Single top production
Theory

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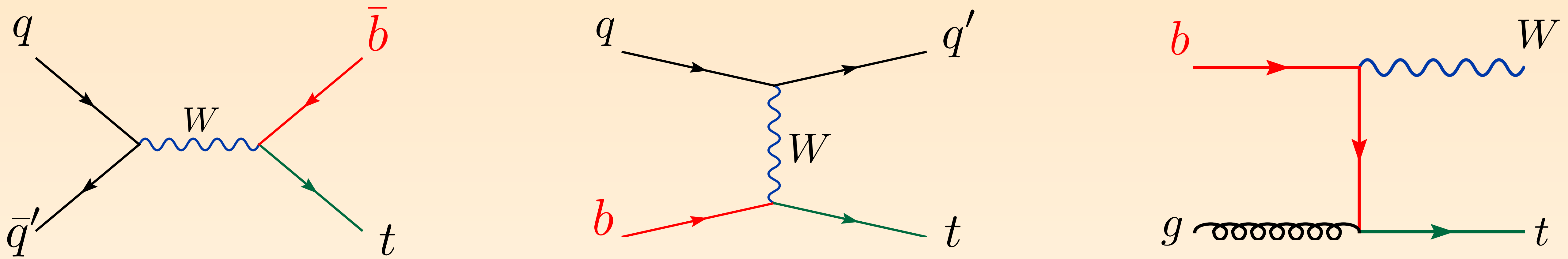
SINGLE TOP PRODUCTION



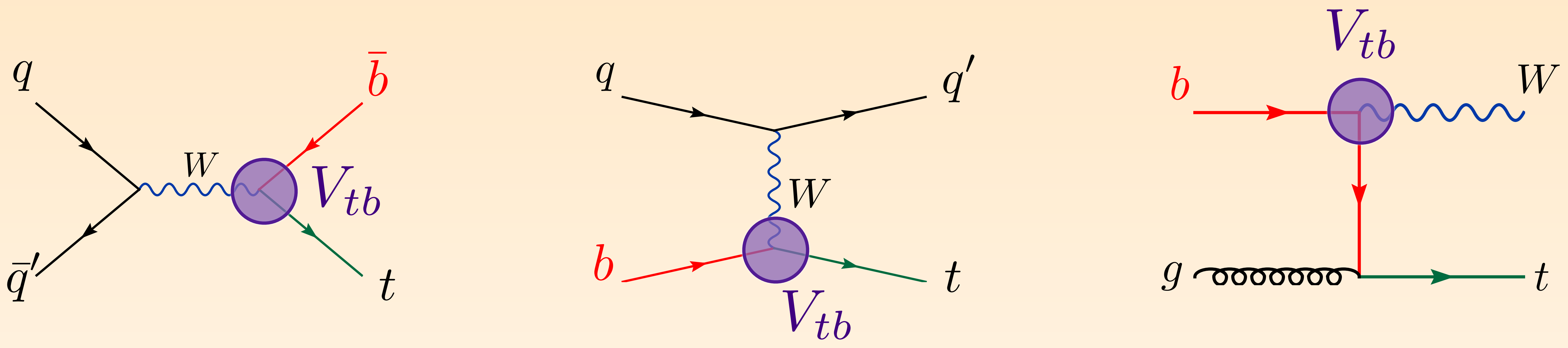
cross section	s-channel	t-channel	Wt-channel
Tevatron 2	1 pb	2 pb	0.1 pb
LHC 7	3 pb	60 pb	10 pb
LHC 14	10 pb	240 pb	60 pb

CONTENTS

- CKM matrix element $|V_{tb}|$
- 4 vs. 5 flavors for t-channel production
- Wt-channel isolation at the LHC
- s- vs t-channel single top production at the Tevatron

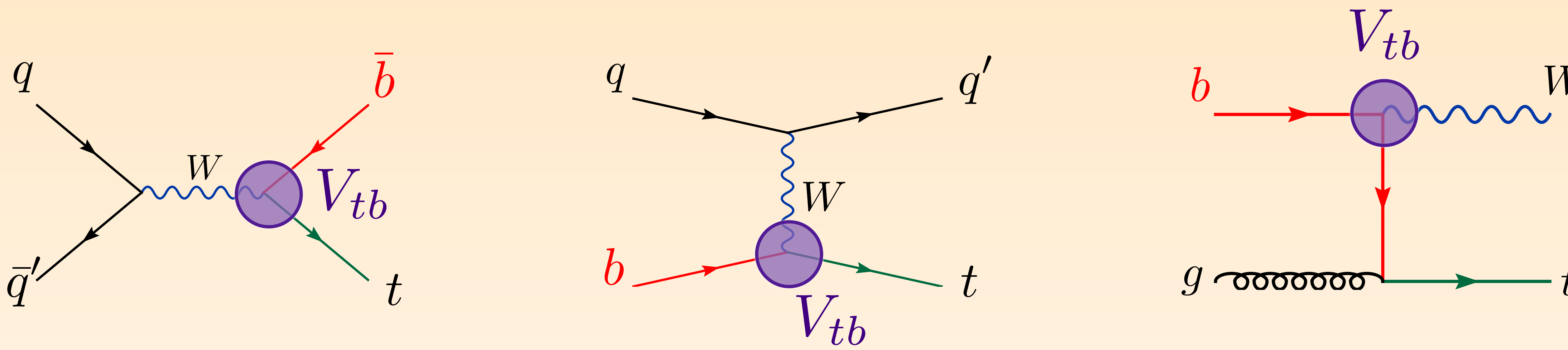
VTB

Measuring $|V_{tb}|^2$



- The three single top production mechanisms are proportional to $|V_{tb}|^2$.
  - Hence, if I would measure the total rate, I can extract its value

Measuring $|V_{TB}|^2$

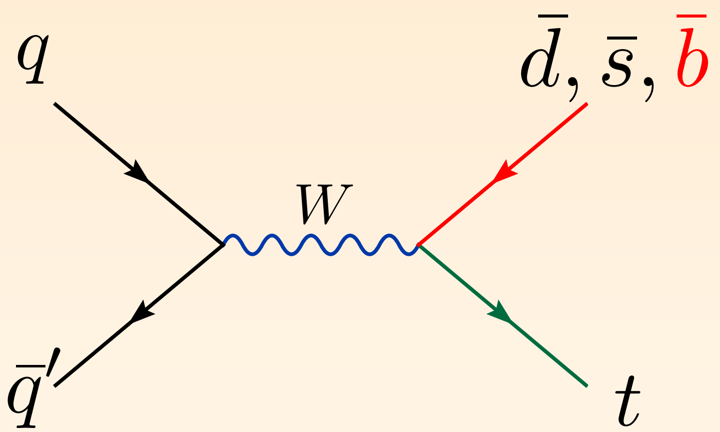


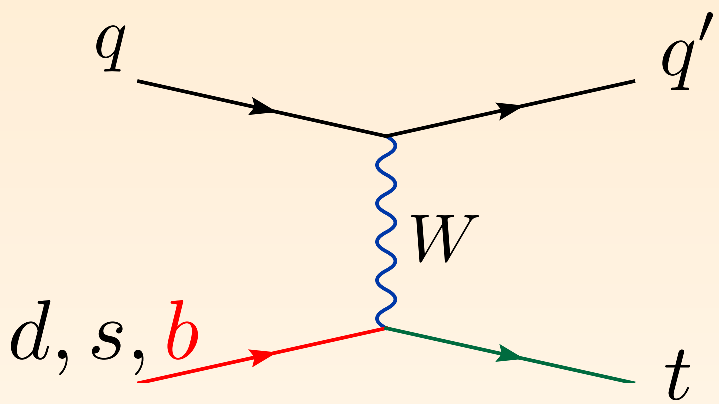
- The three single top production mechanisms are proportional to $|V_{tb}|^2$.
  - Hence, if I would measure the total rate, I can extract its value

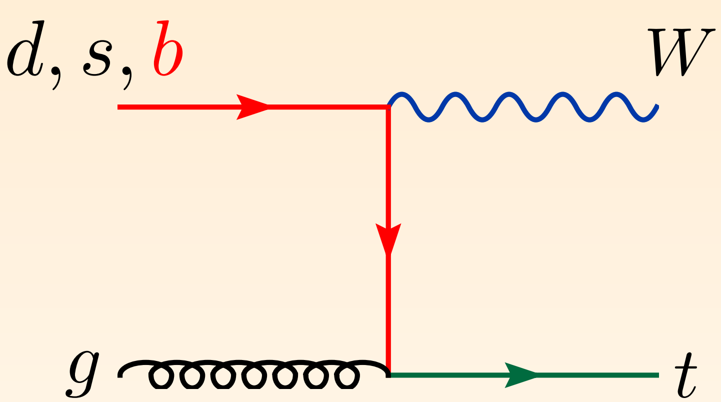
No! This argument is wrong...

Not only V_{tb}

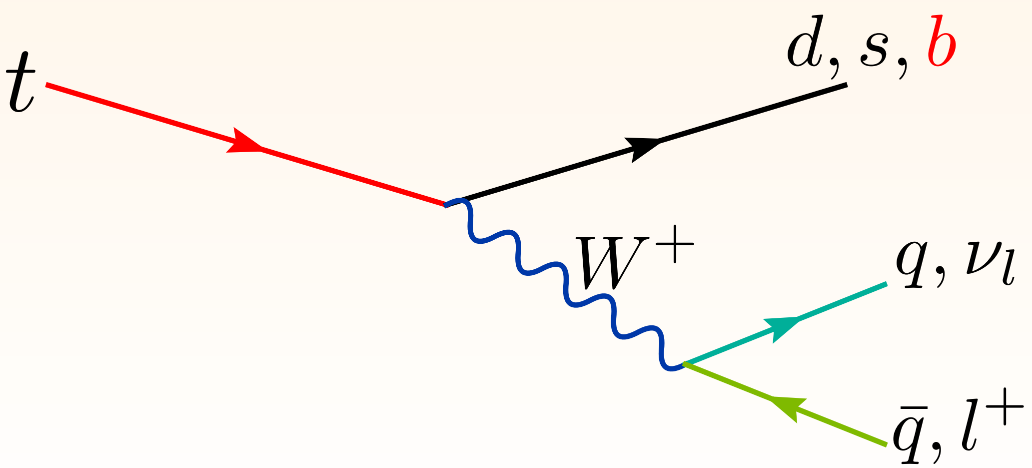
- Only if $|V_{tb}|$ is equal to 1, the previous argument is correct.
- If we want to measure $|V_{tb}|$, there are new 'background' contributions that have to be taken into account







- Also the decay of the top quark changes if $|V_{tb}|$ is not equal to 1.



A WAY OUT?

- A possible way out is to argue that the use of $|V_{tb}|=1$ in my event selection and analysis is okay even though I want to measure $|V_{tb}|$, is to claim that

$$|V_{tb}| \gg |V_{ts}|, |V_{td}|$$

- However, the recent measurement from D0 (from top quark decays in top pair production) suggests otherwise:

$$R = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.90 \pm 0.04$$

  - which translates into

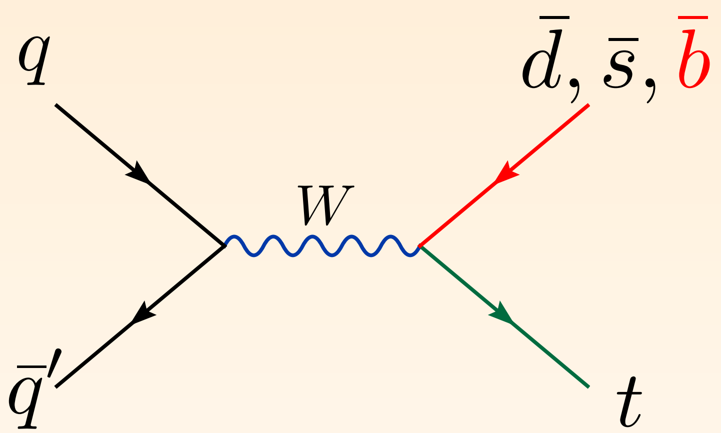
$$\sqrt{|V_{td}|^2 + |V_{ts}|^2} \simeq 0.33\,|V_{tb}|$$

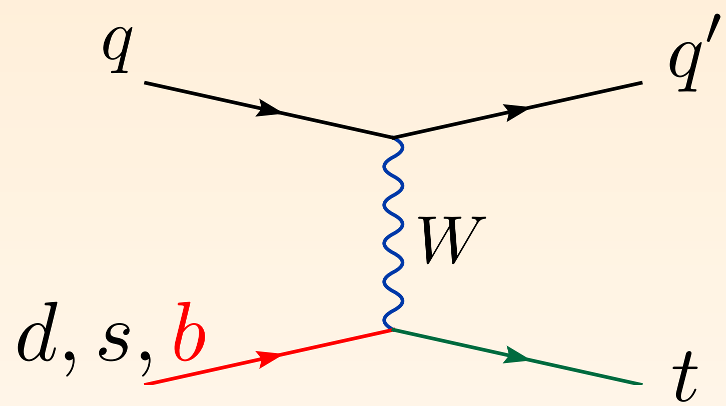
- Which is a bit in conflict with the requirement above

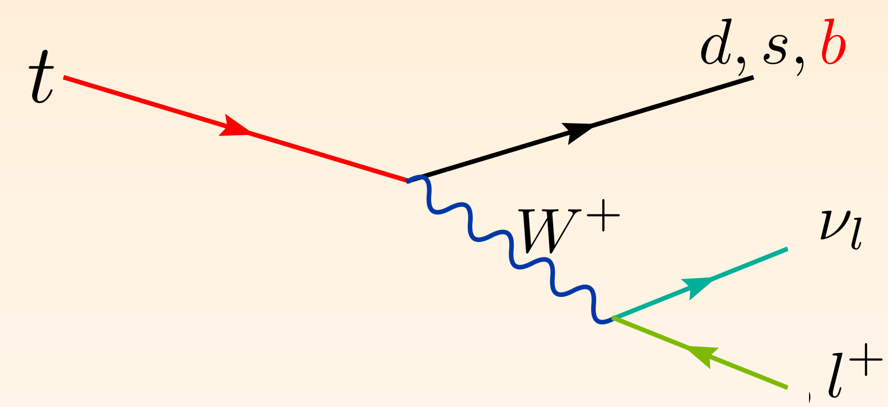
Why not include all contributions...

[*Alwall et al (2006); Lacker et al. (2012)*]

- At the Tevatron (where we can ignore the Wt channel), we have to take all these possibilities into account



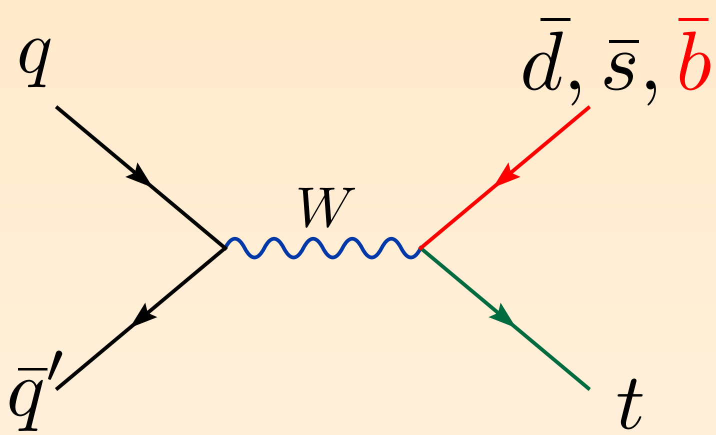


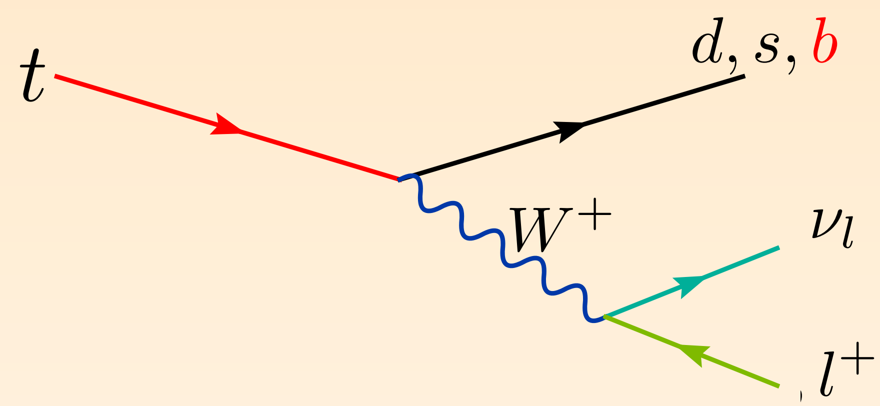


- We can discriminate some of them by looking at the number of b-jets in the final state

E.G. ONE B-JET FROM S-CHANNEL

[*Alwall et al (2006); Lacker et al. (2012)*]





$$N_{1bjet}^{2jets,s} = \mathcal{L} \cdot \sigma^s \cdot R[|V_{tb}|^2 \epsilon^s_{b(t\to bW)} + (|V_{td}|^2 + |V_{ts}|^2)(\epsilon^s_{b(t\to dW)} + \epsilon^s_{d(t\to bW)} + \frac{1-R}{R}\epsilon^s_{d(t\to dW)})]$$

integrated luminosity

(NLO) cross section for s-channel, without CKM matrix element

efficiencies to find exactly one b-jet from the various final state configurations

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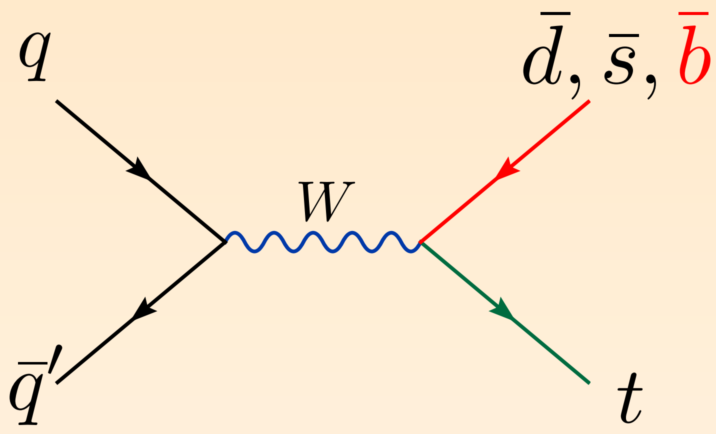
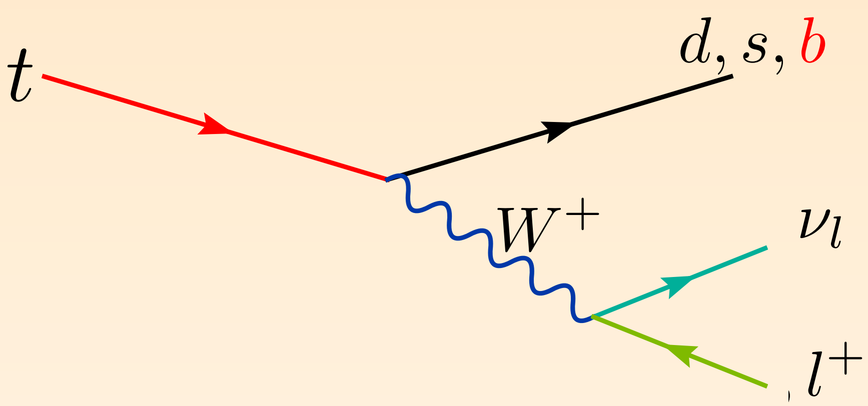




$$N^{2jets,s}_{1bjet} = \mathcal{L} \cdot \sigma^s \cdot R[|V_{tb}|^2 \epsilon^s_{b(t\to bW)} + (|V_{td}|^2 + |V_{ts}|^2)(\epsilon^s_{b(t\to dW)} + \epsilon^s_{d(t\to bW)} + \frac{1-R}{R}\epsilon^s_{d(t\to dW)})]$$

integrated luminosity

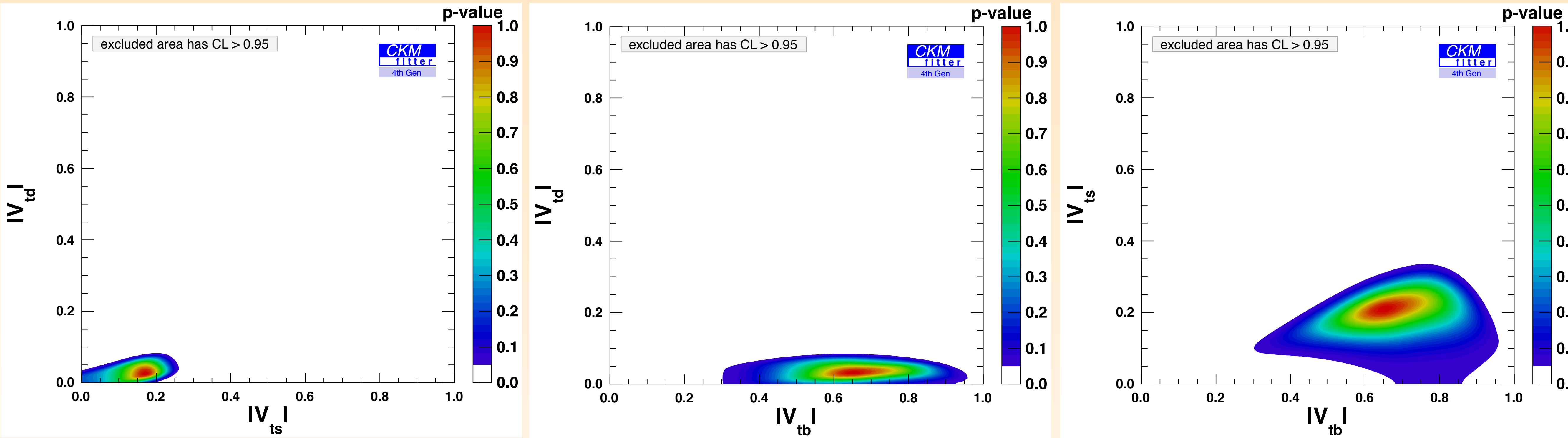
(NLO) cross section for s-channel, without CKM matrix element

efficiencies to find exactly one b-jet from the various final state configurations

And similar for t-channel and for two b-jets

Results

[Lacker et al. (2012)]

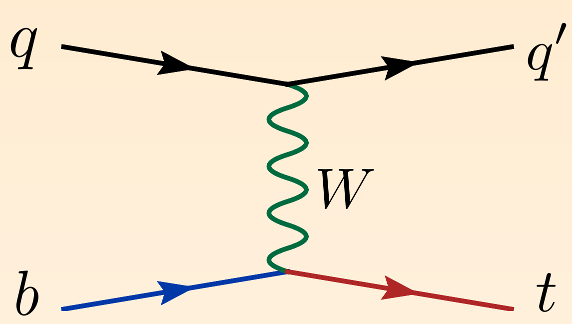


- Only subset of data taken into account: CDF data on one lepton + missing transverse energy + two jets with one reconstructed b-jet and D0 data on the top branching ratio to b quarks
- Assuming a 4x4 CKM matrix (so that 3x3 unitarity constraints don't apply), but direct constraints from flavor physics and from W-boson branching ratios taken into account
- $|V_{tb}| = 1$ lies well outside the 95% C.L. contour

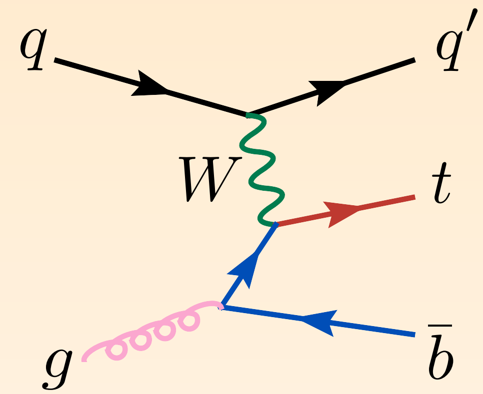
4 vs 5 flavors for t-channel production

Initial state b quark

- "Standard" way of looking at the t-channel single top process



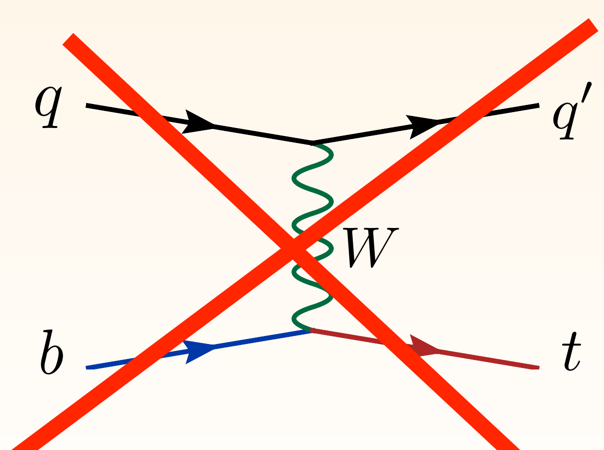
leading order



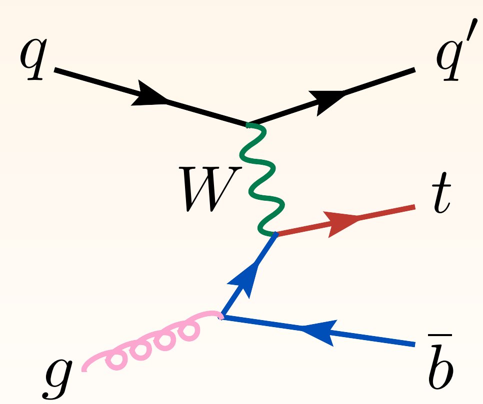
(contribution to) NLO

5-flavor scheme

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



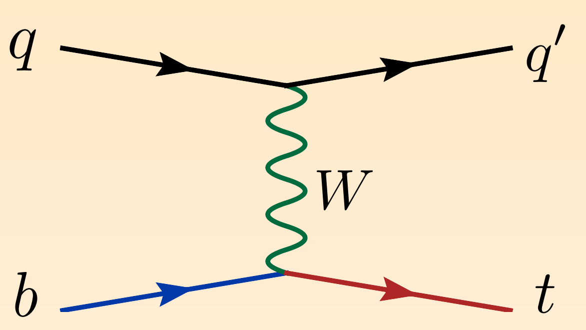
Does not exist



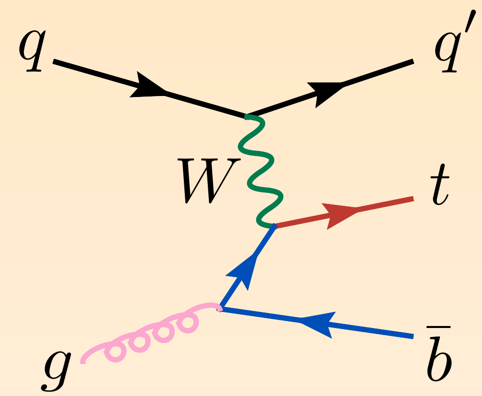
(part of) leading order

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
    - ranges of integration
    - approximation by large logarithm
  - Uses 2 ➞ 2 when interested in total rate, use 2 ➞ 3 when spectator b quark is important.
- At LO they differ. What about NLO?

TOTAL RATES AT NLO

- Estimate of the theory uncertainty: [*Campbell, RF, Maltoni, Tramontano (2009)*]
  - 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

$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2\to 2$ (pb)					$2\to 3$ (pb)				
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

Dependence on x

$\sigma^{\text{NLO}}_{\text{t-ch}}(t+\bar{t})$	$2 \to 2$ (pb)	$2 \to 3$ (pb)
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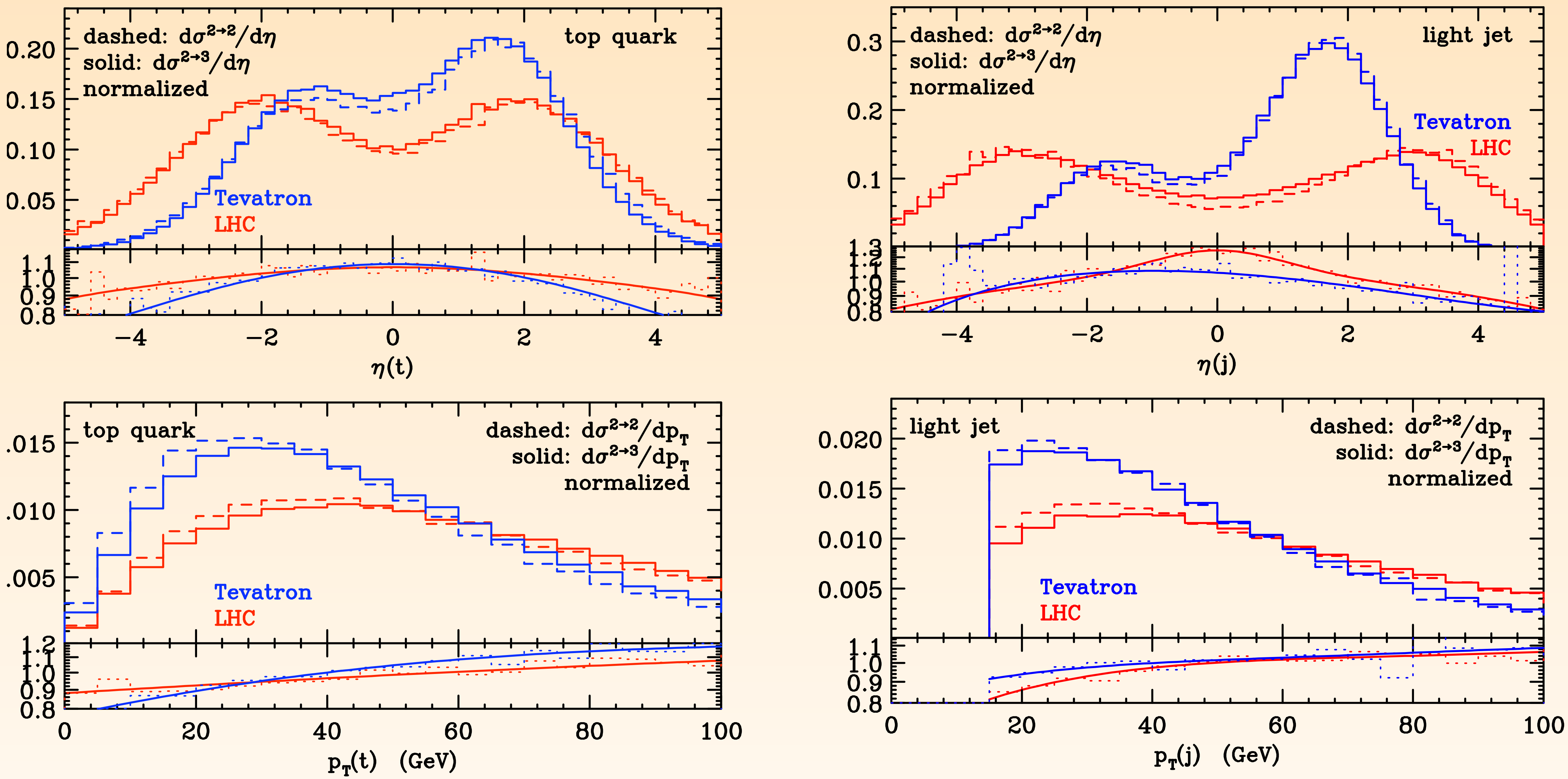
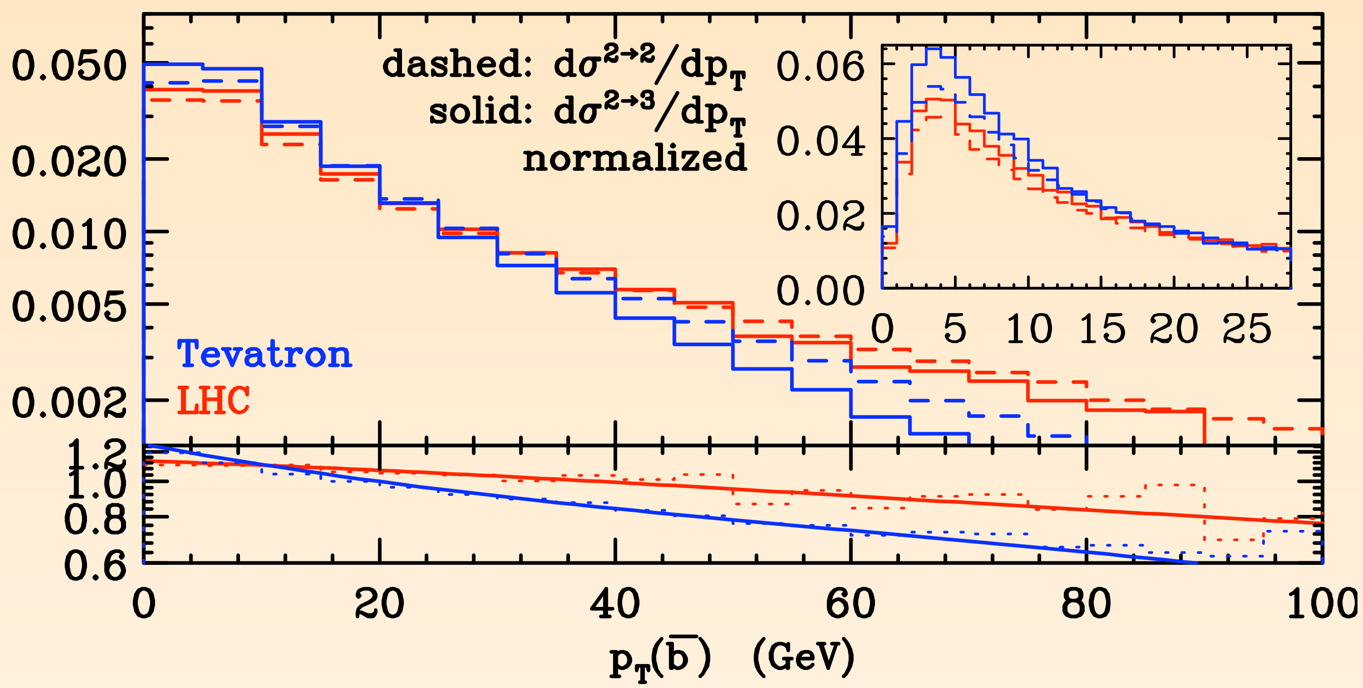
- Interestingly, the agreement seems to be better at the LHC than at the Tevatron
- A recent paper [*Maltoni, Ridolfi & Ubiali (2012)*] explains the reason:
  - The logarithms that are resummed in the b-quark PDF are larger at large x
  - Hence, this resummation is more important at the Tevatron

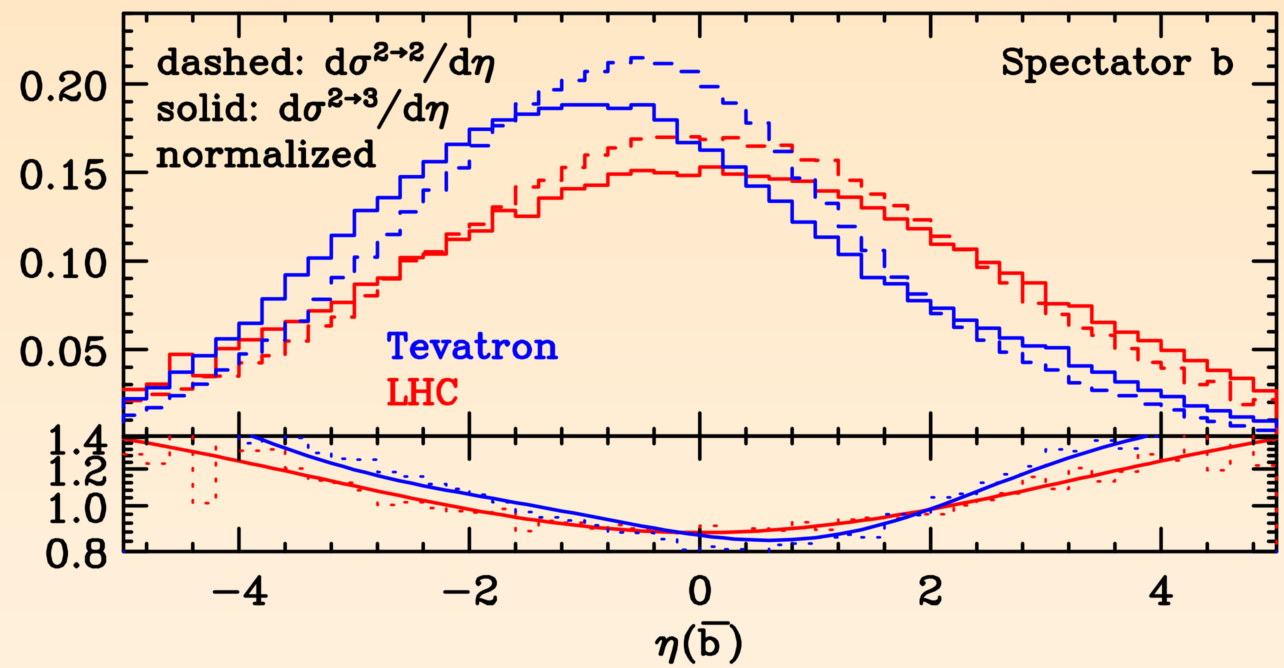
Distributions



- 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)

Bottom quark

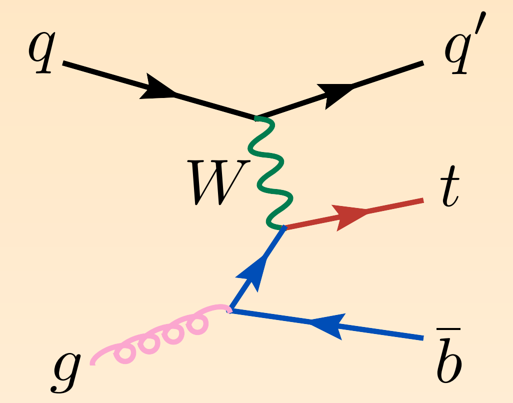


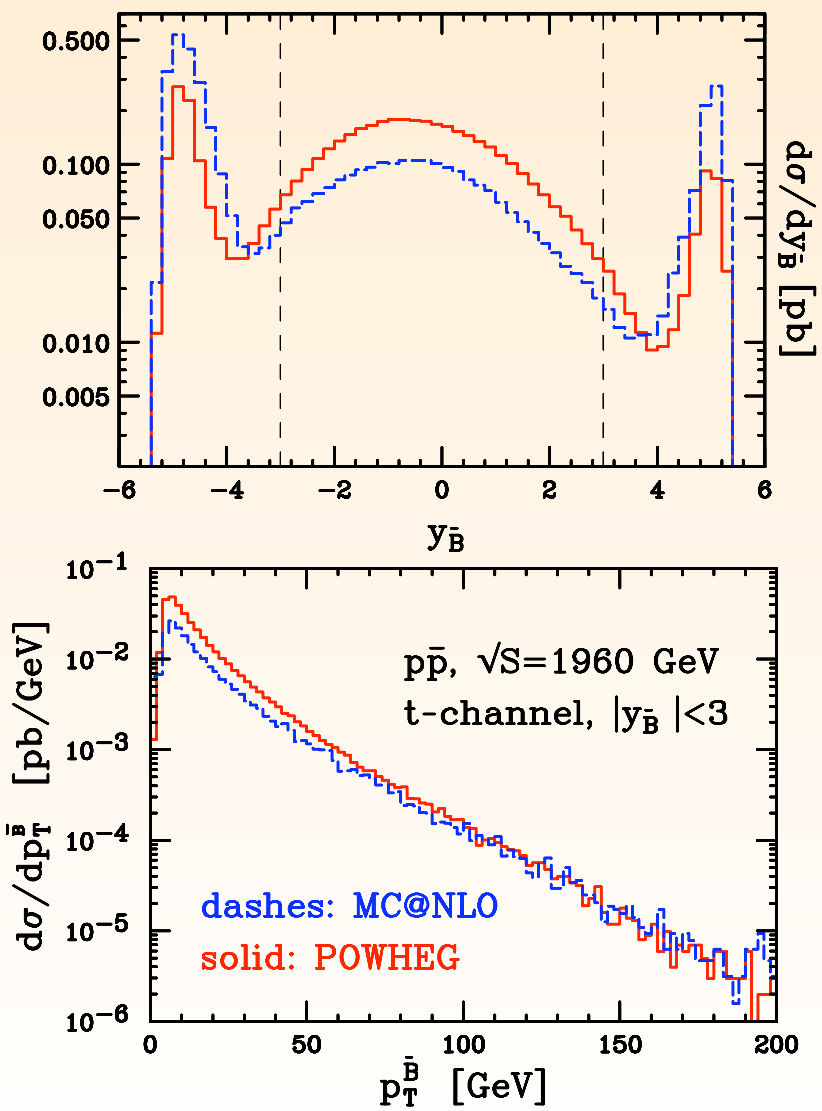


- Dashes: 2 ➞ 2 at “NLO”, with massive (when final state) b quark: the same shape as the 2 ➞ 3 at LO, but different normalization
- Solid: 2 ➞ 3 at NLO: first NLO predictions for these observables
- More forward and softer in 2 ➞ 3, particularly at the Tevatron
- Mild deviations up to ~ 20%
- These plots are normalized: 2 ➞ 3 much larger than 2 ➞ 2, because for 2 ➞ 2 only subset of NLO diagrams contributes to these observables

Recent progress

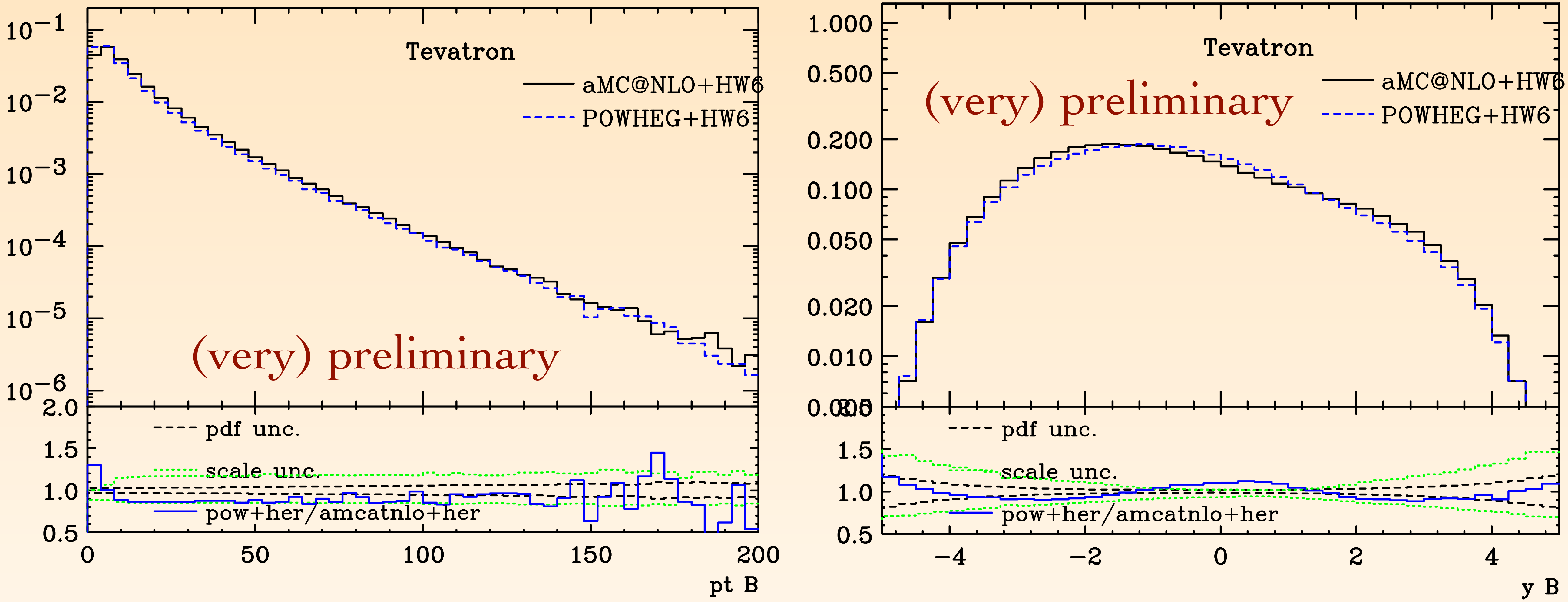
- So, already at NLO the 4 and 5 flavor scheme calculations are in agreement
- However, the 4 flavor (2 -> 3) has a better description of the “spectator b” quark: it’s described with NLO accuracy
- The 5-flavor (2 -> 2) process in POWHEG+HW6 and MC@NLO+HW6 show some non-physical peaks due to the way the backward evolution is done in the HW6 parton shower
- Recent progress: Using POWHEG and MC@NLO, match the 4-flavor NLO results to a parton shower to allow for event generation at NLO accuracy





NLO+PS

[RF, Re, Torrielli]

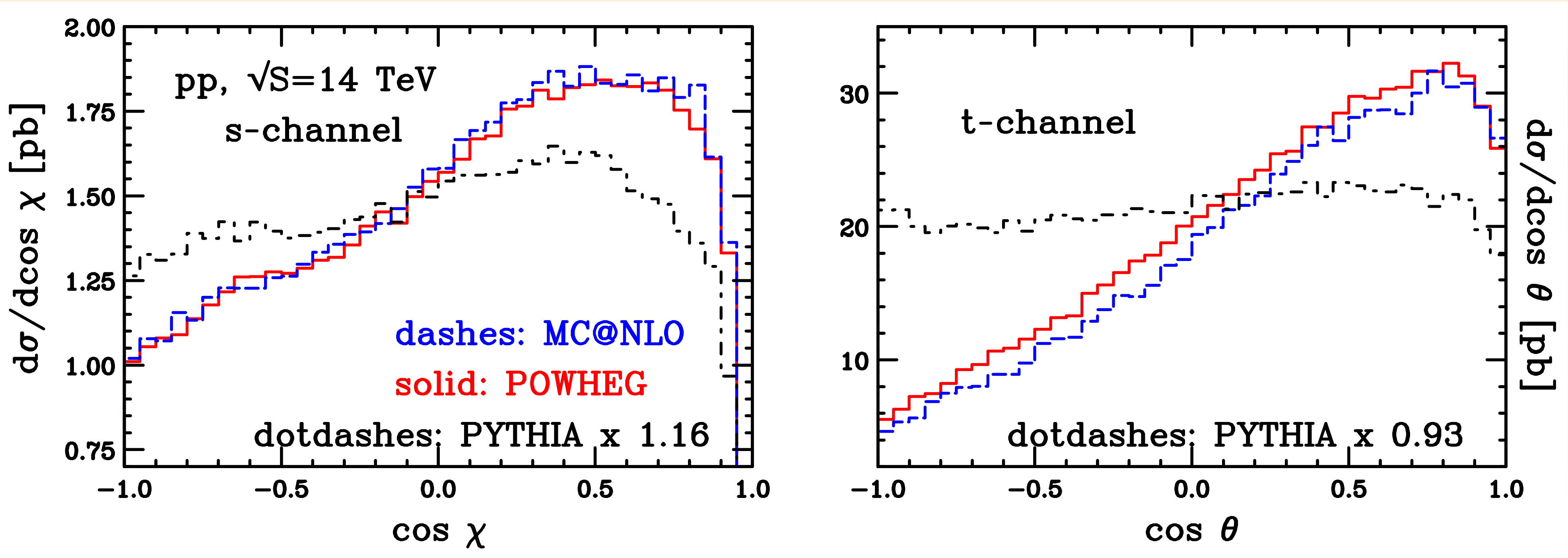


- Stable B-hadron coming from the spectator b-quark (if there are more than one, take the hardest)
- Excellent agreement between aMC@NLO+HW6 and POWHEG+HW6 for transverse momentum, okay-ish for rapidity
- PDF and scale uncertainties generated by aMC@NLO without extra CPU time using reweighting techniques

More work needed
(as always...)

- The 4-flavor (2->3) calculation does not (yet) take spin correlations between the production and decay into account. It has been shown that those are important in the 5-flavor process

[*Frixione et al.; Alioli et al. (2009)*]



- Angles between hardest lepton and beam (left) or hardest jet (right) evaluated in the top rest frame

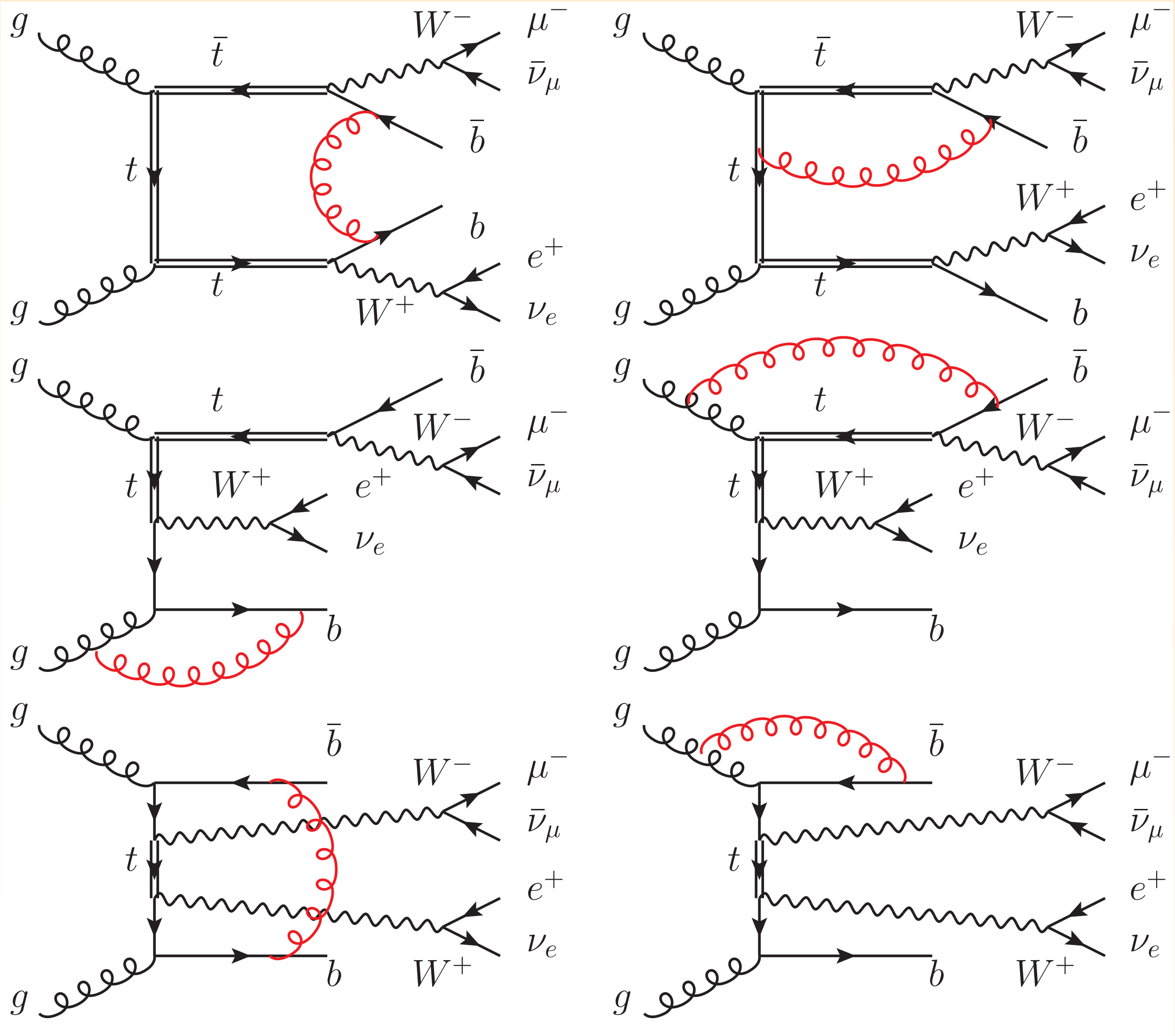
Wt and top pair

Wt-channel

- When including (N)NLO corrections, the s-, t- and Wt-channels start to interfere among each other and also with double resonant (top pair production) and non-resonant contributions
- In particular, the Wt channel is the most dubious one from a theoretical point of view. Already at LO (in the 4-flavor scheme) there are interferences with top pair production
- It has been shown [*C. White et al. (2009)*] that the Wt channel can be isolated from the ttbar background at the LHC
- However, given that there is interference already at LO, how much sense does this make? In particular when tops are backgrounds to other processes

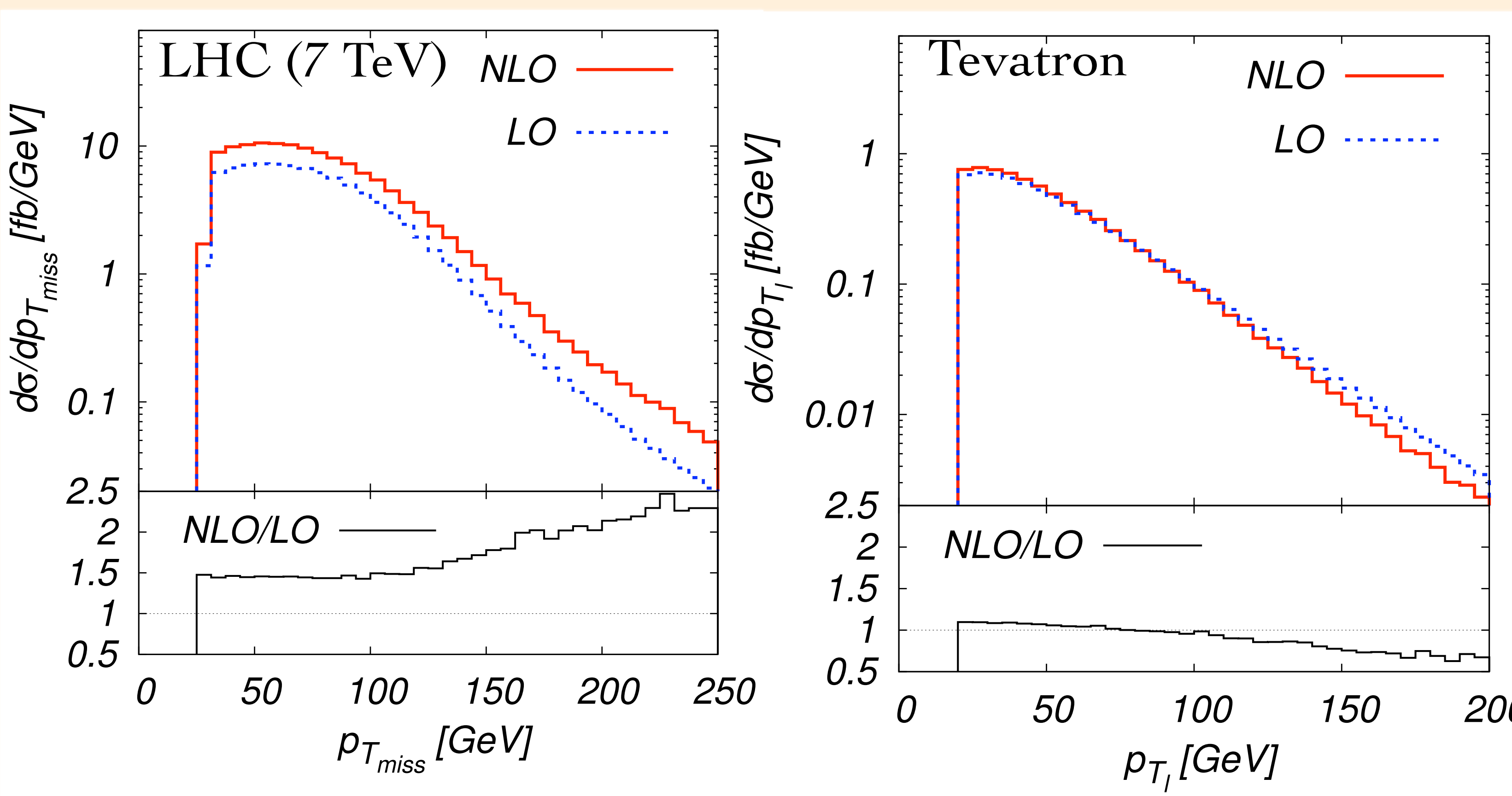
WWbb at NLO

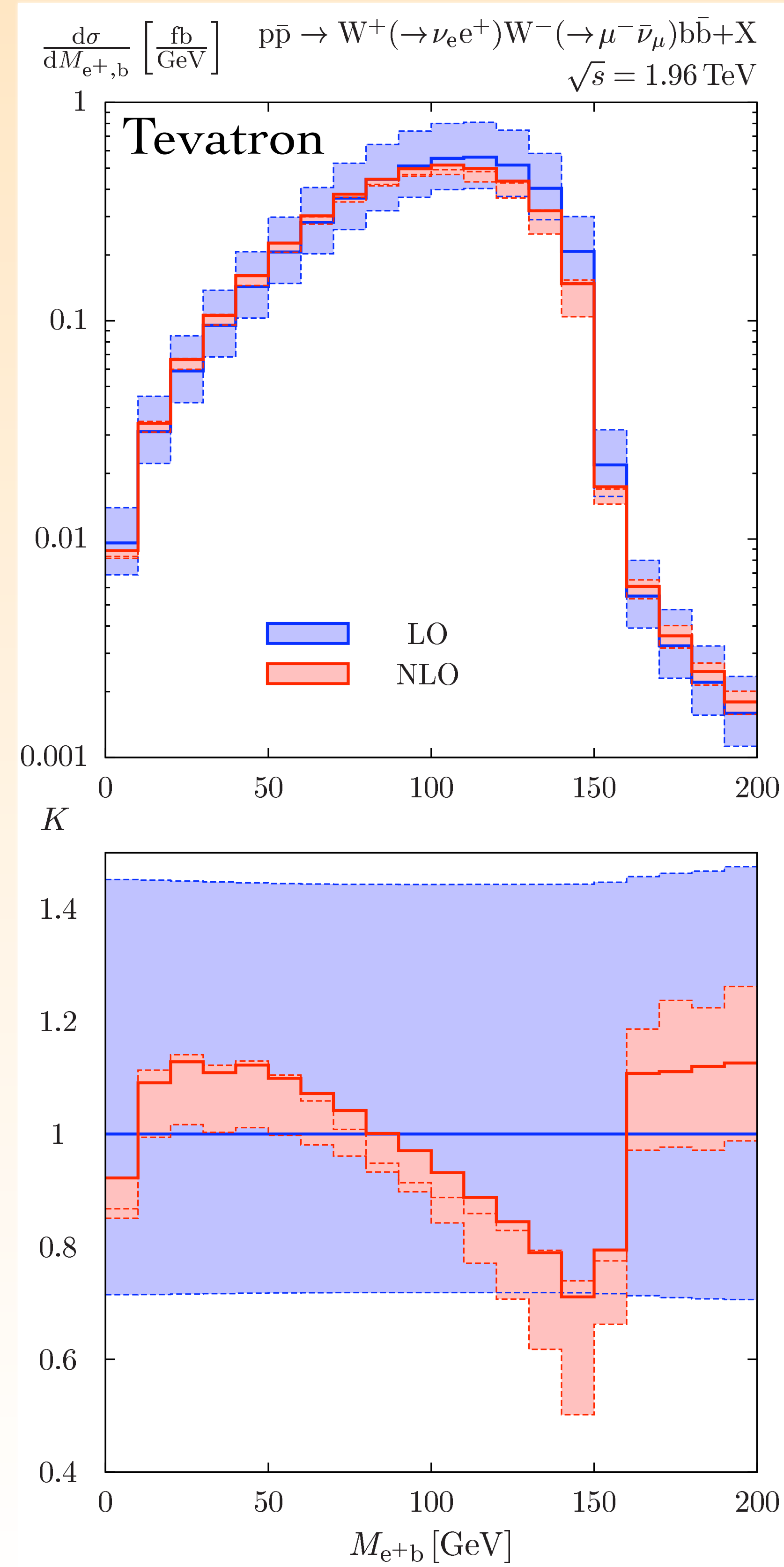
- Recently, the full NLO corrections to the WWbb process were calculated by two independent groups [*Denner et al.; Bevilacqua et al. (2011)*]
- Consistent description of top pair production and irreducible backgrounds
- Particularly important when cuts require (one) top(s) to be off-shell
- Matrix element-level calculation; matching to the parton shower not (yet) available



No constant 'K-factor'

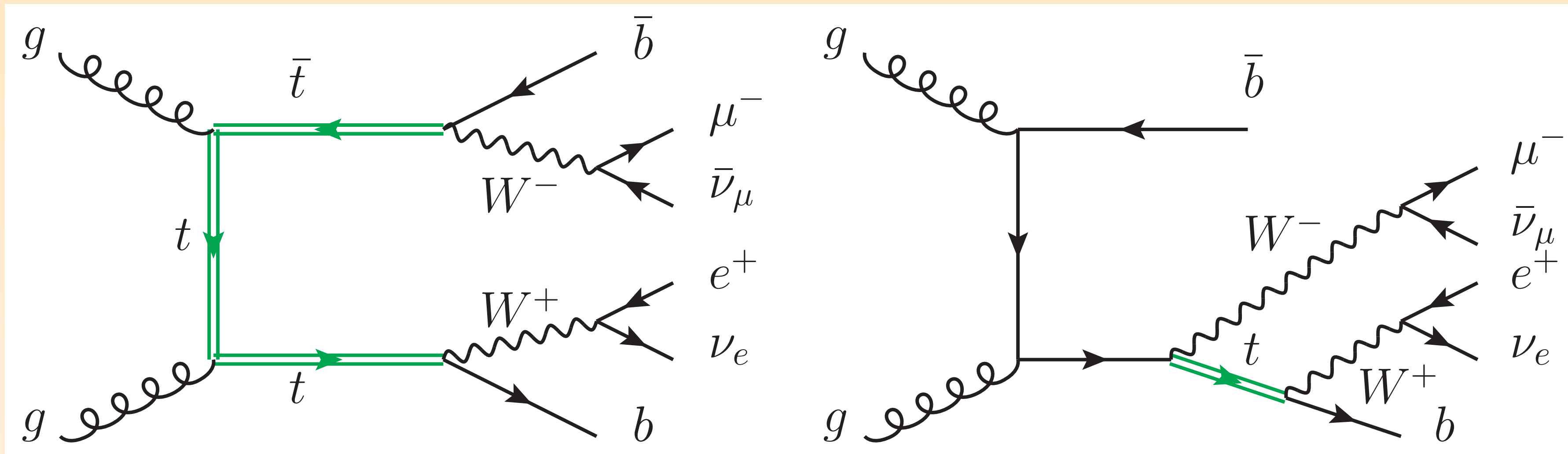
- Corrections are small for most observables
- Compared the LO WWbb production, the NLO corrections are **not** an overall change in normalization





[*Denner et al.; Bevilacqua et al. (2011)*]

MASSLESS B-QUARKS



Top pair production

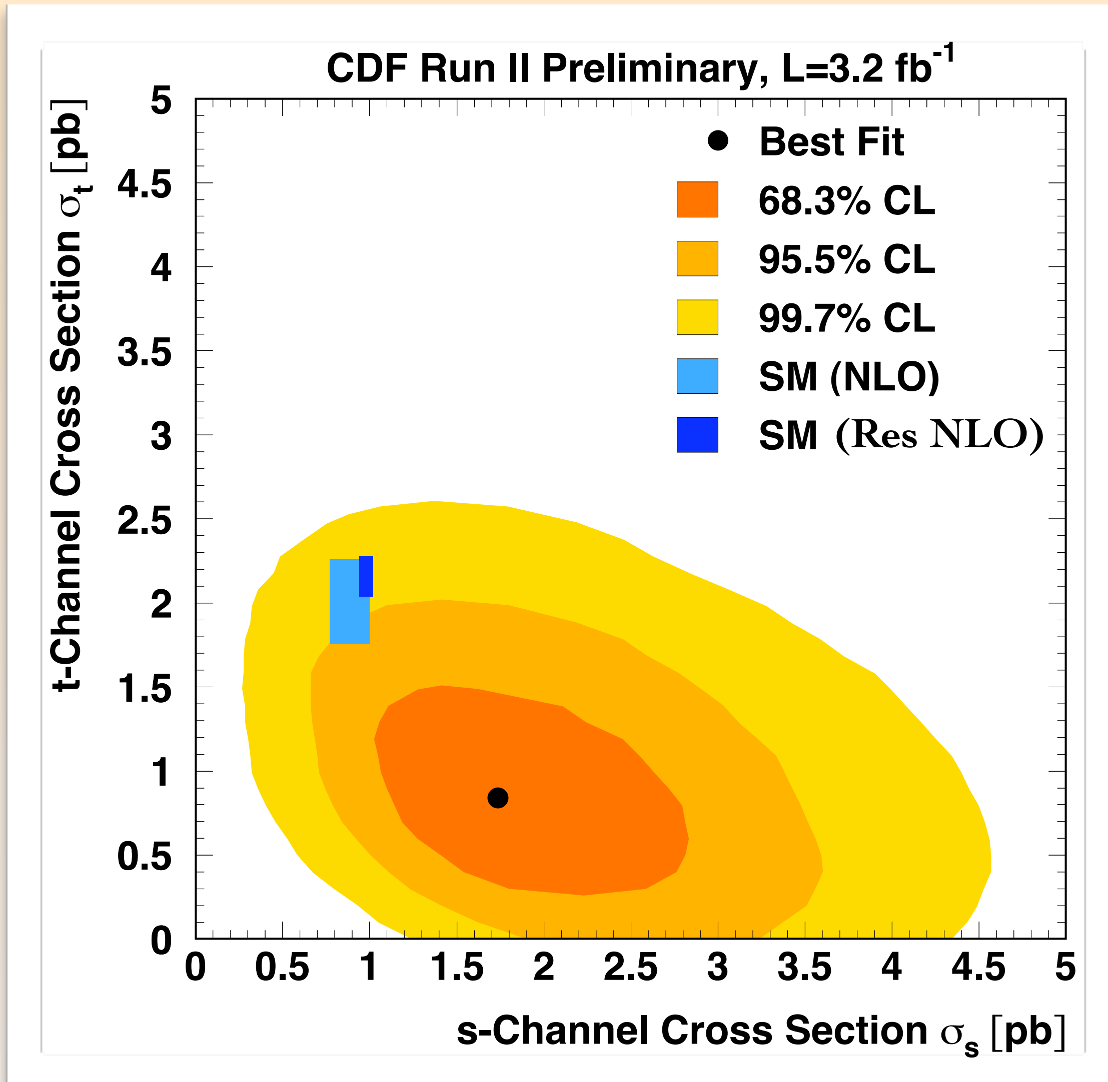
Looks like single top production
(Wt-channel, 4-flavor scheme)
but it isn't really...

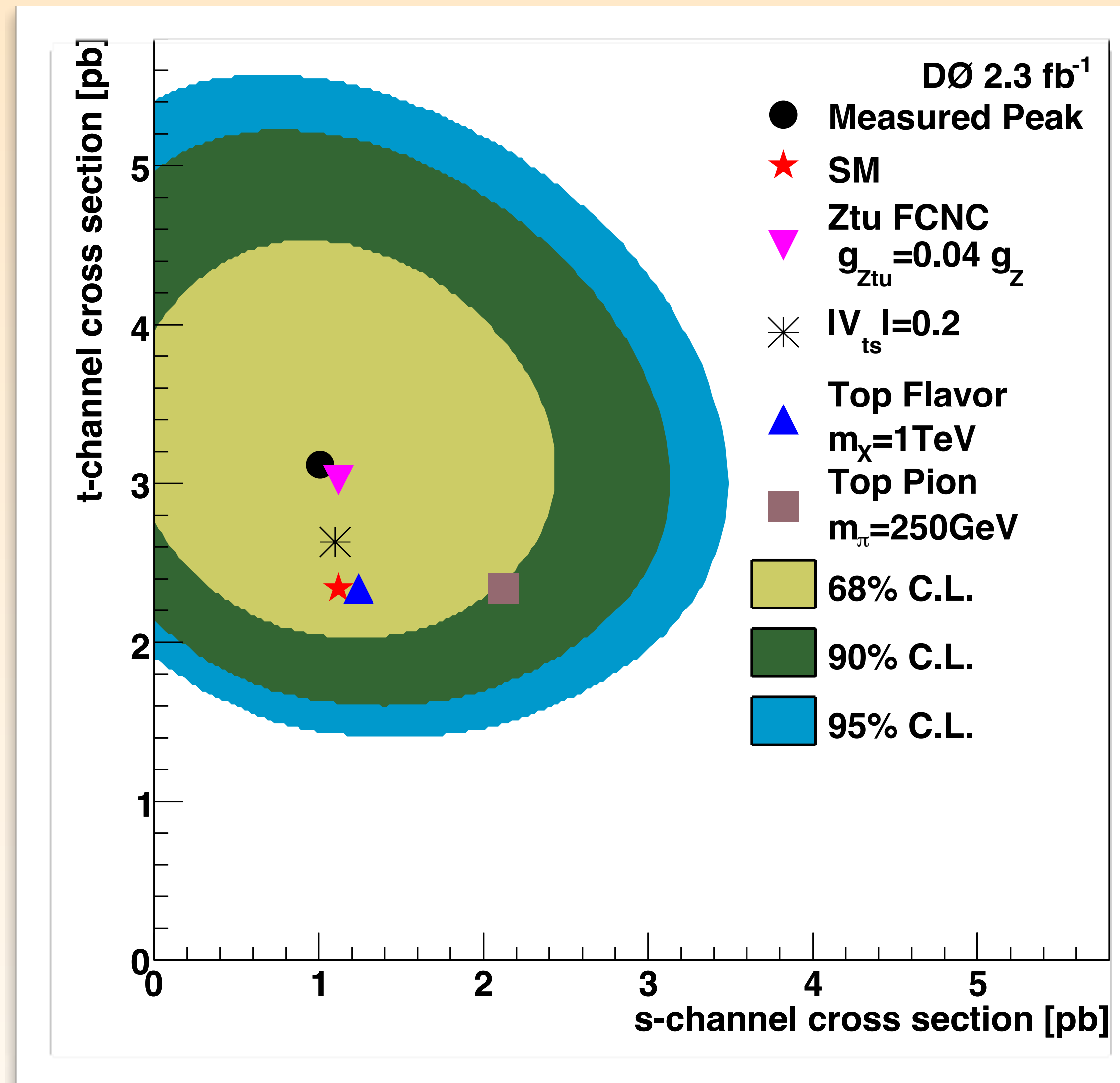
- Unfortunately, b quarks are considered to be massless: need to put cuts on them to make this process finite
  - This calculation cannot be used to predict the rate when one b-quark is too far forward/soft to be observed. So, not so useful when tops are backgrounds to other processes

S- VS T-CHANNEL SINGLE TOP

S- VERSUS T-CHANNEL CROSS SECTION

CDF **DØ**





Why is it that the theory prediction is outside the 95% C.L. contour for CDF?

During the last years, collaboration between theorist and experimentalist trying to pin down this difference. Nothing found that could explain this. Most likely a statistical fluctuation? More data will tell...

Summary

- In general: theory for single top production theoretically well under control
- Experimental determination of $|V_{tb}|$ should be improved. In particular because it is not true that $|V_{tb}| \gg |V_{ts}|, |V_{td}|$
  - Model independent approach (using a small subset of the available data) suggests a value for $|V_{tb}|$ significantly smaller than 1, leading to some tension with a value obtained from a unitairy SM 3x3 CKM matrix
- t-channel single top 4-flavor and 5-flavor calculations agree at NLO for total rate, but 4-flavor has a much better description (ie NLO) of the spectator b quark
  - Recent progress: implementation of 4-flavor process in aMC@NLO and the POWHEG BOX to allow for event generation at NLO accuracy
- Wt-channel isolation from top pair production
- s- vs t-channel cross sections: D0 agrees with theory prediction, CDF sees some tension

Interesting TOPics for further discussion

- Given the recent measurement for *R* by D0, which no longer suggest that $|V_{tb}|$ is much larger than $|V_{ts}|$ or $|V_{td}|$, can we, please, relax this constraint in studies in which we want to measure $|V_{tb}|$?
- t-channel single top is a b-initiated process (in the 5-flavor scheme). Can we use this to constrain the b-quark PDF? Can we get the required experimental precision?
- Any (new) ideas/insights about the s- vs. t-channel cross section determination at CDF? Can we expect a similar plot with the full data set? When?
- Wt-channel single top and top pair production interfere already at LO (in the 4-flavor scheme). How are these processes treated within the experimental community? In particular, when they are backgrounds to other processes? How useful would a NLO calculation for the combined process be?