TOP QUARK PHYSICS
THEORETICAL OVERVIEW

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– top quark properties
– issues in pair production
– issues in single production

Contents

What I will cover:

- top properties - status and needs
- simulation issues in top pair production
- simulation issues in single-top production
- theory task list

What I will not discuss:

- rare top decays
- $t\bar{t}$ or $t\bar{b}$ resonances
- ILC

THE TOP QUARK CANDIDATE

What *is* the top quark in the SM? up-isospin partner of *b*

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R \quad d_R \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad e_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R \quad s_R \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \mu_R$$

$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R \quad b_R \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \tau_R$$

The Top Quark candidate

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$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R \quad d_R \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad e_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R \quad s_R \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \mu_R$$

$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R \quad b_R \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \tau_R$$

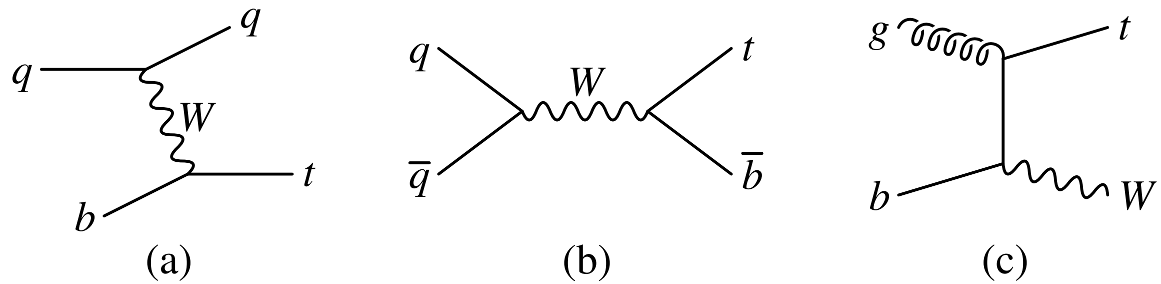
$\longrightarrow$ measure all the candidate's quantum numbers!

1. mass: measured to 1.5%, consistent w/ EW precision data
2. spin: not measured directly, but $\sigma_{t\bar{t}}$ consistent w/ QCD & $S = \frac{1}{2}$
3. charge: $Q = +\frac{2}{3}$ or $-\frac{4}{3}$? Tev2 data consistent w/ $+\frac{2}{3}$
4. lifetime / total width: unknown; need single-top signal
5. gauge couplings: $\sigma_{t\bar{t}}$ consistent w/ QCD;
   $t\bar{t}Z/t\bar{t}\gamma$ constrained but not directly measured;
   $t\bar{b}W$ also not directly measured, but decay consistent w/ $SU(2)_L$
6. Yukawa coupling: not measured (need $t\bar{t}H$ signal @ LHC)

Top properties - is it really SM?

▶ Γ_t (lifetime): $\propto g_W V_{tb}$ $(\tau_t = 4 \times 10^{-25}$ s; $\Gamma_t = \hbar/\Gamma_t = 1.4$ GeV)

$\rightarrow$ need single-top



Process	Tevatron Run 2 (t)	LHC (t)	LHC ($\bar{t}$)
$\sigma^{NLO}_{t-ch.}$ (a)	$0.99^{+.14}_{-.11}$ pb	$155.9^{+7.5}_{-7.7}$ pb	$90.7^{+4.3}_{-4.5}$ pb
$\sigma^{NLO}_{s-ch.}$ (b)	$0.442^{+.061}_{-.053}$ pb	$6.56^{+.69}_{-.63}$ pb	$4.09^{+.43}_{-.39}$ pb
σ^{NLO}_{tW} (c)	$0.070 \pm \mathcal{O}(10\%)$ pb	$33 \pm \mathcal{O}(10\%)$ pb	$33 \pm \mathcal{O}(10\%)$ pb

NLO uncertainties mostly $< 10\%$: [cf. Sullivan, PRD(72)094034(2005)]

$\delta m_t \sim 1$ GeV would improve these a lot, as will PDF meas'mts at LHC

$\twoheadrightarrow$ but σ_{tX} does NOT measure *total* width!

(must convolve with $\sigma_{t\bar{t}}$ result and some assumptions)

Top properties - is it really SM?

- $t\bar{t}$ spin correlation (related to lifetime): $\tau_{\text{flip}} \propto m_t/\Lambda^2_{QCD}$

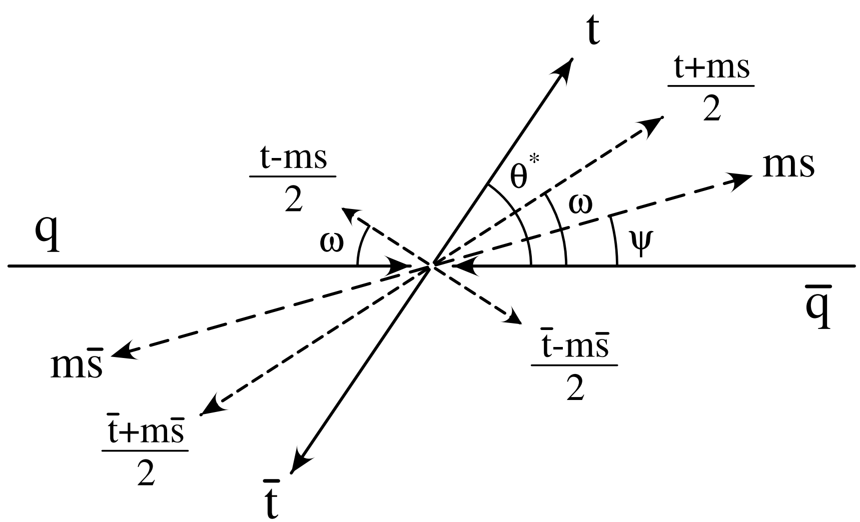
  spin correlations if $\tau_t \ll \tau_{\text{flip}}$: implies $|V_{tb}| > 0.03$

$\rightarrow$ plot $t\bar{t}$ double differential distribution

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_i)d(\cos\theta_{\bar{i}})} = \frac{1}{4}(1 - C\alpha_i\alpha_{\bar{i}}\cos\theta_i\cos\theta_{\bar{i}})$$

C different for $q\bar{q}, gg$ initial states ($C_{q\bar{q}}, C_{gg}$)

$\alpha_i, \alpha_{\bar{i}}$ are the spin-analyzing powers (leptons are best)



Choice of optimal basis depends on initial state.

NLO effects now done — important shifts for all C

Top properties - gauge couplings

- g_{ttg} essentially measured to be QCD

  $\longrightarrow$ do anom. coup. analysis (no Tevatron studies yet!)

- g_{tbW} looks SM-like (but with large uncertainty)

  $\longrightarrow$ convolved with V_{tb}

  $\longrightarrow$ treat deviation as anom. coup. ($\sigma^{\mu\nu}$ term w/ F_2^L, F_2^R)

  study in $t\bar{t}$ decays & single-top prod'n

  Tevatron w/ 2 fb^{-1}: $-0.18 < F_2^L < +0.55$ & $-0.24 < F_2^R < +0.25$

  (but needs much further study)

- $g_{tt\gamma}$, g_{ttZ} essentially unprobed

  $\longrightarrow$ not known directly

  $\longrightarrow$ can't see $q\bar{q} \to Z/\gamma^* \to t\bar{t}$, must measure $t\bar{t}Z$ & $t\bar{t}\gamma$ rates

  $\longrightarrow$ Tev2 can do 1st rough $g_{tt\gamma}$ measurement

Top properties - Yukawa coupling

SM Yukawa Lagrangian term:

$$\mathcal{L}_Y = -Y_t \bar{\Psi}_L \Phi^c t_R + \text{h.c.}$$
$$\rightarrow -Y_t \frac{v}{\sqrt{2}} \bar{t}_L t_R + \text{h.c.} + \cdots$$

$v = 256$ GeV, $m_t = 175$ GeV, so $\boxed{Y_t \approx 1}$ $\longrightarrow$ *very* suspicious!

► Does top have a special role in EWSB?

Need $t\bar{t}H$ observation to say; sadly, Tev can't do this...

Note top quark myth: "W_0 fraction in top decays measures Y_t"

$$\mathcal{F}_0 = \frac{m_t^2/M_W^2}{1 + m_t^2/M_W^2}$$

Here, m_t is *kinematic* mass, not $Y_t \frac{v}{\sqrt{2}}$!

$\longrightarrow$ all EWSB models predict same $\mathcal{F}_0$, regardless of Y_t!

Top properties - CP violation?

Is there *CP*-violation in the top sector? We don't expect it.

- $p\bar{p}$ collisions at Tev2 are ideal!

$$A_t^{CP} = \frac{\sigma(t) - \sigma(\bar{t})}{\sigma(t) + \sigma(\bar{t})}$$

But single-top will barely be seen at Tevatron as it is...

- pp collisions at LHC make this more complicated – compare:

$$\langle \vec{s}_t \cdot \vec{p}_b \times \vec{p}_{\ell^+} \rangle \ \text{v.} \ \langle \vec{s}_{\bar{t}} \cdot \vec{p}_{\bar{b}} \times \vec{p}_{\ell^-} \rangle$$

or

$$p_T(\ell^+) \ \text{v.} \ p_T(\ell^-)$$

Both should work quite well [cf. Schmidt & Peskin, PRL(69)410(1992)]
(but p_T-imbalance subject to non-trivial detector effects)

STUDYING TOP QUARK PAIRS

Must study properties, but *how*?

Points to consider:

- $\sigma_{t\bar{t}}$ at Tev2: NLO+NLL+NNLL correc.'s $\sim +40\%$,
  theory uncer. $\sim 14\%$ but experimental uncer. $< 10\%$
  $\longrightarrow$ need full NNLO (hard!)

- $\sigma_{t\bar{t}}$ in simulation: what we need to include
  · NLO corrections & additional hard radiation
  · spin correlations
  · off-shell kinematics (Breit-wigner lineshape)
  · anomalous couplings
  ?? what's actually available??

- off-shell top production: difficult but crucial issue at LHC:
  top is largest bkg to WBF $H \rightarrow W^+W^- \rightarrow \ell^+\ell^- + X$
  (not yet an issue, but doubles naïve top bkg at LHC)
  $\longrightarrow$ *must* simulate fully off-shell [Kauer, PRD65:014021,2002]

Modeling hard jets in $t\bar{t}$ events

▶ Parton shower MC's underestimate hard jet activity in $t\bar{t}$:

· +1j rates not bad, but serious fine-tuning needed!

· $+ \geq 2j$ rates fall off dramatically compared to matrix elements

▶ Parton shower MC's don't know the correct normalization:

· kinematic distributions change at higher orders

▶ Only PSMC gets soft jets correct (log resummation via shower)

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This is addressed on two fronts: NLO, and LO large jet multiplicity

1. NLO event generation not easy:
   double-counting & matching issues
   how to handle negative weights?

2. For large hard-jet multiplicity, need exact $t\bar{t}+j^n$ matrix elements
   same problem as above → how to merge with PSMC?

NLO $t\bar{t}$ event generators

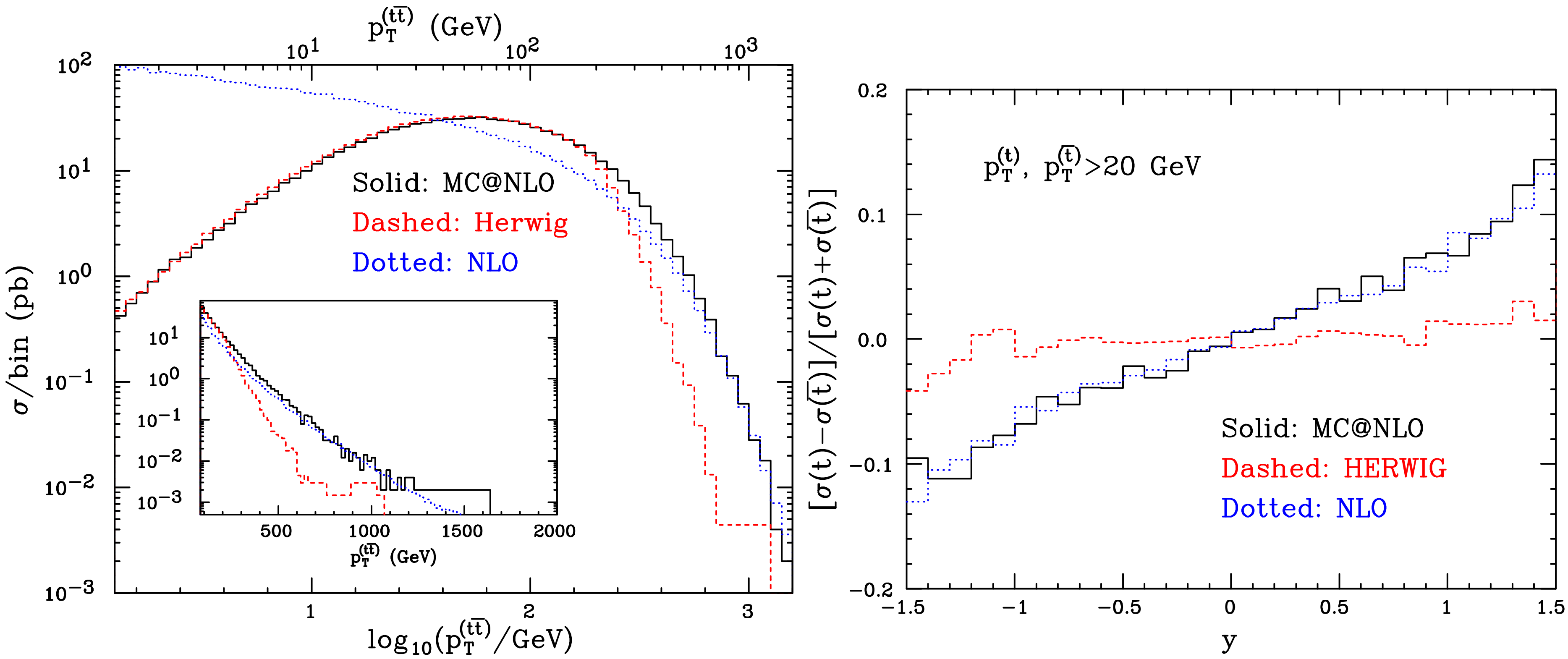
NLO event generator not easy: double-counting & matching issues

→ leading program is MC@NLO, interfaced to HERWIG

[Frixione & Webber, JHEP 0206:029(2002); +Nason, JHEP 0308:007(2003)]

○ M.E. matching by removing 1$^{\rm st}$ shower emission part from NLO calc.

○ formally proven to not double count; produces smooth dist'bns



○ only publicly-available NLO MC code; <u>but doesn't include spin</u>

Summary of available $t\bar{t}$ MC

Code	PSMC	events	NLO	$t\bar{t}$	t_s	t_t	t_{tW}	$+j^n$ME	BW	spin
HERWIG	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$			$\surd$	$\surd$
PYTHIA	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$			$\surd$	$\surd$
SHERPA	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$			$\surd$	$\surd$
ALPGEN		$\surd$		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		$\surd$
ACERMC		$\surd$		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
COMPHEP		$\surd$		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		$\surd$
MADEVENT		$\surd$		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
MC@NLO	*	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$			$\surd$	
MCFM			$\surd$	$\surd$	$\surd$	$\surd$	$\surd$			
SINGLETOP		$\surd$	**		$\surd$	$\surd$	$\surd$		$\surd$	$\surd$
TOPREX					$\surd$	$\surd$	$\surd$		$\surd$	$\surd$
ZTOP			$\surd$		$\surd$	$\surd$				
ONETOP			$\surd$		$\surd$	$\surd$				$\surd$

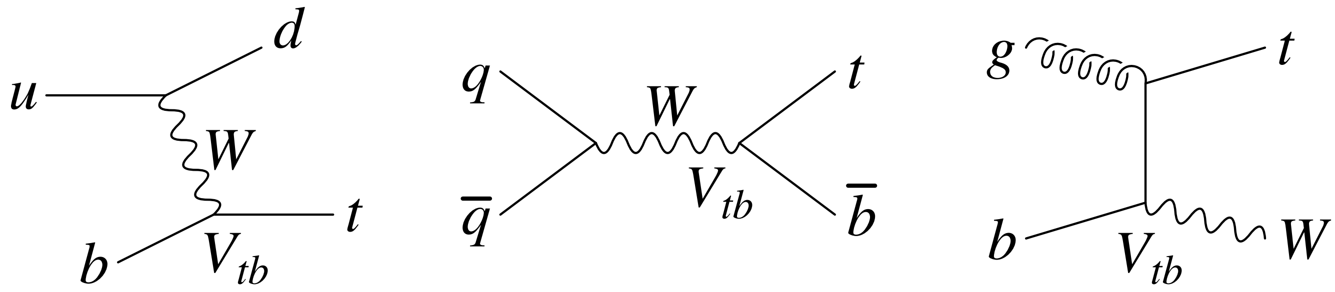
* = interfaces with HERWIG

** = partially

STUDYING SINGLE-TOP

Single-top production at Tev2/LHC

3 possibilities for production, all are $\propto V_{tb}^2$:



(a) (b) (c)

(a) *t*-channel

features forward-scattered light-quark jet

sensitive to FCNC's

(b) *s*-channel

accompanied by 2nd b-jet

sensitive to charged resonances

(c) tW-associated

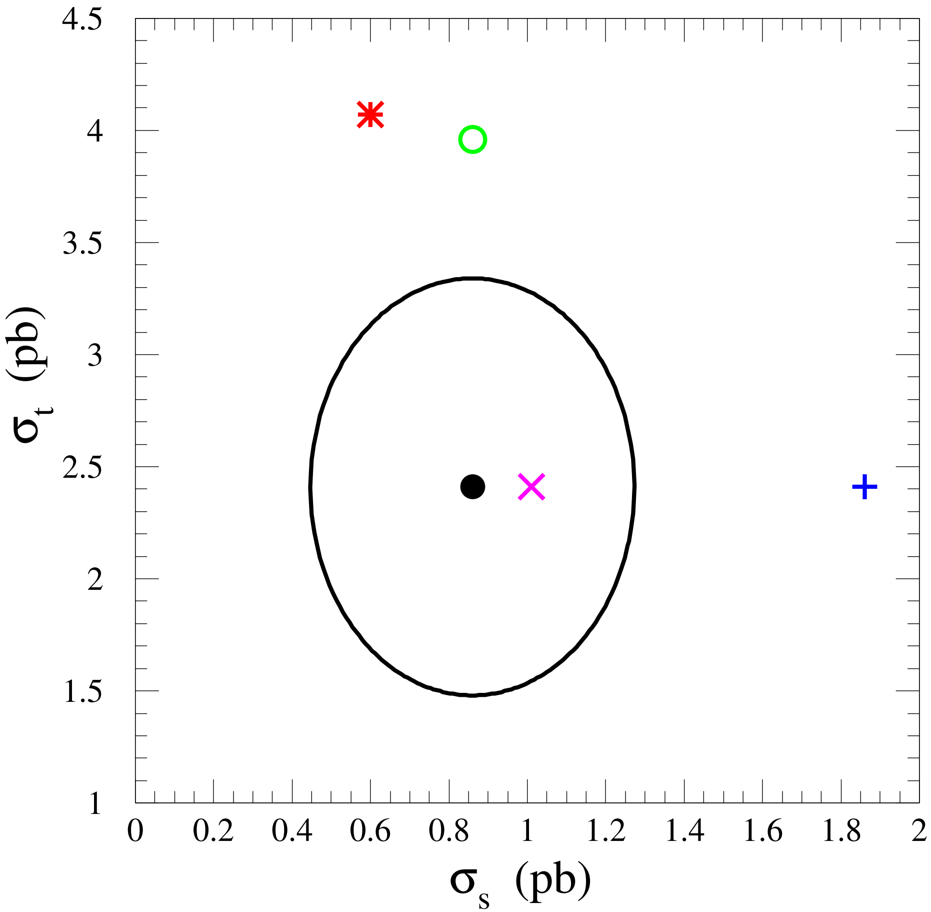
final-state real W; overlaps $t\bar{t}$ signature

most direct measure of V_{tb}, but low rate

s-,t-channels are windows to new physics

[Tait & Yuan, PRD(63)014018(2001)]

Some examples for Tevatron Run II:

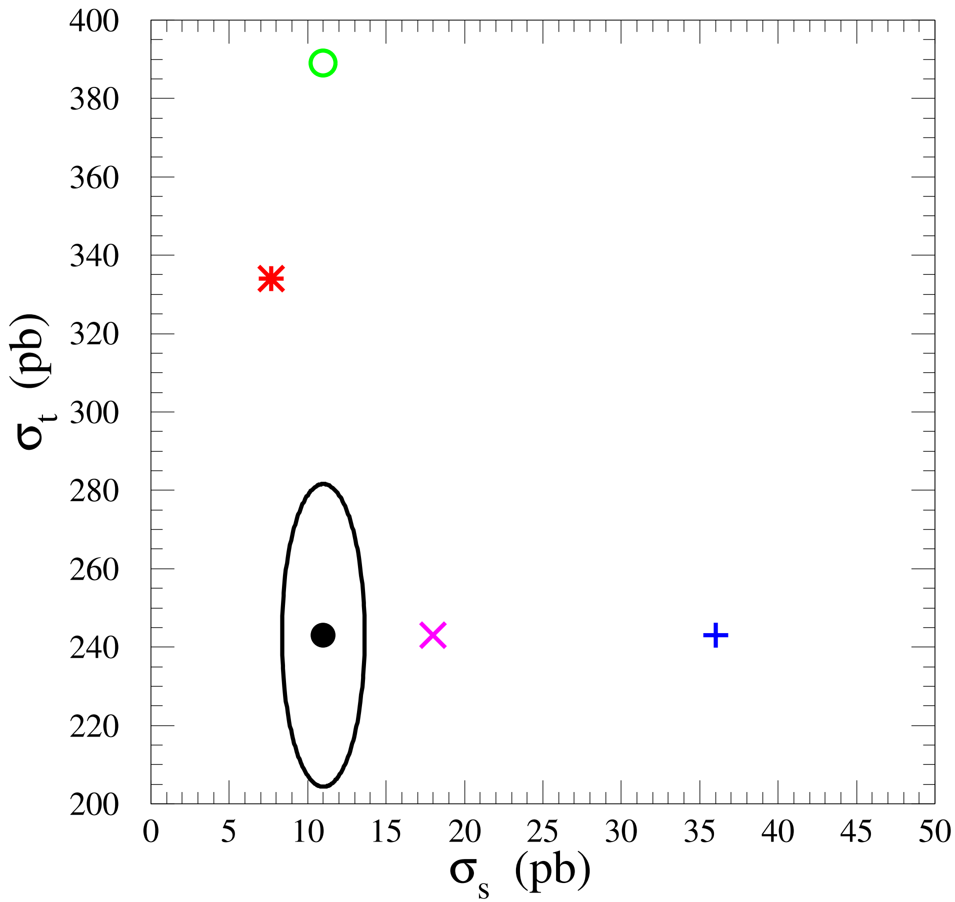


- ● SM
- ○ FCNC Z-t-c vertex, $\kappa = 1$
- × Topflavor, $M_{Z'} = 1$ TeV
- + Topcolor, $m_{\pi^\pm} = 250$ GeV
- $*$ 4th generation, $V_{tb} = 0.835$

s-,t-channels are windows to new physics

[Tait & Yuan, PRD(63)014018(2001)]

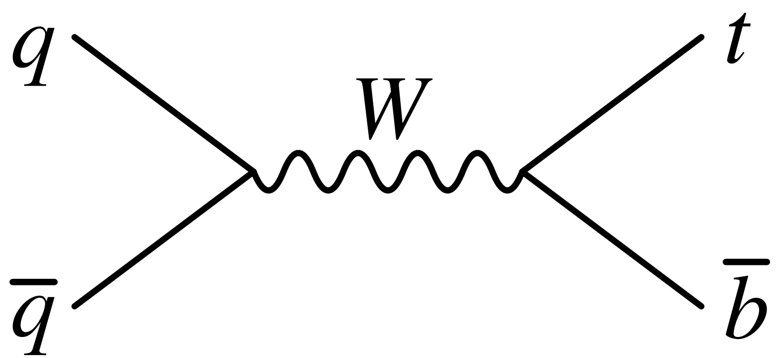
Same examples for LHC:



- ● SM
- ○ FCNC Z-t-c vertex, $\kappa = 1$
- × Topflavor, $M_{Z'} = 1$ TeV
- + Topcolor, $m_{\pi^\pm} = 450$ GeV
- ∗ 4^{th} generation, $V_{tb} = 0.835$

► This leaves tW-associated production as the "purest" measurement of V_{tb}

Theoretical issues for *s*-channel production

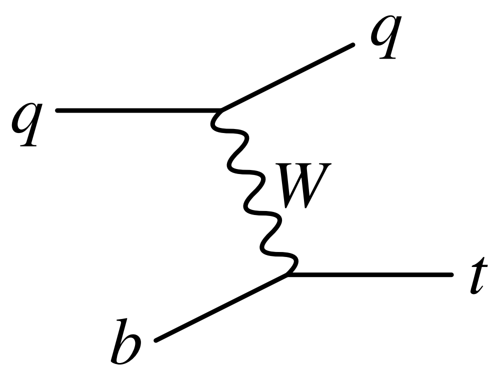


NONE!

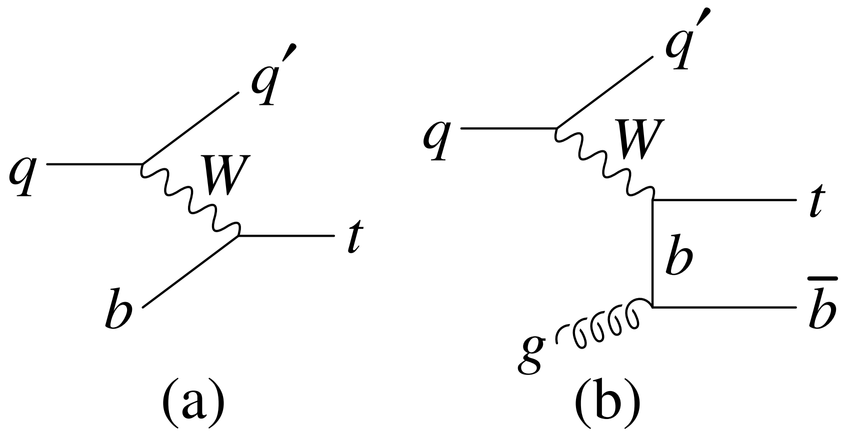
→ NLO distributions change negligibly – just apply K-factor

(doesn't mean $t\bar{t}$ background goes away...)

Theoretical issues for t-channel production



Is a little more complicated, because the above is really:



(b) if an extra b is observed at large scattering angle (high-p_T)

(a) b-q process only when the 2^{nd} b (gluon splitting) is collinear

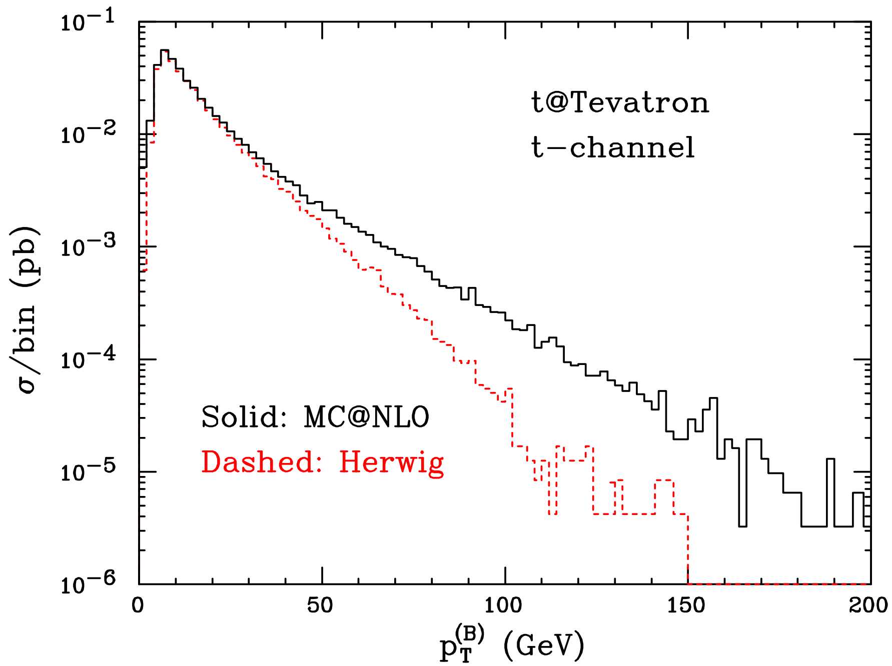
► NLO corrections change distributions significantly

New NLO Monte Carlo for t-channel prod'n

▶ MC@NLO [Frixione, Laenen, Motylinski & Webber, JHEP 0306:092(2006)]

· technically harder than $t\bar{t}$ due to final-state collinearities

· again produces smoothly-merged distributions w/ HERWIG



· confirms feasibility of MC@NLO formalism for general processes

· but no spin correlations!

▶ SINGLETOP [Boos *et al.*; see TeV4LHC proceedings]

· not as complete as MC@NLO, but is 2nd practical package

Discerning s, t-channel signals

Advanced variable-discriminant LO analysis by Bowen *et al.* [PRD(72)074016(2005)] now @ NLO by Sullivan [PRD(72)094034(2005)].

New features:

· full NLO: confirms LO angular correlations are ok

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$\rightarrow$ top-decay b has smallest $\cos\theta^t_{\ell j_i}$ in candidate t rest frame

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· full NLO: confirms LO angular correlations are ok

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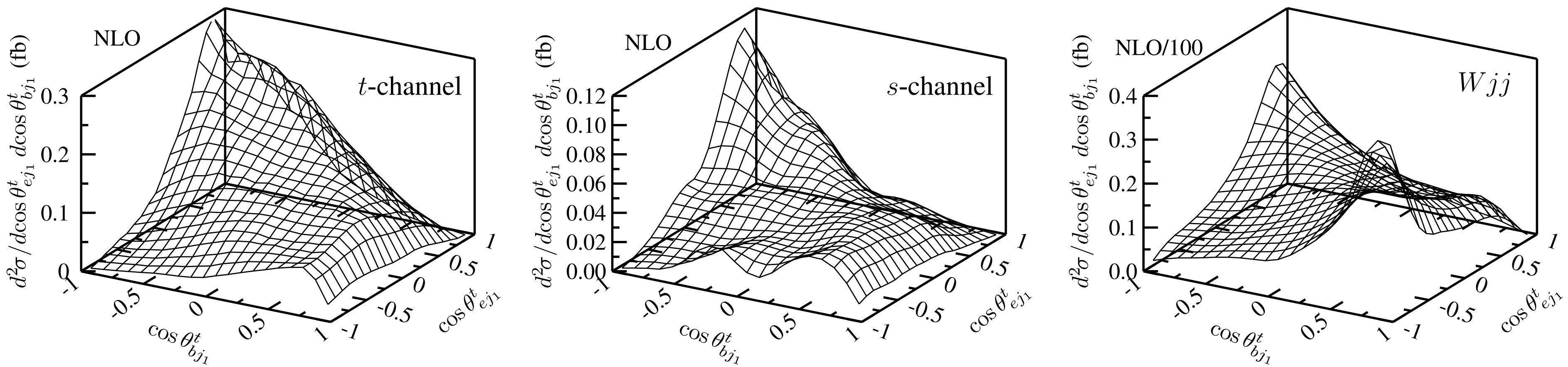
$\rightarrow$ top-decay b has smallest $\cos\theta^t_{\ell j_i}$ in candidate t rest frame

· full angular correlation matrix between chosen b and j,ℓ

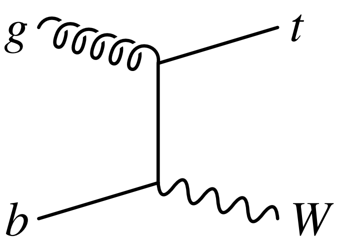


$\rightarrow$ using *both* $\cos^t_{bj_1}$ and $\cos^t_{\ell j_1}$ dramatically improves S/B

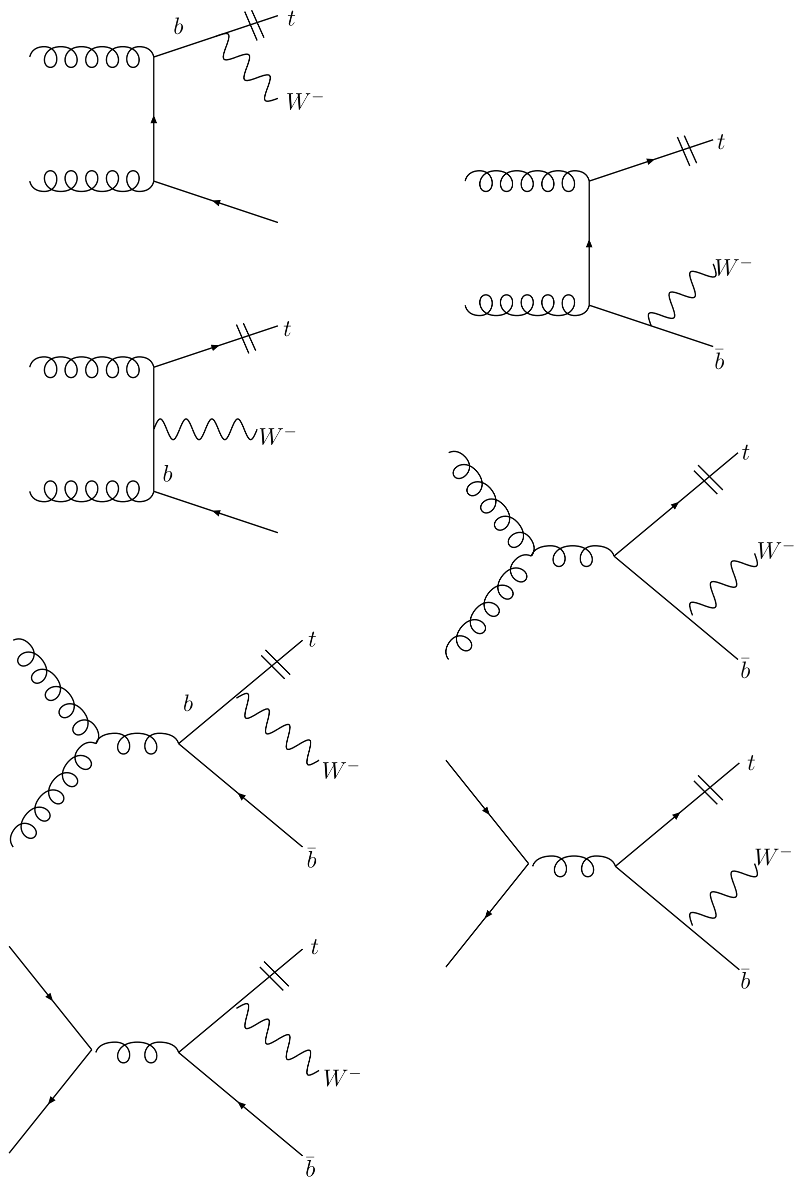
· superior to all previous analyses

Theoretical issues for tW-associated production

Even worse overlap issue than t-ch.!



is really $\longrightarrow$



(a) (b)

○ how to deal with $t\bar{t}$ overlap??

Theory solution for tW-associated production

[Alwall, Campbell, Maltoni & Willenbrock, 2006; see Portugal talk]

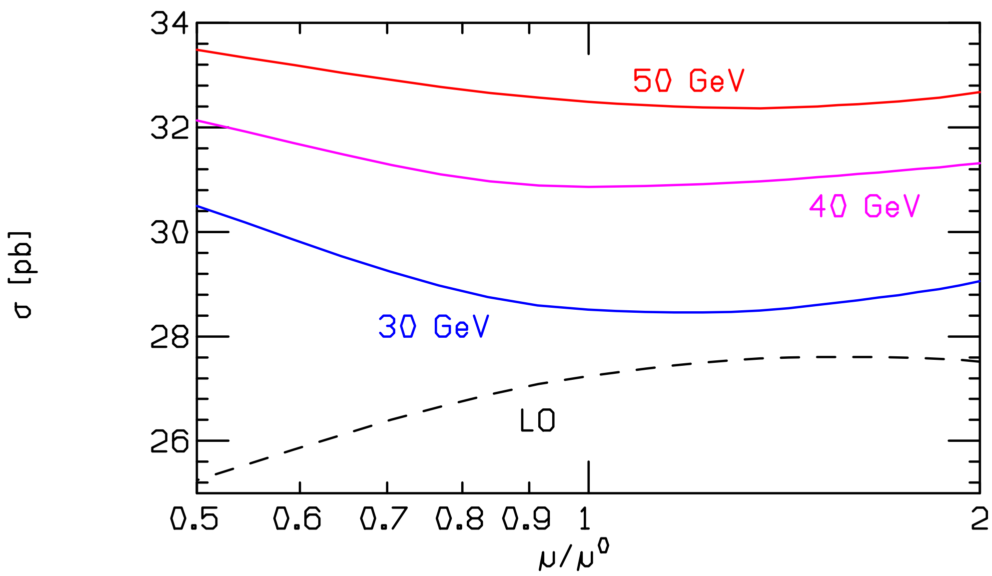
Core issue: at high-p_T, 2^{nd} b gives strong interference with $t\bar{t}$;
tW is ill-defined (to all orders).

Previous schemes to address either can't give event generators or don't preserve gauge invariance.

Proper solution: Veto the 2^{nd} b, demanding only 1 be observed.
$\rightarrow$ calculate at NLO with $\mu_F \equiv p_T^{\text{veto}}$

Nice and stable! $\longrightarrow$

[Campbell & Tramontano, NPB(726)2005]



SUMMARY

- The $m \sim 175$ GeV pole fits SM top, but not fully verified!
- Tev2 has verified charge, can maybe make rough $t\bar{t}\gamma$ and some other measurements ($t\bar{t}$ spin correlations?)
- Right now, theory lags far behind experimental capability.
  · new tools available, but still long way to go
- NLO generators are truly wonderful,
  but now need decays w/ spin correlations
- LHC will be great for top physics,
  but top is also worst background to new physics
  $\rightarrow$ Tev2 is opportunity to improve/test tools before the flood