DIBOSON AS PROBE TO HIGGS (NEW) PHYSICS

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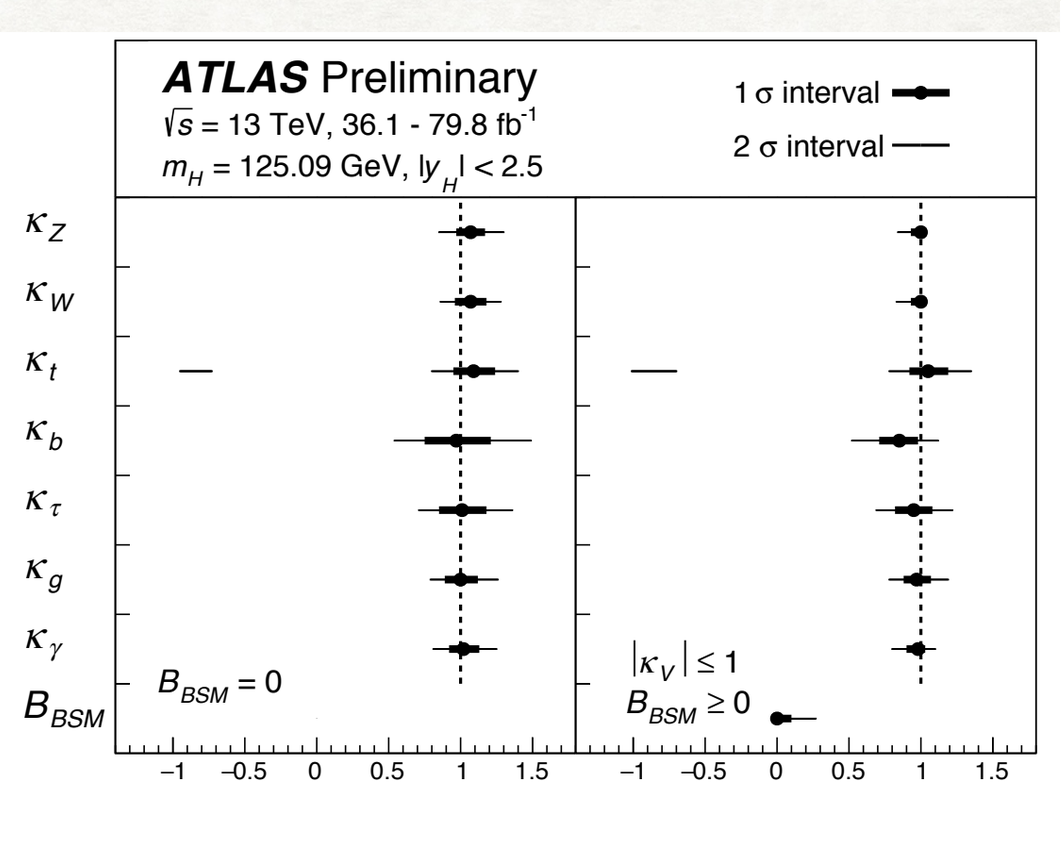
Based on work with S. Lee, M Park arXiv: 1812.02679
S. Kang, J. Song, Y. Yoon: 1810.05229

MOTIVATION

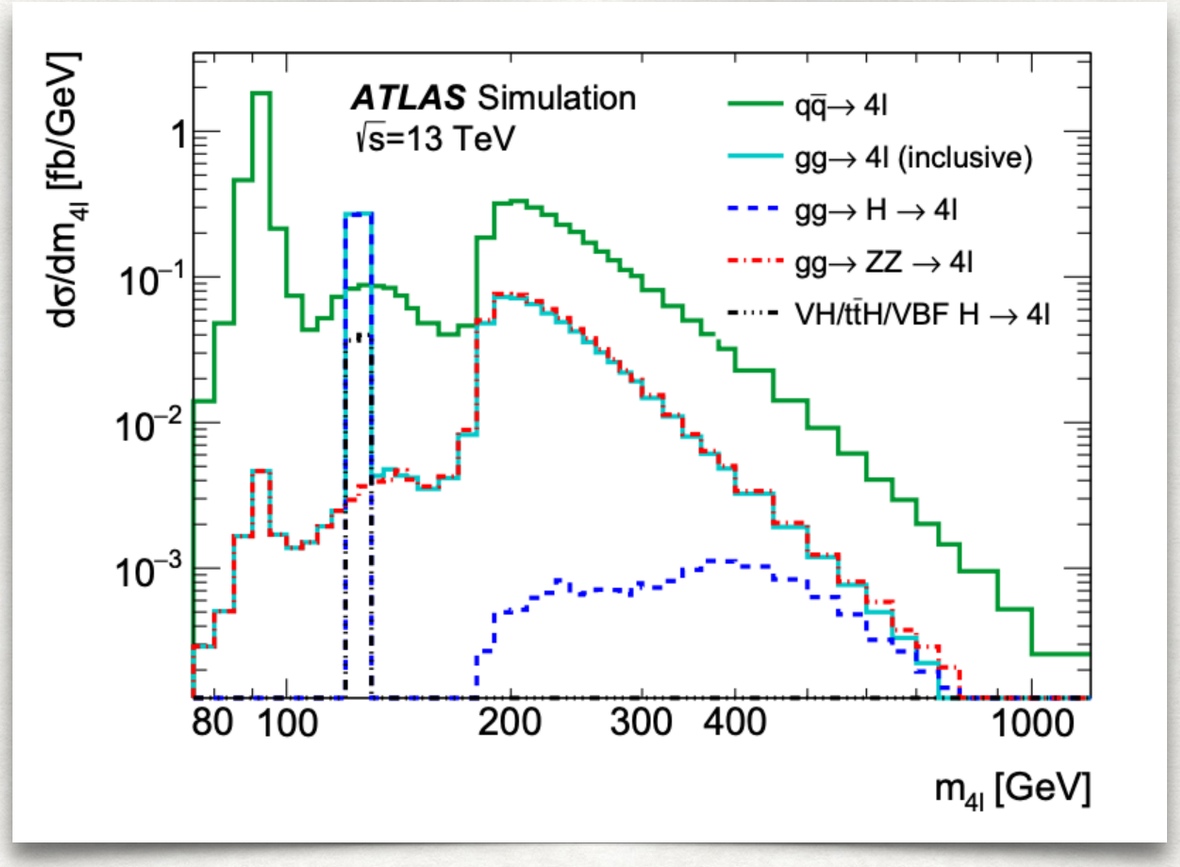
- Since the Higgs discovery, studying its properties has been main focus.
- Likely connection between Higgs and new physics: Extended Scalar Sector, EW symmetry breaking, Fermion masses, Higgs portal DM etc.
- Currently, the Higgs data agrees with the SM, but still allows sizable space for simple extensions to the standard model, which may further link to complete theories.
- Collider possibilities: LHC, future lepton colliders

LHC HIGGS MEASUREMENT



(a)

Higgs on-shell signal Measurement



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* ATLAS: CERN-EP-2018-318, CMS: HIG-16-033

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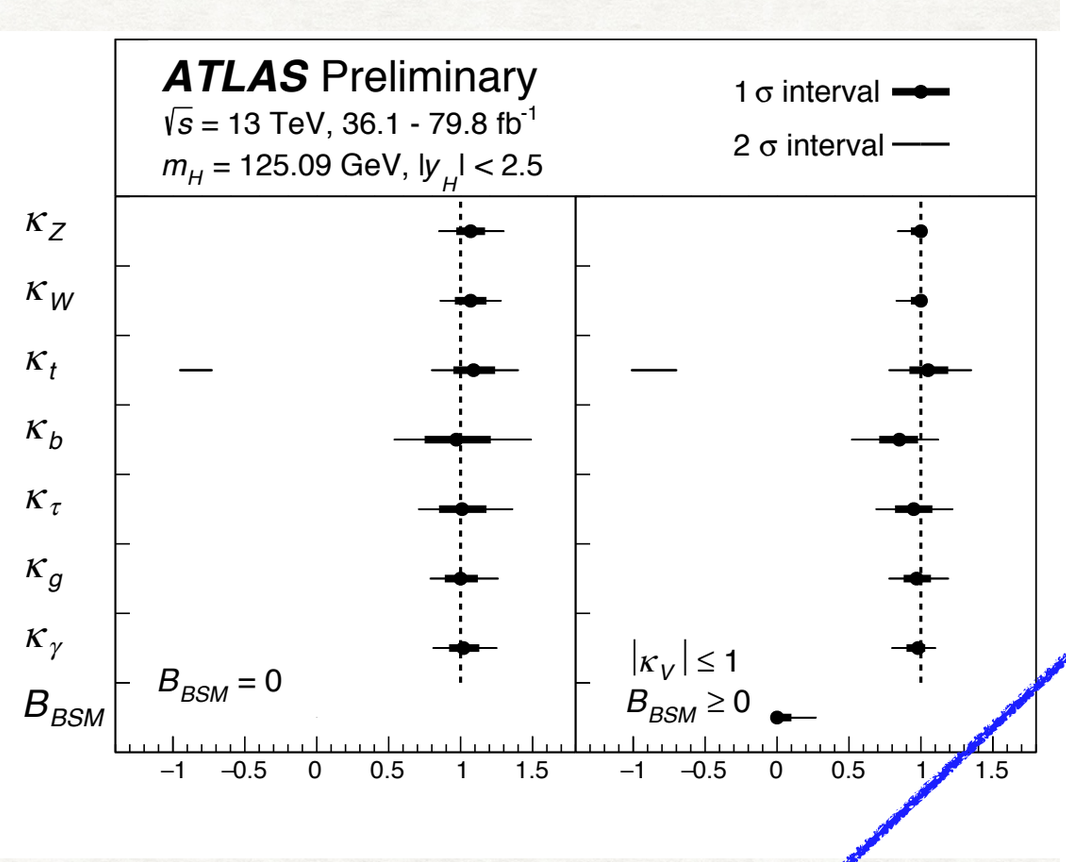

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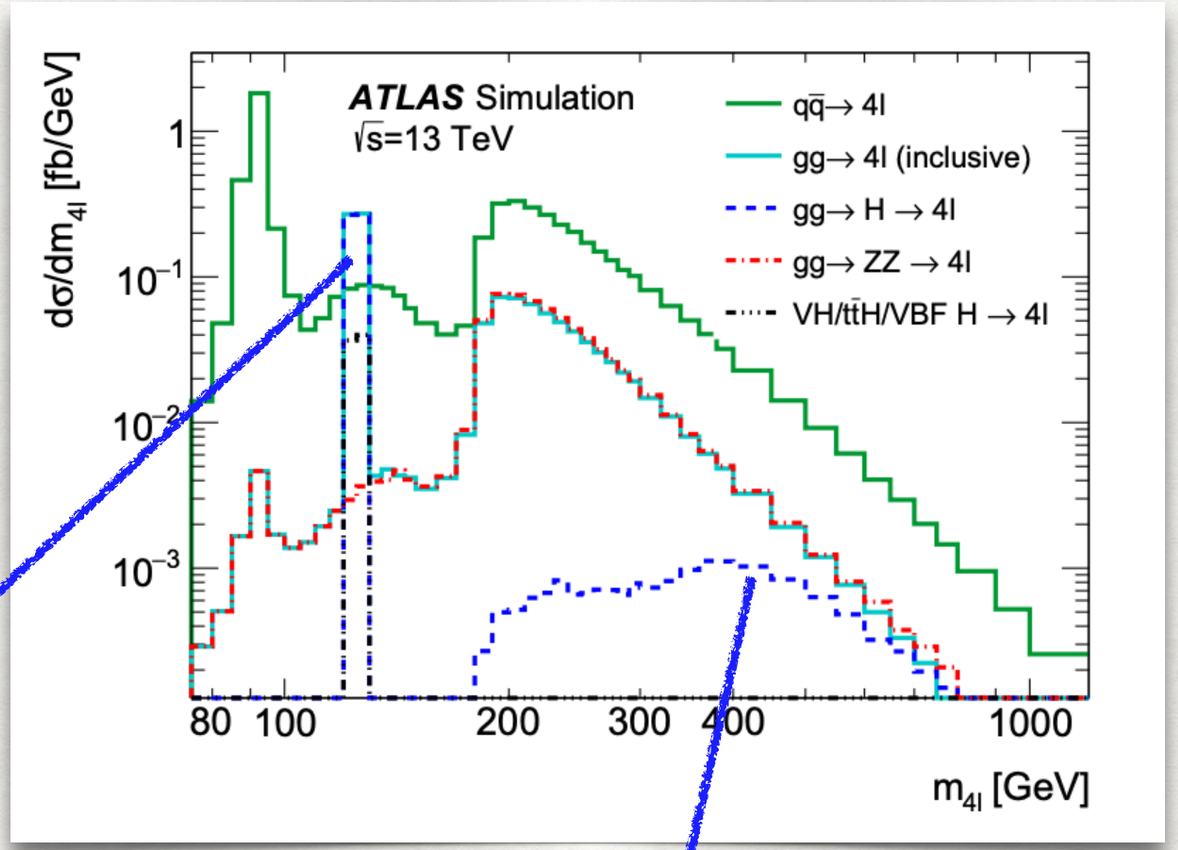

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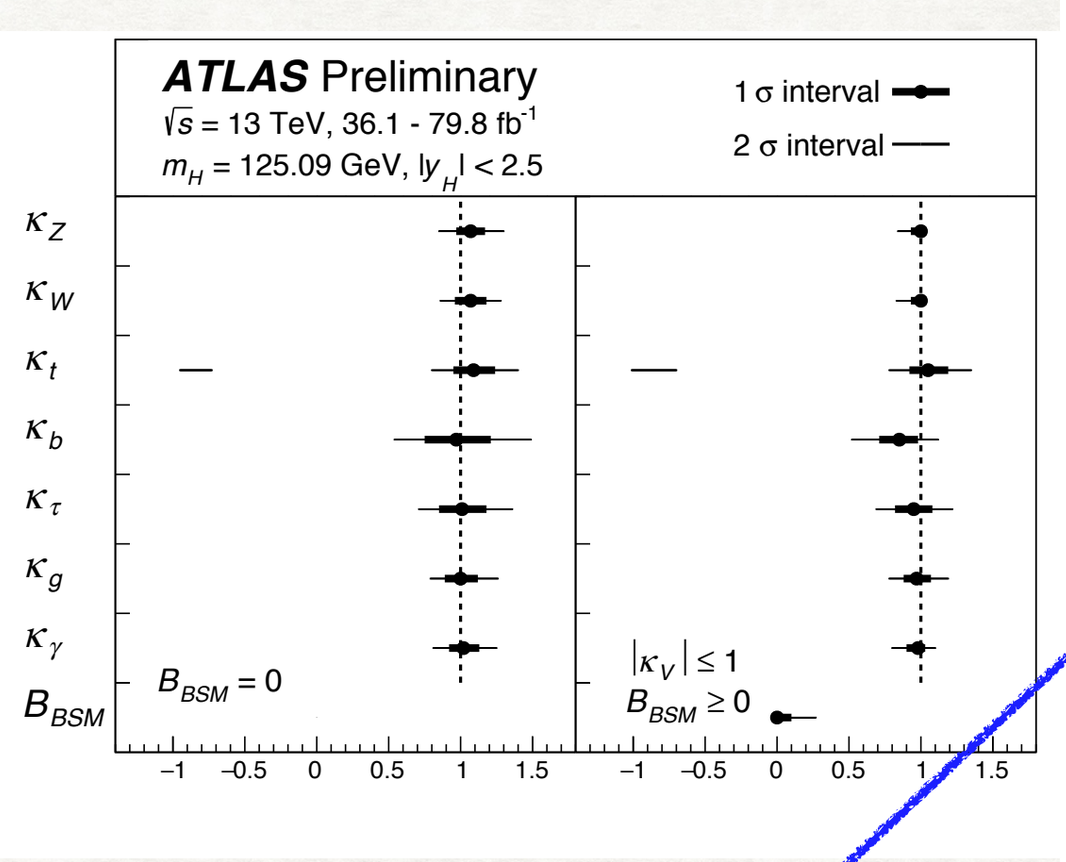

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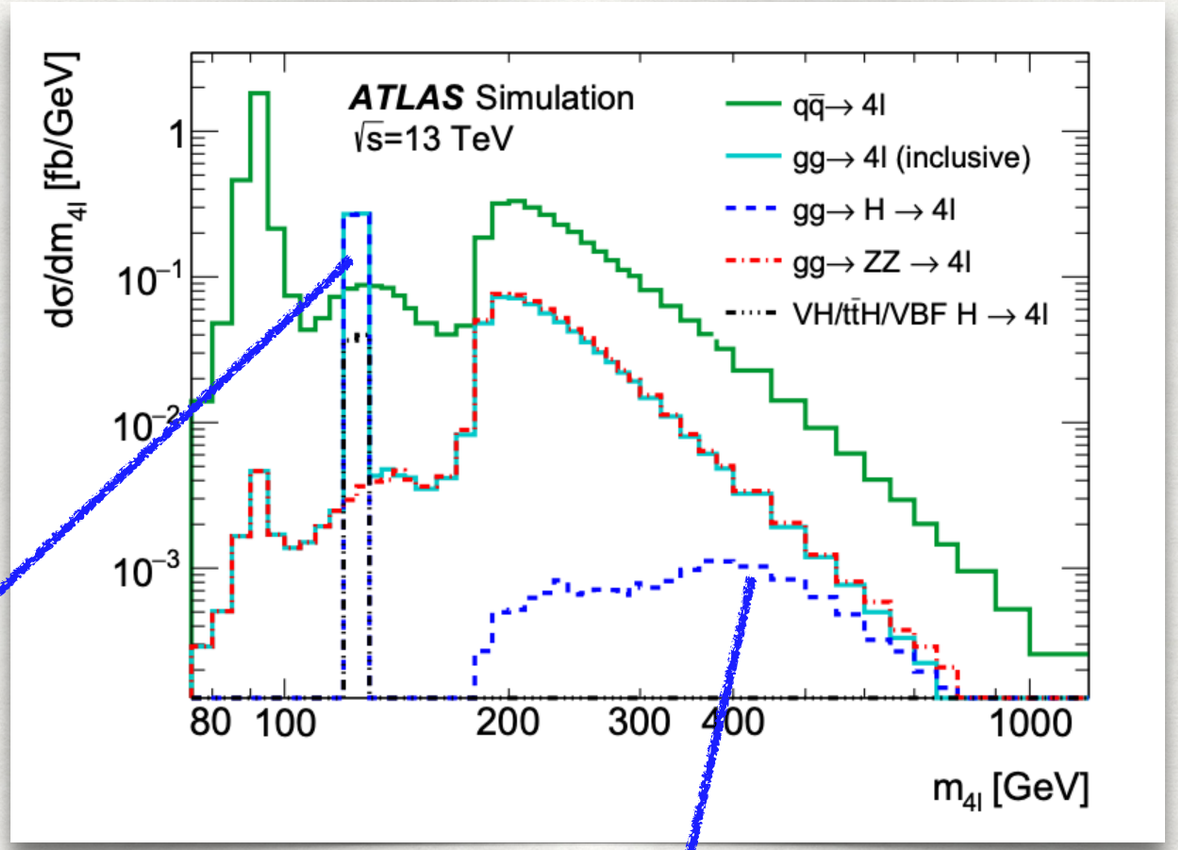

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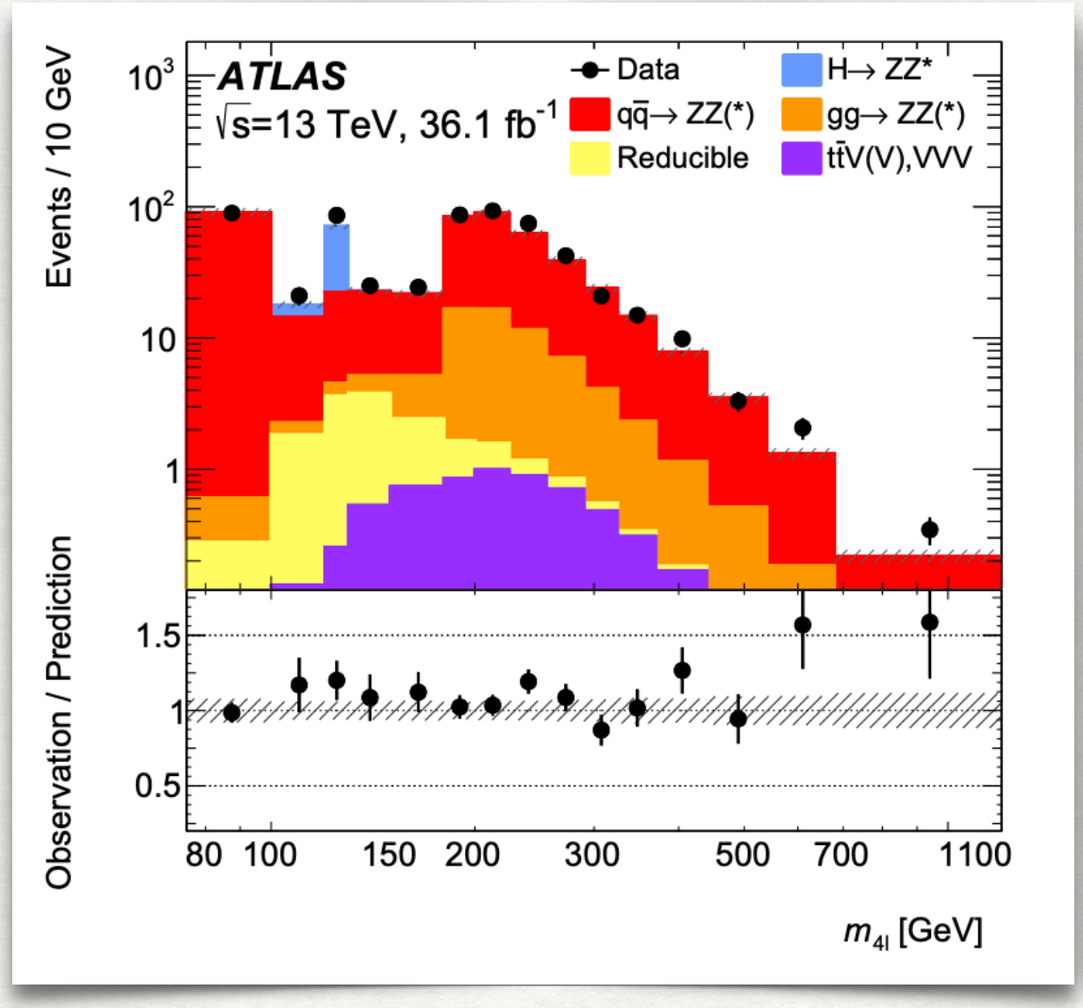

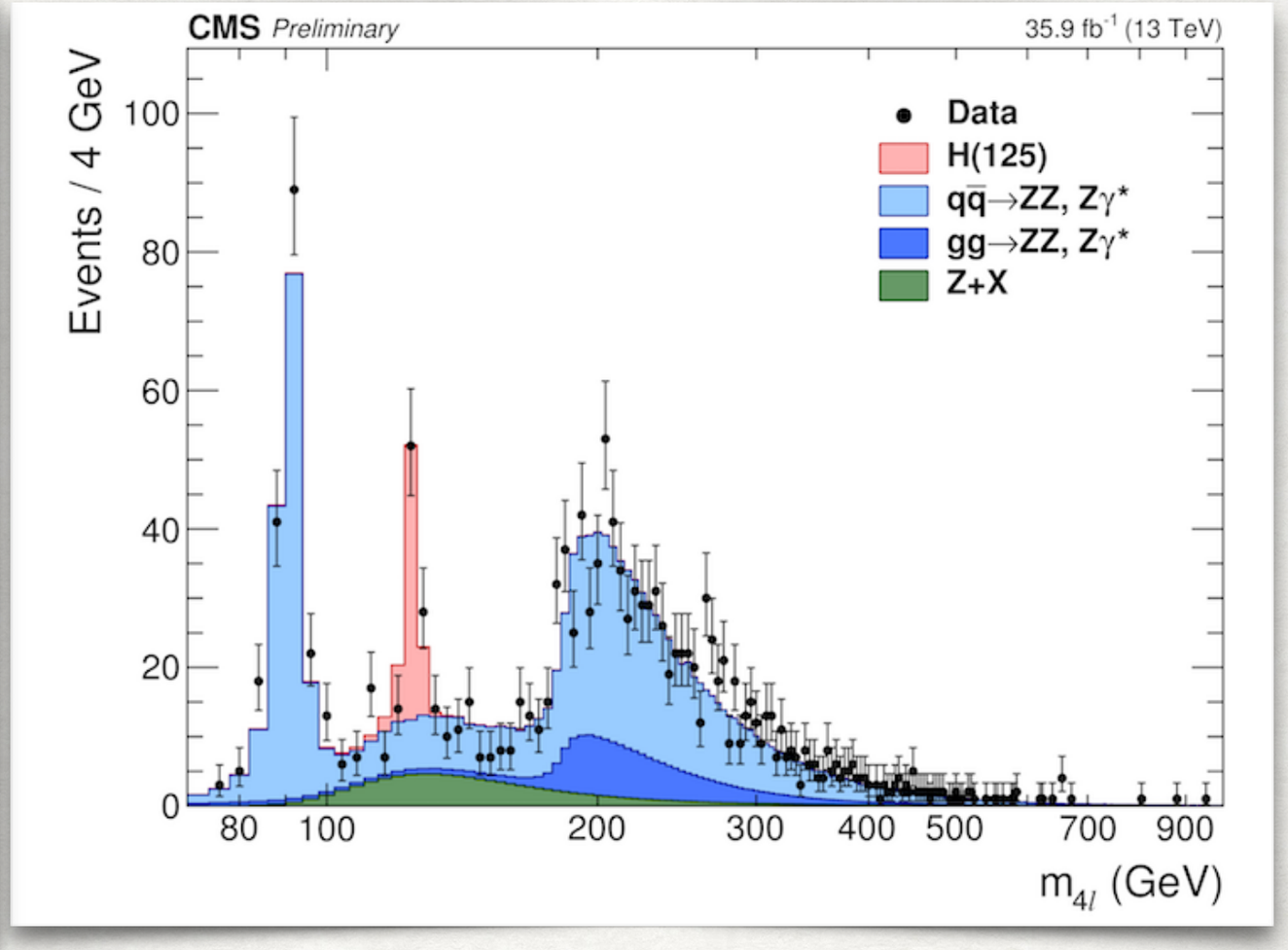

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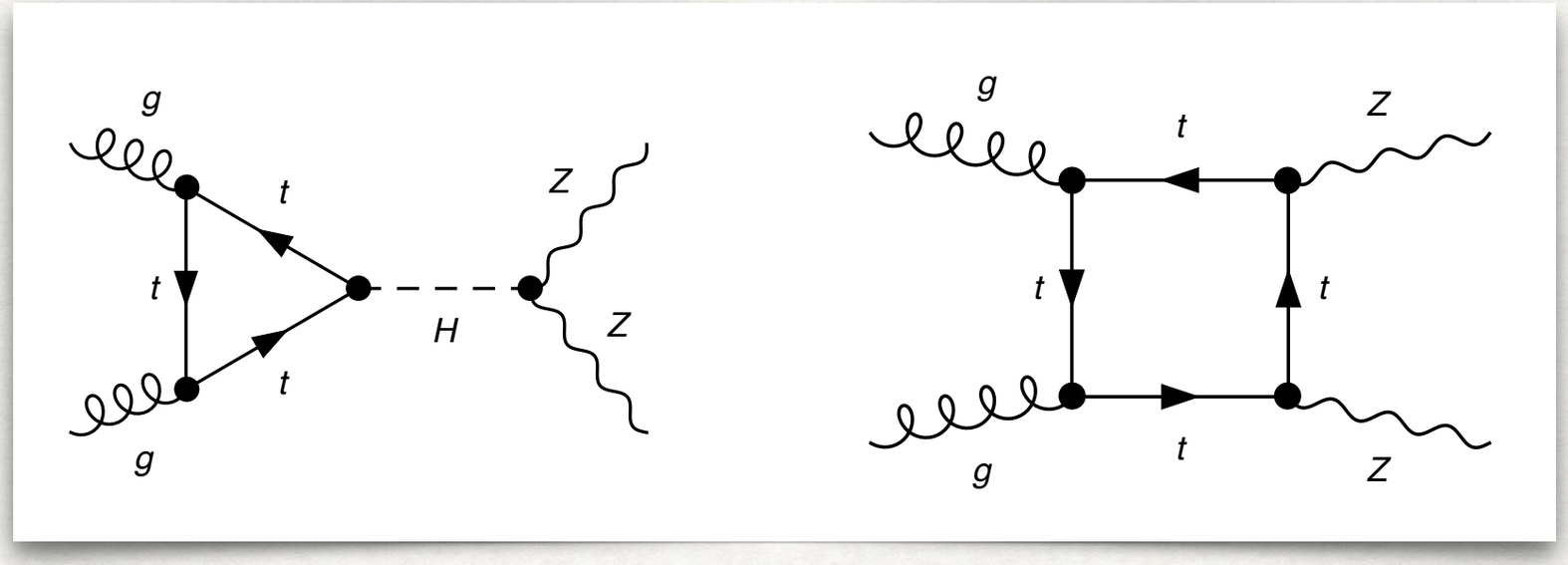

At High energy scale, each diagram diverges:

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

Prominent in Z-longitudinal mode

S. Lee, **M. Park**, ZQ: arXiv:1812.02679

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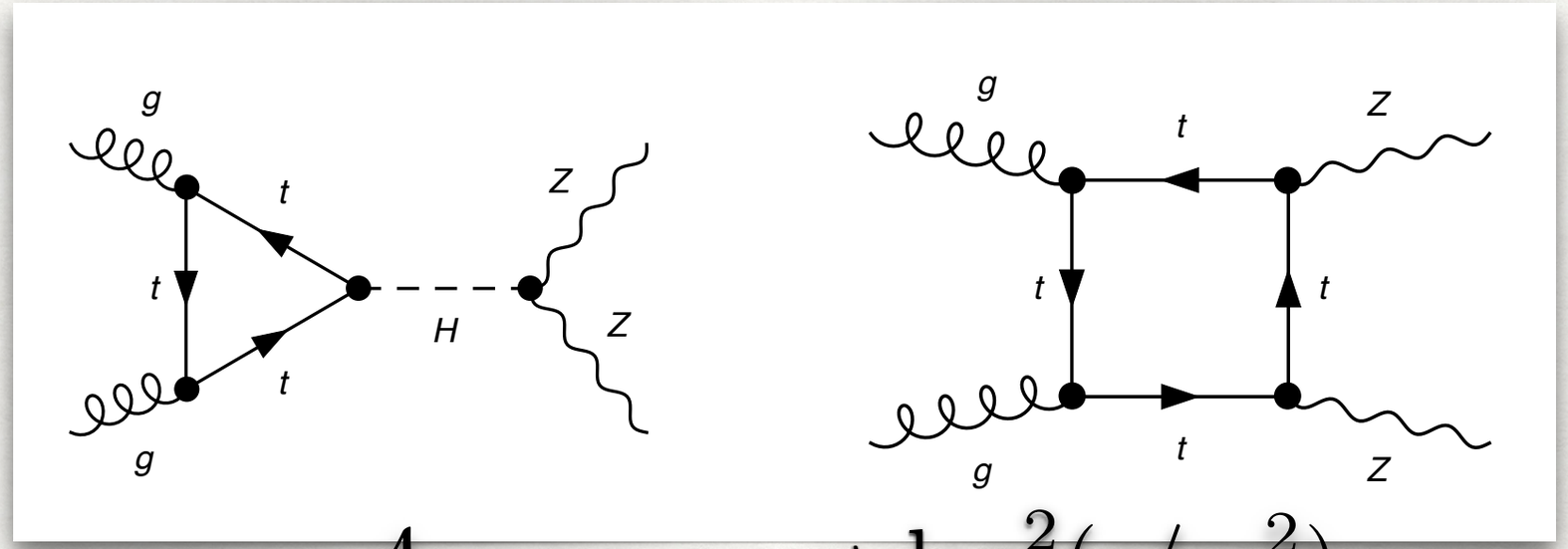

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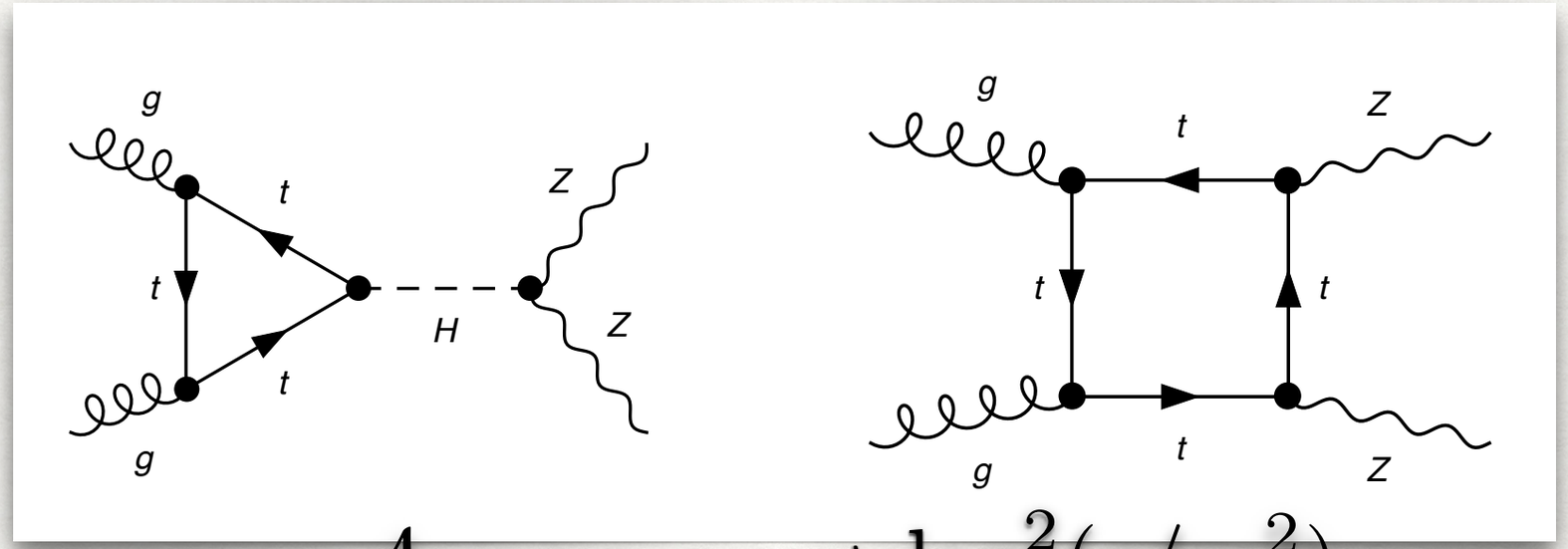

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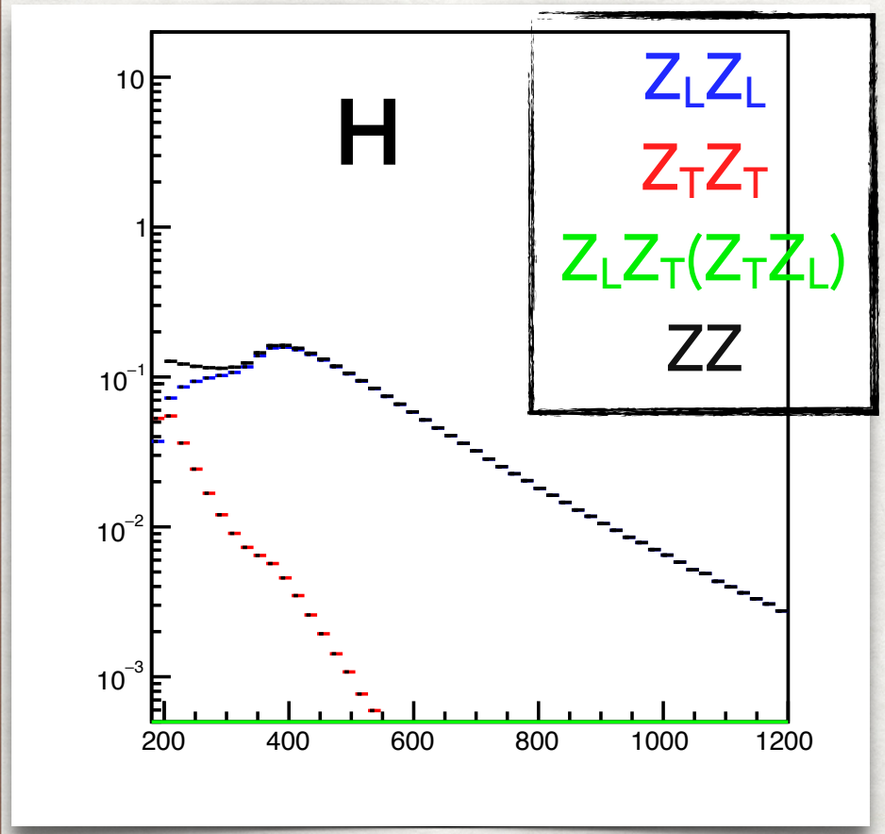

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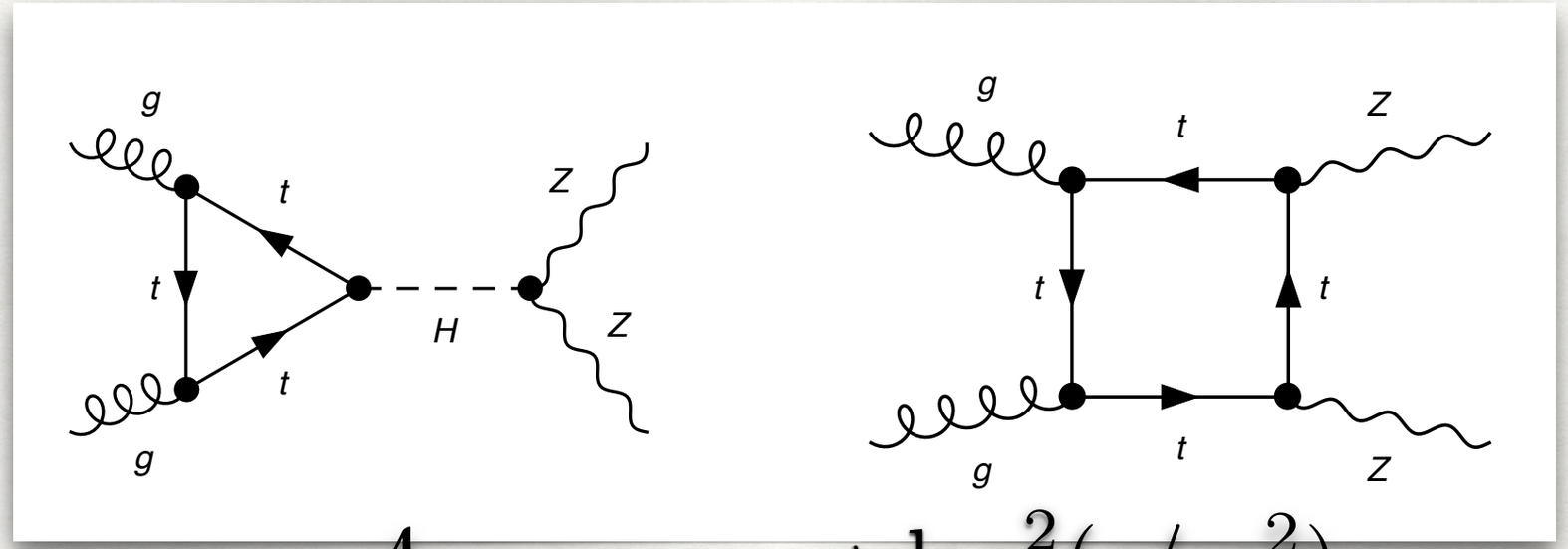

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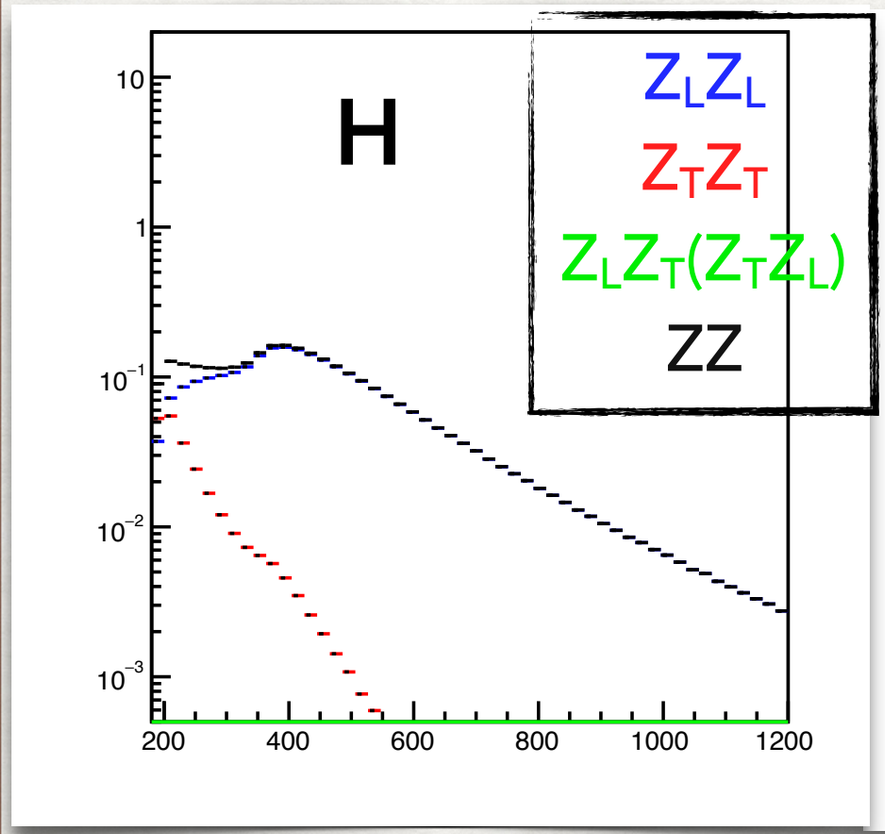

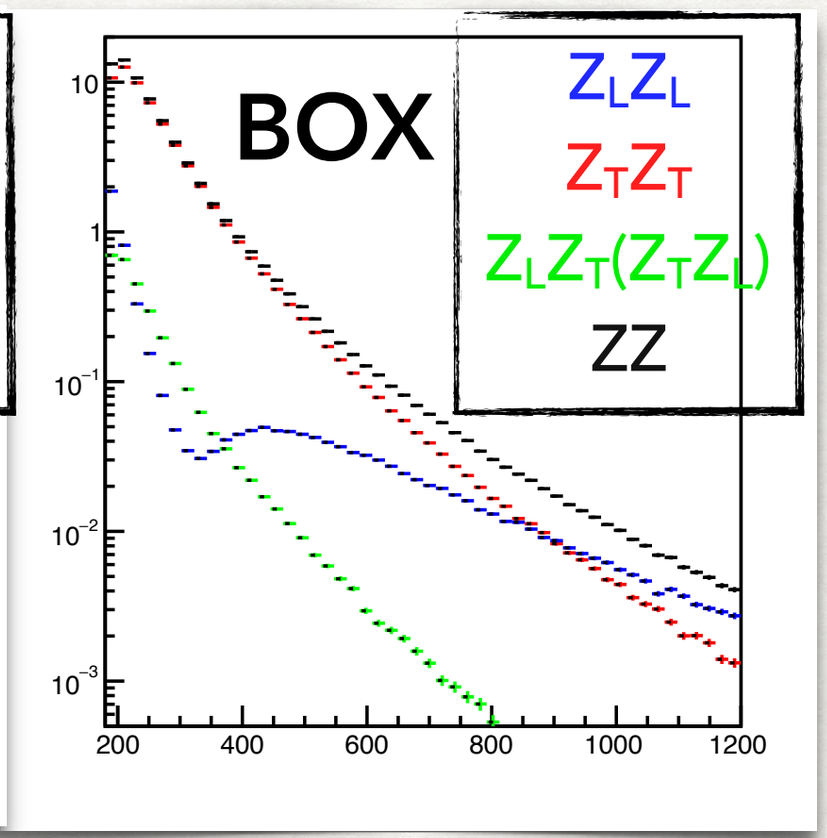

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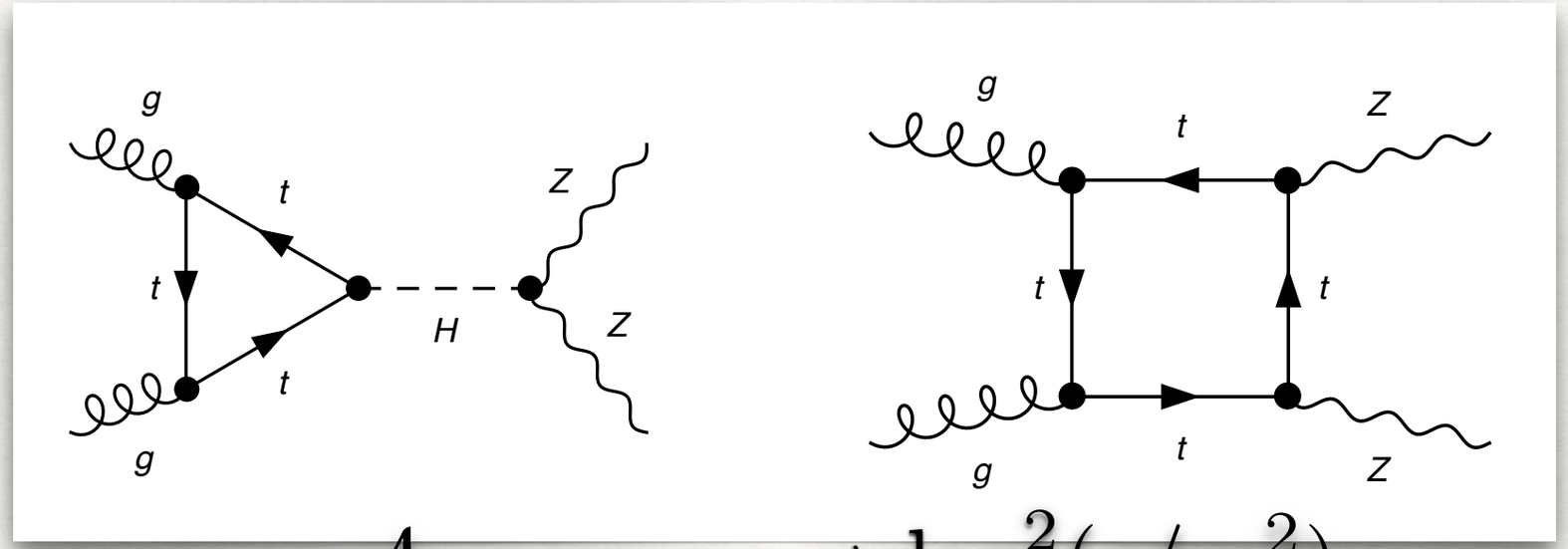

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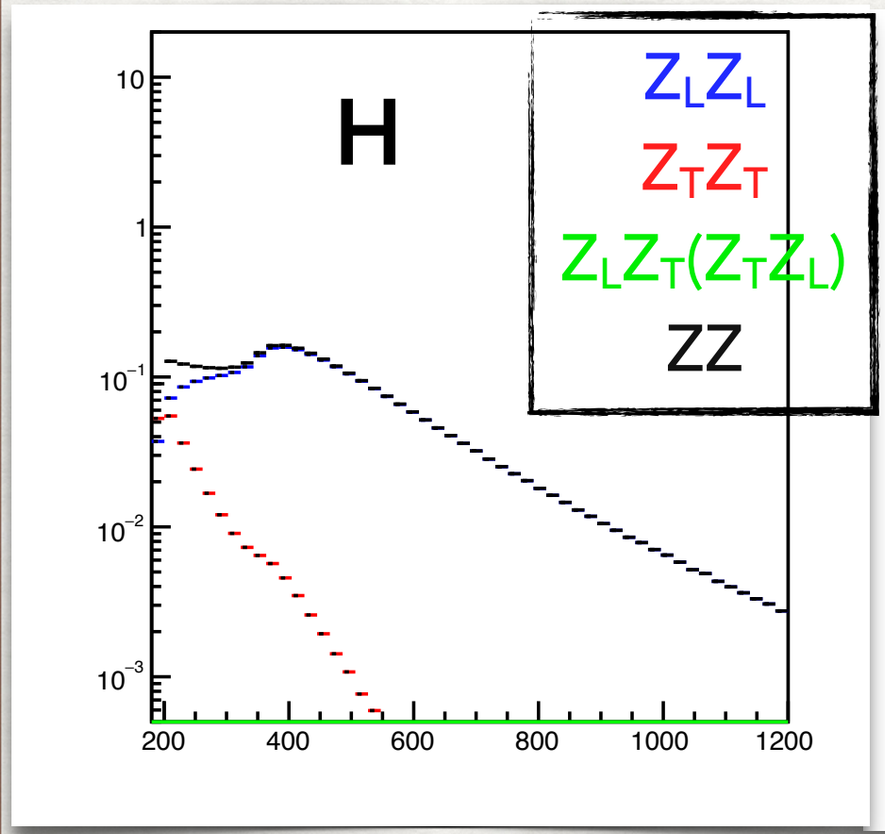

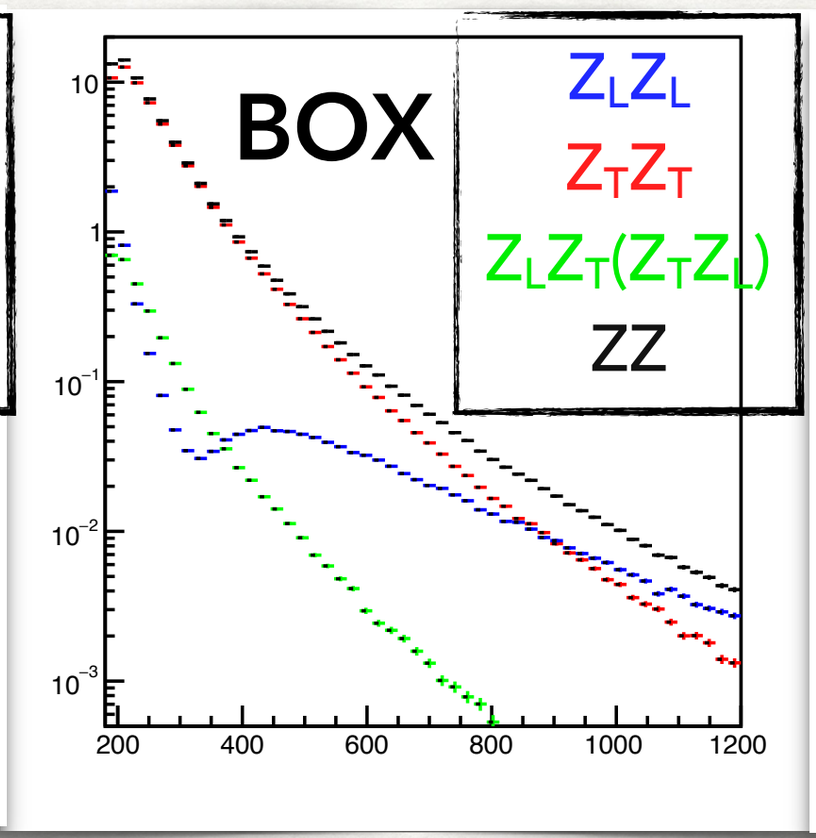

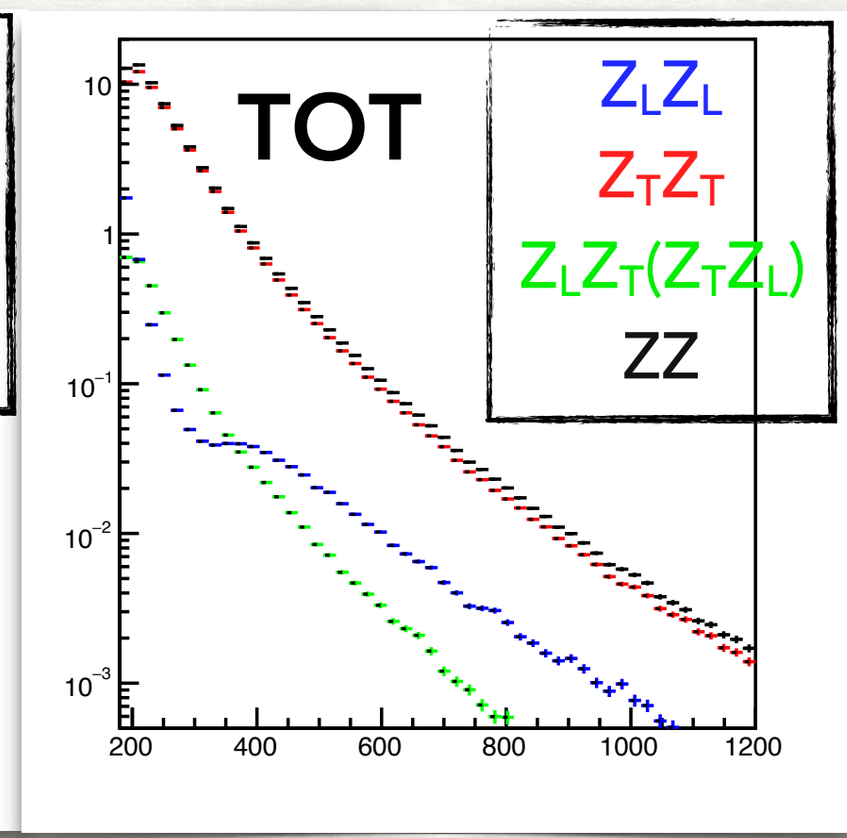

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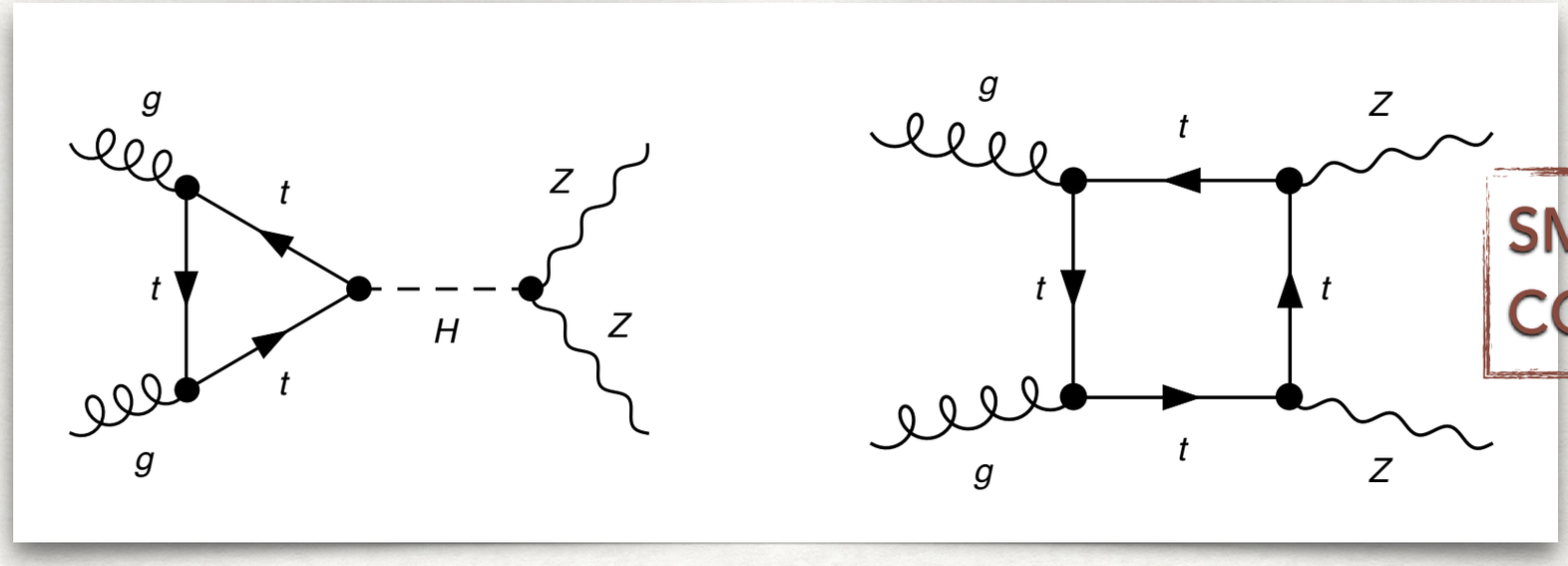

SM(?) BOX-CONTRIBUTION

Modified Higgs sector

Extended SM models:

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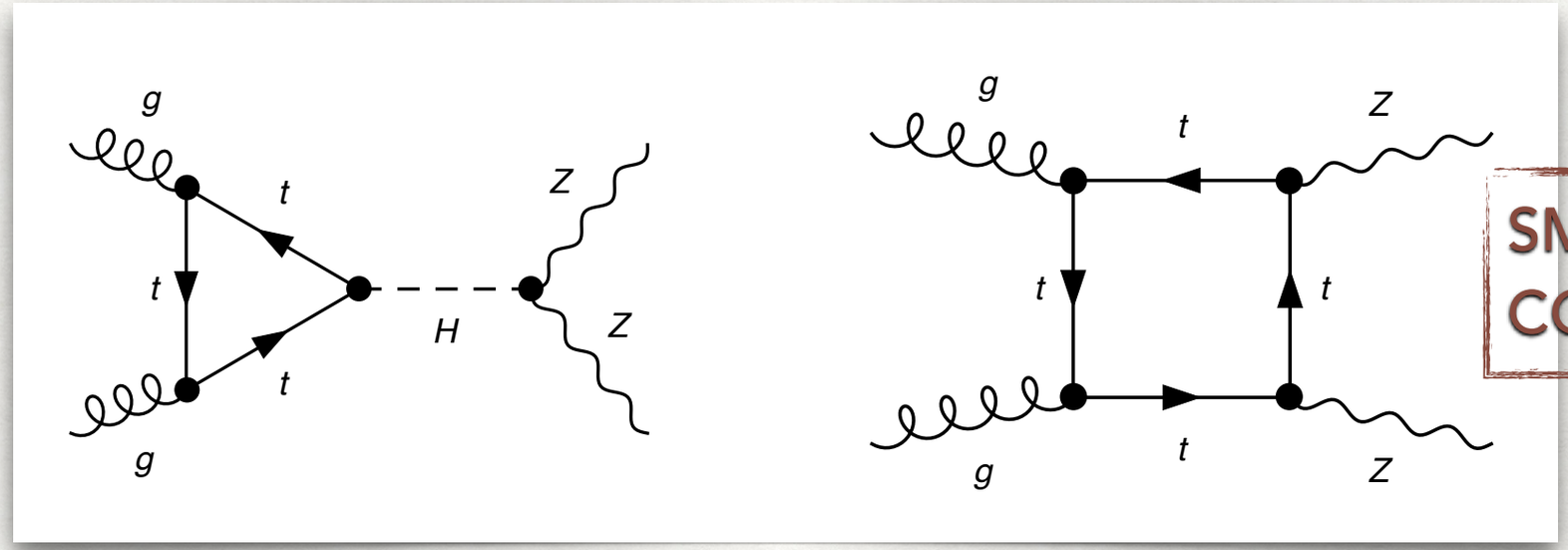

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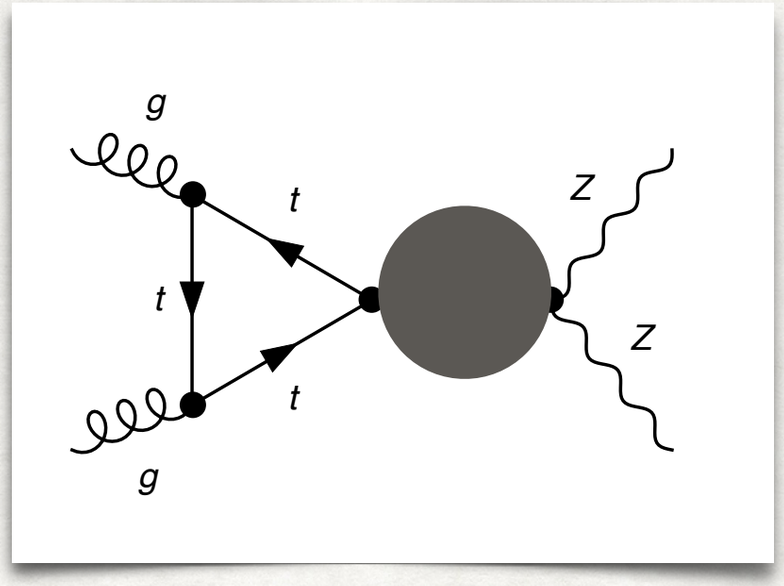


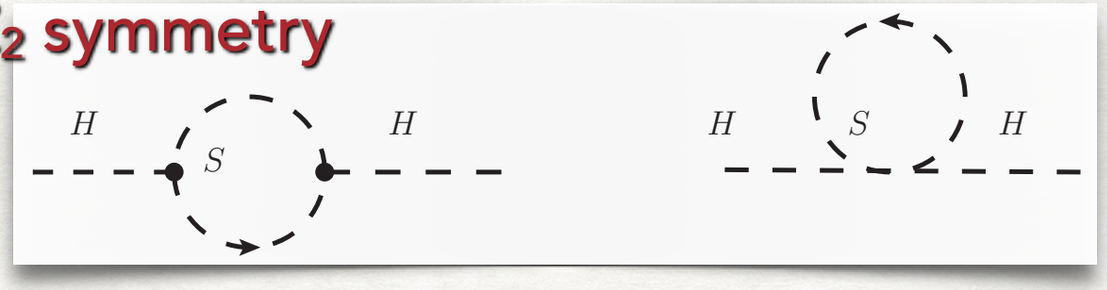
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

QCH: arXiv1511.08218

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

- Case A: Higgs Sector Light scalar with Z_2 symmetry

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



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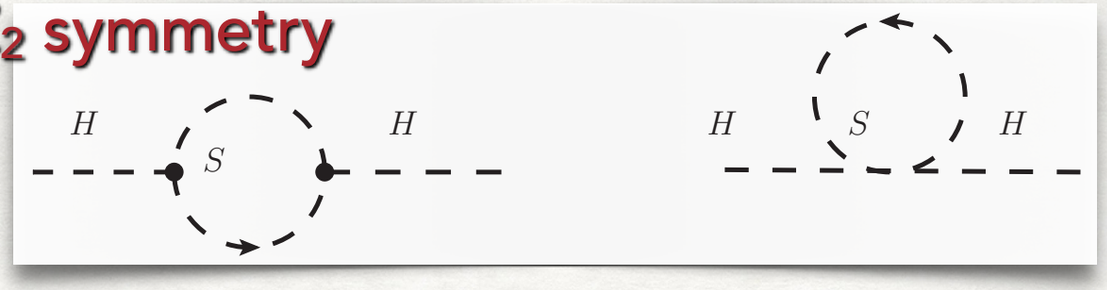
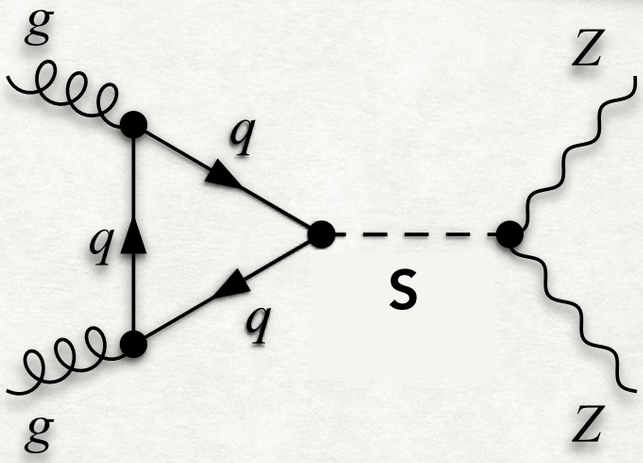


- CaseB: Heavy Higgs with broad decay width

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



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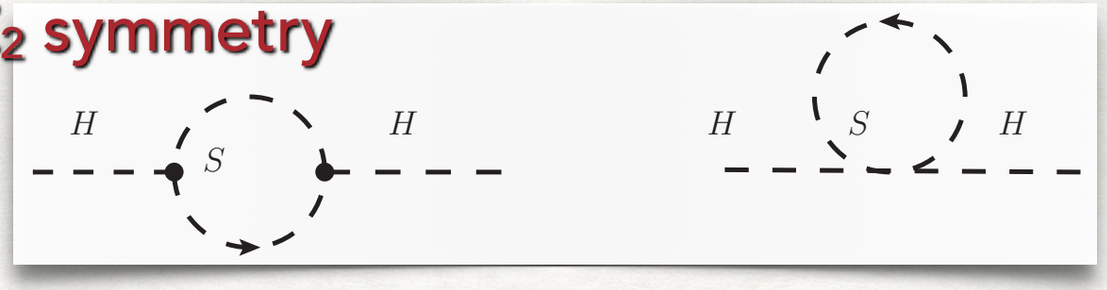

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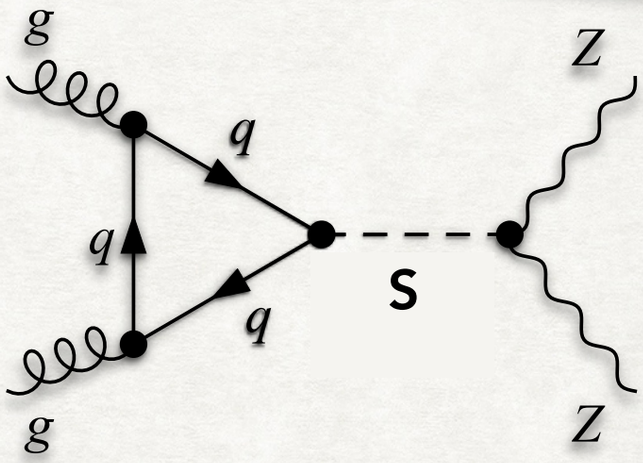
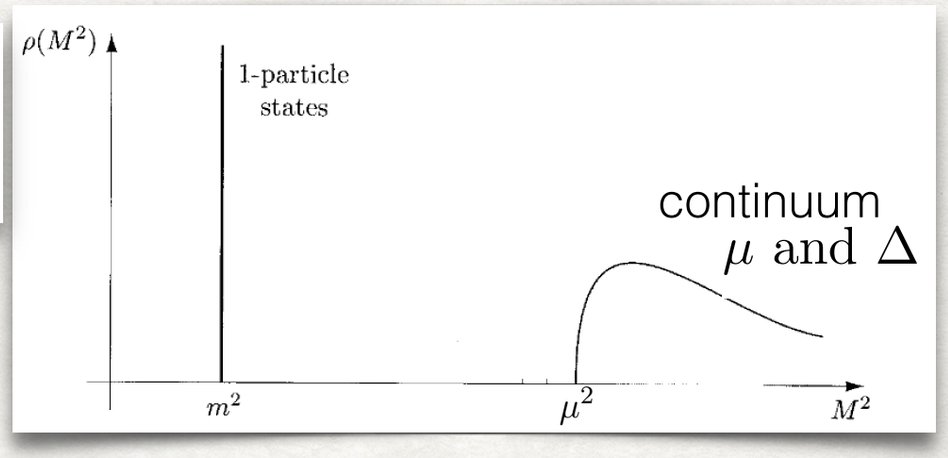


- CaseC: Quantum Critical Higgs modifying the Scalar Sector at high scale

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



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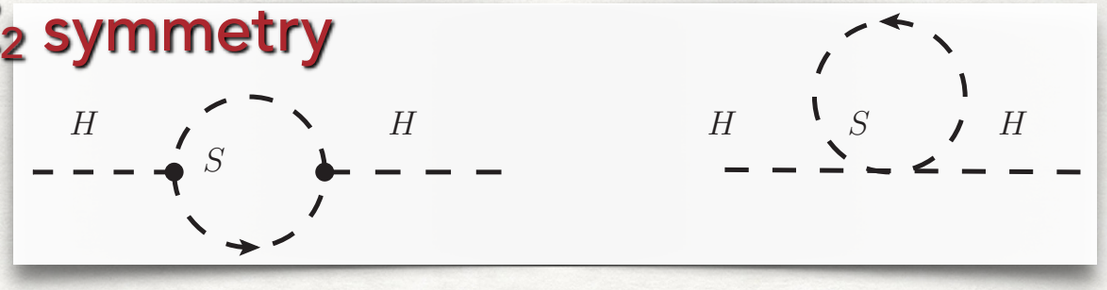

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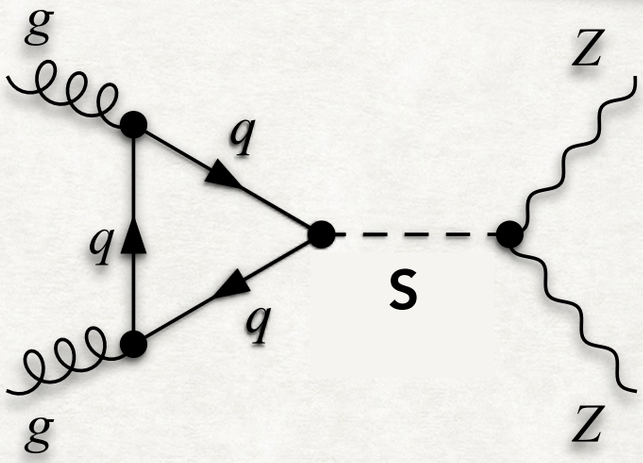

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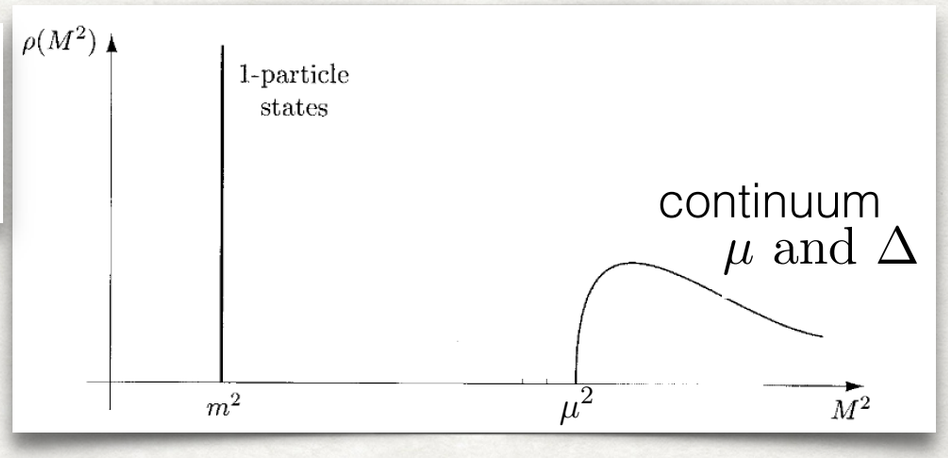

- CaseD: EFT Operator for Example:

$$(\bar\psi^{\{\mu}\partial^{\nu\}}\psi) D_\mu H^\dagger D_\nu H$$

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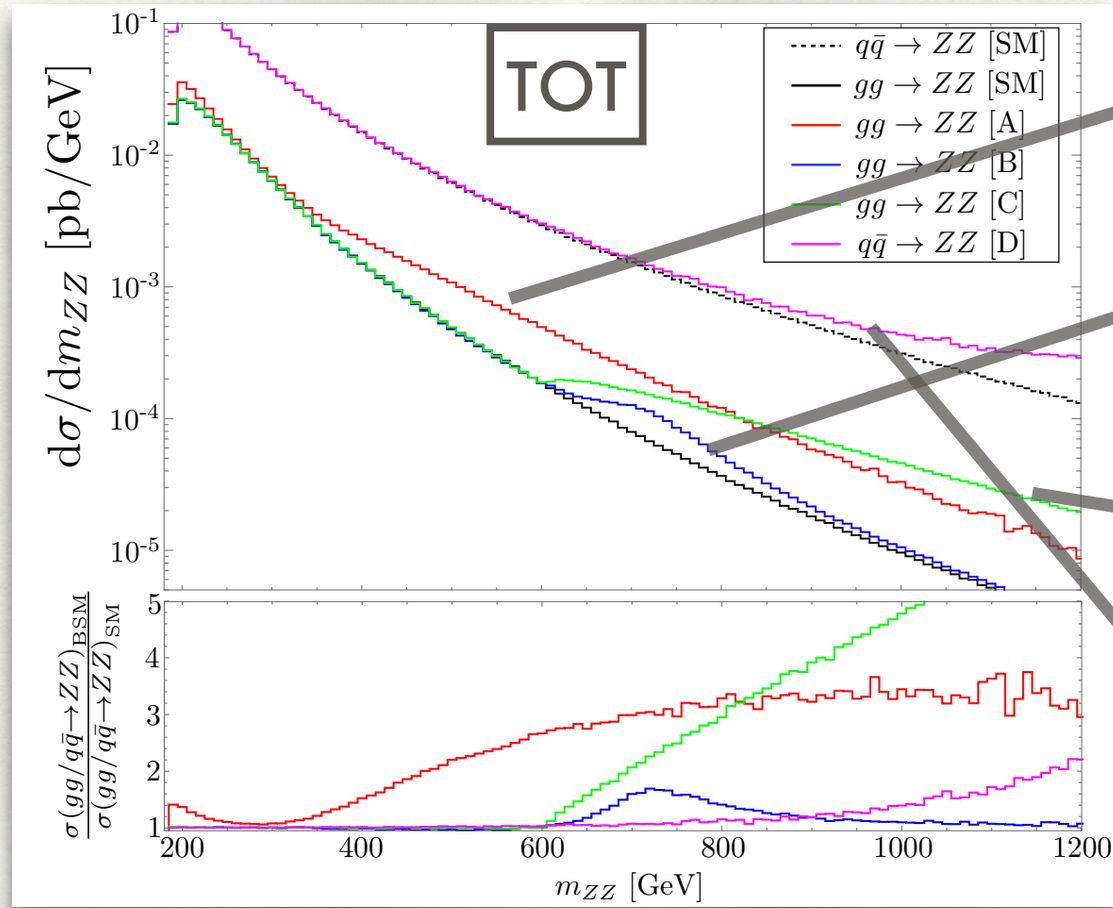

Light scalar

Heavy Higgs

Quantum Critical Higgs

Effective Operator

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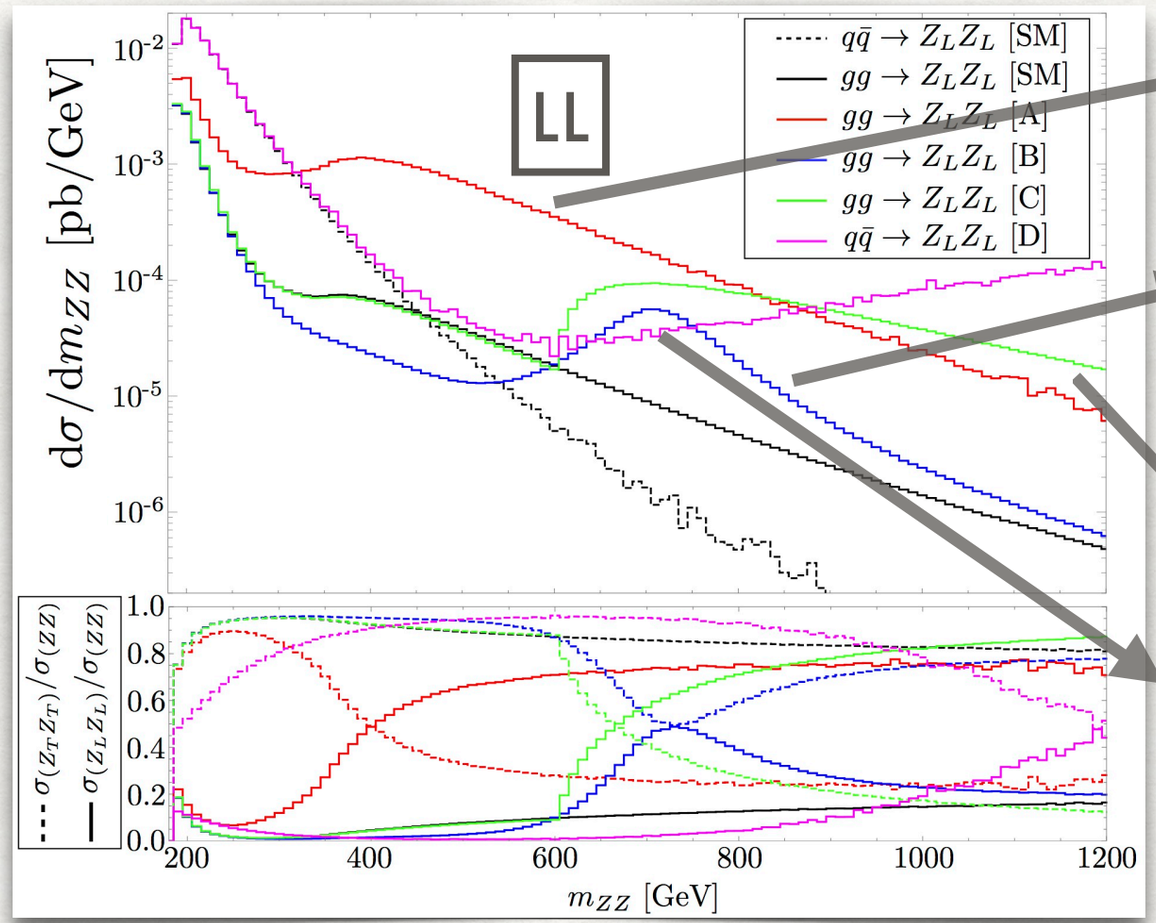

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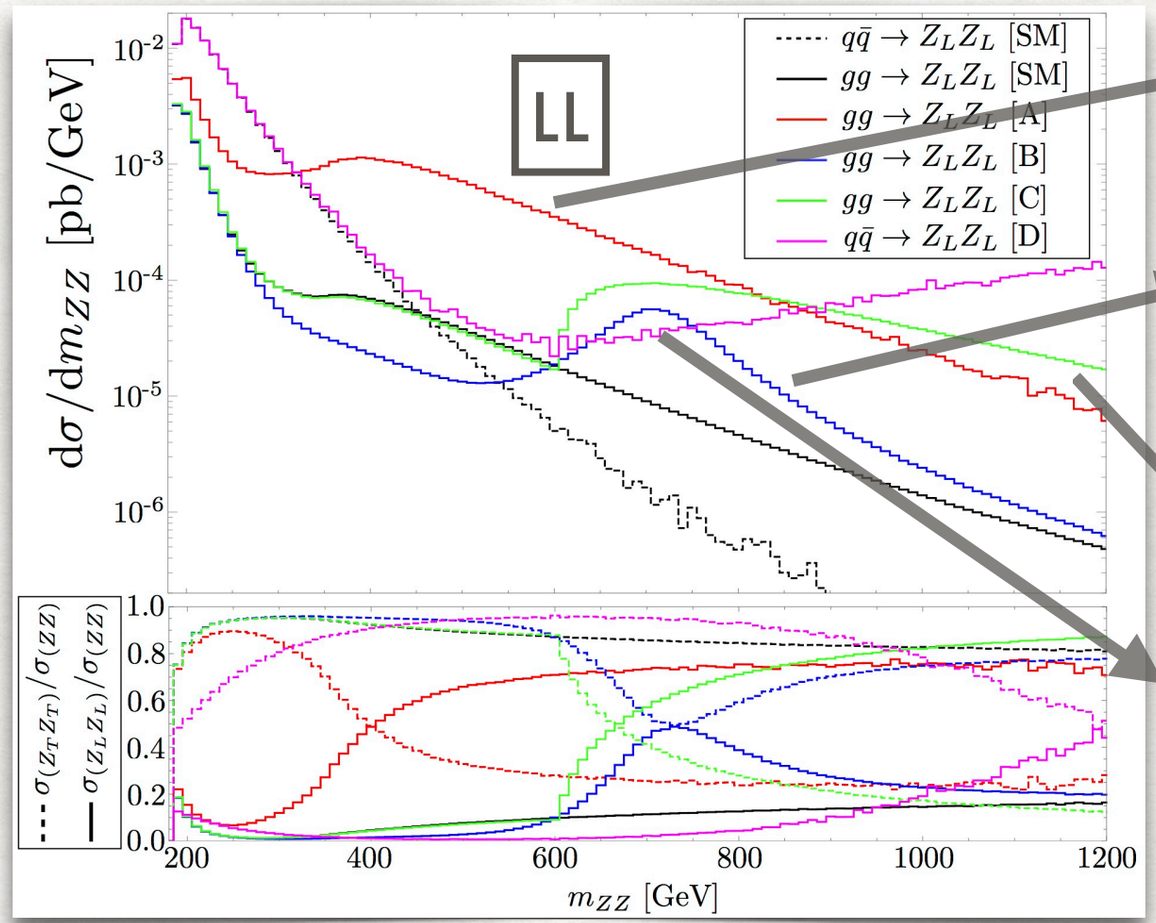

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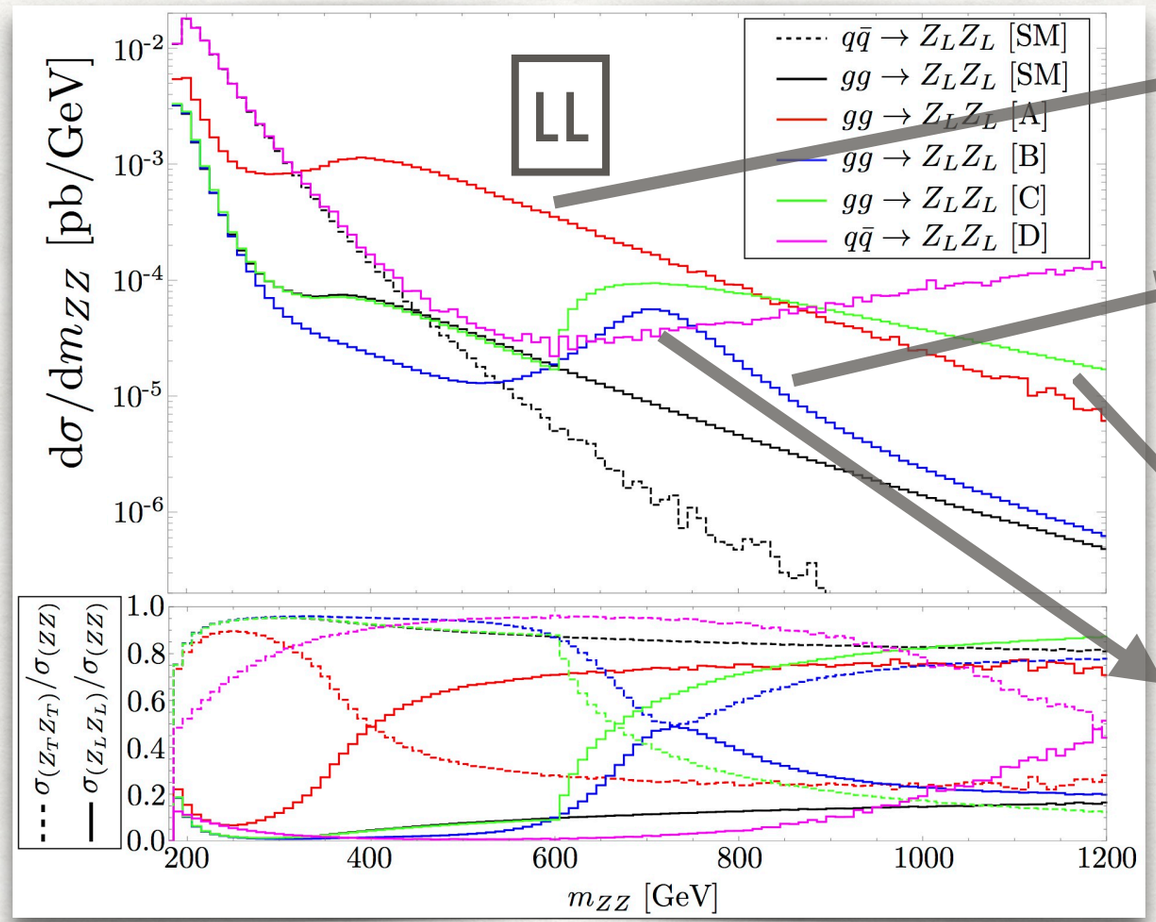

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Significance σ	case A	case B	case C
with basic cuts	2.01	0.634	4.71
with basic + angle cuts	2.32	0.838	5.78
with basic cuts + BDT	2.45	0.92	7.01
Luminosity for 3σ discovery	4.2ab^{-1}	29ab^{-1}	0.5ab^{-1}

4TH GEN FERMION REVEALED BY HEAVY HIGGS

S. Kang, ZQ, J. Song, Y. Yoon: arXiv:1810.05229

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

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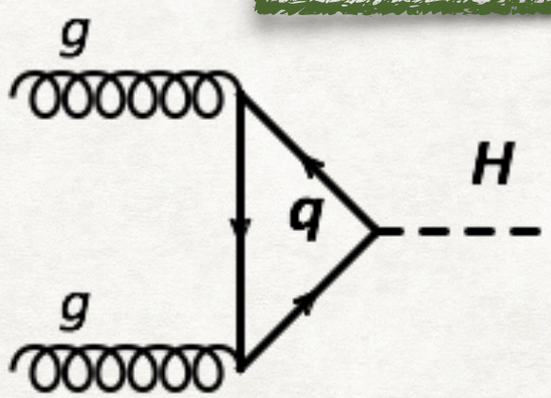

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$$(\kappa_q = \frac{y_q}{y_q^{\rm SM}})$$

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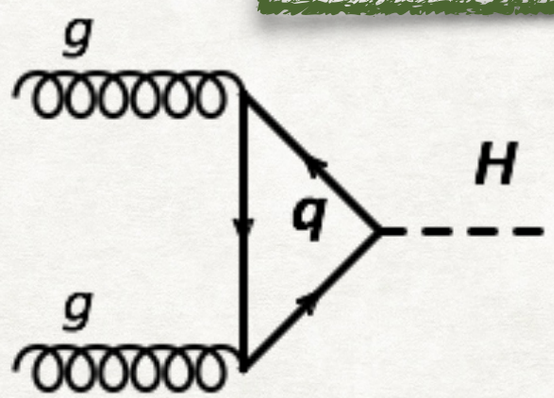

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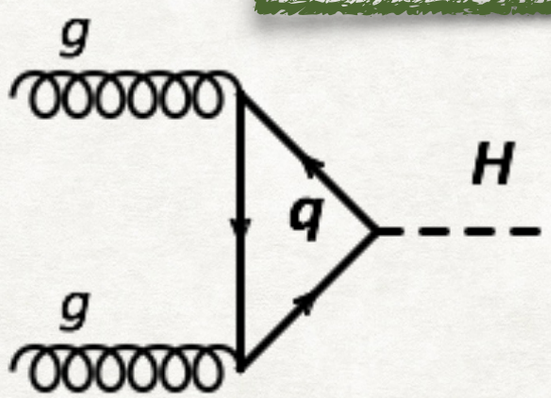

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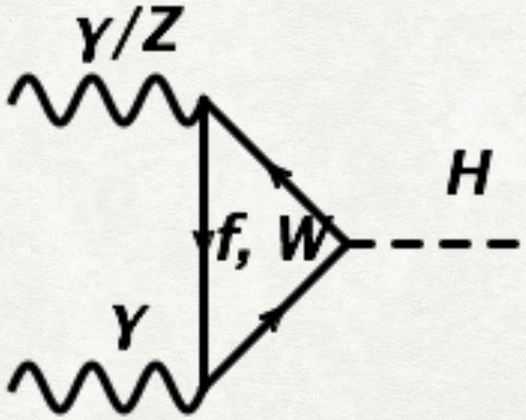
$$\delta\kappa_{\gamma\gamma} \propto \sum_{f=t',b',\tau'} Q_f^2 N_C^f \kappa_f = 0,$$

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



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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

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

2HDM →

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

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

2HDM scalar potential (CP-conservin

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

α: Neutral Higgs mixing angle

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

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- 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

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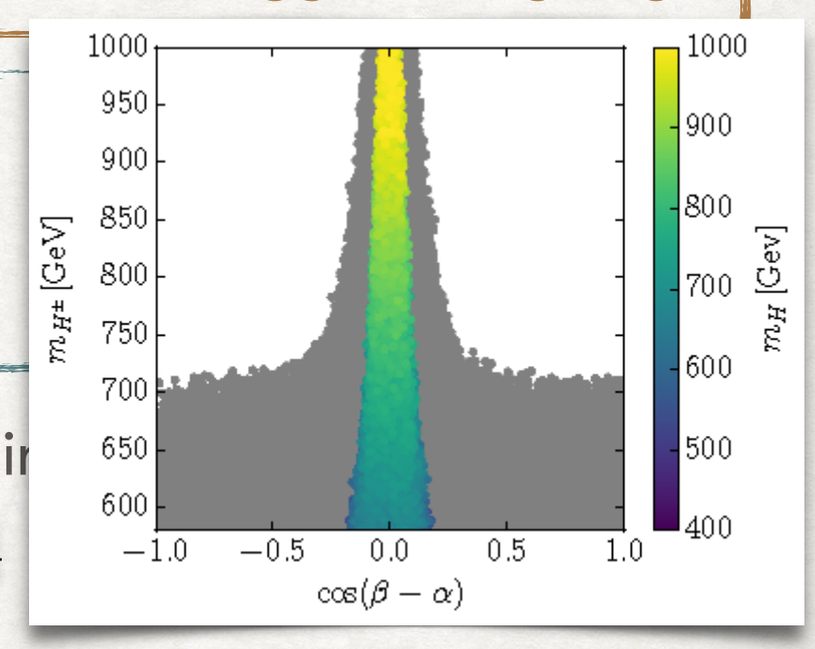

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  (Realized in

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Figure: arXiv1710.10410

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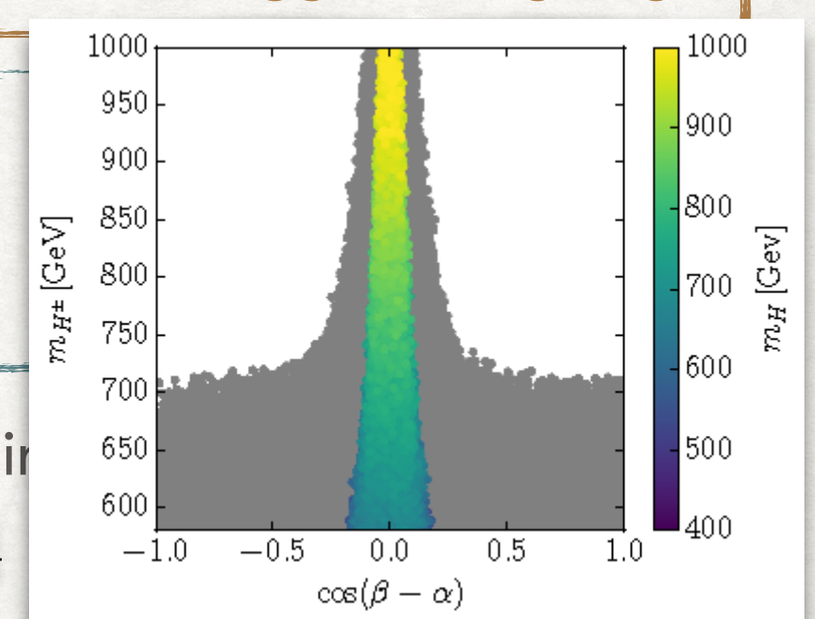

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- EWS Cannot Approach Alignment ⇒ Upper bound on $M_{H,\,A,\,H^\pm} \lesssim 900$ GeV

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]
$pp \to Zh$	A	$[200, 1000]$	LHC Run-1 [66, 67]

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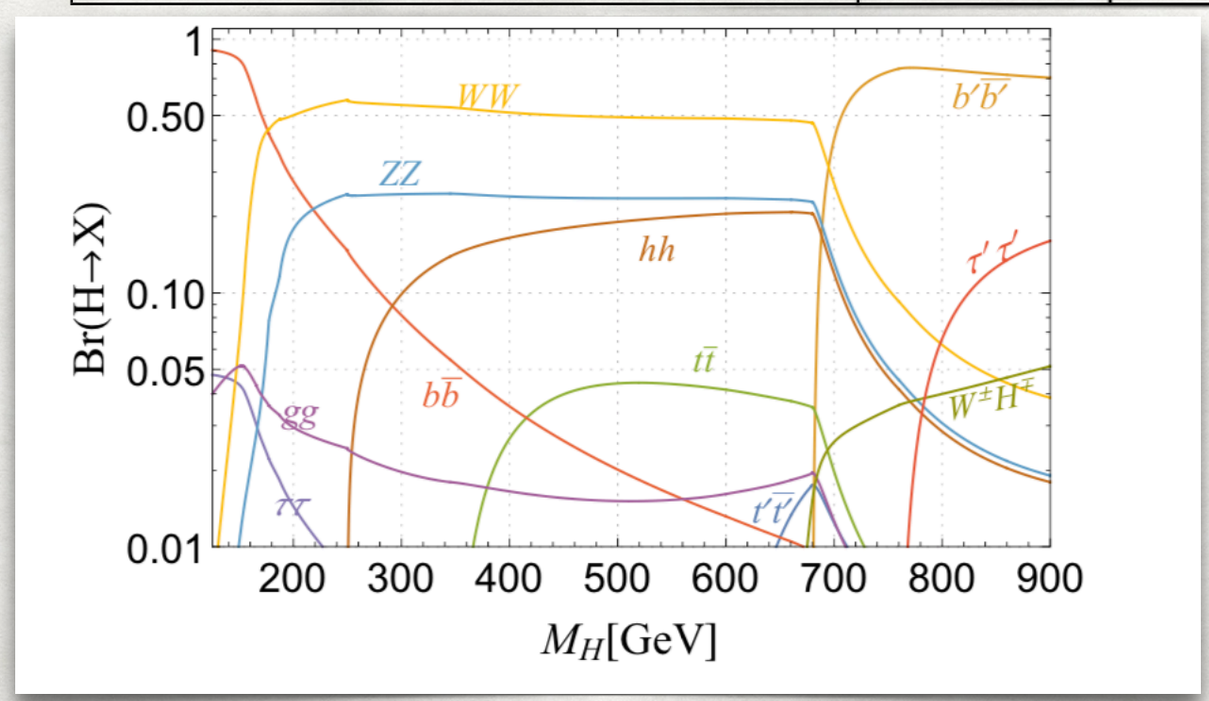
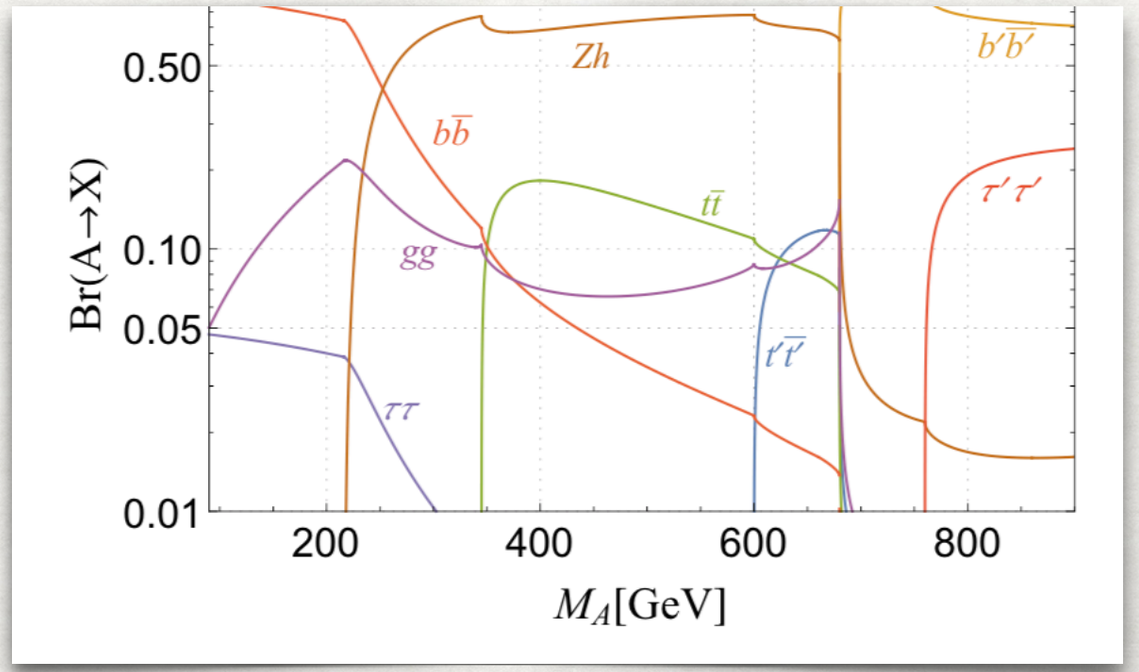
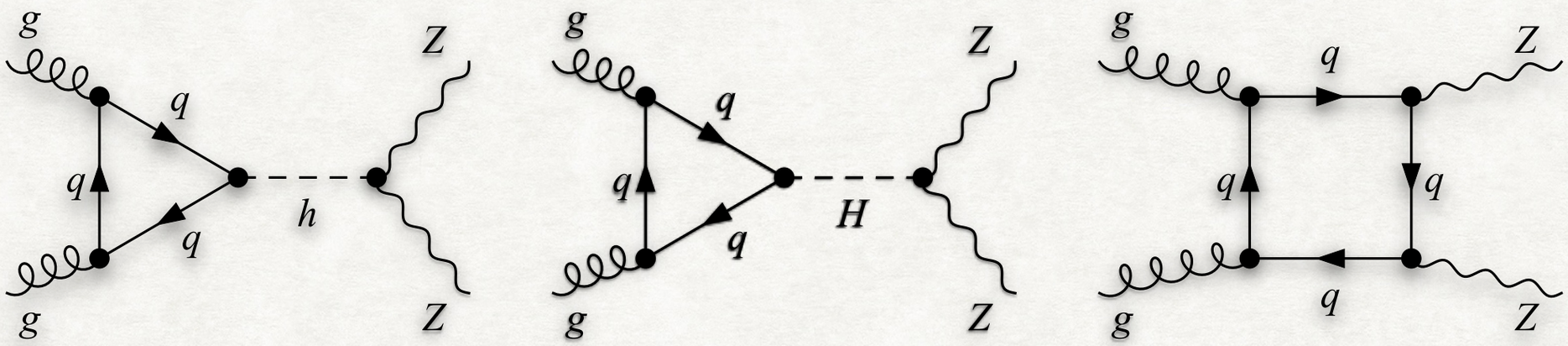
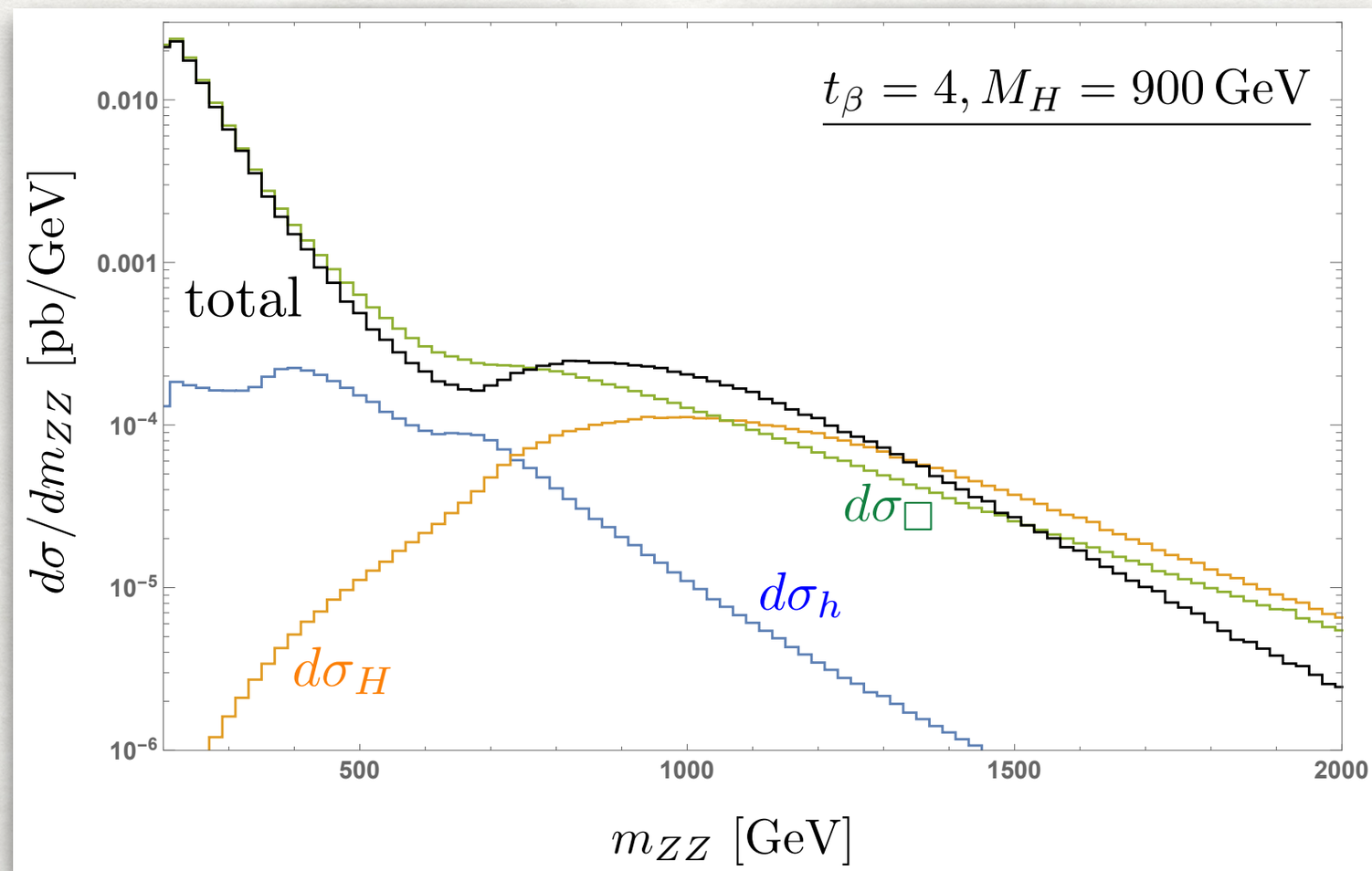




4TH GEN FERMION REVEALED BY HEAVY HIGGS

- Direct Search in ZZ channel for the Additional Higgs





$q =$ SM quarks
+4th Gen $\{t', b'\}$

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

SUMMARY & FUTURE

Discovery of the Higgs completes the SM roster, now what?

LHC at High invariant mass tail and Future Lepton Colliders:

- ZZ channel as Effective probe for Higgs (New) Physics
- ZZ or Z+(Heavy) Higgs Indirect probe of heavy particles contributing through loop