TopReX
Event Generator

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Outline

- generators in CMS
- list of processes
- calculations of $|M|^2$
- heavy fermion decay
- physics details
- top decay channels
- program flow chart
- how to run TopReX
- conclusion

Albert de Roeck and Sergey Slabospitsky

URL = http://cmsdoc.cern.ch/cms/generators/

Information and support for generators used in CMS

- interface with CMS simulation software
- mini-documentation on how to use the program @LHC in CMS
- install/check new releases (contact for each main generator)
- example jobs of problems

generators in use in CMS

general purposes	dedicated
PYTHIA 6.2	HDECAY, ...
HERWIG	TAUOLA
ISAJET	TopReX
CompHEP	Single Top
diffraction	HardDif
HIJING	SIMUB
MC Events Data Base	ALPGEN
PDF	

EVENT GENERATOR T O P R E X

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

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

- dedicated for simulation of "external" process with PYTHIA

TopReX provides a simulation:

$$
\begin{array}{rcl}
qb & \to & q't \quad + \quad qg \to q't\bar{b} \\
gb & \to & tW \\
q\bar{q}' & \to & W^* \to t\bar{b} \\
q\bar{q}' & \to & WQ\bar{Q}, \quad Q = b, c \\
q\bar{q}' & \to & W^* \to \tau\nu, \quad \to W^* \to \tau\nu + jet \\
q\bar{q}' & \to & H^{\pm *} \to t\bar{b}(\tau\nu), \quad \to H^{\pm *} \to t\bar{b}(\tau\nu) + jet \\
gg\,(q\bar{q}) & \to & t\bar{t} \\
q\bar{q} & \to & H^+H^-
\end{array}
$$

- we use the **exact** expressions for $|M|^2$ for all processes

W, Z, and $H^{\pm}$ are of-shell, while t and τ are on-shell,
the polarization of t (or τ) is included

included decay channels:

$$
\begin{array}{rcl}
t & \to & bW^+, \ \to bH^+, \ \to q\gamma, \ qg, \ qZ \\
W, Z & \to & f\bar{f}', \quad f = q, l, \nu \\
H^{\pm} & \to & f\bar{f}', \quad f = q, l, \nu \\
\tau^- & \to & \nu_\tau l^- \nu, \ \nu_\tau \pi^-, \ldots \text{ TAUOLA}
\end{array}
$$

- at present TopReX could be used :
  - ◇ as a stand-alone generator (parton level)
  - ◇ with PYTHIA for hadronization, fragmentation and decays
  - ◇ with PYTHIA + CMSJET for fast MC simulation of CMS,
  - ◇ with PYTHIA + CMKIN-package: routines, data-card, scripts

calculations of $|M|^2$

- we use the exact expressions for $|M|^2$ for all TopReX processes. The helicity amplitude method is used for analytical calculations
- Dirac spinor representations:

$$p_\pm = E \pm p_z, \quad p_{1/2} = p_x \pm i p_y$$

$$u_1 = N \begin{pmatrix} M_+ \\ p_1 \\ M_- \\ -p_1 \end{pmatrix} \qquad u_2 = N \begin{pmatrix} p_2 \\ M_- \\ -p_2 \\ M_+ \end{pmatrix}$$

$$\bar{u}_1 = N(M_- \, -p_2 \; M_+ \; p_2) \qquad \bar{u}_2 = N(-p_1 M_+ \; p_1 \; M_-)$$

$$v_1 = N \begin{pmatrix} -p_2 \\ -M_- \\ -p_2 \\ M_+ \end{pmatrix} \qquad v_2 = N \begin{pmatrix} M_+ \\ p_1 \\ -M_- \\ p_1 \end{pmatrix}$$

$$\bar{v}_1 = N(-p_1 \; M_+ \; -p_1 \; -M_-) \quad \bar{v}_2 = N\,(-M_- \; p_2 \; M_+ \; p_2)$$

where $N \equiv \frac{1}{\sqrt{2(m+E)}} \quad M_\pm \equiv m + p_\pm$

Let $e^\mu_{x,y,z}$ be four-vectors in p frame, corresponding to $e^*_{x,y,z}$ vectors defined in p rest frame,

$$e^*_x = (0,1,0,0), \quad e^*_y = (0,0,1,0), \quad e^*_z = (0,0,0,1)$$

and

$$\hat{e}_{x,y,z} \equiv \gamma^5 \, \gamma^\mu e^\mu_{x,y,z}$$

then one gets

$$\begin{array}{lll}
\hat{e}_x u_1 = u_2, & \hat{e}_y u_1 = iu_2, & \hat{e}_z u_1 = u_1, \\
\hat{e}_x u_2 = u_1, & \hat{e}_y u_2 = -iu_1, & \hat{e}_z u_2 = -u_1, \\
\hat{e}_x v_1 = v_2, & \hat{e}_y v_1 = -iv_2, & \hat{e}_z v_1 = v_1, \\
\hat{e}_x v_2 = v_1, & \hat{e}_y v_2 = iv_1, & \hat{e}_z v_2 = -v_2.
\end{array}$$

- additional representation of Dirac spinors

first set, $N_1 = 1/\sqrt{p_+}$:

$$u_1 = N_1 \begin{pmatrix} 0 \\ m \\ -p_2 \\ p_+ \end{pmatrix} \qquad u_2 = N_1 \begin{pmatrix} p_+ \\ p_1 \\ m \\ 0 \end{pmatrix}$$

$$\bar{u}_1 = N_1\ (-p_1\ p_+\ 0\ m) \qquad \bar{u}_2 = N_1\ (m\ 0\ p_+\ p_2)$$

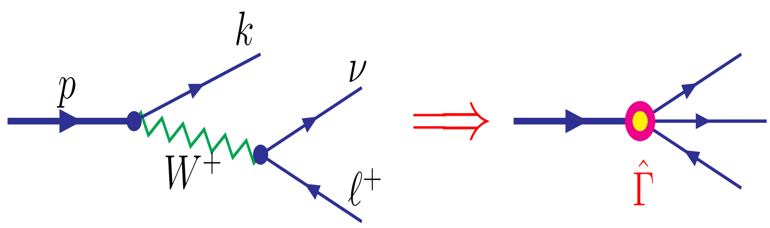
second set, $N_2 = 1/\sqrt{p_-}$:

$$u_1 = N_2 \begin{pmatrix} m \\ 0 \\ p_- \\ -p_1 \end{pmatrix} \qquad u_2 = N_2 \begin{pmatrix} p_2 \\ p_- \\ 0 \\ m \end{pmatrix}$$

$$\bar{u}_1 = N_2\ (p_-\ -p_2\ m\ 0) \qquad \bar{u}_2 = N_2\ (0\ m\ p_1\ p_-)$$

for the antiparticle, i.e. for $v(p)$ or $u(-p)$, one has: $u(m) \Rightarrow u(-m)$

- example: ... $t \to bW^*(\to \nu\ell)$



$$\hat{\Gamma} = \bar{u}(k)\gamma^\alpha(1-\gamma^5)\times\cdots\left[\bar{u}(p_\nu)\gamma^\alpha(1-\gamma^5)v(p_\ell)\right]\frac{g^2}{p_w^2 - M_w^2 + i\epsilon}$$

for $m_\ell = m_\nu = 0$ by using this representation one gets

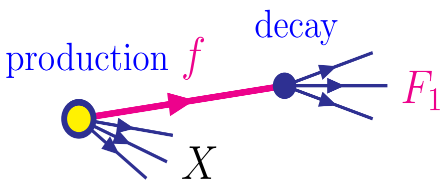
$$\hat{\Gamma} = \frac{g^2}{p_w^2 - M_w^2 + i\epsilon}\sqrt{\frac{2(p_\nu p_k)}{\ell_+}}(0\ 0\ \ell_+\ \ell_2)$$

heavy fermion decay

- we use the method very similar to TAUOLA package

S. Jadach and Z. Was, *Acta Phys. Polon.* B **15** (1984) 1151
P. Richardson, JHEP 0111 (2001) 029, hep-ph-0110108

two assumptions
a) no interference between different groups of final particles
b) decaying heavy fermion (f) is considered as on-shell particle



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

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

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

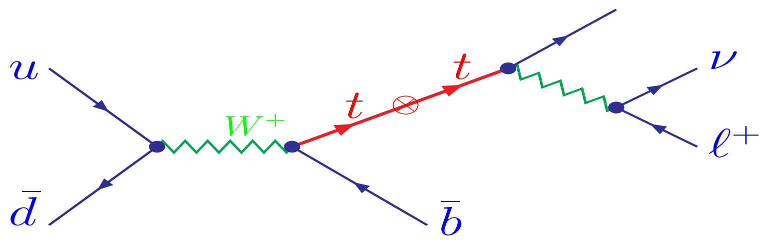
where $|M^0|^2$ is the matrix element squared for production (decay) of **unpolarized** fermion(s) and s is the fermion spin, $(p_f s) = 0$

- $t \to b\ell^+\nu$

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

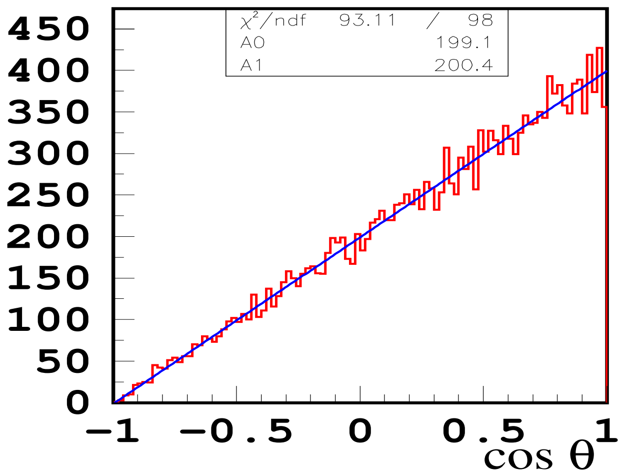
- example: $u\bar{d} \;\longrightarrow\; t\bar{b}$ with $t \longrightarrow b(W^*)\nu\ell$,

$$u\bar{d} \;\longrightarrow\; b\,\nu\,\ell\,\bar{b}$$



$$|M|^2 \quad\propto\quad \left(g^4 \frac{(p_u p_{\bar{b}})(p_t p_{\bar{d}})}{(p_{w1}^2 - M_W^2)^2 + \gamma_W^2 M_W^2}\right) \times$$
$$\left(g^4 \frac{(p_b p_\nu)(p_t p_\ell)}{(p_{w2}^2 - M_W^2)^2 + \gamma_W^2 M_W^2}\right) \times \left(1 + \vec{n}^*_\ell \vec{n}^*_{\bar{d}}\right)$$

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



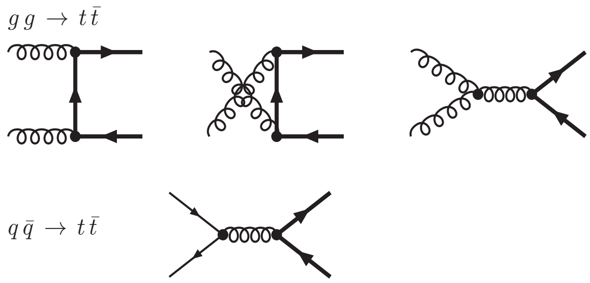
$$\cos\theta \equiv \vec{n}^*_\ell \vec{n}^*_{\bar{d}}$$

PROCESSES

IPROC is the TopReX process number

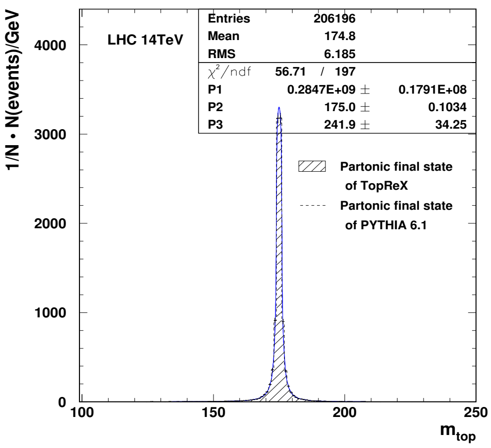
- $t\bar{t}$ production

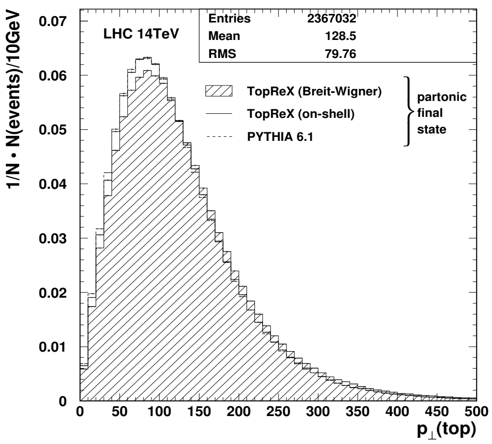
we use the LO $|M|^2$



IPROC = 20 $gg(q\bar{q}) \longrightarrow t\bar{t}$
IPROC = 21 $gg \longrightarrow t\bar{t}$
IPROC = 22 $q\bar{q} \longrightarrow t\bar{t}$
$Q^2 = m_t^2$, CTEQ5M pdf set, for $\sqrt{s} = 14$ TeV

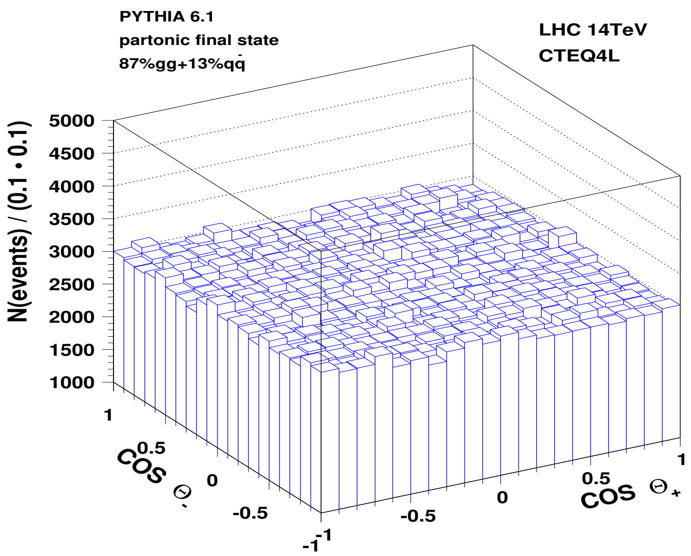
$$\sigma(t\bar{t}) = 700 \quad \text{pb}$$

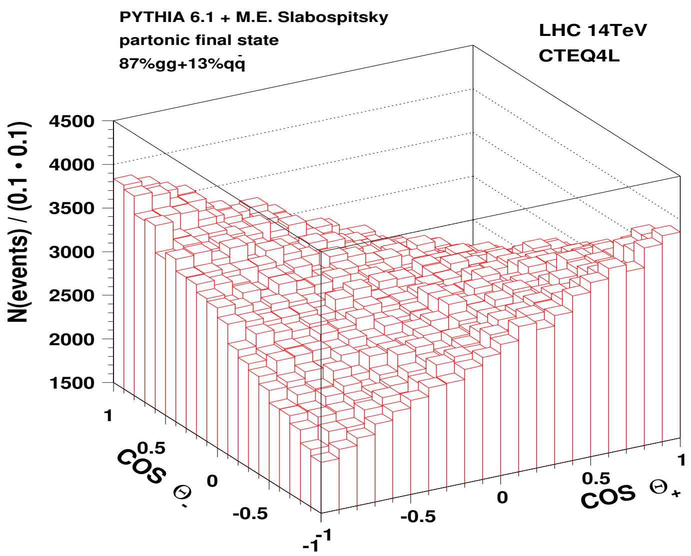




$$
\begin{aligned}
|M(gg(q\bar{q}) \to t\bar{t})|^2 \quad &= \quad |M^0(gg(q\bar{q}) \to t\bar{t})|^2 \\
&\times \quad (1 + (v^1 s^1) + (v^2 s^2) + \omega^{\mu\nu} s^1_\mu s^2_\nu)
\end{aligned}
$$

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

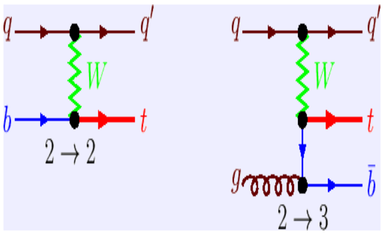




- Electro-weak top production

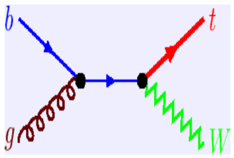
three processes contribute to electro-weak (single) top production

t-channel (Wg)



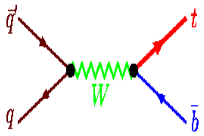
$$qb \to q' t \; + \; qg \to q' t \bar{b}$$

tW-channel



$$qb \to tW^+$$

s-channel (W^*)



$$q\bar{q}' \to t\bar{b}$$

IPROC = 1 $qb \to q' t$

IPROC = 2 $qg \to q' t\bar{b}$

IPROC = 3 $qb \to tW^+$

IPROC = 4 $q\bar{q}' \to t\bar{b}$

IPROC = 11 $qb \to q' t \; + \; qg \to q' t\bar{b}$

channel	Q-scale	σ, in pb
Wg	$m_t/2$	236
tW	$m_t/2$	68
W^*	m_t	8

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

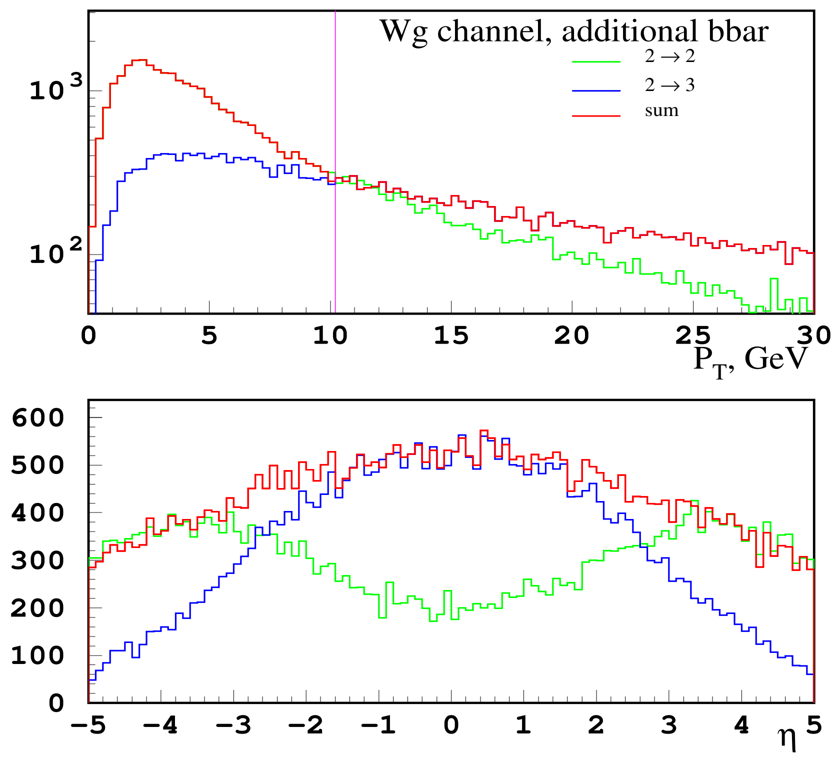
E. Boos, L. Dudko, V. Savrin, CMS Note 2000/065 (2000)

$$\begin{array}{llll} \text{LO} & qb \to q't & + \ \bar{b} & (\text{from} \quad \text{PYTHIA}) \\ \text{NLO} & qg \to q't & + \ \bar{b} & (\text{from} \quad \text{hard process}) \end{array}$$

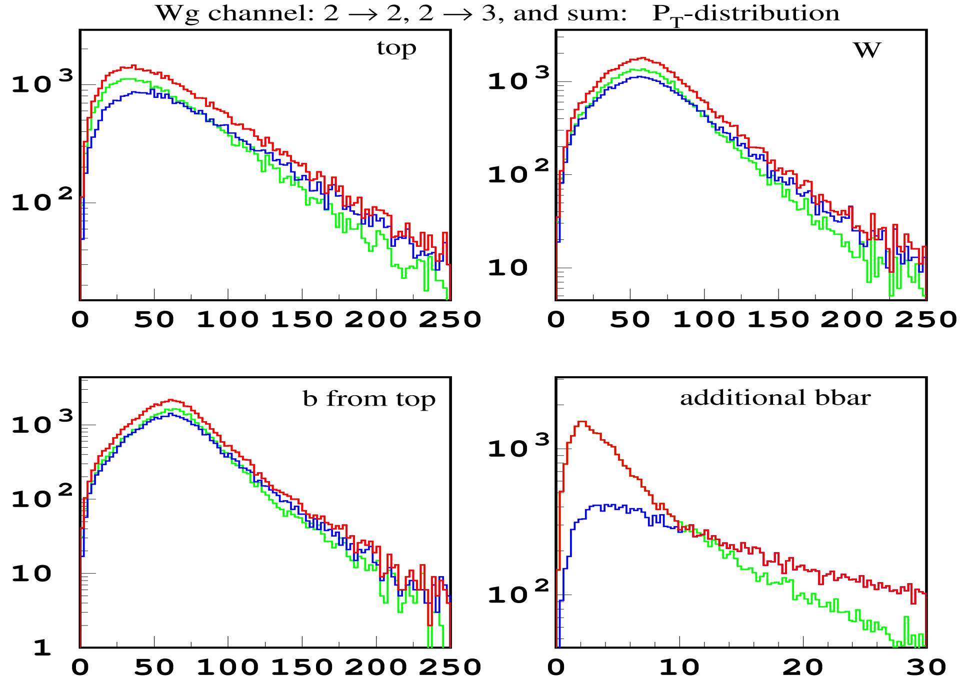
$$\begin{aligned} \sigma(pp \to tX) \quad &= \quad \sigma^{(2\to2)}(pp \to tq;\ p_T(\bar{b}_{\mathrm{PYT}}) < p_0) \\ &+ \quad \sigma^{(2\to3)}(pp \to tq\bar{b}_{\mathrm{hard}}; p_T(\bar{b}_{\mathrm{hard}}) \geq p_0) \\ &\qquad \text{with} \quad p_0 \simeq 10 \quad \text{GeV} \end{aligned}$$

we 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

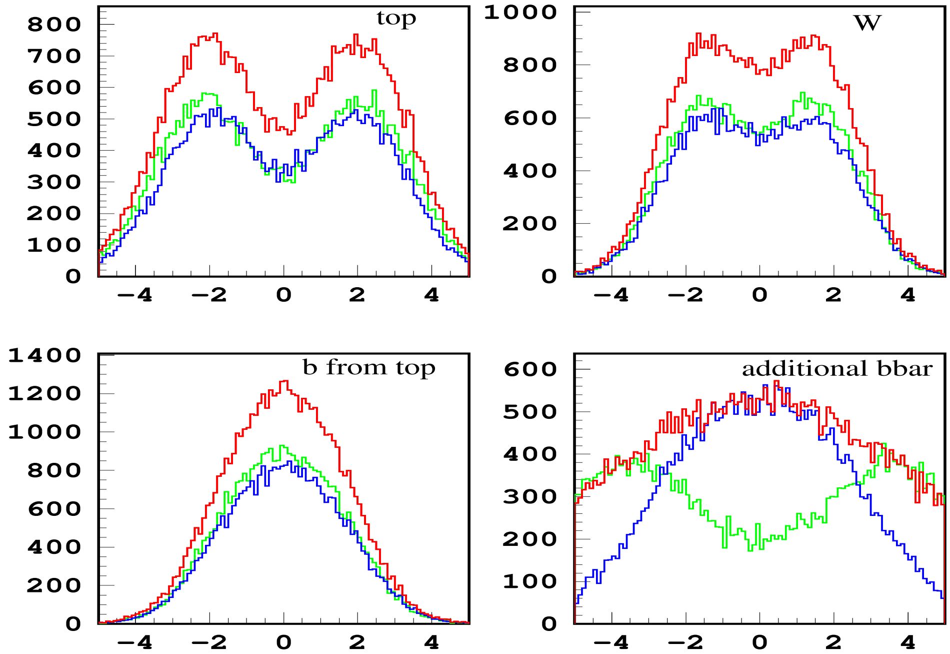
we use this way for simulation other LO+NLO hard processes



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



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



• s-channel charged Higgs production
Lagrangian, describing the $\bar{t}\, H^+\, b$ and $\tau\, H^+\, \nu$ vertexes

$$\begin{aligned}
\mathcal{L}_{SM} &\propto \overline{U}\,\gamma^\alpha P_L D\; W_\alpha\,, \\
& \quad U = u, c, t,\;\; \nu, \qquad D = d, s, b,\;\; \tau \\
\mathcal{L}_{H^\pm qq} &\propto H^+\, \left[\bar{U}\,(m_U \cot\beta\, P_L + m_D \tan\beta\, P_R)\; D\right] \\
\mathcal{L}_{H^\pm \tau\nu} &\propto (m_\tau \tan\beta)\;\, H^+\;\, \bar{\nu}\;\, P_R\;\, \tau
\end{aligned}$$

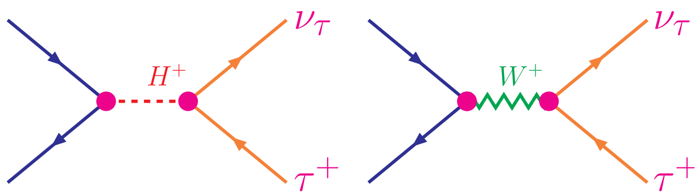
we use the running values of m_q for evaluation of $qH^\pm q'$ couplings

τ-lepton from $H^\pm$ decay has polarization opposite to SM case

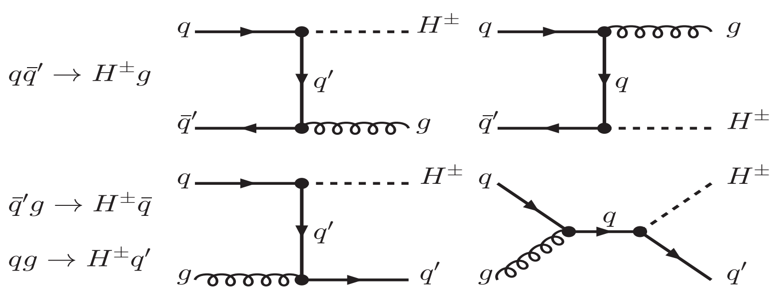
$\Rightarrow$ t-quark

$$\begin{aligned}
\tan\beta \ll 1 \qquad & \mathcal{L}_{Htb} \propto \bar{t}P_L b \;\; \Leftrightarrow \text{opposite to SM} \\
\tan\beta \gg 1 \qquad & \mathcal{L}_{Htb} \propto \bar{t}P_R b \;\; \Leftrightarrow \text{coincides with SM}
\end{aligned}$$

`IPROC = 8` $q\,\bar{q}' \;\rightarrow\; H^\pm,\; \rightarrow t\bar{b}, \quad q = d, u, s, c, b$
`IPROC = 9` $q\,\bar{q}' \;\rightarrow\; H^\pm,\; \tau^\pm \nu_\tau$



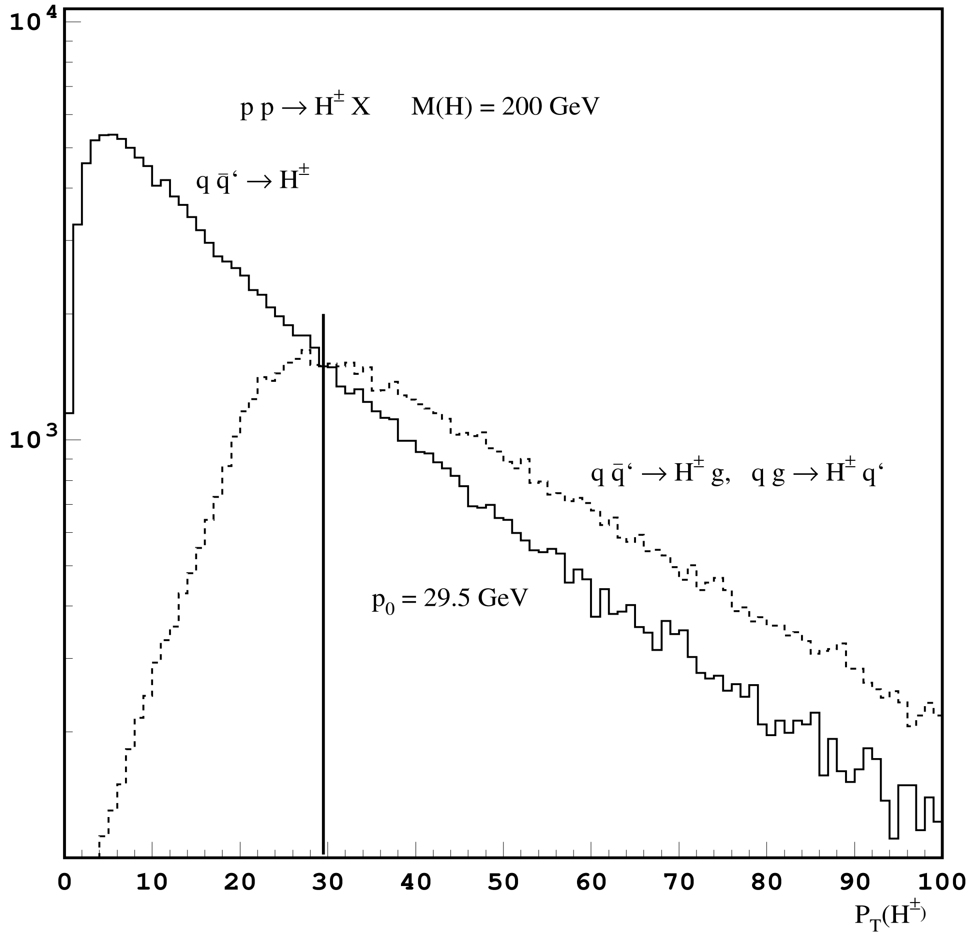
$$q\,\bar{q}' \;\rightarrow\; H^\pm\, g, \quad q\, g \;\rightarrow\; H^\pm\, q'\,, \quad \bar{q}'\, g \;\rightarrow\; H^\pm\, \bar{q}$$



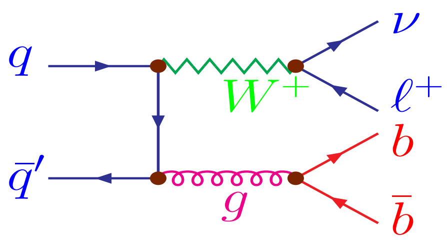
$$\sigma(pp \to H^{\pm}X) \quad = \quad \sigma^{(2\to 1)}(pp \to H^{\pm};\ p_{\top}(H) < p_0)$$
$$+ \quad \sigma^{(2\to 2)}(pp \to H^{\pm}\ jet;\ \hat{k}_{\top} > \hat{k}_0, p_{\top}(H) \geq p_0)$$

the smooth behavior of the resulting $p_{\top}(H)$-distribution can be achieved for the following values of these parameters:

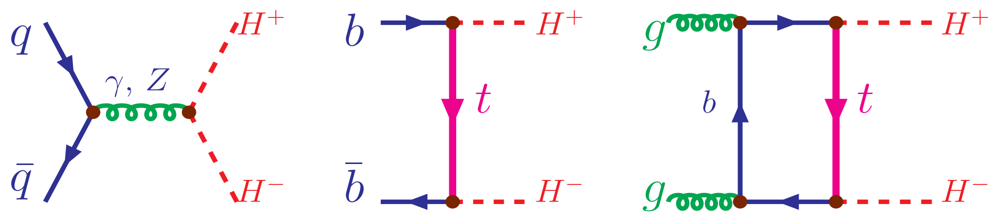
$$\hat{k}_0 \approx 20 \text{ GeV},$$
$$\text{and} \qquad p_0 = 29.5 \text{ GeV, for } M_H = (200 \div 400) \text{ GeV}$$

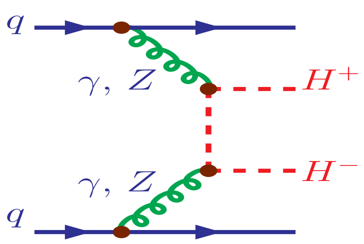


• IPROC = 5 $q\bar{q}' \longrightarrow W\ b\bar{b}$



• IPROC = 31 charged Higgs pair production





• for $M_{H^\pm} = 150$ GeV and $\tan\beta = 5$, $\sqrt{s} = 14$ TeV, CTEQ5M, running quark mass values, $m_b(M_H) = 2.8$ GeV

$gb \longrightarrow tH^\pm$	~ 100 fb
$q\bar{q} \longrightarrow H^\pm$	~ 200 fb
$q\bar{q} \longrightarrow H^+H^-\ (\gamma, Z)$	≈ 50 fb
$qq' \longrightarrow qq'H^+H^-$	≈ 10 fb
$gg \longrightarrow H^+H^-$	≈ 0.1 fb
$b\bar{b} \longrightarrow H^\pm W^\mp$	≈ 60 fb

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

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

$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu$, $A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$,
$q = u, c$, Λ is the New Physics cut-off,
$|f^V|^2 + |h^V|^2 = 1$.

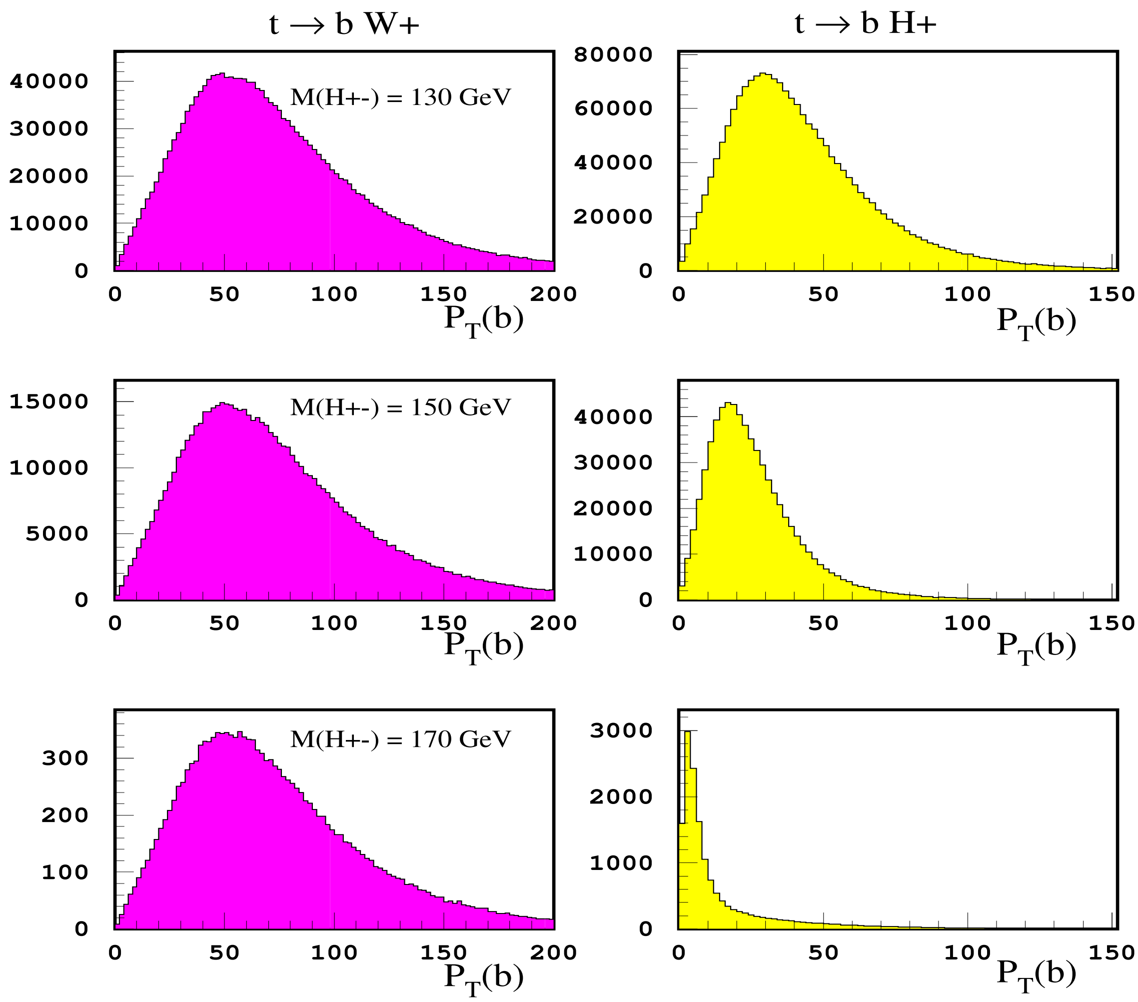
the following decay channels are included:

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

- charged Higgs in top decays

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

$pp \longrightarrow t\bar{t}$ with $t \longrightarrow bH^\pm$ and $H^\pm \longrightarrow \tau^\pm\nu_\tau$



• μ_V-variable

is it possible to reconstruct $m_{H^\pm}$ in $t \to bH^+, \;\; H^+ \to \tau^+\nu$ decay channel ?

we can use the reconstructed transverse momentum of $W(H)$-boson

$$P_\top(W,H) = P_\top(\tau jet) + E_{\top\, miss}$$

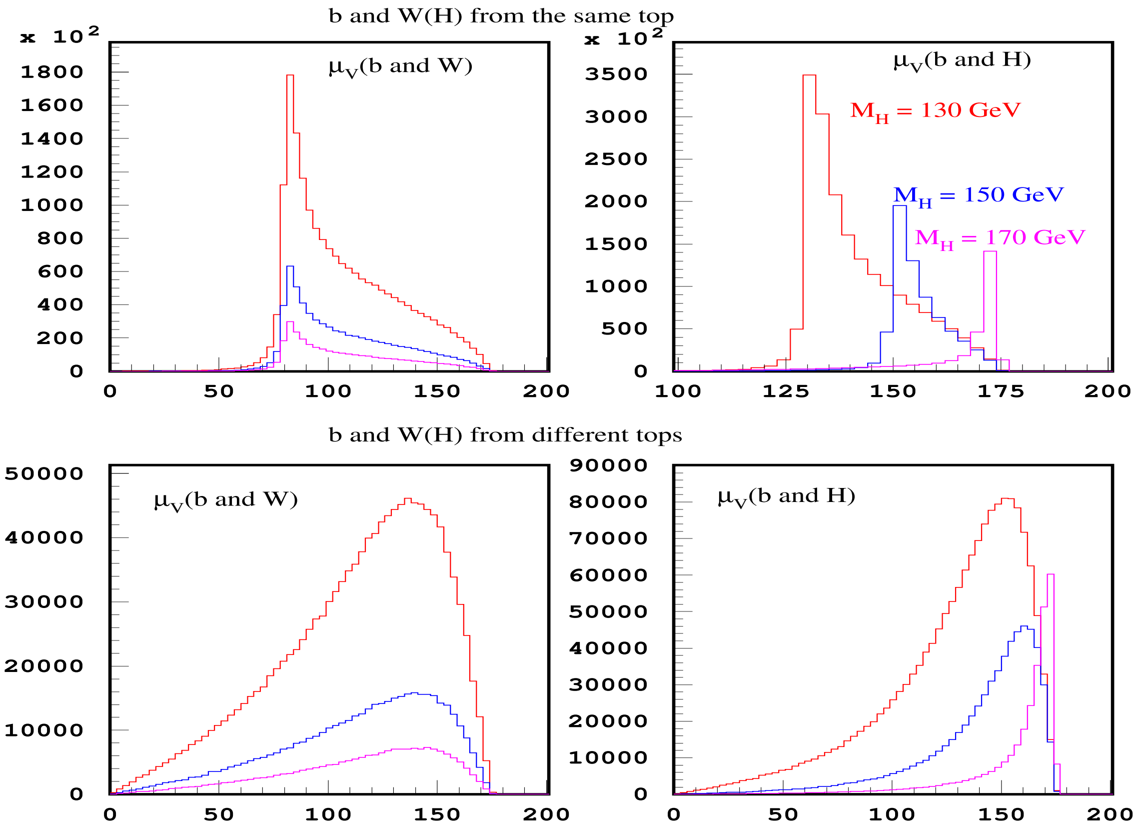
$$m_t^2 = (E_b + E_V)^2 - (\vec{P_b} + \vec{P_V})^2$$

$$\Longrightarrow$$

$$m_t^2 \geq (E_{\top\, b} + \sqrt{M_V^2 + P_{\top\, V}})^2 - (\vec{P}_{\top\, b} + \vec{P}_{\top\, V})^2$$

$$\Longrightarrow \mu_V \equiv \sqrt{(A_t - P_{\top\, b})^2 - P_{\top\, V}^2}$$

$$\text{where} \;\; A_t^2 \equiv m_t^2 + (\vec{P}_{\top\, b} + \vec{P}_{\top\, V})^2, \;\; V = W \;\; \text{or} \;\; H^\pm$$



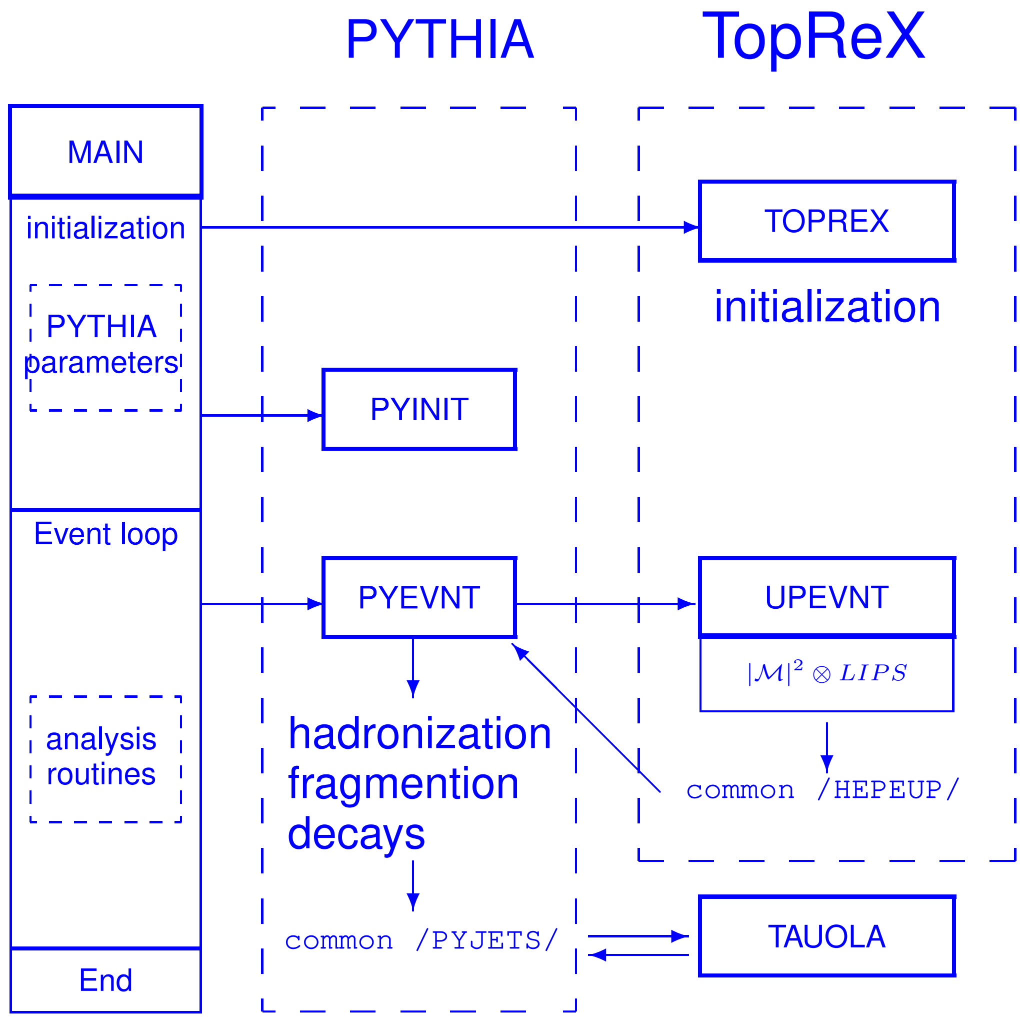
Program flow chart

- TopReX initialization

◇ passage the parameters from PYTHIA to TopReX

◇ estimation of the maximal value of differential cross section

◇ the event loop: PYTHIA $\Rightarrow$ PYEVNT $\Rightarrow$ TopReX



how to run TopReX

TopReX tarball could be found in
/afs/cern.ch/user/s/spitskyc/public/html/toprex/src

- the following versions of TopReX are available:
  - ◇ TX_325.tar.gz - very old version, frozen
  - ◇ TX_329.tar.gz for PYTHIA 6.1xx version
  - ◇ TX_401.tar.gz for PYTHIA 6.2xx version

- TopReX installation
  - ◇ copy TX_xxx.tar.gz file in the working directory
  - ◇ , then type:
    tar -zxvf TX_xxx.tar.gz
  - ◇ new directory `TRXxxx/` will be created

- `MAIN` routine

three examples of such routines are given in
.../TRX401/src/mainrt directory:
main_01.f
main_02.f
main_cms.f

◇ main_01.f is the simplest example

◇ main_02.f presents a possibility to read input data from `txrun.dat` file

◇ main_cms.f demonstrates how to use TopReX with CMSJET package

- COMPILATION
  - ◇ to create an executable file type

```
gmake tx.exe
```

or `gmake tx_cms.exe`

- RUNNING

the output information, like current branching fractions, quark masses, cross-sections, etc. are presented in `toprex.info` file

• main_01.f the simplest example

```
      PROGRAM MAIN
      IMPLICIT NONE
      CHARACTER*8 FRAME, BEAM, TARGET
      DOUBLE PRECISION ENERGY  ! CMS energy
      INTEGER IPROC            ! number of TopReX process
      INTEGER I
      external PYDATA
      INTEGER KCHG, KFIN,  MSTP, MSTI
      DOUBLE PRECISION PMAS, PARF, VCKM, PARP, PARI
      COMMON /PYDAT2/ KCHG(500,4),PMAS(500,4),PARF(2000),VCKM(4,4)
      COMMON /PYPARS/ MSTP(200),PARP(200),MSTI(200),PARI(200)

      FRAME  = 'CMS'
      BEAM   = 'P'
      TARGET = 'P'
      ENERGY =  14000.d0      ! LHC cms energy (in GeV)

      IPROC = 20              ! tt~ production

      PMAS(6,1)  = 175.d0     ! top mass
      PMAS(24,1) =  80.41d0   ! W mass
      MSTP(51) = 11           ! PDF

      CALL TopReX(FRAME, BEAM, TARGET, IPROC, ENERGY)
      CALL PYINIT(FRAME,BEAM,TARGET, ENERGY)

      DO I = 1,10
        PRINT*,'Event number I=',I
        CALL PYEVNT()
        CALL PYHEPC(1)
c...    at this place analysis routines and/or
c...    detector simulations may be called
      ENDDO
      END
```

- reading input data from a file (`txrun.dat`)

special routines provide a possibility to read input data from a file `txrun.dat` (like in FFREAD procedure)

`TXRINT(fkey,'iproc=', iproc, ier)`
   read INTEGER parameter
`TXRFL4(fkey,'top-mass =', PMAS(6,1), ier)`
   read REAL parameter
`TXRFL8(fkey,'pthat min =', CKIN(3), ier)`
   read DOUBLE PRECISION parameter

- `txrun.dat` file

```
*            Input parameters for TopRex
*
 iproc = 20        ! no. of TopRex process
 ntot  = 1000      ! number of events to be generated
*...kinematics
 PThat MIN =  0.   ! PThat low cut
 top-mass = 175.   ! mass of top-quark
```

Conclusion

TopReX event generator provides the simulation of

- $t\bar{t}$-pair production
- three subprocesses of electro-weak top production
- $Wb\bar{b}$ production
- charged Higgs production

- spin properties of decaying t-quark and τ-lepton are taken into account
- it is very easy to include new top decay channels

Acknowledgments
special thanks L. Sonnenschein
and my colleagues: S. Abdullin, E. Boos, M. Foursa, Yu. Gouz, V. Ilyin, R. Mehdiyev, A. Miagkov, F. Moorgat, D. Murashev, A. Nikitenko, A. de Roeck N. Stepanov