NLO Monte Carlo predictions for heavy-quark production

(pp collisions @ ALICE)

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Outline

1. Heavy quark production pp-baseline @ ALICE

2. GM-VFNS, FONLL , POWHEG methods

3. Results and comparison of the methods with ALICE data

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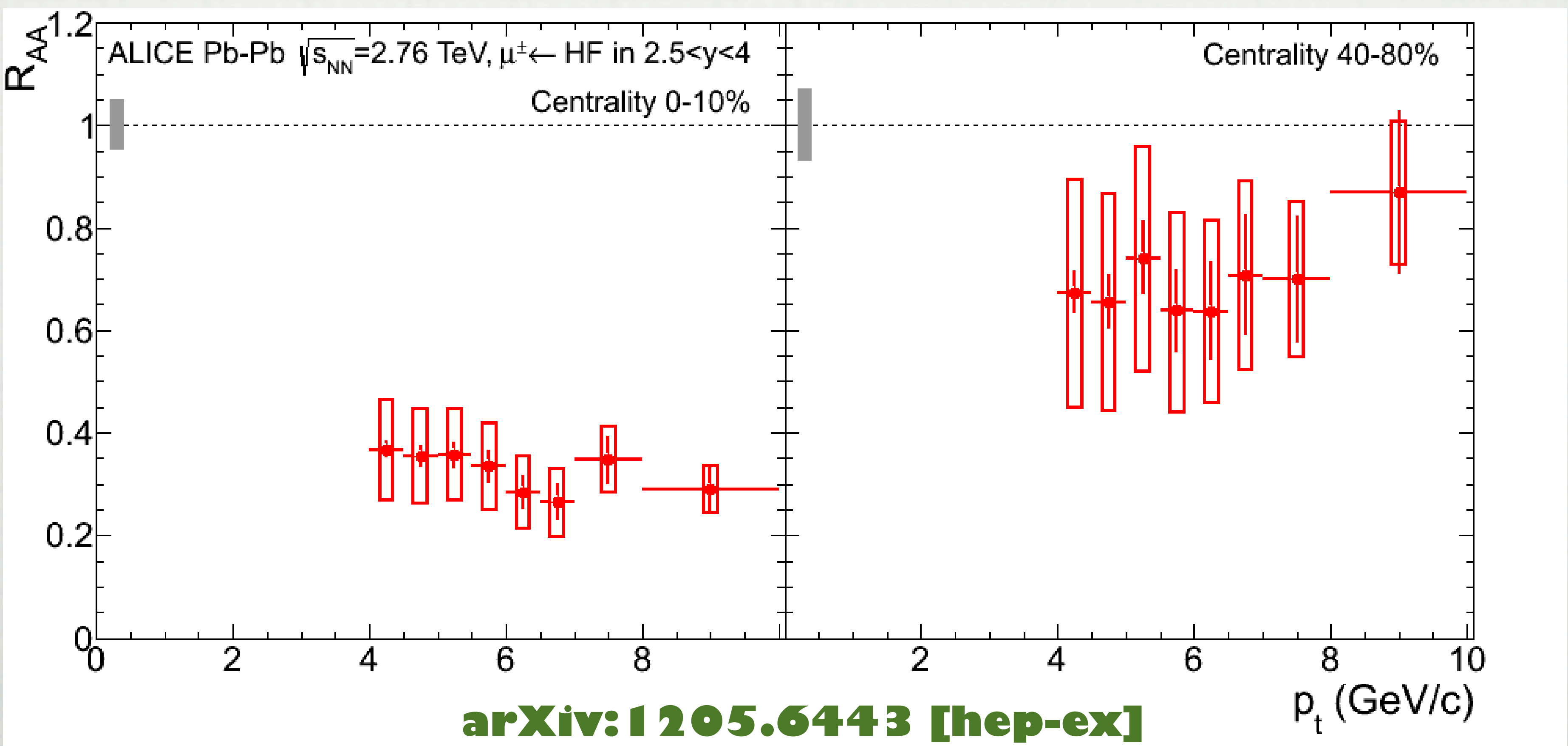
Motivation

- **Goal:**
  - Heavy quarks sensitive to nuclear medium - used @ ALICE to study the suppression factor in PbPb collisions
  - For isolation of nuclear medium effects - understanding of pp baseline needed

$$R_{\mathrm{AA}}(p_{\mathrm{t}}) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{t}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{t}}}$$



arXiv:1205.6443 [hep-ex]

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2. GM-VFNS, FONLL, POWEHG methods

GM-VFNS

- **Main goal**
  - Construct single inclusive cross-section valid in a wide p_T range
  - Combine the massive calculation valid for small p_T with massless calculation valid for large p_T

- **GM-VFNS → ZM-VFNS for $p_T >> m$**
  (this is the case by construction)

- **GM-VFNS → FFNS for $p_T \sim m$**
  (formally this can be shown; numerically problematic in the S-ACOT scheme)

GM-VFNS

List of subprocesses

hep-ph/0502194

	Only light lines	Heavy quark initiated ($m_Q = 0$)	Mass effects: $m_Q \neq 0$
1	$gg \to qX$	-	$gg \to QX$
2	$gg \to gX$	-	-
3	$qg \to gX$	$Qg \to gX$	-
4	$qg \to qX$	$Qg \to QX$	-
5	$q\bar{q} \to gX$	$Q\bar{Q} \to gX$	-
6	$q\bar{q} \to qX$	$Q\bar{Q} \to QX$	-
7	$qg \to \bar{q}X$	$Qg \to \bar{Q}X$	-
8	$qg \to \bar{q}'X$	$Qg \to \bar{q}X$	$qg \to \bar{Q}X$
9	$qg \to q'X$	$Qg \to qX$	$qg \to QX$
10	$qq \to gX$	$QQ \to gX$	-
11	$qq \to qX$	$QQ \to QX$	-
12	$q\bar{q} \to q'X$	$Q\bar{Q} \to qX$	$q\bar{q} \to QX$
13	$q\bar{q}' \to gX$	$Q\bar{q} \to gX$, $q\bar{Q} \to gX$	-
14	$q\bar{q}' \to qX$	$Q\bar{q} \to QX$, $q\bar{Q} \to qX$	-
15	$qq' \to gX$	$Qq \to gX$, $qQ \to gX$	-
16	$qq' \to qX$	$Qq \to QX$, $qQ \to qX$	-

$\oplus$ charge conjugated processes

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GM-VFNS

- **Fragmentation functions**
  - Fragmentation approach in GM-VFNS - treat heavy quark fragmentation as any other FF
  - Scale dependent FF determined from a fit to LEP data

FF ansatz for charmed mesons

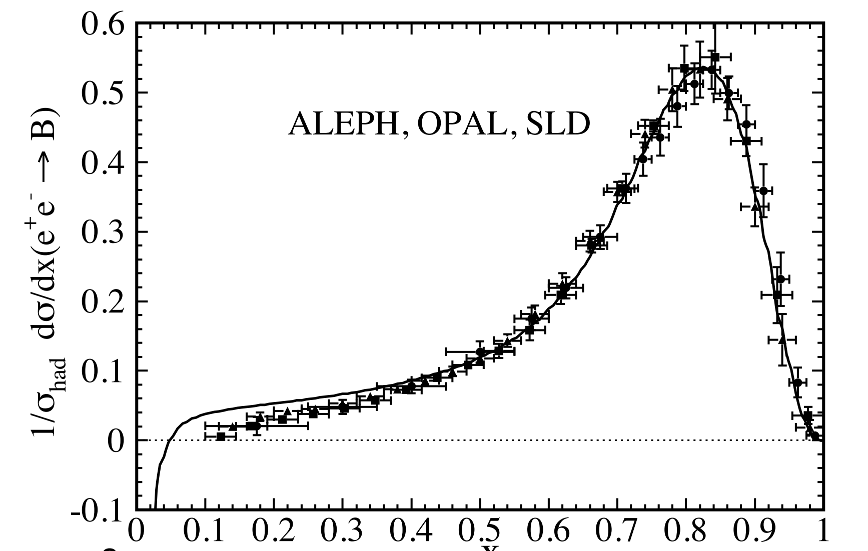
$$D_h(z,\mu_0^2) = N z^{-(1+\gamma^2)}(1-z)^a e^{-\gamma^2/z}$$

arXiv:0712.0481 [hep-ph]

FF ansatz for B-mesons

$$D_h(z,\mu_0^2) = N z^{\alpha}(1-z)^{\beta}$$

arXiv:0705.4392 [hep-ph]



$\chi^2/\text{d.o.f.} = 1.495$

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FONLL

- **FONLL approach to combination of massive & massless**

  hep-ph/9803400

  - Master formula

$$\sigma_{FONLL} = \sigma_{FO} + \left(\sigma_{RS} - \sigma_{FOm0}\right) \times G(m, p_T)$$

fixed order massive calculation
with 4 massless quarks

resummed massless result
with massless HQ

massless limit of the
massive result

  - Suppression factor to regulate a divergence in σ_{RS} for small p_T

$$G(m, p_T) = \frac{p_T^2}{p_T^2 + a^2 m^2}$$

  - Small modification to fixed-order result so that PDFs and strong coupling constant with $n_f = 5$ can be used

Add to $q\bar{q}$ - channel $\quad -\alpha_s \frac{2T_F}{3\pi} \log \frac{\mu^2}{m^2} \sigma^{(0)}_{q\bar{q}}$

Add to gg - channel $\quad -\alpha_s \frac{2T_F}{3\pi} \log \frac{\mu^2}{\mu_f^2} \sigma^{(0)}_{gg}$

FONLL

- **FONLL approach to combination of massive & massless**
  - Fragmentation approach in FONLL

hep-ph/0204025

$$D_i^H(z,\mu'_F) = D_i^Q(z,\mu'_F) \otimes D_Q^H(z)$$

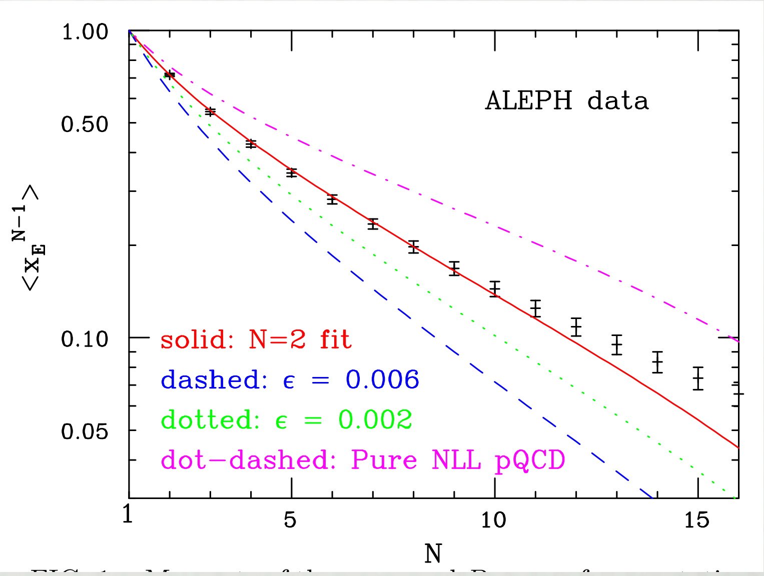
perturbative FF satisfying DGLAP evolution in the scale

non-perturbative part describes hadronisation of heavy quark into heavy hadron (fitted from LEP data)

  - Non-perturbative fragmentation fitted using moments

$$D_N \equiv \int D_Q^H(z)\, z^N \,\frac{dz}{z}$$

$$\frac{d\sigma}{dp_T} = \int dz d\hat{p}_T D_Q^H(z) \frac{A}{\hat{p}_T^N}\,\delta(p_T - z\hat{p}_T) = \frac{A}{p_T^N} D_N$$



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GM-VFNS & FONLL

- **NLO and NLL**
  - which order is included in GM-VFNS or FONLL

Resummed

$L = \ln(m/p_T)$
$a = \alpha_s/(2\pi)$

Fixed Order

	LL	NLL	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	a(aL)	a^2	
...	...	...	...	...

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Resummed

$L = \ln(m/p_T)$
$a = \alpha_s/(2\pi)$

Fixed Order

	LL	NLL	NNLL	...
LO	1 $m\neq0$			
NLO	aL $m\neq0$	a $m\neq0$		
NNLO	$(aL)^2$ $m=0$	$a(aL)$ $m=0$	a^2	
...	... $m=0$	... $m=0$	...	...

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POWHEG

- **POWHEG & MC generators**
  - Complicated machinery needed to go from QFT to simulating real exclusive events
  - A lot of moving parts
    - **hard matrix element**

      - QFT calculations using Feynman diagrams

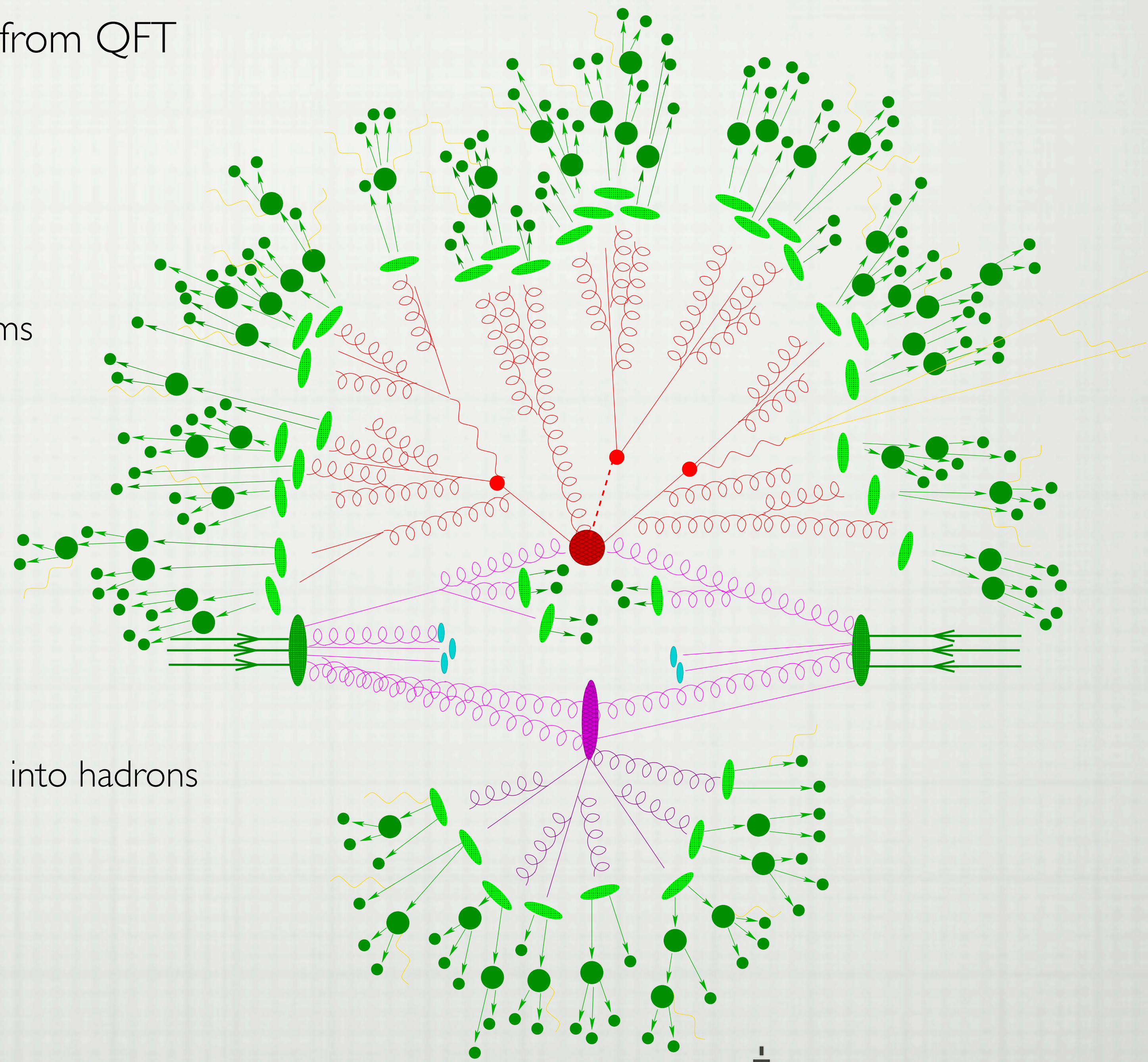
      - most rigorous part of MC
    - **parton showers**

      - generating soft & collinear radiation

      - makes ME more realistic
    - **hadronisation**

      - using color information to turn partons into hadrons

      - very model dependent
    - **underlying event**



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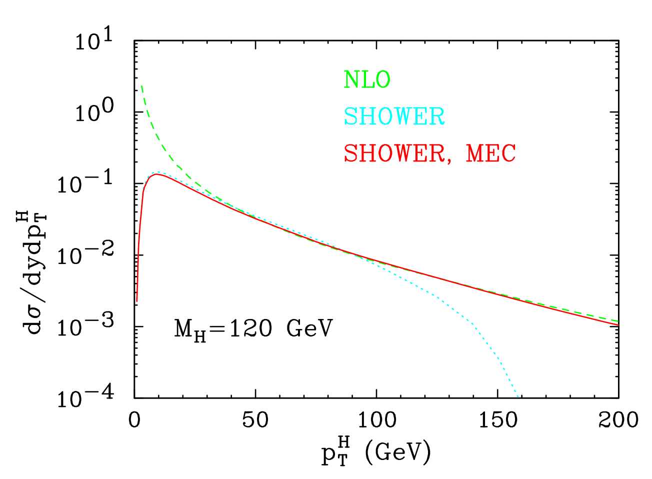
POWHEG

- **NLO cross-sections**
  - NLO cross-sections complicated objects - combining 2 types of processes
    - virtual (loop) corrections - containing UV & IR divergence

      - same phase-space as tree-level Φ_B
    - real emission corrections - containing IR divergence

      - phase-space with n+1 particles Φ_R



$$d\sigma = \Big(B(\Phi_B) + \hat{V}(\Phi_B)\Big) d\Phi_B + R(\Phi_R) d\Phi_R$$

  - Cancellation of UV divergence 'simple' through renormalization of couplings constants etc.
  - Cancellation of IR divergence only in sufficiently inclusive quantities (!)
  - To cancel IR singularities in each part separately, one introduces auxiliary subtraction terms & one has to factorize the phase-space $\Phi_R(\Phi_B, \Phi_{\rm rad})$

$$\sigma = \int d\Phi_B \Big[B(\Phi_B) + \hat{V}(\Phi_B) + \int d\Phi_{\rm rad} C(\Phi_R(\Phi_B, \Phi_{\rm rad}))\Big] + \int d\Phi_R \Big[R(\Phi_R) - C(\Phi_R)\Big]$$

  - Imperfect cancellation of singularities for exclusive quantities e.g. in a Monte Carlo

POWHEG

- **NLO cross-sections & parton shower**
  - How to use NLO cross-sections in parton showers ?
  - In parton shower language an equivalent of a NLO cross-section is a cross-section with one emission

$$d\sigma = d\Phi_B B(\Phi_B)\left(\Delta_i(t_I,t_0) + \sum_{(j,k)} \Delta_i(t_I,t)\frac{\alpha_s(t)}{2\pi}P_{i,jk}(z)\frac{dt}{t}dz\frac{d\phi}{2\pi}\right)$$

no emission

one emission

  - Expanding in α_s we get

$$d\sigma = d\Phi_B B(\Phi_B)\left(1 - \sum_{(j,k)}\int\frac{dt'}{t'}\int dz\frac{\alpha_s(t')}{2\pi}P_{i,jk}(z) + \sum_{(j,k)}\frac{\alpha_s(t)}{2\pi}P_{i,jk}(z)\frac{dt}{t}dz\frac{d\phi}{2\pi}\right)$$

virtual corrections

real corrections

  - Shower cross-section contains approximate virtual & real corrections in the collinear limit
    NOTE: Sudakov form-factor resums universal part of the virtual(!) correction
  - Goal of NLO Monte Carlos is to recover exact NLO cross-sections when we expand the parton shower cross-section in α_s

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POWHEG

- **POWHEG method**
  - Main idea - replace the parton shower approximation for no radiation and the first (hardest) emission by the full NLO calculation
  - Separate the real emission into singular and regular part

$$R = R^S + R^F$$

  - POWHEG cross-section with the hardest emission

$$d\sigma = d\Phi_B \bar{B}^S(\Phi_B)\left(\Delta^S_{t_0} + \Delta^S_t \frac{R^S(\Phi)}{B(\Phi_B)} d\Phi_{\text{rad}}\right) + R^F d\Phi_R$$

where the modified Born contains also the virtual corrections

$$\bar{B}^S = B + V + \int R^S d\Phi_{\text{rad}}$$

  - Modified Sudakov form-factor & modified shower generating emission only with lower p_T than the first emission

$$\Delta^S_t = \exp\left[-\int \theta(t_r - t)\frac{R^S(\Phi_B, \Phi_{\text{rad}})}{B(\Phi_B)} d\Phi_{\text{rad}}\right]$$

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POWHEG

- **POWHEG with heavy flavor** arXiv:0707.3088 [hep-ph]

  - NLO matrix element based on FFNS massive calculation (with 4 active flavors for bottom production)

  - Parton shower in the initial state resums only LL via the splittings in the Sudakov form-factor as opposed to NLL provided by NLO PDFs

  - Parton shower in the final state together with the hadronisation model provides a different (exclusive) information equivalent to the fragmentation function approach (inclusive)

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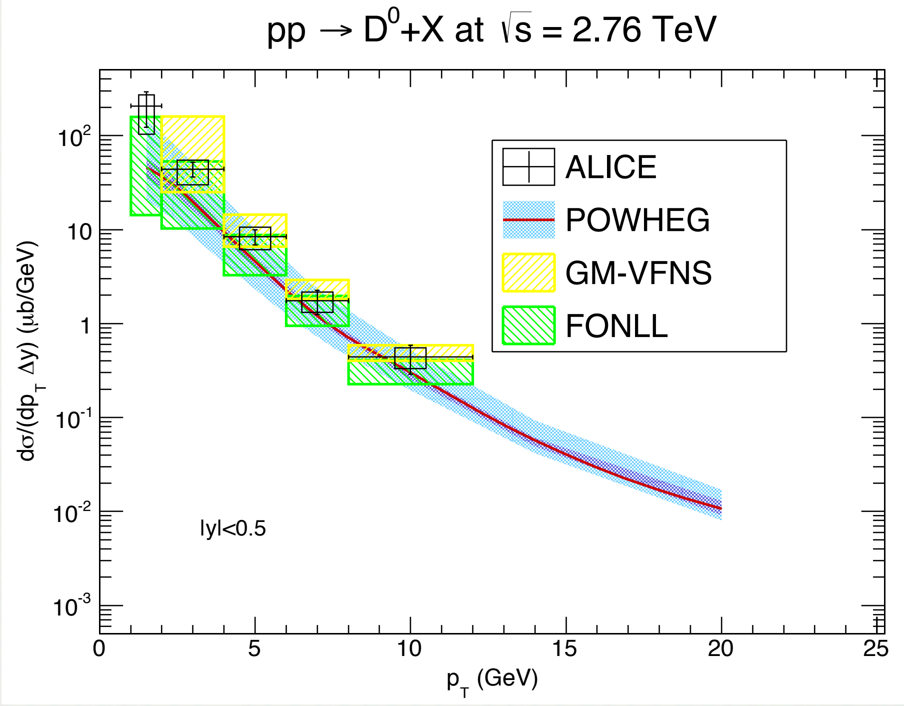
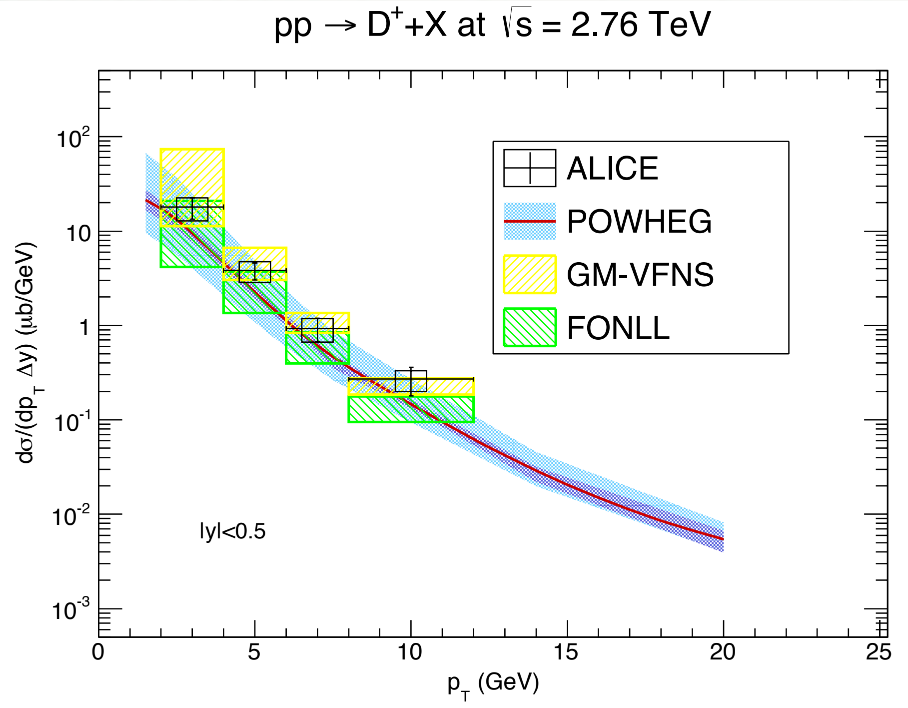
3. Results and comparison of the methods with ALICE data

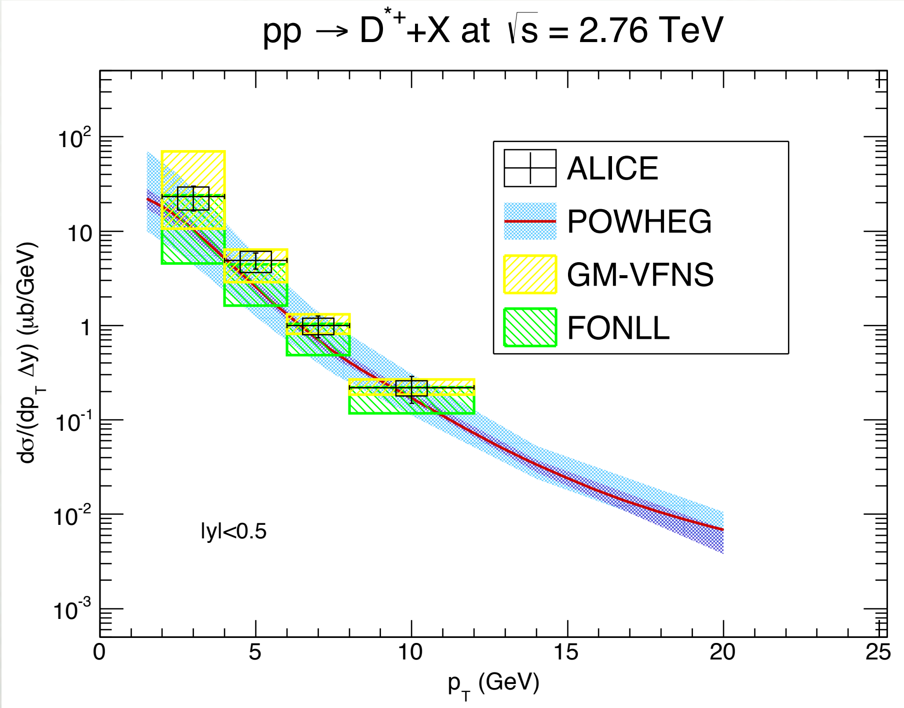
Results

- **Comparison with ALICE data**
  - Single inclusive production @ $\sqrt{s} = 2.76$ TeV and central rapidity $|y| < 0.5$
  - Scales are chosen as $\mu = \mu_f = \sqrt{m^2 + p_T^2}$
  - Dominant theoretical uncertainty - scale uncertainty



arXiv:1205.4007 [hep-ex]

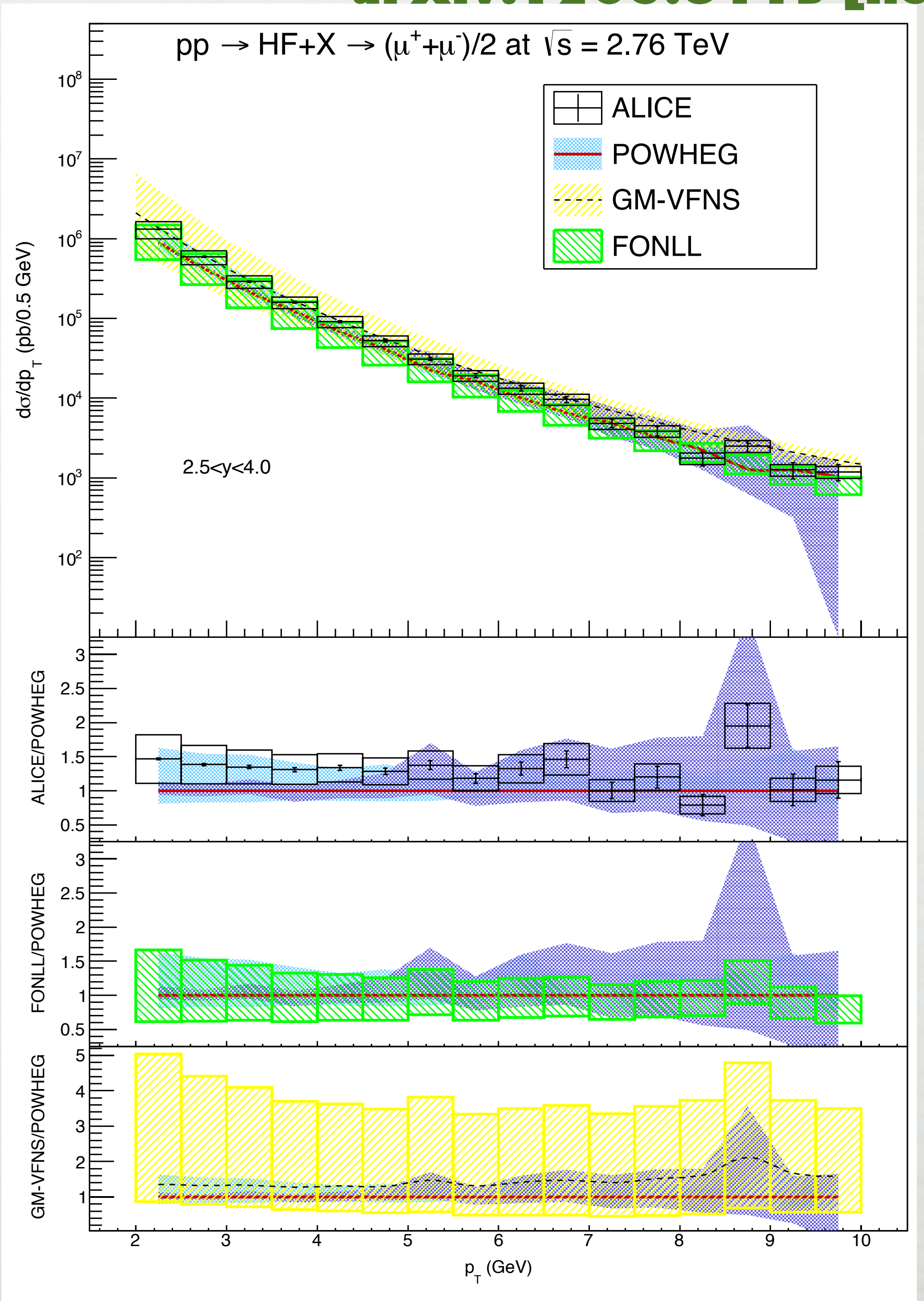




Results

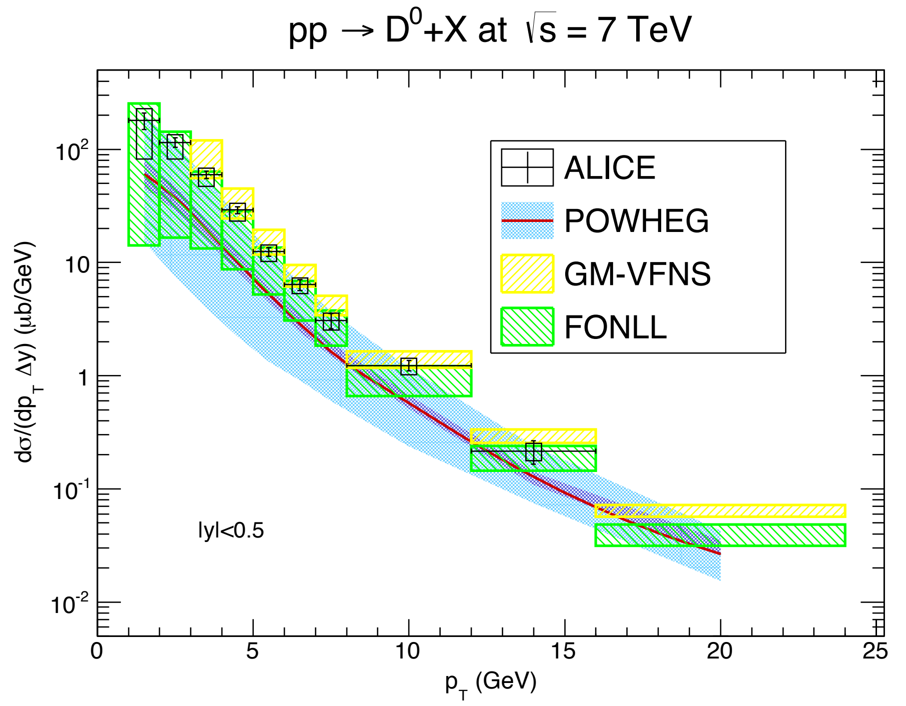
arXiv:1205.6443 [hep-ex]

- **Comparison with ALICE data**
  - Heavy flavor decay into muons @ $\sqrt{s} = 2.76$ TeV and forward rapidity $2.5 < y < 4.0$
  - heavy flavor (bottom & charm channels combined) decaying into muons
  - Dominant theoretical uncertainty
    - PDF uncertainty (included in the POWHEG)

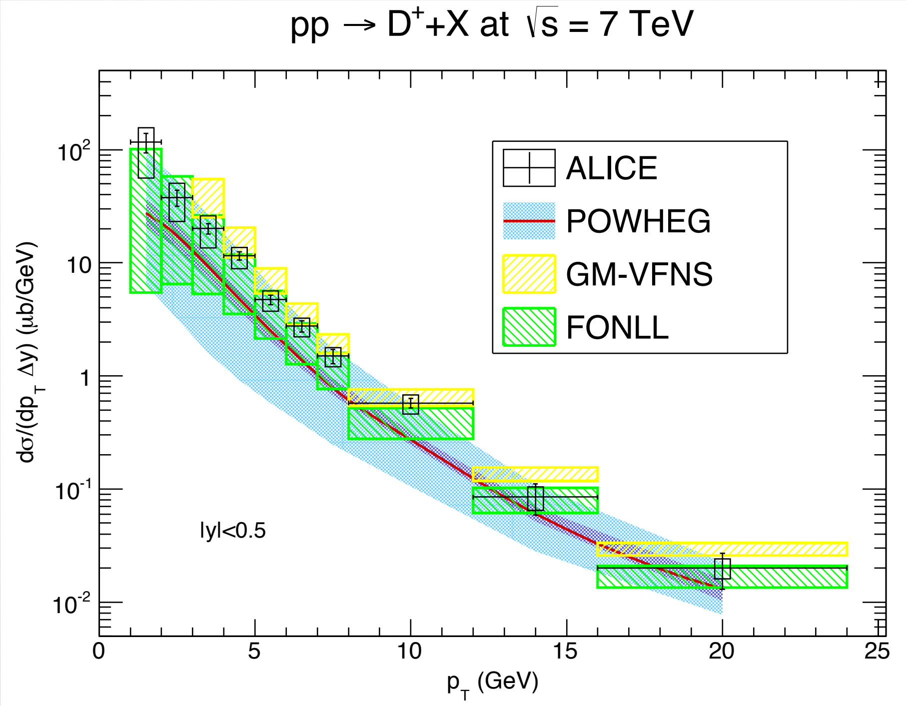


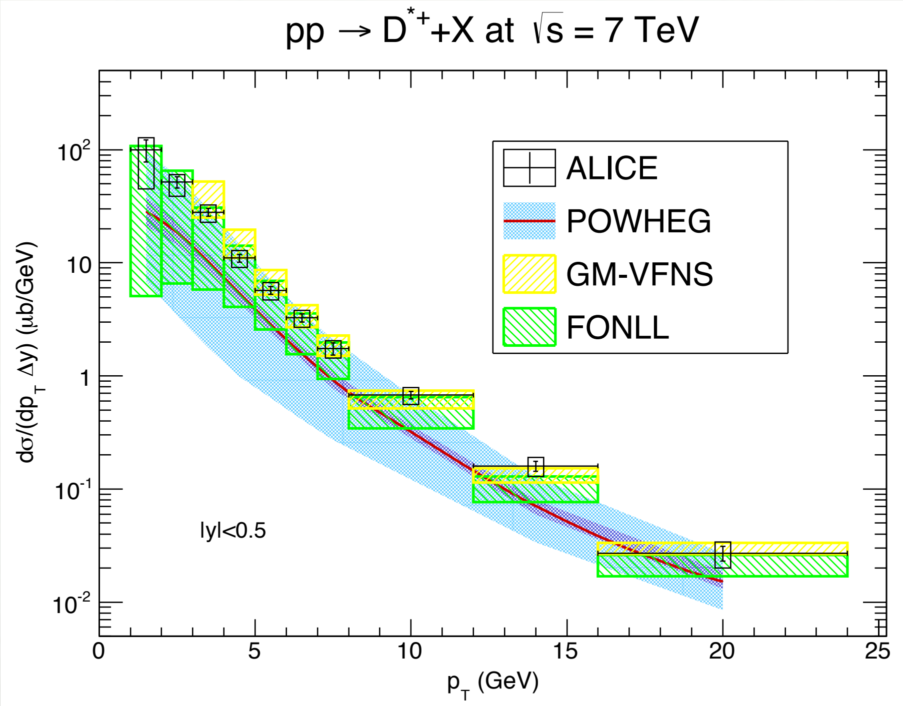
Results

- **Comparison with ALICE data**
  - Single inclusive production @ $\sqrt{s} = 7$ TeV and central rapidity $|y| < 0.5$
  - Dominant theoretical uncertainty - scale uncertainty



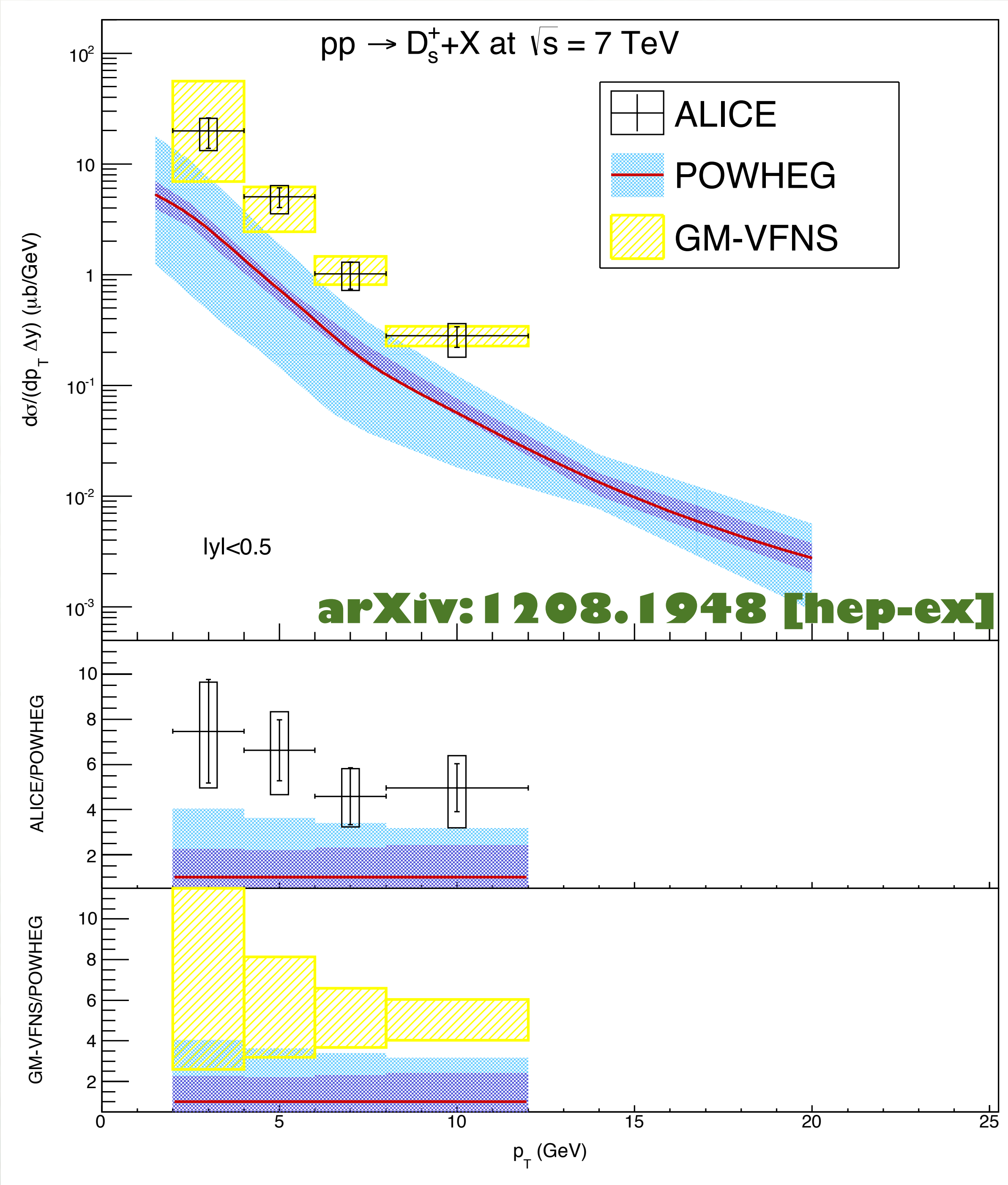
arXiv:1111.1553 [hep-ex]





Results

- **Comparison with ALICE data**
  - Single inclusive production @ $\sqrt{s} = 7$ TeV and central rapidity $|y| < 0.5$
  - Dominant theoretical uncertainty
    - scale uncertainty
  - Problem with the PYTHIA hadronization model in the presence of strange quark ?



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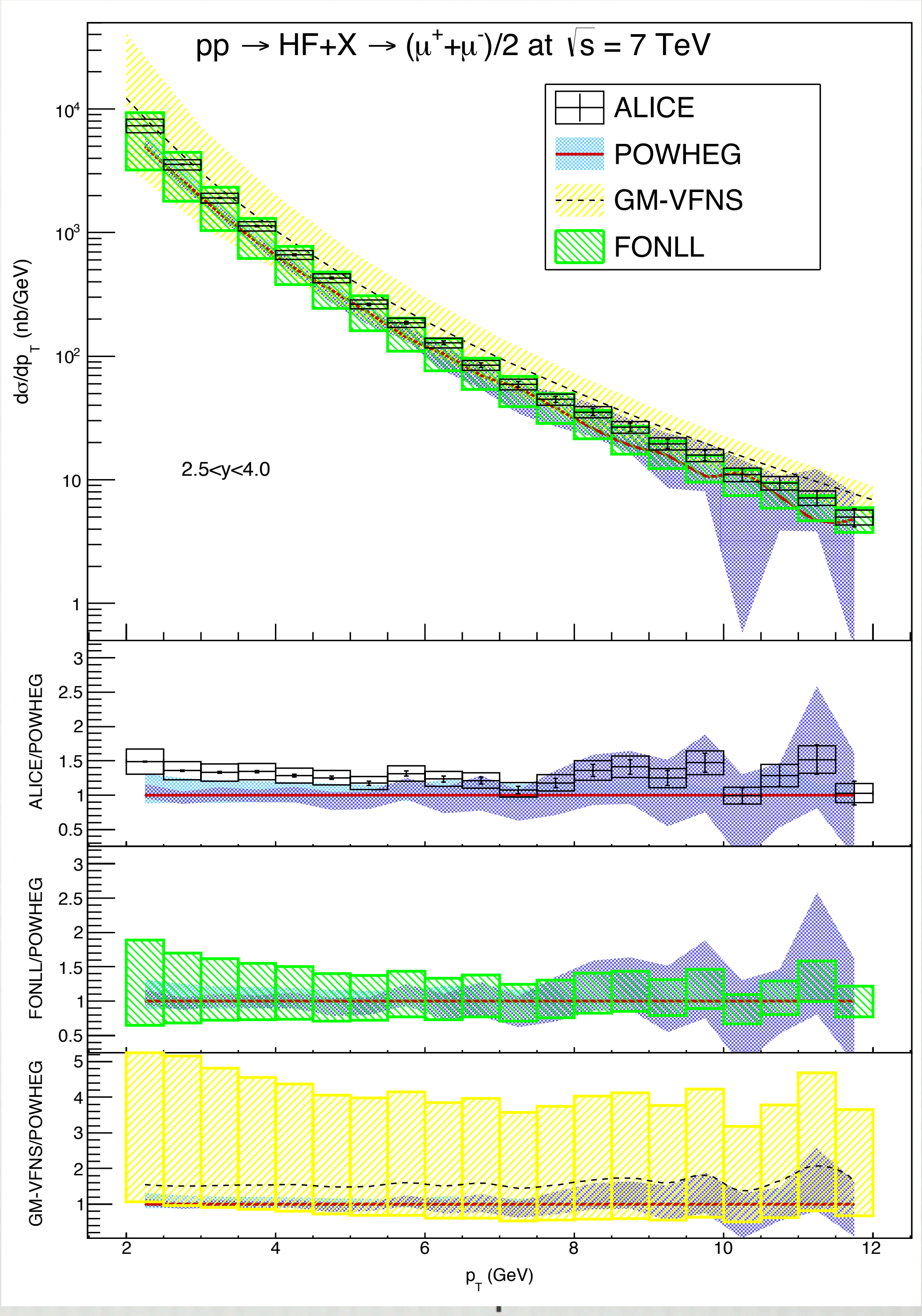
Results

Comparison with ALICE data

- Heavy flavor decay into muons @ $\sqrt{s} = 7$ TeV and forward rapidity $2.5 < y < 4.0$
- heavy flavor (bottom & charm channels combined) decaying into muons
- Dominant theoretical uncertainty
  - PDF uncertainty (included in the POWHEG)

arXiv:1201.3791 [hep-ex]



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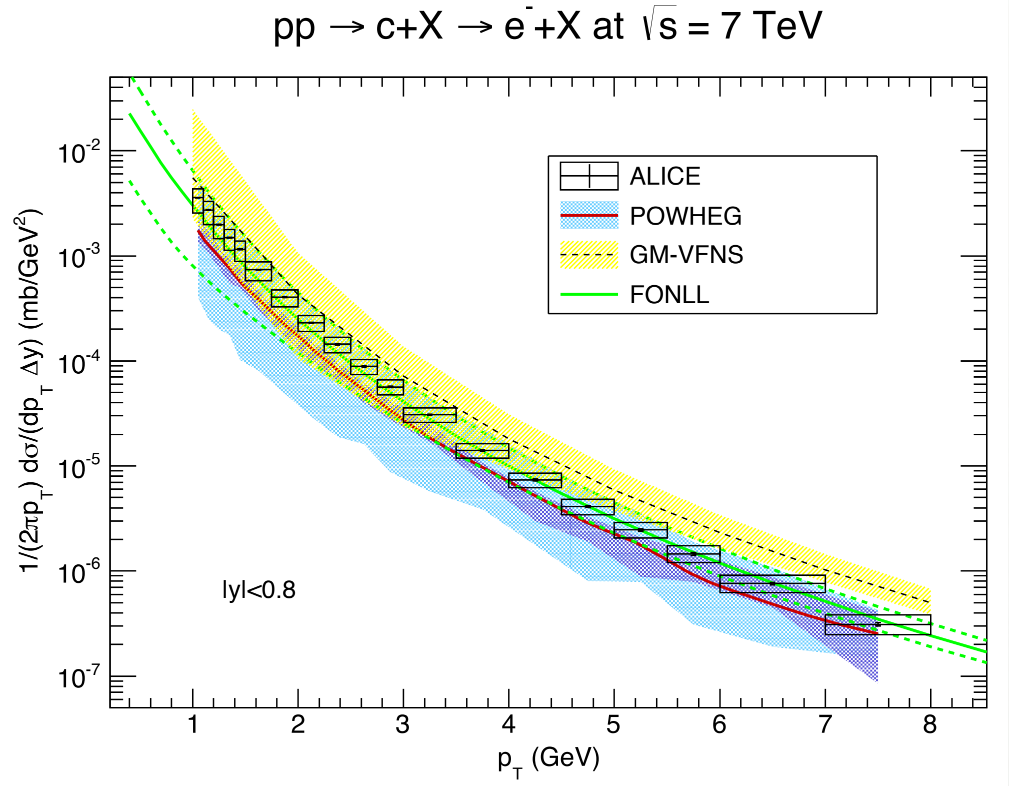
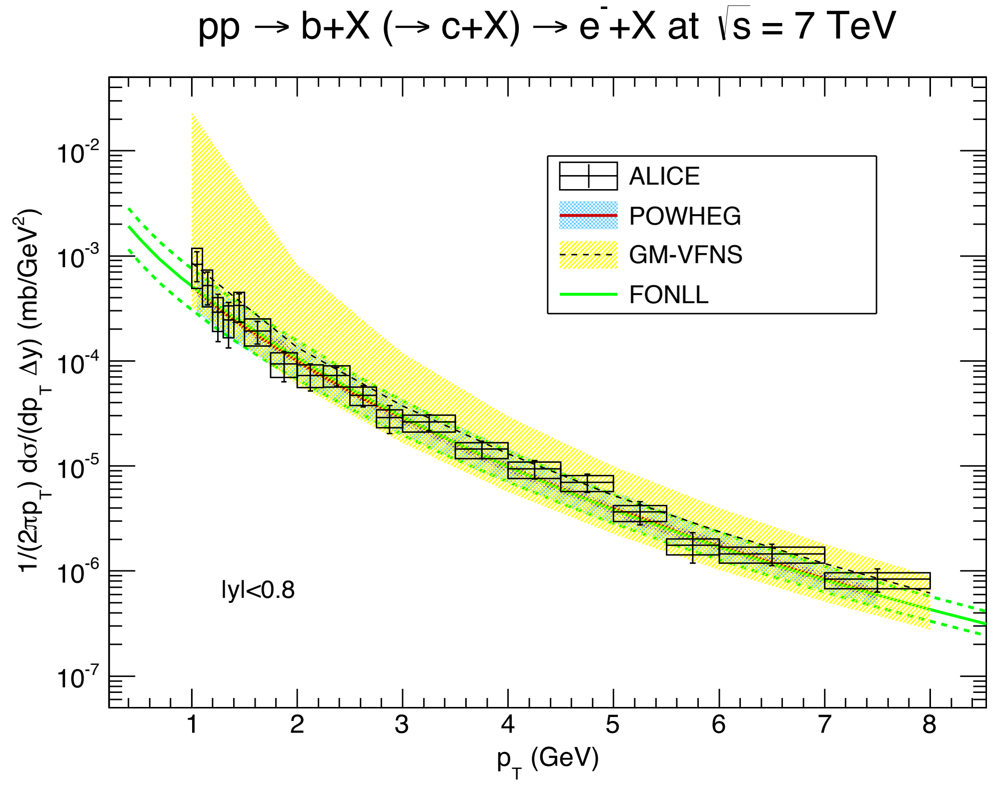
Results

- **Comparison with ALICE data**
  - Heavy flavor decay into electrons @ $\sqrt{s} = 7$ TeV and central rapidity $|y| < 0.8$
  - In GM-VFNS the decay of a B-hadron into lepton parametrized as a "lepton fragmentation"

$$D_{i\to l}(x,\mu_F) = \int_x^1 \frac{dz}{z} D_{i\to B}\left(\frac{x}{z},\mu_F\right) \frac{1}{\Gamma_B}\frac{d\Gamma}{dz}(z,P_B).$$

arXiv:1212.4356 [hep-ph]





arXiv:1208.1902 [hep-ex]

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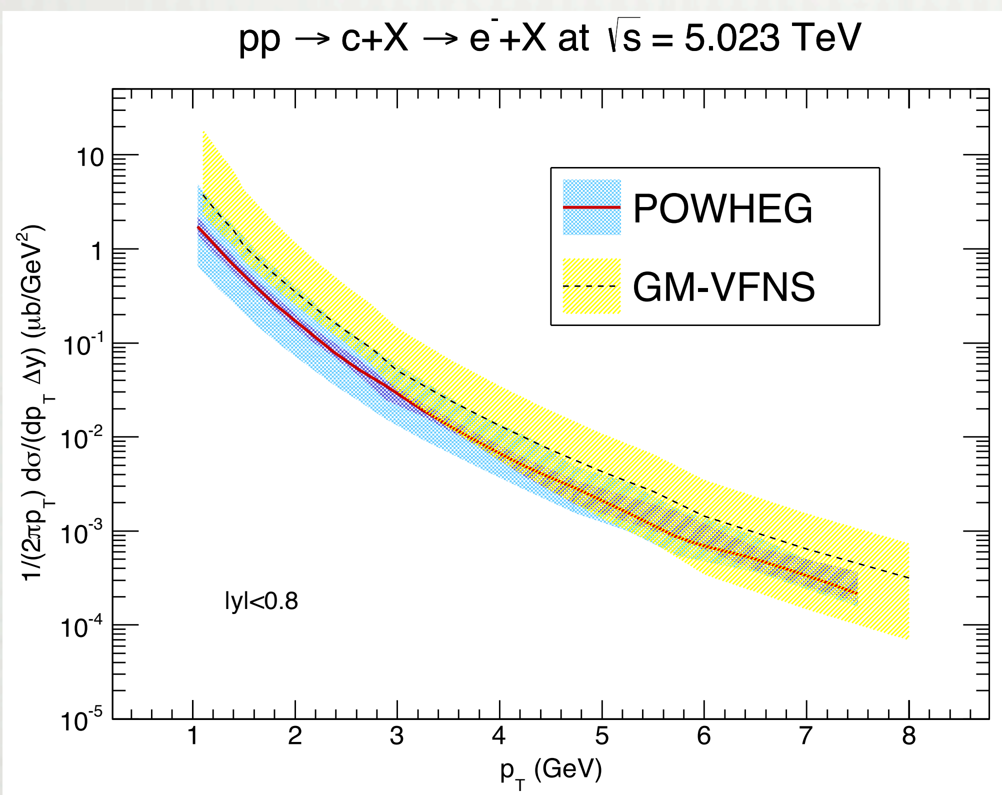
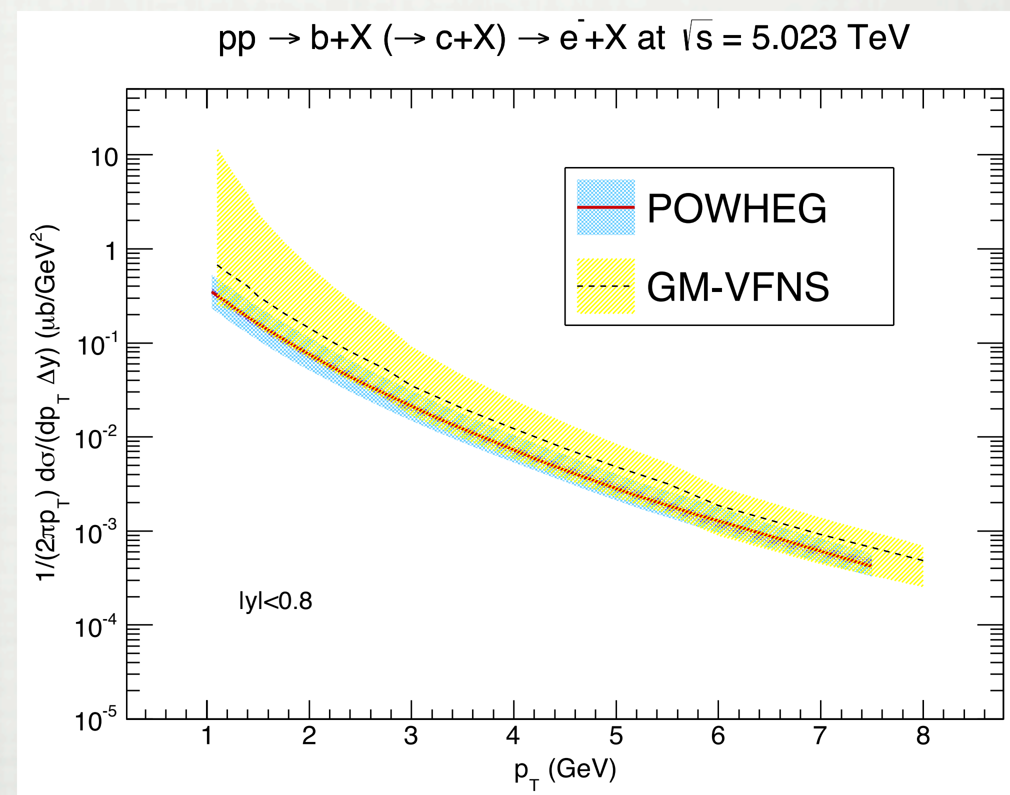
Results

- **Comparison with ALICE data**
  - Heavy flavor decay into electrons @ $\sqrt{s} = 5.023$ TeV and central rapidity $|y| < 0.8$
  - Possible baseline for future heavy quark production measurements in pPb collisions





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Conclusions

- All three methods describe the data within experimental and theoretical errors
- Different treatment of fragmentation functions might explain small discrepancies