Theory status for single-top cross sections
(s and t channel)

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Single top production

- Contrary to top pair production, single tops are not produced via the strong force, but by the weak force
- There are three distinct* production mechanisms, named after the virtuality of the W boson
  - s channel
  - t channel
  - W-associated single-top production

* There are interferences between the three channels at (N)NLO, but they are color suppressed and do not hamper the separation in (most) phenomenological studies

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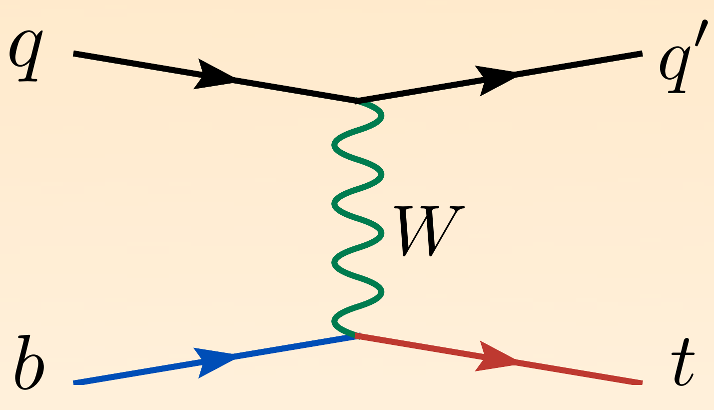
Single top in the SM

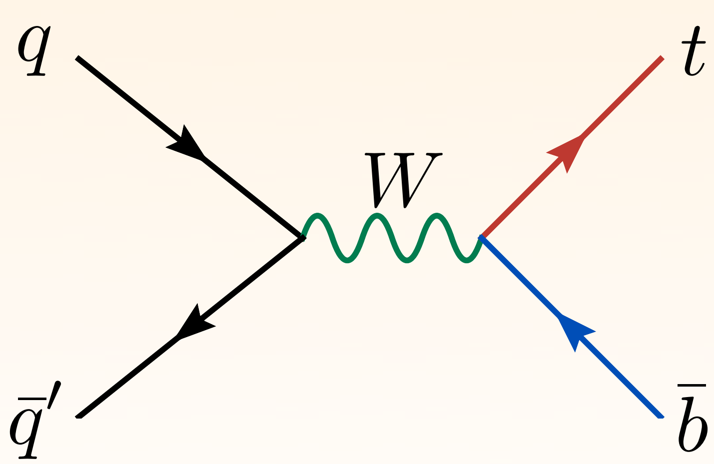
t channel



- relative t-channel enhancement at LHC
- Also enhancement from b quark PDF
- Proportional to $|V_{tb}|^2$

Cross section	
Tevatron	2.0 pb
LHC 14 TeV	240 pb

s channel

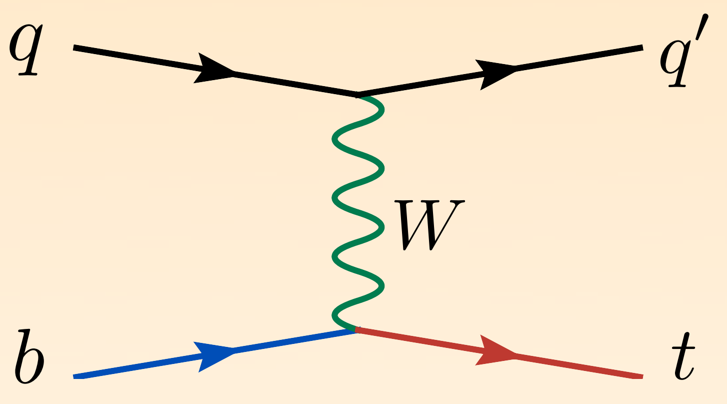


- "Just like Drell-Yan"
- More sensitive to quark valence structure: relative enhancement at the Tevatron
- Proportional to $|V_{tb}|^2$

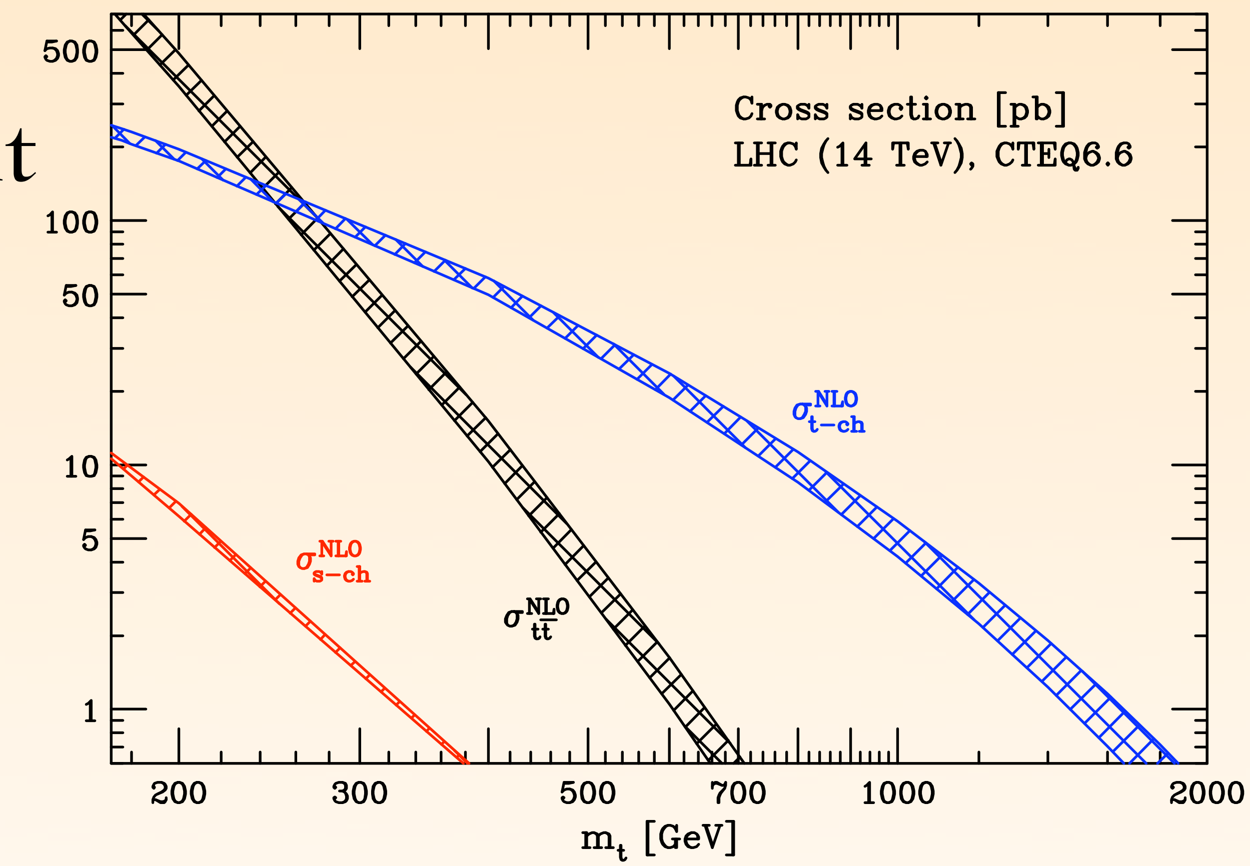
Cross section	
Tevatron	0.86 pb
LHC 14 TeV	10 pb

Single top and BSM

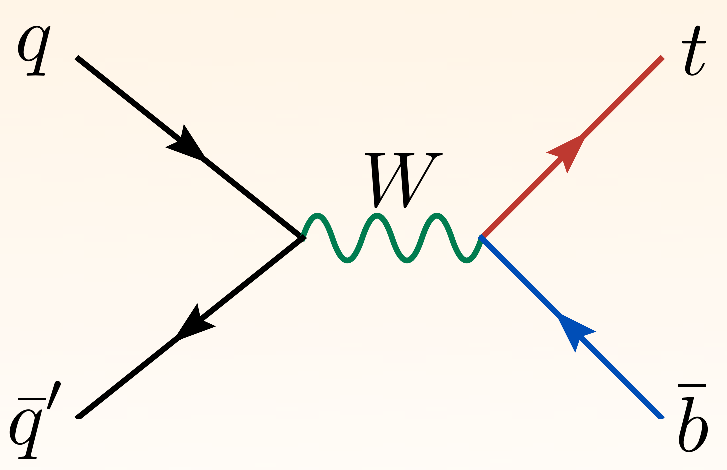
t channel



- Sensitive to FCNCs
- t-channel enhancement for heavy t' quarks



s channel



- Sensitive to heavy (charged) New Physics resonances (W', charged Higgs, ...)
- Falls off like top pair with increasing t' quark mass

Motivation for NLO

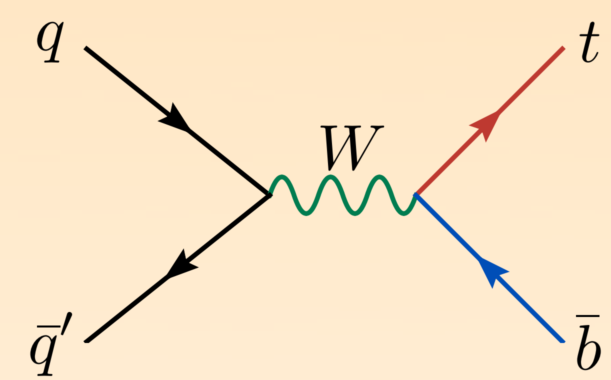
- Because of the small cross section and the high backgrounds, experimental analyses use multi-variance techniques based on using as much (kinematic) information as possible
- These techniques are sensitive to details of the theory predictions
- Need high precision predictions, which go beyond leading order

Beyond leading order

Single top	s channel	t channel (5-Flavor Scheme)	t channel (4-FS)
NLO total rate	*Smith & Willenbrock (1996)*	*Bordes & Van Eijk (1995); Stelzer, Sullivan & Willenbrock (1997)*	*Campbell, RF, Maltoni, Tramontano (MCFM, 2009)*
NLO differential	*Harris, Laenen, Phaf, Sullivan & Weinzierl (2002); Sullivan (ZTOP, 2004)*		
NLO including top quark decay	*Pittau (1996)* *Campbell, Ellis & Tramontano (MCFM, 2004)* *Cao, Schwienworst & Yuan + Benitz & Brock (2005)*		✘
approx. higher orders (total rate only)	*Kidonakis (2006, 2010)*		✘
NLO matched to parton shower	*Frixione, Laenen, Motylinski & Webber (MC@NLO, 2006); Alioli, Nason, Oleari & Re (POWHEG, 2009)*		✘
NLO electroweak corrections	✘	*Beccaria, Carloni Calame, Mirabella, Piccinini, Renard & Verzegnassi (2008)*	✘

S-channel process

- NLO estimate of the theory uncertainty:
  - top mass as central scale with independent variation of renormalization and factorization scales by a factor 2;
  - 44 eigenvector CTEQ6.6 PDF's;
  - top mass: 172 ± 1.7 GeV;

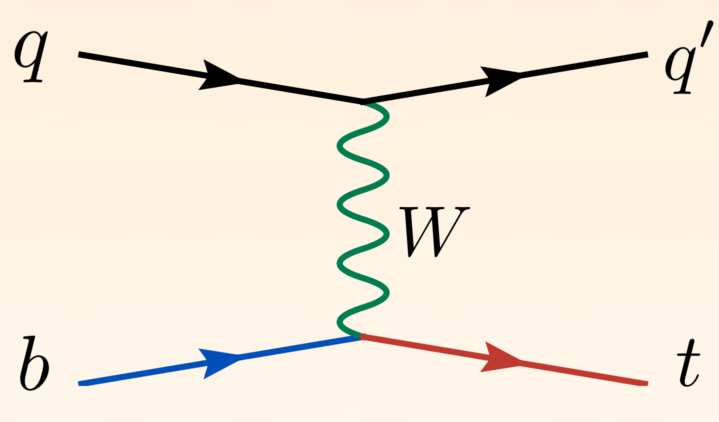


$\sigma^{\rm NLO}_{\rm s-ch}(t+\bar{t})$		scale	PDF	m_t	
Tevatron Run II	0.858	$^{+0.023}_{-0.021}$	$^{+0.015}_{-0.016}$	$^{+0.018}_{-0.017}$	pb
LHC (7 TeV)	4.02	$^{+0.12}_{-0.09}$	$^{+0.15}_{-0.16}$	$^{+0.16}_{-0.15}$	pb
LHC (14 TeV)	10.58	$^{+0.34}_{-0.23}$	$^{+0.34}_{-0.34}$	$^{+0.40}_{-0.35}$	pb

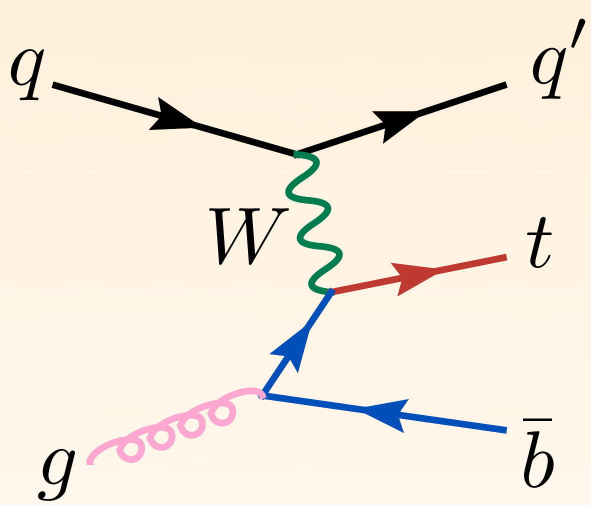
- Preferred tools for event simulation are MC@NLO and/or POWHEG:
  - Narrow-width approximation for the top quark, keeping spin correlations; but spin correlation and decay at LO
  - Completely general CKM matrix

T-channel process

- For the t-channel process the situation is more complicated due to the initial state b quark
- The LO + parton shower greatly underestimates the importance of the spectator b



leading order



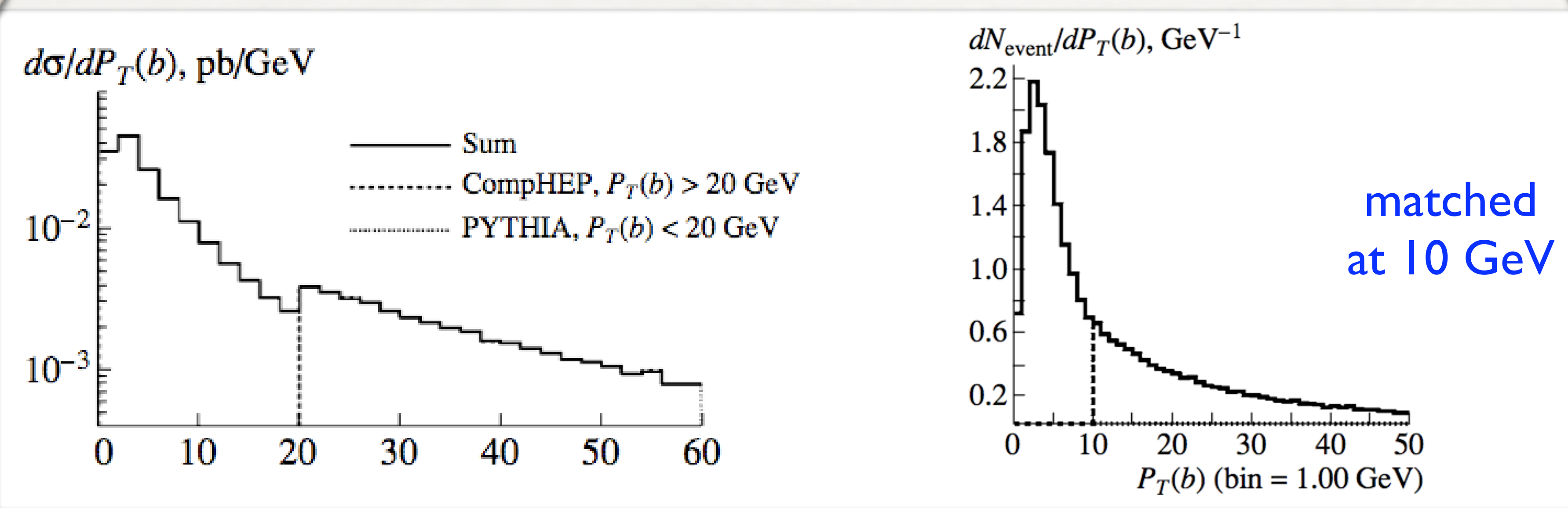
(contribution to) NLO

- With NLO, spectator b spectrum is described only at first non-zero order (thus, in fact, LO)

“Effective NLO” for T-channel

- At LO, no spectator b quark
- At NLO, effects related to the spectator b only enter at this order and not well described by corresponding MC implementations
- ➞ separate regions according to $p_T(b)$ and use LO 5F (2 ➞ 2)+ shower below and LO 4F (2 ➞ 3) above

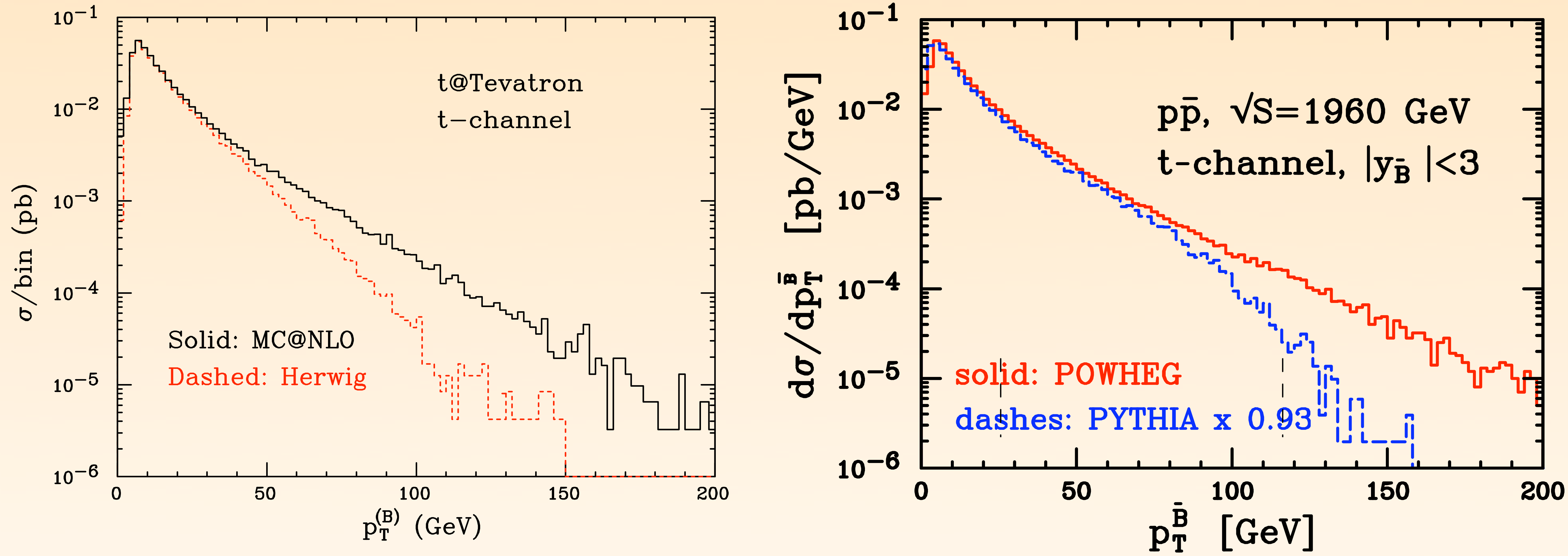
Boos et al., Phys. At. Nucl. 69, 1317 (2006)



- Ad hoc matching well motivated, but theoretically unappealing

MC@NLO & POWHEG

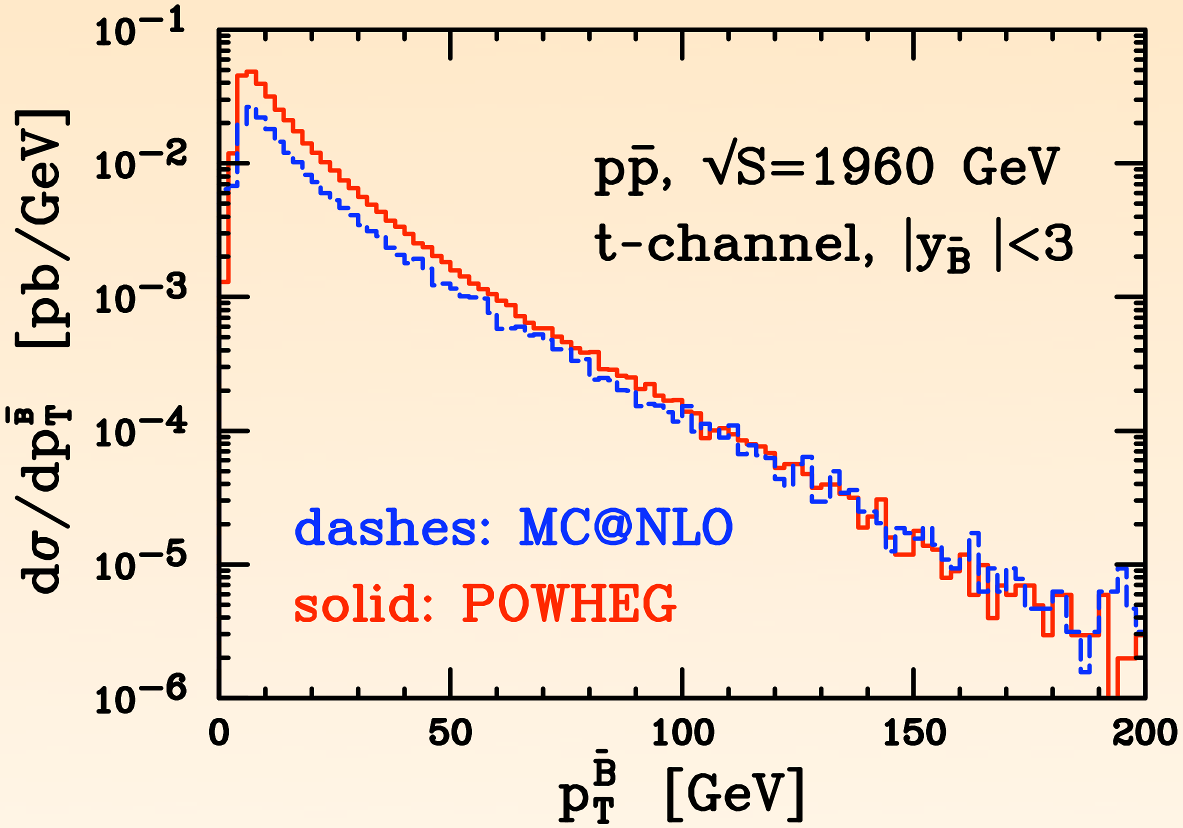
Frixione, Laenen, Motylinski & Webber (2006); Alioli, Nason, Oleari & Re (2009)

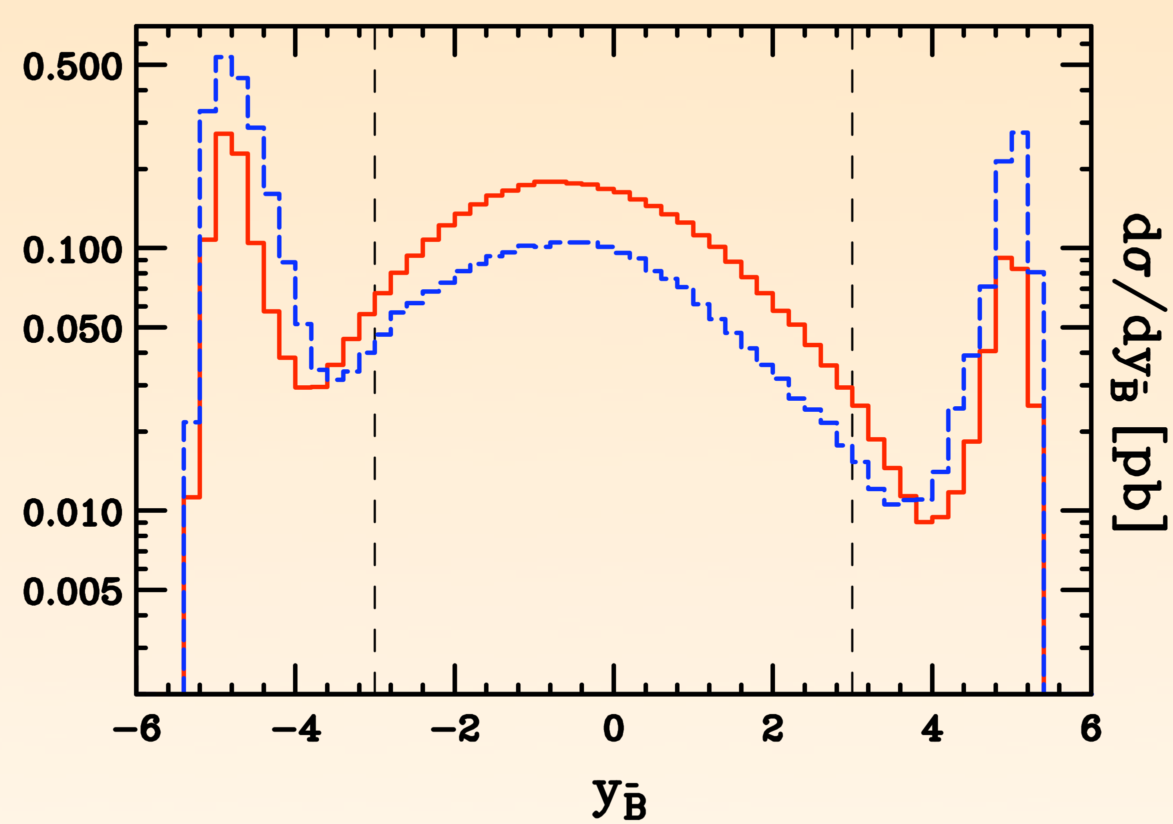


- Consistently implemented in the MC@NLO and POWHEG frameworks
- No ad hoc cut needed to get harder tail for the spectator b

MC@NLO & POWHEG II

Frixione, Laenen, Motylinski & Webber (2006); Alioli, Nason, Oleari & Re (2009)

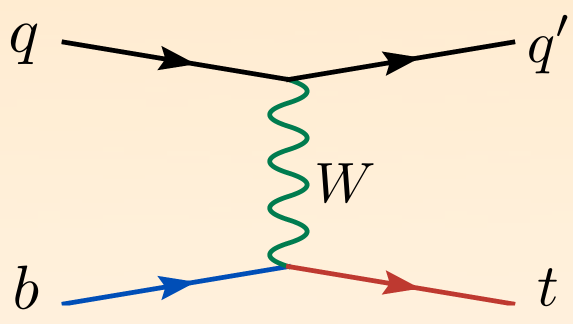




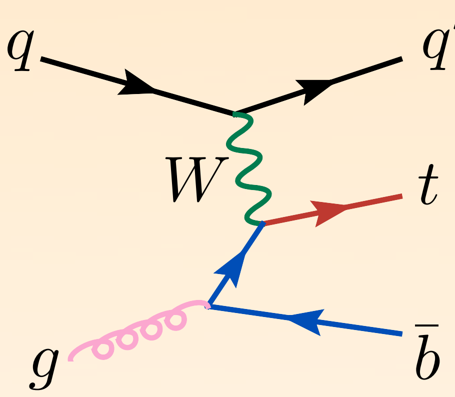
- However...
  - Sizable differences between MC@NLO and POWHEG (with Herwig shower) for spectator b in shape and normalization
  - No real surprise, because the b quarks are treated massless -> low p_T region not well described

Initial state b quark

- "Standard" way of looking at this process



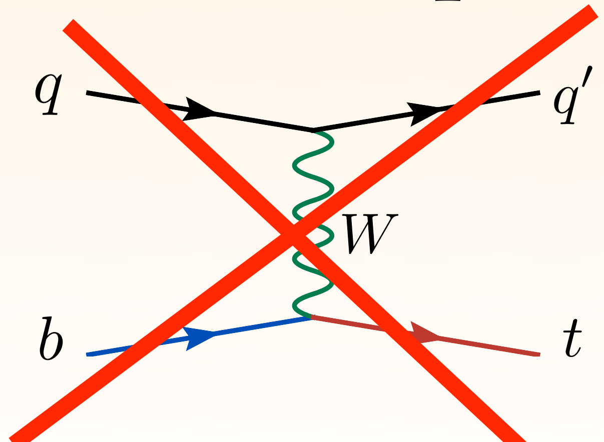
leading order



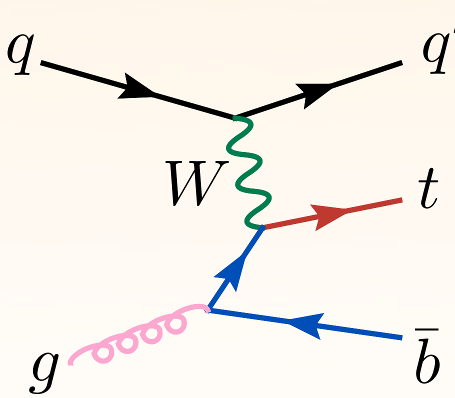
(contribution to) NLO

5-flavor scheme

- But there is an equivalent description with no bottom PDF and an explicit gluon splitting to b quark pairs



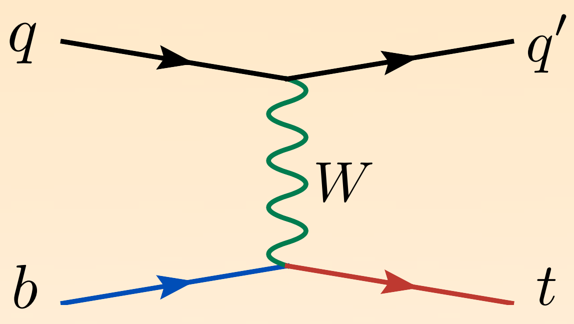
Does not exist



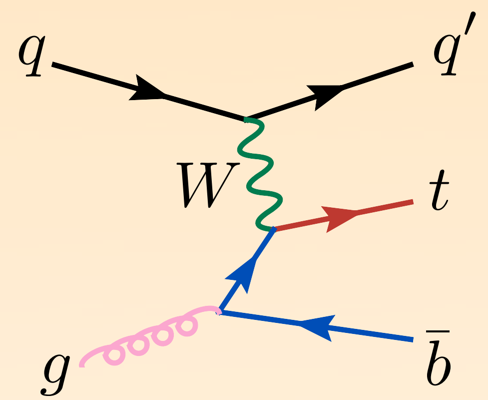
(part of) leading order

4-flavor scheme

The two schemes



5-flavor scheme: "2 ➞ 2"



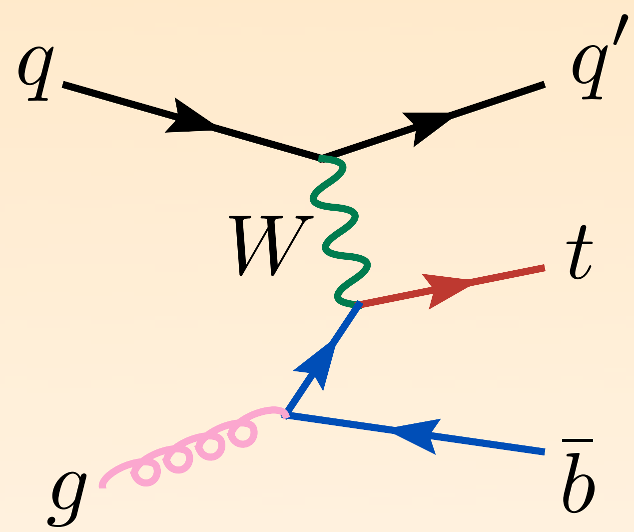
4-flavor scheme: "2 ➞ 3"

- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - available phase space
  - approximation by large logarithm

Four-flavor scheme

Campbell, RF, Maltoni, Tramontano (2009)

- Use the 4-flavor (2 → 3) process as the Born and calculate NLO
  - Much harder calculation due to extra mass and extra parton
  - Spectator b for the first time at NLO
  - Compare to 5F (2 → 2) to asses logarithms and applicability

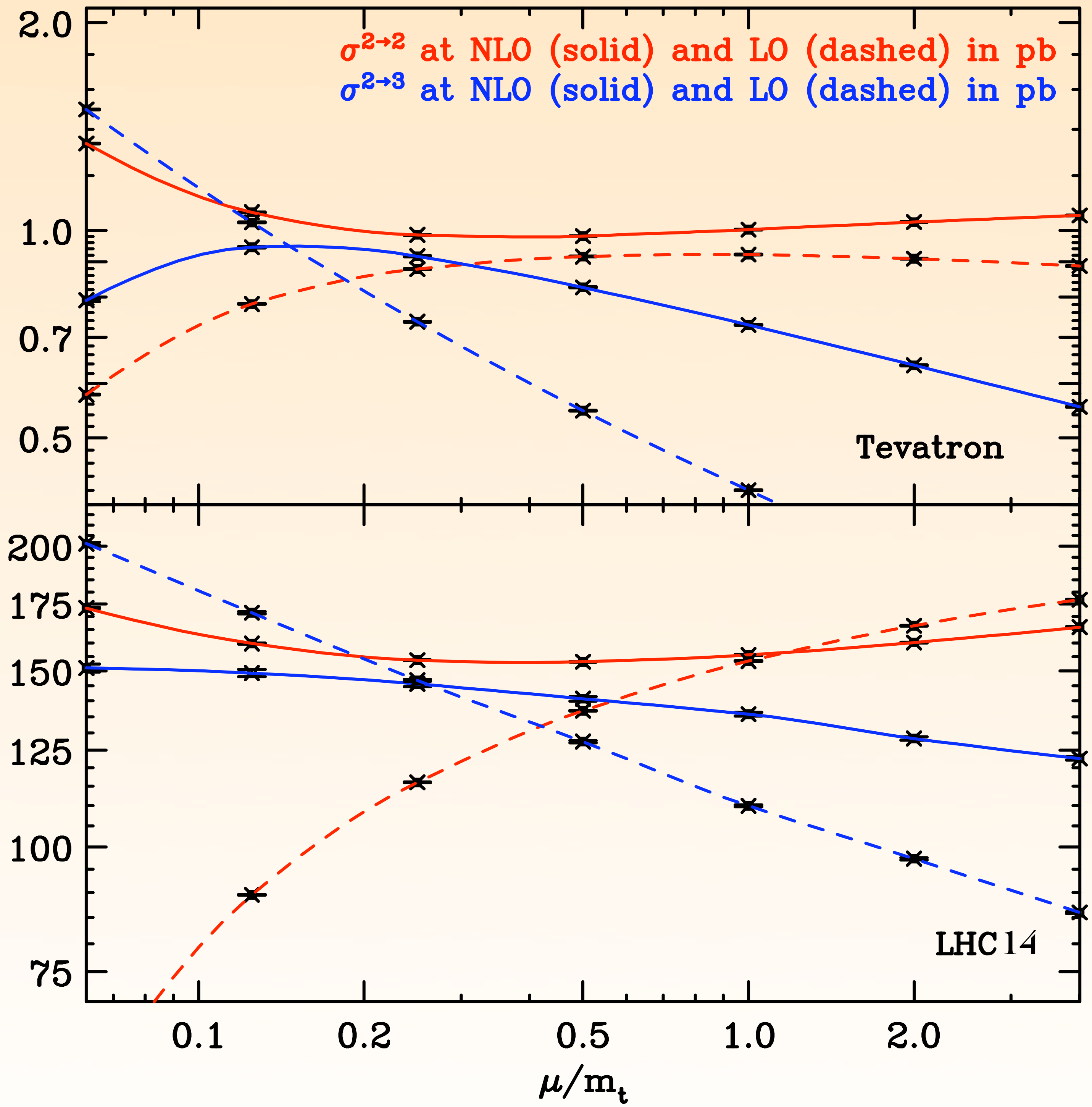


- Process implemented in the MCFM-v5.7 parton-level NLO code
  - Starting point for future NLO+PS beginning at (2 → 3)

PDFs

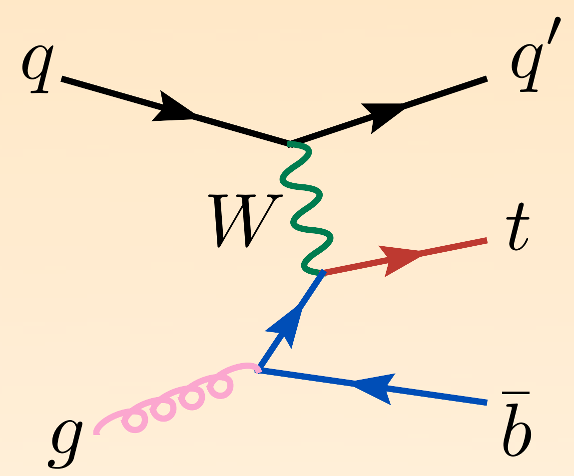
- For the 5F (2 → 2) scheme, use regular PDF
- For 4F (2 → 3) calculation, PDF's need special treatment for consistency
  - the b quark should not enter the evolution of the strong coupling or the PDF: **MRST2004FF4**
  - could also use a 5F PDF and pass to the 4F scheme using transition rules by *Cacciari et al., JHEP05, 007 (1998)*
- We use second option: CTEQ6.6 PDF set for both

Scale dependence



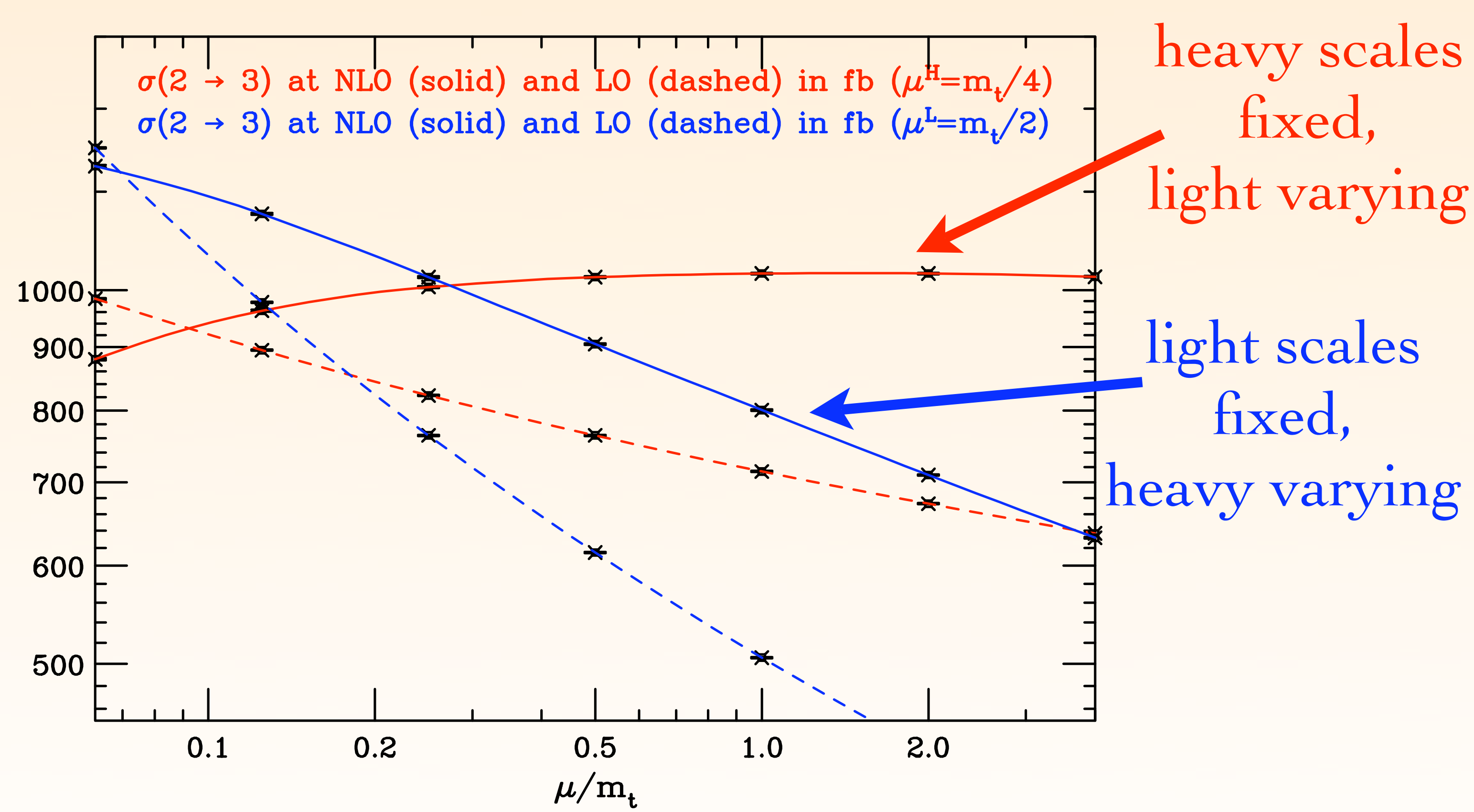
- Both schemes much improved from LO
- 5F (2 → 2) only mildly sensitive to scales at NLO (use m_t in what follows)
- 4F (2 → 3) expected to be worse, but isn't much
- Hardly a region of overlap between the two
- 4F (2 → 3) prefers smaller scales than m_t, particularly at the Tevatron

Scale dependence 2 → 3



- Due to the near-factorization between the heavy and light quark lines we can vary the corresponding scales independently
  - Expect smaller scale for heavy line due to $g \to b\bar{b}$ splitting

- Tevatron, LHC is similar
- Stronger dependence on heavy line, as expected
- Preference for scales smaller than m_t
- Choose central values: $\mu_L = m_t/2,\ \mu_H = m_t/4$



Total rates and theory uncertainties

- Estimate of the theory uncertainty:
  - independent variation of renormalization and factorization scales by a factor 2
  - 44 eigenvector CTEQ6.6 PDF's
  - Top mass: 172 ± 1.7 GeV
  - Bottom mass: 4.5 ± 0.2 GeV

$\sigma^{\mathrm{NLO}}_{\mathrm{t-ch}}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
		Fac. & Ren. scale	PDF	top mass	b mass		Fac. & Ren. scale	PDF	top mass	b mass
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (7 TeV)	62.6	$^{+1.1}_{-0.5}$	$^{+1.4}_{-1.6}$	$^{+1.1}_{-1.1}$	$^{+1.1}_{-1.1}$	59.4	$^{+2.1}_{-3.4}$	$^{+1.4}_{-1.4}$	$^{+1.0}_{-1.0}$	$^{+1.3}_{-1.2}$
LHC (14 TeV)	244	$^{+5}_{-4}$	$^{+5}_{-6}$	$^{+3}_{-3}$	$^{+4}_{-4}$	234	$^{+7}_{-9}$	$^{+5}_{-5}$	$^{+3}_{-3}$	$^{+4}_{-4}$

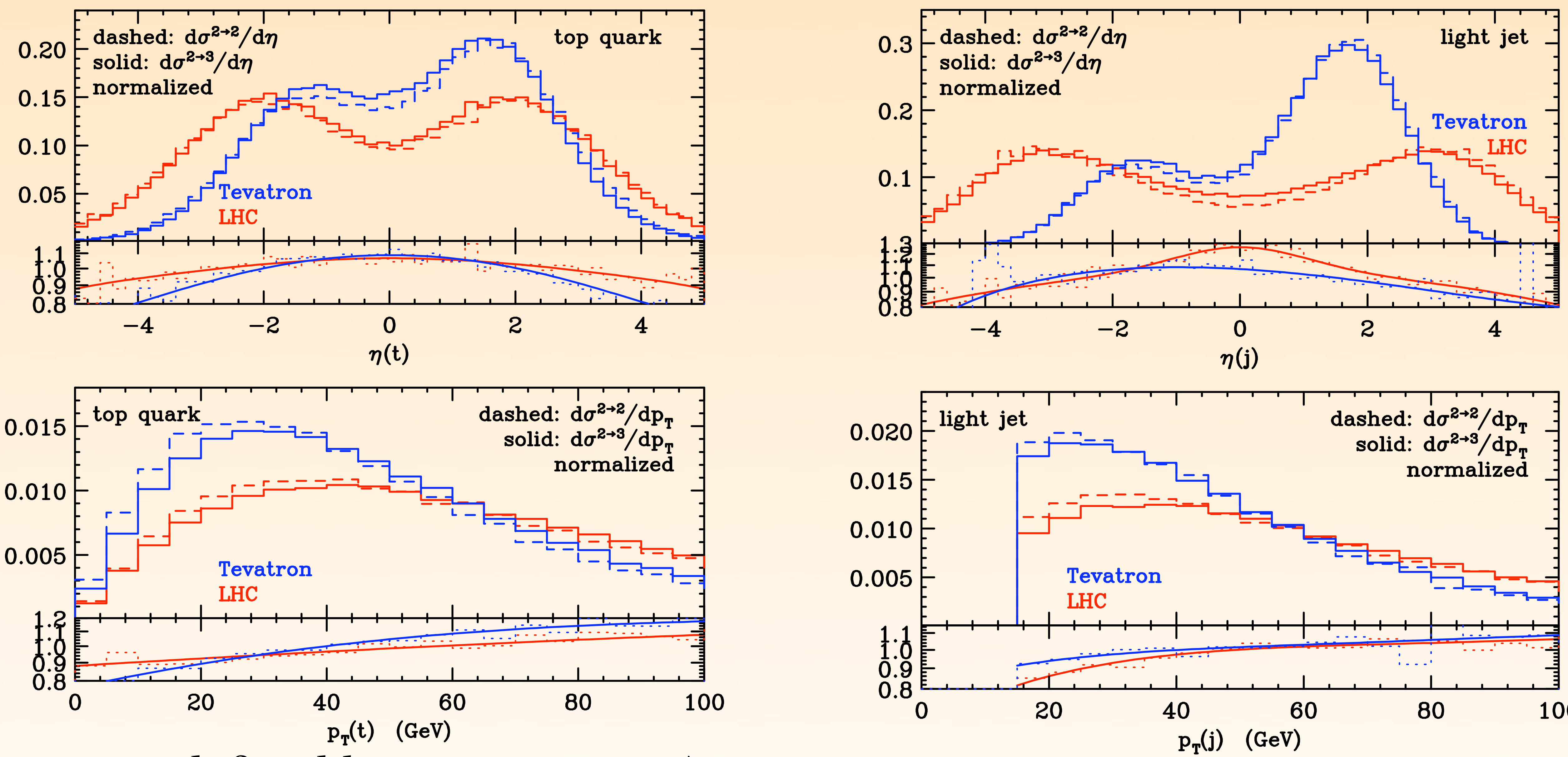
Fac. & Ren. scale

PDF

top mass

b mass

Top quark distributions



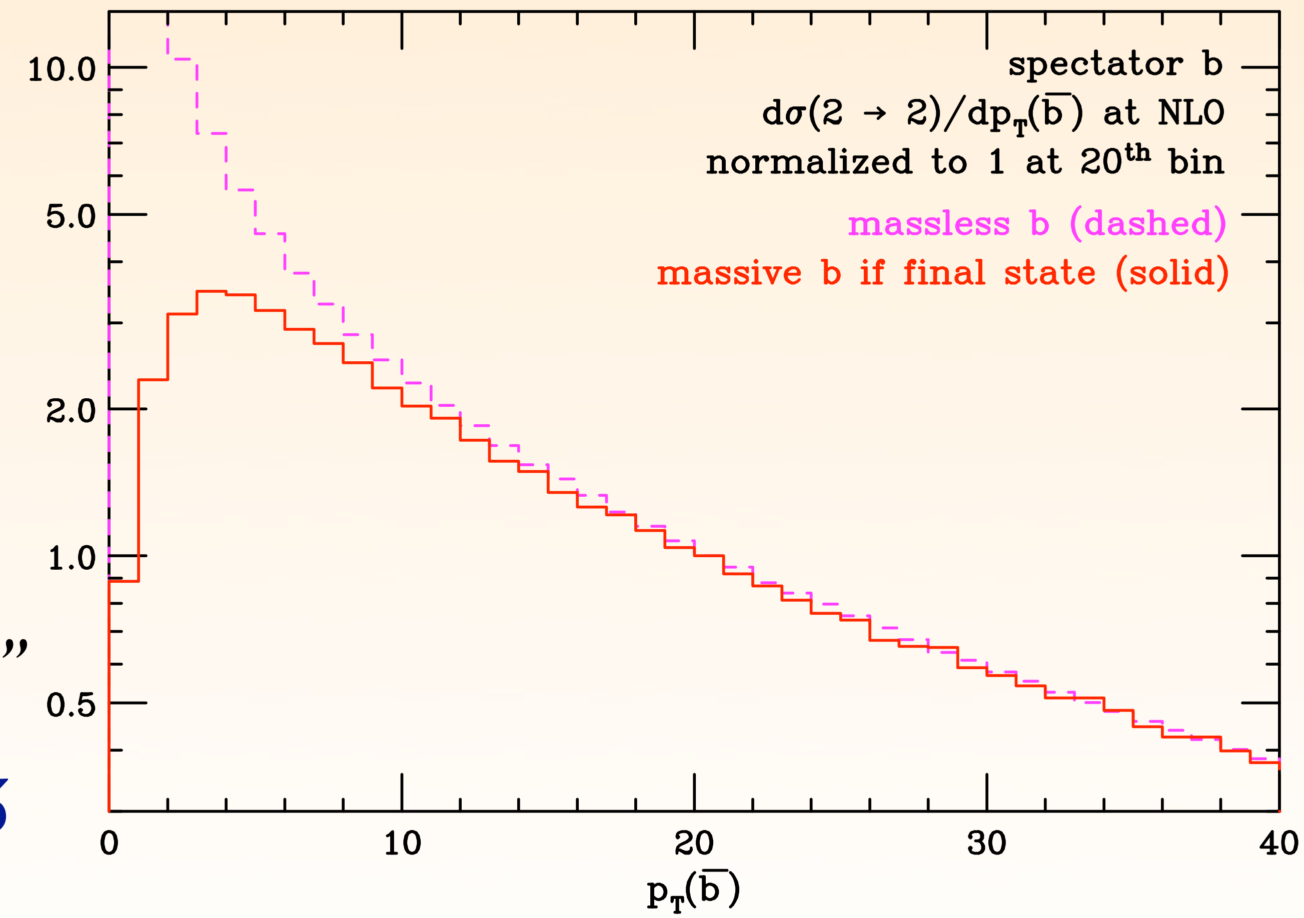
- Jet defined by: $p_T > 15$ GeV, $\Delta R > 0.7$
- Some differences, but typically of the order of ~10% in the regions where the cross section is large
- Shapes are very similar to LO predictions (not shown)

4-FS vs 5-FS

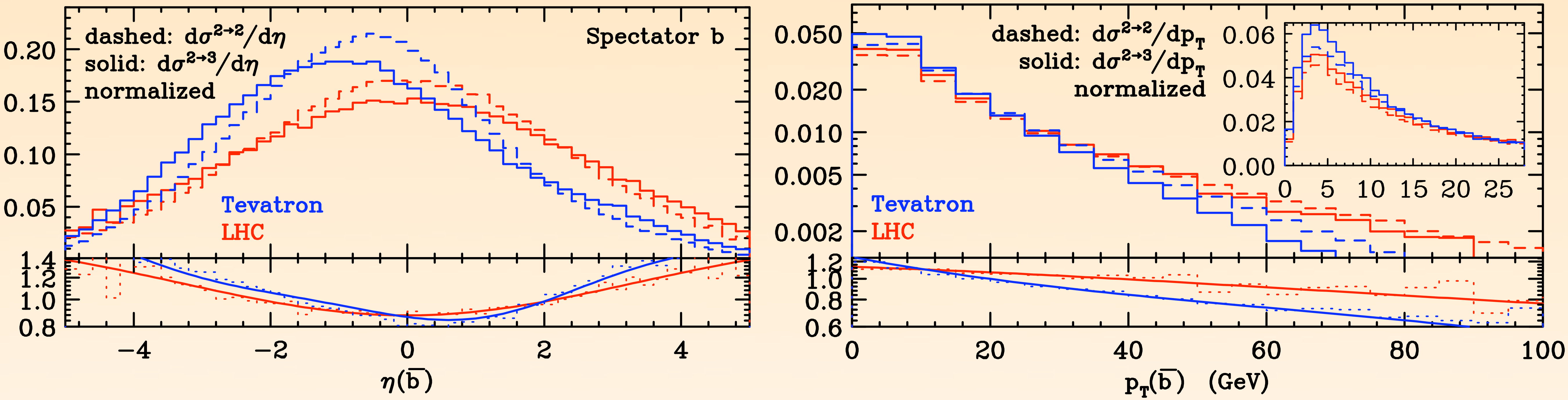
- Calculation in the 4-flavor scheme is well under control: scale dependence is mild
- Total rate in agreement with the 5-Flavor calculation (in particular at the Tevatron)
  - "Large logarithms" which are resummed in the PDF are maybe not so large after all... Should be confirmed in other processes as well
- Also shapes for top and jet distributions are similar
- Improvement: spectator b distributions are now at NLO including b mass effects, see next slides...

Improvement in 2 → 2

- When the b quark is **initial state**: treat it as a **massless** quark as usual
- When the b quark is **finial state**: treat it as a **massive** quark
  - Explicit logarithm cancelled using the ACOT formalism
  - Negligible effect on total rate, distributions of top & light jet
  - Significant effect on the b quark distributions -- mass regulates the “divergence”
  - Shape is the same as LO 2 → 3 with massive b quark

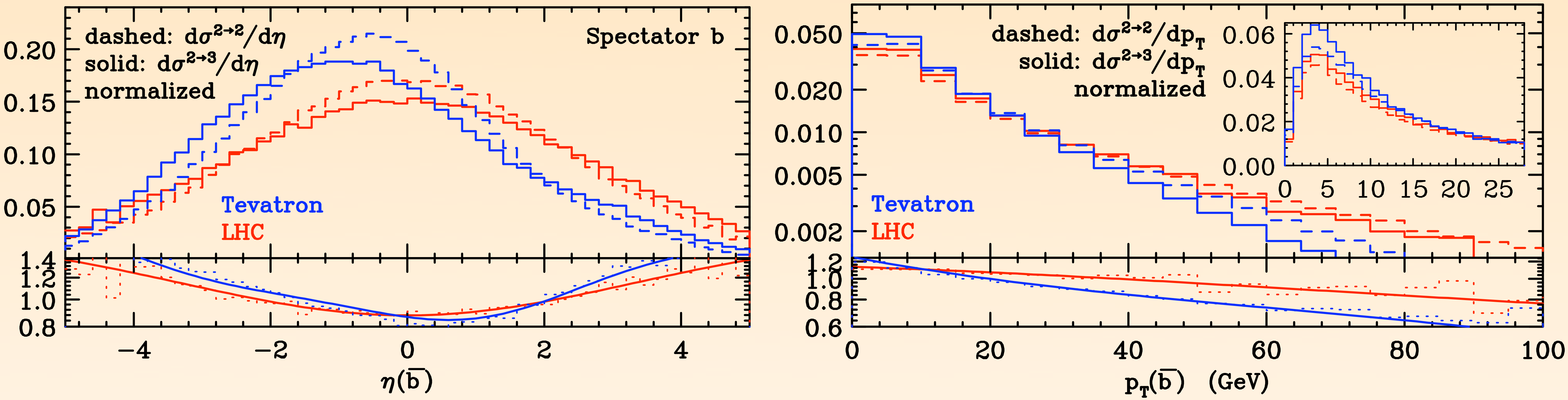


Bottom quark



- Dashes: 2 ➞ 2 at "NLO", with massive (when final state) b quark: the same shape as the 2 ➞ 3 at LO
- Solid: 2 ➞ 3 at NLO: first NLO prediction for these observables
- More forward and softer in 2 ➞ 3, particularly at the Tevatron
- Mild deviations up to ~ 20%

Bottom quark



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- Solid: 2 ➞ 3 at NLO: first NLO prediction for these observables
- More forward and softer in 2 ➞ 3, particularly at the Tevatron
- Mild deviations up to ~ 20%

In fact: 2 ➞ 3 at LO does a pretty good job (for shapes)!

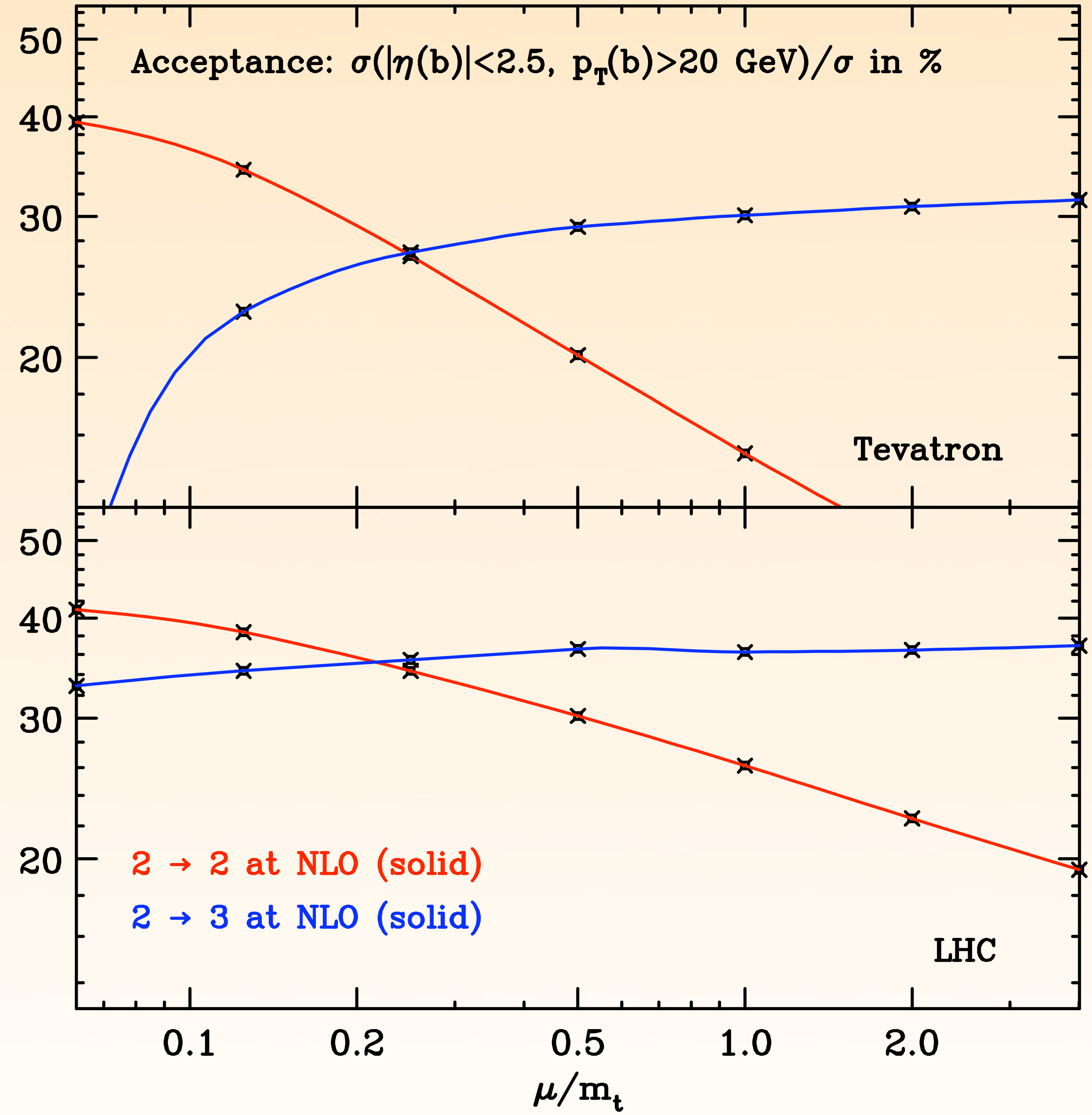
More bottoms in 4F

- However, there are large differences between 5F ($2 \to 2$) and 4F ($2 \to 3$) schemes for more exclusive quantities in the spectator b quark
  - Event though b quarks in the 4F ($2 \to 3$) scheme are more forward and softer, we expect to see more b's than in the 5F ($2 \to 2$)
    - In 5F ($2 \to 2$) only a subset of real emission diagrams have a final state b quark
  - Define "acceptance" as the ratio of events that have a central, hard b over inclusive cross section:

$$\frac{\sigma(|\eta(b)| < 2.5,\, p_T(b) > 20\ \mathrm{GeV})}{\sigma_{\mathrm{inclusive}}}$$

Acceptance

- Very large scale dependence for 5F (2 → 2), → effectively a LO quantity
- NLO 4F (2 → 3) much stabler
- Striking difference at the Tevatron!
- LO 2 → 3 prediction gives ~34% (Tevatron) and ~40% (LHC)



Conclusions

- For **s-channel events**,
  - MC@NLO and/or POWHEG are the preferred event generators
- For **t-channel events**, the situation is more subtle:
  - MC@NLO and POWHEG give a good description of the process:
    - Consistent matching between NLO and parton shower
    - However, the distributions for the spectator b quark show differences -> sizable uncertainty
  - New NLO computation in the **4-flavor scheme** predicts the spectator b spectrum for the first time at NLO including mass effects
    - Corrections compared to 4-flavor LO ($2 \rightarrow 3$) are mild for shapes.
    - "Final" solution would be the NLO 4-flavor calculation matched to a parton shower