DPF-PHENO 2024

Muon Collider and EDM Complementarity

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Electric Dipole Moments (EDMs)

- EDMs are sensitive probes of BSM physics since said models generically contain new sources Charge-Parity (CP) violation
    - Leptonic EDMs are generated by CP violating processes, arising from terms like $\mathscr{L} \in - d_e \frac{i}{2} \bar{\psi} \bar{\sigma}^{\mu\nu} \gamma_5 \psi F_{\mu\nu}$
- The current bound on the electron EDM is $|d_e| < 4.1 \times 10^{-30}$e · cm (arXiv 2212.11841)
    - SM prediction: $|d_e| \approx 10^{-35}$e · cm (arXiv:2202.10524)
- If EDM is produced at the 2-Loop level, the scale of new physics must be $\Lambda_{2-\text{Loop}} \gtrapprox$ TeV

Barr-Zee Diagrams

- Barr-Zee diagrams are two-loop contributions to EDMs
  - ANY particle interacting with the Higgs and electromagnetic gauge bosons will contribution to EDM through such diagrams
- Q: If we observe at eEDM, how do we learn more about the particles that produce it (such as their couplings to the Higgs)?

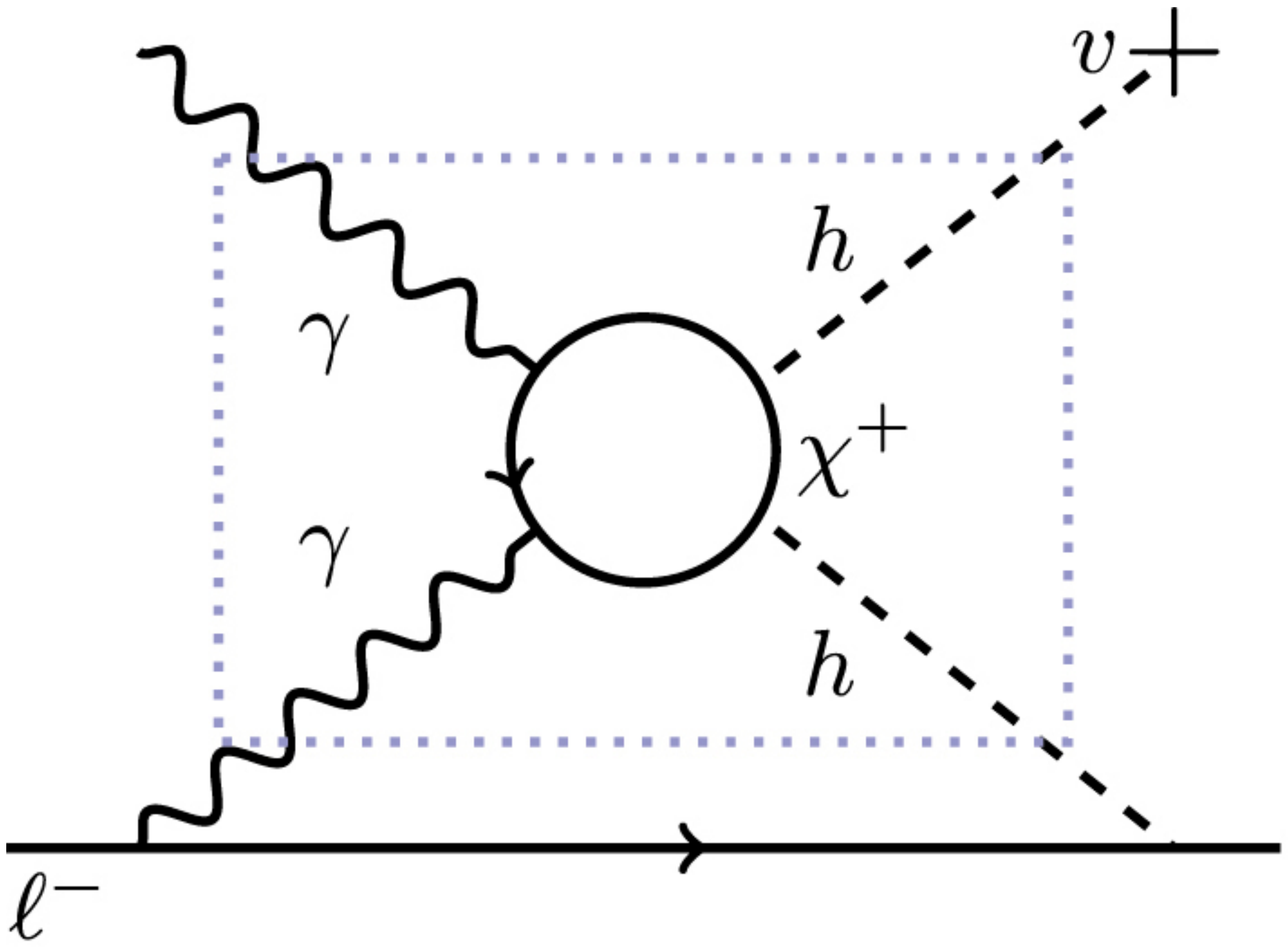
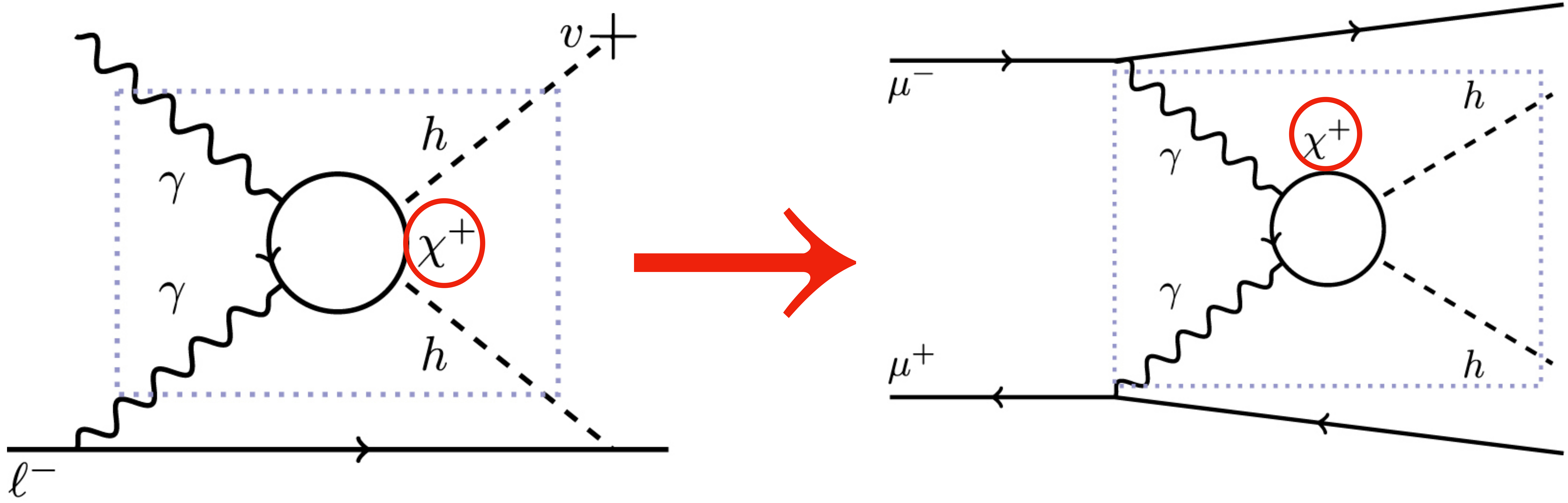


Image from arXiv:2103.14043

Complementary Measurements at Muon Colliders (1)

Barr-Zee Diagrams

VBF at Muon Colliders



Images from arXiv:2103.14043

- Same substructure!

Complementary Measurements at Muon Colliders (2)

VBF Fusion

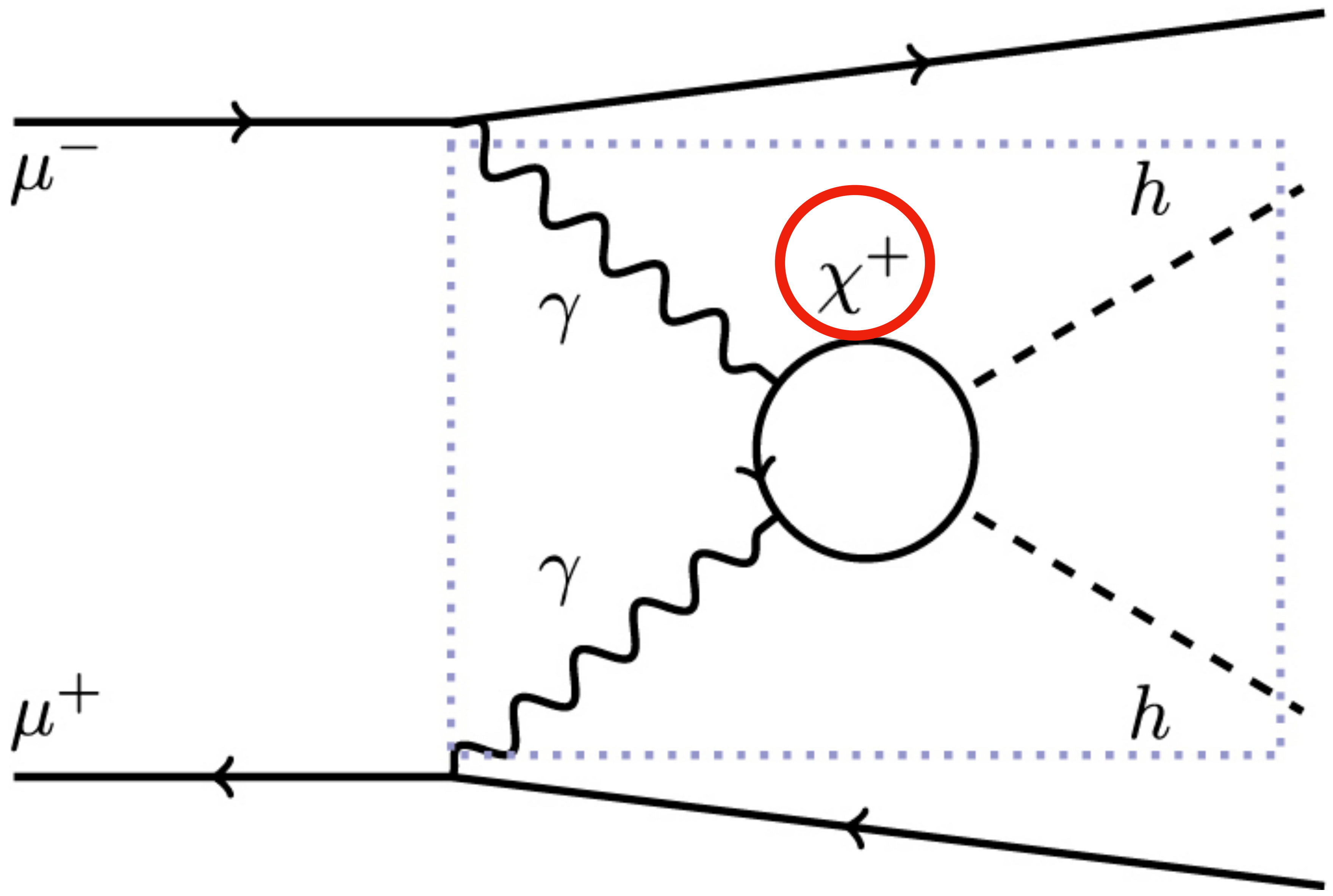
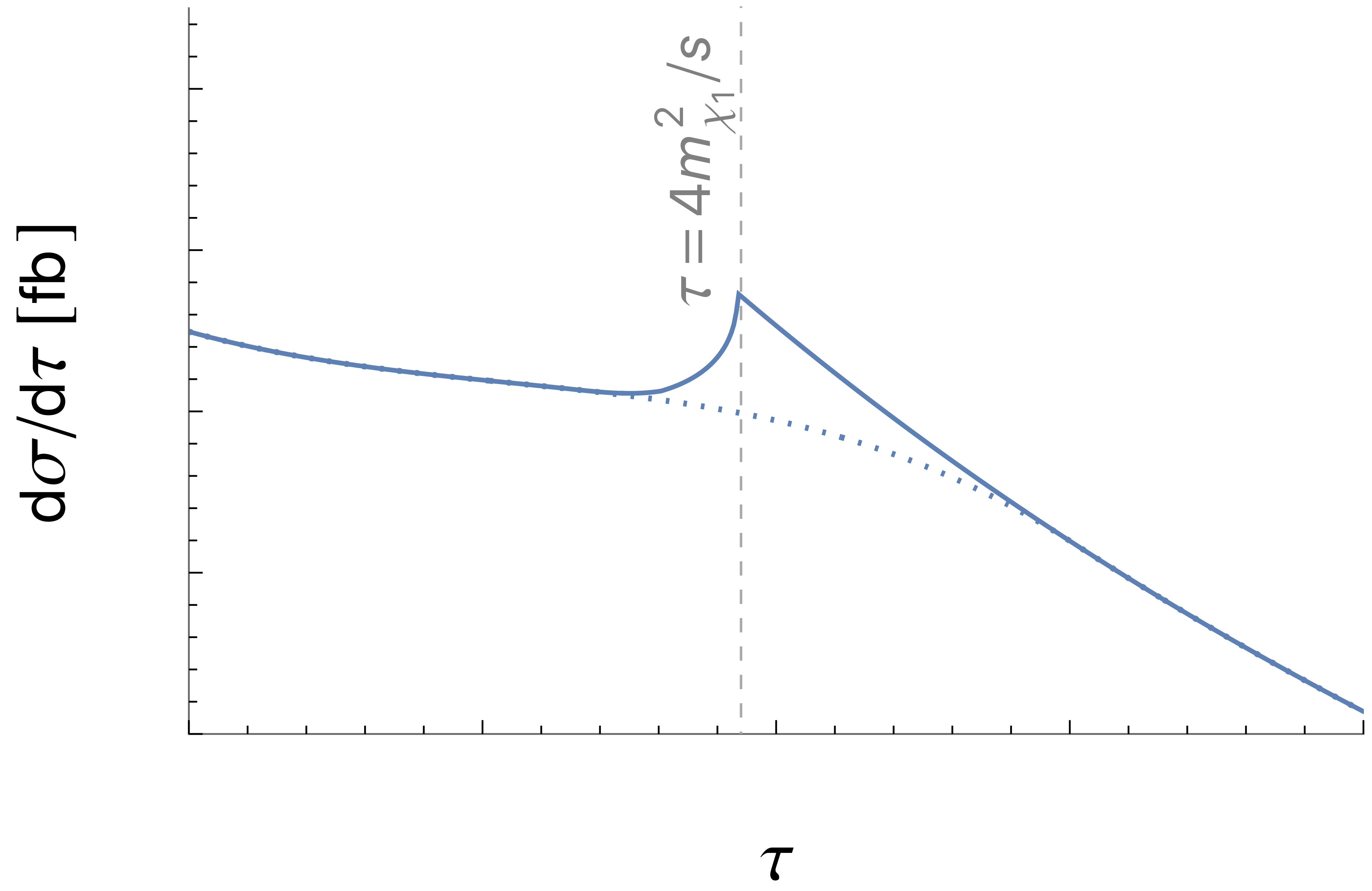


Image from arXiv:2103.14043

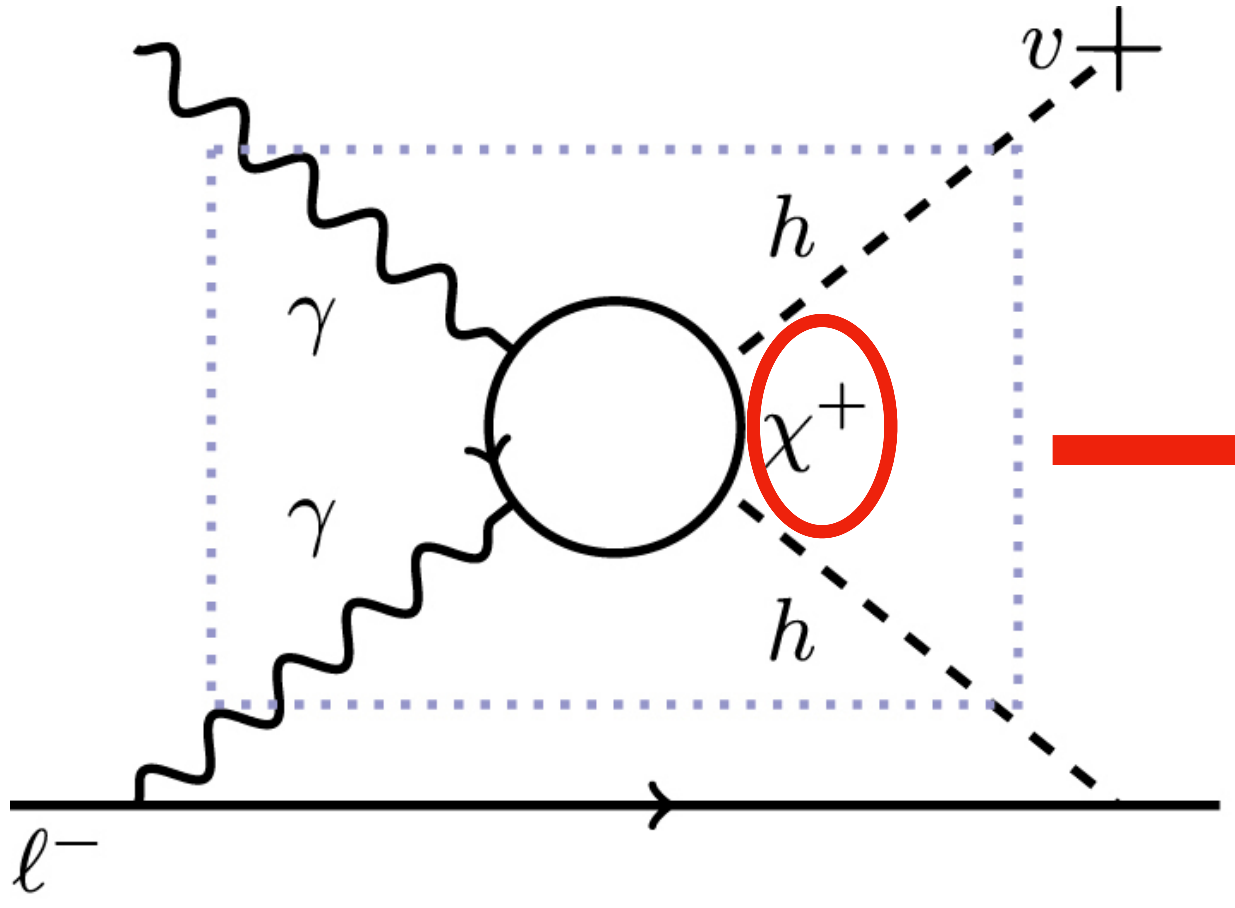
Effect of New Particles in $\frac{d\sigma}{d\tau}$ (Sketch)



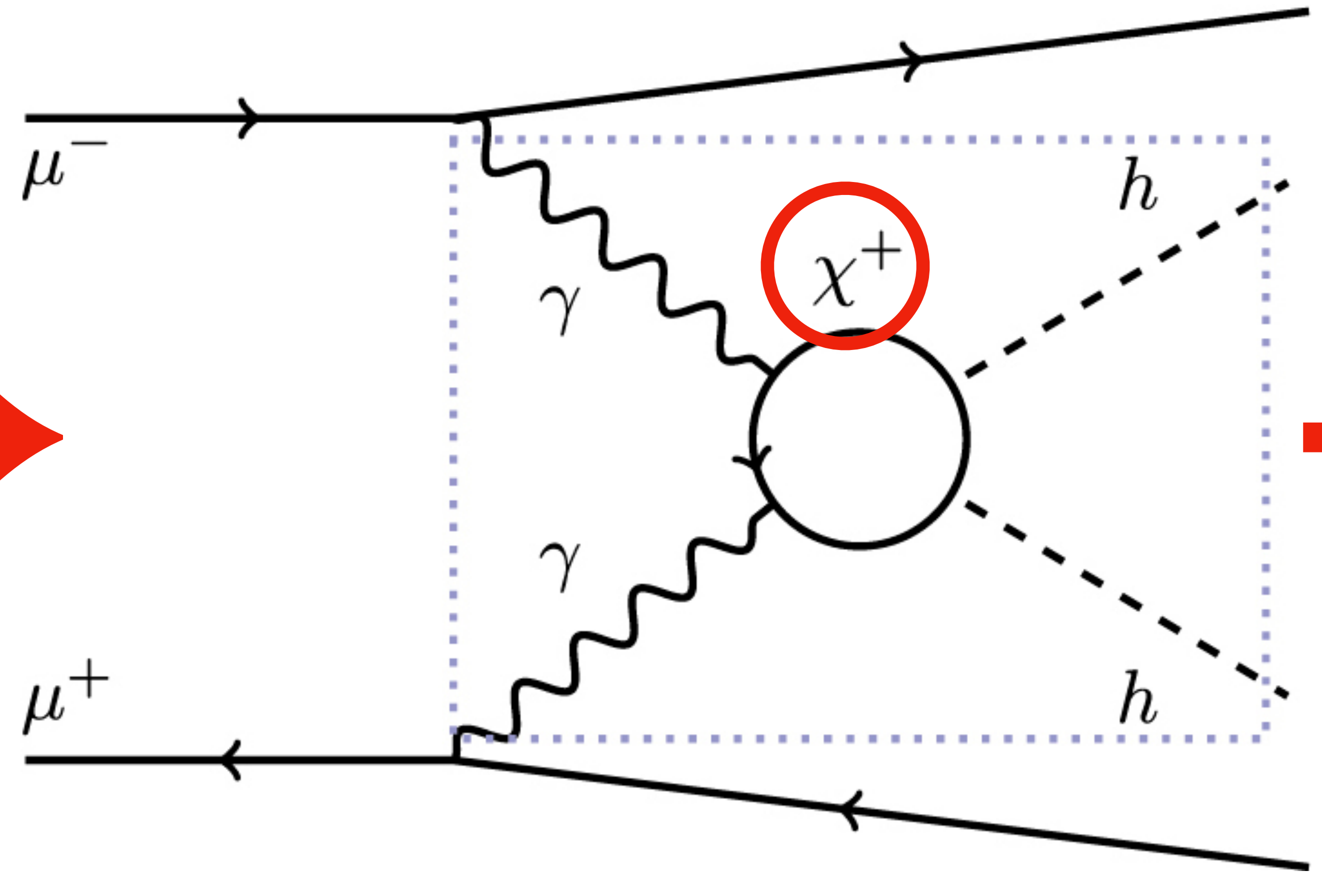
- The heavy new particles that produce an eEDM through Barr-Zee diagrams will produce features at a muon collider that tell us about the new particles

Complementary Measurements at Muon Colliders (3)

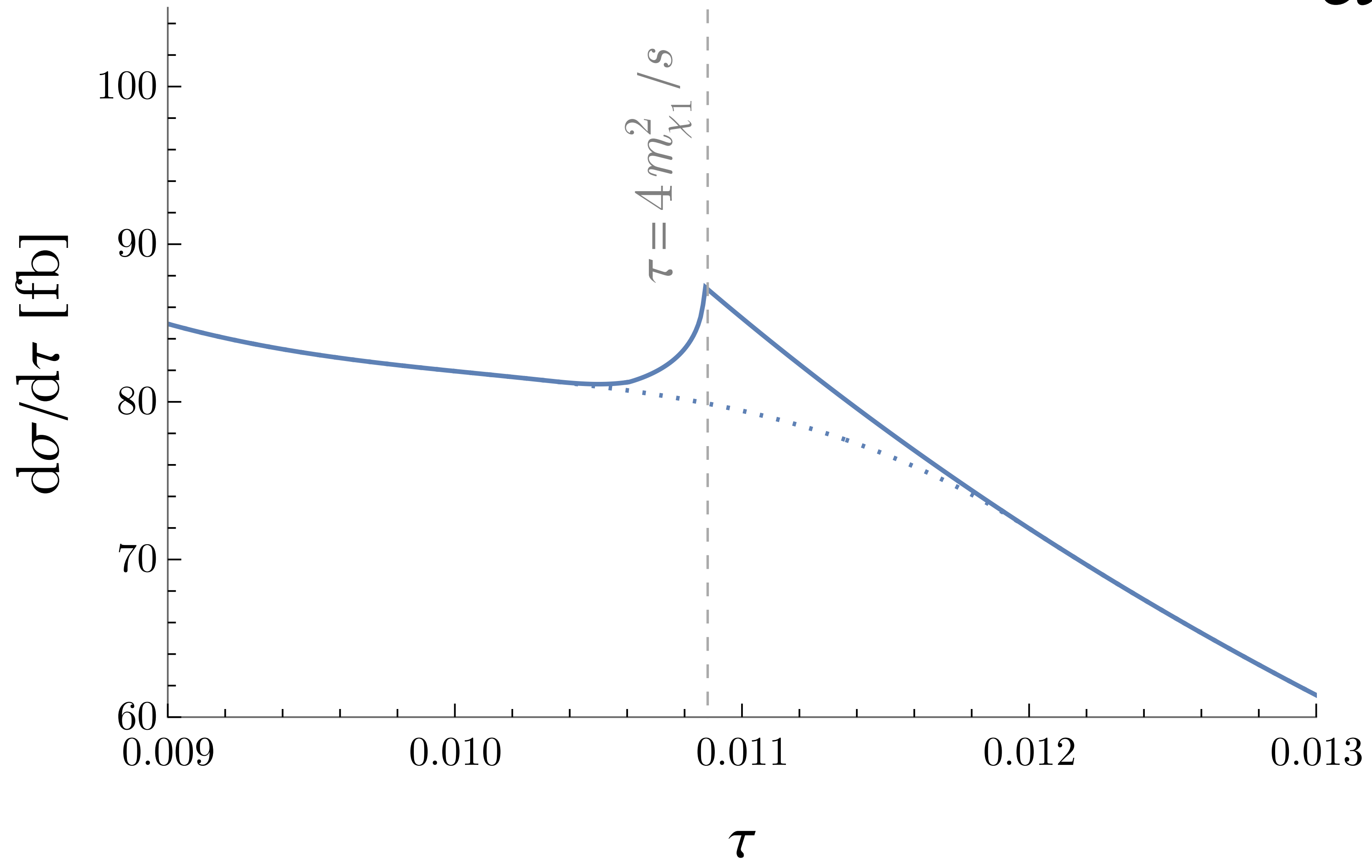
Barr-Zee Diagram



VBF Fusion



Effects of New Particles in $\frac{d\sigma}{d\tau}$



Images from arXiv:2103.14043

- This is NOT discovery mechanism for new particles
  - Would tell us how the new particles couple to the Higgs etc.

Why look in Muon Collider Data?

- Muon colliders are the perfect place to look for VBF processes (as opposed to hadron colliders)
    - Fundamental particles:
        - Collisions clean compared to composite particles
        - C.O.M energy of collisions is known
    - Low background; Fewer colored jets
- Muon colliders are EW gauge boson colliders

Minimal BSM Models

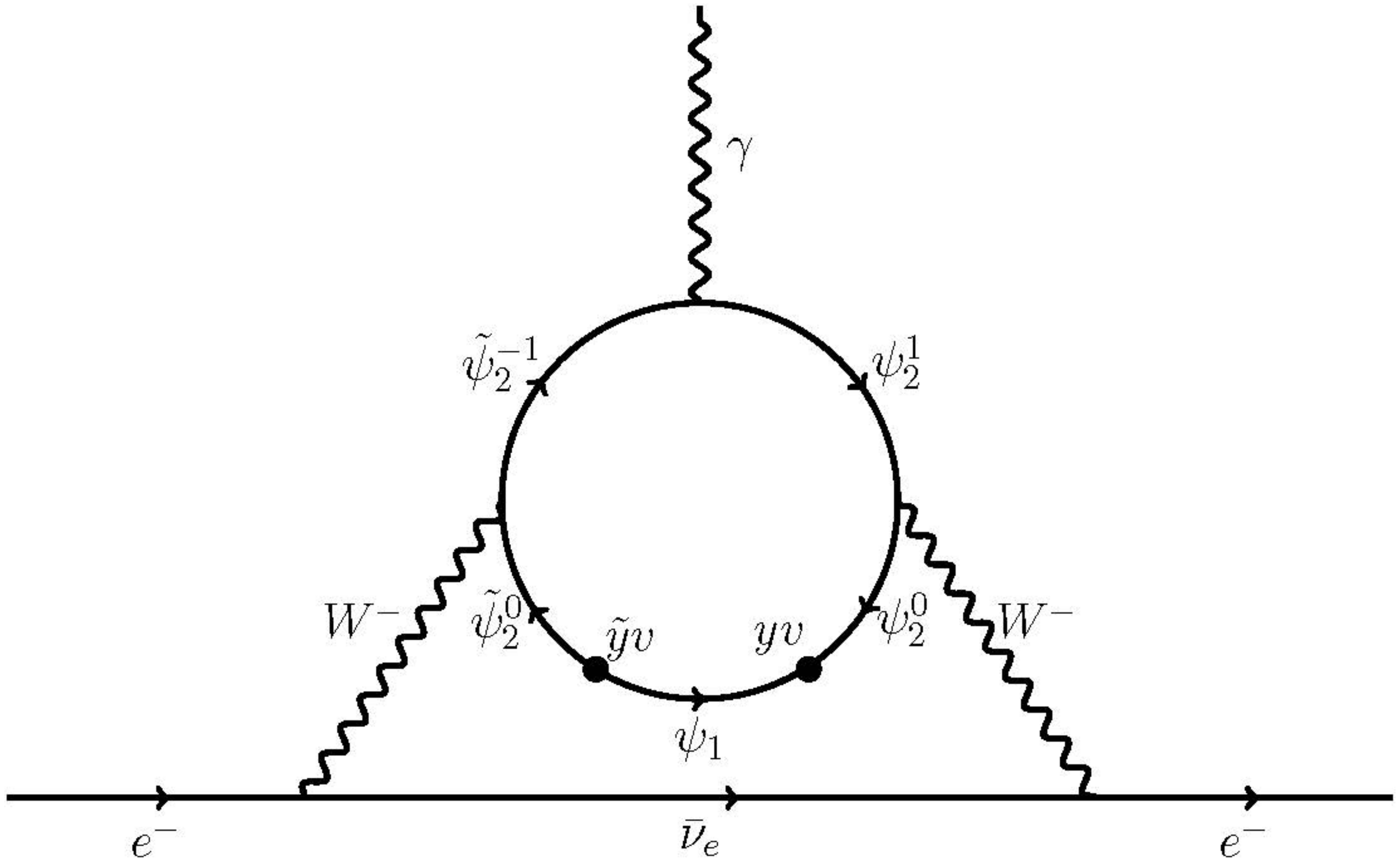
- To produce a leptonic EDM through Barr-Zee diagrams, we need:
  - Coupling to Higgs doublet and Electroweak GB
  - Extra physical phase
- Therefore, need at least one charged BSM particle
- Simplest solution to contracting with Higgs doublet:
  - $2 \otimes \bar{2} = 3 \oplus 1$ →Need an additional SU$(2)_L$ singlet or triplet
- Prevent excess couplings with SM fermions →new particles are fermions
  - Also need to add an oppositely charged SU$(2)_L$ doublet as well

Minimal BSM Models: Singlet Doublet (SD) and Doublet Triplet (DT)

- Two Minimal BSM Models: Singlet Doublet (SD) and Doublet Triplet (DT)
  - Talk will focus on results from the SD model
- Singlet-Doublet Model:
  - Consists of two SU$(2)_L$ doublets ψ_u/ψ_d ($Y = \pm\frac{1}{2}$) and an SU$(2)_L$ singlet ξ ($Y = 0$)
  - $\mathscr{L} \in -\frac{1}{2}M_1\xi\xi - \mu\psi_u\psi_d + Y_u\xi H^\dagger\psi_u - Y_d\xi H\psi_d +$ h.c.
  - In the broken phase, we have one Dirac fermion and three neutral fermions
  - One physical phase only in the neutral fermion sector

Contributions to eEDM and VBF Processes from SD Model

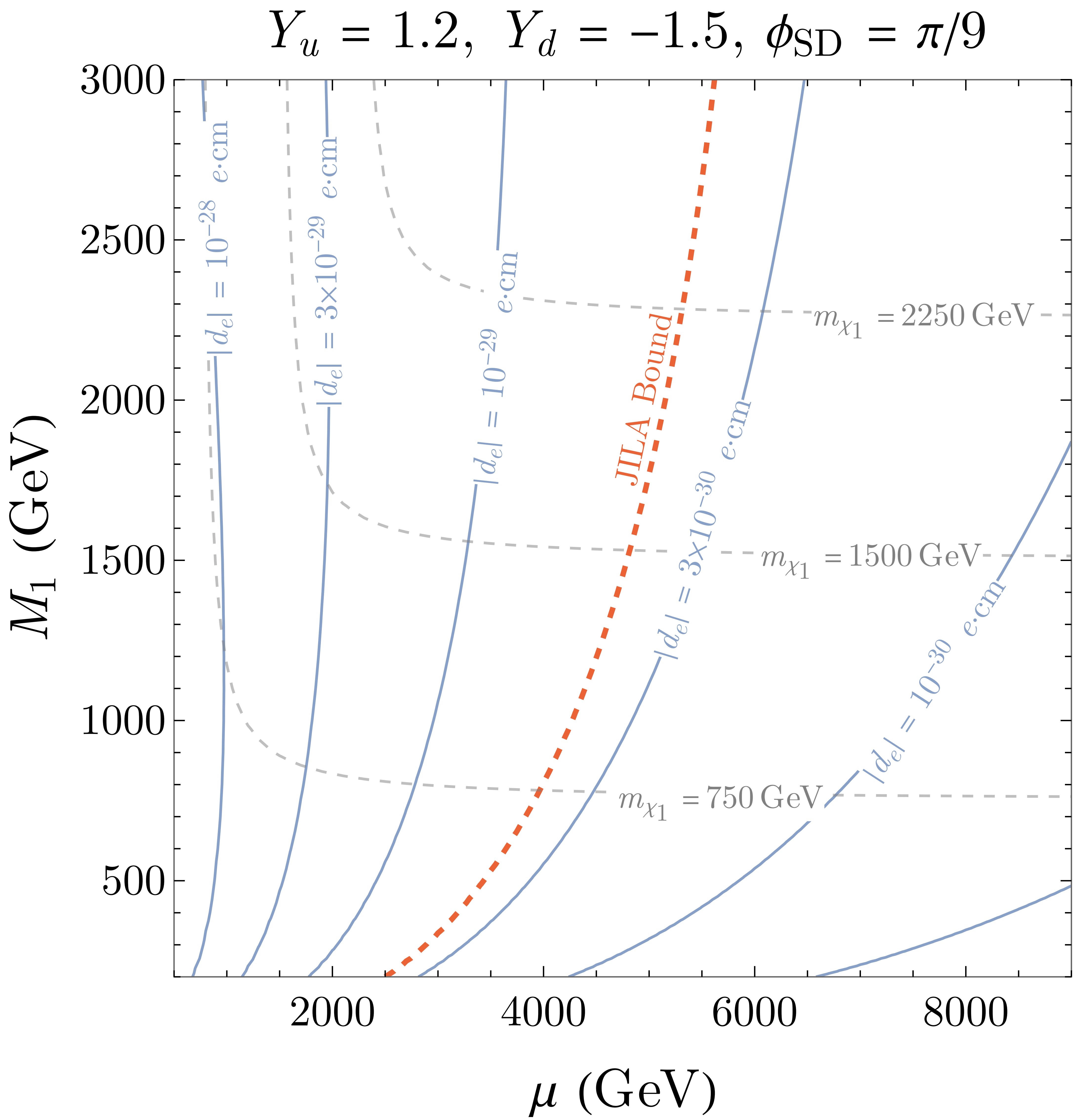
- One additional Barr-Zee diagram contributes to eEDM from SD model
- We found that the best VBF process to observe effects in is $W^+W^- \to hh$ at the one loop level



Figures from arXiv:2010.15129

eEDM Bounds Constrain SD Model

- Current bound on eEDM constrains the new charged fermion mass (μ) to be above 2 TeV
- Then the contribution to the eEDM $\propto 1/\mu^2$, and is relatively insensitive to singlet mass M_1

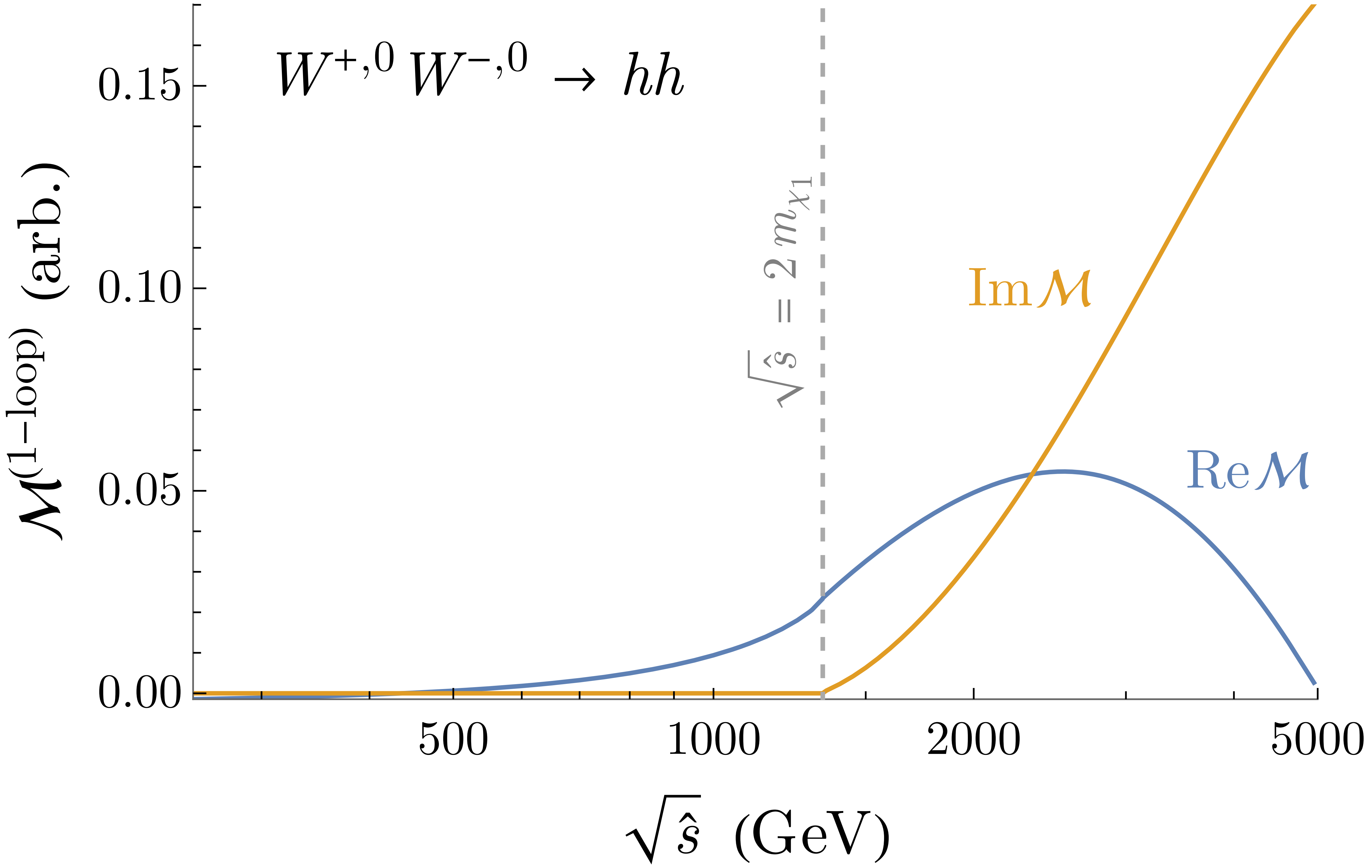


Complication: Renormalization

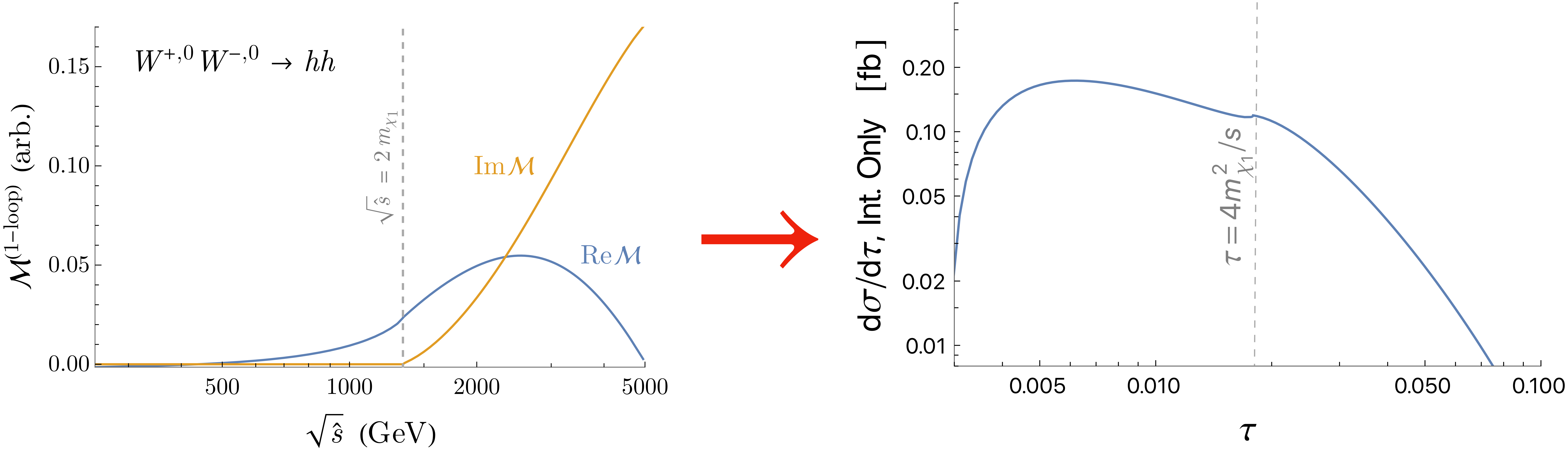
- $W^+W^- \to hh$ is allowed at tree level in the SM; there are no SD contributions before 1-Loop level
- Therefore, we had to renormalize the EW sector of the SM
  - We chose to only include the SD particles in loops. This is allowed because the NLO contribution to the cross section above $\sqrt{s} = 2m_t \propto 2\text{Re}(M_{\text{tree}} * M_{\text{SD Loop}})$, independent of SM 1-loop contributions
- Renormalization was done through via our own FeynArts (arXiv:hep-ph/0012260) model using an on-shell scheme via FormCalc (arXiv:hep-ph/9807565

$W^+W^- \to hh$ Results for the SD Model

- $|\text{Im}(M)| > 0$ after $\sqrt{s} = 2 * M_{\text{Lightest SD Particle}}$
- Occurs because lightest particle running in the loop can be produced on-shell



$W^+W^- \to hh$ Results for the SD Model (2)



- Produces exactly the feature we expected in $\dfrac{d\sigma}{d\tau}$!

Ongoing Work:

- Finish analysis of the allowed parameter space in the SD model
- Repeat for the DT model
- Identify clearest collider signals in both models

Conclusions

- EDMs are powerful probes of BSM physics because they depend on CP violation
- Muon colliders can be used to make complimentary measurements IF a non-zero eEDM above the SM estimate is observed
- The “minimal” BSM models that produce eEDMs through Barr-Zee diagrams are the SD and DT models
- We see the predicted discontinuities in $W^+W^- \to hh$ differential cross section in the SD model, but there is still work to be done on analysis and in the DT model

Selected Sources

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