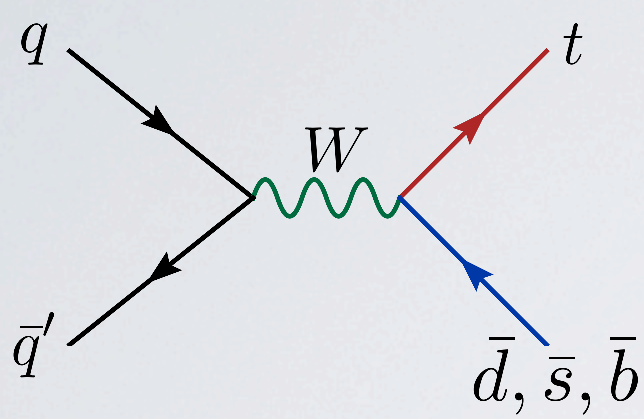
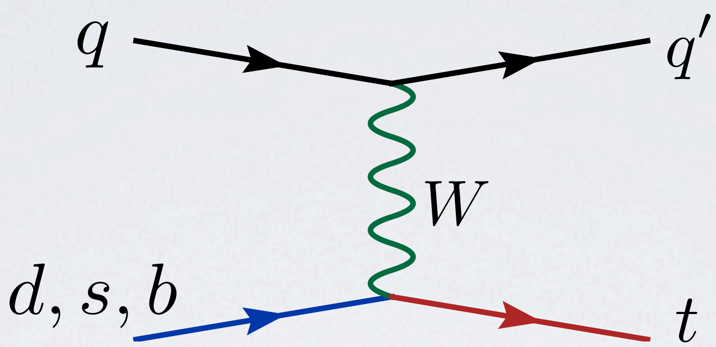
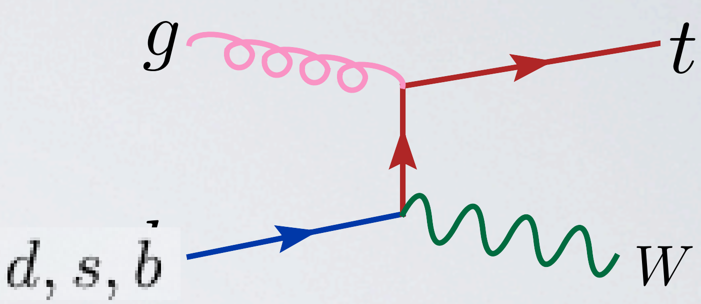
SINGLE TOP THEORY

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

THREEFOLD PRODUCTION







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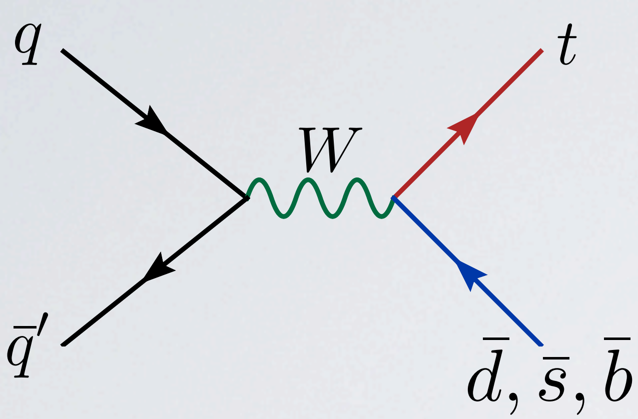

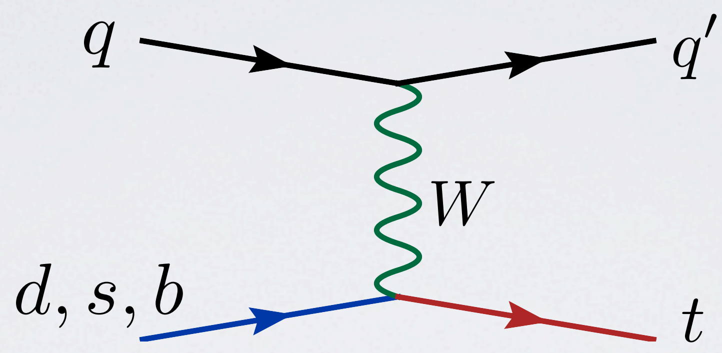

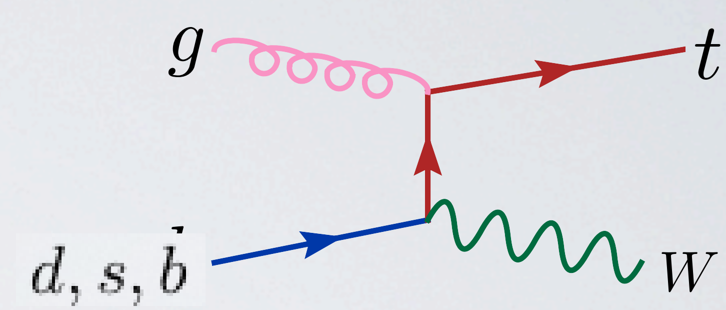

* "Drell-Yan" production mode.
* Tevatron is sizable (~1pb), quite small at the LHC14 (~10 pb).
* Fully inclusive x-sec known at NNLO.
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* Final State: 2 b's + W
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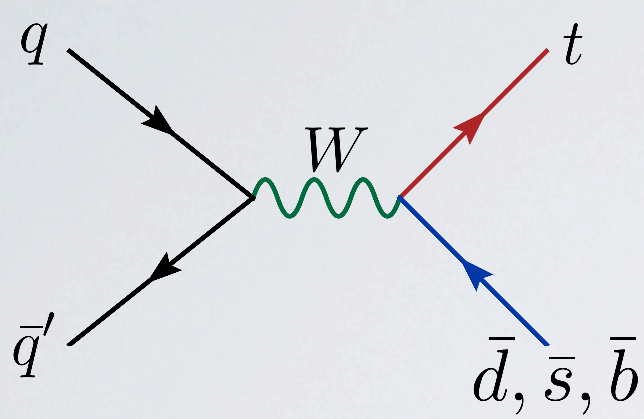

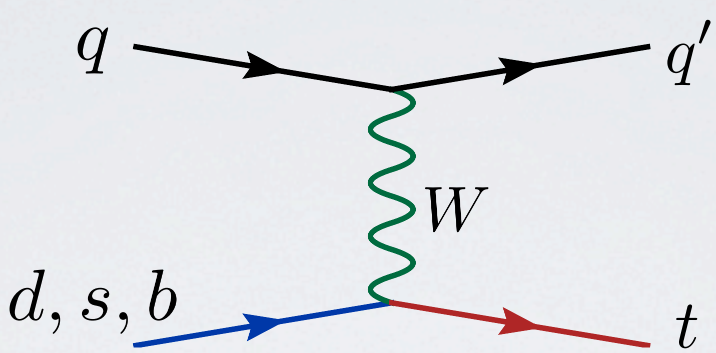

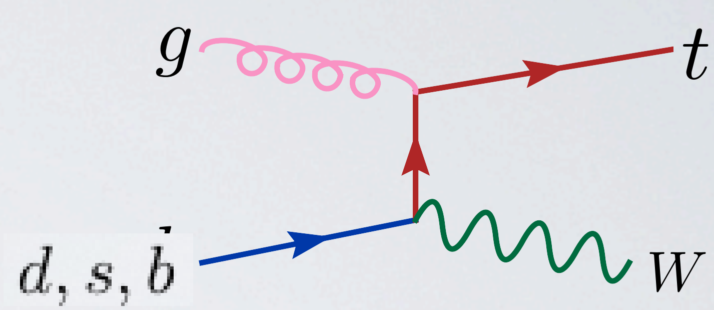

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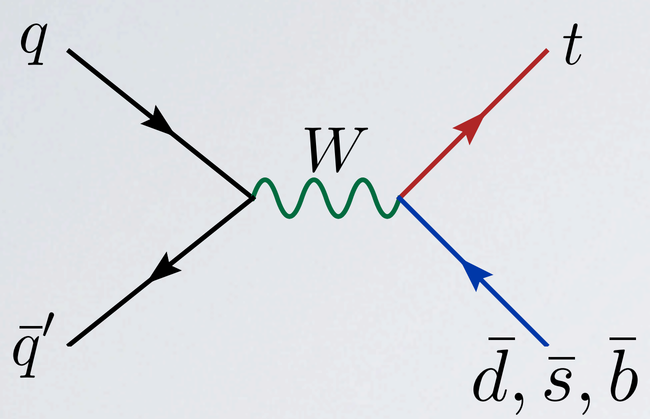

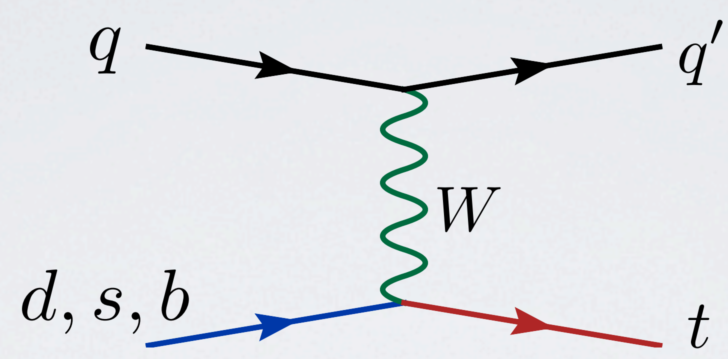

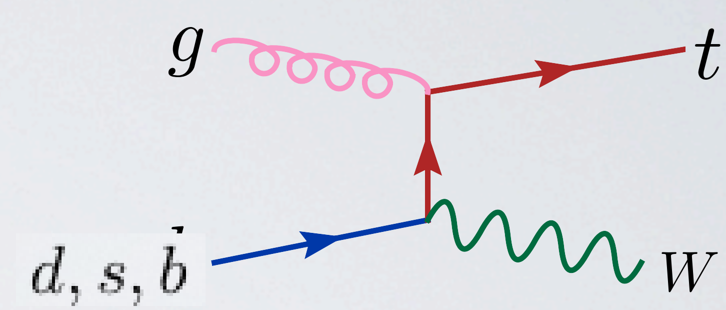

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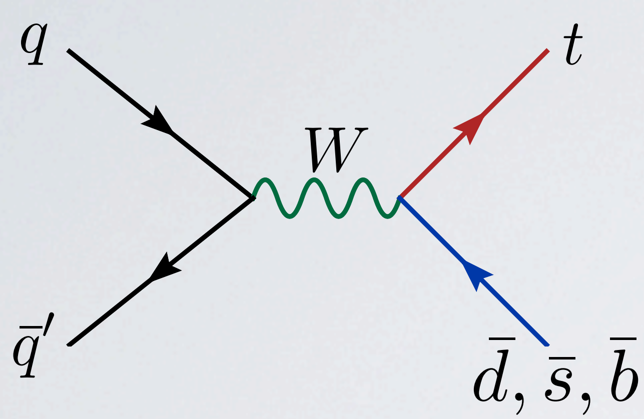

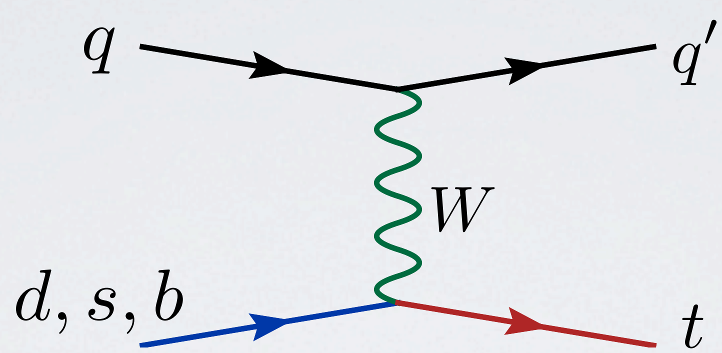

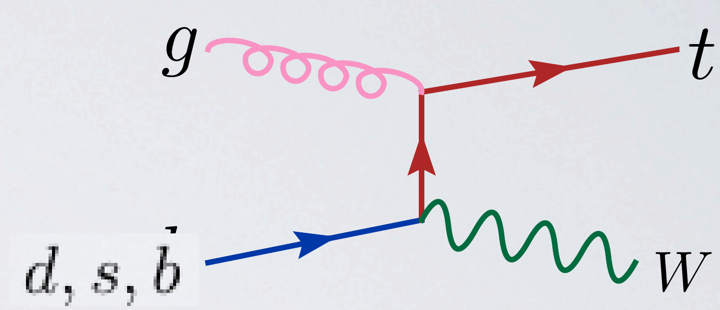

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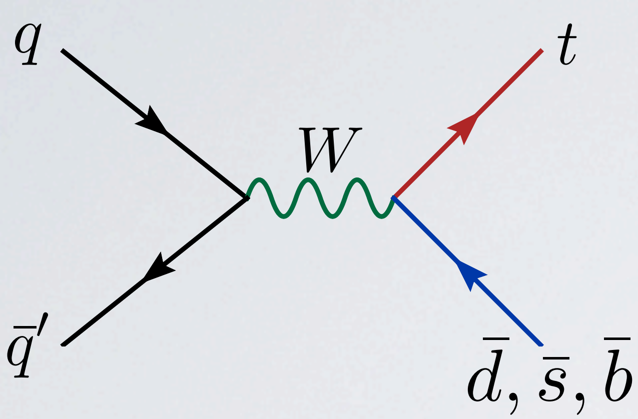

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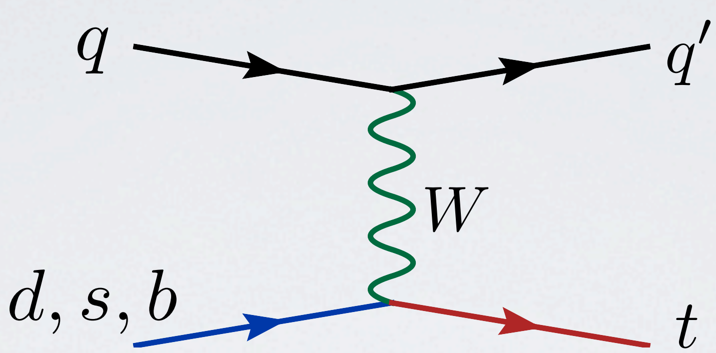

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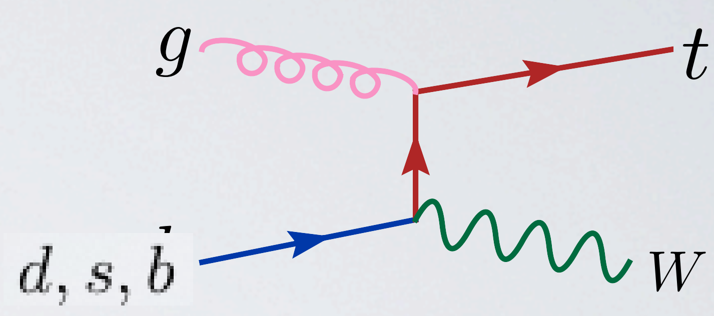

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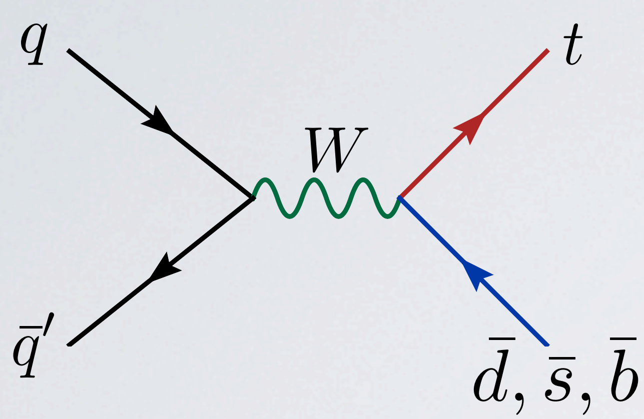

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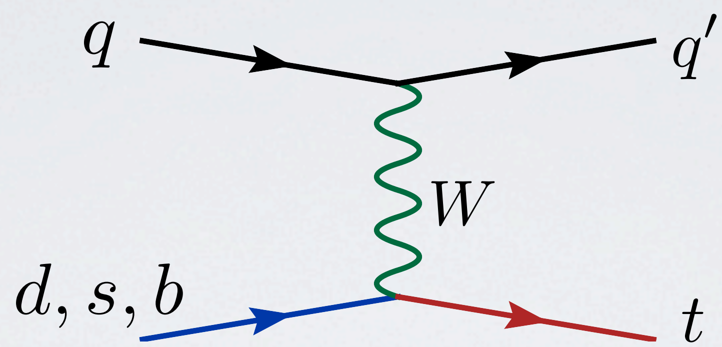

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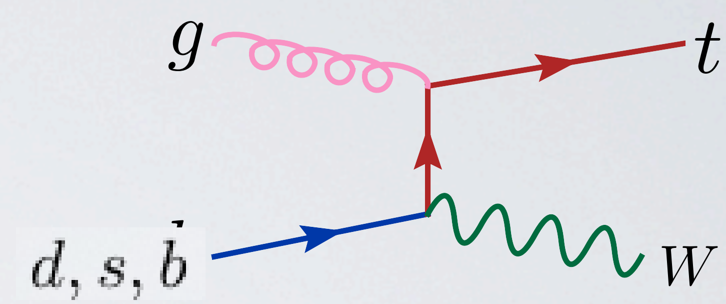

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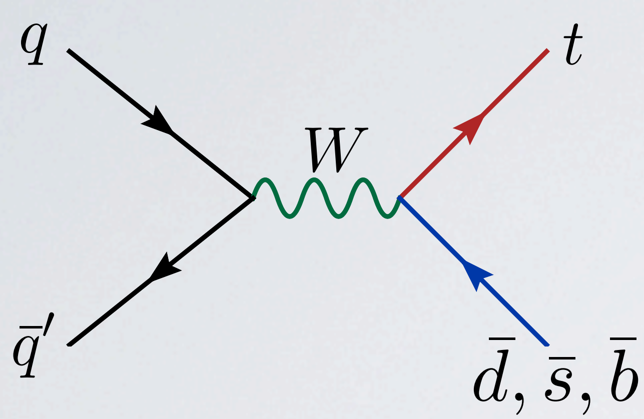

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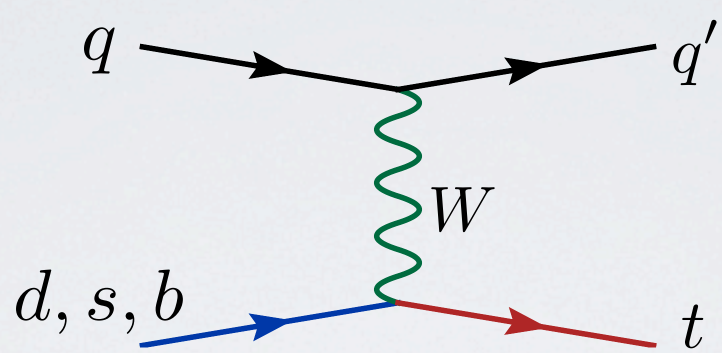

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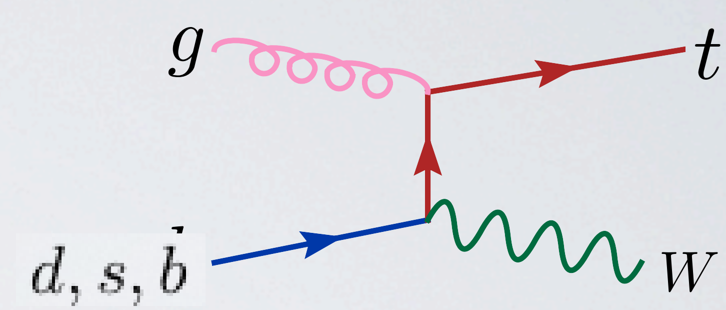

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* Theorist's comments

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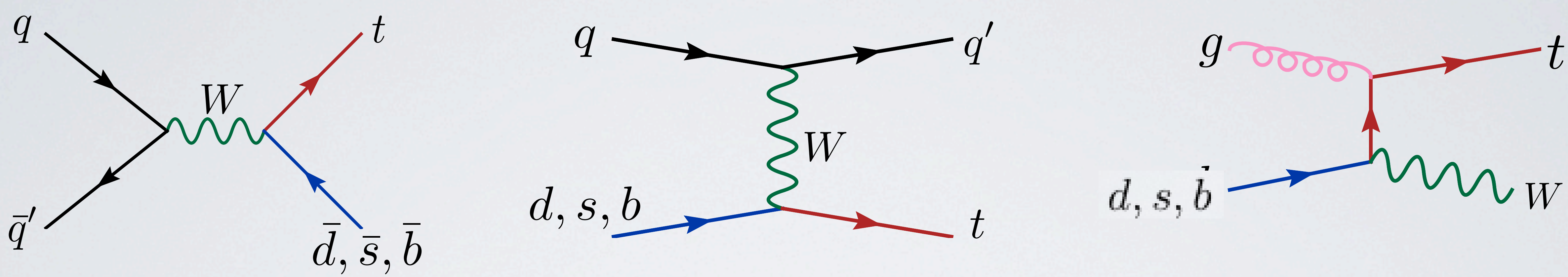

SINGLE TOP	Tevatron	LHC7	LHC14
s-channel t(tbar)	0.45	2.5 (1.5)	7 (4)
t-channel t(tbar)	1.2	40 (20)	150 (90)
tW	0.15	8	45

(not very precise) numbers but useful to keep in mind

MOTIVATIONS FOR PRECISION

- Electroweak process : Production = Decay

    ➡ TH high precision attainable

- "Anomalously" high cross section wrt to pp→ t tbar

    ➡ EXP high precision possible

- Sensitive to New Physics effects in different ways

    ➡ Anomalous couplings, resonances, fourth generation

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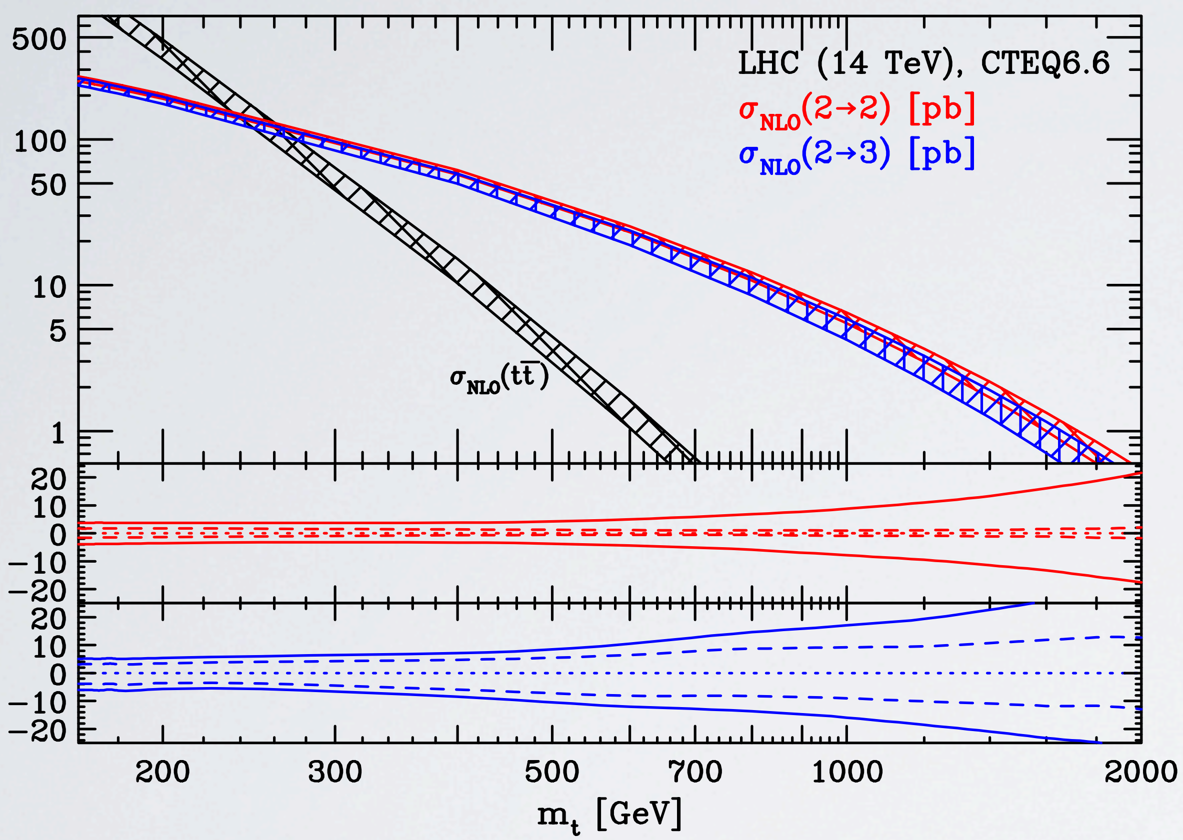
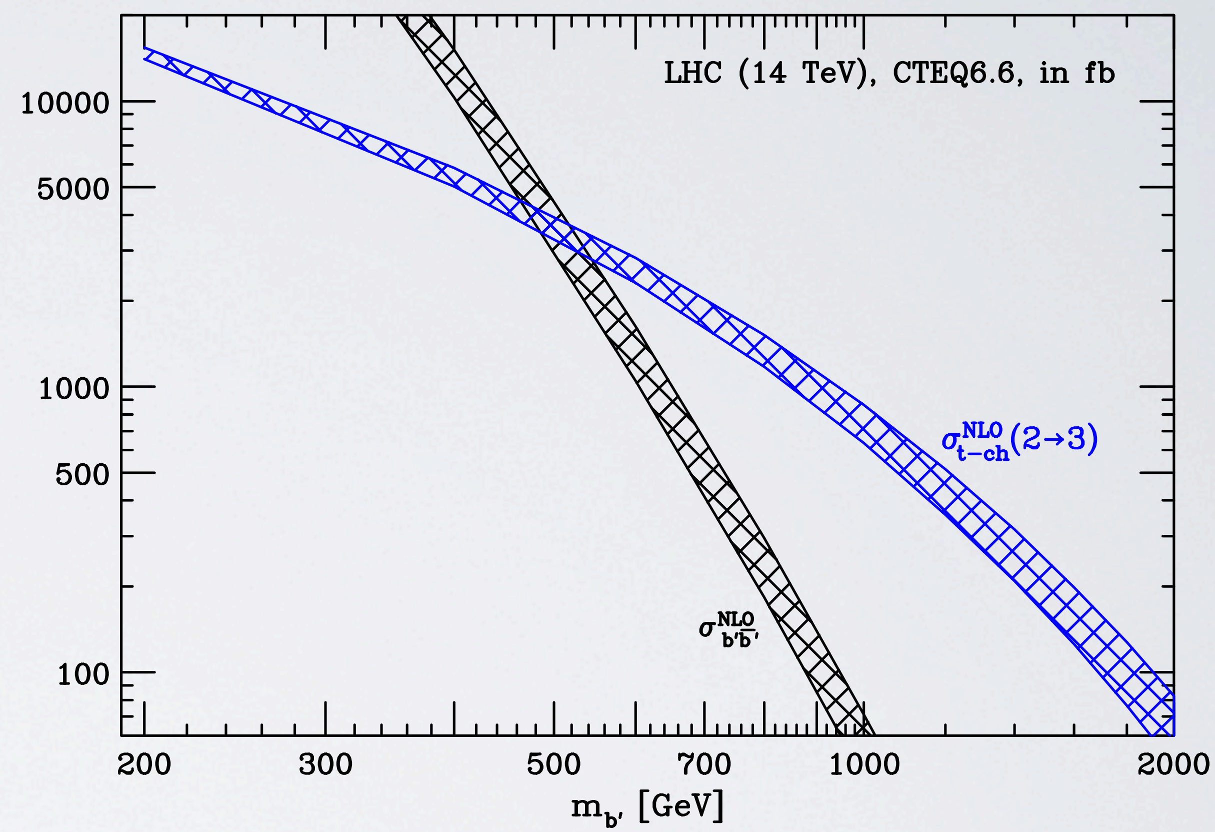
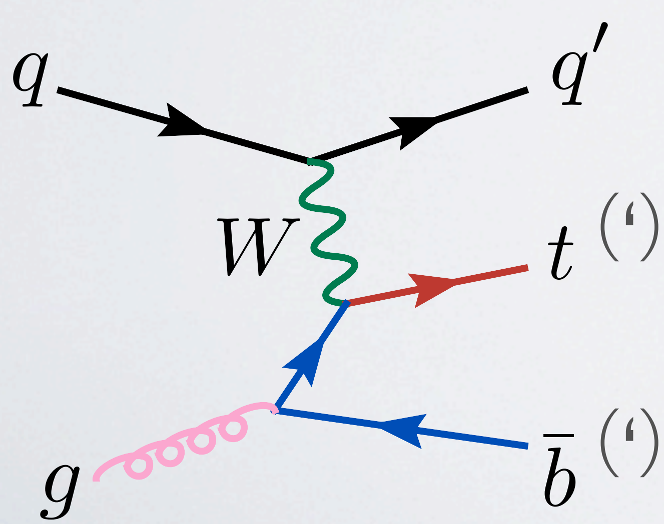
Fourth generation x secs.







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.

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Effective Field Theory Approach to t tbar production

[Aguilar-Saavedra 2010, Willenbrock et al. 2010, Degrande et al 2010]

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{\mathrm{dim}=6}$$

Very few operators of dim-6 affecting top physics.

CP-even

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$gg \to t\bar{t}$
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7 four-quark operators	$q\bar{q} \to t\bar{t}$

CP-odd

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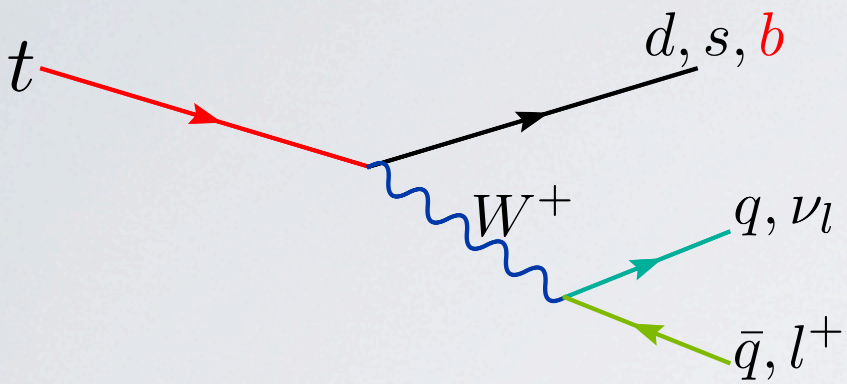
Even less affecting single top production

Example: Constraints the CKM matrix

[Alwall et al., Eur. Phys, J. C49 791 (2007)]

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



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

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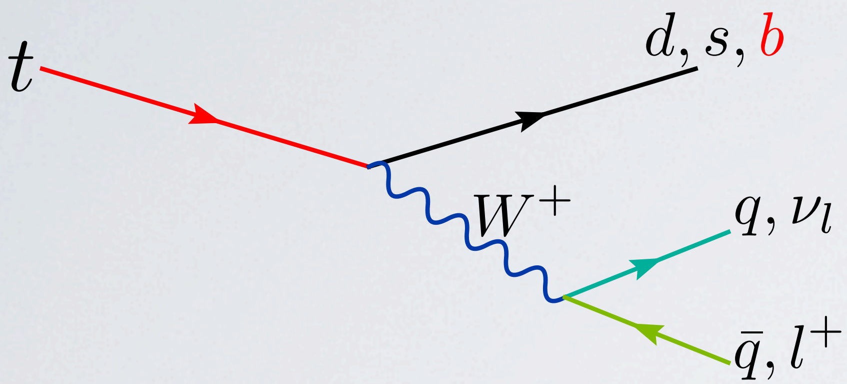

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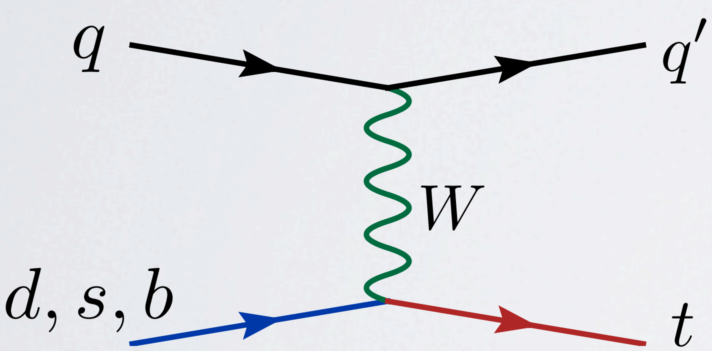
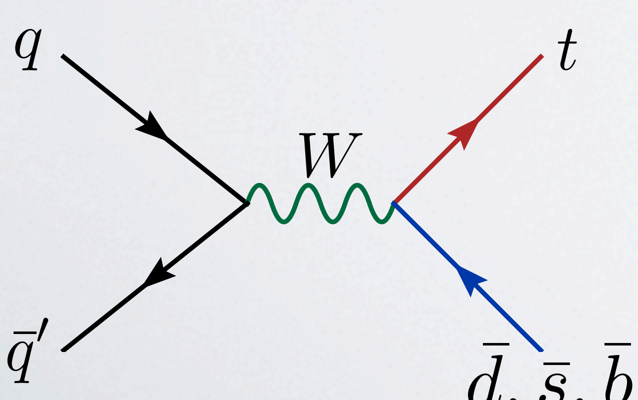
On the other hand, single top is DIRECTLY sensitive to V_{tb}, V_{ts}, V_{td} :



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

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)

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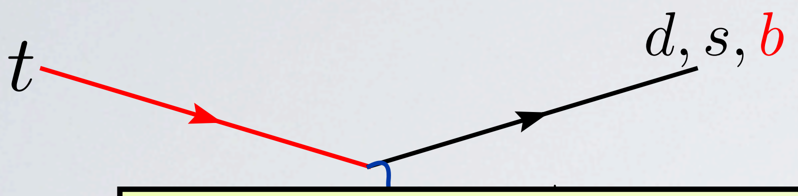

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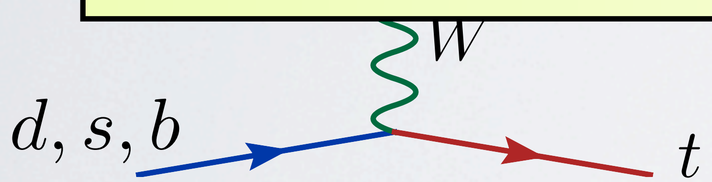
On t

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

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

n.b. : naive estimate

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



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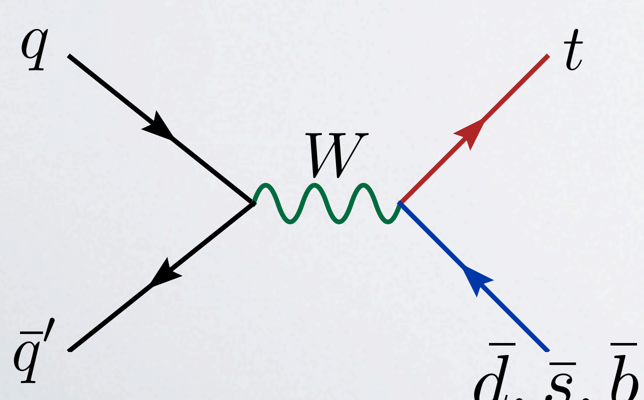

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[Alwall et al., Eur. Phys, J. C49 791 (2007)]

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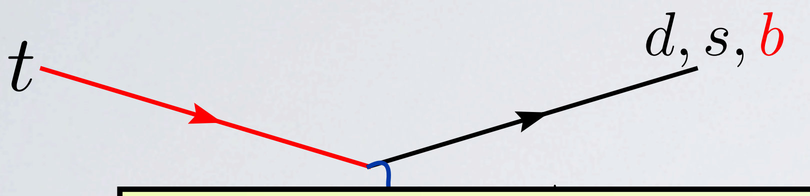


$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to W(\ldots))} = \frac{|V_{tb}|^2}{|V_{..}|^2 + |V_{..}|^2 + |V_{..}|^2}$$

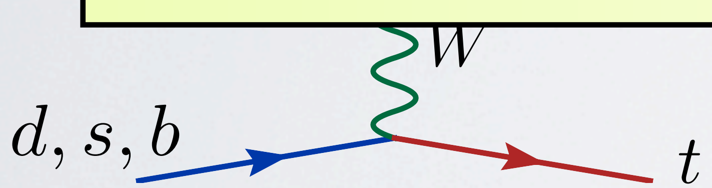
$$\sigma_{1b\text{-tag}} = R\left\{\sum_{i=b,s,d} |V_{ti}|^2\sigma_i^{t-ch} + 2(|V_{td}|^2 + |V_{ts}|^2)\sigma^{s-ch}\right\}$$

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

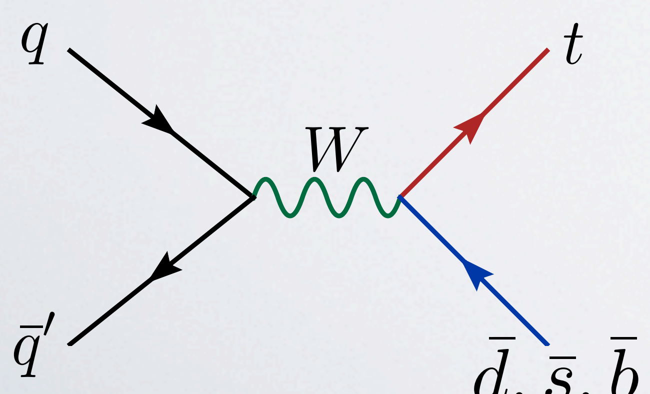
n.b. : naive estimate

On t

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



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



$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V \ldots$$

Now Done by D0!
See Daniel's talk.

Signal becomes similar to t-channe... b-jet)

MOTIVATIONS FOR PRECISION

- Electroweak process : Production = Decay

  ➡ TH high precision attainable

- "Anomalously" high cross section wrt to pp→ t tbar

  ➡ EXP high precision possible

- Sensitive to New Physics effects in different ways

  ➡ Anomalous couplings, resonances, fourth generation

- Sensitive to bottom content of the proton

- Single top is a background to other searches...!

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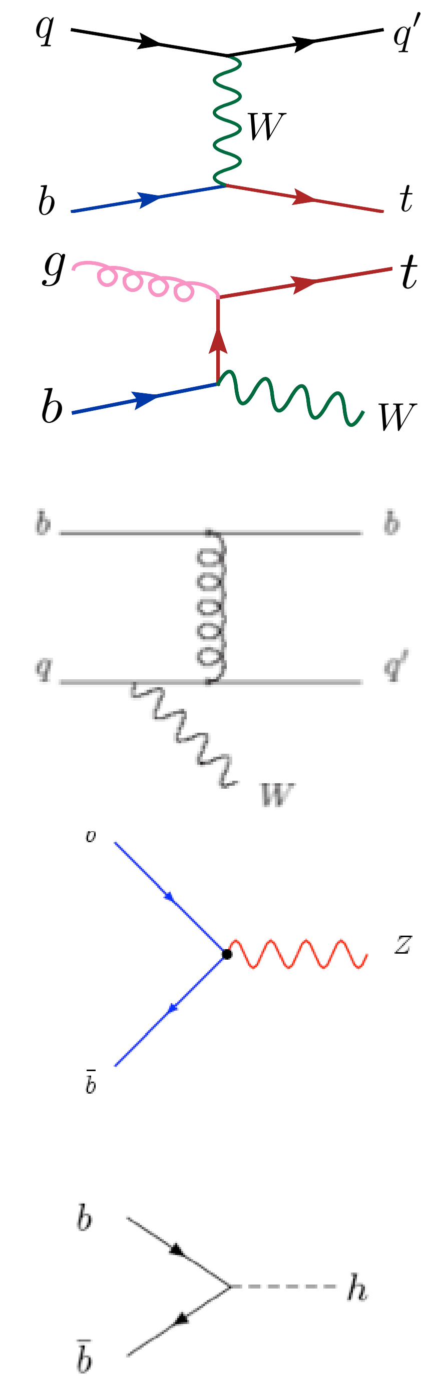
b-initiated processes

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)



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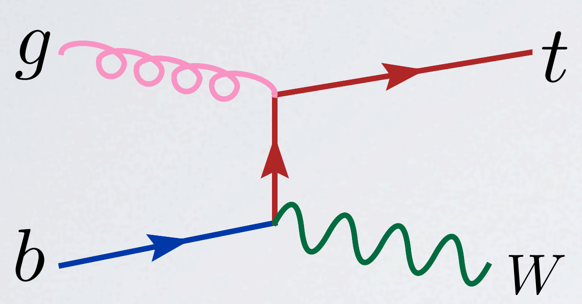
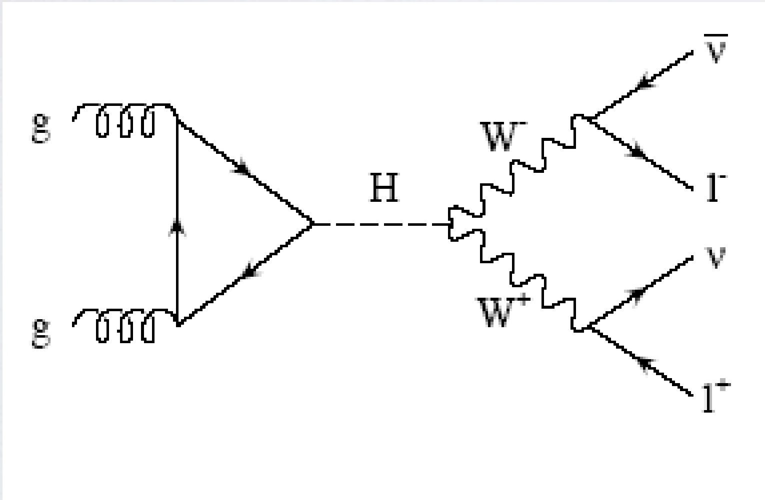
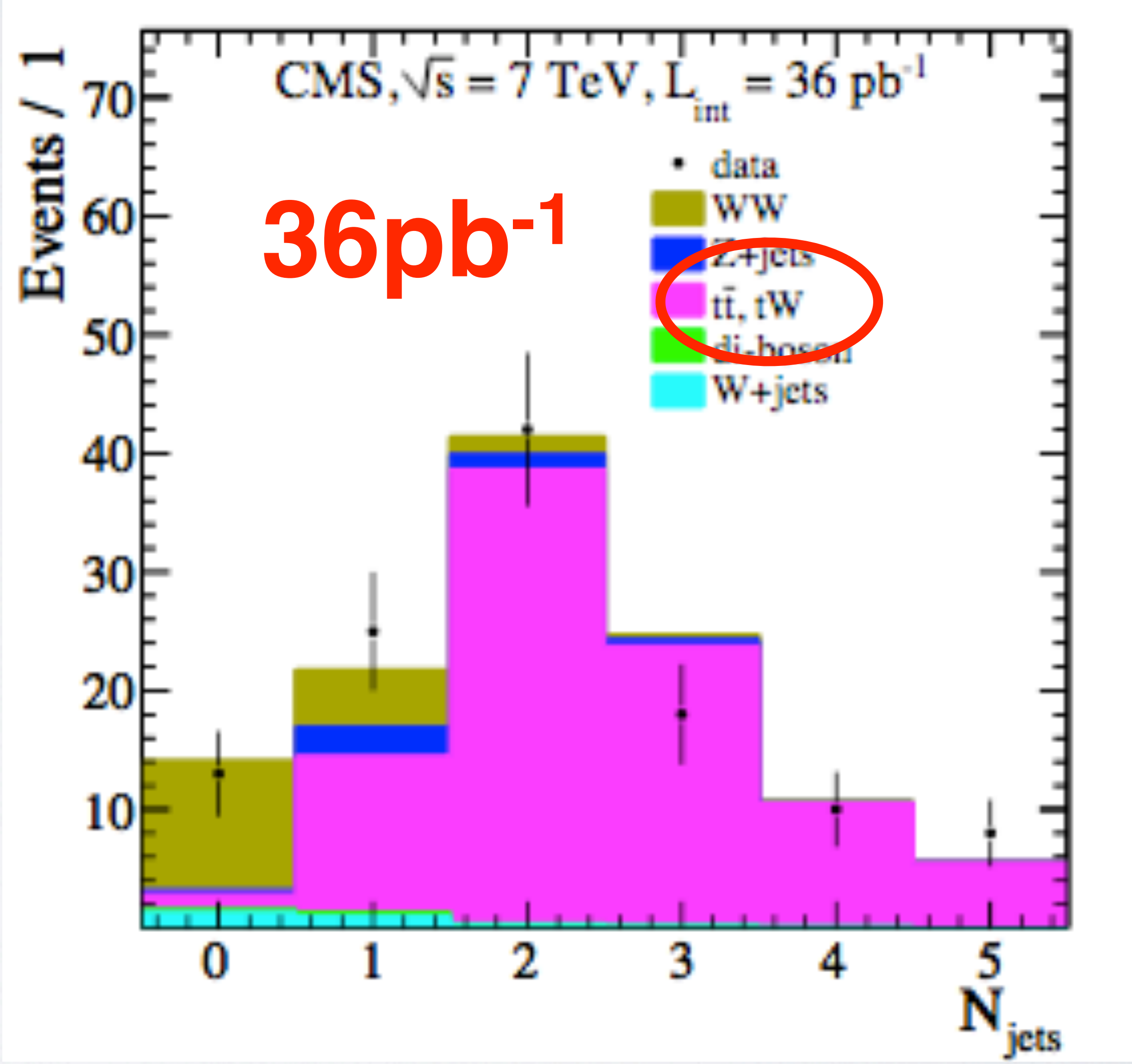
SINGLE TOP AS A BACKGROUND







For total rates tW much smaller than t tbar,
but in this case greatly enhanced by the jet-veto cuts.

NEEDS FOR PRECISION PHYSICS

- Total cross sections at the highest possible order:

  ➡ NNLO in QCD and NLO in EW

- Fully differential NLO cross sections, possibly in an event generator implementation (to be directly used by exp's).

- Accurate knowledge and assessment of the "usual approximations" that are made starting at LO (narrow-width, factorizable corrections, n-flavor schemes and b-mass, interference)

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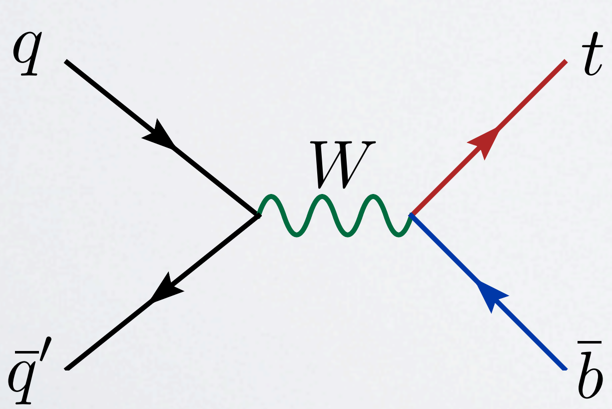

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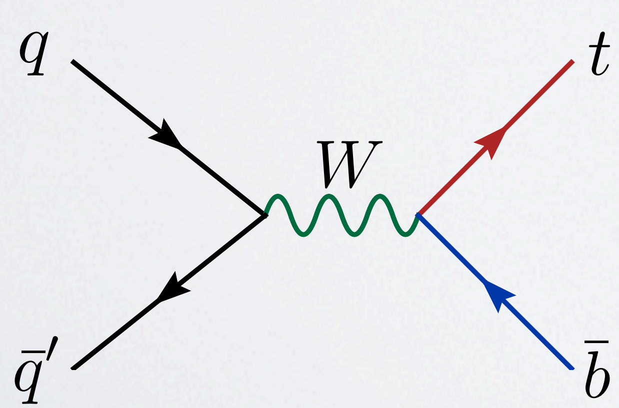

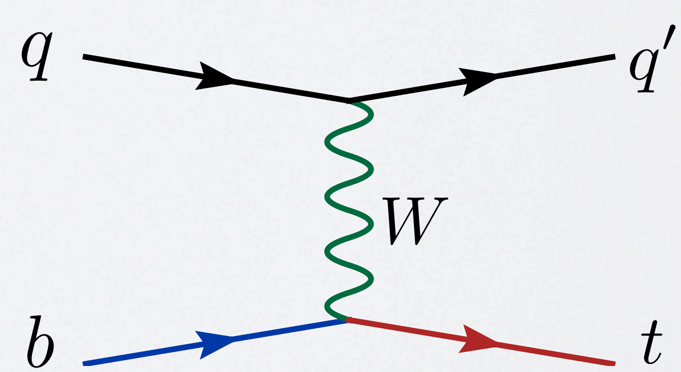

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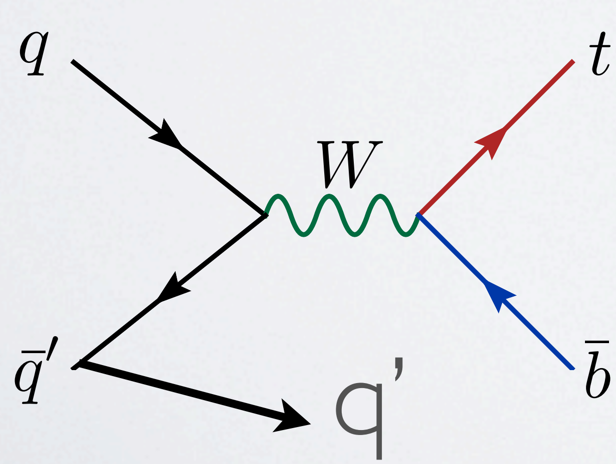

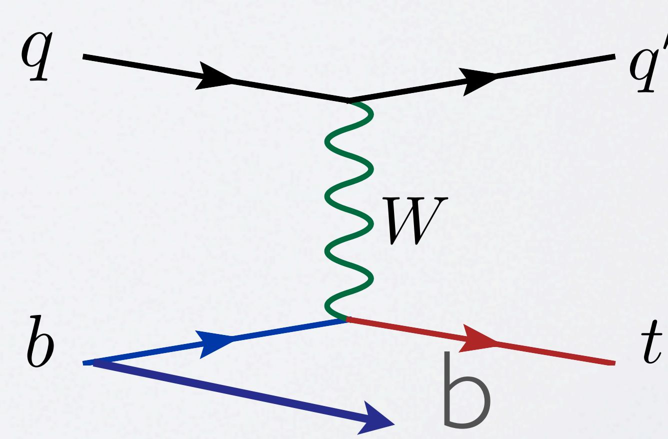

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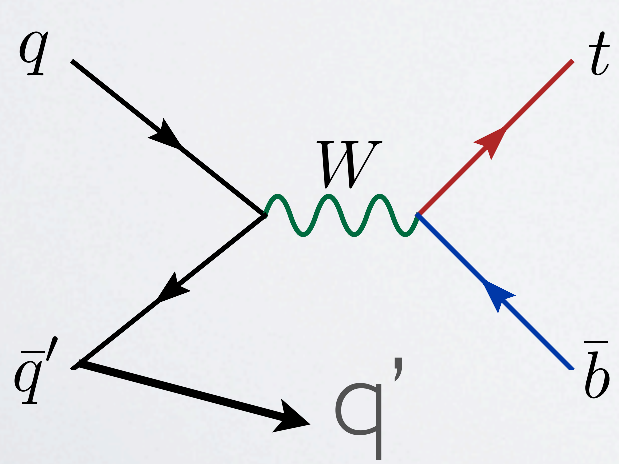
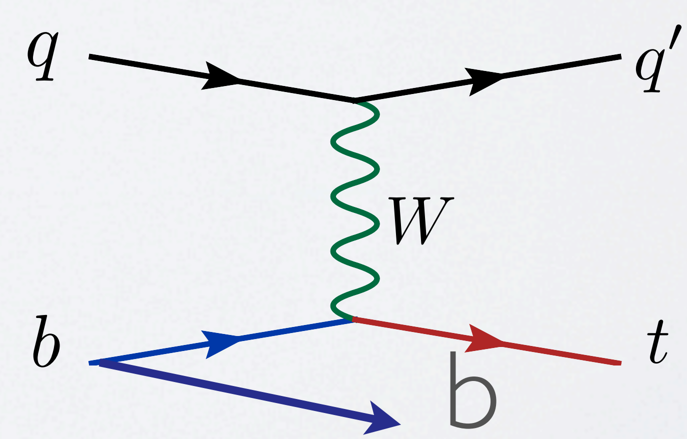
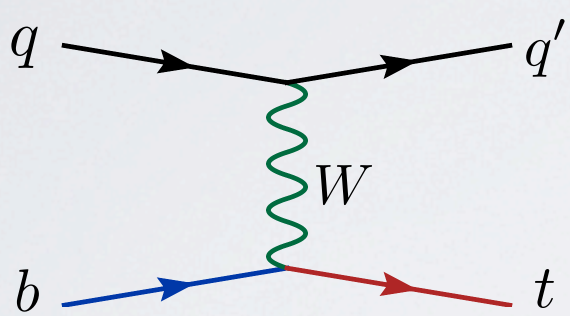


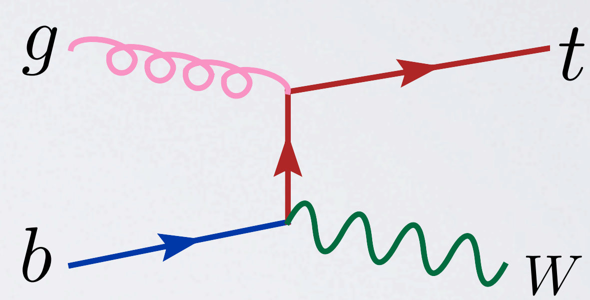


Beware:
no s-t interference
at NLO (5F)!
It starts at NNLO...

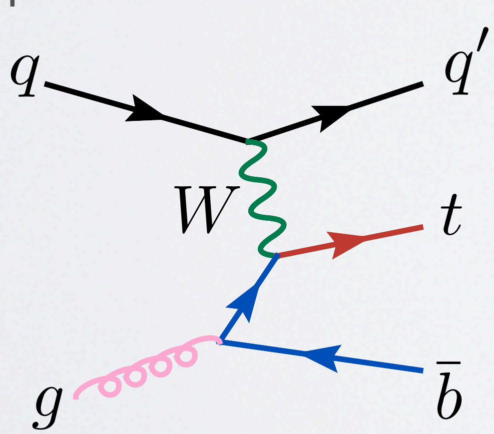
FLAVOR SCHEMES

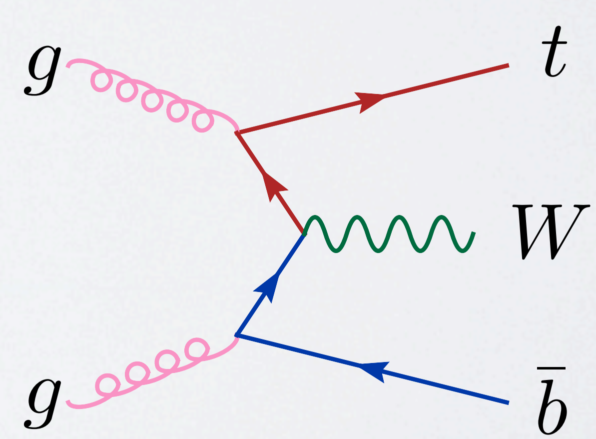
- Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state





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





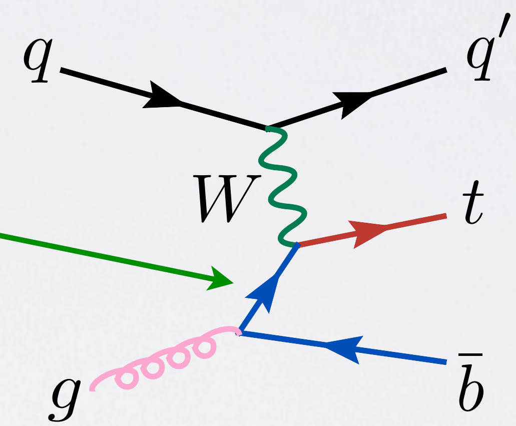
* At all orders. At fixed order differences arise...

FLAVOR SCHEMES

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

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

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



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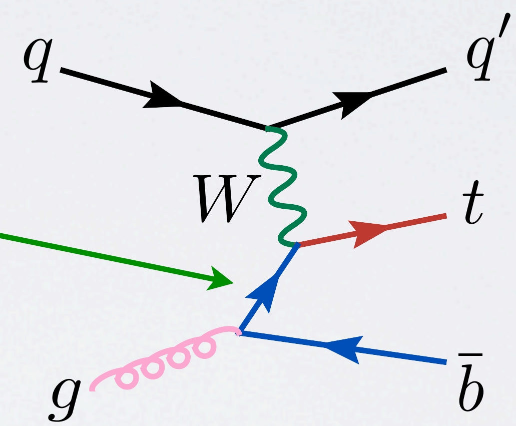
$$\frac{1}{t-m_b^2} \sim \frac{1}{p_T^2+m_b^2}$$

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



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

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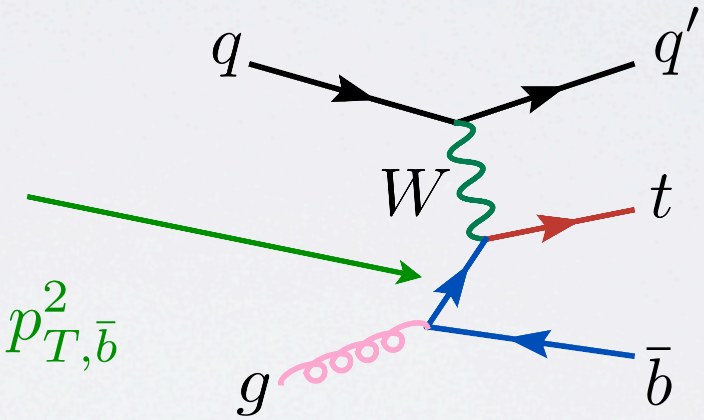

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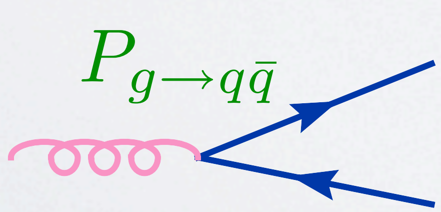
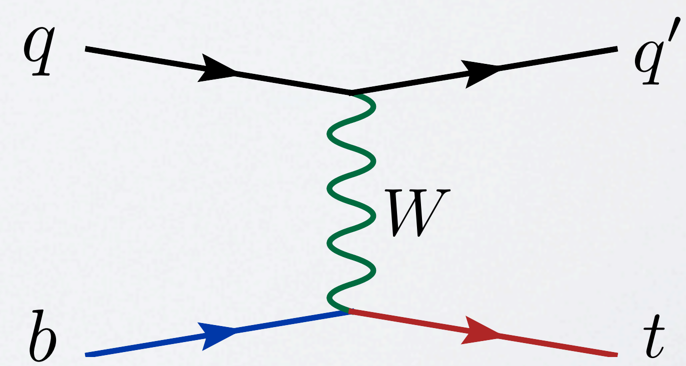
AP splitting function



time



matrix elements with splitting removed

FLAVOR SCHEMES

- 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

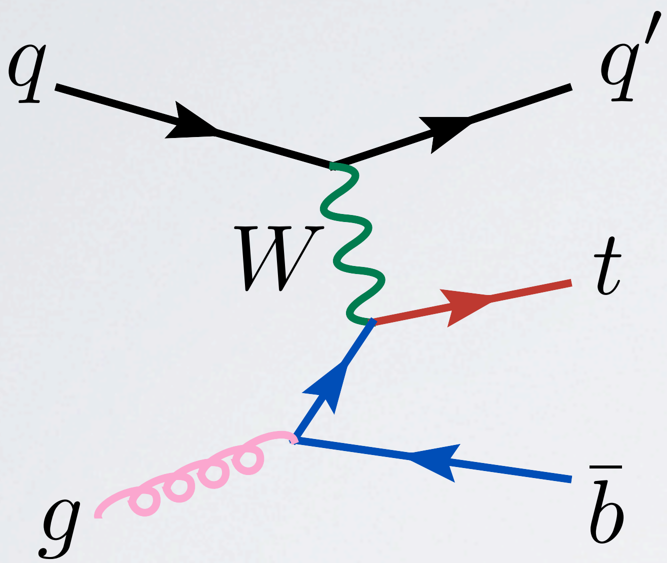
$$\sigma(qg \to q' t\bar{b}) \approx \sigma(qb \to q't)$$

- 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

FLAVOR SCHEMES

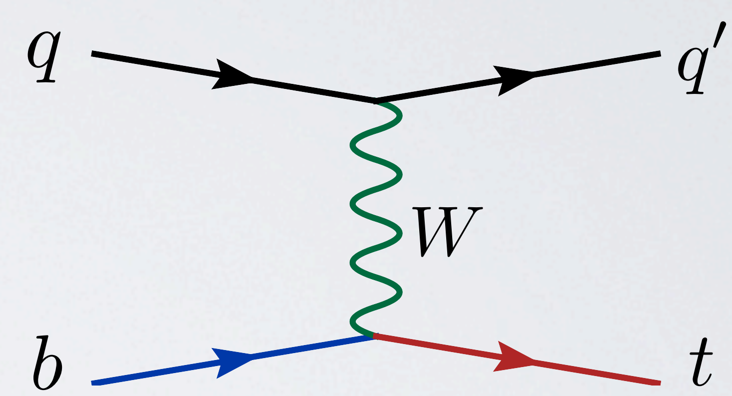
Two different ways of computing the same quantities:

4F



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.

5F



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.

THEORY STATUS 2011 CIRCA

THEORY STATUS 2011 CIRCA

Single top	s-channel	t-channel		Wt	
		2→2	2→3	2→2	2→3

THEORY STATUS 2011 CIRCA

Single top	s-channel	t-channel 2→2	t-channel 2→3	Wt 2→2	Wt 2→3
NLO total	Smith & WIllenbrock	Bordes et al. Stelzer et al.	-	-	-

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NLO total	Smith & WIllenbrock	Bordes et al. Stelzer et al.	-	-	-
NLO diff.	Harris et al., Sullivan et al.	Harris et al., Sullivan et al.	Campbell et al.	Campbell et al.	-

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NLO w/ decays	Campbell et al. Swchwienhorst et al. Falgari et al.	Campbell et al. Swchwienhorst et al. Falgari et al.	Campbell et al.	Campbell et al.	X (Denner et al.; Bevilacqua et al.)

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Higher orders	NNLO : [Chetyrkin, Steinhauser] NNLL [Kidonakis]	NNLL [Kidonakis]	X	X	X

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Higher orders	NNLO : [Chetyrkin, Steinhauser] NNLL [Kidonakis]	NNLL [Kidonakis]	X	X	X
NLOwPS	MC@NLO POWHEG [Frixione et al., Aioli et al.]	MC@NLO POWHEG [Frixione et al., Aioli et al.]	aMC@NLO [Frederix et al.]	MC@NLO POWHEG [Frixione et al., Re]	X

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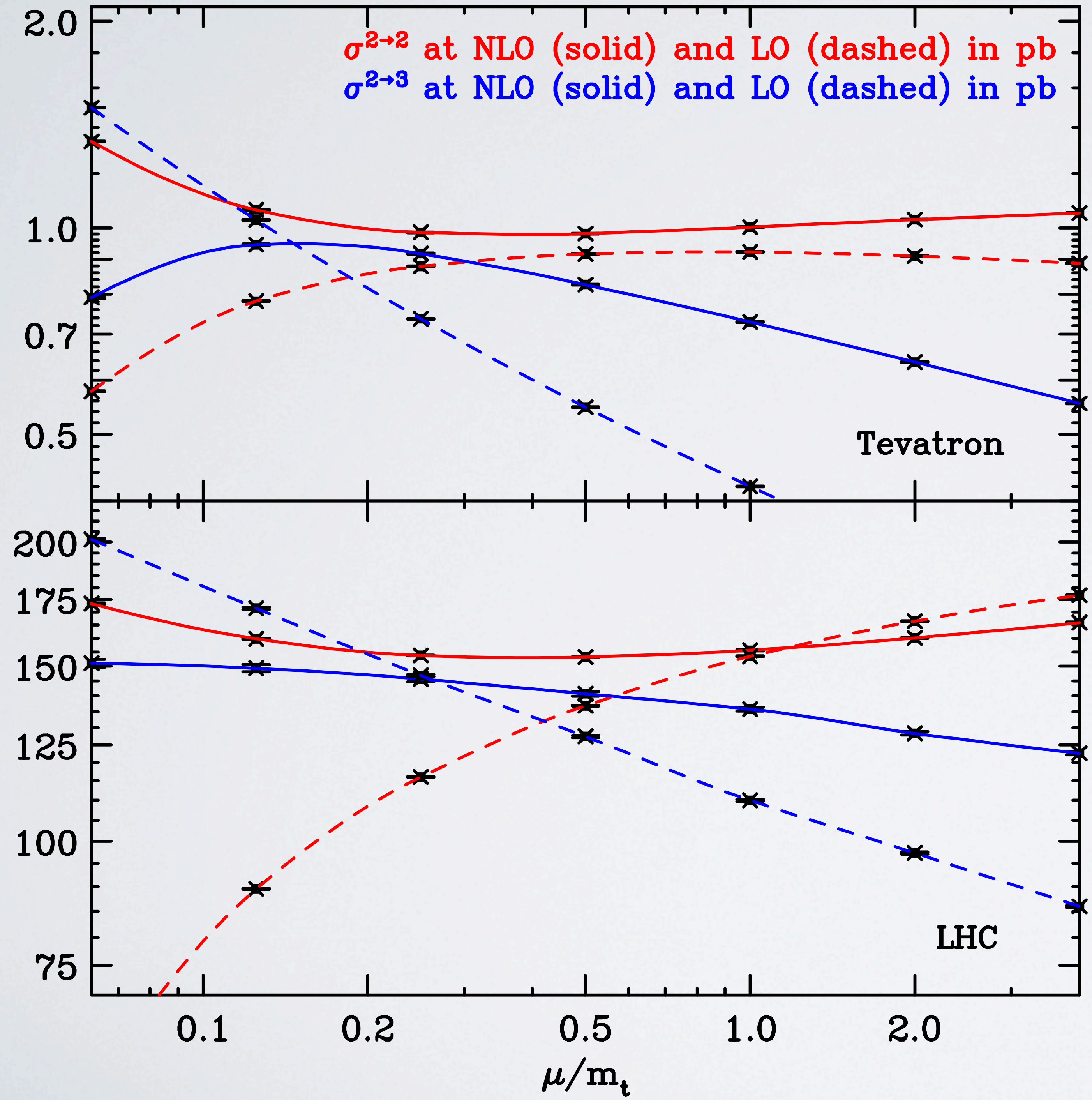
EWNLO	X	Beccaria, Renard, Mirabella, Verzegnazzi, Macorini et al.	X	Beccaria, Renard, Mirabella, Verzegnazzi, Macorini et al.	X

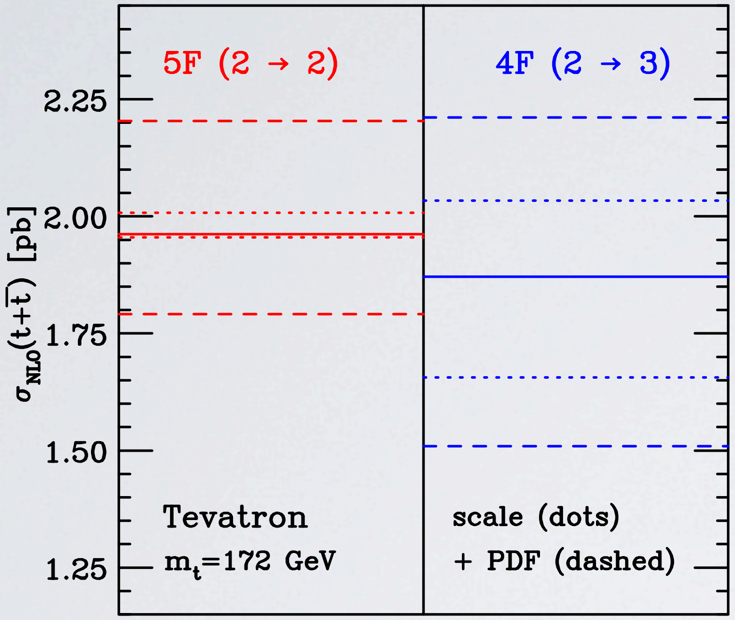
SCALE DEPENDENCE: 2→2 VS 2→3

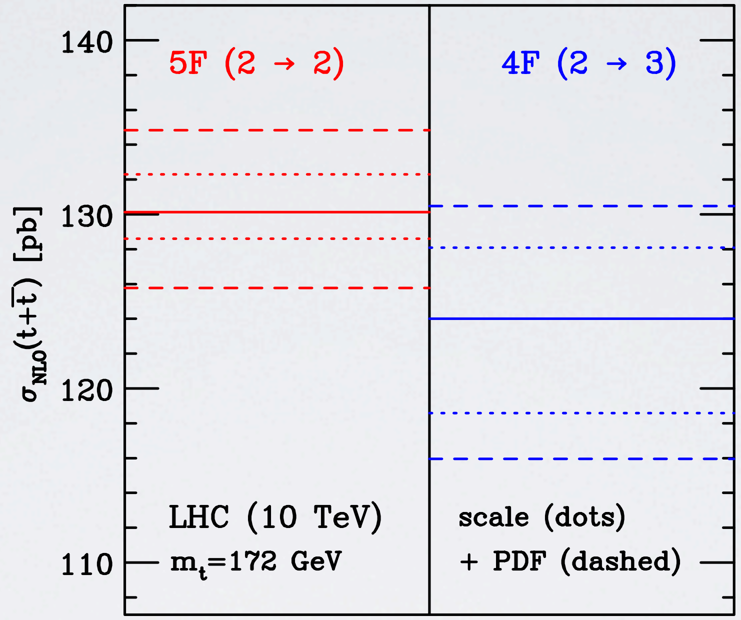


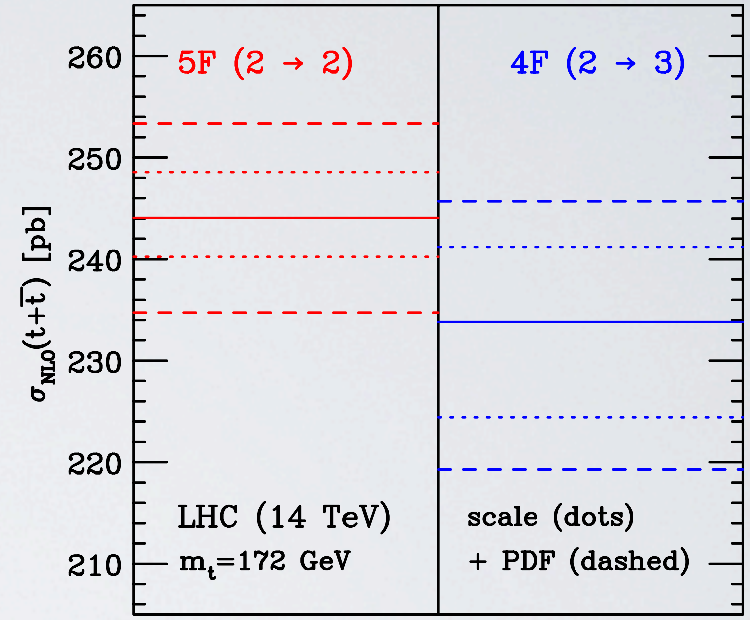
- Both schemes much improved from LO
- 5F (2 → 2) only mildly sensitive to scales at NLO (use m_t in what follows)
- 4F (2 → 3) expected to be worse, but isn't much
- Hardly a region of overlap between the two
- 4F (2 → 3) prefers smaller scales than m_t, particularly at the Tevatron

T-CHANNEL BEST CROSS SECTIONS : 2→2 VS 2→3

[Campbell, Frederix, FM, Tramontano, 0907.3933]







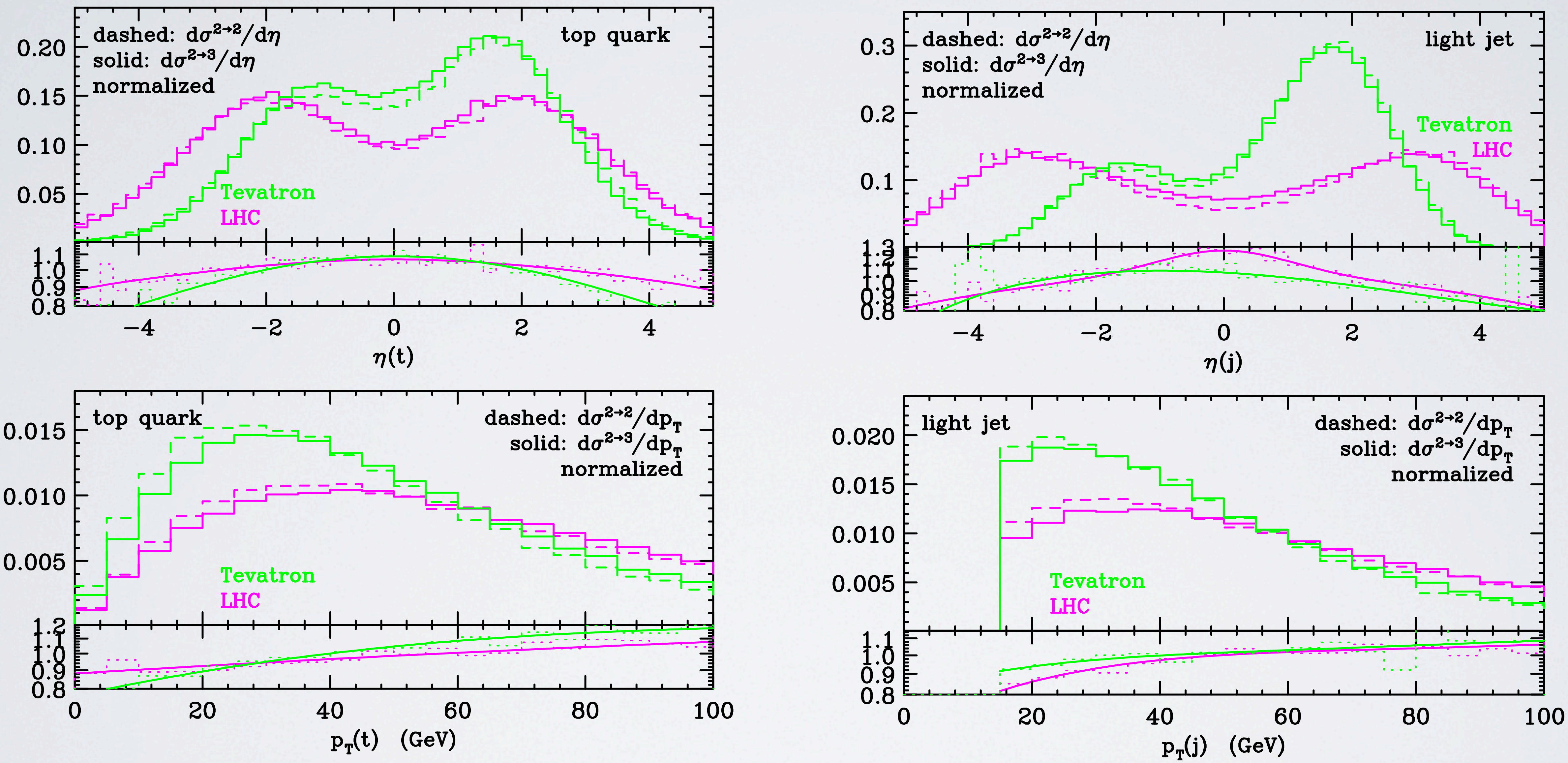
$\sigma^{NLO}_{t-ch}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (10 TeV)	130	$^{+2}_{-2}$	$^{+3}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$	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

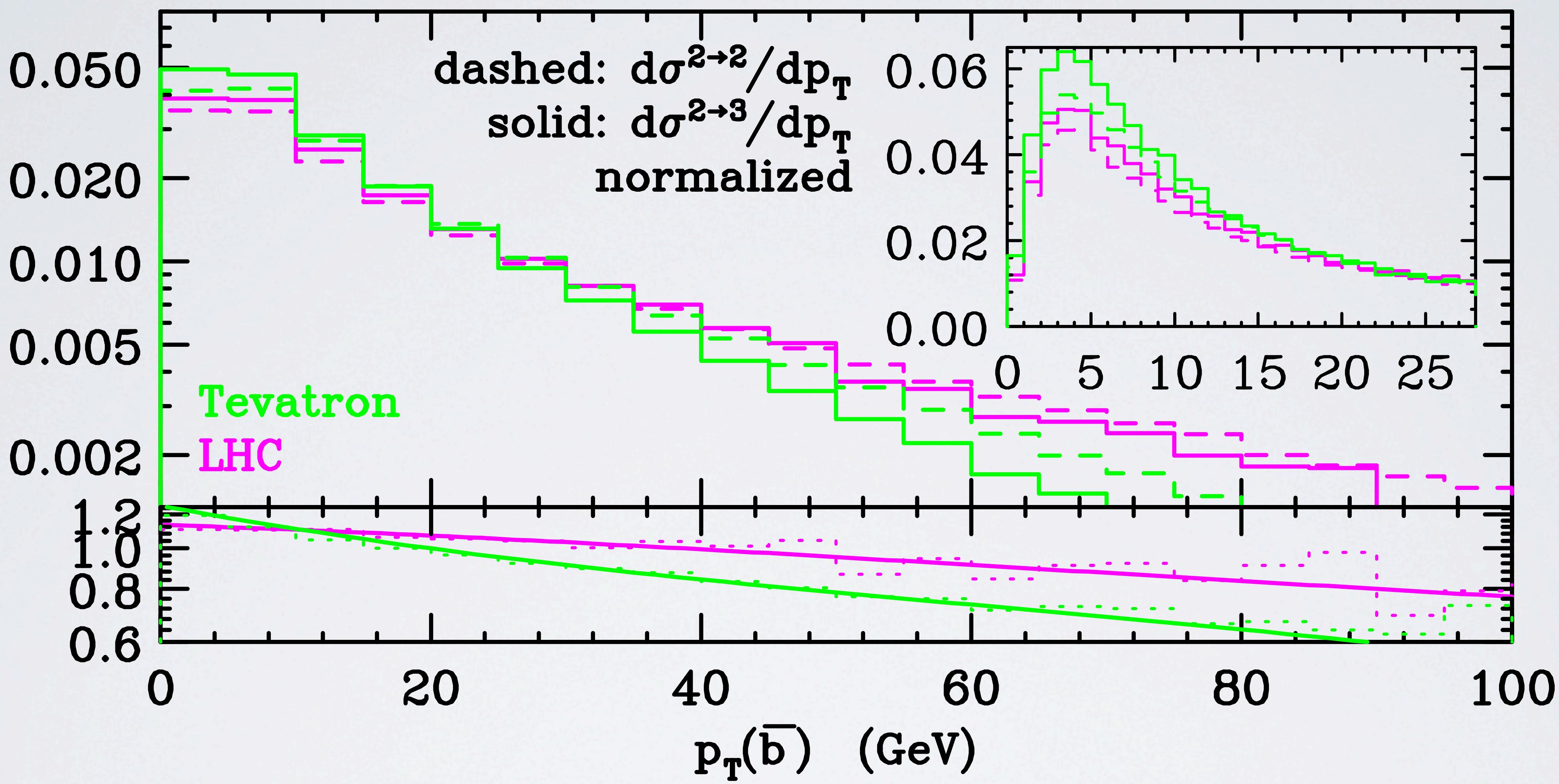
- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- b-mass uncertainties at the same level as t-mass ones [Overseen in previous studies].
- Consistent at the Tevatron: logarithms not so important?
- For the LHC, the minor difference could point to either:
  - large logarithms being resummed
  - b-pdf's might not be accurate...
  - Higher order corrections (NNLO for 2→2) important...

TOP AND LIGHT JET DISTRIBUTIONS



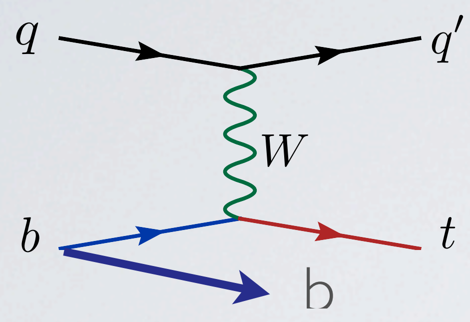
Some differences, but typically of the order of ~10% in the regions where the cross section is large

SPECTATOR B



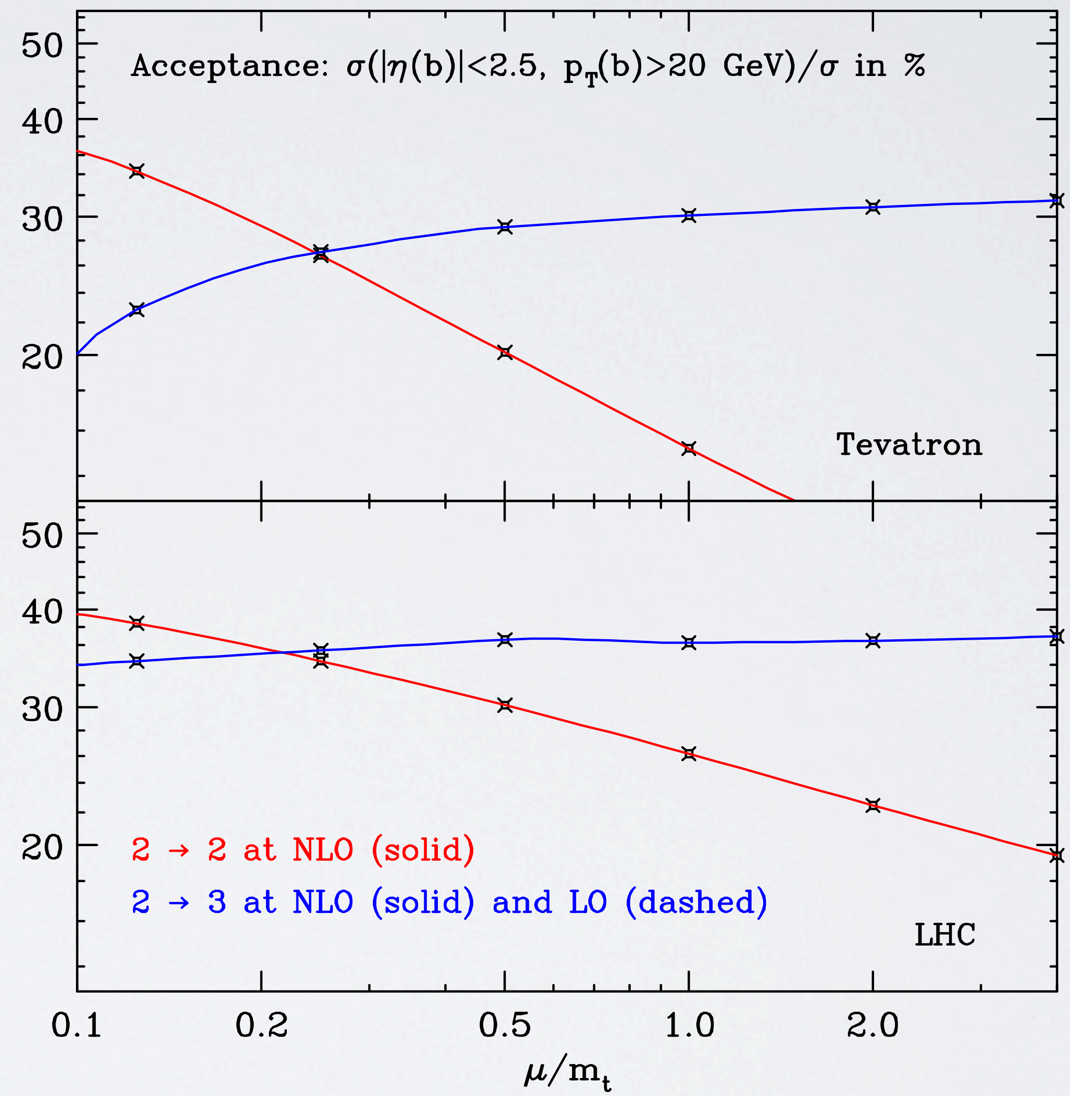
- First NLO prediction for this observable
- Slightly softer in 4F (2 ➞ 3), particularly at the Tevatron
- Deviations up to ~ 20% : perturbatively quite stable

EXAMPLE: ACCEPTANCE SPECTATOR B



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

- 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.



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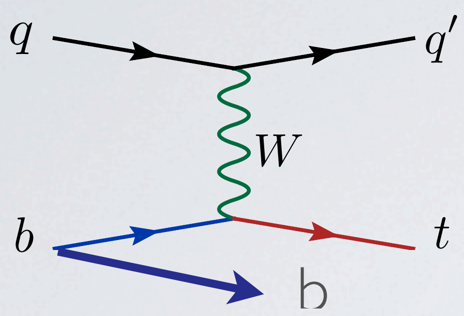
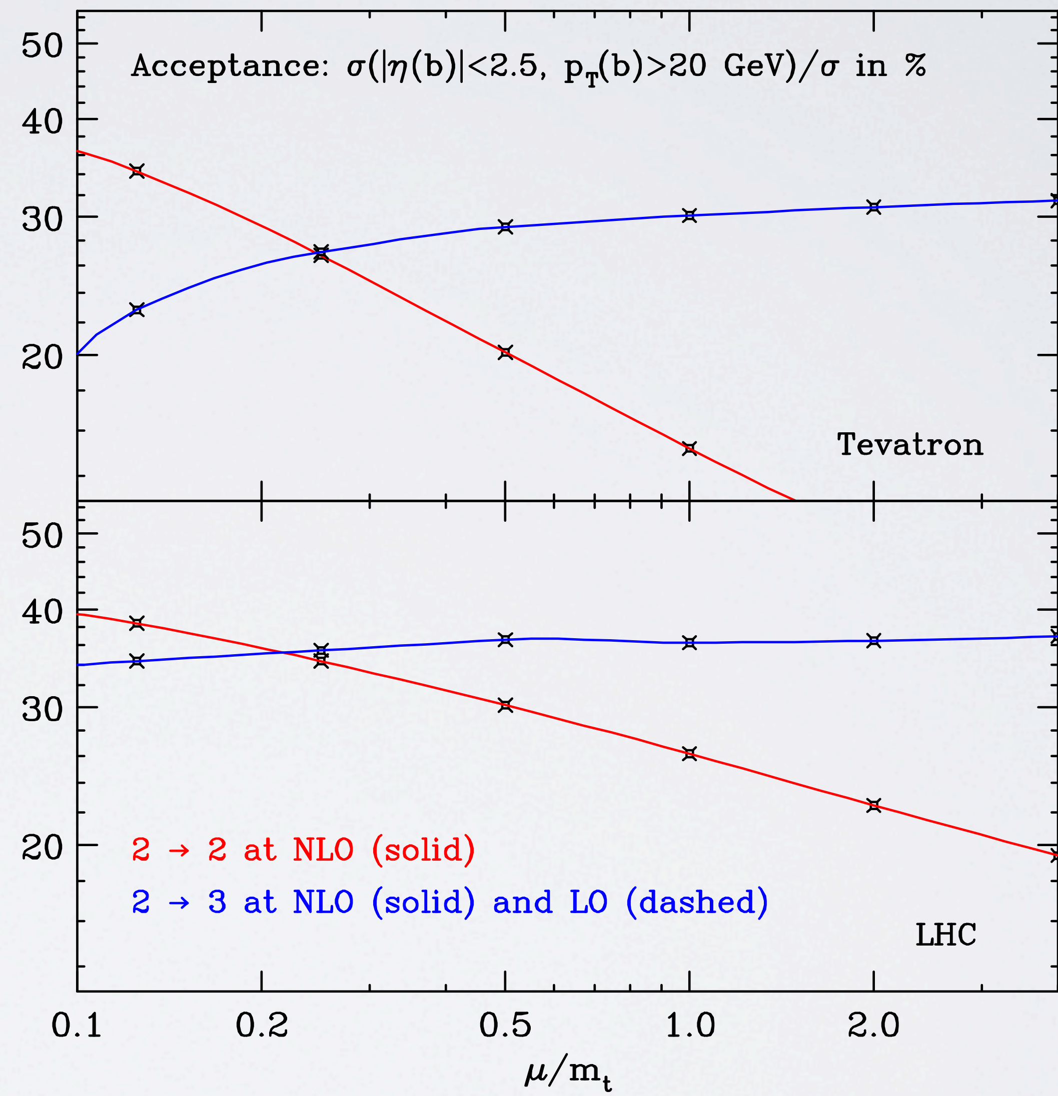


$$\frac{\sigma(|\eta(b)| < 2.5,\, p_T(b) > 20\ \mathrm{GeV})}{\sigma_{\mathrm{inclusive}}}$$



→29%→ best

→36%→ best

- Very large scale dependence for 5F (2 → 2), → effectively a LO quantity
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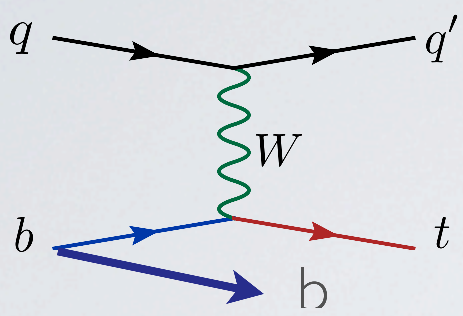

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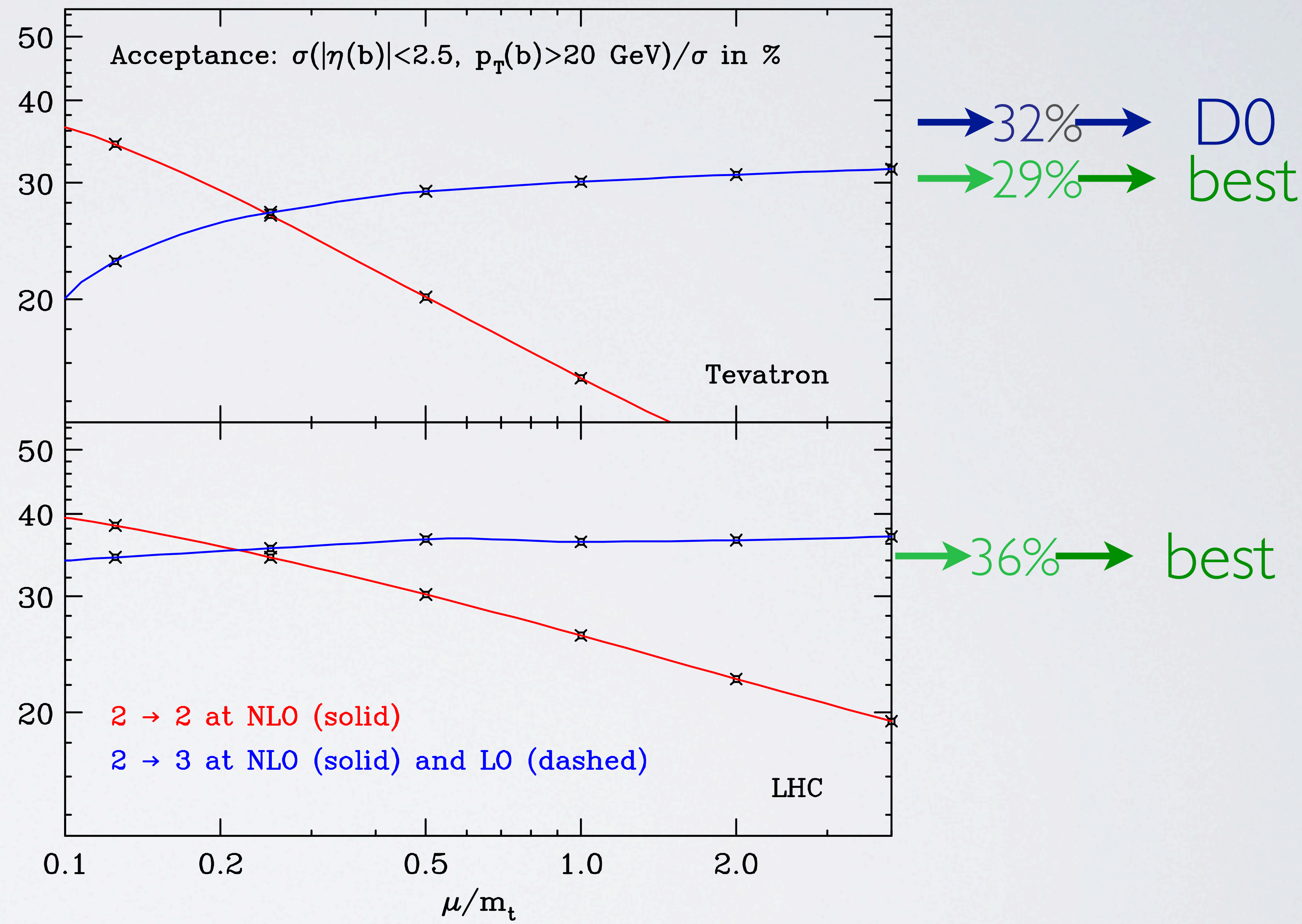

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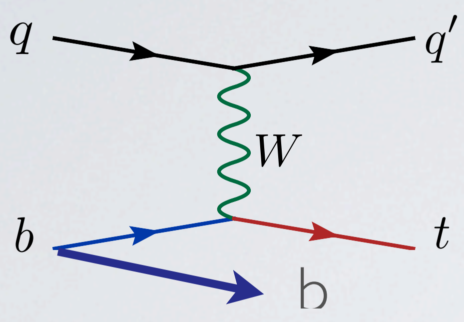

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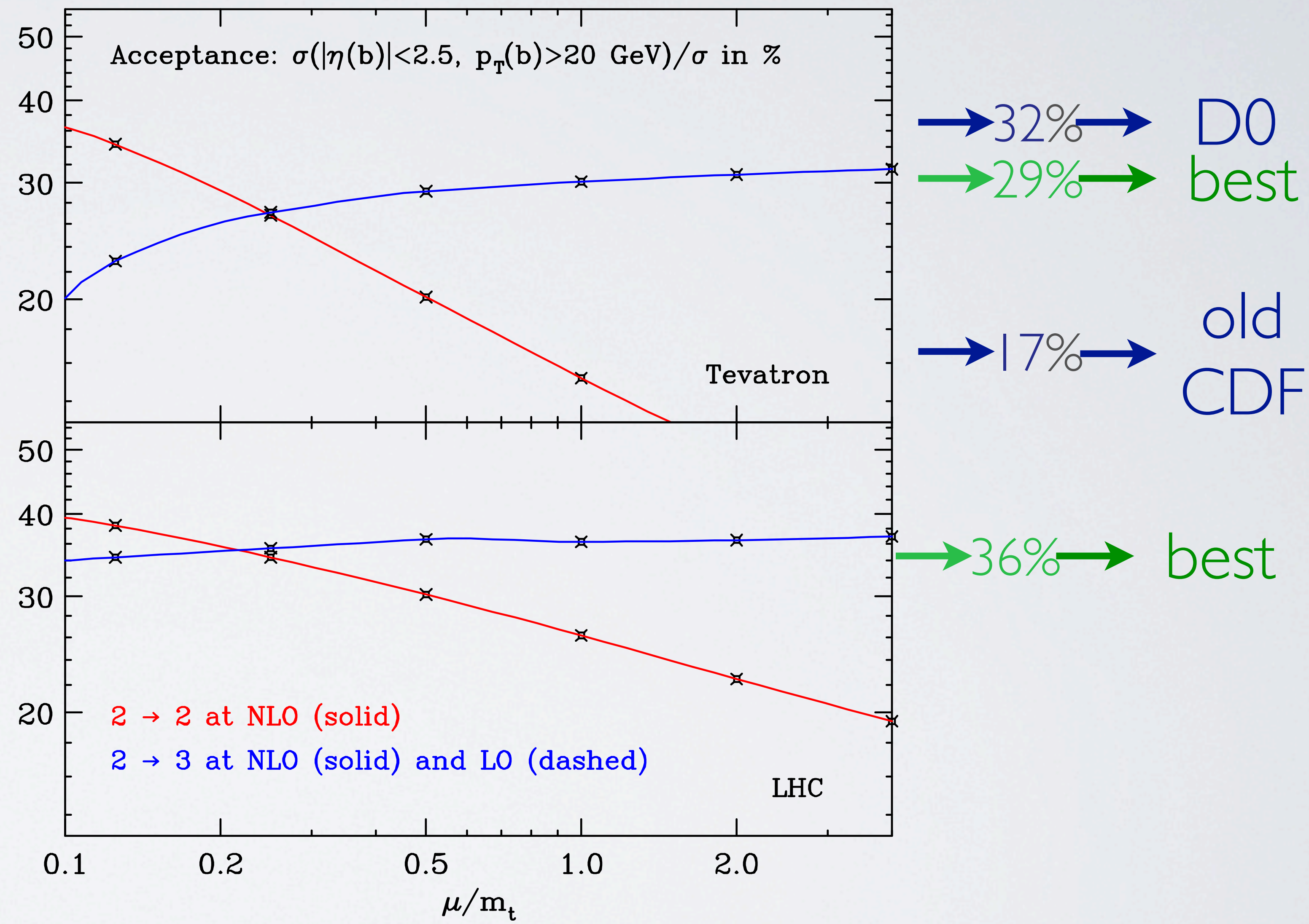

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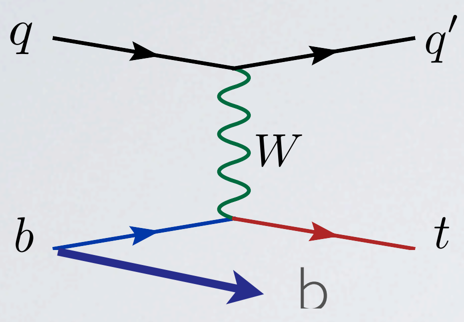

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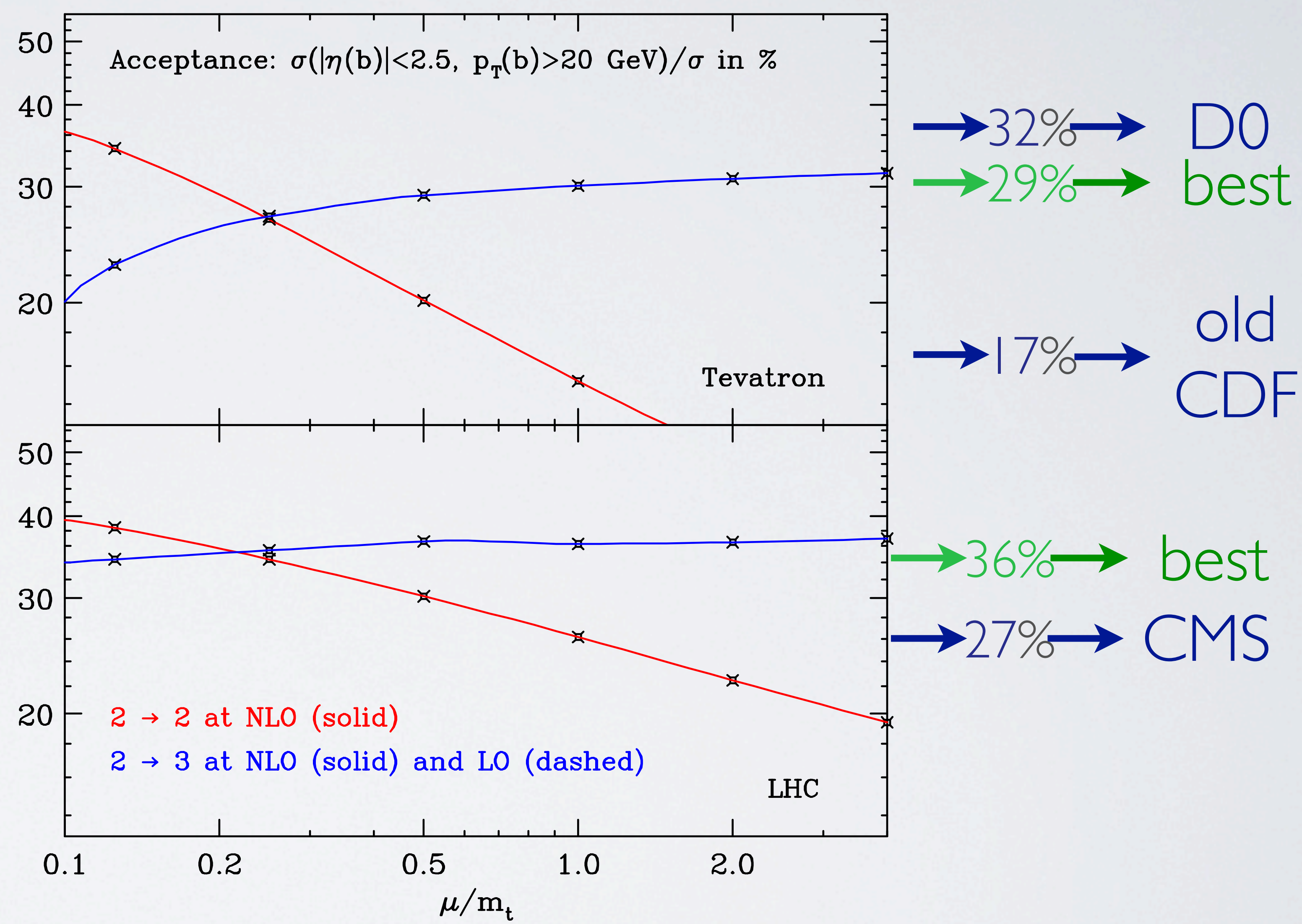
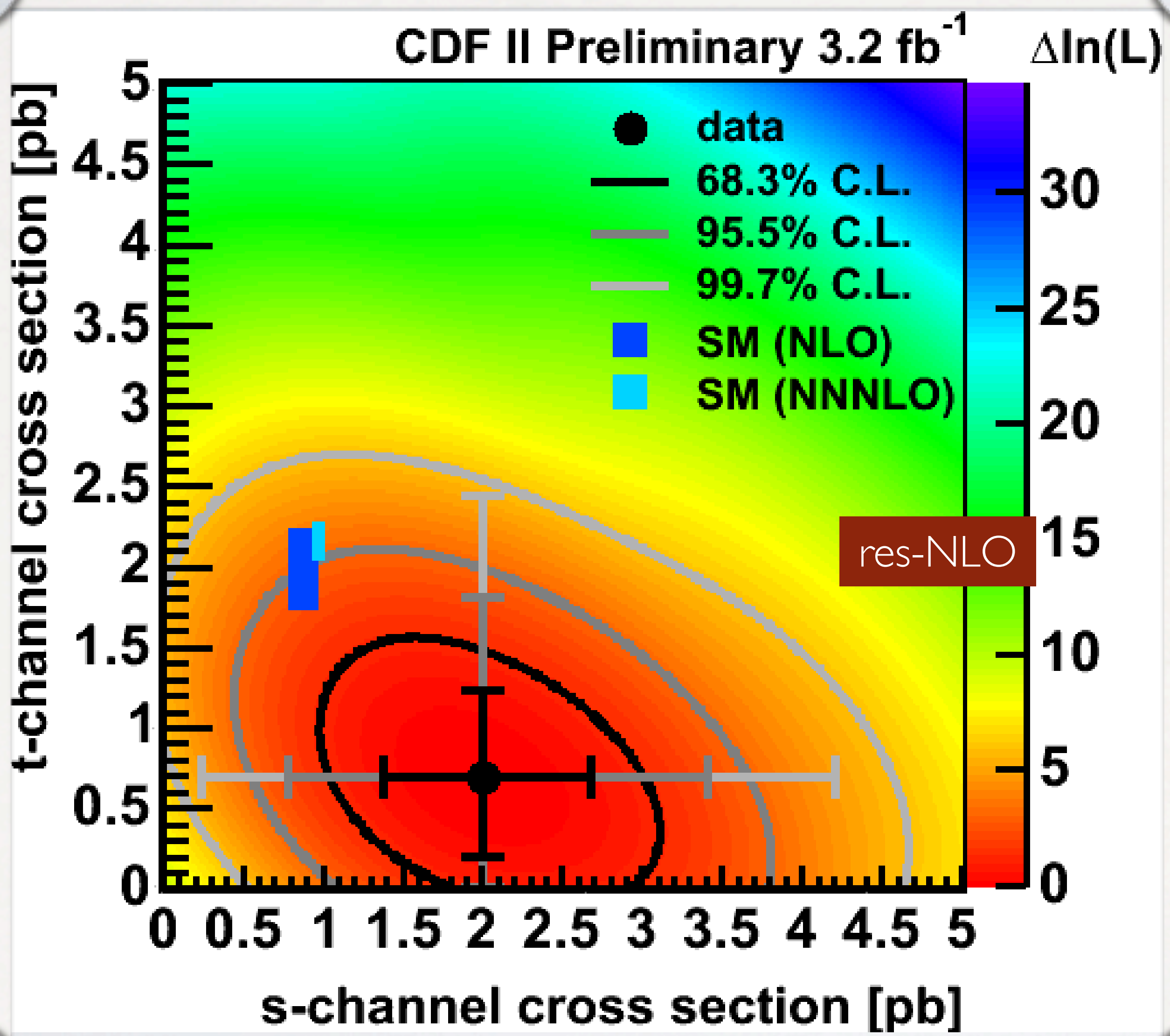
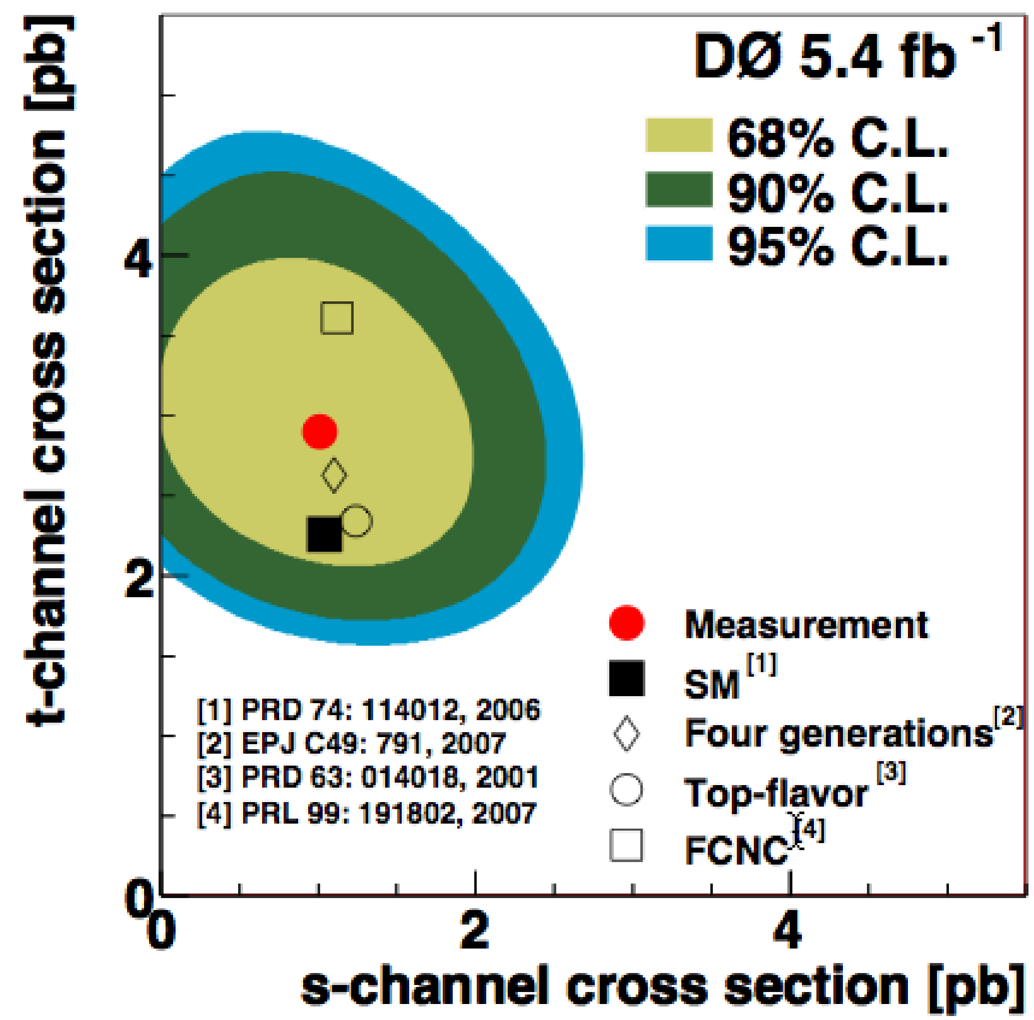
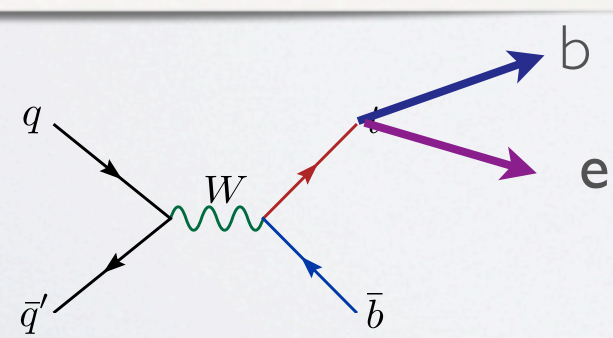
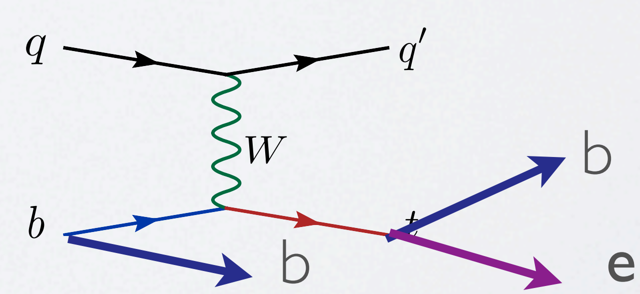


S AND T CHANNEL SEPARATION AT CDF





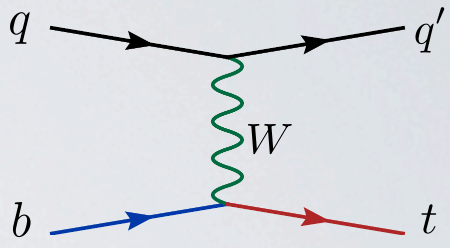




NNLO APPROX+NNLL FOR T-CHANNEL

[Kidonakis, 2010]

$$\hat{\sigma}^{res}(N) = \exp\left[\sum_{i=1,2} E(N_i)\right] \exp\left[E'(N')\right] \exp\left[\sum_{i=1,2} 2\int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu}\, \gamma_{q/q}\left(\tilde{N}_i, \alpha_s(\mu)\right)\right]$$
$$\times \mathrm{Tr}\left\{H\left(\alpha_s(\sqrt{s})\right) \exp\left[\int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}'} \frac{d\mu}{\mu}\, \Gamma_S^\dagger\left(\alpha_s(\mu)\right)\right]\right.$$
$$\left.\times S\left(\alpha_s(\sqrt{s}/\tilde{N}')\right) \exp\left[\int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}'} \frac{d\mu}{\mu}\, \Gamma_S\left(\alpha_s(\mu)\right)\right]\right\}.$$



$$\sigma_{\mathrm{t-ch}}^{\mathrm{top}}(m_t = 173\,\mathrm{GeV}, \sqrt{S} = 7\,\mathrm{TeV}) = 41.7^{+1.6}_{-0.2} \pm 0.8\ \mathrm{pb}$$

$$\sigma_{\mathrm{t-ch}}^{\mathrm{antitop}}(m_t = 173\,\mathrm{GeV}, \sqrt{S} = 7\,\mathrm{TeV}) = 22.5 \pm 0.5^{+0.7}_{-0.9}\ \mathrm{pb}$$

$$\sigma_{\mathrm{t-ch}}^{\mathrm{top}}(m_t = 173\,\mathrm{GeV}, \sqrt{S} = 14\,\mathrm{TeV}) = 151^{+4}_{-1} \pm 3\ \mathrm{pb}$$

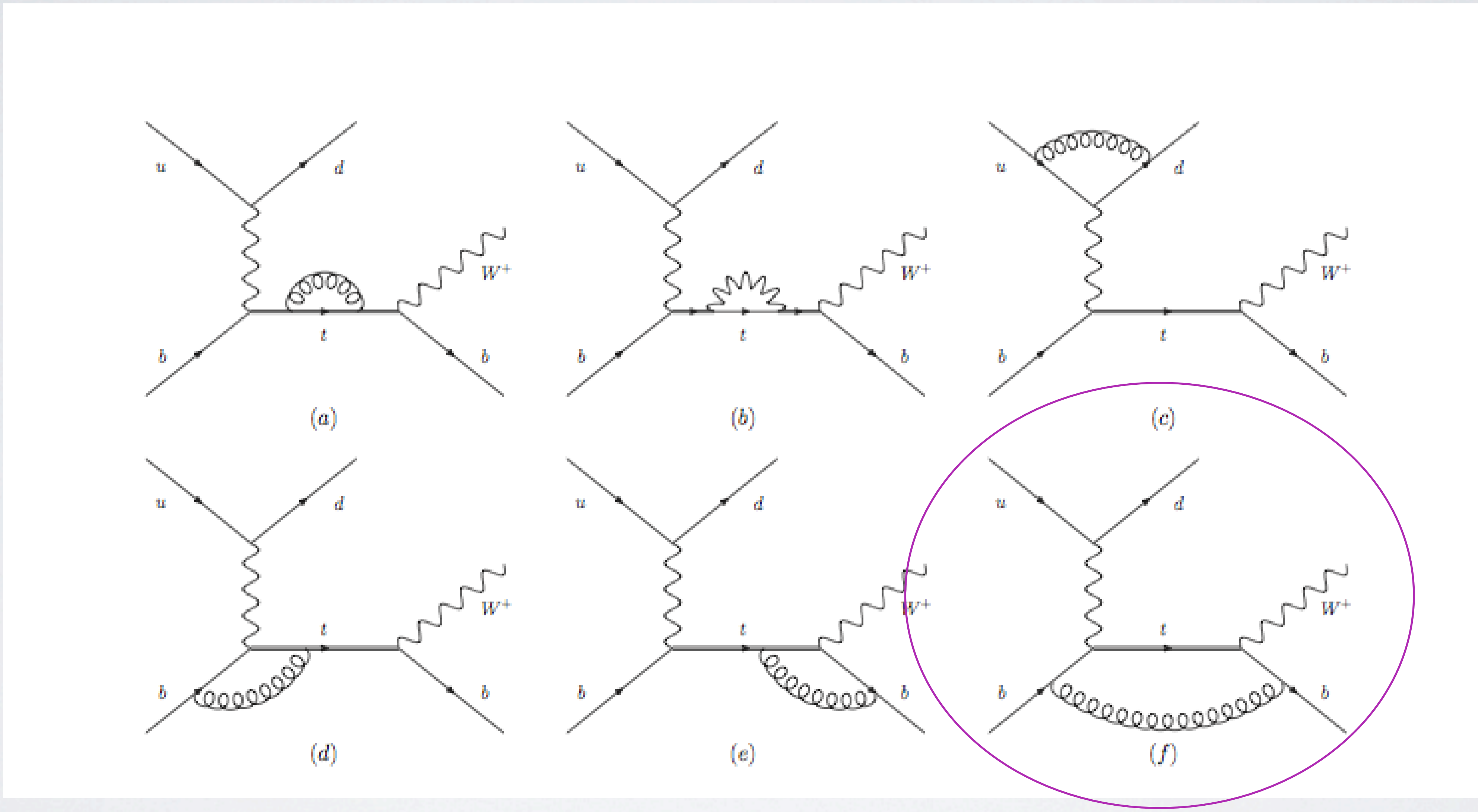
$$\sigma_{\mathrm{t-ch}}^{\mathrm{antitop}}(m_t = 173\,\mathrm{GeV}, \sqrt{S} = 14\,\mathrm{TeV}) = 92^{+2+2}_{-1-3}\ \mathrm{pb}$$

Extremely stable results : quite small differences wrt NLO

Other effects might be more important than pure NNLO QCD!!!

SINGLE TOP BEYOND THE NW APPROX.

[Falgari, Merrol, Signer, 2010]



Non-factorizable term is included keeping a finite width and making a gauge invariant expansion.

SINGLE TOP BEYOND THE NW APPROX.

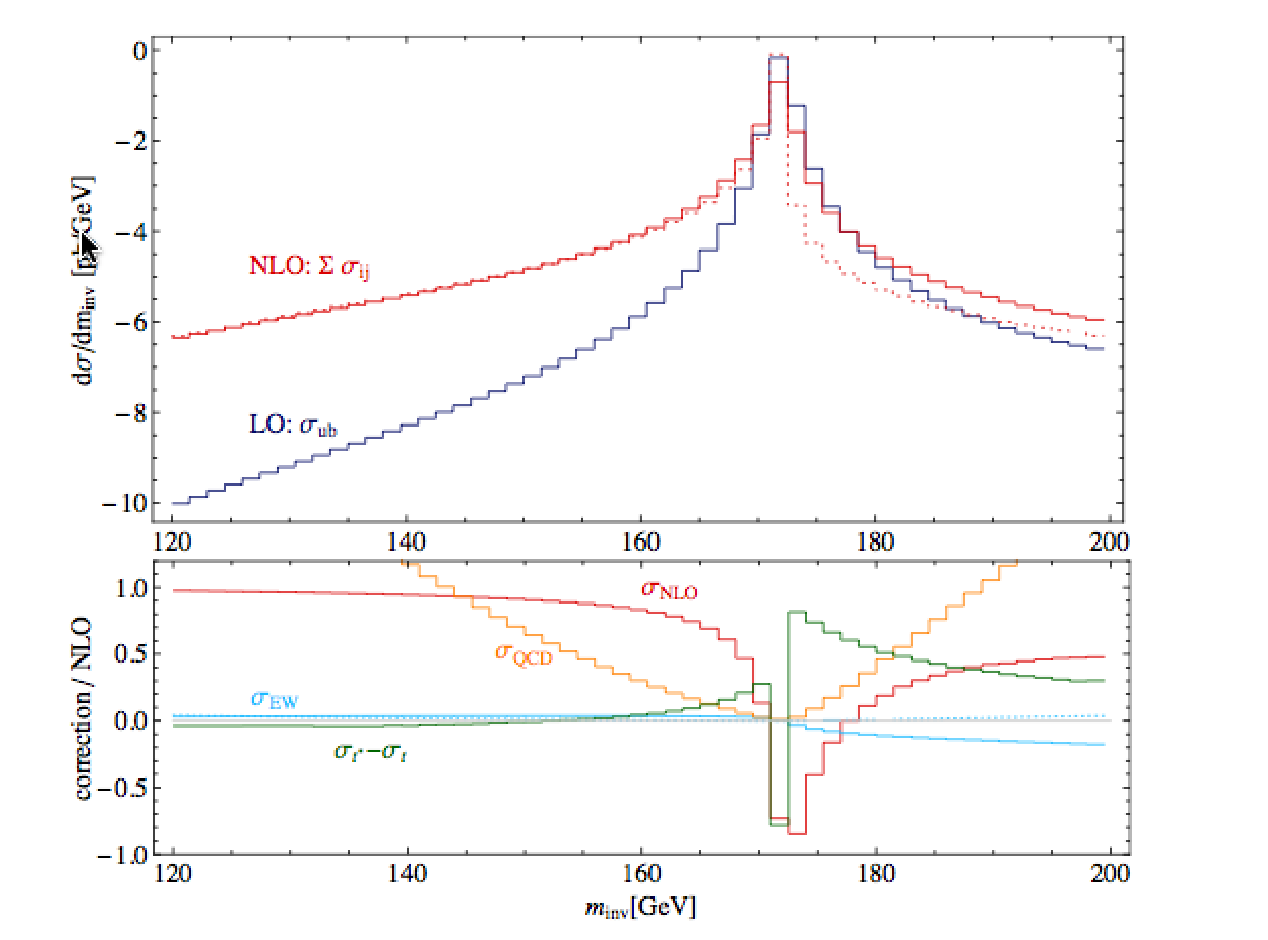
[Falgari, Merrol, Signer, 2010]

	Ref. [26]	$\sigma^{\rm prod}$	σ^{t}	σ^{t^*}
LO (pb)	76.6	76.62(1)	76.62(1)	77.36(5)
NLO (pb)	84.4	84.41(1)	84.91(2)	86.3(3)

LHC10

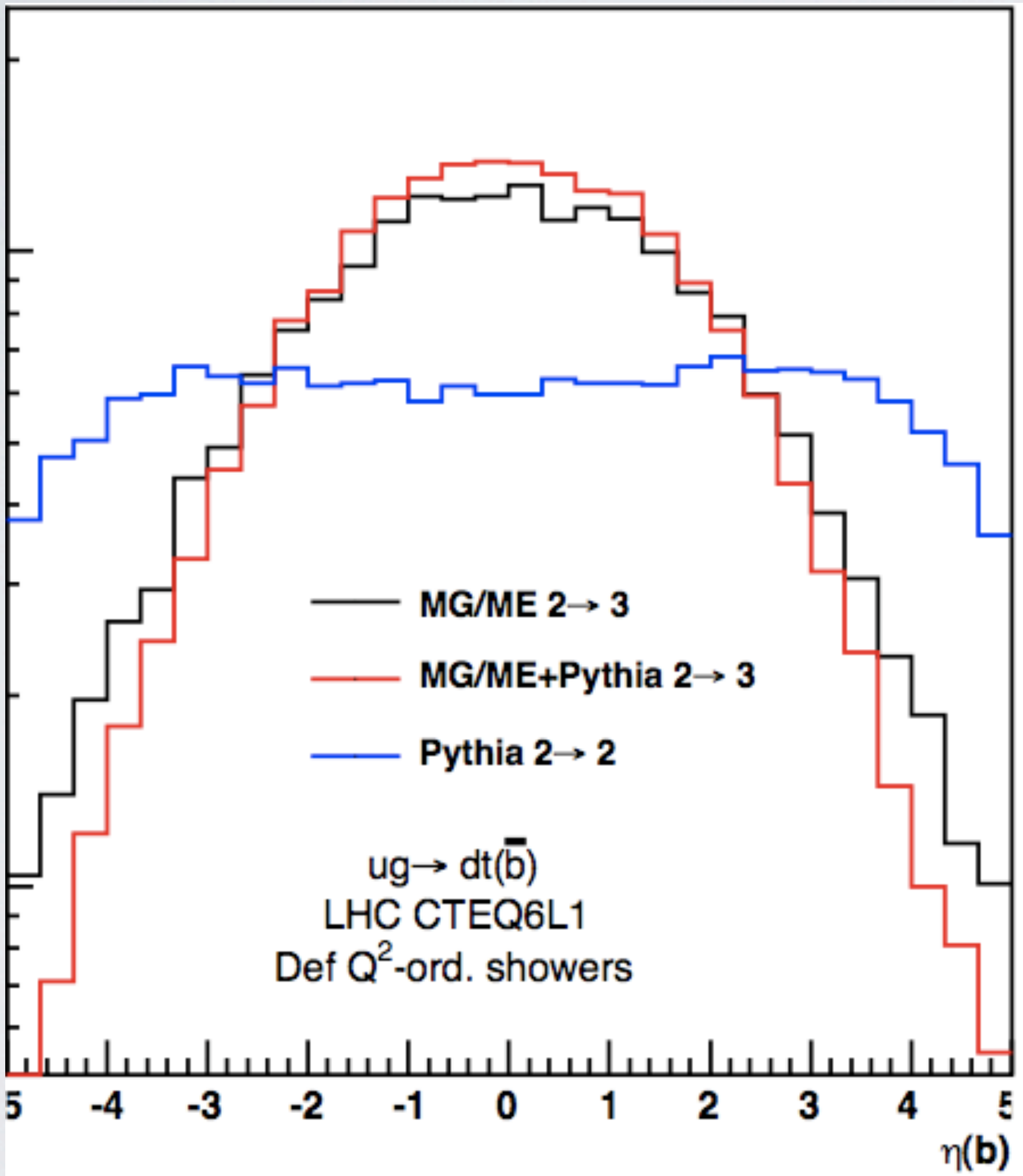
NLO effects on total cross sections are quite small, but differences arise in the shapes.

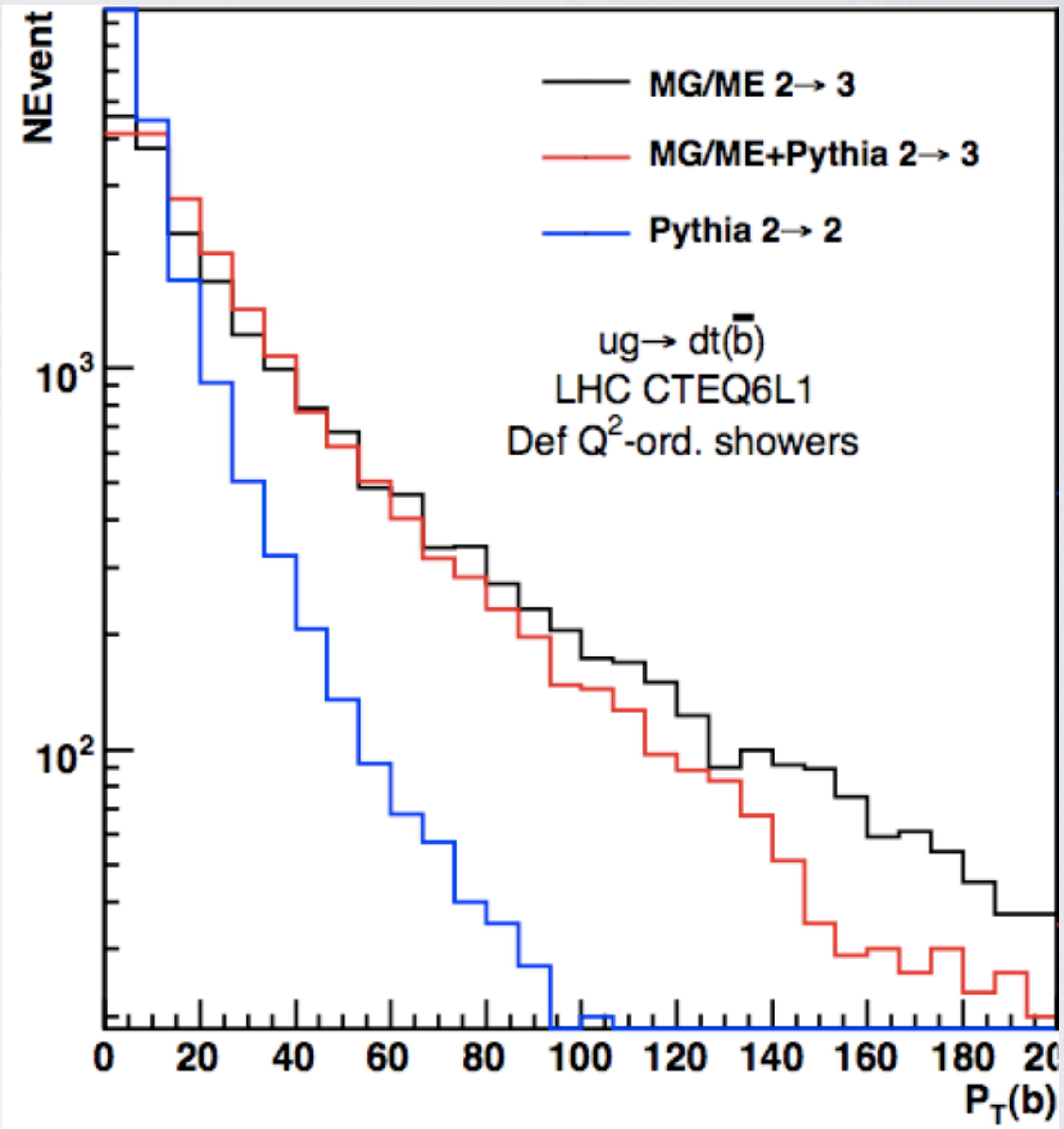
For example in the m_{inv} in the resonant and on-shell case (dash).



NLO SINGLE TOP IN MC'S

ME+PS COMPARISON AT LHC



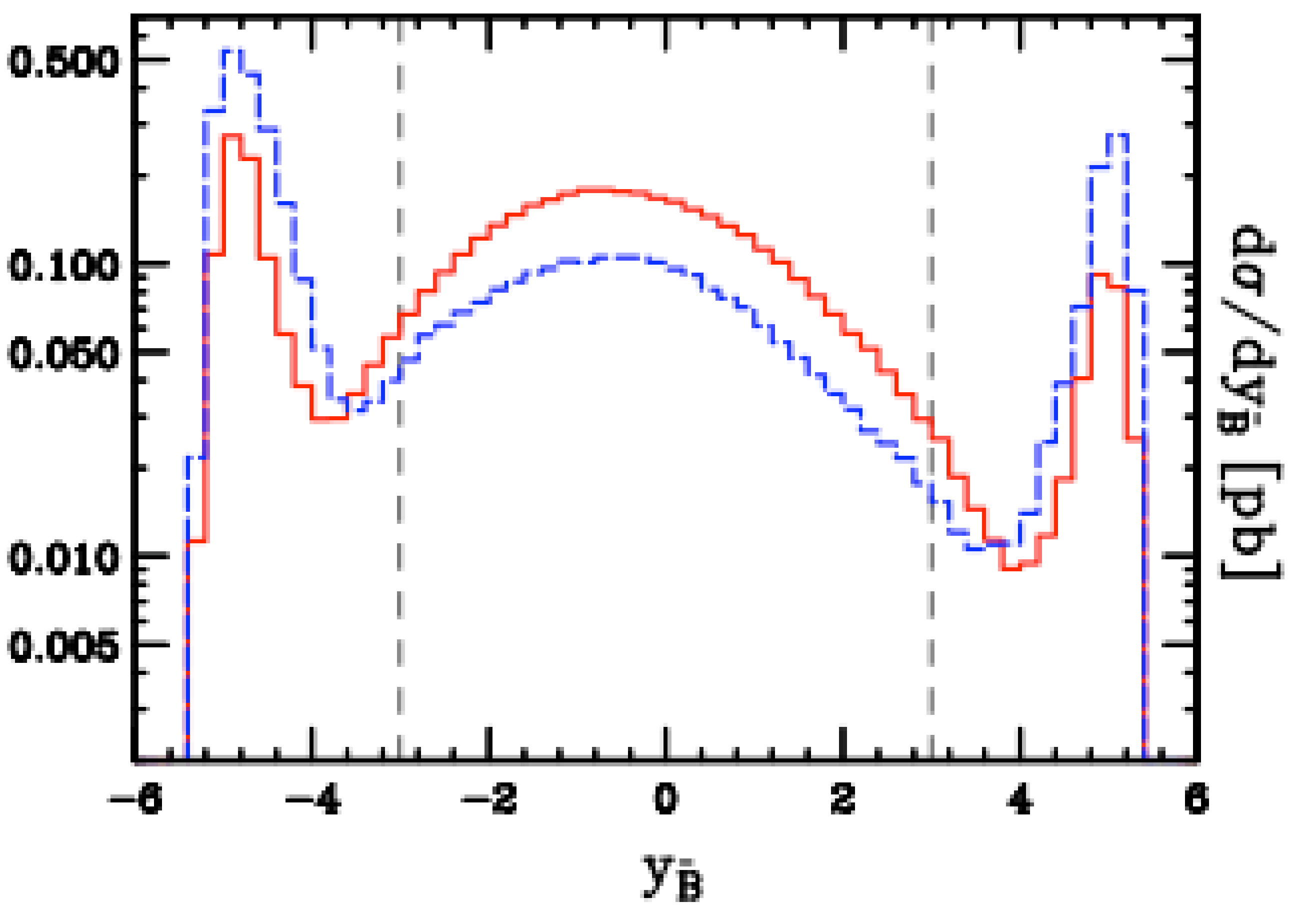


pT and η spectra of the spectator HQ from the 2→3 prediction are accurate and do not need any dangerous matching...

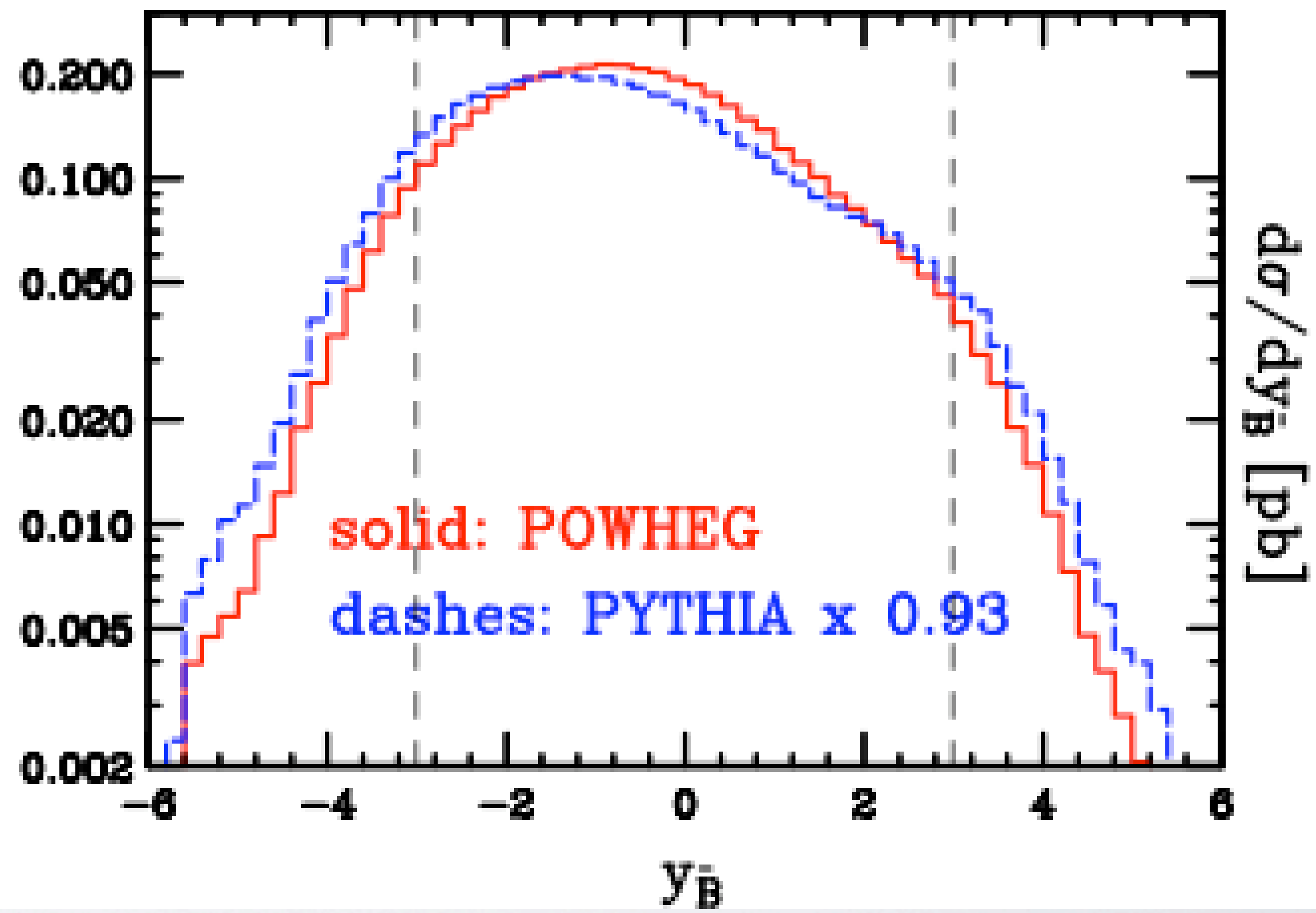
NLO MC at the Tevatron

[Aioli,Nason,Oleari,Re : 0907.4076]

NLOwPS : POWHEG



NLO(2→2) +HERWIG

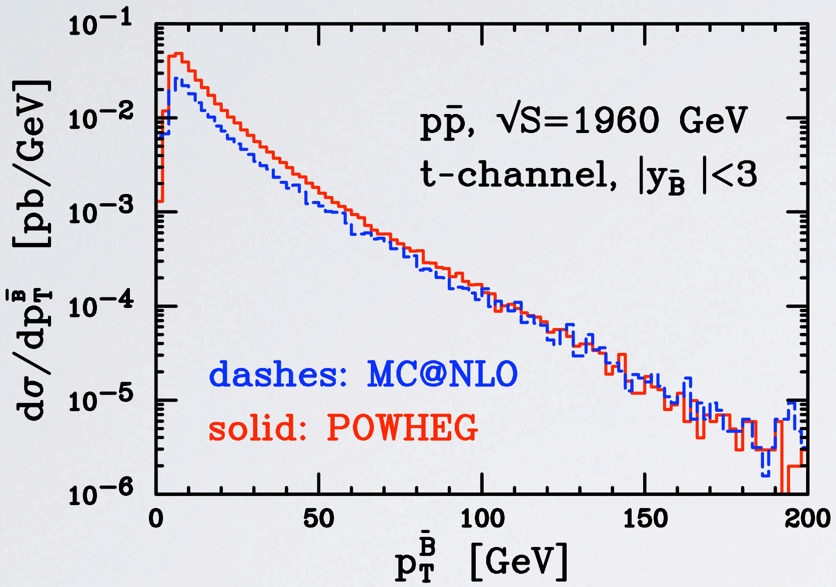


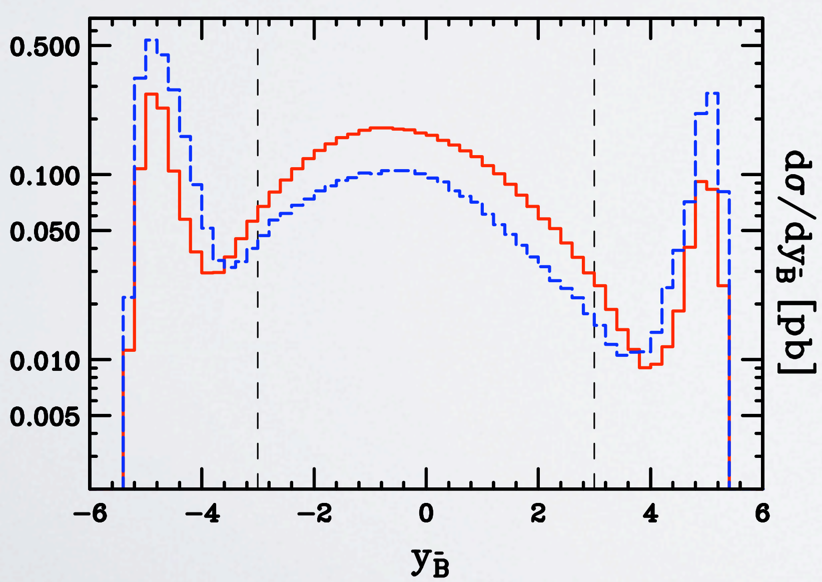
NLO (2→2) +Pythia

Shower for initial states HQ not correct in fortran HERWIG.

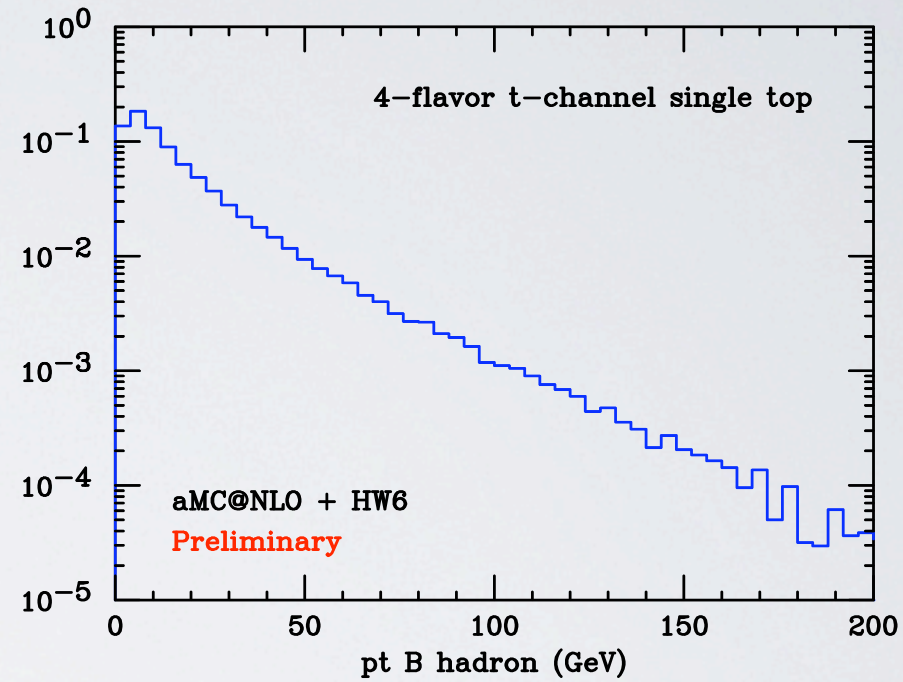
NLO 4 FLAVOR IN AMC@NLO

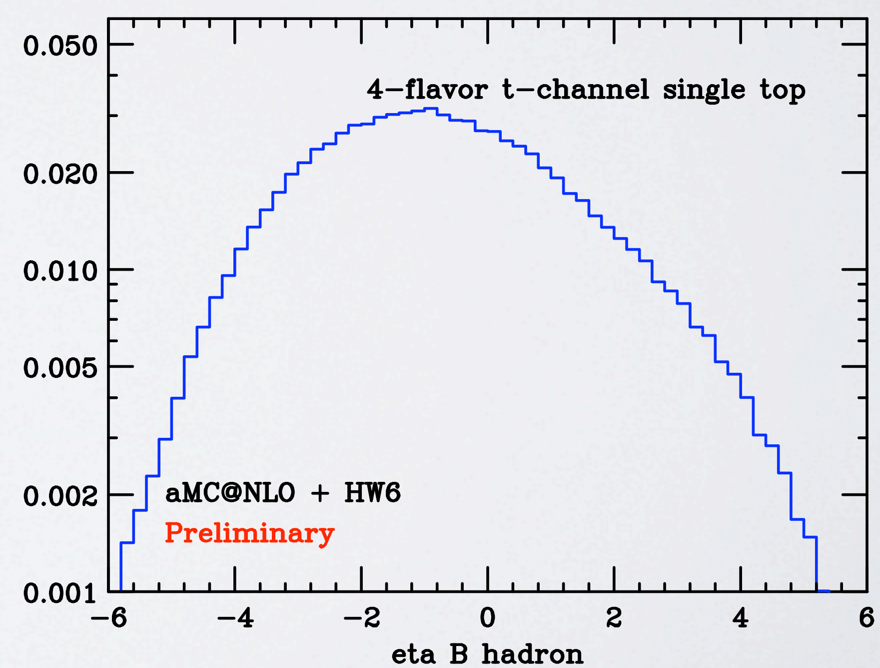
5-flavor scheme



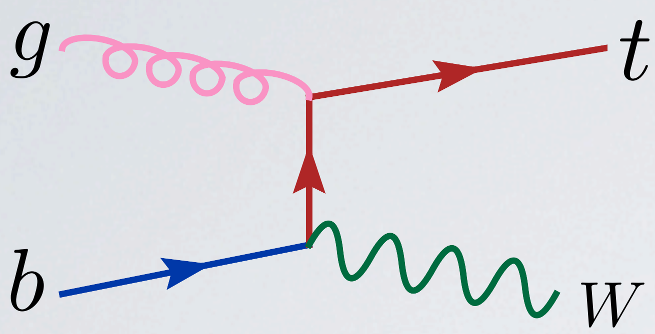


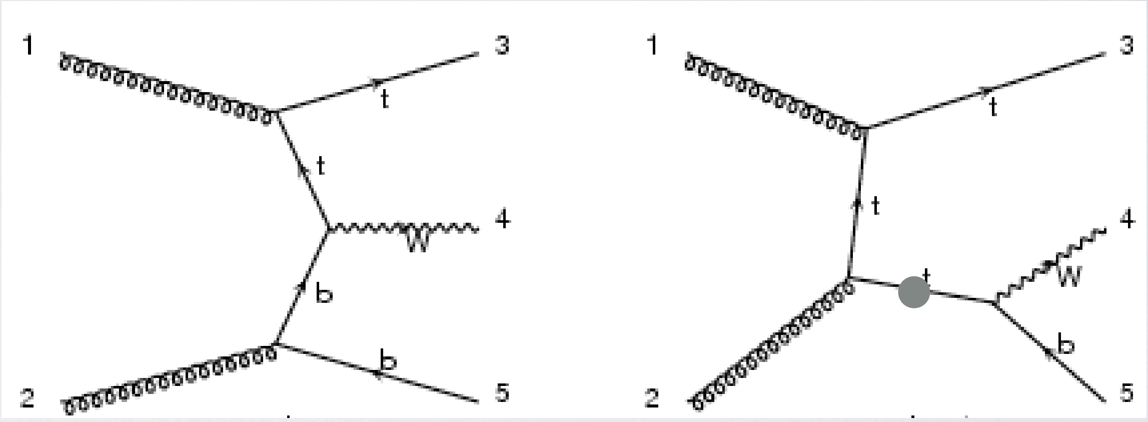
4-flavor scheme





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.

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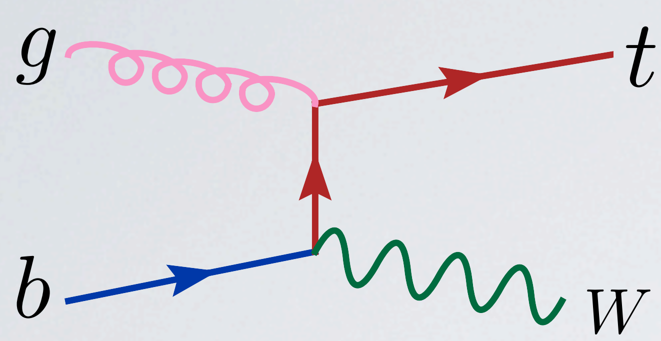

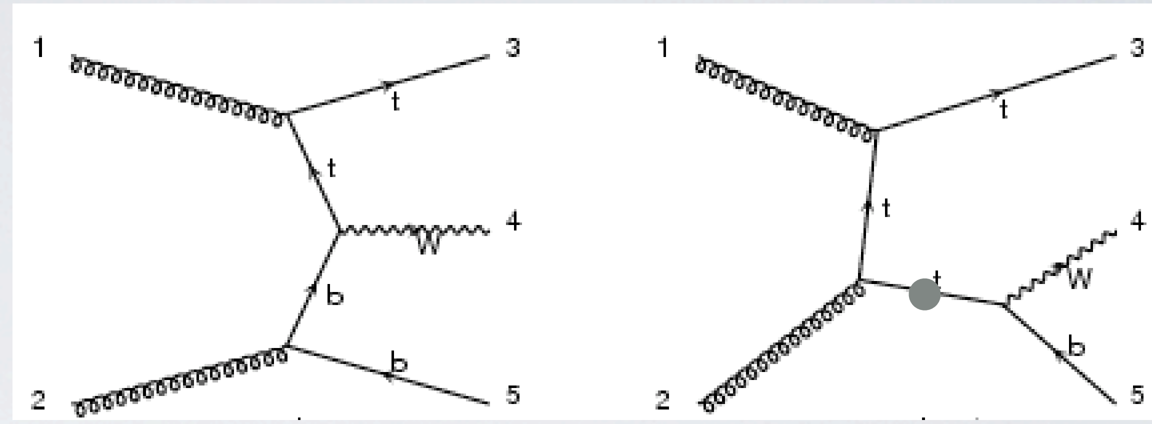

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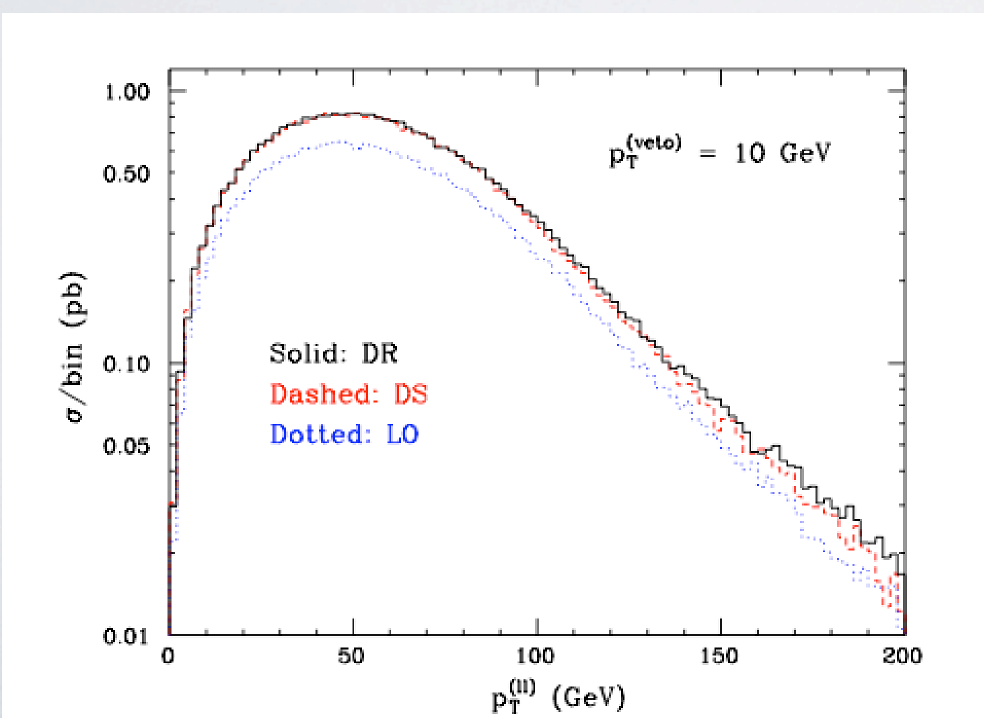

Diagram Removal : $\hat{\mathcal{S}}_{\alpha\beta}$

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]
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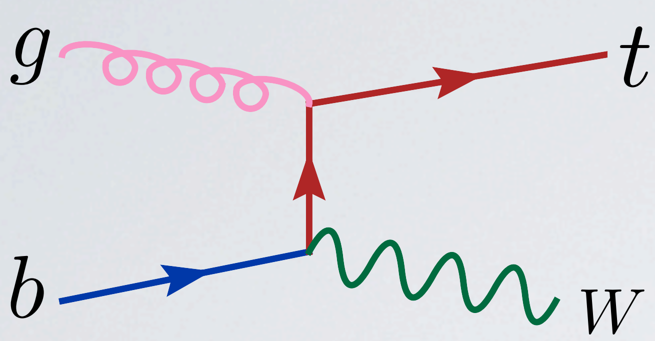

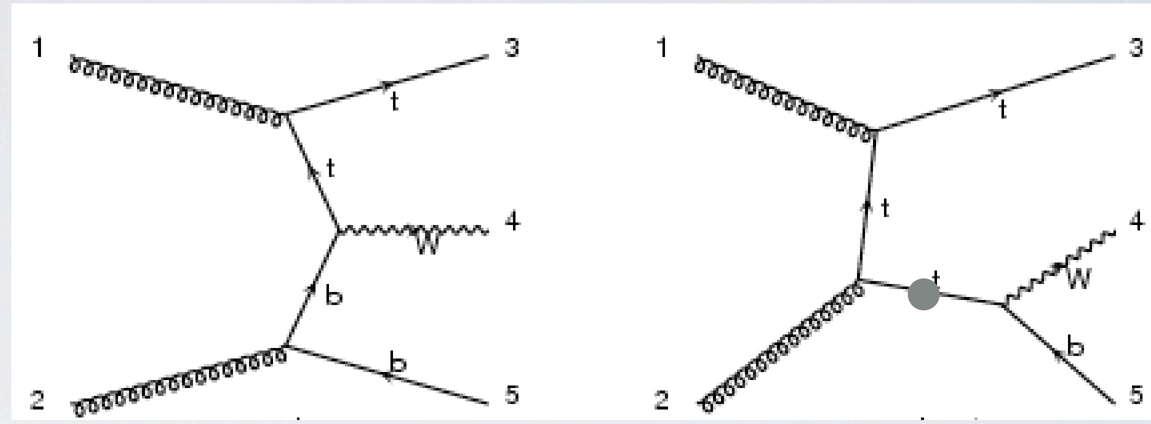

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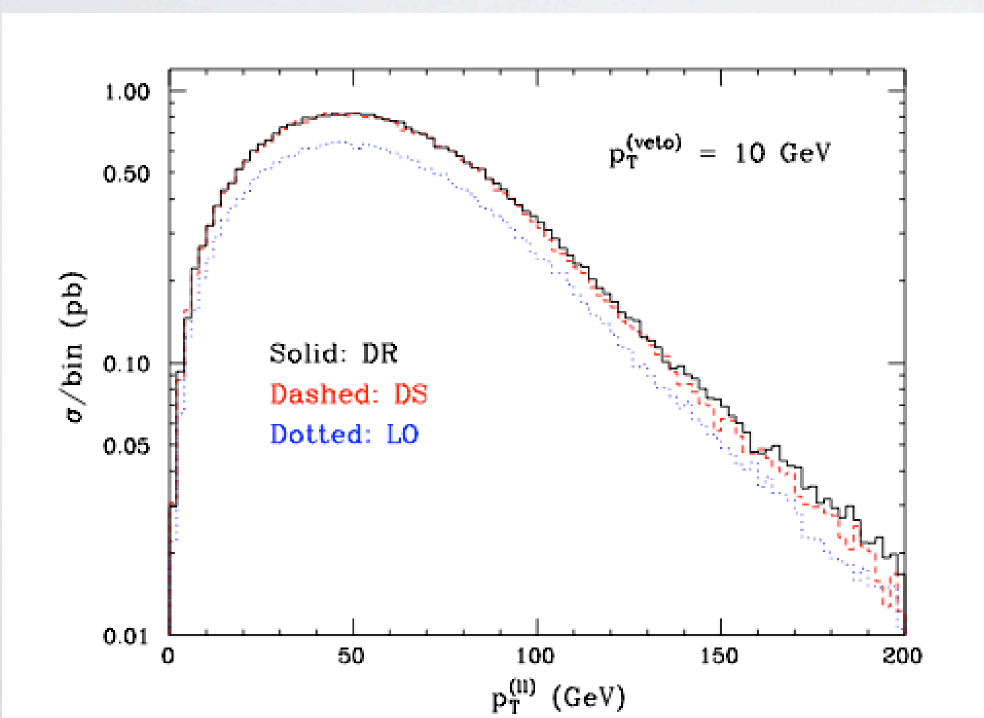

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Upshot: 5F the most convenient choice to move the interference problem one order higher!

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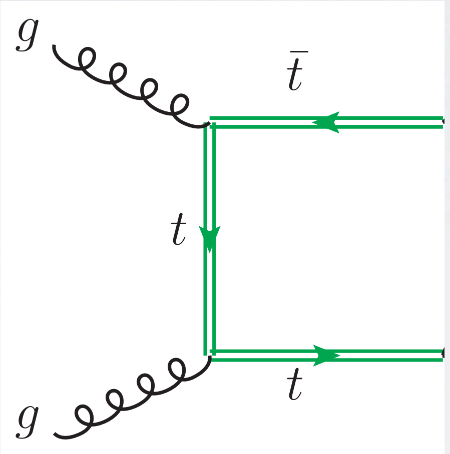

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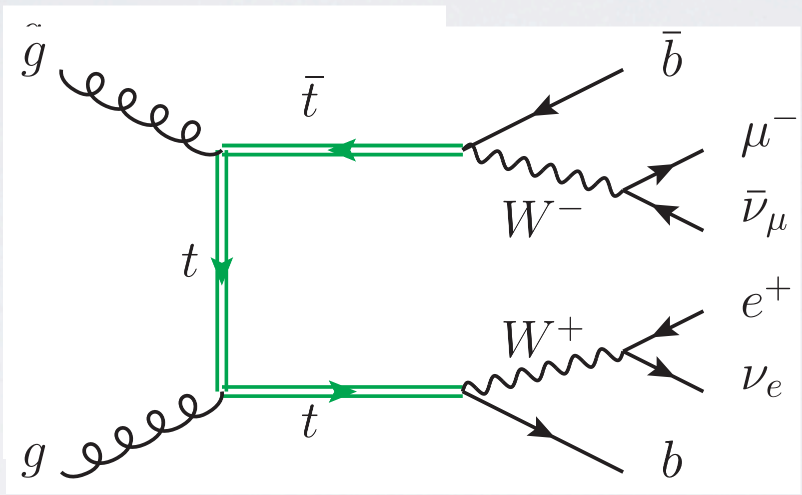

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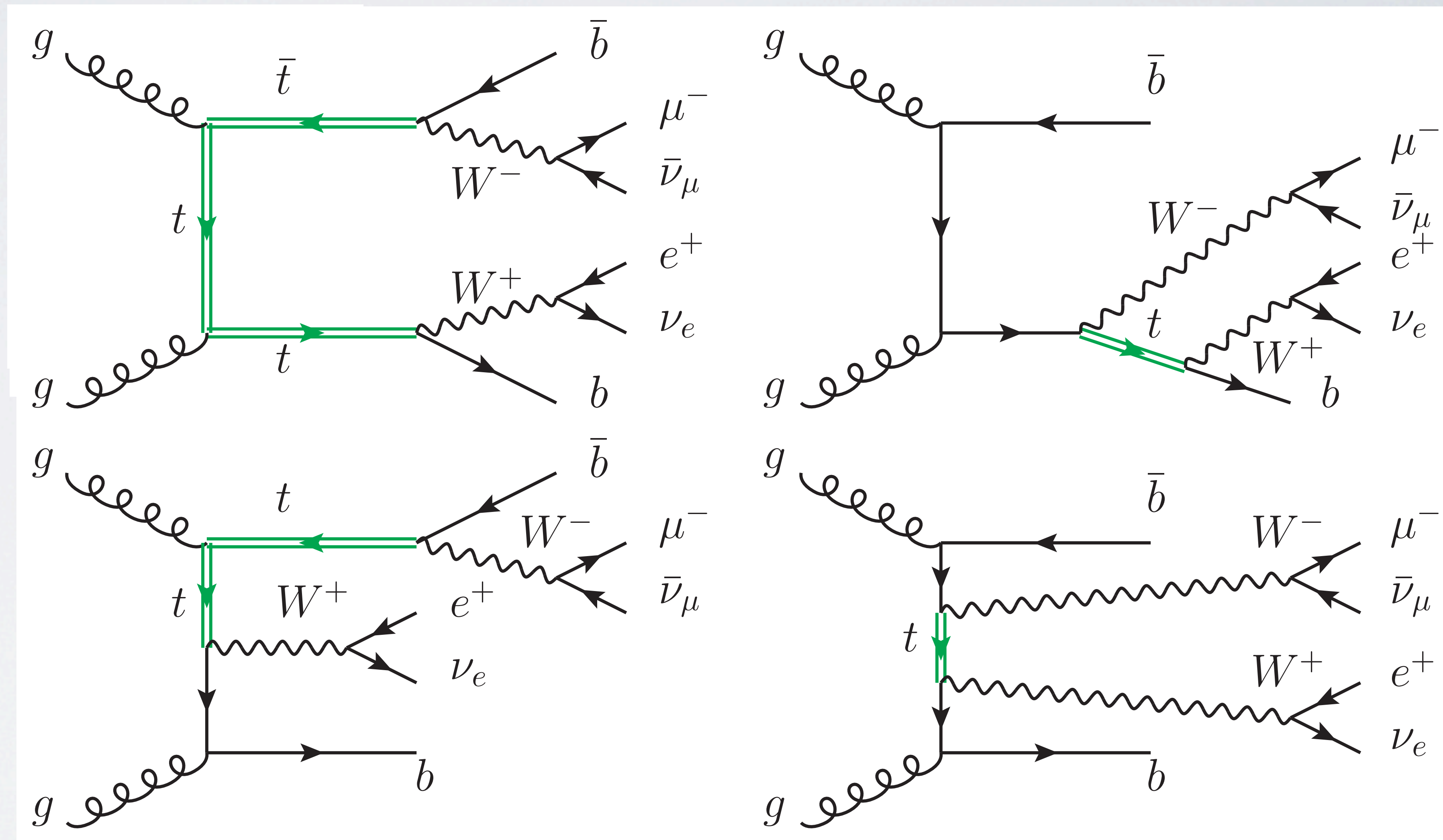

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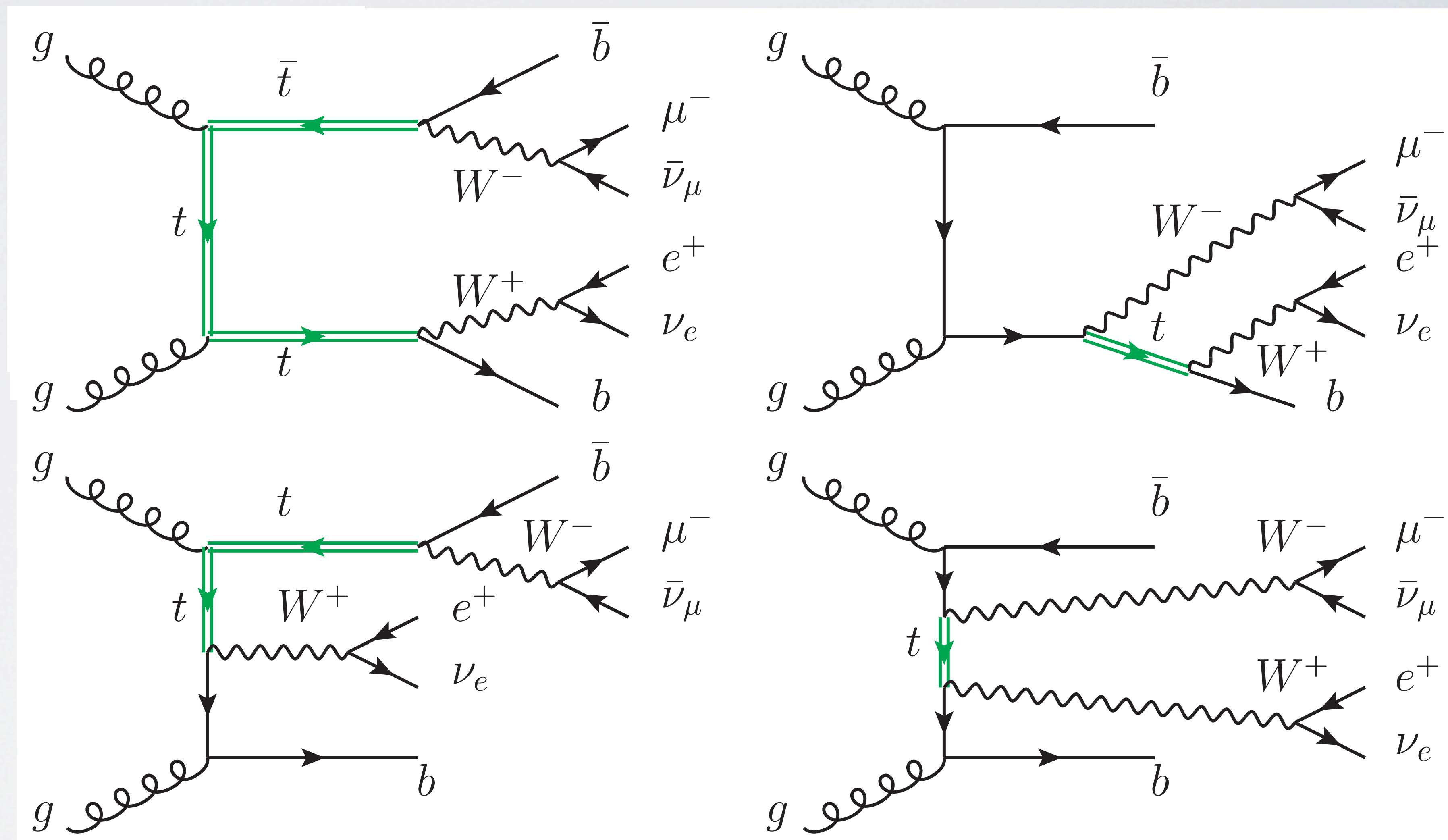

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- Gauge invariance guides us to include also single-resonant and non-resonant production. Note that there is interference between the diagrams above

TW IN THE 4F

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- Consistent description of top pair, single top and non-resonant contributions at NLO
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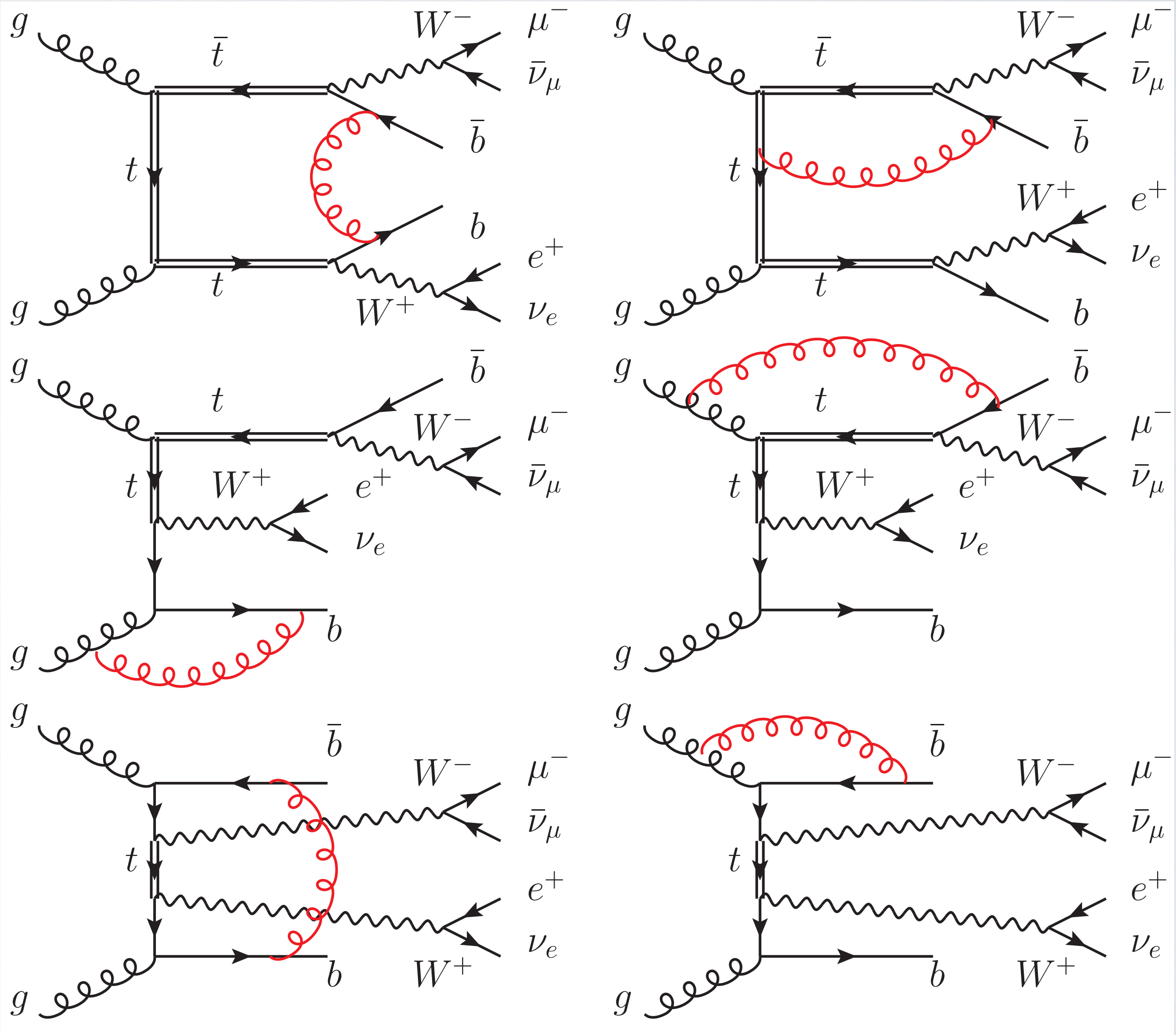

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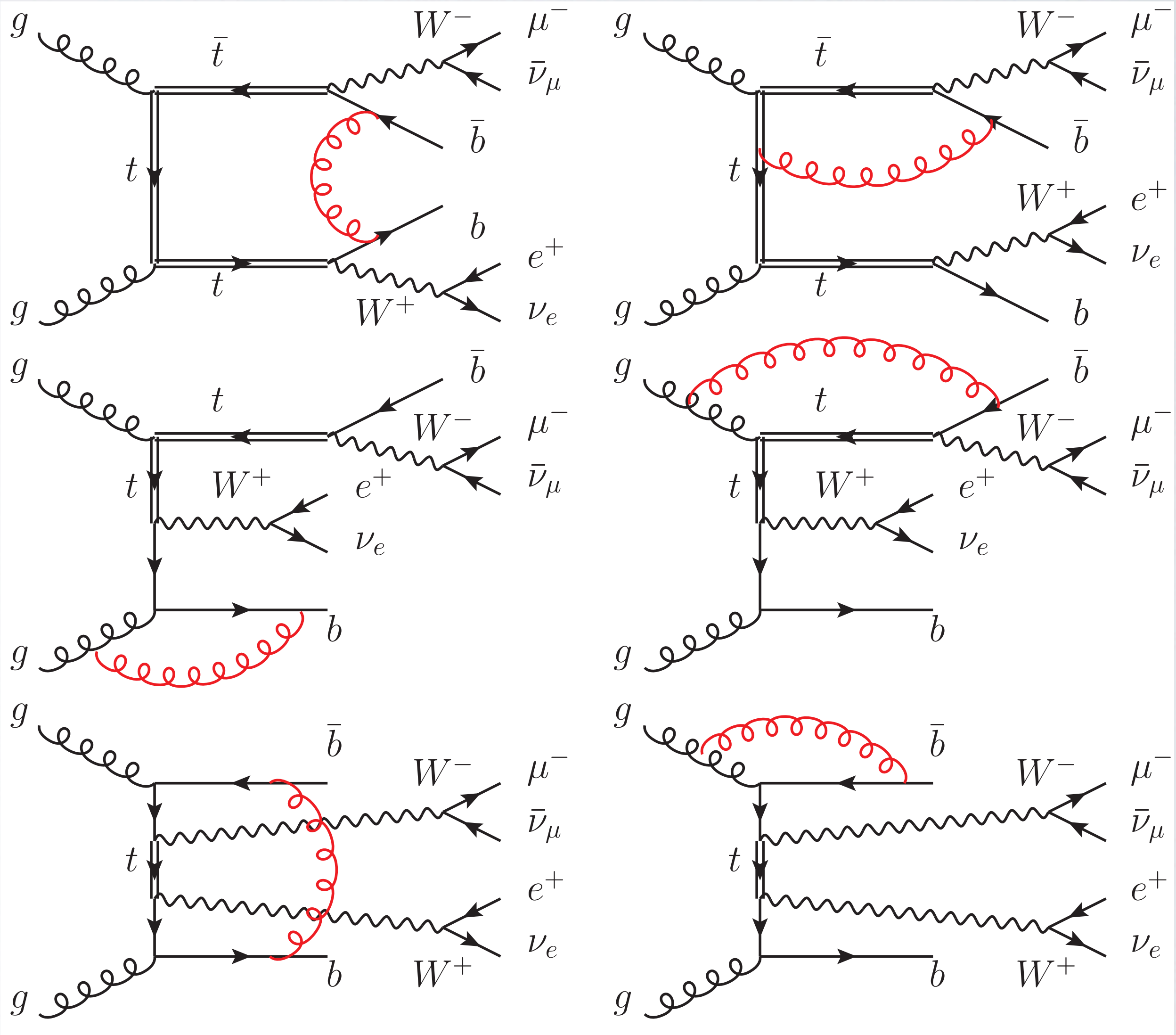
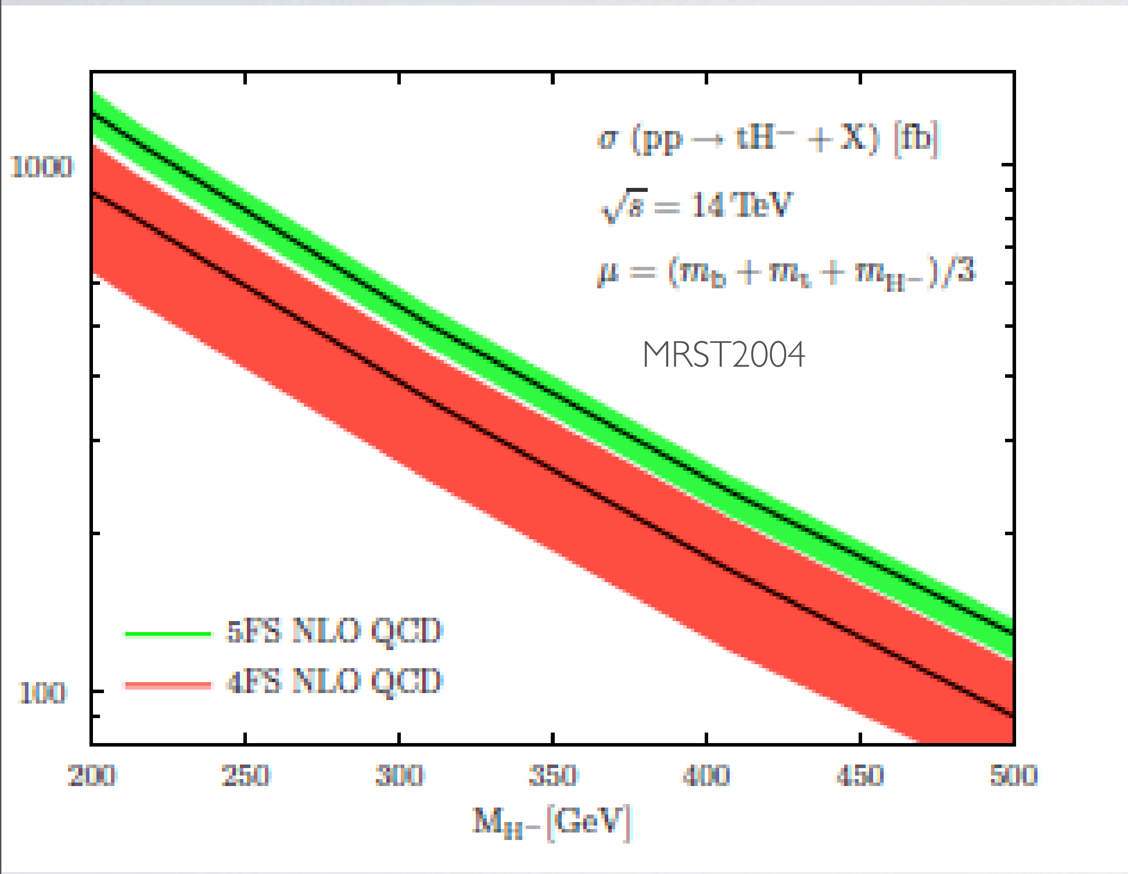
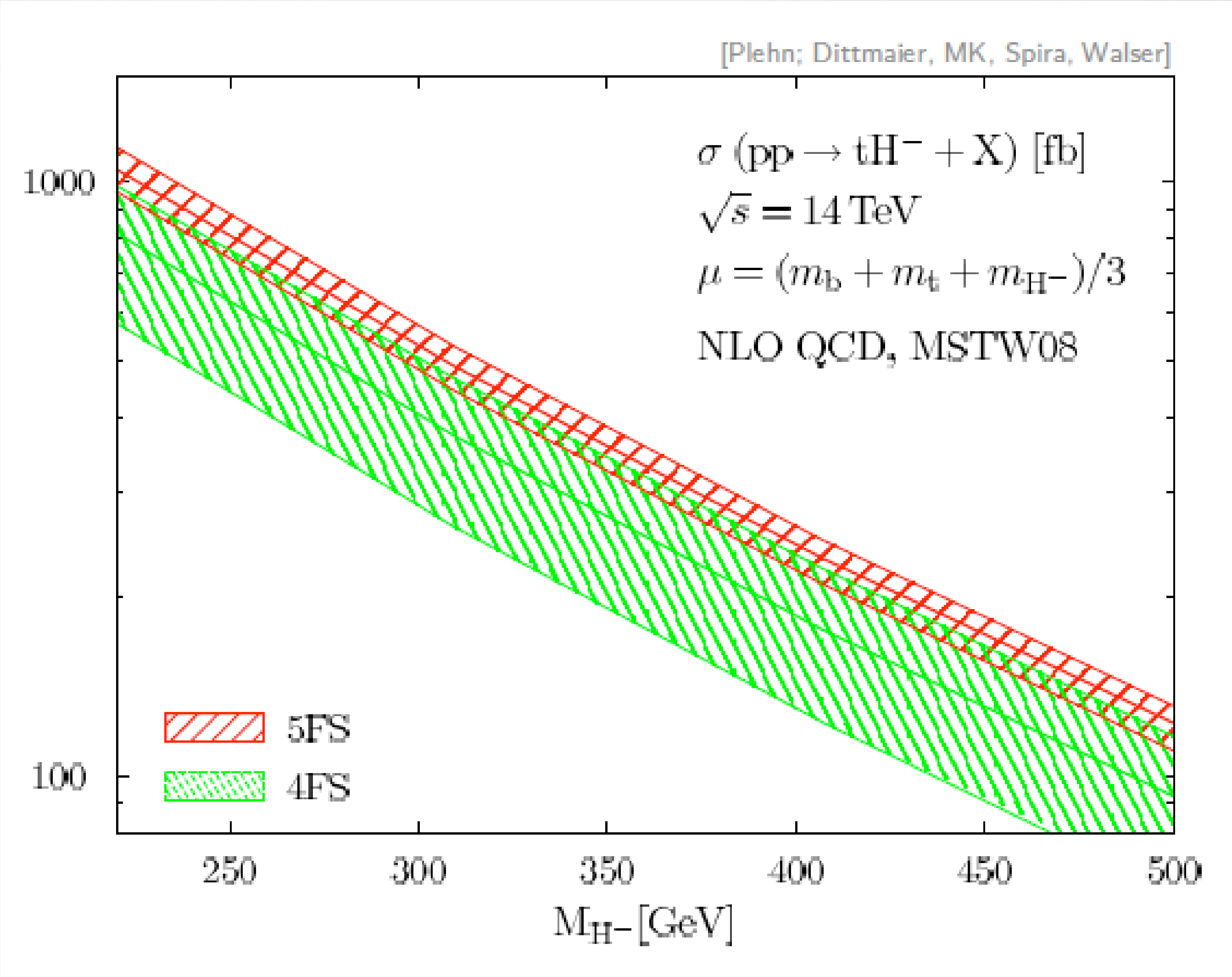


However, mb≠0 is needed to be used for tW!

TH+



[Dittmaier, Kramer, Spira, Walser, 2009]



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- Overall, we are ready to go...