Another look at single top production

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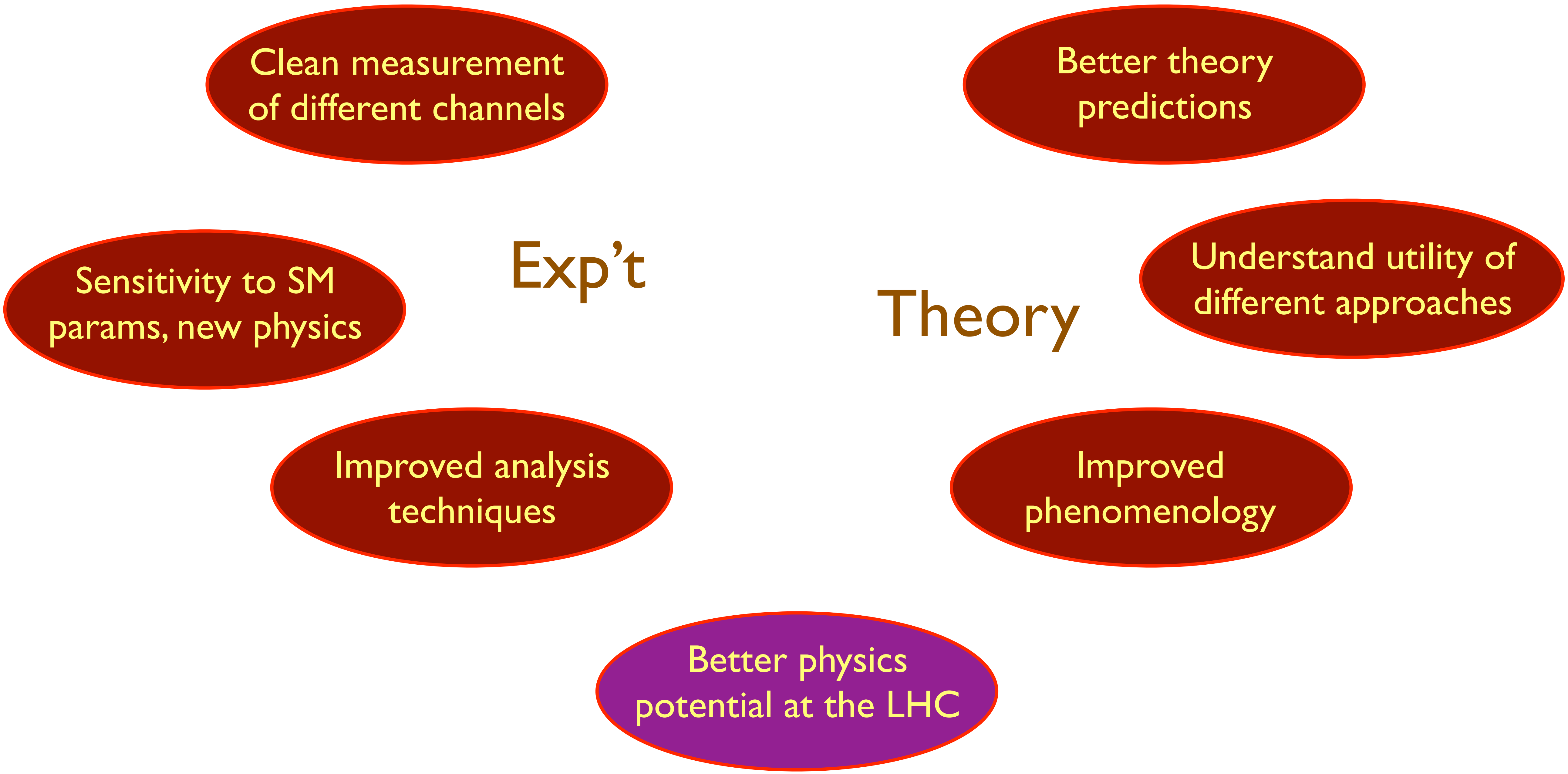
CDF Top group, March 12 2009.

Motivation for single top

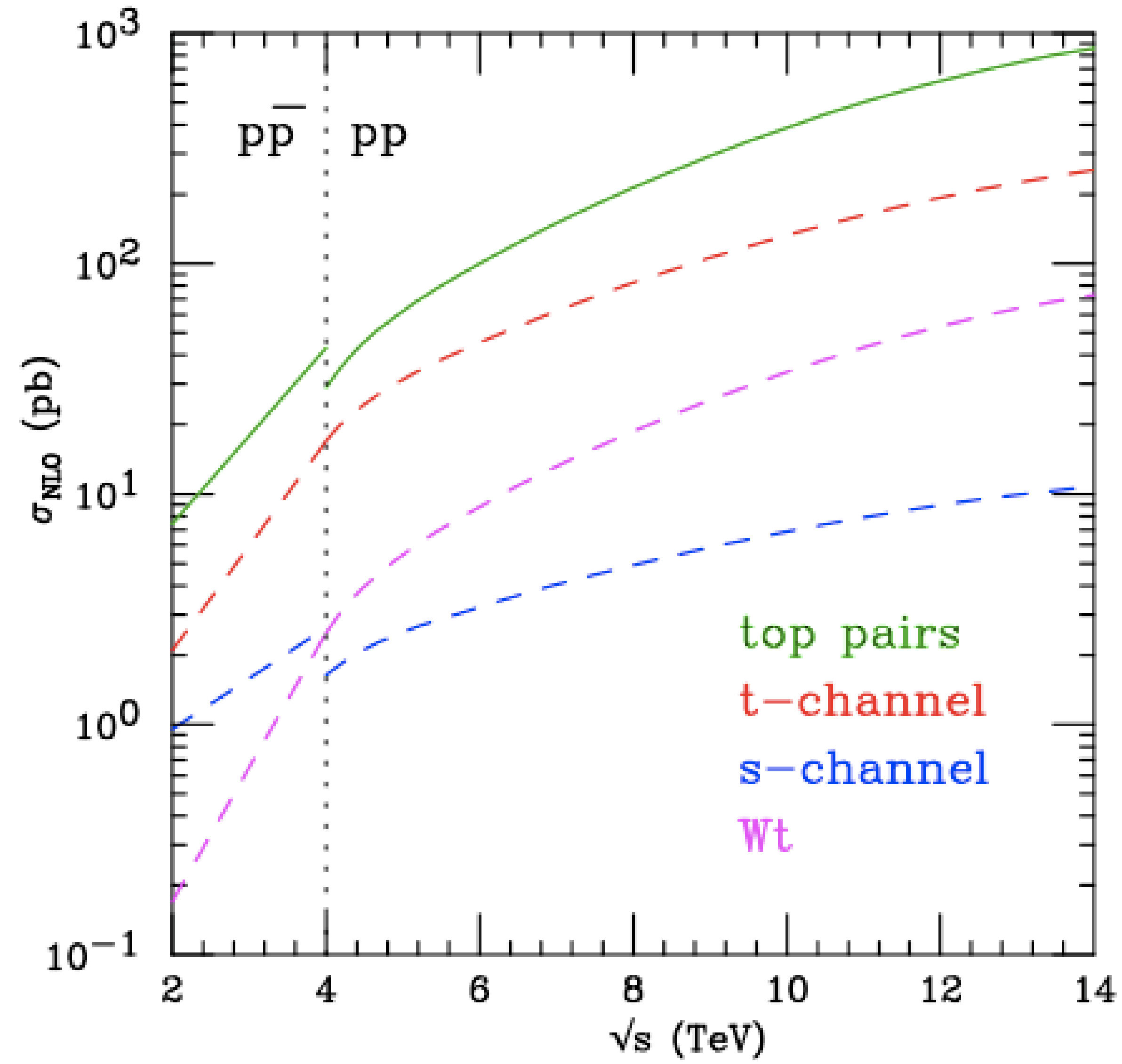
- Why have we worked so hard on single top production?



- Looking to the future: single top as a prototype for new physics searches.

Relative sizes

- t-channel dominant.
- For the s-channel, have to leave it all on the field at the Tevatron.
- Wt significant at the LHC, but similar situation to s- at the Tevatron.
- Both main channels not much affected by lower energies at the LHC, e.g. reduced by a factor of two for 14 → 10 TeV.
- (single top)/(top pairs) relatively independent of energy.

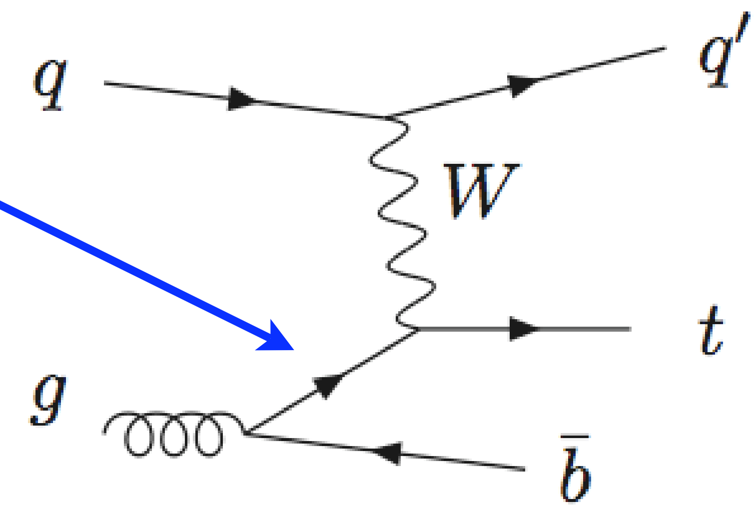


t-channel logarithms

- As already noted, the Wt and t-channel processes are enhanced by a collinear logarithm.
- This results from integrating over the t-channel propagator.

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

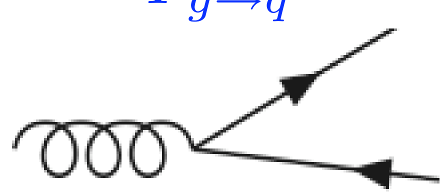
$t = (p_{\bar{b}} - p_g)^2$ (and p_T of anti-b quark)

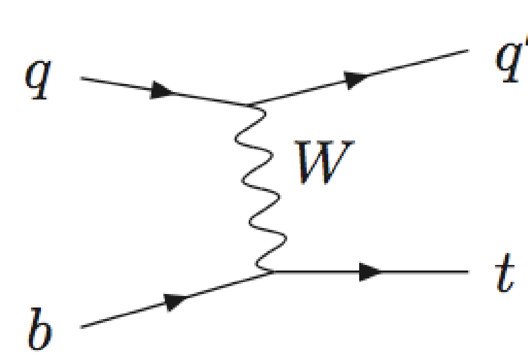


- Contribution to the cross section: $$\int_0^{p^2_{T,max}} \frac{dp_T^2}{p_T^2+m_b^2} = \log\left(\frac{p^2_{T,max}}{m_b^2}\right) + \ldots$$
- Coefficient of the logarithm is:

the Altarelli-Parisi splitting function for a gluon into a pair of quarks

$P_{g\to q}$





matrix elements with splitting removed

Absorbing into PDFs

- Putting it together:

$$\frac{d\sigma(qg \to q'tb)}{d\log p_{T,max}^2} \sim \left(\frac{\alpha_s}{2\pi}\right)\left[\int \frac{dx}{x} P_{g\to q}(x) f_g\right] \times \hat{\sigma}(qb \to q't)$$

- But the first part resembles the evolution equation for a quark:

absent

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

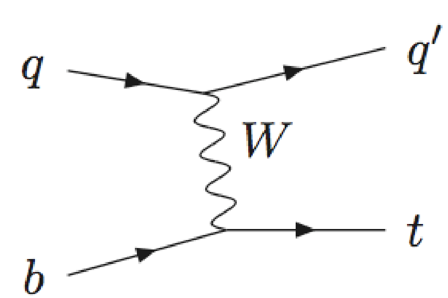
- So, when the logarithms really dominate, can replace this description by an equivalent one: $\sigma(qg \to q'tb) \approx \sigma(qb \to q't)$
- Scale of the bottom quark PDF should be related to $p_{T,max}$.
- At all orders, the two would agree. Otherwise, differ by:
  - evolution of logarithms in b-PDF: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

ACOT

- A sensible way of combining the two approaches was formally identified some time ago, in a procedure now known as the "ACOT" formalism.

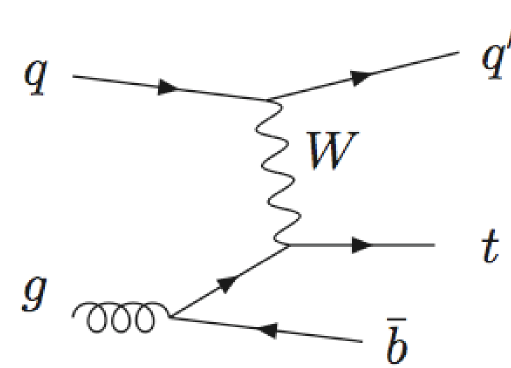
Aivazis, Collins, Olness & Tung, PRD50, 3102 (1994)

- Roughly: use the bottom PDF ("5F scheme") when the spectator b is unimportant, otherwise keep it explicit in the final state ("4F scheme").
- The tricky question is still, what happens in the intermediate region?
- Deciding factor - simpler to calculate with one less external leg.



2→2

- All higher order calculations performed in the 5F scheme.
- Terms from 4F scheme enter at NLO. Properties of final-state b only LO.



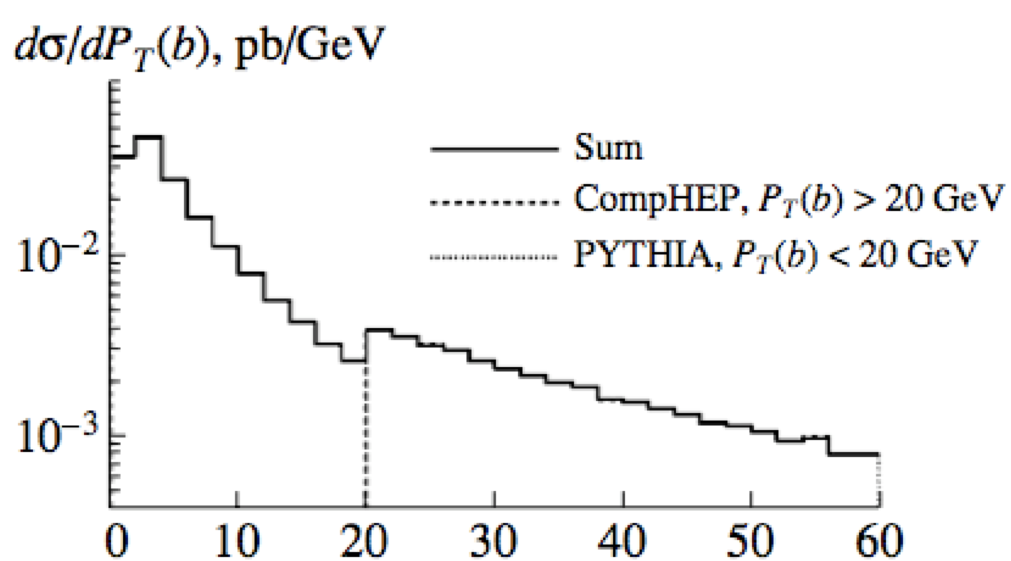
2→3

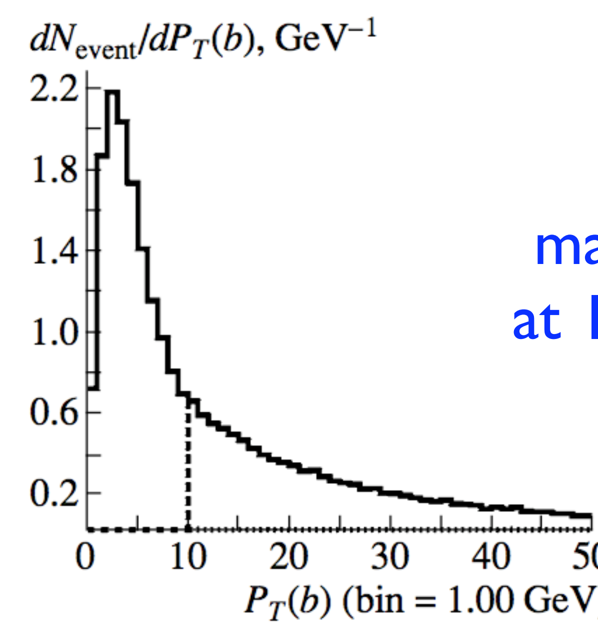
- All calculations presented so far set m_b=0 in final state for simplicity.

CompHep-SingleTop

- Would like:
    - control of large logarithms i.e. in the $p_T(b) \to 0$ region; NLO predictions for the same;
    - faithful description (i.e. m_b non-zero) otherwise.
- ACOT formalism difficult to realise in a parton shower.
- "Effective NLO approximation": separate regions according to $p_T(b)$ and use NLO 2→2 below (+shower) and LO 2→3 above.
    - implemented in (CompHEP) SingleTop and used by D0 and CMS.

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



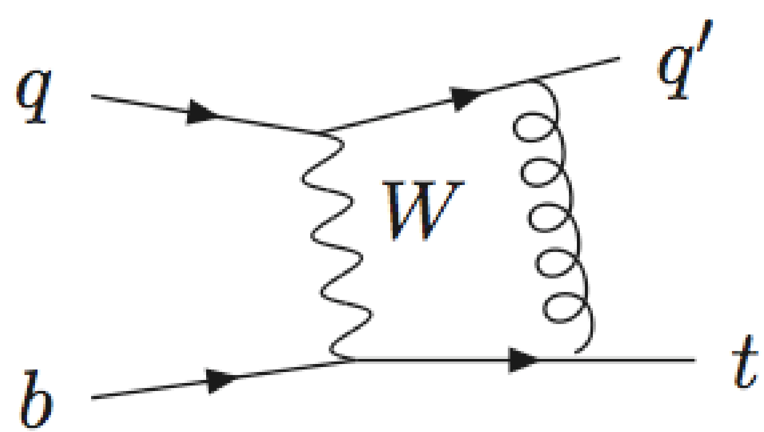


matched at 10 GeV

- Ad-hoc matching well motivated but theoretically unappealing.

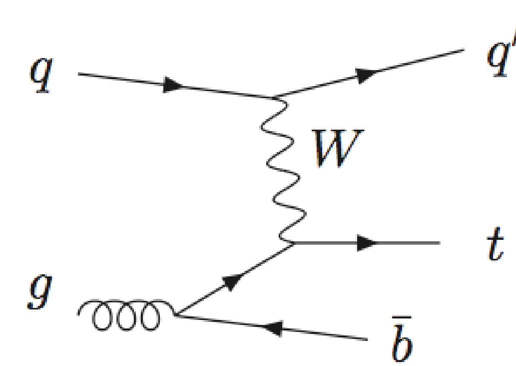
A fresh approach

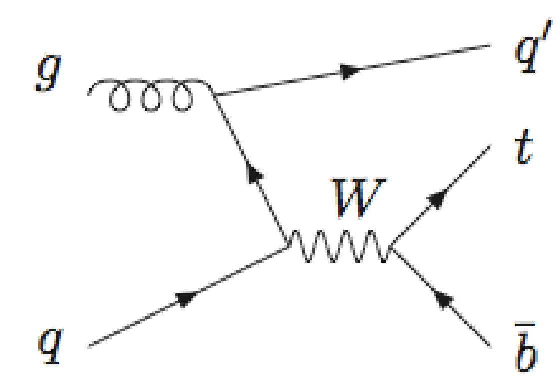
- Use the 4F (2→3) process as the Born and calculate to NLO.
  JC, Frederix, Maltoni, Tramontano, arXiv:0903.0005
  - harder calculation due to extra parton and mass;
  - "spectator b" distributions assessed at NLO;
  - compare with 2→2 to assess logarithms and applicability;
  - starting point for future NLO+PS beginning at 2→3.
- The 5F calculation simplifies greatly due to color.



→0, due to tr(T^a)=0

(virtual diagrams are only vertex corrections on each line separately)





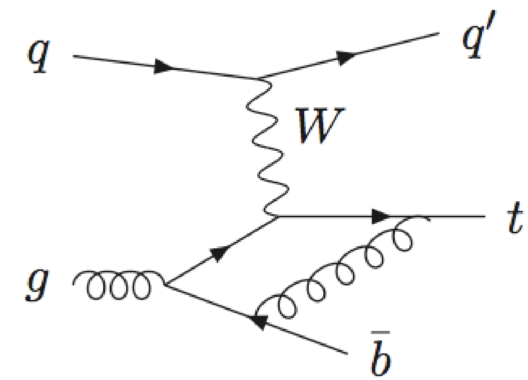
interference vanishes, due to tr(T^a)=0

(s- and t-channels remain separated at NLO)

2→3 factorization

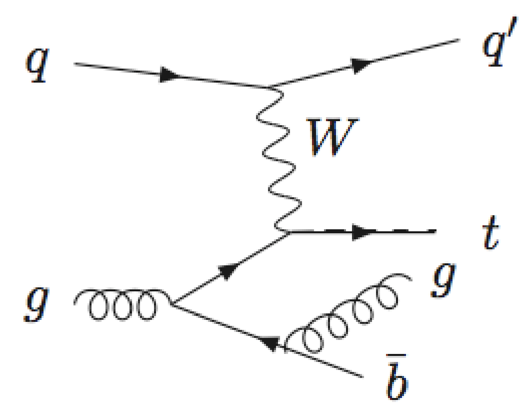
- The same arguments still mostly apply. Majority of matrix elements can be uniquely associated with either the light or heavy quark current.

- Vertex corrections on the light current (as before), but boxes on the heavy current.



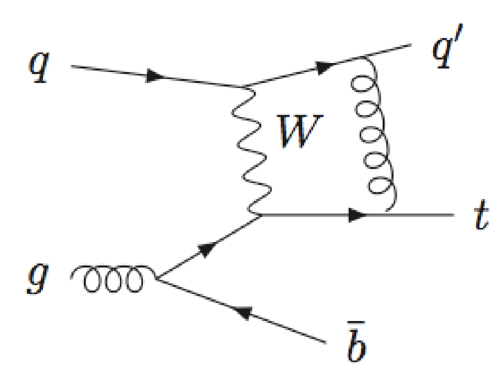
virtual, heavy current

- Most real corrections clearly associated with one or other of the currents.



real emission, heavy current

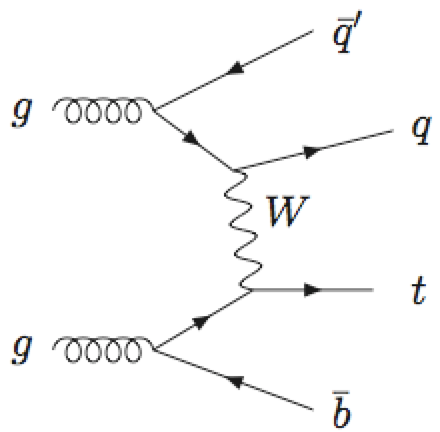
- Most interferences between the two currents vanish by the same color argument once again.



interference, zero (also for corresponding real diagram)

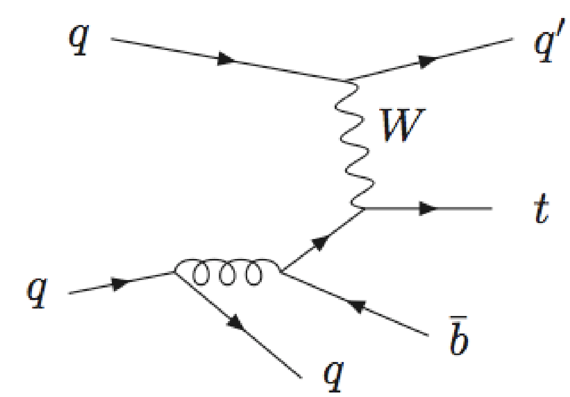
Near-factorization

- Not all real emission pieces factorize so neatly, but non-factorizing pieces are always color-suppressed.



factorizing leading term $N^2C_F^2$

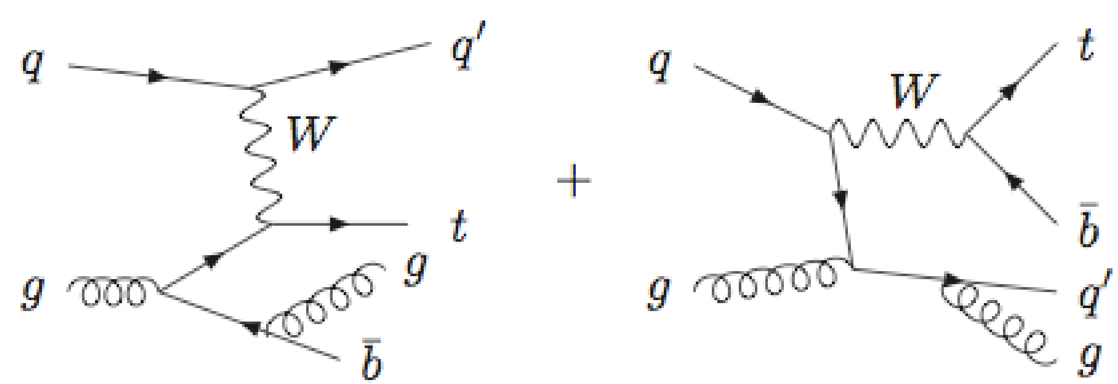
subleading interference N^2C_F



factorizing leading term N^2C_F

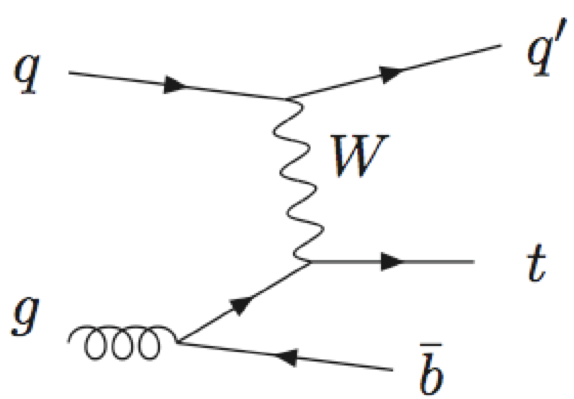
subleading interference NC_F

- s-channel and t-channel in principle mix at this order, although we have checked this interference is small (<0.5%) and dropped.

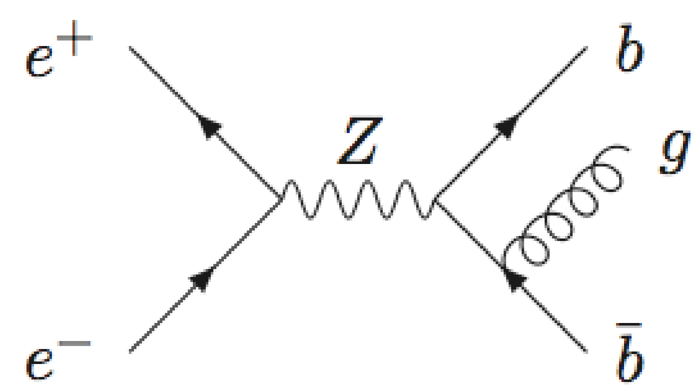


Outline of calculation

- Analytic computation of helicity amplitudes via standard methods.
- Cross-checks: top spin available
  - gauge invariance, CP, $m_b \leftrightarrow m_t$ symmetry;
  - two different reduction schemes;
  - divergences checked by two implementations of dipole method.
- Most interesting check comes from crossing the whole calculation.



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



Nason & Oleari, NPB521, 237 (1998)

- Excellent agreement found.
- Calculation implemented in the MCFM parton-level NLO code.

MCFM commercial

v5.4 as of 3/12/09

- General purpose NLO code: http://mcfm.fnal.gov.
- Unified approach to many signal and background processes at the Tevatron and LHC.

W+0,1,2 jets · Zbb · Zb · Wb+jet · Zb+jet · dibosons · Z+0,1,2 jets · Wbb · gg→H+0,1 jets · Hb · Wc · single top · top pairs · WH, ZH · H (VBF)

- Recent inclusion of numerical approaches to virtual corrections (H+2 jets, WW+jet).
- Also quarkonia (spectrum and polarization of ϒ, J/ψ at HERA).
- Future goal: extend to higher multiplicity final states, e.g. W+3 jets.

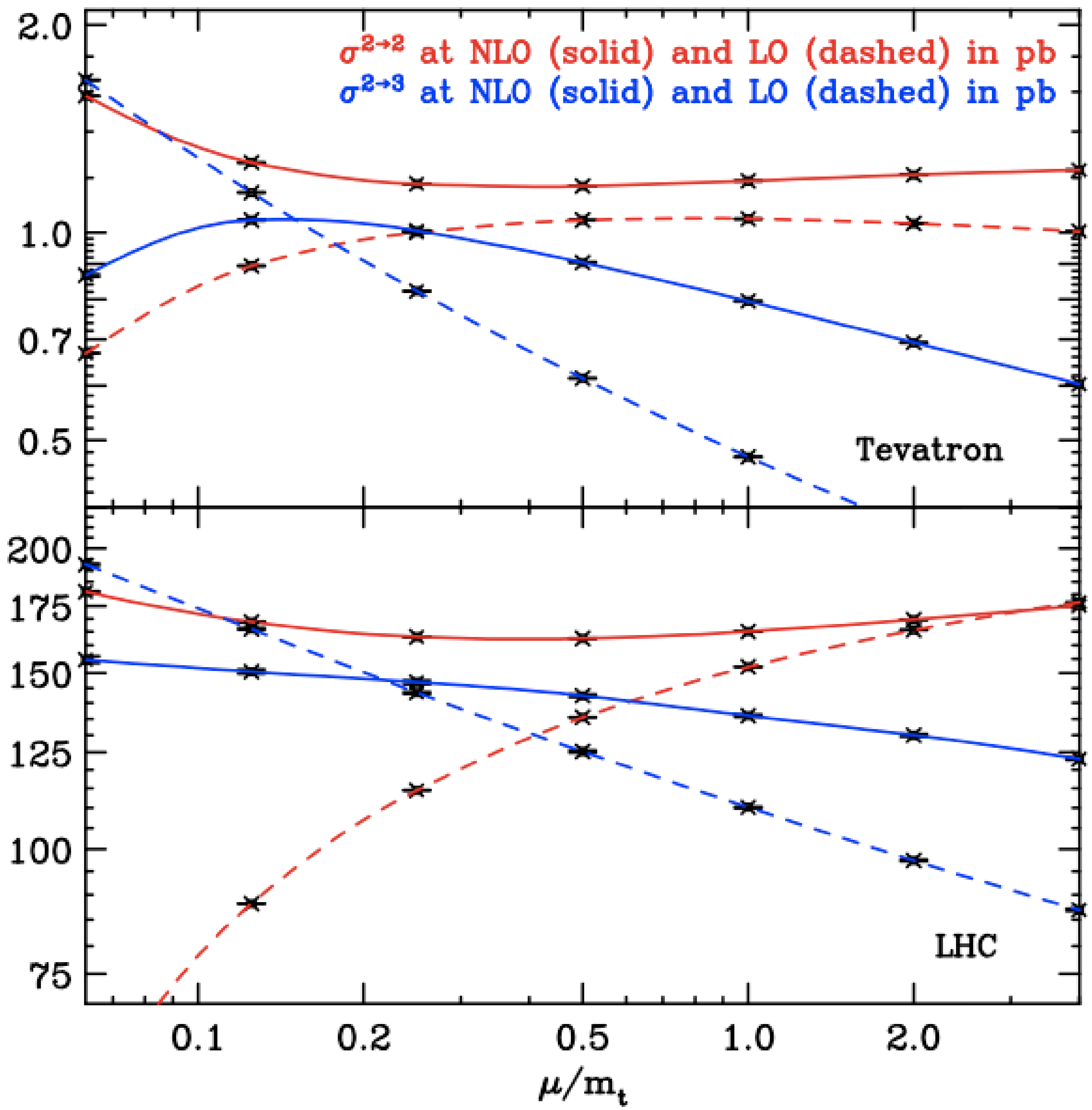
Setup

- Use m_t=172.5 GeV and m_b=4.7 GeV.

- Need to take some care with PDFs for consistency.
  - for the 2→3 (4F) calculation, the b-quark should not enter in the evolution of the strong coupling or the PDFs; MRST2004nlo
  - for the 2→2 (5F scheme), use a regular PDF;
  - alternatively, could use 5F set for both and pass to the 4F scheme using well-known transition rules. *Cacciari et al., JHEP05, 007 (1998).*

- Depart from majority of 2→2 calculations by using m_b non-zero in NLO real emission diagrams.
  - explicit logarithm cancelled using ACOT formalism;
  - negligible effect on total rate, distributions of top, light jet;
  - significant effect on the b jet.

4F vs 5F scale dependence



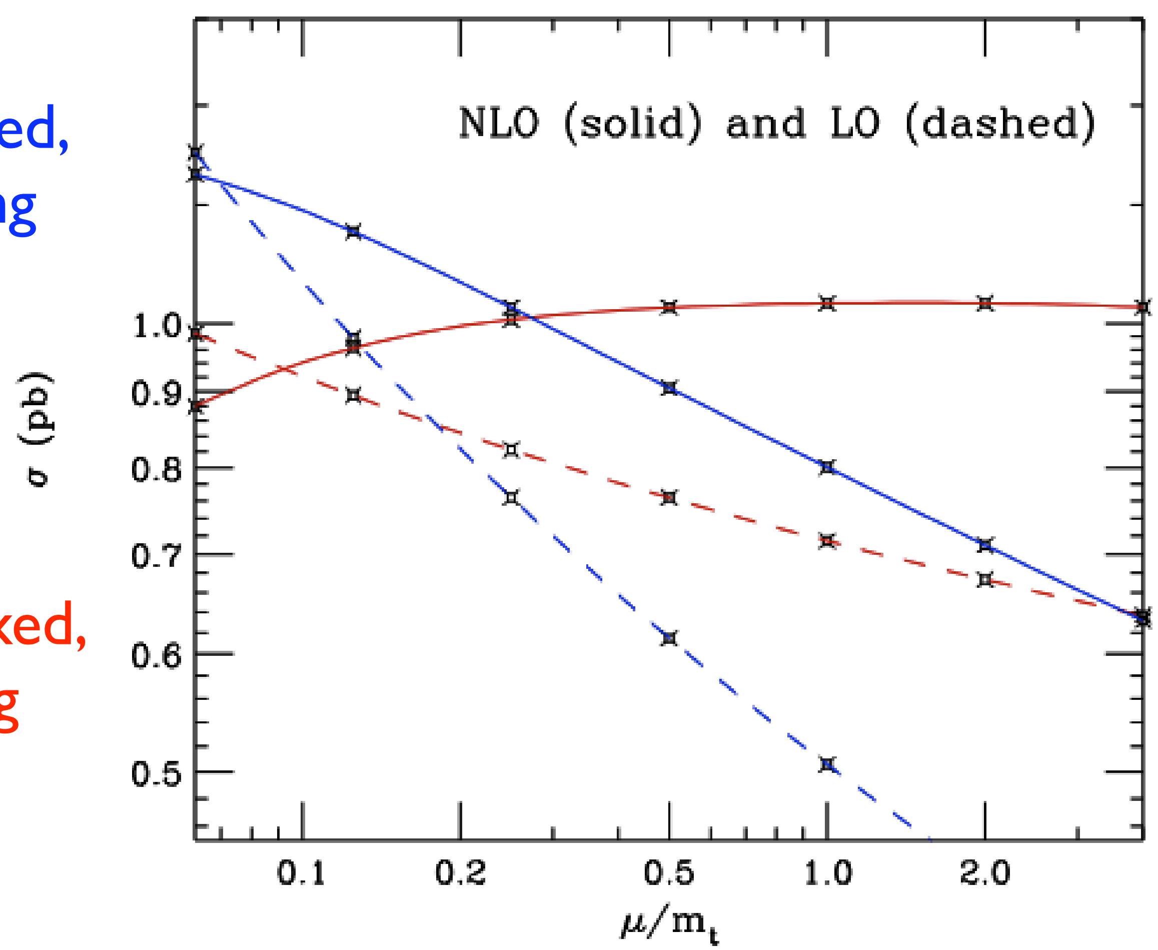
- Both schemes much improved from LO.
- 2→2 calculation only mildly sensitive to scale at NLO (use m_t in what follows).
- 2→3 expected to be worse, but isn't by much.
- No region of overlap between the two.
- 2→3 seems to prefer scales smaller than m_t, particularly at the Tevatron.

Scale dependence of 4F

- Take advantage of heavy/light separation to choose different scales on each line.
  - expect heavy scale to be smaller since related to g→bb splitting.
  - split (subleading) ambiguous terms equally.

light scale fixed, heavy varying

heavy scale fixed, light varying



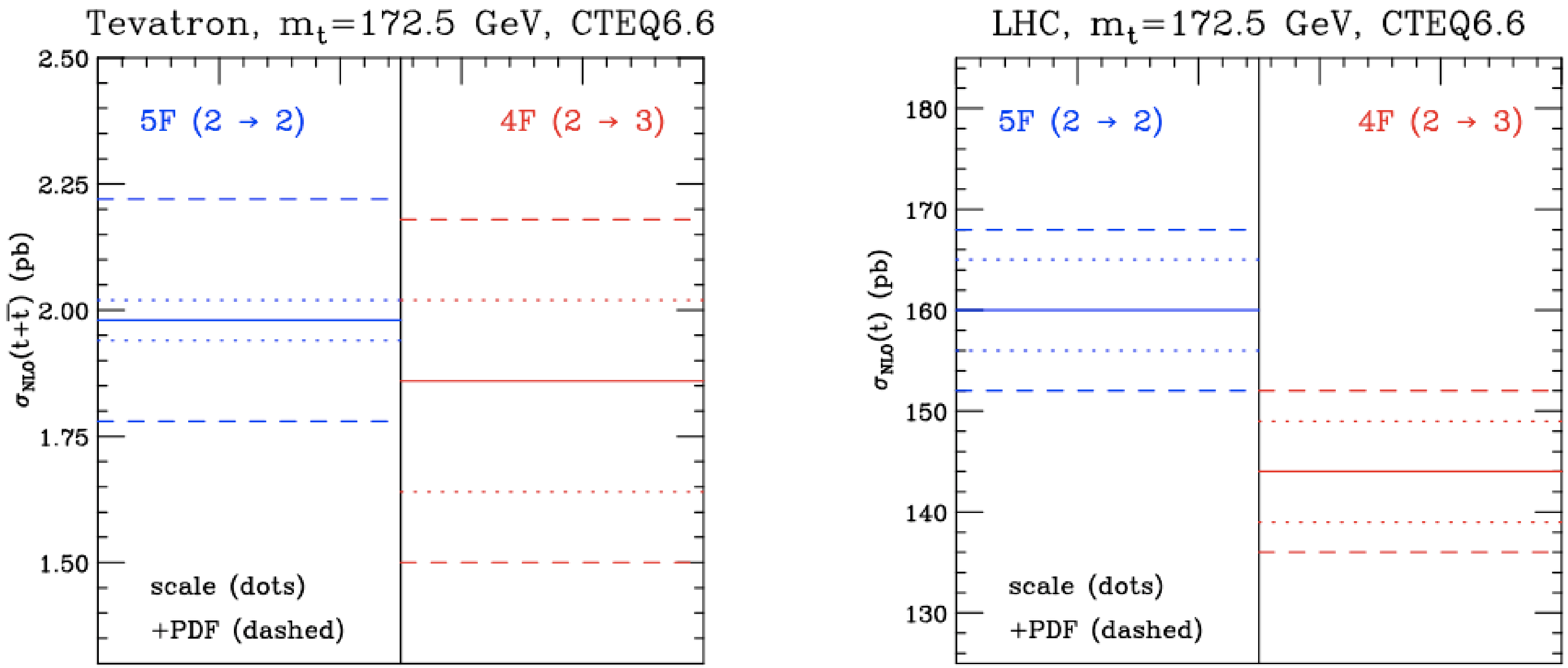
- Tevatron (but LHC similar).
- Stronger dependence on heavy line, as expected.
- Preference for scales smaller than m_t.
- Choose central values: $\mu_L=m_t/2$, $\mu_H=m_t/4$.

Total rates and uncertainties

- Estimate uncertainty from scale dependence: renormalization and factorization independent, variation by a factor of two.
- Switch to more modern PDF (CTEQ6.6).

Scheme	TeV $t\,(=\bar{t})$ (LO) NLO	LHC t (LO) NLO
5-flavor $(2 \to 2)$	$(0.91)\ 0.99^{+0.02}_{-0.02}$	$(153)\ 160^{+5}_{-4}$
4-flavor $(2 \to 3)$	$(0.66)\ 0.93^{+0.08}_{-0.11}$	$(140)\ 144^{+5}_{-5}$

- Tevatron: 30% difference at LO becomes 6% at NLO, well within the combined uncertainty.
- LHC: 10% difference at LO not improved at NLO. Marginally consistent due to <5% uncertainty in both schemes.
- Perturbative expansion is well-behaved
  - small scale uncertainty, corrections are mild.
- Larger differences (and uncertainties) if one uses m_t scale throughout.



- PDF uncertainty dominant at the Tevatron, but not at the LHC.
- Consistency at the Tevatron: logarithms not so dominant?
- Combined NLO estimate (conservative scale/PDF errors only):

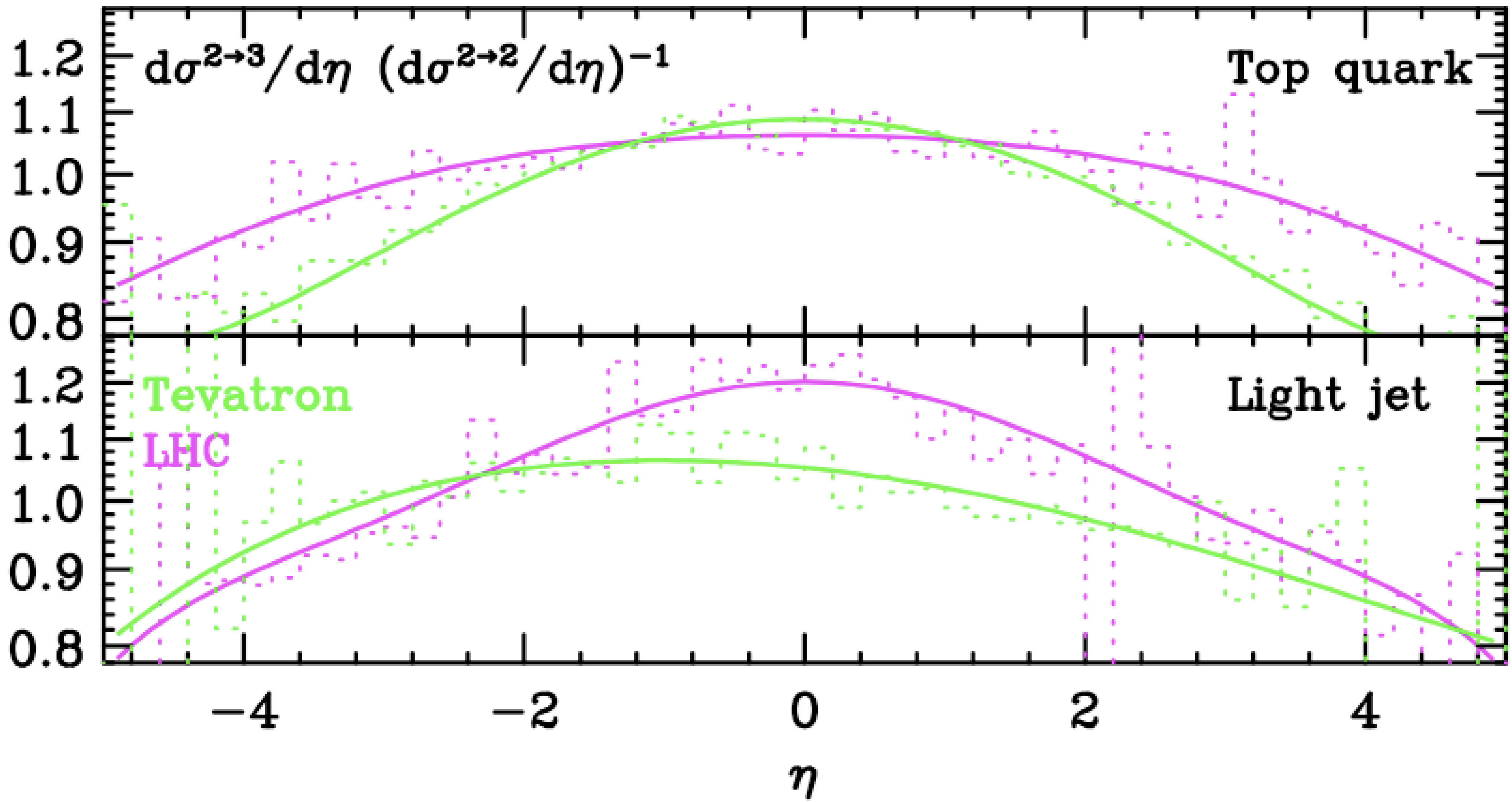
$$\sigma_t(4F/5F) = 1.92 \,{}^{+0.30}_{-0.42}\ \text{pb}$$

slight reduction in central value, but much larger uncertainty

$$\left[\sigma_s = 0.84 \,{}^{+0.09}_{-0.09}\ \text{pb}\right]$$

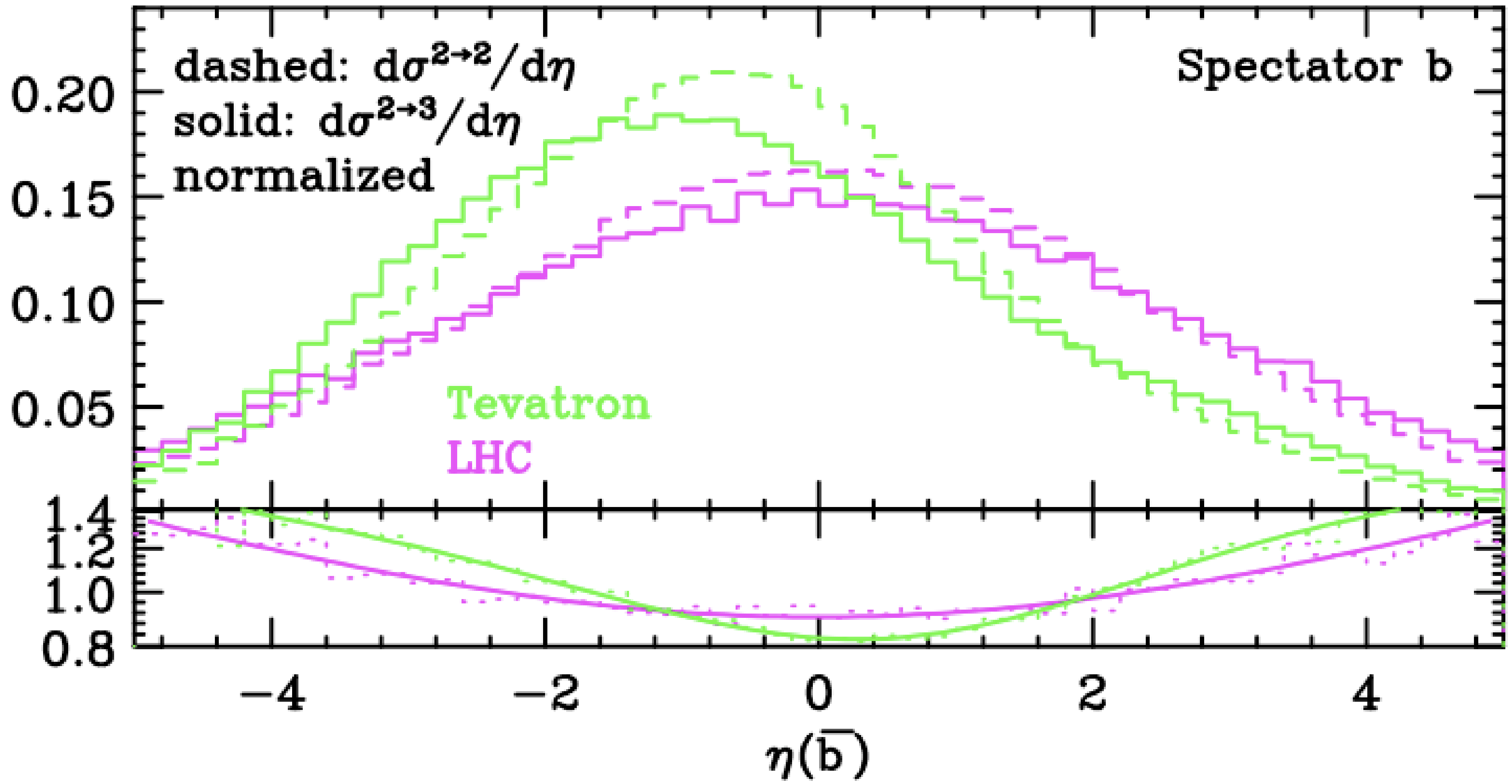
- For the LHC, difference could point to either:
  - large logarithms being resummed;
  - the need for a NNLO calculation for the 2→2 process (2→3 NLO calculation would be included in that).

Top quark and light jet distributions



- 2→3 NLO distribution normalized to 2→3 LO one (= 2→2 NLO).
- Jet defined by p_T>15 GeV, ΔR>0.7.
- Some differences, but typically at the level of 10% or less.
- Similar for transverse momenta.

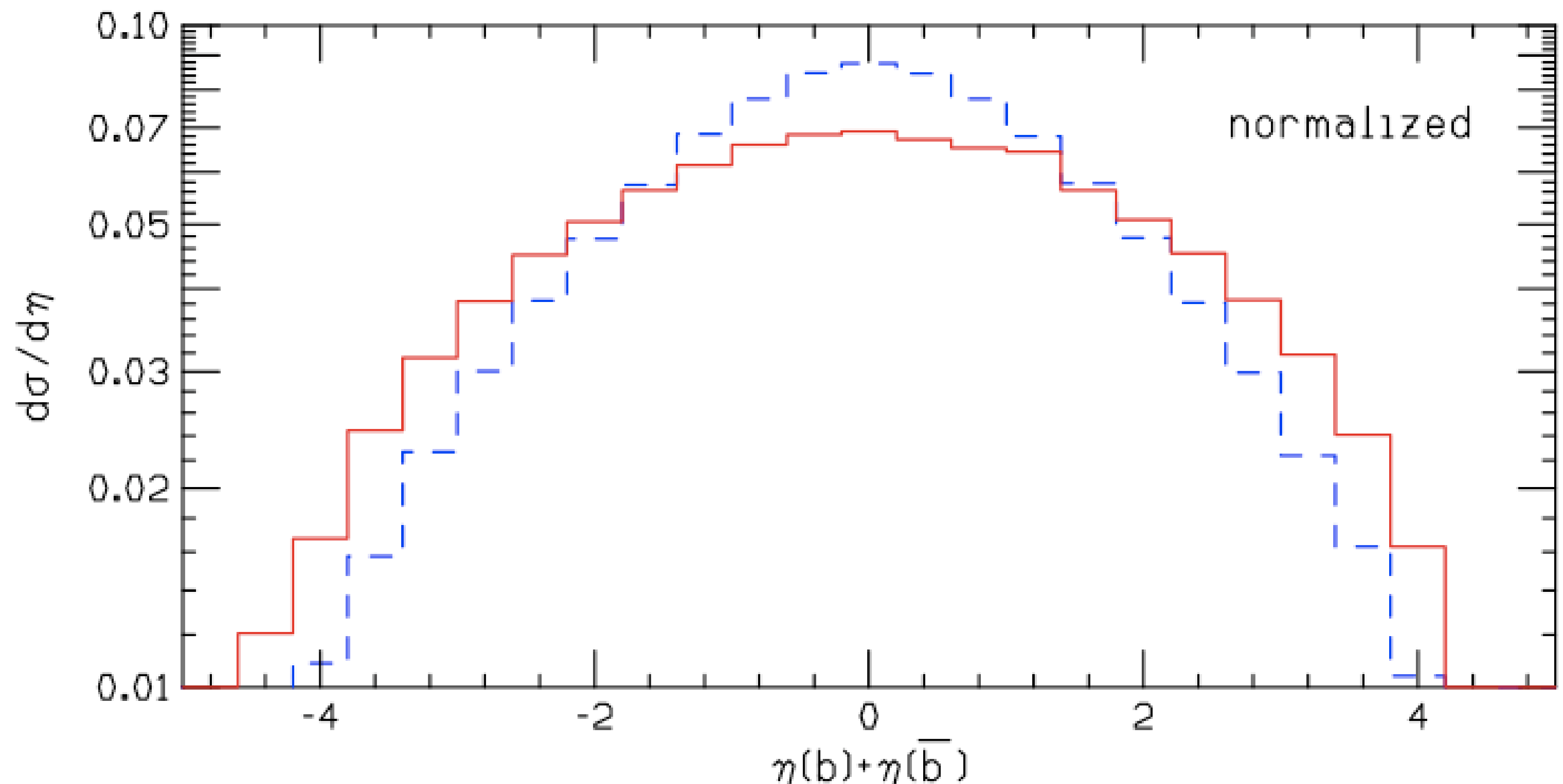
Bottom quark rapidity distribution

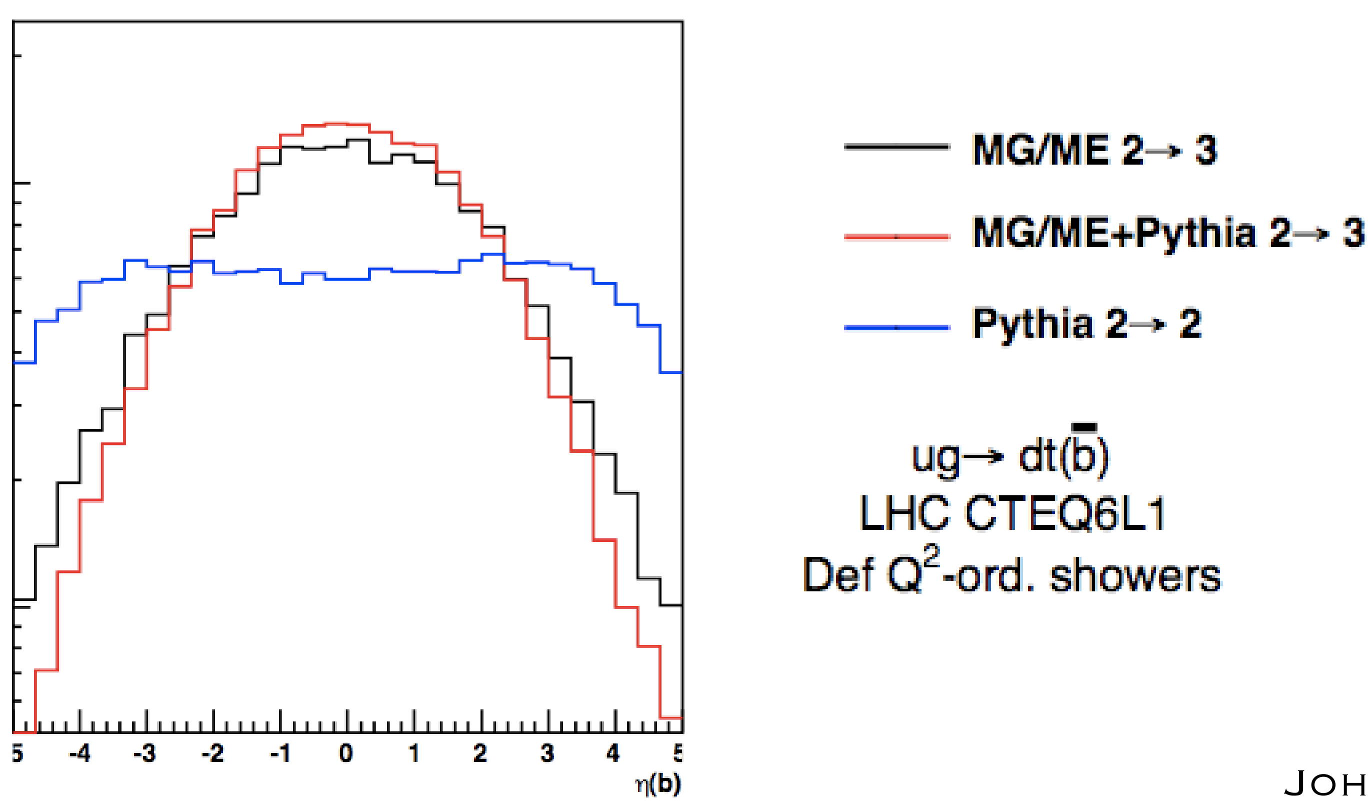


- Would be completely wrong with $m_b=0$.
- First NLO prediction for such a quantity.
- Peak shifted more forward at the Tevatron in the 2→3 calculation
  - for a given sign of the top (and bottom).
- Bigger deviations, up to 20-30%, common.

Rapidity vs. MC

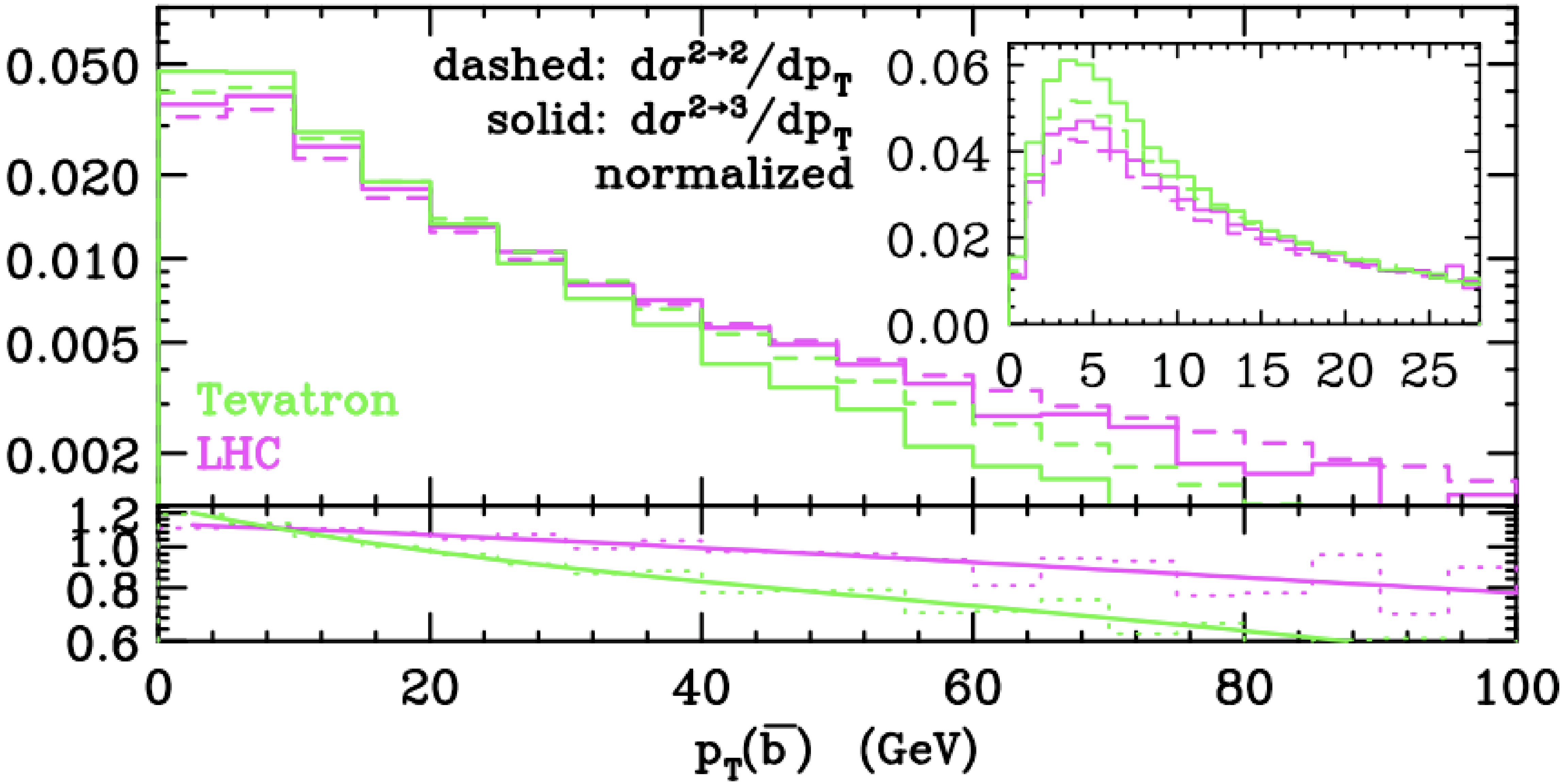
- Combined b and anti-b distribution.
- Significant broadening of peak.





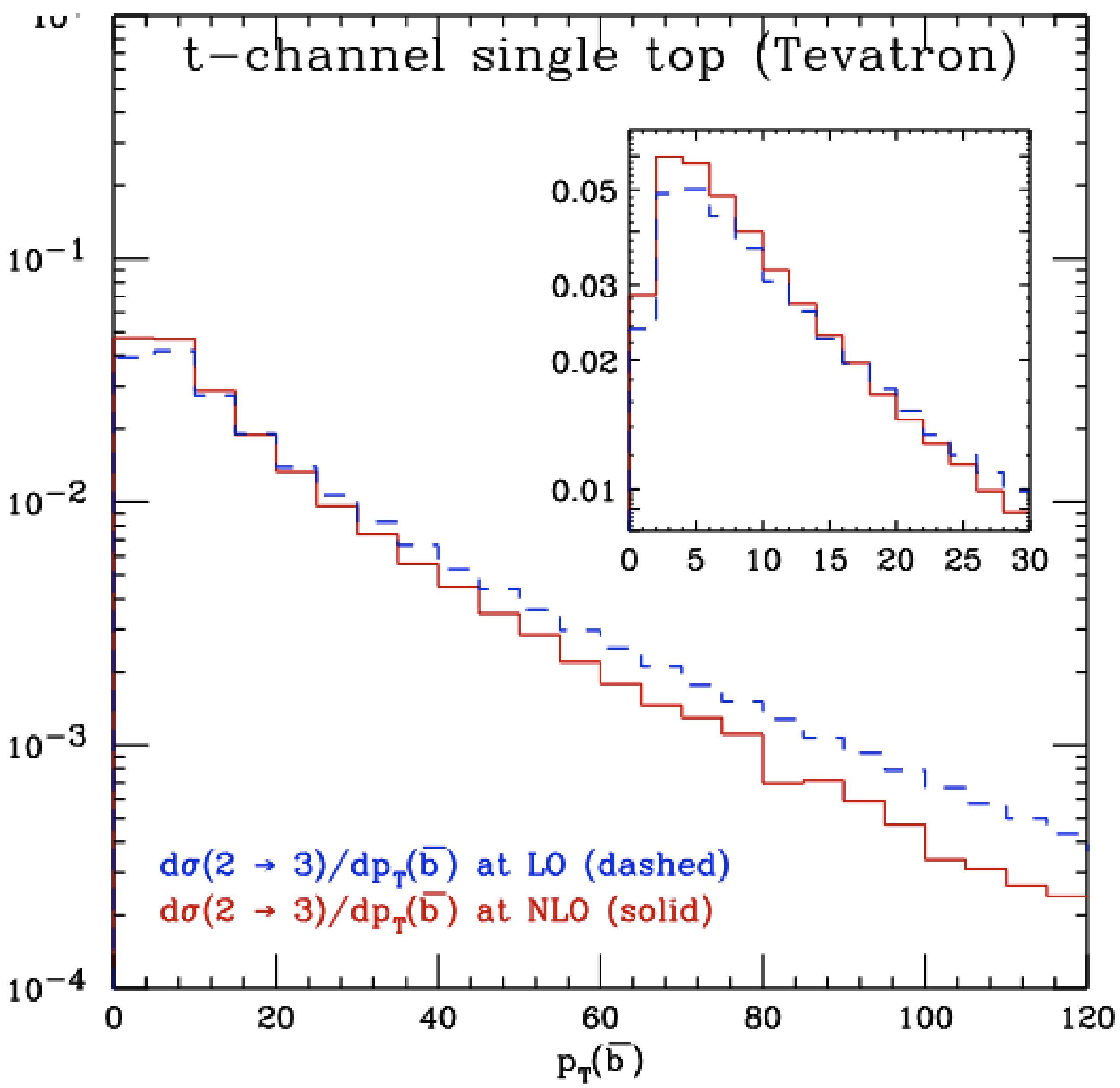
- Comparison with Madgraph/Madevent and Pythia.
- Showering from 2→3 goes the other way from NLO corrections.

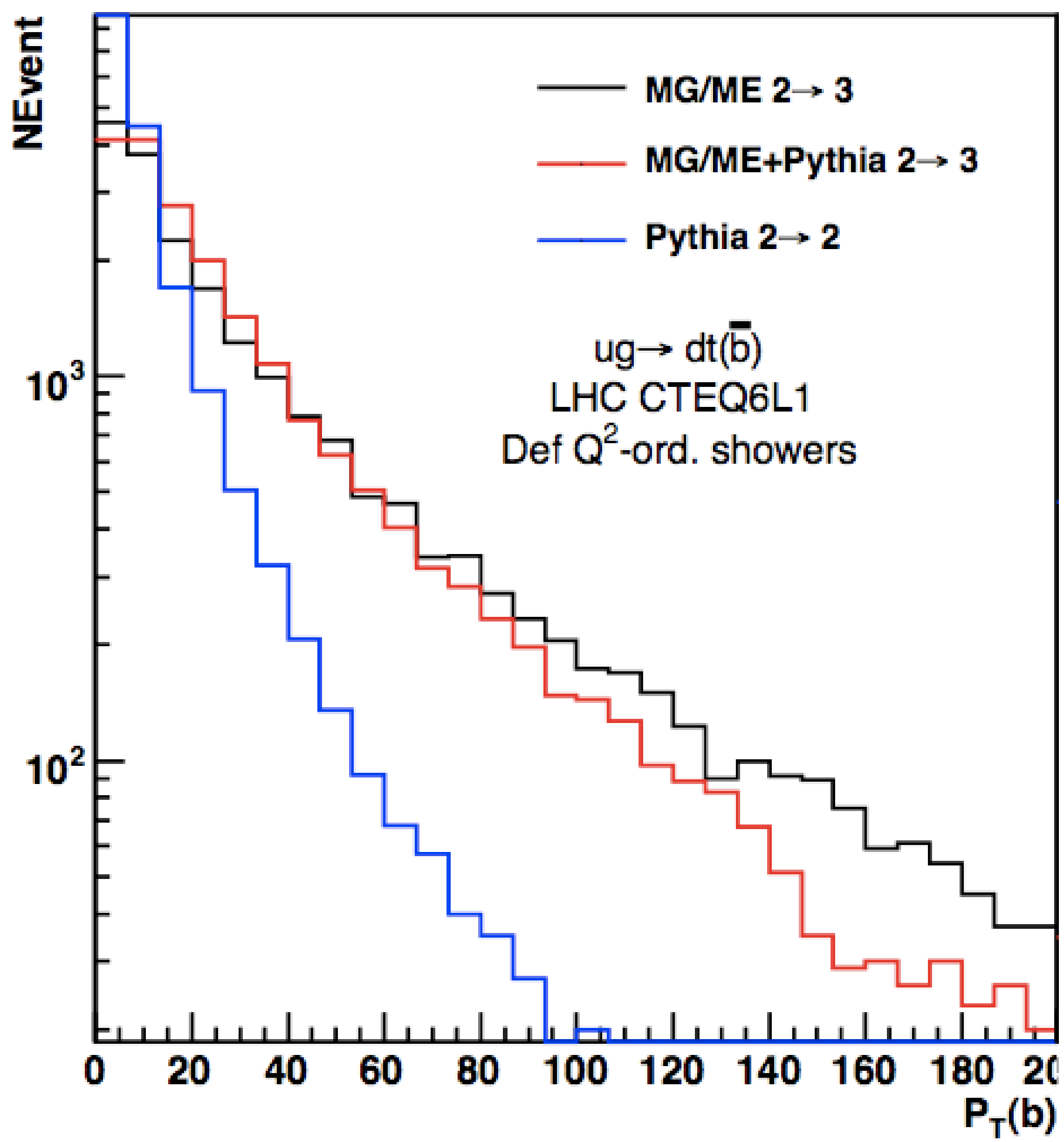
Bottom quark p_T distribution



- NLO prediction throughout the whole range.
  - different slope at the Tevatron: more b's at low p_T.
- Future study: contrast with parton shower, SingleTop, Madevent, etc.

Transverse momentum vs. MC





- Completely different kinematics in default Pythia.
- Showering from 2→3 similar to NLO.

Theory perspective: I

- Understanding backgrounds is hard.
- W+jets including heavy flavor is top of the list.

$$\sigma_{b-\text{jets}}(W + b\text{–jets}) \times BR(W \to \ell\nu) = 2.74 \pm 0.27(stat) \pm 0.42(syst)\text{pb}$$

$$\sigma_{b\text{-jets}}(W + b\text{-jets}) \times BR(W \to \ell\nu)_{ALPGEN} = 0.78 \text{ pb}$$

CDF Note 9321

- Leading order + PS clearly doesn't describe this data well.
- Checking NLO effects at the moment ...
  - ... but hard to account for such a large difference.

JC, Febres-Cordero, Reina et al. (w/ C. Neu)

- Would be fantastic to have an in-situ (i.e. within single top analysis) determination of rates for W+1,2,3 jets with 1 or 2 b-tags.
- Background shapes a large part of final error.
  - Some NLO calculations available; what else can we do to help?

Theory perspective: II

- Extraction of V_{tb}/anomalous coupling very sensitive to theory input.
- Not so much of an issue now, but something for the precision future.
- Top mass important, e.g. 10% change in cross-section for 170→175 GeV.
- Other uncertainties: PDF (beware the bottom quark!), scale, α_s, m_b.

↖ e.g. down by ~10% from 2004 to now

Calculation	Reference	PDF	cross-section	uncert.
s- NLO	e.g. Sullivan, PRD 70 (2004) 114012	CTEQ6.6M	0.42	(+0.4, -0.4)
s- NNNLO*	Kidonakis, PRD 74:114012,2006.	MRST2004NNLO	0.52	(+0.03, -0.03)
t- 2→3 NLO	JC et al., arXiv:0903.0005	CTEQ6.6M	0.93	(+0.16, -0.18)
t- 2→2 NLO	e.g. Sullivan, PRD 70 (2004) 114012	CTEQ6.6M	0.99	(+0.12, -0.10)
t- 2→2 NNNLO*	Kidonakis, PRD 74:114012,2006.	MRST2004NNLO	1.12	(+0.06, -0.06)

* = exact to NLO, leading logs at NNNLO

Summary and to-do list

- ✓ 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. Slight reduction in expected cross section (3-10%).
- ✓ Spectator b distribution predicted at NLO throughout entire region, significant corrections.
- Detailed assessment of impact on current single top searches:
  - comparison with event generators;
  - effect on matrix element method.
- Systematic uncertainty study.
- Application to fourth-generation heavy quark searches (t' and b').
- Inclusion of top quark decay.
- Implications for other heavy-quark initiated predictions (5F vs. 4F).
- Inclusion in a full shower (a la MC@NLO).