# PROBING THE HIGGS SECTOR NEW PHYSICS THROUGH $Z_L Z_L$ FINAL STATES

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Work In Collaboration with Seung Joon Lee, Myeonghun Park

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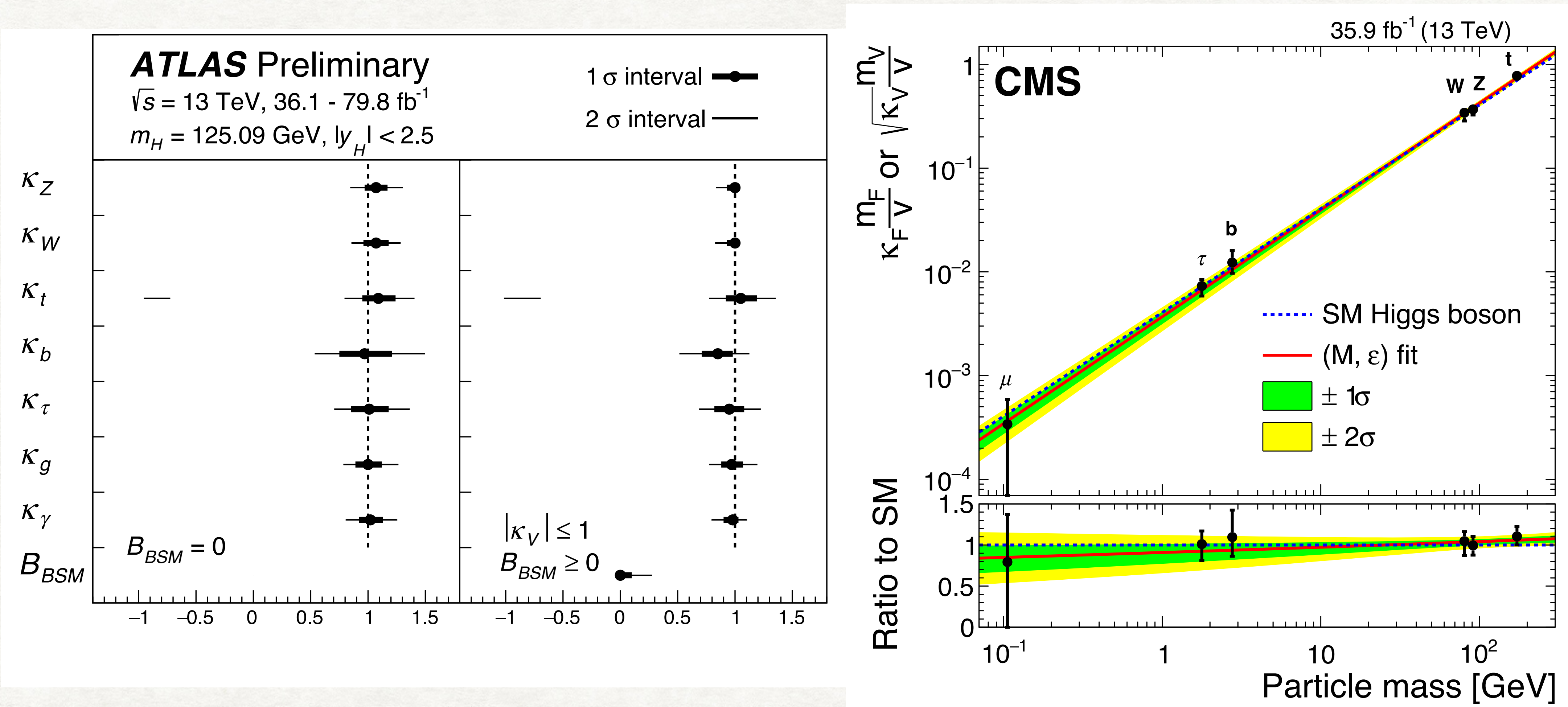


(a)

(b)

Figure 5: Measurements of (a) all $\kappa$ coupling modifier parameters simultaneously for two different assumptions in the ATLAS combined analysis [42] and (b) of the scaling of the Higgs boson couplings as a function of the particle mass in the CMS analysis [41].

UPDATED LHC13 HIGGS DATA

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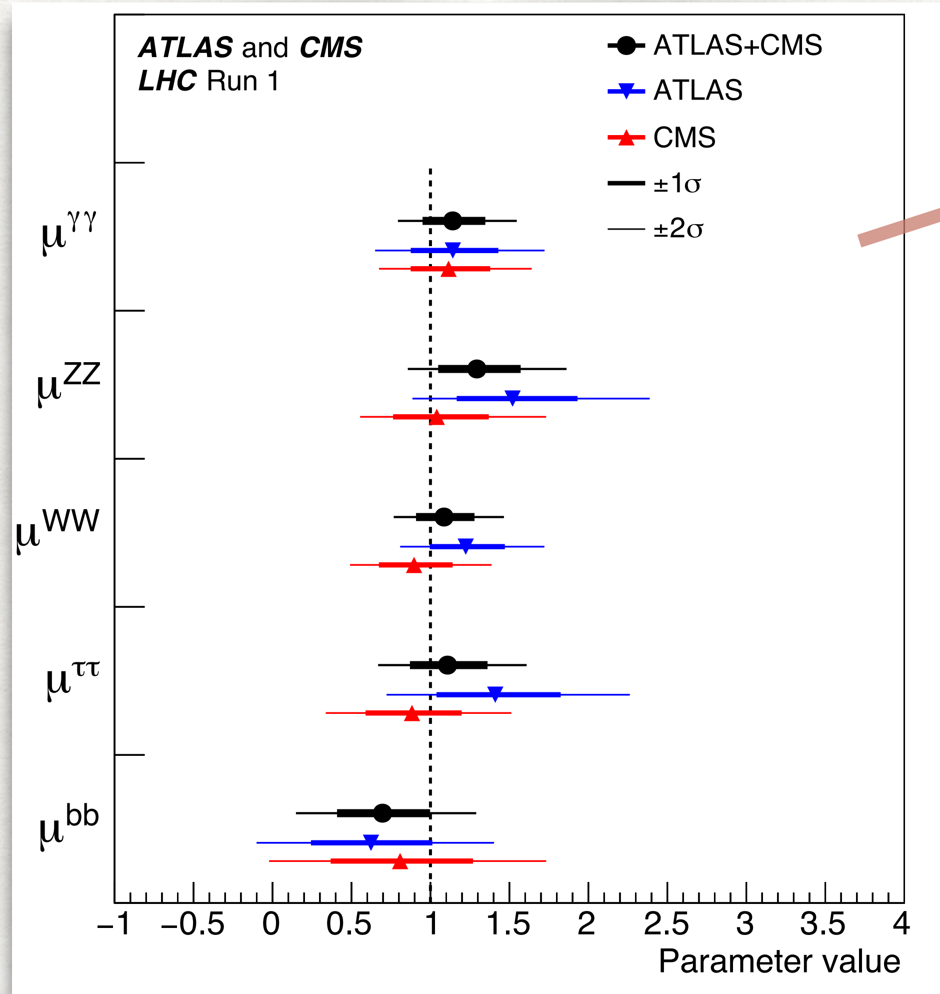
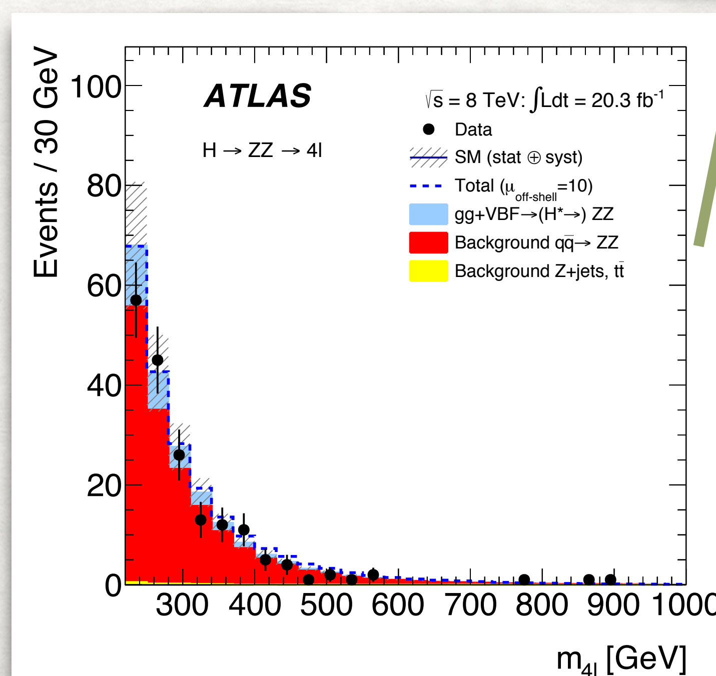



$H \to ZZ$: one of the best measured channels from Higgs discovery




Offer best sensitivity for Higgs off-shell signal to indirectly bound on the total width.

## Constraints on the off-shell Higgs boson signal strength in the high-mass $ZZ$ and $WW$ final states with the ATLAS detector

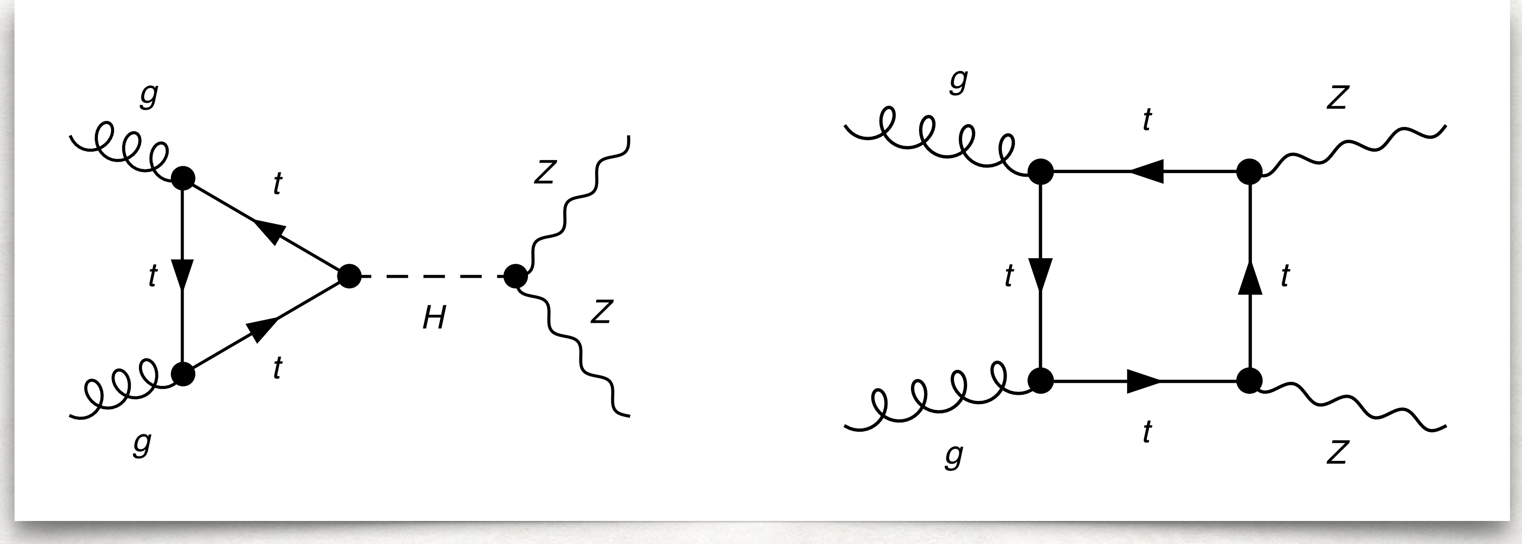
The ATLAS Collaboration

### Abstract

Measurements of the $ZZ$ and $WW$ final states in the mass range above the $2m_Z$ and $2m_W$ thresholds provide a unique opportunity to measure the off-shell coupling strength of the Higgs boson. This paper presents constraints on the off-shell Higgs boson event yields normalised to the Standard Model prediction (signal strength) in the $ZZ \to 4\ell$, $ZZ \to 2\ell 2\nu$ and $WW \to e\nu\mu\nu$ final states. The result is based on $pp$ collision data collected by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at a collision energy of $\sqrt{s}$ = 8 TeV. Using the $CL_s$ method, the observed 95% confidence level (CL) upper limit on the off-shell signal strength is in the range 5.1–8.6, with an expected range of 6.7–11.0. In each case the range is determined by varying the unknown $gg \to ZZ$ and $gg \to WW$ background K-factor from higher-order QCD corrections between half and twice the value of the known signal K-factor. Assuming the relevant Higgs boson couplings are independent of the energy scale of the Higgs production, a combination with the on-shell measurements yields an observed (expected) 95% CL upper limit on $\Gamma_H/\Gamma_H^{SM}$ in the range 4.5–7.5 (6.5–11.2) using the same variations of the background K-factor. Assuming that the unknown $gg \to VV$ background K-factor is equal to the signal K-factor, this translates into an observed (expected) 95% CL upper limit on the Higgs boson total width of 22.7 (33.0) MeV.

There is large cancelation between Higgs and box

# AMPLITUDE OF GG>ZZ



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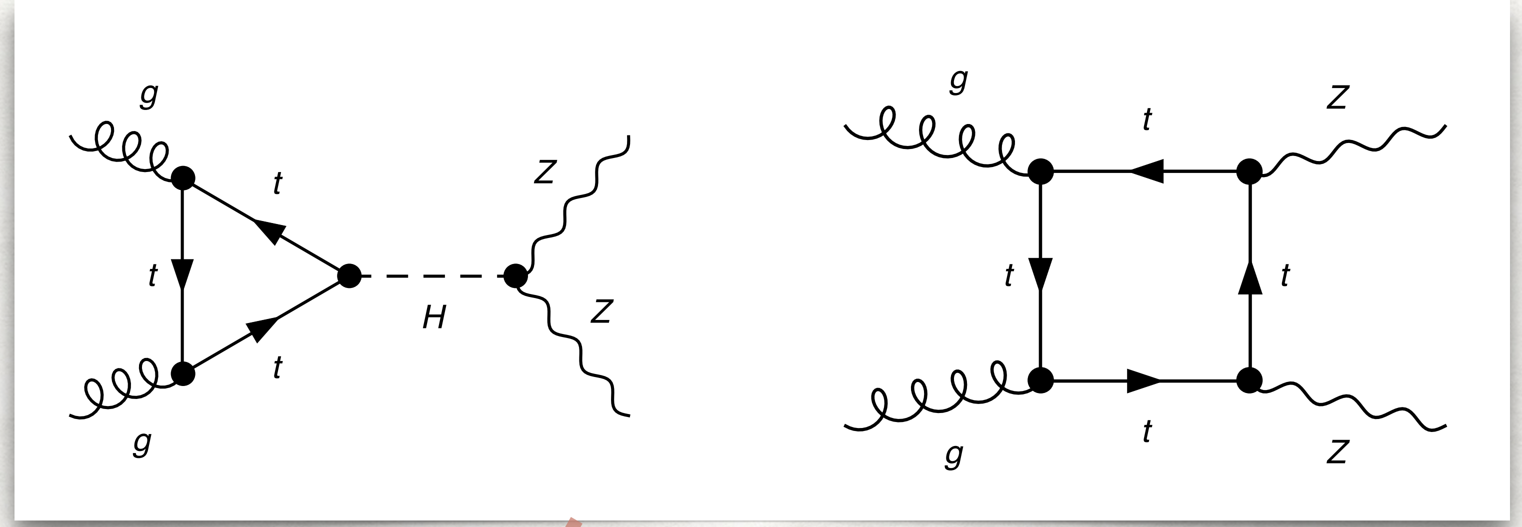

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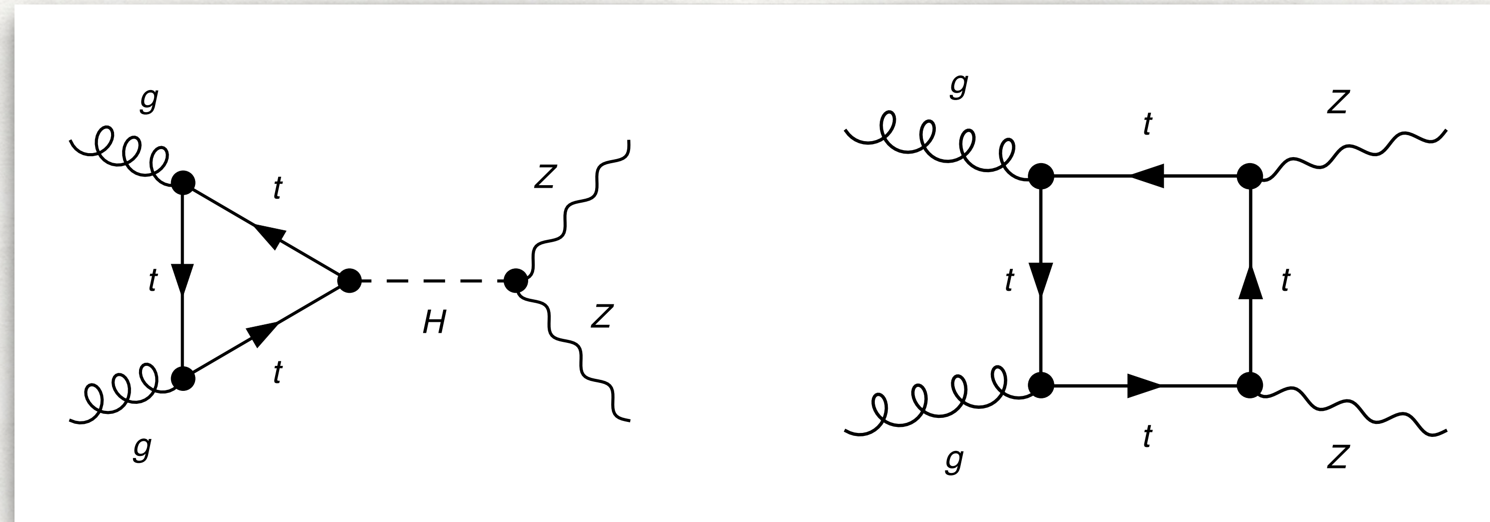

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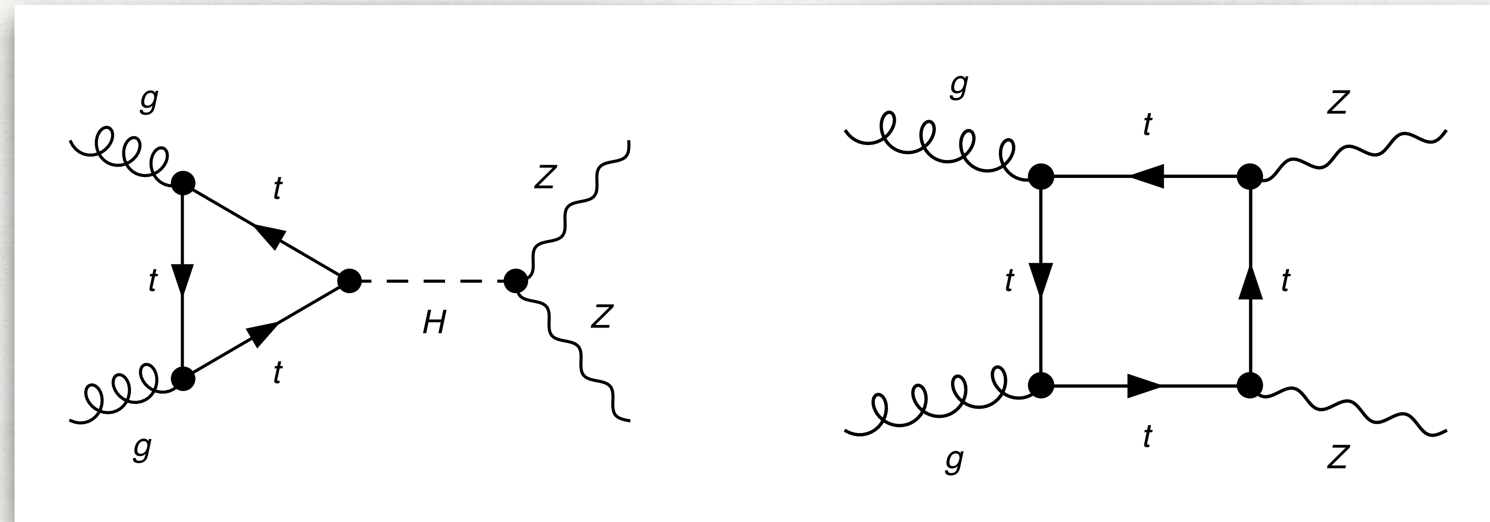


Example Feynman diagrams for $gg \to ZZ$ process.

There is large cancelation between Higgs and box

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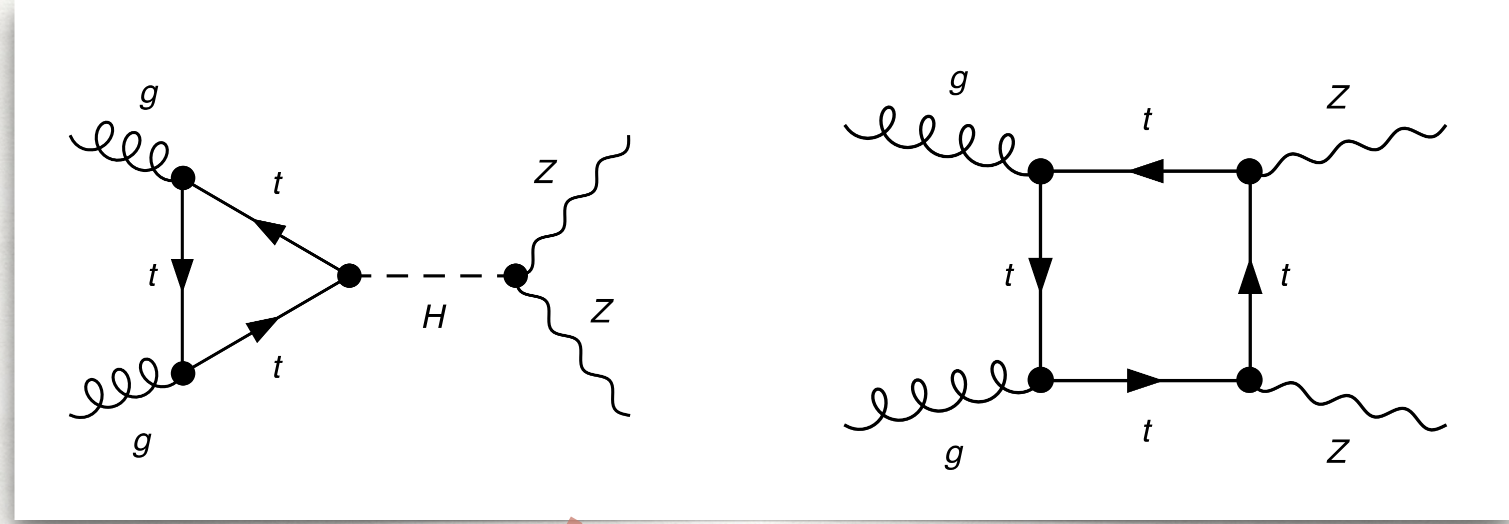


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$\sqrt{s} >> m_t$ limit

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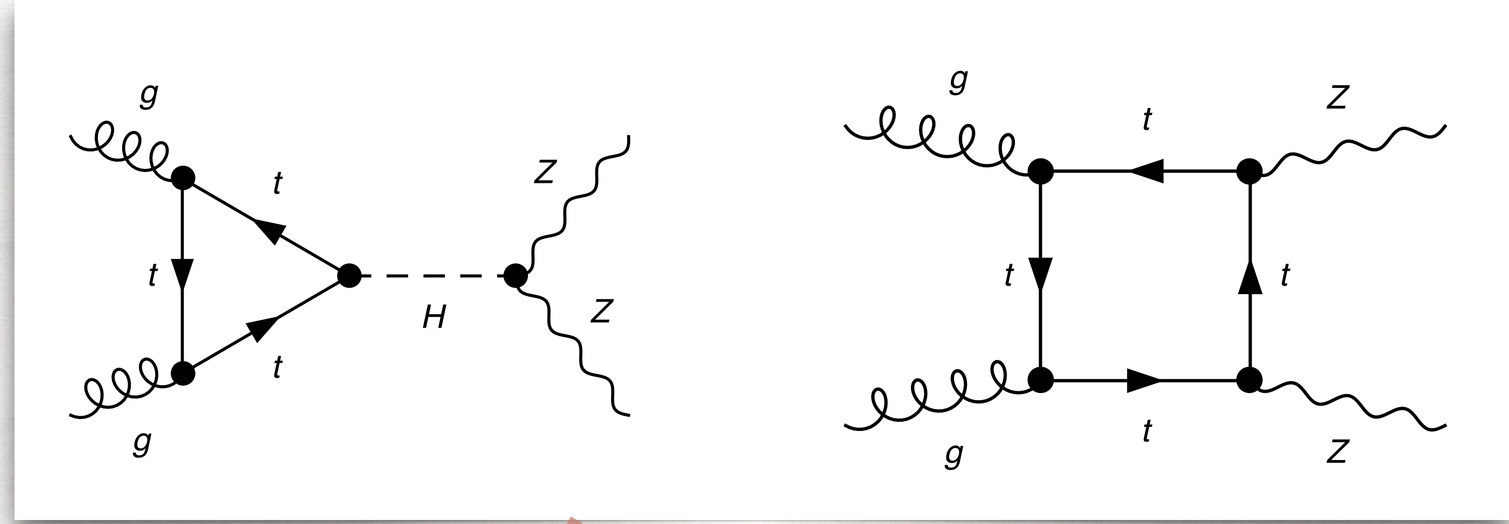


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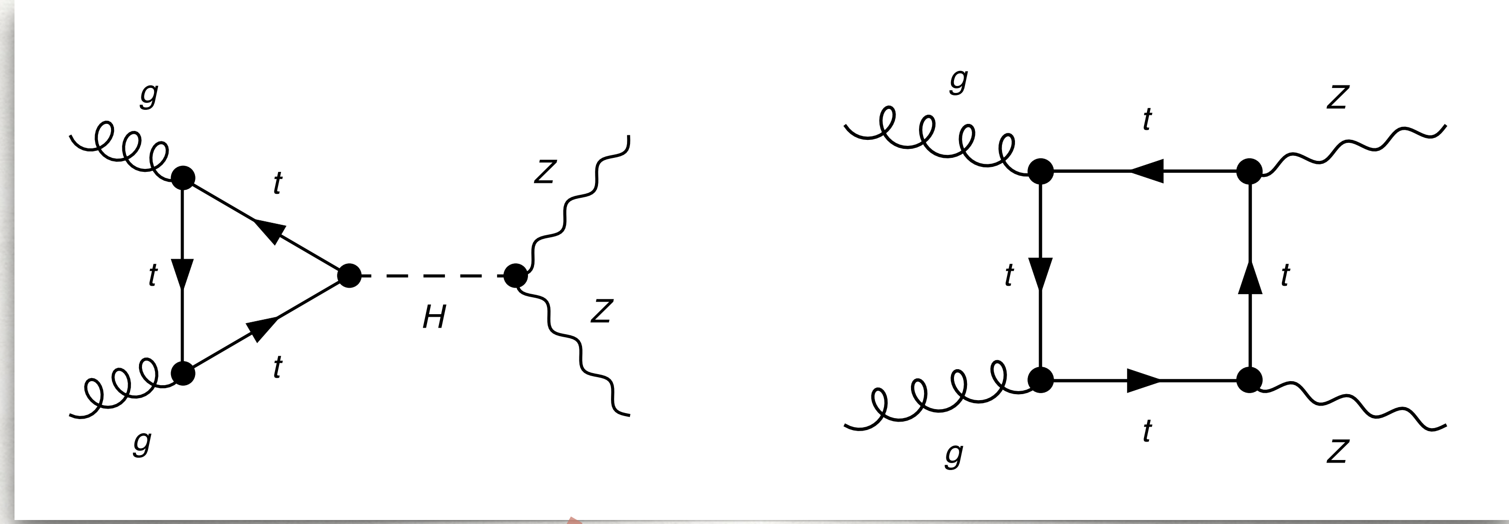
$\sqrt{s} >> m_t$ limit

$$\mathcal{A}^{gg\to Z_L Z_L(\text{box})} \Rightarrow -8C_A^2 \frac{m_q^2}{s} \frac{s}{m_Z^2} \log^2(s/m_t)$$
$$\sim -\log^2(s/m_t).$$

There is large cancelation between Higgs and box

# AMPLITUDE OF GG>ZZ

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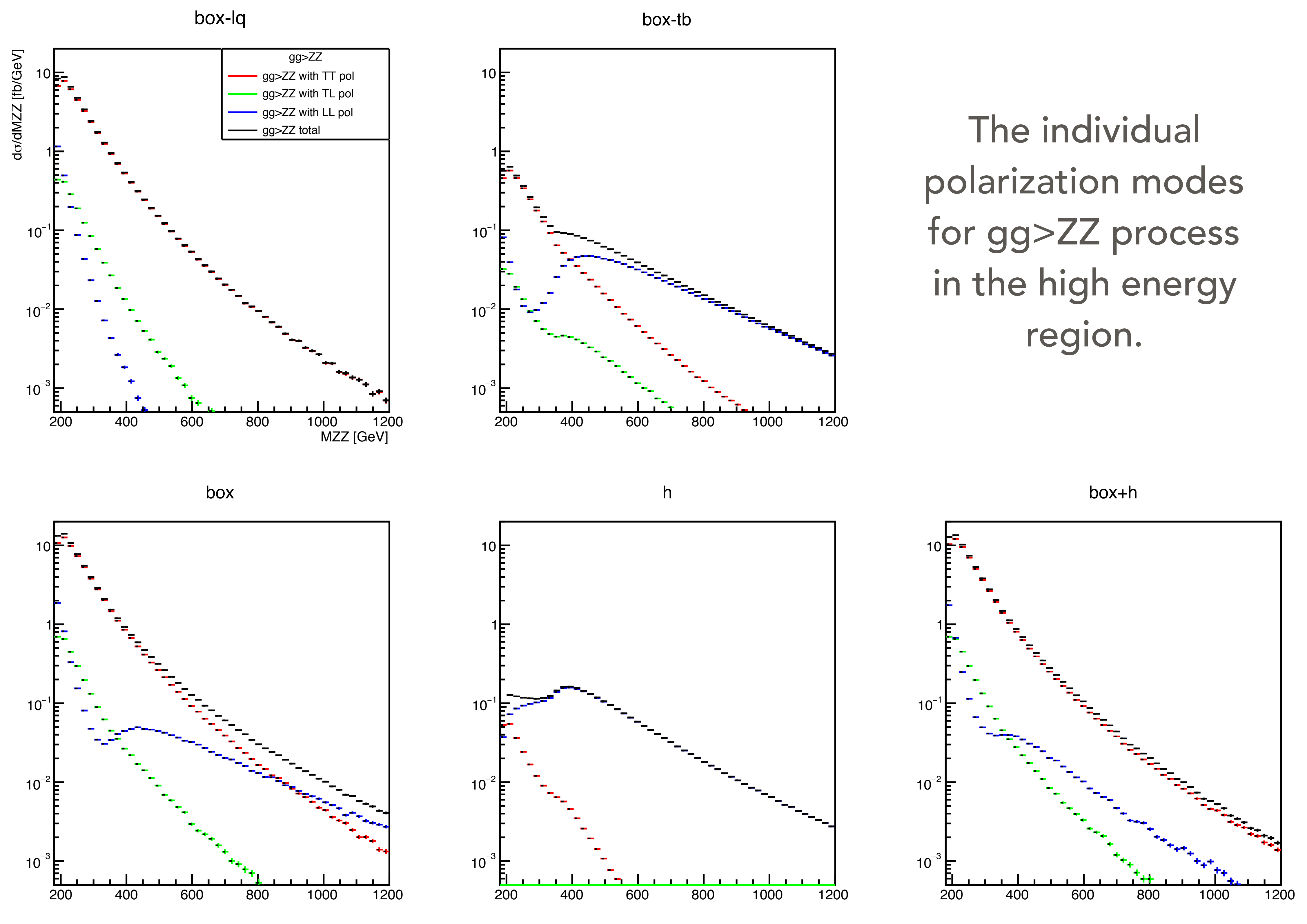
$$\mathcal{A}^{\rm gg\to h^*\to Z_L Z_L} \Rightarrow \frac{m_t^2}{s} \frac{1}{2} \log^2(\frac{m_t^2}{s})(\frac{\sqrt{s}}{m_Z})^2 \sim \log^2(s/m_t).$$

The large log-diverging term cancellation shown in distribution

# AMPLITUDE FOR GG>ZZ




The individual polarization modes for gg>ZZ process in the high energy region.

Class of NP model modify the scalar propagator -> a log-deviating term -> enhanced in LL mode

# AMPLITUDE FOR GG>ZZ

Many cases of NP in the Higgs sector generically modify the scalar propagator:

$$\mathcal{A}^{\mathrm{gg}\to\mathrm{h}^*\to\mathrm{ZZ}} \sim \frac{1}{s - m_h^2 + i\Gamma_h m_h} m_t^2 \left(-2 + (s - 4m_t^2) C_0(s, 0, 0, m_t^2, m_t^2, m_t^2)\right) \epsilon^{\mu}_{\lambda_1} \epsilon_{\lambda_2,\mu}.$$

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The $\epsilon^{\mu}_{\lambda_1}\epsilon_{\lambda_2,\mu}$ term dictates the polarization of the final state Z's, which is dominated by the rising LL mode from $\epsilon_L \sim \frac{E_Z}{m_Z}$ as the energy grows

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The modification of the scalar propagator'll deviate the exact cancellation of the $\log(s/m_t^2)$ term between the Higgs and the box contribution (SM), and reveals the high energy scale diverging behavior in the LL mode.

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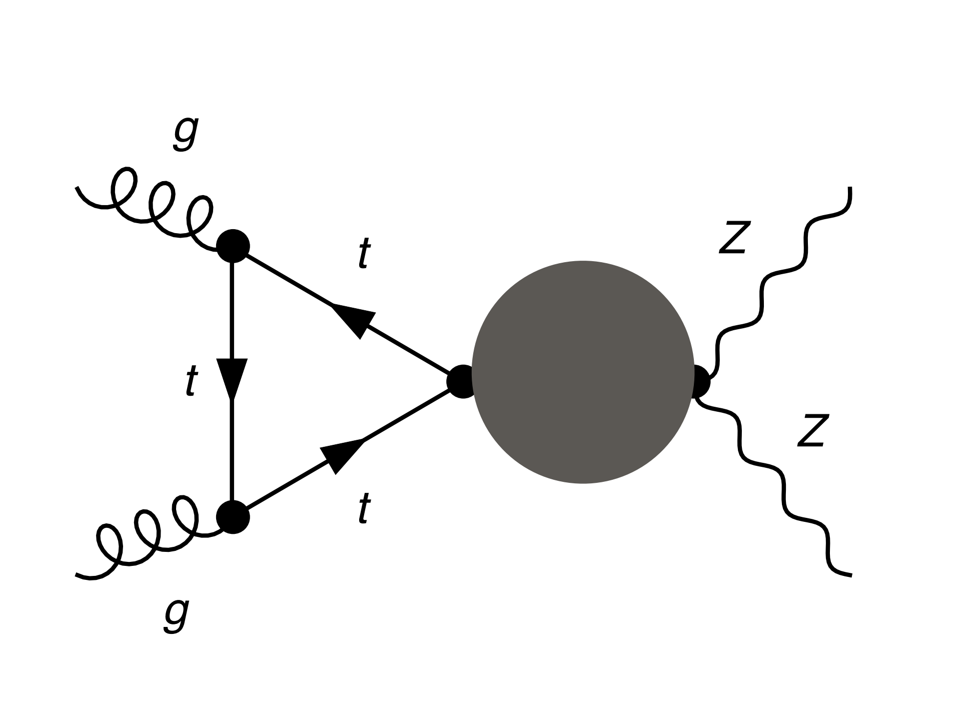


## HIGGS SECTOR NEW PHYSICS OF THE TYPE:

# CASE A: LIGHT SCALAR

We take an example of a complex scalar in the Higgs sector, with mass 80 GeV:

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

With the additional scalar with zero vev, larger than mh/2, the scenario difficult to probe except for at a  lepton collider, but as shown in 1710.02149, deviation would shown through high energy tail of gg->ZZ:

$$\text{Propagator} = \frac{i}{p^2 - m_h^2 + i\Gamma_h m_h - i\hat{\Sigma}_h(p^2)}$$

$\hat{\Sigma}_h(s)$ is the one-loop renormalized two point function of the Higgs propagator

# CASE A: LIGHT SCALAR

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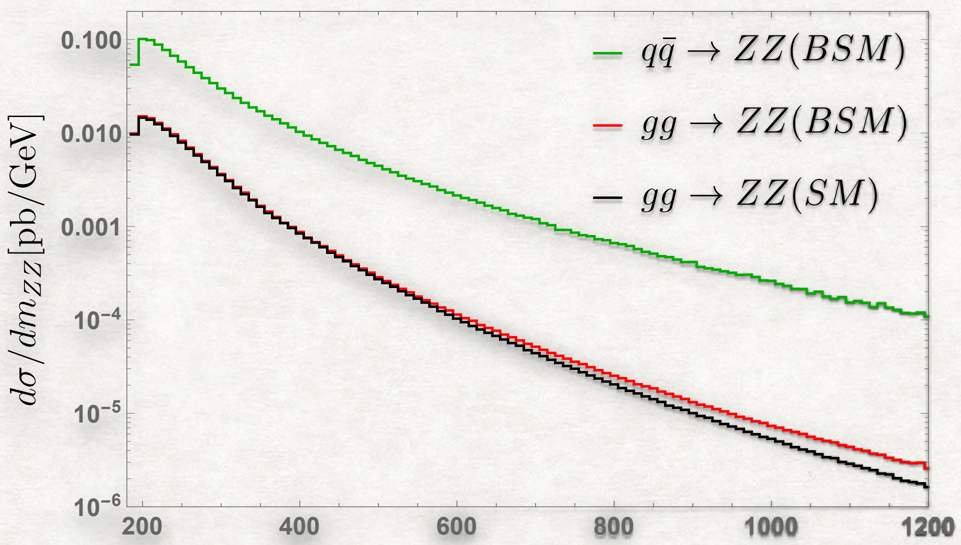
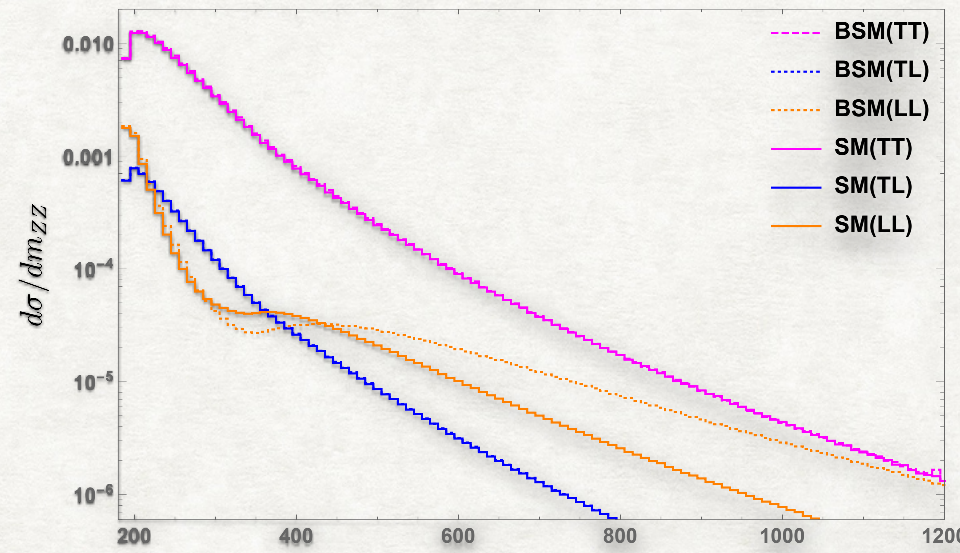
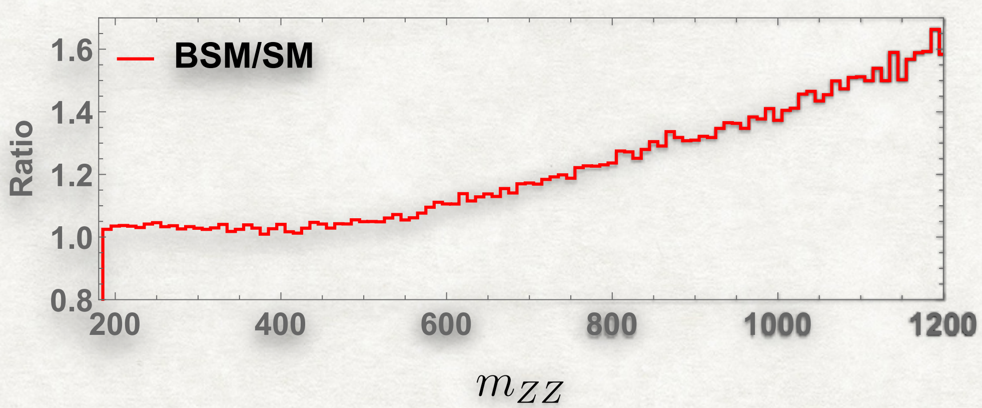
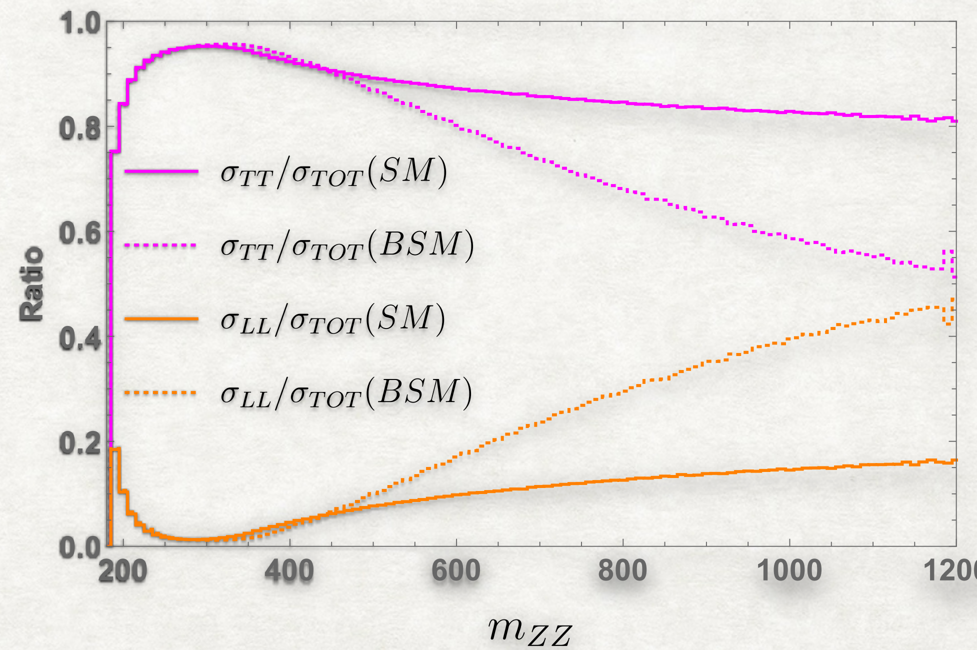


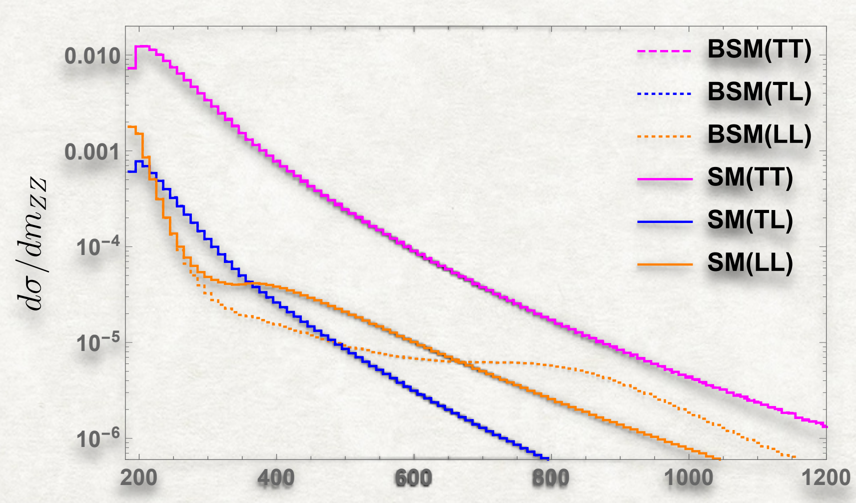
# CASE B: BROAD-WIDTH HEAVY SCALAR

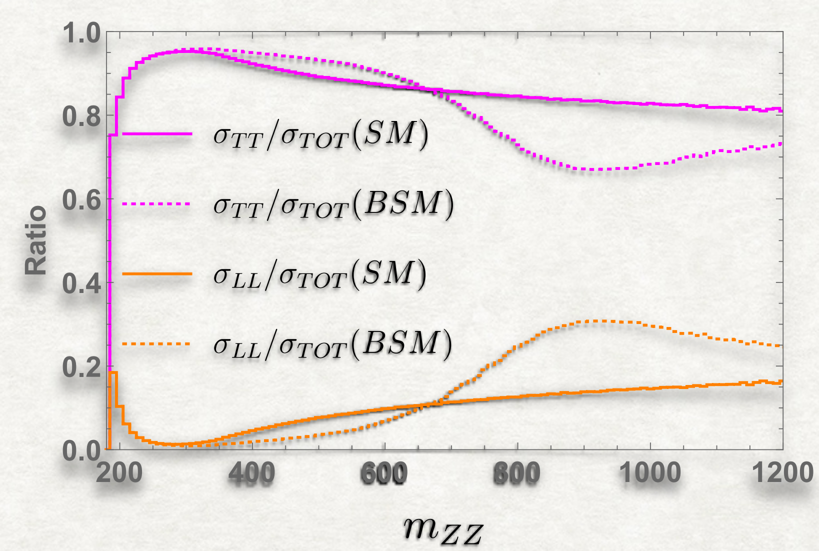
$\mathcal{L} \supset \mathcal{L}_{\text{SM}} - \mu_S S|\Phi|^2$ $\qquad H = \sin\theta \ S^{\text{phy}} + \cos\theta \ H^{\text{pay}}$

$$\tan\theta = \frac{\mu_S v}{\sqrt{(\mu_S v)^2 + (m_S^2 - m_H^2)^2}} \quad (m_S^2 \gg m_H^2) \quad \sim \mu_S v / m_S^2$$

$$\text{Propagator} = \frac{i\cos\theta^2}{p^2 - m_h^2} + \frac{i\sin\theta^2}{p^2 - m_S^2}$$

$M_S = 800$ GeV and $\cos\alpha = 0.4$ $\qquad \Gamma_S = 400$



QCH case shows a sudden enhance in LL  mode above continuum scale

# CASE C: QUANTUM CRITICAL HIGGS

Quantum Critical Higgs predict a higher scale continuum in the scalar sector. The scalar evolves with a different anomalous dimension above some continuum scale. We consider here a minimal scenario where:

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$$G_h(p) = -\frac{iZ_h}{(\mu^2 - p^2 - i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}$$

$$g_{hZZ} = -\frac{(\mu^2)^{2-\Delta} - (\mu^2 - p^2)^{2-\Delta}}{s} g_{hZZ}^{\mathrm{SM}}$$

$$\mu = 400 \text{ GeV}, \quad \Delta = 1.6$$

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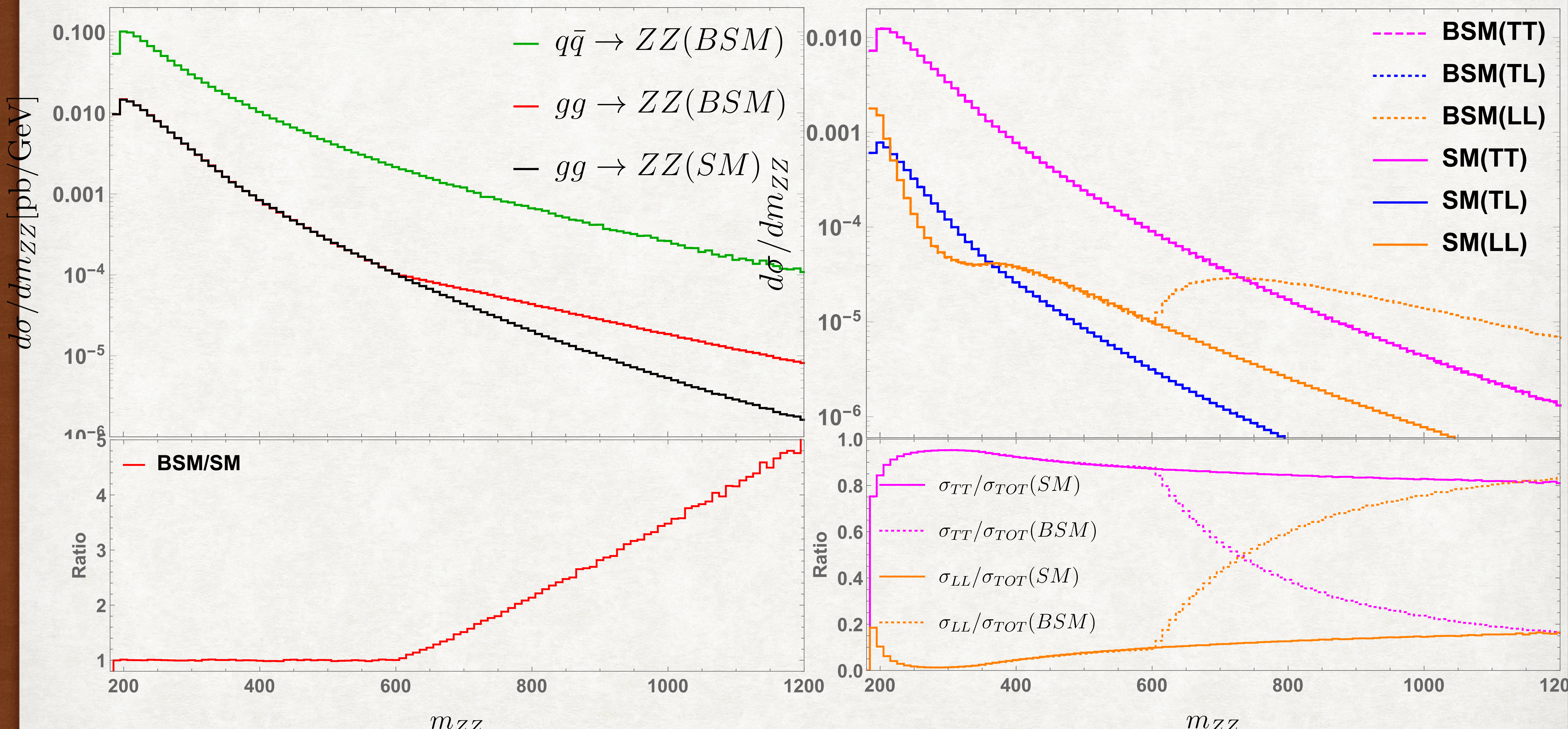

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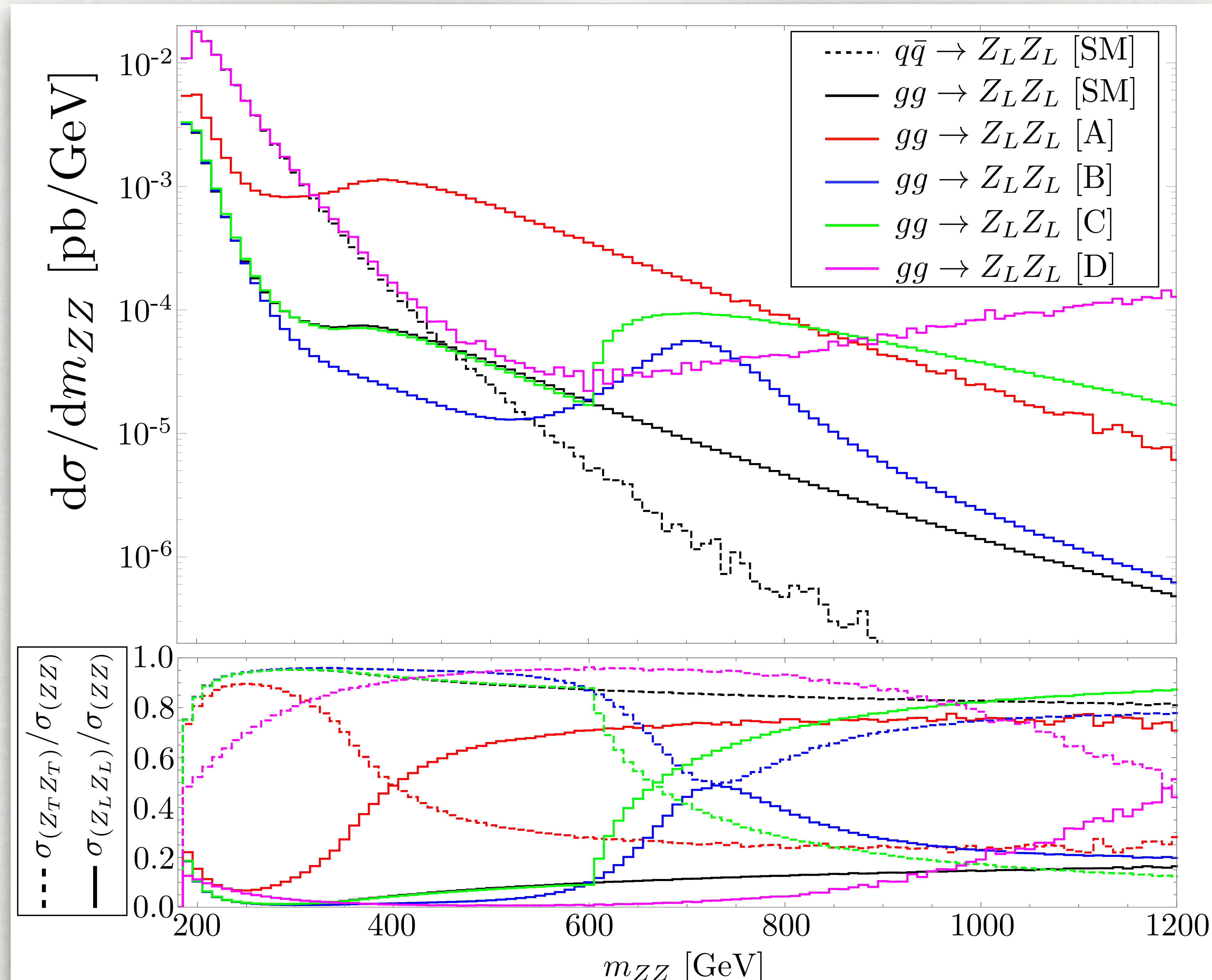
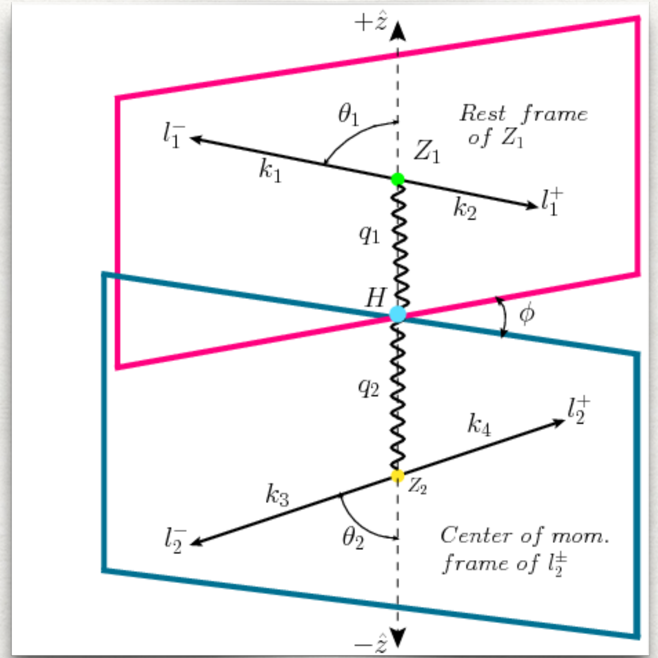


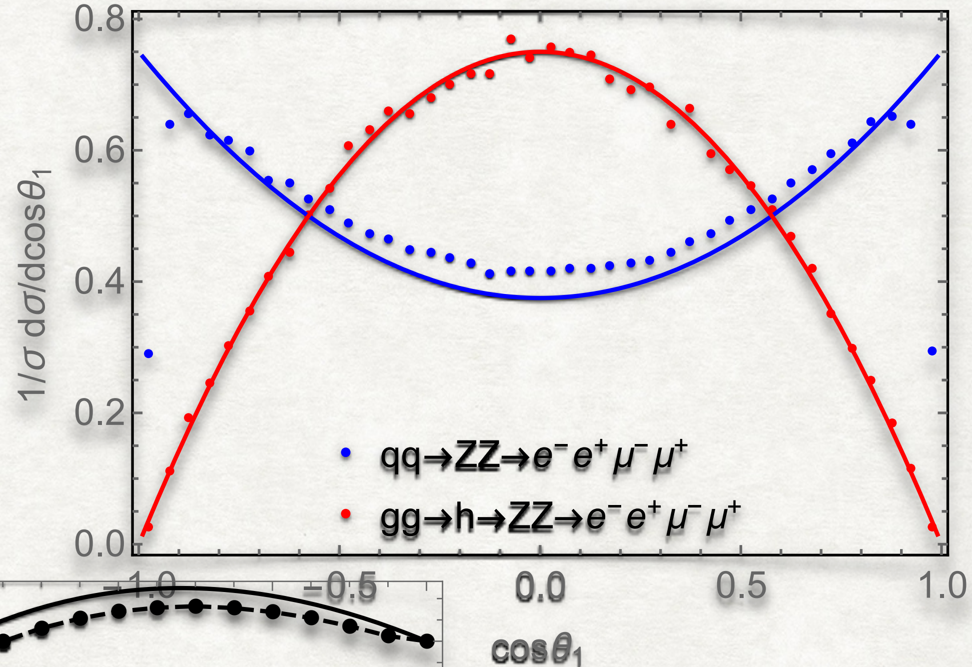
# DISCRIMINANT AND ANALYSIS




Z Polarization ⟷ Angle $\cos\theta$ dist. from decay

$$\text{Transverse}: \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta)$$

$$\text{Longitudinal}: \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{4}(1-\cos^2\theta)$$



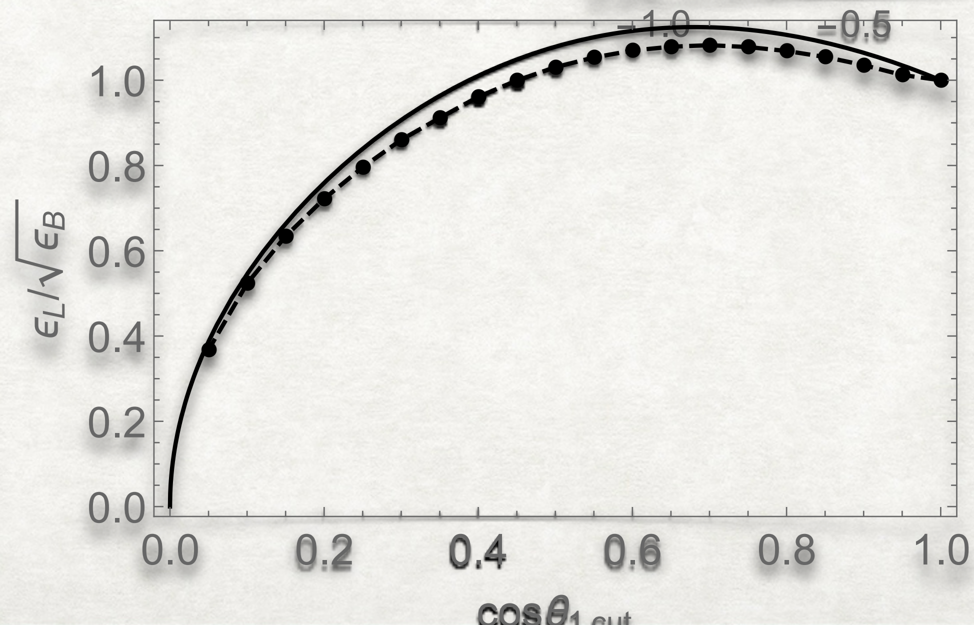

To optimize the longitudinal over transverse mode significance:

$$-0.68 < \cos\theta < 0.68$$

$$\cos\theta_C = 0.68$$

$$\{\epsilon_L,\ \epsilon_T\} = 86\%,\ 59\%$$

$$\text{Significance}: \quad \frac{\mathcal{S}_{\rm cut}}{\mathcal{S}_{\rm no\ cut}} \sim 1.12$$



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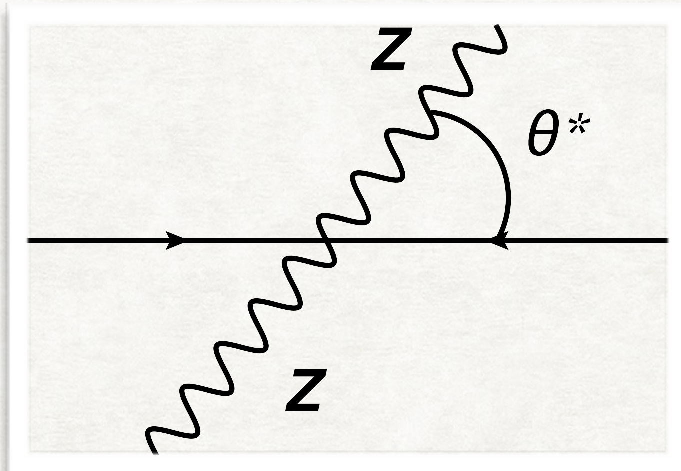
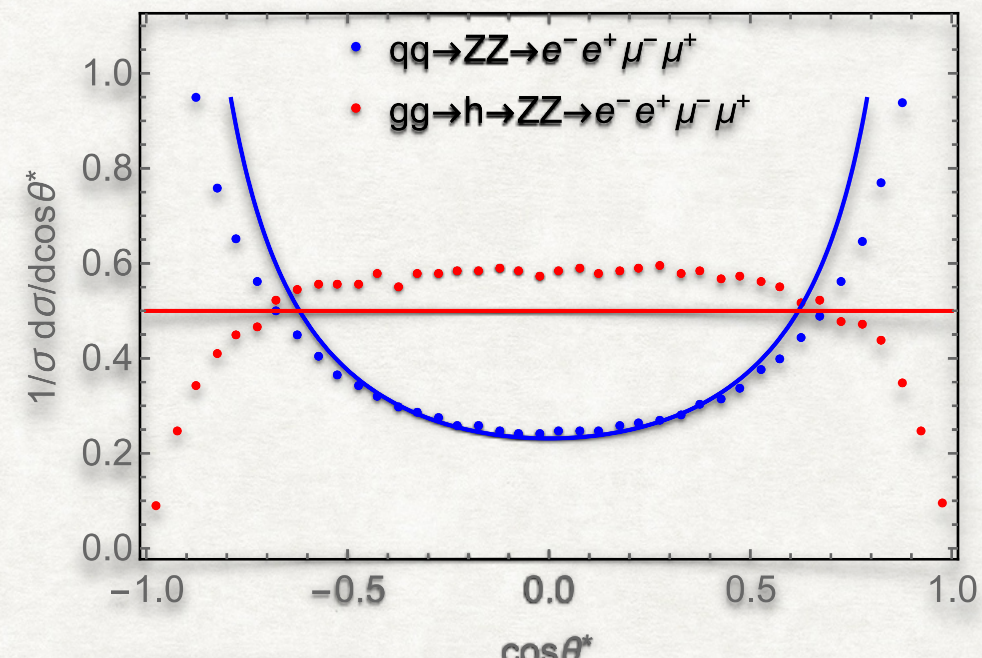



"center of mass rest frame"

$$qq \to ZZ: \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} \propto \frac{\cos^2\theta^* + 1}{\cos^2\theta^* - 1} + \mathcal{O}(\frac{m_Z^2}{s})$$

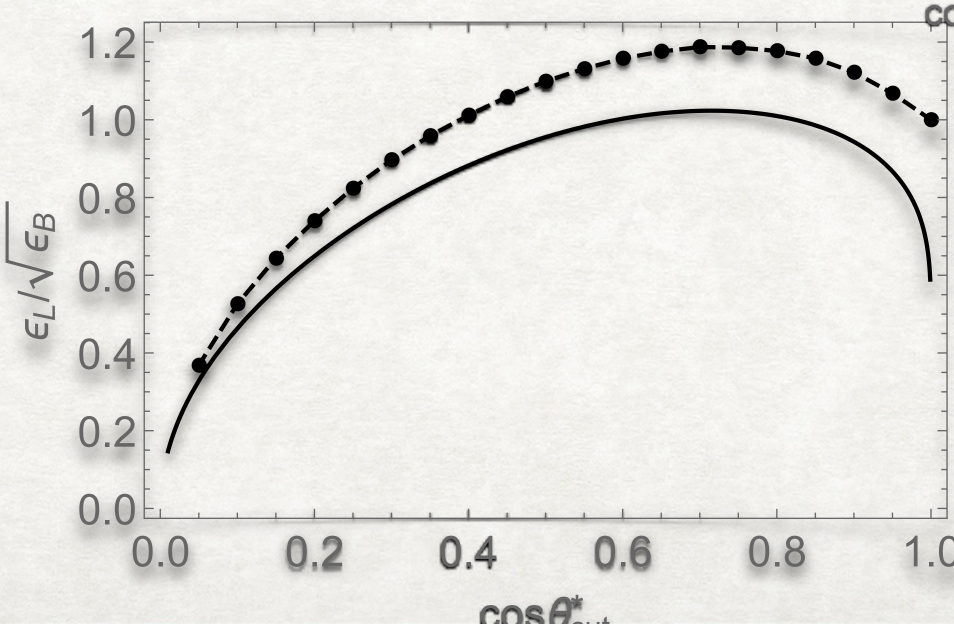
$$gg \to h \to ZZ: \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \text{constant}, \quad \text{“}s\text{−channel scalar”}$$

To optimize over the qq background:



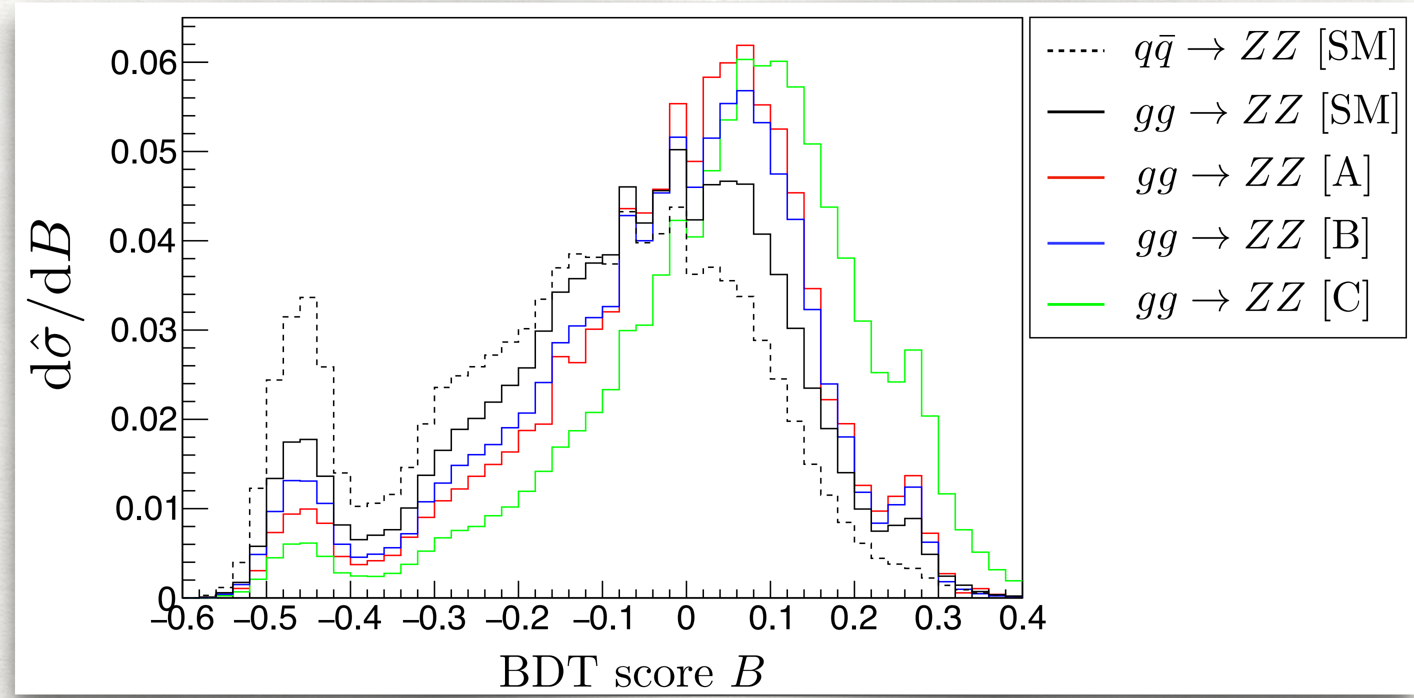

$$\cos\theta^* < 0.7$$

$$\text{Significance}: \quad \frac{\mathcal{S}_{\text{cut}}}{\mathcal{S}_{\text{no cut}}} \sim 1.2$$



# RESULTS

1. For further qq>ZZ reduction: A trained BDT variable optimizing gg>h*>ZZ




2. Final sensitivity:

| | | | |
|---|---|---|---|
| Sig (basic cuts11) | 2.01 | 0.634 | 4.71 |
| Sig (basic+angle cuts13) | 2.32 | 0.838 | 5.78 |
| Sig (basic+BDT cut) | 2.45 | 0.92 | 7.01 |
| Lumi needed for $3\sigma$ | $4.2\mathrm{ab}^{-1}$ | $29\mathrm{ab}^{-1}$ | $0.5\mathrm{ab}^{-1}$ |

* Additional channels $V_LV_L$, $V_LH$ improve sensitivity to the same physics
* Once NP identified, energy-dependence to distinguish among cases

# THANKS!