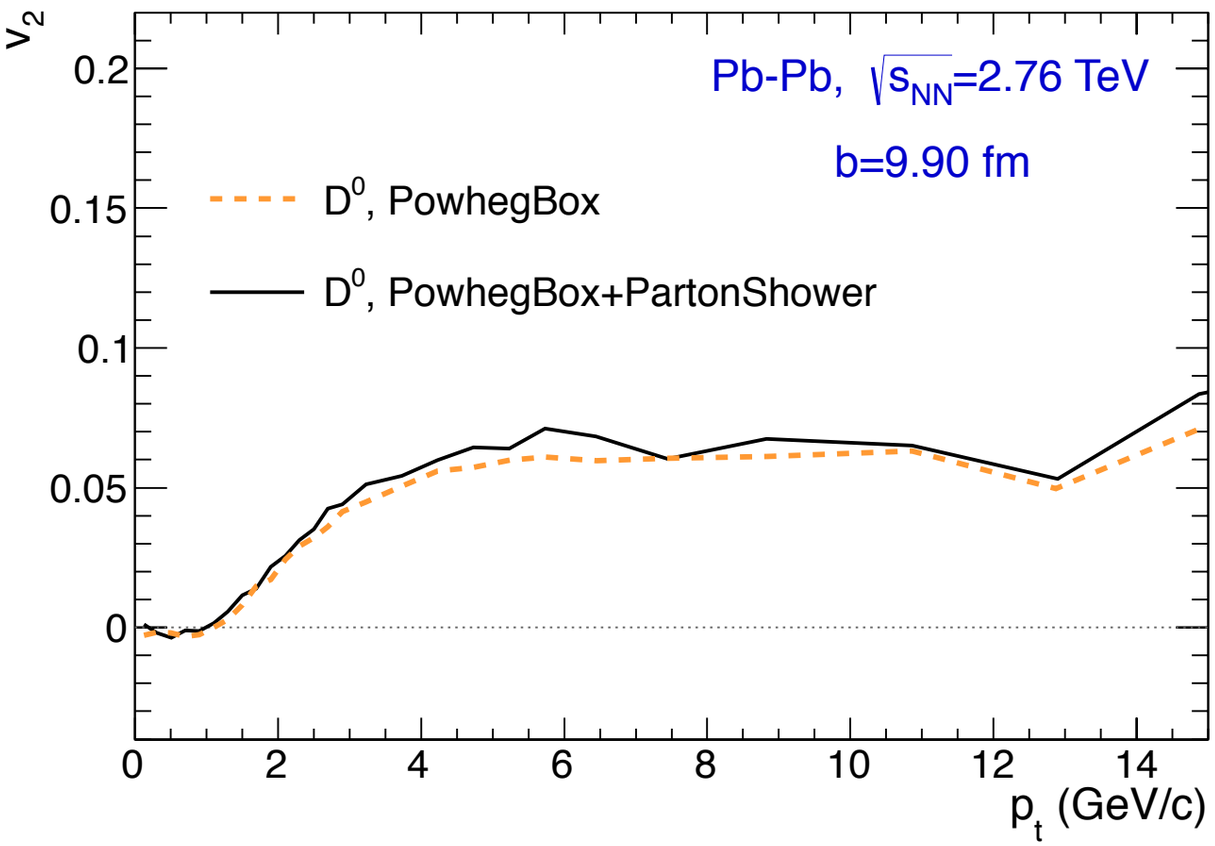


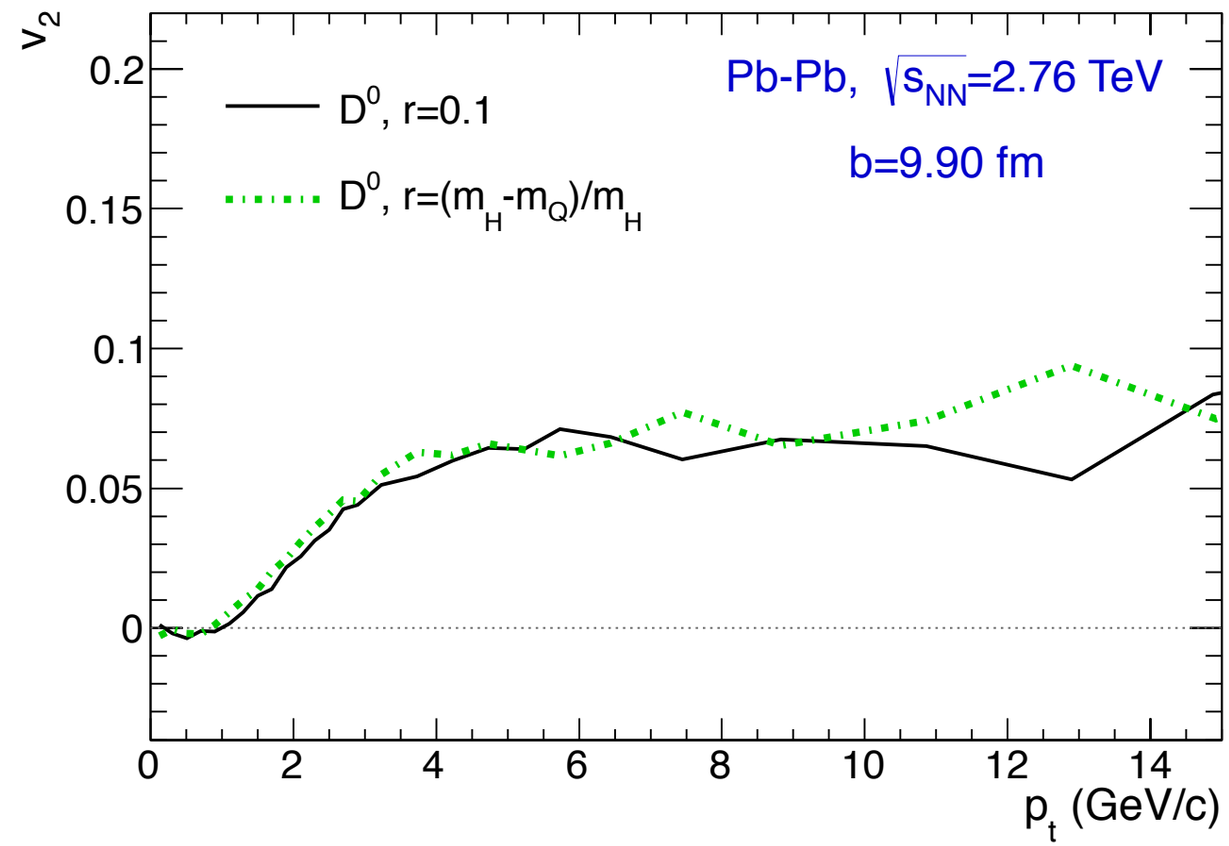
Comparison of changes in R_{AA} with/without PYTHIA Parton Shower and for changes of the r parameter in the charm Braaten fragmentation function

Elliptic flow v_2 in ALICE



v_2 of D^0 mesons in ALICE: systematics





Comparison of changes in v_2 (D^0) with/without PYTHIA Parton Shower and for changes of the r parameter in the charm Braaten fragmentation function

Summary

- Improvements to our simulation of HQ production in pp collisions have been implemented, by interfacing the most recent version of POWHEG with PYTHIA (to perform Parton Showering).
- Systematic studies on the effect of an intrinsic k_T, or a change in FF have been performed.
- First check against data from LHC experiments on pp collisions at $\sqrt{s}$= 7 TeV show a good level of agreement, taking into account the different sources of theoretical uncertainties. Our setup provides a solid benchmark to be used as a reference for results obtained in nucleus-nucleus collisions.
- Preliminary comparisons with ALICE data show a good agreement with the pattern of R_{AA} in central collisions, whereas the elliptic flow v_2 in semi-peripheral collisions appears to be underestimated.

BACKUP SLIDES

Evaluation of transport coefficients $\kappa_{T/L}(p)$

The interaction rate (from the squared matrix element of the process) must be weighted by the squared transverse/longitudinal exchanged momentum.

intermediate cutoff $|t|^* \sim m_D^2$ *introduced to separate the contributions of*

- soft collisions ($|t| < |t|^*$): Hard Thermal Loop (HTL) approximation in a weak-coupling scenario, with the running coupling costant $g(\mu)$ taken at a scale $\mu \sim T$, the Debye screening mass m_D preventing infrared divergencies.

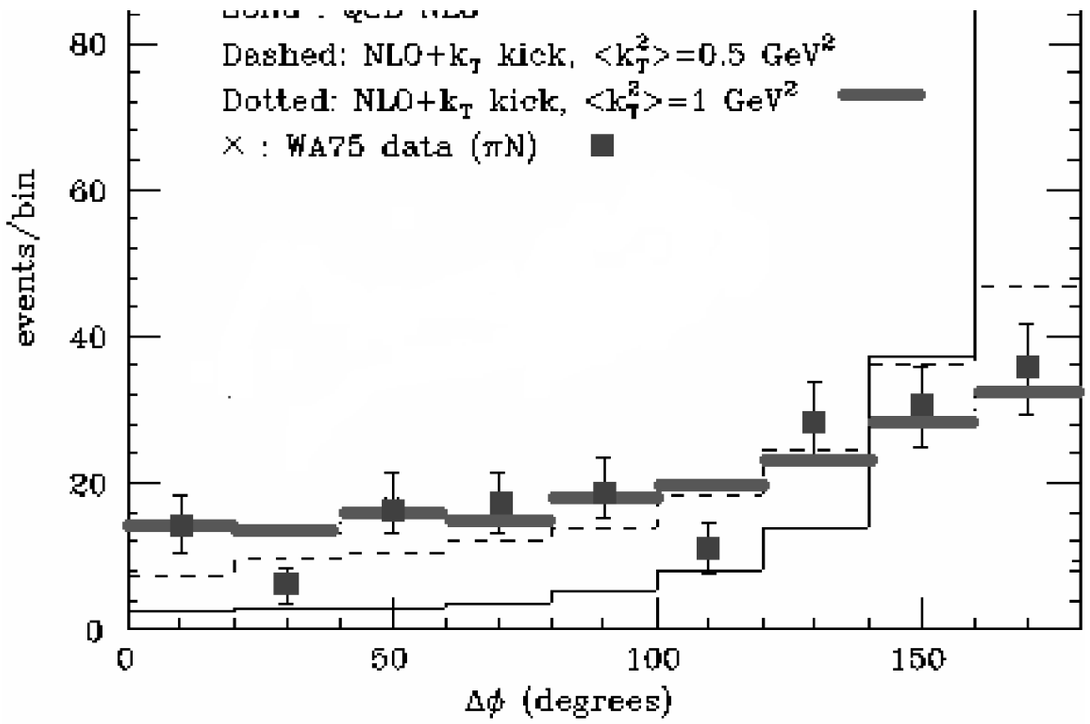
- hard collisions ($|t| > |t|^*$): kinetic pQCD calculation

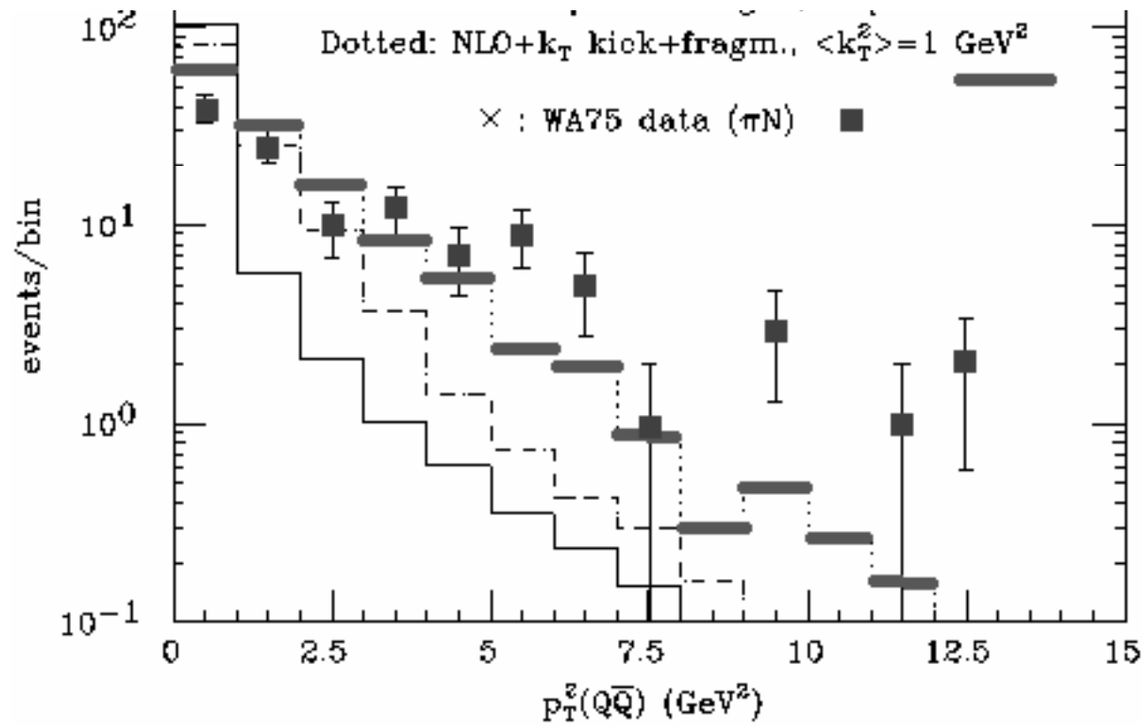
Two calculations, with $g(\mu)$ evaluated at:

$\mu \sim T$ as for the soft component (HTL1)

$\mu = |t| = -Q^2$ (HTL2)

Effect of intrinsic k_T





WA75 (and WA92)

- Azimuthal correlations: $dN/d\Delta\phi$ with $\Delta\phi \equiv \phi_Q - \phi_{\overline{Q}}$
- Pair transverse momentum: $dN/d(p_T^{Q\overline{Q}})^2$ with $\boldsymbol{P}_T^{Q\overline{Q}} \equiv \boldsymbol{P}_T^{Q} + \boldsymbol{P}_T^{\overline{Q}}$

LO: $\Delta\phi = \pi$ $\quad \boldsymbol{P}_T^{Q\overline{Q}} = \mathbf{0}$ $\quad Q \text{ and } \overline{Q}$ back-to-back

NLO: $\Delta\phi = \pi + \mathcal{O}(\alpha_s)$ $\quad \boldsymbol{P}_T^{Q\overline{Q}} = \mathcal{O}(\alpha_s)$ $\quad Q\overline{Q}g$ final-state

Intrinsic k_T looks necessary to reproduce the data!
We can check what happens in our simulations with/without it.