Toponium at the LHC

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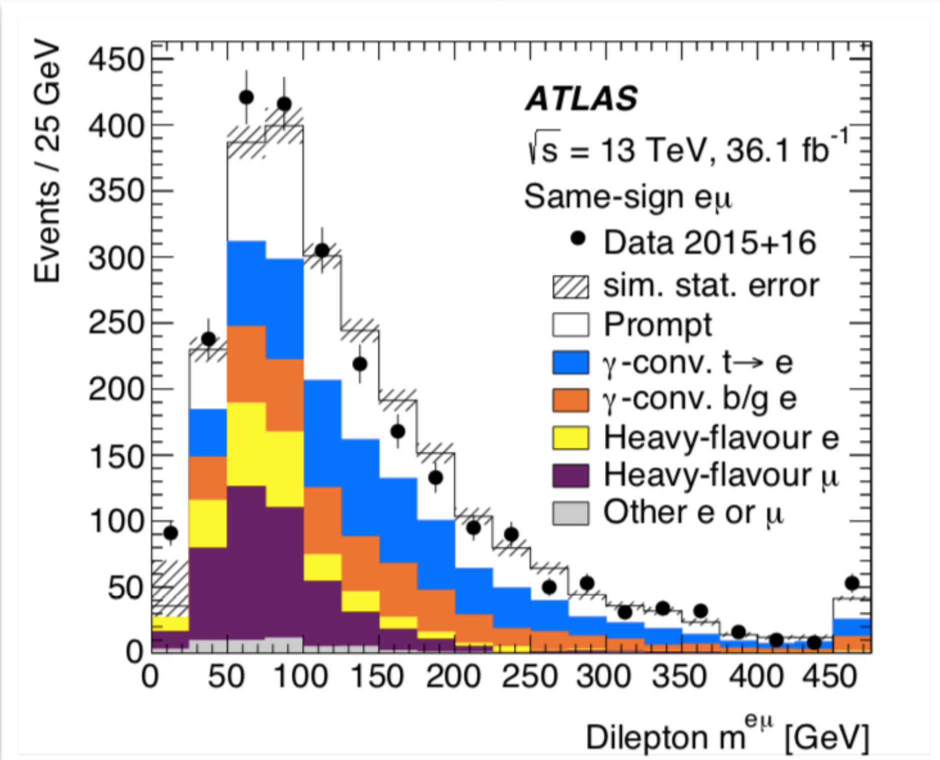
Based on collaboration with Benjamin Fuks, Kaoru Hagiwara and Kai Ma, PRD104,034023 [arXiv:2102.11281]
and work in progress

Outline

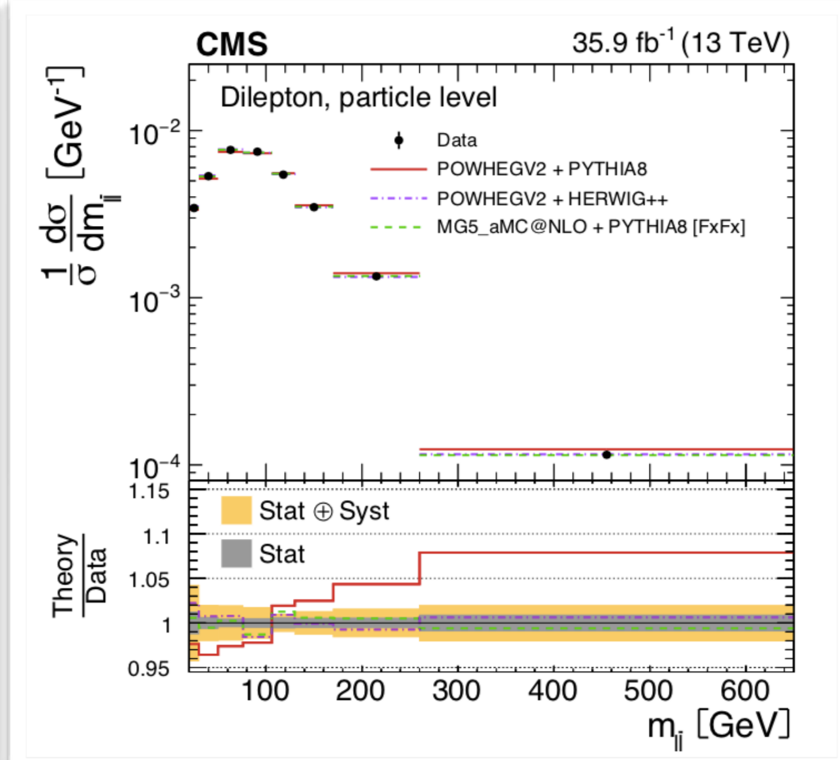
- Toponium
- Production of toponium at the LHC
- Reconstruction of t and $\bar{t}$
- Observables of toponium decay at the LHC

Top pair production at the LHC

- LHC is a top factory. At 13 TeV, with 140/fb of integrated luminosity, we expect about 100 million $t\bar{t}$ events and 5 million are dileptonic ones.



[ATLAS EPJC80,528(2020)]



[CMS JHEP02(2019)149]

- Both ATLAS and CMS observed excess of Data over the 'SM' simulation at low m(ll') bins.
  - This may suggest that tt production is underestimated in the 'SM' simulation at small m(ll').
  - Could it be the signal of toponium, which is missing in the present MC simulation?

Heavy quarkonium

	spin triplet (J=1)	spin singlet (J=0)
$c\bar{c}$ (charmonium)	J/ψ, $\psi(2S)$	η_c
$b\bar{b}$ (bottomonium)	Υ, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(5S)$	η_b, $\eta_b(2S)$
$t\bar{t}$ (toponium)	θ (C=–)	η_t (C=+)
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

$$\vec{S} = \vec{S}_t + \vec{S}_{\bar{t}} \qquad S_z = S_{t,z} + S_{\bar{t},z}$$

Symmetric (S, S_z)

2s+1=3

spin triplet

	Symmetric	(S, S_z)
	$\uparrow\uparrow$	(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

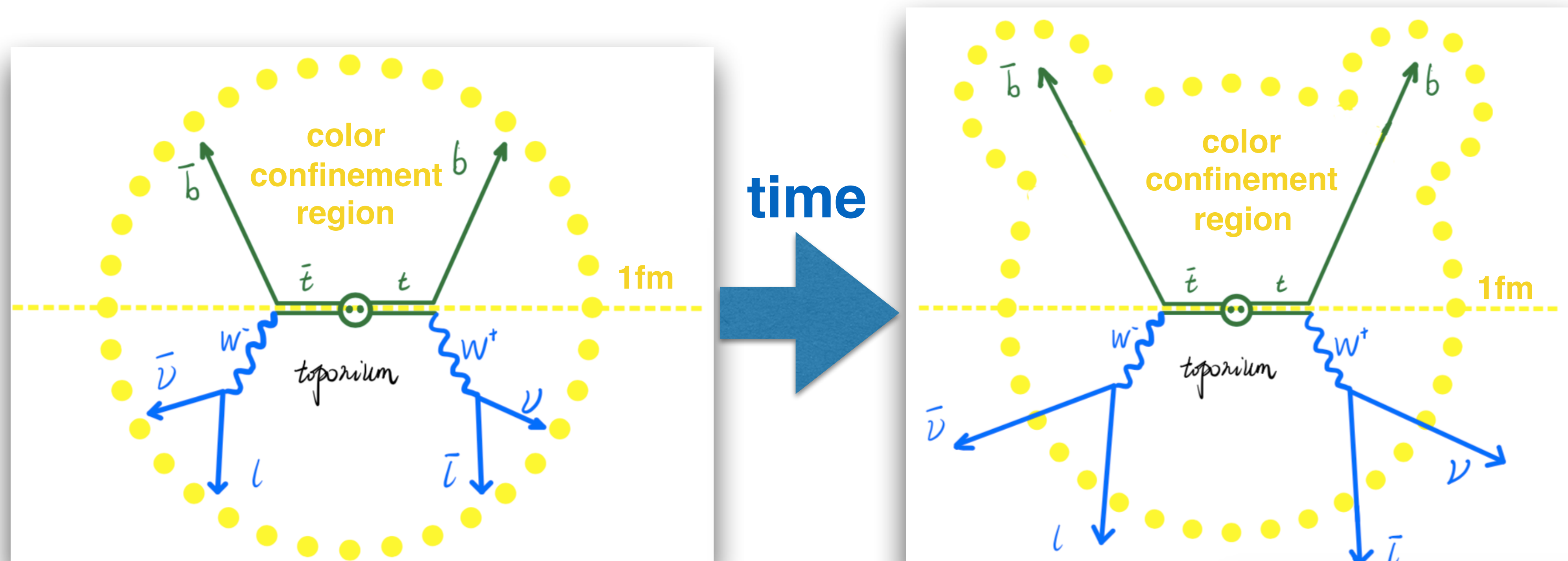
spin singlet

Space time evolution of toponium formation and decay

toponium formation	top decay	hadronization

$$\frac{1}{C_F \cdot \alpha_S \cdot m_t/2} \sim \frac{1}{20\mathrm{GeV}} \ll \frac{1}{\Gamma_t} \sim \frac{1}{1.5\mathrm{GeV}} \ll 1\mathrm{fm} \sim \frac{1}{0.2\mathrm{GeV}}$$

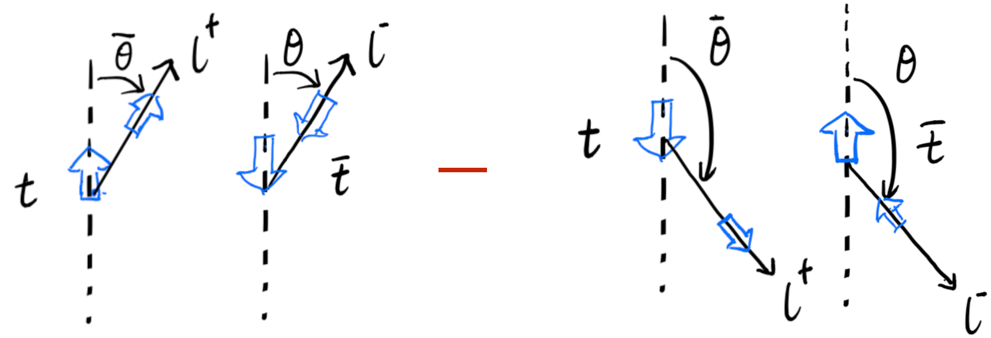
- ✦ Top quark decays before hadronization
- ✦ Toponium forms before top decay



t and $\bar{t}$ 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



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

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

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

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

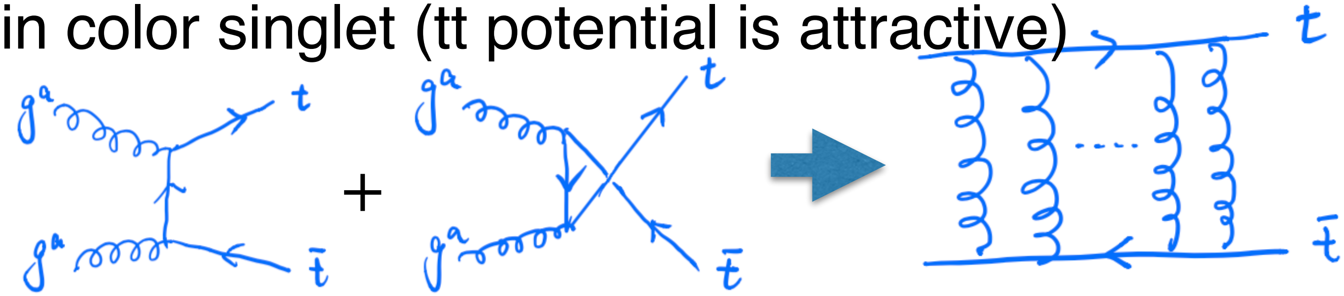
$l^-\uparrow\uparrow l^+$ | $l^-\downarrow\downarrow l^+$ | $l^-\leftarrow$, $l^+\leftarrow$

$m^2_{ll}=(p_1+p_2)^2=2E_1E_2(1-\cos\theta_{12})$ tend to be small

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

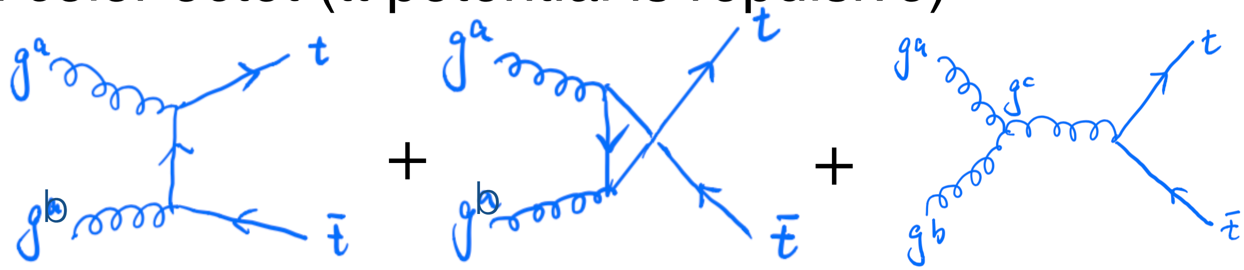
Toponium production at hadron colliders

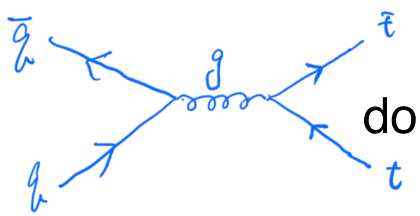
- $t\bar{t}$ in color singlet (tt potential is attractive)



Toponium

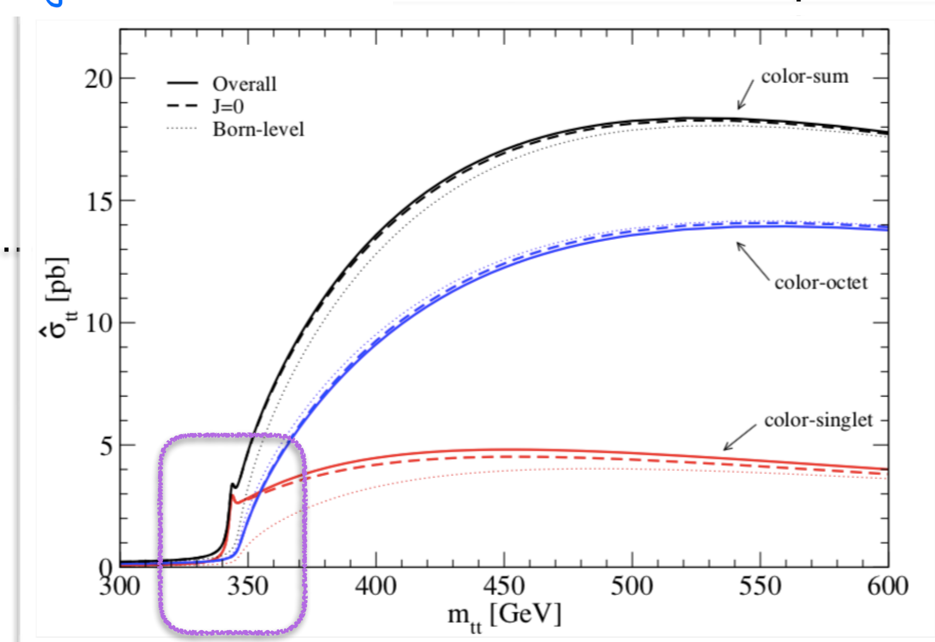
- $t\bar{t}$ in color octet (tt potential is repulsive)





dominates in Tevatron

- ✤ The colour-singlet dominates at the threshold
  - the gg-singlet channel dominates
- ✤ The J=0 state dominates
  - L=S=0
- ✤ The toponium η_t couples to 2 gluons and tops



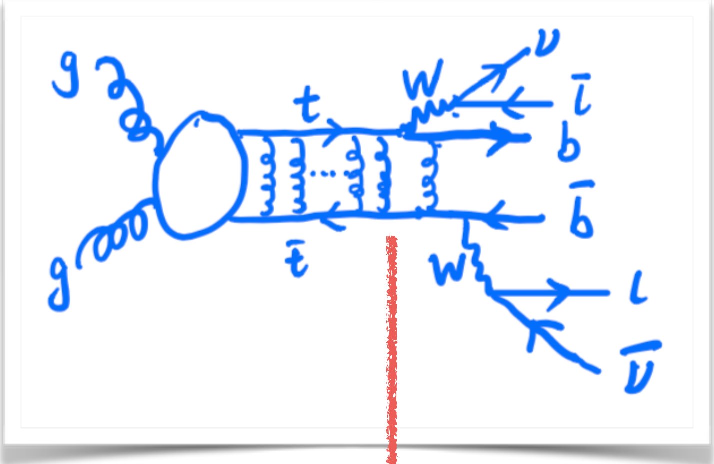
Y.Sumino and H.Yokoya. JHEP 2010

Toponium production cross section at the LHC

$\sqrt{s}$	$\sigma(\eta_t)$ [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

- Cross section of η_t at 7 and 14 TeV are from [Y. Sumino and H. Yokoya, JHEP2010]
- Cross section of tt from [M Czakon, P.Fiedler and A.Mitov PRL2013, M.Czakon, A. Ferroglia, D.Heymes, A.Mitov, B.Peciak, X.Wang, and L.Yang JHEP 2018]

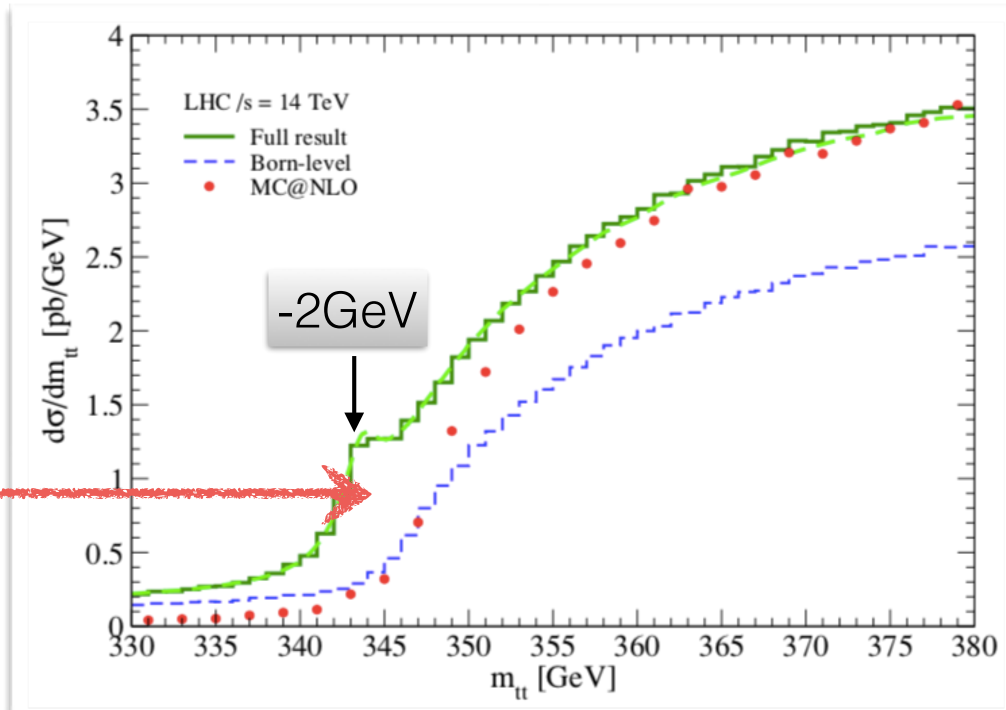
Near threshold



$$\left[(E+i\Gamma_t)-\left\{-\frac{\nabla^2}{m_t}+V_{\rm QCD}(r)\right\}\right]\tilde{G}(E+i\Gamma_t,\vec{r})=\delta^3(\vec{r})$$

$$G(E+i\Gamma_t,\vec{p})=\int d^3\vec{r}e^{-i\vec{p}\cdot\vec{r}}\tilde{G}(E+i\Gamma_t,\vec{r})$$

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



* 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)]

[Y.Sumino and H.Yokoya, JHEP2010]

6-body correlation in toponium (η_t) decay

$$
\begin{aligned}
& M(\eta_t \to t+\bar{t} \to b\bar{l}\nu + \bar{b}l\bar{\nu}) \\
&= \sum_{\sigma,\bar{\sigma}} M\left(\eta_t \to t(\sigma)+\bar{t}(\bar{\sigma})\right) M\left(t(\sigma) \to b\bar{l}\nu\right) M\left(t(\bar{\sigma}) \to \bar{b}l\bar{\nu}\right) \\
&= \sum M\left(t\bar{t}\right)_{\sigma,\bar{\sigma}} M\left(t\right)_{\sigma} M\left(\bar{t}\right)_{\bar{\sigma}}
\end{aligned}
$$

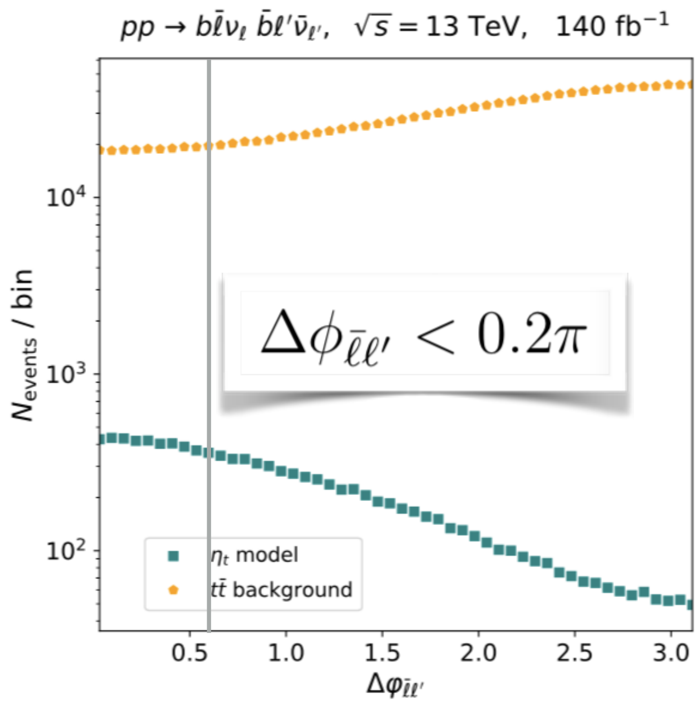
$$
\begin{aligned}
& \left|M(\eta_t \to t+\bar{t} \to b\bar{l}\nu + \bar{b}l\bar{\nu})\right|^2 \\
&= \left|\sum_{\sigma,\bar{\sigma}} M\left(t\bar{t}\right)_{\sigma,\bar{\sigma}} M\left(t\right)_{\sigma} M\left(\bar{t}\right)_{\bar{\sigma}}\right|^2 \\
&= \sum_{\sigma,\bar{\sigma},\sigma',\bar{\sigma}'} M\left(t\bar{t}\right)_{\sigma,\bar{\sigma}} M\left(t\right)_{\sigma} M\left(\bar{t}\right)_{\bar{\sigma}} M\left(t\bar{t}\right)^*_{\sigma',\bar{\sigma}'} M\left(t\right)^*_{\sigma'} M\left(\bar{t}\right)^*_{\bar{\sigma}'} \\
&= \sum_{\sigma,\bar{\sigma},\sigma',\bar{\sigma}'} M\left(t\bar{t}\right)_{\sigma,\bar{\sigma}} M\left(t\bar{t}\right)^*_{\sigma',\bar{\sigma}'} M\left(t\right)_{\sigma} M\left(t\right)^*_{\sigma'} M\left(\bar{t}\right)_{\bar{\sigma}} M\left(\bar{t}\right)^*_{\bar{\sigma}'} \\
&= \sum_{\sigma,\bar{\sigma},\sigma',\bar{\sigma}'} \rho(\eta_t \to t\bar{t})_{\sigma,\bar{\sigma},\sigma',\bar{\sigma}'} \rho(t \to b\bar{l}\nu)_{\sigma,\sigma'} \rho(\bar{t} \to \bar{b}l\bar{\nu})_{\bar{\sigma},\bar{\sigma}'}
\end{aligned}
$$

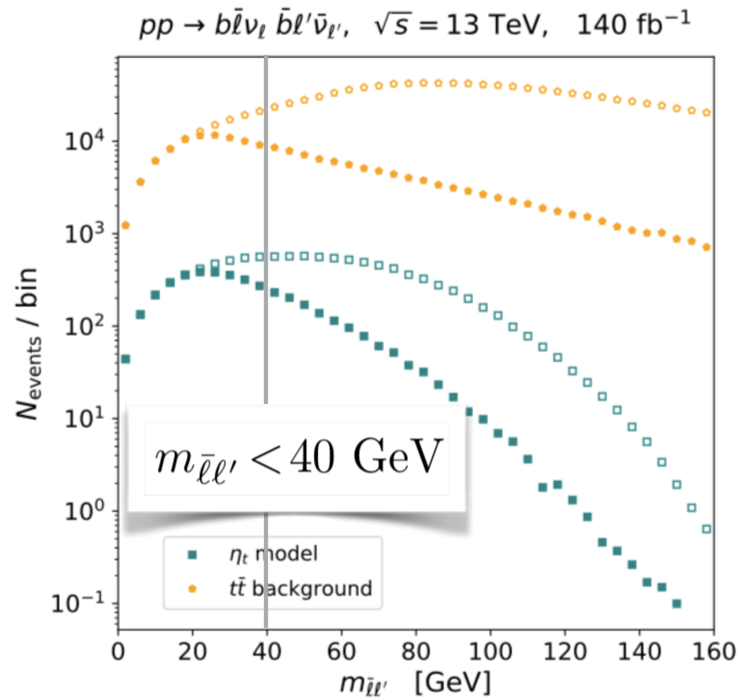
The above correlation can be reproduced by a pseudo-scalar η_t model:

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

We are now preparing $t\bar{t}$ MC event generator with QCD Green's function.

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, $\lvert\eta\rvert$, ΔR	1,370,000	10,300	0.0075
$\Delta\varphi_{\bar{\ell}\ell'}$	178,000	4,060	0.023
$m_{\bar{\ell}\ell'}$	77,000	2,760	0.036
$m_T(\bar{\ell}\ell' b\bar{b}; \nu_\ell\bar{\nu}_{\ell'})$	40,800	2,460	0.060
$t\bar{t}$ kinematical fit	20,400	1,420	0.070

$\sqrt{s} = 13$ TeV

140 fb^{-1}

$m_t = 173.3$ GeV

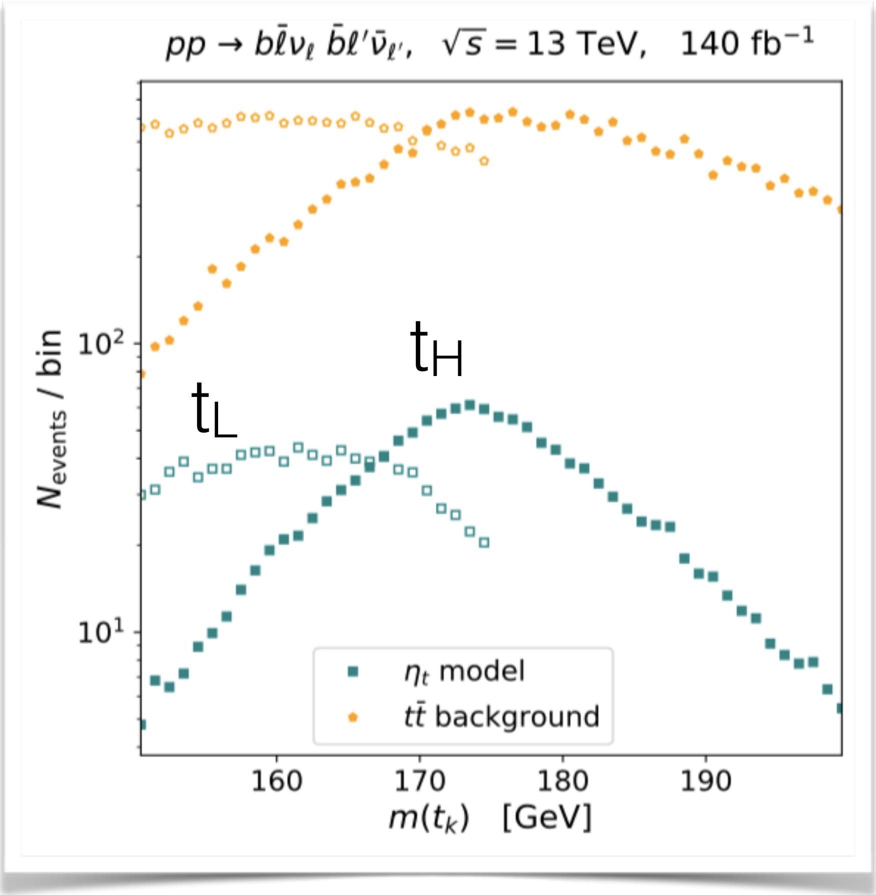
$p_T > 25$ GeV

$\lvert\eta\rvert < 2.5$

$\Delta R > 0.4$

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

kinematical reconstruction of t and $\bar{t}$

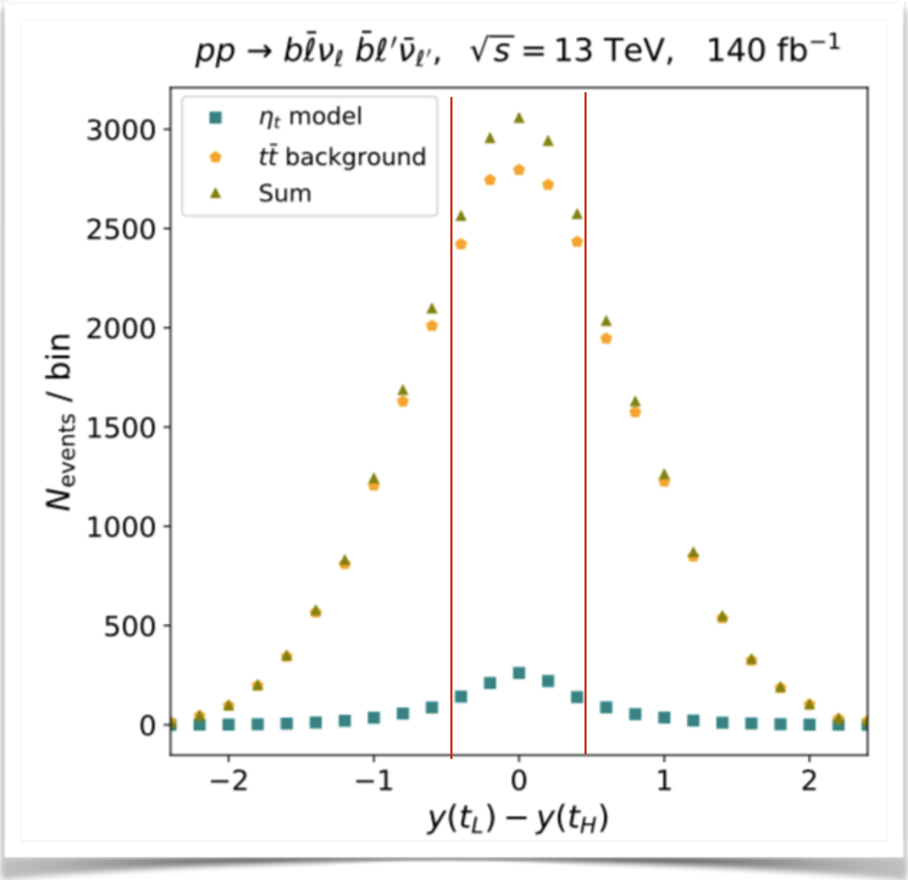


2 neutrinos

- 8 variables (4-mom.)
- -2 from neutrino mass
- -2 from W mass
- -2 from top mass
- -2 assuming $\vec{p}_t^{\,T} = \vec{p}_{\bar{t}}^{\,T}$

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 $\bar{t}$.

Prediction



It tells that t and $\bar{t}$ have similar momentum in the pp collision frame.

toponium

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

- Toponium contribution can enhance S/N by 10% near $|\Delta y|=0$.