The “Top Priority” at the LHC

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(Center for HEP, Tsing-Hua University, July 28, 2009)

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

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(Center for HEP, Peking University, July 20, 2009)

An exciting time:

The triple "Coincidence"

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

Terascale Physics at the LHC

- Unitarity argument for $W_L W_L$ scattering

  ⇒ 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

  ⇒ New physics needed beyond H^0....

- Gauge coupling unification

  ⇒ New threshold at the Terascale.

- Particle dark matter

  ⇒ WIMP at the Terasacle natural.

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What exact form is it realized in nature?

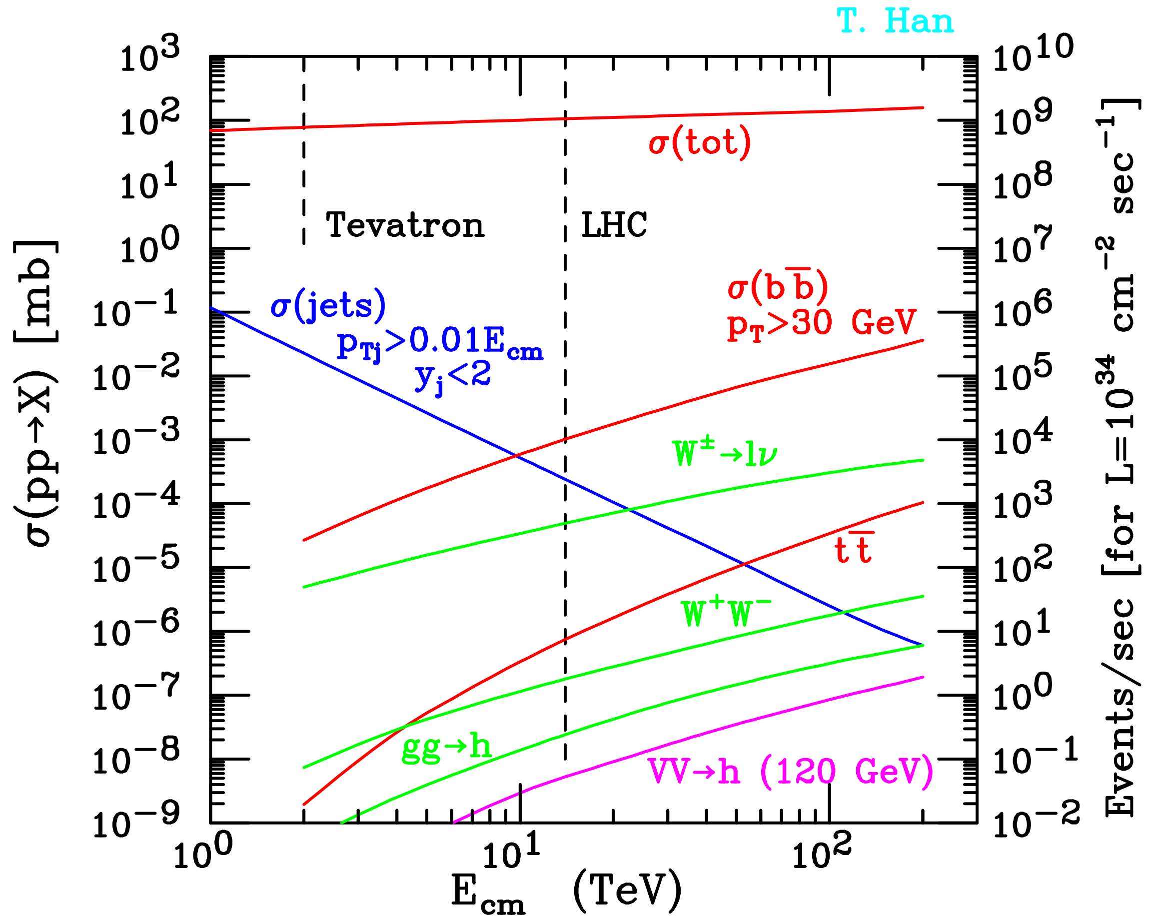
Fundamental scalar in a weakly coupled theory? (SUSY or alike)
Composite Higgs and strongly interacting dynamics? (TC, Little Higgs, Warped extra dim)
Extensions of gauge sector, fermion sector, ... ? (Z', Q, N_R)

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

The LHC will tell!

Top quarks at the LHC

LHC is a top factory:



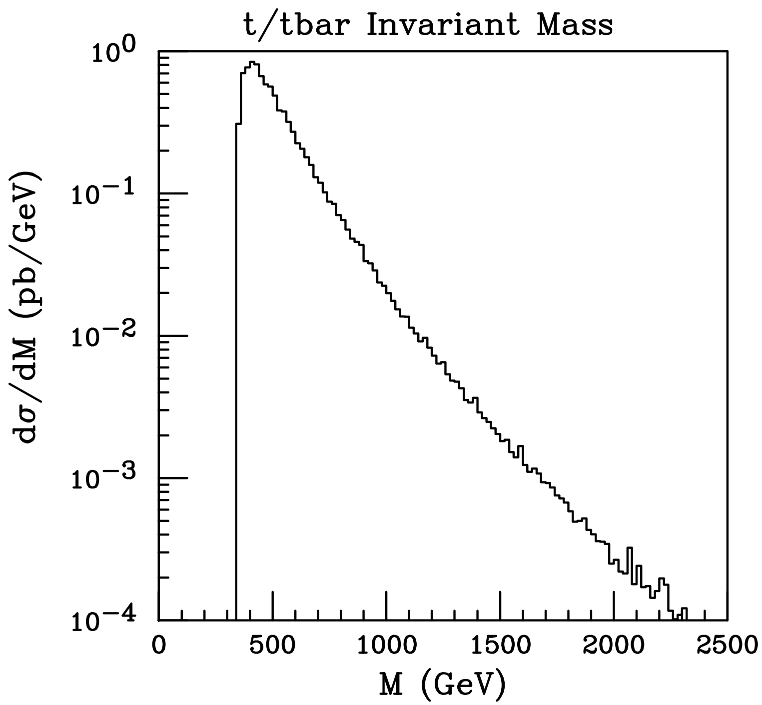
Event rate: 800K $t\bar{t}$ / fb^{-1}, or 8 Hz $@10^{34}$/cm^2/s !

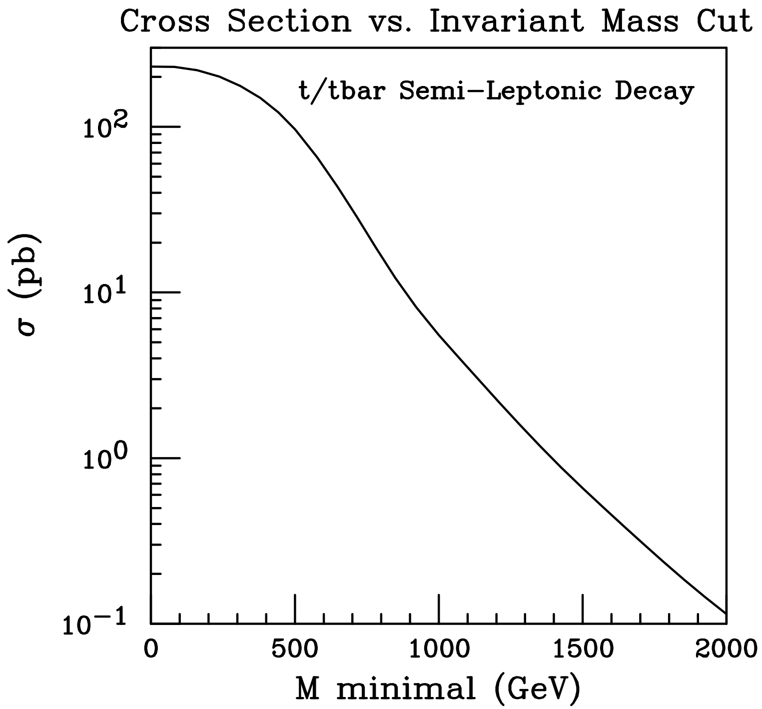
From Tevatron to LHC: $t\bar{t}$ increased by 100; EW increased by 10.

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%.)

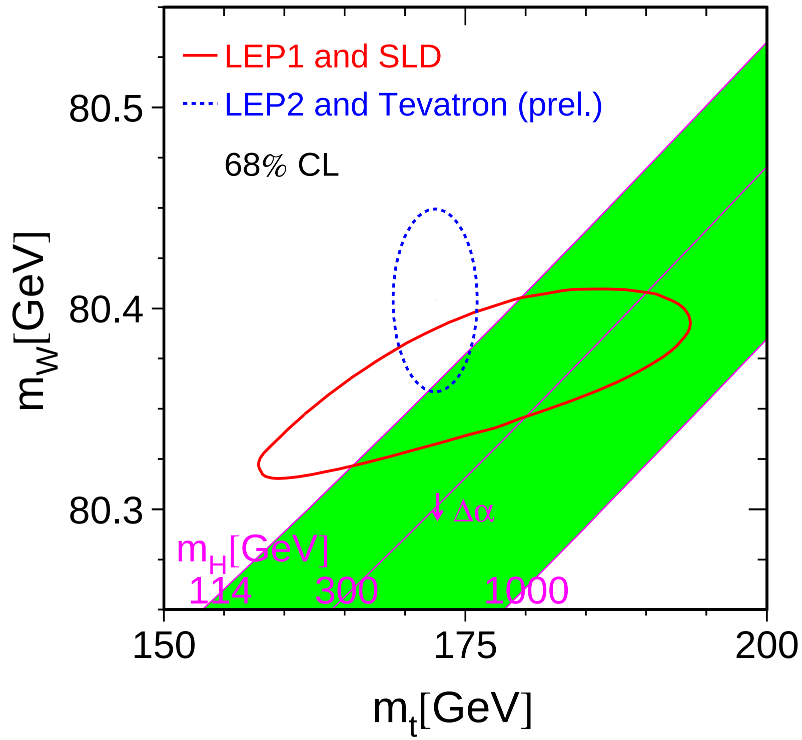




$\sigma(\ell^{\pm} bbjj \not{E}_T) \approx 300$ pb, $\sigma(m(tt) > 1\ TeV) \approx 5$ pb.

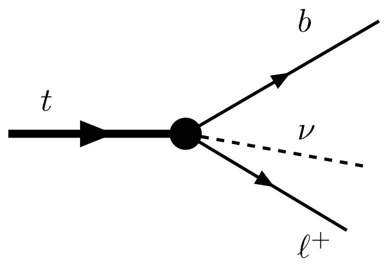
Why Top Quarks? bread & butter:

- 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:



$\theta \approx \gamma^{-1} \approx m_t/E_t$

Test ground for QCD, spin, 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):
  $Z_{KK},\ g_{KK},\ G_{KK} \to t\bar{t}$.
- 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):
  $T \to tA^0$, and thus the dark matter connection!
- To the least, precision test: $t\bar{t}Z,\ t\bar{t}H;\ \ t\bar{t}\gamma, g;\ \ t\bar{b}W$...

The Remainder of the Talk

- Search I: $t\bar{t}$ Resonant Production
  - Model-Independent Search for New Physics
  - Backgrounds
  - Coupling Determination
  - Fast-moving Top Quarks
- Search II: $t\bar{t}+\not{E}_T$ Signal
  - Signal Events Reconstruction
  - Backgrounds
- 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
MSSM :	narrow		
Technicolor/Topcolor/LH:	narrow/broad	narrow/broad	
RS/Stringy :		narrow/broad	narrow

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

[a] Barger, Han, Walker, Phys.Rev.Lett.100:031801 (2008).

Search for New Resonances in m_{tt}

- General searches 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 (Benchmark: 1 TeV)
  - Γ – total width
    - Benchmark studies: $\Gamma_\phi = 0.5\ (m_\phi/TeV)^3,\ \Gamma_V = 5\%\ m_V,\ \Gamma_{\tilde{h}} = 1.2\%\ m_{\tilde{h}}$
  - 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 ...

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

- Top quarks can be reconstructed via $M_W,\ m_t$ constraints.
- Full kinematics available.

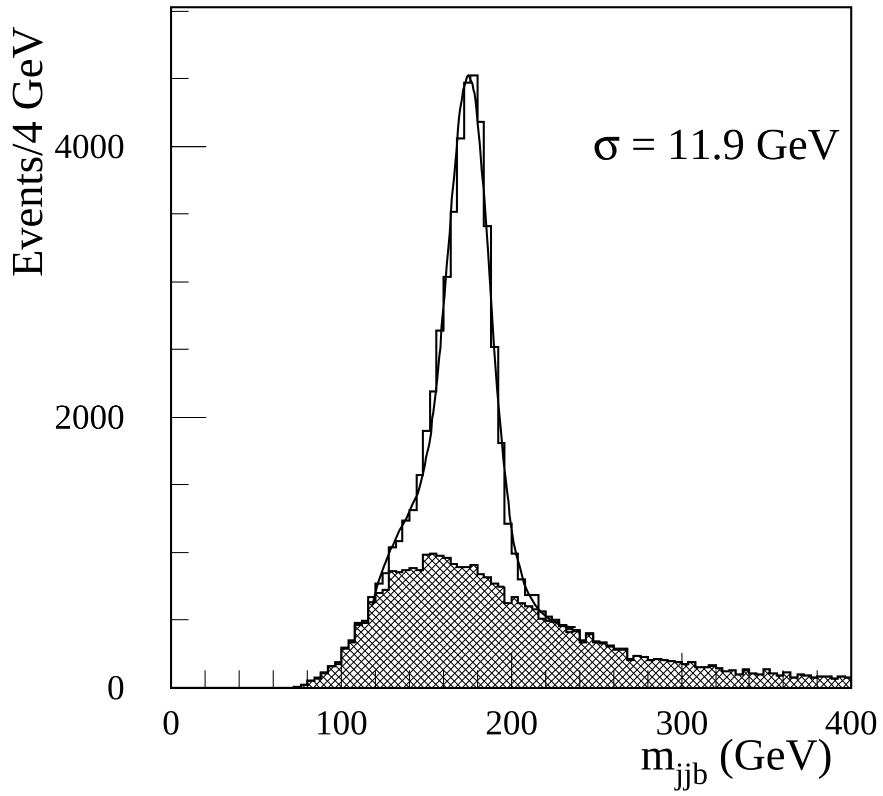
Background Considerations

- 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 $E_T$miss > 20 GeV cuts	As before, with plus $N_{\rm jet} \geq 4$ cut	As before, with plus $N_{\rm b-jet} \geq 2$ cut	Events per 10 $\rm fb^{-1}$
$t\bar{t}$ 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

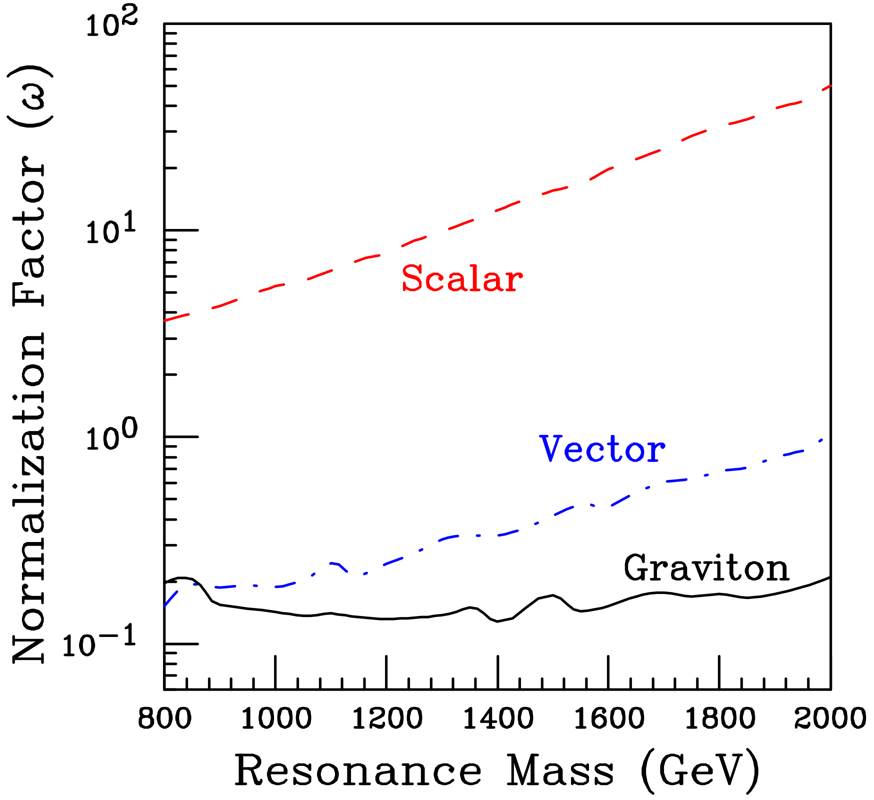
- Reconstructing the hadronic decay ($\bar{t}$, say):
  - From ATLAS collaboration (ATLAS TDR,Volume II, p. 625): The $\bar{t}$ is reconstructed via the hadronic decay $\bar{b}jj$. The wrong b may have some contamination (shaded area).



Discovery Potential for a New Resonance

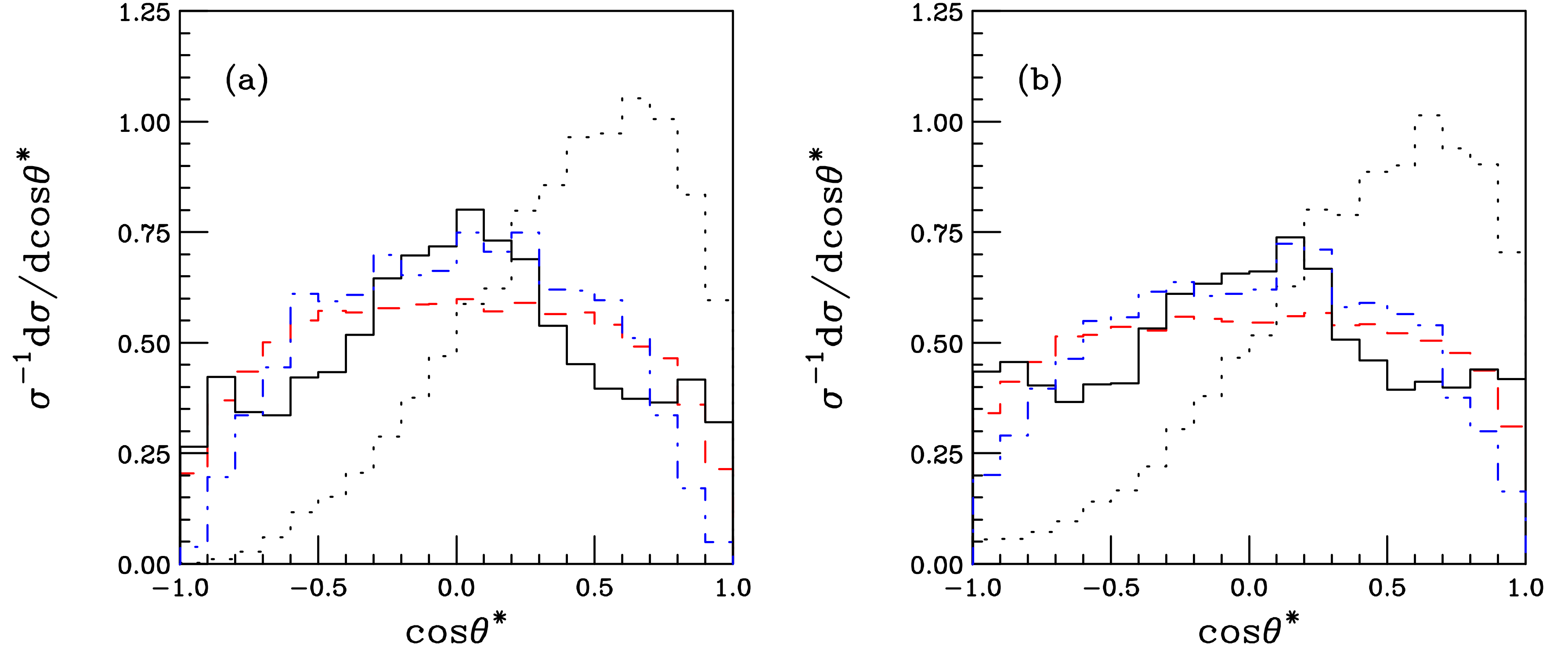
- Determine minimal ω for a 5σ discovery

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



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 $q\bar{q} \rightarrow d^2_{1\pm1} \Rightarrow \sin^4\theta^* + ...$

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 defined w.r.t. the initial quark.
  - Gluon contributions are homogeneous and subtracted out.

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Drawbacks:

  - Which "Forward"? The final state top is thus defined w.r.t. 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.)
  - Symmetric $g_L \leftrightarrow g_R$: cann't tell a left-, right- chiral coupling.

Chirality Cont'd

- Top-quark Spin Correlations: [a]

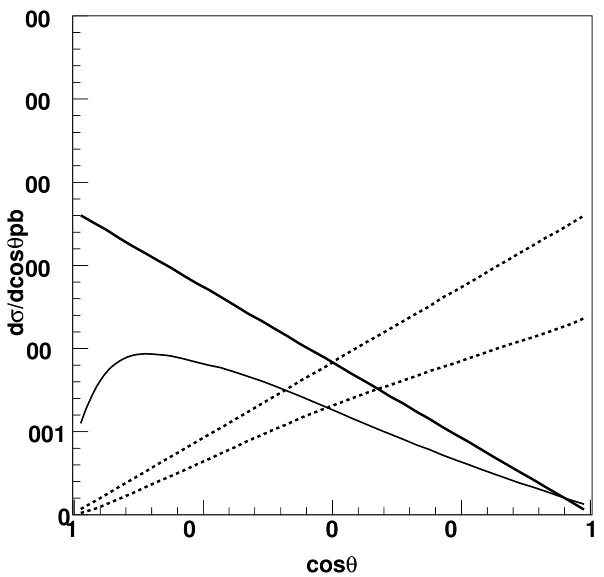
Consider $V \to t + X \to \ell^+ \, b \, \nu + X$:

$$\frac{d\sigma}{d\cos\theta_l} = \frac{1}{2}\,\sigma \left\{ 1 + 2A \;\cos\theta_l \right\},$$

$$A = \frac{\sigma(\cos\theta_l > 0) - \sigma(\cos\theta_l < 0)}{\sigma(\cos\theta_l > 0) + \sigma(\cos\theta_l < 0)} \propto \left(\frac{{g_R^t}^2 - {g_L^t}^2}{{g_R^t}^2 + {g_L^t}^2} \right).$$

where θ_l is defined to be the angle between $\vec{p}_l$ and $\vec{p}_t$.

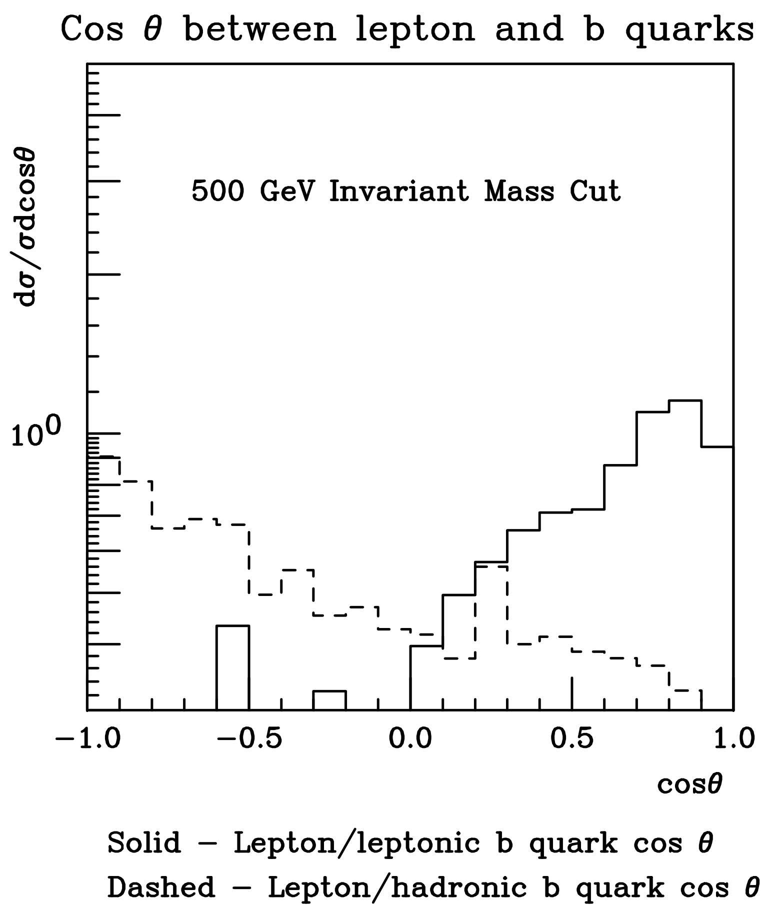
each in their parent rest-frame.

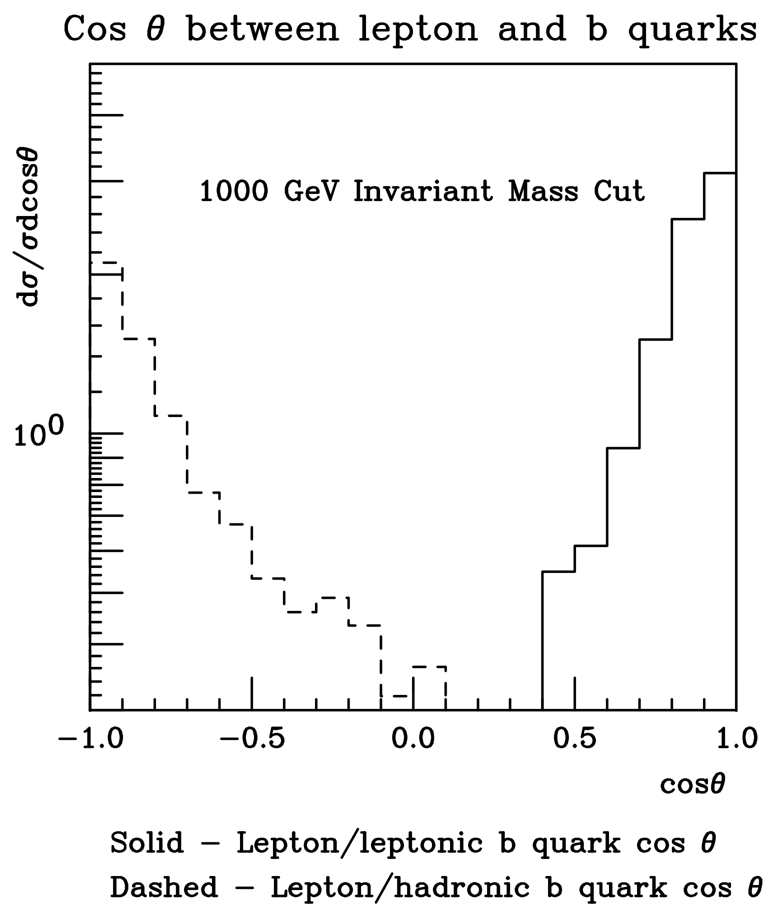


[a] Gopalakrishna, Han, Lewis, Si, Zhou, to appear.

A Caution ...

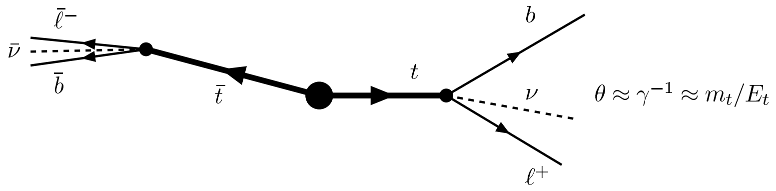
- At high $M_{t\bar{t}}$, the tops are boosted.
  That helps select $(\ell^+\ b)$, rather than $(\ell^+\ \bar{b})$.





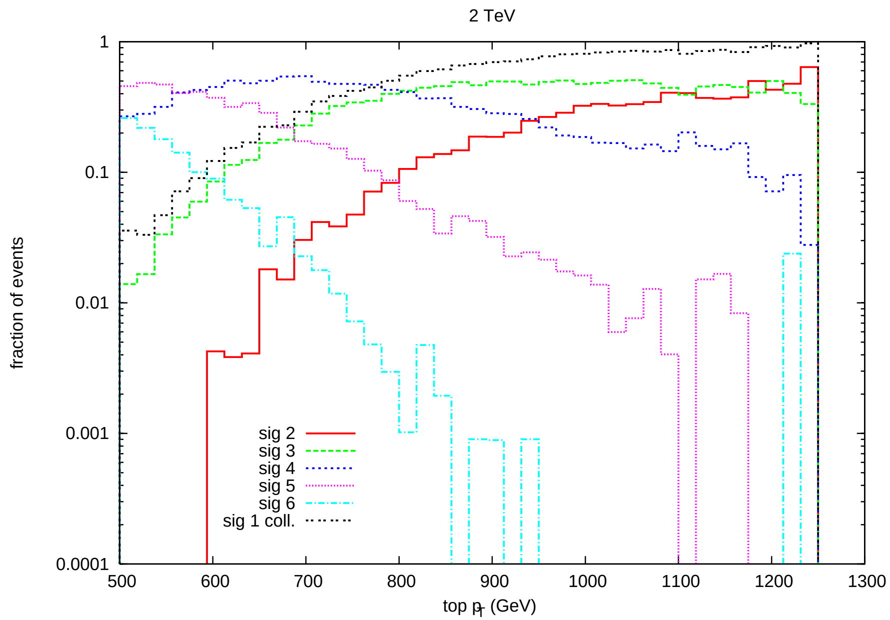
A Caution cont'd

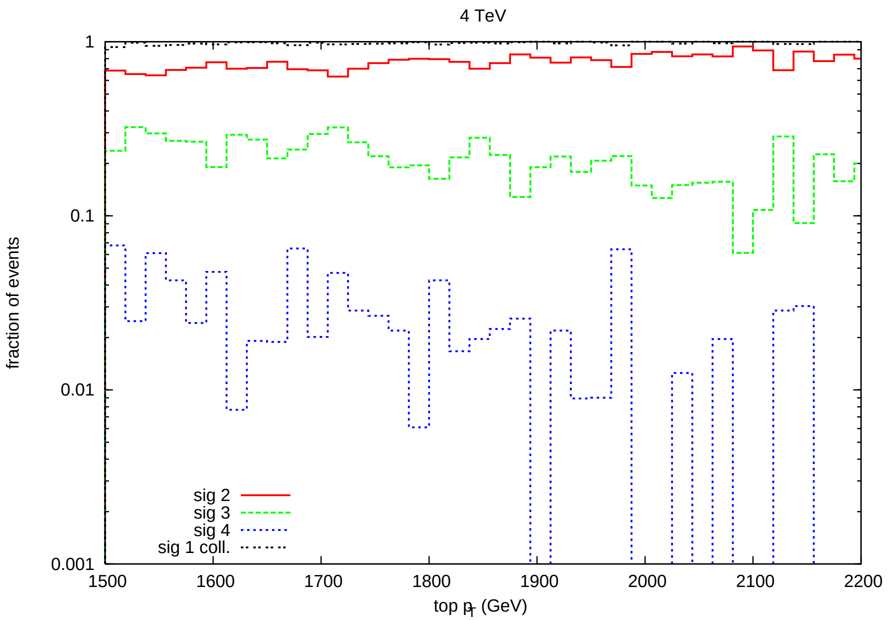
Event topology different for highly boosted top quarks:



How many observable "objects"? [a]

Objects versus $p_T(top)$ $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.4$:



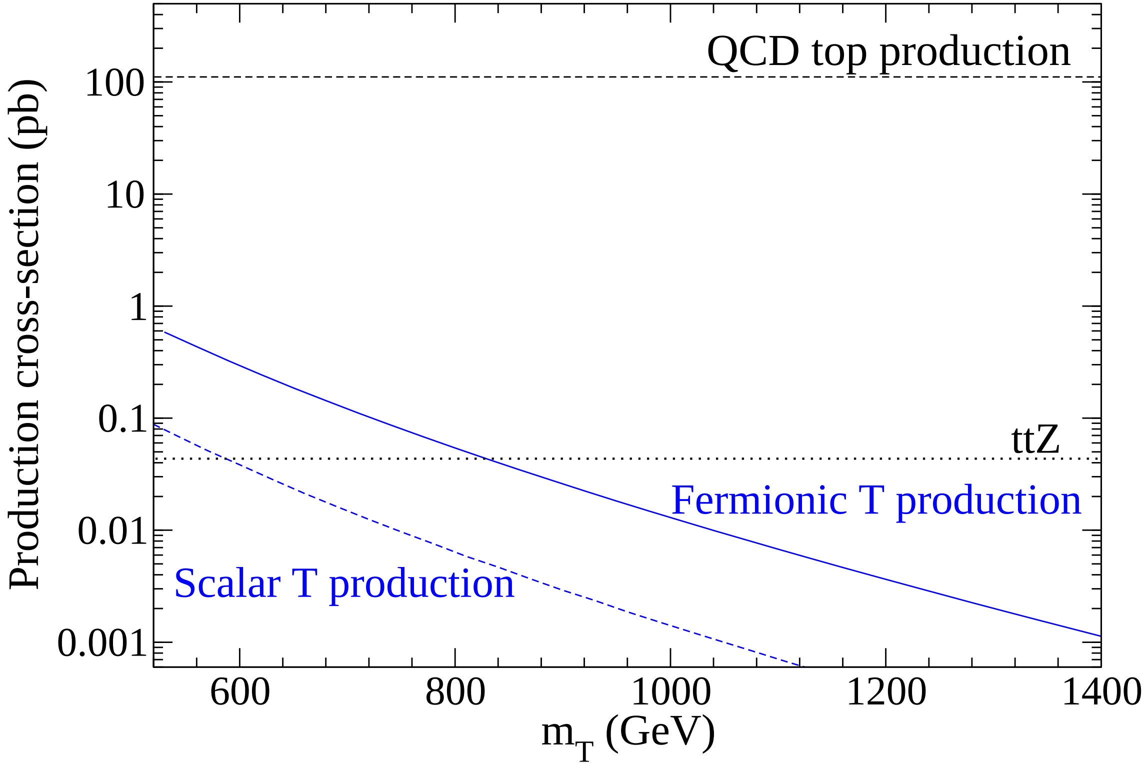


[a] B. Lillie, L. Randall, L.-T. Wang, `hep-ph/0701166`.

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

Quite generically, [a]

$$\begin{aligned} pp &\to T\bar{T}X \to t\bar{t}\, A^0 A^0 X \\ &\to bj_1j_2\, \bar{b}\ell^-\bar{\nu}\, A^0 A^0\, X \to \ell^\pm\, b\bar{b}\, + 2\, jets + \not{E}_T. \end{aligned}$$

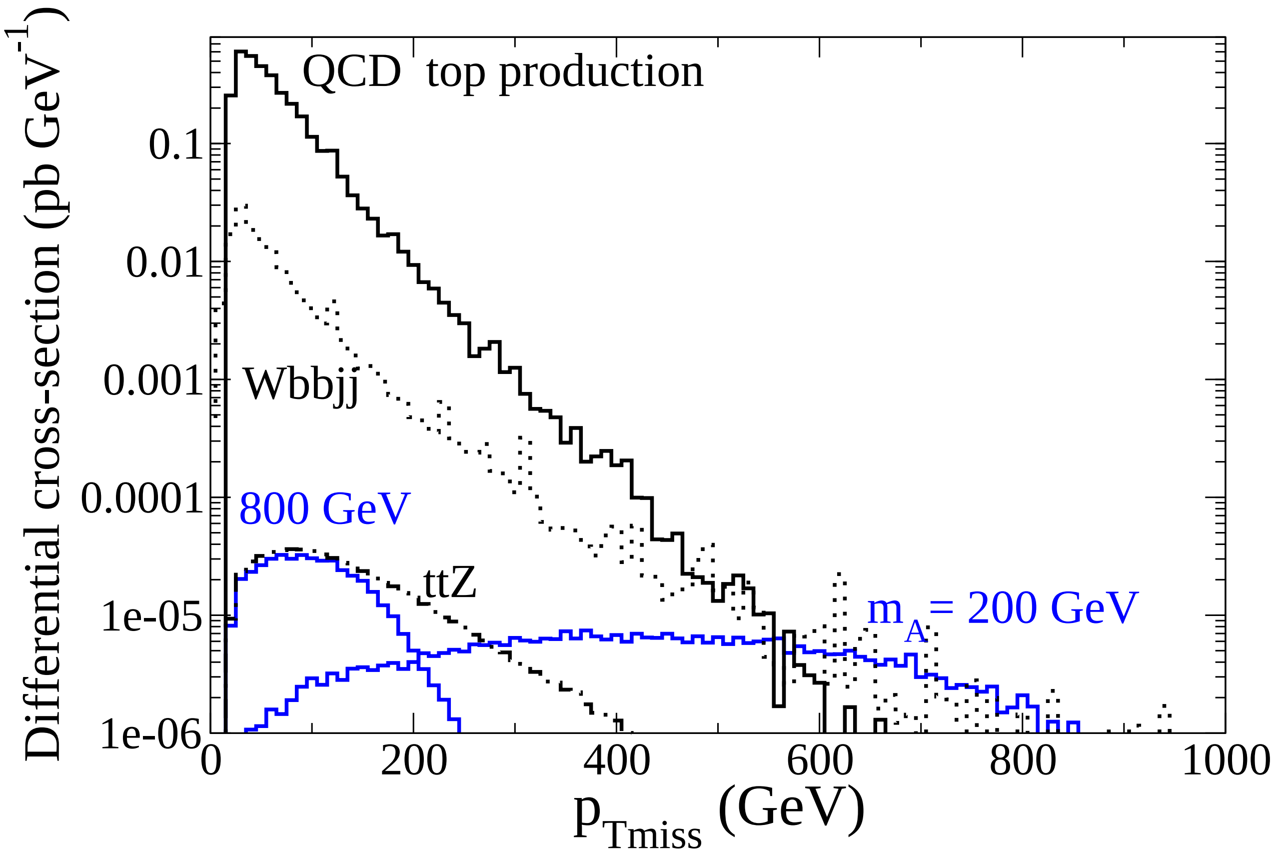


$$\sigma(T\bar{T}) \approx 8\sigma(\tilde{t}\tilde{\bar{t}}).$$

[a] TH, R. Mahbubani, D. Walker and L.-T. Wang, `arXiv:0803.3820`.

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 $\not{E}_T$:

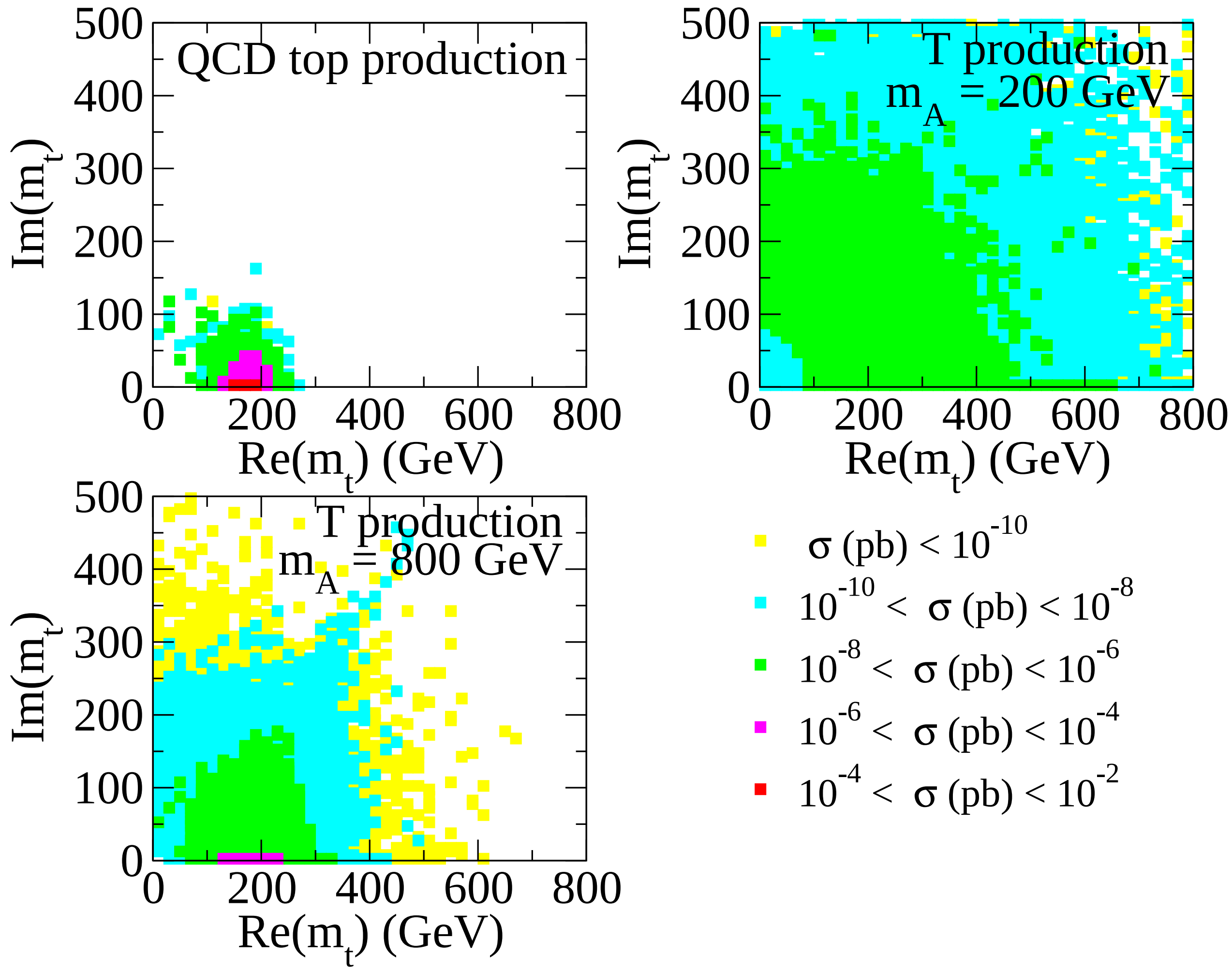


$m_T = 1$ TeV, $m_A = 200,\ 800$ GeV.

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

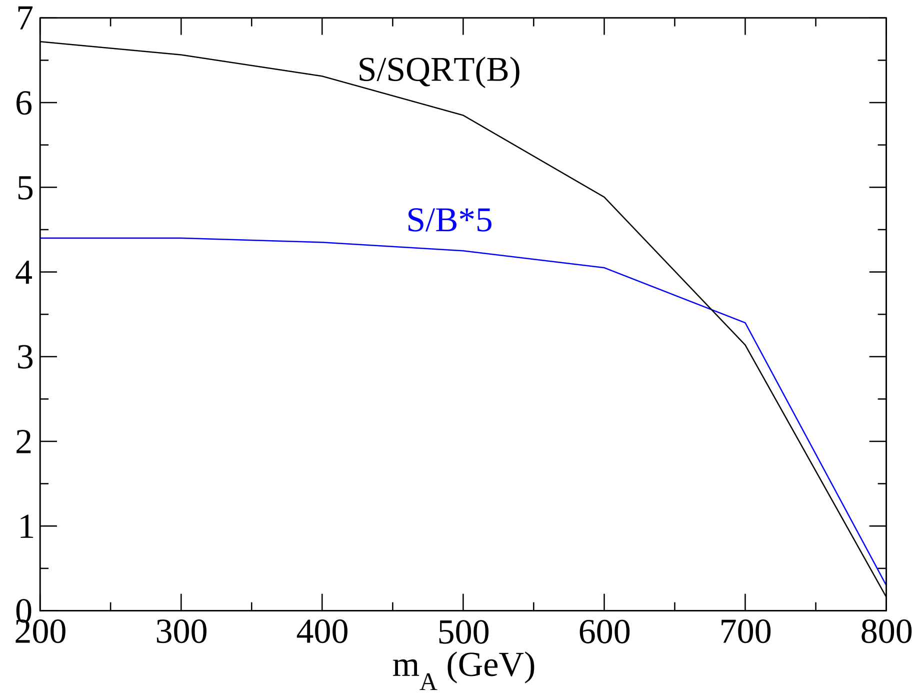
p_ν reconstruction by M_W may yield complex solutions:

$$(p_\nu^{rec} + p_\ell)^2 = M_W^2, \quad m_t^2(rec) = (p_b + p_\ell + p_\nu^{rec})^2.$$



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

After judicious cuts, plus $|m_t - m_t^{rec}| > 110$ GeV,
the $T\bar{T} \to t\bar{t} + \not{E}_T$ signal:



$m_T = 1$ TeV: $m_A = 200 - 700$ GeV.
May learn $m_T - m_A$, but not m_A.

Conclusions

- LHC is a top factory – providing 8 million $t\bar{t}$'s per 10 fb^{-1} .
  Good channel to probe (all kinds of) physics beyond SM.
  May serve as an early indicator for new physics.
- For the resonant signal $t\bar{t}$:
  Reconstruct semi-leptonic $t\bar{t}$ events at high-invariant mass,
  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 direct information for the missing particle mass $m_A,\ m_{\chi^0}$.

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Top quark studies are of high priority!