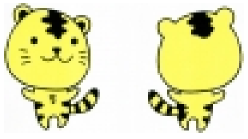
Composite Higgs and Yukawa coupling in walking gauge theories

--- LIO international conference on composite models, EW physics and the LHC ---

Michio Hashimoto (Chubu U.)

§1 Introduction



- Because the SM is almost perfectly consistent with the experiments, composite models have been severely constrained.

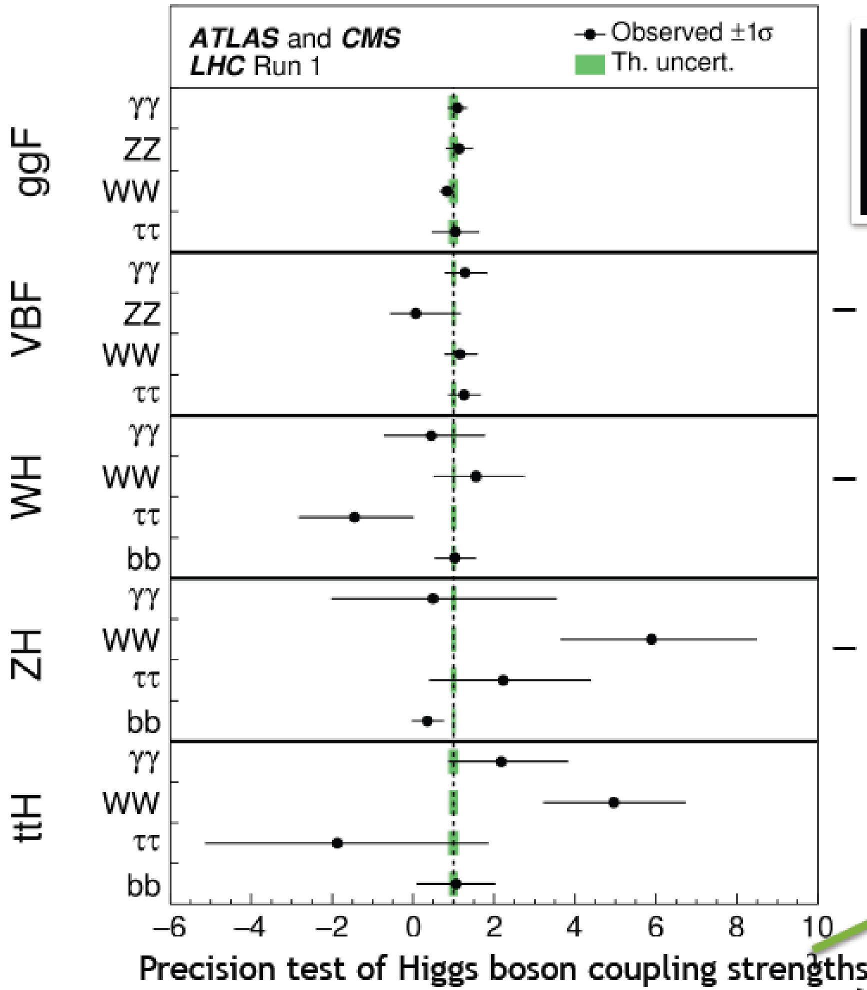
- However, it is still important problem whether or not the 125 GeV Higgs boson (h) is elementary (exact SM Higgs) or composite.

- Also, exotica searches, for example, W'/Z'/ ρ_T , H/A/$H^{\pm}$,VLF, etc. are still going on.

→ Unfortunately, no evidence of BSM is found yet…

ICHEP2016

Higgs Profile in Run 1



CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803
Rates and couplings: arXiv:1606.02266

- Mass has been measured to 0.2% precision m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Coupling strengths

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

ICHEP2016

Higgs→γγ

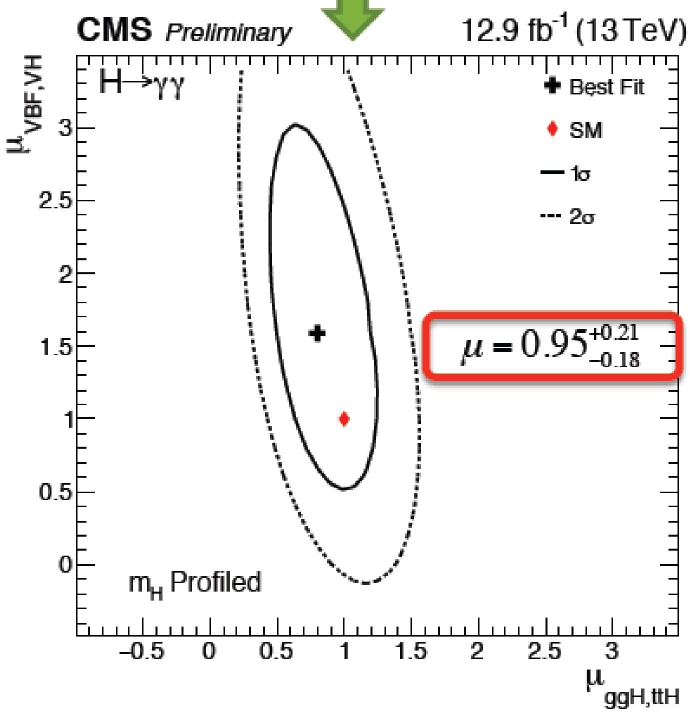
ATLAS -CONF-2016-067

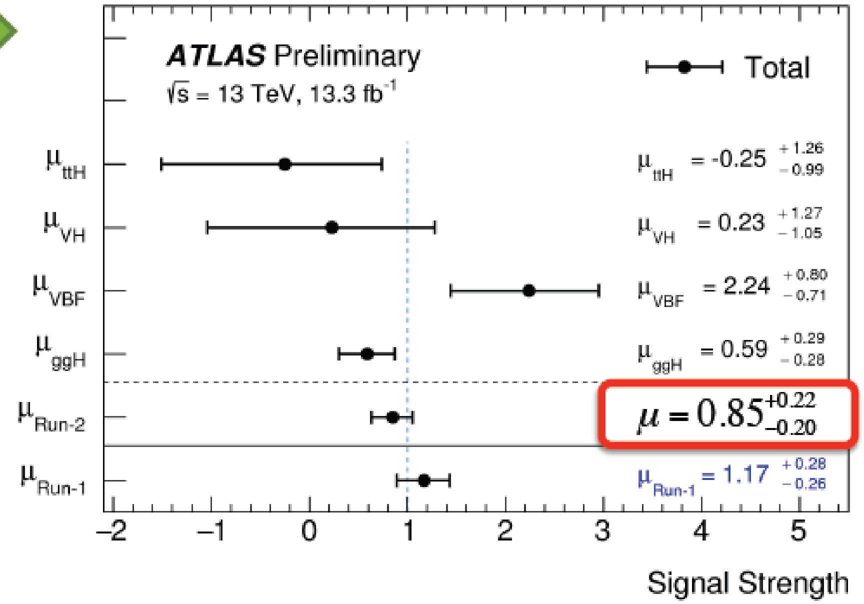
CMS-PAS-HIG-16-020

Production cross section and signal strength

- Events are split into orthogonal categories that exploit topological differences between production mechanisms

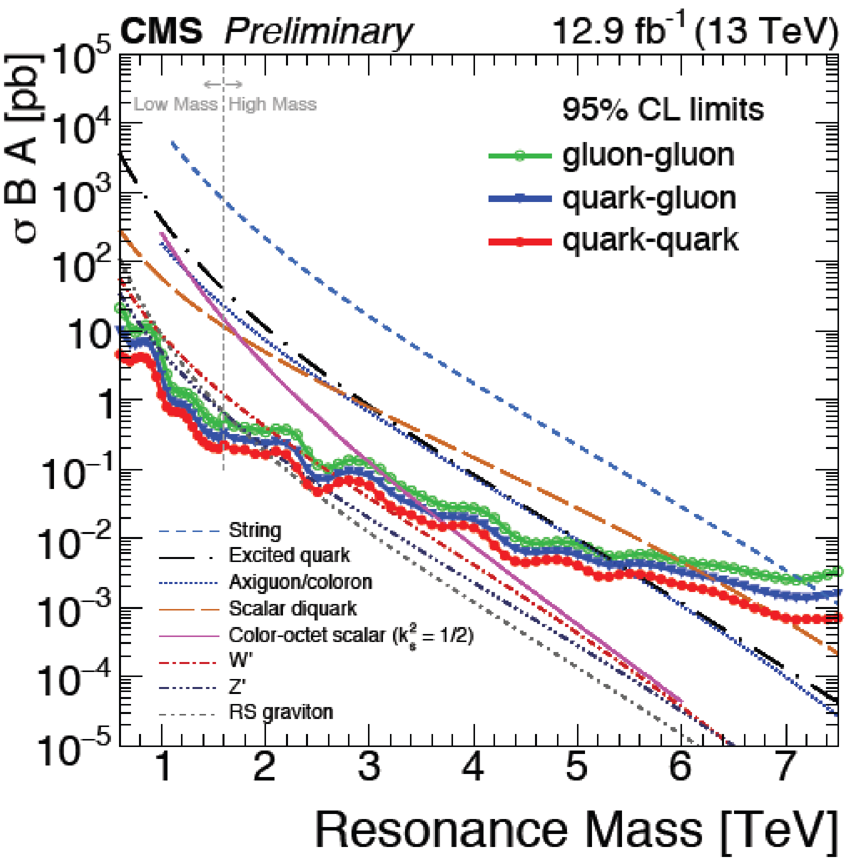
Extract strength of production processes in a 2-parameter fit





- Achieved similar precision to Run 1
- Measurements compatible with SM
- Results still dominated by statistical uncertainty

Dijet resonance search

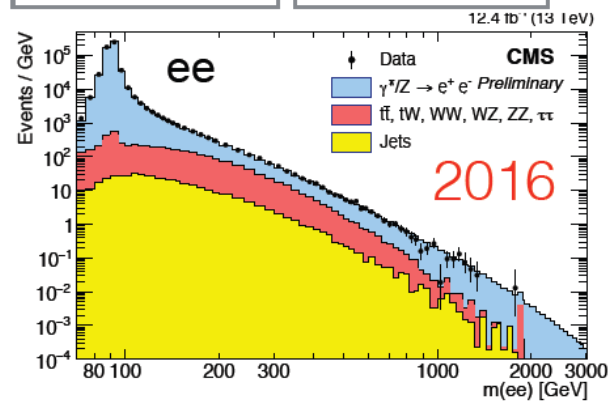


Hsu, "Exotica searches" at ICHEP2016

Dilepton resonance search

Same Flavor Opposite Sign (ee, μμ, ττ)

ATLAS-CONF-2016-045 CMS-PAS-EXO-16-031



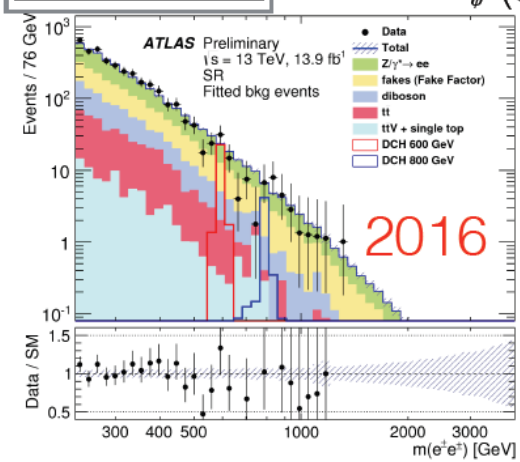
Z'_{SSM}(3% width) >4 TeV

Z'_{ψ} (0.5% width) >3.36 TeV

95% CL exclusion limit

Same Sign (ee, μμ)

ATLAS-CONF-2016-051



$H_R^{\pm\pm}$ >420 GeV

$H_L^{\pm\pm}$ >570 GeV

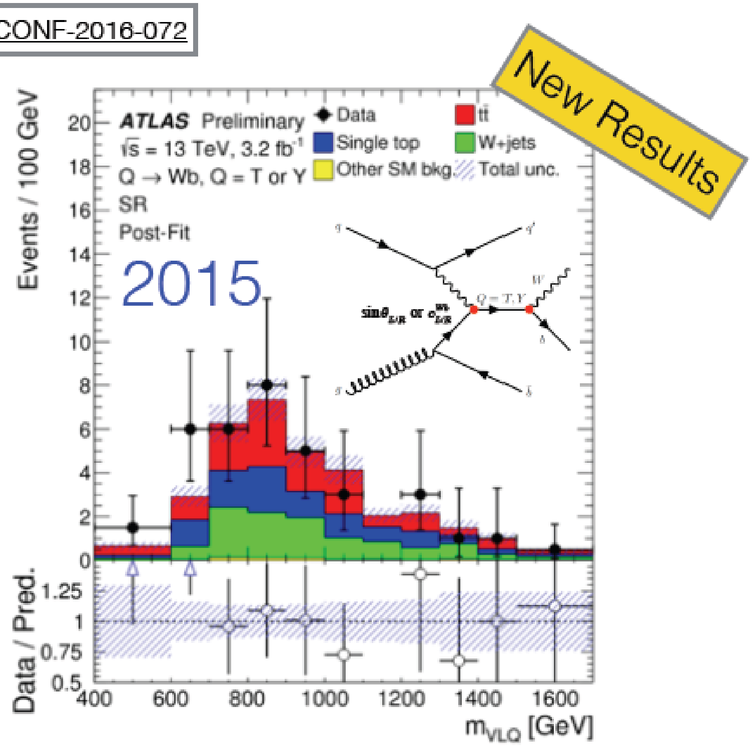
Vector-Like Quark

Georges Azuelos's talk
Anthony Barke's poster
Julie Hogan's tal

VLQ - Spin 1/2, colored, charged particles with both left- and right-handed coupling to charged currents.

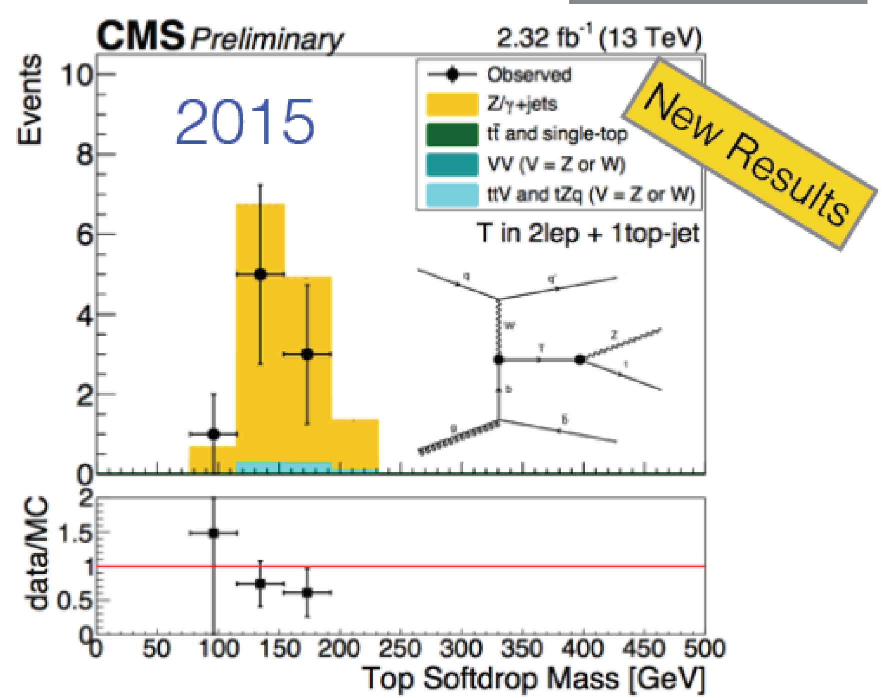
- **pair production** through QCD - dominant in low mass
  Most channels have been updated with 2015 data
- **single production** through EWK coupling - dominant in high mass (model dependent)
  New results shown below.

ATLAS-CONF-2016-072



m(T/Y, $\sqrt{c_L^2 + c_R^2} = 1/\sqrt{2}$) >1.44 TeV

CMS-PAS-B2G-16-001



mT(C(bW)=1, BR(tZ)=0.25) >1.37 TeV

- **Once some excesses are reported by experiments, many authors propose composite models matched with the data.**

Japanese NEBUTA festival in Aomori prefecture (2 mill. in 1 week!)


After the festival...

In any case,

Diboson excesses   X → WW/ZZ/WZ

2015 June   Mx=2TeV

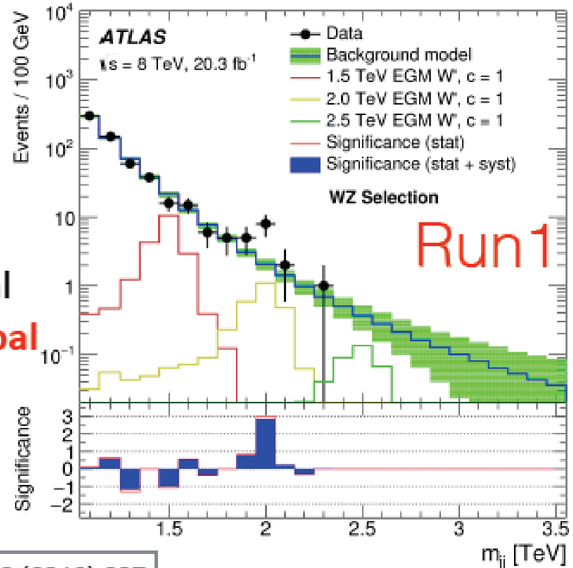
Diphoton excesses   X → 2 gamma

2015 December   Mx=750GeV

⇒ What is lesson?

ICHEP2016 Revisit diboson excesses in Run1

JHEP12(2015)055

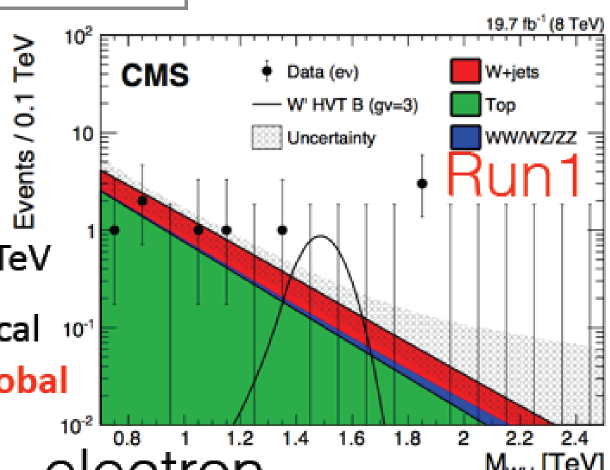


m= 2TeV

3.4σ local

2.5σ global

EPJC 76 (2016) 237



m=1.8 TeV

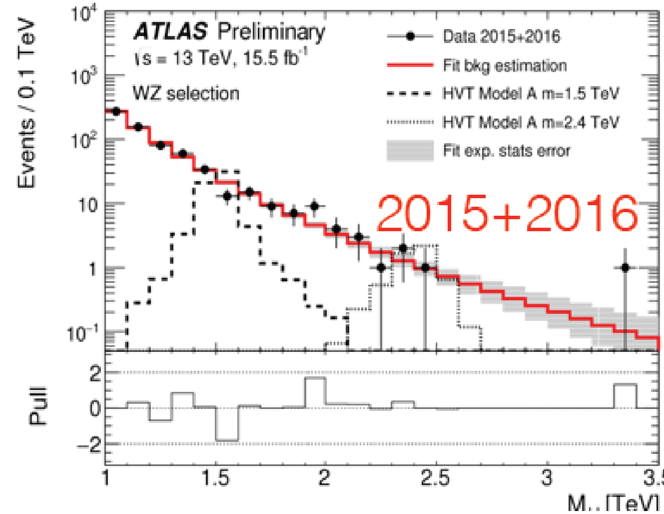
2.9σ local

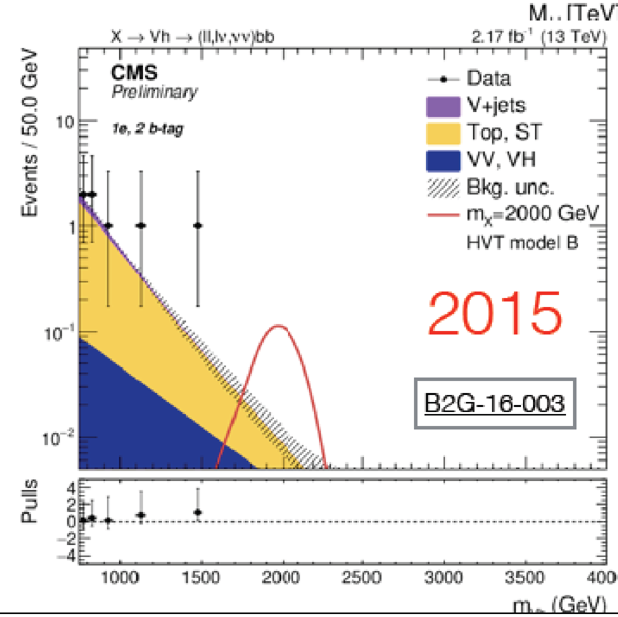
1.9σ global

electron

Excesses not confirmed in Run2

ATL-CONF-2016-055





B2G-16-003

It was a *good exercise*

for theory (model-building) people!

1. **Unitarity-controlled resonances after the Higgs boson discovery**
   Christoph Englert (Glasgow U.), Philip Harris (CERN), Michael Spannowsky (Durham U., IPPP), Michihisa Takeuchi (Tokyo U., IPMU). Mar 25, 2015. 9 pp.
   Published in **Phys.Rev. D92 (2015) 1, 013003**
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2. **2 TeV Walking Technirho at LHC?**
   Hidenori S. Fukano (KMI, Nagoya), Masafumi Kurachi (KEK, Tsukuba), Shinya Matsuzaki (Nagoya U.), Koji Terashi (Tokyo U. & Tokyo U., ICEPP), Koichi Yamawaki (KMI, Nagoya). J
   2015. 9 pp.
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   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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3. **Interpretations of the ATLAS Diboson Resonances**
   Junji Hisano (KMI, Nagoya & Nagoya U. & Tokyo U., IPMU), Natsumi Nagata (Tokyo U., I
   IPMU15-0083, FTPI-MINN-15-31
   e-Print: **arXiv:1506.03931 [hep-ph]** | PDF
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4. **Diboson Signals via Fermi Scale Spin-One States**
   Diogo Buarque Franzosi, Mads T. Frandsen, Francesco Sannino (Southern Denmark U.
   CP3-ORIGINS-2015-023-DNRF90, DIAS-2015-23
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   ADS Abstract Service
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5. **Interpretations of the ATLAS Diboson Anomaly**
   Kingman Cheung (Konkuk U. & NCTS, Hsinchu & Taiwan, Natl. Tsing Hua U.), Wai-Yee K
   Tzu-Chiang Yuan (NCTS, Hsinchu & Taiwan, Inst. Phys.). Jun 19, 2015. 17 pp.
   e-Print: **arXiv:1506.06064 [hep-ph]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service

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11. **A composite Heavy Vector Triplet in the ATLAS di-boson excess**
    Andrea Thamm (U. Mainz, PRISMA & Mainz U.), Riccardo Torre, Andrea Wulzer (INFN, Padua & Padua U.). Jun 29, 2015. 6 pp.
    DFPD-2015-TH-16, MITP-15-044
    e-Print: **arXiv:1506.08688 [hep-ph]** | PDF
    References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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12. **Symmetry Restored in Dibosons at the LHC?**
    Johann Brehmer (Heidelberg U.), JoAn
    MITP-15-046-SLAC-PUB-16319-TKK-
    e-Print: **arXiv:1507.00013 [hep-ph]** | I
    References | BibTeX | LaTeX(US
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    Qing-Hong Cao (Peking U. & Peking U
    e-Print: **arXiv:1507.00268 [hep-ph]** | I
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14. **Unitarity implications of dibc**
    Giacomo Cacciapaglia (Lyon U. & Lyor
    e-Print: **arXiv:1507.00900 [hep-ph]** | I
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15. **Unitarity sum rules, three sit**
    Tomohiro Abe (KEK, Tsukuba), Ryo Na
    KEK-TH-1844
    e-Print: **arXiv:1507.01185 [hep-ph]** | I
    References | BibTeX | LaTeX(US
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16. **Minimal Left-Right Dark Matter**
    Julian Heeck (Brussels U.), Sudhanwa Patra (Heidelberg, Max Planck Inst. & Siksha O Anusandhan U., Bhubaneswar). Jul 6, 2015. 6 pp.
    ULB-TH-15-10
    e-Print: **arXiv:1507.01584 [hep-ph]** | PDF
    References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
    ADS Abstract Service
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17. **Prospects for Spin-1 Resonance Search at 13 TeV LHC and the ATLAS Diboson Excess**
    Tomohiro Abe, Teppei Kitahara (KEK, Tsukuba), Mihoko M. Nojiri (KEK, Tsukuba & Tsukuba, Graduate U. Adv. Studies & Tokyo U., IPMU). Jul 7, 2015. 37 pp.
    KEK-TH-1843, IPMU-15-0101
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18. **Diboson resonant production in non-custodial composite Higgs models**
    Adrian Carmona (Zurich, ETH), Antonio Delgado (Notre Dame U & CERN), Mariano Quiros (Barcelona, IFAE & ICREA, Barcelona), Jose Santiago (CAFPE, Granada & Granada U., Theor. Phys. Astrophys.). Jul 7, 2015. 15 pp.
    CERN-PH-TH-2015-154
    e-Print: **arXiv:1507.01914 [hep-ph]** | PDF
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19. **Anatomy of the ATLAS diboson anomaly**
    B.C. Allanach (Cambridge U., DAMTP), Ben Gripaios, Dave Sutherland (Cambridge U.). Jul 6, 2015. 9 pp.
    DAMTP-2015-32, CAVENDISH-HEP-15-05
    e-Print: **arXiv:1507.01638 [hep-ph]** | PDF
    References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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20. **Heavy Higgs bosons and the 2 TeV W' boson**
    Bogdan A. Dobrescu (Fermilab), Zhen Liu (Fermilab & Pittsburgh U.). Jul 7, 2015. 21 pp.
    FERMILAB-PUB-15-286-T, PITT-PACC-1510
    e-Print: arXiv:1507.01923 [hep-ph] | PDF
    References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
    ADS Abstract Service
    レコードの詳細 - Cited by 10 records

We pointed out a possibility of a pseudoscalar candidate.

Aldo, Giaccomo, MH, PRL115, 171802 (2015).

At that time, many authors studied spin 1 candidate such as Z' and W', and nobody considered spin 0 particle. I think there were two reasons:

- smallness of the cross section

$$\sigma \sim O(0.1\text{fb}) \text{ -- } O(1\text{fb})$$

- No WW/ZZ decay channels for a pseudoscalar in popular dynamical models

(The diphoton channel was CONSTRAINT in this case…)

No WW/ZZ decay channels in popular dynamical models

(pseudo-scalar candidate)

TC models	PNGB and content		v/F_P	A_{gg}	$A_{\gamma\gamma}$	λ_l	λ_f
FS one family[38]	P^1	$\frac{1}{4\sqrt{3}}(3\bar{L}\gamma_5 L - \bar{Q}\gamma_5 Q)$	2	$-\frac{1}{\sqrt{3}}$	$\frac{4}{3\sqrt{3}}$	1	1
Variant one family[35]	P^0	$\frac{1}{2\sqrt{6}}(3\bar{E}\gamma_5 E - \bar{D}\gamma_5 D)$	1	$-\frac{1}{\sqrt{6}}$	$\frac{16}{3\sqrt{6}}$	$\sqrt{6}$	$\sqrt{\frac{2}{3}}$
LR multiscale[39]	P^0	$\frac{1}{6\sqrt{2}}(\bar{L}_\ell\gamma_5 L_\ell - 2\bar{Q}\gamma_5 Q)$	4	$-\frac{2\sqrt{2}}{3}$	$\frac{8\sqrt{2}}{9}$	1	1
TCSM low scale[40]	$\pi_T^{0'}$	$\frac{1}{4\sqrt{3}}(3\bar{L}\gamma_5 L - \bar{Q}\gamma_5 Q)$	$\sqrt{N_D}$	$-\frac{1}{\sqrt{3}}$	$\frac{100}{27\sqrt{3}}$	1	1
MR Isotriplet [31]	P^1	$\frac{1}{6\sqrt{2}}(3\bar{L}\gamma_5 L - \bar{Q}\gamma_5 Q)$	4	$-\frac{1}{\sqrt{2}}$	$24\sqrt{2}y^2$	1	1

The amplitude is $N_{TC}\mathcal{A}_{V_1V_2}\frac{g_1g_2}{8\pi^2F_P}\epsilon_{\mu\nu\lambda\sigma}\varepsilon_1^\lambda\varepsilon_2^\sigma k_1^\mu k_2^\nu$

No WW coupling and negligibly small ZZ channel

R. S. Chivukula, P. Ittisamai, E. H. Simmons and J. Ren, Phys. Rev. D **84**, 115025 (2011) [Phys. Rev. D **85**, 119903 (2012)] [arXiv:1110.3688 [hep-ph]].

- We proposed a vector-like confinement model.

- In this case, we can easily evade the constraints from the precision measurements unlike Technicolor models. Thus we can focus our mind on the new data.

- small cross section ⟹ Internal degrees of freedom

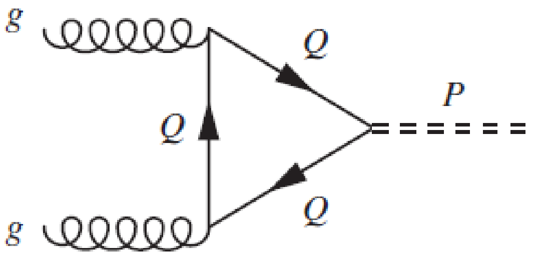
  Nc=3 is essential in $\pi^0 \to \gamma\gamma$

- WW/ZZ couplings ⟹ New type of model-building

Dynamical model (just an example)

Aldo, Giaccomo, MH.
PRL115, 171802 (2015).

	$SU(N)$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$Q_L = (Q_1, Q_2)_L$	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{2}$	0
$Q_R = (Q_1, Q_2)_R$	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{2}$	0
$L_L = (L_1, L_2)_L$	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	0
$L_R = (L_1, L_2)_R$	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	0
N_L	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0
N_R	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0



vector-like model under the new strong dynamics $SU(N)$

The broken current corresponding to $\eta_{\rm WZ}$ is

$$J_5^\mu \sim \bar{Q}\gamma^\mu\gamma_5 Q + \bar{L}\gamma^\mu\gamma_5 L - (N_f - 1)\bar{N}\gamma^\mu\gamma_5 N.$$

WZW term (anomalous int.)

$$\mathcal{L}_{\eta gg} = \kappa_g^\eta \frac{g_3^2}{32\pi^2} \frac{\eta_{\rm WZ}}{F_\eta} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma},$$

$$\mathcal{L}_{\eta WW} = \kappa_W^\eta \frac{g_2^2}{32\pi^2} \frac{\eta_{\rm WZ}}{F_\eta} \epsilon^{\mu\nu\rho\sigma} W^i_{\mu\nu} W^i_{\rho\sigma},$$

$$\mathcal{L}_{\eta BB} = \kappa_B^\eta \frac{g_Y^2}{32\pi^2} \frac{\eta_{\rm WZ}}{F_\eta} \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma},$$

$$\kappa_g^\eta = \frac{1}{2} N(N-1) \cdot 2n_Q, \qquad \kappa_W^\eta = \frac{1}{2} N(N-1) \cdot (N_c n_Q + n_L)$$

$$\kappa_B^\eta = \kappa_{WB}^\eta = 0$$

(For scalar, the NDA contains large uncertainties unlike the WZW term.)

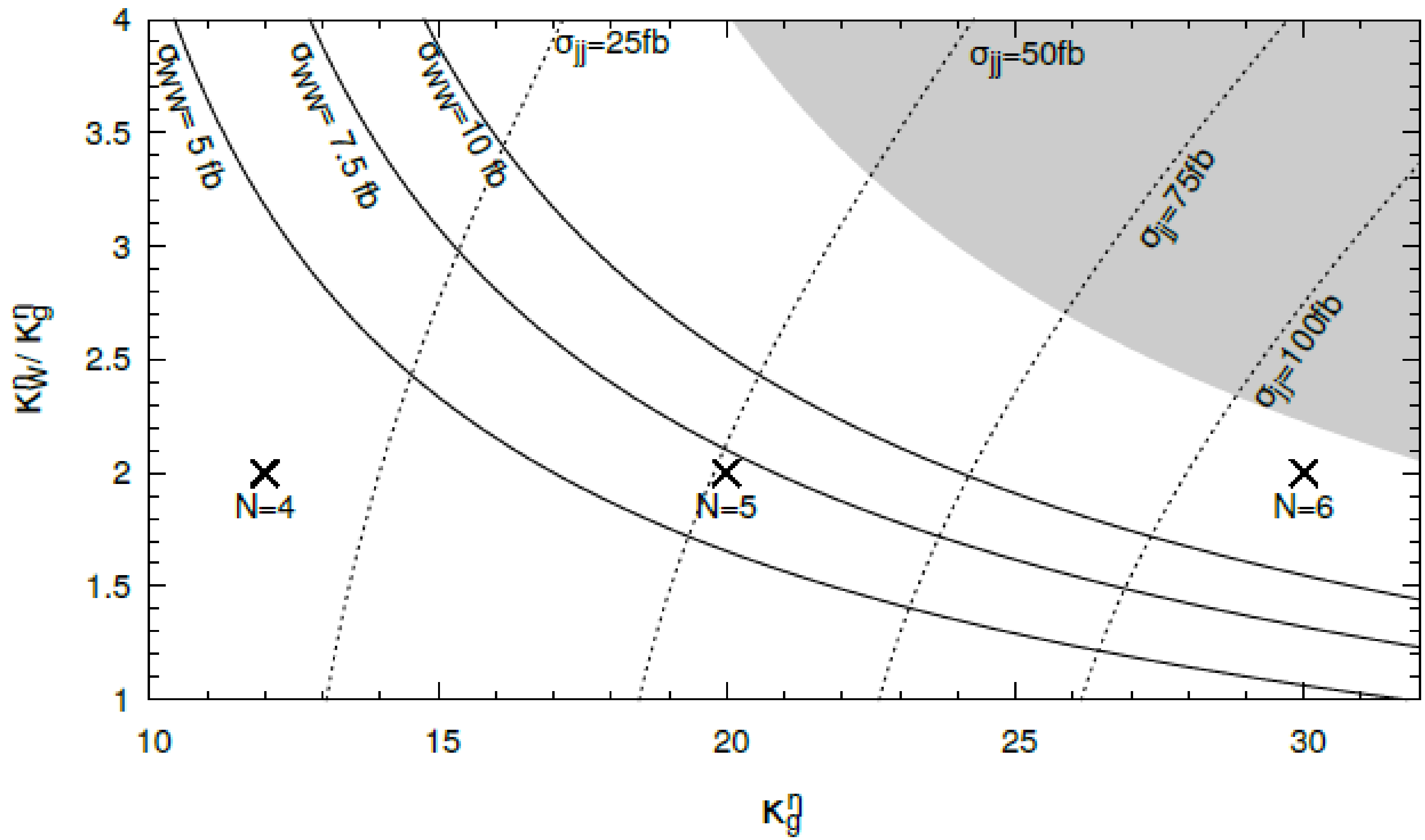


FIG. 1: Cross section times branching ratios on the κ_g^η–$\kappa_W^\eta/\kappa_g^\eta$ plane for $F_\eta = 500$ GeV and $\kappa_B^\eta = 0$. The shaded region in the right upper area is excluded owing to $\sigma(gg \to \eta_{\rm WZ}) \cdot {\rm Br}(\eta_{\rm WZ} \to \gamma\gamma) >$ 0.5fb. The numbers $N = 4, 5, 6$ represent the corresponding values for the vector-like model with $n_Q = n_L = 1$.

- We provided a toolkit for model-building based on the DSB.

→ Mx: input value at the excess

→ κ_V, F_X : fitting parameters to the new data

→ If there is an appropriate parameter space, the matter contents and number of color in the fundamental theory should be chosen appropriately.

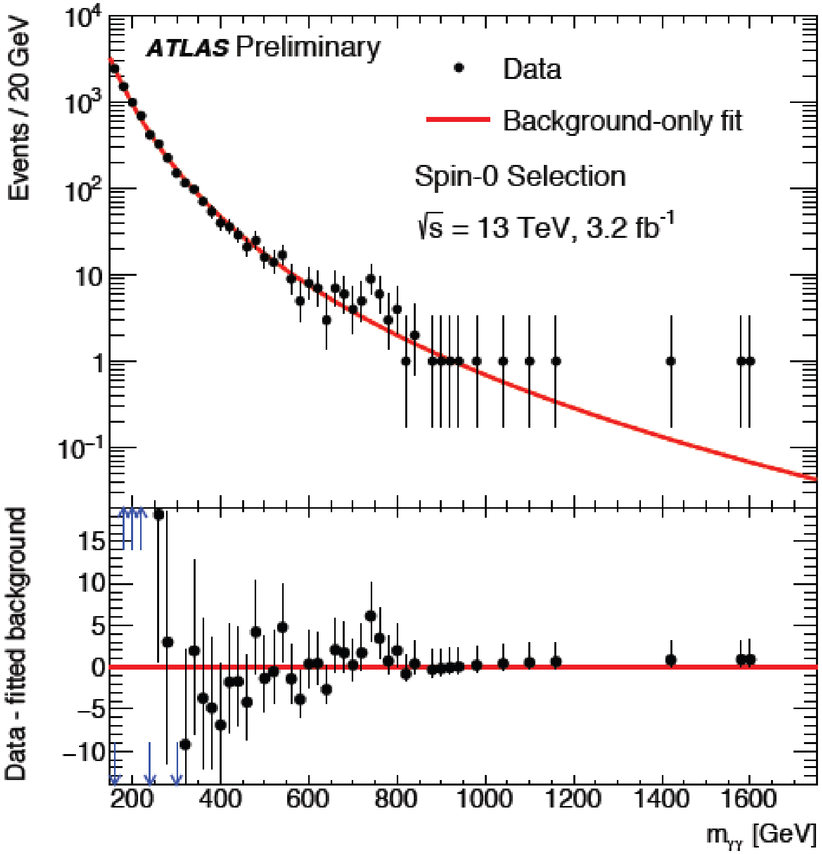
→ The width by the anomaly terms is usually narrow.

Diphoton status @ Moriond, 2016 March

Results

SPIN-0 ANALYSIS

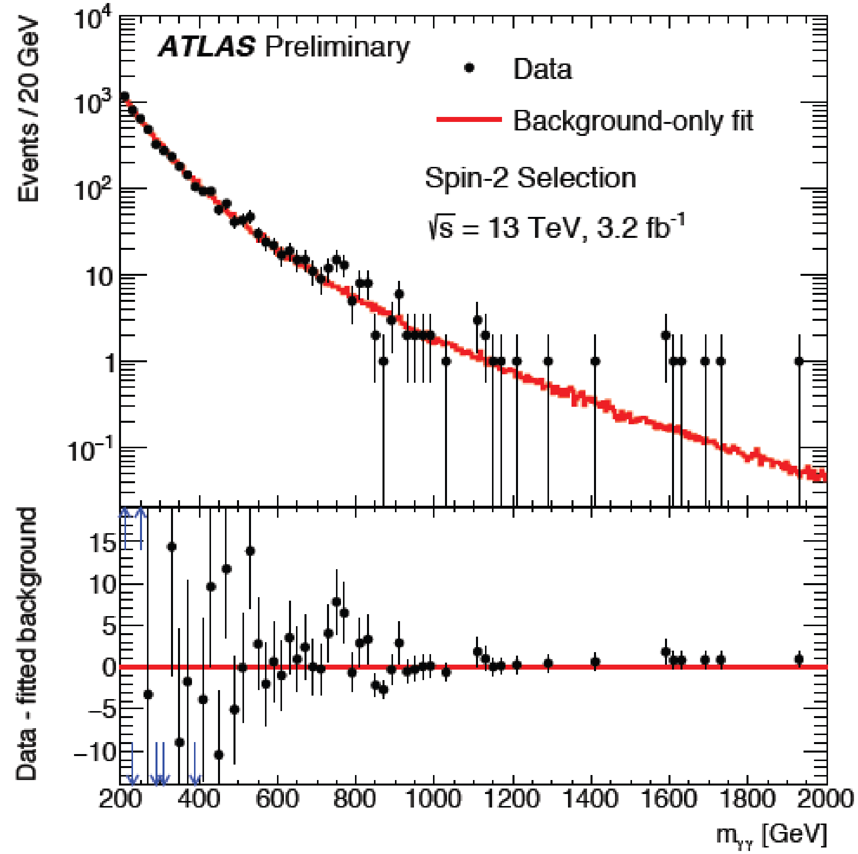
background-only fit



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

SPIN-2 ANALYSIS

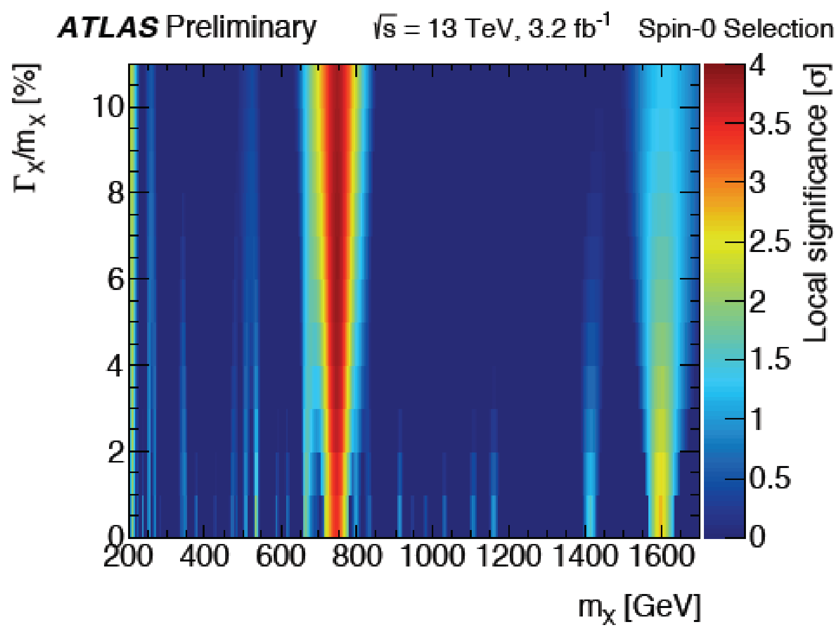
background-only fit



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

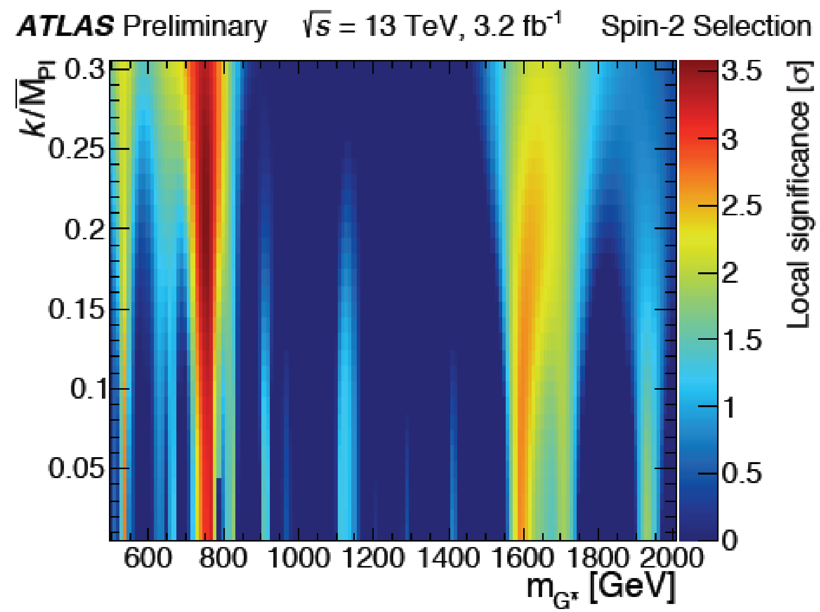
Results

SPIN-0 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

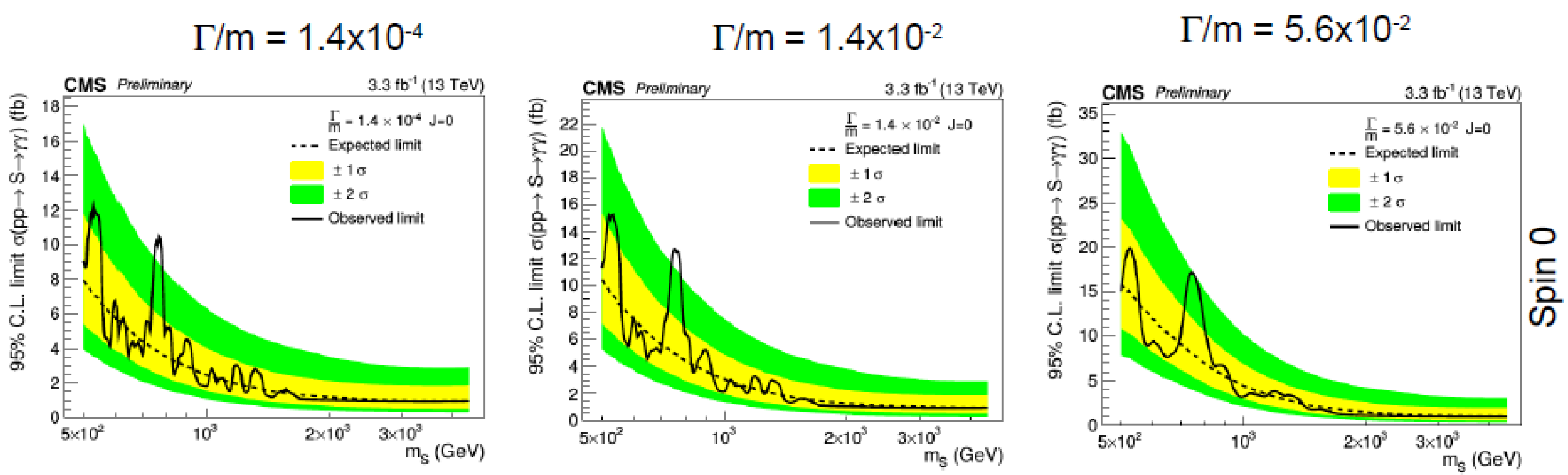
SPIN-2 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ m_G ~ 750 GeV, κ/M_{Pl} ~ 0.2 (Γ_G ~ 6% m_G)
  - ✓ Local Z = **3.6 σ**
  - ✓ Global Z = **1.8 σ**
    - m_X = [500 GeV – 3.5 TeV]
    - κ/M_{Pl} = [0.01 – 0.3]

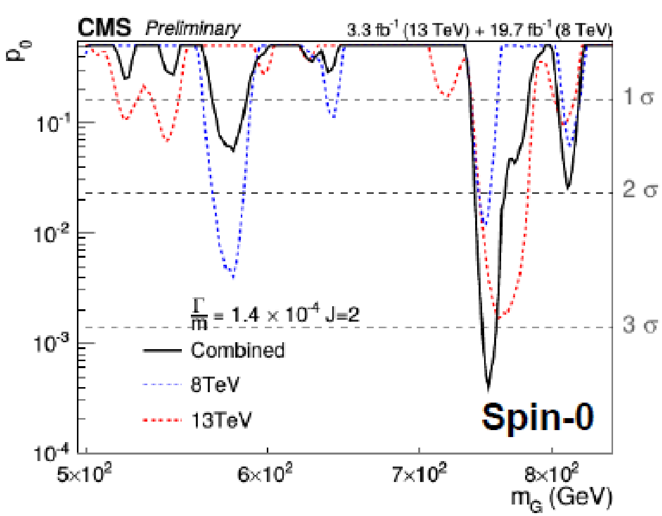
Upper limits

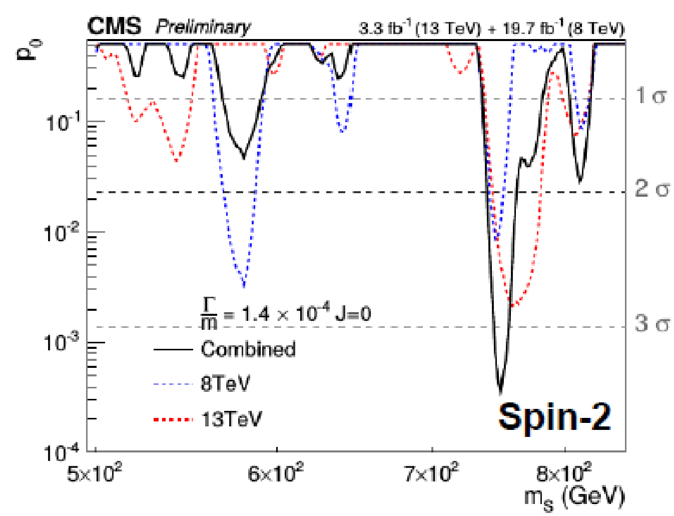
- Shown here for the spin-0 hypotheses
  - Spin-2 version gives equivalent message (and it's available in backup)



p-values

- Largest excess observed at $\mathbf{m_x}$ **= 750GeV** and for **narrow** width.
  - **Local** significance: **3.4σ**
  - Taking into account mass range 500-3500GeV (and all signal hypotheses), “**global**” significance becomes **1.6σ**





Composite Models for the 750 GeV Diphoton Excess

arXiv: 1512.04850

Keisuke Harigaya and Yasunori Nomura

HIDDEN PION: MINIMAL MODEL

	G_H	$SU(3)_C$	$U(1)_Y$	$U(1)_A$
Q_1	$\square$	$\bar{\square}$	a	$1/3$
Q_2	$\square$	$\mathbf{1}$	b	-1
$\bar{Q}_1$	$\bar{\square}$	$\square$	$-a$	$1/3$
$\bar{Q}_2$	$\bar{\square}$	$\mathbf{1}$	$-b$	-1

$$\mathcal{L} = -\frac{N g_3^2}{32\sqrt{6}\pi^2 f}\phi G^{a\mu\nu}\tilde{G}^a_{\mu\nu} - \frac{9(a^2-b^2)N g_1^2}{80\sqrt{6}\pi^2 f}\phi B^{\mu\nu}\tilde{B}_{\mu\nu},$$

$$\sigma_{pp\to\phi}B_{\phi\to\gamma\gamma} \simeq 8.9\ \text{fb}\left(\frac{N(a^2-b^2)}{5}\,\frac{600\ \text{GeV}}{f}\right)^2$$

Footprints of New Strong Dynamics via Anomaly

Yuichiro Nakai[1], Ryosuke Sato[2,3] and Kohsaku Tobioka[2,3,4]

arXiv: 1512.0492

They studied a vector-like confinement model:

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(N)$
ψ	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$\mathbf{N}$
χ	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{N}$
$\bar{\psi}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\bar{\mathbf{N}}$
$\bar{\chi}$	$\mathbf{1}$	$\mathbf{1}$	-1	$\bar{\mathbf{N}}$

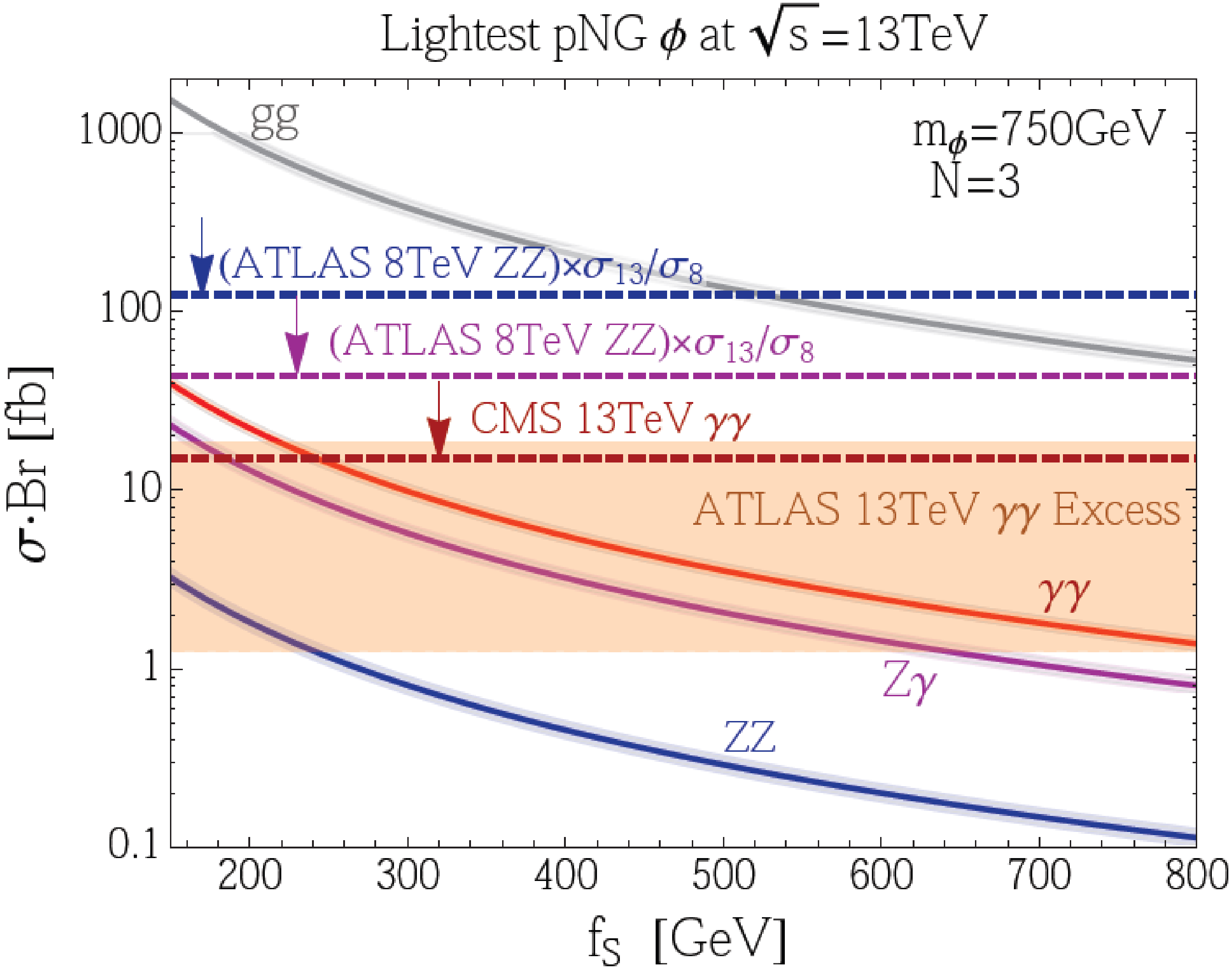
$$\sigma(pp \to \phi + X)\mathrm{Br}(\phi \to gg)$$

$$\simeq \left(\frac{N}{3}\right)^2 \left(\frac{f_S}{400\ \mathrm{GeV}}\right)^{-2} \times \begin{cases} 56\ \mathrm{fb} & (\sqrt{s} = 8\ \mathrm{TeV}) \\ 220\ \mathrm{fb} & (\sqrt{s} = 13\ \mathrm{TeV}) \end{cases}$$

$$\Gamma(gg) : \Gamma(\gamma\gamma) : \Gamma(\gamma Z) : \Gamma(ZZ)$$
$$\simeq 0.965 : 0.021 : 0.012 : 0.002\,.$$

$$\sigma(pp \to \phi + X)\mathrm{Br}(\phi \to \gamma\gamma)$$

$$\simeq \left(\frac{N}{3}\right)^2 \left(\frac{f_S}{400\ \mathrm{GeV}}\right)^{-2} \times \begin{cases} 1.2\ \mathrm{fb} & (\sqrt{s} = 8\ \mathrm{TeV}) \\ 5.8\ \mathrm{fb} & (\sqrt{s} = 13\ \mathrm{TeV}) \end{cases}$$

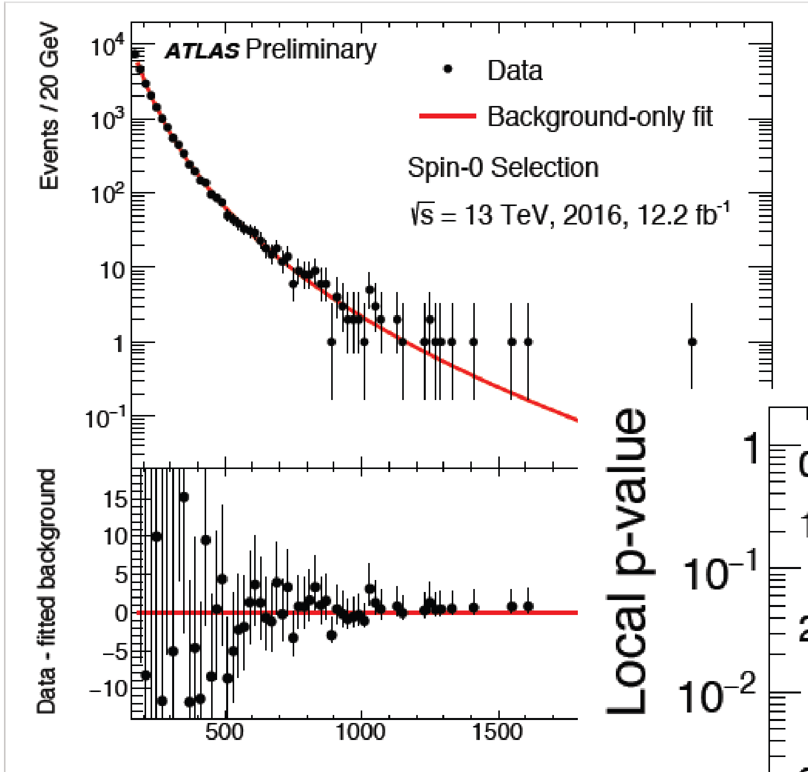


$\Gamma \sim 0.04$ GeV

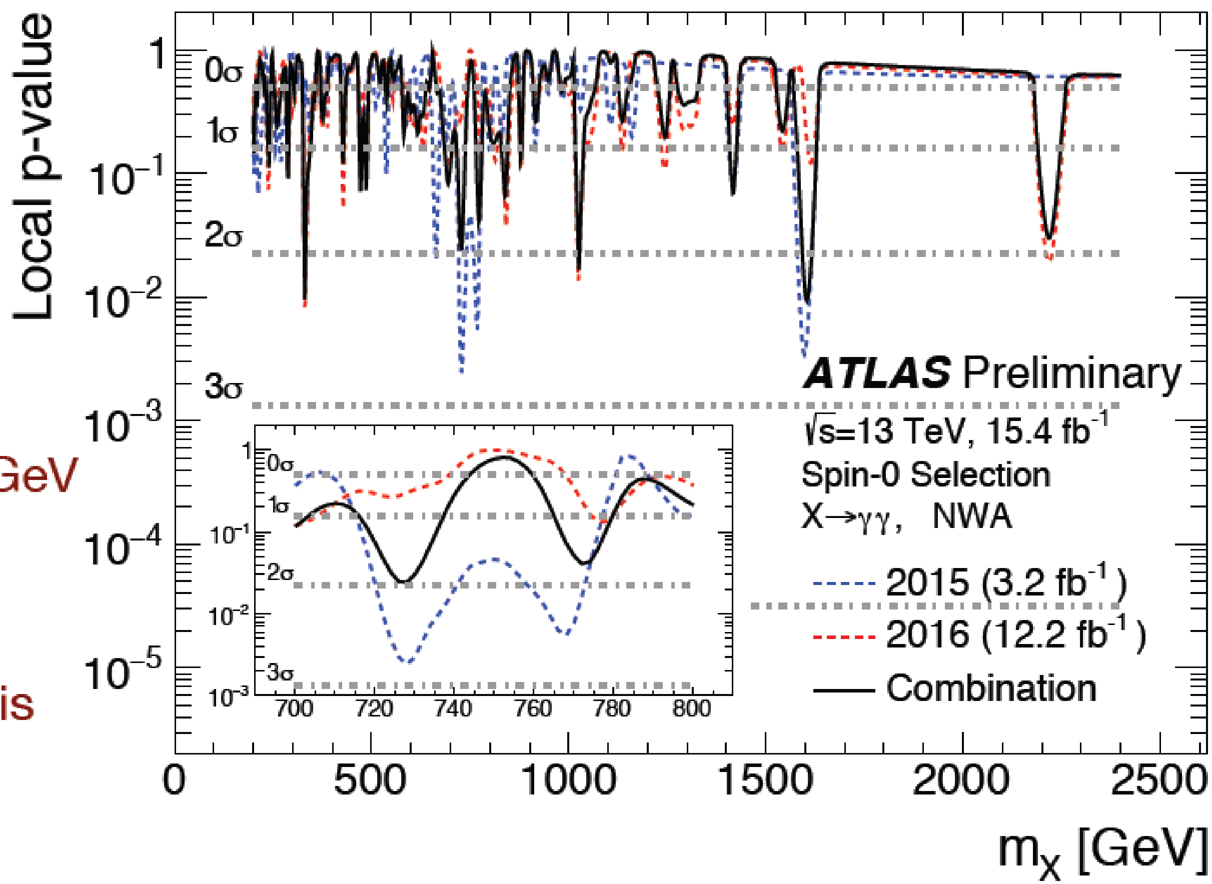
Narrow width!

Diphoton status @ ICHEP, 2016 August

2016-only



ATLAS



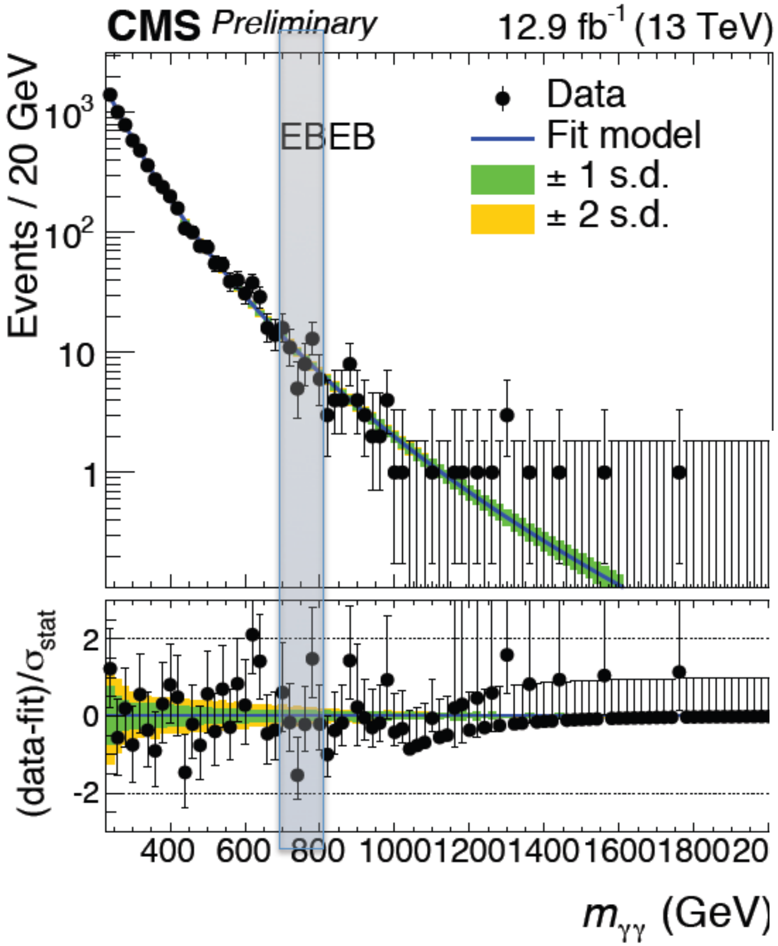
Broad excess around 750 GeV

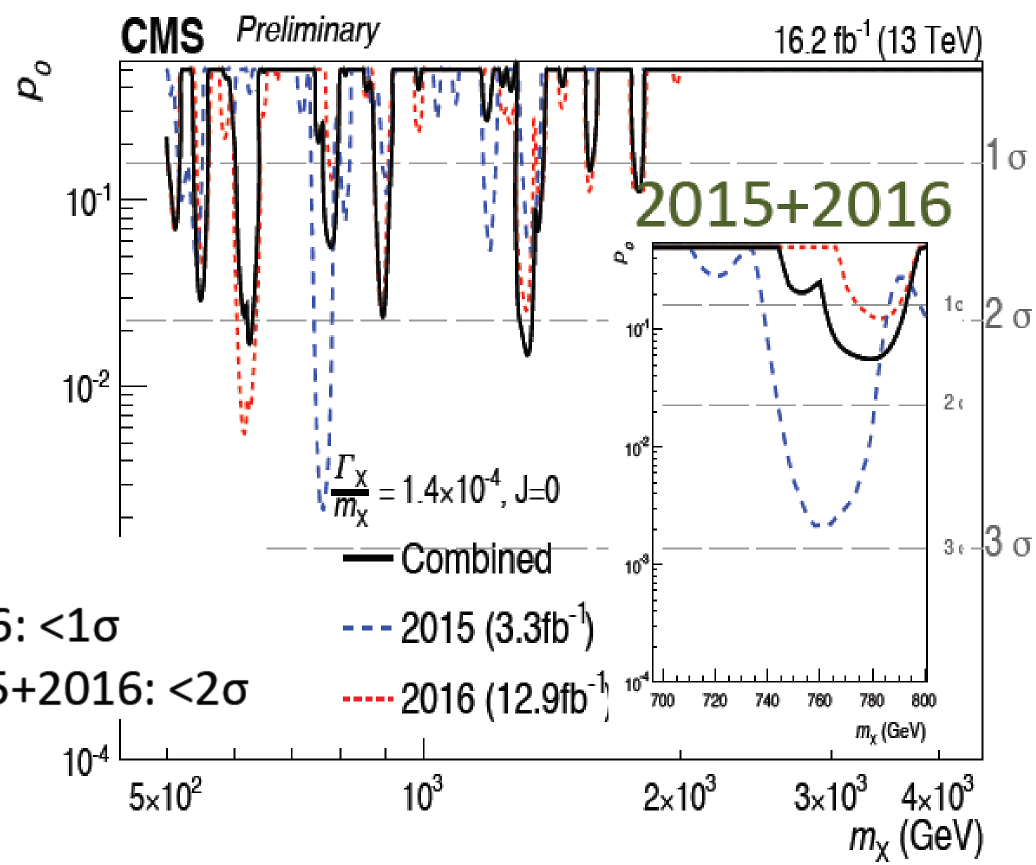
in 2015 data not seen

in 2016 data for spin-0 analysis

Bruno Lenzi (CERN)

CMS





Local excesses around 750GeV:

2015 only: 2.9σ → 2015+2016: <1σ

8TeV+2015: 3.4σ → 8TeV+2015+2016: <2σ

The excesses had been gone,
 but the technique for a model-building is left.

If another non-standard candidate in the diboson channels
 will be observed at the LHC, we are now ready.

§2 Yukawa coupling in walking gauge theories

We discussed an approach of the effective theory for the DSB.

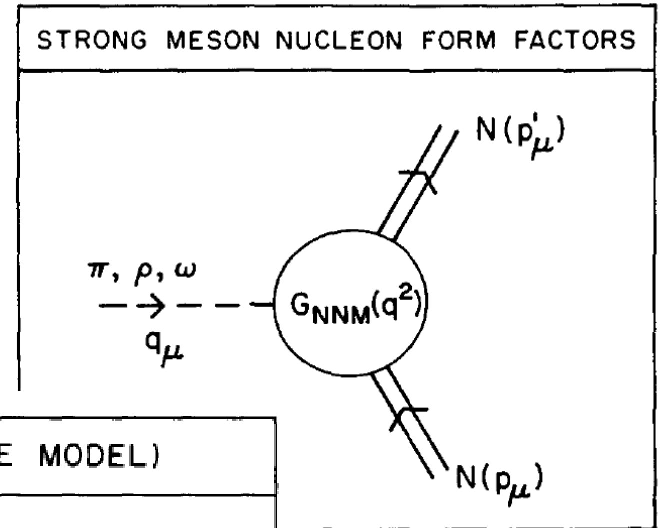
Now we turn to study a dynamical approach to the walking gauge theory.

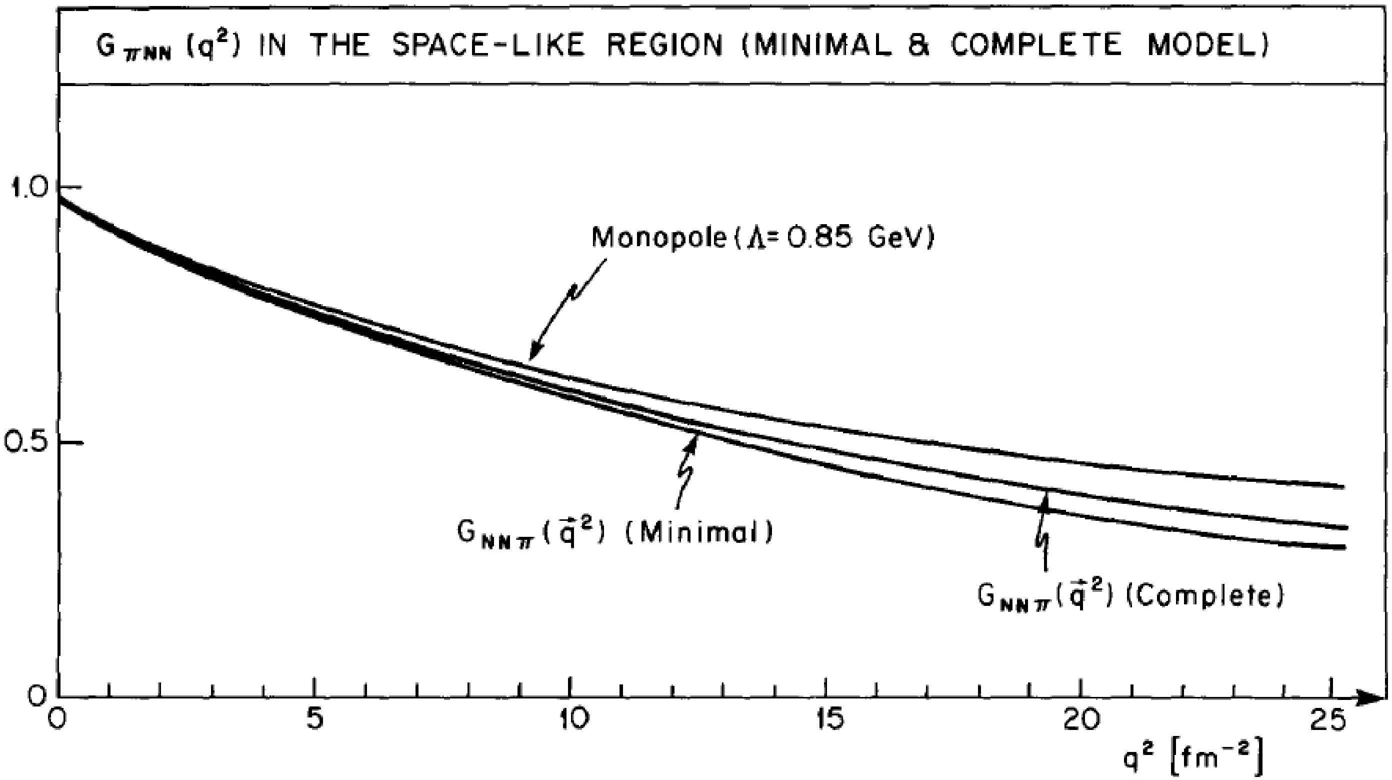
In particular, we estimate the Yukawa coupling. This is still mysterious in the framework of the SM.

It might give some suggestions to the hQQ coupling, etc., where Q is the vector-like quark.

Yukawa (pi-N-N) coupling in QCD

$$g_{NN\pi} = (13.5 \pm 0.1)$$





$$g_{\pi NN}(q^2) = g_{\pi NN}(q^2 = -m_\pi^2)\, G_{\pi NN}(q^2)$$

§2-1. Scalar decay constant and Yukawa coupling

M.Hashimoto, PRD83(2011)096003.

We assume the ETC interaction for the SM fermion and "Techni"-fermion, whose condensate is responsible for the EWSB.

$$\mathcal{L}_{4F} = G_f \bar{\psi}\psi \bar{f} f,$$

f: SM fermion
ψ : techni-fermion

Mass of the SM fermion:

$$m_f = -G_f Z_m^{-1} \langle \bar{\psi}\psi \rangle_R$$

$$(\bar{\psi}\psi)_R = Z_m (\bar{\psi}\psi)$$

$$Z_m \sim m/\Lambda_{\rm ETC}$$ (renormalization constant)

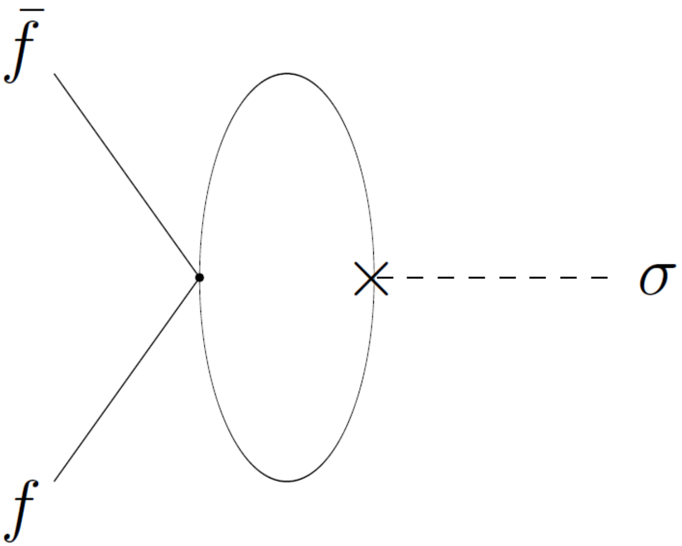
Scalar decay constant:

$$\langle 0|(\bar{\psi}\psi(0))_R|\sigma(q)\rangle \equiv F_\sigma M_\sigma$$

Yukawa coupling :

$$g_{\sigma ff} = Z_m^{-1} G_f F_\sigma M_\sigma$$

$$= \frac{m_f}{\frac{-\langle\bar{\psi}\psi\rangle_R}{F_\sigma M_\sigma}}$$



How to calculate F_σ

correlation function Π_σ

$$\mathcal{F}.\mathcal{T}.i\langle 0|(\bar{\psi}\psi(x))_R(\bar{\psi}\psi(0))_R|0\rangle \equiv \Pi_\sigma(q)$$

spectral representation

$$\Pi_\sigma(q) = \frac{F_\sigma^2 M_\sigma^2}{-q^2 + M_\sigma^2}$$

Note that

$$\Pi_\sigma(0) \;=\; F_\sigma^2 \;\text{ in this normalization.}$$

It is connected with the second derivative of the effective potential.

$$\frac{d^2V}{d\sigma_R^2} = \Pi_\sigma^{-1}(0) = \frac{1}{F_\sigma^2}$$

Therefore

$$\sigma_R^2 \frac{d^2V}{d\sigma_R^2} = \left(\frac{-\langle\bar{\psi}\psi\rangle_R}{F_\sigma} \right)^2$$

Yukawa coupling ⟷ V

§2-2. Formalism of the eff. potential

formalism

generating functional

$$W[J] \equiv \frac{1}{i} \ln \int [d\psi d\bar{\psi}][\text{gauge}] e^{i \int d^4x (\mathcal{L} + J\bar{\psi}\psi)}$$

effective action

$$\Gamma[\sigma] \equiv W[J] - \int d^4x J\sigma \qquad \sigma(x) \equiv \bar{\psi}(x)\psi(x)$$

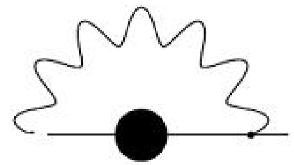
effective potential

$$V = -\Gamma[\sigma] / \int d^4x$$

By using $\frac{dV(\sigma)}{d\sigma} = J$ we formally obtain $V(\sigma) = \int d\sigma J$

Note that J corresponds to current mass m0.

We perform a non-perturbative calculation via the gap equation (Schwinger-Dyson equation).

$B(p) =$ 

$$iS_f^{-1}(p) = \not{p} - B(-p^2)$$

$$x \equiv -p^2$$

$$B(x) = m_0 + \int_0^{\Lambda^2} dy \frac{yB(y)}{y + B^2(y)} \frac{\lambda(\max(x,y))}{\max(x,y)},$$

$$\lambda(x) \equiv \frac{3C_F\,\alpha(\mu^2 = x)}{4\pi}$$

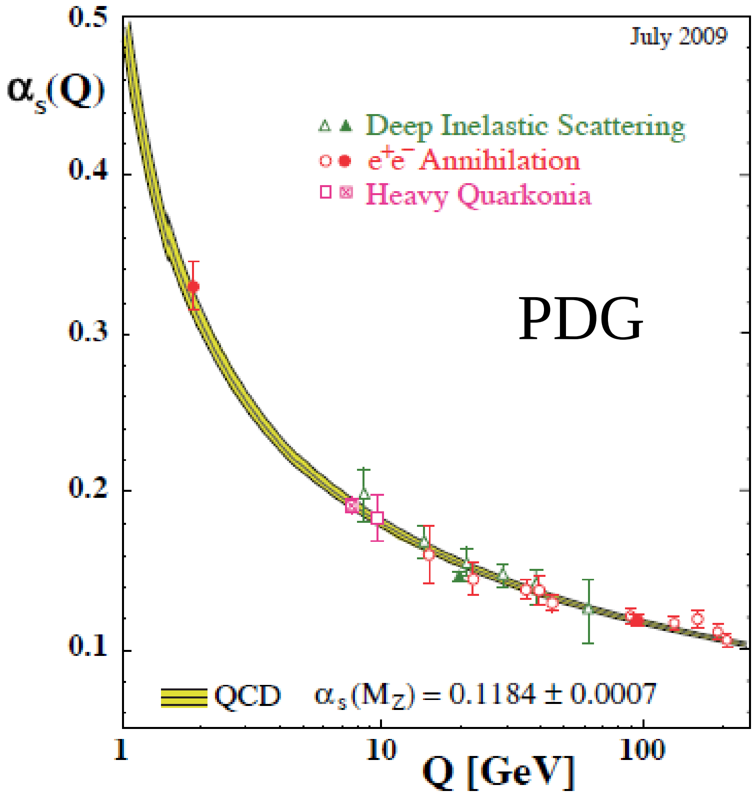
We use 2-loop running coupling (walking gauge theory).

$$\alpha(\mu^2) = \frac{\alpha_*}{1 + W(z(\mu^2))},$$

$$z(\mu^2) \equiv \frac{1}{e}\left(\frac{\mu^2}{\Lambda_{\mathrm{TC}}^2}\right)^{b_0\alpha_*}$$

W(z): Lambert function $z = W(z)e^{W(z)}$

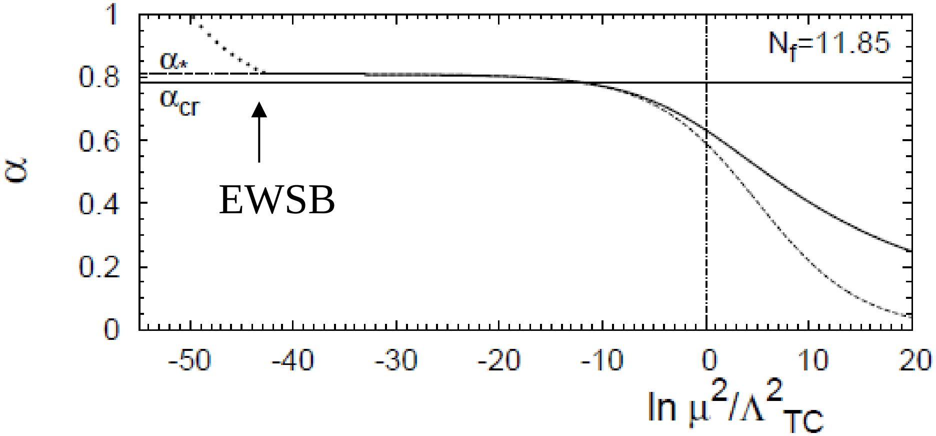
running effects in QCD



$$\gamma_m \sim 0$$

Walking gauge theory

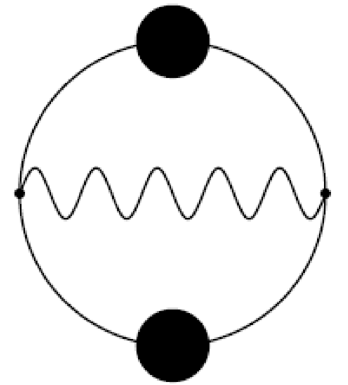
slowly running



Schematic running behavior in WTC

$$\gamma_m \sim 1$$

Vacuum energy



$$V = V_{\mathrm{CJT}}(B = B_{\mathrm{sol}})$$

$$= -\frac{N_c N_f}{8\pi^2}\left[\int_0^{\Lambda^2} dx x\left(\ln\left(1+\frac{B^2(x)}{x}\right) - \frac{B^2(x)}{x+B^2(x)}\right)\right]$$

2-loop numerical result

$$\langle \theta_\mu^\mu \rangle = 4V \simeq -0.76\,\eta\,m^4, \quad \text{with} \quad \eta \equiv \frac{N_{\mathrm{TC}} N_f}{2\pi^2}$$

Chiral condensate: $\langle\bar{\psi}\psi\rangle_R = -\frac{N_{\rm TC}N_f}{4\pi^2}\frac{A}{\lambda_*\sqrt{1+\tilde{\omega}^2}}\,m^3$

Vacuum energy: $V_{\rm sol} = V|_{B_0=m} = -\frac{N_{\rm TC}N_f}{4\pi^2}\frac{A^2}{16\lambda_*}\,m^4$

Scalar decay const.: $\frac{1}{F_\sigma^2} = \left.\frac{d^2V}{d\sigma_R^2}\right|_{B_0\to m} = \frac{1+\tilde{\omega}^2}{\frac{N_{\rm TC}N_f}{4\pi^2}(5-\tilde{\omega}^2)}\frac{\lambda_*}{m^2}$

Result:

$$\left(\frac{-\langle\bar{\psi}\psi\rangle_R}{F_\sigma}\right)^2 = \sigma_R^2\frac{d^2V}{d\sigma_R^2} = \frac{N_{\rm TC}N_f}{4\pi^2}\frac{A^2}{\lambda_*}\frac{1}{5-\tilde{\omega}^2}\,m^4$$

$N_{\rm TC}$: Num. of TC

N_f: Num. of Flavor

N_D: Num. of weak doublets

§2-3. Numerical values

λ_*	$\frac{m}{\Lambda_{\rm ETC}}$	κ_V	κ_F	A	$\sqrt{\frac{N_D}{N_f}}\frac{F_\sigma}{v}$	$\frac{g_{\sigma ff}}{g_{hff}^{\rm SM}}\frac{v}{N_D M_\sigma}$
0.305	1.12×10^{-3}	0.685	1.38	1.29	2.59	0.142
0.287	1.08×10^{-4}	0.709	1.42	1.28	2.71	0.148
0.258	5.88×10^{-10}	0.756	1.48	1.25	2.93	0.157

$$\frac{g_{\sigma ff}}{g_{hff}^{\rm SM}} = \sqrt{\frac{N_D}{N_f}}\frac{\kappa_F\sqrt{5-\tilde{\omega}^2}}{2\sqrt{2\kappa_V}}\frac{M_\sigma}{m} \simeq \sqrt{\frac{N_D}{N_f}}\frac{\kappa_F\sqrt{5-\tilde{\omega}^2}}{2\sqrt{\kappa_V}}$$

We used $M_\sigma \simeq \sqrt{2}m$

(Hashimoto, PLB441('98)389.)

More simply,

$$\frac{g_{\sigma ff}}{g_{hff}^{\rm SM}} \simeq 1.8\sqrt{\frac{N_D}{N_f}} \simeq 1.2 \sim 1.3$$

with $N_D = \frac{N_f}{2}$

This approach is NOT applicable directly to the top and Higgs (125GeV), because of the problems of mt and mh.

However, it might give some suggestions to the system of the composite scalar and fermions in the walking gauge theories.

As for the form factor of the Yukawa coupling, more complicated approach such as the Bethe-Salpeter amp. is needed. Otherwise, we may employ an effective model via the AdS/CFT correspondence.

§3. Summary

- Although the composite models are severely constrained, it is still worthwhile to study them.
  I overviewed the latest circumstance of the diboson and diphoton excesses observed at the LHC and the explanations via the composite models.

- In the walking gauge theory, the Yukawa coupling can be deviated from an expected value from the SM.
  We studied the formalism for the estimate of the Yukawa coupling and concretely showed the numerical results from the non-perturbative approach by using the SDE (gap eq.).
  This formalism might be useful for the system of the composite scalar and fermions.

Thank you!