Prospects for t' quark discovery at the Tevatron

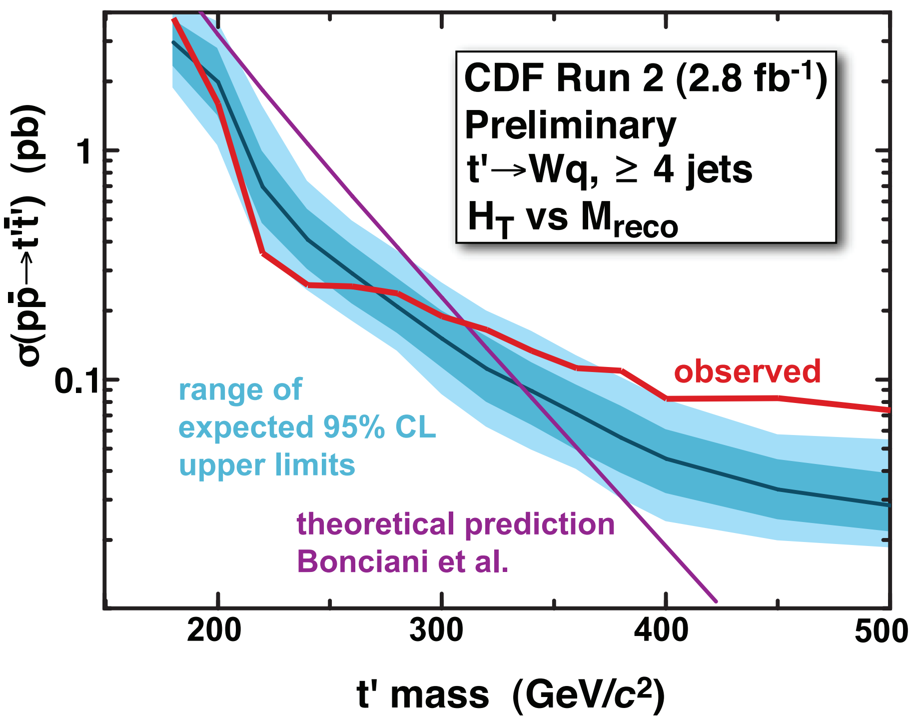
K.C. Kong

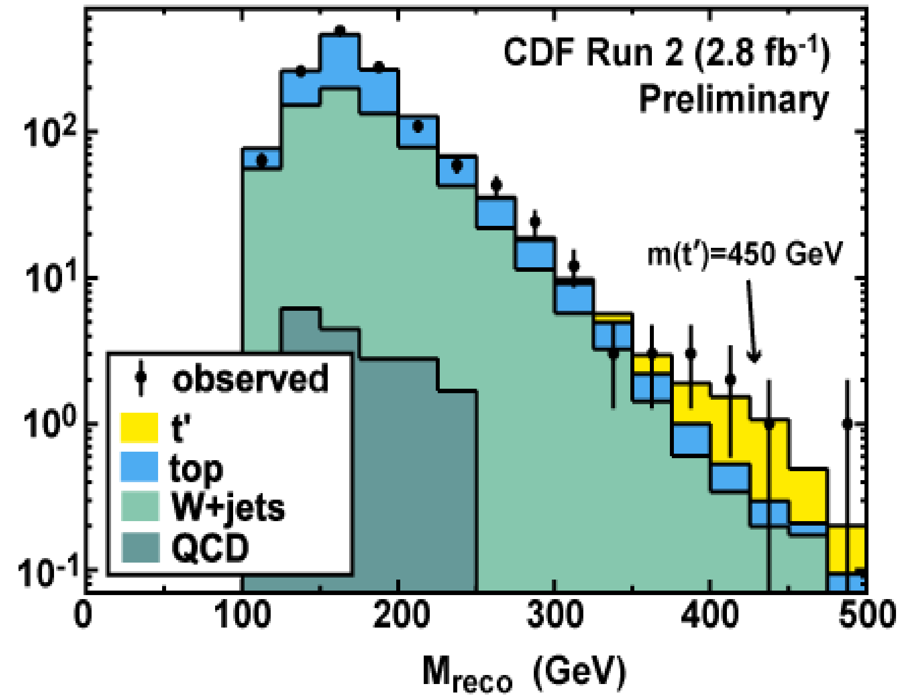
SLAC

with B. Dobrescu and R. Mahbubani

JHEP 0906:001,2009, arXiv:0902.0792 [hep-ph]

Top @ Tevatron 4 LHC
University of California Davis
Nov. 20-21, 2009





- A simple model with t' and G' (known as top-color model)
  - $\sigma(p\,\bar{p} \rightarrow t'\bar{t'}) \sim 20$ fb

- Comments on kinematics in $t\bar{t}$ events

t' ?

- t' : top-partners (stop, KK top, heavy top ...), vector-like top, 4th generation ...

- In many models, t' mixes with SM top
  - Introduce χ quark with (3, 1, 2/3)

$$\begin{pmatrix} t_{L,R} \\ t'_{L,R} \end{pmatrix} = \begin{pmatrix} c_{L,R} & -s_{L,R} \\ s_{L,R} & c_{L,R} \end{pmatrix} \begin{pmatrix} u^3_{L,R} \\ \chi_{L,R} \end{pmatrix}$$

$s_{L,R} = \sin\theta_{L,R}$ and $c_{L,R} = \cos\theta_{L,R}$

$$s_R^2 = \frac{s_L^2 m_{t'}^2}{s_L^2 m_{t'}^2 + c_L^2 m_t^2} \tag{1}$$

t' couplings

- Z :

$$\frac{g}{\sqrt{2}} W_\mu^+ \, \bar{b}_L \gamma_\mu \left(c_L t_L + s_L t'_L \right) + \text{H.c.}$$

- W:

$$\frac{g}{\cos\theta_W} Z_\mu \left[\left(\frac{c_L^2}{2} - \frac{2}{3} \sin^2\theta_W \right) \bar{t}_L \gamma_\mu t_L + \left(\frac{s_L^2}{2} - \frac{2}{3} \sin^2\theta_W \right) \overline{t'}_L \gamma_\mu t'_L \right.$$

$$\left. + \frac{s_L c_L}{2} \left(\overline{t'}_L \gamma_\mu t_L + \text{H.c.} \right) \right]$$

- h:

$$\frac{-1}{v_H \sqrt{2}} h^0 \left(c_L^2 m_t \, \bar{t}_L t_R + s_L^2 m_{t'} \, \overline{t'}_L t'_R + c_L s_L m_{t'} \, \bar{t}_L t'_R + c_L s_L m_t \, \overline{t'}_L t_R \right) + \text{H.c.}$$

- γ: the same as SM top

Constraints ?

- t-W-b coupling : $s_L < 0.57$ from $c_L \simeq V_{tb} \geq 0.82$
- CDF 3.2 fb^{-1} + D0 2.3 fb^{-1} $\rightarrow |V_{tb}| > 0.77 \rightarrow s_L < 0.64$
- correction to T parameter (Chivukula, Dobrescu, Georgi, Hill 1999)

$$T = \frac{3}{16\pi \sin^2\theta_W} \frac{m_t^2 s_L^2}{M_W^2} \left(s_L^2 \frac{m_{t'}^2}{m_t^2} + \frac{4 c_L^2 m_{t'}^2}{m_{t'}^2 - m_t^2} \ln \frac{m_{t'}}{m_t} - 1 - c_L^2 \right) - \Delta(M_h) \ .$$

  - $M_h = 115$ GeV: $T \leq 0.36$ at 95% CL (assuming optimal contribution to S)
  - $M_h = 115$ GeV and $m_{t'} = 450$ GeV: $s_L \leq 0.32$
  - $M_h = 500$ GeV and $m_{t'} = 450$ GeV: $s_L \leq 0.38$
  - Unknown new physics could give negative contribution to T, allowing larger values for s_L

t' decays

- t' to Z/W:

$$\Gamma(t' \to W^+ b) = \frac{s_L^2 m_{t'}^3}{32\pi v_H^2} \left(1 - \frac{M_W^2}{m_{t'}^2}\right)^2 \left(1 + \frac{2M_W^2}{m_{t'}^2}\right)$$

$$\Gamma(t' \to Z^0 t) = \frac{c_L^2 s_L^2 m_{t'}^3}{64\pi v_H^2} \left[\left(1 - \frac{m_t^2}{m_{t'}^2}\right)^3 + O\left(\frac{M_Z^4}{m_{t'}^4}\right)\right]$$

- For $m_{t'} > M_h + m_t$:

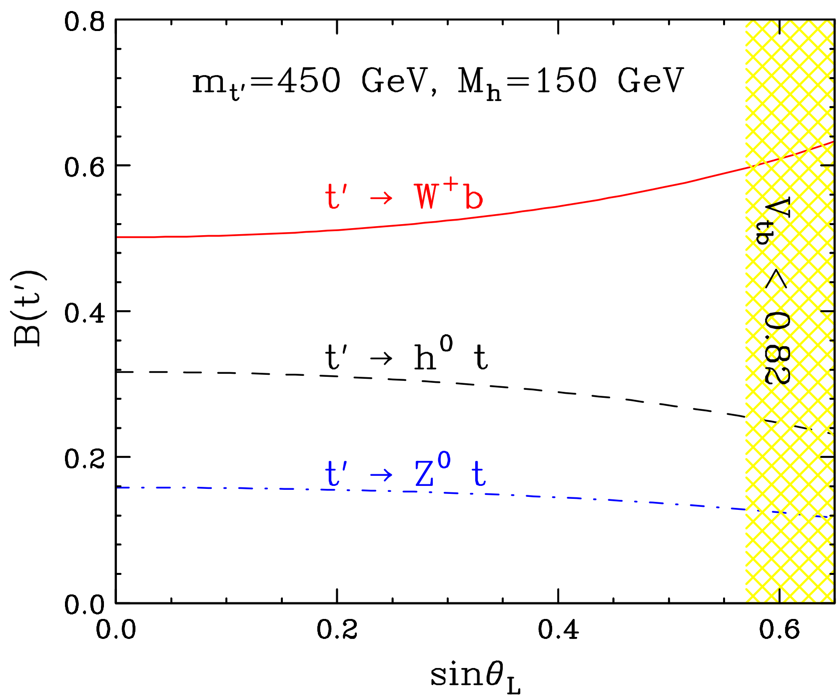
$$\Gamma(t' \to h^0 t) = \frac{c_L^2 s_L^2 m_{t'}^3}{64\pi v_H^2} \left(1 + \frac{6m_t^2 - M_h^2}{m_{t'}^2} + \frac{m_t^4 - m_t^2 M_h^2}{m_{t'}^4}\right) \beta\left(\frac{m_t^2}{m_{t'}^2}, \frac{M_h^2}{m_{t'}^2}\right)$$

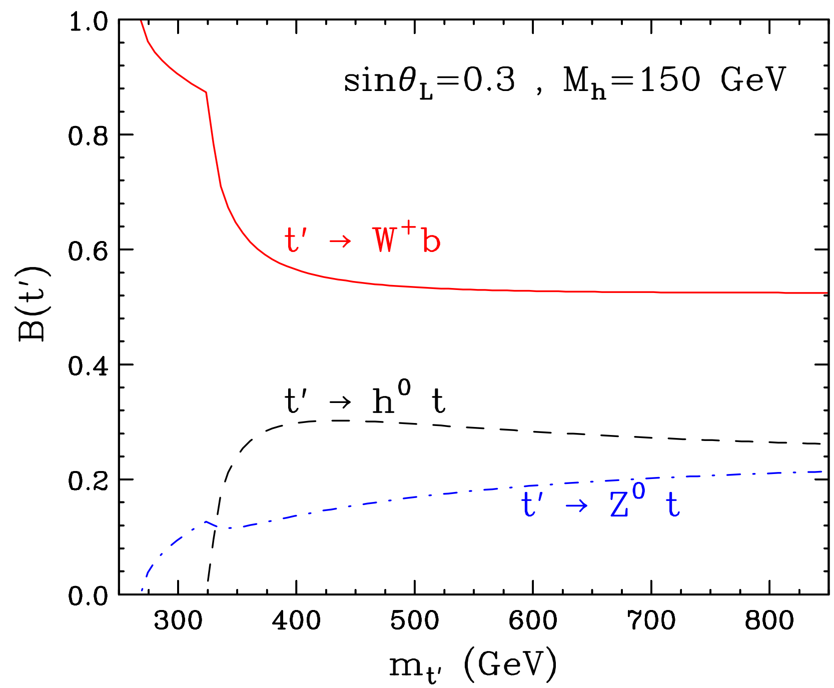
$$\beta(x_1, x_2) = \left[(1 - x_1 - x_2)^2 - 4x_1 x_2\right]^{1/2}$$

- In the limit of $m_{t'} \gg m_t + M_h$

$$B(t' \to W^+ b) = \frac{1}{1 + c_L^2} \geq 50\% \ ,$$

$$B(t' \to Z^0 t) = B(t' \to h^0 t) = \frac{c_L^2}{2\left(1 + c_L^2\right)} \leq 25\%$$





- For $m_{t'} < m_t + M_h$, $B(t' \to W^+ b) > 2/(2 + c_L^2) > 2/3$

G' ?

	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_Y$
SM quarks: q_L^i, u_R^i, d_R^i	3	1	2, 1, 1	+1/6, +2/3, −1/3
vectorlike quark: χ_L, χ_R	1	3	1	+2/3
scalar with VEV: Σ	3	$\overline{3}$	1	0

$$\begin{pmatrix} G_\mu^1 \\ G_\mu^2 \end{pmatrix} = \frac{1}{\sqrt{h_1^2 + h_2^2}} \begin{pmatrix} h_2 & -h_1 \\ h_1 & h_2 \end{pmatrix} \begin{pmatrix} G_\mu \\ G'_\mu \end{pmatrix}$$

$$g_s = \frac{h_1 h_2}{\sqrt{h_1^2 + h_2^2}}$$

G' couplings

- The gluon-prime interaction with light quarks is also vectorlike, but of different strength:

$$g_s r\, G'^a_\mu\, \overline{q}\gamma^\mu T^a q, \qquad r \equiv \frac{h_1}{h_2}$$

- For $r \ll 1$ ($r \gg 1$), theory becomes non-perturbative

- Imposing some loose perturbative condition, h_2 (h_1) $< 4\pi/\sqrt{N_c}$ with $N_c = 3$, with $\alpha_s \equiv g_s^2/(4\pi) \approx 0.1$, tree-level computation can be trusted for:

$$0.15 \lesssim r \lesssim 6.7$$

- The gluon-prime interactions with the t and t' (chiral)

$$g_s G'^a_\mu \left[\bar{t}\gamma^\mu \left(g_L P_L + g_R P_R\right) T^a t + \overline{t'}\gamma^\mu \left(g''_L P_L + g''_R P_R\right) T^a t'\right]$$

- flavor-changing terms,

$$g_s G'^a_\mu \, \bar{t}\gamma^\mu \left(g'_L P_L + g'_R P_R\right) T^a t' + \mathrm{H.c.}$$

- The left- and right-handed projection operators are given as usual by $P_{L,R} = (1 \mp \gamma_5)/2$, the couplings of the left-handed quarks are

$$g_L = r c_L^2 - \frac{s_L^2}{r} \quad , \quad g''_L = r s_L^2 - \frac{c_L^2}{r} \quad , \quad g'_L = \left(r + \frac{1}{r}\right) s_L c_L \quad ,$$

- g_R, g''_R and g'_R, are analogous to the left-handed ones except for the replacements $s_L \to s_R$ and $c_L \to c_R$.

- 5 parameters: $m_{t'}$, $M_{G'}$, s_L, r, M_h

G' decays and production cross sections

- Decay widths of G'_μ into light quarks.

$$\Gamma\left(G'_\mu \to \sum q\bar{q}\right) = \frac{5}{6}\,\alpha_s r^2 M_G \ .$$

- Decay width into $t\bar{t}$ for $M_G \gg m_t$

$$\Gamma\left(G'_\mu \to t\bar{t}\right) = \frac{\alpha_s}{12}\left(g_L^2 + g_R^2\right) M_G \ .$$

- Including the exact phase-space suppression, the decay width into $t'\bar{t}'$ is

$$\Gamma\left(G'_\mu \to t'\bar{t}'\right) = \frac{\alpha_s}{12}\left[\left(g_L''^2 + g_R''^2\right)\left(1 - \frac{m_{t'}^2}{M_G^2}\right) + 6 g''_L g''_R \frac{m_{t'}^2}{M_G^2}\right]\left(1 - \frac{4m_{t'}^2}{M_G^2}\right)^{1/2} M_G$$

- Gluon-prime may decay into a top and a top-prime quark

$$\Gamma\left(G'_\mu \to t\bar{t}' + t'\bar{t}\right) = \frac{\alpha_s}{6}\left[\left(g_L'^2 + g_R'^2\right) F\left(\frac{m_{t'}^2}{M_G^2}, \frac{m_t^2}{M_G^2}\right) + 6 g'_L g'_R \frac{m_{t'} m_t}{M_G^2}\right] \beta\left(\frac{m_{t'}^2}{M_G^2}, \frac{m_t^2}{M_G^2}\right) M_G$$

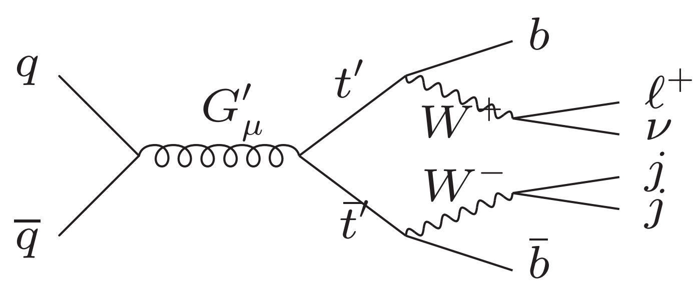
$$F(x_1,x_2) = 1 - \frac{1}{2}(x_1+x_2) - \frac{1}{2}(x_1-x_2)^2$$

$$\beta(x_1,x_2) = \left[(1-x_1-x_2)^2 - 4x_1x_2\right]^{1/2}$$

- For $M_G \gg 2m_{t'}$, the total width is independent of the quark mixing angles:

$$\Gamma_G = \frac{\alpha_s}{6}\left(6r^2 + \frac{1}{r^2}\right) M_G \ .$$

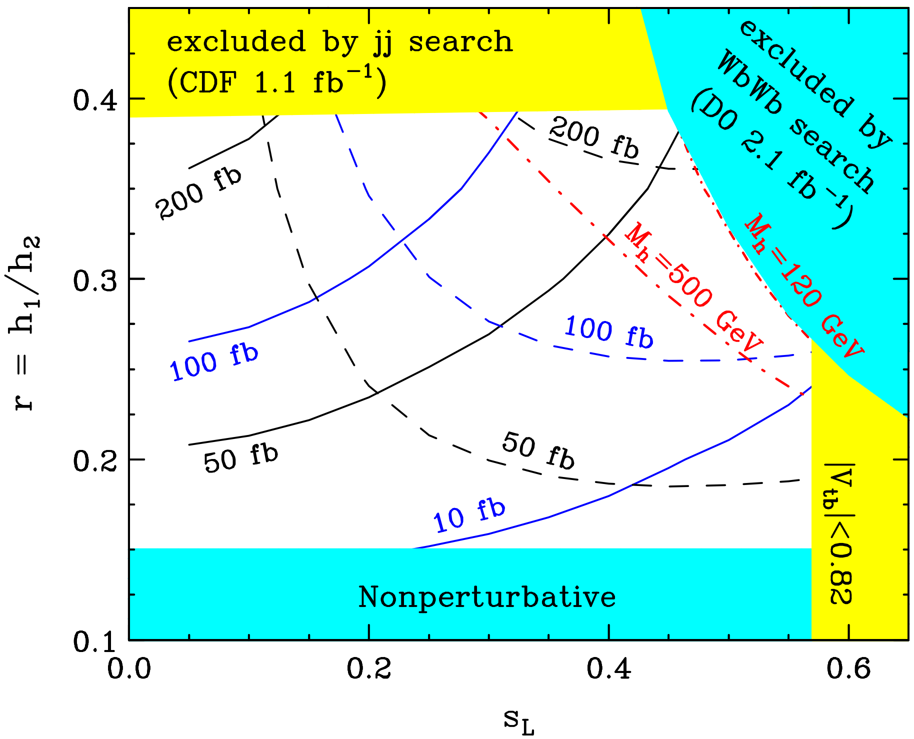
- Resonant $t'\bar{t}'$ production followed by $t' \to Wb$



- 20 fb is required to give 5 excess events for an 8.8% acceptance
- For large higgs mass, $B(t \to Wb) \approx 70\% \to \sigma(t'\bar{t}') \approx 40$ fb

- Want $\sigma(t'\bar{t}') \sim 40$ fb

- For $M_G = 1$ TeV and $m_{t'} = 450$ GeV,



- In the region, $0.3 \le s_L < 0.5$ and $0.3 \le r \le 0.4$, $t\bar{t}' + t'\bar{t}$ cross section (in dashed lines) is larger than $t'\bar{t}'$ (in solid lines)

- $m_{t'}$ reach at Tevatron is about 600 GeV

- At $M_G = 2m_{t'}$ threshold, the G'_μ width becomes very small because the $t'\bar{t'}$ decay is no longer kinematically available.

- For small s_L, $\Gamma_G \approx \alpha_s r^2 M_G$.

- Taking $M_G = 1.2$ TeV, $m_{t'} = 600$ GeV, $s_L = 10^{-2}$ and $r = 0.2$ we find $\sigma(p\bar{p} \to G'_\mu \to t'\bar{t'}) \approx 35$ fb

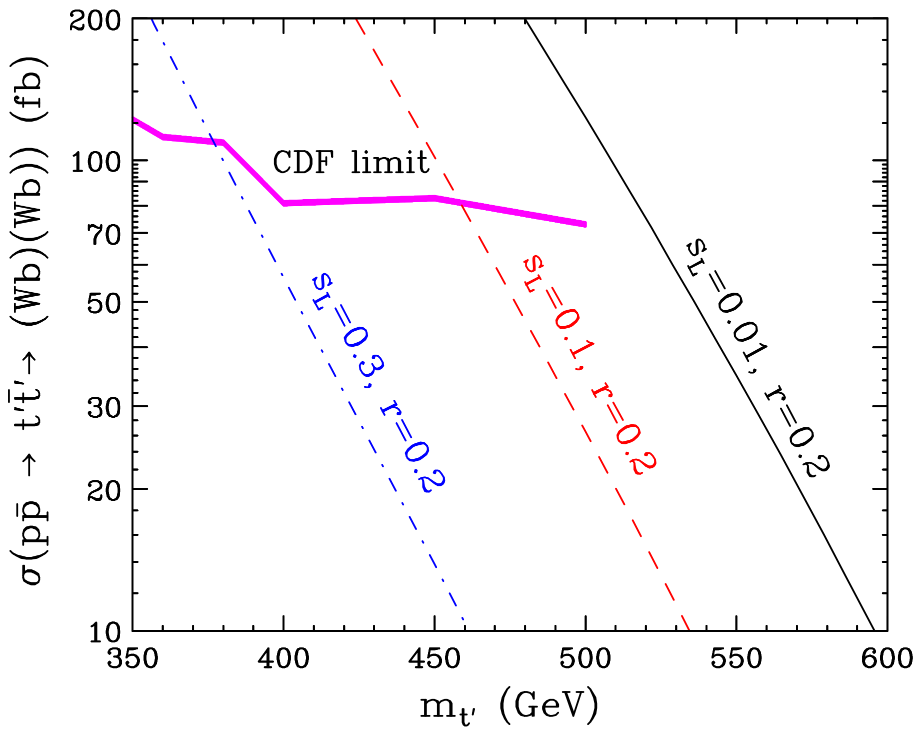
- For $M_h > m_{t'} - m_t$, $B(t' \to Wb) \sim 72\% \to \sigma(t'\bar{t'} \to (W^+b)(W^-\bar{b})) \sim 18$ fb

- QCD pair production $\sim$ 0.1 fb $m_{t'} = 600$ GeV

- Assuming a $\sim 9\%$ acceptance for a semileptonic $(Wj)(Wj)$ event at $m_{t'} = 600$ GeV, approximately 10 events in 10 fb^{-1} of data are expected.

- For a lighter Higgs boson, the smaller $t' \to Wb$ branching fractions leads to a decrease in the $(Wb)(Wb)$ signal.

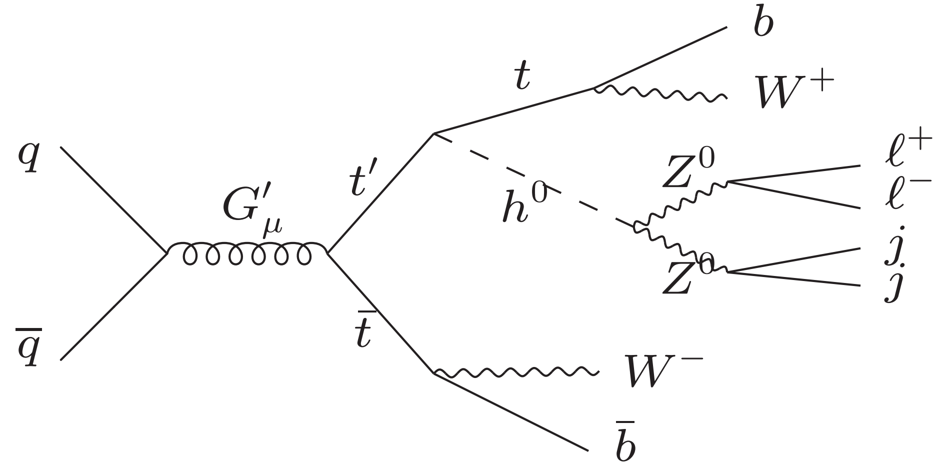
- $p\bar{p} \to G' \to t'\bar{t}' \to (Wb)(Wb)$ for $M_G = 2m_{t'}$, $M_h = 120$ GeV, $r = 0.2$, and $s_L = 0.01$, 0.1 or 0.3



Other signatures

- $p\bar{p} \to G'_\mu \to t'\bar{t}' \to \ (tZ^0)(W^-\bar{b}) \ / \ (t\,h^0)(W^-\bar{b})$

- $p\bar{p} \to G'_\mu \to t'\bar{t} \to \ (tZ^0)\,\bar{t} \ / \ (t\,h^0)\,\bar{t} \ / \ (W^+b)\,\bar{t}$
- $t'\bar{t} + t\bar{t}' \to t\bar{t}h$
  - $B(h^0 \to Z^0Z^0 \to \ell^+\ell^- jj) \approx 2.8\%$ for $M_h \sim 200$ GeV
  - $B(t' \to h^0 t) \approx 20\%$ for $m_{t'} = 450$ GeV
  - $\sigma(p\bar{p} \to G'_\mu \to t't)$ can be as large as 200 fb for $M_G = 1$ TeV.
  - $\sigma(t't \to h^0 \to Z^0Z^0 \to (\ell^+\ell^-)(jj)) \approx 1$ fb



- $\sigma(p\bar{p} \to t'j) \approx 4$ fb $(s_L/0.4)^2$ without cuts, for $m_{t'} = 450$ GeV (could be important at the LHC)

- $t\bar{t}$ resonance

- Possible to have axial coupling in G'-q-$\bar{q}$, which may lead to A_{FB}

	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_Y$
SM quarks: q_L^i, u_R^i, d_R^i	3	1	2, 1, 1	$+1/6$, $+2/3$, $-1/3$
vectorlike quark: χ_L, χ_R	1	3	1	$+2/3$
scalar with VEV: Σ	3	$\overline{3}$	1	0

- <u>Questions</u>
  - Does it really work? dijet limit seems strong
  - Suppose $t't$ production is dominant. Can it lead A_{FB}?

- b-lepton invariant mass distribution - mass, spins and couplings

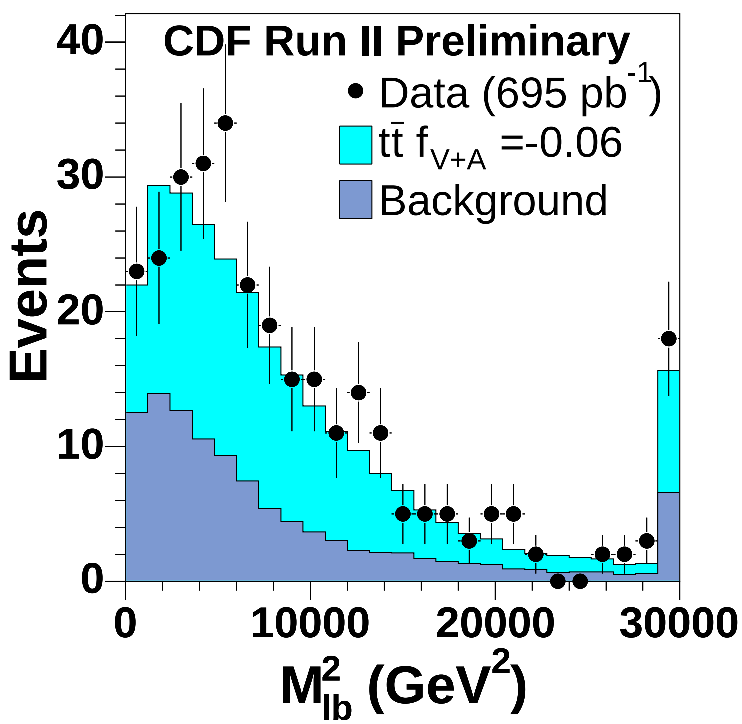
- Tevatron as an ILC ?

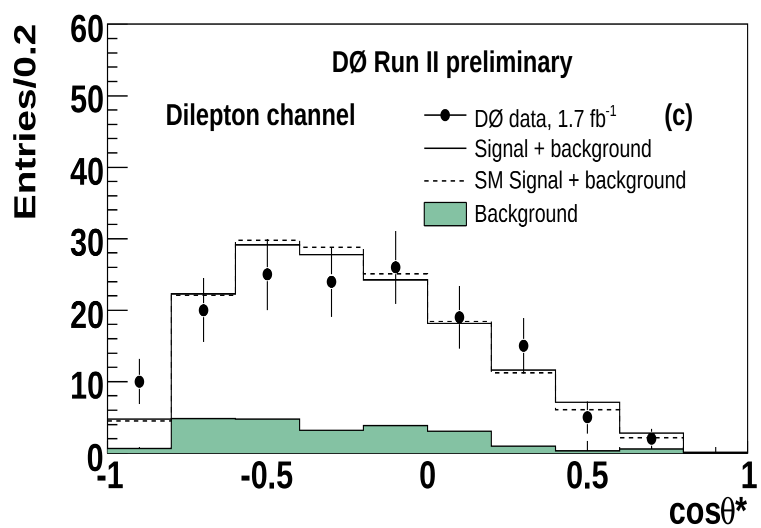
- W mass measurement with $t\bar{t}$ sample in dilepton channel?

- alternative to H_T ?

- $t\bar{t}$ in the dilepton is the closest channel to BSM physics !

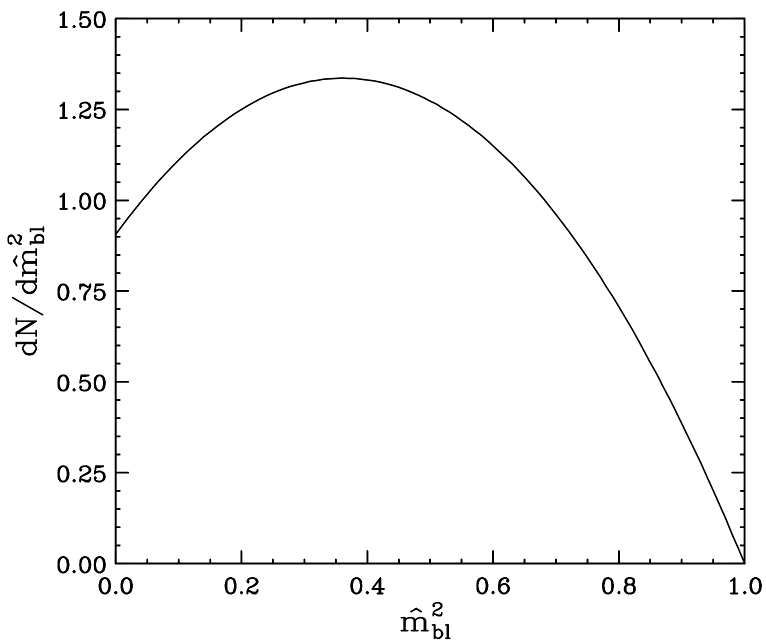
What do you see/think when you look at lepton-bjet invariant mass distribution ?

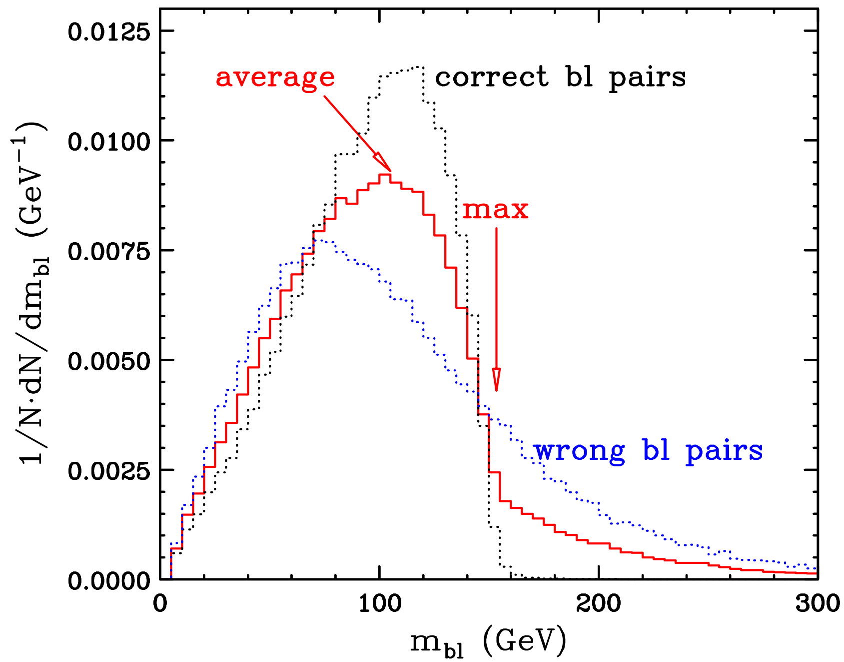




- End point? : $(m^{max}_{b\ell})^2 \approx 24000$ GeV^2
- Shape?: upside down parabola, $y = ax^2 + bx + c$ with $a < 0$

Lepton-bjet invariant mass distribution



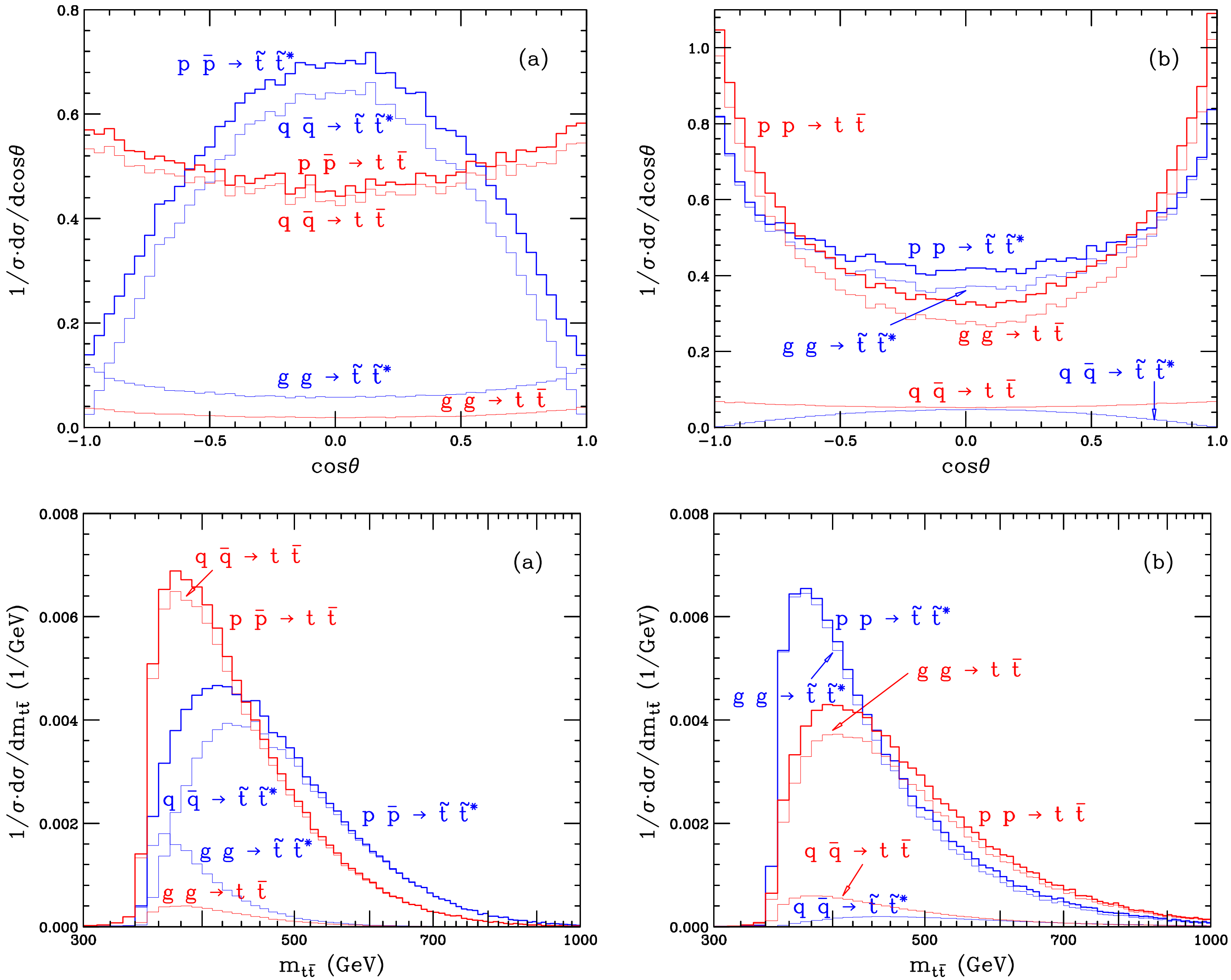


- End point: $m_{b\ell}^{max} = \sqrt{m_t^2 - m_W^2}$
- SM predicts $\frac{1}{N}\frac{dN}{d\hat{m}^2_{b\ell}} = 0.91 + 2.34\hat{m}^2 - 3.28\hat{m}^4$ ($0 \leq \hat{m} \leq 1$)
- Non-zero $\hat{m}^4$ confirms FVF spin chain (top-W-neutrino)
- The values of coefficients give $\cos 2\phi_{tWb} \cos 2\phi_{W\ell\nu} = 1$, *i.e.*, tWb and $W\ell\nu$ have the same chiral structure (either left-handed or right-handed) (Anomalous top quark couplings at D0, Note 5838-CONF)

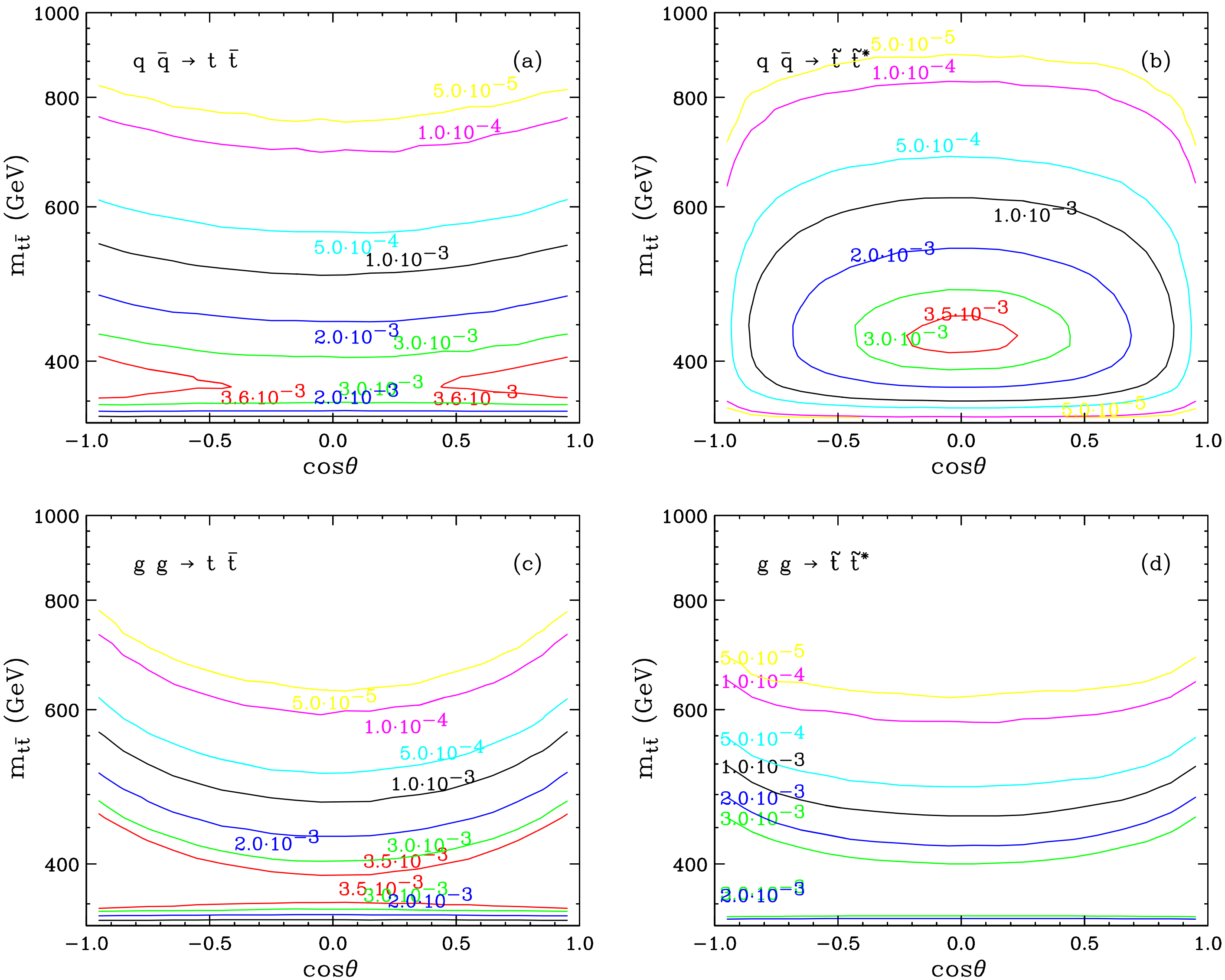
A few comments on kinematics

- t and $\bar{t}$ are fully reconstructed in semi-leptonic channel
- We know center-of-mass frame for each event
- Can we use some of LC-tricks at hadron colliders ?
  - angular distribution at CM frame
  - threshold ($t\bar{t}$ invariant mass distribution)

Spin determination - production angle and threshold



Spin determination - production angle and threshold



A variable with leptons only

- 1D decomposed MT2 or MCT
  - $\vec{P}_T$: upstream momentum

$$\vec{p}_{iT_{\parallel}} \equiv \frac{1}{P_T^2}\left(\vec{p}_{iT}\cdot\vec{P}_T\right)\vec{P}_T$$

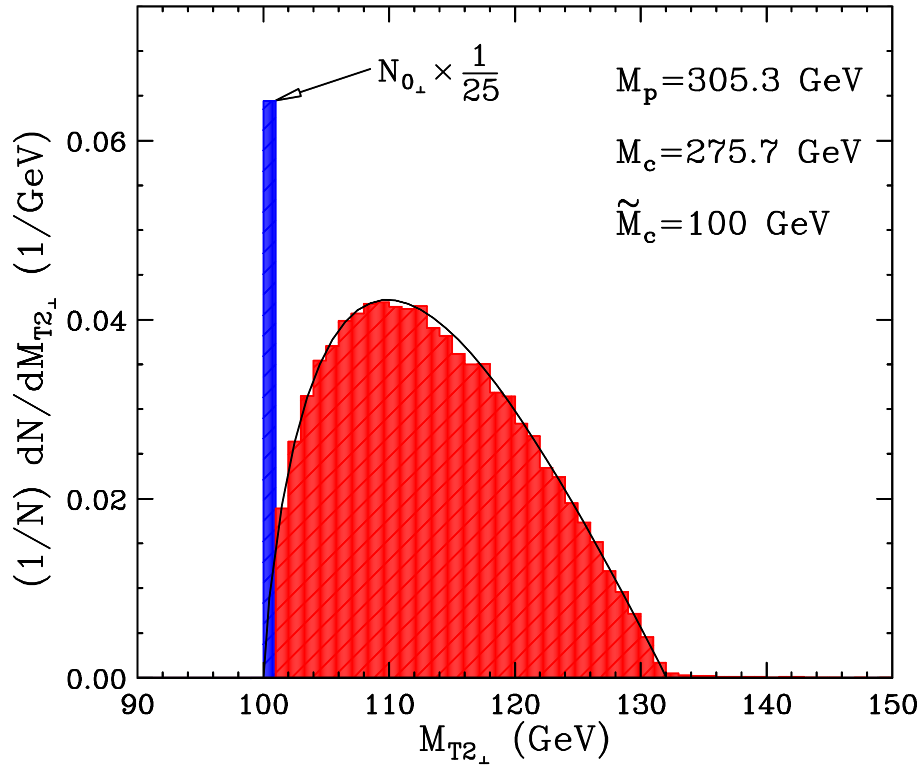
$$\vec{p}_{iT_{\perp}} \equiv \vec{p}_{iT} - \vec{p}_{iT_{\parallel}} = \frac{1}{P_T^2}\vec{P}_T\times\left(\vec{p}_{iT}\times\vec{P}_T\right)$$

$$M_{T2_{\perp}} = \sqrt{2\left(|\vec{p}_{1T_{\perp}}||\vec{p}_{2T_{\perp}}| + \vec{p}_{1T_{\perp}}\cdot\vec{p}_{2T_{\perp}}\right)}$$

$$M_{T2_{\perp}}^{(max)}(\tilde{M}_c) = \mu + \sqrt{\mu^2 + \tilde{M}_c^2}$$

$$\mu \equiv \frac{M_p}{2}\left(1 - \frac{M_c^2}{M_p^2}\right)$$

  - mass measurement of chargino and sneutrino in the inclusive same sign dilepton channel (CMS-LM6)
  - W mass measurement with $t\bar{t}$ samples in dilepton channel



$$\frac{\mathrm{d}\bar{N}}{\mathrm{d}M_{T2_\perp}} = N_{0_\perp}\,\delta(M_{T2_\perp} - \tilde{M}_c) + \left(1 - N_{0_\perp}\right)\frac{\mathrm{d}\bar{N}}{\mathrm{d}M_{T2_\perp}},$$

$$\frac{\mathrm{d}\bar{N}}{\mathrm{d}M_{T2_\perp}} = \frac{M_{T2_\perp}^4 - \tilde{M}_c^4}{\mu^2\, M_{T2_\perp}^3} \ln\left(\frac{2\mu\, M_{T2_\perp}}{M_{T2_\perp}^2 - \tilde{M}_c^2}\right).$$

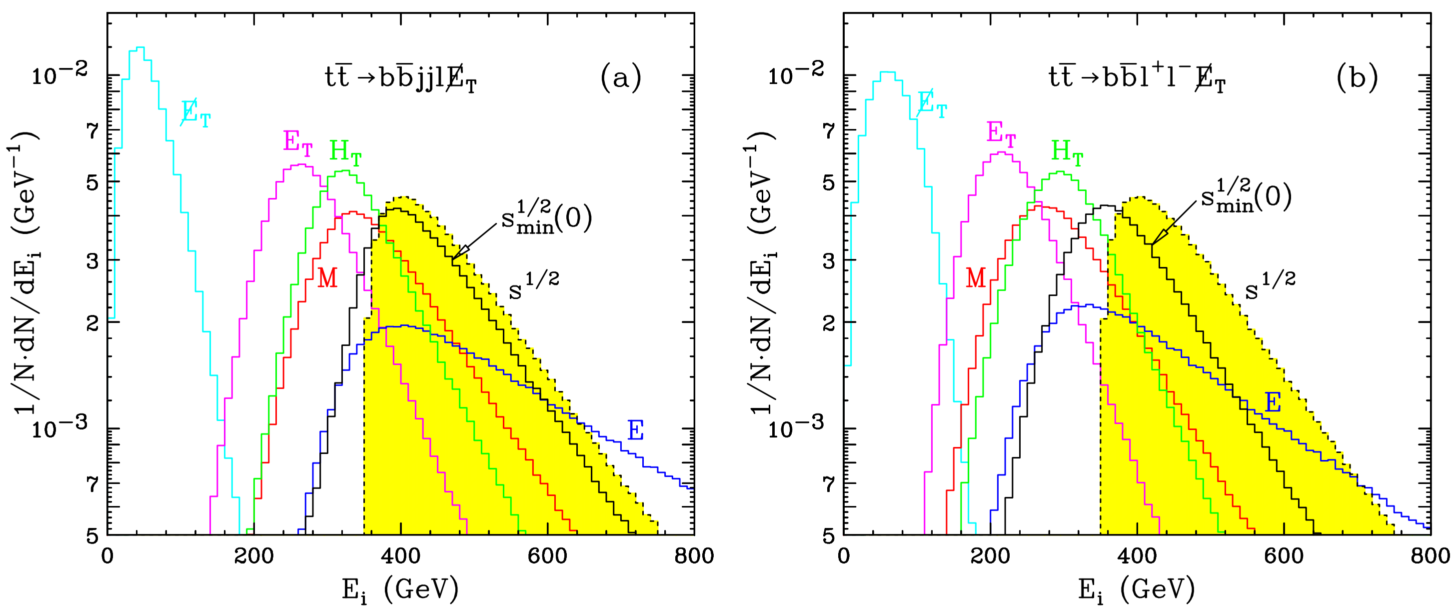
Alternative to HT ?

- $H_T \equiv E_T + \not{E}_T$

- $M_{vis} \equiv \sqrt{E^2 - P_x^2 - P_y^2 - P_z^2} = \sqrt{E^2 - \not{P}_T^2 - P_z^2}$

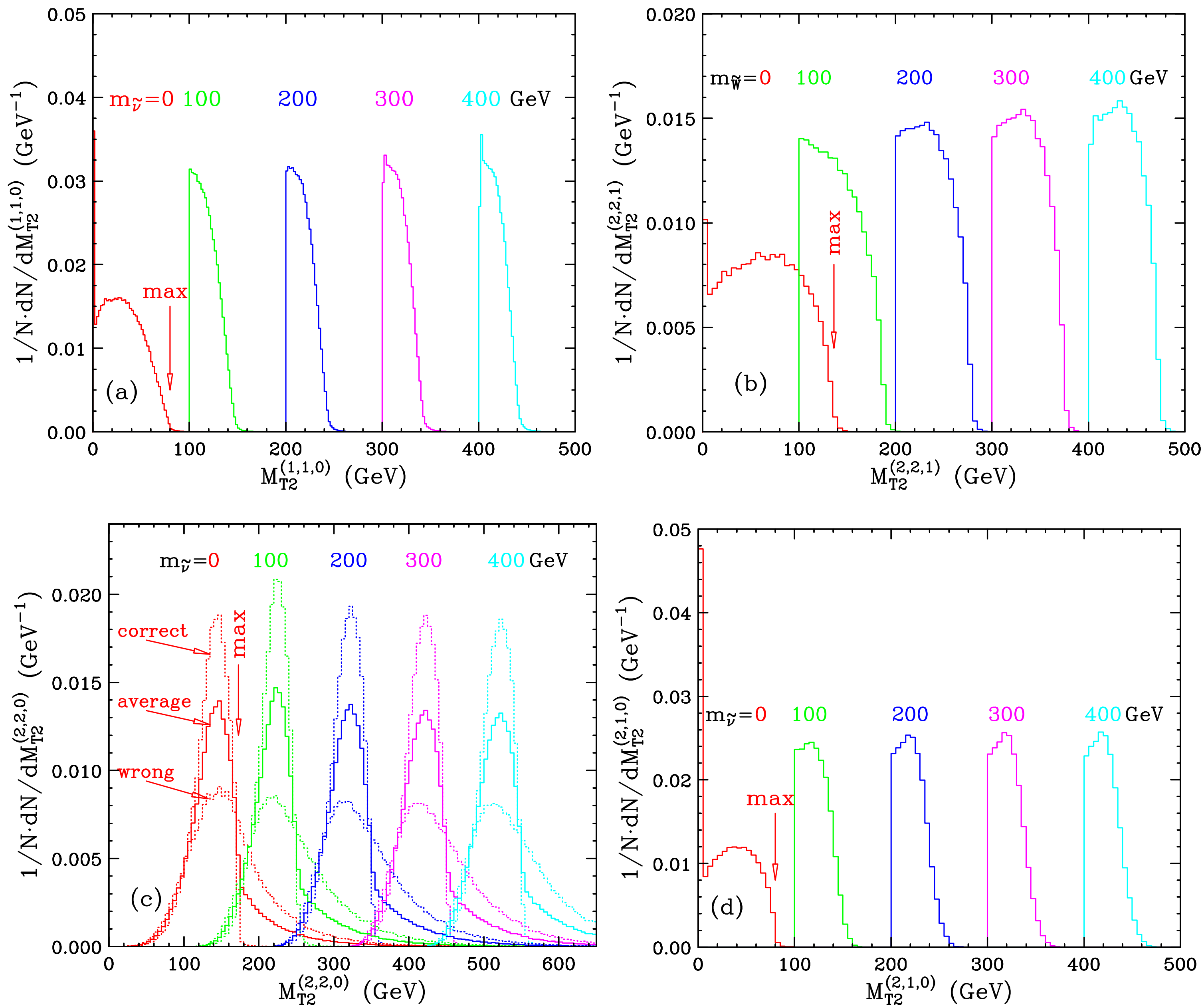
- $\hat{s}_{min}^{1/2}(M_{inv}) = \sqrt{\not{E}_T^2 + M_{vis}^2} + \sqrt{\not{E}_T^2 + M_{inv}^2}$

- $\hat{s}_{min}^{1/2}(0) = \sqrt{E^2 - P_z^2} + \not{E}_T$



A few more comments on kinematics

- $t\bar{t}$ in dilepton channel is an excellent example for preparing for BSM signatures at the LHC (in fact, it is one of difficult examples)
- can we reconstruct all masses (t, W, ν) without any assumptions ?
- can we measure spins of t, W and ν ?
- can we measure couplings ?
- try to develop new methods ! (MT2, kinematic constraints ...)



m_ν̃=0 100 200 300 400 GeV
max
(a)
1/N·dN/dM_T2^(1,1,0) (GeV^-1)
M_T2^(1,1,0) (GeV)
m_W̃=0 100 200 300 400 GeV
max
(b)
1/N·dN/dM_T2^(2,2,1) (GeV^-1)
M_T2^(2,2,1) (GeV)
m_ν̃=0 100 200 300 400 GeV
correct
average
wrong
max
(c)
1/N·dN/dM_T2^(2,2,0) (GeV^-1)
M_T2^(2,2,0) (GeV)
m_ν̃=0 100 200 300 400 GeV
max
(d)
1/N·dN/dM_T2^(2,1,0) (GeV^-1)
M_T2^(2,1,0) (GeV)