What is the 750 GeV $\gamma\gamma$ resonance?

... and what to do with it?

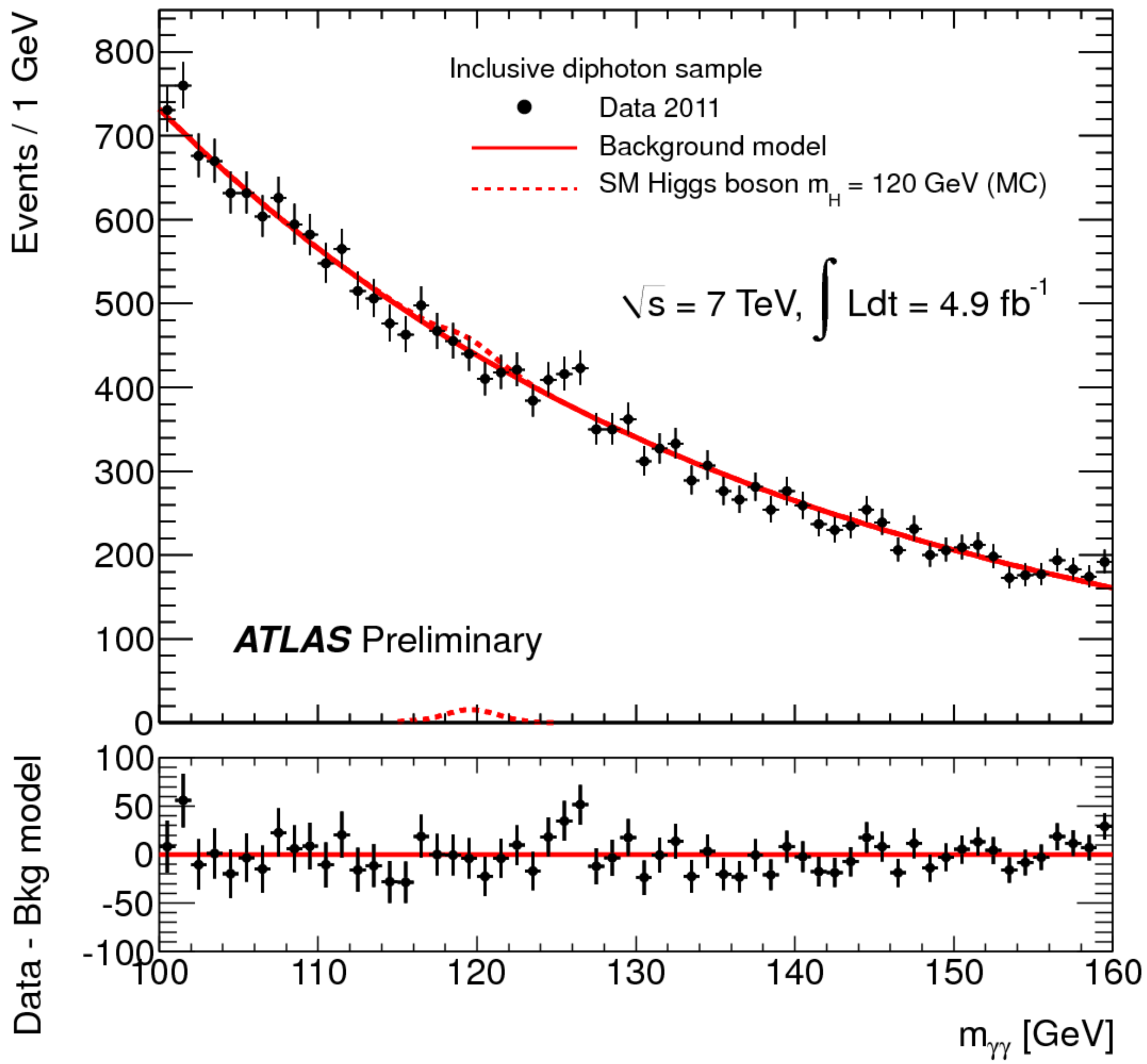
Roberto Franceschini (CERN)

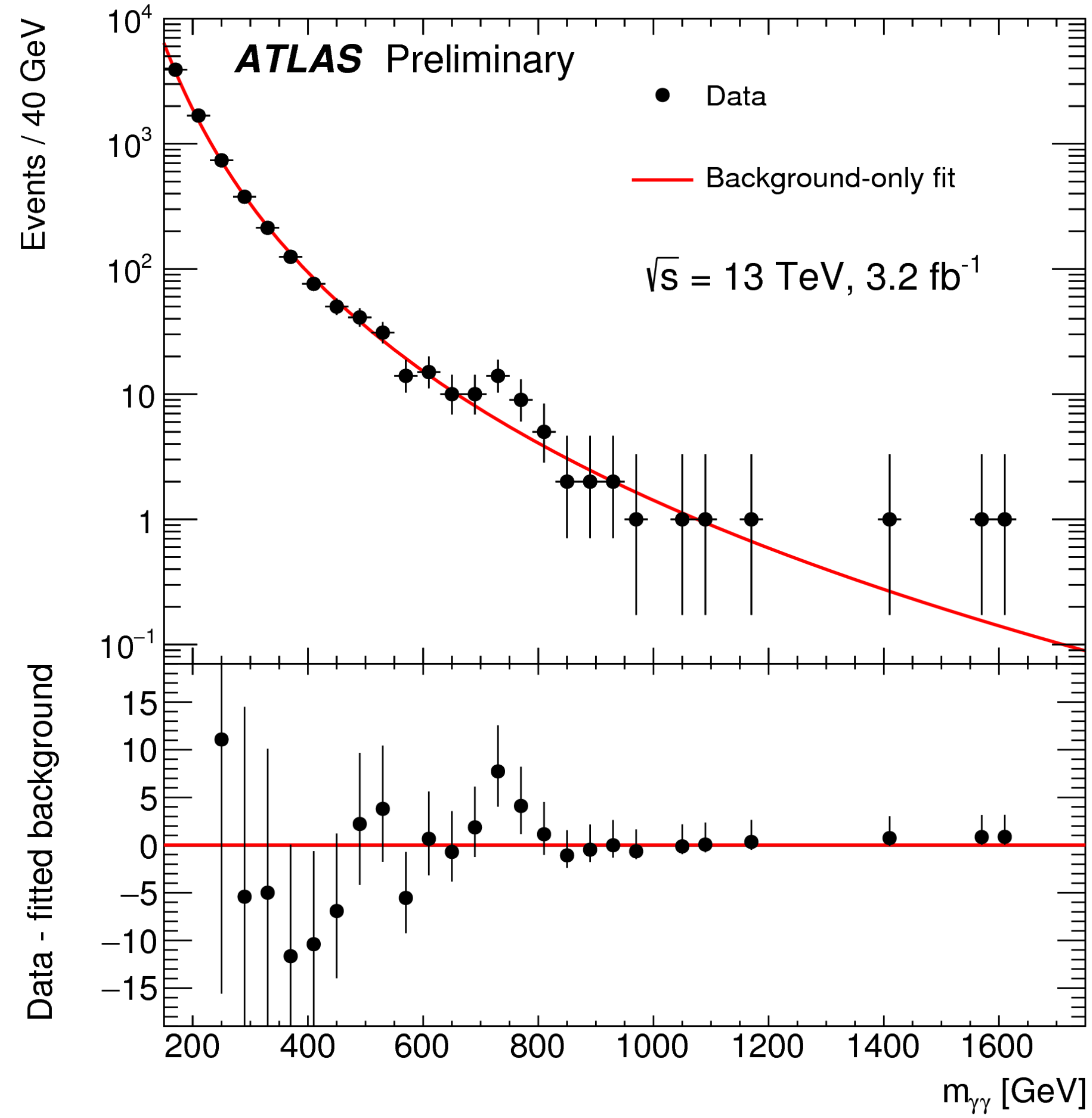
May 30th 2016 - MPI Kernphysik (Heidelberg)

1512.04933, 1512.05330, 1604.06446
with
Bellazzini, Sala, Serra, Giudice, Kamenik, McCullough, Pomarol, Rattazzi, Redi, Riva, Strumia, and Torre

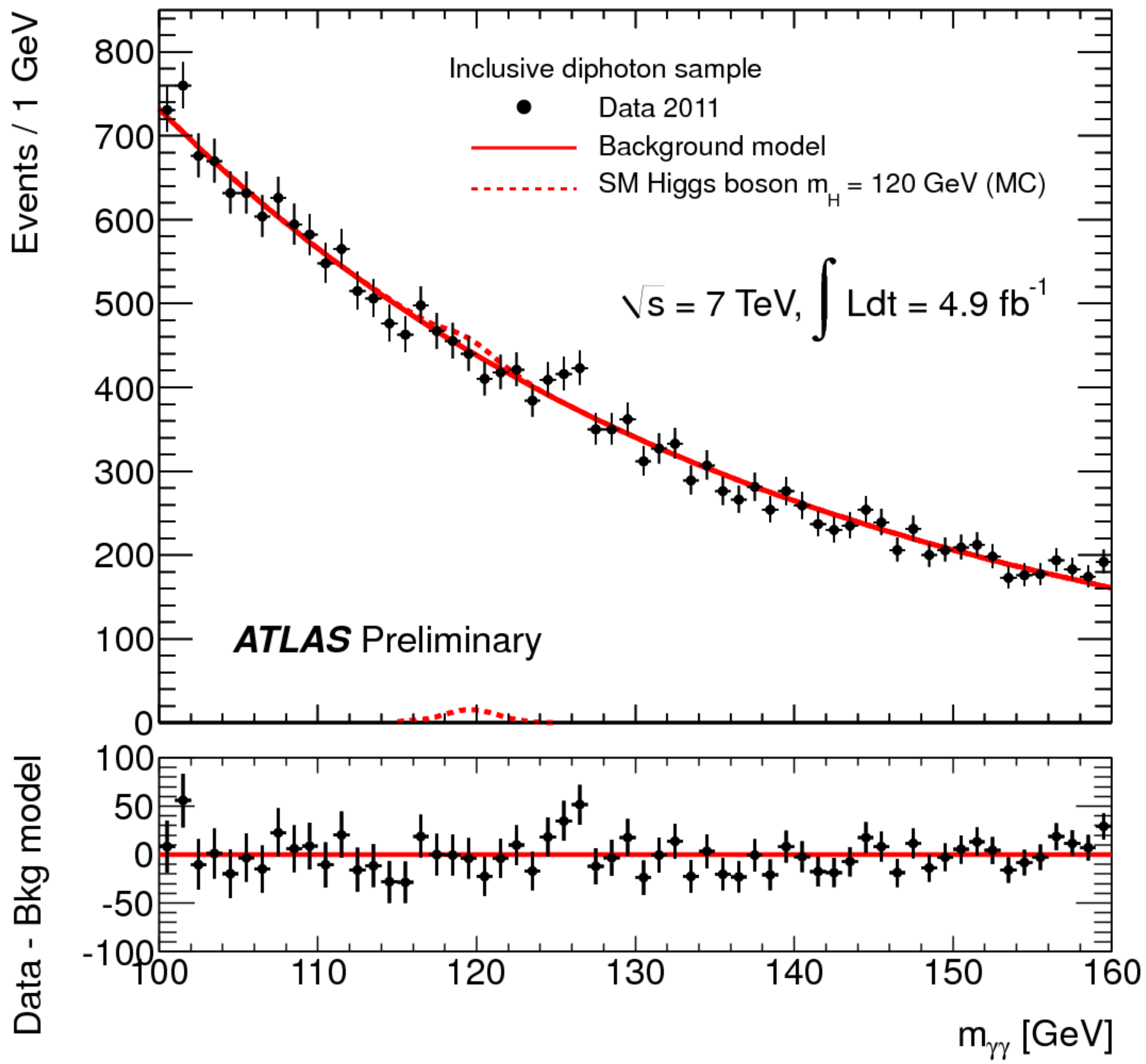
Déjà vu ?

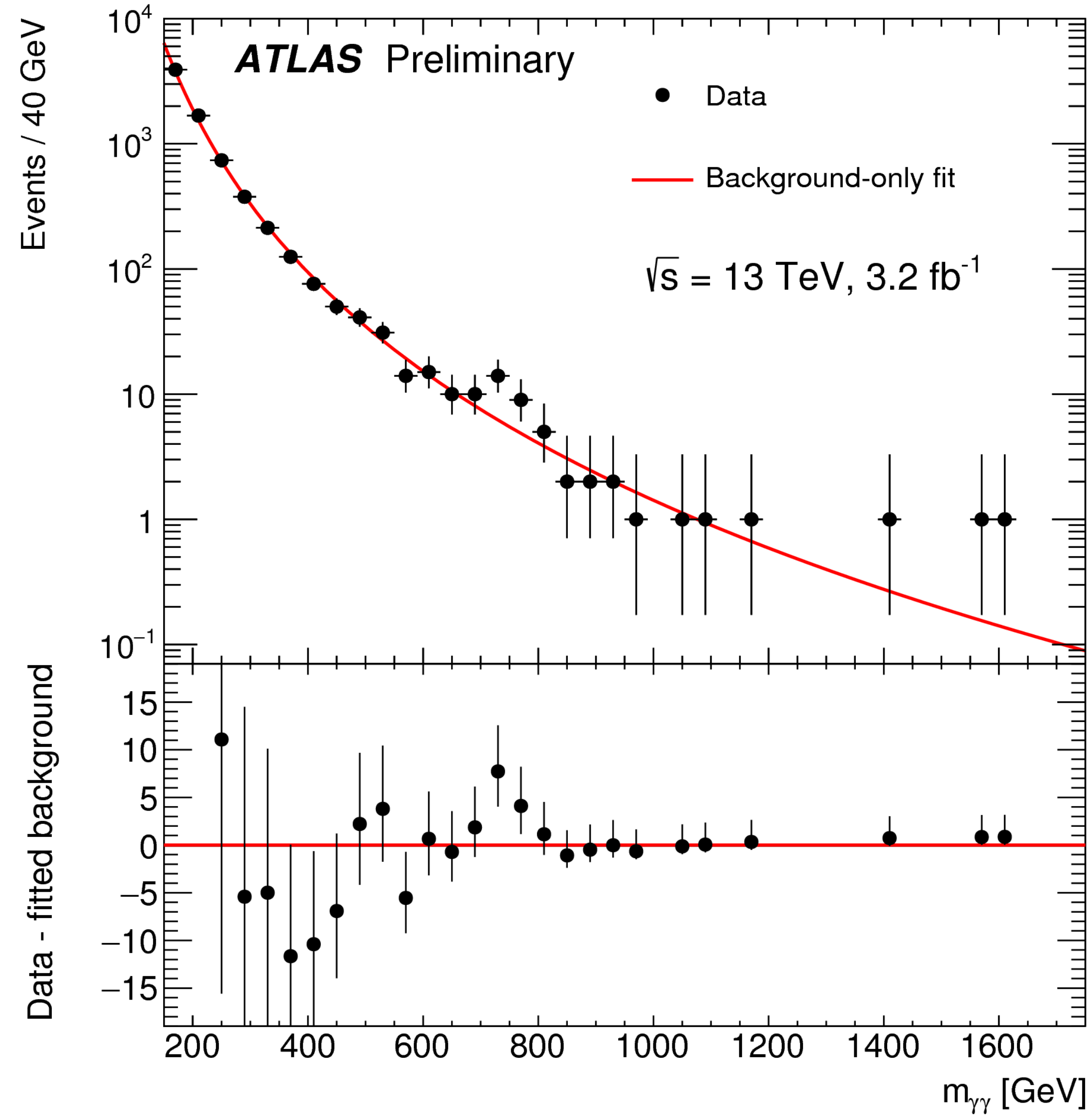
Jamboree 2011-15





Jamboree 2011-15





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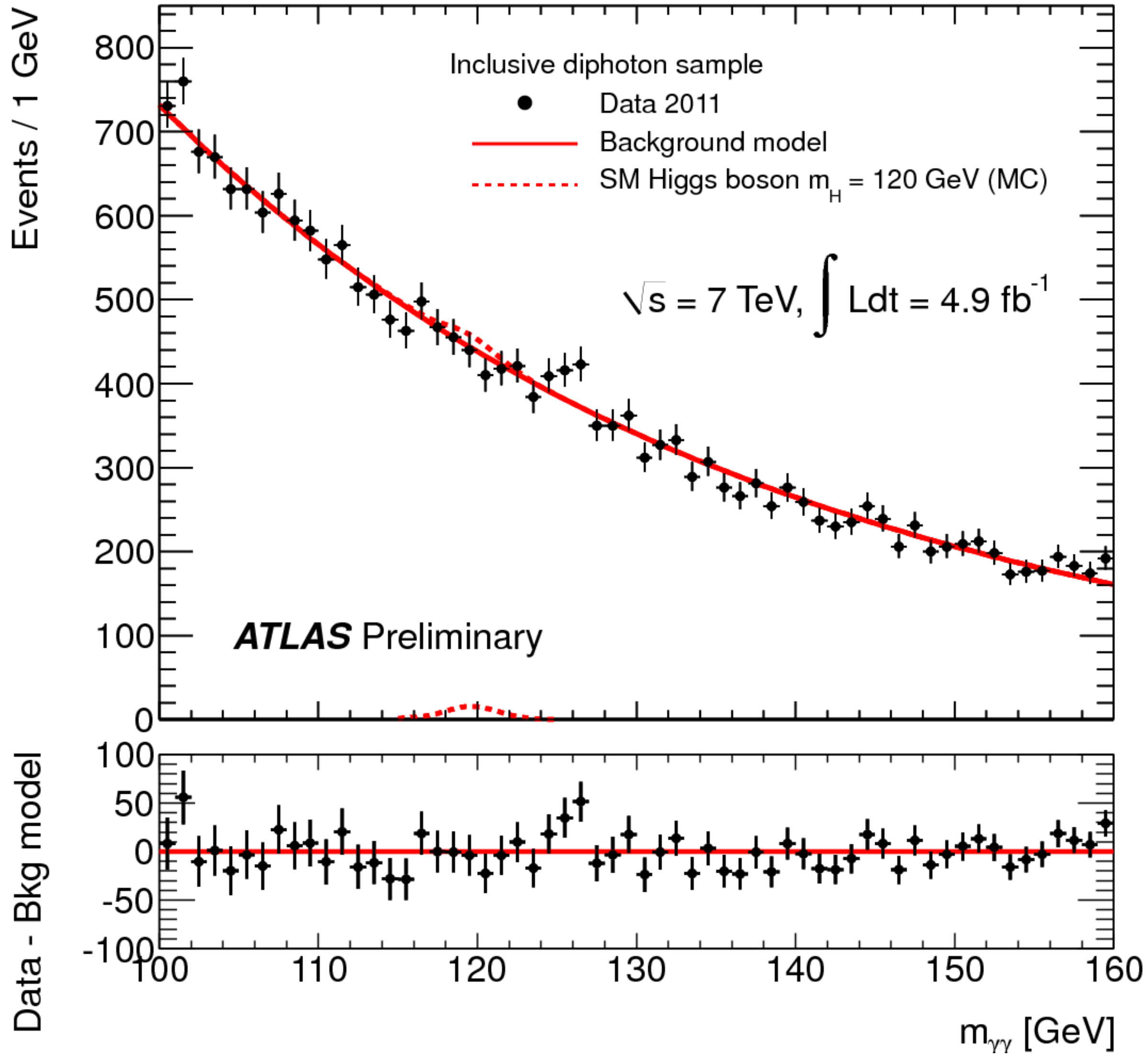
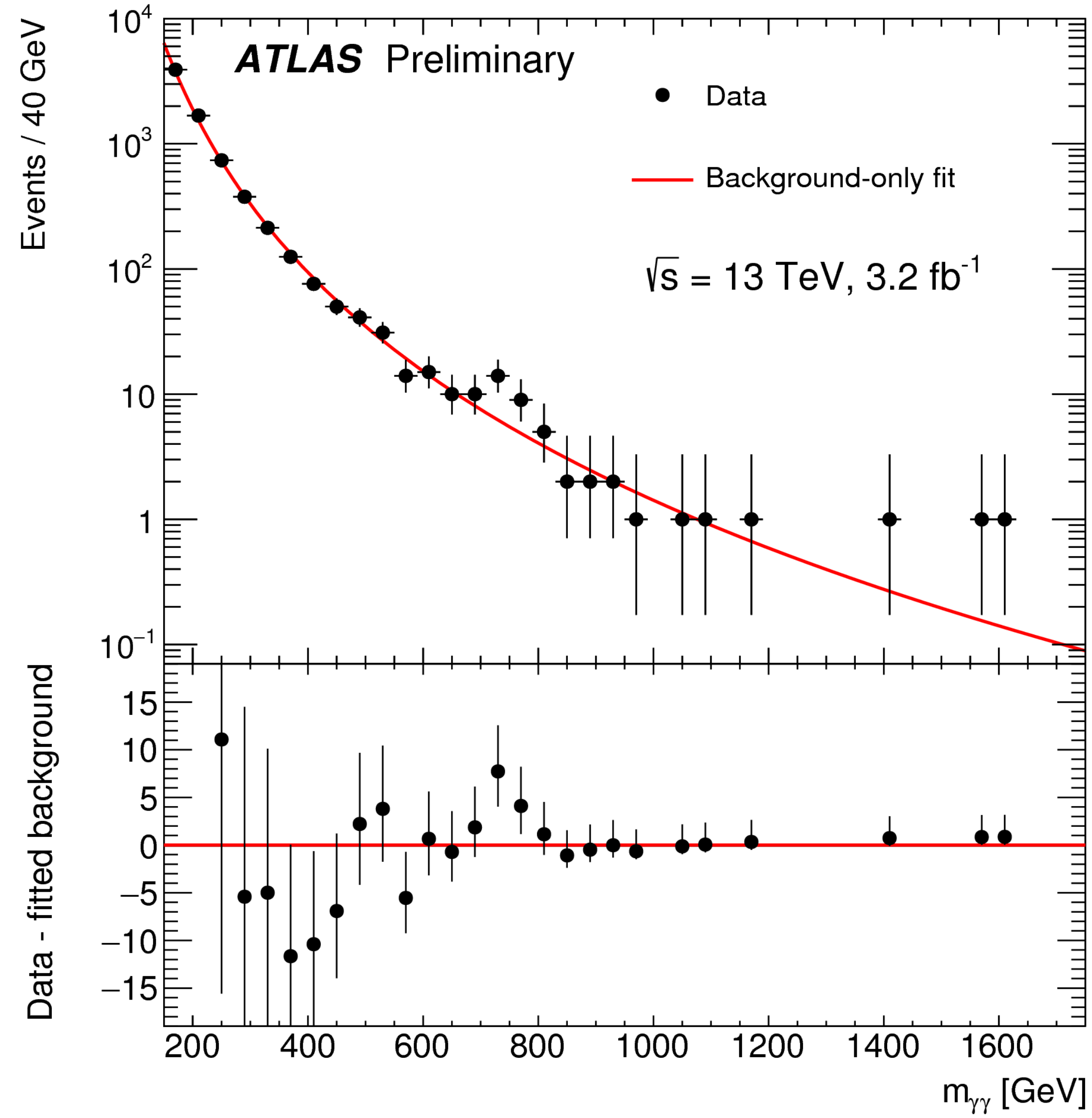
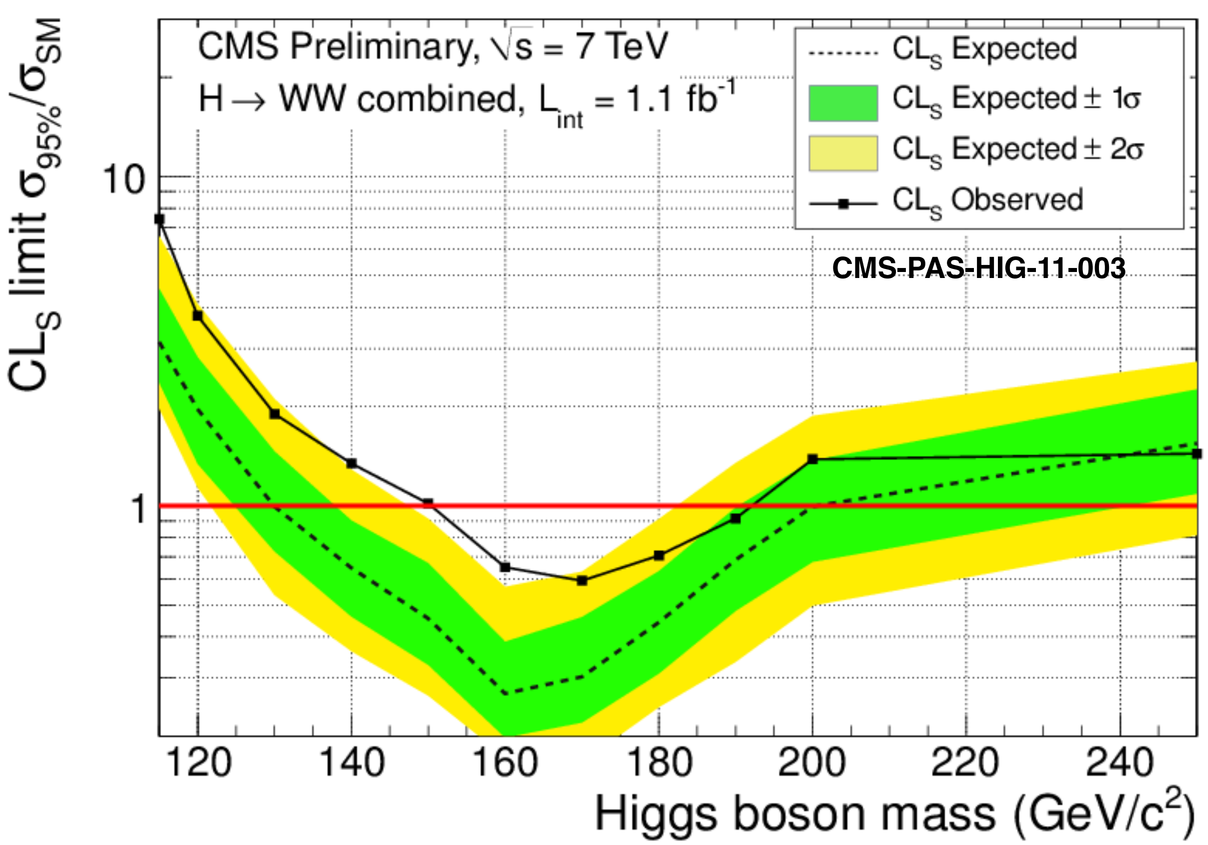
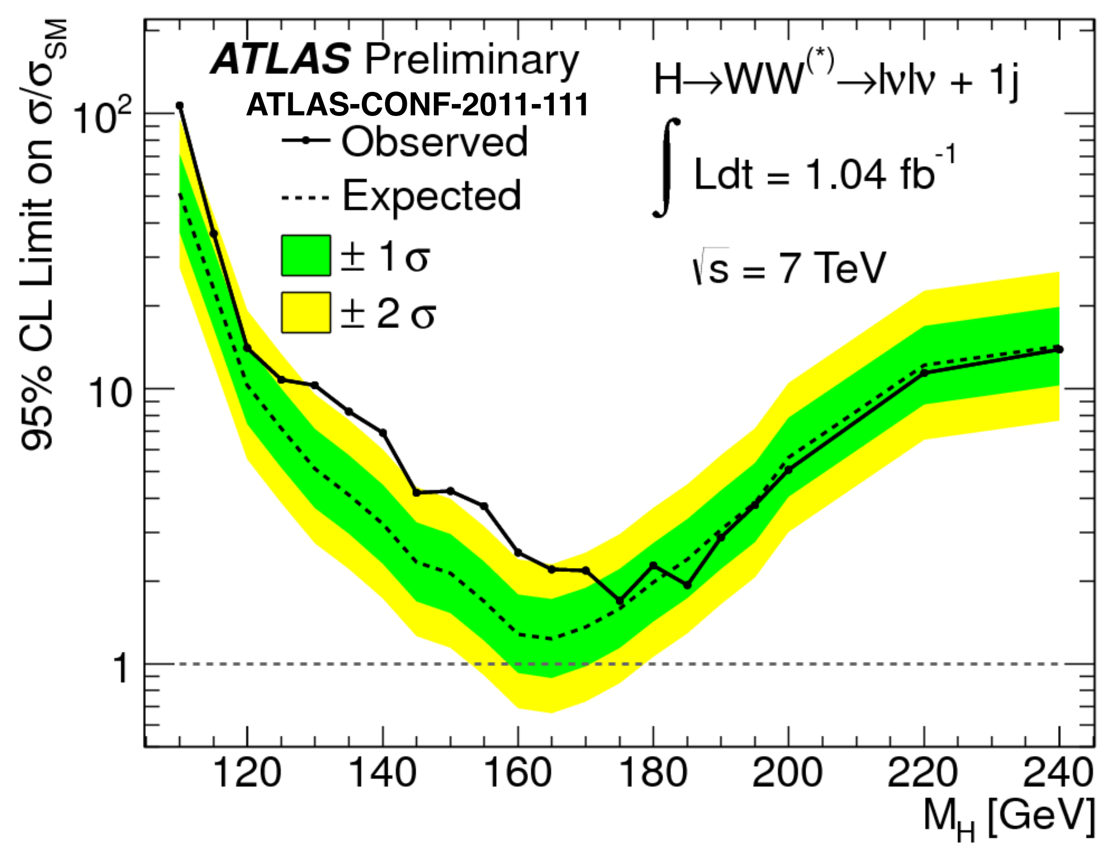




EPS 2011





BSM means operating in this moving field

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Join the dots

Join the dots

DM

Strong CP

Flavor

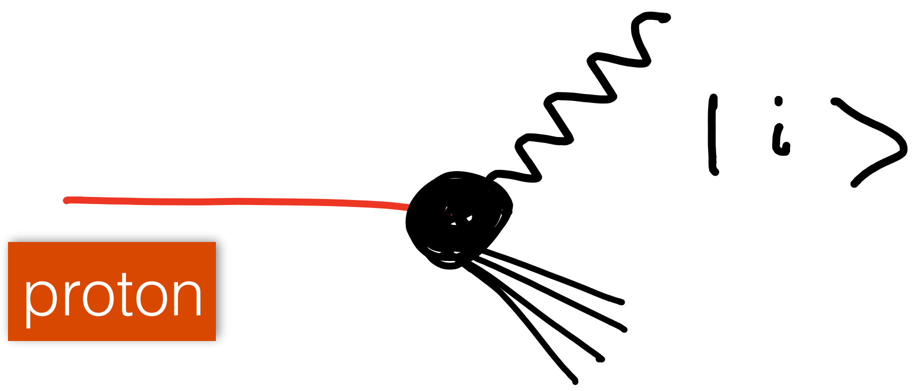
Overwhelming amount of interpretations

ν

Weak/ Planck Hierarchy

DE?

The basics



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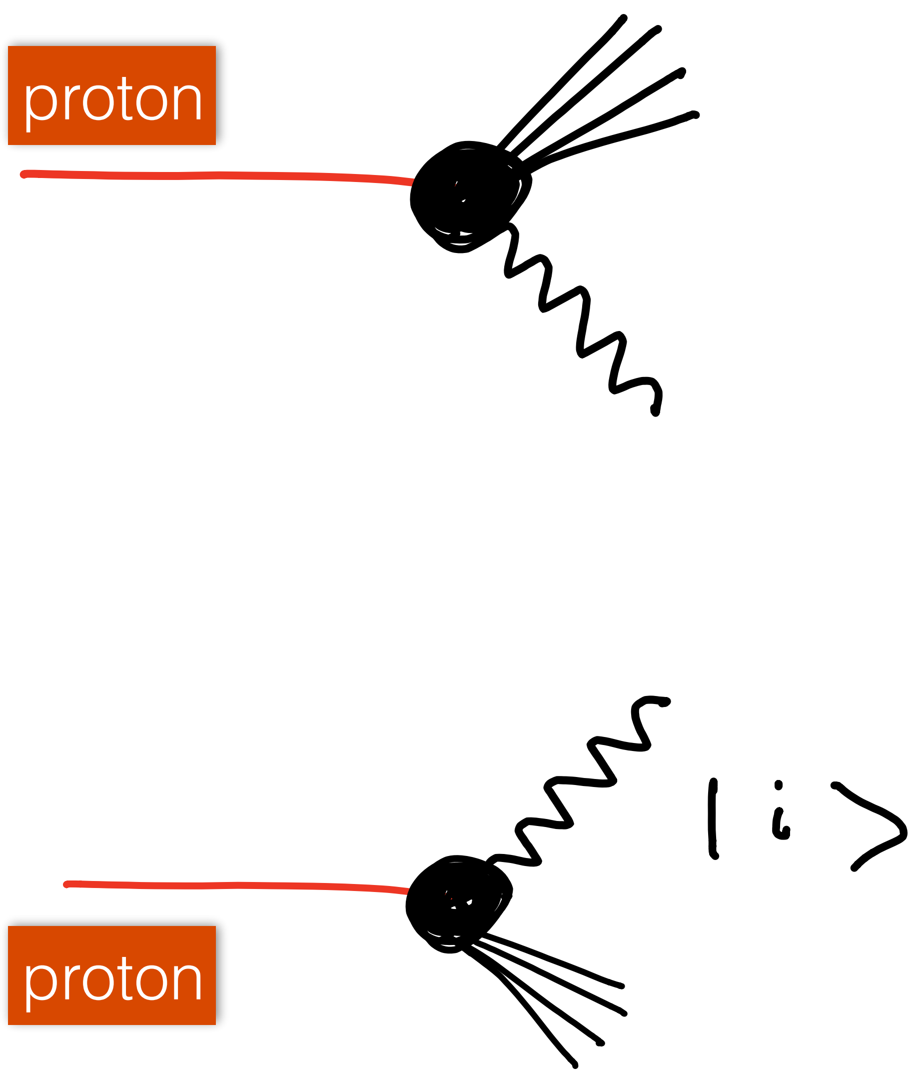

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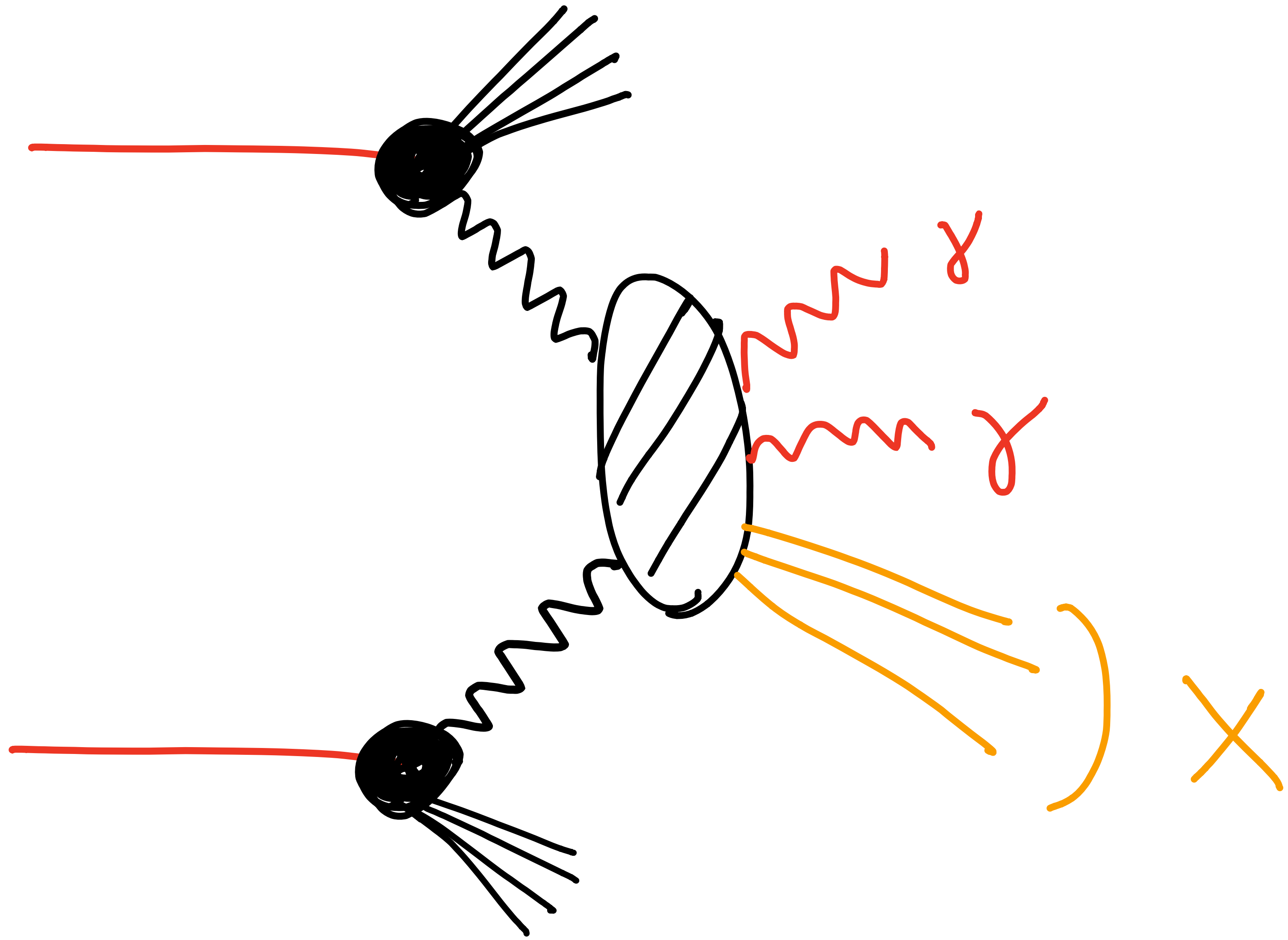
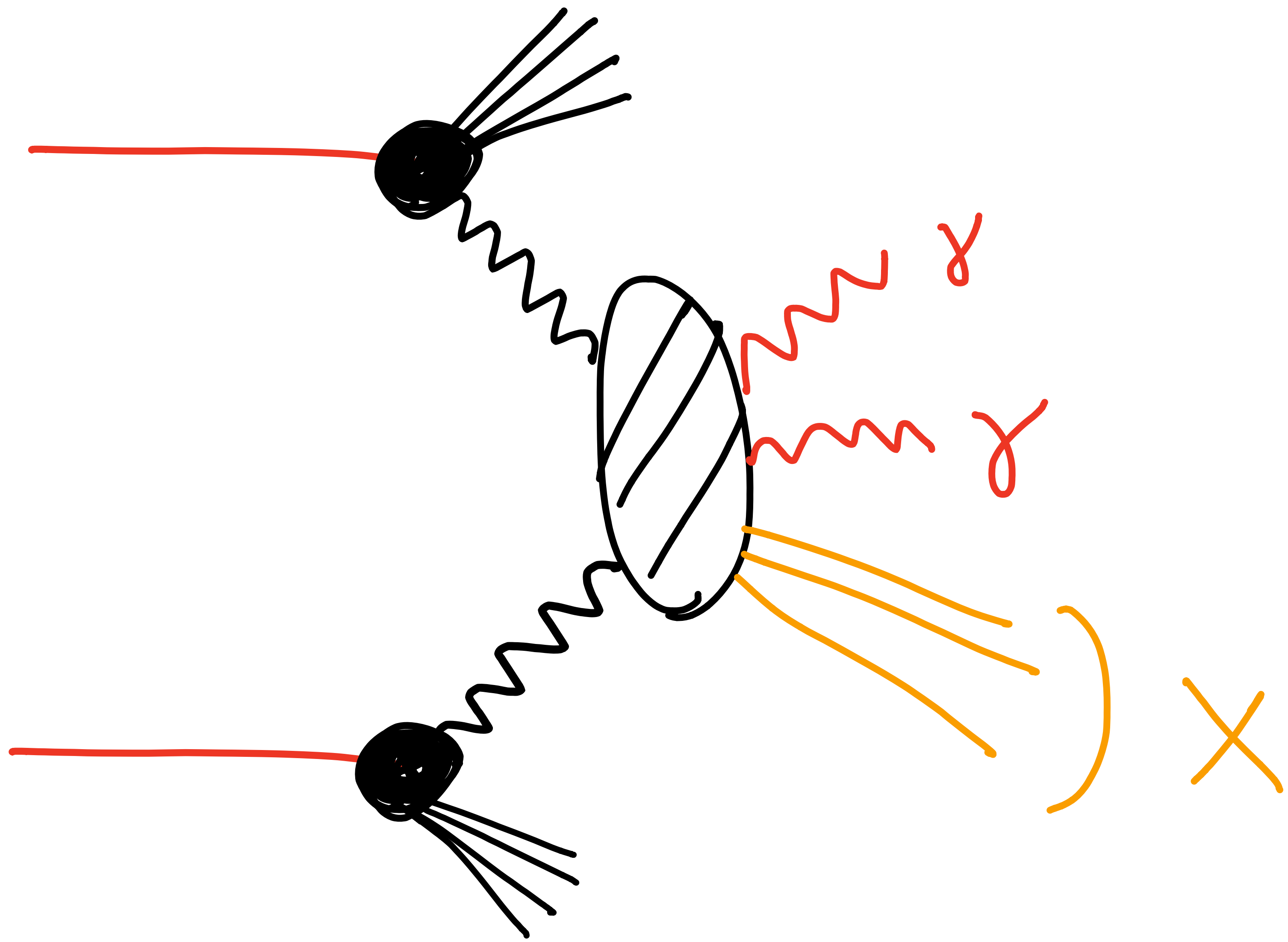
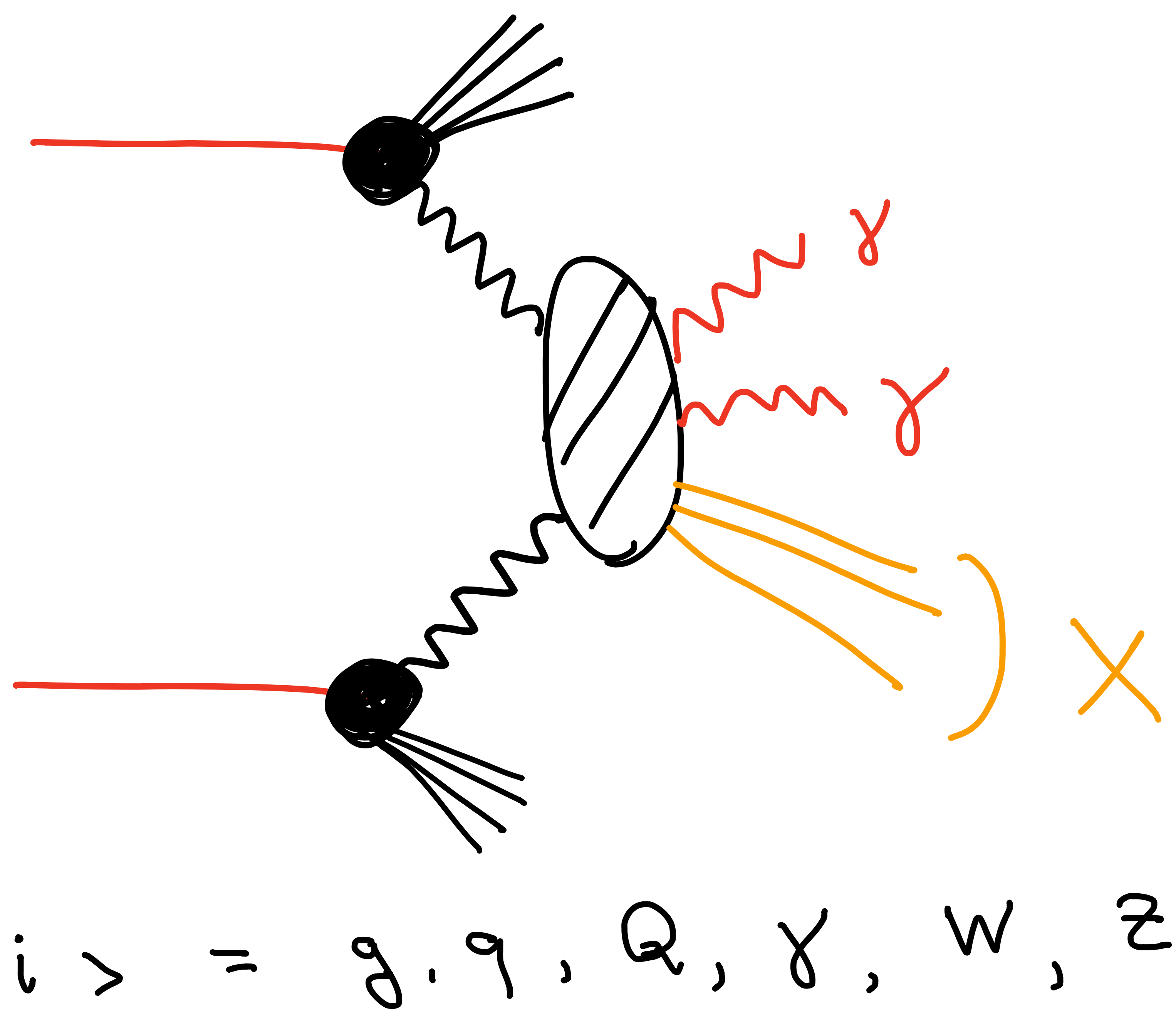


The basics



$|i\rangle = g, q, Q, \gamma, W, Z$

The basics



is there any X in pp → γγ X

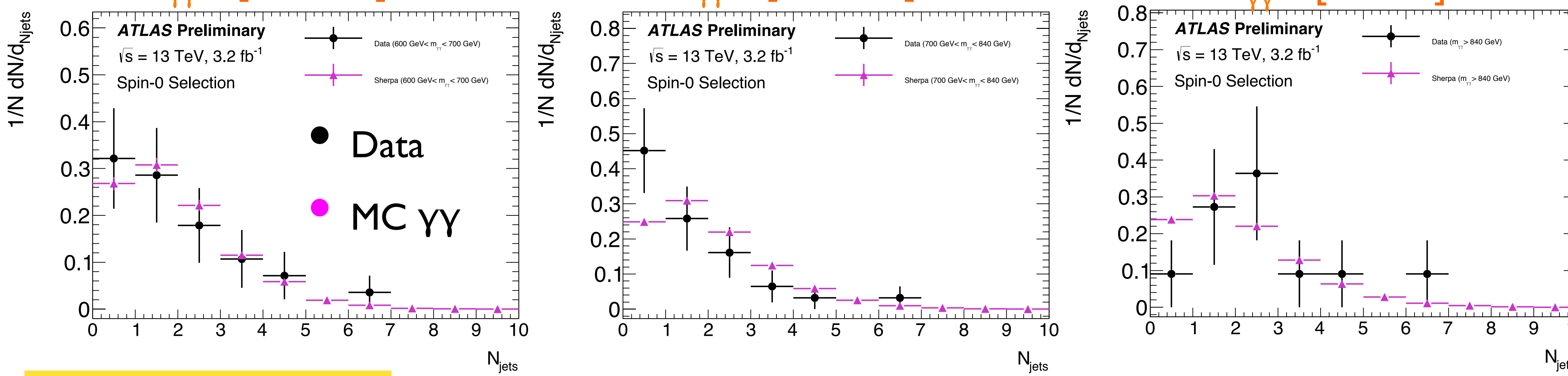
which proton constituents are initials states?

ATLAS-CONF-2016-018

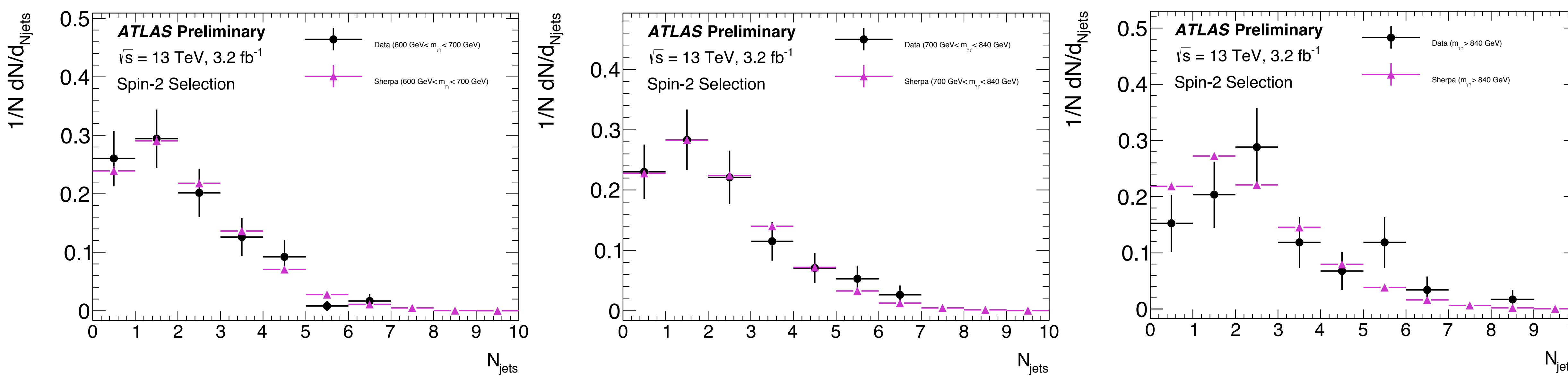
Properties of sideband and excess regions N_{jets}

SPIN-0 ANALYSIS

$m_{\gamma\gamma}$ = [600-700] GeV $m_{\gamma\gamma}$ = [700-840] GeV $m_{\gamma\gamma}$ =[840-∞] GeV



SPIN-2 ANALYSIS



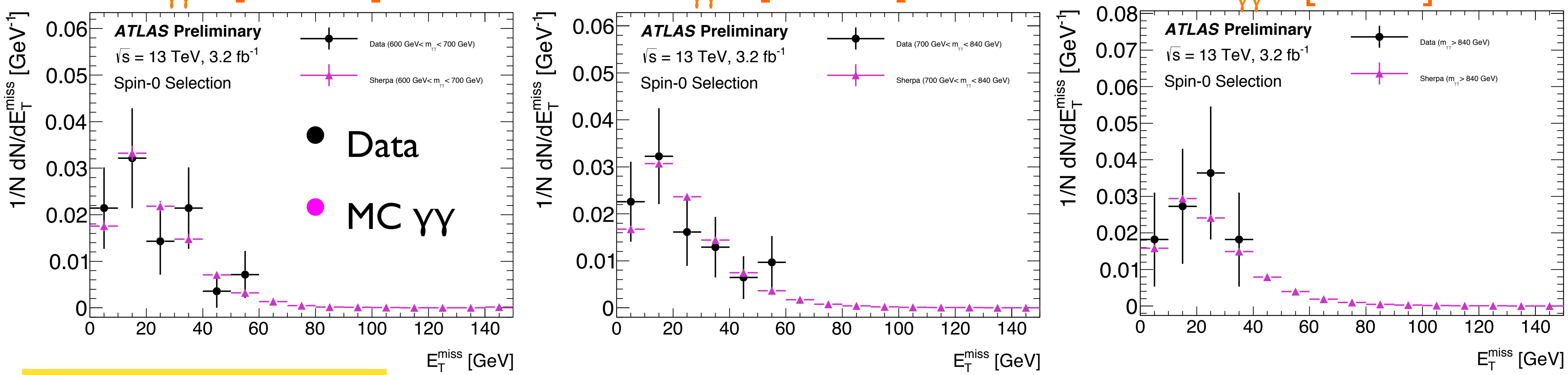
anti-k_t R-0.4 y_j < 2.4 → p_T^j > 25 GeV + JVT < 0.64   2.4 < y_j < 4.4 → p_T^j > 50 GeV

ATLAS-CONF-2016-018

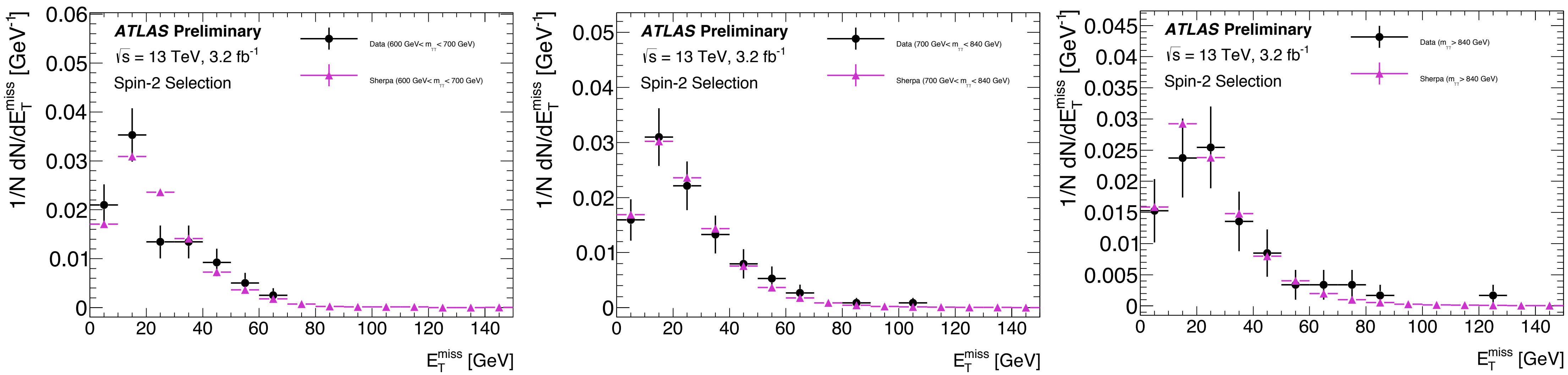
Properties of sideband and excess regions E_T^{miss}

SPIN-0 ANALYSIS

$m_{\gamma\gamma}$ = [600-700] GeV | $m_{\gamma\gamma}$ = [700-840] GeV | $m_{\gamma\gamma}$ =[840-∞] GeV



SPIN-2 ANALYSIS



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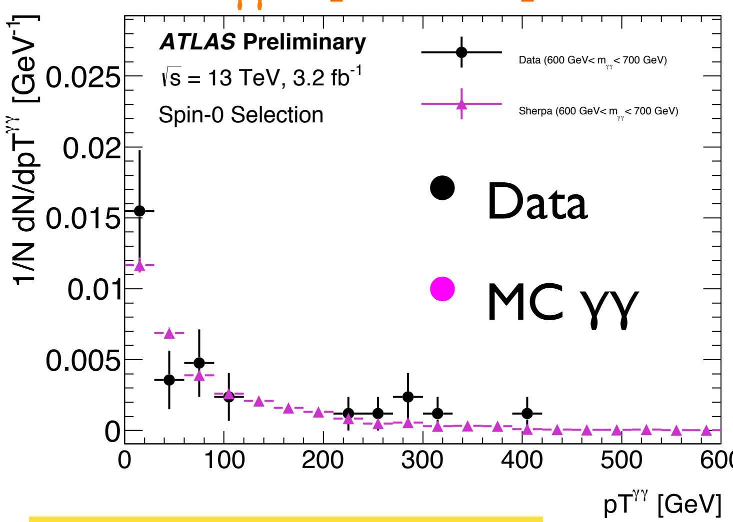
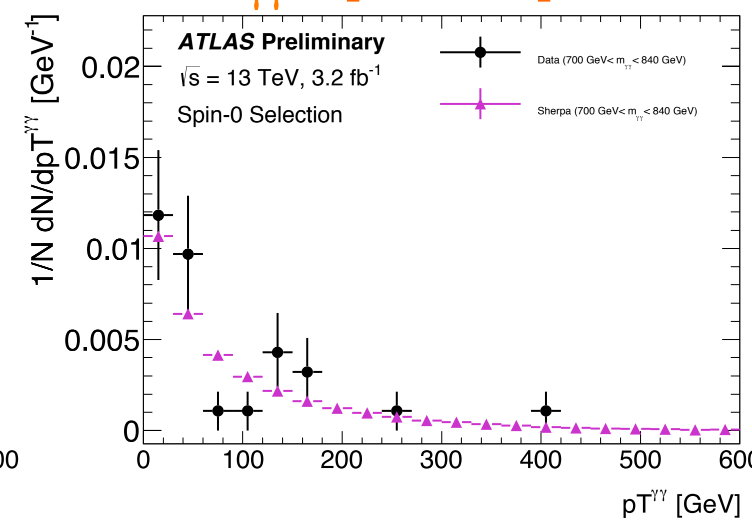
Properties of sideband and excess regions $p_T^{\gamma\gamma}$

SPIN-0 ANALYSIS

$m_{\gamma\gamma}$ = [600-700] GeV



$m_{\gamma\gamma}$ = [700-840] GeV



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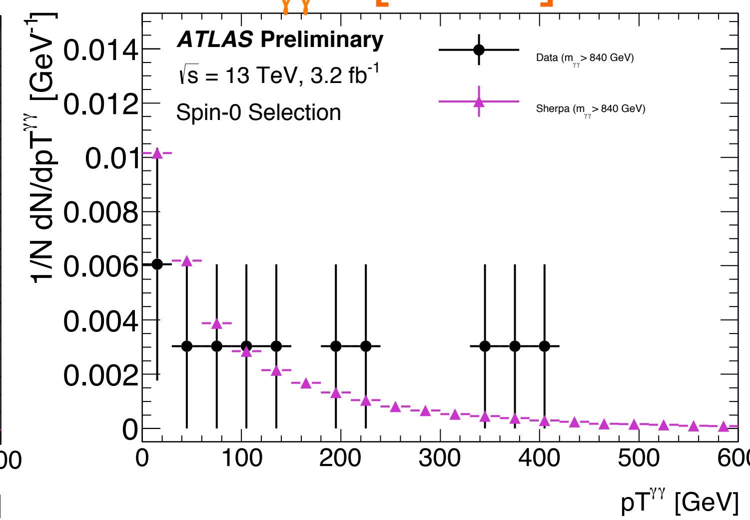
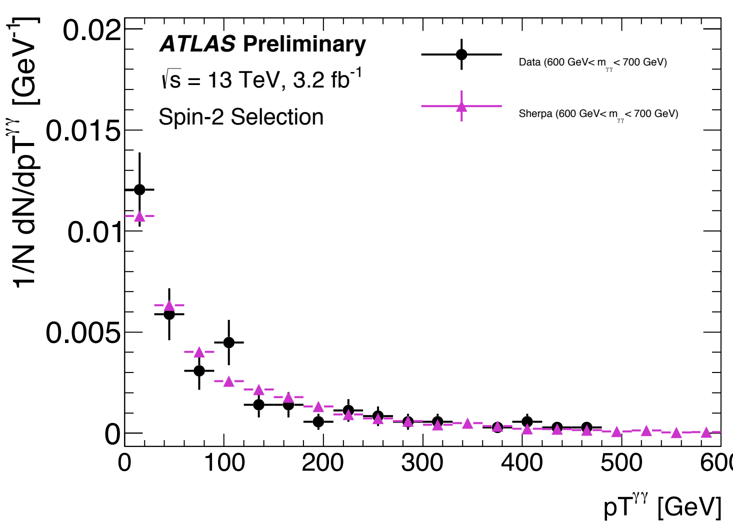
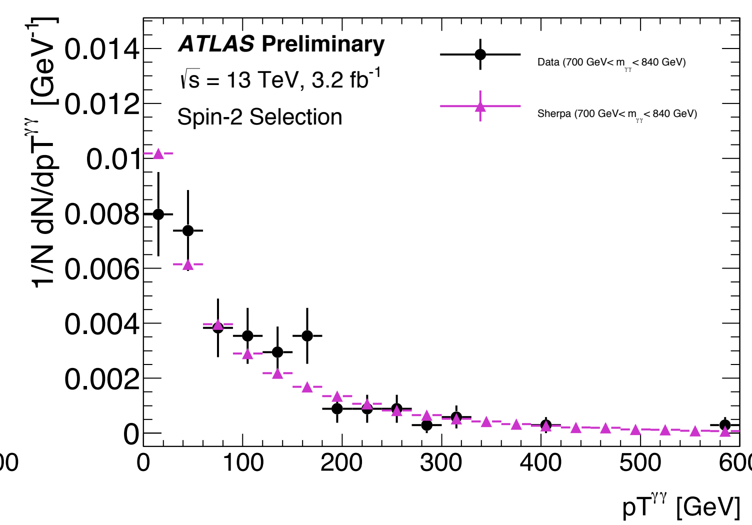
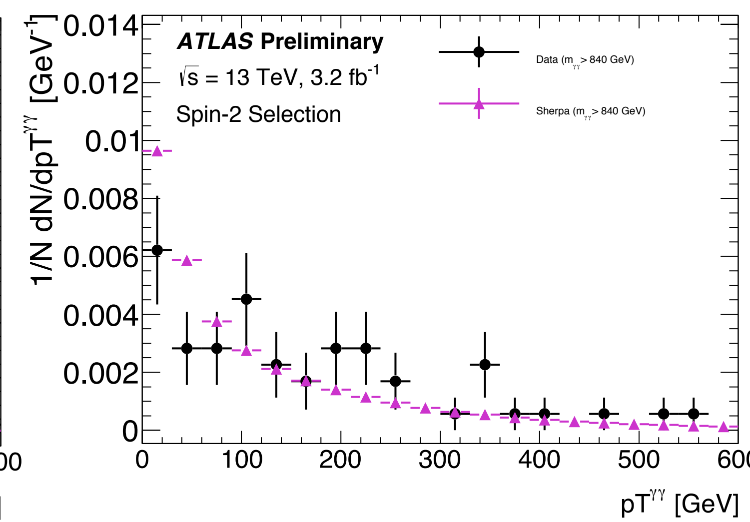


SPIN-2 ANALYSIS







ATLAS-CONF-2016-018

Properties of sideband and excess regions $\cos\theta^*_{\gamma\gamma}$

SPIN-0 ANALYSIS

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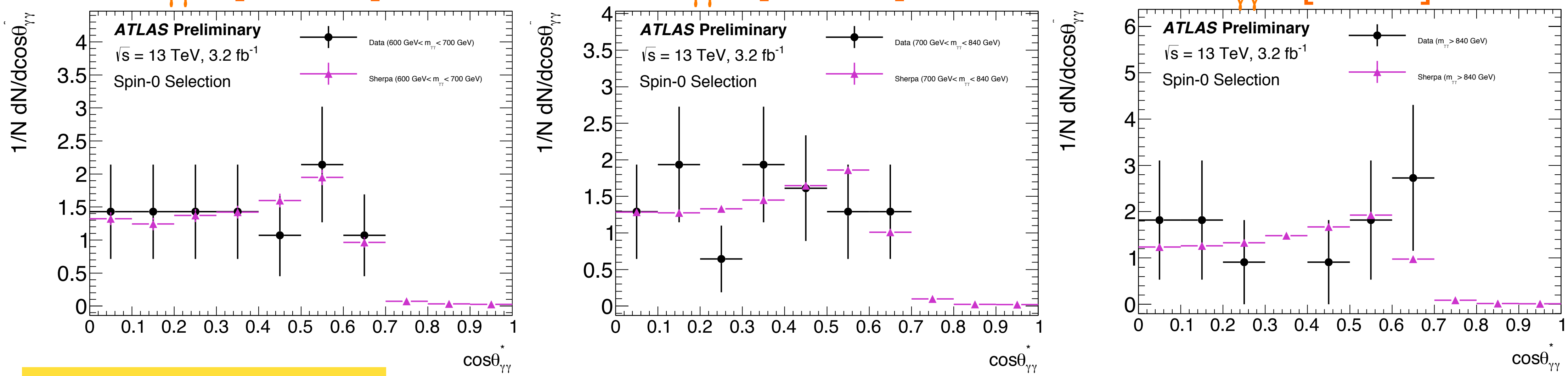
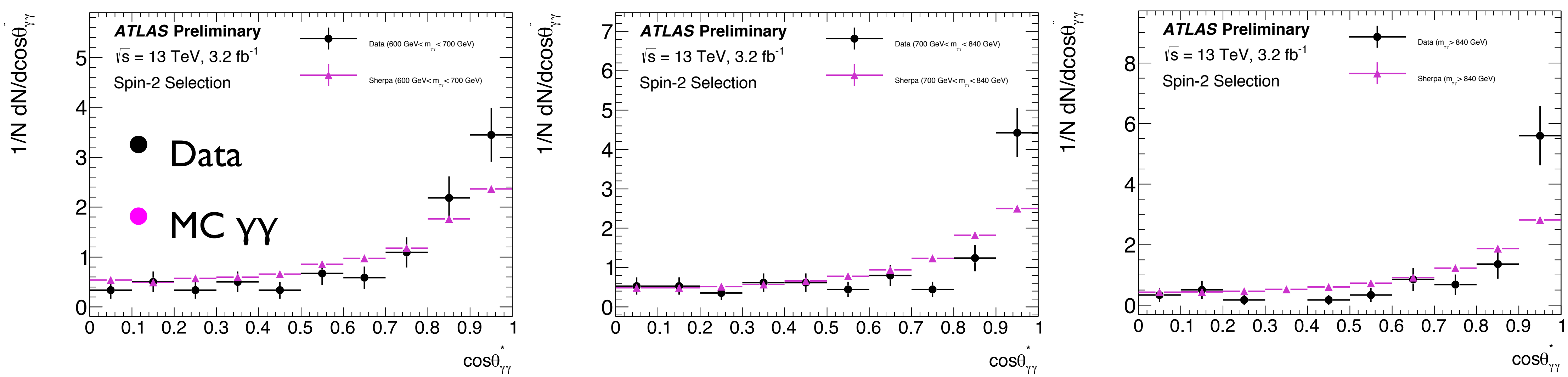
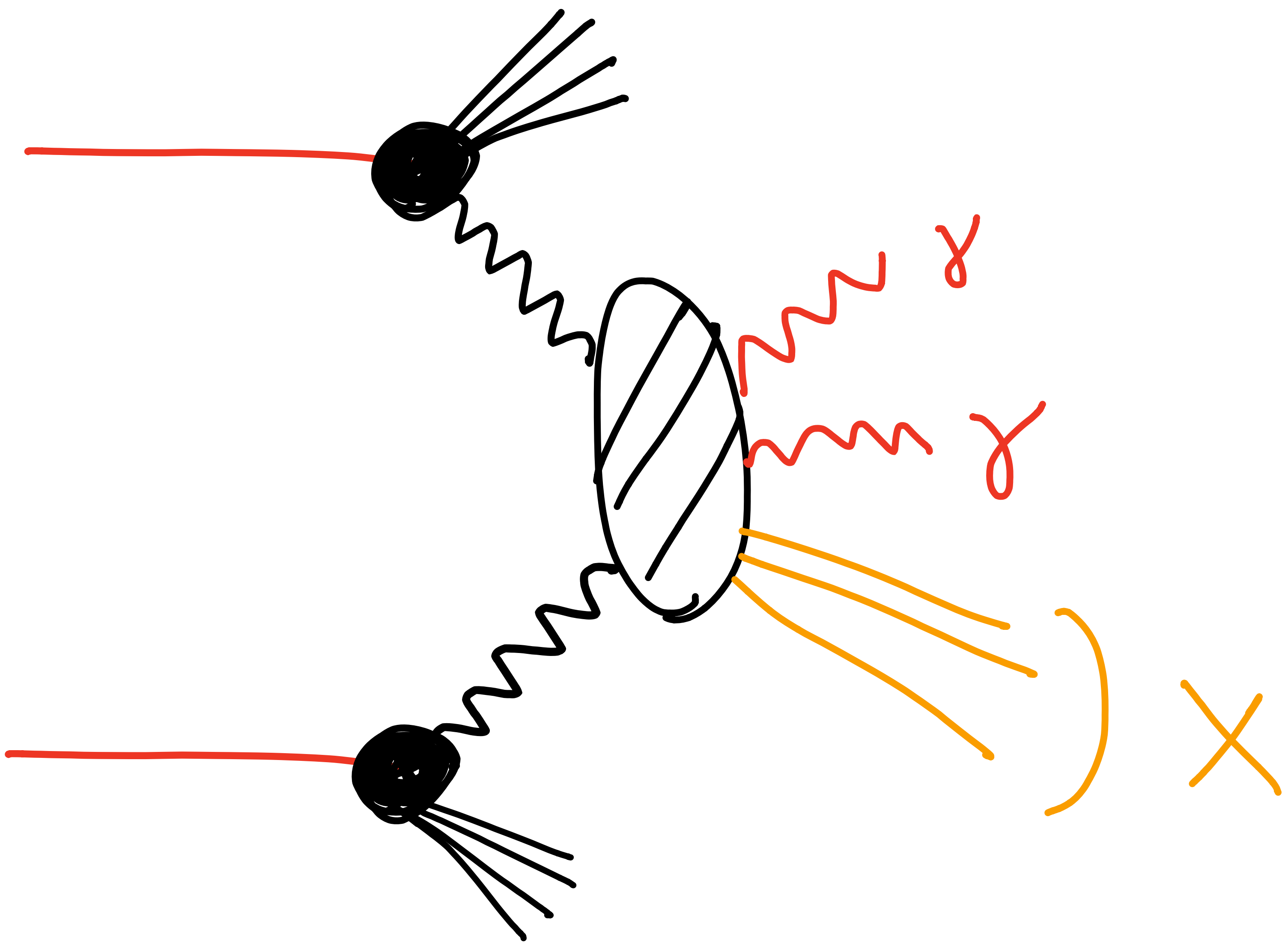


SPIN-2 ANALYSIS



simple resonance



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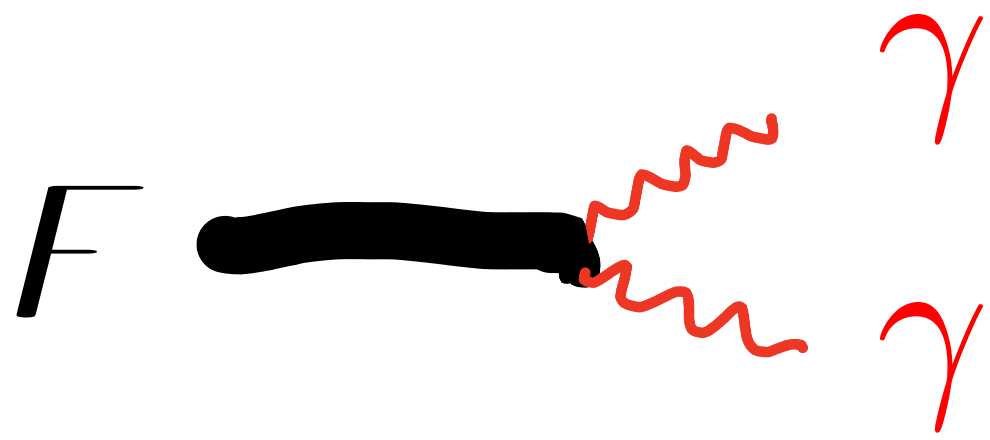
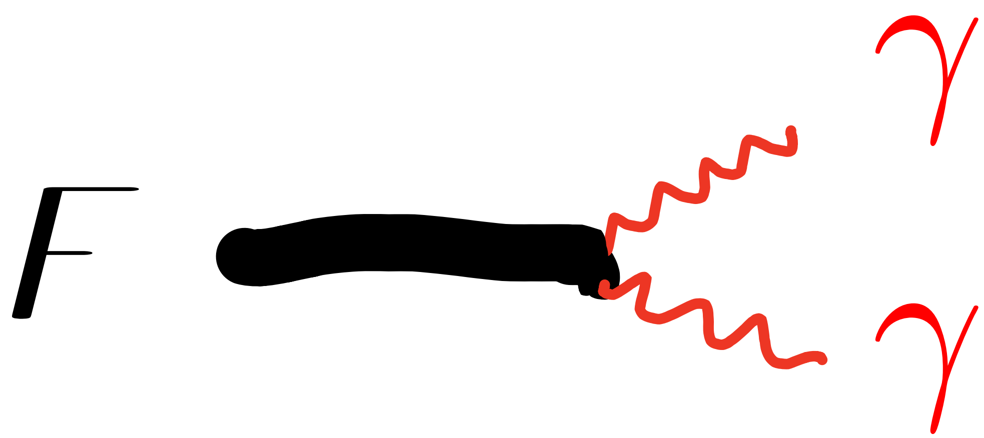


$$F \to \gamma\gamma$$

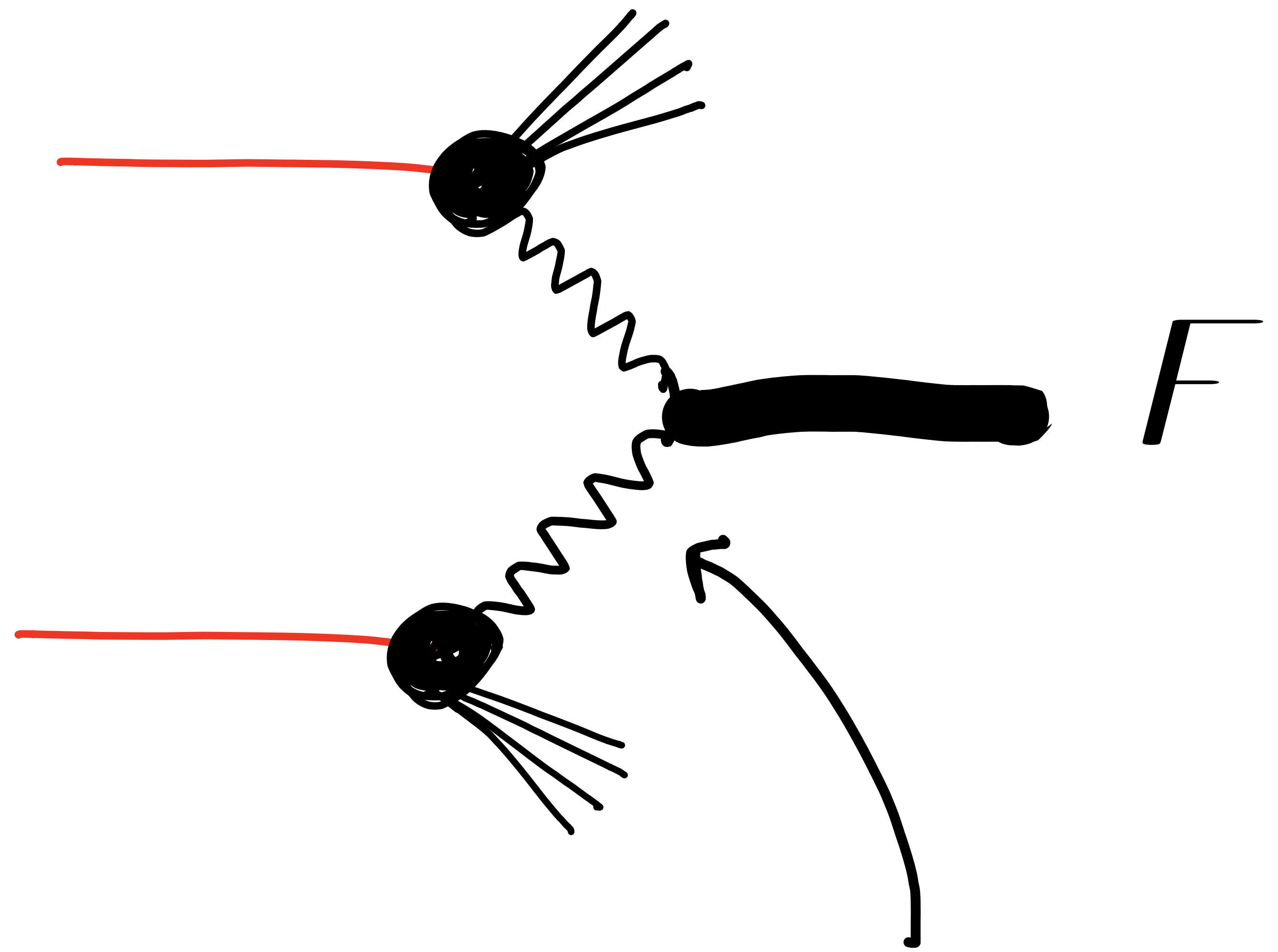
simple resonance



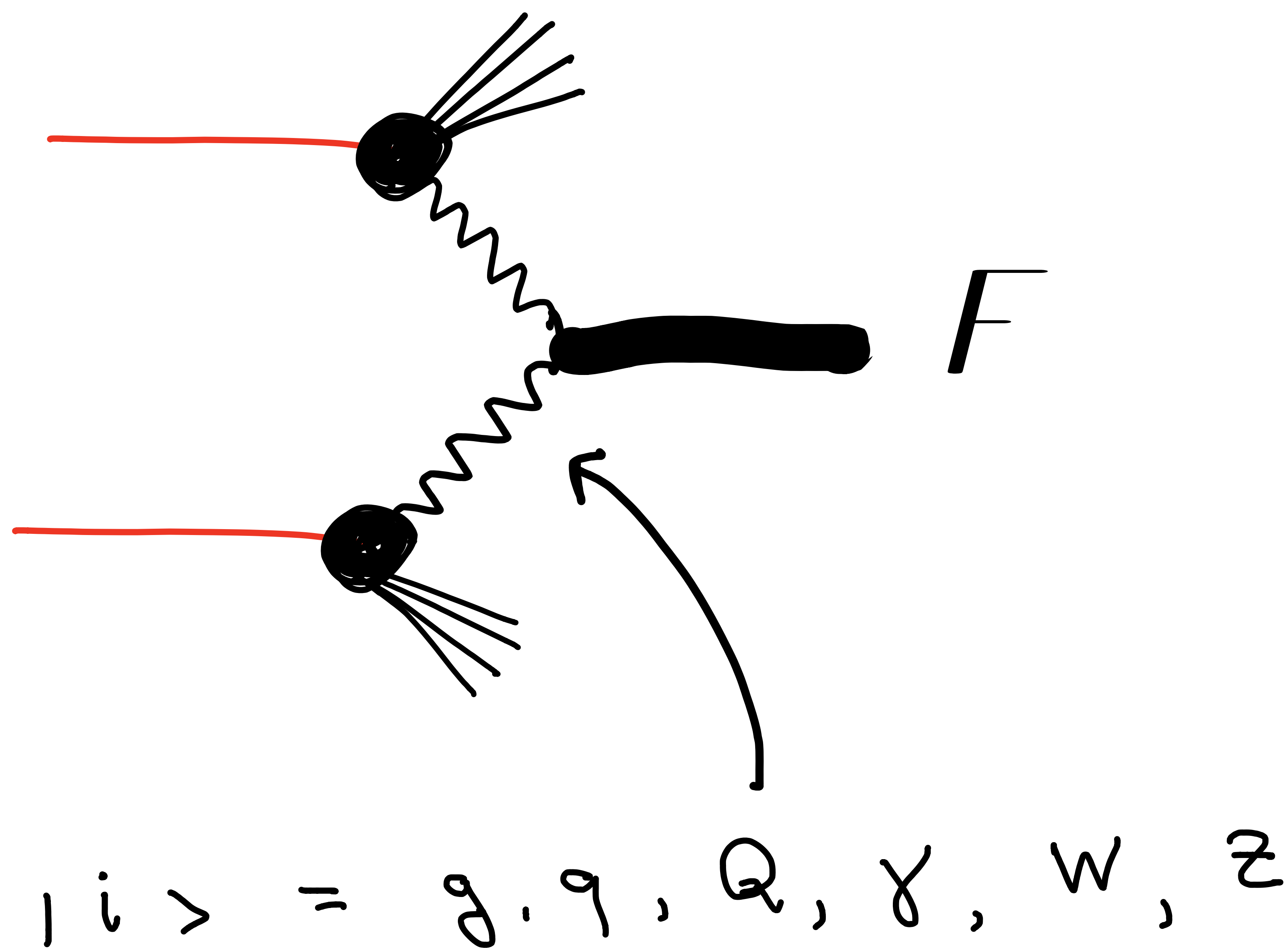
$$F \to \gamma\gamma$$

- spin
- CP (eigenstate?)
- flavor properties
- SU(2) charge

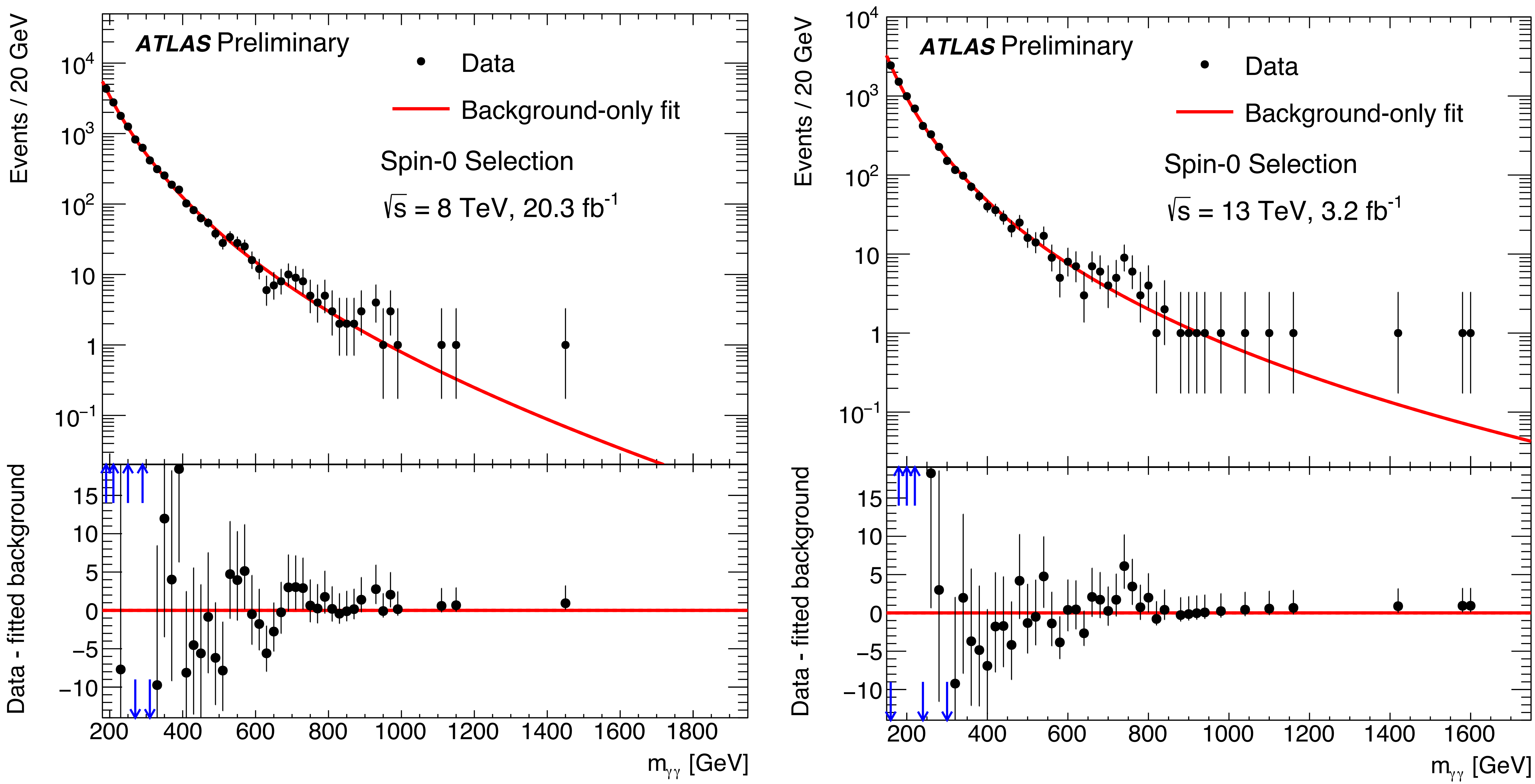
simple resonance



simple resonance

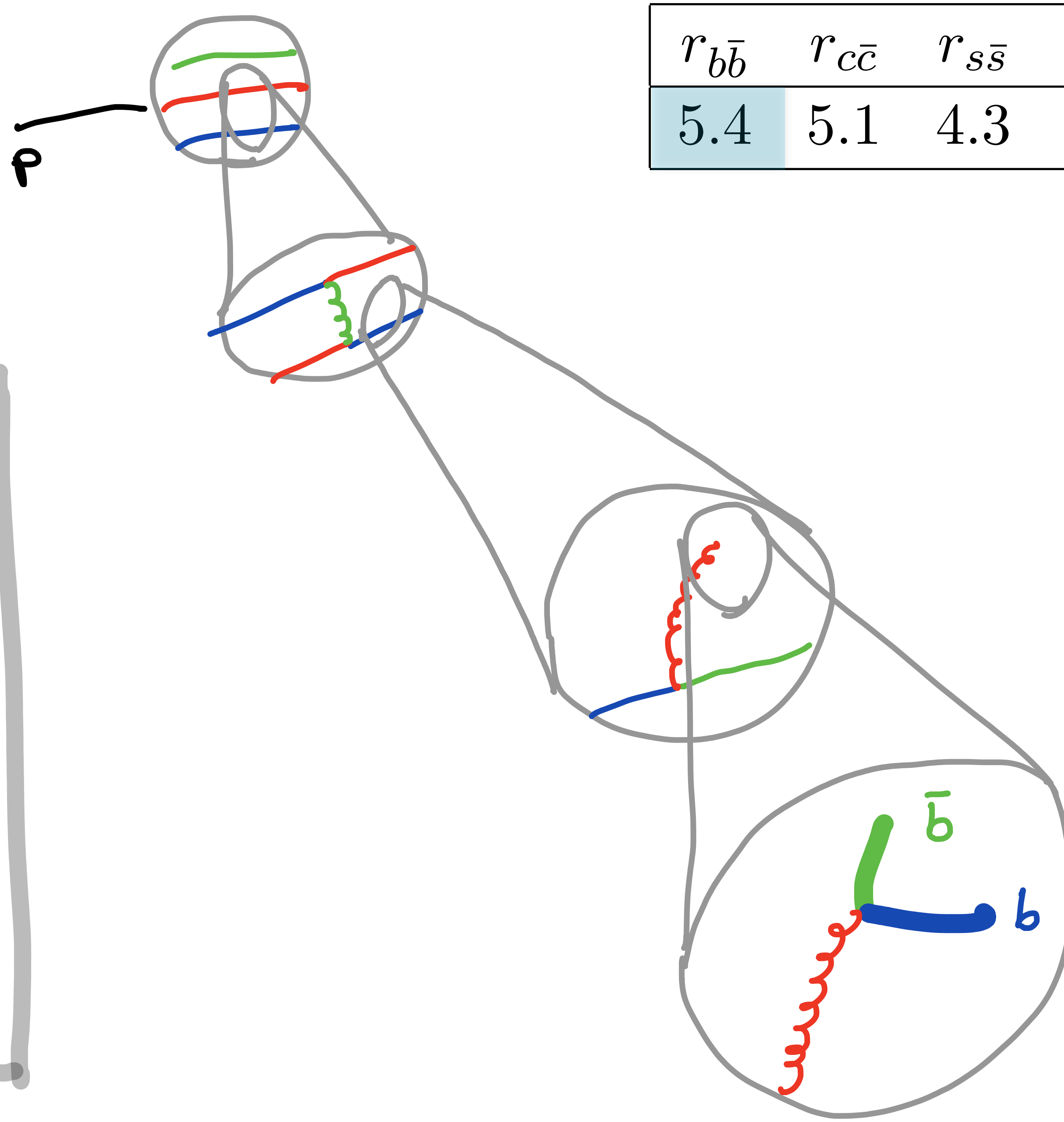


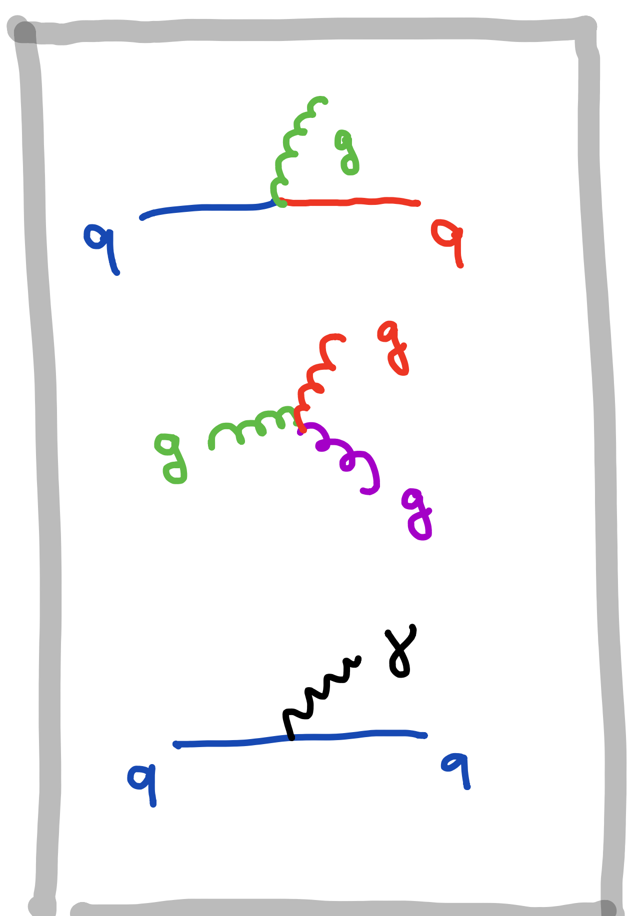
Comparison with 8 TeV



Comparison with 8 TeV

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}	$r_{\gamma\gamma}$
5.4	5.1	4.3	2.7	2.5	4.7	1.9





Spin

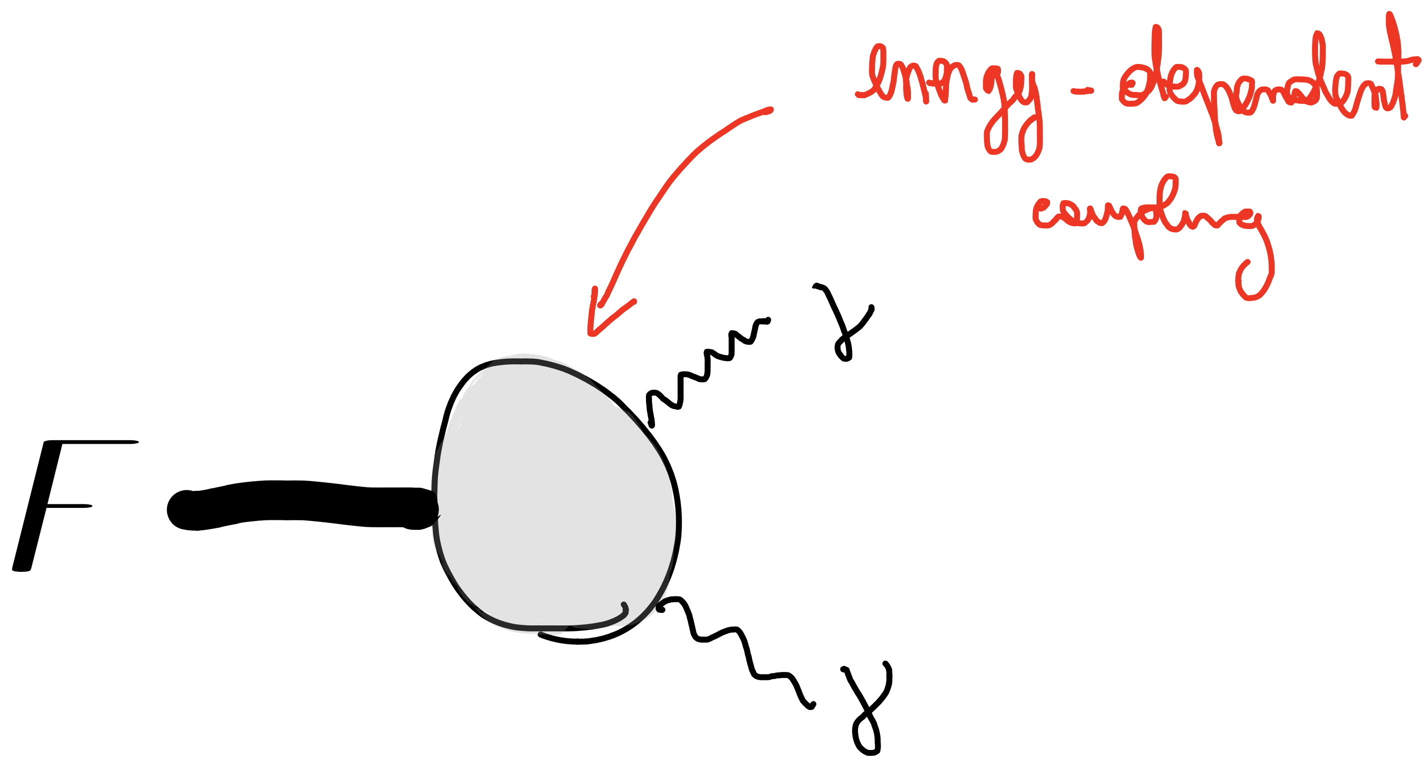
1602.02793
1603.04248
1604.06948

Spin-0: dim-5 $\mathcal{F} \cdot F^{\mu\nu} F_{\mu\nu}$

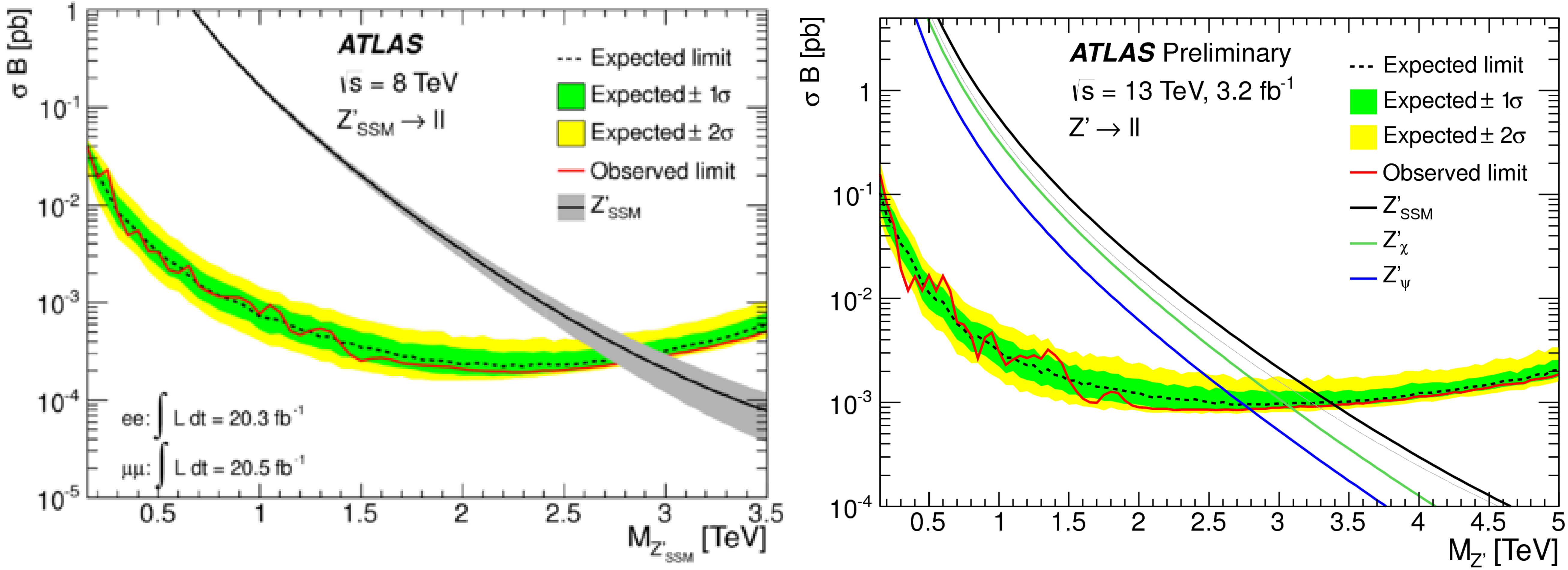
Spin-1: Landau-Yang

Spin-2: Tree-level coupling (*e.g.* $h_{\mu\nu} \cdot T^{\mu\nu}$)

…



Spin-2 and leptons

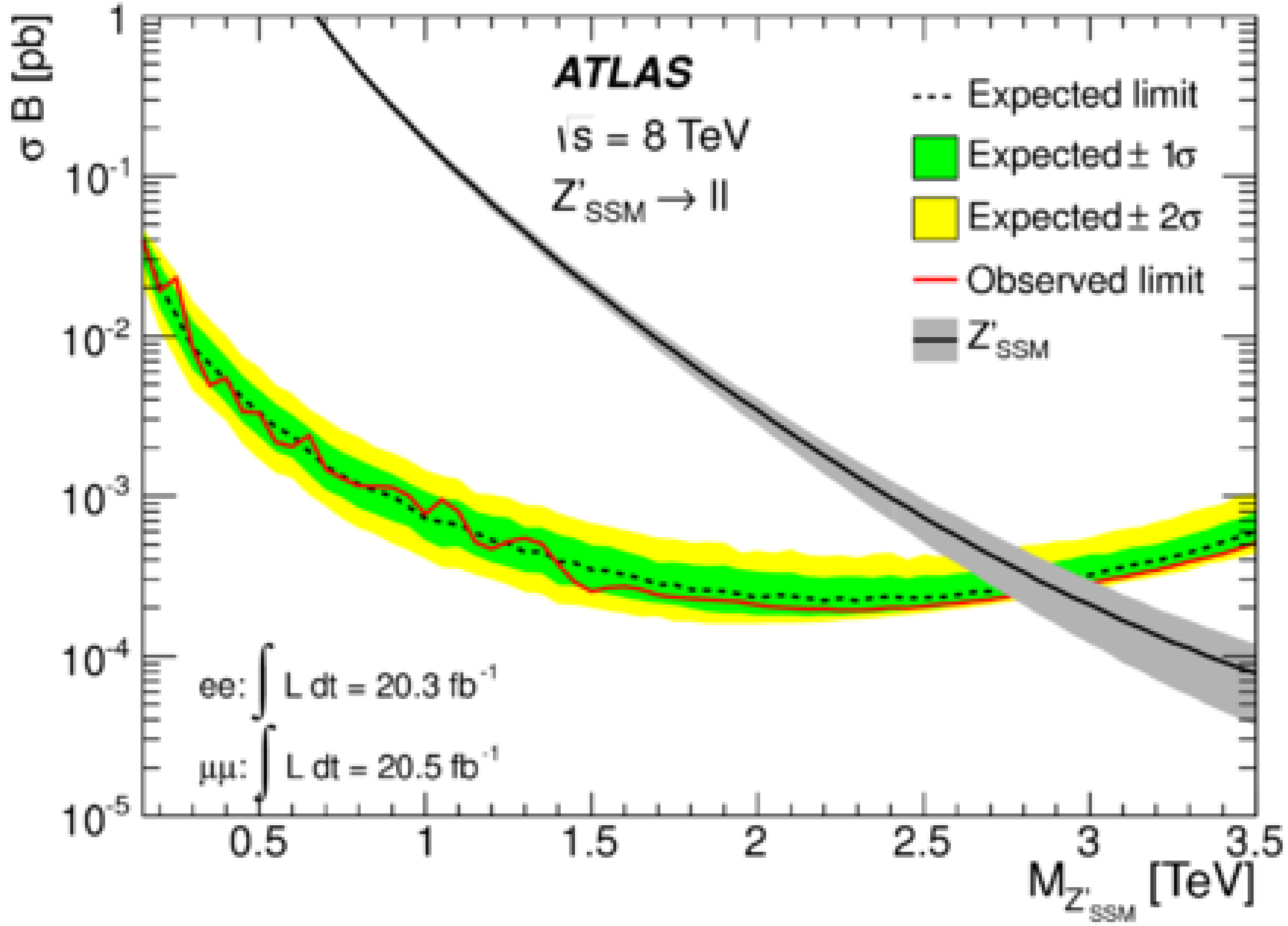


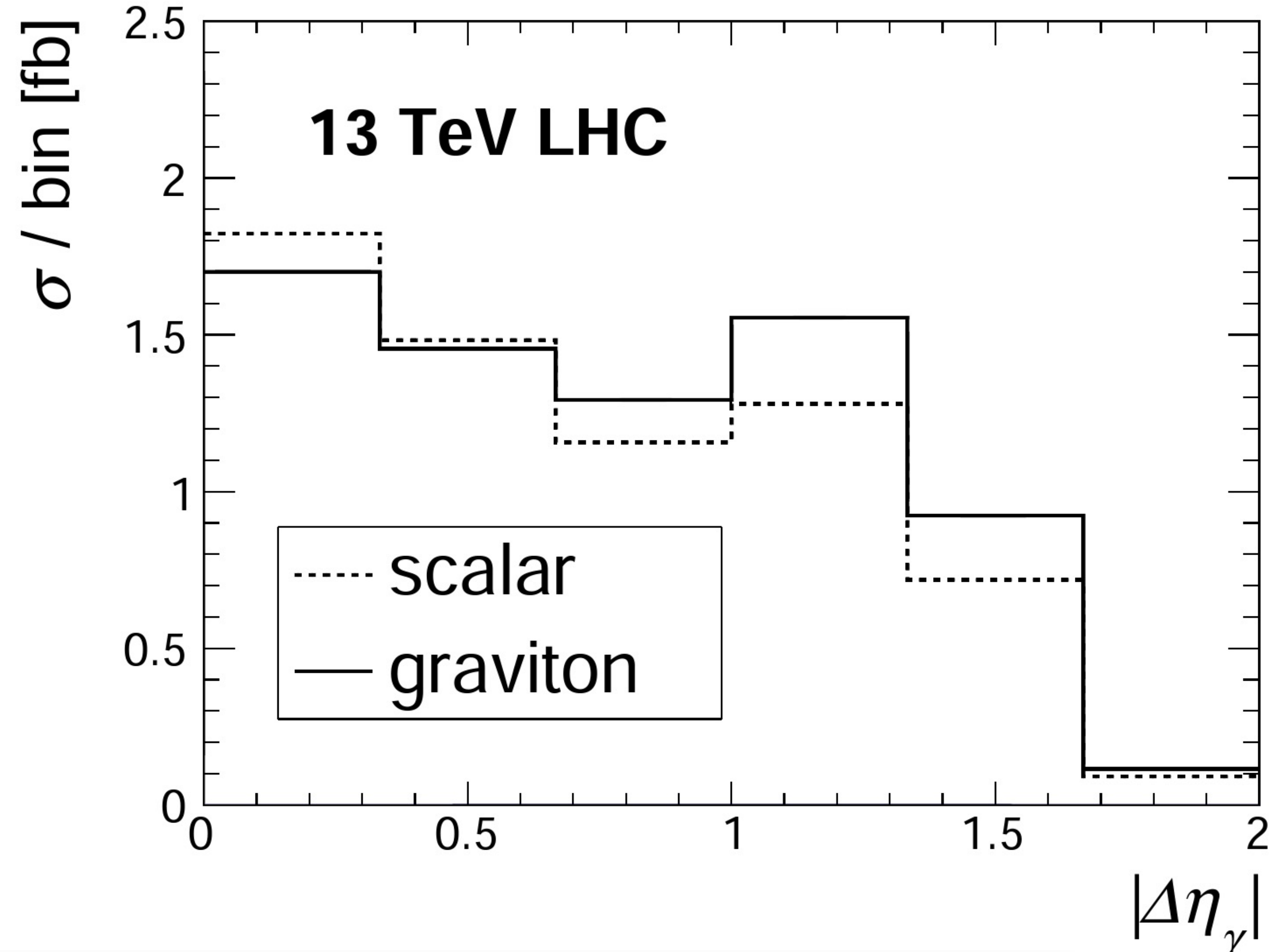
the absence of a signal in leptons points to a non-universally coupled spin-2

1603.08913
1603.06980
1603.08250
1602.02793
1603.05574

strong interactions at the TeV are typical in such frameworks

Spin-2 and leptons





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1603.08913
1603.06980
1603.08250
1602.02793
1603.05574

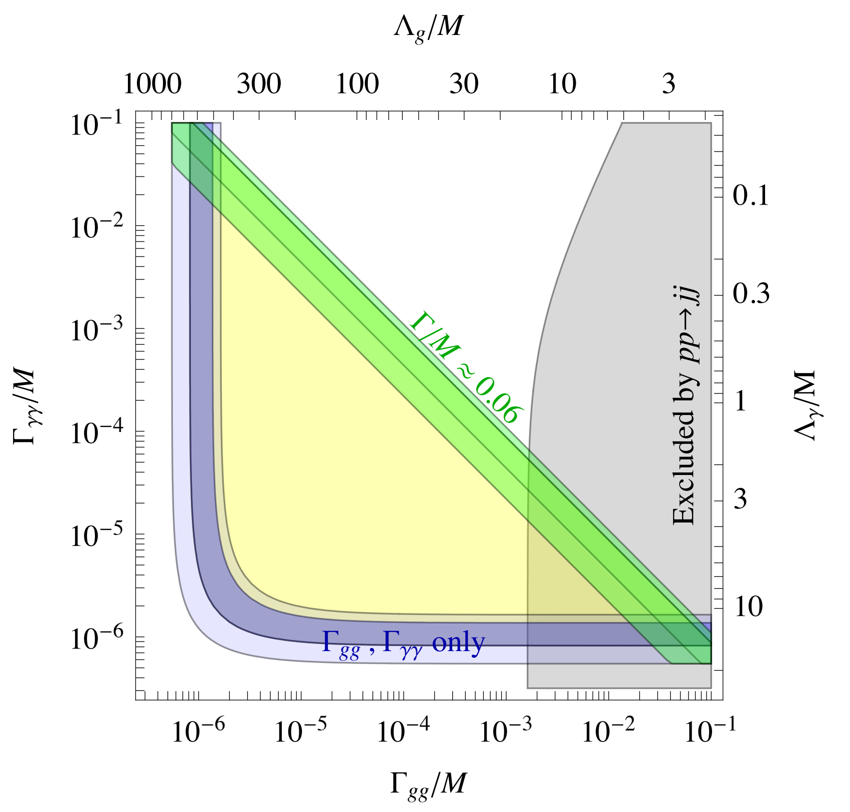
strong interactions at the TeV are typical in such frameworks

Spin-0

focus on a weak singlet for simplicity

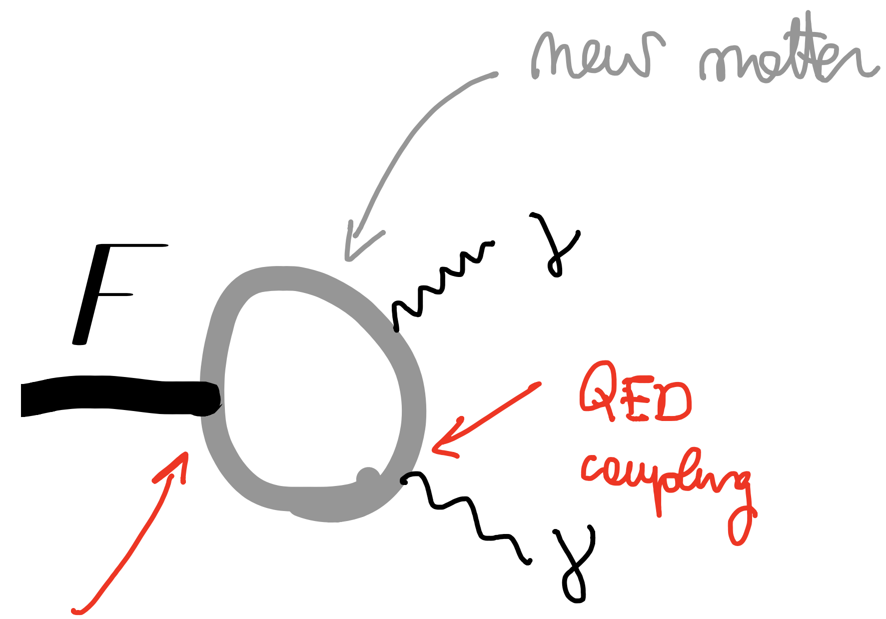
F

$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{M\Gamma s}\left[\sum_{\wp} C_{\wp\bar{\wp}}\Gamma(S \to \wp\bar{\wp})\right]\Gamma(S \to \gamma\gamma)$$



Spin-0

focus on a weak singlet for simplicity



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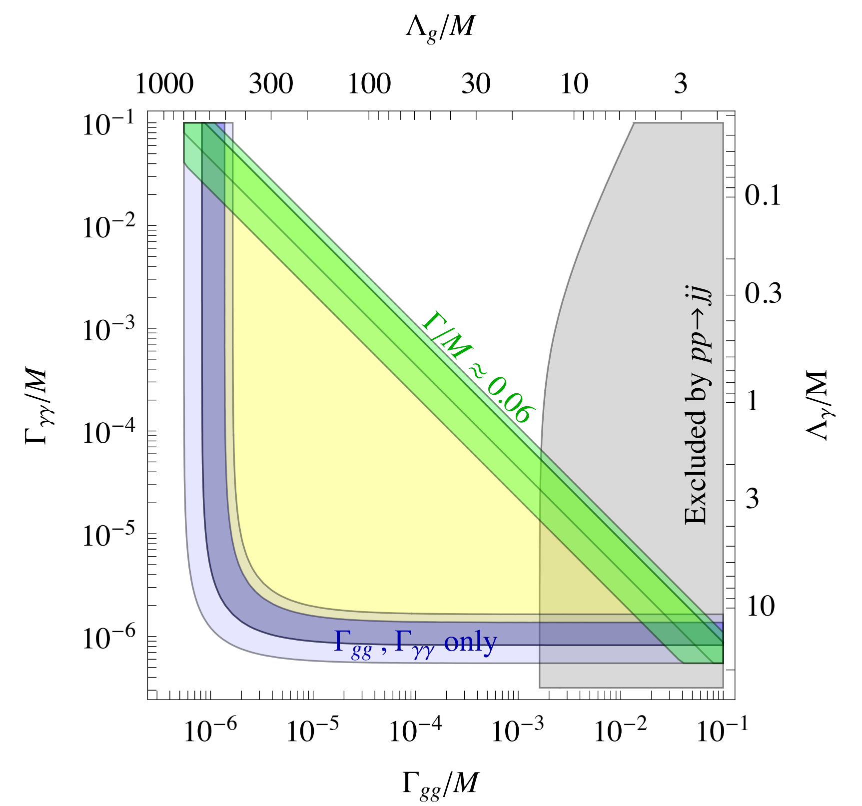

Spin-0

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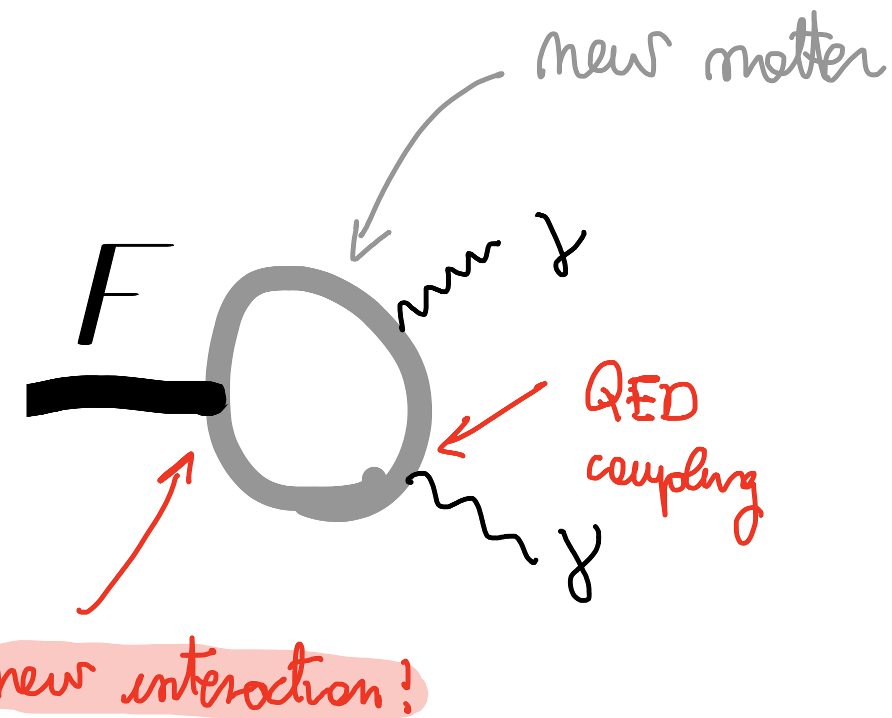

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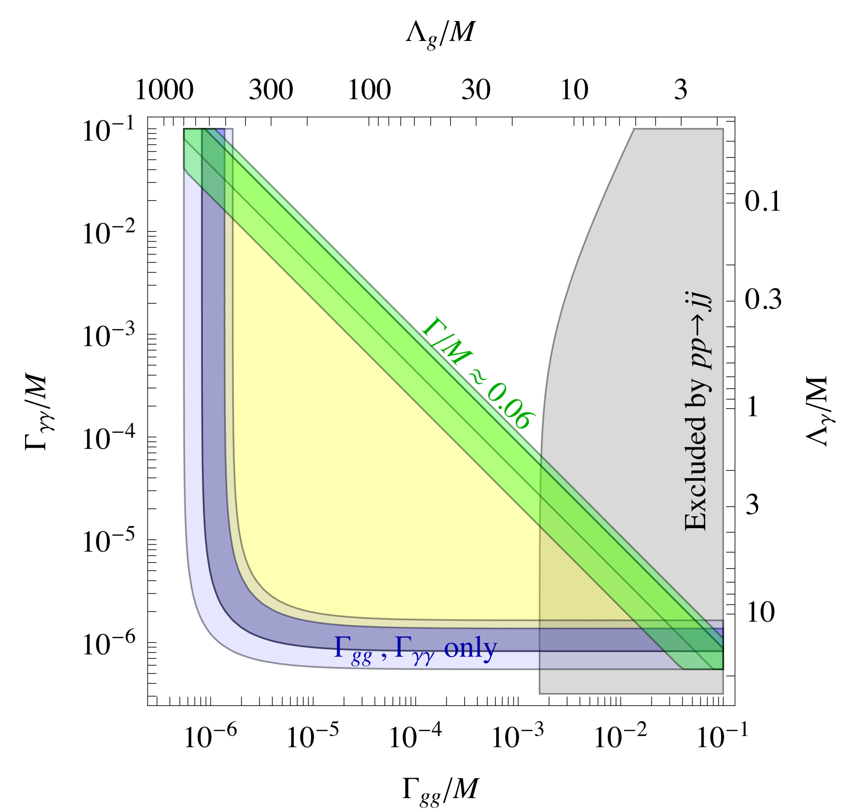

Spin-0

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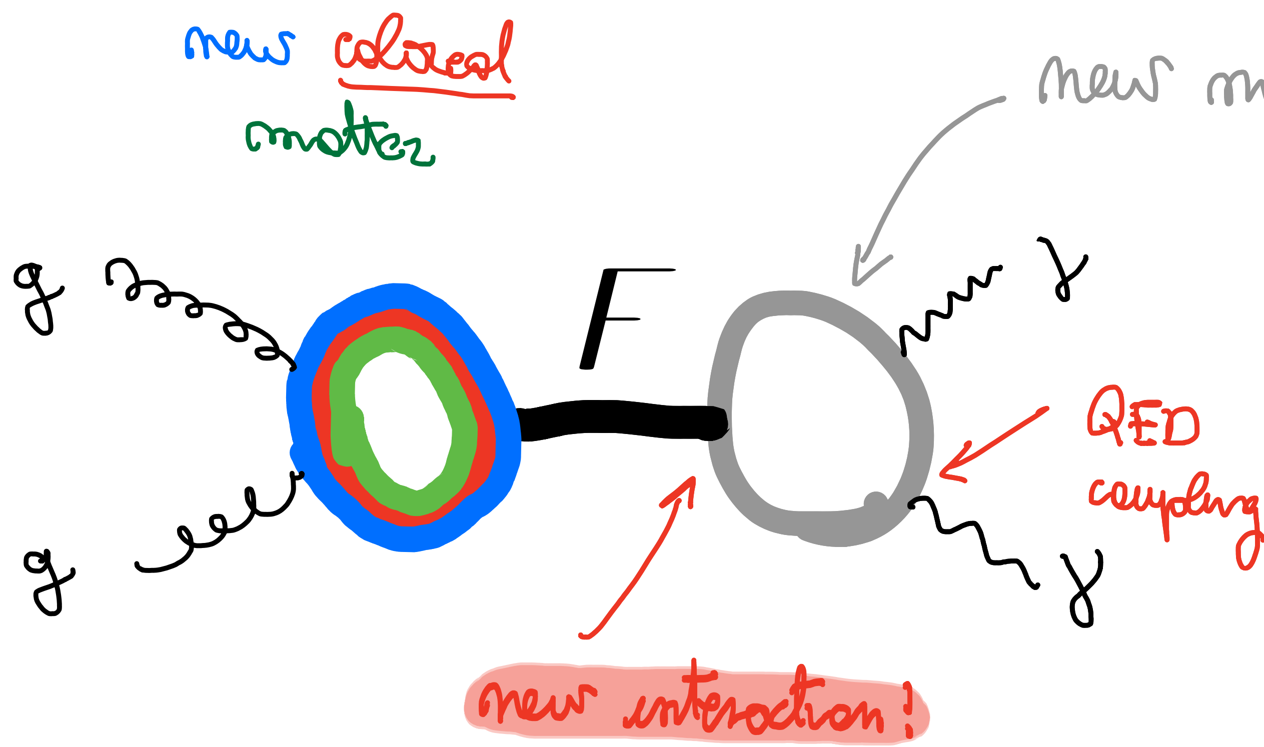

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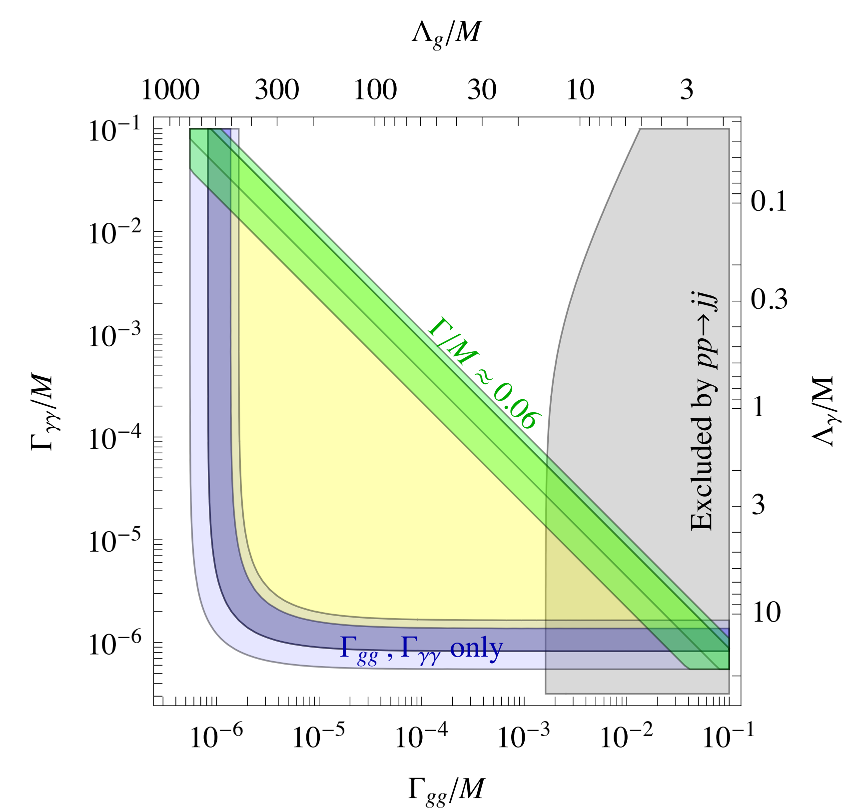

Spin-0

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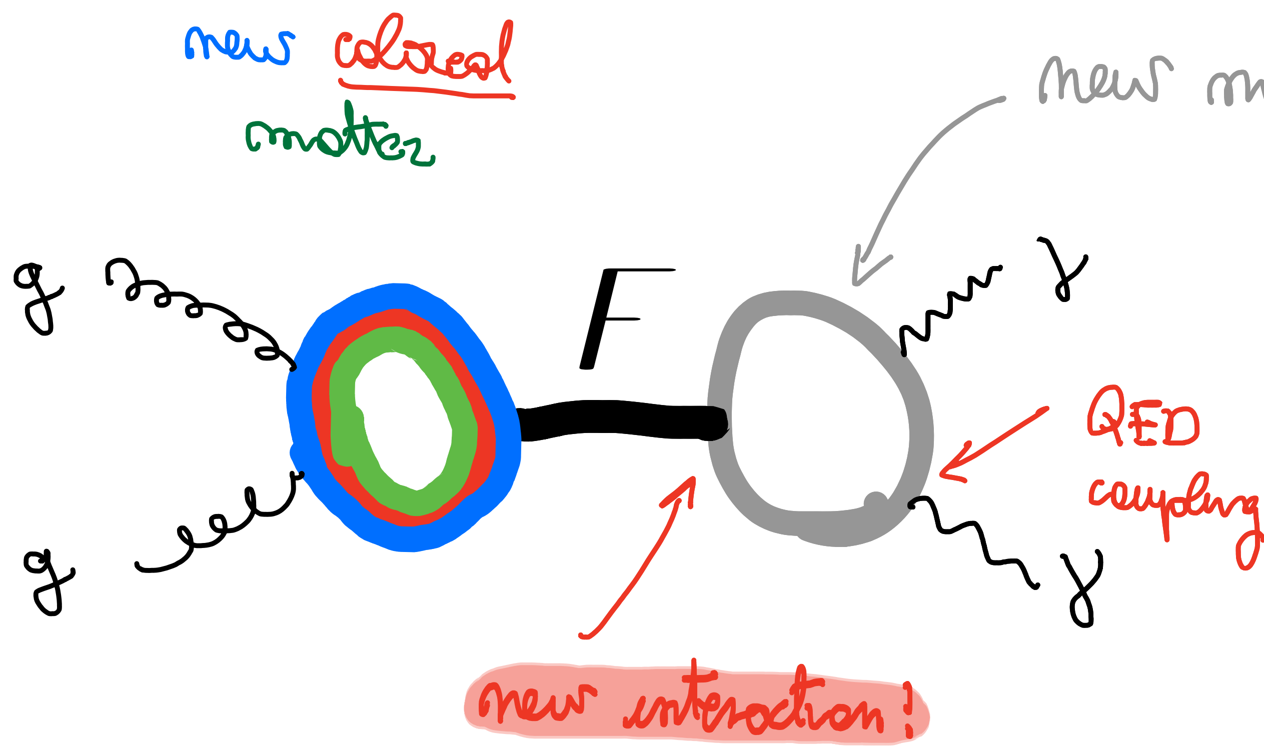

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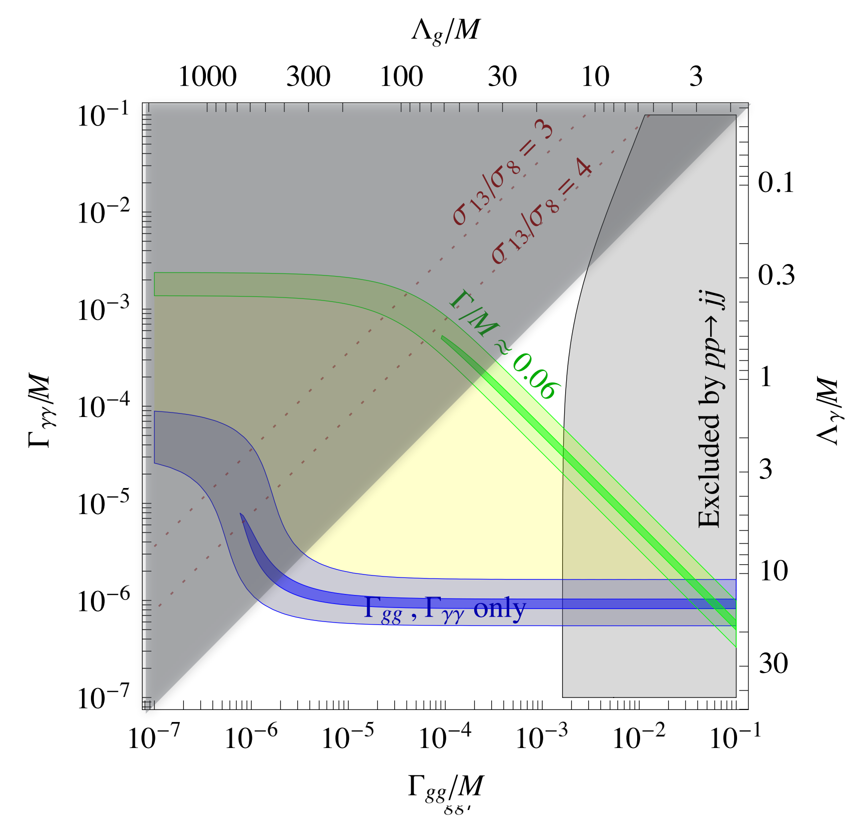
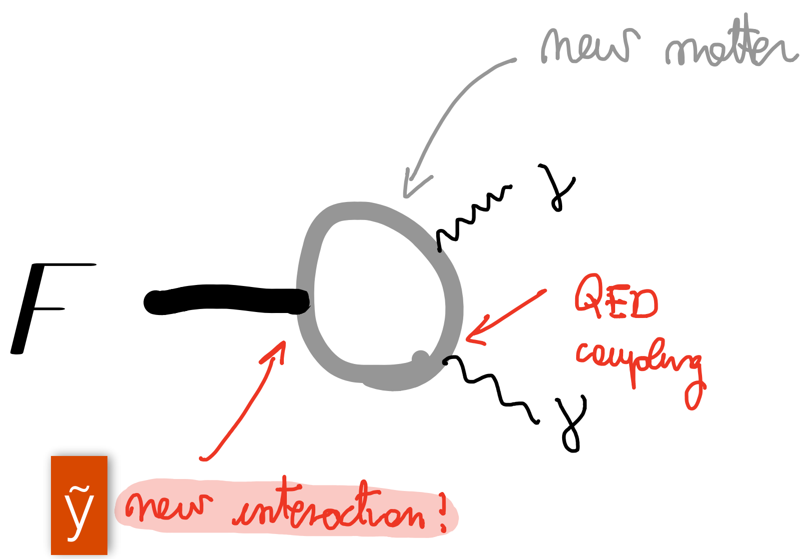


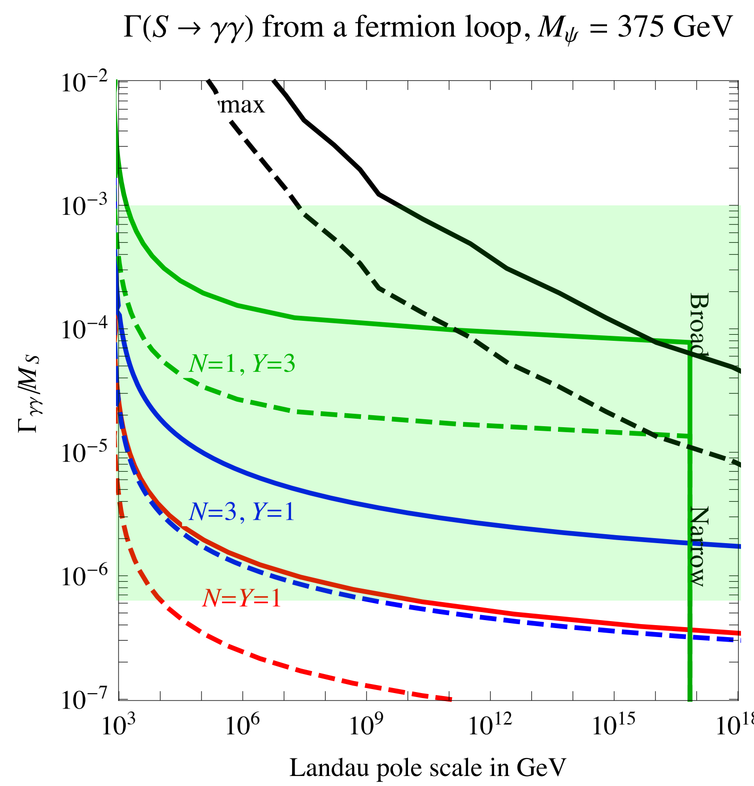
Spin-0

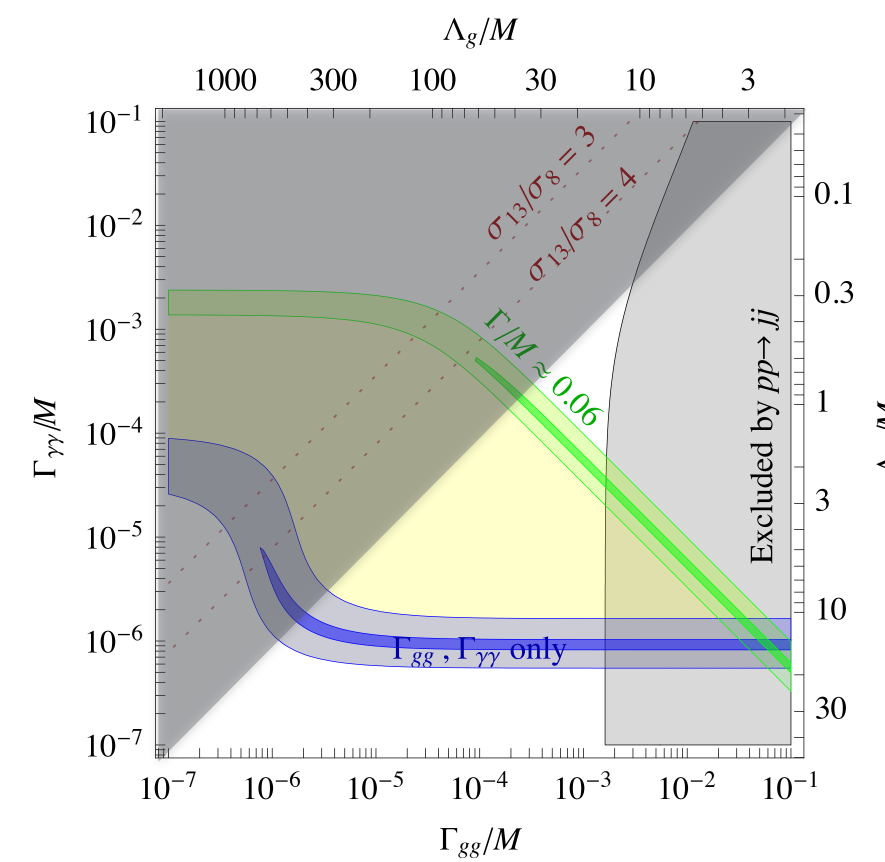
1512.08307
1512.08500
1602.01460

focus on a weak singlet for simplicity



$$\frac{\Gamma_{\gamma\gamma}}{M} \approx 0.6\ 10^{-6} N^2 \tilde{y}^2 Y^4$$





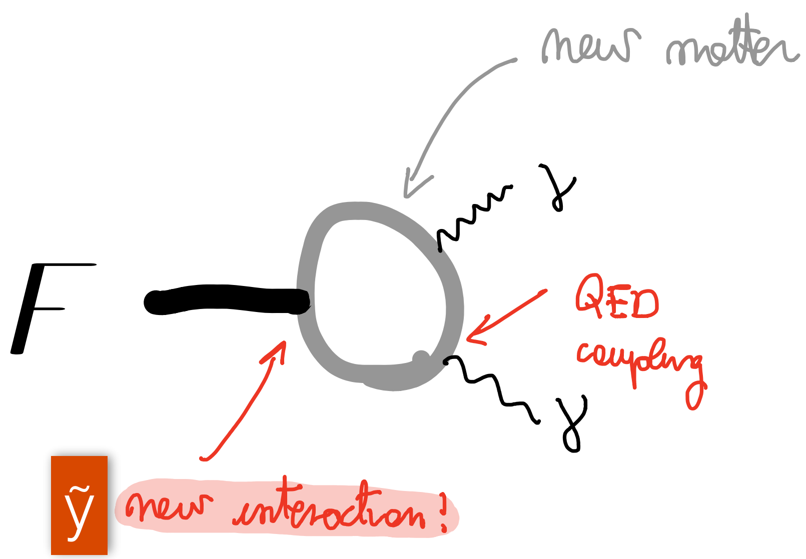
$$\frac{d\tilde{y}}{d\ln\mu} \propto \tilde{y}^3 \left(2Nd\right) - \text{gauge terms}$$

$$\frac{dg_1}{d\ln\mu} \propto g_1^3 \left(\frac{41}{6} + \underbrace{\frac{4}{3} Y^2 N d}_{\text{new matter (fermions)}}\right)$$

1512.08307
1512.08500
1602.01460

Spin-0

focus on a weak singlet for simplicity



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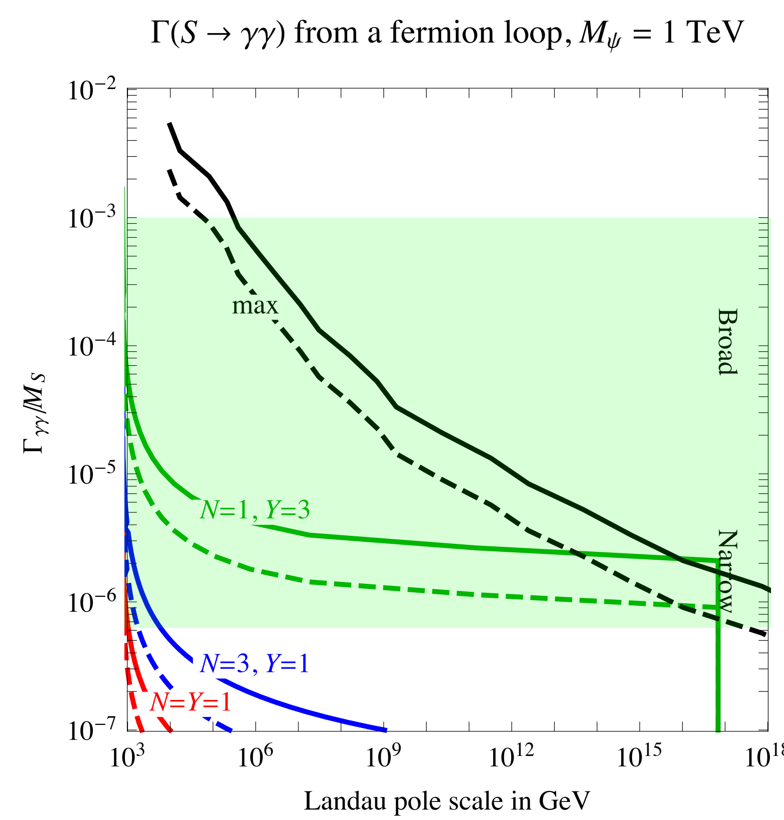

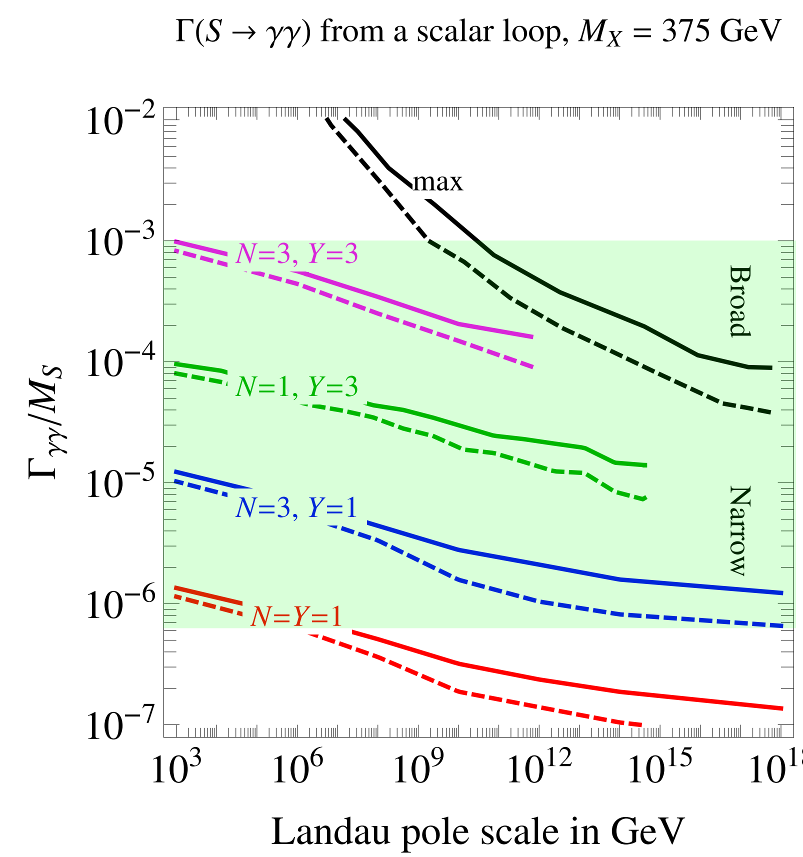

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Spin-0

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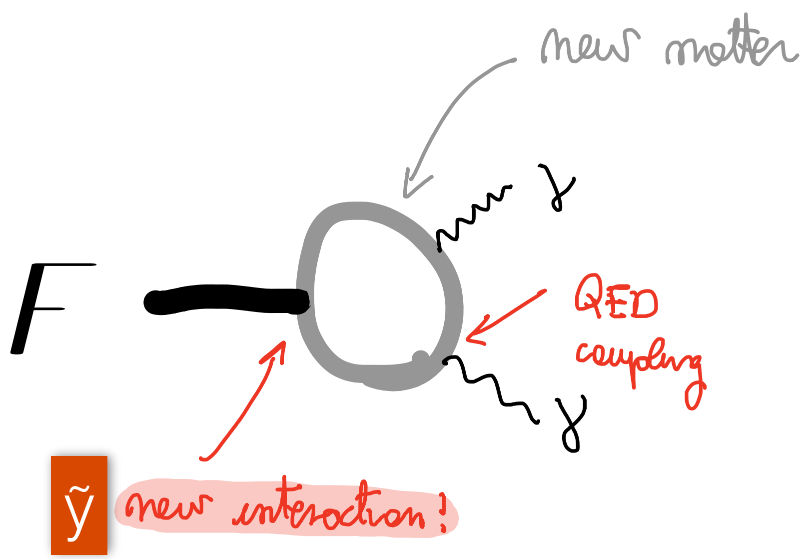

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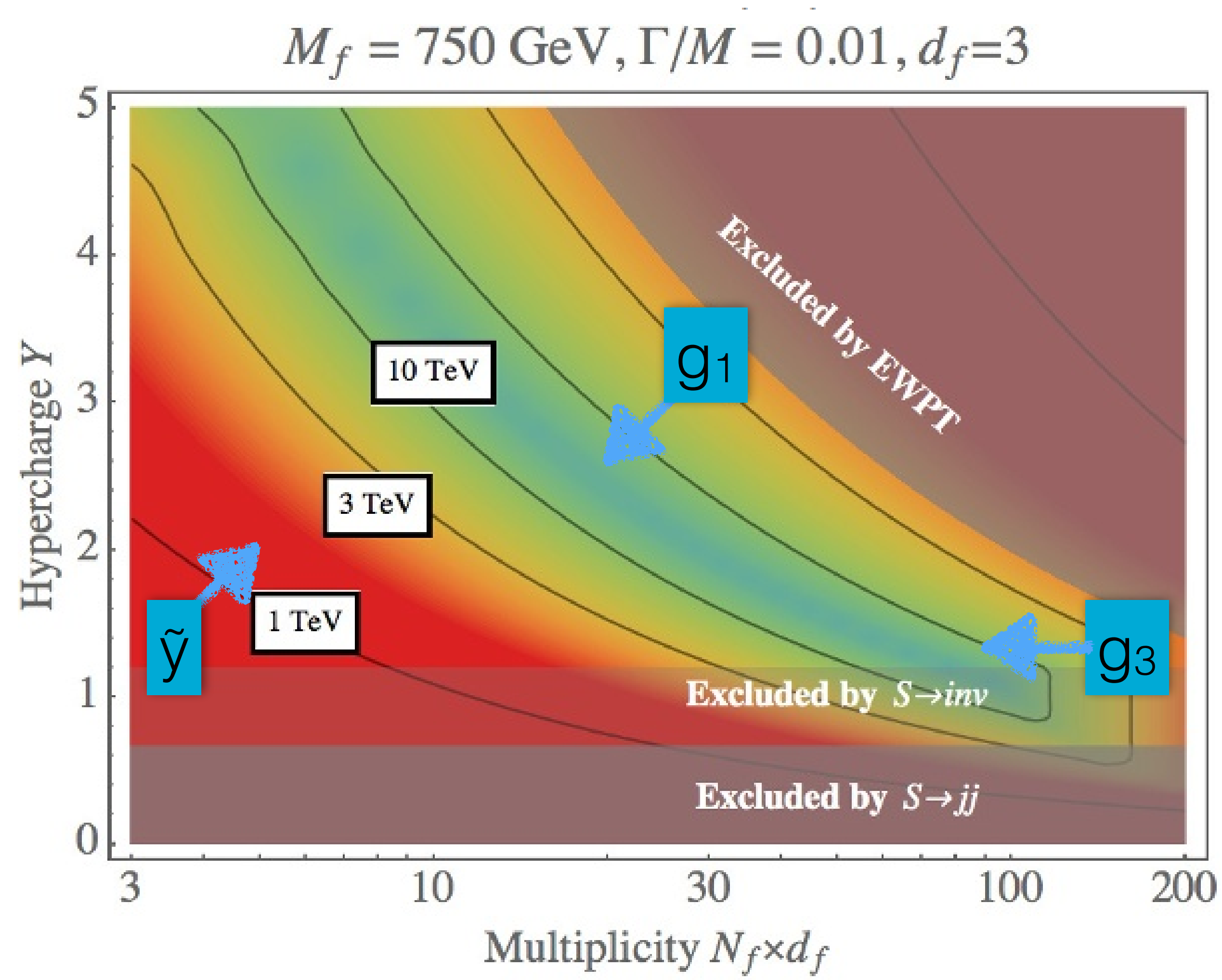

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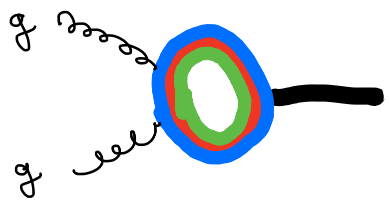
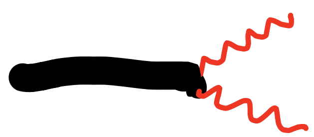
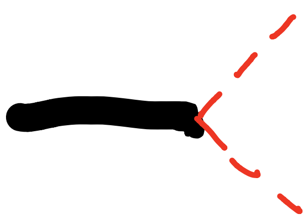
new strong
interactions

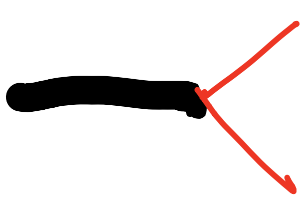
Other resonance channels



$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$ narrow	broad	$\sqrt{s} = 13\,\text{TeV}$ narrow	broad
CMS	$0.63 \pm 0.31\,\text{fb}$	$0.99 \pm 1.05\,\text{fb}$	$4.8 \pm 2.1\,\text{fb}$	$7.7 \pm 4.8\,\text{fb}$
ATLAS	$0.21 \pm 0.22\,\text{fb}$	$0.88 \pm 0.46\,\text{fb}$	$5.5 \pm 1.5\,\text{fb}$	$7.6 \pm 1.9\,\text{fb}$







final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\text{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[78]
$\tau^+\tau^-$	< 12 fb	< 15 fb	[3]	< 60 fb	< 67 fb	[79]
$Z\gamma$	< 11 fb	< 11 fb	[3]	< 28 fb	< 40 fb	[80]
ZZ	< 12 fb	< 20 fb	[3]	< 200 fb	< 220 fb	[81]
Zh	< 19 fb	< 28 fb	[3]	< 116 fb	< 116 fb	[82]
hh	< 39 fb	< 42 fb	[3]	< 120 fb	< 110 fb	[83]
W^+W^-	< 40 fb	< 70 fb	[3]	< 300 fb	< 300 fb	[84]
$t\bar{t}$	< 450 fb	< 600 fb	[3]			
invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

	$\frac{\sigma_{13\,\text{TeV}}}{\sigma_{8\,\text{TeV}}}$	$10^2\times$	r^γ_{WW}	r^γ_{ZZ}	$r^\gamma_{Z\gamma}$	r^γ_{hh}	$r^\gamma_{t\bar{t}}$	$r^\gamma_{\tau\bar{\tau}}$	$r^\gamma_{\ell\bar{\ell}}$	r^γ_{gg}
ATLAS	2.9 [5]*		3.0 [7]	13 [9]*	19 [10]*	4.1 [11]*	0.22 [13]	15 [15]	124 [17]*	0.14 [19]
CMS	4.0 [6]		0.5 [8]	4.6 [8]	—	2.8 [12]*	0.33 [14]	7.4 [16]	114 [18]*	0.083 [20]*

Strong interactions

- pseudo-Nambu-Goldstone bosons of:
  A. internal symmetries
  B. “susy”
  C. conformal
- Quarkonium (and quirks)
- …

Goldstone bosons

1512.05330

π^0 in QCD is an inspiring template

$$\pi^0 \to \gamma\gamma$$

unlike the QCD pion

1. the large absolute width $\Gamma(\mathbf{F} \to \gamma\gamma)$ suggest lots of states ($\Gamma(\mathbf{F} \to \gamma\gamma)/M \gtrsim 10^{-6}$, 10^{-4} in most scenarios, vs $\Gamma(\pi^0 \to \gamma\gamma)/m_\pi \sim 10^{-7}$)
2. for a generic scalar expect a proportionally large contribution to the mass of **F**

shift symmetry protection to the mass of the GB!

Goldstone bosons

1512.05330

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2. for a generic scalar expect a proportionally large contribution to the mass of **F**

shift symmetry protection to the mass of the GB!

coupling to all gauge bosons (can) naturally arise at the same order

couplings to fermions protected by chiral symmetry

$$\mathcal{L}_I^{\Phi=\eta} = -i\frac{\eta}{f}\left(C_t m_t \bar{t}\gamma^5 t + C_b m_b \bar{b}\gamma^5 b + C_\tau m_\tau \bar{\tau}\gamma^5 \tau\right)$$
$$-\frac{\eta}{f}\left(C_{gg}\frac{\alpha_3}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + C_{\gamma\gamma}\frac{\alpha_e}{8\pi}F_{\mu\nu}\tilde{F}_{\mu\nu}\right)$$
$$-\frac{\eta}{f}\left(C_{WW}\frac{\alpha_2}{4\pi}W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + C_{ZZ}\frac{\alpha_2\cos^2\theta_W}{8\pi}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{Z\gamma}\frac{\alpha_e}{4\pi\tan\theta_W}Z_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

CP odd

Higgs + F as Goldstone (η)

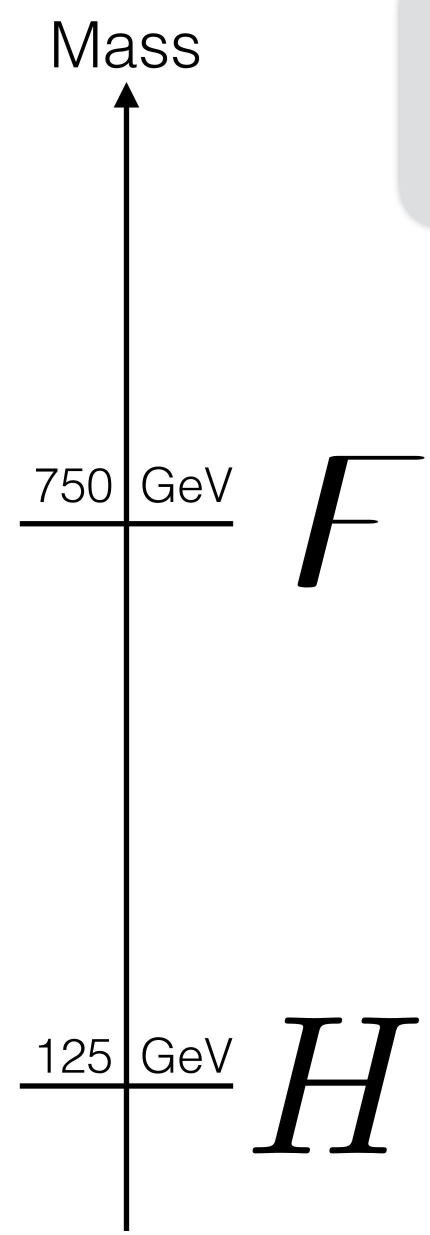
global symmetry breaking G→ H (*e.g.* SU(3)^2 → SU(2))

1512.05330

$$\mathcal{L}_I^\eta = -\frac{\eta}{f}\left(iC_t\frac{\sqrt{2}m_t}{v}\bar{q}_L\tilde{H}t_R + h.c. + \dots\right)$$
$$-\frac{\eta}{f}\left(C_G\frac{\alpha_3}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + C_W\frac{\alpha_2}{8\pi}W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu} + C_B\frac{\alpha_1}{8\pi}B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

F is (less) light compared to the scale of symmetry breaking

Higgs is light compared to the scale of symmetry breaking



$$\Gamma_{\gamma\gamma} = \left(\frac{\alpha_e}{8\pi f}\right)^2\frac{m_\eta^3}{\pi}\left|C^{\text{eff}}_{\gamma\gamma}\right|^2,$$
$$C^{\text{eff}}_{\gamma\gamma} = C_{\gamma\gamma} + \frac{1}{2}C_t N_c^{(t)}Q_t^2\,A_{1/2}(x_t)\,,$$

$$\Gamma_{gg} = 8\left(\frac{\alpha_3}{8\pi f}\right)^2\frac{m_\eta^3}{\pi}\left|C^{\text{eff}}_{gg}\right|^2,$$
$$C^{\text{eff}}_{gg} = C_{gg} + \frac{1}{4}C_t\,A_{1/2}(x_t)\,,$$

$$\Gamma_{t\bar{t}} \simeq 3\frac{C_t^2}{8\pi}\frac{m_t^2 m_\eta}{f^2}$$

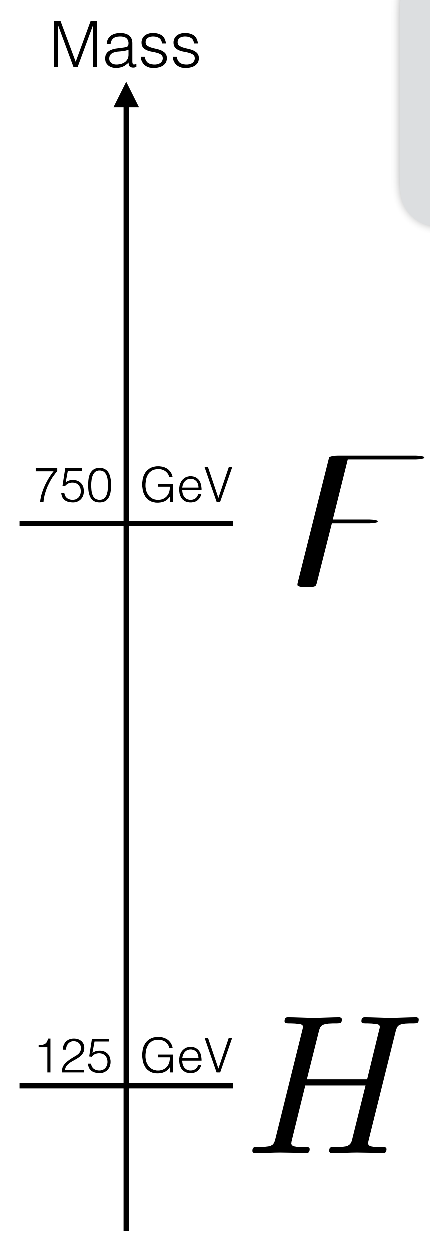
Higgs + F as Goldstone (η)

global symmetry breaking G→ H (*e.g.* SU(3)² → SU(2))

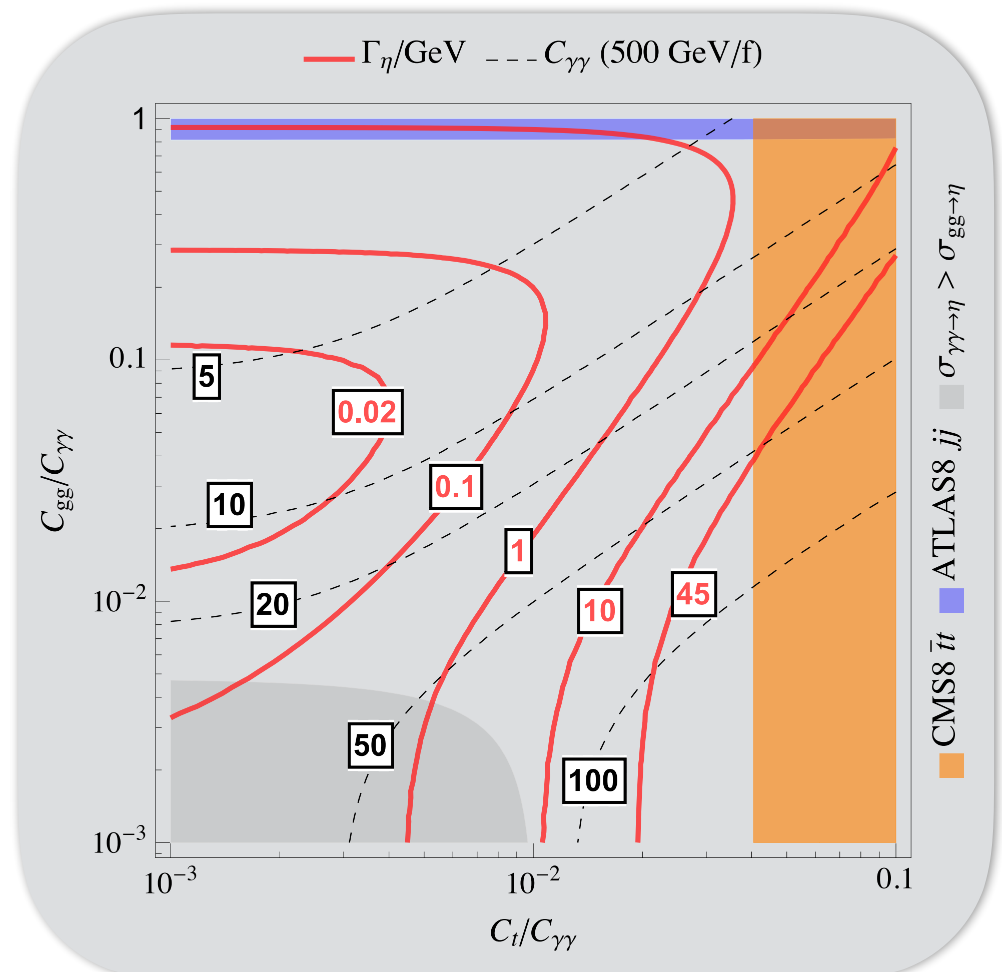
1512.05330

F is (less) light compared to the scale of symmetry breaking

Higgs is light compared to the scale of symmetry breaking



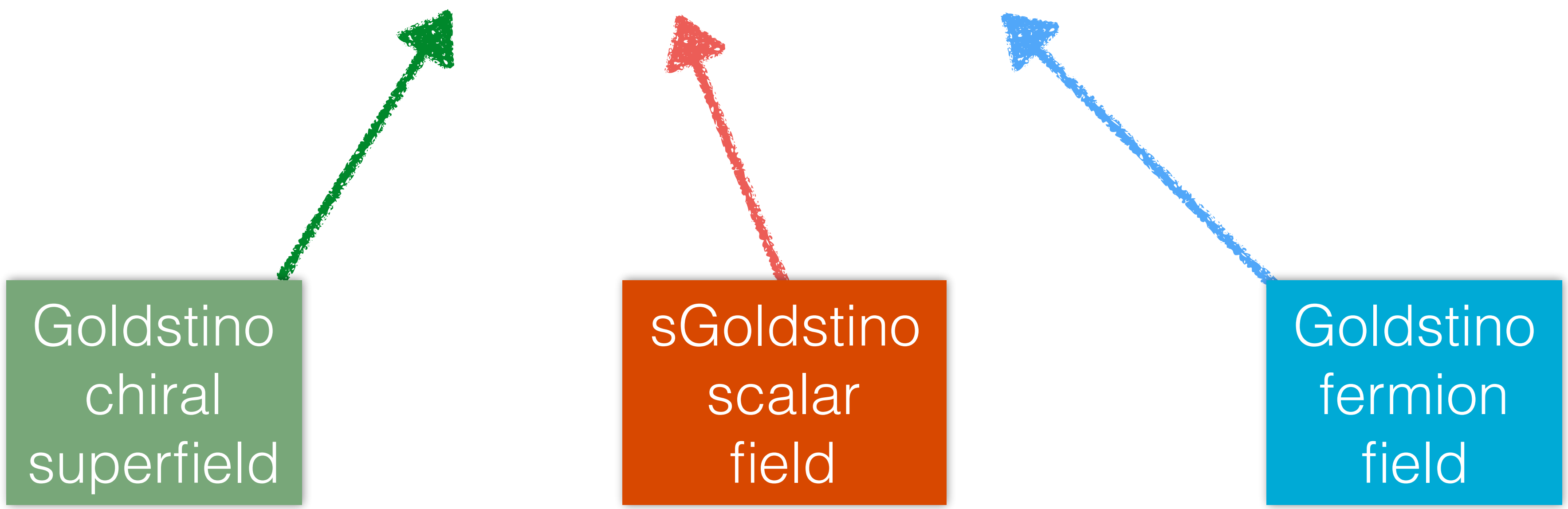
$$\mathcal{L}_I^\eta = -\frac{\eta}{f}\left(iC_t\frac{\sqrt{2}m_t}{v}\bar{q}_L\tilde{H}t_R + h.c. + \dots\right) - \frac{\eta}{f}\left(C_G\frac{\alpha_3}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + C_W\frac{\alpha_2}{8\pi}W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu} + C_B\frac{\alpha_1}{8\pi}B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$



F as a sGoldstino (Φ)

1512.05330

$$X = \Phi + \sqrt{2}\theta G + \theta^2 F_X$$



$$-\frac{1}{2\mathcal{F}}\int d^2\theta X\left(m_1 W^\alpha W_\alpha + m_2 W^{\alpha\, a_2} W_\alpha^{a_2} + m_3 W^{\alpha\, a_3} W_\alpha^{a_3}\right) + h.c.$$

coupling of the sGoldstino are proportional to the SUSY breaking masses

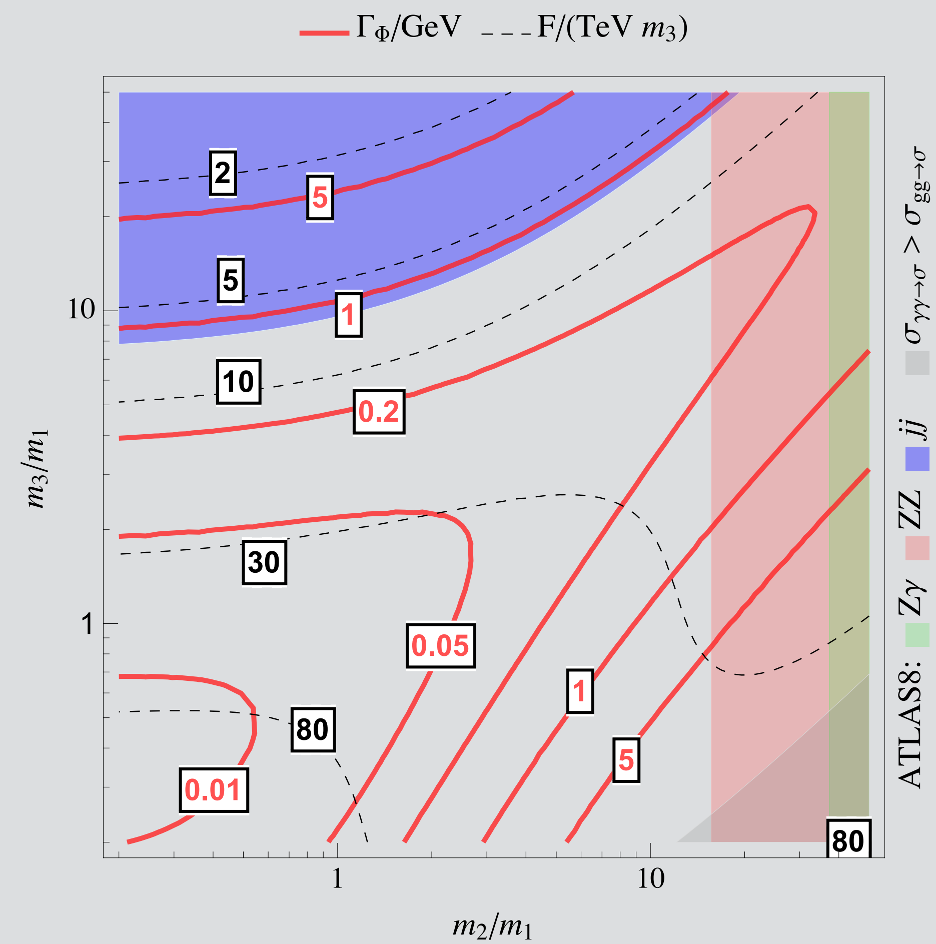
$$\Gamma_{gg} = \left(\frac{m_3}{2\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}\,, \qquad \Gamma_{\gamma\gamma} = \frac{1}{2}\left(\frac{m_{\sigma\gamma\gamma}}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}\,,$$

negligible decay to 2 invisible Goldstino

$$\Gamma_{ZZ} \simeq \frac{1}{2}\left(\frac{m_{\sigma ZZ}}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}\,, \qquad \Gamma_{WW} \simeq \left(\frac{m_2}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}\,, \qquad \Gamma_{Z\gamma} \simeq \left(\frac{m_{\sigma Z\gamma}}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}\,.$$

F as a sGoldstino (Φ)

1512.05330



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$$\Gamma_{gg} = \left(\frac{m_3}{2\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}, \qquad \Gamma_{\gamma\gamma} = \frac{1}{2}\left(\frac{m_{\sigma\gamma\gamma}}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi},$$

negligible decay to 2 invisible Goldstino

$$\Gamma_{ZZ} \simeq \frac{1}{2}\left(\frac{m_{\sigma ZZ}}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}, \qquad \Gamma_{WW} \simeq \left(\frac{m_2}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}, \qquad \Gamma_{Z\gamma} \simeq \left(\frac{m_{\sigma Z\gamma}}{4\mathcal{F}}\right)^2 \frac{m_\sigma^3}{\pi}.$$

F as a Dilaton (σ)

spontaneous symmetry breaking of conformal symmetry

1512.05330

$\sigma\, T^{\mu}{}_{\mu} \sim$ masses + β-functions

$$\frac{\sigma}{f} T^{\mu\,\mathrm{CFT}}_{\mu} = \frac{\sigma}{f}\left(\frac{\alpha_3}{8\pi}\kappa_3 G^2_{\mu\nu} + \kappa_e \frac{\alpha_e}{8\pi} F^2_{\mu\nu} - y_t(1+\epsilon_t)\bar{q}_L \tilde{H} t_R + h.c. + 2(1+\epsilon_H)|D_\mu H|^2 + \ldots\right)$$

tree-level coupling to Z and W (massive vectors)

loop-level coupling to gluon and photon (beta functions)

$$\Gamma_{ZZ} \simeq \Gamma_{WW}/2 \simeq \Gamma_{hh} \simeq \frac{m_\sigma^3}{32\pi f^2}$$

$$r^{\gamma}_{ZZ} \approx 0.05 \left(\frac{\kappa_e}{240}\right)^2$$

β functions of $O(16\pi^2)$ → large dilaton mass correction

CP of F

1604.06446

critical importance

- greatest discriminator of many scenarios
- truly "fitfy-fitfy" (unlike for the Higgs boson CP)

shortcuts: $F \to$ HH or ZH

several challenges

important differences w.r.t the Higgs CP measurement

1. no $F \to 4$ fermion final state
2. $M_F \gg m_h \Rightarrow$ small boost

only $g^+ g^+ \to g^+ g^+ F$ scattering is sensitive to CP for other helicities $\mathcal{A} \sim M_F$

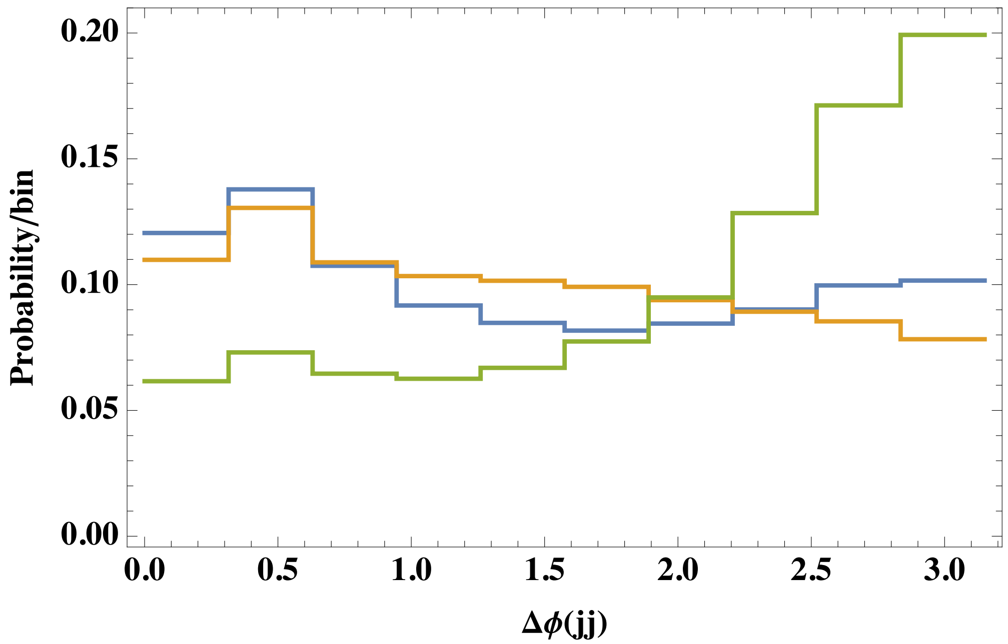
Thrust and Δϕ(jj)

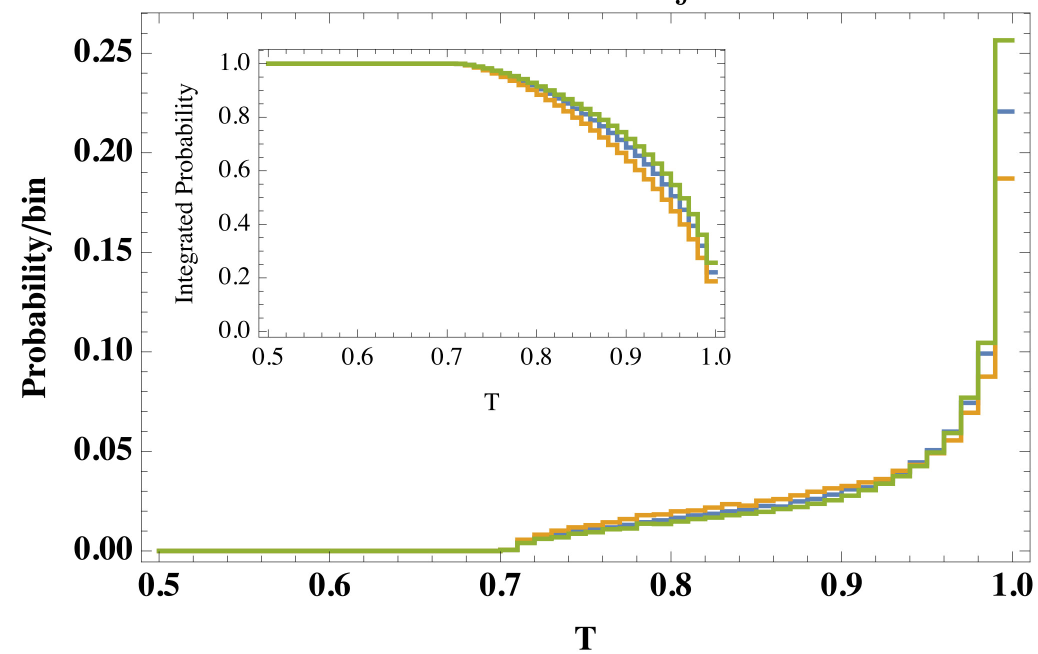
1604.02029
1604.06446

pp → *F* jj

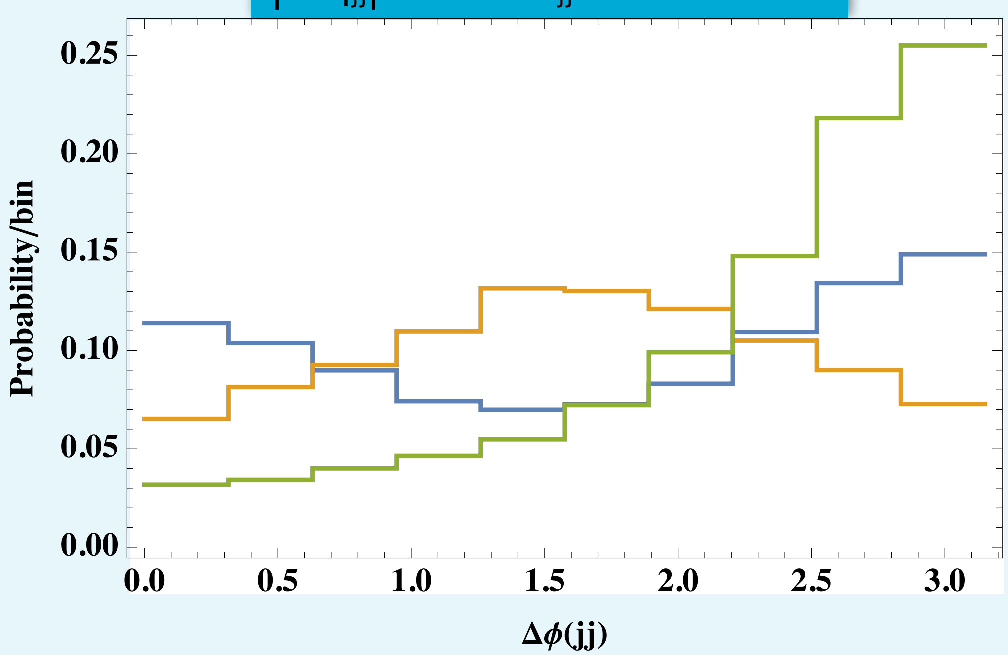
$\Delta\phi_{jj}$

$$T = \max_n \frac{\sum_{i \in \text{jets}} |n \cdot p_i|}{\sum_{i \in \text{jets}} |p_i|} .$$





|Δη$_{jj}$|>2.5 m$_{jj}$>500 GeV



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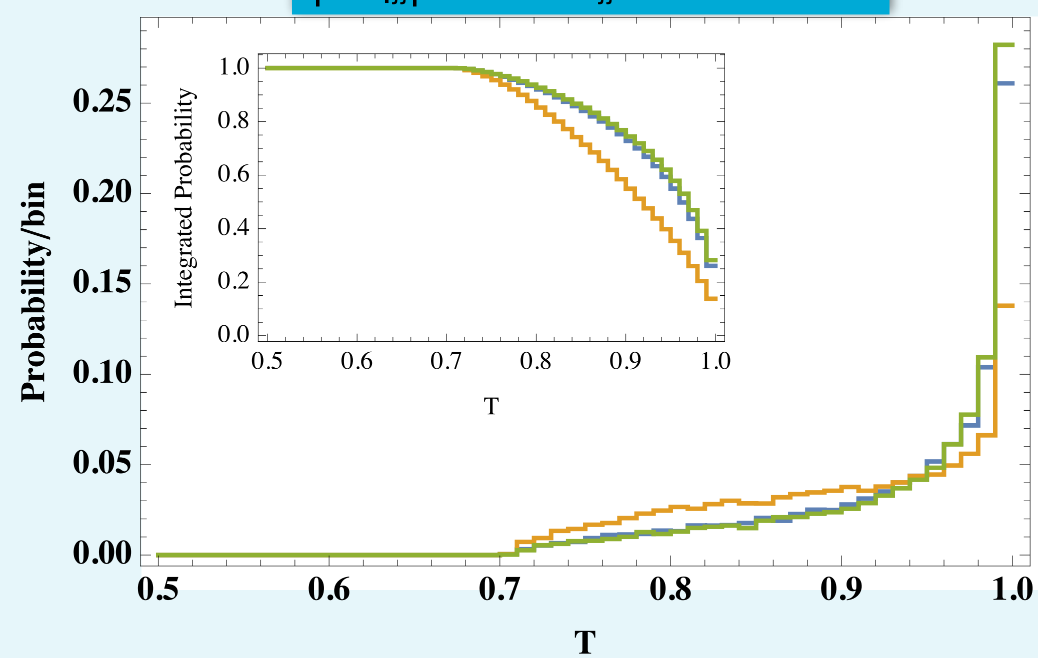


Pair production of **F**

if strong interactions are behind F, multiple production is expect with no big suppression

$$U(\pi) = e^{i\pi/f} = 1 + \frac{\pi}{f} + \left(\frac{\pi}{f}\right)^2 + \ldots$$

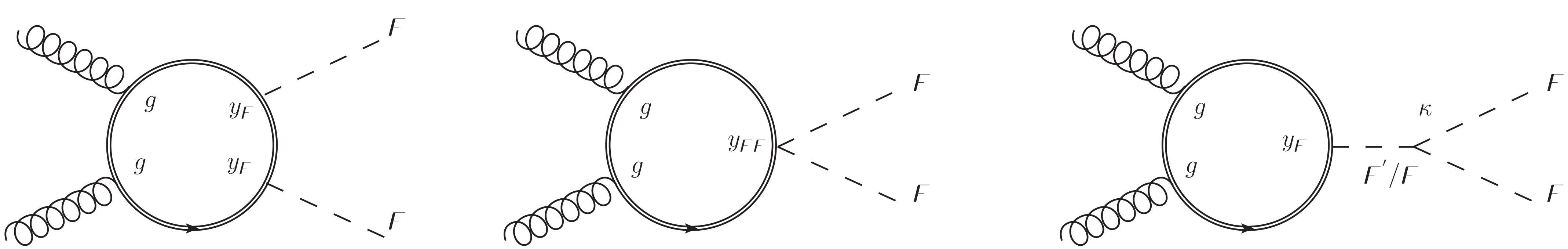
$$\mathcal{L} \sim \frac{c_5}{\Lambda} \cdot F\mathcal{L}_5 + \frac{c_6}{\Lambda^2} \cdot F^2\mathcal{L}_6$$

$\sigma_{FF}/\sigma_F \sim (10^{-2} - 10^{-4}) \cdot (c_6/c_5)^2$

internal symmetries more easily suppress single production than double production

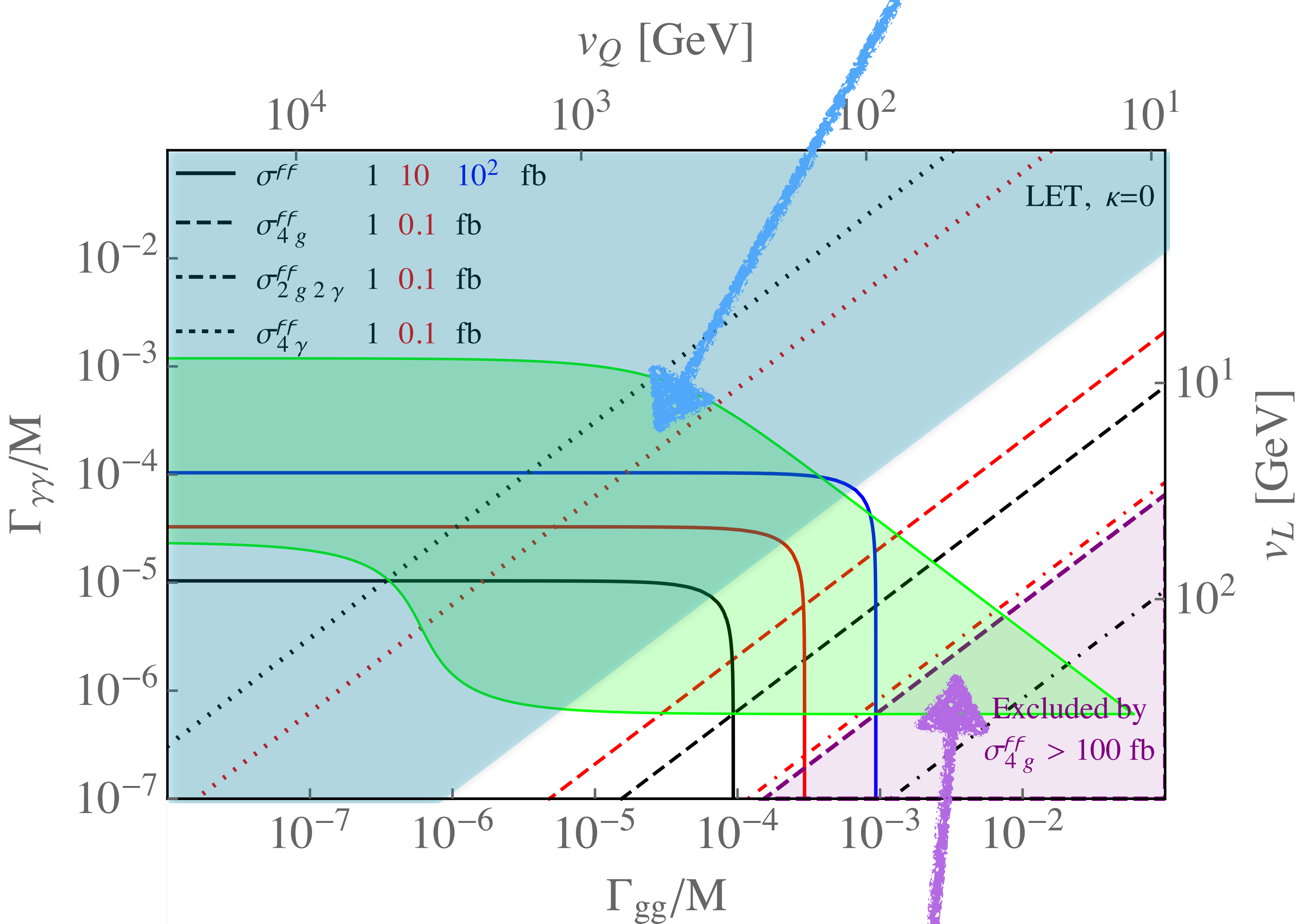
$$|F|^2 G_{\mu\nu} G^{\mu\nu}$$

F couples to	$\sigma_{FF}/\sigma_F = \sigma_{\gamma\gamma F}/2\sigma_{\gamma\gamma}$
$b\bar{b}$	$0.015\%\,(\mathrm{TeV}/\Lambda)^2\,(c_b^{(6)}/c_b)^2$
$d\bar{d}$	$0.050\%\,(\mathrm{TeV}/\Lambda)^2\,(c_d^{(6)}/c_d)^2$
GG	$0.13\%\,(\mathrm{TeV}/\Lambda)^2\,(c_{gg}^{(6)}/c_{gg})^2$
$\gamma\gamma$	$1.9\%\,(\mathrm{TeV}/\Lambda)^2\,(c_{\gamma\gamma}^{(6)}/c_{\gamma\gamma})^2$



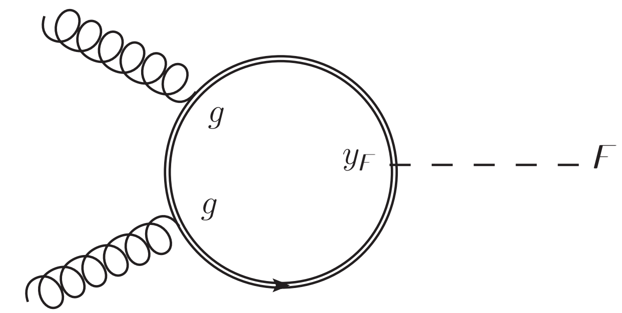
$\sigma_{FF}/\sigma_F \sim y_F/M \sim 1/f$

Large 4γ, probes γγ initial state



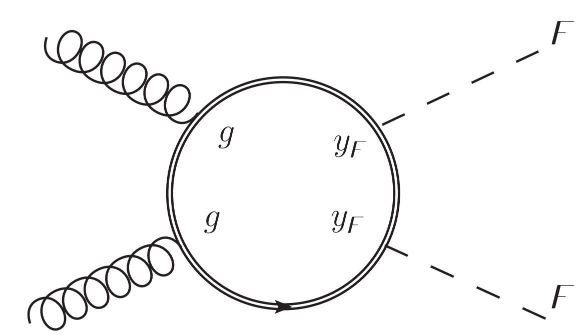
2γ2j or ttγγ ???

Large 4j and 4t final states



$$\Gamma_{\gamma\gamma} = \frac{\alpha^2\, q_L^4 N_L^2\, M_F^3}{144\pi^3\, v_L^2}.$$

$$\Gamma_{gg} = \frac{\alpha_3^2\, N_Q^2 I_Q^2\, M_F^3}{18\pi^3\, v_Q^2},$$



pp→ F→	4j	4γ	4t
LHC8	<100 fb	<26 fb	<70 fb

$$v_Q \equiv M_Q/y_Q \text{ and } v_L \equiv M_L/y_L$$

Conclusions

- **gg → F → γ γ** is the most compelling
- **heavy quark** initial state is also possible(*b*,*c*,*s*)
- light, coupling to gauge bosons → **Goldstone boson**
  - ☑ GB of internal symmetry linked to **strong EWSB**
  - ☑ SUSY partner of GB of **SUSY**
  - ☐ GB of conformal invariance
- **CP of F** is one of the most pressing questions
- **F pair production** is worth searching, <u>great reward</u>
- <u>Outlook:</u>
  - more decay channels *F*→ jj, tt, Zγ, ZZ, WW, HH, invisible, 3&4-body
  - direct search of states in the loop
  - other companions from the new theory of TeV physics

Conclusions

Citation: Particle Data Group, 2016 update

$\digamma$ (750_{000})

$I(J^P) = ?(0^?)$
J needs confirmation

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$\digamma$ MASS

VALUE (GeV)	EVTS	DOCUMENT ID	TECN	COMMENT
750 ± 30 OUR AVERAGE		ATLAS, CMS		$pp \to \digamma$

• • • We do not use the following data for average, fits, limits, etc. • • •

$\digamma$ WIDTH

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<100	95	ATLAS, CMS		$pp \to \digamma$

• • • We do not use the following data for average, fits, limits, etc. • • •

$\digamma$ DECAY MODES

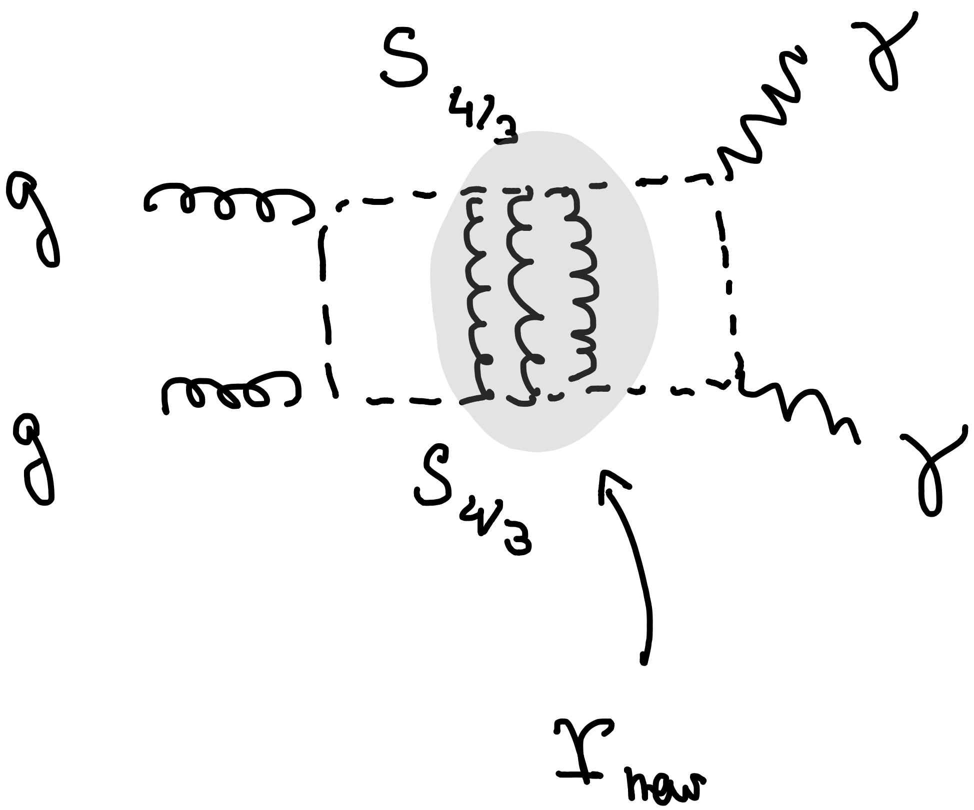
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\gamma$	seen(?)
Γ_2	$\gamma Z, ZZ, WW, jj$	expected
Γ_3	$t\bar{t}$, $b\bar{b}$, invisible	possible
Γ_4	3-body, 4-body	predicted

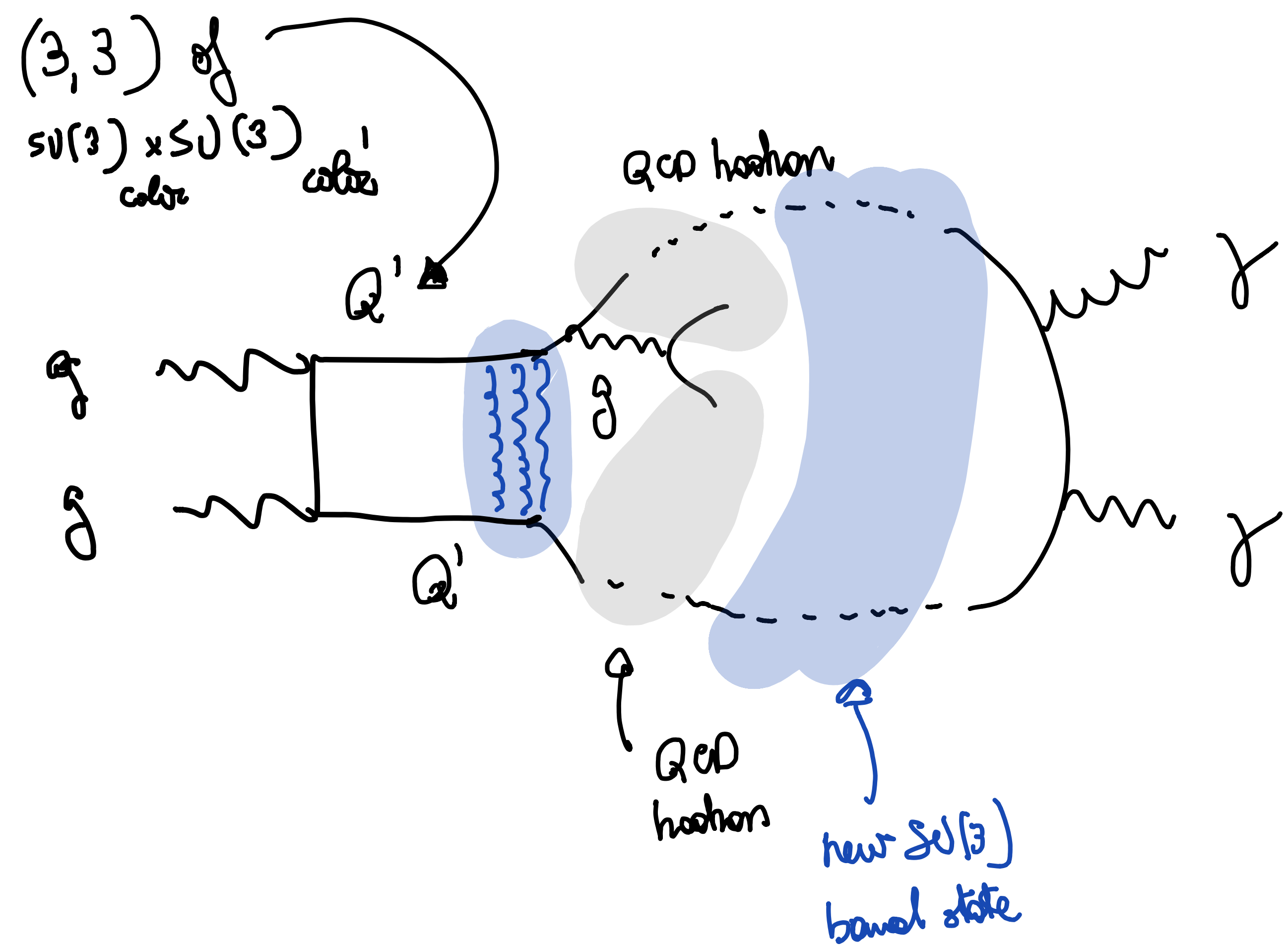
Thank you!

Quarkonium and Quirks

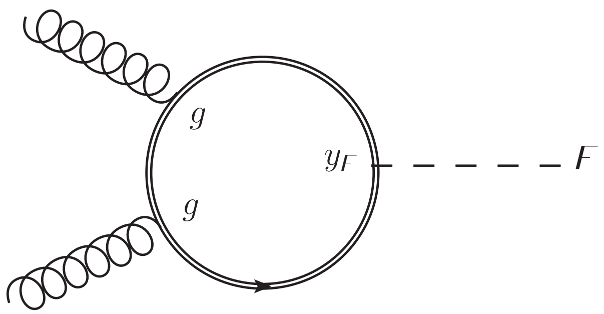
1602.08819

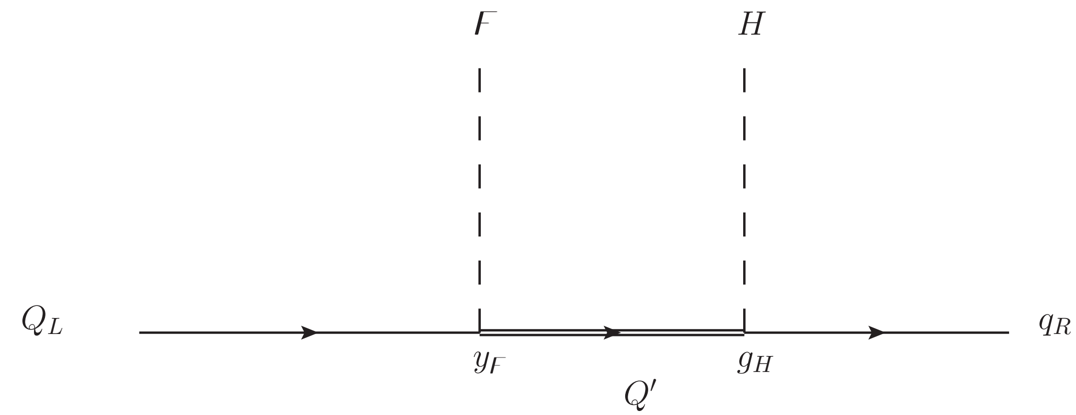
1604.06180

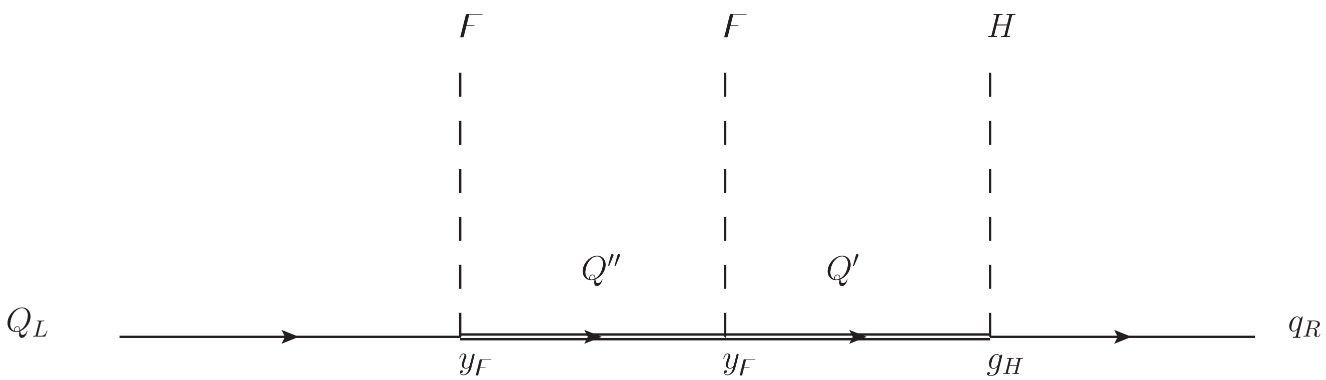


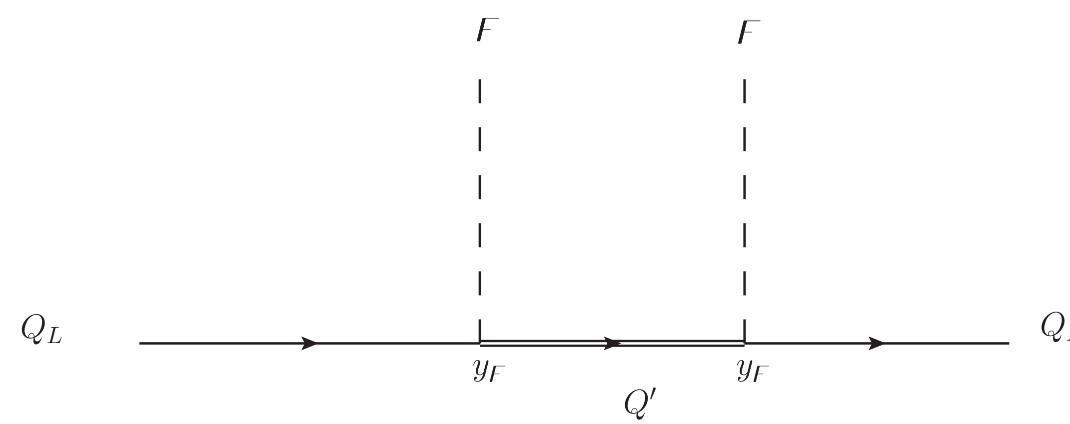


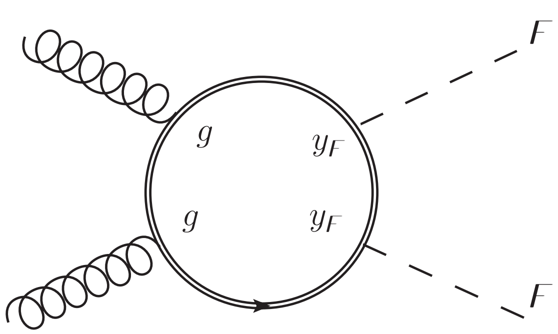
Pair production mechanism

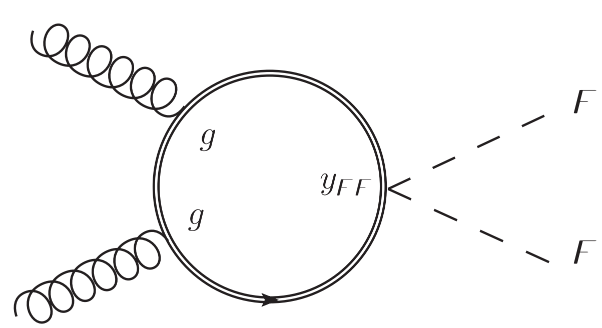


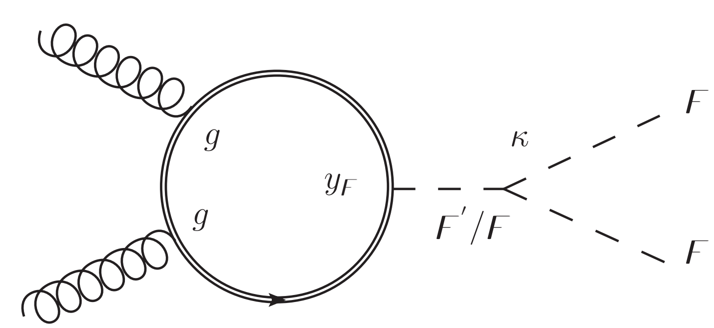












QCD Goldstone bosons and Quarkonium

	BR		Mass
$\pi 0$	Photon Photon	0.98798	134.9766 MeV/c^2
K_L	Photon Photon	0.000547	497.648 MeV/c^2
K_S	Photon Photon	2.71×10^{-6}	497.648 MeV/c^2
η	Photon Photon	0.3938	547.51 MeV/c^2
η^'(958)	Photon Photon	0.0212	957.78 MeV/c^2
f_0(980)	Photon Photon	—	980. MeV/c^2
a_0^0(980)	Photon Photon	—	984.7 MeV/c^2
f_0(1370)	Photon Photon	—	1350. MeV/c^2
D0	Photon Photon	$0. \times 10^{-5}$	1864.5 MeV/c^2
D0−bar	Photon Photon	$0. \times 10^{-5}$	1864.5 MeV/c^2
f_2(1950)	Photon Photon	—	1944. MeV/c^2
f_2(2300)	Photon Photon	—	2297. MeV/c^2
η_c(1S)	Photon Photon	0.000240	2980.4 MeV/c^2
χ_c0(1P)	Photon Photon	0.000235	3414.76 MeV/c^2
χ_c2(1P)	Photon Photon	0.000243	3556.2 MeV/c^2
η_c(2S)	Photon Photon	$0. \times 10^{-4}$	3638. MeV/c^2
ψ(2S)	Photon Photon	$0. \times 10^{-4}$	3686.093 MeV/c^2