Toponium phenomenology at the LHC

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Top LHC working Group Meeting

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Outline

1. Towards a simplified model for toponium production

2. Toponium phenomenology at the LHC

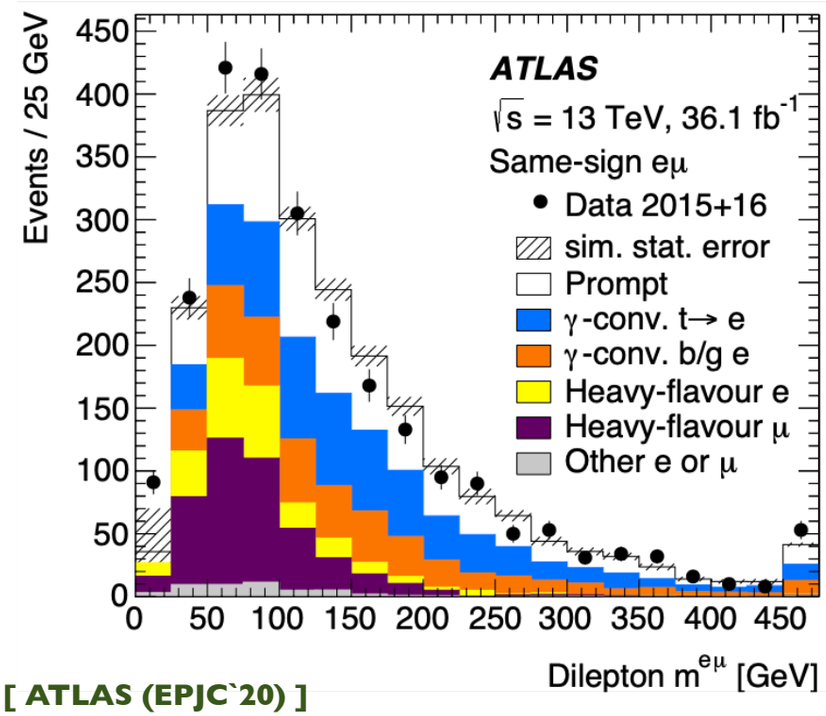
3. Summary

Top pair production at the LHC

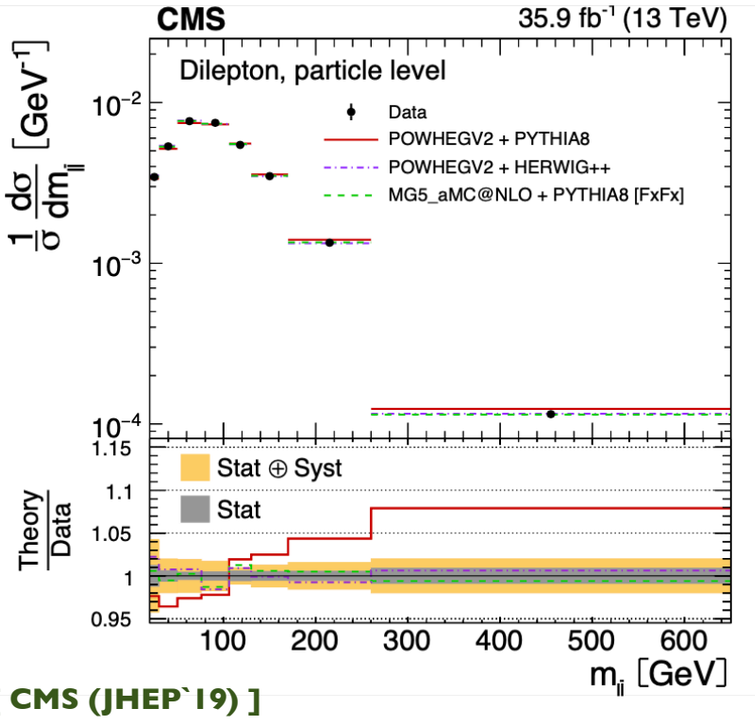
✦ Copious top quark production at the LHC [σ(13 TeV) ~ 810 pb]

✤ Detailed analysis of the top properties possible (mass, width, *etc.*)

✤ Many differential distributions precisely measurable



[ATLAS (EPJC`20)]



[CMS (JHEP`19)]

✦ Bound-state effects significant near threshold

✤ Especially as top pair-production is gluon-fusion dominated

✤ Could they be observed?

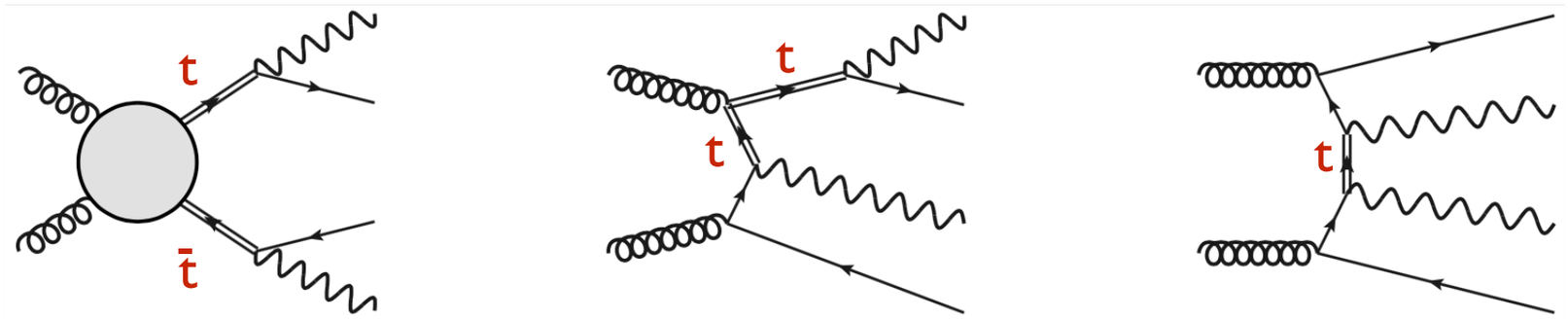
Close to threshold

✦ Incorporating bound state effects in theory predictions

- ✤ Close to threshold, the non-relativistic approximation is valid ($\beta \ll 1$)
- ✤ Resummation of the Coulomb singularities $\left(\alpha_s/\beta\right)^n$
  - ⇝ gluon exchanges between slowly-moving top quarks ≡ bound-state effects
- ✤ Predictions in the pNRQCD framework (Potential Non-Relativistic QCD)

✦ *Wb Wb* production in the threshold regime

- ✤ 3 classes of contributions with 0, 1 or 2 (possibly off-shell) tops



- ✤ Bound-state effects ⇝ first class of diagrams in the colour-singlet channel
  - ★ Below or slightly above threshold
  - ★ One off-shell top quark
  - ★ Binding energy ⇔ Coulomb gluon exchanges
    - ⇝ to be added to the perturbative treatment
    - ⇝ better top pair-production modelling

Top pair production with toponium effects

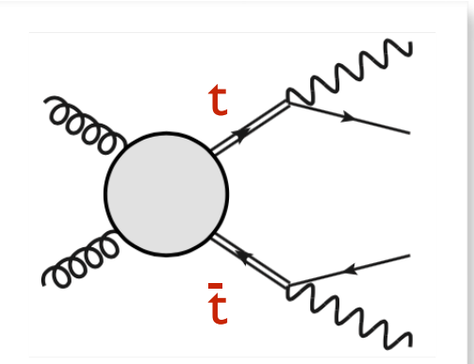
✦ The (tree-level) amplitude is enhanced close to threshold

✤ Involving non-relativistic Green's functions

$$i\mathcal{M}^{(c)} \to i\mathcal{M}^{(c)} \times \frac{G(E;p^*)}{G_0(E;p^*)}$$

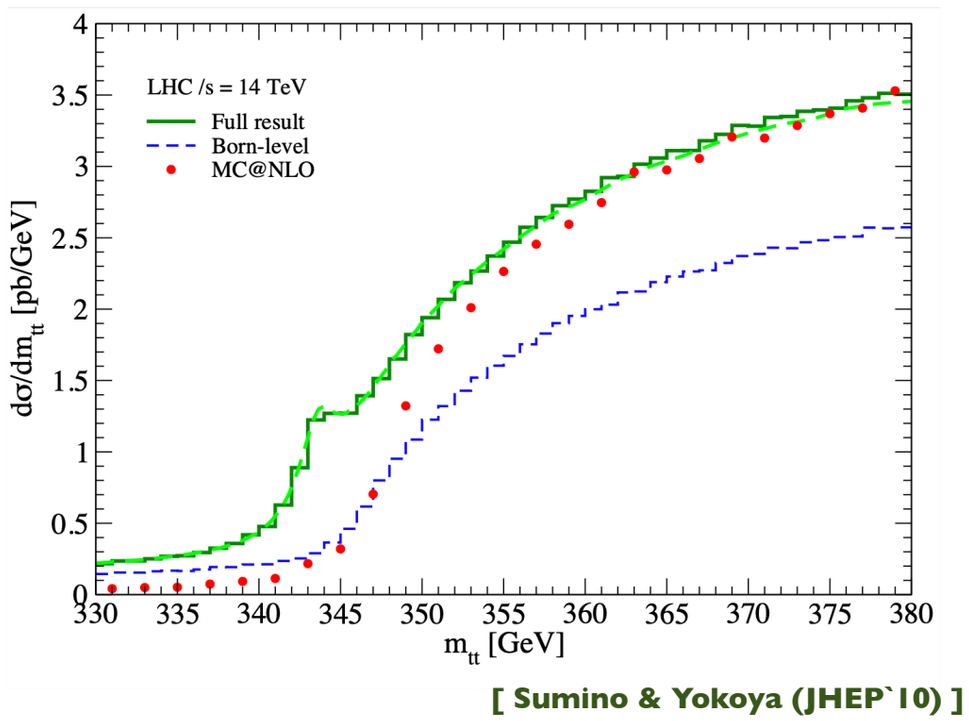
★ Ratio of Green's functions of the Hamiltonians with/without V_{QCD}

★ Different channels (*gg*/*qq*; ***1***/***8***)



[Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)]
[Jezabek, Kuhn & Teubner (Z.Phys.C`92)]

✦ Threshold enhancement



[Sumino & Yokoya (JHEP`10)]

✤ Full *WbWb* differential distribution (green)

★ Bound-state effects

★ Finite top-width effects

★ NLO effects: ISR, differential *K*-factors

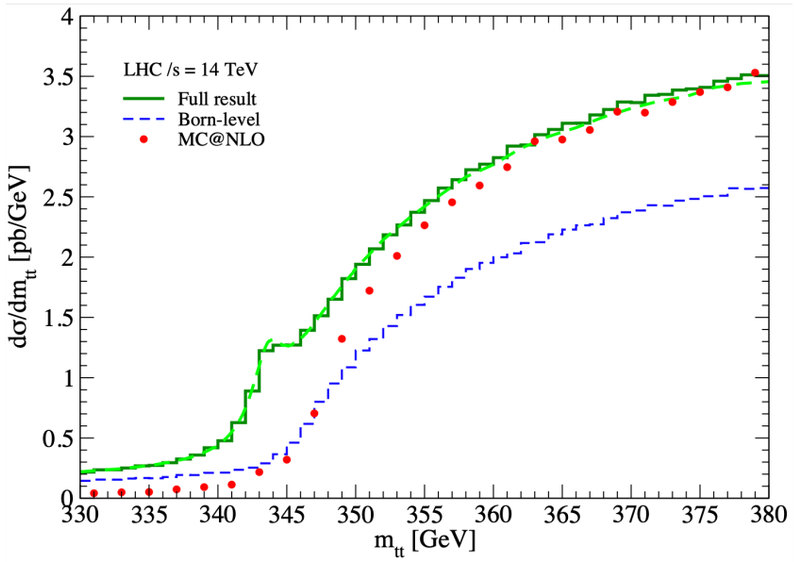
✤ NLO *WbWb* differential distribution (red)

★ No bound-state effects

✤ Pure toponium contribution: "green - red"

Towards a toponium simplified modelling (I)

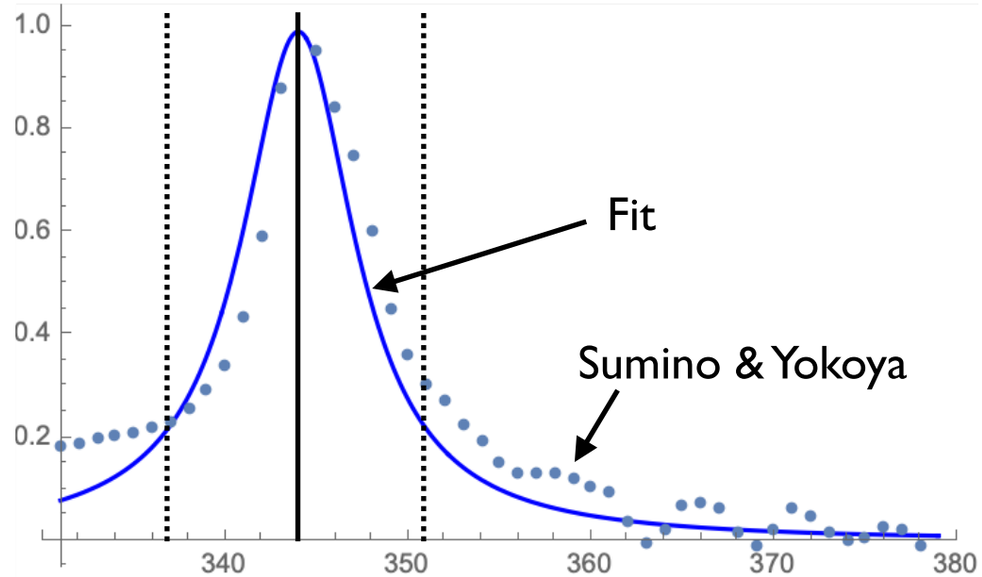
✦ Breit-Wigner modelling: a resonance of 344 GeV with a 7 GeV width



[Sumino & Yokoya (JHEP`10)]

green - red

⇒



Toponium signal:

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

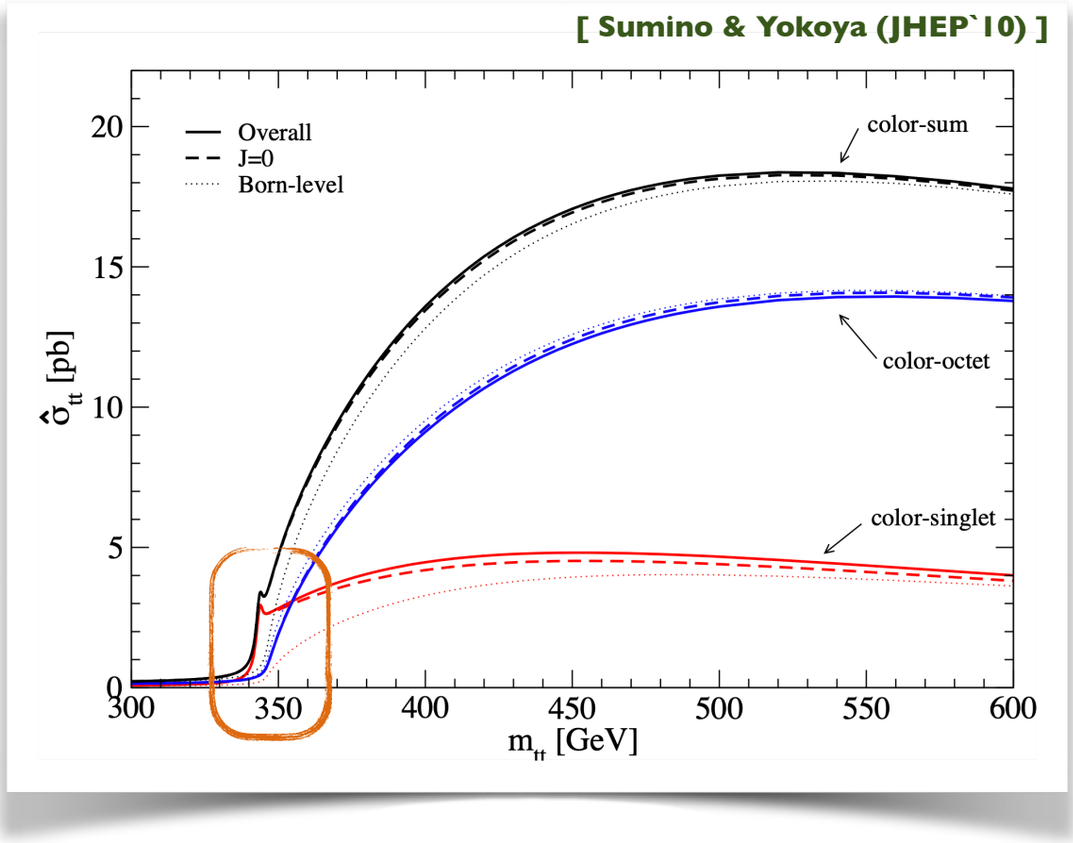
$$m_{\eta_t} = 344 \text{ GeV}; \quad \Gamma_{\eta_t} \approx 7 \text{ GeV}$$

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

Towards a toponium simplified modelling (2)

✦ Colour-singlet *versus* colour-octet; partonic process

[Sumino & Yokoya (JHEP`10)]



- The colour-singlet dominates at threshold
  - ⇝ the *gg-singlet* channel dominates
- The *J=0* state dominates
  - ⇝ *L = S = 0*

The toponium η_t couples to top quarks and gluons

A toponium toy model - ingredients

✦ Quantum numbers for the toponium state η_t

✤ Bound state of a top and anti-top system

★ Parity: $P(\eta_t) = P(t)\ P(\bar{t})\ (-1)^L$

★ Charge conjugation: $C(\eta_t) = (-1)^{L+S}$

✤ Ground state ($S = L = 0$) ⇒ $\eta_t \equiv J^{PC} = 0^{-+}$

★ The J=0 state is the only one that can be produced in the colour-singlet *gg* channel

✦ A simplified toponium toy model

✤ Standard Model + gauge-singlet pseudo-scalar

✤ Dominant production via gluon-fusion ⇝ coupling to gluons

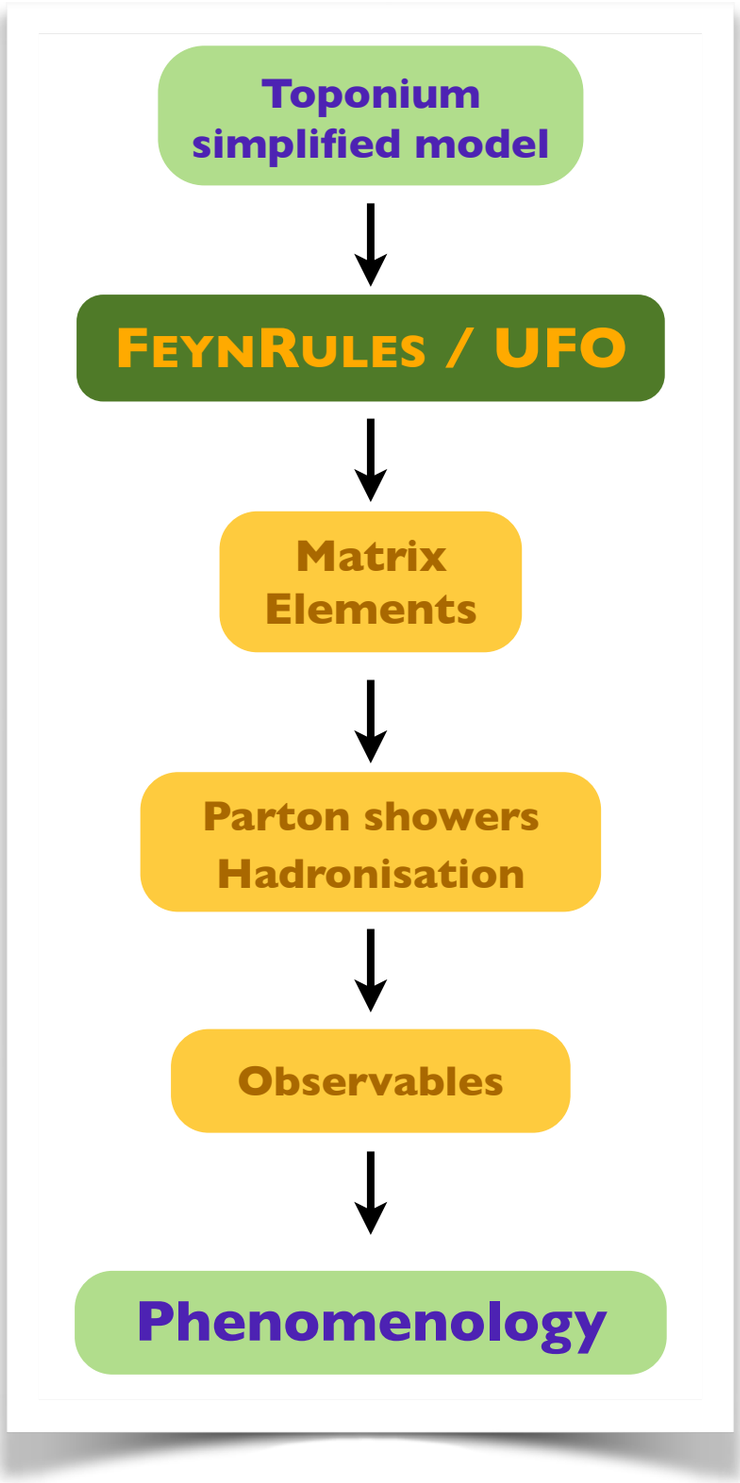
✤ Connection with the top quark ⇝ coupling to top quarks

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

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

A comprehensive approach to new physics simulations

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]



✦ Model building: from Lagrangian to tools

- ✤ FeynRules ⇝ UFO [Alloul, Christensen, Degrande, Duhr & BF (CPC'14)] [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]

✦ Hard scattering

- ✤ LO Feynman diagrams, matrix elements
- ✤ MadGraph5_aMC ⇝ collider signals [Alwall et al. (JHEP'14)]
- ✤ Comparison: model and analytical calculations

✦ QCD environment with Pythia 8.2

- ✤ Matching matrix elements with parton showers
- ✤ Hadronisation [Sjöstrand et al. (CPC'15)]

✦ Toponium phenomenology @ colliders

- ✤ Reconstruction (anti-k_T) with FastJet
- ✤ Analysis (cuts & plots) with MadAnalysis 5
- ✤ Towards a toponium discovery at the LHC

[Cacciari, Salam & Soyez (JHEP'08); Cacciari, Salam & Soyez (EPJC'12)]
[Conte, BF & Serret (CPC`12); Conte & BF (IJMPA`19); Araz, BF & Polykratis (EPJC`21)]

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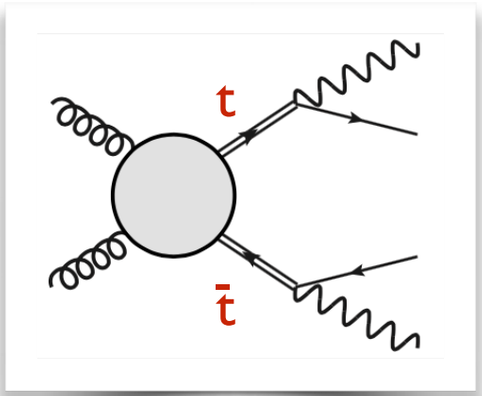
Necessary cuts on the signal

✦ MG5_aMC generates events for all *m(WbWb)* values



✤ The signal lies in [338, 350] GeV

⇝ extra cut to implement right after event generation

⇝ 63% events are lost

✤ Spectrum of the top momentum in the toponium rest frame

⇝ The distribution is off at a given binding energy

⇝ Re-weighting

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

Checks and main toponium characteristics

✦ Verification: we assume a di-leptonic toponium decay

- ✤ Check of a few observables
- ✤ Expectation from spin density matrices

$$\sum_{\sigma,\bar{\sigma},\sigma',\bar{\sigma}'} \rho^{\eta_t}_{\sigma\bar{\sigma};\sigma'\bar{\sigma}'}\ \rho^{t\to b\bar{\ell}\nu_\ell}_{\sigma,\sigma'}\ \rho^{\bar{t}\to\bar{b}\ell'\bar{\nu}_{\ell'}}_{\bar{\sigma},\bar{\sigma}'}$$

- ✤ Angular separation between the two leptons in the top/antitop rest frames

$$(1+\cos\bar{\theta})(1+\cos\theta)+(1-\cos\bar{\theta})(1-\cos\theta)+2\sin\bar{\theta}\sin\theta\cos(\bar{\varphi}-\varphi)$$

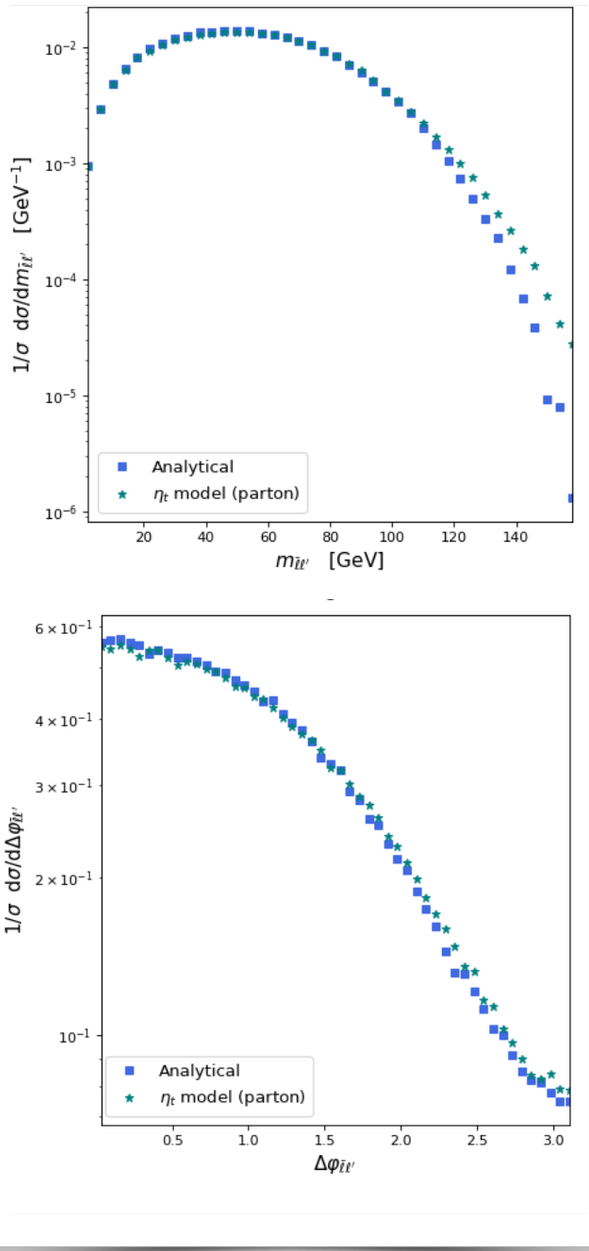
[Hagiwara, Yokoya & Zheng (JHEP'18)]

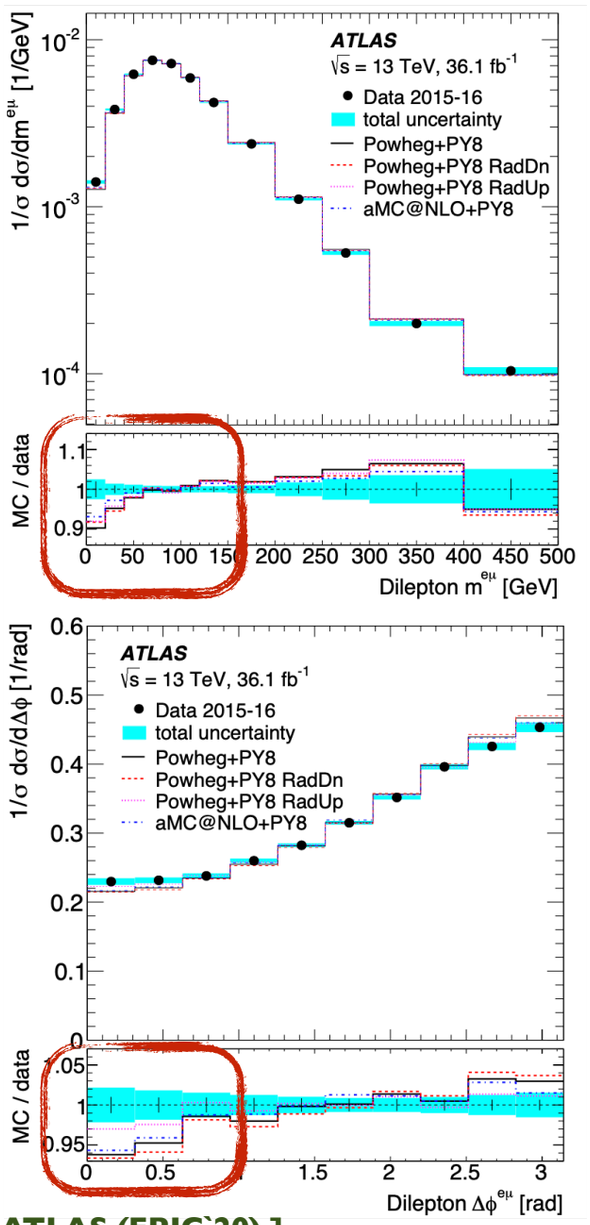
- ⇝ small azimuthal angle separation (survives the lab frame boost)
- ⇝ small di-lepton invariant mass (ignoring the binding energy):

$$m^2_{\bar{\ell}\ell'} = 2E_{\bar{\ell}}E_{\ell'}\left(1-\sin\bar{\theta}\sin\theta\cos(\bar{\varphi}-\varphi)-\cos\bar{\theta}\cos\theta\right)$$

- ✤ Toponium characteristic: small $m_{\ell\ell}$ and small $\Delta\varphi_{\ell\ell}$

Toponium decays in two leptons





[ATLAS (EPJC`20)]

✦ Modelling good enough

- ✤ Reproduction of the toponium properties
  - ★ At large m_{ll}: widths & b-mass effects
- ✤ Toponium formation could be present in ATLAS data
  - ★ At small $m_{\ell\ell}$
  - ★ At small $\Delta\varphi_{\ell\ell}$

How to confirm it?

$\sigma(\eta_t)$ [pb]	$\sigma(t\bar{t})$ [pb]	Ratio
6.43	810	0.0079

⇝ Proper analysis

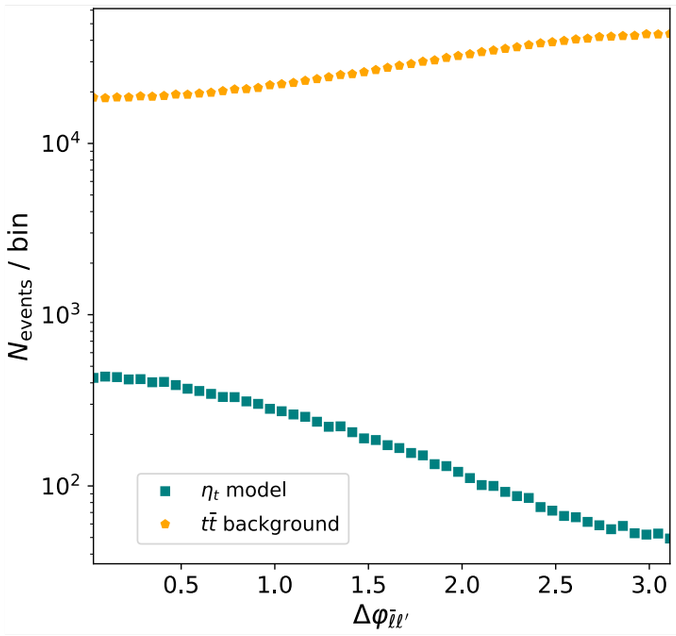
Towards toponium observation with di-leptons

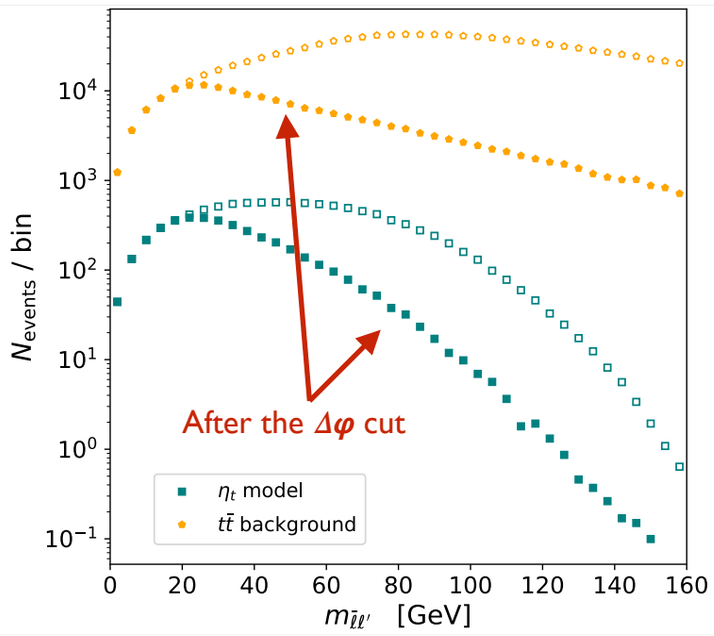
✦ Final-state composition

✤ Two isolated leptons + two isolated *b*-jets (p_T > 25 GeV; $|\eta|$ < 2.5; ΔR < 0.4)

✦ ATLAS excess location ≡ bulk of the toponium events

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





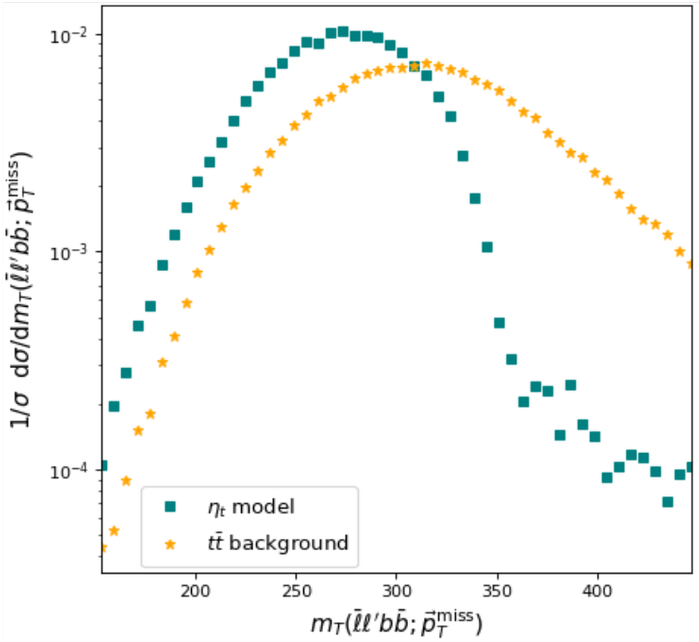
13 TeV, 140/fb

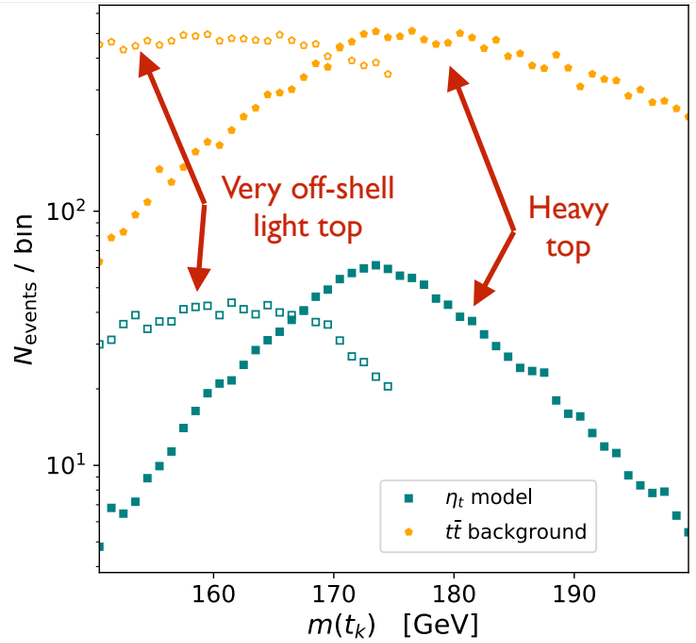
Cut	$t\bar{t}$	Toponium	Ratio
Initial	113,000,000	900,000	0.0079
Di-lepton	1,450,000	10,300	0.0071
$\Delta\varphi_{\bar{\ell}\ell'}$	189,000	4,060	0.021
$m_{\bar{\ell}\ell'}$	82,800	2,760	0.033

⇝ Further background rejection needed

Cornering toponium formation at the LHC

- Constraining the transverse mass of the $\bar{\ell}\ell' b\bar{b} + \not{E}_T$ system (<320 GeV)
- Kinematical reconstruction of the toponium system (t_L/t_H)
  - Assumption: $\vec{p}_T(t) = \vec{p}_T(\bar{t})$
  - Definition of the leptons: ℓ_1 is the leading lepton, ℓ_2 the sub-leading one
  - Definition of the *b*-jets: $m(\ell_1, b_1) > m(\ell_1, b_2)$
  - Definition of the neutrinos: *W* reconstruction, '*top*' reconstruction





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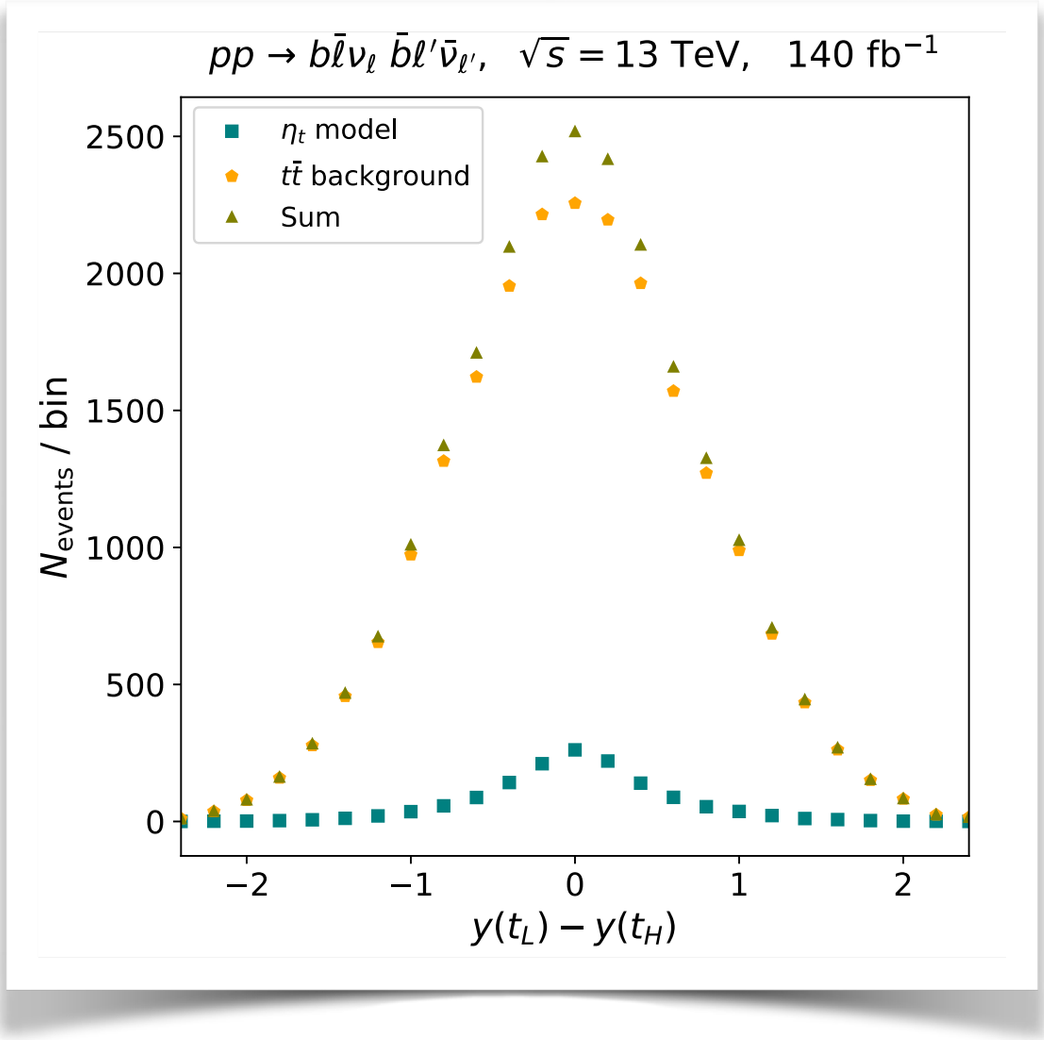
$\Delta\varphi_{\bar{\ell}\ell'}$	189,000	4,060	0.021
$m_{\bar{\ell}\ell'}$	82,800	2,760	0.033
$m_T(\bar{\ell}\ell' b\bar{b}; \nu_\ell\bar{\nu}_{\ell'})$	43,800	2,460	0.057
$t\bar{t}$ kinematical fit	21,700	1,420	0.066

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%

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Summary

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

✤ Resummation of the Coulomb singularities $(\alpha_s/\beta)^n$ in the pNRQCD 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