A fresh look at single top production

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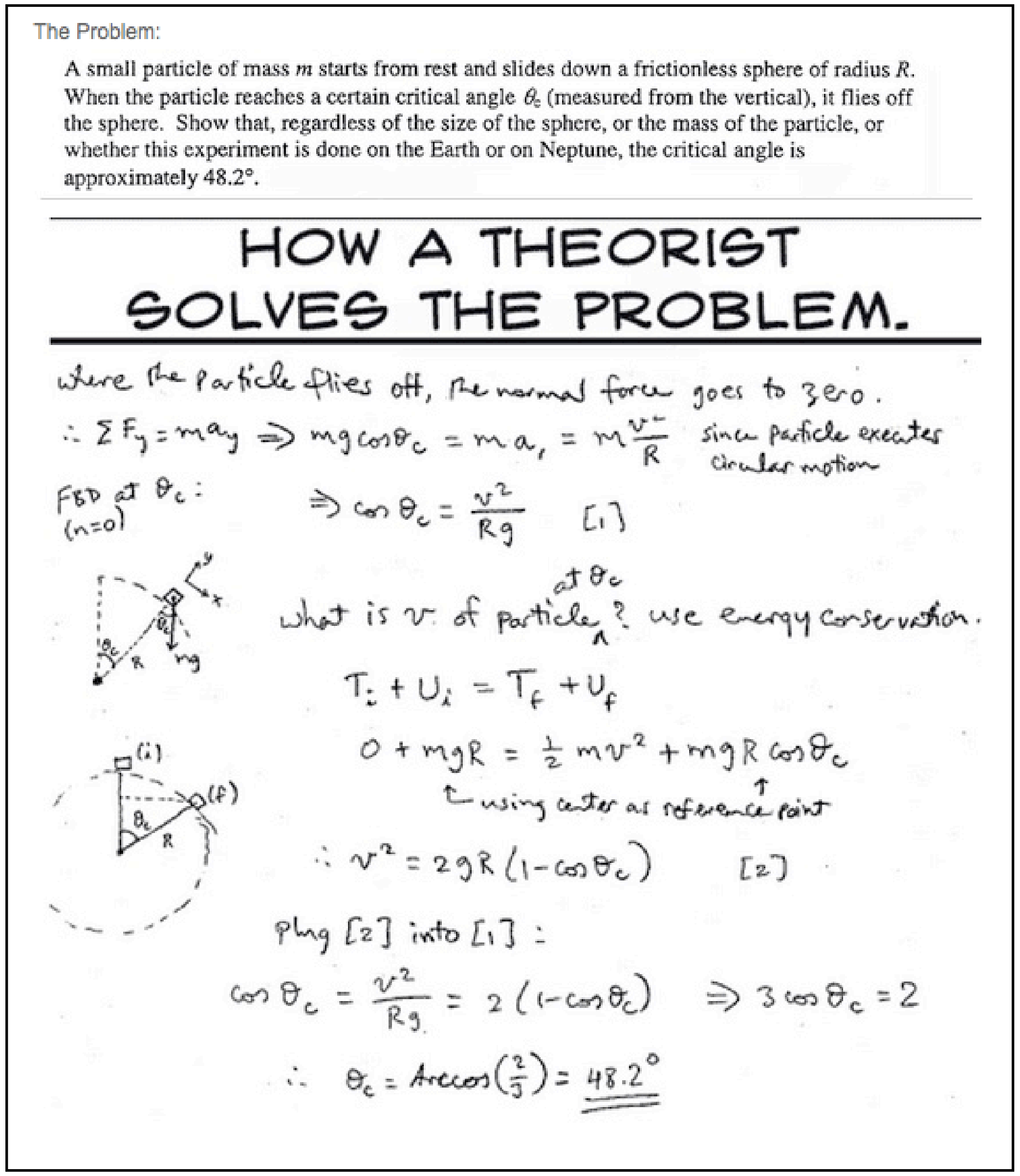
University of Glasgow

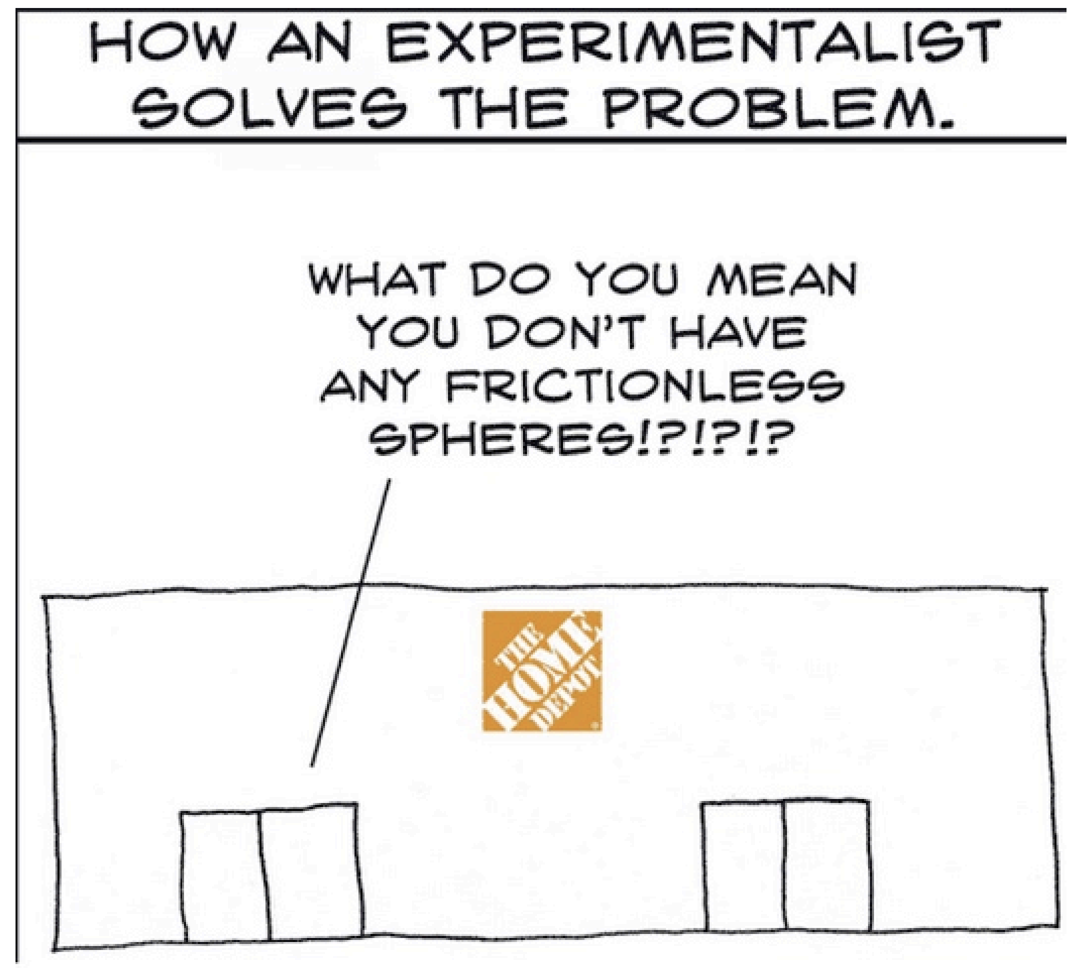
Fermilab Wine & Cheese, March 6 2009.

Full disclosure

- I am a theorist.



http://www.brightlywound.com/



- Those expecting a different talk will have to wait until next Tuesday.

Congratulations!

- This week has been momentous for everyone involved in CDF and D0.
- The culmination of many years of heroic endeavor.

CDF
(arXiv: 0903.0885)

"We observe single top production for the first time with a significance of 5 standard deviations."

D0
(arXiv: 0903.0850)

"The measured single top quark signal corresponds to an excess over the predicted background with a significance of 5.0 SD"

Motivation for single top

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

Clean measurement of different channels

Better theory predictions

Sensitivity to SM params, new physics

Exp't

Theory

Understand utility of different approaches

Improved analysis techniques

Improved phenomenology

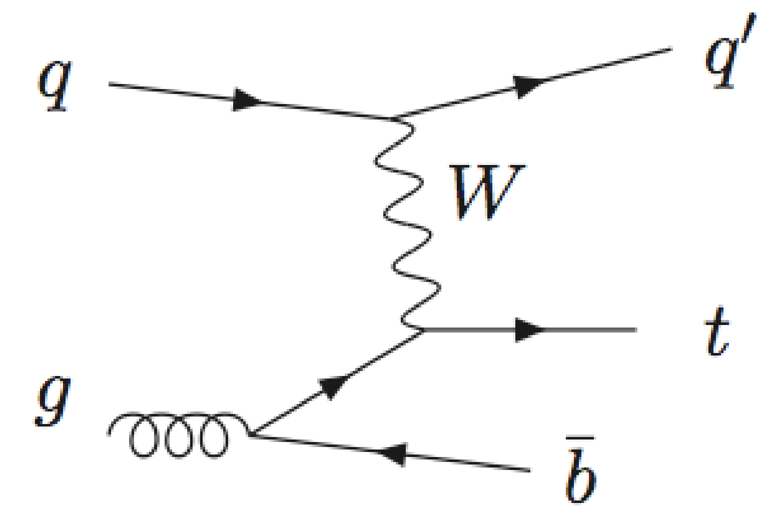
Better physics potential at the LHC

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

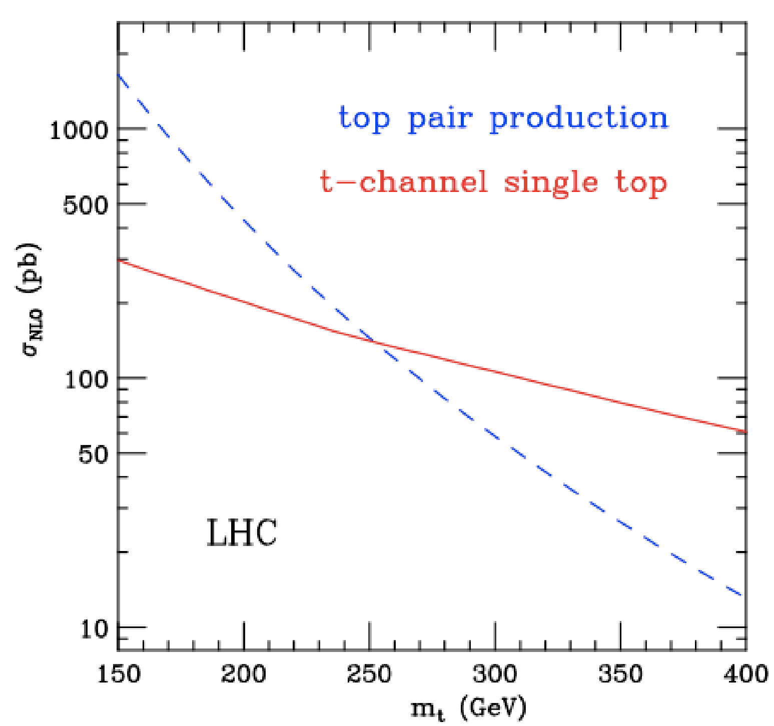
History

- The idea of single top production has been with us for ~ 20 years.

  Dicus & Willenbrock, PRD34, 155 (1986)



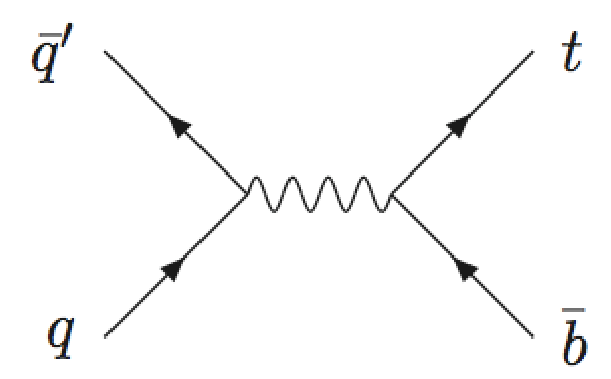
- Take advantage of:
  - t-channel rather than s-channel growth;
  - more available phase space.
- Collinear enhancement of the form log(Q/m_b) with Q ~ m_t.



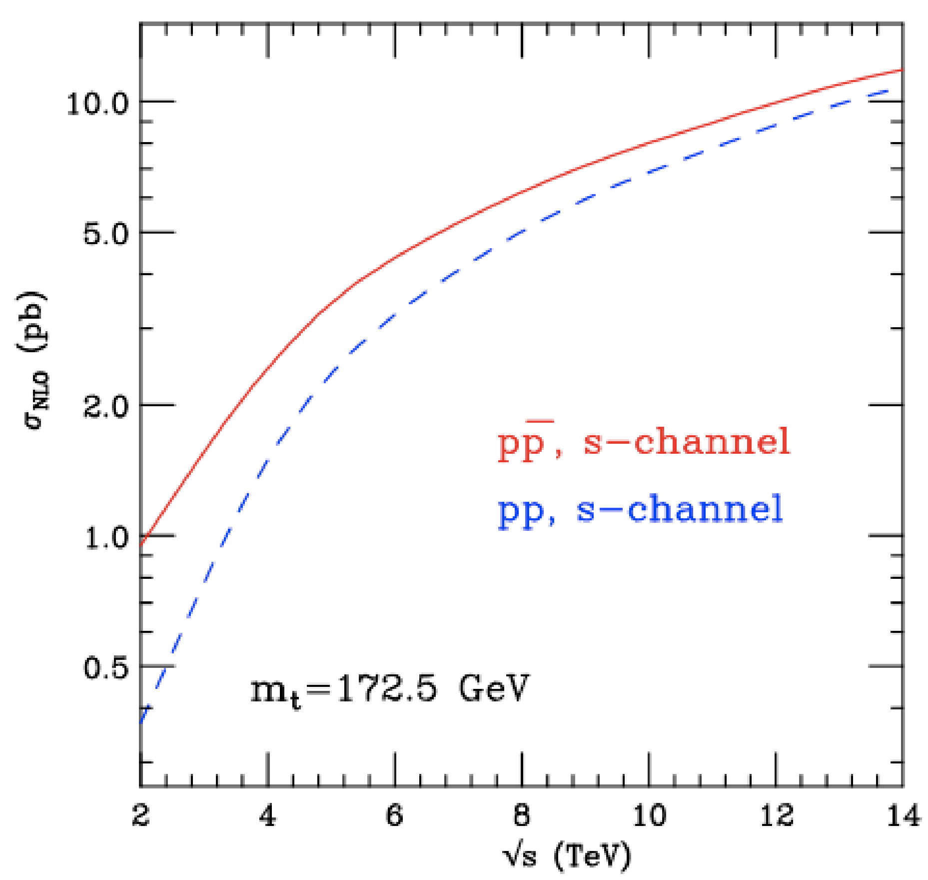
- Initial motivation was for very heavy quarks, where single production dominates.
- Large cross sections at the LHC, a useful probe of possible t' production.
- Mechanism is sensitive to V_{tb} in the production stage, FCNC, ...

s-channel single top

- The other main channel is just Drell-Yan.
- Falls off with increasing mass in a similar way to pair production.
- Look beyond the SM through new resonances instead.



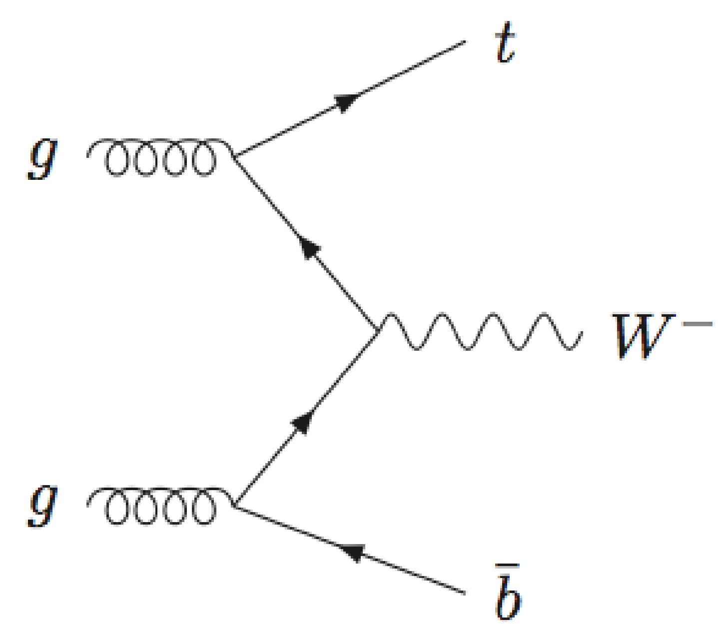
- At LHC energies scattering is dominated by partons from the sea, so cross section is small relative to other channels.
- At the Tevatron scattering is more sensitive to valence structure. The role of the anti-protons provides an important enhancement.



Associated production

- The last channel is irrelevant at the Tevatron due to gluon luminosity and kinematics.

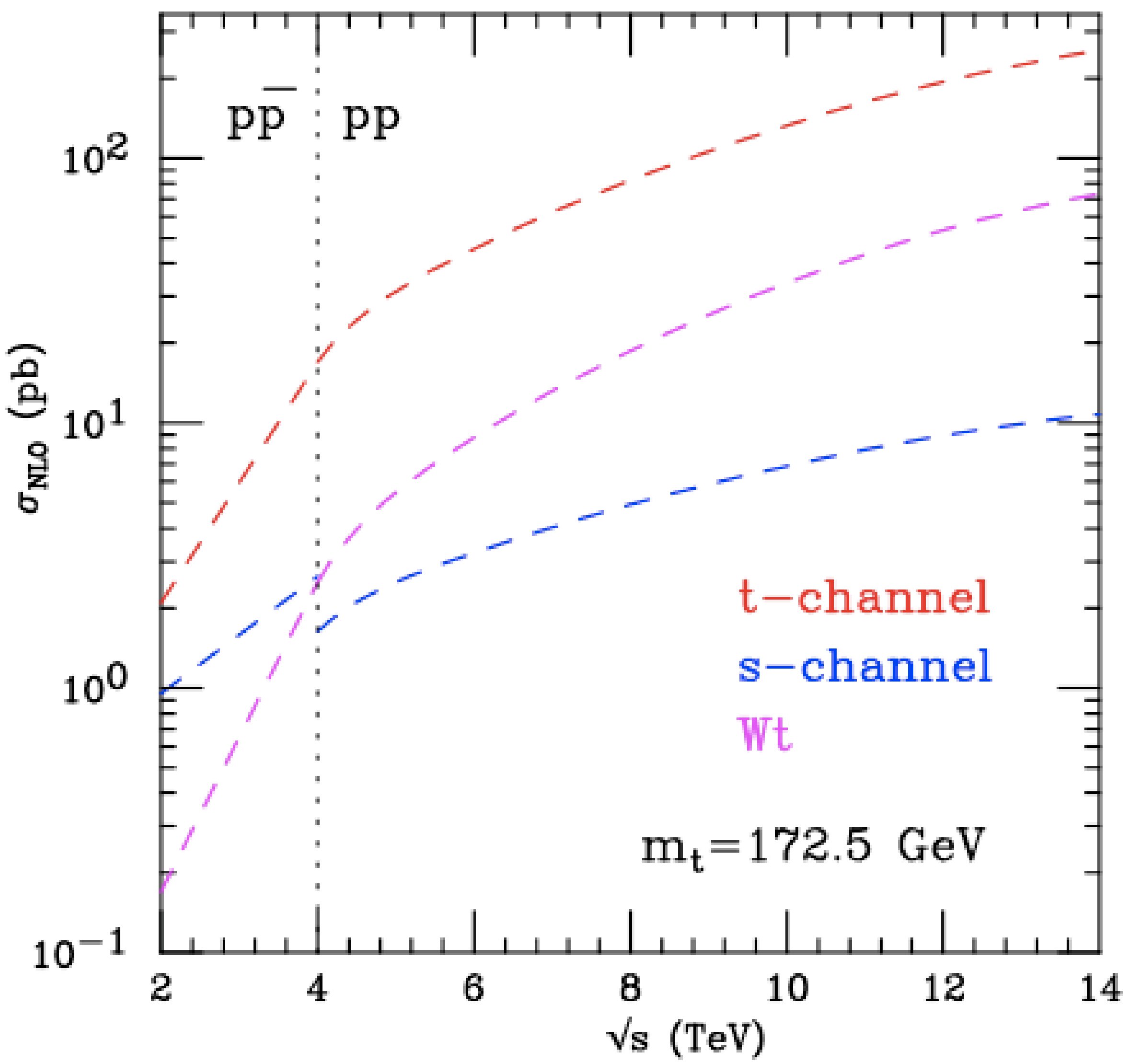
  Belyaev et al., PRD59, 075001 (1999); Tait, PRD61, 034001 (2000)



- Can play a significant role at the LHC (not least as a background - e.g. to $H \rightarrow WW^*$).
- Very similar to top pair production; in fact must be defined very carefully to avoid overlap.
- Collinear enhancement from gluon splitting again, with the b quark primarily not far from the beam direction.
- Qualitatively different from s- and t-channel production due to presence of (hard) strong coupling.

Relative sizes

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



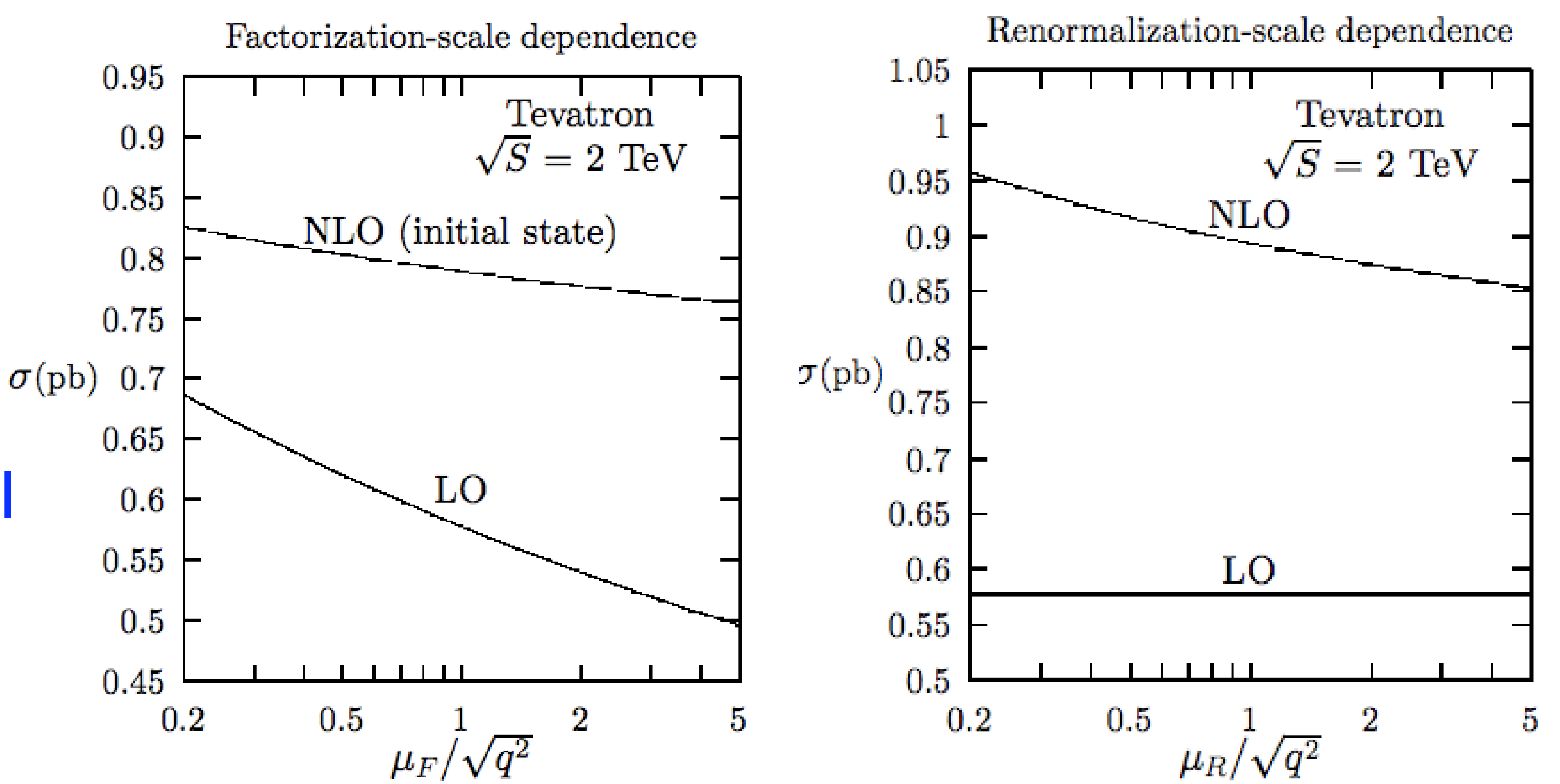
NLO corrections

- The importance of these channels demands theoretical predictions at NLO.
- First priority: accurate cross sections and uncertainty estimates for Tevatron channels.

t: *Bordes & van Eijk, NPB435, 23 (1995)*

s: *Smith & Willenbrock, PRD54, 6696 (1996)*

s-channel



- No meaningful uncertainty at LO due to weak process.

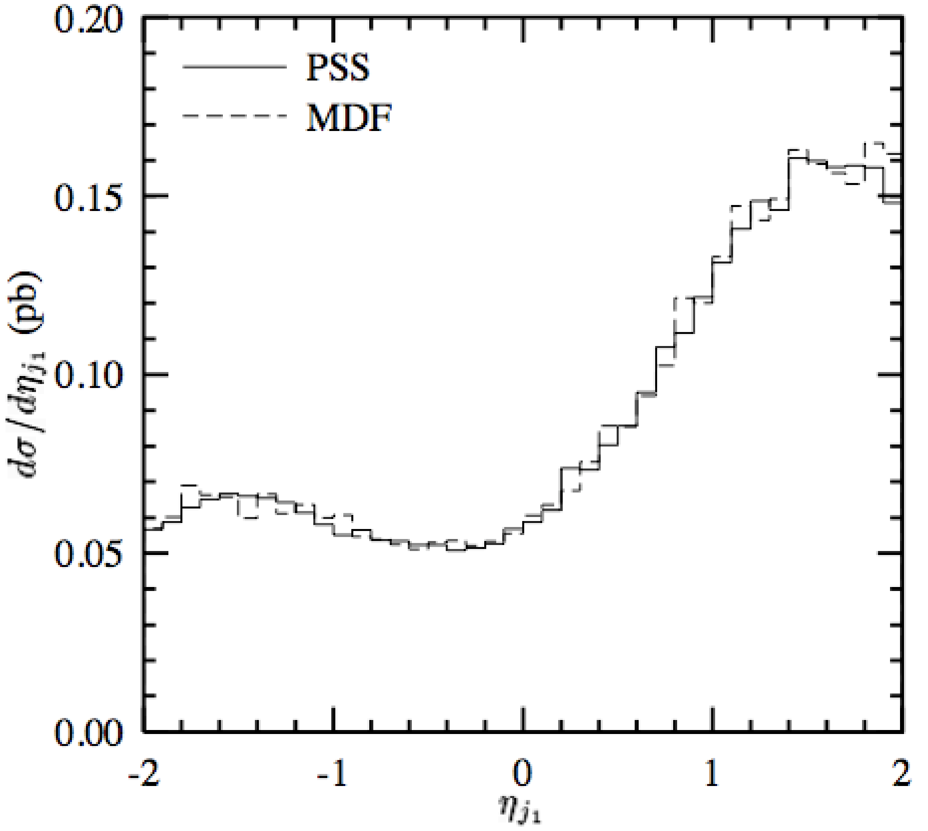
NLO distributions

- Predictions evolved to provide differential distributions for both s- and t-channels.

Harris et al., PRD66, 054024 (2002)

- Requires a parton-level Monte Carlo and associated NLO formalism.

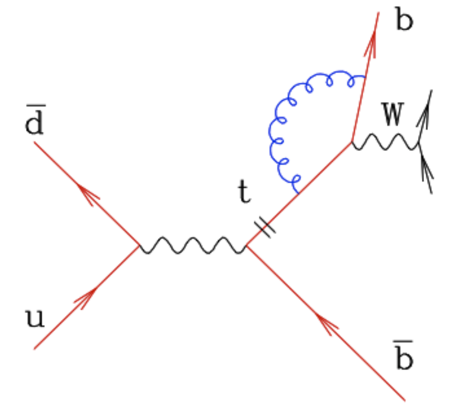
rapidity of leading jet in the t-channel

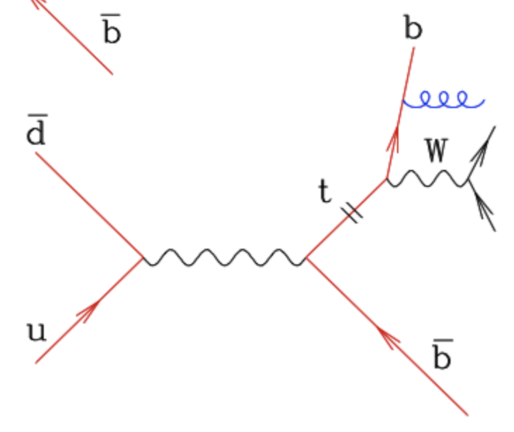


- More detailed information on spin correlations and the effect of radiative corrections in the top quark decay.

JC et al.,PRD70, 094012 (2004)

Q.-H. Cao et al.,PRD71, 054023 (2005)





- Better match with experimental cuts.

NLO Wt

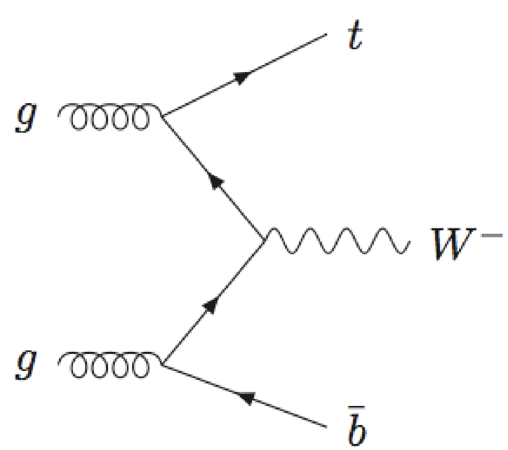
- Not so much urgency for the Wt channel.

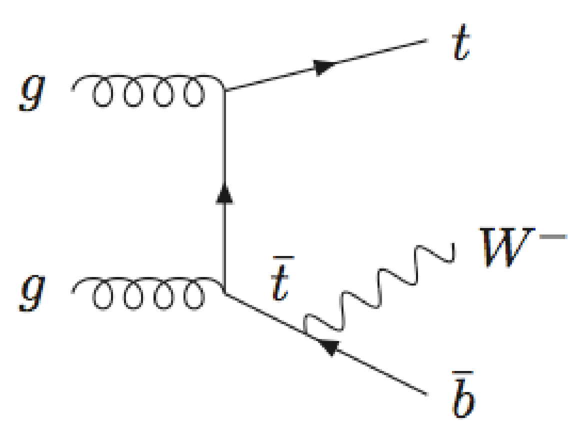
  Zhu, PLB524, 283 (2002)

- Distributions and spin correlations too.

  JC & Tramontano, NPB726, 109 (2005)

- Additional complication, since a gauge invariant set of diagrams includes resonant top pair production.



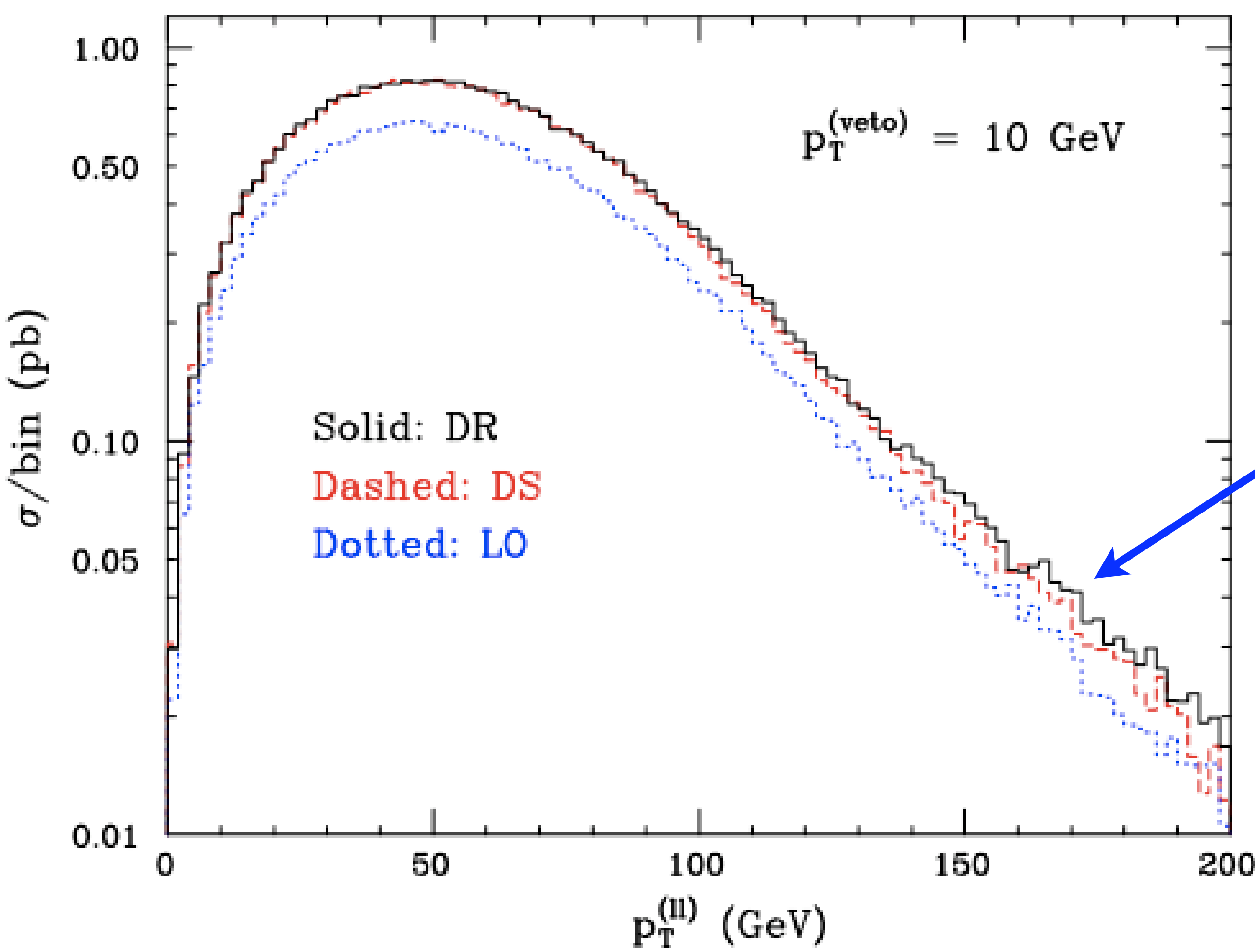


- "Solutions" include:
  - invariant mass cuts;
  - subtraction of resonant cross section;
  - kinematic separation, $p_T(b)$ small (large) corresponds to Wt (tt).

Single top in MC@NLO

- All of these processes have been merged (at NLO) with a parton shower, in the form of MC@NLO. *Frixione et al., JHEP 0603:092 (2006); JHEP 0807:029 (2008).*

- Usual advantages: NLO prediction + hadrons, full event simulation.
- Particularly useful for trying to disentangle Wt/top pair channels in a fully exclusive context.



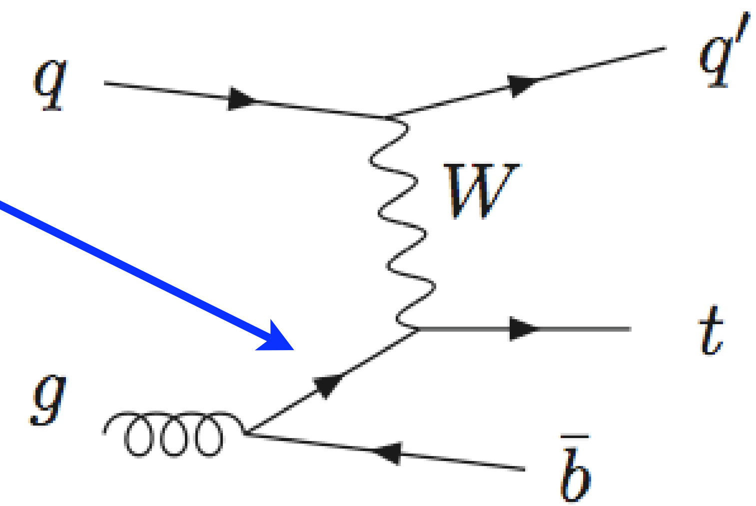
sensitivity to interference between Wt and tt diagrams

t-channel logarithms

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

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

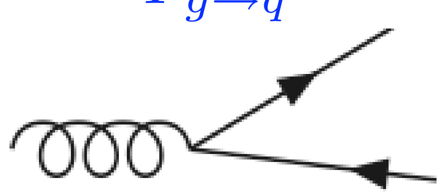
$t = (p_{\bar{b}} - p_g)^2$ (and p_T of anti-b quark)

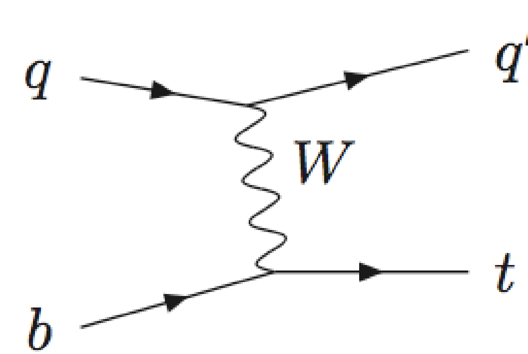


- Contribution to the cross section: $$\int_0^{p_{T,max}^2} \frac{dp_T^2}{p_T^2 + m_b^2} = \log\left(\frac{p_{T,max}^2}{m_b^2}\right) + \ldots$$
- Coefficient of the logarithm is:

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

$P_{g\to q}$





matrix elements with splitting removed

Absorbing into PDFs

- Putting it together:

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

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

absent

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

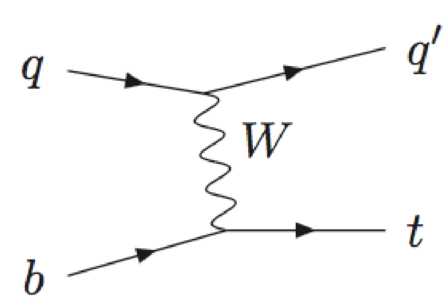
- So, when the logarithms really dominate, can replace this description by an equivalent one: $\sigma(qg \to q'tb) \approx \sigma(qb \to q't)$
- Scale of the bottom quark PDF should be related to $p_{T,max}$.
- At all orders, the two would agree. Otherwise, differ by:
    - evolution of logarithms in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

ACOT

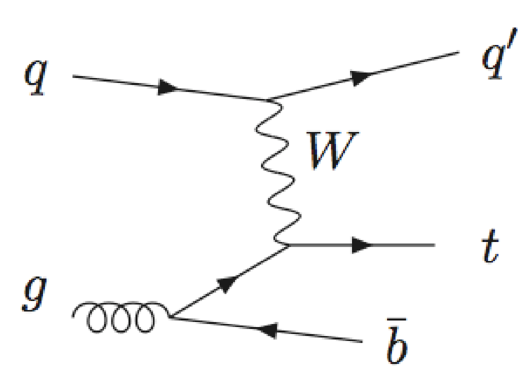
- A sensible way of combining the two approaches was formally identified some time ago, in a procedure now known as the "ACOT" formalism.

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

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



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

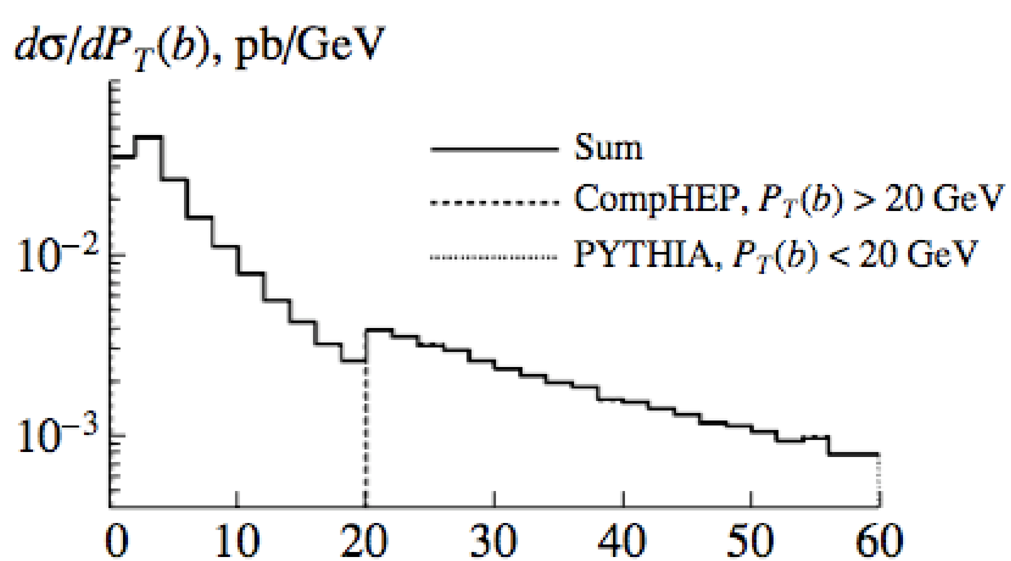


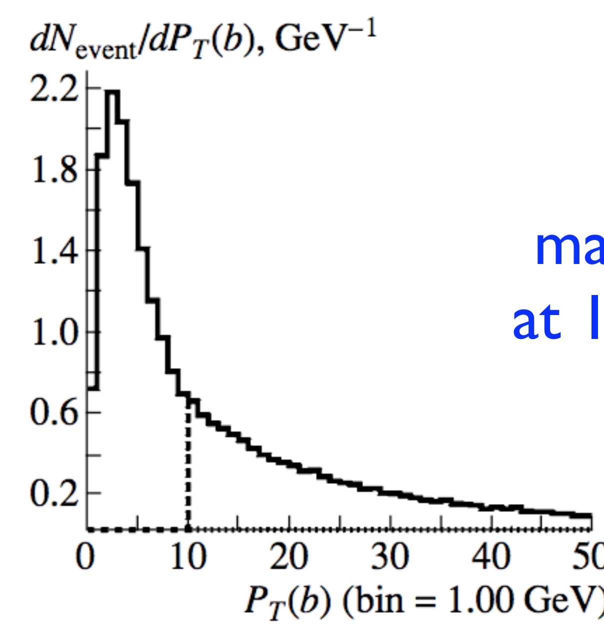
- All calculations presented so far set m_b=0 in final state for simplicity.

CompHep-SingleTop

- Would like:
  - control of large logarithms i.e. in the $p_T(b) \to 0$ region; NLO predictions for the same;
  - faithful description (i.e. m_b non-zero) otherwise.
- ACOT formalism difficult to realise in a parton shower.
- "Effective NLO approximation": separate regions according to $p_T(b)$ and use NLO 5F below (+shower) and LO 4F above.
  - implemented in (CompHEP) SingleTop and used by D0 and CMS.

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





matched at 10 GeV

- Ad-hoc matching well motivated but theoretically unappealing.

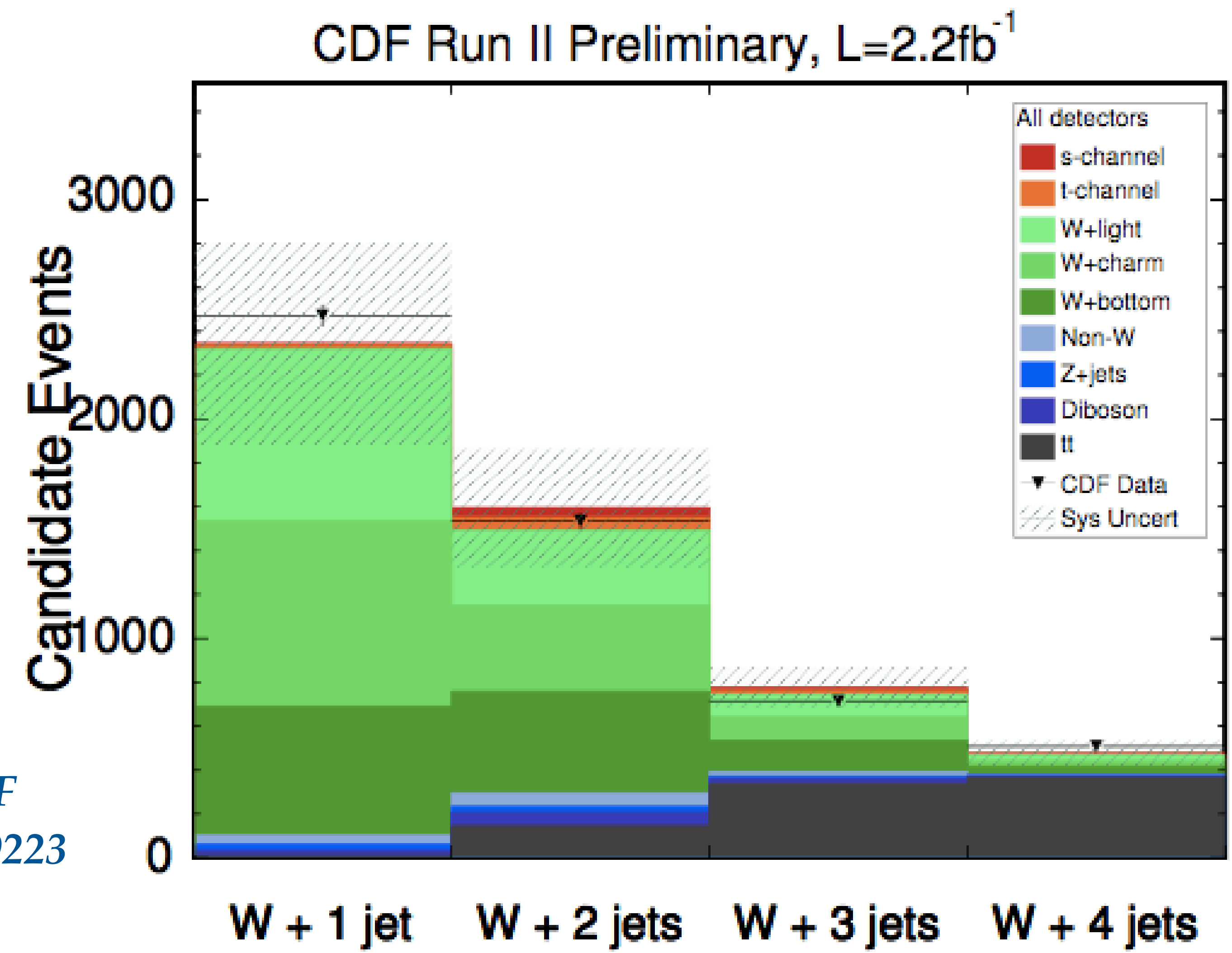
Backgrounds

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

- Need control of events with jets tagged as containing heavy quarks.

- A very challenging measurement indeed.

CDF Note 9223

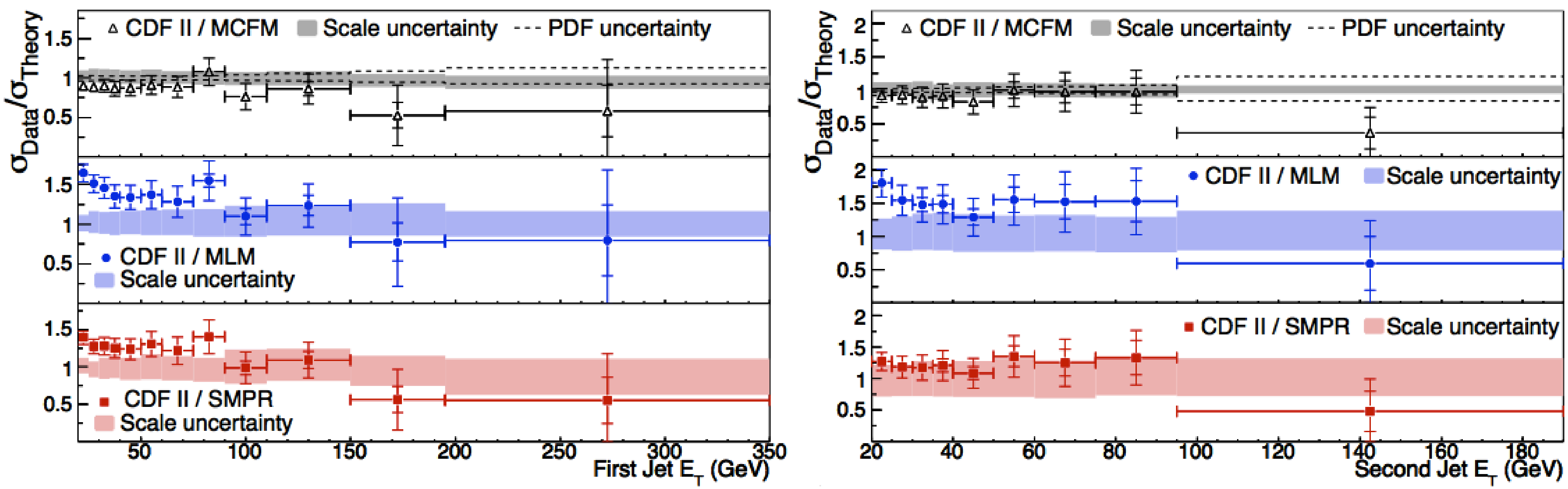


- Detailed information about the properties of signal and background events is required in order to make any headway.

Sullivan, PRD70, 114012 (2004)

W+jets understanding

- The properties of W+jet events are in general well described by theoretical predictions.



Aaltonen et al., PRD77, 011108 (2008)

- In particular, NLO prediction (MCFM) describes both the normalization and shape of the data very well.

W+charm

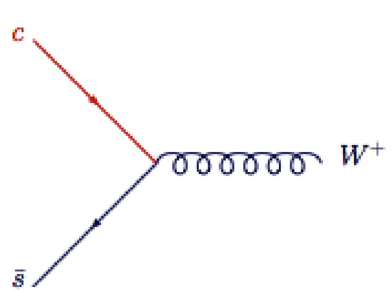
- Different game once heavy quarks are included: isolating clean event samples is not so easy.
- Serious studies only recently undertaken.

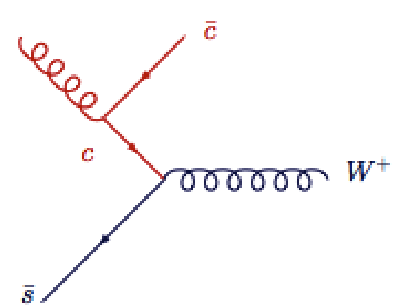
$$\frac{\sigma\left[W+c\text{-jet}\right]}{\sigma\left[W+\text{jets}\right]} = 0.074 \pm 0.019(\text{stat.})^{+0.012}_{-0.014}(\text{syst.})$$

$$\left.\frac{\sigma[W+c\text{-jet}]}{\sigma[W+\text{jets}]}\right|_{ALPGEN} = 0.044$$

$$\left.\frac{\sigma[W+c\text{-jet}]}{\sigma[W+\text{jets}]}\right|_{MCFM} = 0.045$$

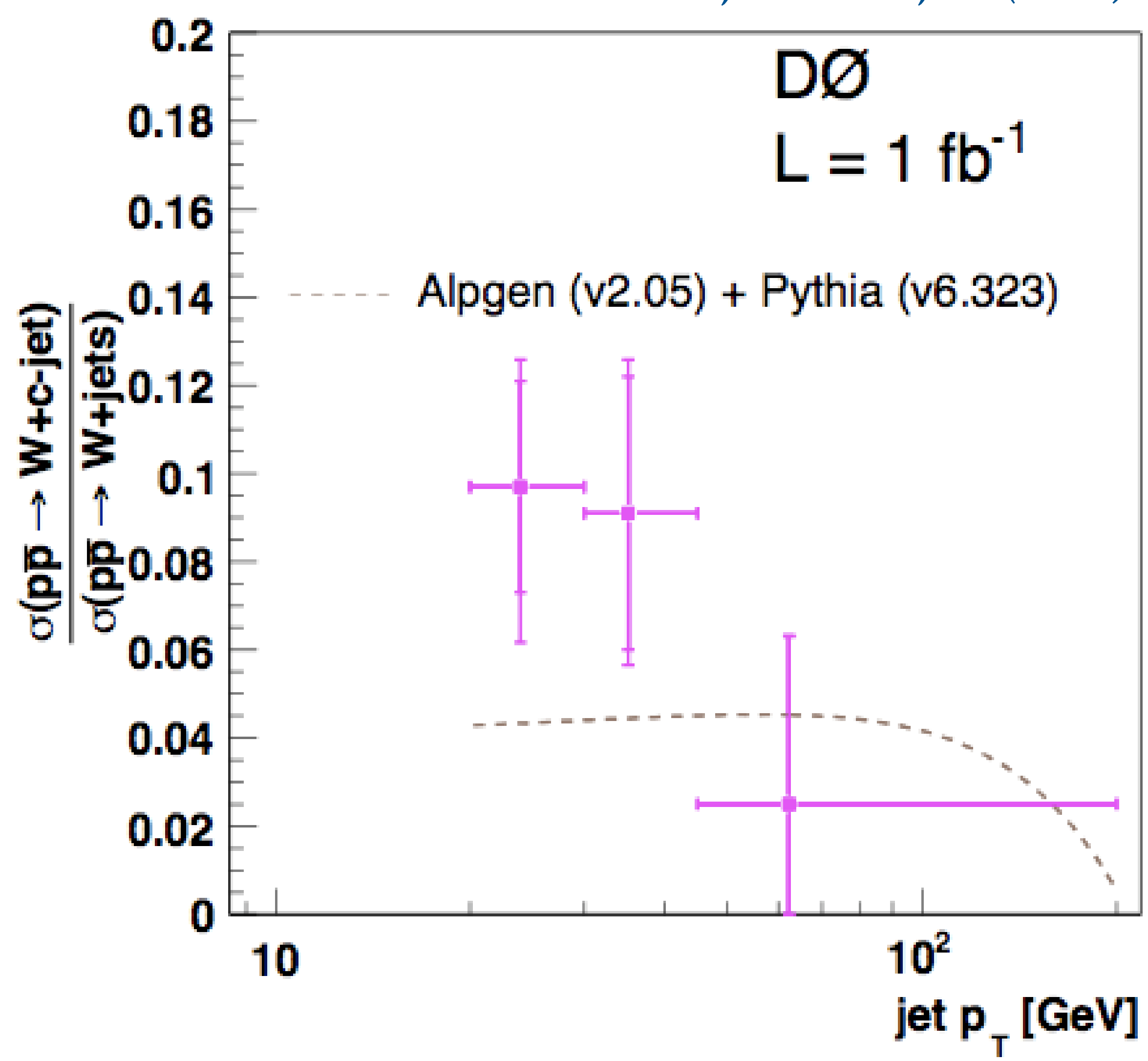
theory error ~ 10%





NB: large logs and charm PDF

Abazov et al., PLB666, 23 (2008)



- Jury still out, kinematic study essential.

W+bottom

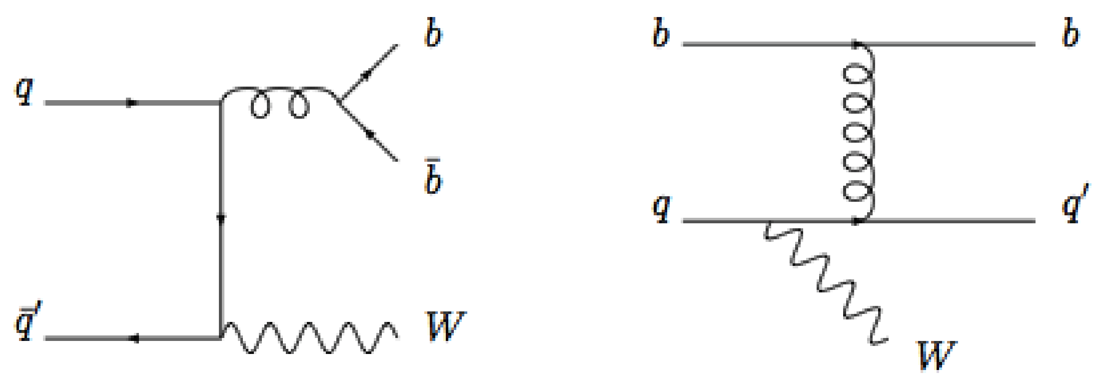
- W+1 or 2 jets, either or both of which may be b-tagged.
- Most important for single top study.
- CDF measurement:

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

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

CDF Note 9321

- Ongoing work to compare with ACOT formalism combining (at NLO) two sources of W+b events.



JC et al., arXiv:0809.3003 [hep-ph]

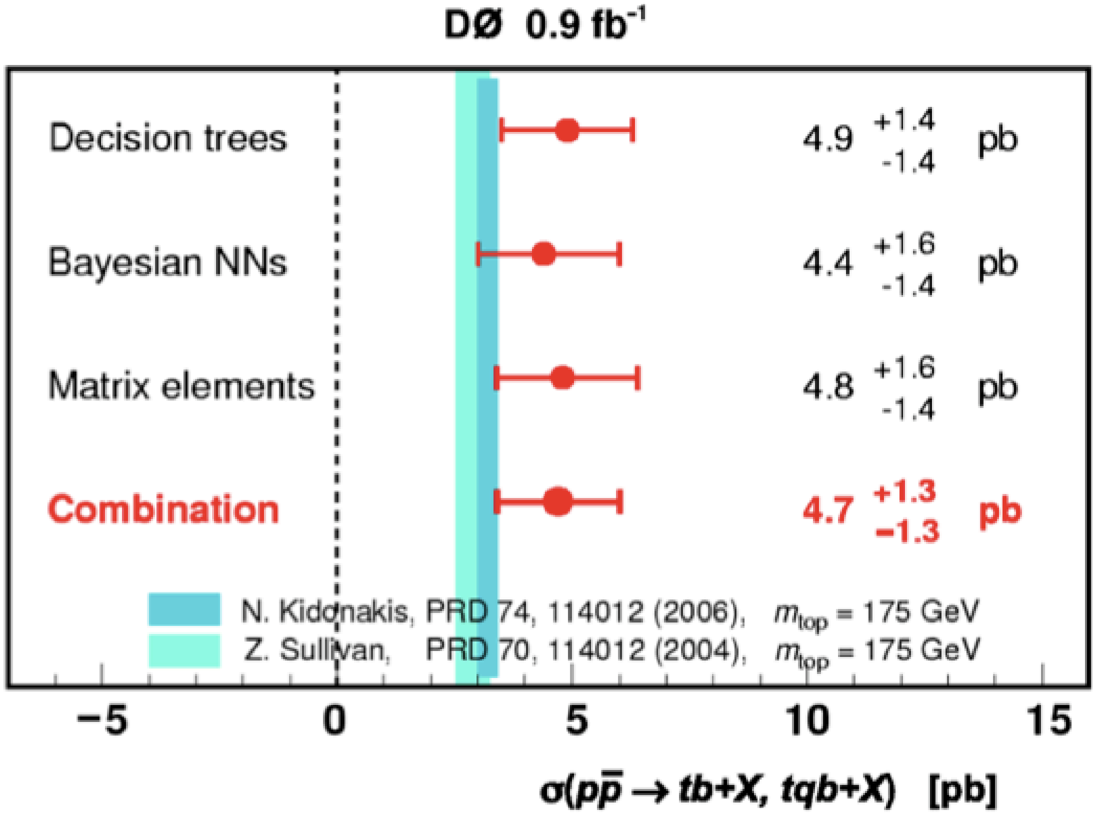
... but still hard to explain factor of 3-4

(NB: role of bottom PDF again)

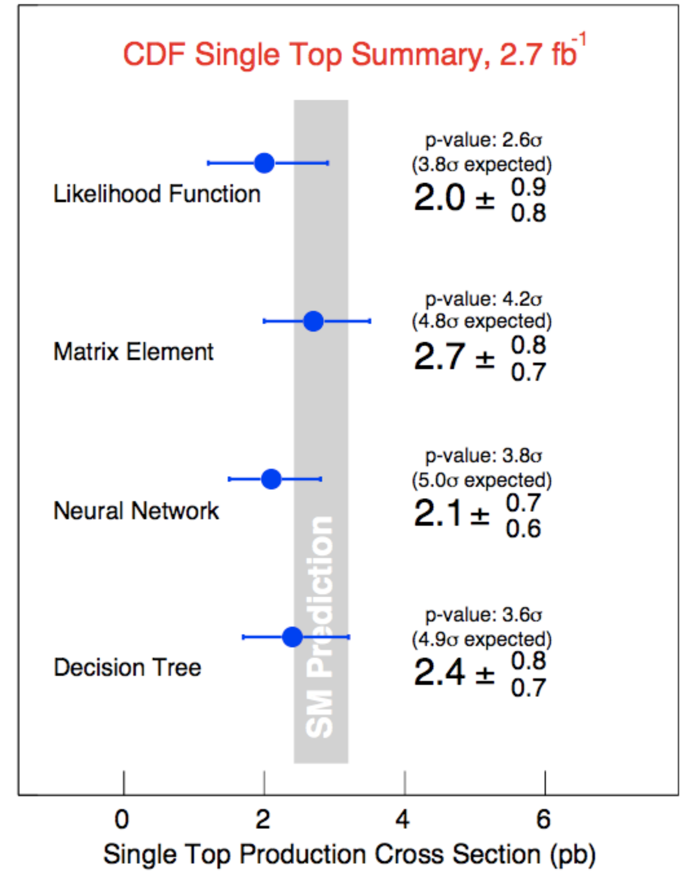
Experimental status

- Determination of backgrounds data-driven:
  - W+jets normalized to data;
  - Wcc and Wbb fraction scaled by measurements or NLO K-factor.
- Signal is LO matched to NLO:
  - CompHep-Singletop (D0), Madevent (CDF)
- Plethora of methods for implementing kinematic separation of signal and background: likelihood function, matrix element, neural networks, boosted decision trees.
  - complex algorithms; potential sensitivity to details of higher order corrections and matching scheme.
- Prospects for LHC: just as hard (even more jets). Can also be a significant source of background events that needs to be controlled.
  - e.g. $bg \to Wt \to WWb$ background to Higgs search $gg \to H \to WW^*$ and $bg \to bH \to bWW^*$.

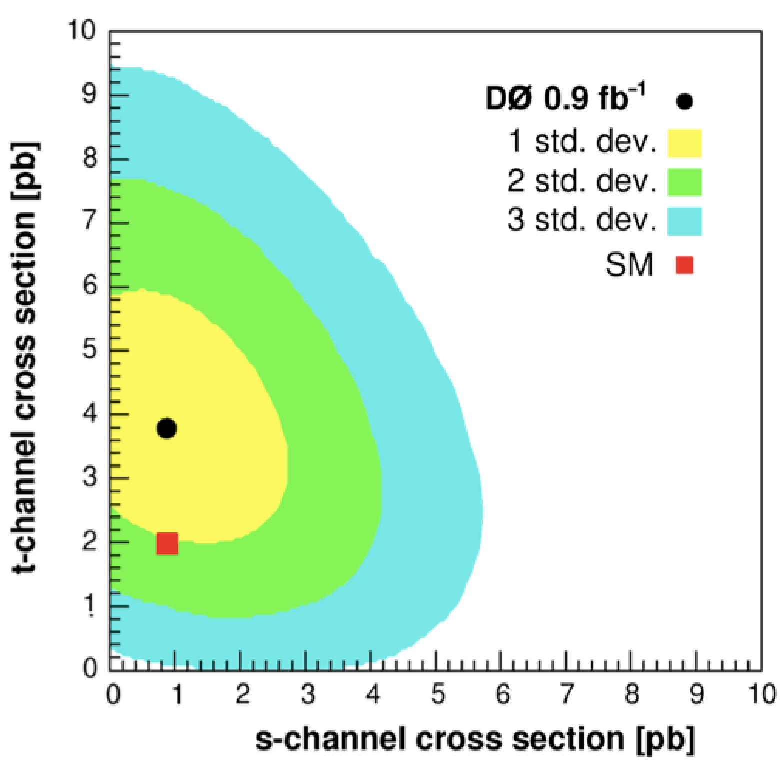
Monday, March 2
≈ 3.5σ evidence

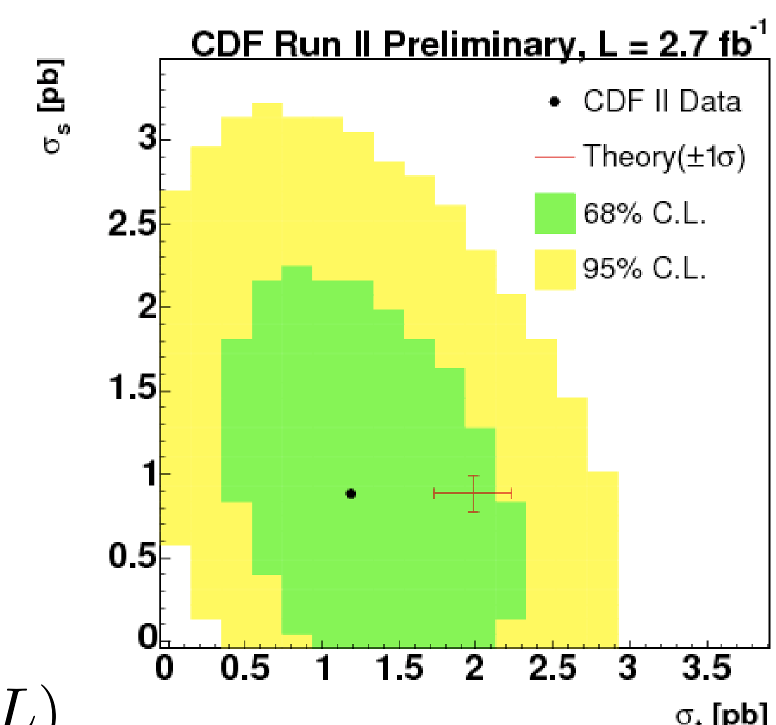


PRD78, 012005 (2008)



CDF Single Top summary





$$|V_{tb}| = 0.88^{+0.13}_{-0.12}$$

$$|V_{tb}| > 0.66 \ (95\% \ CL)$$

PRL 101, 252001 (2008)

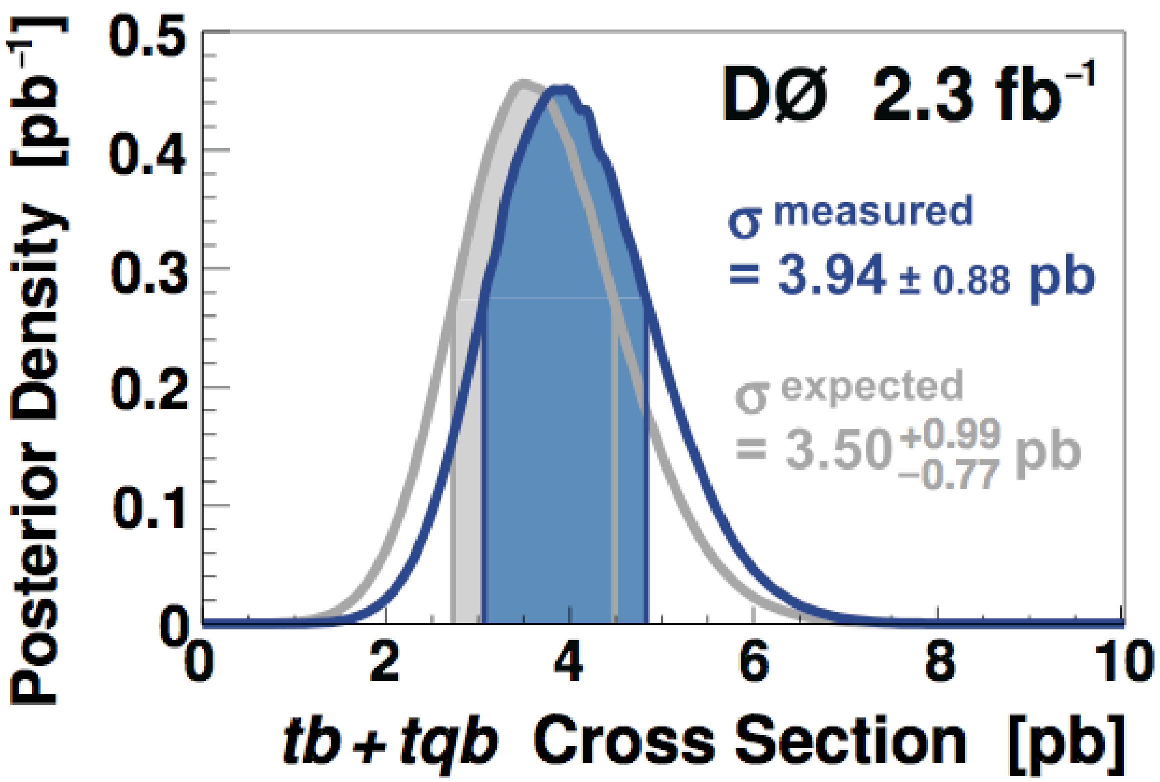
CDF Note 9460

$$|V_{tb}| = 1.00^{+0.00}_{-0.12} \ , \ |V_{tb}| > 0.68 \ (95\% \ CL)$$

Today, March 6 - discovery!

D0: arXiv: 0903.0850

2.3 fb^{-1}, a luminosity increase of a factor 2.5



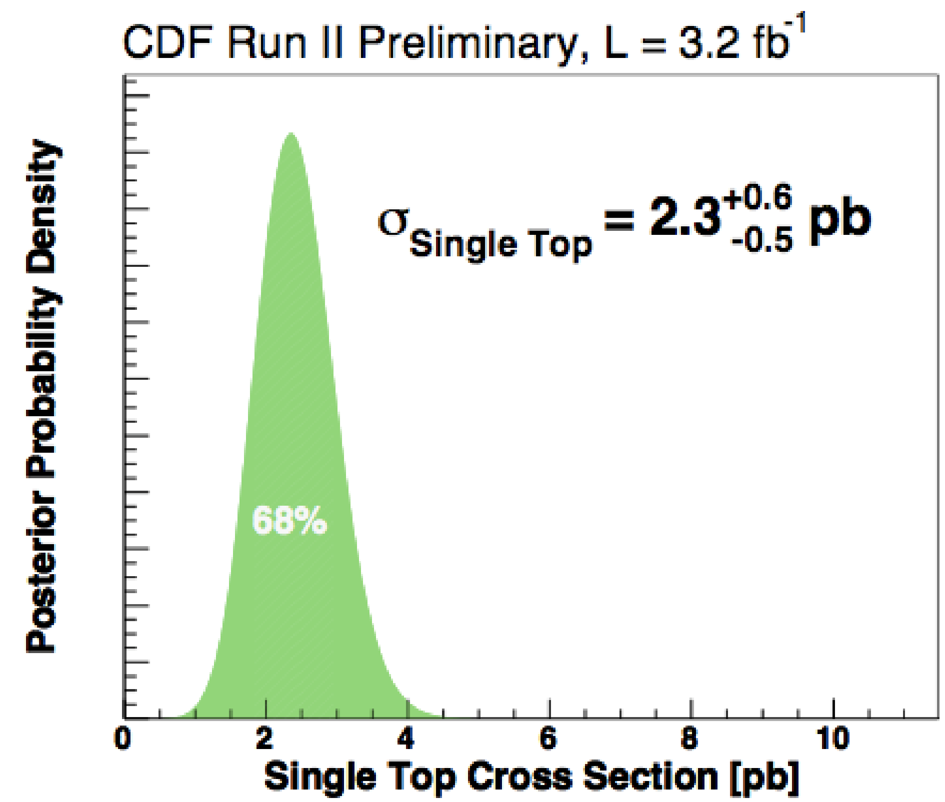
m_t=170 GeV

$$|V_{tb} f_1^L| = 1.07 \pm 0.12$$

$$|V_{tb}| > 0.78 \ (95\% \ CL)$$

CDF: arXiv: 0903.0885

3.2 fb^{-1}, three new analyses



[theory: -10% from 170 to 175 GeV]

m_t=175 GeV

$$|V_{tb}| = 0.91^{+0.11}_{-0.11}(\text{exp.}) \pm 0.07(\text{theory})$$

$$|V_{tb}| > 0.71 \ (95\% \ CL)$$

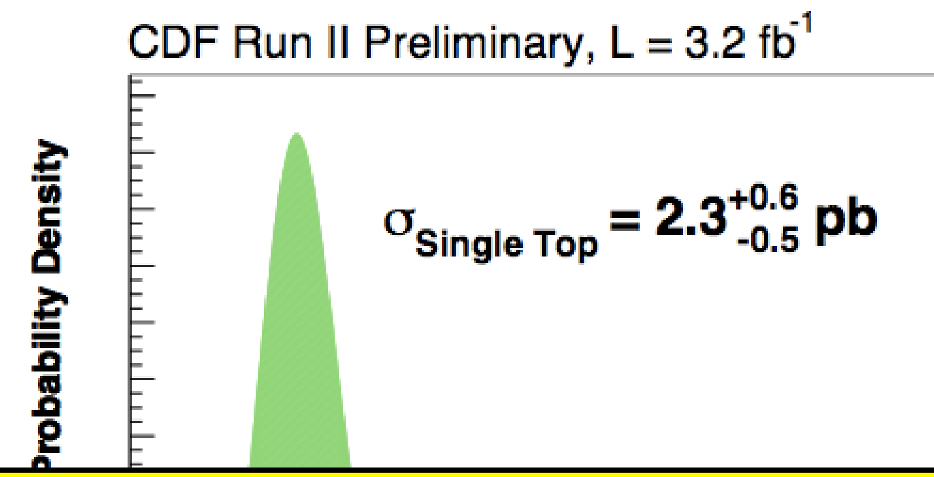
Today, March 6
- discovery!

D0: arXiv: 0903.0850

2.3 fb^{-1}, a luminosity increase of a factor 2.5

CDF: arXiv: 0903.0885

3.2 fb^{-1}, three new analyses



[theory: -10%
from 170 to
GeV]

"Observation of single top"
C. Gerber (UIC/D0), R. Wallny (UCLA/CDF)

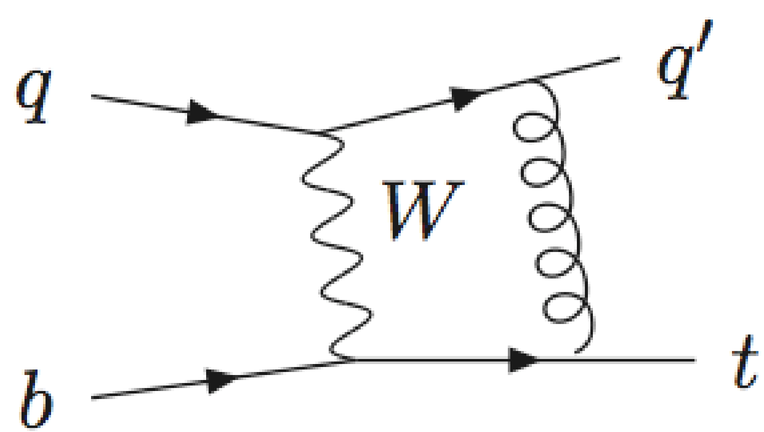
Tuesday, March 10, 2-3:30pm 1 West

$|V_{tb}| > 0.78\ (95\%\ CL)$

$|V_{tb}| > 0.71\ (95\%\ CL)$

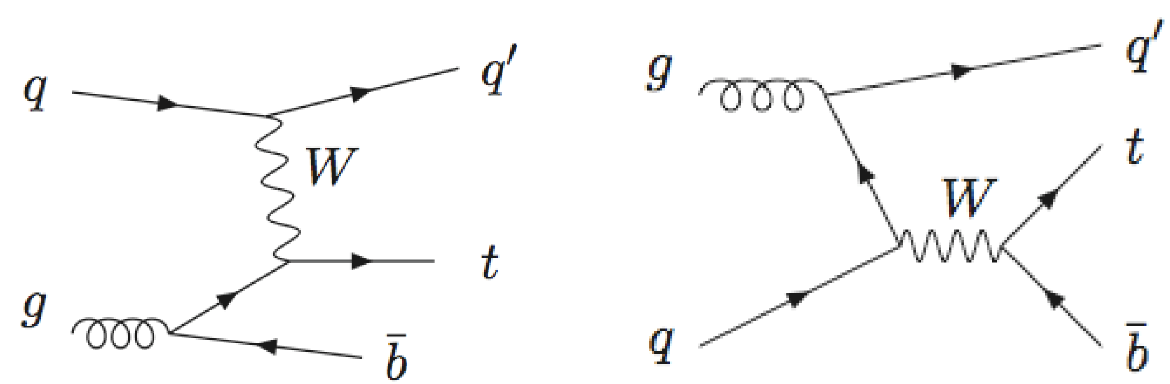
A fresh approach

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



→0, due to tr(T^a)=0

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



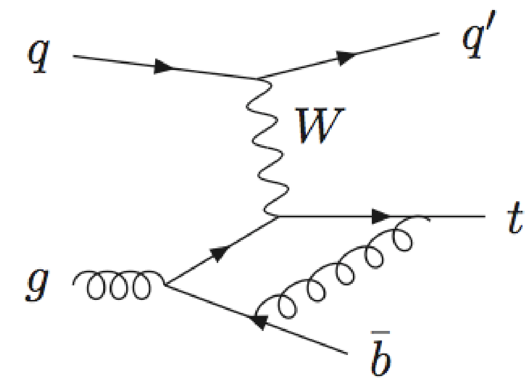
interference vanishes, due to tr(T^a)=0

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

2→3 factorization

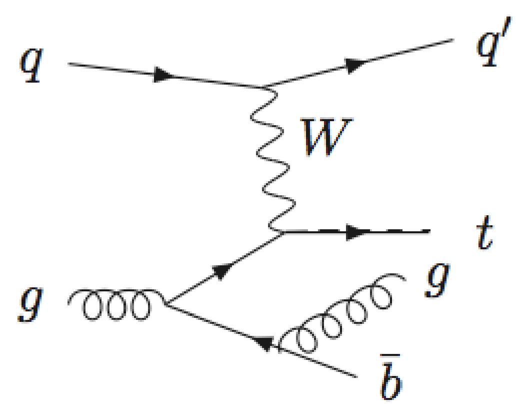
- The same arguments still mostly apply. Majority of matrix elements can be uniquely associated with either the light or heavy quark current.

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



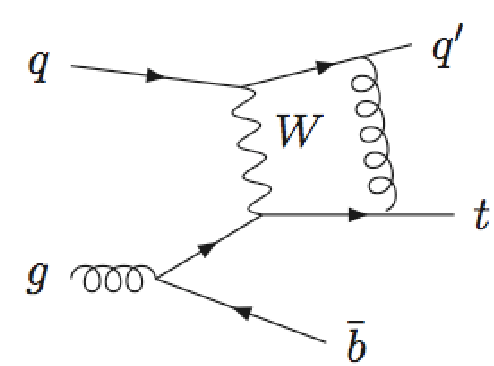
virtual, heavy current

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



real emission, heavy current

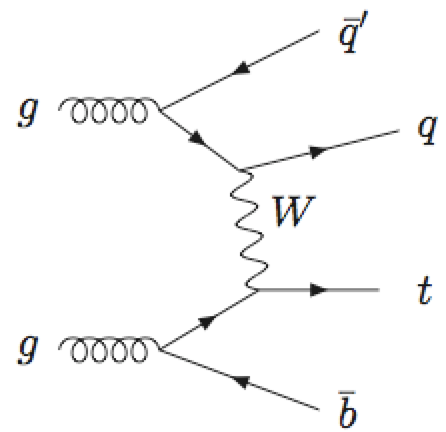
- Most interferences between the two currents vanish by the same color argument once again.



interference, zero (also for corresponding real diagram)

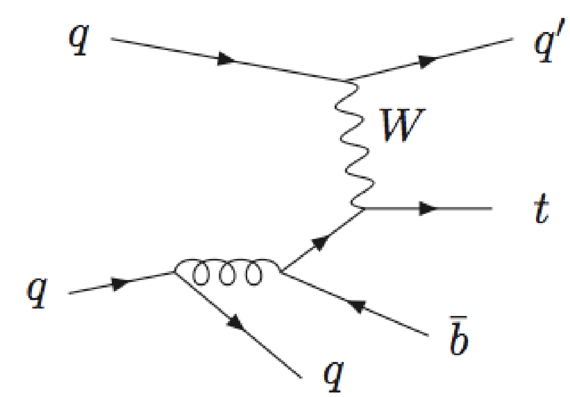
Near-factorization

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



factorizing leading term $N^2C_F^2$

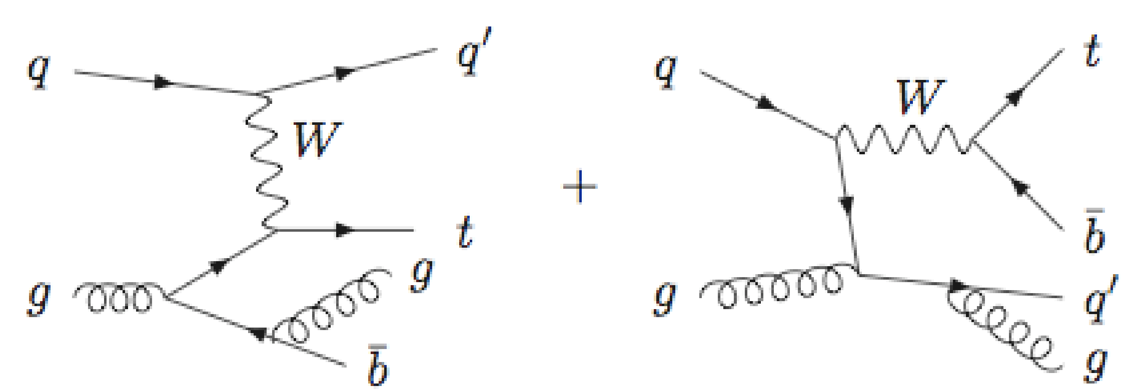
subleading interference N^2C_F



factorizing leading term N^2C_F

subleading interference NC_F

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

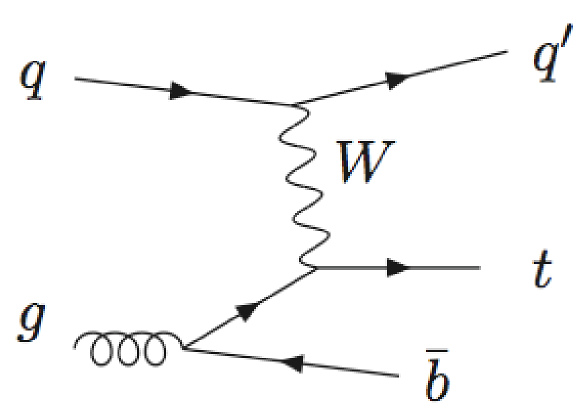


Outline of calculation

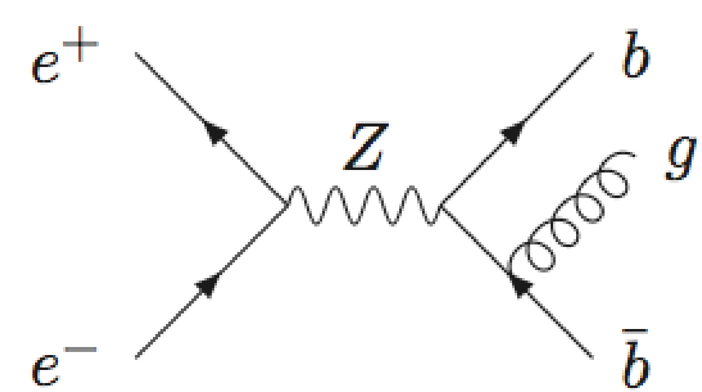
- Analytic computation of helicity amplitudes via standard methods.

top spin available

- Cross-checks:
  - gauge invariance, CP, $m_b \leftrightarrow m_t$ symmetry;
  - two different reduction schemes;
  - divergences checked by two implementations of dipole method.
- Most interesting check comes from crossing the whole calculation.



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



Nason & Oleari, NPB521, 237 (1998)

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

MCFM commercial

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

W+0,1,2 jets

Zbb

Zb

Wb+jet

Zb+jet

dibosons

Z+0,1,2 jets

Wbb

gg→H+0,1 jets

Hb

Wc

single top

top pairs

WH, ZH

H (VBF)

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

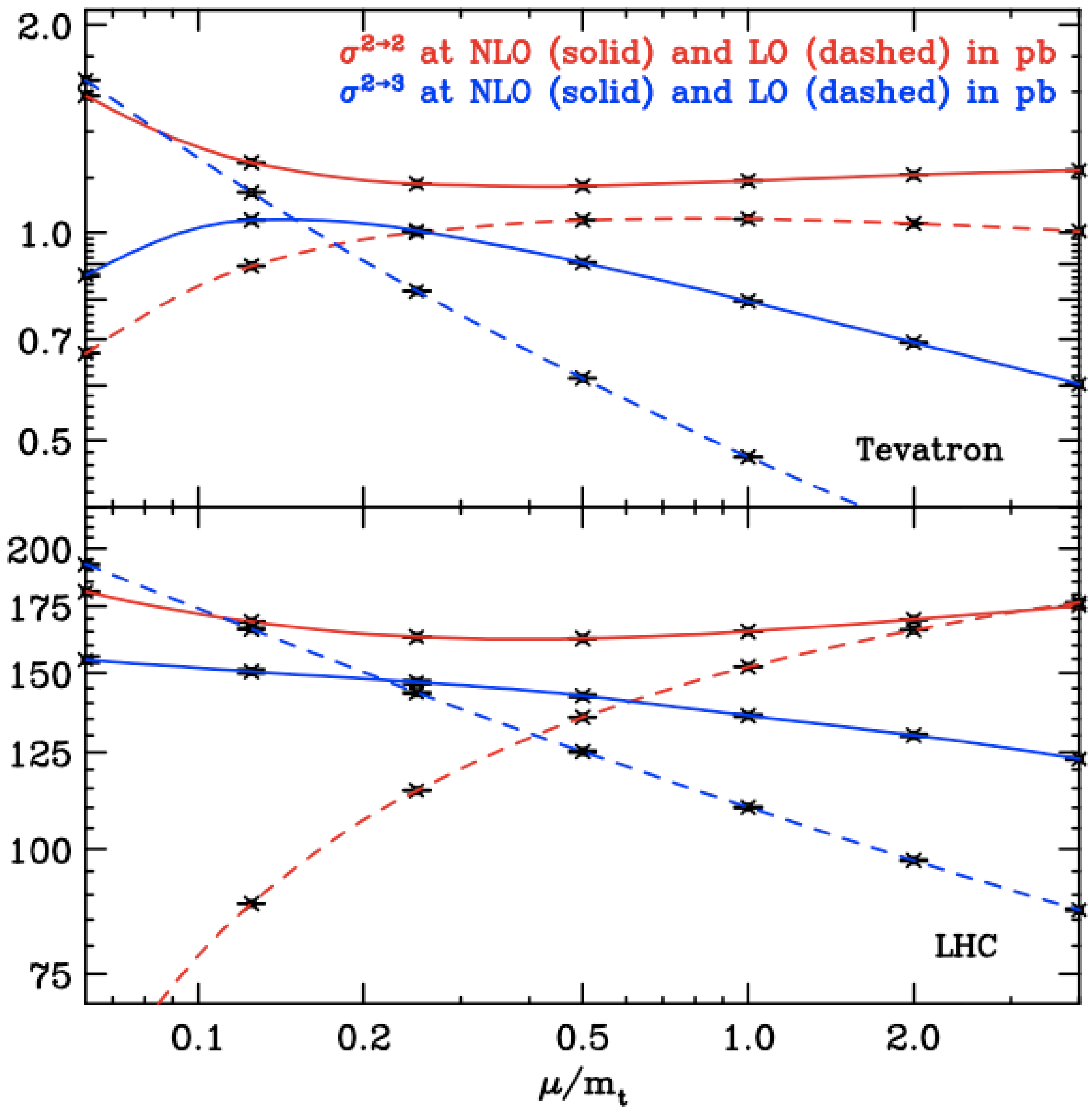
Setup

- Use m_t=172.5 GeV and m_b=4.7 GeV.
- Need to take some care with PDFs for consistency.
  - for the 4F calculation, the b-quark should not enter in the evolution of the strong coupling or the PDFs;
  - for the 5F scheme, use a regular PDF;

  MRST2004nlo
  - alternatively, could use 5F set for both and pass to the 4F scheme using well-known transition rules.

  Cacciari et al., JHEP05, 007 (1998).
- Depart from majority of 5F calculations by using m_b non-zero in NLO real emission diagrams.
  - explicit logarithm cancelled using ACOT formalism;
  - negligible effect on total rate, distributions of top, light jet;
  - significant effect on the b jet.

4F vs 5F scale dependence



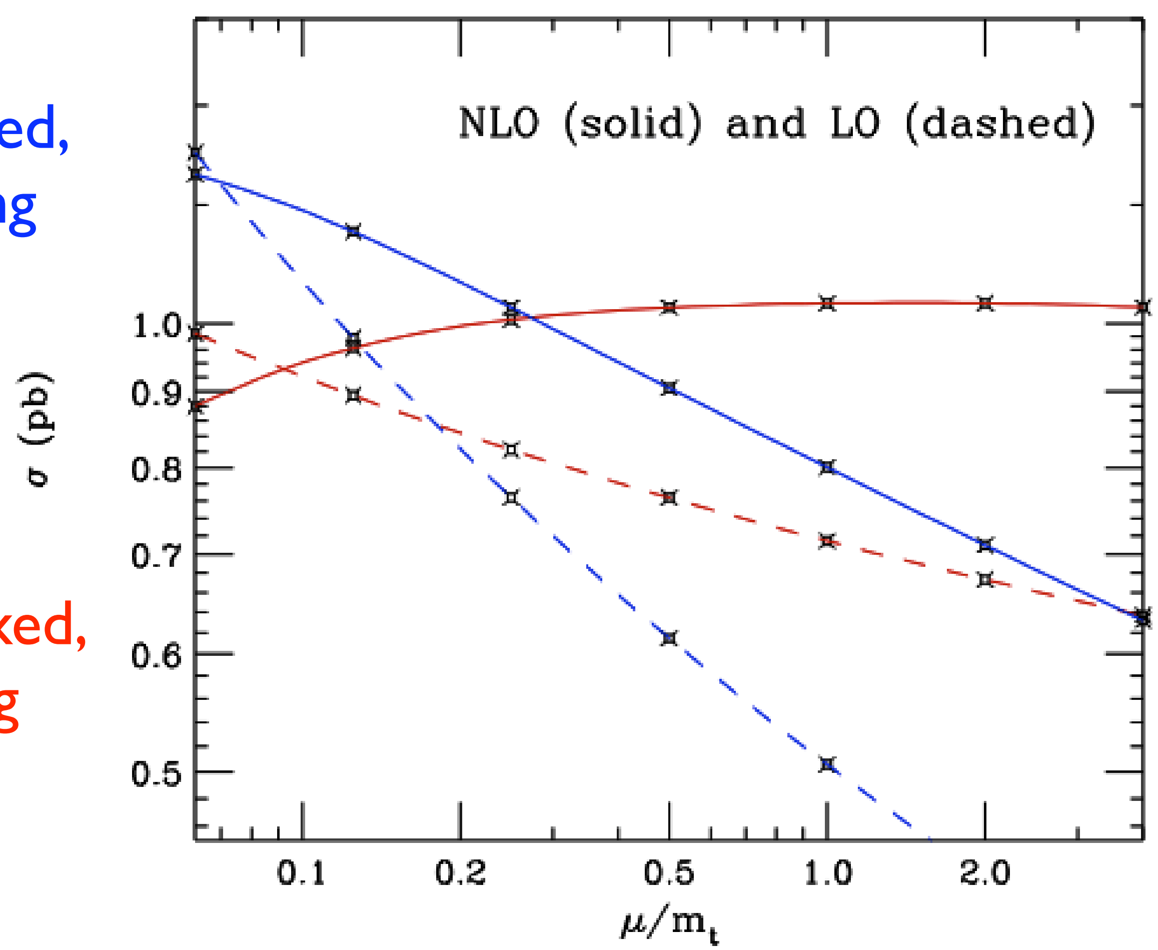
- Both schemes much improved from LO.
- 5F calculation only mildly sensitive to scale at NLO (use m_t in what follows).
- 4F expected to be worse, but isn't by much.
- No region of overlap between the two.
- 4F seems to prefer scales smaller than m_t, particularly at the Tevatron.

Scale dependence of 4F

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

light scale fixed, heavy varying

heavy scale fixed, light varying



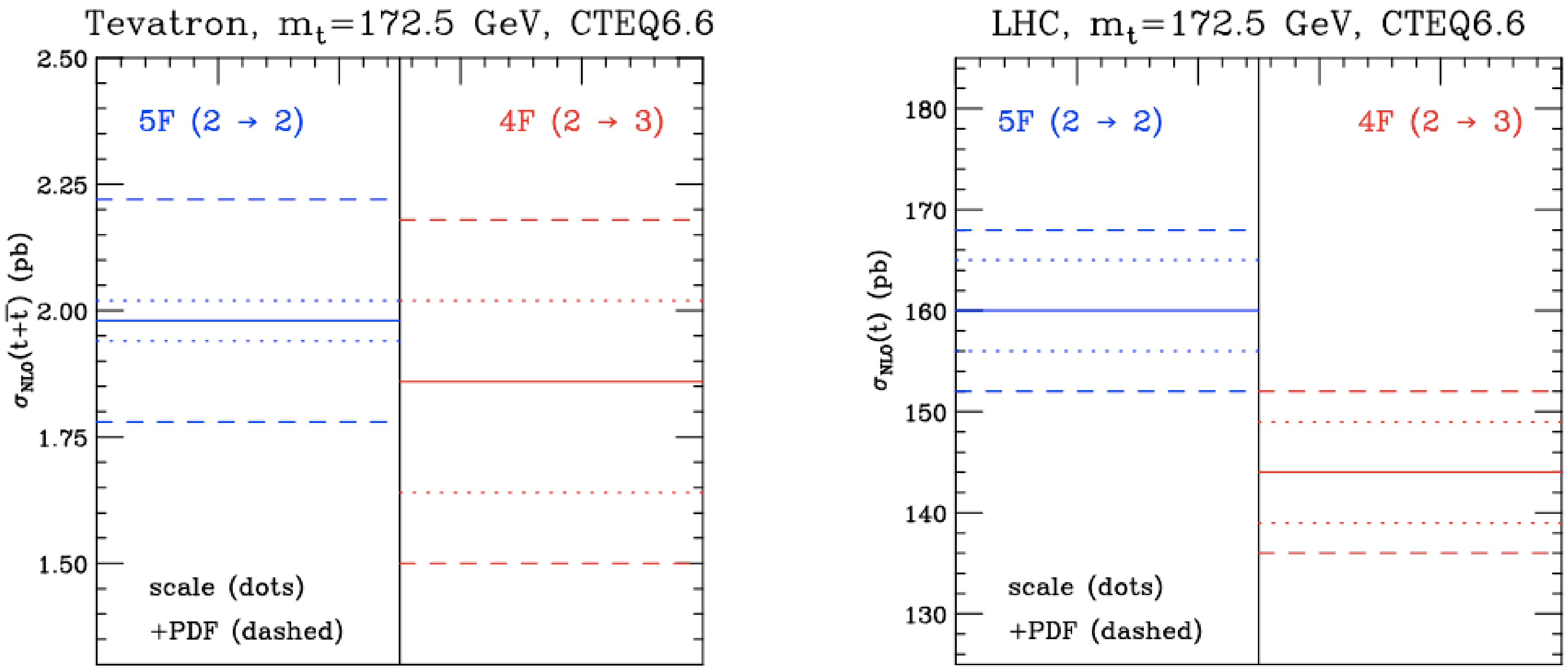
- Tevatron (but LHC similar).
- Stronger dependence on heavy line, as expected.
- Preference for scales smaller than m_t.
- Choose central values: $\mu_L=m_t/2$, $\mu_H=m_t/4$.

Total rates and uncertainties

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

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

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



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

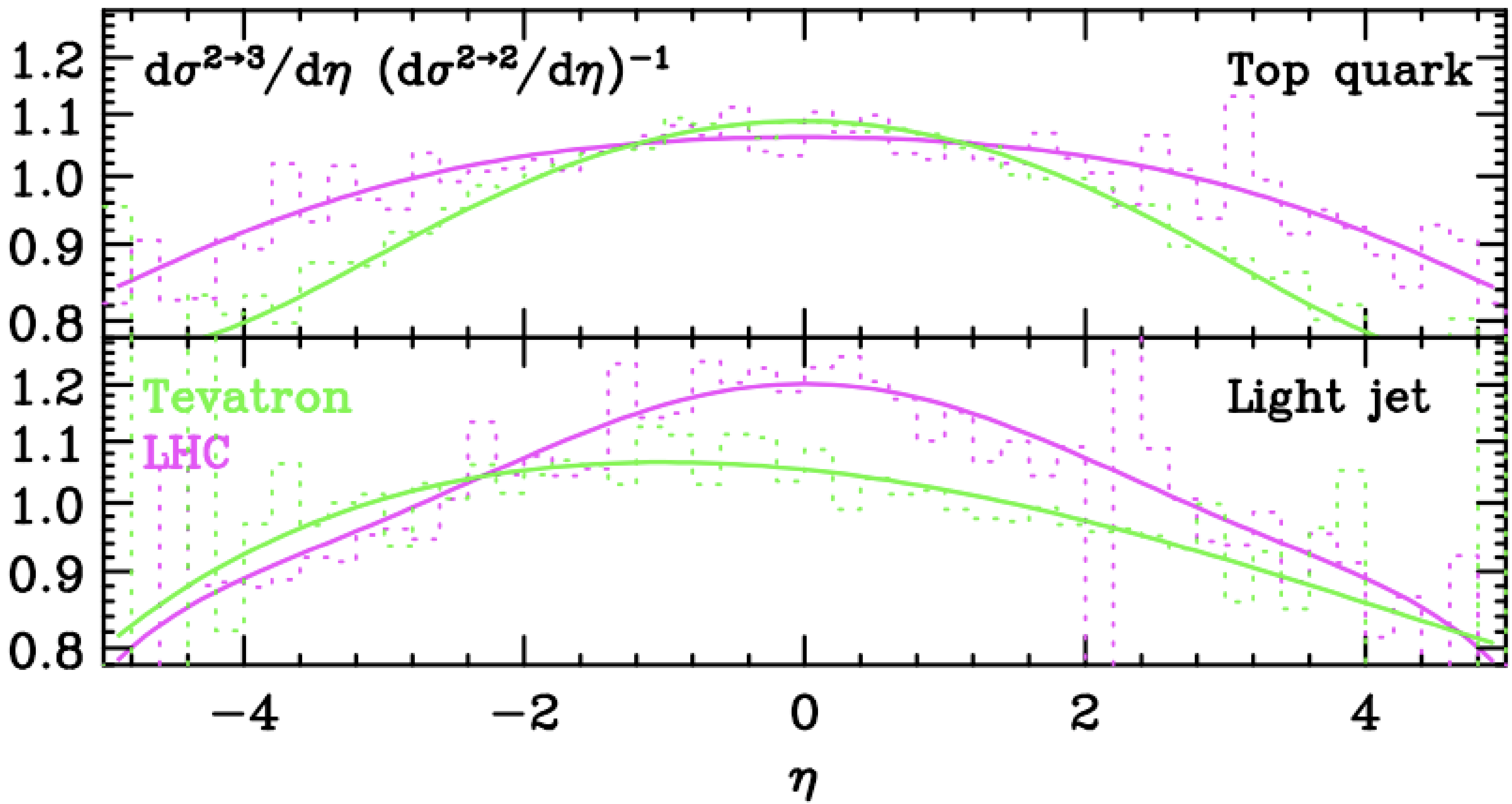
$$\sigma_t(4F/5F) = 1.92 \,^{+0.30}_{-0.42} \text{ pb}$$

slight reduction in central value, but much larger uncertainty

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

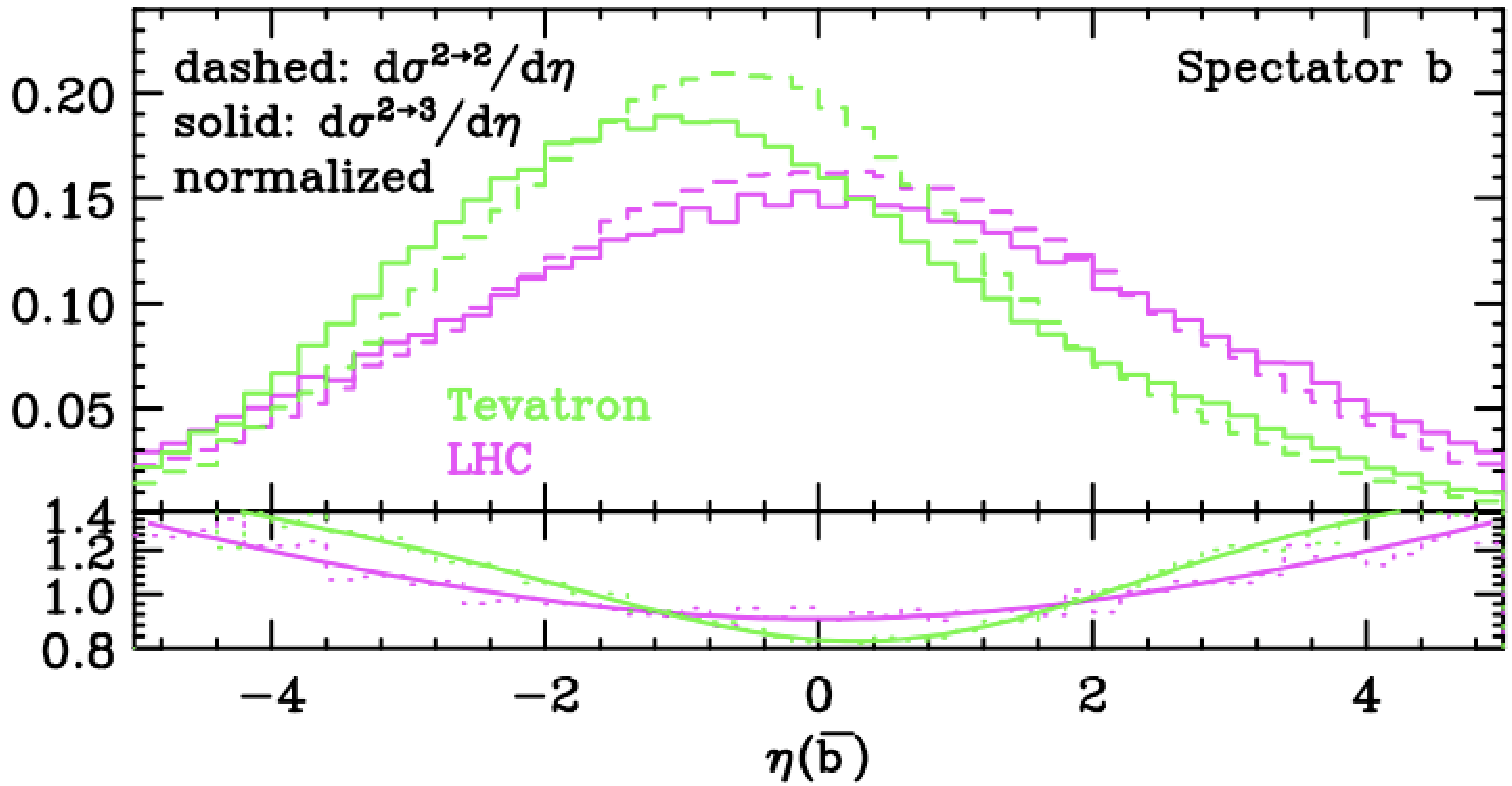
- For the LHC, difference could point to either:
  - large logarithms being resummed;
  - the need for a NNLO calculation in the 5F scheme (for which 4F NLO already forms a part).

Top quark and light jet distributions



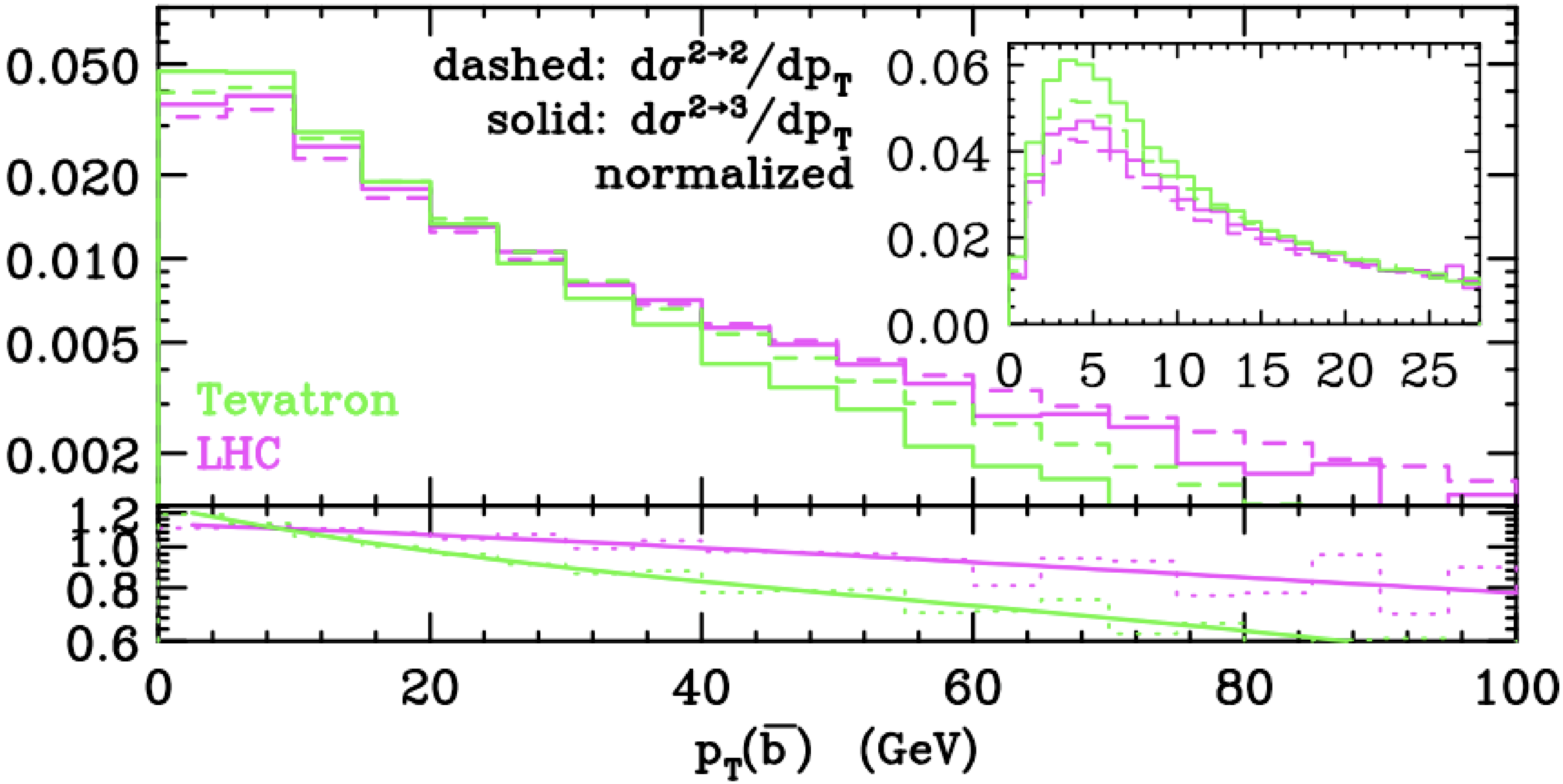
- 4F distribution normalized to 5F one.
- Jet defined by p_T>15 GeV, ΔR>0.7.
- Some differences, but typically at the level of 10% or less.
- Similar for transverse momenta.

Bottom quark rapidity distribution



- Would be completely wrong with m_b=0.
- First NLO prediction for such a quantity.
- Tendency to be more forward at the Tevatron in the 4F calculation.
- Bigger deviations, up to 20-30%, common.

Bottom quark p_T distribution



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

Summary and to-do list

- ✓ Different, but equivalent, calculation of t-channel single top.
- ✓ Allows exploration of theoretical assumptions and prejudice.
- ✓ The two calculations are in excellent agreement at the Tevatron, but marginal at the LHC. Slight reduction in expected cross section (3-10%).
- ✓ Spectator b distribution predicted at NLO throughout entire region, significant corrections.
- Detailed assessment of impact on current single top searches:
    - comparison with event generators;
    - effect on matrix element method.
- Systematic uncertainty study.
- Application to fourth-generation heavy quark searches (t' and b').
- Inclusion of top quark decay.
- Implications for other heavy-quark initiated predictions (5F vs. 4F).
- Inclusion in a full shower (a la MC@NLO).

Summary and to-do list

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- ✓ The two calculations are in excellent agreement at the Tevatron, but marginal at the LHC. Slight reduction in expected cross section (3-10%).
- ✓ Spectator b distribution predicted at NLO throughout entire region, significant corrections.

Exciting times for single top!

"Observation of single top"
C. Gerber (UIC/D0), R. Wallny (UCLA/CDF)

Tuesday, March 10, 2-3:30pm 1 West