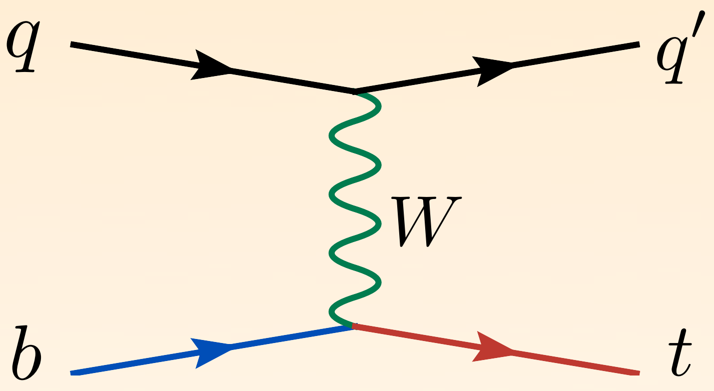
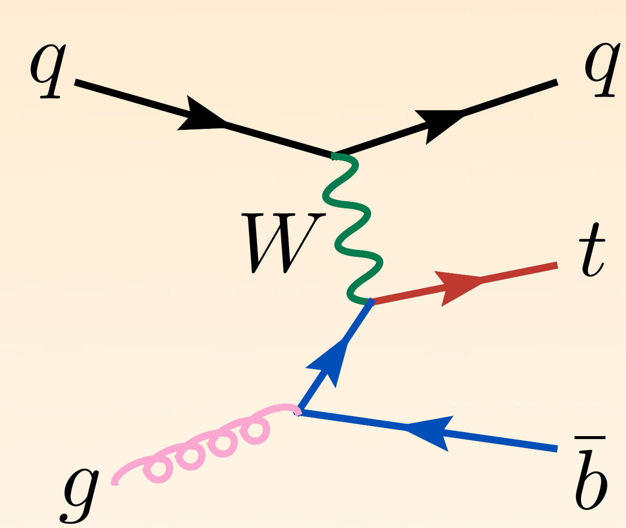
T-channel single top production



Rikkert Frederix

CP3 @ UCLouvain

CERN-TH



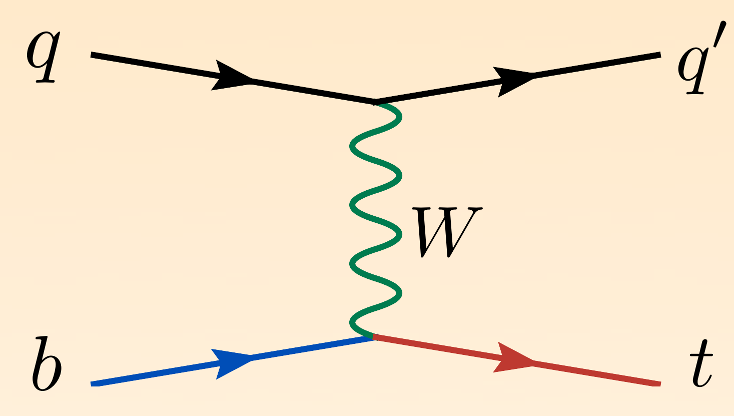
Work in progress, based on:

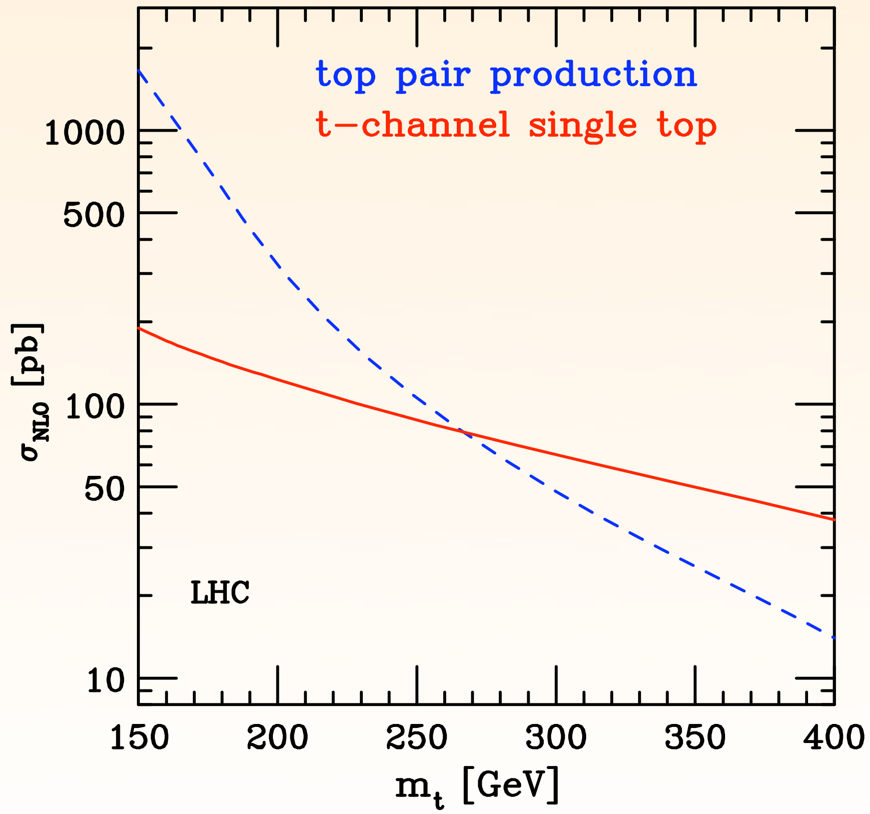
J. Campbell, RF, F. Maltoni and F. Tramontano

arXiv:0903.0005 [hep-ph] (PRL)

T-CHANNEL SINGLE TOP

- Already thought of more than 20 years ago
  Dicus & Willenbrock, PRD34, 155 (1986)
- Take advantage of (compared to pair production):
  - t-channel enhancement over s-channel growth
  - more available phase space

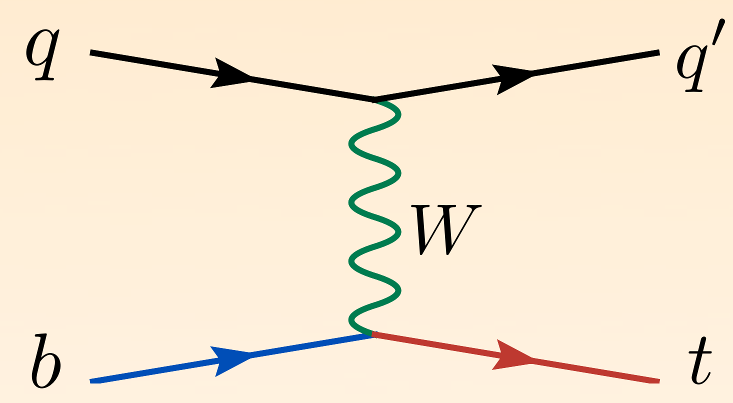




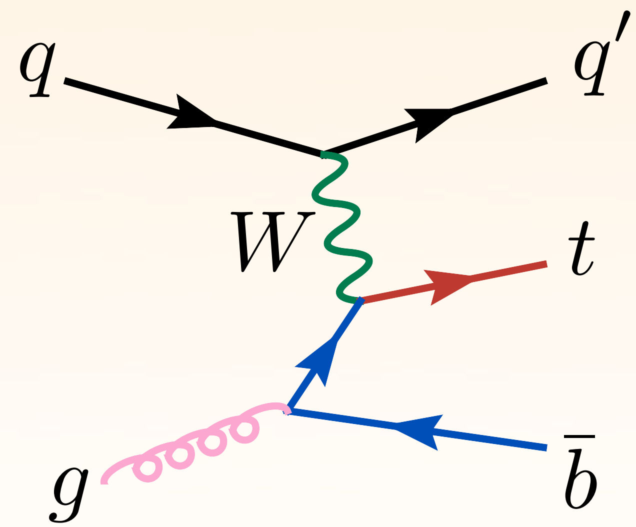
- Large cross section at LHC
- For very heavy quarks single top dominates -- t' searches
- Sensitive to V_{tb}, FCNC, ...
- NLO corrections by
  Bordes & Van Eijk (1995); Harris et al. (2002); Campbell et al. (2004); Q.-H. Cao et al. (2005); Frixione et al. (2006)

Heavy initial state quarks

- The t-channel single top production has a (heavy) b quark in the initial state



- There is an equivalent description with a gluon splitting to b quark pairs

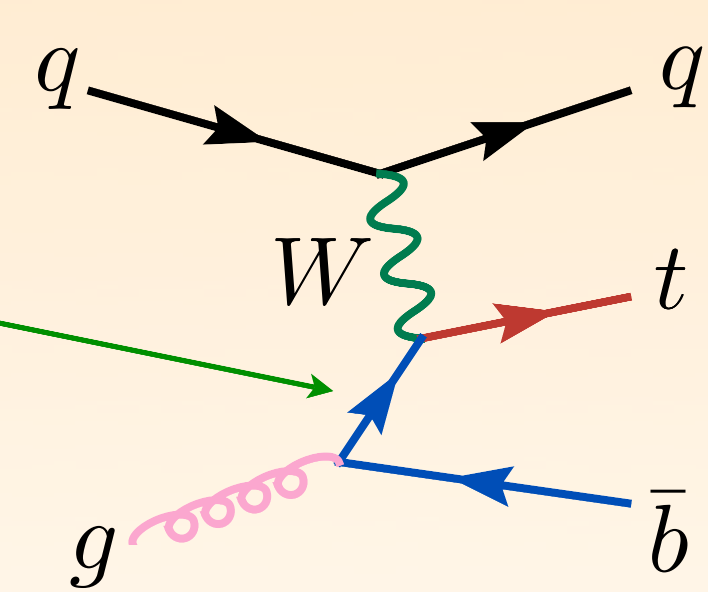


Collinear logarithms

- Both t-channel and Wt production are enhanced by a collinear logarithm
- This results from integrating over a t-channel propagator

$$\frac{1}{t - m_b^2} \sim \frac{1}{p_T^2 + m_b^2}$$

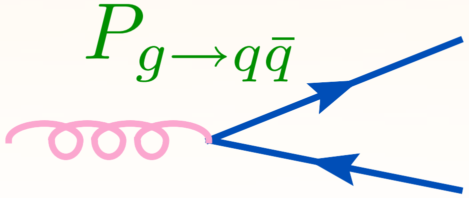
$$t = (p_{\bar{b}} - p_g)^2,\ p_T^2 = p_{T,\bar{b}}^2$$



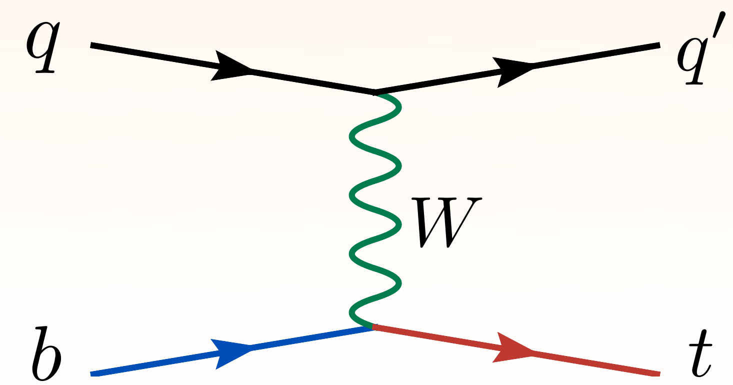
- Contribution to the cross section: $\int_0^{p_{T,\max}^2} \frac{dp_T^2}{p_T^2 + m_b^2} = \log\left(\frac{p_{T,\max}^2}{m_b^2}\right) + \ldots$
- Coefficient of the logarithm is:

AP splitting function

$P_{g\to q\bar{q}}$



times



matrix elements with splitting removed

Resummation into PDF

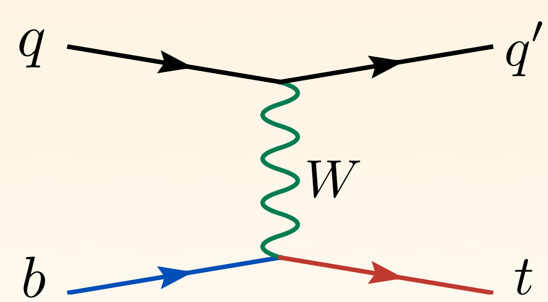
- Putting it together: $\dfrac{d\sigma(qg\to q' t\bar{b})}{d\log p_{T,\max}^2} \sim \left(\dfrac{\alpha_s}{2\pi}\right)\left[\int \dfrac{dx}{x} P_{g\to q\bar{q}} f_g\right] \times \hat{\sigma}(qb\to q't)$
- But the first part resembles the evolution equation for a quark:

$$\frac{df_q}{d\log q^2} \sim \left(\frac{\alpha_s}{2\pi}\right)\int \frac{dx}{x}\left[P_{g\to q\bar{q}} f_g + P_{q\to qg} f_q\right]$$

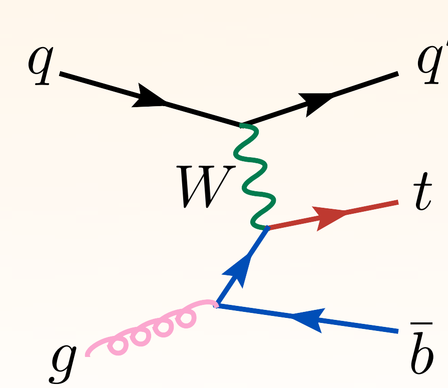
- So when the logarithms really dominate, we can replace this description by $\sigma(qg\to q' t\bar{b}) \approx \sigma(qb\to q't)$
- Scale of the bottom quark PDF should be related $p_{T,\max}$
- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - ranges of integration (obscured here)
  - approximation by large logarithm

ACOT formalism

- Sensible way to combine the two approaches was formally identified some time ago: ACOT formalism *Aivazis, Collins, Olness & Tung, PRD50, 3102 (1994)*
- Roughly: use the bottom PDF ("5 flavor scheme", $2 \to 2$) when the "spectator b" is not important, otherwise keep it explicit ("4 flavor scheme", $2 \to 3$)
- But what to do in the intermediate region?
  - Deciding factor -- simpler to calculate with one less external leg
- All higher order calculations so far have been performed in the 5F ($2 \to 2$) scheme

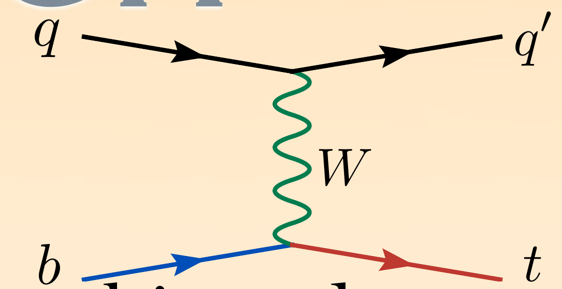


- Terms from 4F ($2 \to 3$) enter at NLO. Properties of spectator b are only LO



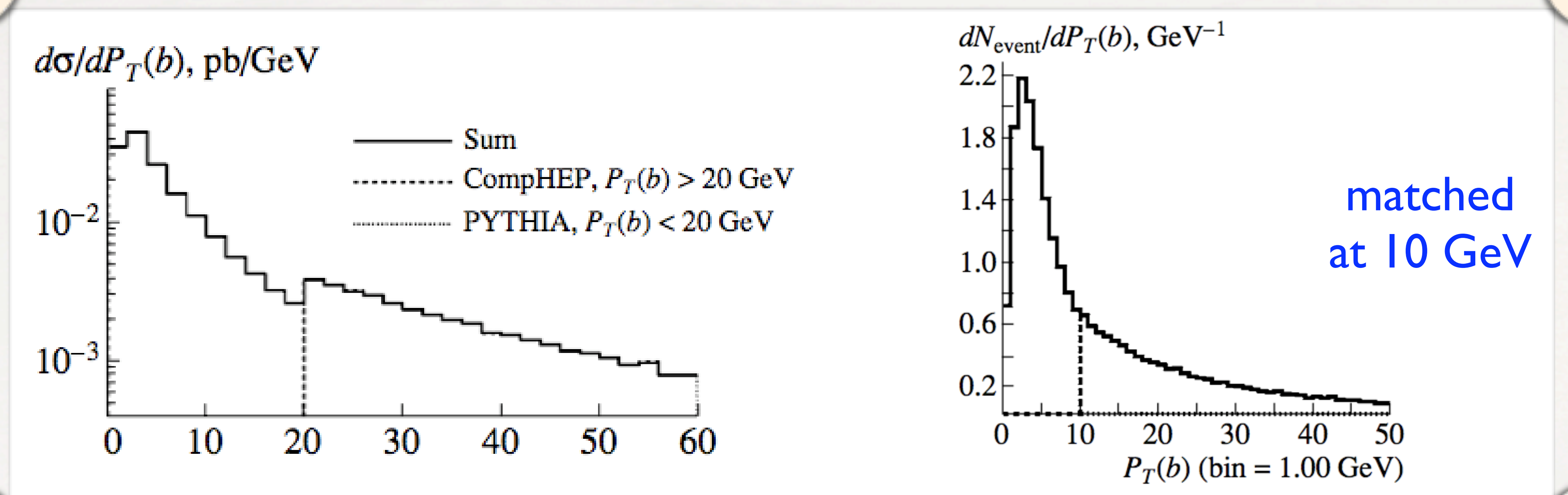
- All calculations presented so far set m_b=0 in final state for simplicity

Need for matching in the 5F (2 → 2) approach



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

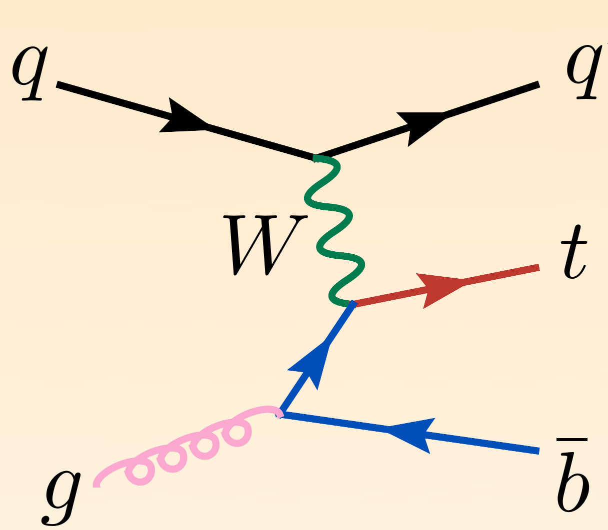
Boos et al., Phys. At. Nucl. 69, 1317 (2006)



- Ad hoc matching well motivated, but theoretically unappealing

Four-flavor scheme

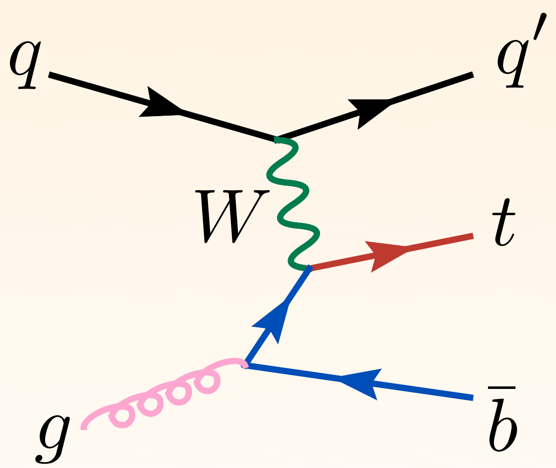
- Use the 4-flavor ($2 \to 3$) process as the Born and calculate NLO
  - Much harder calculation due to extra mass and extra parton
  - Spectator b for the first time at NLO
  - Compare to 5F ($2 \to 2$) to asses logarithms and applicability
  - Starting point for future NLO+PS beginning at ($2 \to 3$)



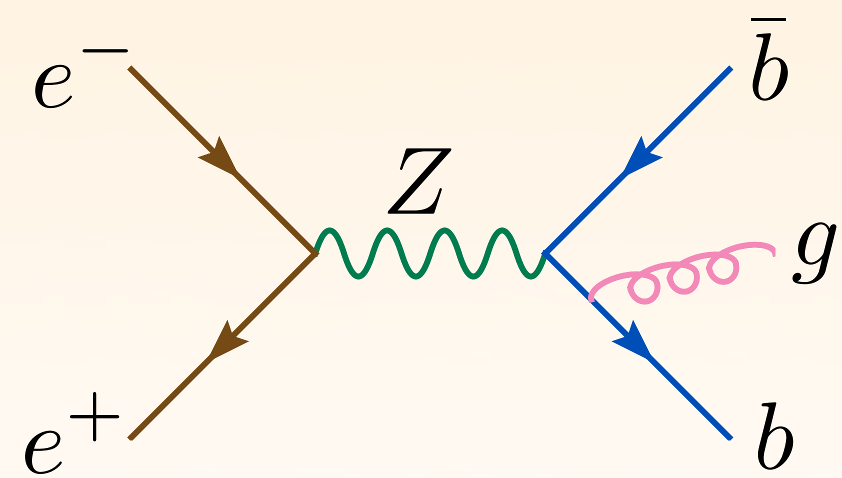
Checks of the calculation

- Real emission including subtraction terms checked against MadGraph & MadDipole
- Gauge invariance, CP, $m_t \Leftrightarrow m_b$ symmetry
- Two different reduction schemes

- Most interesting check comes from crossing the whole calculation



Change couplings, $m_t \rightarrow m_b$, sign of boson virtuality



Nason & Oleari, NPB 521, 237 (1998)

- Excellent agreement found

Setup

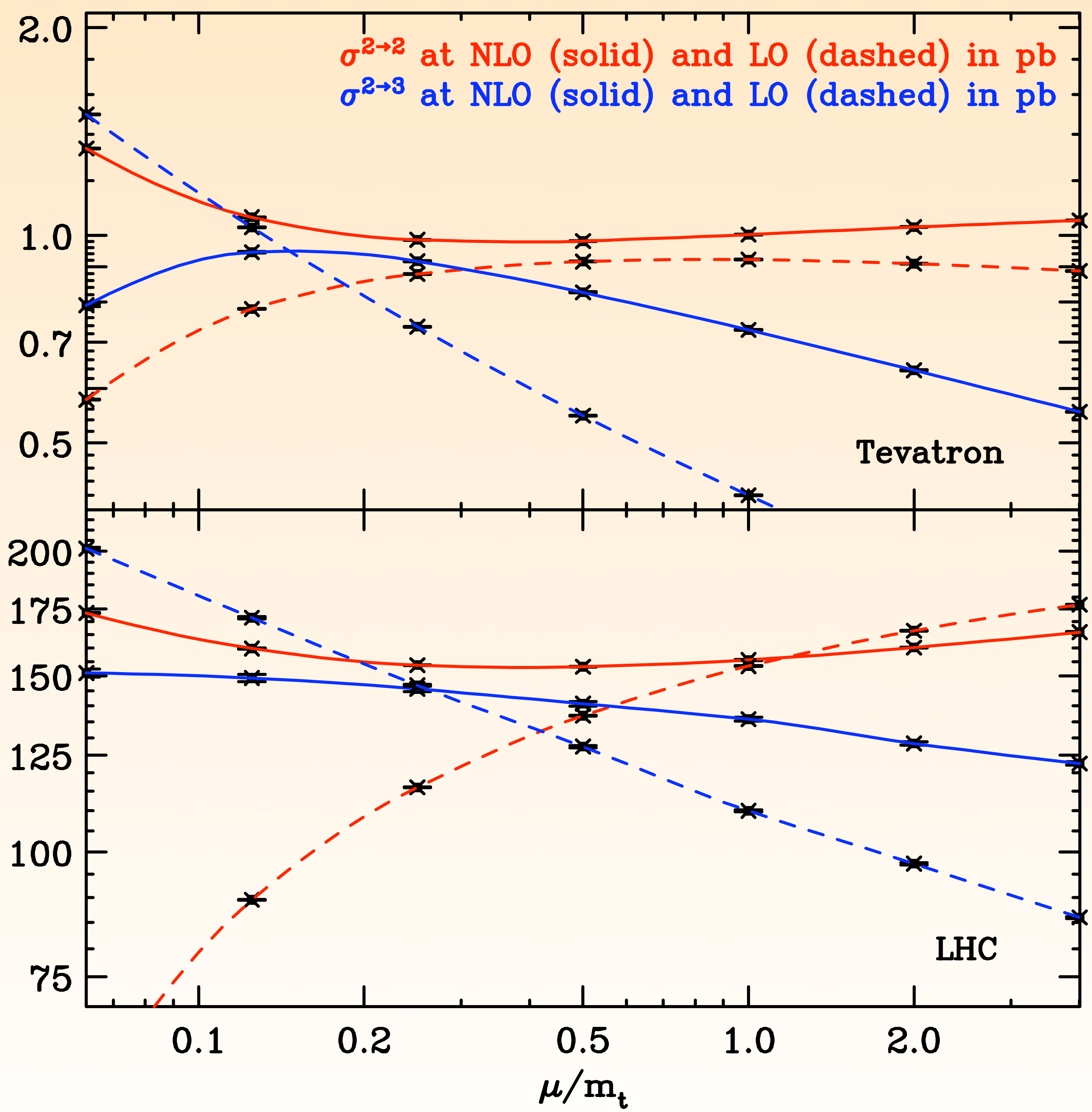
- Process implemented in the MCFM parton-level NLO code
- Use m_t=172 GeV and m_b=4.7 GeV
- For the 5F (2 → 2) scheme, use regular PDF
- For 4F (2 → 3) calculation, PDF's need special treatment for consistency
  - the b quark should not enter the evolution of the strong coupling or the PDF: **MRST2004FF4**
  - 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

4 FLAVOR CALCULATION 5 FLAVOR PDF

M. Cacciari, M. Greco, P. Nason, JHEP05, 007 (1998)

- To the calculation in the 4 flavor scheme add
  - For each initial state gluon include a term to compensate for the smaller gluon luminosity in a 5F PDF:
  $$-\alpha_s \frac{T_F}{3\pi} \log \frac{m_b^2}{\mu_F^2} \mathcal{M}_{\rm Born}$$
  - For each QCD coupling in the Born compensate for the running of the coupling:
  $$-\alpha_s \frac{T_F}{3\pi} \log \frac{\mu_R^2}{m_b^2} \mathcal{M}_{\rm Born}$$

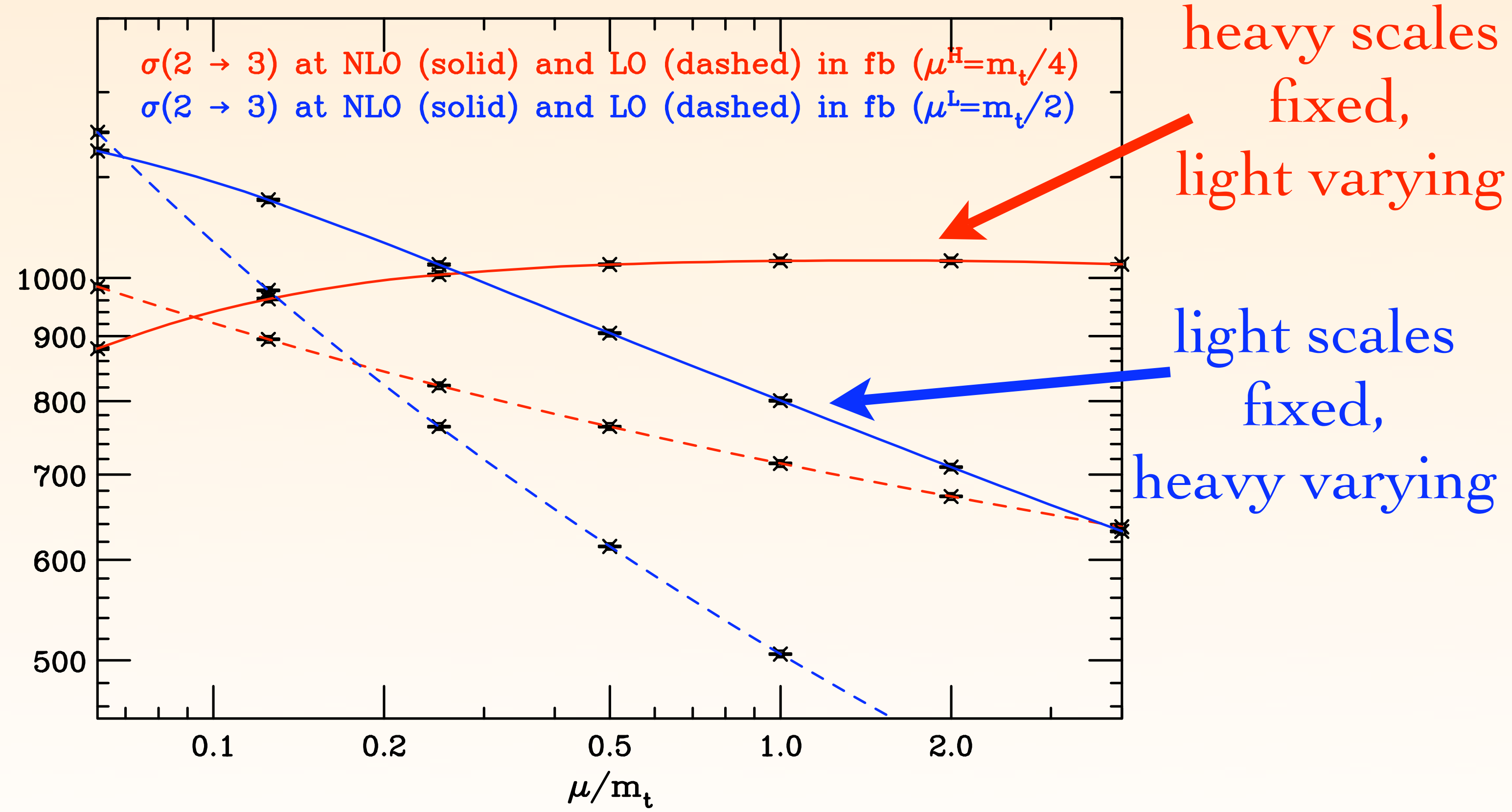
Scale dependence



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

Scale dependence $2 \to 3$

- 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: $\mu_L = m_t/2,\ \mu_H = m_t/4$

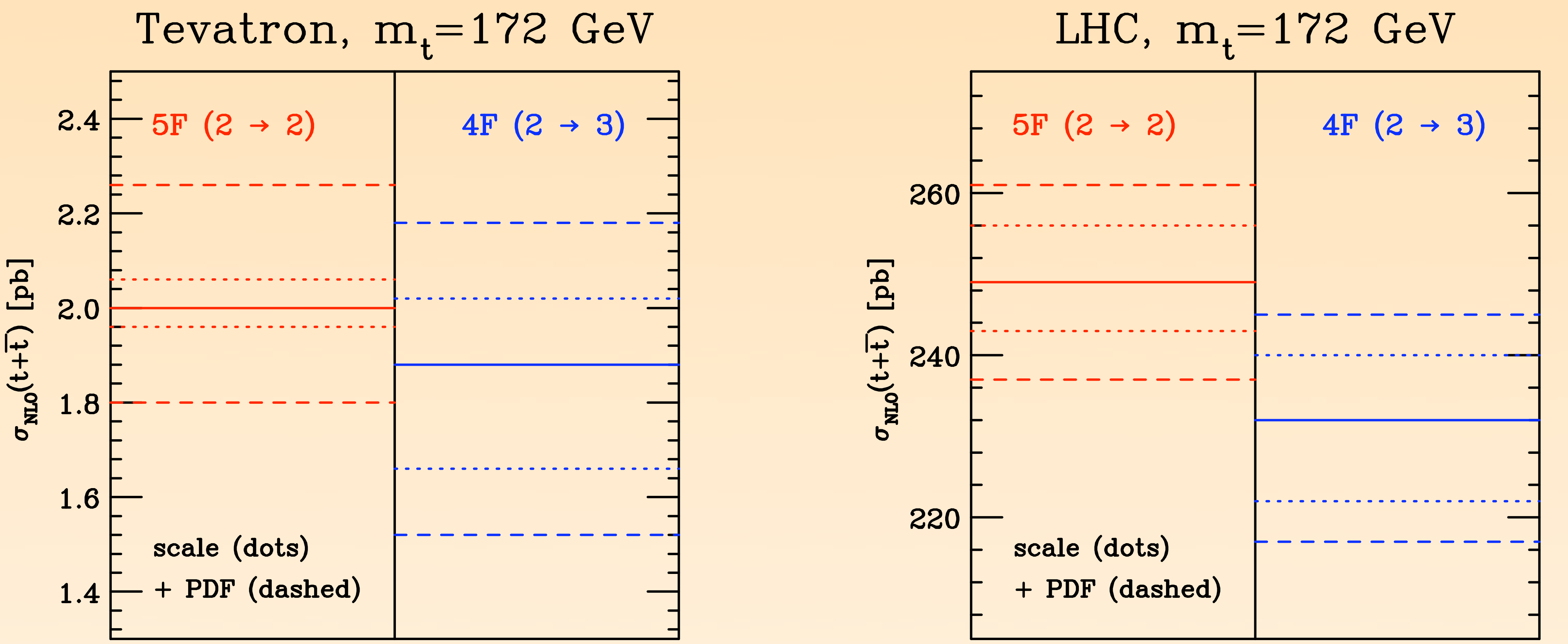


Total rates and theory uncertainties

- Estimate of the theory uncertainty:
  independent variation of renormalization and factorization scales by a factor 2 and 44 eigenvector CTEQ6.6 PDF's

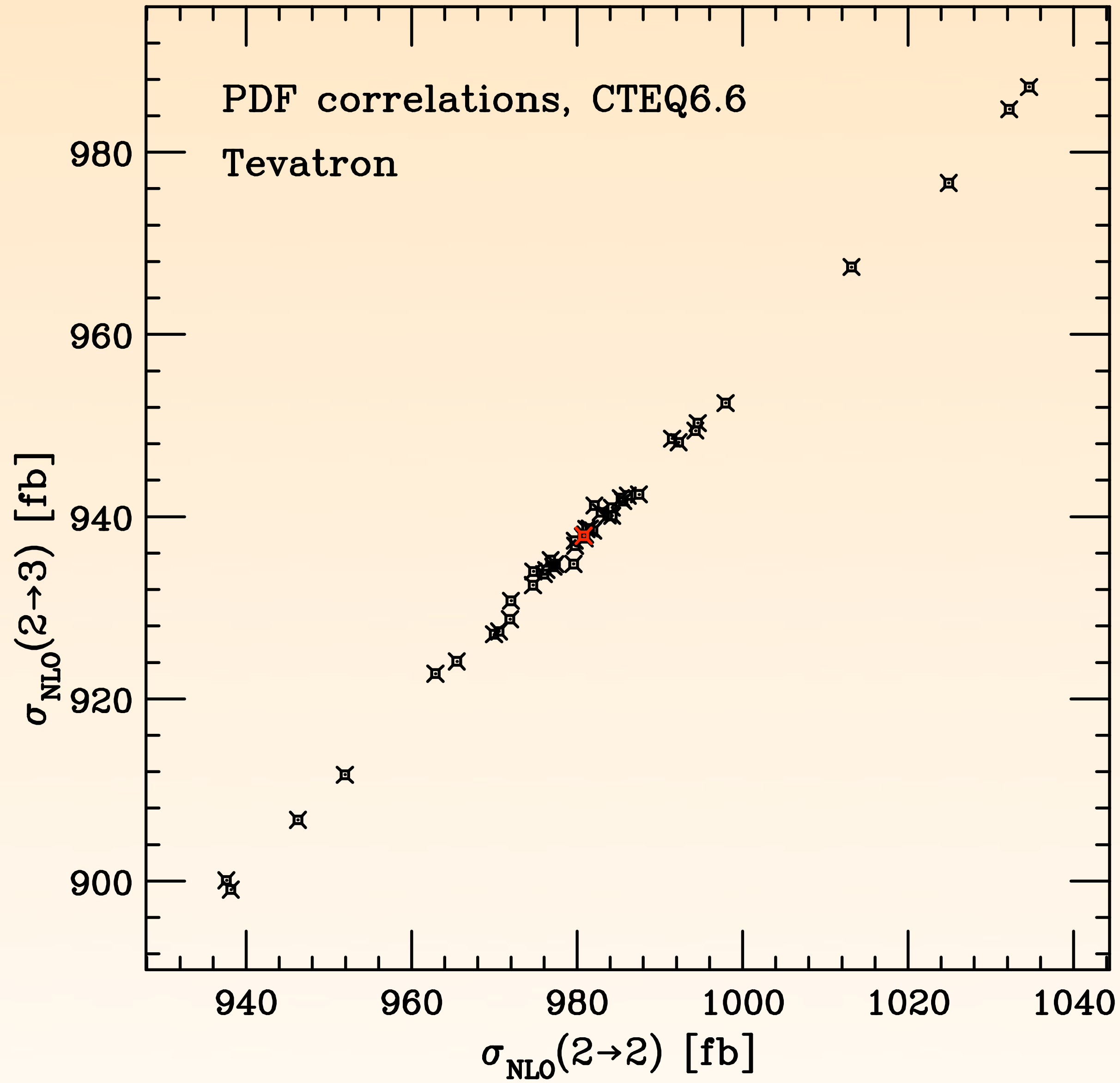
Born	TeV $t\,(=\bar{t})$ (LO) NLO	LHC t (LO) NLO	LHC $\bar{t}$ (LO) NLO
$2 \to 2$	$(0.92)\ 1.00^{+0.03+0.10}_{-0.02-0.08}$	$(153)\ 156^{+4+3}_{-4-4}$	$(89)\ 93^{+3+2}_{-2-2}$
$2 \to 3$	$(0.68)\ 0.94^{+0.07+0.08}_{-0.11-0.07}$	$(143)\ 146^{+4+3}_{-7-3}$	$(81)\ 86^{+4+2}_{-3-2}$

- Tevatron: 30% difference at LO becomes 6% at NLO, well within the combined uncertainties
- LHC: 8% difference at LO not improved at NLO, only marginally consistent due to < 5% uncertainty in both schemes
- Perturbative expansion is well behaved: small scale uncertainty and corrections are mild
- Larger differences (and uncertainties) if one uses m_t scale throughout



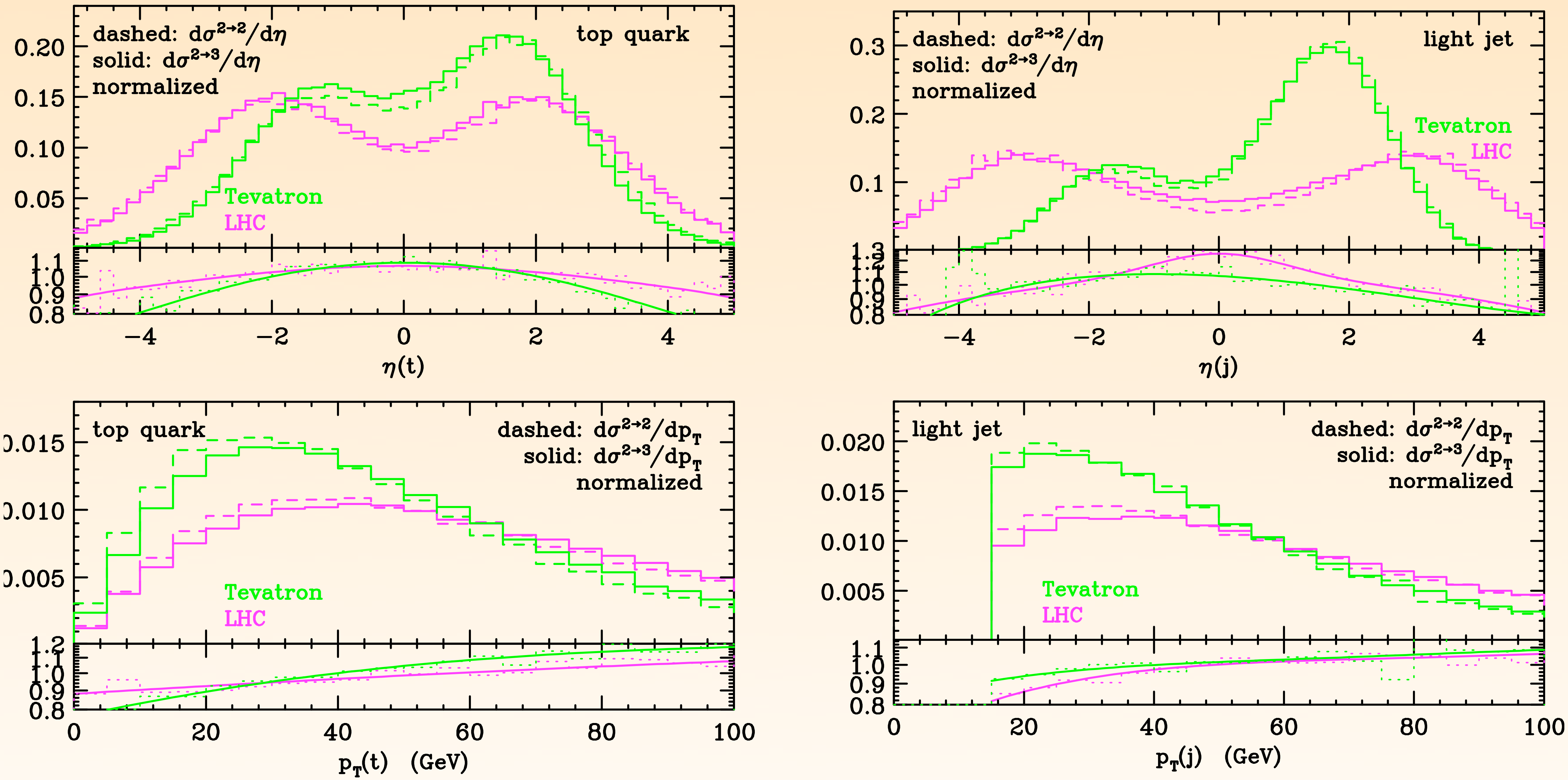
- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- Consistent at the Tevatron: logarithms not so important?
- For the LHC, the minor difference could point to either
  - large logarithms being resummed
  - the need for a NNLO calculation in the 5F (2 → 2) scheme (for which the 4F (2 → 3) NLO already forms a part)

PDF correlation



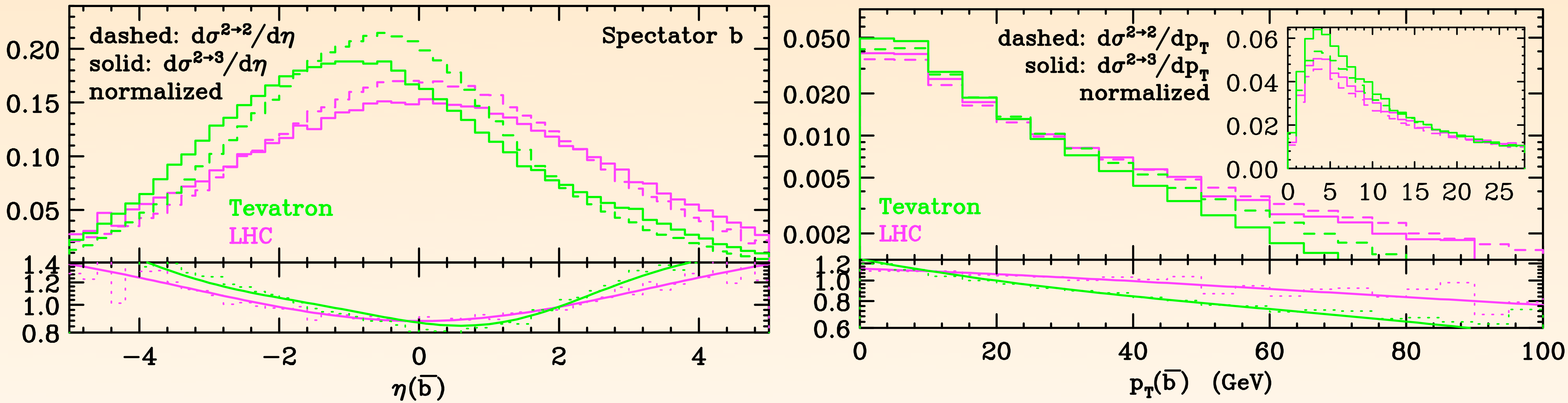
- PDF correlation between $2 \to 2$ and $2 \to 3$ (almost) 100%

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

Bottom quark pseudo-rapidity



- First NLO prediction for this observable
- More forward and softer in 4F ($2 \to 3$), particularly at the Tevatron
- Deviations up to ~ 20%

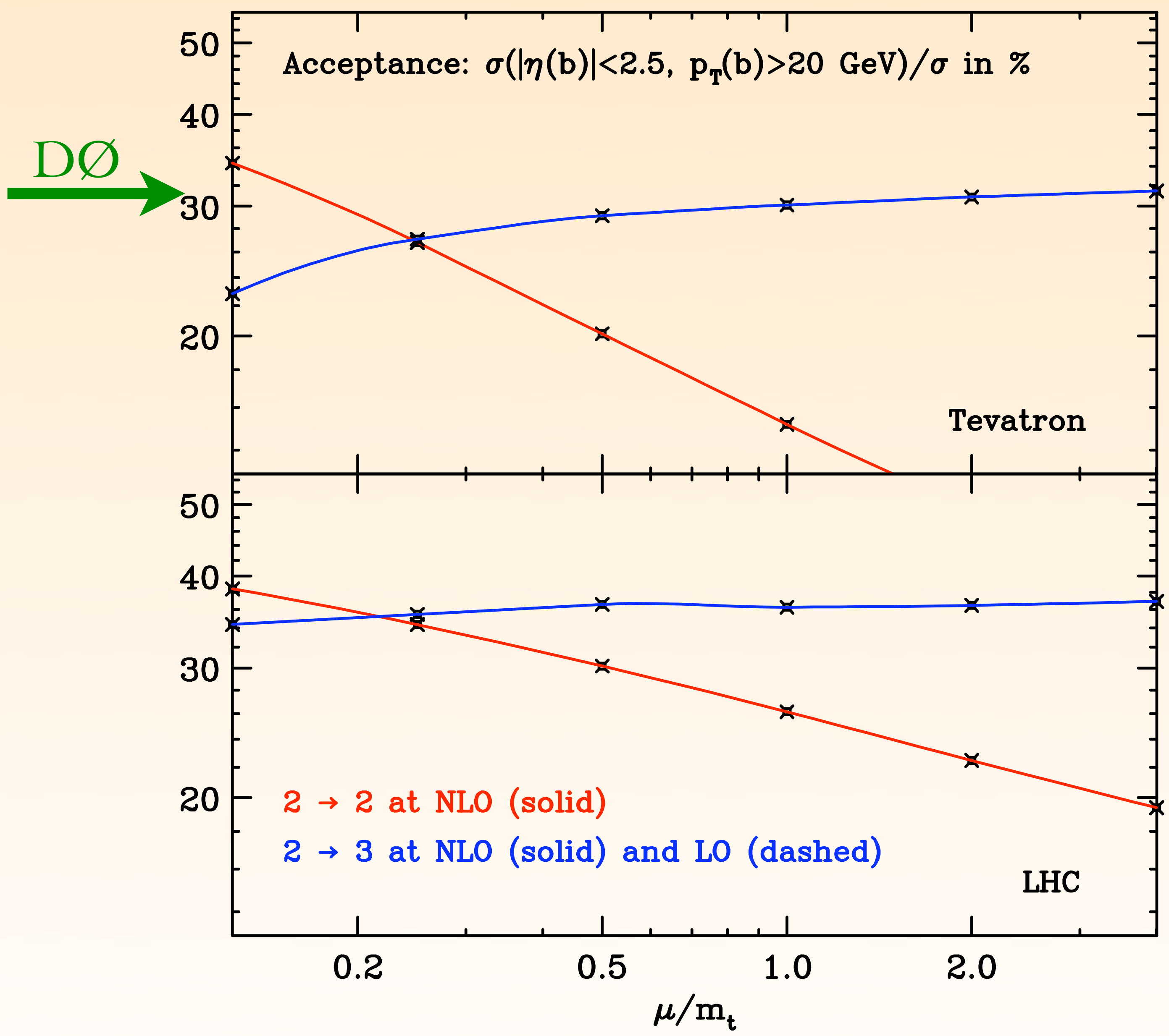
More bottoms in 4F

- 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:

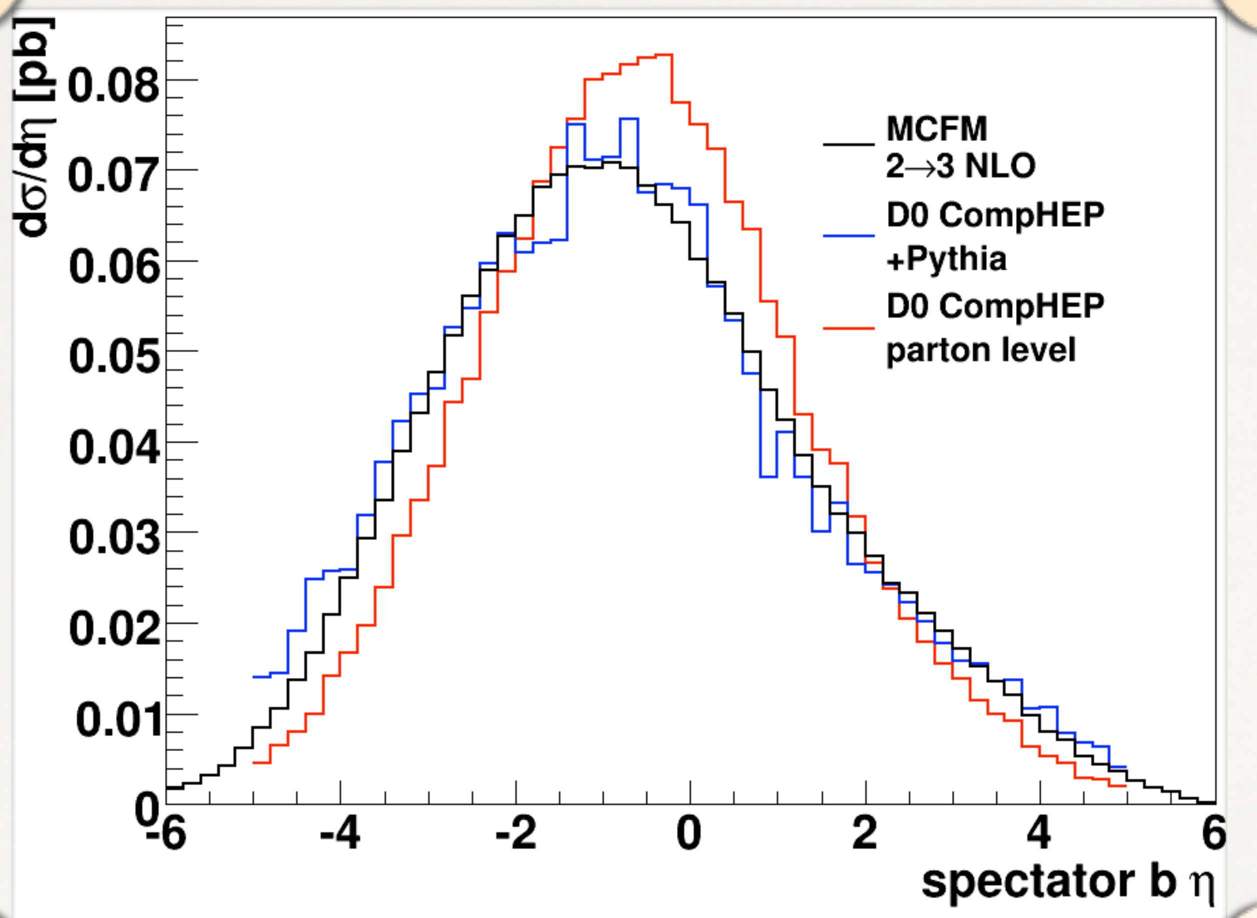
$$\frac{\sigma(|\eta(b)| < 2.5,\ p_T(b) > 20\ \mathrm{GeV})}{\sigma_{\mathrm{inclusive}}}$$

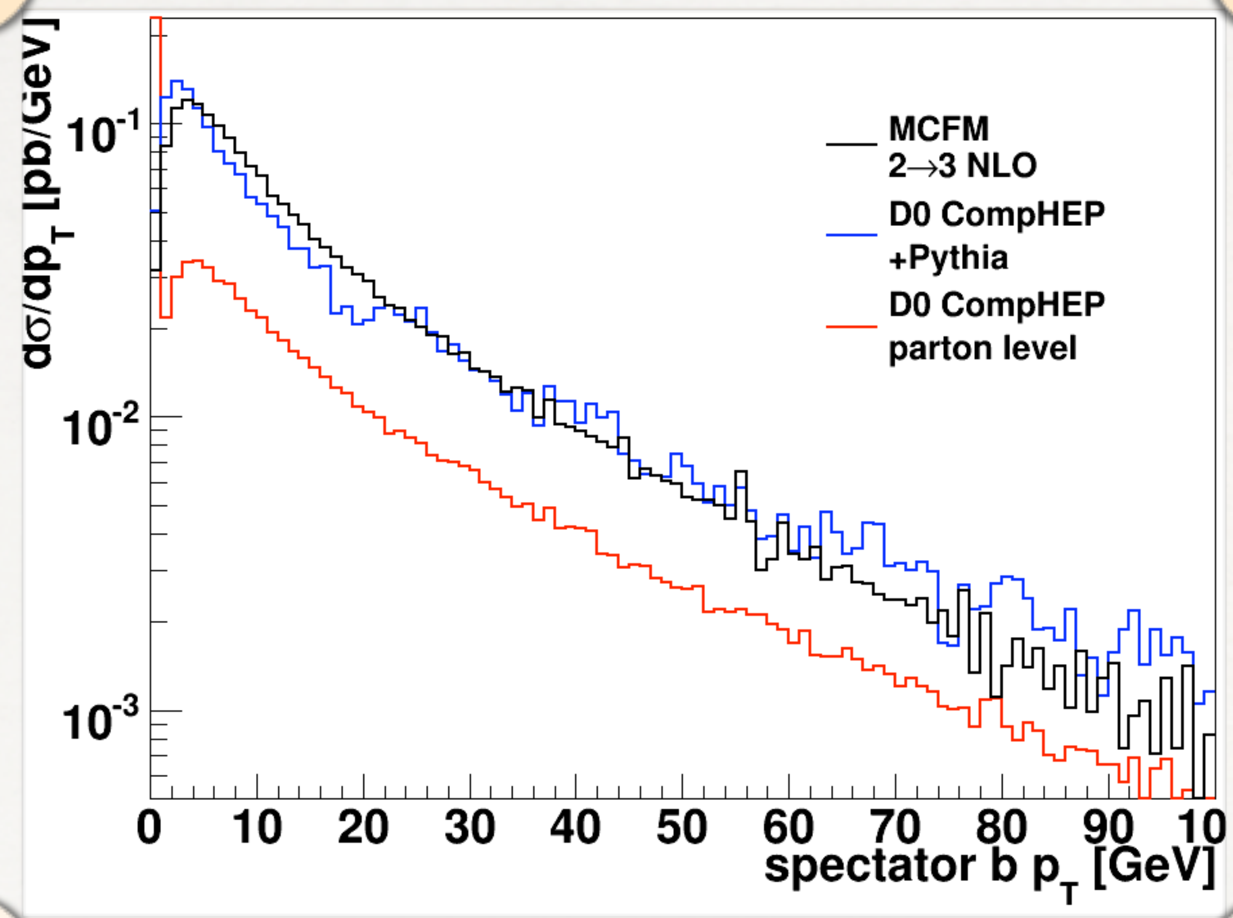
Acceptance

- Very large scale dependence for 5F (2 → 2), → effectively a LO quantity
- NLO 4F (2 → 3) much stabler
  - 2 → 3 LO underestimates the uncertainty
- Striking difference at the Tevatron!



DØ





- Results look pretty good!
- *Thanks to Reinhard Schwienhorst*

Acceptance

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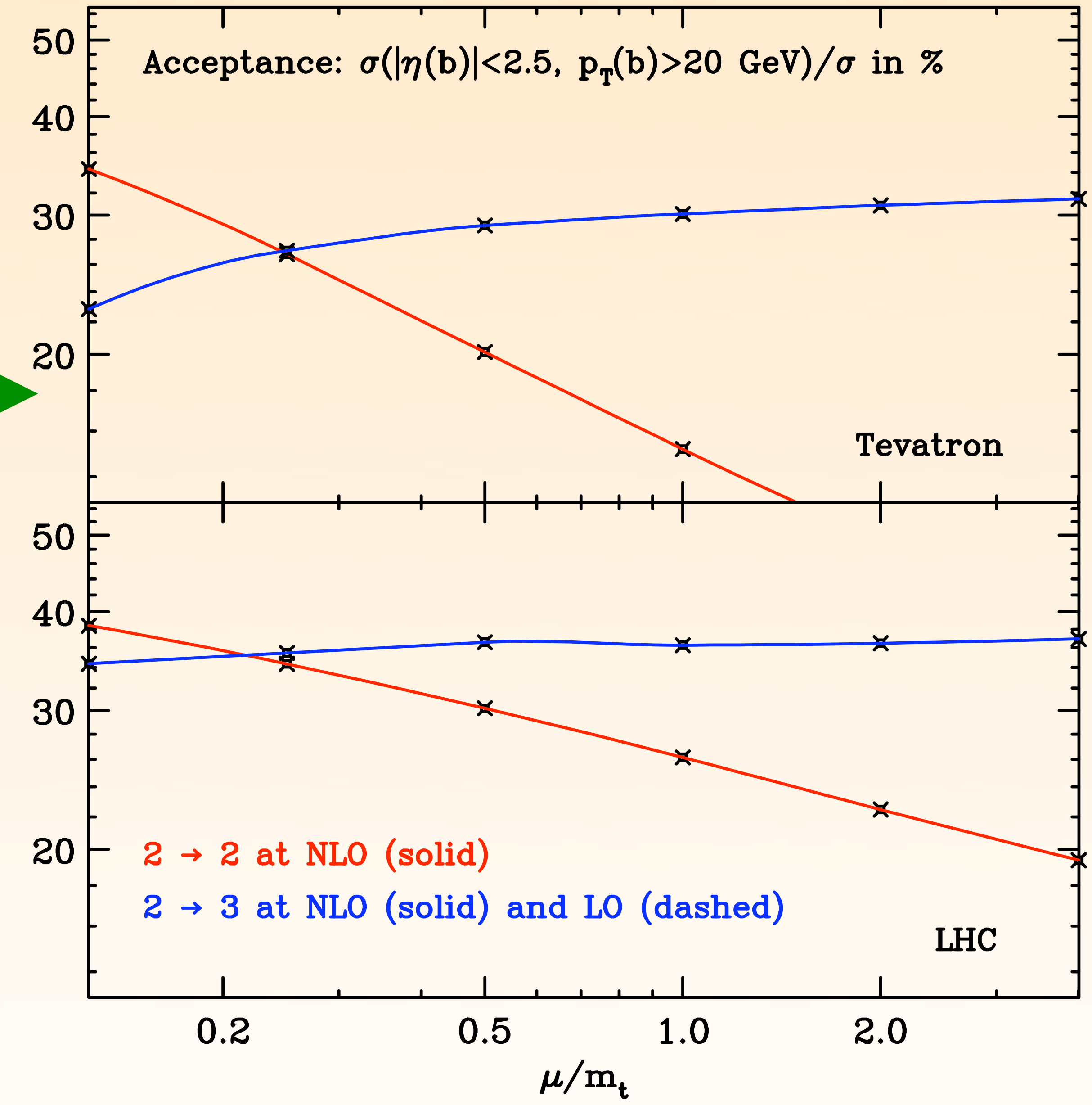
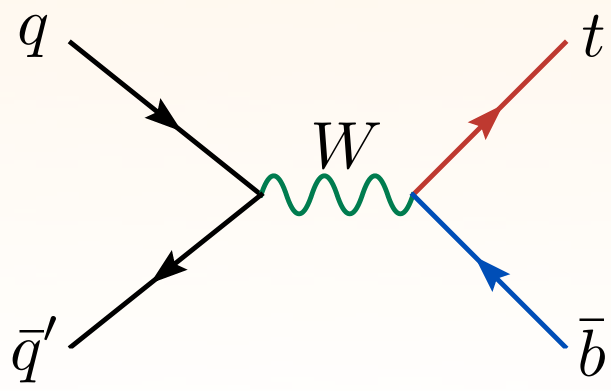
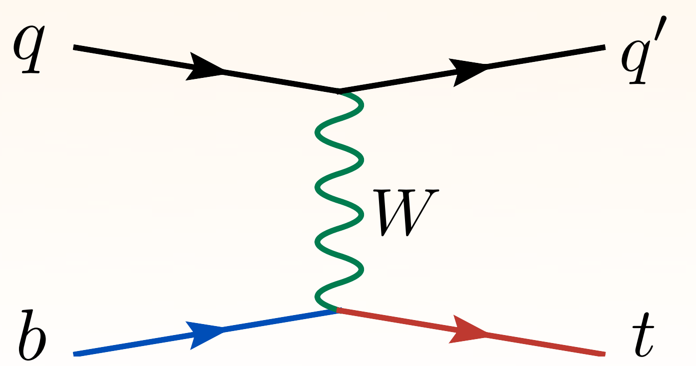
CDF →



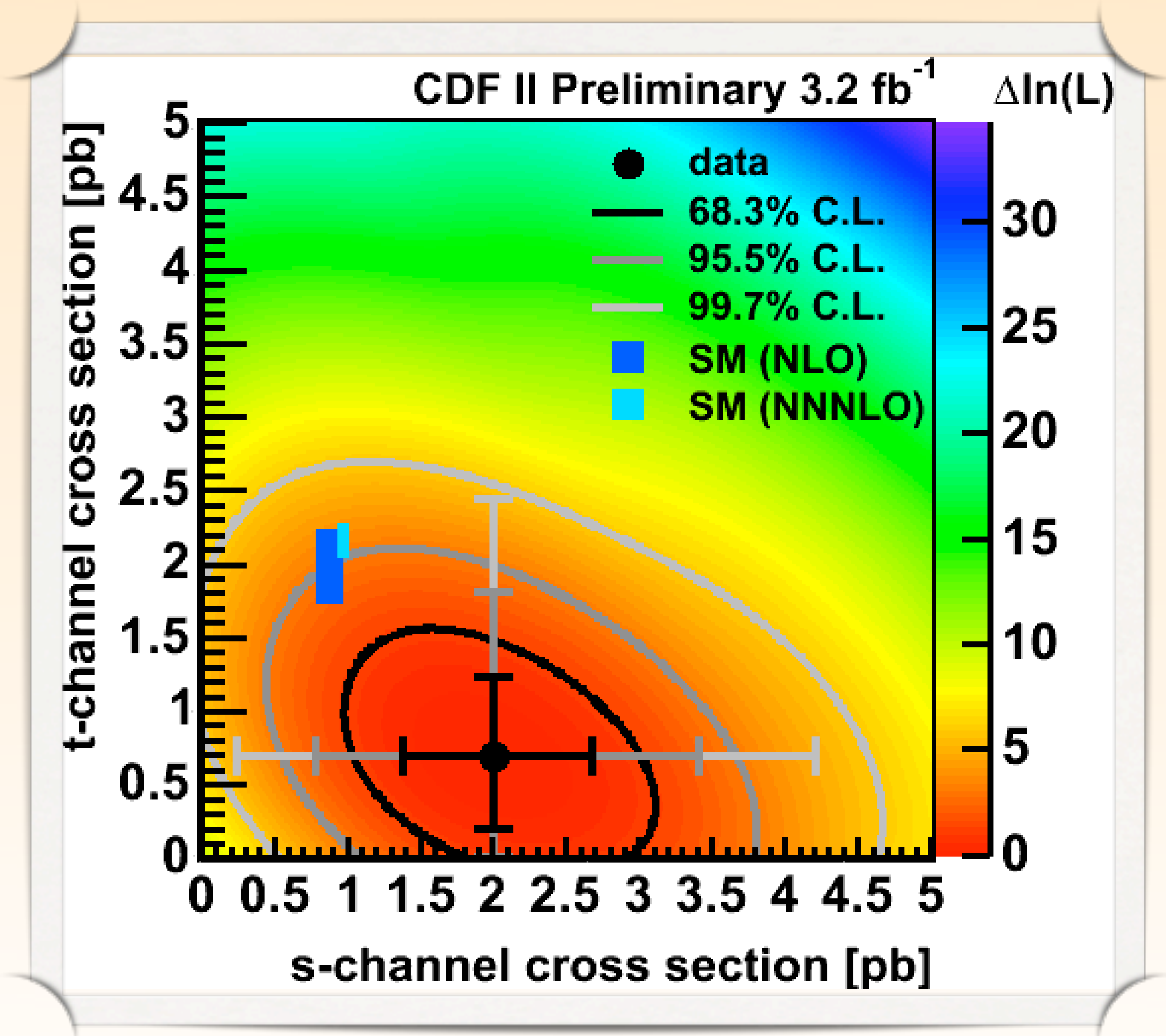
Consequences for single top observation?

- Difficult to say a priori...
- Naively:
  - No change in total cross section (s + t channel)
  - Measured t channel goes up, s channel goes down
    - More events that were considered s channel before are in fact t channel, because more t channel events have also a spectator b quark





S AND T CHANNEL SEPARATION AT CDF



CDF note 9716

- Could this explain (part of) this 2 sigma deviation?
- We are in contact with CDF and DØ single top groups to address these issue

Summary

- Different but equivalent calculation of t-channel single top
- Allows exploration of theoretical assumptions and prejudice
- The two calculations are in excellent agreement at the Tevatron, but marginal at the LHC.
- Spectator b distribution predicted at NLO throughout entire region
  - Probably a significant impact on discrimination of t- and s-channel events