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

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Zhuoni Qian (CTPU-IBS, South Korea)

기초과학연구원
Institute for Basic Science

In Collaboration with Seung Joon Lee (Korea Univeristy), Myeonghun Park(Seoul Tech)

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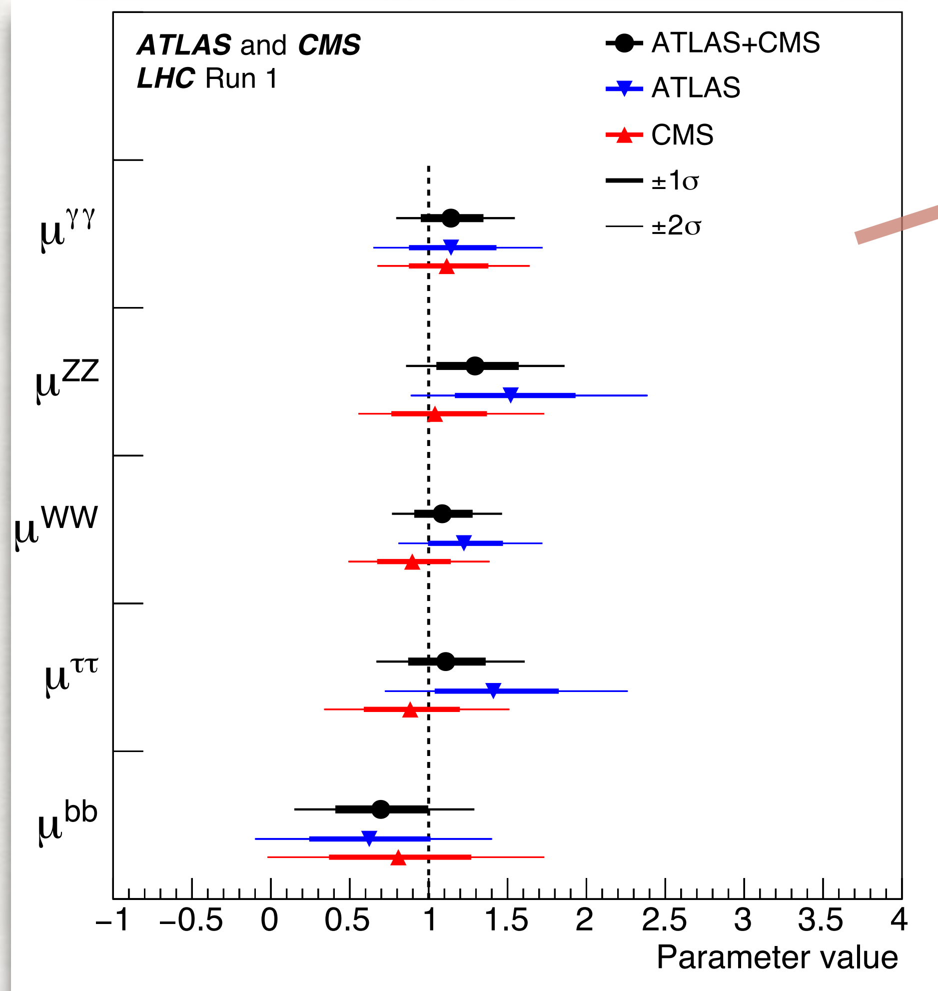
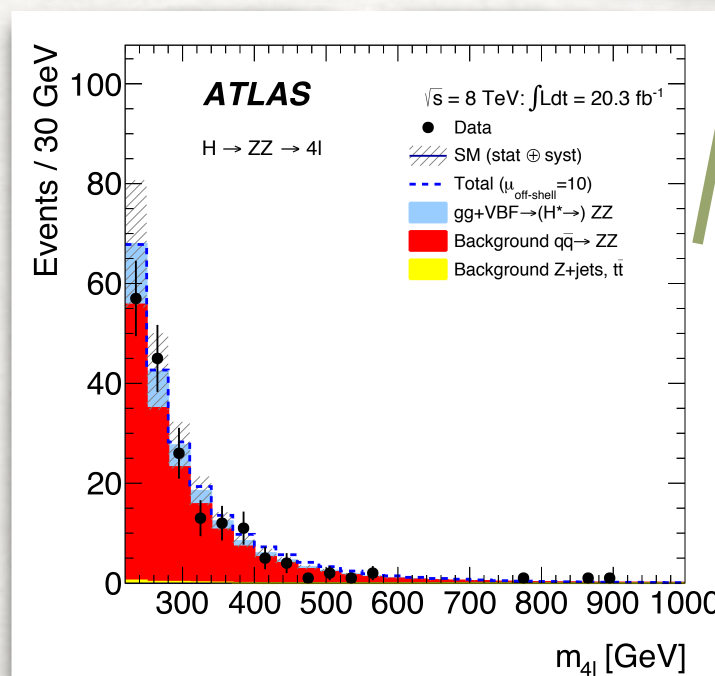


$H \to ZZ$: one of the best measured channels from Higgs discovery

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 Γ_H/Γ_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

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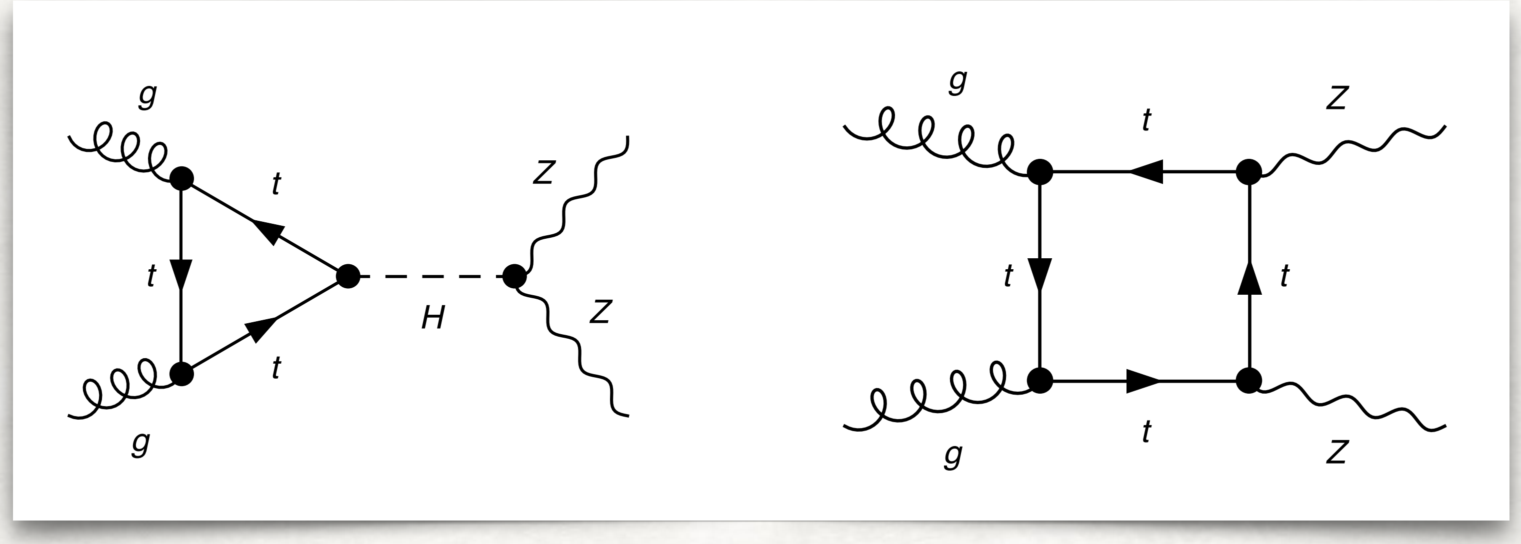

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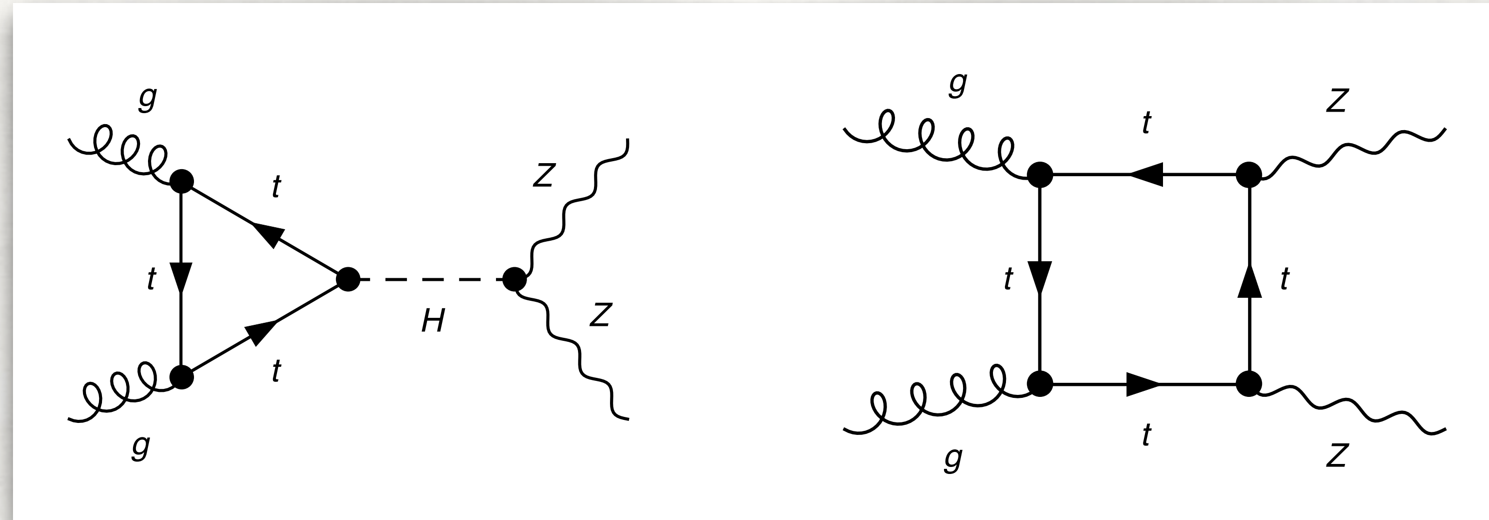

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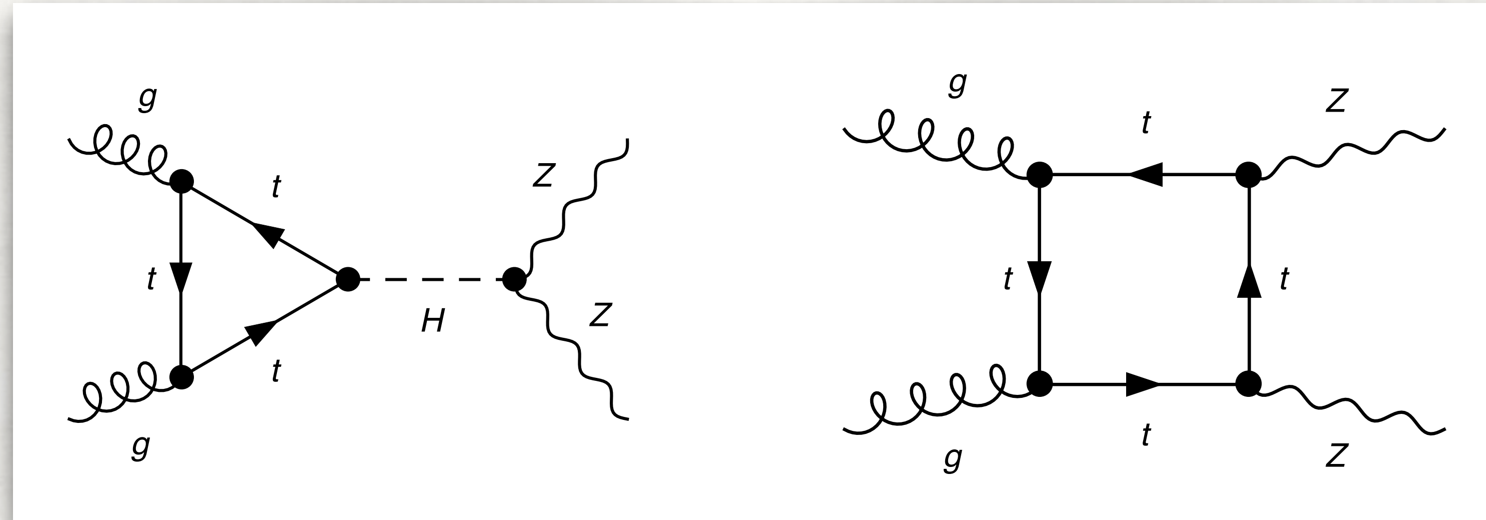

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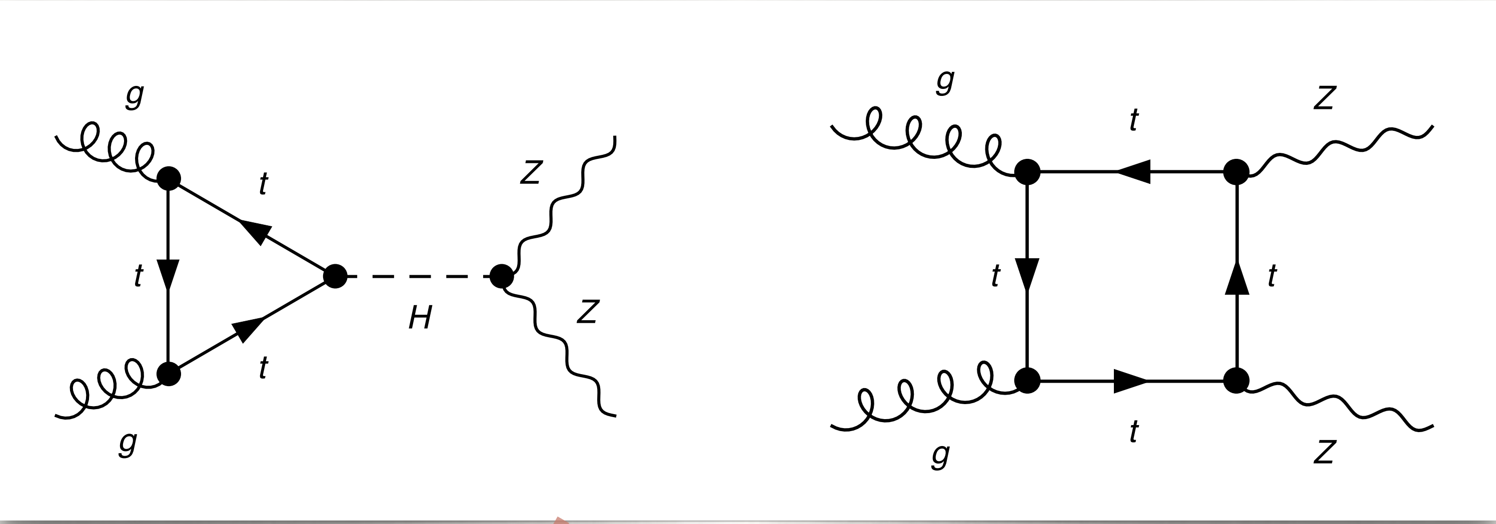

Example Feynman diagrams for $gg \to ZZ$ process.

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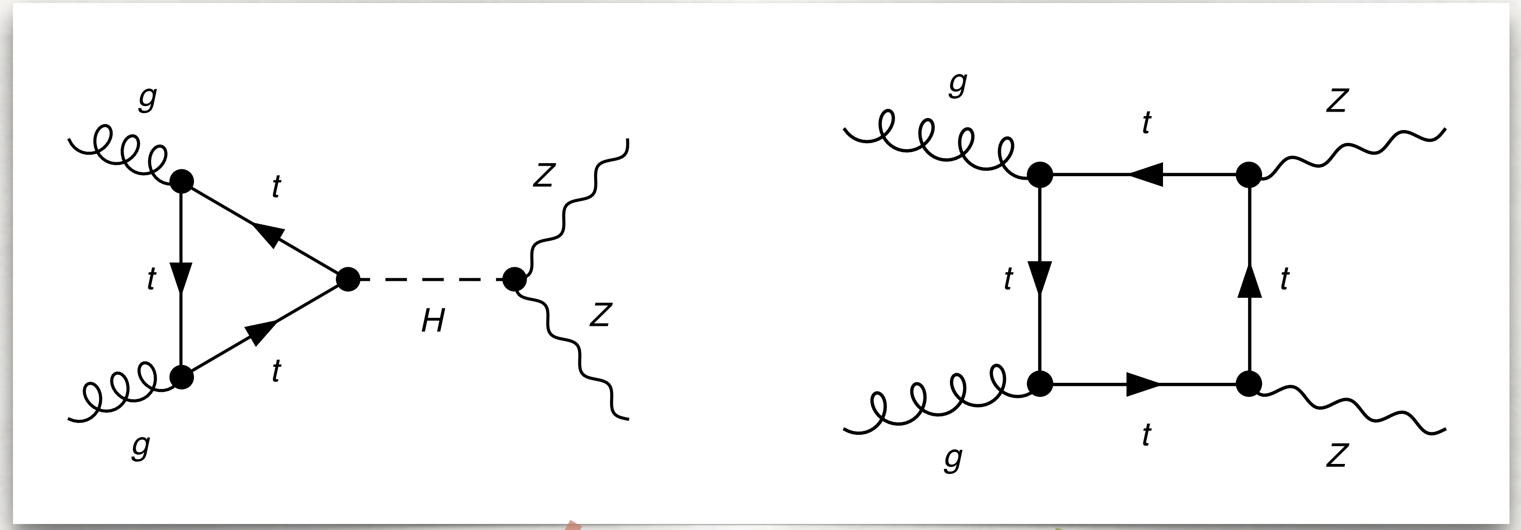

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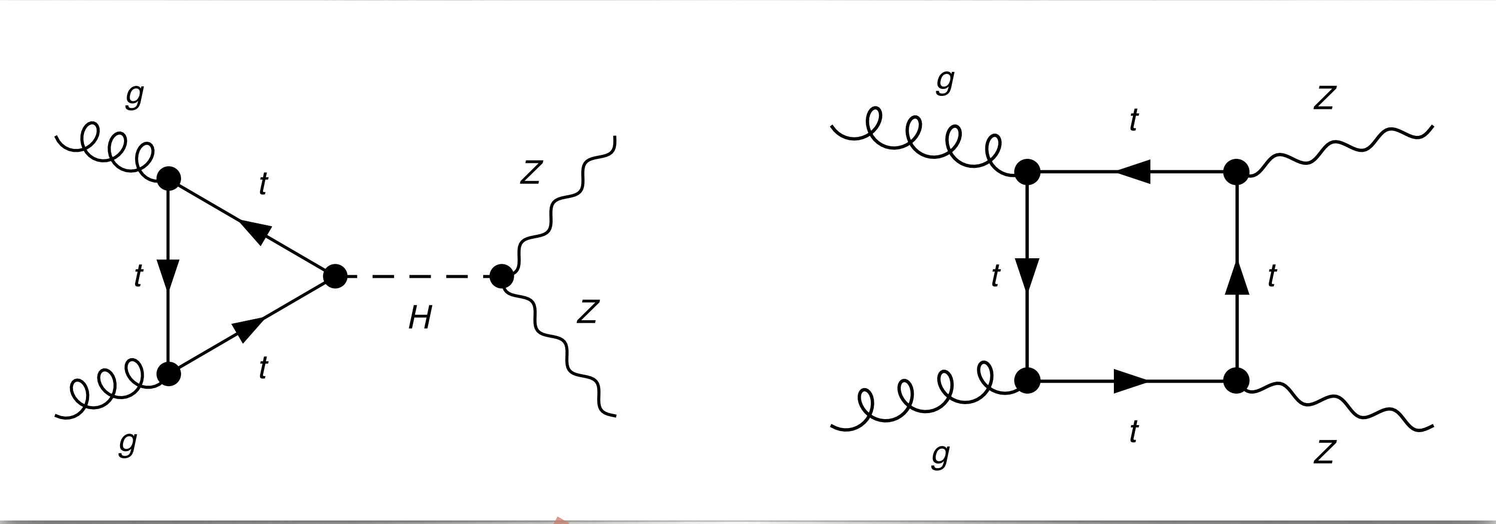

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$$\mathcal{A}^{gg\to Z_L Z_L(\text{box})} \Rightarrow -8C_A^2 \frac{m_q^2}{s} \frac{s}{m_Z^2} \log^2(s/m_t)$$
$$\sim -\log^2(s/m_t).$$

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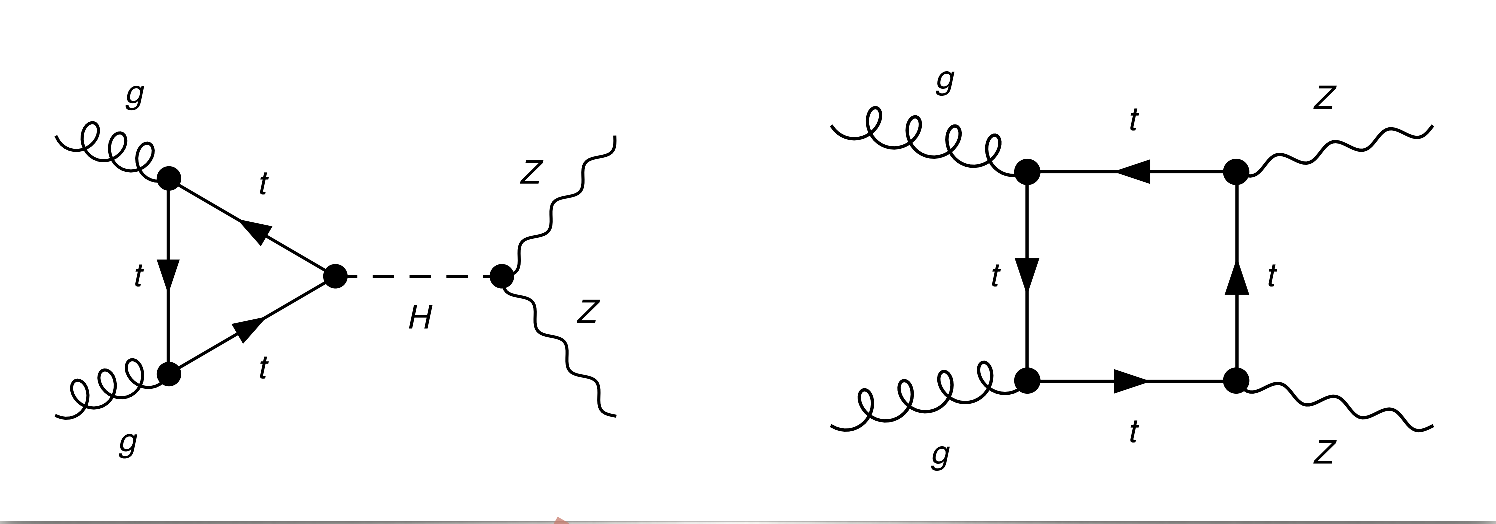

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$$\mathcal{A}^{\mathrm{gg \to h^* \to Z_L Z_L}} \Rightarrow \frac{m_t^2}{s} \frac{1}{2} \log^2(\frac{m_t^2}{s})(\frac{\sqrt{s}}{m_Z})^2 \sim \log^2(s/m_t).$$

The large log-diverging term cancellation shown in distribution

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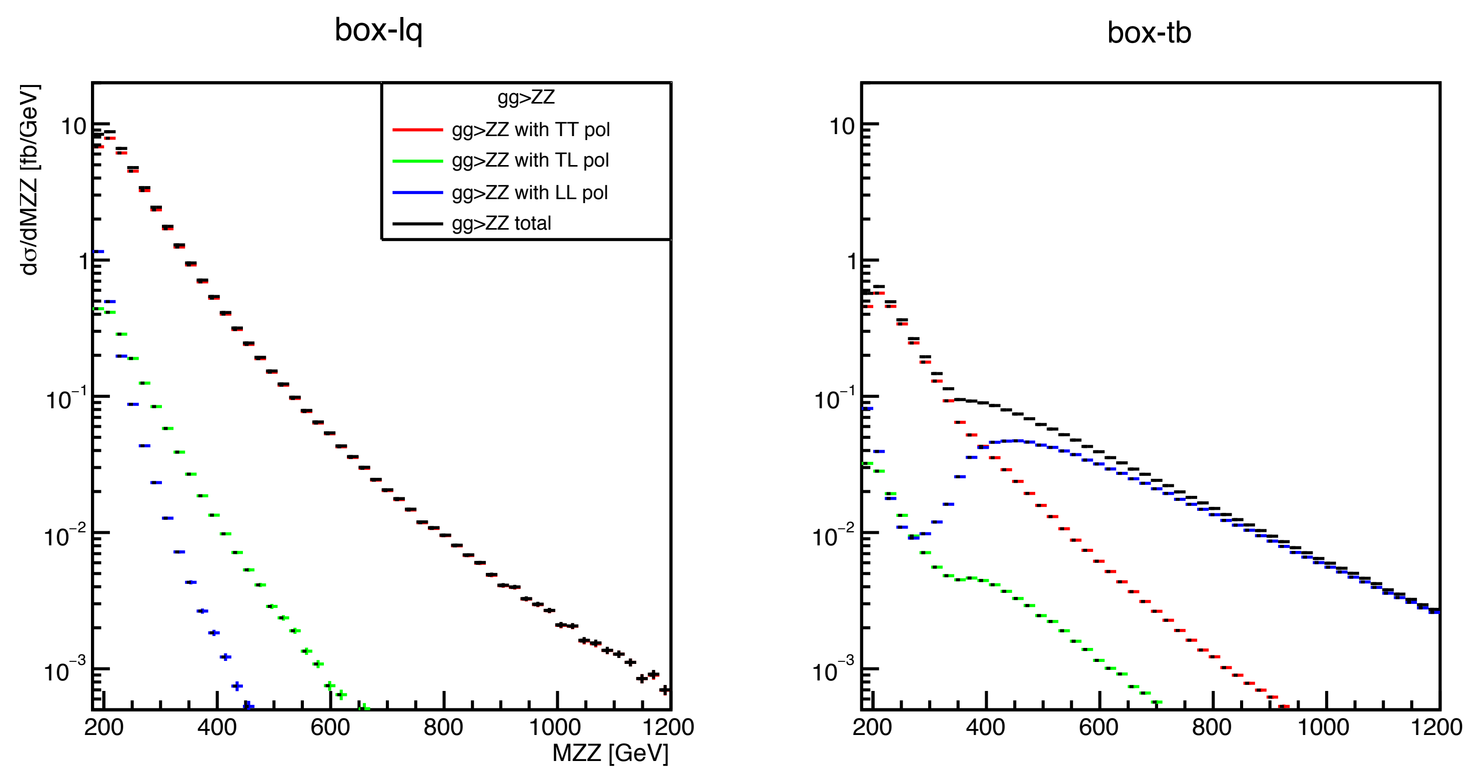
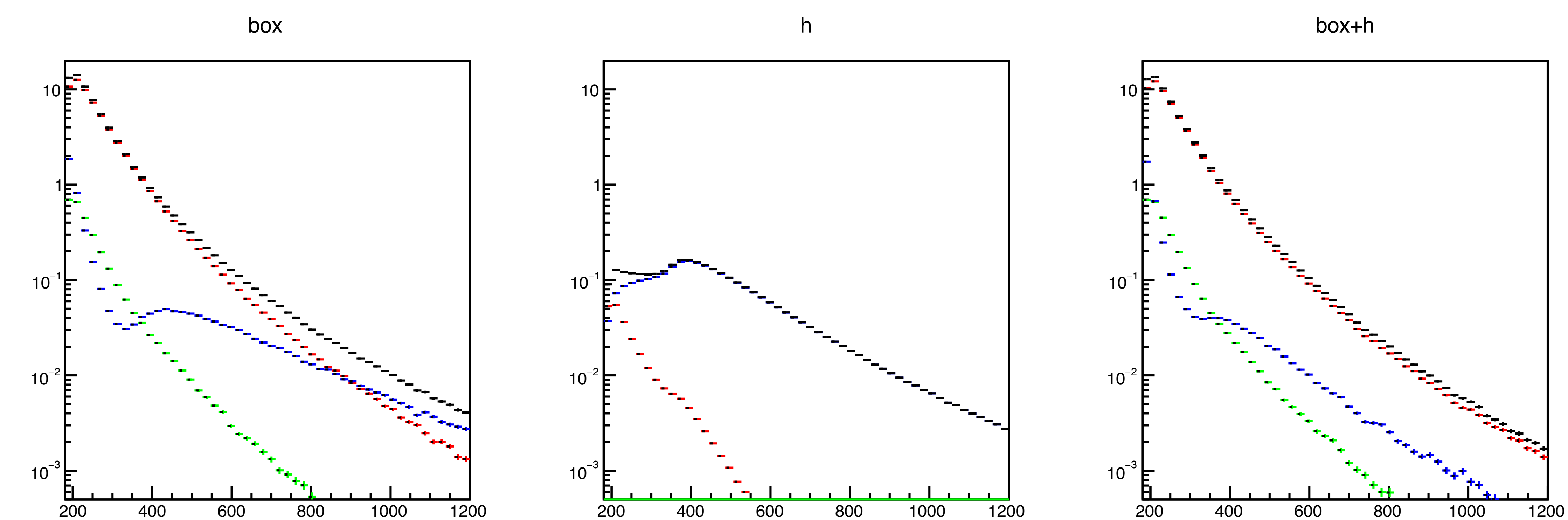


The individual polarization modes for gg>ZZ process in the high energy region.



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

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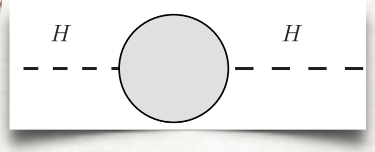
Many cases of NP in the Higgs sector generically modify the scalar propagator:

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



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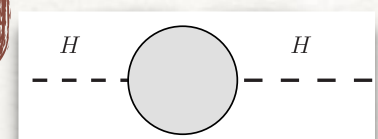

The $\epsilon^{\mu}_{\lambda_1}\epsilon_{\lambda_2,\mu}$ term dictate the polarization of the final state Z's, which is dominated by the rising LL mode from $\epsilon_L \sim \frac{E_Z}{m_Z}$ as the energy grows

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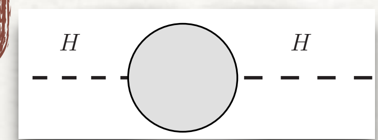

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The modification of the scalar propagator destroys the exact cancellation of the $\log(s/m_t^2)$ term between the Higgs and the box contribution (SM), and reveals the high energy scale diverging behavior in the LL mode.

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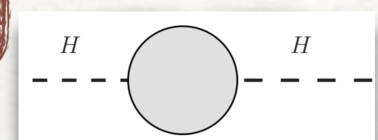

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* Additional form factor such as dim-6 operator $|\Phi|^2 Z_{\mu\nu} Z^{\mu\nu}$ would change the Lorentz structure of the HZZ coupling. The general form $p_\mu p_\nu$ and $\epsilon_{\mu\nu\rho\sigma} p_\rho p_\sigma$
* could be independently probed by energy dependence and CPV angle distribution. So we can leave these further complication to future discussion.

CASE A: LIGHT SCALAR

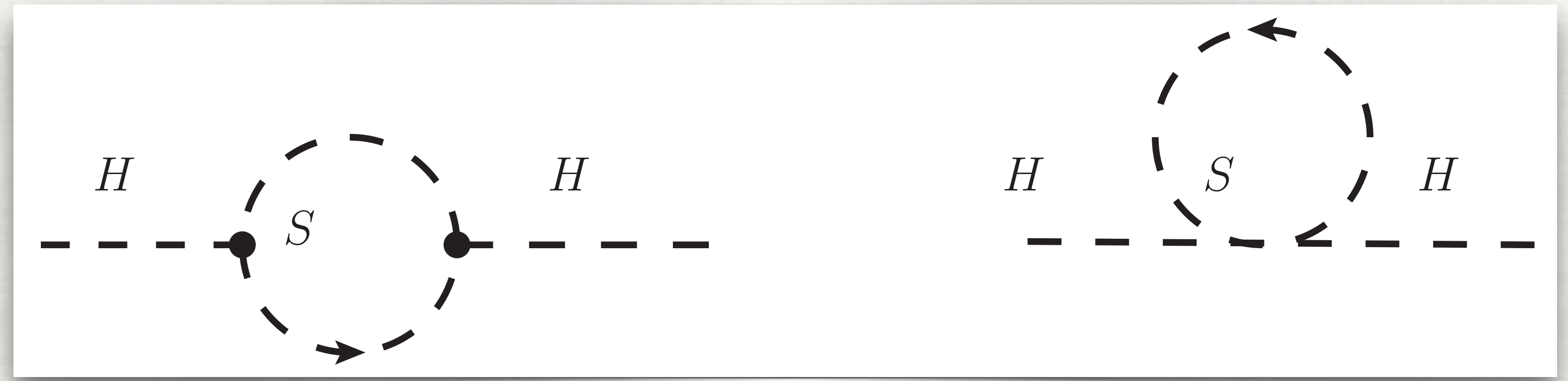
We take an example of a complex scalar in the Higgs sector, with mass 80 GeV:

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

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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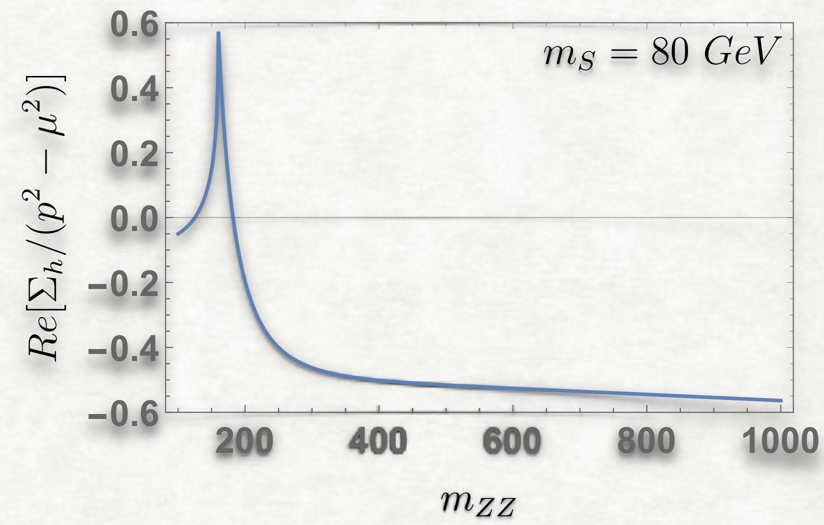
$$\kappa = 4,\ \mu^2 \to \text{large enough},\ m_S = 80\ \text{GeV}$$



The real part corresponds to when S in the loop gets on shell, which does not vanish as energy rises.

→

ANGULAR SHIFT IN THE COMPLEX AMPLITUDE

NON-CANCELLATION OF THE LOG-TERM

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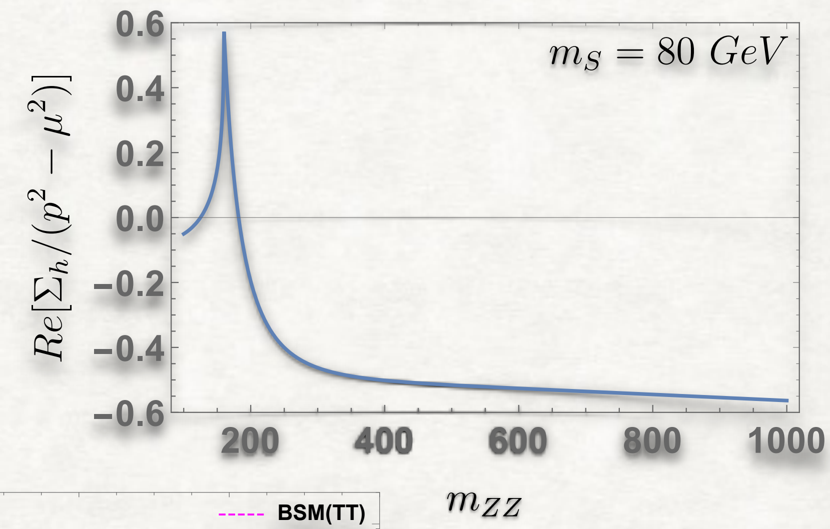

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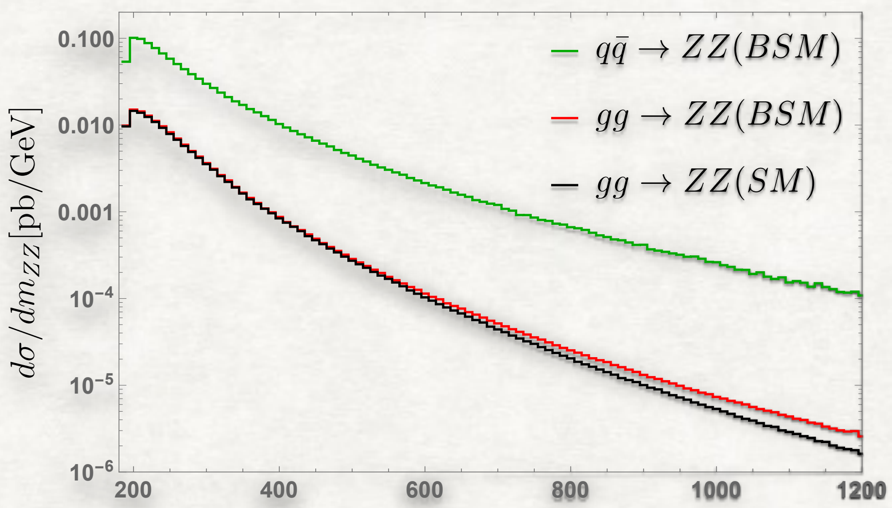
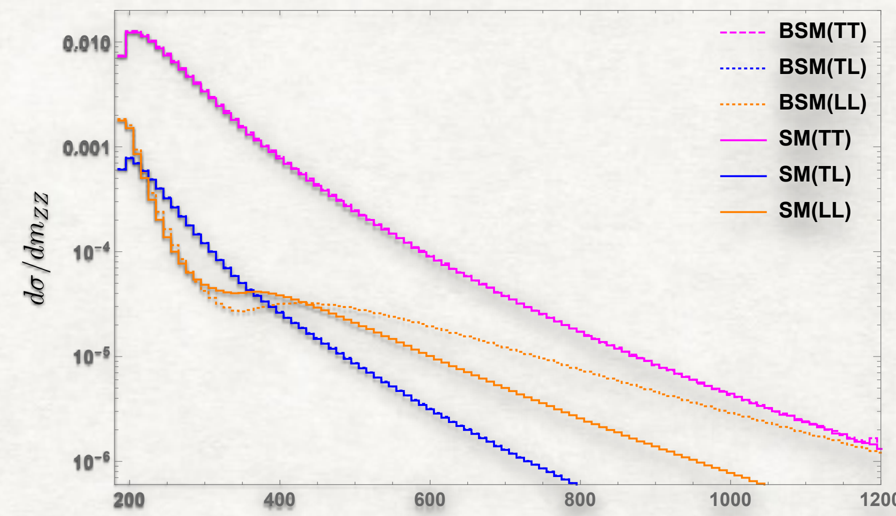
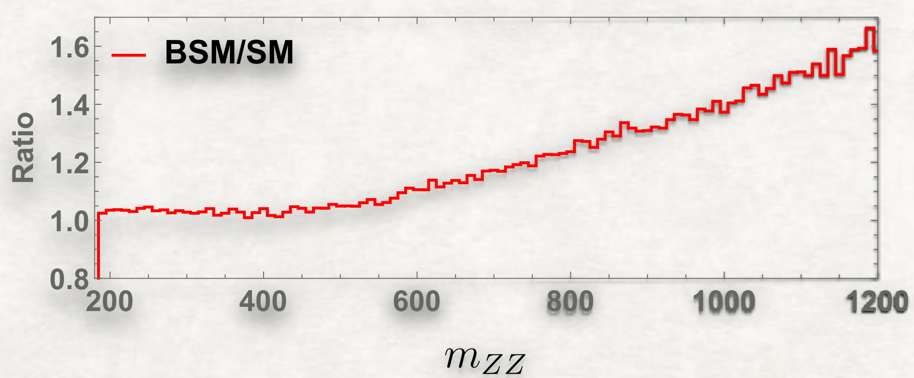
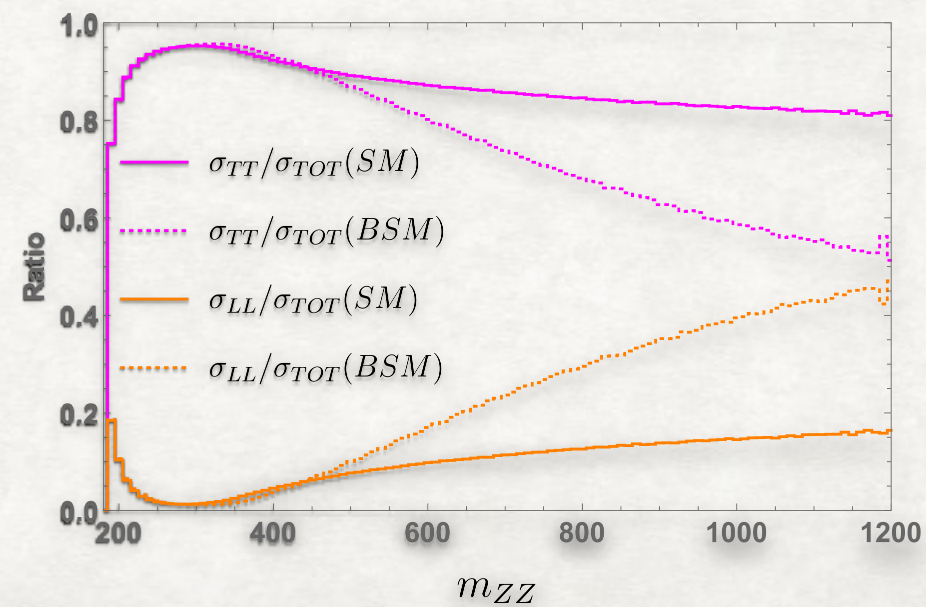








CASE B: BROAD-WIDTH HEAVY SCALAR

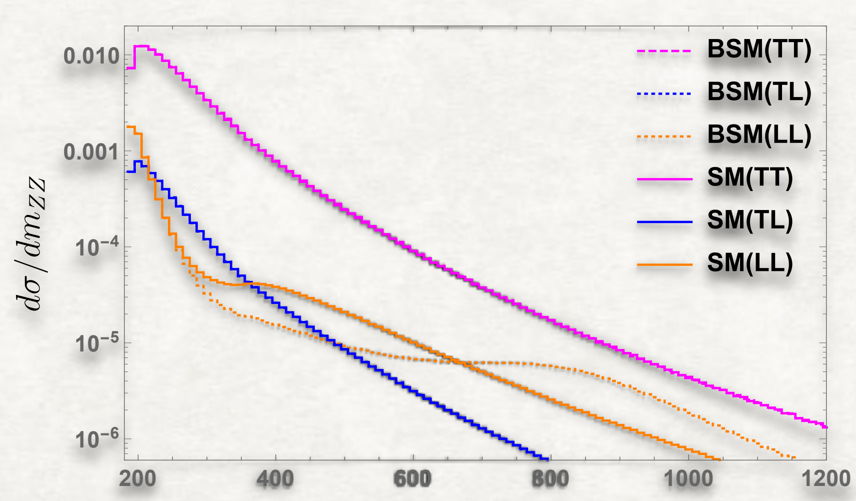
$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \mu_S S|\Phi|^2$

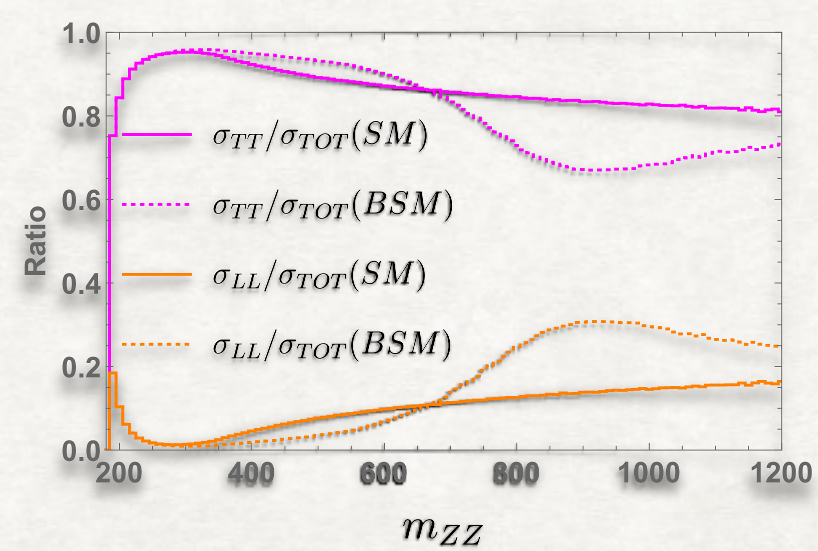
$H = \sin\theta\ S^{\rm phy} + \cos\theta\ H^{\rm pay}$

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

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

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





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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CASE C: QUANTUM CRITICAL HIGGS

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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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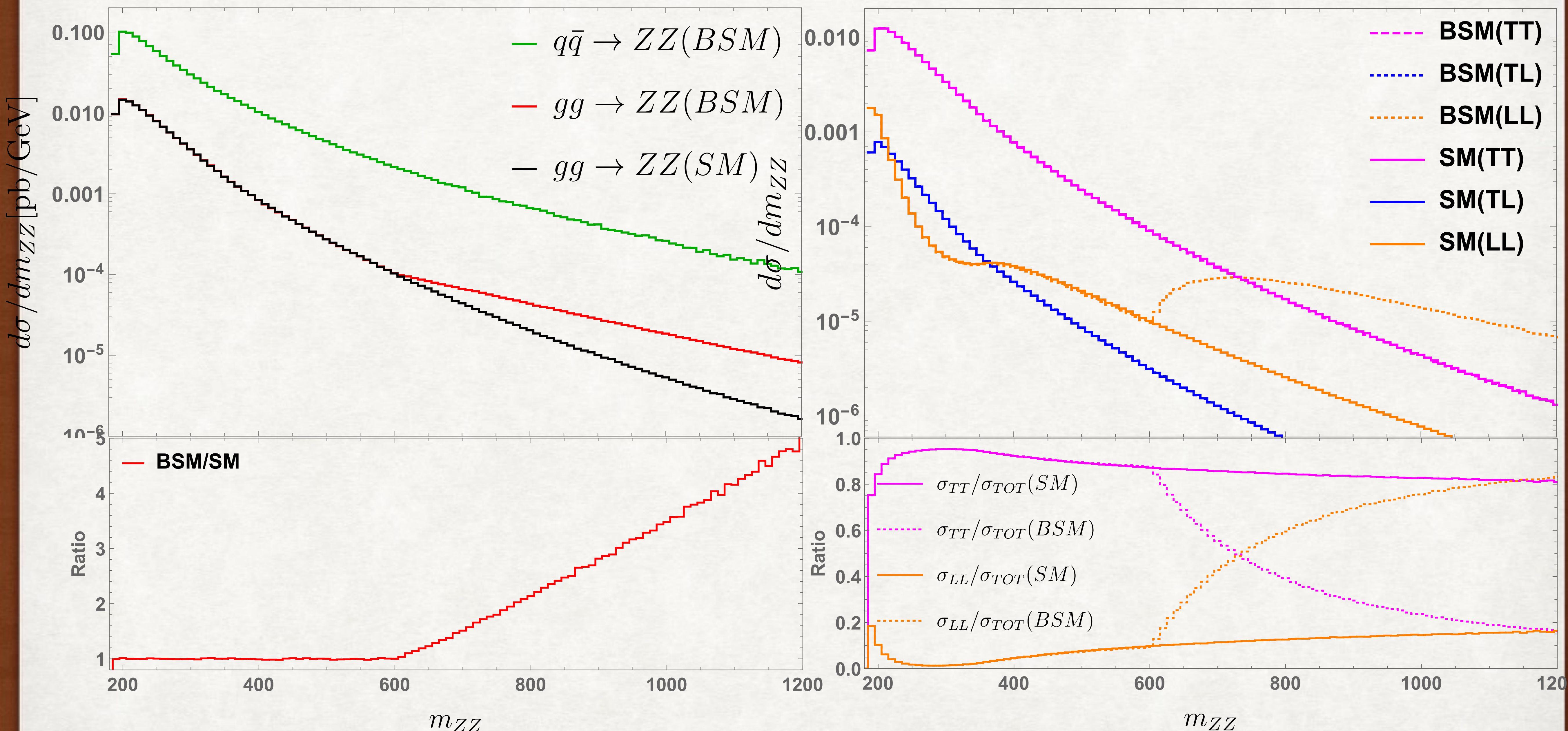
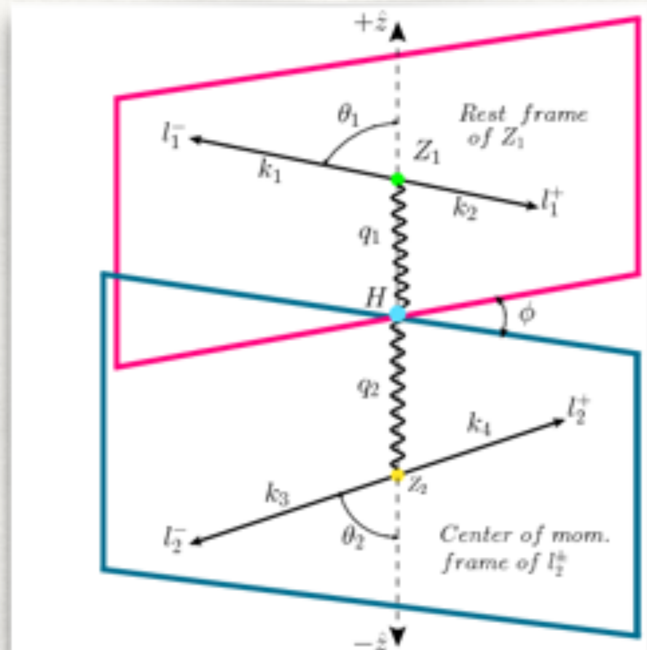


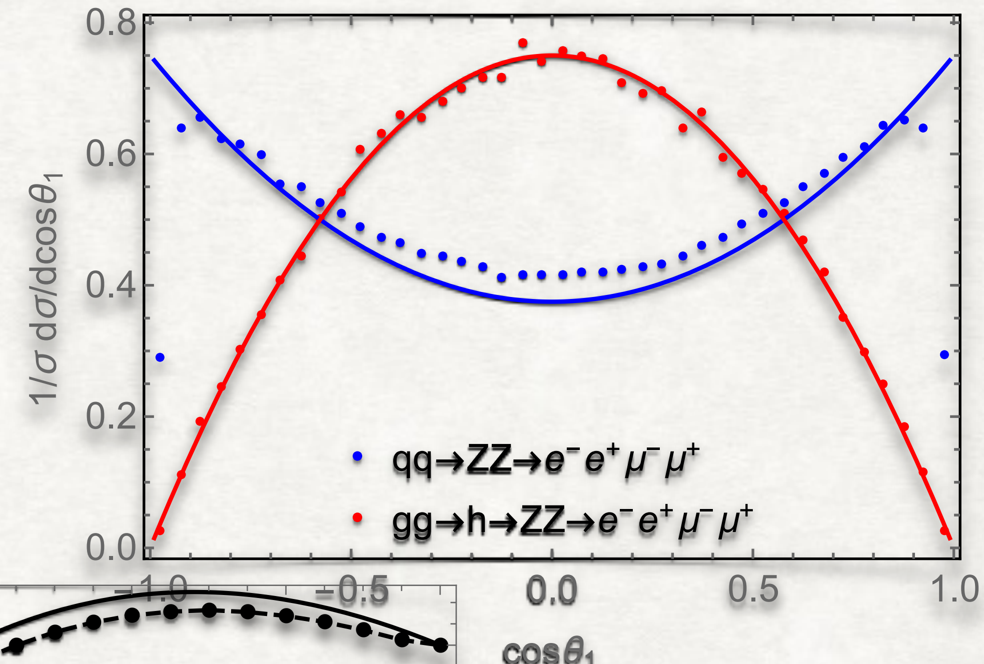
DISCRIMINANT AND ANALYSIS



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

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

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



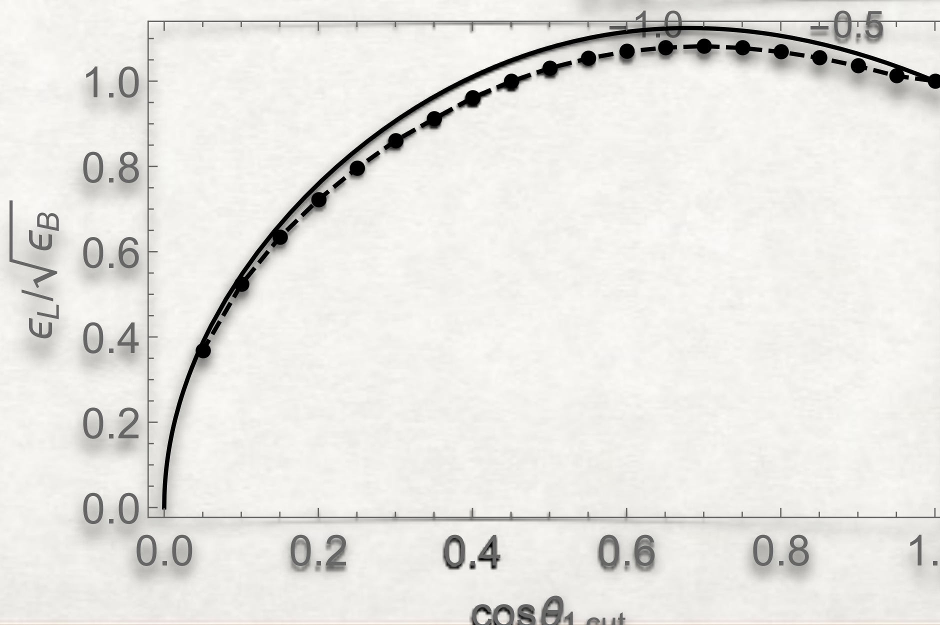
To optimize the longitudinal over transverse mode significance:

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

$$\cos\theta_C = 0.68$$

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

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



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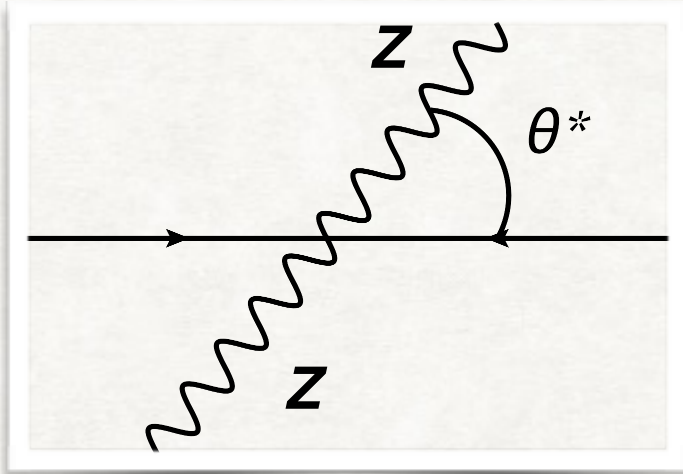
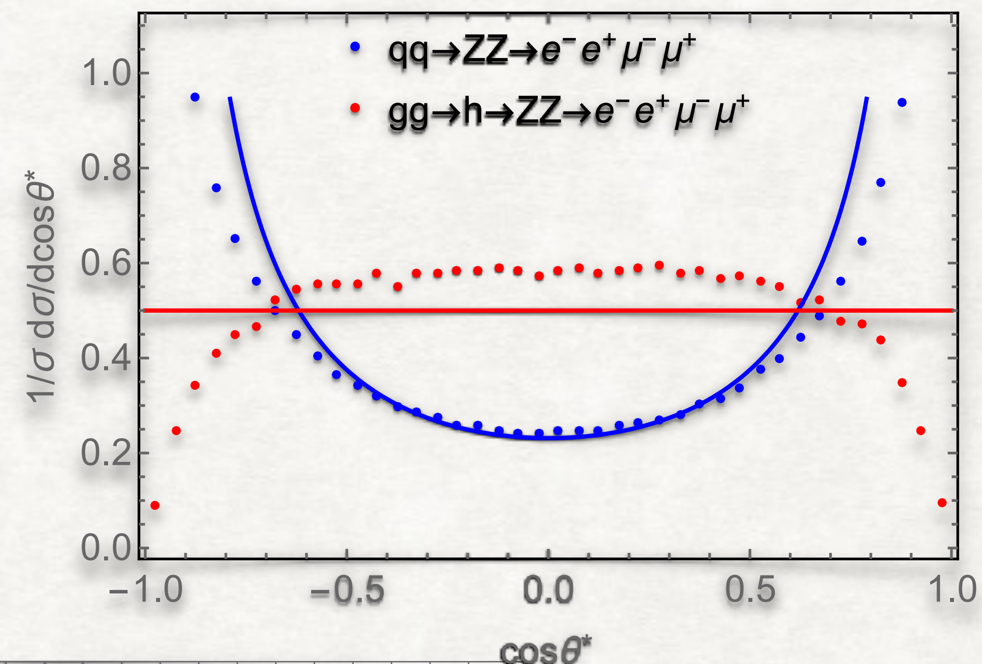


"center of mass rest frame"

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

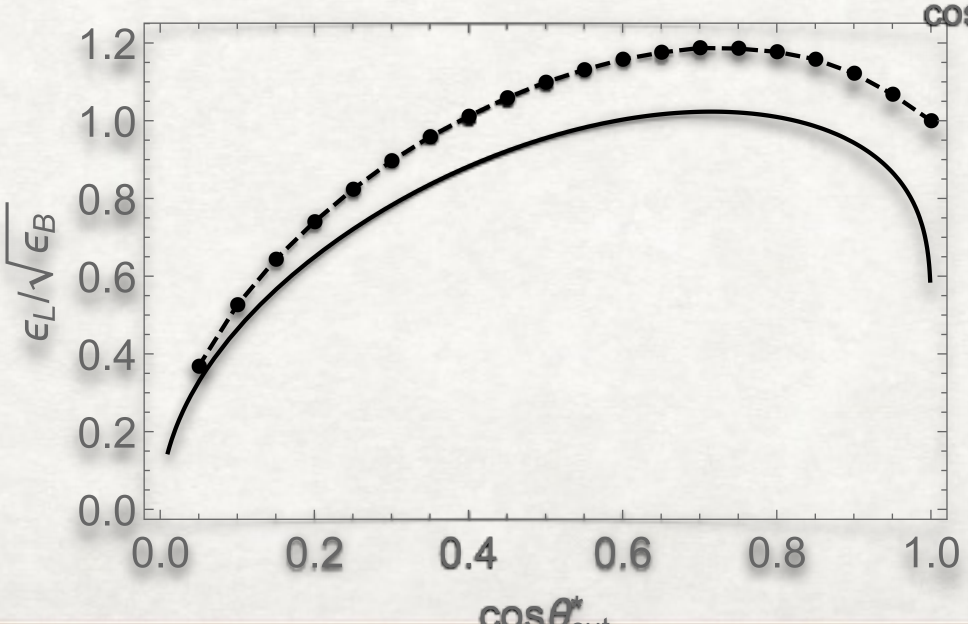
$$gg \to h \to ZZ: \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \text{constant}, \qquad \text{"}s\text{−channel scalar"}$$

To optimize over the qq background:



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

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



Cut based Analysis results show minor improvement e.g. QCH

DISCRIMINANT AND ANALYSIS

pp>e-e+mu-mu+ (bcut: pt_l>10,eta_l<2.5, mll>50, scut: m_4l>600)						**Delphes_Detector_Effects**				
	qq>ZZ [SM]	gg>h>ZZ	**gg>ZZ [SM]**	gg>ZZ[case A]tot	gg>ZZ[case A]nlo2	gg>ZZ[case A]	gg>ZZ[case B]	**gg>ZZ[case C]**	h/sqrt(qq)	(BSM-SM)/sqrt(SM)
no_cut	24.45		3.7							
bcut	10.8		1.754				1.632			
LO_xsec (bcut,scut, fb)	2.55E-01	2.03E-02	1.82E-02	2.42E-02	2.66E-03	2.15E-02	2.13E-02	2.64E-02		
k-factor weighted	3.06E-01	4.06E-02	3.64E-02	4.84E-02	5.33E-03	4.31E-02	4.26E-02	5.28E-02		
NEvents (3ab-1)	9.18E+02	1.22E+02	1.09E+02	1.45E+02	1.60E+01	1.29E+02	1.28E+02	1.58E+02	4.02E+00	
2e2mu-jets	4.95E+02		6.36E+01					9.31E+01	0.00E+00	1.25E+00
80<mll<100	3.76E+02	1.06E+02	5.19E+01	1.22E+02	1.40E+01	1.08E+02	1.06E+02	7.72E+01	5.48E+00	1.22E+00
costh*<0.7	1.85E+02	8.46E+01	3.42E+01	8.01E+01	1.11E+01	6.90E+01	7.07E+01	5.49E+01	6.23E+00	1.40E+00
costh1<0.68	1.20E+02	7.29E+01	2.40E+01	5.97E+01	9.55E+00	5.02E+01	5.24E+01	4.22E+01	6.66E+00	1.52E+00

*MEM, BDT in progress

THANKS!