DIBOSON AS PROBE TO HIGGS (NEW) PHYSICS

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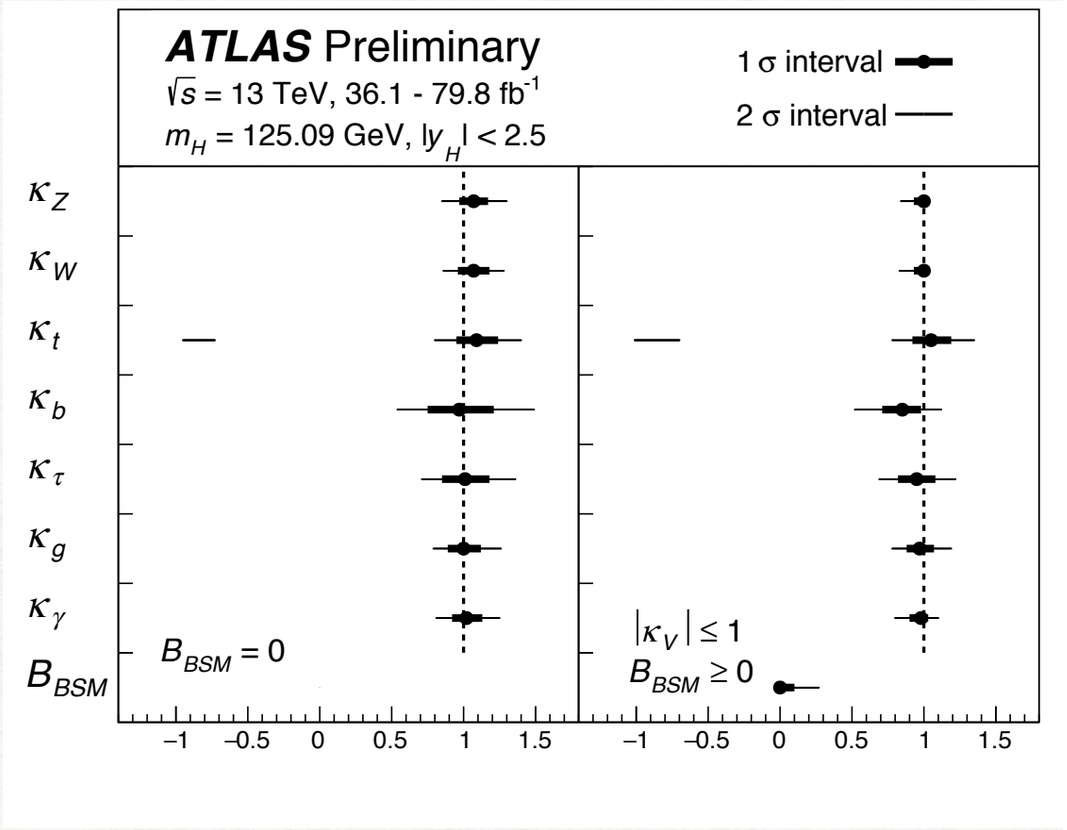
Work in collaboration with S. Lee, M Park arXiv: 1812.02679
S. Kang, J. Song, Y. Yoon: 1810.05229

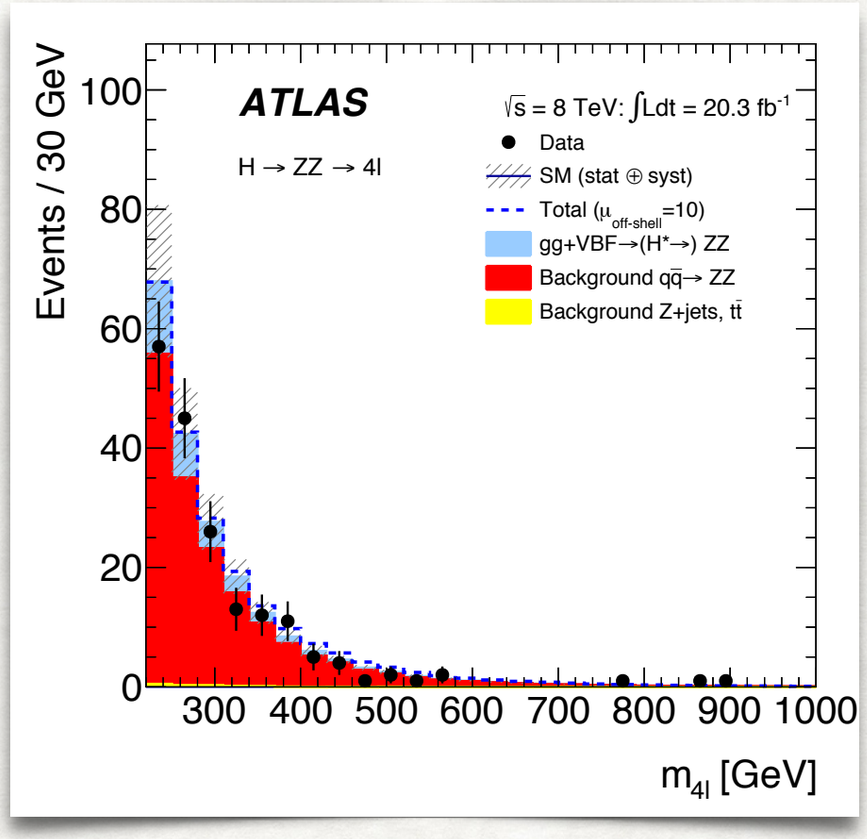
MOTIVATION

- Since the Higgs discovery, studying its properties has been main focus.
- Likely connection between Higgs and new physics: Dark matter or their mediator, EW symmetry breaking, Fermion masses, etc.
- Currently, the Higgs data agrees with the SM, but allows sizable space for simple extensions to the standard model, which further links to complete theories.
- Collider possibilities: LHC, future lepton colliders

CURRENT HIGGS MEASUREMENT



(a)

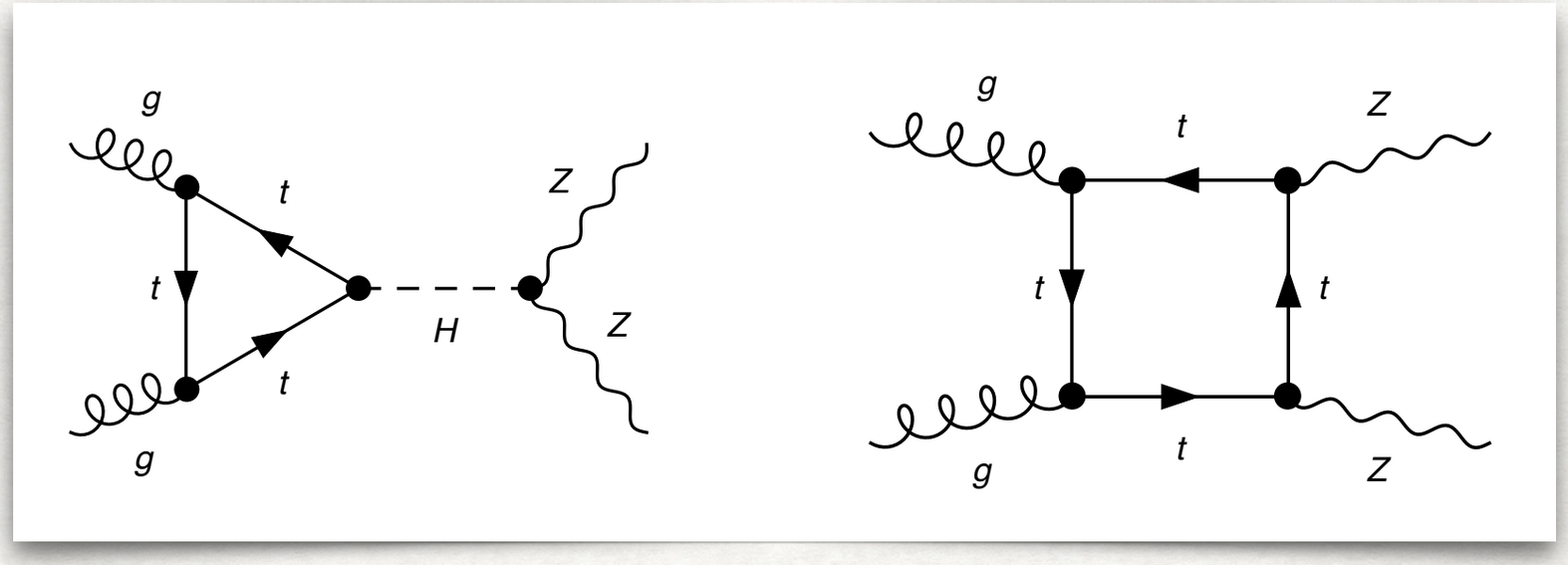


Higgs on-shell signal Measurement

Higgs off-shell signal

* arXiv:1811.10215: Higgs measurement at LHC run2

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS



At High energy scale, each diagram diverges:

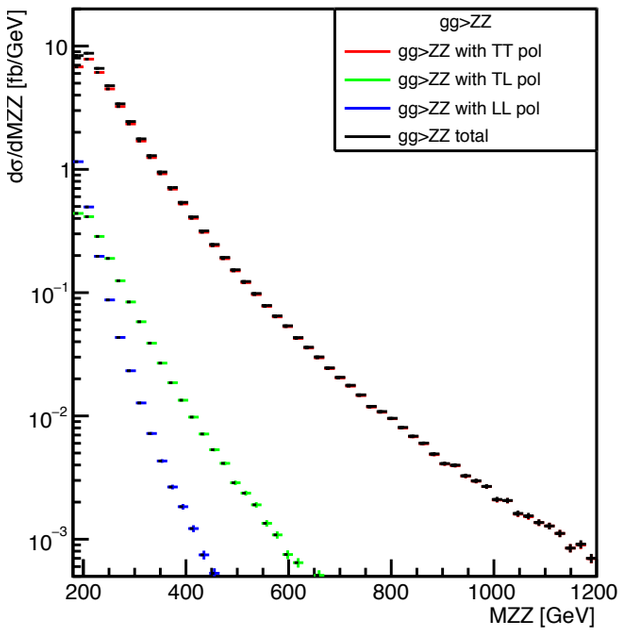
$$\mathcal{A}_{gg\to Z_L Z_L} \to \log^2(s/m_t^2)$$

Prominent in Z-longitudinal mode

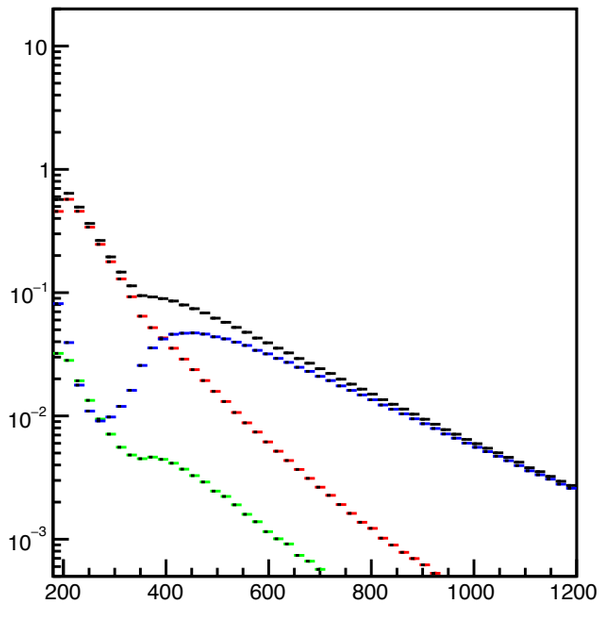
S. Lee, **M. Park**, ZQ: arXiv:1812.02679

DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

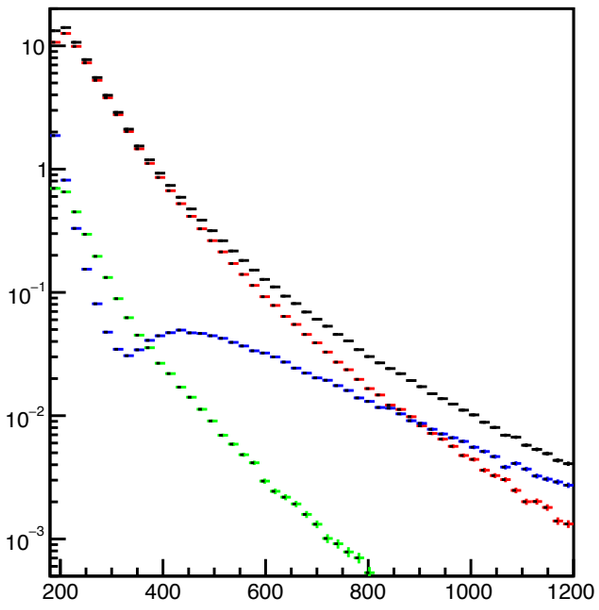
box-lq



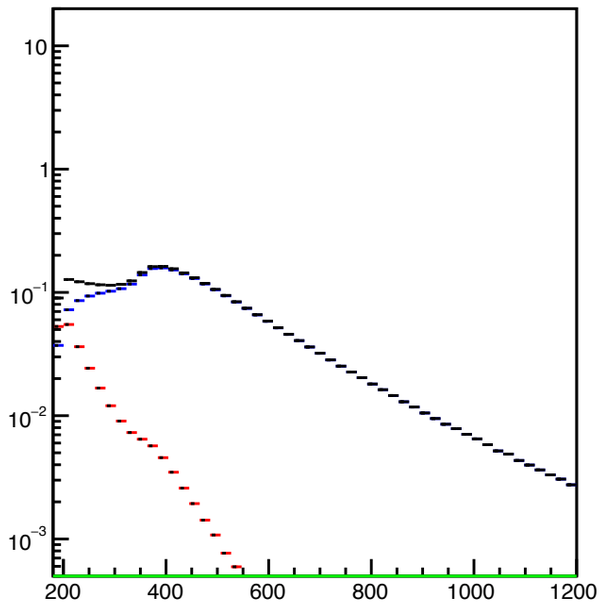
box-tb



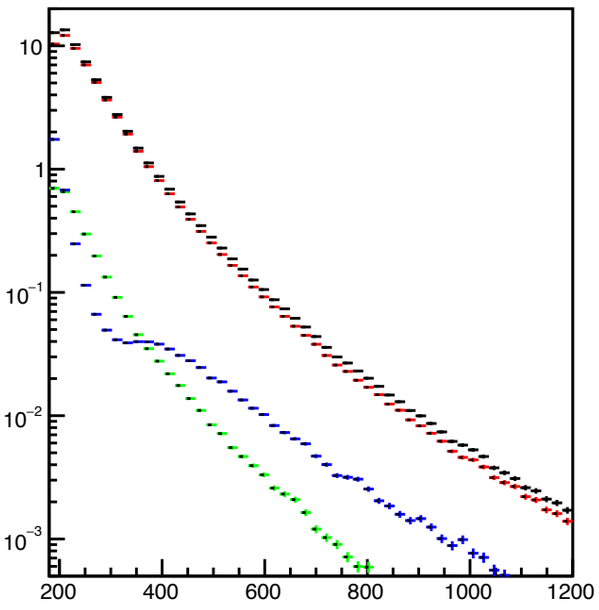
box



h



box+h



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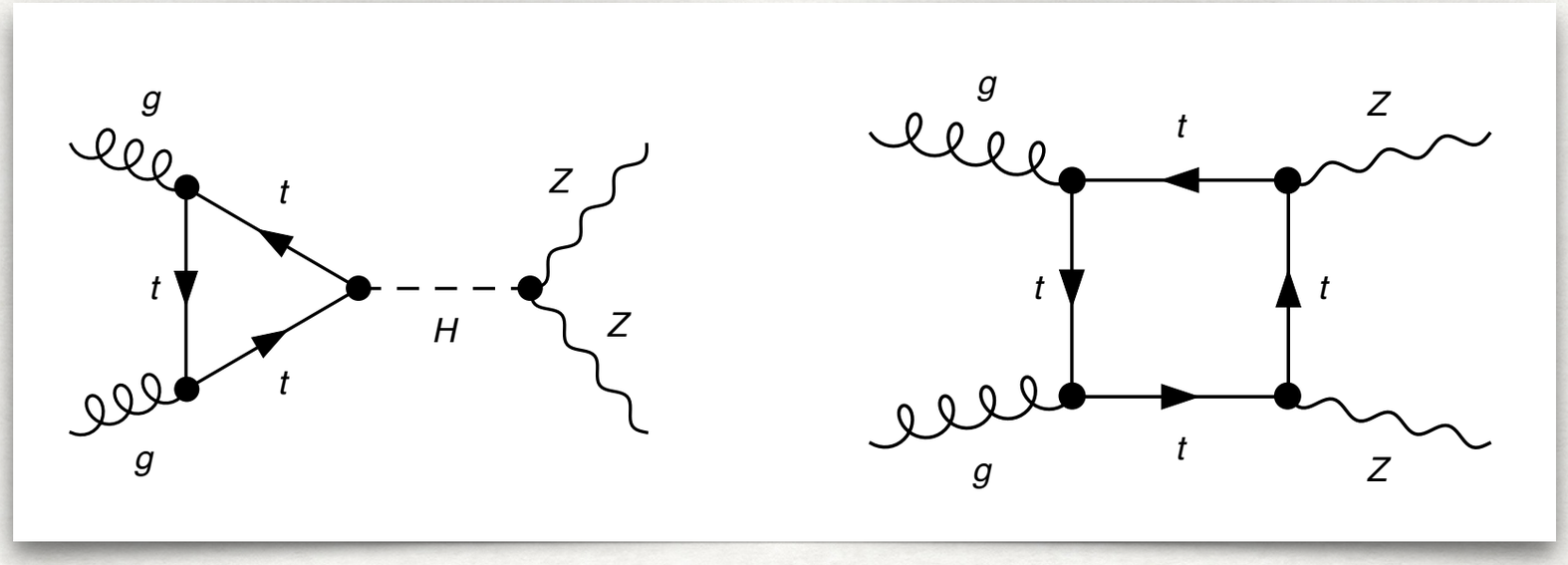
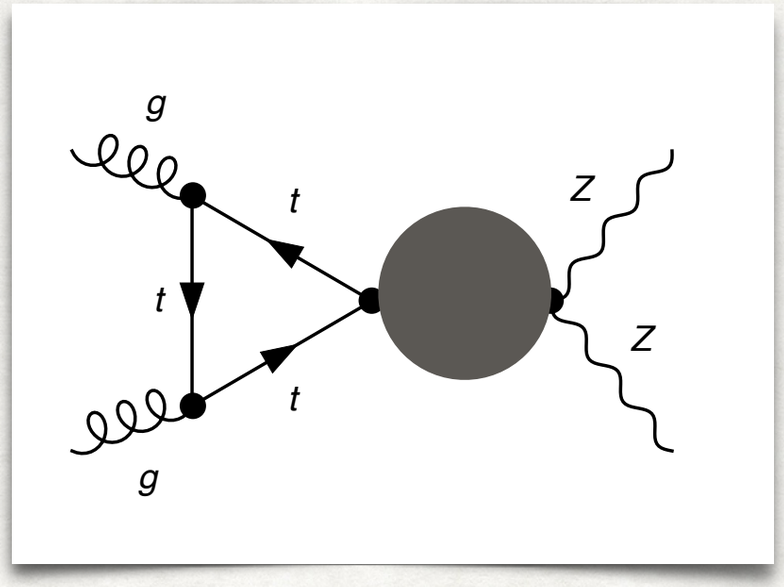


Modified Higgs sector

Extended SM models:



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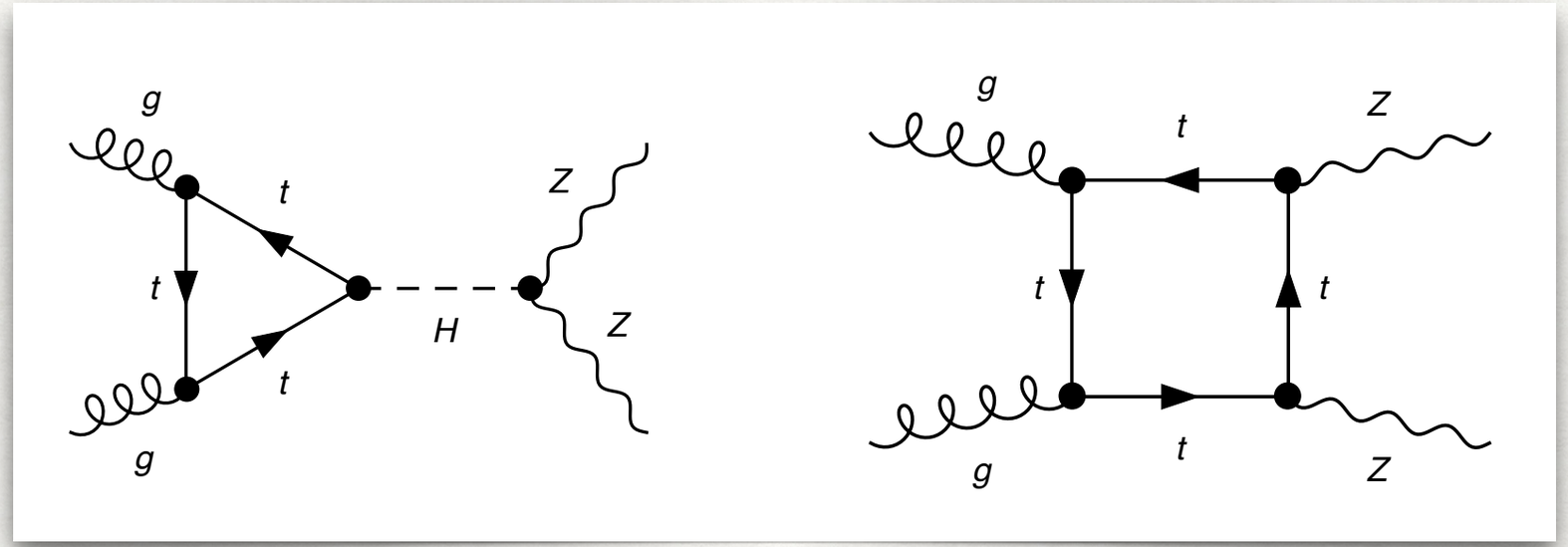

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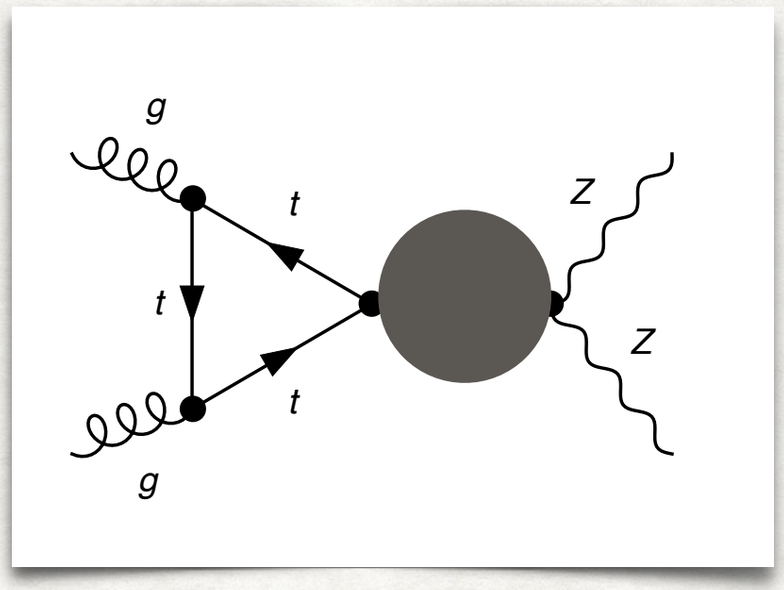
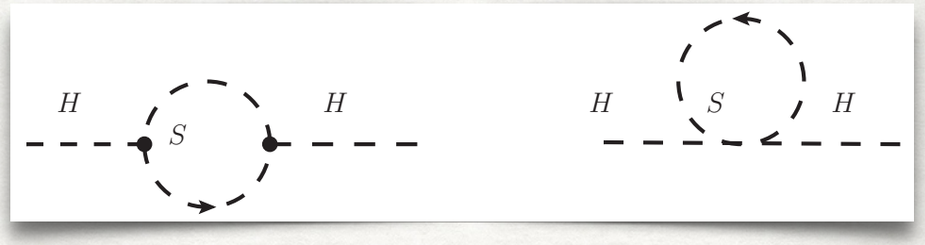


DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

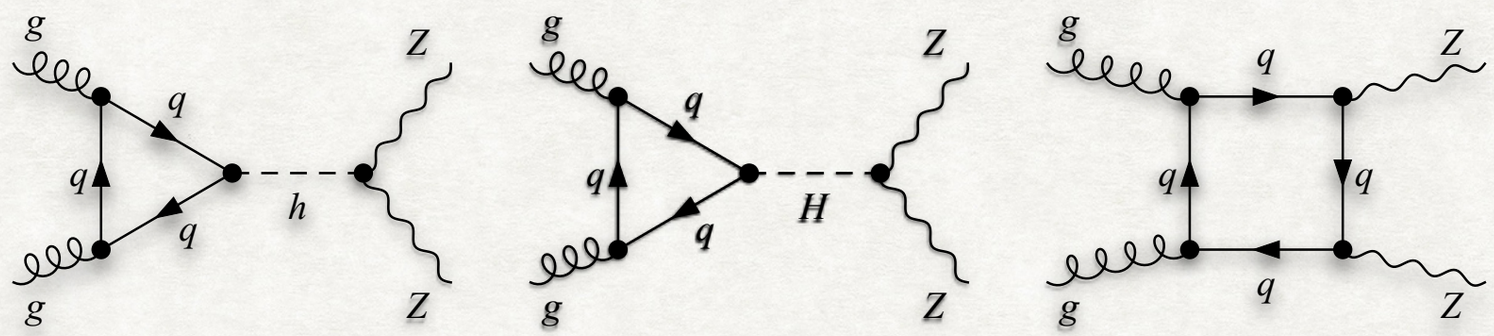
- Higgs Sector Light scalar with Z_2 symmetry

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



- Heavy Higgs with broad decay width

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



- Quantum Critical Higgs modifying the Scalar Sector at high scale
- EFT Operator e.g. $(\bar{\psi}^{\{\mu}\partial^{\nu\}}\psi) D_\mu H^\dagger D_\nu H$

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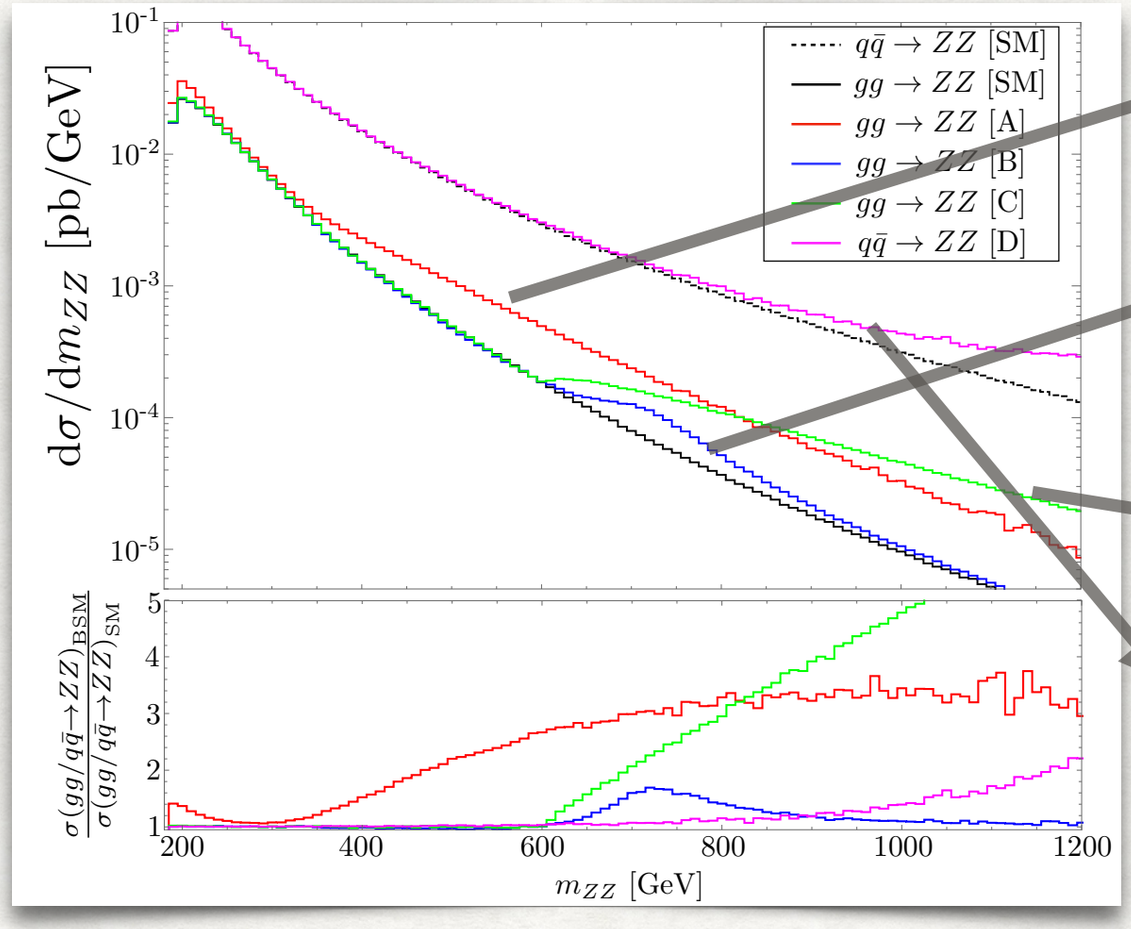

Light scalar

Heavy Higgs

Quantum Critical Higgs

Effective Operator

⇒ 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}

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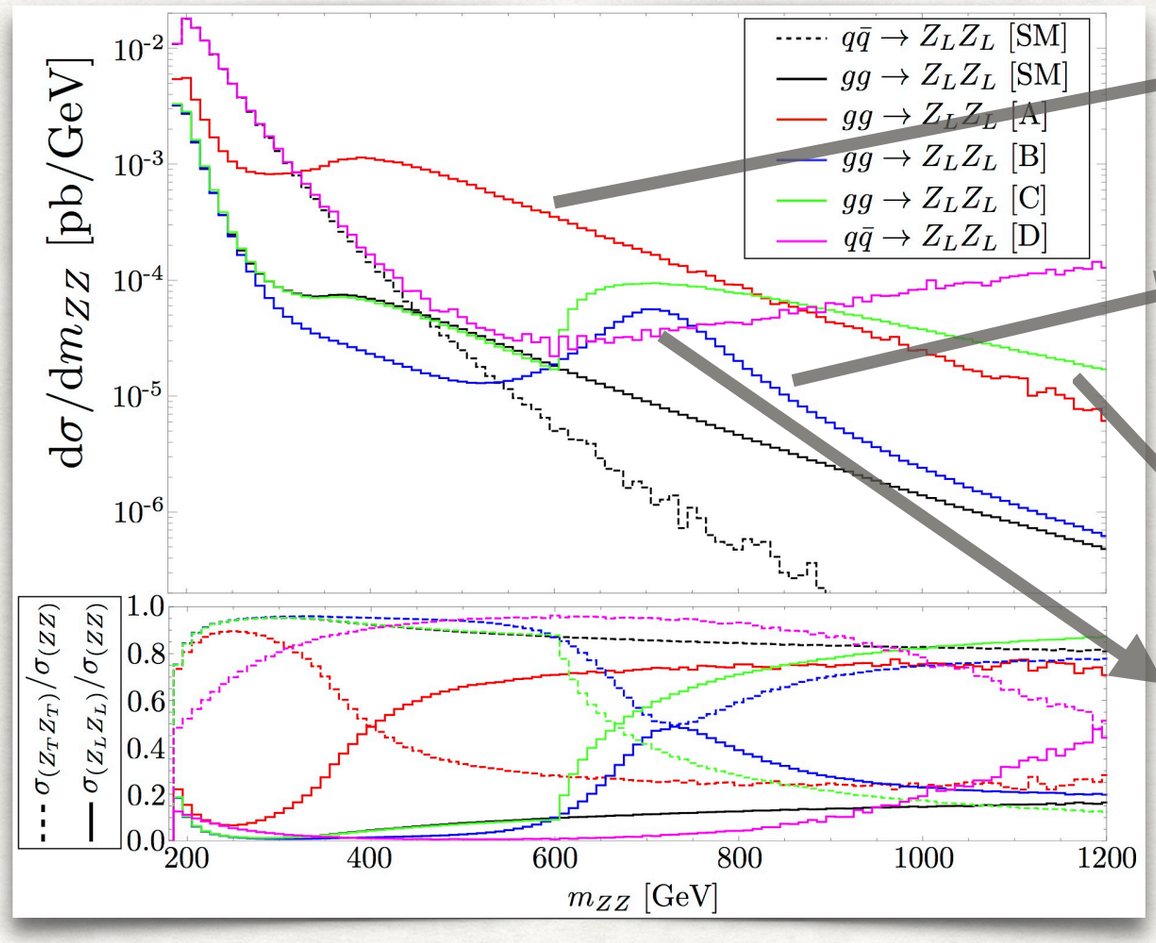

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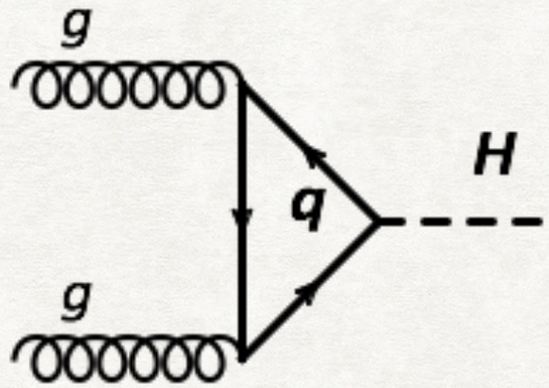
4TH GEN FERMION REVEALED BY HEAVY HIGGS

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

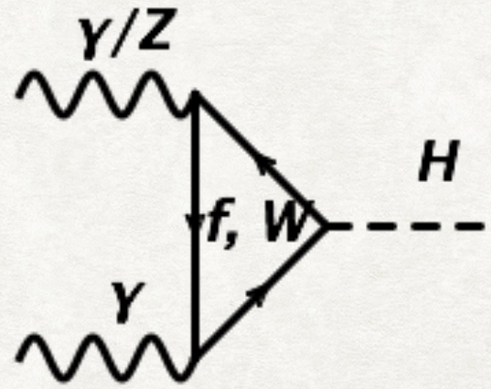
$$\kappa_g = \frac{\kappa_t A^h_{1/2}(\tau_t) + \sum_F \kappa_F A^h_{1/2}(\tau_F)}{A^h_{1/2}(\tau_t)}$$



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

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

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



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

4TH GEN FERMION REVEALED BY HEAVY HIGGS

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

2HDM scalar potential

α: Neutral Higgs mixing angle

- Exact Wrong Sign Limit (EWS): $\alpha = \frac{\pi}{2} - \beta$
- Alignment Limit: $\sin(\beta - \alpha) = 1$

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

- EWS Cannot Approach Alignment
- ⇒ Upper bound on Higgs Masses H, A $H^\pm \lesssim 900$ GeV

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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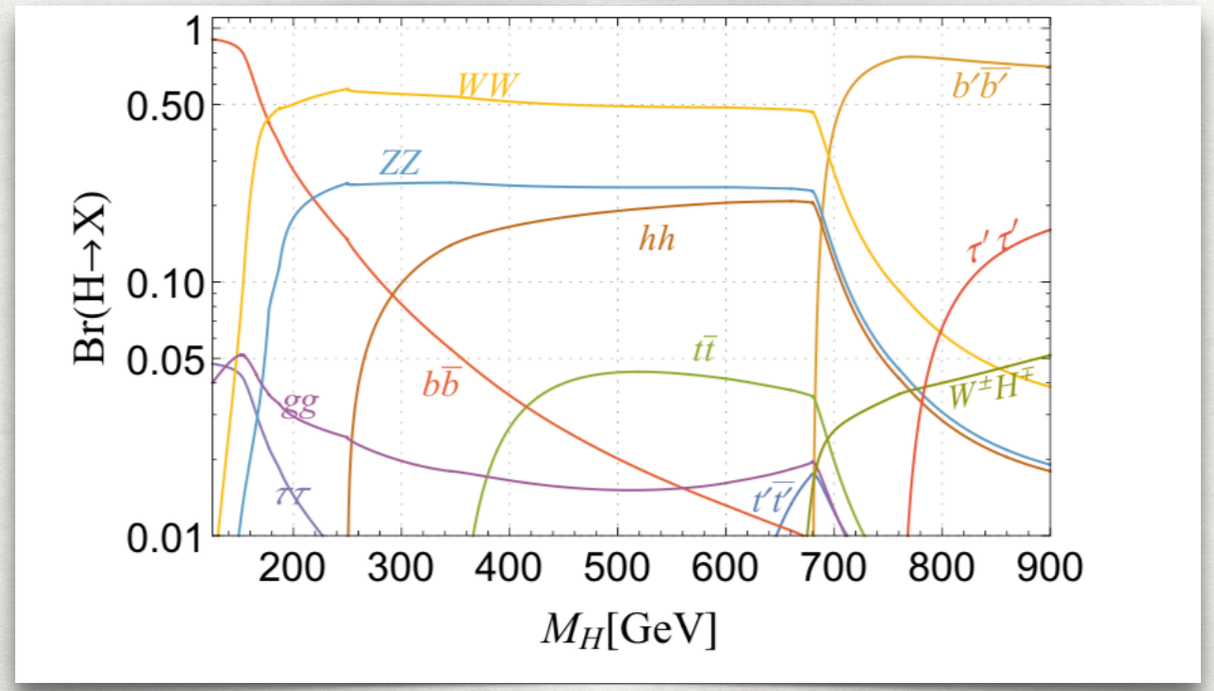
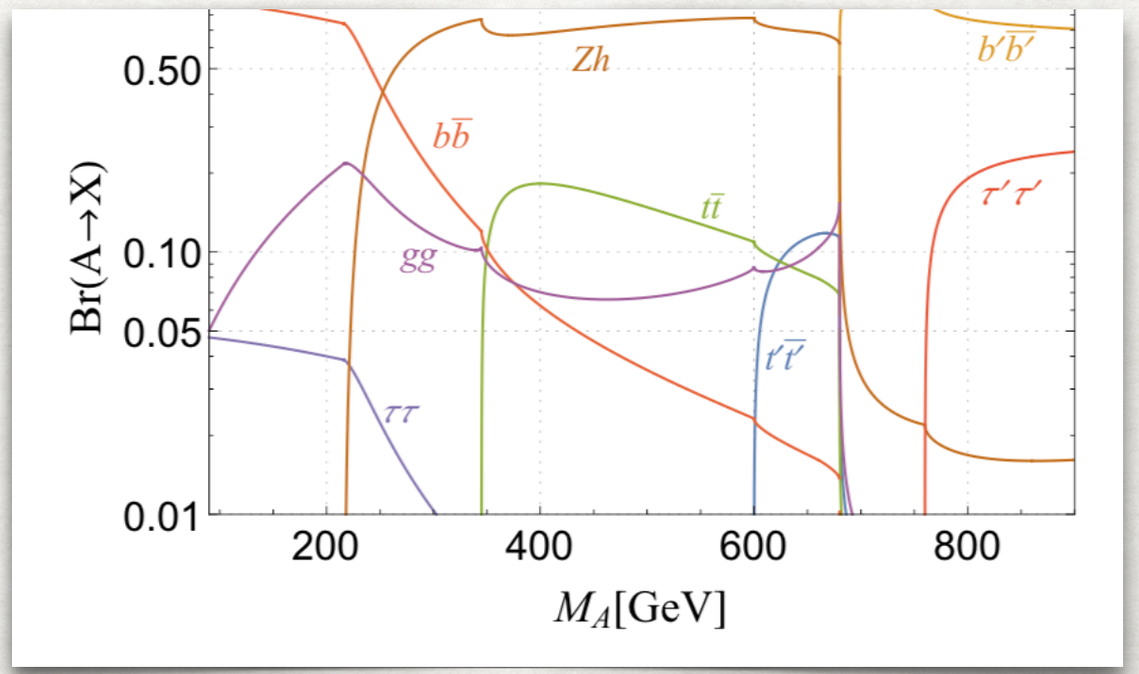
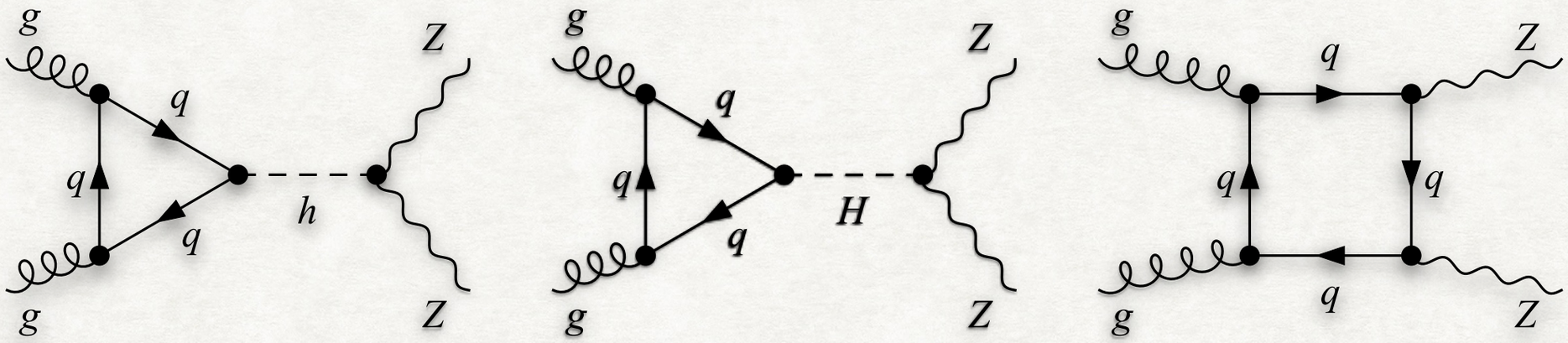
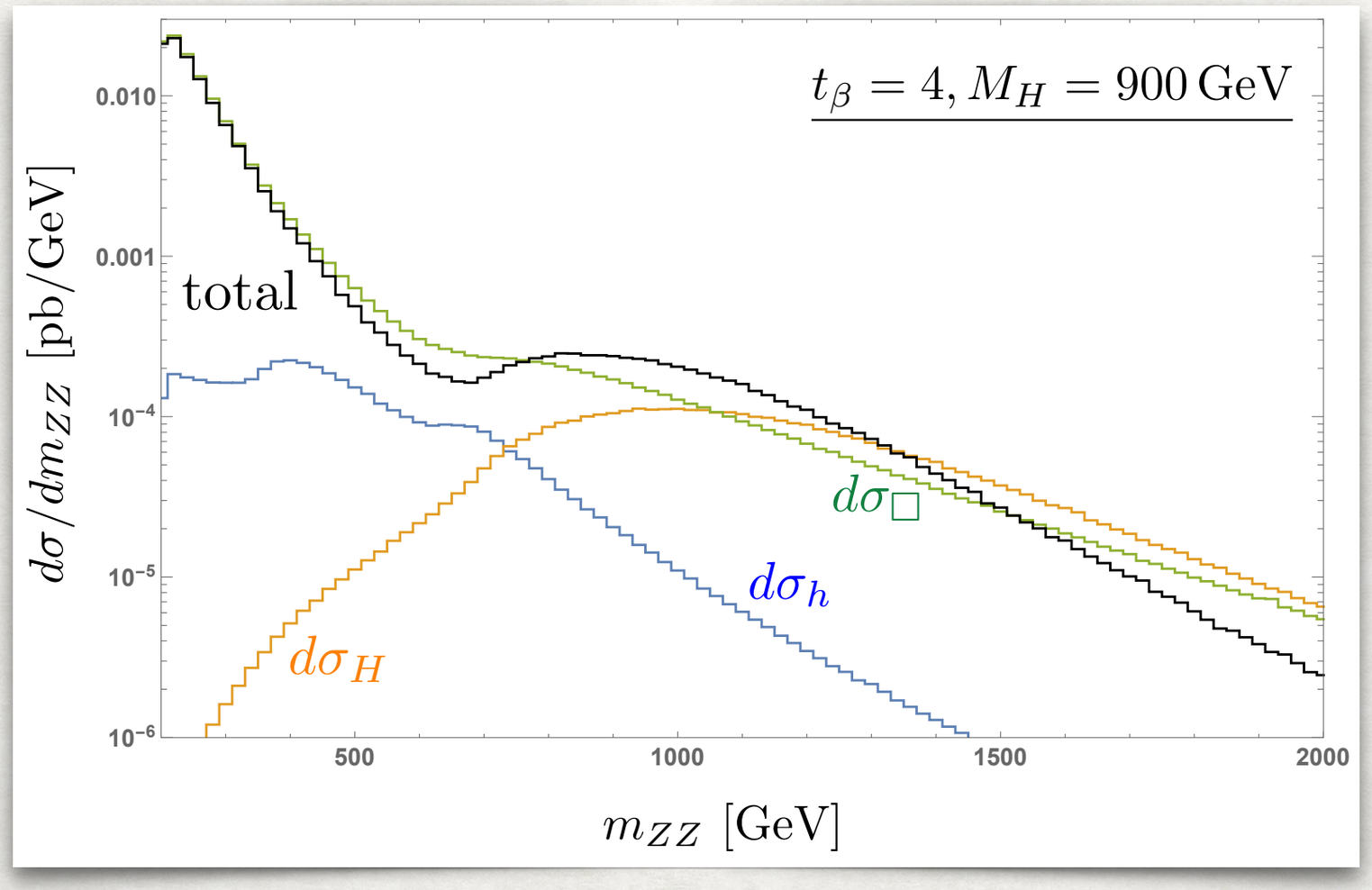




4TH GEN FERMION REVEALED BY HEAVY HIGGS

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





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

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