# Observing ‘threshold channel’ in collider

The heuristic estimation

# Target : Unstable massive scalar $X$, much heavier than Higgs

Question : "Is there any hidden decay channel of $X$ whose threshold is close to $m_X$?

I will call this 'a threshold channel' for simplicity

Precondition : The target resonance itself must be visible.

What would be the cleanest decay channel?

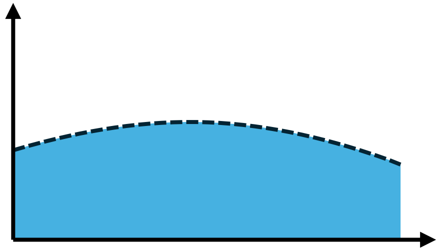
Candidates : diphoton $(X \to \gamma\gamma)$, dilepton $(X \to e^+e^- \text{ or } \mu^+\mu^-)$

# Hypothesis testing scenarios

Our case!

## Scenario 1: Discovering an NP resonance

Fixed SM prediction



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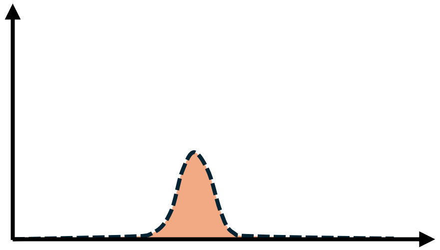
Model parameters (mass, width, … , etc.)

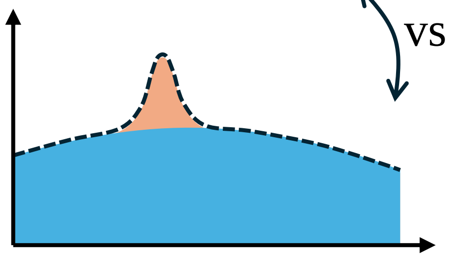


**Null hypothesis** (B)
(there is no NP resonance)

Signal by NP resonance (S)

vs

=

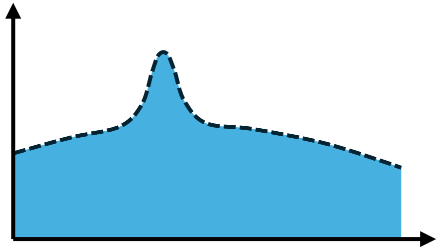


**Alt hypothesis** (B+S)
(there is NP resonance)

If the experiment result is not explainable under B with statistical fluctuation but explainable under B+S (best fit), then we may claim that we discovered a new physics signal.

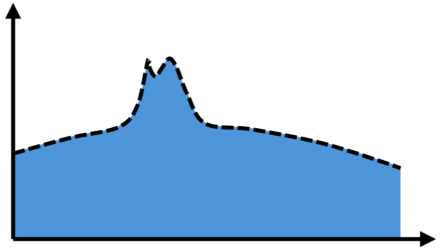
## Scenario 2: Discovering a threshold channel

Few model parameters
(mass, width, … , etc.)



vs

More model parameters
(mass, width, threshold, couplings, … , etc.)



**Null hypothesis**
(Breit-Wigner, no threshold channel)

**Alt hypothesis**
(threshold channel loop effect)

In theory, we can perform a hypothesis testing between null hypothesis and alt hypothesis as in scenario 1 to determine whether the null hypothesis is rejected or not.

However, the full statistical analysis would be lengthy, so we have to pre-restrict the parameter space.

Hence, we need a heuristic estimation.

# ‘Heuristic estimation’

Many papers on sensitivity of detecting resonance are based on scenario 1. We should harvest something out of these papers and apply it in our case.
In a rough sense, if S is big enough comparing to fluctuations of B then we can distinguish between S and B.

However, **in scenario 2, it is ambiguous what is signal and what is background.**
In scenario 1, the background B = (Null) and the signal S = (Alt – Null).
By analogy, **we want to regard B = (Null) and S = (Alt – Null) also in scenario 2.**
The difference is that the null hypothesis also contains some model parameters, so we may alter the definition so that
**B = (Best fit under Null) and S = (Alt – Best fit under Null).**

Another obstacle is that there is a **detector smearing** due to the limited resolution of invariant mass measurement.
A detector smearing effectively blurs the positive part and negative part of S so it is cancelled.
Intuitively speaking, the lower the precision of the measurement, the harder it is to find out the details of the resonance signal.

Instead of explicitly convoluting the smearing function(Gaussian or crystal-ball function), we will **simply require that the width of X should be greater than the uncertainty scale of invariant mass measurements.**

Our strategy: calculate the ‘pseudo-cross-section’ based on |S| to see whether we can discover threshold effects.

# Benchmark analysis points and parameters

Charged leptons

Model: $\mathcal{L}_{X,\chi} = \frac{1}{2}\partial_\mu X \partial^\mu X - \frac{M^2}{2}X^2 + \partial_\mu \chi^\dagger \partial^\mu \chi - m_\chi^2 \chi^\dagger \chi - gX\chi^\dagger\chi - y_l X \boxed{\bar{l}l}$

Experiment: $(e^+e^- \to e^+e^- X \to e^+e^-\mu^+\mu^-)$ in linear electron collider, $1\,\mathrm{TeV}$, $4.0\,\mathrm{ab}^{-1}$

Same Yukawa coupling for all charged leptons

Mass $M$ : 400 GeV (Can be produced in both ILC and LHC)

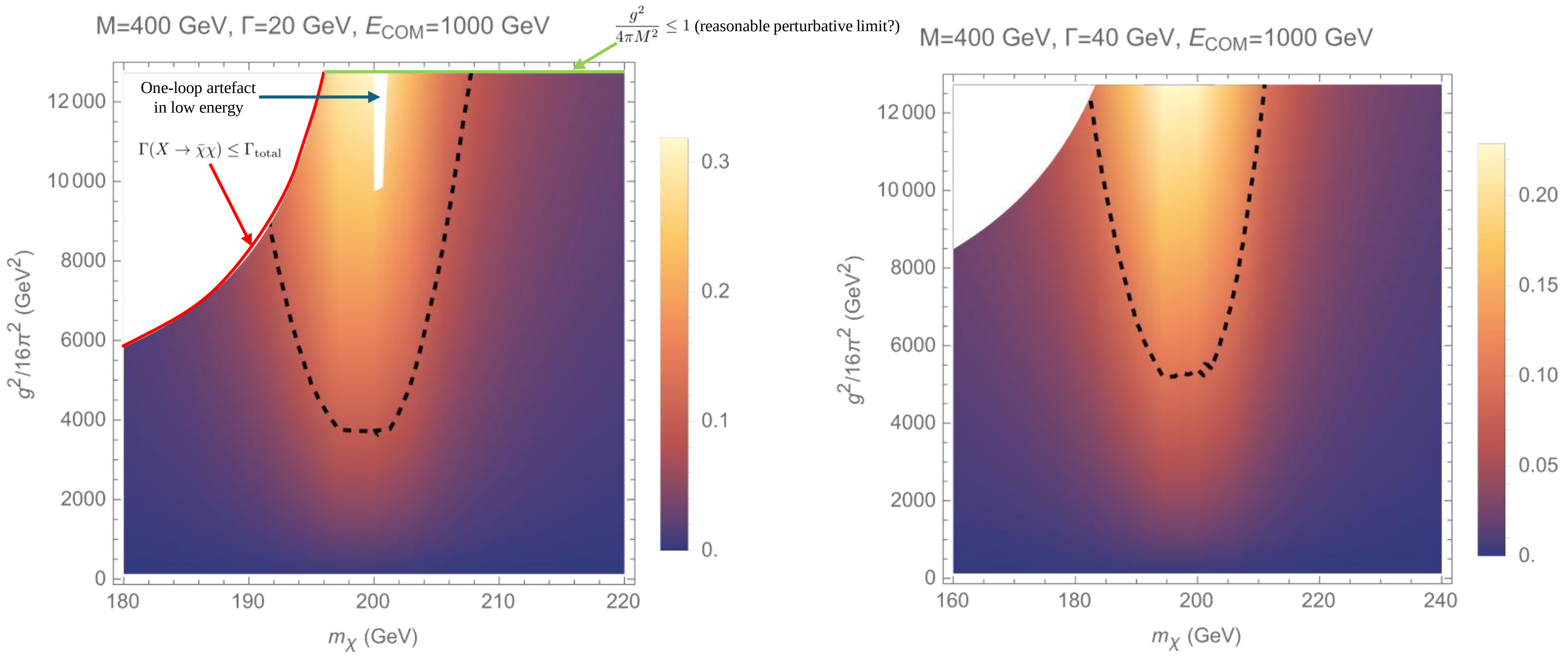
Momentum resolution: ~5% for dimuon (typical in ATLAS, CMS) 2212.07338

$\Rightarrow \Gamma_{\mathrm{total}} \gtrsim 20\,\mathrm{GeV}$

Every calculation is done in real-on-shell scheme.

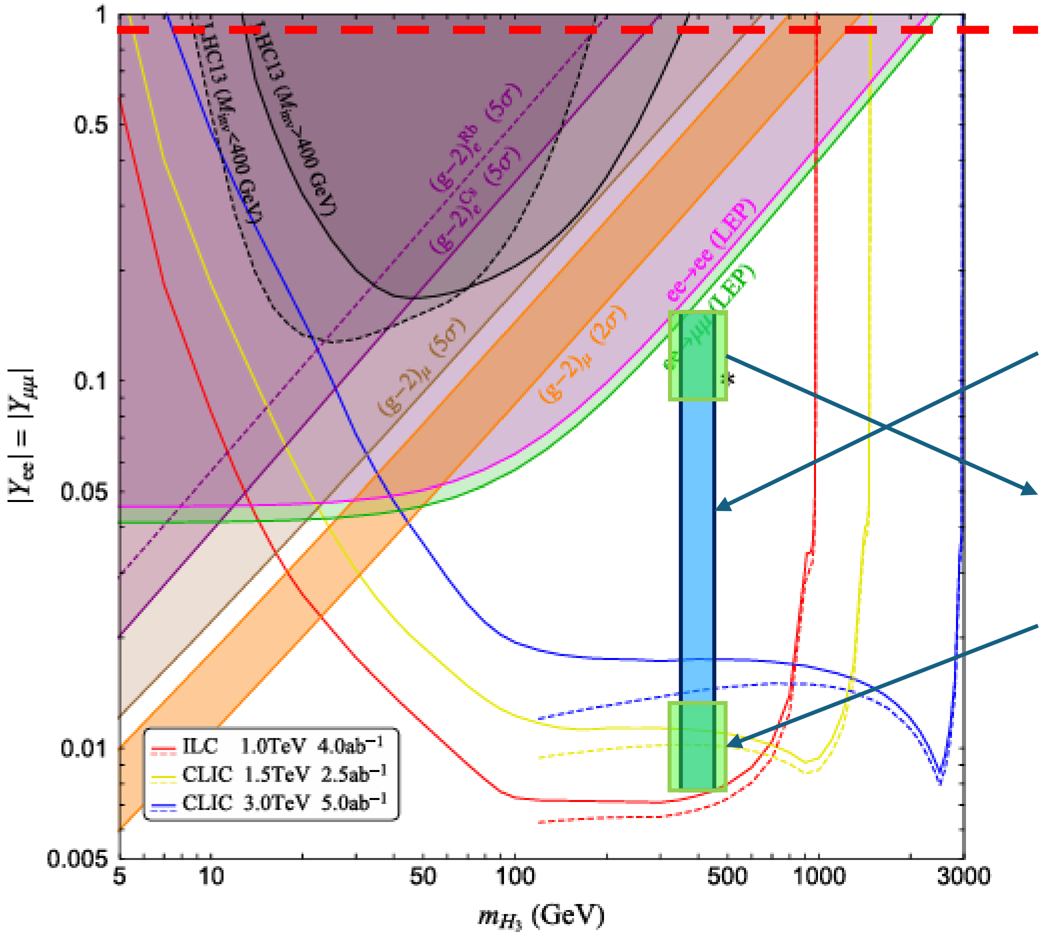
# Resonance signal cross section vs Threshold channel signal cross section

Above the dashed line, threshold channel signal is bigger than 0.1 times the resonance signal. This means that less than about 100 times larger luminosity is required to confirm threshold channel than the luminosity required to detect the particle X at the first place.




The result looks identical if we scale dimensionful parameters altogether.

# $(e^+e^- \to X \to \mu^+\mu^-)$ sensitivities in future lepton colliders




(a) $m_{H_3}$, $|Y_{ee}| = |Y_{\mu\mu}| \neq 0$

Large window (about 20 times) of Yukawa coupling is accessible for ILC.

If the Yukawa coupling lies in this region, ILC may barely detect the threshold channel…

whose cross-section is roughly similar with the signal in this region.

Of course, factors such as detector smearing make things worse.


Xu, Fang. "Neutral and doubly charged scalars at future lepton colliders." *Physical Review D* 108.3 (2023): 036002. arXiv:2302.08653

# Detector smearing: Not terribly bad?

dashed lines: cross sections, shades: statistical reliability

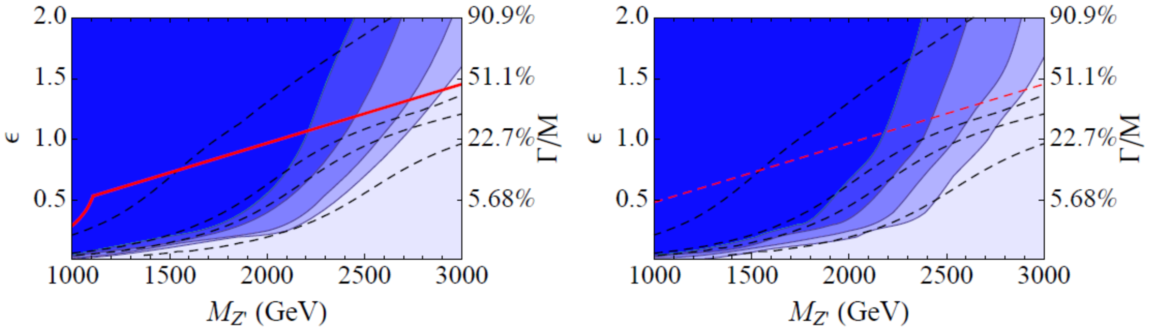



Figure 19: Comparison of statistical analysis without (left) and with (right) Gaussian smearing of the final muon states for the non-universal $Z'$ compared to a VV destructive contact interaction. The reliability shadings are as in Fig. 9, as are the cross sections.

arXiv:1011.0728

The above result is from the study about distinguishing broad resonances from contact interactions or backgrounds. Not directly applicable for our study, but it suggests that the smearing affects the result only slightly, if the typical momentum variance scale is bigger than the detector resolution.