Top Quark Signature of New Physics

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Work in collaboration with:

1. T. Han, R. Mahbubani, and D. Walker (to appear)
2. B. Lillie, L. Randall (to appear)

- Outline

  - Motivation

  - Two Case Studies:

    1. NP$\rightarrow t\bar{t}\,\not{E}_T$

    2. NP$\rightarrow t\bar{t}$, $m_{t\bar{t}} \sim$ several TeV

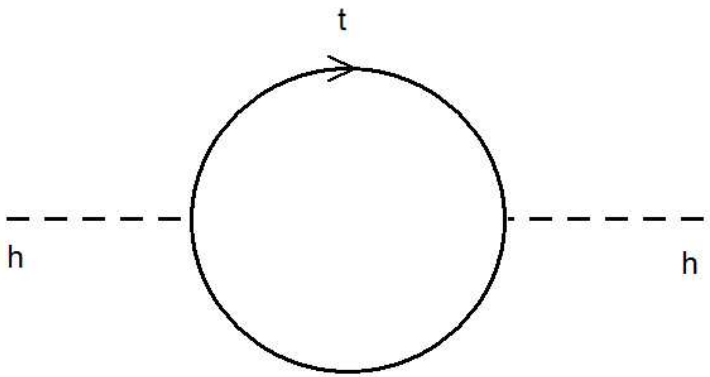
       briefly, see Lisa Randall's talk.

  - Conclusion

Work in progress, results preliminary.

Motivation:

- Naturalness:



$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

Within the SM, largest quadratically divergent correction to Higgs mass.

Naturalness $\longrightarrow$ "top partner", $M_{\text{top-partner}} \sim \Lambda \sim$ TeV

Signature of top partner often involve top quarks!

Motivation:

- Top is special:

  Much heavier than other fermions in the SM.

  Higher dimensional operators $\longrightarrow y_t$ may not be enough.

  Something unique (only "known" to top quark)!

  $\longrightarrow$ NP signals involve top quarks

Detailed measurements of the properties of the top quark, such as its mass, production and decay, provide a great deal of information.

Precision tests of the SM, signals of NP.

Talks by: R. Wallny, M. Kruse, and R. Erbacher

Single top.

Talks by: Z. Sullivan, Y. Coadou

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I will focus on NP $\longrightarrow t\bar{t} + \ldots.$

Different event topology.

Different kinematics.

New experimental challenge to discover/understand them.

• Case 1: $t\,\bar{t} + \not{E}_T$

Highly motivated from naturalness problem

Top partner typically has SM quantum numbers, couples to top.

Additional ingredient:

discrete symmetry $\longrightarrow$ removal of unwanted operators

EWPT, dark matter, proton decay...

$\longrightarrow$ End product of NP decay is stable, e.q., A_H.

$\longrightarrow t\,\bar{t} + \not{E}_T$

Typical Examples:

1. $\tilde{t}$ in low energy supersymmetry

$$\tilde{t} \to t + \text{LSP}$$

2. T' (odd under T-parity) in Little Higgs models*.

$$T' \to t + \text{LTP}(A_H)$$

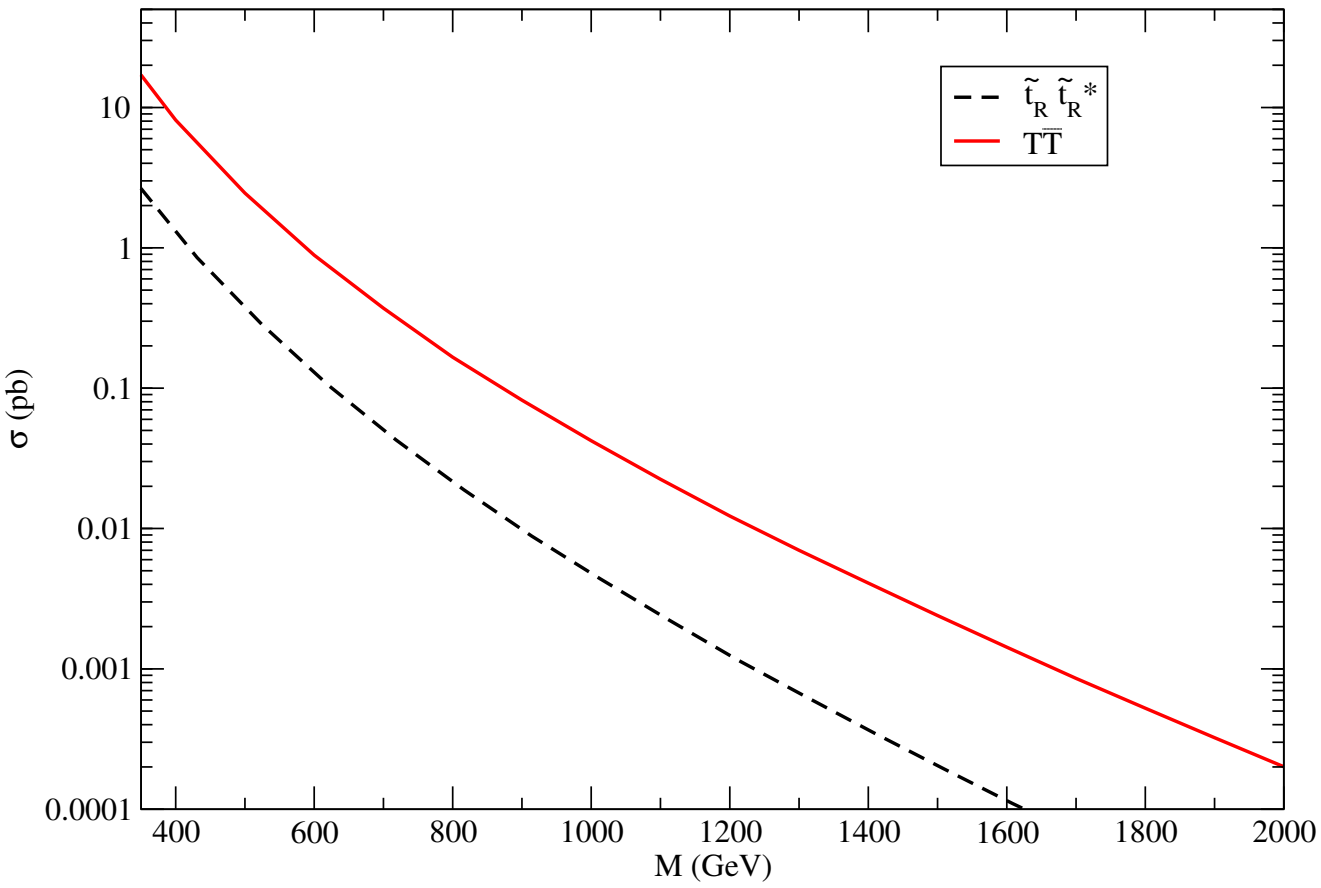
Similar signature, KK-top in UED†.

Pair production of $\tilde{t}$ or T' $\longrightarrow t\bar{t} + \not{E}_T$

*H. C. Cheng, I. Low, LW hep-ph/0510225

†T. Appelquist, H. C. Cheng and B. A. Dobrescu, hep-ph/0012100

Rate*



*H. C. Cheng, I. Low, LW hep-ph/0510225

Searching for $t\,\bar{t} + \not{E}_T$

- Hadronic channel: $b\bar{b}jjjj$ final states*†.

- We focus on the semi-leptonic channel $b\bar{b}jj\ell\nu$

  Cleaner, isolated lepton, less jets.

We are exploring a variety of kinematical cuts.

We also want to understand the dependence of discovery reach on mass spectrum.

*P. Meade and M. Reece, hep-ph/0601124

†A special case has been studied: S. Matsumoto, M. M. Nojiri and D. Nomura, hep-ph/0612249

Our benchmark:

Fermionic partner, T'. $M_T = 1$ TeV.

Decay: $T' \to t + A_H$.

Look for large $\not{E}_T$

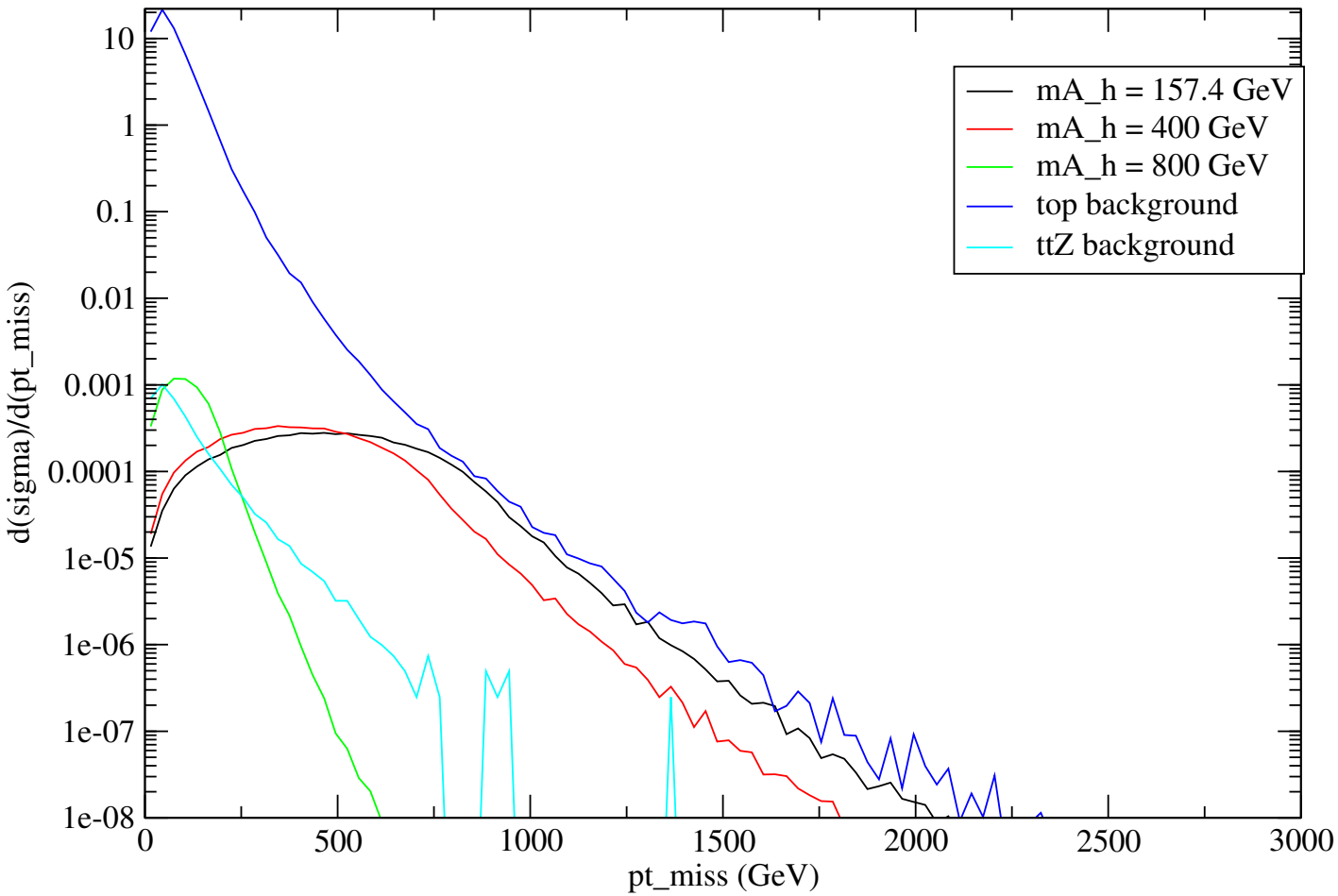
Potential backgrounds:

1. $t\bar{t} \to b\bar{b} + jj + \ell\nu$. (Huge rate.)

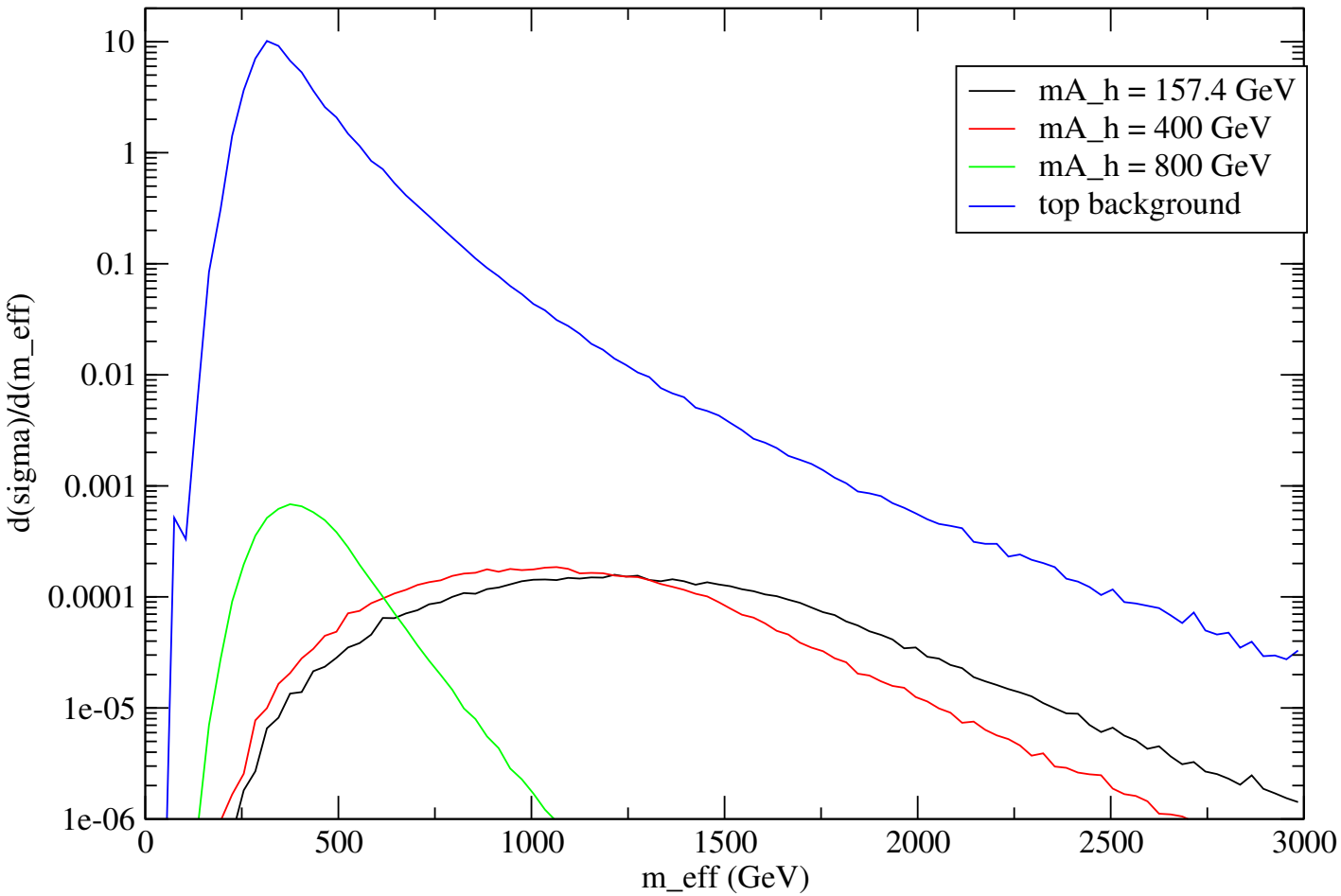
2. $t\bar{t}Z(\to \nu\nu)$ ("irreducible")

3. $W(\to \ell\nu)bbjj$.

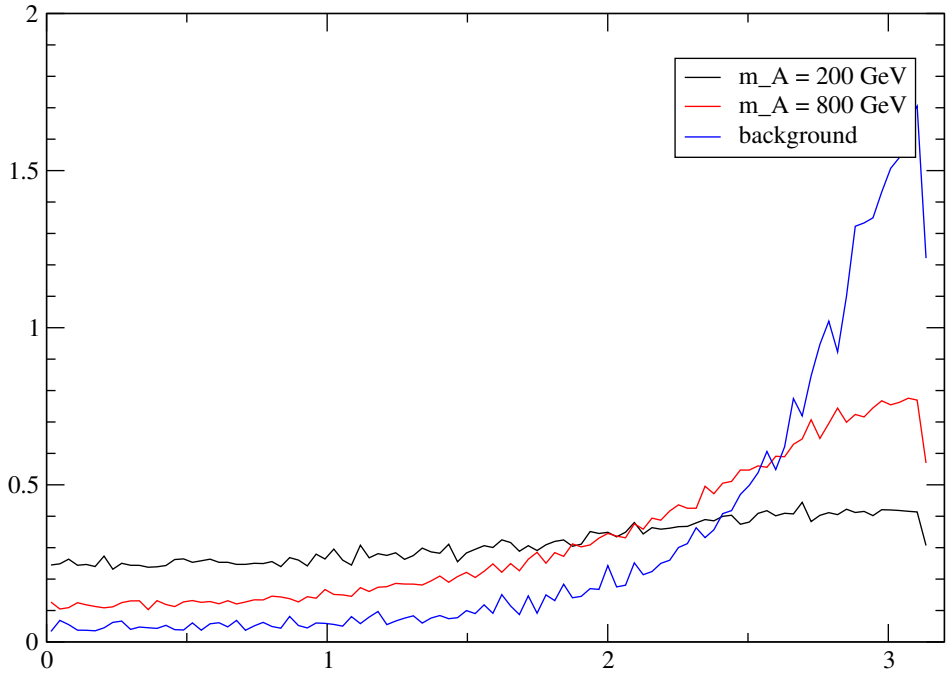
SM background



Other variables? For example: $M_{\text{eff}} = \sum |P_T| + \not{E}$



Kinematical features?



Normalized to 1.

$\Delta\phi$ between t_{hadronic} and the plane of (ℓ, b)

Will only help at the level of $\mathcal{O}(1)$

SM background: summary

Dominant background: missing energy tail of $t\bar{t}$

$t\bar{t}Z$ could be cut away by requiring $\not{E}_T > 300 - 400$ GeV.

$W(\to \ell\nu)bbjj$ typically gives $\not{E}_T < 100$ GeV, negligible after imposing cuts on $\not{E}_T$ for $t\bar{t}Z$.

The most difficult case is $M_{T'} - M_{A_H} \sim m_t$.

Can we do better?

We have not used the fact that we can reconstruct tops in the SM $t\bar{t}$ production.

Reconstruction

SM: $t\bar{t} \to b\bar{b} + jj + \ell\nu$

•Using $\not{p}_T$, and $m_\nu = 0$, m_{W}, we can solve for p_ν.

•Remove ambiguity by $m_t^{\mathrm{had}} \sim m_t^{\mathrm{lep}}$, and/or minimizing $|(m_t^{\mathrm{had}}, m_t^{\mathrm{lep}}) - m_t|$.

•m_t^{lep} will have a peak around m_t whose width determined by the resolution.

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For signal:

•We will assume (wrongly) that $\not{E}_T$ is from ν, and do the same reconstruction.

•Wrong, (often) imaginary solutions $\to$ signal!.

Take all $b\bar{b}jj\ell + \not{E}_T$ events.

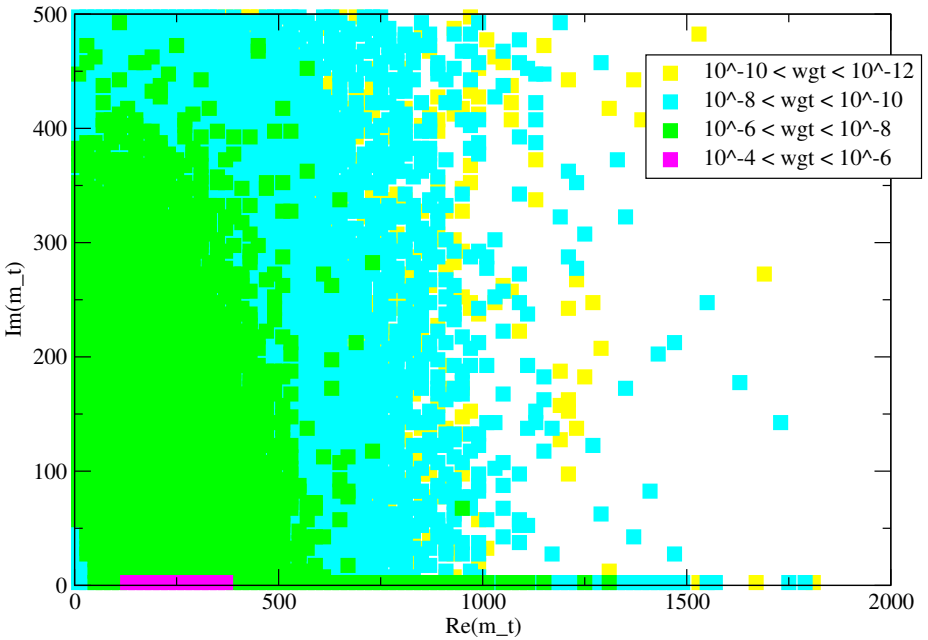
Reconstruction

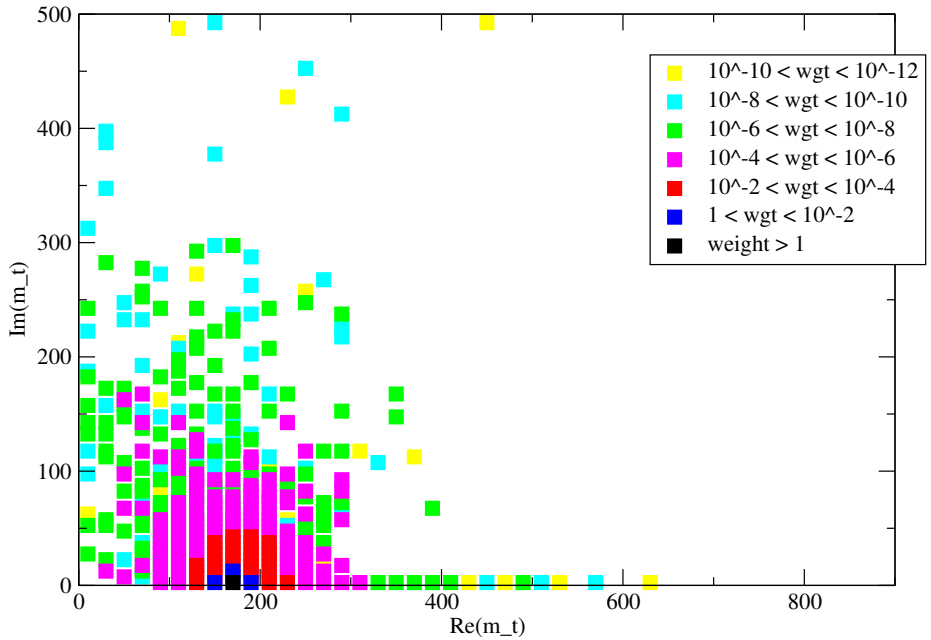
Plot, for example, m_t^{lep} on the complex plane

Reconstruction:

$M_{T'} = 1$ TeV, $M_{A_H} = 200$ GeV

SM





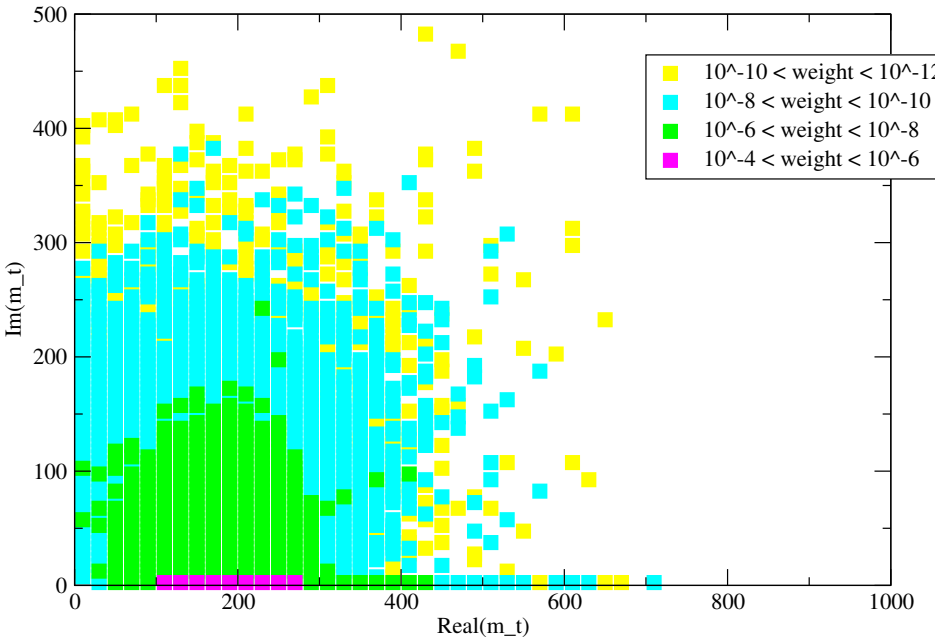
Rough estimates: require $Re(m_t) > 500$ GeV, $Im(m_t) > 200$ GeV.

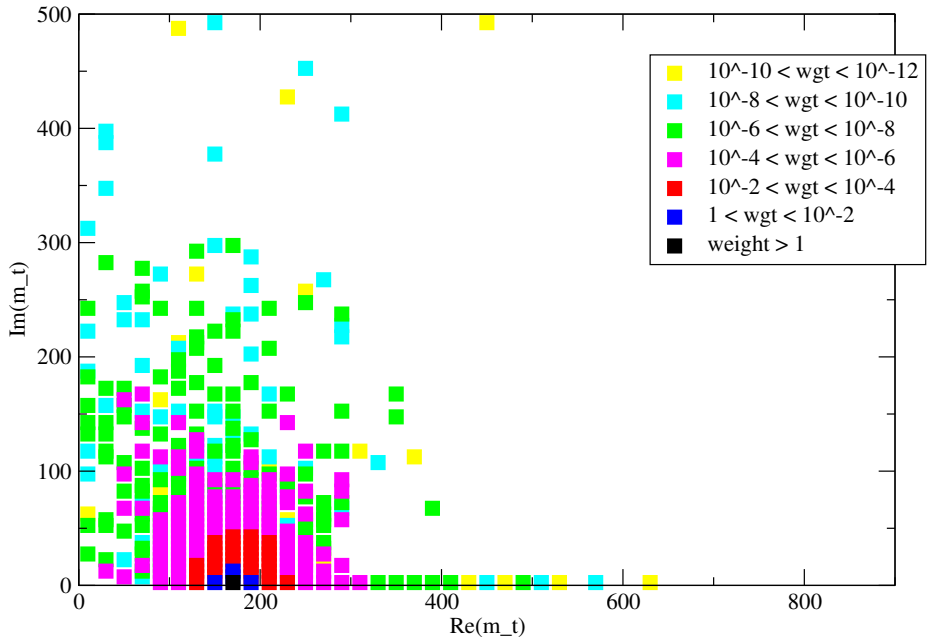
Signal: $\sim$ 10-15 fb, background: 1-2 fb.

Reconstruction:

$M_{T'} = 1$ TeV, $M_{A_H} = 800$ GeV

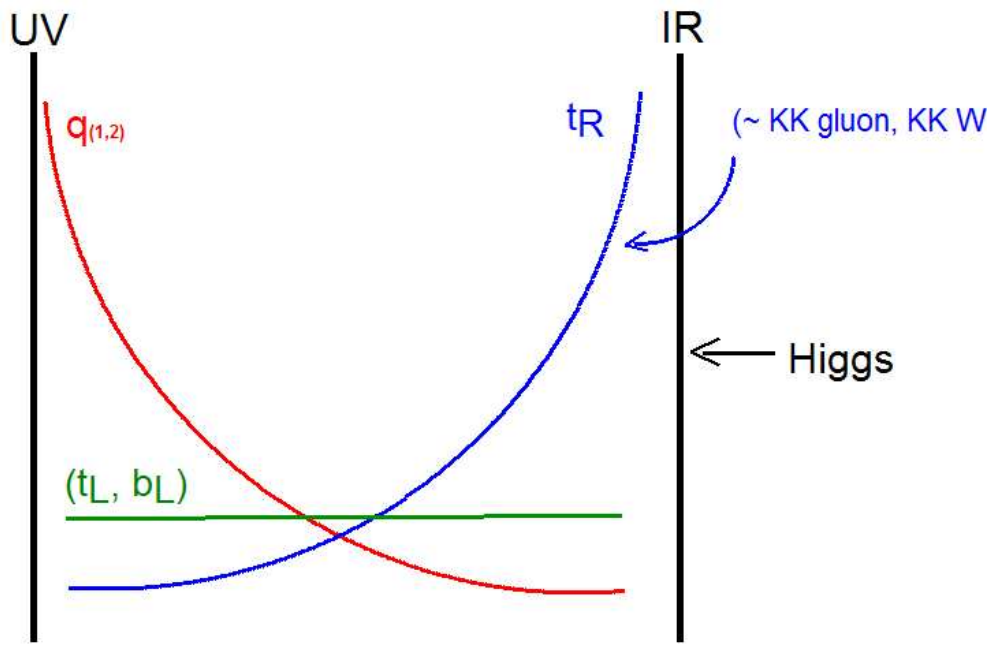
SM





The near threshold case is still difficult. Small $\not{E}_T$...

Case 2: NP resonances $\rightarrow$ $t\ \bar{t}$*



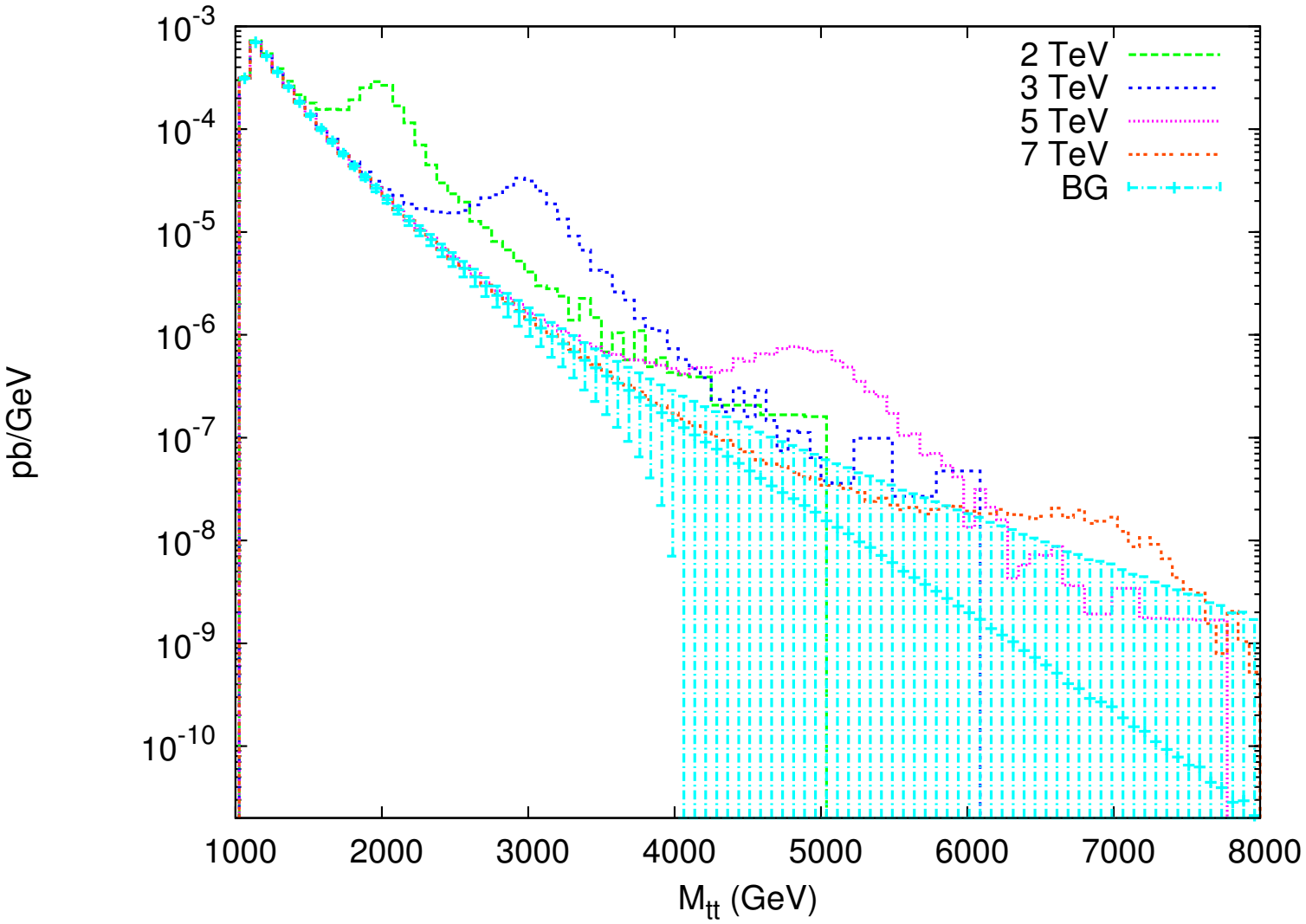
top is composite $\longrightarrow$ top is heavy

Other composite states (KK gluon, KK W) dominantly decay into $t\bar{t}$.

Bump searching.

*K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036

Singal vs SM $t\bar{t}$, $\sqrt{N}$ error bar



Challenges

1. SM $t\bar{t}$ has long tail in $m_{t\bar{t}}$.

2. Wider resonances, $\Gamma \sim 0.2M$. PDF distorts the shape of resonances.

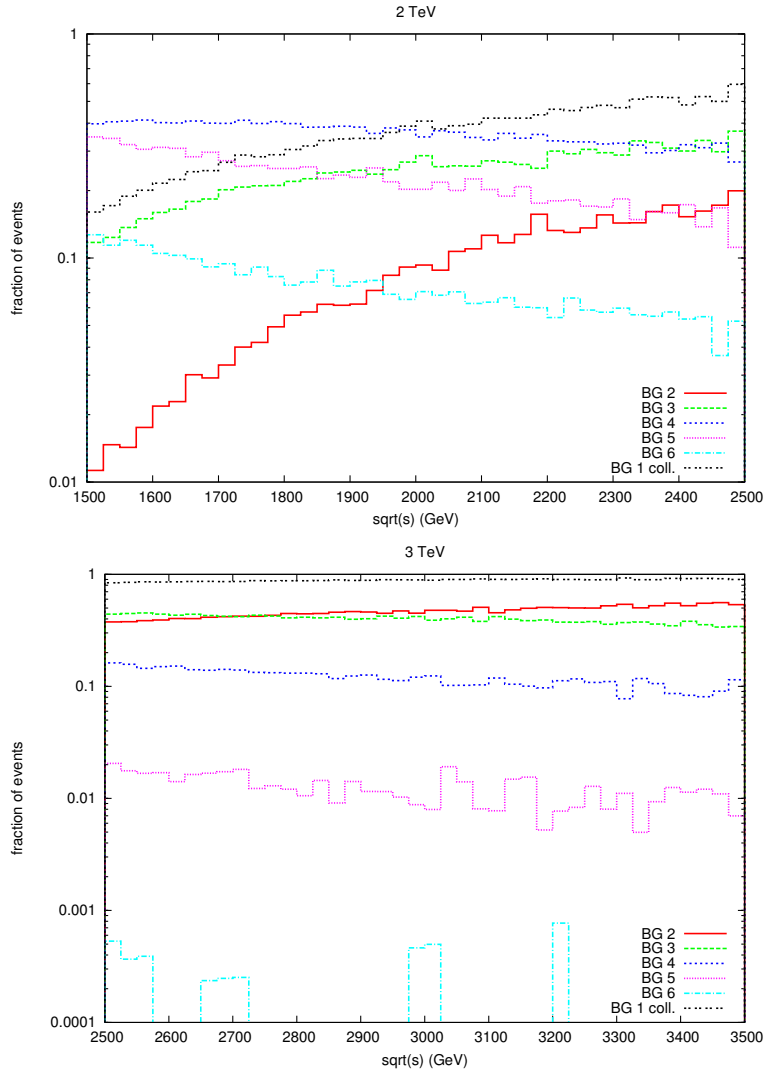
3. EWPT typically constrains the composites to be quite heavy $\geq$ 3TeV*.

$$\longrightarrow \text{ Very energetic tops}$$

Reconstruction of tops based on isolated objects is likely to fail.

*K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036

Collimation: in the window of $|m_{t\bar{t}} - M| < 500$ GeV.



- $\Delta R = 0.4$.
- For $m_{t\bar{t}} > 3$ TeV, $> 90\%$ events with at least one top fully collimated.
- Large fraction of events "2-object"-like. QCD $b\bar{b}$, jj background.

Find collimated tops

Treat them as jets*.

Some lepton isolation, hard cut on jet p_T. Lost events. Discovery possible.

We should try to do better.

Comprehensive study of 2, 3, 4 object cases, with different backgrounds, necessary.

Energetic tops $\rightarrow$ massive jets, with some substructures†.

How well this can be distinguished from, say massive QCD jets, demands much more detailed study.

*K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, hep-ph/0612015

†WW scattering. J. M. Butterworth, B. E. Cox and J. R. Forshaw, hep-ph/0201098

- Conclusion:

Top sector is one of the most probable place for new physics to show up.

Important to study top as part of the final states from NP, both for discovery and interpretation.

Top with other stuff: $t\bar{t}\,\not{E}$, $t\bar{t}+$ (leptons, jets...)

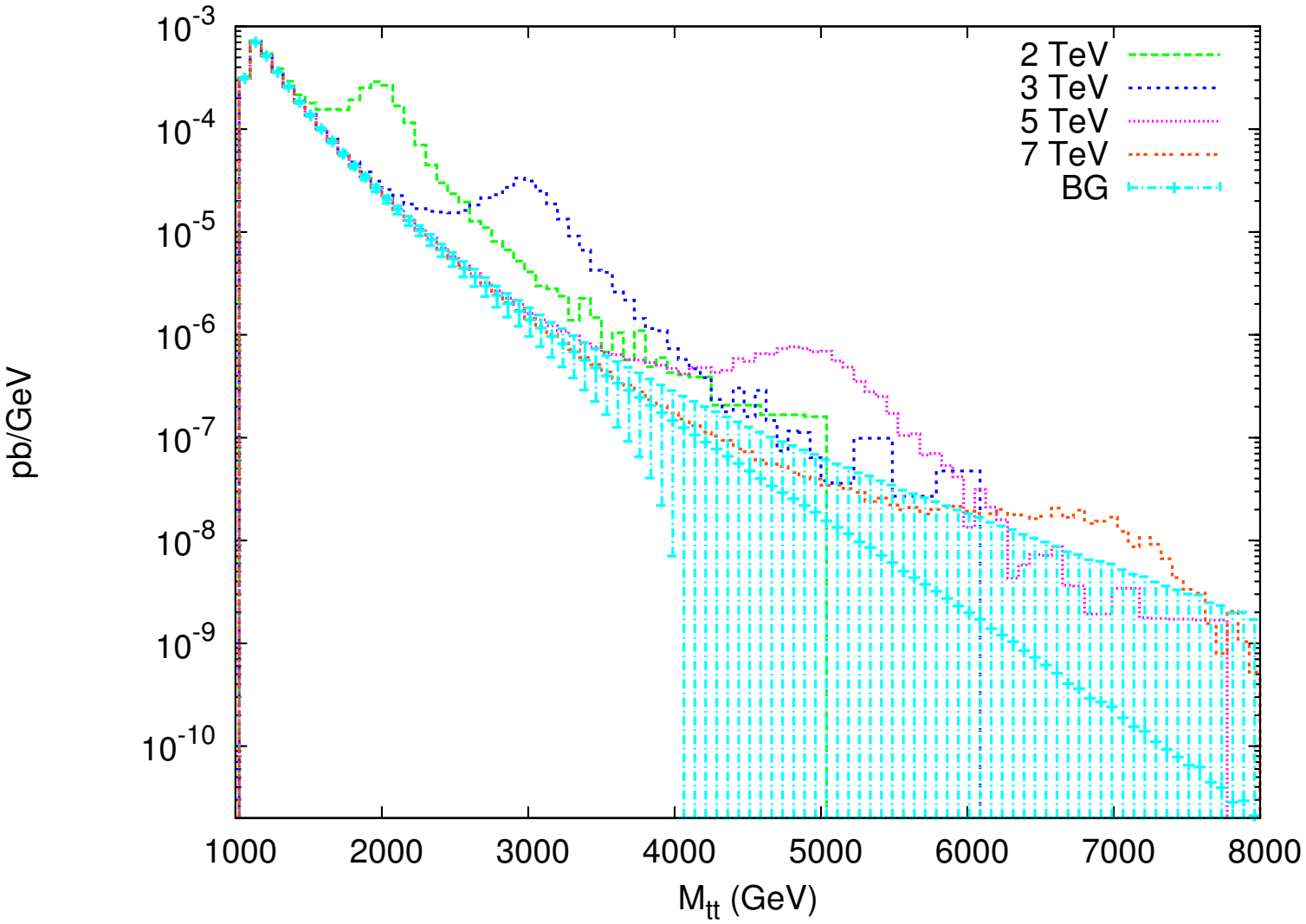
Energetic tops, $m_{t\bar{t}} \sim$ several TeV

...

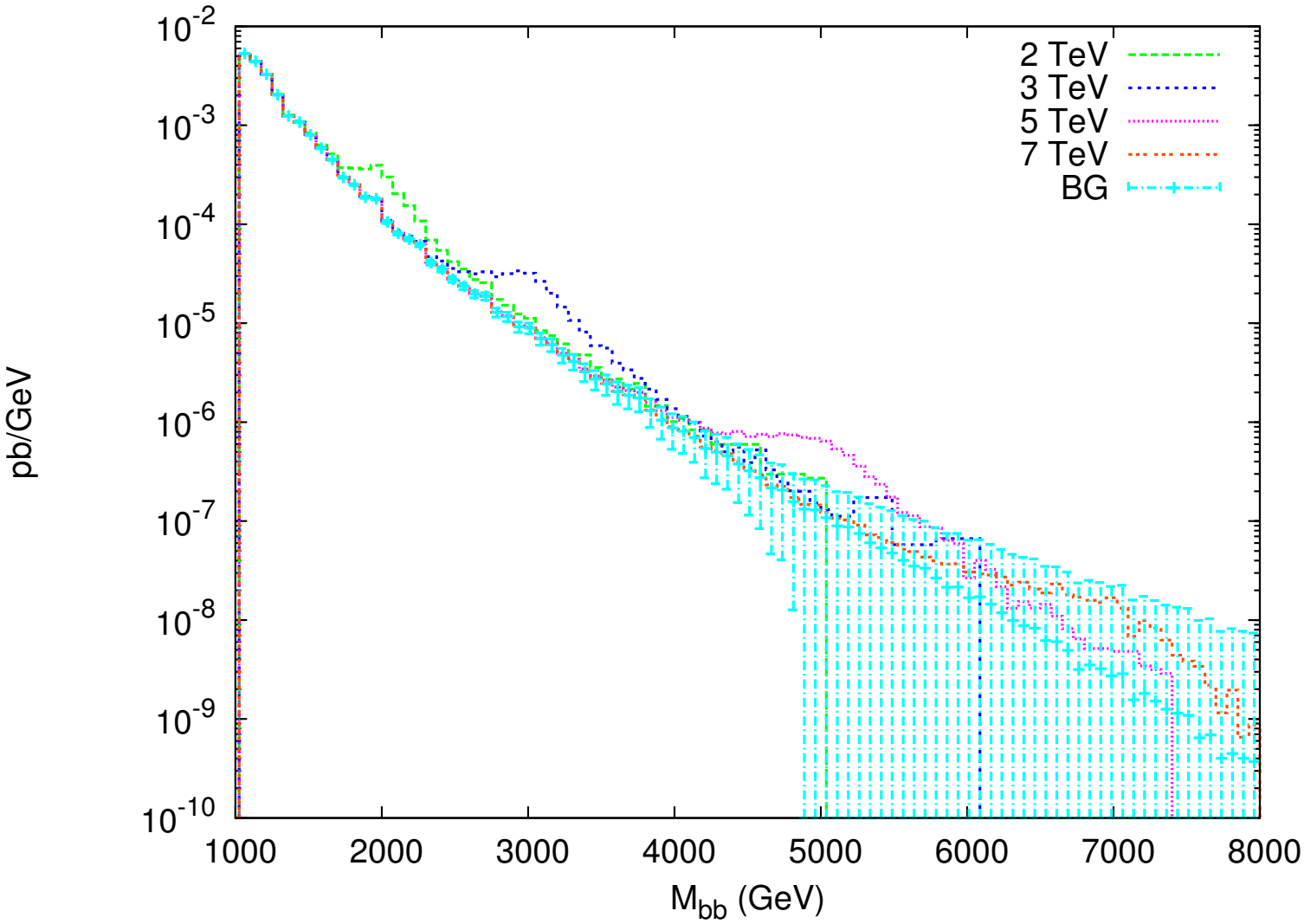
Need a comprehensive top finder!

- backup

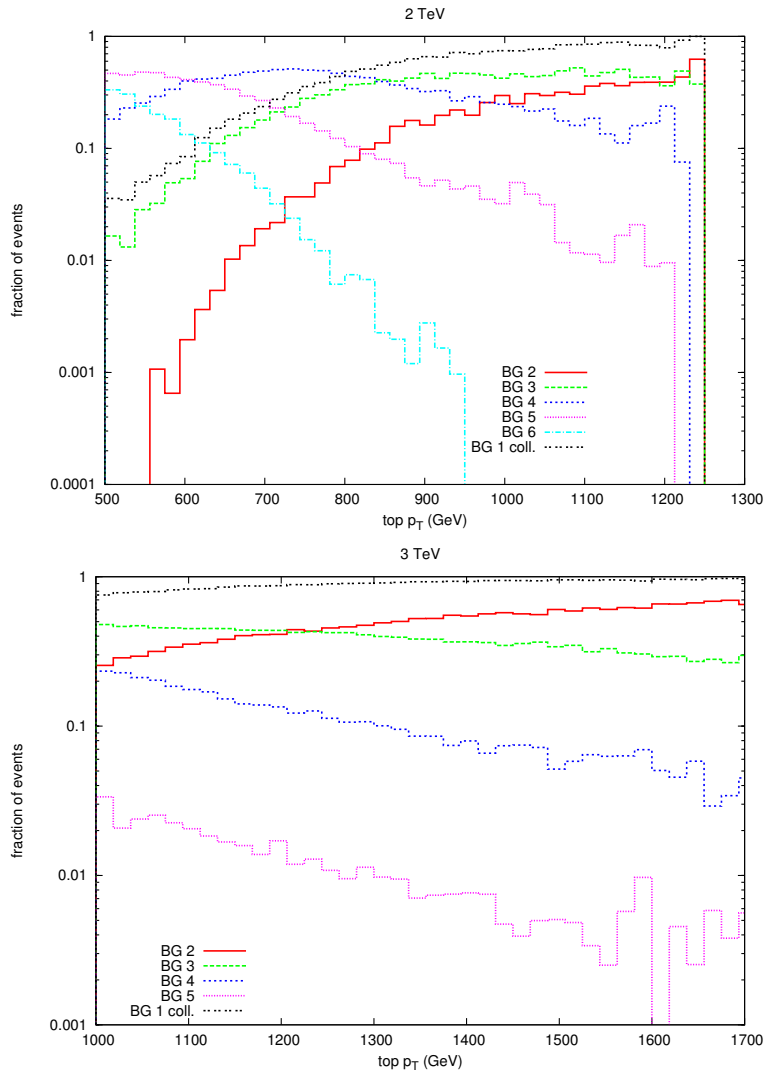
Singal vs SM $t\bar{t}$, $\sqrt{N}$ error bar



Singal vs SM $b\bar{b}$, $\sqrt{N}$ error bar

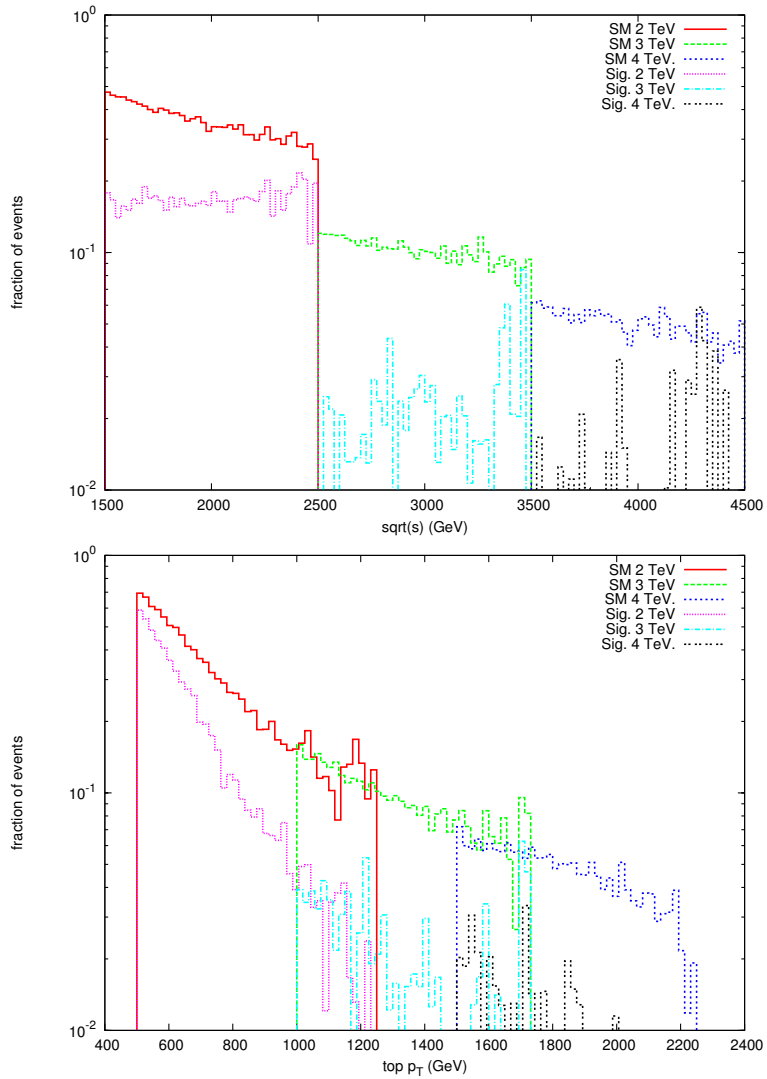


Collimation as a function of p_T



- p_T cut forces tops to be more central.

Lepton Isolation



•Maybe one can go to smaller ΔR, or more detailed analysis, but...