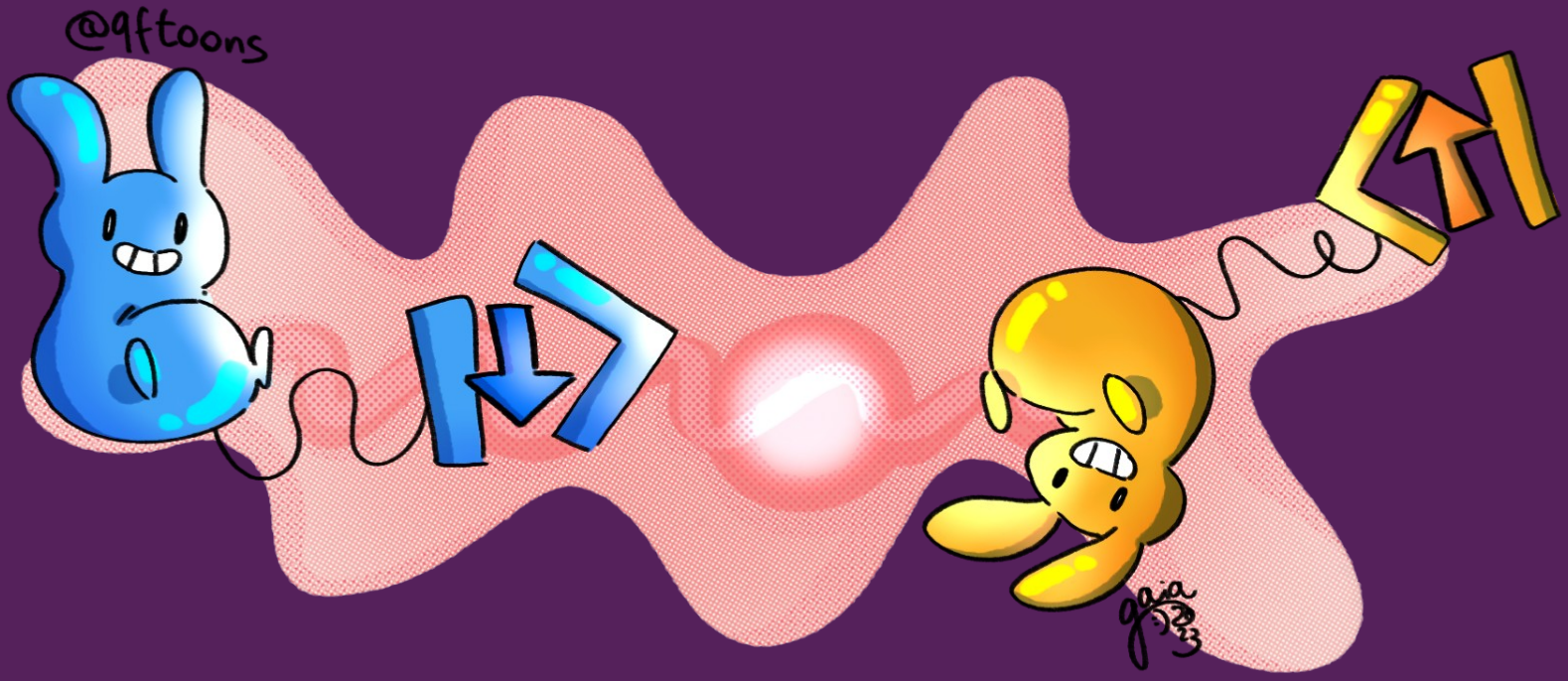
Threshold and bound state effects in top pair production



Drawings by Gaia Fontana @QFToons

26/04/24 Claudio Severi - U. Manchester

Threshold and bound state effects in top pair production

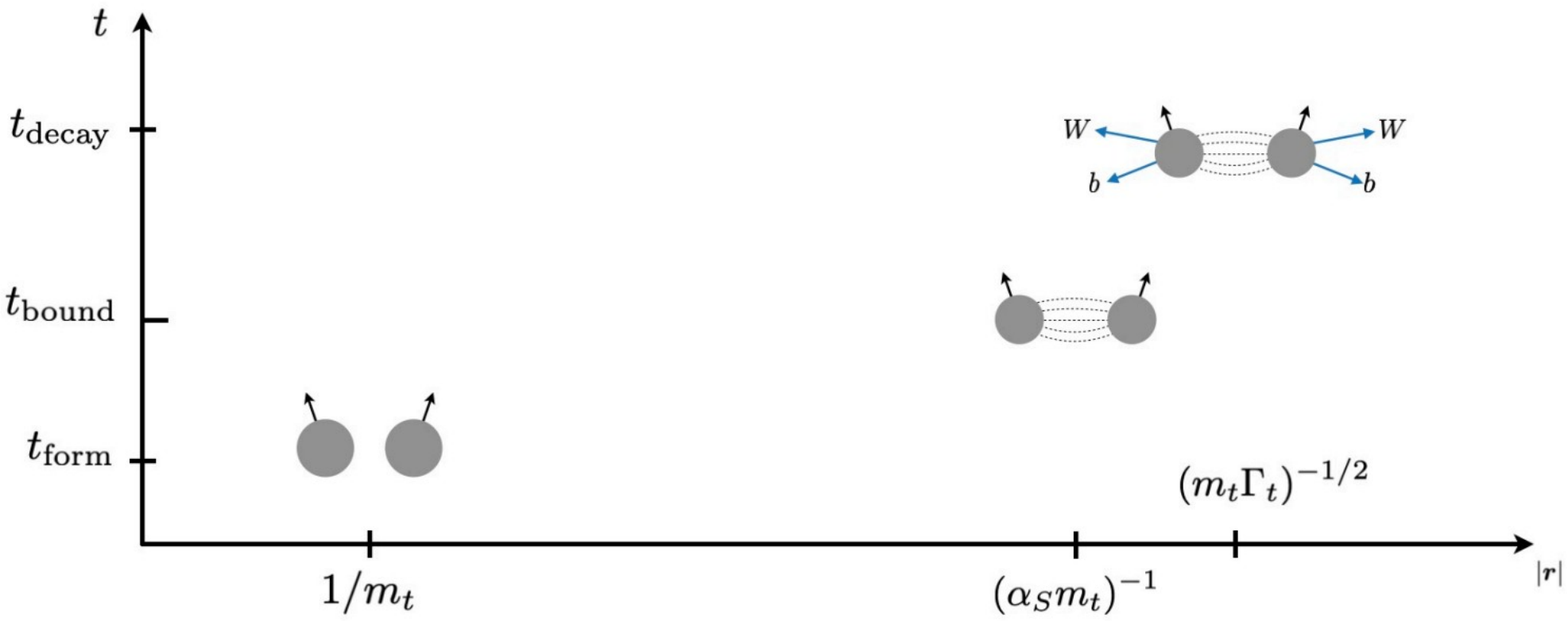
Y.Sumino et al, PRD47, 56 (1992)
K.Hagiwara et al, PLB 666 (2008)
Kiyo et al, EPJC 60 (2009)
F.Bach et al, JHEP 03 (2018) 184
Ju et al, Chin.Phys.C 44 (2020) 9
B. Fuks et al, Phys.Rev.D 104 (2021) 3
F.Maltoni et al, JHEP 03 (2024) 099 and 2404.08049
R.Aoude et al, *in preparation*

MANCHESTER 1824
The University of Manchester

Funded by the European Union

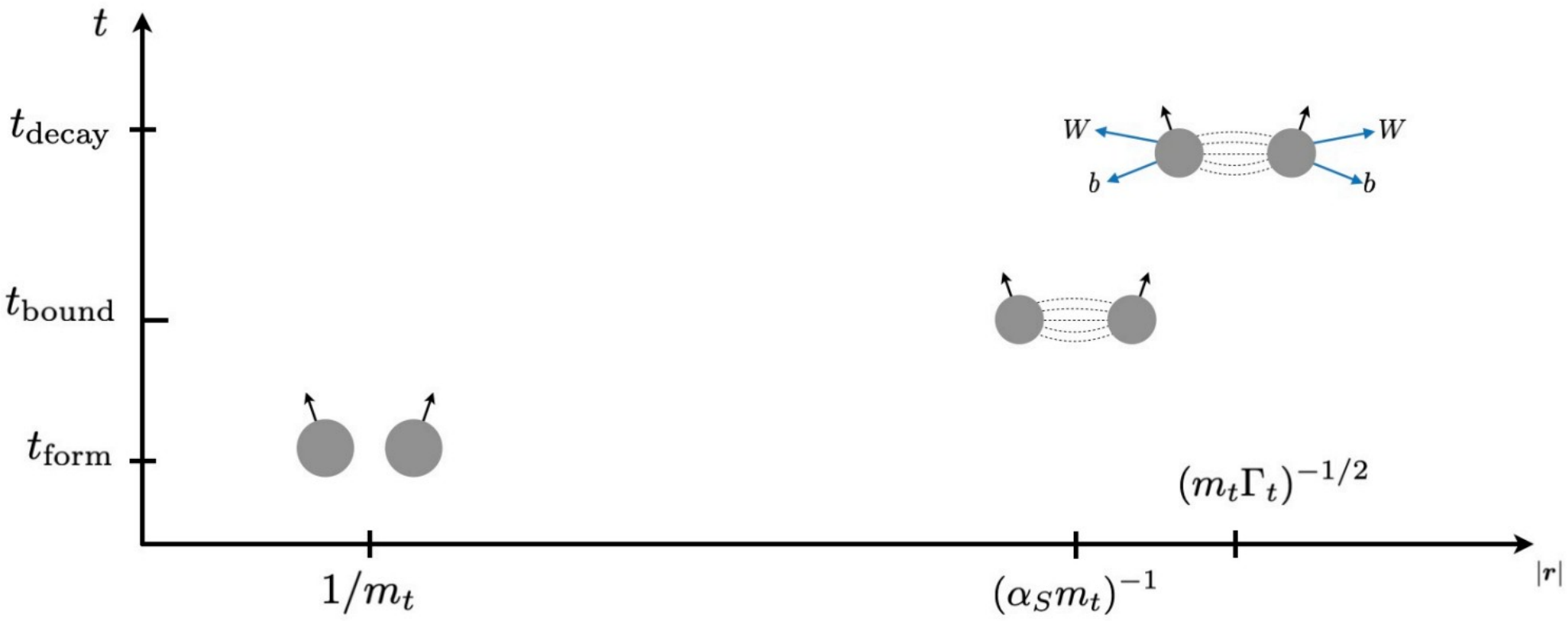
Toponium

"bound" state of two top quarks



artwork by Rafael Aoude

Toponium "bound" state of two top quarks



artwork by Rafael Aoude

Lifetime driven by top lifetime ---> width $2\Gamma_t$

Sumino et al, PhysRevD.47.56 1992

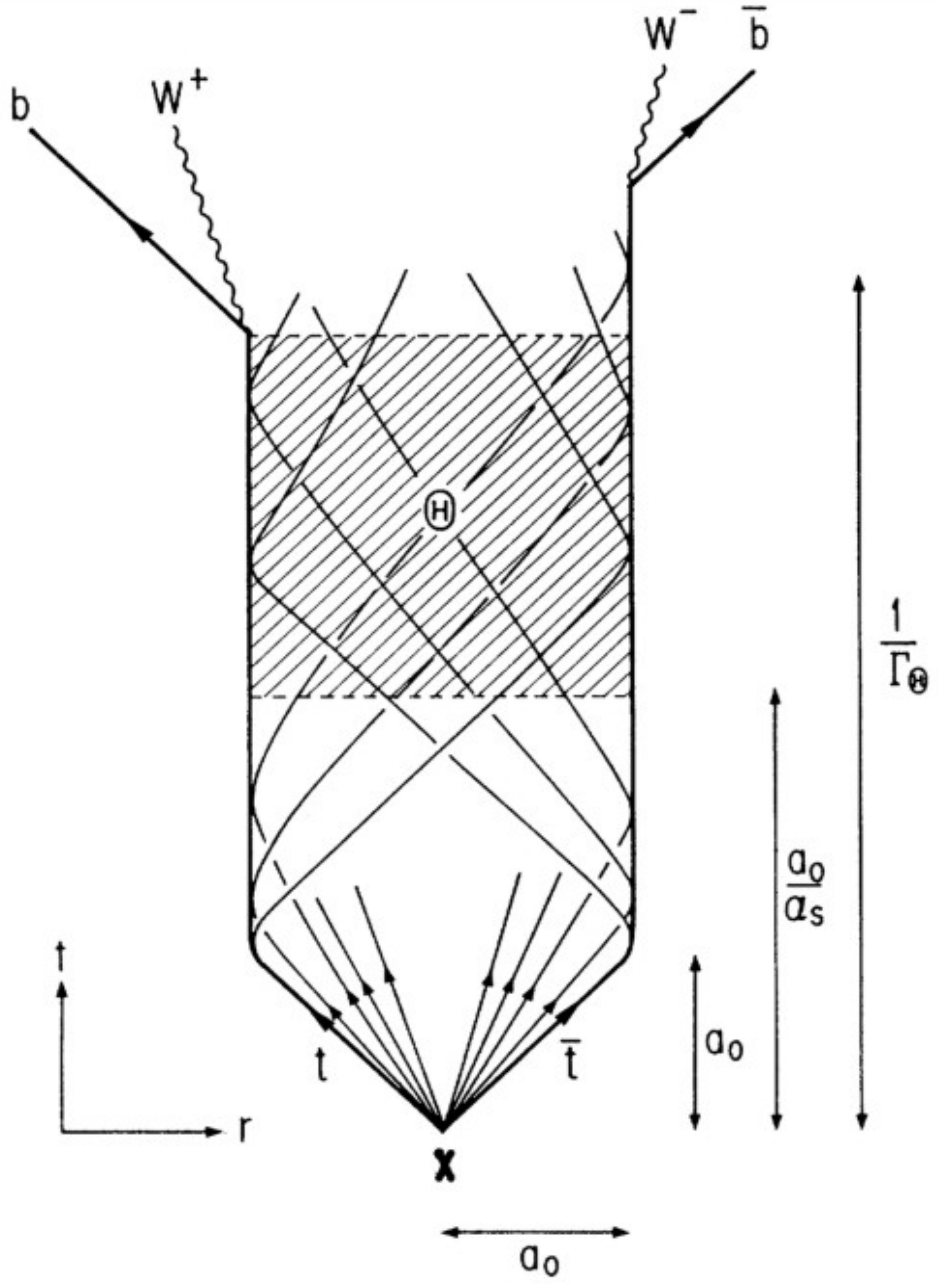


FIG. 2. A figure that shows the time evolution of the non-relativistic $t\bar{t}$ system.

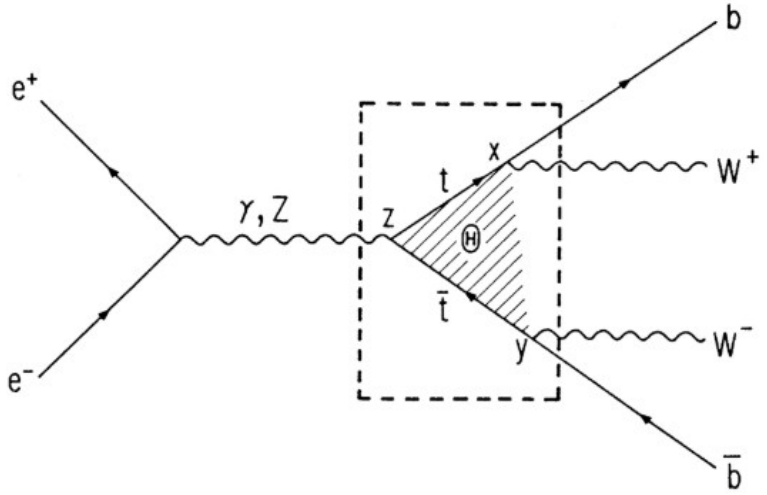


FIG. 1. The diagram for the $t\bar{t}$ pair production process and their subsequent decays into bW's. The box with the dashed line shows the three-point function $K(x,y,z)$ that carries the information of the toponium resonance.

Simple way to model:

Schroedinger equation with potential

$$\left[(E+i\Gamma_t)-\left(\frac{\boldsymbol{\nabla}^2}{m_t}+V(\boldsymbol{r})\right)\right]G(\boldsymbol{r},E+i\Gamma_t)=\delta^{(3)}(\boldsymbol{r})$$

- Non-relativistic
  fine at/near threshold
  needs to be matched into the continuum
- Takes into account top lifetime by replacing E -> E + i Γ

QCD potential:

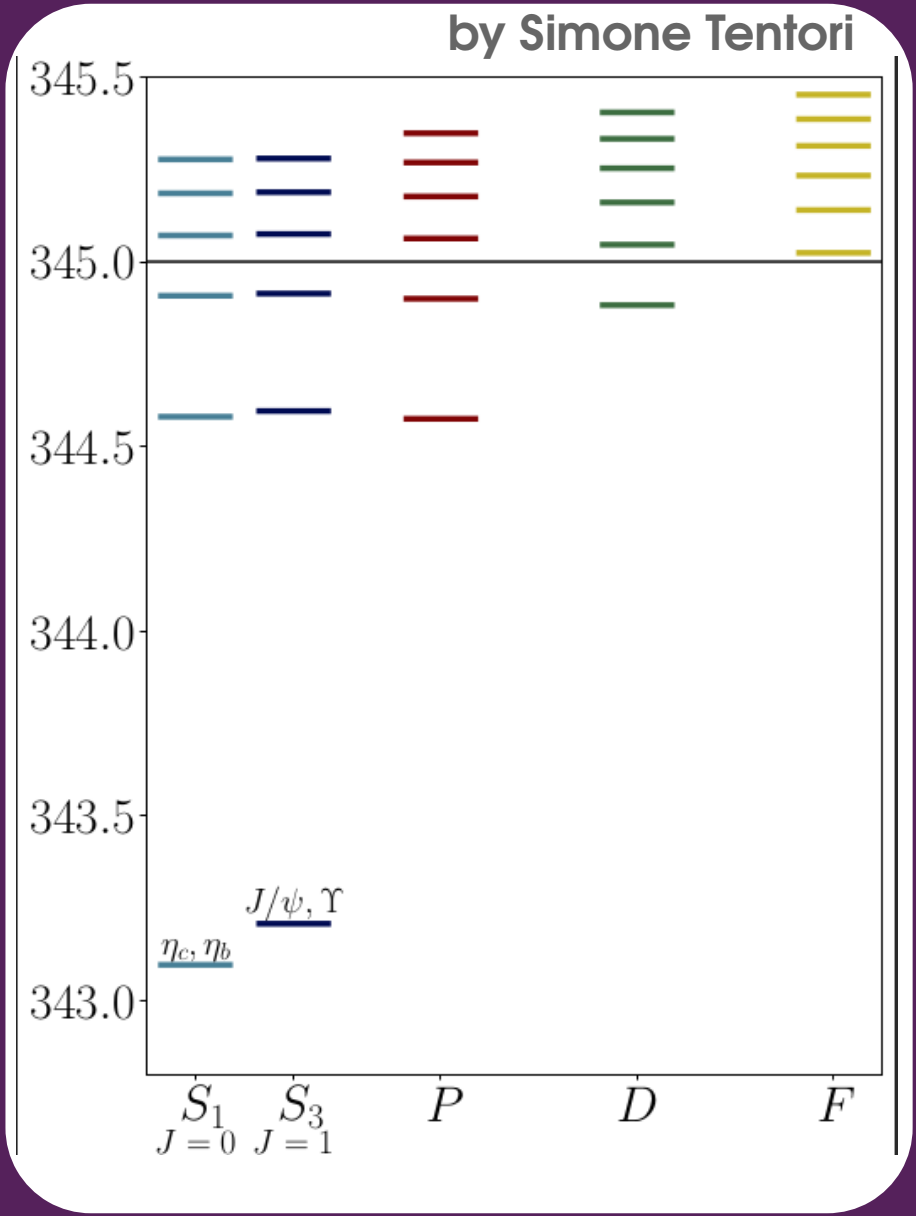
$$V_{\rm QCD}(r,\mu_B)=C^{[\rm col]}\,\frac{\alpha_s(\mu_B)}{r}\left[1+\frac{\alpha_s}{4\pi}\left(2\,\beta_0\log(e^\gamma\mu_B\,r)+\frac{31}{9}C_A-\frac{10}{9}n_f\right)+\mathcal{O}(\alpha_s^2)\right],$$

$$C^{[\,\mathbf{1}\,]}=-C_F=-4/3 \qquad C^{[\,\mathbf{8}\,]}=C_A/2-C_F=1/6$$

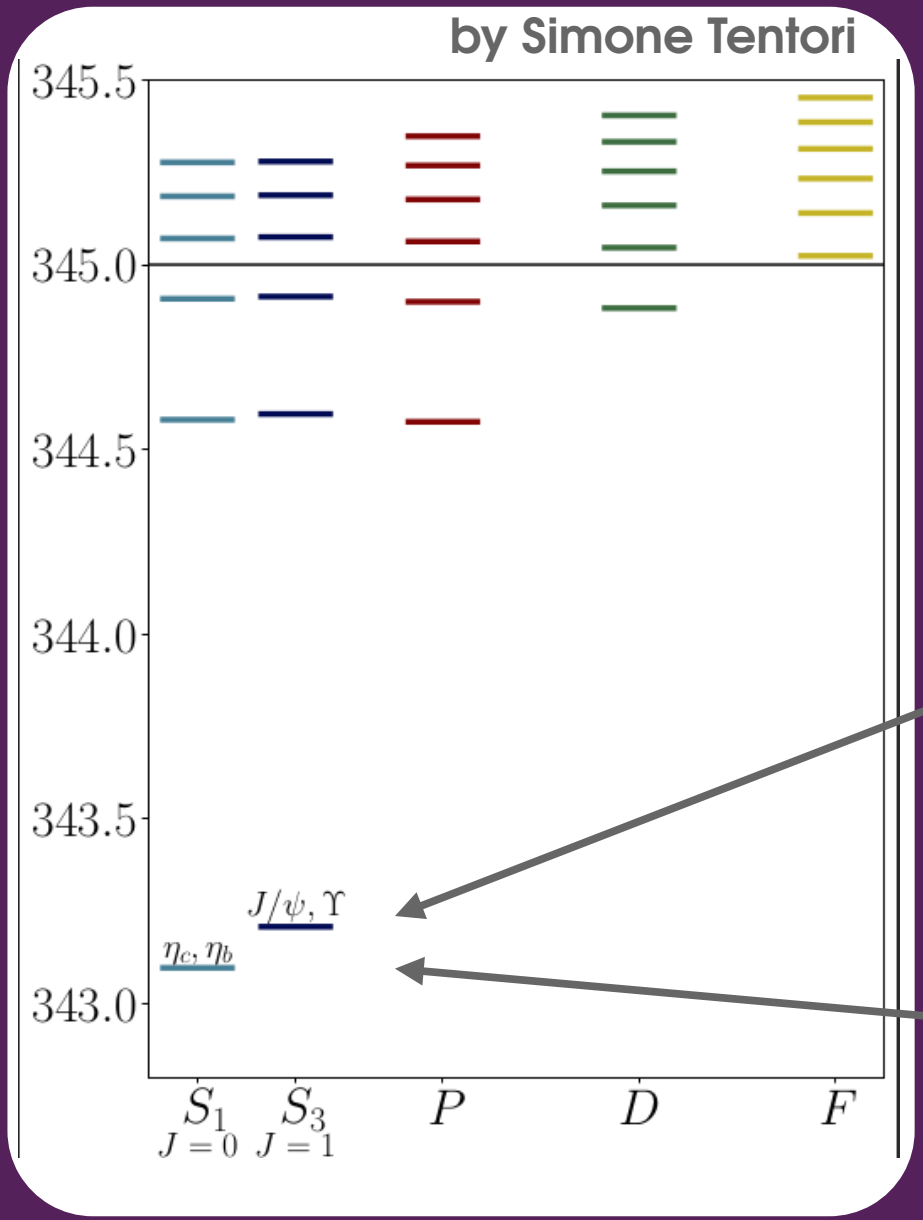
Known much more accurately than this, Hoang Teubner Phys.Rev.D 60 (1999)

In practice the calculation is done using EFT methods in nrQCD…. I'm skipping details

Energy levels predicted



Energy levels predicted



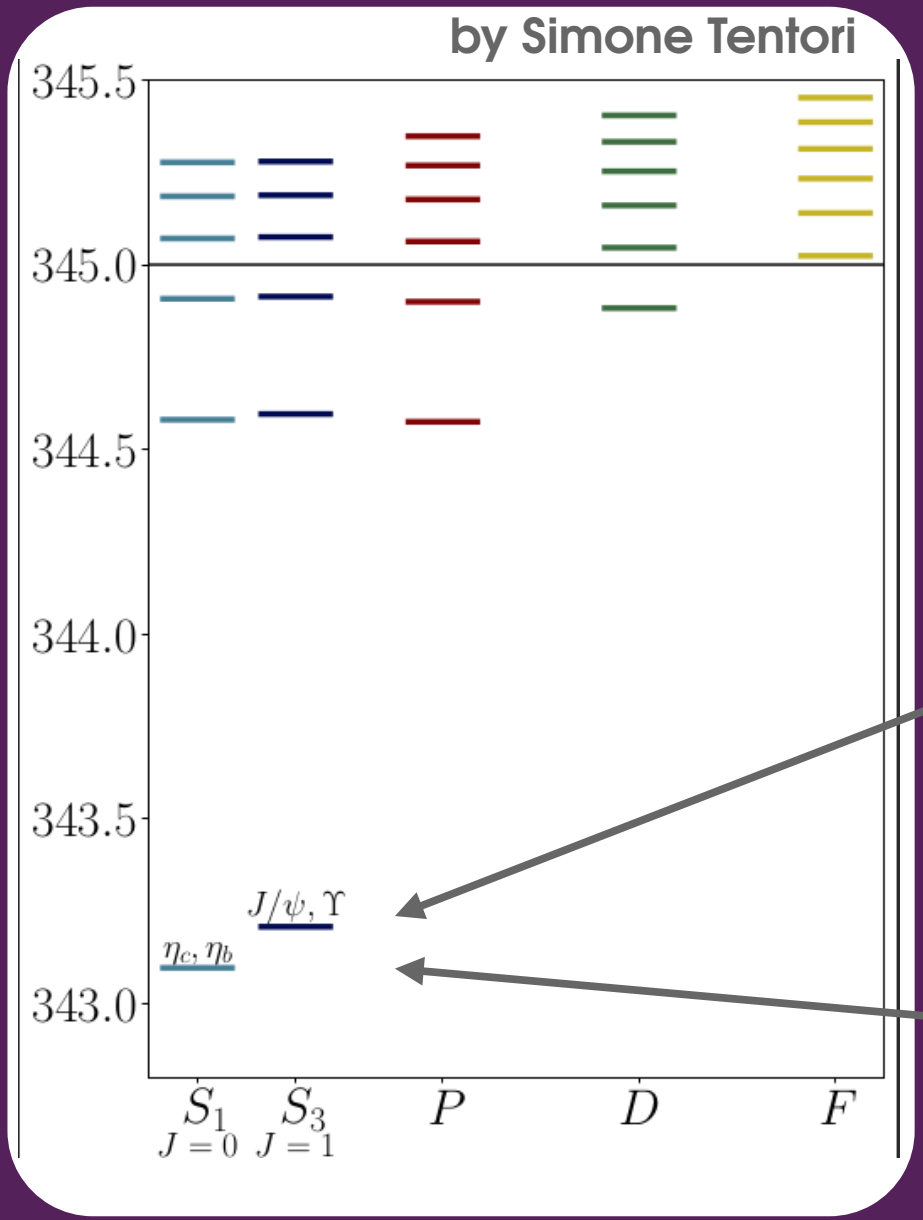
vector – like J/Ψ

D = +1/3

pseudoscalar – like η

D = -1

Energy levels predicted



invisible

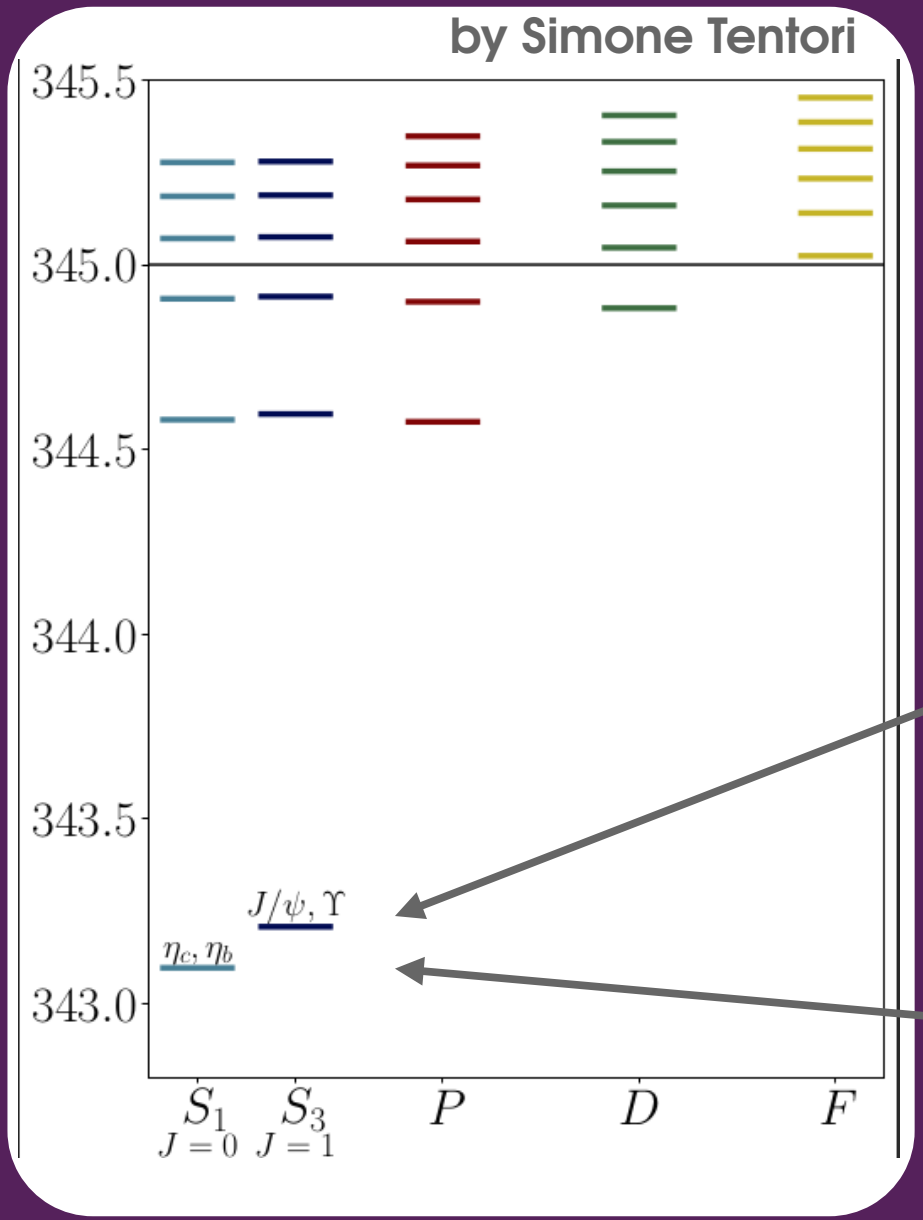
vector – like J/Ψ

D = +1/3

pseudoscalar – like η

D = -1

Energy levels predicted

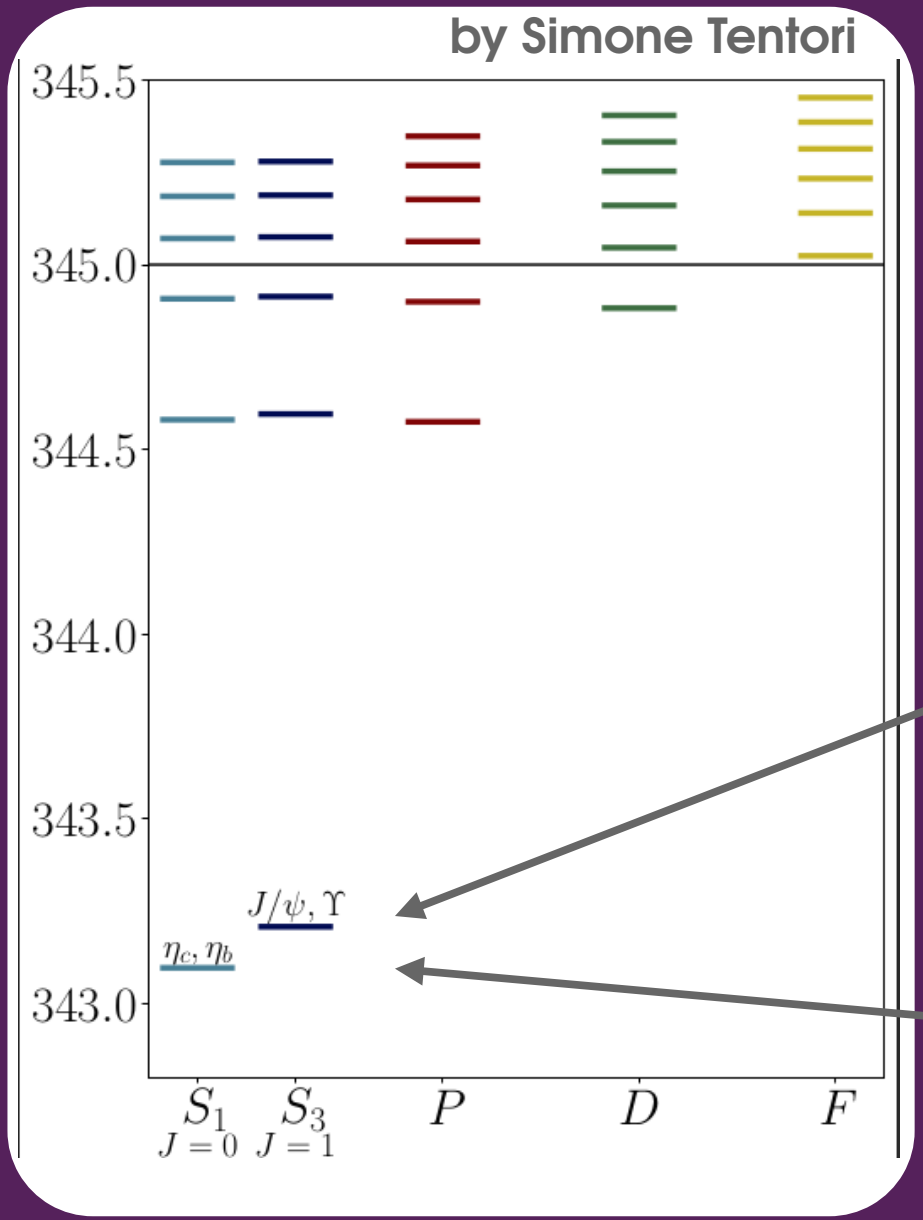


invisible

vector – like J/Ψ
D = +1/3

pseudoscalar – like η
D = -1
(visible at the LHC)

Energy levels predicted



invisible

vector – like J/Ψ

D = +1/3

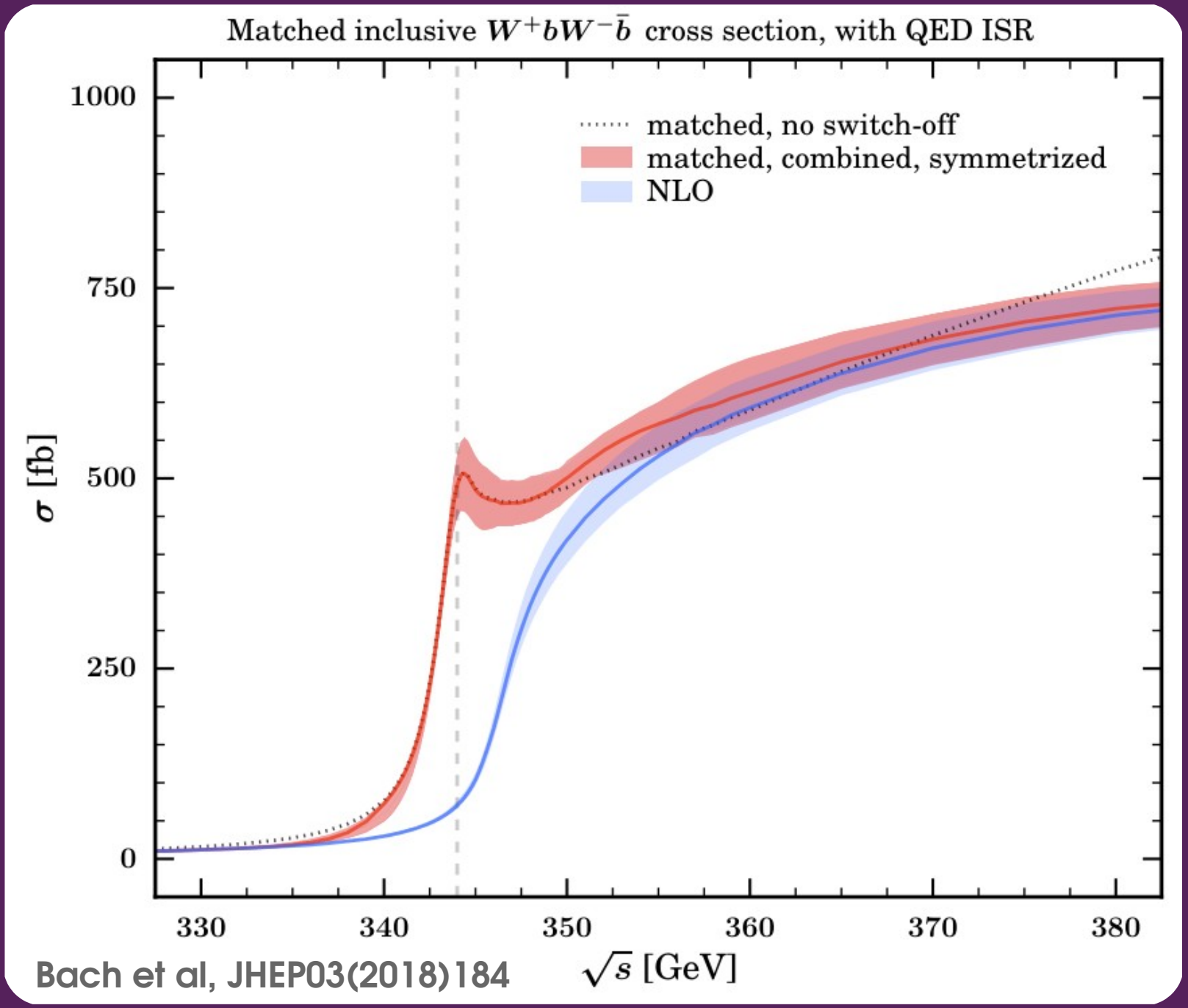
(needs an e+e-)

pseudoscalar – like η

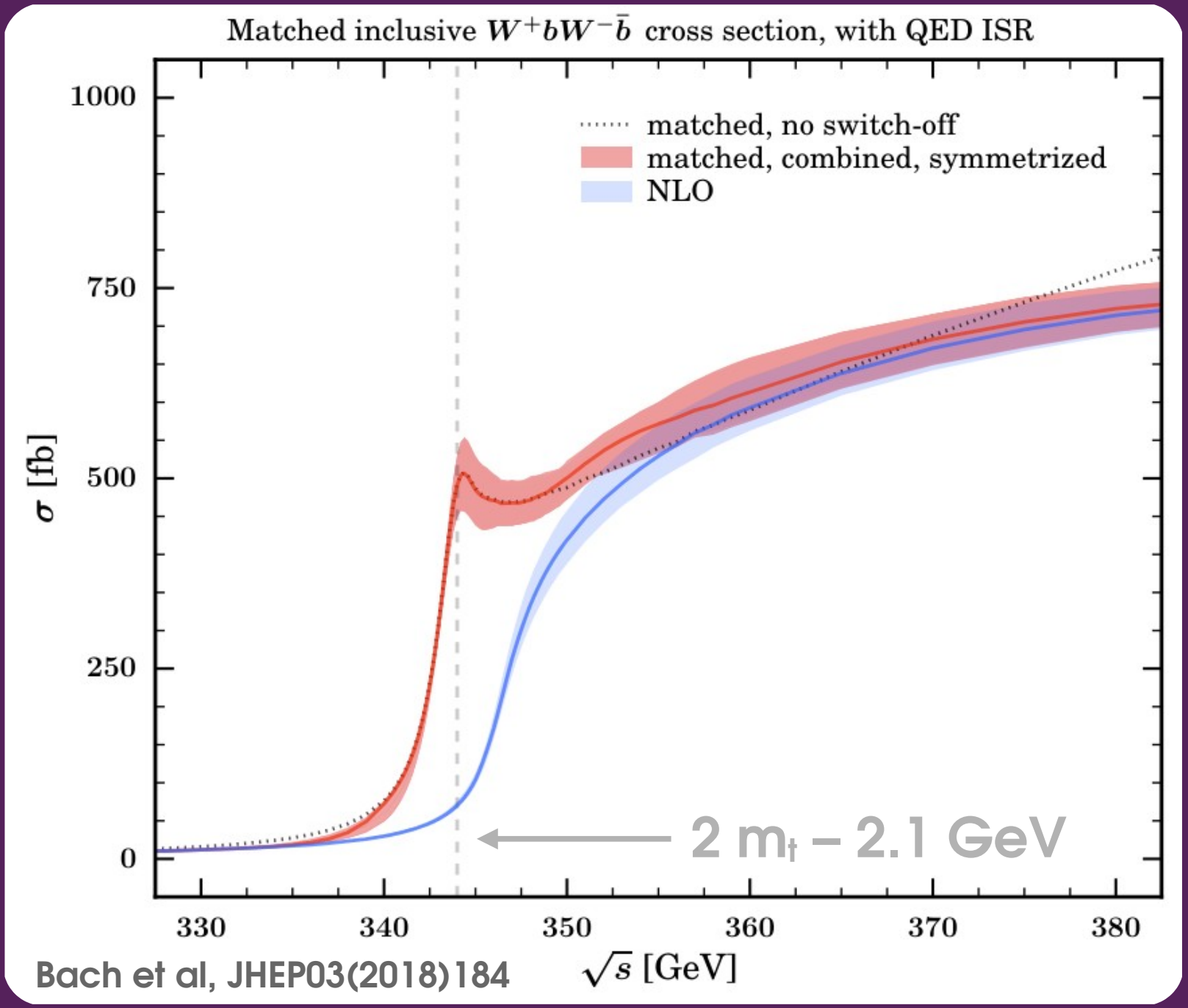
D = -1

(visible at the LHC)

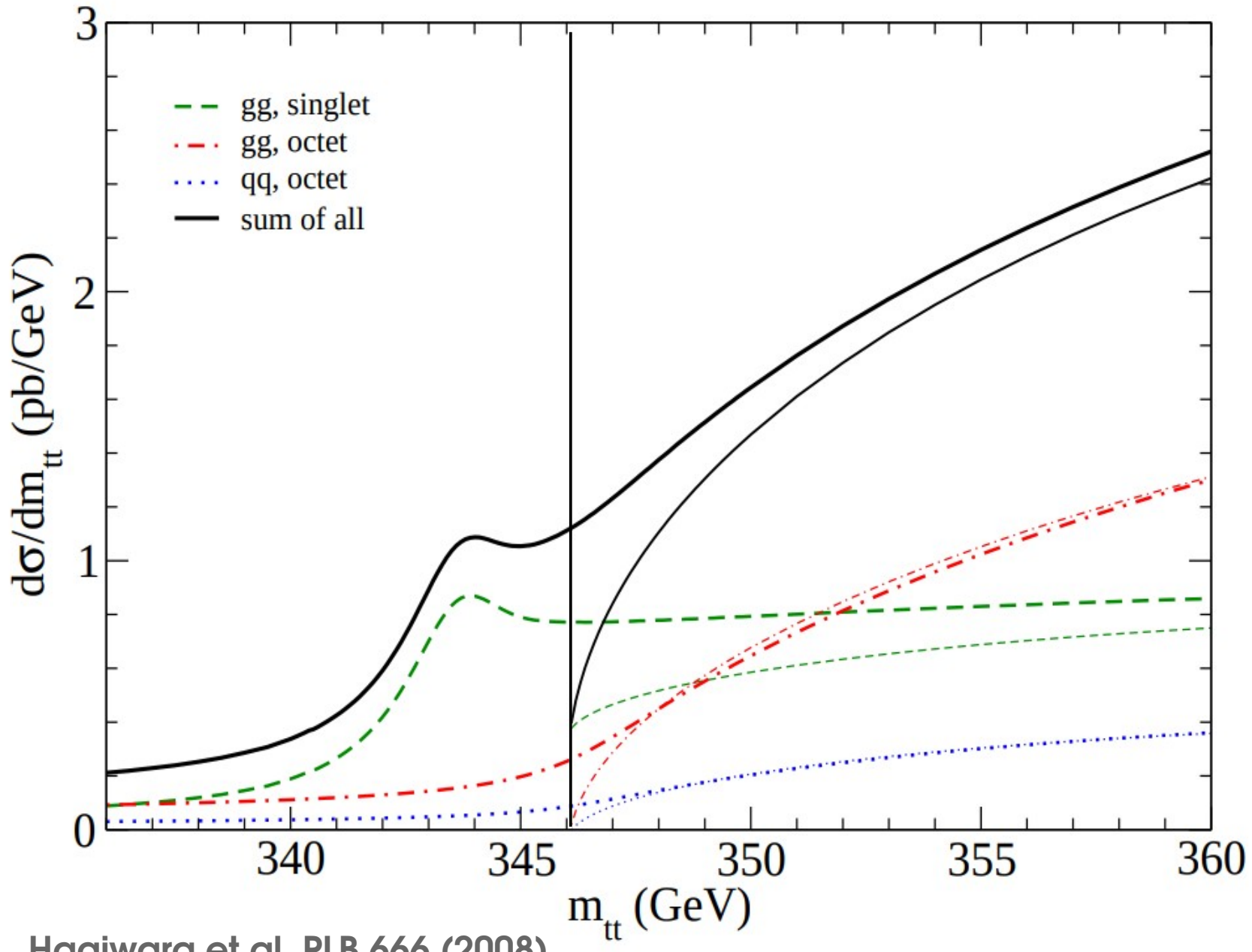
Cross-section in a e+e- threshold scan



Cross-section in a e+e- threshold scan

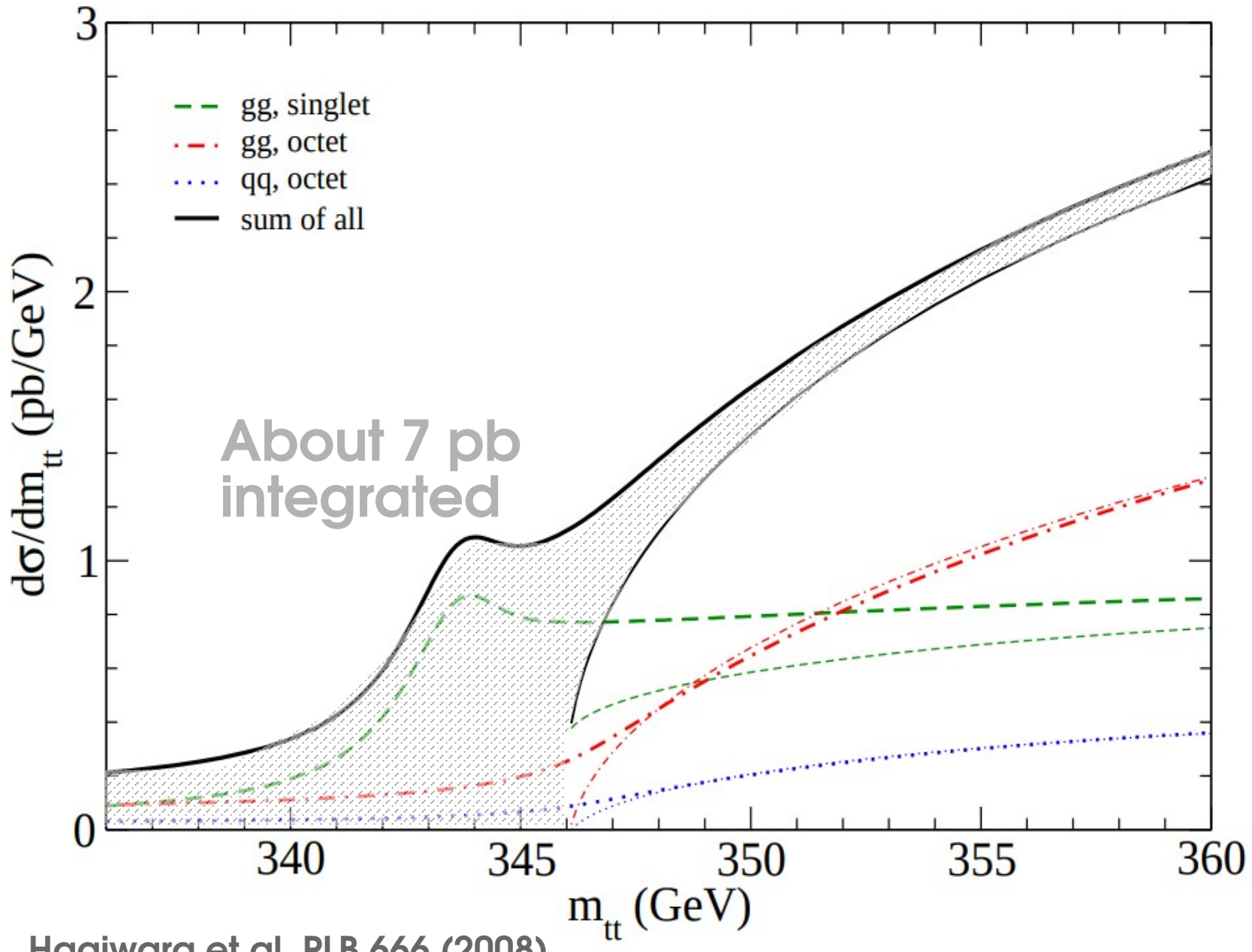


Spectrum at the LHC



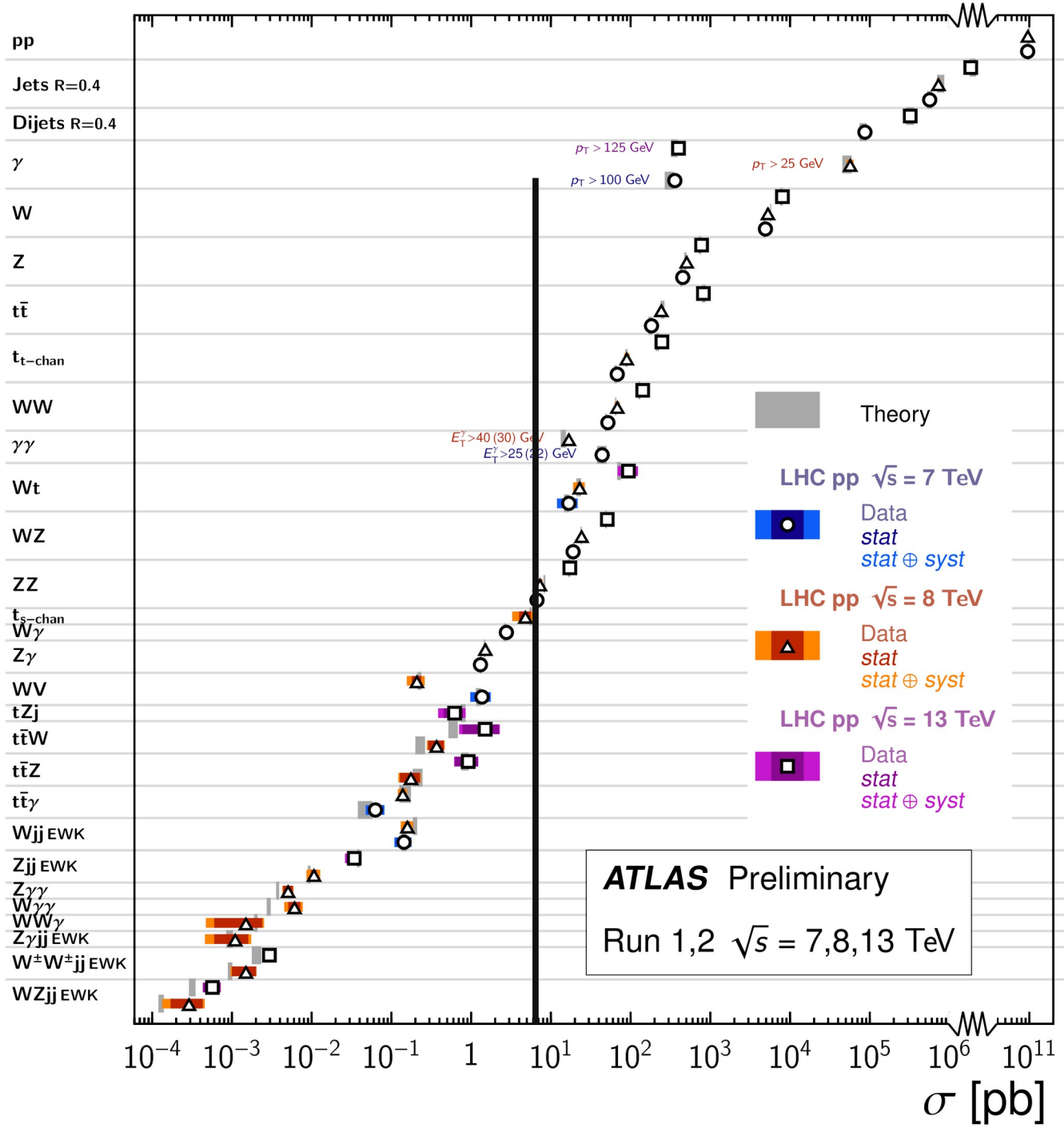
Hagiwara et al, PLB 666 (2008)

Spectrum at the LHC

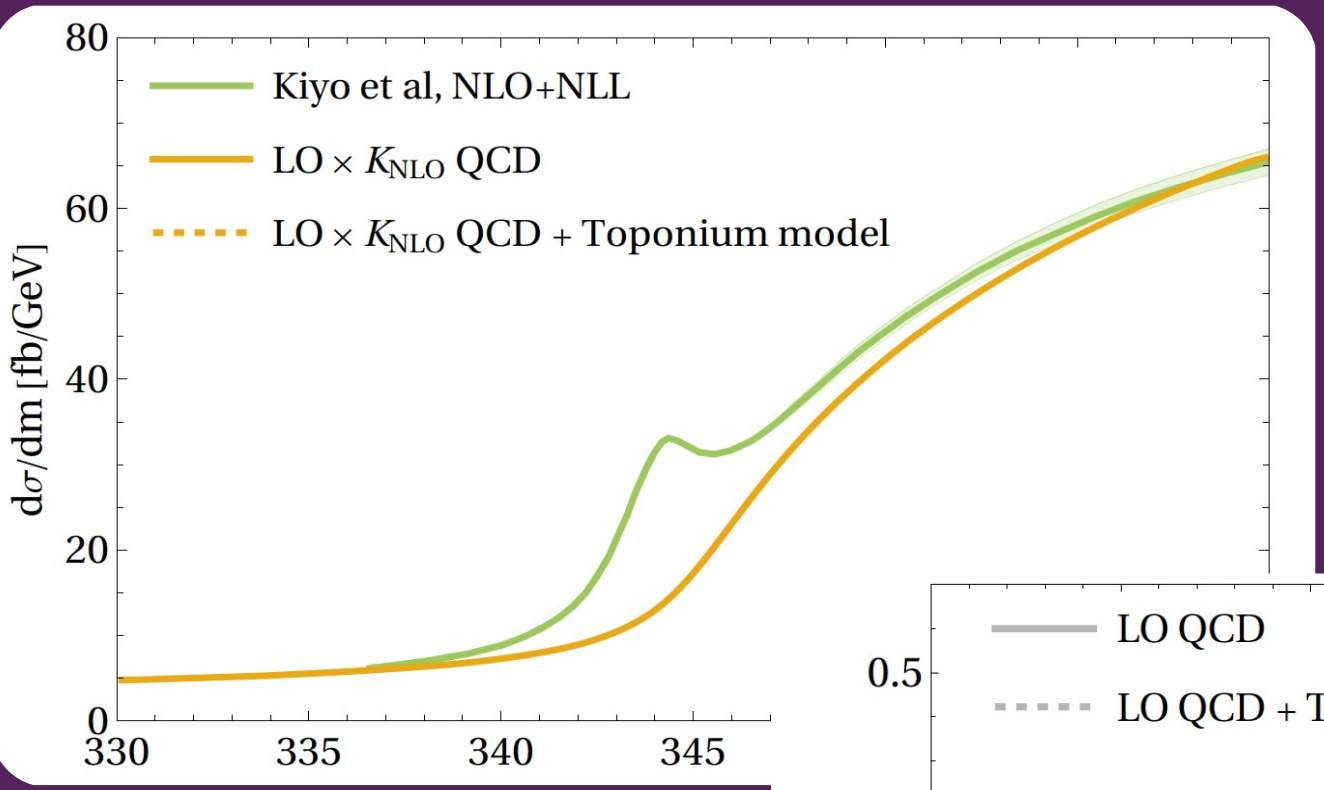


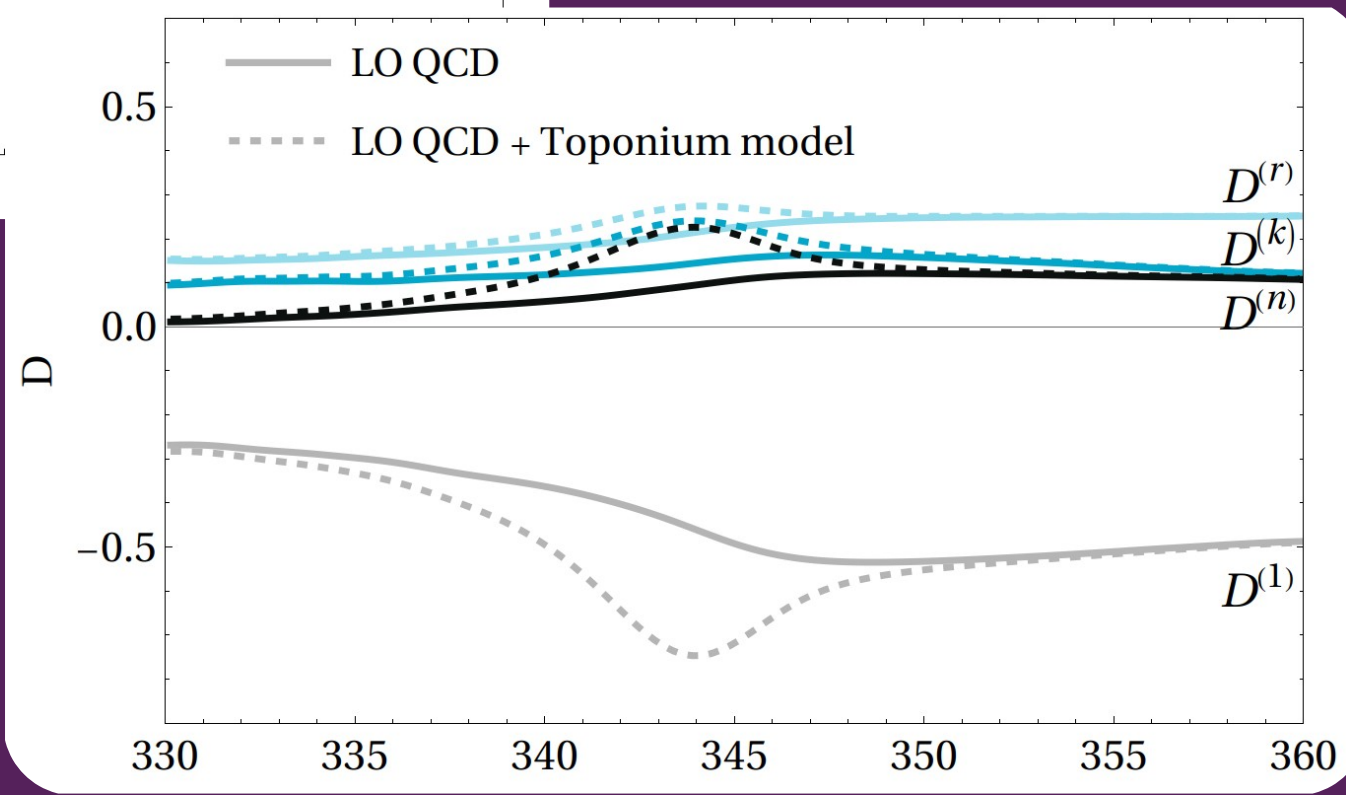
Hagiwara et al, PLB 666 (2008)

Standard Model Production Cross Section Measurements



Recap for the LHC: 2404.08049

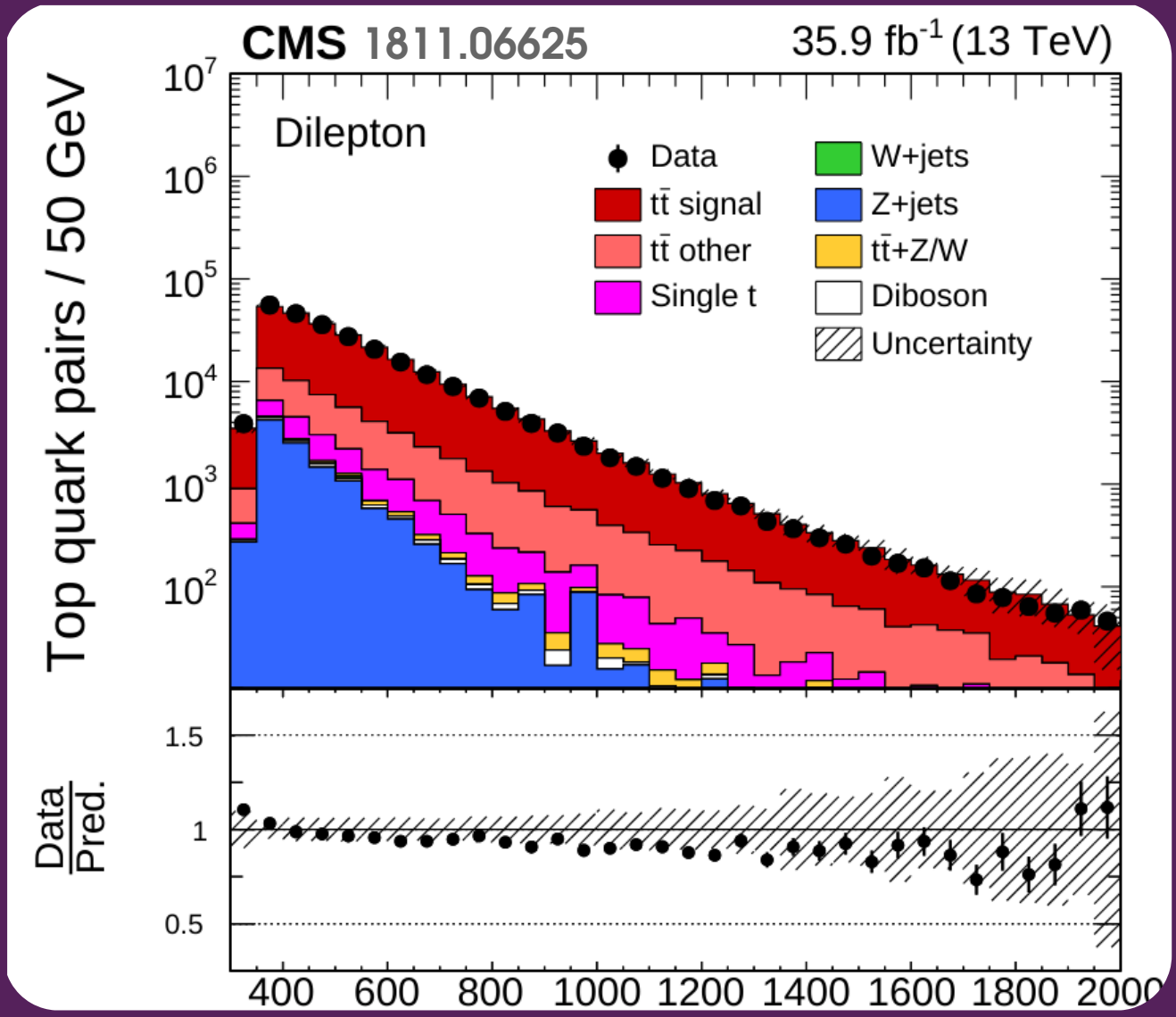




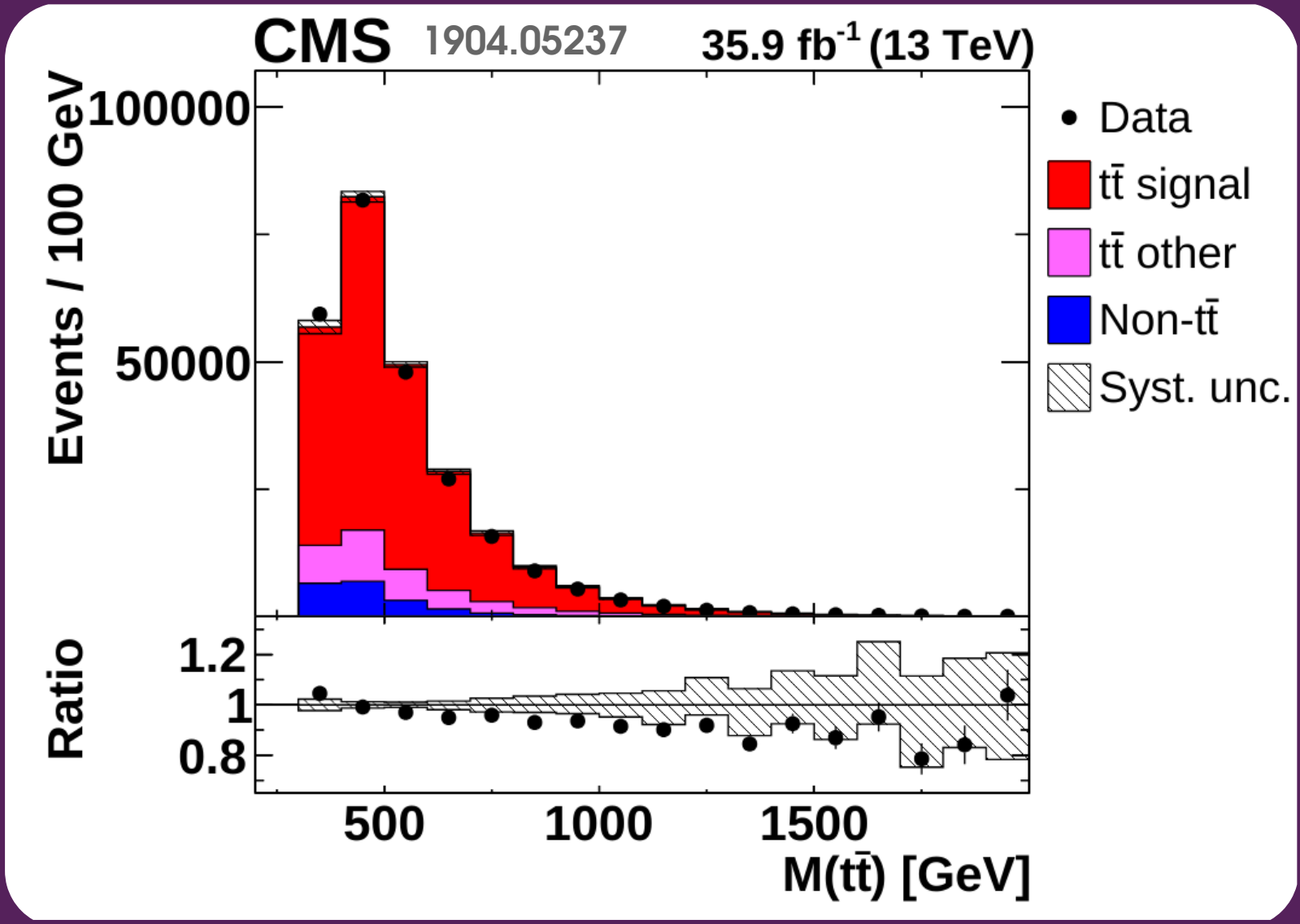
Signature for η_t formation:

- increase in total rate
- increase in spin singlet (more negative D)
- increase in color singlet

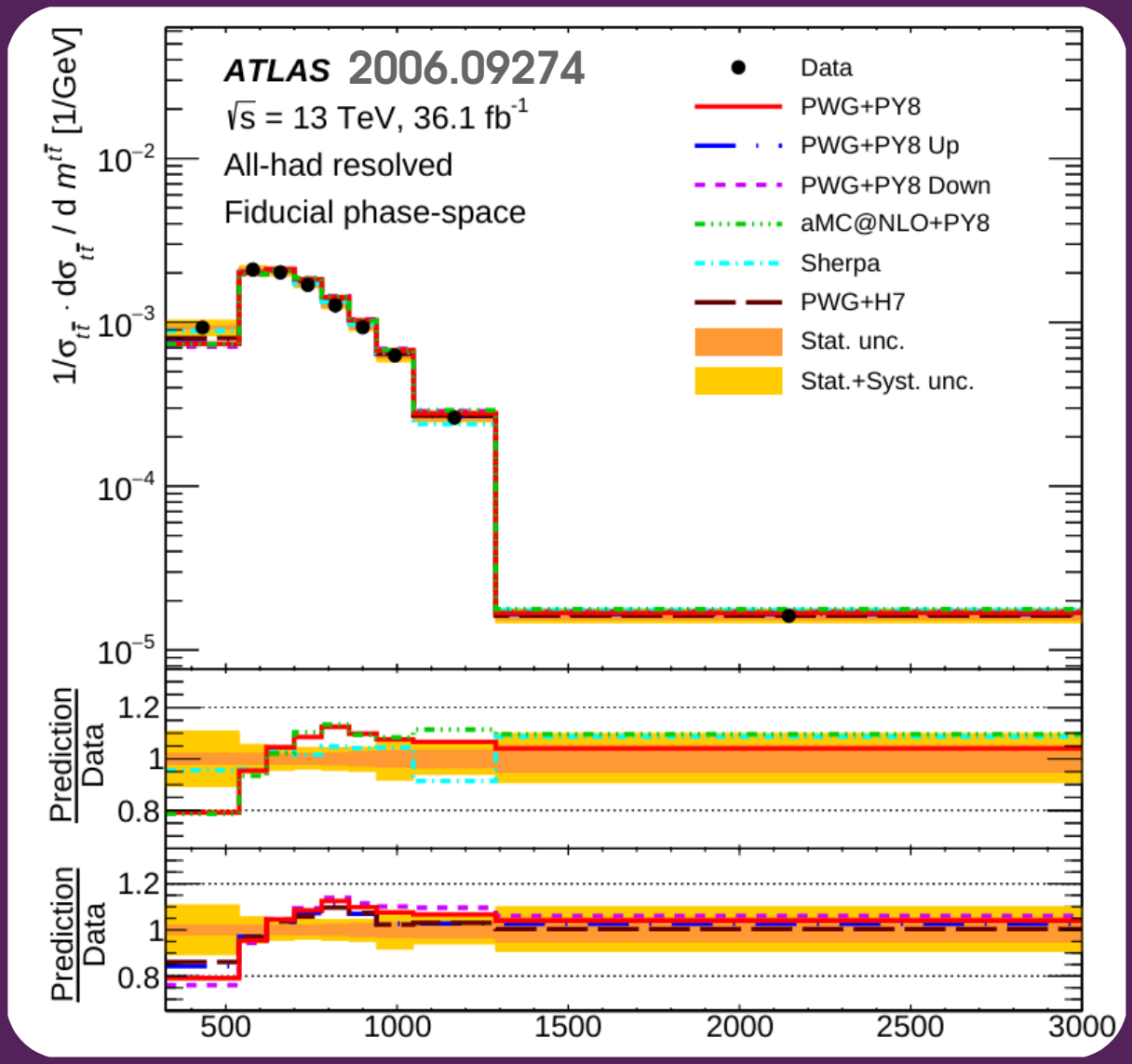
Signature for η_t formation:
- increase in total rate



Signature for η_t formation:
- increase in total rate

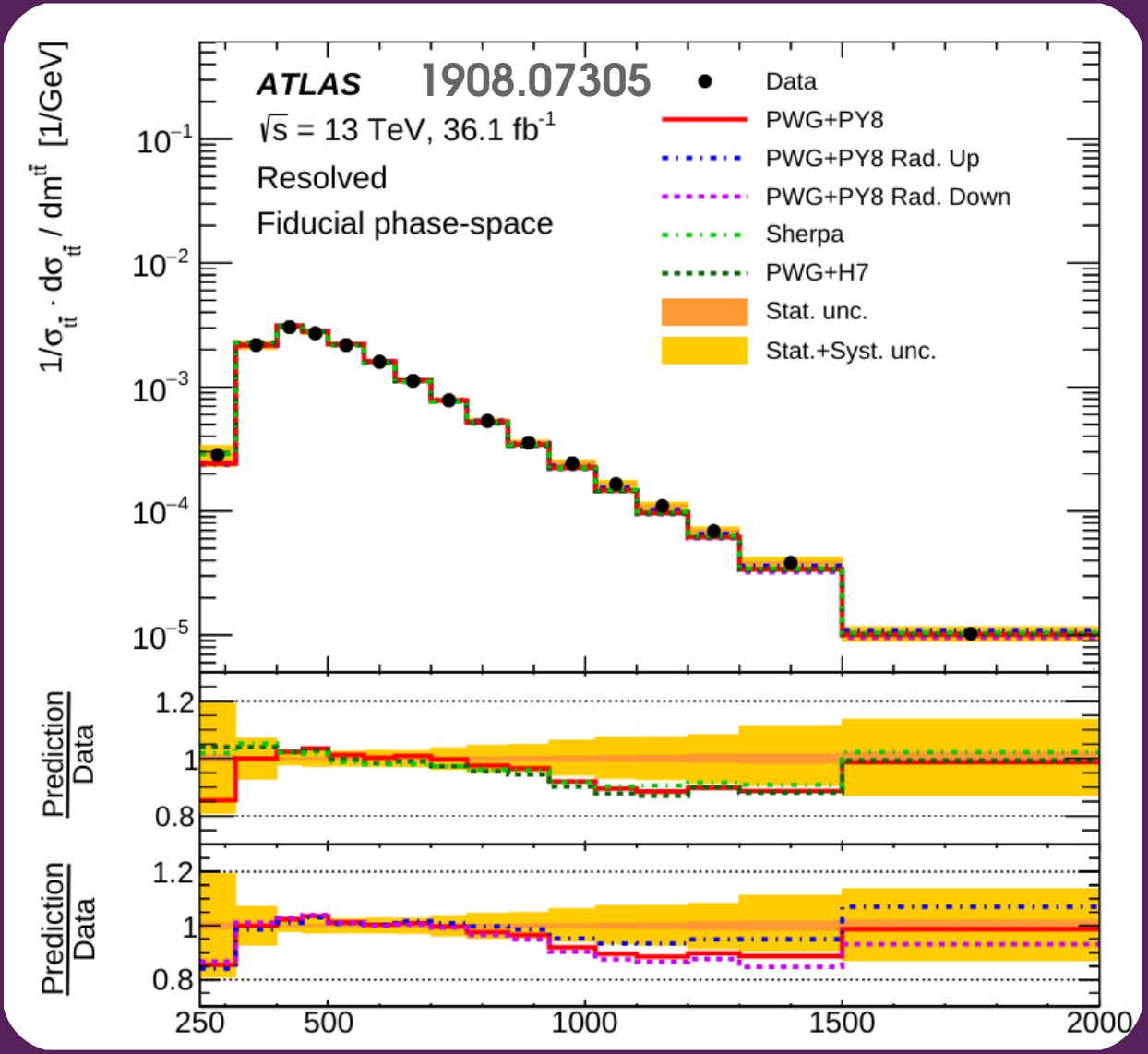


Signature for η_t formation:
- increase in total rate

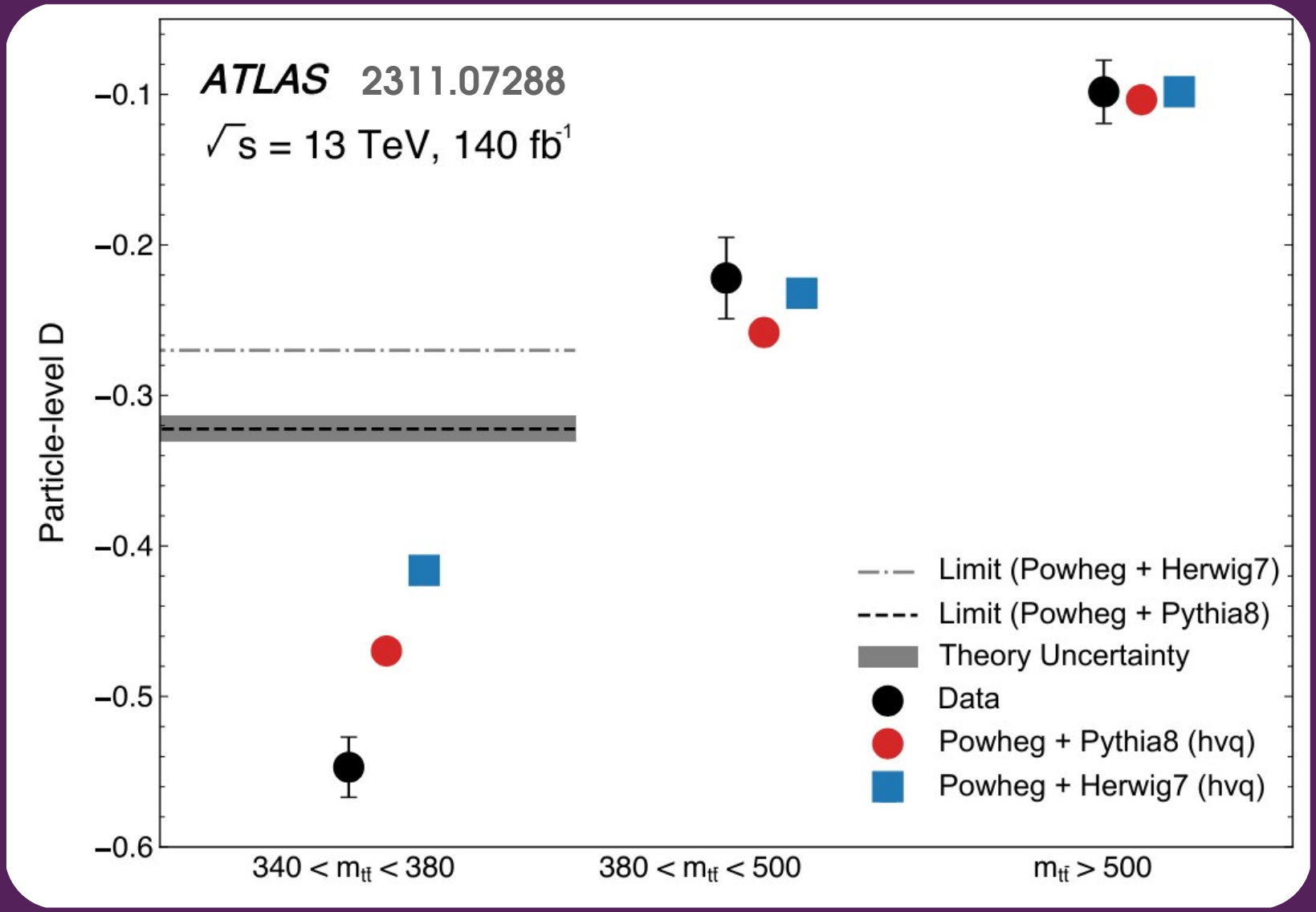


MC/data (ATLAS)
data/MC (CMS)

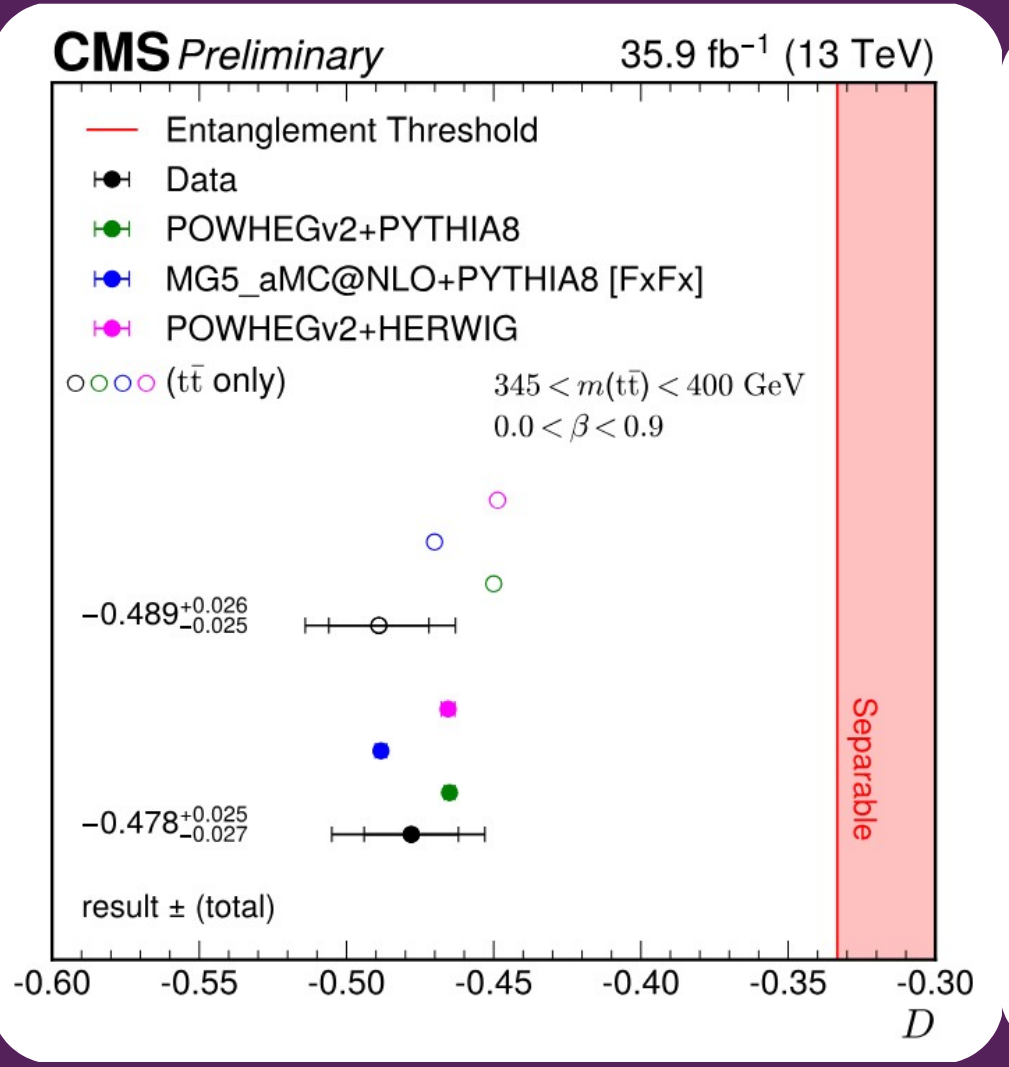
Signature for η_t formation:
- increase in total rate

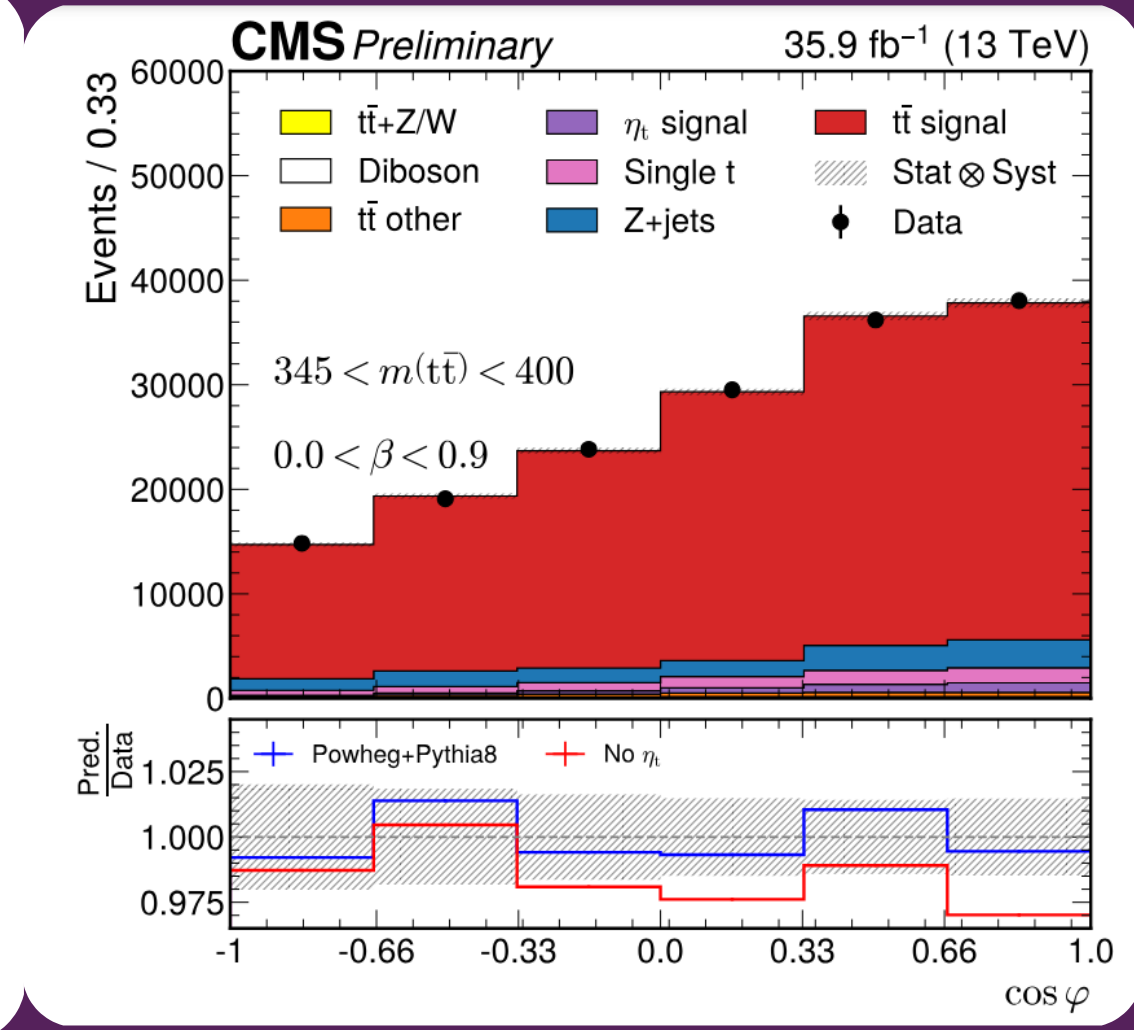


Signature for η_t formation:
- increase in spin singlet (more negative D)



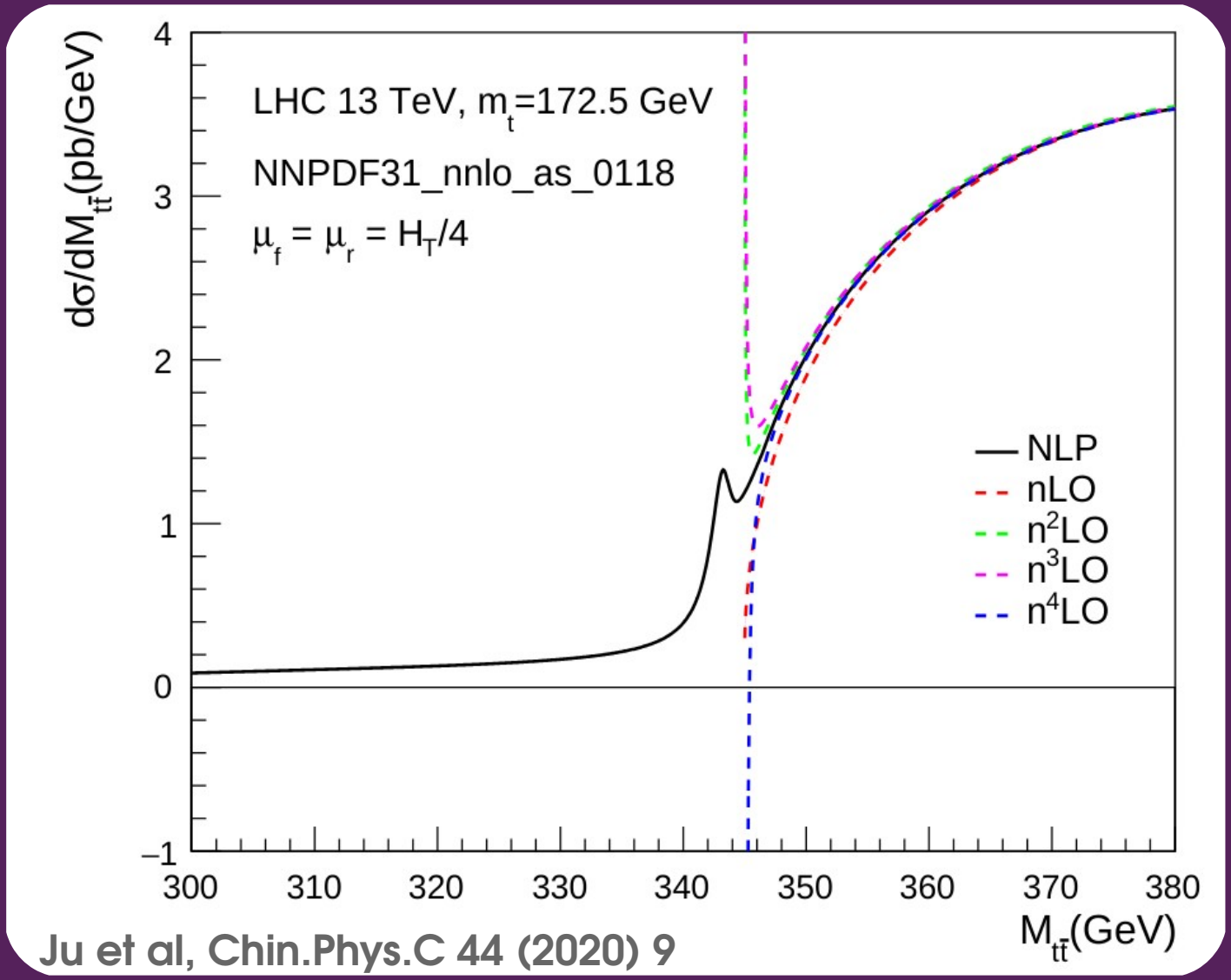
Signature for η_t formation:
- increase in spin singlet (more negative D)





Challenges in modelling

- normal monte carlo tools do not include VQCD
- fixed-order calculations will never see the bound state:



Ju et al, Chin.Phys.C 44 (2020) 9

Effective models are available in MadGraph,

Fuks et al, 2102.11281

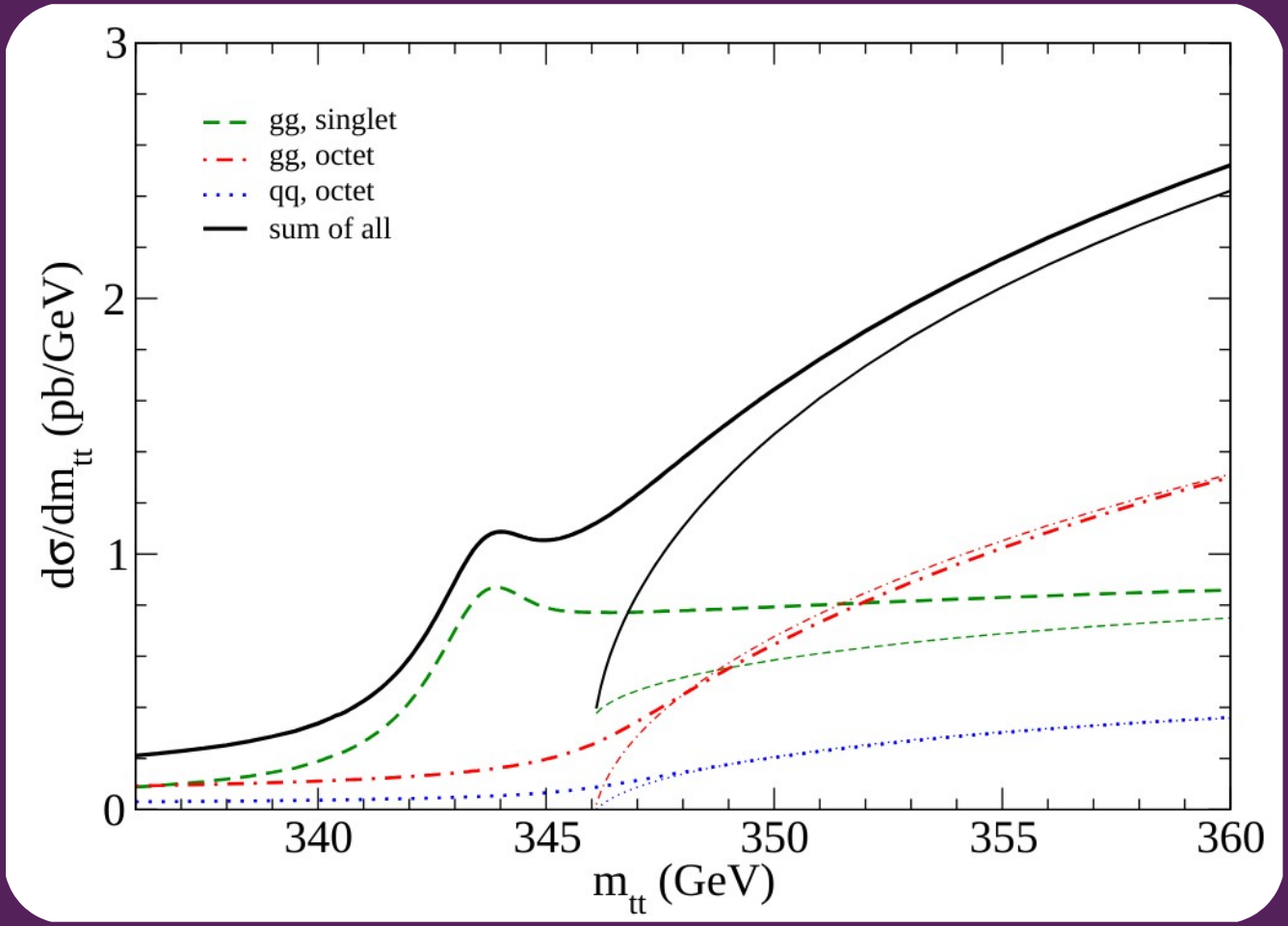
Maltoni et al, 2401.08751 and 2404.08049

capture the color singlet + spin singlet component = bulk of bound state effects

Effective models are available in MadGraph,

Fuks et al, 2102.11281
Maltoni et al, 2401.08751 and 2404.08049

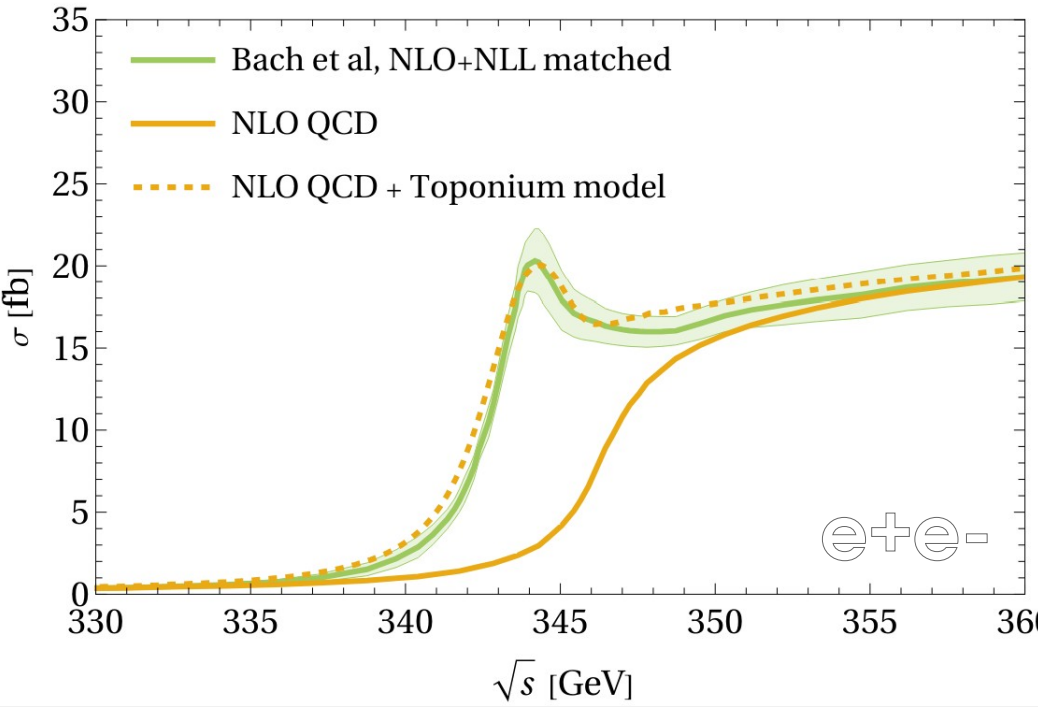
capture the color singlet + spin singlet component = bulk of bound state effects

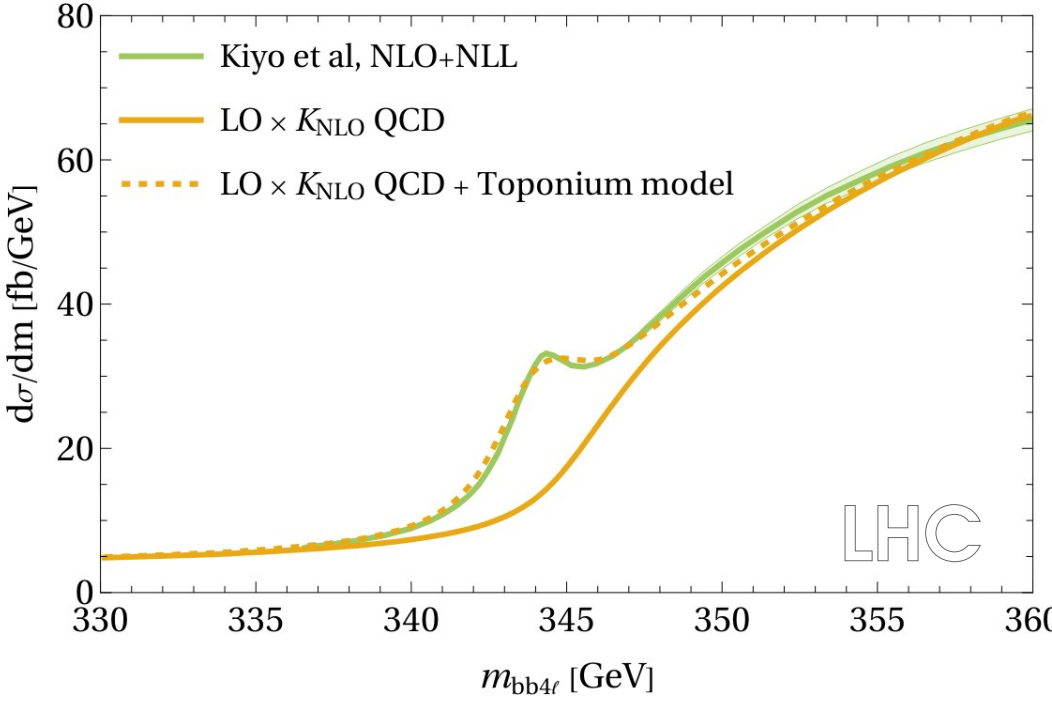


Effective models are available in MadGraph,

Fuks et al, 2102.11281
Maltoni et al, 2401.08751 and 2404.08049

capture the color singlet + spin singlet component = bulk of bound state effects





Effective models tuned to the QCD calculation reproduce the lineshape within theory uncertainty

However

Binding energy ~ Lifetime ~ Λ_{QCD}

Steady state $\mathcal{H}\psi = E\psi$ or dynamical description?

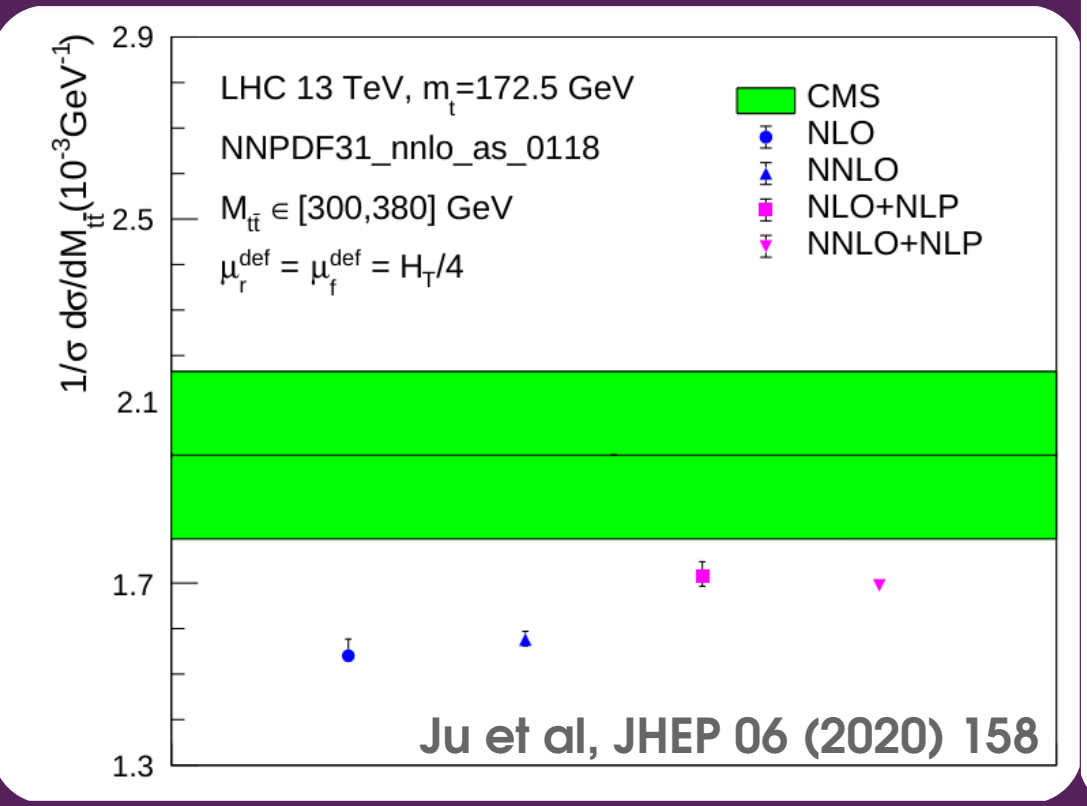
Probably better to use data to measure toponium properties, not vice versa.

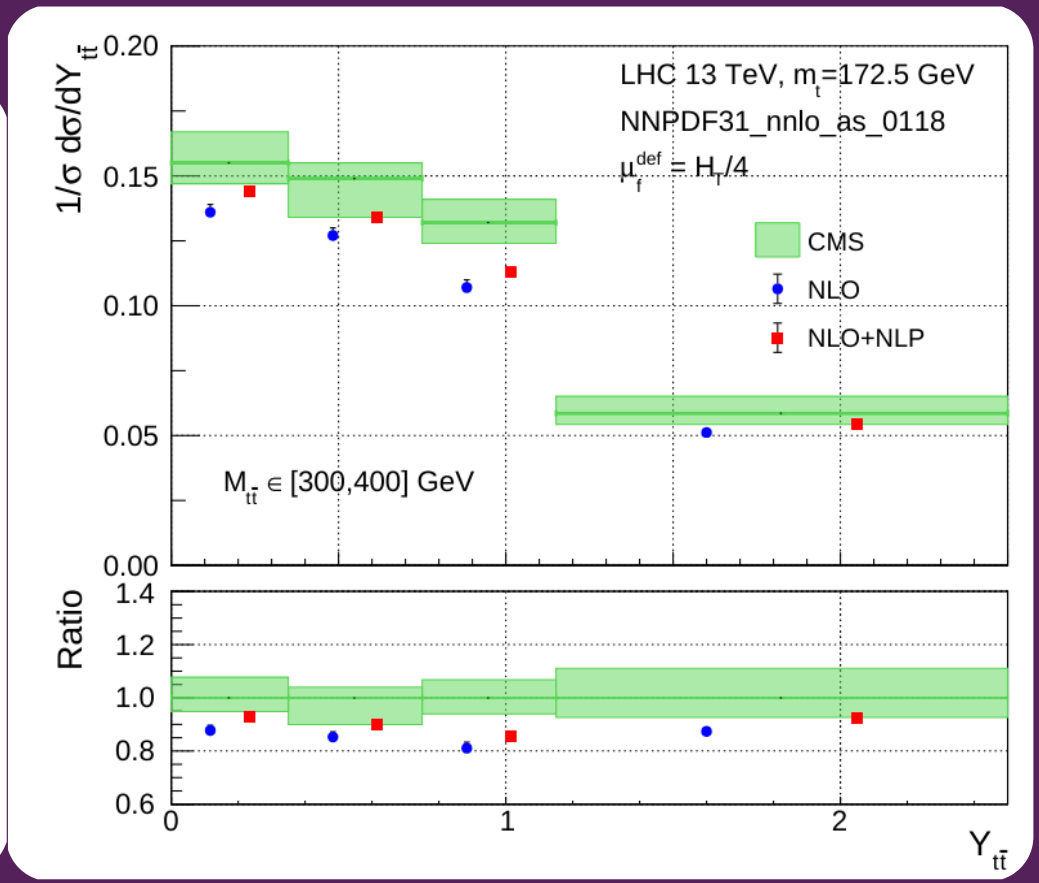
However

Binding energy ~ Lifetime ~ Λ_{QCD}

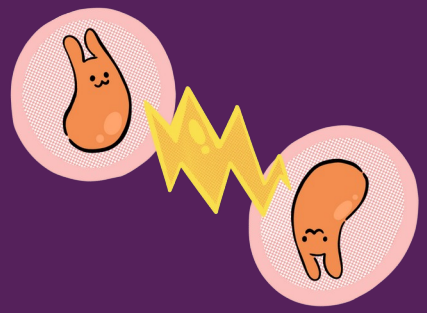
Steady state $\mathcal{H}\psi = E\psi$ or dynamical description?

Probably better to use data to measure toponium properties, not vice versa.

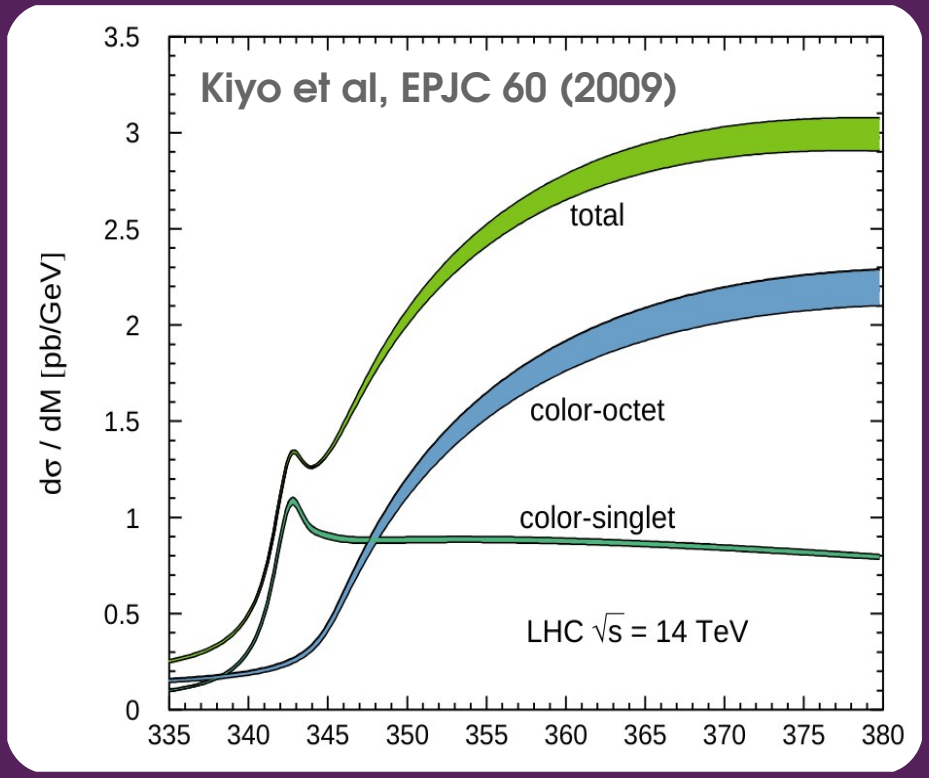




A few final remarks



New interest in ttbar threshold region because of entanglement
-> exciting (unforseen) opportunity to study QCD



Hints of bound state effects in Run 2 data: mtt, D, $\Delta\varphi$, ...

Modelling needs improvements

Is it possible to extract properties of the bound state from data?

Simultaneous measurement of D and σ_η?