t-channel single top anew

Fabio Maltoni
Center for Particle Physics and Phenomenology
Université Catholique de Louvain, Belgium

<u>work in progress</u> based on:
J. Campbell, R. Frederix, F.M., F. Tramontano,
arXiv:0903.0005 [hep-ph] (PRL) and arXiv:0906.xxxx [hep-ph]

Why single top is way cooler than ttbar?

Reason #1 : Teenager vs Newborn

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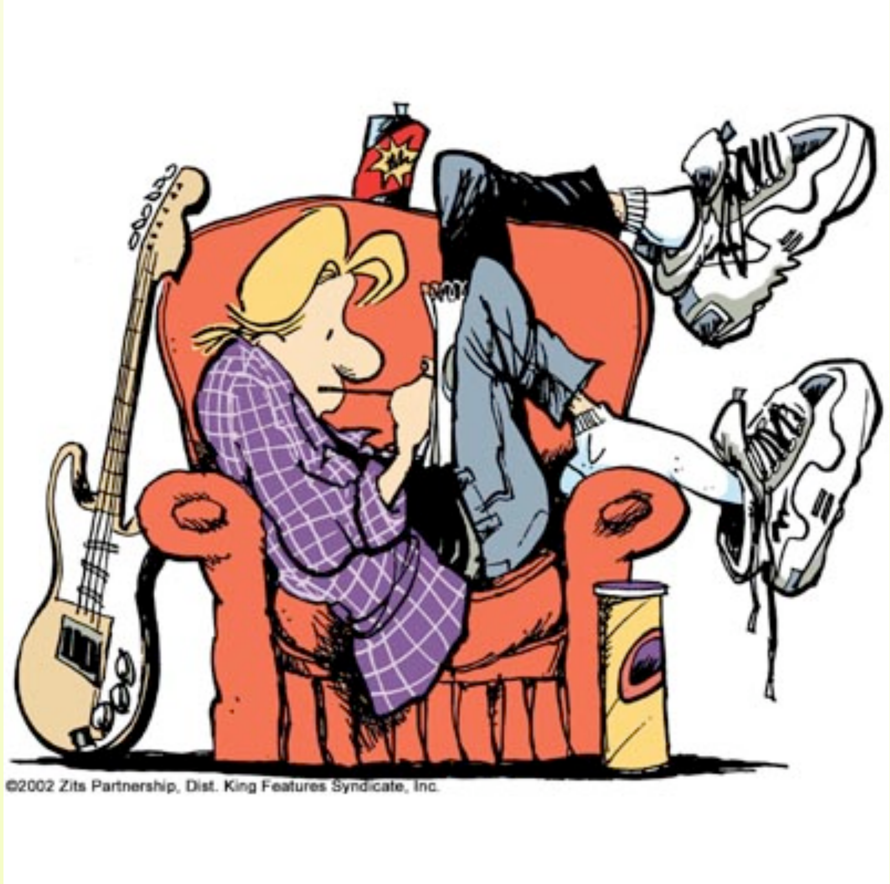
t tbar



Reason #1 : Teenager vs Newborn

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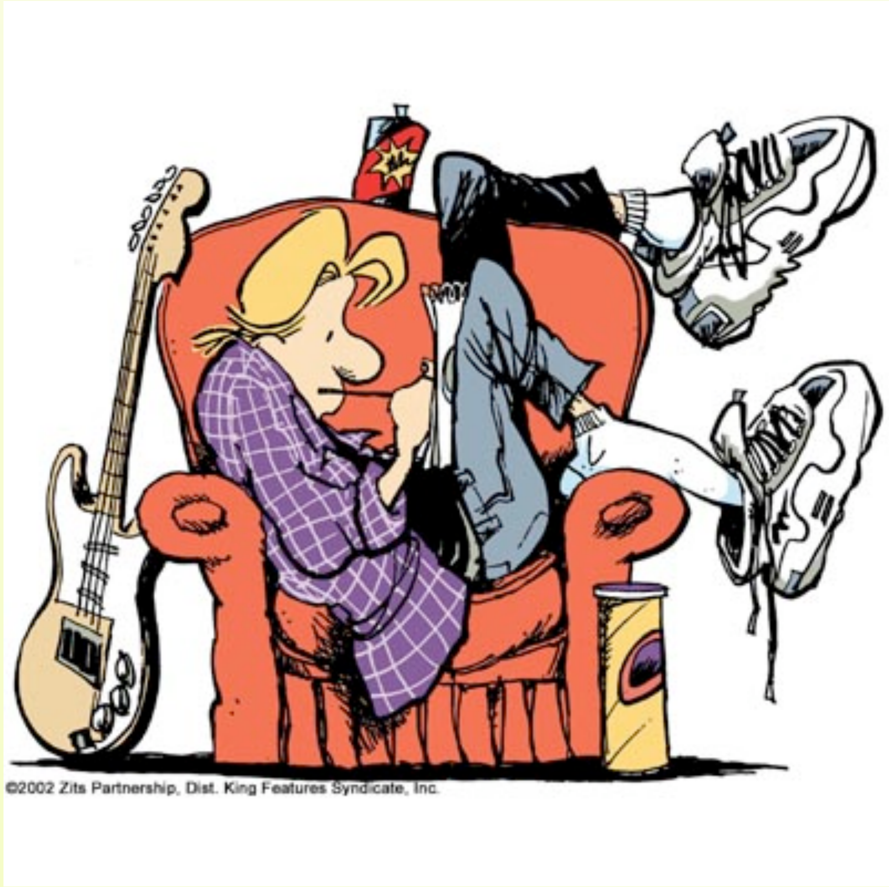

- Born in 1995
- Good : We already know him well
- Bad : We ask him a lot!

Reason #1 : Teenager vs Newborn

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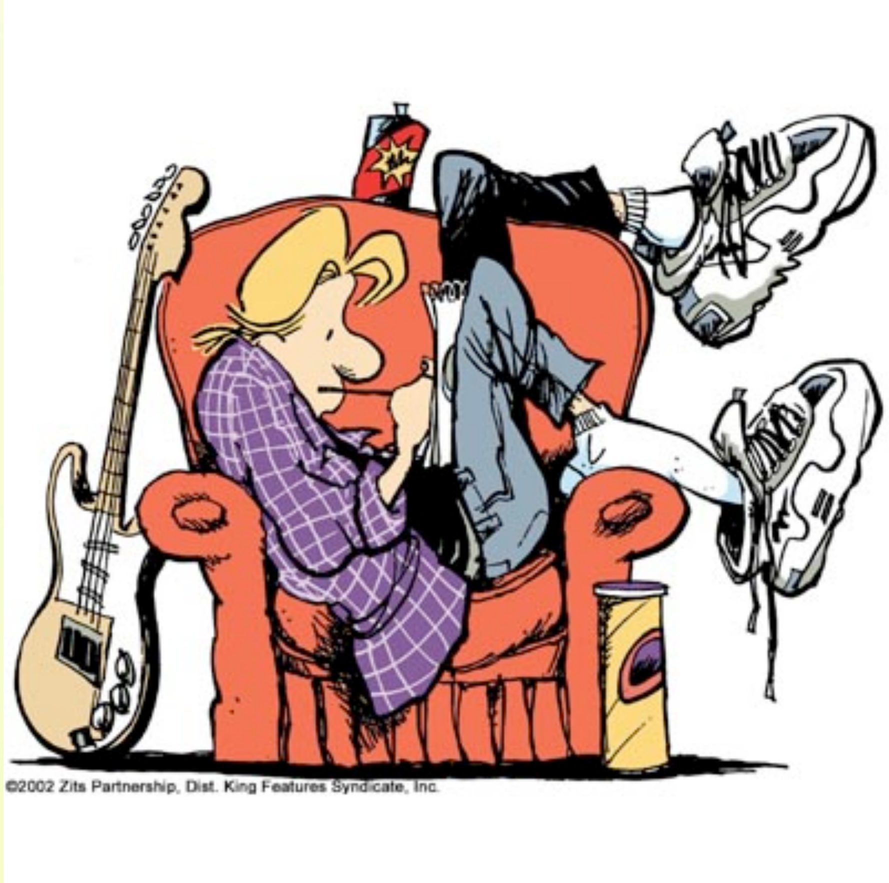
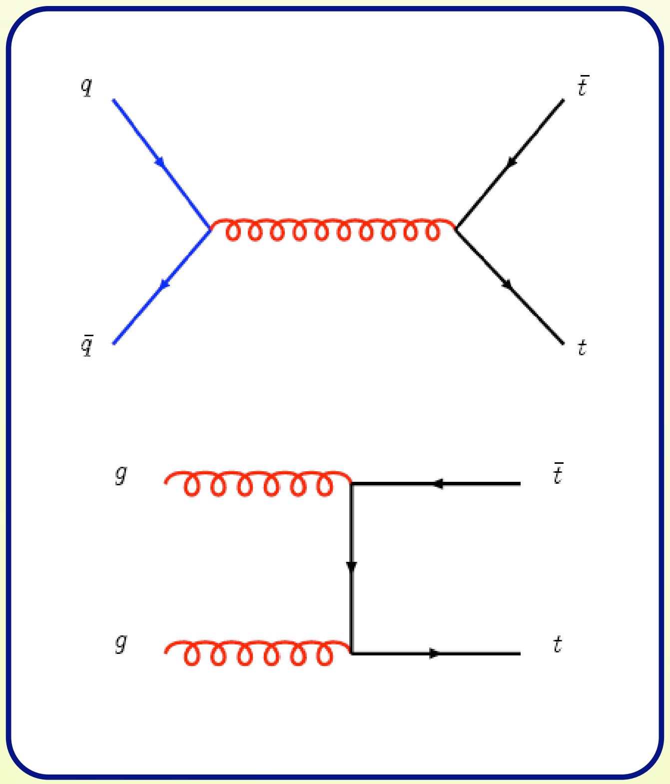


- Born in 1995
- Good : We already know him well
- Bad : We ask him a lot!

single-top

- Just a few weeks old!
- Good : a whole new world to explore
- Bad : sleep deprivation...

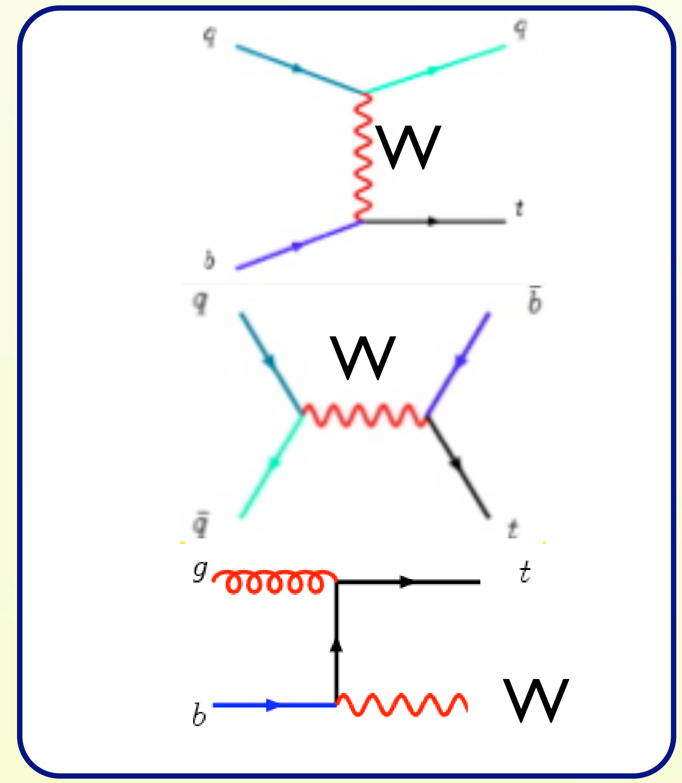
Reason #2 : Single top comes in more shapes and forms!



Largest cross section (LO at α_S^2):

~ 10 pb at Tevatron
~ 1 nb at the LHC

Top discovery mode.

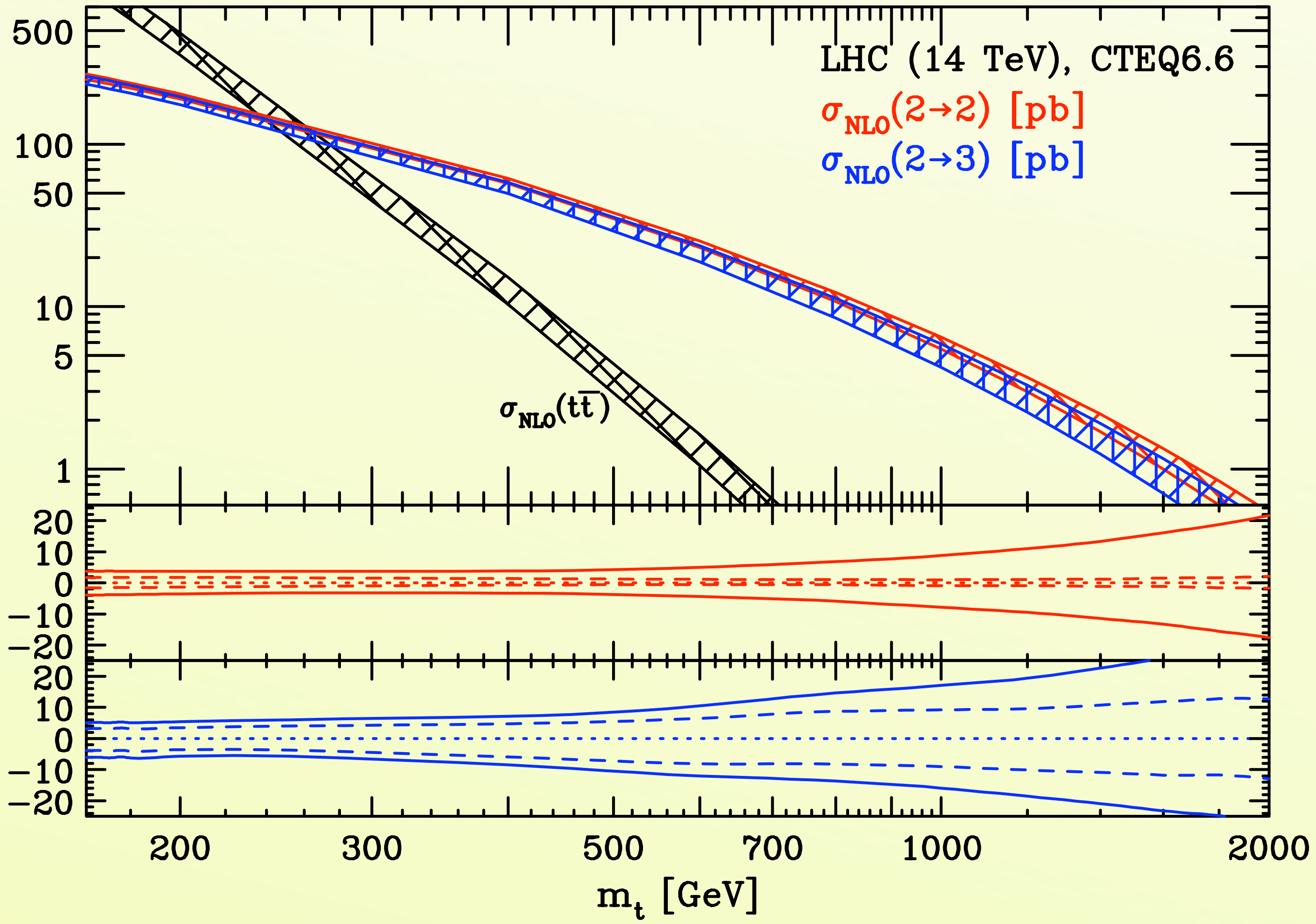


Weak process : same diagrams as the top decay!

Cross sections smaller than QCD but enhanced by a lower energy cost:

~ 3 pb at Tevatron
~ 300 pb at the LHC

Reason #3: Rich potential for new physics



- Direct access to V_{tb}
- Heavy top or bottom partners can be probed.
- FCNC
- W' resonances
- Charged Higgs associated production

Reason #4 : More work for theorists

- Extraction of V_{tb}/anomalous coupling very sensitive to theory input.
- Not so much of an issue now, but something for the precision future.
- Top mass important, e.g. 10% change in cross-section for 170→175 GeV.
- Other uncertainties: PDF (beware the bottom quark!), scale, α_s, m_b.

↖ e.g. down by ~10% from 2004 to now

Calculation	Reference	PDF	cross- section	uncert.
s- NLO	e.g. Sullivan, PRD 70 (2004) 114012	CTEQ6.6M	0,42	(+0.4, -0.4)
s- resNLO*	Kidonakis, PRD 74:114012,2006.	MRST2004NNLO	0,52	(+0.03, -0.03)
t- 2→3 NLO	JC et al., arXiv:0903.0005	CTEQ6.6M	0,93	(+0.16, -0.18)
t- 2→2 NLO	e.g. Sullivan, PRD 70 (2004) 114012	CTEQ6.6M	0,99	(+0.12, -0.10)
t- 2→2 resNLO*	Kidonakis, PRD 74:114012,2006.	MRST2004NNLO	1,12	(+0.06, -0.06)

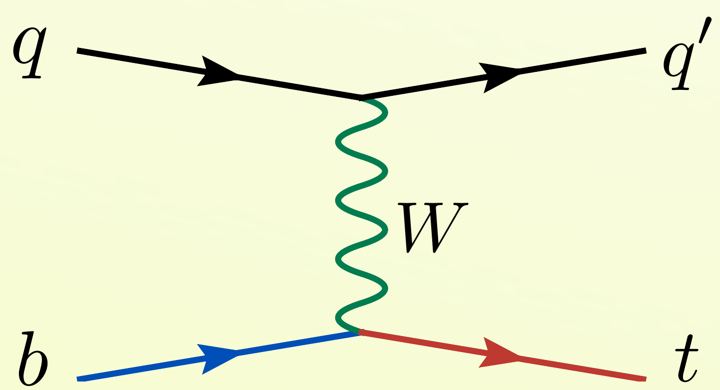
All three channels available in MC@NLO [Frixione et al.], w/ spin correlations!

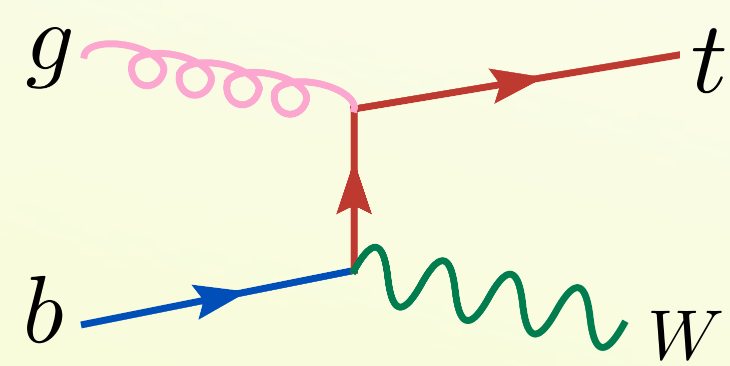
Outline

- A new look at t-channel production:
  - motivations and outline of the new NLO computation in the four-flavor scheme
  - results and comparison with the traditional five-flavor scheme approach
- Outlook

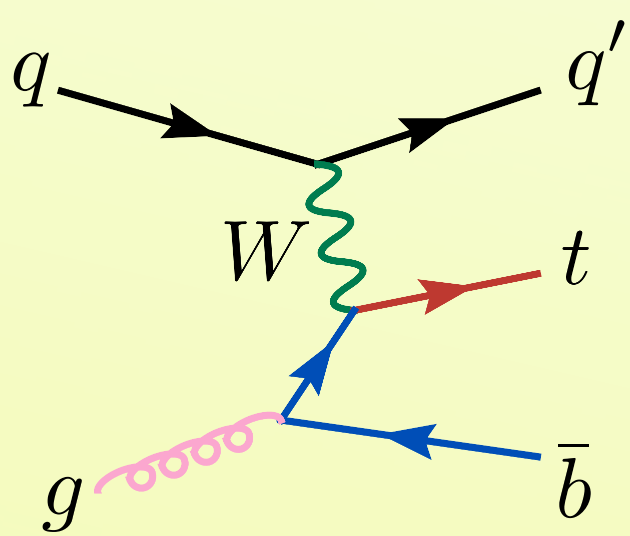
Heavy initial state quarks

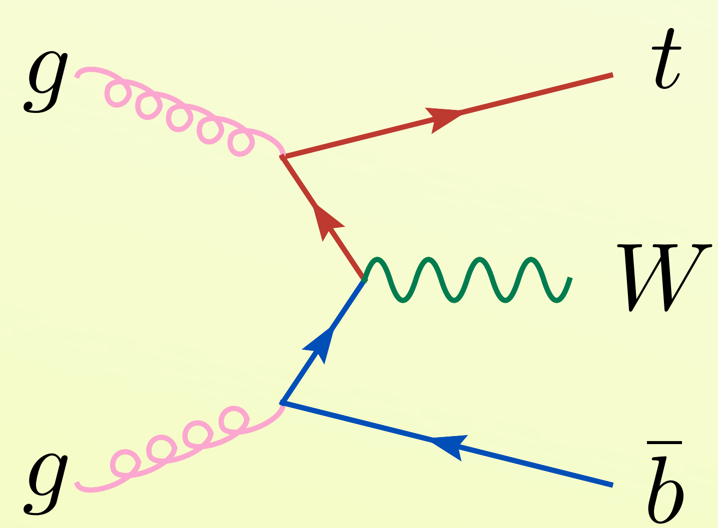
- Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state





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



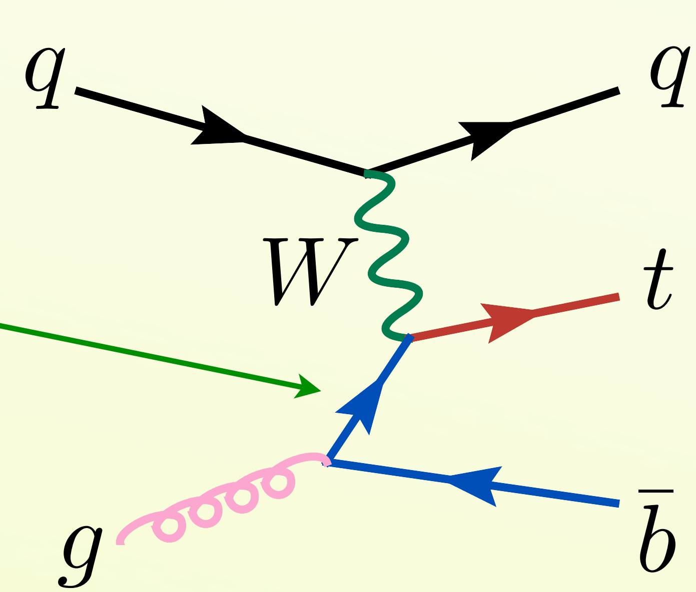


Collinear logarithms

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

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

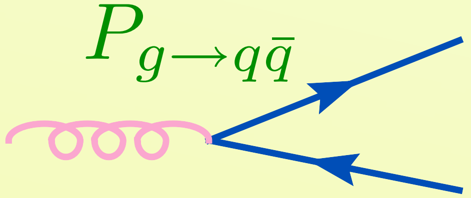
$$t=(p_{\bar b}-p_g)^2,\; p_T^2 = p_{T,\bar b}^2$$



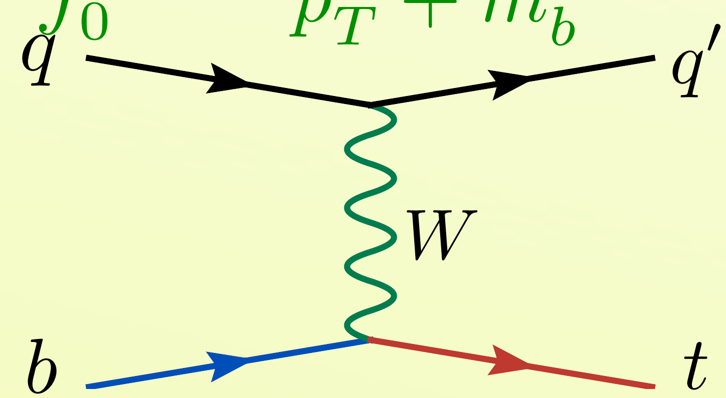
- Contribution to the cross section: $\int_0^{p^2_{T,\max}} \frac{dp_T^2}{p_T^2+m_b^2} = \log\left(\frac{p^2_{T,\max}}{m_b^2}\right)+\ldots$
- Coefficient of the logarithm is:

AP splitting function

$P_{g\to q\bar q}$



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:

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

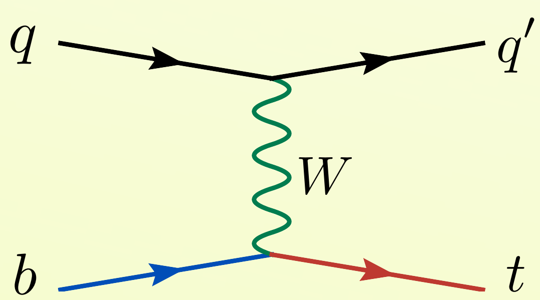
- So when the logarithms really dominate, we can replace this description by $\sigma(qg \to q' t\bar{b}) \approx \sigma(qb \to q't)$
- Scale of the bottom quark PDF should be related $p_{T,\max}$
- At all orders both description should agree; otherwise, differ by:
    - evolution of logarithms in PDF: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

Some examples of b-initiated processes

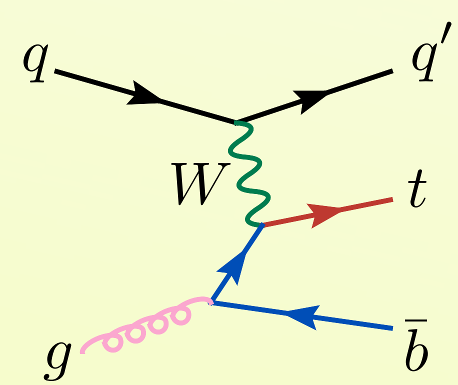
Process	Interest	Accuracy
qb→tq (t-channel)	SM, top EW couplings and polarization, Vtb. Anomalous couplings.	NLO
gb→tW		NLO
qb→Wbj	SM, bkg to single top	NLO
qb→Zbj		NLO
gb→gamma+b	SM, SUSY bkg, b-pdf	NLO
gb→Z+b		NLO
qq+qb→W+b		NLO
bb→ h,A	SUSY discovery/ measurements at large tan(beta)	NNLO
gb→(h,A)+b		NLO
gb→H + t	SUSY discovery, couplings	NLO

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 → 2) when the "spectator b" is not important, otherwise keep it explicit ("4 flavor scheme", 2 → 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 → 2) scheme



- Terms from 4F (2 → 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

Need for macthing in the 2 → 2 calculation

- 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

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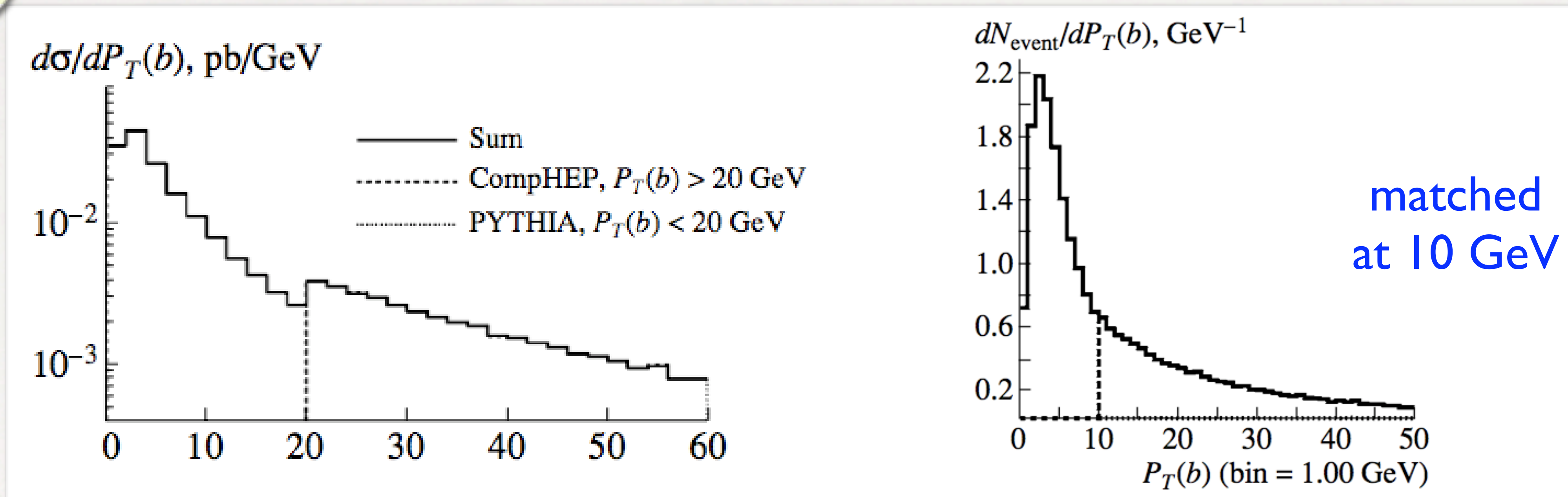

Boos et al., Phys. At. Nucl. 69, 1317 (2006)

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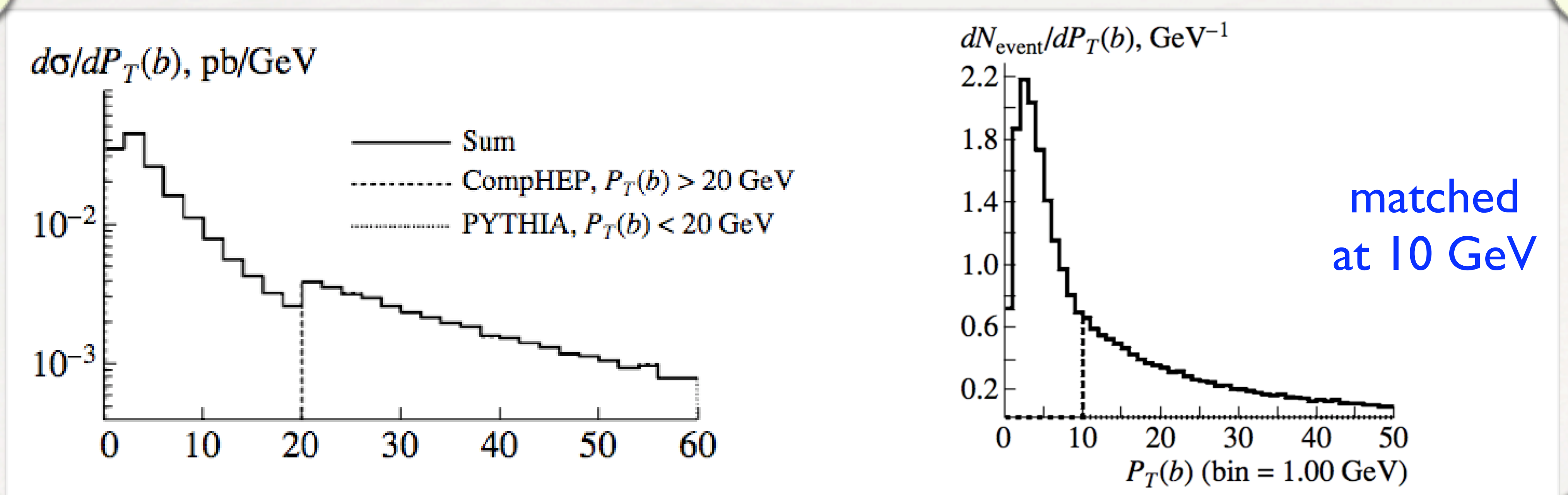

Boos et al., Phys. At. Nucl. 69, 1317 (2006)

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

Need for matching in the 2 → 2 calculation

- All current single-top analyses are based on such a matching!
- The need for matching builds on THREE "prejudices":

1. Effects of the resummation are important ⇒ use the 2→2 calculation
2. The shower does the resummation for the HQ's accurately
3. Matching 2→2 with 2→3 for the b's promotes the prediction of spectrum of the b to NLO

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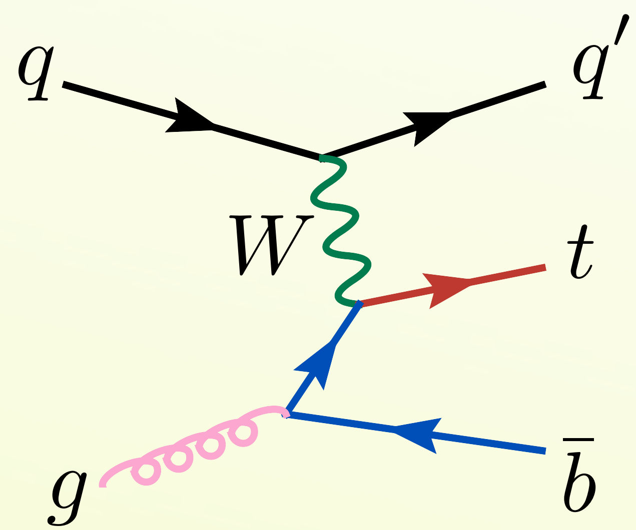
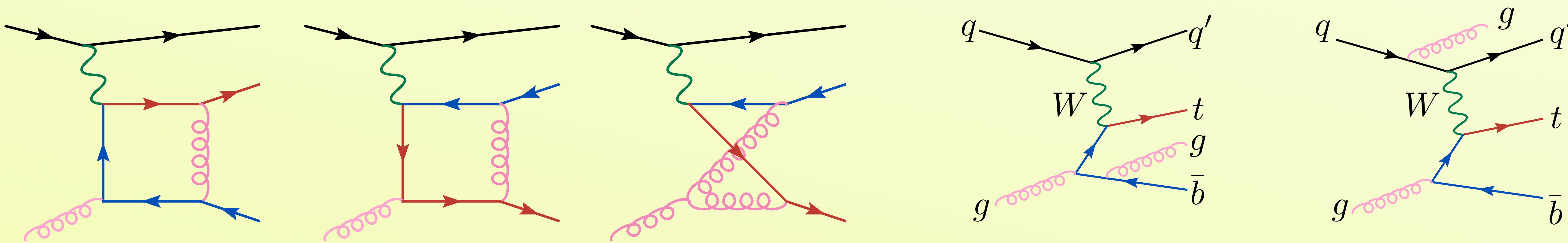
Q: truths or myths?

NLO in the four-flavor scheme

- Use the 4-flavor $(2 \to 3)$ process as the Born and calculate NLO
  - Much harder calculation due to two different masses 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 $(2 \to 3)$

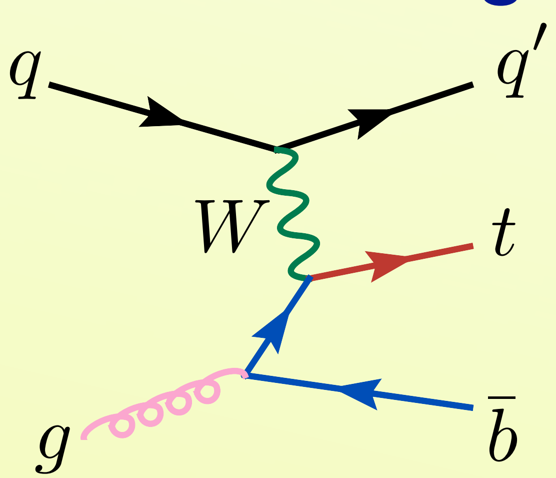




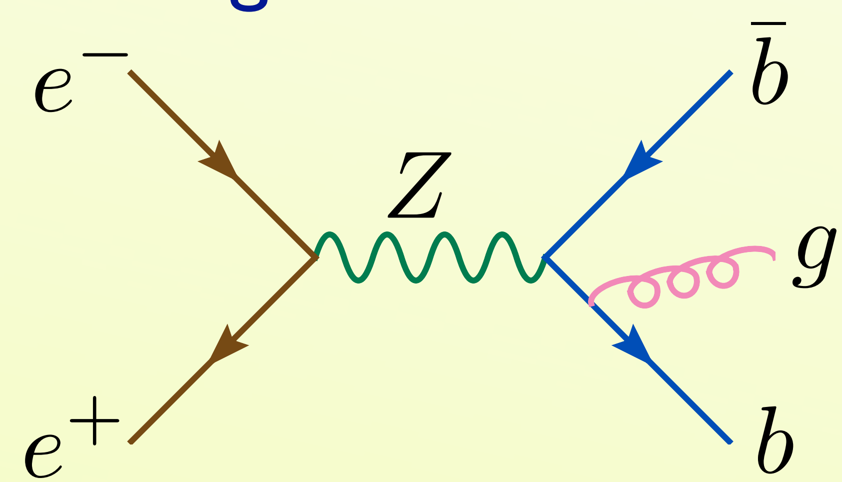
Checks of the calculation

- 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



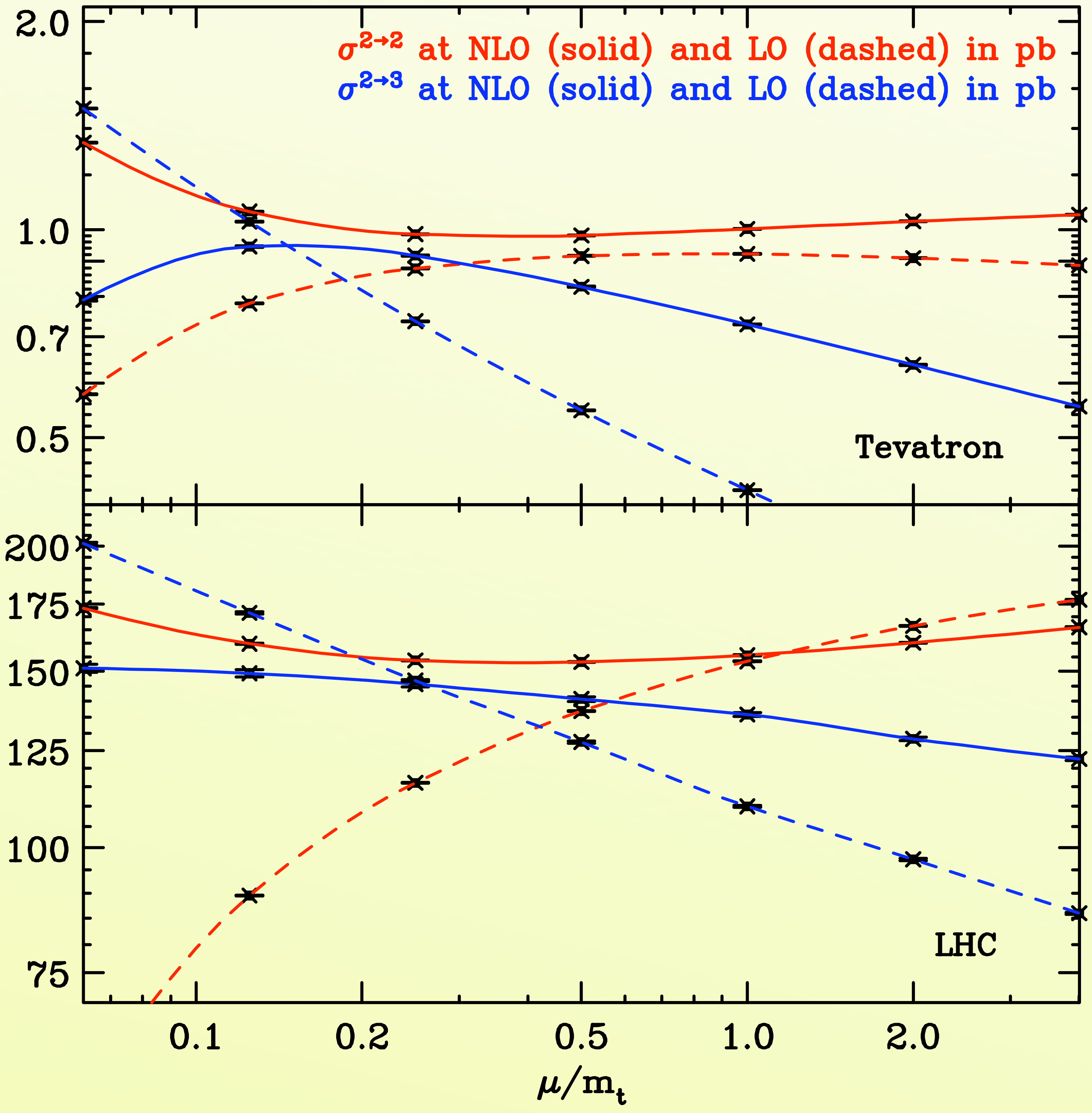
Nason & Oleari, NPB 521, 237 (1998)

- 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 ($2 \to 2$) scheme, use regular PDF
- For 4F ($2 \to 3$) 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

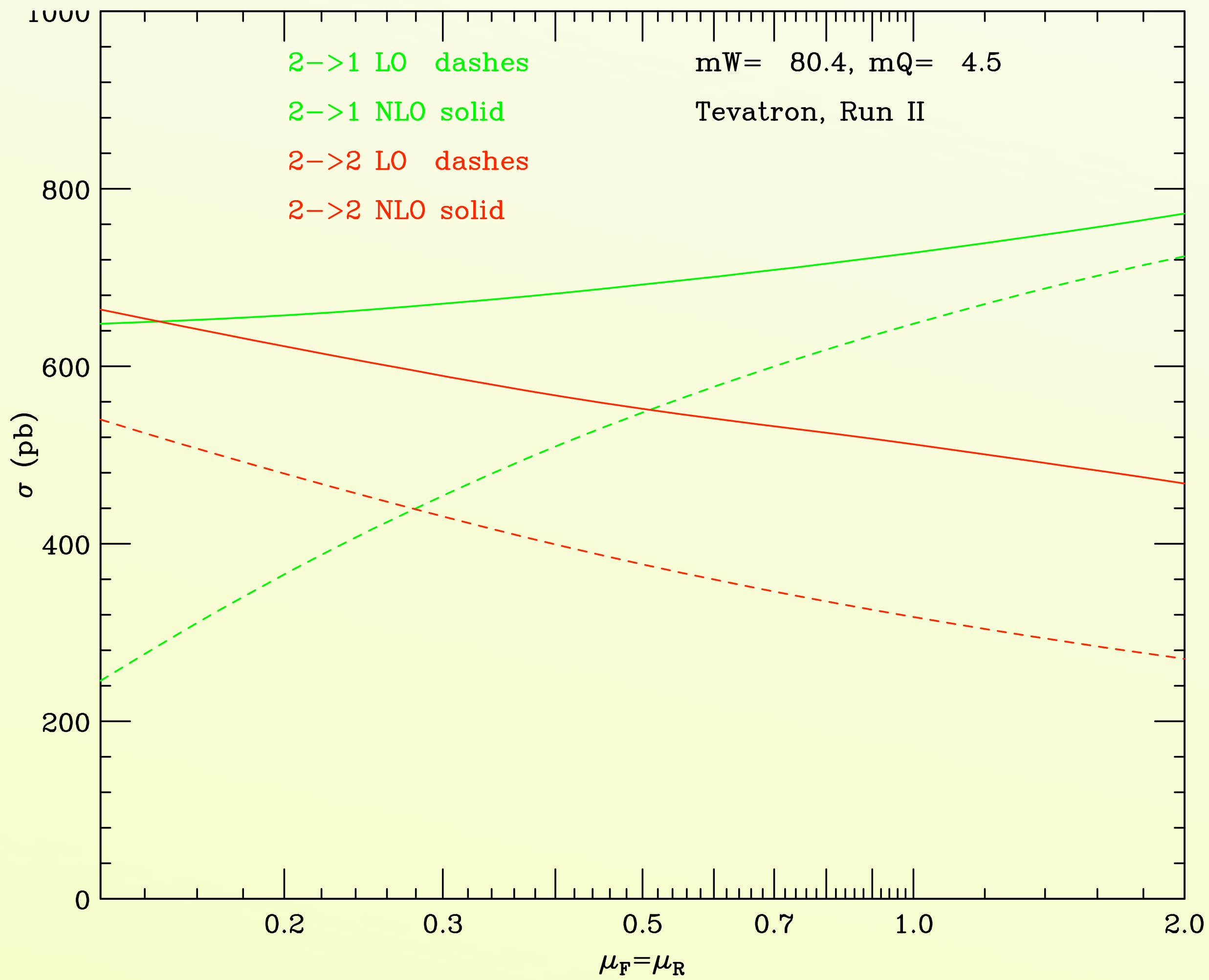
Scale dependence

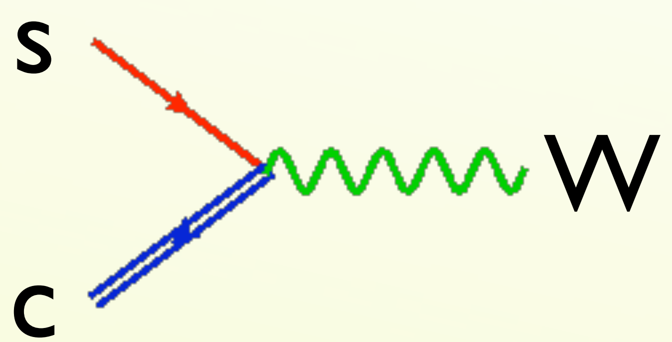


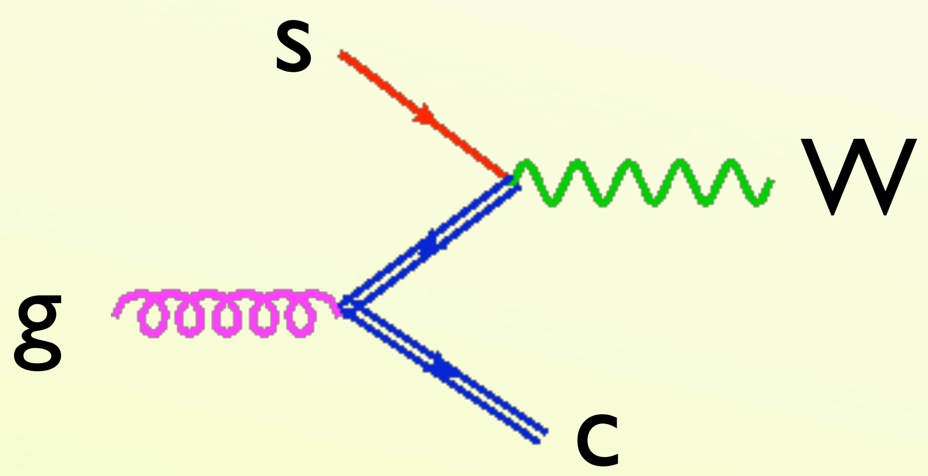
- Both schemes much improved from LO
- 5F (2 → 2) only mildly sensitive to scales at NLO (use m_t in what follows)
- 4F (2 → 3) expected to be worse, but isn't much
- Hardly a region of overlap between the two
- 4F (2 → 3) prefers smaller scales than m_t, particularly at the Tevatron

Similar behavior in WQ : 2→1 vs 2→2

Campbell, Maltoni, Mangano, Tramontano, in progress





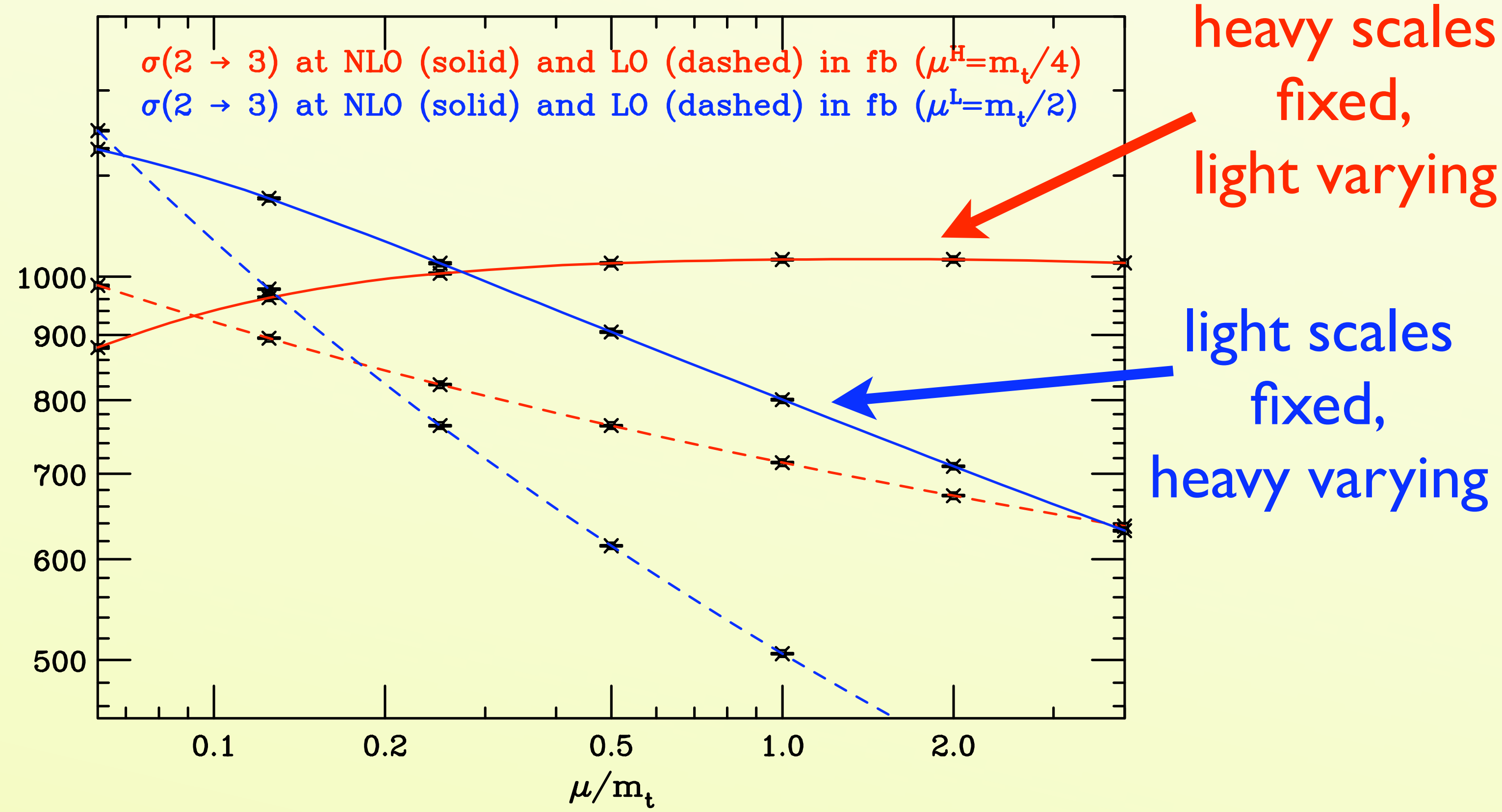


Conjecture: "Universal behaviour" for the scale dependence of the 5F and 4F calculations. No clear need for resummation.

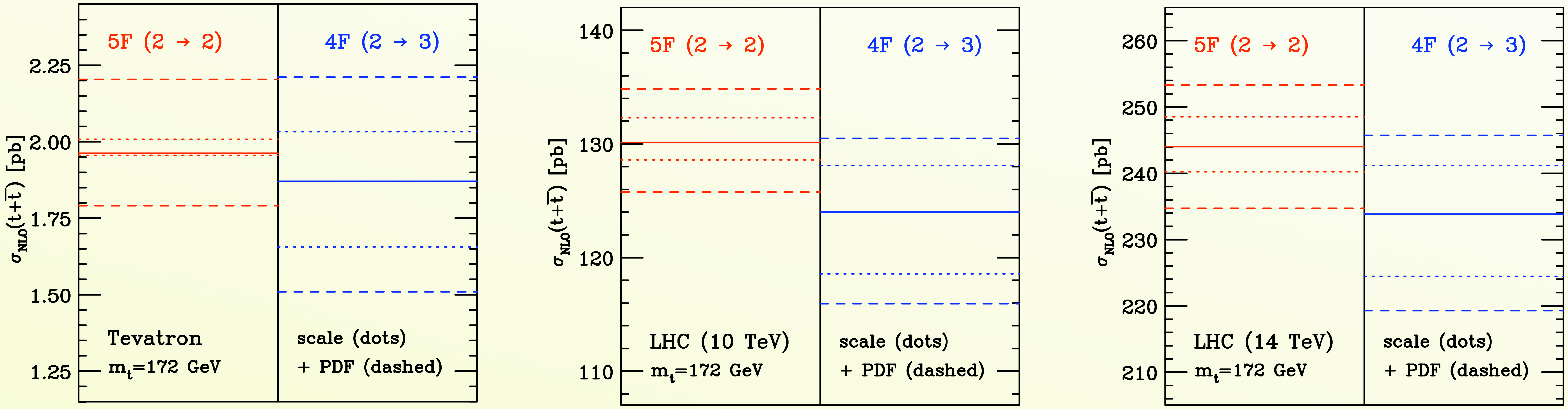
Scale dependence 2 → 3

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

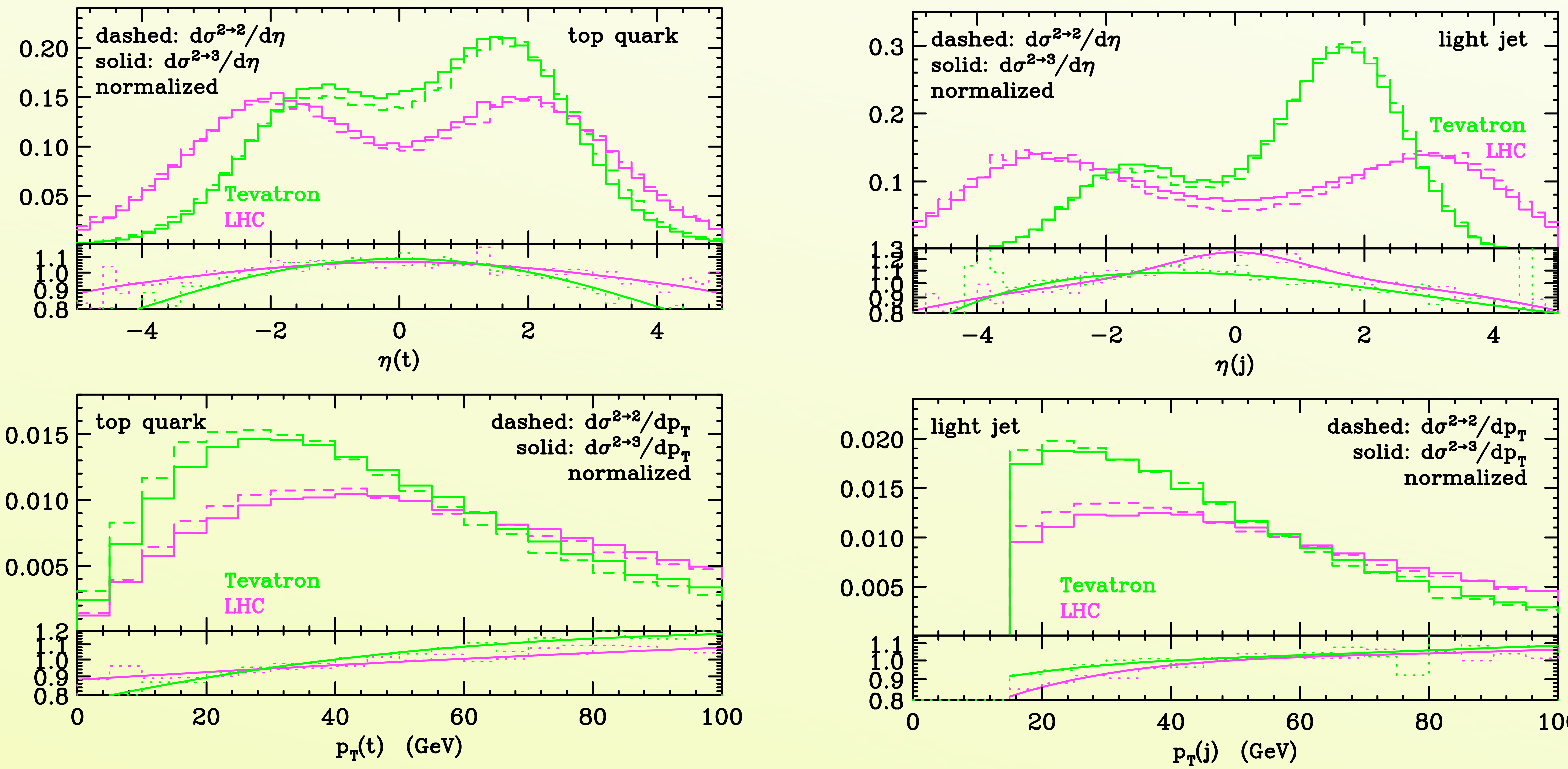


Total rates and theory uncertainties



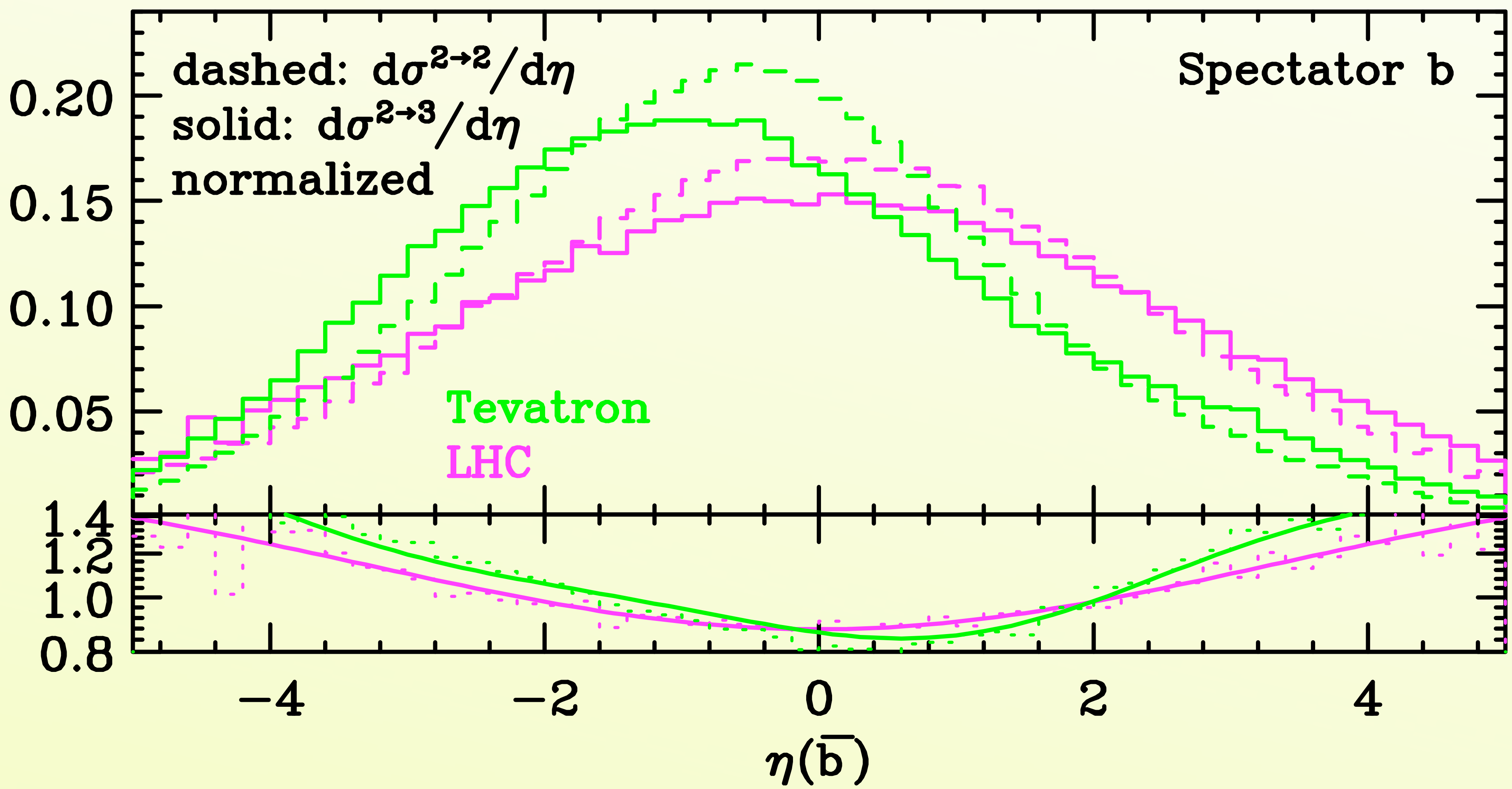
- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- Consistent at the Tevatron: logarithms not so important?
- For the LHC, the minor difference could point to either:
  - "large" logarithms being resummed
  - b-pdf's are not accurate
  - Higher order corrections (NNLO for 2→2) important...

Top and light jet distributions



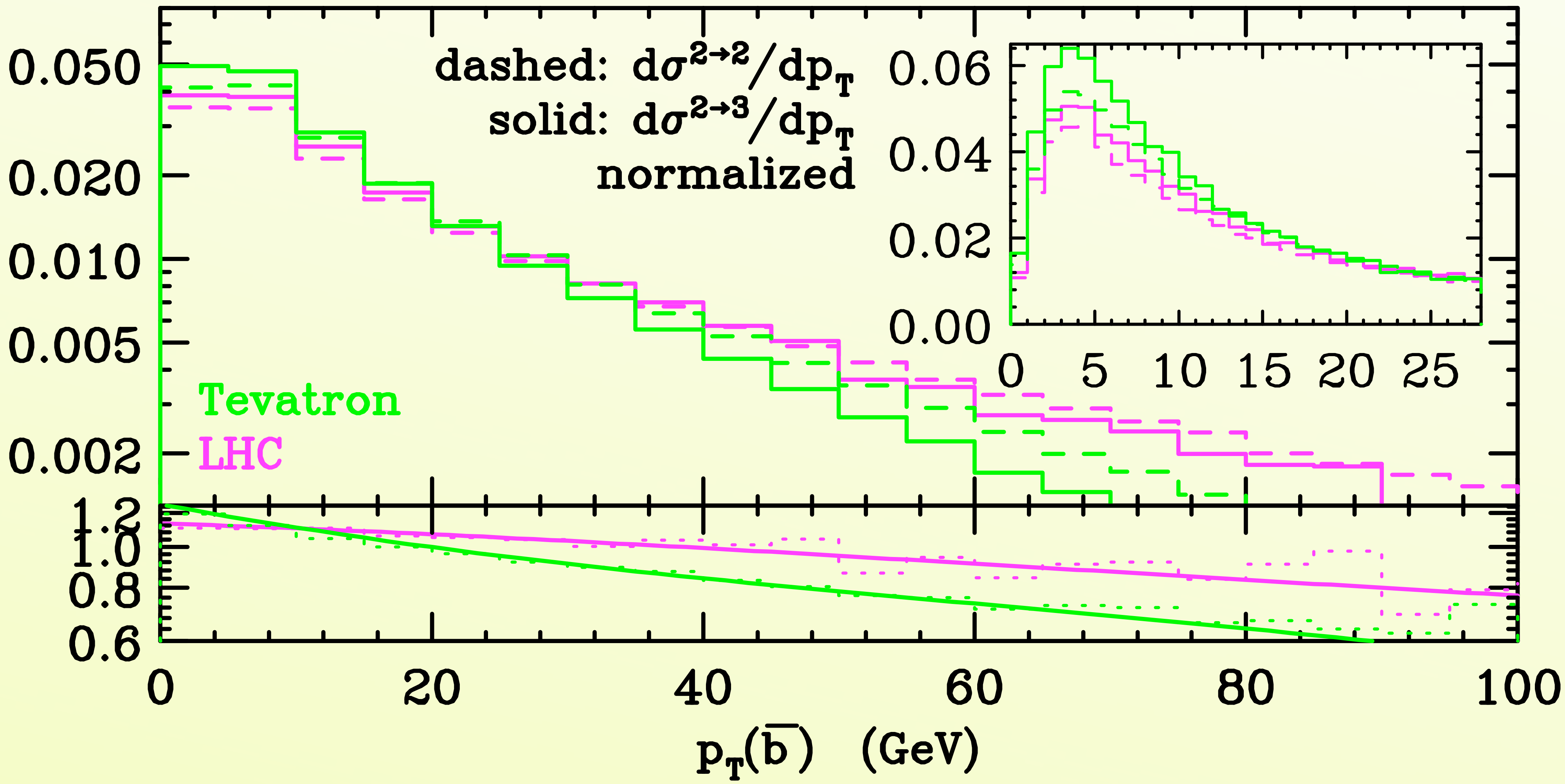
Some differences, but typically of the order of ~10% in the regions where the cross section is large

Spectator b



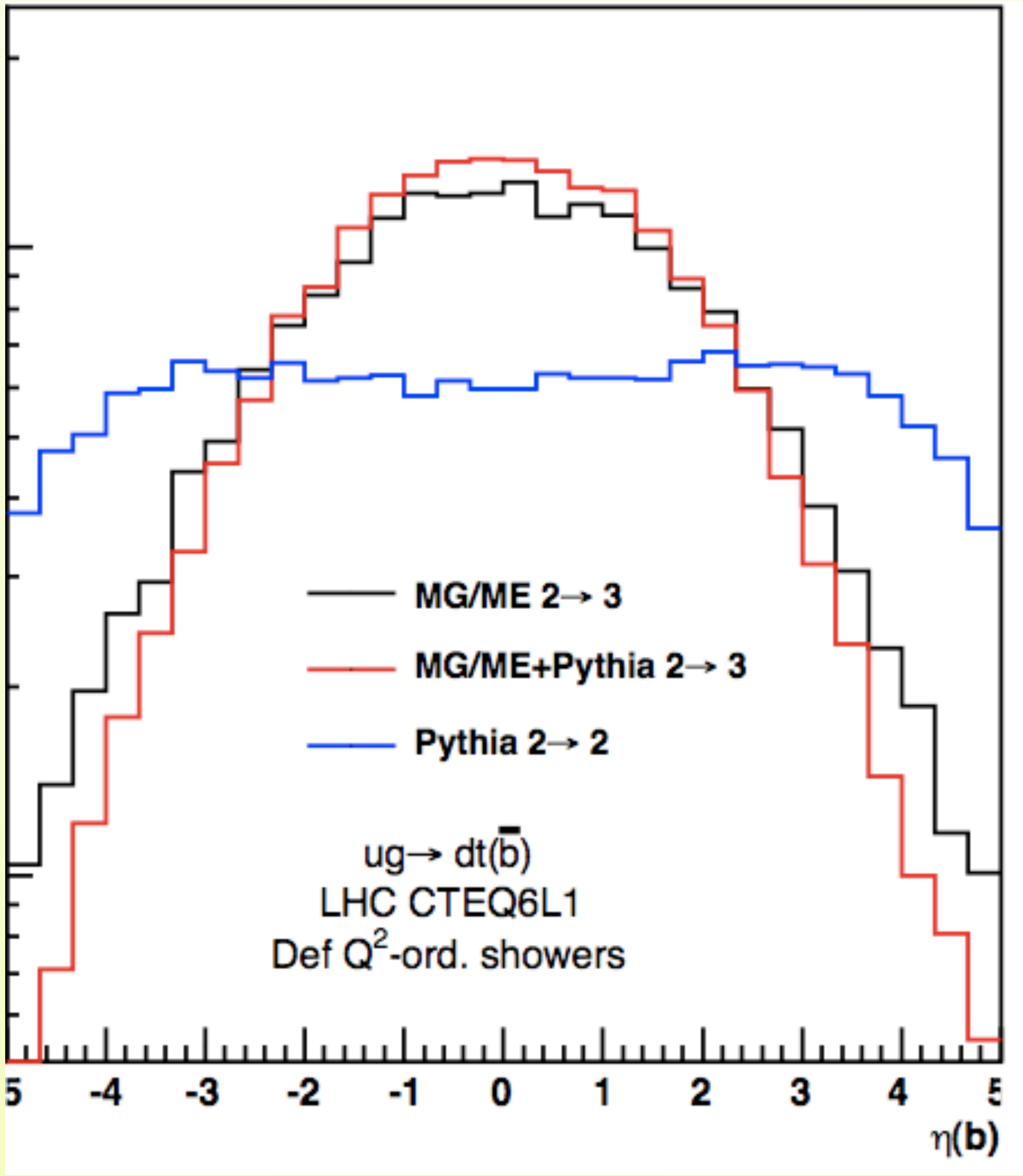
- First NLO prediction for this observable
- Slightly more forward in 4F (2 → 3), particularly at the Tevatron
- Deviations up to ~ 20%

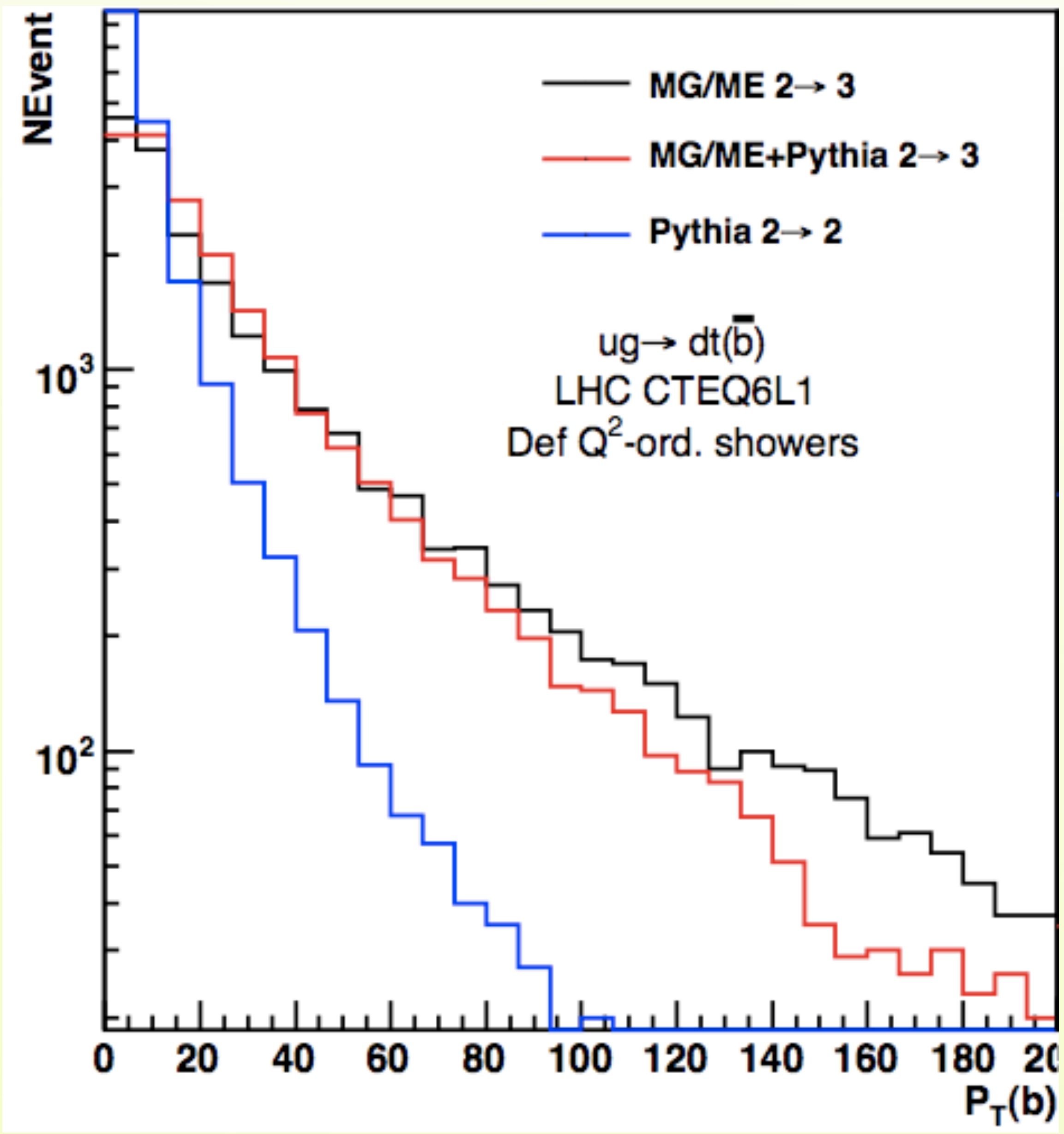
Spectator b



- First NLO prediction for this observable
- Slightly softer in 4F (2 → 3), particularly at the Tevatron
- Deviations up to ~ 20% : perturbatively quite stable

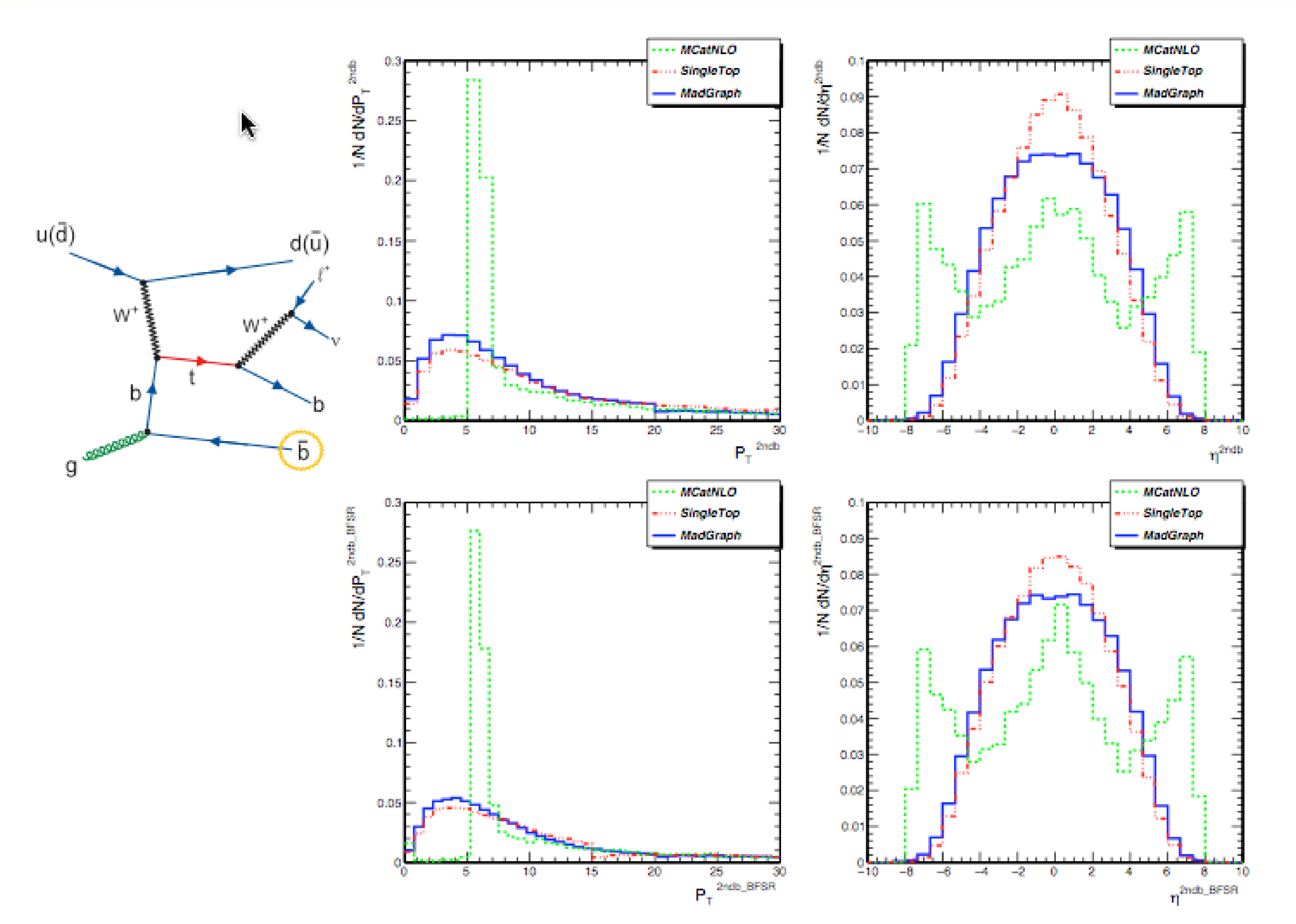
MC comparison at LHC





pT and η spectra of the spectator HQ from the 2→3 prediction are accurate and do not need any dangerous matching...

MC comparison at LHC

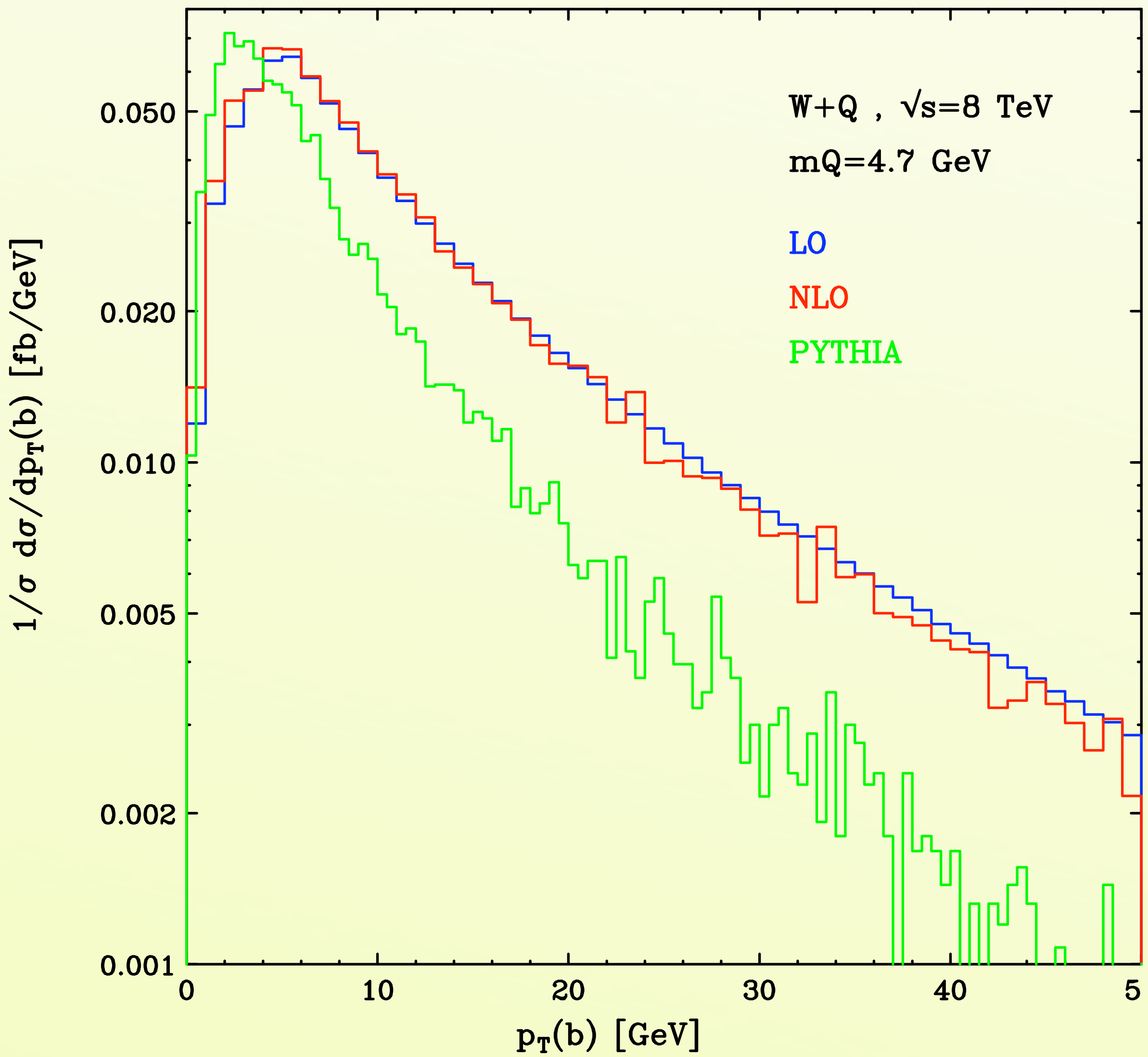


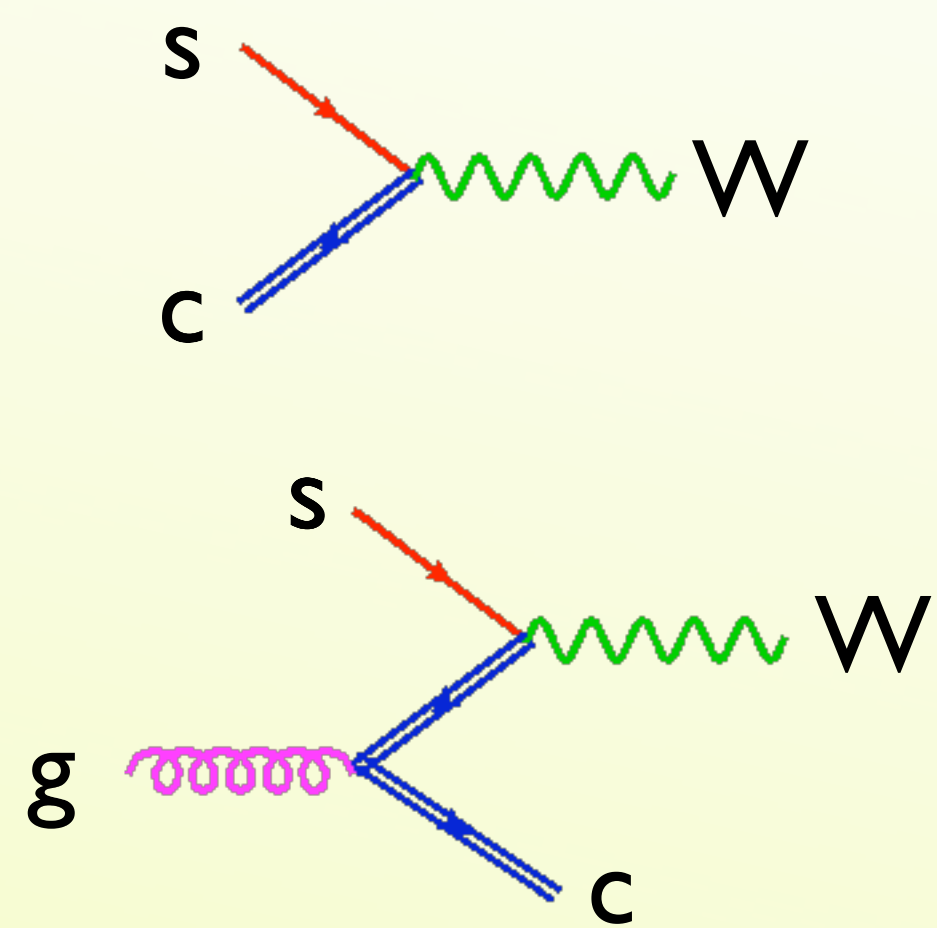
Shower for initial states HQ needs to be improved!

CMS AN-2009/024

Similar behavior in WQ : 2→1 vs 2→2

Campbell, Maltoni, Mangano, Tramontano, in progress





- pT spectrum of the spectator HQ unchanged
- no call for resummation
- the 2→2 prediction for the spectator theoretically solid.

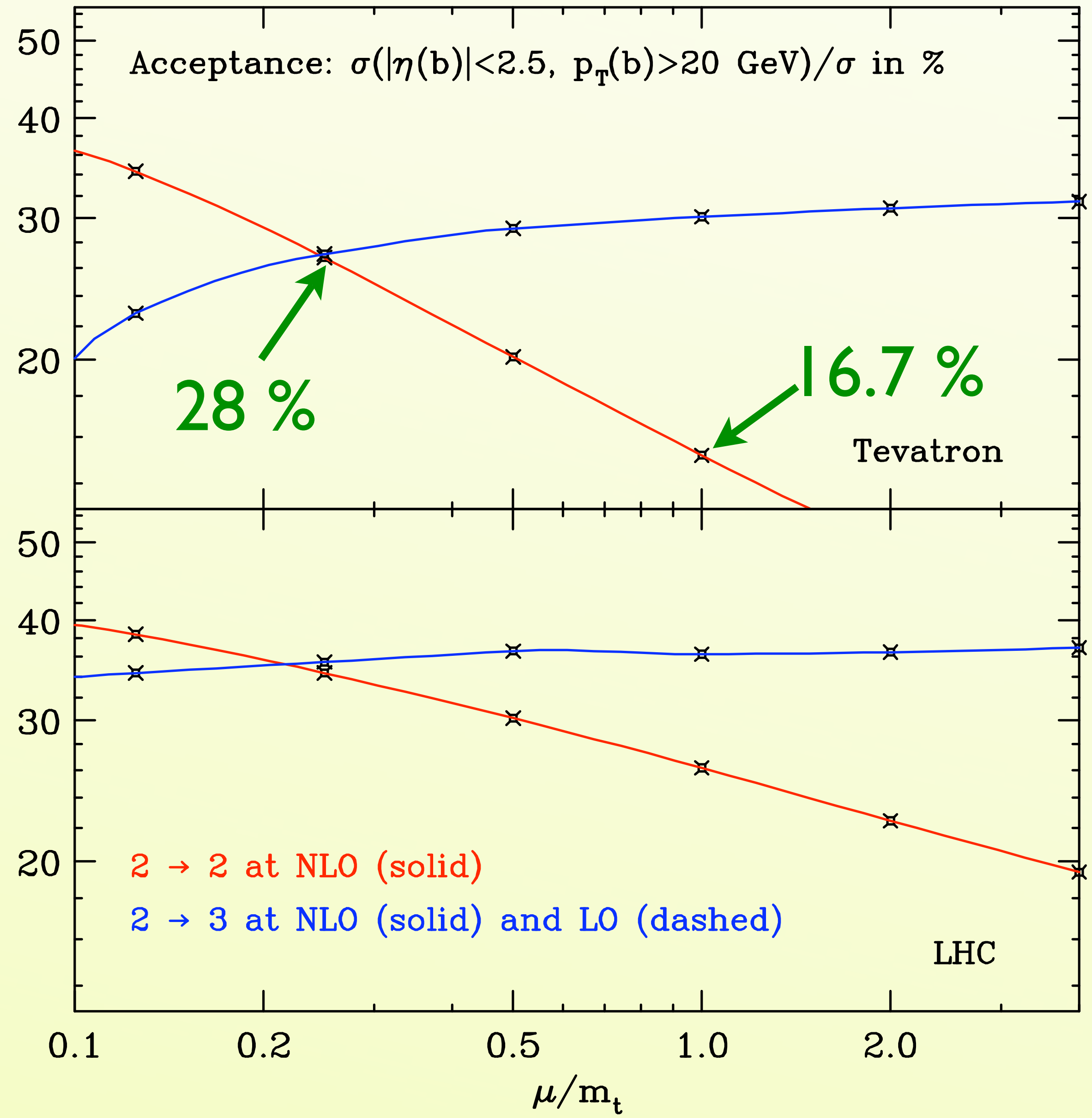
Applications of the new NLO calculation

- 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
- Dramatic effect at the Tevatron, less so at the LHC.



Consequences for single top observation?

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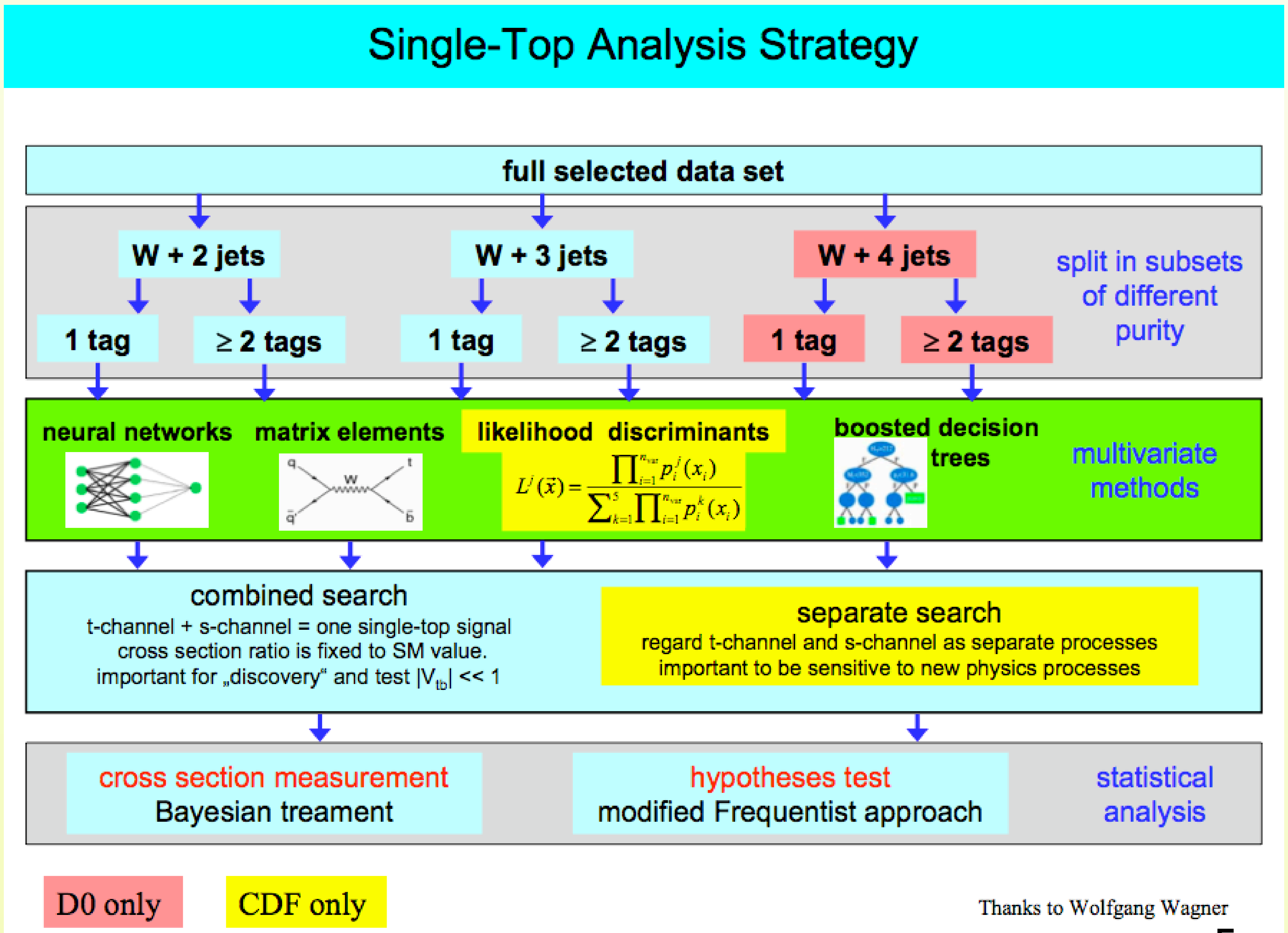

From Tony Liss' talk

Consequences for single top observation?

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- Naively:
  - No change in total cross section (s + t channel) ⇒ significance of the observation and Vtb not affected. Needs to be carefully checked!

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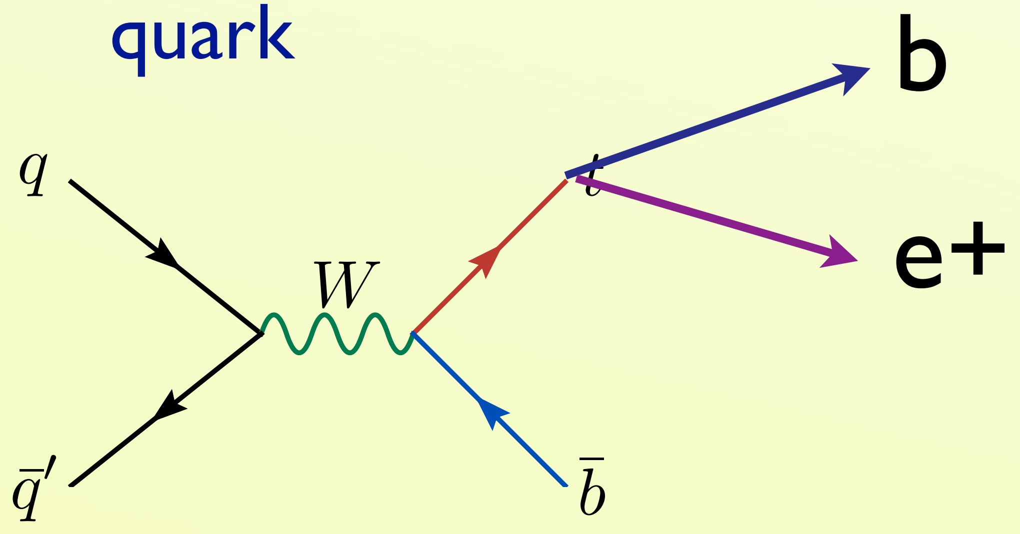
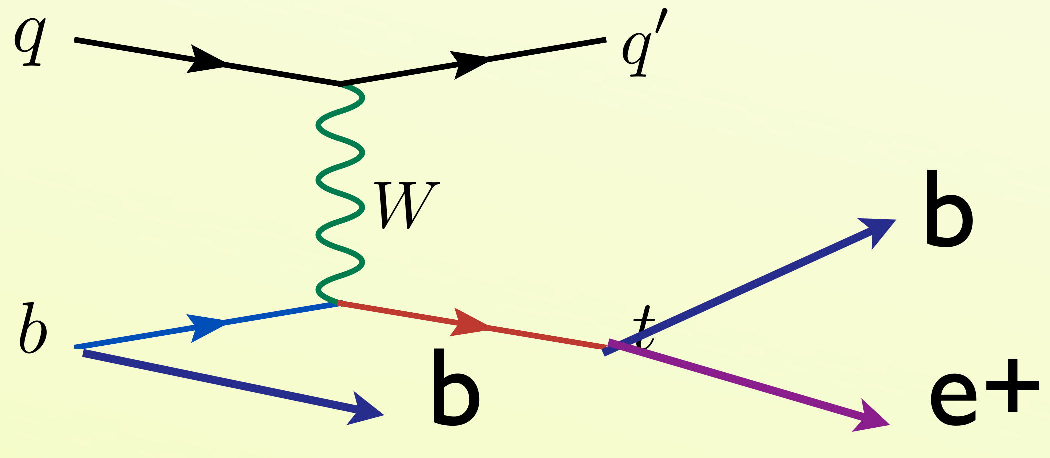
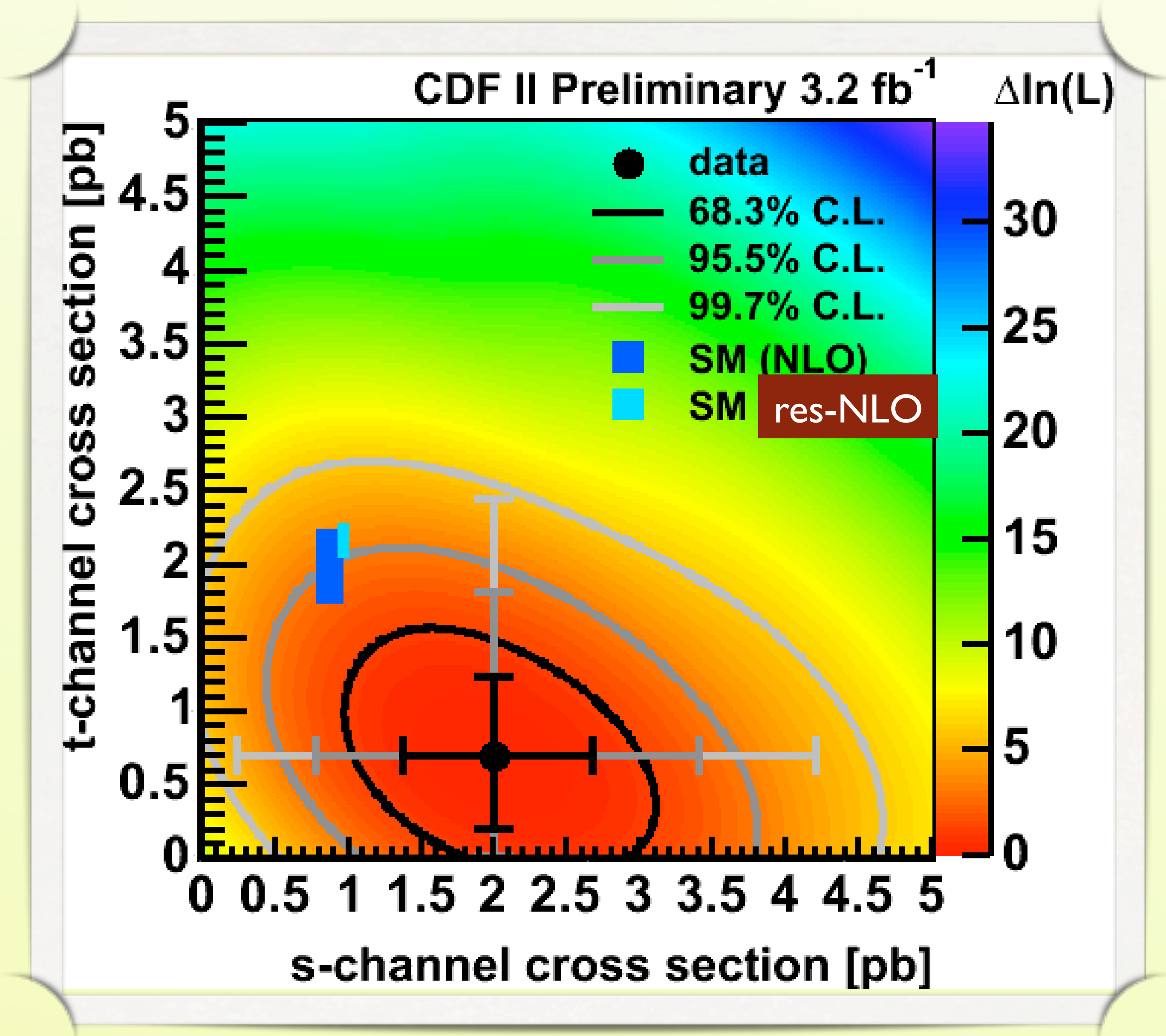
- Naively:
  - No change in total cross section (s + t channel) ⇒ significance of the observation and Vtb not affected. Needs to be carefully checked!
  - More events that were considered s channel before are in fact t channel, because more t channel events have also a spectator b quark





Measured t channel might go up, s channel might go down!!

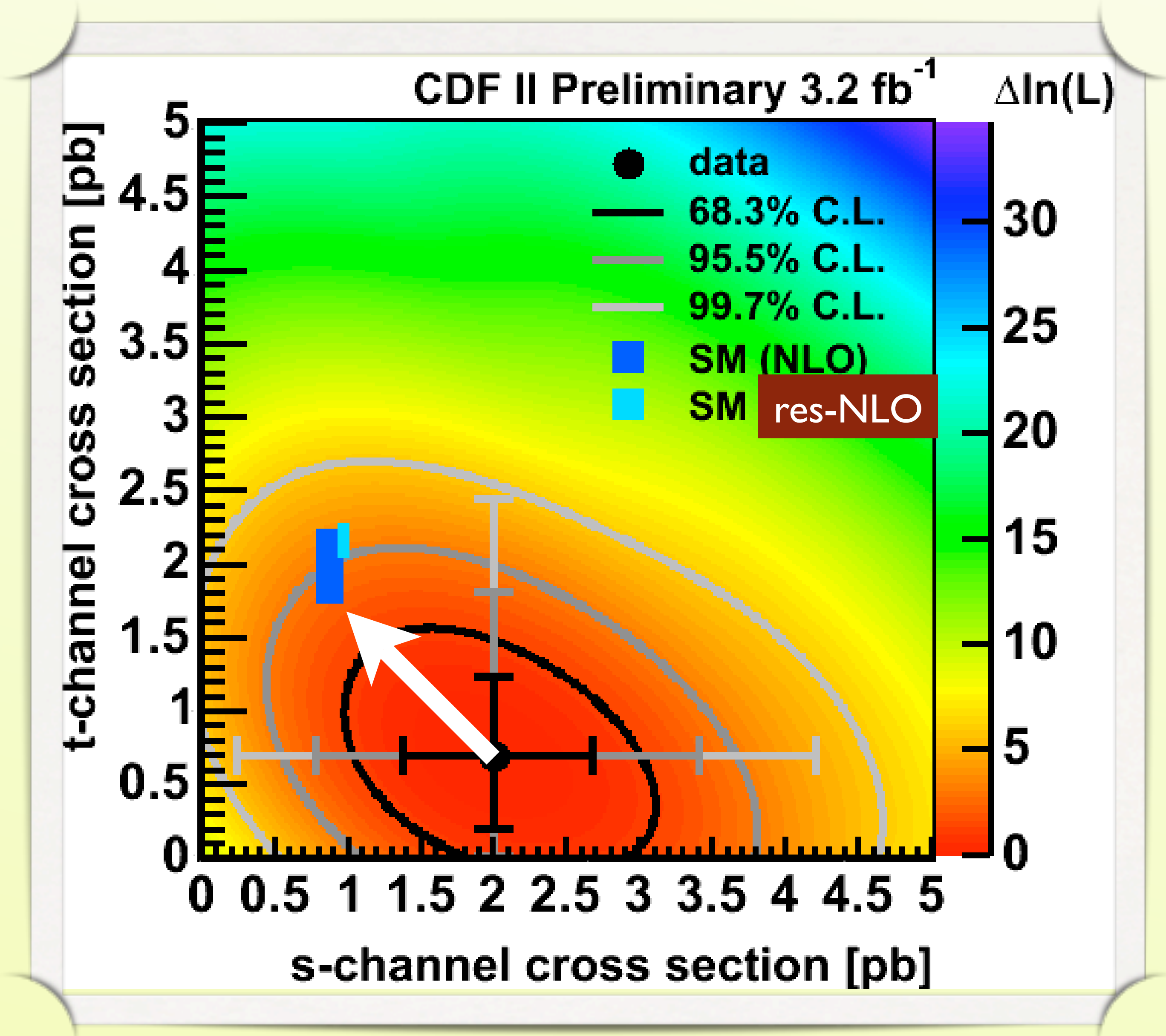
s and t channel separation at CDF



CDF note 9716

- CDF has published separated results for the cross sections based on the 17% acceptance.
- Could this explain (at least part of) this 2 sigma deviation?
- CDF (and hopefully DØ) single top groups are addressing this issue.

s and t channel separation at CDF



CDF note 9716

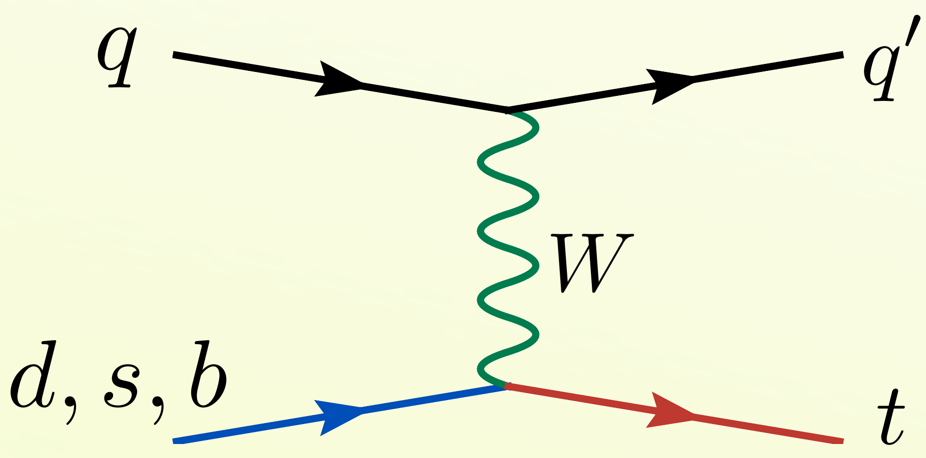
- CDF has published separated results for the cross sections based on the 17% acceptance.
- Could this explain (at least part of) this 2 sigma deviation?
- CDF (and hopefully DØ) single top groups are addressing this issue.

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 in the acceptances.
- Systematic uncertainty study
- Application to fourth-generation heavy quark searches (t' and b')
- Comparison with event generators
- ◉ Detailed assessment of impact on current single top searches
- ◉ Implications for other heavy-quark initiated predictions (5F vs. 4F)
- ◉ Inclusion in a full shower (a la MC@NLO) and top decay

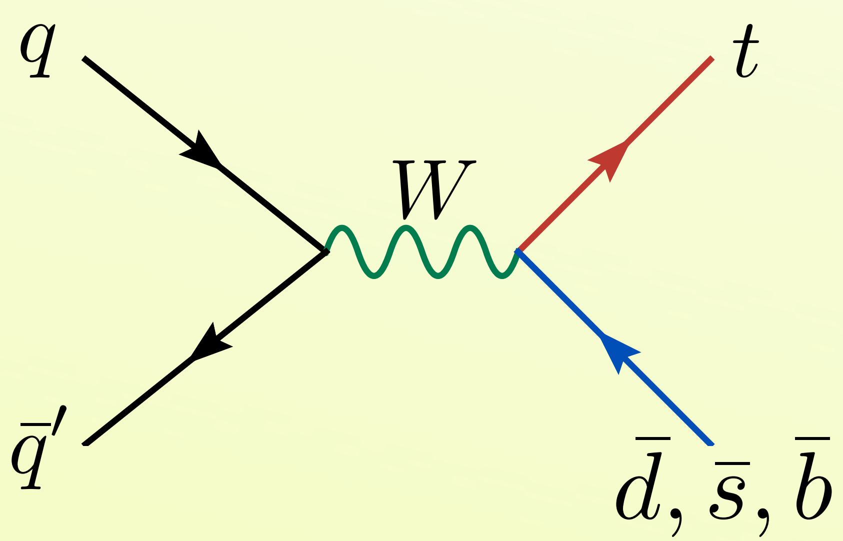
More slides

More subprocesses



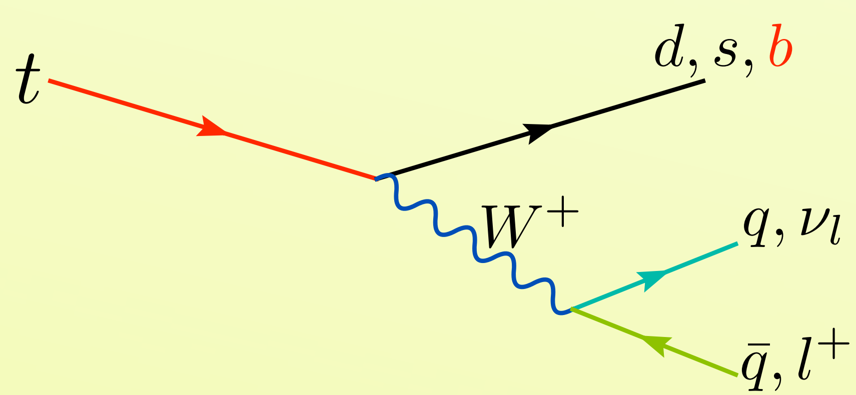
$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

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



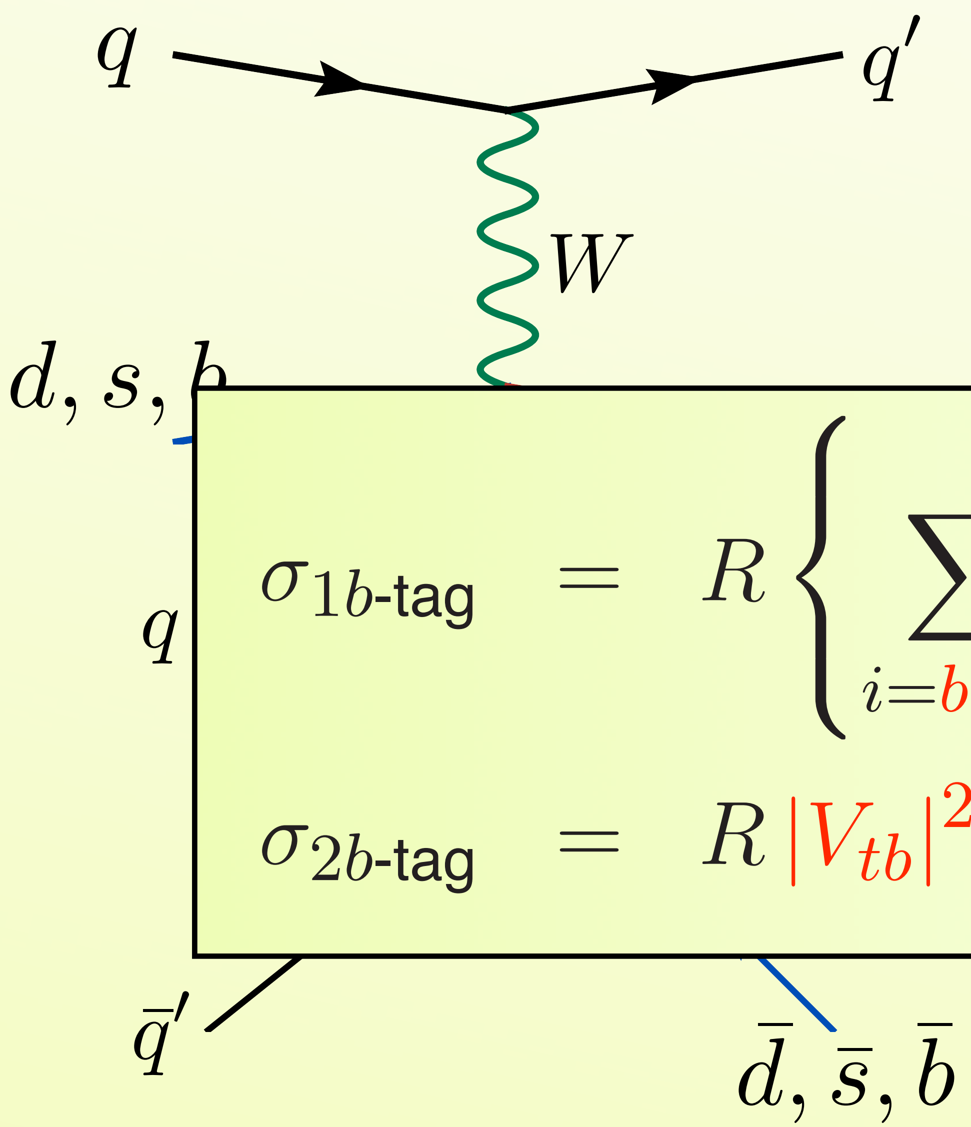
$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)\sigma^{\text{s-ch}}$$

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



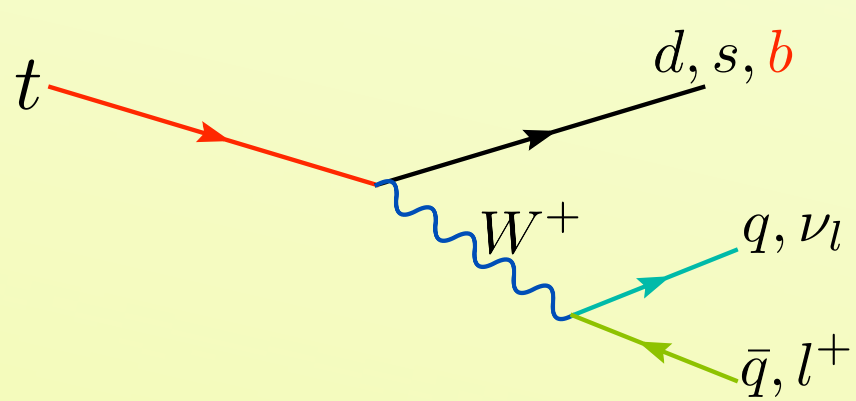
$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

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

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

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

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



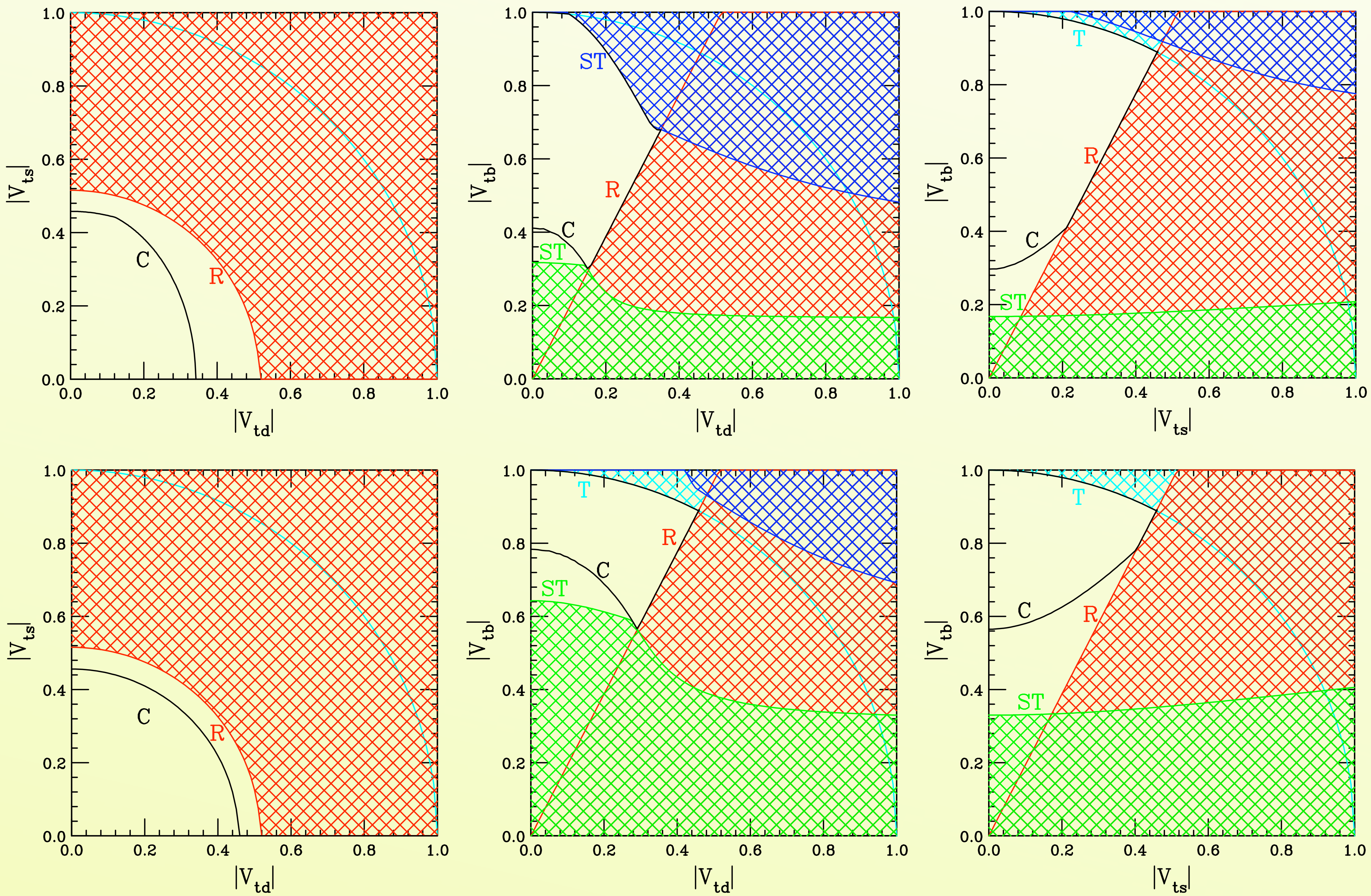
$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq(=d,s,b))} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Constraints on 3rd row of the CKM matrix

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

CDF

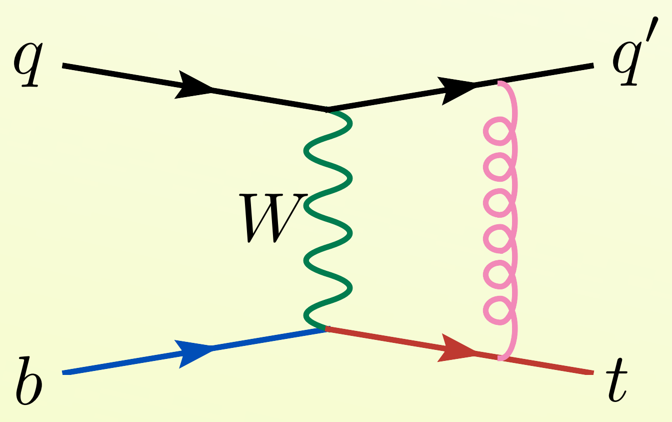
DØ



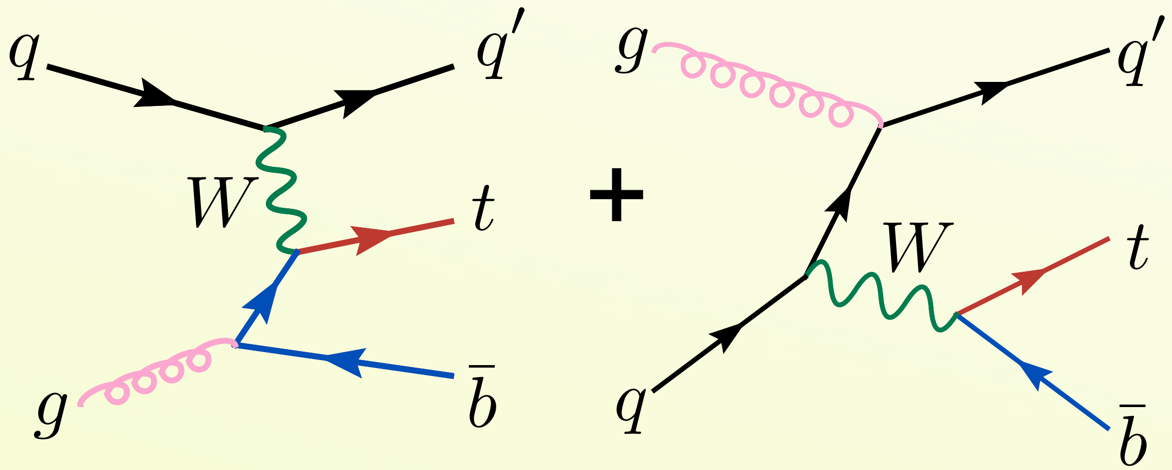
Alwall et al., Eur. Phys, J. C49 791 (2007) + updates

Factorization in 2 → 2

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



Vanishes: Tr[t^a]=0

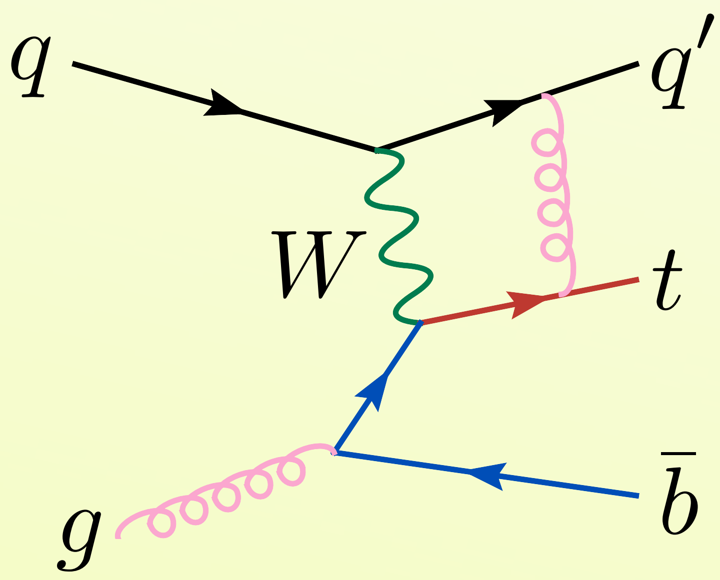


Interference between t and s channel vanishes: Tr[t^a]=0

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

Factorization in 2 → 3

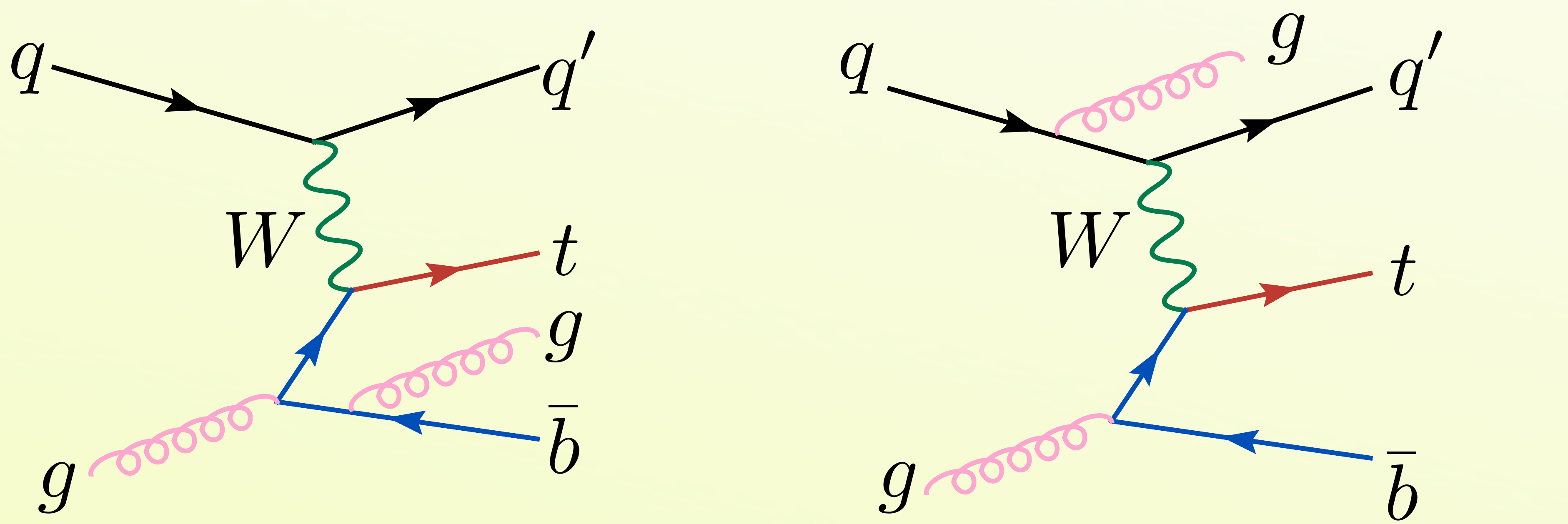
- The same arguments still mostly apply to the 2 → 3
- No mixing between light and heavy quark lines from the virtual corrections



Vanishes: Tr[t^a]=0

Factorization in 2 → 3: real emission

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



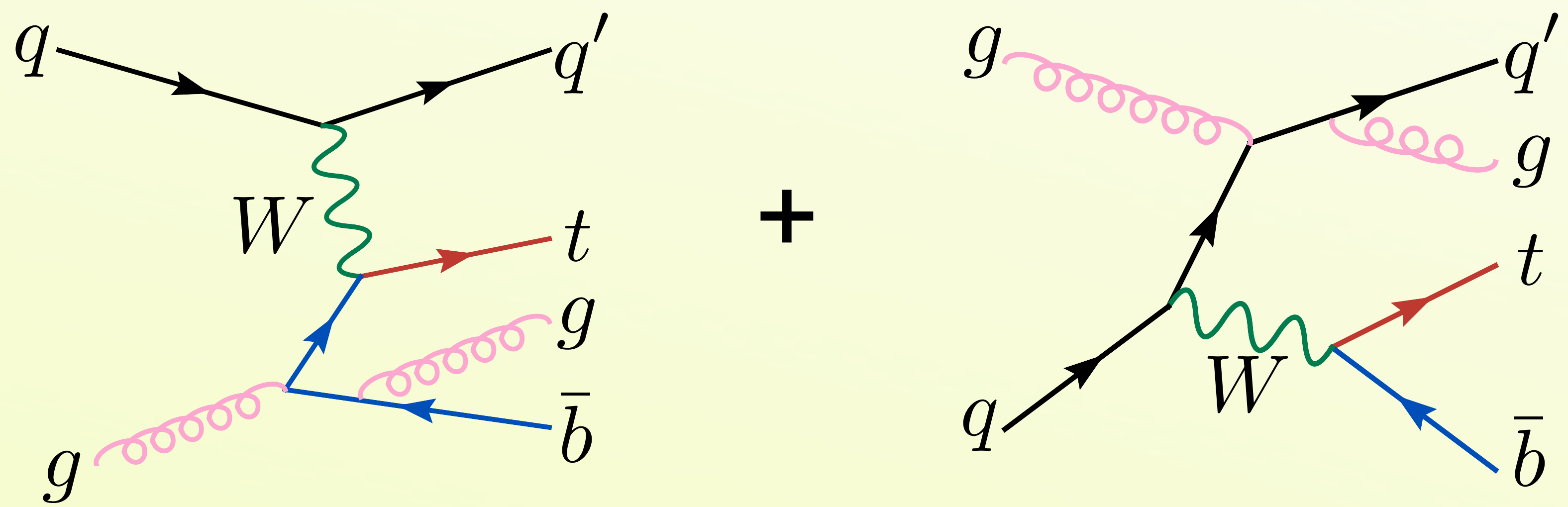
Correction to heavy line   Correction to light line

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

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

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