DIBOSON AS PROBE TO HIGGS (NEW) PHYSICS

Zhuoni Qian
IBS-CTPU

2019-10-14 @ IHEP Mini-Workshop

MOTIVATION

- **Since the Higgs discovery, Higgs coupling measurement has been one main focus.**

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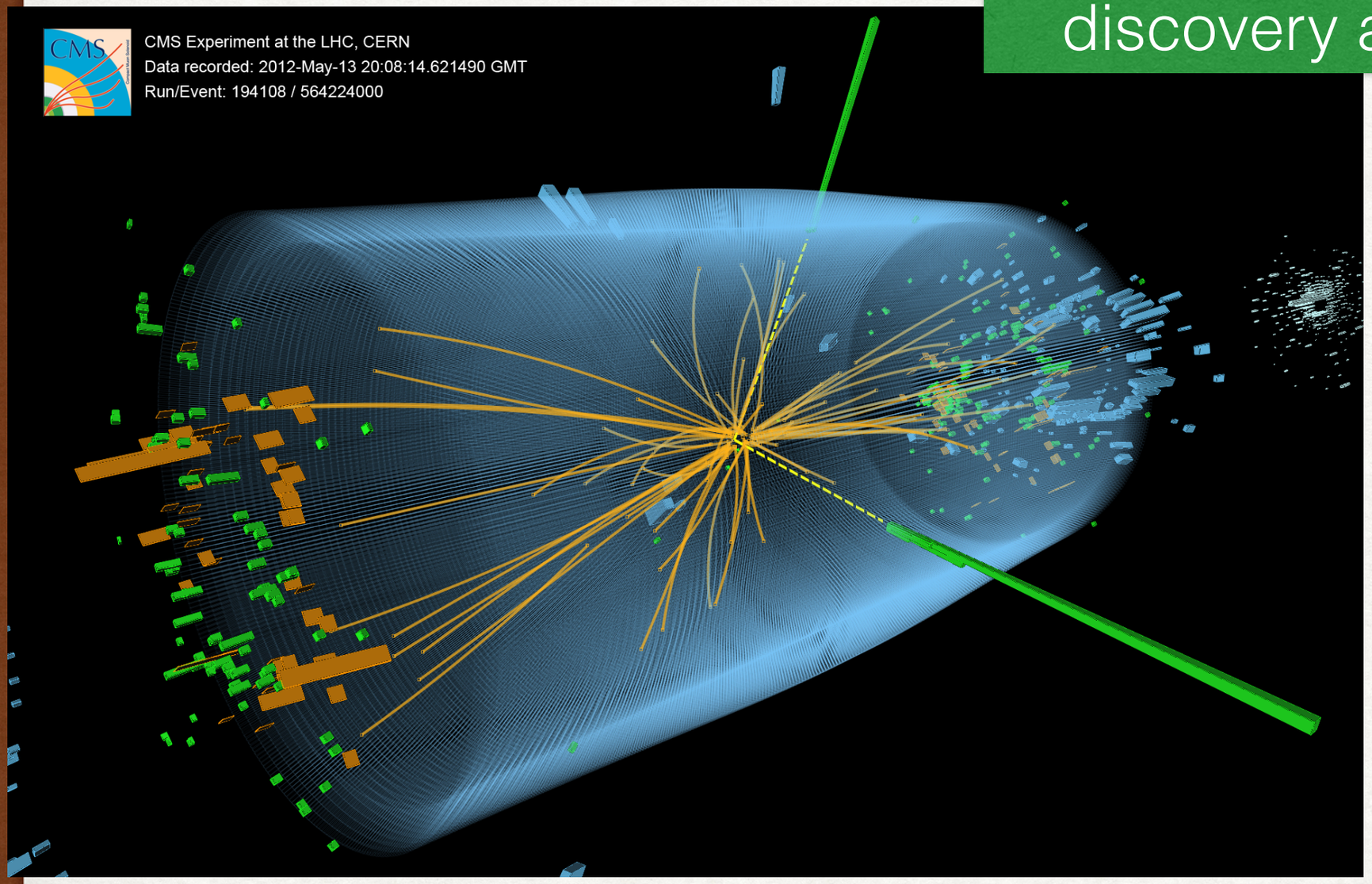

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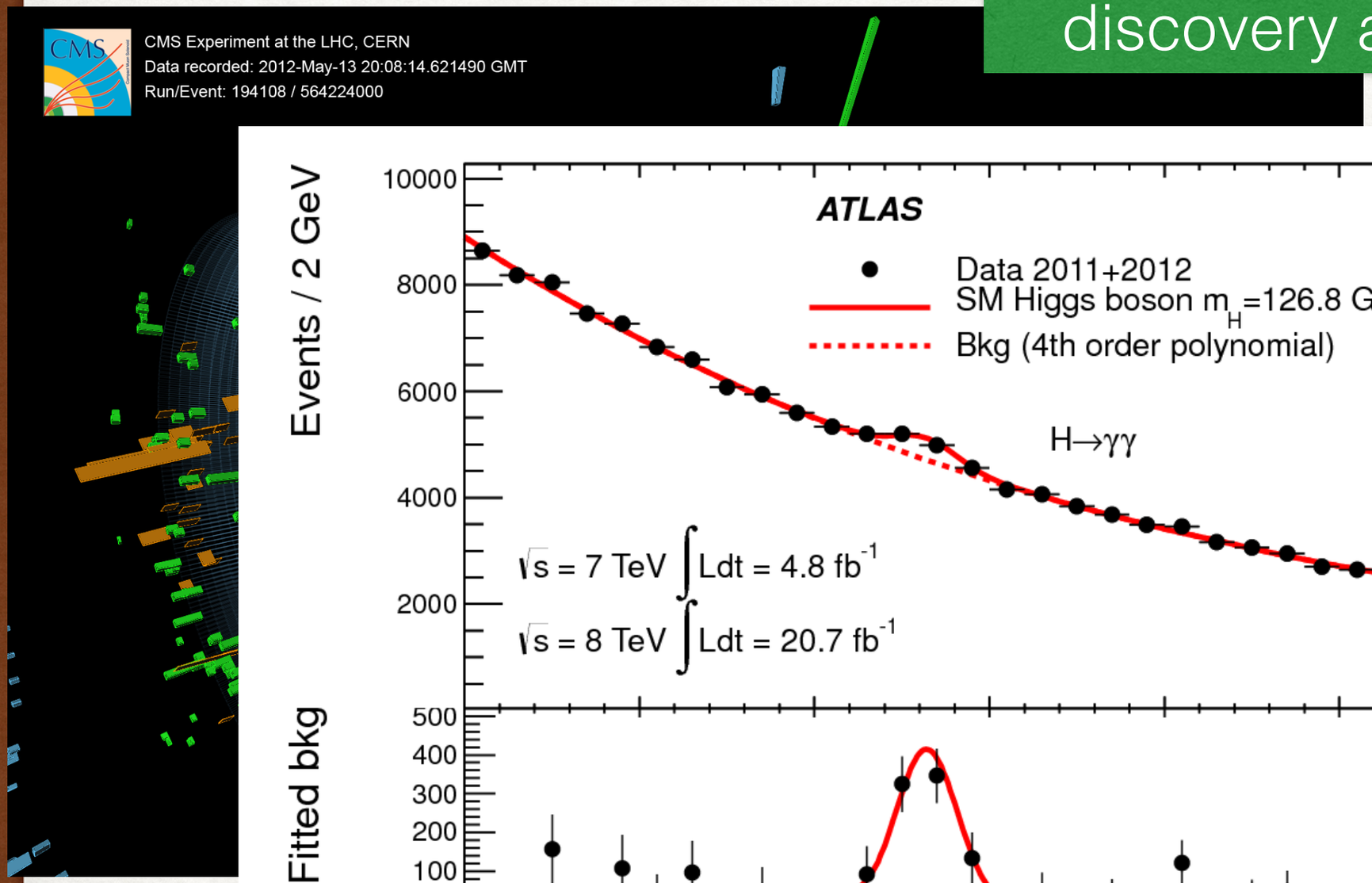

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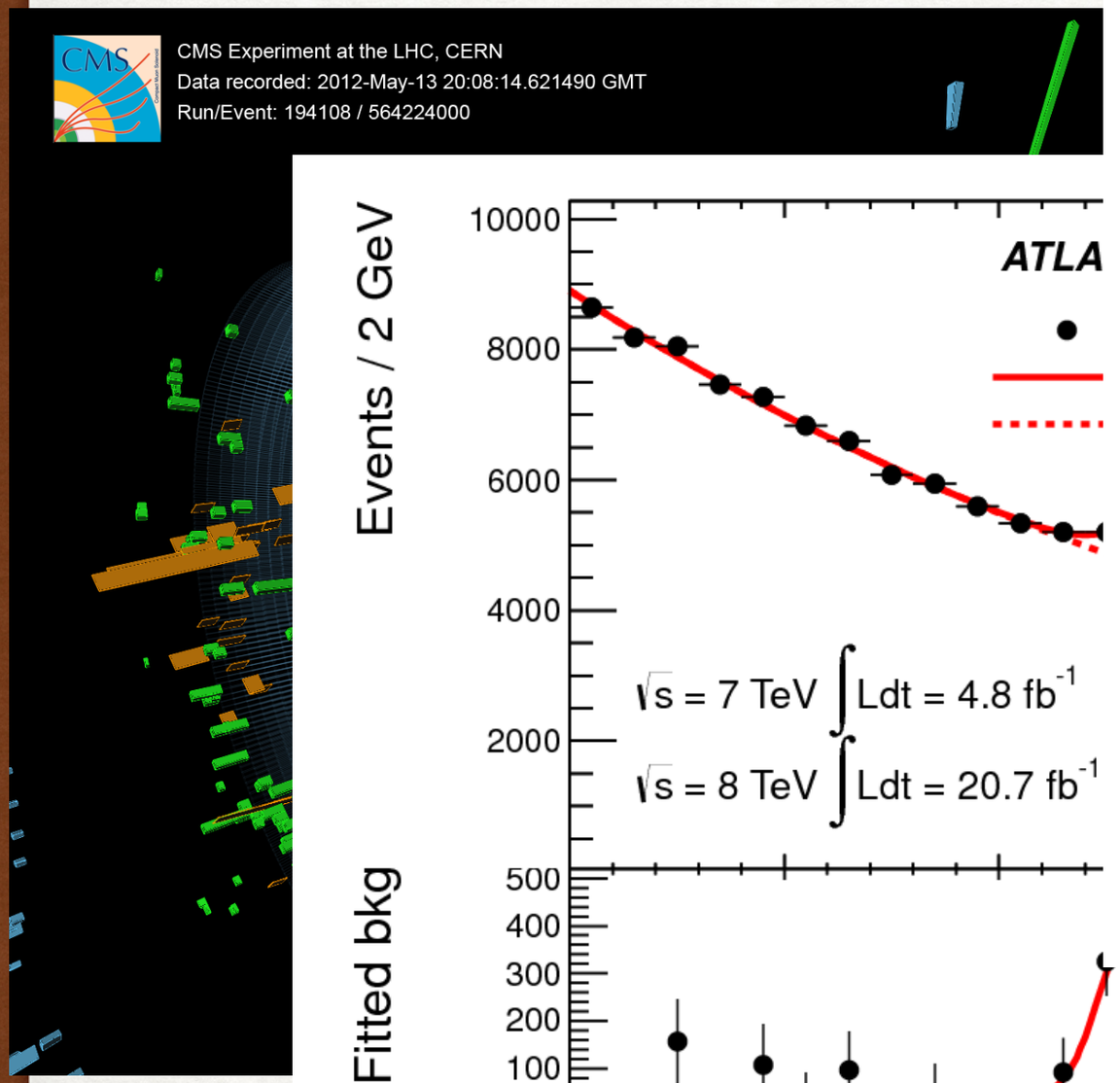

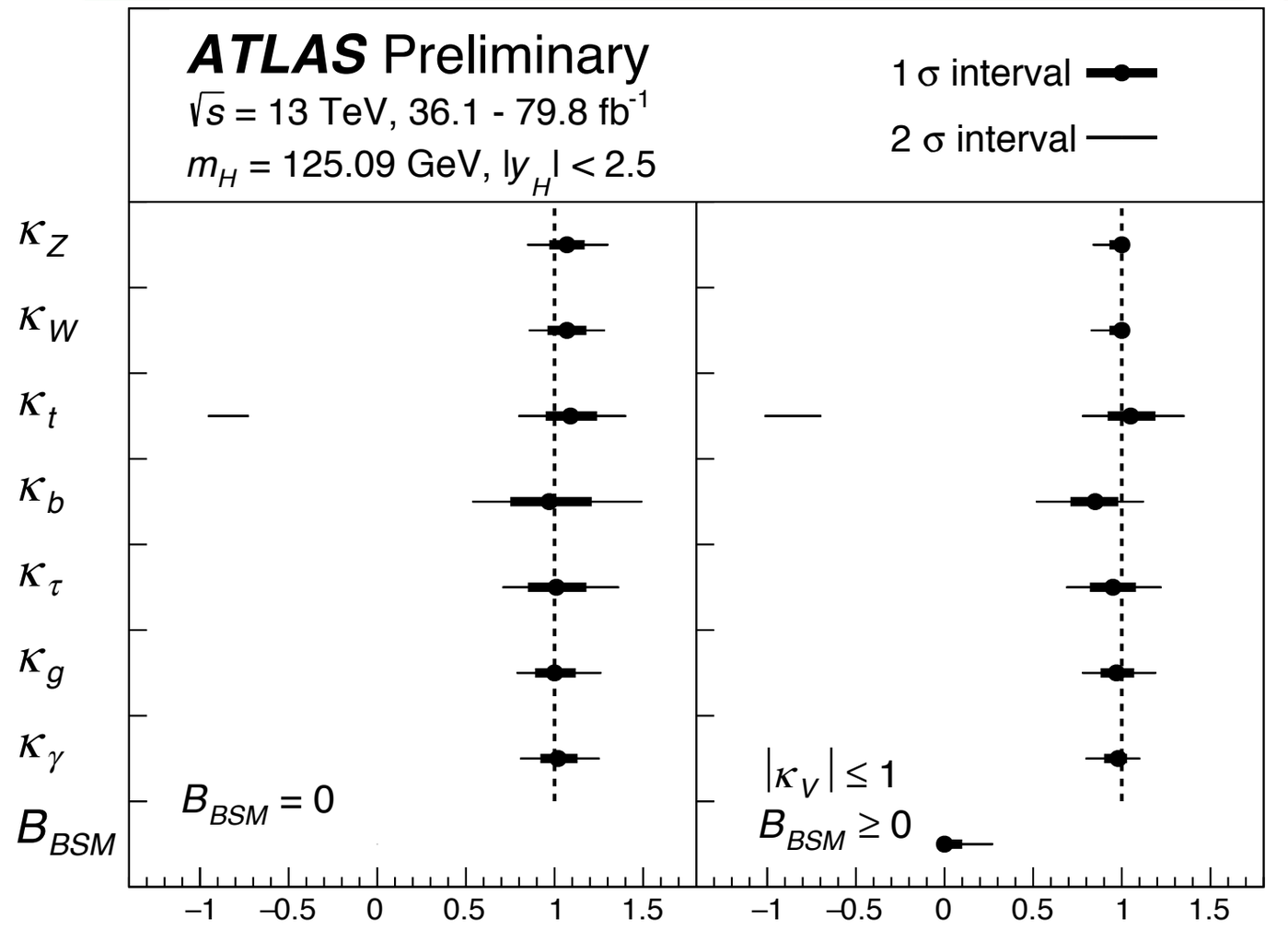

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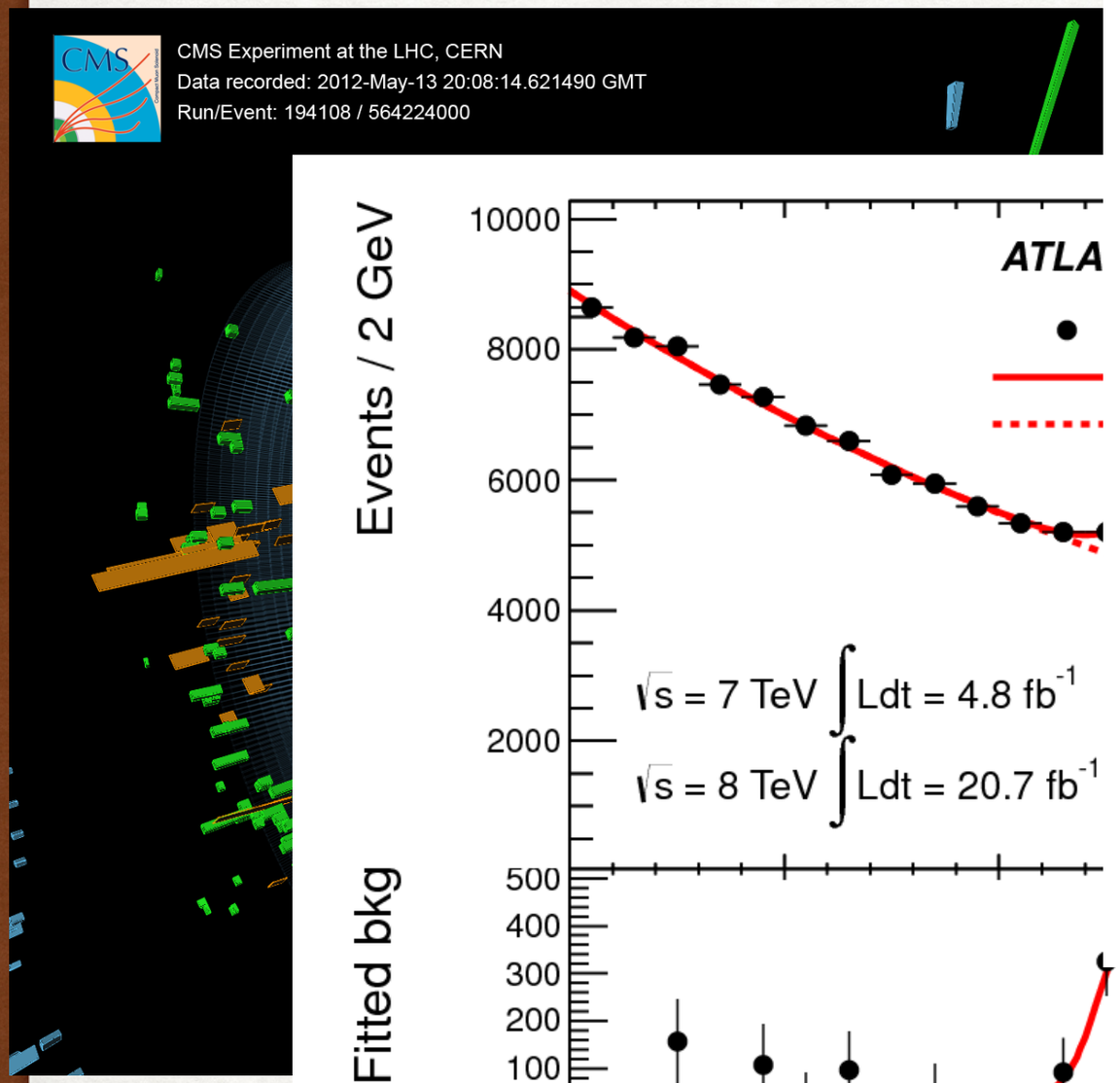

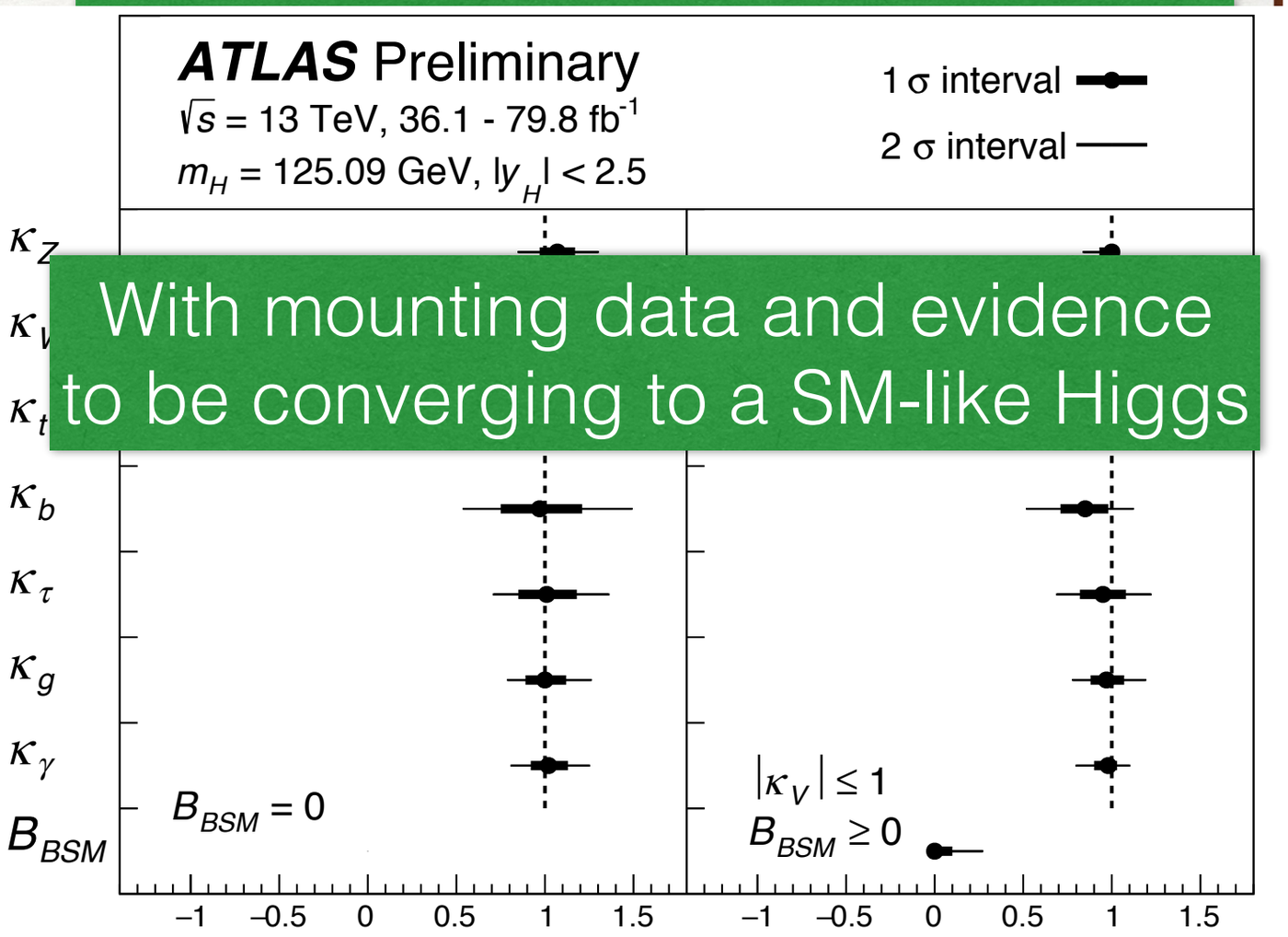

With mounting data and evidence to be converging to a SM-like Higgs

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pic credit: wallpapersden.com

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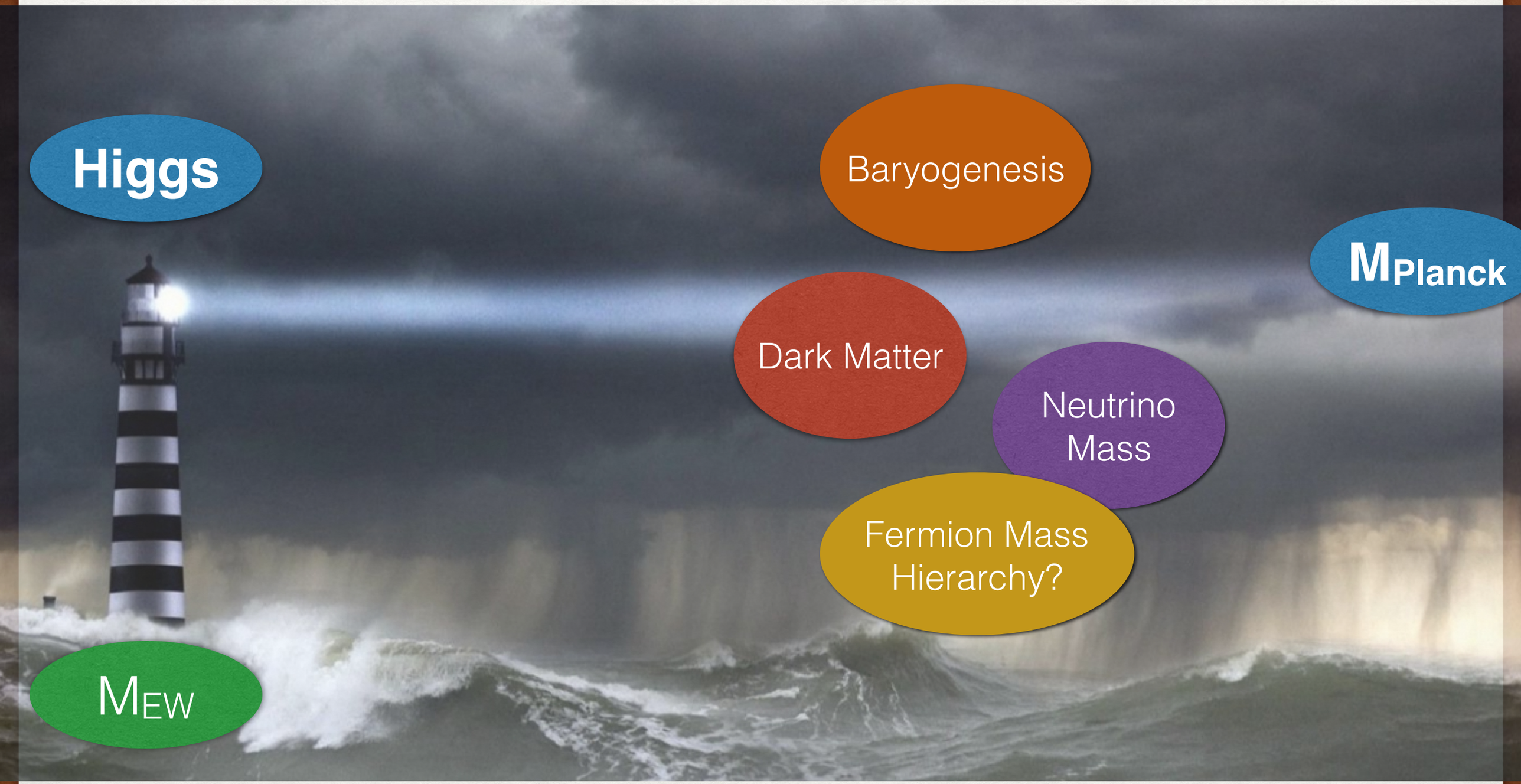

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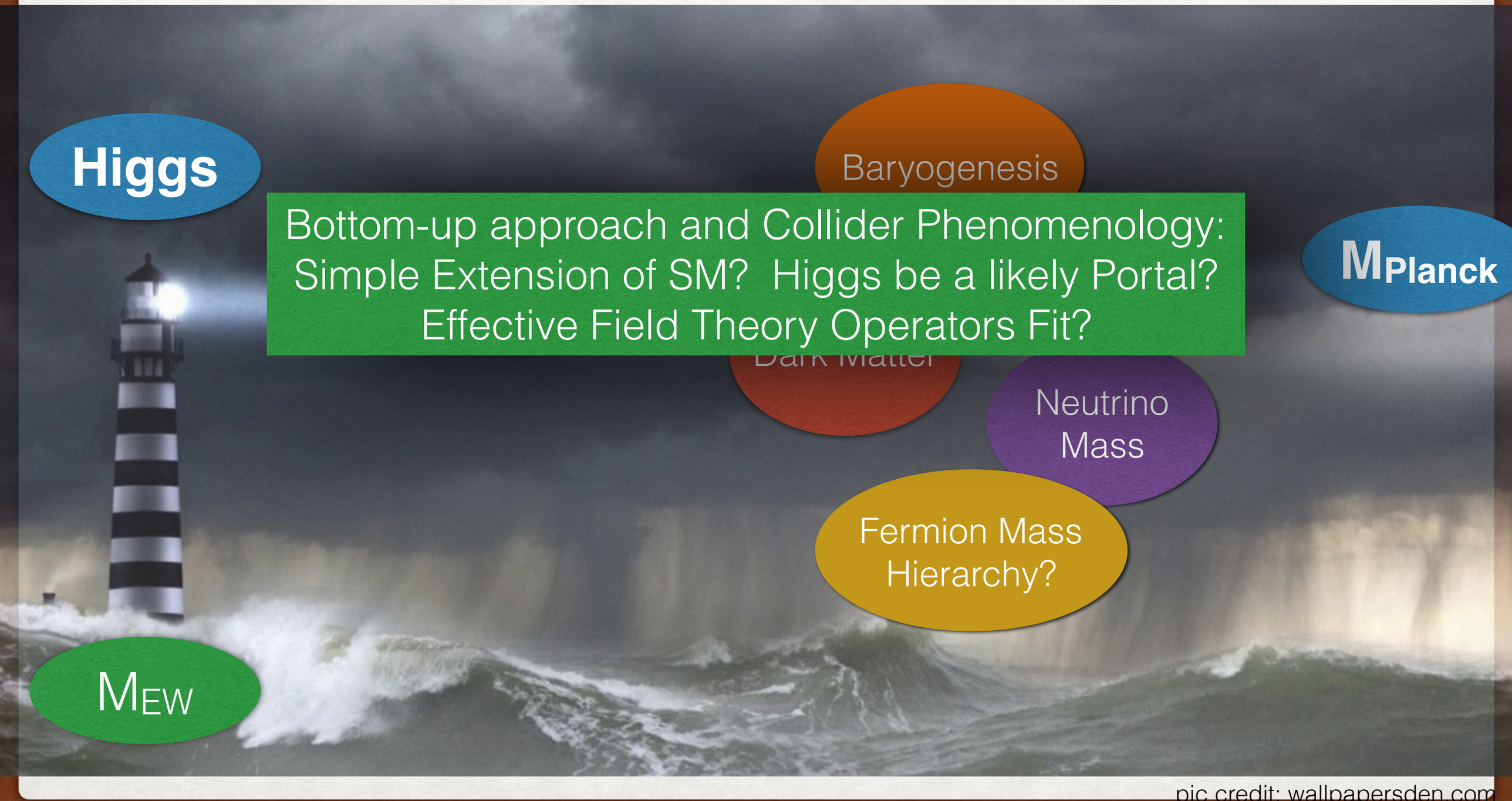

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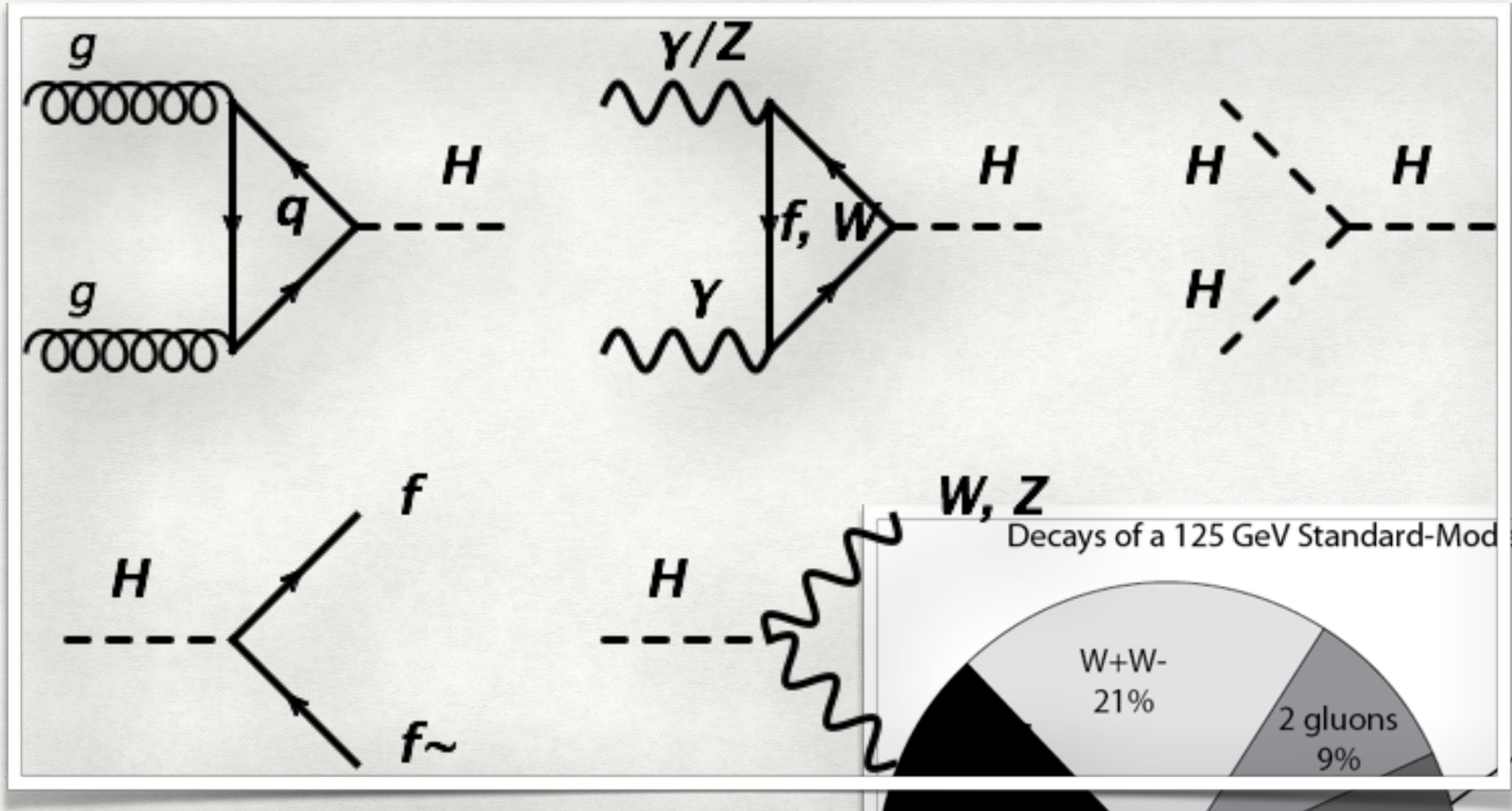
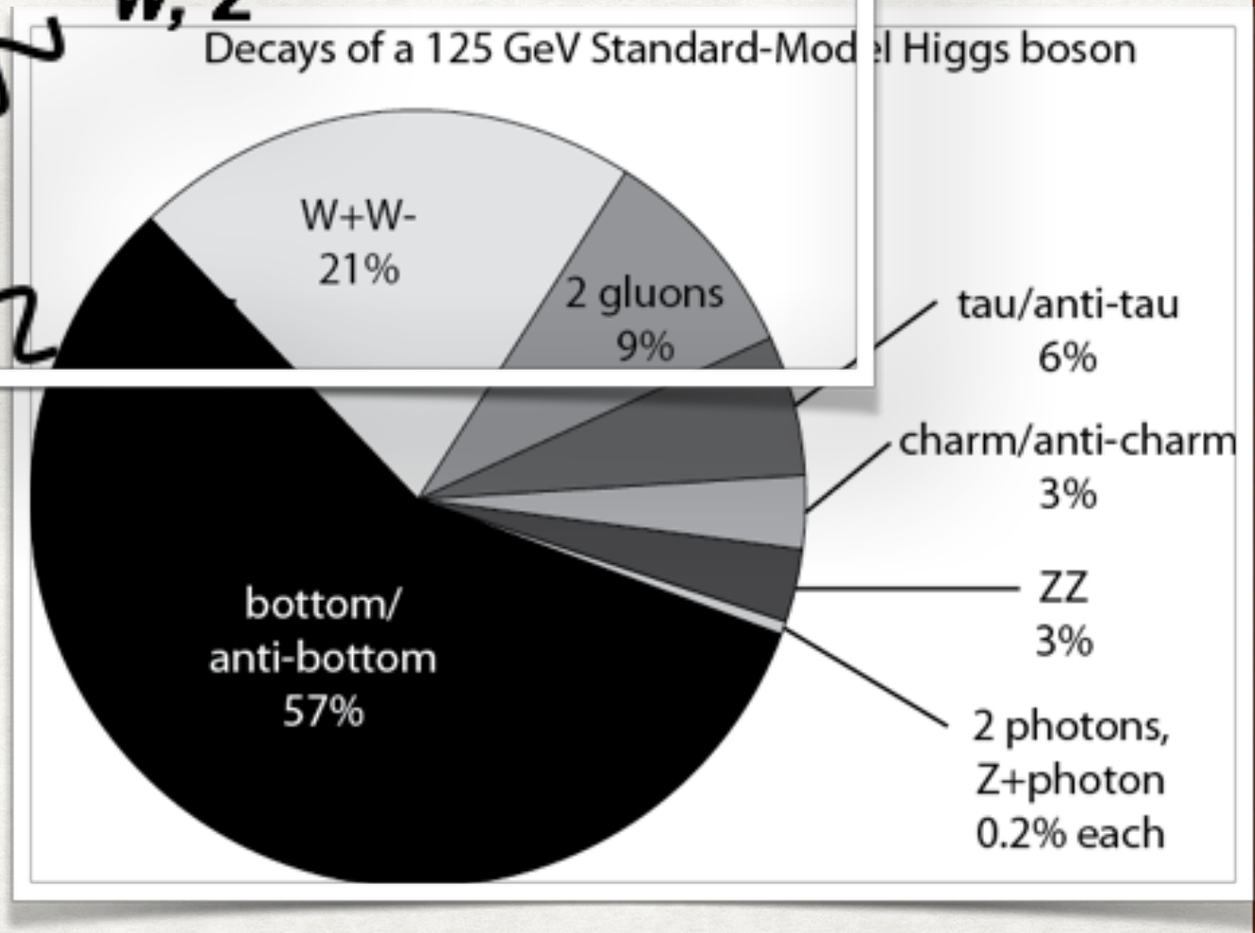
SM HIGGS? (YUKAWA)





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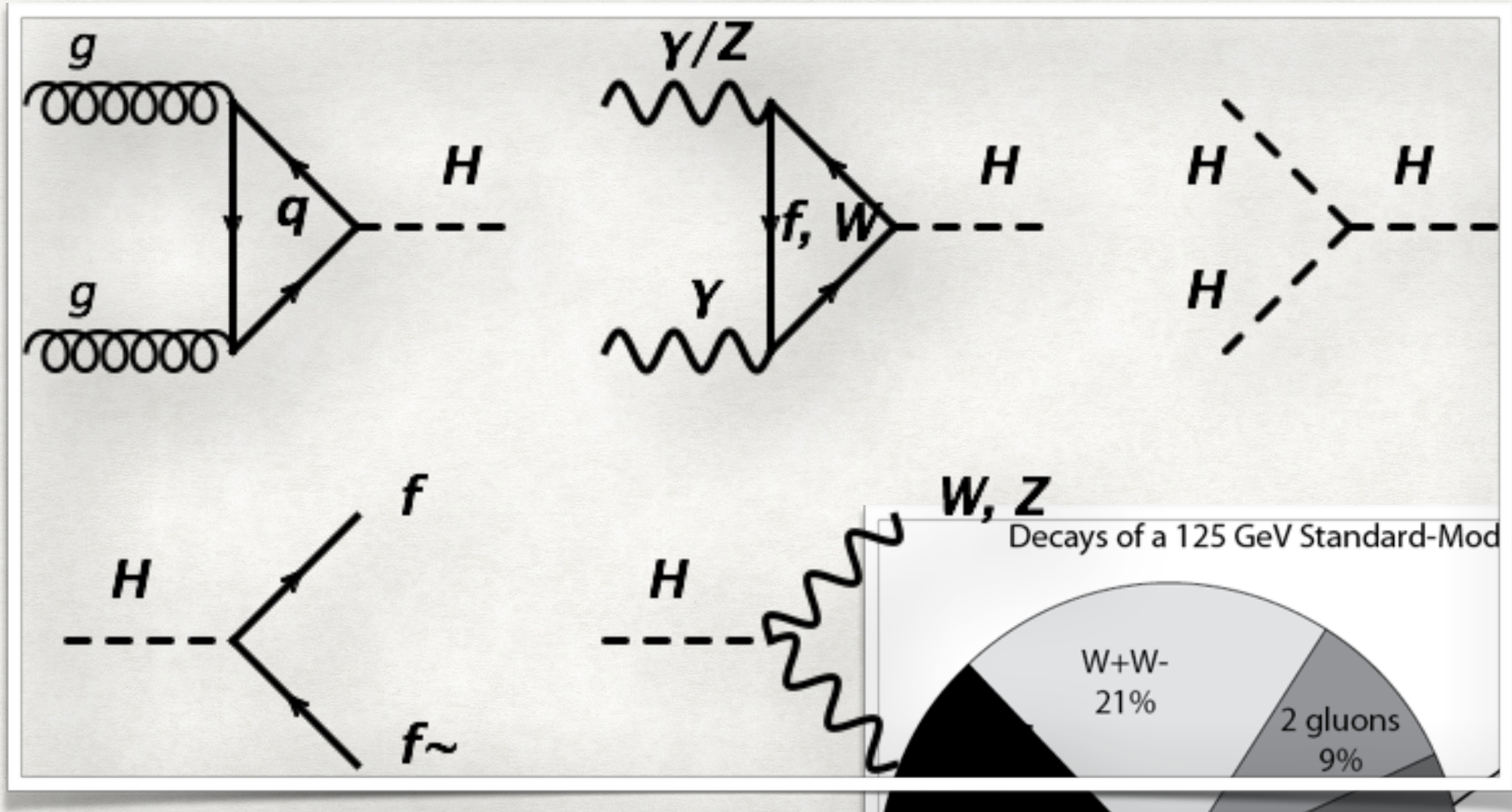

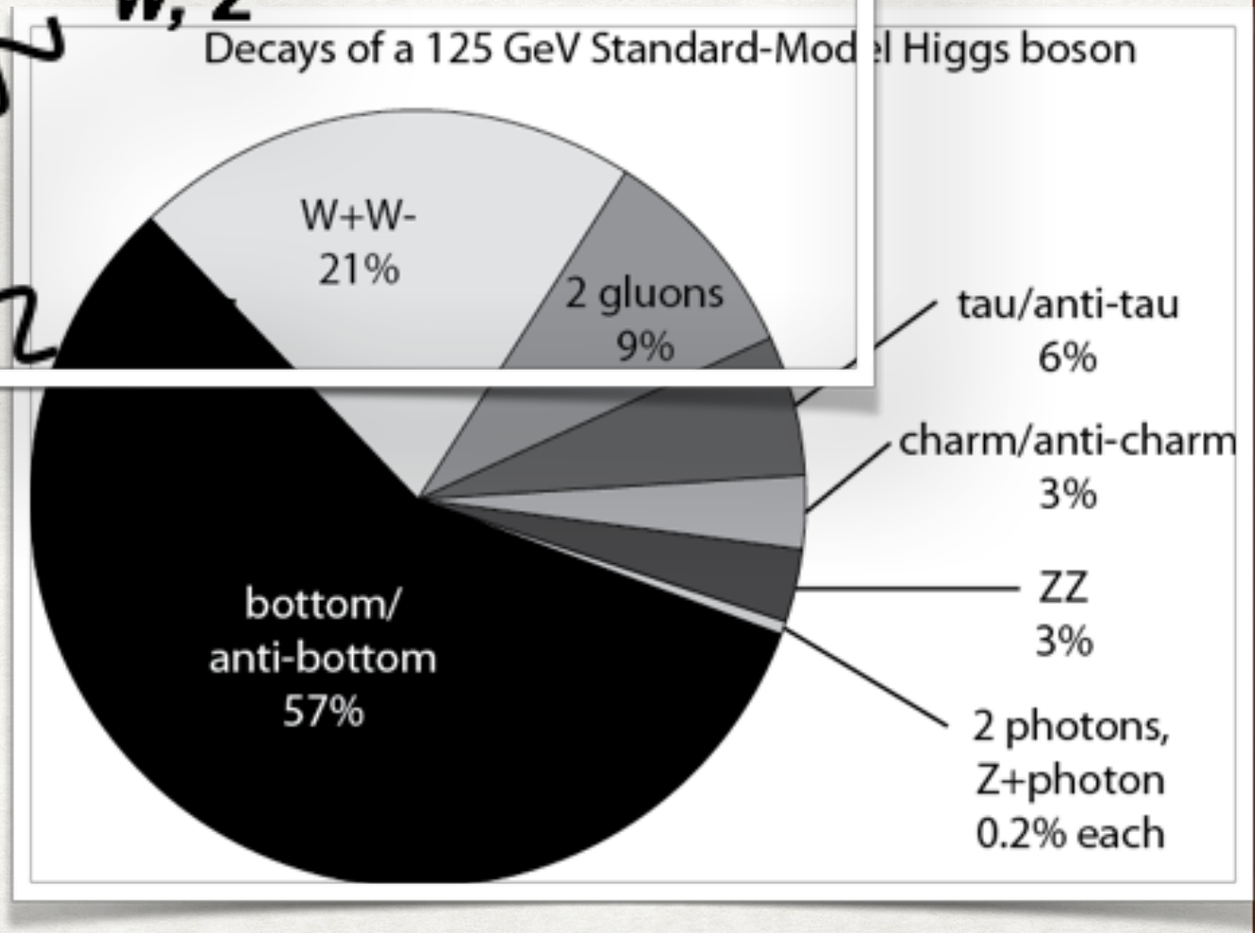

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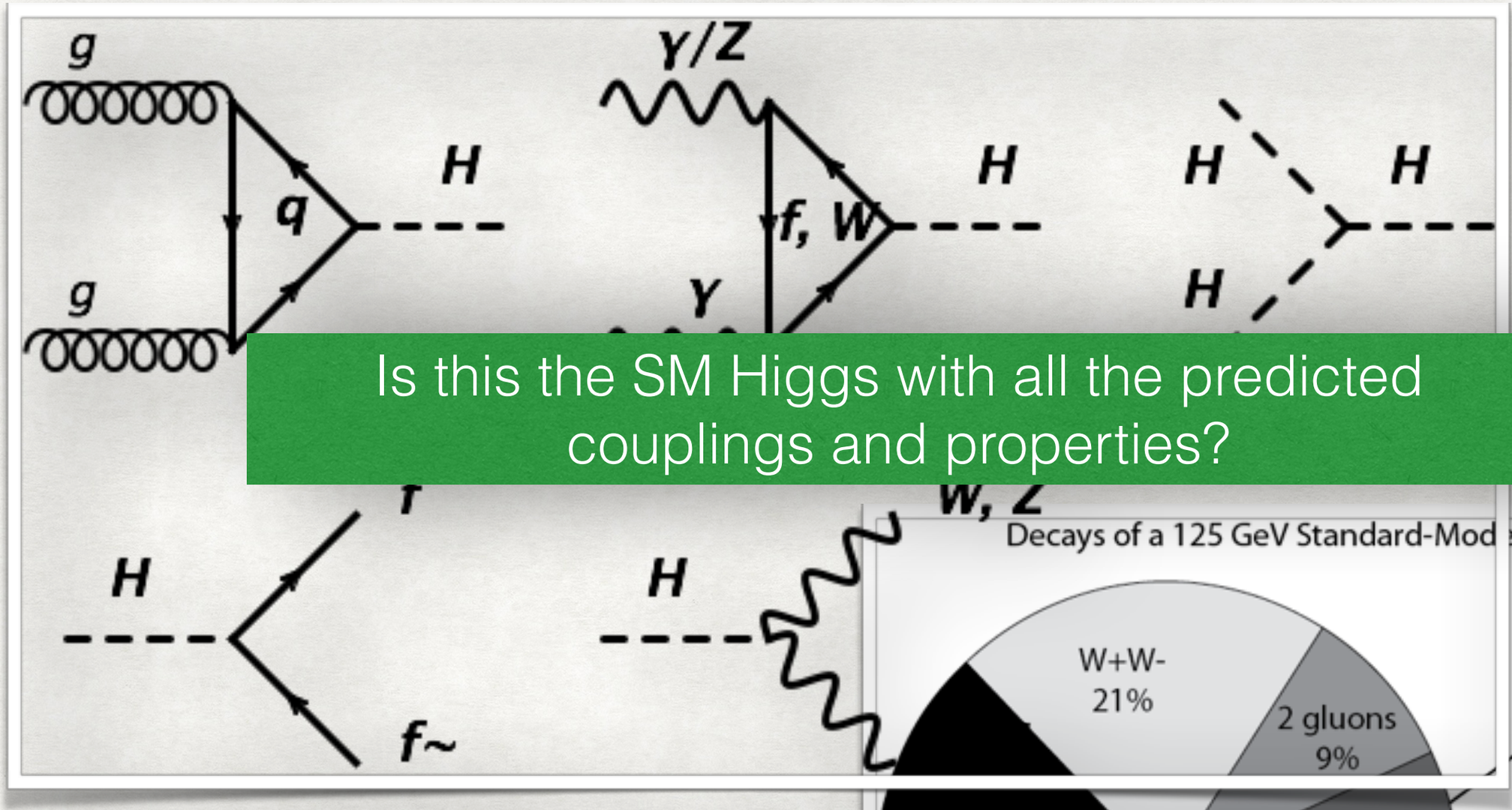
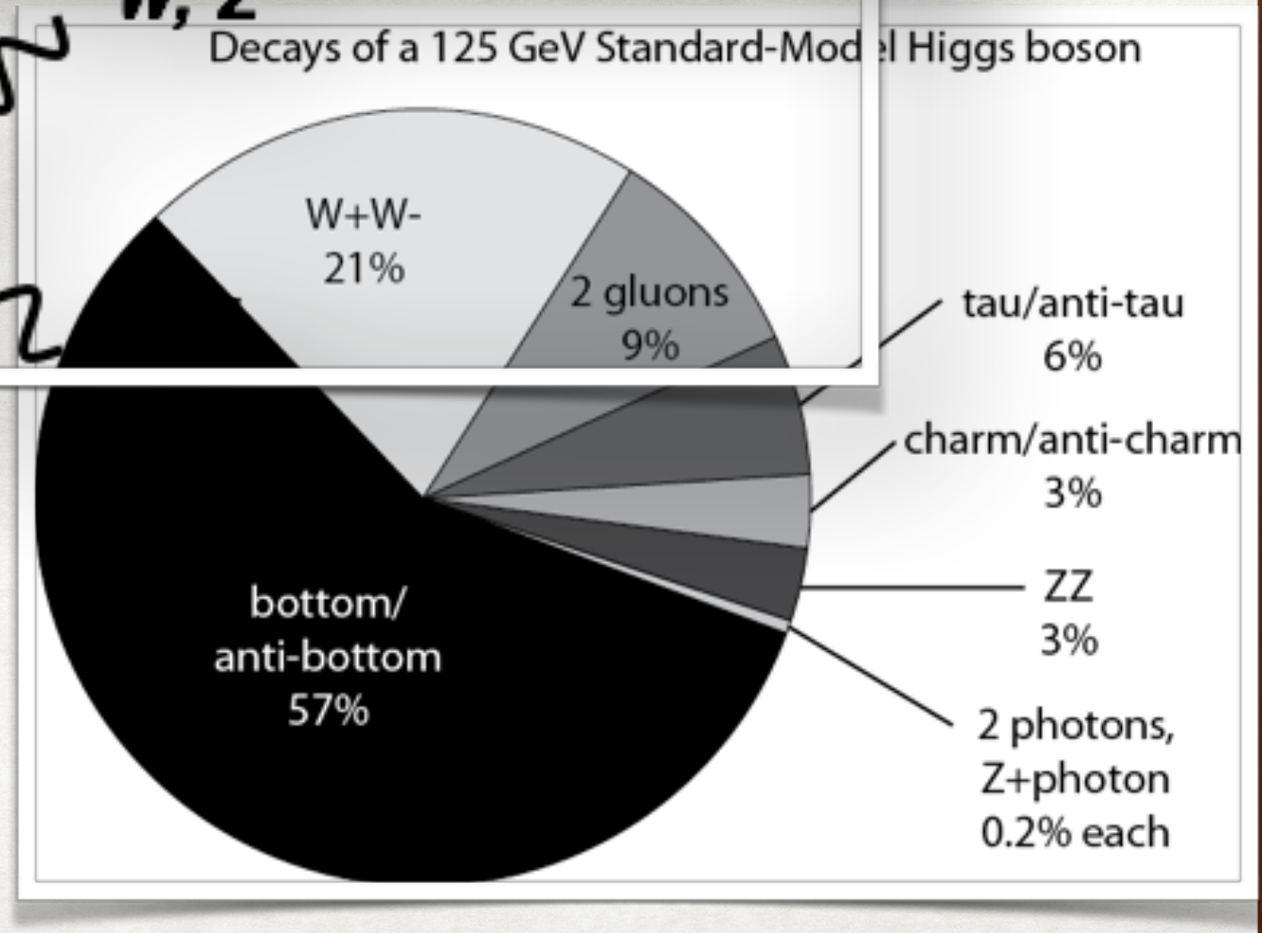


Is this the SM Higgs with all the predicted couplings and properties?



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Decay: ZZ, γγ, WW, ττ, bb, μμ, Zγ (4),
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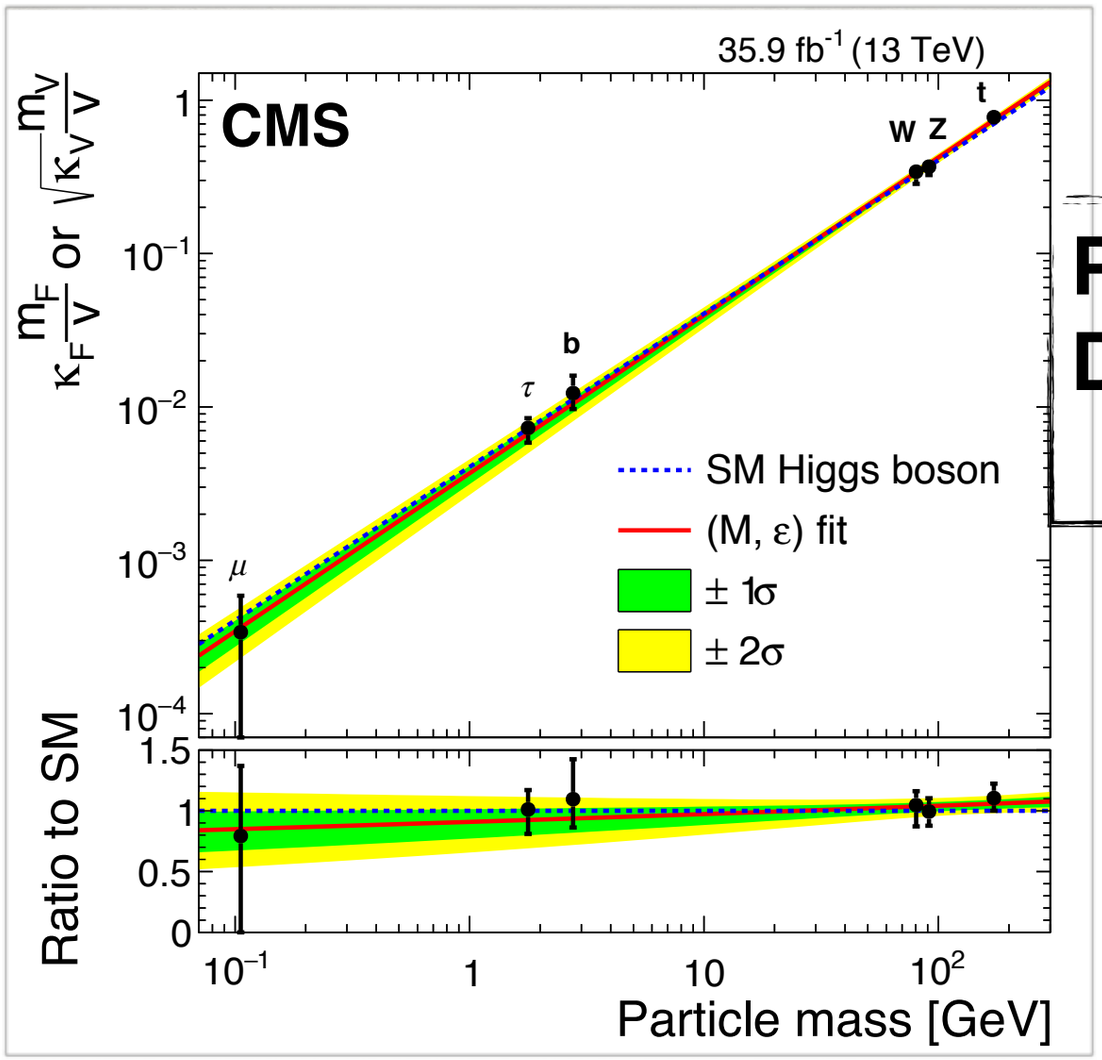

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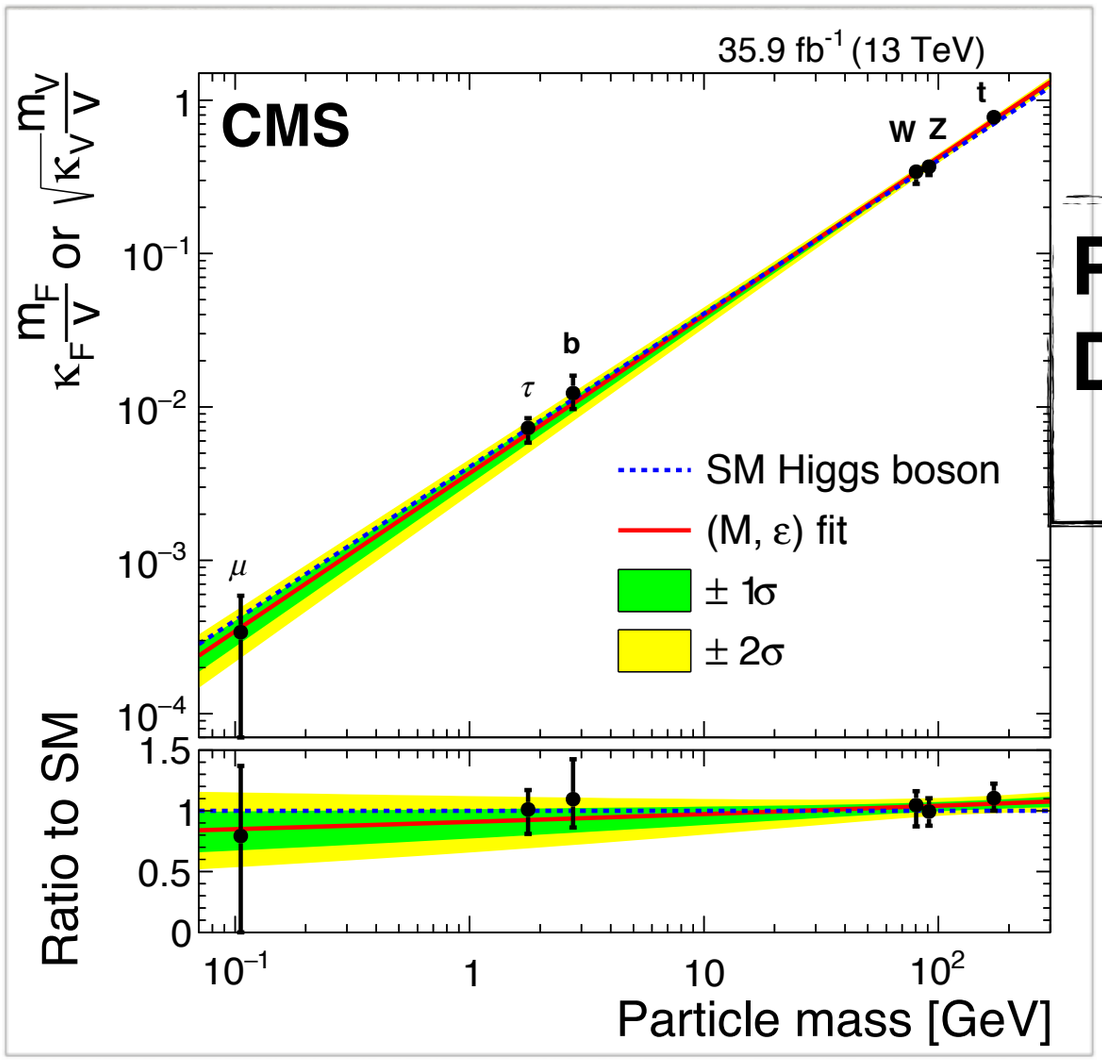

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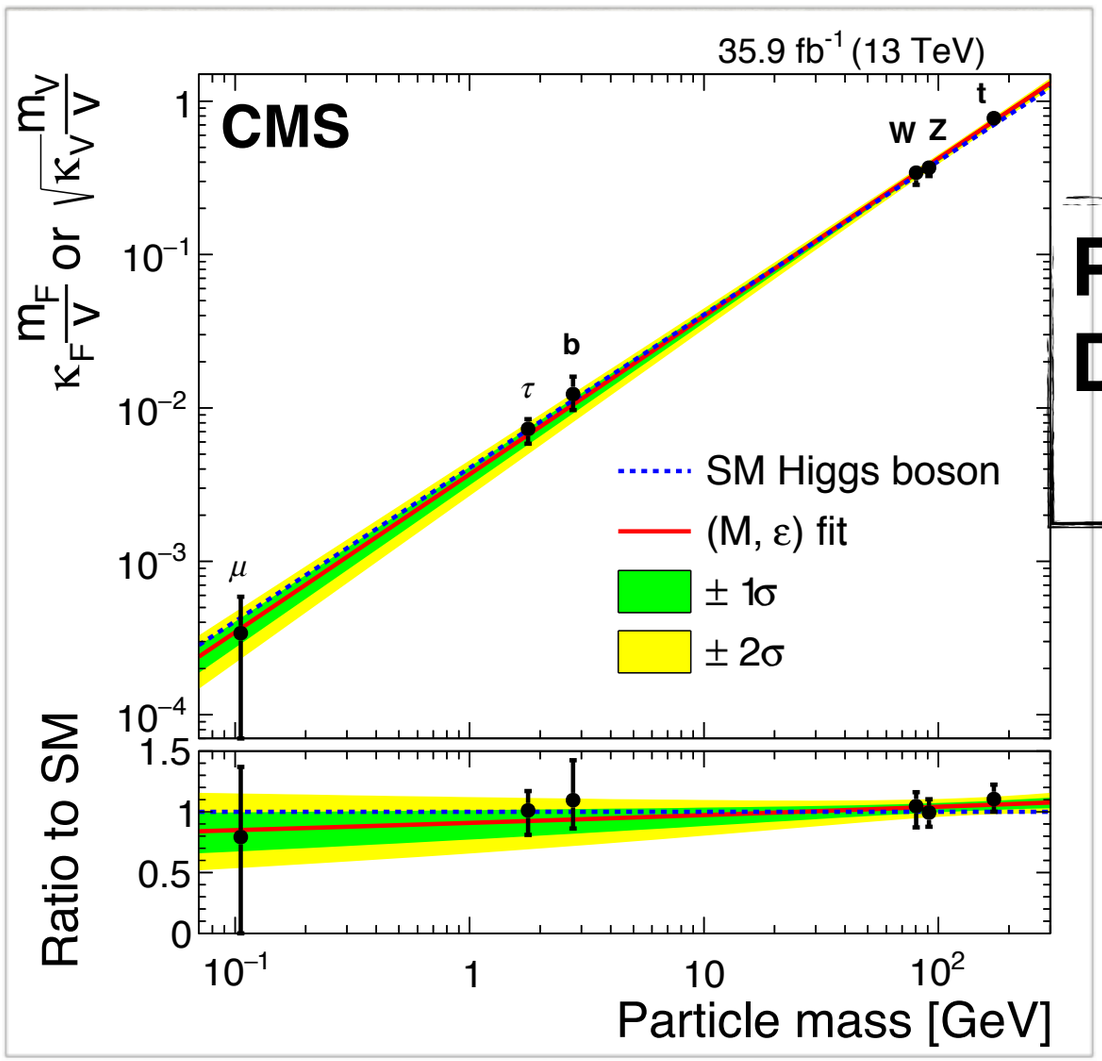

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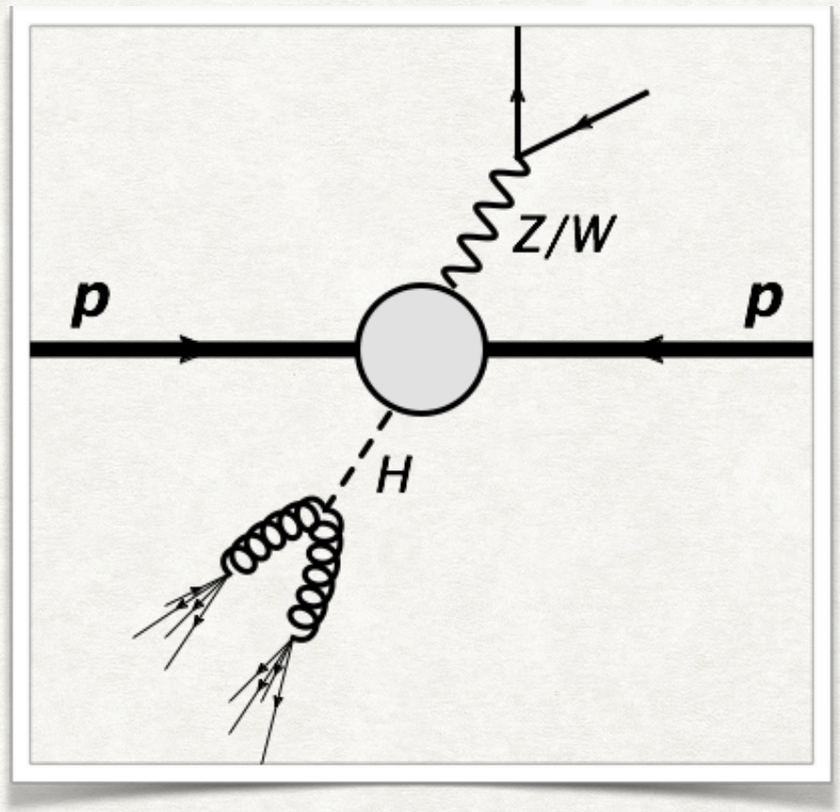

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$$\mathcal{S}^2 > \sum_a \chi_a^2 = \sum \frac{(x_a - \overline{x}_a)^2}{\sigma_a^2}$$

$$= \sum_a \frac{(\sum_i \epsilon_{ai}^2 \mathrm{BR}_i N_{\mathrm{sig}}^{prod} - \sum_i \epsilon_{ai}^2 \mathrm{BR}_i^{\mathrm{SM}} N_{\mathrm{sig}}^{prod})^2}{(\sqrt{N_{\mathrm{bkg}}})^2}$$

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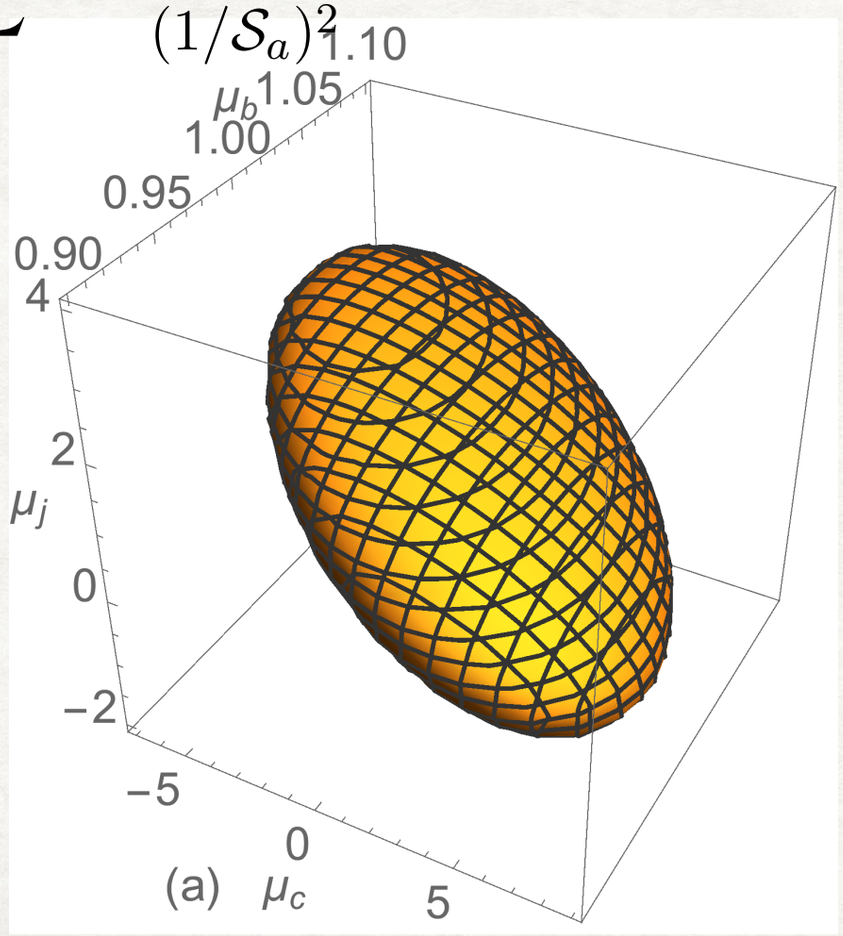

μ_j

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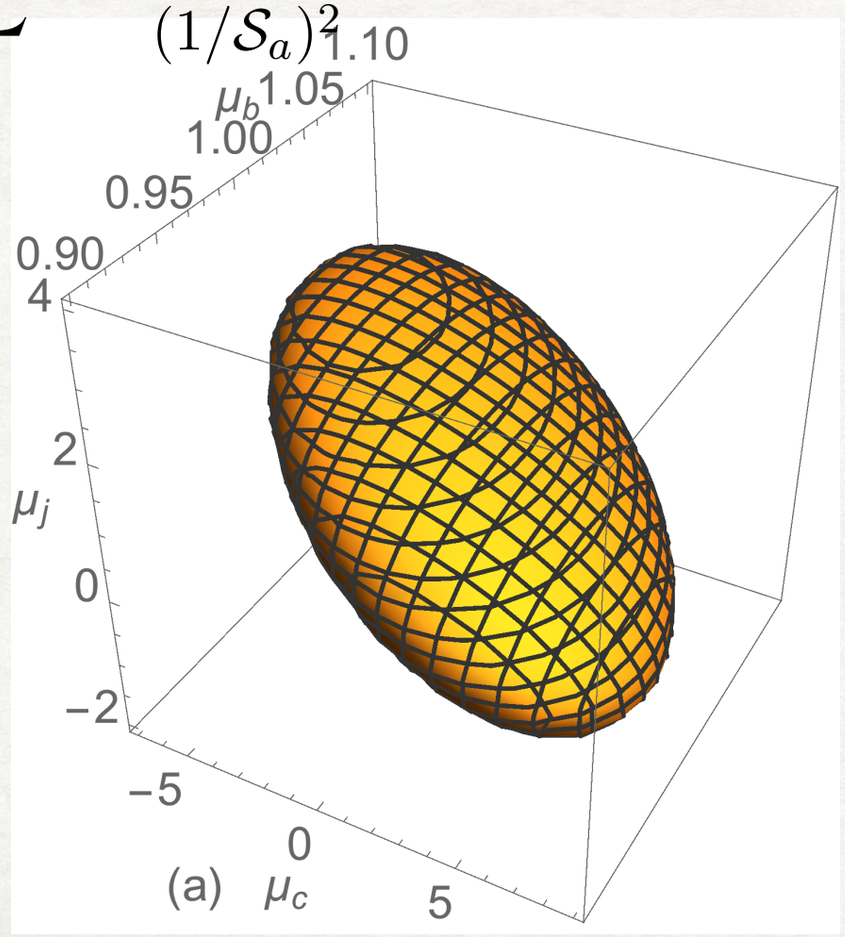

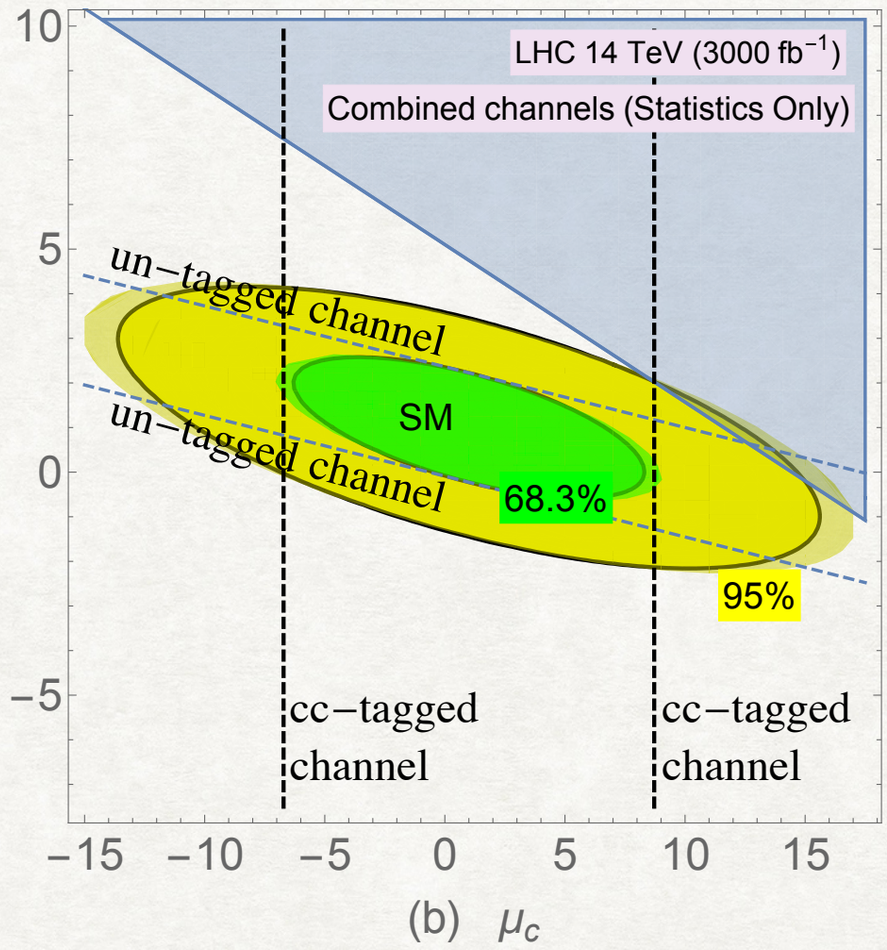

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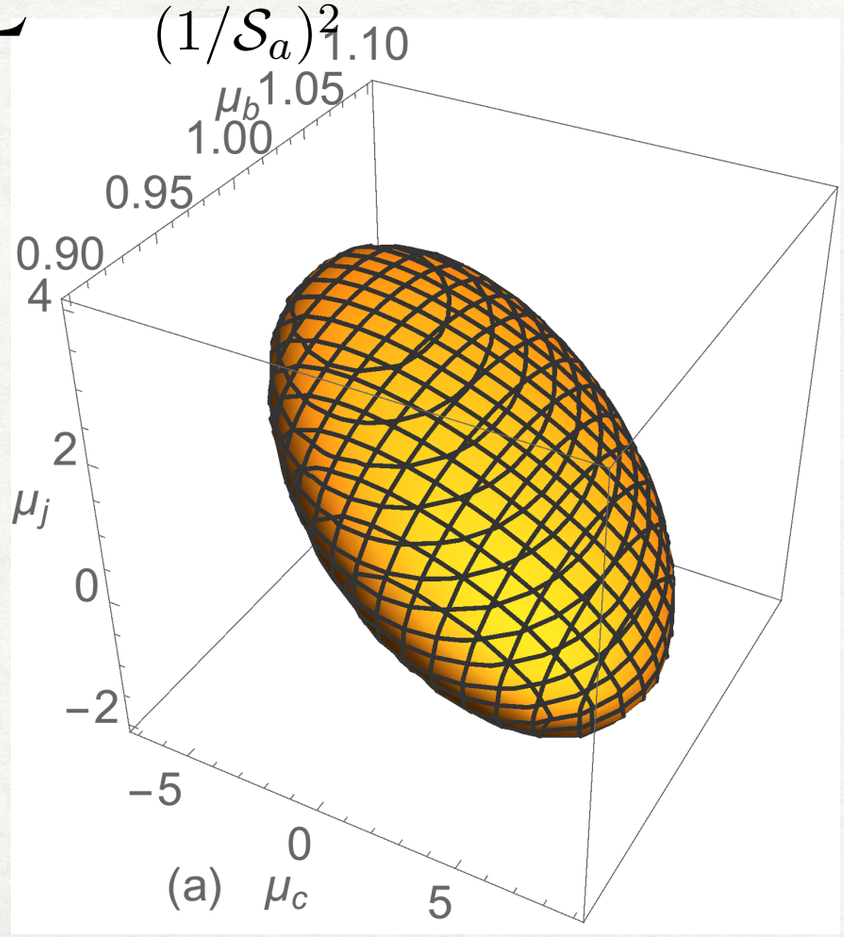

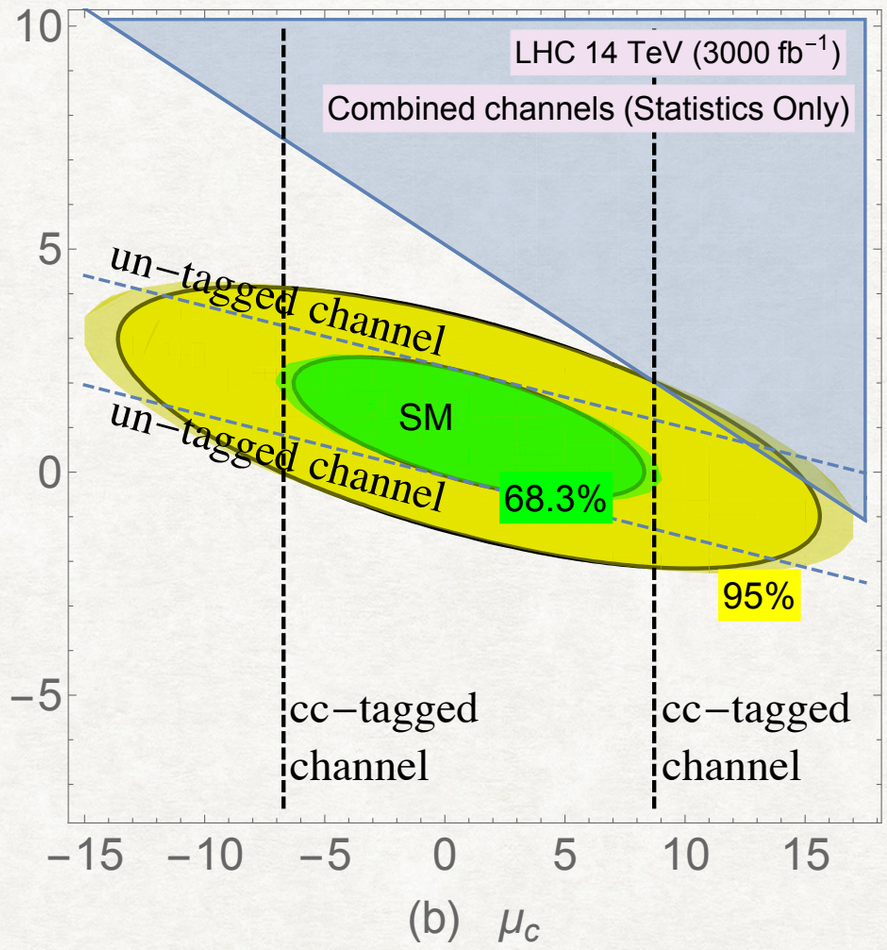

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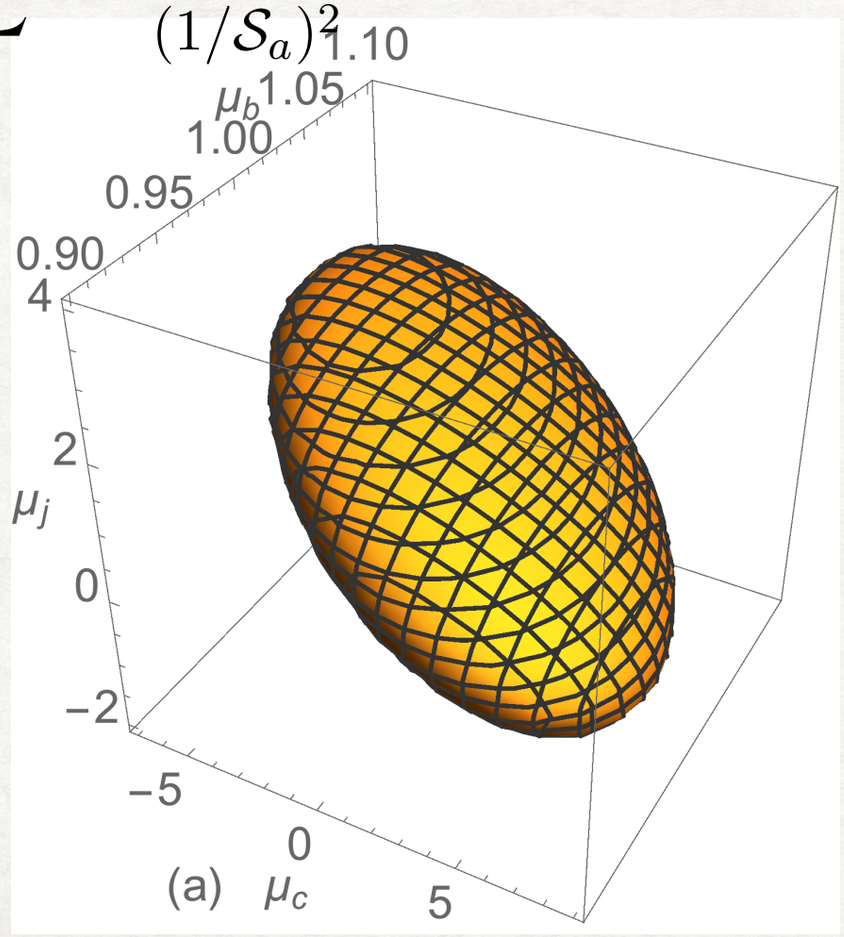

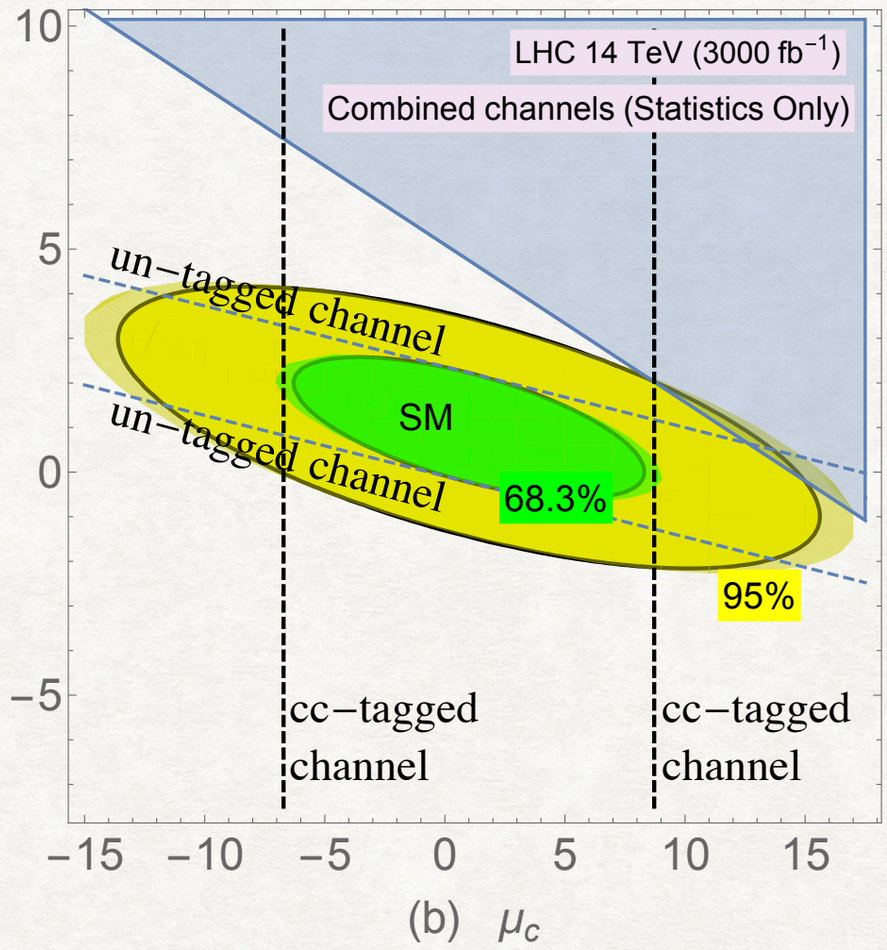

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$$\sigma \propto y_q^2, \quad y_c \lesssim 4 y_c^{SM}$$

SM HIGGS? (YUKAWA)

Enhanced Light Quark Yukawa Constraints: Bound state J/Ψ, Higgs threshold pT distribution, fH, γH, HH production, Lepton collider event shape, Wh charge assymmetry, etc. (arXiv: 1606.09621, 1608.01746, 1609.06592, 1801.00363, 1804.02400, 1904.09895)

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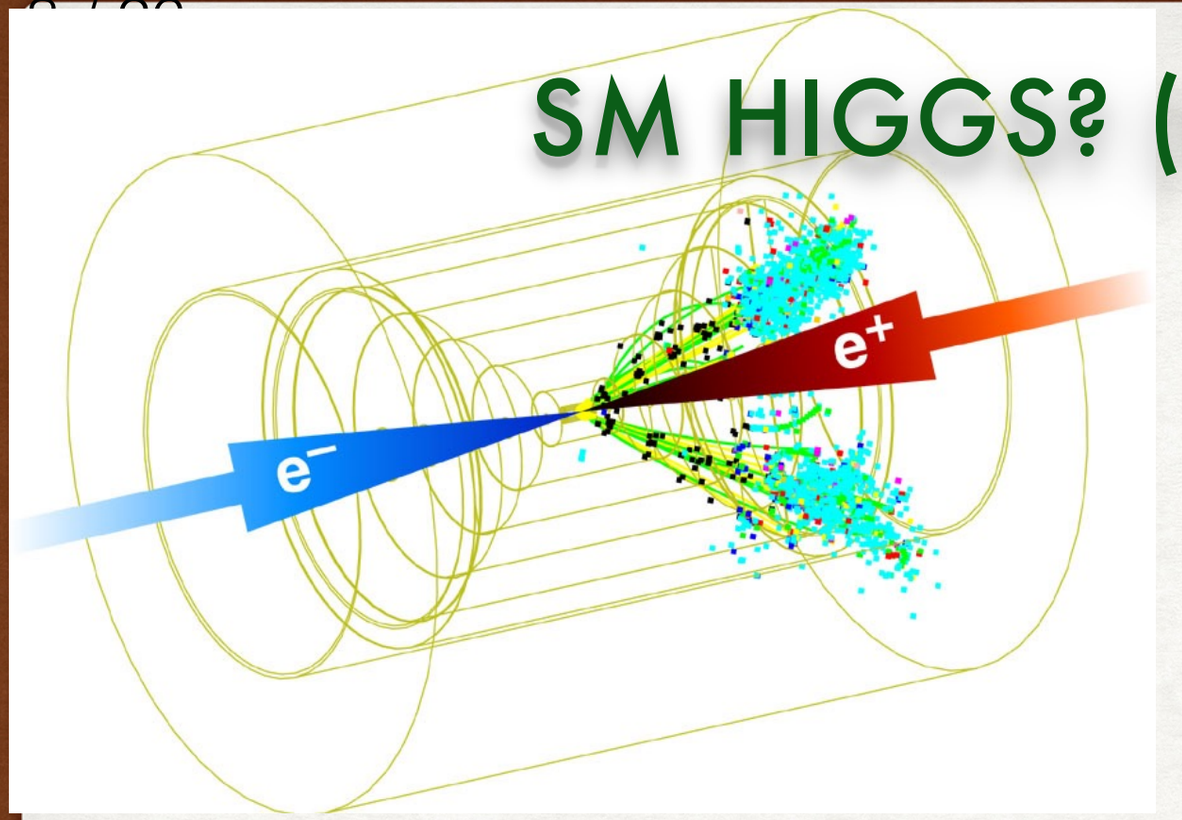
TABLE X. Extrapolated upper bounds at 95% CL on the light-quark Yukawa couplings $\bar{\kappa}_q = y_q/y_b^{\rm SM}(\kappa_q = y_q/y_q^{\rm SM})$ for $q = u,\ d,\ s$.

$\mathcal{L}(\text{fb}^{-1})$	$\bar{\kappa}_u(\kappa_u)$	$\bar{\kappa}_d(\kappa_d)$	$\bar{\kappa}_s(\kappa_s)$
300 (untagged $j'j'$)	1.2 (2600)	1.2 (1200)	1.2 (61)
3000 (untagged $j'j'$)	0.65 (1500)	0.65 (680)	0.65 (34)

SM HIGGS? (GAUGE SECTOR)



Tao Han, Zhen Liu, ZQ, Joshua Sayre (2015)

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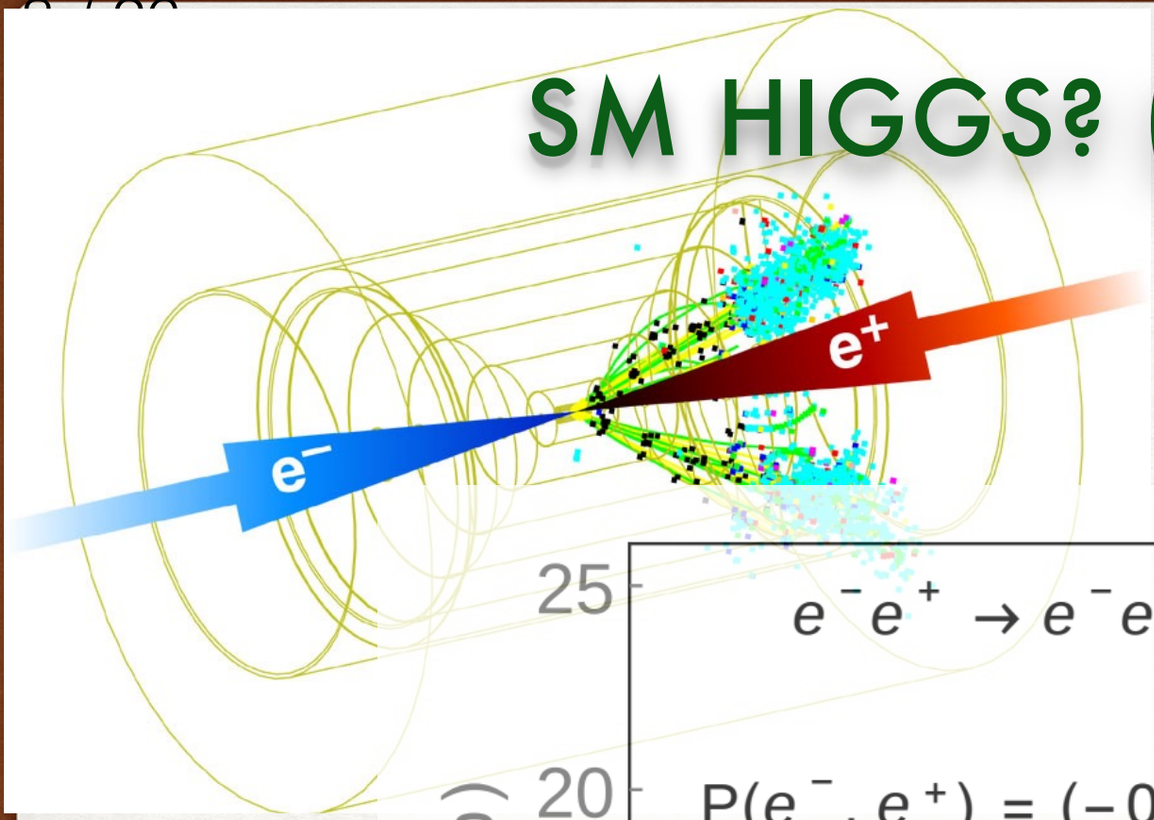

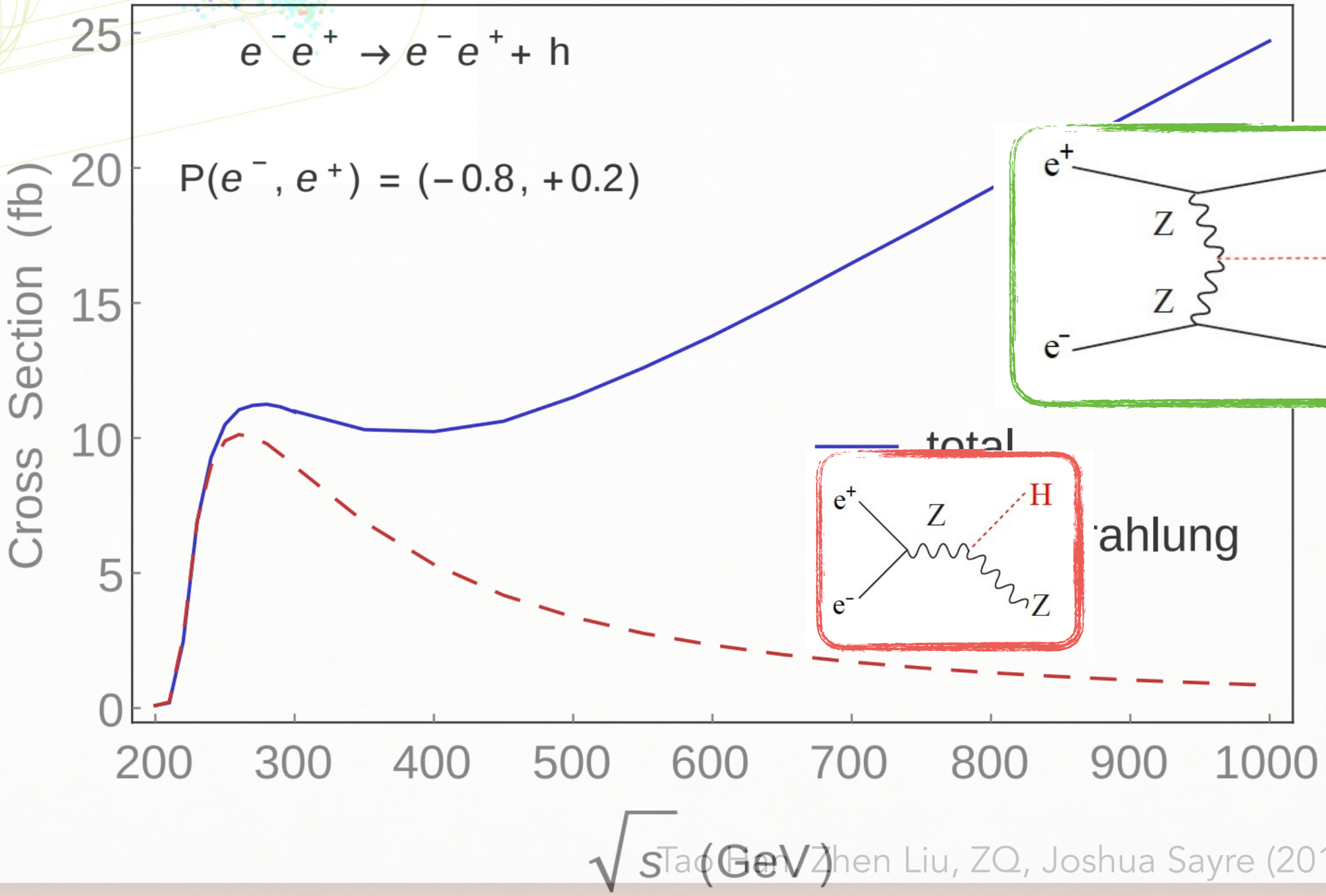

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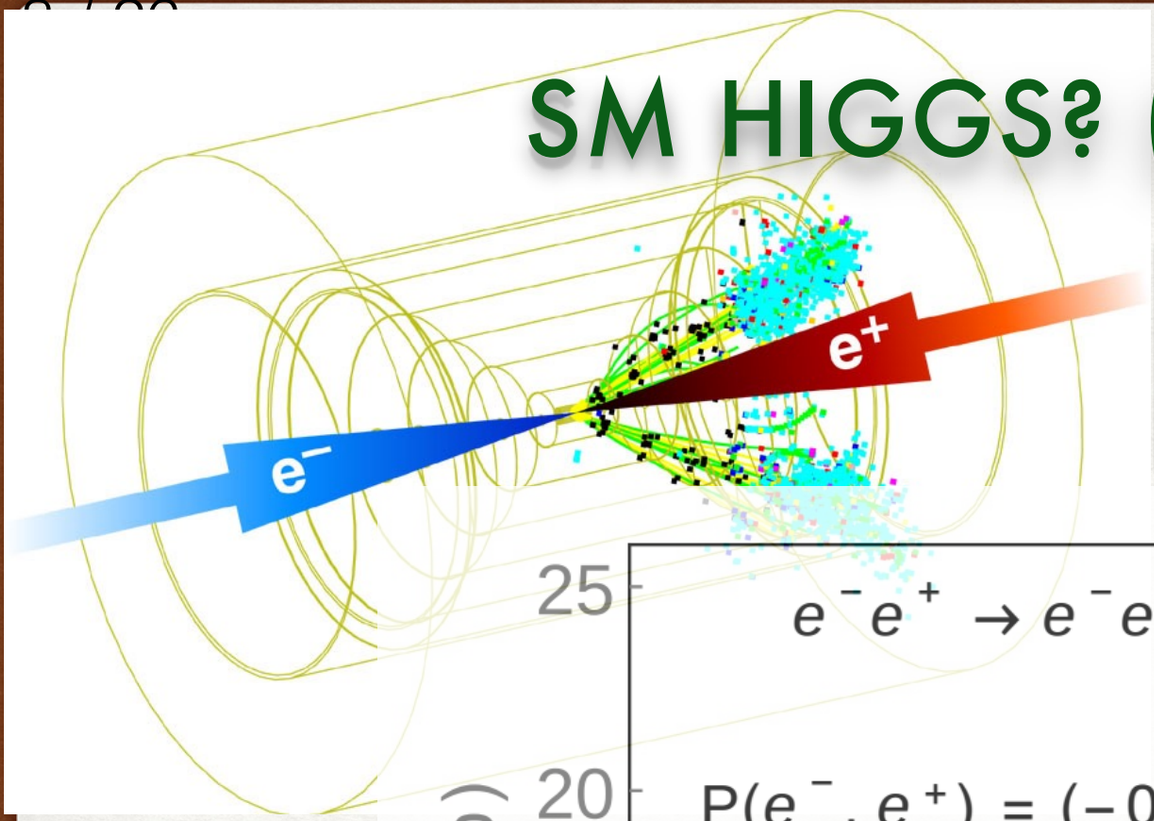
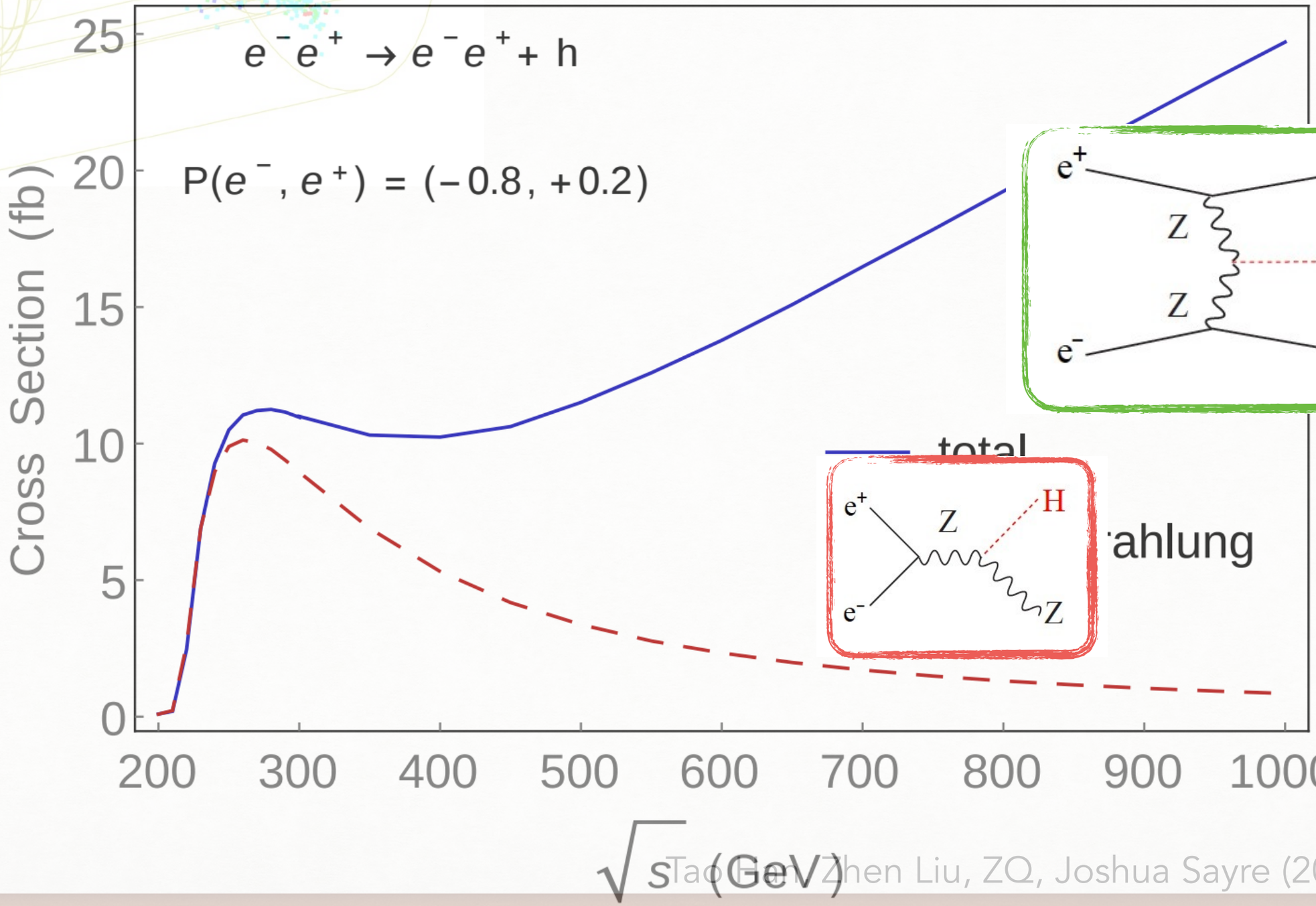


$$m_H^2 \xrightarrow{\text{LO}} m_{rec}^2 \equiv s - 2\sqrt{s}E_{ee} + m_{ee}^2$$



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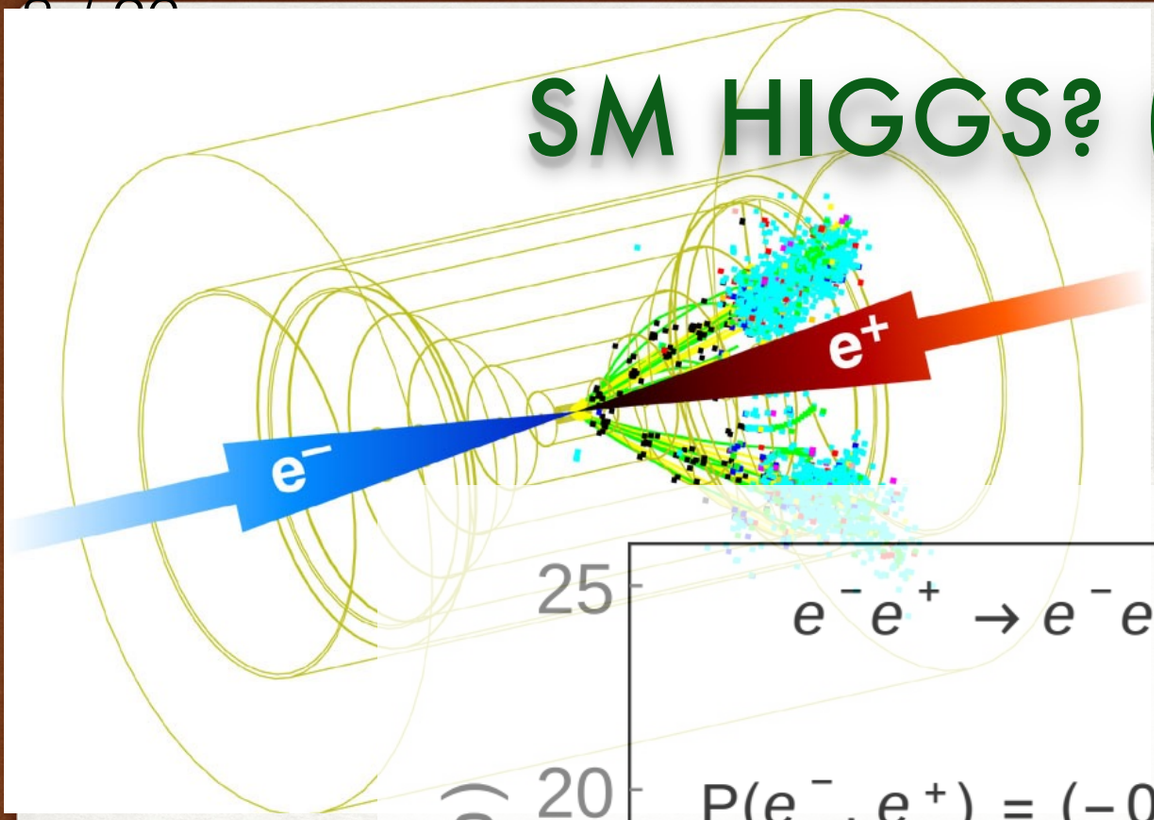

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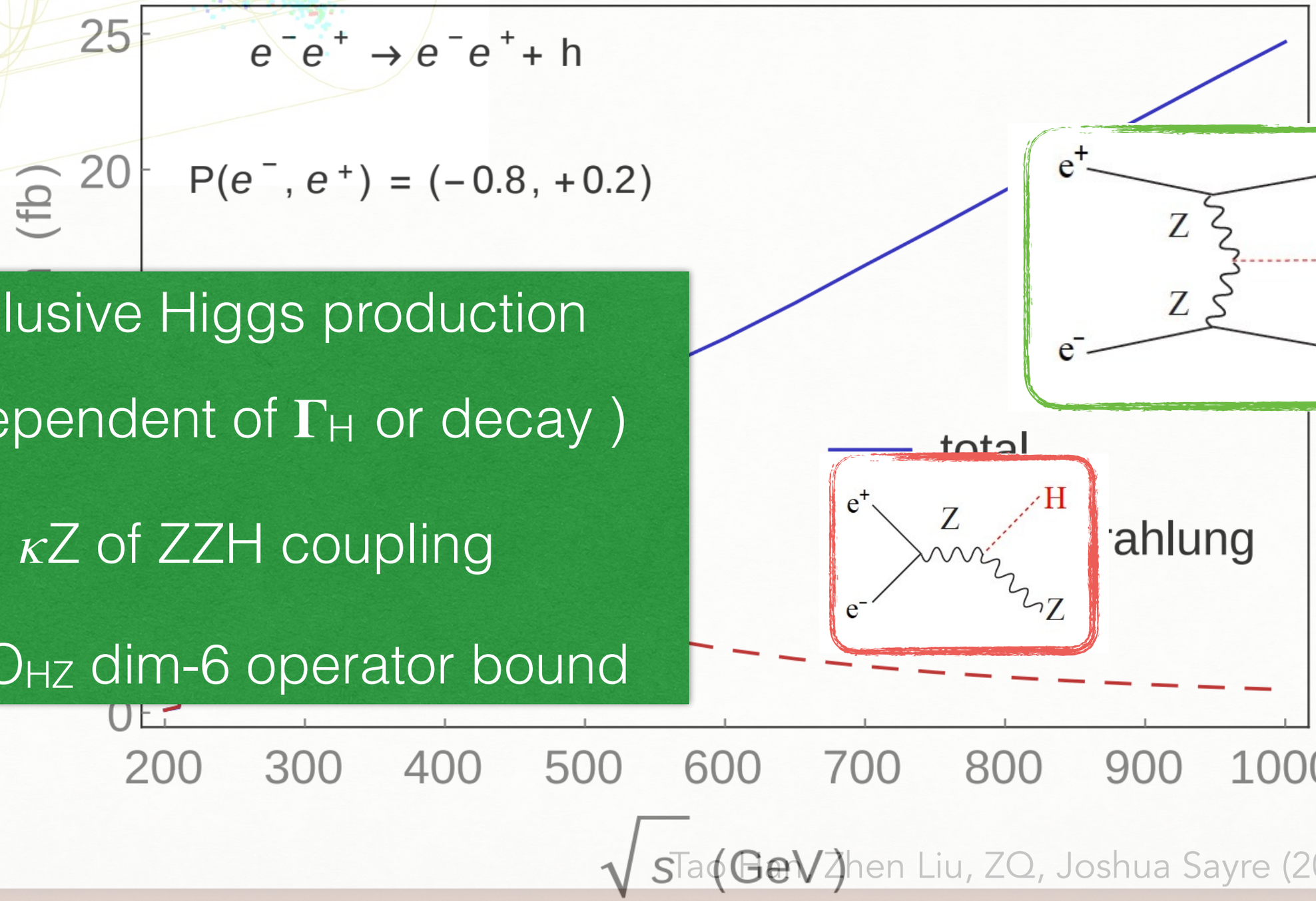

- Inclusive Higgs production (independent of Γ_H or decay)
- κZ of ZZH coupling
- O_H, O_{HZ} dim-6 operator bound

Tao Han, Zhen Liu, ZQ, Joshua Sayre (2015)

SM HIGGS? (GAUGE SECTOR)

- (Relatively) Low Scale Electroweak Precision: S,T,U parameter
- MZ, MW, ΓZ, ΓW, $\sin\theta_W$, etc. (Recent Review: 1407.3792, 1803.01853)

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where the SM Higgs Restores Unitarity

- ***VV(Di-boson)***, VVV (Triple Gauge Boson: 1903.10415-exp)
- Vector Boson Scattering (Recent review: 1801.04203)
- HVV, Vector Boson Fusion Higgs (1504.01399, 1610.08420)
- (H)HVV, (H)Htt~ (1611.03860, 1902.00134, 1904.07886)
- (Dim-6 Operator fit, Composite scale)

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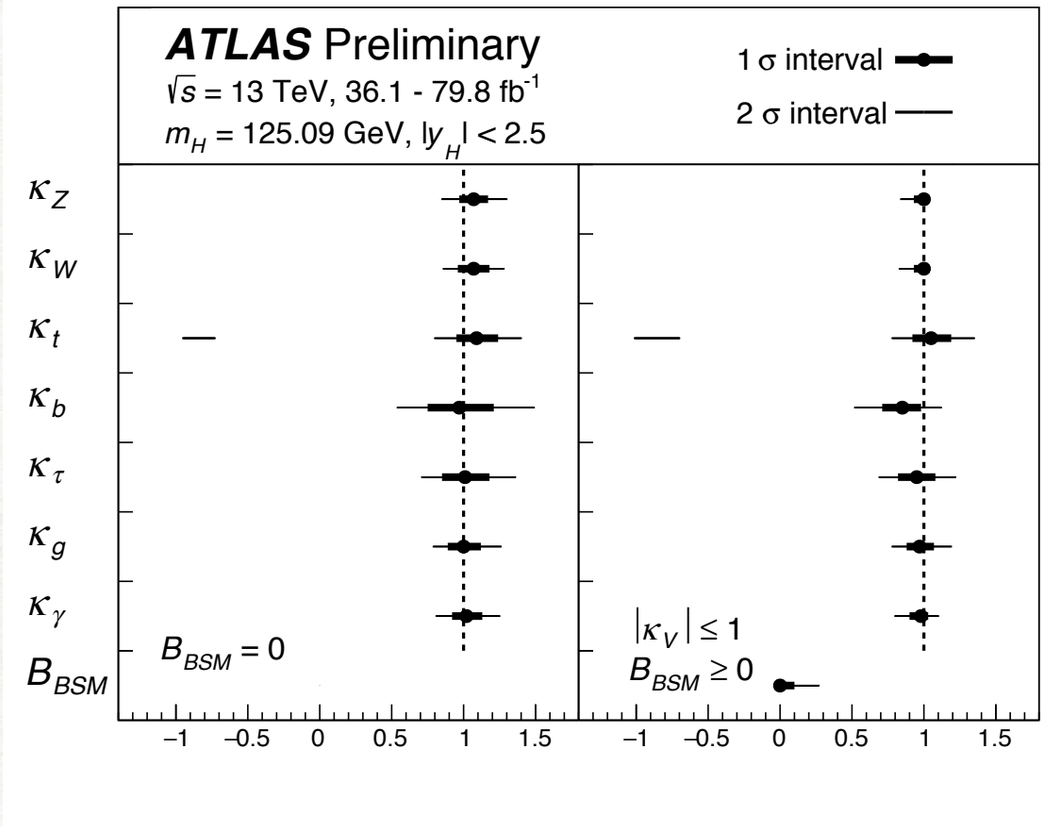
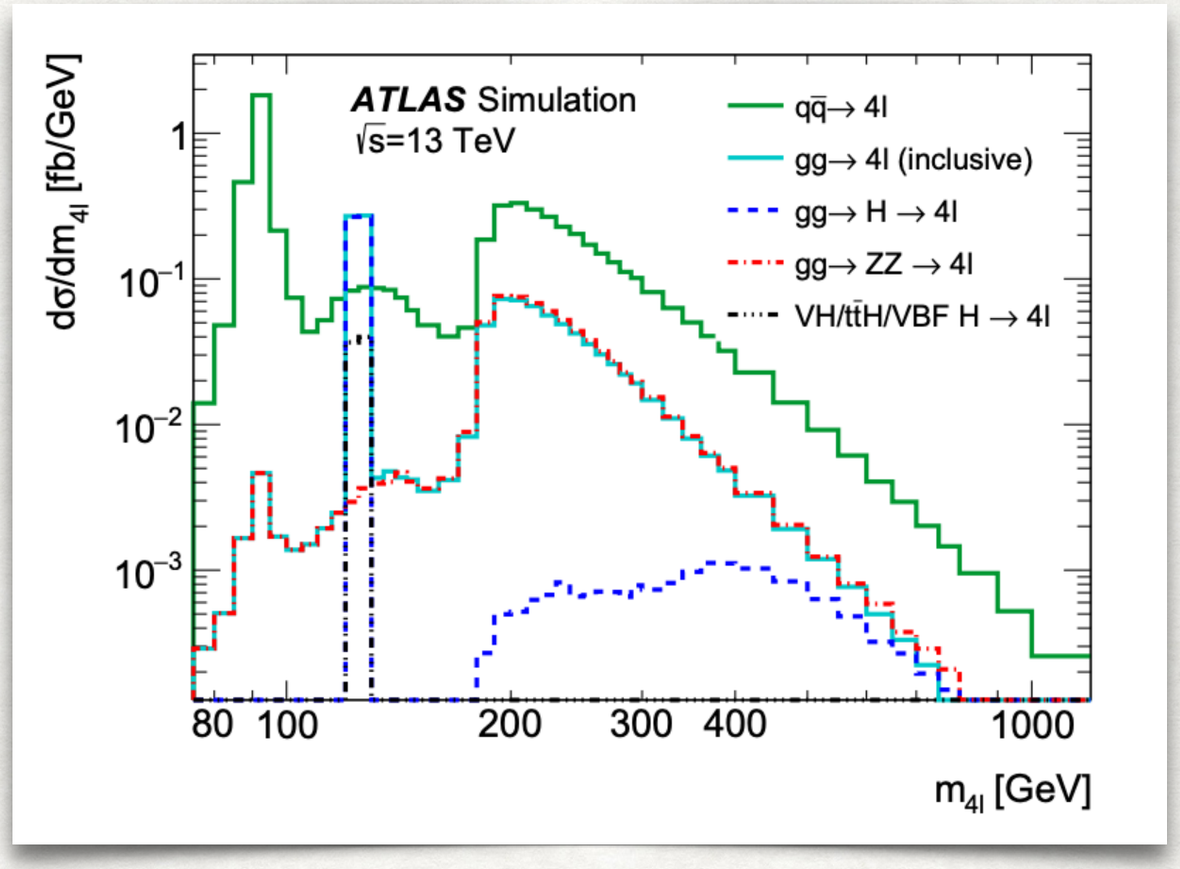


(a)

Higgs on-shell signal Measurement



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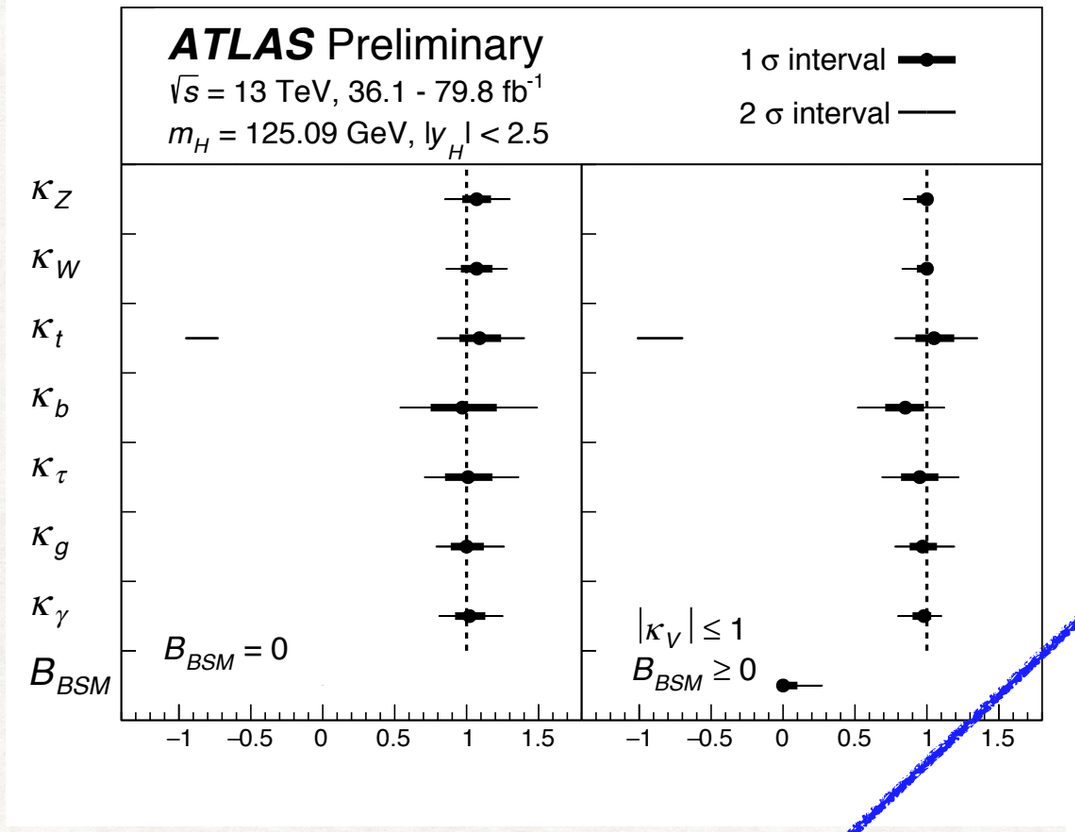

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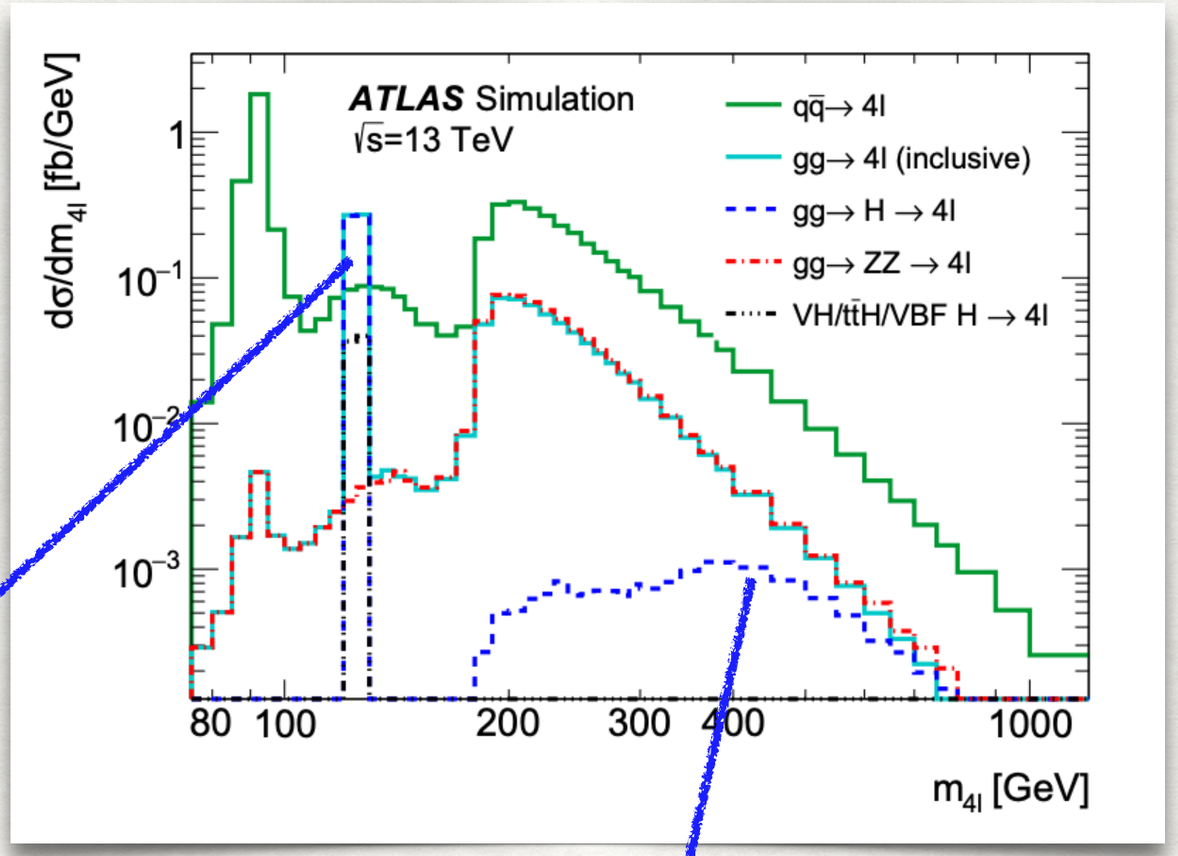

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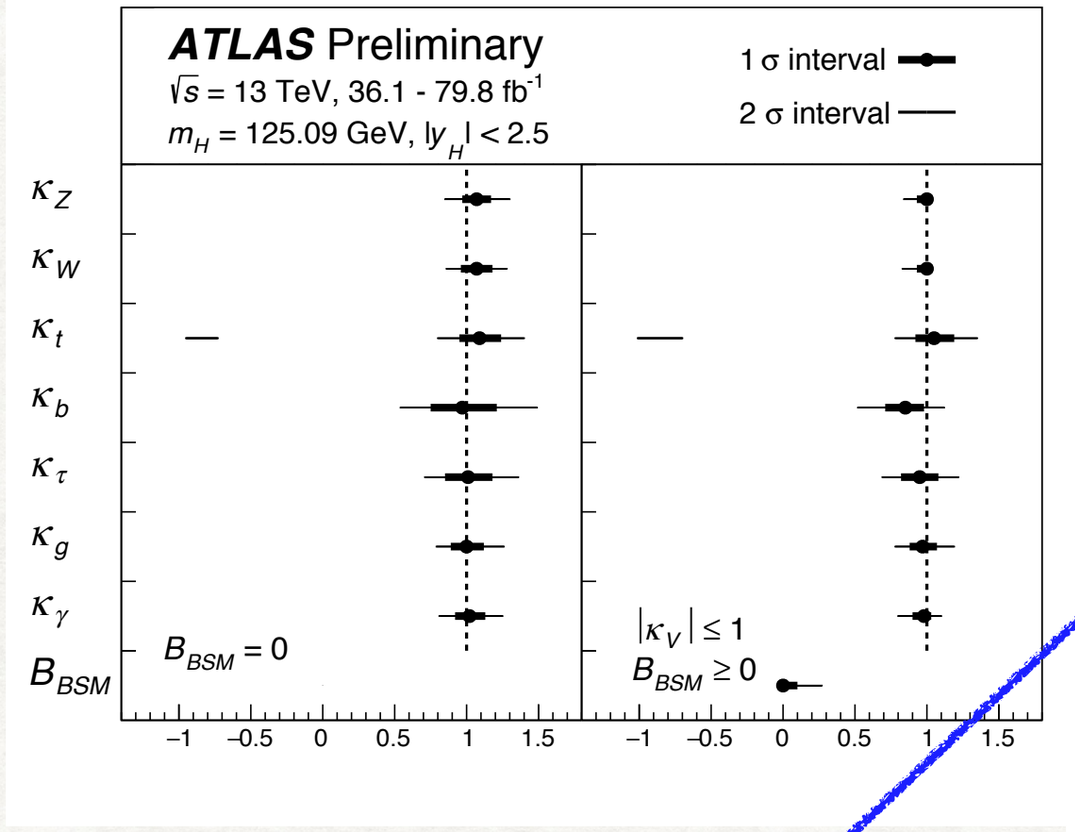

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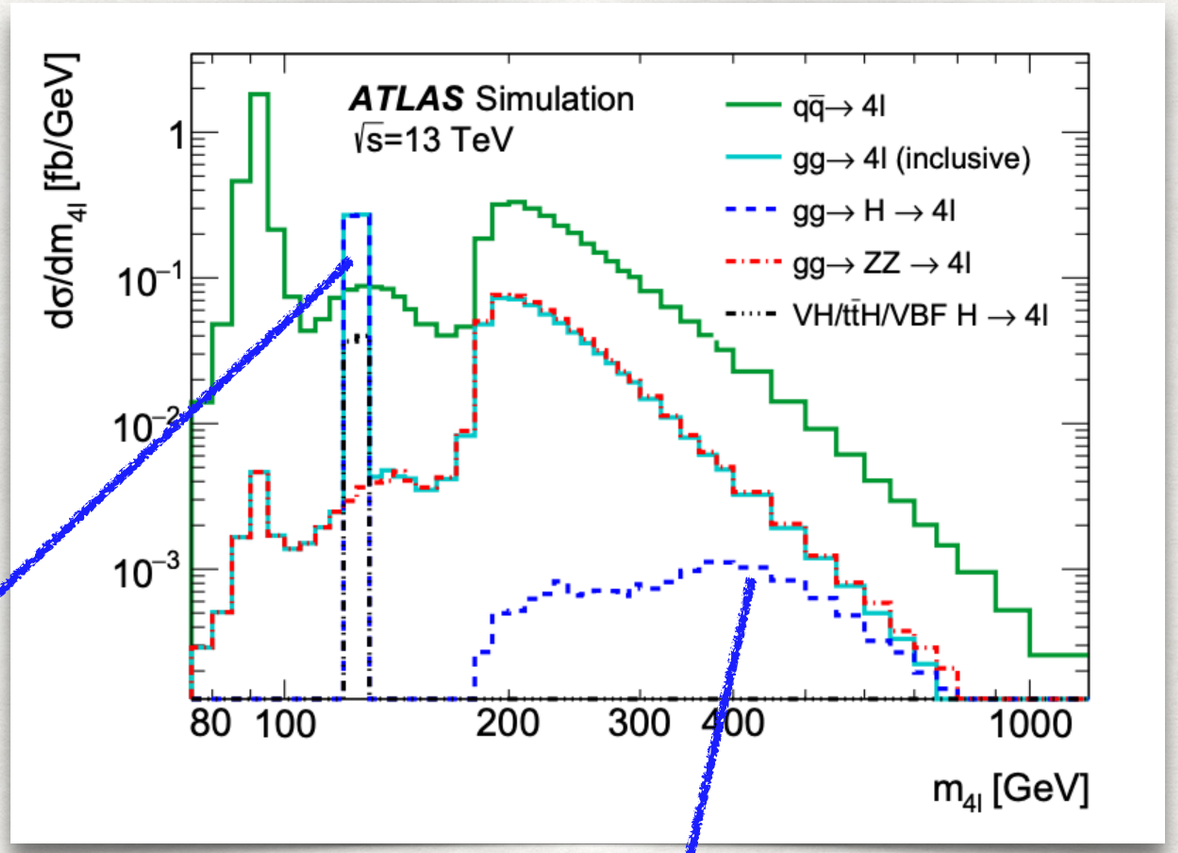

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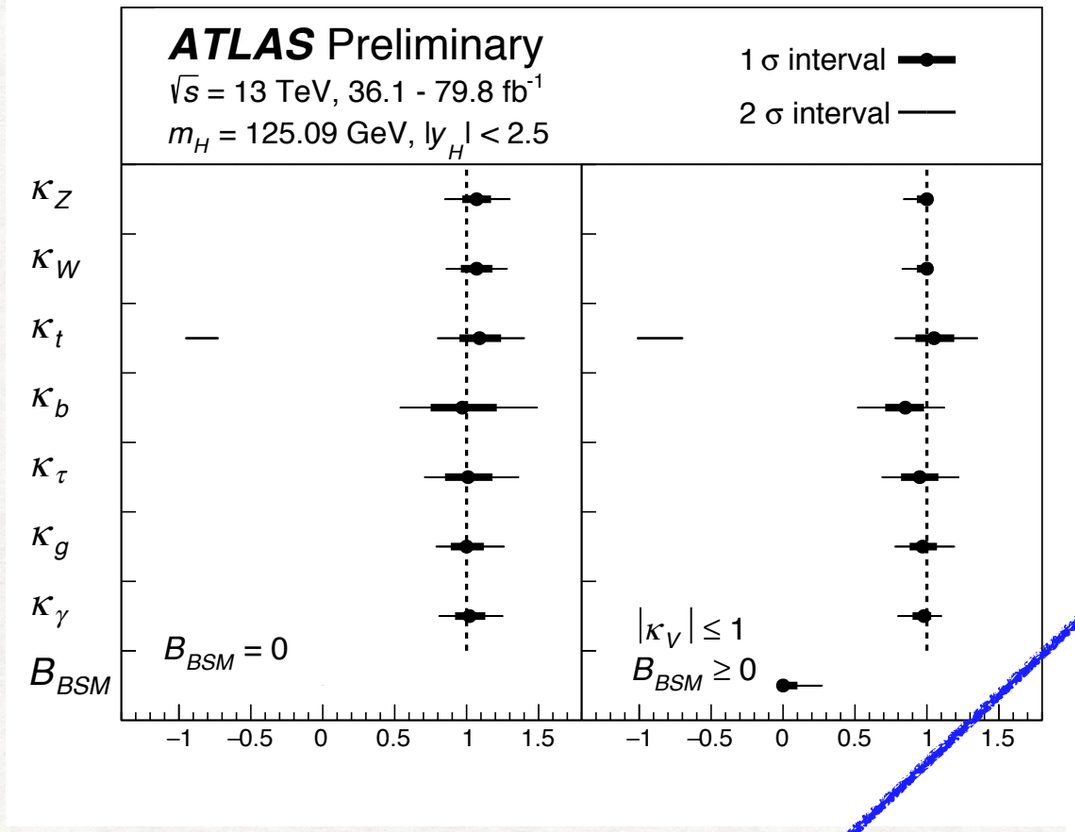
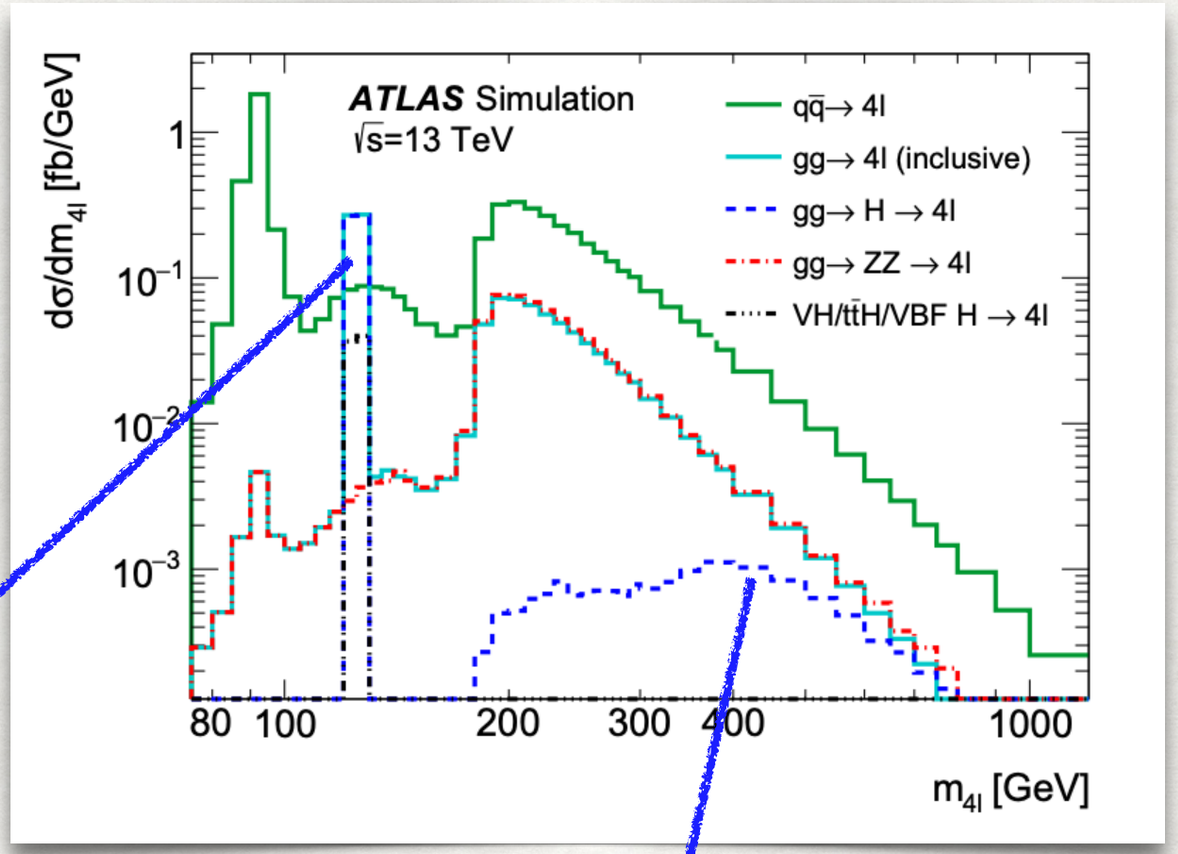


(a)



Higgs on-shell signal Measurement

Higgs off-shell signal

Di-boson production to probe Higgs sector new physics

- arXiv:1811.10215: Higgs measurement at LHC run2
- ATLAS: CERN-EP-2018-318, CMS: HIG-16-033

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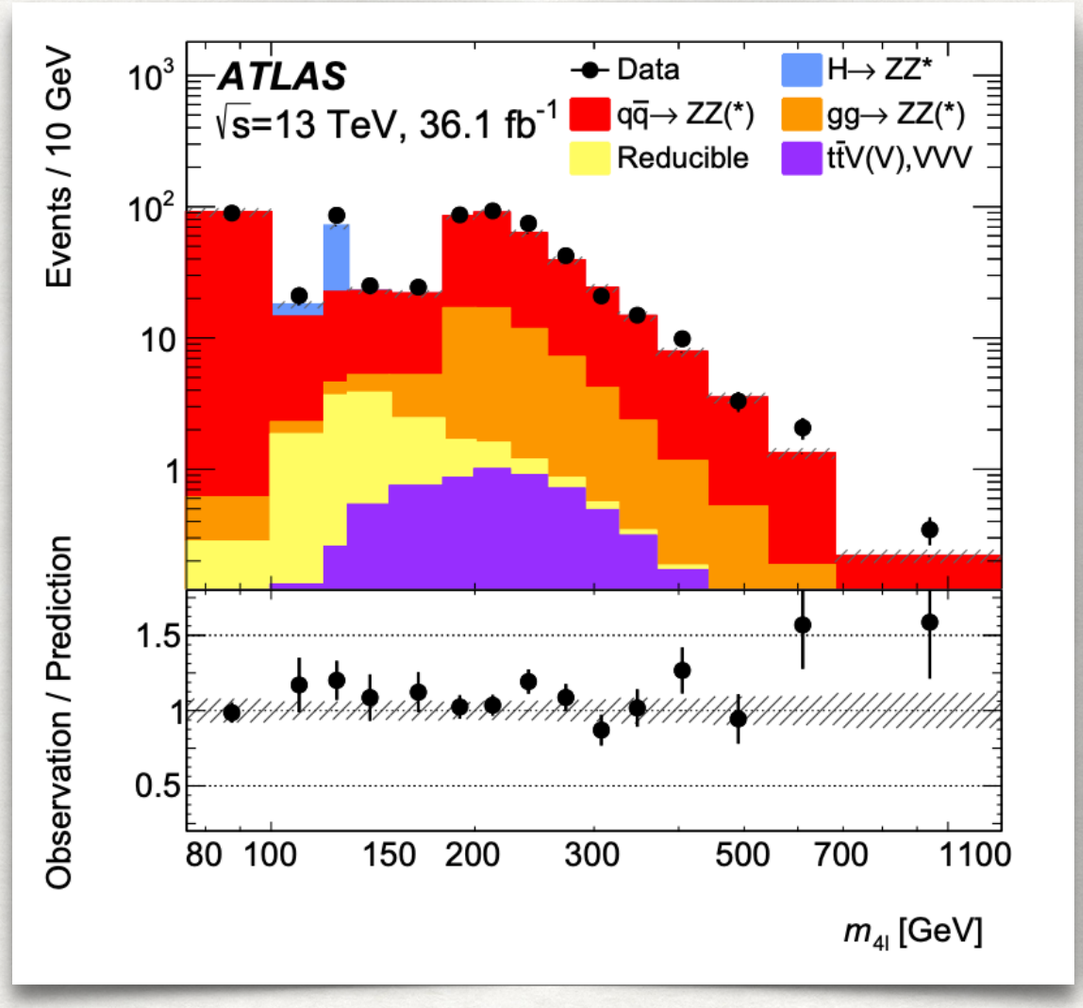

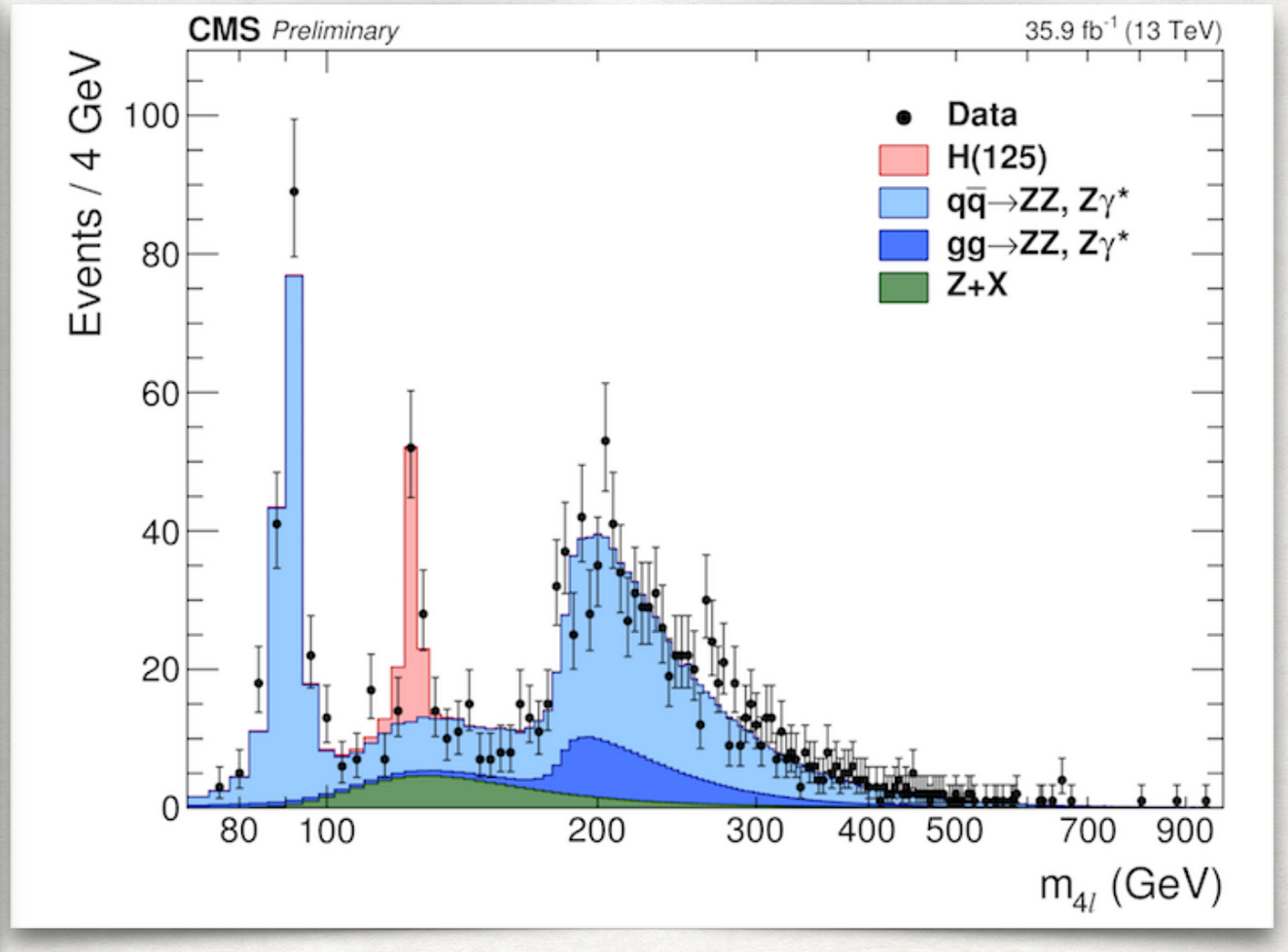

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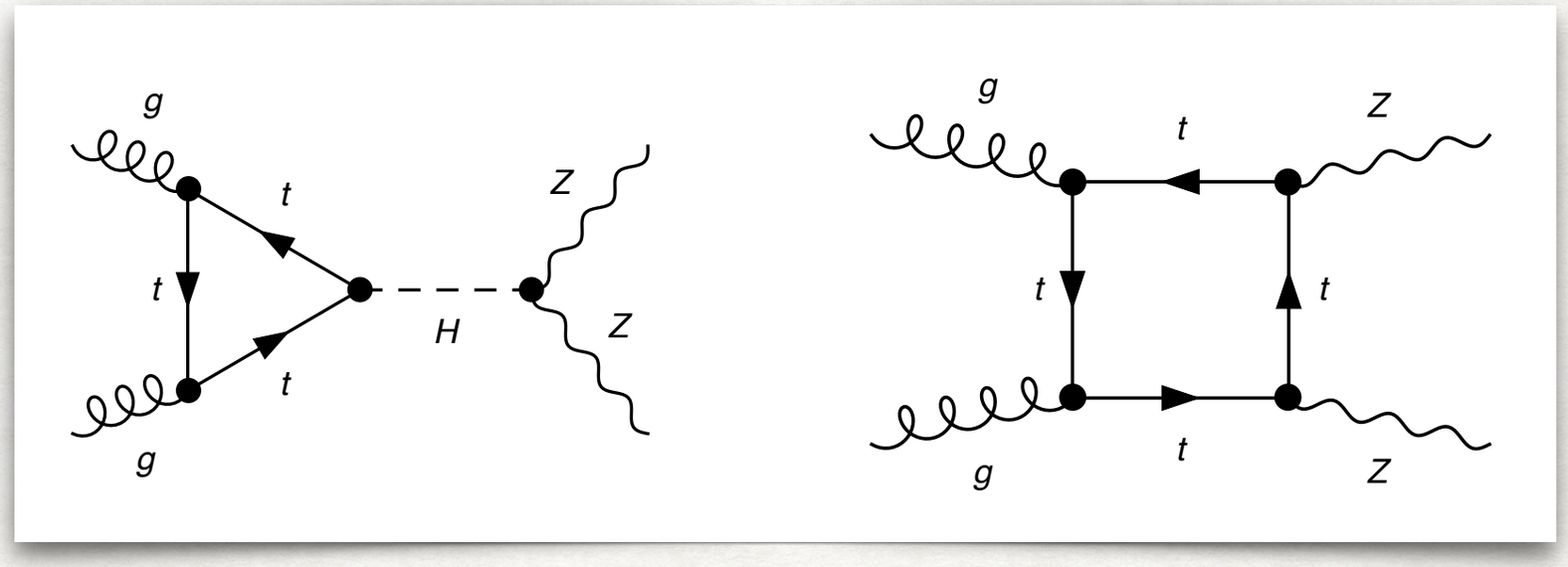
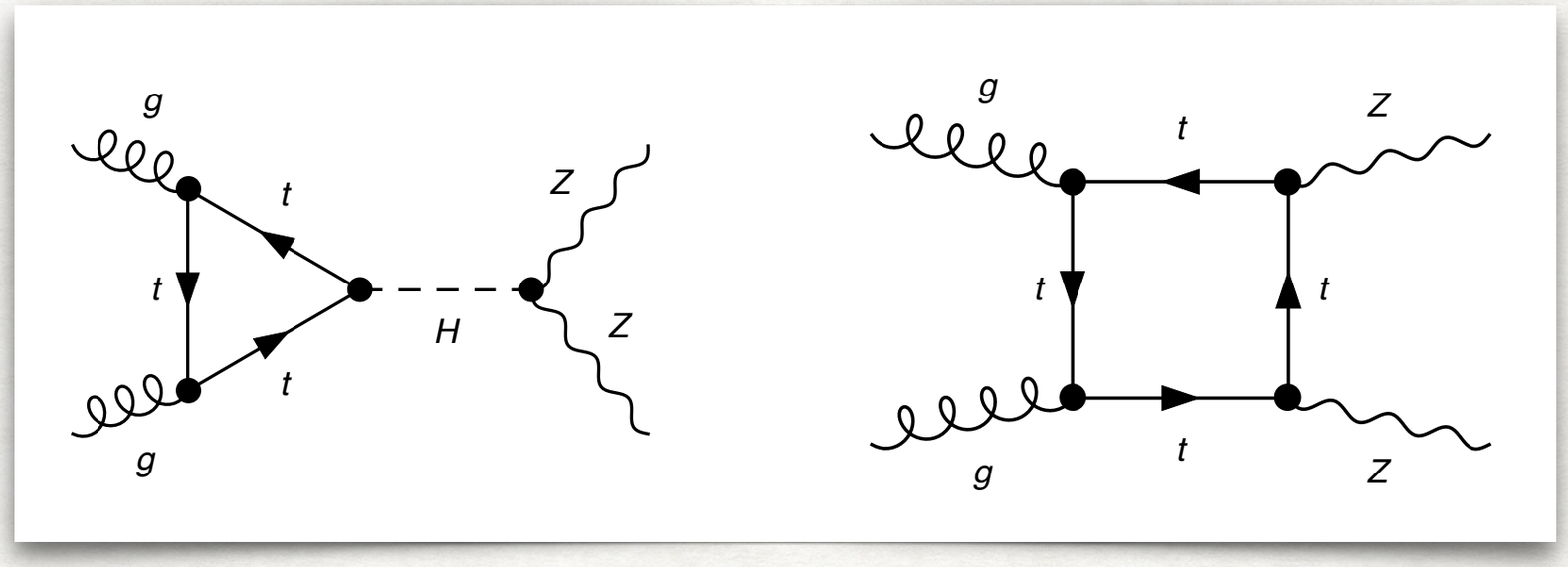
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



S. Lee, M. Park, ZQ (2019)

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



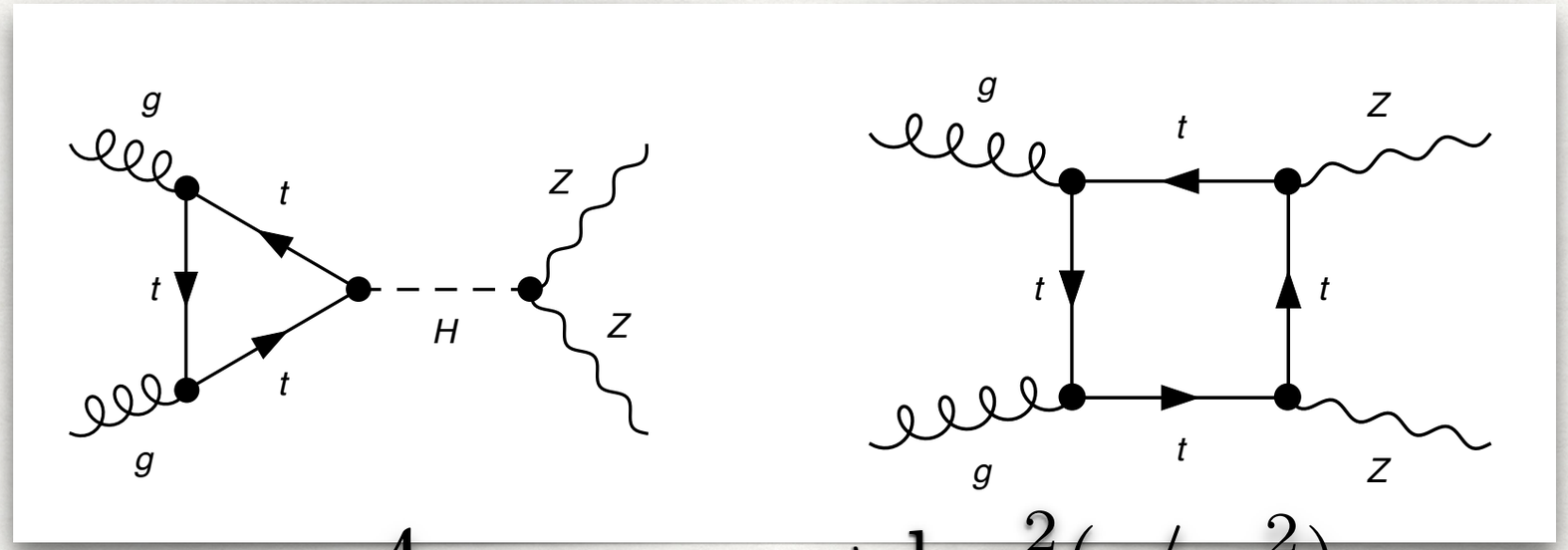
At High energy scale, each diagram diverges:

$$\mathcal{A}_{gg\to Z_L Z_L} \to \log^2(s/m_t^2)$$

Prominent in Z-longitudinal mode

S. Lee, M. Park, ZQ (2019)

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



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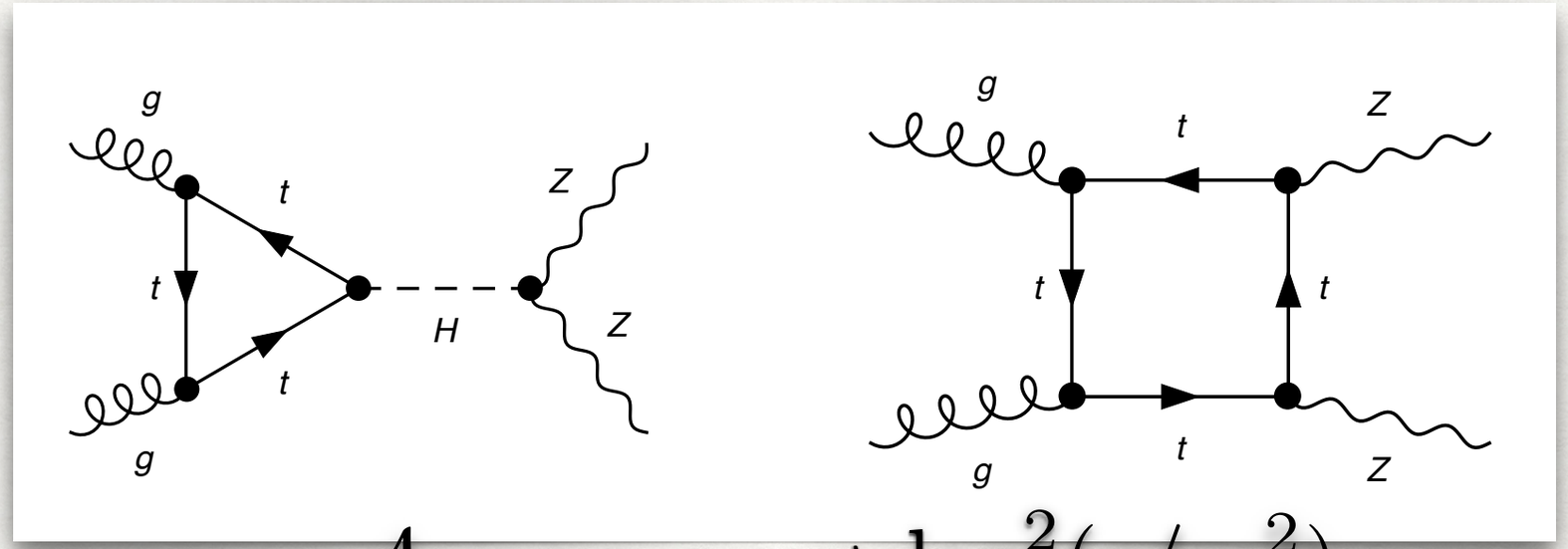

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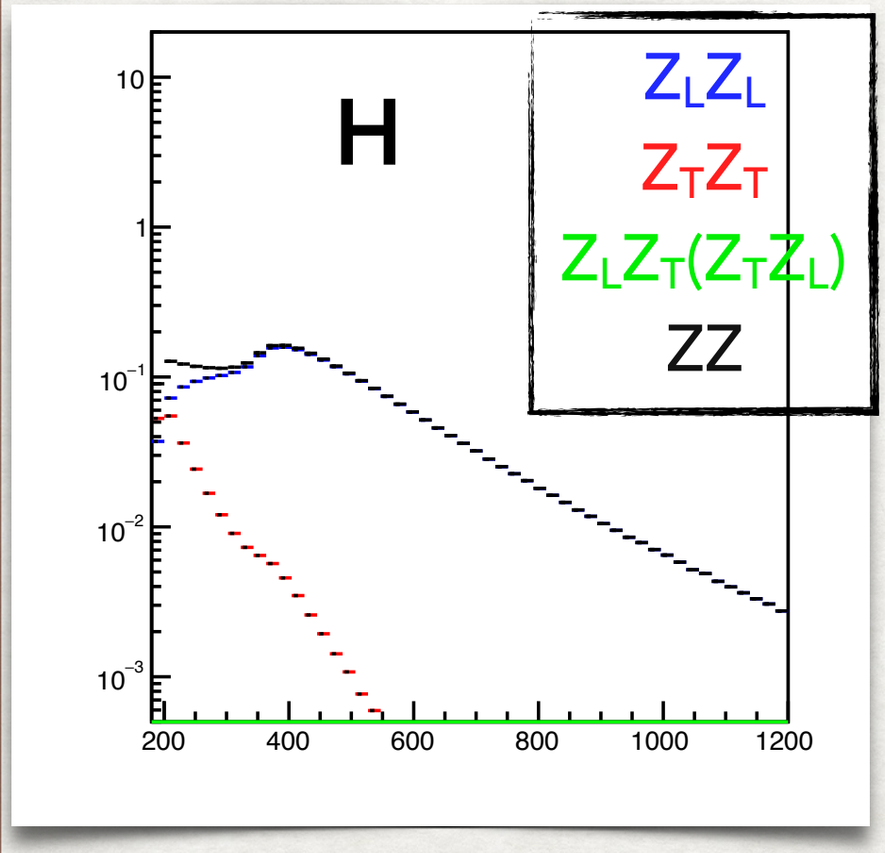

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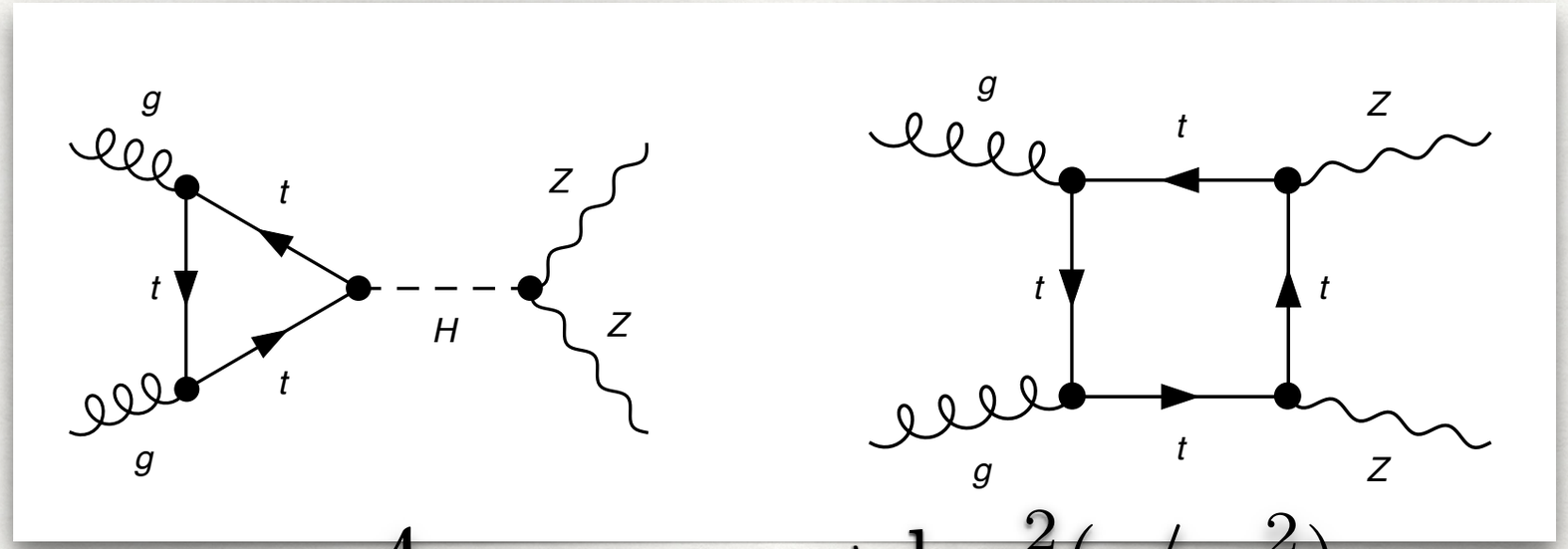

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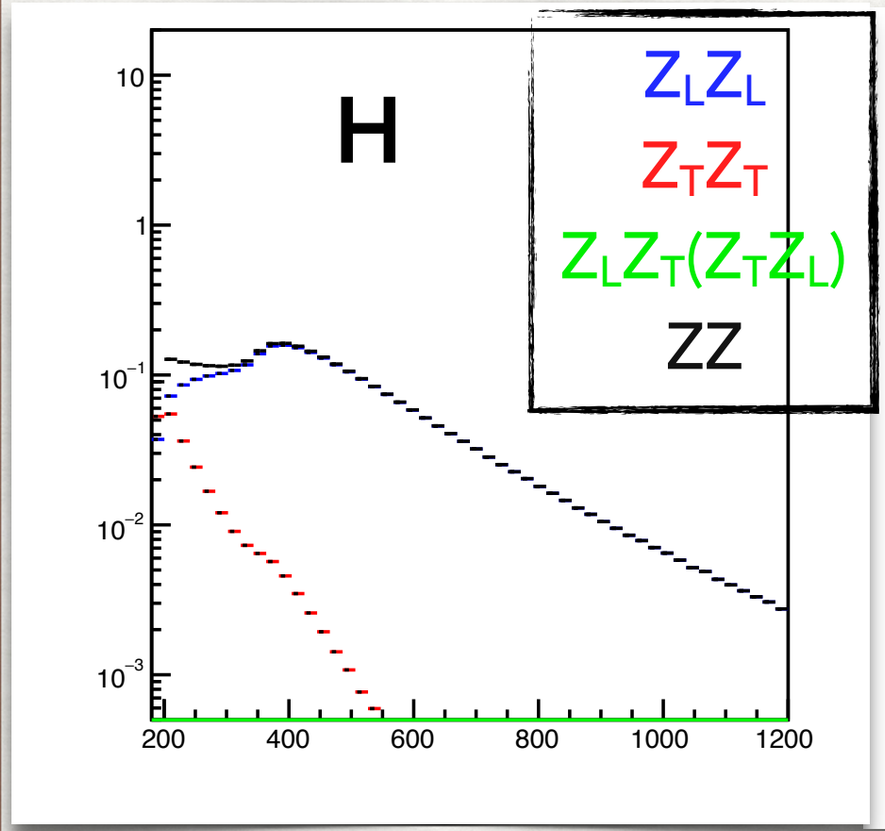

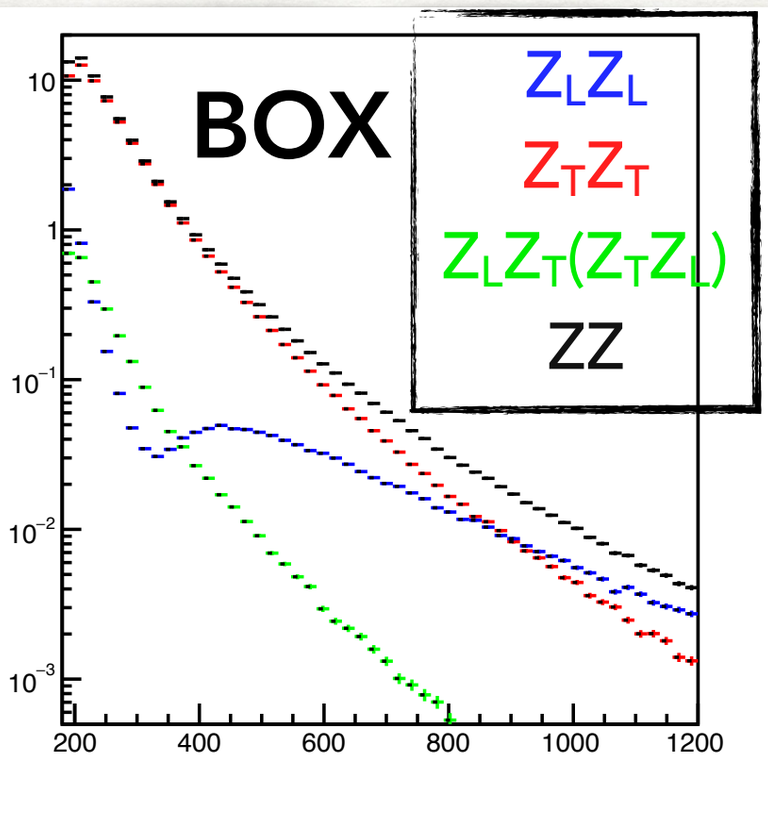

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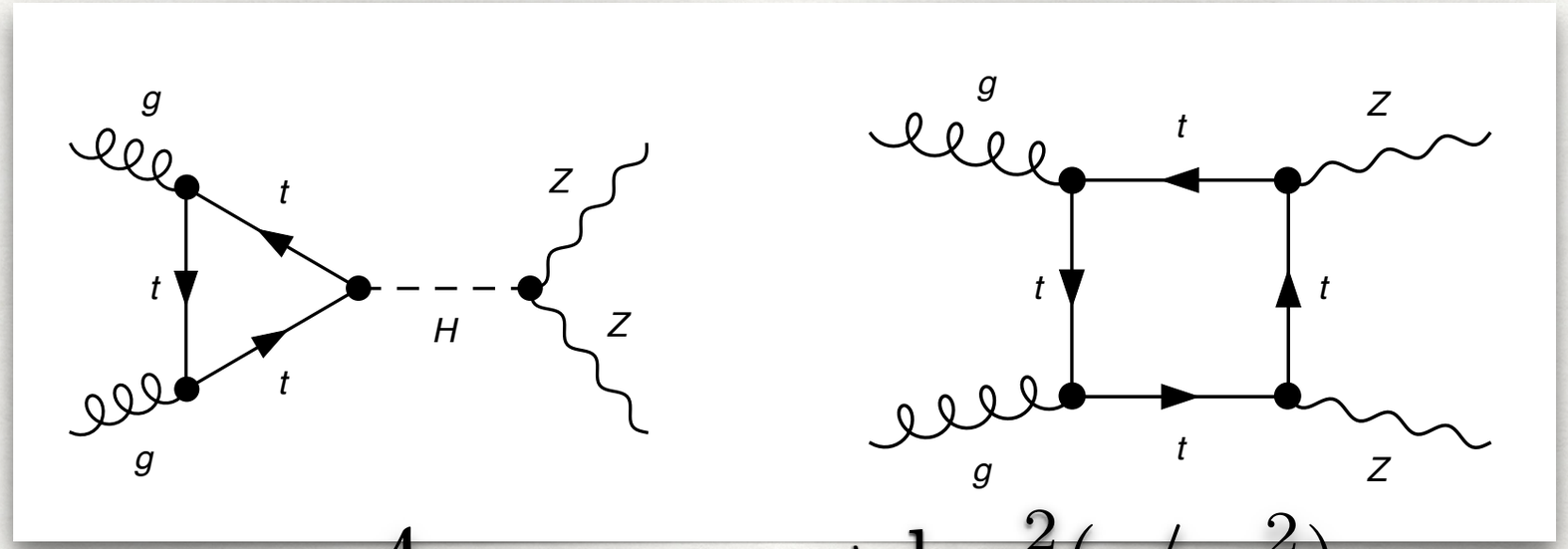

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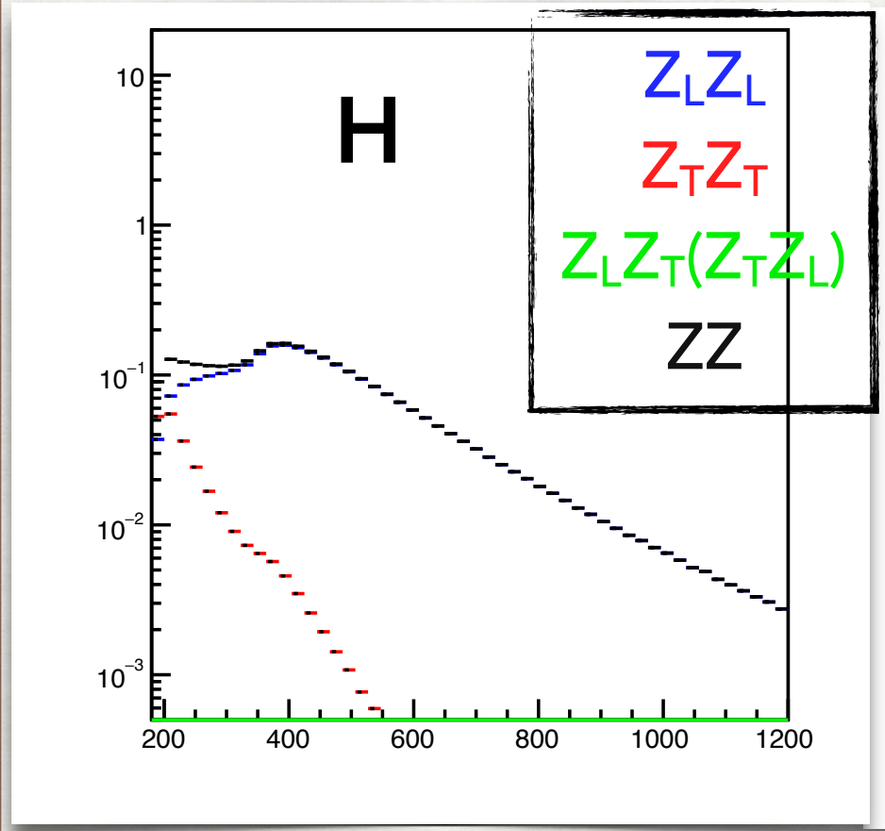

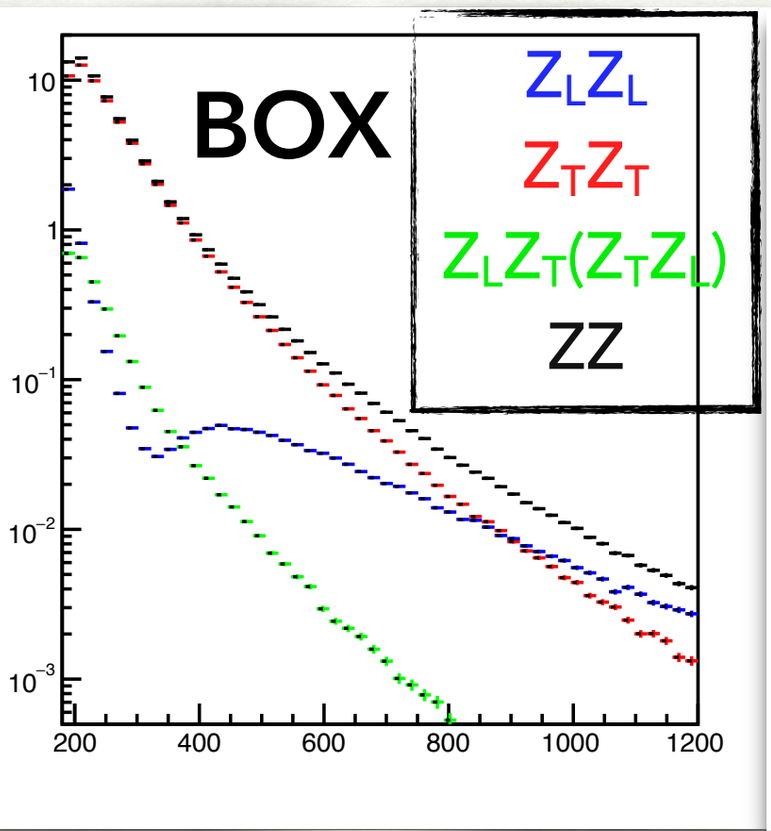

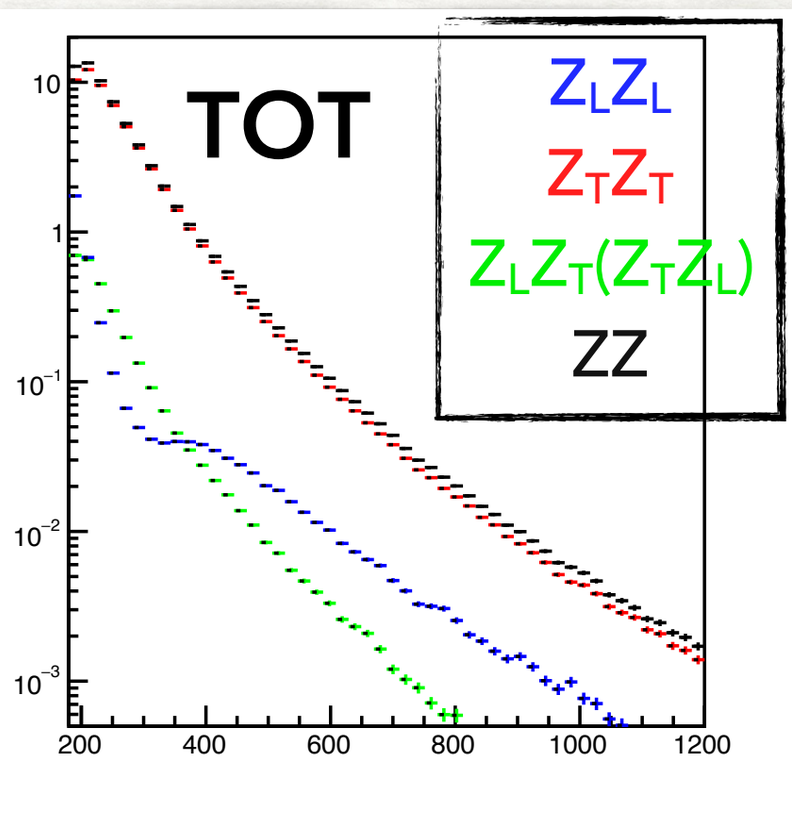

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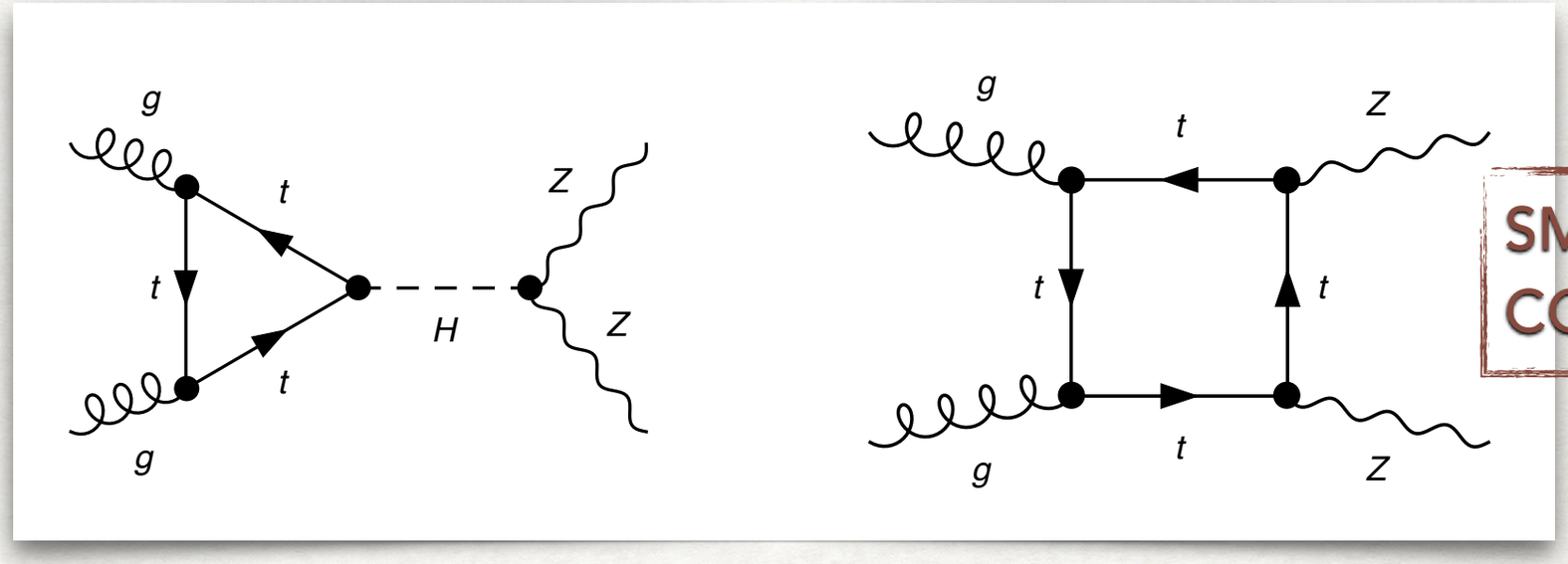
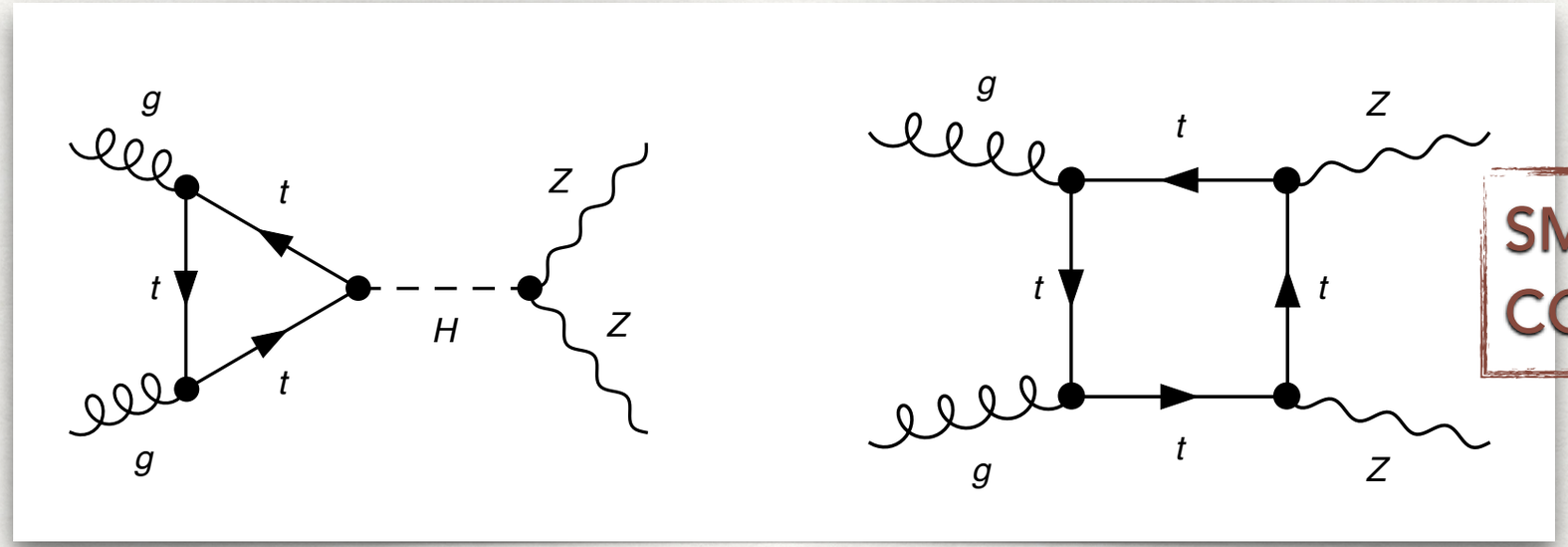


SM(?) BOX-CONTRIBUTION

Modified Higgs sector

Extended SM models:

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



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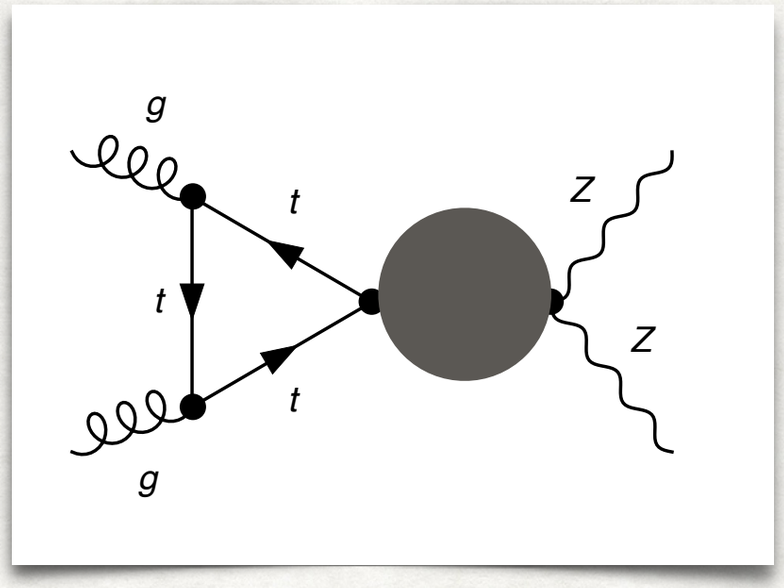
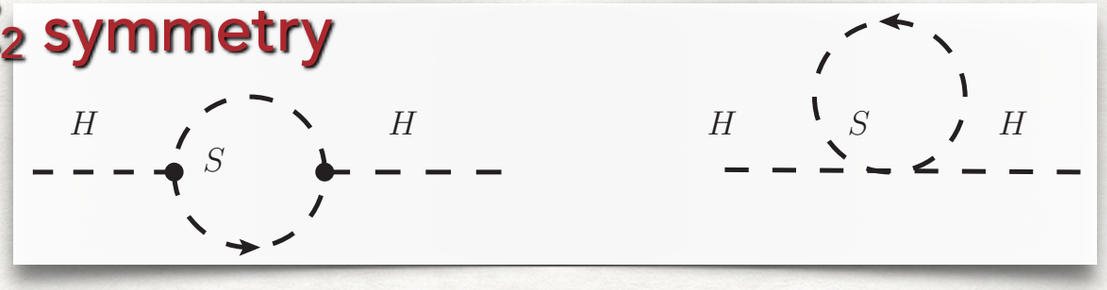


DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

- **Case A: Higgs Sector Light scalar with Z_2 symmetry**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \kappa |S|^2 |\Phi|^2.$$



- Well motivated extension to the SM:
- Scalar Dark Matter (J McDonald 1994, C.P. Burgess 2000, etc.)
- Strong 1st Order Phase Transition (Y. Kondo 1991, hep-ph/0701192, etc.)
- Additional PNGB from Strong Dynamics (0902.1483, etc.)

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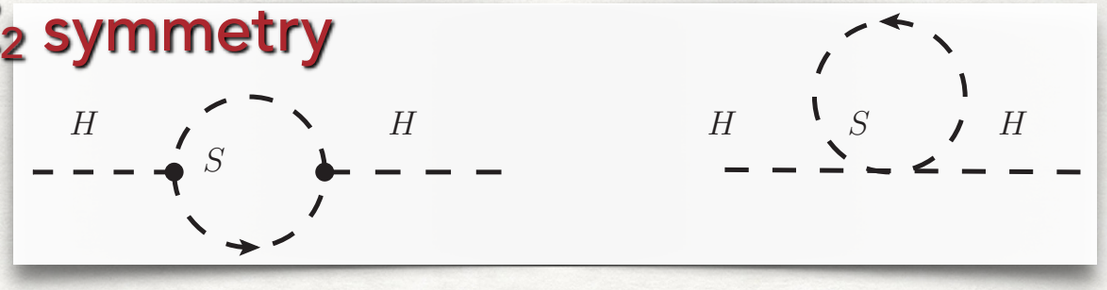
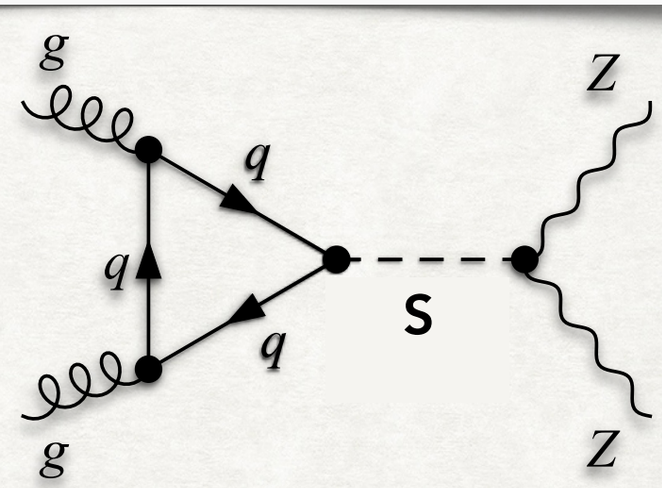


- CaseB: Heavy Higgs with SM Higgs Mixing

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \mu_S S |\Phi|^2 \quad H = \sin\alpha\ S^{\rm phy} + \cos\alpha\ H^{\rm phy}$$



- Additional Electroweak Charged Scalars
- (2HDM, nHDM, Georgi-Machacek, etc.)

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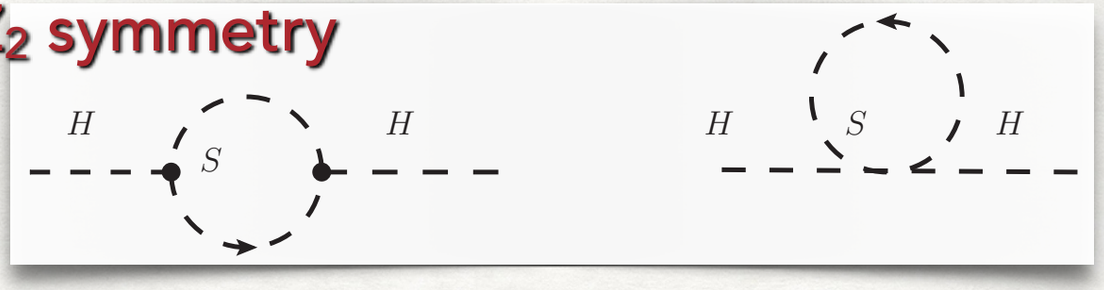

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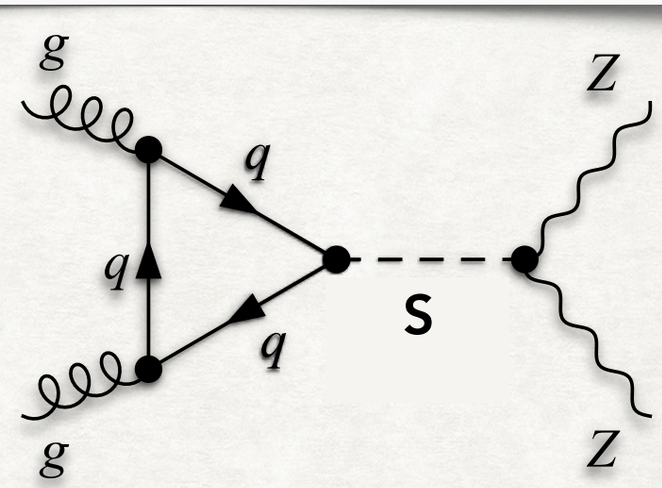
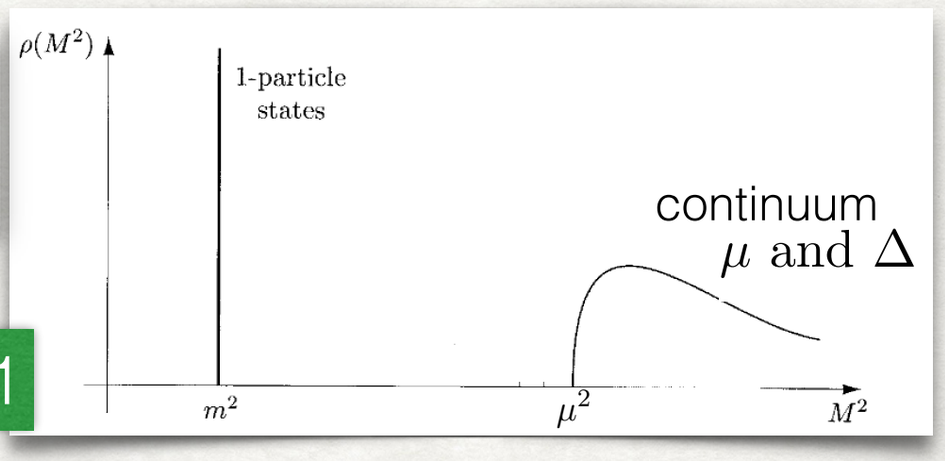


- CaseC: Quantum Critical Higgs modifying the Scalar Sector at high scale

$$G_\hbar(p) = -\frac{i\, Z_\hbar}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}$$



- QCH and Probe: 1511.08218, 1803.09751

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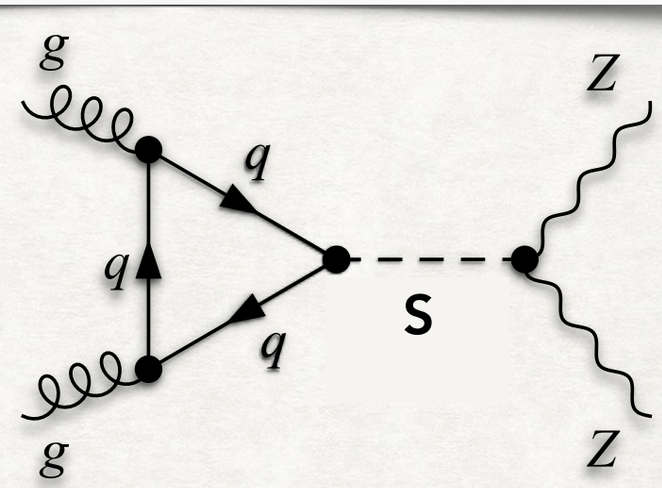

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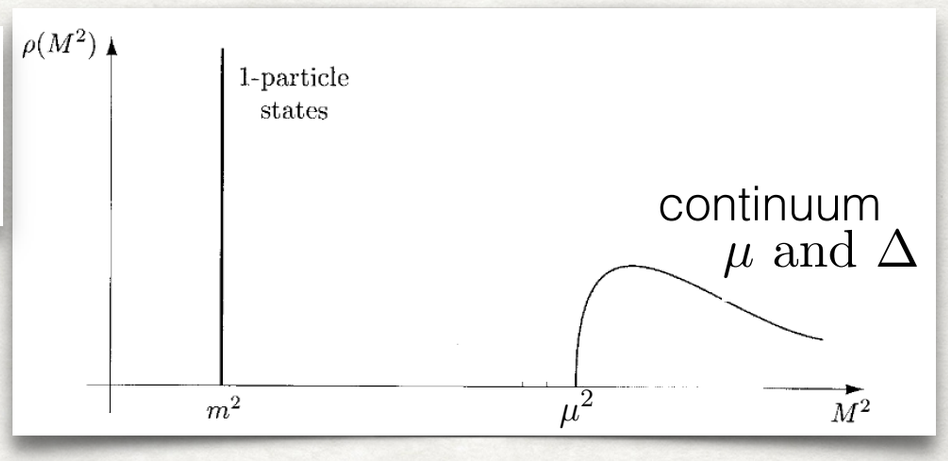
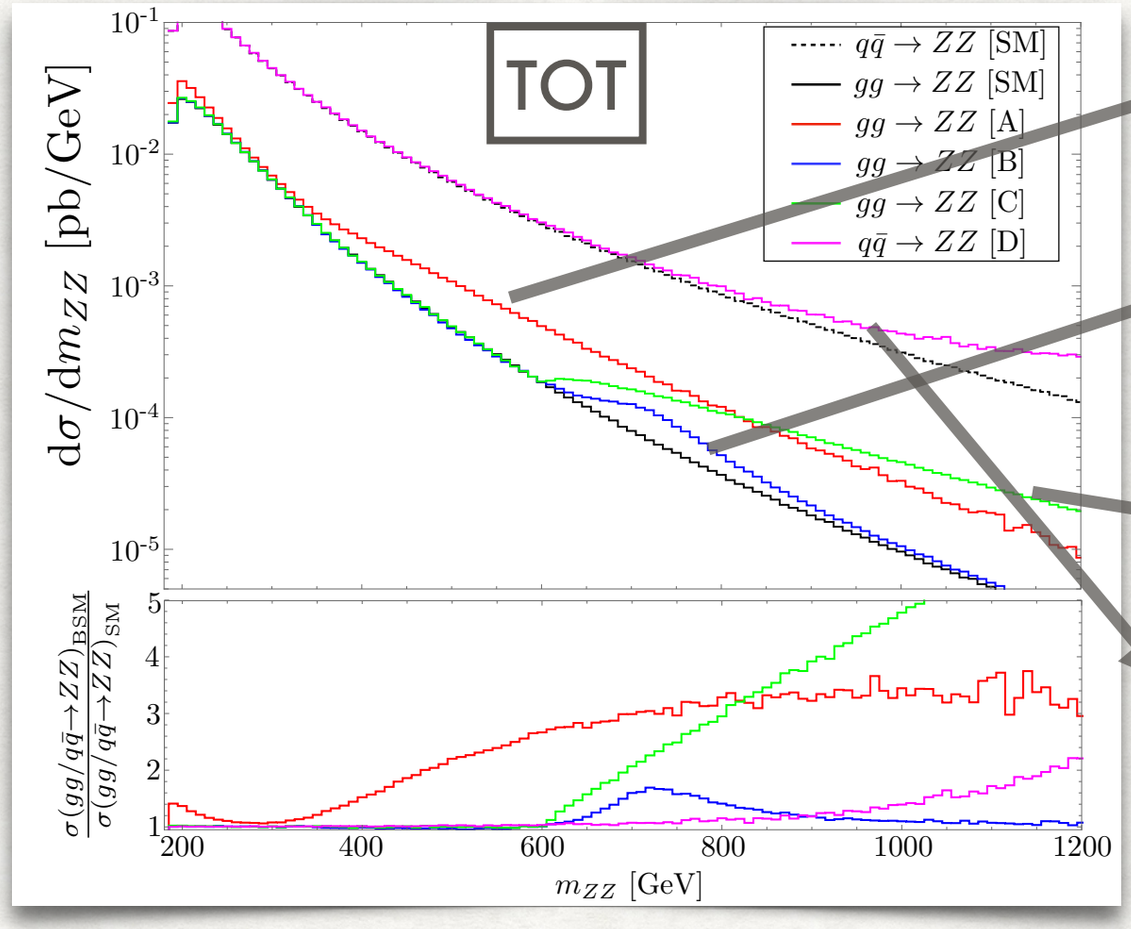


- CaseD: EFT Operator for Example:

$G_{\mu\nu}G^{\mu\nu}H^\dagger H$, $(\bar{\psi}\{^\mu \partial^{\nu\}}\psi) D_\mu H^\dagger D_\nu H$ etc.

QQVV dim-8 operator: 1806.09640

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



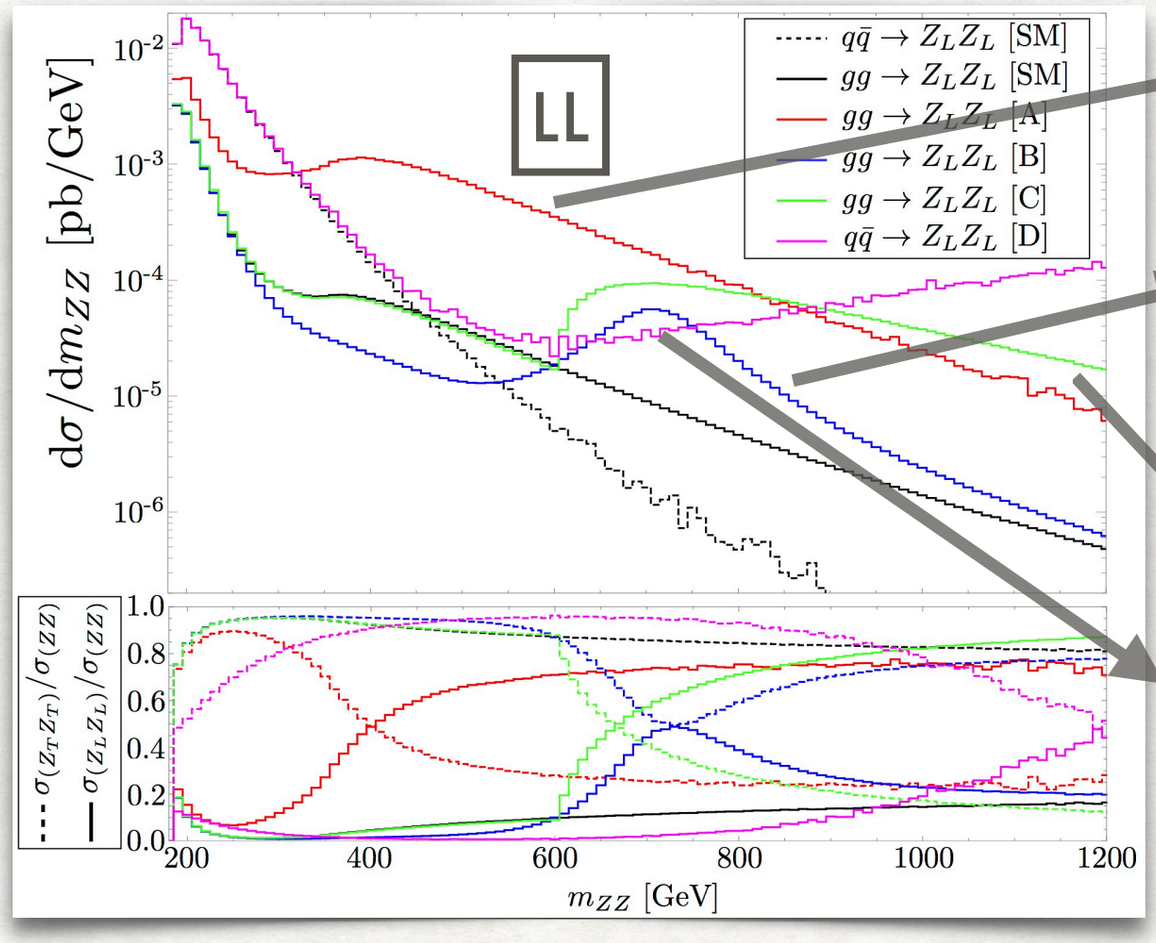
Light scalar

Heavy Higgs

Quantum Critical Higgs

Effective Operator

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



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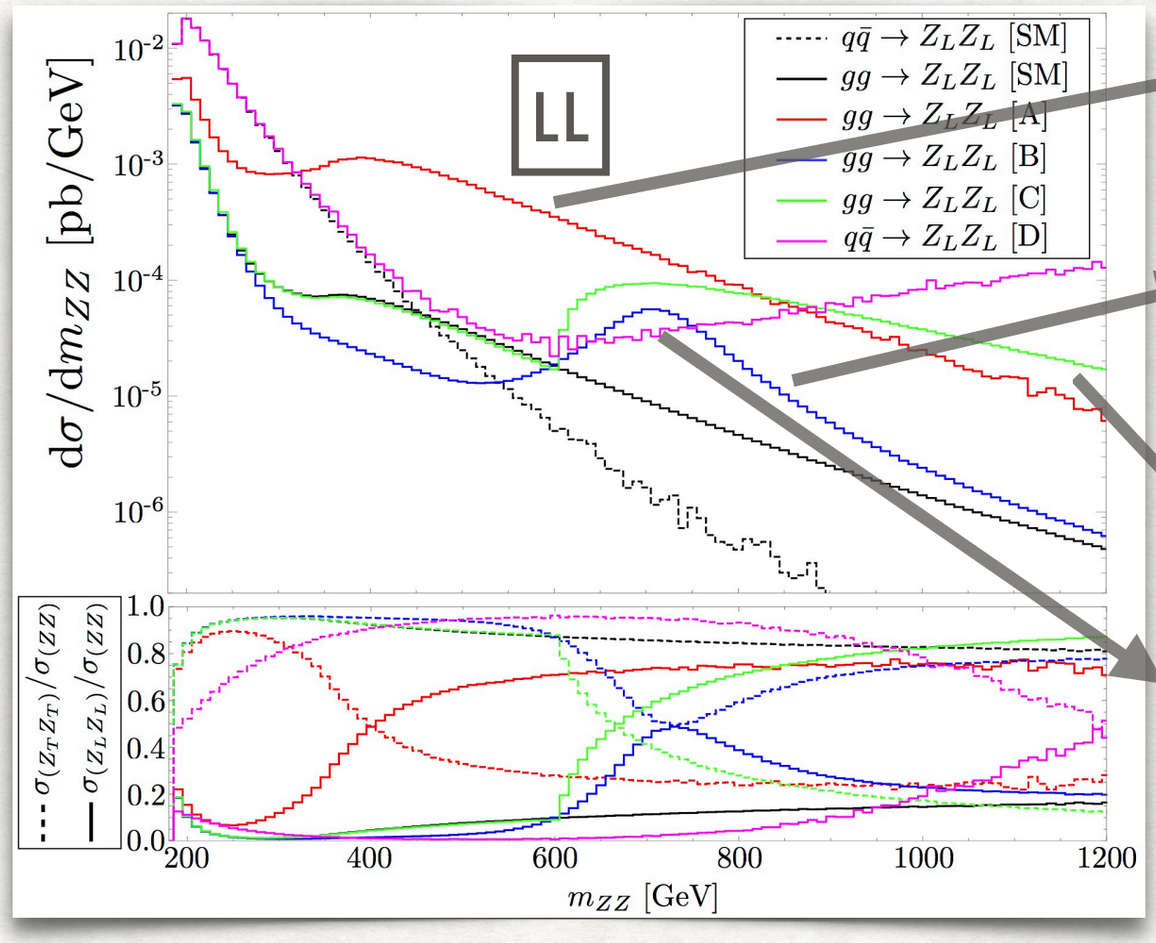

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⇒ Through tagging the polarization of Z's (Cuts, Multi-Variable Analysis on the final states)

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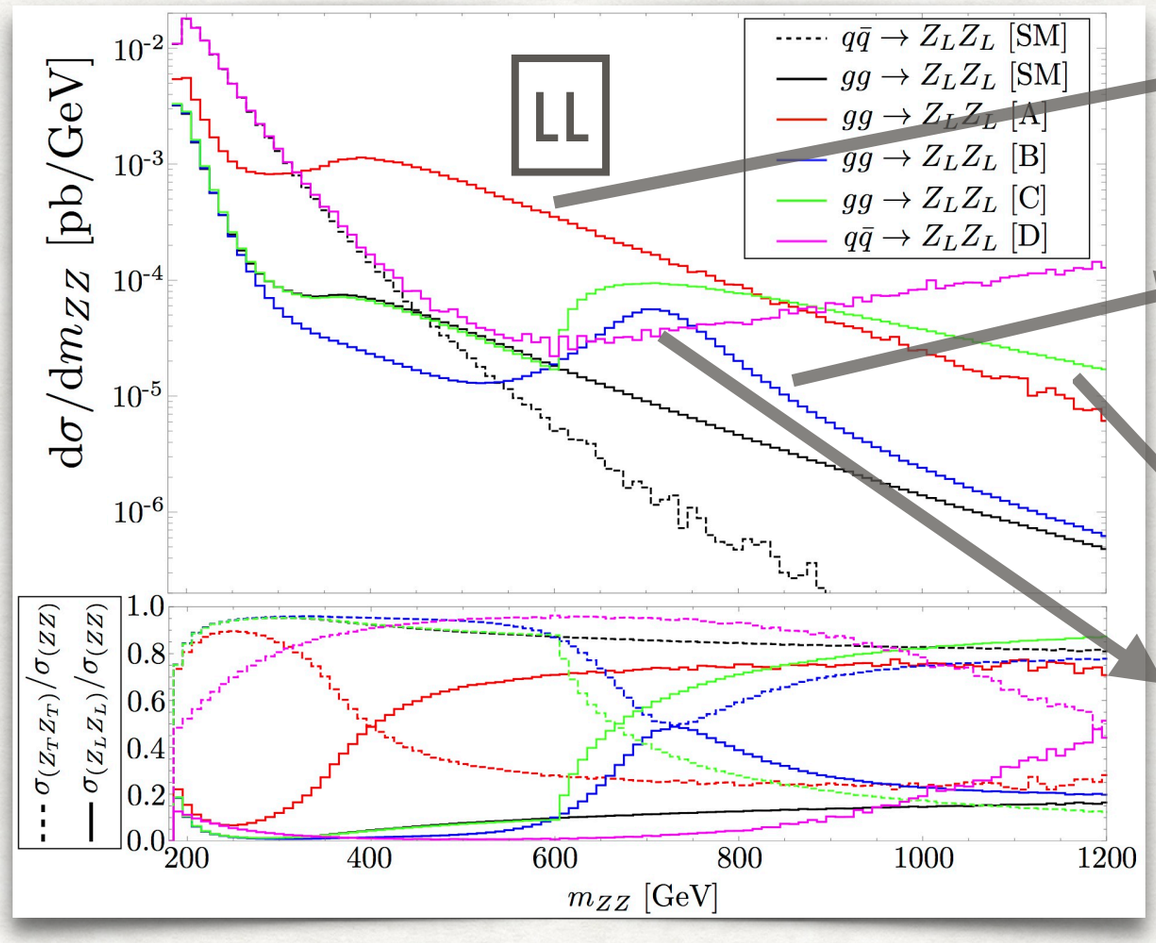

Light scalar

Heavy Higgs

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Effective Operator

⇒ Through tagging the polarization of Z's (Cuts, Multi-Variable Analysis on the final states)

Significance σ	case A	case B	case C
with basic cuts	2.01	0.634	4.71
with basic + angle cuts	2.32	0.838	5.78
with basic cuts + BDT	2.45	0.92	7.01
Luminosity for 3σ discovery	4.2ab^{-1}	29ab^{-1}	0.5ab^{-1}

4TH GEN FERMION REVEALED

S. Kang, ZQ, J. Song, Y. Yoon (2018)

4TH GEN FERMION REVEALED

- **Model:** { 2HDM + $\begin{pmatrix} t'_L \\ b'_L \end{pmatrix}, \quad t'_R, \quad b'_R, \quad \begin{pmatrix} \nu'_L \\ \tau'_L \end{pmatrix}, \quad \nu'_R, \quad \tau'_R$ }

arXiv:
1707.03000,
1707.00100,
1708.06882,
1805.00615

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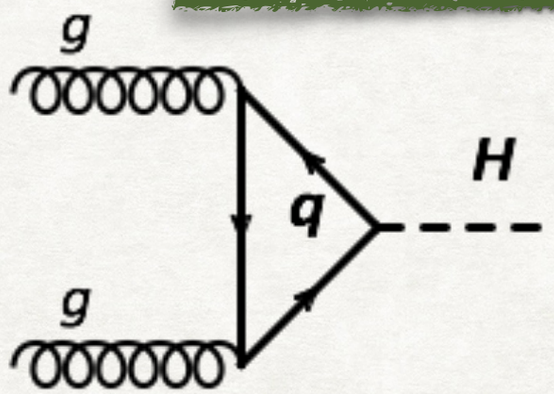

$$\frac{g_{ggH}}{g_{ggH}^{\rm SM}} = \frac{\kappa_t A_{1/2}^h(\tau_t) + \sum_F \kappa_F A_{1/2}^h(\tau_F)}{A_{1/2}^h(\tau_t)}$$

$$(\kappa_q = \frac{y_q}{y_q^{\rm SM}})$$

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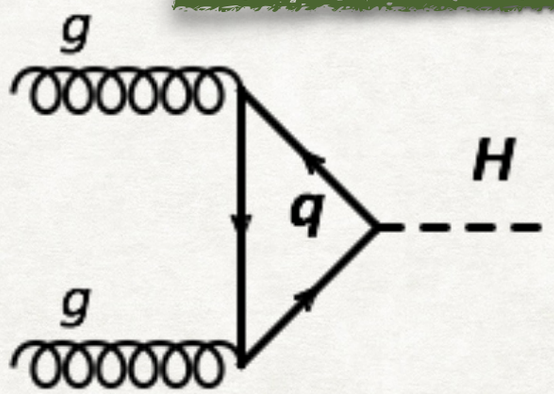

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- **Solution:** $\kappa_u = 1, \quad \kappa_d = -1, \quad \delta\kappa_g \to 0$

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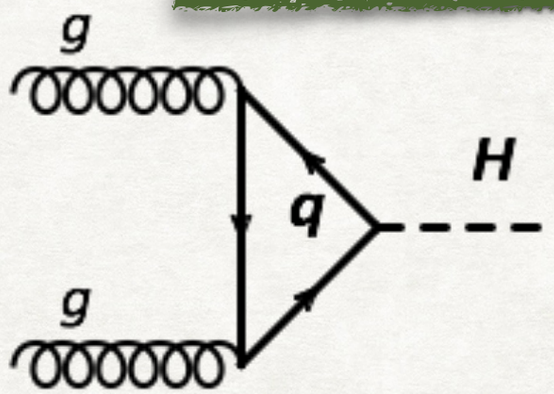

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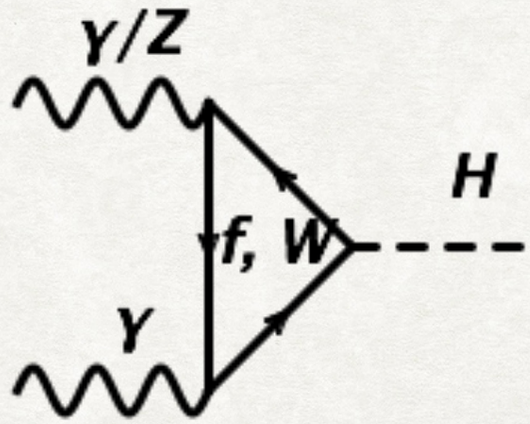
$$\delta\kappa_{\gamma\gamma} \propto \sum_{f=t',b',\tau'} Q_f^2 N_C^f \kappa_f = 0,$$

$$\delta\kappa_{Z\gamma} \propto \sum_{f=t',b',\tau'} Q_f (T_3^f)_L N_C^f \kappa_f = 0,$$



S. Kang, ZQ, J. Song, Y. Yoon (2018)

4TH GEN FERMION REVEALED BY HEAVY HIGGS

Figure: arXiv1710.10410

4TH GEN FERMION REVEALED BY HEAVY HIGGS

$$M_i = y_i \frac{v}{\sqrt{2}}$$

2HDM

$$\mathcal{L}_Y = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$$

$$M_{ij} = y^1_{ij}\frac{v_1}{\sqrt{2}} + y^2_{ij}\frac{v_2}{\sqrt{2}}$$

$Z2 : \delta_{ij}$

~~$FCNC$~~

Figure: arXiv1710.10410

4TH GEN FERMION REVEALED BY HEAVY HIGGS

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$Z2 : \delta_{ij}$

~~$FCNC$~~

$$\begin{aligned} V_\Phi = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{H.c.}) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}\right]. \end{aligned}$$

2HDM scalar potential (CP-conservin

$$\Rightarrow \{m_h, m_H, m_A, m_H^{+/-}, v, \lambda, \tan\beta, \cos\alpha\}$$

α: Neutral Higgs mixing angle

β: Ratio between the VEV scale of the two scalar fields

Figure: arXiv1710.10410

4TH GEN FERMION REVEALED BY HEAVY HIGGS

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2HDM

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$Z2 : \delta_{ij}$

~~$FCNC$~~

$$\begin{aligned} V_\Phi = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{H.c.}) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}\right]. \end{aligned}$$

2HDM scalar potential (CP-conservin

α: Neutral Higgs mixing angle

β: Ratio between the VEV scale of the two scalar fields

$$\Rightarrow \{m_h, m_H, m_A, m_H^{+/-}, v, \lambda, \tan\beta, \cos\alpha\}$$

- **Exact Wrong Sign Limit (EWS):** $\alpha = \frac{\pi}{2} - \beta$ (Realized in 2HDM Type II)
- **Decoupling through Alignment:** $\sin(\beta - \alpha) = 1$

Figure: arXiv1710.10410

4TH GEN FERMION REVEALED BY HEAVY HIGGS

$$M_i = y_i \frac{v}{\sqrt{2}} \xrightarrow{\text{2HDM}} \mathcal{L}_Y = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$$

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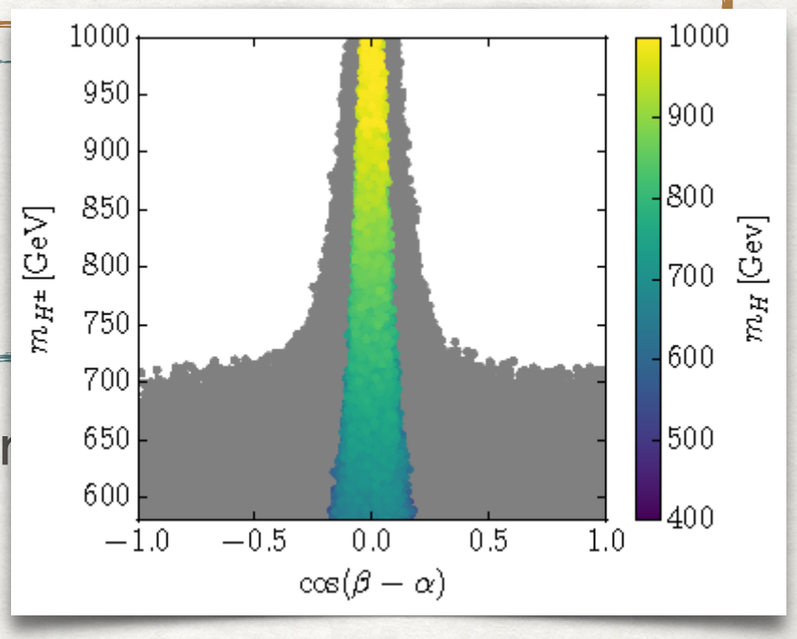

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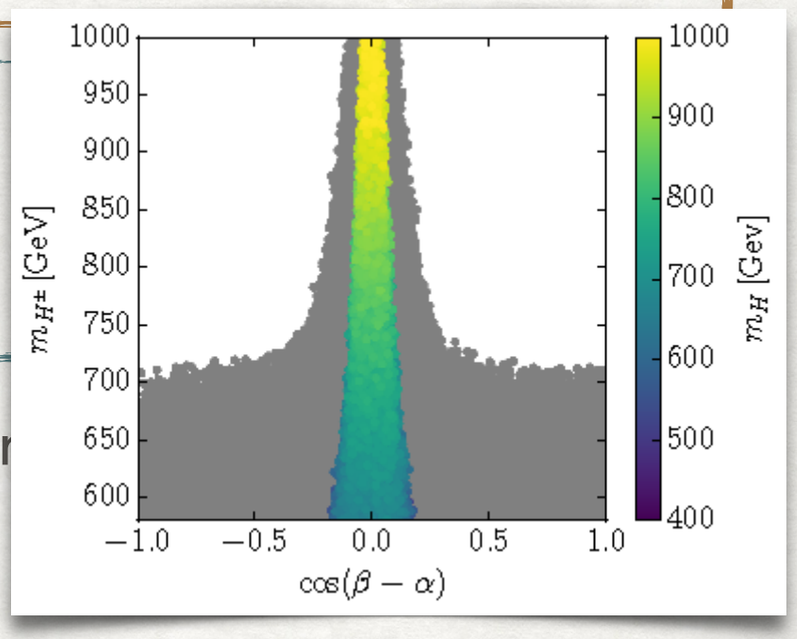

EWS Cannot Approach Alignment ⇒ Upper bound on $M_{H,\,A,\,H^\pm} \lesssim 900$ GeV

Figure: arXiv1710.10410

4TH GEN FERMION REVEALED BY HEAVY HIGGS

- **Direct Search for the Additional Higgs**

process	target	mass range	experiment
$e^+e^- \to 4b, 4\tau, b\bar{b}\tau\tau$	A	$[2m_\tau, 100\ \text{GeV}]$	LEP [57]
$pp \to \tau\tau$	$H,\ A$	$[100\ \text{GeV}, 1\ \text{TeV}]$ $[90\ \text{GeV}, 3.2\ \text{TeV}]$	LHC Run 1 [58, 59] LHC Run 2 [60, 61]
$pp \to ZZ^{(*)}$	H	$[110\ \text{GeV}, 1\ \text{TeV}]$	LHC Run-2 [62–65]
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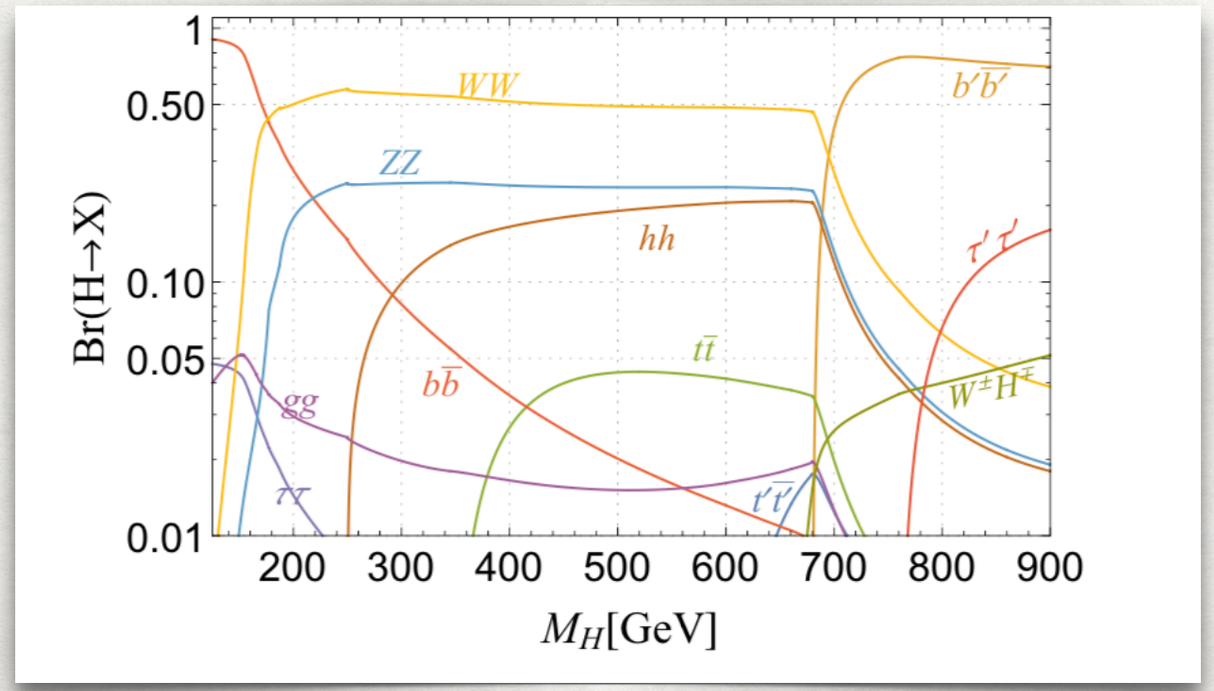
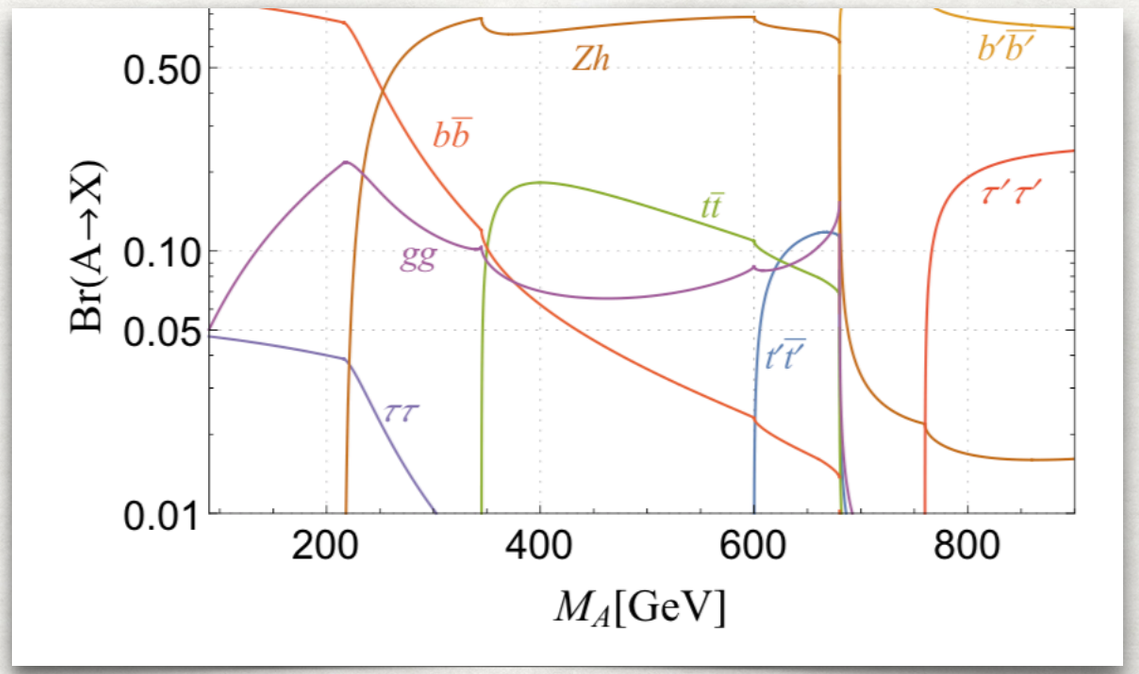


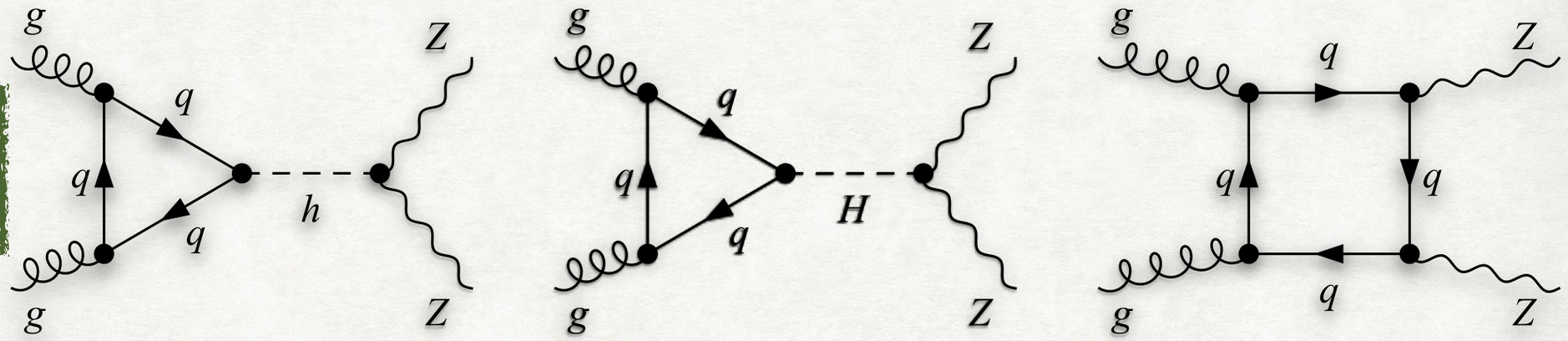


4TH GEN FERMION REVEALED BY HEAVY HIGGS

- **Direct Search in ZZ channel for the Additional Higgs**

$q = \text{SM quarks}$

$+\text{4th Gen } \{t',\ b'\}$



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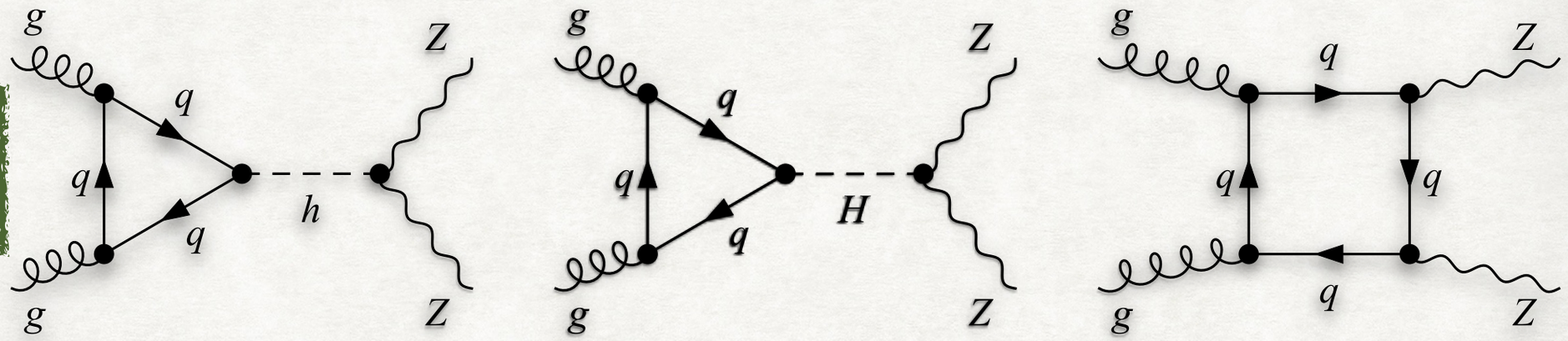

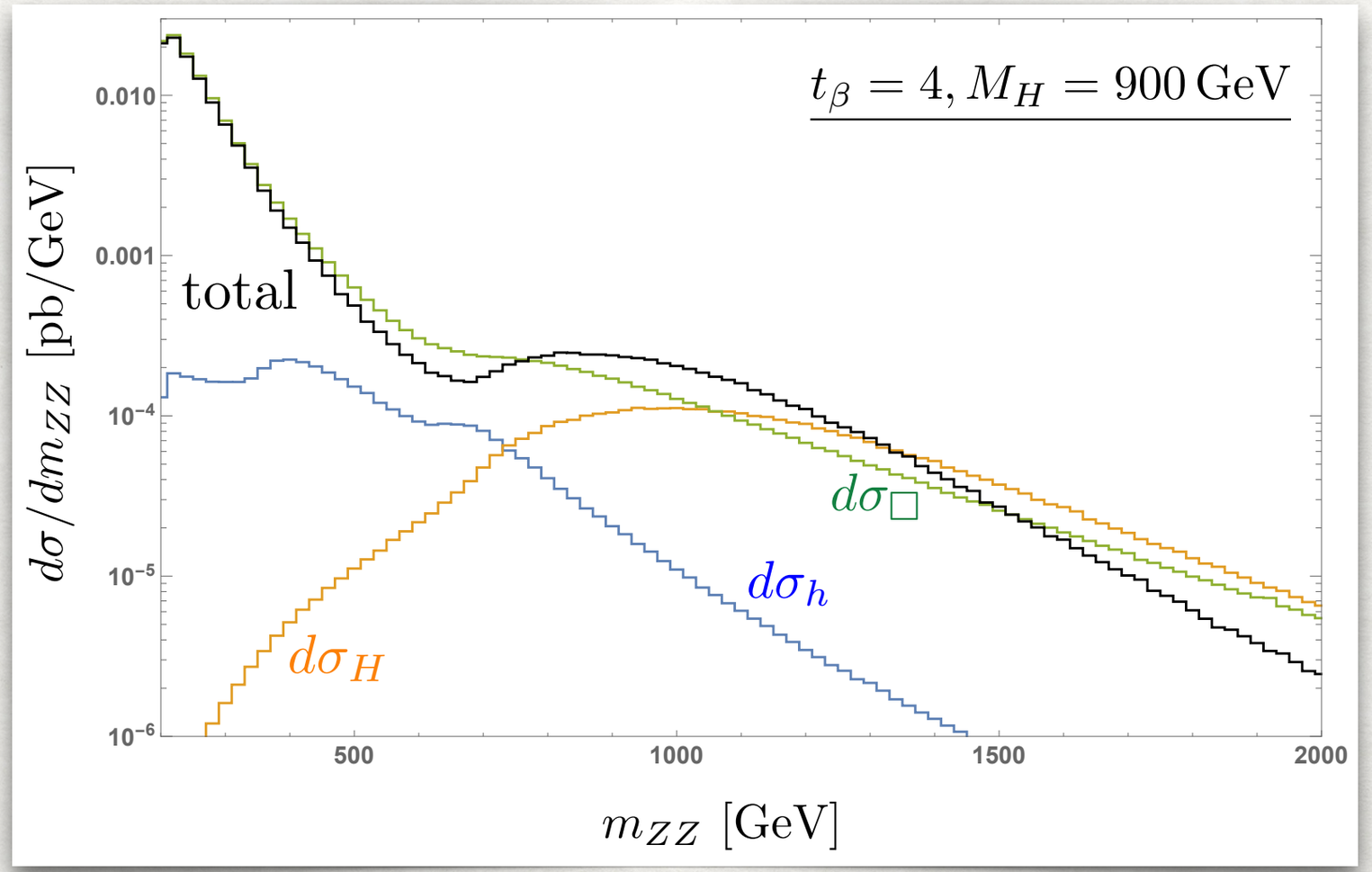

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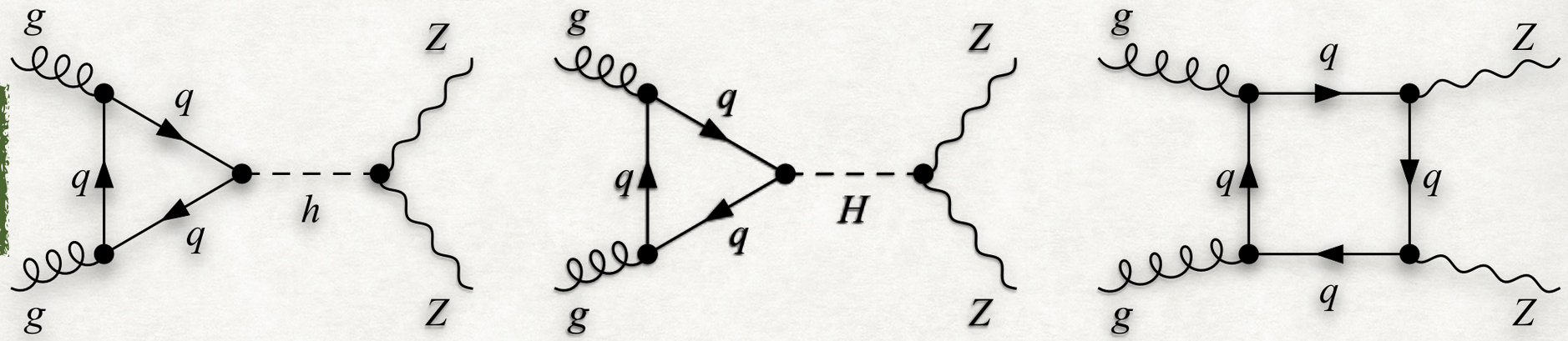

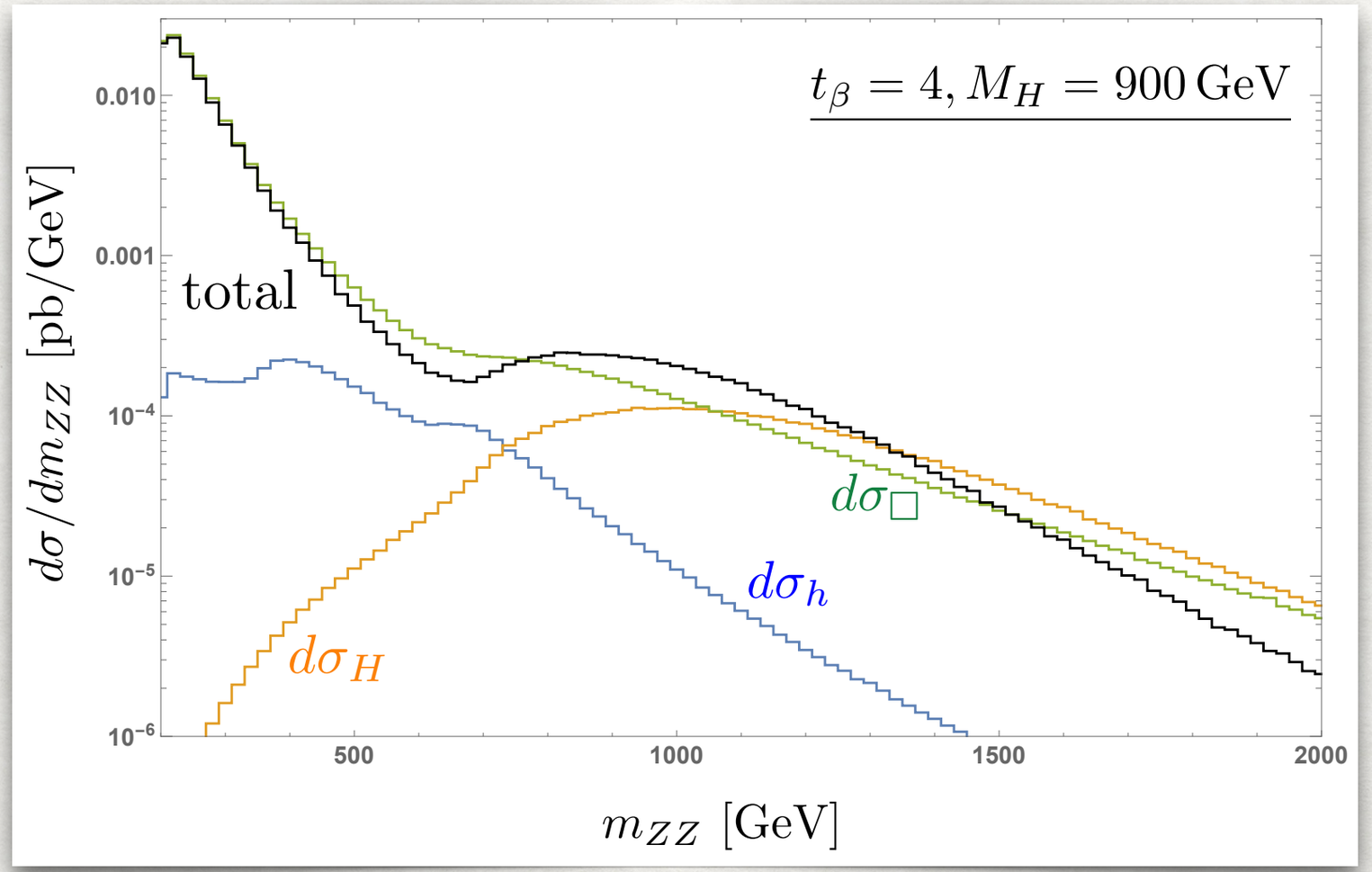

2HDM-4SM signal shows a large mass threshold and broad resonance deviation, and constrained by LHC ZZ data

SUMMARY

Discovery of the Higgs completes the Standard Model roster, now what?

LHC at High invariant mass tail and Future Lepton Colliders:

- Higgs Precision Measurement to find/quantify deviation from the SM
- Motivated Collider Signals for Higgs (New) Physics

- Vector boson pair production with LL polarization
- ``generic" signal: sensitive to simplified Higgs sector extension models and sets of HEFT operators (Unitary violating terms)