Progress in single-top predictions and simulations

Fabio Maltoni
Center for Particle Physics and Phenomenology (CP3)
Université Catholique de Louvain, Belgium

Outline

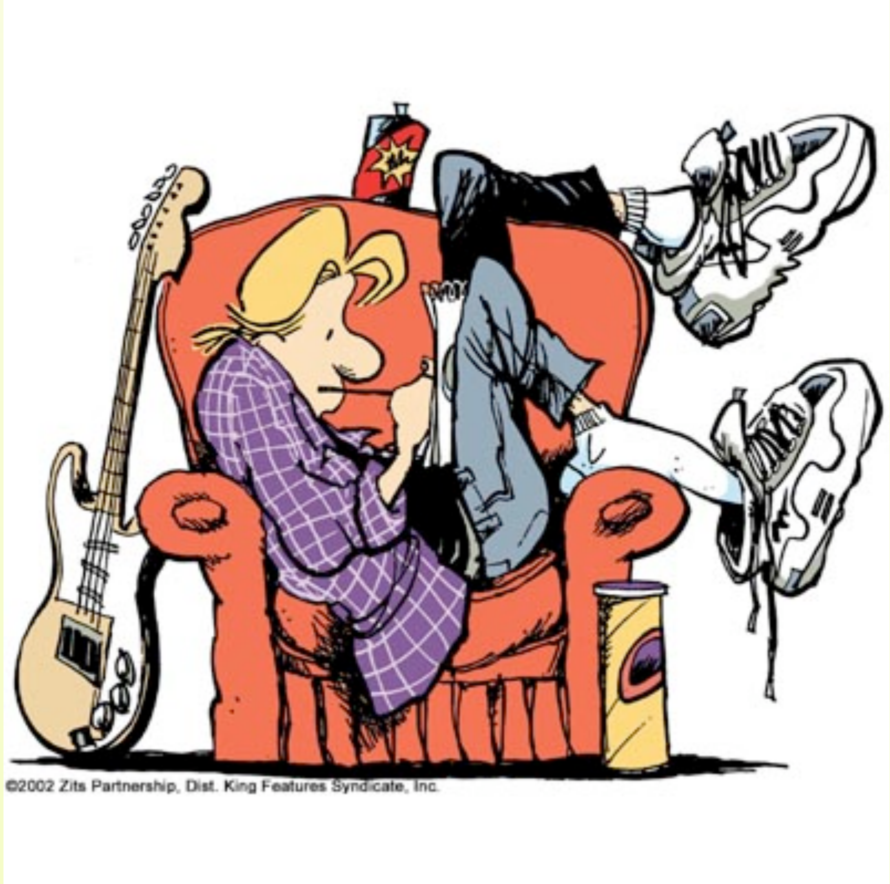
- Introduction and state of the art
- Progress in the predictions for t-channel @ NLO
- Conclusion

Why single top is way cooler than ttbar?

At least three reasons...

Reason #1 : Teenager vs Newborn

t tbar

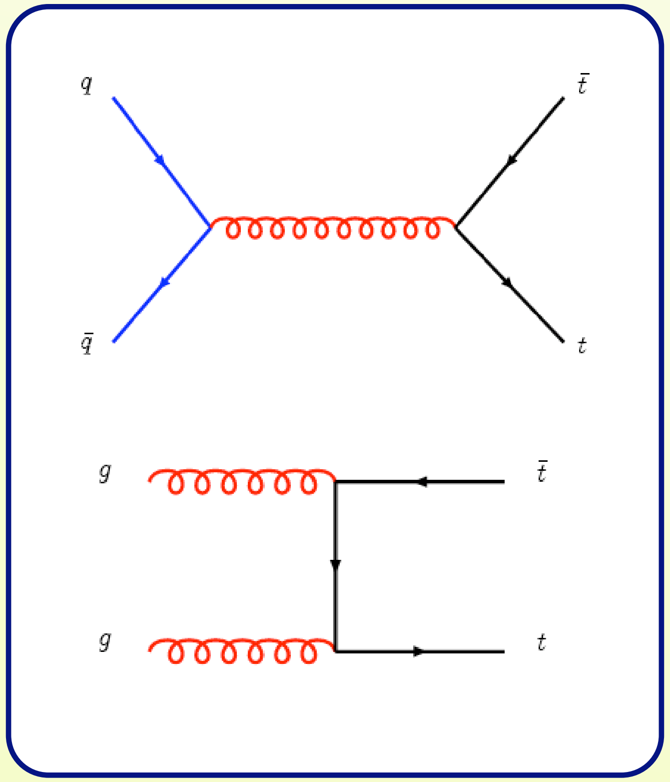


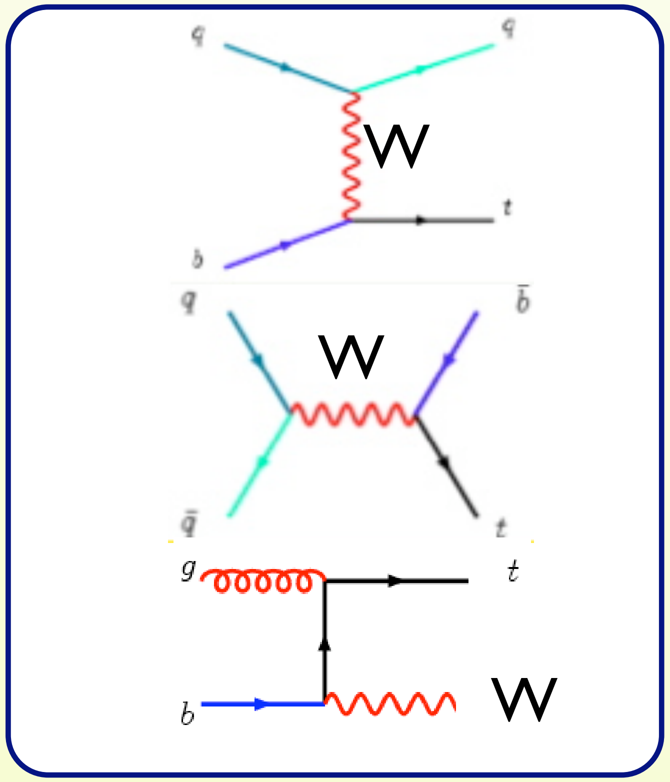
- Born in 1995
- Good : We already know him well
- Bad : We ask him a lot!

single-top

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

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

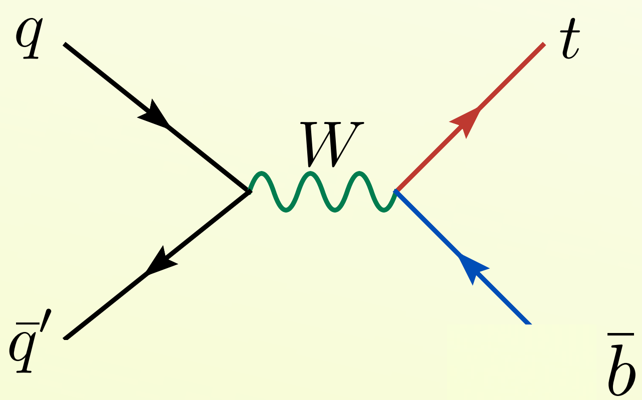




* Strong process: (LO at α_S^2):
  ~ 10 pb at Tevatron
  ~ 1 nb at the LHC14
* Top discovery mode.
* Weak Potential : m_t
* BSM Potential : Large

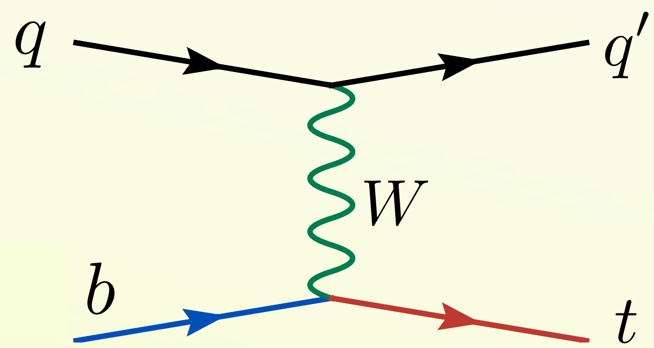
* Weak process : same diagrams as the top decay!
* " Surprising" large cross section:
  ~ 3 pb at Tevatron
  ~ 300 pb at the LHC14
* Weak Potential : CKM, anomalous couplings.
* BSM Potential : Large

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



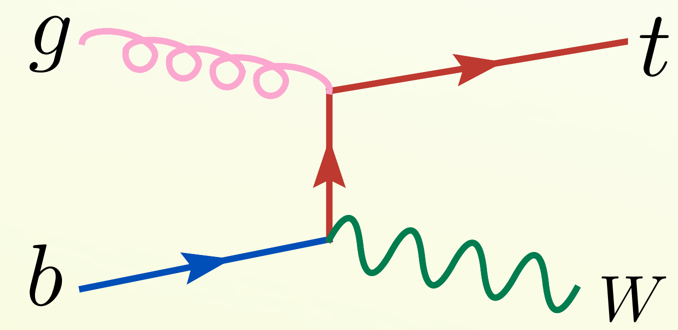
* “Drell-Yan” production mode.
* Tevatron is sizable (~1pb), quite small at the LHC14 (~10 pb).
* Fully inclusive x-sec known at NNLO (leading Nc).
* Channel to search for new charged resonances (H^+ or W'). Four-fermion interactions.
* Final State: 2 b’s + W

“No brainer”



* “DIS” production mode.
* Largest cross sections thanks to the t-channel W.
* Sensitive to FCNC involving top. Four-fermion interactions.
* b initiated
* Final State: 1 or 2 b’s, W, forward jet

“Interesting!”



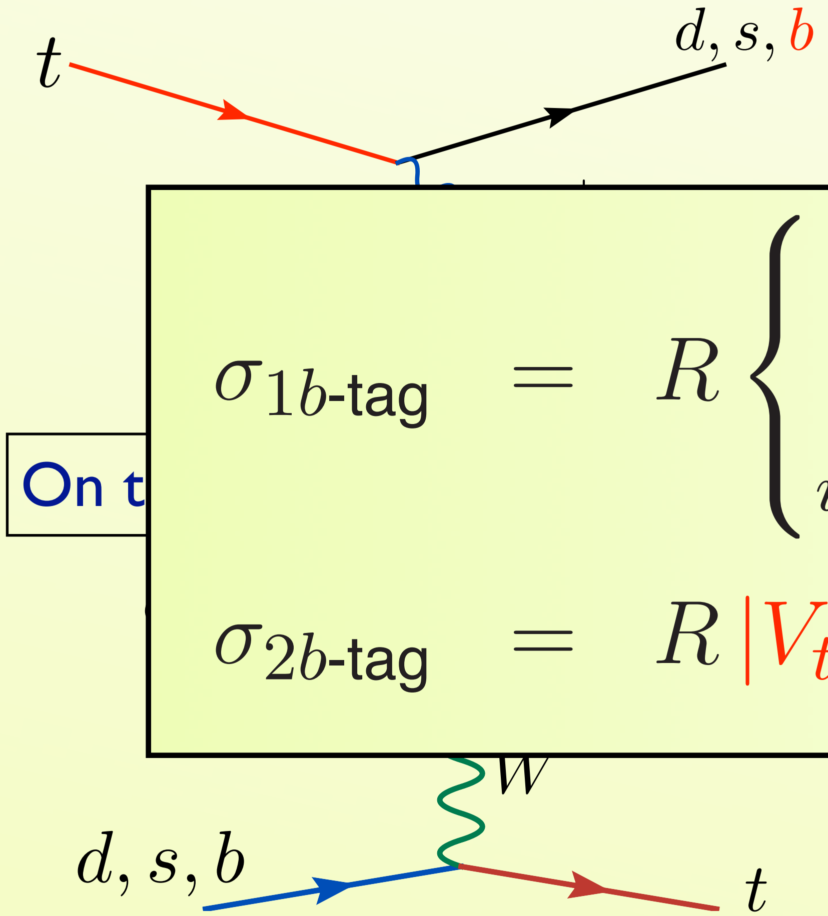
* Associated production
* Sizable cross section (60 pb) at LHC14, but difficult.
* Template for tH^+ production.
* b initiated
* Interferes with ttbar at NLO : subtle definition.
* Final State: 1b, 2W and jet veto

“Challenging!!” *

*Theorist’s comments

Example: Direct constraints on the 3rd row of CKM

Remember that R is not so sensitive to V_{tb} as we already know that $V_{tb} > V_{ts}, V_{td}$



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

On t

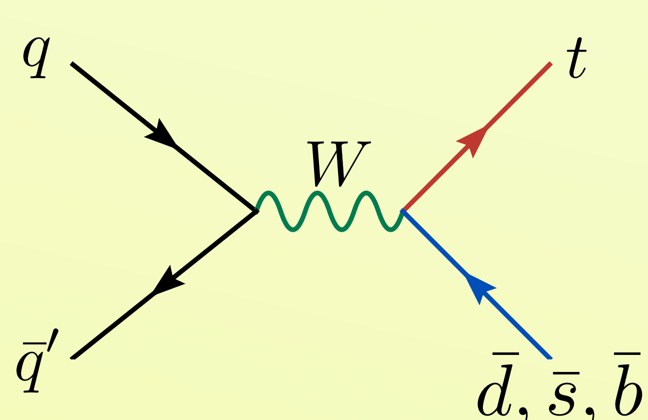
$$\sigma_{1b\text{-tag}} = R \left\{ \sum_{i=b,s,d} |V_{ti}|^2 \sigma_i^{\mathrm{t-ch}} + 2(|V_{td}|^2 + |V_{ts}|^2) \sigma^{\mathrm{s-ch}} \right\}$$

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

n.b. : naive estimate

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

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



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

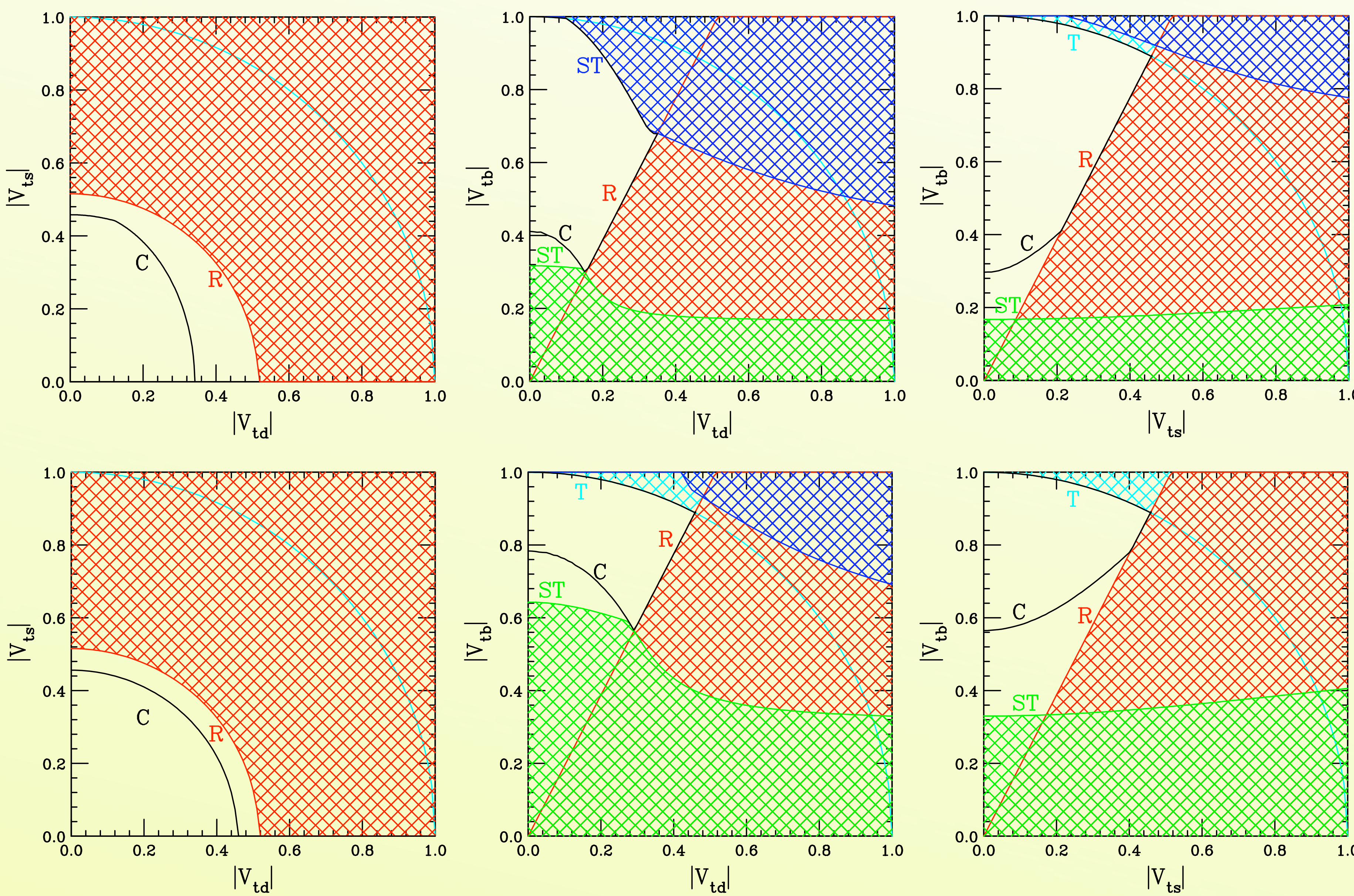
Signal becomes similar to t-channel (only 1 *b*-jet)

Example: Direct constraints on the 3rd row of CKM

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

CDF

DØ



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

Reason #3 : More work for theorists

- Current observation relies quite strongly on our confidence that signal is well described by theory and MC's.
- Uncertainty on the Vtb extraction obviously depends on precision of theory predictions. Source of errors : PDF (beware the bottom quark!), scales, α_s, m_b, m_t.
- Still work to do to match the accuracy of the older brother :

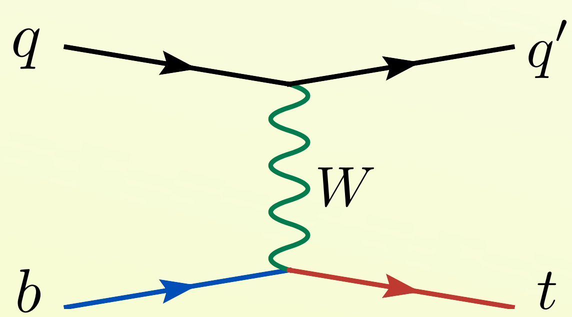
Calculation	t tbar	t-channel (2→2)	t-channel (2→3)	s-channel	tW
NLO QCD	yes	yes	yes	yes	yes
NLOwPS QCD	yes	yes	no	yes	yes
Resummed NLO	yes	yes	no	yes	no
X+1 jet at NLO	yes	no	no	no	no
NNLO	work in progress	no	no	yes	no
NLO EW	yes	yes	no	yes	yes

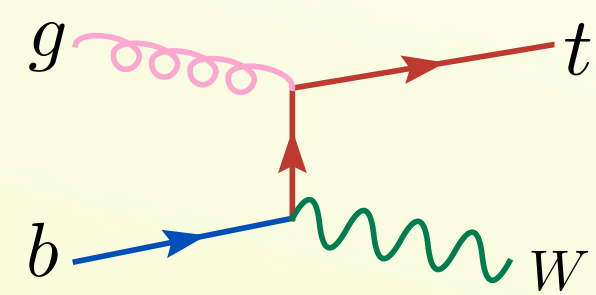
☺ All three 2→2 channels available in MC@NLO [Frixione et al.], w/ spin correlations!

☹ All MC implementations currently available for single top processes neglect m_b.

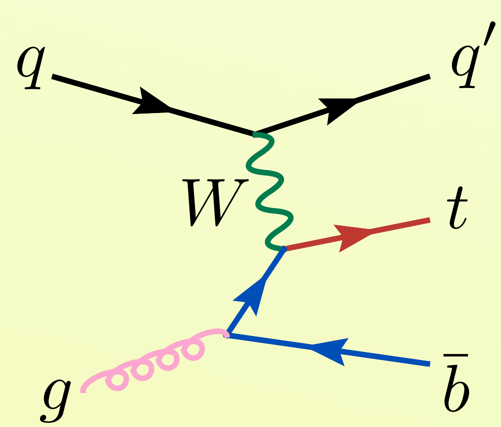
Heavy initial state quarks

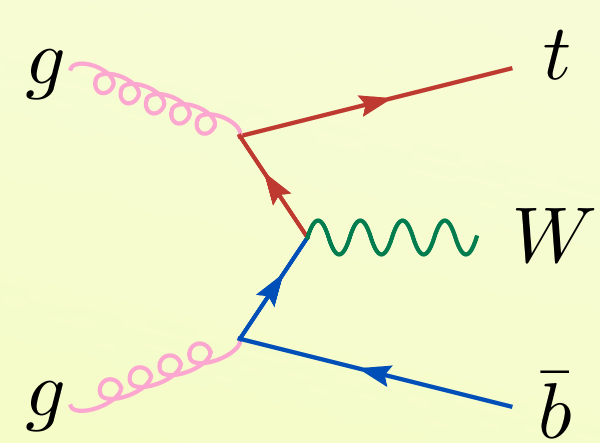
- Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state





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





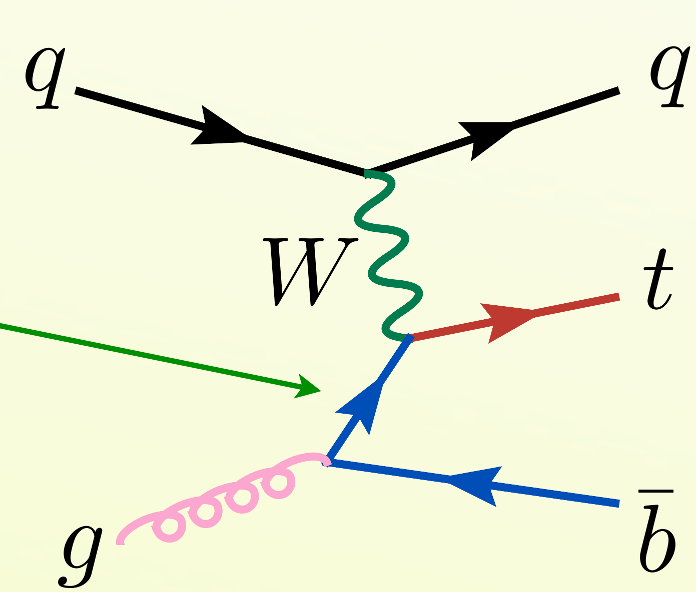
* At all orders. At fixed order differences arise...

Collinear logarithms

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

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

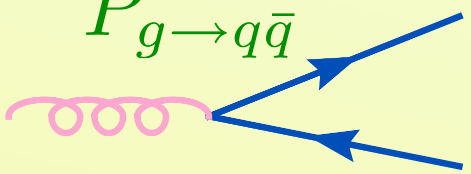
$$t=(p_{\bar{b}}-p_g)^2,\; p_T^2=p_{T,\bar{b}}^2$$



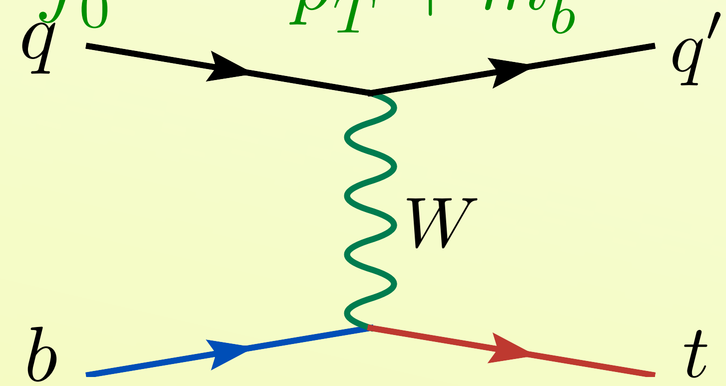
- Contribution to the cross section: $\displaystyle\int_0^{p_{T,\max}^2} \frac{dp_T^2}{p_T^2+m_b^2} = \log\left(\frac{p_{T,\max}^2}{m_b^2}\right) + \ldots$
- Coefficient of the logarithm is:

AP splitting function

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



times



matrix elements with splitting removed

Resummation into PDF

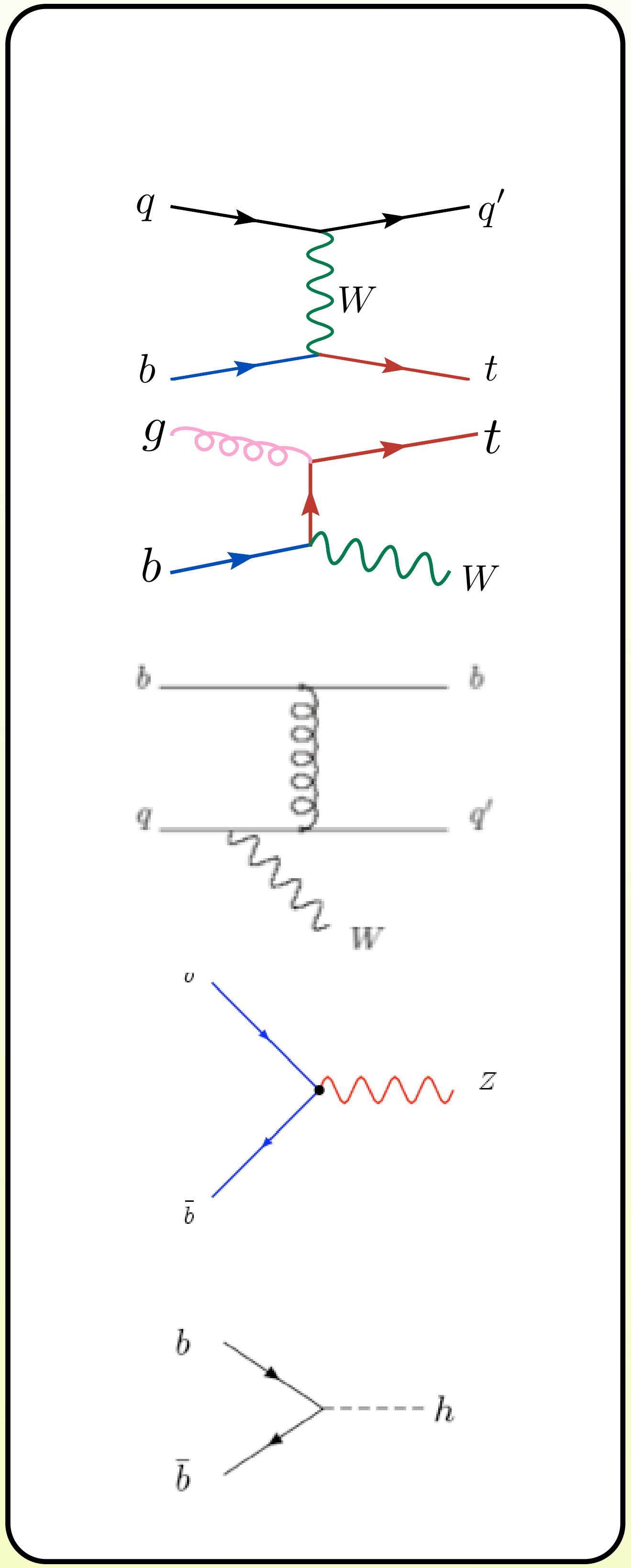
- Putting it together: $\dfrac{d\sigma(qg \to q' t\bar{b})}{d\log p^2_{T,\max}} \sim \left(\dfrac{\alpha_s}{2\pi}\right)\left[\int \dfrac{dx}{x} P_{g\to q\bar{q}} f_g\right] \times \hat{\sigma}(qb \to q't)$
- But the first part resembles the evolution equation for a quark:

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

- 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

b-initiated processes

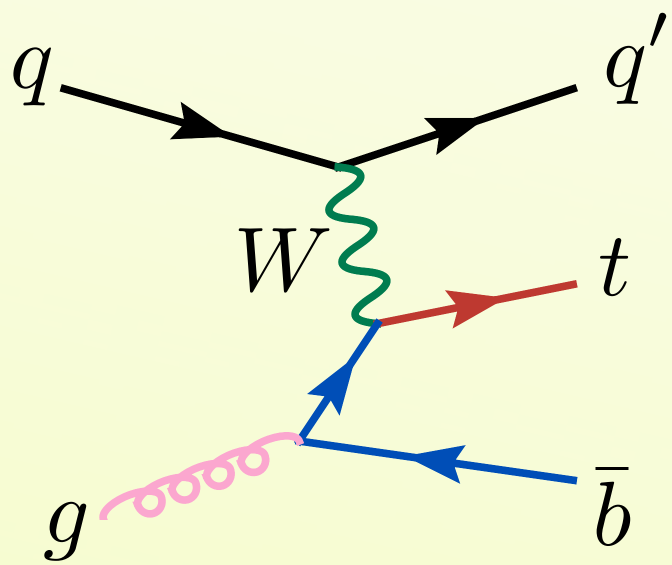
Class	Process	Interest
Top	qb→tq (t-channel)	SM, top EW couplings and polarization, Vtb. Anomalous couplings. H+ : SUSY,2HDM
	gb→t(W,H+)	
Vector Bosons	pp→Wb pp→Wbj	SM, bkg to single top
	bb→Z gb→Zb pp→Zbj	Standard candle: SM BSM bkg, b-pdf
	gb→gamma+b	
Higgs	bb→ (h,A) gb→(h,A)+b	SUSY discovery/ measurements at large tan(beta)



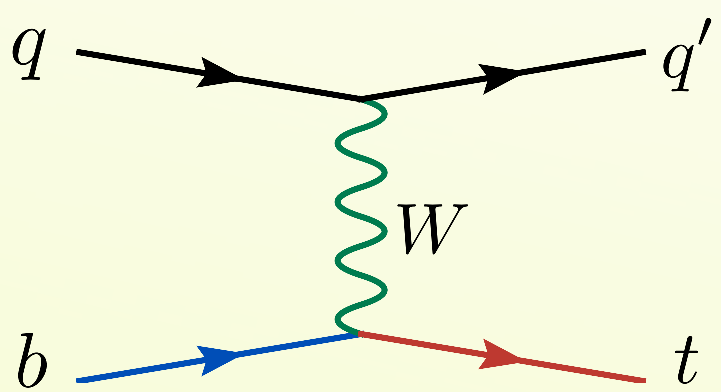
Schemes

Two different ways of computing the same quantities:

4F



5F

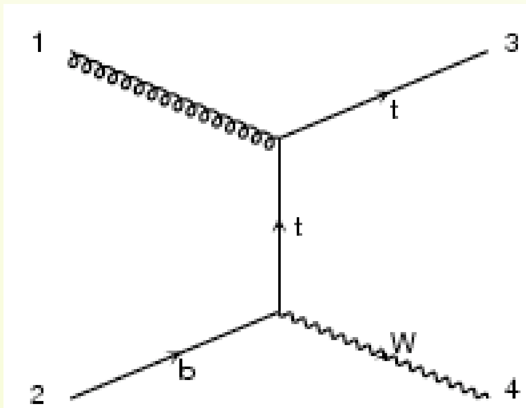


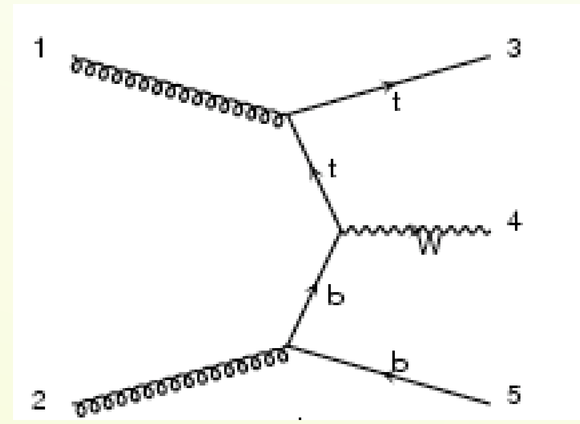
1. It does not resum (possibly) large logs (⇒norm. uncertainties)
2. Going NLO might be difficult.
3. Mass effects are there at any order in PT.
4. MC implementation with ME/PS merging a bit involved.

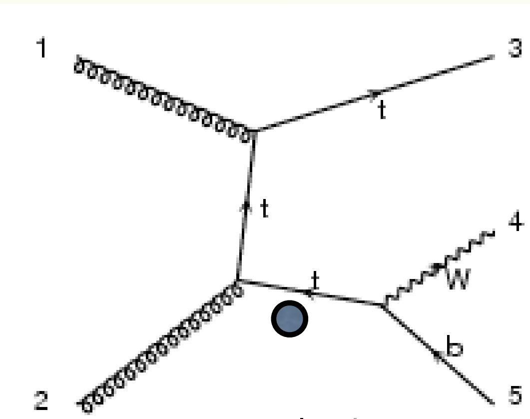
1. It resums initial state large logs in the b pdf, leading to more stable predictions
2. Going NLO (and NNLO) “easy”.
3. Mass effects are normally corrections and enter at higher orders.
4. Implementation in MC relies on mass effects given by the PS, which are presently not very accurate.

Let’s see a couple of examples...

tW in the 5F







Interference with tt at NLO⇒ non trivial problem : definition of the process is at stake

[Tim Tait:(2000),A.Belyaev & E. Boos(2001)]. First MC viable solution proposed **[Campbell,FM,Willenbrock,LH2005]** and implemented in MCFM **[Campbell, Tramontano, 2006].**

However, interference is tamed with a (b-)jet veto ⇒ sensitivity to low pt partons ⇒ soft resummation ⇒ MC with PS and with NLO needed.

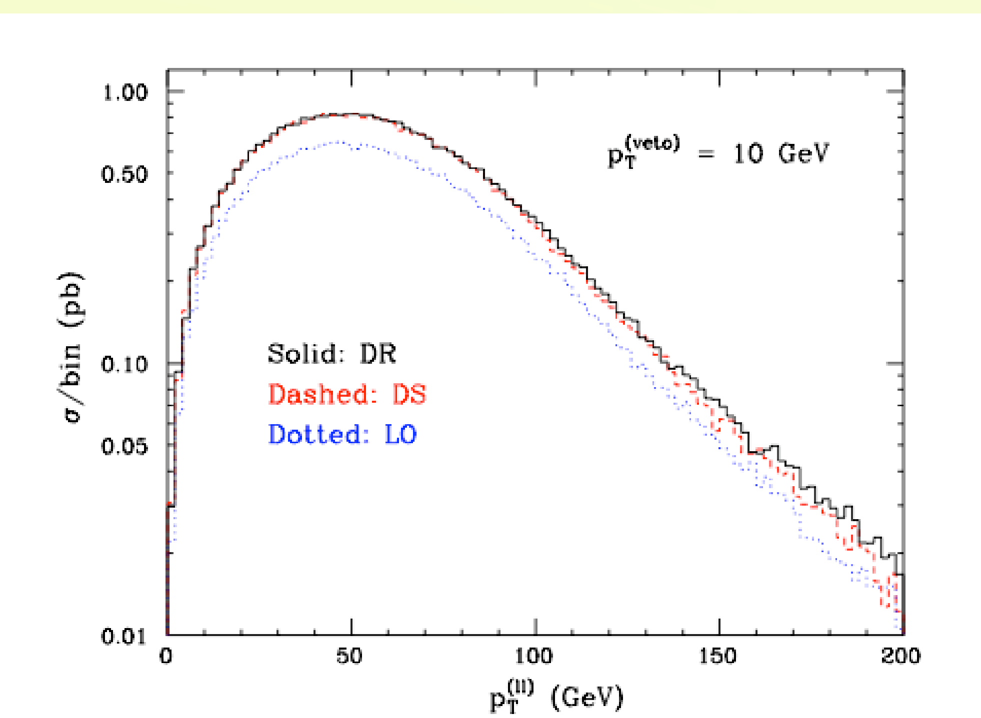


Diagram Removal : $\hat{\mathcal{S}}_{\alpha\beta}$

Diagram Subtraction : $\left(\mathcal{S}_{\alpha\beta}+\mathcal{I}_{\alpha\beta}+\mathcal{D}_{\alpha\beta}-\widetilde{\mathcal{D}}_{\alpha\beta}\right)$

Result: tW can be defined in

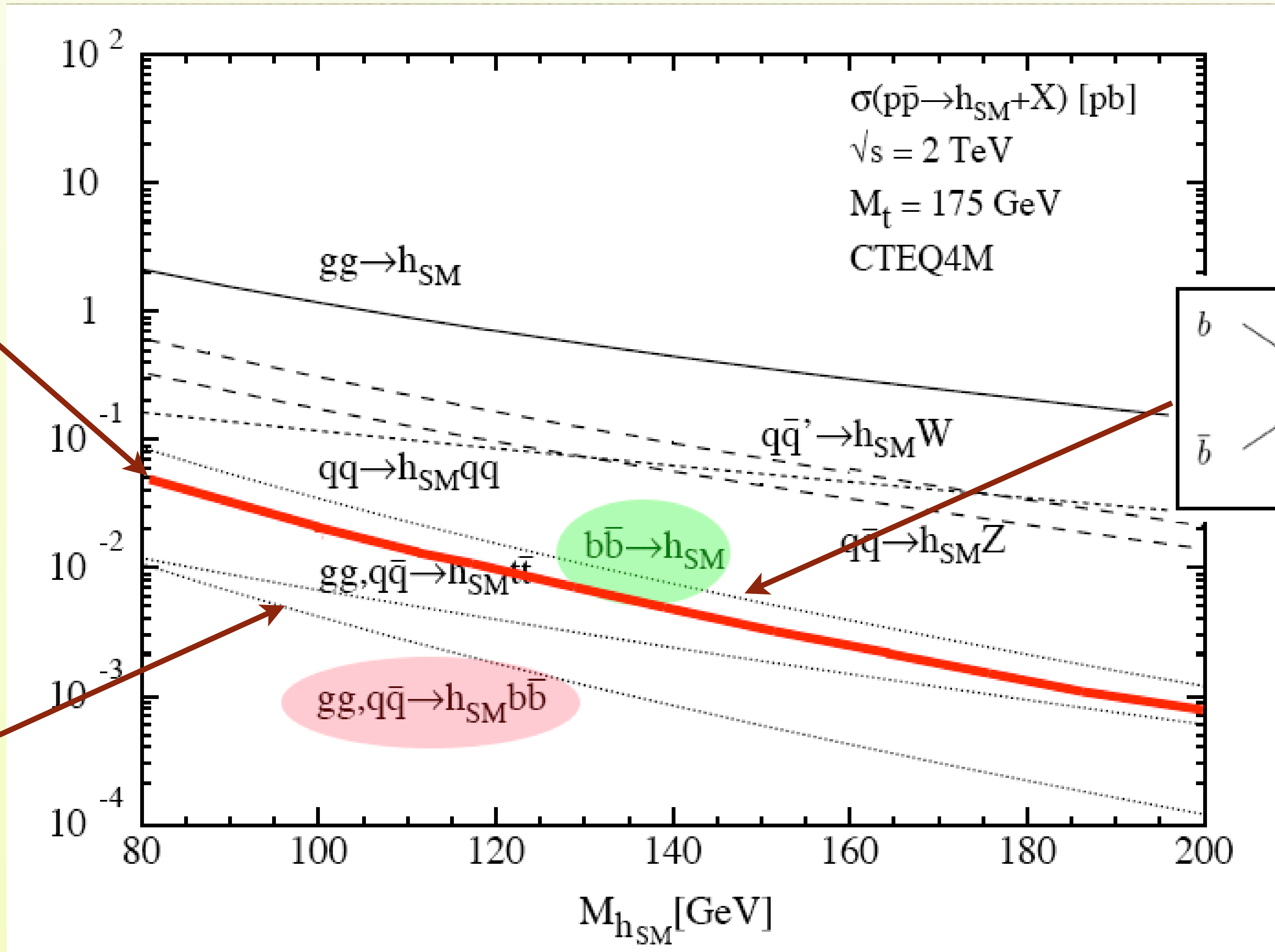
* a MC-friendly way
* (de facto) non-ambiguous way.

[Frixione, Laenen, Motylinski, Webber, White,2008]
[White, Frixione, Laenen, FM ,arXiv:0908.0631]

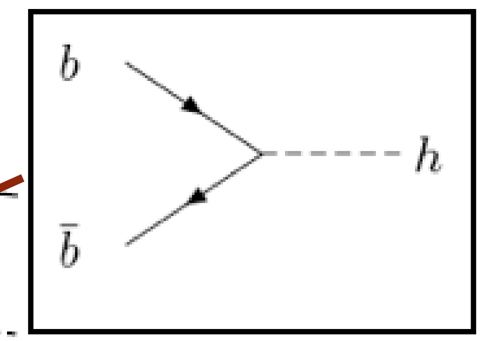
Upshot: 5F the most convenient choice to move the interference problem one order higher!

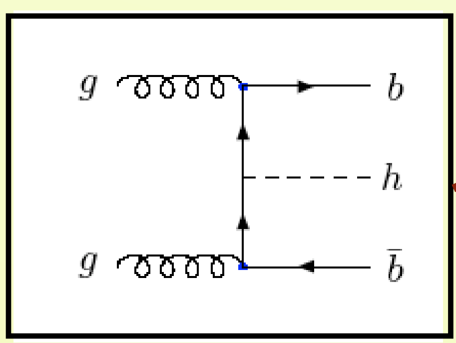
Scheme choice in Higgs production

Les Houches 03
HO corrections+
Scale choice!



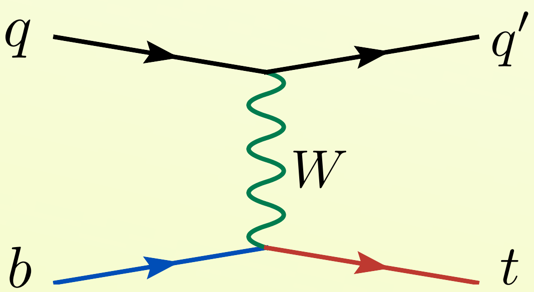
Higgs Tevatron Workshop 1998

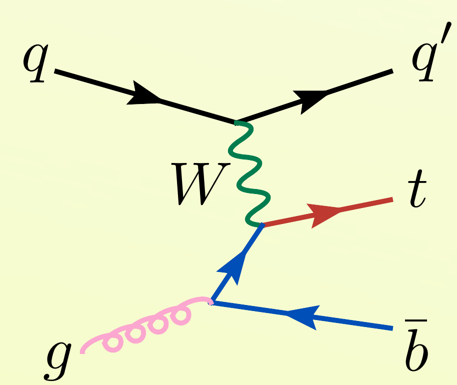




ACOT formalism

- 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



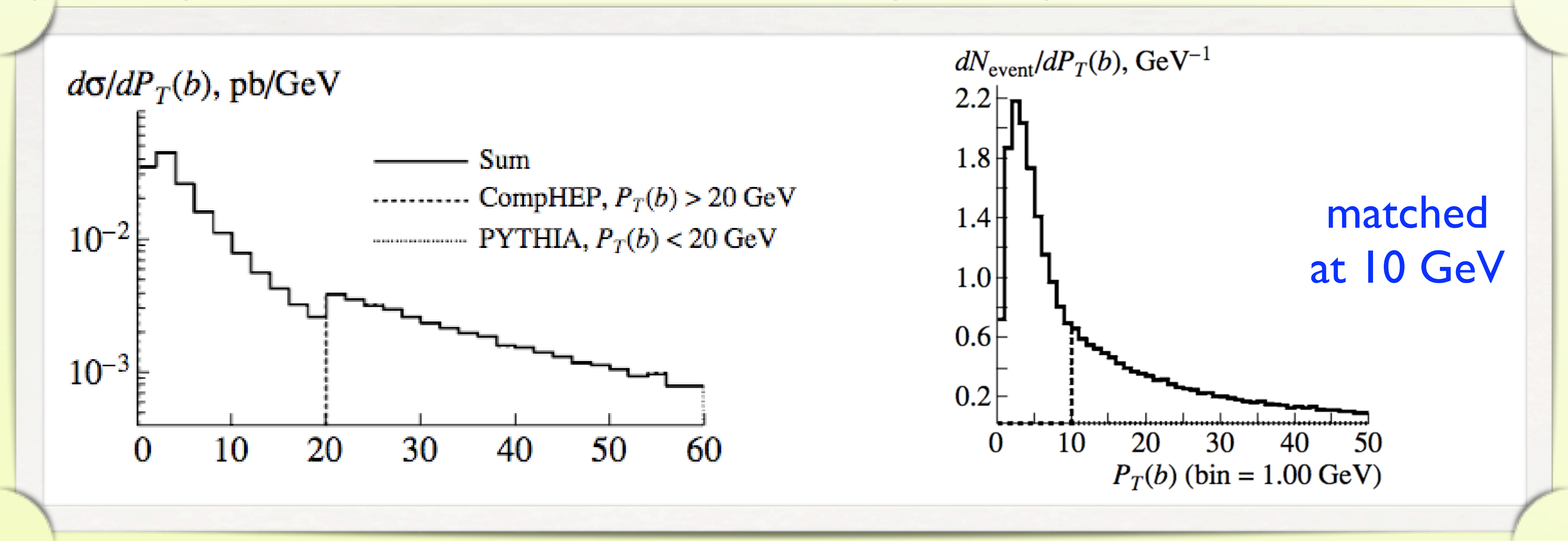


- Terms from 4F (2 → 3) enter at NLO. Properties of spectator b are only LO
- All calculations presented so far set m_b=0 in final state for simplicity

Need for matching 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

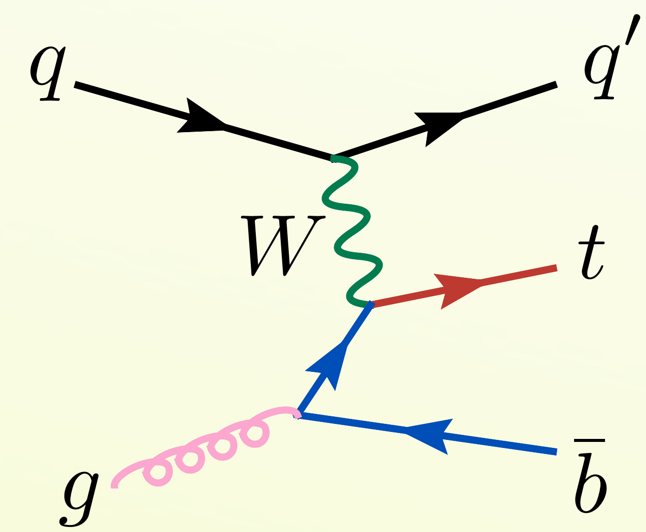
Boos et al., Phys. At. Nucl. 69, 1317 (2006)

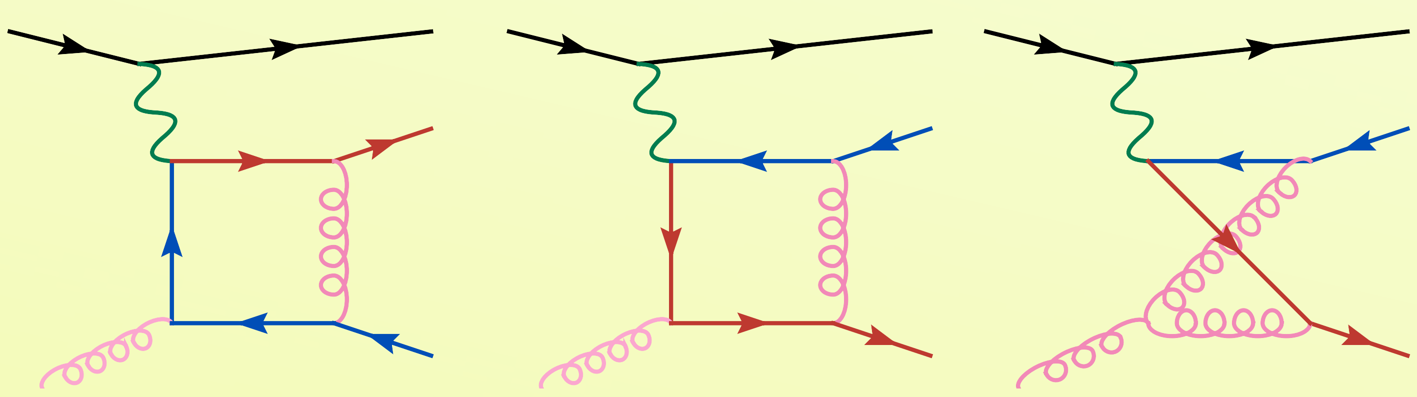


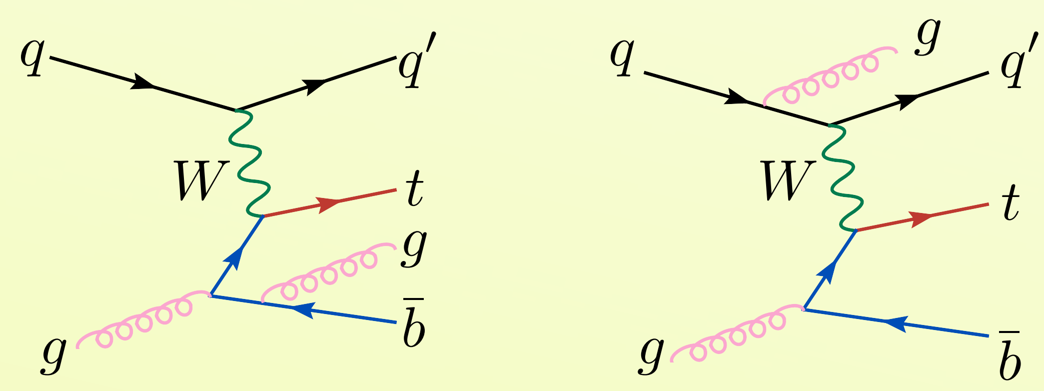
- Ad hoc matching motivated by necessity, but theoretically unappealing.
- Done in a formally consistent way in MC@NLO (but with m_b=0)

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 $(2 \to 3)$

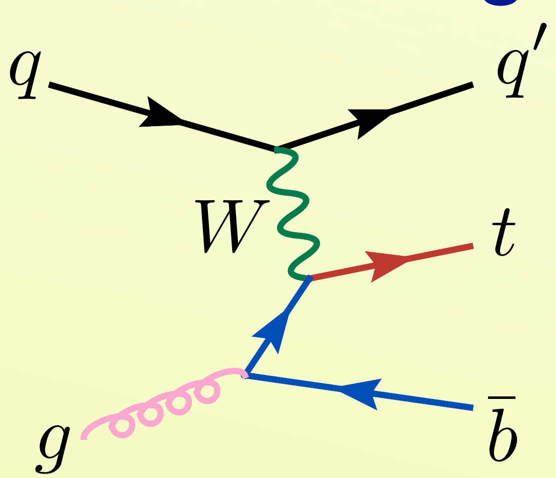




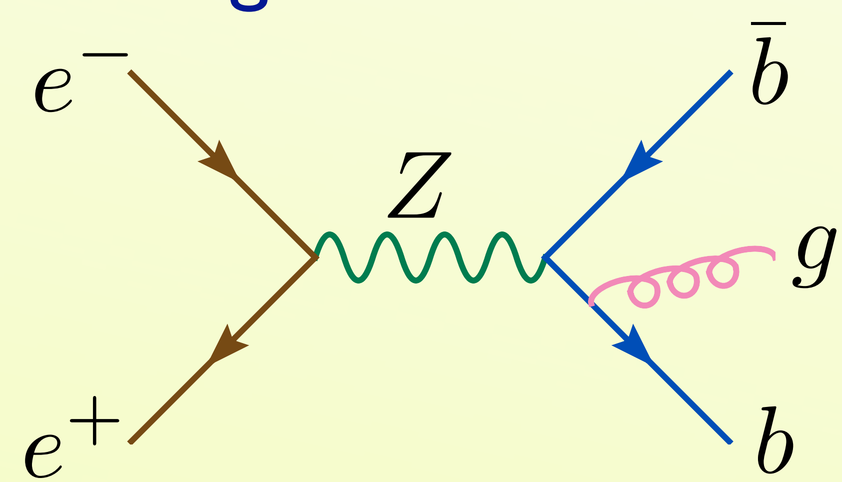


Checks of the calculation

- 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



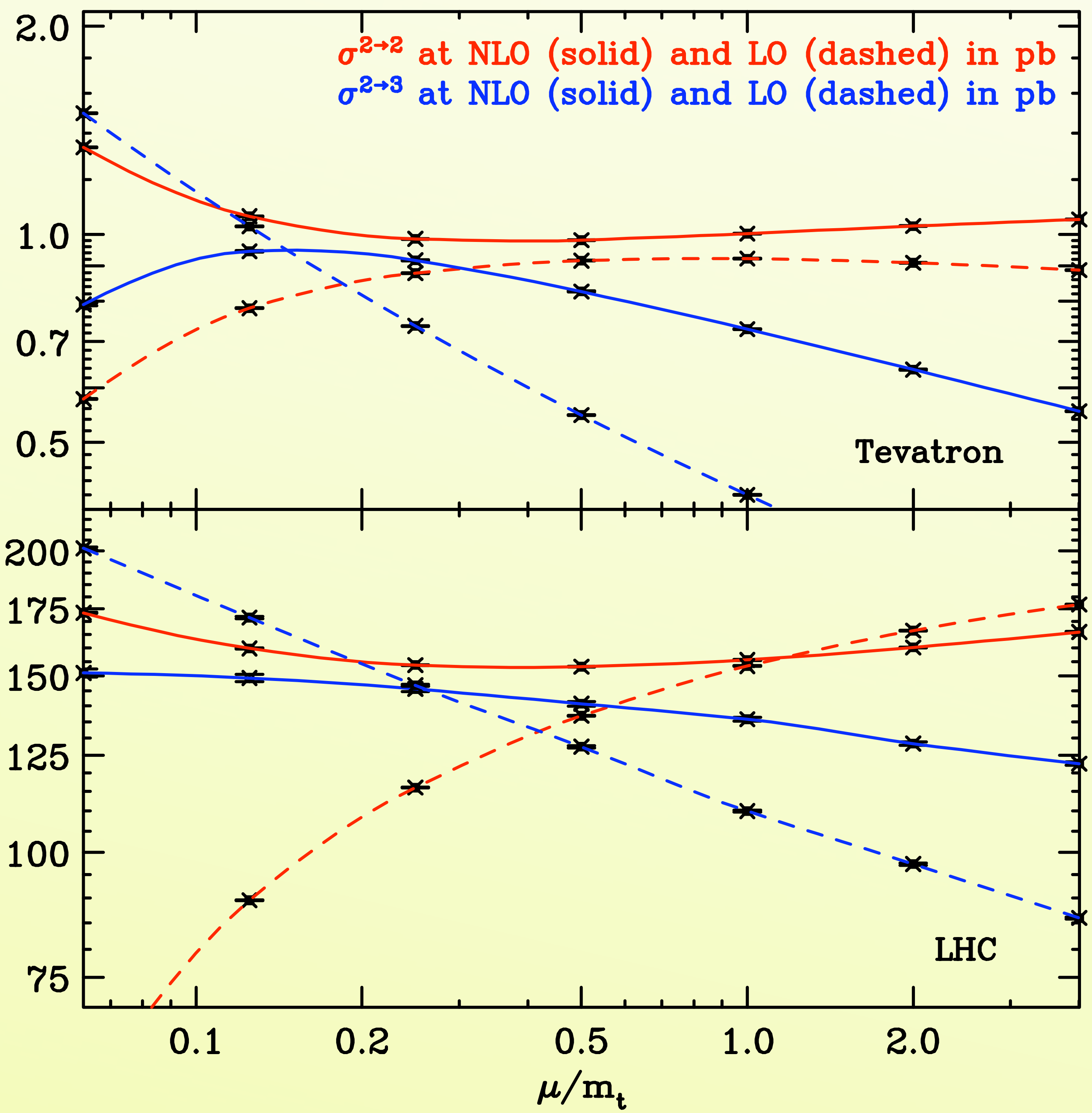
Nason & Oleari, NPB 521, 237 (1998)

- Excellent agreement found

Setup

- Process implemented in the MCFM parton-level NLO code
- Use m_t=172 GeV and m_b=4.5 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

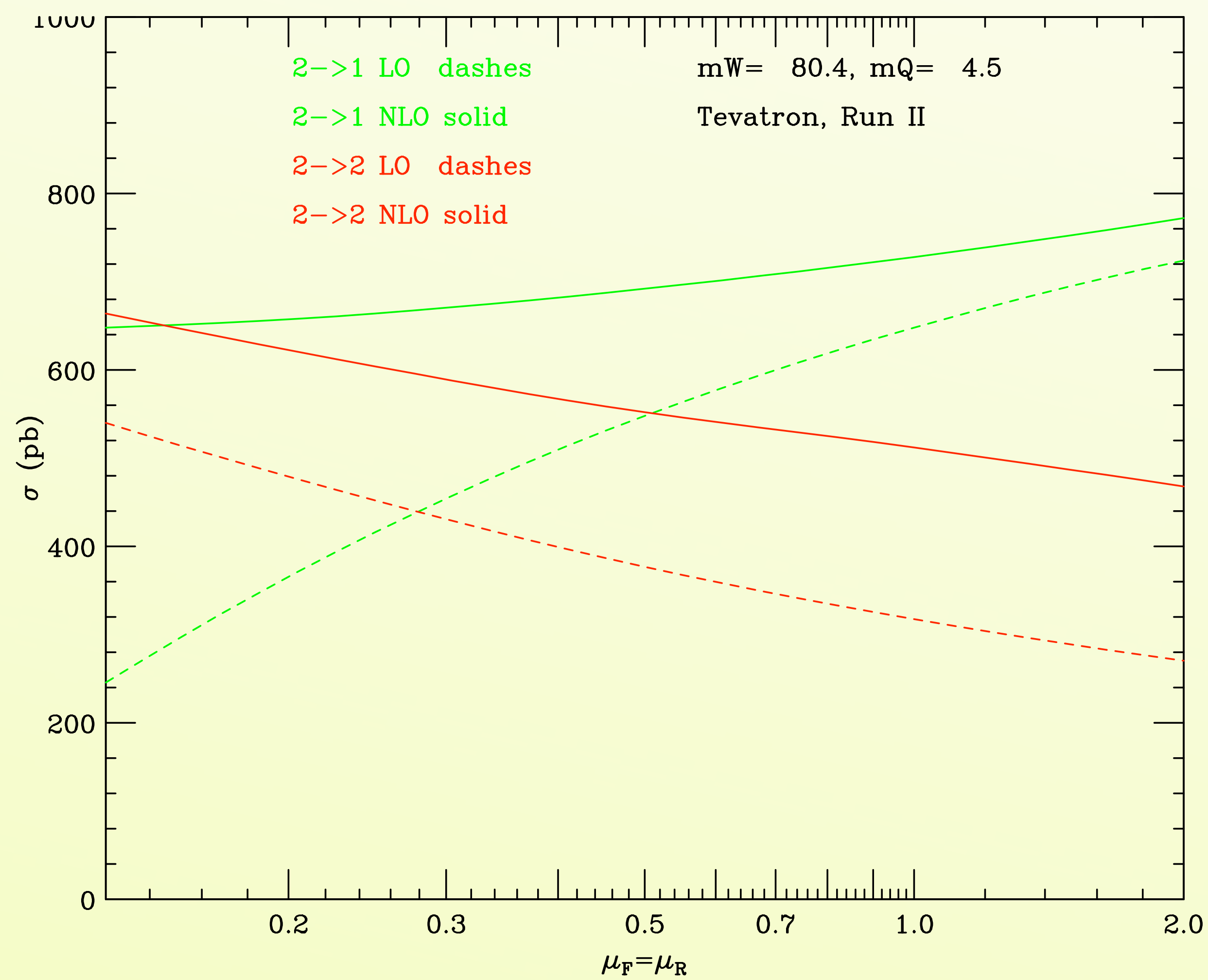
Scale dependence

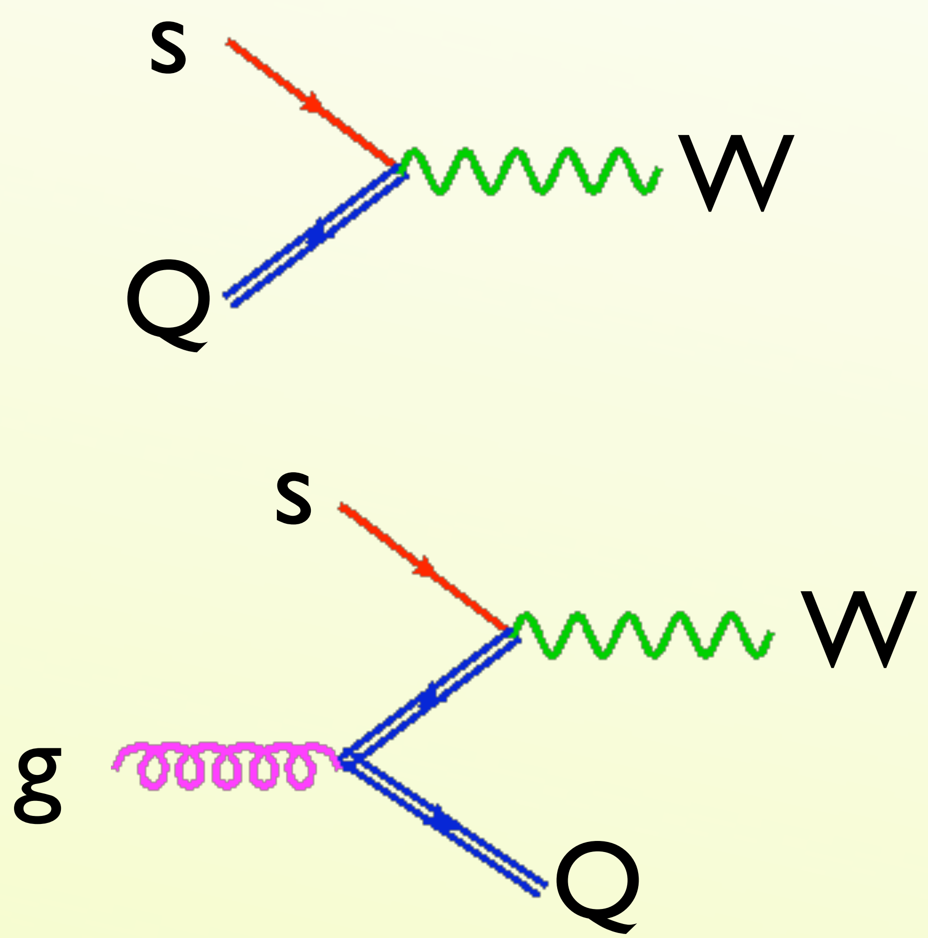


- Both schemes much improved from LO
- 5F (2 → 2) only mildly sensitive to scales at NLO (use m_t in what follows)
- 4F (2 → 3) expected to be worse, but isn't much
- Hardly a region of overlap between the two
- 4F (2 → 3) prefers smaller scales than m_t, particularly at the Tevatron

Similar behavior in WQ : 2→1 vs 2→2

[Campbell, FM, Mangano, Tramontano, in progress]



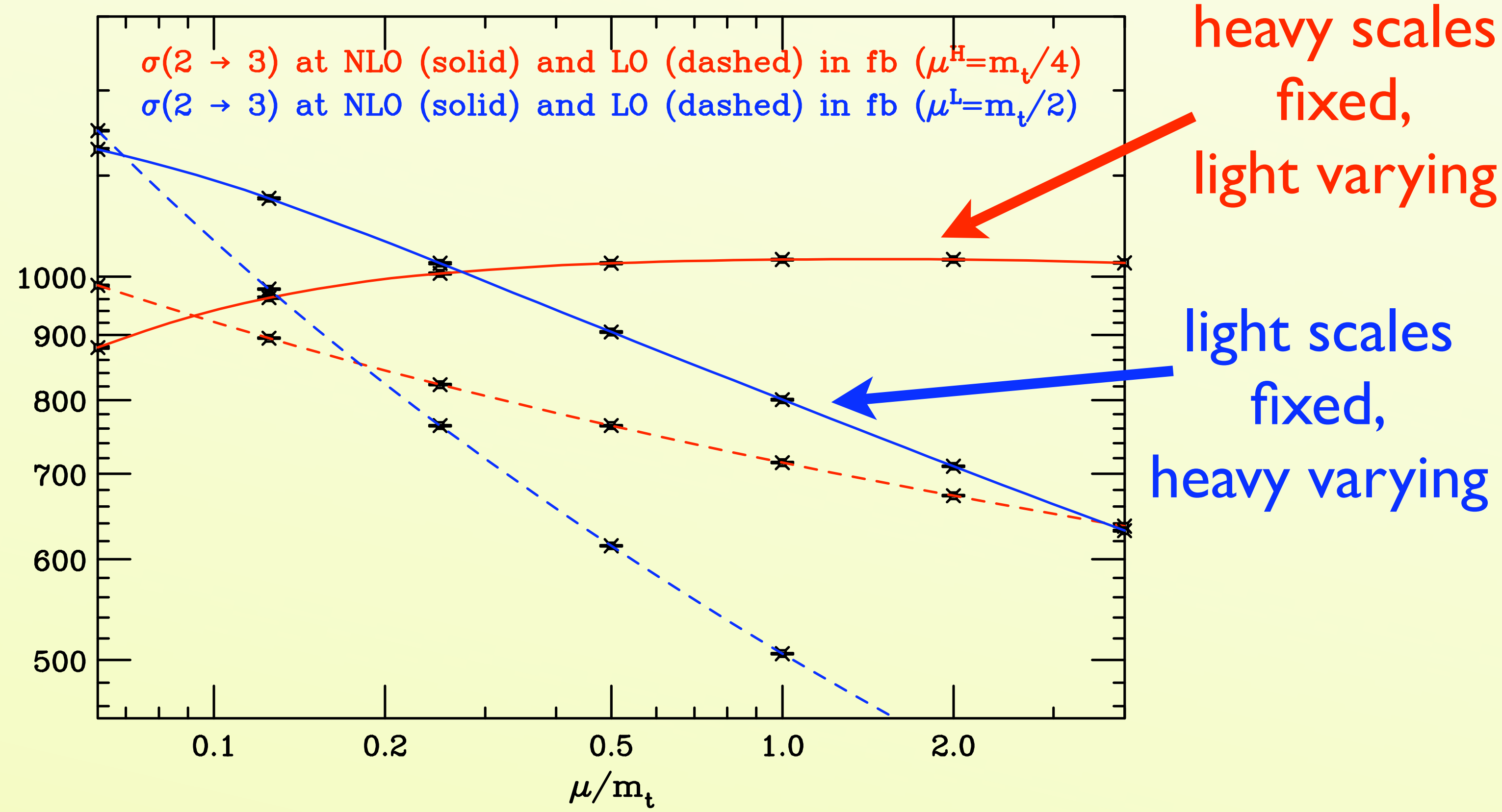


Conjecture: "Universal behaviour" for the scale dependence of the 5F and 4F calculations.

Scale dependence 2 → 3

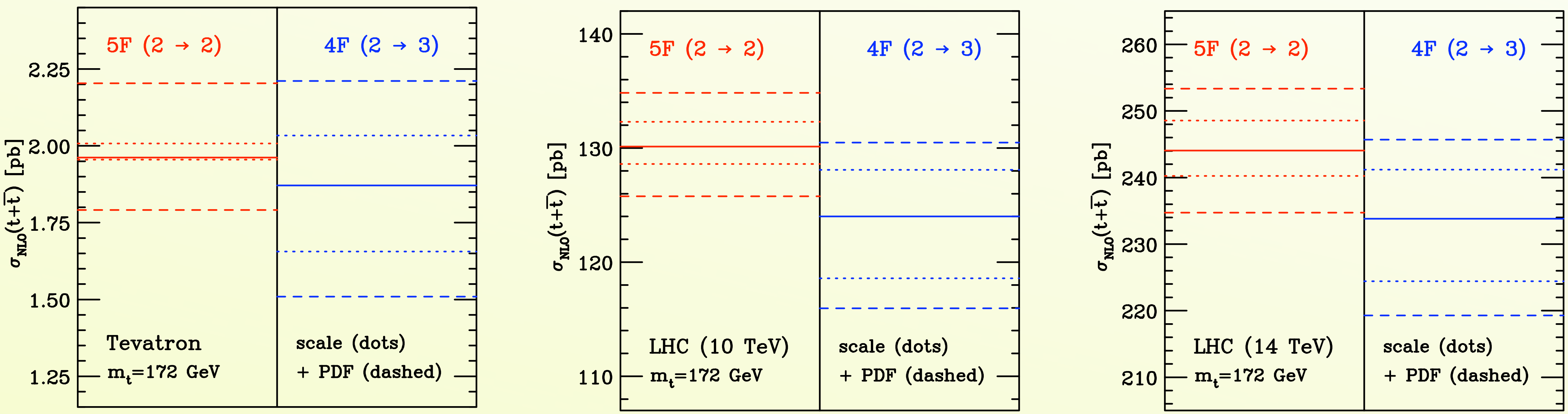
- Due to the near-factorization between the heavy and light quark lines we can vary the corresponding scales independently
  - Expect smaller scale for heavy line due to $g \to b\bar{b}$ splitting

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



t-channel best cross sections : 2→2 vs 2→3

[Campbell, Frederix, FM, Tramontano, 0907.3933]



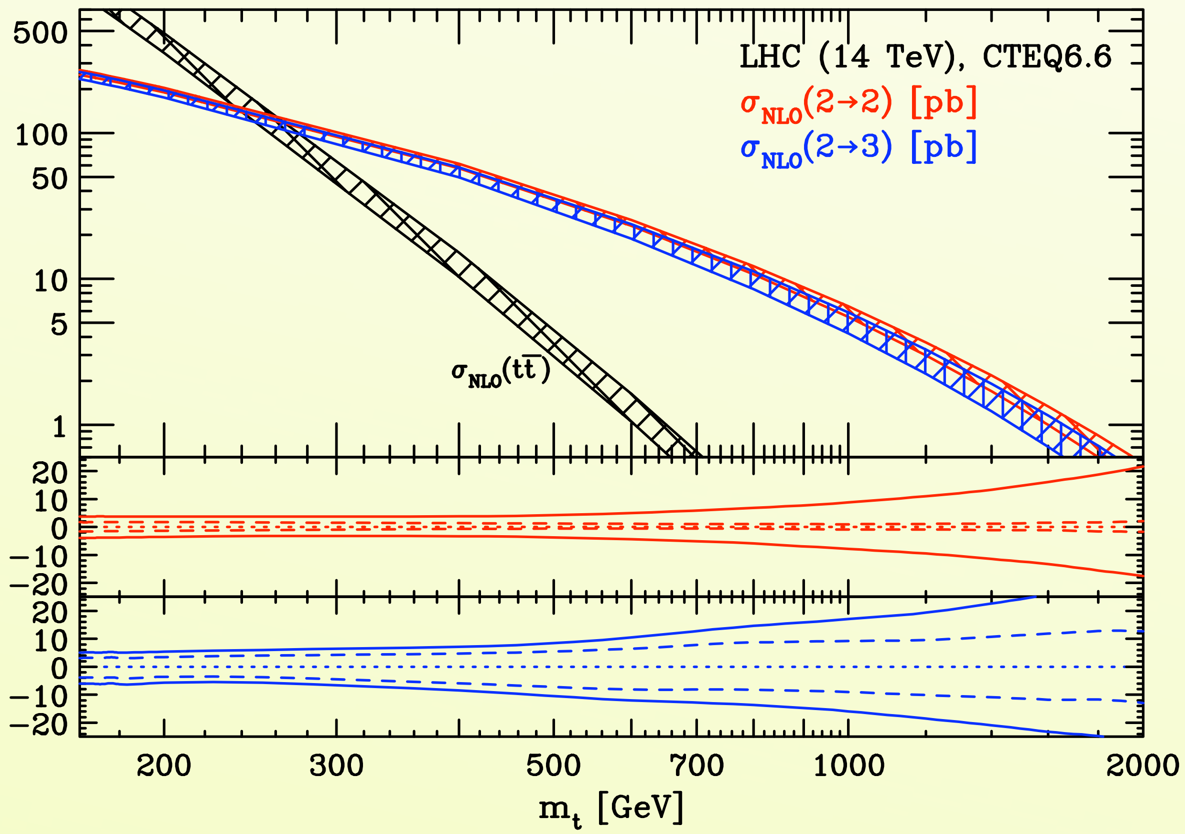
$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2 \to 2$ (pb)				$2 \to 3$ (pb)			
Tevatron Run II	$1.96\ ^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	$1.87\ ^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (10 TeV)	$130\ ^{+2}_{-2}$	$^{+3}_{-3}$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

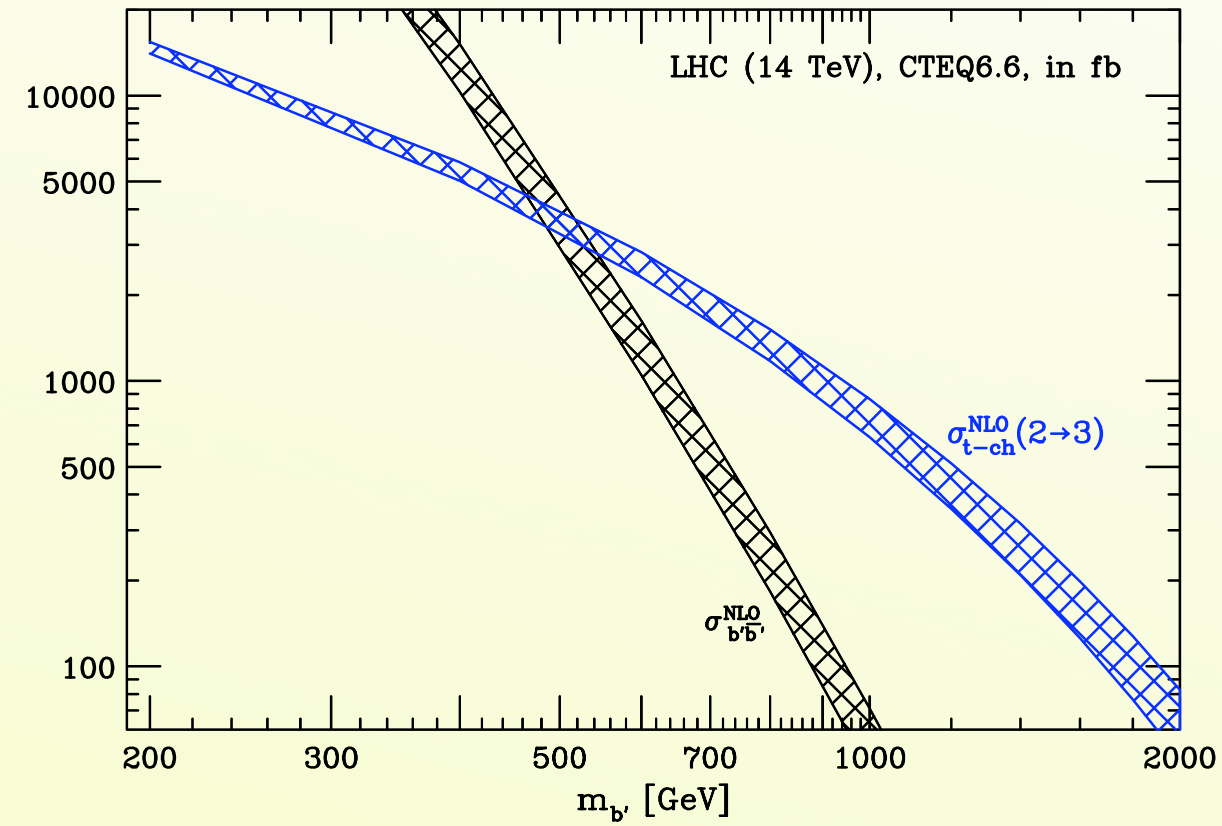
Uncertainties: scales, PDF, m_t (1%), m_b(4%)

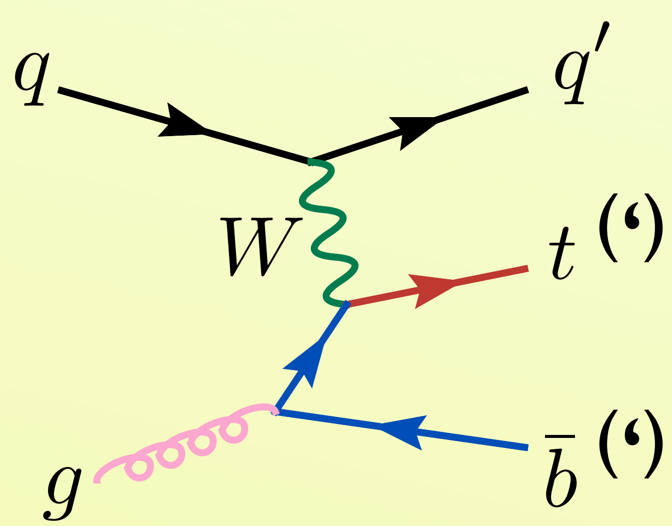
t-channel best cross sections : 2→2 vs 2→3

- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- b-mass uncertainties at the same level as t-mass ones [Overseen in previous studies].
- 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 might not be accurate...
    - Higher order corrections (NNLO for 2→2) important...

Fourth generation x secs.





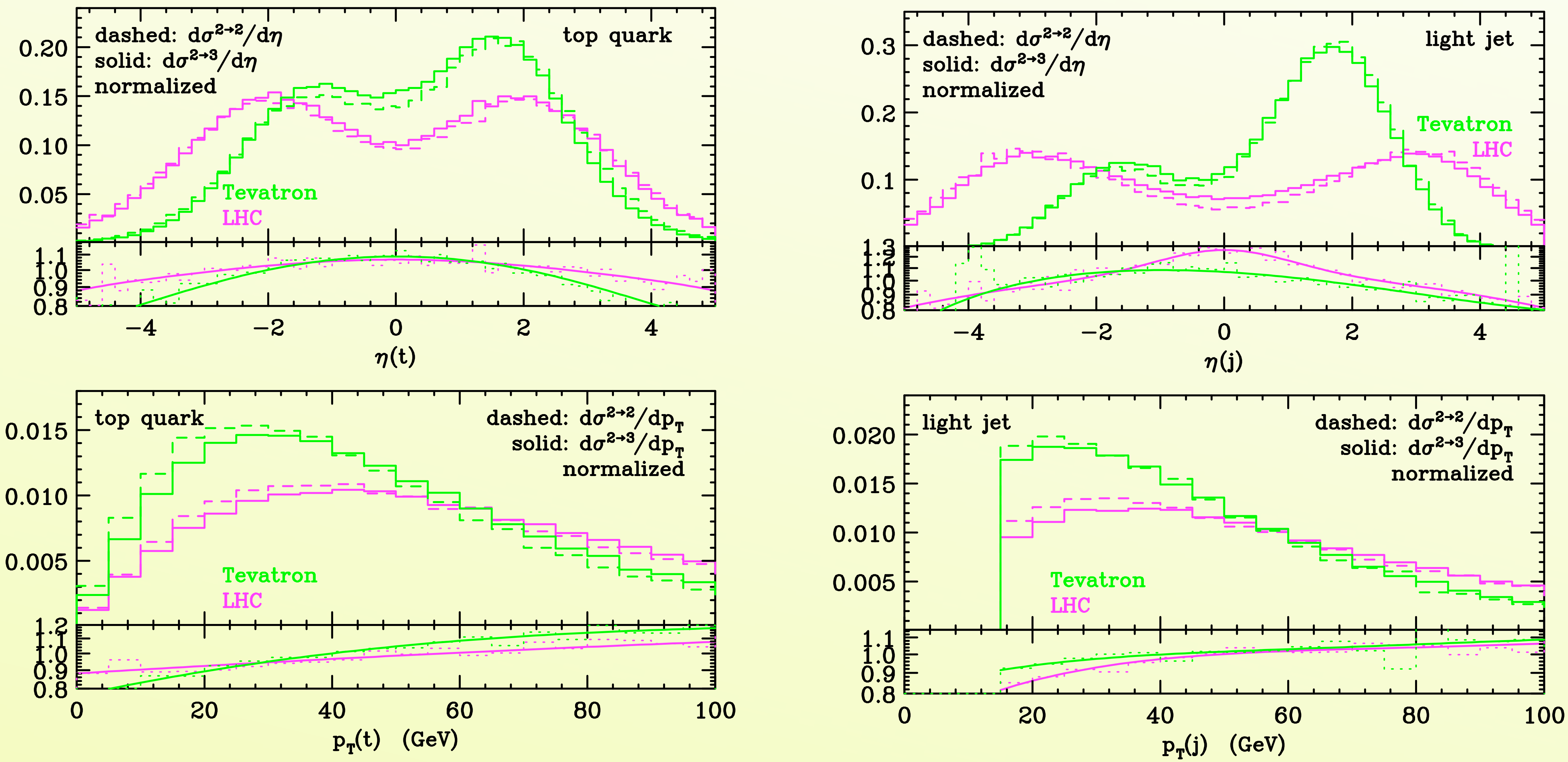


The NLO 2→3 massive calculation can be also used to make reliable predictions for t’b, b’t and b’t’ cross sections.

It is interesting to see where the cross over between the QCD and the EW productions are at the LHC.

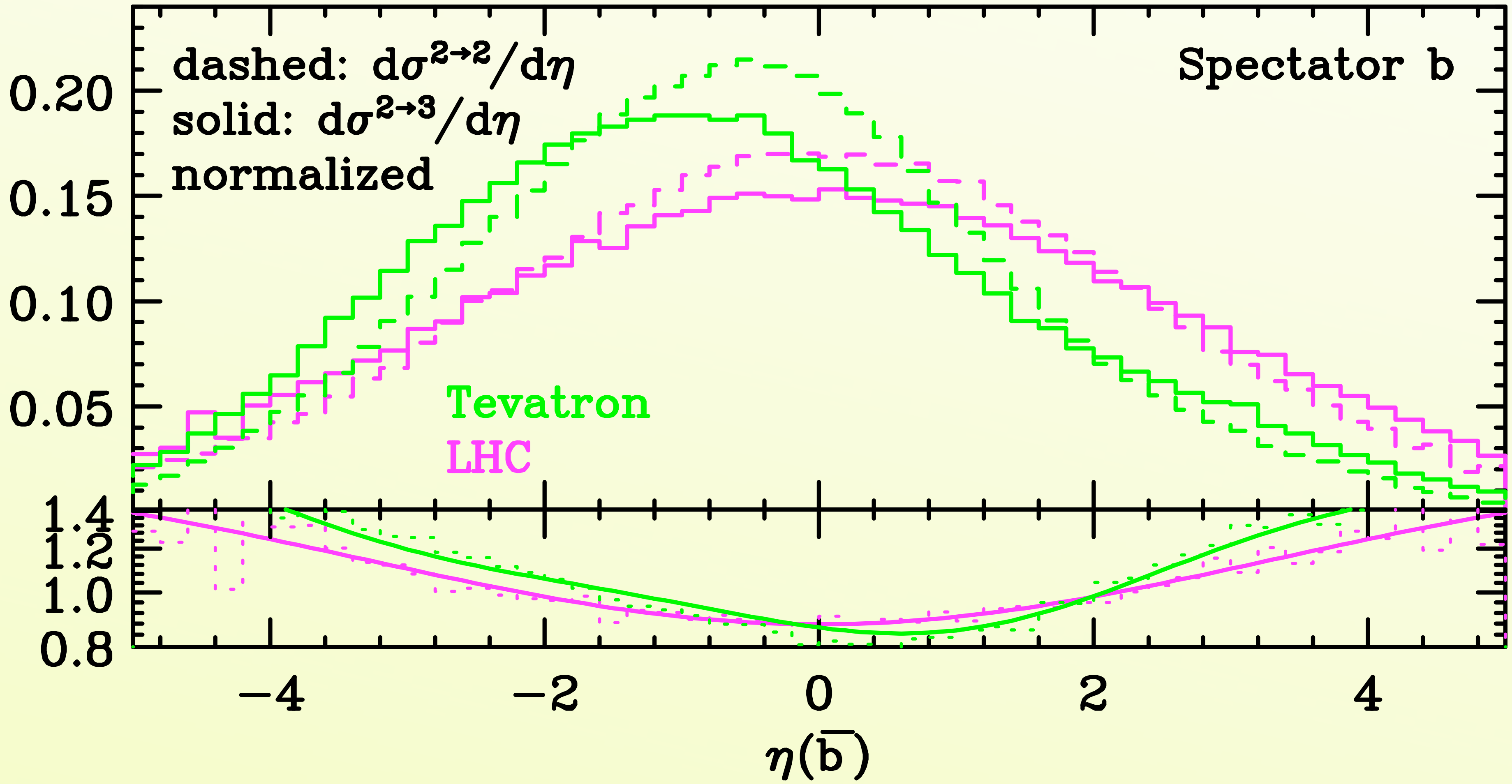
In these plots all the relevant CKM elements are set to one.

Top and light jet distributions



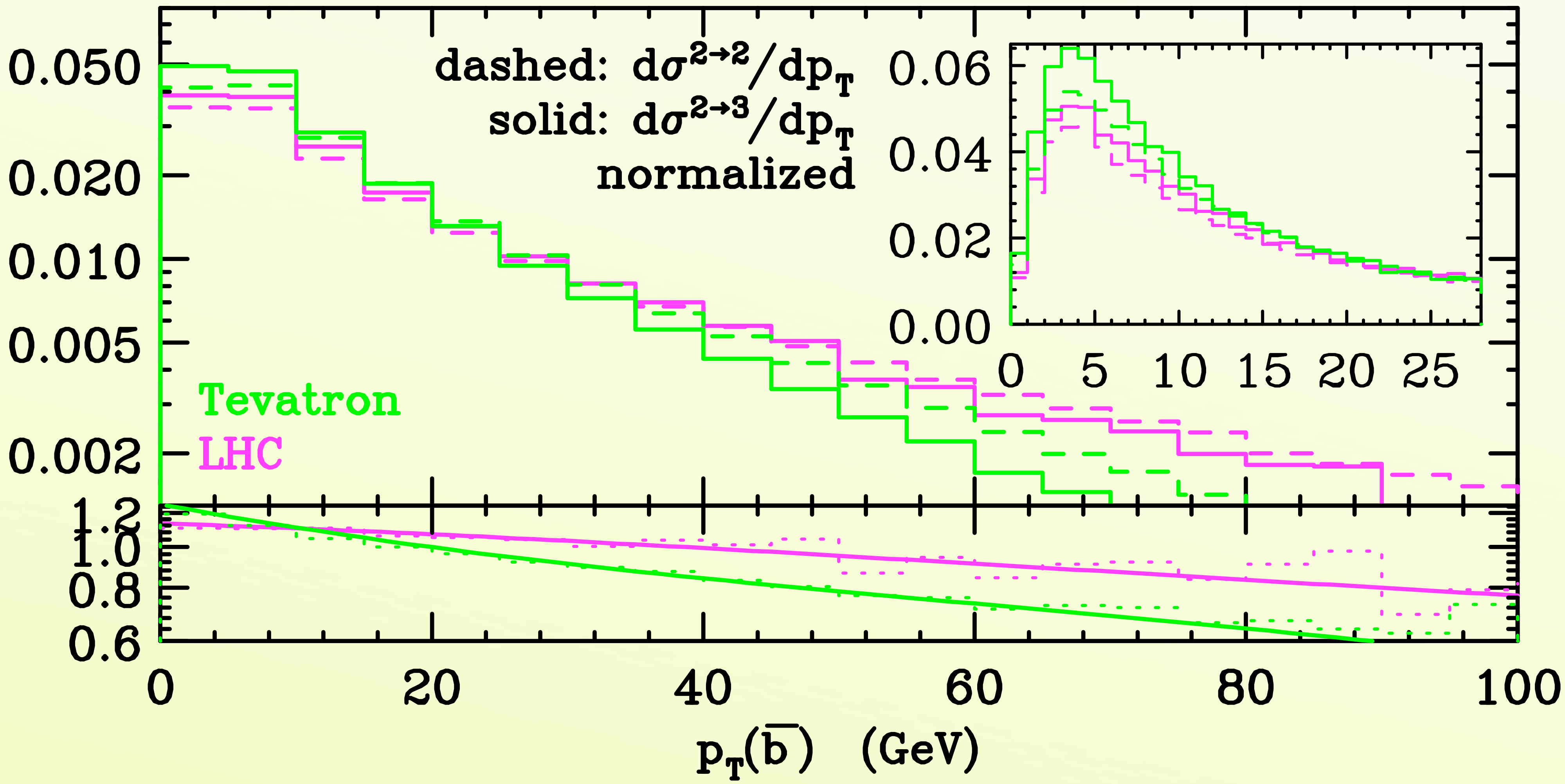
Some differences, but typically of the order of ~10% in the regions where the cross section is large

Spectator b



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

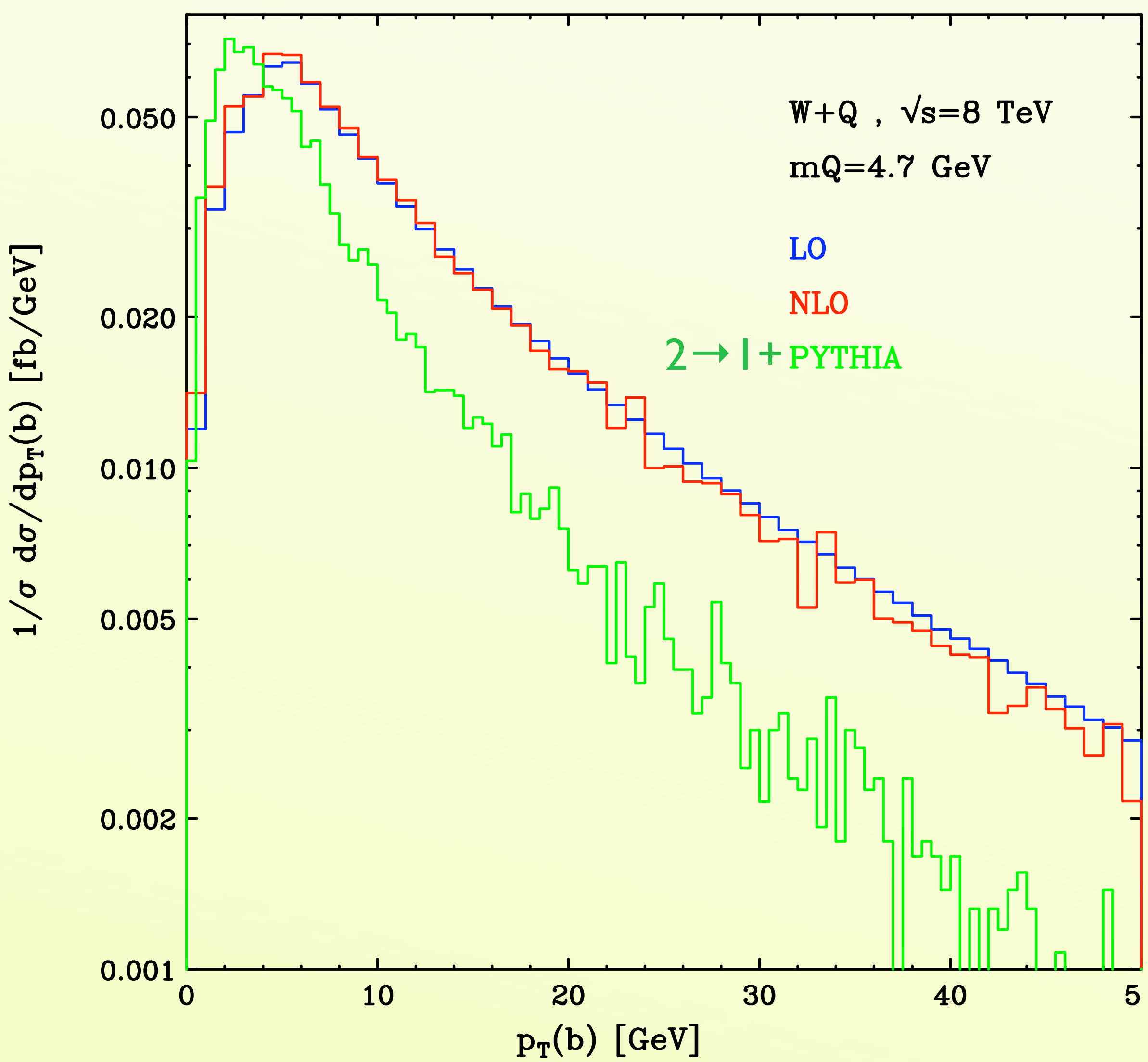
Spectator b

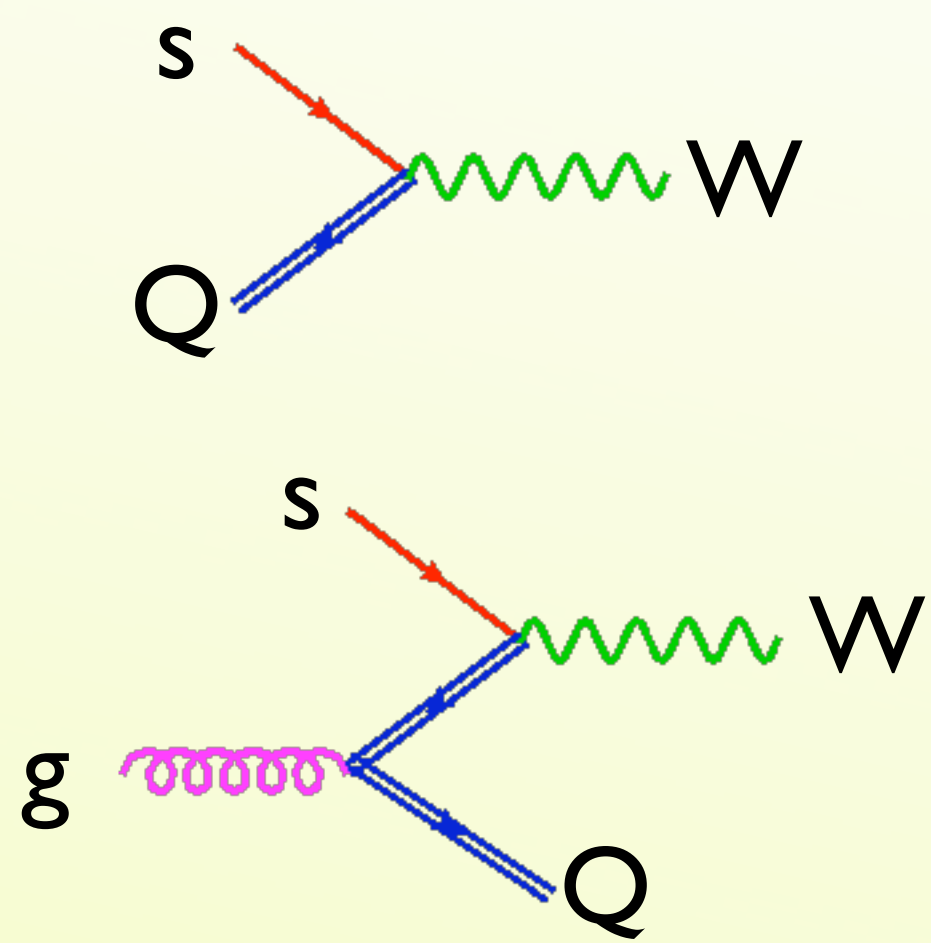


- First NLO prediction for this observable
- Slightly softer in 4F (2 → 3), particularly at the Tevatron
- Deviations up to ~ 20% : perturbatively quite stable

Similar behavior in WQ : 2→1 vs 2→2

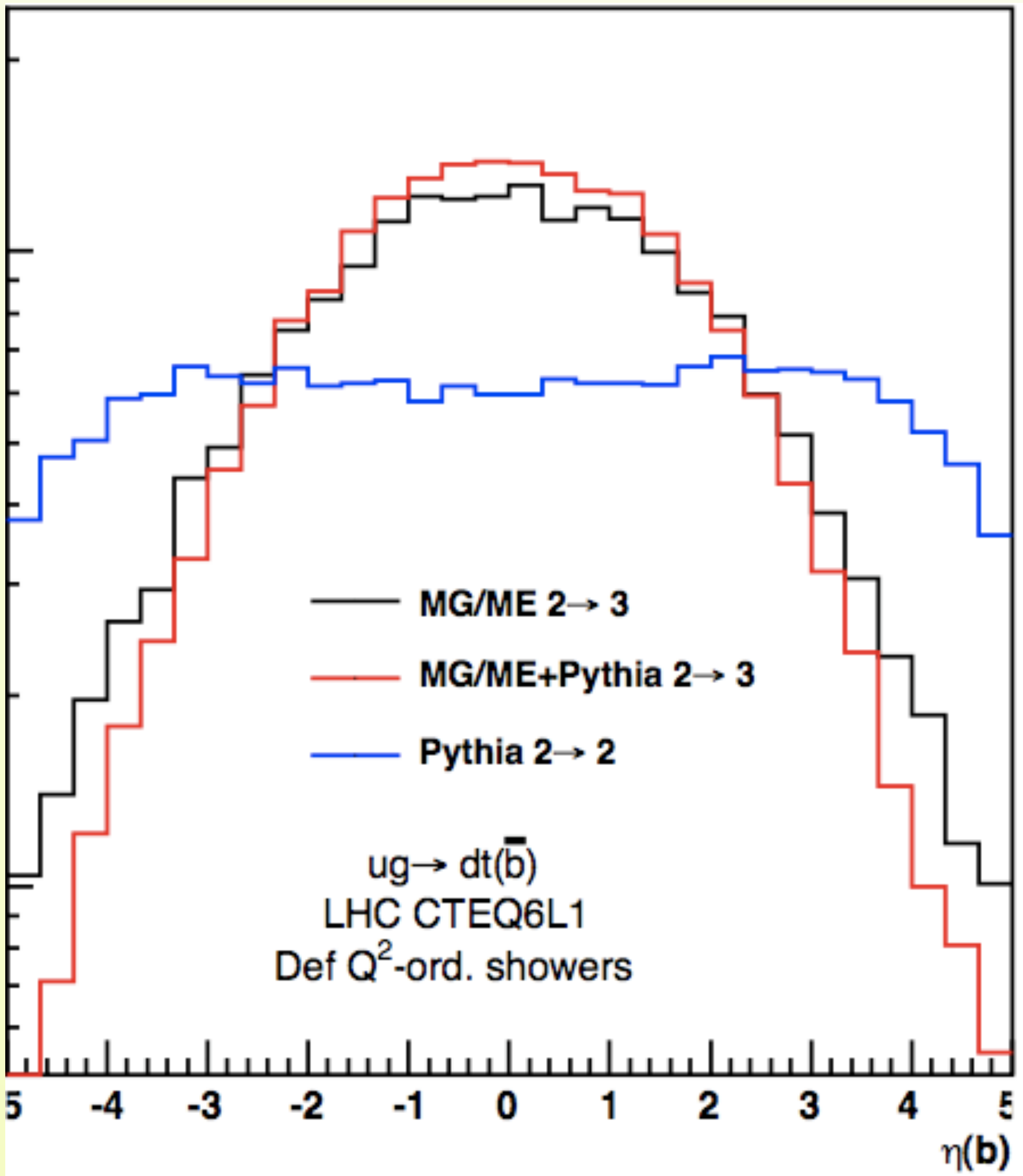
[Campbell, FM, Mangano, Tramontano, in progress]

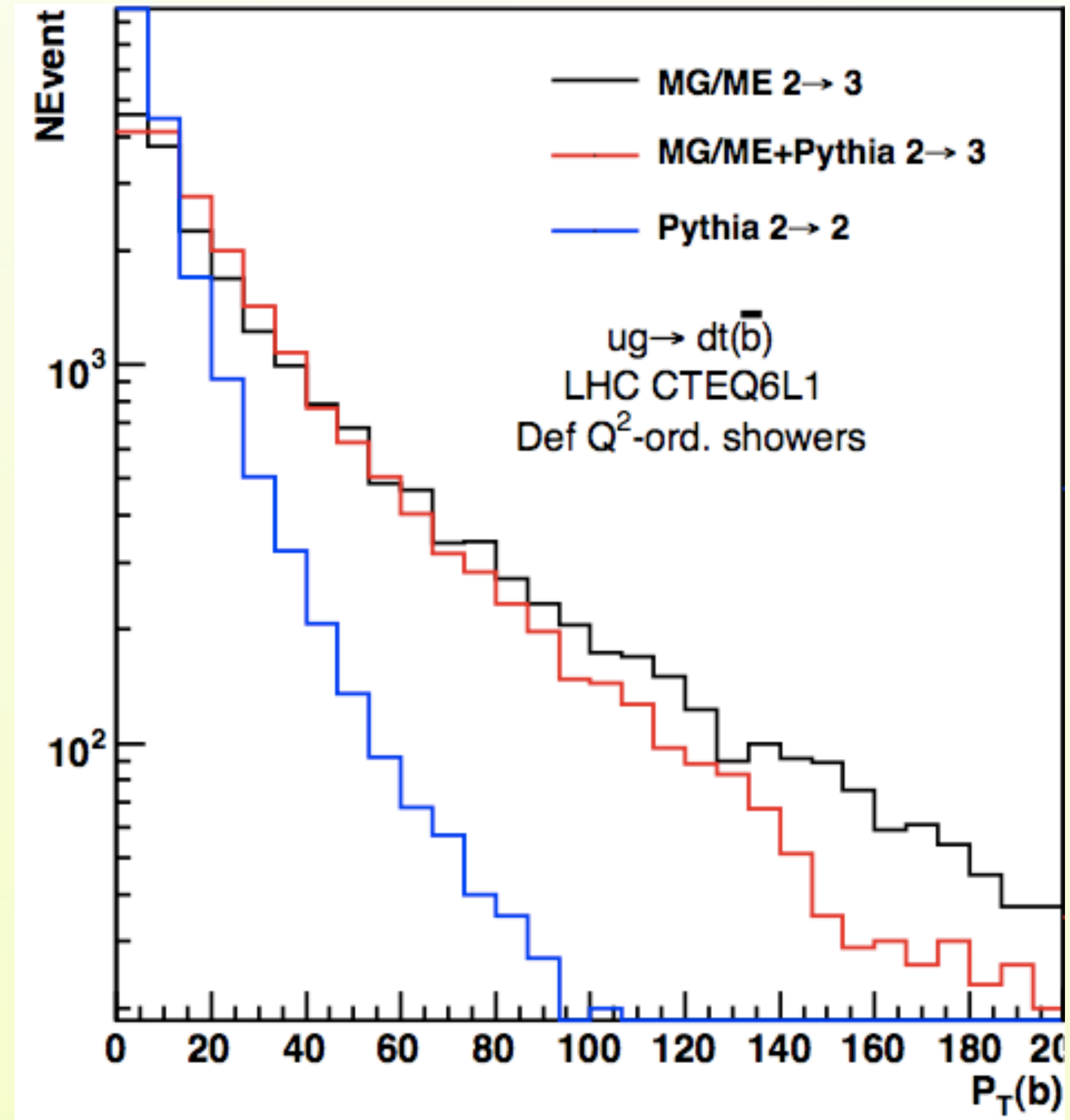




- pT spectrum of the spectator HQ unchanged
- no call for resummation
- the 2→2 prediction for the spectator theoretically solid.

ME+PS comparison at LHC





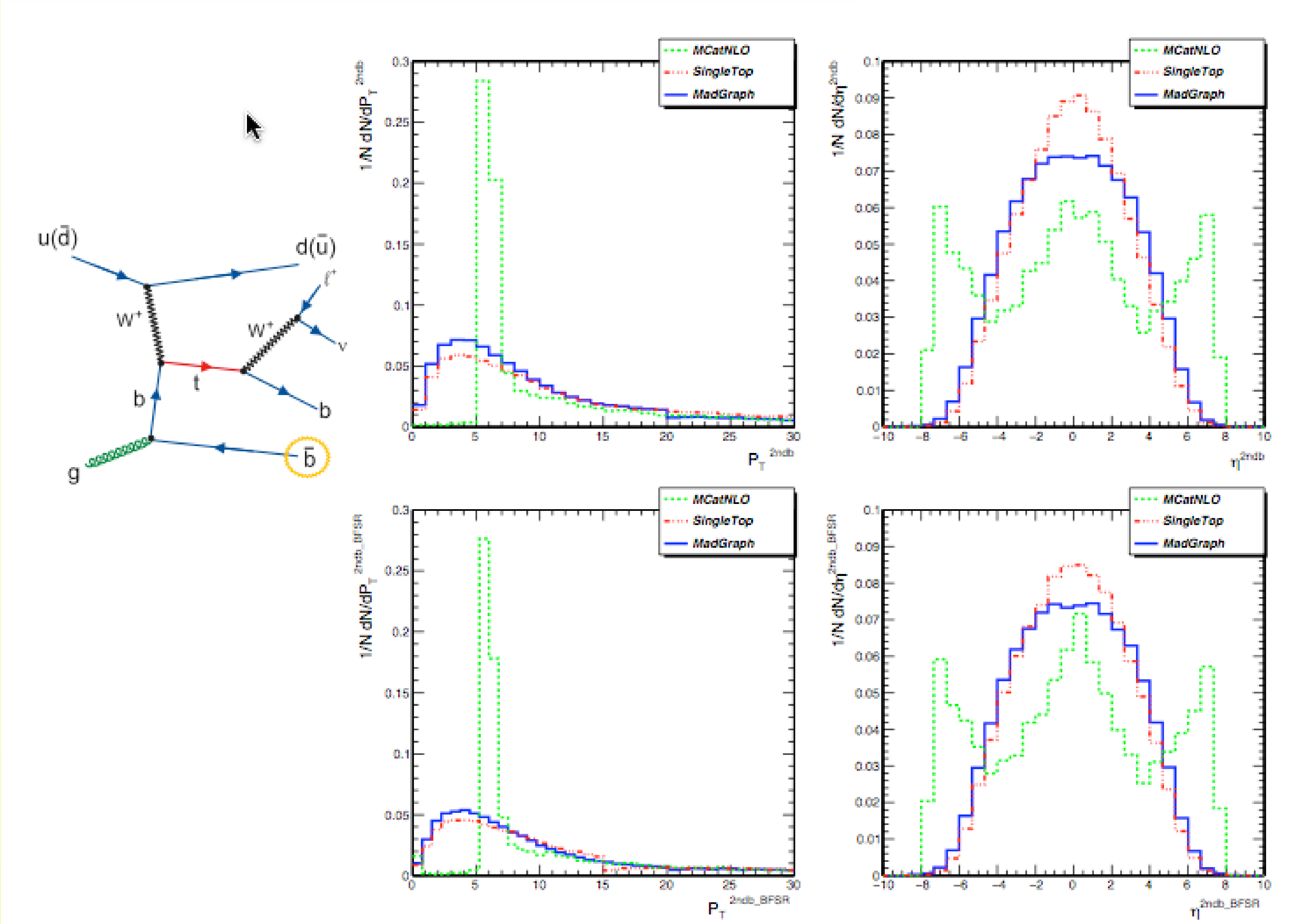
pT and η spectra of the spectator HQ from the 2→3 prediction are accurate and do not need any dangerous matching...

More work in progress with A. Giammanco, J. Bauer and R. Frederix.

NLO MC at the LHC

NLOwPS : MC@NLO

Konstantinov et al., CMS AN-2009/024

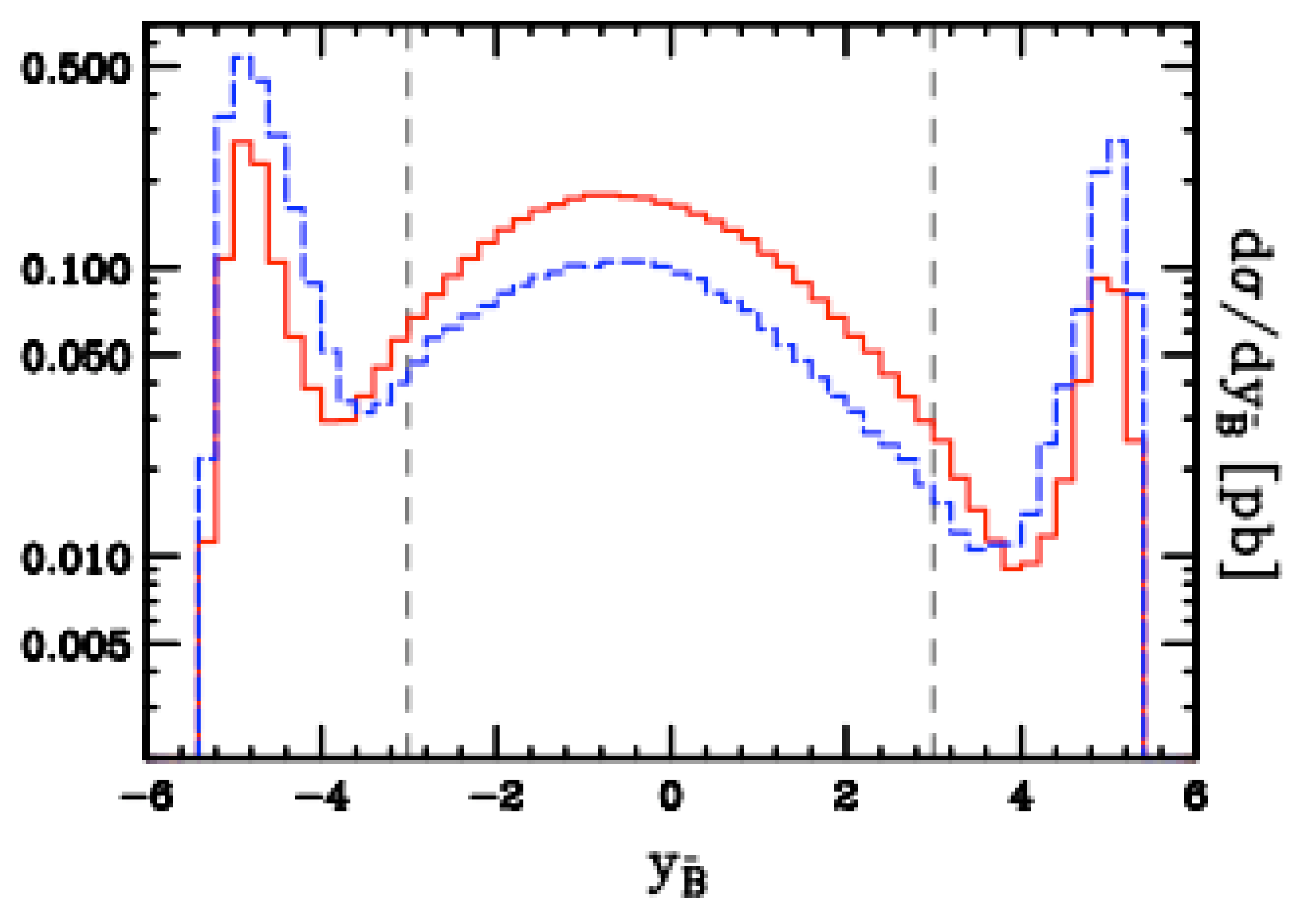


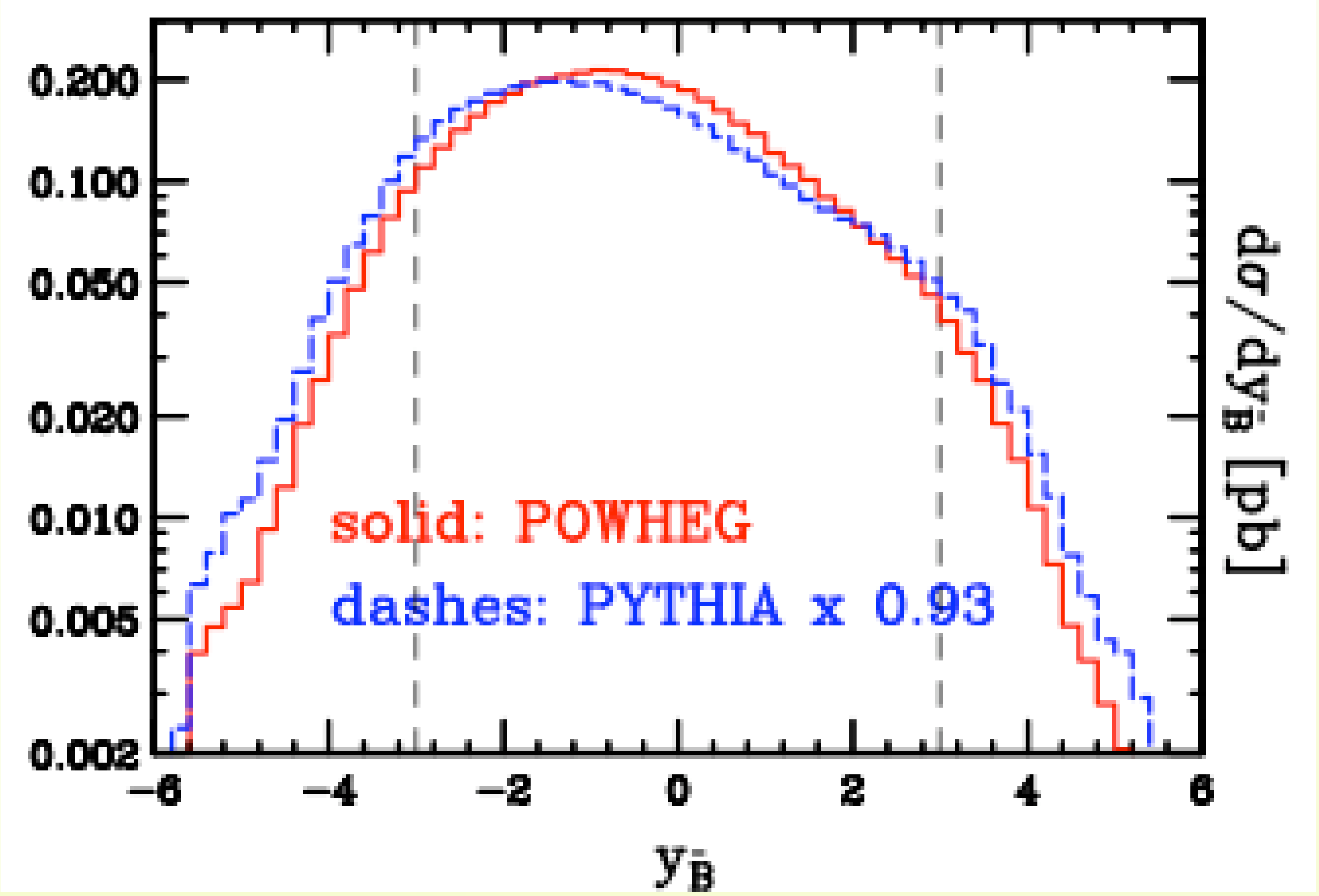
☹All MC implementations currently available for single top processes neglect m_b.

NLO MC at the Tevatron

[Aioli,Nason,Oleari,Re : 0907.4076]

NLOwPS : POWHEG





NLO(2→2) +HERWIG

NLO (2→2) +Pythia

Shower for initial states HQ needs to be corrected in HERWIG and in general improved! Work in progress... [M.Seymour. et al.]

☹All MC implementations currently available for single top processes neglect m_b.

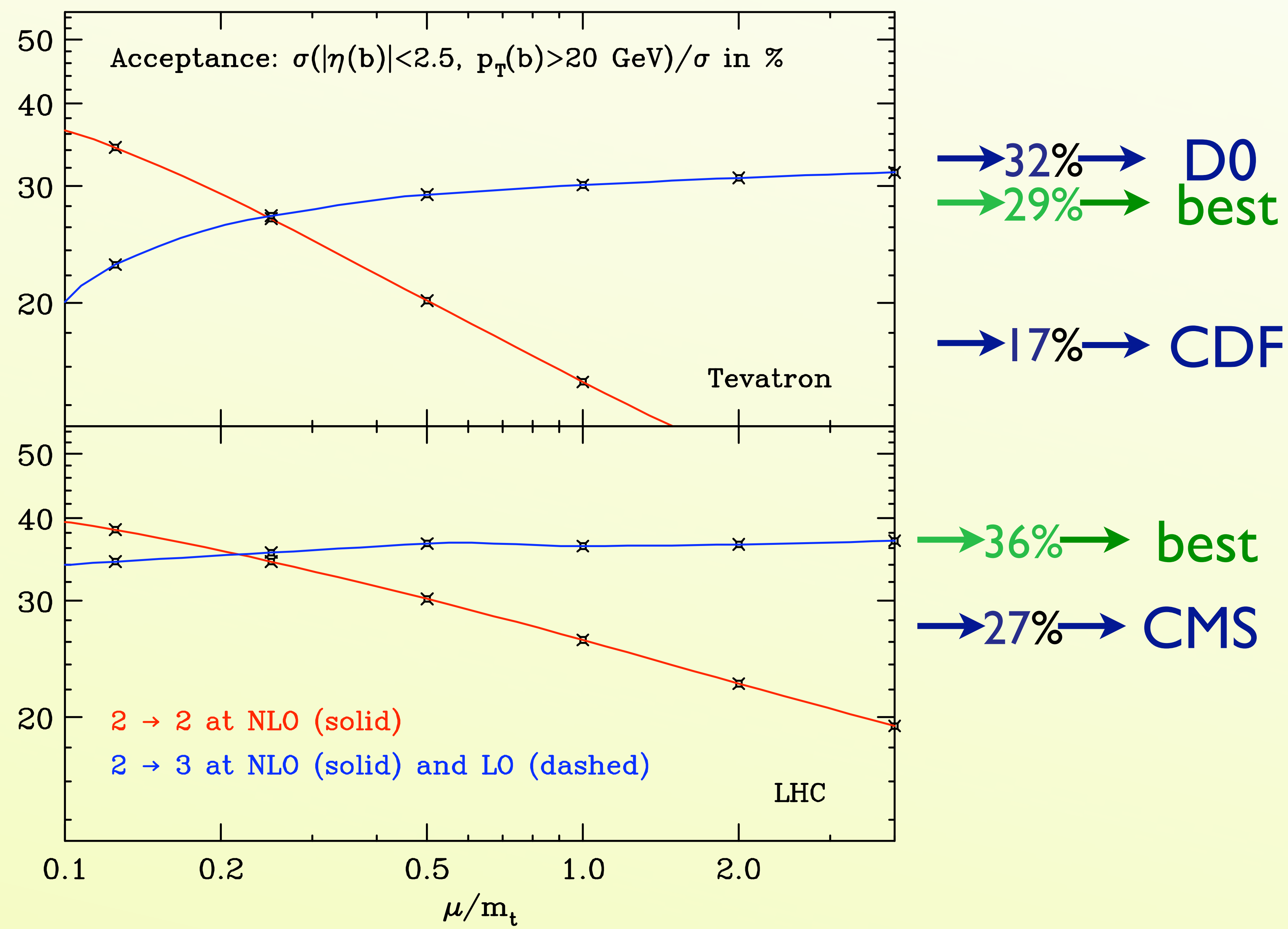
Applications of the new NLO calculation

- Event though b quarks in the 4F ($2 \rightarrow 3$) scheme are more forward and softer, we expect to see more b's than in the 5F ($2 \rightarrow 2$)
- In 5F ($2 \rightarrow 2$) 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:

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

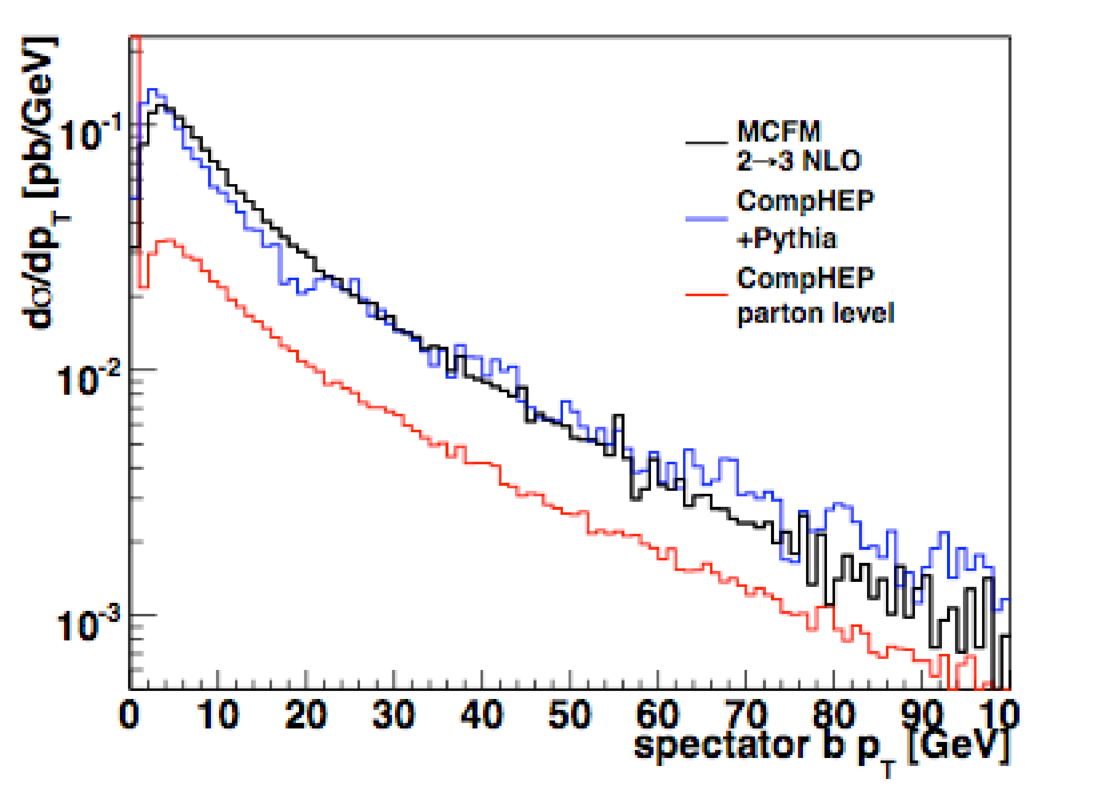
Acceptance

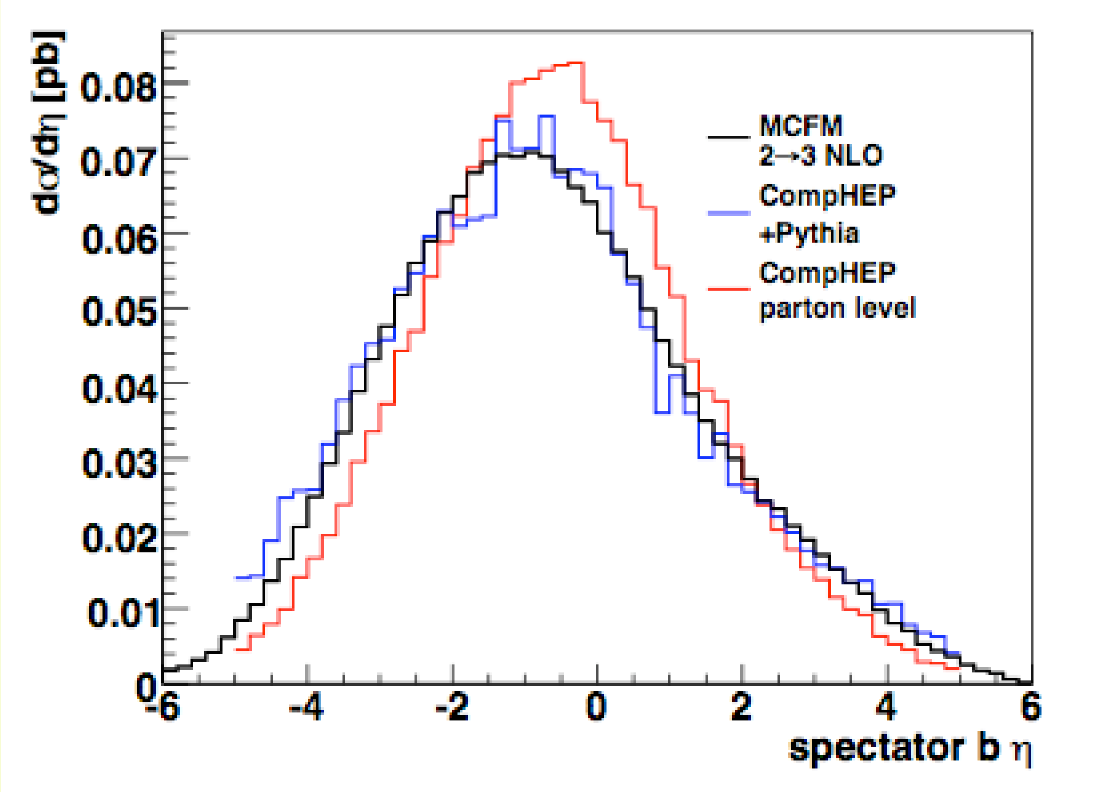
- Very large scale dependence for 5F (2 → 2),
  → effectively a LO quantity
- NLO 4F (2 → 3) much more stable
- Dramatic effect at the Tevatron, important at the LHC.



t-channel single top at Tevatron

[Frederix, FM, Schwienhorst, Les Houches 2009]





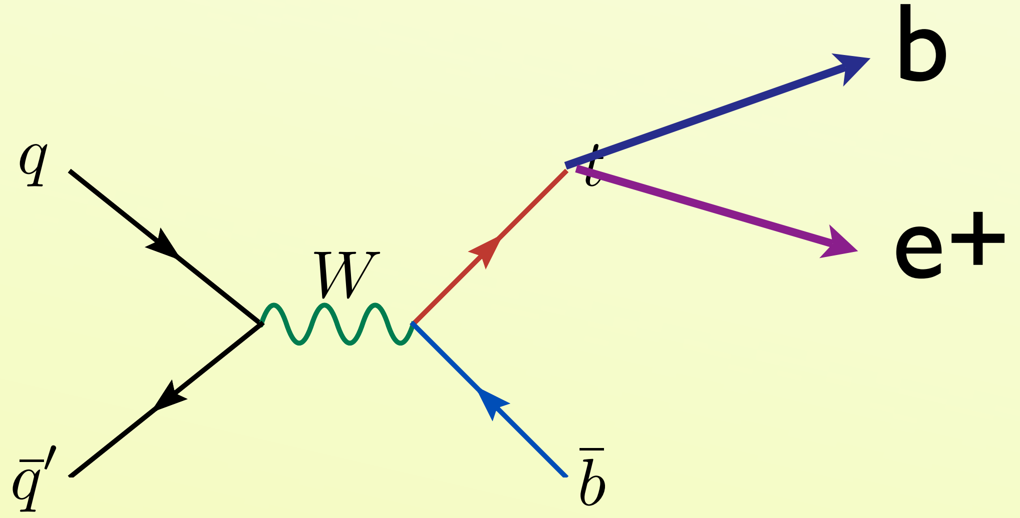
D0 has used samples obtained by COMPHEP+Pythia with a "hard pt matching" that are in good agreement with the 2→3 NLO predictions.

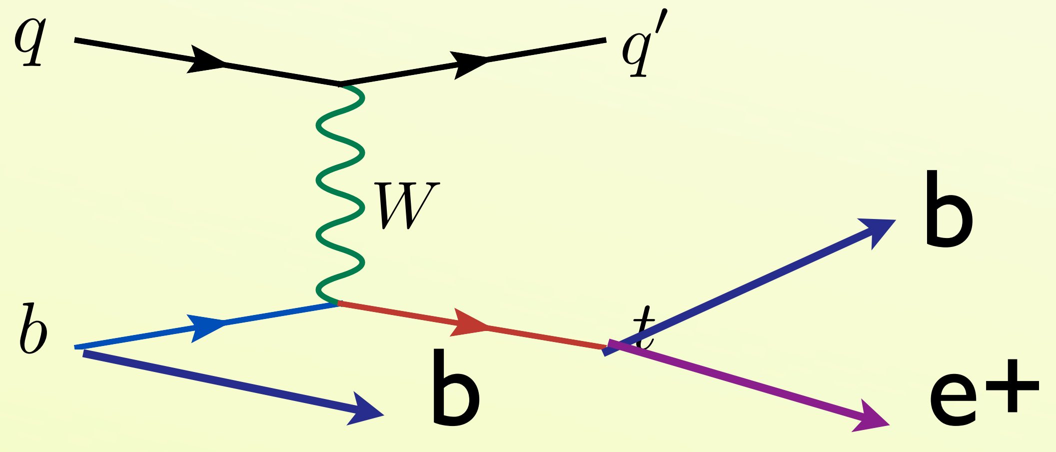
Consequences for single top observation?

- Difficult to say a priori, but work in progress
- Naively:
  - No change in total cross section (s + t channel) ⇒ significance of the observation and Vtb not much 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

Consequences for single top observation?

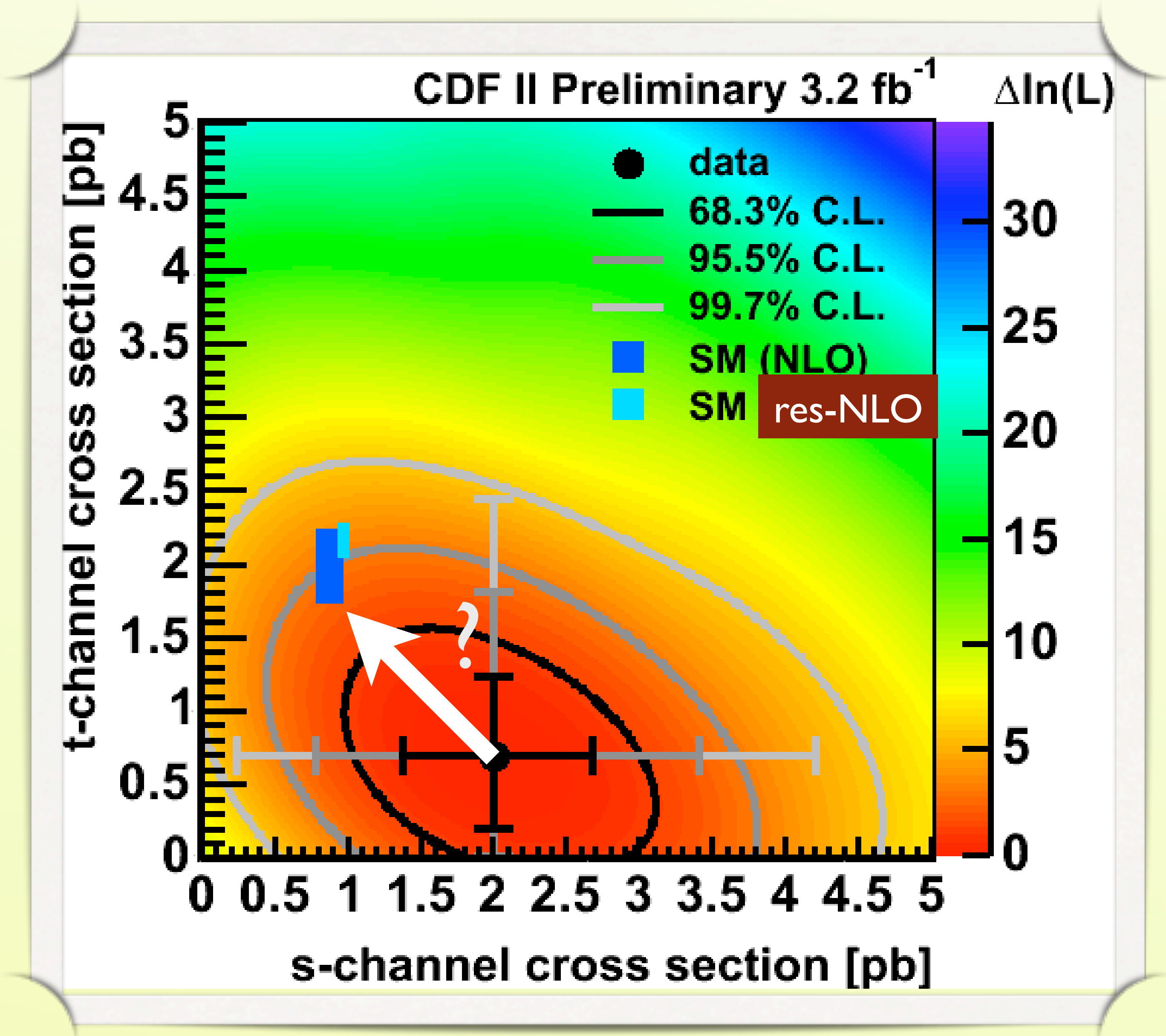
- Difficult to say a priori, but work in progress
- Naively:
  - No change in total cross section (s + t channel) ⇒ significance of the observation and Vtb not much affected. Needs to be carefully checked!
  - More events that were considered s channel before are in fact t channel, because more t channel 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 single top groups are addressing this issue.

Lesson from the 2→3 t-channel calculations

i. Single top (multivariate) analyses rely heavily on the MC's for the expected signal (and to a less extent background) distributions.

ii. We should always keep in mind that the adjective "NLO" can only be meaningfully associated to an observable NOT to a calculation!!

iii. In any case, the effect of theoretical uncertaintes (scale and PDF uncertaintes) on the analysis should be always estimated in situ.

iv. Single top can also be thought as a template to other difficult searches at the LHC.

Conclusions

- Single top offers unique and exciting opportunities for testing the SM and probing new physics at the Tevatron and even more at the LHC.
- Theory and MC's under continuous improvement to match the needs of the experimental analyses (which are more demanding than those of ttbar!).
- Single top is also one of most "influential" examples of processes that can be described with heavy quarks in the initial state : known but always hot QCD issue.
- A lot of work and fun ahead...