Recent Developments in Quarkonium and Open Flavour Production Calculations

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Production and decay rates of Heavy Quarkonia

Heavy Quarkonia: Bound states of heavy quark and antiquark.

- Charmonia ($c\bar{c}$) and Bottomonia ($b\bar{b}$)
- Top decays to fast for bound state.

The classic approach: Color-singlet model

- Calculate cross section for heavy quark pair in physical **color singlet** (=color neutral) state. In case of J/ψ: $c\bar{c}[^3S_1^{[1]}]$
- Multiply by quarkonium wave function (or its derivative) at origin
- Mid 90's: Strong disagreement with Tevatron data apparent

Nonrelativistic QCD (NRQCD):

- Rigorous effective field theory: Bodwin, Braaten, Lepage (1995)
- Based on **factorization of soft and hard scales** (Scale hierarchy: $Mv^2, Mv \ll \Lambda_{QCD} \ll M$)
- Could explain hadroproduction at Tevatron

J/ψ Production with NRQCD

Factorization theorem: $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \cdot \langle O^{J/\psi}[n] \rangle$

- ***n***: Every possible Fock state, including **color-octet** states.
- $\boldsymbol{\sigma_{c\bar{c}[n]}}$: Production rate of $c\bar{c}[n]$, calculated in perturbative QCD
- $\boldsymbol{\langle O^{J/\psi}[n] \rangle}$: Long distance matrix elements (LDMEs): describe $c\bar{c}[n] \rightarrow J/\psi$, universal, extracted from experiment.

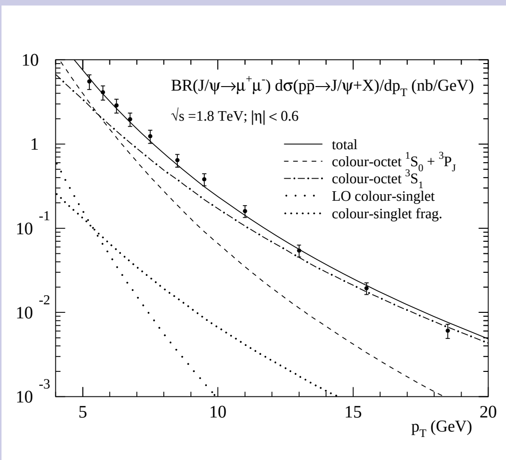
Scaling rules: LDMEs scale with definite power of v ($v^2 \approx 0.2$):

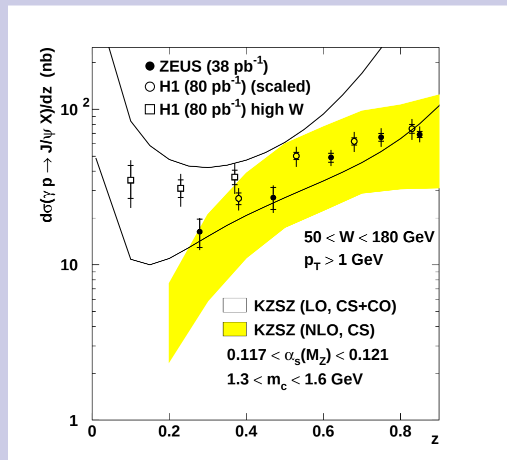
scaling	v^3	v^7	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$	...

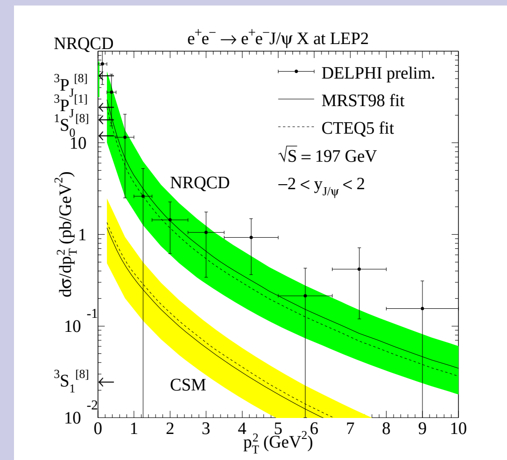
- **Double expansion** in v and α_s
- Leading term in v ($n = {}^3S_1^{[1]}$) equals **color-singlet model**.

J/ψ Production with NRQCD: Knowledge until 2005

Hadroproduction at Tevatron:	**Photoproduction at HERA:**	**γγ Scattering at LEP:**







- CO LDMEs extracted from **Born fit to Tevatron** (one linear combination). Used for predictions at HERA and LEP.
- No **NLO** calculations for color-octet (CO) contributions yet!
- **Universality** of CO LDMEs open question.

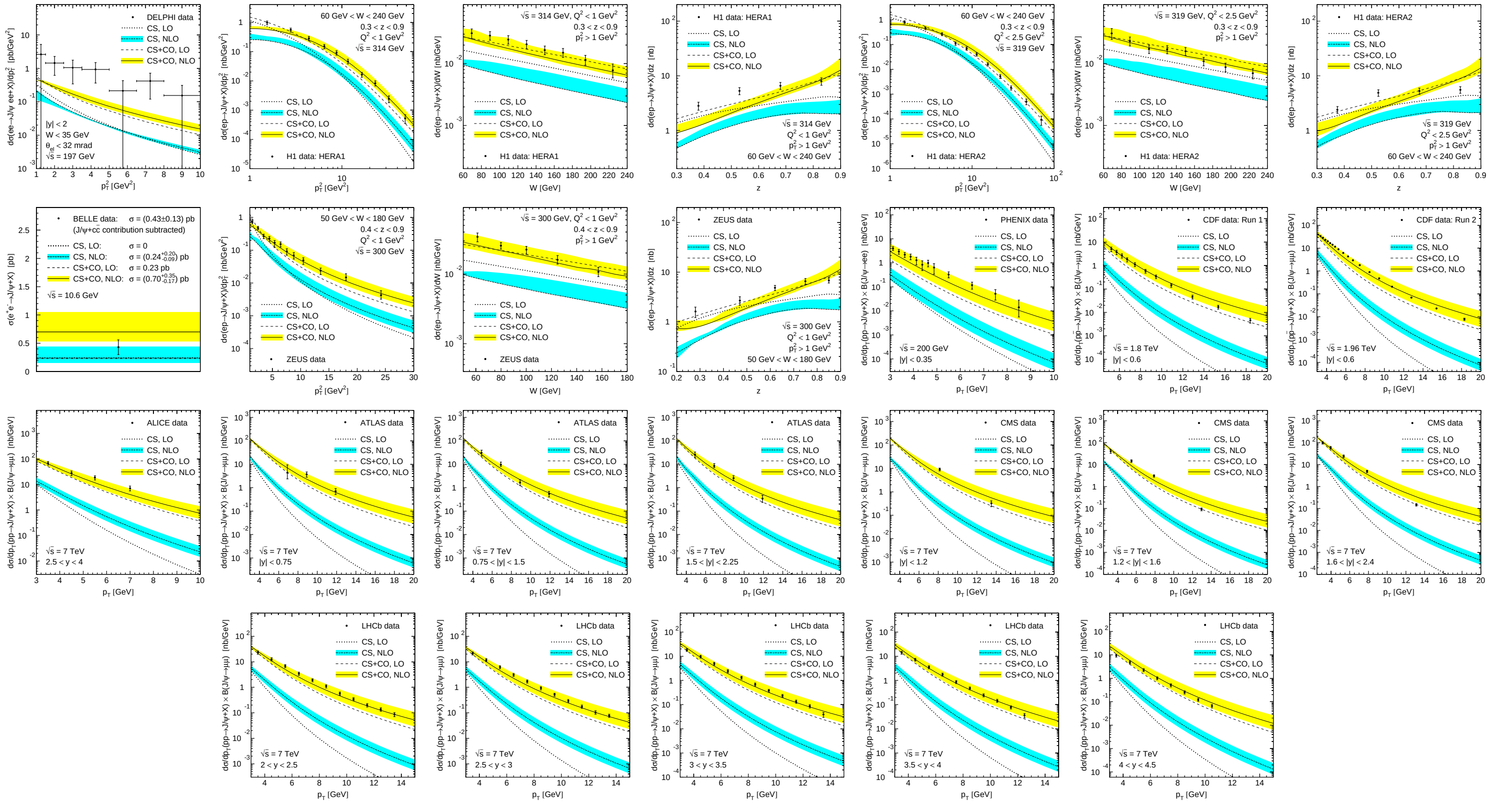
NLO Corrections to Color Octet Contributions

- Petrelli, Cacciari, Greco, Maltoni, Mangano (1998):
  Photo- and hadroproduction (Only 2 → 1 processes)
- Klasen, Kniehl, Mihaila, Steinhauser (2005):
  γγ scattering at LEP (neglecting resolved photons)
- M.B., Kniehl (2009):
  Photoproduction at HERA (neglecting resolved photons)
- Zhang, Ma, Wang, Chao (2009):
  e^+e^- scattering at *B* factories
- Ma, Wang, Chao (2010):
  Hadroproduction (including feed-down contributions)
- M.B., Kniehl (2010):
  Hadroproduction (combined HERA-Tevatron fit)

Necessary: A rigorous **global** data analysis!

Only recently: Fit CO LDMEs to 194 data points from 10 experiments.
➡ Test LDME universality. [M.B., Kniehl (2011)]

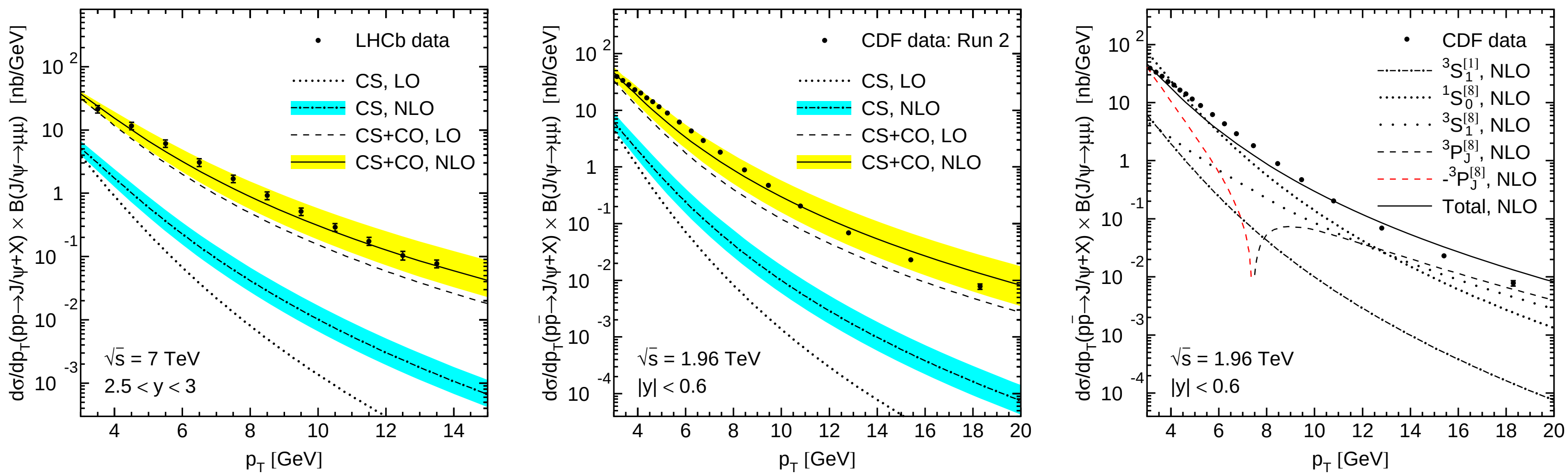
M.B., Kniehl (2011): Global Fit of CO LDMEs



$<O[^1S_0^{[8]}]> = (4.97 \pm 0.44)\cdot 10^{-2}\ \mathrm{GeV}^3$ $<O[^3S_1^{[8]}]> = (2.24 \pm 0.59)\cdot 10^{-3}\ \mathrm{GeV}^3$

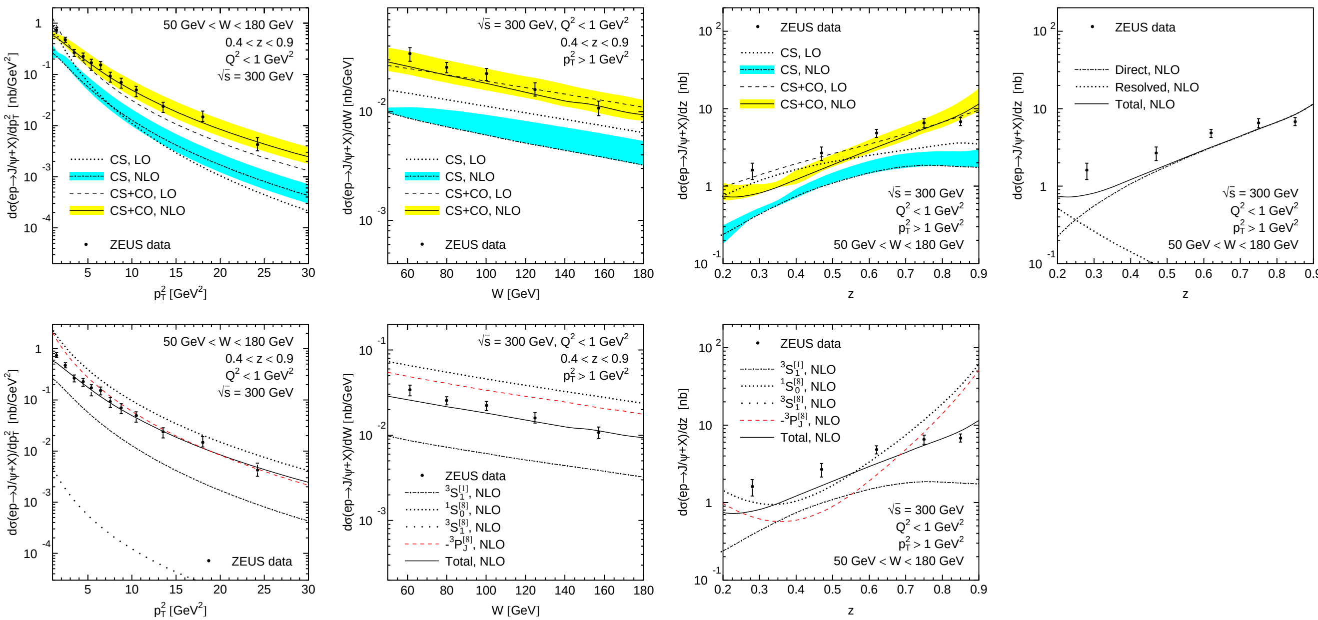
$<O[^3P_0^{[8]}]> = (-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$

In Detail: Hadroproduction (LHC, Tevatron)



- Color singlet model **not enough** to describe data (although increase from Born to NLO)
- **CS+CO** can describe data.
- ${}^3P_J^{[8]}$ short distance cross section **negative** at $p_T > 7$ GeV.
- But: Short distance cross sections and LDMEs **unphysical**
  ➡ No problem!

In Detail: Photoproduction (HERA)

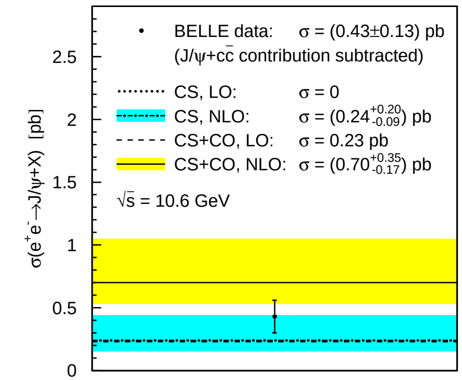


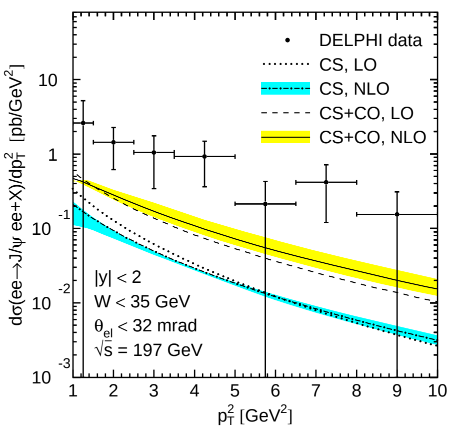
- **Photoproduction** = Photon-proton scattering in *ep* collider
- **Distributions:** Transverse momentum (p_T), photon-proton c.m. energy (W), and z = Fraction of photon energy going to J/ψ.
- Again: Color singlet alone **below** the data, **CS+CO** describes data well.
- Calculation includes **resolved** photon contributions: Important at low z.

In Detail: e^+e^- and $\gamma\gamma$ Collisions

Electron-Positron Collisions at BELLE:

- CS: Large overlap with data, CS+CO: Small overlap.
- Experimentally measurement of total cross section difficult, discrepancies between BELLE and BABAR .
- For e^+e^- color singlet, NNLO terms been calculated, increasing cross section. Not part of the global fit. [Ma, Zhang, Chao (2009); Gong, Wang (2009)]



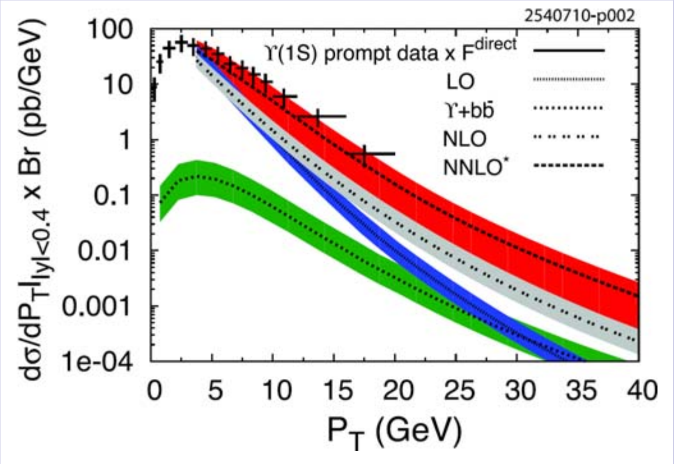


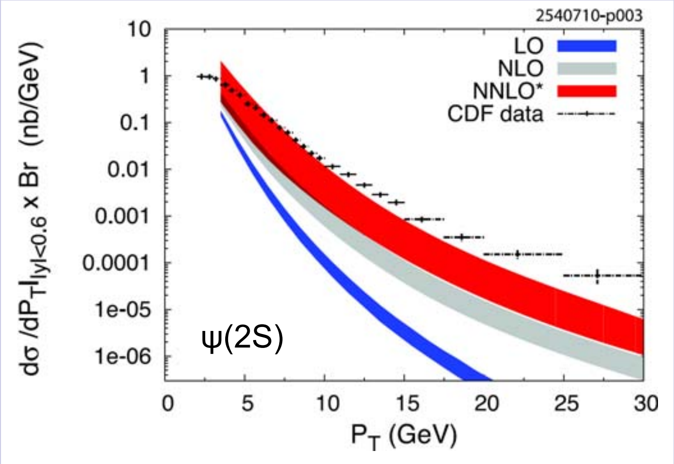
Two Photon scattering at DELPHI (LEP):

- Includes direct, single and double resolved photons.
- CS below data, but also **CS+CO** prediction **too low**. Possible explanations:
  - Uncertainties in the measurement (Just 16 events involved!)
  - Hint at problems with LDME universality.

Improve the Color Singlet Model: “NNLO*”

- **Idea:** At large p_T gluon fragmentation channels dominate, but in CSM is **NNLO** process. ➡ Try to estimate these and similar contributions without performing full NNLO calculation.
- **NNLO*:** Consider only tree level $p\bar{p} \to QQ$ + 3 Jets and impose IR cutoffs.
- **Result:** For bottomonium ϒ(1S) and charmonium ψ(2S), color singlet contributions might be enough to describe data [Artoisenet, Campbell, Lansberg, Maltoni, Tramontano (2008); Lansberg (2009)]:

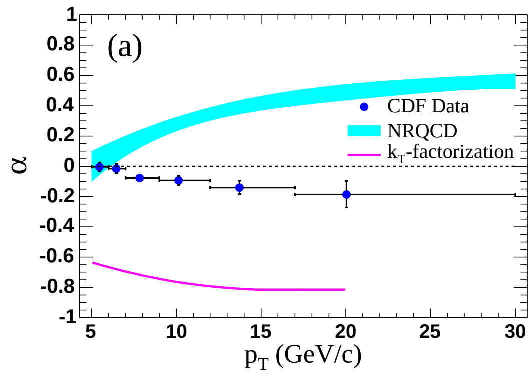


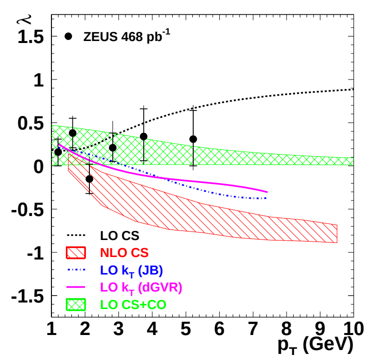


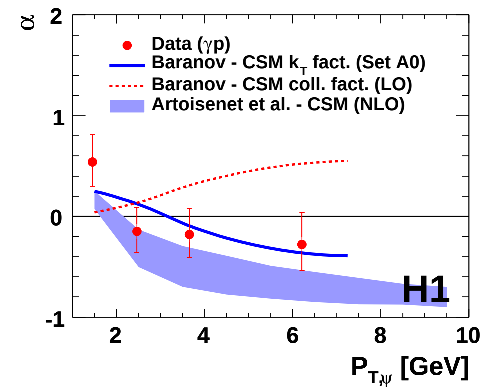
Status for *J/ψ* Polarization

Available calculations for photo- and hadroproduction:

- **NLO color singlet model** predictions [Gong, Wang (2008); Artoisenet, Campbell, Maltoni, Tramontano (2009); Chang, Li, Wang (2009)]
- ***k_T* factorization** predictions [Baranov (2002); Baranov (2008)]
- **Color octet** contributions so far only at leading order.







- *α* or *λ* = -1 (+1): Fully longitudinally (transversely) polarized *J/ψ*.
- Still large **theoretical and experimental uncertainties**. LHC data awaited.
- Will be **crucial** observable to distinguish production mechanisms.

Open Flavour Production

Open flavour production: (D, B, Λ, ...)

- Hadrons with one heavy quark (c, b) and one or two light quarks (u, d, s)
- Production through fragmentation of outgoing QCD partons.

Two traditional methods: (Example: Heavy quark c)

- Fixed-Flavour-Number-Scheme (FFNS):
  - Incoming quarks: u, d, s ($m = 0$). Outgoing: u, d, s ($m = 0$), c ($m = m_c$)
  - Reliable only at $m_c^2 \lesssim p_T^2$, because of $\log(p_T^2/m_c^2)$ terms.
- Zero-Mass-Variable-Flavour-Number scheme (ZM-VFNS):
  - Incoming quarks: u, d, s, c ($m = 0$). Outgoing: u, d, s, c ($m = 0$)
  - Reliable only at $m_c^2 \ll p_T^2$, because of missing mass terms.

Interpolating schemes: Combining FFNS and ZM-VFNS:

- General-Mass-Variable-Flavour-Number-Scheme (GM-VFNS)
- Fixed-Order NLL scheme (FONLL)

S-ACOT: Theoretical Basis for the GM-VFNS

Factorization Formula: [1]

$$d\sigma(p\bar{p} \to DX) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_{i/p}(x_1, \mu_F)\, f_{j/\bar{p}}(x_2, \mu_F) \times \mathrm{d}\hat{\sigma}_{ij\to kX}\left(\mu_F, \mu_F', \alpha_s(\mu_R), \frac{m_c}{p_T}\right) D_k^D(z, \mu_F')$$

- $\mathrm{d}\hat{\sigma}_{ij\to kX}\left(\mu_F, \mu_F', \alpha_s(\mu_R), \frac{m_c}{p_T}\right)$: Hard scattering cross sections. Heavy quark mass m_c kept.
- PDFs $f_{i/p}(x_1, \mu_F)$, $f_{j/\bar{p}}(x_2, \mu_F)$: $i, j = g, u, d, s, c$
- FFs $D_k^D(z, \mu_F')$: $k = g, u, d, s, c$
- Factorization and PDF/FF DGLAP evolution like in zero-mass case. [1]

$\Longrightarrow$ Need short distance coefficients including heavy quark masses.

[1] J. Collins, 'Hard-scattering factorization with heavy quarks: A general treatment', PRD58(1998)094002

GM-VFNS: List of Subprocesses

	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

GM-VFNS: Heavy Quark Mass Terms

Mass terms contained in the hard scattering coefficients:

$$d\hat{\sigma}(\mu_F, \mu_{F'}, \alpha_s(\mu_R), \frac{m_Q}{p_T})$$

Two ways to derive them:

1. Compare massless limit of a massive fixed-order calculation
   with a massless $\overline{\text{MS}}$ calculation
   to determine subtraction terms
   [Kniehl, Kramer, Schienbein, Spiesberger, PRD71(2005)014018]

OR:

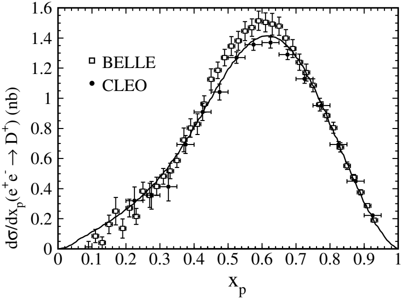
2. Perform mass factorization using partonic (perturbative) PDFs and FFs
   [Kniehl, Kramer, Schienbein, Spiesberger, EPJC41(2005)199]

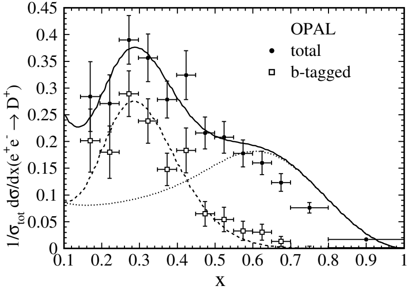
GM-VFNS: Applications

Applications available for

- $\gamma + \gamma \rightarrow D^{*\pm} + X$
  direct and resolved contributions — EPJC22, EPJC28
- $\gamma^* + p \rightarrow D^{*\pm} + X$
  photoproduction — EPJC38, EPJC62
- $p + \bar{p} \rightarrow (D^0, D^{*\pm}, D^\pm, D_s^\pm, \Lambda_c^\pm) + X$
  good description of Tevatron and new LHC data — PRD71, PRL96, PRD79
- $p + \bar{p} \rightarrow B + X$
  works for Tevatron data at large p_T — PRD77
- work in progress for $e + p \rightarrow D + X$

Fitting the Fragmentation Functions (KKKSc)





FFs for $c \to D$
from fitting to e^+e^- data

2008 analysis based on GM-VFNS
$\mu_0 = m_c$

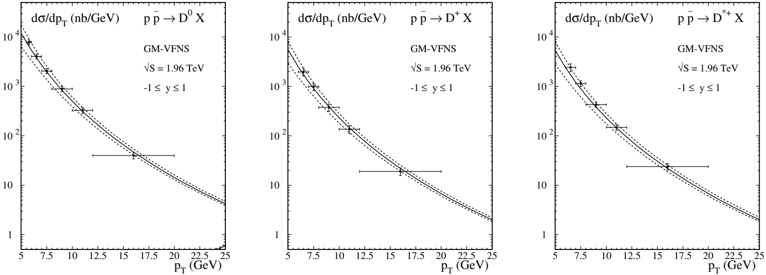
Global fit: Data from
ALEPH, OPAL, BELLE, CLEO

[Kneesch, Kramer, Kniehl, Schienbein
NPB799 (2008)]

Tension between low and high energy data sets $\to$ Speculations about non-perturbative (power-suppressed) terms

HADROPRODUCTION OF D^0, D^+, D^{*+}, D_s^+ AT TEVATRON

- GM-VFNS results using KKKSc FFs [1]:



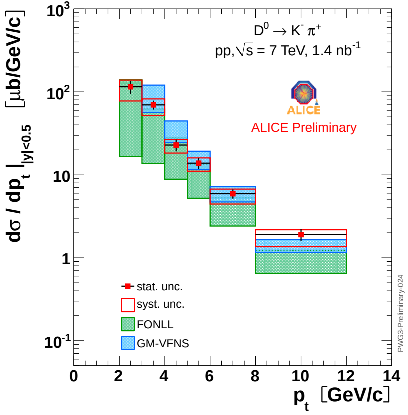
- $d\sigma/dp_T$ [nb/GeV] $|y| \leq 1$, prompt charm ($b \to D$ subtracted)
- Uncertainty band: $1/2 \leq \mu_R/m_T, \mu_F/m_T \leq 2 \quad (m_T = \sqrt{p_T^2 + m_c^2})$
- CDF data from run II [2]
- GM-VFNS describes data within errors.

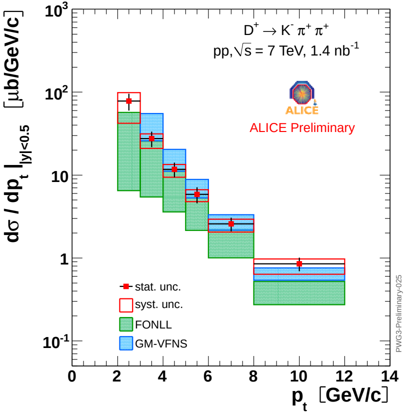
[1] Kniehl, Kramer, Schienbein, Spiesberger, PRD79(2009)094009

[2] Acosta et al., PRL91(2003)241804

ALICE: D^0 and D^+ Cross Sections

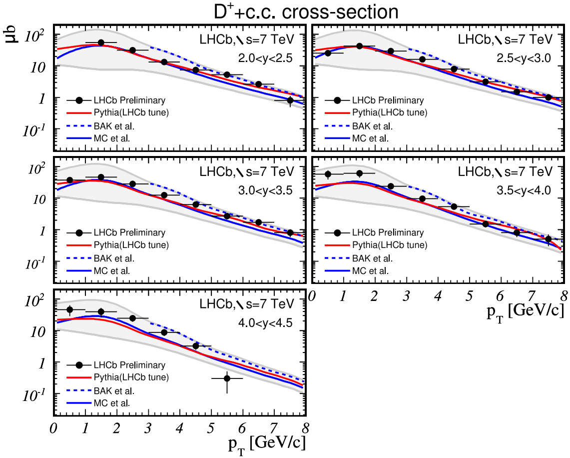
- Prelim. results presented by A. Dainese at LHC Physics Day, 3. Dec. 2010:





- Both FONLL and GM-VFNS predictions compatible with data.

- Prelim. results for $D^+ \to K^-\pi^+\pi^+$. Data: 14 % correlated error not shown.



- BAK et al.= GM-VFNS: Kniehl, Kramer, Schienbein, Spiesberger
- MC et al.= FONLL: Cacciari, Frixione, Mangano, Nason, Ridolfi

THE SUMMARY

Production of heavy quarkonia:

- NRQCD provides rigorous factorization theorem for production of quarkonia. But: Necessary to proof LDME universality.
- Recent global NLO analysis: All inclusive J/ψ production data except $\gamma\gamma$ can be described by NRQCD with unique CO LDME set.
- Color singlet alone falls short of data everywhere except in e^+e^-.
- LHC results coming in for J/ψ polarization, higher charmonia and bottomonia.

Open flavour production:

- Two schemes interpolating between FFNS (low p_T) and ZM-VFNS (high p_T): FONLL and GM-VFNS.
- Both schemes can describe D, B and Λ photo- and hadroproduction data well.
- FONLL also applicable for $p_T < 2m_Q$ region.
- Factorization theorem of GM-VFNS on more solid theoretical ground.