The "Top" Priority at the LHC

Tao Han

University of Wisconsin-Madison

(LHC Workshop, Princeton, March 21, 2007)

With Vernon Barger and Devin Walker hep-ph/0612016

Rakhi Mahbubani, Devin Walker and Lian-Tao Wang, to appear.

The "Top" Priority at the LHC
– Top quark: A Window to New Physics

Tao Han

University of Wisconsin-Madison

(Tsinghua University, Jan. 8, 2008)

With Vernon Barger and Devin Walker hep-ph/0612016

Rakhi Mahbubani, Devin Walker and Lian-Tao Wang, to appear.

An exciting time:

The triple “Coincidence”

(1). A highly successful theory: the Standard Model.

An exciting time:

The triple “Coincidence”

(1). A highly successful theory: the Standard Model.

(2). Terascale new physics must exist!

An exciting time:

The triple "Coincidence"

(1). A highly successful theory: the Standard Model.

(2). Terascale new physics must exist!

(3). Upcoming the LHC: Uncover the underlying physics.

Terascale Physics at the LHC

- Unitarity argument for $W_L W_L$ scattering

  $\Rightarrow$ New physics must show up at the Terascale: A Higgs boson $m_H < 1$ TeV or alike.

- Naturalness argument for a m_H or EW scale

  $\Rightarrow$ New physics needed beyond H^0....

- Gauge coupling unification

  $\Rightarrow$ New threshold at the Terascale.

- Particle dark matter

  $\Rightarrow$ WIMP at the Terasacle natural.

Terascale Physics at the LHC

- Unitarity argument for $W_L W_L$ scattering

  $\Rightarrow$ New physics must show up at the Terascale: A Higgs boson $m_H < 1$ TeV or alike.

- Naturalness argument for a m_H or EW scale

  $\Rightarrow$ New physics needed beyond H^0....

- Gauge coupling unification

  $\Rightarrow$ New threshold at the Terascale.

- Particle dark matter

  $\Rightarrow$ WIMP at the Terasacle natural.

What exact form is it realized in nature?

Fundamental scalar in a weakly coupled theory? (SUSY or alike)
Composite Higgs and strongly interacting dynamics? (TC, Little Higgs)
Low scale string/gravity? (Large extrad dim., RS, ...)

Dark matter connection? (WIMP: LSP ...)

The LHC will tell!

In anticipation of the LHC

Re-discover the SM!

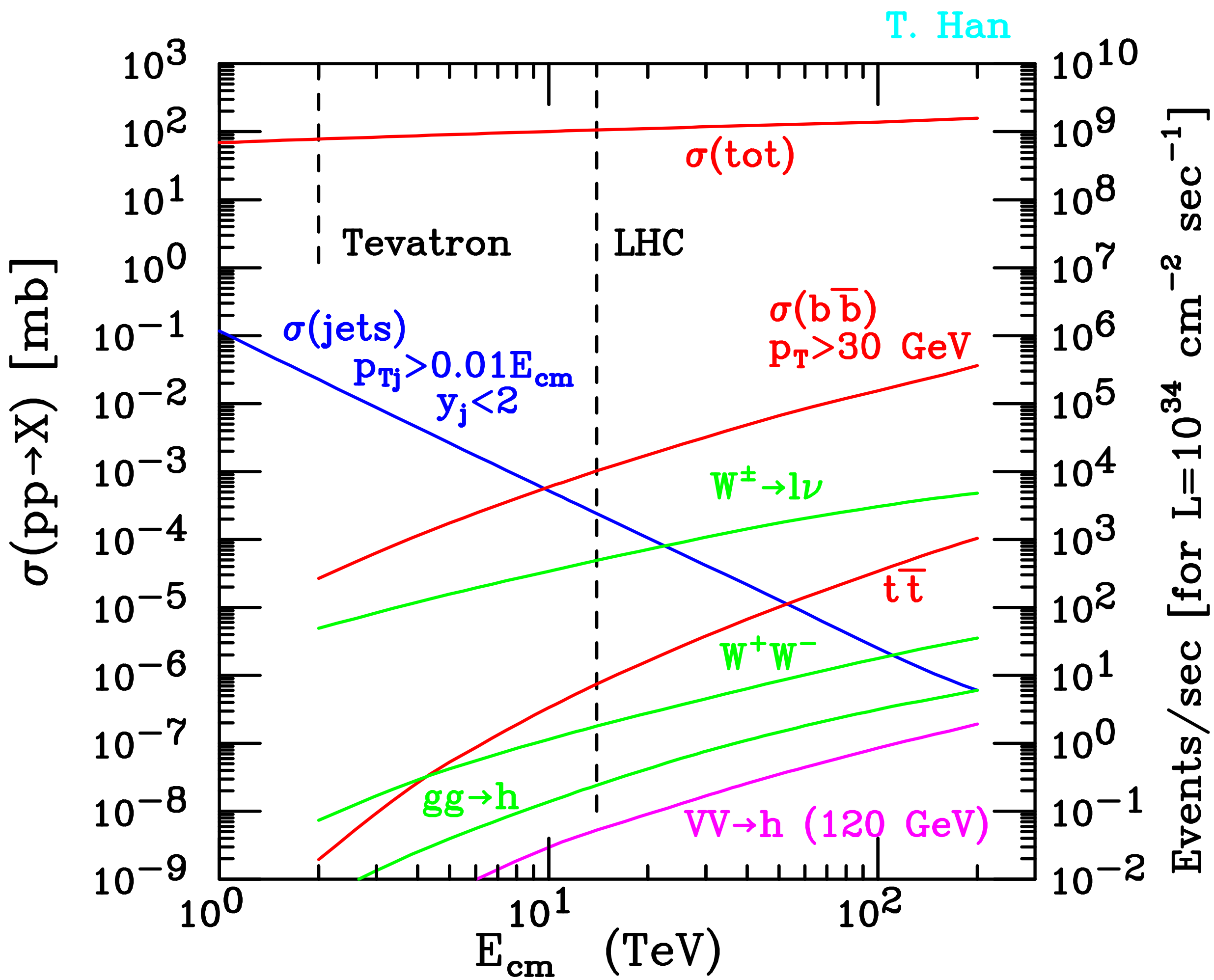
DY: $Z \to \ell^+\ell^-, W^\pm \to \ell^\pm\nu$

Jet inclusive $E_T(j)$

Heavy quarks $\Upsilon, J/\psi, b\bar{b}, t\bar{t}$

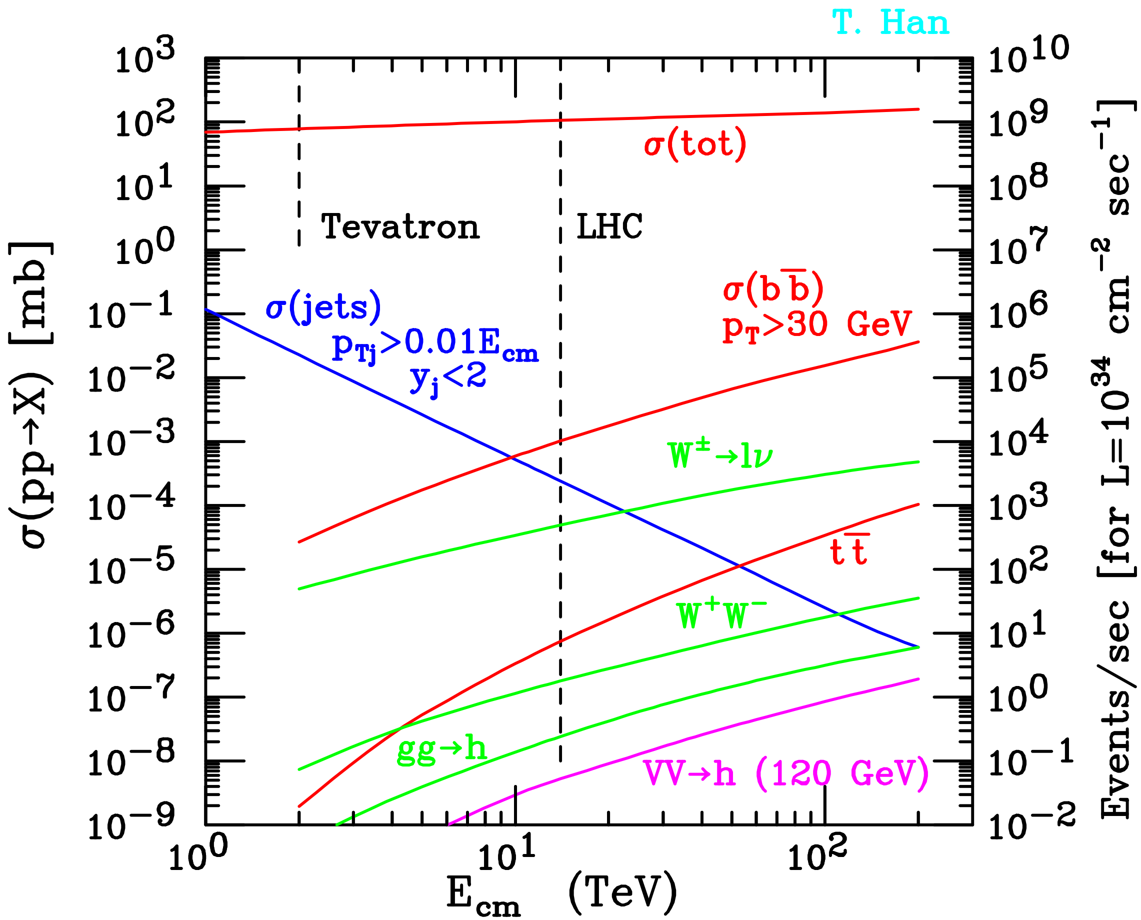
Gauge boson pairs WW, ZZ

Large $\not{E}_T + X$



Top quarks at the LHC

LHC is a top factory:



Event rate: 800K $t\bar{t}$ / fb^{-1}, or 8 Hz @10^{34}/cm^2/s !

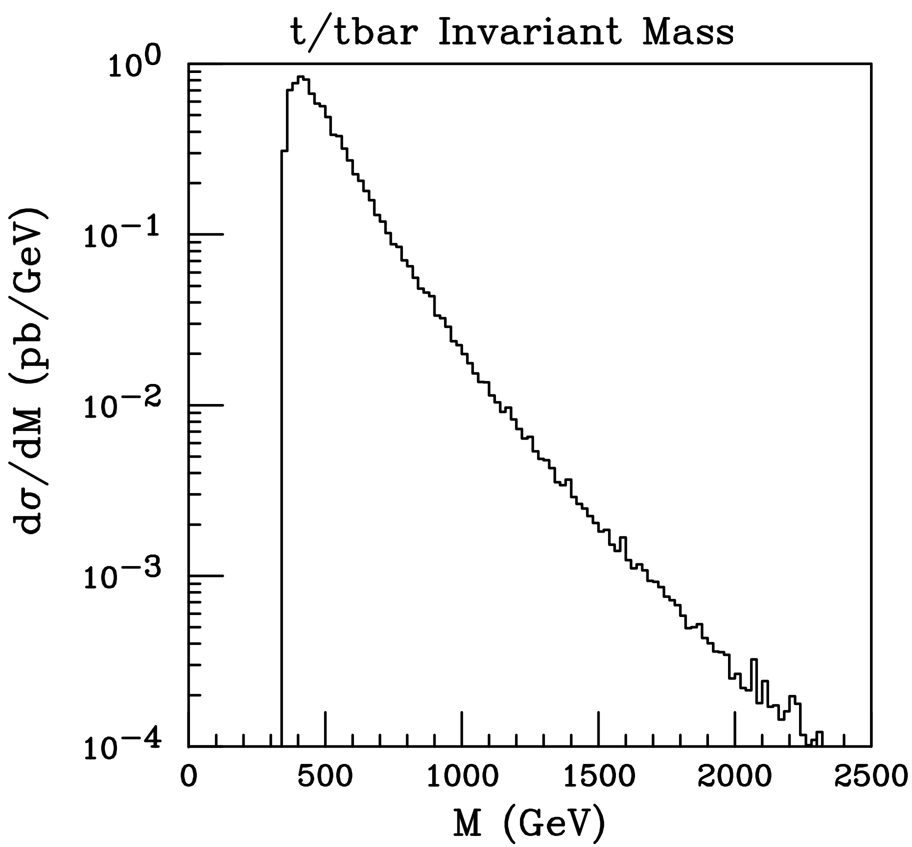
From Tevatron to LHC: $t\bar{t}$ increased by 100; EW increased by 10.

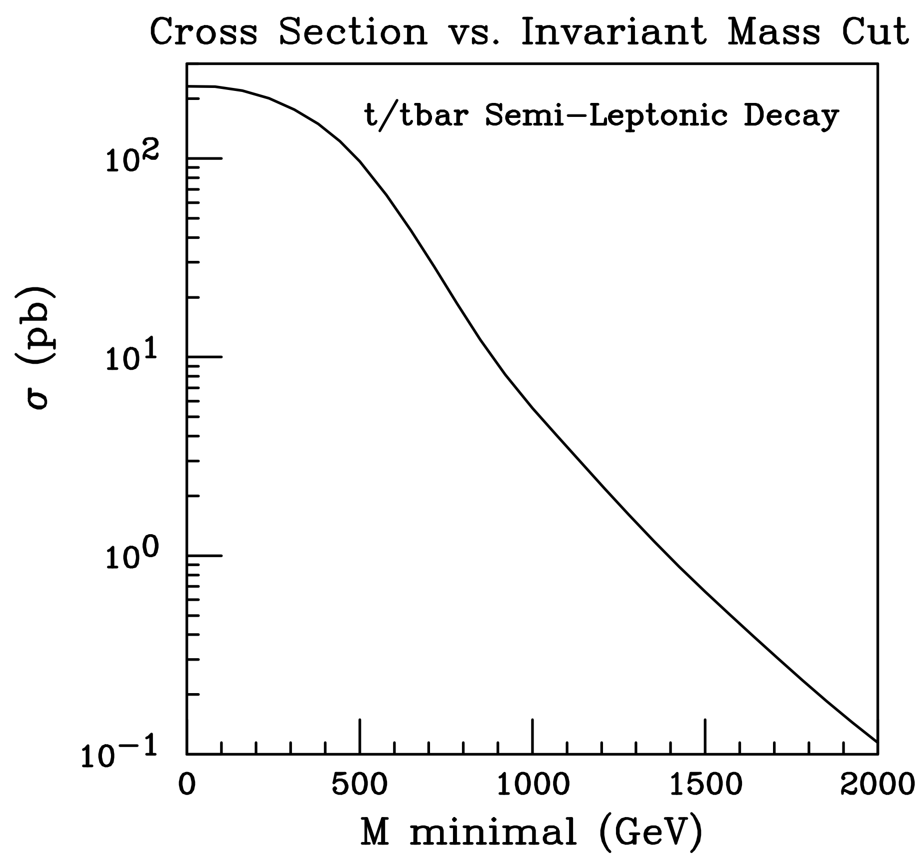
Top quarks at the LHC:

Production well predicted in the SM:

At the LHC: gg 90%, $q\bar{q}$ 10%;

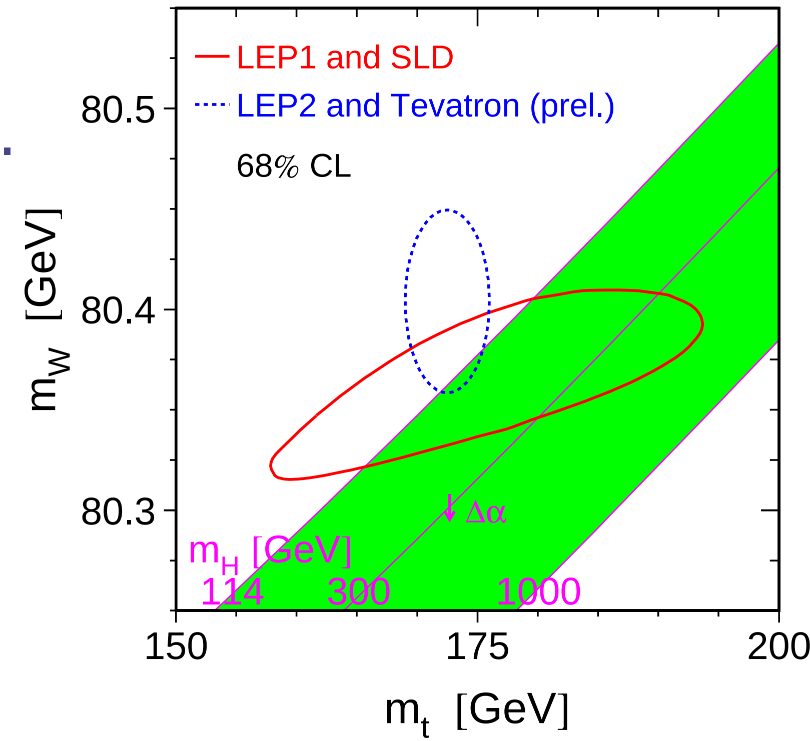
(At the Tevatron: gg 10%, $q\bar{q}$ 90%.)





Why Top Quarks? bread & butter:

- Top quark exists,
  as the heaviest particle in the SM.
- m_t is the most precisely measured quark mass — Important for precision physics of the SM and beyond:



- Top decays before it hadronizes:

  Good test ground for QCD, spin correlation, couplings, CP property...

- Possible deep connection to electroweak symmetry-breaking:
  $m_t \approx v/\sqrt{2}$.

Why Top Quarks? A window to new physics

- Largest Yukawa coupling (proportional to $m_t, \cot\beta$):
  $H,\ A \to t\bar{t}$.
- Strong Dynamics (TC, Topcolor/Top See-Saw, Little Higgs):
  $\rho_{TC},\ \eta_{TC},\ \pi_{TC},\ Z_L \to t\bar{t}$.
- Extra-dimensions (warped and universal):
  $g_{KK},\ G_{KK} \to t\bar{t}$.
- Flavor physics at high scale: $t \to Zc,\ \gamma c,\ gc\ (u)$.
- Supersymmetry ($\tilde{t}$ often the lightest squark): $\tilde{t}_R \to t\tilde{\chi}^0$.
- LH with T-parity (theories with naturalness argument):
  $T \to tA^0$.
- To the least, precision couplings: $t\bar{t}Z,\ t\bar{t}H;\ \ t\bar{t}\gamma, g;\ \ t\bar{b}W$...

The Remainder of the Talk

- Search I: $t\bar{t}$ Resonant Production
  - Backgrounds
  - Reconstruction Methods
  - Search for New Physics
- Search II: $t\bar{t}+\not{E}_T$ Signal
  - Backgrounds
  - Signal Events Reconstruction
- Conclusions

Search I: $t\bar{t}$ Resonant Production

- "Bump searches" in the $M_{t\bar{t}}$ distribution.
- Representative features:

Model Class	Spin-0	Spin-1	Spin-2
Technicolor/Topcolor/RS	$\times$ (nrw/brd)	$\times$ (nrw/brd)	$\times$ (narrow)
MSSM	$\times$ (narrow)		
Little Higgs	$\times$ (narrow)	$\times$ (narrow)	

- A model-independent approach:
  Parametrize each resonance with a few parameters:
  $m,\ \Gamma$, σ-normalization, chirality, CP violation

Strategy

To maximumly extract the resonant information:
(Spin, chirality couplings, CP properties ...)
$\Longrightarrow$ Need full kinematics and top-ID.

- Using the clean channel: “Semi-leptonic"

$$t\bar{t} \to b\ell^\pm\nu,\ bjj \to 2b\, 2j\ \ell^\pm\ \not{E}_T.$$

  - Total Hadronic Channel: $\sigma_{\rm t/tbar} \times (6/9)^2 \Longrightarrow$ large background, no top-ID ...
  - Semi-Leptonic Channel: $\sigma_{\rm t/tbar} \times 6/9 \times 2/9 \times 2 \Longrightarrow$ current interest.
  - Pure leptonic Channel: $\sigma_{\rm t/tbar} \times (2/9)^2 \Longrightarrow$ small rate, incomplete kinematics ...
  - Semi-leptonic/hadronic ratio: 2/3
  - Leptonic/hadronic ratio: 1/9

- We propose new/refined top reconstruction methods.
- Take advantage of the tops being highly boosted.

Background Considerations

- W + jets, Z + jets, WW, WZ, ZZ backgrounds:
  - Consider table of efficiencies reproduced from the ATLAS TDR (Volume II, p. 624). The expected events are in the last column.

Process	Efficiency with $p_T^l > 20$ GeV $E_T\mathrm{miss} > 20$ GeV cuts	As before, with plus $N_{\mathrm{jet}} \geq 4$ cut	As before, with plus $N_{\mathrm{b-jet}} \geq 2$ cut	Events per 10 fb^{-1}
$t\bar{t}$ signal	64.7	21.2	5.0	126,000
$W+$ jets	47.9	0.1	0.002	1658
$Z+$ jets	15.0	0.05	0.002	232
WW	53.6	0.5	0.006	10
WZ	53.8	0.5	0.02	8
ZZ	2.8	0.04	0.008	14
Total Background				1922
S/B				65

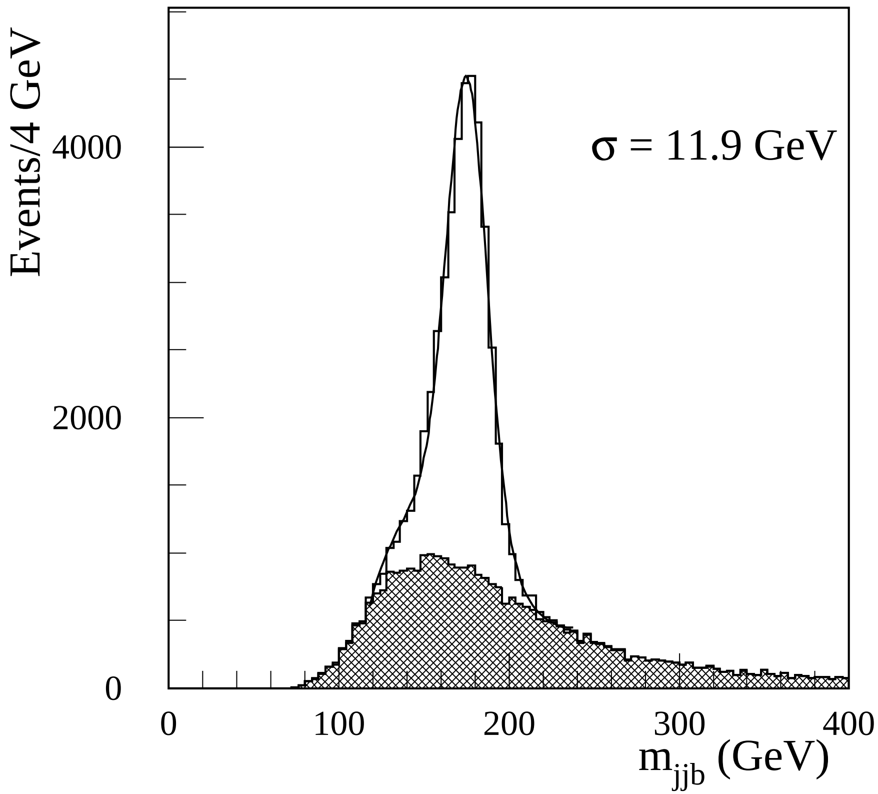
Background Cont'd

- W + jets, W + 4 jets, Wbb + 2j, Wbb + 3j backgrounds:
  - Efficiencies from CMS TDR (Volume II, p. 238).

	Semi-leptonic $t\bar{t}$	**Other $t\bar{t}$**	**W+4j**	**Wbb+2j**	**Wbb+3j**	**S/B**
Before cuts	365k	1962k	82.5k	109.5k	22.5k	5.9
L1+HLT Trigger	62.2%	5.3%	24.1%	8.35%	8.29%	7.8
Four jets $E_T > 30$ GeV	25.4%	1.01%	4.1%	1.48%	3.37%	9.9
$p_T^{\rm lepton}$ **cut**	24.8%	0.97%	3.9%	1.41%	3.14%	10.3
b-tag criteria	6.5%	0.24%	0.064%	0.52%	0.79%	25.4
Kinematic fit	6.3%	0.23%	0.059%	0.48%	0.72%	26.7
Cross section (pb)	5.21	1.10	0.10	0.08	0.05	26.7
Scaled to $\mathcal{L} = 1\ fb^{-1}$	5211	1084	104	82	50	26.7

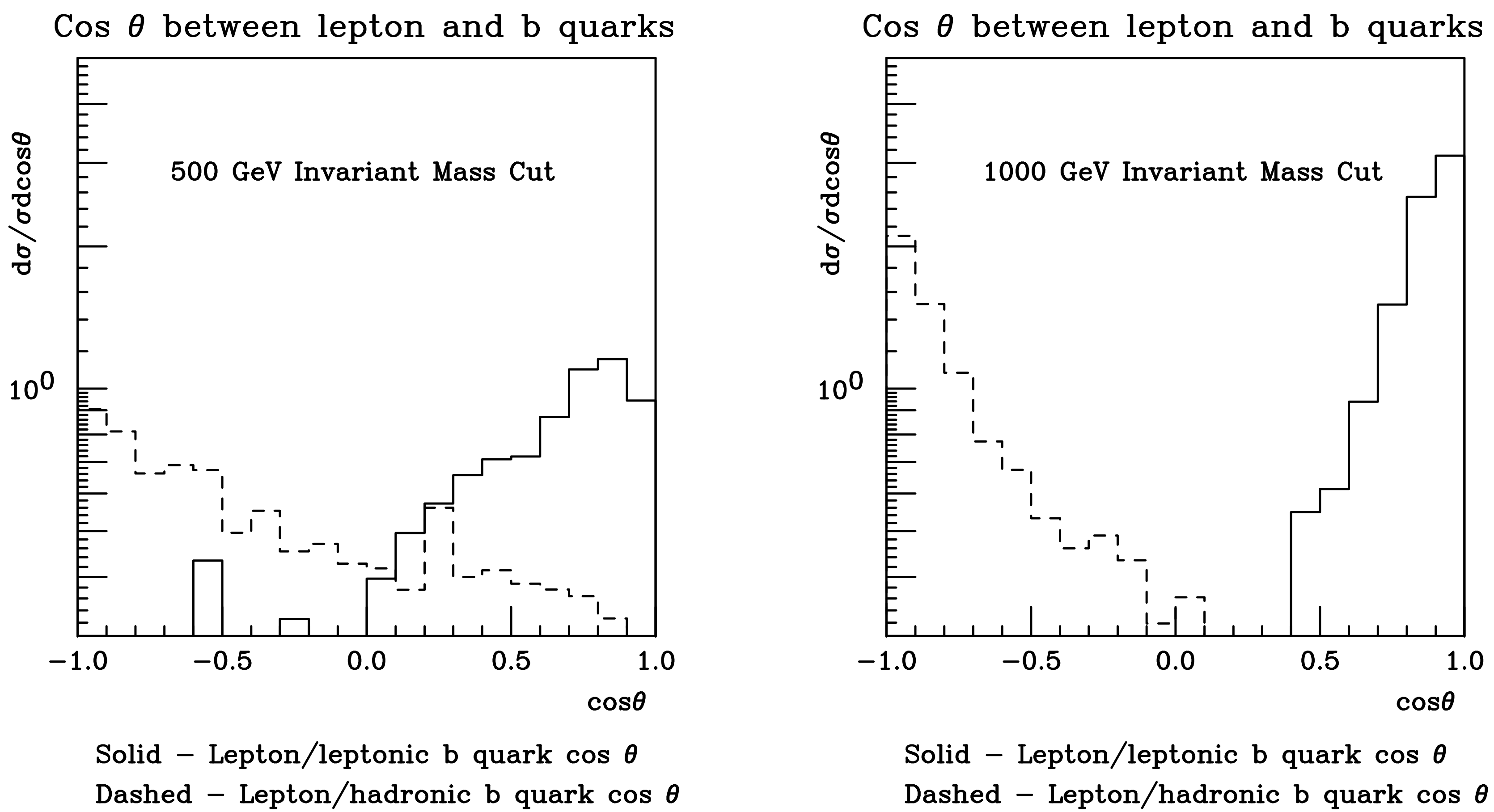
Background Cont'd

- Reconstructing the hadronic decay ($\bar{t}$, say):
  - From ATLAS collaboration (ATLAS TDR,Volume II, p. 625): The $\bar{t}$ is reconstructed via the hadronic decay $\bar{b}jj$. The wrong b may have some contamination (shaded area).



Background Cont'd

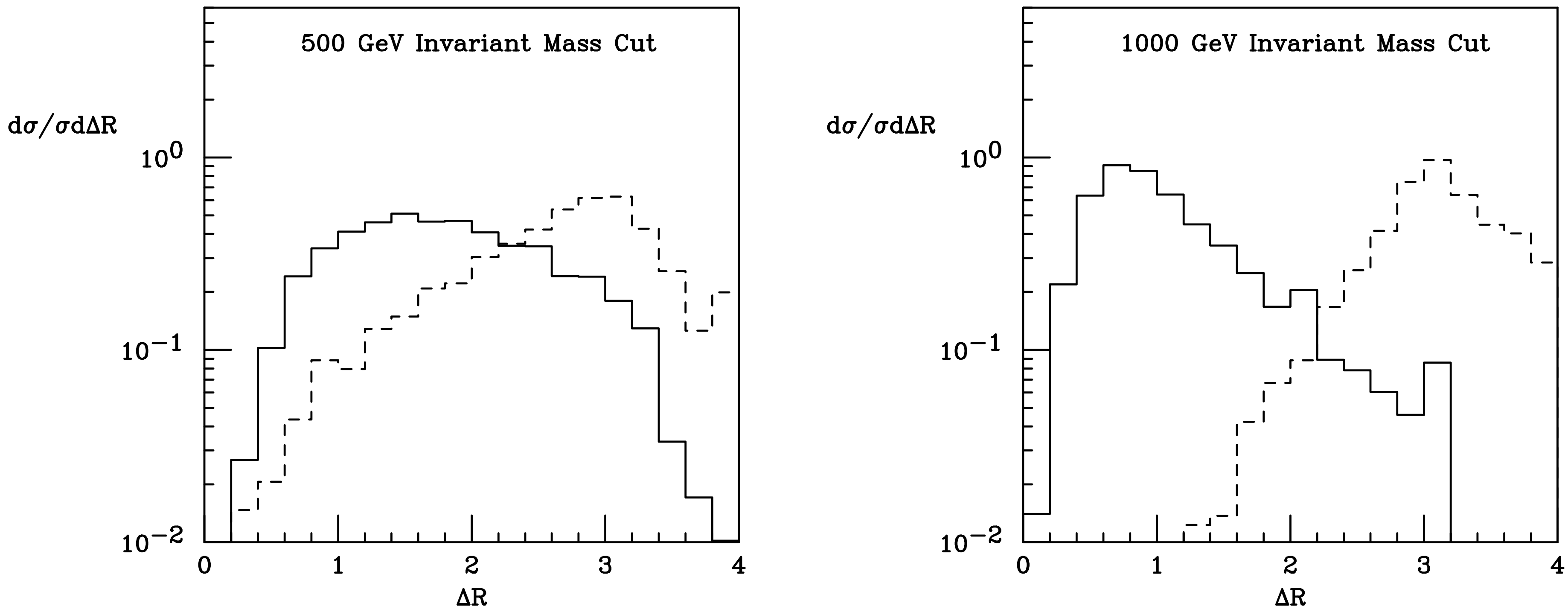
- At high $M_{t\bar{t}}$, the tops are boosted.
  That helps select $(\ell^+ \, b)$, rather than $(\ell^+ \, \bar{b})$.



Background Cont'd

- Lepton isolation does not effect the signal appreciably:

$$\Delta R > 0.4$$



Event Selection

- When indicated we apply the following acceptance cuts:
  - Jets: $p_T > 20$ GeV, $|\eta_j| \leq 2.5$
  - Leptons: $p_T \geq 20$ GeV, $|\eta_l| \leq 2.5$, $\Delta R > 0.4$
  - $\not{E}_T \geq 20$ GeV (tightened the ATLAS cuts)
  - Minimum Transverse Mass: $M_T(t\bar{t}) > 600$ GeV
- Detector effects (Gaussian smearing) taken into account:

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E/GeV}} \oplus b.$$

  - CMS ECAL resolution: $a = 0.03$, $b = 0.005$
  - CMS HCAL resolution: $a = 1.1$, $b = 0.05$
  - pT CMS resolution: $a = 1.5 \times 10^{-4}$, $b = 0.05$

ATLAS/CMS simulations:

SM processes not a threat to the top-quark sample.

Kinematics Reconstruction

- Present two schemes:

  Reconstruction of the missing neutrino!

  - $(M_W,\ m_t)$* scheme: the masses as known inputs.
  - Small angle scheme: t decay products collimated.

*Similar to the three-constraint kinematic fit used at the Tevatron to determine the top mass.
CDF Collaboration, Phys. Rev. Lett. **80** (1998) 2767;
D0 Collaboration, Phys. Rev. **D27** (1983) 052001.

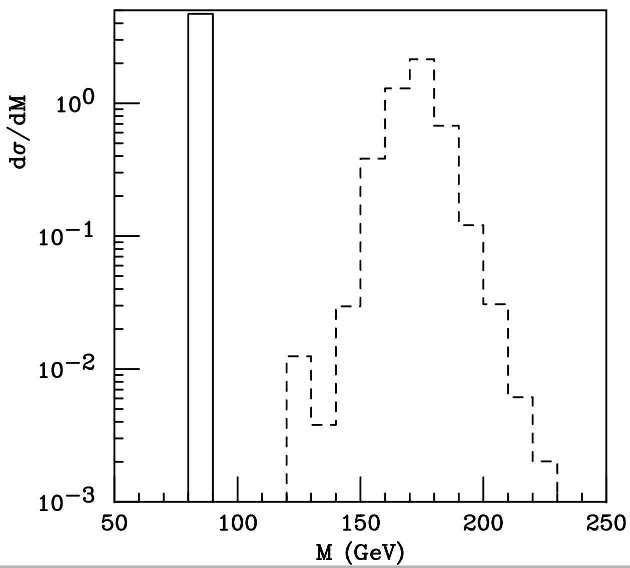
(M_W, m_t) Scheme

- Step 1: Reconstruct W boson with the constraint: $M_W^2 = m_{l\nu}^2$.
  Yields two-fold ambiguity for the neutrino longitudinal momentum:

$$p_{\nu L} = \frac{A\, p_{eL} \pm E_e \sqrt{A^2 - 4\, \vec{p}_{eT}^{\,2}\, \vec{\not{E}}_T^{\,2}}}{2\, p_{eT}^2}, \quad \text{where} \;\; A = M_W^2 + 2\, \vec{p}_{eT} \cdot \vec{\not{E}}_T.$$

• If $A^2 - 4\, \vec{p}_{eT}^{\,2}\, \vec{\not{E}}_T^{\,2} \geq 0$, then choose the value that reconstructs $m_t^2 = m_{l\nu b}^2$.
• If not, go to Step 2.

Expected distributions from this reconstruction alone:



(M_W, m_t) Scheme Cont'd

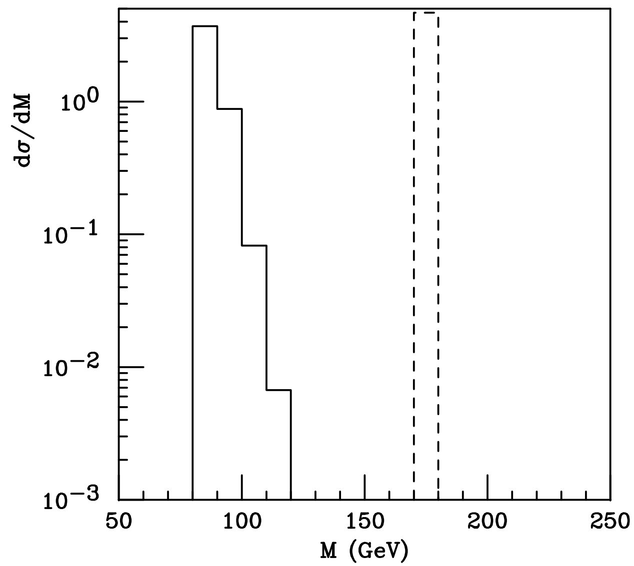
- Step 2: If Step 1 gives complex solutions, first reconstruct top quark with: $m_t^2 = m_{l\nu b}^2$.
  Yields two-fold ambiguity for the neutrino longitudinal momentum:

$$p_{\nu L} = \frac{A' \, p_{blL} \pm \sqrt{p_{blL}^2 A'^{\,2} + (E_{bl}^2 - p_{blL}^2)\,(A'^{\,2} - 4E_{bl}^2 \not{E}_T^2)^{\,2}}}{2\,(E_{bl}^2 - p_{blL}^2)},$$

$$A' = m_t^2 - M_{bl}^2 + 2\,\vec{p}_{blT} \cdot \vec{\not{E}}_T.$$

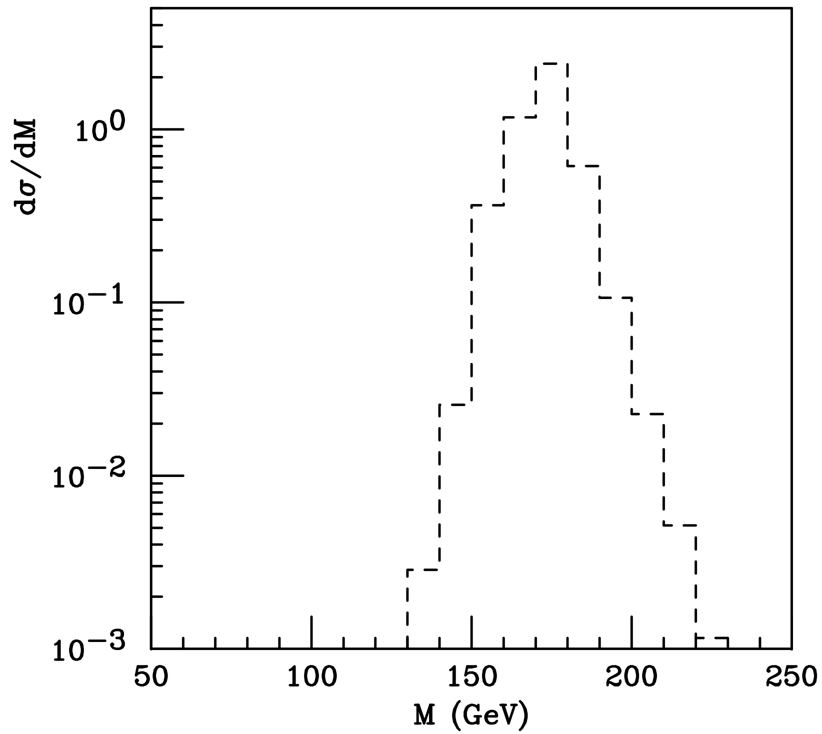
• If $p_{blL}^2 A'^{\,2} + (E_{bl}^2 - p_{blL}^2)\,(A'^{\,2} - 4E_{bl}^2 \not{E}_T^2)^{\,2} \geq 0$, then choose $M_W^2 = m_{l\nu}^2$.
• If not, go to Step 3.

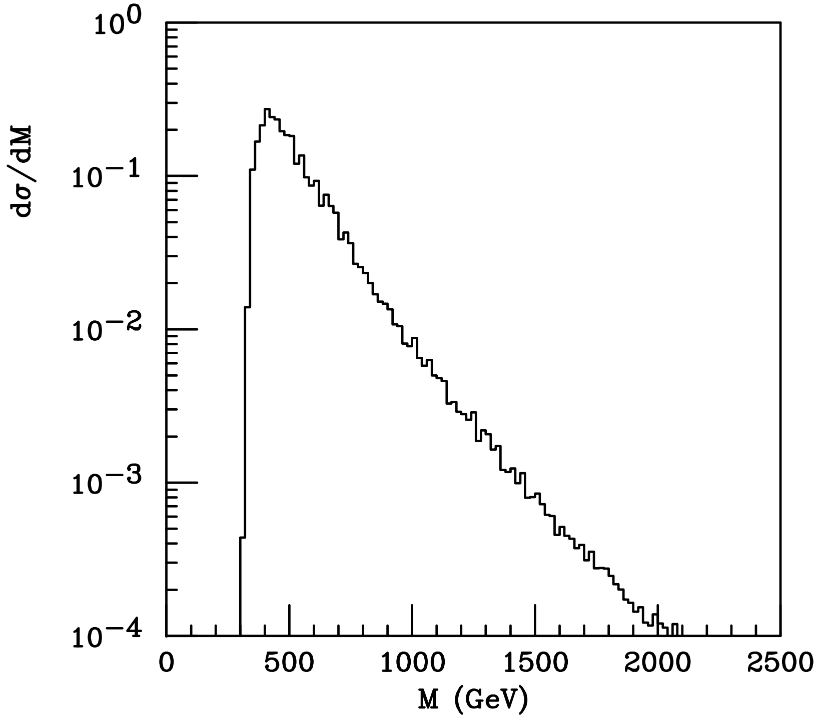
Expected distributions from this reconstruction alone:



$(M_W,\ m_t)$ Scheme Cont'd

- Step 3: If the solution fails to reconstruct for both times, the event is discarded.
  - The discarded event rate $\sim 16\%$.
  - Choosing to keep the discarded solutions (by taking the real components) results in a distortion of high/low invariant mass tails.
- Resulting reconstructions of m_t and M_{tt}:





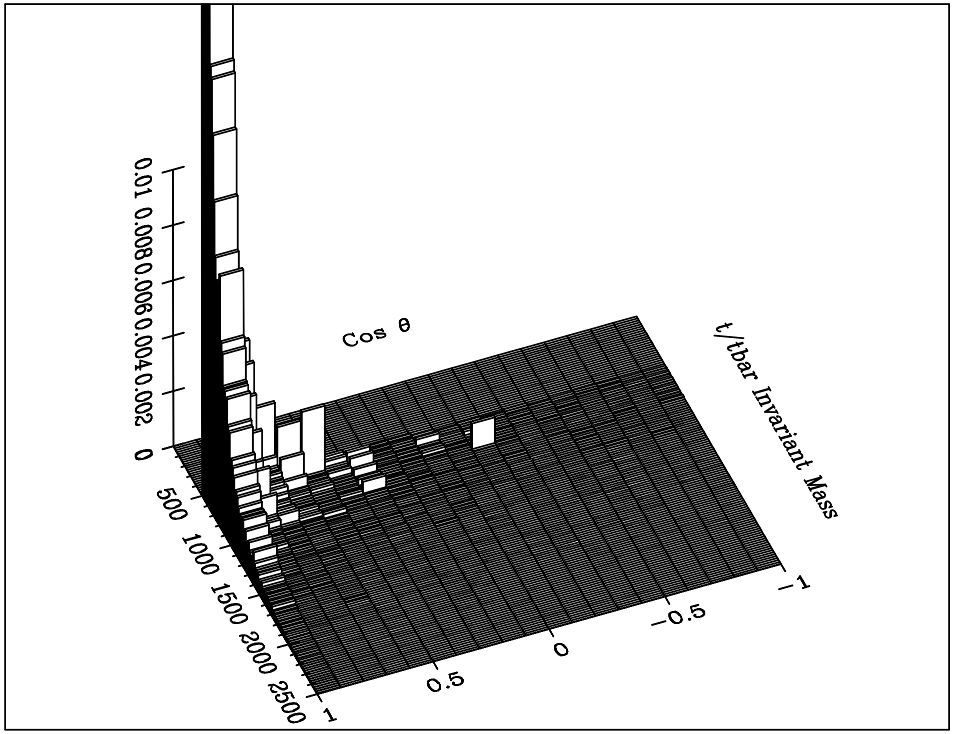
We have the full $t\bar{t}$ kinematics!

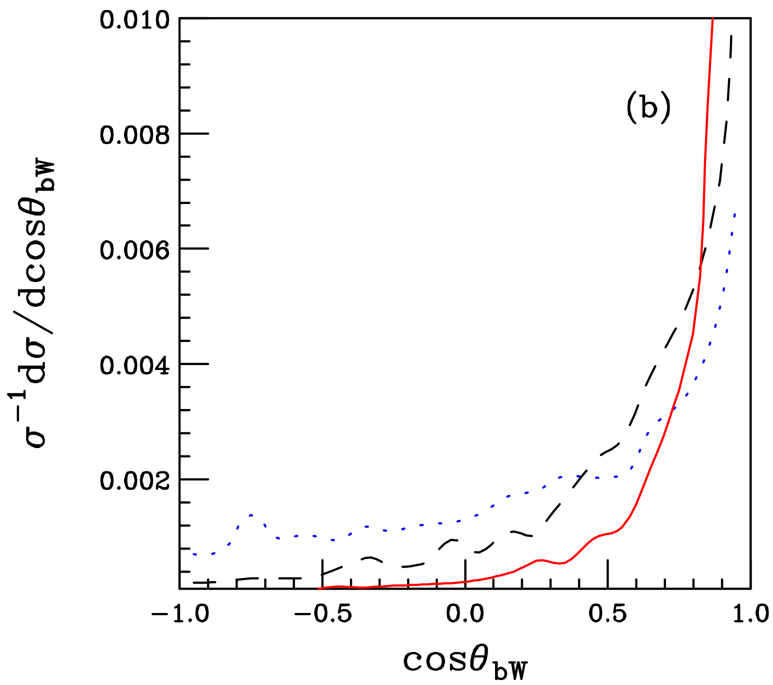
Small Angle Selection Scheme

Wish not to rely on m_t input, because ...

- High $t\bar{t}$ invariant mass limit: Tops quarks highly energetic/boosted:
- Expect a small angle $\theta_{l\nu}$, or in turn, θ_{bW} to give the correct solution.

Consider $\cos\theta_{bW}$:



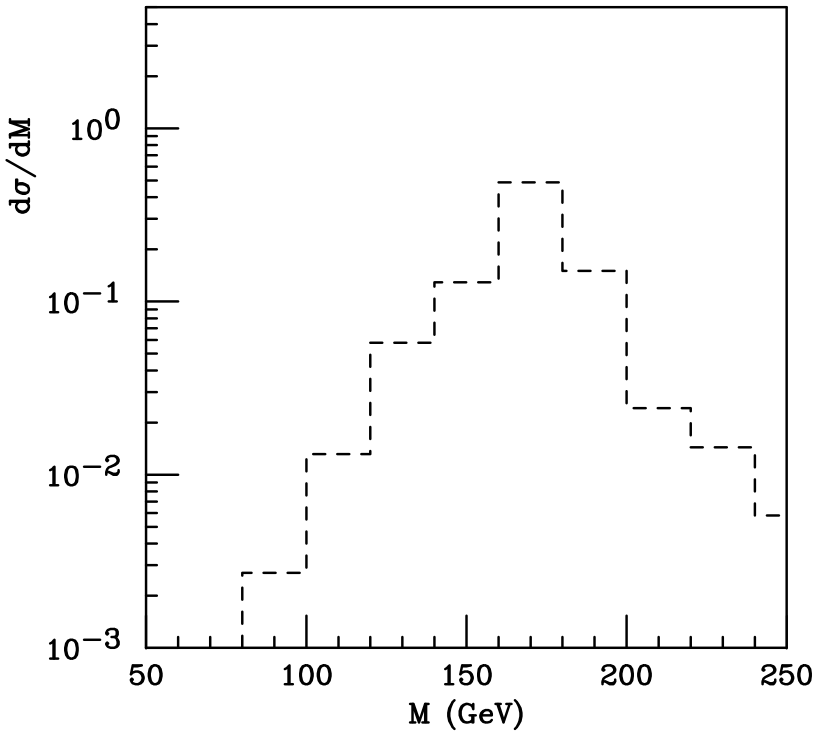


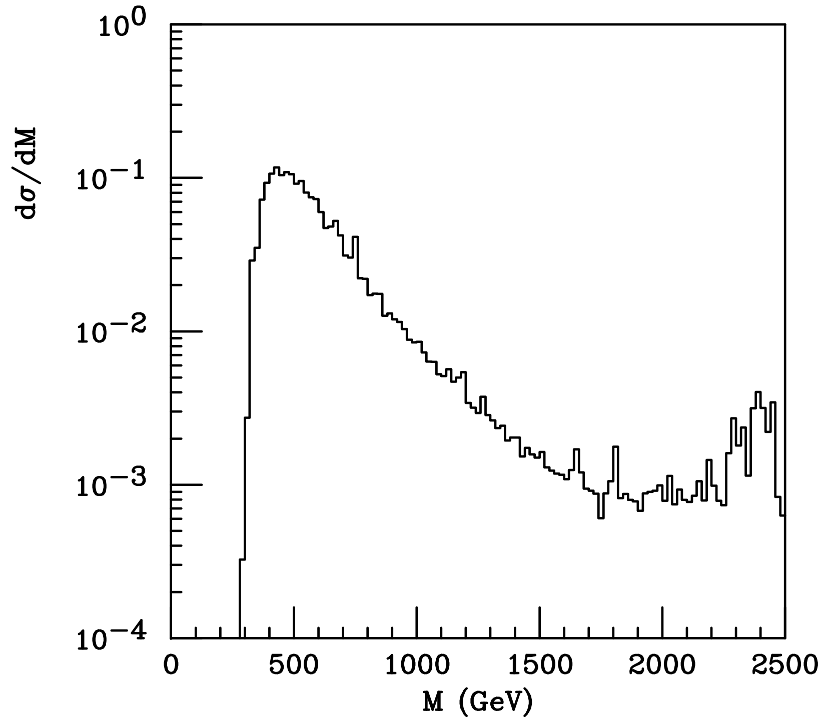
$M_T > 0,\ 600,$ and 1000 GeV.

Small Angle Selection Scheme Cont'd

Thus,

- Again, $M_w^2 = m_{l\nu}^2 \implies$ two-fold ambiguity in $p_{\nu L}$ and thus p_W.
- The scheme: selecting the solution with the smaller angle between the b and the W.
- Resulting reconstruction of m_t and m_{tt}:

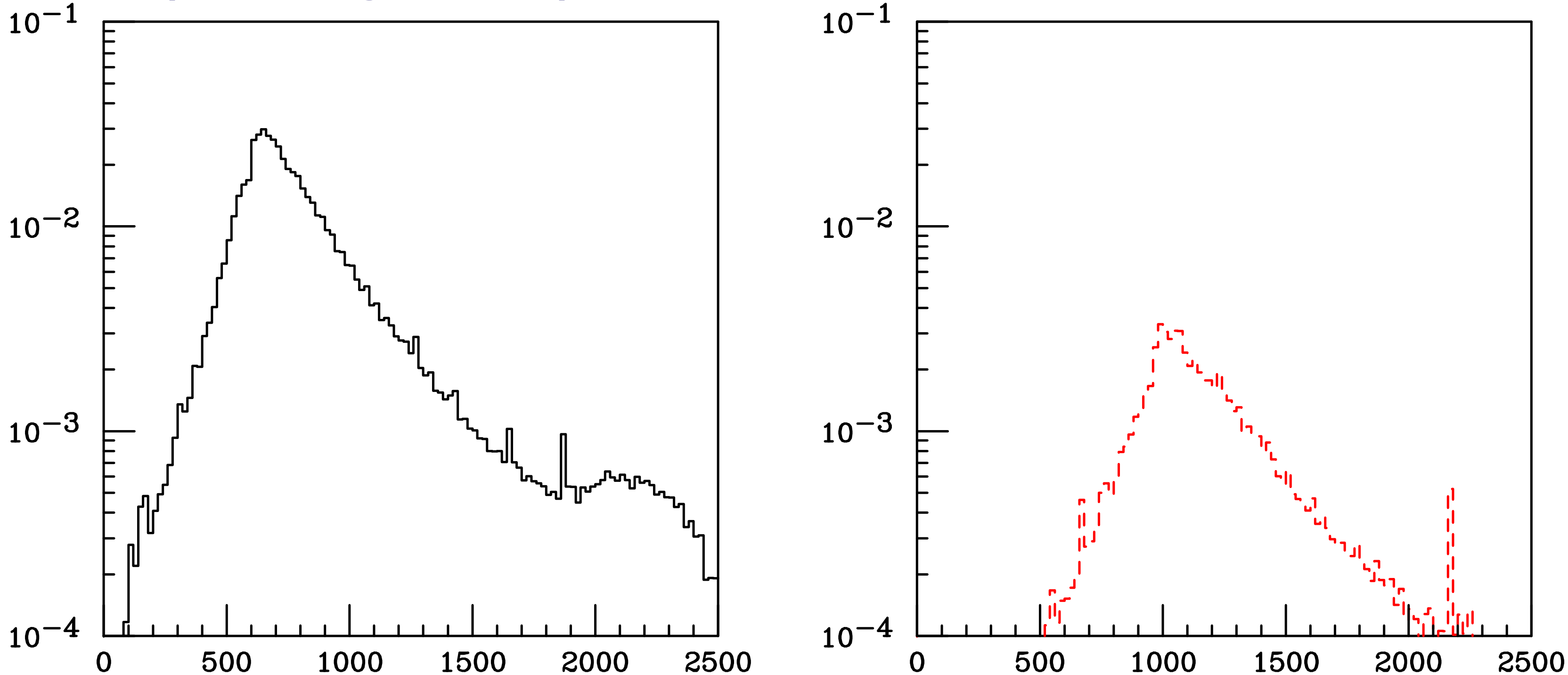




Note the leakage at the high m_{tt} region...

Small Angle Selection Scheme Cont'd

- High Invariant mass tail is due to smearing and the wrong solution in small angle selection.
- A solution: Provide an incrementally higher transverse mass cut depending on expected resonance.



$M_T >$650 and 950 GeV.

Search for New Resonances in m_{tt}

- Search for integer spin resonances via

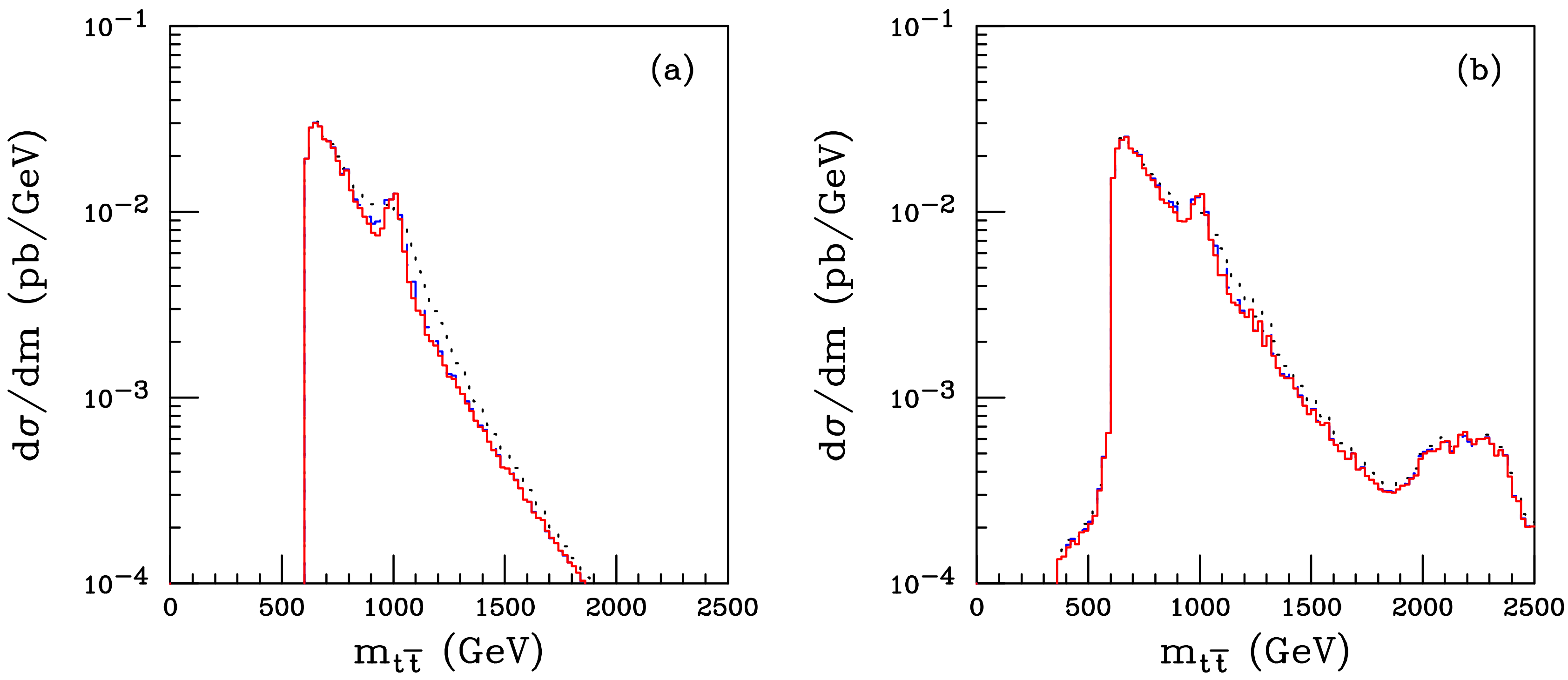
$$\begin{aligned} gg &\rightarrow \phi_0 \rightarrow \bar{t} + t \\ q\bar{q} &\rightarrow V_1 \rightarrow \bar{t} + t \\ q\bar{q},\ gg &\rightarrow \tilde{h}_2 \rightarrow \bar{t} + t \end{aligned}$$

where $\phi,\ V$ and $\tilde{h}$ are $J = 0,\ 1,\ 2$ resonaces.

- Parametrize each interaction with five parameters:
  - m – mass of the resonance (1 TeV for benckmark study)
  - Γ – total width
    - $\Gamma_\phi = 0.5(m_\phi/TeV)^3,\ \Gamma_V = 5\% m_V,\ \Gamma_{\tilde{h}} = 1.2\% m_{\tilde{h}}$
  - ω^2 – cross section normalization factor
    - $\omega_\phi = 1$ recovers SM higgs
    - $\omega_V = 1$ recovers Z' with electroweak couplings
    - $\omega_{\tilde{h}} = 1$ recovers RS graviton
  - Chirality CP violation ...

Resonance Distributions in m_{tt}

- $(M_W,\ m_t)$ and small angle selection, respectively:

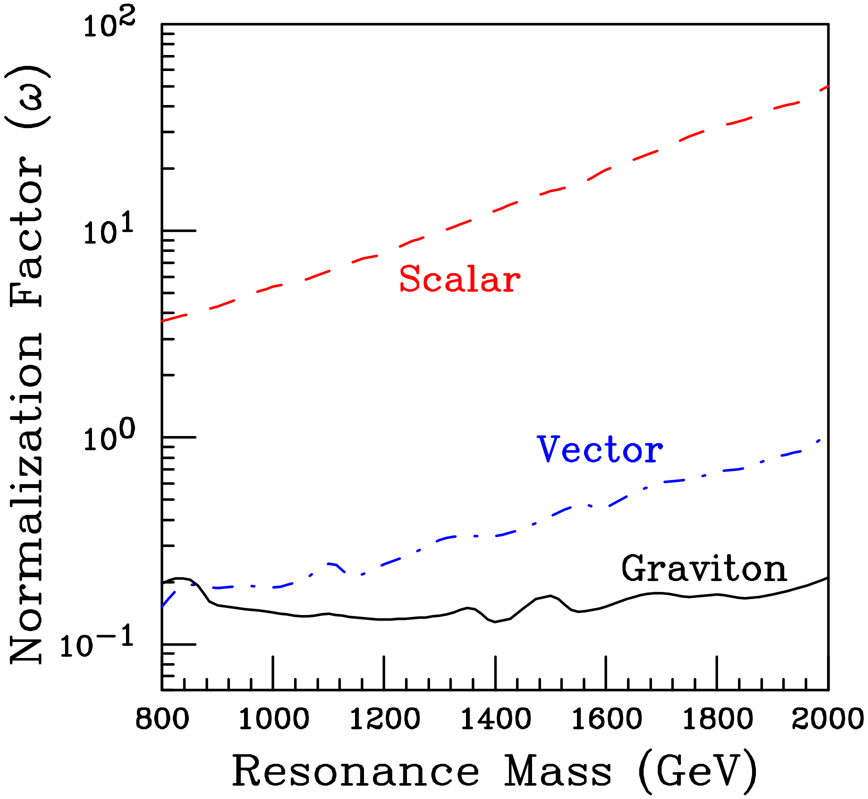


$$\Gamma_{tot} = 2\%\ m,\ \ 5\%\ m,\ \ 20\%\ m.$$

Discovery Potential

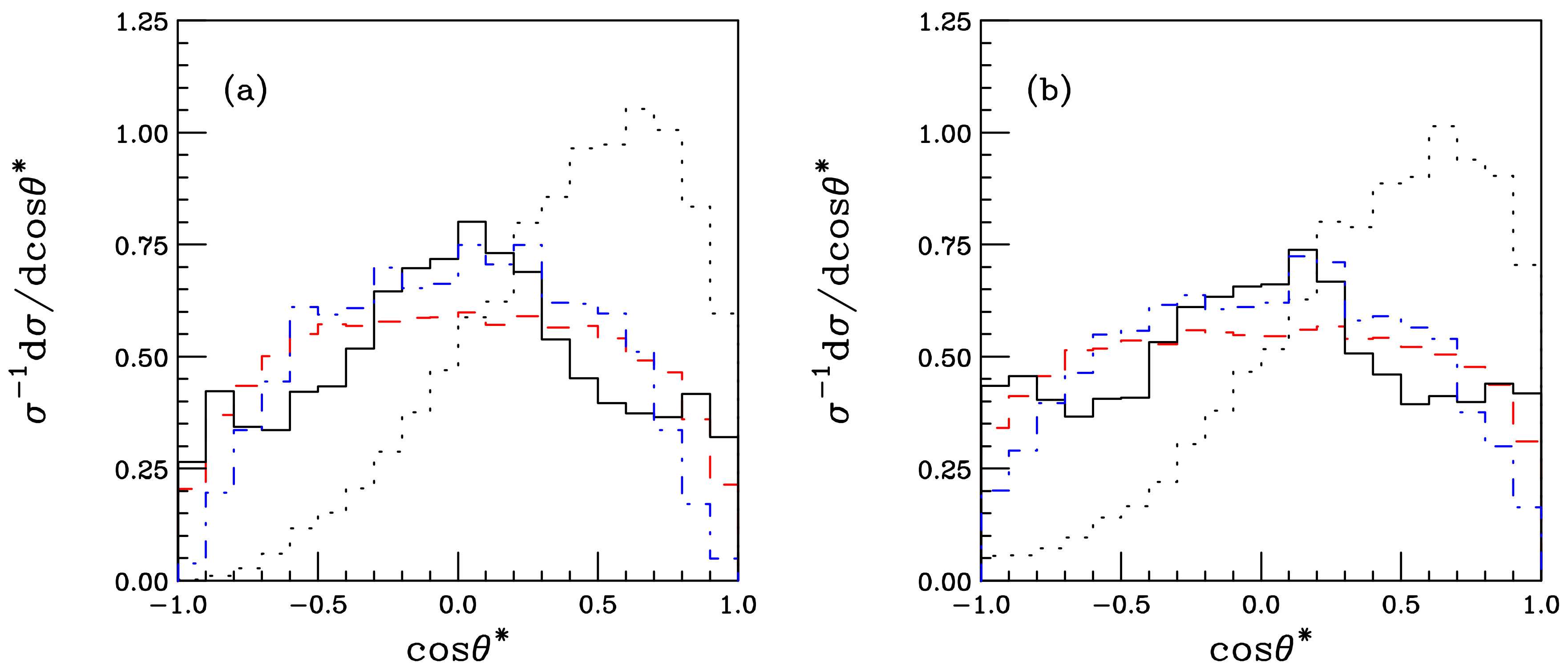
- Determine minimal ω for a 5σ discovery

$$S/\sqrt{B+S} = 5$$



Angular Distributions in $t\bar{t}$ c.m. frame

- $(M_W,\ m_t)$ and small angle selection, respectively



Red dashed: scalar $\rightarrow$ flat;

Black dots: Chiral vector $\rightarrow d^1_{11} \Rightarrow (1+\cos\theta^*)^2$;

Blue dash-dots: graviton from $gg \rightarrow d^2_{2\pm1} \Rightarrow \sin^2\theta^*$;

Black solid: graviton from $q\bar{q} \rightarrow d^2_{1\pm1} \Rightarrow \sin^4\theta^* + \ldots$.

Chirality

- Forward/Backward Asymmetry for Parity-Violation:

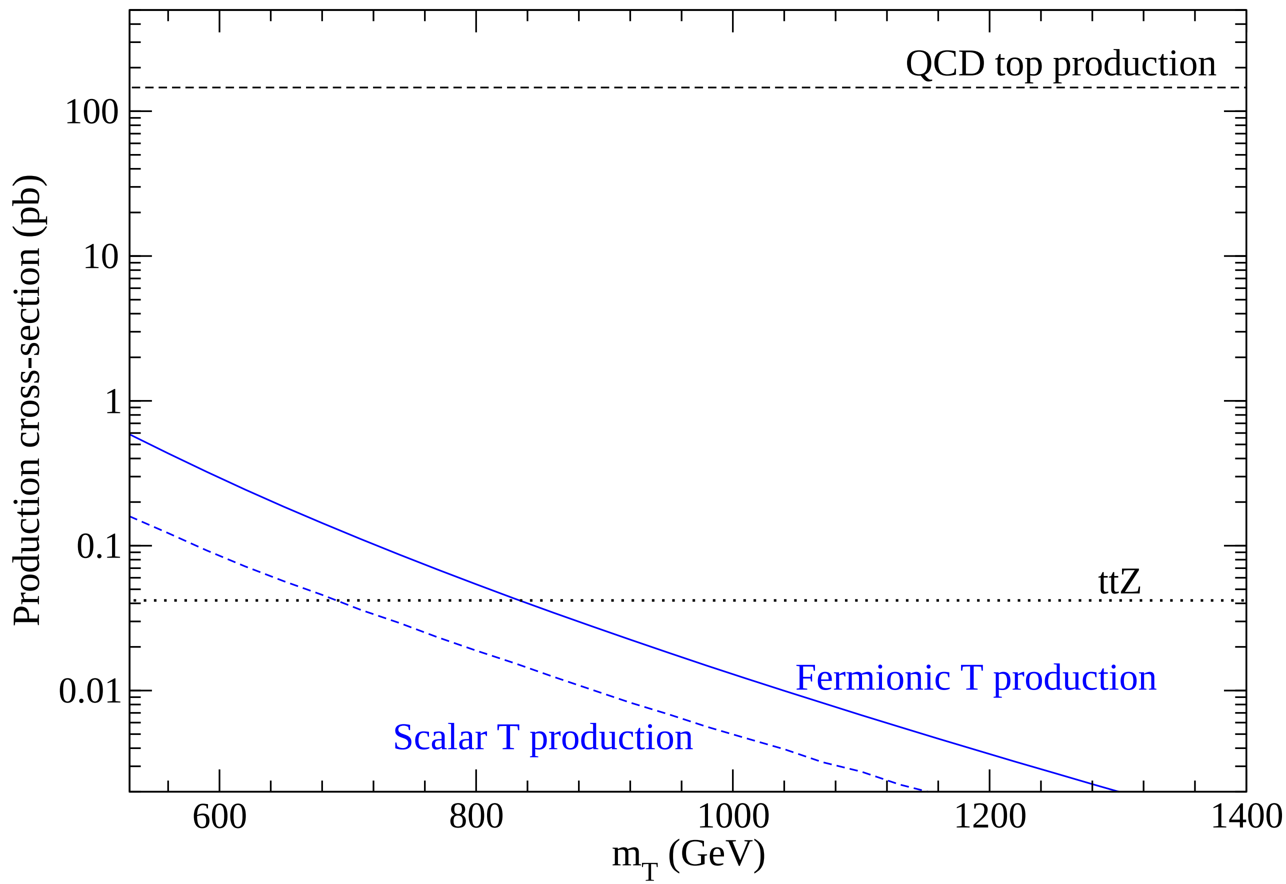
$$\mathcal{A}_f^{\rm had} = \frac{N_F - N_B}{N_F + N_B}$$

  - N_F (N_B) is the number of events with the top quark momentum $\vec{p}_{top}$ in the forward (backward) direction defined relative to the quark moving direction $\vec{p}_q$,
  - "Forward" for the final state top is thus defined relative to the boost direction from the resonance c.m. frame (because the valence quarks tend to carry a higher-momentum fractions than the sea (anti-) quarks.)
  - Gluon contributions are homogeneous and subtracted out.
- Similarly, one may consider CP-asymmetry.
  (work in progress.)

Search II: $t\bar{t} + \not{E}_T$ Signal

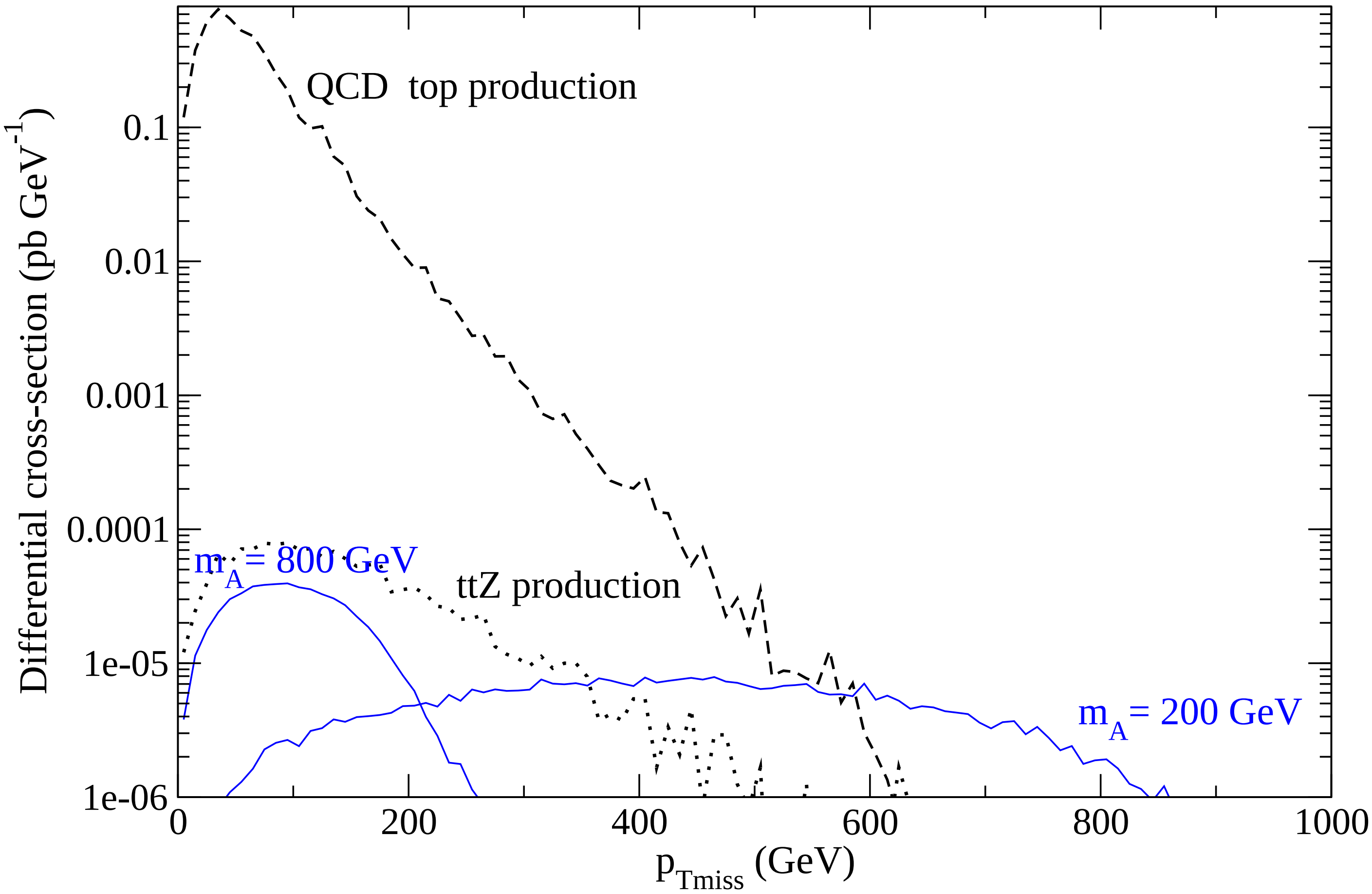
Quite generically,

$$pp \;\to\; T\bar{T}X \to t\bar{t}\; A^0 A^0 X$$
$$\;\to\; t\bar{t}\; A^0 A^0 X \to b j_1 j_2\; \bar{b}\ell^- \bar{\nu}\; A^0 A^0\; X + c.c.$$



Features: No Bump, but much $\not{E}_T$

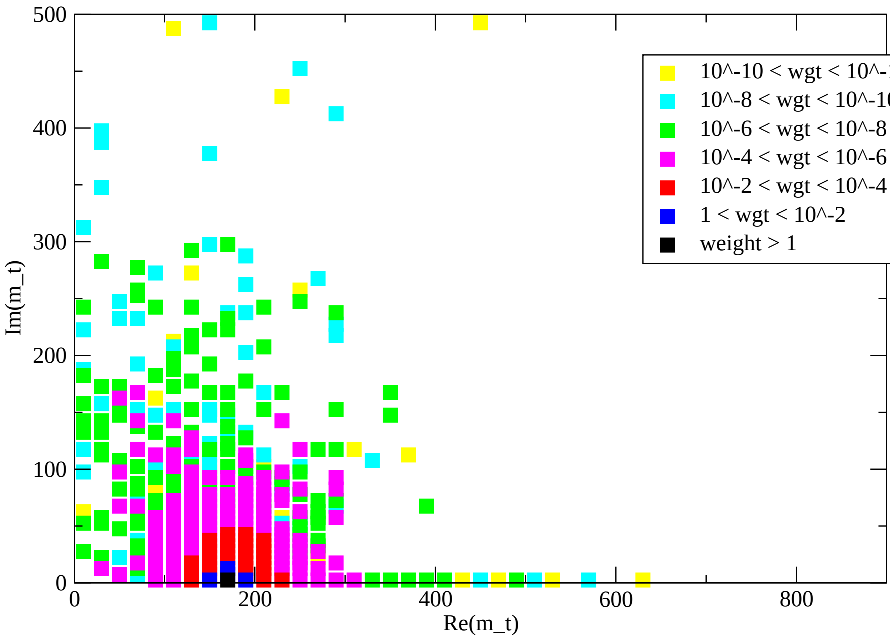
Due to more missing particles from both T and $\bar{T}$,
no p_ν can be reconstructed. Instead, may lead to larger $\not{E}_T$:

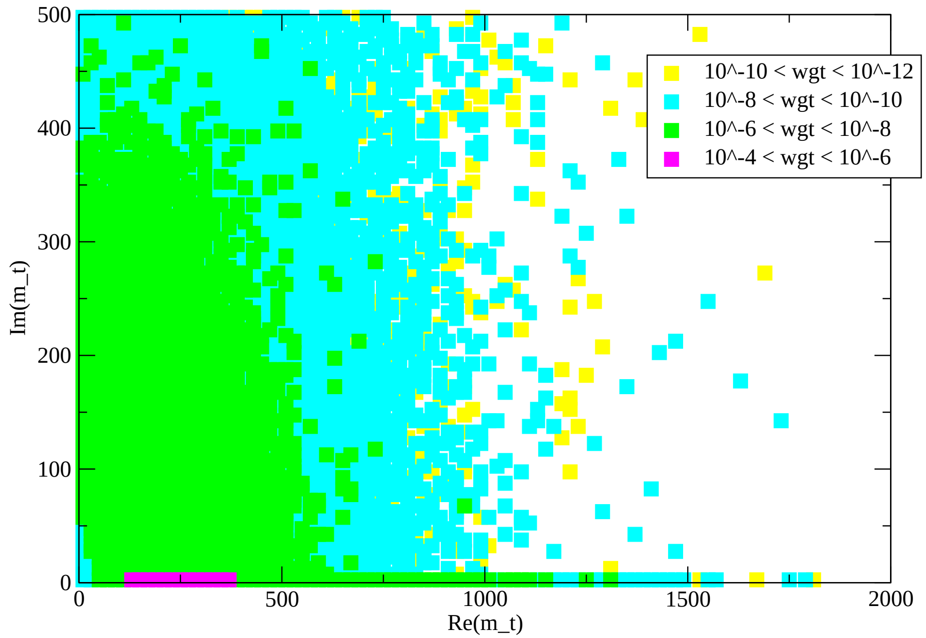


$m_T = 1$ TeV.

It's Good or Bad: A complex m_t^r

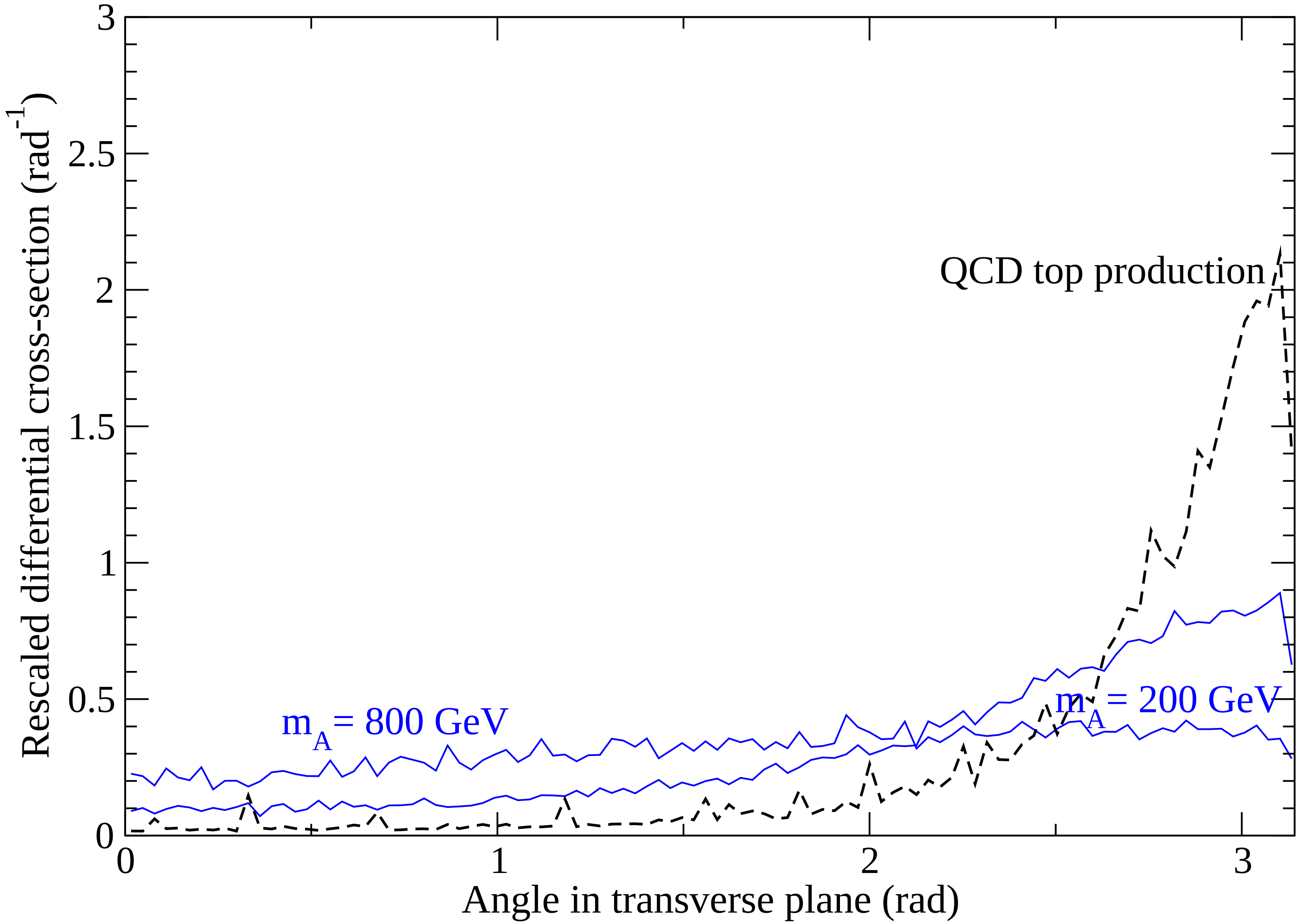
p_ν reconstruction by M_W may yield complex solutions:





Back-to-back $t - \bar{t}$

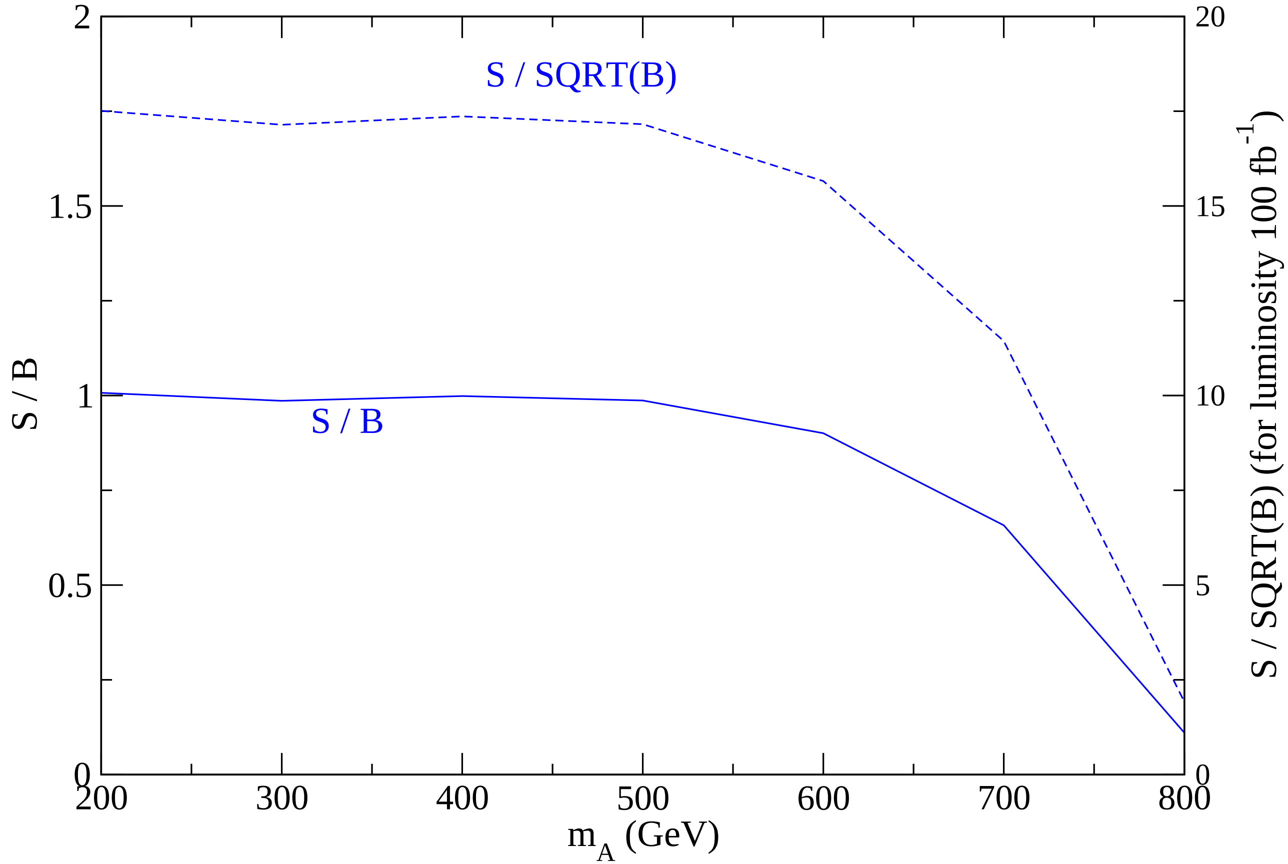
SM $t - \bar{t}$ are back-to-back in the transverse plane, while those from $T\bar{T}$ are kicked randomly:



LHC Reach for $T\bar{T}$ Signal

After judicious cuts, plus

$$|m_t - m_t^r|^2 > 110 \text{ GeV},$$



$m_T = 1$ TeV.

Conclusions

- LHC is a top factory – providing 8 million $t\bar{t}$'s per 10 fb^{-1} .
  Good channel to probe physics beyond SM.
  May serve as an early indicator for new physics.
- For the resonant signal $t\bar{t}$: Two methods to reconstruct semi-leptonic $t\bar{t}$ events at high-invariant mass,
  to study resonant spin, Chiral coupings, CP properties ...
- For non-resonant signal $t\bar{t} + \not{E}_T$: Observation of the semi-leptonic channel promising, but kinematics difficult:
  No information for the missing particle mass $m_A,\ m_{\chi^0}$.

Conclusions

- LHC is a top factory – providing 8 million $t\bar{t}$'s per 10 fb^{-1} .
  Good channel to probe physics beyond SM.
  May serve as an early indicator for new physics.
- For the resonant signal $t\bar{t}$: Two methods to reconstruct semi-leptonic $t\bar{t}$ events at high-invariant mass,
  to study resonant spin, Chiral coupings, CP properties ...
- For non-resonant signal $t\bar{t} + \not{E}_T$: Observation of the semi-leptonic channel promising, but kinematics difficult:
  No information for the missing particle mass $m_A, \ m_{\chi^0}$.

Top quark studies are of high priority!