Signatures of toponium formation in LHC run 2 data

Benjamin Fuks

LPTHE / Sorbonne Université

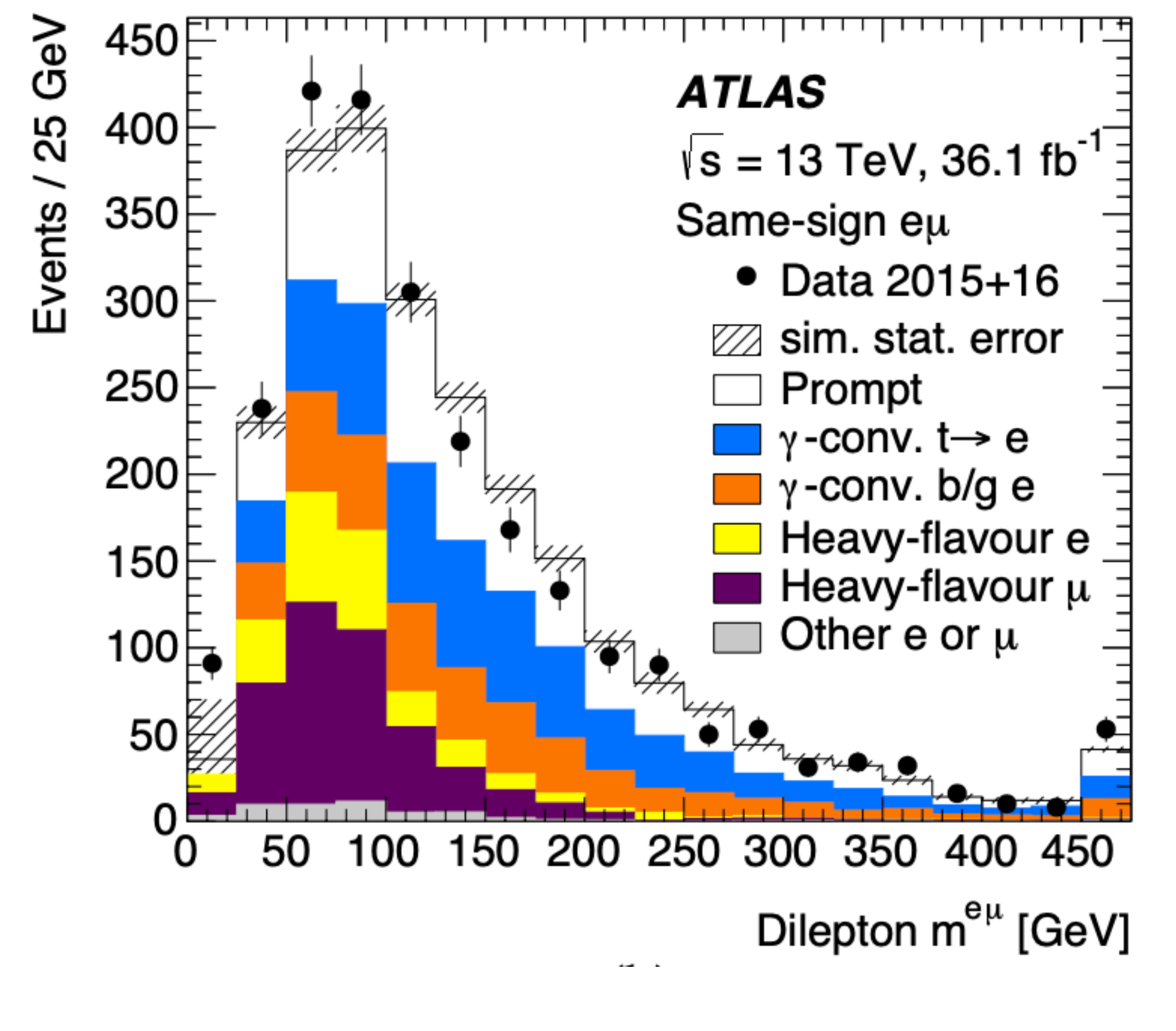
[In collaboration with Kaoru Hagiwara, Kai Ma & Ya-Juan Zhang: PRD 104 (2021) 034023]

High-energy physics seminar @ BCTP [Bonn, 09 October 2023]

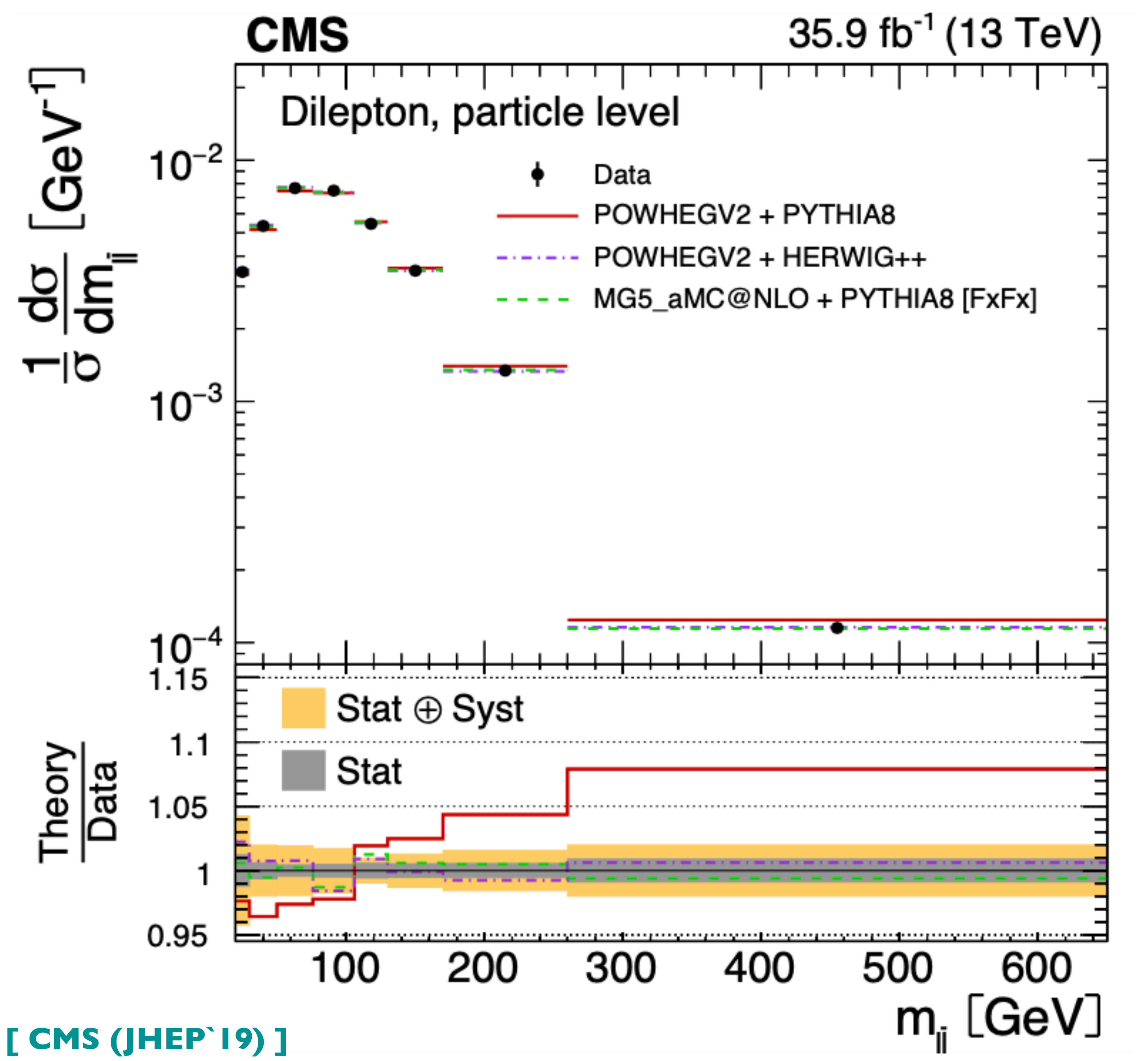
Top pair production at the LHC

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 (and measured)



[ATLAS (EPJC`20)]



[CMS (JHEP`19)]

Potential issues at low invariant masses

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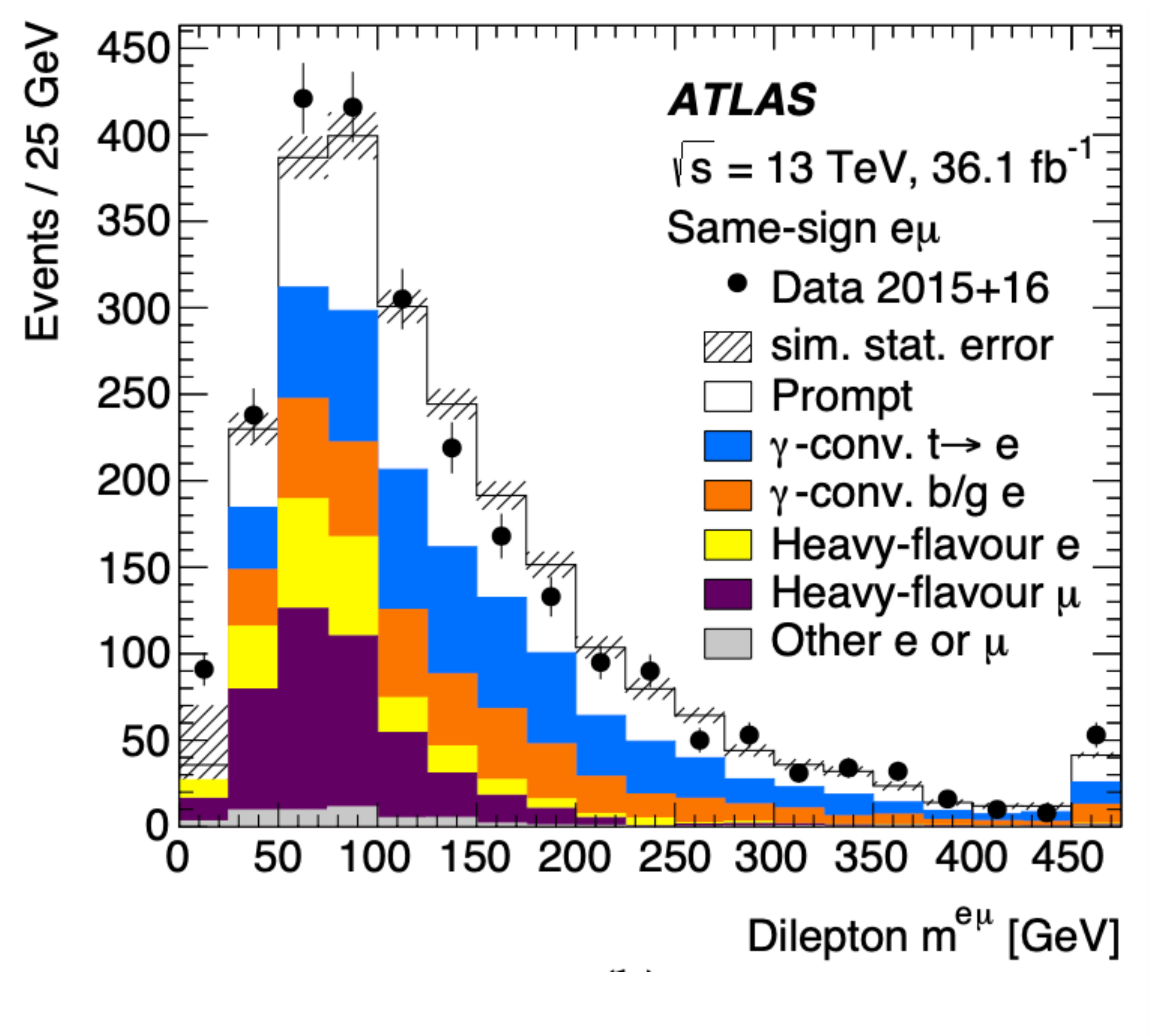

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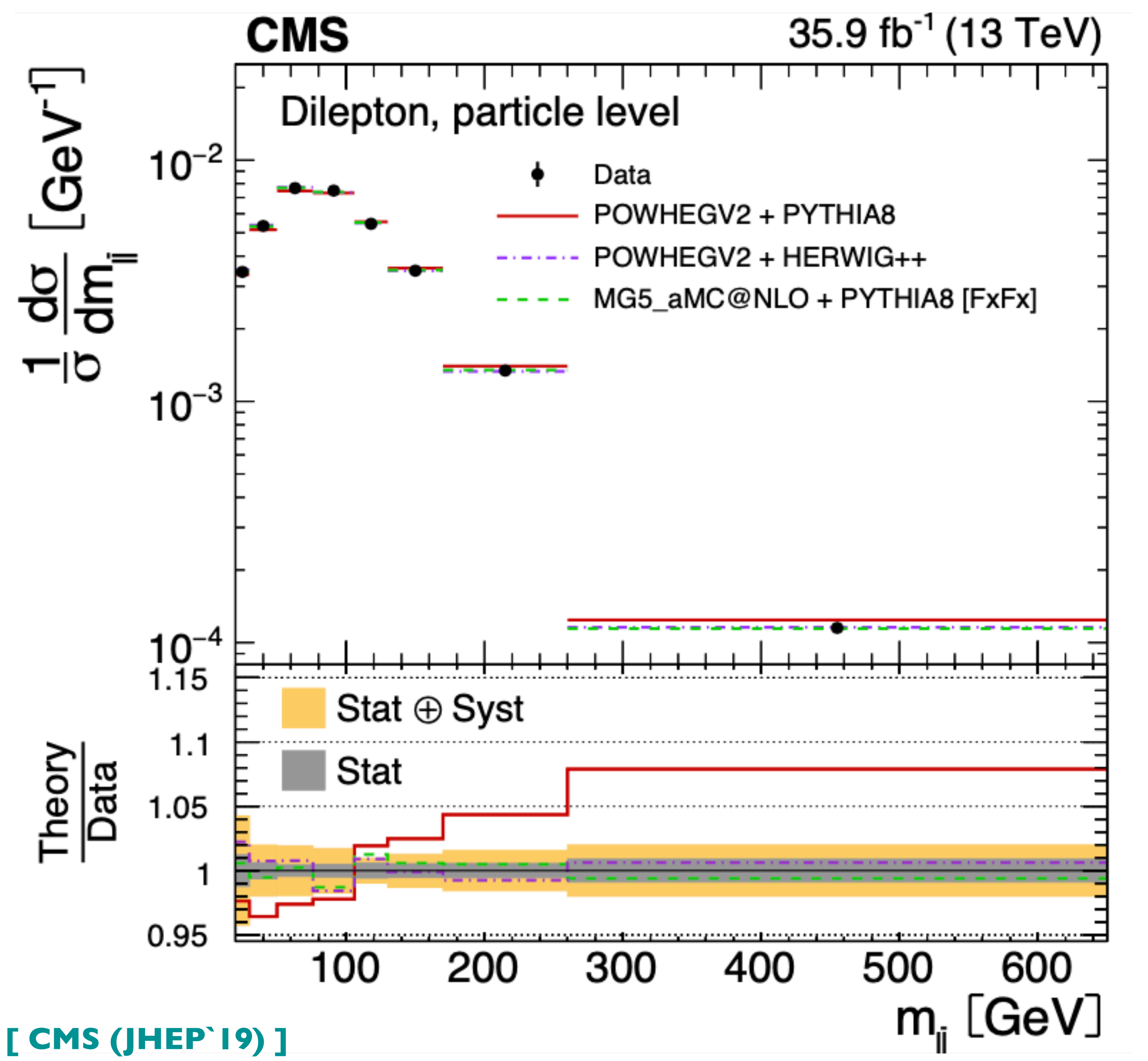

[CMS (JHEP`19)]

Top-antitop bound-state effects

- Significant near threshold
- Spin-0 bound state
  ➞ $t\bar{t}$ @LHC: *gg*-dominated
- Considered negligible (< 1%)
- Could they be observed?

A top-antitop bound state?

Potential issues at low invariant masses

Fermion-antifermion bound states

Positronium bound states predicted in 1934

[Mohorovičić (Astron.Nachtrichten`34)]

- Experimental discovery in 1951 (Deutsch @ MIT)
- Two spin configurations
  - ➞ Para-positronium: $^1S_0$, decays into 2 photons, C-even
  - ➞ Ortho-positronium: $^3S_1$, decays into 3 photons, C-odd

$$(e^+e^-)_0 \to \gamma\gamma$$

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Effects impacting QED precision tests (α measurements)

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Colour-singlet $q\bar{q}$ bound states (colour-octet contributions ⇔ higher-order effects)

- C-odd, spin singlets
- C-even, spin triplets

$$(c\bar{c})_0 : \eta_c, \eta_c'(2S); \quad (b\bar{b})_0 : \eta_b, \eta_b'(2S), \ldots$$
$$(c\bar{c})_1 : J/\Psi, \Psi(2S); \quad (b\bar{b})_1 : \Upsilon, \Upsilon(2S), \Upsilon(3S), \ldots$$

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Also for $t\bar{t}$ systems (virtual bound states)

- Gluon exchanges between top quarks before decay (a_0~20 GeV)
- Decay before hadronisation ($\Lambda_{\rm QCD} \ll \Gamma_t$)
- Two classes of bound state
  - ➞ η_t: C-odd, spin-0 (a case for the LHC through gg production)
  - ➞ θ_t: C-odd, spin-1

$$\frac{1}{\alpha_s m_t} \ll \frac{1}{\Gamma_t} \ll 1\ \text{fm}$$

(20 GeV)$^{-1}$ (1.5 GeV)$^{-1}$ (0.2 GeV)$^{-1}$

Outline

1. Towards a simplified model for toponium production

2. Toponium phenomenology at the LHC

3. Summary

Toponium bound state effects

Incorporating bound state effects in theory predictions

- Close to threshold: non-relativistic approximation valid ($\beta \ll 1$)
- Resummation of the Coulomb singularities $(\alpha_s/\beta)^n$
  ➙ gluon exchanges between slowly-moving top quarks ≡ bound-state effects
- Predictions in the pNRQCD framework (Potential Non-Relativistic QCD)
  ➙ replacement of free NR Green's functions in the matrix elements

$$\frac{1}{E - \frac{\mathbf{p}^2}{M_t} + i\frac{\Gamma_\theta}{2}} \quad \Rightarrow \quad \langle \mathbf{p} | \frac{1}{E - \frac{P^2}{M_t} - V(r) + i\frac{\Gamma_\theta}{2}} | \mathbf{x} = 0 \rangle$$

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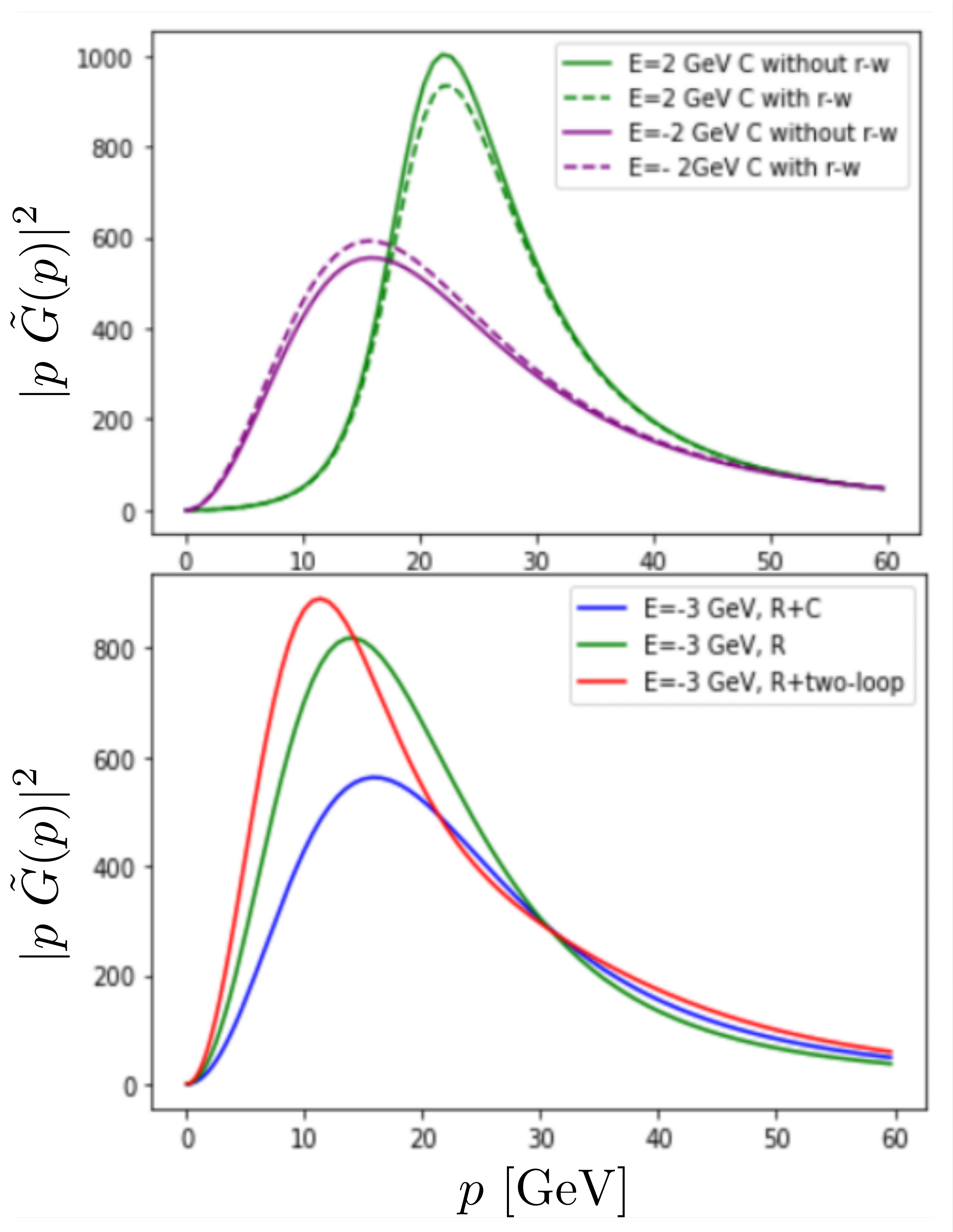
- Choice of the QCD potential inspired by charmonia/bottomonia
  → Richardson's at low energies ⊕ Coulomb-like at high energies
  → Two-loop corrections included in the Coulomb potential
  → Running top-width effects studied

$$V_R(q^2) = -\frac{4}{3}\frac{16\pi^2}{b_0}\frac{1}{q^2 \ln(1 + \frac{q^2}{\Lambda_R^2})},$$

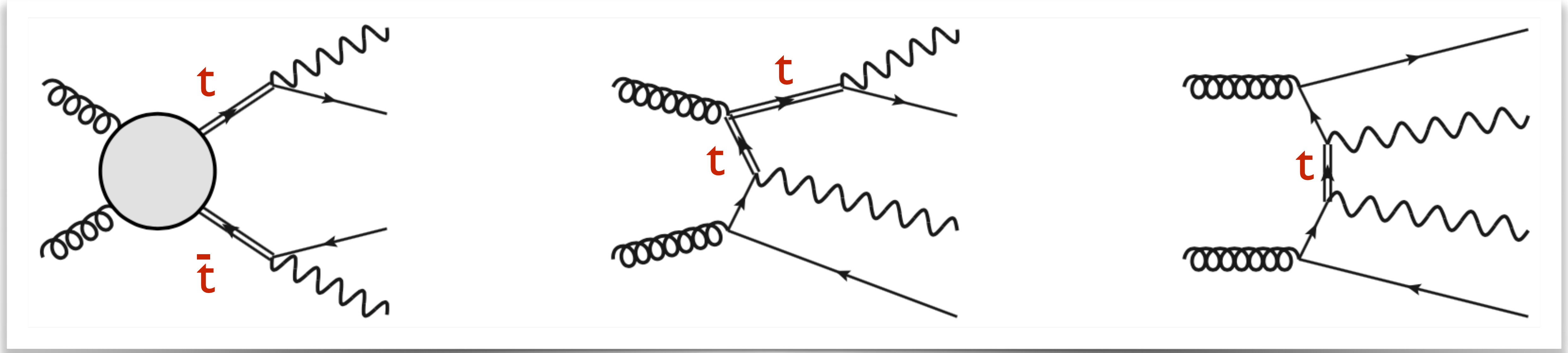
[Richardson (PLB`79)]



Top-antitop production near threshold

Wb Wb production in the threshold regime

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



- Bound-state effects ➙ first class of diagrams
  - ⋆ Below or slightly above threshold
  - ⋆ One off-shell top quark
  - ⋆ Binding energy ⇔ Coulomb gluon exchanges

➙ To add to the perturbative treatment
➙ Better $t\bar{t}$ modelling
➙ SM explanation to excesses?

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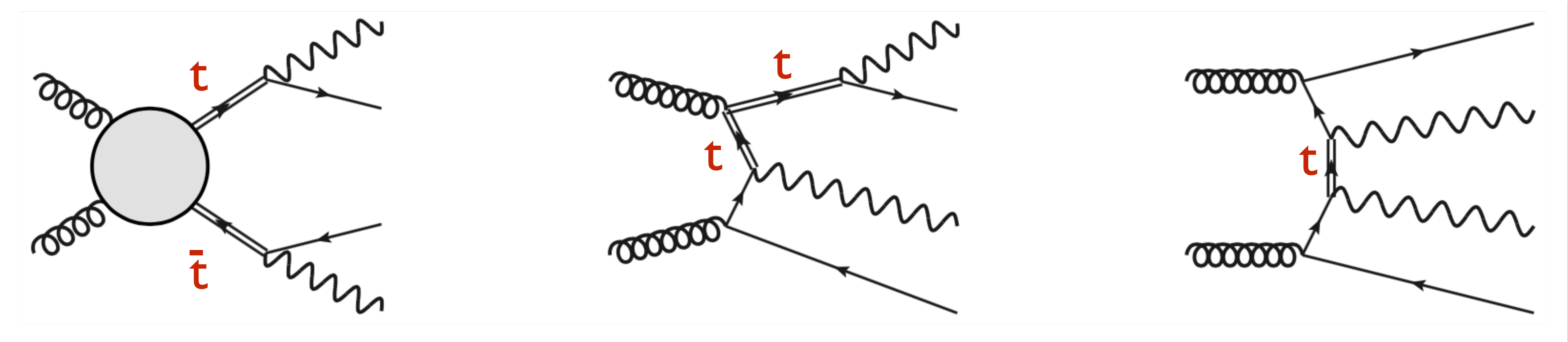

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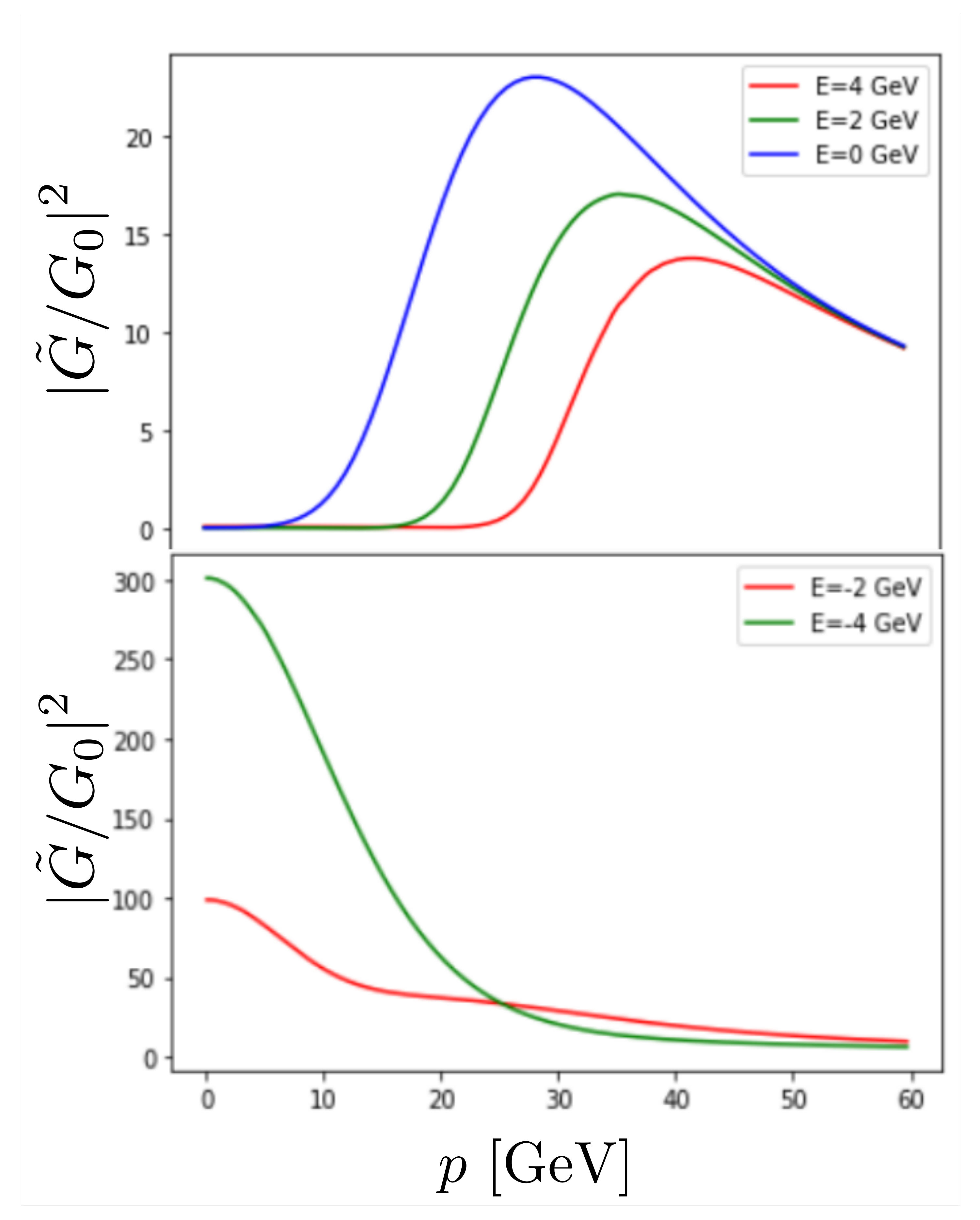


The (tree-level) amplitude is enhanced close to threshold

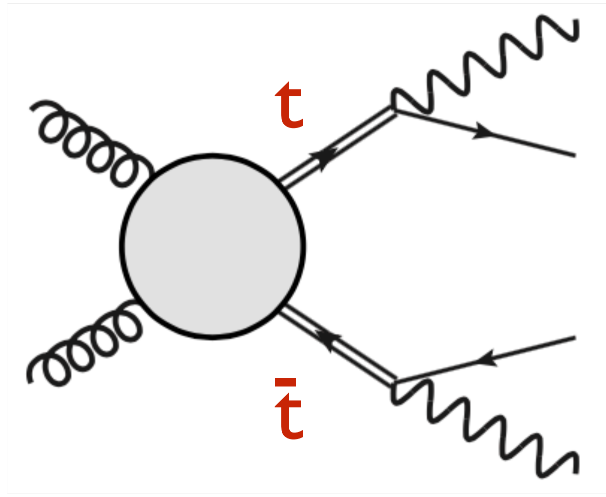
- Involving ratios of non-relativistic Green's functions

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

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

- ⋆ Ratio of Green's functions of the Hamiltonians with/without V_{QCD}
- ⋆ Different channels (*gg*/*qq*; ***1***/***8***)

Top pair production with toponium effects



Amplitude re-weighting close to threshold

- Below and above threshold
- All contributions (singlet/octet, $gg/q\bar{q}$)
- Explanation for CMS/ATLAS excesses?

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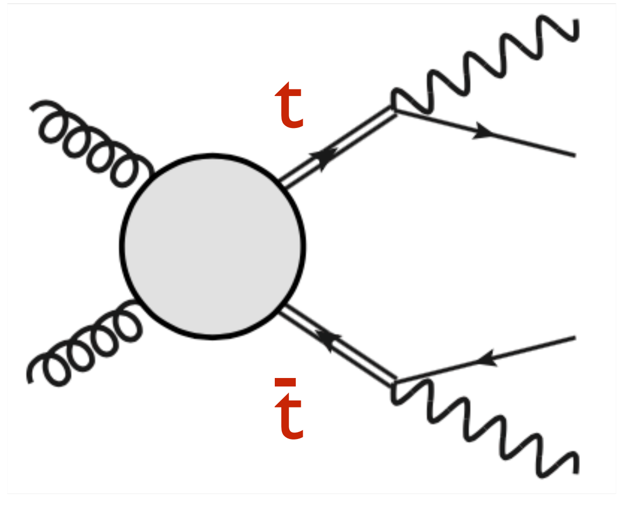

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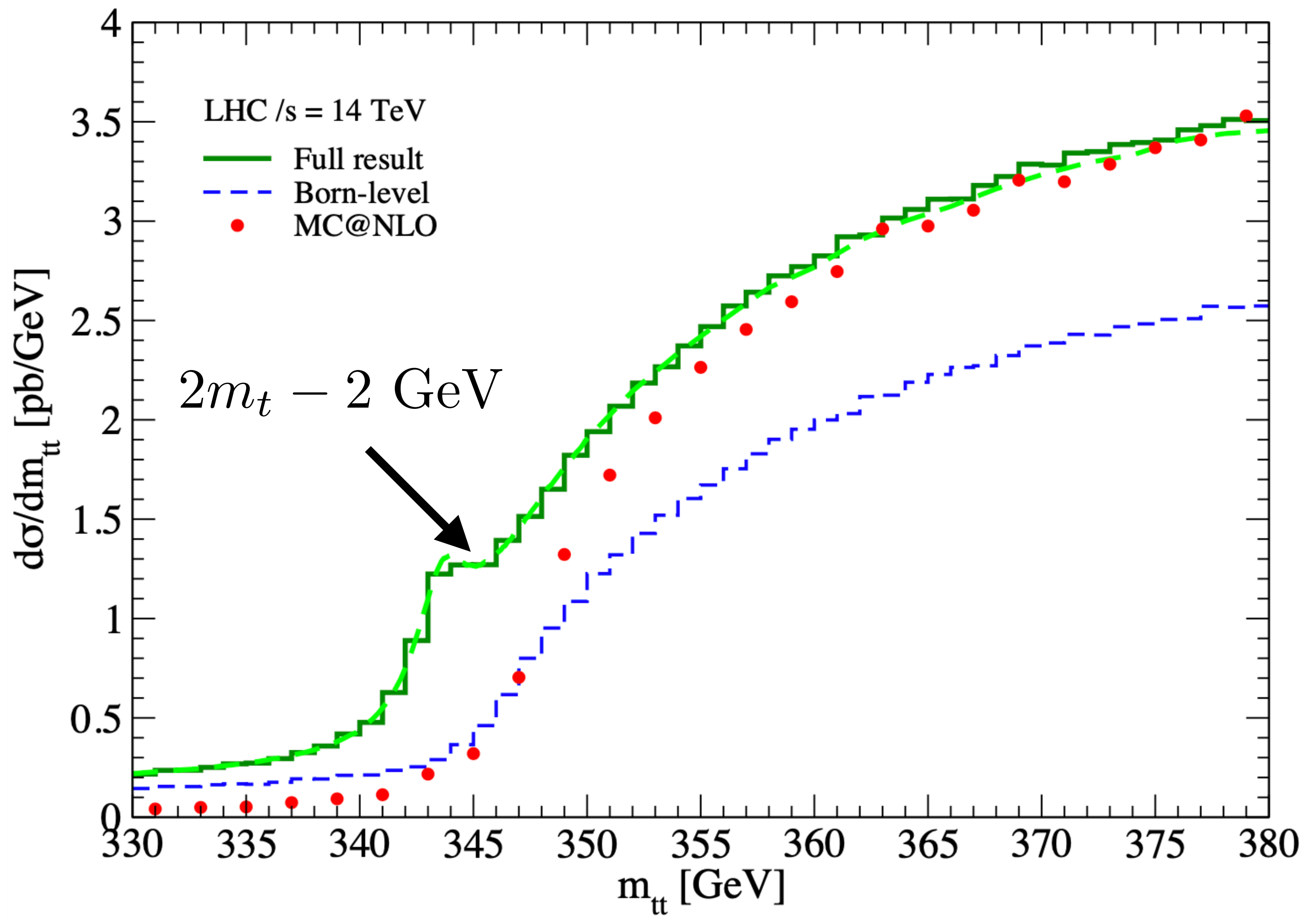
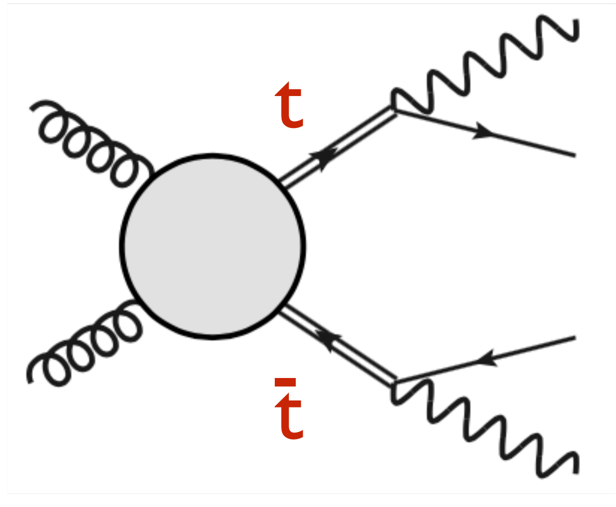


[Sumino & Yokoya (JHEP`10)]

Impact on $t\bar{t}$ modelling

- Full *WbWb* differential distribution (green)
  - ➙ with bound-state effects
  - ➙ finite top-width effects
  - ➙ with NLO effects (ISR, differential K-factors)
- *WbWb* production at NLO (red)
  - ➙ NLO + top offshell effects (from MG5_aMC)
- Toponium = "green - red"

Top pair production with toponium effects



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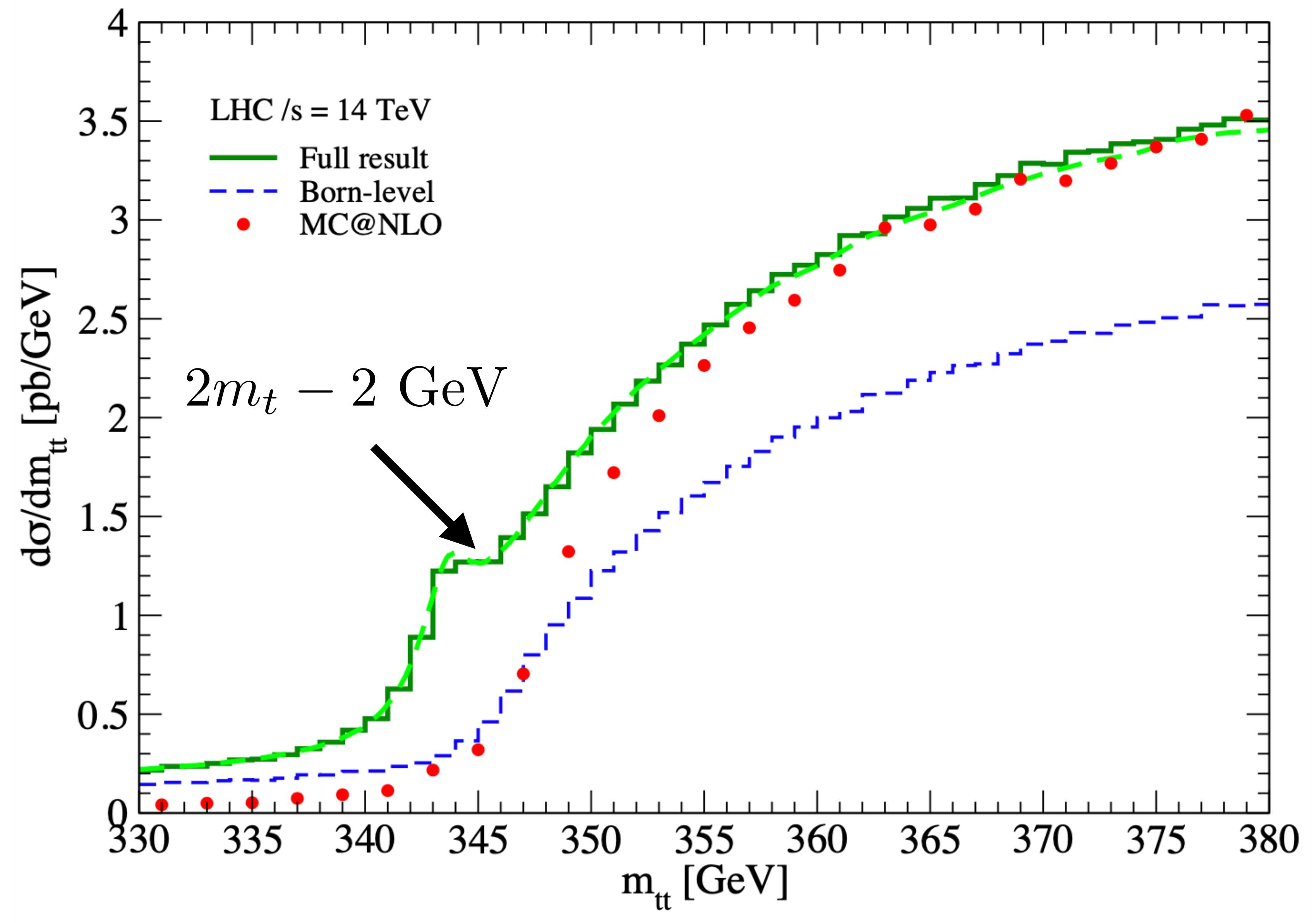

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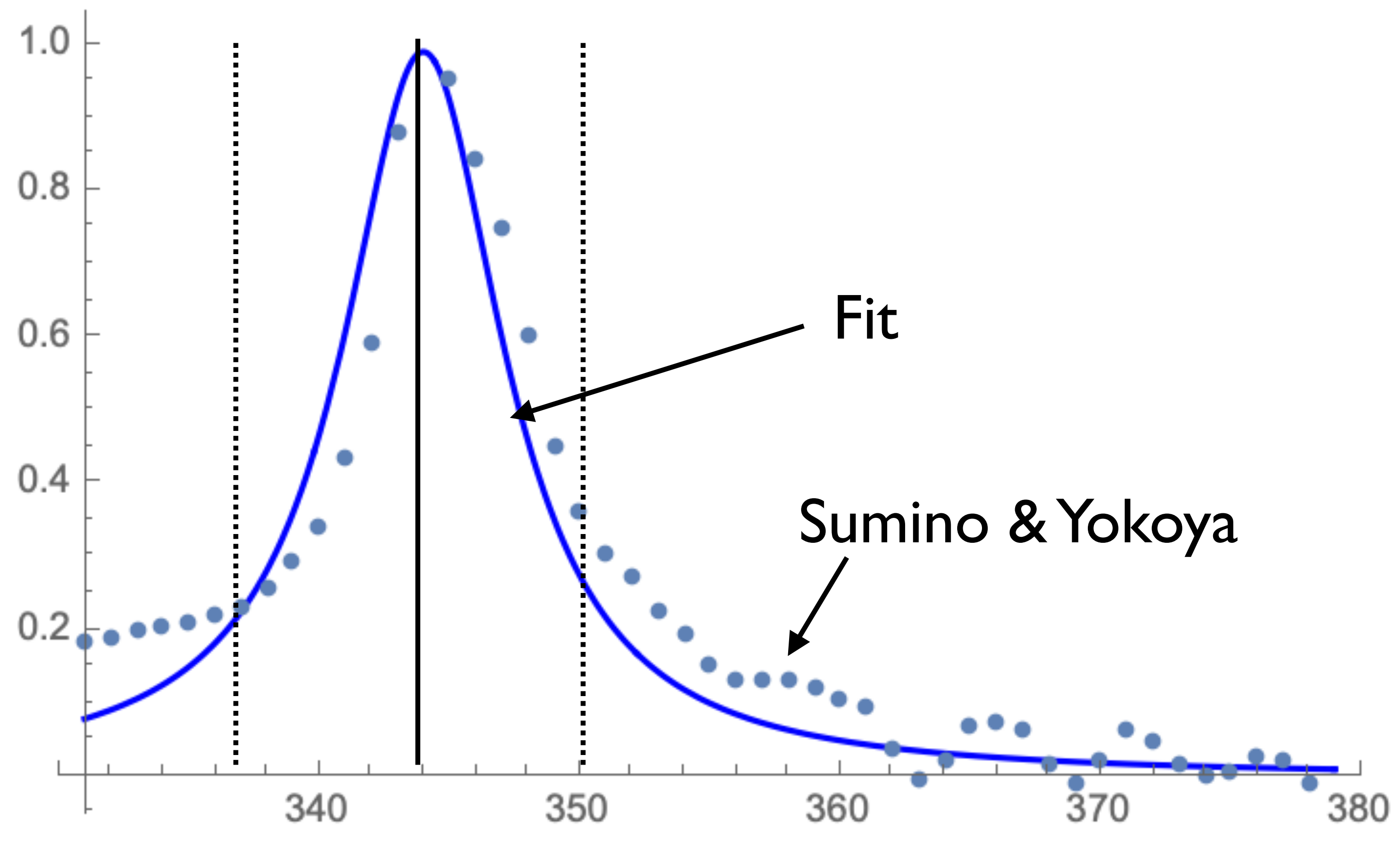

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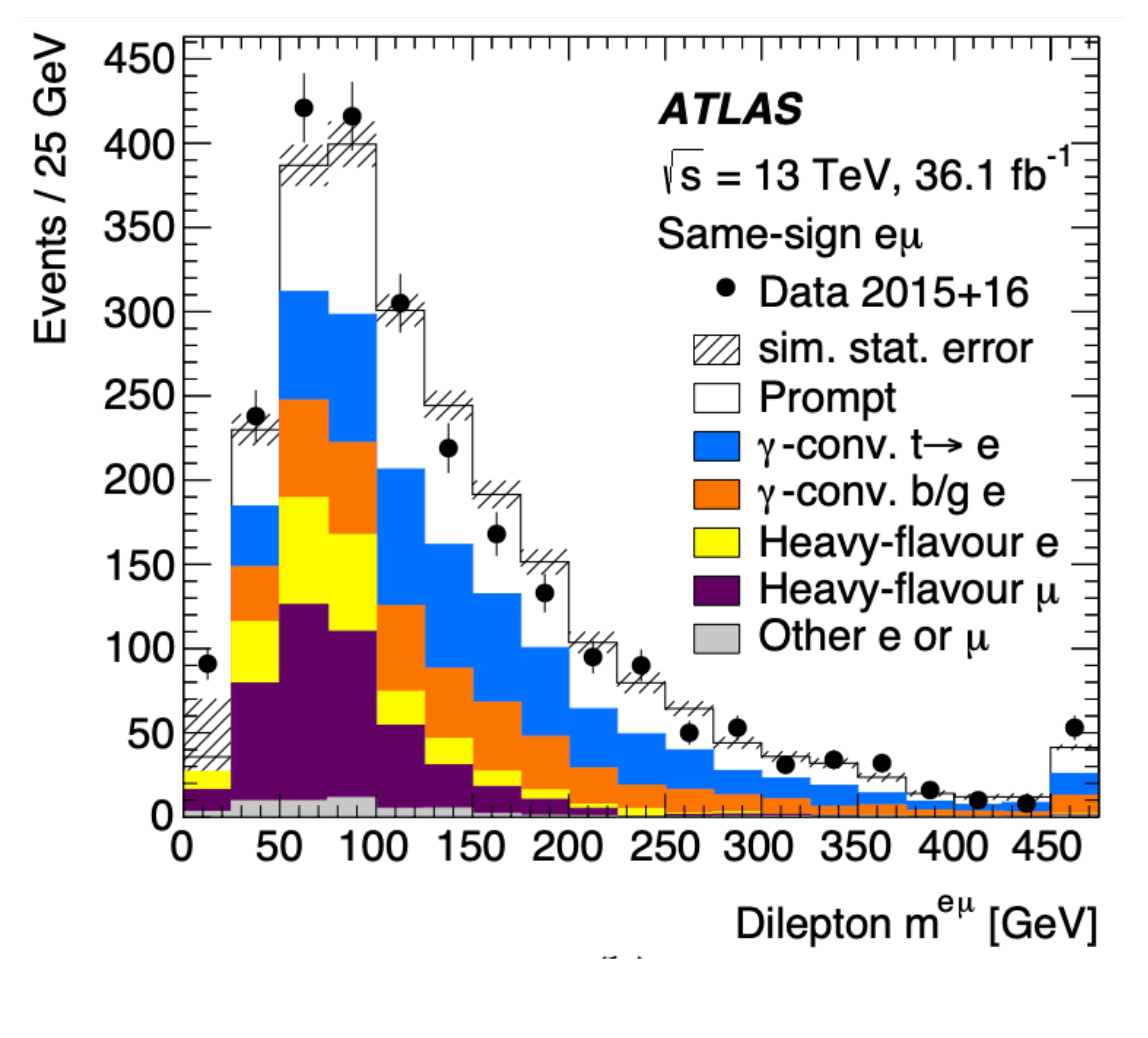
Toponium modelling with a resonance

Could toponium effects explain ATLAS/CMS observations in the low $m_{t\bar{t}}$ regime?

- Toy scenario: simplified modelling at tree-level
  → Breit Wigner resonance



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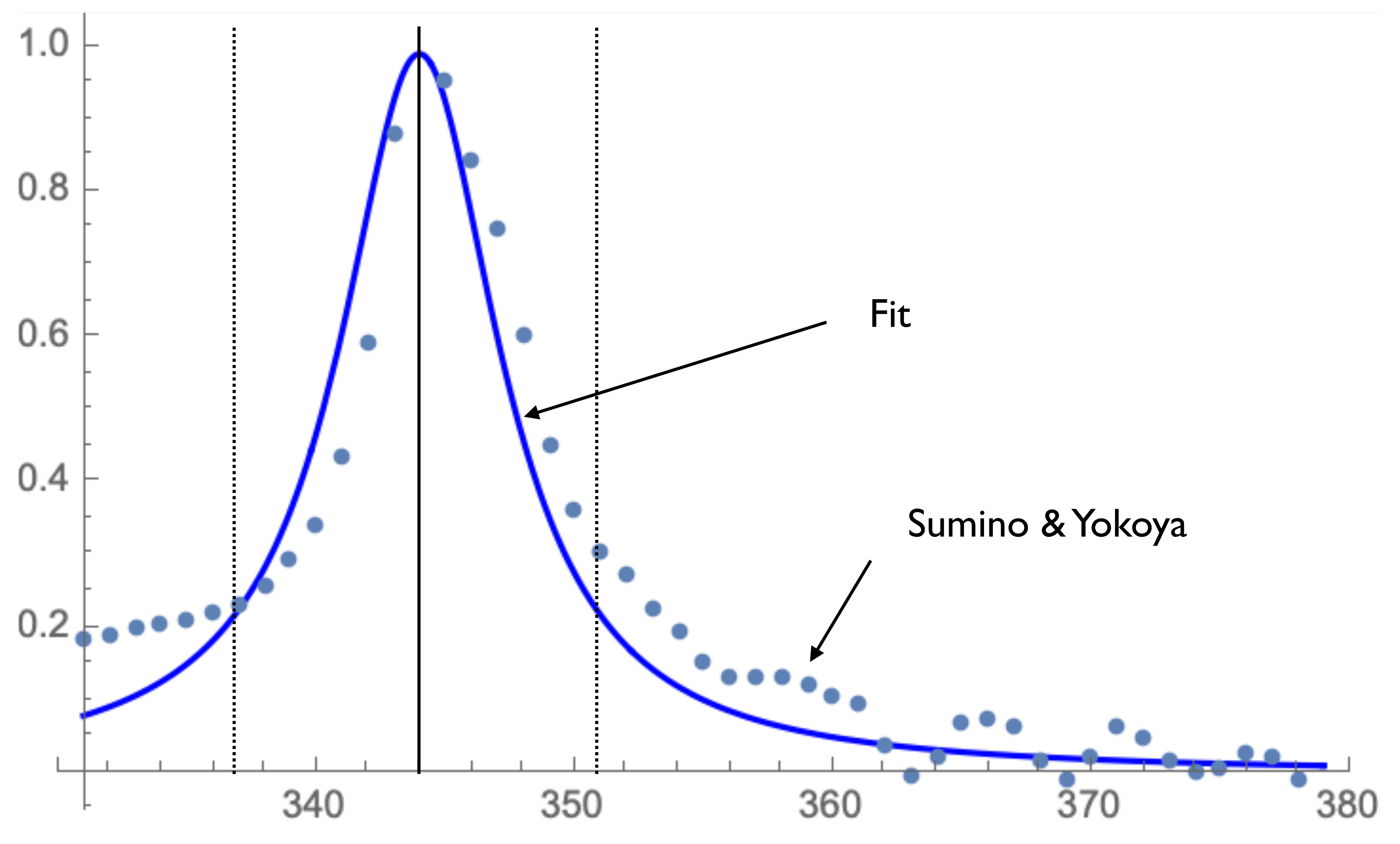


Toponium signal: $pp \to \eta_t \to t^{(*)}\bar{t}^{(*)} \to W^+ b W^- \bar{b}$

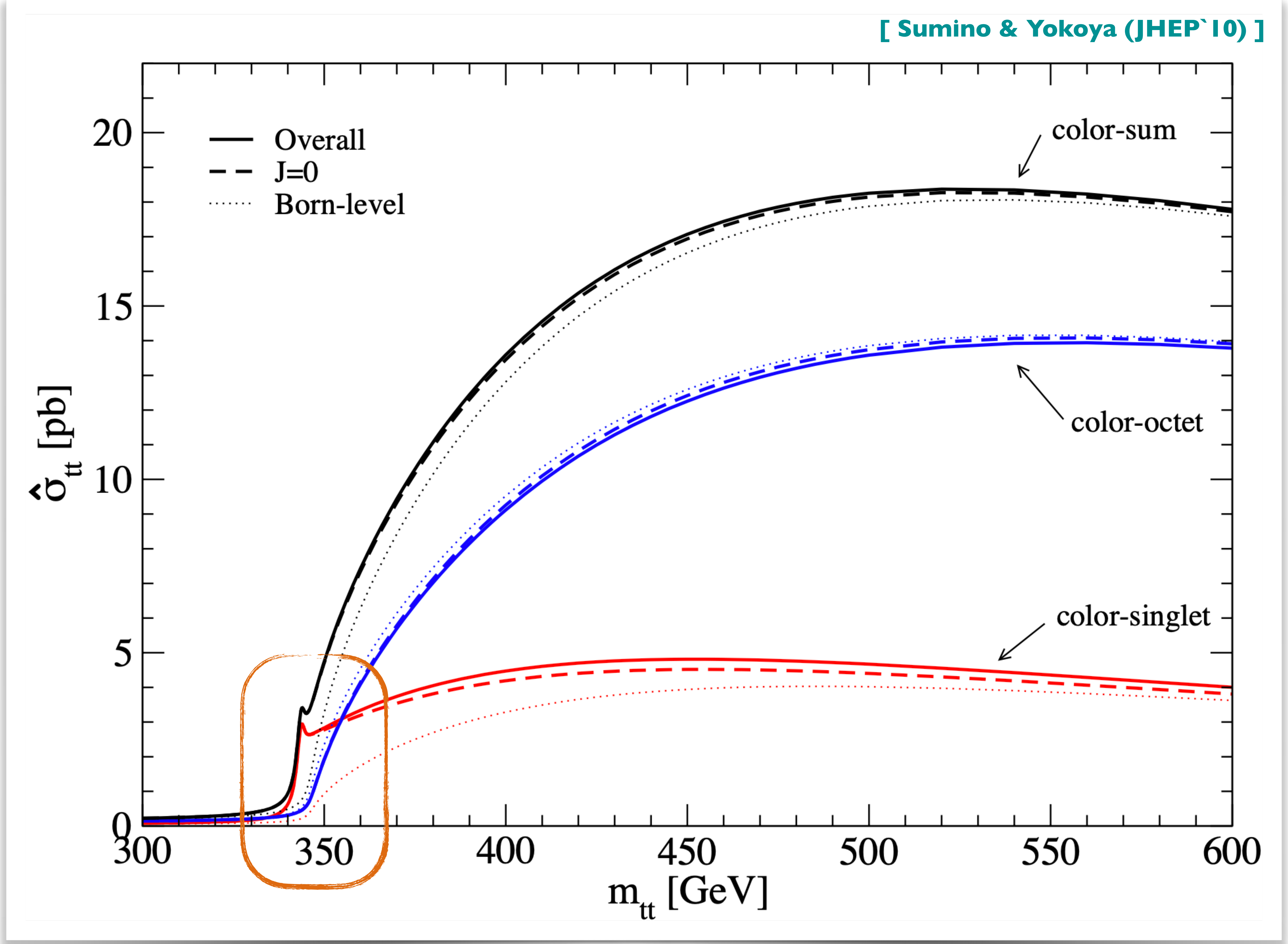
$m_{\eta_t} = 344$ GeV $\Gamma_{\eta_t} \approx 7$ GeV $\sigma(13\text{ TeV}) \sim 6.5$ pb

Quantum numbers

Different contributions to top-antitop production close and far from threshold

- Colour-singlet domination close to threshold
  - ➙ domination of the *gg*-singlet channel
  - ➙ toponium coupling to gluon pairs and $t\bar{t}$ pairs
- Colour-octet significant far from threshold

Octet effects ignored



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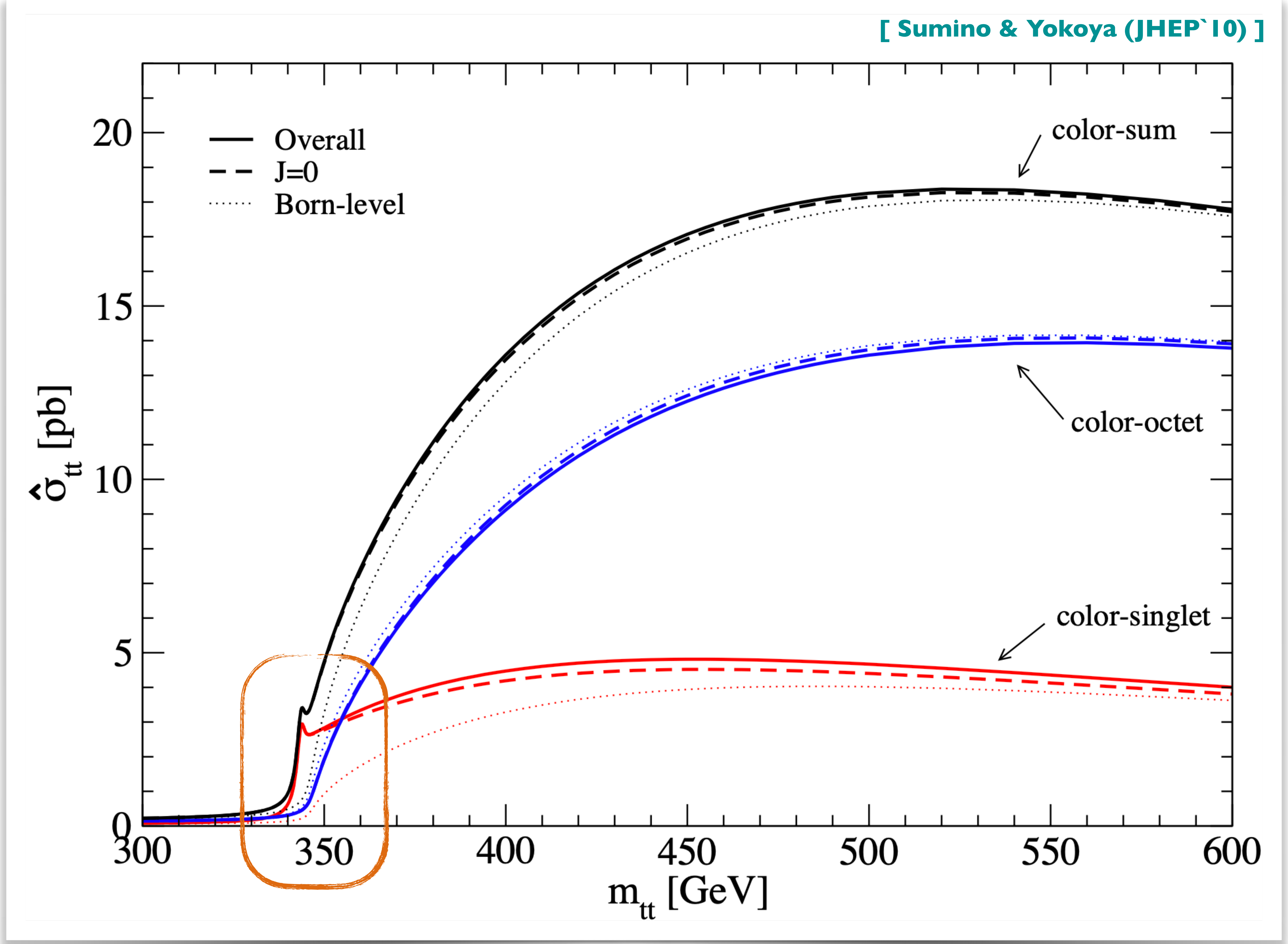


Towards a simplified modelling

- Large domination of the *J=0* state
  - ➙ *L = S = 0*
- Resonance in the $J^{PC} = 0^{-+}$ state

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

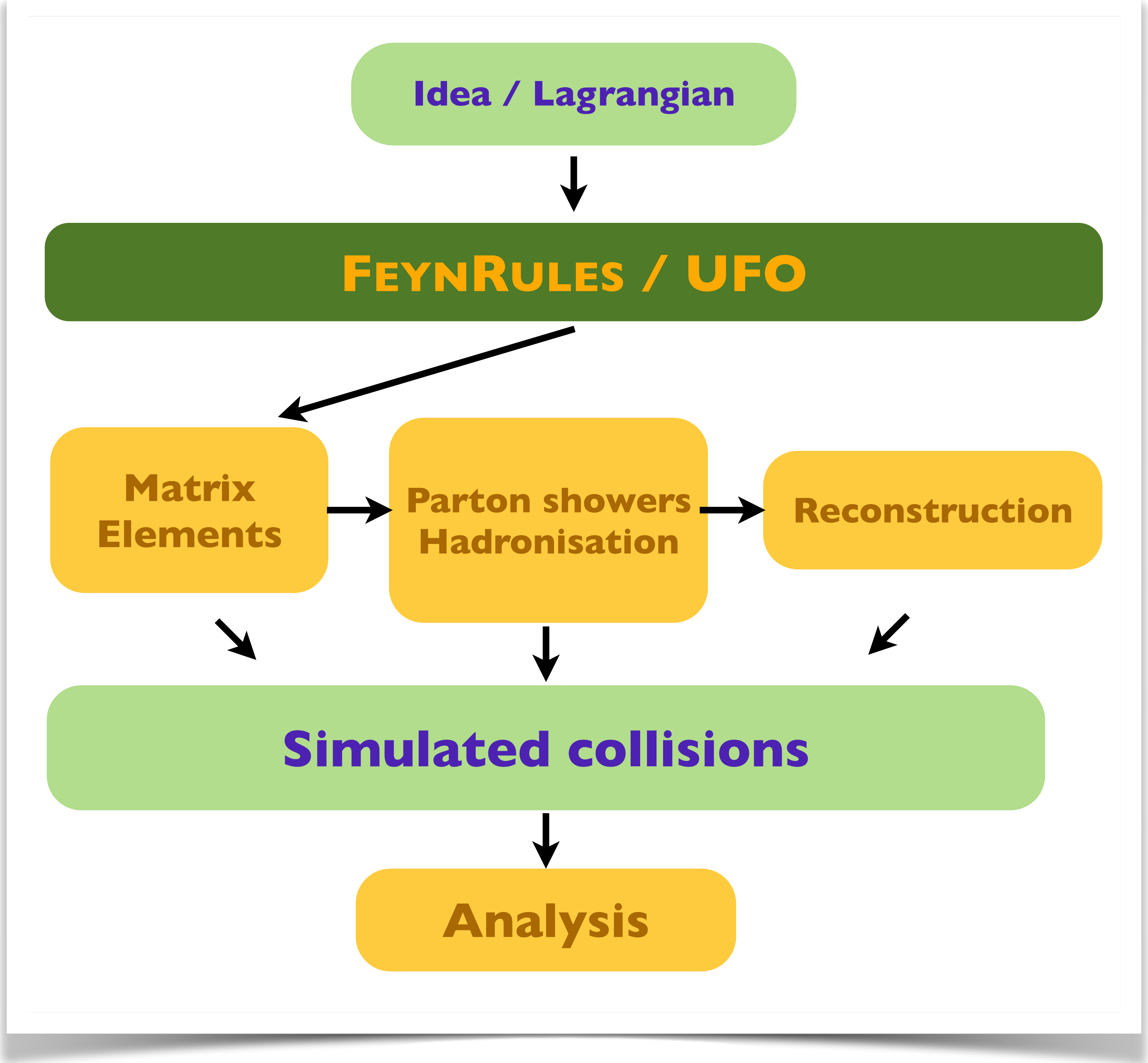
$$C(\eta_t) = (-1)^{L+S}$$

Higher-spin effects ignored

- Definition of our BSM simplified setup
  - ➙ a colourless pseudoscalar state $m_{\eta_t} = 344\ \text{GeV}$
  - ➙ two couplings: gluons (production) and tops (decay)

Connecting ideas to simulations…

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



- Model building → FeynRules / UFO

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
[Darmé et al. (EPJC'23)]

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

No free parameters [$m/\Gamma/\sigma$ known]

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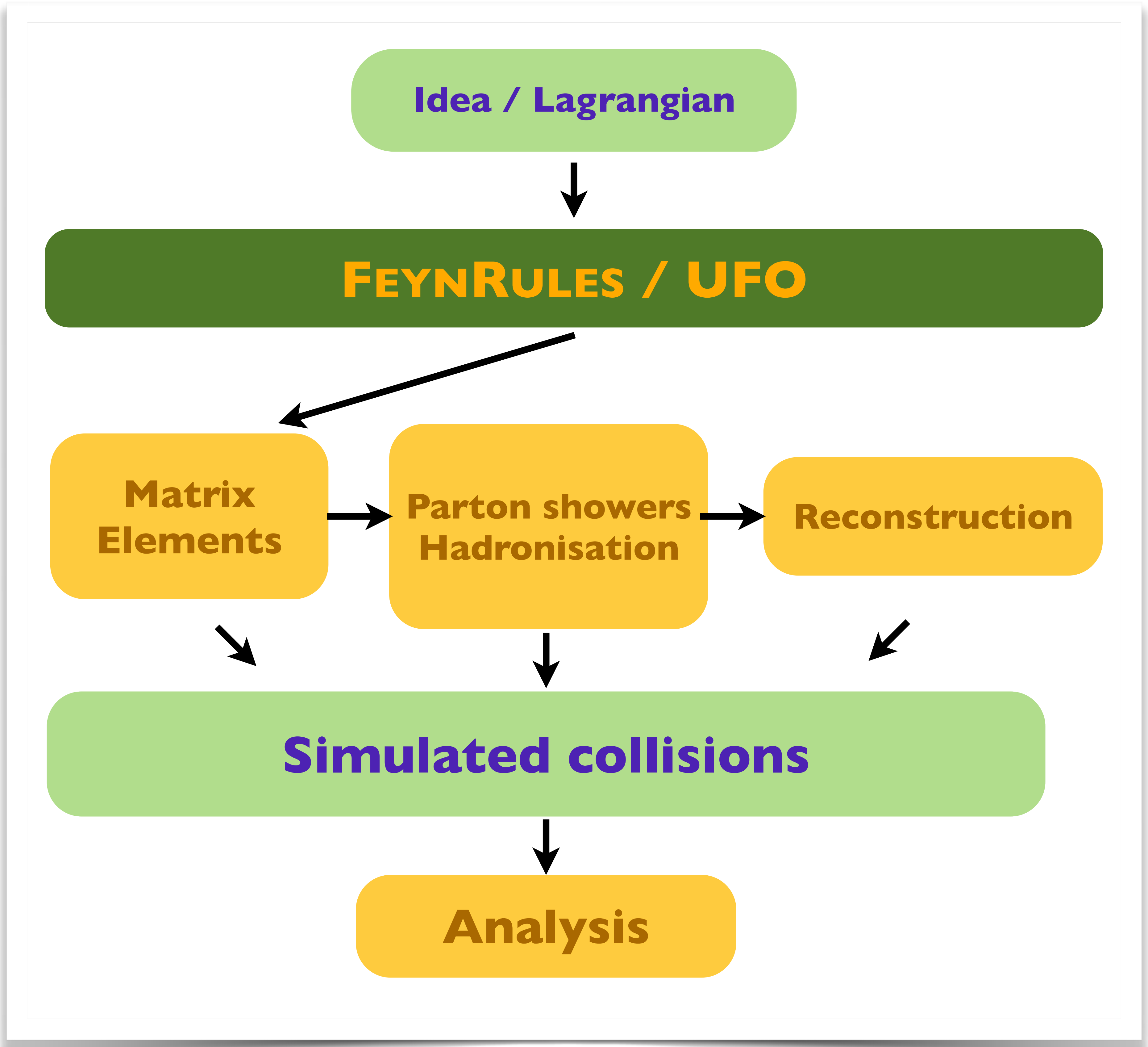

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No free parameters [$m/\Gamma/\sigma$ known]

- Hard scattering
  - ⋆ Feynman diagram and amplitude generation
  - ⋆ Monte Carlo integration
  - ⋆ Event generation

  → MG5_AMC [Alwall et al. (JHEP'14)] [Frederix et al. (JHEP`18)]

- QCD environment
  - ⋆ Parton showering
  - ⋆ Hadronisation

  → PYTHIA 8 [Sjöstrand et al. (CPC'15)]

- Object reconstruction
  - ⋆ Anti-k_T algorithm
  - ⋆ Perfect detector

  → FASTJET & MADANALYSIS 5 [Cacciari, Salam & Soyez (JHEP'08); Cacciari, Salam & Soyez (EPJC'12)] [Conte, BF & Serret (CPC`12); Conte & BF (IJMPA`19)] [Araz, BF & Polykratis (EPJC`21)]

- Event analysis
  - ⋆ Signal/background analysis (cuts & plots)
  - ⋆ Towards a toponium discovery at the LHC

Signal modelling in action

MG5_aMC: event generation for all *m(WbWb)* values

- The signal lies in [338, 350] GeV
  ➙ extra cut to be implemented after event generation
  ➙ 63% events lost (room for improvement)
- Spectrum of the top momentum in the η rest frame
  ➙ The distribution is off at a given binding energy
  ➙ Re-weighting

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

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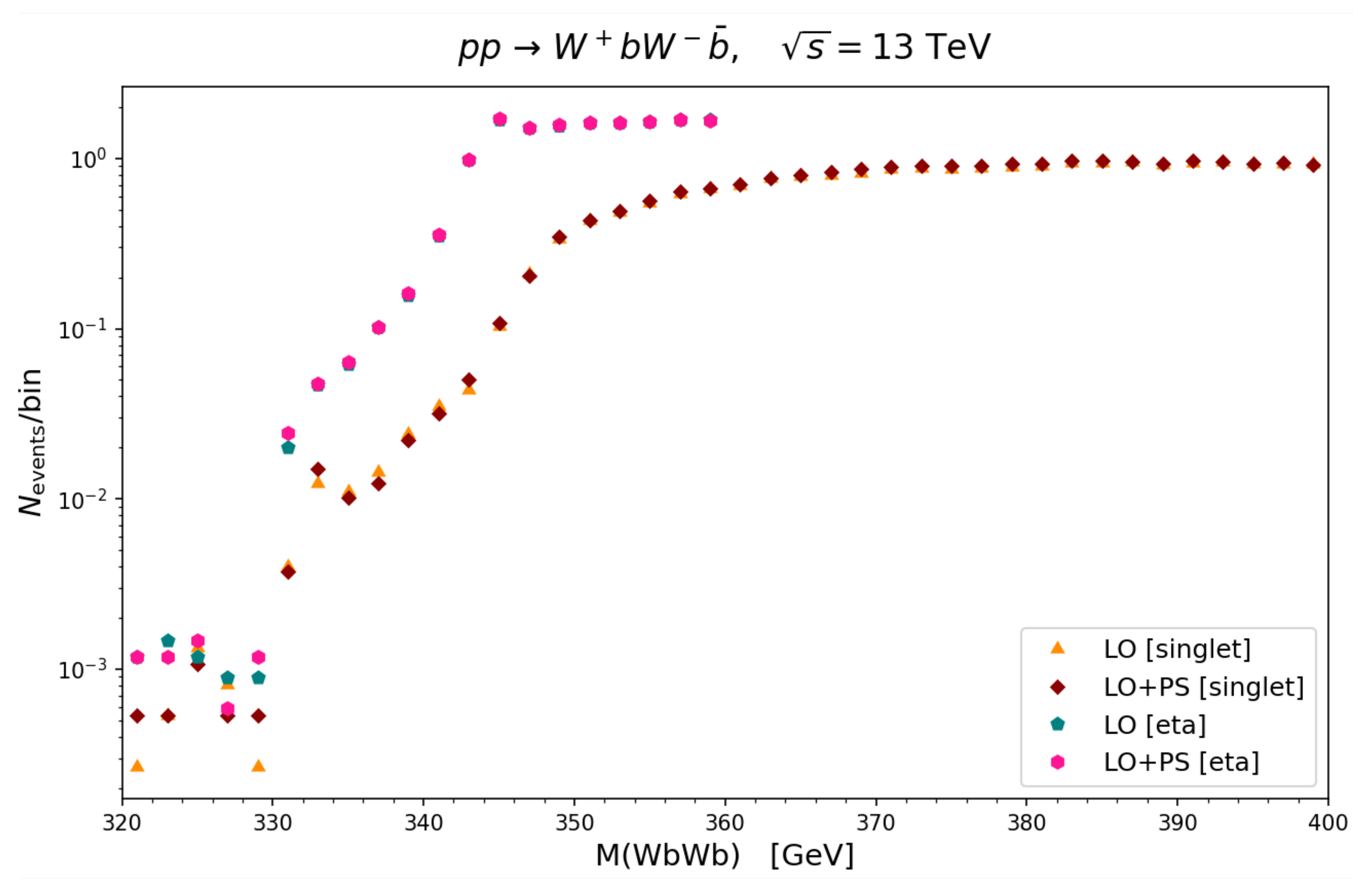

Signal modelling close to threshold

- $(t\bar{t})_{\mathbf{1}}$ + toponium (pink)
- Comparison with usual $(t\bar{t})_{\mathbf{1}}$ (green)
- Parton shower effects negligible

Checks and main toponium characteristics

Verification: in the case of a di-leptonic toponium decay

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

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

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- 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):

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

- Toponium characteristic: small $m_{\ell\ell}$ and small $\Delta\boldsymbol{\varphi}_{\ell\ell}$

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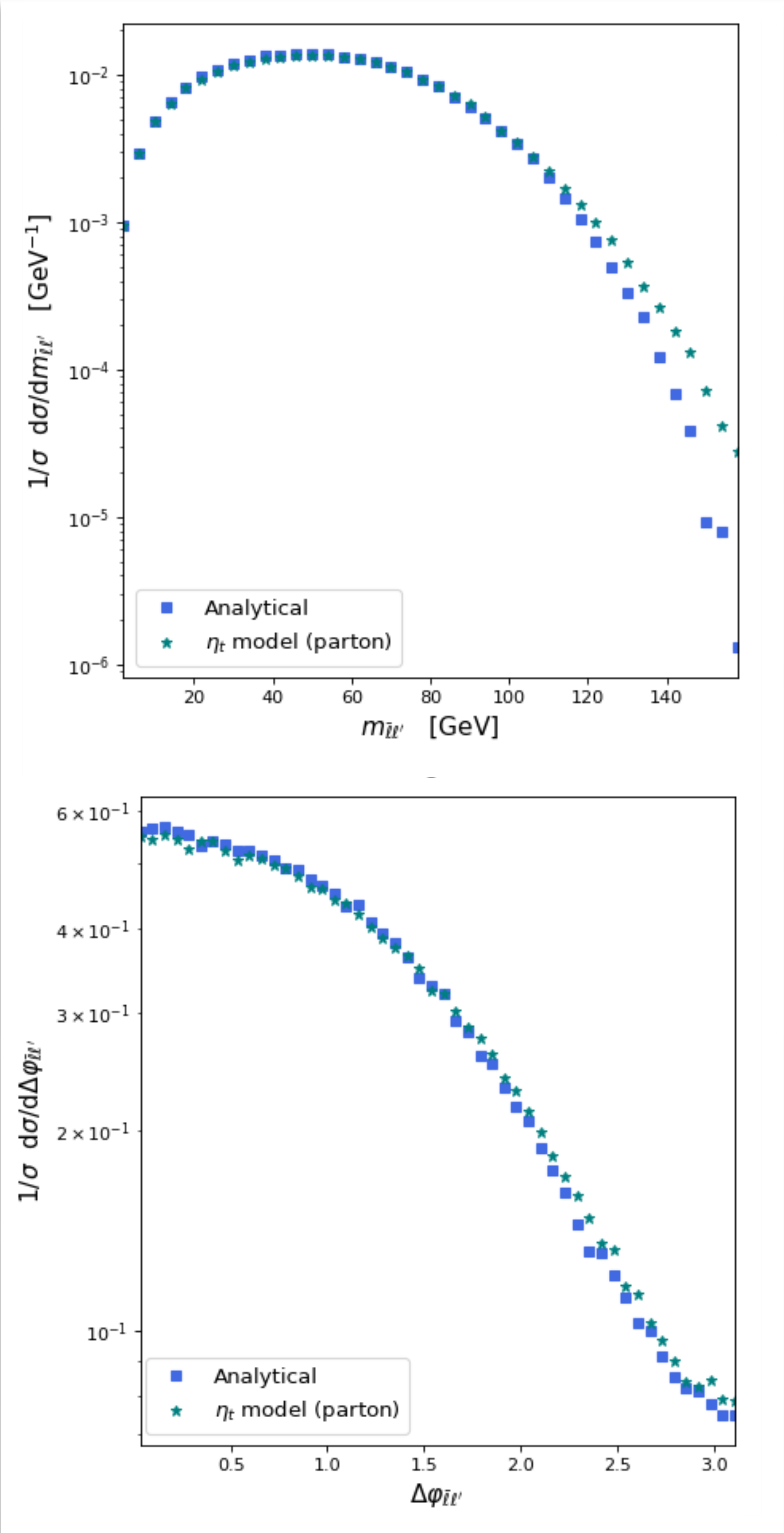
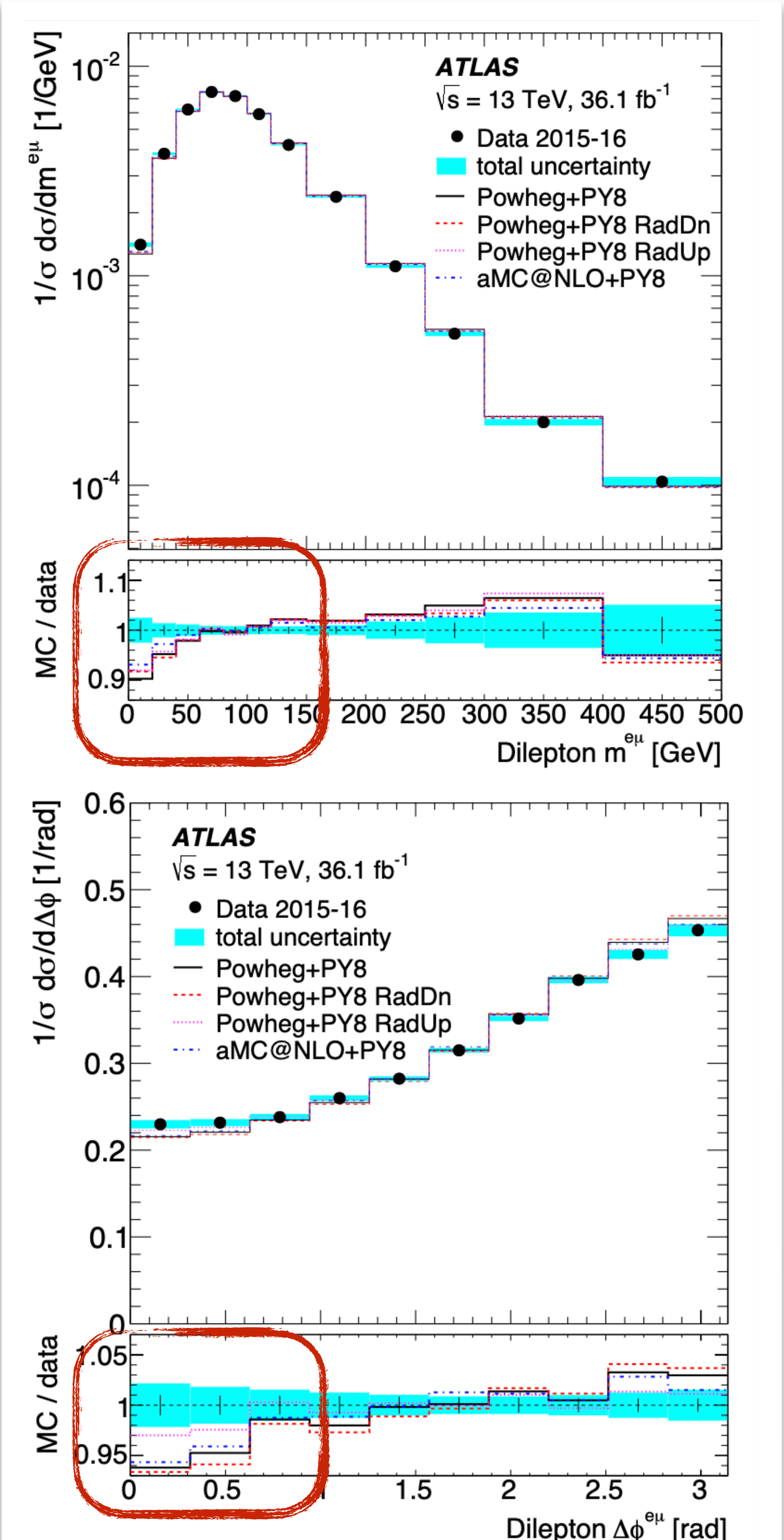
Correlations (in principle) reproduced in the pseudoscalar model

Toponium decays in two leptons





[ATLAS (EPJC`20)]

Modelling good enough

- The η-model yields correct toponium properties
  - ➙At large $m_{\ell\ell'}$: widths and b-mass effects
- Toponium formation in ATLAS data ?
  - ➙ At small $m_{\ell\ell'}$ and small $\Delta\varphi_{\ell\ell'}$:

$$\frac{\text{MC[no toponium]}}{\text{data}} < 1$$

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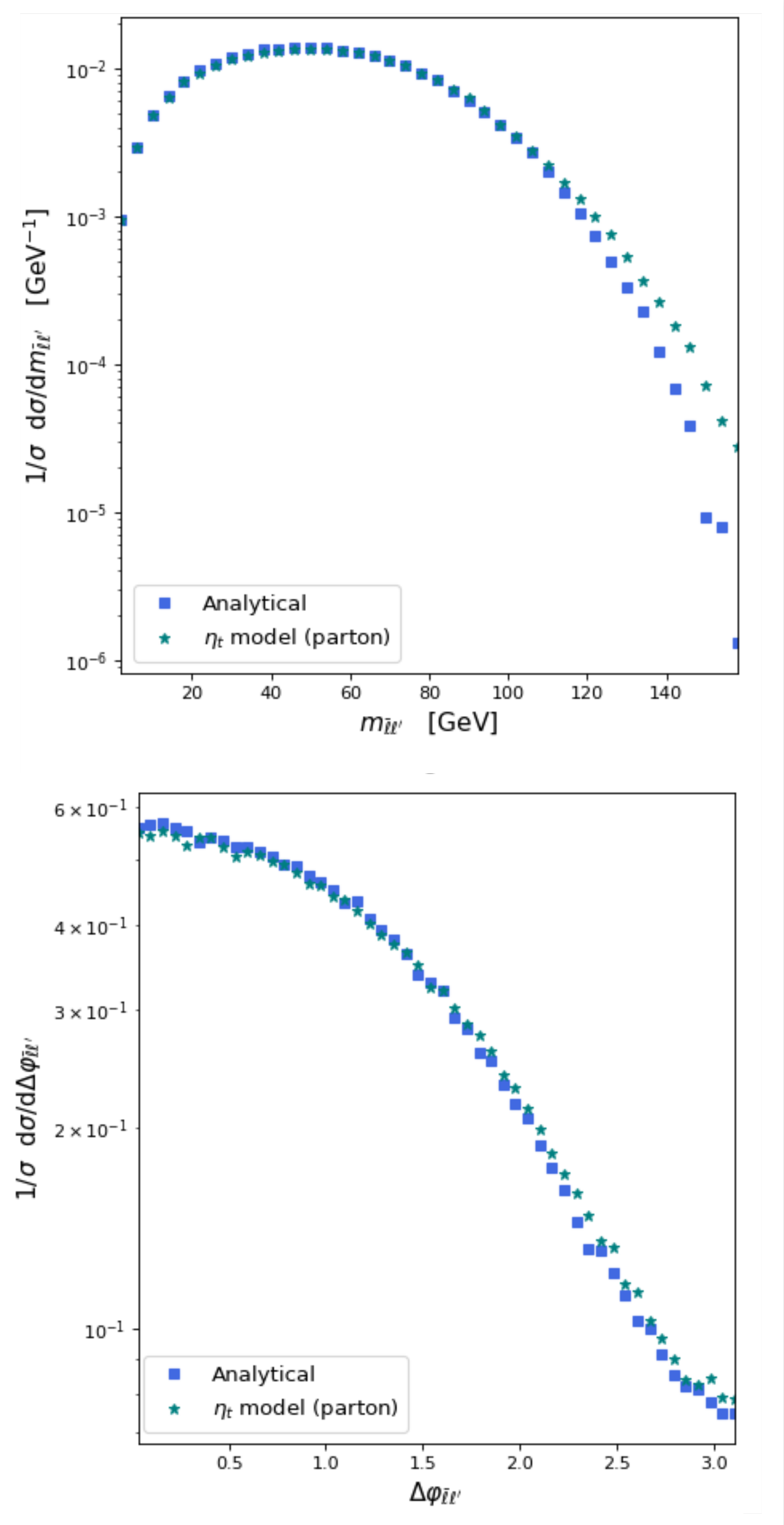
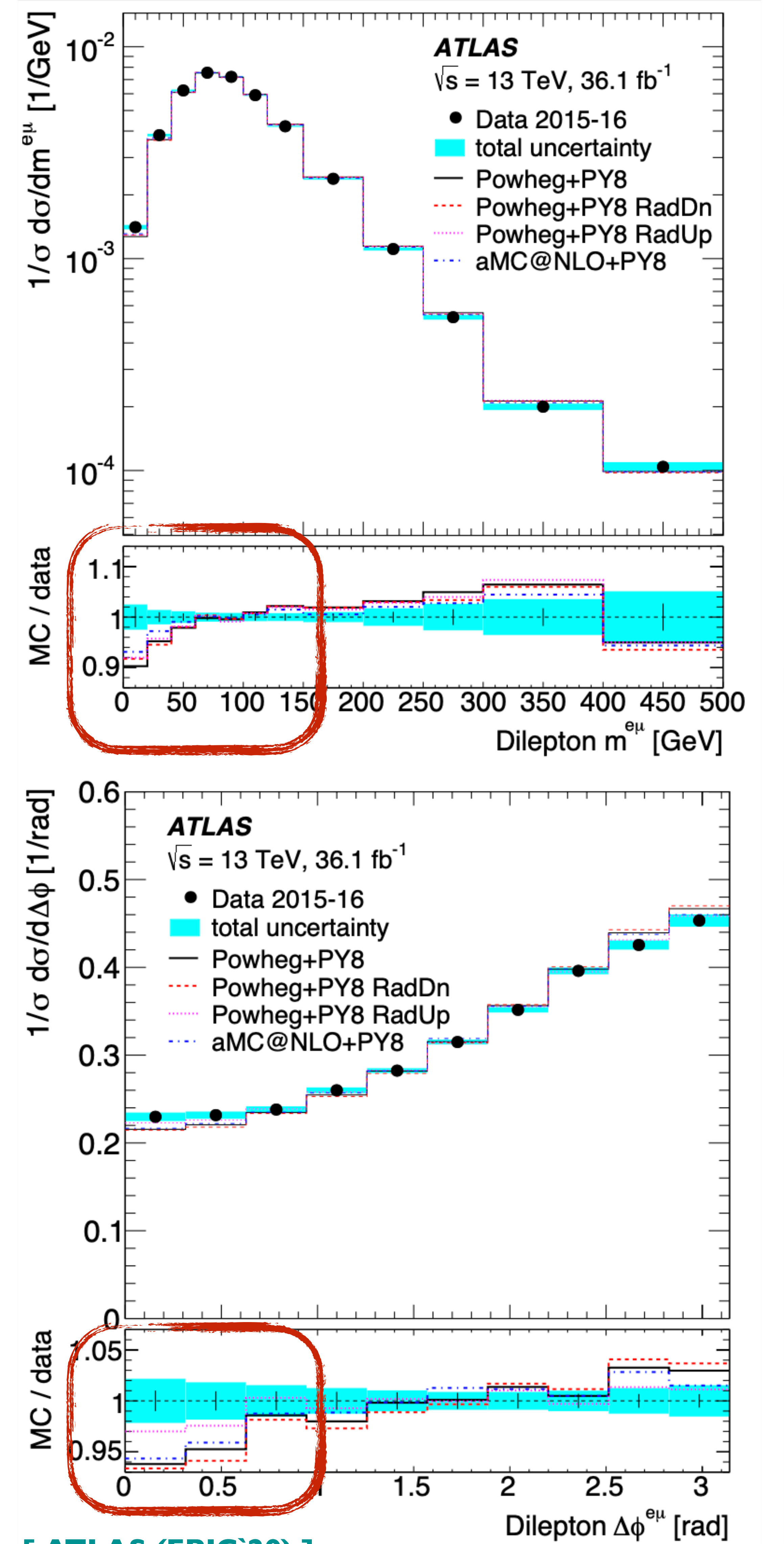




[ATLAS (EPJC`20)]

Modelling good enough

- The η-model yields correct toponium properties
  - ➞At large $m_{\ell\ell'}$: widths and b-mass effects
- Toponium formation in ATLAS data ?
  - ➞ At small $m_{\ell\ell'}$ and small $\Delta\varphi_{\ell\ell'}$:

$$\frac{\text{MC[no toponium]}}{\text{data}} < 1$$

How to confirm it?

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

➞ Proper analysis

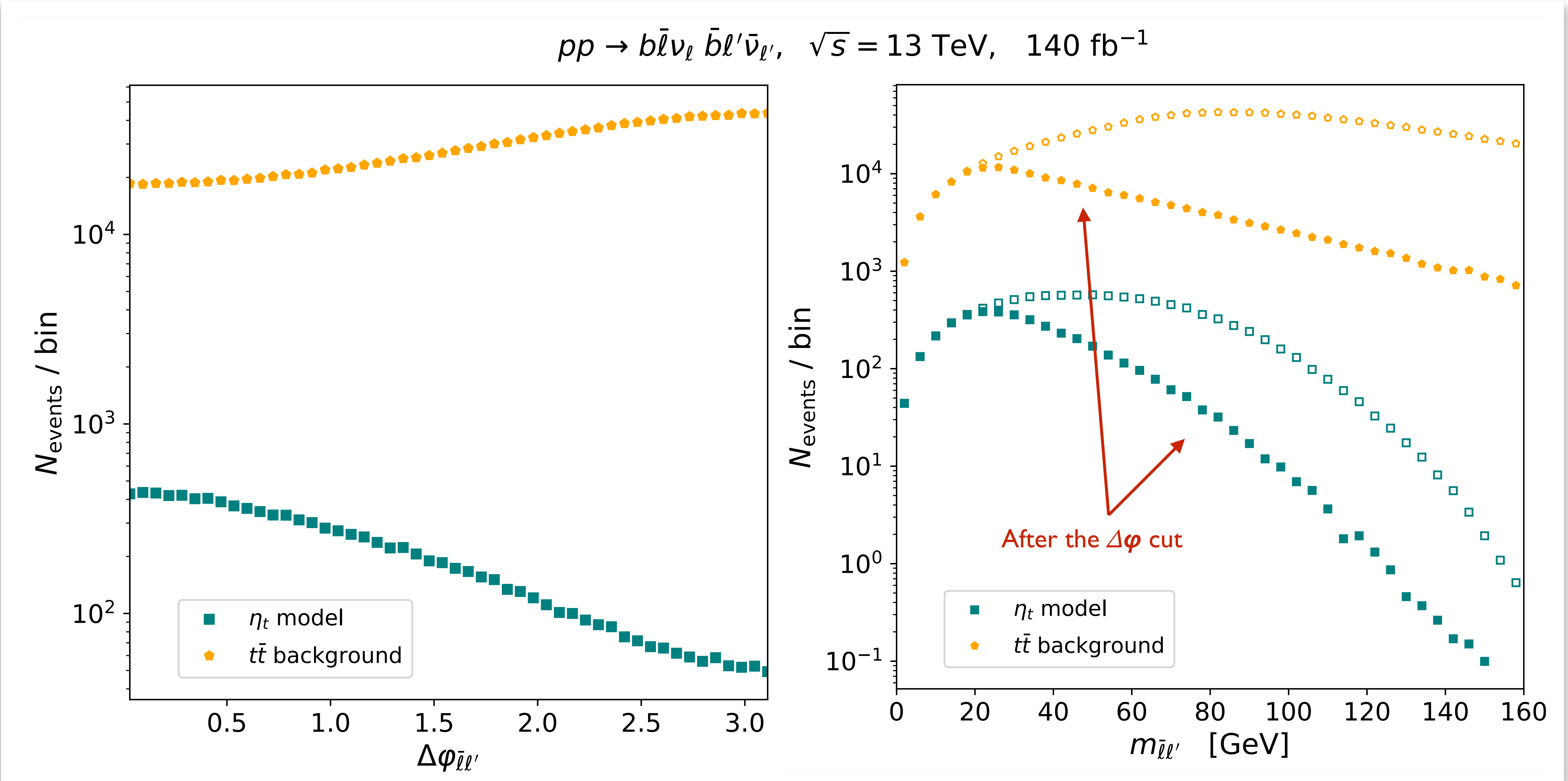
Towards toponium observation with di-leptons

Basic cuts: final-state composition

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

Targeting LHC excesses / bulk of toponium events

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



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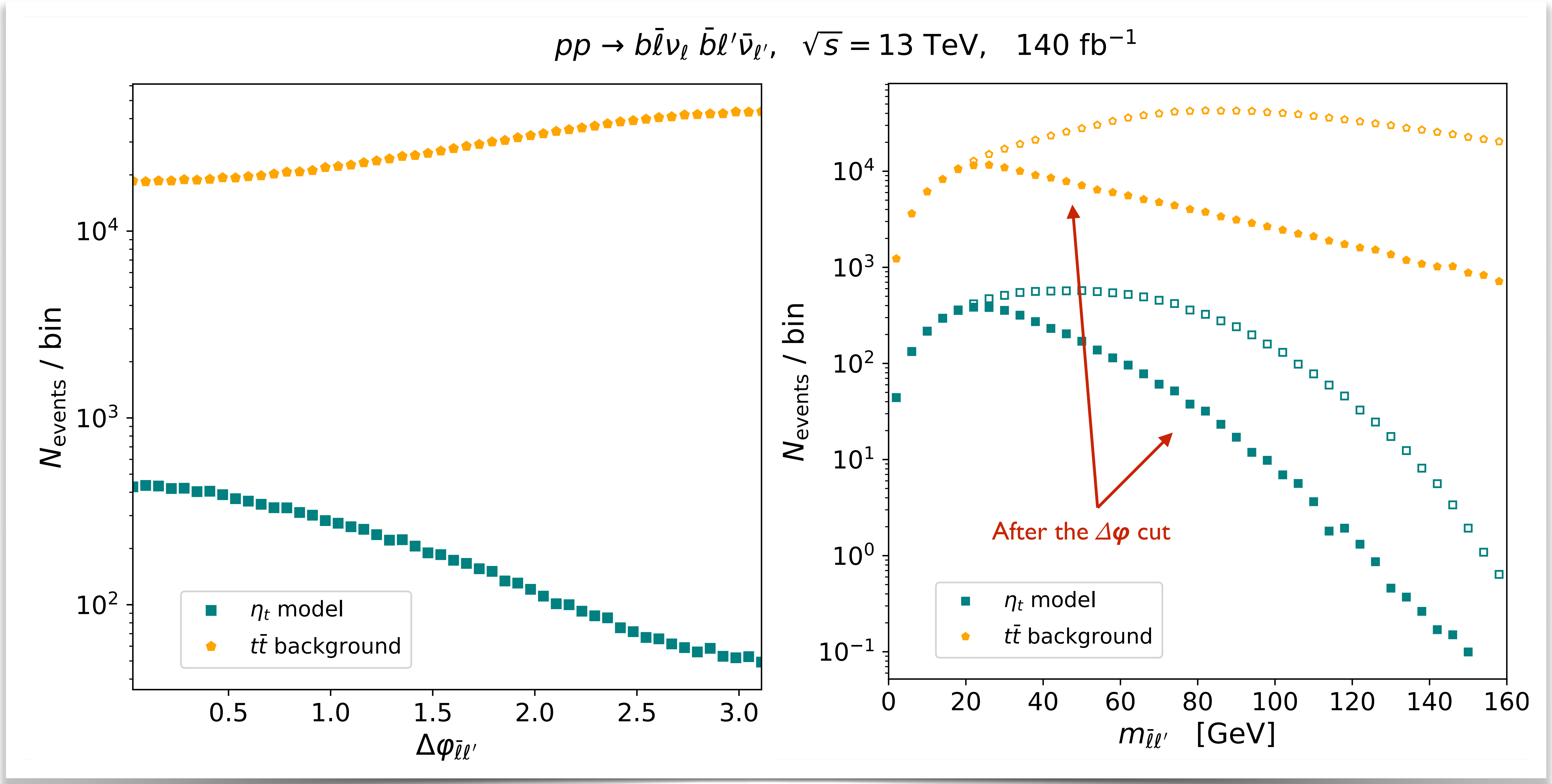
13 TeV, 140/fb

Cut	$t\bar{t}$	Toponium	Ratio
Initial	113,000,000	900,000	0.0079
Di-lepton	1,370,000	10,300	0.0076
$\Delta\varphi_{\bar{\ell}\ell'}$	178,000	4,060	0.023
$m_{\bar{\ell}\ell'}$	77,900	2,760	0.035

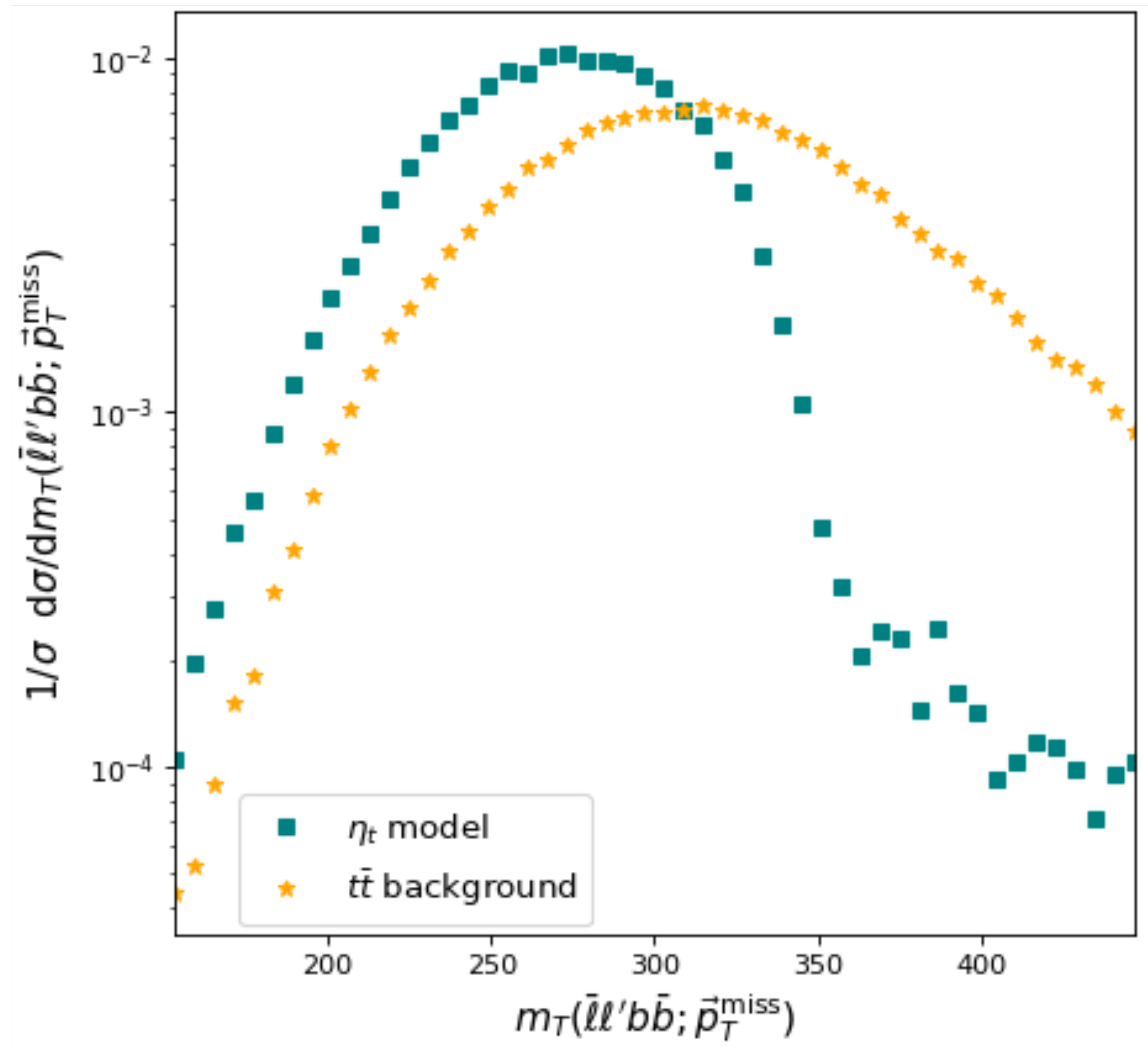
→ Further background rejection needed



Cornering toponium formation at the LHC

Insights from the entire toponium system

- The $\ell^+\ell^- b\bar{b} + E_T^{\rm miss}$ system produced at low transverse mass (m_T < 320 GeV)



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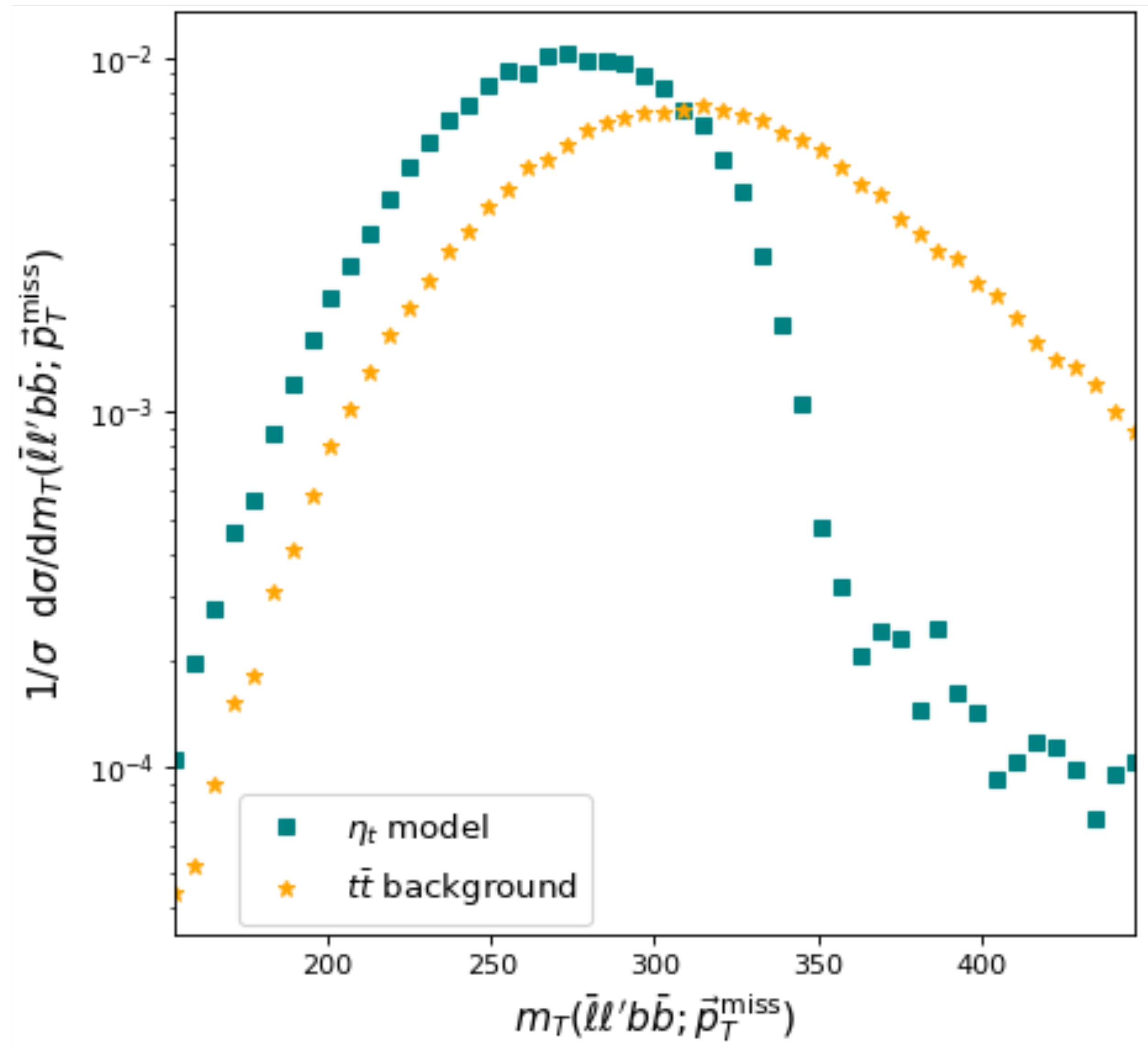
Kinematical reconstruction of the toponium system

- Toponium decaying into a light and a heavy (off-shell) top ($\eta \to t_L\, t_H$)
  - ➞ Assumption: equal p_T sharing $\mathbf{p}_T(t_H) = \mathbf{p}_T(t_L)$
- Identification of all final-state objects
  - ➞ ℓ_1 is the leading lepton, ℓ_2 the sub-leading one
  - ➞ *b*-jet pairing: enforcing $m(\ell_1, b_1) > m(\ell_2, b_2)$
- Determination of the neutrino momenta
  - ➞ *W* mass ⊕ top mass ⊕ ν mass ⊕ $\boldsymbol{p}_T$ assumptions
- '*top*' reconstruction (t_L/t_H)



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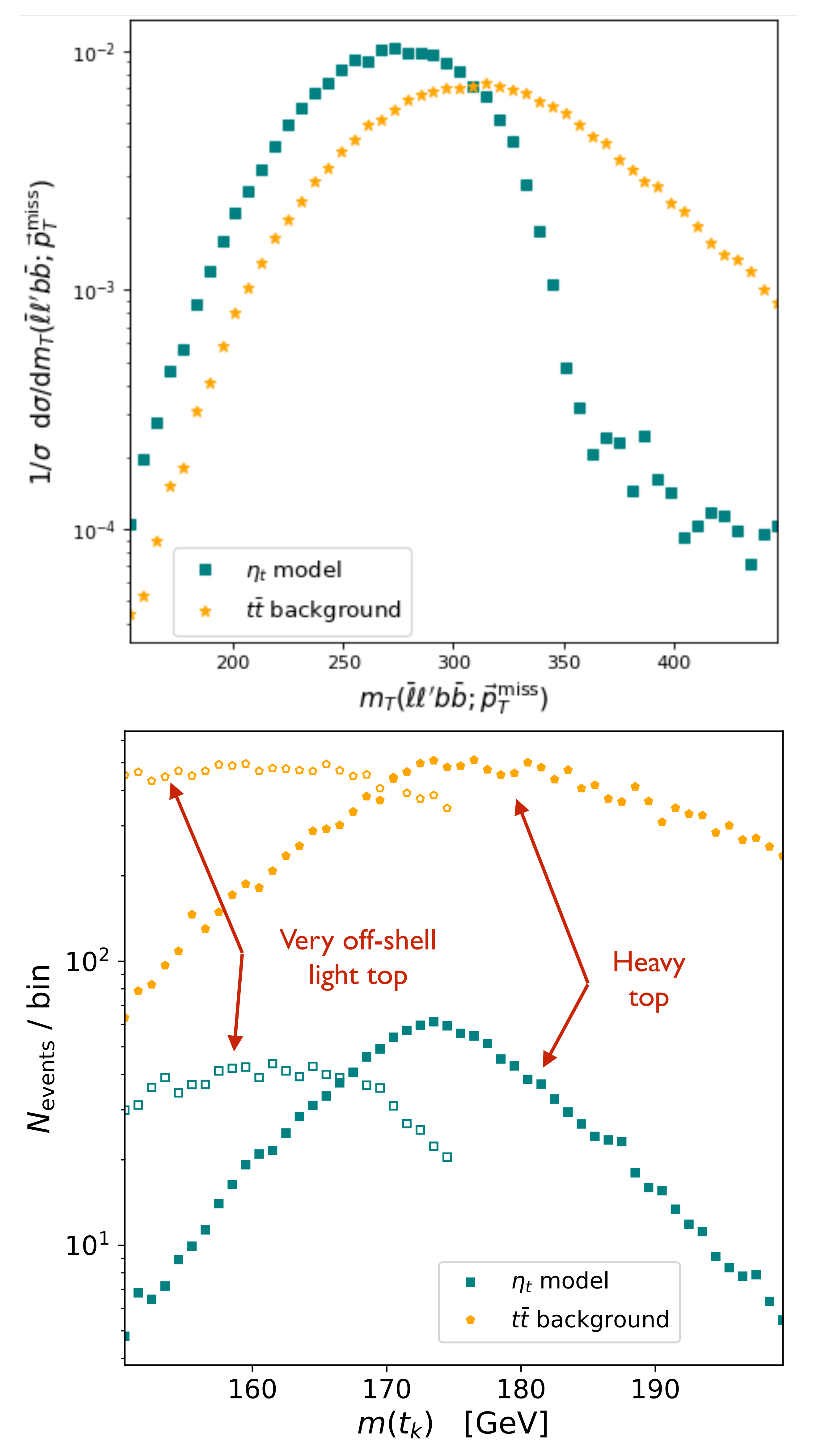

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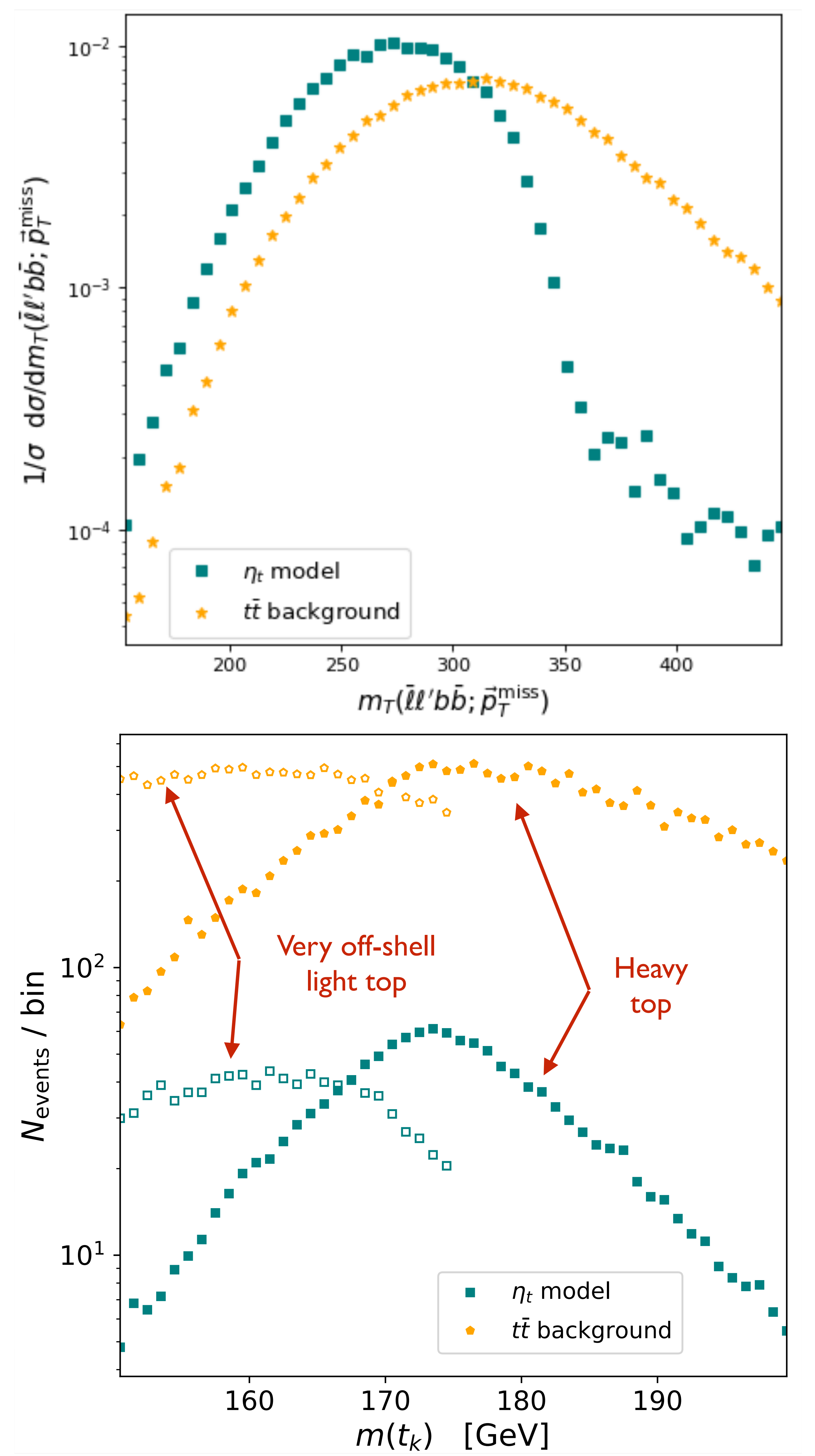
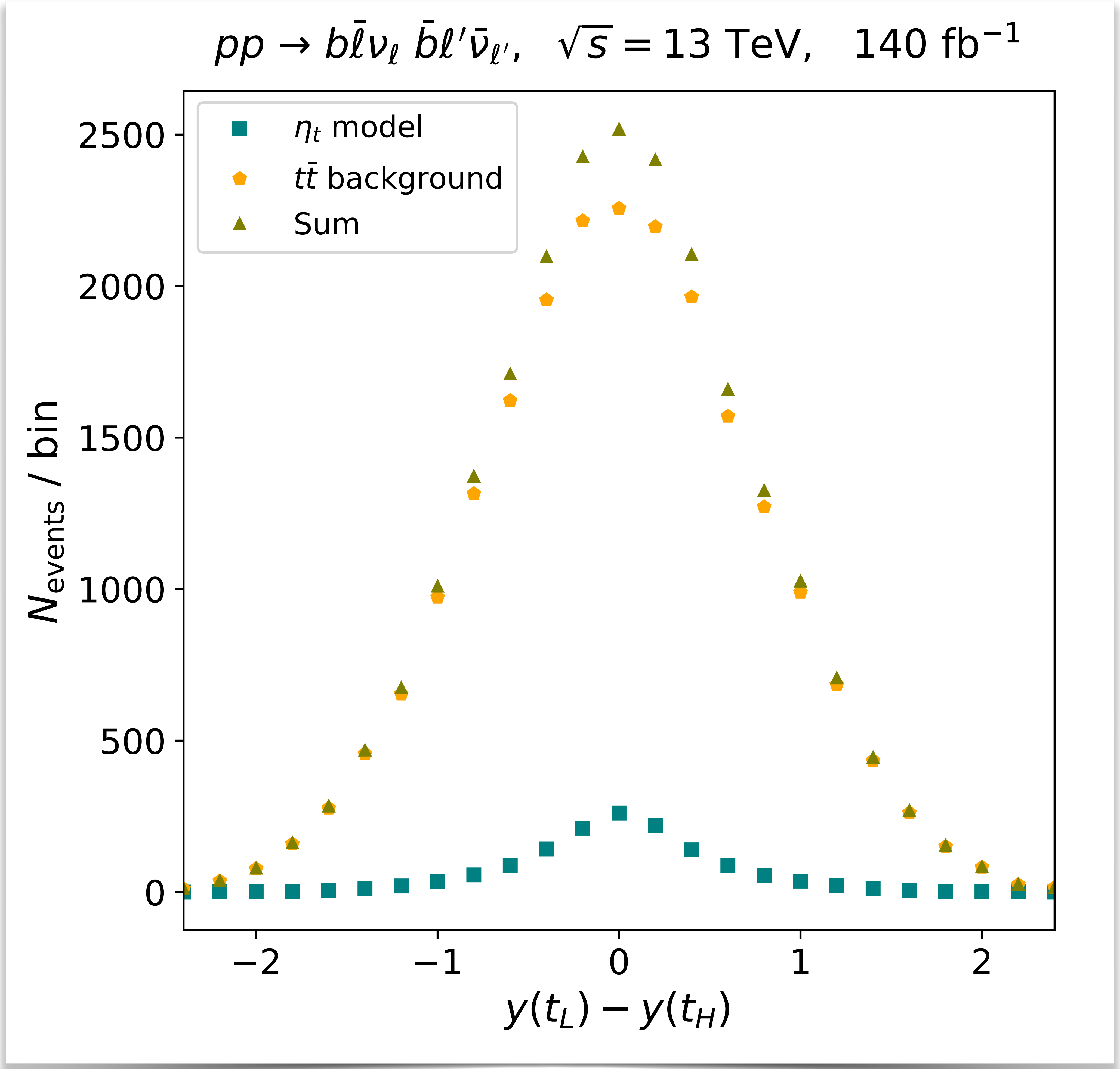
$m_{\bar{\ell}\ell'}$	77,900	2,760	0.035
$m_T(\bar{\ell}\ell' b\bar{b}; \nu_\ell \bar{\nu}_{\ell'})$	40,800	2,460	0.060
$t\bar{t}$ kinematical fit	20,400	1,420	0.070



Key observable for toponium discovery



The rapidity difference distribution

- Peak at the origin
  - ➙ small and similar t_L/t_H momentum in the η rest frame
- Toponium effects ≡ 10% enhancement near $\Delta y = 0$

Impossible to miss?

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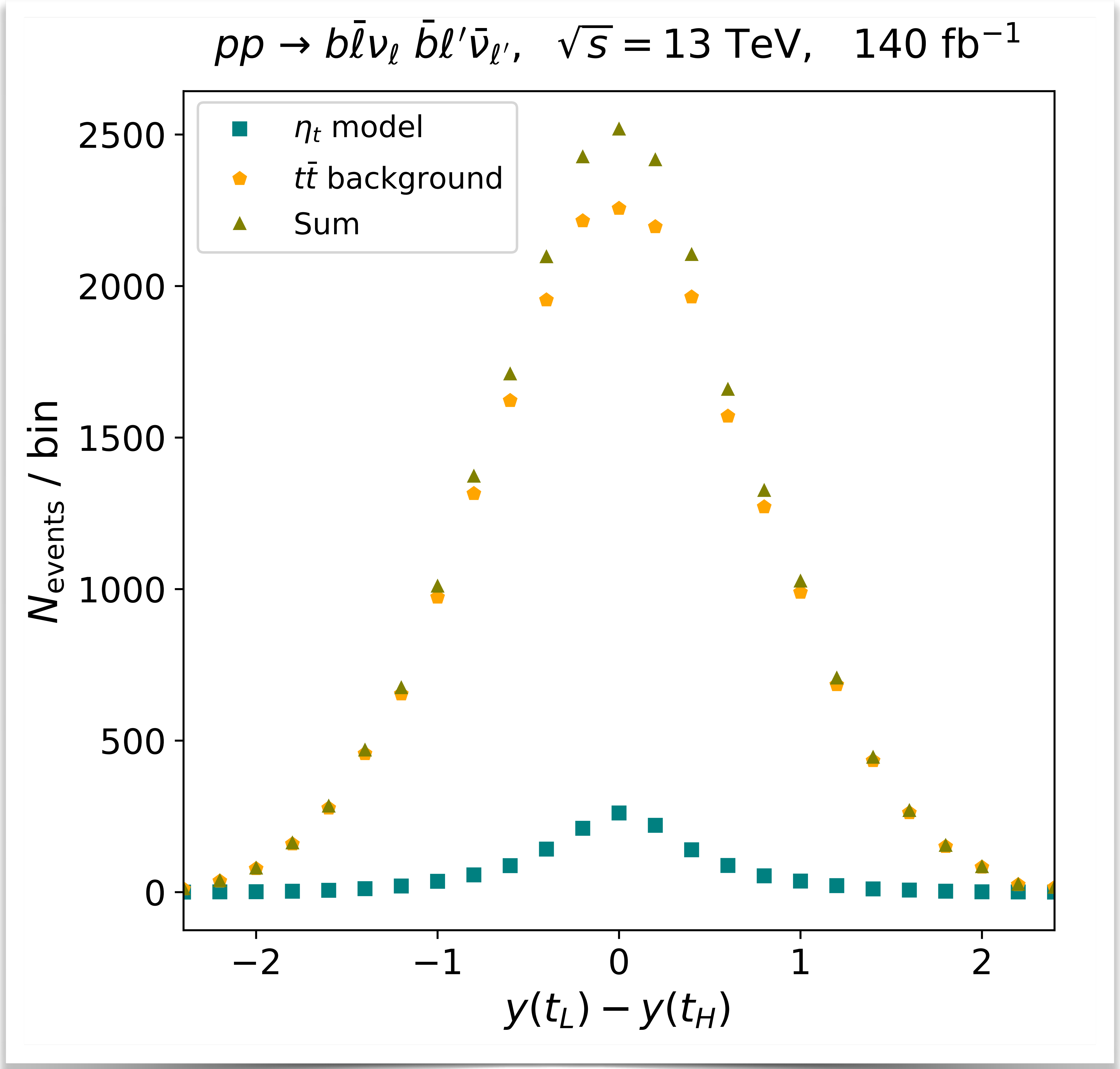

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Remark

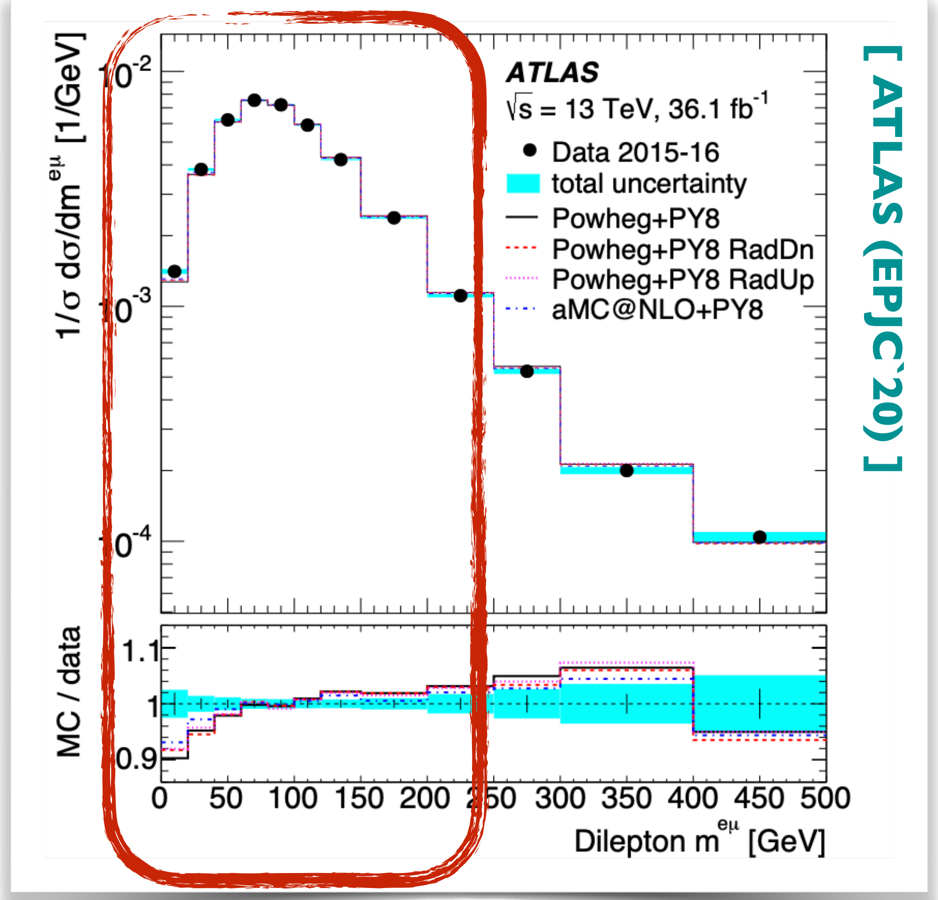
- Results obtained on the basis of a toy-model
- Strong motivation for a better calculation
  → all effects included in the modelling
  → on-going efforts…

Summary

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

- Resummation of Coulomb singularities $(\alpha_s/\beta)^n$ in the pNRQCD framework
- Replacement of top-propagators in $gg \to WbWb$ matrix elements
  ➙ Free Green's functions by counterparts including bound state effects

$$\frac{1}{E - \frac{\mathbf{p}^2}{M_t} + i\frac{\Gamma_\theta}{2}} \quad \Rightarrow \quad \langle \mathbf{p} | \frac{1}{E - \frac{P^2}{M_t} - V(r) + i\frac{\Gamma_\theta}{2}} | \mathbf{x} = 0 \rangle$$



Impact at the LHC: investigation of the di-leptonic mode ($pp \to t_L t_H \to \ell^+\ell^- b\bar{b} + E_T^{\rm miss}$)

- Toponium formation ➙ events at small $\Delta\varphi_{\ell\ell}$ and small $m_{\ell\ell}$
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  ➙ fake excesses due to SM background mis-modelling

Path towards a toponium discovery
[our work: Hagiwara, BF, Ma & Zhang (PRD 104 (2021) 034023)]

- A simple description for spin-0 toponium modelling
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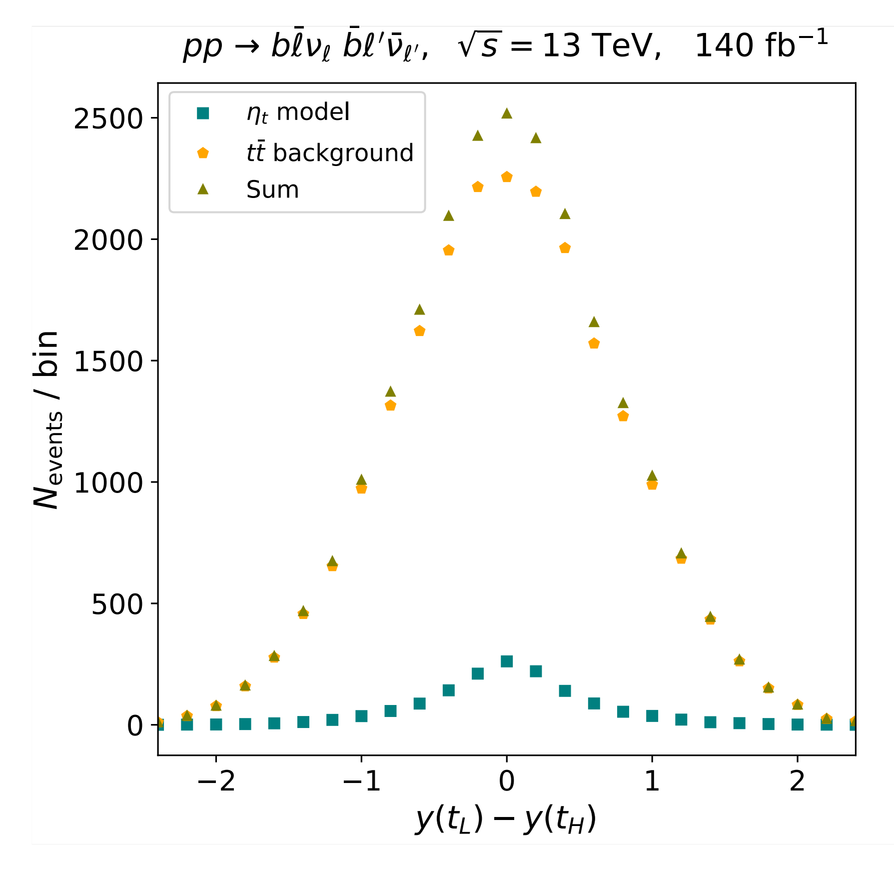

Hagiwara, BF, Ma & Zhang (PRD'21)

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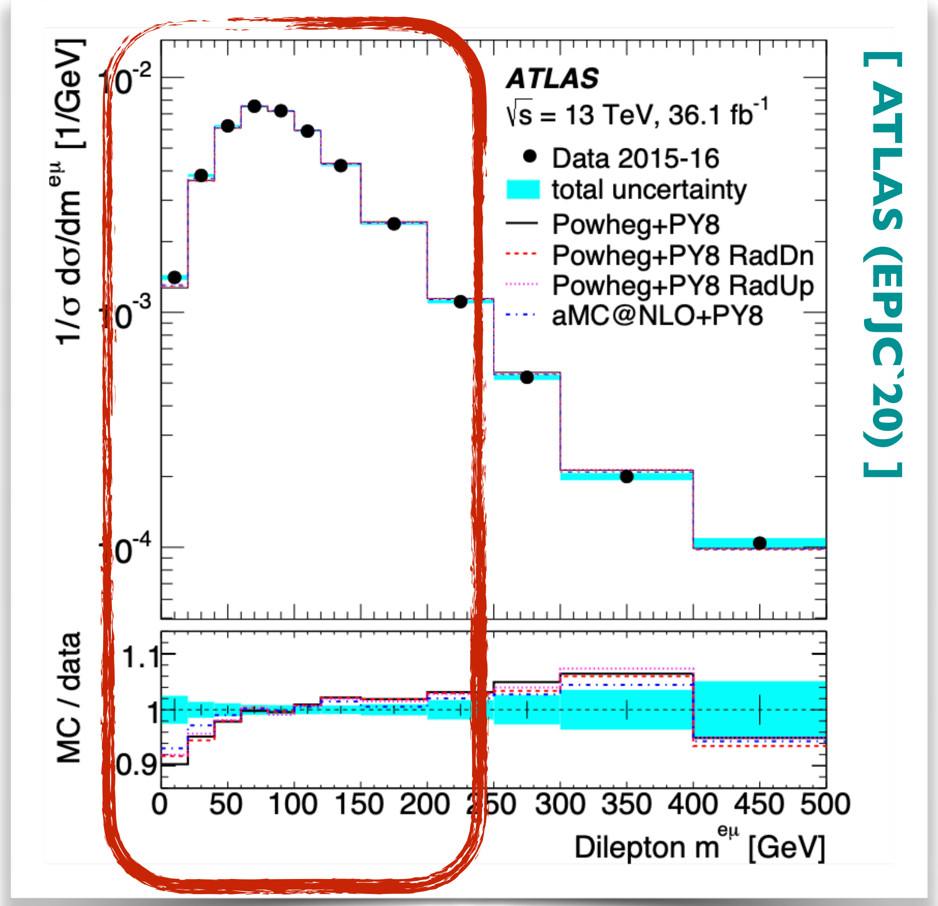

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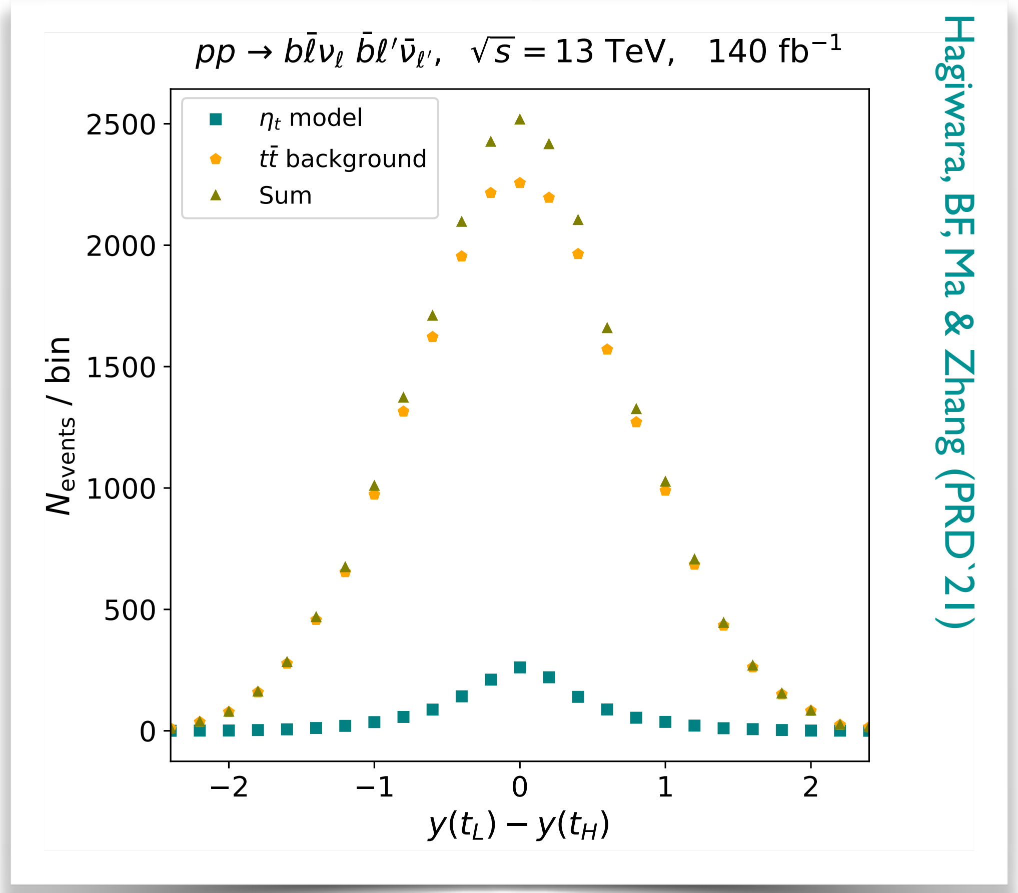

Outlook:

- Beyond the toy model
- Higher-spin contributions
- Tests again data
  (also: $t\bar{t}$ spin correlations)