Event generators for top quark production and decays

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Why is the top quark an interesting and worthwhile object to study ?

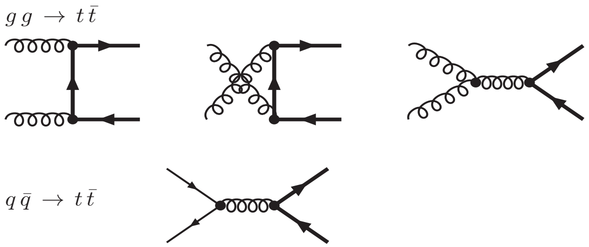
- ◇ the processes with top quark provide a very precise test for perturbative SM
- ◇ we would like to know if the top-quark is just an ordinary quark, or if it is exotic in some way
- ◇ the top-quark may be useful to discover new particles
- ◇ events containing top quarks are backgrounds to new physics

all top-quark production properties and decays are evaluated within the Standard Model with high accuracy without any phenomenological parameters

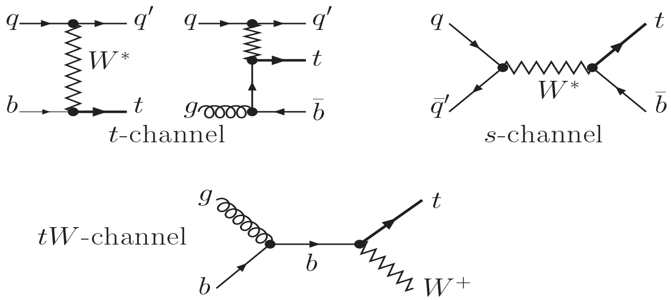
- ◇ the total cross section production as well as the differential distributions are calculated with $\mathcal{O}(10\%)$ accuracy
- ◇ the top quark decays through ONE decay channel, $t \rightarrow bW^+$ (other decay channels have very small BR)
- ◇ due to a very small life-time of t-quark ($\sim 10^{-24}$ sec, $\tau_t \ll 1/\Lambda_{\rm QCD}$) we could not expect the formation top-hadrons, $T(t\bar{t})$- or $M(t\bar{q})$-mesons and $\Lambda(tqq)$-baryons

BASIC PROCESSES

- $t\bar{t}$ production (QCD)



- single top production (electro-weak)



- $t\,\bar{t}\,b\,\bar{b}$
- $t\,\bar{t}\,H$, $t\,\bar{t}\,W^{\pm}$, $t\,\bar{t}\,Z$
- t-quark production due to new interactions

  ◇ how to include top decays
  ◇ higher order corrections

TOP DECAYS

to calculate an exact amplitude
practical realization - use a Narrow Width Approximation (NWA)

$$\int dp_t^2 \frac{1}{(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2} = \frac{\pi}{m_t\Gamma_t}\delta(p_t^2 - m_t^2) + \mathcal{O}(\ldots)$$

$\Longrightarrow$ t-quark is on-shell object

◇ how to include top decays ?

◇ how to reproduce Breit-Wigner resonance shape ?

◇ how to include top spin (polarization) ?

top decays

- only <u>one</u> decay channel within SM
  - $\oplus$ $t \longrightarrow bW, \quad W \longrightarrow f\bar{f}', \qquad t \longrightarrow bW(99\%), sW, dW$

$$|M(t \to b\ell^+\nu)|^2 \propto \frac{(p_b p_\nu)(p_t p_\ell)}{(p_W^2 - M_W^2)^2 + \Gamma_W^2 M_W^2}$$

- other channels
  - $\diamond$ $t \longrightarrow bW^*Z^* \;\longrightarrow\; bf\bar{f}'\ell^+\ell^-$
  - $\oplus$ $t \longrightarrow bH^+$
  - $\oplus$ $t \longrightarrow qg, \; qZ, \; q\gamma$ (FCNC)
  - $\diamond$ $t \longrightarrow ch$
  - $\diamond$ $t \longrightarrow bW(\longrightarrow f\bar{f}')$ with anomalous interactions ($V + A$, tensor couplings)

Breit-Wigner resonance shape

- usage Narrow Width Approximation (NWA) assumes that the top-quark in any event has the same default mass (i.e. m_t)
- modified NWA (C.P. Yuan)

  ◇ generate new $\tilde{m}_t$ for all t-quarks in the event by using of Breit-Wigner distribution $\left(\propto \frac{1}{(p_W^2 - M_W^2)^2 + \Gamma_W^2 M_W^2}\right)$

  ◇ calculate the squared matrix element ($|M|^2$) with this $\tilde{m}_t$

$\Longrightarrow$ can be used for the single-top production processes, not for $t\bar{t}$

- "smearing-mass" method (PYTHIA)

  ◇ calculate $|M|^2$ with the default m_t

  ◇ for each t_i-quark in the event generate its own new $\tilde{m}_t(t_i)$ by using Breit-Wigner distribution

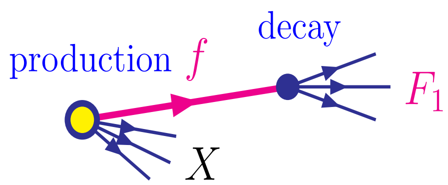
  ◇ re-evaluate the energies of all t-quark(s) in the event

$$t\bar{t} \quad : \quad E^*(t) = E^*(\bar{t}) = \sqrt{\hat{s}}/2 \quad \Longrightarrow \quad \tilde{E}^*(t) = \frac{\sqrt{\hat{s}} + \tilde{m}^2(t) - \tilde{m}^2(\bar{t})}{2\sqrt{\hat{s}}}$$

can be used for event with any number of top quarks (t, $t\bar{t}$, ...)

how to include top polarization

- the helicity amplitudes /P. Richardson, JHEP 0111 (2001) 029, hep-ph-0110108/
- an equivalent method (S. Jadach and Z. Was, *Acta Phys. Polon.* B**15** (1984) 1151) is realized in TAUOLA package



$|M|^2$ could be represented in the “factorized” form

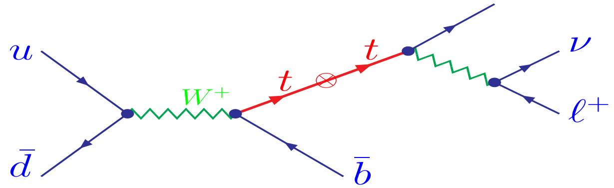
$$|M(A \to F_1 + X)|^2 = \frac{\pi}{\Gamma_f m_f}\delta(p_f^2 - m_f^2) \times |M_P^0(A \to f + X)|^2 \;\; (1 + v_i h_i) \;\; |M_D^0(f \to F_1)|^2$$

$$|M_P(A \to f + X)|^2 = |M_P^0(A \to f + X)|^2 (1 + (vs))$$

$|M^0|^2$ describes the production (decay) of **unpolarized** top-quark, $(p_f s) = 0$

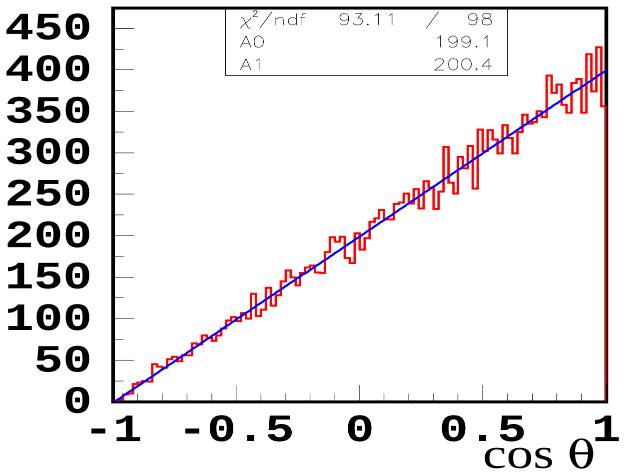
- $t \to b\ell^+\nu \quad |M|^2 \propto \frac{(p_b p_\nu)(p_t p_\ell)}{(p_W^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \left[1 - \frac{m_t (p_\ell s)}{(p_t p_\ell)}\right] \Rightarrow v^\mu = -\frac{m_t p_\ell^\mu}{(p_t p_\ell)} \;\Rightarrow\; -\vec{n}_\ell^*$

- example: $u\bar{d} \longrightarrow t\bar{b}$ with $t \longrightarrow b(W^*)\nu\ell$



$$|M|^2 \propto \frac{(p_u p_{\bar{b}})(p_t p_{\bar{d}})}{(p_{w1}^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \frac{(p_b p_\nu)(p_t p_\ell)}{(p_{w2}^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \left(1 + \vec{n}_\ell^* \vec{n}_{\bar{d}}^*\right)$$

$\vec{n}_\ell^*$ and $\vec{n}_{\bar{d}}^*$ are directions of ℓ^+ and $\bar{d}$-quark momenta in t-quark rest frame



$$\cos\theta \equiv \vec{n}_\ell^* \vec{n}_{\bar{d}}^*$$

TOP PRODUCTION WITH ADDITIONAL JETS

◇ ALPGEN, CompHEP, Madevent, MCFM

merging of multi-jet ME and shower evolution

- to eliminate the dependence of physical cross-section on the cuts used at the generator level
- to eliminate the double counting, where jets can arise from both the higher-order calculation and from the hard emission during the shower evolution
- to construct inclusive event samples describing arbitrary jet multiplicities, free of double-counting

• CKKW prescription

/Catani, Krauss, Kuhn, Webber, JHEP 0111:063,2001, L.Lonnblad JHEP 0205:046,2002/

◇ separate multi-jet phase-space into

- ◇ domains covered by the ME calculation
- ◇ domains covered by the shower evolution

◇ Sudakov reweight the ME weight to reproduce the probability of an exclusive N-jet final state from the inclusive parton-level N-jet rate. This allows to add parton-level event samples of different jet multiplicity

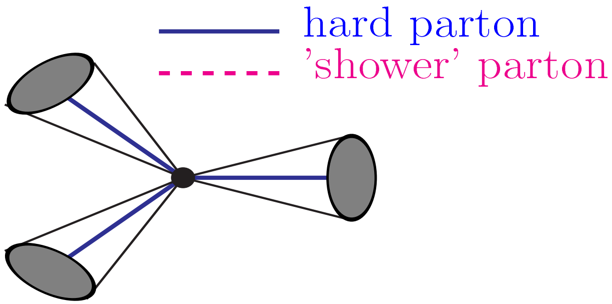
◇ veto showers with hard emissions which are supposedly already included in the higher-order ME phase-space ($\Longrightarrow$ requires consistent definition of Sudakov weights in the ME and shower)

MLM matching

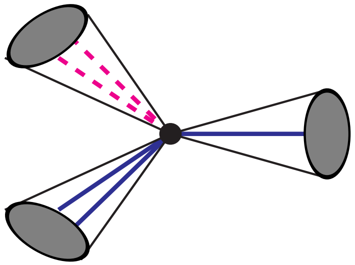
an alternative, simpler prescription of Mangano

- generate parton-level configurations for a given hard-parton multiplicity N_{part}, with partons constrained by $p_T > p_{T\,min}$ and $\Delta R_{jj} > R_{min}$
- perform the jet showering, using the default HERWIG/PYTHIA algorithms
- process the showered event (before hadronization) with a cone jet algorithm, defined by $E_{T\,min}$ and R_{jet})
- match partons and jets:
  - ◇ for each hard parton, select the jet with min $\Delta R_{j-parton}$
  - ◇ if $\Delta R_{j-parton} < R_{jet}$ the parton is "matched"
  - ◇ a jet can only be matched to a single parton
  - ◇ if all partons are matched, keep the event, else discard it
- this prescription defines an inclusive sample of $N_{jet} = N_{part}$ jets
- define an exclusive N-jet sample by requiring that the number of reconstructed showered jets N_{jet} be equal to N_{part}
- after matching, combine the exclusive event samples to obtain an inclusive sample containing events with all multiplicities

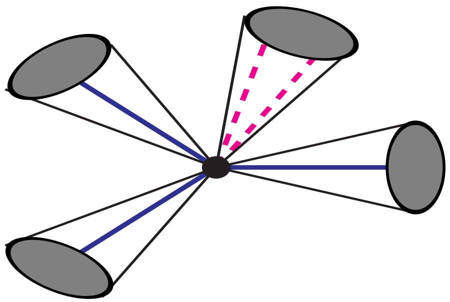
- few examples of matching:



event matched, $N_{jet} = N_{part} = 3$, keep



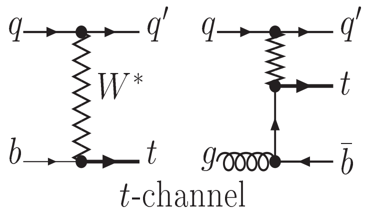
NOT matched, $N_{jet} = N_{part} = 3$,
but $N_{matched} = 2$, throw away,
collinear double-logarithmic double-counting



event matched, $N_{jet} > N_{part} = 3$,
throw away for exclusive samples

SINGLE TOP PRODUCTION. T-channel

- double counting problem: t-channel : $2 \to 2$ versus $2 \to 3$

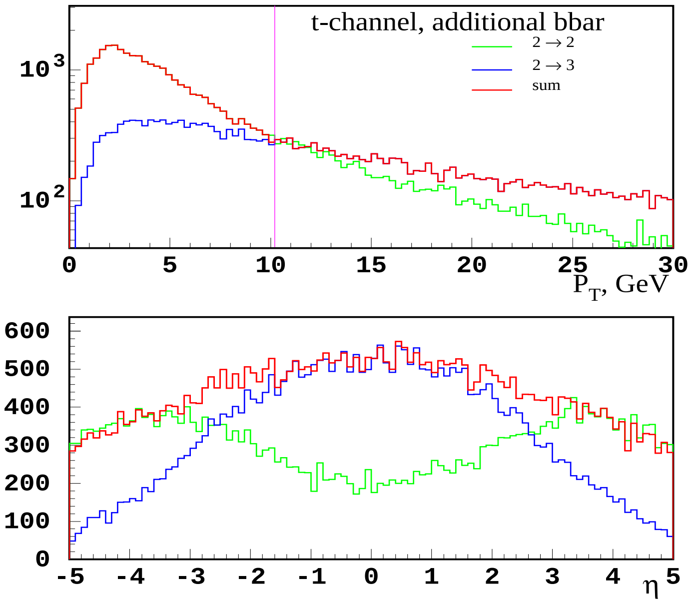


SingleTop: E.Boos, L.Dudko, V.Savrin, CMS Note 2000/065 (2000)

TopReX: S.Slabospitsky and L.Sonnenschein

$2 \to 2 \; qb \to q't \; + \; \bar{b}$ from PYTHIA

$2 \to 3 \; qg \to q't \; + \; \bar{b}$ from the hard process



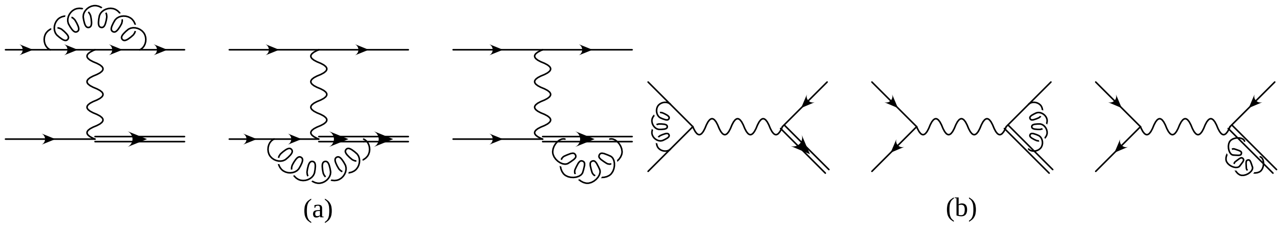
$$\sigma(pp \to tX) = \sigma^{(2\to 2)}(pp \to tq;\, p_T(\bar{b}_{\rm PYT}) < p_0)$$
$$+\sigma^{(2\to 3)}(pp \to tq\bar{b}_{\rm hard};\, p_T(\bar{b}) \geq p_0)$$

with $p_0 \simeq 10$ GeV

NLO CORRECTIONS

substantial progress in single-top production

the radiation effects are included in the initial and final states, as well as into decays



- **ZTOP** B.Harris, E.Laenen, L.Phaf, Z.Sullivan, S.Weizierl, PR D66 (2002) 054024;

Z.Sullivan, PR D70 (2004) 114012

- **MCFM** J.Campbell, R.K.Ellis, F.Tramontano, PR D70 (2004) 094012

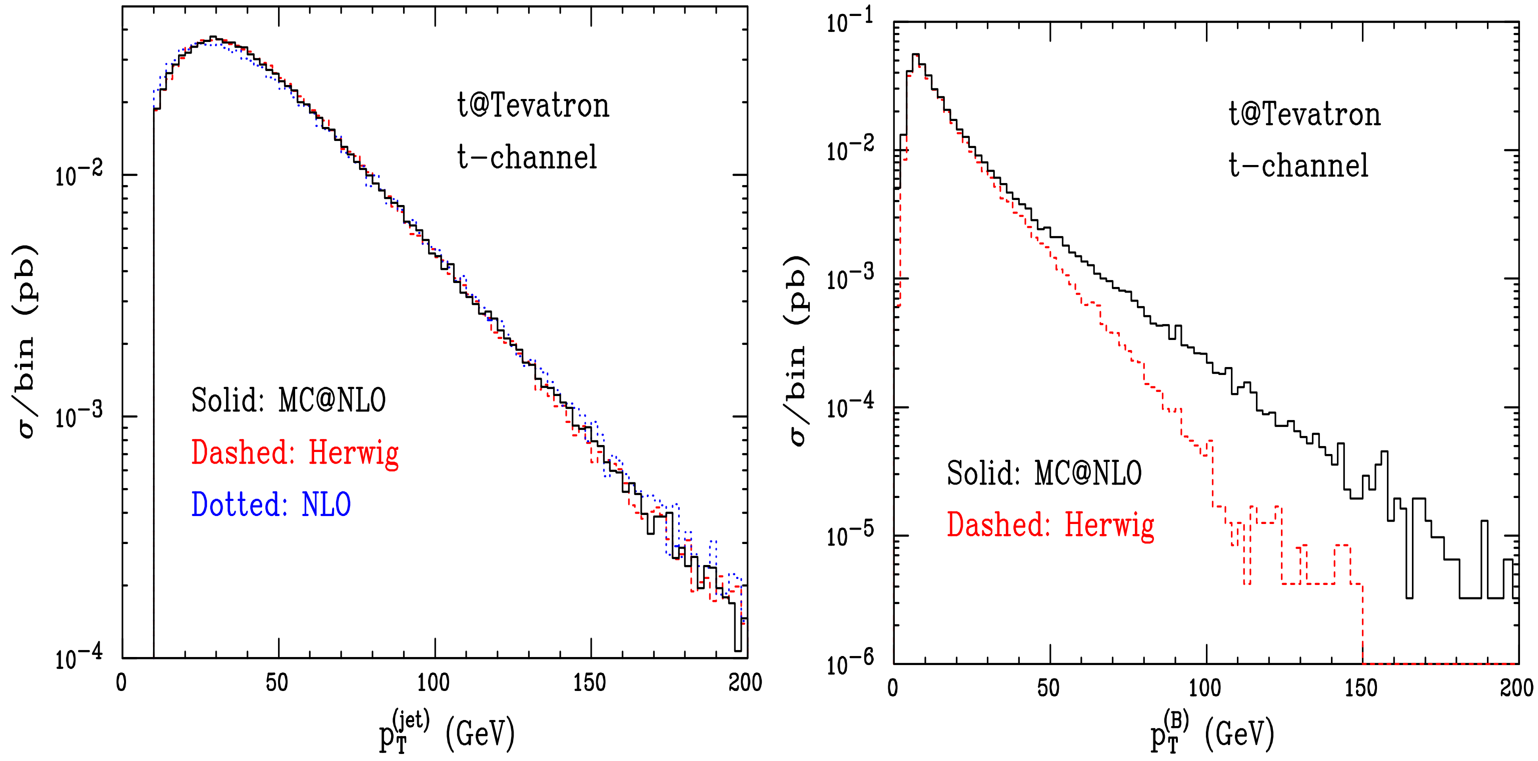
- Qing-Hong Cao, C.-P.Yuan, PR D71 (2005) 054022;

Qing-Hong Cao, R.Schwienhorst, C.-P.Yuan, PR D71 (2005) 054023;

Qing-Hong Cao, R.Schwienhorst, J.A.Benitez, R.Brock, C.-P.Yuan, PR D72 (2005) 094027

- **MC@NLO** S.Frixione, E.Laenen, P.Motylinski, B.R.Webber, hep-ph/0512250 (2005)

◇ p_T distribution for the higest p_T and b jets



EVENT GENERATORS

M.Dobbs et al. *"Les Houches Guidebook to Monte Carlo Generators for Hadron Collider Physics"*, hep-ph/0403045

- General purpose generators provided full simulation of event
  - ◇ hard process
  - ◇ showering
  - ◇ hadronization
  - ◇ decay of the unstable hadrons
  - ◇ underlying event simulation

- HERWIG

G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour, B.R. Webber

http://hepwww.rl.ac.uk/theory/seymour/herwig/

HERWIG is particularly sophisticated in its treatment of the subsequent decay of unstable resonances, including full spin correlations for most processes

processes: $t\bar{t}$, single top, $t\bar{t}H$, $Zt\bar{t}$, $gb \to tH^+$

- ISAJET H. Baer, F.E. Paige, S.D. Protopescu, and X. Tata, http://www.phy.bnl.gov/ isajet/

processes: $t\bar{t}$, no spin correlations

- PYTHIA T.Sjostrand, L.Lonnblad, S.Mrenna, P.Skands

http://www.thep.lu.se/tf2/staff/torbjorn/Pythia.html

processes: $t\bar{t}$, single-top (t, s channels), $t\bar{t}H$, $gb \to tH^+$, no spin correlations

- SHERPA T.Gleisberg, F.Krauss, A.Schalicke, S.Schumann, J.Winter

http://www.physik.tu-dresden.de/ krauss/hep/

is a new multi purpose event generator with a powerful matrix element generator (AMEGIC++), processes ?

Tree level matrix element generators

an information about initial and final-state partons (the masses, the momenta, the spins, the colors, and the flavors) is stored in the “Les Houches” format

- ALPGEN M.L.Mangano, M.Moretti, F.Piccinini, R.Pittau, A.D.Polosa

http://m.home.cern.ch/m/mlm/www/alpgen/

dedicated to the study of multi-parton hard processes in hadronic collisions.
processes: $t\bar{t}$ + up to 6jets, single top: tq, tb, tW, tbW (no extra jets), $t\bar{t}t\bar{t}$ + up to 4jets, $t\bar{t}b\bar{b}$ + up to 4jets, $Ht\bar{t}$ + up to 4jets, $W/Zt\bar{t}$ + up to 4jets, spin correlations are included

- AcerMC B.P.Kersevan, E.Richter-Was, http://borut.home.cern.ch/borut/ (see talk of B.Krersevan)

is dedicated for generation of the Standard Model background processes in pp collisions at the LHC
processes: $t\bar{t}$, single top (?), $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$, $W/Zt\bar{t}$, spin correlations are included

- CompHEP

E.Boos, M.Dubinin, V.Edneral, V.Ilyin, D.Kovalenko, A.Kryukov, A.Pukhov, V.Savrin, S.Shichanin, A.Semenov

http://theory.sinp.msu.ru/dokuwiki/doku.php?id=chep:comphep

a package for evaluation of Feynman diagrams and integration over multi-particle phase space

processes: $t\bar{t}$, single top, (? $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$,) $W/Zt\bar{t}$, spin correlations are included

- MadEvent F.Maltoni, T.Stelzer

http://madgraph.hep.uiuc.edu/index.html

combines MADGRAPH matrix element calculations with phase space integration

processes: $t\bar{t}$ + up to 3jets, single top (?), $t\bar{t}b\bar{b}$ + up to 1jet, $Ht\bar{t}$ up to 2jets

- MC@NLO S. Frixione, P. Nason, B. Webber

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

combines a Monte Carlo event generator with exact NLO calculations of rates for QCD processes at hadron colliders

processes: $t\bar{t}$, single top (t- and s-channel)

- SingleTop E.Boos, L.Dudko, V.Savrin, A.Sherstnev

based on the CompHEP

processes: t-channel single top production ($2 \to 2$ + $2 \to 3$, spin correlations are included

- TopReX S.Slabospitsky, L.Sonnenschein

http://cmsdoc.cern.ch/ spitsky/toprex/toprex.html

processes: $t\bar{t}$, single top (t-, s-, and tW-channel), $W/ZQ\bar{Q}, \;\; Q = c, b, t$, spin correlations are included

- MCFM J.Campbell, K.Ellis, http://mcfm.fnal.gov/

matrix elements are included at next-to-leading order and incorporate full spin correlations

processes: $t\bar{t}$, single top (t- and s-channel), $Ht\bar{t}$, $W/Zt\bar{t}$

- ZTOP B.Harris, E.Laenen, L.Phaf, Z.Sullivan, S.Weizierl

full NLO-corrections to single top production (t- and s-channel)

EVENT GENERATOR TOPREX

URL = http://cmsdoc.cern.ch/ spitsky/toprex/toprex.html

(S. Slabospitsky, L. Sonnenschein, *CPC* **148**, 87 (2002) [hep-ph/0201292])

- dedicated for simulation of "external" process with PYTHIA:

	$gg\ (q\bar{q}) \longrightarrow t\bar{t}$
t-channel	$qb \longrightarrow q' t \quad + \quad qg \longrightarrow q' t\bar{b}$
tW-channel	$gb \longrightarrow tW$
s-channel	$q\bar{q}' \longrightarrow W^* \longrightarrow t\bar{b}$
	$q\bar{q}' \longrightarrow H^{\pm *} \longrightarrow t\bar{b}(\tau\nu)$ + $q\bar{q}' \longrightarrow H^{\pm *} \longrightarrow t\bar{b}(\tau\nu)$ + jet
	$q\bar{q} \longrightarrow W^*/Z^* Q\bar{Q},\ W^*/Z^* \longrightarrow f\bar{f},\ Q = c, b, t$
	$gg \longrightarrow ZZ$
FCNC	$gu(c) \longrightarrow t \longrightarrow bW$

- top-quark is on-shell, the polarization of top is included

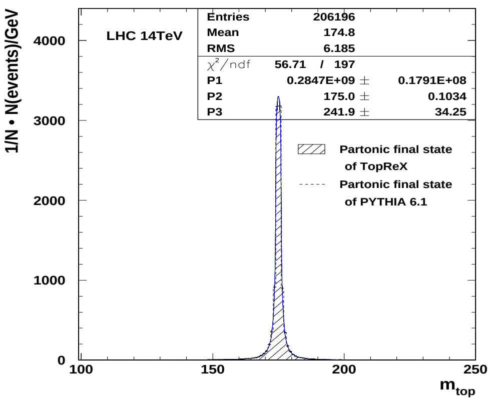
included decay channels:

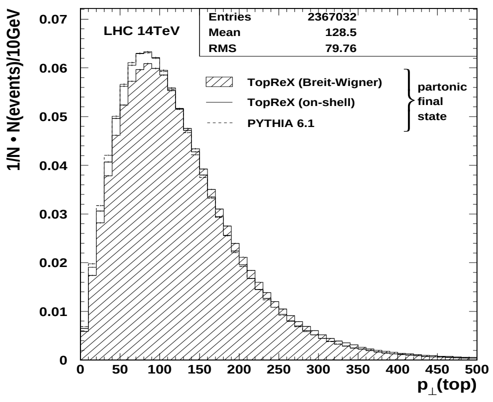
$$t \longrightarrow bW^+,\ \longrightarrow bH^+,\ \longrightarrow q\gamma,\ qg,\ qZ$$
$$W, Z \longrightarrow f\bar{f}',\quad f = q, l, \nu$$
$$H^{\pm} \longrightarrow f\bar{f}',\quad f = q, l, \nu$$

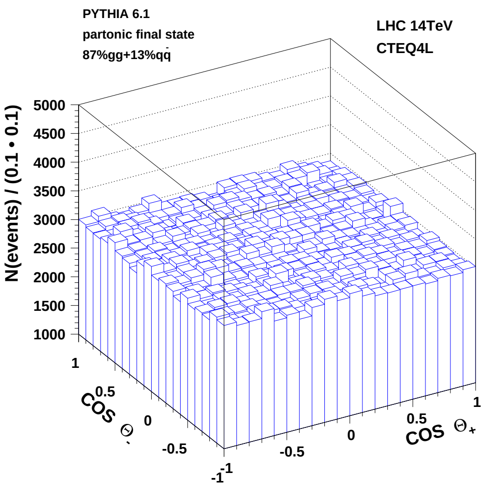
- at present TopReX could be used :
  - ◇ as a stand-alone generator (parton level)
  - ◇ with PYTHIA for hadronization, fragmentation and decays

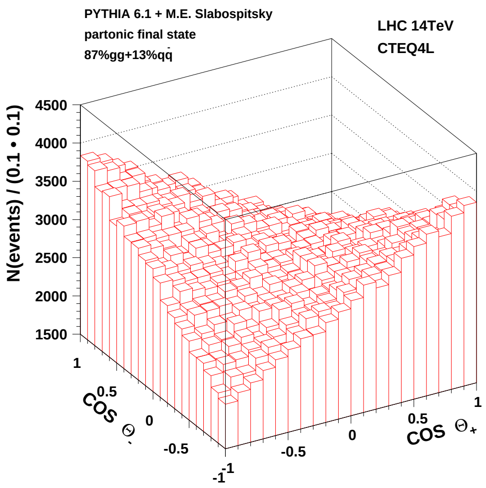
PROCESSES

- $t\bar{t}$ production (LO $|M|^2$) $gg(q\bar{q}) \to t\bar{t}$









$$pp \to t\bar{t} \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}X$$

• Electro-weak top production

three processes contributed to electro-weak (single) top production

t-channel $qb \to q' t \quad + \quad qg \to q' t\bar{b}$

tW-channel $gb \to tW$

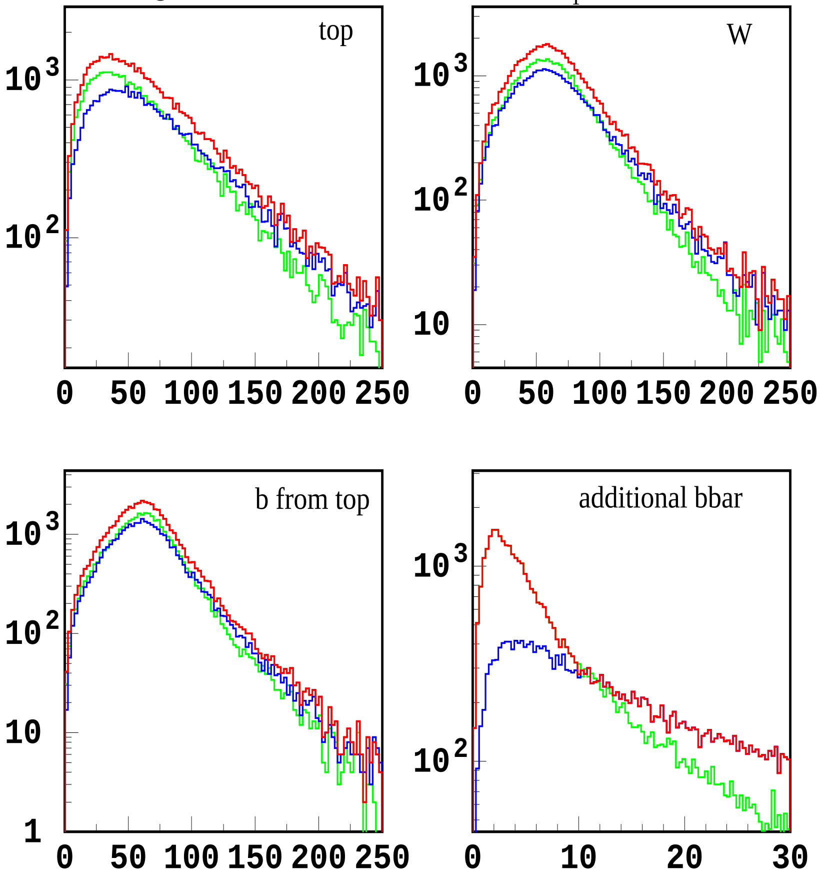
s-channel $q\bar{q}' \to W^* \to t\bar{b}$

• double counting problem: t-channel : $2 \to 2$ versus $2 \to 3$

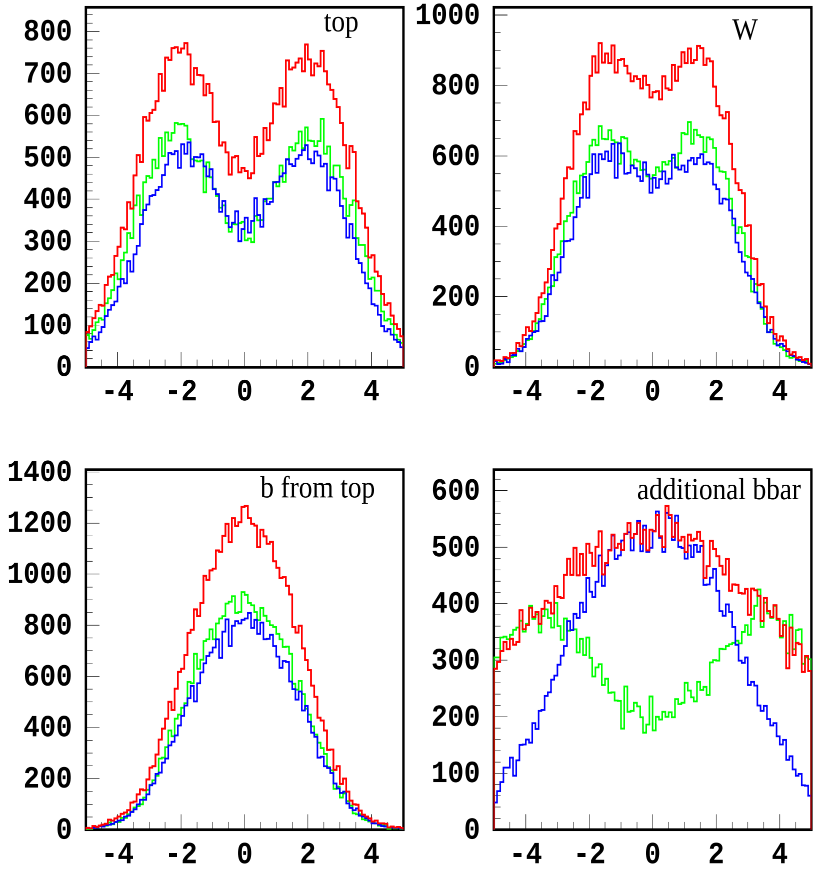
$$\begin{aligned} \sigma(pp \to tX) &= \sigma^{(2\to2)}(pp \to tq;\, p_\top(\bar{b}_{\rm PYT}) < p_0) \\ &+ \sigma^{(2\to3)}(pp \to tq\bar{b}_{\rm hard}; p_\top(\bar{b}_{\rm hard}) \geq p_0) \text{with} \quad p_0 \simeq 10 \quad \text{GeV} \end{aligned}$$

generate simultaneously the both $2 \to 2$ and $2 \to 3$ processes and perform the adjustment of p_0 parameter during TopReX run (in PYEVNT routine)

Wg channel: $2 \to 2$, $2 \to 3$, and sum: P_T-distribution



Wg channel: $2 \to 2$, $2 \to 3$, and sum: η-distribution

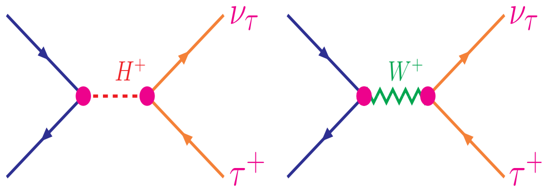


- s-channel charged Higgs production due an annihilation of the light quarks

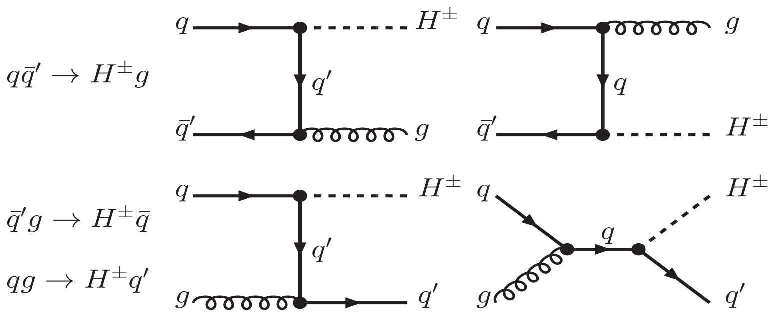
$$\mathcal{L}_{H^\pm f f} \propto H^+ \left[\bar{U} \left(m_U \cot\beta\, P_L + m_D \tan\beta\, P_R \right) D + \left(m_\tau \tan\beta \right) \, H^+ \; \bar{\nu} \; P_R \; \tau \right]$$

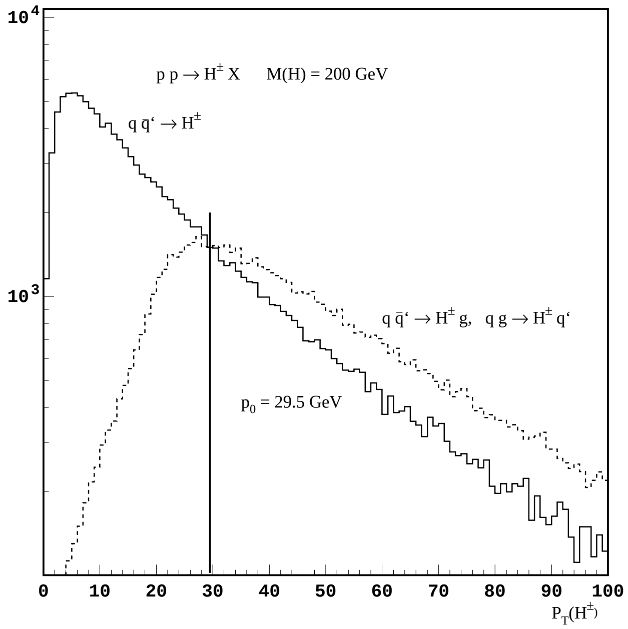
the running values of m_q are used for evaluation of $qH^\pm q'$ couplings

$$q\,\bar{q}' \;\to\; H^\pm, \;\to t\bar{b}(\tau^\pm \nu_\tau), \quad q = d, u, s, c, b$$



$$q\,\bar{q}' \;\to\; H^\pm\, g, \quad q\, g \;\to\; H^\pm\, q', \quad \bar{q}'\, g \;\to\; H^\pm\, \bar{q}$$





$$\sigma(pp \to H^\pm X) = \sigma(pp \to H^\pm;\, p_\top(H) < p_0)$$
$$+\sigma(pp \to H^\pm\, jet;\, \hat{k}_\top > \hat{k}_0, p_\top(H) \geq p_0)$$

$\hat{k}_0 \approx 20$ GeV, and $p_0 = 30$ GeV for $M_H = (200 - 400)$ GeV

- $q\bar{q}' \to W\, Q\bar{Q}, \quad Q = c, b, t$
- $q\bar{q}(gg) \to Z\, Q\bar{Q}, \quad Q = c, b, t$
- $gu(c) \to t \to bW$

top decay channels

- $t \to bW^+$ with $W^\pm \to q\bar{q}'$, $\to \ell^\pm \nu_\ell$
- t-quark decays due to anomalous Flavor Changing Neutral couplings

$$\mathcal{L} = -g_s \frac{\kappa_g}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f^g + h^g \gamma_5) q G^a_{\mu\nu} - e \frac{\kappa_\gamma}{\Lambda} t\sigma^{\mu\nu} (f^\gamma + h^\gamma \gamma^5) q\, A_{\mu\nu} - \frac{g\kappa_Z}{2\cos\theta_W} \bar{t}\gamma^\mu (f^Z - h^Z \gamma_5) q Z_\mu$$

$q = u, c$, Λ is the New Physics cut-off, $|f^V|^2 + |h^V|^2 = 1$
the following decay channels are included:

$$\begin{aligned} t &\to g\ q, \quad q = u, c \\ t &\to \gamma\ q, \quad q = u, c \\ t &\to g\ Z, \quad q = u, c; \quad Z \to q\bar{q};\ \ \ell^+\ell^-;\ \ \nu\bar{\nu} \end{aligned}$$

- charged Higgs in top decays

$$\begin{aligned} t &\to bH^+ \\ t &\to bH^*(\to t^*\bar{b};\quad t^* \to bW^\pm) \ \Rightarrow\ t \to bW^\pm \bar{b}b, \text{with} \quad H^\pm \to q\bar{q}';\ \ \ell^\pm \nu_\ell \end{aligned}$$

CONCLUSIONS

- new processes describing the top-quark production and decays are included in the generators provided full simulation of event
- event generators for top-quark production with spin correlations
- event generators for single top production included $2 \to 2$ + $2 \to 3$ with a proper matching
- tree level generators for top production processes with additional multi-jets in the final state
- generators with full NLO corrections to top production processes
- event generators for top production and decays due to interactions beyond SM