Top Quark Phenomenology

an overview

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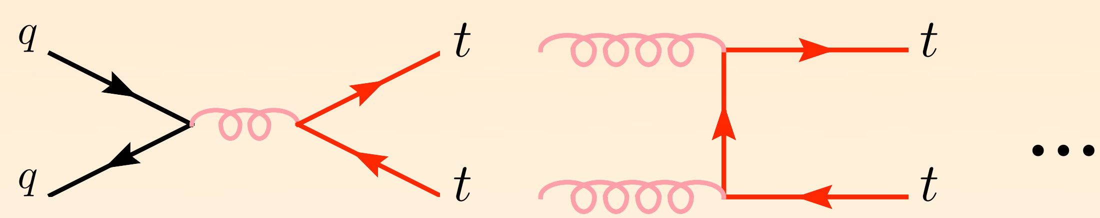
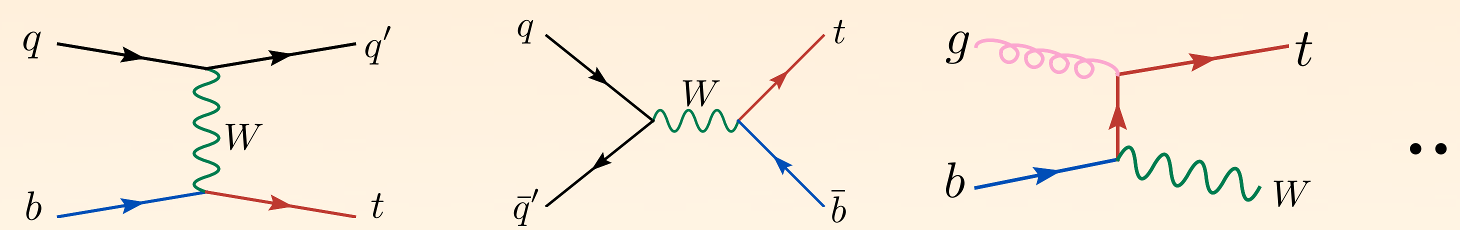
Top quark

- The top quark is the heaviest fundamental particle that we know
  m_t = 173.3 ± 1.1 GeV
- Because of its heavy mass, its Yukawa coupling is of order 1 in SM
- Two production mechanisms:
  - top pair production



  - single top production



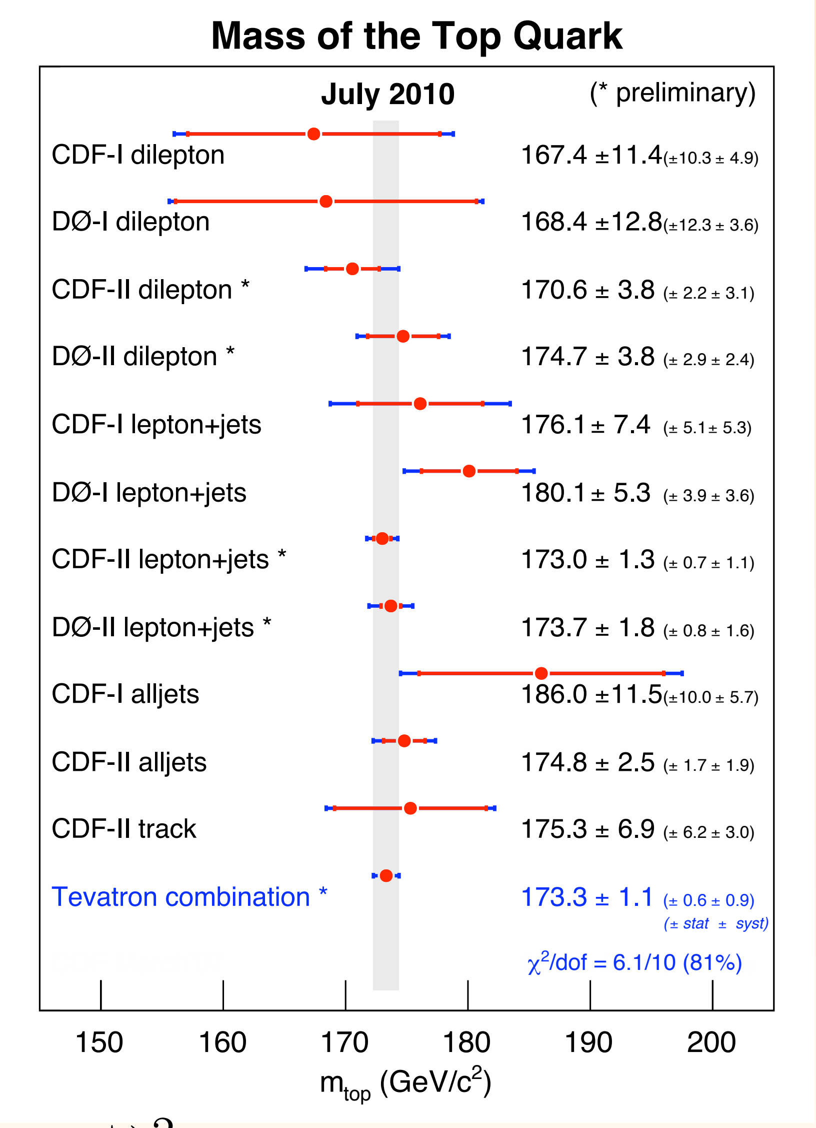
- Top quarks do not hadronize (its decay is an order of magnitude faster than the hadronization time). Opportunity to study a “bare” quark:
  - Spin properties
  - Interaction vertices
  - Top quark mass
- Decays almost exclusively to $t \to W^+ b$ in the SM: $|V_{tb}|^2 \gg |V_{ts}|^2, |V_{td}|^2$

Top quarks at the Tevatron

- Everything we know about the top quark we know from the Tevatron
- Discovery in 1995
- $O(10^3)$ top pairs produced (after selection/acceptance), cross section is ~7 pb.
- Mainly (~85 %) from quark-anti-quark annihilation
- Produced close to threshold in a $^3S_1[8]$ state, spins in same direction, 100% correlated in the off-diagonal basis
- Only last year also single top discovery, cross section is ~2 pb.

TEVATRON RESULTS TOP PAIR

- Top quark mass is a fundamental parameter of the SM. Its relative precision (0.75%) is the highest among all the quarks $m_t = 173.3 \pm 1.1$ GeV



- Total top pair cross section (input: $m_t = 175$ GeV)

$$\sigma_{t\bar{t}} = \frac{N_{\rm data} - N_{\rm bkgr}}{\epsilon L} = 7.0 \pm 0.6 \text{ pb}$$

- W helicity fractions measured fitting the θ^*-distribution using a Template method

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^\star} = \frac{3}{4}F_0 \sin^2\theta^\star + \frac{3}{8}F_-(1-\cos\theta^\star)^2 + \frac{3}{8}F_+(1+\cos\theta^\star)^2$$

$$F_0 + F_+ + F_- = 1$$

$$F_0 = 0.66 \pm 0.16 \pm 0.05, \qquad F_+ = -0.03 \pm 0.06 \pm 0.03$$

TEVATRON RESULTS TOP PAIR

SM- like

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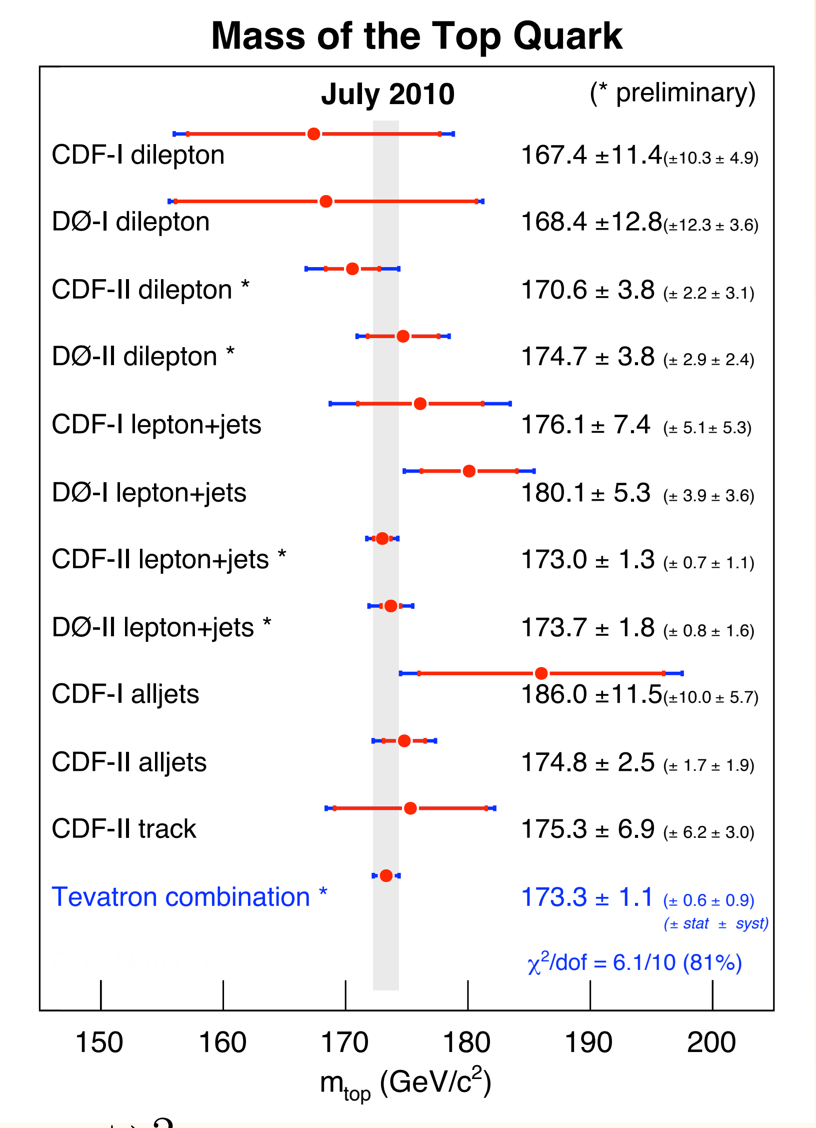

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Tevatron results top pair

- Spin correlations between the top quarks are measured by fitting a double distribution $\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1+\kappa\cos\theta_1\cos\theta_2)$ $\quad -0.455 < \kappa < 0.865\,(68\%\,CL)$
- Forward-backward asymmetry: $A_{FB} = 0.19 \pm 0.07 \pm 0.02$
- H_T distribution
- Decay width: $\Gamma_t < 13.1$ GeV at 95% C.L.
- Branching fraction: $(t\rightarrow W^+ b)/(t\rightarrow W^+ q) > 0.61$ at 95% C.L.
- Electric charge: $Q_t = -4/3$ excluded at 87% C.L.
- Anomalous couplings
- Resonance searches (spin-1 and spin-2)
- Decay to charged Higgs
- Search for heavy (4th generation) t'

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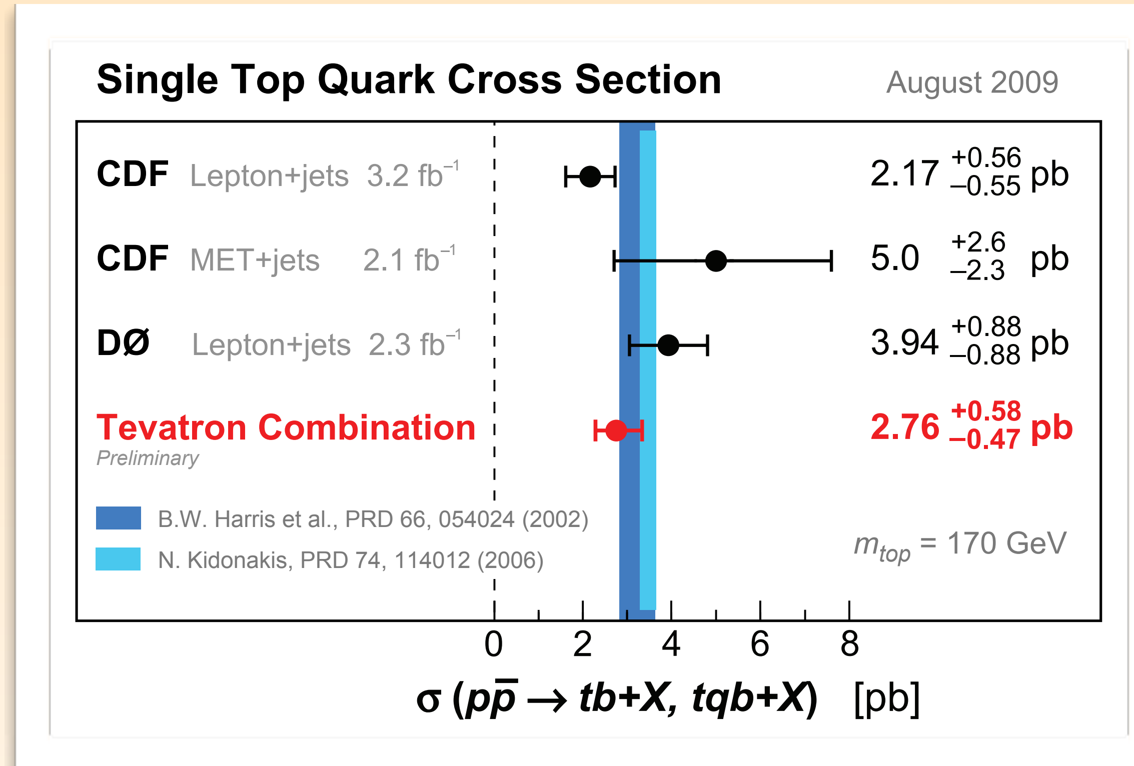
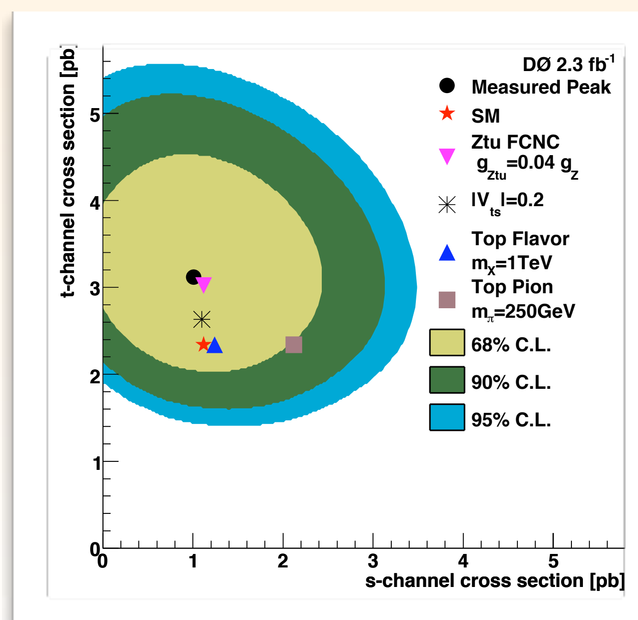
Tevatron results single top

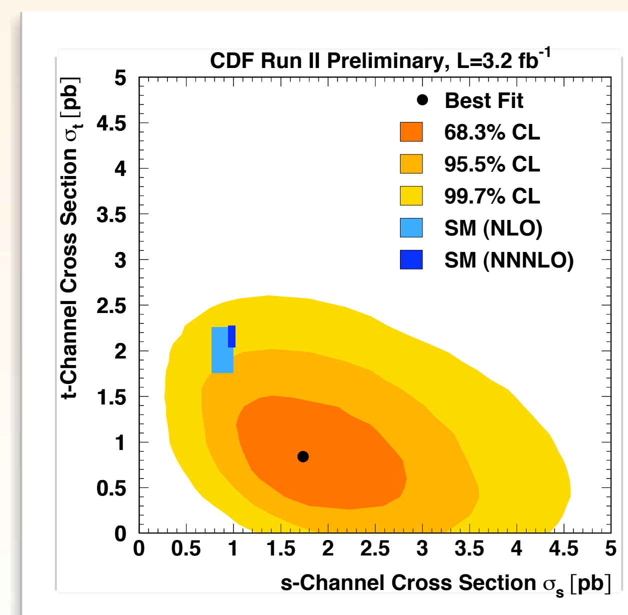
- Single top cross section



The CKM matrix element $|V_{tb}|$ is close to one in the SM, extracted value from the total cross section is $|V_{tb}| = 0.88 \pm 0.07$

- s- versus t-channel





Tevatron results single top

SM- like

✓ ✺ Single top cross section

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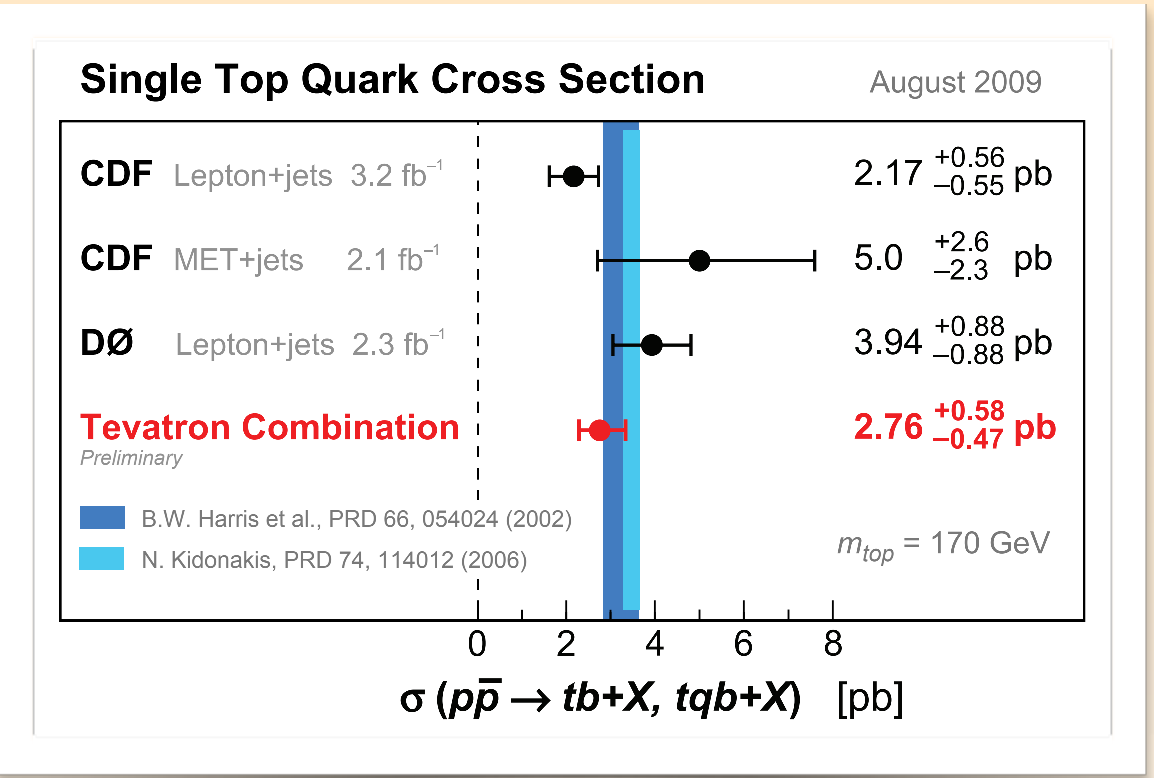
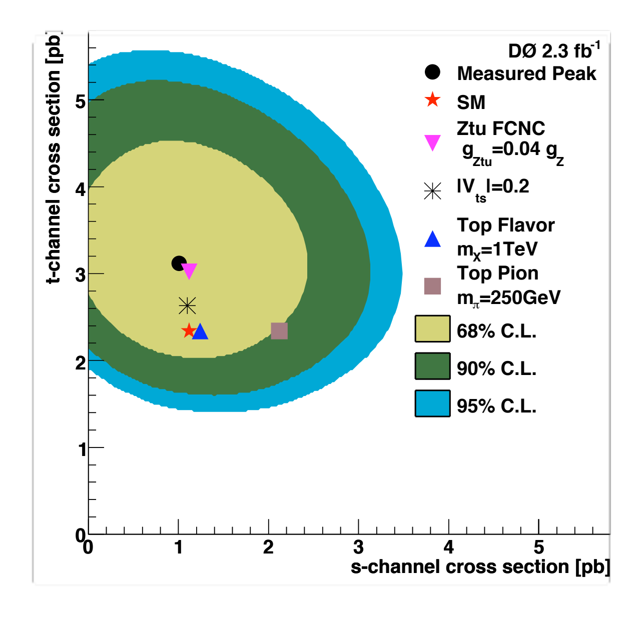
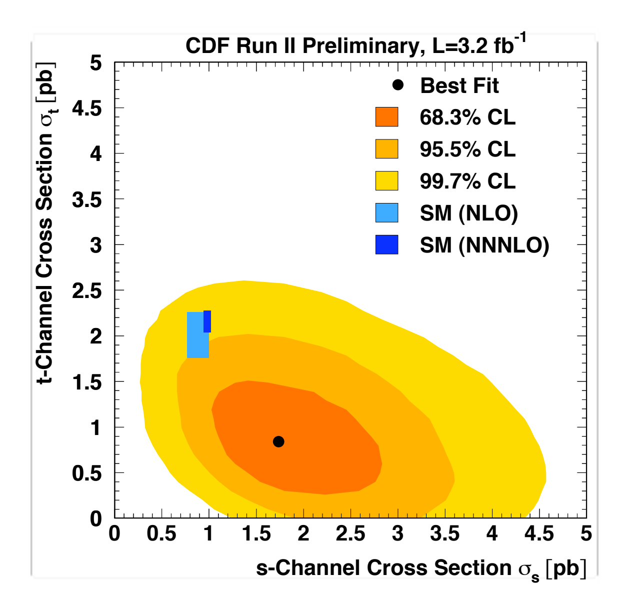




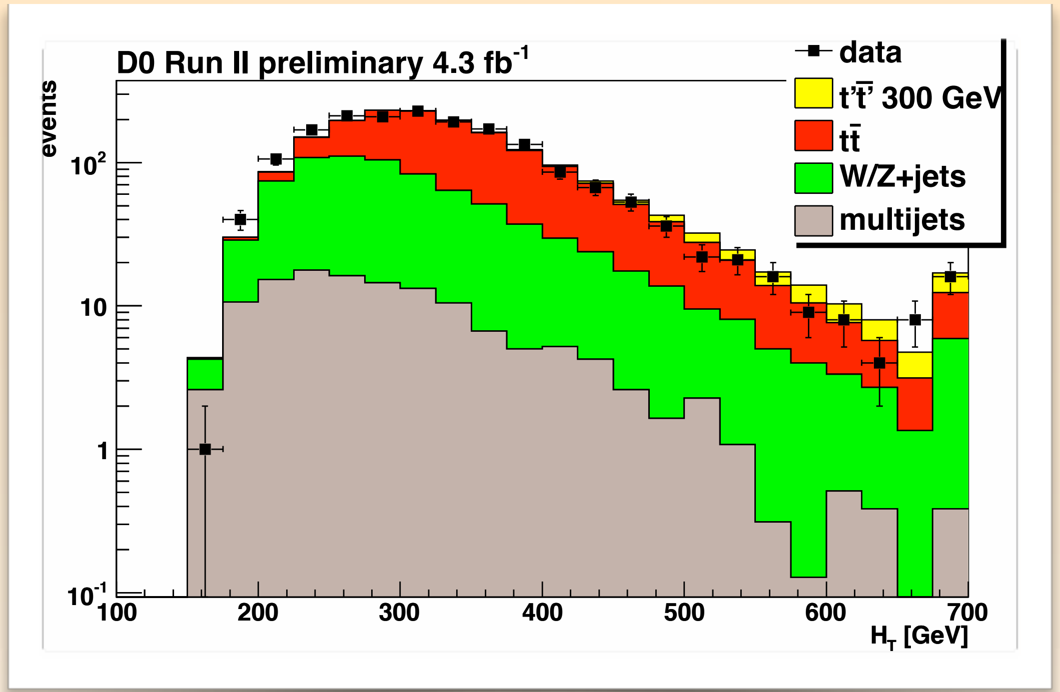


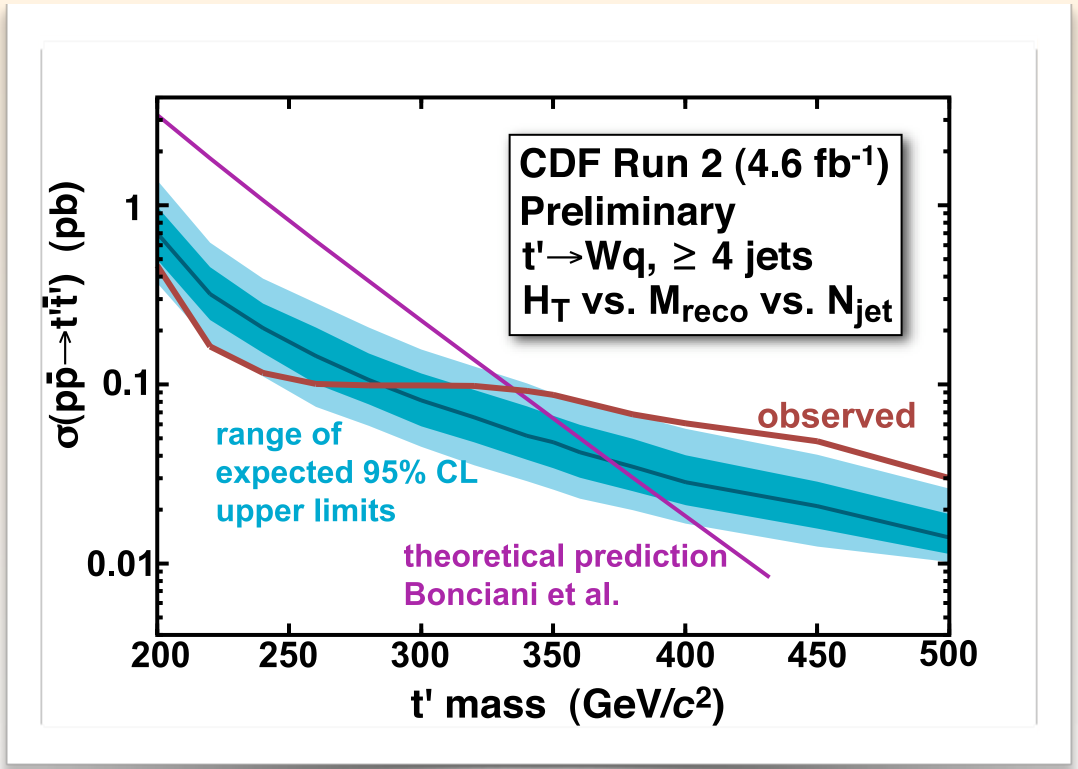
ANOMALIES IN TOP QUARK EVENTS

- There are a couple of measurements which are slightly off by 2-3 standard deviations compared to SM predictions
  - Excess in the H_T distribution (CDF & D0)
  - Top pair charge asymmetry (CDF & D0)
  - s- versus t-channel cross sections in single top (only CDF)
- Statistical fluctuations?

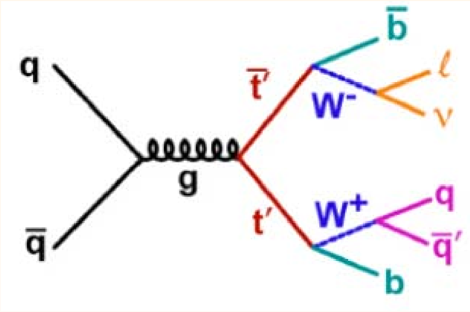
H_T DISTRIBUTION

2 sigma excess





- Both D0 and CDF have an ~2 sigma excess in the tail of the H_T distribution
- H_T is the (scalar) sum of all E_T's, known to be difficult to model with MC: sensitive to higher order effects
- Nothing to see in the top pair invariant mass
- Compatible with a t' of 450 GeV
- More data (or LHC!)will tell

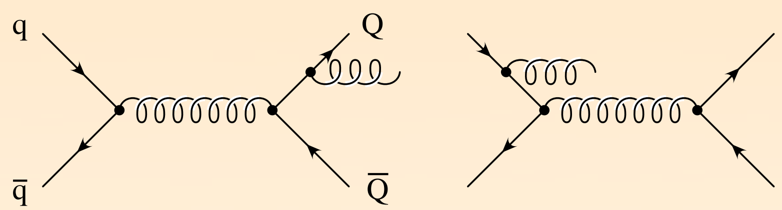


Top pair charge asymmetry

Top pair charge asymmetry

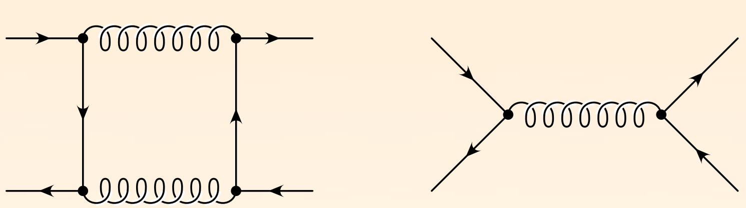
Kühn, Rodrigo 1998

At leading order: top and anti-top have identical angular distributions



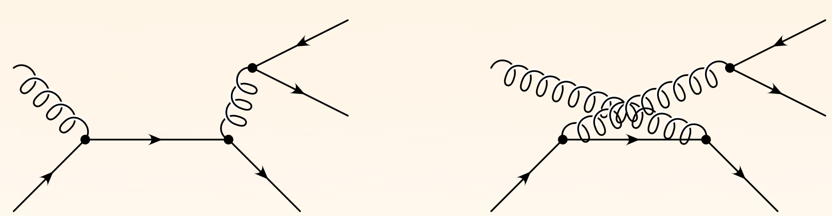
(a) (b)

Real emission corrections: **negative** contribution



(c) (d)

Virtual corrections: **positive** contribution



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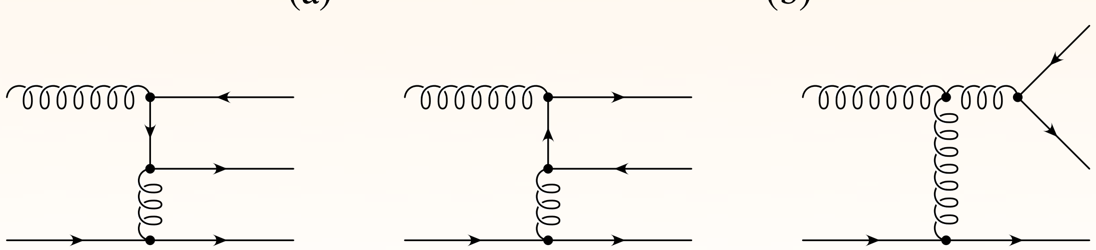

(c) (d) (e)

Real emission flavor excitations: negligibly small

Top pair charge asymmetry

Kühn, Rodrigo 1998

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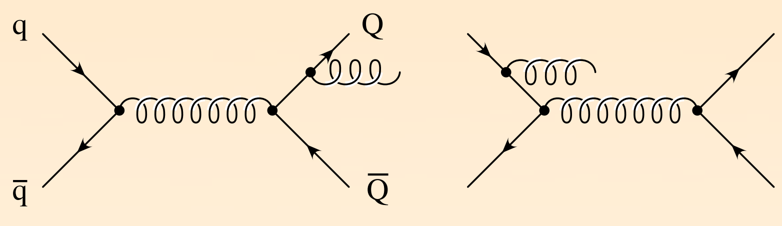

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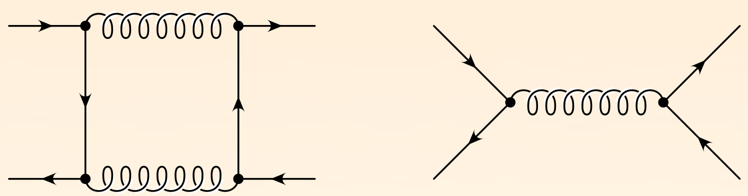


(c) (d)

Virtual corrections: **positive** contribution

Corrections from the virtuals are larger than the real emission corrections:

Top quarks are preferentially emitted in the direction of the incoming quark

Quantitive description

- Due to CP invariance, charge asymmetry is the same as forward-backward asymmetry. The precise definition is frame dependent

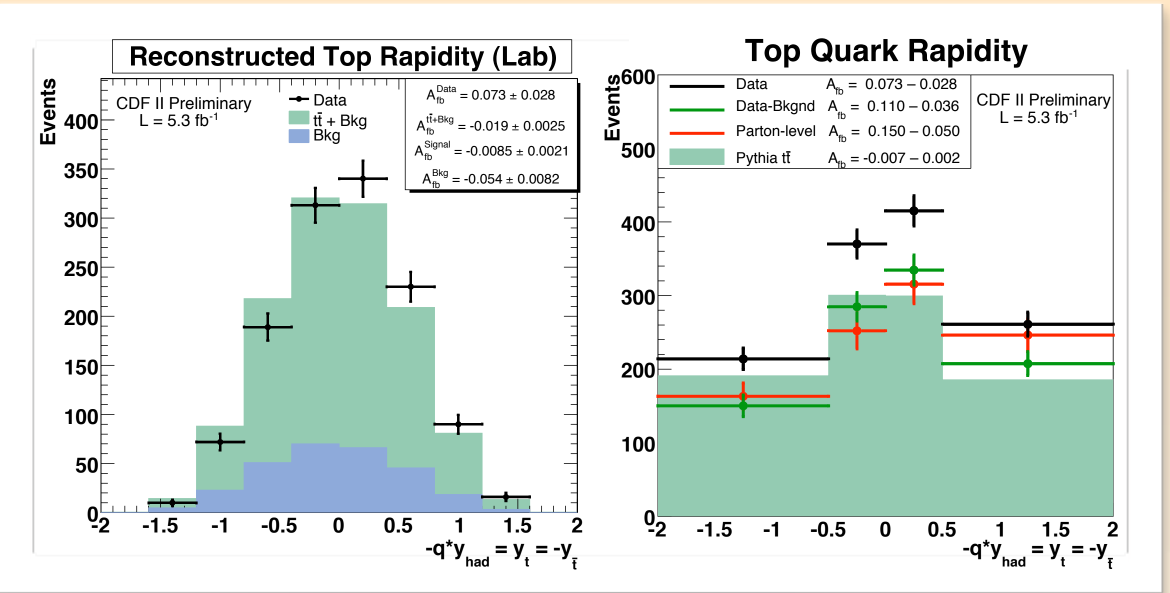
$$A_{fb}(\text{lab}) = \frac{\int\limits_{y>0} N_t(y) - \int\limits_{y>0} N_{\bar{t}}(y)}{\int\limits_{y>0} N_t(y) + \int\limits_{y>0} N_{\bar{t}}(y)}$$

$$A_{fb}(\text{ttbar}) = \frac{\int N(\Delta y > 0) - \int N(\Delta y < 0)}{\int N(\Delta y > 0) + \int N(\Delta y < 0)}, \quad \Delta y = y_t - y_{\bar{t}}$$

- Theory (NLO+EW, *Kühn, Rodrigo*):
  A_{fb}(lab) = 0.051 ± 0.006
  A_{fb}(ttbar) = 0.078 ± 0.009

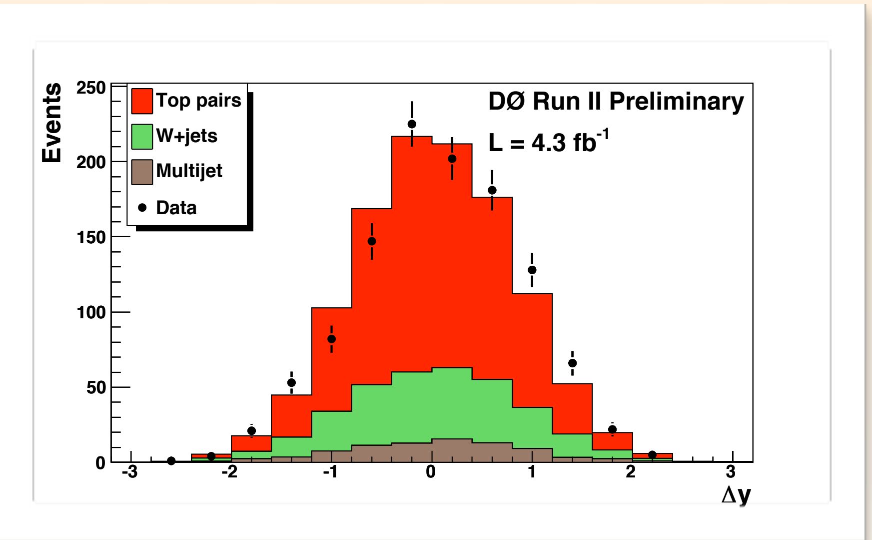
- Results are very stable when including threshold logarithms
  A_{fb}(ttbar) = 0.073 + 0.011 - 0.007 (NLO+NNLL, *Ahrens et al. 2010*)

Results



- CDF (5.3 fb-1):
  A_{fb}(lab) = 0.073 ± 0.028 (uncorrected)
  A_{fb}(ttbar) = 0.057 ± 0.028 (uncorrected)

  Corrected (bkg, and parton level):
  A_{fb}(lab) = 0.150 ± 0.050 stat ± 0.024 syst
  A_{fb}(ttbar) = 0.158 ± 0.072 stat ± 0.017 syst



- DØ (4.3 fb-1):
  A_{fb}(ttbar) = 0.08 ± 0.04 stat ± 0.01 syst (uncorrected)

- Theory:
  A_{fb}(lab) = 0.051 ± 0.006 (NLO+EW, *Kühn, Rodrigo*)
  A_{fb}(ttbar) = 0.073 + 0.011 - 0.007 (NLO+NNLL threshold resum, *Ahrens et al.*)

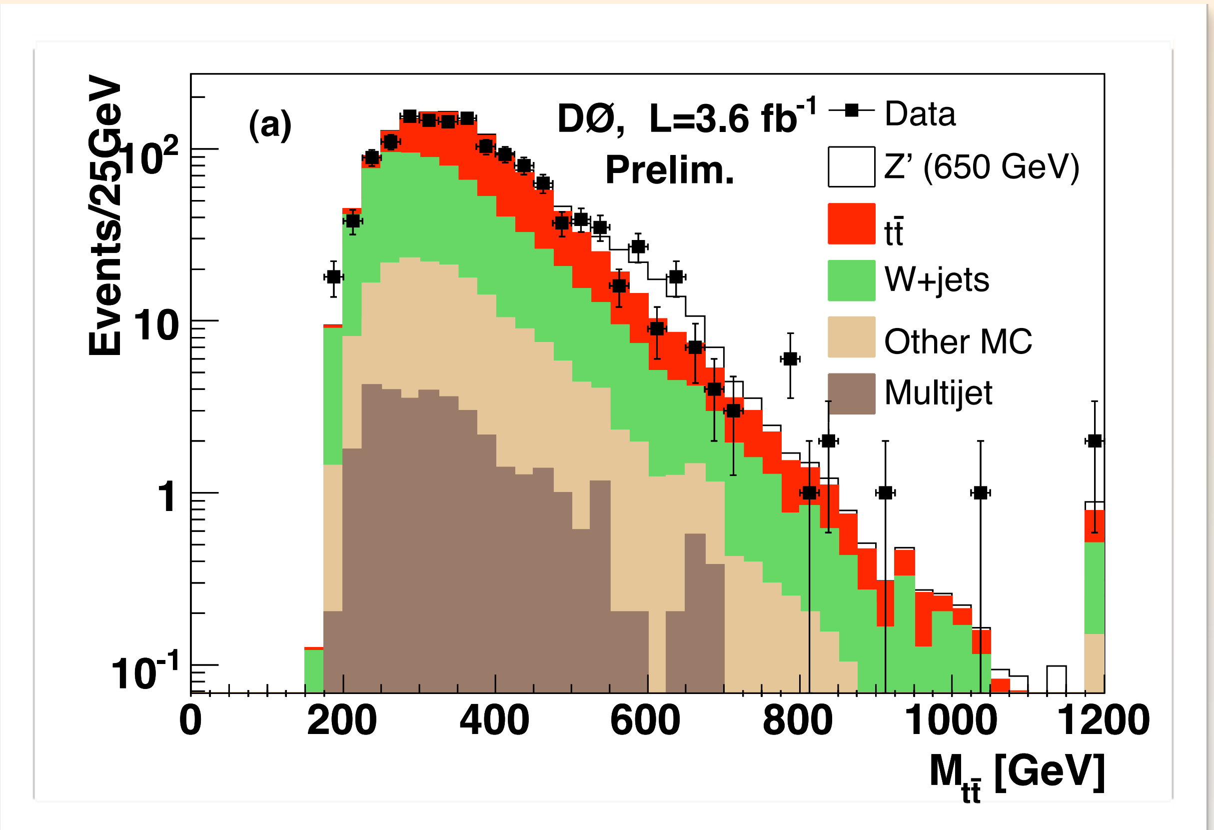
Difference between theory and experiment is sizable, but below 2 sigma

BSM

- Many BSM models studied
  Djouadi, Moreau, Richard, Singh, Jung, Murayama, Pierce, Wells, Cheung, Keung, Yuan, Frampton, Shu, Wang, Tait, Arhrib, Benbrik, Chen, Ferrario, Rodrigo, Dorsner, Fajfer, Kamenik, Kosnik, Ko, Lee, Nam, Cao, Heng, Wu, Barger, Yu, Antunano, Kuhn, McKeen, Rosner, Shaughnessy, Wagner, ... and many more ...

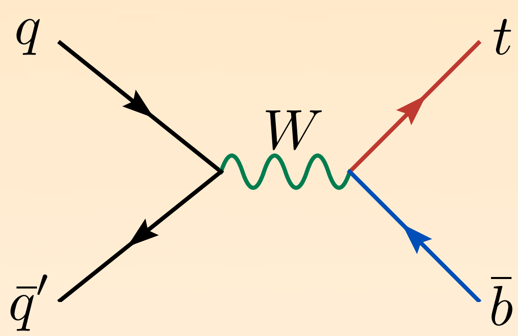
- Not trivial to find a model: invariant mass agrees well with SM predictions

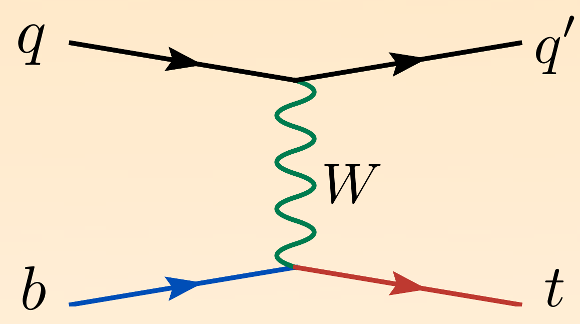
- Need for full NNLO, i.e. first complete corrections to charge asymmetry



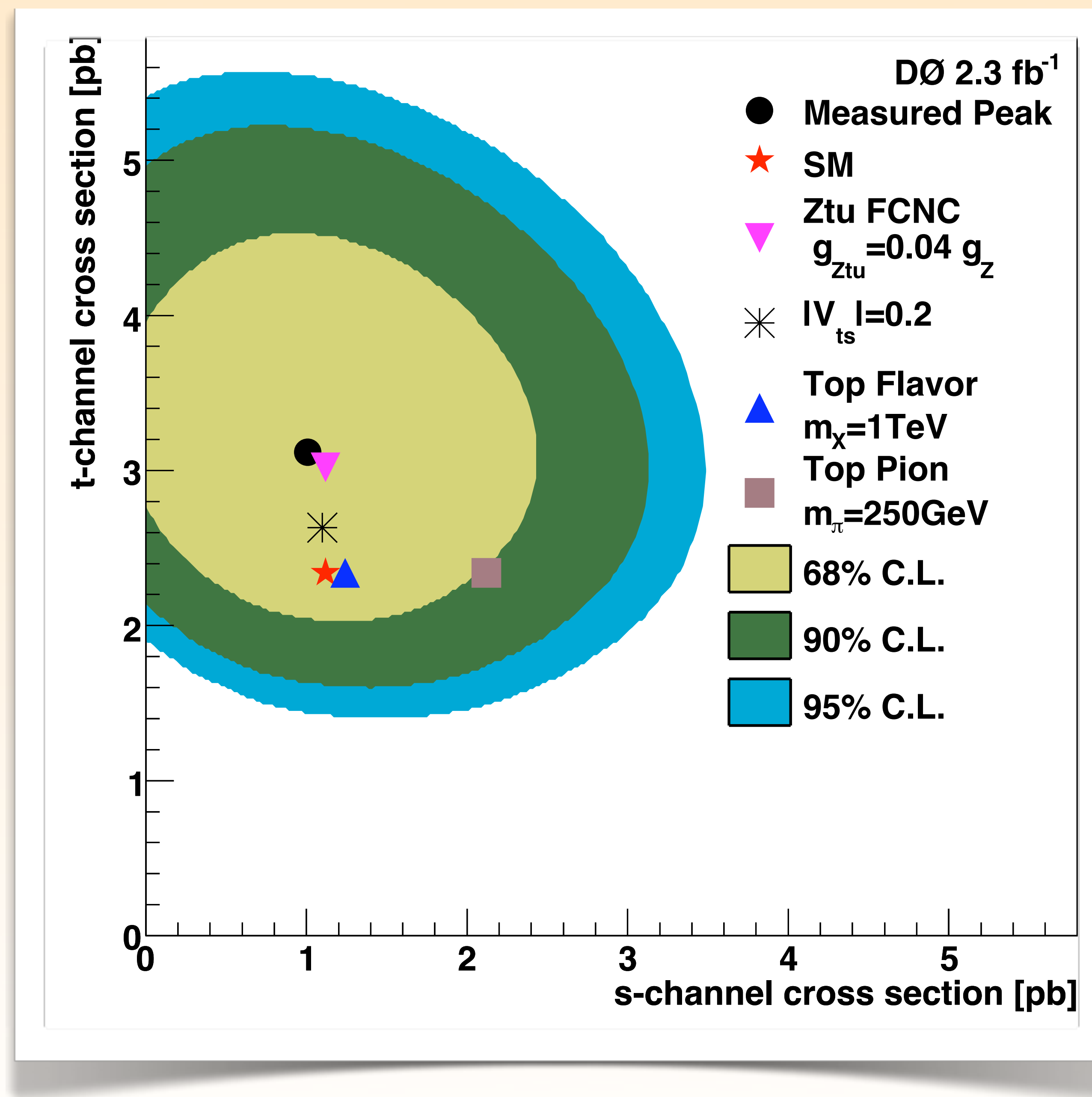
S- & T-CHANNEL SINGLE TOP

S- VERSUS T-CHANNEL CROSS SECTION



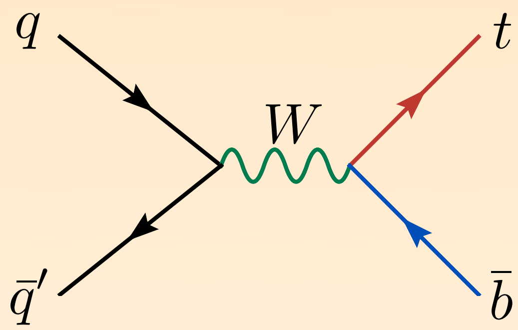


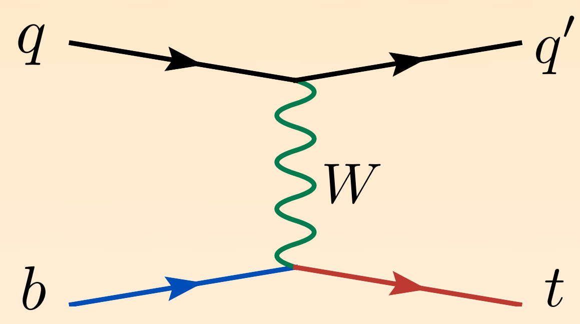
DØ



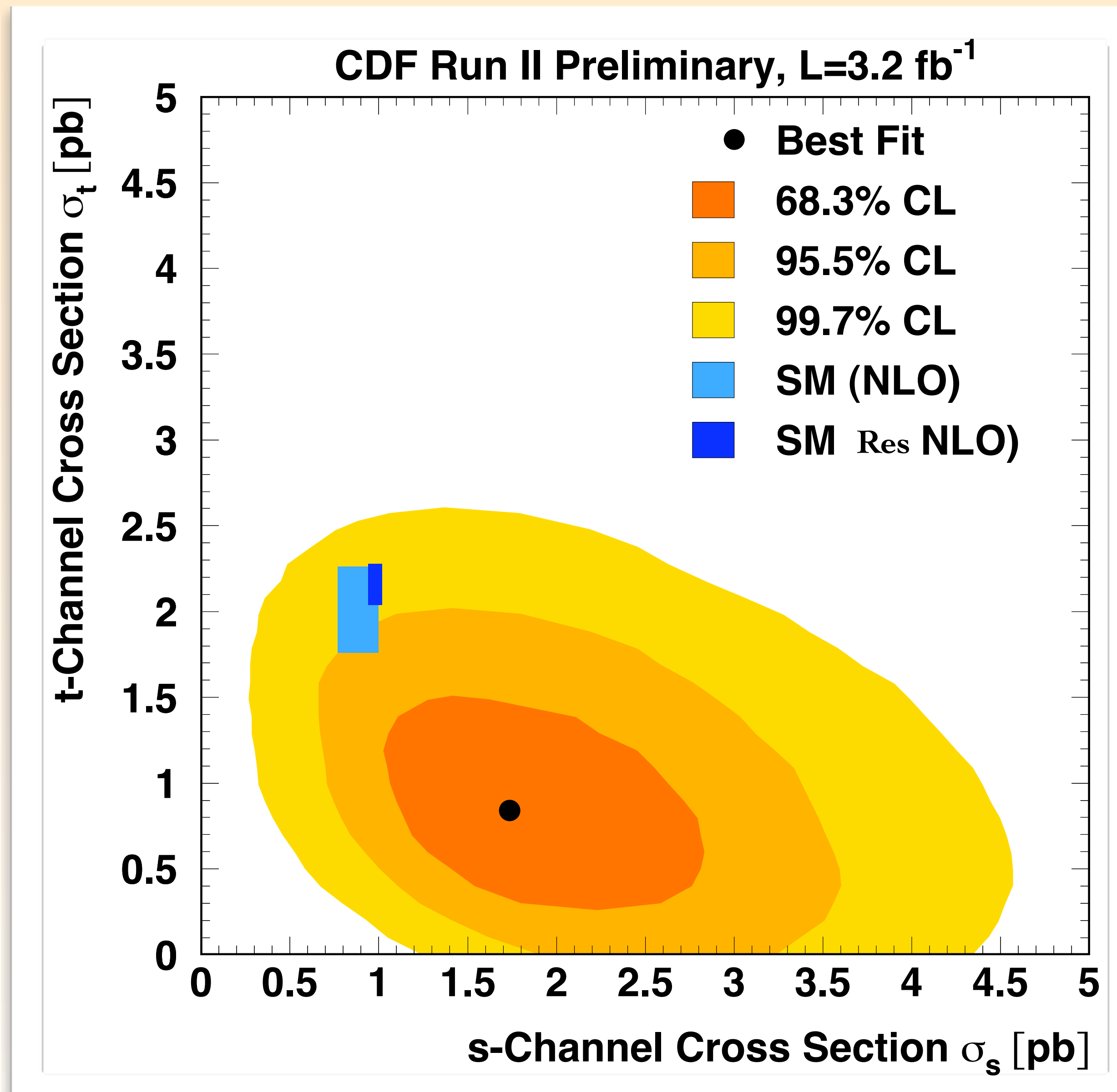
- Multivariate techniques are used to discriminate between s- and t-channel events
- Naively, the difference is the one more b jet for the s-channel events
- Sensitive to MC predictions
- How to treat initial state b quark?

S- VERSUS T-CHANNEL CROSS SECTION





CDF



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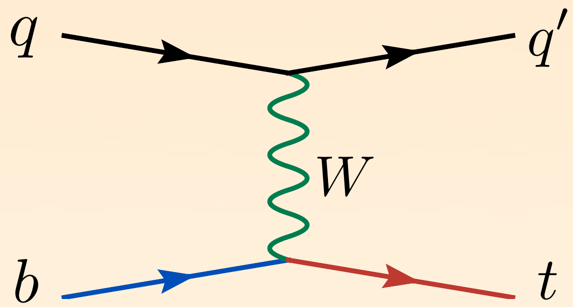
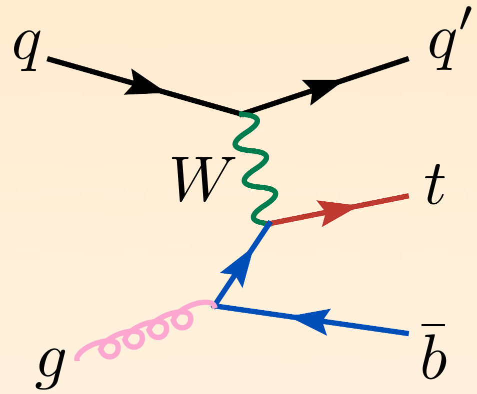
Initial state b quark

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



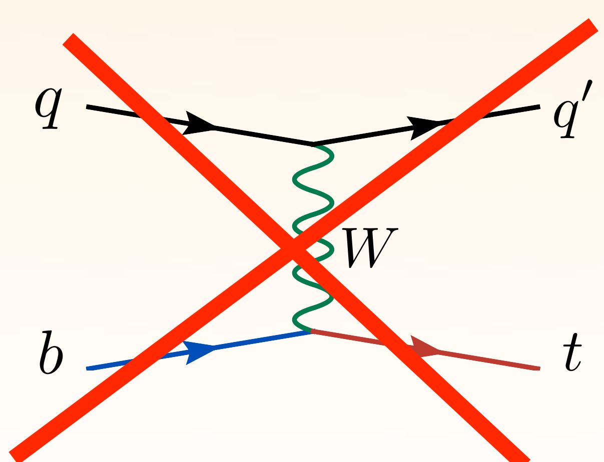
leading order



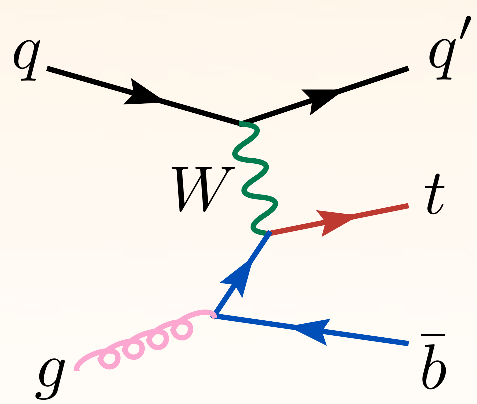
(contribution to) NLO

5-flavor scheme

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



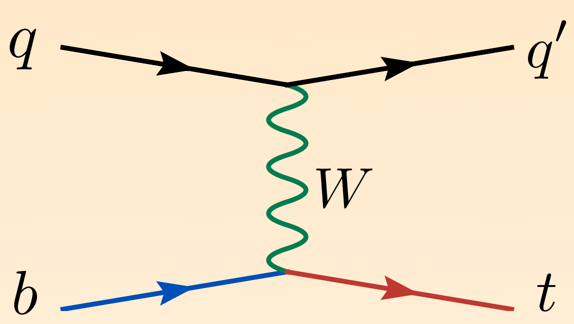
Does not exist



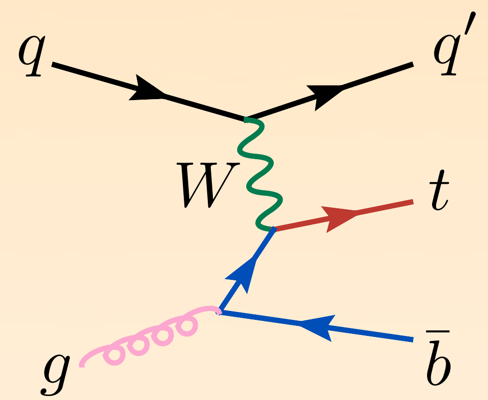
(part of) leading order

4-flavor scheme

The two schemes



5-flavor scheme: "2 ➞ 2"

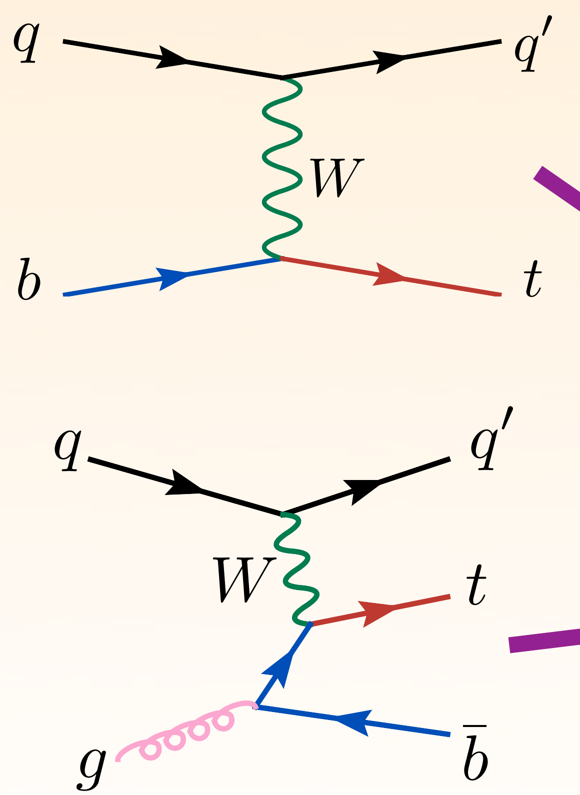


4-flavor scheme: "2 ➞ 3"

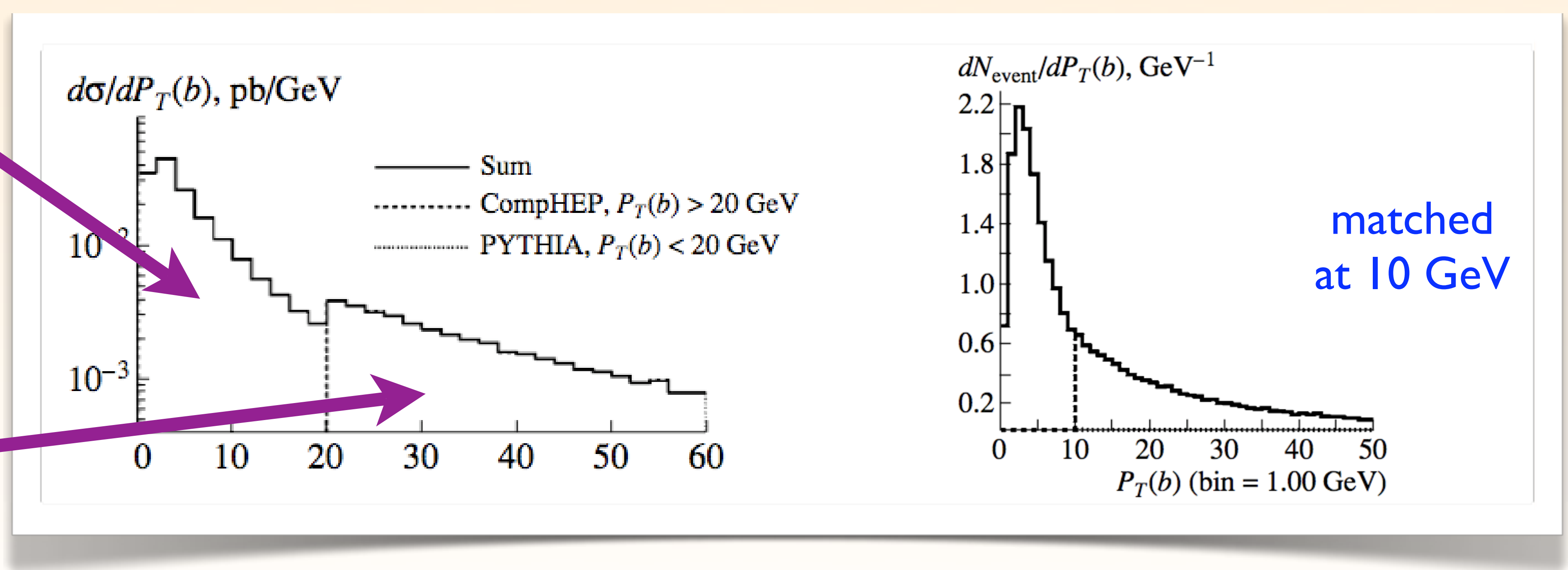
- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - available phase space
  - approximation by large logarithm

"Effective NLO" for t-channel

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



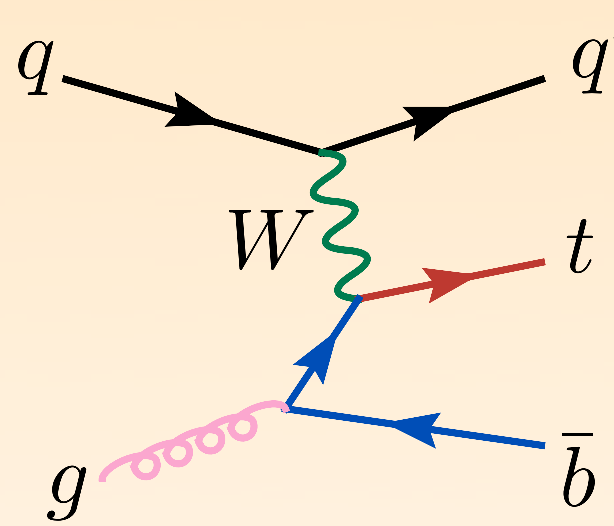
Boos et al., Phys. At. Nucl. 69, 1317 (2006)



- Ad hoc matching well motivated, but theoretically unappealing

Four-flavor scheme

Campbell, RF, Maltoni, Tramontano (2009)



- 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
- Process implemented in the *MCFM-v5.7* parton-level NLO code
  - Starting point for future NLO+PS beginning at $(2 \to 3)$

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 (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	$^{+7}_{-9}$	$^{+5}_{-5}$	$^{+3}_{-3}$	$^{+4}_{-4}$

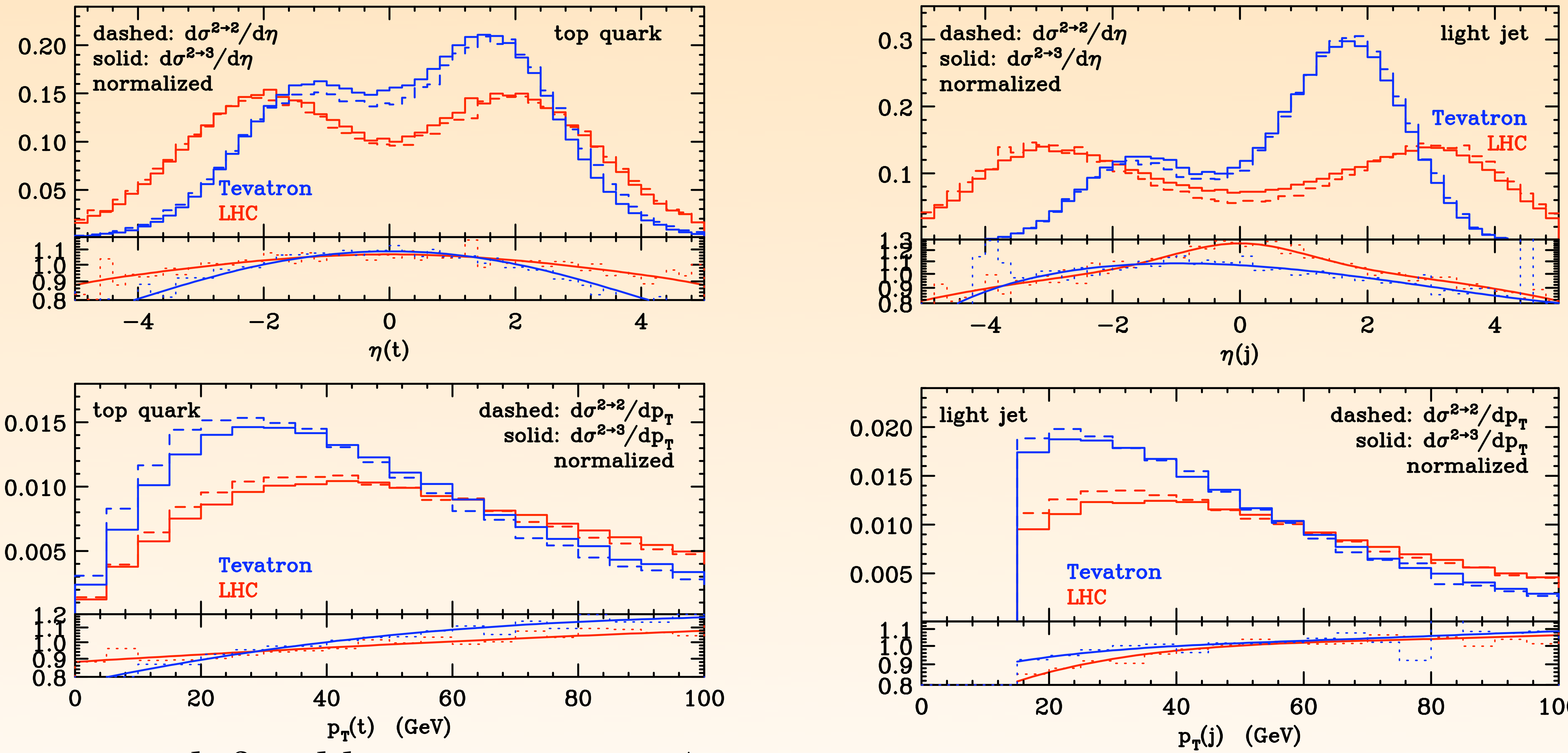
Fac. & Ren. scale

PDF

top mass

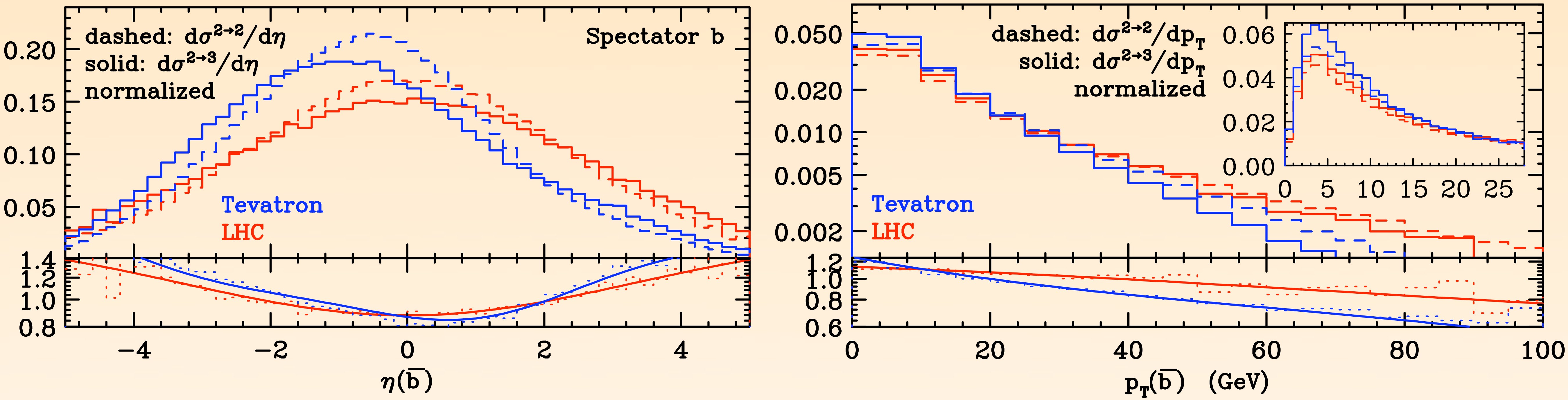
b mass

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
- 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%

More bottoms in 4F

- However, there are large differences between 5F (2 → 2) and 4F (2 → 3) schemes for more exclusive quantities in the spectator b quark
  - Event though b quarks in the 4F (2 → 3) scheme are more forward and softer, we expect to see more b's than in the 5F (2 → 2)
    - In 5F (2 → 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:

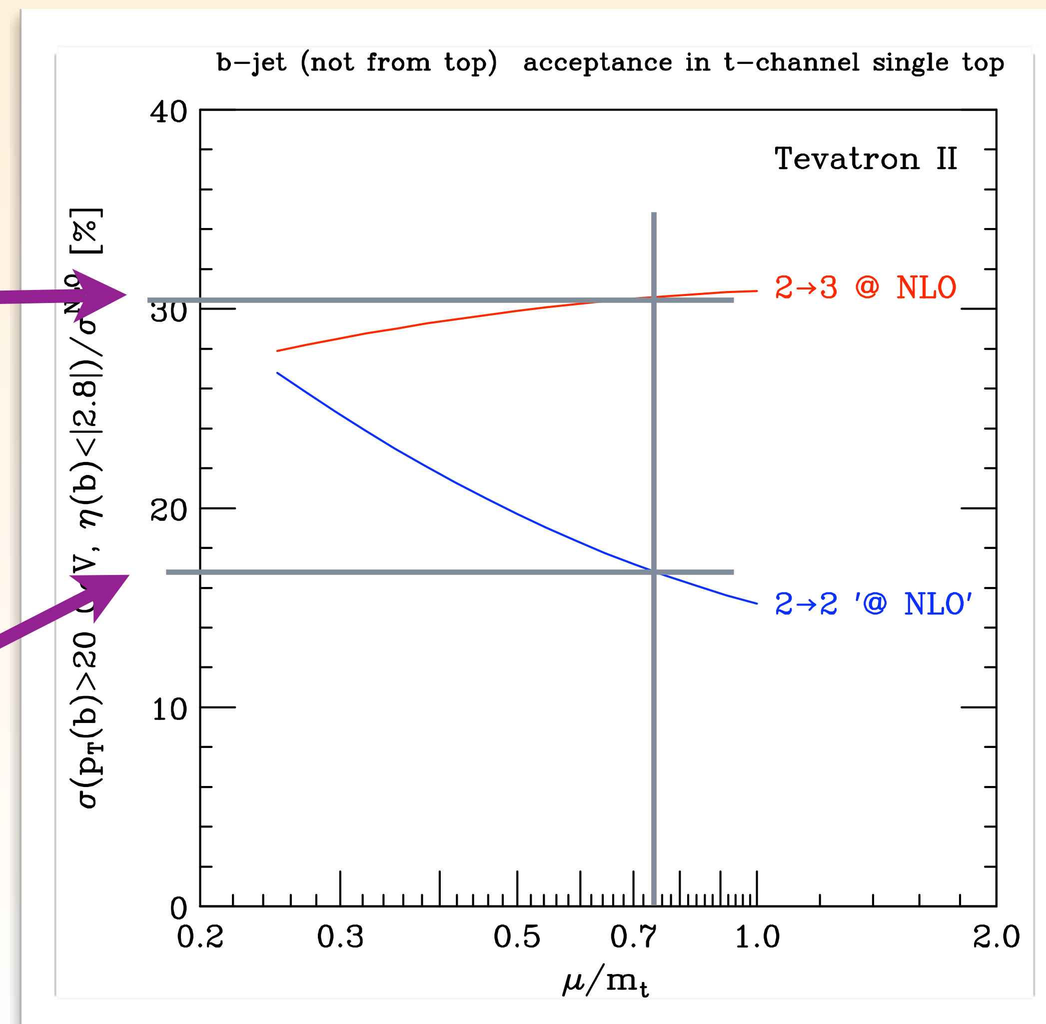
$$\frac{\sigma(|\eta(b)| < 2.5,\ p_T(b) > 20\ \mathrm{GeV})}{\sigma_{\mathrm{inclusive}}}$$

Acceptance

- In the Monte Carlo samples used by CDF (based on ZTOP), almost half as many b-jets (not from top decay) compared to best NLO predictions
  - What is the impact on the recent measurements for single top?
- DØ predictions are consistent with best theory prediction (by accident!)

Best theory prediction: 30.5%

Value from ZTOP: 16.7%

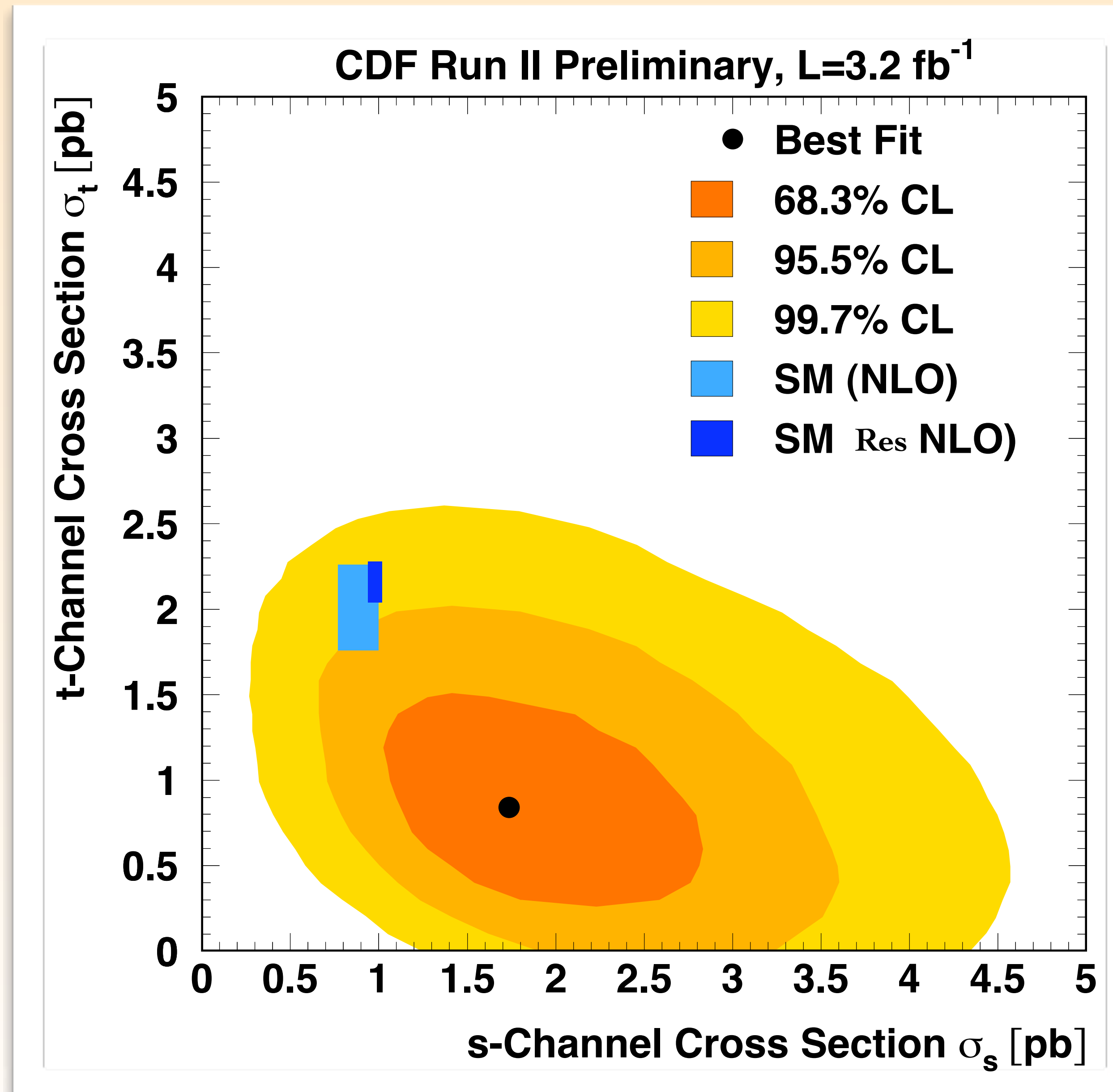


Impact on measurement

- Naively:

  Because

  - s-channel has one more b-jet in the final state compared to the 5 flavor t-channel, and
  - in the 4 flavor more t-channel events have the same # of b-jets as s-channel,
  - many t-channel events were assigned to the s-channel



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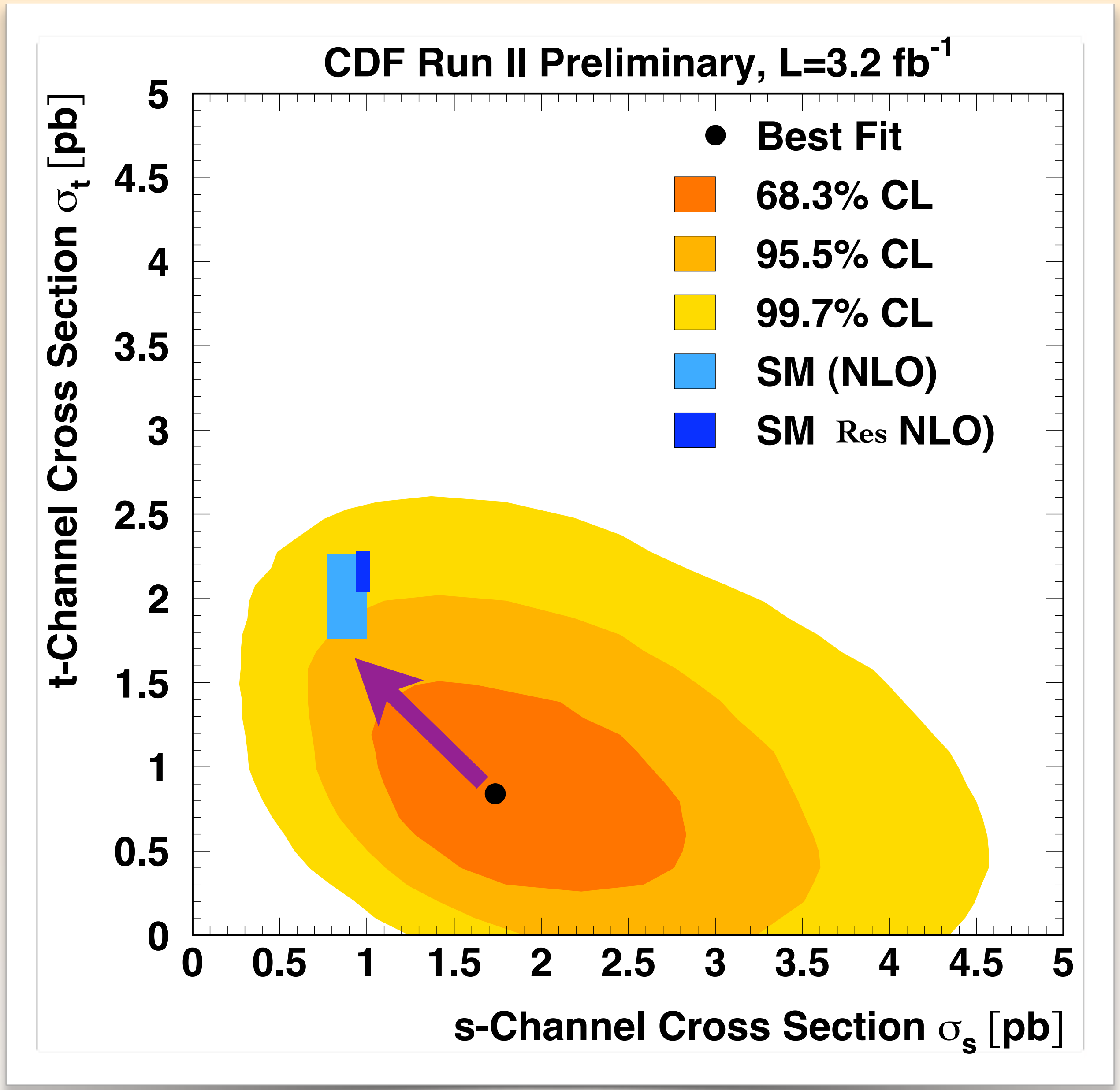
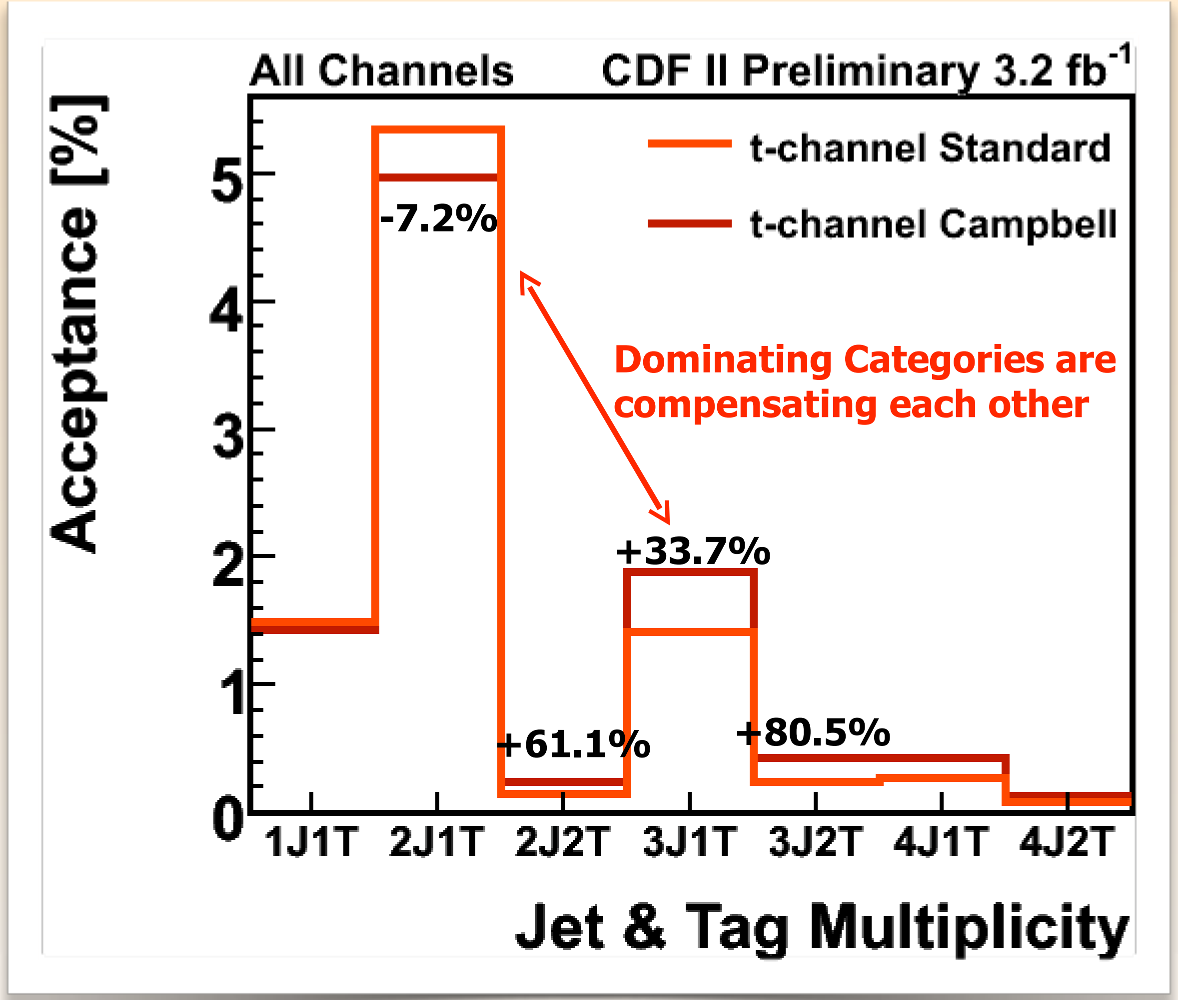


Impact on measurement

Jan Lueck et al. @ CDF

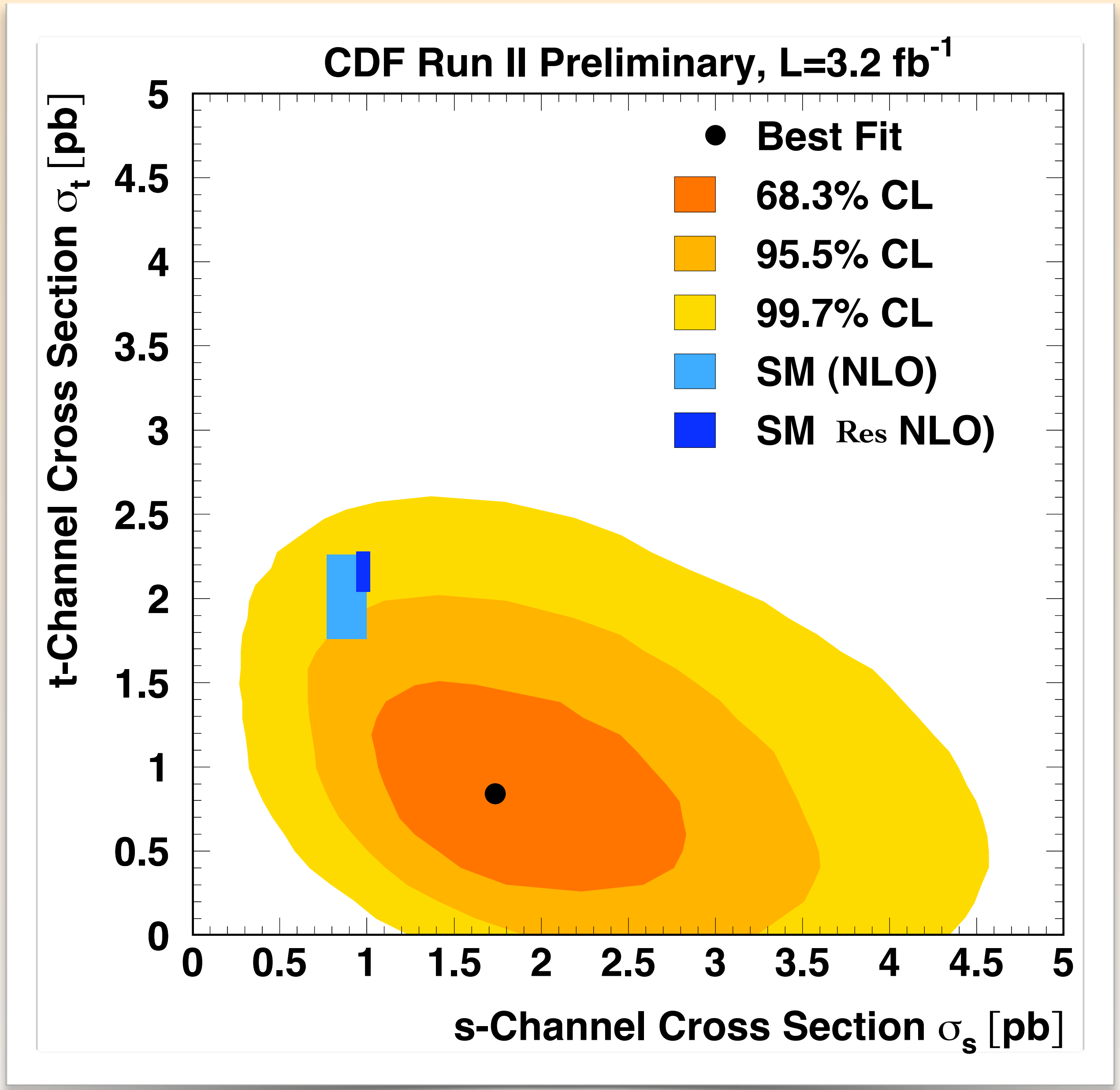
- In practice...
  It's slightly more complicated:

  Dominating categories are compensating each other. Large differences for channels with only minor contributions



Impact on measurement

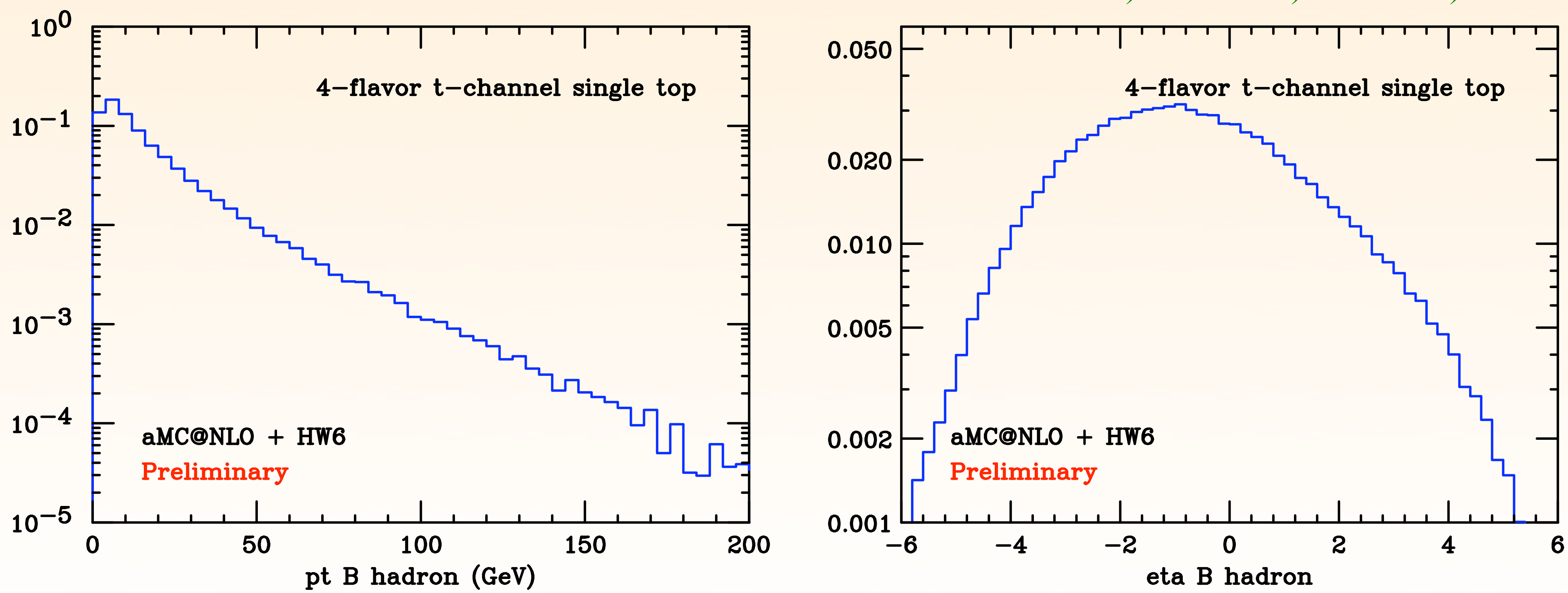
- So that the effects on the final results are negligible
- The 2 sigma deviation remains



Work in progress

- Work in progress is to match the NLO 4 flavor calculation to a parton shower a la MC@NLO (using the MadFKS framework)
- First results are promising and seem to confirm fixed order calculations, but need more work to check results

RF, Frixione, Maltoni, Torrielli



Conclusions

- No clear hints, but there are a couple of 2 sigma deviations in the SM top quark sector
  - H_T distribution: slight excess, but observable is quite sensitive to extra radiation
  - Need for complete NNLO computation for the top quark charge asymmetry
  - s- versus t-channel deviation by CDF not explained by new NLO calculation: work in progress to match this to a parton shower for event better description
- **Exciting times with the LHC starting to produce top quark events**