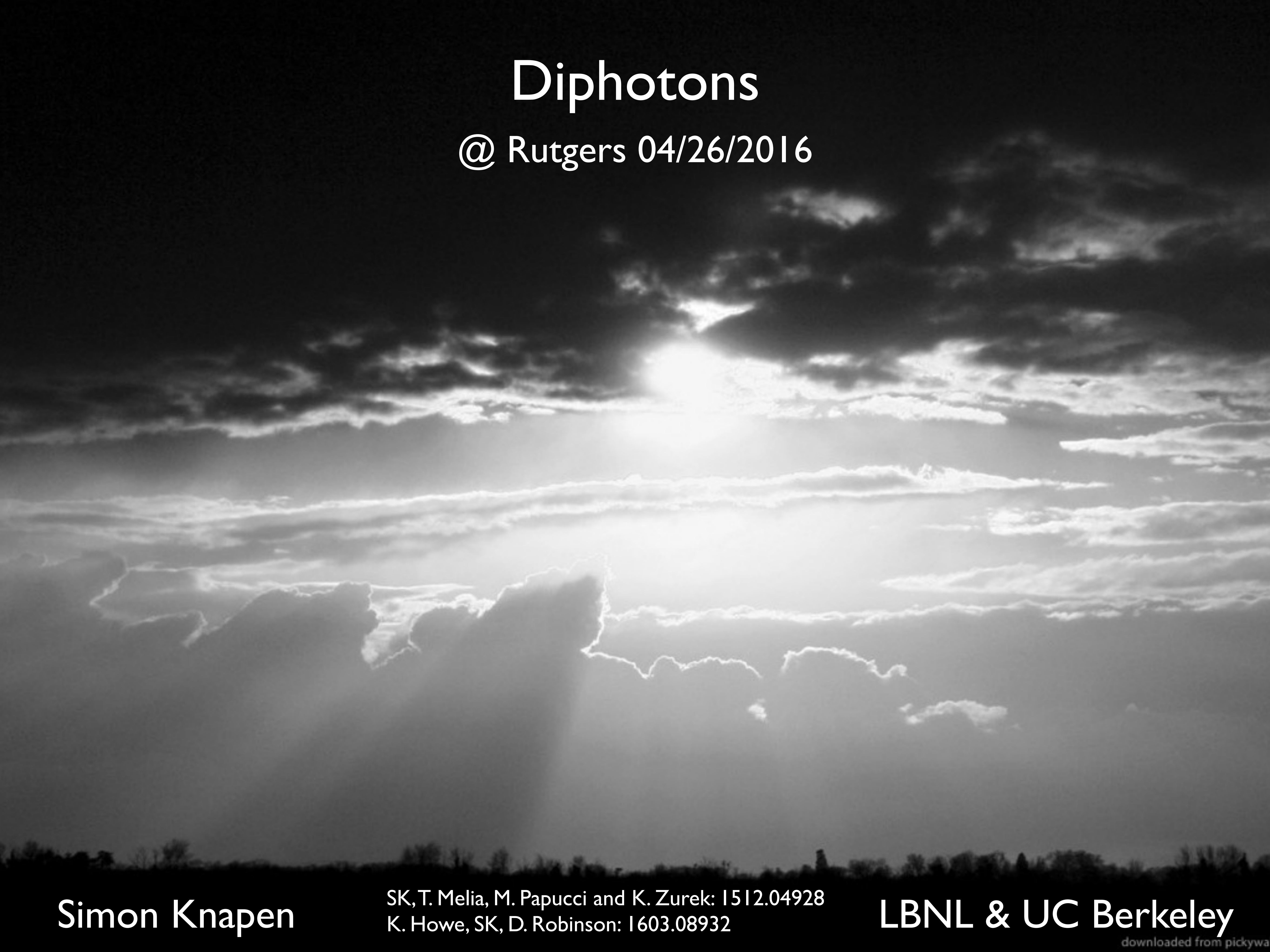


Diphotons

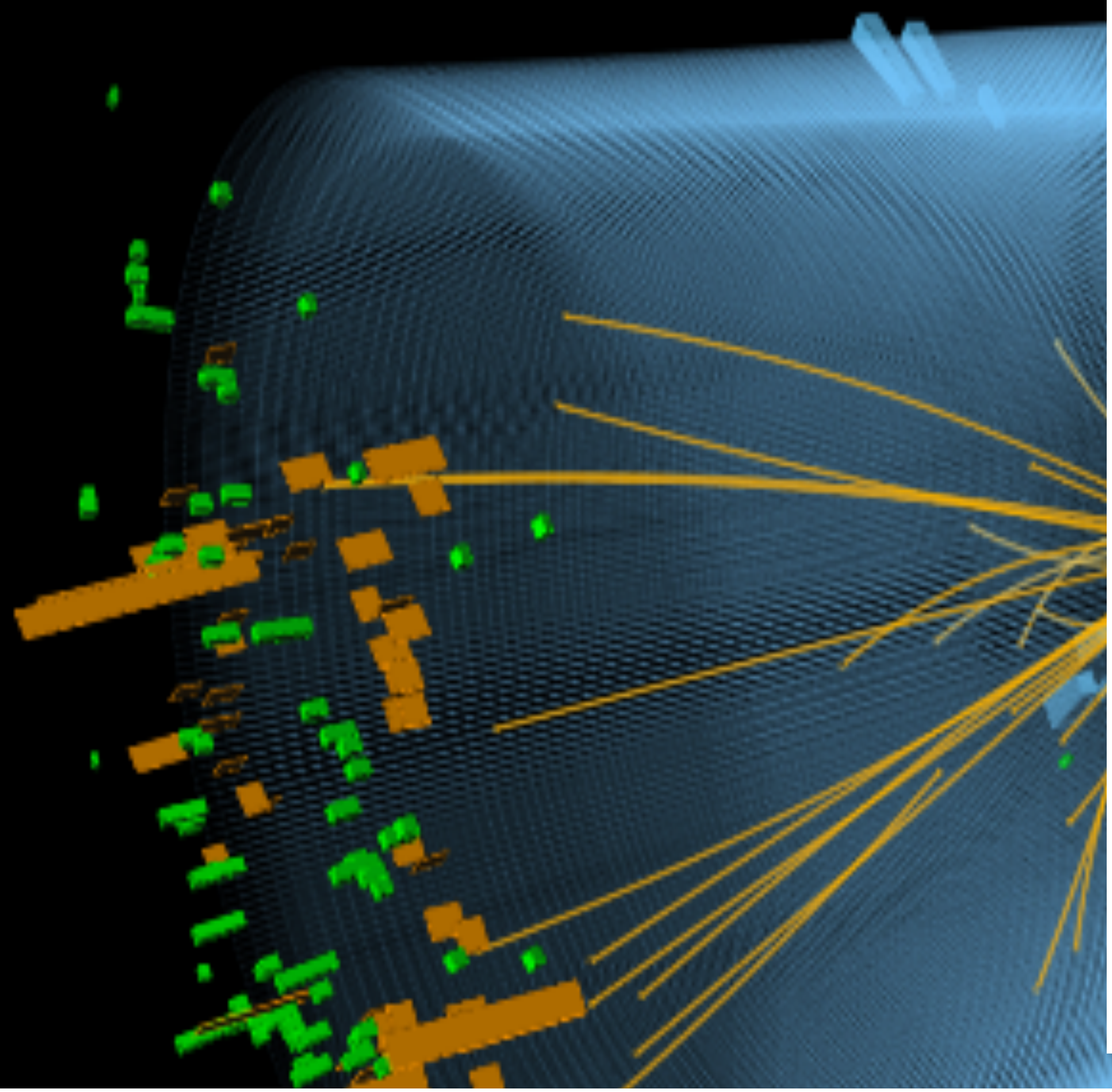
@ Rutgers 04/26/2016

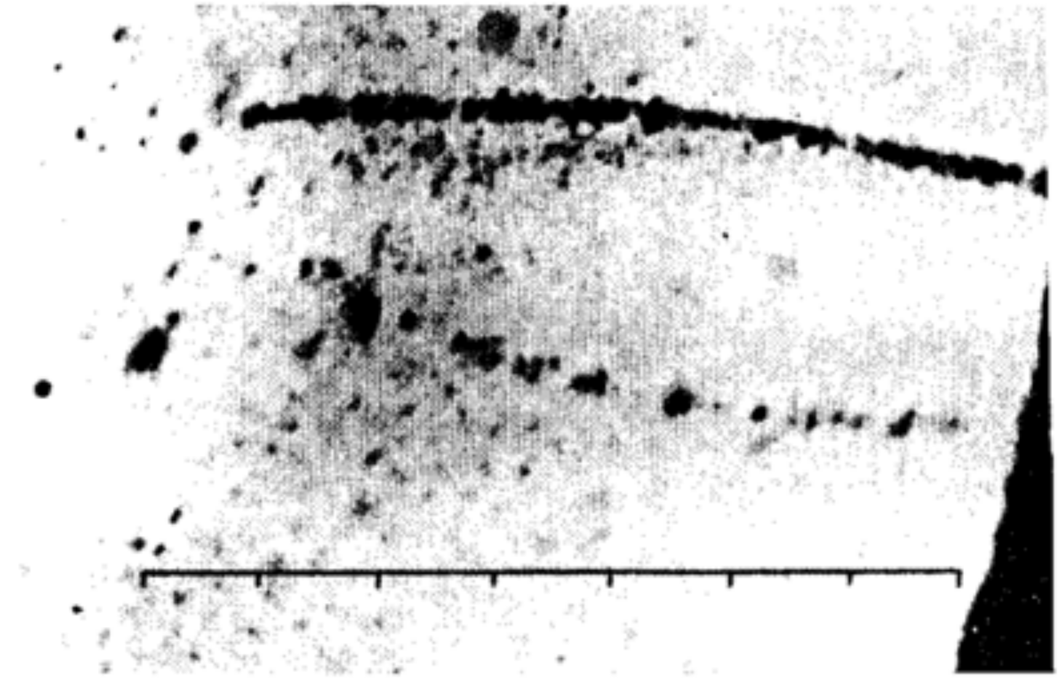
Simon Knapen

LBNL & UC Berkeley

SK, T. Melia, M. Papucci and K. Zurek: 1512.04928
K. Howe, SK, D. Robinson: 1603.08932

A sign of hope?





"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

Who ordered that? - I. Rabi

Goal of this talk:
A review of the theory work related to this excess
+ one idea of my own

A fascinating puzzle!

INSPIRE HEP

Welcome to INSPIRE, the High Energy Physics information system. Please direct questions, comments or co

HEP :: HepNames :: Institutions :: Conferences :: Jobs :: Experiments :: Journals :: Help

referstto:recid:1410174 | Brief format | Search | Easy Search | Advanced Search

find j "Phys.Rev.Lett.,105*" :: more

Sort by: earliest date | desc. | - or rank by -

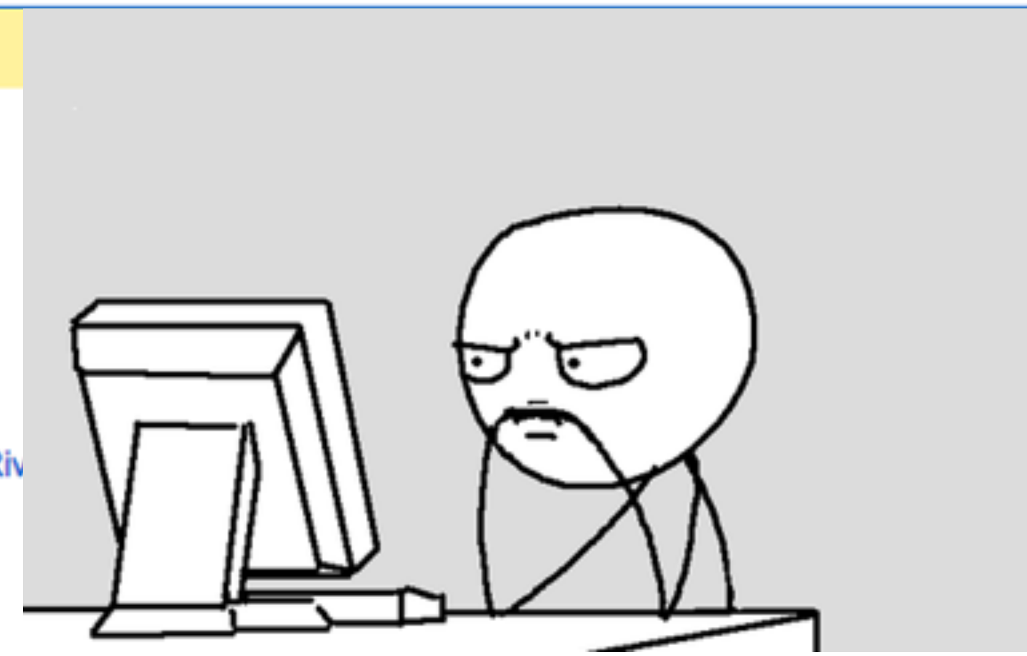
Display results: 25 results | single list

HEP 305 records found 1 - 25 jump to record: 1

1. **The Dual Standard Model and the 750 GeV Events at the LHC**
   Xavier Calmet. Apr 21, 2016.
   e-Print: **arXiv:1604.06185 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

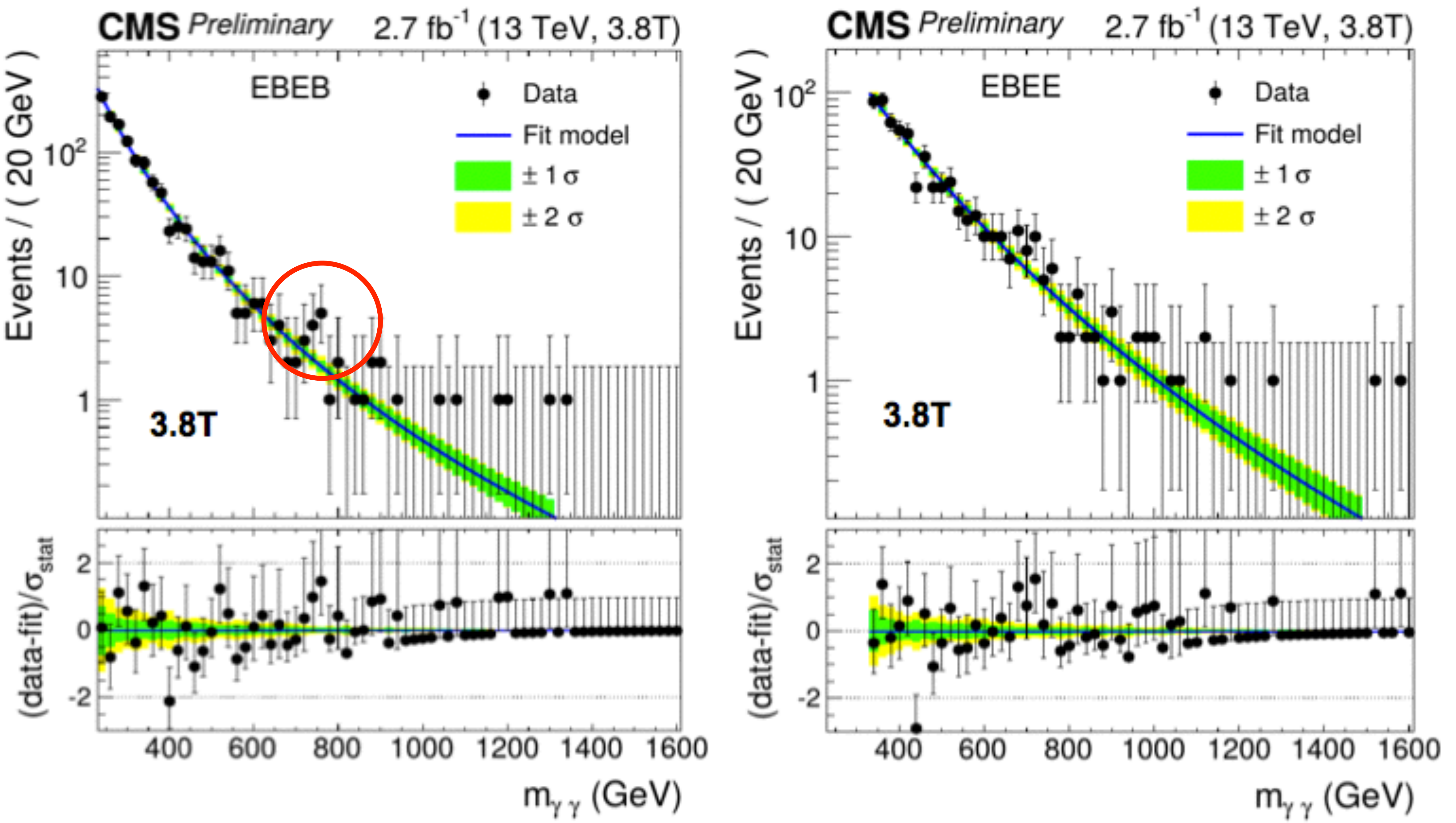
2. **Digamma, what next?**
   Roberto Franceschini, Gian F. Giudice, Jernej F. Kamenik, Matthew McCullough, Francesco Riv
   CERN-TH-2016-090
   e-Print: **arXiv:1604.06446 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; ADS Abstract Service
   Detailed record

3. **Composite Weak Bosons at the Large Hadronic Collider**
   Harald Fritzsch. Apr 20, 2016. 6 pp.
   e-Print: **arXiv:1604.05818 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote



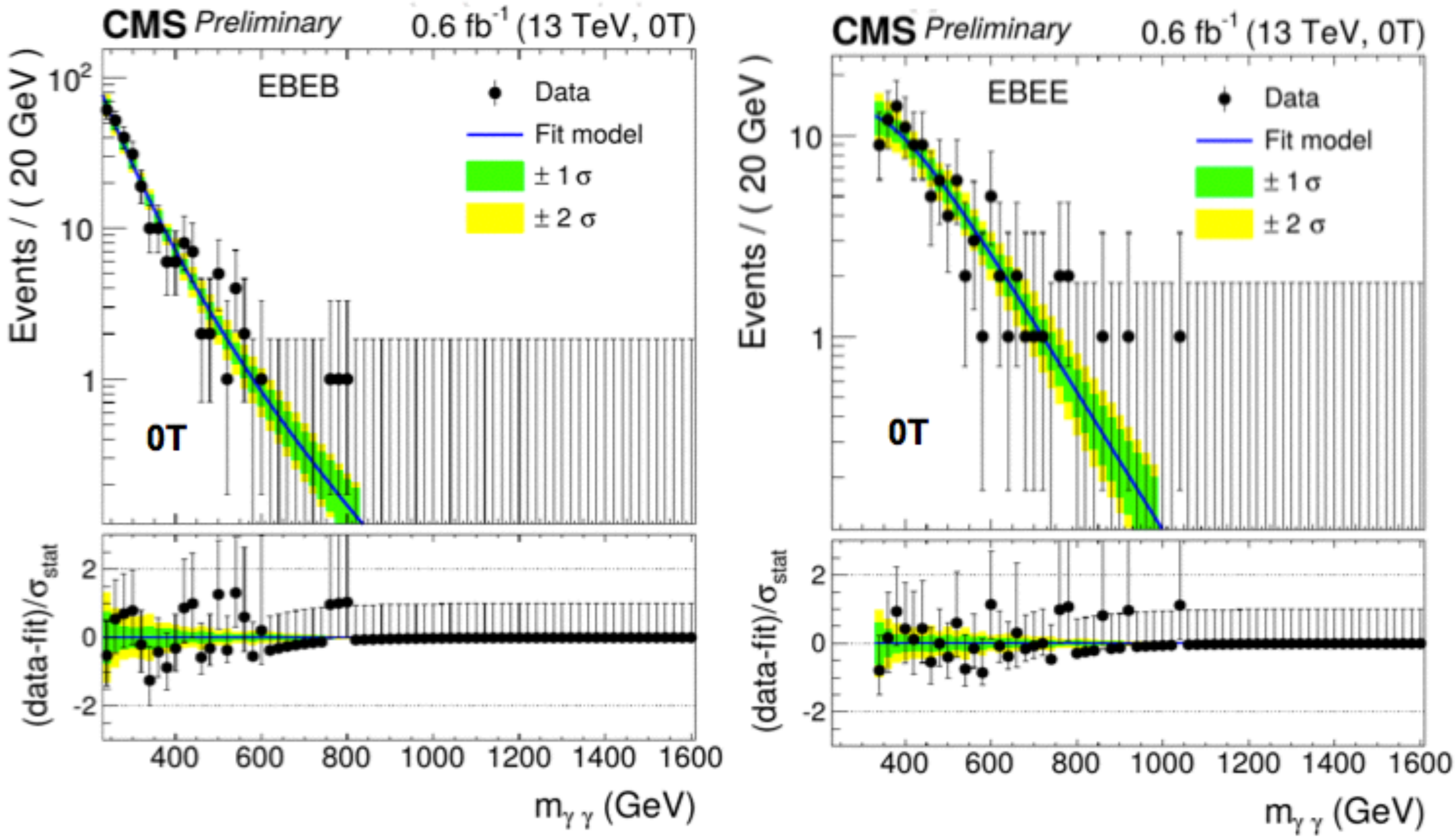
Compromise:
- Focus on signatures
- Somewhat biased towards what I find interesting

A closer look at CMS



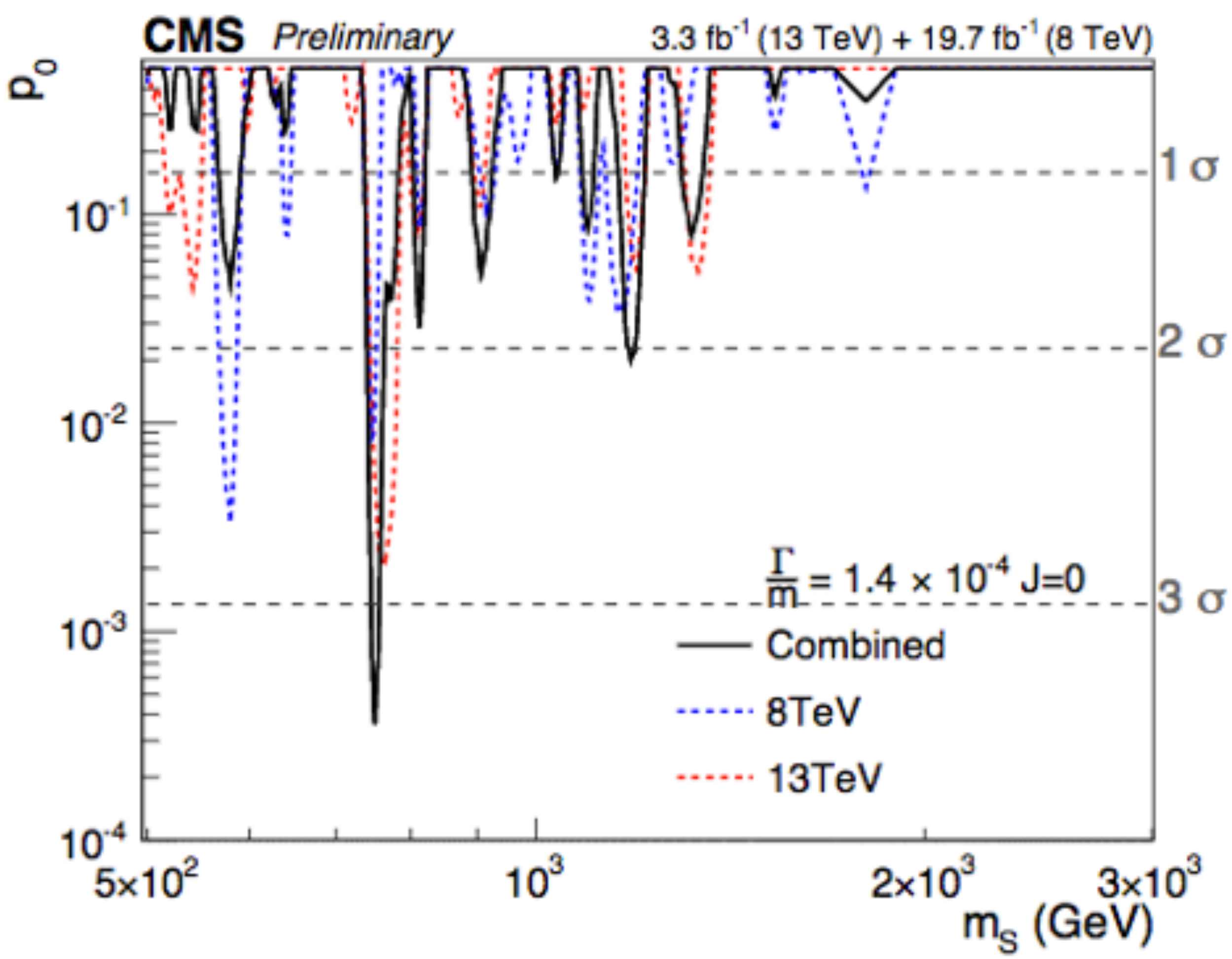
Also small excess at 8 TeV

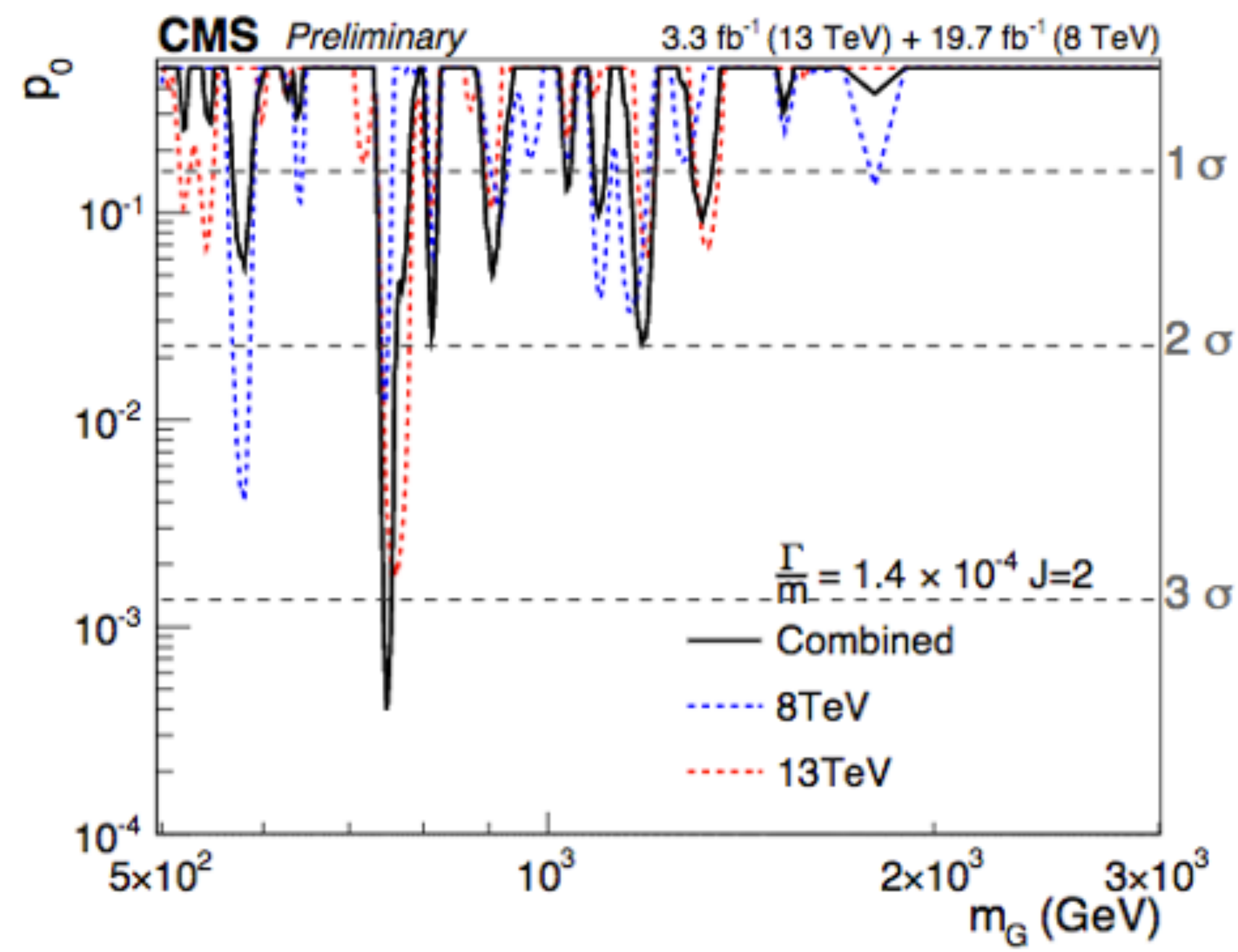
CMS at 0T



small excess at in 0T data

CMS Significance



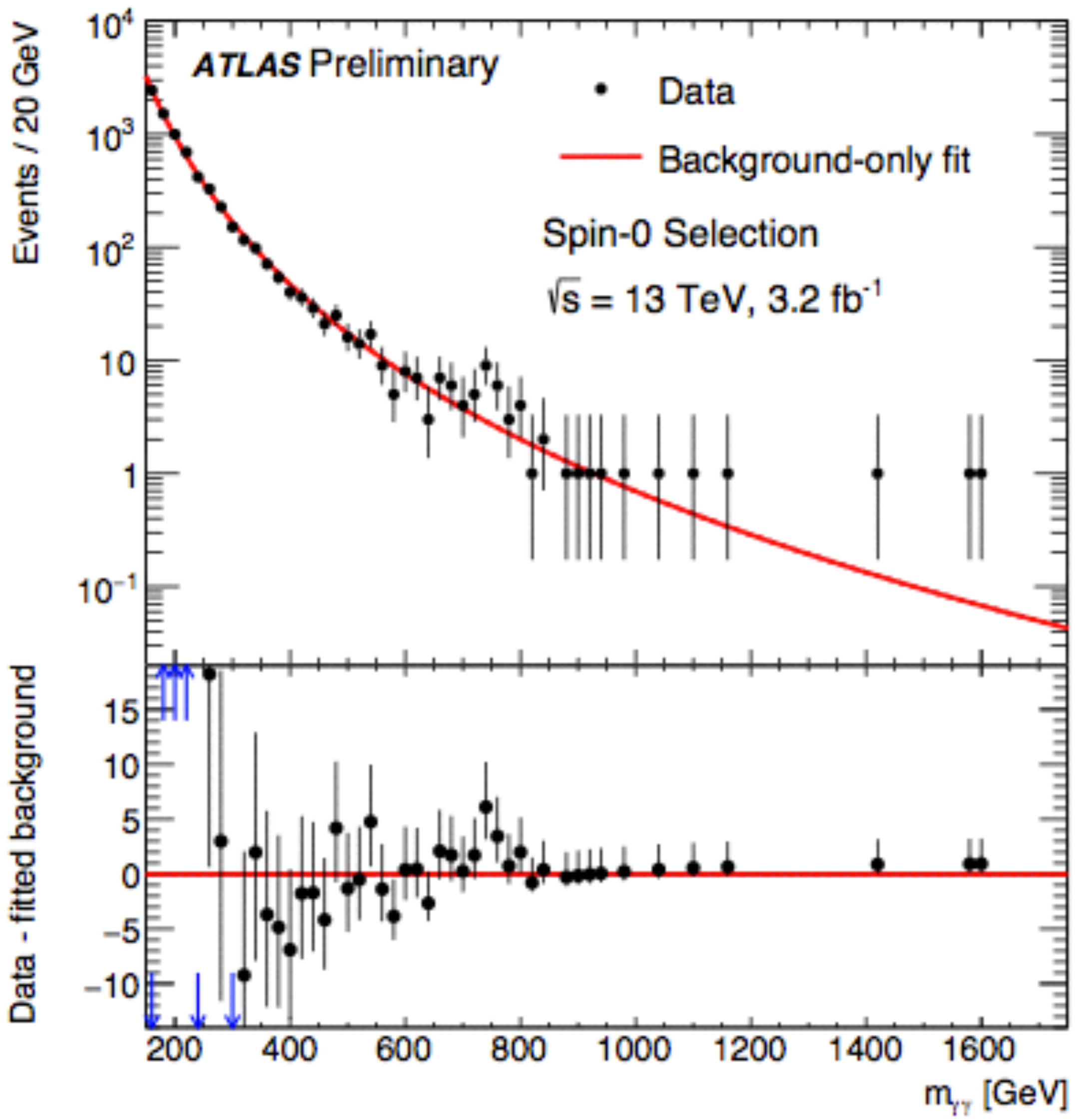


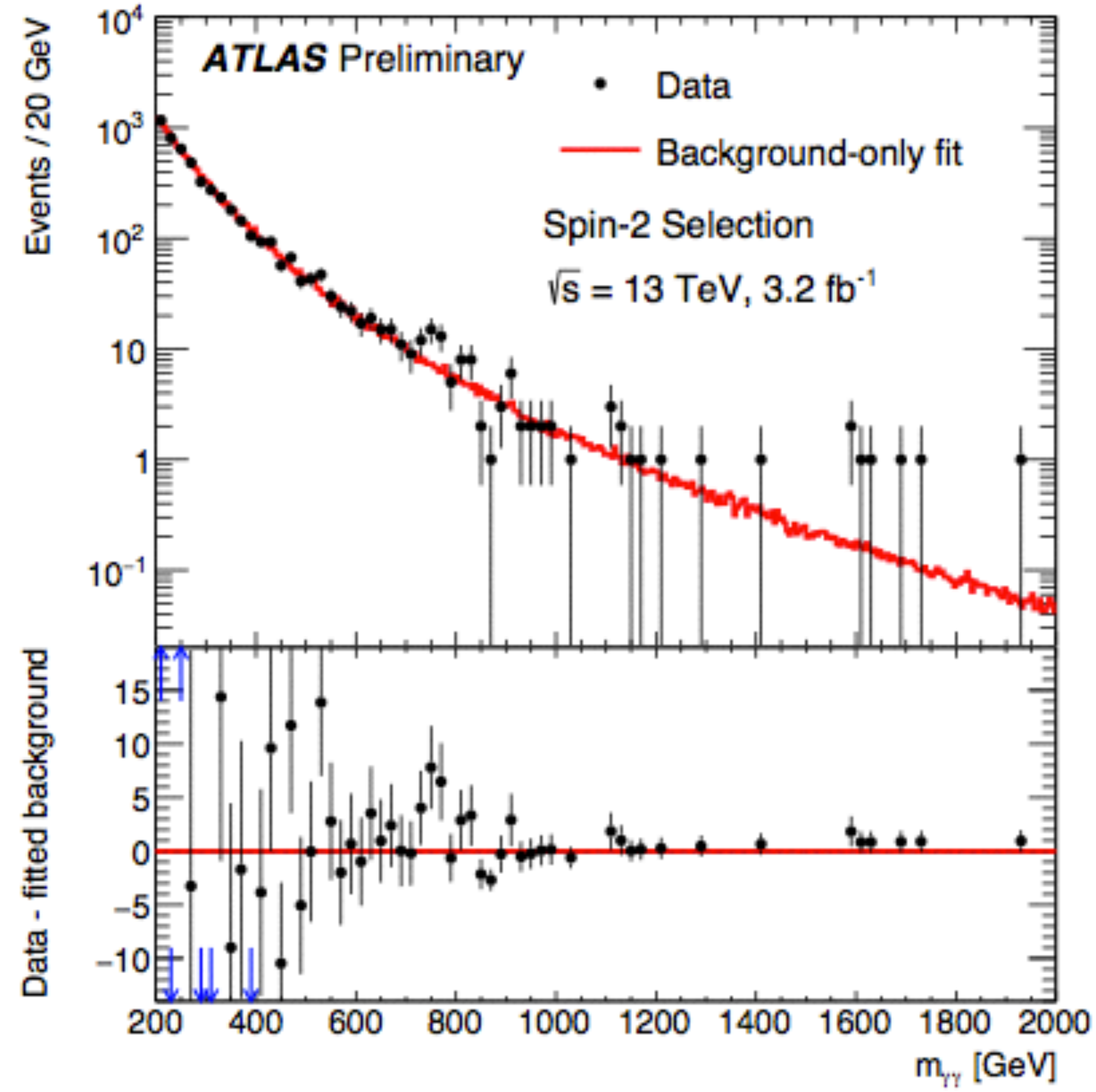
Local: 3.4σ
Global: 1.6σ

Slight preference for narrow width

ATLAS data

Two different analysis strategies





2878 events ($m_{\gamma\gamma}$ > 200 GeV)

5066 events ($m_{\gamma\gamma}$ > 200 GeV)

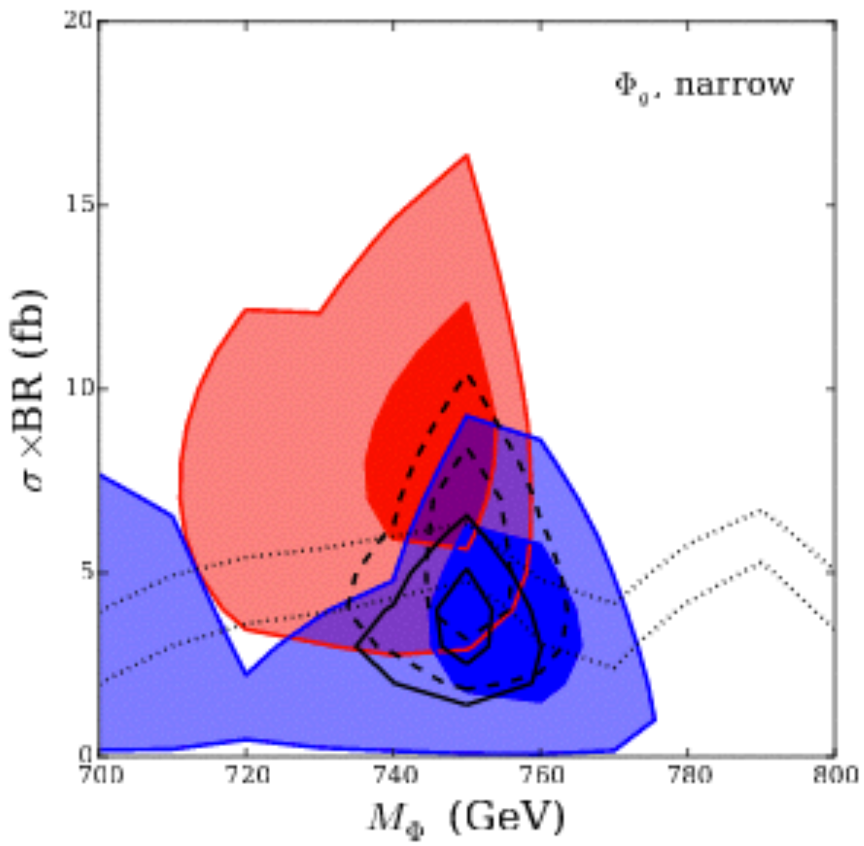
Local: 3.9σ
Global: 2σ

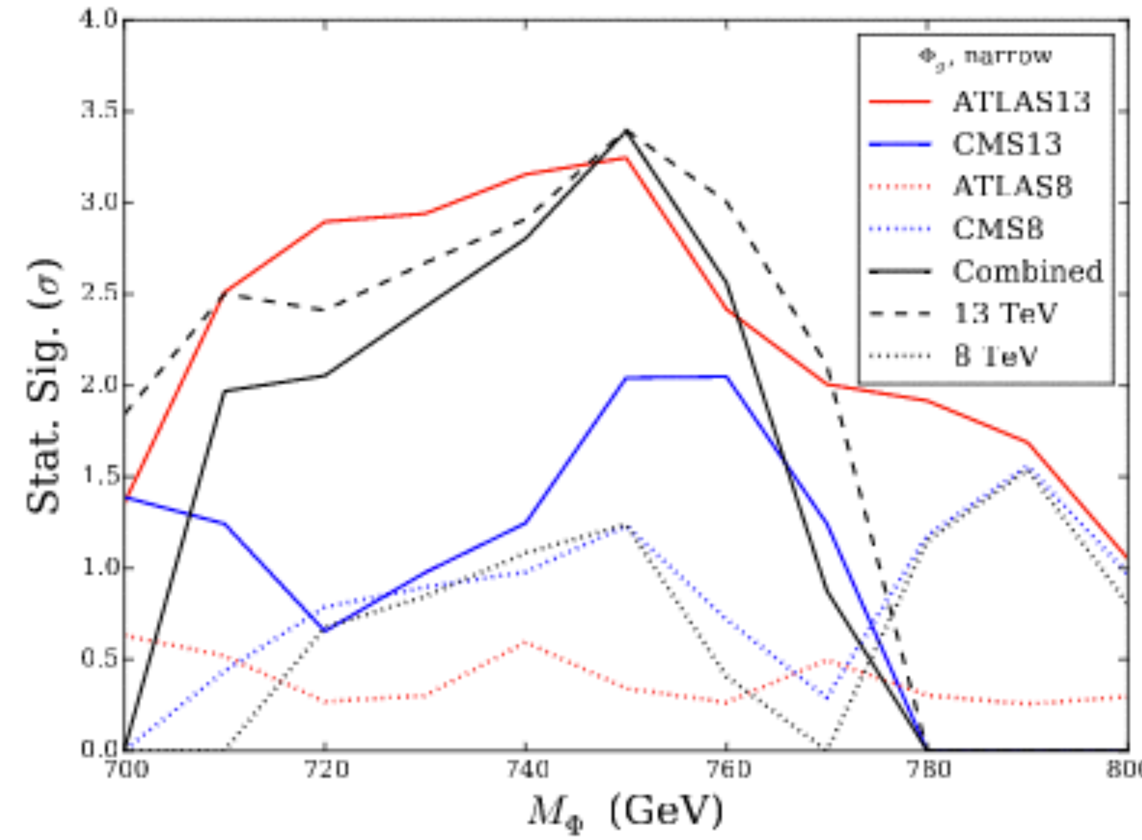
Local: 3.6σ
Global: 1.8σ

Slight preference for large width

Statistical combination

Assuming spin 0 + gluon fusion + narrow width
(all significances are local)





We need roughly 5 fb

M. Buckley: 1601.04751

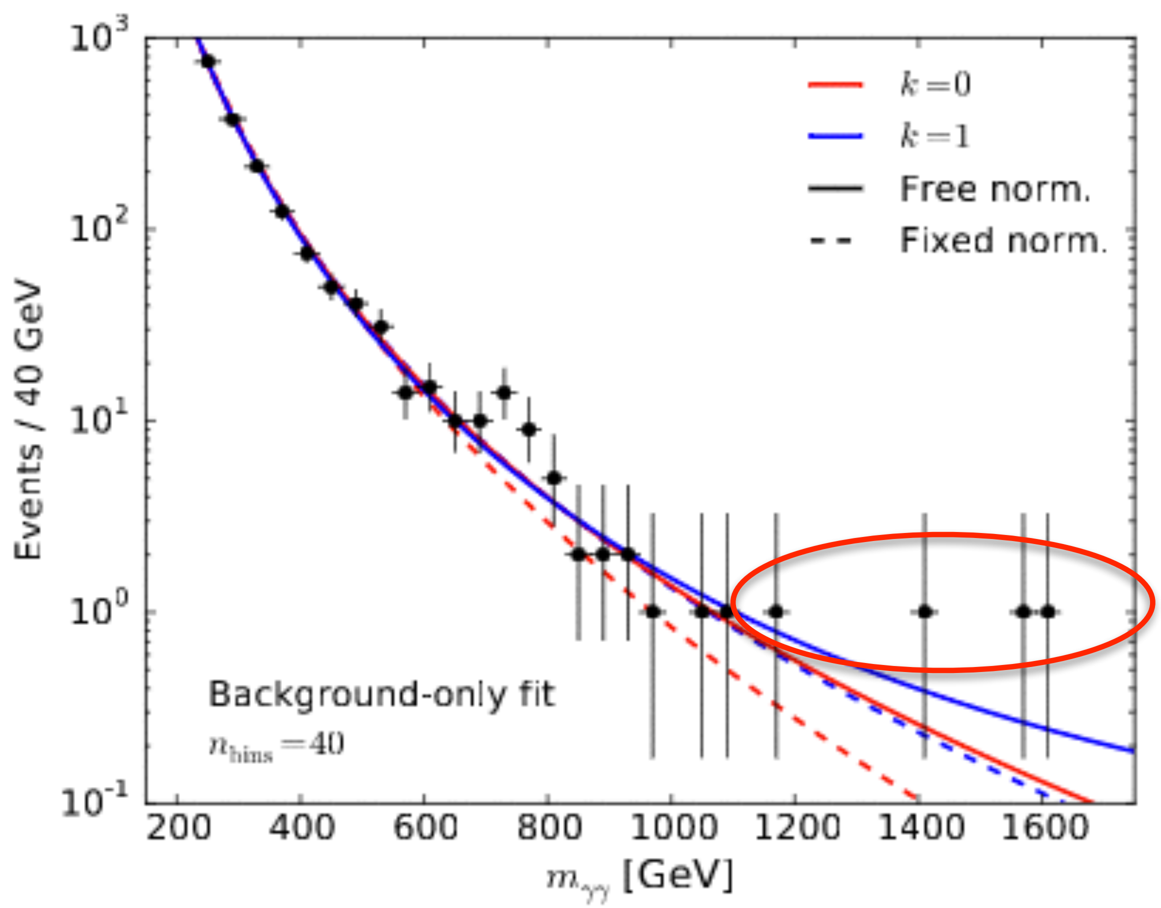
	spin 0	spin 2
gg initial state	1.2 σ	2.7 σ
qq initial state	2.1 σ	3.3 σ

(+ Theory bias against spin 2)

ATLAS, Moriond

Background fit

Background model: $f_k(x) = \mathcal{N}(1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$



Background function	NWA	Free-width
Fixed normalisation		
$k = 0$	4.2σ	4.9σ
$k = 1$	3.4σ	3.7σ
$k = 2$	3.4σ	3.7σ
Free normalisation		
$k = 0^{\dagger}$	3.4σ	3.6σ
$k = 1$	3.5σ	3.8σ
$k = 2$	3.4σ	3.6σ
ATLAS reported	3.6σ	3.9σ

- Lack of events in the tail constrains the background fit
- Significance broadly consistent with the official ALTAS result.

B. J. Kavanagh: 1601.07330

arXiv.org > hep-ph > arXiv:1512.06562v1

Search or A

High Energy Physics - Phenomenology

Scalar Dark Matter Explanation of Diphoton Excess at LHC

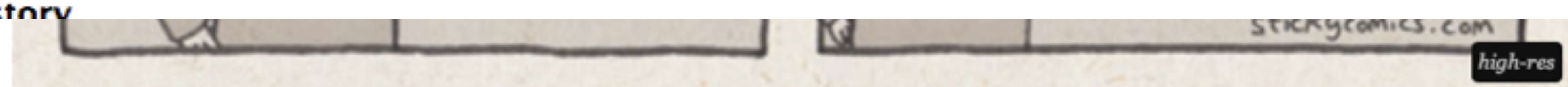
Huayong Han, Shaoming Wang, Sibo Zheng

(Submitted on 21 Dec 2015 (this version), latest version 2 Apr 2016 (v4))

We consider a 750 GeV scalar dark matter as an explanation of diphoton signal excess observed at the LHC run 2 through direct Yukawa interaction with a SM top- or bottom-like fermion partner. In this setup the scalar dark matter is mainly produced by gluon fusion, and decays at the one-loop level to SM diboson channels $\gamma\gamma$, ZZ, WW and gg. we show that fermion partner with mass m_ψ in the range between $(375, 410)$ GeV or $(745, 750)$ GeV for exotic electric charge $Q=\pm 2$ can account for scalar dark matter as the origin of diphoton excess.

Comments: 7 pages, four figures
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:1512.06562 [hep-ph]
(or arXiv:1512.06562v1 [hep-ph] for this version)

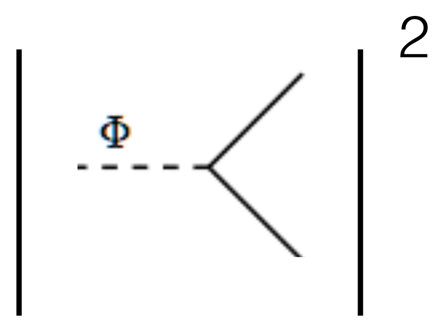
Submission history



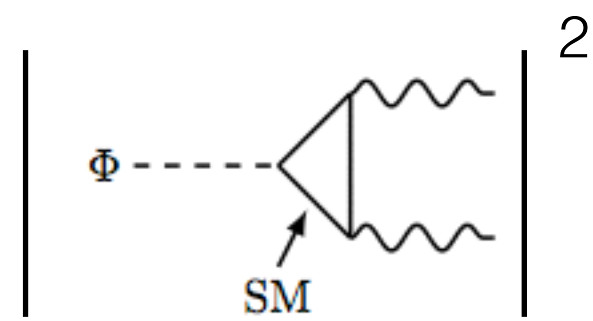
~ 50 papers in the first 2 days

- I will (mostly) focus on topologies, rather than models
- List of scenarios (possibly) incomplete
- Reference list definitively incomplete

SM + one scalar



$\sim 10^5$



Already excluded!

Final State	95% CL U.L. on $\sigma \times$ BR [fb]	lim. normalized to $\sigma_{\gamma\gamma} = 5 \div 10\,\text{fb}$
WW (gluon fusion)	174	$17.4 \div 34.8$ ←
WW (VBF)	70	$7 \div 14$
ZZ (gg prod.)	89	$9 \div 18$
ZZ (VBF prod.)	40	$4 \div 8$
$Z\gamma$	42	$4.2 \div 8.4$
Zh	572	$57 \div 114$
hh	209	$21 \div 42$
bb	10^4	$1 \div 2 \times 10^3$
tt	3.28×10^3	$328 \div 656$ ←
$\tau\tau$ (gg prod.)	56	$6 \div 11$
$\tau\tau$ (assoc. b production)	42	$4 \div 8.5$
qq	10^4	$1 \div 2 \times 10^3$
$\ell\ell$	3.5	$0.35 \div 0.7$

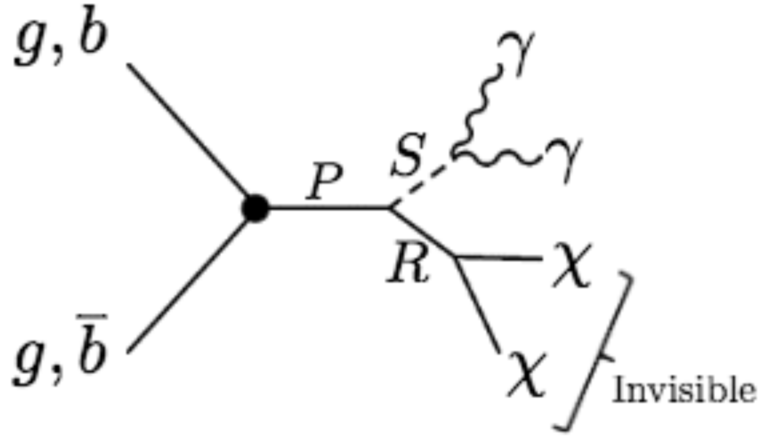
Guestimate for partial width: $\Gamma_{\gamma\gamma} \sim \dfrac{\alpha^2}{128\pi^3} m_\Phi \sim 10\ \text{keV}$

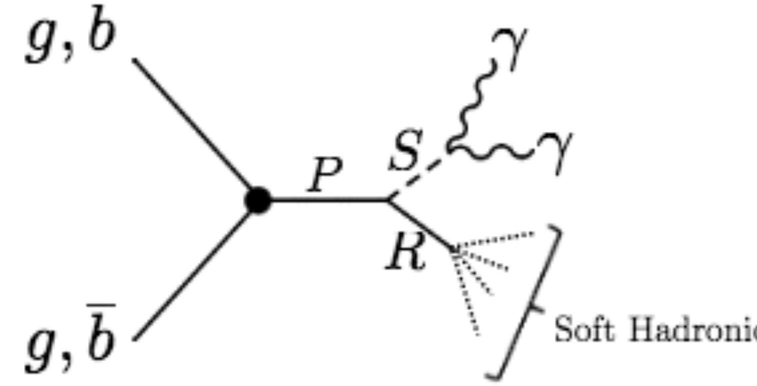
Topologies

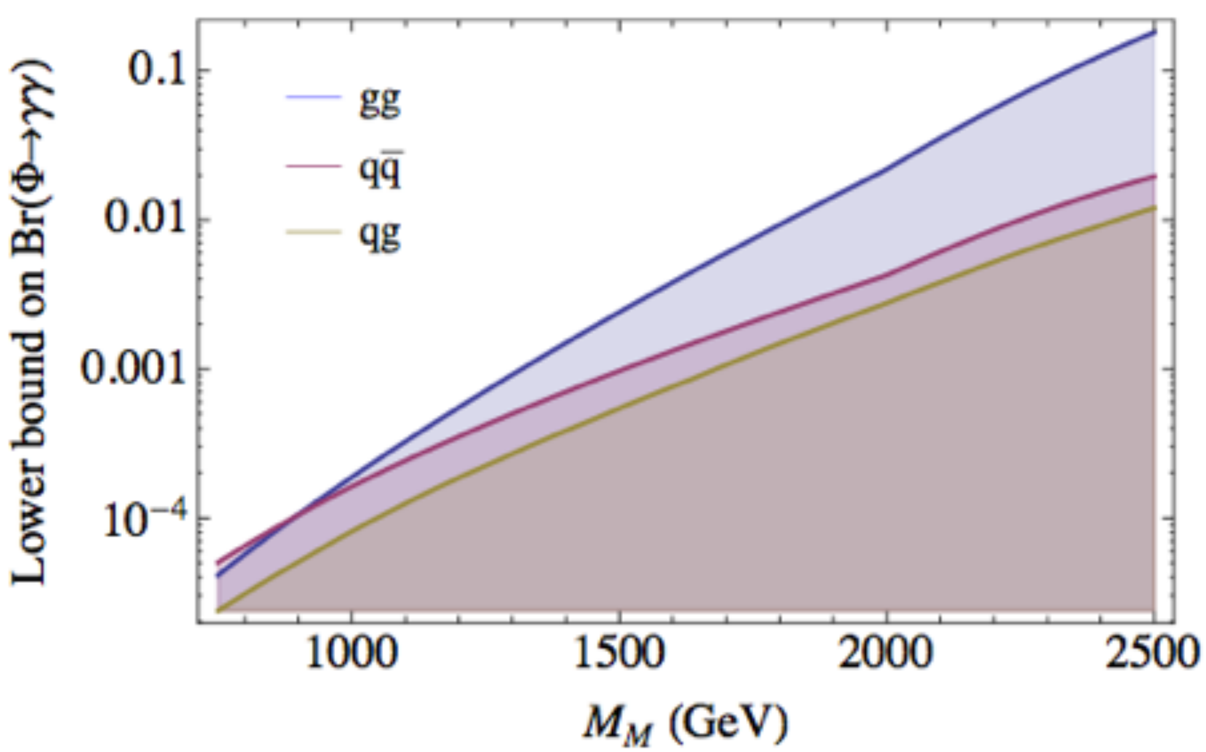
1. Exotic stuff
    1. cascades
    2. fake photons
2. $2 \to 2$ process
    1. Production
    2. Decay
3. Conclusions and outlook

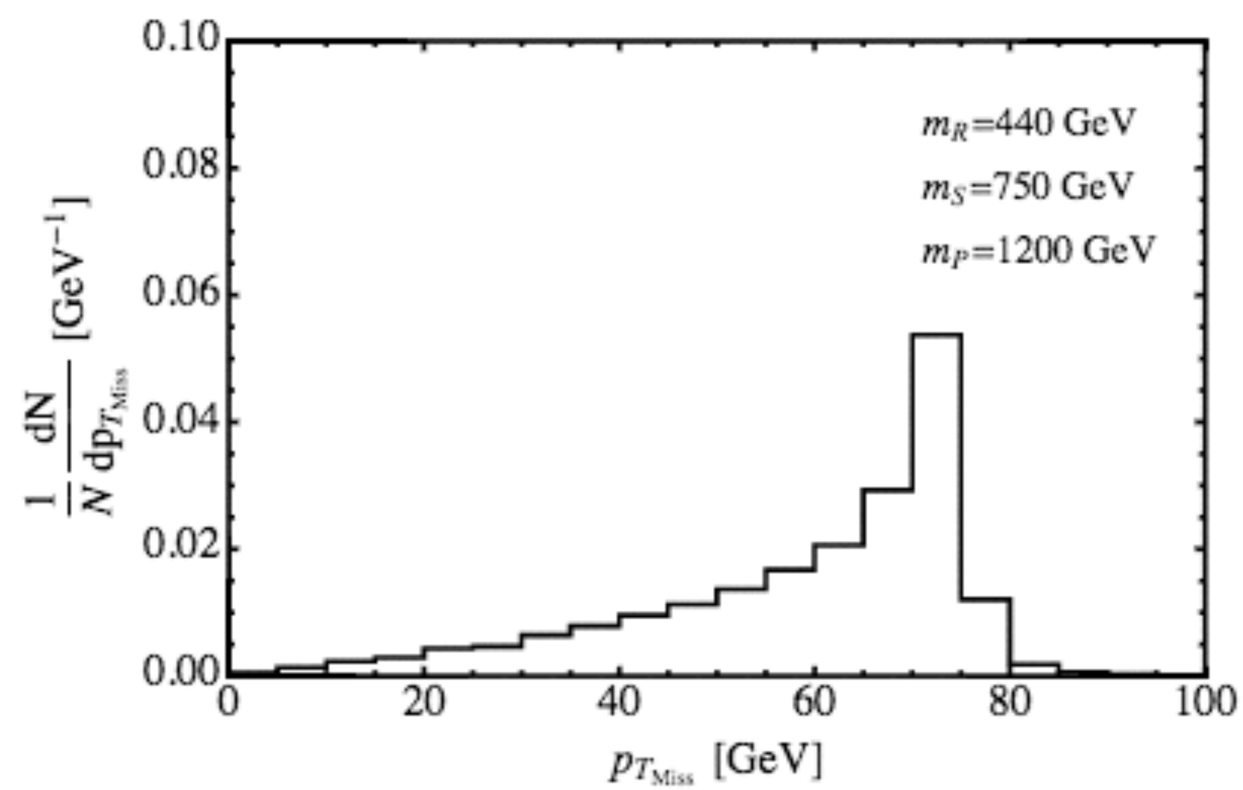
Cascade decay

Improved compatibility with 8 TeV





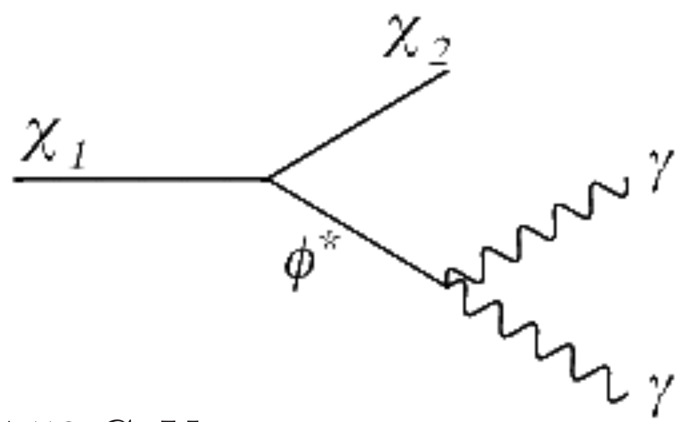




SK, T. Melia, M. Papucci and K. Zurek: 1512.04928

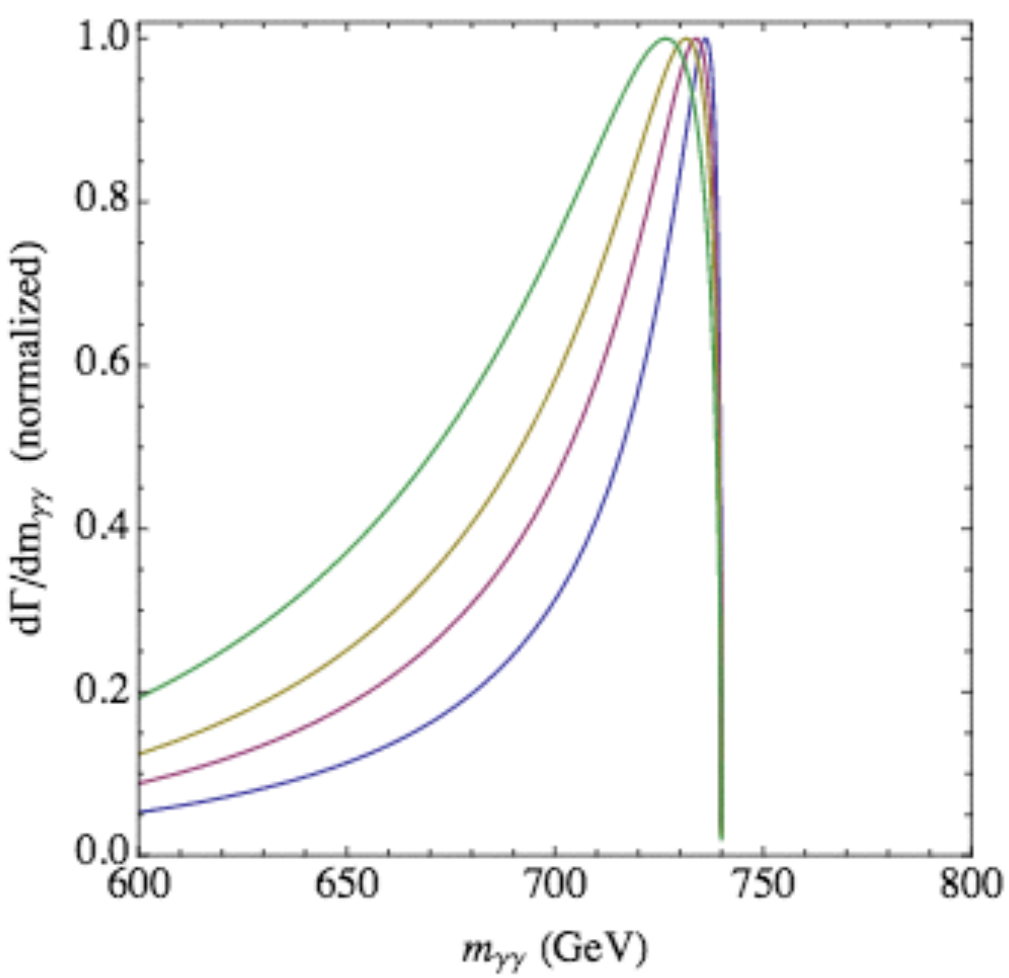
Francescini et. al. : 1512.04933

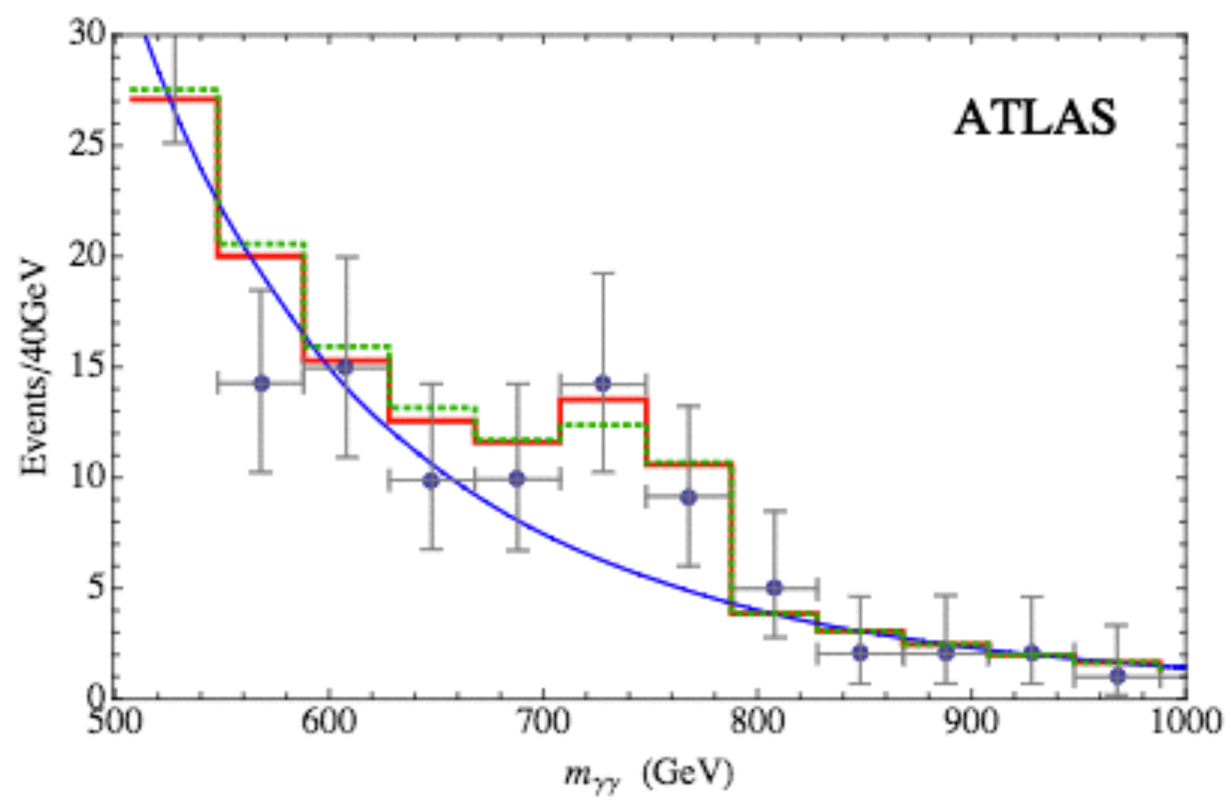
Off-shell Cascade



A slightly off-shell scalar can fake a broad resonance

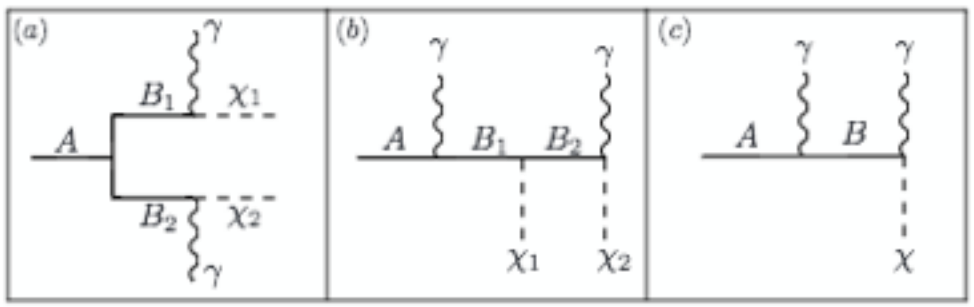
$m_{\chi_1} = 750$ GeV
$m_{\chi_2} = 10$ GeV
$750 \text{ GeV} \leq m_\phi \leq 770$ GeV

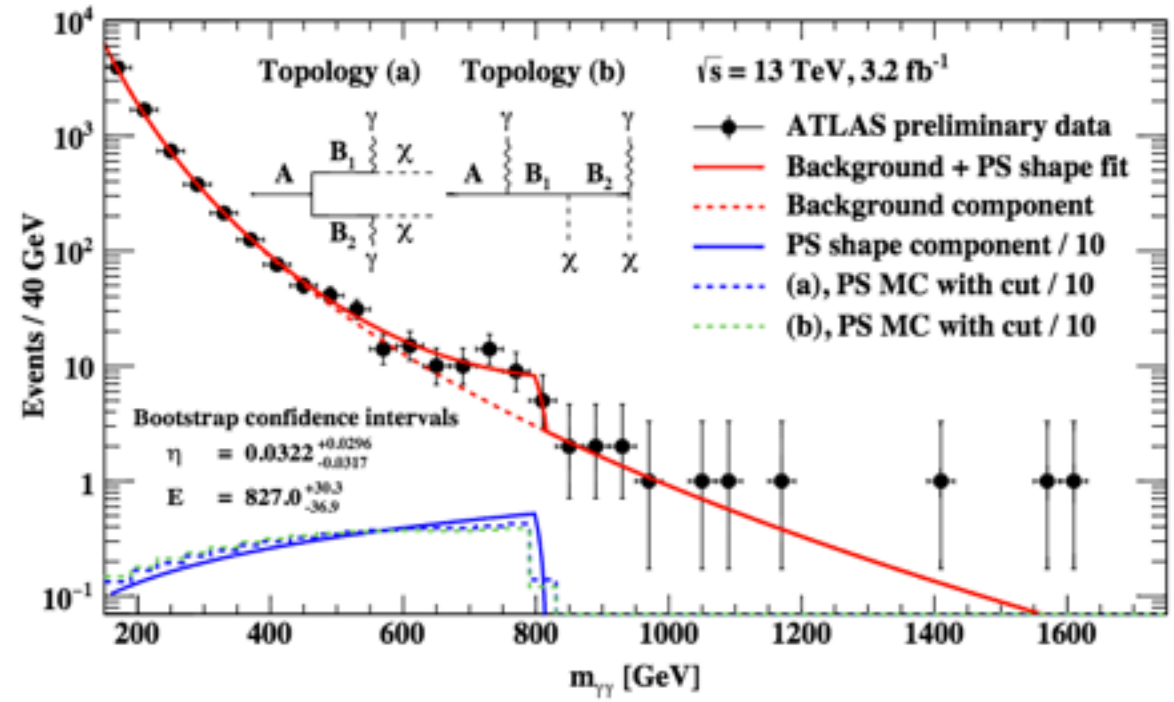


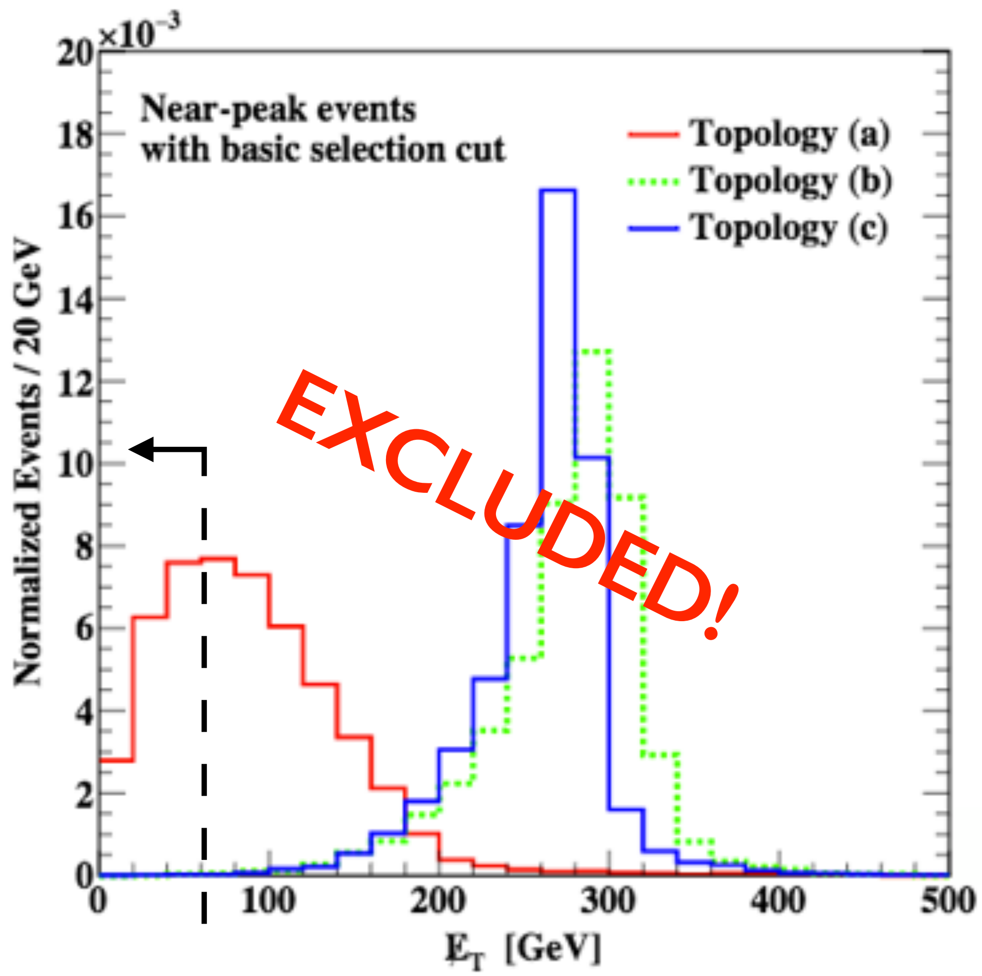


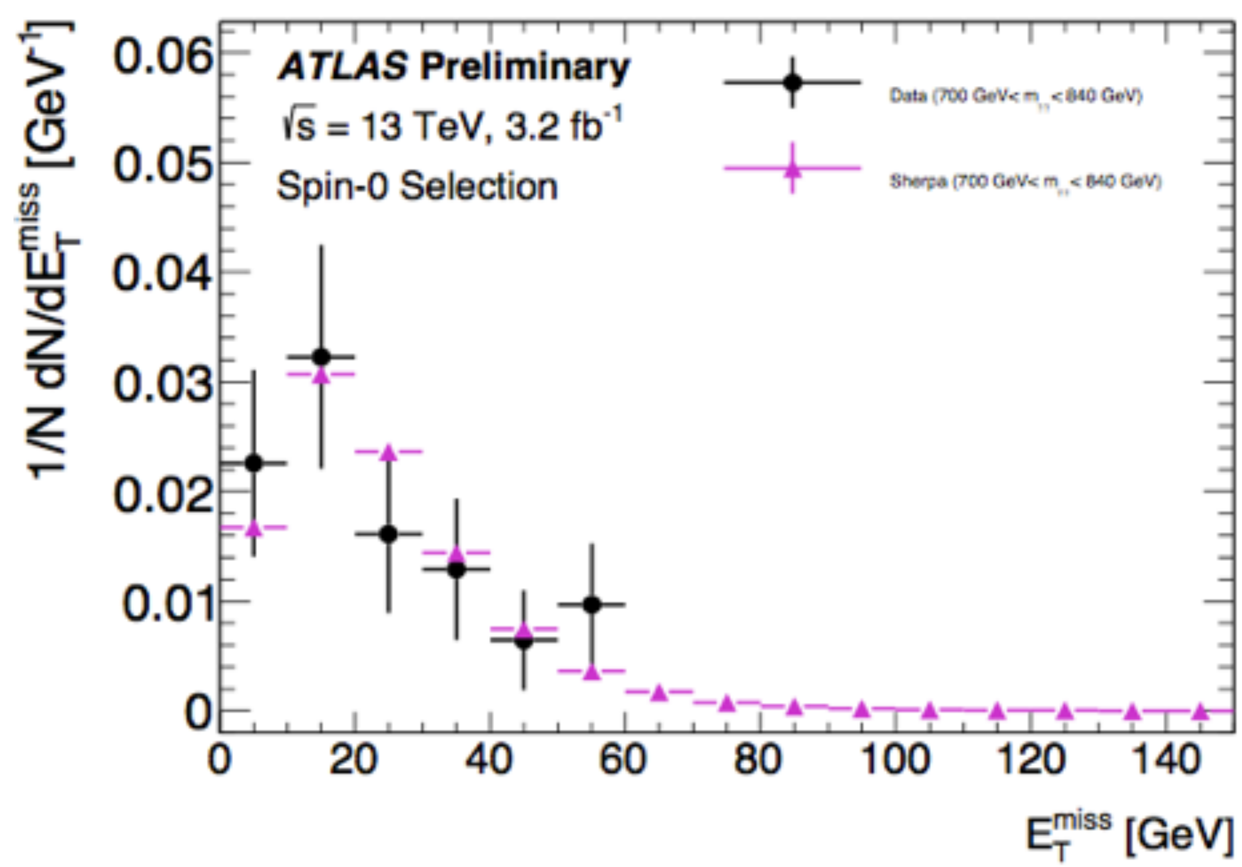
H. An, C. Cheung, and Y. Zhang: 1512.08378
(see also J. Bernon, C. Smith 1512.06113)

Faking a resonance



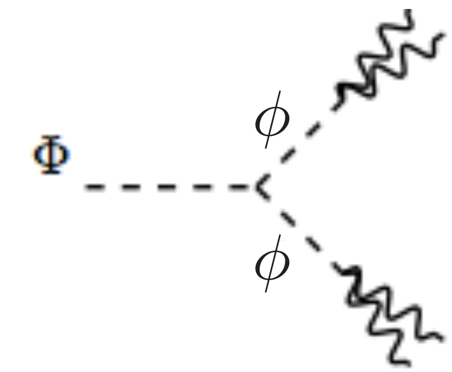




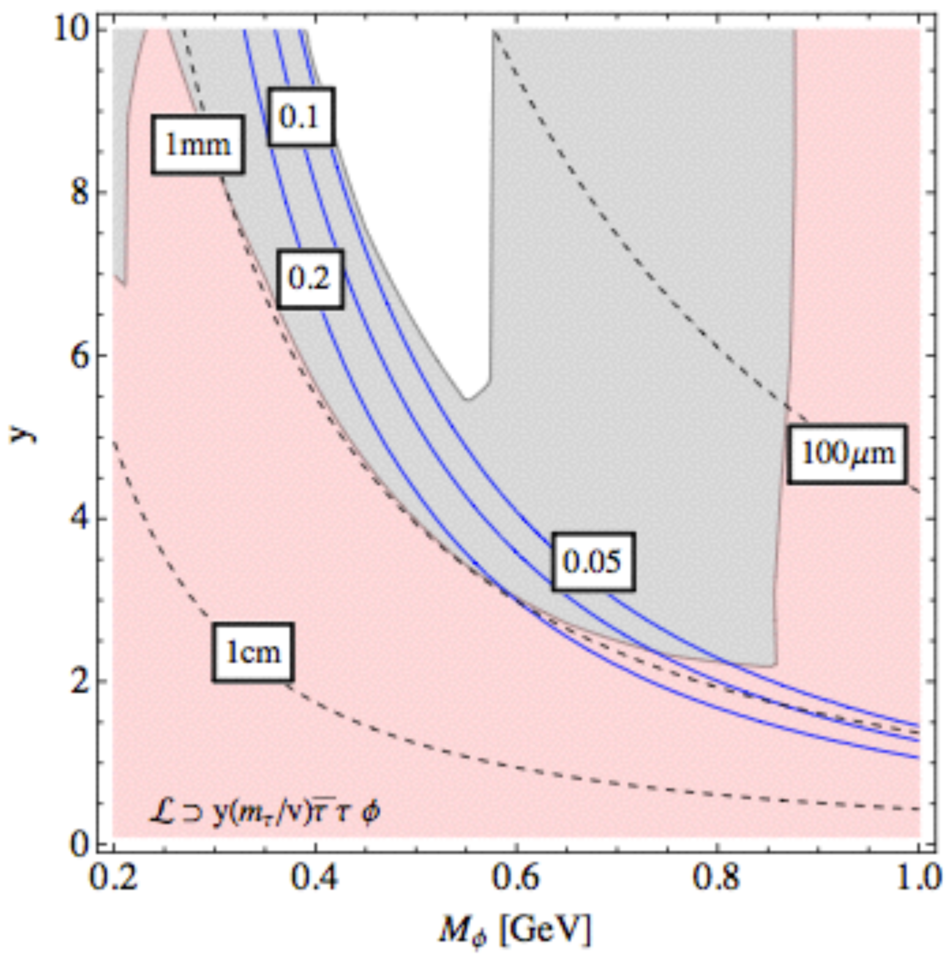


W. S. Cho: et. al 1512.06824

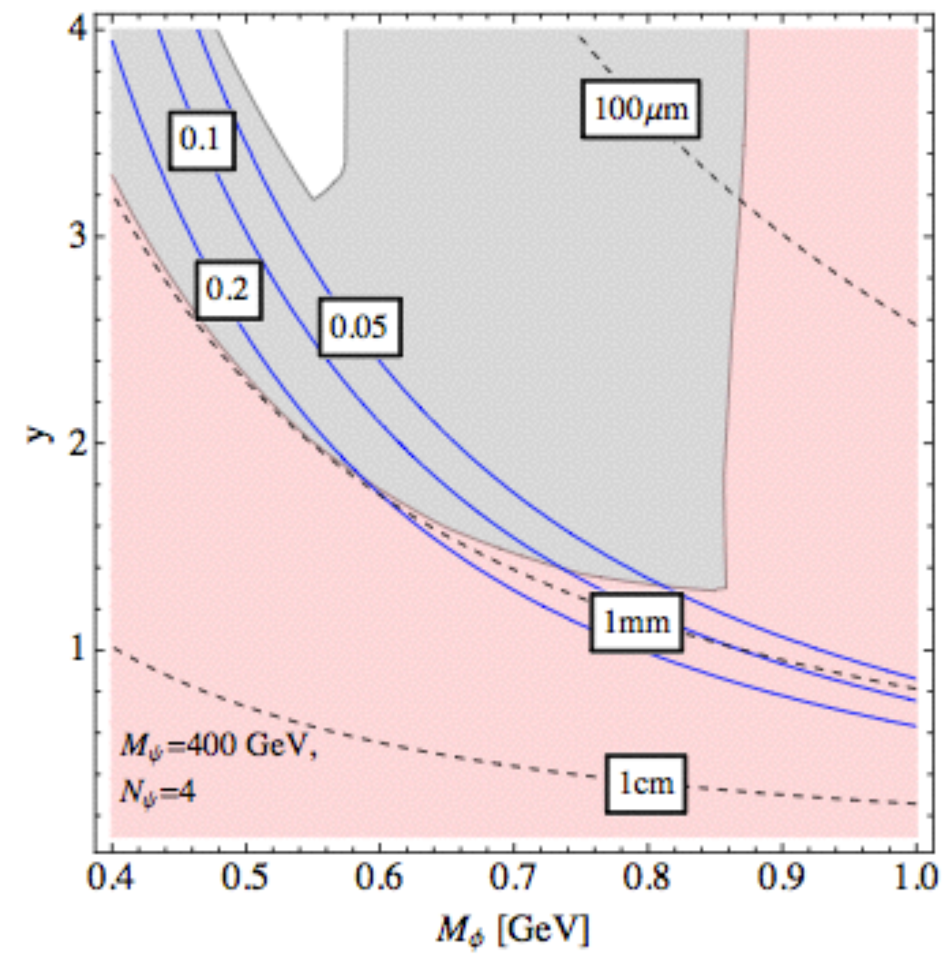
Faking photons



$$\mathcal{L} \supset y \frac{m_\tau}{v} \phi \bar{\tau} \tau$$



$$\mathcal{L} \supset y \phi \bar{\Psi} \Psi$$



Works, but probably non-perturbative

ZZ, Zγ and WW channels are absent

SK, T. Melia, M. Papucci and K. Zurek: 1512.04928
(see also e.g. P. Agrawal et. al.: 1512.05775, L. Aparicio et. al. 1602.00949)

Topologies

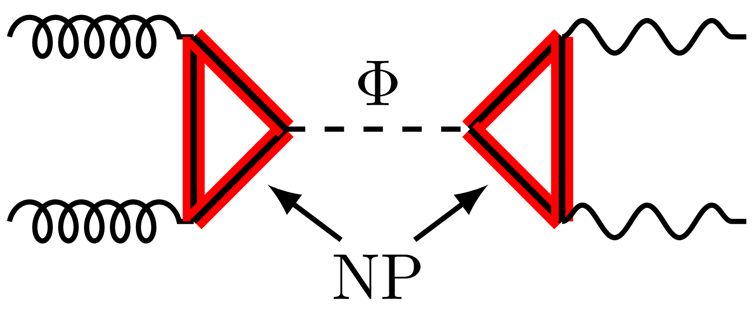
1. Exotic stuff
    1. cascades
    2. fake photons

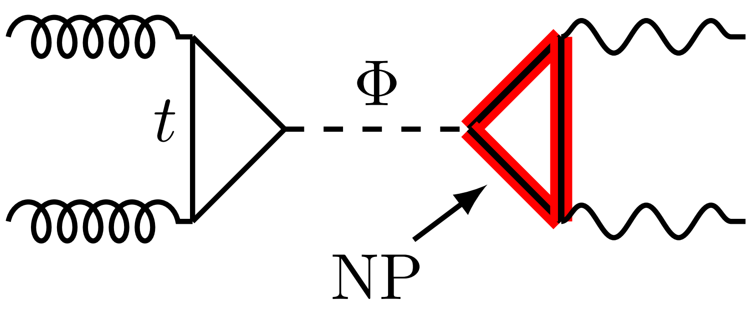
2. $2 \to 2$ process
    1. Production
    2. Decay

3. Conclusions and outlook

Gluon Fusion

$$\frac{\mathcal{L}_{gg}^{(13)}}{\mathcal{L}_{gg}^{(8)}} \sim 4.6 \quad \longrightarrow$$ 8 and 13 TeV data more or less compatible





$$R_{\gamma\gamma} \sim \frac{\Gamma_{\gamma\gamma}}{m_\Phi} \mathcal{L}_{gg} \sim \frac{\Gamma_{\gamma\gamma}}{\text{MeV}}\,\text{fb}$$

$$\hookrightarrow \frac{\Gamma_{\gamma\gamma}}{M} \sim 10^{-6}$$

SM: $\frac{\Gamma_{\gamma\gamma}}{m_h} \sim 10^{-7}$

$$R_{\gamma\gamma} \sim \frac{\Gamma_{gg}}{\Gamma_{tt}} \frac{\Gamma_{\gamma\gamma}}{m_\Phi} \mathcal{L}_{gg} \sim \frac{\Gamma_{\gamma\gamma}}{\text{GeV}}\,\text{fb}$$

$$\hookrightarrow \frac{\Gamma_{\gamma\gamma}}{M} \sim 10^{-3}$$

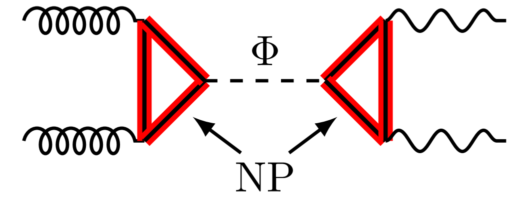
total width dominated by di-jets

$$\frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}} \lesssim 1000$$

total width dominated by $t\,\bar{t}$

$$\frac{\Gamma_{tt}}{\Gamma_{\gamma\gamma}} \lesssim 500 \quad \Rightarrow \quad \Gamma_{gg} \lesssim \Gamma_{\gamma\gamma}$$

Benchmarks



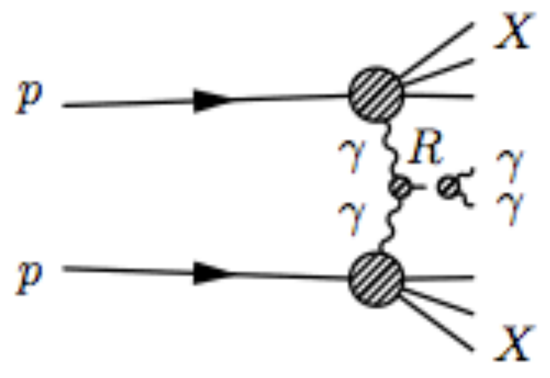
Model	Representation	$\gamma Z/\gamma\gamma$	$WW/\gamma\gamma$	$ZZ/\gamma\gamma$	$gg/\gamma\gamma$	$R^0_{\Phi\to\gamma\gamma}$ [fb]	Γ_{tot} [MeV]	$\Gamma_{\Phi\to\gamma\gamma}$ [MeV]	Decay mode
Scalars									
S1	$(3, 1, -\frac{4}{3})$	0.6	0.	0.09	9.54	0.02	0.03	$3. \times 10^{-3}$	$d^c + e^c$
S2	$(\bar{3}, 1, \frac{4}{3})$	0.6	0.	0.09	9.54	0.02	0.03	$3. \times 10^{-3}$	$2\ u^c$
S3	$(3, 2, \frac{7}{6})$	0.06	0.91	0.6	11.62	0.06	0.14	9.9×10^{-3}	$u^c + l$
S4	$(\bar{3}, 2, -\frac{7}{6})$	0.06	0.91	0.6	11.62	0.06	0.14	9.9×10^{-3}	$e^c + q$
S5	$(\bar{3}, 3, \frac{1}{3})$	4.44	27.78	8.48	49.84	0.02	0.47	5.2×10^{-3}	$q + l$
S6	$(3, 3, -\frac{1}{3})$	4.44	27.78	8.48	49.84	0.02	0.47	5.2×10^{-3}	$2\ q$
S7	$(\bar{3}, 1, -\frac{2}{3})$	0.6	0.	0.09	1.5×10^{2}	1.4×10^{-3}	0.03	1.9×10^{-4}	$2\ d^c$
S8	$(3, 2, \frac{1}{6})$	5.07	30.62	9.26	3.9×10^{2}	$2. \times 10^{-3}$	0.13	2.9×10^{-4}	$d^c + l$
S9	$(3, 1, -\frac{1}{3})$	0.6	0.	0.09	2.4×10^{3}	8.7×10^{-5}	0.03	1.2×10^{-5}	$e^c + u^c$
S10	$(\bar{3}, 1, \frac{1}{3})$	0.6	0.	0.09	2.4×10^{3}	8.7×10^{-5}	0.03	1.2×10^{-5}	$d^c + u^c$
Fermions									
F1	$(3, 2, \frac{7}{6})$	0.06	0.91	0.6	11.62	3.52	8.19	0.58	u^c + V/h
F2	$(\bar{3}, 3, -\frac{2}{3})$	1.55	13.61	4.53	24.42	2.49	27.86	0.62	q + V/h
F3	$(3, 2, -\frac{5}{6})$	0.01	2.65	1.22	33.8	1.29	7.67	0.2	d^c + V/h
F4	$(\bar{3}, 3, \frac{1}{3})$	4.44	27.78	8.48	49.84	1.23	27.7	0.3	q + V/h
F5	$(\bar{3}, 1, -\frac{2}{3})$	0.6	0.	0.09	1.5×10^{2}	0.08	1.69	0.01	q + V/h
F6	$(3, 2, \frac{1}{6})$	5.07	30.62	9.26	3.9×10^{2}	0.11	7.49	0.02	u^c + V/h
F7	$(\bar{3}, 1, \frac{1}{3})$	0.6	0.	0.09	2.4×10^{3}	5.1×10^{-3}	1.68	6.9×10^{-4}	q + V/h

Rate scales ~ Q^4 !

SK, T. Melia, M. Papucci and K. Zurek: 1512.04928
(See also Franceschini et. al. : 1512.04933 and many others)

Photon Fusion

Inclusive

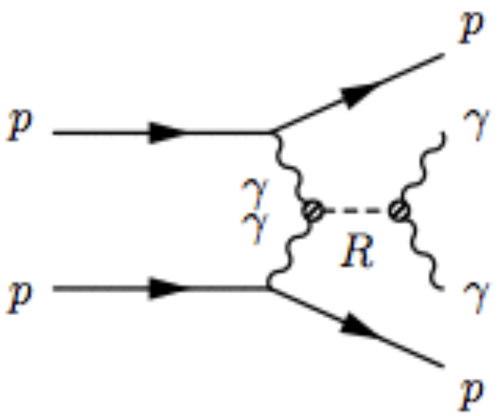


$$\frac{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s}=13\,\text{TeV})}{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s}=8\,\text{TeV})}=2.9$$

slight tension with 8 TeV

$$R_{\gamma\gamma}\sim\frac{\Gamma_{\gamma\gamma}}{50\ \text{MeV}}\times\text{Br}(\Phi\to\gamma\gamma)\times 5\ \text{fb}$$

Exclusive



$$\frac{R^{(inel)}_{\gamma\gamma}}{R^{(el)}_{\gamma\gamma}}=0.073$$

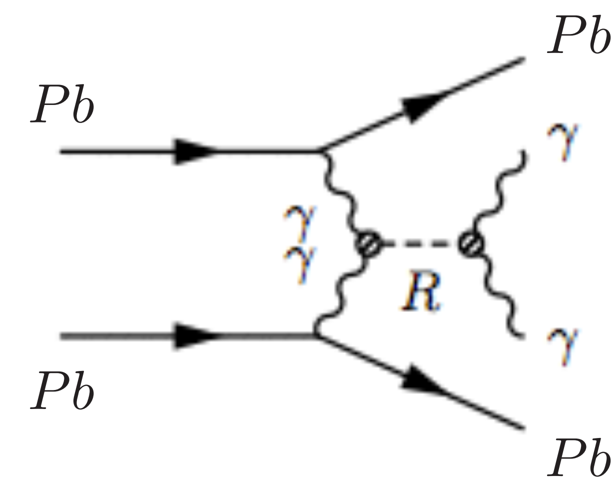
proton tagging possible?
(with AFP @ ATLAS and CT-PPS @ CMS)

Very clean, but rate could be small

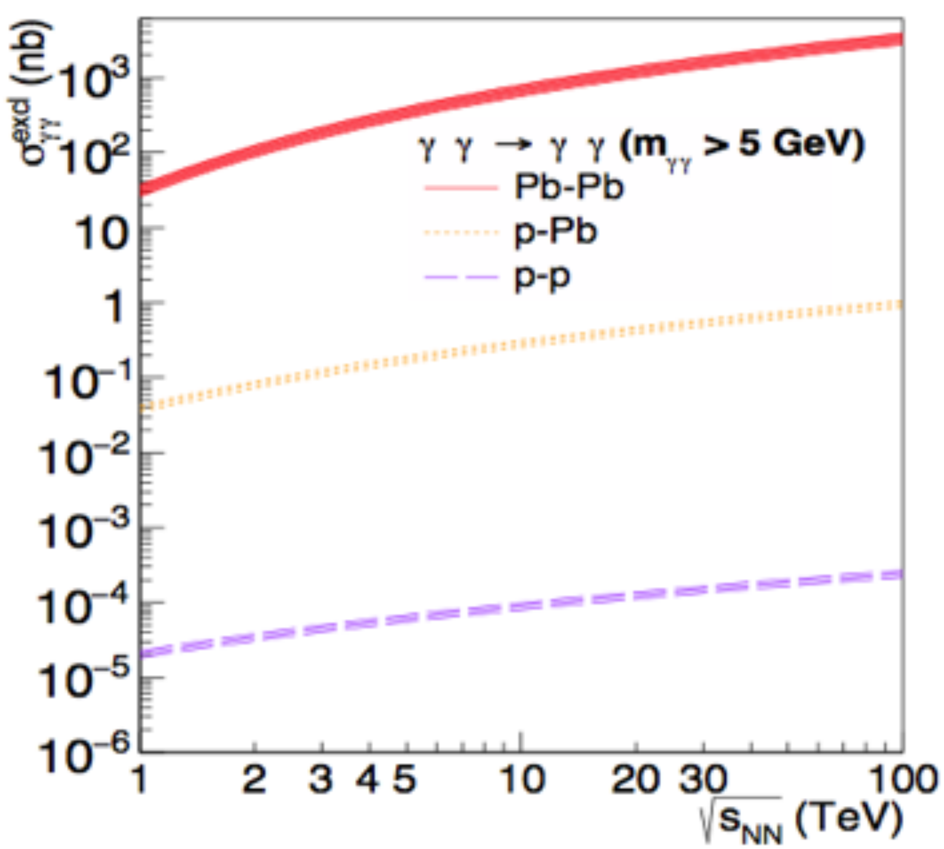
L.A. Harland–Lang, V.A. Khoze, M. G. Ryskin: 1601.07187

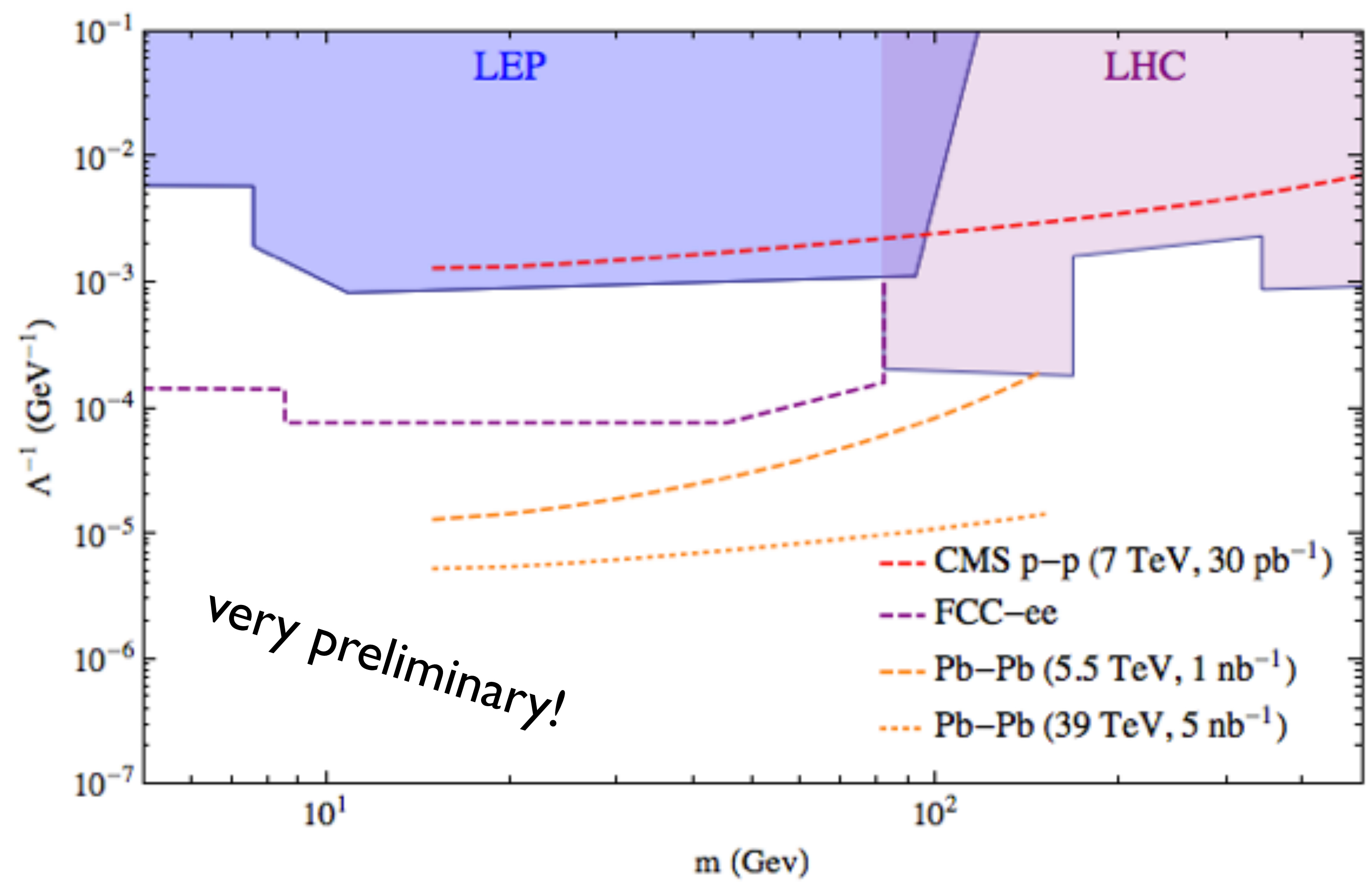
Digression: Heavy Ion collisions

Look for heavy axions in heavy ion collisions



Cross section scales like ~ Z^4

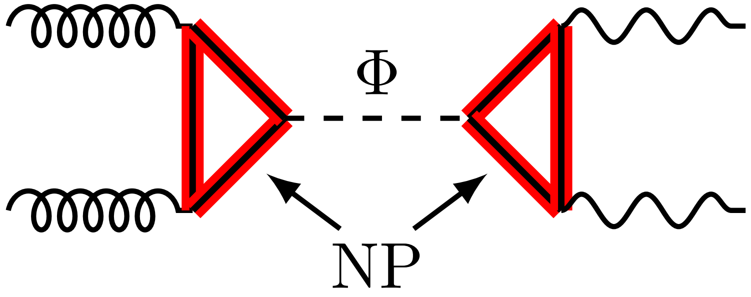


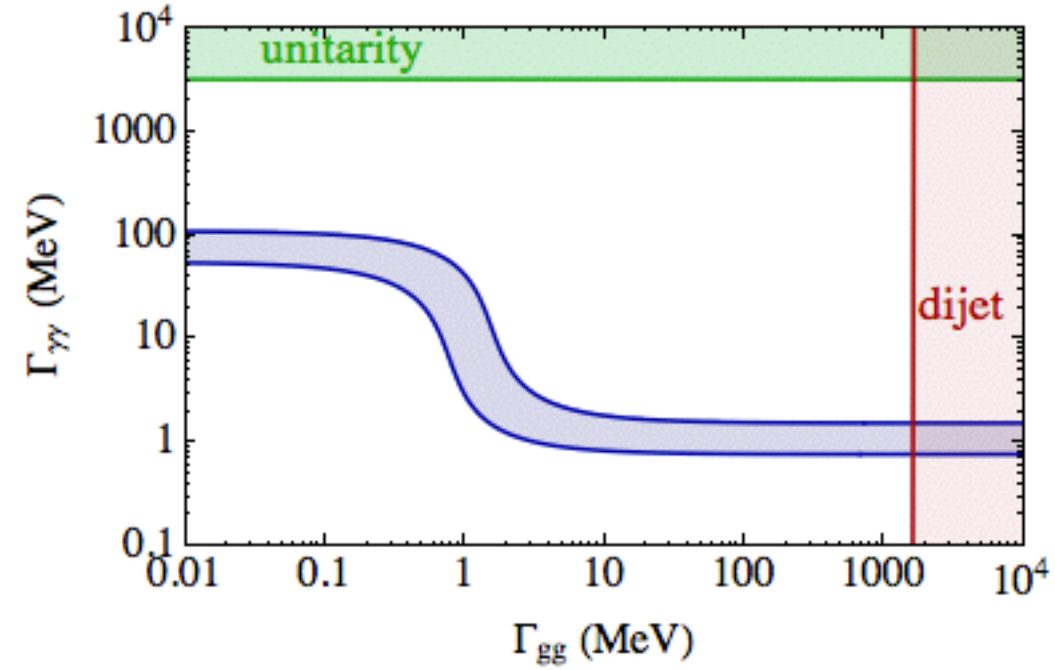


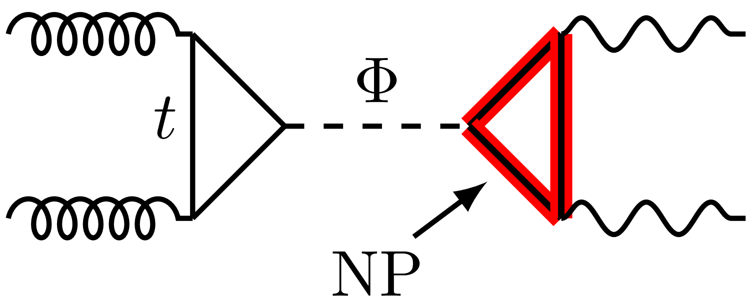
D. d'Enterria, G. G. da Silveira: 1602.08088

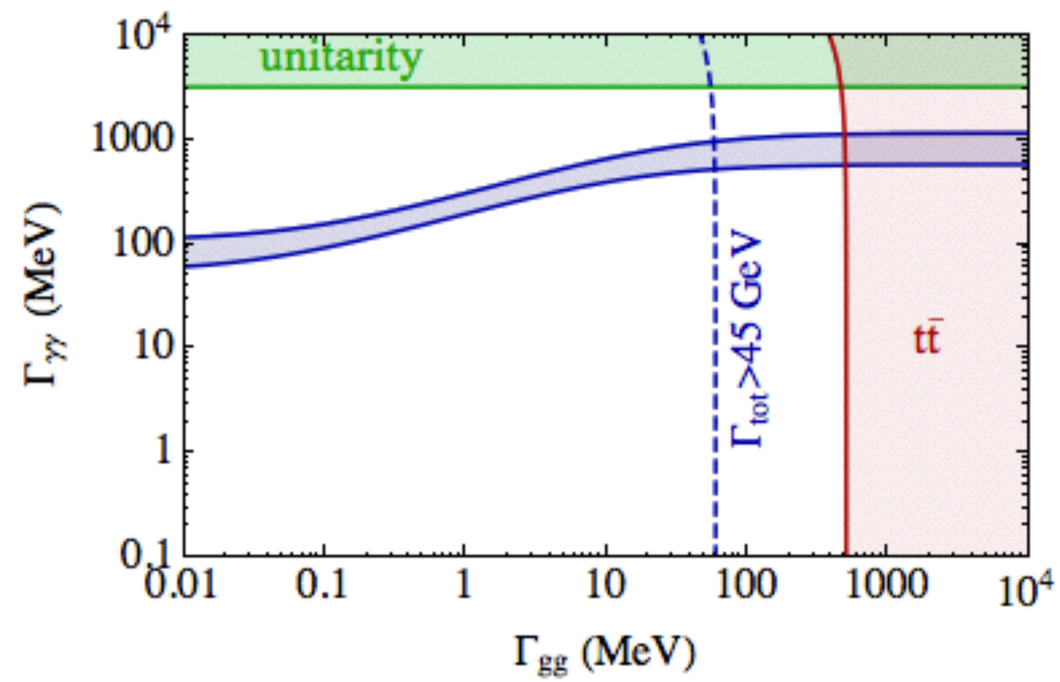
SK, T. Lin, T. Lou, T. Melia: In progress

Putting it together



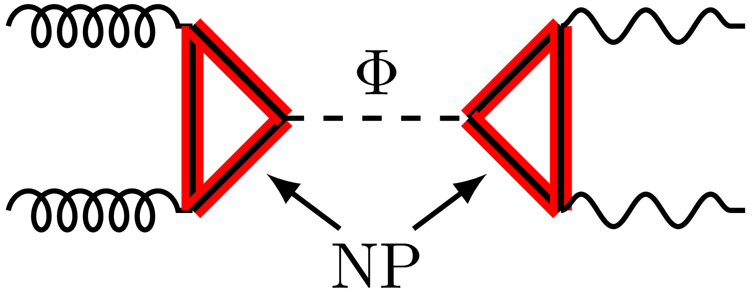




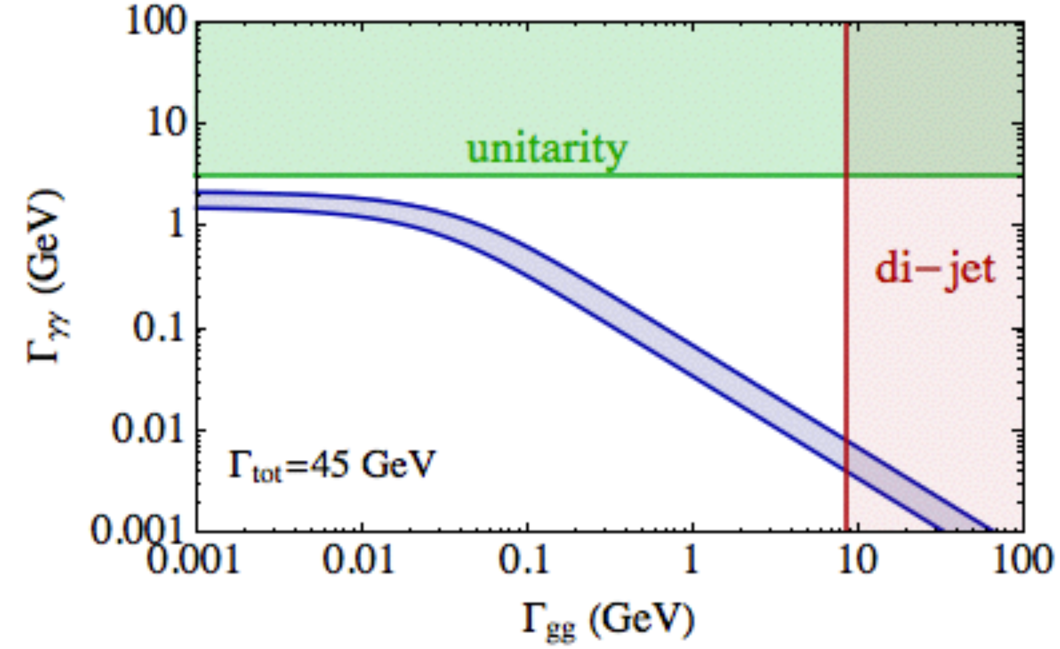


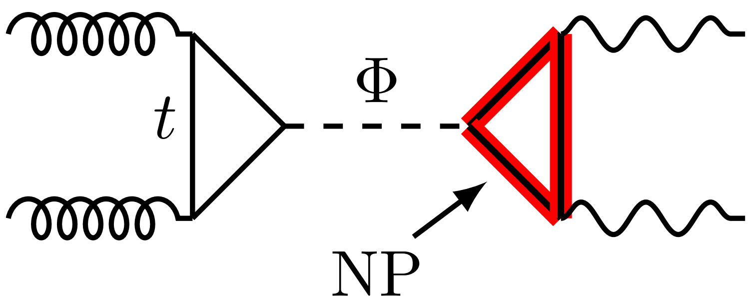
$$\Gamma_{tt} \approx 750\,\Gamma_{gg}$$

Making it wide

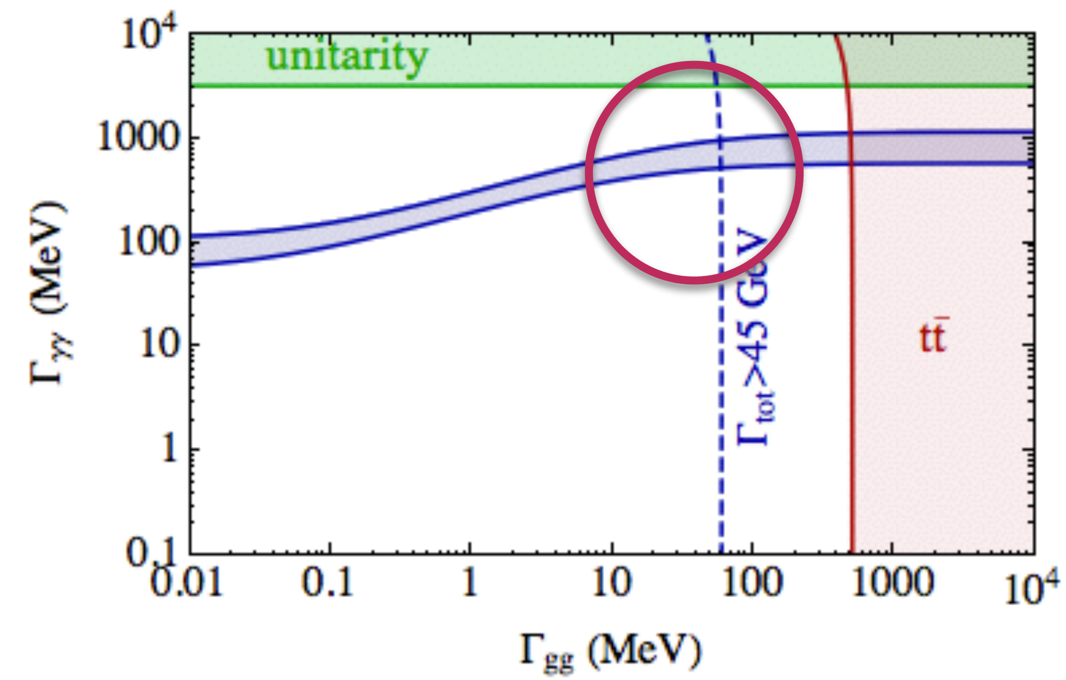


Additional decay mode needed



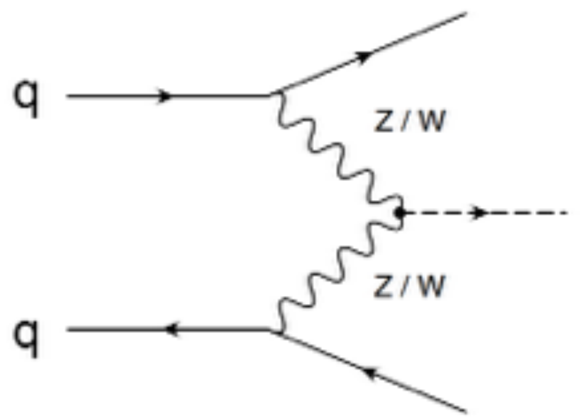


Possible with $t\bar{t}$ alone



VBF (W_L)

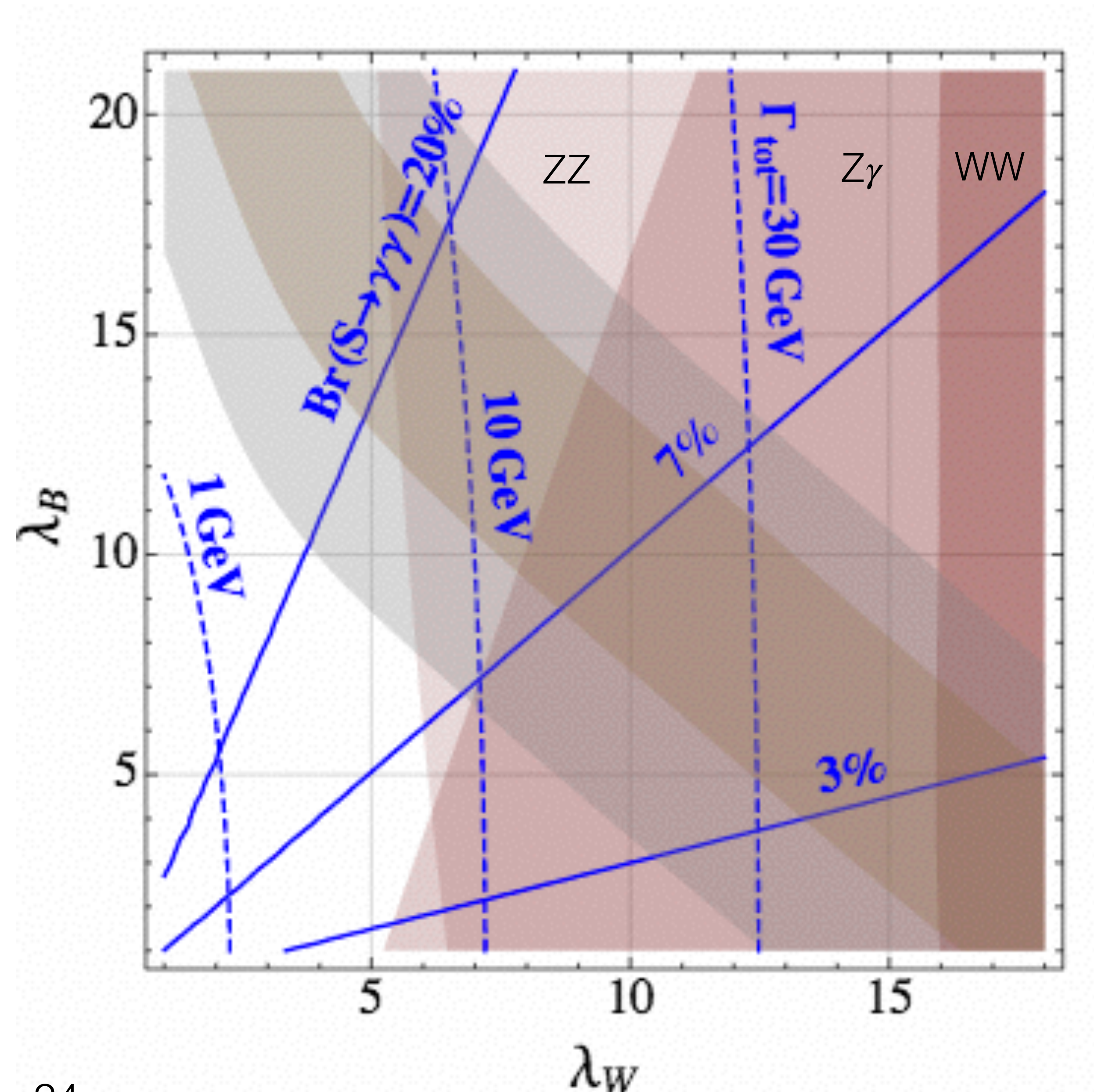
Through SM $SU(2)_L$



$$\mathcal{L} \supset \lambda_B \frac{\alpha}{\pi\, c_W^2\, v} \Phi B_{\mu\nu} B^{\mu\nu} + \lambda_W \frac{\alpha}{\pi\, s_W^2\, v} \Phi W_{\mu\nu} W^{\mu\nu}$$

Relatively large couplings needed, especially to hypercharge

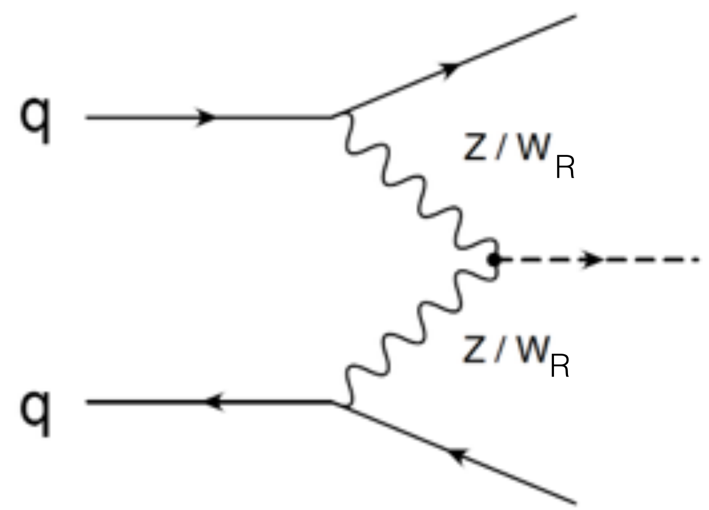
Large width not possible

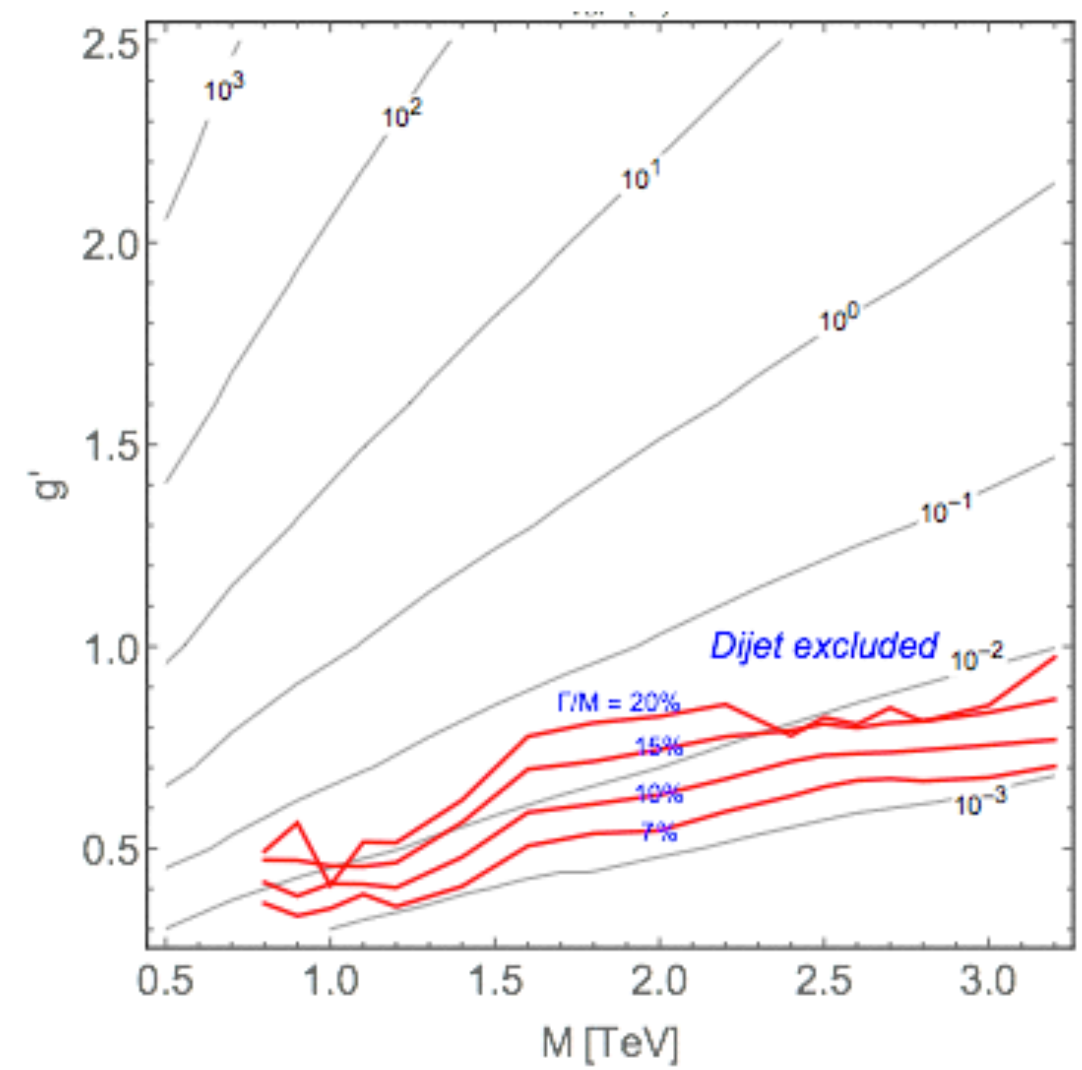


W. Altmannshofer, J. Galloway, S. Gori, A. Kagan, A. Martin, J. Zupan: 1512.07616

VBF (W_R)

Through heavy $SU(2)_R$





Excluded by di-jet search

SK, T. Melia, M. Papucci and K. Zurek: 1512.04928

Topologies

1. Exotic stuff
    1. cascades
    2. fake photons

2. 2 → 2 process
    1. Production
    2. Decay modes

More focus on what I find interesting

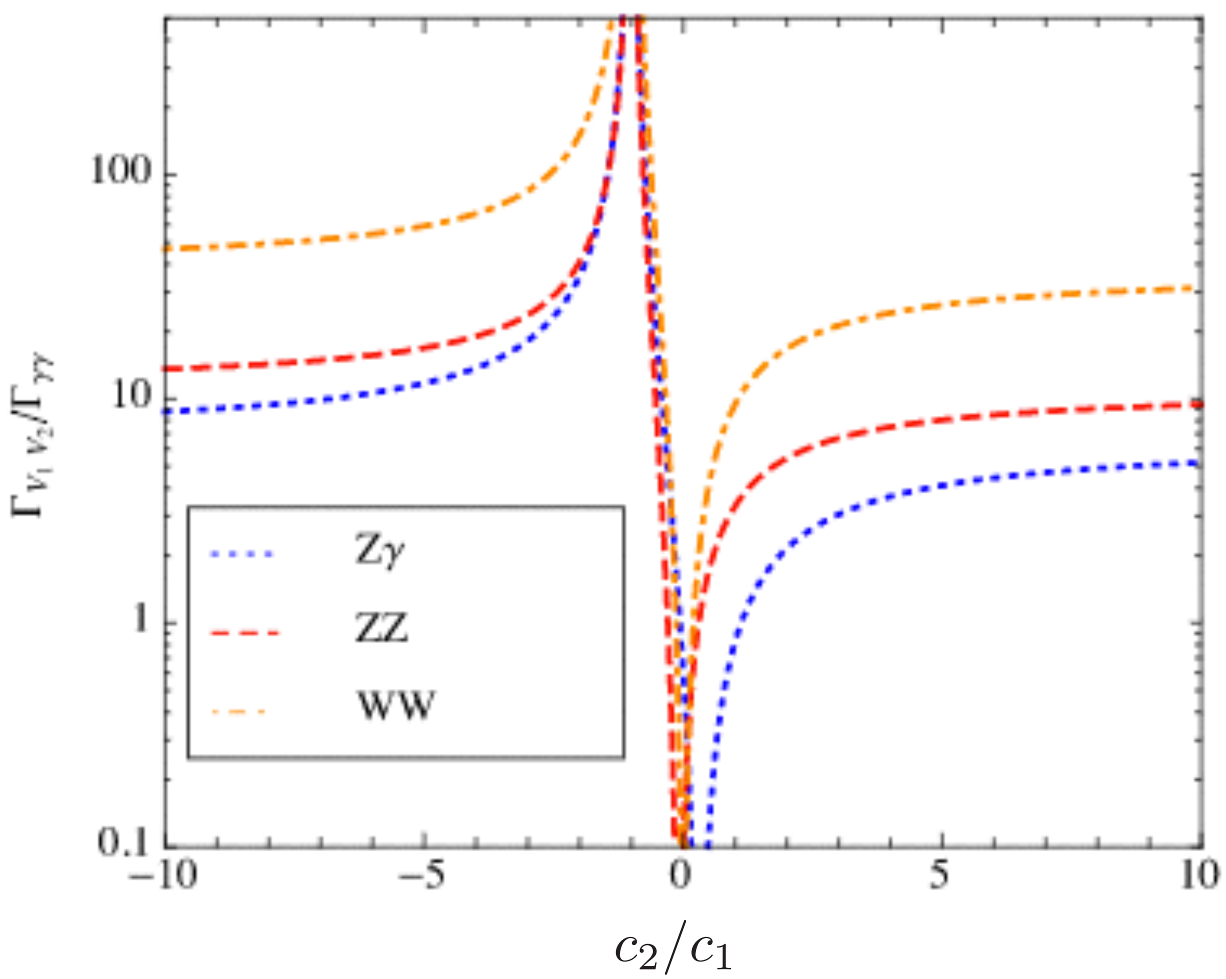
3. Conclusions and outlook

Singlet

If no mixing with Higgs

$$\frac{\alpha_1}{8\pi}\frac{c_1}{f}\Phi B_{\mu\nu}B^{\mu\nu} + \frac{\alpha_2}{8\pi}\frac{c_2}{f}\Phi \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] + \frac{\alpha_3}{8\pi}\frac{c_3}{f}\Phi G_{\mu\nu}G^{\mu\nu} \longrightarrow \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}}, \frac{\Gamma_{Z\gamma}}{\Gamma_{\gamma\gamma}}, \frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} \text{ and } \frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}}$$

Over constrained system



If mixing with Higgs, longitudinal modes are enhanced:

$$\Gamma(\Phi \to W_L W_L) \sim \sin^2\alpha \frac{m_\Phi^3}{m_W^2}$$

in addition to decays to $t\bar{t}$ and hh.
(but with rather small branching ratio's)

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{\gamma\gamma}} \lesssim 5.4 \qquad \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} \lesssim 11.3 \qquad \frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} \lesssim 34.8$$

N. Craig, P. Draper, C. Kilic, S. Thomas: 1512.07733
I. Low, J. Lykken: 1512.09089

Triplet

Real pseudo-scalar triplet

$$\hat{\Pi} = \begin{pmatrix} \hat{\pi}^+ \\ \hat{\pi}^0 \\ \hat{\pi}^- \end{pmatrix}$$

$$\mathcal{L} \supset \sqrt{2}\frac{\alpha_1\alpha_2}{8\pi}\frac{c_{\hat{\Pi}}}{f}B_{\mu\nu}\mathrm{Tr}[\hat{\Pi}\tilde{W}^{\mu\nu}]$$

- Only one operator, so branching ratio's fully fixed
- Drell-Yan pair production always present

$\hat{\pi}^0 \to \gamma\gamma$	35.5%
$\hat{\pi}^0 \to ZZ$	35.5%
$\hat{\pi}^0 \to Z\gamma$	29%
$\hat{\pi}^0 \to WW$	0
$\hat{\pi}^\pm \to W^\pm\gamma$	80%
$\hat{\pi}^\pm \to W^\pm Z$	20%

$\hat{\pi}^0$ production trough

- photon fusion
- cascade decay
- mixing

Additional state(s) needed

K. Howe, SK, D. Robinson: 1603.08932

Triplet - Singlet mixing

Setup:

$$\frac{\alpha_1}{8\pi}\frac{c_1}{f}\hat{\eta}B_{\mu\nu}\tilde{B}^{\mu\nu} + 2\frac{\alpha_2}{8\pi}\frac{c_2}{f}\hat{\eta}\mathrm{Tr}[W_{\mu\nu}\tilde{W}^{\mu\nu}] + \frac{\alpha_3}{8\pi}\frac{c_3}{f}\hat{\eta}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$
$$+\sqrt{2}\frac{\alpha_1\alpha_2}{8\pi}\frac{c_{\hat{\Pi}}}{f}B_{\mu\nu}\mathrm{Tr}[\hat{\Pi}\tilde{W}^{\mu\nu}]$$

$\hat{\eta}$ pseudo-scalar singlet

$\hat{\Pi}$ pseudo-scalar triplet

$c_1,\ c_2,\ c_3,\ c_\Pi$ coupling constants

(I use pseudo-scalars because they may be goldstone bosons, but this makes little difference for the phenomenology)

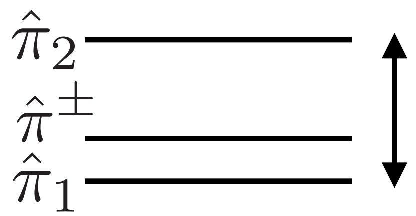
Mixing

$$\lambda H^\dagger \hat{\Pi} H \hat{\eta} \longrightarrow \begin{pmatrix}\hat{\pi}_1\\ \hat{\pi}_2\end{pmatrix} = \begin{pmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}\hat{\pi}^0\\ \hat{\eta}\end{pmatrix},$$

Either π_1, π_2 or both could be responsible for the excess

K. Howe, SK, D. Robinson: 1603.08932

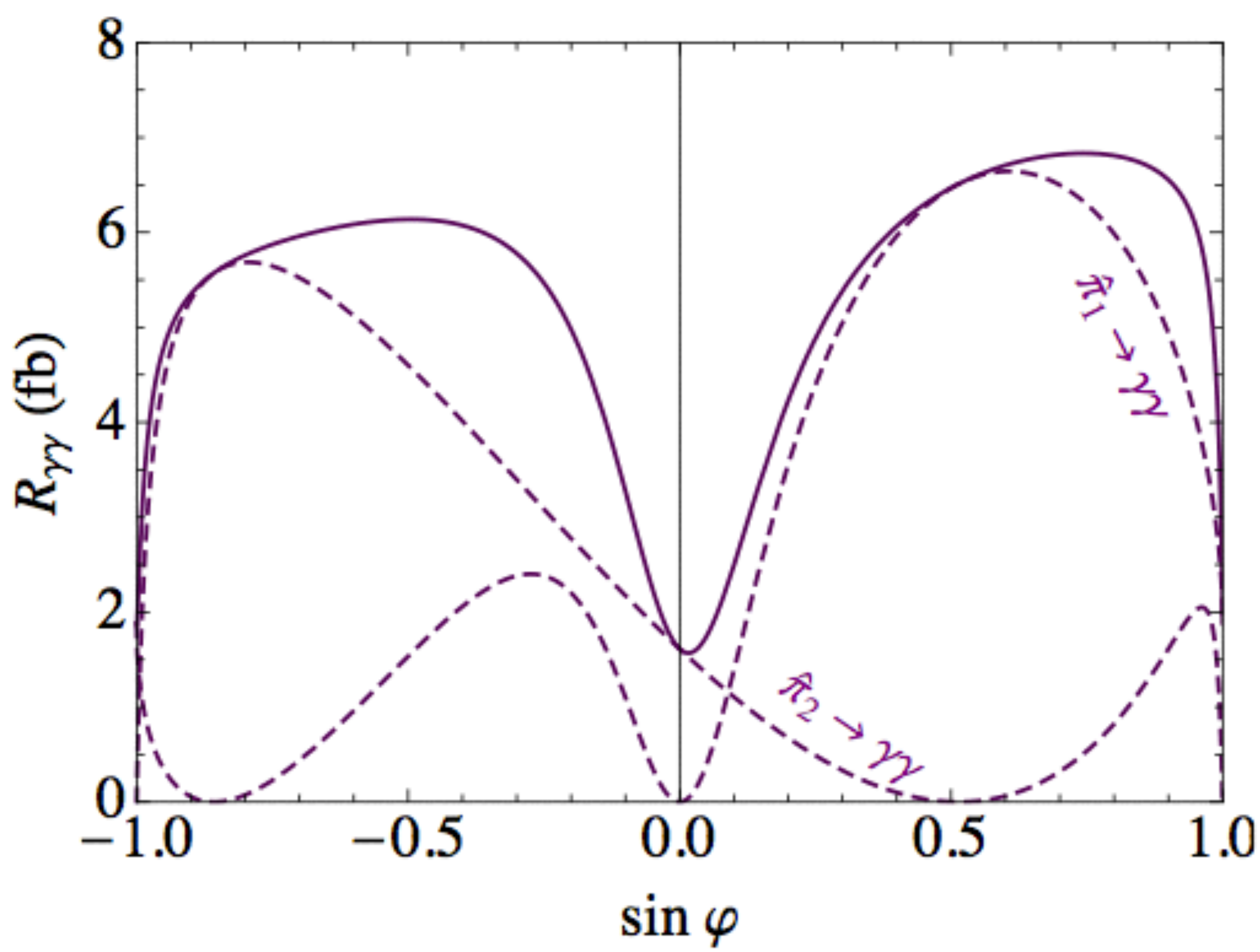
Case 1: merged resonances



< 40 GeV

π_1 and π_2 both within $\gamma\gamma$ resolution

→ looks like a single, broad resonance

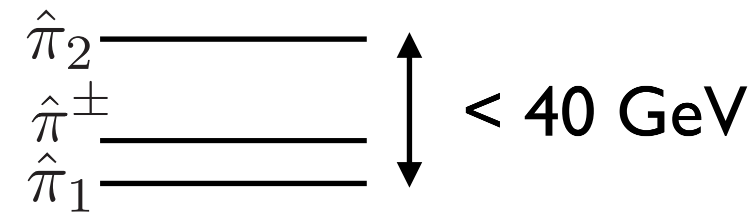


for

$$f = 1 \text{ TeV}$$
$$m_{\hat{\pi}_1} = 730 \text{ GeV}$$
$$m_{\hat{\pi}_2} = 770 \text{ GeV}$$

K. Howe, SK, D. Robinson: 1603.08932

Branching ratios



$$\frac{\alpha_1}{8\pi}\frac{c_1}{f}\hat{\eta}B_{\mu\nu}B^{\mu\nu} + \frac{\alpha_2}{8\pi}\frac{c_2}{f}\hat{\eta}\mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] + \frac{\alpha_1\alpha_2}{8\pi}\frac{c_\Pi}{f}B_{\mu\nu}\mathrm{Tr}\left[\hat{\Pi}W^{\mu\nu}\right]$$

Define auxiliary variables:

$$\tan\bar{\psi} \equiv c_2/c_1, \quad \bar{r} \equiv \left|\frac{\sqrt{c_1^2 + c_2^2}}{c_\Pi}\right|$$

Ratio's of branching ratios can be written in closed form:

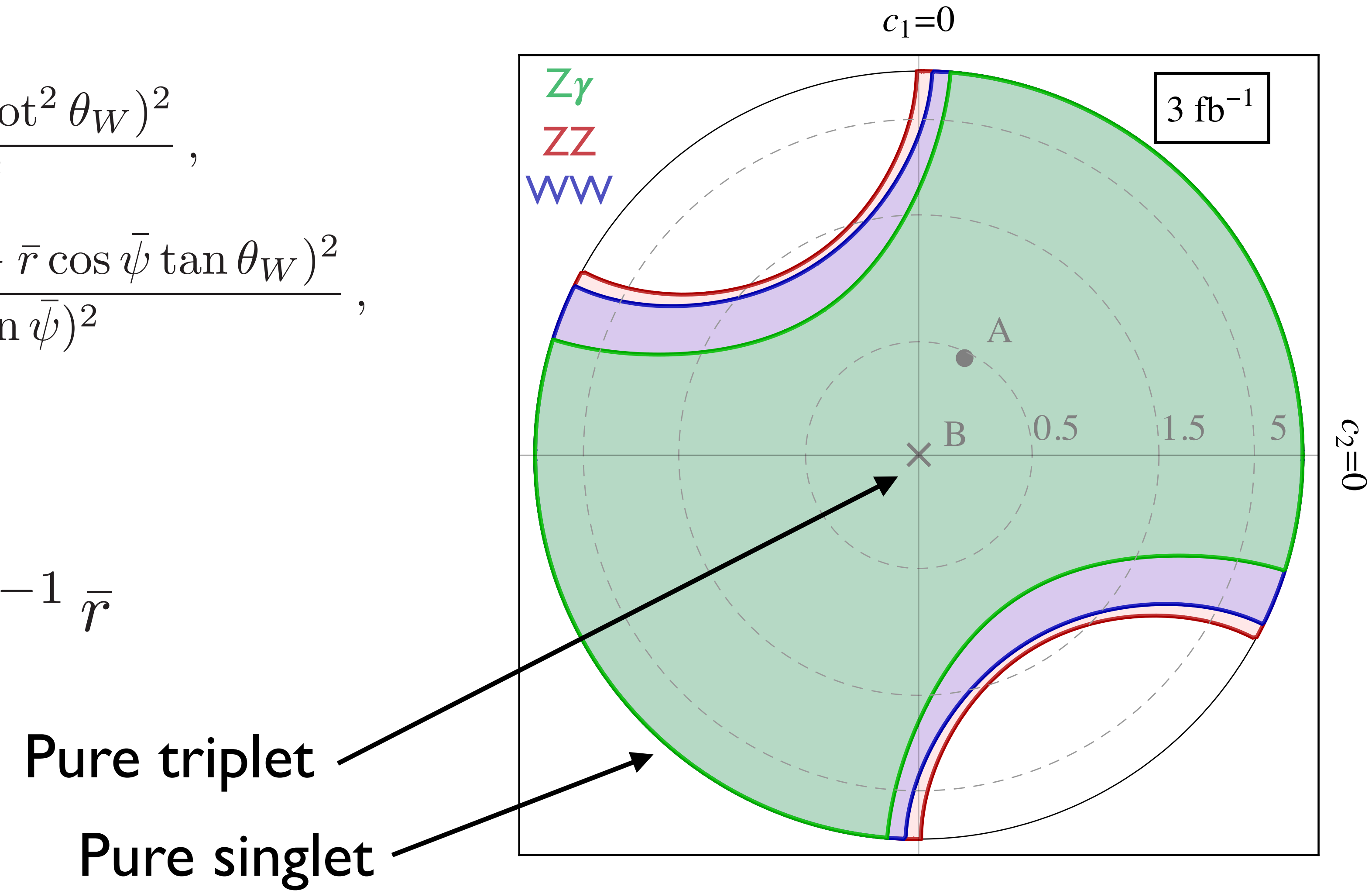
Assuming $\sin\phi \gg 0$

$$\frac{R^{\mathrm{eff}}_{ZZ}}{R^{\mathrm{eff}}_{\gamma\gamma}} = \frac{1 + (\bar{r}\cos\bar{\psi}\tan^2\theta_W + \bar{r}\sin\bar{\psi}\cot^2\theta_W)^2}{1 + (\bar{r}\cos\bar{\psi} + \bar{r}\sin\bar{\psi})^2},$$

$$\frac{R^{\mathrm{eff}}_{Z\gamma}}{R^{\mathrm{eff}}_{\gamma\gamma}} = 2\frac{\cot^2(2\theta_W) + (\bar{r}\sin\bar{\psi}\cot\theta_W - \bar{r}\cos\bar{\psi}\tan\theta_W)^2}{1 + (\bar{r}\cos\bar{\psi} + \bar{r}\sin\bar{\psi})^2},$$

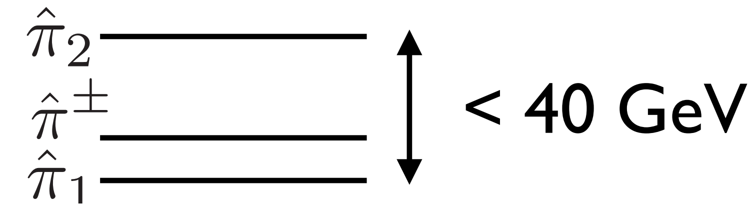
$$\frac{R^{\mathrm{eff}}_{WW}}{R^{\mathrm{eff}}_{\gamma\gamma}} = \frac{2}{s_W^4}\frac{\bar{r}^2\sin^2\bar{\psi}}{1 + (\bar{r}\cos\bar{\psi} + \bar{r}\sin\bar{\psi})^2}.$$

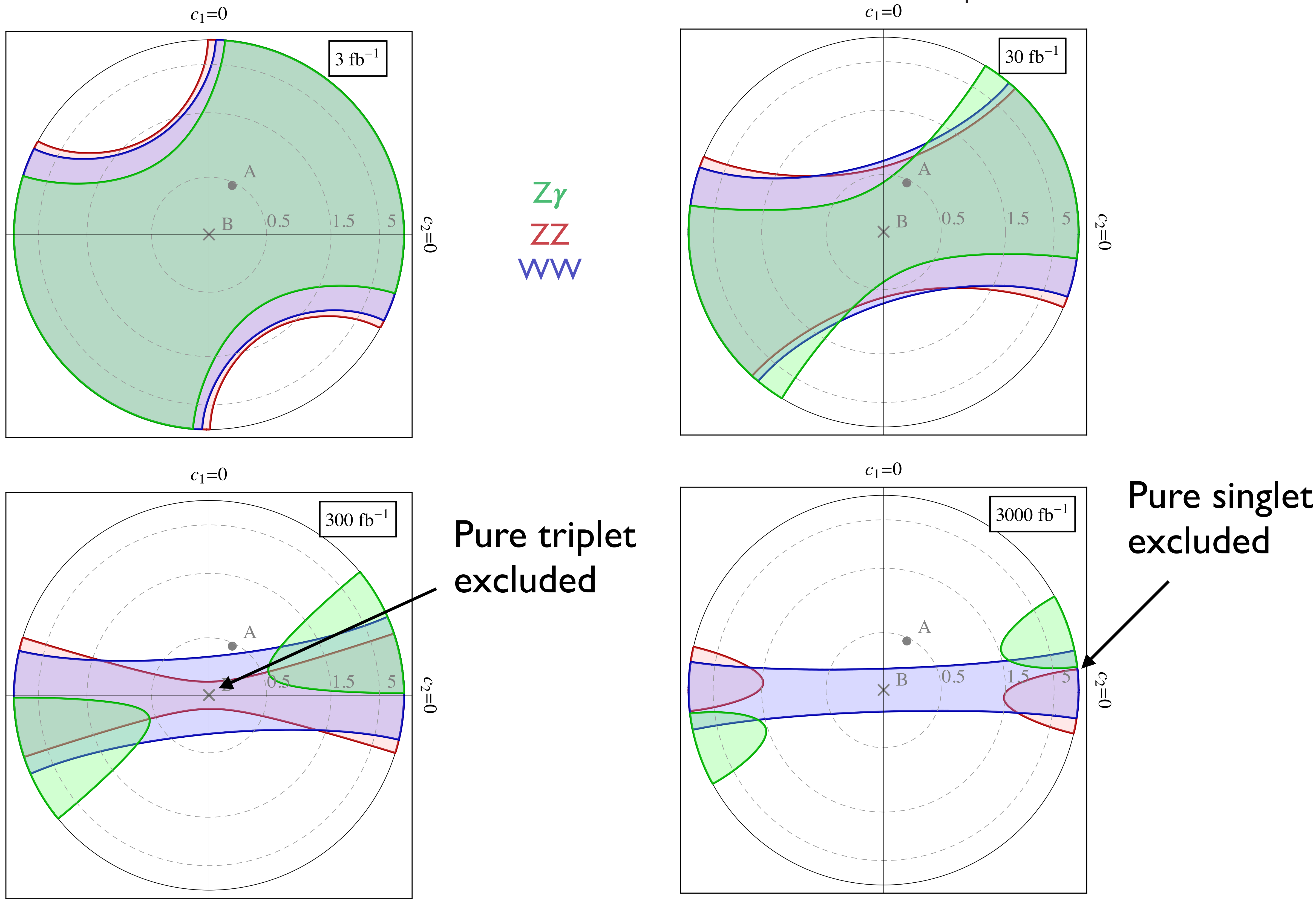
Use conformal map $\bar{r} \to \tan^{-1}\bar{r}$



K. Howe, SK, D. Robinson: 1603.08932

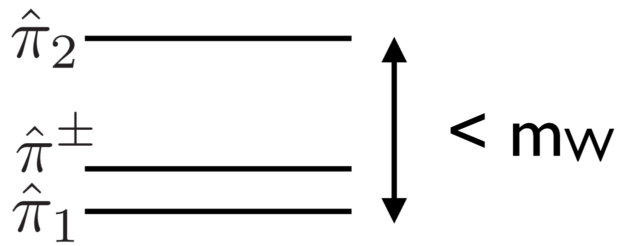
Branching ratios





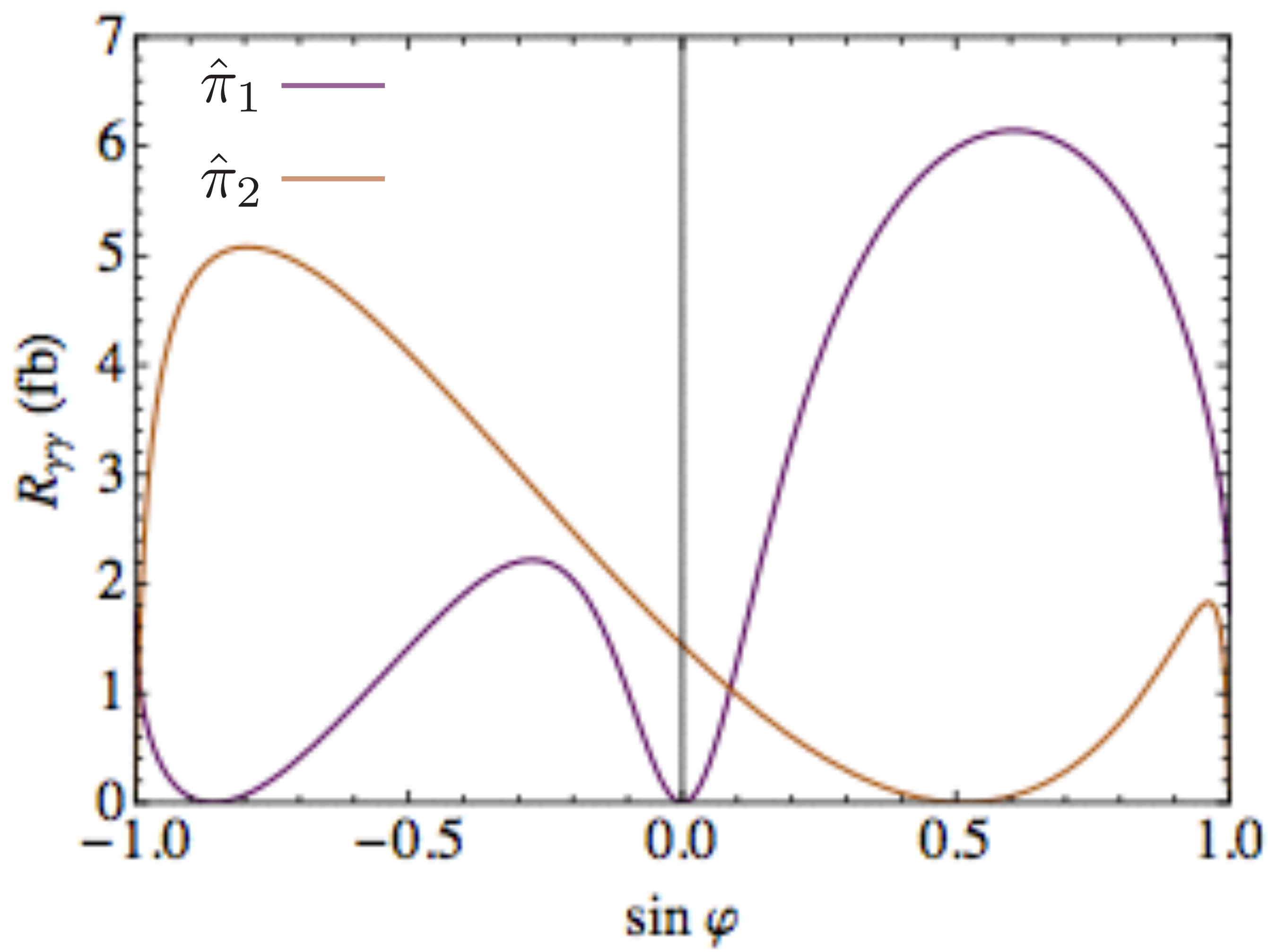
K. Howe, SK, D. Robinson: 1603.08932

Case 2: resolved resonances



π_1 and π_2 resolved separately

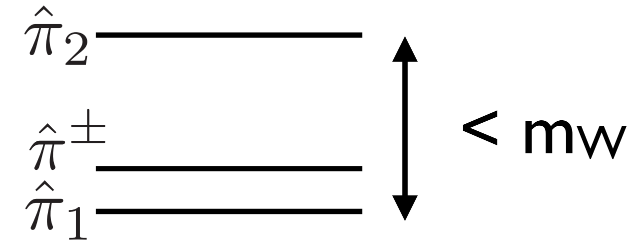
→ Expect another resonance nearby



for
$$f = 1 \text{ TeV}$$
$$m_{\hat{\pi}_1} = 730 \text{ GeV}$$
$$m_{\hat{\pi}_2} = 800 \text{ GeV}$$

K. Howe, SK, D. Robinson: 1603.08932

Branching ratios



$$\frac{\alpha_1}{8\pi}\frac{c_1}{f}\hat{\eta}B_{\mu\nu}B^{\mu\nu} + \frac{\alpha_2}{8\pi}\frac{c_2}{f}\hat{\eta}\mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] + \frac{\alpha_1\alpha_2}{8\pi}\frac{c_\Pi}{f}B_{\mu\nu}\mathrm{Tr}\left[\hat{\Pi}W^{\mu\nu}\right]$$

Define auxiliary variables:

$$\tan\psi \equiv c_2/c_1, \quad r \equiv \left|\frac{\sqrt{c_1^2+c_2^2}}{c_\Pi}\tan\varphi\right|$$

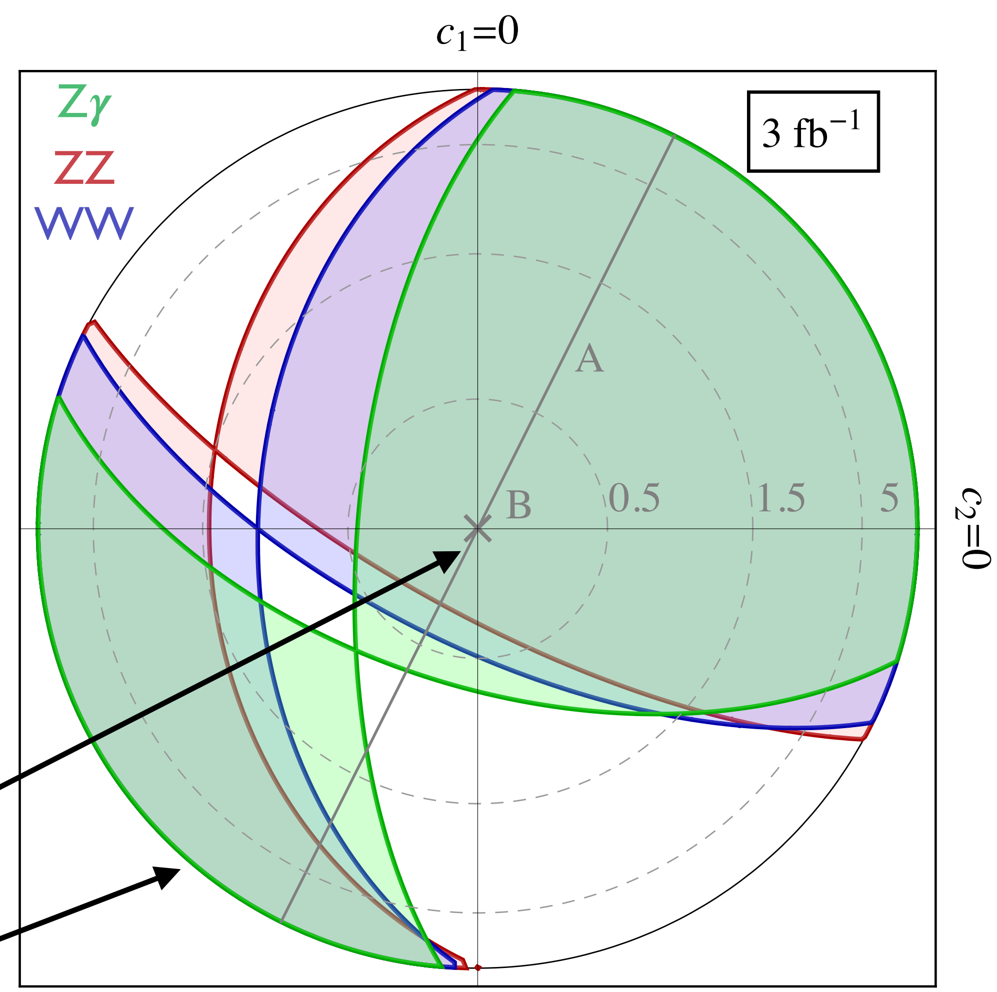
Ratio's of branching ratios can be written in closed form:

$$\frac{R_{ZZ}^{\hat{\pi}_1}}{R_{\gamma\gamma}^{\hat{\pi}_1}} = \left(\frac{1 - r\cos\psi\tan^2\theta_W - r\sin\psi\cot^2\theta_W}{1 + r\cos\psi + r\sin\psi}\right)^2,$$

$$\frac{R_{Z\gamma}^{\hat{\pi}_1}}{R_{\gamma\gamma}^{\hat{\pi}_1}} = \frac{1}{2}\left(\frac{\cot\theta_W(2r\sin\psi+1) - \tan\theta_W(2r\cos\psi+1)}{1 + r\cos\psi + r\sin\psi}\right)^2,$$

$$\frac{R_{WW}^{\hat{\pi}_1}}{R_{\gamma\gamma}^{\hat{\pi}_1}} = \frac{2}{s_W^4}\left(\frac{r\sin\psi}{1 + r\cos\psi + r\sin\psi}\right)^2.$$

Use conformal map $\bar{r} \to \tan^{-1}\bar{r}$

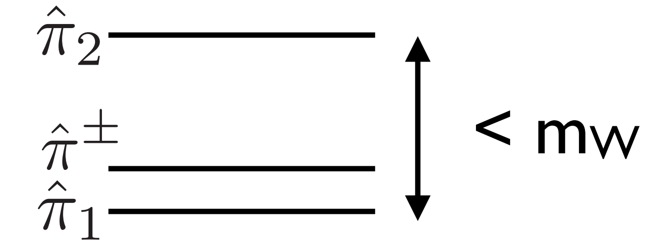


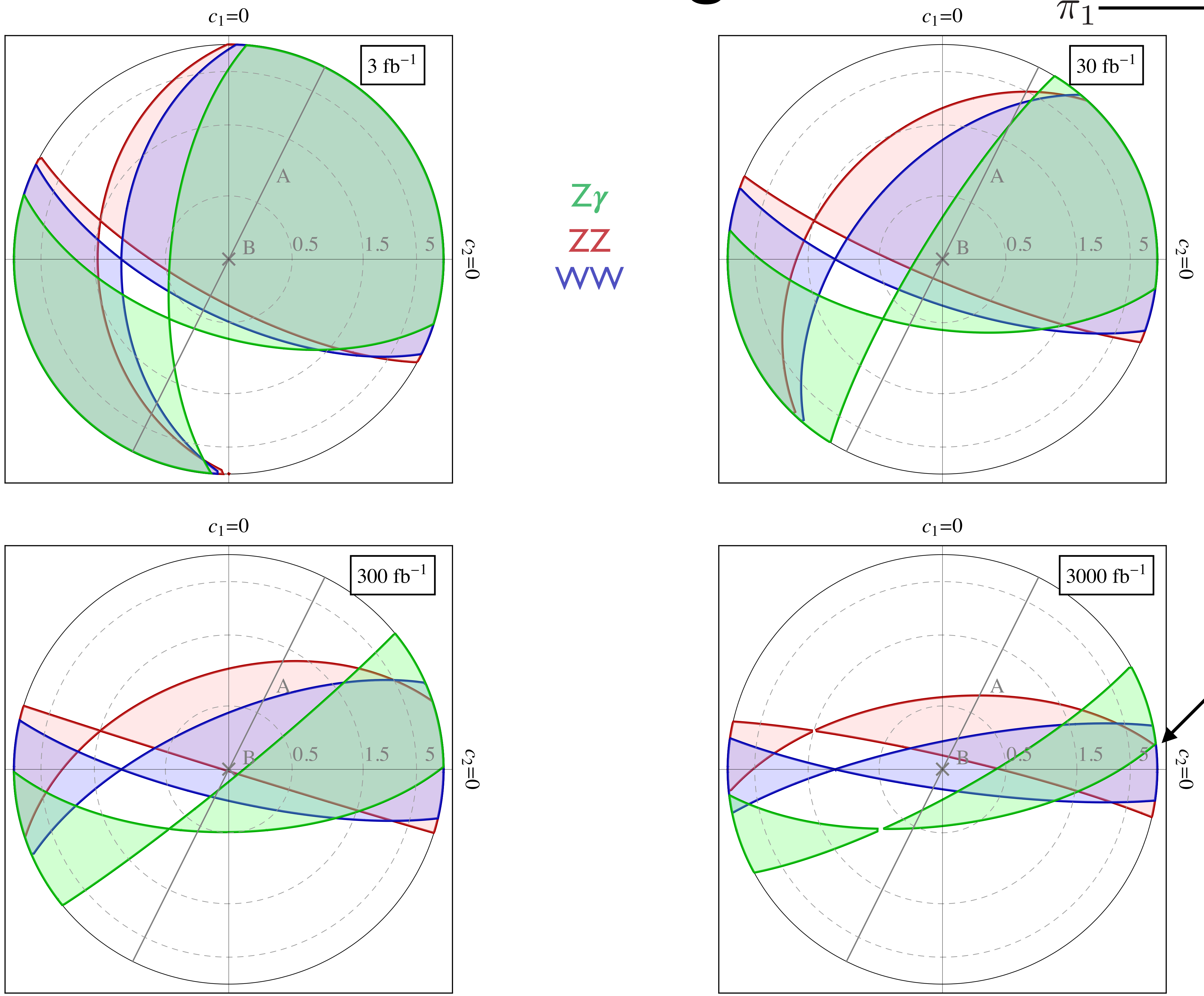
Pure triplet

Pure singlet

K. Howe, SK, D. Robinson: 1603.08932

Branching ratios

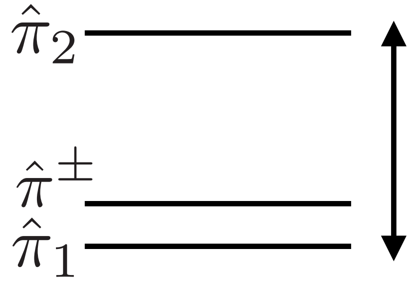




Pure singlet excluded

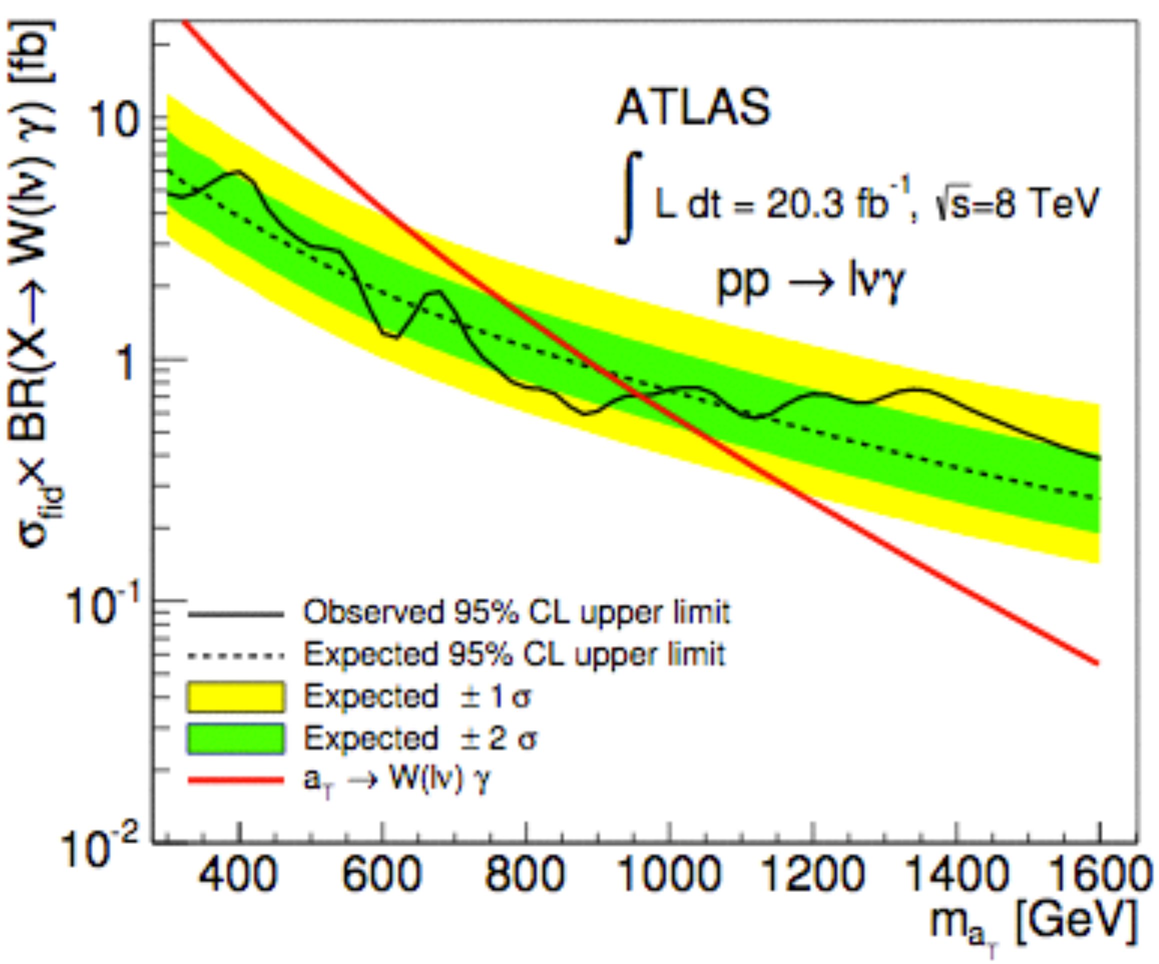
K. Howe, SK, D. Robinson: 1603.08932

Case 3: Cascade decay



$$\hat{\pi}_2 \to \hat{\pi}^{\pm} W^{\mp} \to \gamma W^{\pm} W^{\mp}$$ @ tree-level

$$\Gamma^{\hat{\pi}_2}_{\hat{\pi}^{\pm} W^{\mp}} \simeq \frac{\alpha}{s_W^2} \frac{m_{\hat{\pi}_2}^3 \sin^2 \varphi}{m_W^2}$$

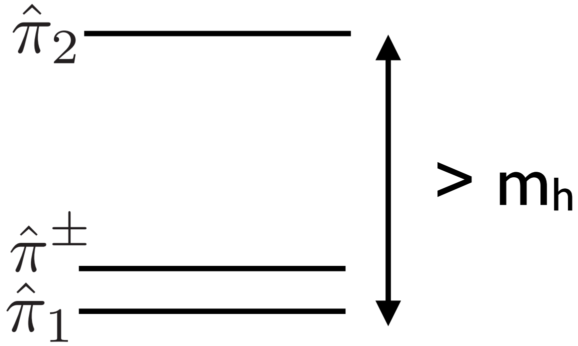


→ $|\sin\varphi| \lesssim 0.022$

Very difficult to get sizable $\gamma\gamma$ rate

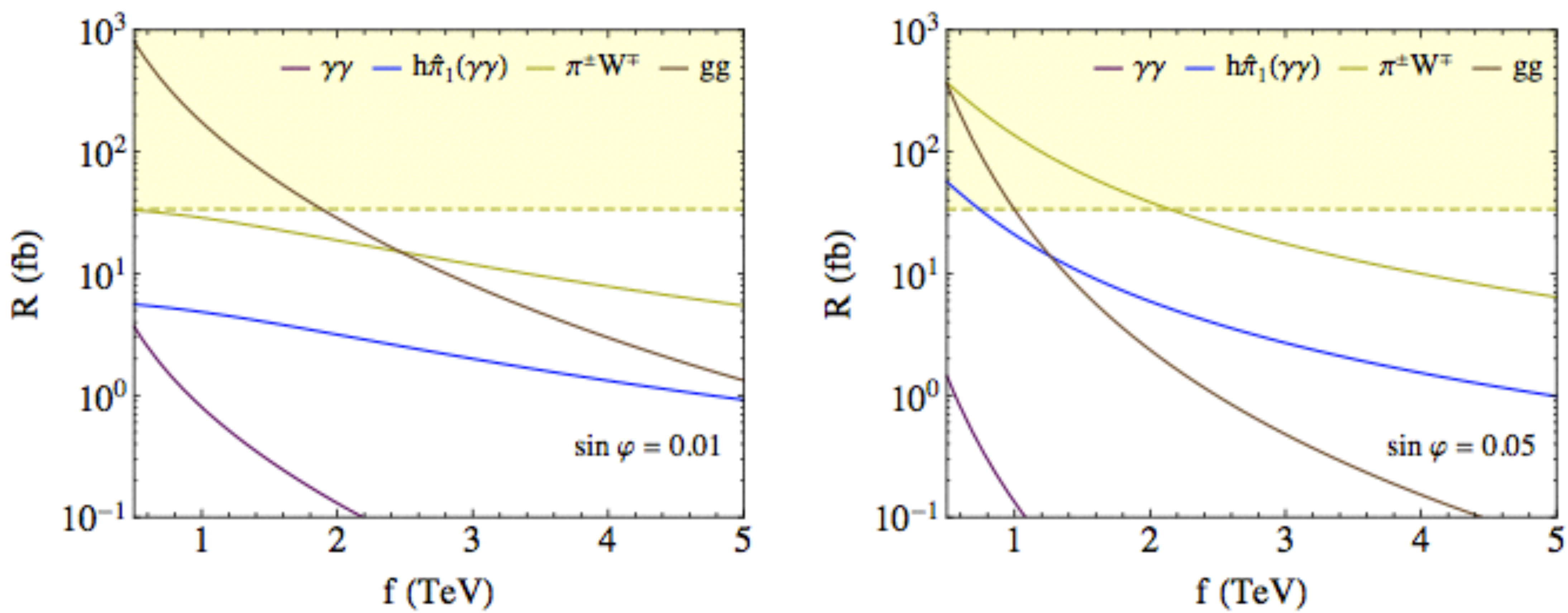
K. Howe, SK, D. Robinson: 1603.08932

Case 4: Cascade decay



Cascade decay now open… $\hat{\pi}_2 \to h\hat{\pi}_1 \to bb\gamma\gamma$

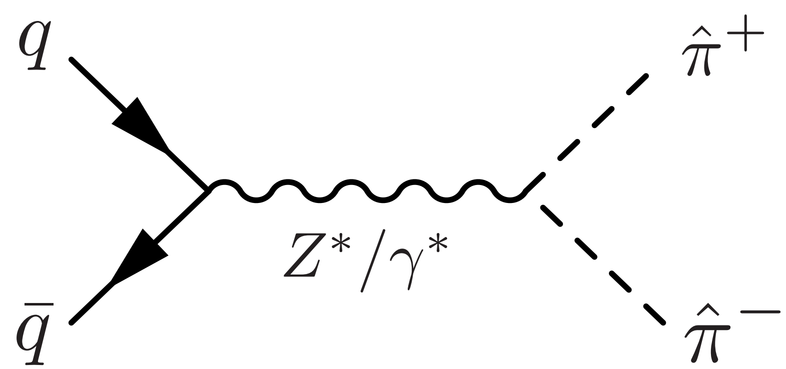
…but disfavored due to apparent lack of b-tags



K. Howe, SK, D. Robinson: 1603.08932

Back to Drell-Yan

Only depends on the mass of the triplet, which is ~ 750 GeV

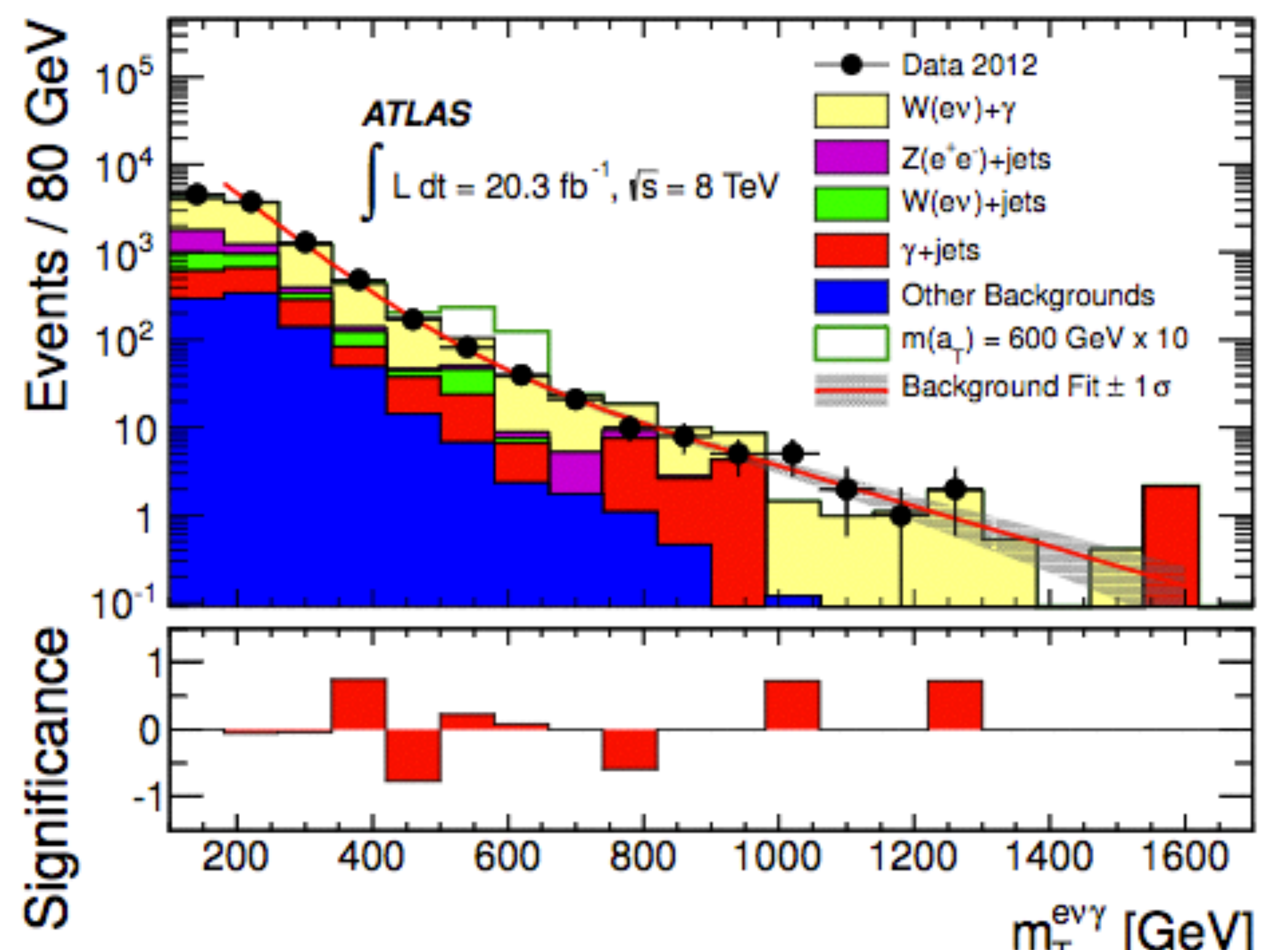


$$q\bar{q} \to \hat{\pi}^+\hat{\pi}^- \to W^+\gamma W^-\gamma : \qquad 0.27\ \mathrm{fb}^{-1}$$

Very robust signature

Current bound from single resonance search ~ 10 fb^{-1}

Improve sensitivity by looking for pair production



K. Howe, SK, D. Robinson: 1603.08932

Conclusions

In the standard model we have two types of particles that decay to $\gamma\gamma$

In which category is the 750 GeV state?

<u>Higgs</u>

- Scalar
- Elementary (?)
- Narrow
- Small branching ratio to $\gamma\gamma$

(fermions!)

<u>π^0, η, η'</u>

- Pseudo-scalar
- Composite
- Narrow
- Large branching ratio to $\gamma\gamma$

If wide, we are dealing something REALLY new

Outlook

Experimental:

Does it stay? Summer will be exciting!

Also look for:

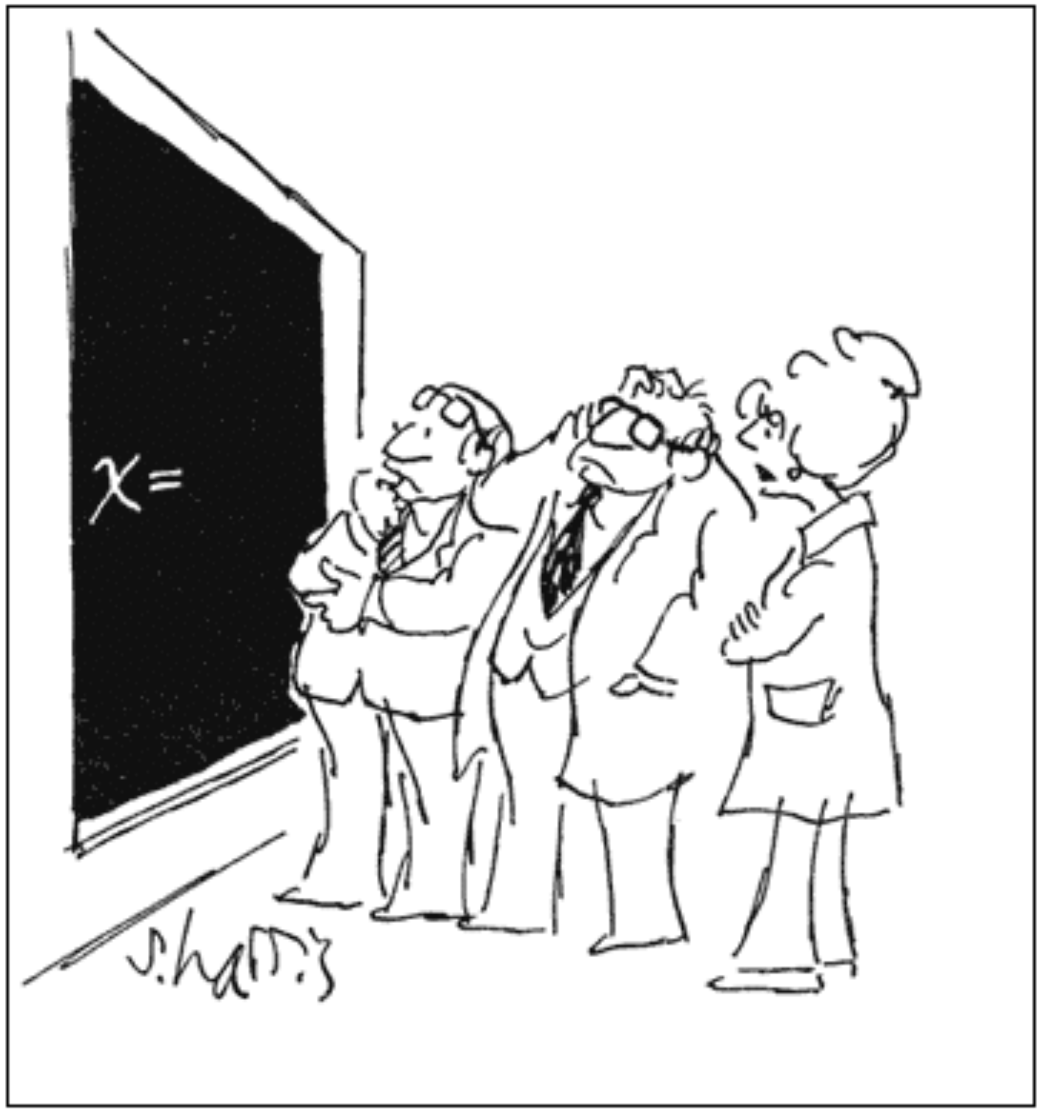
- Other decay modes
- Messengers
- Other similar states (pair production!)
- p_T spectrum, b-tags, rapidity gap…

Theory:

What does it do for us?

What I didn't talk about

- Interference (S. Jung et al:1601.00006)
- Models (susy) (many)
- Models (composite) (many)
- New gauge groups (many)
- Dark matter (F. D'Eramo, et. al.:1601.0157,M. Backovic, et.al. ::1512.04917)
- Unification (L. Hall, et. al: 1512.07904)
- Landau poles (Salvio, et. al. :1602.01460)
- Quirks (P. Agrawal, et. al.: 1512.05775, D. Curtin, et. al.: 1512.05753)
- Flavor anomalies (M. Bauer, M. Neubert:1512.06828, C.W. Murphy1512.06976)
- Spin 2 (C. Geng, D. Huang:1601.07385, A. Martini et. al. :1601.05729)
- Future colliders (A. Djouadi et, al.:1601.03696)
- ….



Questions?

Comments?

Complaints?

Omissions?

Bibliography

(Apologies for any omissions)

EW singlets

Buttazzo et. al. 1512.04929
Falkowski et. al. 1512.05777
Raidal et. al. 1512.04939
Gupta et. al. 1512.05332
Craig et. al. 1512.07733
Knapen et. al. 1512.04928
Francescini et. al. : 1512.04933

Falkowski. et. al. 1512.05777
Aloni et. al. : 1512.05778
Trott et. al. 1512.06799
McDermott et. al.1512.05326
Ellis et al. 1512.05327
Benbrik et. al.1512.06028
Low et. al. 1512.05328
…

2HDM’s

Altmannshofer et. al. 1512.07616
Becirevic et. al. 1512.05623
Bertuzzo et. al. 1601.07508
Badziak et. al. 1512.07497
Chakrabortty et. al. 1512.05767
Gupta et. al. 1512.05332

Bizot et. al. 1512.08508

Photon fusion

Harland–Lang, et. al: 1601.07187
Martina et. al: 1601.07774
Csaki et. al. :1601.00638
Csaki et. al. :1512.05776

Fichet et. al. : 1512.05751
Fichet et. al. : 1601.01712

Special thanks to Kiel Howe for sharing his bibliography. Any important omissions are of course mine.

Flavor anomalies

Bauer et. al. 1512.06828
Murphy 1512.06976
Bizot et. al 1512.08508

Dark matter

Backovic et al. 1512.07992
Bi et al. 1512.06787
Han et al. 1512.04917
Park et al. 1512.08117
D'eramo et al. 1601.01571
Bhattacharya et al. 1601.01569
Huang et al. 1512.08992
Dev et al. 1512.07243
+ many others

Special thanks to Kiel Howe for sharing his bibliography. Any important omissions are of course mine.

SUSY

Bellazini et. al. :1512.05330
Torre et. al. :1512.05333
Demidov et. al. :1512.05723
Carpenter et. al. :1512.06107
Perez et. al. :1512.05332
Chiara et. al. :1512.04939
Buttazzo et. al. :1512.04929
Wang et. al. :1512.08434
Tang et. al. :1512.08323
Wang et. al. : 1512.06715

Composite

Nomura et. al. 1512.04850
Quiros et. al. 1512.06106
Cox et. al. 1512.05618
Nakai et. al. 1512.04924
Bellazini et. al. 1512.05330
Low et. al. 1512.05328
Sanz et. al. 1512.05700
Belyaev et. al. 1512.07242
Francescini et. al. : 1512.04933
+ many many more

Special thanks to Kiel Howe for sharing his bibliography. Any important omissions are of course mine.

Spin 2

Arun et al. 1512.06335
Han et al. 1512.06376
Martini et al. 1601.05729
Geng et al. 1601.07385

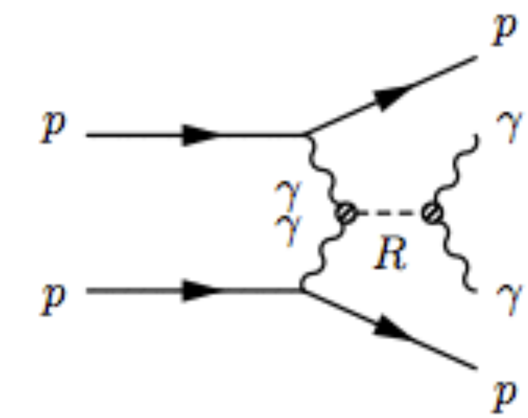
Alternative decay topologies

Knapen et. al. 1512.04928,
Agrawal et. al. 1512.05775,
Kim et. al. 1512.06083
Chang, J et. al. 1512.06671
Bi et al. 1512.08497
Chala et. al. 1512.06833
Cho et. al. 1512.06824
Cheung et. al. 1512.08378
Bernon et. al. 1512.06113

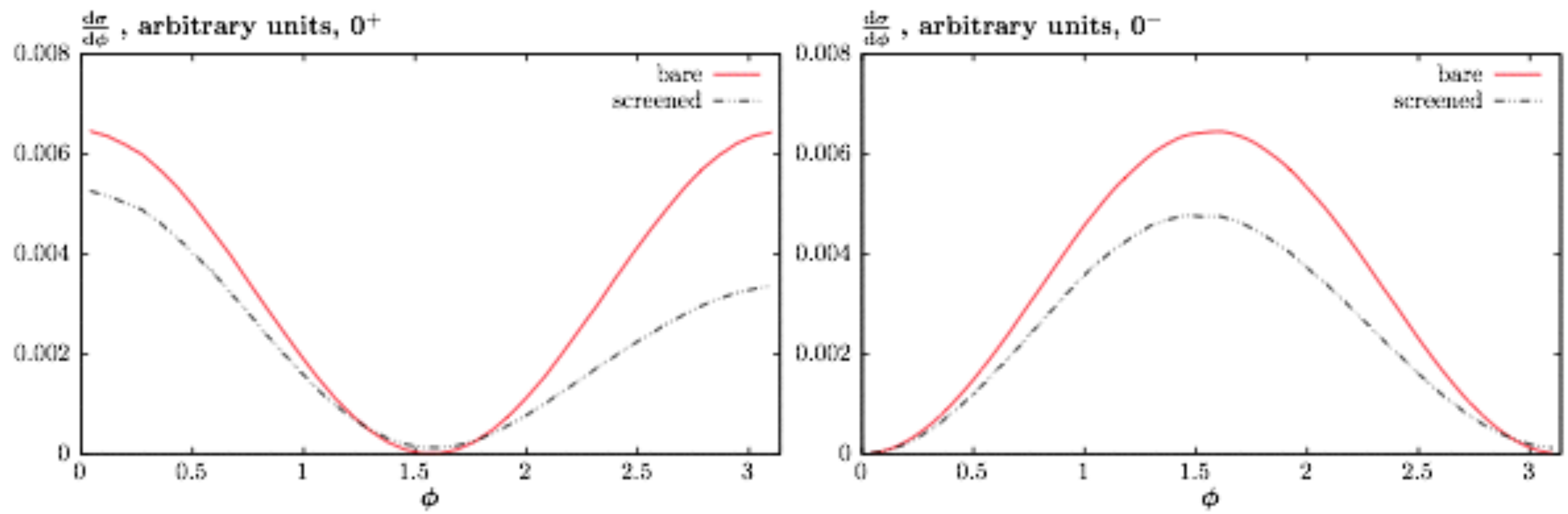
Special thanks to Kiel Howe for sharing his bibliography. Any important omissions are of course mine.

Back-up slides

Elastic scattering



- QCD background is tiny
- Measure the coupling to photons
- Parity measurement

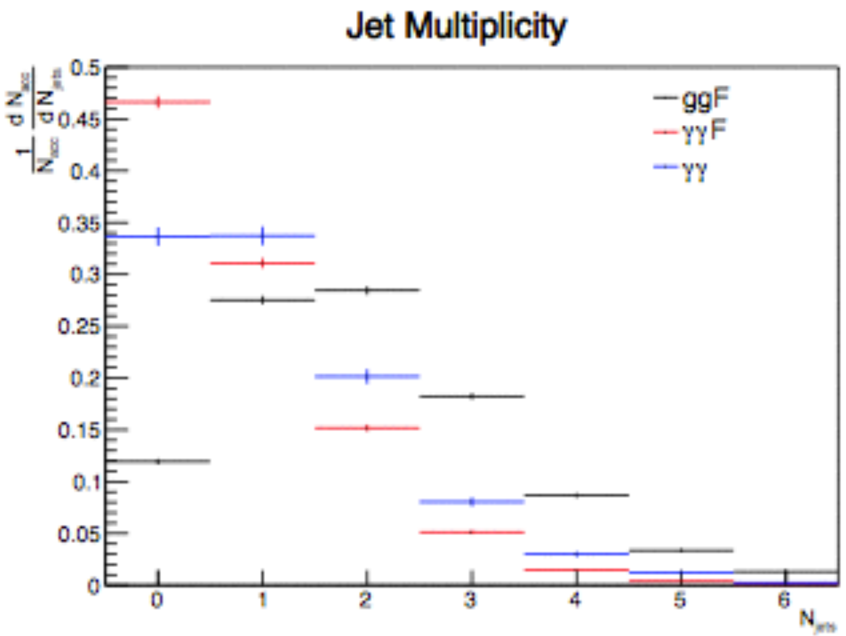


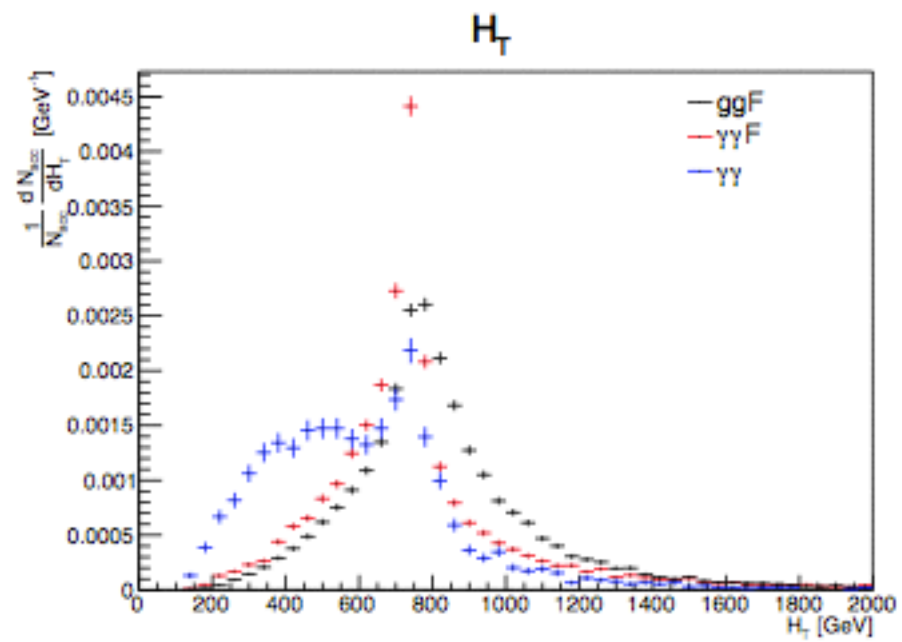
- CP violation (asymmetry in forward protons)
- Better mass resolution (~ 10 GeV)
- Other decay modes (Zγ etc)

L.A. Harland–Lang, V.A. Khoze, M. G. Ryskin: 1601.07187
A.D. Martina and M.G. Ryskin: 1601.07774

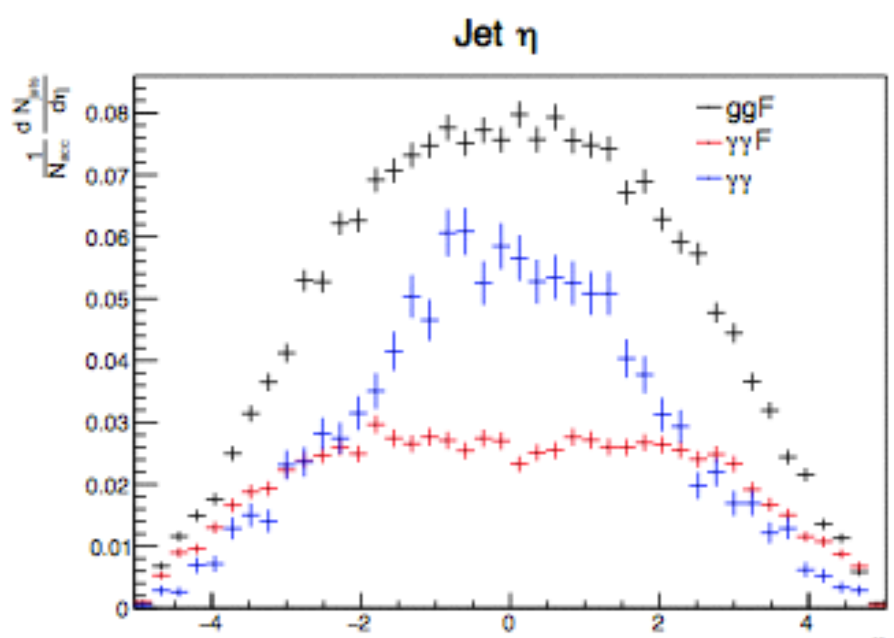
ggF vs $\gamma\gamma$F

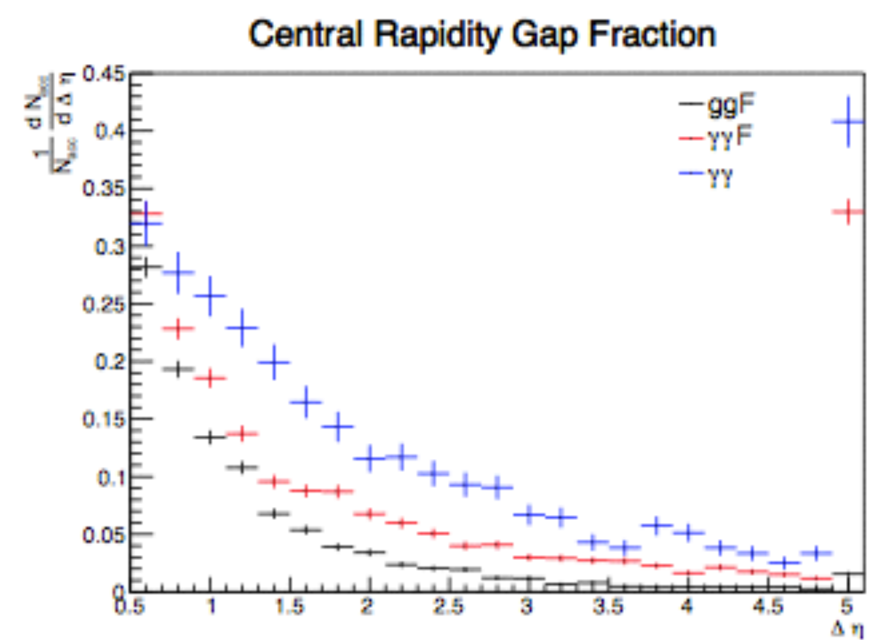
ggF events are more jet-rich





Jets in $\gamma\gamma$F events are more forward

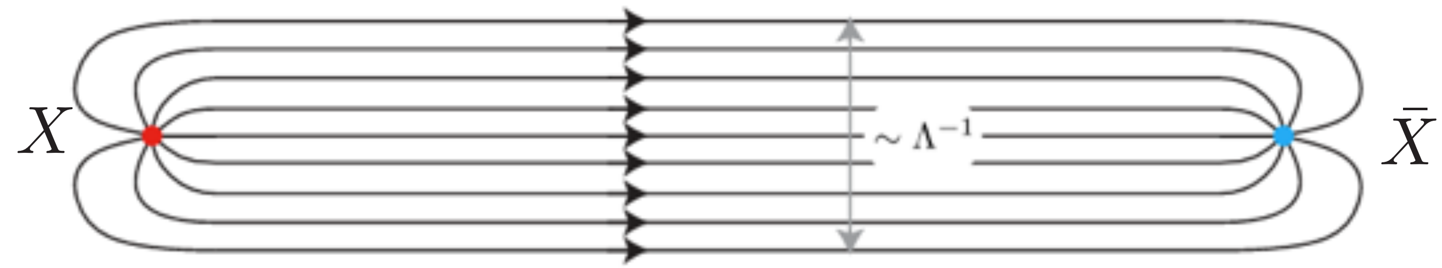




C. Csaki. J. Hubisz, S. Lombardo, J. Terning: 1601.00638

Quirks

ϕ may be a bound state



If $m_X > \Lambda_c$, the flux tube cannot break

⟶ the X - $\overline{X}$ system annihilates to (hidden) gauge bosons

Features:

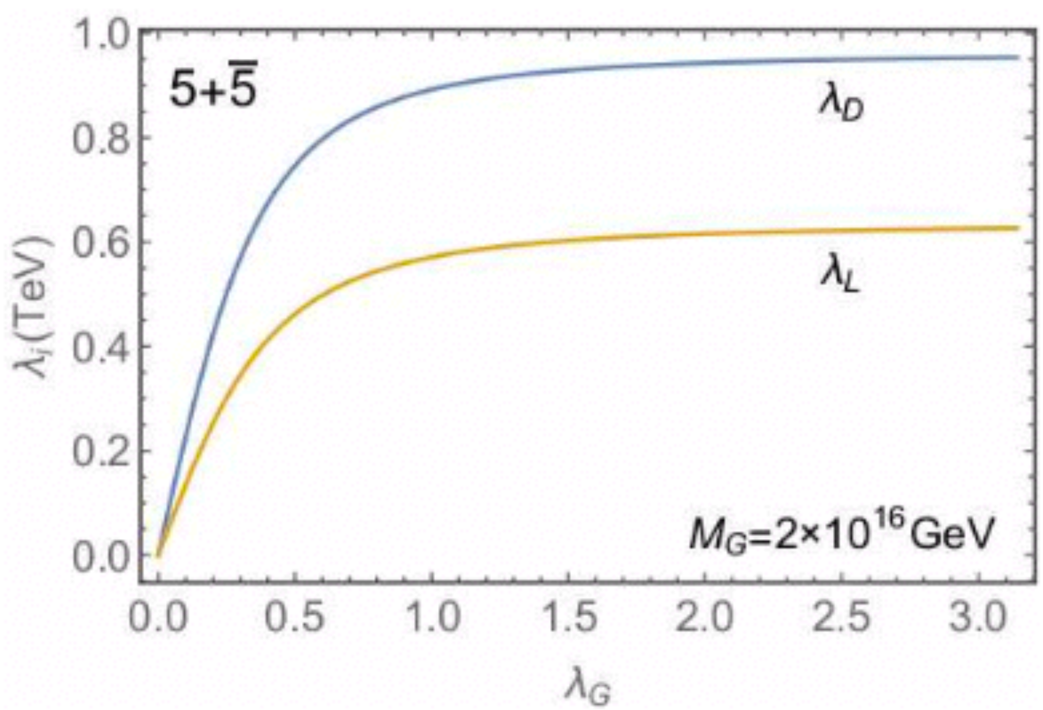
- fermionic quirks disfavored (di-lepton resonances)
- if colored, large production cross section (> 5 pb)
- color octet states could be nearby (dijet or photon + jet)
- soft jets or pions from de-excitation
- possible displaced hidden glueball decays

P. Agrawal, J. Fan, B. Heidenreich, M. Reece, M. Strassler: 1512.05775
D. Curtin, C.B. Verhaaren: 1512.05753

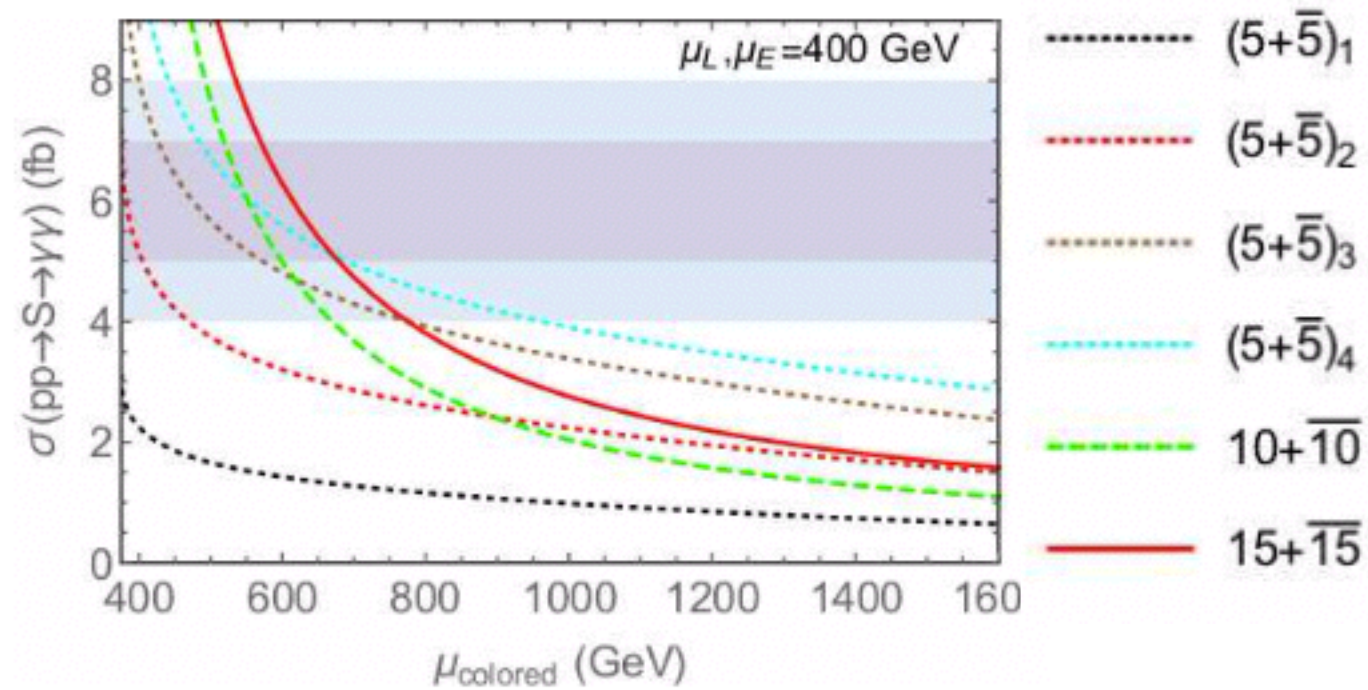
Unification

$$W_{eff} = W_{MSSM} + \frac{1}{2} m_\Phi \Phi^2 + \Phi \sum_i \lambda_i \psi \bar{\psi} + \mu_i \psi \bar{\psi}$$

Couplings have attractor solution



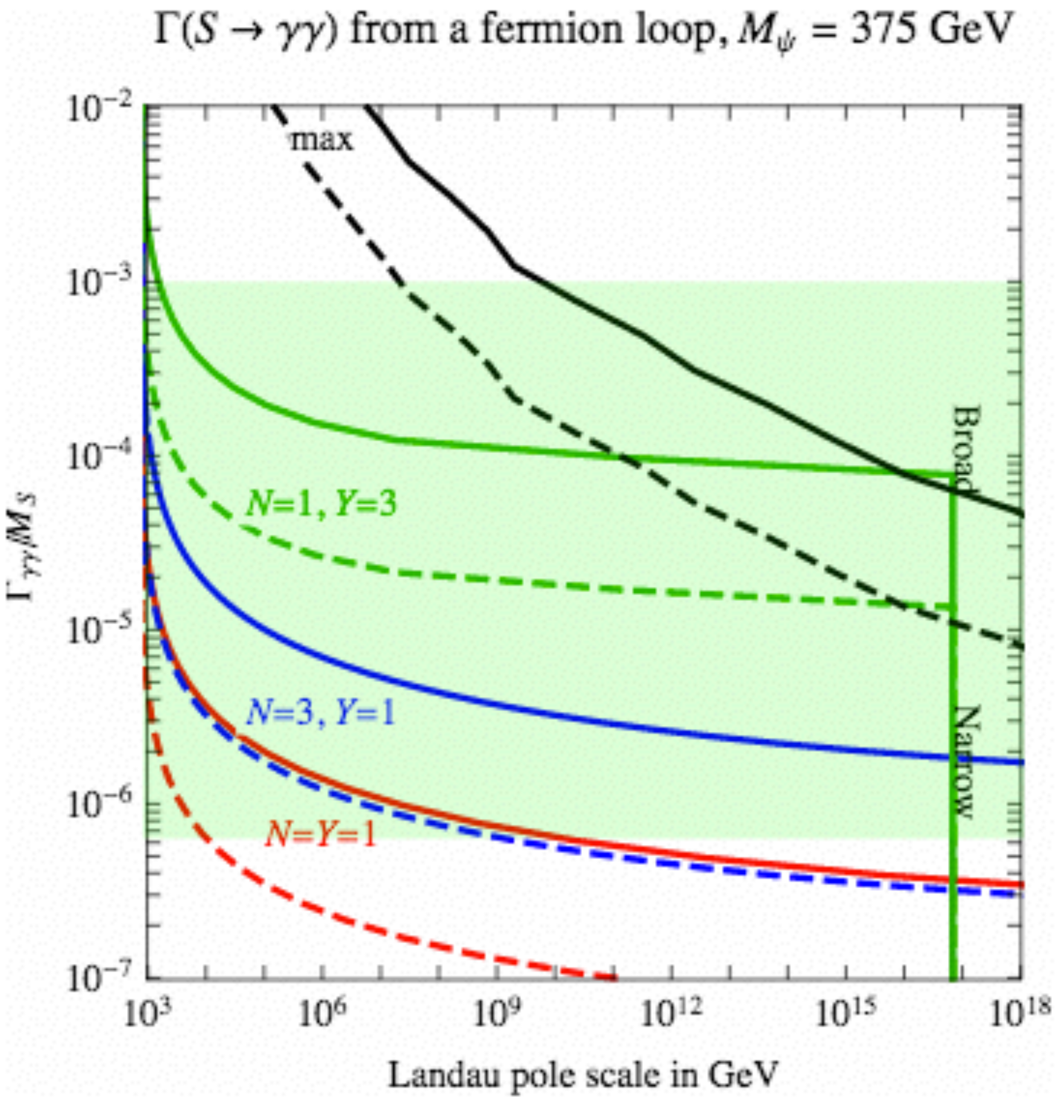
(similar for other representations)

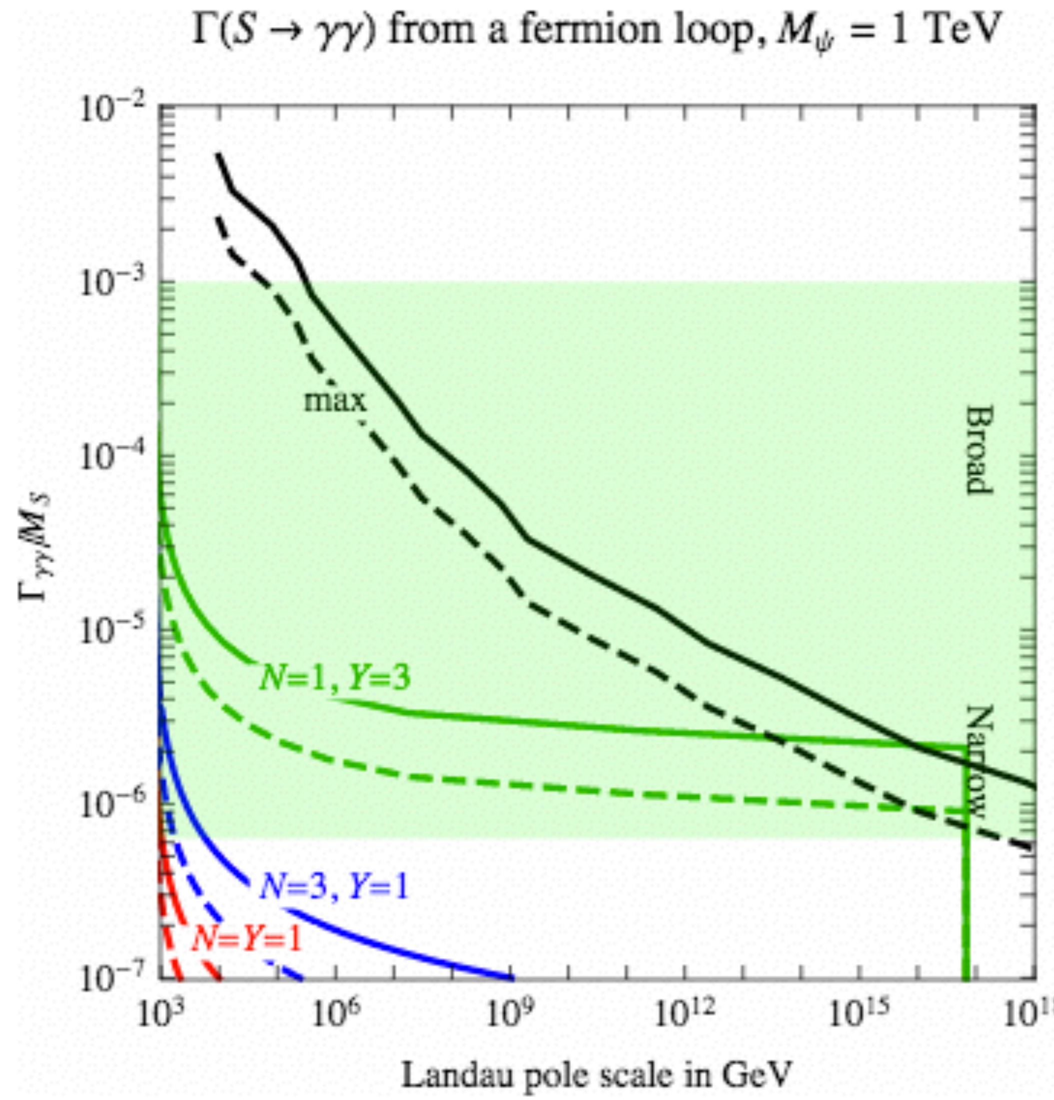


- Need vector-like leptons right above $m_\phi/2$
- Colored stuff below 1 TeV

L. Hall, K. Harigaya, Y. Nomura: 1512.07904

Landau poles





- - - scalar

—— pseudoscalar

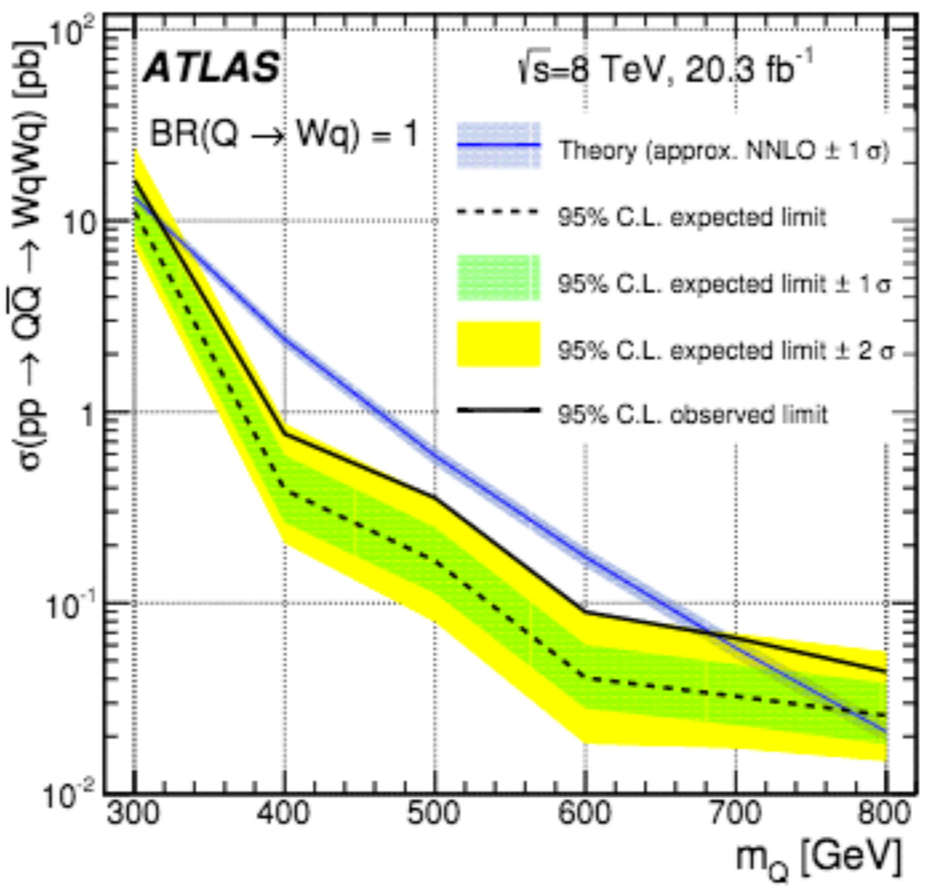
A. Salvio, F. Staub, A. Strumia, A. Urbano: 1602.01460
(see also: Z. Liu et. al. 1512.07624)

Messengers

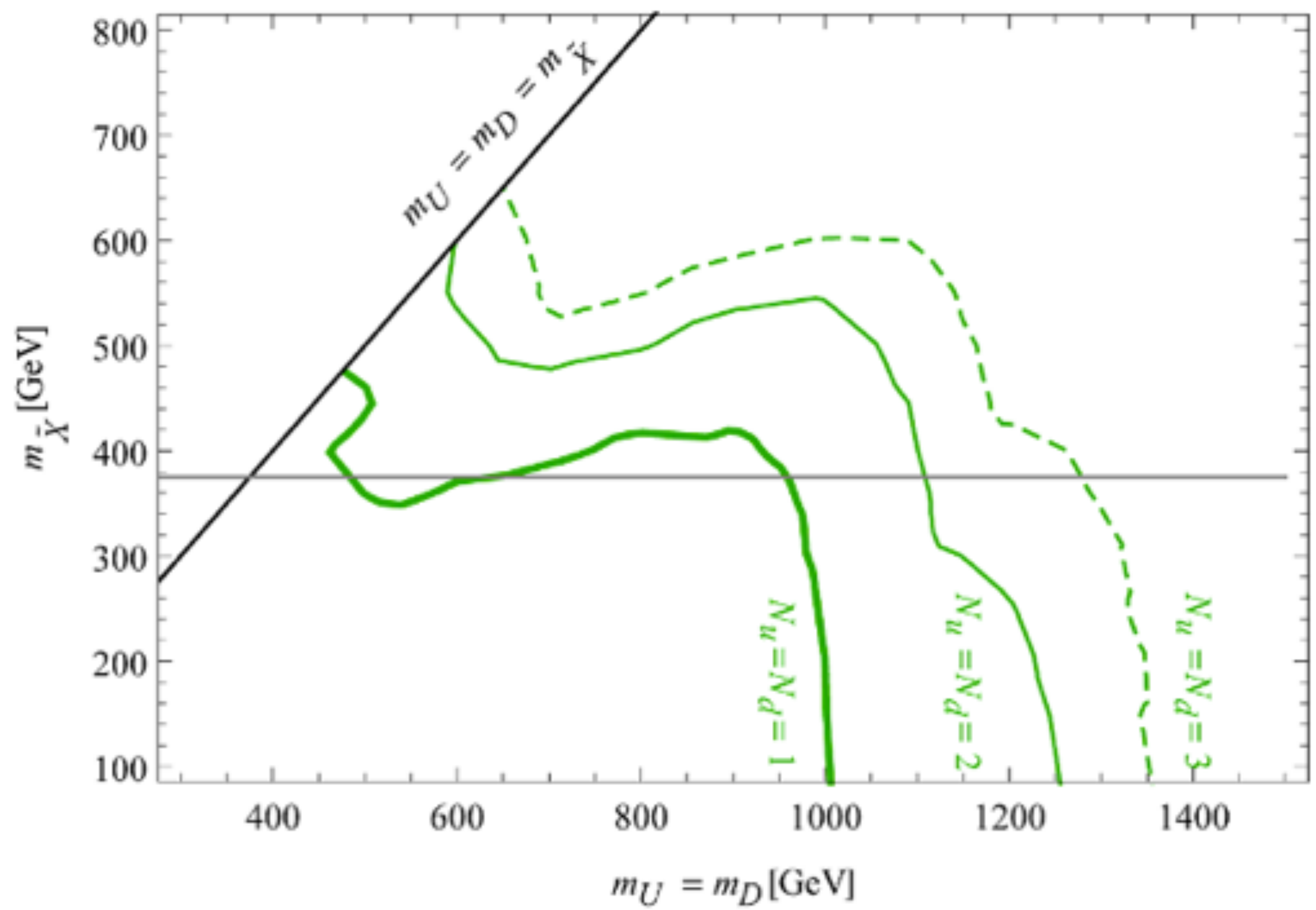
Collider constraints:

$$\psi \to q + W$$

$$\psi \to q + X \quad \text{(jets + MET)}$$



(limits for chiral quarks)

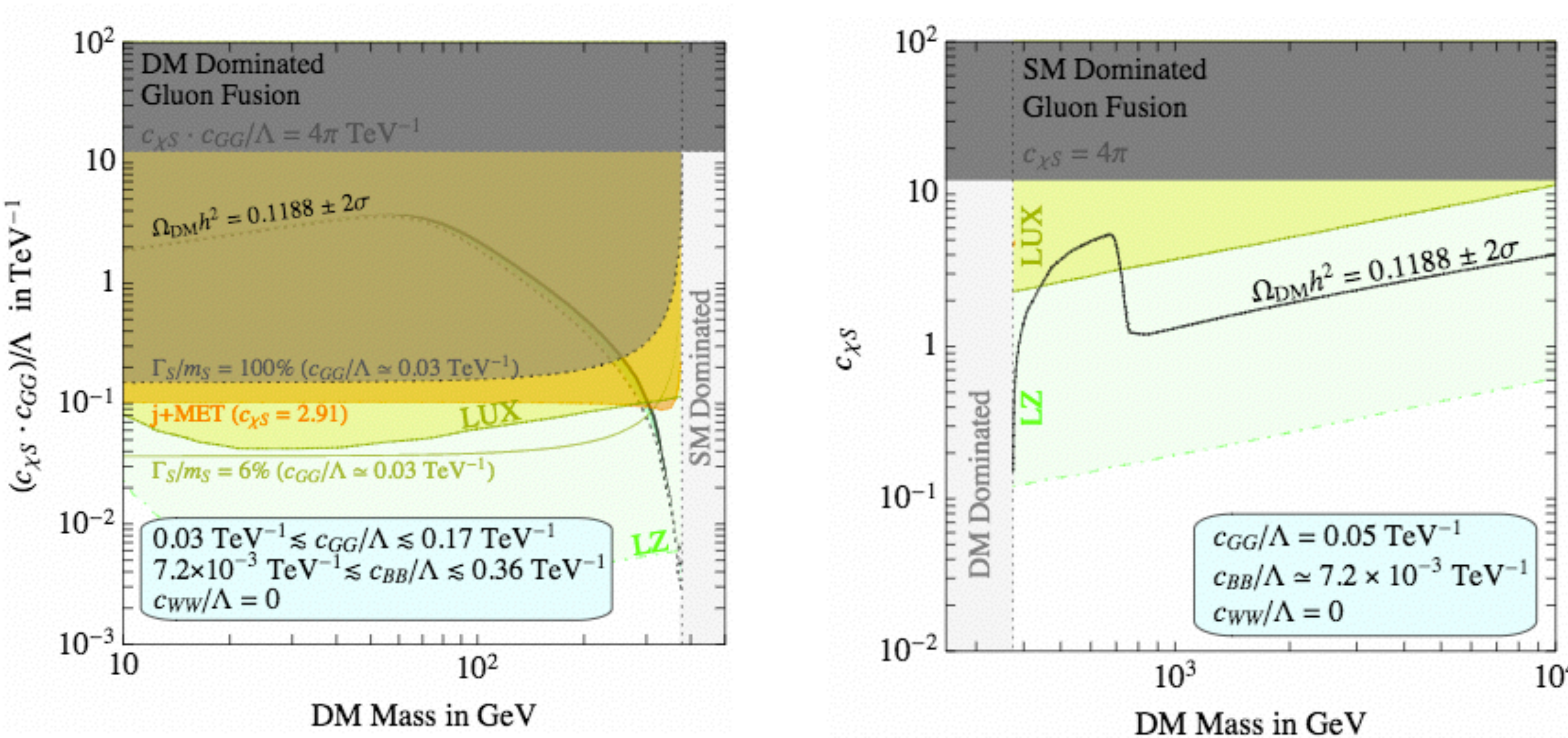


ATLAS: 1509.04261

J. Kawamura and Y. Omura:1601.07396

Dark Matter

New scalar could be responsible for DM freeze out:



If DM is lighter than 375 GeV, it can explain the large width of the resonance

F. D'Eramo, J. de Vries, P. Panci: 1601.01571
(see also M. Backovic, et.al. : 1512.04917 + many others)

2HDM

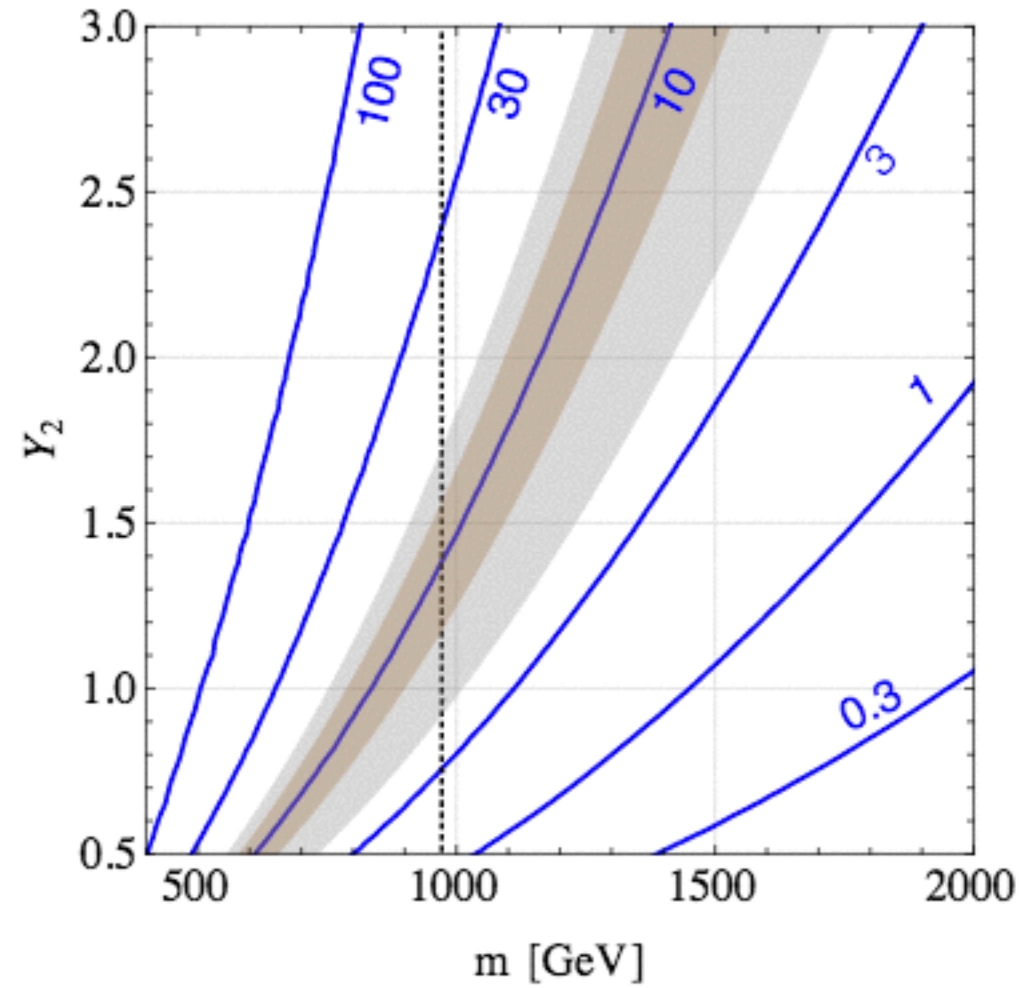
If ϕ is a doublet, the messengers must have chiral coupling:

$$\mathcal{L} \supset y\,\Phi\psi\chi + m\,\psi\bar{\psi} + m\,\chi\bar{\chi}$$

$$\longrightarrow \quad \frac{y^2}{m^2}\Phi\Phi^\dagger B^{\mu\nu}B_{\mu\nu} \quad \text{etc}$$

vanishes of ϕ has no vev!

6 flavor of triplets with Q=5/3



W. Altmannshofer, J. Galloway, S. Gori, A. Kagan, A. Martin, J. Zupan: 1512.07616

In general

If no mixing with Higgs

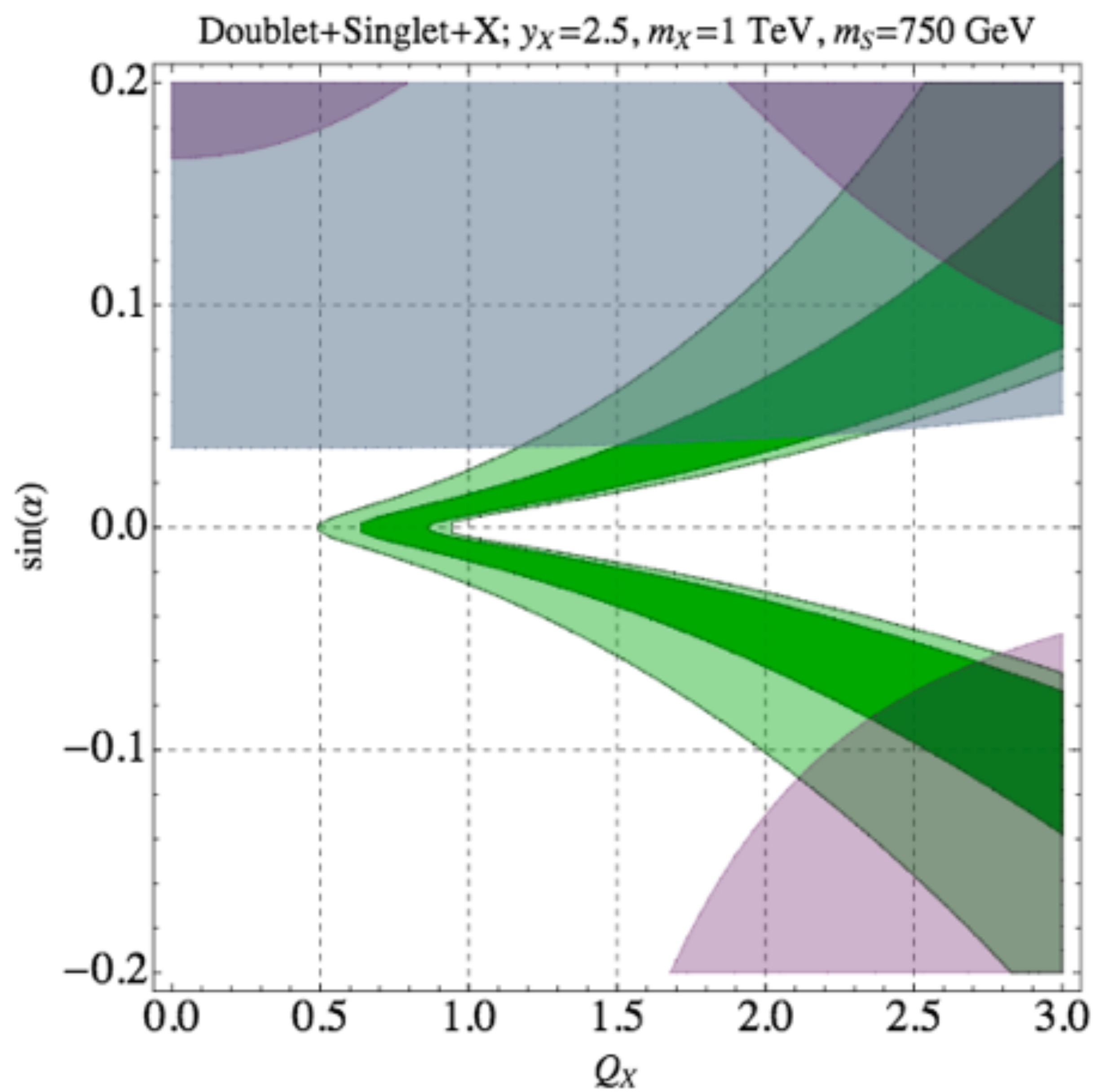
$$\frac{c_B}{\Lambda}\Phi B^{\mu\nu}B_{\mu\nu} + \frac{c_W}{\Lambda}\Phi W^{\mu\nu}W_{\mu\nu} + \frac{c_g}{\Lambda}\Phi G^{\mu\nu}G_{\mu\nu} \longrightarrow \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}}, \frac{\Gamma_{Z\gamma}}{\Gamma_{\gamma\gamma}}, \frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} \text{ and } \frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}}$$

Overconstrained system

If mixing with Higgs, longitudinal modes are enhanced:

$$\Gamma(\Phi \to W_L W_L) \sim \sin^2\alpha \frac{m_\Phi^3}{m_W^2}$$

in addition to decays to $t\bar{t}$ and hh.
(but with rather small branching ratio's)



N. Craig, P. Draper, C. Kilic, S. Thomas: 1512.07733
I. Low, J. Lykken: 1512.09089

A. Falkowski, O. Slone, T. Volansky: 1512.05777