

Toponium phenomenology at the LHC

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[With K. Hagiwara, K. Ma & Y. Zheng — 2102.11281 [hep-ph]]

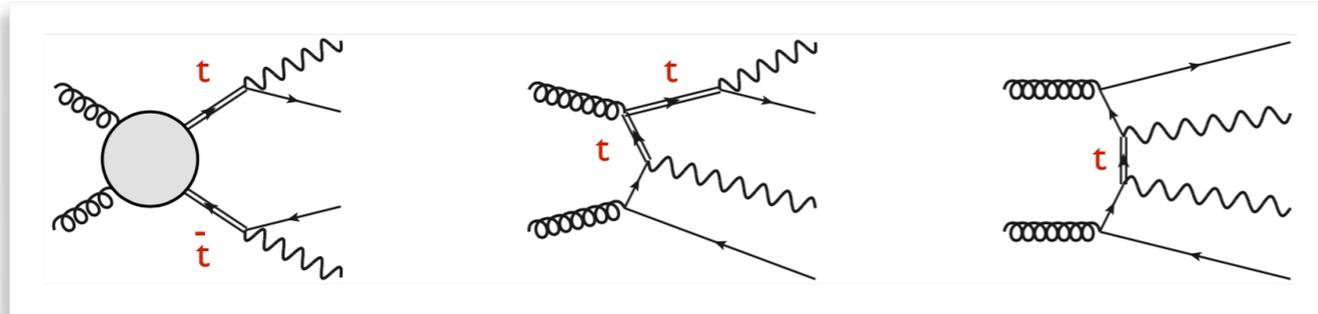
Top LHC France

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Top pair production at the LHC

- ◆ Copious top quark production at the LHC [$\sigma(13 \text{ TeV}) \sim 810 \text{ pb}$]
 - ♣ Detailed analysis of the top properties possible (mass, width, etc.)
- ◆ Could bound-state effects significant near threshold be observed?

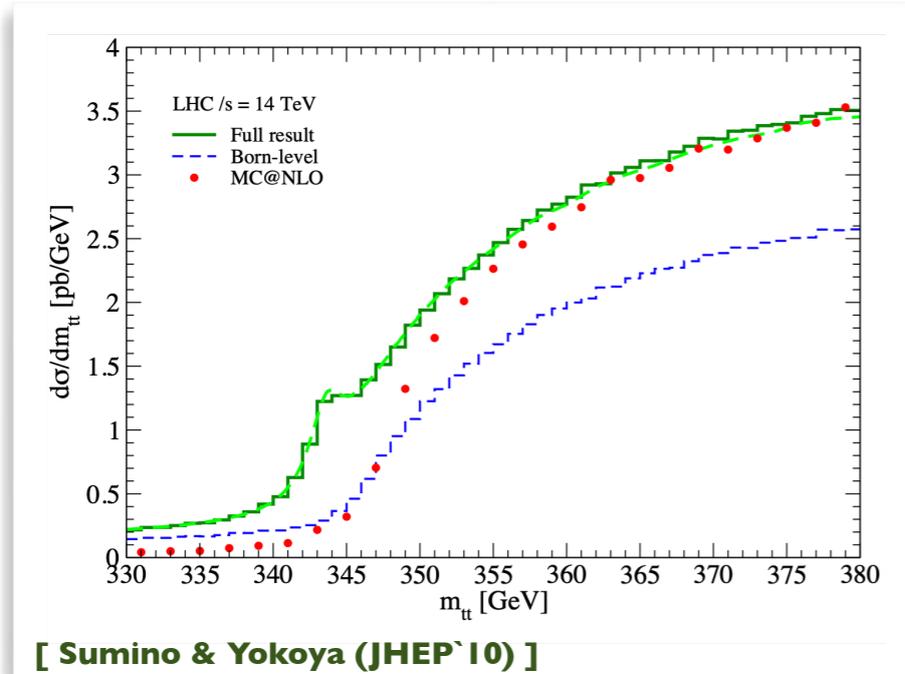
- ◆ Incorporating bound state effects in theory predictions
 - ♣ Close to threshold, the non-relativistic approximation is valid ($\beta \ll 1$)
 - ♣ Resummation of the Coulomb singularities
 - \sim gluon exchanges between slowly-moving top quarks \equiv bound-state effects
 - ♣ Predictions in the NRPQCD framework (Non-Relativistic Potential QCD)
- ◆ $Wb Wb$ in the threshold regime (with 0, 1 or 2 possibly off-shell tops)



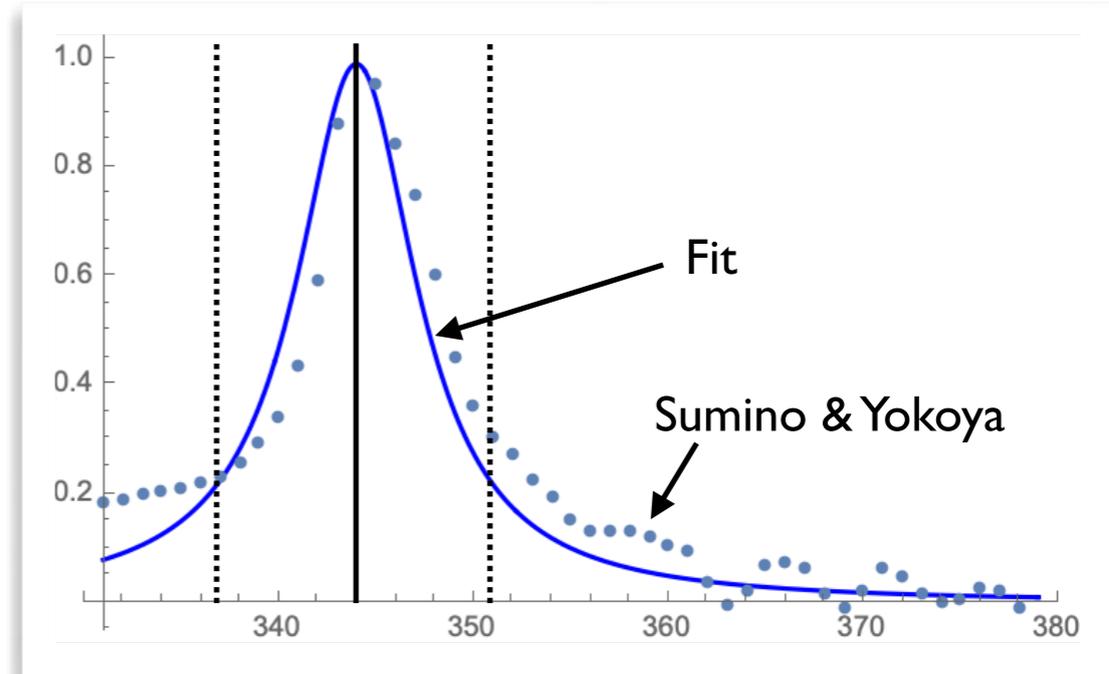
- ♣ First class of diagrams in the colour-singlet channel
 - ★ Below or slightly above threshold (one off-shell top quark)
 - ★ Binding energy \Leftrightarrow Coulomb gluon exchanges
 - \sim to be added to the perturbative treatment
 - \sim better top pair-production modelling

Towards a toponium simplified modelling

◆ The (tree-level) amplitude is enhanced close to threshold



green - red
⇒



❖ Full $WbWb$ differential distribution (green)

- ★ Bound-state effects
- ★ Finite top-width effects
- ★ NLO effects: ISR, differential K -factors

❖ NLO $WbWb$ differential distribution (red)

- ★ No bound-state effects

❖ Pure toponium contribution: “green - red”

❖ The $J=0$ state dominates $\sim L = S = 0 \sim J^{PC} = 0^{-+}$

Toponium signal:

$$pp \rightarrow \eta_t \rightarrow t^{(*)}\bar{t}^{(*)} \rightarrow W^+ b W^- \bar{b}$$

$$m_{\eta_t} = 344 \text{ GeV}; \quad \Gamma_{\eta_t} \approx 7 \text{ GeV}$$

$$\sigma(13 \text{ TeV}) \sim 6.5 \text{ pb}$$

A toponium toy model - ingredients

◆ A simplified toponium toy model: SM + gauge-singlet pseudo-scalar

♣ Dominant production via gluon-fusion \sim coupling to gluons

♣ Connection with the top quark \sim coupling to top quarks

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

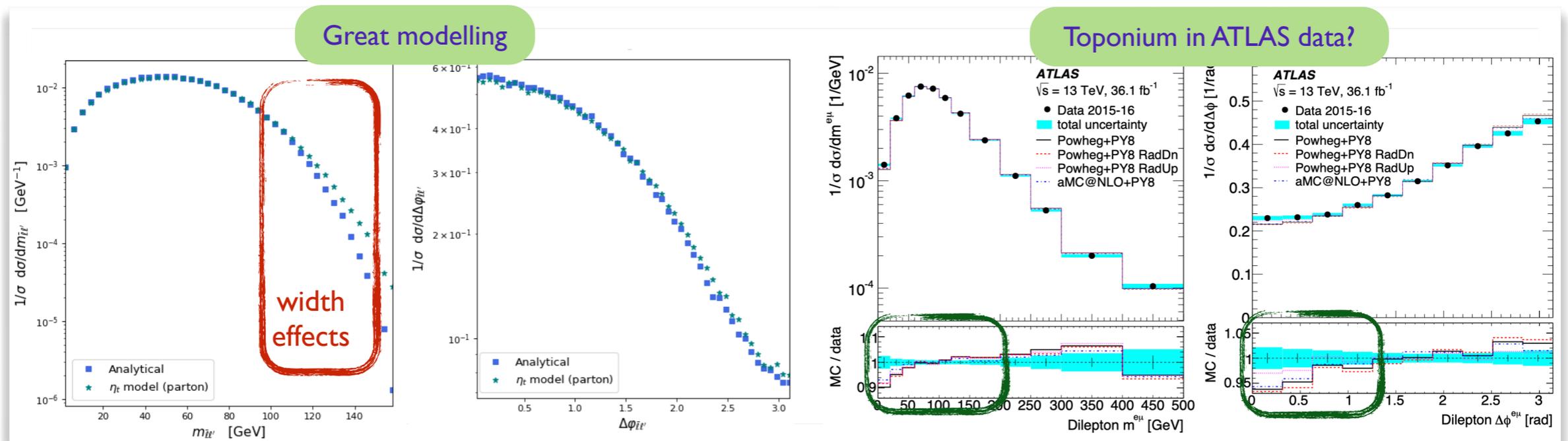
3 fixed parameters
[$m/\Gamma/\sigma$ known]

◆ MG5_aMC would generate events for all $m(WbWb)$ values

♣ Mandatory cut: signal in [338, 350] GeV

♣ Top momentum in the toponium rest frame off \sim re-weighting (NRPQCD)

◆ Does it work? Tests in the di-lepton channel



Towards toponium observation with di-leptons

◆ Final-state composition

♣ Two isolated leptons + two isolated b -jets ($p_T > 25$ GeV; $|\eta| < 2.5$; $\Delta R < 0.4$)

◆ ATLAS excess location \equiv bulk of the toponium events

♣ Small $\Delta\varphi_{\ell\ell}$ ($< \pi/5$), small $m_{\ell\ell}$ (< 40 GeV)

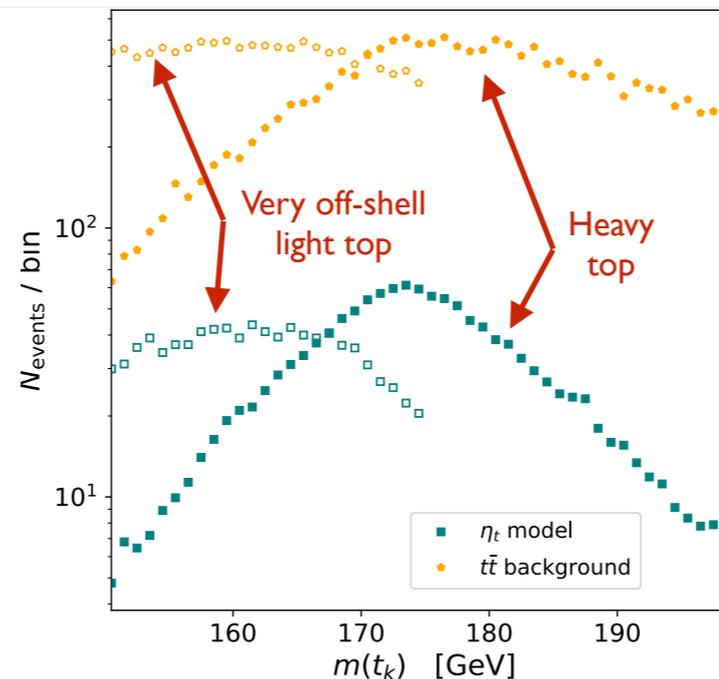
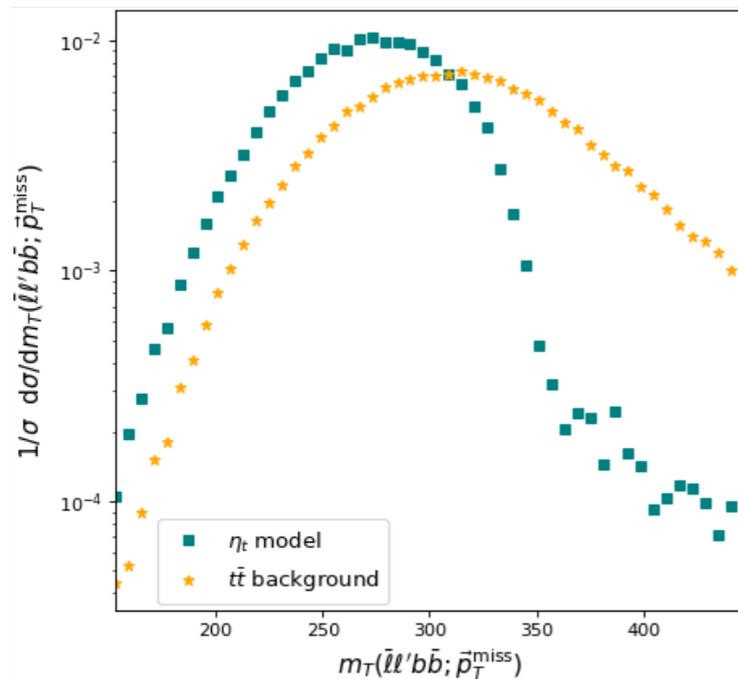
◆ Constraining the transverse mass of the $\bar{\ell}\ell' b\bar{b} + \cancel{E}_T$ system (< 320 GeV)

◆ Kinematical reconstruction of the toponium system (t_L/t_H): $\vec{p}_T(t) = \vec{p}_T(\bar{t})$

♣ Leptons: ℓ_1 is the leading lepton, ℓ_2 the sub-leading one

♣ b -jets: $m(\ell_1, b_1) > m(\ell_1, b_2)$

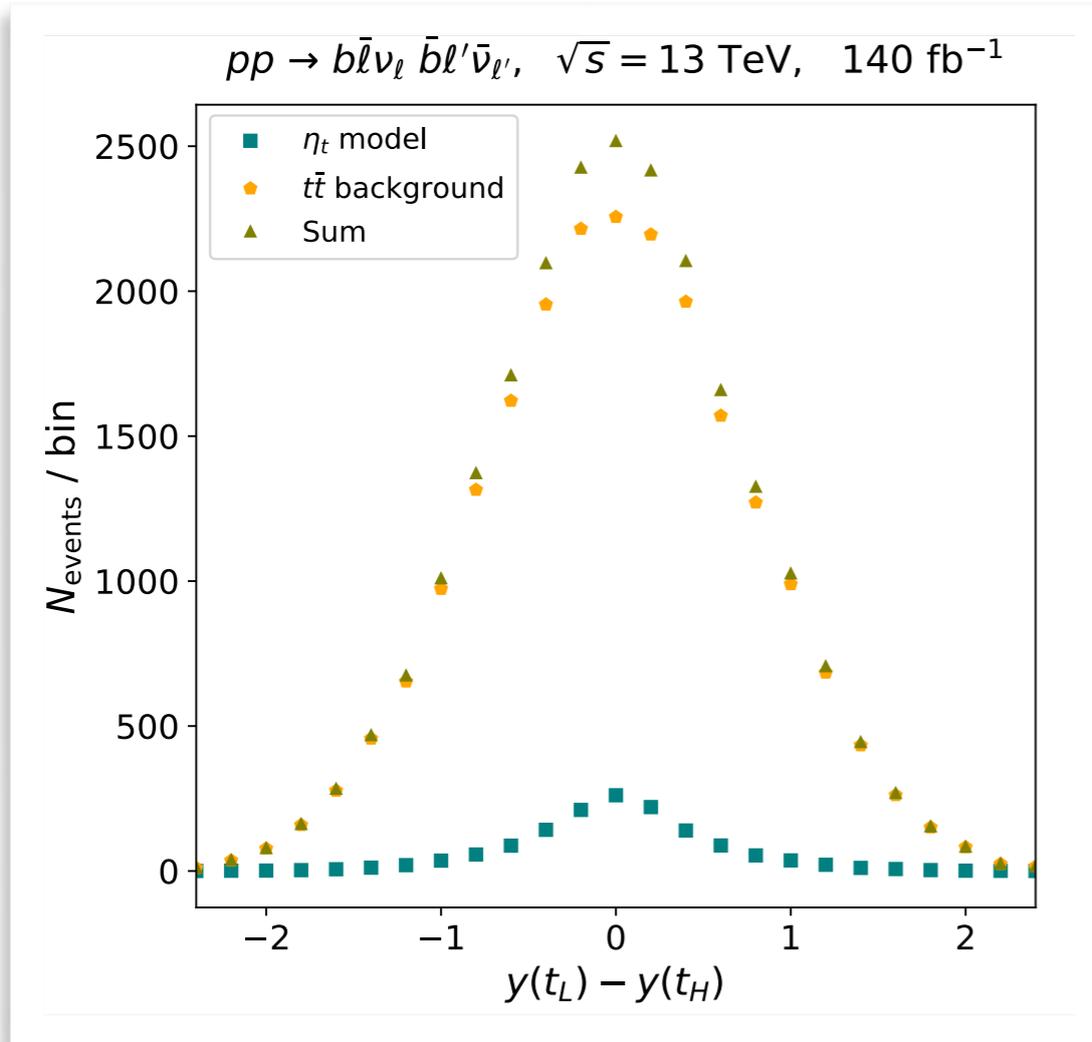
♣ Neutrinos: W reconstruction, 'top' reconstruction



13 TeV, 140/fb

Cut	$t\bar{t}$	Toponium	Ratio
Initial	113,000,000	900,000	0.0079
Di-lepton	1,450,000	10,300	0.0071
$\Delta\varphi_{\ell\ell'}$	189,000	4,060	0.021
$m_{\ell\ell'}$	82,800	2,760	0.033
$m_T(\bar{\ell}\ell' b\bar{b}; \nu_\ell \bar{\nu}_{\ell'})$	43,800	2,460	0.057
$t\bar{t}$ kinematical fit	21,700	1,420	0.066

Key observable for a discovery



◆ The rapidity difference distribution

✿ Peak at the origin

~ smaller t_L/t_H momentum in the toponium rest frame

★ t_L is the light reconstructed top

★ t_H is the heavy reconstructed top

Potential for a S/B ratio of 10%

Summary

◆ Close to threshold, bound state effects impact top pair-production

- ❖ Resummation of the Coulomb singularities $(\alpha_s/\beta)^n$ in the NRPQCD framework

◆ Investigation of the di-leptonic mode

- ❖ Toponium formation yields small $\Delta\varphi_{\ell\ell}$ and small $m_{\ell\ell}$ events
- ❖ Could tame excesses in ATLAS data
(that would be due to background mis-modelling)

◆ Towards a discovery

- ❖ The toponium system can be reconstructed (t_L/t_H)
- ❖ The rapidity difference between the tops could be a representative observable

◆ Outlook: investigation of the single-lepton channel

- ❖ Easier reconstruction of the toponium system (t_L/t_H)
- ❖ Access to the top momentum in the toponium rest frame