Summary of the Heavy Flavours Working Group

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HF WG: Theory Talks

- **DIS** structure functions: Blümlein, Olness, Moch
- **Open c, b**:
    - Inclusive D and B mesons: Spiesberger
    - Jet production in the ACOT scheme: Kotko
    - Photon+Q: Kovarik
    - kT factorization + double parton scattering: Szczurek
- **Charmonium** production and polarization in NRQCD: Kniehl
- **Top**: Yang, Mitov, Bierenbaum, Kidonakis, Moch, Kardos

DIS structure functions at $O(\alpha_S^3)$

DIS structure functions F_2^c, F_L^c

Charm contribution to the inclusive structure functions in fixed order:

Heavy quark Wilson coefficient known to $O(\alpha_S^2)$ [Laenen, Riemersma, Smith, Neerven '93]

PDFs

$$F^c(x,Q^2) = H_j(x, \frac{Q^2}{\mu^2}, \frac{m^2}{\mu^2}) \otimes f_j(x,\mu^2)$$

Mass factorization for $Q^2 >> m^2$:

$$H_j = C_i(x, \frac{Q^2}{\mu^2}) \otimes A_{ij}(x, \frac{m^2}{\mu^2})$$

light flavor Wilson coefficients; known to $O(\alpha_S^3)$ [Moch, Vermaseren, Vogt, NPB96]

OME's; Known to $O(\alpha_S^2)$ [BMNS, NPB96] **Needed** at $O(\alpha_S^3)$

Talk by Johannes Blümlein

Recent results on Three Loop Corrections to F_2^c, F_L^c

Mellin N space: $$H_j = C_i(N, \frac{Q^2}{\mu^2}) A_{ij}(\frac{m^2}{\mu^2}, N)$$ (for $Q^2 >> m^2$)

Partial results for A_{ij} $O(\alpha_S^3)$

Variable Flavor Number Scheme

Main application: Matching conditions for the VFNS needed in global analyses of PDFs

$$f_i^{(n_f+1)}(x, \mu^2) = A_{ij}(x, \frac{m^2}{\mu^2}) \otimes f_j^{(n_f)}(x, \mu^2)$$

Talk by Johannes Blümlein

Status of OME calculations

Leading Order: [Witten, 1976 Nucl.Phys.B; Babcock, Sivers, 1978 Phys.Rev.D; Shifman, Vainshtein, Zakharov, 1978 Nucl.Phys.B; Leveille, Weiler, 1979 Nucl.Phys.B; Glück, Reya, 1979 Phys.Lett.B; Glück, Hoffmann, Reya, 1982 Z.Phys.C.]

Next-to-Leading Order : [Laenen, van Neerven, Riemersma, Smith, 1993 Nucl. Phys. B]
[Large Q^2/m^2: Buza, Matiounine, Smith, Migneron, van Neerven, 1996 Nucl.Phys.B] IBP
[Bierenbaum, Blümlein, Klein, 2007 Nucl.Phys.B] via ${}_pF_q$'s, more compact results
[Bierenbaum, Blümlein, Klein 2008 Nucl.Phys.B, 2009 Phys.Lett.B]:$O(\alpha_s^2\varepsilon)$ contributions (all N)

NNLO:[Bierenbaum, Blümlein, Klein 2009 Nucl.Phys.B] Moments for F_2: $N = 2...10(14)$
[Blümlein, Klein, Tödtli 2009 Phys. Rev. D] contrib. to transversity: $N = 1...13$
[Ablinger, Blümlein, Klein, Schneider, Wißbrock 2011 Nucl.Phys.B] contrib. $\propto n_f$ to F_2 (all N):

At 3-loop order known:

- $A_{qq,Q}^{\mathrm{PS}}$, $A_{qg,Q}$: complete
- A_{Qg}, A_{Qq}^{PS}, $A_{qq,Q}^{\mathrm{NS}} A_{qq,Q}^{\mathrm{NS,TR}}$: all terms of $O(n_f T_F^2 C_{A/F})$
- A_{Qq}^{PS}, $A_{qq,Q}^{\mathrm{NS}} A_{qq,Q}^{\mathrm{NS,TR}}$: all terms of $O(T_F^2 C_{A/F})$
- $A_{gq,Q}$, $A_{gg,Q}$: see this talk $\longrightarrow$ all terms of $O(n_f T_F^2 C_{A/F})$

Talk by Sven Moch

Plan

- Talk based on results on . . .
  - . . . improved heavy-quark coefficient functions at NNLO
    H. Kawamura , S.M., A. lo Presti and A. Vogt to appear
  - . . . a determination of the running charm-quark mass
    S. Alekhin , K. Daum , K. Lipka and S.M. to appear
  - . . . a spin-off on top-quark hadro-production
    S.M., P. Uwer and A. Vogt to appear

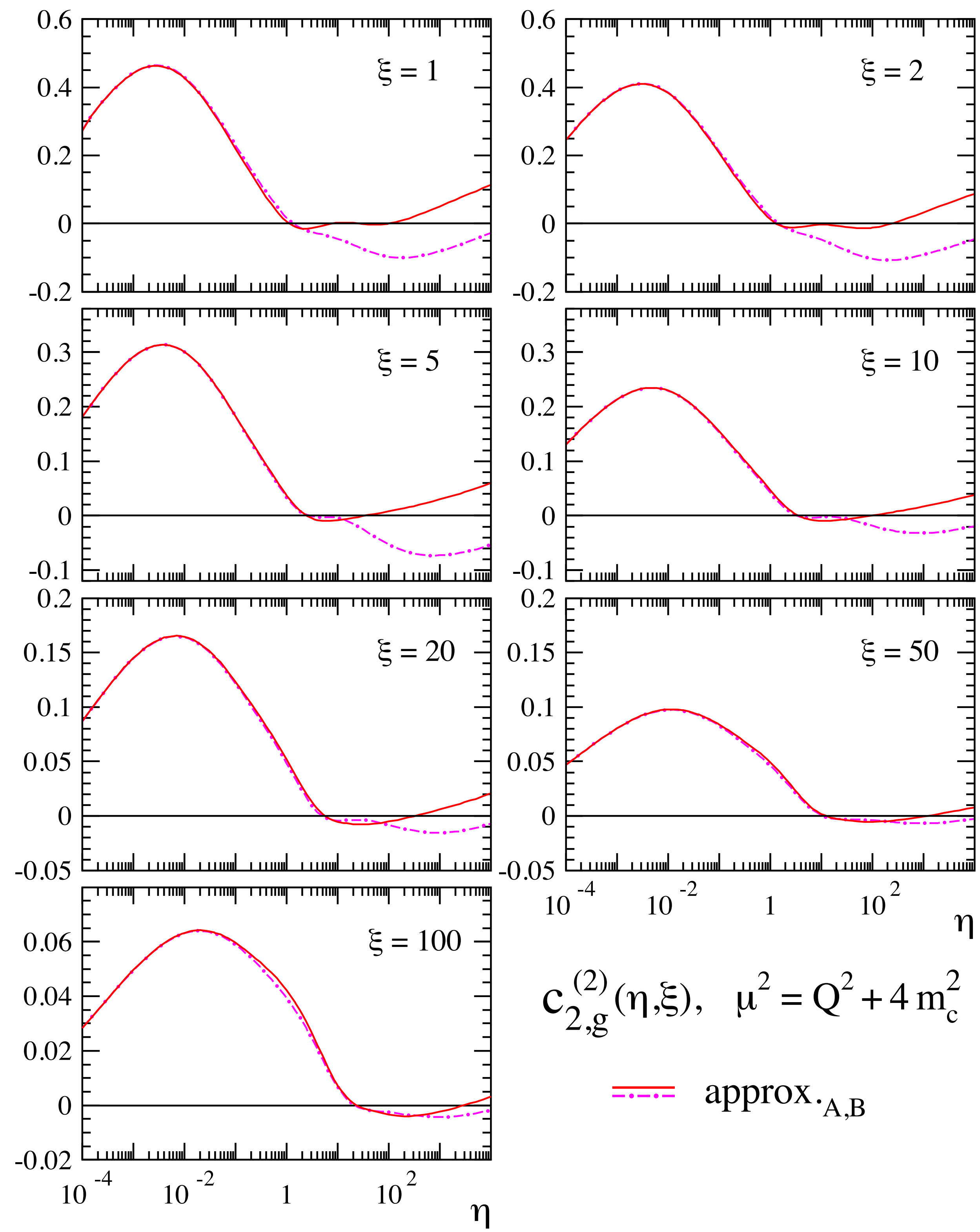
Construct approximate H_i at $O(\alpha_S^3)$

- H_i known at $O(\alpha_S^2)$
- Threshold region dominated by Sudakov log's $\ln(\beta)$ where $\beta=(1-4\,m^2/s)^{1/2}$
  close to threshold $\beta \simeq 0$
- Sudakov log's can be resummed. Predicts fixed orders in perturbation theory
- Asymptotic region $Q^2 >> m^2$ (see talk by Blümlein)
  complete functional dependence now known to $O(\alpha_S^3)$
  [Presti,Kawamura,Moch,Vogt]
- High energy limit: k_T-factorization at small x
  Information on leading and next-to-leading small-x log's
- Combine all limits. Construct approximate result for full kinematic range

Approximate coefficient functions at NNLO

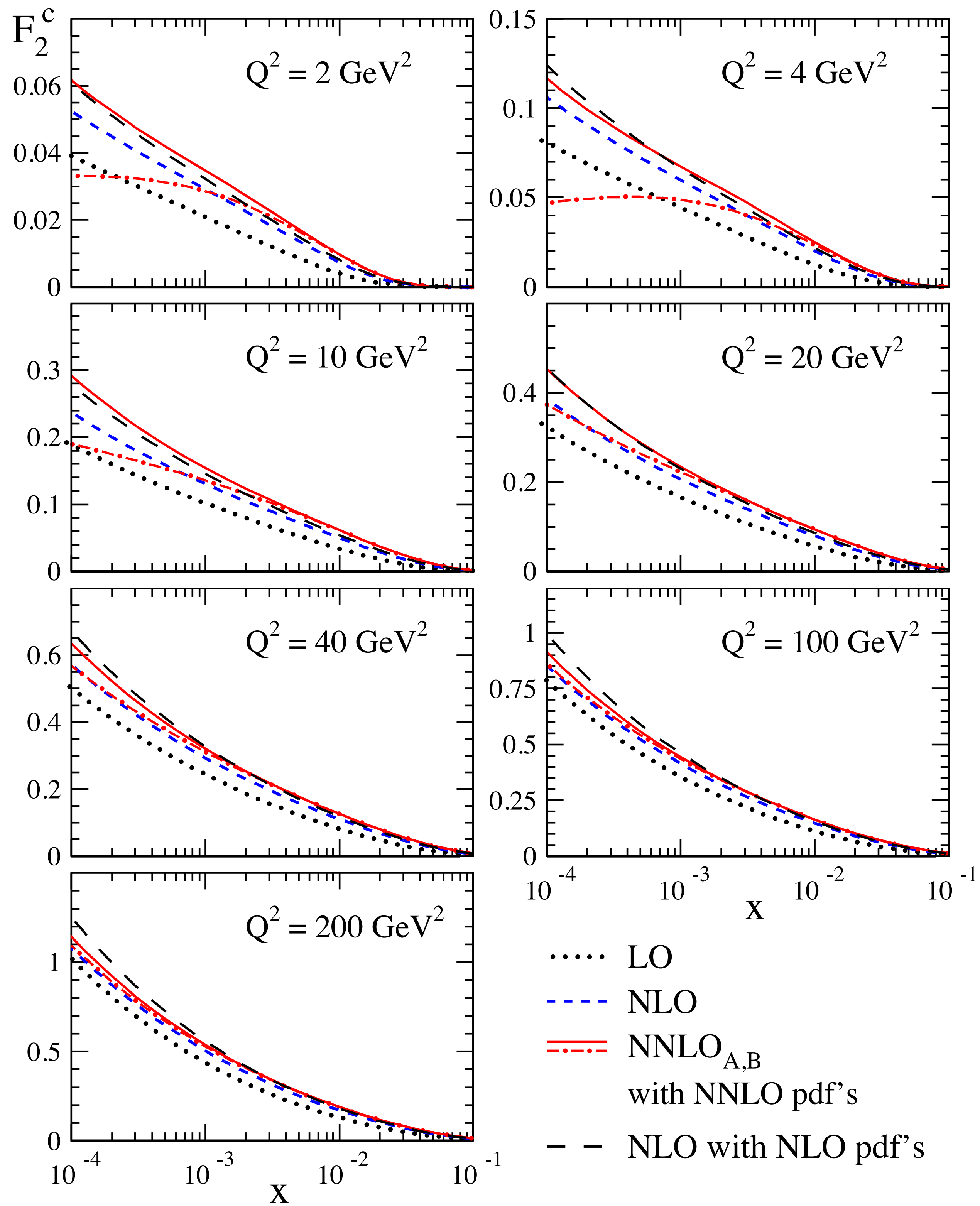
$$\eta = s/(4m^2) - 1\,,\ \xi = Q^2/m^2$$

- New approximate NNLO result
  - very well constrained at large ξ
  - sizable uncertainties for $\xi \lesssim 10$
- Realistic estimate of uncertainty through combination of all limits
- Progress would require
  - more Mellin moments for A_{ji}
  - computation of $c_{2,k}^{\mathrm{NLL_x}}$ (NLO impact factor for k_t-factorization)



Approximate charm structure functions at NNLO

- New approximate NNLO result
  - convolution with ABM11 PDF set
- Uncertainty on NNLO dominates kinematic region in Q^2 relevant for HERA
  - very well constrained at large Q^2
  - sizable uncertainties for $Q^2 \lesssim 20\,\mathrm{GeV}^2$ (even at not so small x)
  - gluon PDF does not fall fast enough as η grows larger



Fixed Flavour and Variable Flavour Number Schemes

- Heavy Quark coefficient functions H_i not IR-safe:

$$H_i \to \infty \quad \text{for} \quad \frac{Q^2}{m^2} \to \infty$$

- VFNS:
  Subtract large log's from H_i and resum via evolved heavy quark PDF; used in global analyses of PDFs

- Keep finite mass terms m^2/Q^2 in subtracted Wilson coefficients $\hat{H}_i$

Talk by Fred Olness

Heavy Quark Production in the ACOT scheme at NNLO and N^3LO

- $\hat{H}_i$ in the ACOT scheme known to $O(\alpha_S)$;
  Need $O(\alpha_S^2)$ for PDF analyses at NNLO

- Idea: Combine exact ACOT scheme at $O(\alpha_S)$
  with known massless Wilson coefficients C_i at $O(\alpha_S^2)$ and $O(\alpha_S^3)$

- Observation with exact ACOT at $O(\alpha_S)$:
  mass effect due to χ-scaling more important than powerlike mass terms m^2/Q^2 in the subtracted massive Wilson coefficients

$$\chi = x(1 + \frac{(nm)^2}{Q^2})$$

- Approximation for $O(\alpha_S^2)$ and $O(\alpha_S^3)$ terms:
  Use C_i combined with χ-scaling prescription

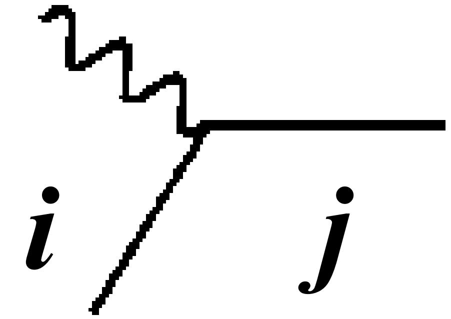
Master formula for decomposing the flavor components

needed to extract F^c

T.P. Stavreva, I Schienbein

$$F = \sum_{i,j}^{6} F^{ij}$$

The Goal: Convert from {s, ns, ps} to {q,g, ...}

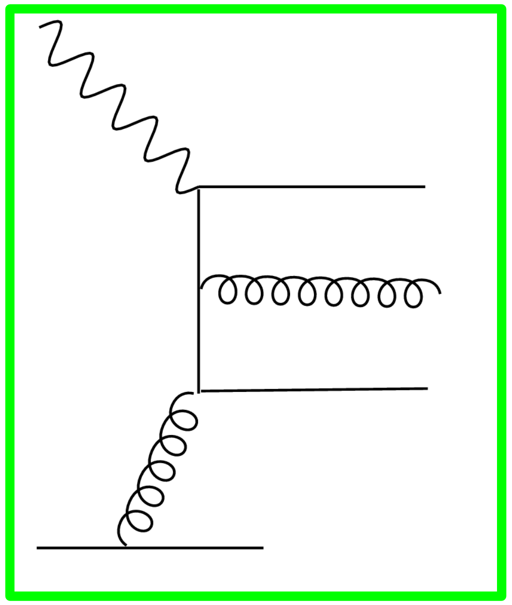


$$x^{-1} F_a^{ij} = q_i^+ \otimes \Big\{ e_i^2 \Big[C_{a,q}^{\rm ns}(n_f = 0)\ \delta_{ij} + C_{a,q}^{\rm ns}(j) - C_{a,q}^{\rm ns}(j-1) \Big] - \langle e^2 \rangle^{(j)}\ C_{a,q}^{\rm ps}(j) - \langle e^2 \rangle^{(j-1)}\ C_{a,q}^{\rm ps}(j-1) \Big\}$$

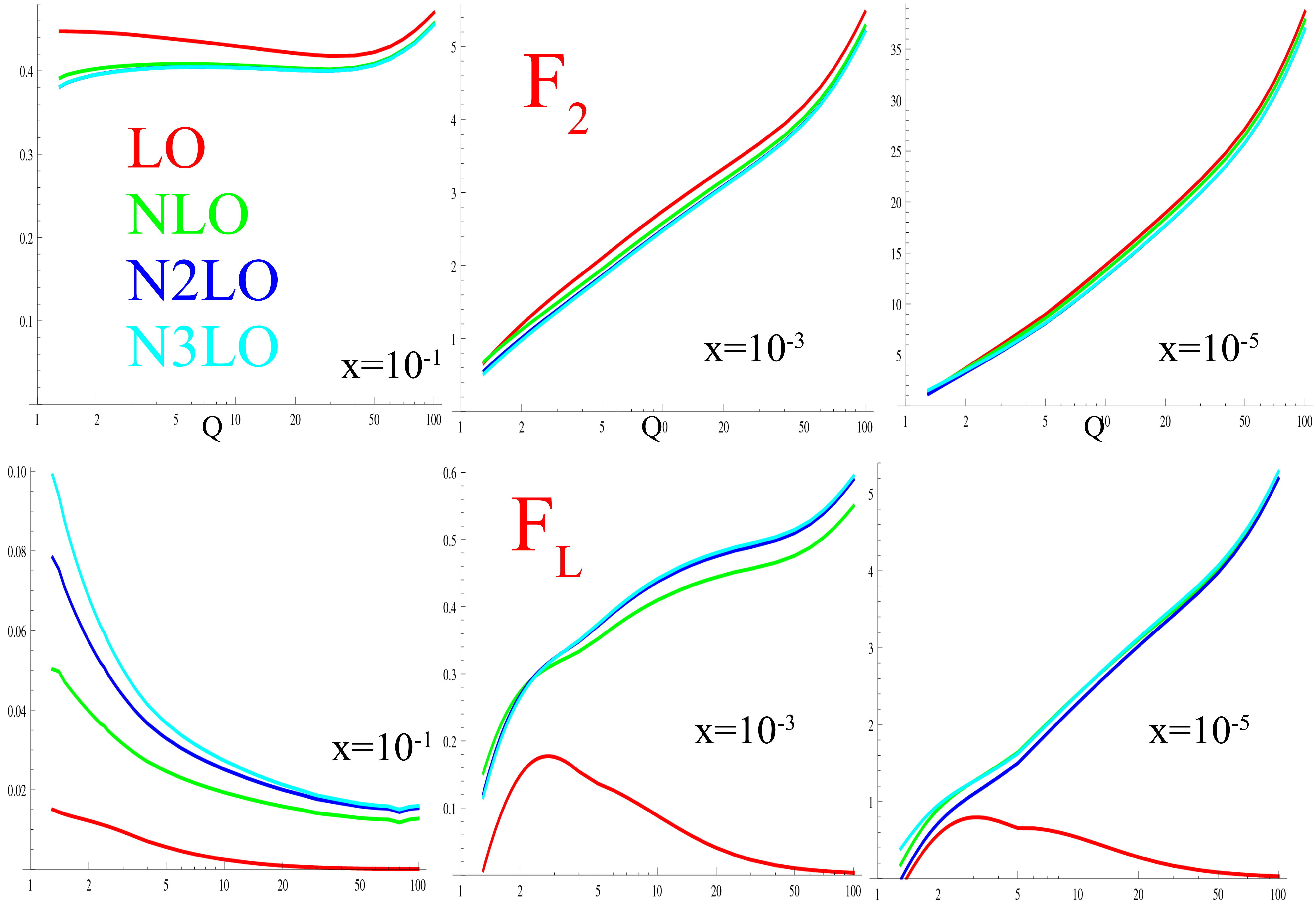
Issues: Flavor separation:

New diagrams at this order

- c,b, goes down beam pipe
- both c & b in final state



$F_{2,L}$ @ N3LO



Open charm and bottom

Less inclusive heavy quark production

- More observables, more tests of pQCD, experimentally more direct (less extrapolation)
- Heavy flavour schemes
  - Mainly for inclusive DIS; used in global analyses of PDFs
  - Schemes have to be applicable to less inclusive cases! Spiesberger, Kotko (otherwise not a general pQCD formalism)
- Exclusive processes useful to probe heavy flavour PDFs. Spiesberger, Kovarik

  Most global analyses generate charm/bottom PDFs perturbatively. Should be tested! Important for various SM and BSM processes! (t-channel single top, top+charged Higgs, ..., whenever new physics couples to the SM fermions via the fermion mass)

PRD84(2011)094026; arXiv:1202.0439

- Theoretical framework:

GM-VFNS≃ACOT

the General-Mass Variable-Flavor-Number Scheme for
1-particle inclusive heavy-meson production
measure p_T and η of observed heavy meson

- Numerical results for *D*- and *B*-meson production:

$p + p \to D + X$, $(D = D^{\pm}, D^0, D^{*\pm}, D_s^{\pm})$,
$p + p \to B + X$, $(B = B^{\pm}, B^0, B_s)$

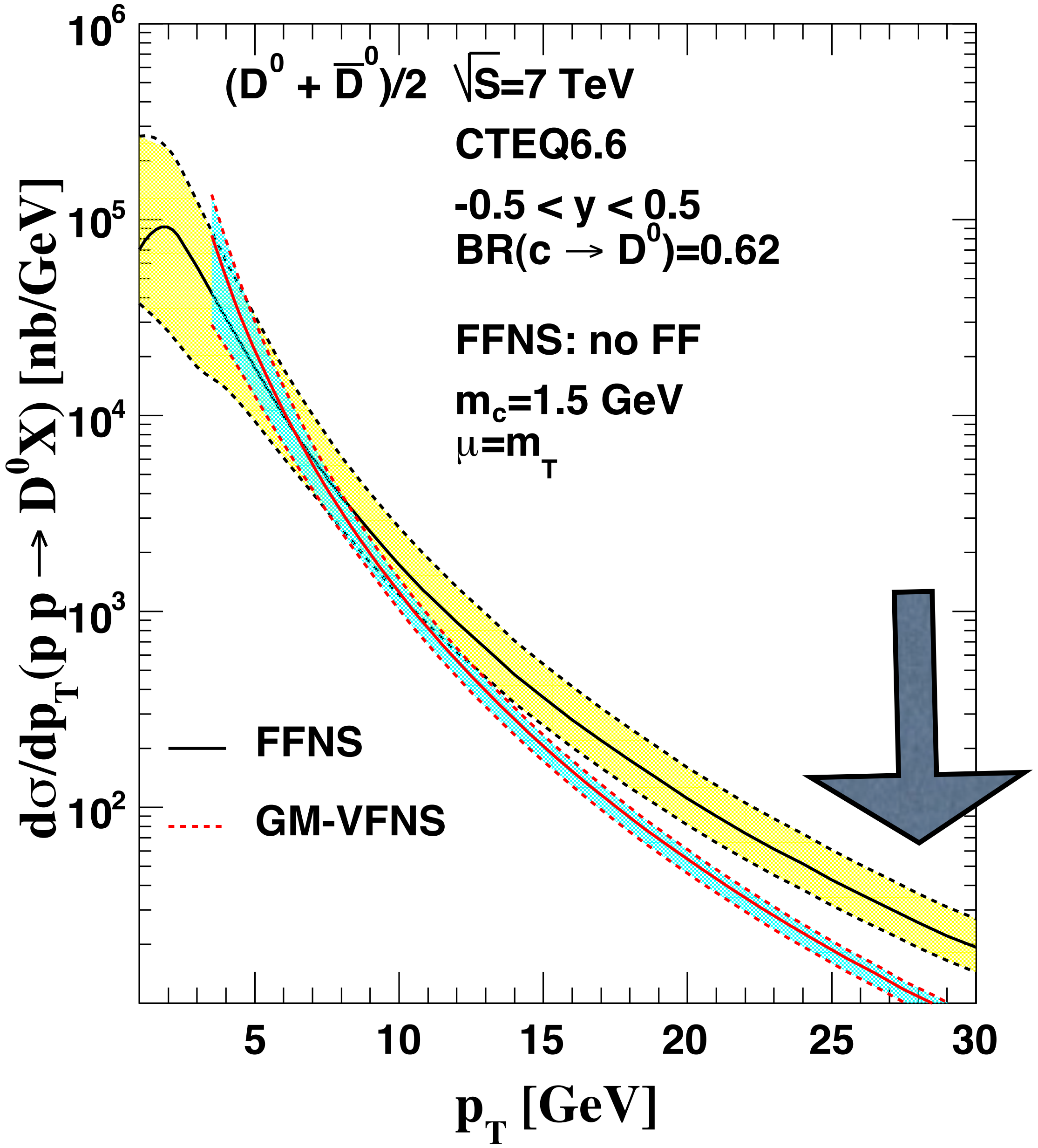
for comparison with LHC data from ATLAS, ALICE, LHCb, CMS

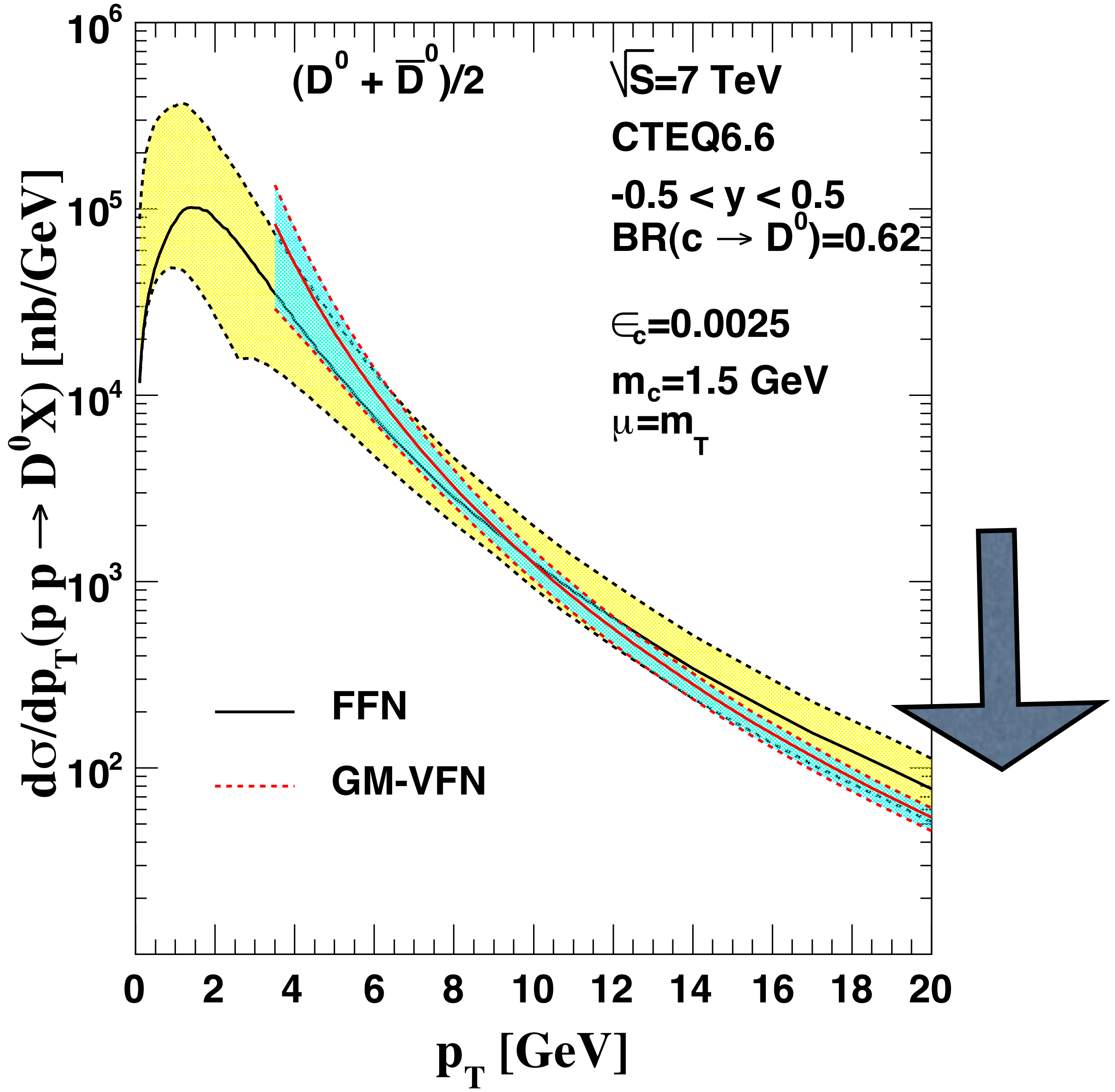
- At the LHC: expect higher statistics, higher transverse momentum

➜ more reliable test of QCD,

➜ better understanding of background for new physics searches

Need results at large pT to distinguish FFNS from VFNS





no evolved fragmentation function

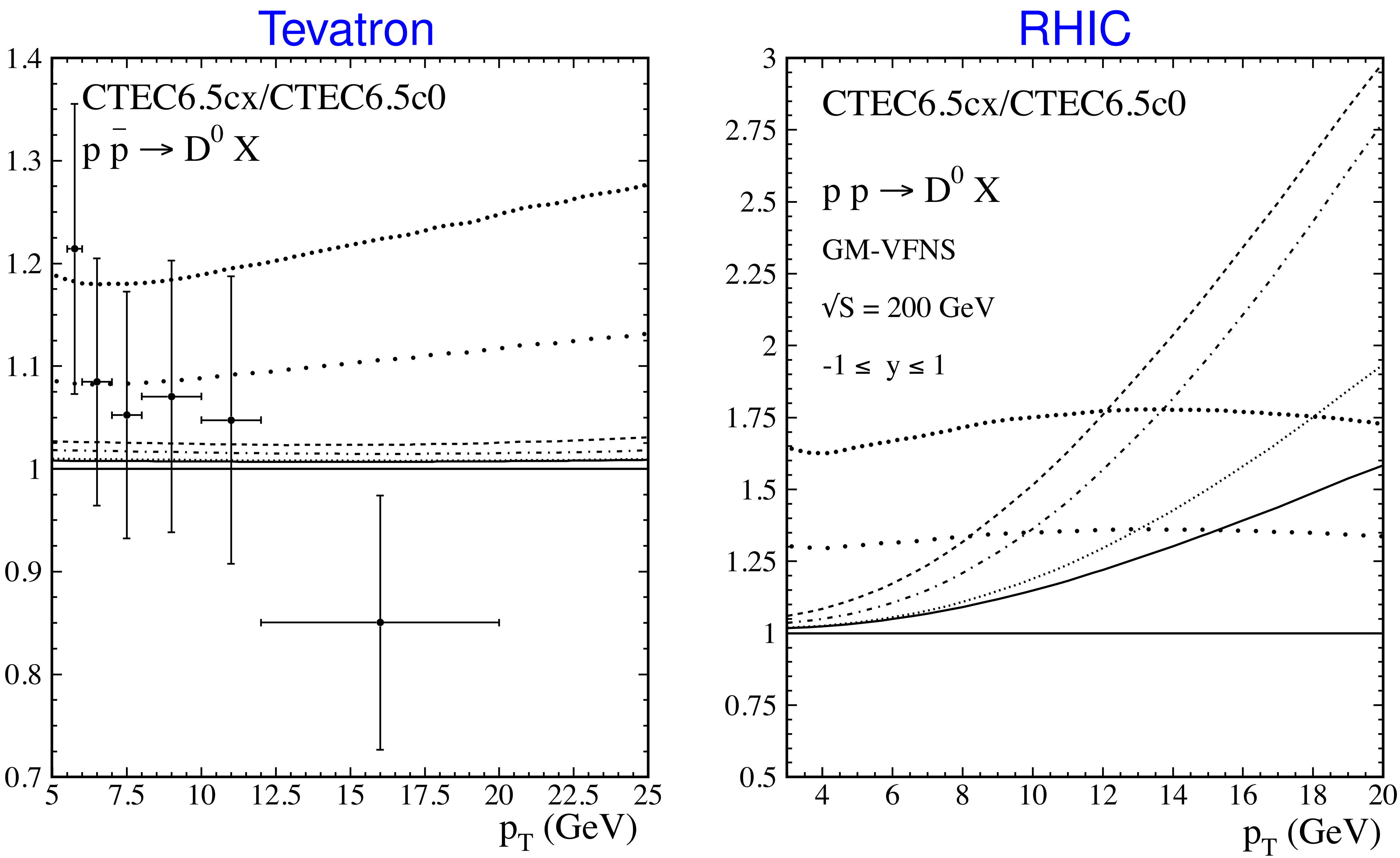
Peterson FF: FFNS closer to GM-VFNS, but still too steep

A colleague: "If QCD is right, there has to be IC"
(which normalization?)

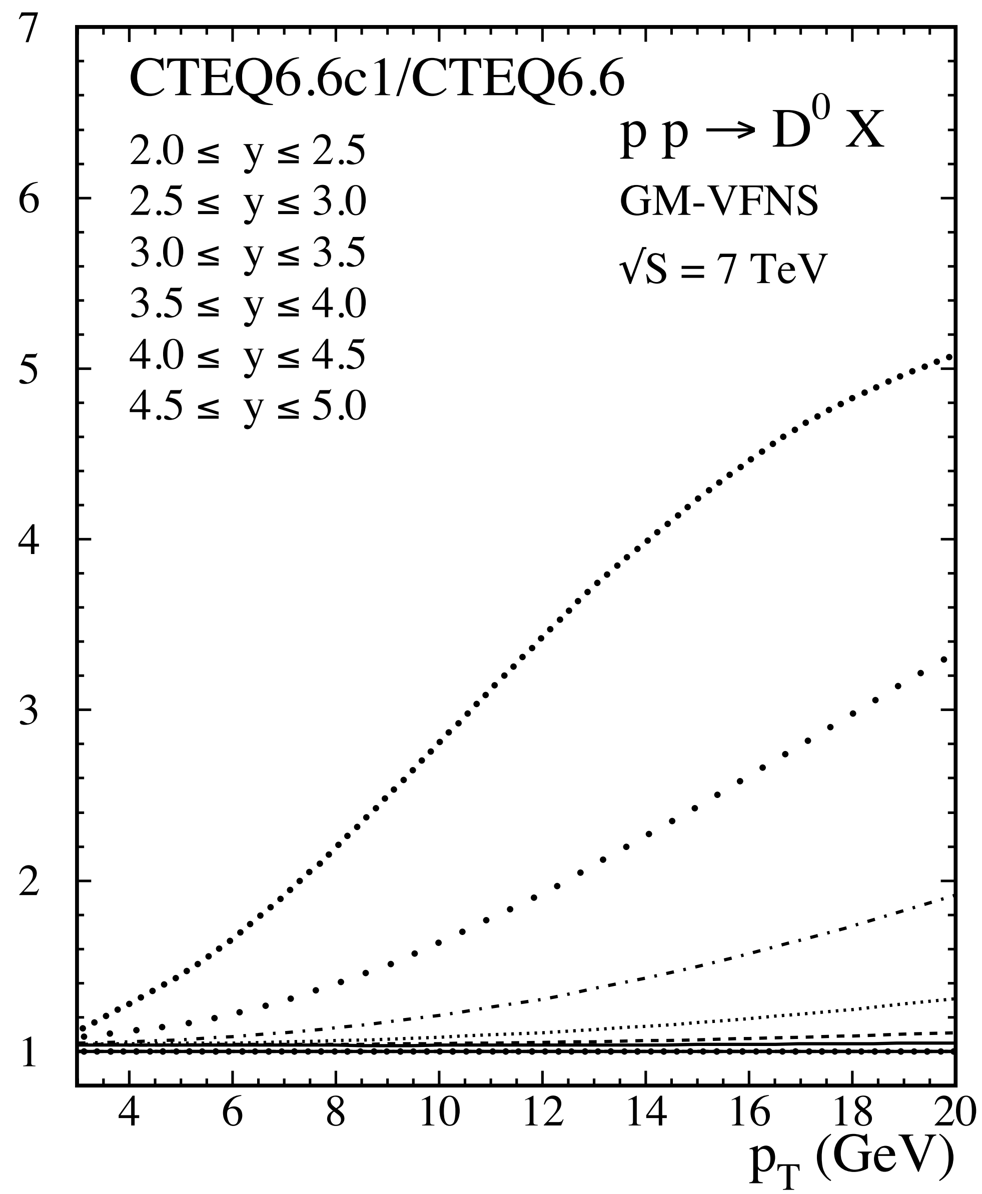
Intrinsic charm:
$c(x, \mu_0) \neq 0$ at initial scale $\mu_0 = m_c$

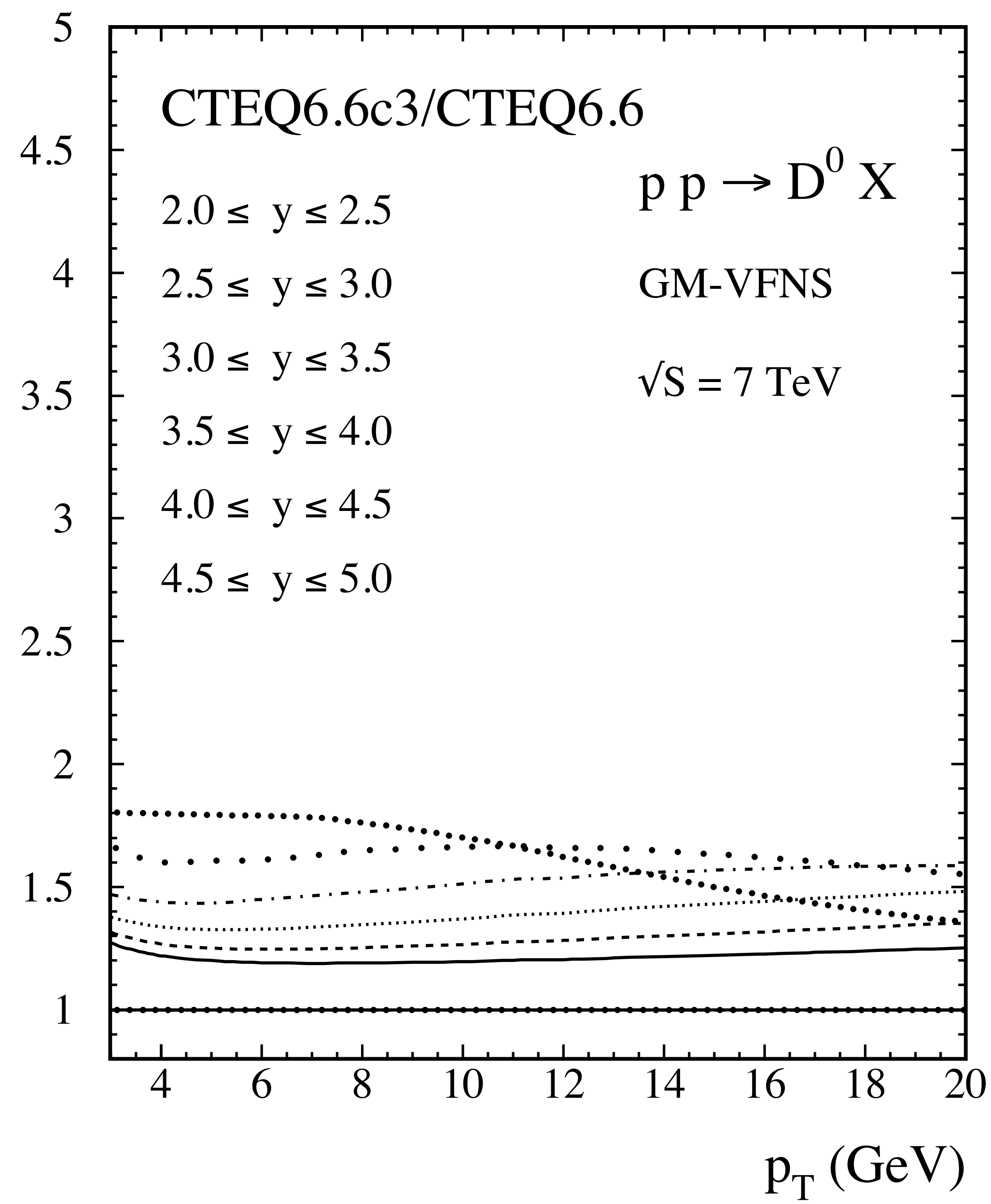
Models implemented in CTEQ 6.5C (PRD75, 2007)
global fit allows average momentum $\langle x \rangle_{c+\bar{c}}$ or order 1 %

1. Light-cone Fock-space picture (Brodsky et al.), concentrated at large x
   $\langle x \rangle_{c+\bar{c}} = 0.57, 2.0\,\%$
2. Meson-cloud model (Navarra et al.)
   $\langle x \rangle_{c+\bar{c}} = 0.96, 1.8\,\%$
3. Phenomenological model: sea-like charm, broad in x
   $\langle x \rangle_{c+\bar{c}} = 1.1, 2.4\,\%$


Tevatron
CTEC6.5cx/CTEC6.5c0
$p\bar{p} \to D^0 X$
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
5
7.5
10
12.5
15
17.5
20
22.5
25
p_T (GeV)
RHIC
CTEC6.5cx/CTEC6.5c0
$pp \to D^0 X$
GM-VFNS
$\sqrt{S}$ = 200 GeV
$-1 \leq y \leq 1$
3
2.75
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
4
6
8
10
12
14
16
18
20
p_T (GeV)

PRD79, 2009





CTEQ6.6 updated:

BHPS, 3.5 % $(c+\bar{c})$ at $\mu = 1.3$ GeV

high-strength sea-like charm

➜ large effects expected at large rapidities

Talk by Karol Kovarik

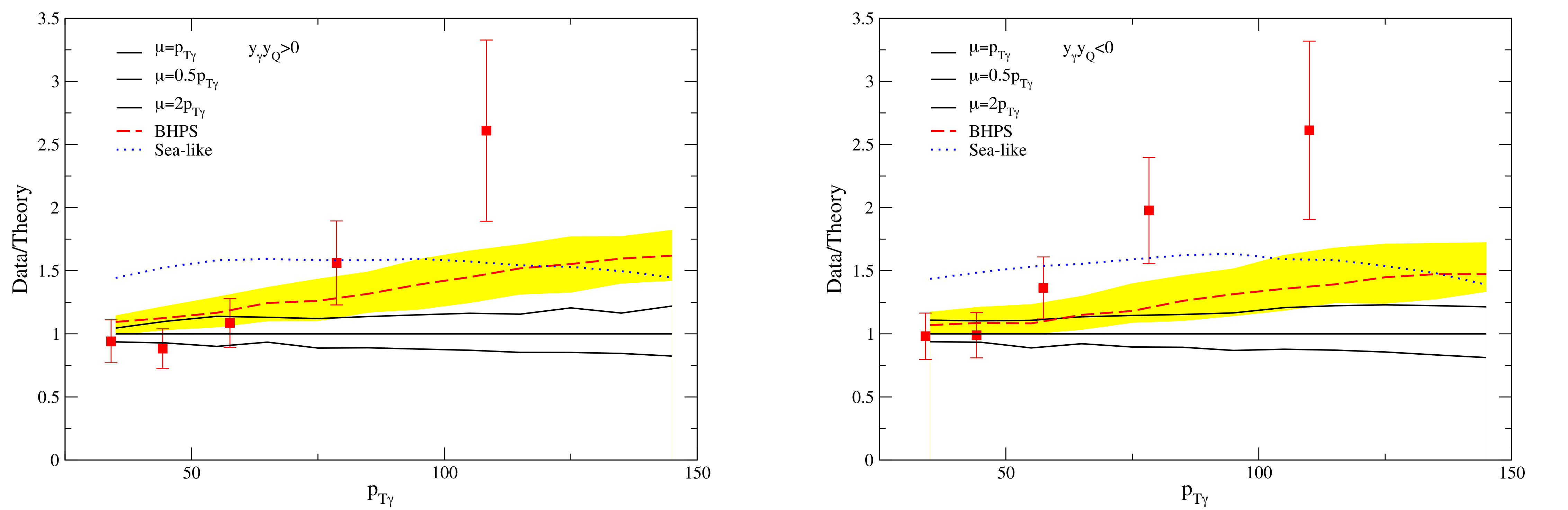
Intrinsic charm/bottom PDF via direct photon + heavy quark production

- LO: Compton hard scattering process $g + Q \rightarrow \gamma + Q$
  direct access to the gluon PDF and the heavy quark PDF
- Full NLO calculation including photon fragmentation contribution
  (photon isolation suppresses photon fragmentation)
  [Owens, Stavreva, PRD79]
- In pA collisions useful to constrain nuclear gluon PDF [arXiv:1012.1178]
- In AA collisions probe of heavy quark energy loss
- In pp collisions probe of IC and IB

TEVATRON-D0

- Direct photon in association with charm / bottom quark jets @ D0
  - comparison of NLO theory predictions with D0 measurements [arXiv:0901.3791, arXiv:0901.0739]
  - bottom quark agrees well but charm quark theory is off
  - discrepancy in photon+charm description allows for testing models of intrinsic charm

photon + charm



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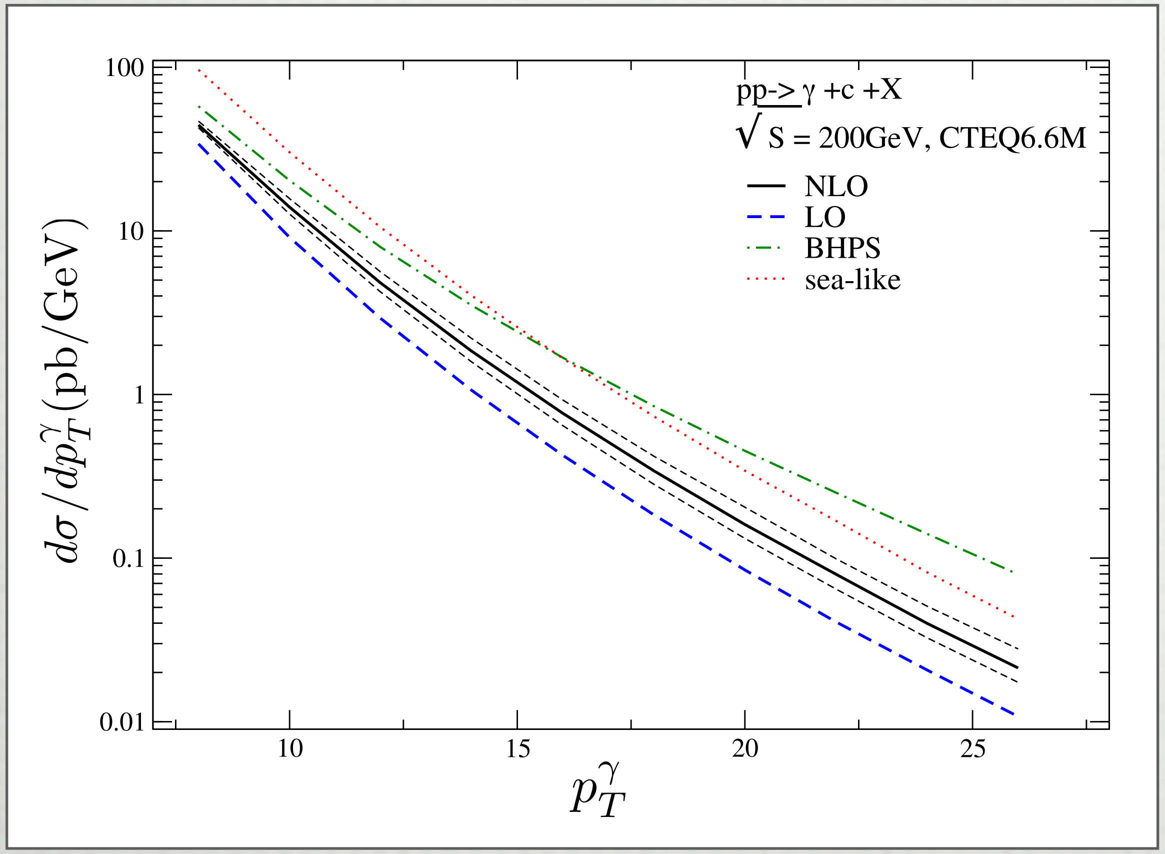
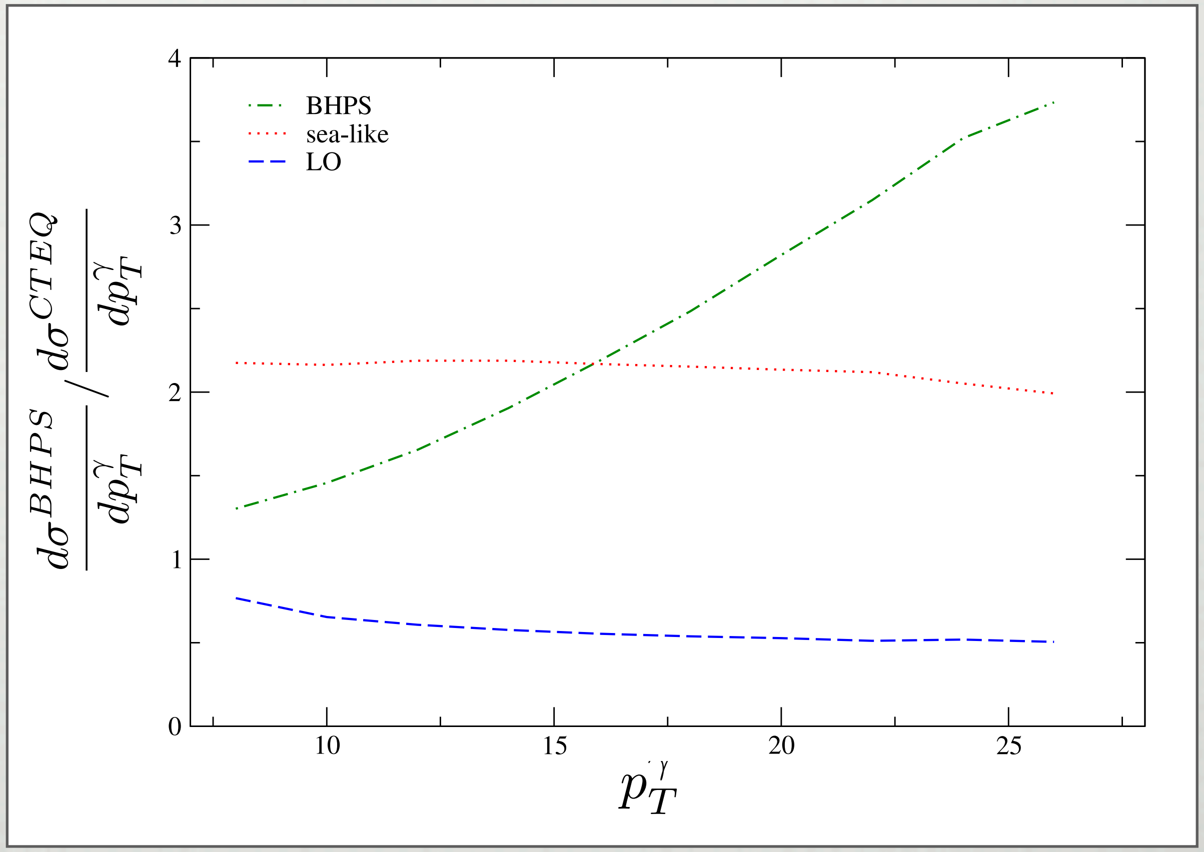
RHIC-PHENIX

- Direct photon in association with charm / bottom quark jets @ RHIC
  - smaller c.m.s energy @ RHIC probes higher x - very sensitive to intrinsic charm

	p_T min	Rapidity	Isolation
Photon	7 GeV	$\|y_\gamma\|<0.35$	R=0.5, p_T = 0.7GeV
Heavy Jet	5 GeV	$\|y_Q\|<0.8$	---

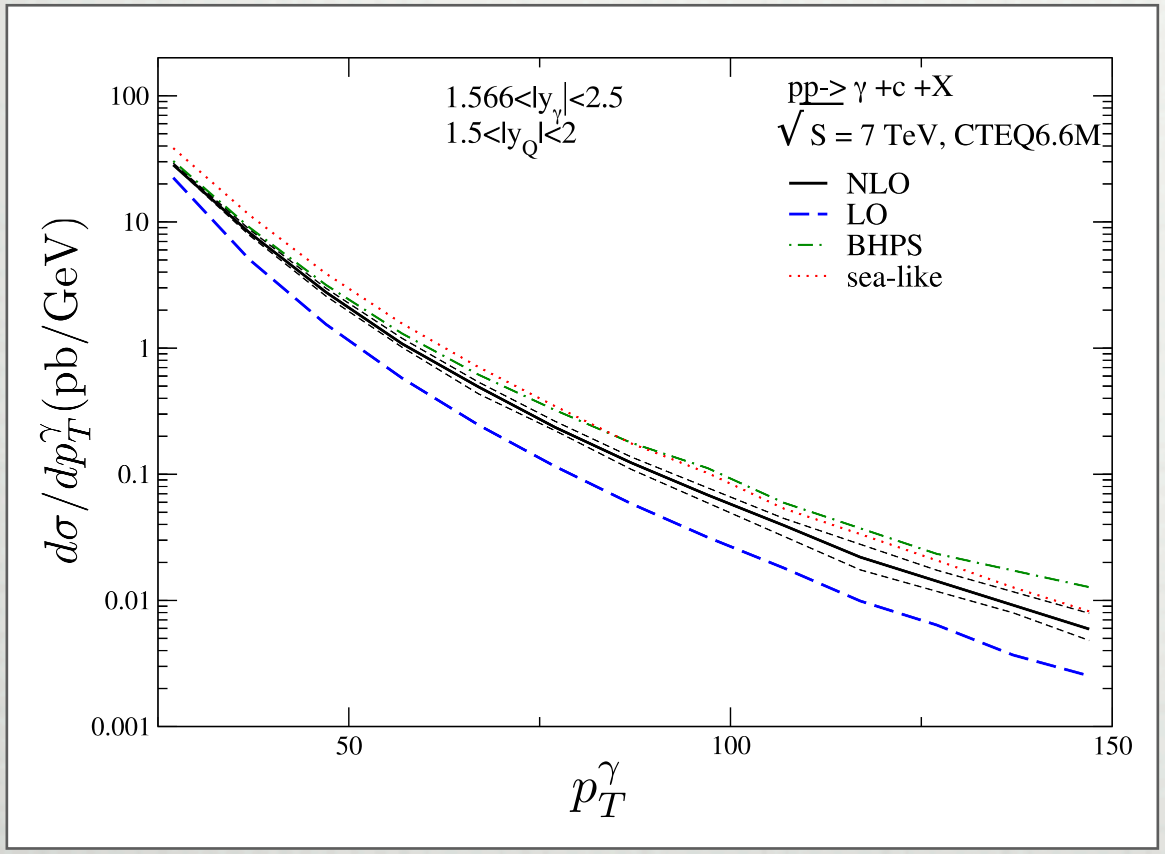


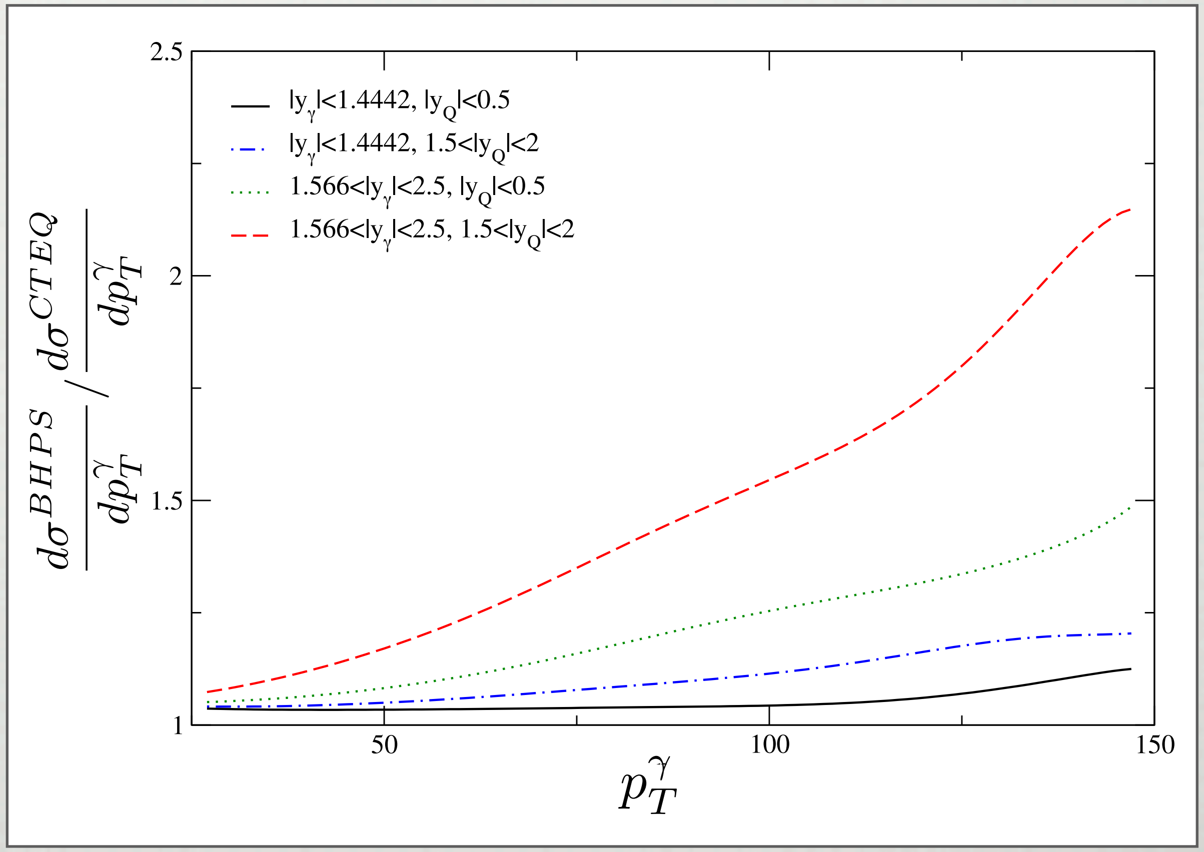


LHC-CMS

- Direct photon in association with charm / bottom quark jets @ CMS
  - CMS cuts on photon & HQ transverse momentum, rapidity & isolation cuts

	p_T min	Rapidity	Isolation
Photon	20 GeV	$\lvert y_\gamma \rvert<1.4442$	R=0.4, p_T = 4.2GeV
		$1.56<\lvert y_\gamma \rvert<2.5$	
Heavy Jet	18 GeV	$\lvert y_Q \rvert<2.0$	---





[CMS notes: CMS PAS EGM-10-005, CMS PAS BPH-10-009]

Charmonium

Testing NRQCD factorization with J/Ψ yield and polarization

B. Kniehl, M. Butenschön
PRL104,106,107,PRD84
arXiv:1201.1872

- NRQCD factorization:
  - Existence of CO states
  - Calculable short distance cross sections
  - Universal Long Distance Matrix Elements (LDMEs)
- **First global analysis of unpolarized world J/Ψ data at NLO**

NRQCD factorization in a nutshell

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.
- $\sigma_{c\bar{c}[n]}$: production rate of $c\bar{c}[n]$, calculated in perturbative QCD.
- $\langle O^{J/\psi}[n] \rangle$: long-distance matrix elements (LDMEs), nonperturbative, extracted from experiment, universal?

Scaling rules: LDMEs scale with relative velocity v ($v^2 \approx 0.2$).
For J/ψ:

scaling	v^3	v^7	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}$	$\ldots$

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

Global fit at NLO in NRQCD

Fit CO LDMEs to all available world data on J/ψ inclusive production:

type	$\sqrt{s}$	collider	collaboration	reference
pp	200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\bar{p}$	1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\bar{p}$	1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
pp	7 TeV	LHC	ALICE	NPB(PS)214(2011)56
			ATLAS	PoS(ICHEP 2010)013
			CMS	EPJC71(2011)1575
			LHCb	EPJC71(2011)1645
γp	300 GeV	HERA I	H1, ZEUS	EPJ25(2002)25; 27(2003)173
γp	319 GeV	HERA II	H1	EPJ68(2010)401
$\gamma\gamma$	197 GeV	LEP II	DELPHI	PLB565(2003)76
e^+e^-	10.6 GeV	KEKB	BELLE	PRD79(2009)071101

- Fit values:

10^{-2} GeV^{3+2L}	
$\langle \mathscr{O}(^1S_0^{[8]})\rangle$	4.97 ± 0.44
$\langle \mathscr{O}(^3S_1^{[8]})\rangle$	0.224 ± 0.059
$\langle \mathscr{O}(^3P_0^{[8]})\rangle$	-1.61 ± 0.20

- $\chi^2/\text{d.o.f.} = 857/194 = 4.42$ for default prediction
- $\propto v^4 \langle O_1(^3S_1)\rangle \rightsquigarrow$ NRQCD velocity scaling rules $\surd$

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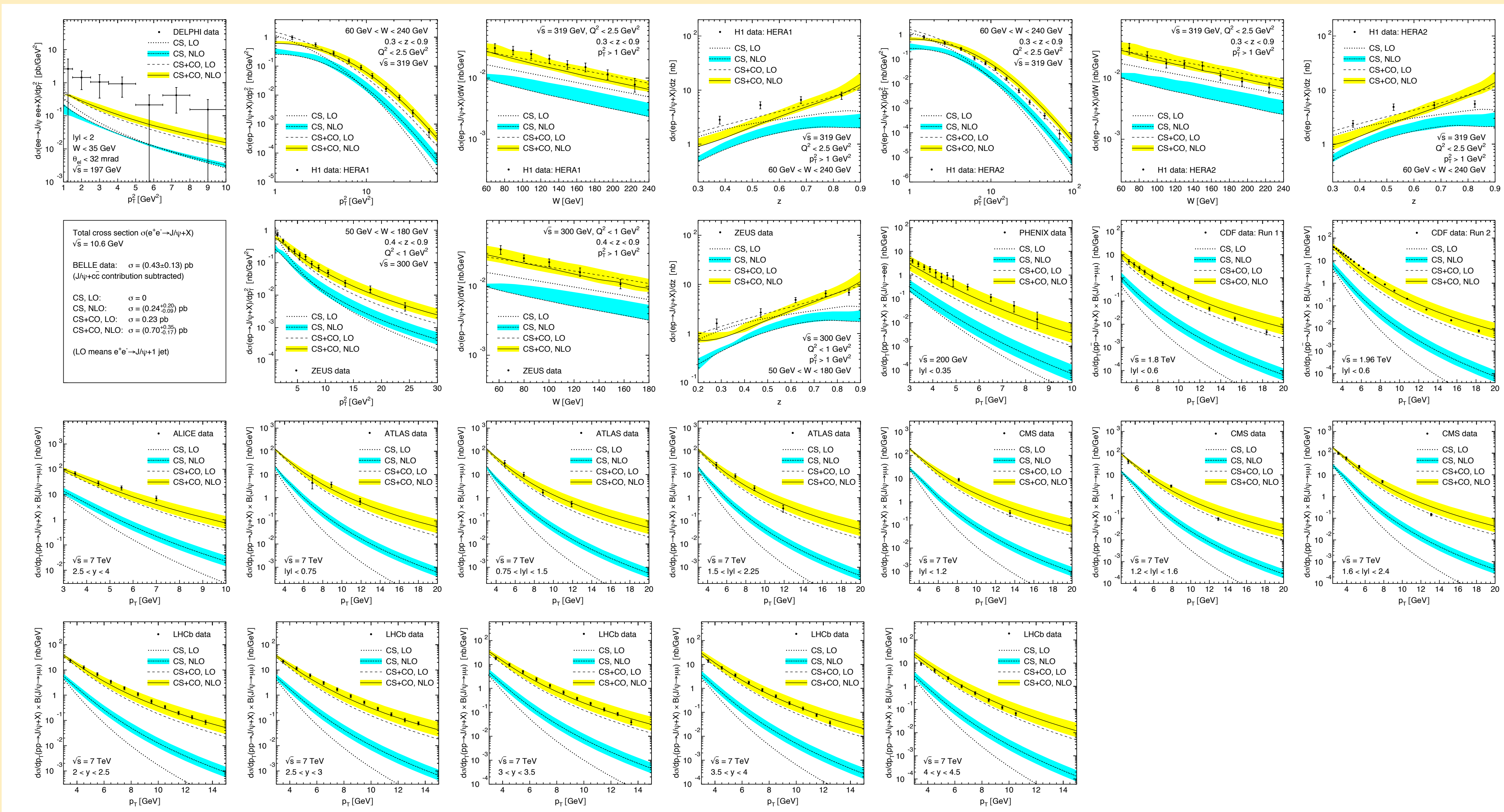
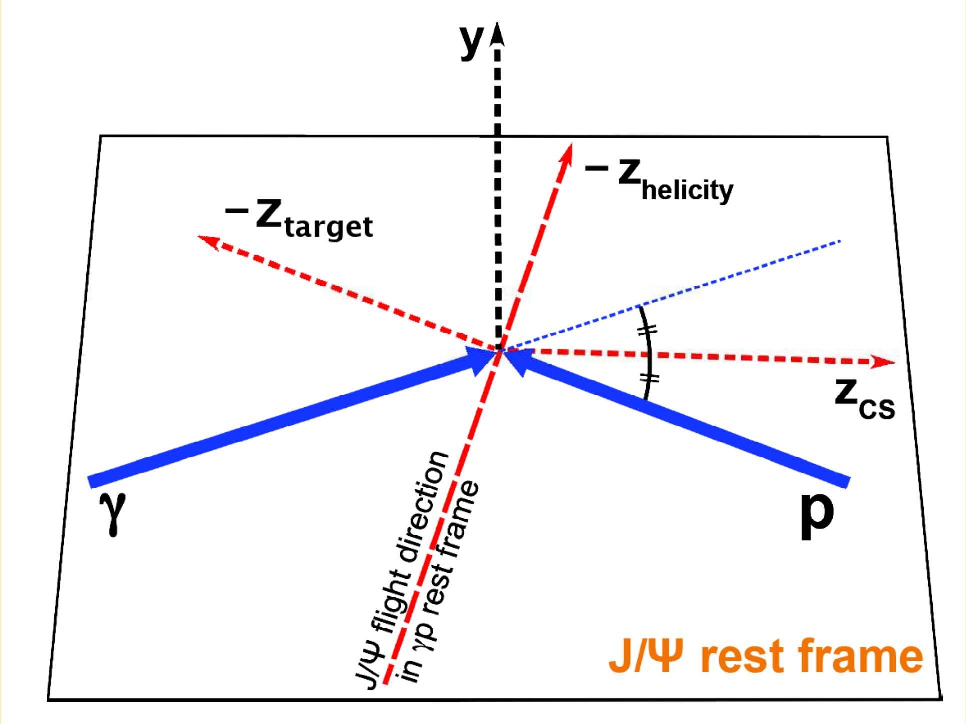
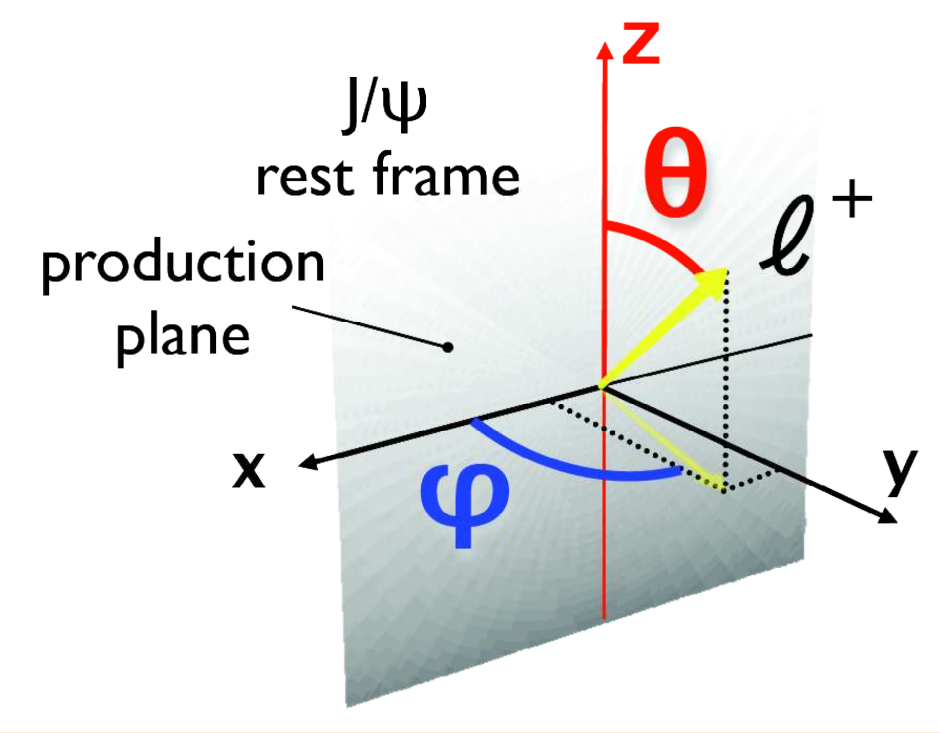
Comparison with world data



Polarized J/ψ photoproduction





Decay angular distribution:

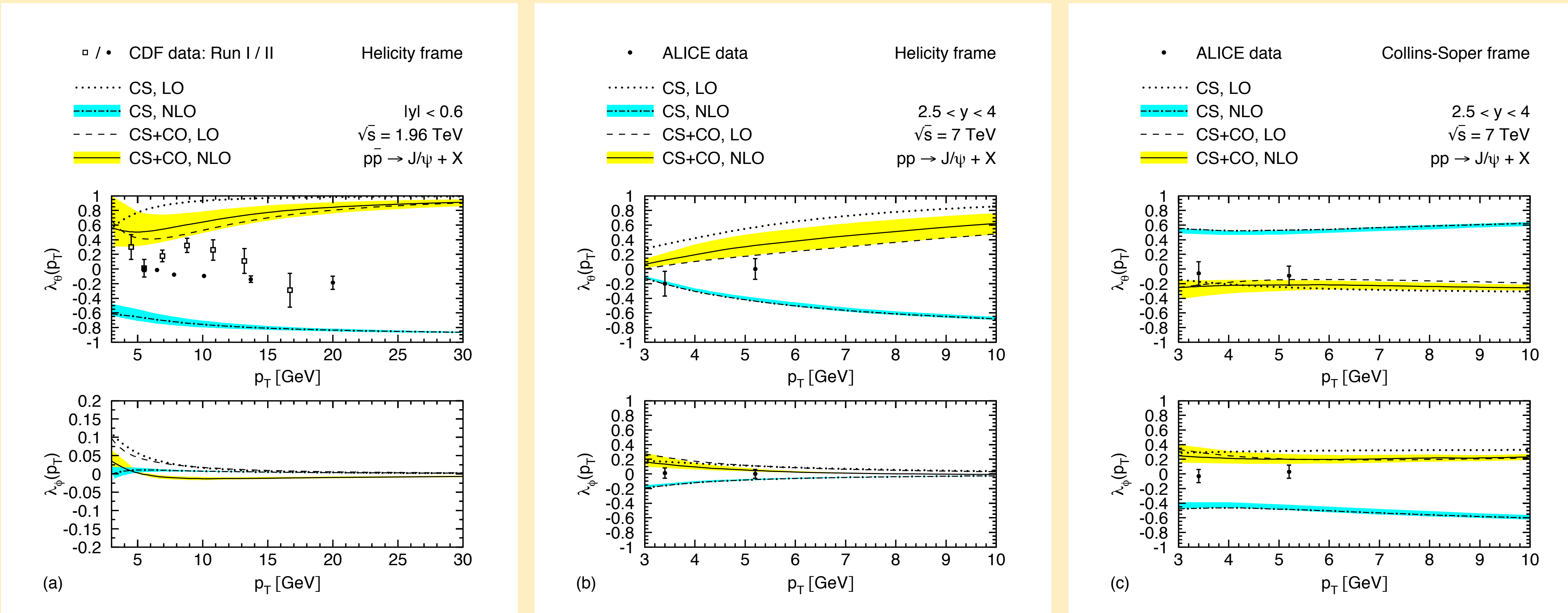
$$\frac{d\Gamma(J/\psi \to l^+ l^-)}{d\cos\theta\, d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi$$

Polarization observables in spin density matrix formalism:

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_\phi = \frac{d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}\, d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}}$$

$\lambda = 0, +1, -1$: unpolarized, transversely and longitudinally porarized.

Comparison with CDF and ALICE



- CDF I and II data mutually inconsistent for $p_T < 12$ GeV.
- CDF J/ψ polarization anomaly persits at NLO (10–20σ).
- 4/8 ALICE points agree w/ NLO NRQCD within errors, others $< 2\sigma$ away.

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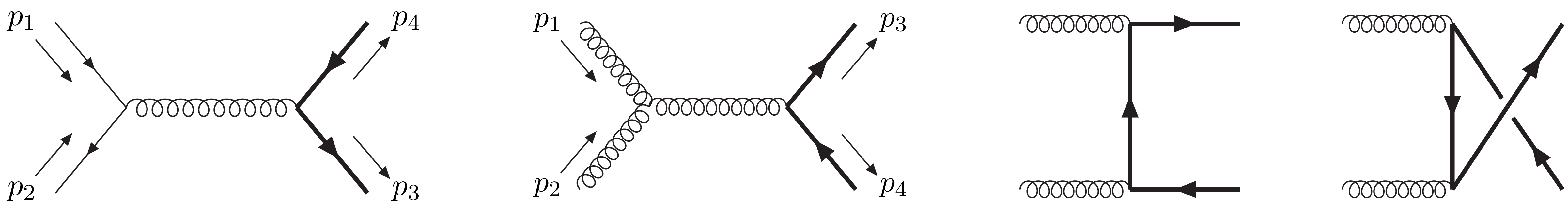
Top

Top quark pair production



- Two channels at tree-level
- Quark-antiquark annihilation dominant at the Tevatron (~ 90%)
- Gluon fusion dominant at the LHC (~ 75% for 7 TeV)

Top quark pair production

- Observables:
  - Cross section
  - Distributions: t-tbar invariant mass M, pT, y
  - Asymmetries: A_{FB} , A_C (charge asymmetry)
- Calculations:
  - exact NNLO (talk by A. Mitov)
  - NLO + Resummed: NLO+NNLL (L. Yang, N. Kidonakis)
    (Note: different resummations are used)
  - approximate NNLO (L. Yang)

Status of fixed-order calculations

- NLO results known since ~20 years

  Nason, Dawson, Ellis ('88-'90); Beenakker, Kujif, van Neerven, Smith, Schuler ('89-'91); Mangano, Nason, Ridolfi ('92); Czakon, Mitov ('08)

  - Scale uncertainty ~15%, need to go beyond for LHC!
  - Off-shell effects found to be small

    Denner, Dittmaier, Kallweit, Pozzorini ('10); Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek ('10)

- NNLO in progress

  $\text{Channels: } q\bar{q},\ gg,\ qg$

  - Two-loop virtual is the main obstacle $M_2^{(0)} + M_2^{(1)} + M_2^{(2)}$

    Analytic approach: Bonciani, Ferroglia, Gehrmann, Maitre, Studerus, von Manteuffel ('08-'10); Numeric approach: Czakon et al.

  - Virtual+real Dittmaier, Uwer, Weinzierl ('08) $M_3^{(0)} + M_3^{(1)}$
  - New subtraction method for double real Czakon ('10-'11) $M_4^{(0)}$
  - May be available in the near future!

Talk by Alexander Mitov

NNLO result for qq→ tT at Tevatron and LHC

Work with M. Czakon, P. Barnreuther

✓ First ever hadron collider calculation at NNLO with more than 2 colored partons.

✓ First ever NNLO hadron collider calculation with massive fermions.

Computed partonic reactions. Dominant at Tevatron (~85%)

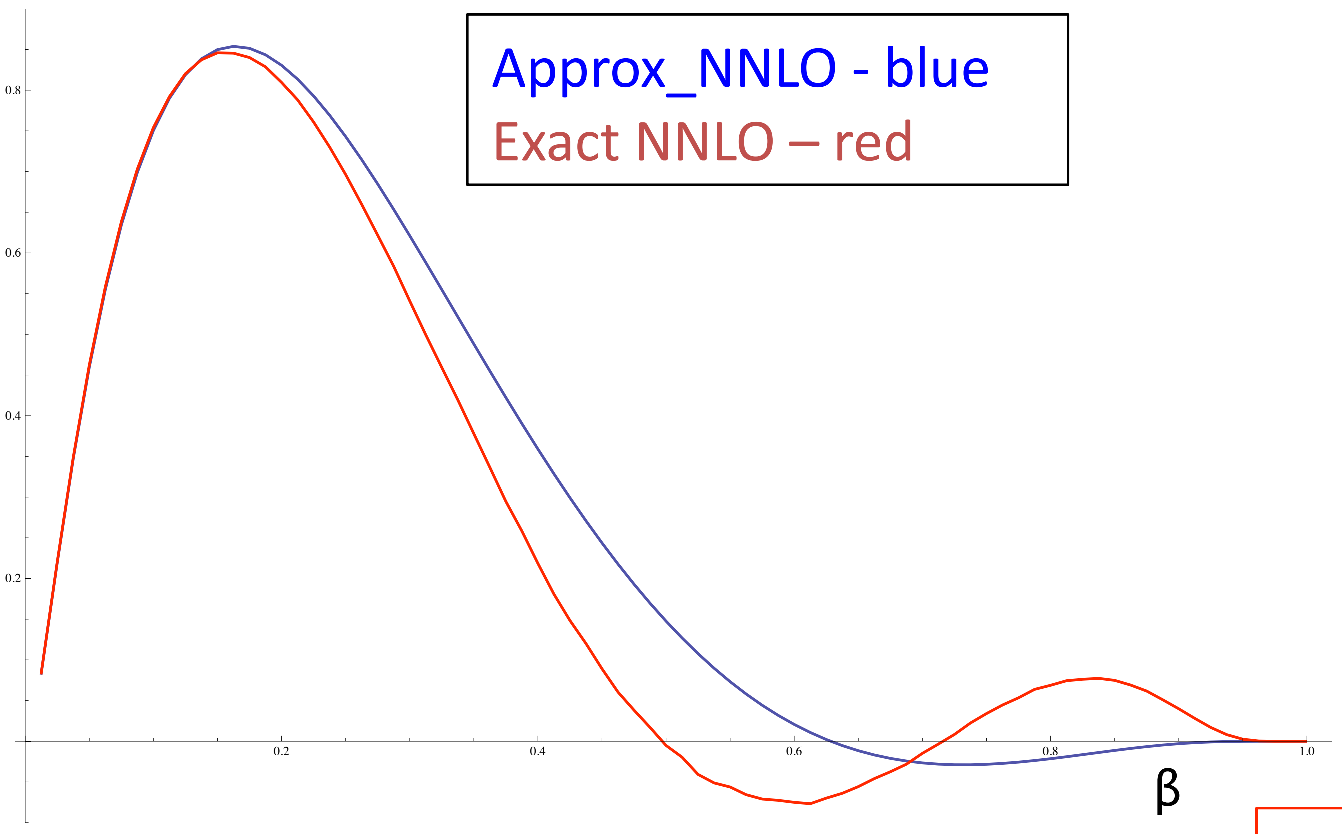
$$q\bar{q} \to t\bar{t}$$
$$q\bar{q} \to t\bar{t}g$$
$$q\bar{q} \to t\bar{t}gg$$
$$q\bar{q} \to t\bar{t}q'\bar{q}' , \quad q \neq q'$$

$$gg \to t\bar{t}$$
$$gg \to t\bar{t}g$$
$$gg \to t\bar{t}gg$$
$$gg \to t\bar{t}q\bar{q}$$

$$qg \to t\bar{t}q$$
$$qg \to t\bar{t}qg$$
$$qq' \to t\bar{t}qq' , \quad q \neq \bar{q}'$$
$$q\bar{q} \to t\bar{t}q\bar{q}$$

In progress

Partonic cross-section, convoluted with partonic flux:



$$\sigma = \frac{\alpha_s^2}{m_t^2} \sum_{ij} \int_0^{\beta_{\max}} \mathcal{L}_{ij}(\beta)\hat{\sigma}(\beta)$$

✓ 50% scales reduction compared to the NLO+NNLL!

Numerical predictions for the Tevatron (preliminary)

Pure NNLO:
sigma_tot = 7.004 + 2.9 % - 4.4 % [pb].

With resummation NNLO+NNLL:
sigma_tot = 7.048 + 1.9 % - 3.2 % [pb].

Unmatched precision at the Tevatron!

Recent results

✓ We have also prepared the tools for top physics:

Top++ : a C++ program for the calculation of the total cross-section:

Czakon, Mitov `11

✓ Includes:

- fixed order (NLO and NNLO_approx at present)
- and resummation (full NNLL already there)

✓ It is meant to incorporate the full NNLO once available (to appear)

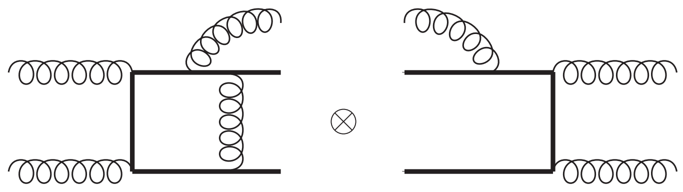
✓ Very user friendly.

The singular behavior of one-loop massive QCD amplitudes with one external soft gluon

talk by Isabella Bierenbaum, based on work with M. Czakon and A. Mitov
Nucl. Phys. B **856** (2012) 228 [arXiv:1107.4384]

Contributing "virtual + real diagrams" in the framework of the NNLO $t\bar{t}$ calculation:

Integration over the real external gluon generates a divergence when the gluon is soft and/or collinear to the external legs $\Leftrightarrow$



$\rightarrow$ Construct a subtraction term in the soft limit for the squared amplitude $|M|^2$
$\rightarrow$ Following the approach for the massless case by Catani & Grazzini, (2000):

"Factorize" the singularities:

$$M_a^{(1)}(n+1,q) \simeq \underbrace{J_a^{(0)}(q)M^{(1)}(n)}_{factorizable} + \underbrace{J_a^{(1)}(q)M^{(0)}(n)}_{non-factorizable}$$

$J_a^{(1)}(q)$ is the universal one–loop soft–gluon current in the massive case.

$J_a^{(1)}(q)$ is calculated here for three kinematical cases of one or two massive external fermions.

Talk by Li Lin Yang

Threshold enhancement and resummation

- Can improve fixed-order results by adding or resumming ***threshold enhanced*** terms in higher orders

- Schematically, the threshold enhanced terms looks like (in Laplace or Mellin space)

$$d\hat{\sigma} = 1 + \alpha_s \left(L^2 + L + 1\right) + \alpha_s^2 \left(L^4 + L^3 + L^2 + L + 1\right) + \cdots \quad \text{+ power corrections}$$

- Can be resummed to all orders at certain logarithmic accuracy using re-factorization and renormalization-group equations

NLO+NNLL

- Alternatively, can construct an ***approximate NNLO*** cross section

NNLO_approx

Three types of threshold

- Production threshold (small-β) —— relevant for total cross section

$$\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}} \to 0$$

Berger, Contopanagos, Bonciani, Catani, Mangano, Nason, Langenfeld, Moch, Uwer, Beneke, Falgari, Klein, Schwinn, Cacciari, Czakon, Mitov...

- PIM threshold —— relevant for invariant mass distribution, charge asymmetry in $t\bar{t}$ frame (and total cross section)

$$z = \frac{M_{t\bar{t}}^2}{\hat{s}} \to 1$$

Sterman, Kidonakis, Oderda, Vogelsang, Laenen, Moch, Vogt, Almeida...

- 1PI threshold —— relevant for transverse momentum and rapidity distribution, charge asymmetry in $p\bar{p}$ frame (and total cross section)

$$s_4 = \hat{s} + \hat{t}_1 + \hat{u}_1 \to 0$$

Sterman, Oderda, Laenen, Kidonakis, Moch, Vogt...

We work in these two

Additional differences between PIM vs PIM_{SCET} and PI vs PI_{SCET}

Approximate NNLO

- Two-loop anomalous dimension matrices

  Ferroglia, Neubert, Pecjak, LLY [arXiv:0907.4791] [arXiv:0908.3676]

- One-loop hard matrix

  Ahrens, Ferroglia, Neubert, Pecjak, LLY [arXiv:1003.5827]

- One-loop soft matrix for PIM kinematics

- One-loop soft matrix for 1PI kinematics

  Ahrens, Ferroglia, Neubert, Pecjak, LLY [arXiv:1103.0550]

$$d\hat{\sigma}^{(2)} \approx \alpha_s^2 \left(L^4 + L^3 + L^2 + L + 1 \right)$$

Predict all log terms at NNLO

missing: exact NNLO

Total cross section

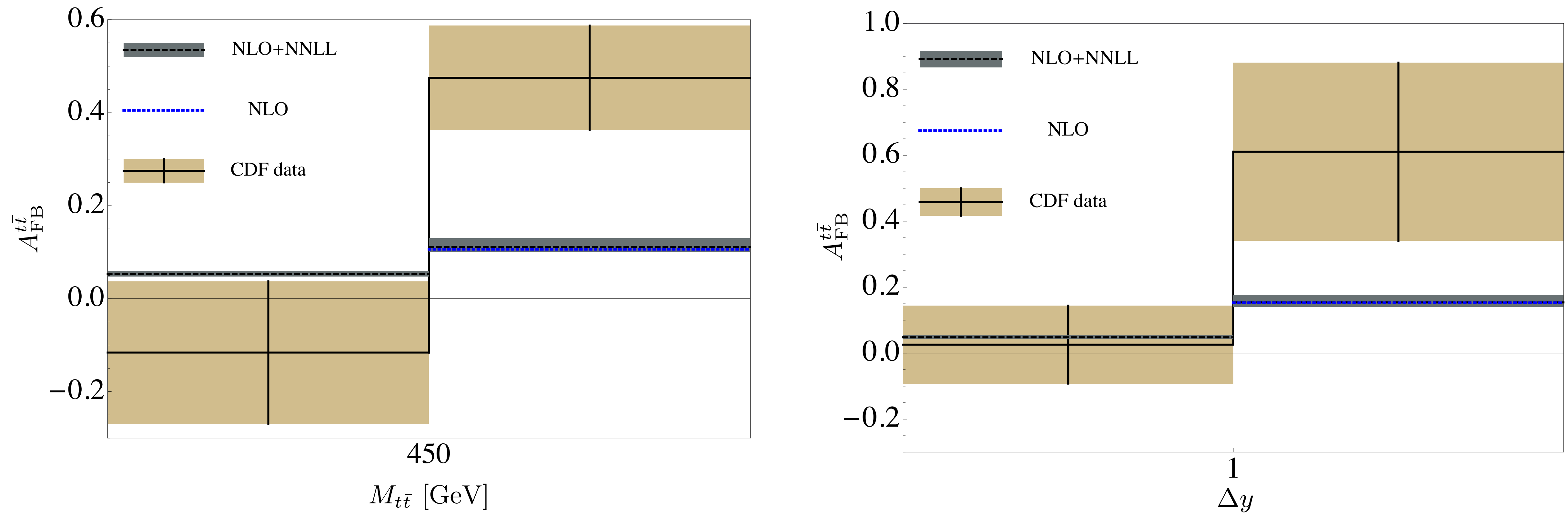
Ahrens, Neubert, Pecjak, Ferroglia, LLY [arXiv:1105.5824]

- Can integrate both PIM and 1PI distributions to get the total cross section
- We find nice agreement between the two kinematics —— use the difference as an additional uncertainty
- Computer code available (parallel enabled): http://www.physik.uzh.ch/~llyang/TopNNLO.tar.gz

$m_t = 173.1$ GeV	Tevatron	LHC7	LHC8
NLO	$6.72^{+0.41+0.47}_{-0.76-0.45}$	159^{+20+14}_{-21-13}	228^{+28+19}_{-30-17}
NNLO approx.	$6.63^{+0.07+0.63}_{-0.41-0.48}$	155^{+8+14}_{-9-14}	221^{+12+19}_{-12-19}

Charge asymmetry —— $M_{t\bar{t}}$ and y dependence

Ahrens, Ferroglia, Neubert, Pecjak, LLY [arXiv:1106.6051]



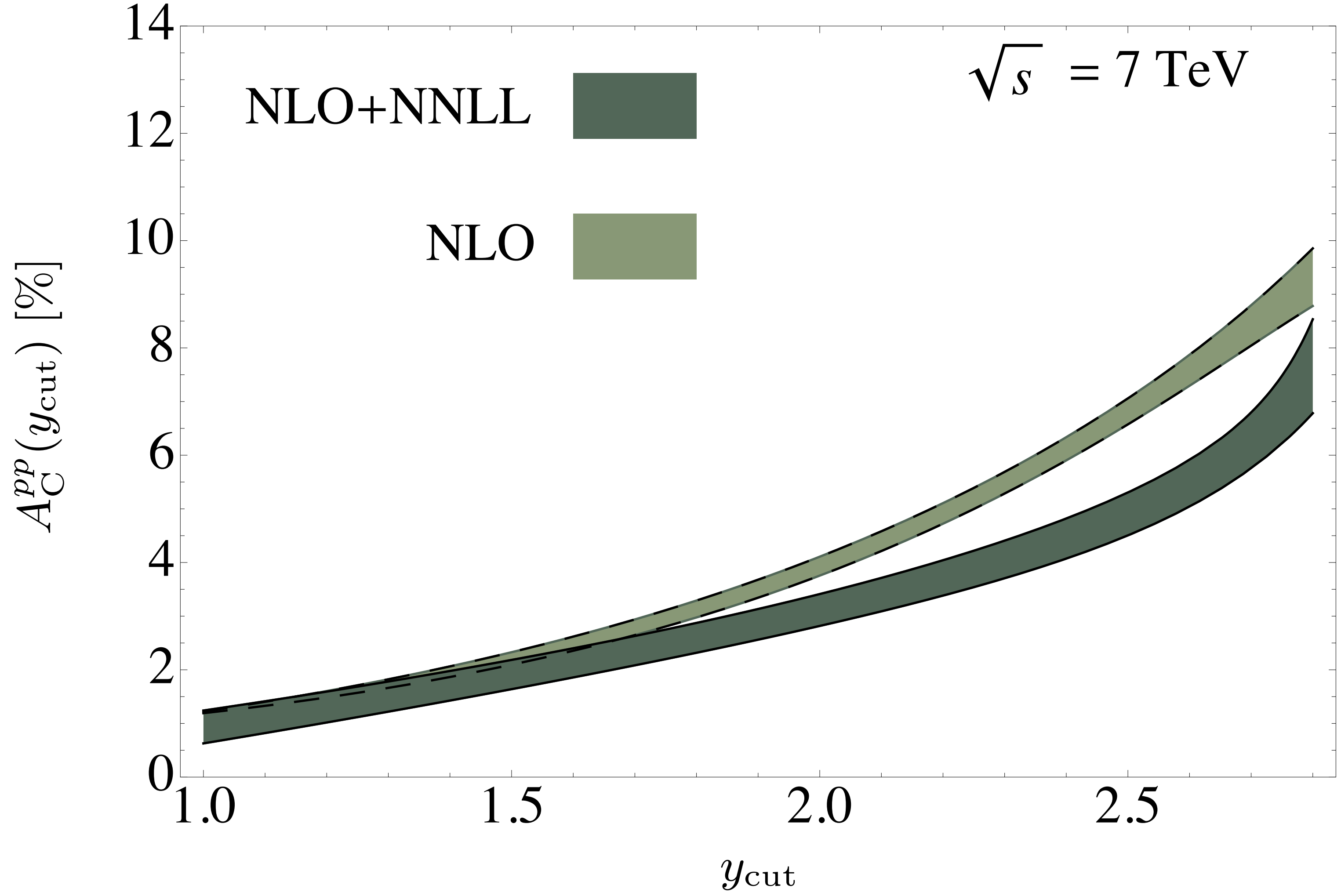
- Higher order predictions consistent with NLO

Of course, exact NNLO can change the picture!

- Discrepancies at high invariant mass and rapidity not resolved

Charge asymmetry at the LHC

Ahrens, Ferroglia, Neubert, Pecjak, LLY [arXiv:1106.6051]



- Increase with higher rapidity cut —— but less statistics
- NLO prediction depends a lot on whether or not to expand the ratio in α_s

Talk by N. Kidonakis

Single top

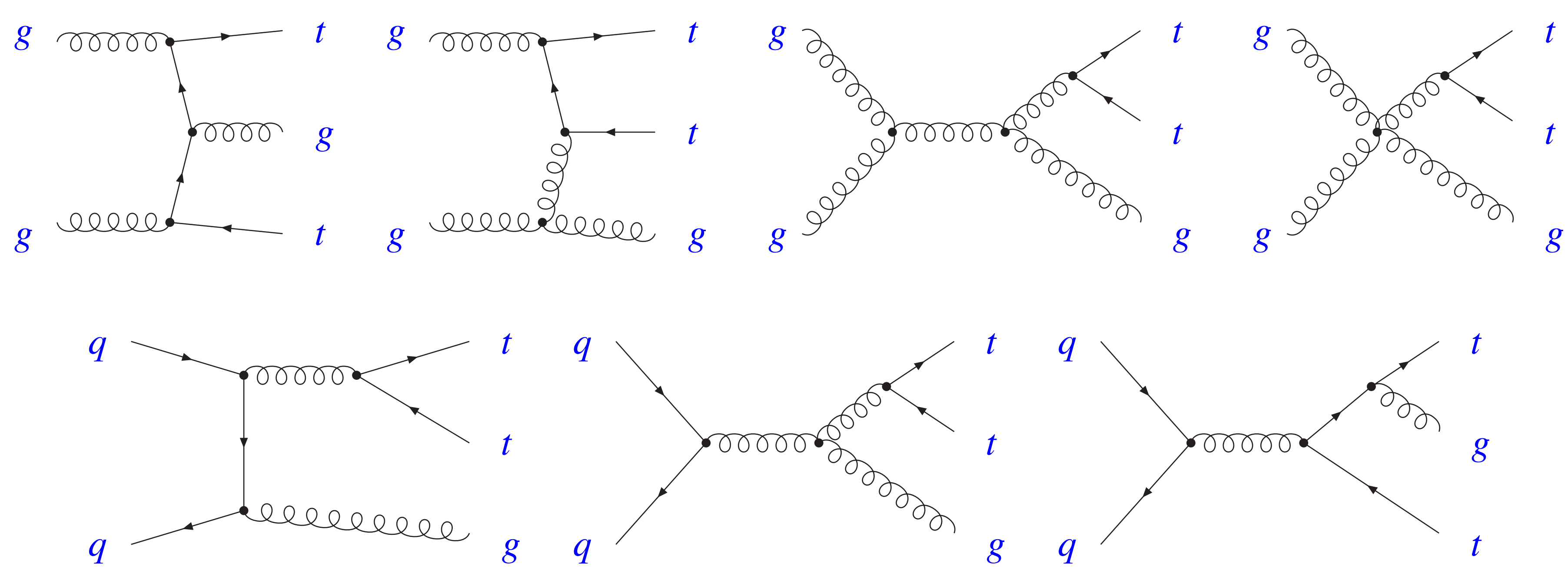
- Large number of results/figures for LHC7, LHC8, LHC14 and Tevatron
- t-channel, Wt production, s-channel
- cross section vs m_t
- p_T-distribution
- see slides for details

Talk by S. Moch

Top-quark pairs with one jet

Production of $t\bar{t}$+jet at fixed order

- LHC: large rates for production of $t\bar{t}$-pairs with additional jets
- Scale dependence at LO large



- Feynman diagrams (sample) for $t\bar{t}+$ jet production at LO

t-tbar + j

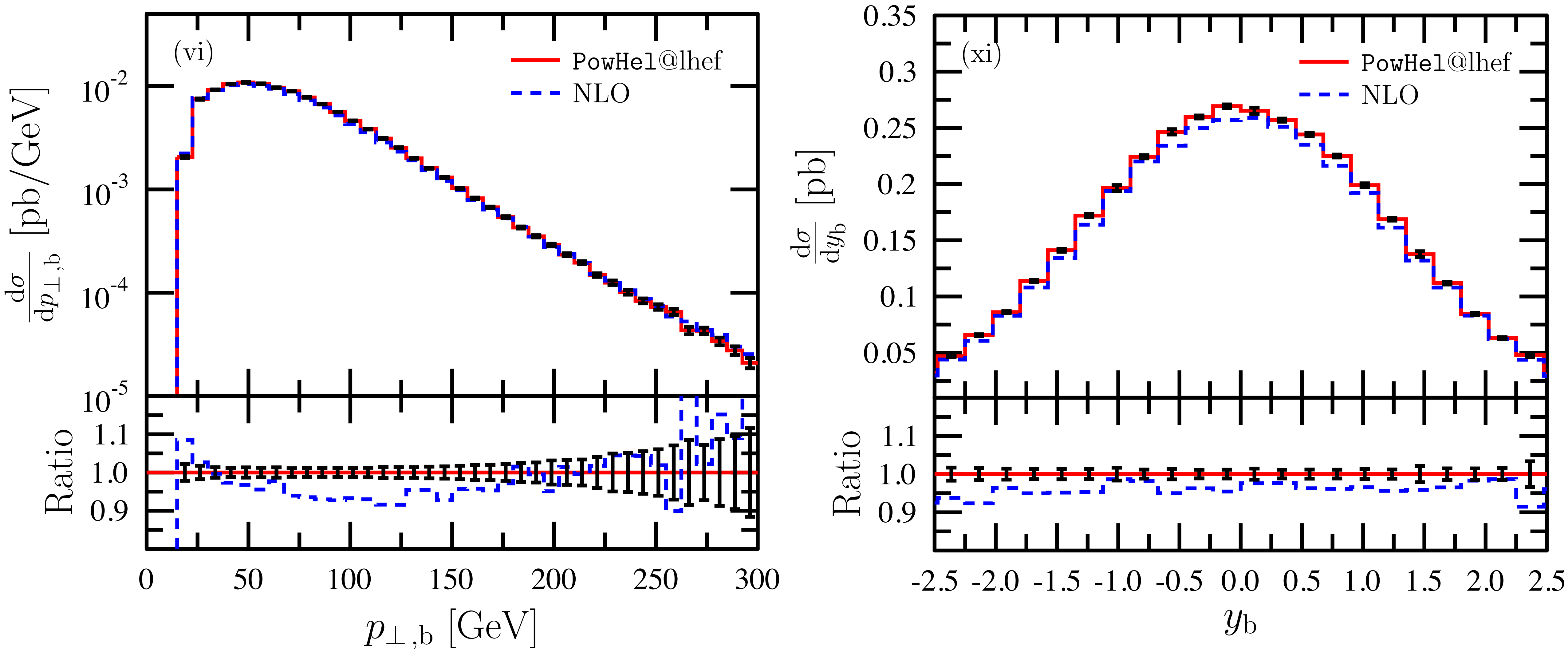
- NLO corrections calculated.
  Considerably reduced scale dependence
- Implemented in POWHEGBOX
  - NLO + Parton Shower. Public release soon
  - Important for A_{FB} and A_C in t-tbar+jet samples
  - Top quark decay in included
    → generate events with stable t-tbar with POWHEG
    → generate decay products using ME for full production and decay
    → reshuffle momenta of t-tbar decay products
    → obtain off-shell t, tbar, W
- New observables:
  - independent measurement of m_t
  - spin-correlations

A. Kardos, Z. Trocsanyi, M. Garzelli

t-tbar + j, t-tbar +Z, t-tbar+ H/A, W^+W^-b-bbar in POWHEL

- POWHEL = POWHEG-BOX + HELAC-1LOOP (NLO + Parton Shower)
- New: HELAC-1LOOP@dd (more than double precision)
- New: Decay with DECAYER
  - Post-event generation run
  - Spin correlations
  - CPU efficient

$W^+ W^- b \bar{b}$



Transverse momentum and rapidity distribution for the b at 7TeV LHC

based on the full NLO calculation by

Bevilacqua in arXiv:1012:4230