Top Quark Signature of New Physics

Lian-Tao Wang
Princeton University

Work in collaboration with:

1. T. Han, R. Mahbubani, and D. Walker (to appear)
2. B. Lillie, L. Randall (hep-ph/0701166)
3. L. Randall and J. Thaler, work in progress

- Outline

- Motivation

- Two Case Studies:

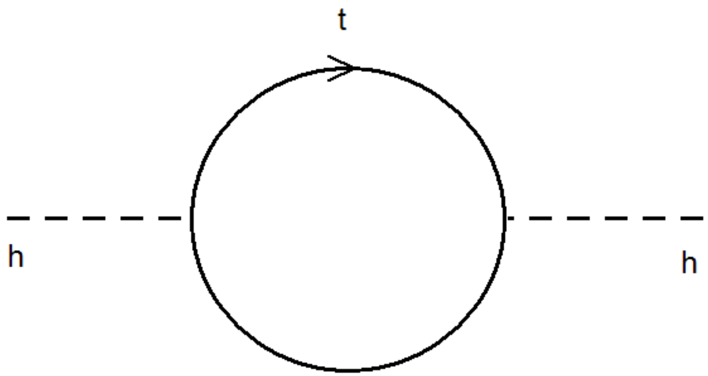
  1. NP$\rightarrow t\bar{t}\, \not\!\!E_T$

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

- Conclusion

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.

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.

Single top.

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

Different event topology.

Different kinematics.

New experimental challenge to discover/understand them.

- Two case studies

1. Top partner (Naturalness)
2. Top compositeness (m_t)

- 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 $\rightarrow$ 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*.

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

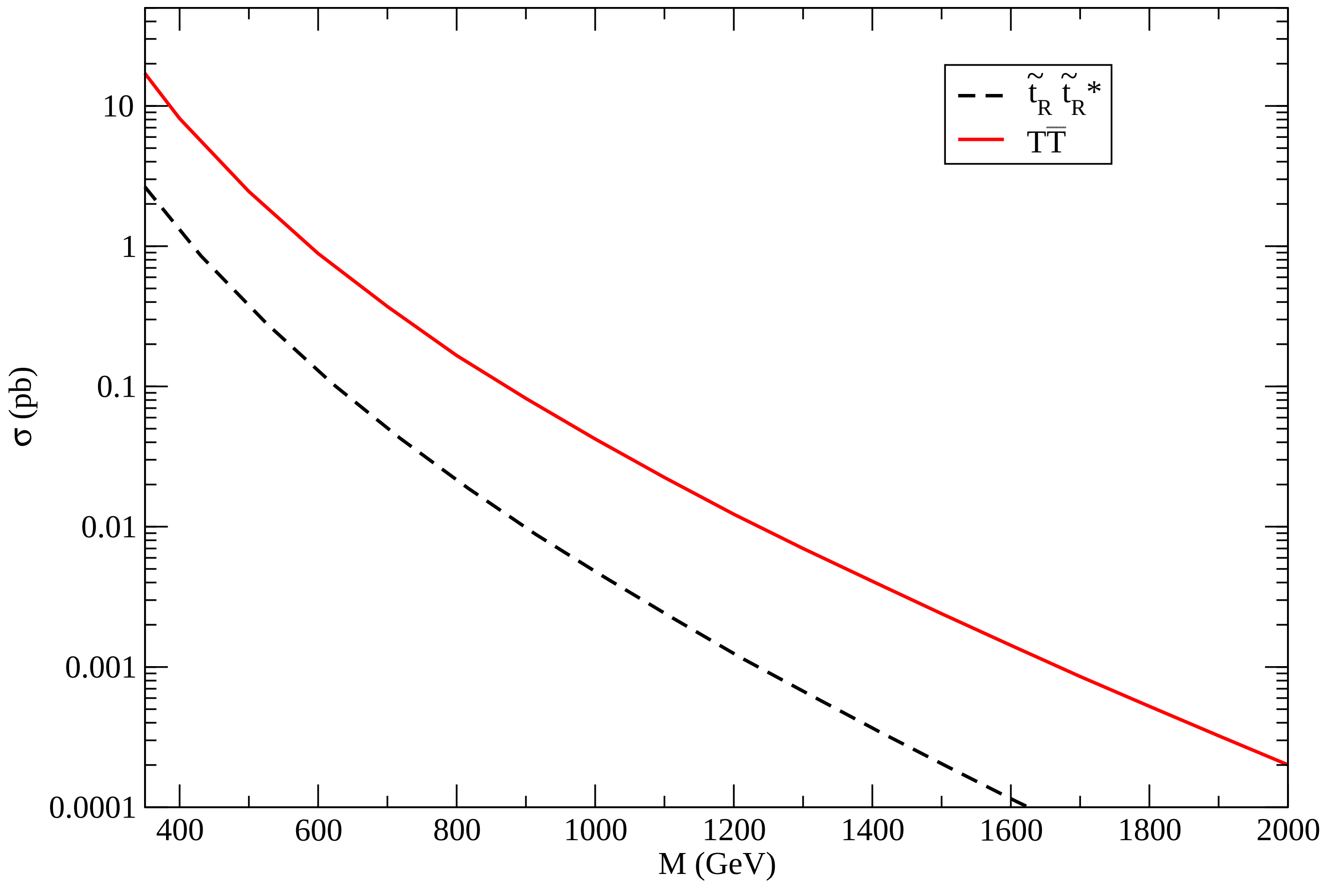
Similar signature, KK-top in UED†.

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

†S. Matsumoto, M. M. Nojiri and D. Nomura, hep-ph/0612249

Our study:*

Fermionic partner, T'. $T' \to t + A_H$. Stop, $\tilde{t}_R$, $\tilde{t}_R \to t +$ LSP.

Cleaner semileptonic channel:

$$pp \to T'\bar{T}' \to t\bar{t}A^0A^0X \to bj_1j_2\,\bar{b}\ell^-\bar{\nu}\;A^0A^0\;X$$

Potential SM backgrounds:

1. $t\bar{t} \to b\bar{b} + jj + \ell\nu$. (Huge rate ~ 800 pb.)

2. $t\bar{t}Z(\to \nu\nu)$ ("irreducible" ~ 1 pb $\sim 10\sigma_{T'\bar{T}'}$ for $M_{T'} \sim 1$ TeV)

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

*T. Han, R. Mahbubani, D. Walker, LW, Work in progress.

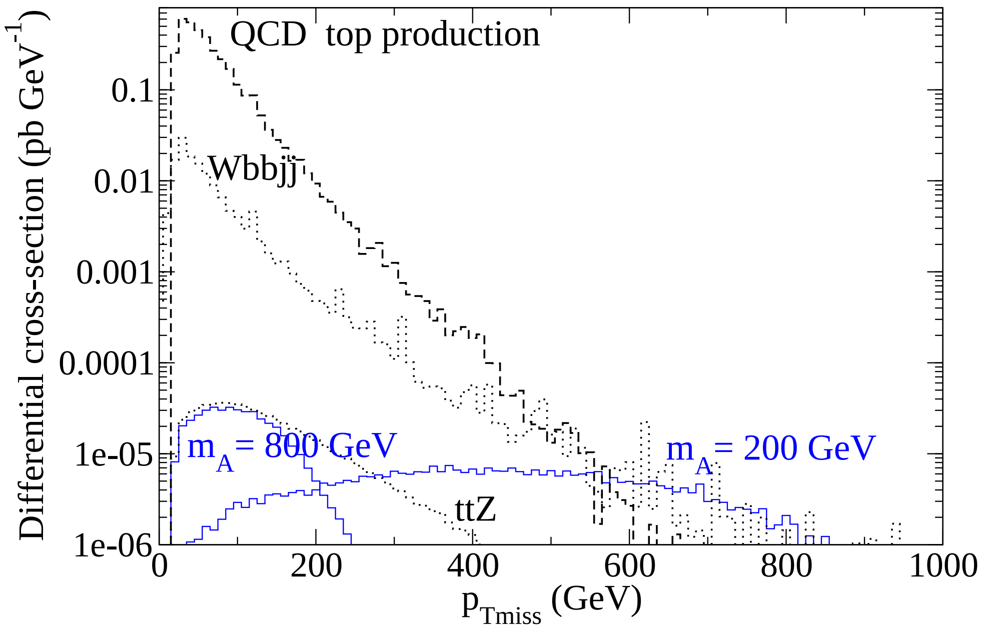
Details:

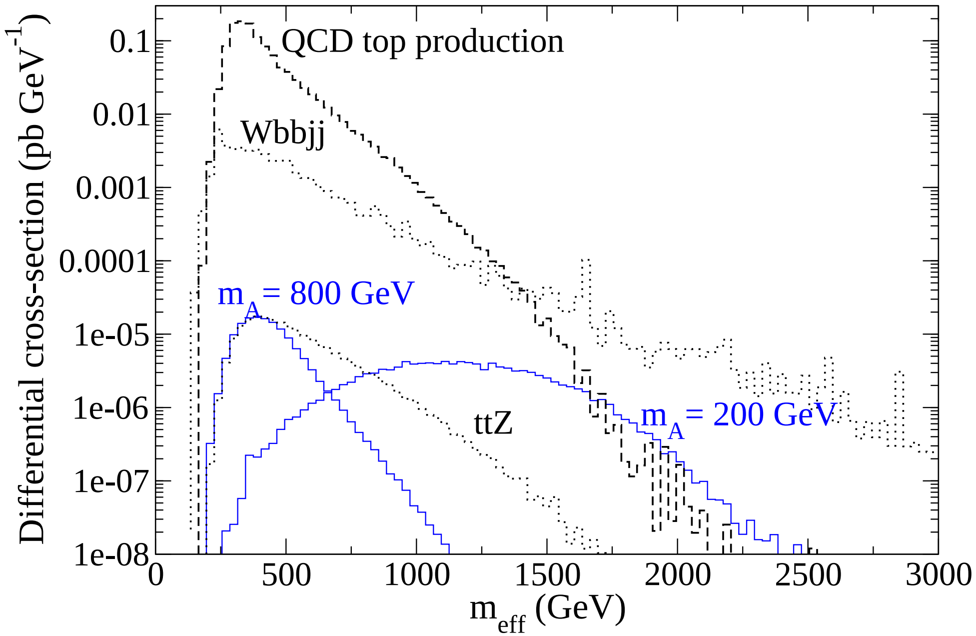
signal: $pp \to TT' \to bjj\bar{b}\ell\nu + \not{E}_T$	Special MC code is developed for this process: efficient phase-space int. with large # of final states; full spin correlation.
SM: $t\bar{t}$	PYTHIA
SM: $t\bar{t}Z(\to \nu\bar{\nu})$	Madgraph→PYTHIA. ALPGEN.
SM: $pp \to Wb\bar{b}jj$	ALPGEN.

Basic cuts (typical TDR numbers):

$$
\begin{aligned}
&p_T^\ell > 20 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad \Delta R_\ell > 0.3, \\
&E_T^j > 25 \text{ GeV}, \quad |\eta_j| < 2.5, \quad \not{E}_T > 25 \text{ GeV}, \\
&E_T^b > 30 \text{ GeV}, \quad |\eta_b| < 2.5, \quad \Delta R_j,\ \Delta R_b > 0.4,
\end{aligned}
$$

SM background

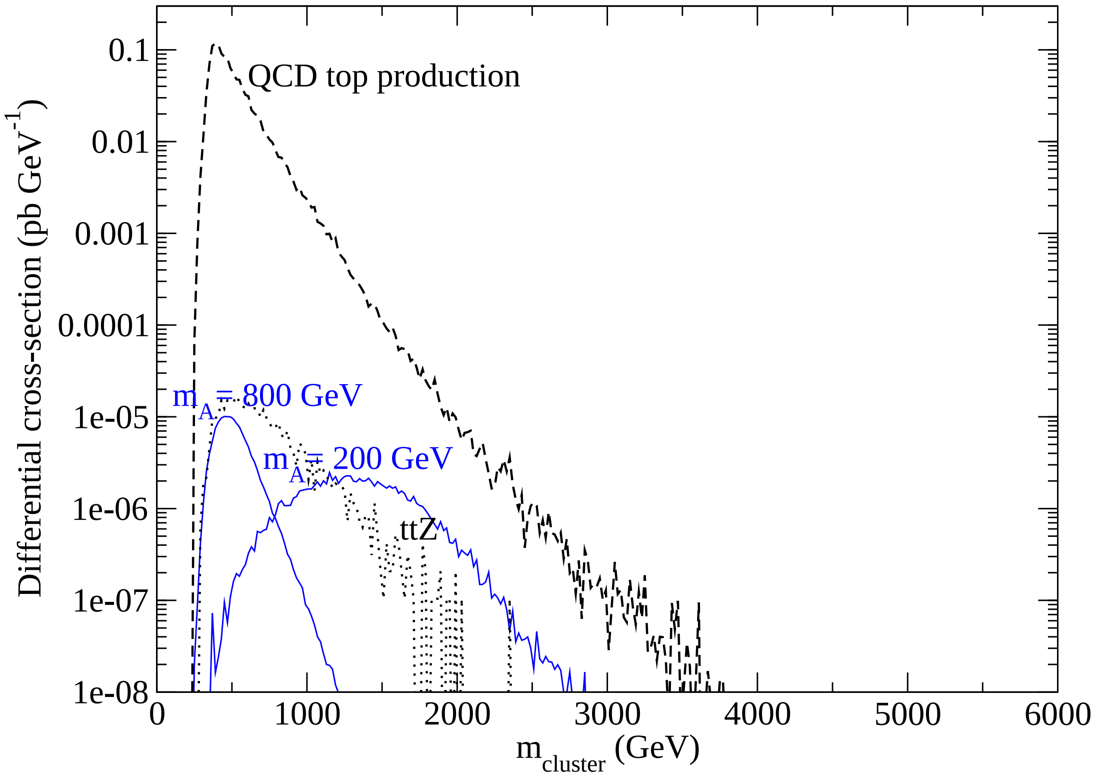




Simple cuts on transverse variables such as $\not{E}_T$ and M_{eff} are not sufficient.

Small mass splitting $\rightarrow$ more challenging.

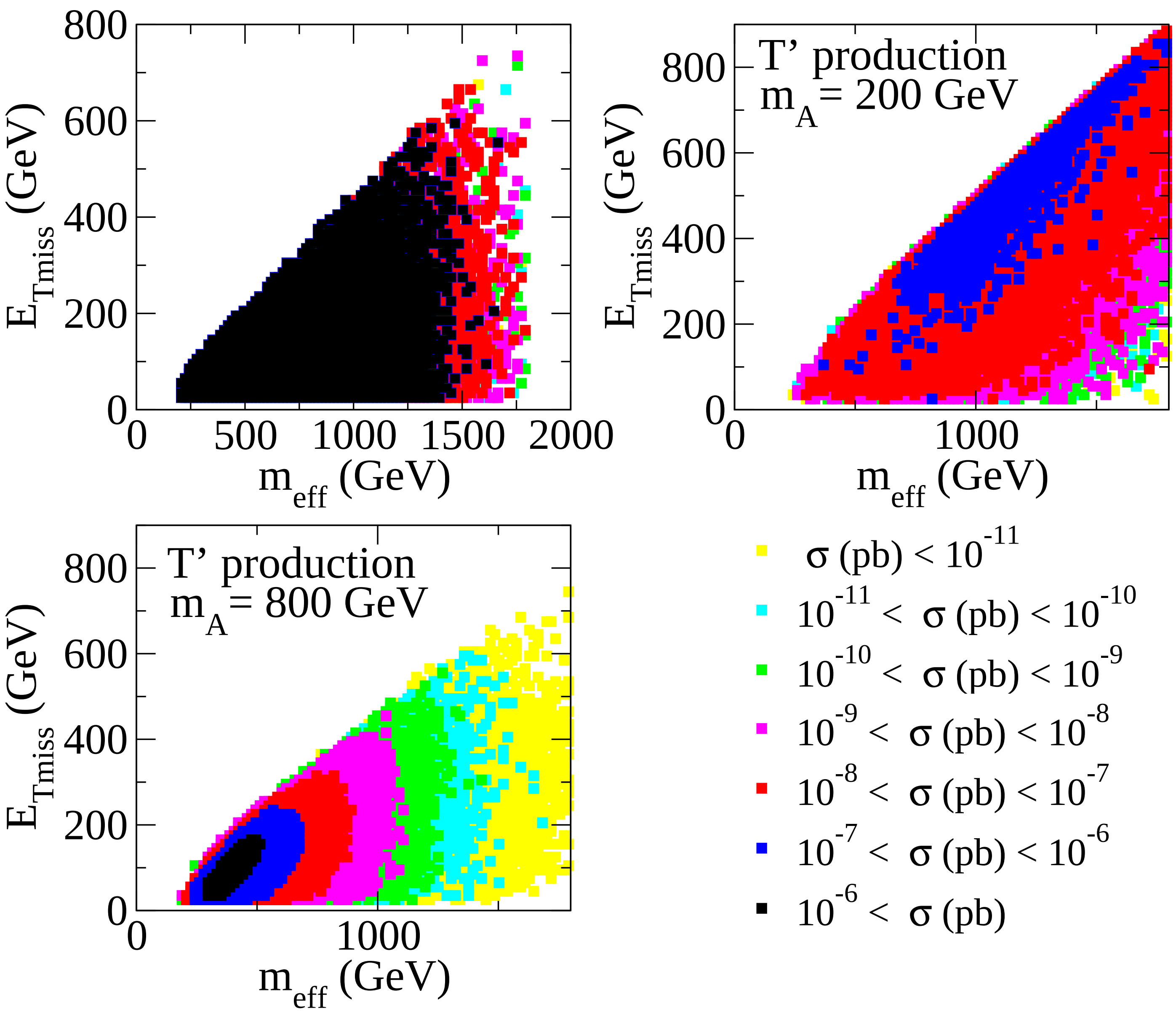
Other variables? For example:



$$M_T^c = \sqrt{m_c^2 + \vec{p}_{cT}^{\,2}} + \not{E}_T$$

$$m_c^2 = (p_b + p_{\bar{b}} + p_{j_1} + p_{j_2} + p_\ell)^2 \quad \text{and} \quad \vec{\not{E}}_T = -(\vec{p}_b + \vec{p}_{\bar{b}} + \vec{p}_{j_1} + \vec{p}_{j_2} + \vec{p}_\ell)_T$$

SM background: some correlations?



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.

$W(\rightarrow \ell\nu)bbjj$ also requires additional handles.

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 $m_t^{\text{had}} \sim m_t^{\text{lep}}$, and/or minimizing $|(m_t^{\text{had}}, m_t^{\text{lep}}) - m_t|$.
•m_t^{lep} will have a peak around m_t whose width determined by the resolution.

For signal:

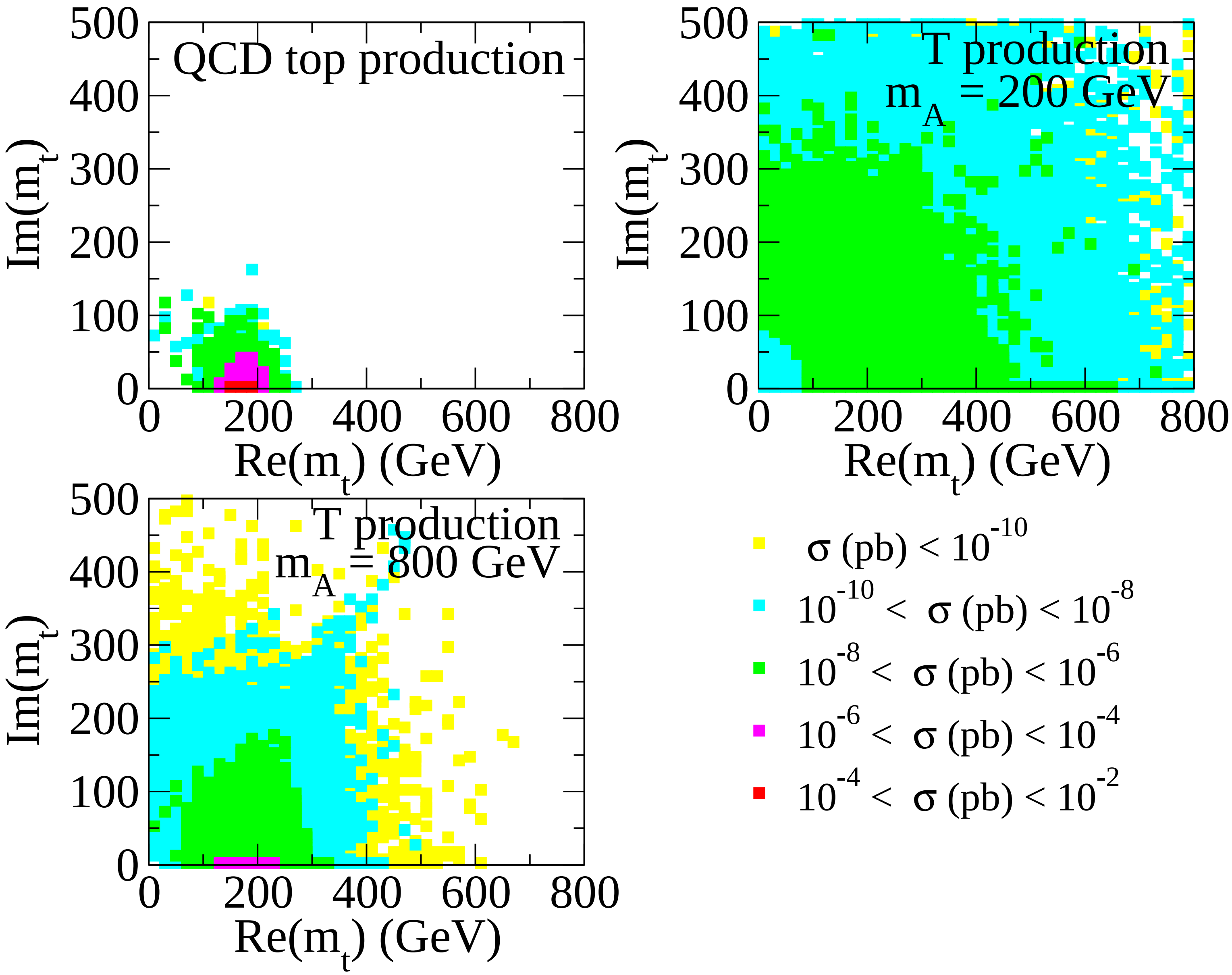
•We will assume (wrongly) that $\not{E}_T$ is from ν, and do the same reconstruction.
•Wrong, (often) imaginary solutions $\to$ signal!.

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

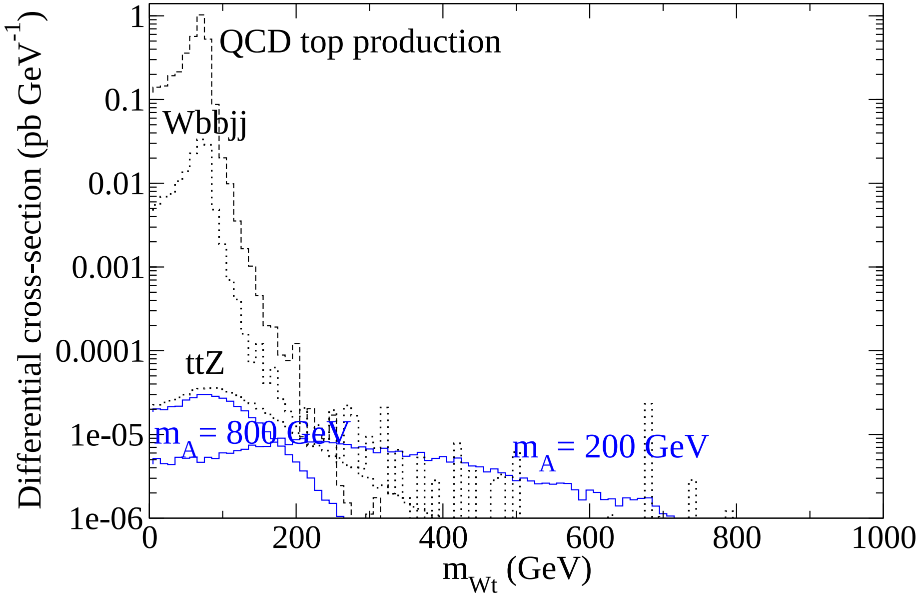
Reconstruction

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

Reconstruction:



• Other reconstruction variables



$$M_T(W) = \left((E_{\ell T} + E_{\nu T})^2 - (\vec{p}_{\ell T} + \vec{p}_{\nu T})^2\right)^{1/2}$$

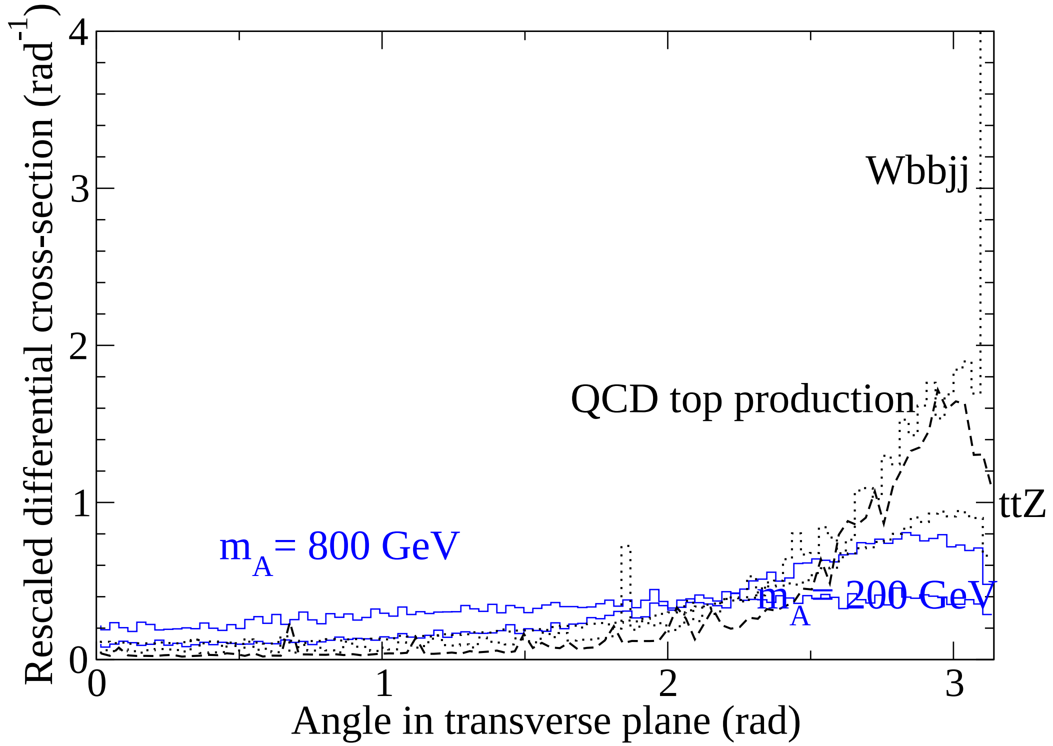
Similar to reconstructed top mass.

Further suppressing the $Wbbjj$ background.

m_{jj}: dijet invariant mass. Close to m_W in top decay.

$m_t^r|_{\text{had}}$: Reconstructed top mass on the hadronic side $\sim m_t$ from top decay.

More kinematical features.



Normalized to 1.
$\Delta\phi$ between t_{hadronic} and the plane of (ℓ, b)

- Will only help at the level of $\mathcal{O}(1)$
- Less useful for $m_A = 800$ GeV
- Suggest $\Delta\phi < 2.5$.

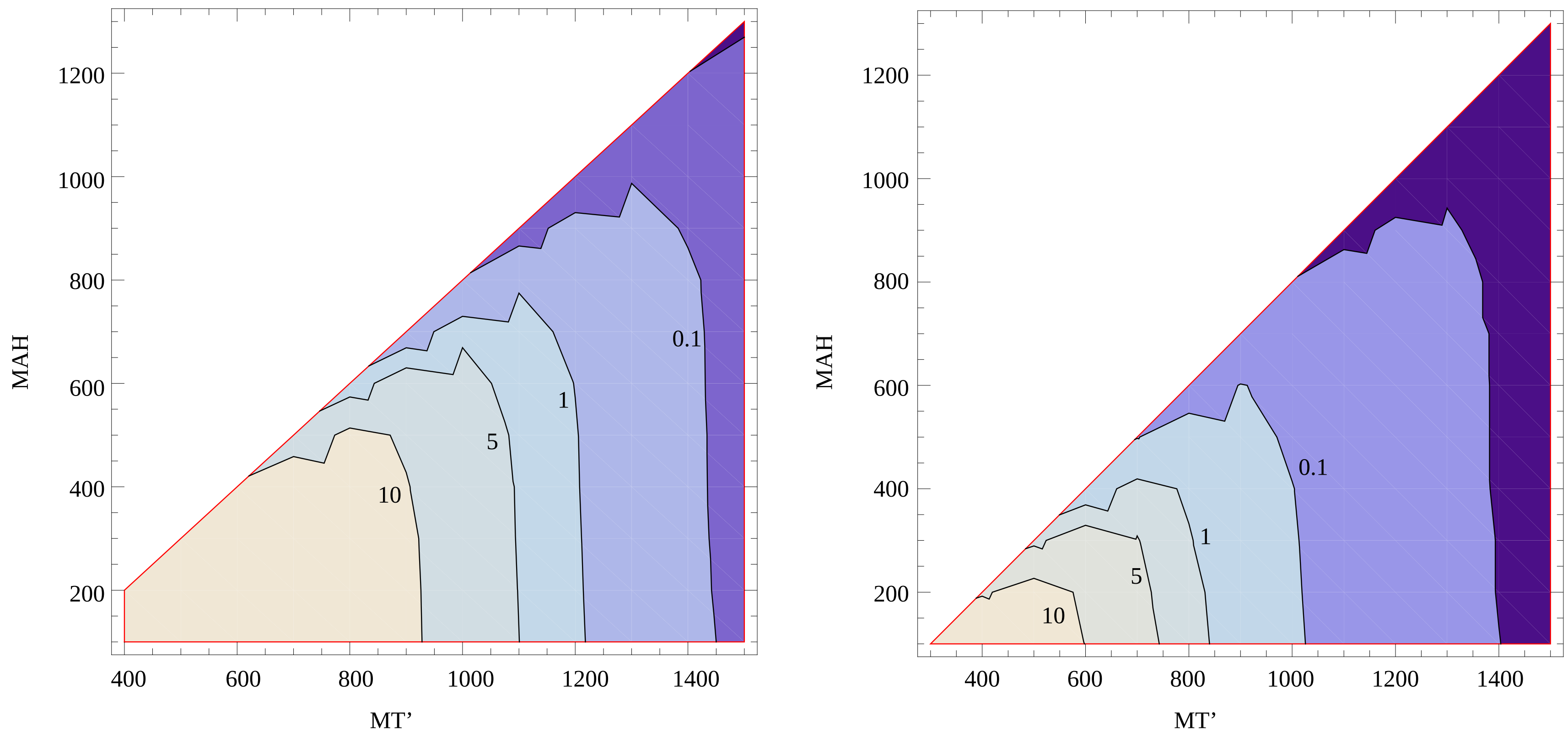
- Discovery reach: T'(left), $\tilde{t}_R$(right) $S/\sqrt{B}$, 100 fb^{-1}

2 b-tags, $\epsilon_b = 0.5$

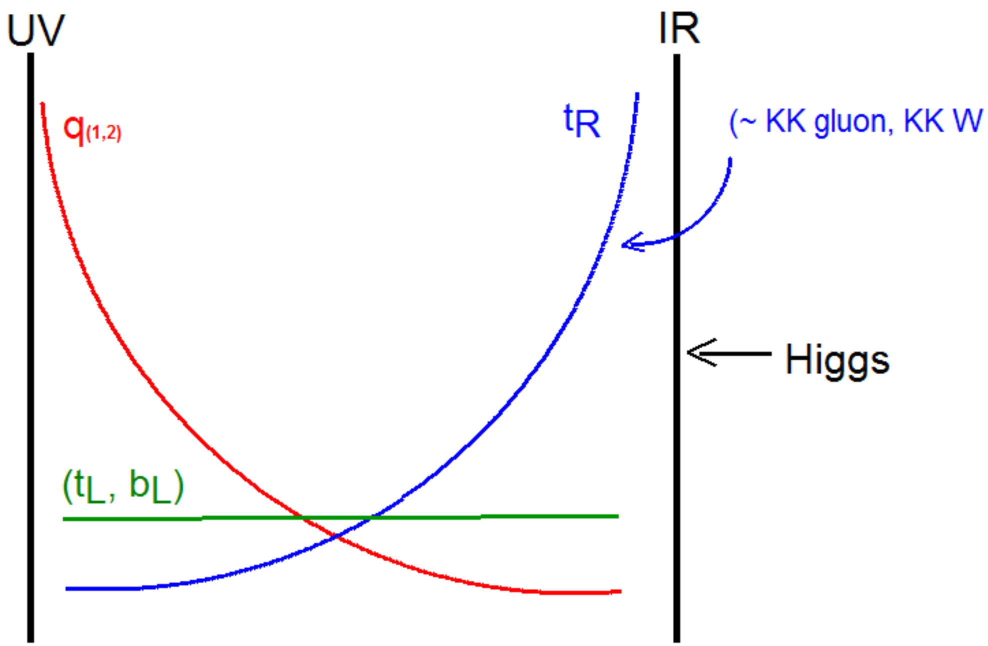
70 GeV $< m_{jj} <$ 90 GeV, $|m_t^r - 175| > 110$

$\phi_{t-bl} < 2.5$, 120 GeV $< m_t^r|_{had} < 180$

$\not{E}_T > 0.2 \times (M_T - M_A)$



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



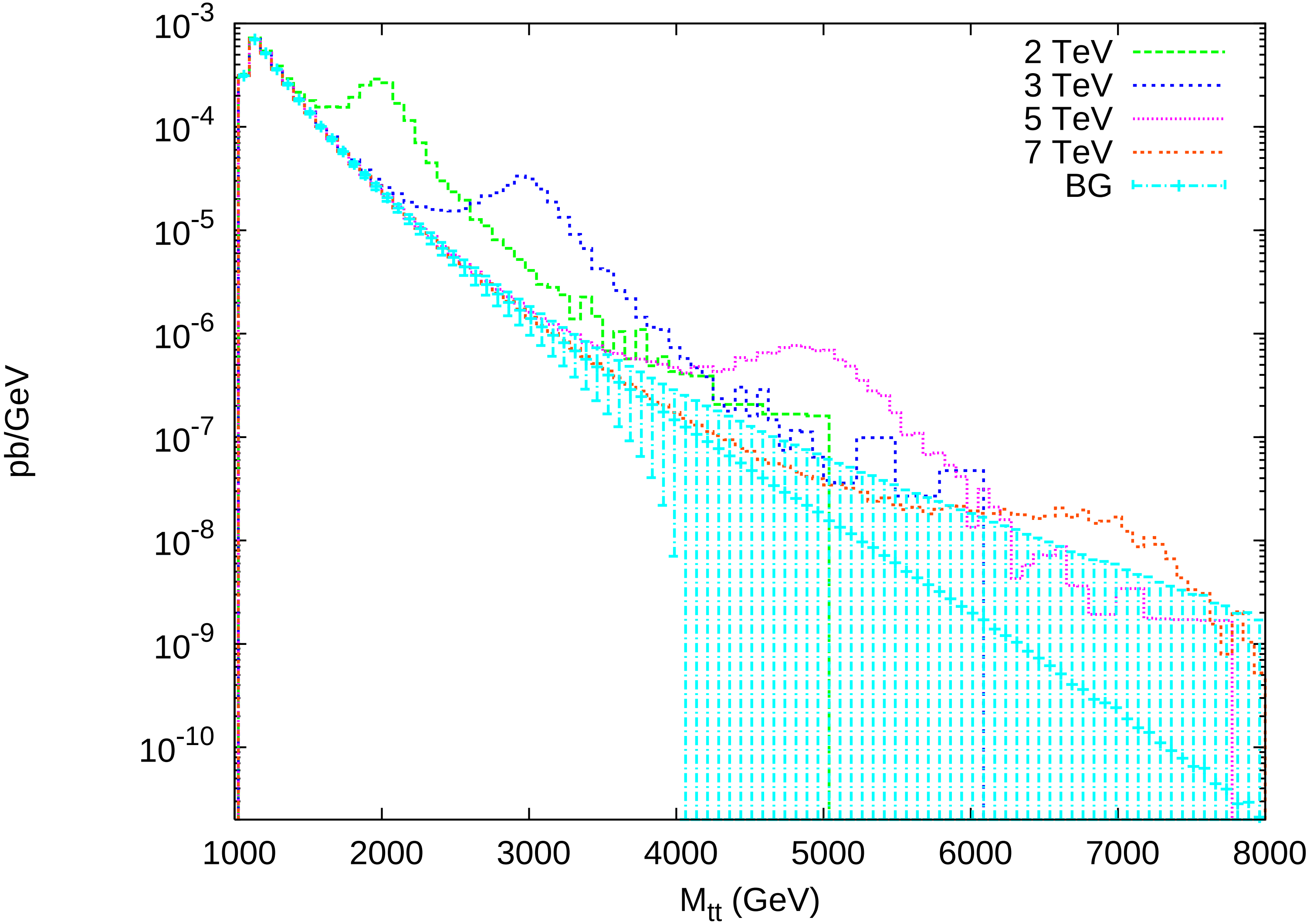
top is composite $\longrightarrow$ top is heavy

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

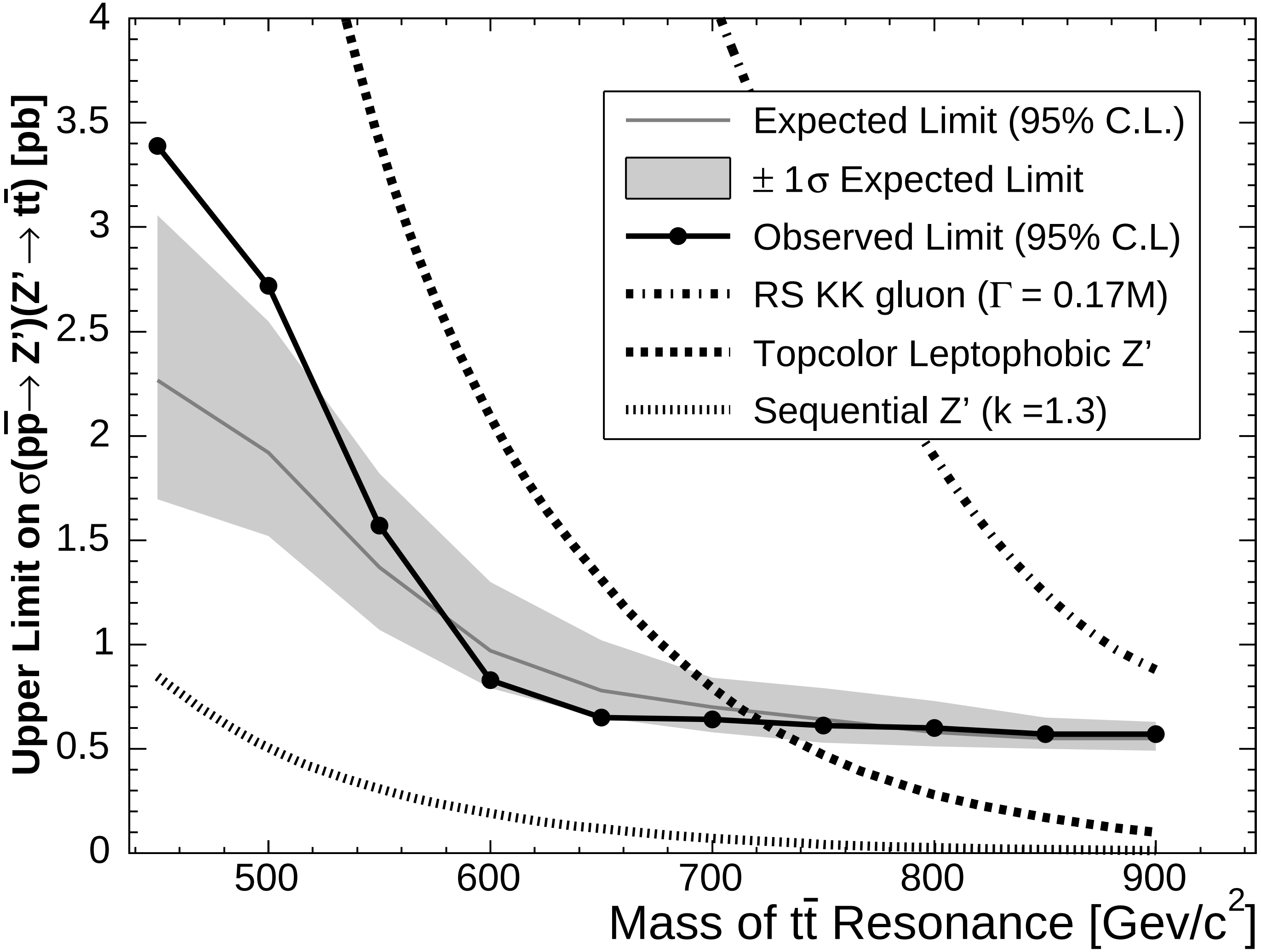
Bump searching.

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

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



- New $t\bar{t}$ resonance: A limit from Tevatron.*



Aaltonen et al. [CDF Collaboration], arXiv:0710.5335 [hep-ex].

Challenges at the LHC

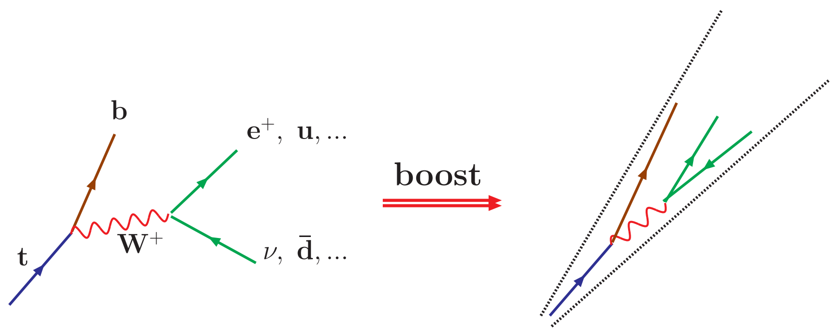
1. SM $t\bar{t}$ has long tail in $m_{t\bar{t}}$.

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*.

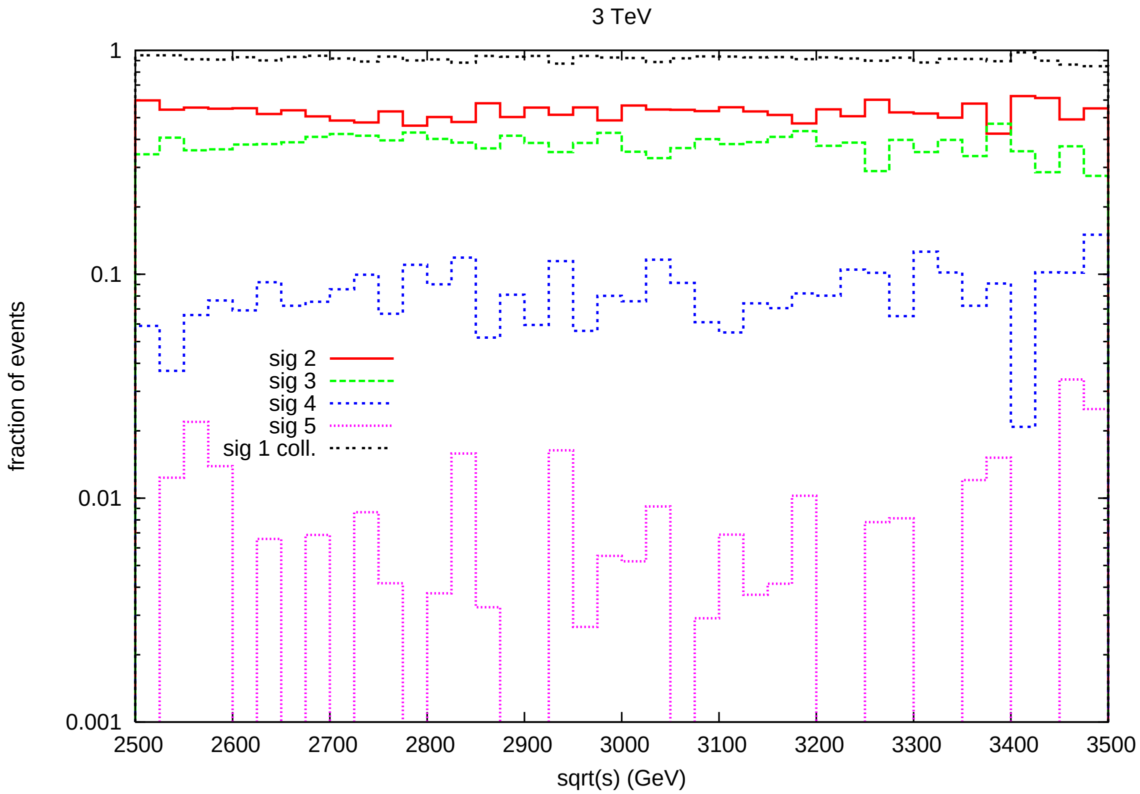
$\longrightarrow$ Very energetic tops

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



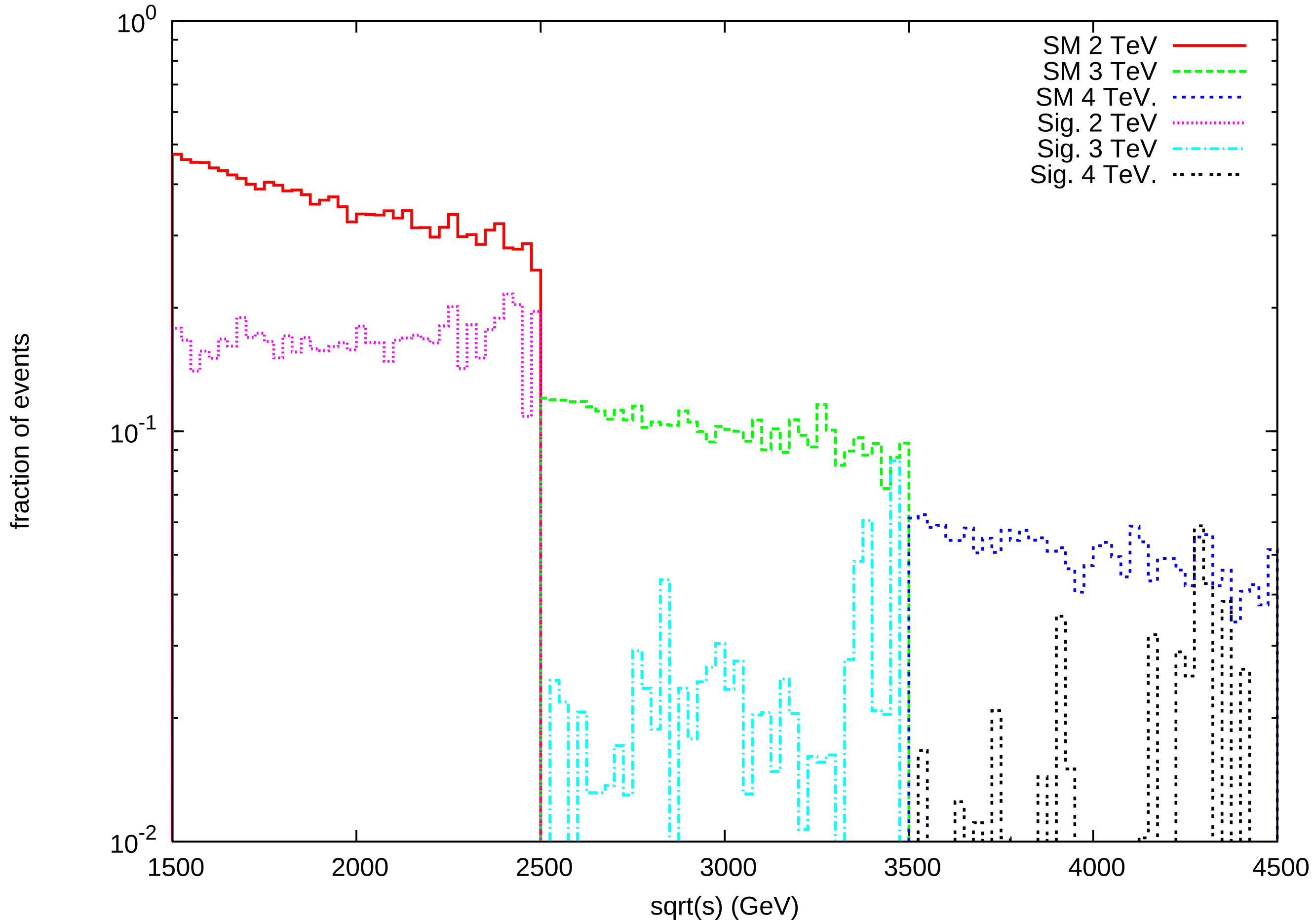
*K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036

Collimation: $\Delta R = 0.4$, $m_{\rm NP} \sim 3$ TeV



- 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.

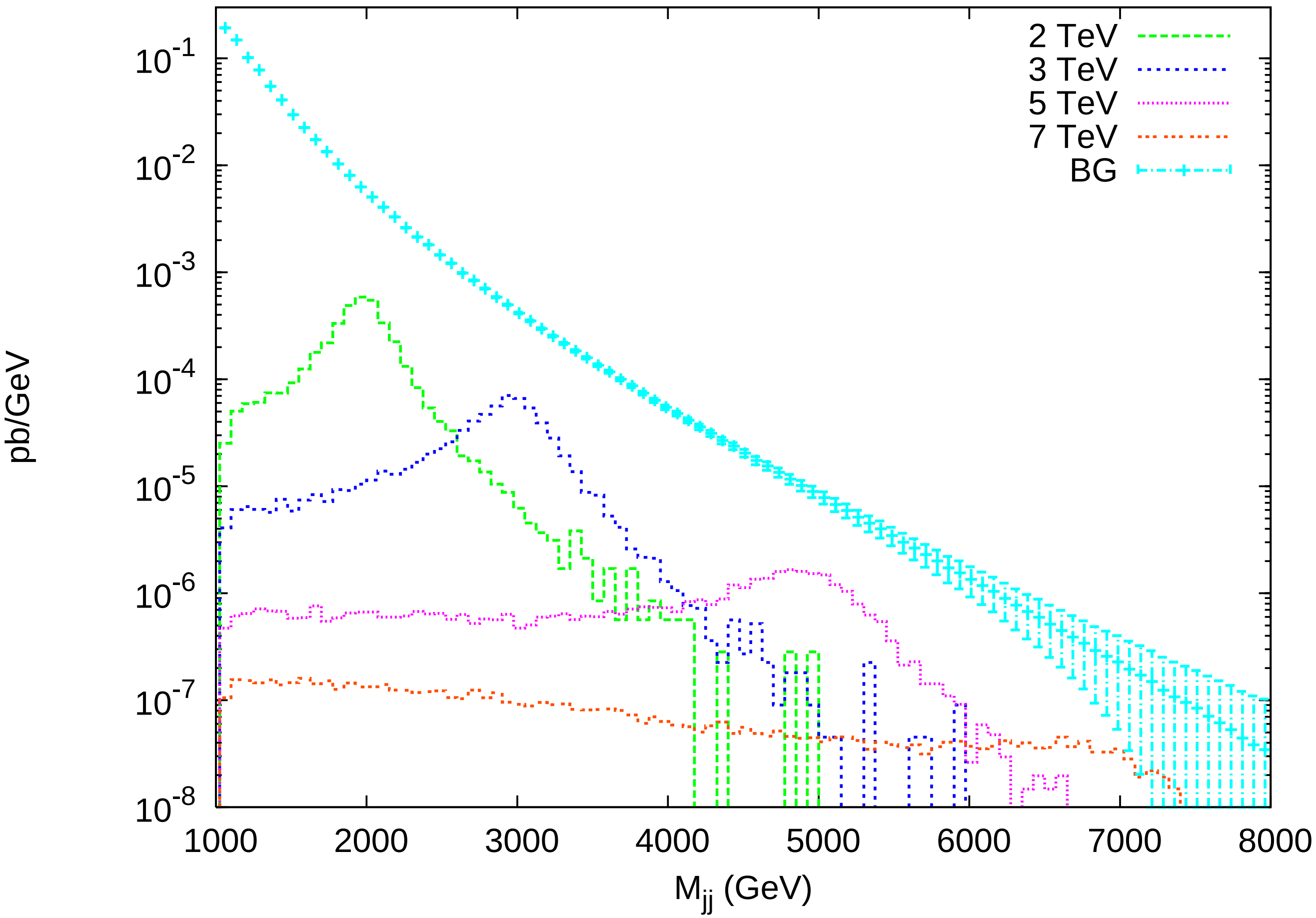
Lepton isolation?



For $M_{t\bar{t}} \geq 3$ TeV, a few % with lepton isolation.

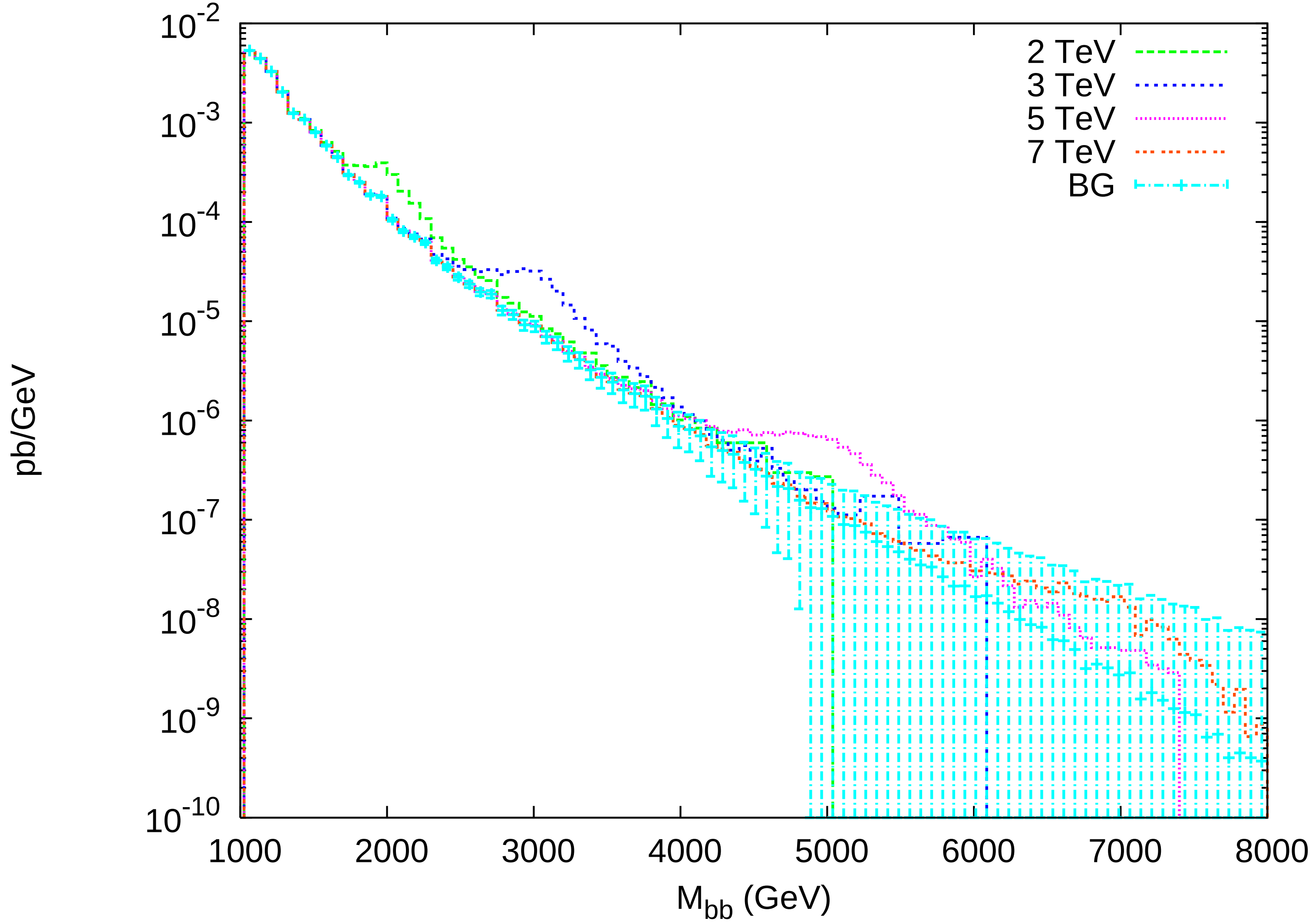
If we cannot do better

QCD di-jet background.



b-tag, ...

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



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 muons in top jet. Compare them with muons in b-jet. more detailed study necessary.

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

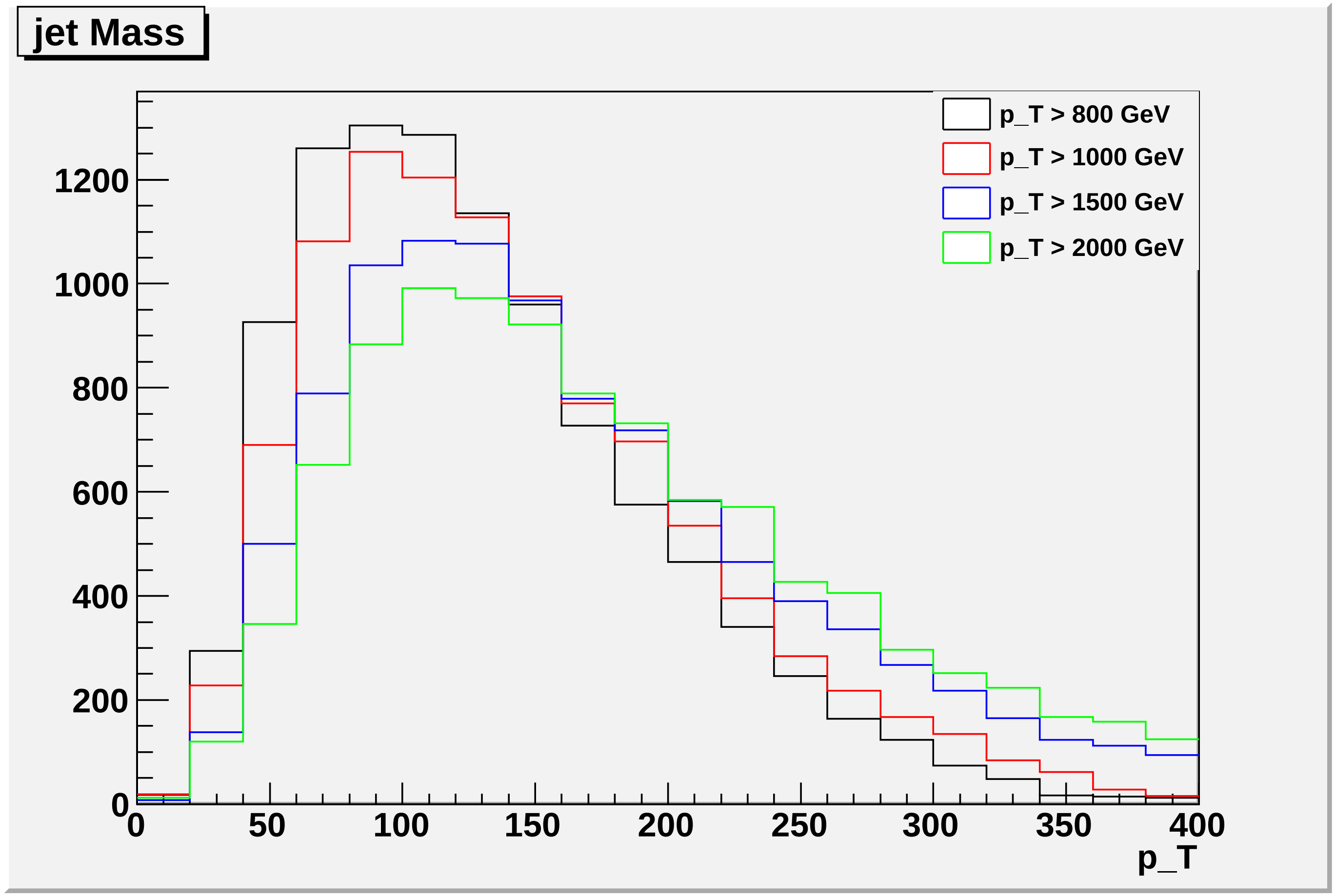
How well this can be distinguished from (massive) QCD jets?

*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

• Top jets vs QCD jets

Using jet mass? However, $< m_{j_{\rm QCD}} > \sim 0.07 - 0.1 \times p_T^j{}^*$



Additional variable?

*Simulation: PYTHIA shower→FASTJET.

- QCD jets: robust feature at leading log

Parton $\rightarrow$ radiation/branching $\rightarrow$ shower

Consider branching $0 \rightarrow 1+2$

A shower history is characterized by

t: evolution variable, such as virtuality, p_T

z: energy fraction of branching $E_{1,2}/E_0$

or equivalently: $\cos\theta_0$, angle between 1or 2 and boost in 0 restframe

Branching probability for given t and z

$$dP = dtdz\frac{\alpha_s(t)}{t}f(z)\Delta(t_0, t)$$

$f(z)$ Altarelli-Parisi splitting function.

Singularity at $z \rightarrow 0$.

$\Delta(t_0, t)$ Sudakov form factor. (resuming the leading log, collinear + IR)

- Top jets

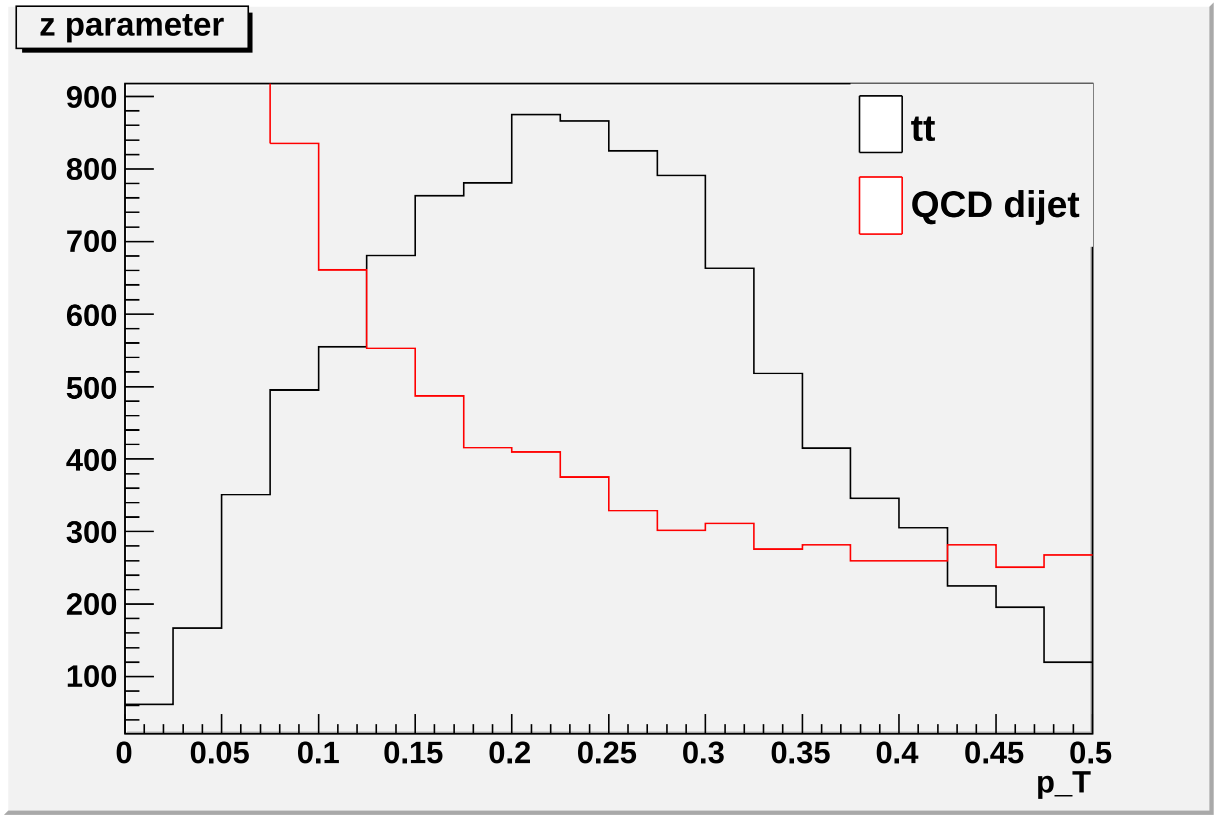
First branching: $t \rightarrow bW$: $\min(z_{1,2}) \rightarrow 0.25$

- Top jets vs QCD jets*

"Following" the branching History

k_T jets. k_T close to an evolution variable.

k_T clustering history $\sim$ branching history.



*L. Randall, J. Thaler, LW, work in progress.

- More on z variable

Things could change z distribution at $z \to 0$

Running scale for α_S

Definition of z

Choice of evolution variable

e.g.: $p_T = tz(1-z)$ evolution, $z \to 0$ $p_T \to 0$, Sudakov suppression.

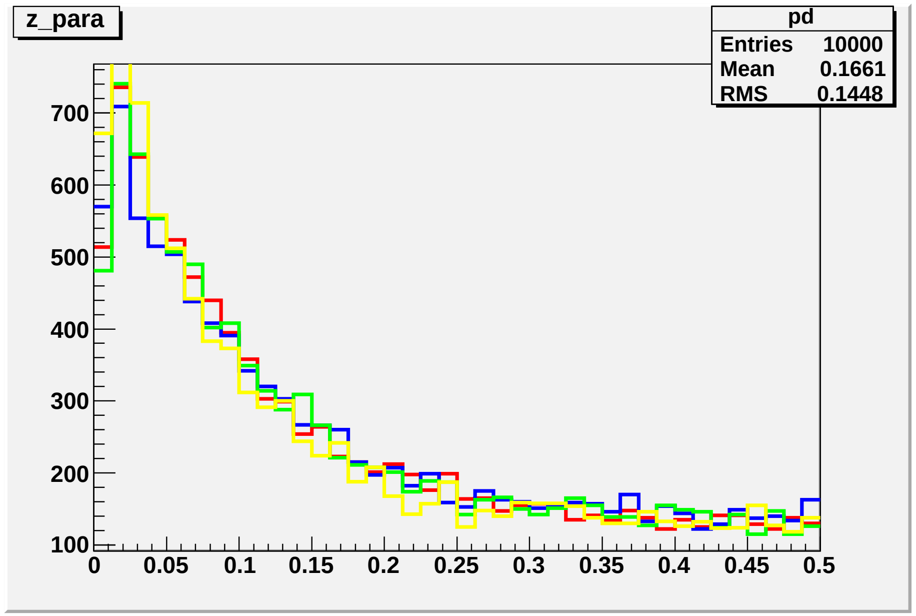
NLO+matching, or operator mixing in Soft Collinear Effective Theory

Difference between k_T and the "true" evolution variable.

Treatment of color coherence.

"tune"...

All at subleading log. Could be important $z \to 0$.



red: Pythia default.

blue: z with massive daughter

green: "intermediate" color-ordering

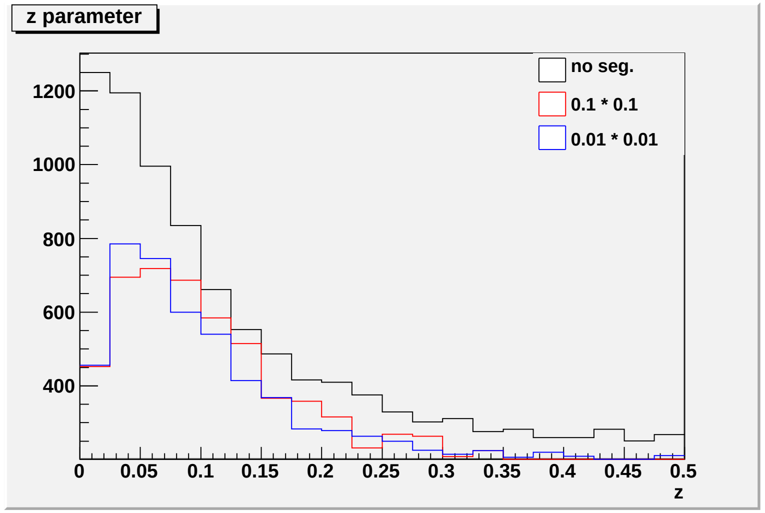
yellow: p_T order showering.

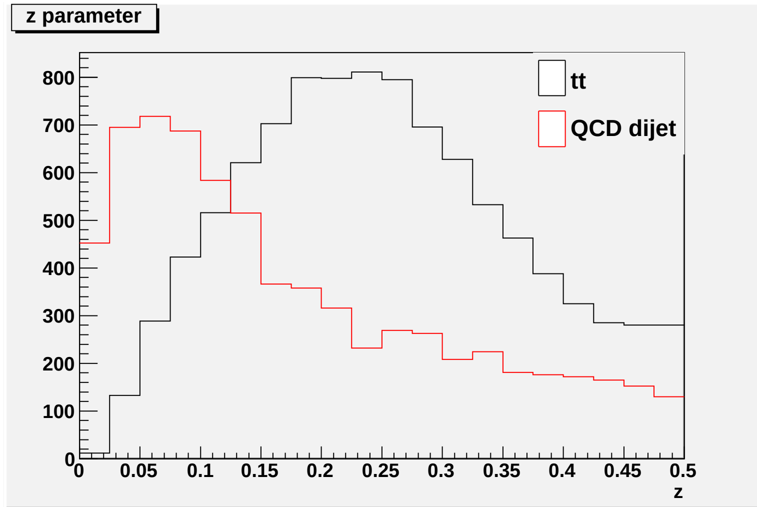
• A More important effect: granularity of the detector

$$\cos\theta_0 = \frac{1}{\beta_0}\frac{2(1-z)-(1+t_1/t_0-t_2/t_0)}{\lambda(t_0,t_1,t_2)}$$

$\beta_0 \to 1,\ t_i \to 0,\ z \to 0,\ \cos\theta_0 \to 0.$

Suppression at $z \sim 0$ due to finite granularity of the detector.





More important than the subleading log effects.

Still peak towards 0. different from top

- Top jets vs QCD jets.

z useful discriminator.

Could even use W branching.

	SM $t\bar{t}$	QCD di-jet	SM $b\bar{b}$	SM W+jet
$p_T^j > 1000$ GeV (pb)	12	12000	29	46
$z_t > 0.15$, $z_W > 0.15$	0.1	0.0055	0.0038	0.003
$150 <$ jet mass < 190	0.24	0.15	0.13	0.12

More detailed study and optimization underway.

Using ECAL and tracking ?

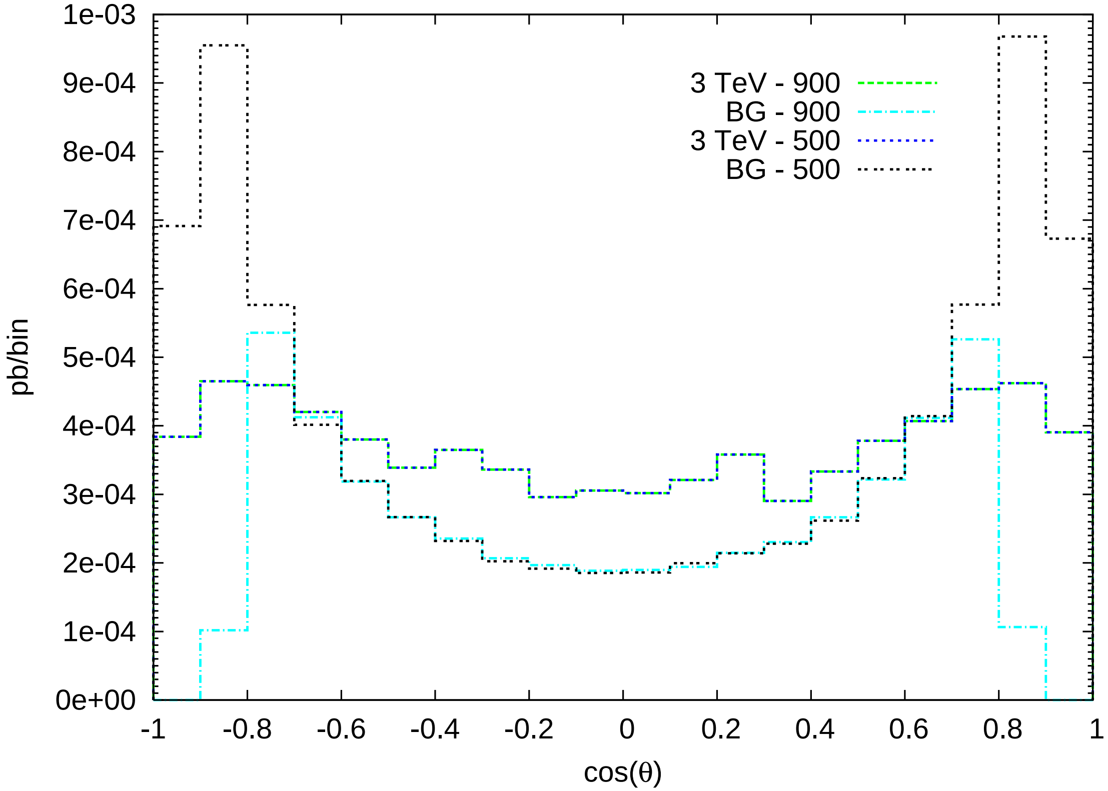
Other variables similar to z?

- Using tops to learn about the new resonance

  Spin

  Chirality of the coupling

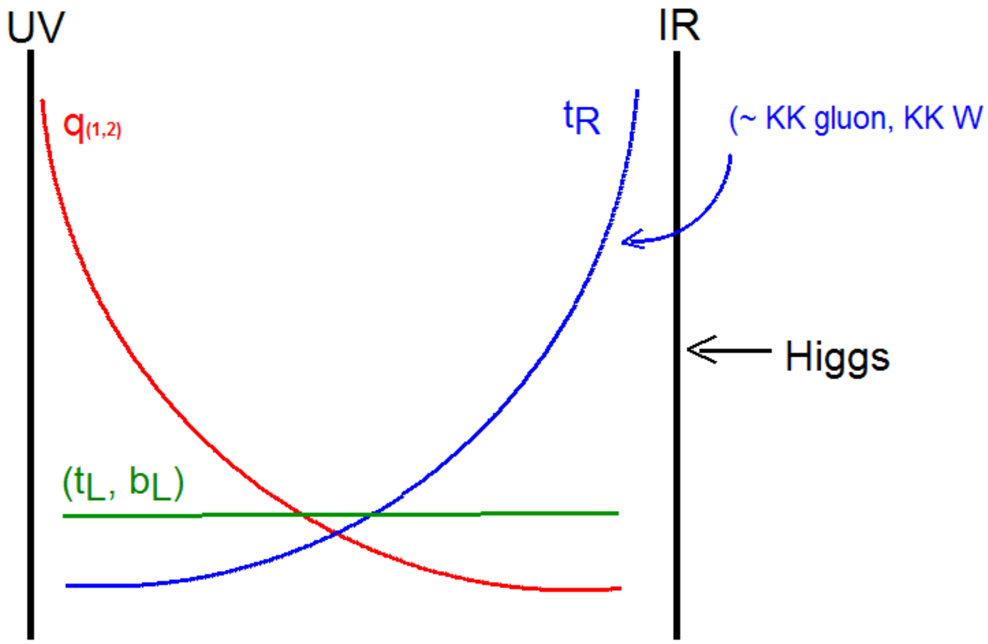
- Spin



Signal: spin-1 resonance $\rightarrow \propto (1 + \cos\theta)^2$

Background: QCD, more forward

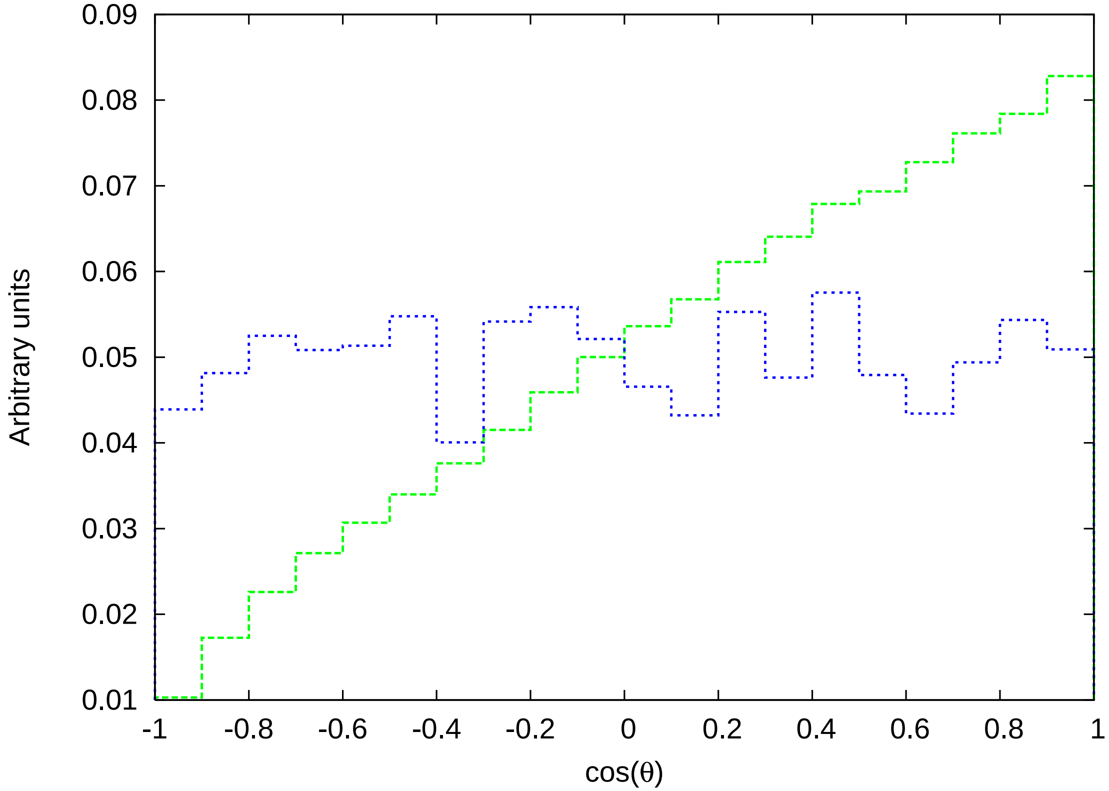
• Chiral coupling



$SU(2)_L$, m_t/m_b, composite Higgs, $\rightarrow$

$g^{(1)}t\bar{t}$ coupling mostly righthanded.

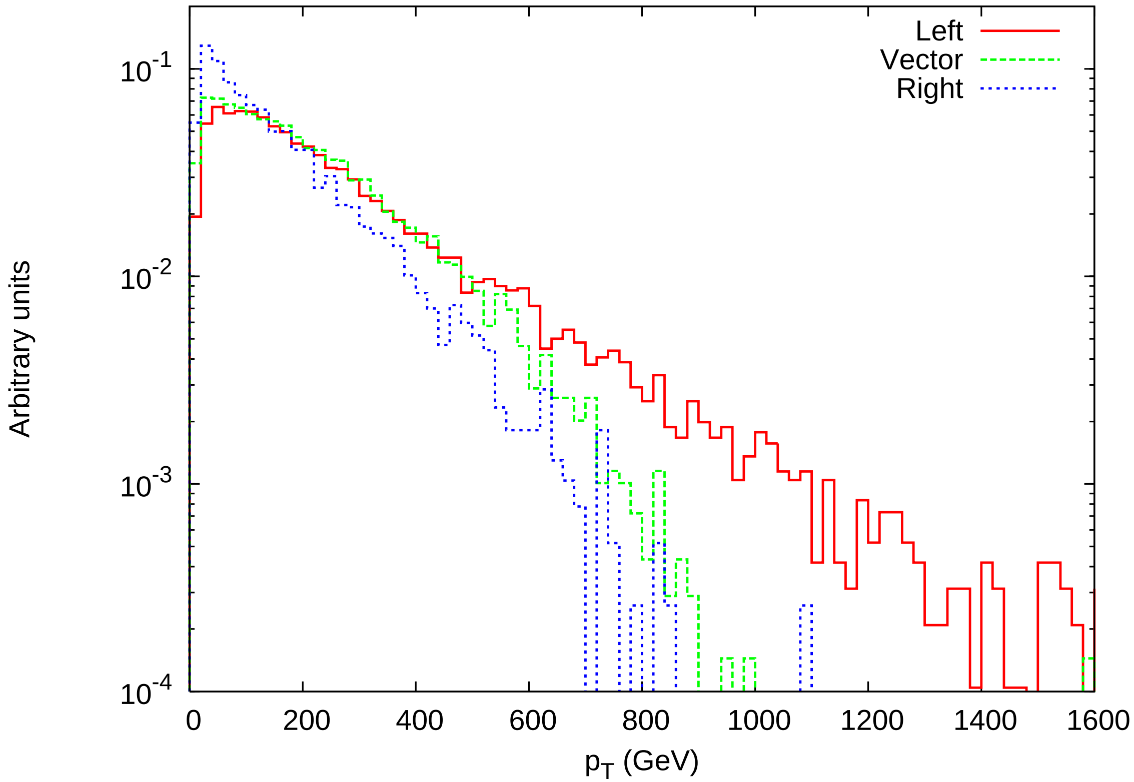
• Correlations



Right-handed (helicity) polarized top:

ℓ^+ tends to go along with the directions of the top quark.

• Lepton p_T spectrum $\leftrightarrow$ chirality



Highly boosted top: Chirality $\leftrightarrow$ helicity.

- Conclusion:

Top sector is one of the most probable places 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...)

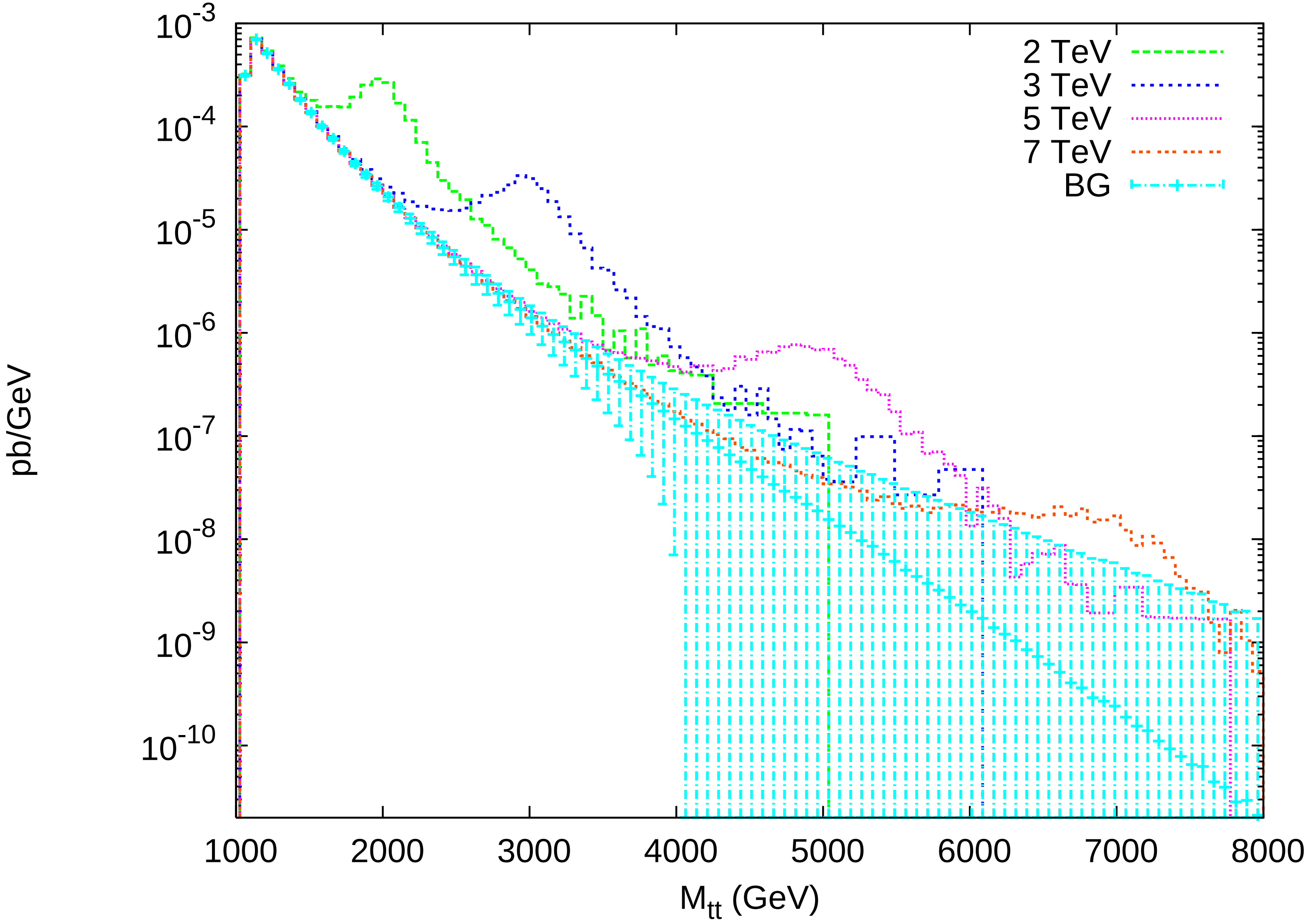
Energetic tops, $m_{t\bar{t}} \sim$ several TeV

...

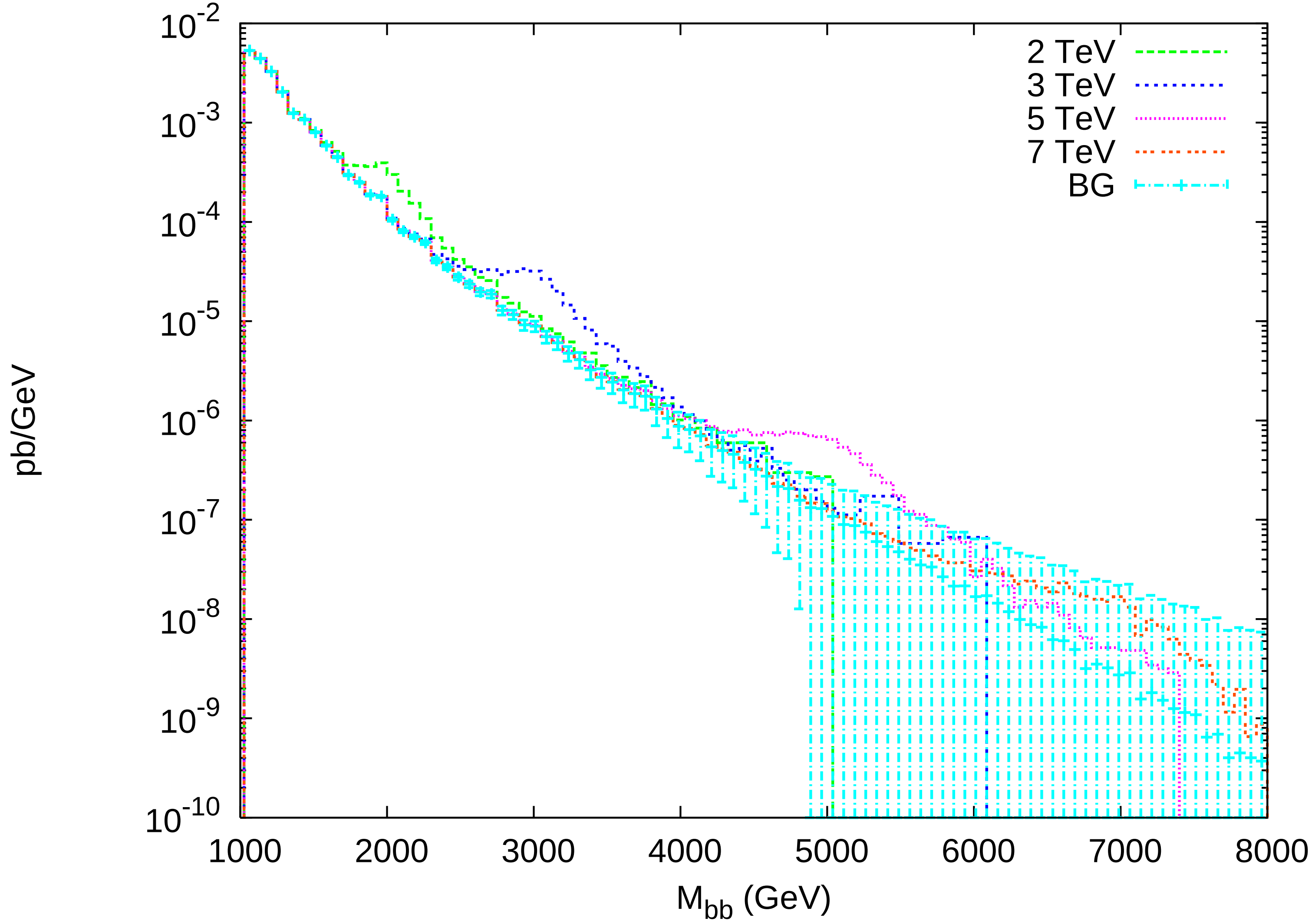
Need a comprehensive top finder!

- backup

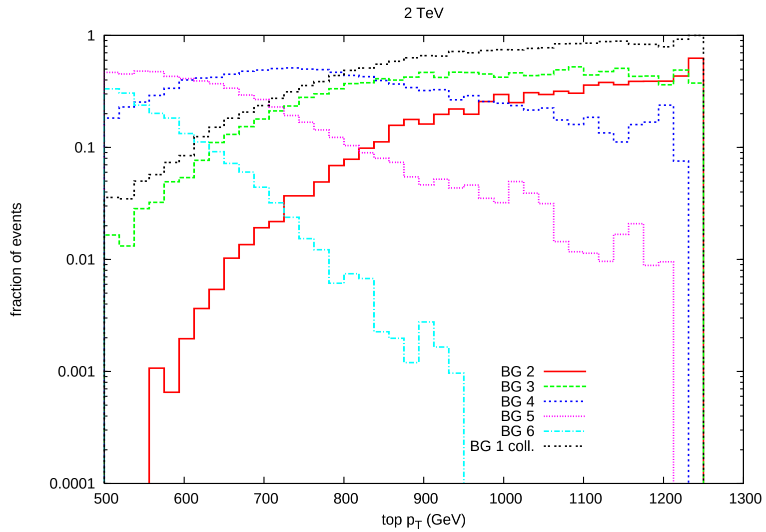
Singal vs SM $t\bar{t}$, $\sqrt{N}$ error bar

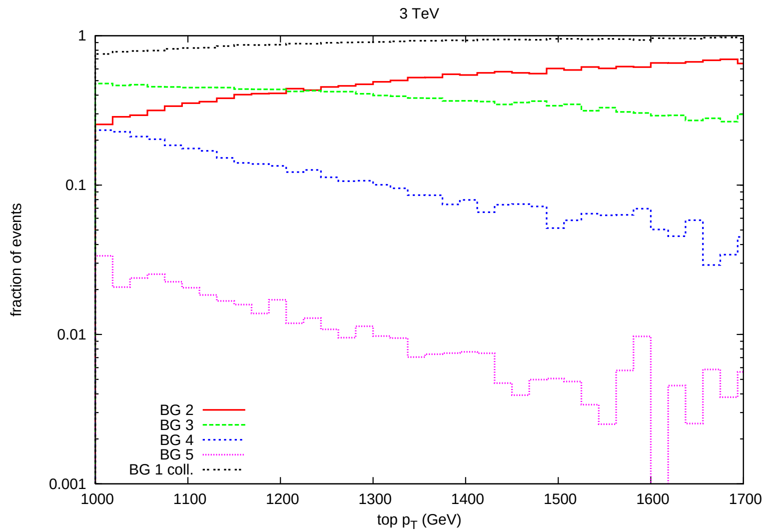


Singal vs SM $b\bar{b}$, $\sqrt{N}$ error bar



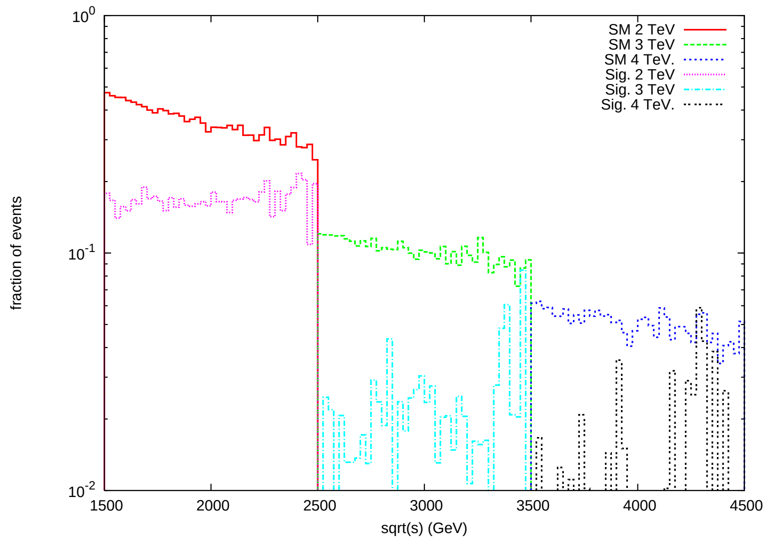
Collimation as a function of p_T

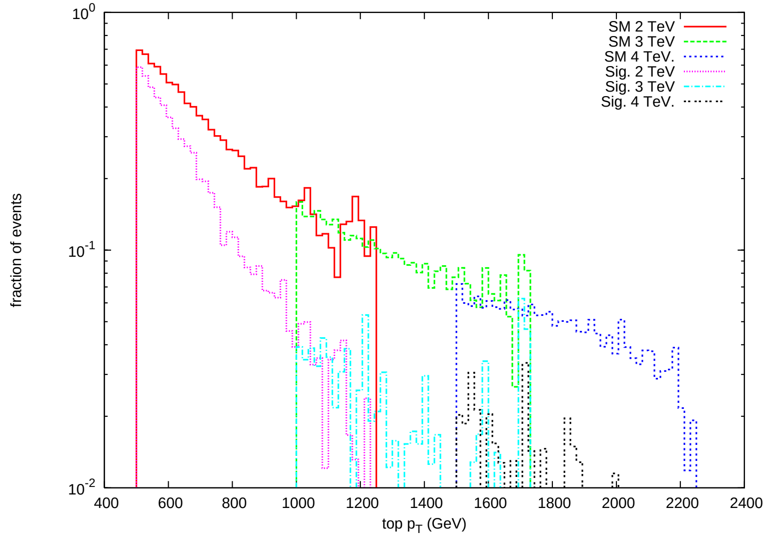




• p_T cut forces tops to be more central.

Lepton Isolation





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