A FRESH LOOK AT T-CHANNEL SINGLE TOP PRODCTION

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in collaboration with

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Jozef Stefan Institute, Ljubljana, November 26, 2009

Outline

- Introduction to single top production
- New insights on the t-channel:
  - Outline of a new NLO calculation in the four-flavor scheme
  - Results and comparison with the traditional five-flavor approach
- Conclusions

Why study top quarks?

- It's a recent discovered fundamental particle
  (CDF and DØ collaborations)
  - Pair production in 1995
  - Observation of EW production in March this year
    - Direct measurement of $|V_{tb}|$
- It's heavy: 173.1 ± 0.6(stat) ± 1.1(syst) GeV
- It has a short lifetime ~ $5 \cdot 10^{-25}$ s
  - Study of 'bare' quarks: spin correlations unperturbed by hadronization

Top is heavy

- Heavy top due to large Yukawa coupling

$$m_{\rm top} = \lambda_{\rm top} v/\sqrt{2}$$

  - Numerically $\lambda_{\rm top} \approx 0.99$

- Large coupling to the Higgs boson
  - Large radiative corrections to the Higgs boson mass
  - $$m_H^2 = (m_H^0)^2 + \frac{3\Lambda_{\rm UV}^2}{8\pi^2 v^2}\Big(-4m_t^2 + 2m_W^2 + m_Z^2 + m_H^2\Big)$$
  - This fine tuning is known as the 'hierarchy problem'

Possible solutions to the hierarchy problem

- Weakly coupled models at the TeV scale,
  e.g. "Supersymmetry" or "Little Higgs"

- Strongly coupled models at the TeV scale,
  e.g. "Topcolor assisted technicolor" or "top see-saw"

- New space-time structures,
  e.g. "ADD" or "RS"

- Other interesting class of models relevant for top quark phenomenology: extended quark sector, i.e. extended CKM matrix

(t-channel) Single top

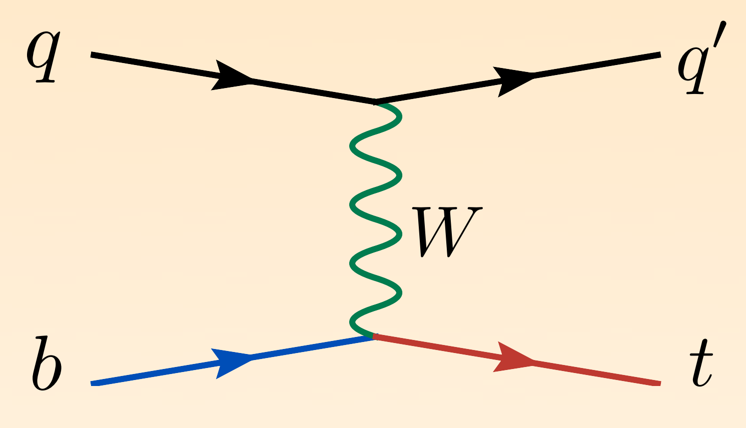
Single top production

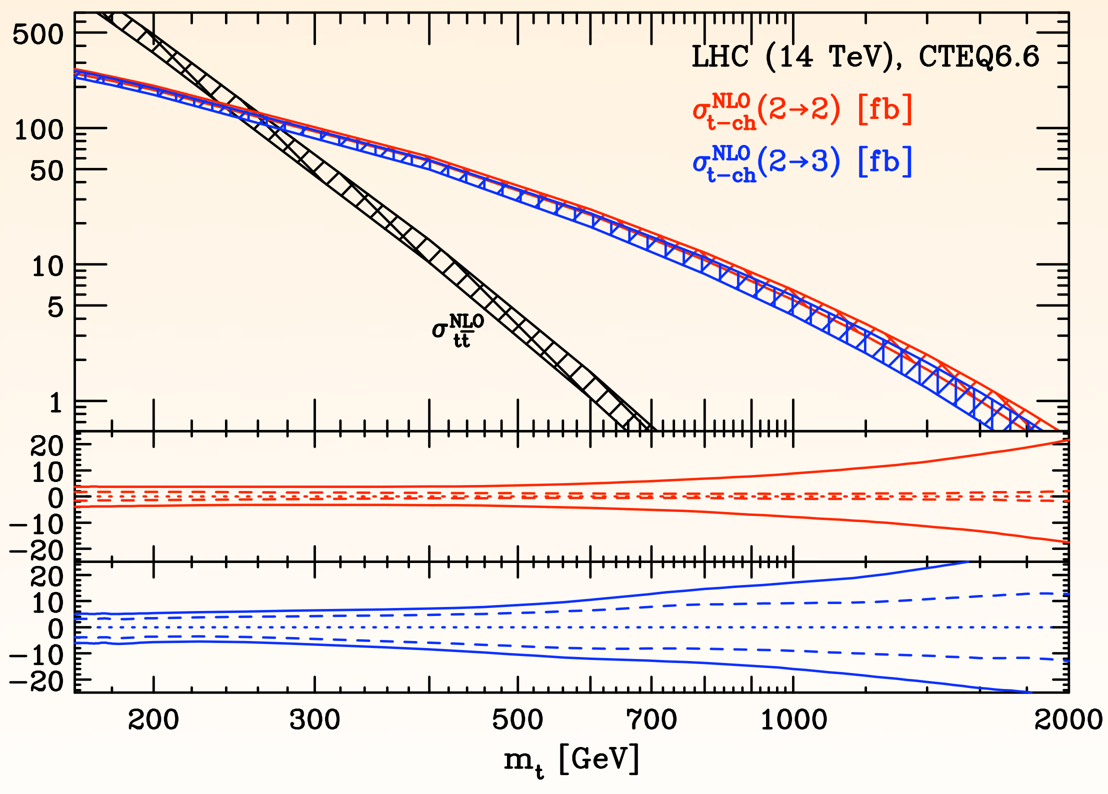
- Contrary to top pair production, single tops are not produced via the strong force, but by the weak force
- There are three distinct* production mechanisms, named after the virtuality of the W boson
  - t channel
  - s channel
  - W associated single top production

* 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

T-CHANNEL SINGLE TOP

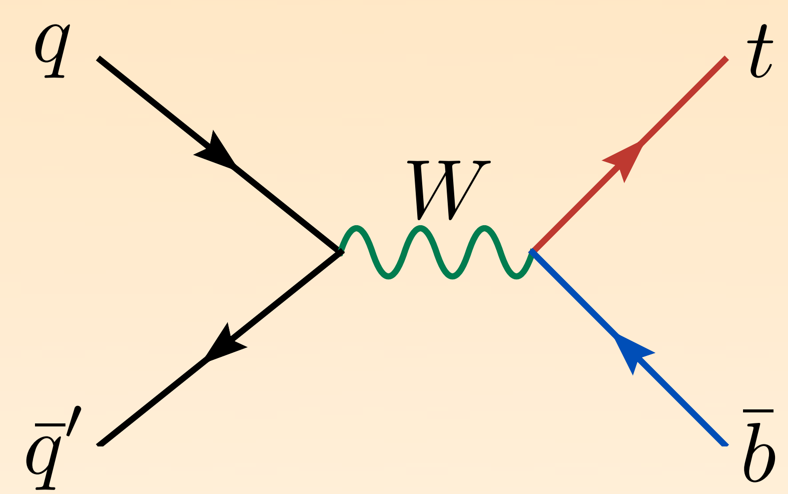
- Already thought of more than 20 years ago
  Dicus & Willenbrock, PRD34, 155 (1986)
- Take advantage of (compared to pair production):
  - t-channel enhancement over s-channel growth
  - more available phase space





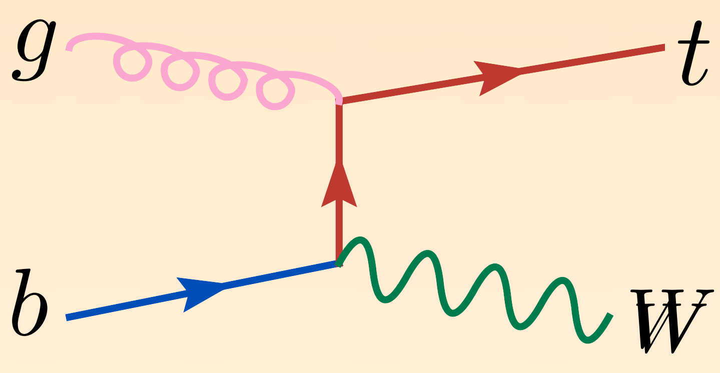
- Large cross section at LHC
- For very heavy quarks single top dominates -- t' searches
- Sensitive to V_{tb}, FCNC, ...
- NLO corrections by
  Bordes & Van Eijk (1995); Harris et al. (2002); Campbell et al. (2004); Q.-H. Cao et al. (2005); Frixione et al. (2006)

S-CHANNEL SINGLE TOP



- Just like Drell-Yan
- Falls off with increasing mass in a similar way to top pair production
- Sensitive to New Physics resonances
- At Tevatron scattering is more sensitive to quark valence structure: relative enhancement due to anti-proton

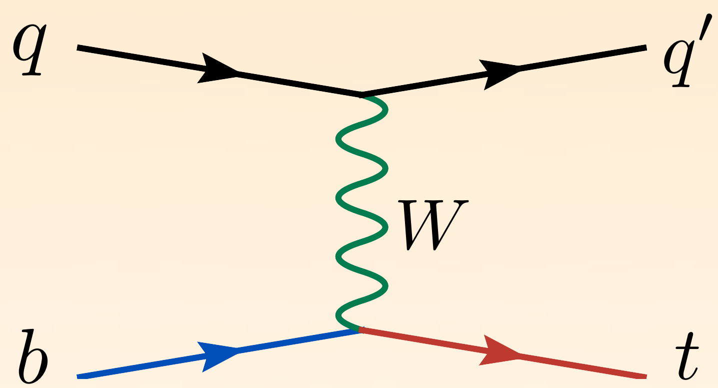
Wt associated production

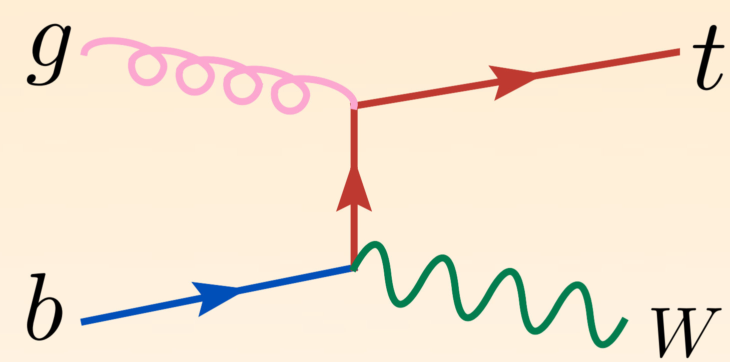


- Irrelevant for Tevatron, due to gluon luminosity and kinematics
  Belyaev et al., PRD59, 075001 (1999); Tait, PRD61, 034001 (2000)
- Can play significant role at the LHC (not least as background - e.g. to H → WW*)
- Very similar top pair production with possible large interference effects between the two -- careful treatment at NLO
  Campbell & Tramontano, NPB726, 109 (2005); Frixione et al. JHEP 0807:029 (2008)
- Different from s- and t-channel production due to (hard) strong coupling at LO

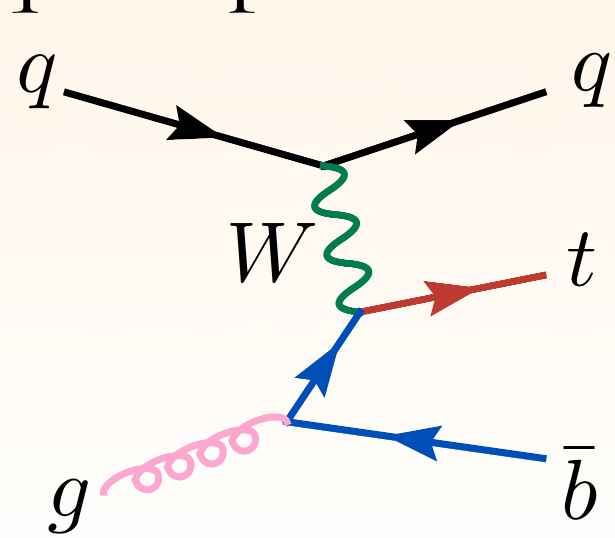
Heavy initial state quarks

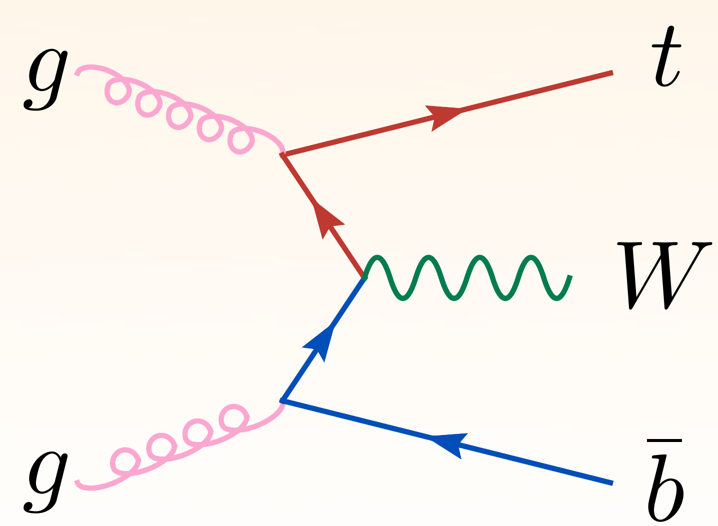
- Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state





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



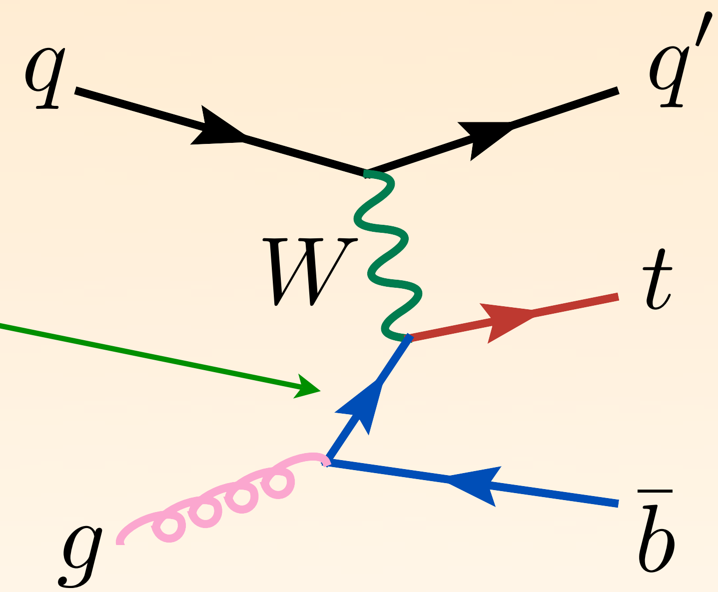


Collinear logarithms

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

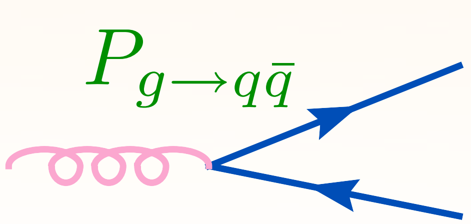
$$\frac{1}{t - m_b^2} \sim \frac{1}{p_T^2 + m_b^2}$$

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

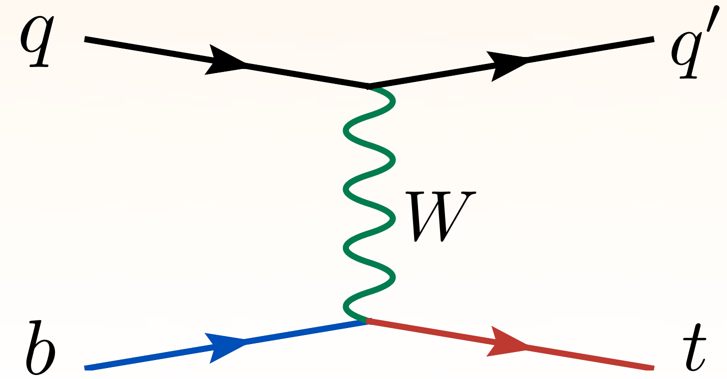


- Contribution to the cross section: $\int_0^{p^2_{T,\max}} \frac{dp_T^2}{p_T^2 + m_b^2} = \log\left(\frac{p^2_{T,\max}}{m_b^2}\right) + \ldots$
- Coefficient of the logarithm is:

AP splitting function



times



matrix elements with splitting removed

Resummation into PDF

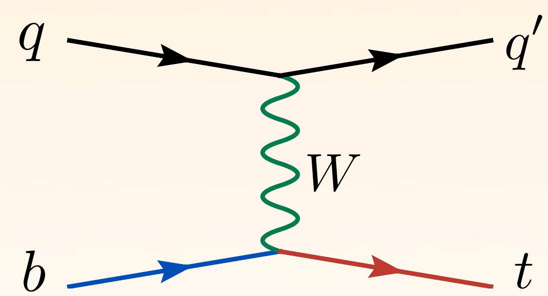
- Putting it together: $\frac{d\sigma(qg \to q' t\bar{b})}{d\log p_{T,\max}^2} \sim \left(\frac{\alpha_s}{2\pi}\right)\left[\int \frac{dx}{x} P_{g\to q\bar{q}} f_g\right] \times \hat{\sigma}(qb \to q't)$
- But the first part resembles the evolution equation for a quark:

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

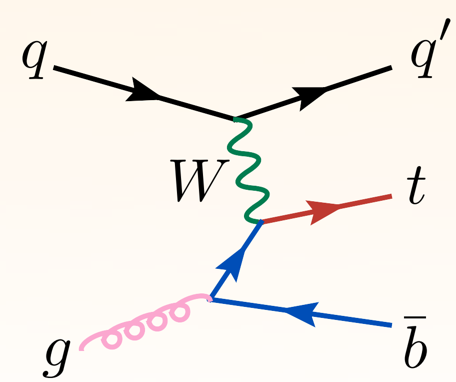
- So when the logarithms really dominate, we can replace this description by $\sigma(qg \to q' t\bar{b}) \approx \sigma(qb \to q't)$
- Scale of the bottom quark PDF should be related $p_{T,\max}$
- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: 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", $2 \rightarrow 2$) when the "spectator b" is not important, otherwise keep it explicit ("4 flavor scheme", $2 \rightarrow 3$)
- 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 ($2 \rightarrow 2$) scheme



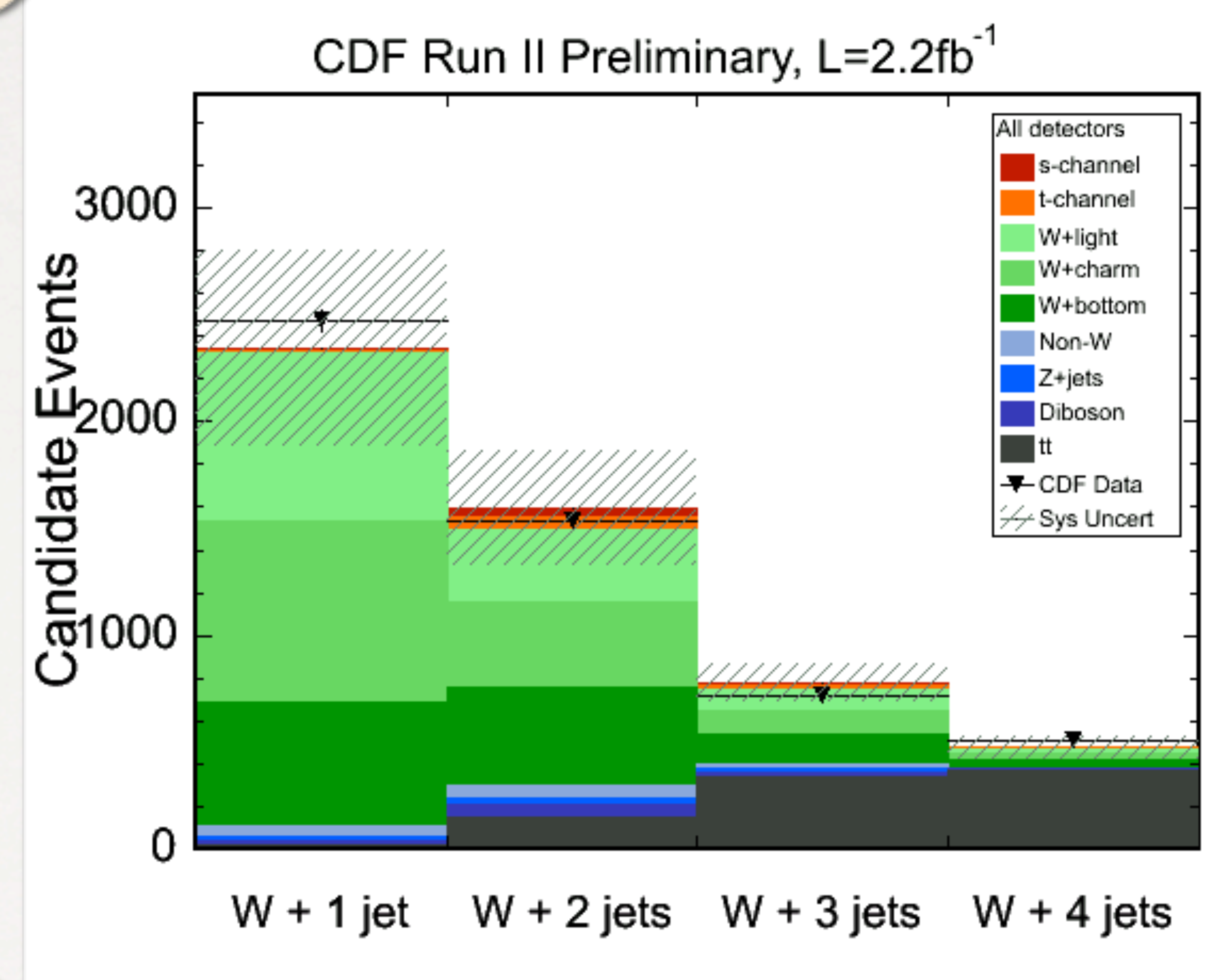
- Terms from 4F ($2 \rightarrow 3$) enter at NLO. Properties of spectator b are only LO



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

BACKGROUNDS

- Large backgrounds from W+jets and top pair production -- much bigger than the original estimates
- A very challenging measurement indeed
- Detailed information about signal and backgrounds is required to extract a signal

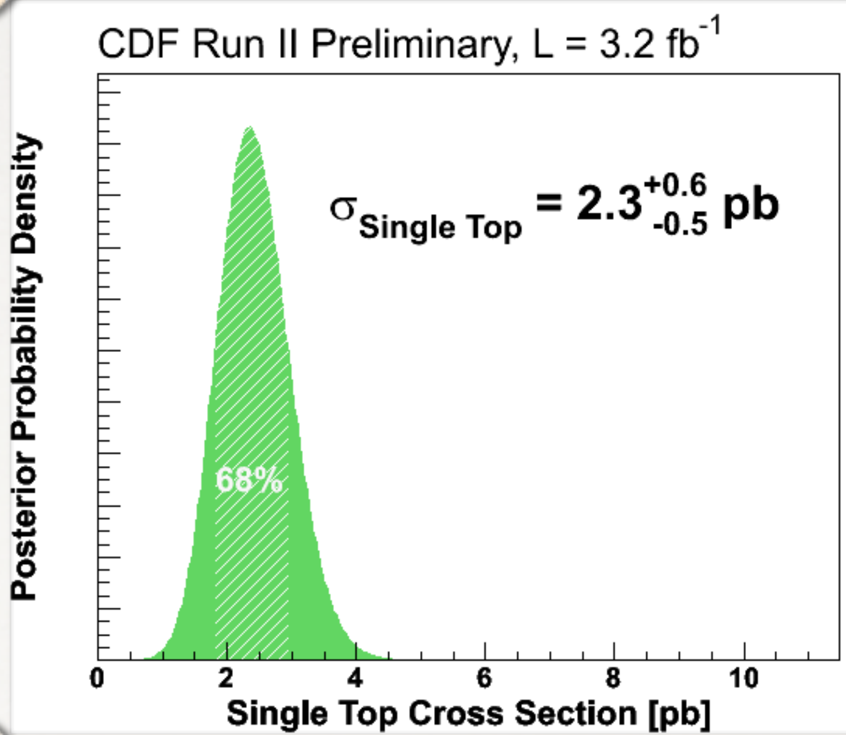


CDF Note 9711

Observation! (March 4, 2009)

- CDF

  m_t=175 GeV

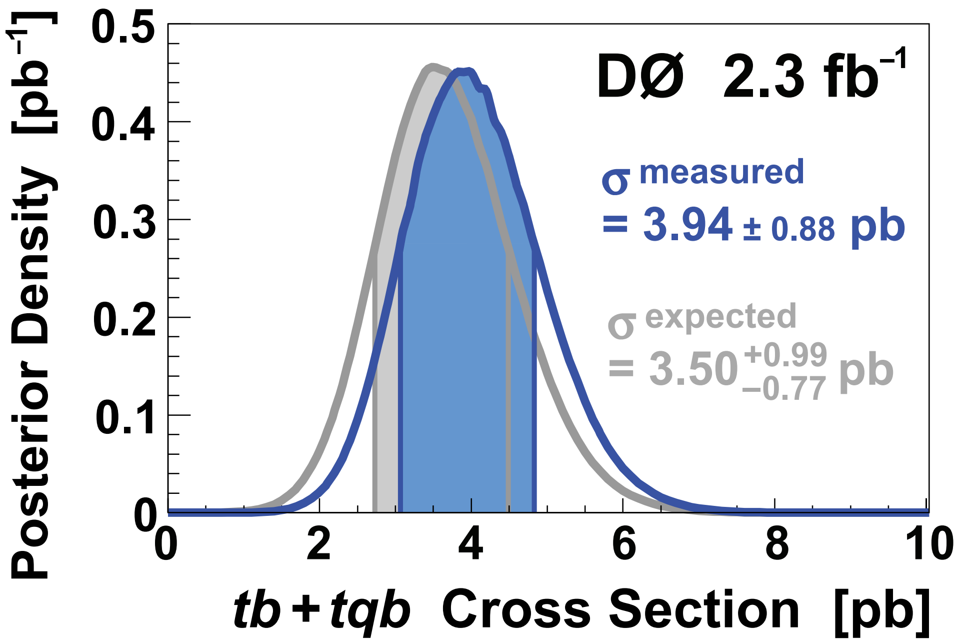


arXiv: 0903.0885

$$|V_{tb}| > 0.71\,(95\%\,\text{C.L.})$$

- DØ

  m_t=170 GeV



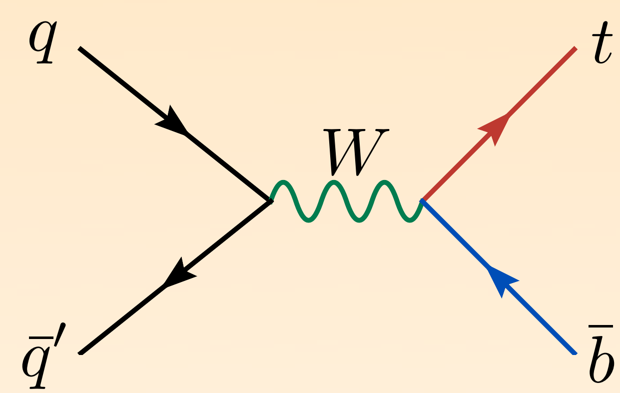
arXiv: 0903.0850

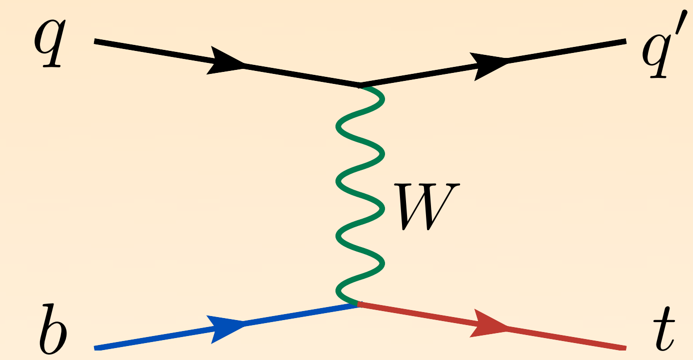
$$|V_{tb}| > 0.78\,(95\%\,\text{C.L.})$$

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

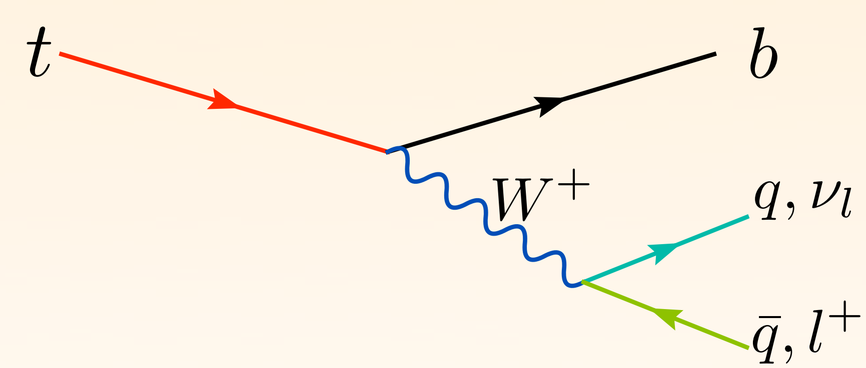
Signatures of s- and t-channel events

- To release this constraint we need to have a closer look at s- and t-channel signatures





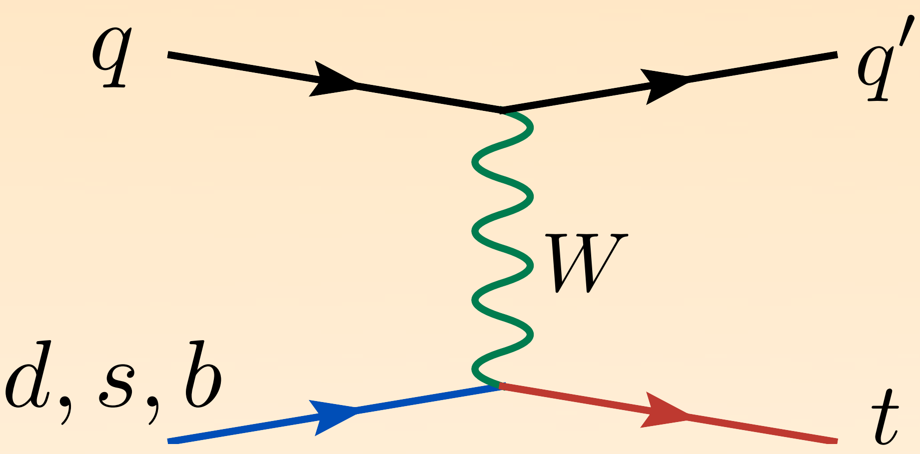
- s-channel events have in general one more b jet in the final state, roughly:
  - 1 b-tag: t-channel event
  - 2 b-tags: s-channel event



- In the CDF and DØ analyses it is assumed that these signatures do not change due to non-standard CKM. This is what is meant by:

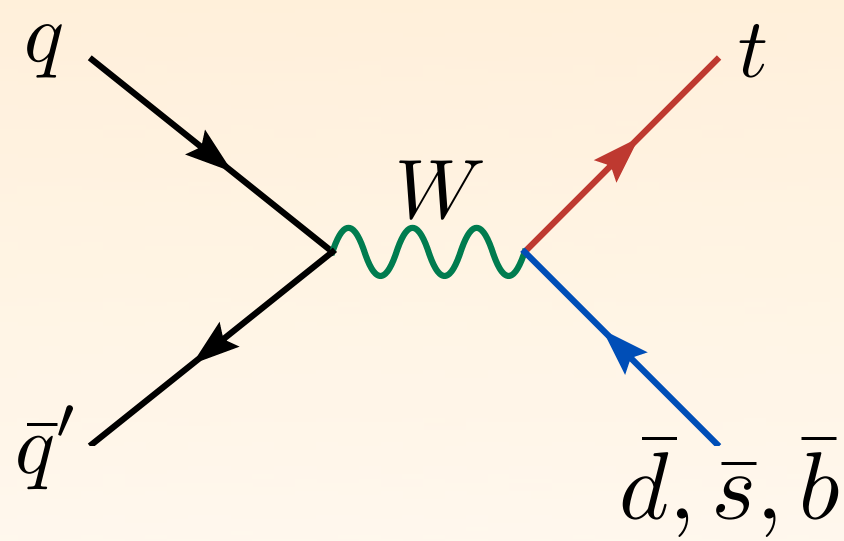
$$\text{assuming } |V_{tb}| \gg |V_{ts}|, |V_{td}|$$

More subprocesses



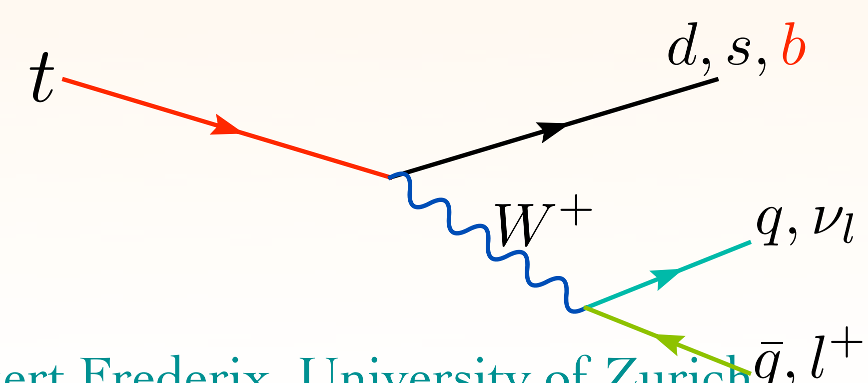
$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

Enhancement due to large *d* and *s* densities



$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)\sigma^{\text{s-ch}}$$

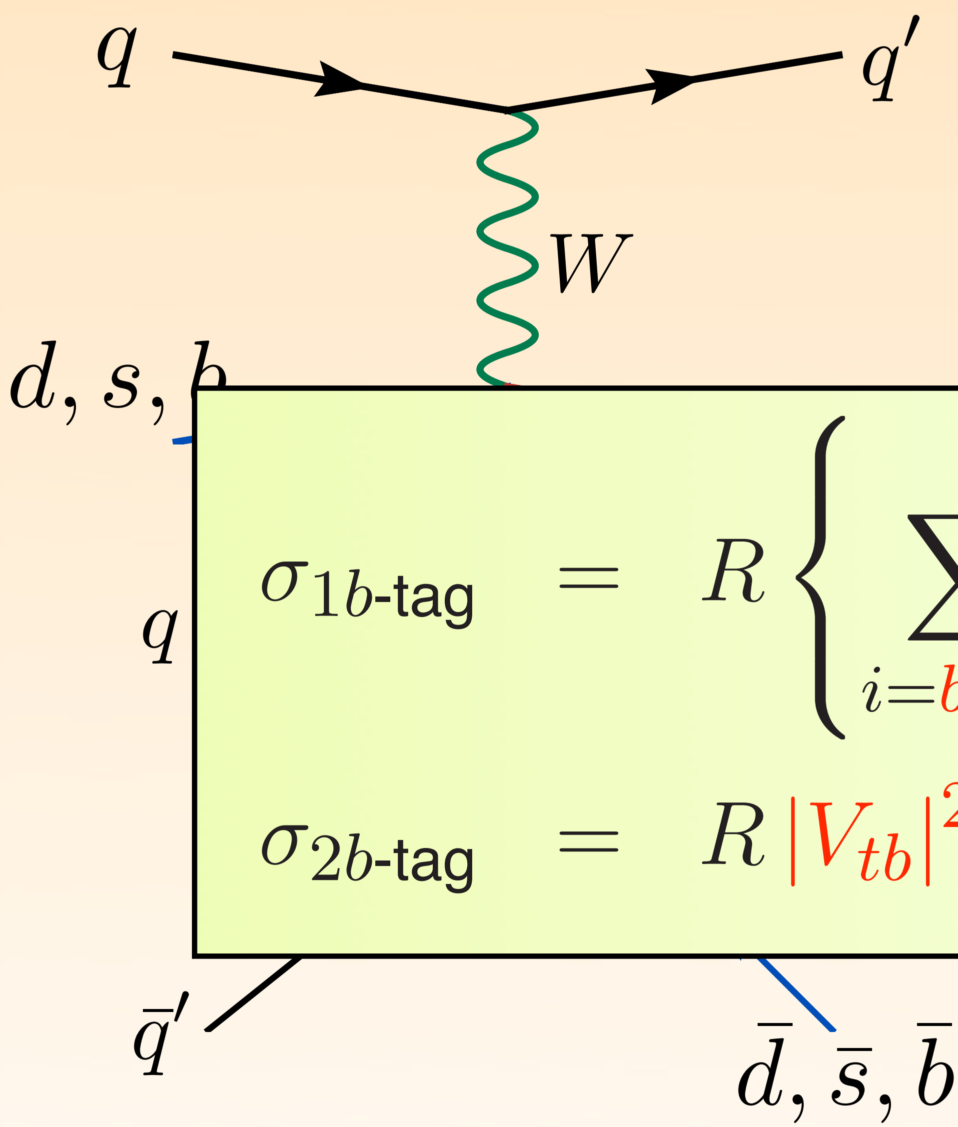
Signal becomes similar to t-channel (only 1 *b*-jet)



$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq(= d, s, b))} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Exp: R > 0.79 @ 95% C.L.

More subprocesses



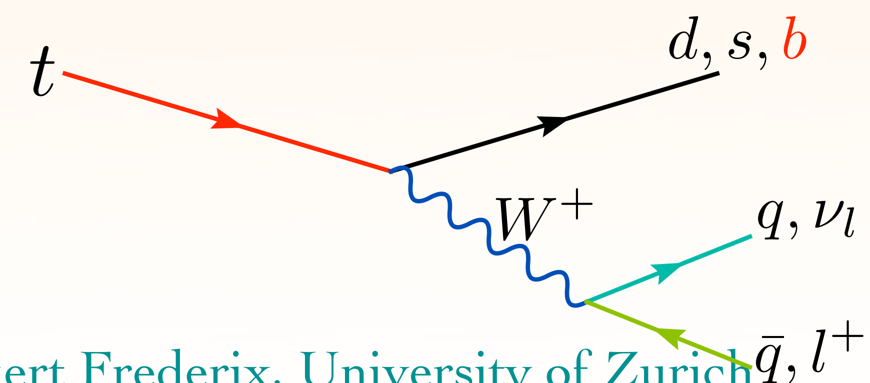
$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

Enhancement due to

$$\sigma_{1b\text{-tag}} = R \left\{ \sum_{i=b,s,d} |V_{ti}|^2 \sigma_i^{\text{t-ch}} + 2(|V_{td}|^2 + |V_{ts}|^2) \sigma^{\text{s-ch}} \right\}$$

$$\sigma_{2b\text{-tag}} = R\, |V_{tb}|^2\, \sigma^{\text{s-ch}}$$

t-channel (only 1 *b*-jet)



$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq(= d, s, b))} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

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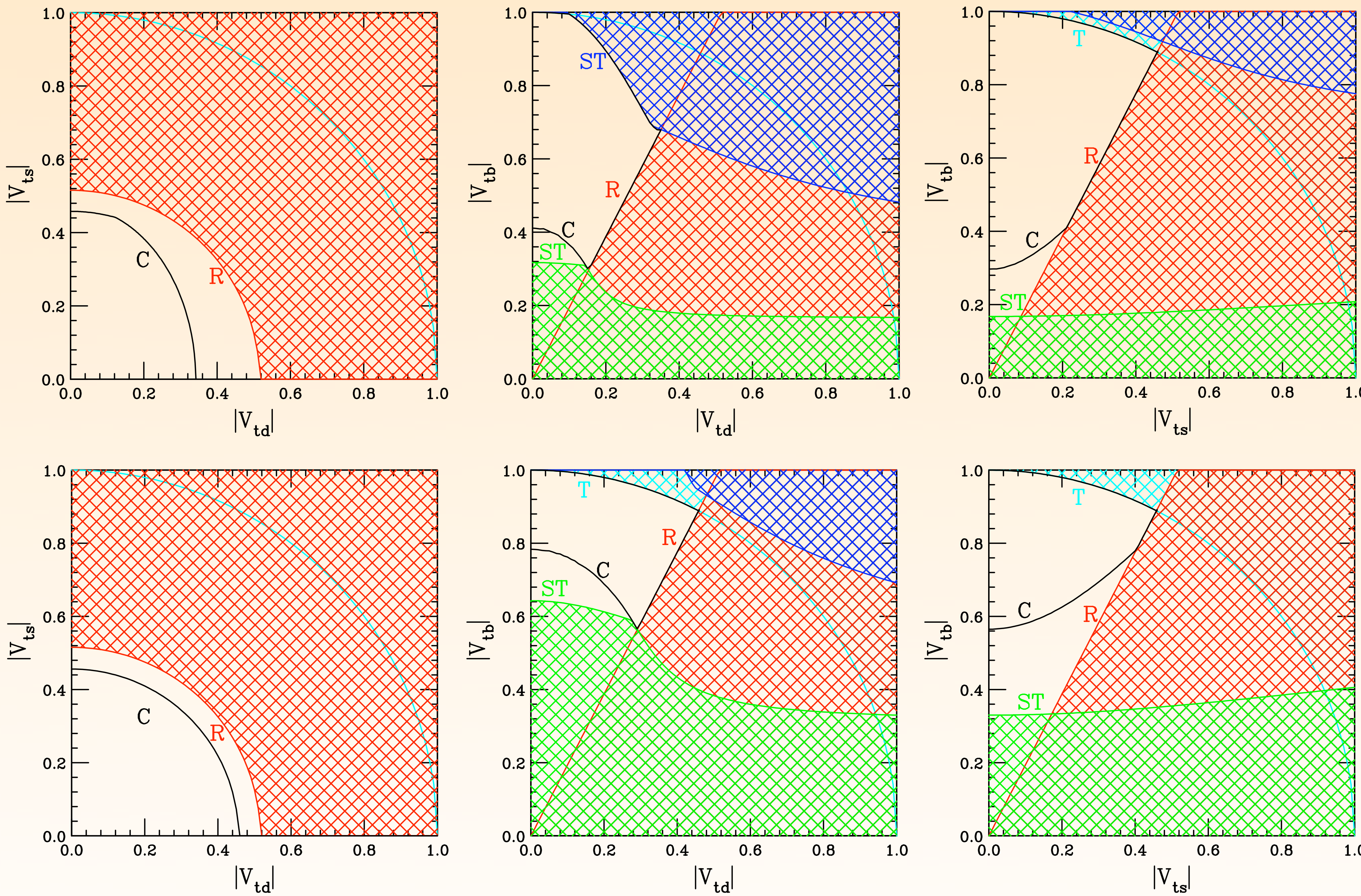
Constraints on 3rd row of the CKM matrix

$|V_{td}|$ vs $|V_{ts}|$ $|V_{td}|$ vs $|V_{tb}|$ $|V_{ts}|$ vs $|V_{tb}|$

CDF

DØ

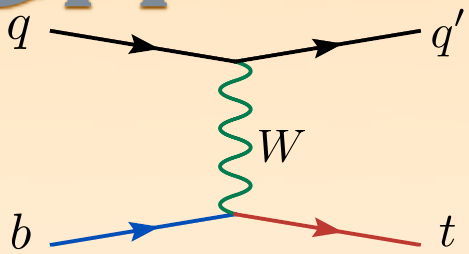


95% C.L.

Alwall et al., Eur. Phys, J. C49 791 (2007); RF, Top2008 Conf. Proc. (2008)

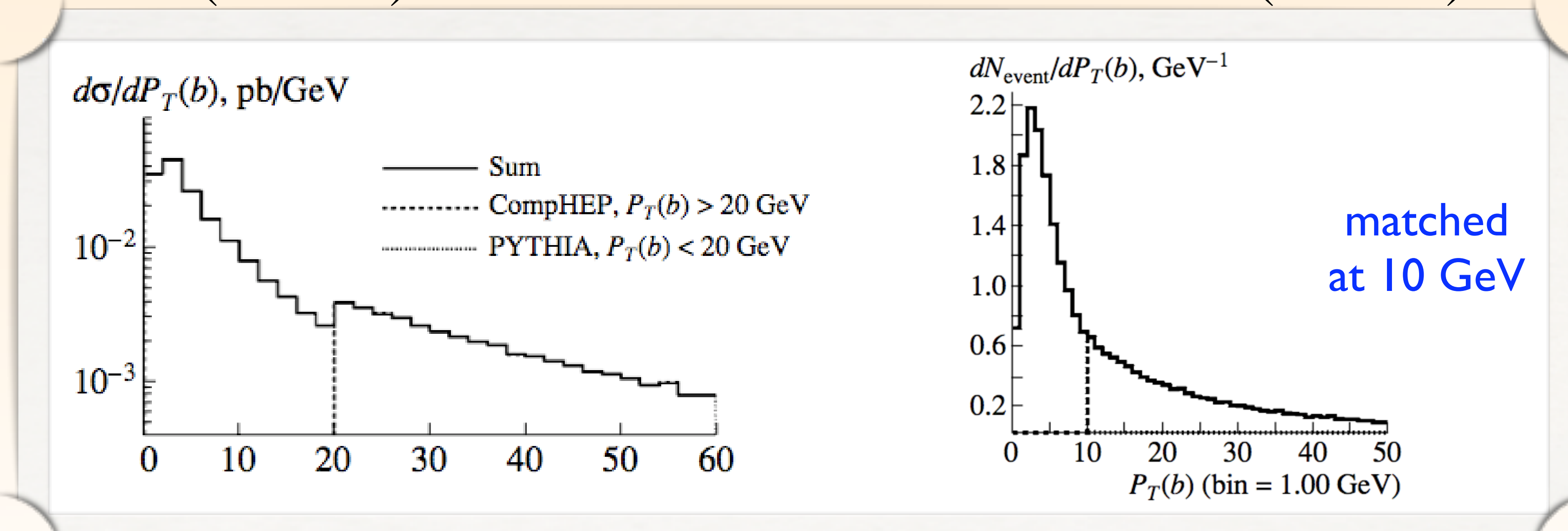
Warning: theory plots, proper experimental analysis needed!

Need for matching in the 5F ($2 \to 2$) 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 ($2 \to 2$)+ shower below and LO 4F ($2 \to 3$) above

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



- Ad hoc matching well motivated, but theoretically unappealing
- Done in a formally consistent way in MC@NLO

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

- All current single-top analyses are based on such a matching!
- The need for matching builds on three "prejudices":
  - Effects of the resummation are important: use the 2 → 2 calculation
  - The shower does the resummation of the heavy b quarks accurately
  - Matching (N)LO 2 → 2 and LO 2 → 3 for the b's promotes the prediction of the spectrum of the b to NLO

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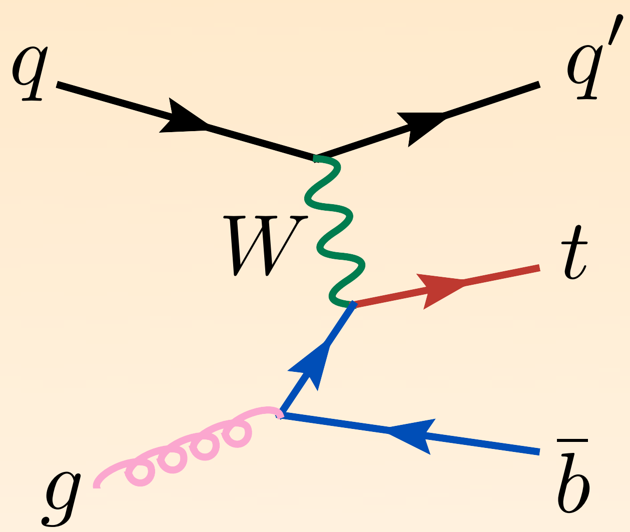
Question: truths or myths?

A fresh approach

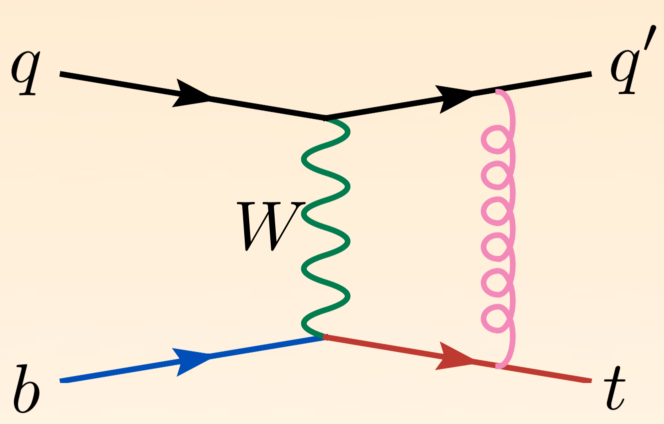
Four-flavor scheme

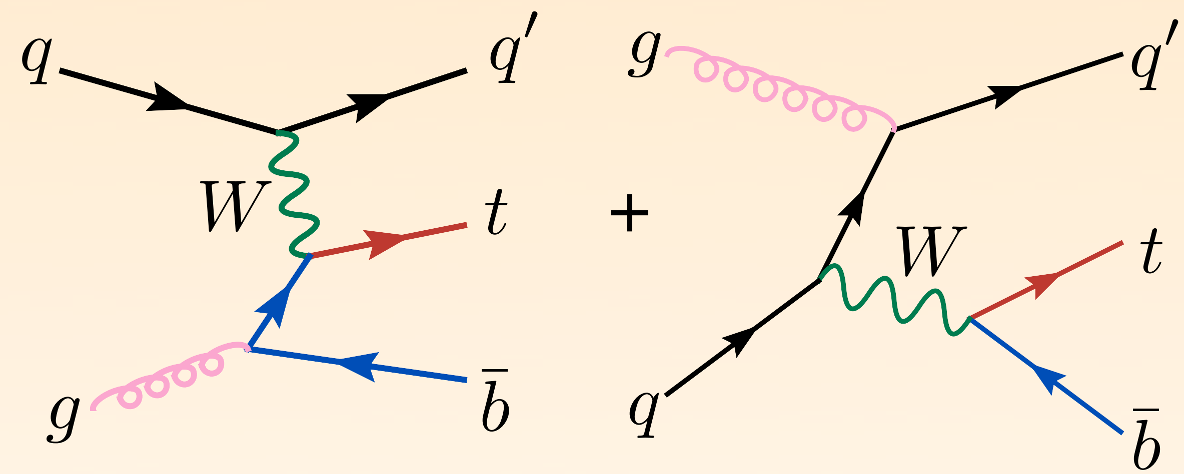
- Use the 4-flavor $(2 \rightarrow 3)$ process as the Born and calculate NLO
  - Much harder calculation due to extra mass and extra parton
  - Spectator b for the first time at NLO
  - Compare to 5F $(2 \rightarrow 2)$ to asses logarithms and applicability
  - Starting point for future NLO+PS beginning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



Factorization in 2 → 2

- NLO 5F (2 → 2) simplifies greatly due to color:





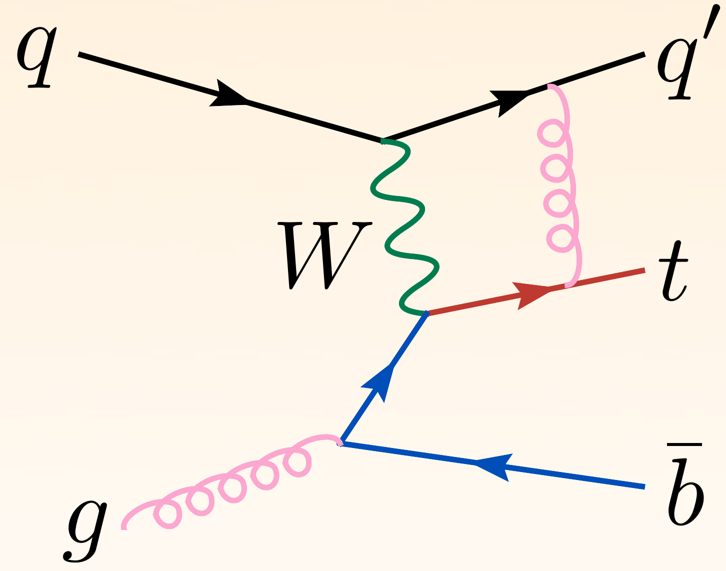
Vanishes: Tr[t^a]=0

Interference between t and s channel vanishes: Tr[t^a]=0

- No corrections that mix light and heavy quark lines
- No mixing of t and s channel at NLO

Factorization in 2 → 3

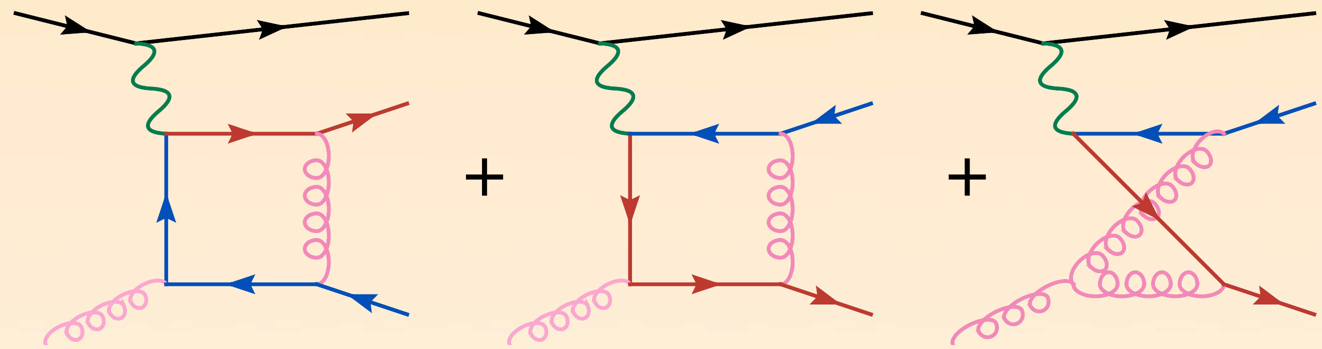
- The same arguments still mostly apply to the 2 → 3
- No mixing between light and heavy quark lines from the virtual corrections



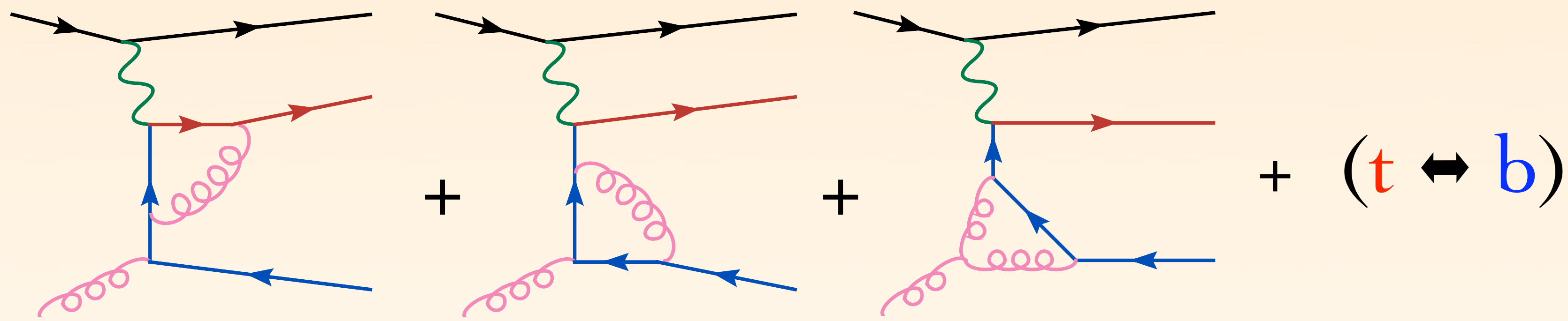
Vanishes: $\mathrm{Tr}[t^a]=0$

Virtual corrections

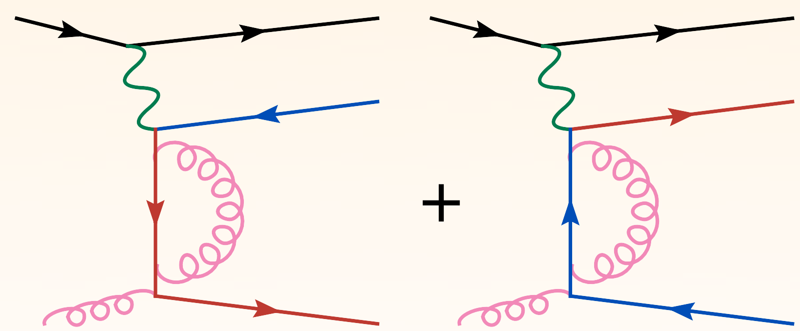
- Corrections to the light quark line (same as for $2 \rightarrow 2$)
- Three boxes



- Six triangles



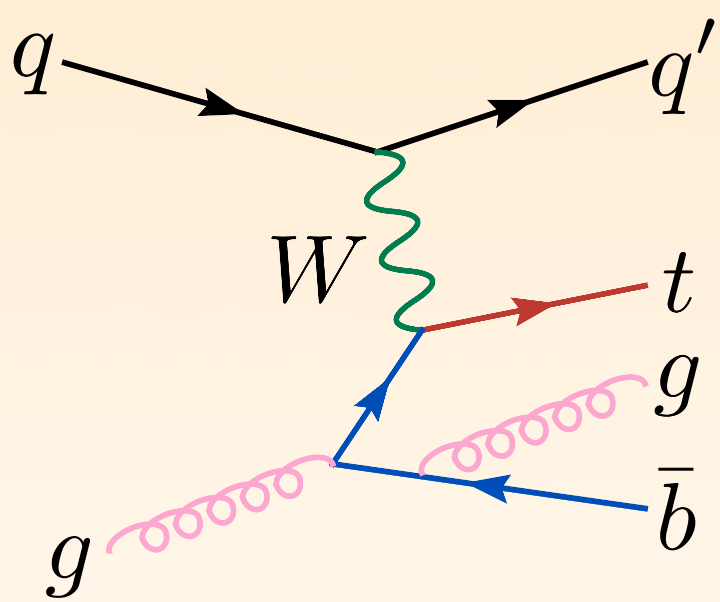
- Two bubbles



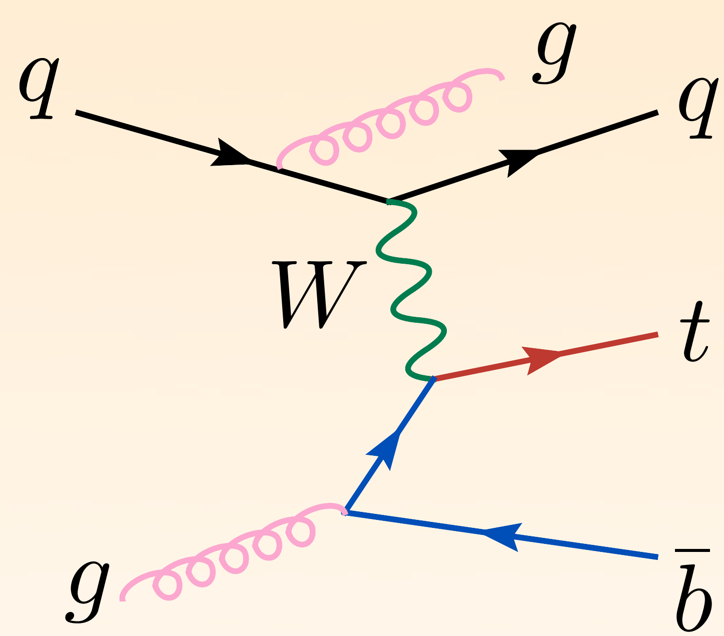
- Analytic computation of helicity amplitudes using standard techniques -- top spin is available

Factorization in 2 → 3: real emission

- Most real corrections can also be uniquely assigned to the light or heavy quark line, e.g.



Correction to heavy line

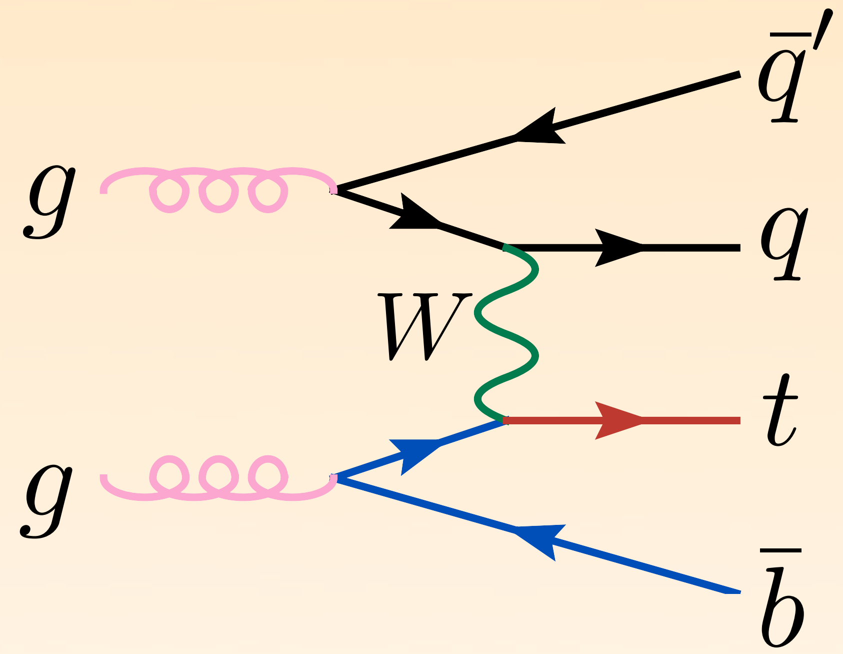


Correction to light line

Interference is zero due to color: Tr[t^a]=0

Near factorization

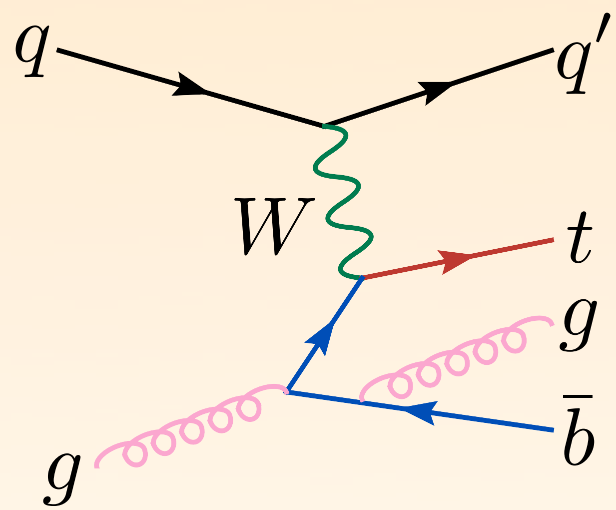
- Not all real emission pieces factorize so neatly, but non-factorizing pieces are always color-suppressed



- Split the (sub-leading) terms equally
  - We can use different renormalization and factorization scales for heavy and light quark currents

Interferences

- s-channel and t-channel contributions mix at this order, although color-suppressed. We have checked that the interference is small (<0.5%) and can be dropped



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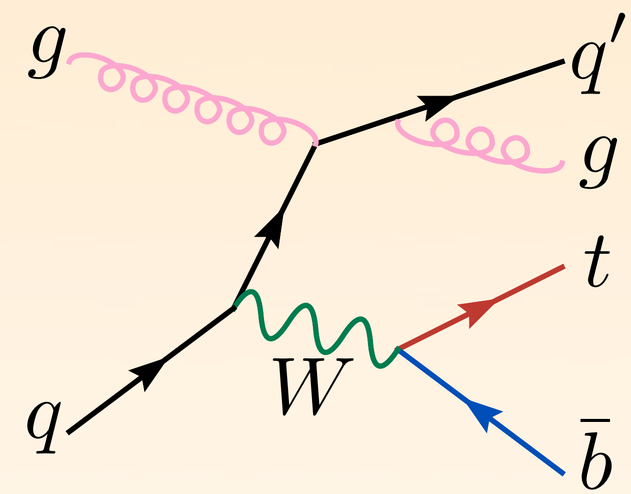
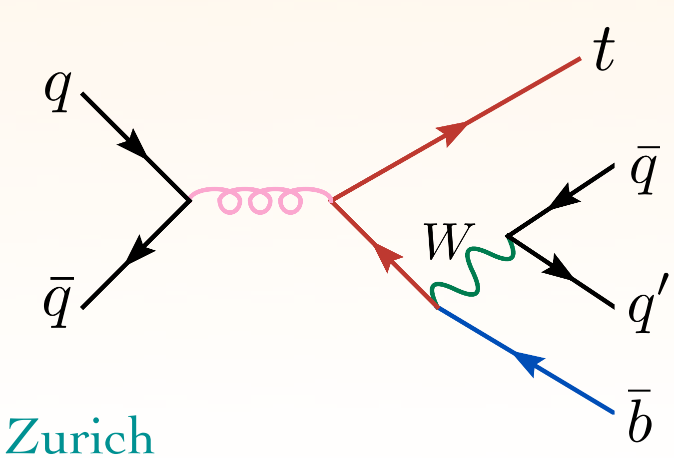


- There is also interference with top pair production, but this vanishes in the narrow width approximation and is not included



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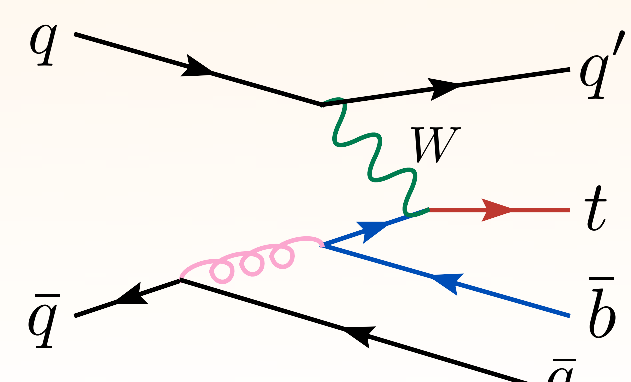


Subtraction terms

- Only the sum of real and virtual emissions is finite

- For implementation in MC program we need to subtract divergences in real and virtual emission separately

$$\sigma^{\rm NLO} = \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A \right] + \int_m \left[\int_{\rm loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A \right]_{\epsilon=0}$$

- We use the dipole subtraction method

Catani & Seymour (1997); Catani et al. (2002)

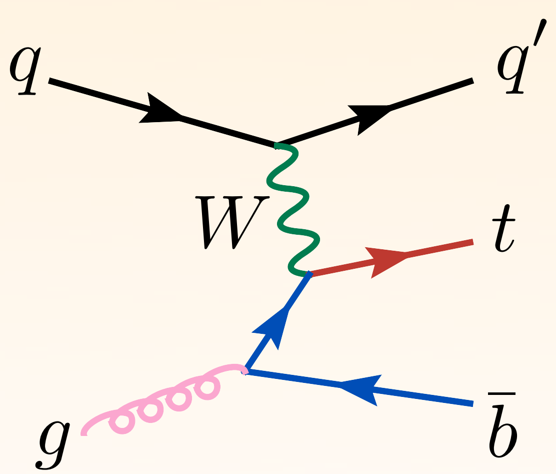
- Excellent agreement found with independent check against MadDipole

RF, Gehrmann & Greiner (2008)

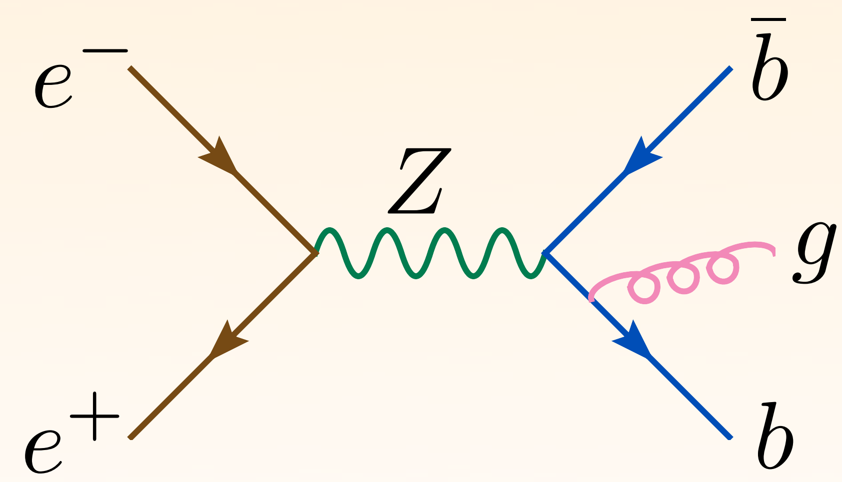
Checks of the calculation

- Real emission including subtraction terms checked against MadGraph & MadDipole *RF, Gehrmann & Greiner (2008)*
- 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)

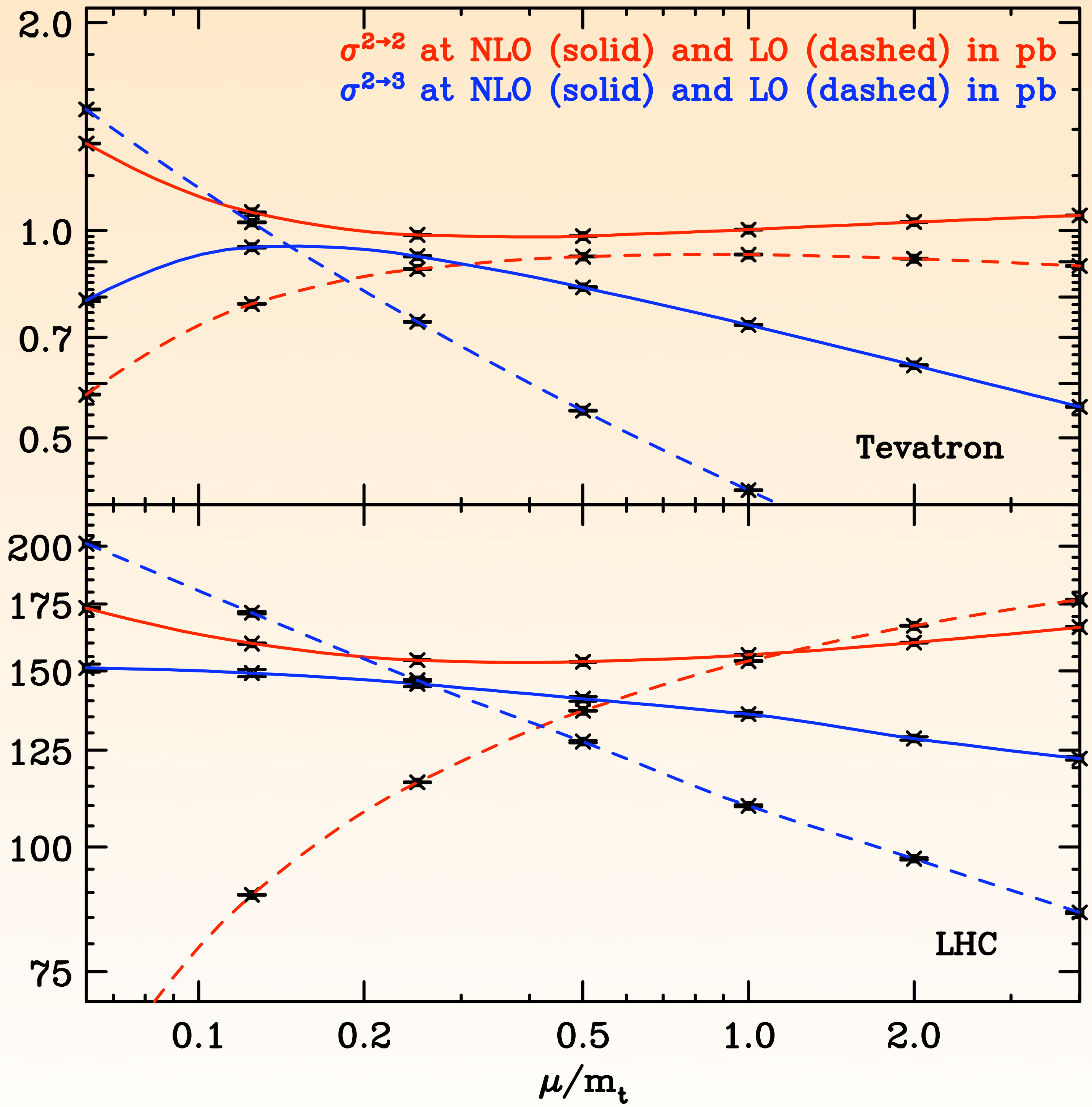
- To the calculation in the 4 flavor scheme add
  - For each initial state gluon include a term to compensate for the smaller gluon luminosity in a 5F PDF:

$$-\alpha_s \frac{T_F}{3\pi} \log \frac{m_b^2}{\mu_F^2} \mathcal{M}_{\mathrm{Born}}$$

  - For each QCD coupling in the Born compensate for the running of the coupling:

$$-\alpha_s \frac{T_F}{3\pi} \log \frac{\mu_R^2}{m_b^2} \mathcal{M}_{\mathrm{Born}}$$

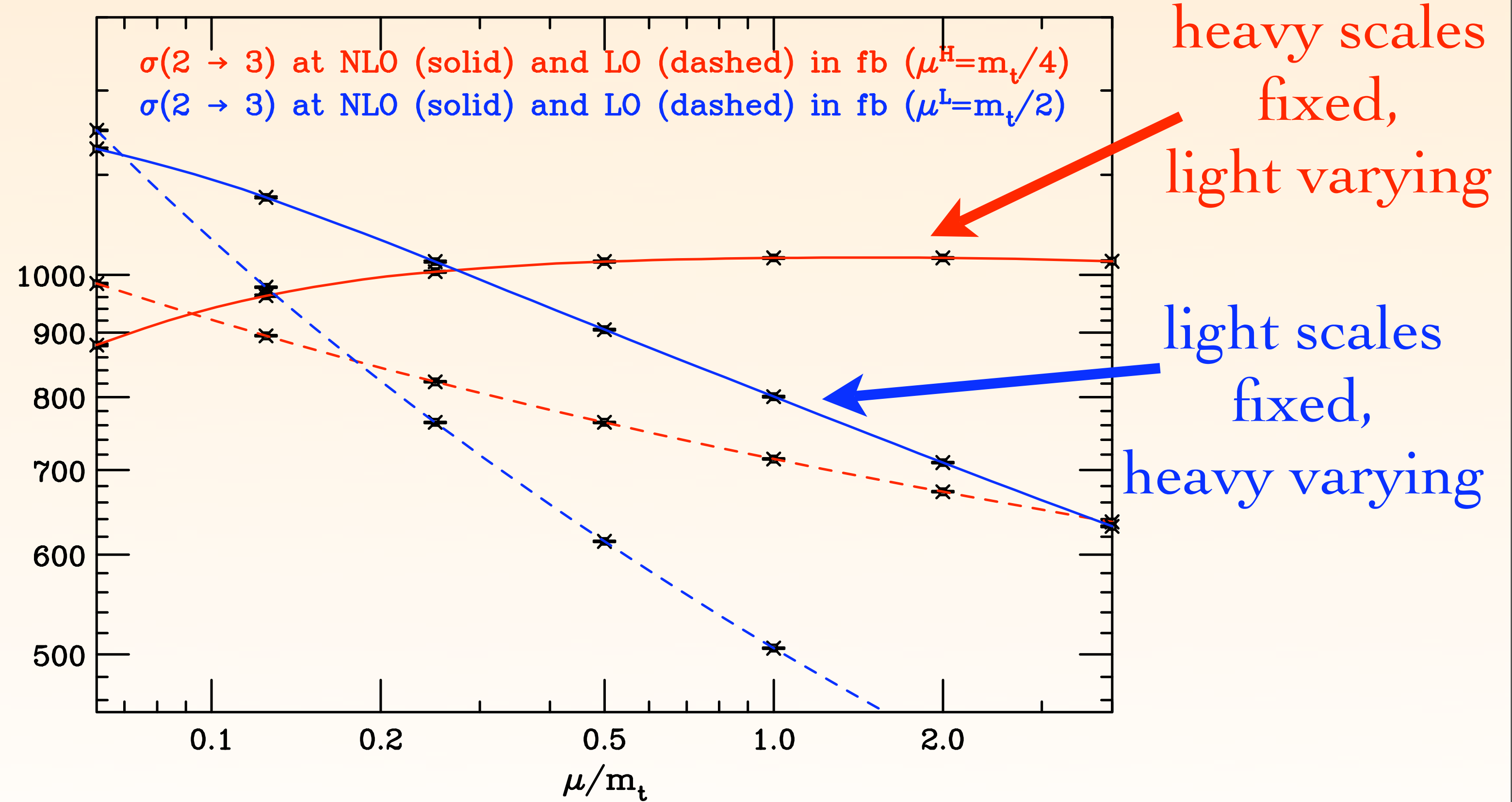
Scale dependence



- 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
  - 44 eigenvector CTEQ6.6 PDF's
  - Top mass: 172 ± 1.7 GeV
  - Bottom mass: 4.5 ± 0.2 GeV

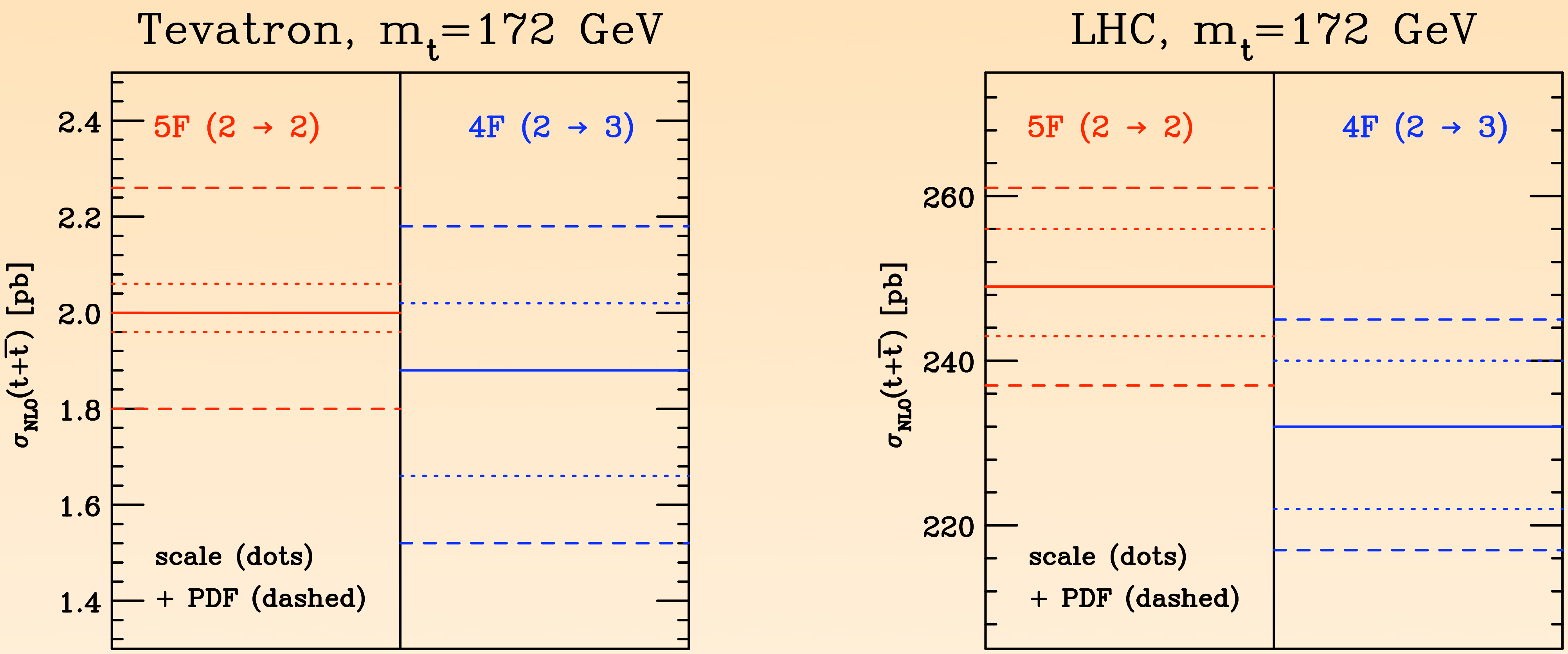
$\sigma^{\mathrm{NLO}}_{\mathrm{t-ch}}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (10 TeV)	130	$^{+2}_{-2}$	$^{+3}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$	124	$^{+4}_{-5}$	$^{+2}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$
LHC (14 TeV)	244	$^{+5}_{-4}$	$^{+5}_{-6}$	$^{+3}_{-3}$	$^{+4}_{-4}$	234	$^{+7}_{-9}$	$^{+5}_{-5}$	$^{+3}_{-3}$	$^{+4}_{-4}$

Fac. & Ren. scale

b mass

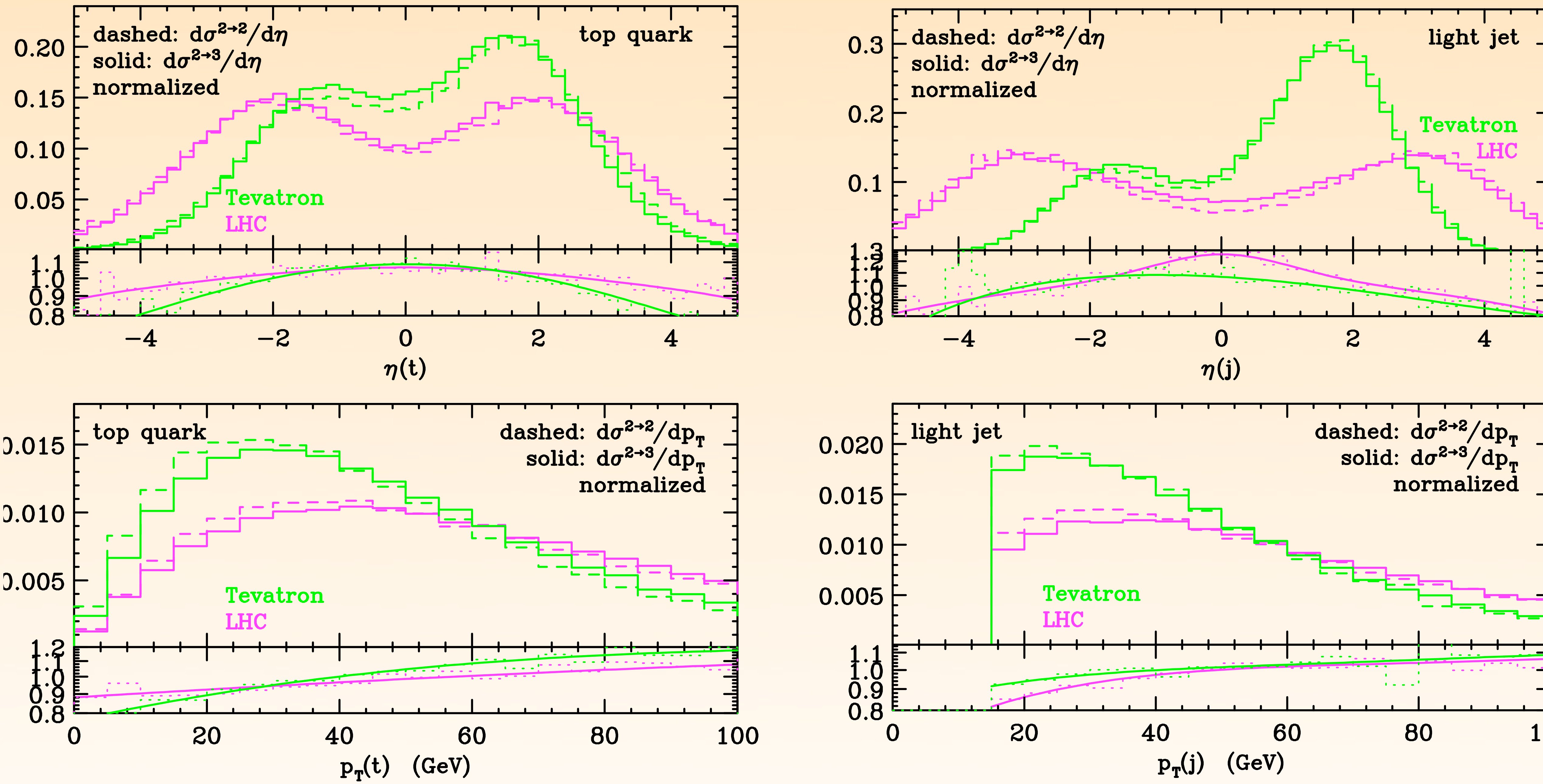
top mass

PDF



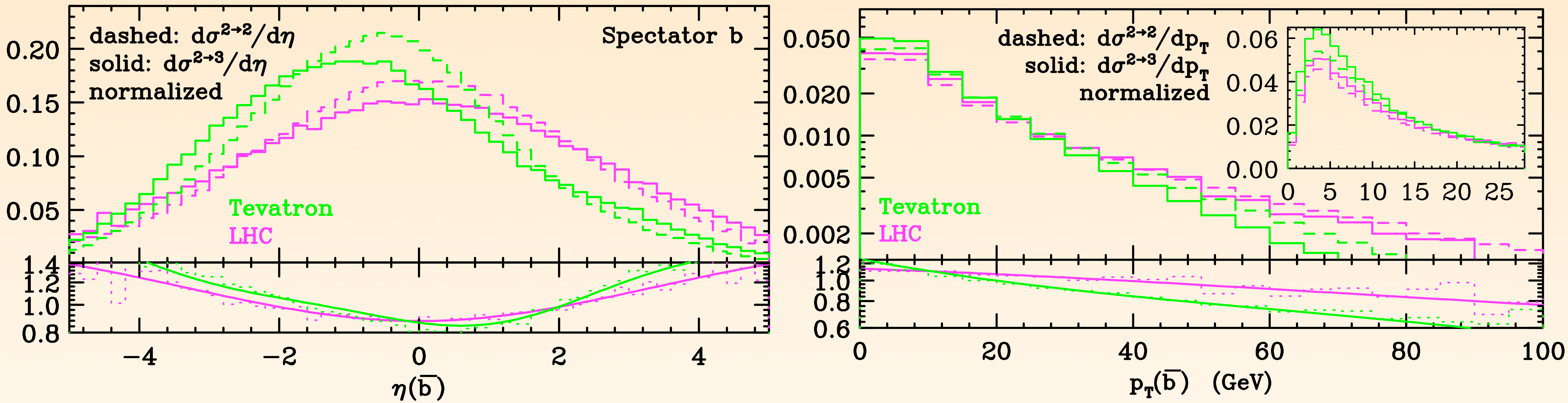
- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- Consistent at the Tevatron: logarithms not so important?
- For the LHC, the minor difference could point to either
  - large logarithms being resummed
  - the need for a NNLO calculation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

Top quark distributions



- Jet defined by: p_T>15 GeV, ΔR > 0.7
- Some differences, but typically of the order of ~10% in the regions where the cross section is large

Bottom quark



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

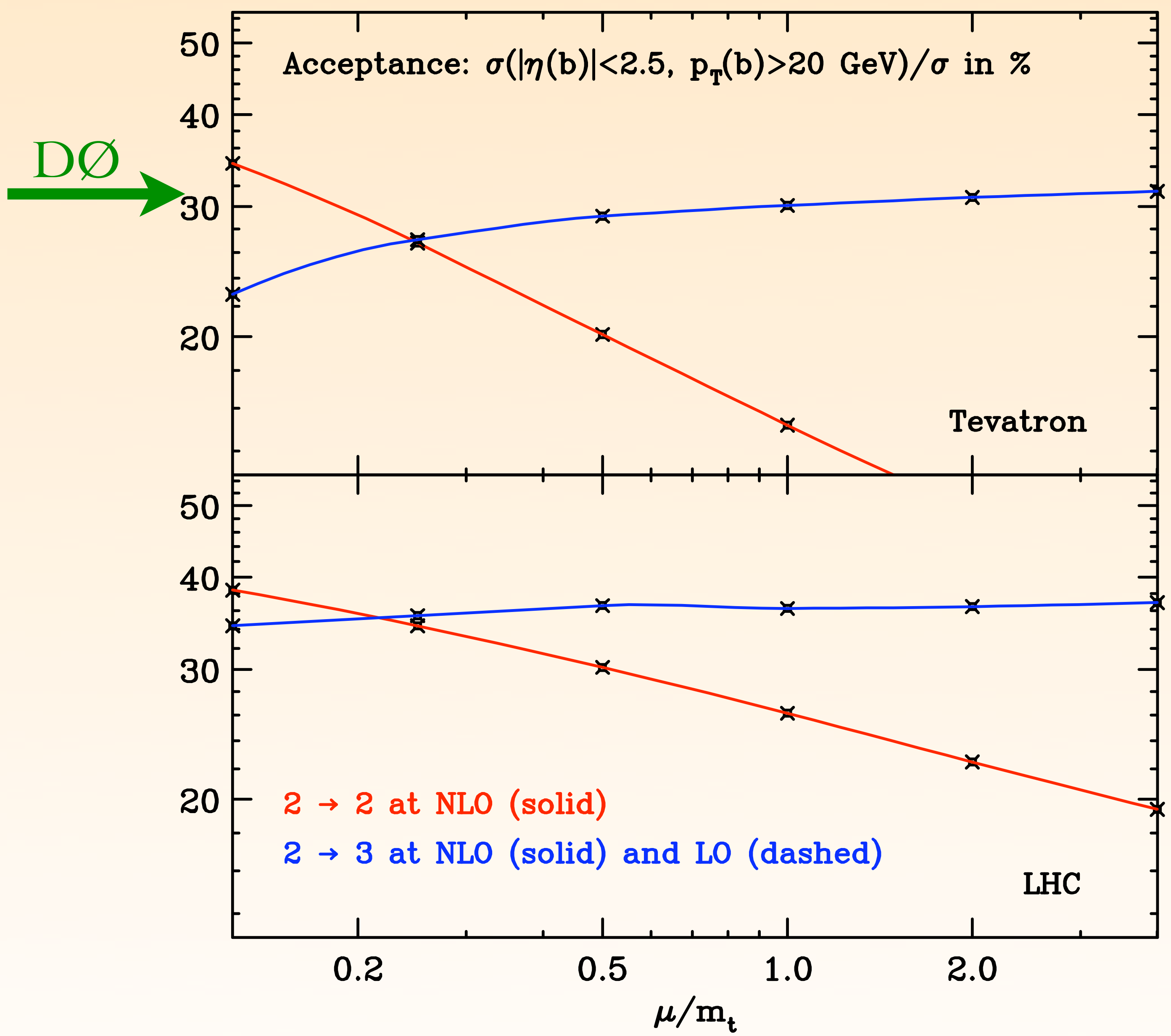
More bottoms in 4F

- 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:

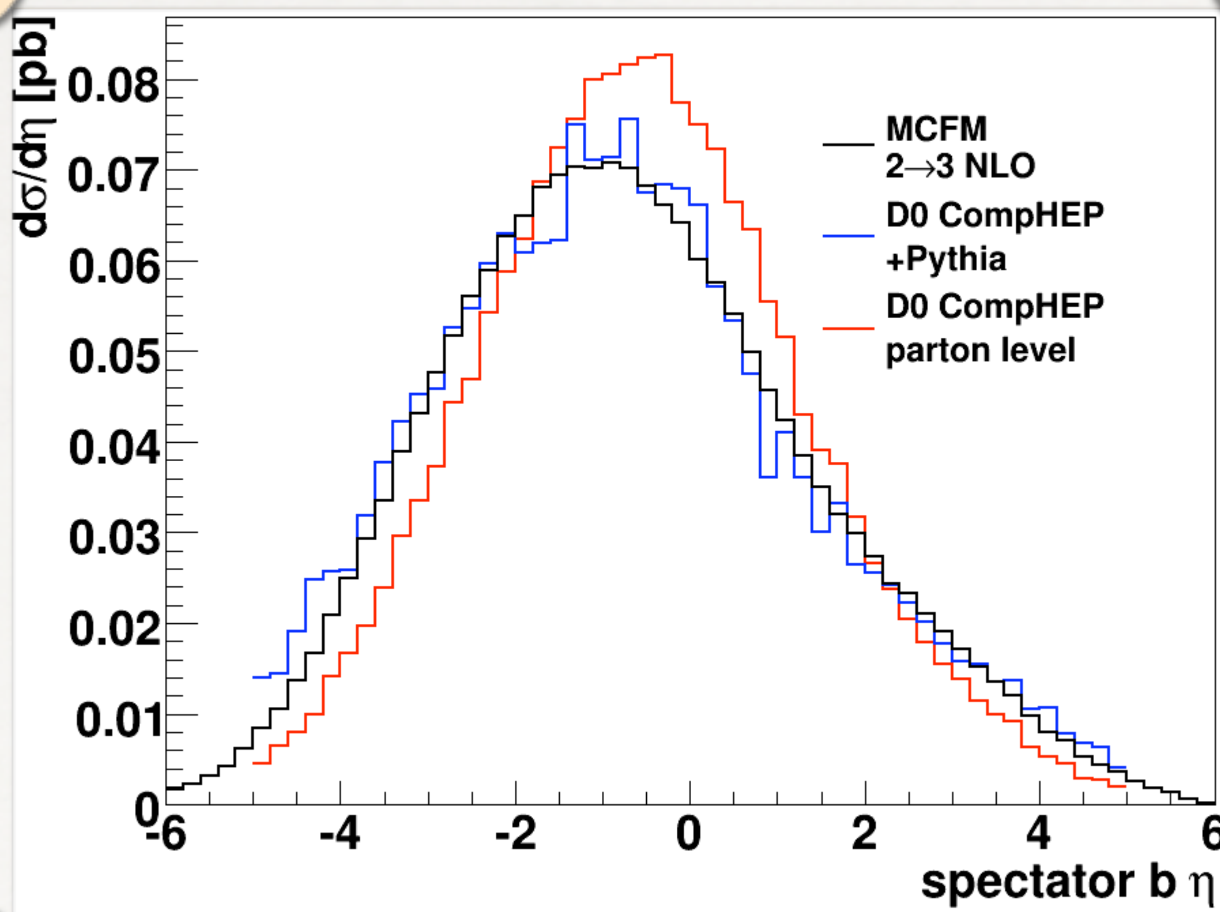
$$\frac{\sigma(|\eta(b)| < 2.5,\ p_T(b) > 20\ \mathrm{GeV})}{\sigma_{\mathrm{inclusive}}}$$

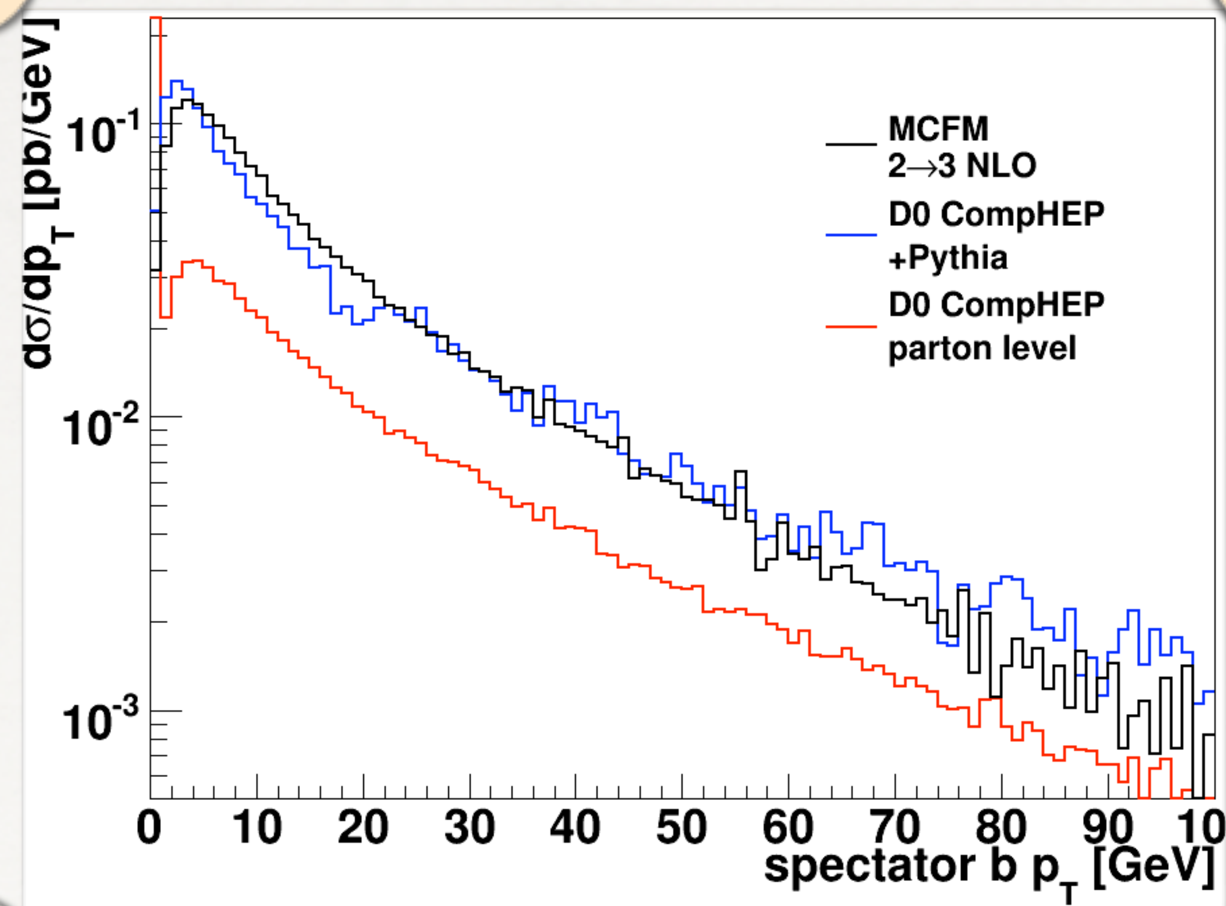
ACCEPTANCE

- 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!

RF, Fabio Maltoni & Reinhard Schwienhorst

Acceptance

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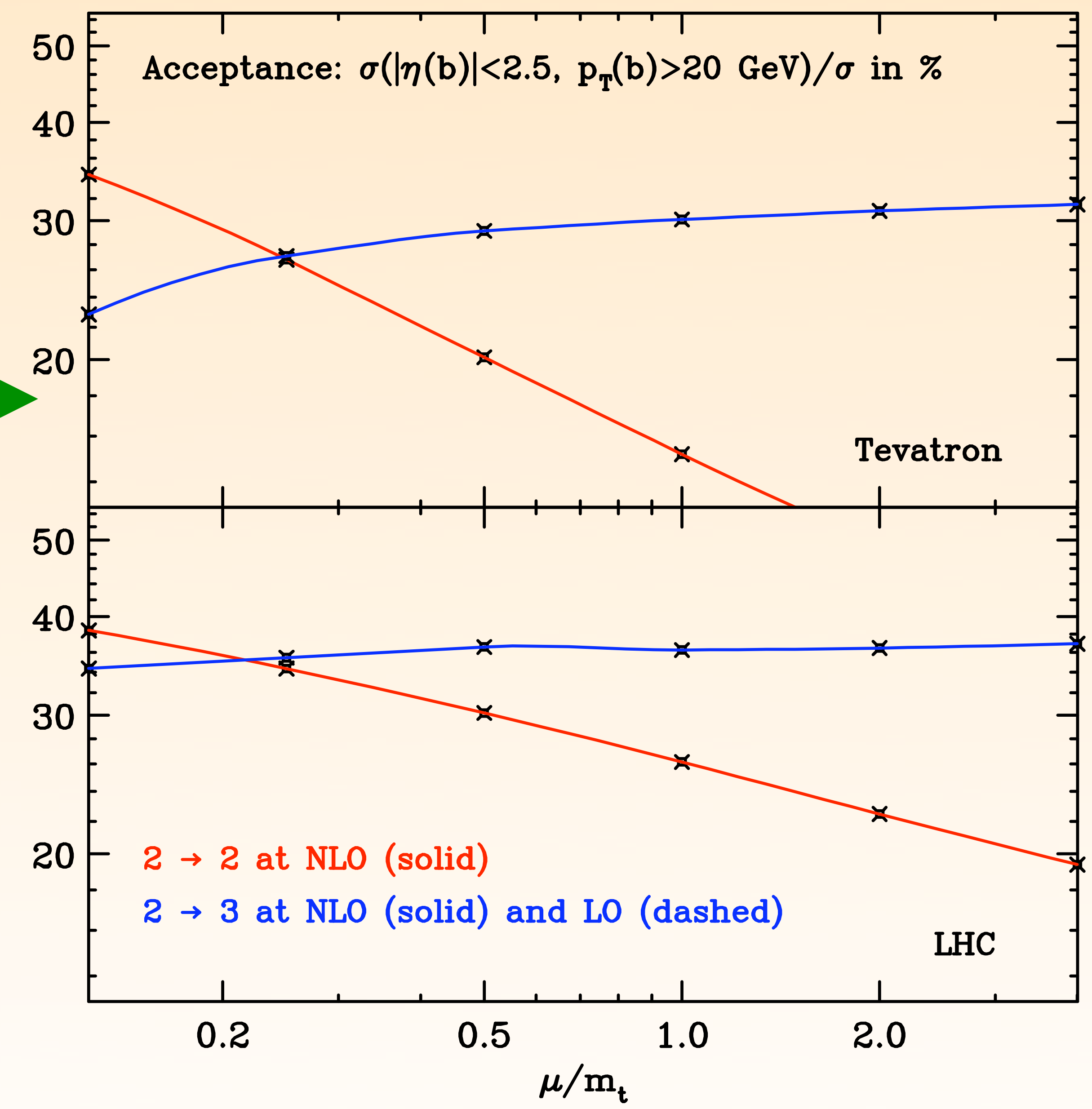
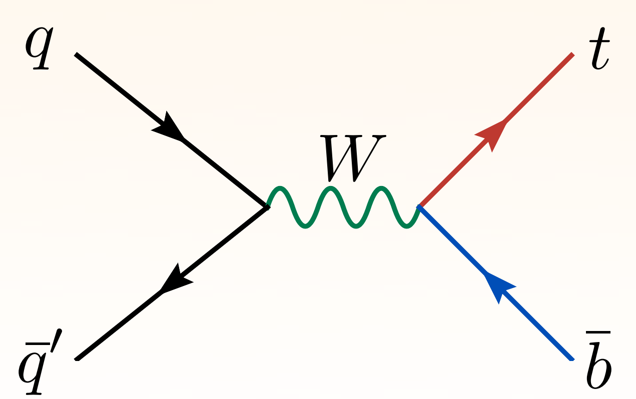
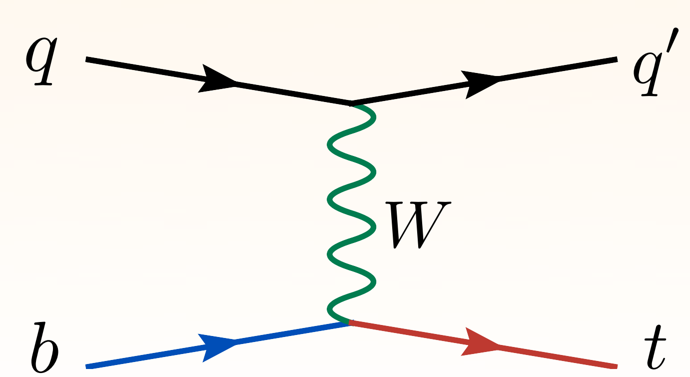
CDF



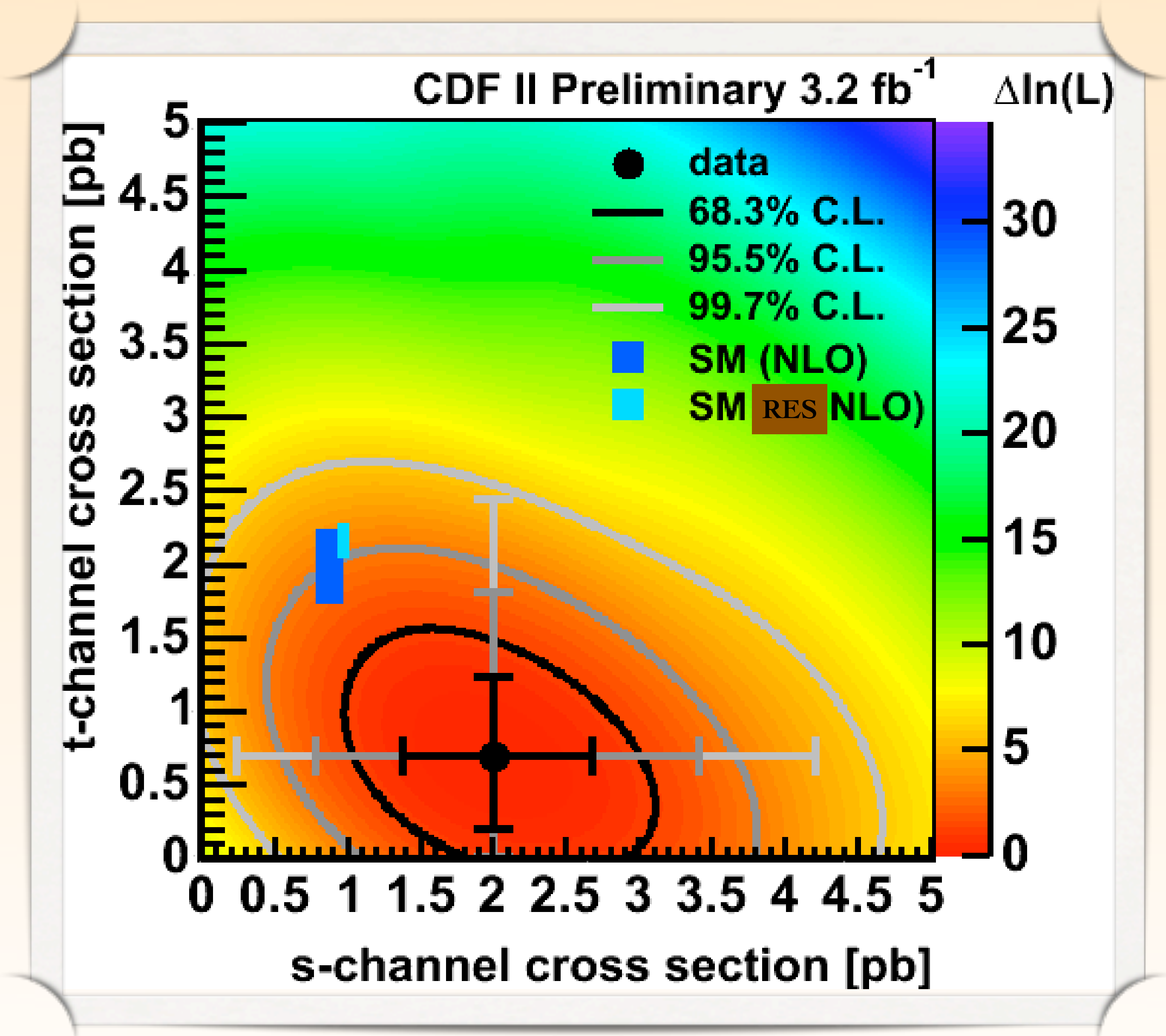
Consequences for single top observation?

- 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

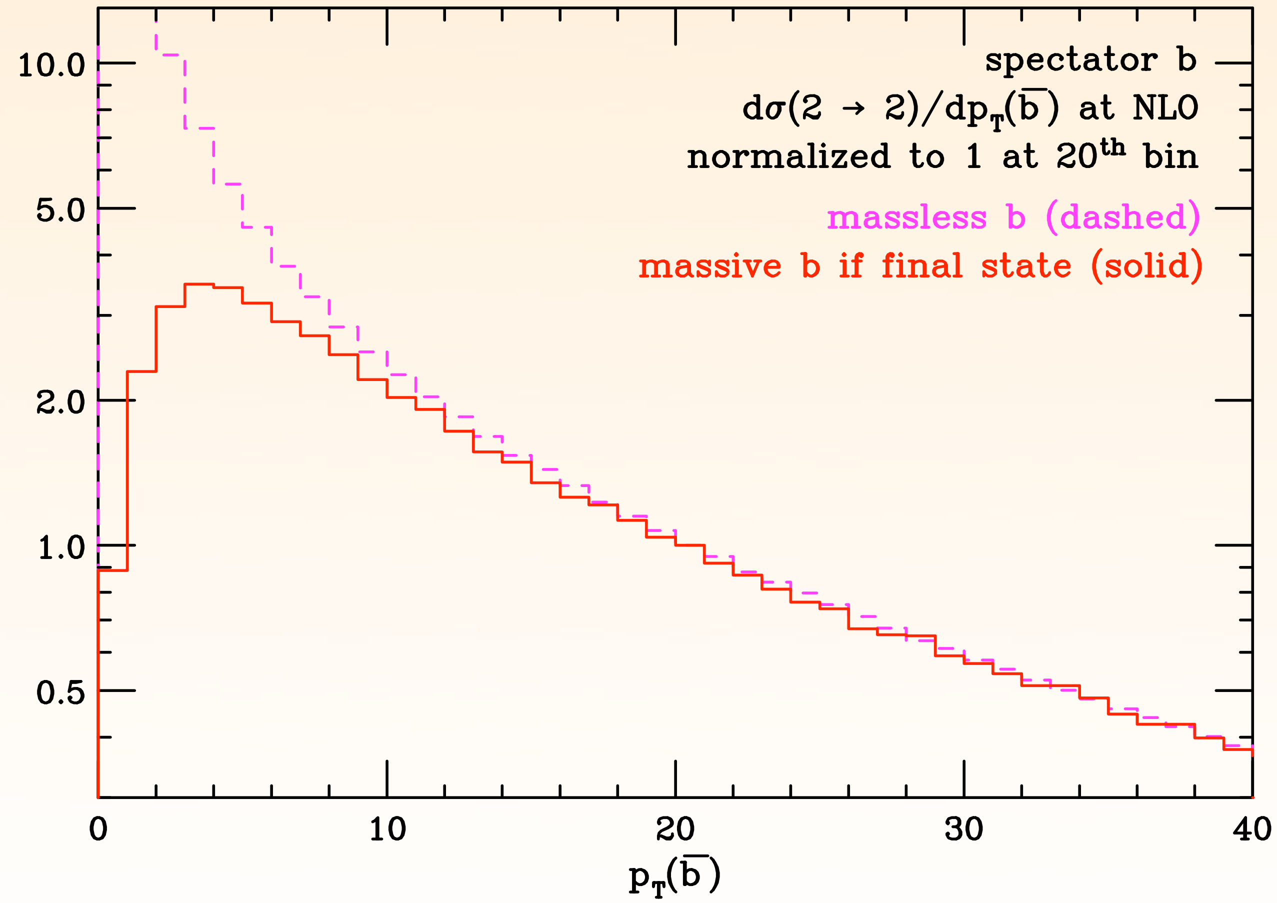
Conclusions

- Single top has just been observed with a significance larger than 5 S.D.
- Simple improvement possible for a more model-independent determination of $|V_{tb}|$, i.e. relaxing the constraint that $|V_{tb}| >> |V_{ts}|, |V_{td}|$
- Comparison of NLO computations of t-channel single top (in the 4F and 5F schemes) allows for the 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 phase space
  - Probably a significant impact on discrimination of t- and s-channel events for CDF (DØ is probably in good shape)

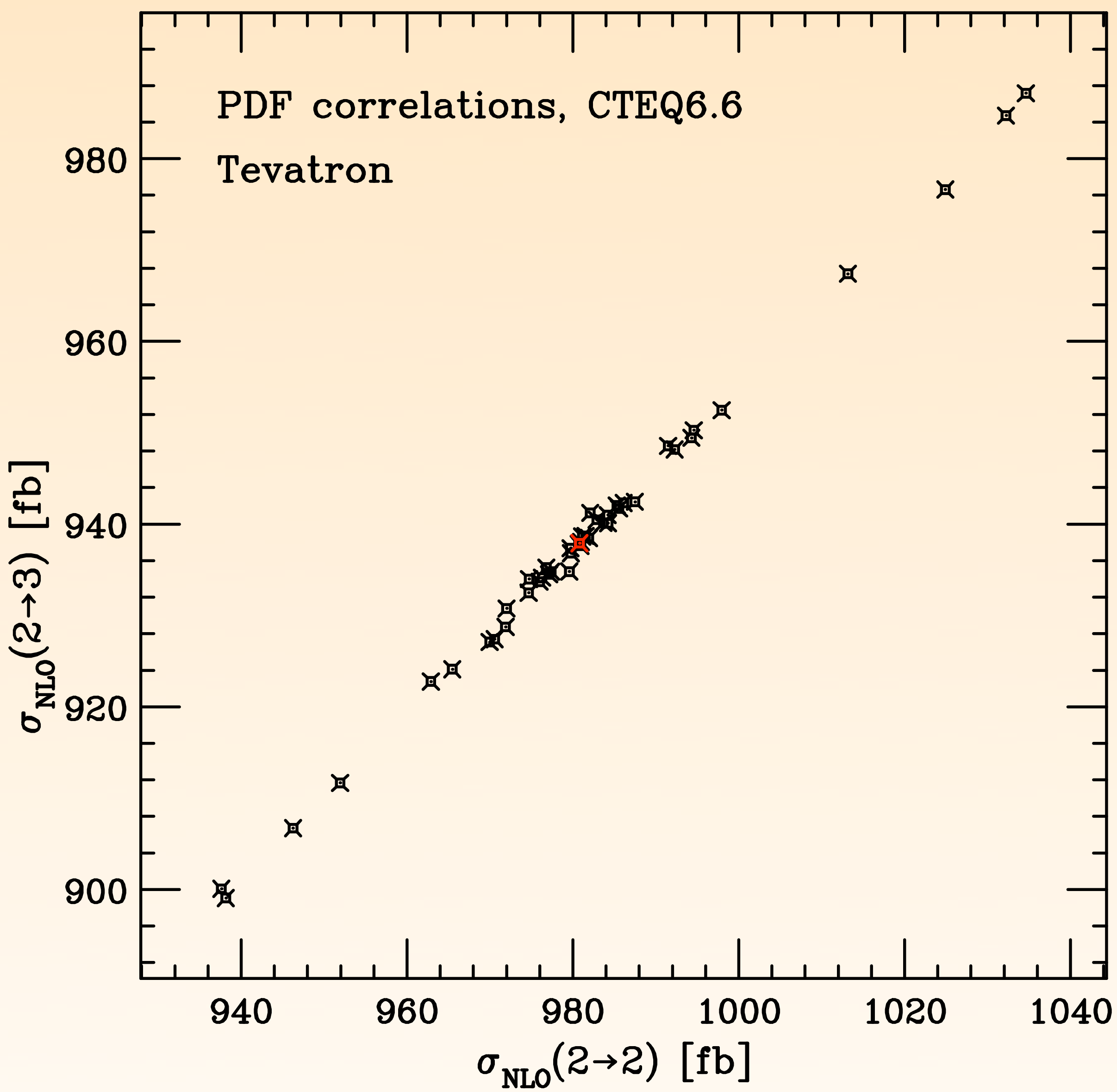
Backup slides

Spectator b quark mass in $2 \to 2$

- A non-zero b quark mass can be used in real emission diagrams
  - Explicit logarithm cancelled using the ACOT formalism
  - Negligible effect on total rate, distributions of top & light jet
  - Significant effect on the b quark -- "diverges" for m_b=0 at zero p_T



PDF correlation



- PDF correlation between 2 → 2 and 2 → 3 (almost) 100%

Tevatron vs LHC

top pair (LO)	Cross section in pb (percentage from gg)	
	1.96 TeV	14 TeV
pp	1.08 (26.8%)	537 (86.7%)
ppbar	5.62 (5.07%)	554 (83.7%)

s-channel single top (t+tbar) (LO)	Cross section in pb	
	1.96 TeV	14 TeV
pp	0.578	8.29
ppbar	0.226	7.53