NCTS Annual Theory Meeting 2016: Particles, Cosmology and Strings (Hsinchu, Taiwan)

Blessings of a phantom: What remains of the 750 GeV diphoton resonance?

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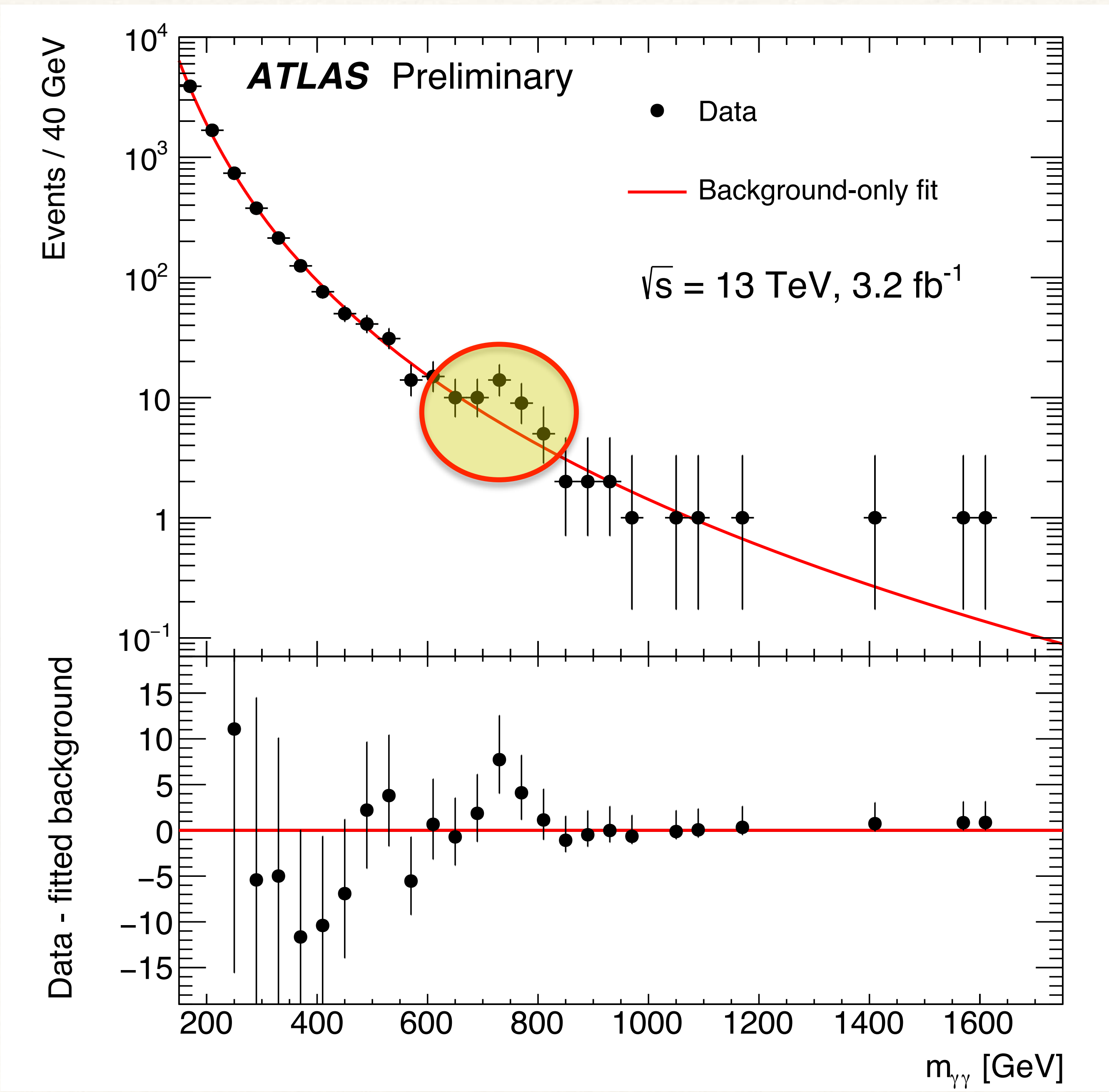
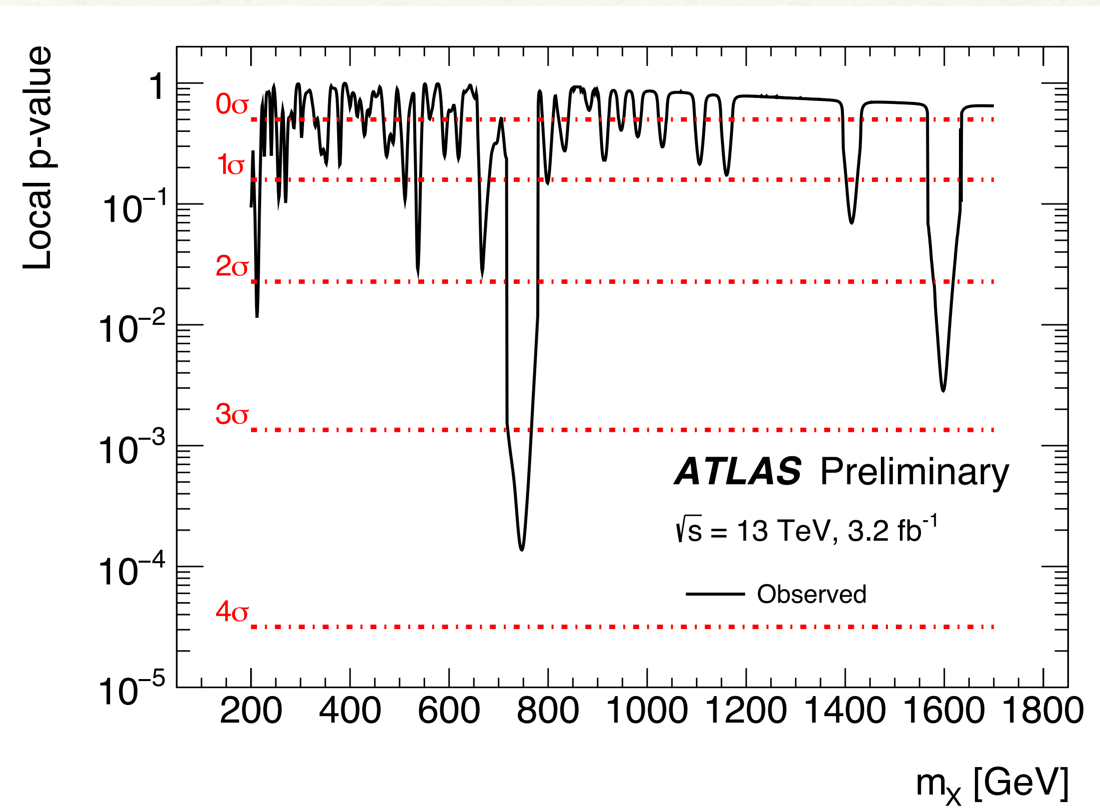
9 December 2016

Run-II ATLAS Data (12/15/2015)

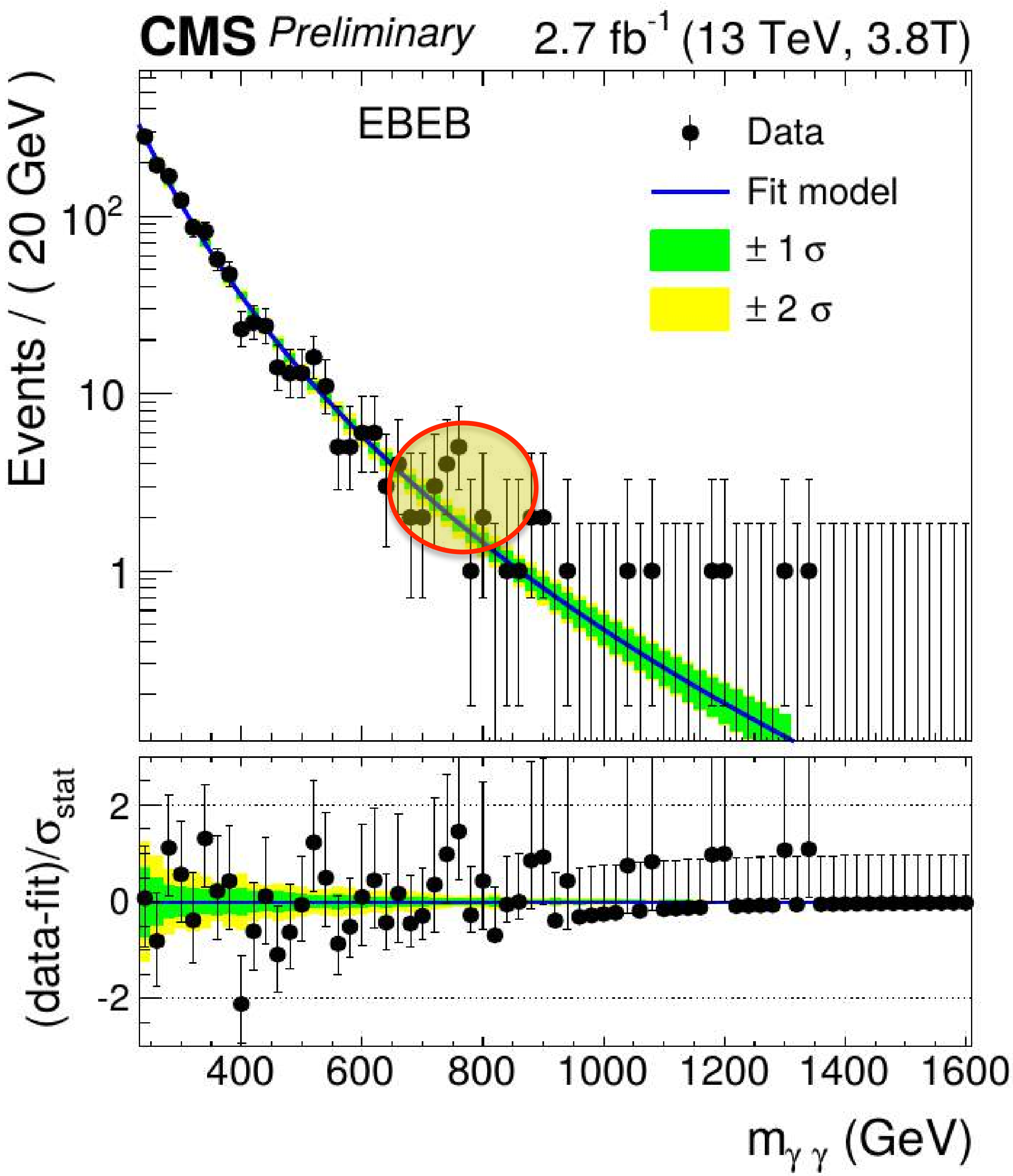


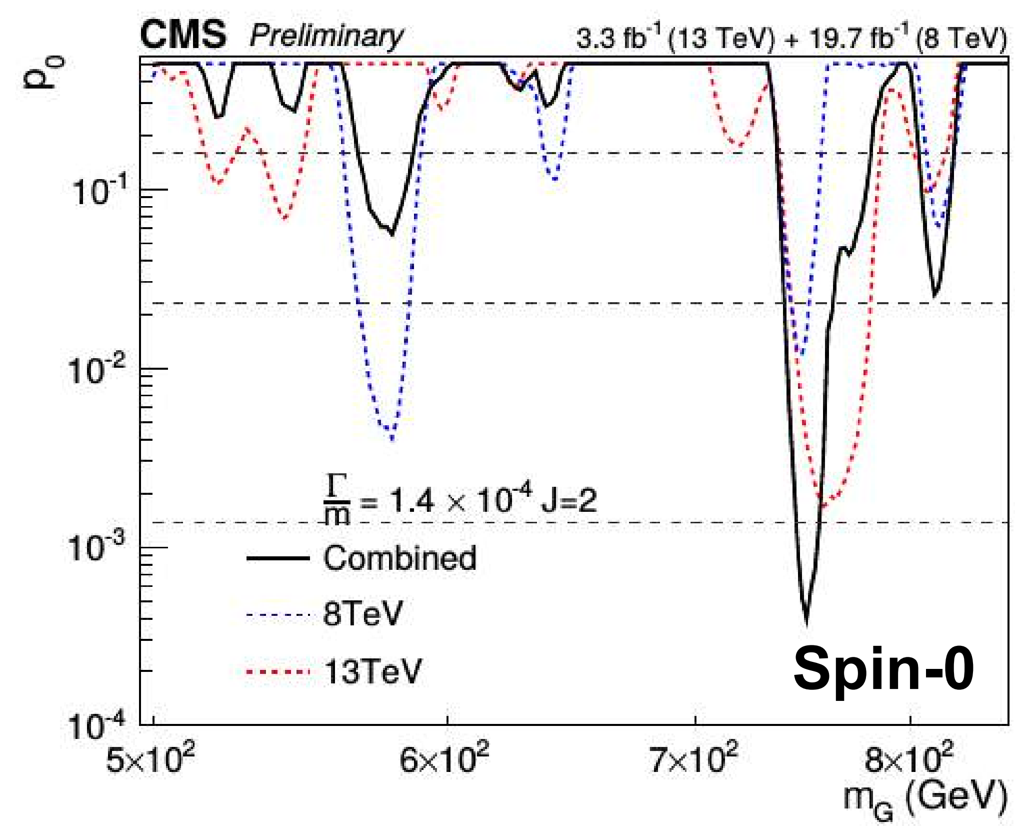


Fact sheet (update 3/17/2016):

- local significance 3.9σ (global 2.0σ)
- best fit $m_S \approx 750$ GeV
- 1.9σ effect in Run-I data (8 TeV)

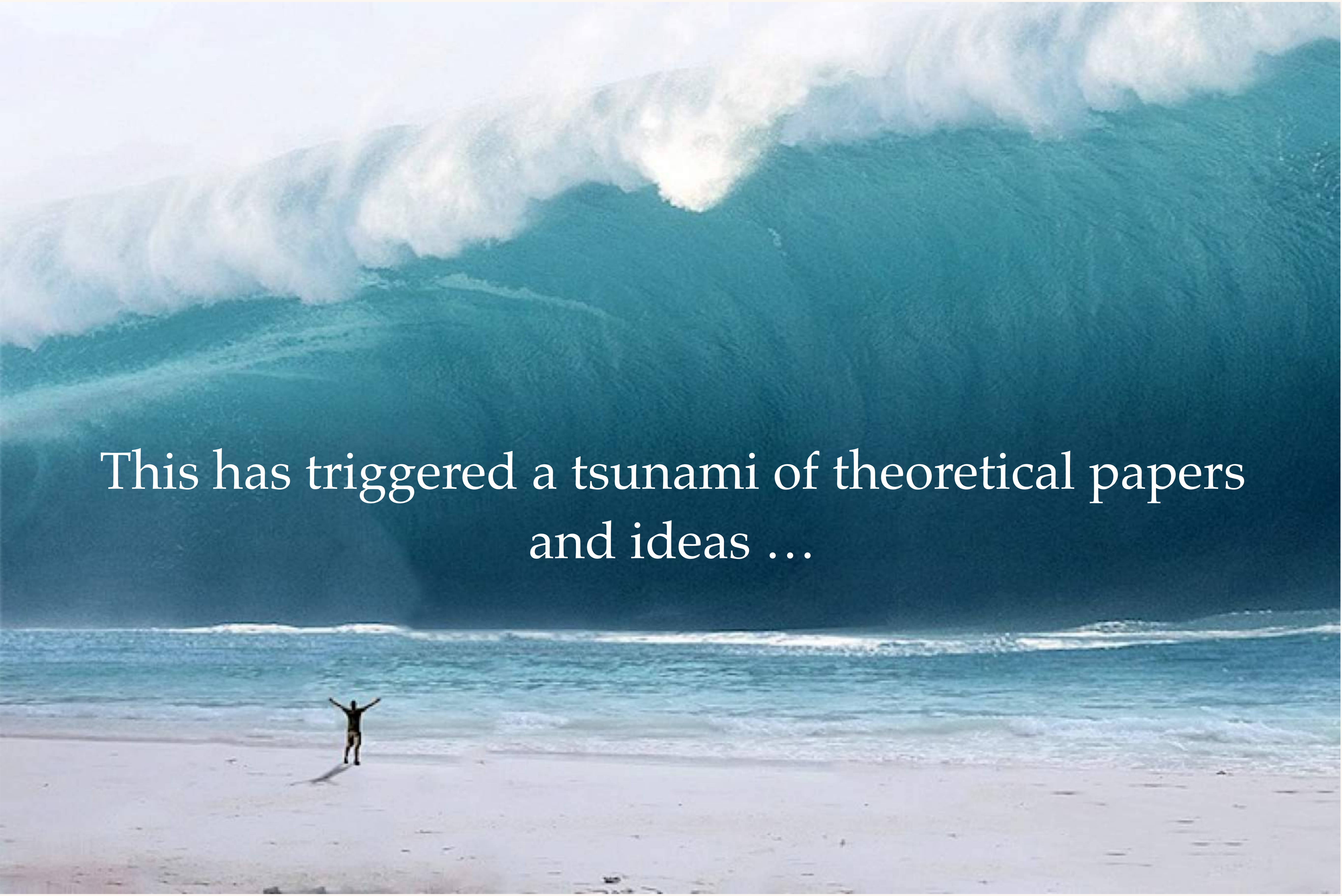
Run-II CMS Data (3/17/2016)





Fact sheet (update 3/17/2016):

- local significance 3.4σ (global 1.6σ) in combined analysis of Run-I and Run-II data
- best fit $m_S \approx 750$ GeV


This has triggered a tsunami of theoretical papers
and ideas …

THE 750 MAY BE DEAD!

ACCORDING TO THE RUMORS*..

* THE SPEAKER DOES NOT APPROVE OF NOR ENCOURAGES RUMOR SPREADING. BUT PLEASE LET HIM** KNOW IF YOU KNOW ANYTHING ELSE...

**and STRUMIA

T. Volansky @ NKPI 2016

Blessings of a phantom

- The 750 GeV diphoton resonance was, at the same time, the most exciting new-physics hint after the Higgs discovery and the most spectacular over-reaction of the high-energy physics community to a (global) 2σ effect!
- While perhaps too many papers have been written in response to this effect, the "swarm intelligence" of the community has produced, in a rather short time, a comprehensive picture of the physics of such a particle!
- Several very useful lessons have been learned!

What has remained after the resonance
turned out to be
a statistical fluctuation ?

The photon PDF of the proton

CERN-TH/2016-155

How bright is the proton? A precise determination of the photon PDF

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It has become apparent in recent years that it is important, notably for a range of physics studies at the Large Hadron Collider, to have accurate knowledge on the distribution of photons in the proton. We show how the photon parton distribution function (PDF) can be determined in a model-independent manner, using electron–proton (ep) scattering data, in effect viewing the $ep \to e + X$ process as an electron scattering off the photon field of the proton. To this end, we consider an imaginary BSM process with a flavour changing photon–lepton vertex. We write its cross section in two ways, one in terms of proton structure functions, the other in terms of a photon distribution. Requiring their equivalence yields the photon distribution as an integral over proton structure functions. As a result of the good precision of ep data, we constrain the photon PDF at the level of 1−2% over a wide range of x values.

The photon PDF of the proton

- Model-independent determination using available, high-precision data on electron-proton scattering
- Key observation is a statement of duality: the process $e+p \rightarrow e+X$ can be described in terms of proton structure functions, but it can equally be viewed as the scattering of the electron off the photon field in the proton

The photon PDF of the proton

- Key relation:

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\}$$

- Contains all large logs of the form $\alpha L (\alpha_s L)^n,\ \alpha (\alpha_s L)^n$ and $\alpha^2 L^2 (\alpha_s L)^n$
- Contains both inelastic and elastic contributions
- Basis for a precise determination

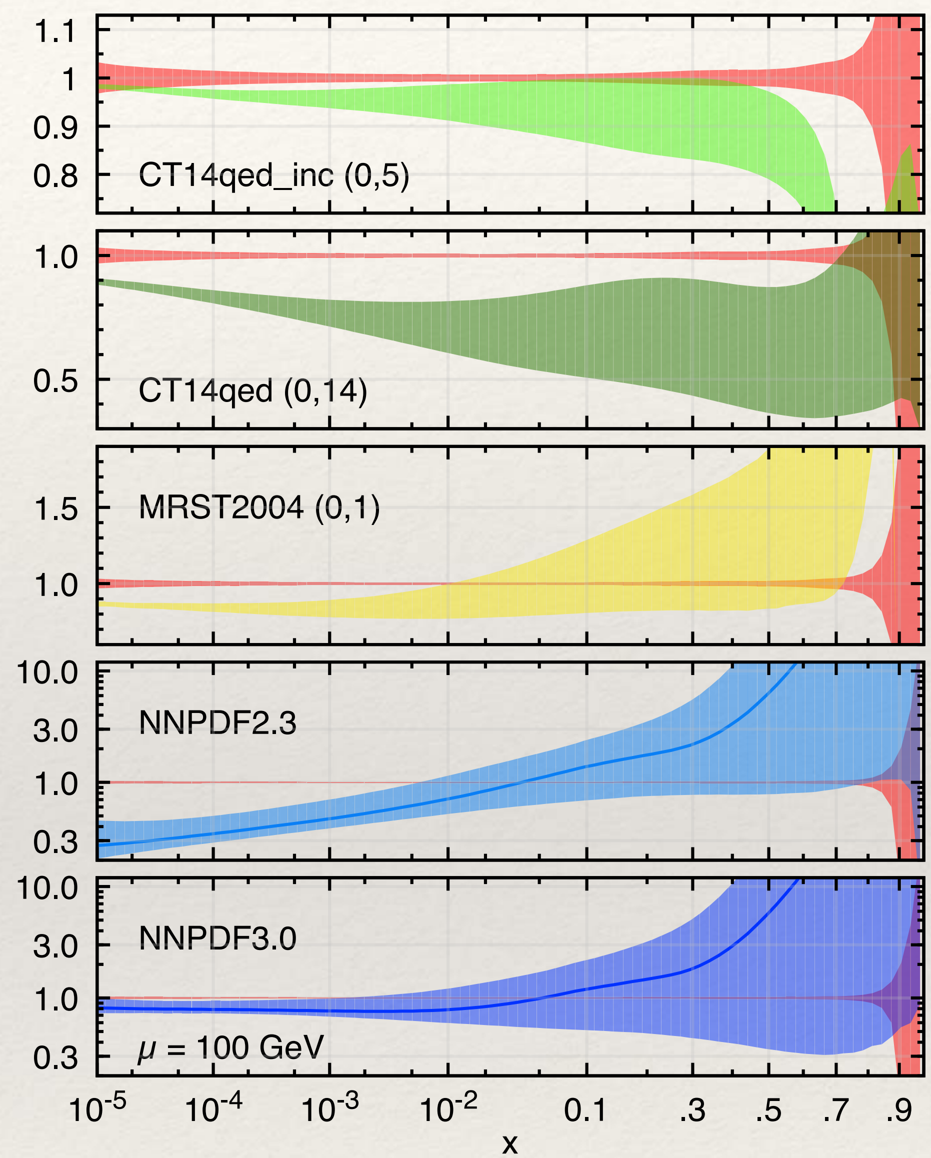
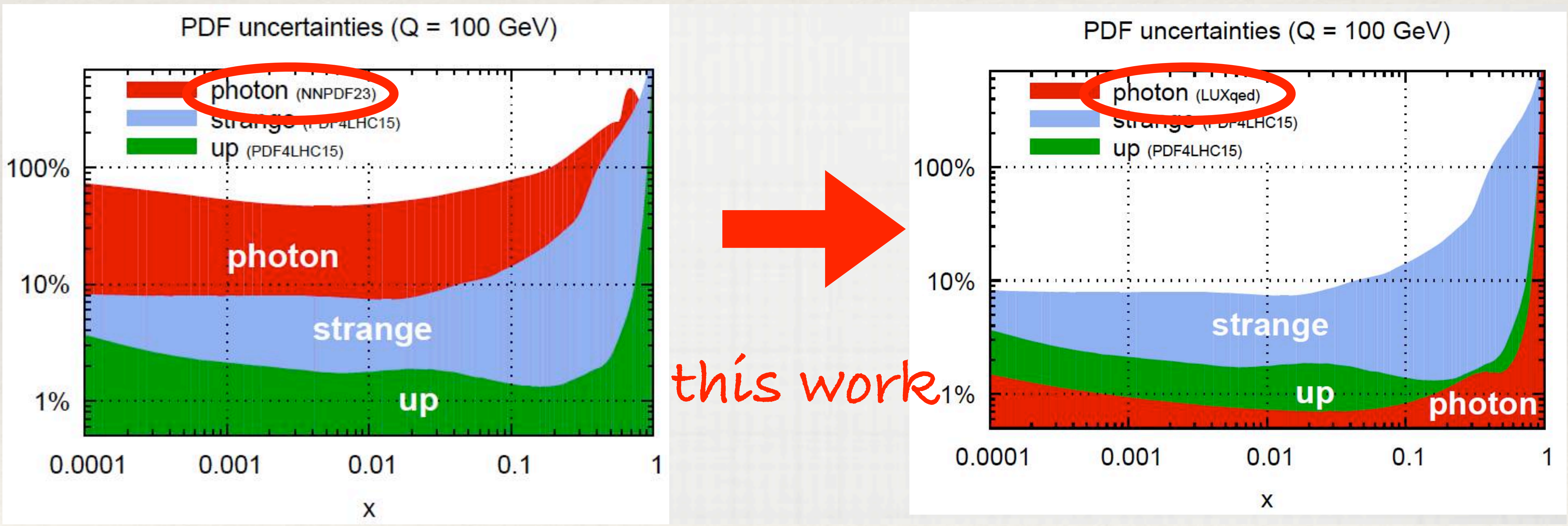


FIG. 4. The ratio of common PDF sets to our LUXqed result, along with the LUXqed uncertainty band (light red). The CT14 and MRST bands correspond to the range from the PDF members shown in brackets (95% cl. in CT14's case). The NNPDF bands span from $\max(\mu_r - \sigma_r, r_{16})$ to $\mu_r + \sigma_r$, where μ_r is the average (represented by the blue line), σ_r is the standard deviation over replicas, and r_{16} denotes the 16^{th} percentile among replicas. Note the different y-axes for the panels.

The photon PDF of the proton

- Amazing improvement over previous work, making the photon PDF one of the best known structure functions of the proton:



- This will have an impact on many other LHC analyses!

New spin-0 particles

Spin-0 gauge singlets play an important role in many extensions of the SM, e.g. as mediators to a hidden sector or in solutions to the strong CP problem

Motivation

- Consider a spin-0 particle S, which is a singlet under the SM gauge group
- Its only renormalizable interactions with the SM arise through the Higgs portals:

$$\mathcal{L}_{\rm portal} = -\lambda_1\, S\, \phi^\dagger \phi - \frac{\lambda_2}{2}\, S^2\, \phi^\dagger \phi$$

- First term gives rise to a mixing of S with the Higgs, with mixing angle $\alpha \sim v\lambda_1/m_S^2$ which naturally can be large
- Affects Higgs phenomenology (α must be small) and potentially the phenomenology of S decays

[Bauer, MN 2016; Dawson, Lewis 2016; …]

Motivation

- Finding ways of suppressing the coupling λ_1 is a challenge to model building (coupling λ_2 is harmless)

  [Carmona, Goertz, Papaefstathiou 2016]

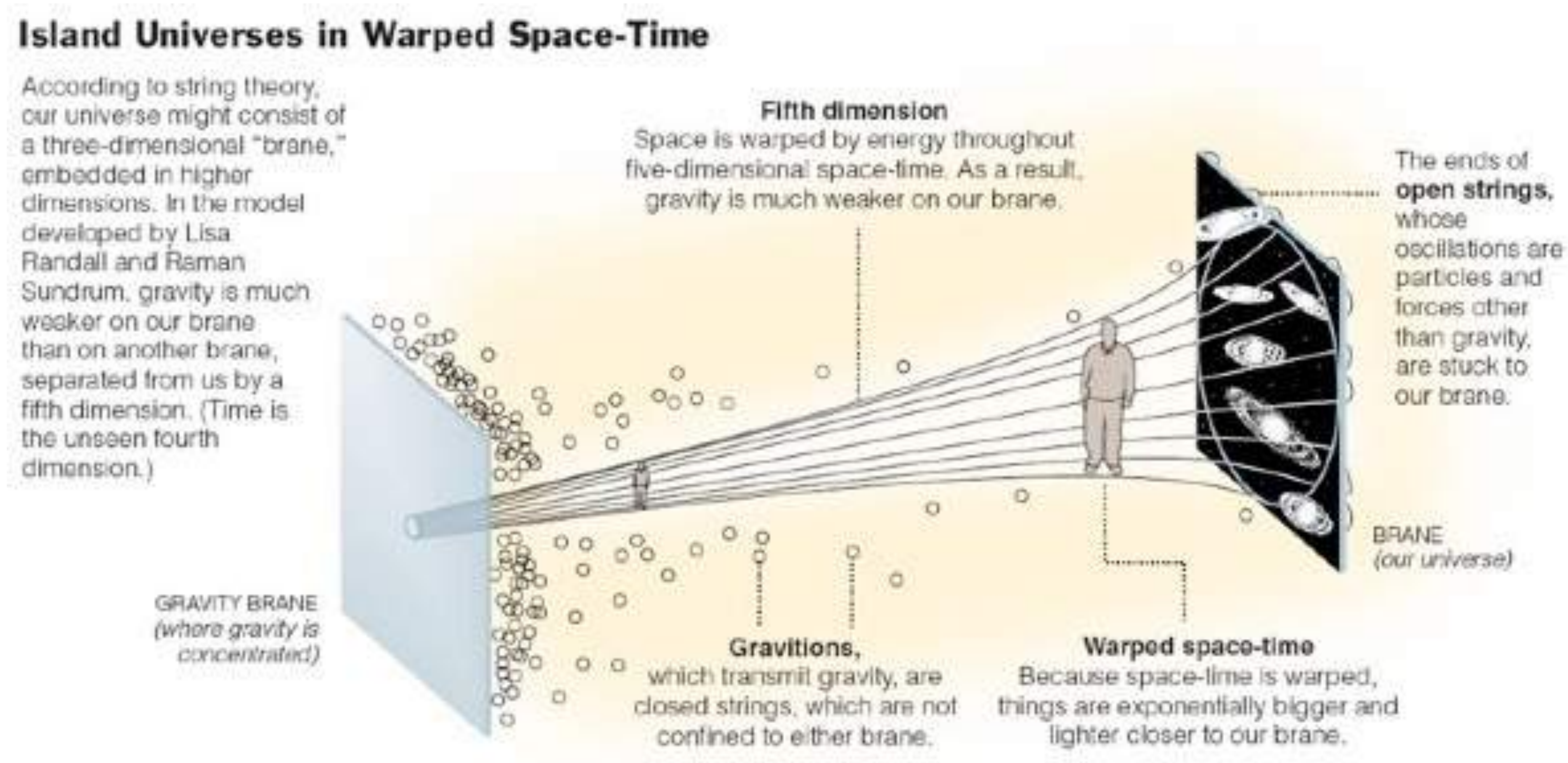
- Two options:
  - dynamically, e.g. sequestering in WEDs, where λ_1 is suppressed by a small wave-function overlap or a loop factor
  - by means of a discrete symmetry, such as CP invariance, as λ_1 is forbidden if S is a pseudoscalar boson

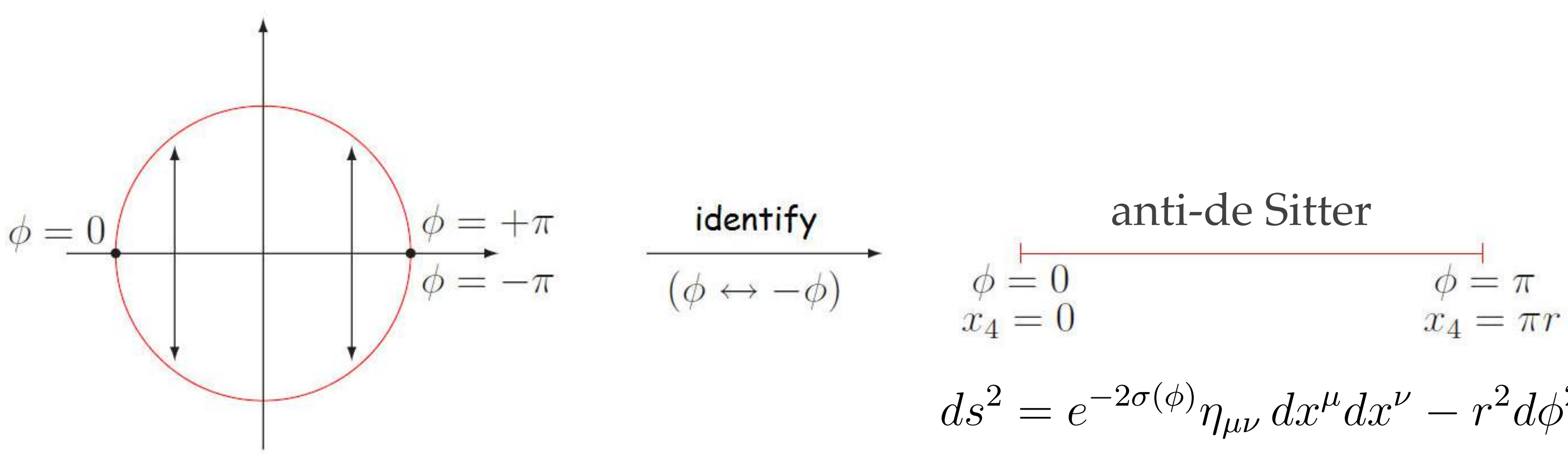
Sequestering in a warped extra dimension

Bauer, Hörner, MN: arXiv:1603.05978 (JHEP)
Csaki, Randall: arXiv:1603.07303 (JHEP)

Randall-Sundrum models

Randall & Sundrum: *A large mass hierarchy from a small extra dimension*, PRL 83 (1999) 3370

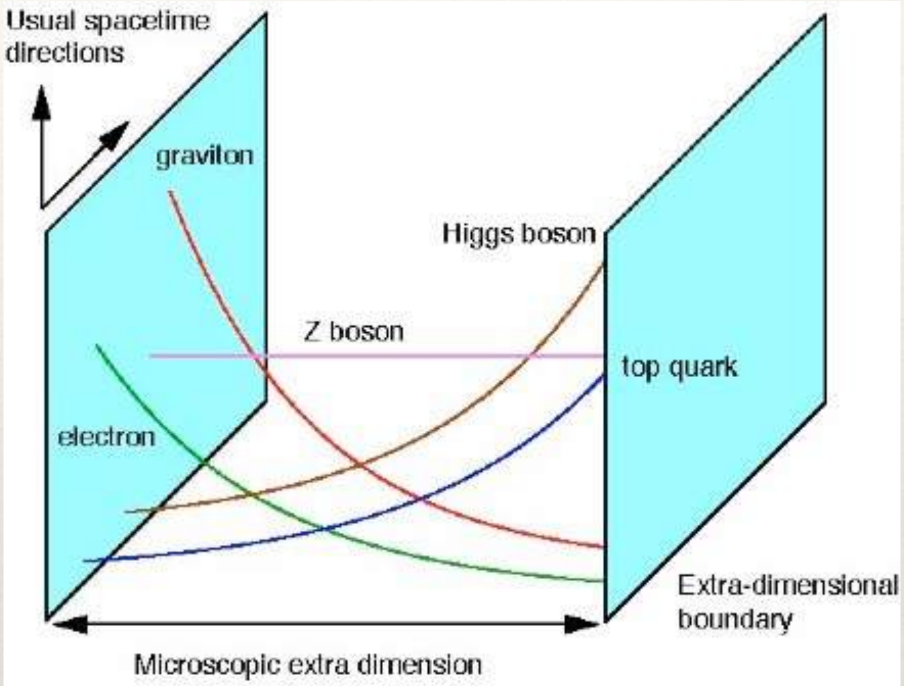




$$ds^2 = e^{-2\sigma(\phi)}\eta_{\mu\nu}\, dx^\mu dx^\nu - r^2 d\phi^2$$

Living in the bulk

- Moving fermions into the bulk offers new possibilities for model building:
  - lowest-lying states (zero modes, corresponding to SM fermions) are chiral
  - zero-mode profiles are localized near the IR or UV branes



[Grossman, MN 1999; Gherghetta, Pomarol 2000]

- Explains two striking features of the SM, namely **chiral matter** fields with **hierarchical masses** and mixing angles
- RS models address both the **hierarchy problem** and the **flavor puzzle** of the SM by means of the same geometrical mechanism!

Localizer field for bulk fermions

- The mass term for a 5D bulk fermion is necessarily an odd function on the S^1/Z_2 orbifold:

$$\int d^4x \int_{-\pi}^{\pi} d\phi\, r\, e^{-4\sigma(\phi)} \left[-\sum_f \mathrm{sgn}(\phi)\, \bar{f}\, M_f\, f \right]$$

- But any coordinate-dependent coupling in a Lagrangian should be derived from the VEV of a field:

$$\int d^4x \int_{-\pi}^{\pi} d\phi\, r\, e^{-4\sigma(\phi)} \left[\frac{g^{MN}}{2} (\partial_M S)(\partial_N S) - V(S) - \sum_f \Big(\mathrm{sgn}(\phi)\, \bar{f}\, \boldsymbol{M}_f f + S\, \bar{f}\, \boldsymbol{G}_f f \Big) \right]$$

due to VEV of the field

coupling of S to fermions

- Such a particle should be included in all RS models containing bulk matter fields!

Localizer field for bulk fermions

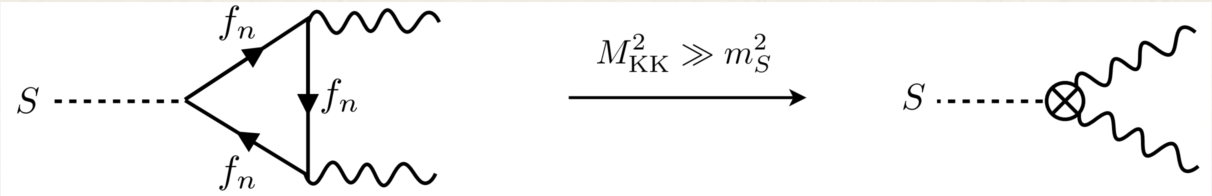
- The mass of the lowest-lying KK state of S is predicted to be of order the KK scale (i.e. few TeV), but a smaller mass (e.g. 750 GeV) could be arranged by a tuning of boundary conditions
- With the Higgs localized near the IR brane, the linear Higgs portal interaction λ_1 is suppressed by a small wave-function overlap or by a loop factor
- The matrices $\boldsymbol{G_f}$ are automatically diagonal in the bulk mass basis (built-in flavor protection mechanism)

[König, MN, Novotny, to appear]

Phenomenology

- Integrating out the heavy KK fermion states gives:

$$\mathcal{L}_{\text{eff}} = c_{gg}\,\frac{\alpha_s}{4\pi}\,S\,G^a_{\mu\nu}G^{\mu\nu,a} + c_{WW}\,\frac{\alpha}{4\pi s_w^2}\,S\,W^a_{\mu\nu}W^{\mu\nu,a} + c_{BB}\,\frac{\alpha}{4\pi c_w^2}\,S\,B_{\mu\nu}B^{\mu\nu}$$



- The Wilson coefficients "count" the fermion degrees of freedom in the bulk: [Bauer, Hörner, MN 2016]

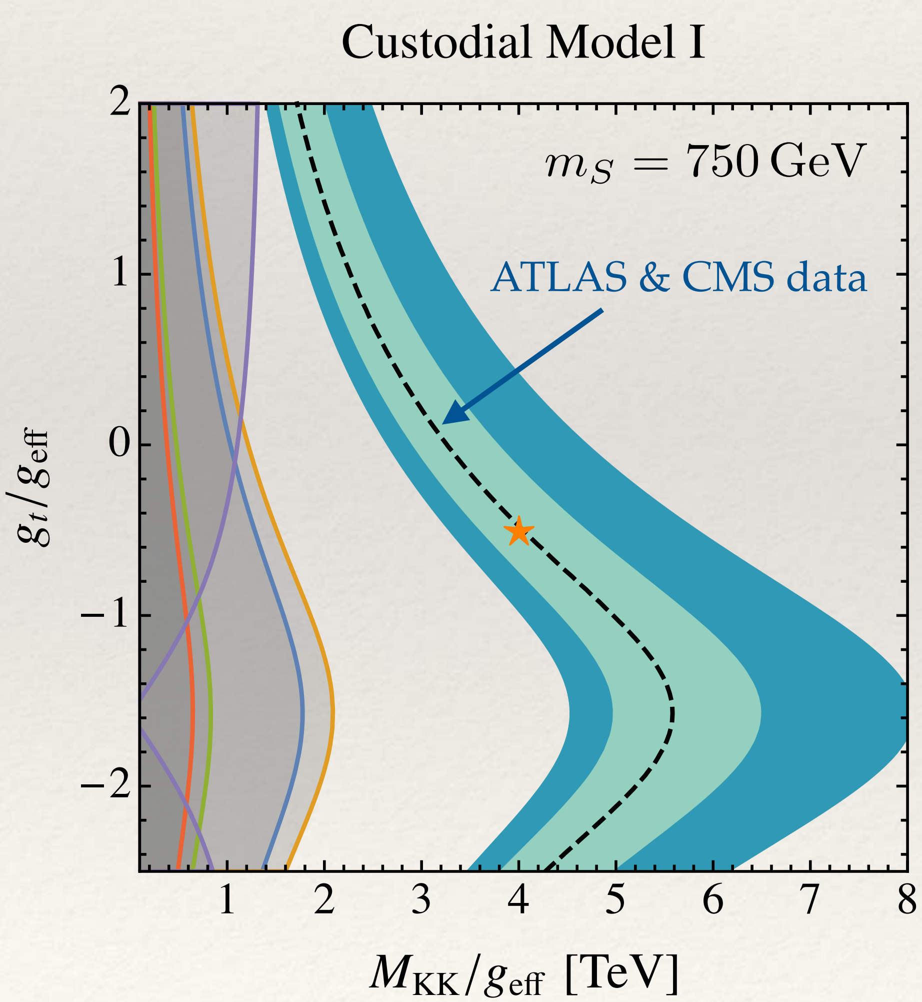
$$c_{gg} = -\frac{1}{3M_{\text{KK}}}\,\text{Tr}\left(2\boldsymbol{g}_Q + \frac{1}{2}\,\boldsymbol{g}_u + \frac{3}{2}\,\boldsymbol{g}_d + \frac{3}{2}\,\boldsymbol{g}_{\tau_1}\right) \approx -\frac{16 g_{\text{eff}}}{3M_{\text{KK}}} - \frac{g_t}{6M_{\text{KK}}}$$

$$c_{WW} = -\frac{1}{3M_{\text{KK}}}\,\text{Tr}\left(3\boldsymbol{g}_Q + 6\boldsymbol{g}_{\tau_1} + \boldsymbol{g}_L + 2\boldsymbol{g}_{\tau_3}\right) \approx -\frac{12 g_{\text{eff}}}{M_{\text{KK}}}$$

$$c_{BB} = -\frac{1}{3M_{\text{KK}}}\,\text{Tr}\left(\frac{25}{3}\,\boldsymbol{g}_Q + \frac{4}{3}\,\boldsymbol{g}_u + 10\boldsymbol{g}_d + 4\boldsymbol{g}_{\tau_1} + \boldsymbol{g}_L + 2\boldsymbol{g}_e\right) \approx -\frac{236 g_{\text{eff}}}{9M_{\text{KK}}} - \frac{4 g_t}{9M_{\text{KK}}}$$

Phenomenology

- Results depend on the KK mass scale and the coupling of S to top quarks, both normalized to the average g_{eff}:



Predicted branching ratios: [Bauer, Hörner, MN 2016]

$\text{Br}(S \to XX)$	gg	$\gamma\gamma$	WW	ZZ	$Z\gamma$	$t\bar{t}$	hh	$t\bar{t}h$	Γ_{tot}	λ_1/m_S
Custodial I	43.0%	1.30%	5.1%	2.1%	0.10%	47.9%	0	0.50%	0.08 GeV	
Custodial II	28.4%	0.68%	2.1%	0.9%	0.02%	67.2%	0	0.70%	0.22 GeV	0
Minimal	89.2%	0.37%	2.7%	1.0%	0.16%	6.6%	0	0.07%	0.14 GeV	
Custodial I	32.2%	0.97%	9.9%	4.6%	0.08%	48.5%	3.1%	0.60%	0.11 GeV	
Custodial II	24.1%	0.58%	4.3%	2.0%	0.01%	66.9%	1.3%	0.77%	0.25 GeV	0.02
Minimal	78.0%	0.32%	6.3%	2.8%	0.14%	10.2%	2.1%	0.14%	0.16 GeV	
Custodial I	21.5%	0.65%	18.0%	8.7%	0.05%	42.1%	8.4%	0.59%	0.16 GeV	
Custodial II	19.2%	0.46%	9.1%	4.4%	0.01%	61.9%	4.2%	0.77%	0.32 GeV	0.04
Minimal	60.4%	0.25%	13.7%	6.5%	0.11%	12.3%	6.5%	0.21%	0.21 GeV	

CP-odd pseudoscalar resonance

Bauer, MN, Thamm: arXiv:1607.01016 & 1610.00009 (PRL)

Motivation

- How can one probe if S is a scalar (CP even), a pseudoscalar (CP odd), or a particle with mixed CP properties?
- Traditionally (Higgs case): [Soni, Xu 1993; Chala et al. 2016; Franceschini et al. 2016]
  - study angular distributions in $S \to ZZ \to 4l$ decay
  - but method requires large statistics and fails if S only weakly couples to Z bosons

Motivation

- Our idea:
  - search for the decay $S \to Z + h$ ($\to l^+ l^- b\bar{b}$), which can only be mediated via CP-odd interactions of S
  - observing a single event proves that S is a pseudo-scalar (if CP is conserved in the UV theory), or that it has pseudoscalar interactions (in case it is a mixture of CP eigenstates)

Introductory remarks

- We assume that S is heavy enough to decay into Z+h, i.e. $m_S > 216$ GeV
- For illustration we will sometimes consider the cases $m_S = 750$ GeV and $m_S = 1.5$ TeV
- An analogous discussion can be made for the Higgs decay $h \to Z+a$ involving a light pseudoscalar a with mass $m_a < 34$ GeV (work in progress) [with M. Bauer, A. Thamm]

Introductory remarks

- Besides the Higgs portals, all other interactions of S with SM particles arise from higher-dimensional operators starting at dimension 5
- The pseudoscalar couplings at D=5 order are: [too many refs.!]

$$\mathcal{L}_{\rm eff}^{\rm gauge} = \frac{\tilde{c}_{gg}}{M}\,\frac{\alpha_s}{4\pi}\,S\,G_{\mu\nu}^a\widetilde{G}^{\mu\nu,a} + \dots$$

$$\mathcal{L}_{\rm eff}^{\rm ferm} = -\tilde{c}_{tt}\,\frac{y_t}{M}\,S\left(i\bar{Q}_L\tilde{\phi}\,t_R + \text{h.c.}\right) + \dots$$

- They induce couplings such as gg → S, S → γγ, S → ZZ, S → $t\bar{t}$ etc.

Caveat: EFT does not really make sense if $M_{\rm NP} \sim m_S$!

Operator analysis of $S \to Z + h$ decay

(not in 2HDM, but for a SM gauge singlet!)

Operator analysis at D=5

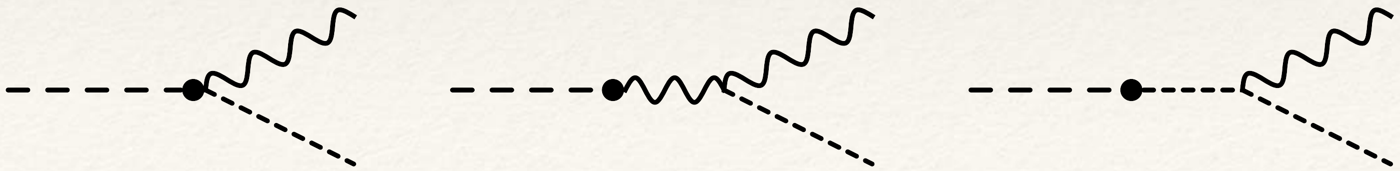
- There does not exist a dimension-5 operator giving rise to a tree-level S → Z+h matrix element!
- The obvious candidate

$$(\partial^\mu S)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right) \to -\frac{g}{2c_w}(\partial^\mu S)\, Z_\mu\, (v+h)^2$$

can be eliminated using the equations of motion:

$$\partial^\mu\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right) \to -\left(1+\frac{h}{v}\right)\sum_f 2T_3^f m_f \bar{f}\, i\gamma_5 f$$

- The corresponding S → Zh(h) matrix elements vanish!

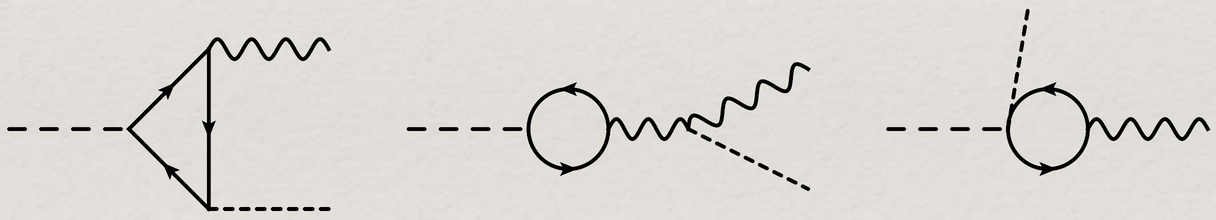


Operator analysis at D=5

- The unique operator giving rise to a one-loop S → Z+h matrix element is:

$$\mathcal{L}_{\rm eff}^{D=5} = -\tilde{c}_{tt}\,\frac{y_t}{M}\,S\left(i\bar{Q}_L\tilde{\phi}\,t_R + \text{h.c.}\right)$$

- Evaluating the resulting diagrams



we obtain:

$$i\mathcal{A}(S\to Zh) = -\frac{2m_Z\,\epsilon_Z^*\cdot p_h}{M}\,C_5^{\rm top}\,, \quad \text{with} \quad C_5^{\rm top} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F$$

$$F = \int_0^1 d[xyz]\,\frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xzm_S^2 - xym_h^2 - yzm_Z^2 - i0}$$

Operator analysis at D=5

- We obtain:

$$i\mathcal{A}(S \to Zh) = -\frac{2m_Z\, \epsilon_Z^* \cdot p_h}{M}\, C_5^{\text{top}}\,, \quad \text{with} \quad C_5^{\text{top}} = -\frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, \tilde{c}_{tt}\, F$$

$$F = \int_0^1 d[xyz]\, \frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xzm_S^2 - xym_h^2 - yzm_Z^2 - i0}$$

- Z boson is longitudinally polarized ($\epsilon_Z^\mu \approx p_Z^\mu / m_Z$)
- Loop integral scales like:

$$F = -\frac{m_t^2}{m_S^2}\left(\ln\frac{m_S^2}{m_t^2} - i\pi\right)^2 + \mathcal{O}\left(\frac{m_t^4}{m_S^4}\right)$$

- Numerically, $F \approx -0.01 + 0.67i$ for m_S = 750 GeV, and $F \approx -0.09 + 0.23i$ for m_S = 1.5 TeV

Operator analysis at D=5

- We find

$$\Gamma(S \to Zh)_{D=5} = \frac{m_S^3}{16\pi M^2} \left| C_5^{\rm top} \right|^2 \lambda^{3/2}(1, x_h, x_Z)$$

$$\approx 0.6\,\text{MeV}\; \tilde{c}_{tt}^2\, (\text{TeV}/M)^2$$

in both cases, which is a very small decay rate

- If the decay into top-quark pairs is kinematically allowed, one obtains

$$\frac{\Gamma(S \to Zh)_{D=5}}{\Gamma(S \to t\bar{t})} = \frac{3y_t^2}{16\pi^2} \left(\frac{m_S}{4\pi v} \right)^2 |F|^2 \, \frac{\lambda^{3/2}(1, x_h, x_Z)}{\sqrt{1 - 4x_t}}$$

yielding $3.6 \cdot 10^{-4}$ ($1.8 \cdot 10^{-4}$) for $m_S = 750$ GeV (1.5 TeV)

Operator analysis at D=5

- The current experimental bounds on $pp \to S \to t\bar{t}$ then imply $pp \to S \to Zh$ rates less than 1.1 fb and 0.1 fb (at D=5), respectively, which is two orders of magnitude smaller than the experimental upper bounds of 123 fb and 40 fb [ATLAS-CONF-2016-015]
- However, it is by no means guaranteed that the D=5 contributions to the S → Z+h decay rates are the dominant ones!

Operator analysis at D=7

- At dimension 7, there is a unique operator mediating the decay S → Z+h at tree level: [see also: Gripaios, Sutherland 2016]

$$O_7 = (\partial^\mu S)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\phi^\dagger\phi \;\hat{=}\; -S\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\partial^\mu(\phi^\dagger\phi)$$
$$\to \frac{g}{2c_w}\, S\, Z_\mu\,(v+h)^3\,\partial^\mu h$$

- It yields the decay rate:

$$\Gamma(S\to Zh) \approx \frac{m_S^3}{16\pi M^2}\left|C_5^{\text{top}} + \frac{v^2}{2M^2}\,C_7\right|^2 \lambda^{3/2}(1,x_h,x_Z)$$

- With $C_7 = 1$ and M = 1 TeV this rate is 7 MeV for $m_S = 750$ GeV and 60 MeV for $m_S = 1.5$ TeV

- If S is produced in gluon fusion and dominantly decays into dijets, these rates are close to the current experimental upper bounds!

Operator analysis at D=7

- Beyond tree level, there are several fermionic operators contributing to the S → Z+h decay rate at dimension 7; those mixing under renormalization are:

$$\mathcal{L}_{\rm eff}^{D=7} = \frac{C_7}{M^3}\, O_7 + \frac{c_6^t}{M^2}\, \bar{t}_R\, \tilde{\phi}^\dagger i\not{D}\, \tilde{\phi}\, t_R + \frac{c_{7a}^t}{M^3}\left[iS\, \bar{Q}_L i\not{D}\, i\not{D}\, \tilde{\phi}\, t_R + \text{h.c.}\right] + \frac{c_{7b}^t}{M^3}\, (\partial^\mu S)\, \bar{t}_R\, \tilde{\phi}^\dagger \gamma^\mu \tilde{\phi}\, t_R$$

- Only the sum of these contributions is scale invariant at one-loop order

Non-polynomial operators at D=5

- Recall the result from the top-loop amplitude arising at dimension 5:

$$i\mathcal{A}(S \to Zh) = -\frac{2m_Z\,\epsilon_Z^* \cdot p_h}{M}\,C_5^{\rm top}\,, \quad \text{with} \quad C_5^{\rm top} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F$$

$$F = \int_0^1 d[xyz]\,\frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xzm_S^2 - xym_h^2 - yzm_Z^2 - i0}$$

- Consider the fictitious limit where $m_t \gg m_S$, in which case $F = 1 + \mathcal{O}(m_S^2/m_t^2)$
- The top quark is then a very heavy particle, which should be integrated out

Non-polynomial operators at D=5

- This yields a short-distance, D=5 matching contribution!
- However, we found that no corresponding dimension-5 operator exists on the effective Lagrangian!?!
- What's going on?

Non-polynomial operators at D=5

- This yields a short-distance, D=5 matching contribution!
- However, we found that no corresponding dimension-5 operator exists on the effective Lagrangian!?!
- What's going on?
- When one integrates out particles whose mass arises from electroweak symmetry breaking, then non-polynomial operators in the Higgs field can arise in the effective Lagrangian! [see e.g.: Pierce, Thaler, Wang 2006]

Non-polynomial operators at D=5

- In our case, the relevant operator is:

$$O_5 = (\partial^\mu S)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right) \ln \frac{\phi^\dagger \phi}{\mu^2} \quad \hat{=} - S\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right) \frac{\partial^\mu (\phi^\dagger \phi)}{\phi^\dagger \phi}$$

- Assuming that S is produced in gluon fusion, we then obtain the production times decay rate:

$$\sigma(pp \to S)\,\text{Br}(S \to Zh) = \frac{\pi m_S^2}{128 s} \frac{K_{pp\to S}}{K_{S\to gg}} \lambda^{3/2}(1, x_h, x_Z)$$
$$\times ff_{gg}\left(\frac{m_S^2}{s}\right) \text{Br}(S \to gg) \left| \frac{C_5}{M} + \frac{v^2 C_7}{2M^3} \right|^2,$$

where:

$$C_5 = C_5^{\text{top}} + C_5^{\text{non-pol}} \quad \text{with} \quad C_5^{\text{top}} = -\frac{N_c\, y_t^2}{8\pi^2} T_3^t\, \tilde{c}_{tt}\, F$$

Comparison with ATLAS bounds

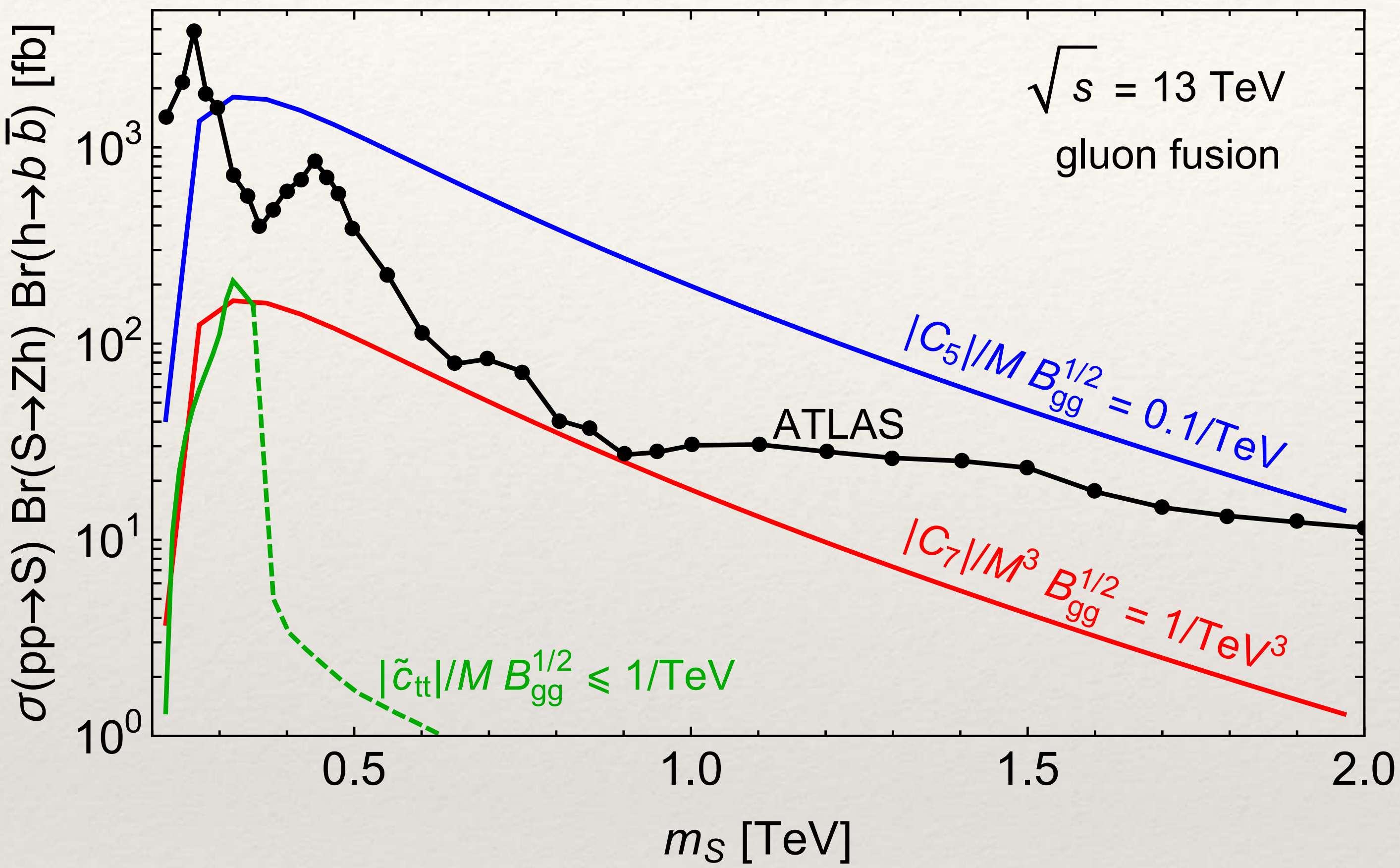
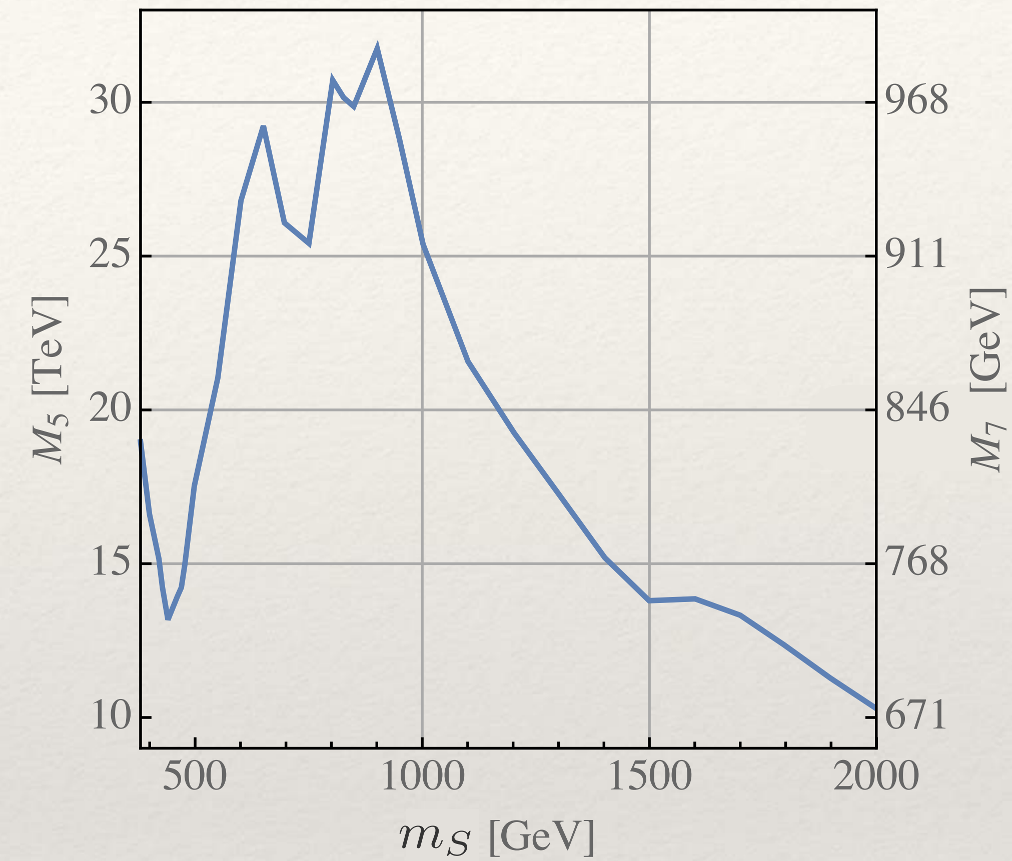


FIG. 3. Predictions for the $pp \to S \to Zh \to Zb\bar{b}$ signal rate vs. m_S, compared with the ATLAS upper bounds [10]. The red line shows the contribution from C_7 evaluated with $B_{gg}^{1/2}\,|C_7|/M^3 = 1/\text{TeV}^3$, while the blue line shows a generic dimension-5 contribution with $B_{gg}^{1/2}\,|C_5|/M = 0.1/\text{TeV}$ (see Section II C), where $B_{gg} \equiv \text{Br}(S \to gg)$. The green line shows the contribution from C_5^{top} for $B_{gg}^{1/2}\,|\tilde{c}_{tt}|/M = 1/\text{TeV}$, while the dashed green line incorporates the upper bound on $|\tilde{c}_{tt}|$ implied by the ATLAS limits on the $pp \to S \to t\bar{t}$ rate [15].



Bounds implies by the ATLAS data on the effective new-physics scales:

$$M_5 \equiv \frac{M}{|C_5|\, B_{gg}^{1/2}}\,, \qquad M_7 \equiv \frac{M}{|C_7|^{1/3}\, B_{gg}^{1/6}}$$

Heavy vector-like fermions

Heavy vector-like quarks

- To illustrate our results, we have considered a heavy, $SU(2)_L$ doublet $\psi = (T \;\; B)^T$ of vector-like quarks, which mix with the SM quarks

- The most general renormalizable Lagrangian reads:

$$\begin{aligned}\mathcal{L} = &\bar{\psi}\,(i\not{D} - M)\,\psi + \bar{Q}_L\, i\not{D}\, Q_L + \bar{t}_R\, i\not{D}\, t_R + \bar{b}_R\, i\not{D}\, b_R \\ &- y_t\big(\bar{Q}_L\tilde{\phi}\, t_R + \text{h.c.}\big) - \big(g_t\bar{\psi}\,\tilde{\phi}\, t_R + g_b\bar{\psi}\,\phi\, b_R + \text{h.c.}\big) \\ &- c_1 S\,\bar{\psi}\, i\gamma_5\,\psi - ic_2 S\big(\bar{Q}_L\psi - \bar{\psi}\, Q_L\big)\end{aligned}$$

- Tree-level matching gives:

$$\tilde{c}_{tt} = -c_2\, g_t/y_t \qquad c_6^f = g_f^2 \qquad c_{7a}^f = c_2\, g_f \qquad c_{7b}^f = c_1\, g_f^2$$

Heavy vector-like quarks

- The coefficient c_6^b is constrained by precision measurements of the Z-boson couplings at LEP:

$$c_6^b = g_b^2 = (0.76 \pm 0.27) \left(\frac{M}{\mathrm{TeV}} \right)^2$$

- The pull away from 0 is driven by the b-quark forward-backward asymmetry, which is 2.8σ below its SM value
- Our model can easily account for this effect

Heavy vector-like quarks

- Performing the matching at one-loop order, we find

$$\frac{v^2}{2}C_7 = c_1 \sum_{f=t,b} \frac{N_c\, g_f^2}{16\pi^2}\left\{2T_3^f\left[m_f^2\left(L-\frac{3}{2}\right)-\frac{m_h^2}{12}+\frac{m_Z^2}{36}+\frac{g_f^2\, v^2}{4}\right]-\frac{2}{3}Q_f s_w^2 m_Z^2\left(L-\frac{3}{2}\right)\right\}$$
$$+\tilde{c}_{tt}\frac{N_c\, y_t^2}{16\pi^2}\left\{2T_3^t\left[3m_t^2\left(L-\frac{3}{2}\right)-\frac{m_h^2}{2}\left(L-\frac{7}{6}\right)-\frac{m_Z^2}{6}\left(L+\frac{19}{6}\right)-g_t^2v^2\left(L-\frac{9}{4}\right)\right]+Q_t s_w^2 m_Z^2\right\}$$

where $L = \ln(M^2/\mu^2)$

- This can naturally lead to sizable values, e.g. with $g_t = 2$ and $\mu = m_Z$:

$$C_7 \approx \left[c_1\left(5.30\, g_t^2 + 0.95\, g_t^4 + 0.16\, g_b^2 - 0.95\, g_b^4\right) + \tilde{c}_{tt}\left(10.18 - 6.90\, g_t^2\right)\right]\cdot 10^{-2}$$
$$\approx (0.36\, c_1 - 0.17\, \tilde{c}_{tt})$$

Conclusions

- Thanks to the phantom of the 750 GeV resonance, several interesting new development have been started, which are of lasting value!
- I have discussed three examples (several others exist):
  - precision determination of the photon PDF, because it finally mattered
  - realization that models of warped extra dimensions should contain a new bulk scalar field (the "fermion localizer"), whose lowest-lying KK mode is a gauge-singlet scalar particle with TeV-scale mass
  - $S \to Z+h$ decay offers a novel way for probing the CP properties of a new, heavy spin-0 boson
- This motivates continued experimental searches for heavy scalar particles in the LHC Run-2!

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