Signatures of Toponium Formation in the LHC Run 2 Data

Ya-Juan Zheng
(University of Kansas)

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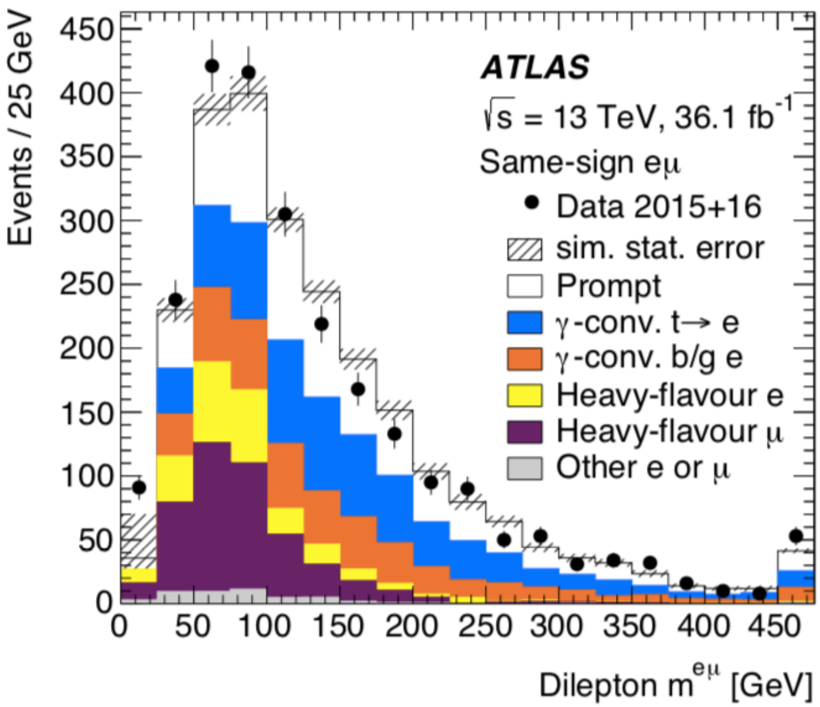
Based on Collaboration with Benjamin Fuks, Kaoru Hagiwara and Kai Ma. [arXiv:2102.11281]

Outline

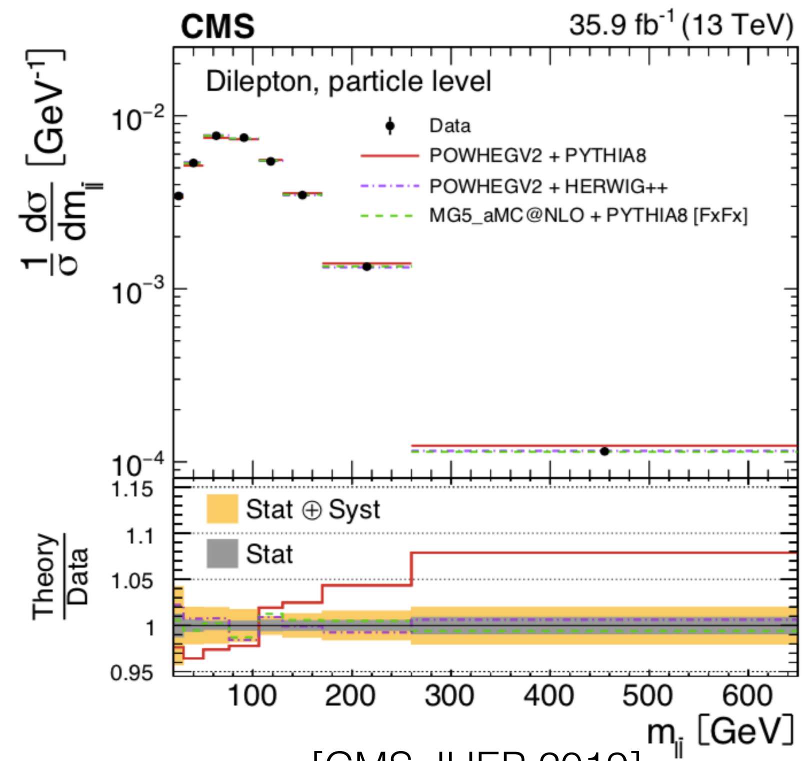
- Toponium
- Production of Toponium at the LHC
- Observables and Resconstruction

Top pair production at the LHC

- LHC is a top factory. With 140/fb of integrated luminosity, we expect about 100 million events and 5 million are di-leptonic ones.



[ATLAS EPJC2020]



[CMS JHEP 2019]

- Both ATLAS and CMS observed excess of Data over the 'SM' prediction at low m(ll') bins.
  - ★ This may suggest that tt production near the threshold is underestimated in the 'SM' prediction
  - ★ Could it be a signal of toponium formation below the tt threshold?

Heavy Quarkonium

	spin triplet (J=1)	spin singlet (J=0)
cc (charmonium)	J/ψ, $\psi(2S)$	η_c
bb (bottomonium)	Υ,$\Upsilon(2S)$,$\Upsilon(3S)$, $\Upsilon(4S)$,$\Upsilon(5S)$	η_b, $\eta_b(2S)$
tt (toponium)	θ_t	η_t
e+e- (positronium)	**ortho-positronium** $^3S_1$ -> $\gamma\gamma\gamma$ (C=−)	**para-positronium** $^1S_0$ -> $\gamma\gamma$ (C=+)

Toponium: Color singlet bound state of top&anti-top quark

J=1 Spin triplet θ_t

J=0 Spin singlet η_t

$$\vec{S}=\vec{S}_q+\vec{S}_{\bar{q}} \qquad s_z=s_{q,z}+s_{\bar{q},z}$$

Symmetric (s,s_z)

2s+1=3 spin triplet

$\uparrow\uparrow$ (1,1)

$\frac{\uparrow\downarrow+\downarrow\uparrow}{\sqrt{2}}$ (1,0)

$\downarrow\downarrow$ (1,-1)

anti-Symmetric (s,s_z)

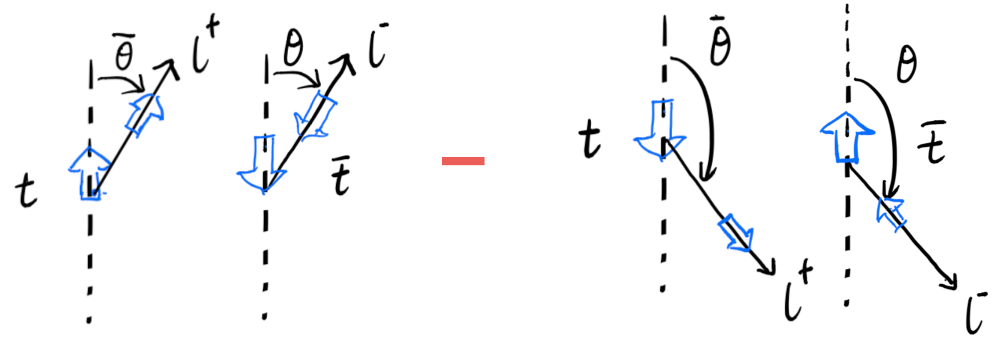
$\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}$ (0,0)

2s+1=1 spin singlet

t and t spin polarisation in $J^{PC}=0^{-+}$ toponium η_t

$$|\eta_t\rangle = \frac{|\uparrow\rangle_t\,|\downarrow\rangle_{\bar t} - |\downarrow\rangle_t\,|\uparrow\rangle_{\bar t}}{\sqrt{2}}$$

$\mathcal{M}$: η_t



$|\mathcal{M}|^2$:

$$\left(\cos\frac{\bar\theta}{2}\cos\frac{\theta}{2}\right)^2 = \frac{1+\cos\bar\theta}{2}\,\frac{1+\cos\theta}{2} = 1 \qquad \text{when } \theta=\bar\theta=0$$

$$\left(\sin\frac{\bar\theta}{2}\sin\frac{\theta}{2}\right)^2 = \frac{1-\cos\bar\theta}{2}\,\frac{1-\cos\theta}{2} = 1 \qquad \text{when } \theta=\bar\theta=\pi$$

$$+\,2\left(\cos\frac{\bar\theta}{2}\cos\frac{\theta}{2}\right)\left(\sin\frac{\bar\theta}{2}\sin\frac{\theta}{2}\right)\cos(\bar\phi-\phi) = \frac{1}{2}\sin\bar\theta\sin\theta\cos(\bar\phi-\phi) = \frac{1}{2} \qquad \text{when } \theta=\bar\theta=\frac{\pi}{2},\ \bar\phi-\phi=0$$

$l^-\uparrow\uparrow l^+$

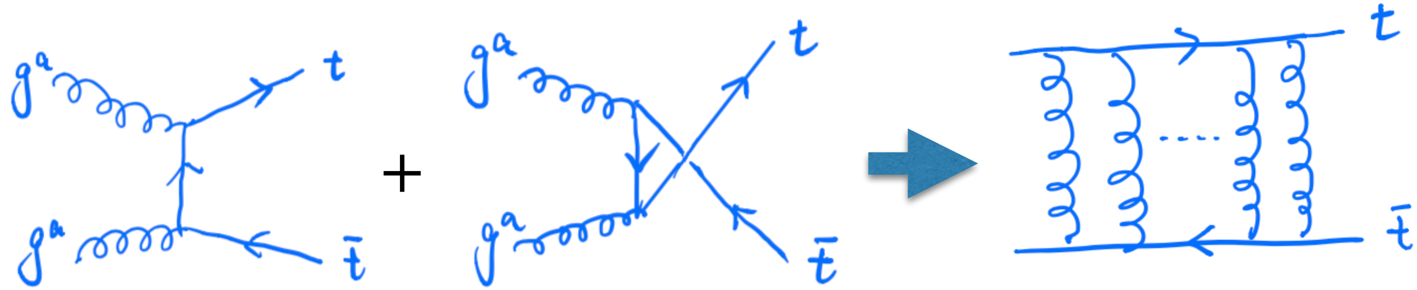
$l^-\downarrow\downarrow l^+$

$l^-\leftarrow$
$l^+\leftarrow$

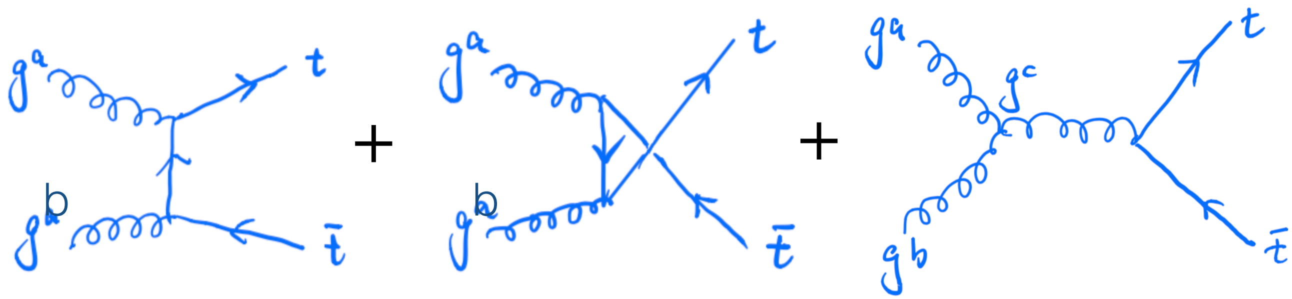
Appendix A in [Kaoru Hagiwara, Hiroshi Yokoya, and YJZ, JHEP2018]

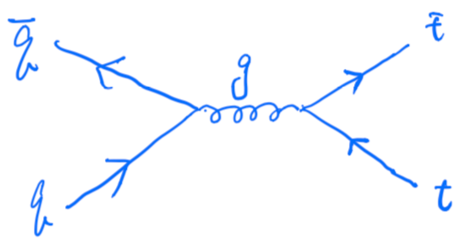
Production at Colliders

- tt in color singlet



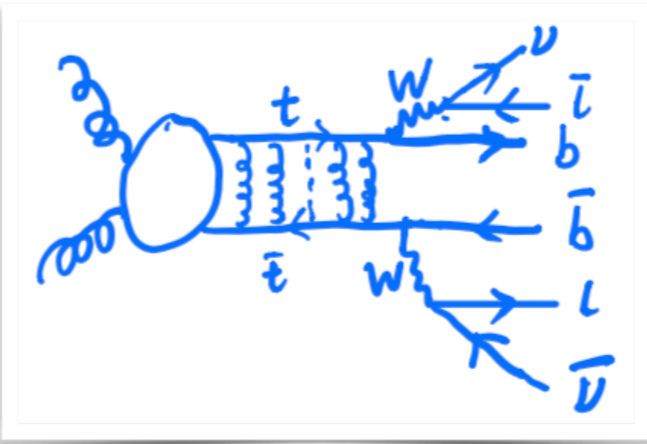
- tt in color octet





dominates in Tevatron

Simplified model for η_t production and decay at the LHC



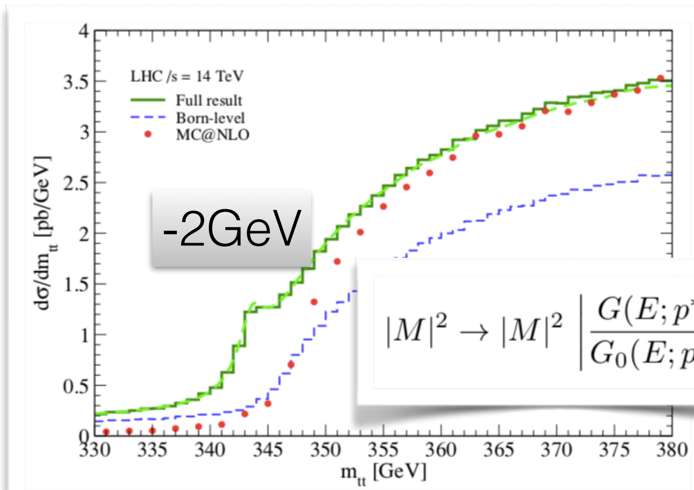
$$\mathcal{L}_{\eta_t} = \frac{1}{2}\partial_\mu \phi_{\eta_t}\partial^\mu \phi_{\eta_t} - \frac{1}{2} m_{\eta_t}\phi_{\eta_t}^2 - \frac{1}{4} g_{gg\eta_t}\phi_{\eta_t} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - i g_{tt\eta_t}\phi_{\eta_t}\bar{t}\gamma_5 t$$

$$M_{\sigma,\bar{\sigma}} = M\Big(\eta_t \to t(p,\sigma/2)\ \bar{t}(\bar{p},\bar{\sigma}/2)\Big)$$

$$\rho^{\eta_t}_{\sigma\bar{\sigma};\sigma'\bar{\sigma}'} = \frac{M_{\sigma\bar{\sigma}} M^*_{\sigma'\bar{\sigma}'}}{\sum_{\sigma\bar{\sigma}} |M_{\sigma\bar{\sigma}}|^2}$$

* Multiple gluon exchange effects are evaluated by using Green's function of the non-relativistic Hamiltonian with Coulomb potential. [V.S.Fadin and V.A.Khoze (JETP1987) (Sov.J.Nucl.Phys1988)]

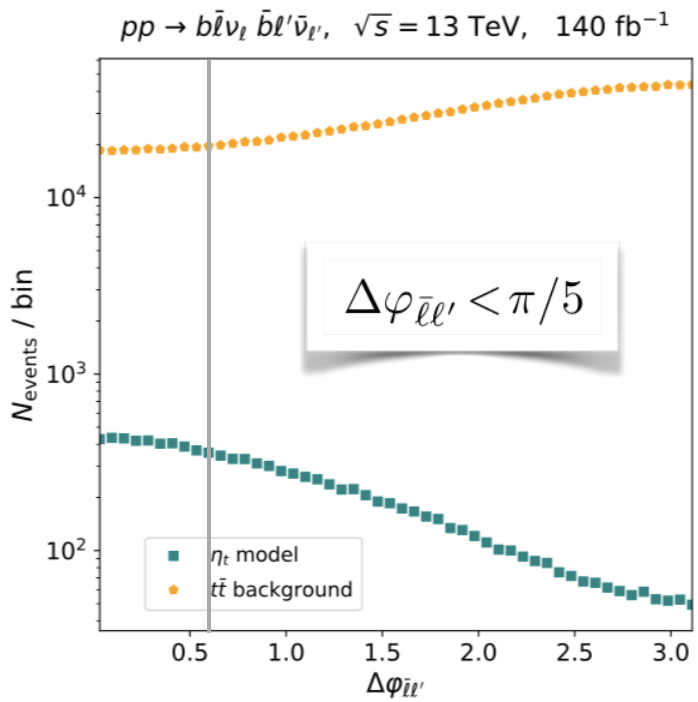
$\sqrt{s}$	$\sigma(\eta_t)$ [pb]	$\sigma(t\bar{t})$ [pb]	Ratio
7 TeV	1.55	172	0.0090
8 TeV	2.19	246	0.0089
13 TeV	6.43	810	0.0079
14 TeV	7.54	954	0.0079

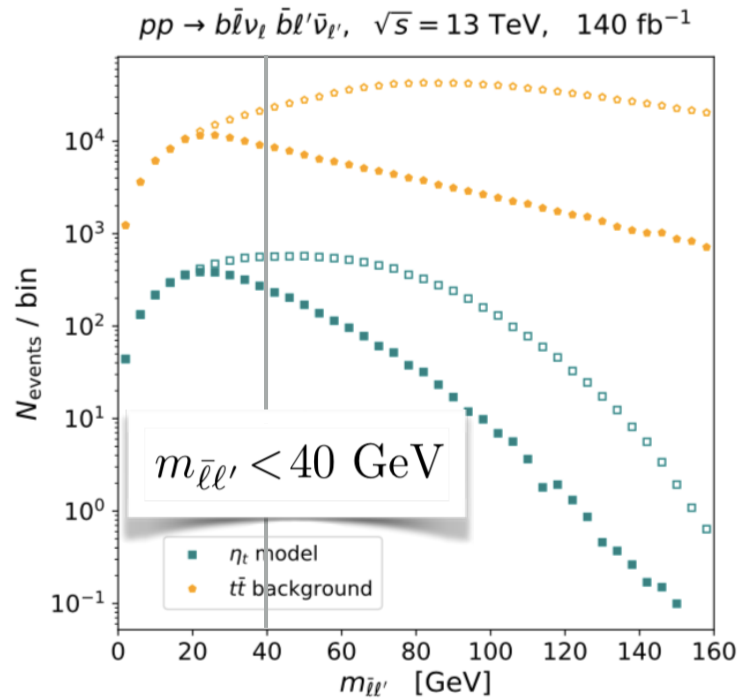


$$|M|^2 \to |M|^2 \left|\frac{G(E;p^*)}{G_0(E;p^*)}\right|^2$$

[Yukinari Sumino and Hiroshi Yokoya, JHEP2010]

Distributions





Cut	$t\bar{t}$	Toponium	Ratio
Initial	113,000,000	900,000	0.0079
Di-lepton	5,160,000	41,000	0.0079
$p_T, \lvert\eta\rvert, \Delta R$	1,450,000	10,300	0.0071
$\Delta\varphi_{\bar{\ell}\ell'}$	189,000	4,060	0.021
$m_{\bar{\ell}\ell'}$	82,000	2,760	0.033
$m_T(\bar{\ell}\ell' b\bar{b}; \nu_\ell\bar{\nu}_{\ell'})$	43,300	2,460	0.057
$t\bar{t}$ kinematical fit	21,700	1,420	0.066

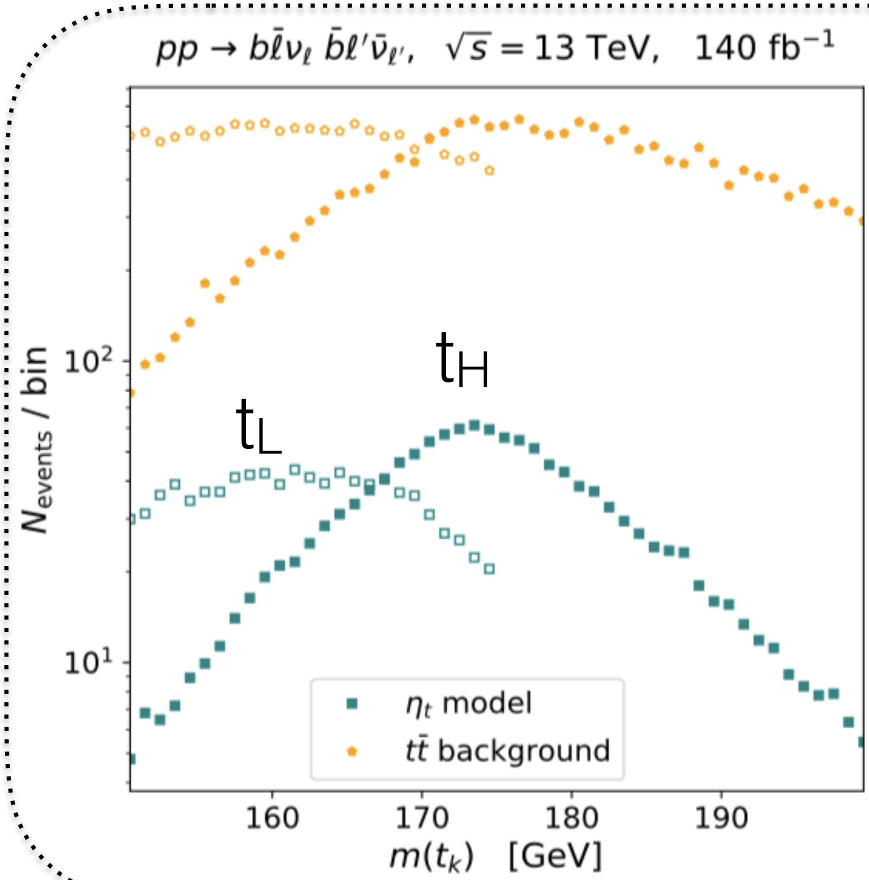
$p_T > 25$ GeV

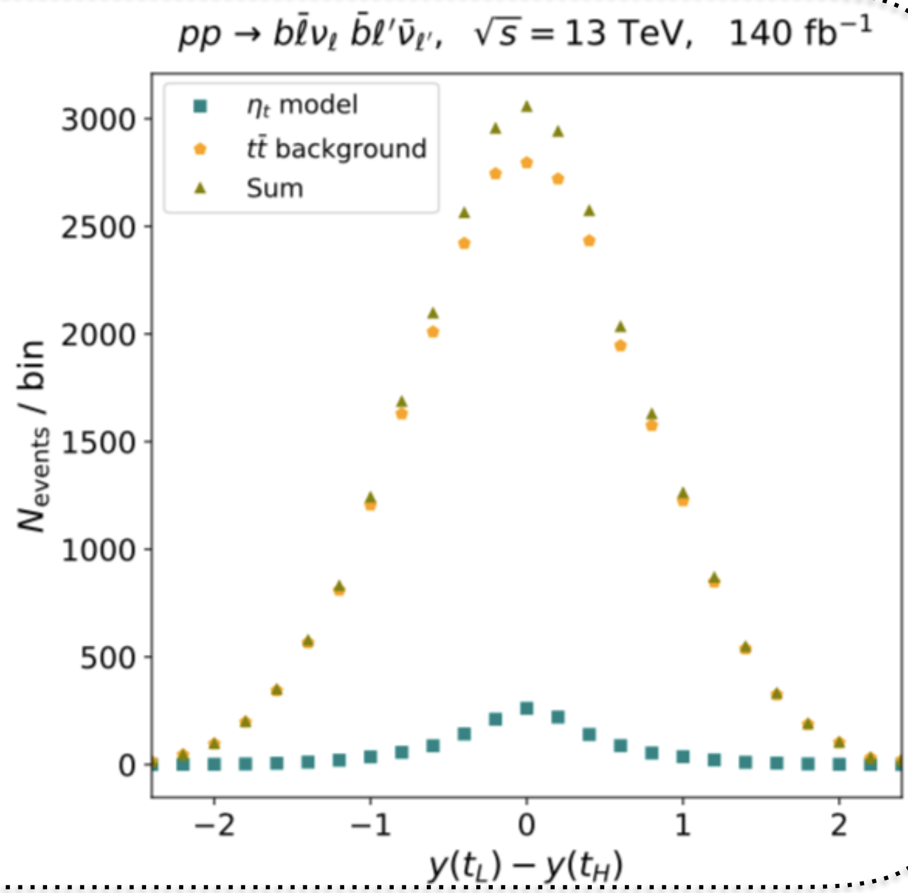
$\lvert\eta\rvert < 2.5$

$\Delta R > 0.4$

$m_T(\bar{\ell}\ell' b\bar{b}; \nu_\ell\bar{\nu}_{\ell'}) < 320$ GeV

kinematical reconstruction of t and t





t and $\bar{t}$ can be reconstructed since the t and $\bar{t}$ momentum p in the $t\bar{t}$ rest frame is small ($\lesssim$ 20 GeV). By assuming $\vec{p}_t^{\,T} = \vec{p}_{\bar{t}}^{\,T}$ for the selected events, we can reconstruct t and $\bar{t}$.

$|y_t - y_{\bar{t}}|$ should also be small for the toponium events.