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Update on top processes with MC@NLO

LPSC, Grenoble, 18/10/2007

SF & B. Webber, JHEP 0206(2002)029 [hep-ph/0204244]
SF, P. Nason & B. Webber, JHEP 0308(2003)007 [hep-ph/0305252]
SF, E. Laenen, P. Motylinski & B. Webber, JHEP 0603(2006)092 [hep-ph/0512250]
SF, E. Laenen, F. Maltoni, P. Motylinski, B. Webber & C. White, in preparation

MC@NLO 3.3 [hep-ph/0612272]

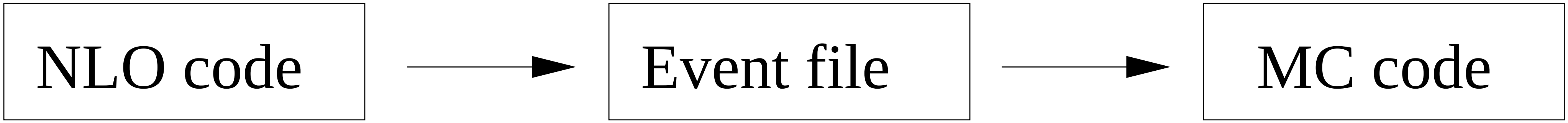
IPROC	IV	IL$_1$	IL$_2$	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{\rm IL}\bar{l}_{\rm IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{\rm IL}\bar{l}_{\rm IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{\rm IL}\bar{l}_{\rm IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{\rm IL}\nu_{\rm IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{\rm IL}\bar{\nu}_{\rm IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
–1706		i	j	✓	$H_1H_2 \to (t \to) bl^+_i\nu_i(\bar{t} \to)\bar{b}l^-_j\bar{\nu}_j + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to) bl^+_i\nu_i/(\bar{t} \to) bl^-_i\bar{\nu}_i + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}l^-_i\bar{\nu}_i + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to) bl^+_i\nu_i + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i(W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

Recent activities:

- Lepton spin correlations in $t\bar{t}$ and single-top production released with v3.3
- Hadron spin correlations in $t\bar{t}$ now into ATLAS software (v3.31)
- W and Z production with interface to HERWIG++
- Early stage of interface to PYTHIA
- Wt is now completed

`http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO`

Running MC@NLO


NLO code → Event file → MC code

- NLO code: integrates and unweights the matrix elements
- Event file: a list of hard events, i.e. the kinematics configurations emerging from hard subprocesses (typically, $2 \to 2$ and $2 \to 3$)
- MC code: HERWIG, which reads the hard events and showers them

The flowchart is the same as in MEC-based simulations. Features:

- Less than 1 hour for $1/2$ million $t\bar{t}$ hard events on my (2003) laptop
- Unweighting efficiency: 10-40%
- Events have weights ± 1

Top decays in $t\bar{t}$ production

The inclusion of spin correlations to hadronic decays implies the necessity of extending the range of variables `IL1CODE` and `IL2CODE` (used to be 1,2,3)

`ILxCODE`	Decay
0	$e+\mu+\tau+q$
1	e
2	μ
3	τ
4	$e+\mu$
5	q
6	$e+\mu+q$
7	no decay

- The mass of the top need not coincide with the pole mass any longer
- Variables `xGAMMAX`, `xMASSINF` and `xMASSSUP` control top mass ranges, `x=T1,T2` for t and $\bar{t}$
- Variable `TOPDECAY` controls Wtd_i vertex.
  If `TOPDECAY=Wb` then $t \to Wb$,
  if `TOPDECAY=ALL` then $t \to Wd_i$

- If `T1GAMMAX`> 0

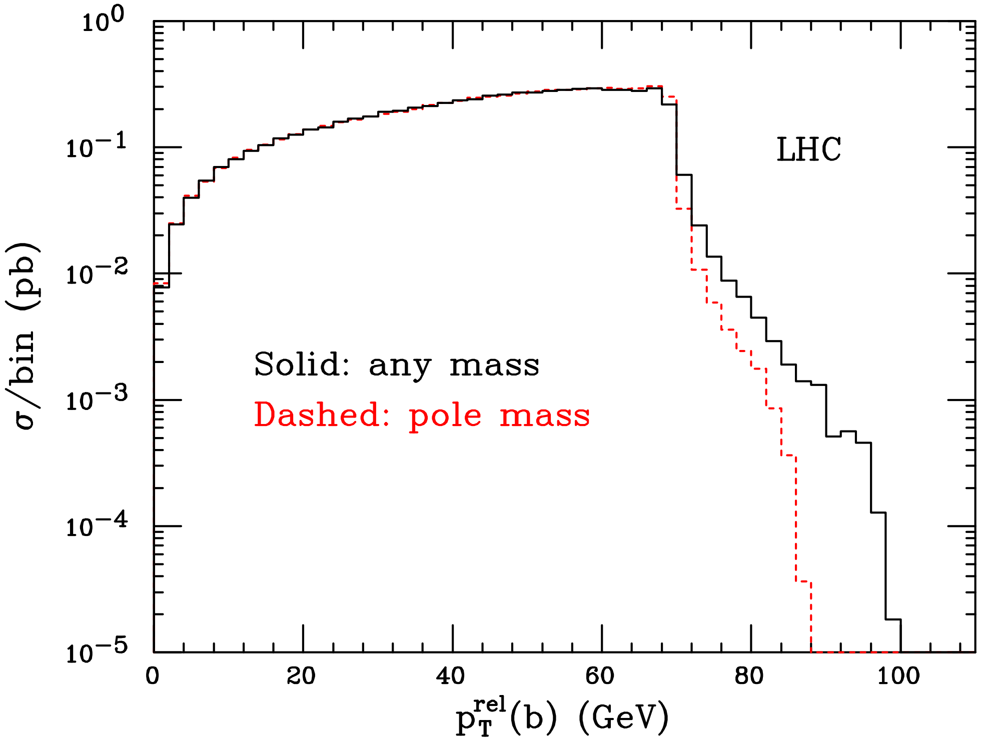
$$\texttt{HVQMASS} - \texttt{T1GAMMAX TWIDTH} \quad \leq m_t \leq \quad \texttt{HVQMASS} + \texttt{T1GAMMAX TWIDTH}$$

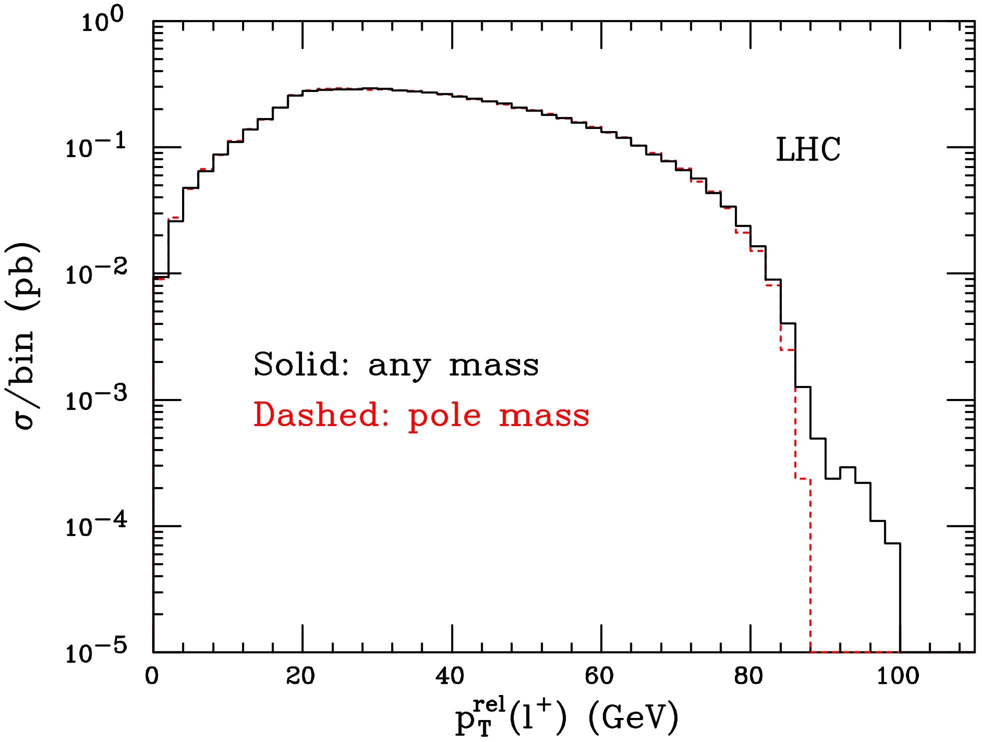
- If `T1GAMMAX`< 0

$$\texttt{T1MASSINF} \quad \leq m_t \leq \quad \texttt{T1MASSSUP}$$

- Same for `T1`$\longrightarrow$`T2`

Sample $t\bar{t}$ results





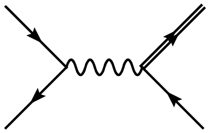
- There is *no difference* due to off-shell effects in single-inclusive distributions (p_T, y) and correlations (pair p_T, M, $\Delta\phi$)
- The quantity p_T^{rel} is the transverse momentum of the decay product wrt the top direction of flight, in the top rest frame. The differences above are obvious kinematics effects

Single-top: production channels

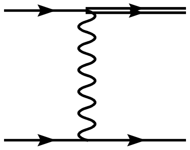
Single-top production will be systematically studied for the first time at the LHC. There is a lot of interesting physics to do

- Measurement of V_{tb}
- Constraints (measure?) on the b parton density
- An effective way to study new physics phenomena

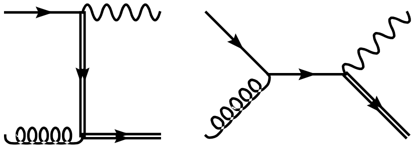
There are several production mechanisms



s channel



t channel



Wt mode

Single-top in Wt mode

- ◆ As with the other channels, a direct probe of top weak interactions
- ◆ A background to $t\bar{t}$ and to $gg \to H(\to W^+W^-)$

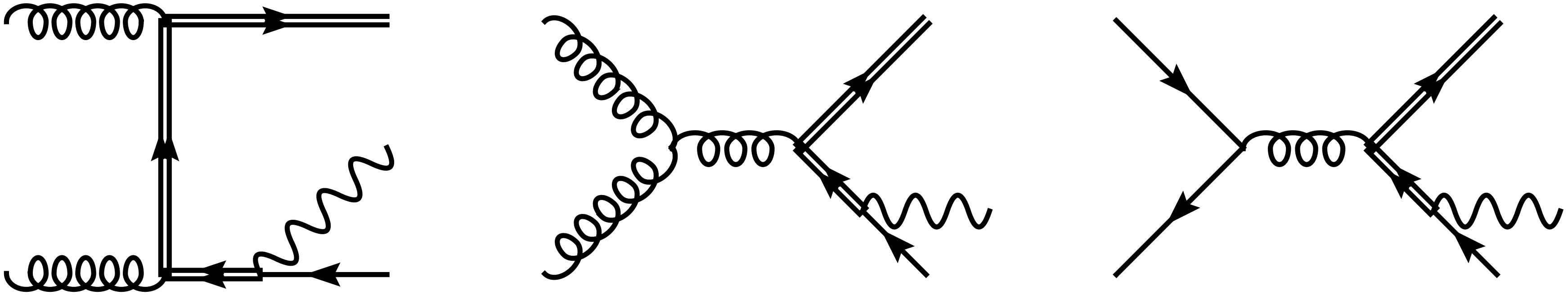
Apart from putting Wt MC predictions on firmer ground, the inclusion of this process into MC@NLO allows one to discuss a very interesting problem

$$\begin{aligned}
b+g &\longrightarrow t+W \\
b+g &\longrightarrow t+W+g \\
g+g &\longrightarrow t+W+\bar{b} \\
q+\bar{q} &\longrightarrow t+W+\bar{b} \\
b+q &\longrightarrow t+W+q \\
b+\bar{b} &\longrightarrow t+W+\bar{b} \\
b+b &\longrightarrow t+W+b
\end{aligned}$$

The b's are massless

Troubles...

...are due to (part of) the real corrections



One just can't tell whether these diagrams are relevant to $t\bar{t}$ (with the t decay not drawn) or to Wt production

- $t\bar{t}$ and Wt production *interfere*

So the theoretically cleanest solution is: compute $W^+W^-b\bar{b}$ production (Kauer, Zeppenfeld) and live with it. There will be troubles (eg gauge invariance) but *in principle* we should be able to solve them

In practice. . .

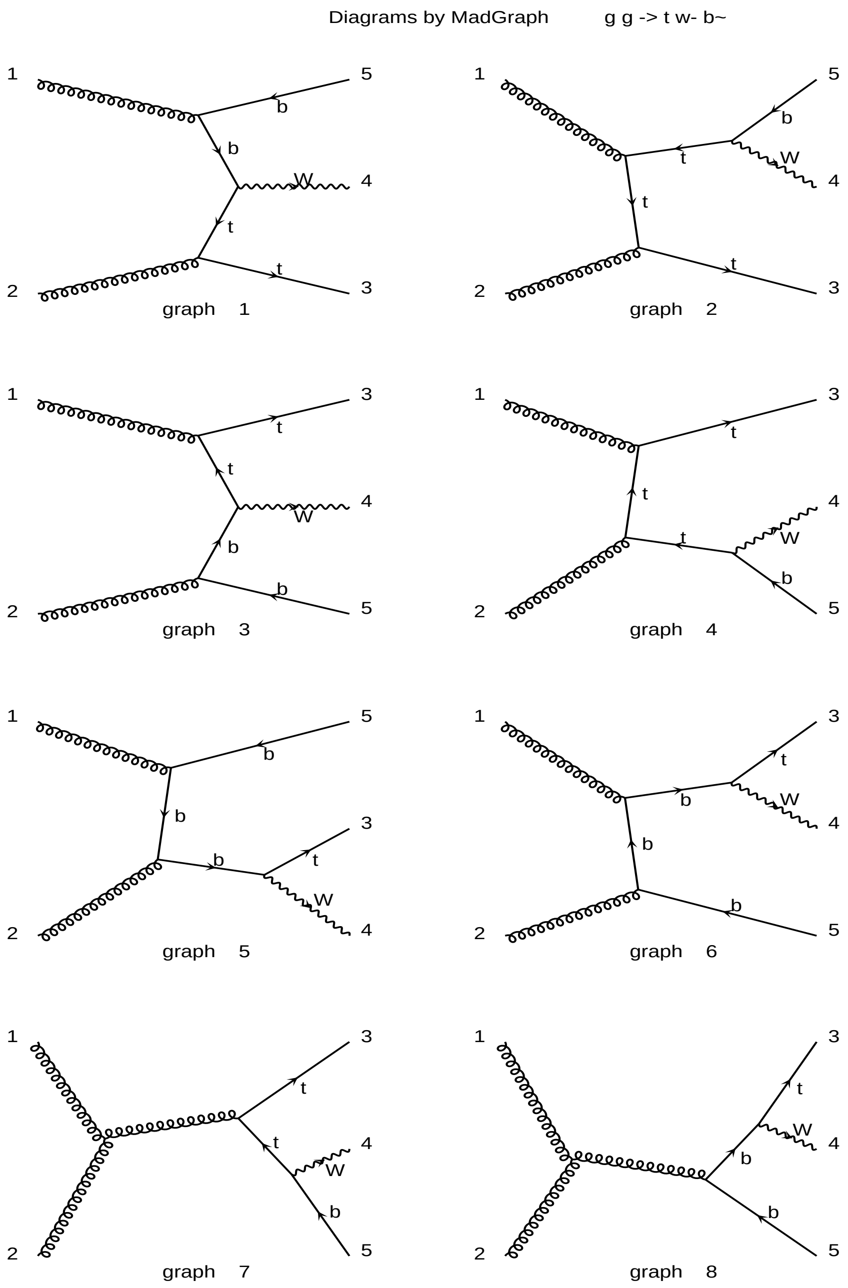
- Don't panic: at least we have measured $t\bar{t}$ production, so there must be a way out
- Also: $W^+W^-b\bar{b}$ is fairly complicated, and NLO results won't be computed any time soon. Resummation of $p_T(b)$ also an issue

We know what we want: there must be at least a Wb pair whose invariant mass is way off the top mass shell

- Cut on $M(bW)$ (Belyaev, Boos, Dudko)
- Subtract doubly-resonant diagrams (Tait)

For total rates, the two approaches are shown to coincide if one imposes $|M(bW) - m_t| > 15\Gamma_t$

The MCFM approach (Campbell & Tramontano)



- Graphs 2,4,7 are doubly resonant
- The others can be seen as obtained from backward evolution of the b quark, which relates them to the b quark density
- For a suitable choice of μ_F, the contribution from singly-resonant diagrams integrates to zero, $\mu_F \simeq (m_t + m_W)/4$
- Roughly speaking, PDFs at μ_F are obtained by integrating over $p_T \leq \mu_F$
- Doubly resonant contributions must be small if $p_T(b)$ is small

Prescription: apply a veto $p_T^{(veto)}$ to the p_T of the additional b quark at the NLO. Set $\mu_F = p_T^{(veto)}$. Don't include gg contribution

- The prescription is unphysical, since it is based on a diagrammatic idea (the “extra” b at the NLO)
- Partonic processes “mix” anyhow at higher orders
- When $\mu_F \neq p_T^{(veto)}$, only singly-resonant gg diagrams are included (violation of gauge invariance)
- If gg is not included, *RGI* is violated
- The prescription can’t be applied to $q\bar{q}$ contributions: they have nothing to do with b PDF (they are small anyhow)
- Most worrisome of all, one heavily relies on a purely-perturbative description of the b PDF. Scale choice is part of the definition

Bottom line: in practice, it may work fine, but IMHO theoretically fragile

MC@NLO

Retain the basic idea of MCFM: impose a veto. Do so on the *second hardest* b (parton level) or B (hadron level) of the event. Variants are possible, which do not involve b-tagging capabilities

We do so in three different ways:

DR: *Diagram removal:* eliminate all doubly-resonant diagrams

DS: *Diagram subtraction:* subtract locally $t\bar{t}$ contributions

PR: *Process removal:* do not include the contributions from processes which interfere with $t\bar{t}$

- All of these have problems. However, if the veto idea is satisfactory, they should give similar results

Critique

All the three approaches have been implemented into MC@NLO, and therefore we have proven them viable at the event generator level.
Are they meaningful?

DR: Violation of gauge invariance. Very naive estimate:
$\Gamma_t^2 m_t^2/(m_t^2 - m_b^2)^2 \simeq 7\cdot 10^{-5}$

DS: Restores gauge invariance, but does so by means of a procedure which is arbitrary. Error estimate similar to that for DR

PR: Violation of renormalization group invariance. Leftover terms are not logarithmically enhanced, and can be estimated within a given NLO subtraction scheme

The implementation of DS is non trivial in an EvG context

Implementation of Diagram Subtraction

This amounts to the definition of Wt through $\sigma_{ab}^{(subt)}$

$$\sigma_{ab\to Wt} \quad = \quad \sigma_{ab} - \sigma_{ab}^{(subt)}$$

with σ_{ab} collecting all contributions to $ab \to tWb$. By assuming one deals with tW^- production

$$\sigma_{ab}^{(subt)} \quad = \quad \left|\mathcal{A}(ab \to t\bar{t})\right|^2 BW(M(\bar{b}W)) \left|\mathcal{A}(\bar{t} \to W\bar{b})\right|$$

- The kinematics is that of $ab \to tWb$, but we need the $\bar{t}$ on shell to compute $\mathcal{A}(ab \to t\bar{t})$
- The NLO matrix elements are typically computed with $\Gamma_t = 0$, but we need $\Gamma_t \neq 0$ in the Breit Wigner

- Reshuffle the kinematics before computing the $t\bar{t}$ amplitude

$$\mathcal{A}(ab \to t\bar{t}) \;\longrightarrow\; \tilde{\mathcal{A}}(ab \to t\bar{t})$$

  This is a standard procedure in MC's

- Use $\Gamma_t \neq 0$ in the BW only: we are modeling the decay anyhow

Not quite working yet. Although spin correlations are very small in $t\bar{t}$, we better be careful since we need a *local* subtraction term, ie a precise matching of the matrix elements. Thus, define

$$\sigma_{ab}^{(subt)} \;=\; \left|\tilde{\mathcal{A}}(ab \to tW\bar{b})_{\mathrm{dbl-res}}\right|^2$$

This is not diagram subtraction: t and $\bar{t}$ are both on shell

- But it doesn't work yet

$\tilde{A}(ab \to tW\bar{b})_{\rm dbl-res}$ is divergent when $\Gamma_t = 0$. Thus, set $\Gamma_t \neq 0$, and define

$$\sigma_{ab}^{(subt)} = \left| \tilde{A}(ab \to tW\bar{b})_{\rm dbl-res} \right|^2 \frac{BW(M(\bar{b}W)}{BW(m_t)}$$

We have added by hand a BW damping factor which is present in the $\bar{t}$ decay in $t\bar{t}$ production, but not in the (reshuffled) amplitude above

This is working fine, but since $\Gamma_t \neq 0$ in the subtraction term, the same value must be adopted in the computation of $ab \to tW\bar{b}$. The fixed-width prescription then violates gauge invariance

- Numerical evidence: when $\Gamma_t \neq 0$, the collinear limits of Madevent amplitudes diverge twice as fast as the correct QCD result

This is not a bug: Madevent implements the finite-width prescription. An analytical computation would behave the same

We have a couple of ways out

- Implement (e.g) a complex-mass scheme in Madevent, which would restore the correct behaviour
- Perform an analytical computation using (e.g) a complex-mass scheme

Both are fine, that's why we prefer a wrong solution:

- Keep on using Madevent as is, setting $\Gamma_t = 0$ in singly-resonant diagrams, and $\Gamma_t \neq 0$ in doubly-resonant diagrams

This is not elegant, and violates gauge invariance again. However, it is simply a quick way out of a technical problem, not to be confused with the problem of principle we have in DR. If need be, we know how to do things in a correct way

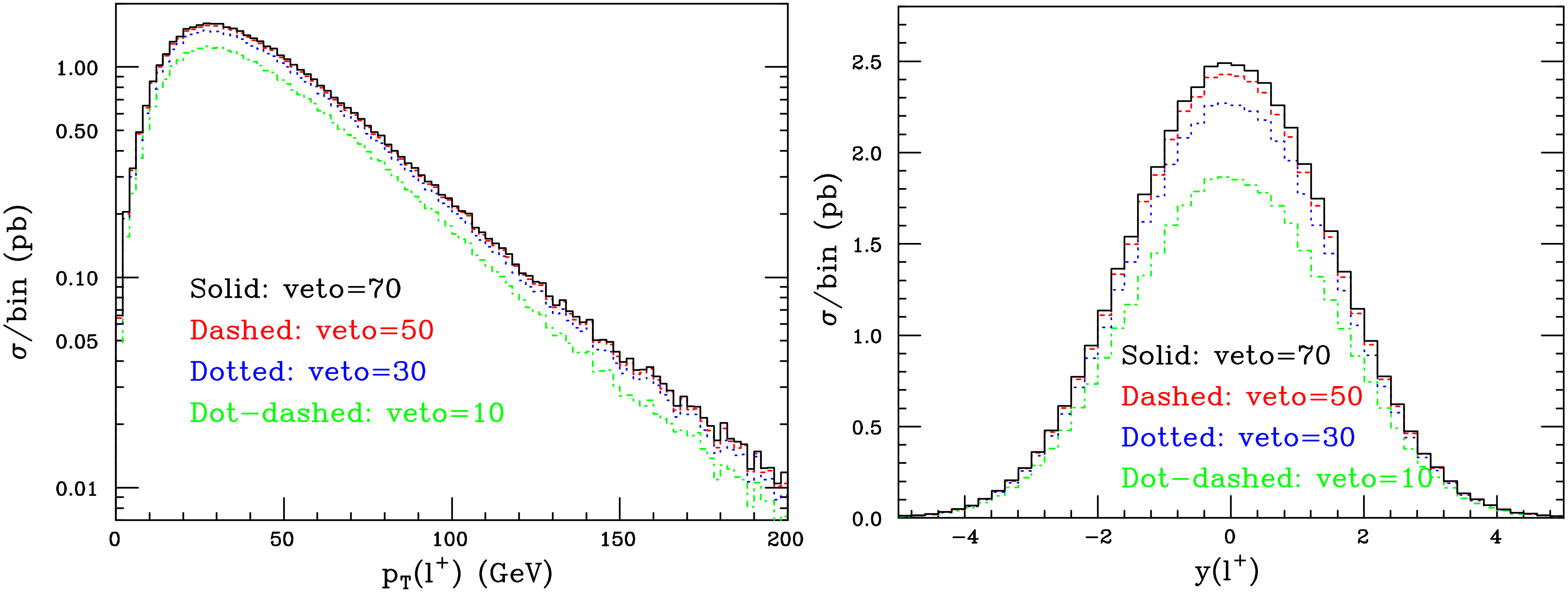
Results (preliminary)

It should be stressed that DR and DS feature one crucial difference: the latter contains interference terms, and the former does not

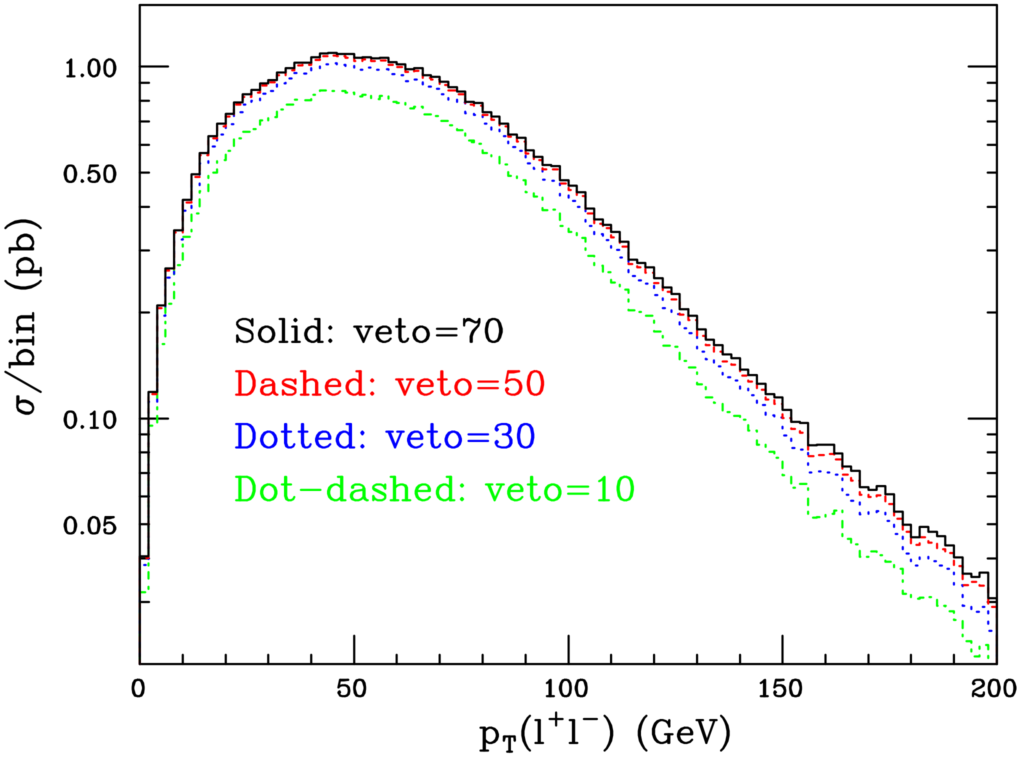
Therefore, if one is convinced that gauge-invariance violations are numerically unimportant, the difference between the two approaches is a measure of the “contamination” of the tW process due to $t\bar{t}$ production

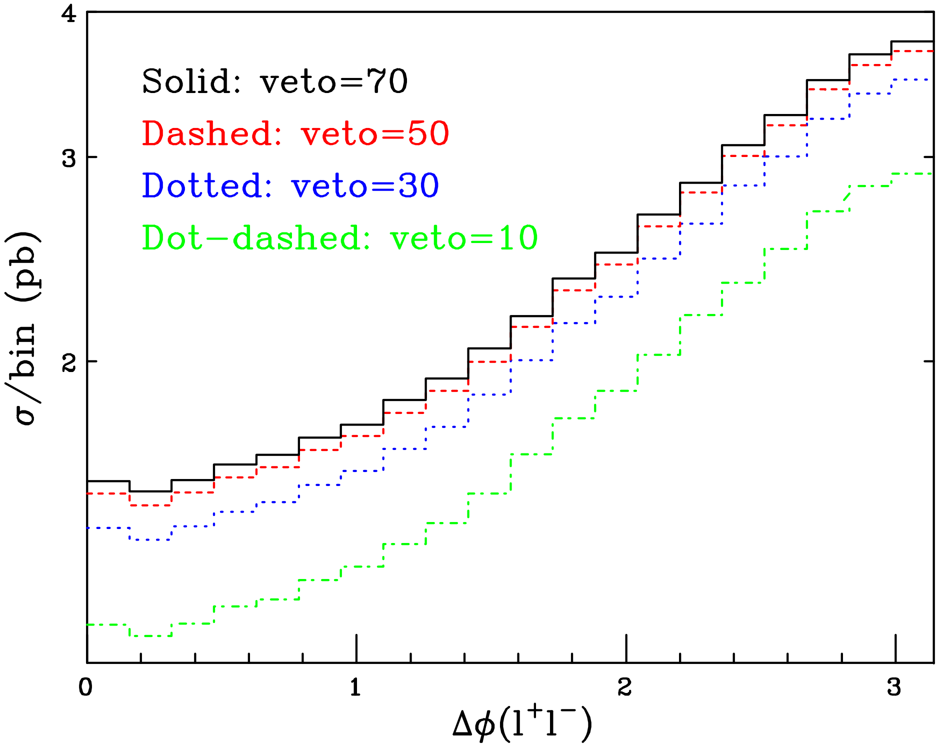
- We veto on the second-hardest B of the event, with $|y(B)| \leq 2.5$
- We consider $p_T^{(veto)} = 10, 30, 50, 70$ GeV
- We compare the results of the three approaches with the four vetos, for $p_T(t)$, $y(t)$, $p_T(l^\pm)$, $y(l^\pm)$, $p_T(l^+l^-)$, $\Delta\phi(l^+l^-)$

DR results

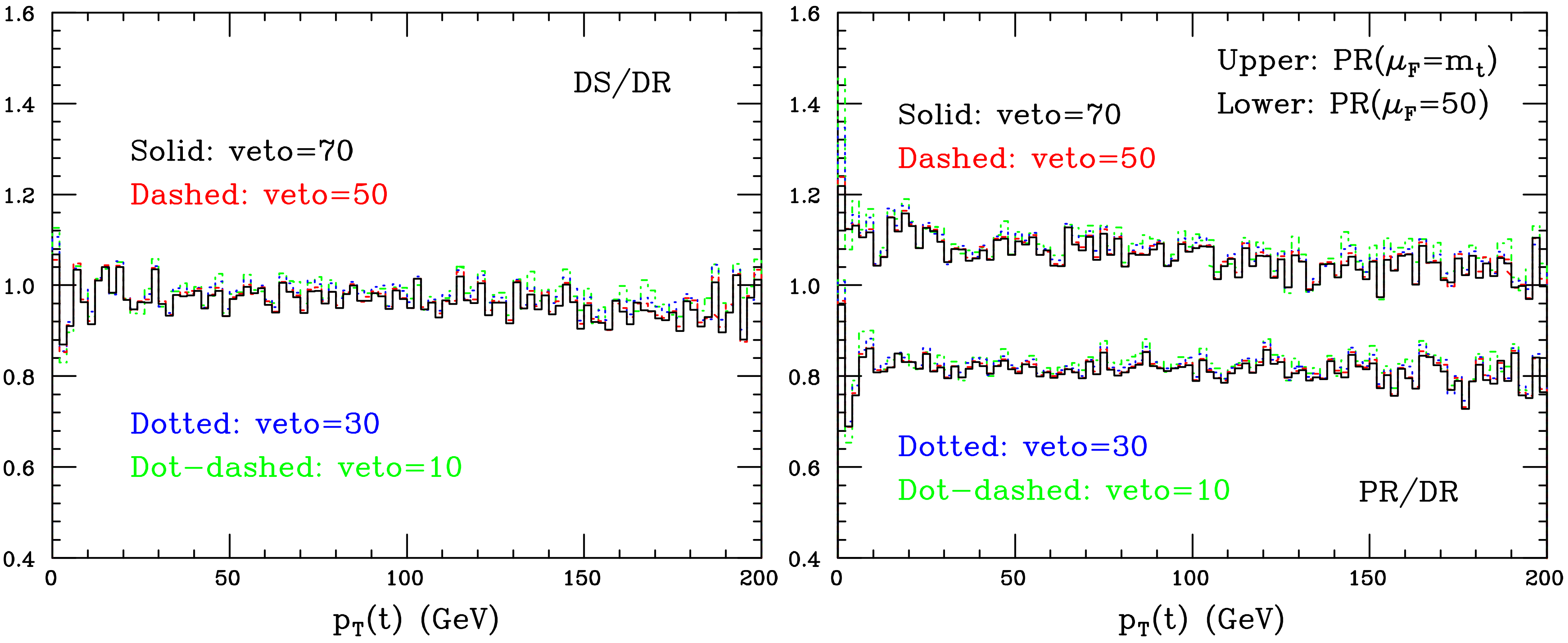

σ/bin (pb)
1.00
0.50
0.10
0.05
0.01
0
50
100
150
200
p_T(l^+) (GeV)
Solid: veto=70
Dashed: veto=50
Dotted: veto=30
Dot−dashed: veto=10
σ/bin (pb)
2.5
2.0
1.5
1.0
0.5
0.0
−4
−2
0
2
4
y(l^+)
Solid: veto=70
Dashed: veto=50
Dotted: veto=30
Dot−dashed: veto=10

DR results


Solid: veto=70
Dashed: veto=50
Dotted: veto=30
Dot−dashed: veto=10
σ/bin (pb)
1.00
0.50
0.10
0.05
0
50
100
150
200
$p_T(l^+l^-)$ (GeV)

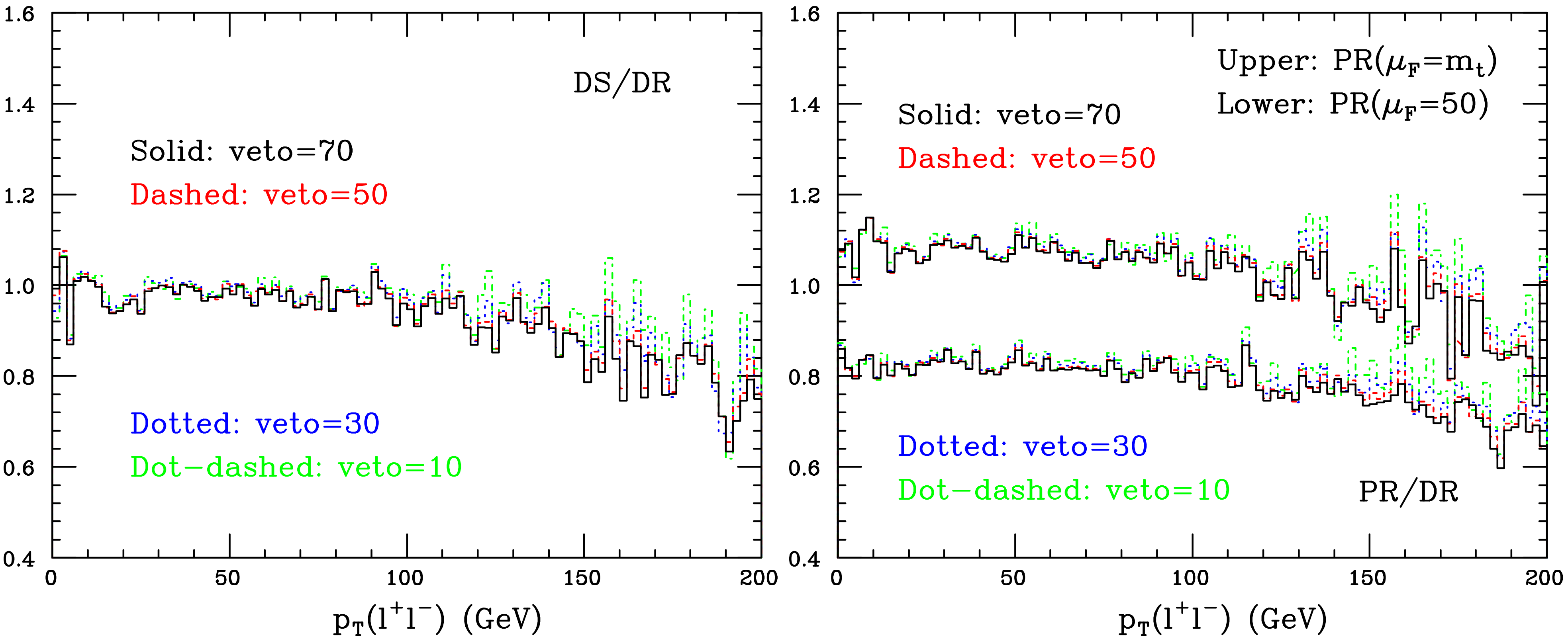

Solid: veto=70
Dashed: veto=50
Dotted: veto=30
Dot−dashed: veto=10
σ/bin (pb)
4
3
2
0
1
2
3
$\Delta\phi(l^+l^-)$

DR vs DS vs PR



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
50
100
150
200
$p_T(t)$ (GeV)
DS/DR
Solid: veto=70
Dashed: veto=50
Dotted: veto=30
Dot−dashed: veto=10
Upper: PR(μ_F=m_t)
Lower: PR(μ_F=50)
PR/DR

DR vs DS vs PR

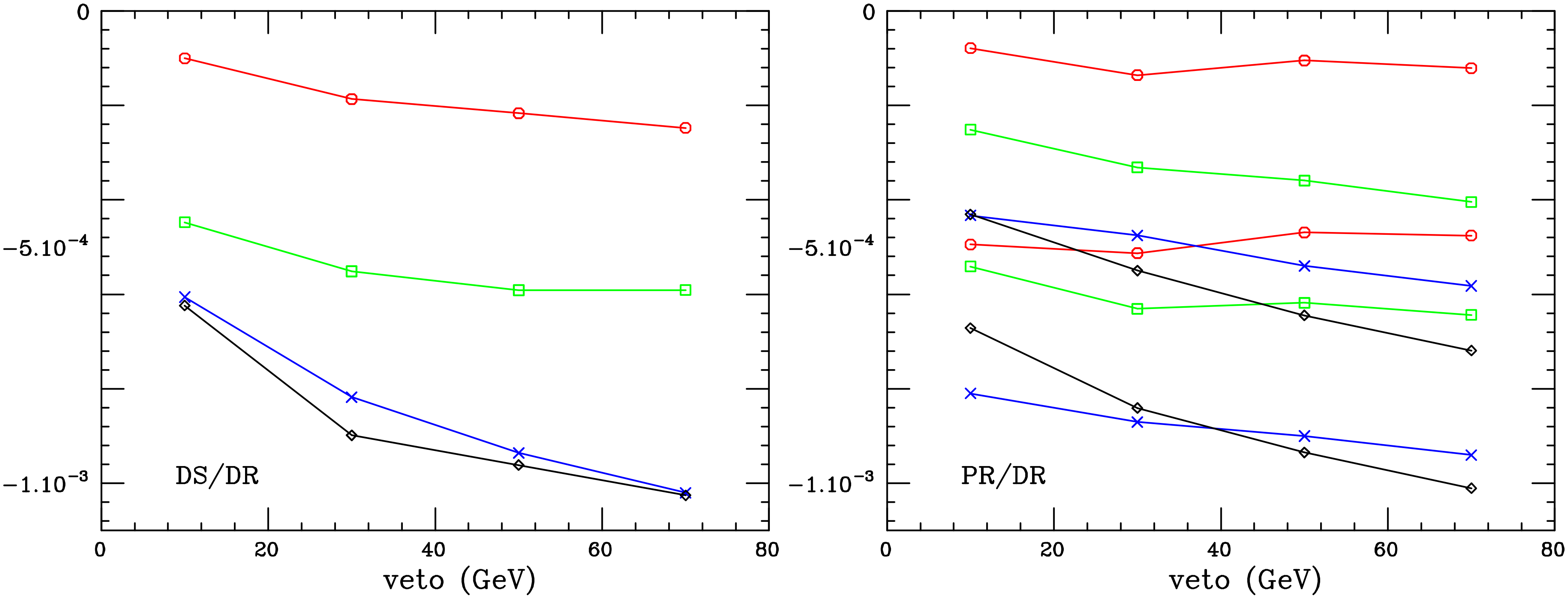


This variable, and the p_T of the lepton emerging from W decay, are the only ones that display a pattern

Note that the range presented here corresponds to a much more extended range in the top transverse momentum, ie $\sigma(p_T(t) = 200\ \text{GeV}) \gg \sigma(p_T(l^+l^-) = 200\ \text{GeV})$

DR vs DS vs PR

Fit the ratios of p_T distributions with $R = a + bp_T$, and plot b



Results for $p_T(t)$, $p_T(l^+)$, $p_T(l^-)$, $p_T(l^+l^-)$ in tW^- production

Conclusions

- In an MC context, $\log p_T(b)$ are resummed. Thus, in MC@NLO vetos can be as small as one likes
- The three approaches give very similar results for shapes. DR and DS rates are almost identical, not so for PR
- Interference effects begin to be non-negligible in the large-p_T tail of some distributions. Small vetos help reduce them
- PR is in better agreement if a small factorization scale is chosen
- We have implemented spin correlations in DR and PR. Their effects on shapes are much more significant that the differences between the three approaches
- Being done: veto in $t\bar{t}$ $\Rightarrow$ upper bound on interference terms