A novel look at single top production

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arXiv: 0903.0005 [hep-ph]

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Recent news (March 4th, 2009):

- First observation of single top events at the Tevatron!
  - CDF:
    "We observe single top production for the first time with a significance of 5 standard deviations."
  - DØ:
    "The measured single top quark signal corresponds to an excess over the predicted background with a significance of 5.0 SD."

Outline

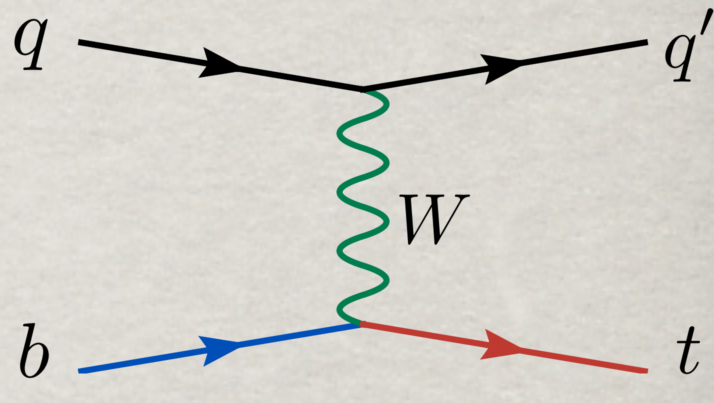
- Introduction to single top production
- New insights on the t channel:
    - outline of the new NLO computation in the four-flavor scheme
    - results and comparison with the traditional five-flavor scheme approach
- Conclusions

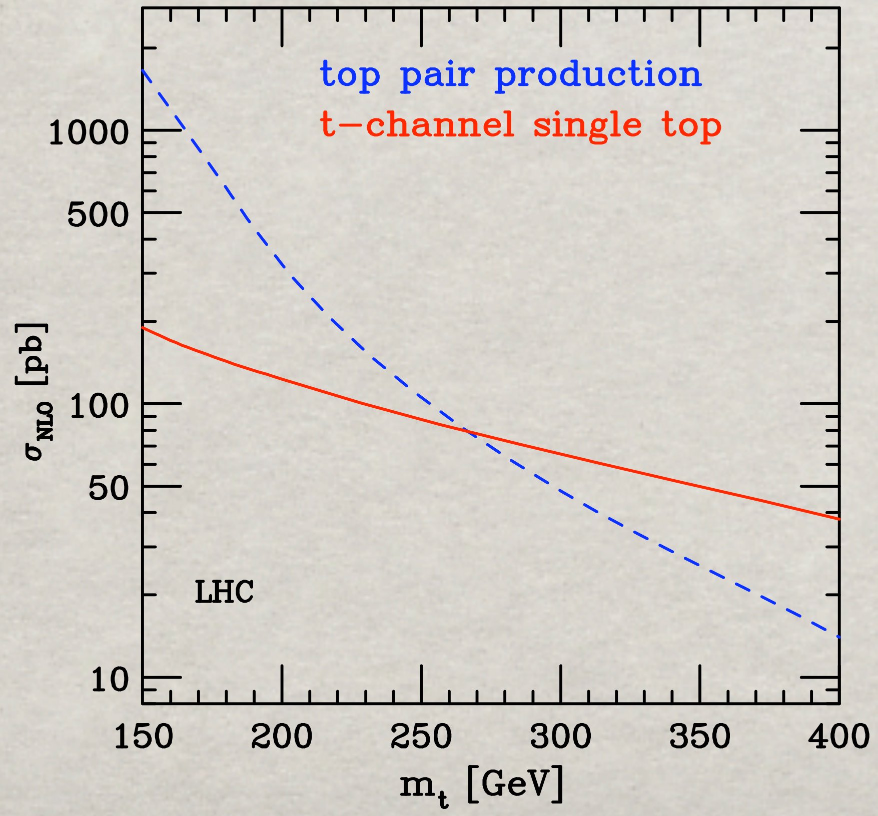
Motivation for Single top searches

- Electroweak production of top quarks via the charged current
  - Production process is proportional to the CKM matrix element $|V_{tb}|^2$
    - which is close to one in the SM, but could have significant deviations in more elaborate models. In particular models with an extra (quark) family
- t-channel is sensitive to FCNC's and anomalous couplings
- s-channel is sensitive to BSM heavy W' resonances
- Background to e.g. SUSY searches (or anything else that has W+jets as background)

T-CHANNEL SINGLE TOP

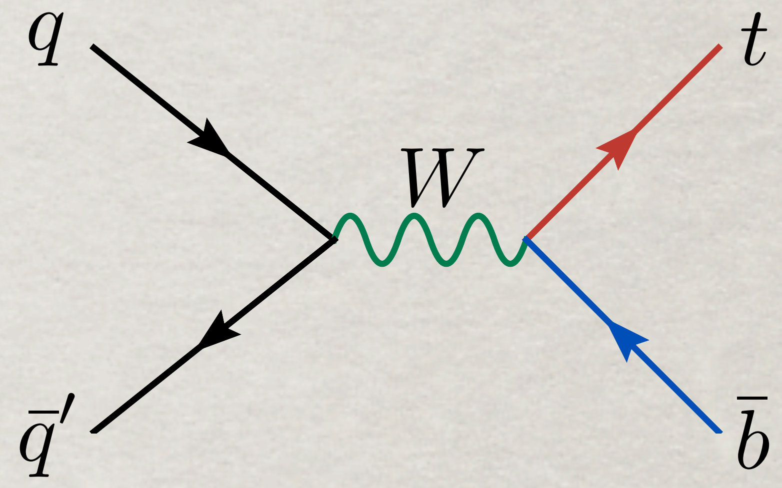
- Already thought of more than 20 years ago
  Dicus & Willenbrock, PRD34, 155 (1986)
- Take advantage of (compared to pair production):
  - t-channel enhancement over s-channel growth
  - more available phase space





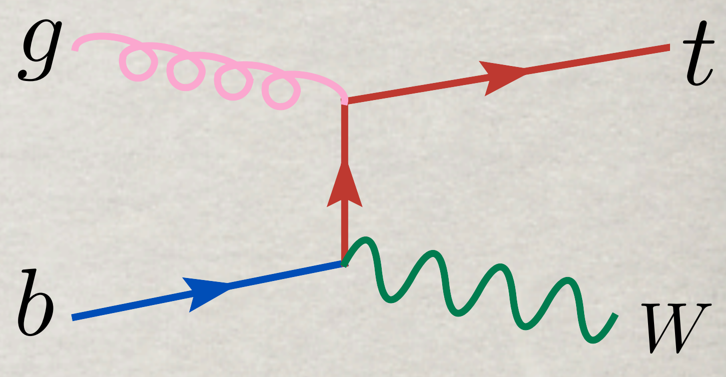
- Large cross section at LHC
- For very heavy quarks single top dominates -- t' searches
- Sensitive to V_{tb}, FCNC, ...
- NLO corrections by
  Bordes & Van Eijk (1995); Harris et al. (2002); Campbell et al. (2004); Q.-H. Cao et al. (2005); Frixione et al. (2006)

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

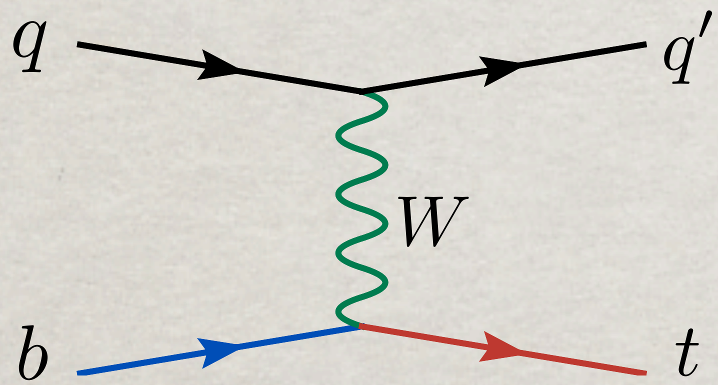
Wt associated production

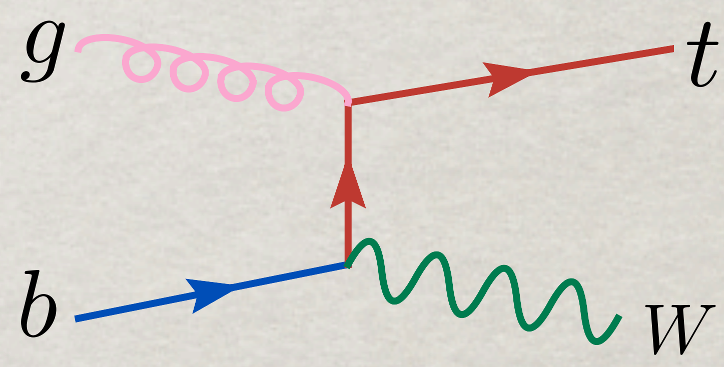


- Irrelevant for Tevatron, due to gluon luminosity and kinematics
  Belyaev et al., PRD59, 075001 (1999); Tait, PRD61, 034001 (2000)
- Can play significant role at the LHC (not least as background - e.g. to H ➞ WW*)
- Very similar top pair production with possible large interference effects between the 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

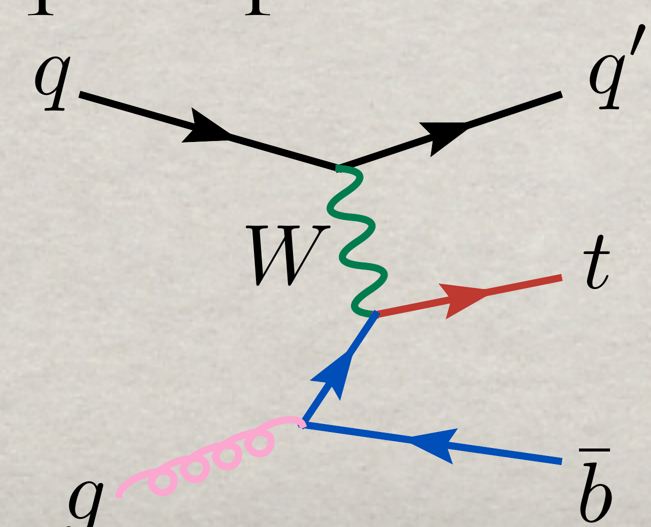
Heavy initial state quarks

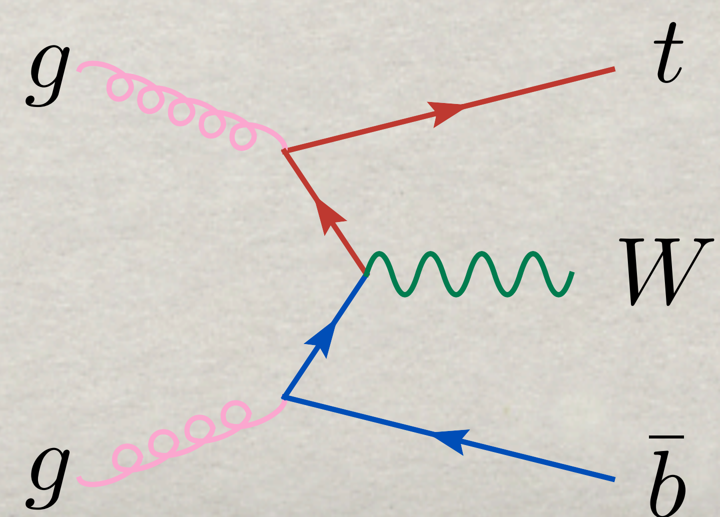
- Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state





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



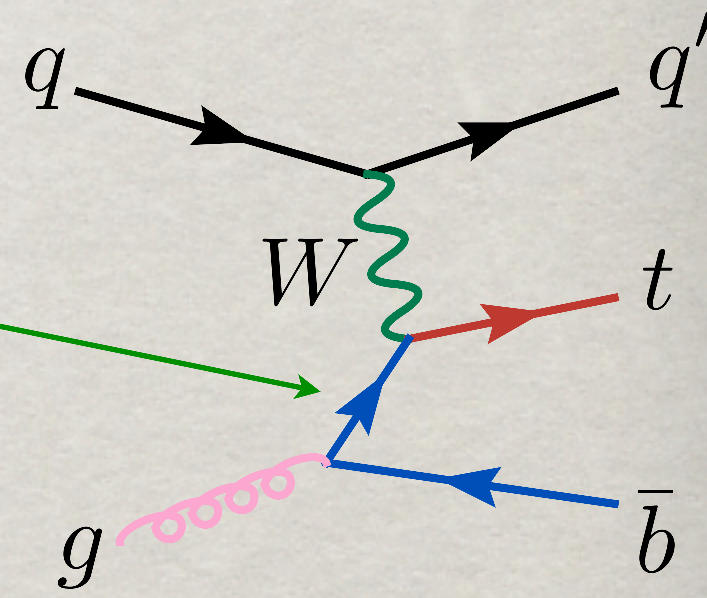


Collinear logarithms

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

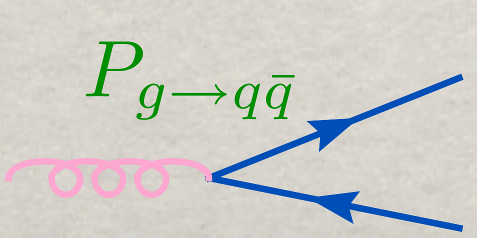
$$\frac{1}{t - m_b^2} \sim \frac{1}{p_T^2 + m_b^2}$$

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

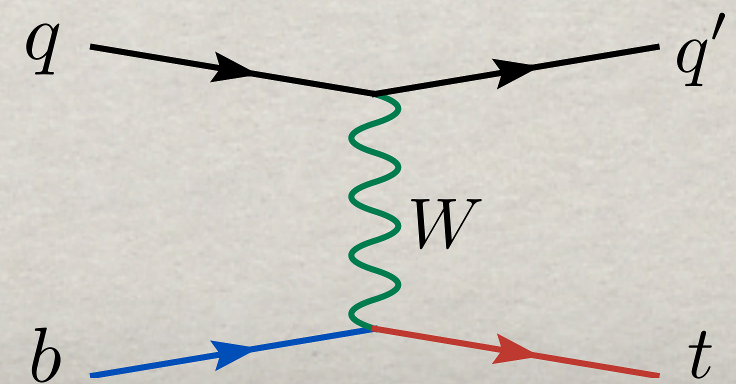


- Contribution to the cross section: $\int_0^{p_{T,\max}^2} \frac{dp_T^2}{p_T^2 + m_b^2} = \log\left(\frac{p_{T,\max}^2}{m_b^2}\right) + \ldots$
- Coefficient of the logarithm is:

AP splitting function



times



matrix elements with splitting removed

Resummation into PDF

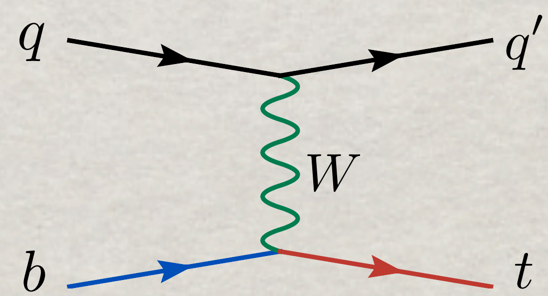
- Putting it together: $\frac{d\sigma(qg \to q' t\bar{b})}{d\log p^2_{T,\max}} \sim \left(\frac{\alpha_s}{2\pi}\right)\left[\int \frac{dx}{x} P_{g\to q\bar{q}} f_g\right] \times \hat{\sigma}(qb \to q' t)$
- But the first part resembles the evolution equation for a quark:

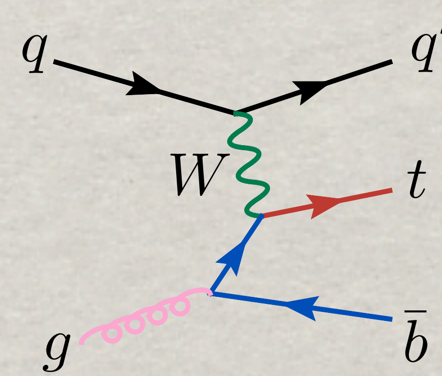
$$\frac{df_q}{d\log q^2} \sim \left(\frac{\alpha_s}{2\pi}\right) \int \frac{dx}{x} \left[P_{g\to q\bar{q}} f_g + P_{q\to qg} f_q\right]$$

- 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

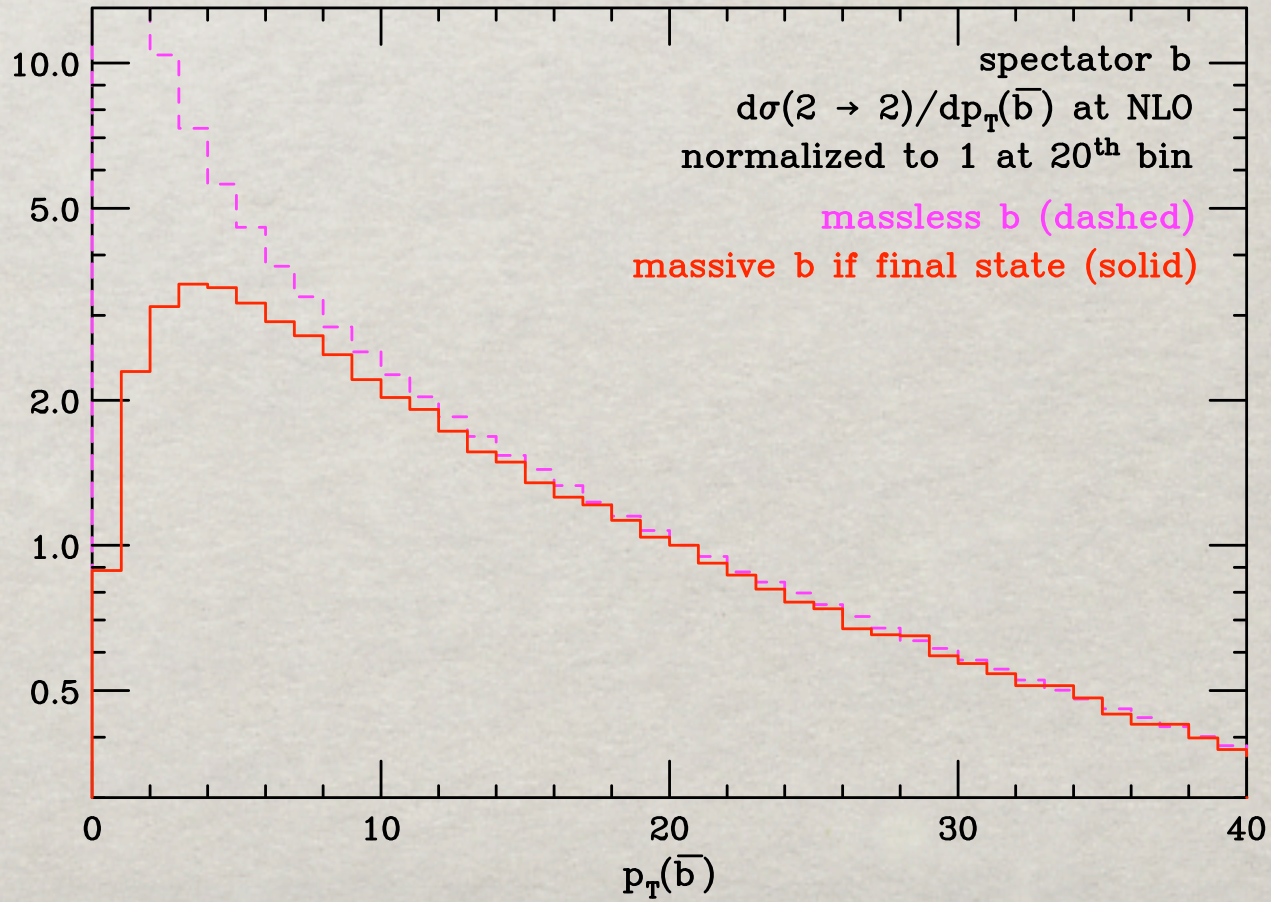




- Terms from 4F ($2 \rightarrow 3$) enter at NLO. Properties of spectator b are only LO
- All calculations presented so far set m_b=0 in final state for simplicity

Spectator b quark mass in 2 → 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

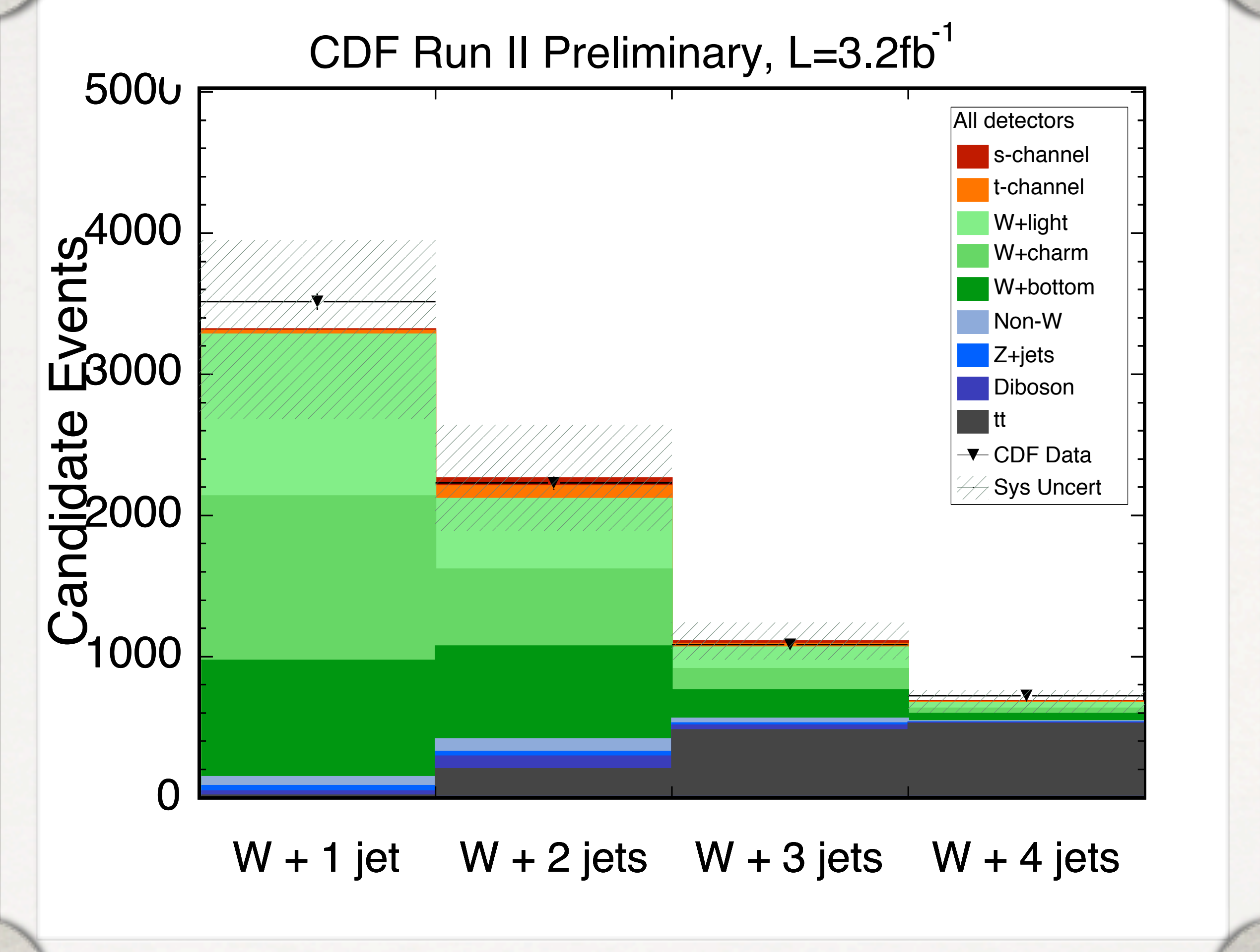


Backgrounds

- Large backgrounds from W+jets and top pair production -- much bigger than the original estimates

- A very challenging measurement indeed

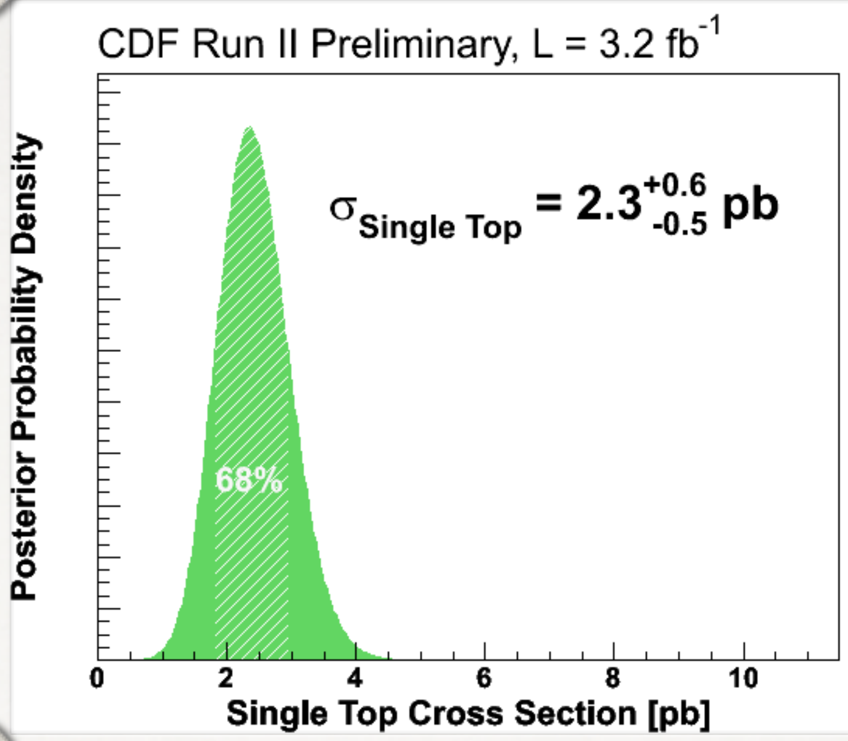
- Detailed information about signal and backgrounds is required to extract a signal



CDF Note 9711

Discovery!

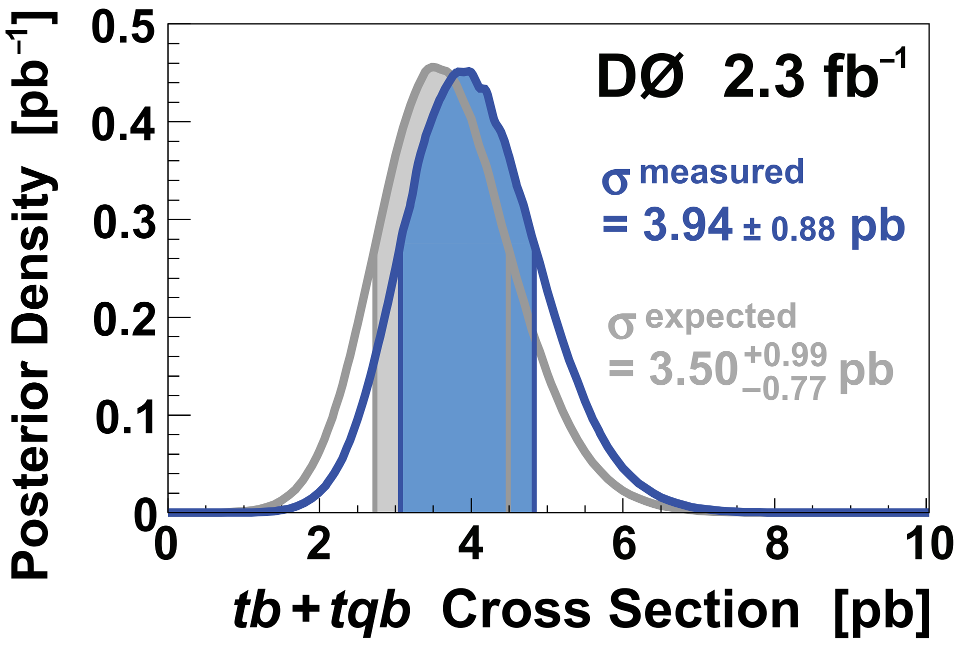
- CDF
  m_t=175 GeV



arXiv: 0903.0885

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

- DØ
  m_t=170 GeV



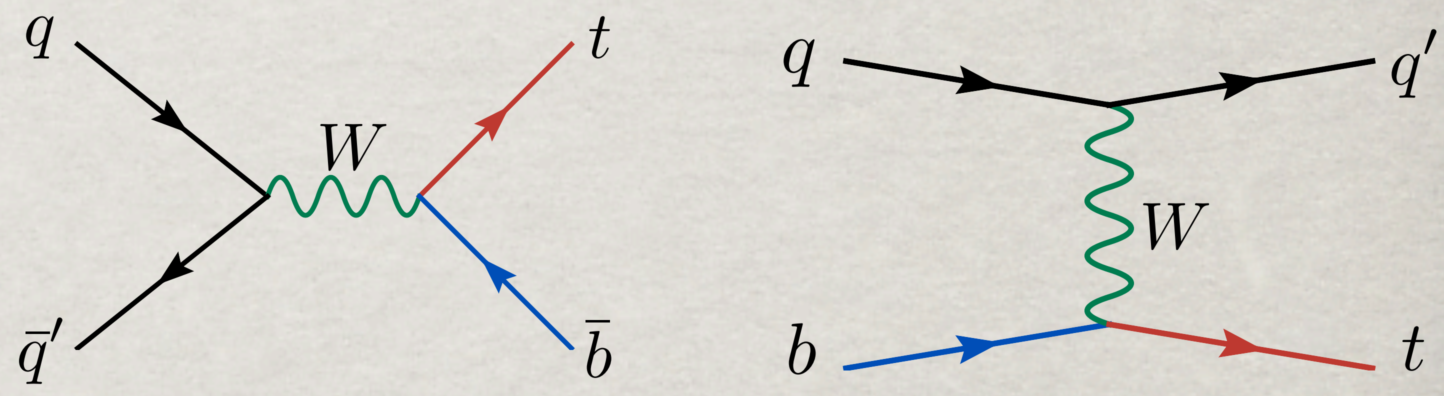
arXiv: 0903.0850

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

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

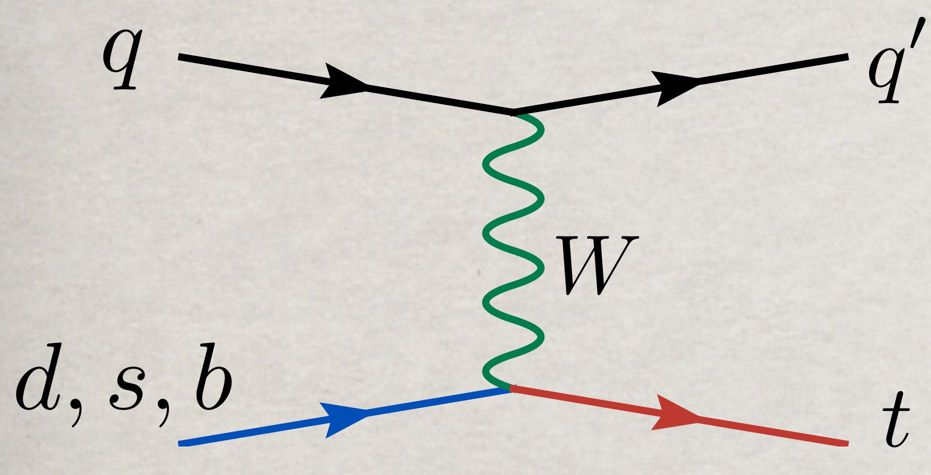
Signatures of s- and t-channel events

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



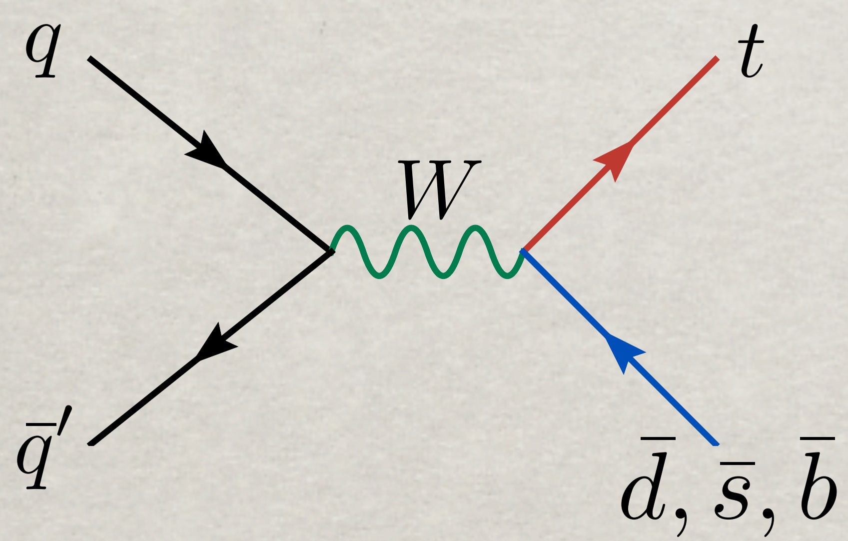
- s-channel events have in general one more b jet in the final state, roughly:
  - 1 b-tag: t-channel event
  - 2 b-tags: s-channel event
- In the analysis it is assumed that these signatures do not change

More subprocesses



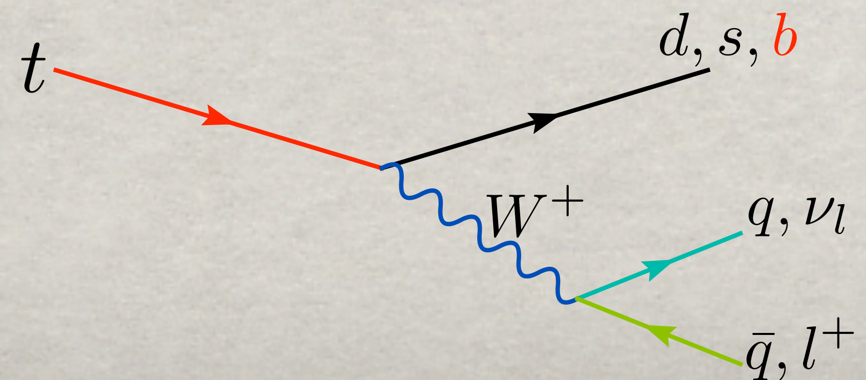
$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

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



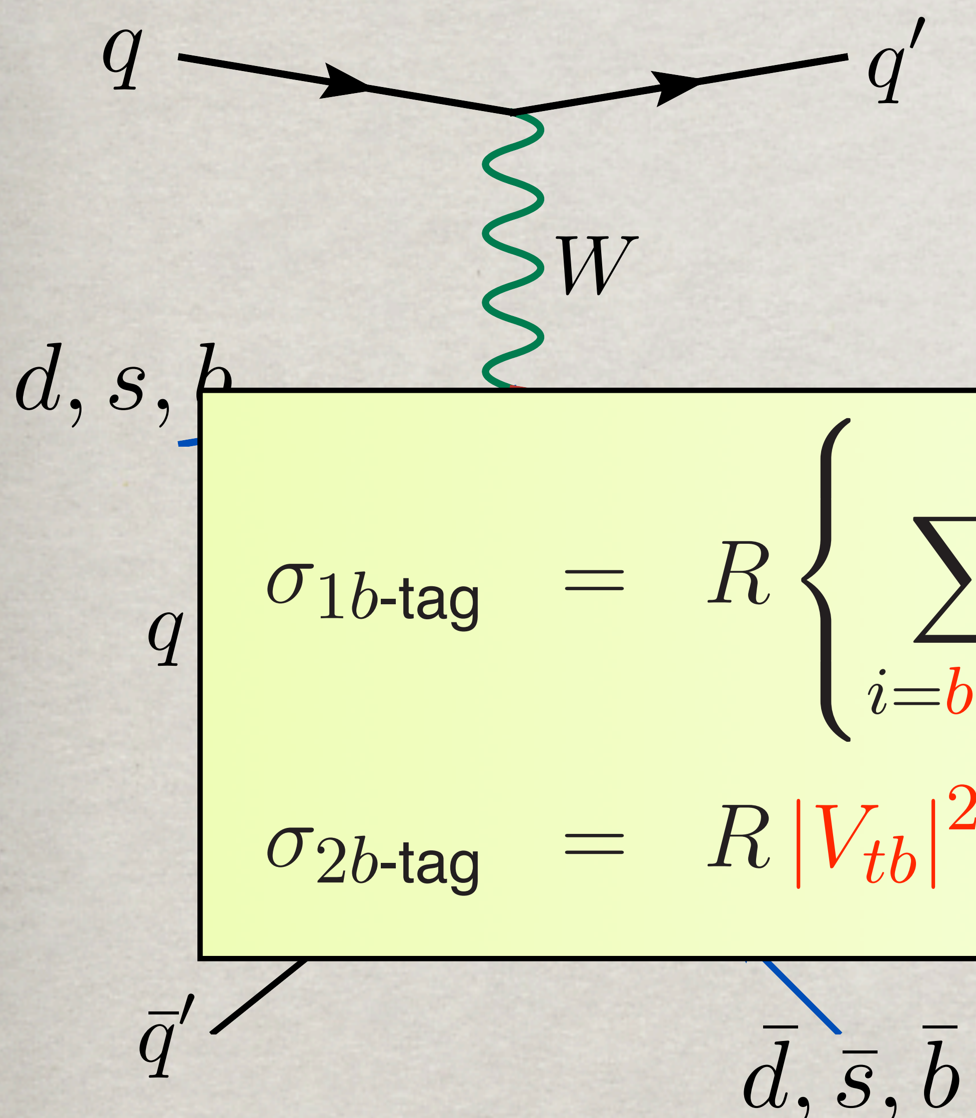
$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)\sigma^{\text{s-ch}}$$

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



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

More subprocesses



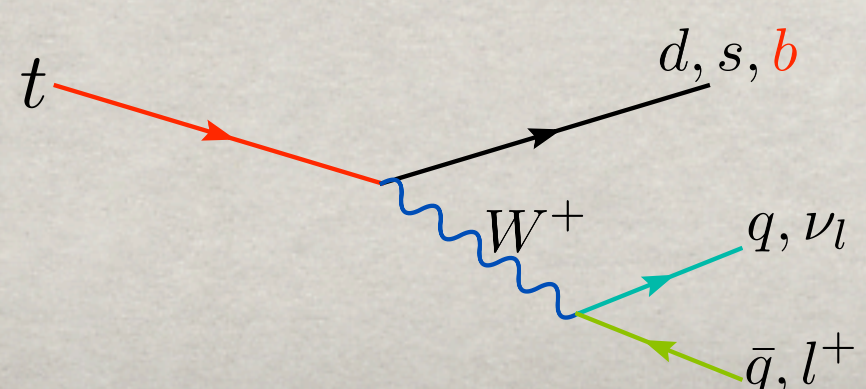
$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

Enhancement due to

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

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

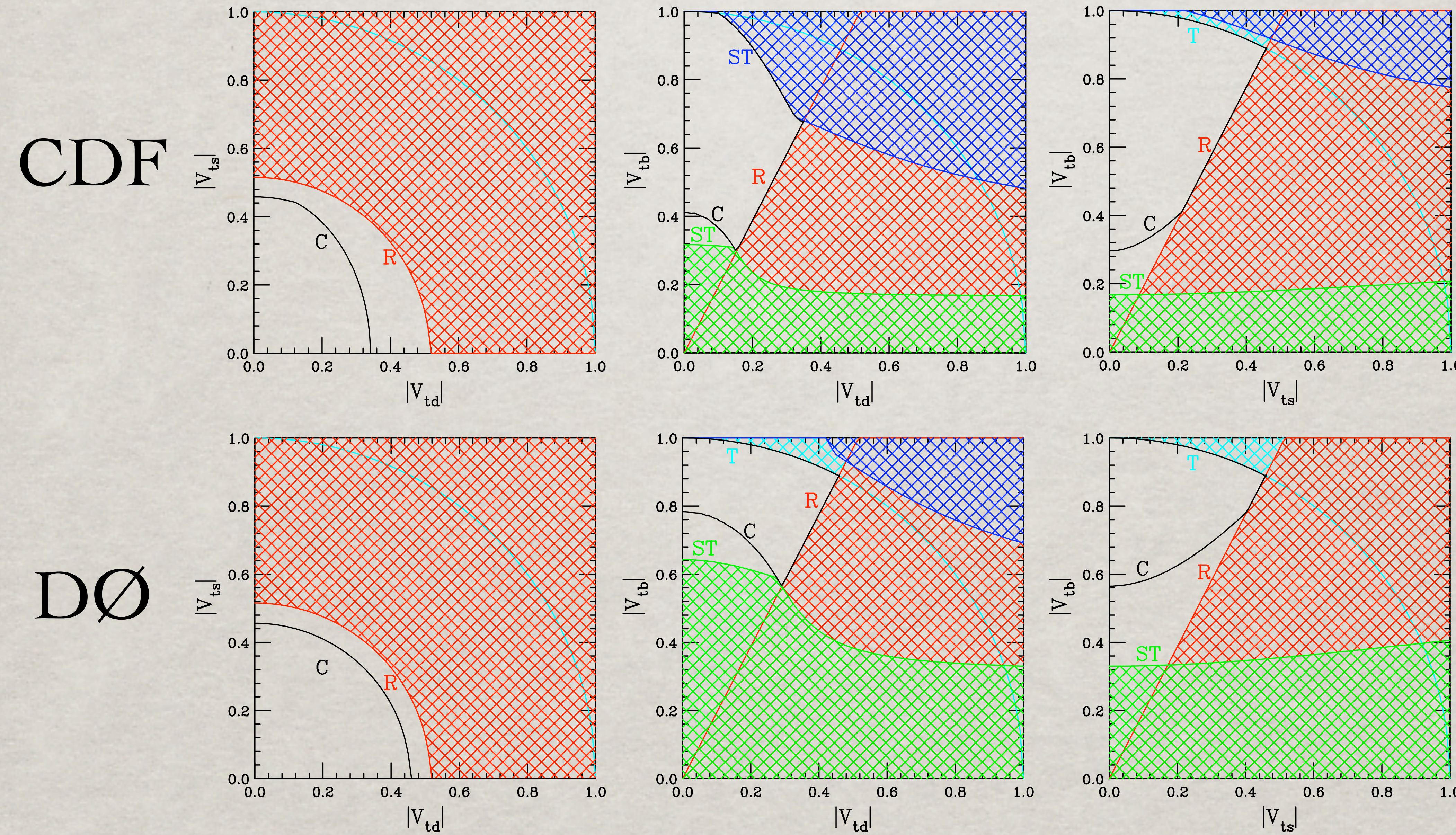
t-channel (only 1 *b*-jet)



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

Constraints on 3rd row of the CKM matrix

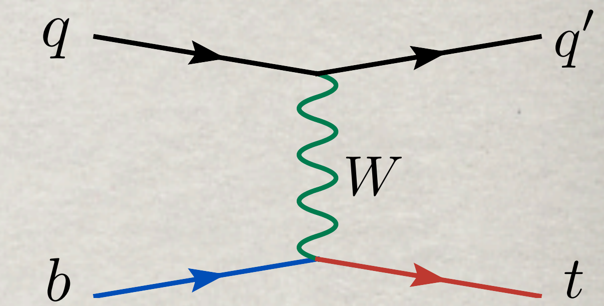
$|V_{td}|$ vs $|V_{ts}|$ $|V_{td}|$ vs $|V_{tb}|$ $|V_{ts}|$ vs $|V_{tb}|$



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

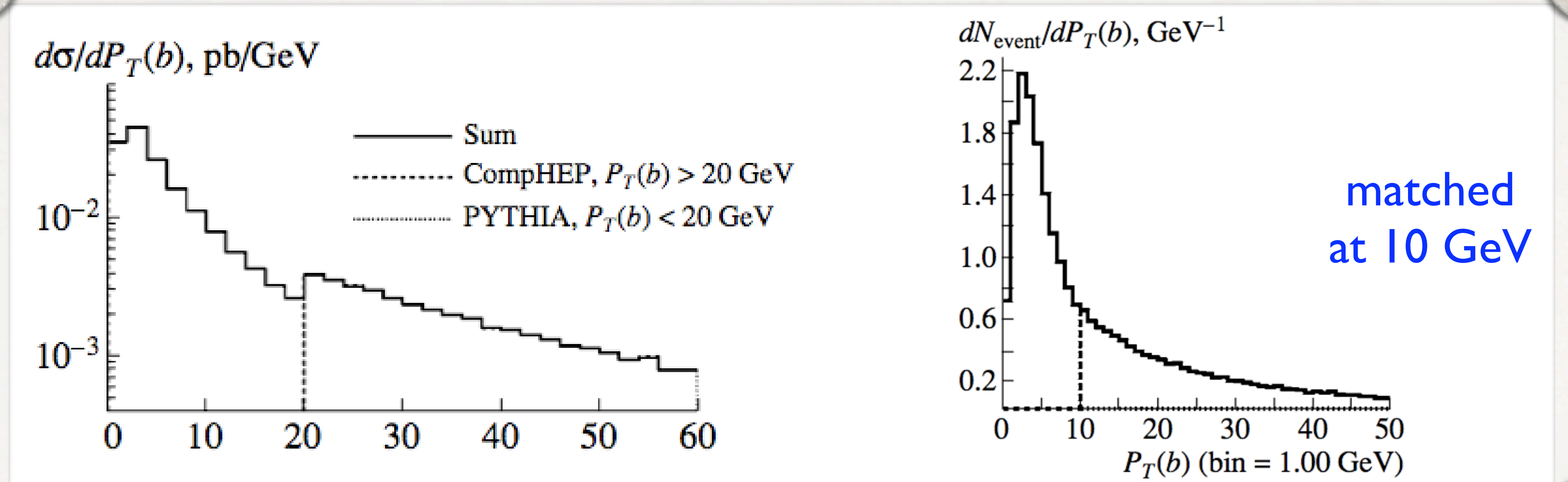
Warning: theory plots, proper experimental analysis needed!

Limitations of 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)

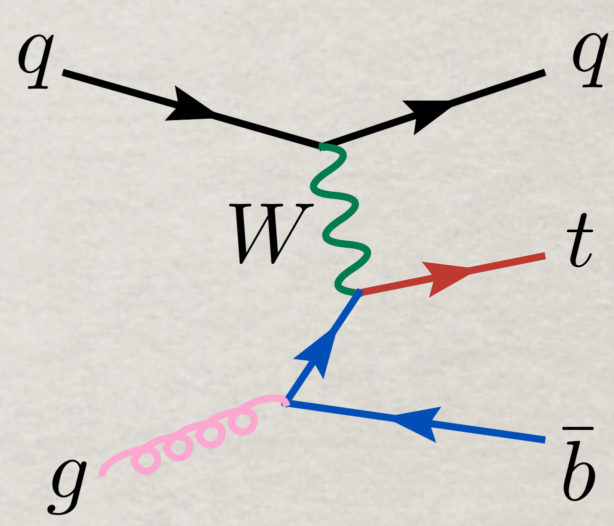


- Ad hoc matching well motivated, but theoretically unappealing

A fresh approach

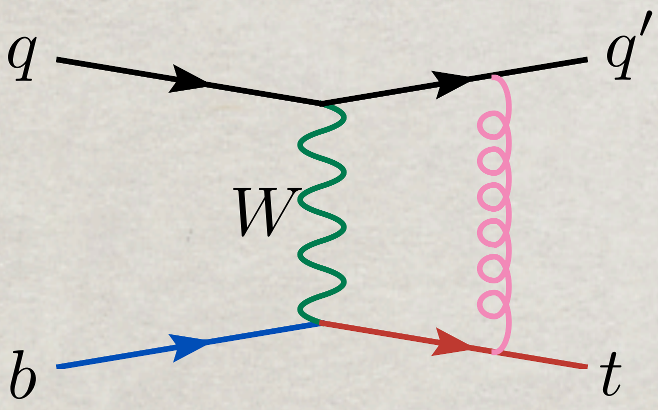
Four-flavor scheme

- 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 $(2 \to 3)$

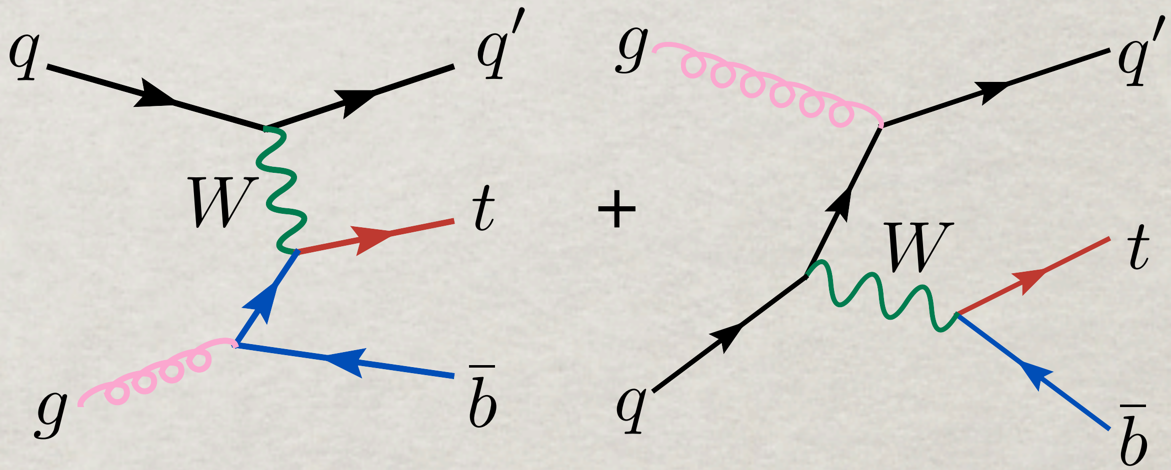


Factorization in 2 → 2

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



Vanishes: Tr[t^a]=0

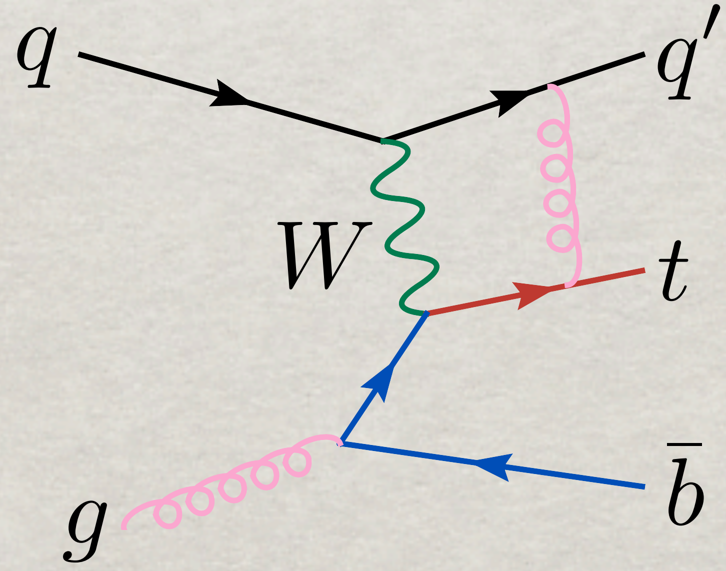


Interference between t and s channel vanishes: Tr[t^a]=0

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

Factorization in 2 → 3

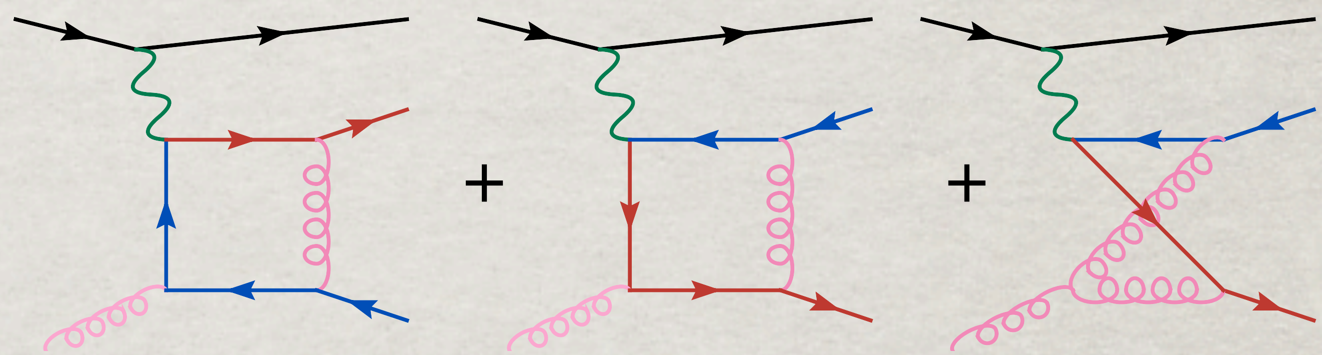
- The same arguments still mostly apply to the 2 → 3
- No mixing between light and heavy quark lines from the virtual corrections



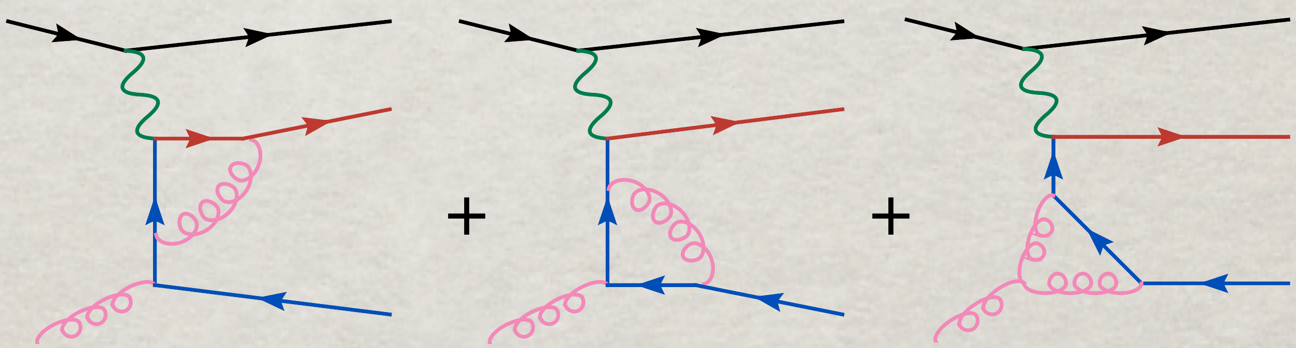
Vanishes: $\mathrm{Tr}[t^a]=0$

Virtual corrections

- Corrections to the light quark line (same as for 2 ➞ 2)
- Three boxes

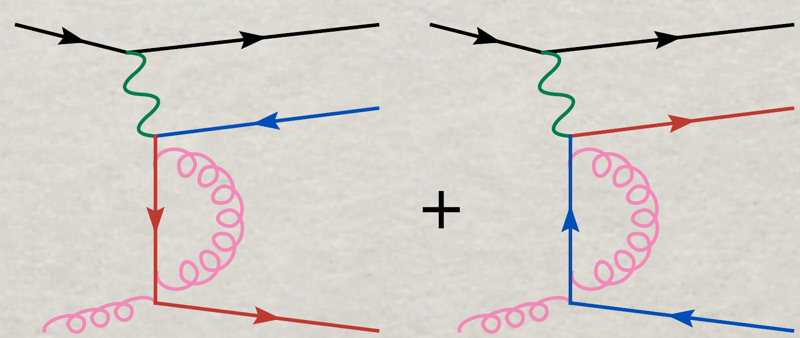


- Six triangles



+ (t ⬌ b)

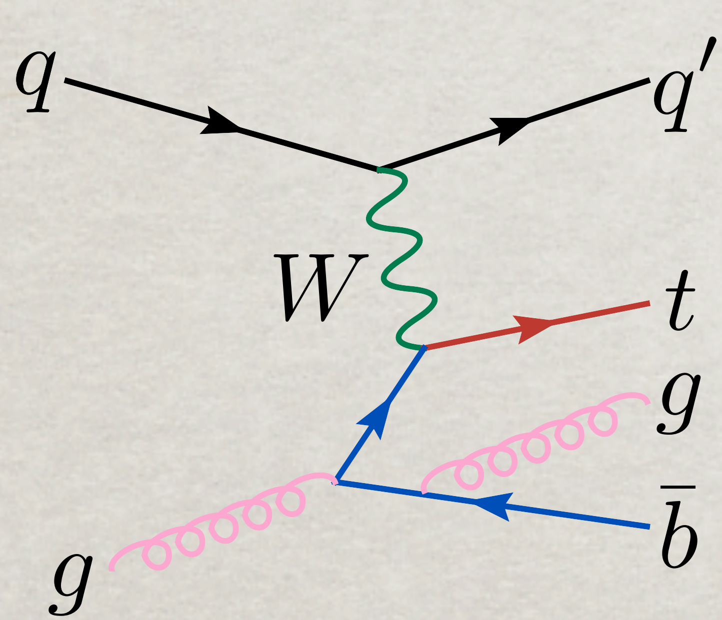
- Two bubbles



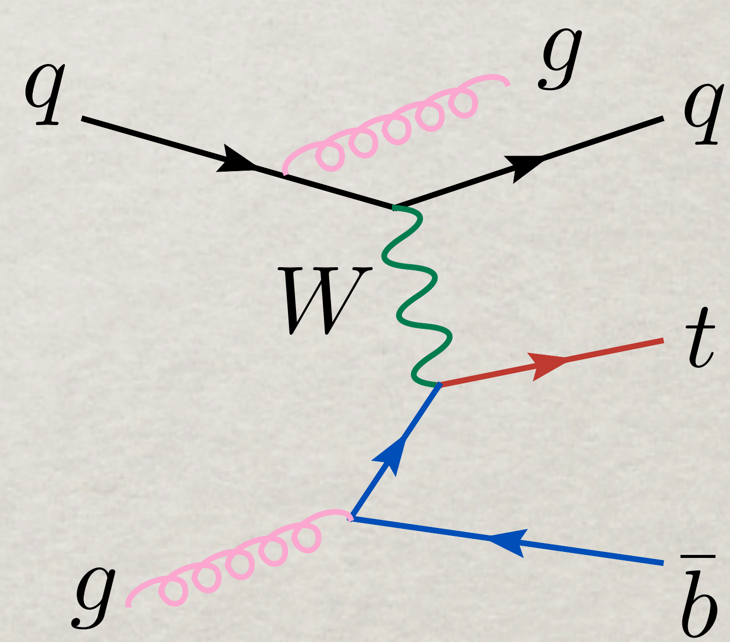
- Analytic computation of helicity amplitudes using standard techniques -- top spin is available

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

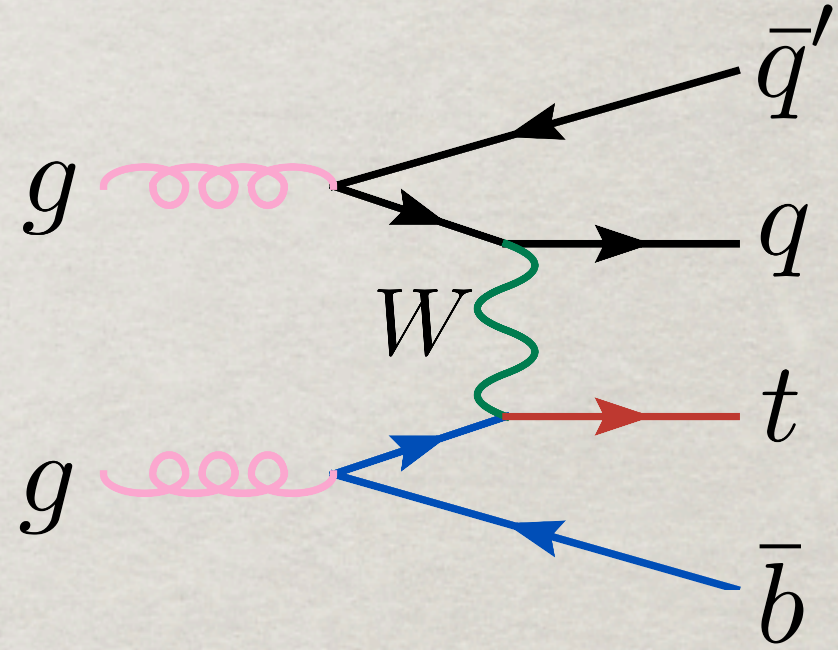


Correction to light line

Interference is zero due to color: $\mathrm{Tr}[t^a]=0$

Near factorization

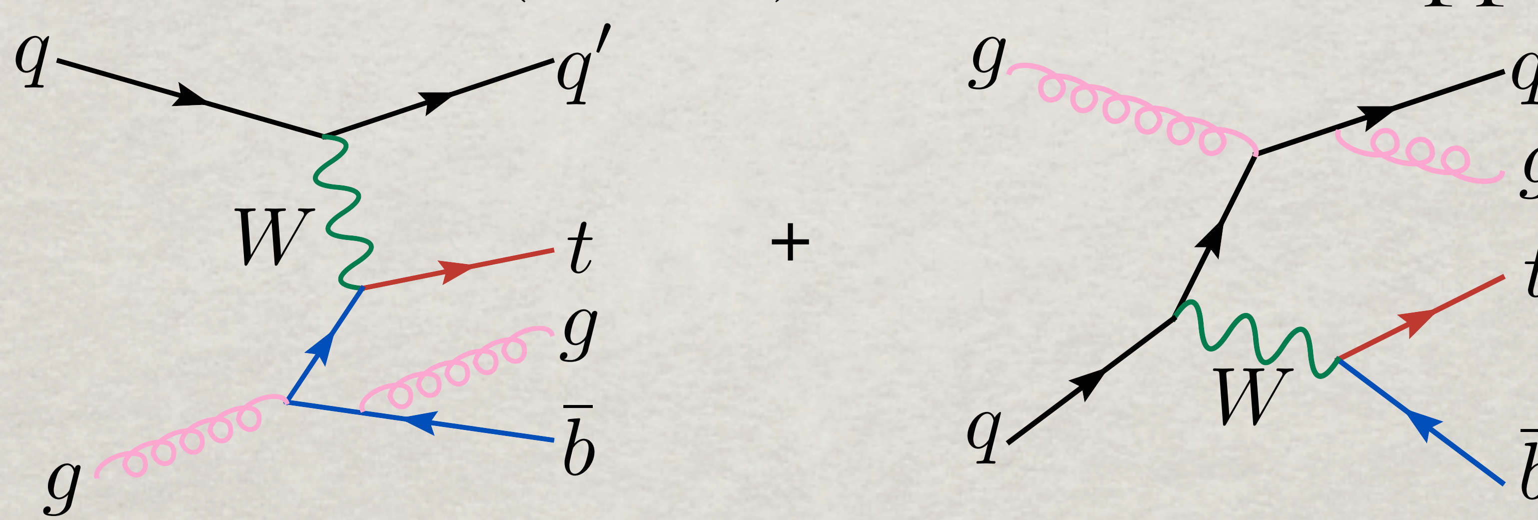
- Not all real emission pieces factorize so neatly, but non-factorizing pieces are always color-suppressed



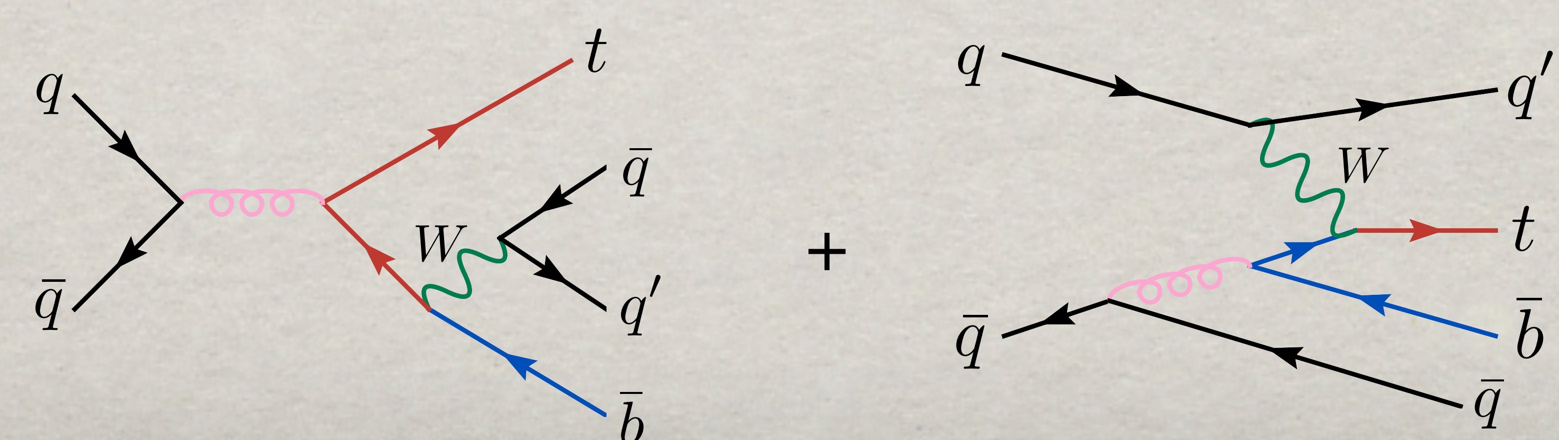
- Split the (sub-leading) terms equally
  - We can use different renormalization and factorization scales for heavy and light quark currents

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



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



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

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

- We use the dipole subtraction method

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

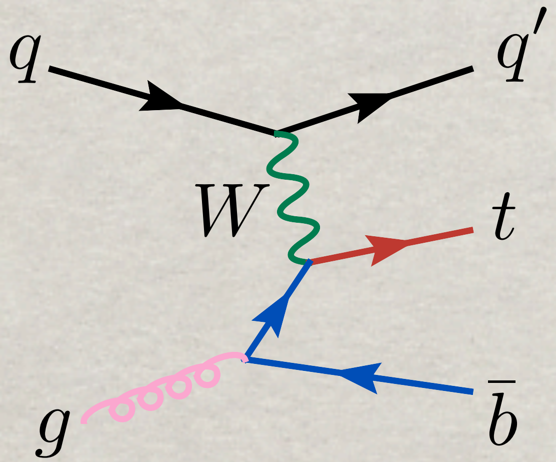
- Excellent agreement found with independent check against MadDipole

RF, Gehrmann & Greiner (2008)

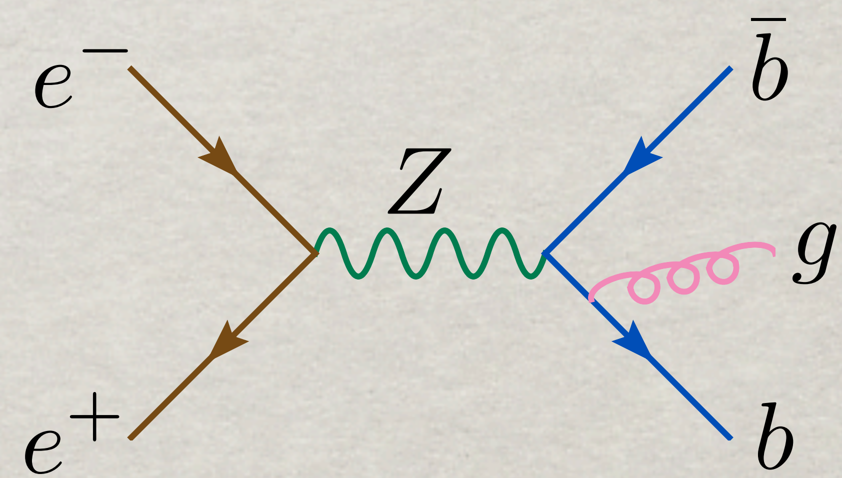
Checks of the calculation

- Real emission including subtraction terms checked against MadGraph & MadDipole
- 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



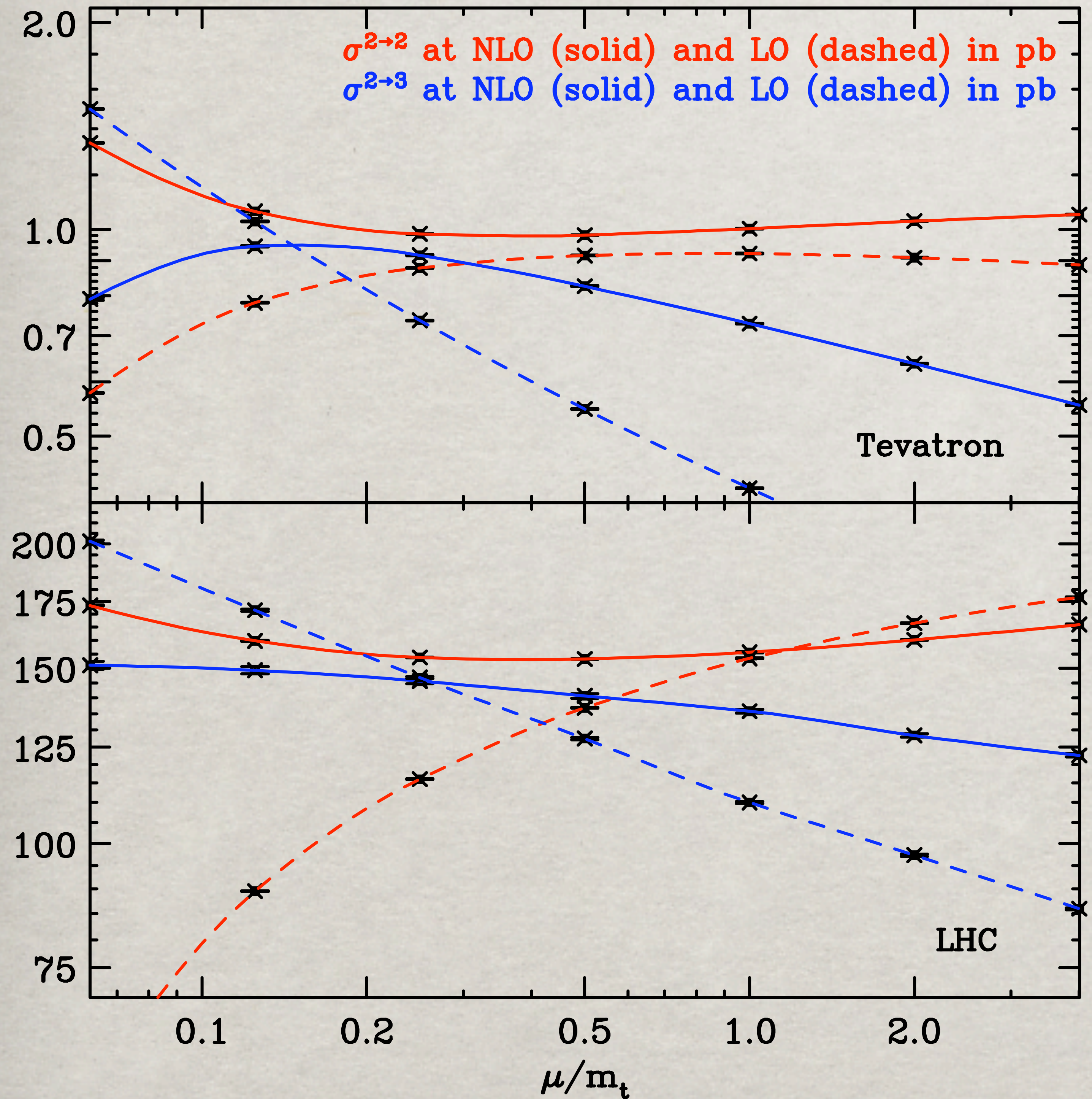
Nason & Oleari, NPB 521, 237 (1998)

- 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

Scale dependence

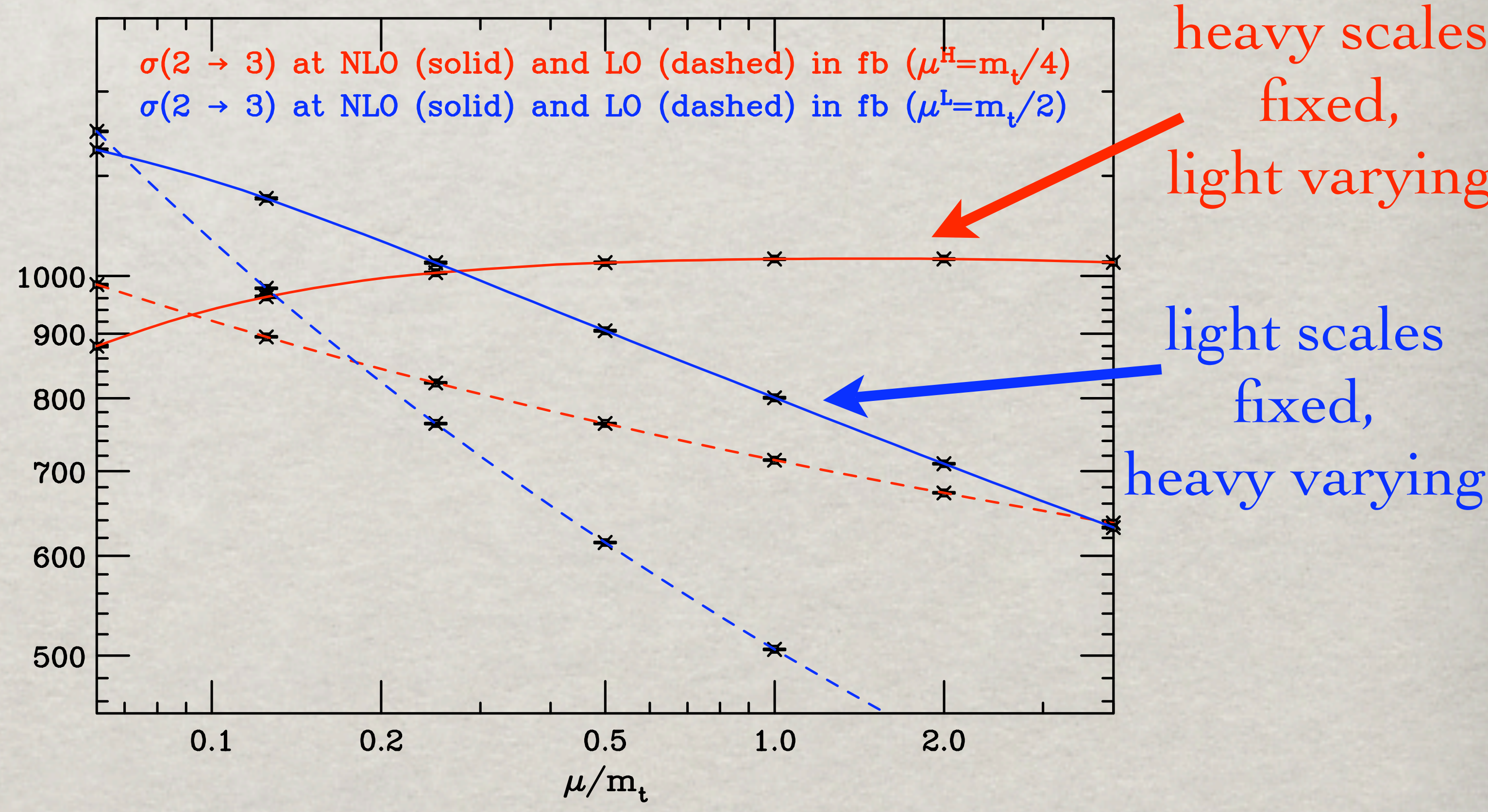


- Both schemes much improved from LO
- 5F (2 → 2) only mildly sensitive to scales at NLO (use m_t in what follows)
- 4F (2 → 3) expected to be worse, but isn't much
- Hardly a region of overlap between the two
- 4F (2 → 3) prefers smaller scales than m_t, particularly at the Tevatron

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

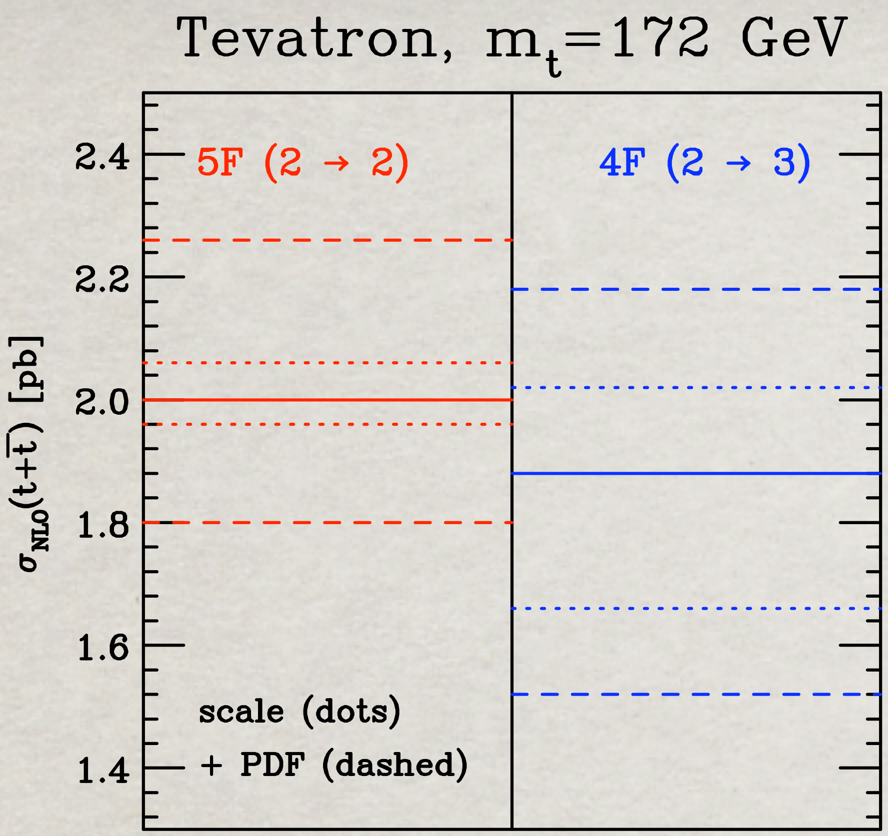


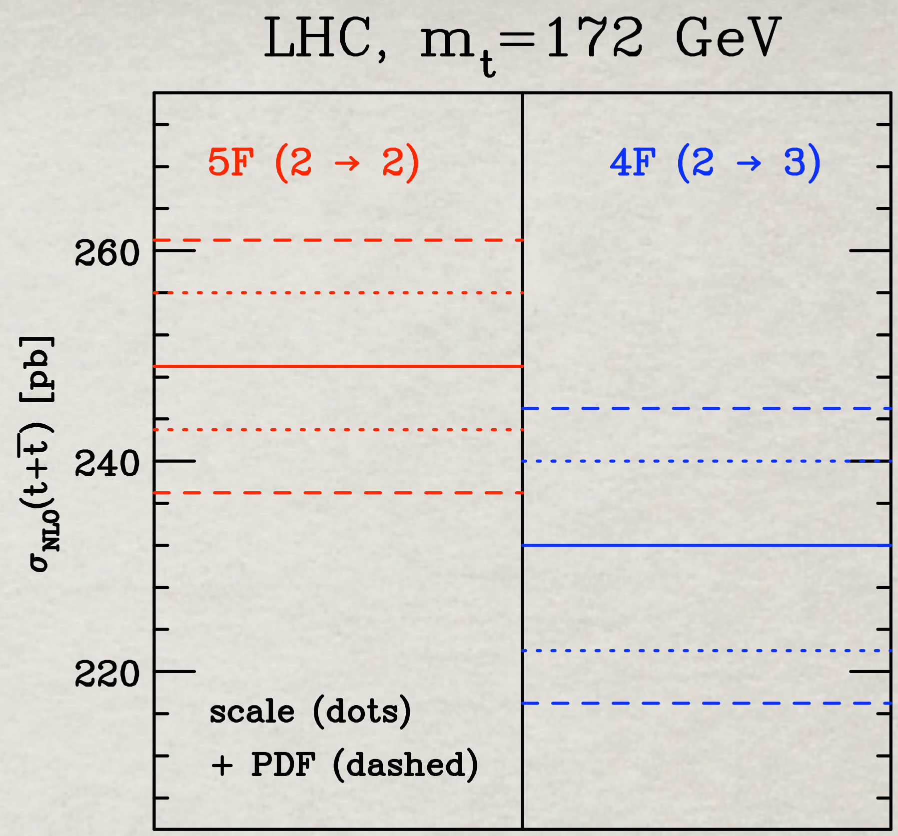
Total rates and theory uncertainties

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

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

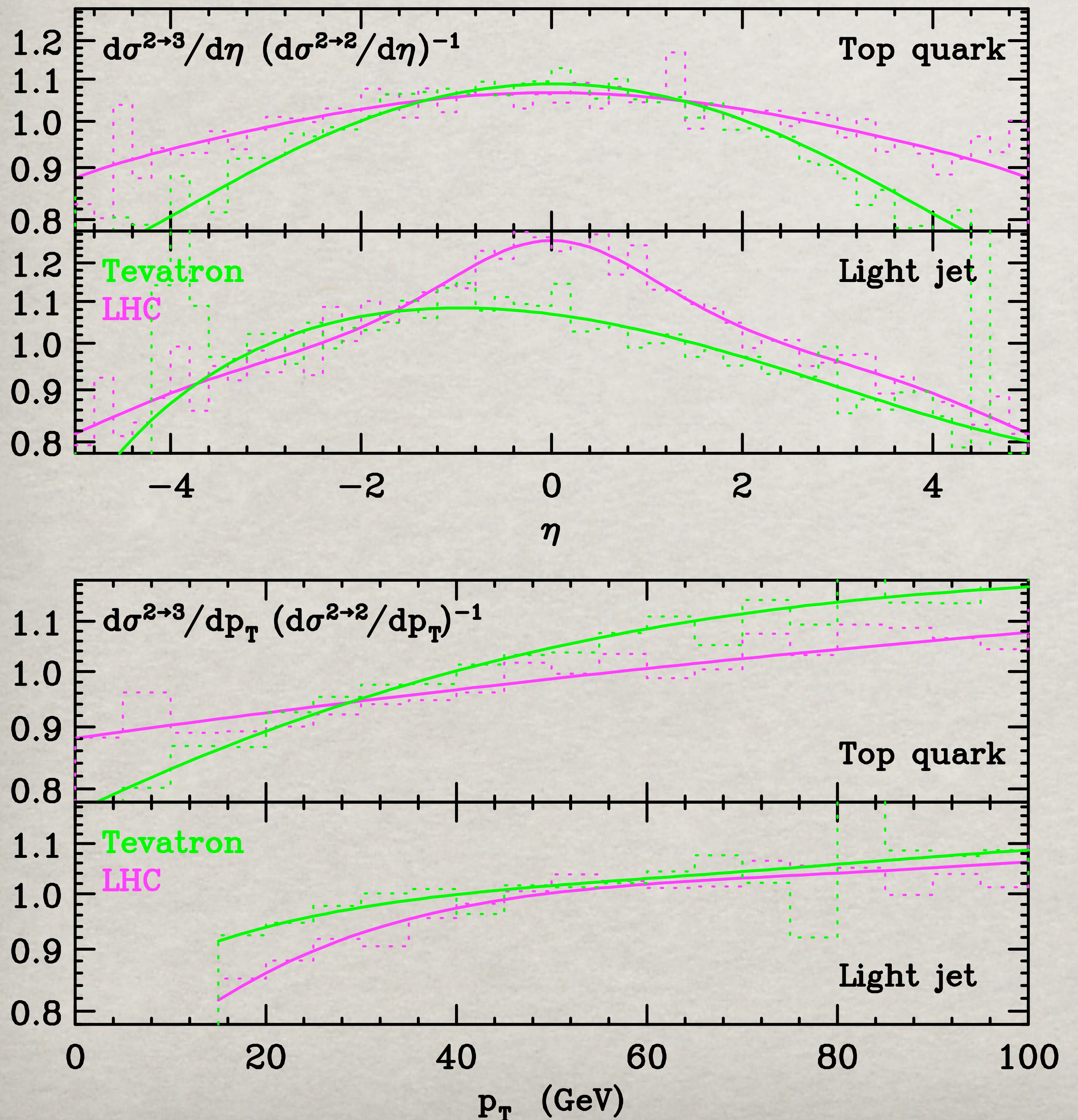
- Tevatron: 30% difference at LO becomes 6% at NLO, well within the combined uncertainties
- LHC: 8% difference at LO not improved at NLO, only marginally consistent due to < 5% uncertainty in both schemes
- Perturbative expansion is well behaved: small scale uncertainty and corrections are mild
- Larger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





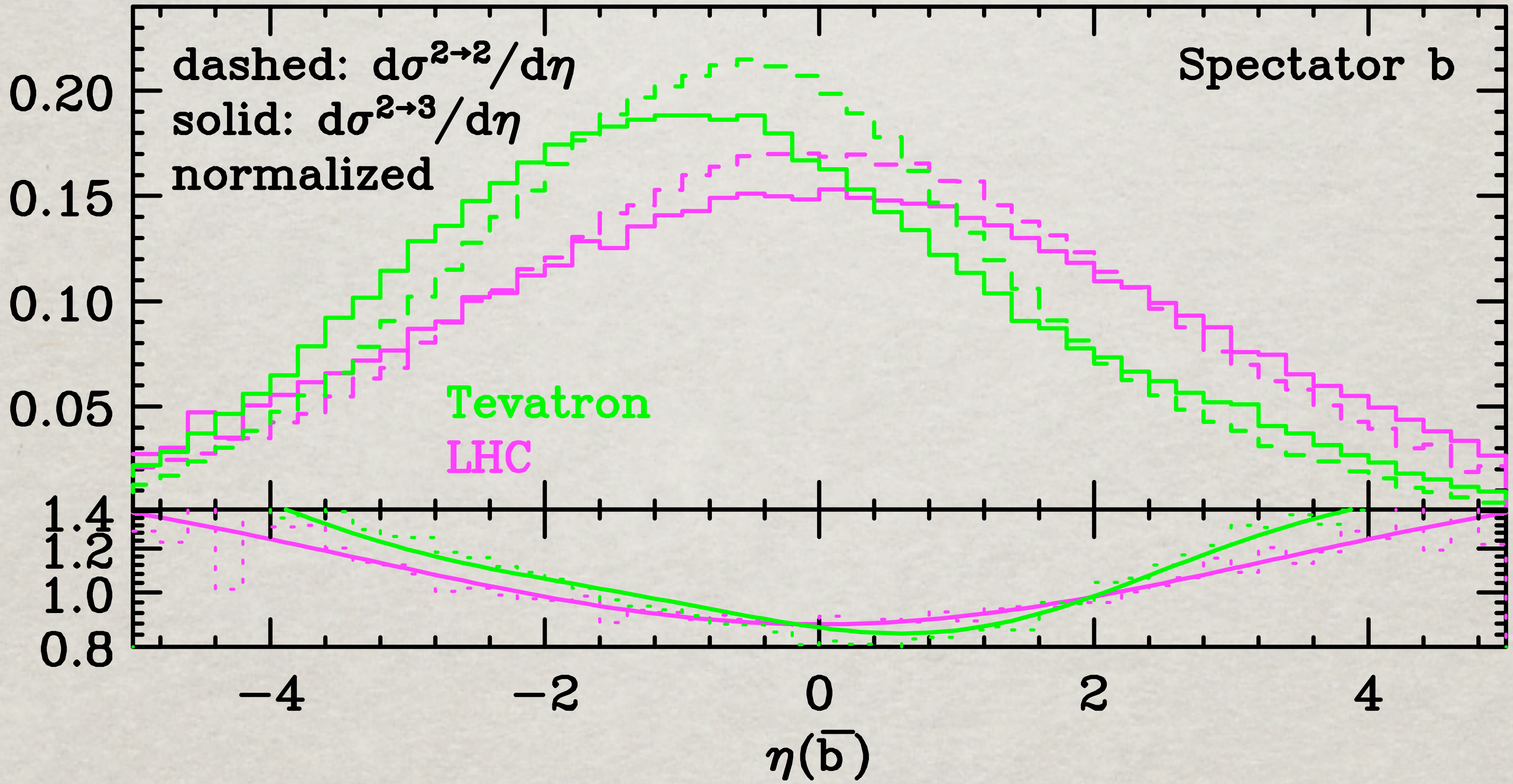
- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- Consistent at the Tevatron: logarithms not so important?
- For the LHC, the minor difference could point to either
  - large logarithms being resummed
  - the need for a NNLO calculation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

Top and light jet distributions



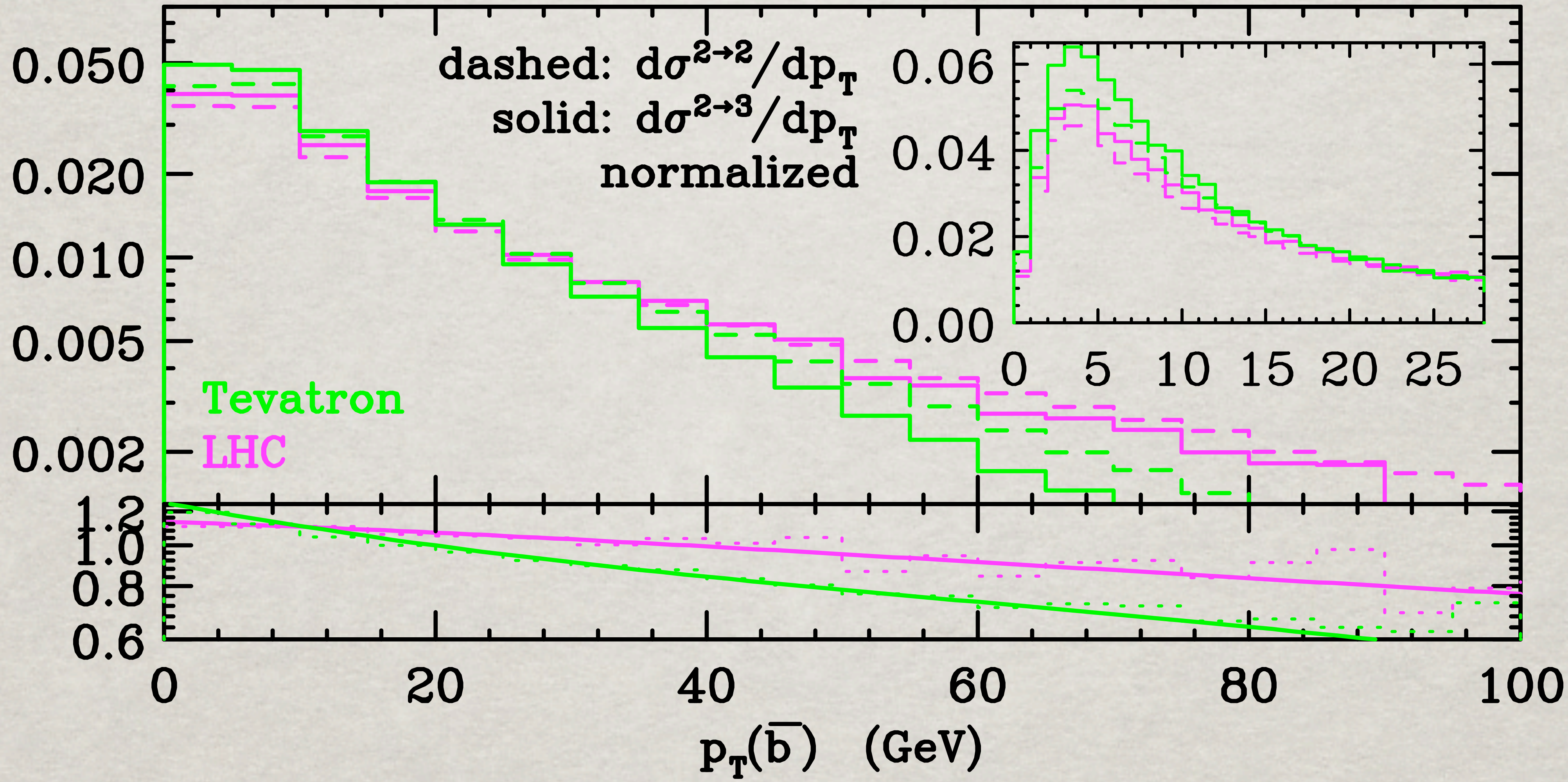
- Ratio of normalized distributions
- Jet defined by p_T>15 GeV, $\Delta R > 0.7$
- Some differences, but typically of the order of ~10% in the regions where the cross section is large

Bottom quark pseudo-rapidity



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

Bottom quark p_T distribution



- First NLO prediction for this observable
- Softer in 4F (2 → 3), particularly at the Tevatron
- Deviations up to ~ 20%

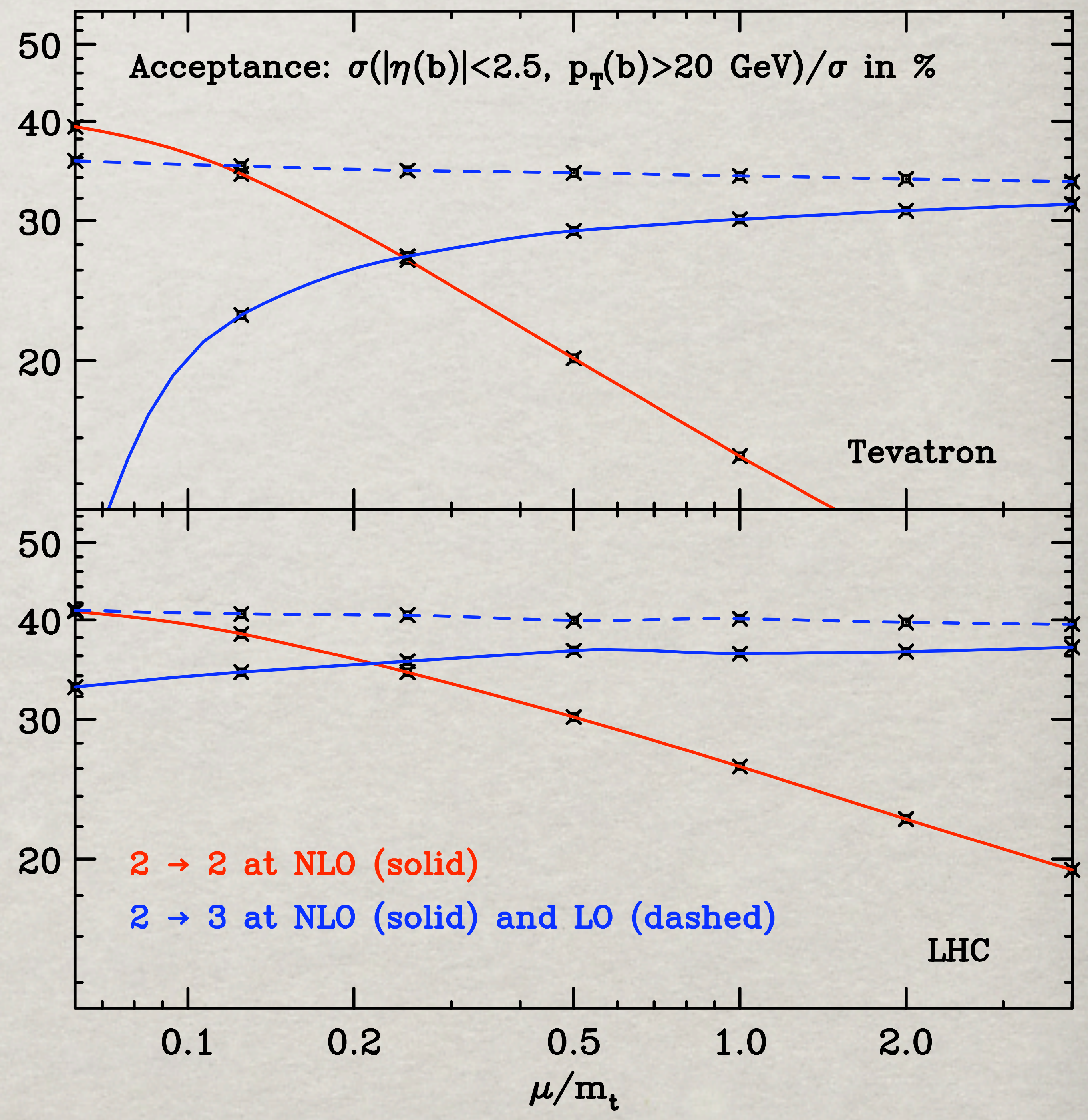
More bottoms in 4F

- 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:

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

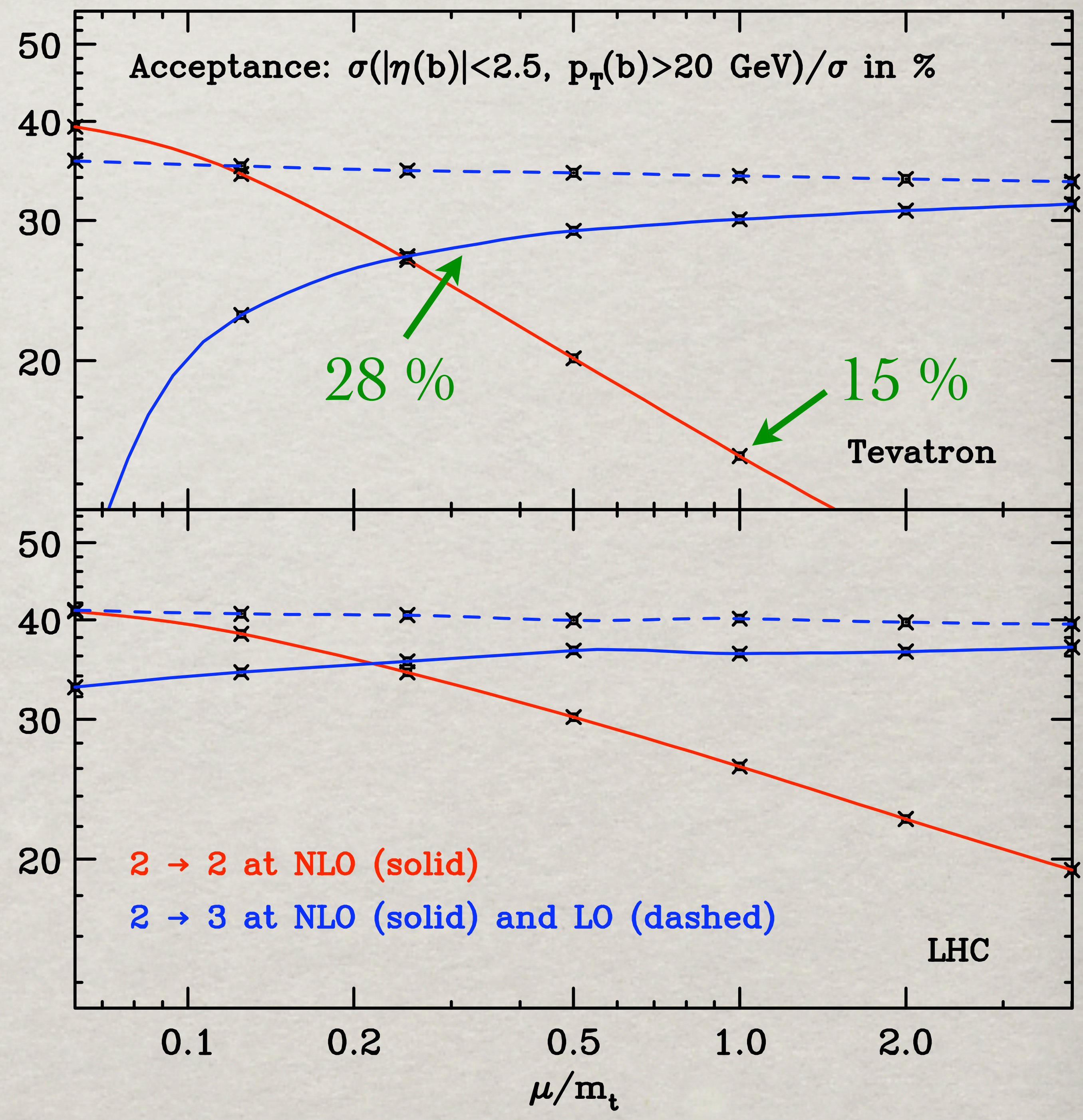
Acceptance

- Very large scale dependence for 5F ($2 \to 2$), → effectively a LO quantity
- NLO 4F ($2 \to 3$) much stabler
  - $2 \to 3$ LO underestimates the uncertainty



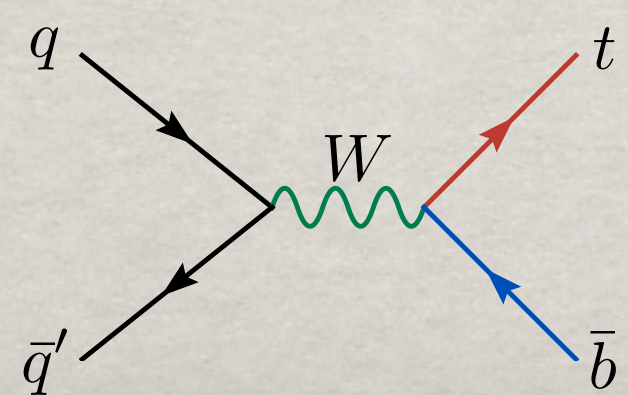
Acceptance

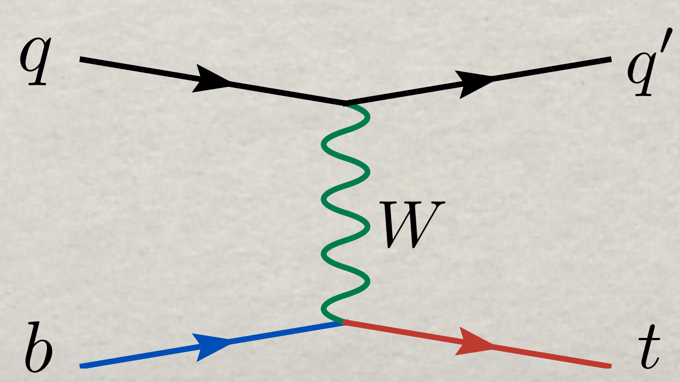
- Very large scale dependence for 5F ($2 \to 2$), $\to$ effectively a LO quantity
- NLO 4F ($2 \to 3$) much stabler
  - $2 \to 3$ LO underestimates the uncertainty
- For our best scale choices: almost twice as many t-channel events have a spectator b, and therefore a signature similar to s-channel



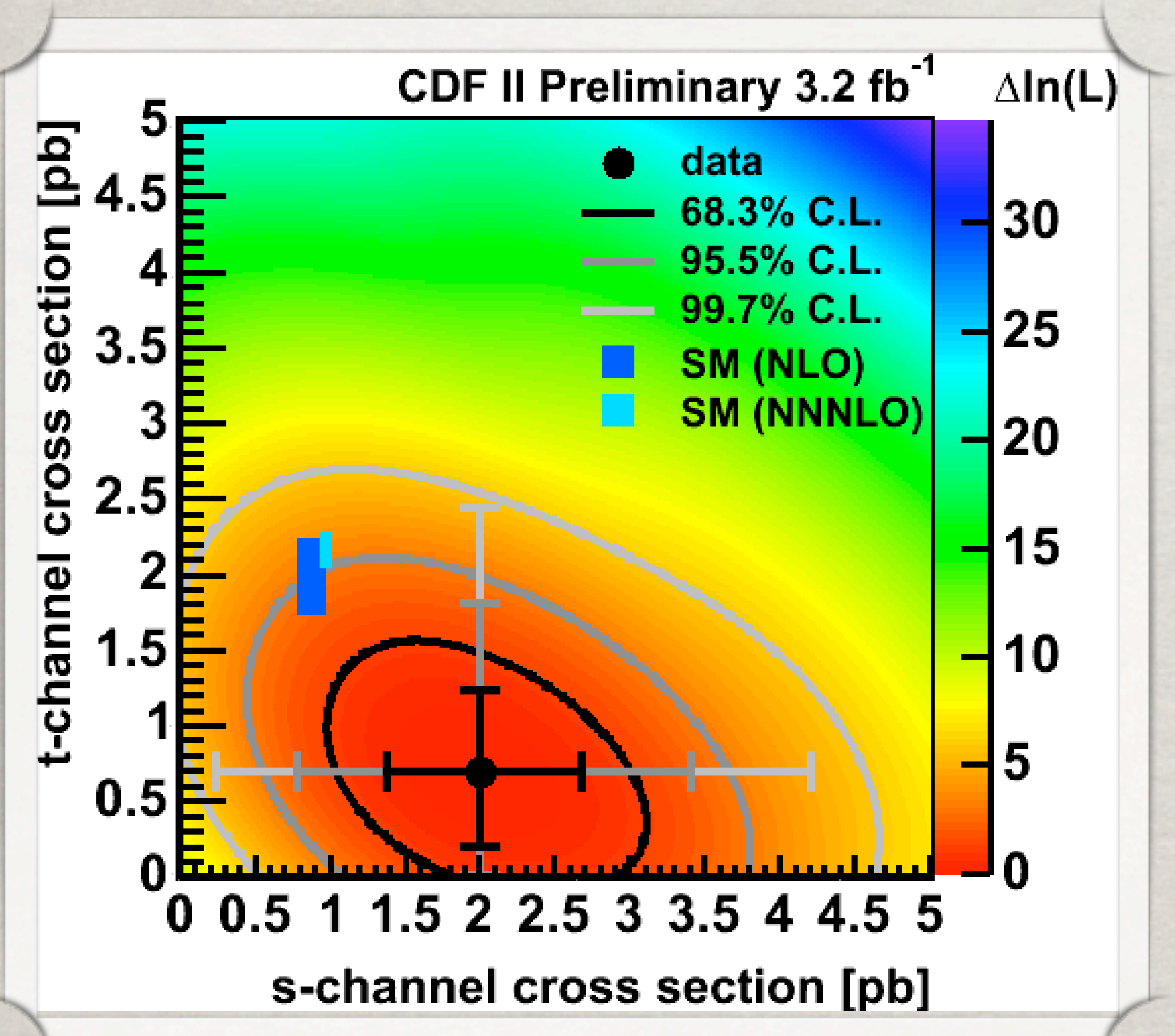
Consequences for single top observation?

- 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 this 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

...AND TO-DO LIST

- More detailed assessment of impact on current top quark studies:
  - Comparison with PS event generators
  - Effect on matrix element method
- Applications to fourth-generation heavy quark searches (t' and b')
- Inclusion of top quark decay
- Inclusion in a full shower MC (a la MC@NLO or POWHEG)