Peking University • Quarkonium 2017 • 10 Nov 2017

Partnerium at the LHC

Yevgeny Kats

אוניברסיטת בן-גוריון בנגב
Ben-Gurion University of the Negev
جامعة بن غوريون في النقب

JHEP 1004, 016 (2010) [arXiv:0912.0526] w/Schwartz

JHEP 1109, 099 (2011) [arXiv:1103.3503] w/Kahawala

JHEP 1211, 097 (2012) [arXiv:1204.1119] w/Strassler

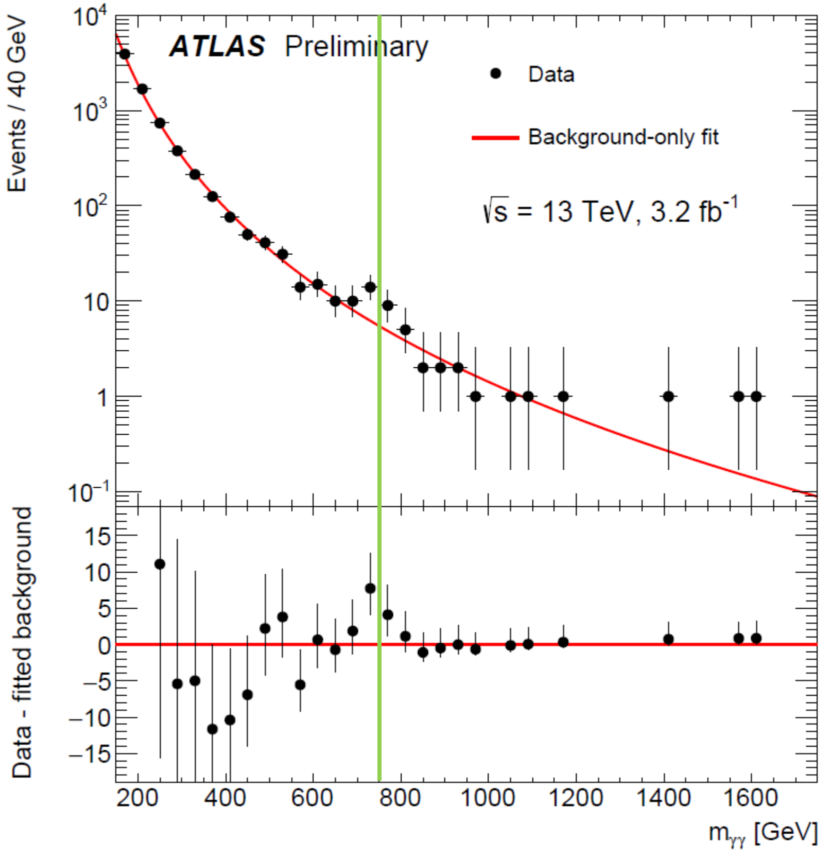
JHEP 1605, 092 (2016) [arXiv:1602.08819] w/Strassler

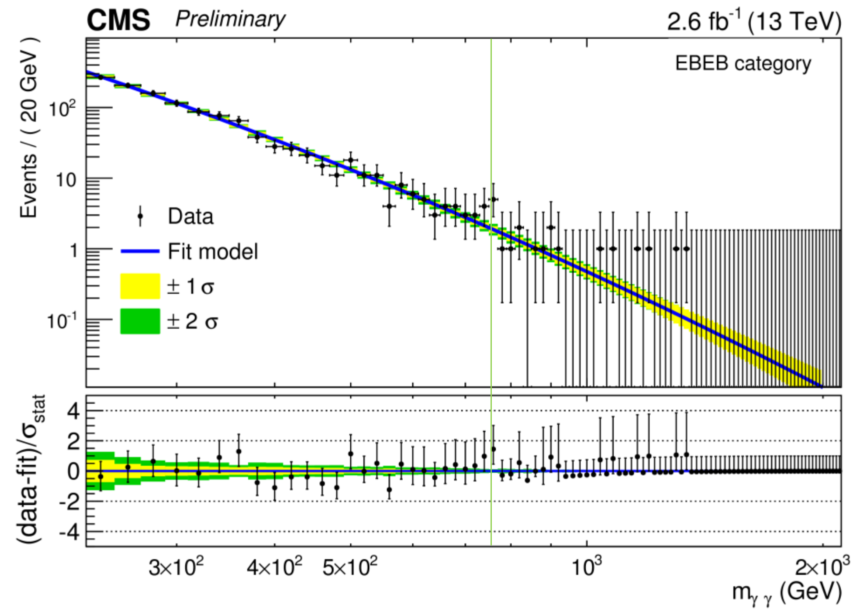
JHEP 1706, 126 (2017) [arXiv:1704.03393] w/McCullough, Perez, Soreq, Thaler

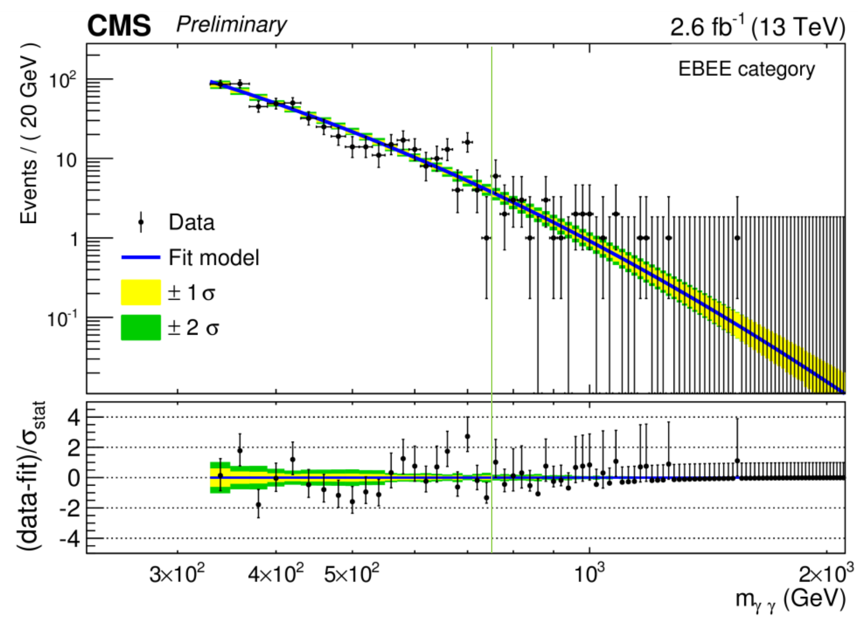
Motivation and Introduction

Original motivation

Resonant diphoton excesses
in ATLAS and CMS







$M \approx 750\,\text{GeV}, \;\; \Gamma \sim 0\text{-}100\,\text{GeV}$

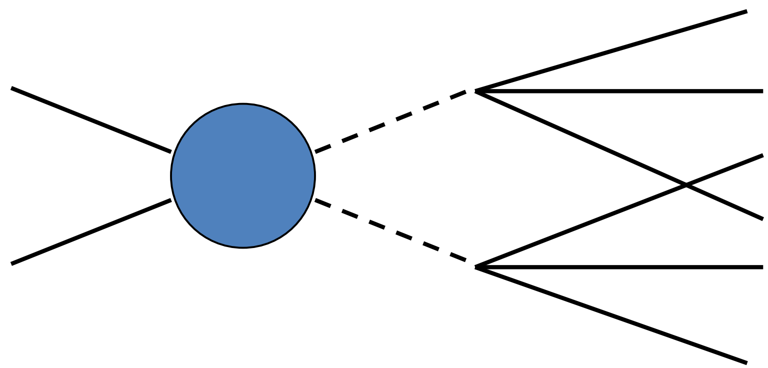
$\sigma \times \text{BR}(\gamma\gamma) \sim 3\text{-}10\,\text{fb}$

A simple explanation

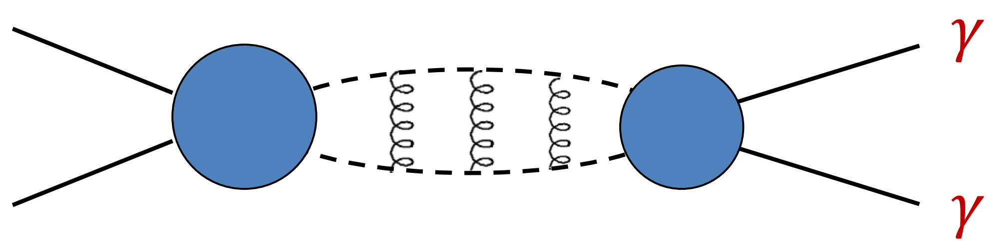
Annihilation of a near-threshold **QCD bound state** (X-onium) of a new colored and charged particle X with $m_X \approx 375$ GeV.

arXiv:1512.06670 Luo, Wang, Xu, Zhang, Zhu
arXiv:1602.08100 Han, Ichikawa, Matsumoto, Nojiri, Takeuchi
arXiv:1602.08819 Kats, Strassler
arXiv:1604.07828 Hamaguchi, Liew

Most of the time



Sometimes, near the production threshold

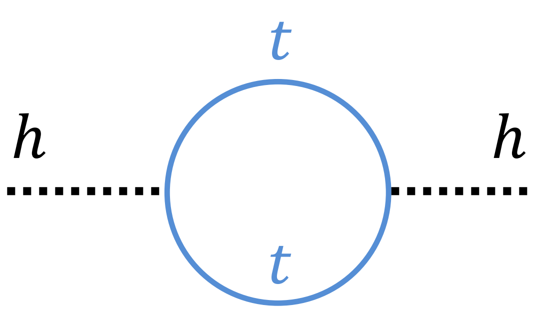


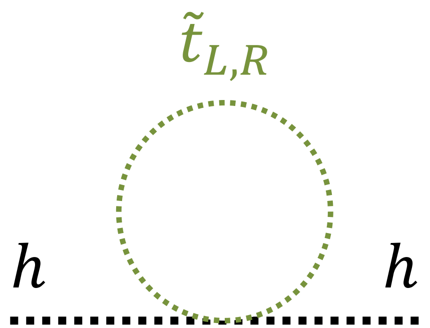
A simple explanation

Annihilation of a near-threshold **QCD bound state** (X-onium) of a new colored and charged particle X with $m_X \approx 375$ GeV.

arXiv:1512.06670 Luo, Wang, Xu, Zhang, Zhu
arXiv:1602.08100 Han, Ichikawa, Matsumoto, Nojiri, Takeuchi
arXiv:1602.08819 Kats, Strassler
arXiv:1604.07828 Hamaguchi, Liew

Long-anticipated colored and charged particles are the **stops** (top-quark superpartners). “The 750” is part of the solution to the **hierarchy problem**?!



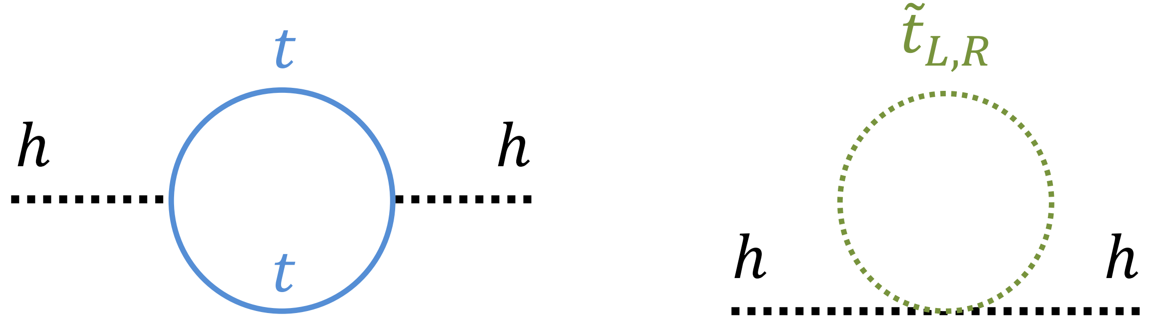


A simple explanation

Annihilation of a near-threshold **QCD bound state** (X-onium) of a new colored and charged particle X with $m_X \approx 375$ GeV.

arXiv:1512.06670 Luo, Wang, Xu, Zhang, Zhu
arXiv:1602.08100 Han, Ichikawa, Matsumoto, Nojiri, Takeuchi
arXiv:1602.08819 Kats, Strassler
arXiv:1604.07828 Hamaguchi, Liew

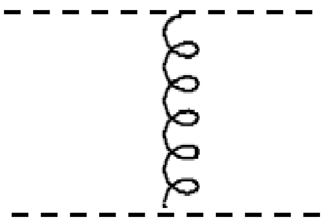
Long-anticipated colored and charged particles are the **stops** (top-quark superpartners). "The 750" is part of the solution to the **hierarchy problem**?!



However, **larger electric charge** was needed to account for the "signal".

Bound state physics

Coulomb approximation:



$$V(r) = -C\,\frac{\bar{\alpha}_s}{r}$$

$$\bar{\alpha}_s \equiv \alpha_s(r_{\rm rms})$$

For particles in R forming a bound state in $\mathcal{R} \subset R \otimes \bar{R}$:

$$C = C_R - \tfrac{1}{2}\,C_{\mathcal{R}}$$

Assumptions: $r_{\rm rms} \ll \Lambda_{\rm QCD}^{-1}\,,\quad \bar{\alpha}_s \ll 1\,,\quad v^2 = C^2\bar{\alpha}_s^2 \ll 1$

Similar to the hydrogen atom, for S-wave ground states:

$$r_{\rm rms} = \frac{2\sqrt{3}}{C\bar{\alpha}_s m} \qquad E_b = -\,\frac{C^2\bar{\alpha}_s^2}{4}\,m \qquad |\psi(\mathbf{0})|^2 = \frac{C^3\bar{\alpha}_s^3 m^3}{8\pi}$$

More detailed potential model: $|\psi(\mathbf{0})|^2$ smaller by a factor of ~2.

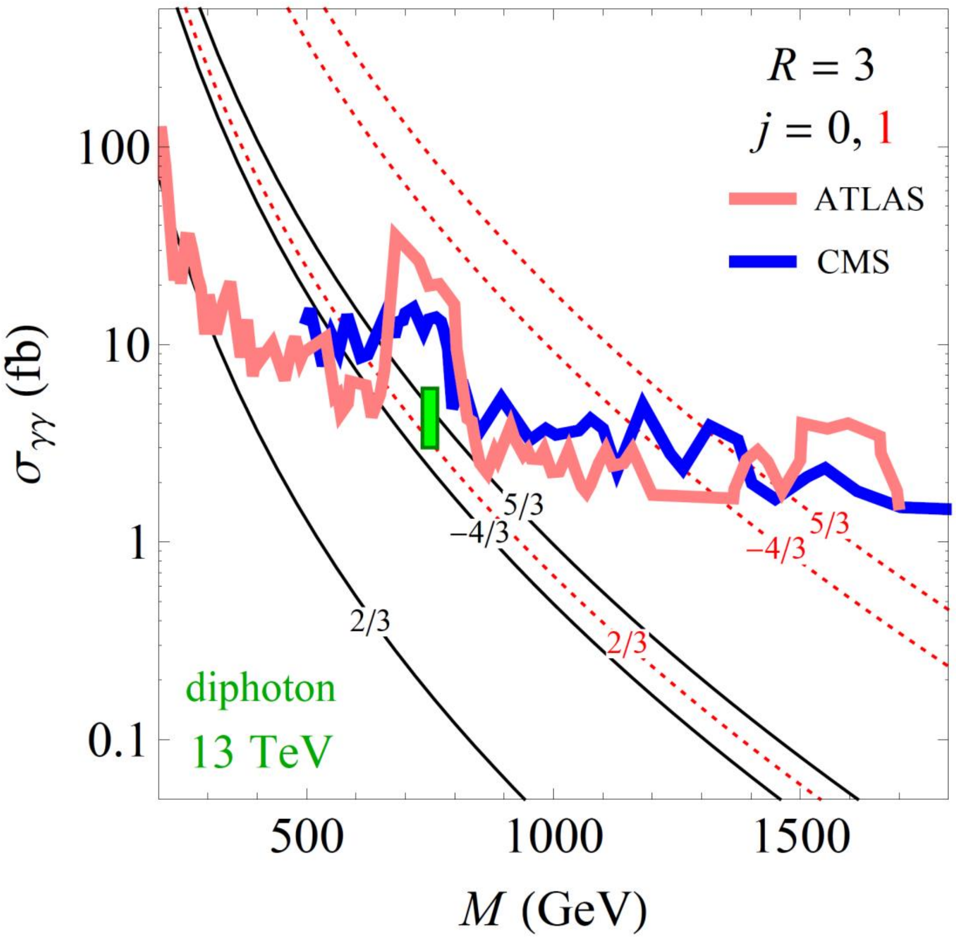
Hagiwara, Kato, Martin, Ng, NPB 344 (1990) 1

Lattice QCD: $|\psi(\mathbf{0})|^2$ bigger by a factor of ~2.

Kim, PRD 92, 094505 (2015) [arXiv:1508.07080]

We use the Coulomb approximation; keep factor-of-2 uncertainty in mind.

Annihilation to photons



ATLAS (13 TeV, 3.2/fb)

ATLAS-CONF-2015-081

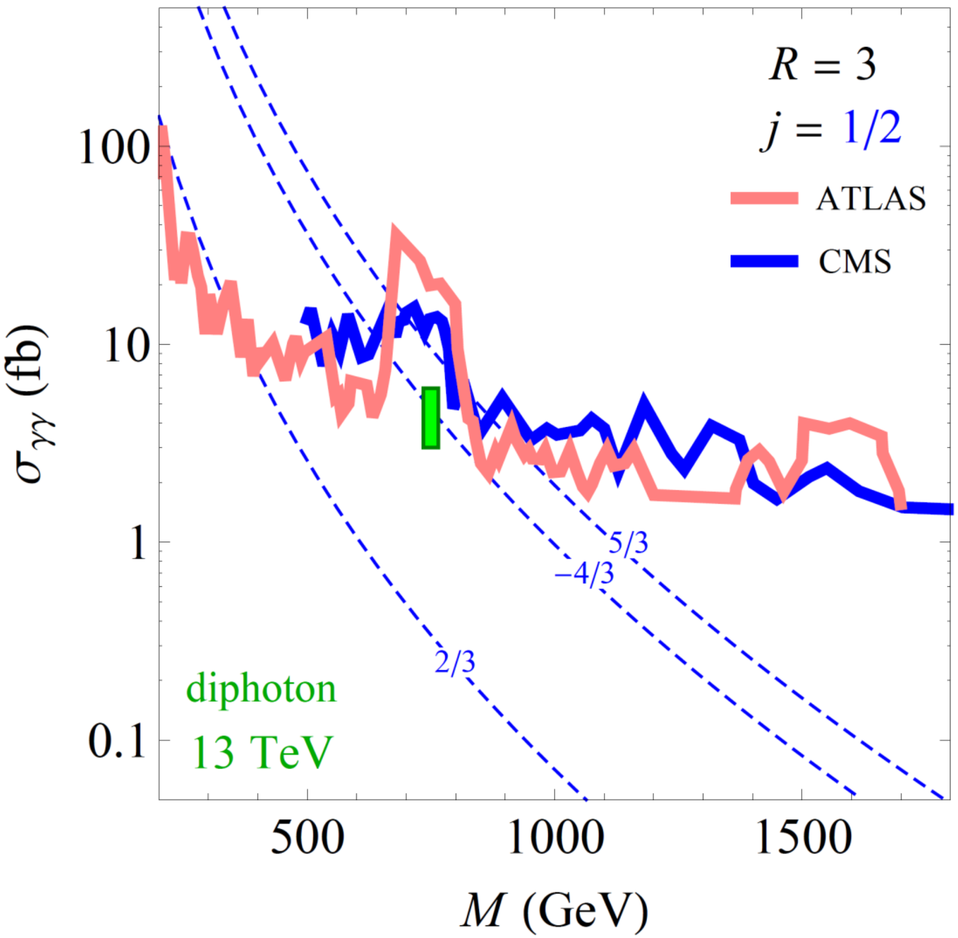
CMS (13 TeV, 2.6/fb)

CMS PAS EXO-15-004

Color-triplet scalars with $Q = -4/3$ or $5/3$ were candidates.

(In principle, also a vector with $Q = 2/3$.)

Annihilation to photons



ATLAS (13 TeV, 3.2/fb)

ATLAS-CONF-2015-081

CMS (13 TeV, 2.6/fb)

CMS PAS EXO-15-004

Color-triplet fermion with $Q = -4/3$ was a candidate.

Example scenario

BSM particle content

scalar $X(3,1)_{-4/3}$ $\qquad m_X \approx 375$ GeV

BSM interactions

$$\mathcal{L}_{\text{int}} = -\frac{c_{ij}}{2}\epsilon_{\alpha\beta\gamma}X^{*\alpha}\bar{u}_i^{\beta}\bar{u}_j^{\gamma} + \text{h.c.}$$

Main LHC phenomenology

$$gg,\, q\bar{q} \to XX^*, \qquad X \to \bar{u}\bar{c},\, \bar{t}\bar{u},\, \bar{t}\bar{c}$$

unconstrained

$$gg \to (XX^*) \to \underbrace{gg, ZZ, Z\gamma,}_{\text{unconstrained}}\ \gamma\gamma$$

excess

But why would there be such a particle?

Wouldn't the scalar even introduce a new hierarchy problem?

Example scenario

BSM particle content

scalar $X(3,1)_{-4/3}$ $\quad m_X \approx 375$ GeV

BSM interactions

$$\mathcal{L}_{\text{int}} = -\frac{c_{ij}}{2}\epsilon_{\alpha\beta\gamma}X^{*\alpha}\bar{u}_i^{\beta}\bar{u}_j^{\gamma} + \text{h.c.}$$

Main LHC phenomenology

$$gg,\, q\bar{q} \to XX^*, \quad X \to \bar{u}\bar{c},\, \bar{t}\bar{u},\, \bar{t}\bar{c}$$

unconstrained

$$gg \to (XX^*) \to \underbrace{gg, ZZ, Z\gamma,}_{\text{unconstrained}}\ \gamma\gamma$$

excess

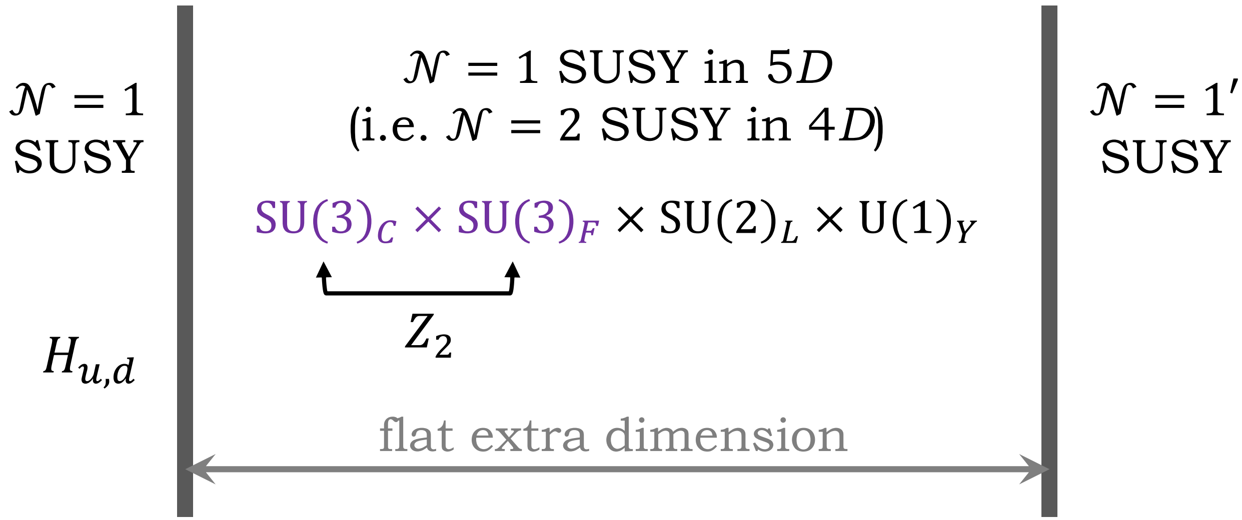
But why would there be such a particle?

Maybe it is actually a top partner ;)

Scalar top partners with arbitrary electric charges

Reminder of Folded SUSY

Burdman, Chacko, Goh, Harnik, JHEP 02 (2007) 009 [hep-ph/0609152]



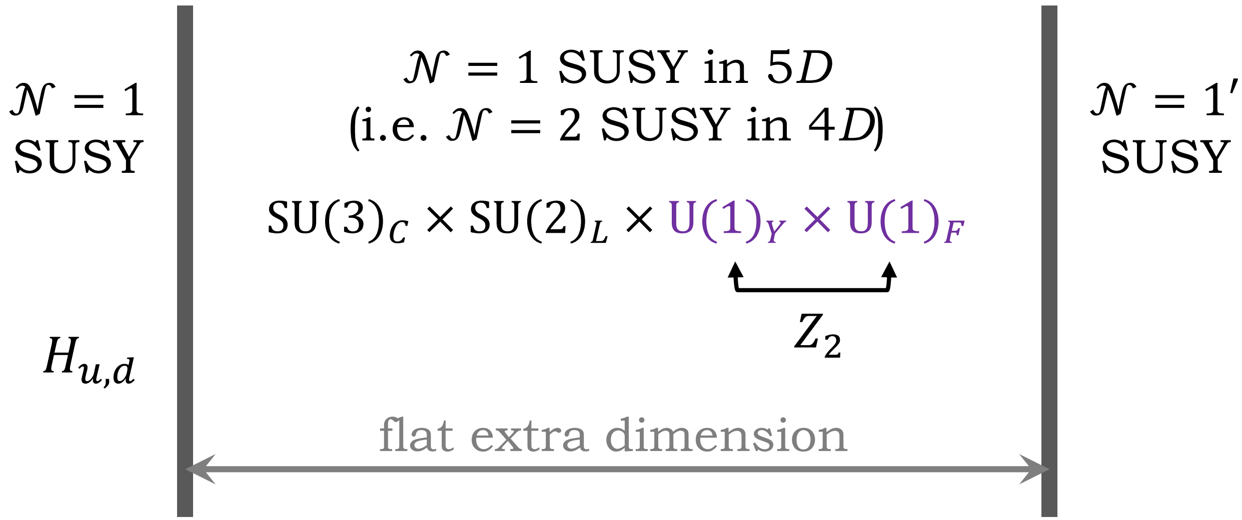
Members of $\mathcal{N}=2$ supermultiplets and their boundary conditions

Z_2	**Quarks** $(\mathbf{3},\mathbf{1},\mathbf{SM},\mathbf{SM})$	$\psi(++)$	$\psi^c(--)$	$\phi(+-)$	$\phi^c(-+)$
	Folded quarks $(\mathbf{1},\mathbf{3},\mathbf{SM},\mathbf{SM})$	$\psi_F(+-)$	$\psi_F^c(-+)$	$\phi_F(++)$	$\phi_F^c(--)$

Importantly, the Z_2 is preserved on the Higgs brane.

Divergences from top (ψ) are canceled by (colorless) "folded stops" (ϕ_F).

Our setup: Hyperfolded SUSY



Members of $\mathcal{N}=2$ supermultiplets and their boundary conditions

Z_2	**Quarks** $(\mathrm{SM},\mathrm{SM},Y_{\mathrm{SM}},Y_F)$	$\psi(++)$	$\psi^c(--)$	$\phi(+-)$	$\phi^c(-+)$
	Folded quarks $(\mathrm{SM},\mathrm{SM},Y_F,Y_{\mathrm{SM}})$	$\psi_F(+-)$	$\psi_F^c(-+)$	$\phi_F(++)$	$\phi_F^c(--)$

Importantly, the Z_2 is preserved on the Higgs brane.

Divergences from top (ψ) are canceled by **colored** "folded stops" (ϕ_F) with **unconventional hypercharges**.

Our setup: Hyperfolded SUSY

	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_F$	
$\boldsymbol{H_u}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$1/2$	
$\boldsymbol{H_d}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$-1/2$	
$\boldsymbol{Q}, \boldsymbol{Q_F}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}(1, 6q-3)$	$\frac{1}{6}(6q-3, 1)$	
$\boldsymbol{U^c}, \boldsymbol{U^c_F}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}(-2, -3q)$	$\frac{1}{3}(-3q, -2)$	
$\boldsymbol{D^c}, \boldsymbol{D^c_F}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}(1, 3-3q)$	$\frac{1}{3}(3-3q, 1)$	
$\boldsymbol{L}, \boldsymbol{L_F}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}(-1, 3-6q)$	$\frac{1}{2}(3-6q, -1)$	
$\boldsymbol{E^c}, \boldsymbol{E^c_F}$	$\mathbf{1}$	$\mathbf{1}$	$(1, 3q-1)$	$(3q-1, 1)$	
$\boldsymbol{N^c}, \boldsymbol{N^c_F}$	$\mathbf{1}$	$\mathbf{1}$	$(0, 3q-2)$	$(3q-2, 0)$	$\leftarrow$ to avoid gauge anomaly
$\boldsymbol{S}, \boldsymbol{S_F}$	$\mathbf{1}$	$\mathbf{1}$	$(q_S, 0)$	$(0, q_S)$	to break $\mathrm{U}(1)_F$
$\boldsymbol{S^c}, \boldsymbol{S^c_F}$	$\mathbf{1}$	$\mathbf{1}$	$(-q_S, 0)$	$(0, -q_S)$	

- Folded stops with **any charge** can be obtained by varying q. Gauge-invariant Yukawas and anomaly cancellation fix the charges of the other fields.

- The charge q_S determines the $\mathrm{U}(1)_F$-allowed operators for **decays**: $W \propto S_F \mathcal{O}_F$, where the operator $\mathcal{O}_F$ respects the SM gauge symmetries but not $\mathrm{U}(1)_F$.

Our setup: Hyperfolded SUSY

Interesting decay examples

For a folded RH stop with $Q = -4/3$:

$$W \supset U_F^c U^c U^c$$

allows the decays

$$X \rightarrow \bar{u}\bar{c},\ \bar{t}\bar{u},\ \bar{t}\bar{c}$$

top+jet decays are almost unconstrained

Now studying further with Giammanco, Schlaffer, Shlomi

Our setup: Hyperfolded SUSY

Interesting decay examples

For a folded RH stop with $Q = -4/3$:

$$W \supset U_F^c U^c U^c$$

allows the decays

$$X \rightarrow \bar{u}\bar{c}, \bar{t}\bar{u}, \bar{t}\bar{c}$$

top+jet decays are almost unconstrained

Now studying further with Giammanco, Schlaffer, Shlomi

Same is possible for LH sbottom with $Q = -4/3$ via

$$W \supset D_F^c U^c U^c$$

in the presence of mixing.

Our setup: Hyperfolded SUSY

Interesting decay examples

For a folded RH stop with $Q = -4/3$:

$$W \supset U^c_F U^c U^c$$

allows the decays

$$X \rightarrow \bar{u}\bar{c},\ \bar{t}\bar{u},\ \bar{t}\bar{c}$$

top+jet decays are almost unconstrained
Now studying further with Giammanco, Schlaffer, Shlomi

Same is possible for LH sbottom with $Q = -4/3$ via

$$W \supset D^c_F U^c U^c$$

in the presence of mixing.

The sbottom may also decay via

$$W \supset (H_u Q_F)(QQ)$$

as

$$X \rightarrow W^- \bar{u}\bar{d}$$

Wjj decays are unconstrained
Blum, Efrati, Frugiuele, Nir
JHEP 1702, 104 (2017)
[arXiv:1610.06582]

Fermionic top partners with arbitrary electric charges

– To be skipped –

Hypertwisted Composite Higgs

Symmetry breaking pattern:

$$\mathrm{SU}(3)_G \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z \to \mathrm{SU}(2)_L \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Y$$

$$\Phi \sim (\bar{3}, 1)_{\frac{1}{3}} = \exp\left(-i\frac{\pi^a T_G^a}{f}\right)\begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \supset \begin{pmatrix} H \\ f - \frac{H^\dagger H}{2f} \end{pmatrix}$$

SM electroweak group generators:

$$T_L^{1,2,3} = T_G^{1,2,3} \qquad\qquad Y = Z - \frac{T_G^8}{\sqrt{3}} + \left(\frac{2}{3} - Y_T\right) T_X^3$$

free parameter, to become the top-partner hypercharge

An analogous model with custodial protection can be obtained with $\mathrm{SO}(5)_G \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z \to \mathrm{SO}(4) \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z$.
See appendix of our paper for details.

Hypertwisted Composite Higgs

Symmetry breaking pattern:

$$\mathrm{SU}(3)_G \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z \to \mathrm{SU}(2)_L \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Y$$

$$\Phi \sim (\bar{3}, 1)_{\frac{1}{3}} = \exp\left(-i\frac{\pi^a T_G^a}{f}\right)\begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \supset \begin{pmatrix} H \\ f - \frac{H^\dagger H}{2f} \end{pmatrix}$$

SM electroweak group generators:

$$T_L^{1,2,3} = T_G^{1,2,3} \qquad Y = Z - \frac{T_G^8}{\sqrt{3}} + \left(\frac{2}{3} - Y_T\right) T_X^3$$

free parameter, to become the top-partner hypercharge

The top sector:

$$Q \sim (3,2)_{\frac{Y_T}{2}} = \begin{pmatrix} b & q_d' \\ -t & -q_u' \\ t' & T \end{pmatrix} \qquad Q^c \sim (1,2)_{-\frac{Y_T}{2}-\frac{1}{3}} = \begin{pmatrix} t^c & -T^c \end{pmatrix}$$

$\mathrm{SU}(2)_X$

$$\mathcal{L}_Y = \lambda_t Q \Phi Q^c + \text{h.c.}$$

Hypertwisted Composite Higgs

The Yukawa coupling $\mathcal{L}_Y = \lambda_t Q \Phi Q^c + \text{h.c.}$ expands as

$$\mathcal{L}_Y \supset -\lambda_t q H t^c - \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) T T^c + \lambda_t q' H T^c + \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) t' t^c + \mathcal{O}(1/f^2)$$

i.e., divergences due to the top are canceled by the charge-Y_T partner.

Hypertwisted Composite Higgs

The Yukawa coupling $\mathcal{L}_Y = \lambda_t Q \Phi Q^c + \text{h.c.}$ expands as

$$\mathcal{L}_Y \supset -\lambda_t q H t^c - \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) T T^c + \lambda_t q' H T^c + \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) t' t^c + \mathcal{O}(1/f^2)$$

i.e., divergences due to the top are canceled by the charge-Y_T partner.

The q' and t' fields can be given a vectorlike mass (which breaks the symmetry only softly): $\mathcal{L}_{\text{soft}} = -M' \left(t' t'^c + q' q'^c \right)$

Hypertwisted Composite Higgs

The Yukawa coupling $\mathcal{L}_Y = \lambda_t Q \Phi Q^c + \text{h.c.}$ expands as

$$\mathcal{L}_Y \supset -\lambda_t q H t^c - \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) T T^c + \lambda_t q' H T^c + \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) t' t^c + \mathcal{O}(1/f^2)$$

i.e., divergences due to the top are canceled by the charge-Y_T partner. The q' and t' fields can be given a vectorlike mass (which breaks the symmetry only softly): $\mathcal{L}_{\text{soft}} = -M' \left(t' t'^c + q' q'^c \right)$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Q_{EM}	
H	1	2	$1/2$		
q	3	2	$1/6$	$2/3, \ -1/3$	SM
t^c	$\bar{3}$	1	$-2/3$	$-2/3$	
T	3	1	Y_T	Y_T	Top partner X with arbitrary charge
T^c	$\bar{3}$	1	$-Y_T$	$-Y_T$	
q'	3	2	$Y_T - 1/2$	$Y_T, \ Y_T - 1$	Heavy extra states
q'^c	$\bar{3}$	2	$-(Y_T - 1/2)$	$-Y_T, \ -(Y_T - 1)$	
t'	3	1	$2/3$	$2/3$	
t'^c	$\bar{3}$	1	$-2/3$	$-2/3$	

Hypertwisted Composite Higgs

The Yukawa coupling $\mathcal{L}_Y = \lambda_t Q \Phi Q^c + \text{h.c.}$ expands as

$$\mathcal{L}_Y \supset -\lambda_t q H t^c - \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) T T^c + \lambda_t q' H T^c + \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) t' t^c + \mathcal{O}(1/f^2)$$

i.e., divergences due to the top are canceled by the charge-Y_T partner.

Top partner decays

Since T does not mix with quarks, the **usual decays** to W / Z / h + quark (which have strong limits) **are absent!**

Instead, the decay may proceed via a high-dimension operator. For example,

$$\mathcal{L} \propto T^{c\,\dagger} u_i^{c\,\dagger} d_j^c d_k^c + \text{h.c.}$$

may give the potentially elusive decays

$$T \;\rightarrow\; jjj,\; tjj$$

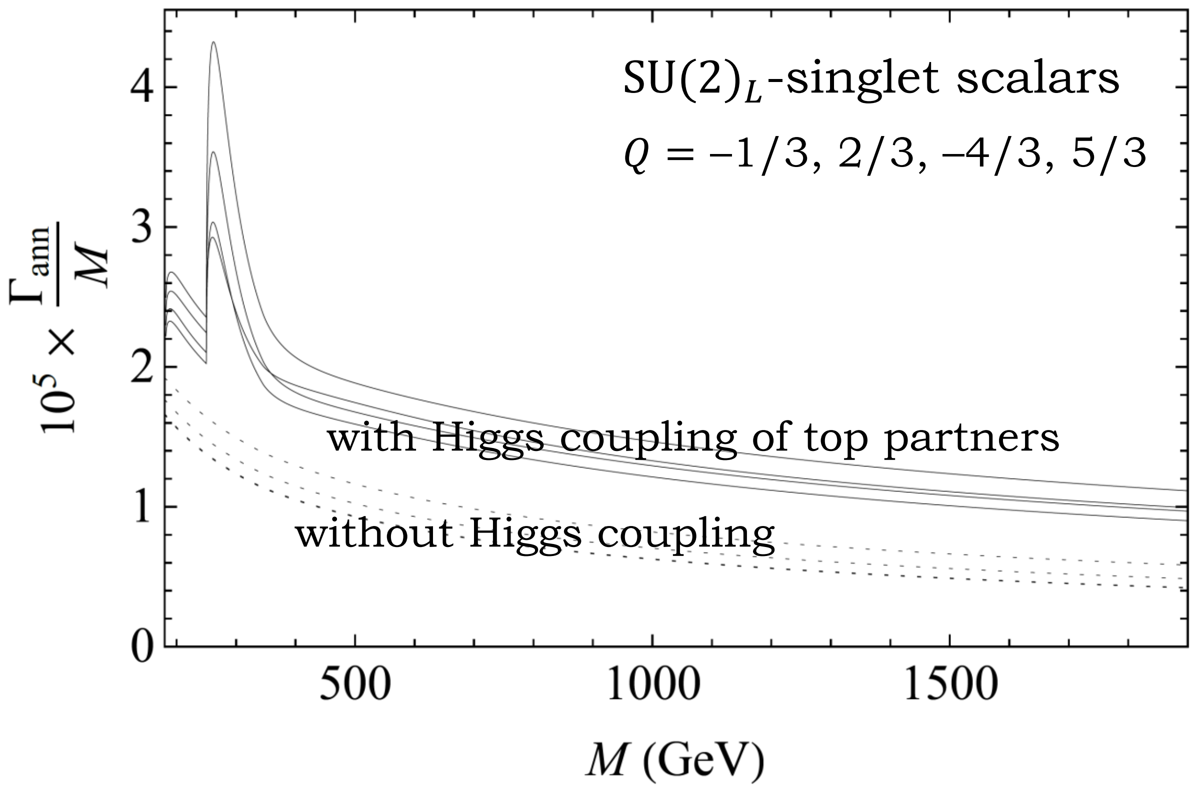
Importantly, **decay rates are suppressed**, so partnerium annihilation signals are a generic feature.

Partnerium annihilation signals

Partnerium annihilation signals

For annihilation signals to be observable, intrinsic decays need to be somewhat suppressed:

$$\frac{\Gamma_{\text{decay}}}{m} \lesssim \frac{\Gamma_{\text{ann}}}{M} \sim \alpha_s^5 \sim 10^{-5}$$



Partnerium annihilation signals

For annihilation signals to be observable, intrinsic decays need to be somewhat suppressed:

$$\frac{\Gamma_{\text{decay}}}{m} \lesssim \frac{\Gamma_{\text{ann}}}{M} \sim \alpha_s^5 \sim 10^{-5}$$

For example, the $\gamma\gamma$ signal of toponium is tiny because

$$\frac{\Gamma_{\text{decay}}}{m} \approx 8 \times 10^{-3}$$

Partnerium annihilation signals

For annihilation signals to be observable, intrinsic decays need to be somewhat suppressed:

$$\frac{\Gamma_{\text{decay}}}{m} \lesssim \frac{\Gamma_{\text{ann}}}{M} \sim \alpha_s^5 \sim 10^{-5}$$

For example, the $\gamma\gamma$ signal of toponium is tiny because

$$\frac{\Gamma_{\text{decay}}}{m} \approx 8 \times 10^{-3}$$

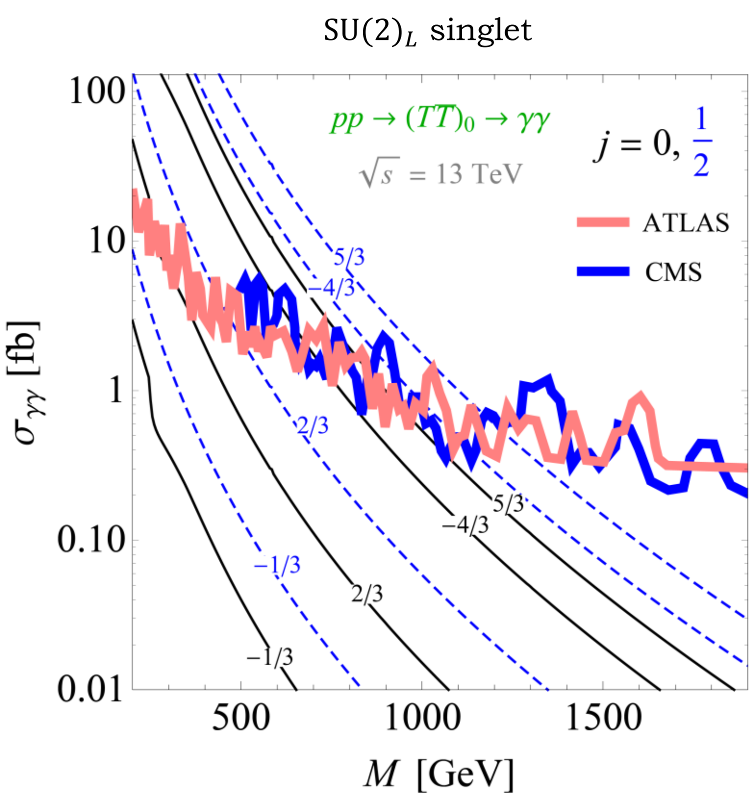
Exotic top partners typically do not have unsuppressed 2-body decays. (Even the naively renormalizable $X \to \bar{u}\bar{c}$, $\bar{t}\bar{u}$, $\bar{t}\bar{c}$ decays of scalars required $\text{U}(1)_F$ breaking).

Thus, resonance searches constrain such scenarios in a rather model-independent fashion!

Partnerium annihilation signals

Scalar partners: Higgs coupling induces sizable WW, ZZ, hh rates, leading to a reduction (e.g., factor of ~2) in the $\gamma\gamma$ rate.

Fermionic partners: the spin-0 bound state is a pseudoscalar, rates are unaffected by the Higgs coupling.



Limits from:

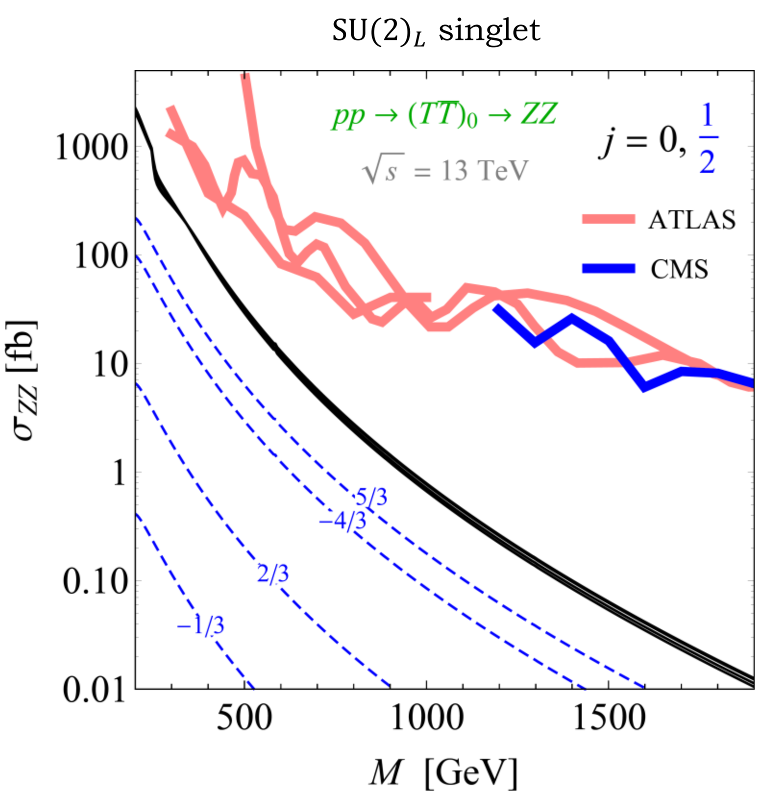
ATLAS-CONF-2016-059 (15/fb)

CMS-PAS-EXO-16-027 (13/fb)

Partnerium annihilation signals

Scalar partners: Higgs coupling induces sizable WW, ZZ, hh rates, leading to a reduction (e.g., factor of ~2) in the $\gamma\gamma$ rate.

Fermionic partners: the spin-0 bound state is a pseudoscalar, rates are unaffected by the Higgs coupling.



Limits from:

ATLAS-CONF-2016-056 ($\ell\ell\nu\nu$, 13/fb)

ATLAS-CONF-2016-082 ($\ell\ell qq$, 13/fb
$\nu\nu qq$, 13/fb)

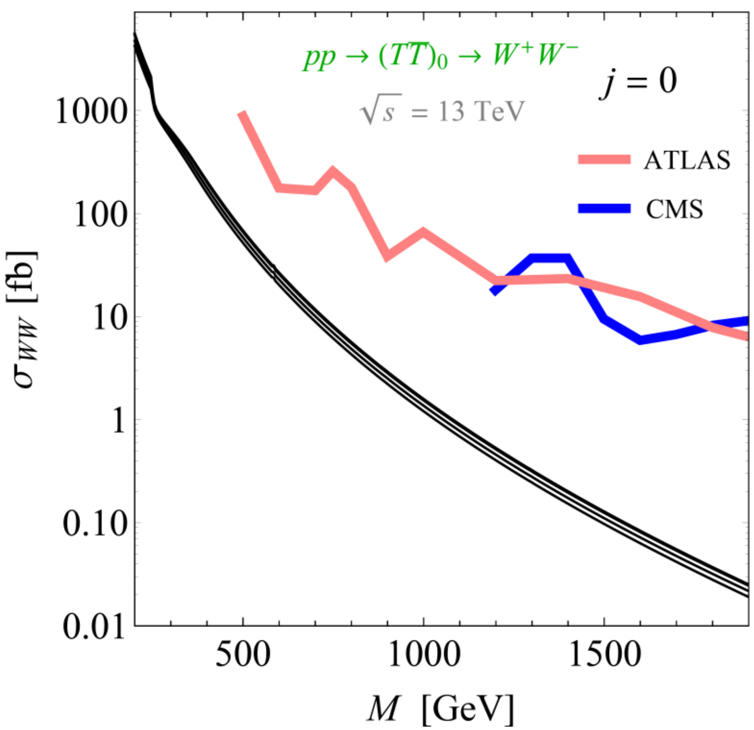
CMS-PAS-B2G-17-001 (JJ, 36/fb)

Partnerium annihilation signals

Scalar partners: Higgs coupling induces sizable WW, ZZ, hh rates, leading to a reduction (e.g., factor of ~2) in the $\gamma\gamma$ rate.

Fermionic partners: the spin-0 bound state is a pseudoscalar, rates are unaffected by the Higgs coupling.

$\mathrm{SU}(2)_L$ singlet



Limits from:

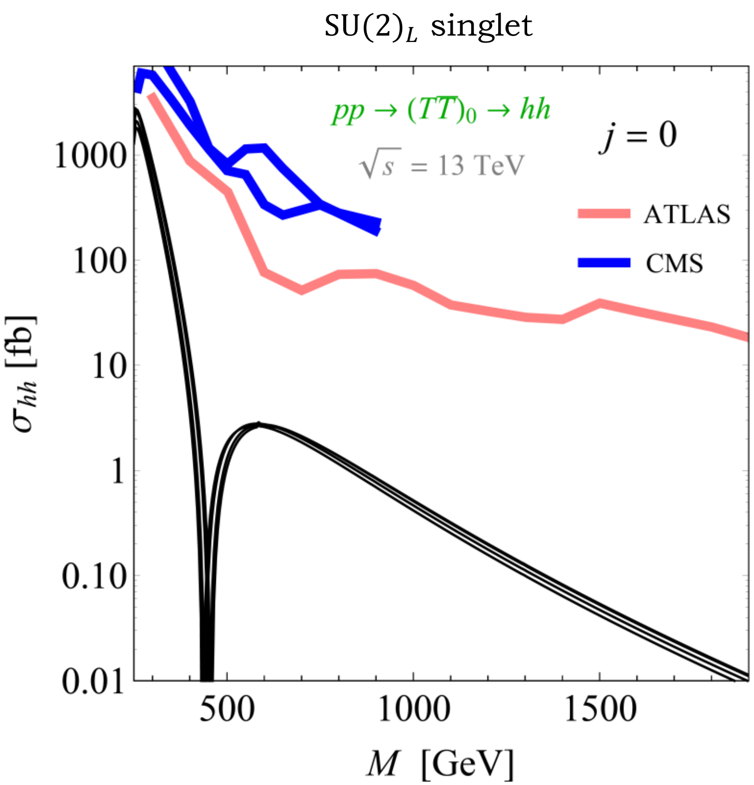
ATLAS-CONF-2016-062 ($\ell\nu qq$, 13/fb)

CMS-PAS-B2G-17-001 (JJ, 36/fb)

Partnerium annihilation signals

Scalar partners: Higgs coupling induces sizable WW, ZZ, hh rates, leading to a reduction (e.g., factor of ~2) in the $\gamma\gamma$ rate.

Fermionic partners: the spin-0 bound state is a pseudoscalar, rates are unaffected by the Higgs coupling.



Limits from:

ATLAS-CONF-2016-049 ($bbbb$, 13/fb)

CMS-PAS-HIG-17-002 ($bb\tau\tau$, 36/fb)

CMS-PAS-HIG-17-006 ($bbl\nu l\nu$, 36/fb)

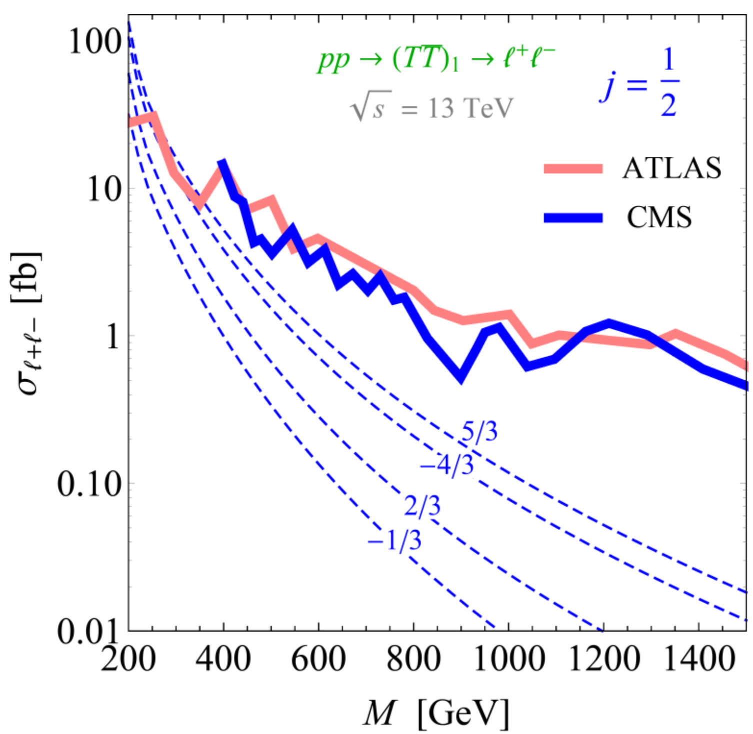
Partnerium annihilation signals

For fermionic partners, spin-1 S-wave bound states are possible.

- Production from gg in association with a g, γ or Z.
- Electroweak production from $q\bar{q}$.
- Deexcitation of gg-produced P waves.

Interesting signature: dilepton (somewhat suppressed by enhanced Zh decays).

$SU(2)_L$ singlet



Limits from:

ATLAS-CONF-2016-045 (13/fb)

CMS-PAS-EXO-16-031 (13/fb)

Conclusions

- Can construct (somewhat complex) models with scalar or fermionic top partners with arbitrary electric charges.
- Partner decays are very model-dependent, not always covered by existing searches.
- Resonant signals from partnerium annihilation are a generic and largely model-independent feature.
- Can be relevant also in other scenarios with new colored particles (outside the context of top partners).
- It would be useful to resolve the discrepancy between the potential model and lattice estimates for $|\psi(\mathbf{0})|^2$.

Thank You!