Expanding Detector Reach Through Loops

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GUINEA PIG 2023 Workshop on Light Dark Matter
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Canadian Astroparticle Physics Research Institute

GUINEAPIG: GeV and Under Invisibles with New Experimental Assays for Particles In the Ground

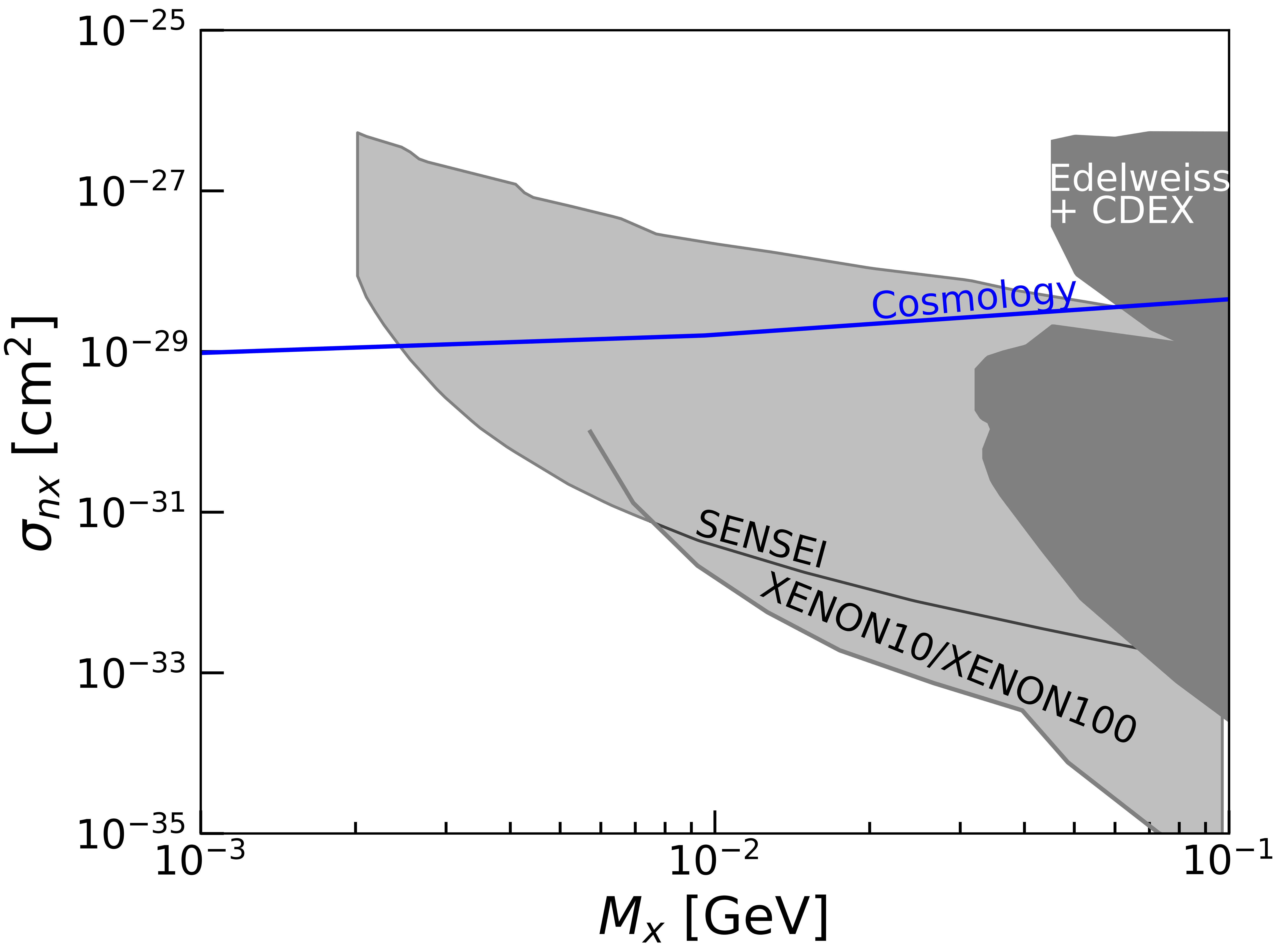
Queen's University

The Big Picture Motivation

- DM that interacts with the one part of SM interacts with all of the SM through loops
- Constraints from DM interactions with one particle can produce effective constraints on DM interactions with other particles
- Expand parameter space accessible to DM detectors

More specific motivation

Nuclear recoil detectors have weaker sensitivity to DM lighter than a GeV due to high target mass and low momentum exchange



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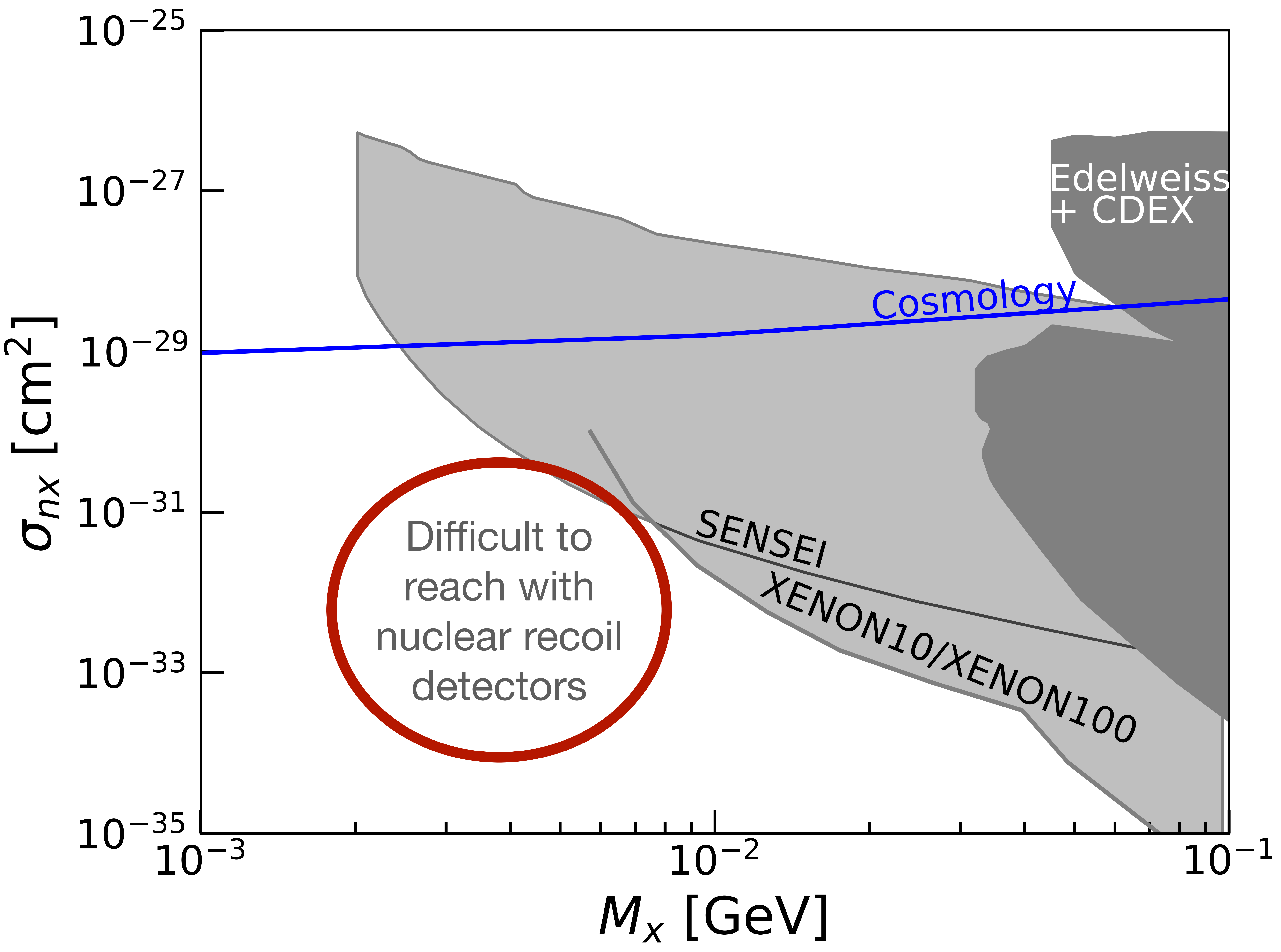
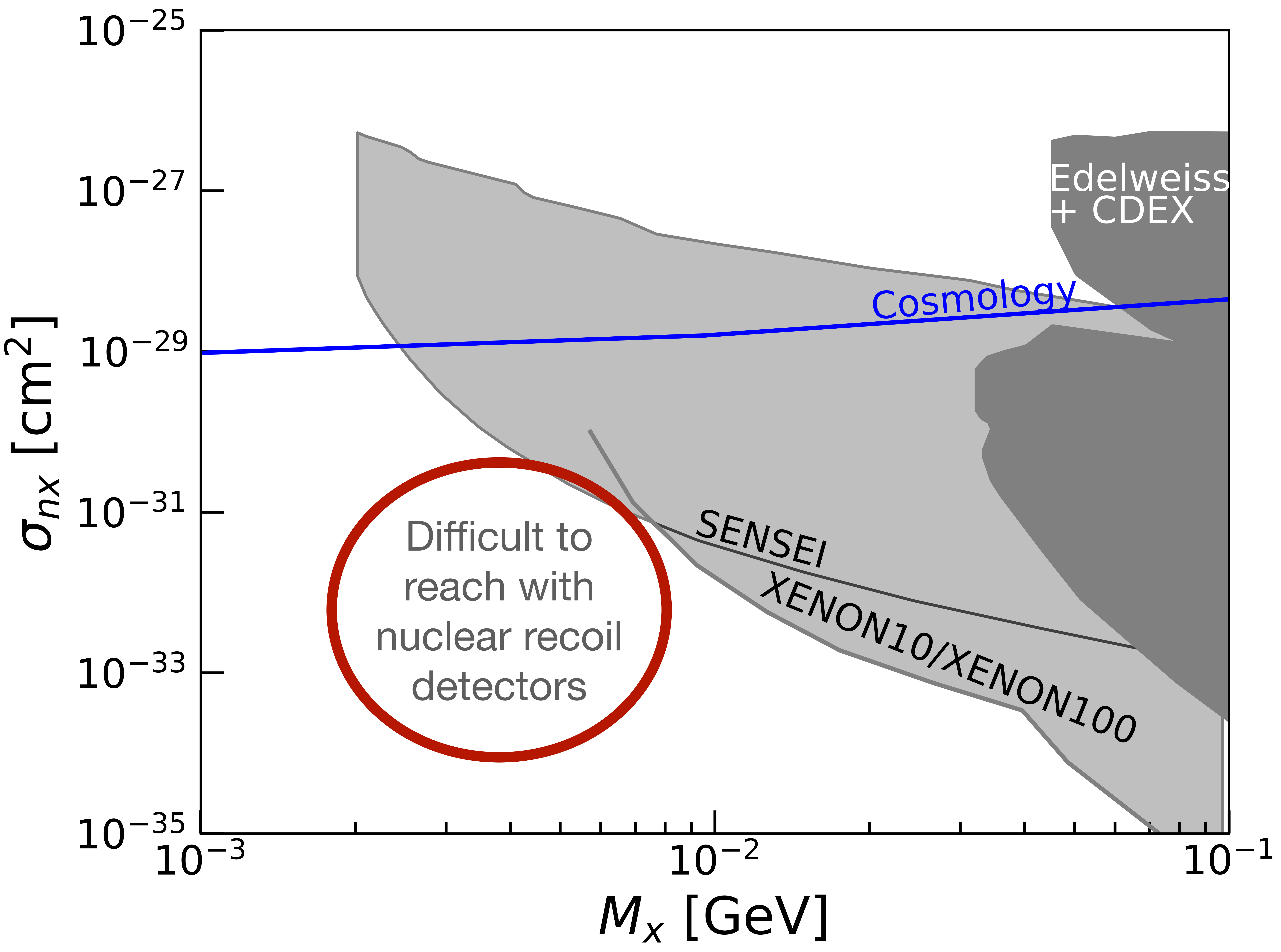


More specific motivation

Nuclear recoil detectors have weaker sensitivity to DM lighter than a GeV due to high target mass and low momentum exchange

Electron recoil detectors can preform better in this part of parameter space

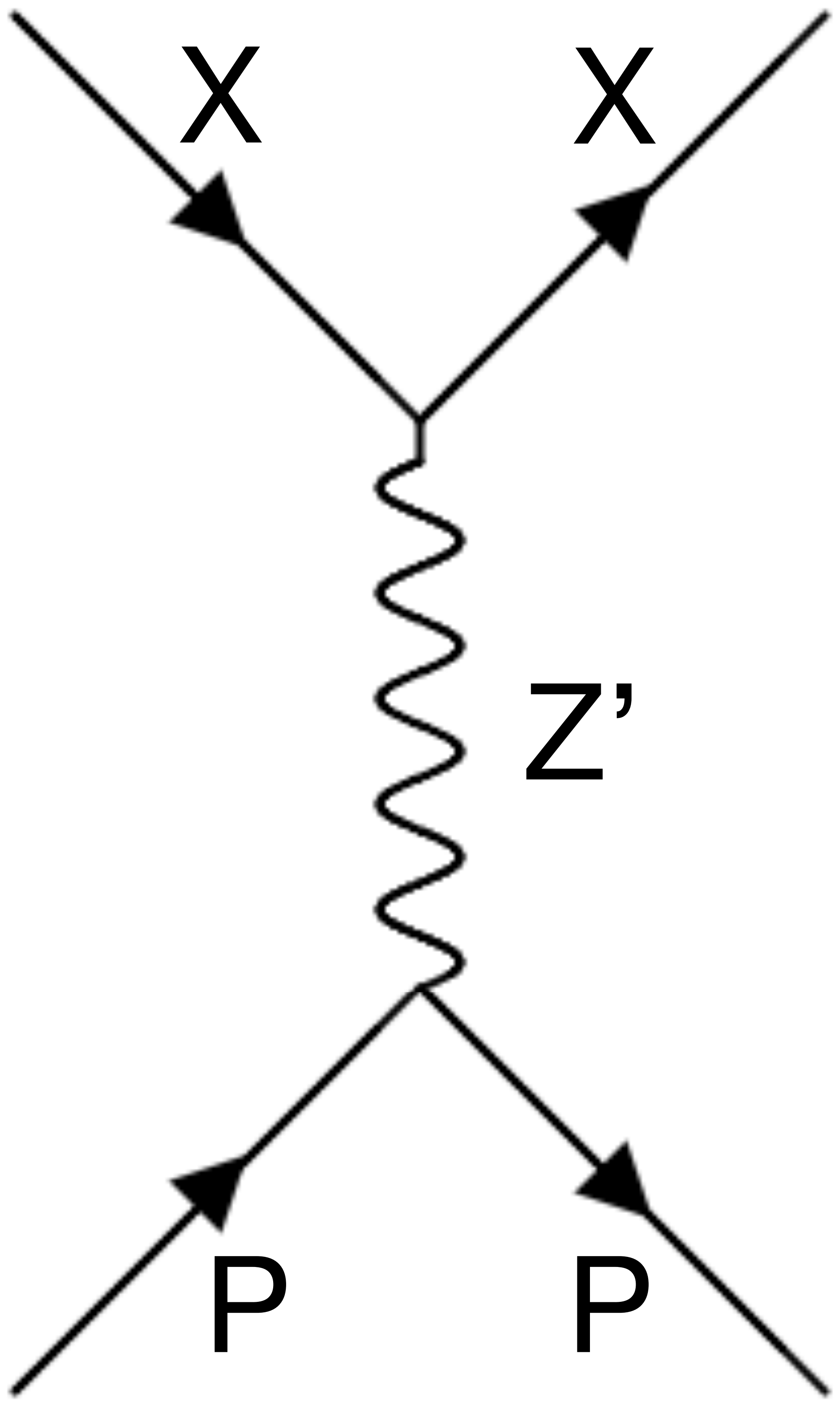


Specific to this work

- Relating DM-proton cross section to DM-electron cross section through hadronic loops
- Fermionic DM with a vector mediator
- 1-100 MeV
- $\sigma_{pX} = 10^{-34} - 10^{-26}\text{cm}^2$
- Use Electron recoil direct detectors to derive new constraints on σ_{pX}

LOOPS

Loops produce effective interactions



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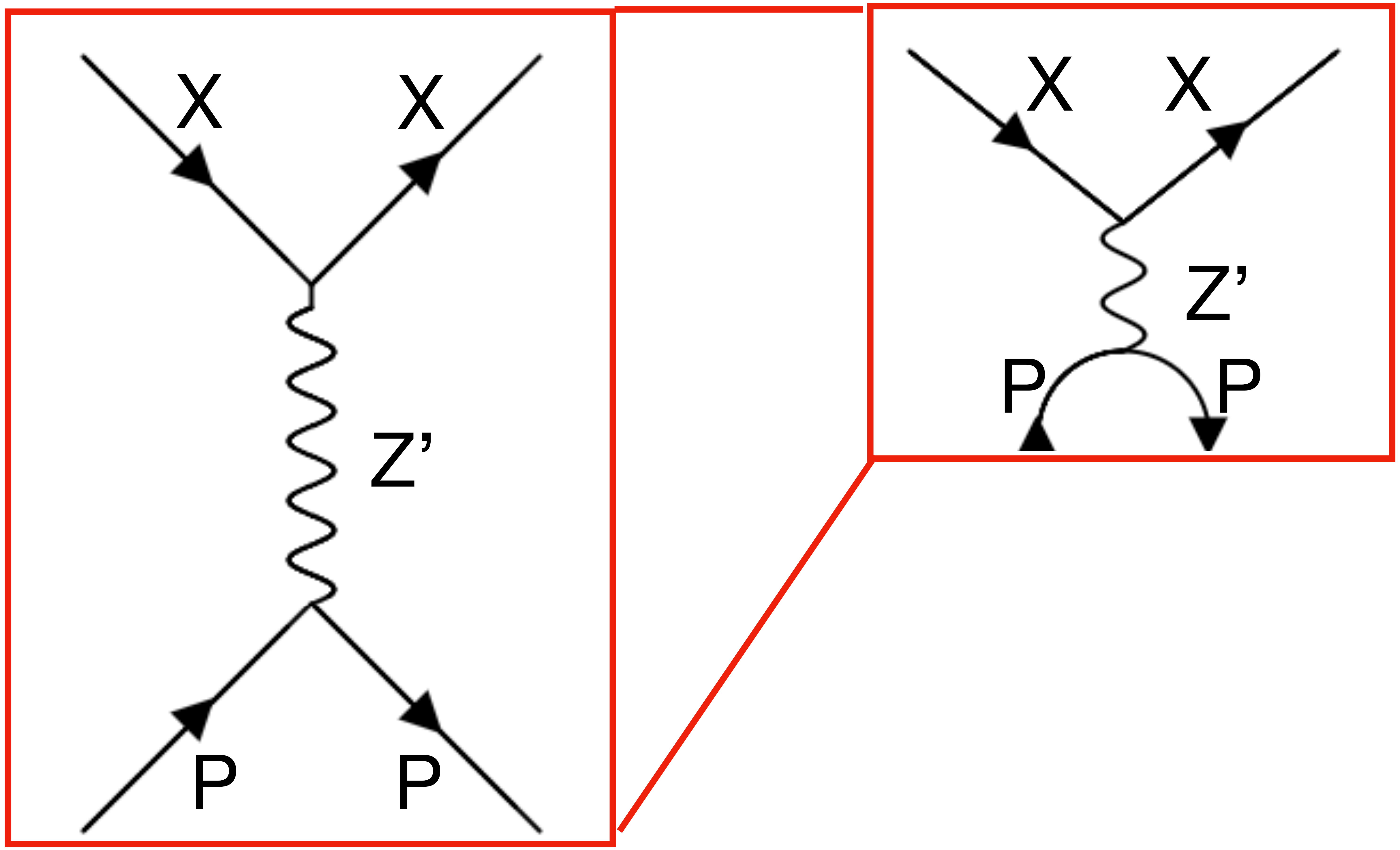

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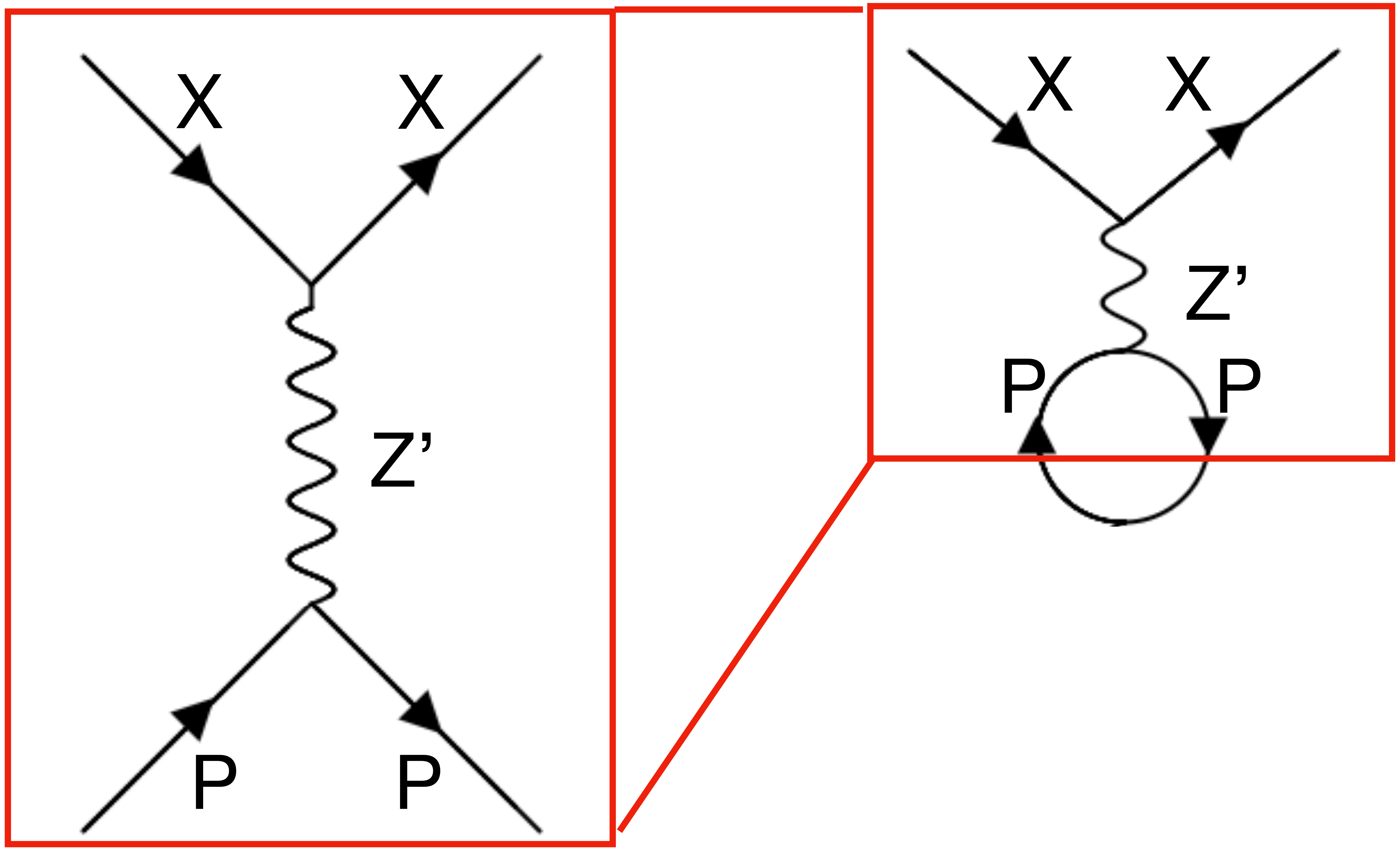

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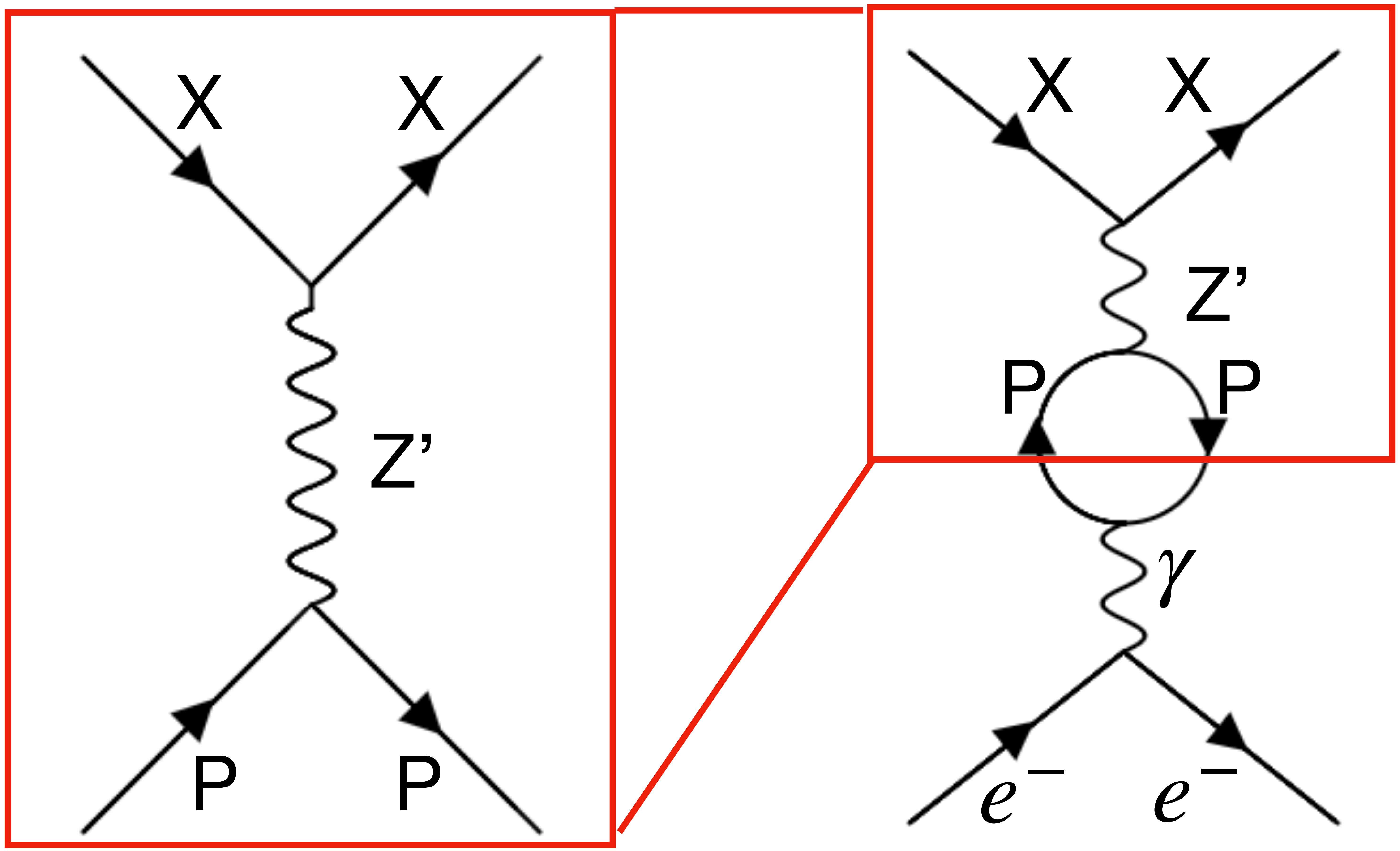

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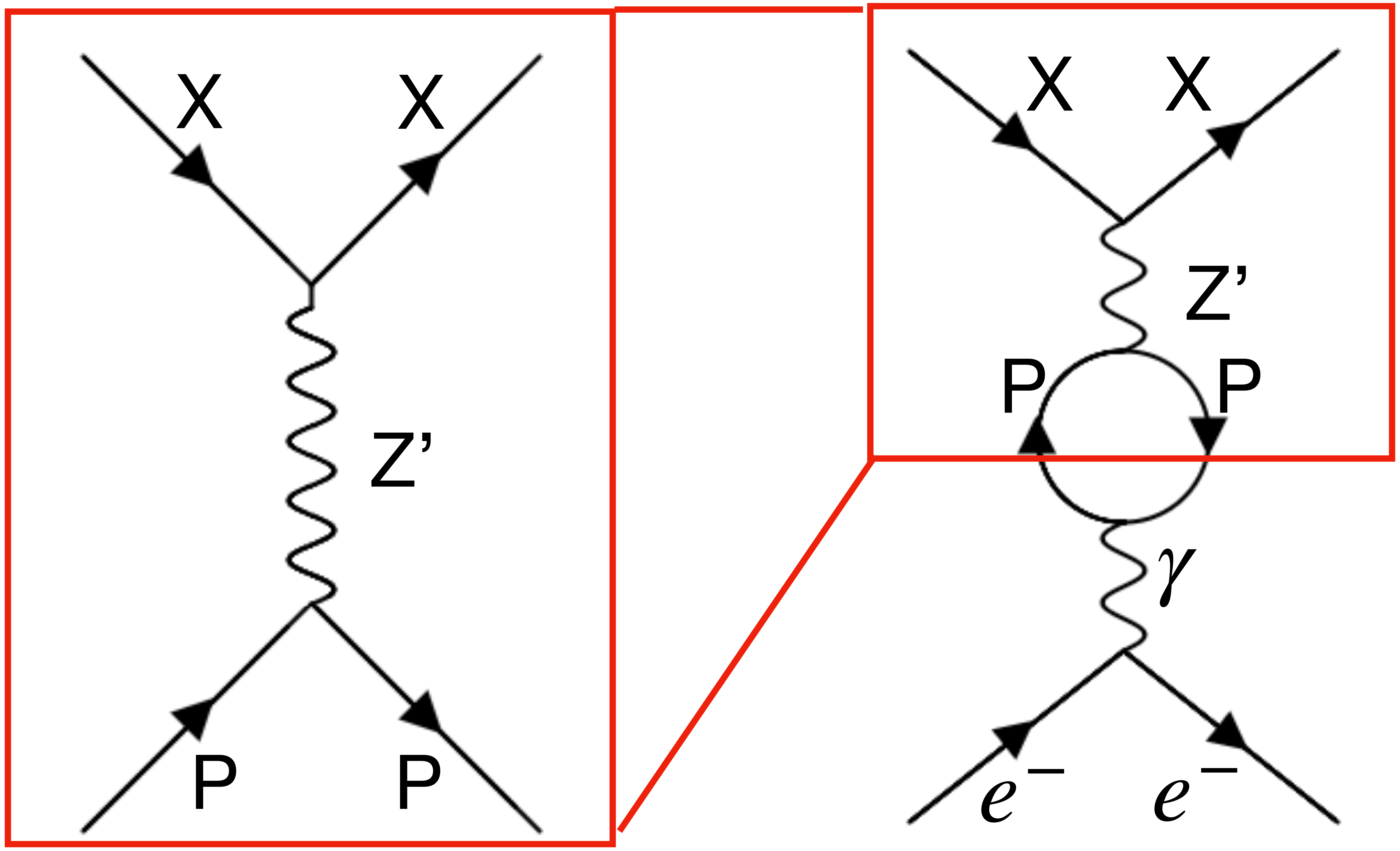
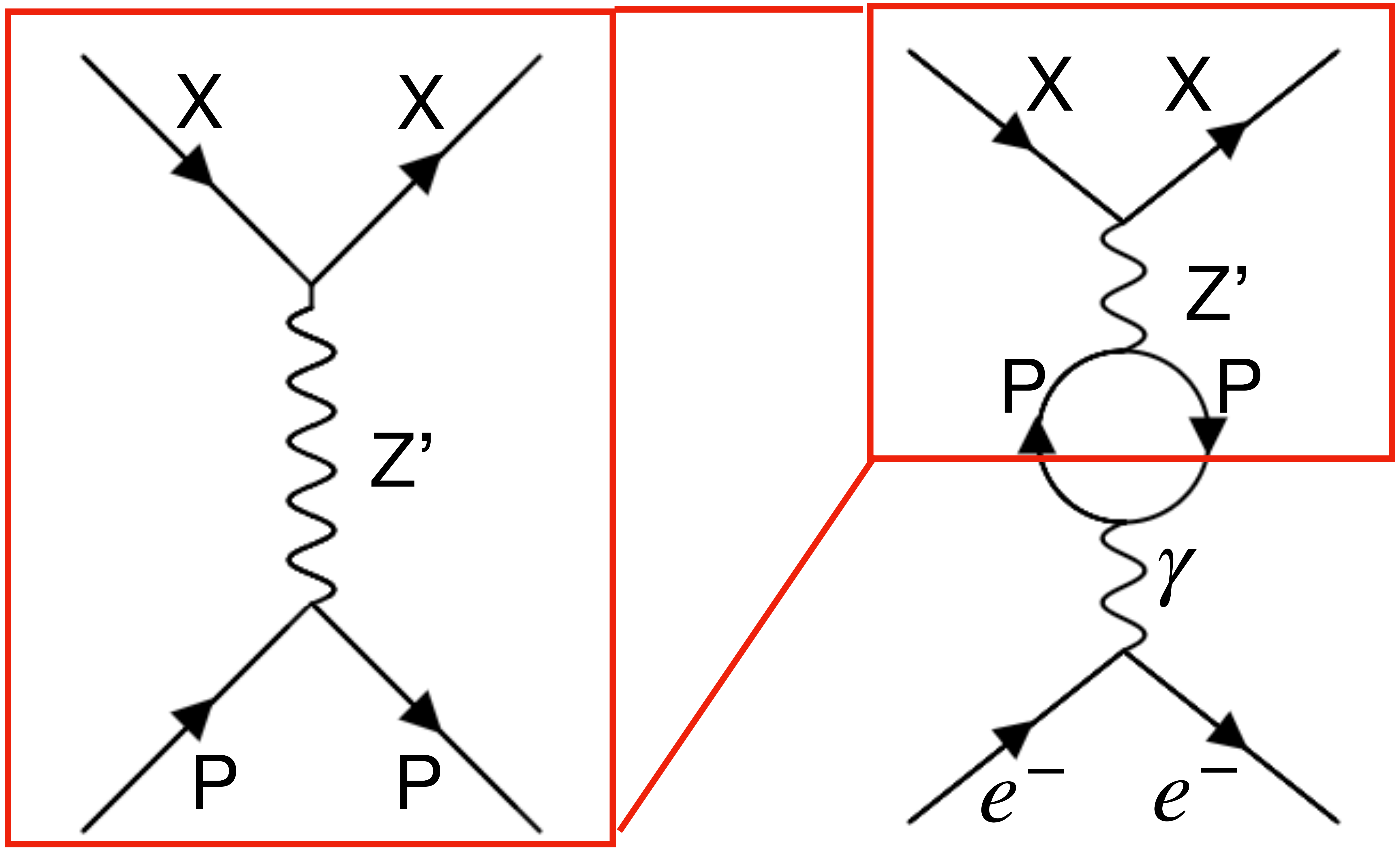


Lepton loops used to look for leptophillic DM at LHC

[Bell, Cai, Leane, Medina (2014)]

Loops produce effective interactions



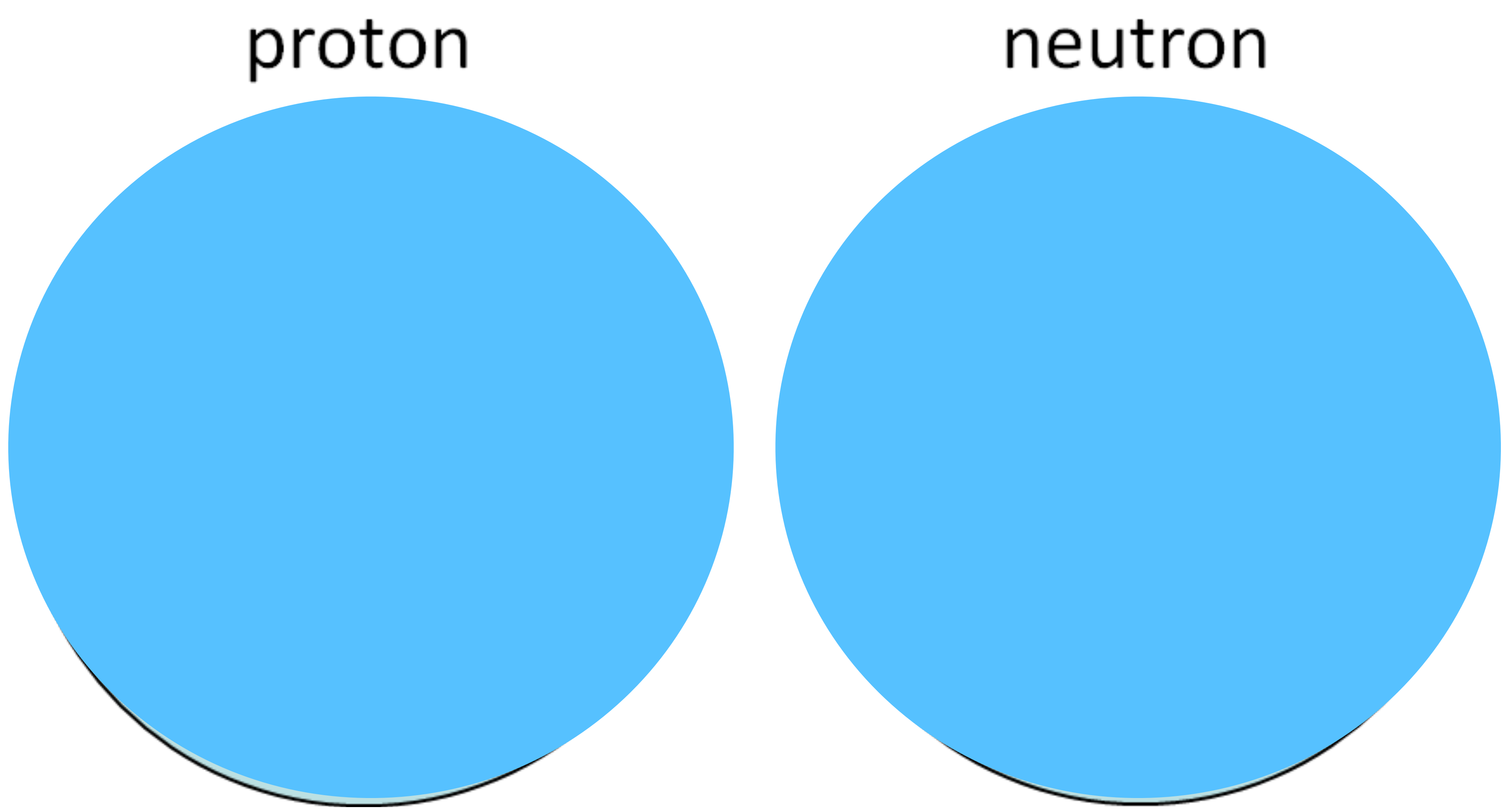
Lepton loops used to look for leptophillic DM at LHC

[Bell, Cai, Leane, Medina (2014)]

Lepton loops used to rule out parts of leptophillic DM parameter space through Nucleon recoil direct detection experiments

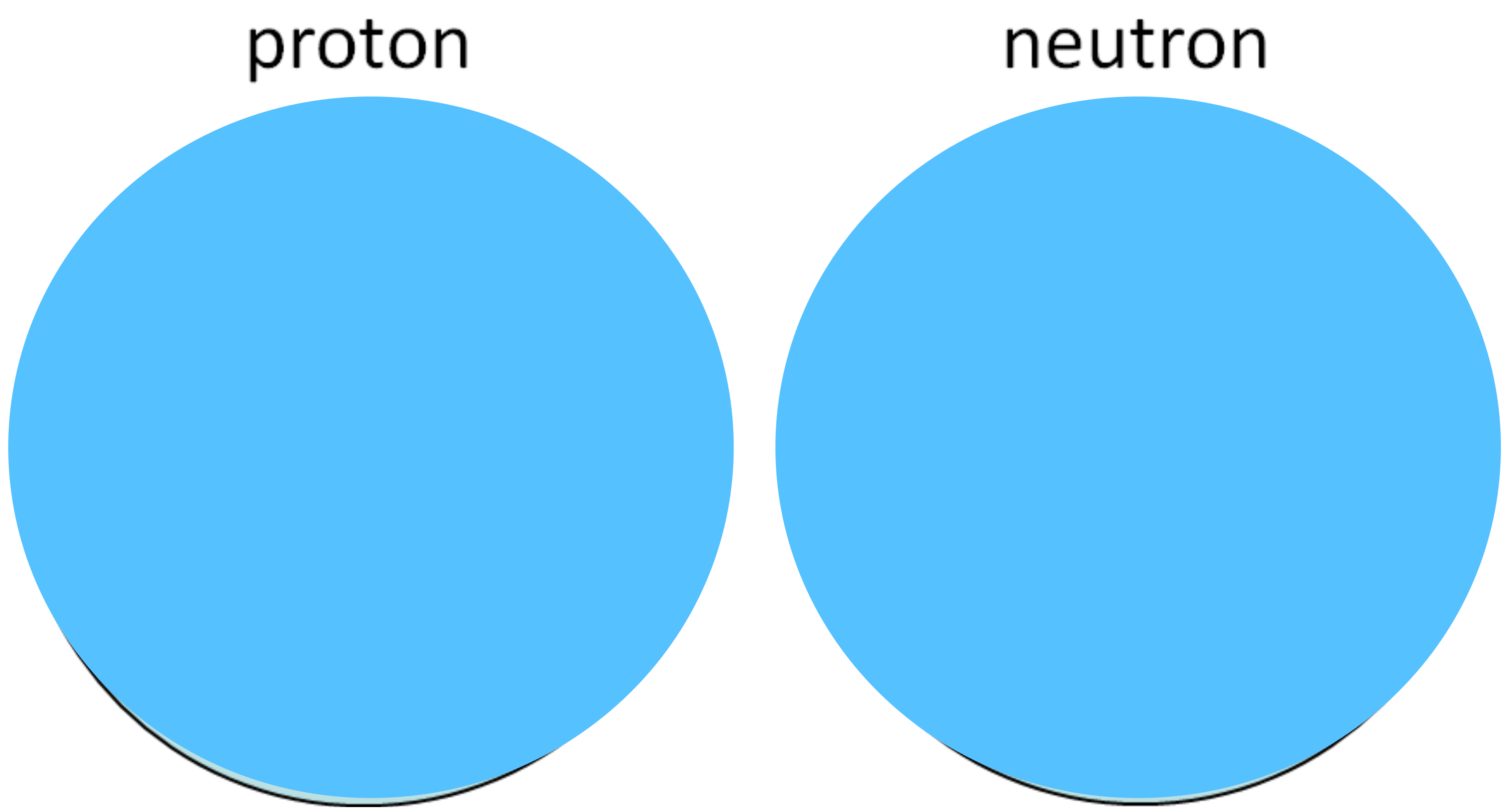
[Kopp, Michaels, Smirnov (2014)]

Introducing QCD to DM Loops



Introducing QCD to DM Loops

- DM scattering off nucleons => DM scattering off of quarks



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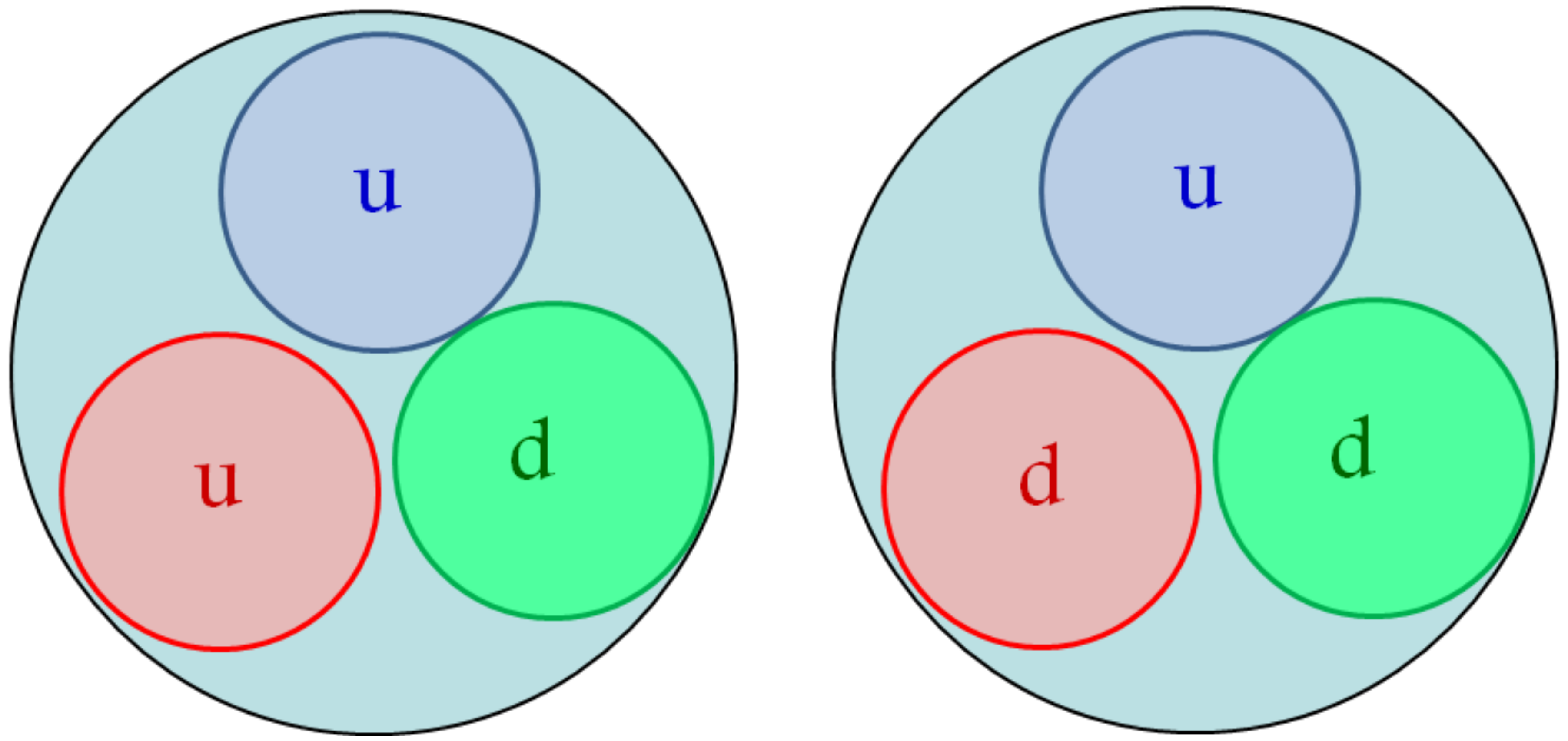
Quarks!



Introducing QCD to DM Loops

- DM scattering off nucleons => DM scattering off of quarks
- DM scattering with quarks => QCD

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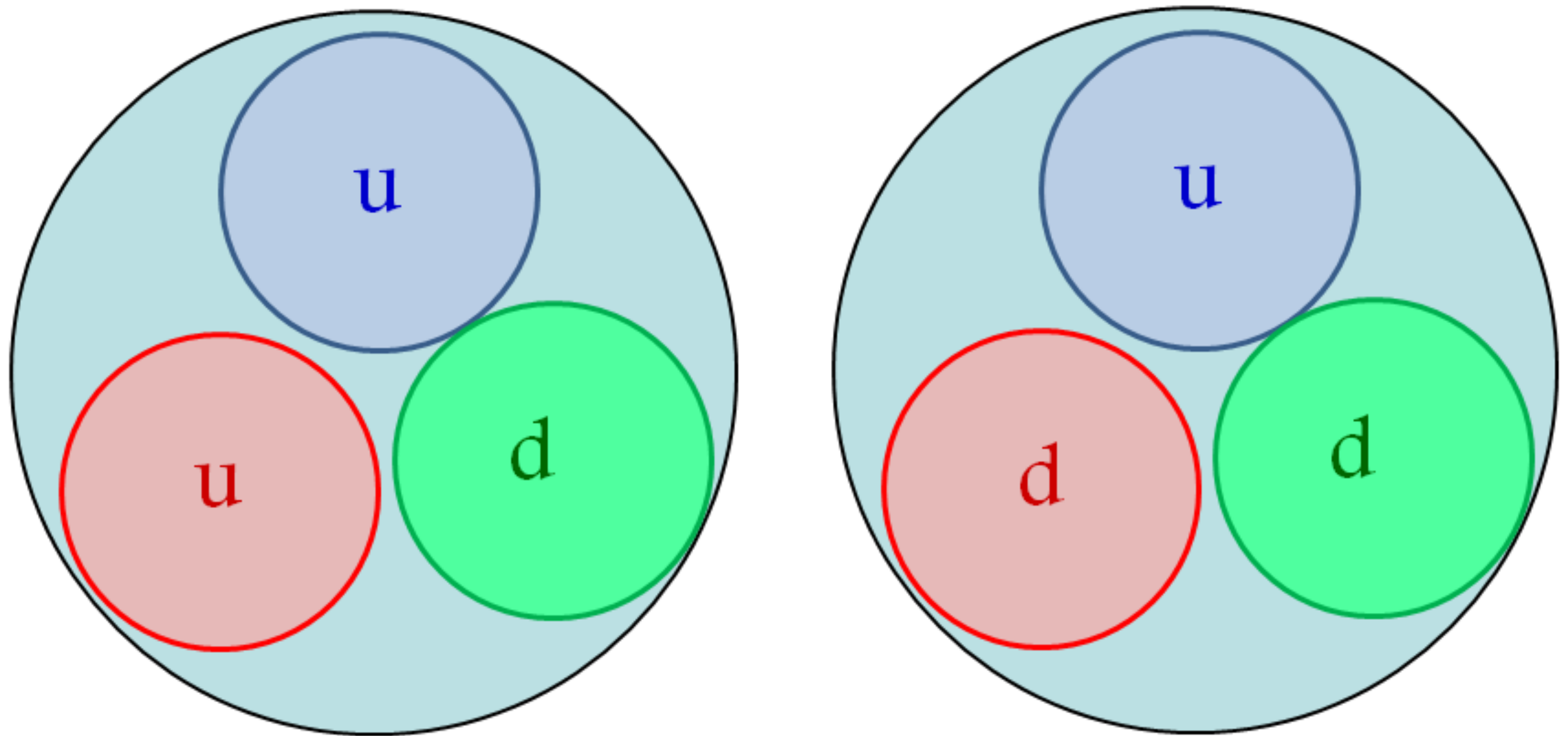
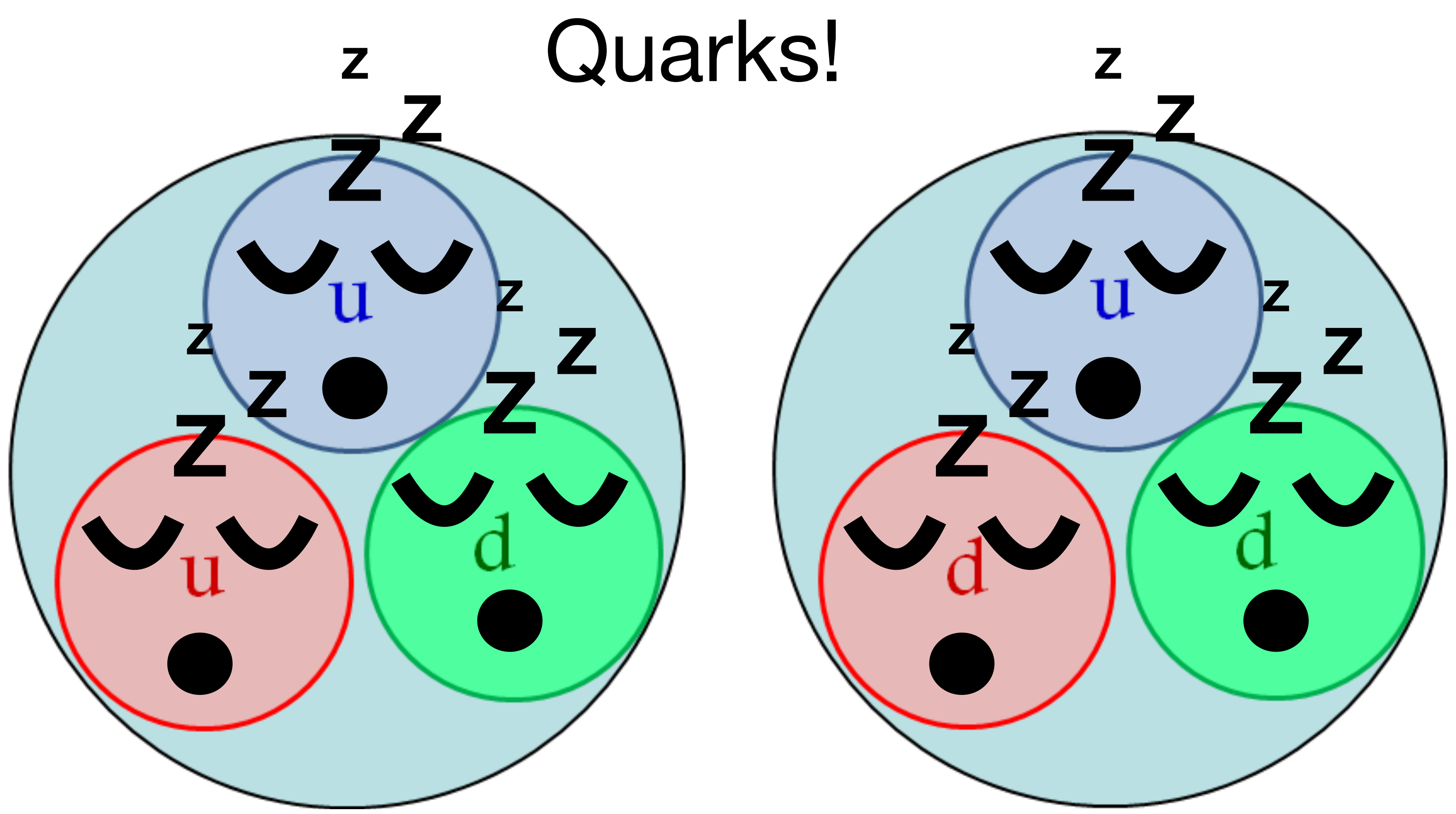


Introducing QCD to DM Loops

- DM scattering off nucleons => DM scattering off of quarks
- DM scattering with quarks => QCD
- Low energy scattering => low energy QCD (aka Chiral effective field theory)



Low Energy

Introducing QCD to DM Loops

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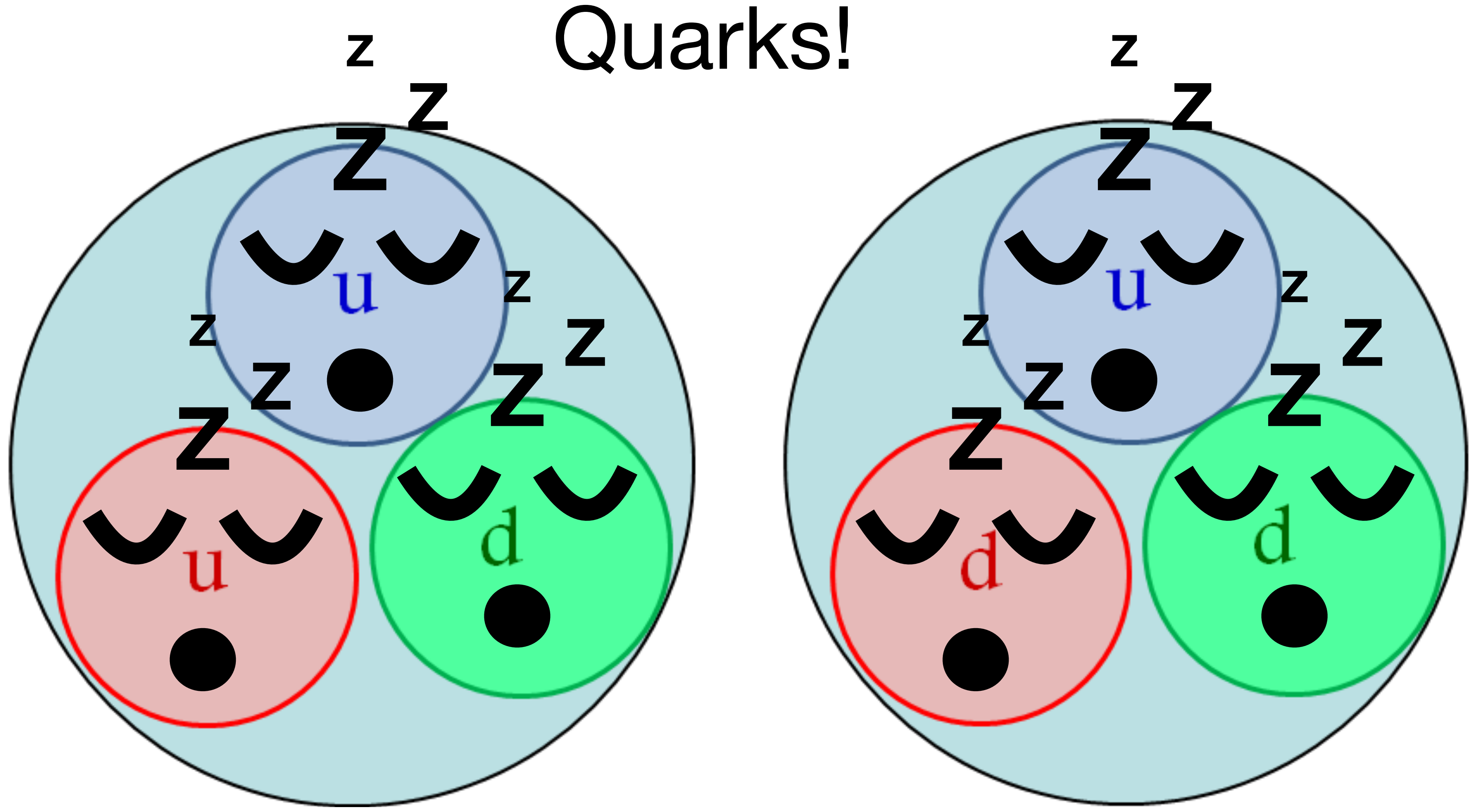
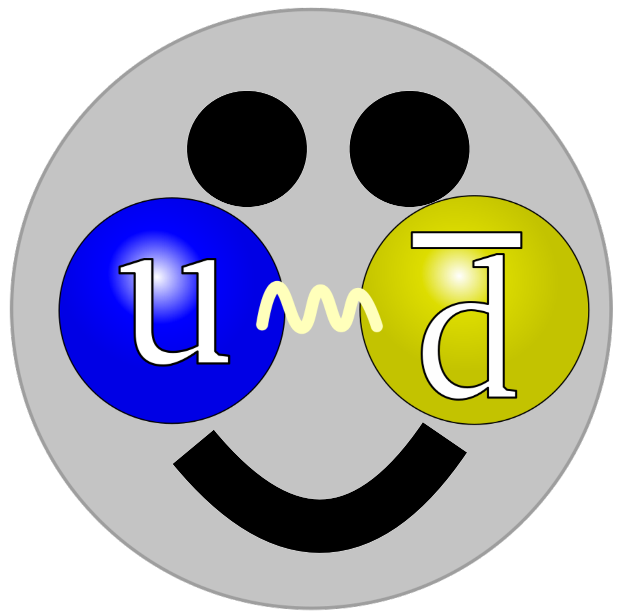


Low Energy

Light Mesons (pions)



Chiral Effective Interaction

1. Start with DM interaction with quarks

Sum over all quarks

Vector coupling

$$\mathscr{L} \supset \Sigma_q \ \alpha_q Z'_\mu q \gamma^\mu \bar{q}$$

Coupling to each quark

Chiral Effective Interaction

Quark interaction

$$\mathscr{L} \supset \Sigma_q \; \alpha_q Z'_\mu q \gamma^\mu \bar{q}$$

1. Start with DM interaction with quarks

2. Find effective interaction with nuclei

Proton Interaction

$$\mathscr{L} \supset (2\alpha_u + \alpha_d)\; Z'_\mu p \gamma^\mu \bar{p}$$

Effective coupling from quark Composition of proton

Vector coupling

Chiral Effective Interaction

1. Start with DM interaction with quarks

2. Find effective interaction with nuclei

3. Find effective coupling with light mesons

Quark interaction

$$\mathscr{L} \supset \Sigma_q \, \alpha_q Z'_\mu q \gamma^\mu \bar{q}$$

Proton Interaction

$$\mathscr{L} \supset (2\alpha_u + \alpha_d) \, Z'_\mu p \gamma^\mu \bar{p}$$

Pion interaction

$$\mathscr{L} \supset (\alpha_u - \alpha_d) \, Z'_\mu \, (\partial^\mu \pi^+ \pi^- - \partial^\mu \pi^- \pi^+)$$

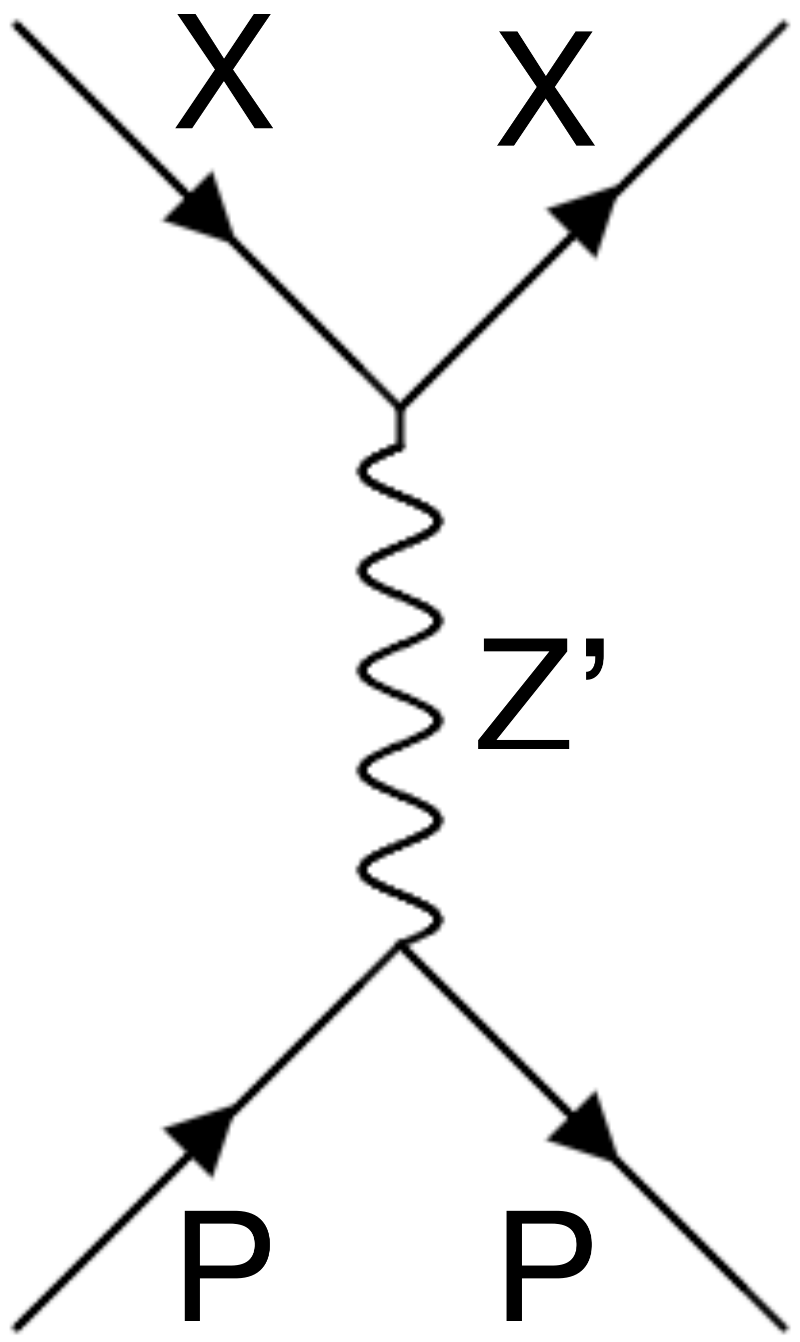
Effective coupling from quark
Composition of pion

Scalar coupling

Calculating the Cross Sections

$$\mathscr{L} \supset \Sigma_q \, \alpha_q Z'_\mu q \gamma^\mu \bar{q}$$

Calculating the Cross Sections



Proton scattering

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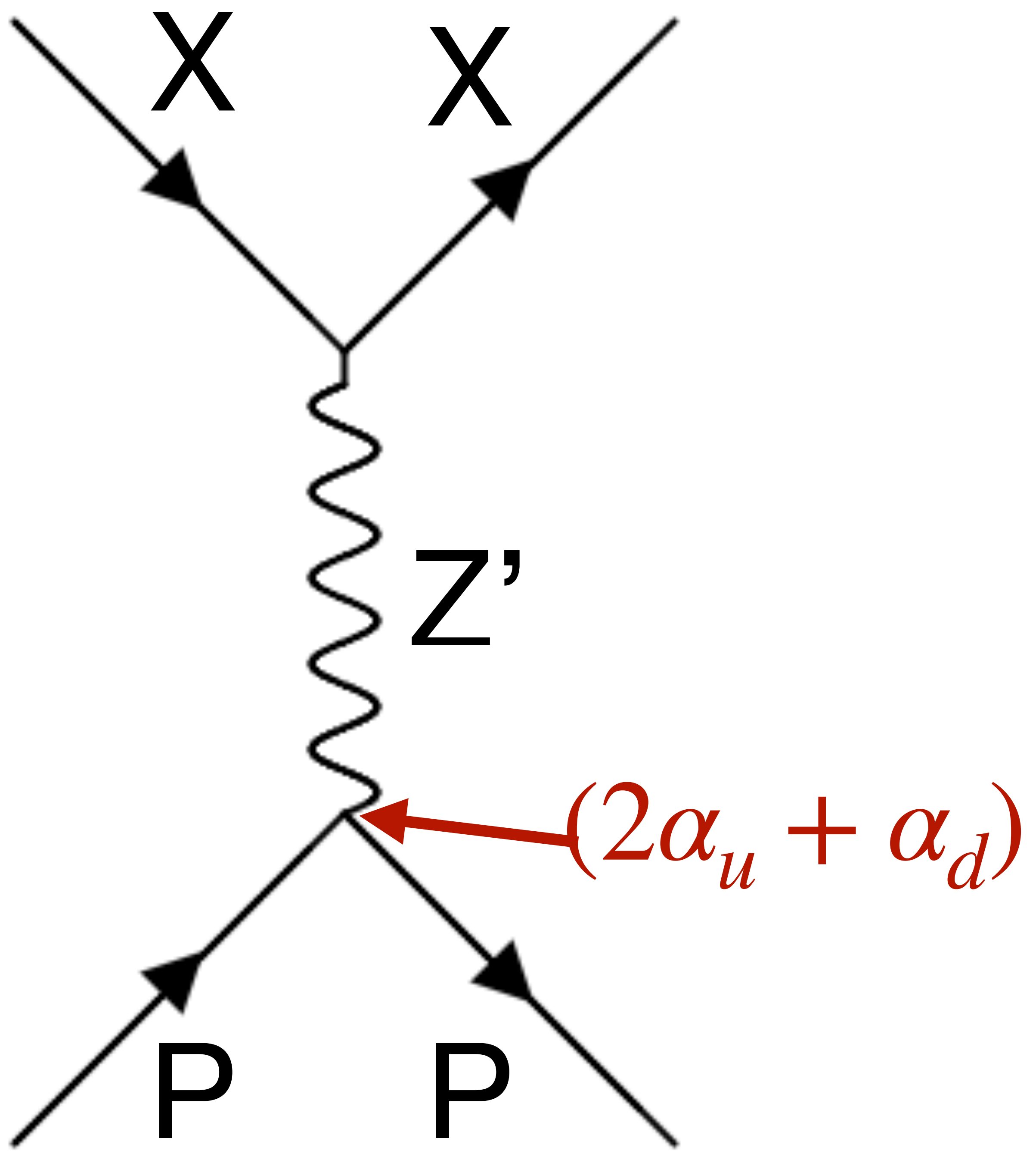
Calculating the Cross Sections



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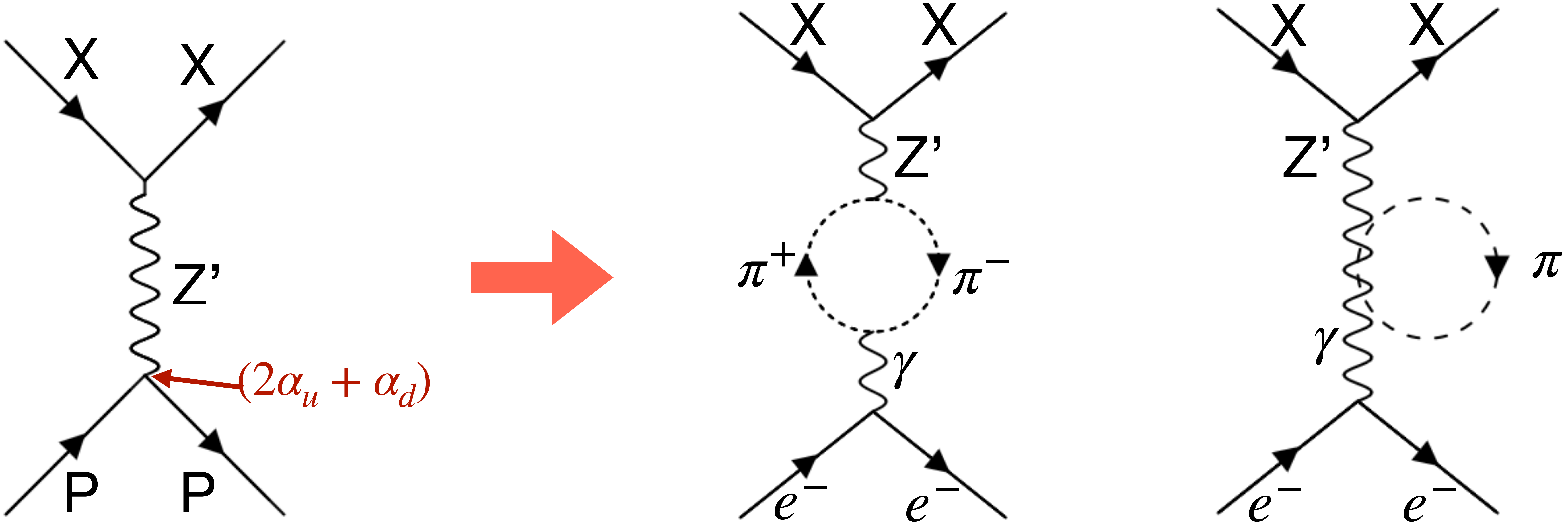

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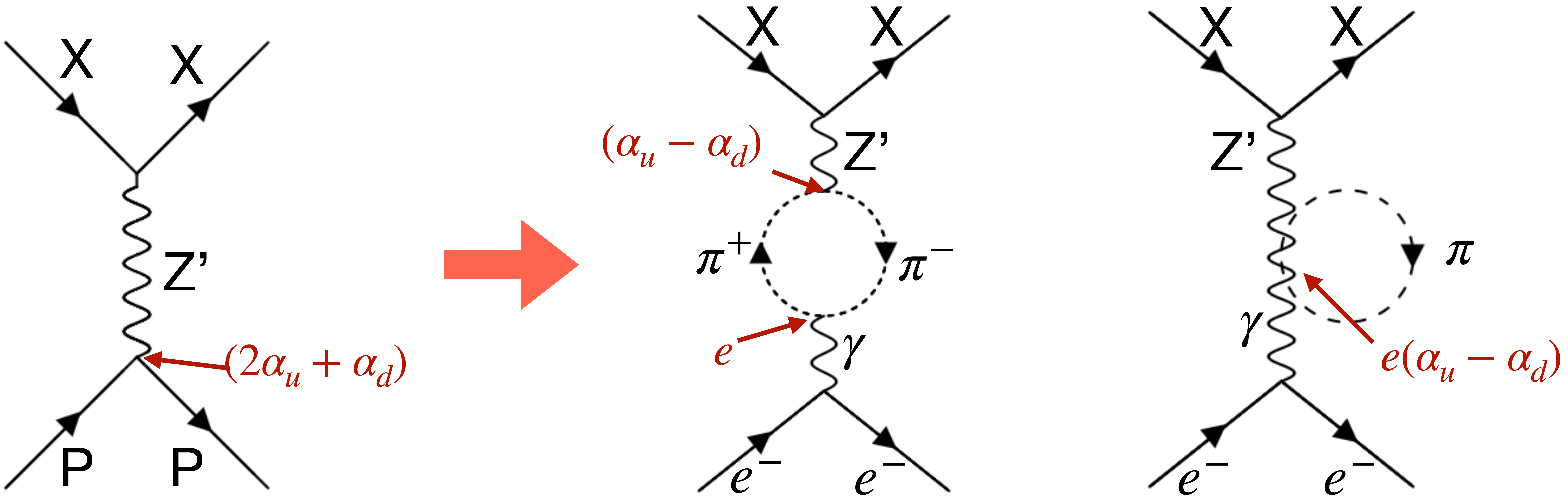

Proton scattering

Electron scattering
Through pion loops

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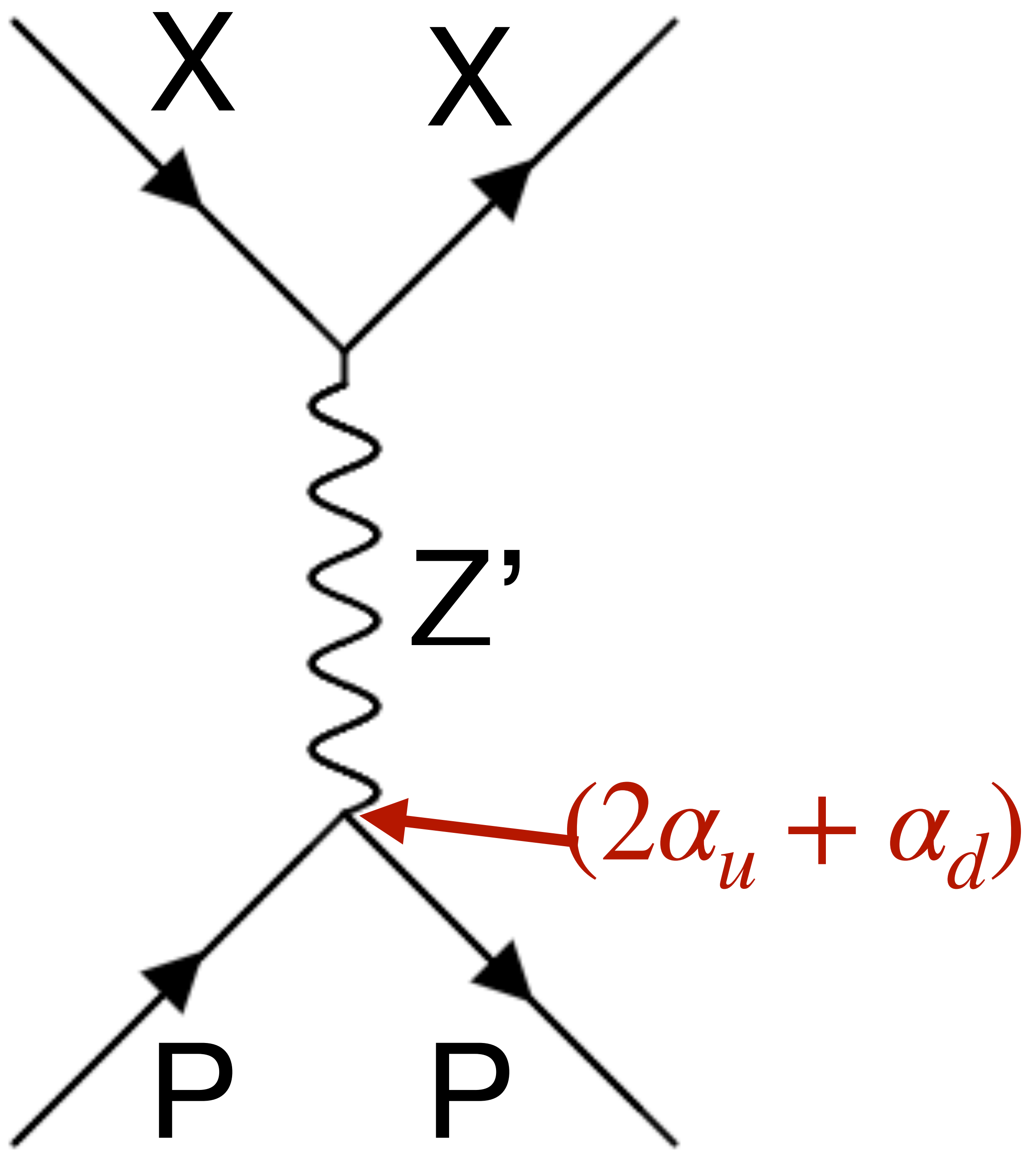
Calculating the Cross Sections



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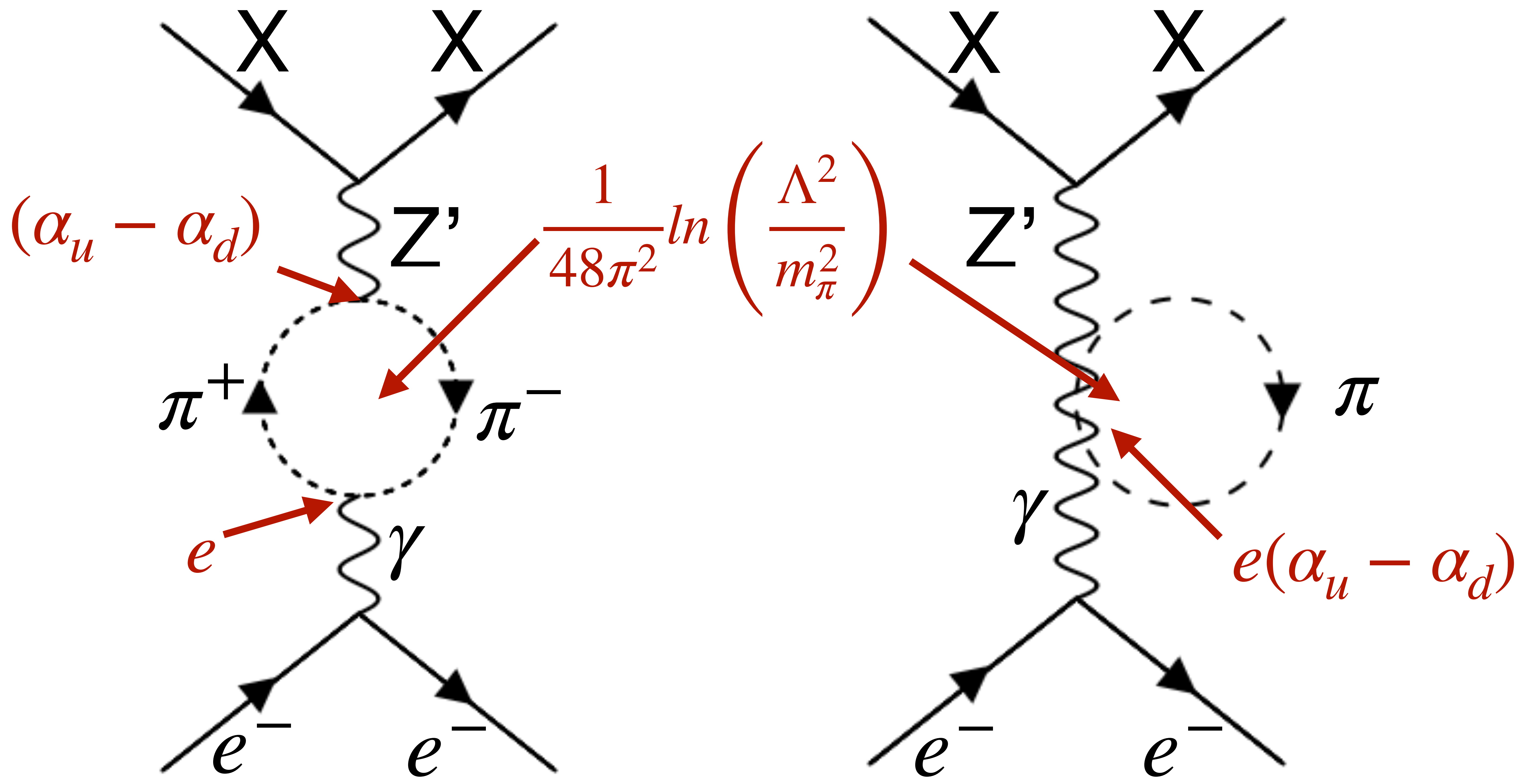

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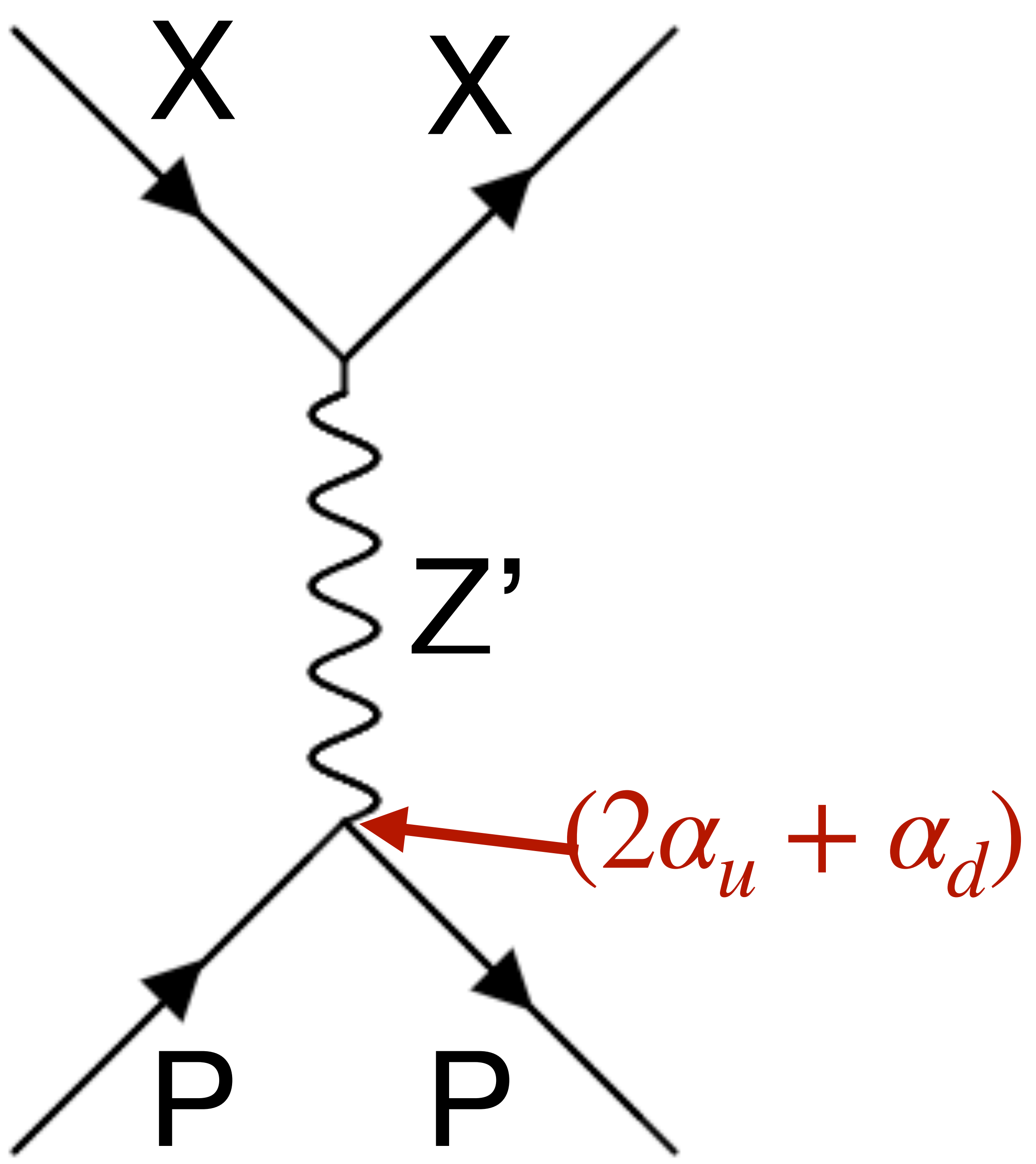

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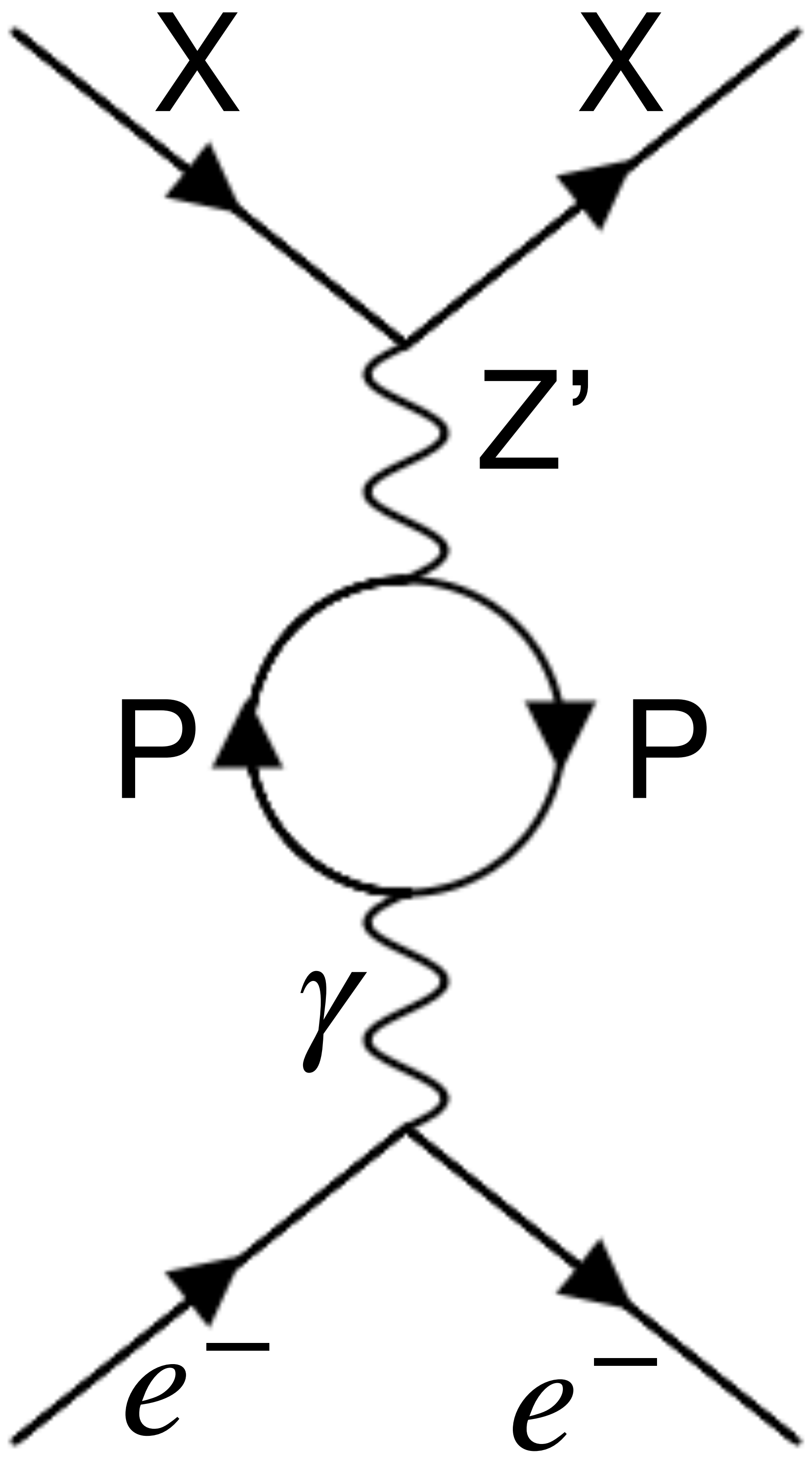
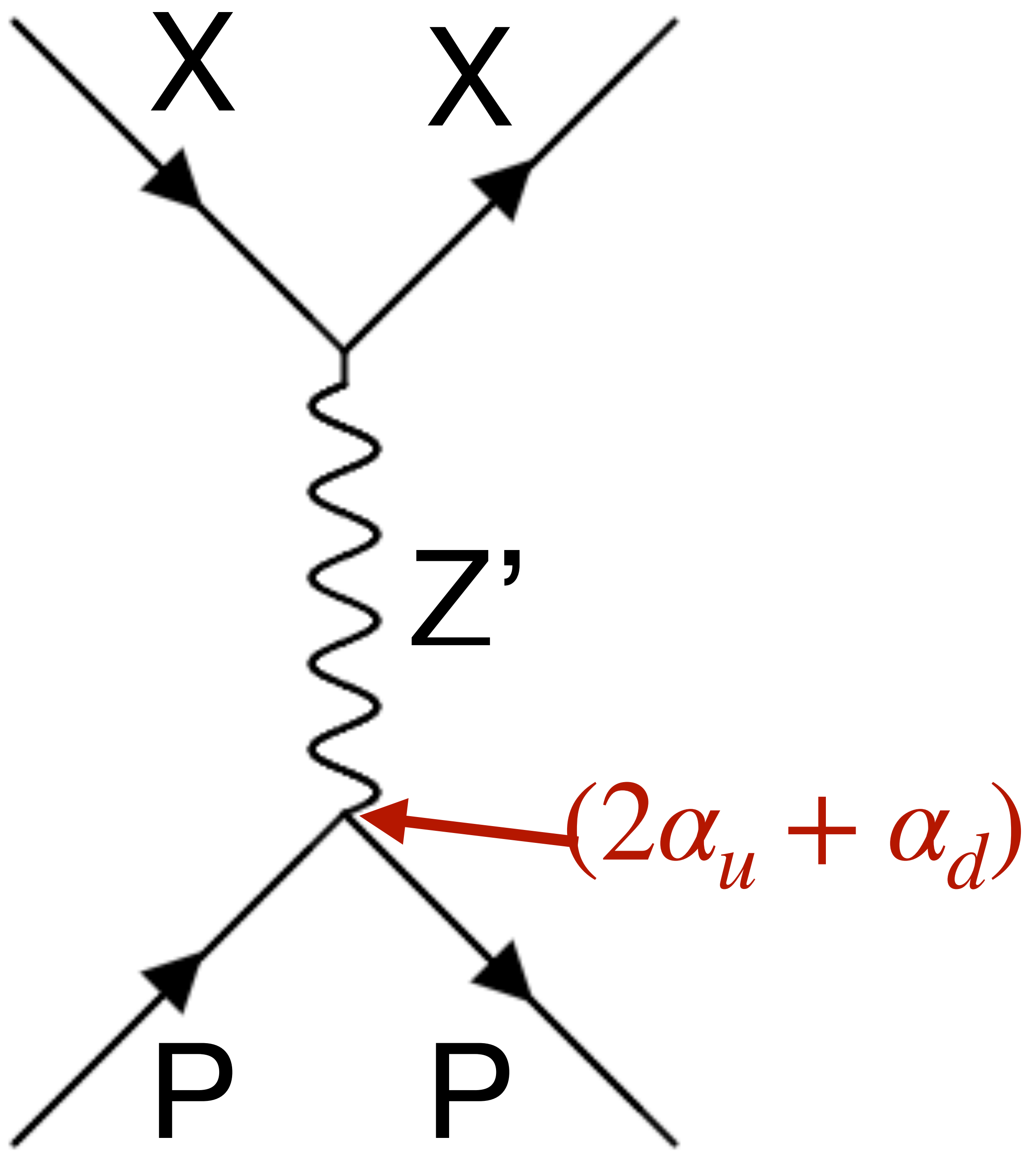


Electron scattering through Proton loop

$$\mathscr{L} \supset \Sigma_q \, \alpha_q Z'_\mu q \gamma^\mu \bar{q}$$

Calculating the Cross Sections



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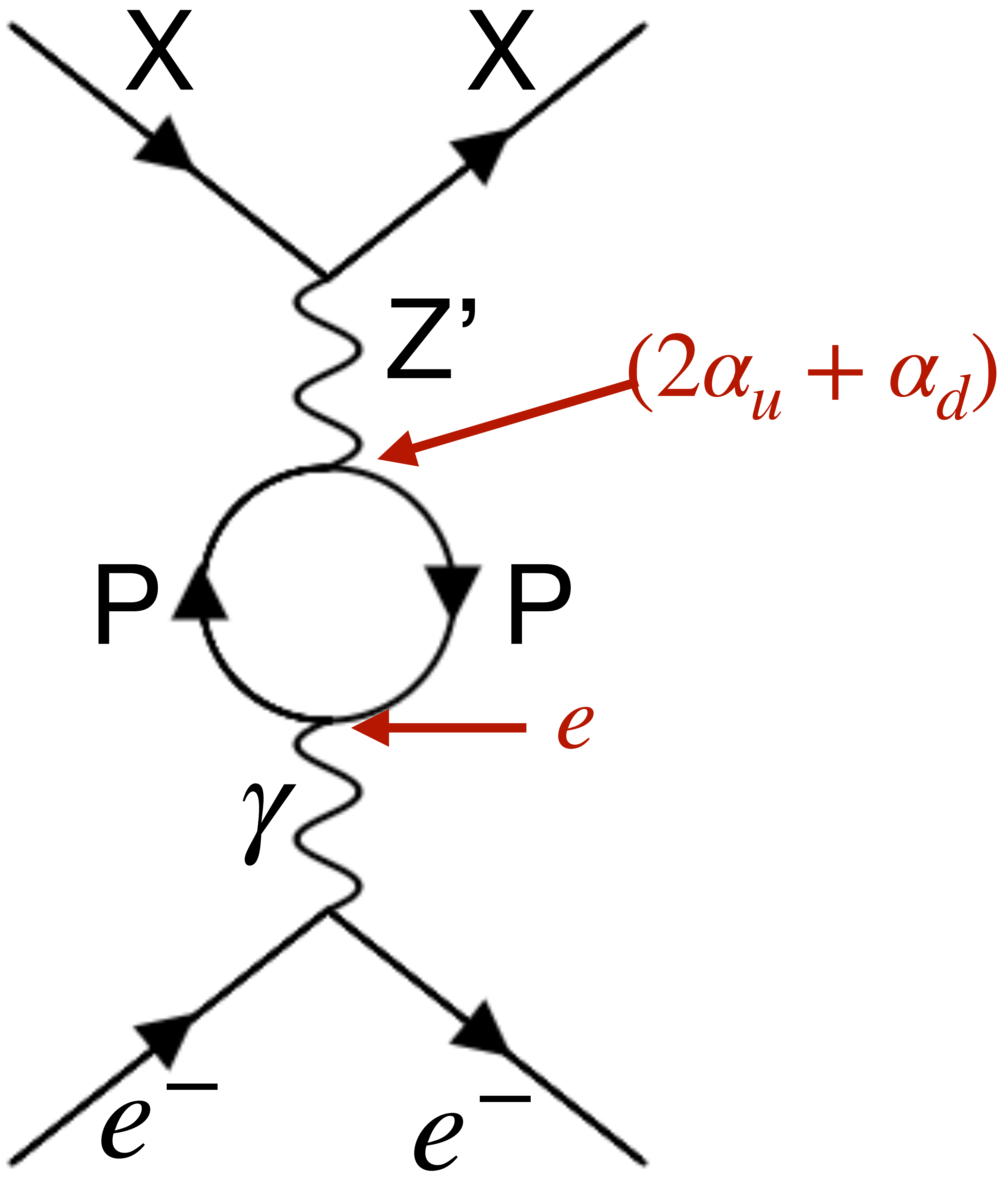

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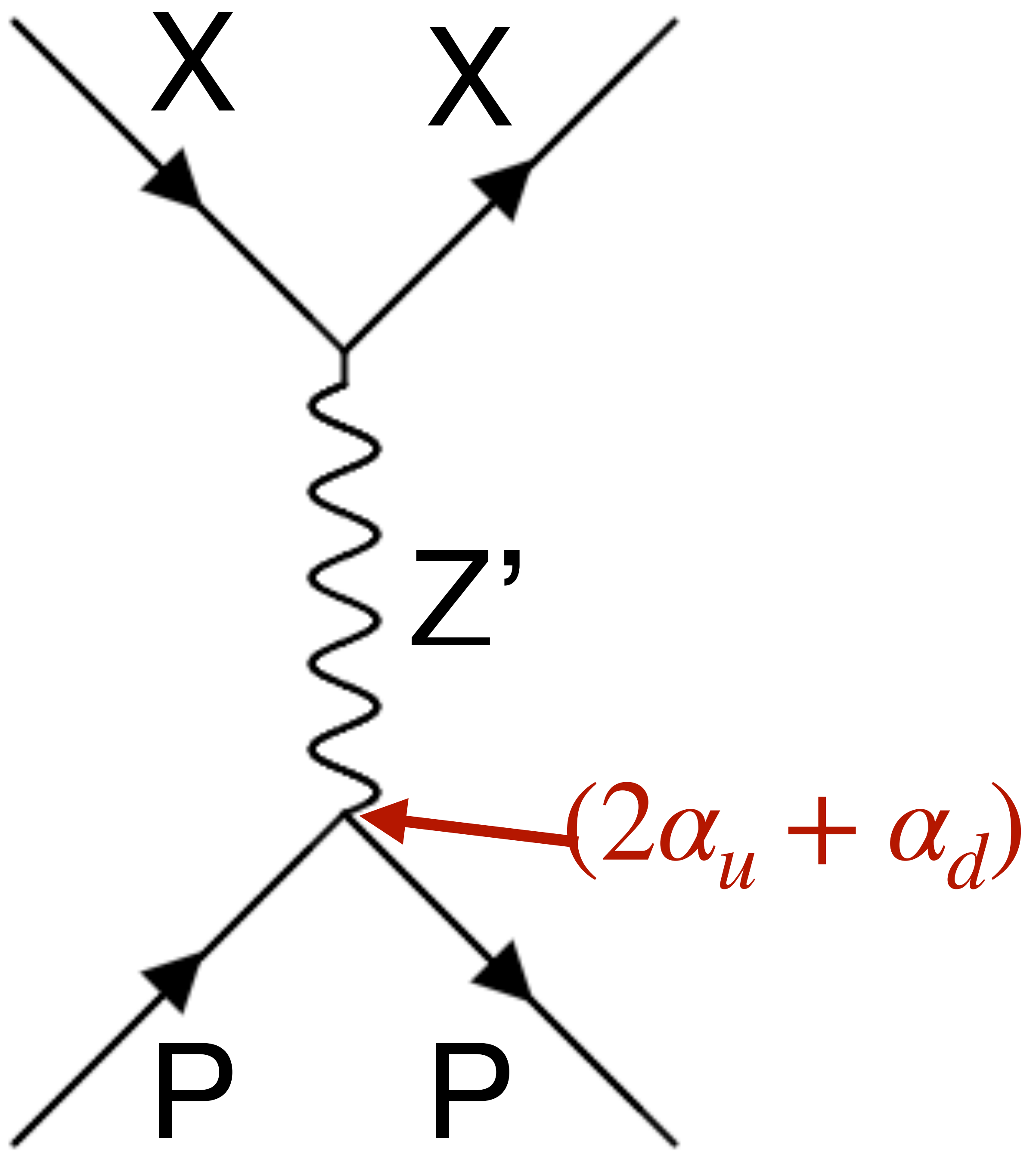

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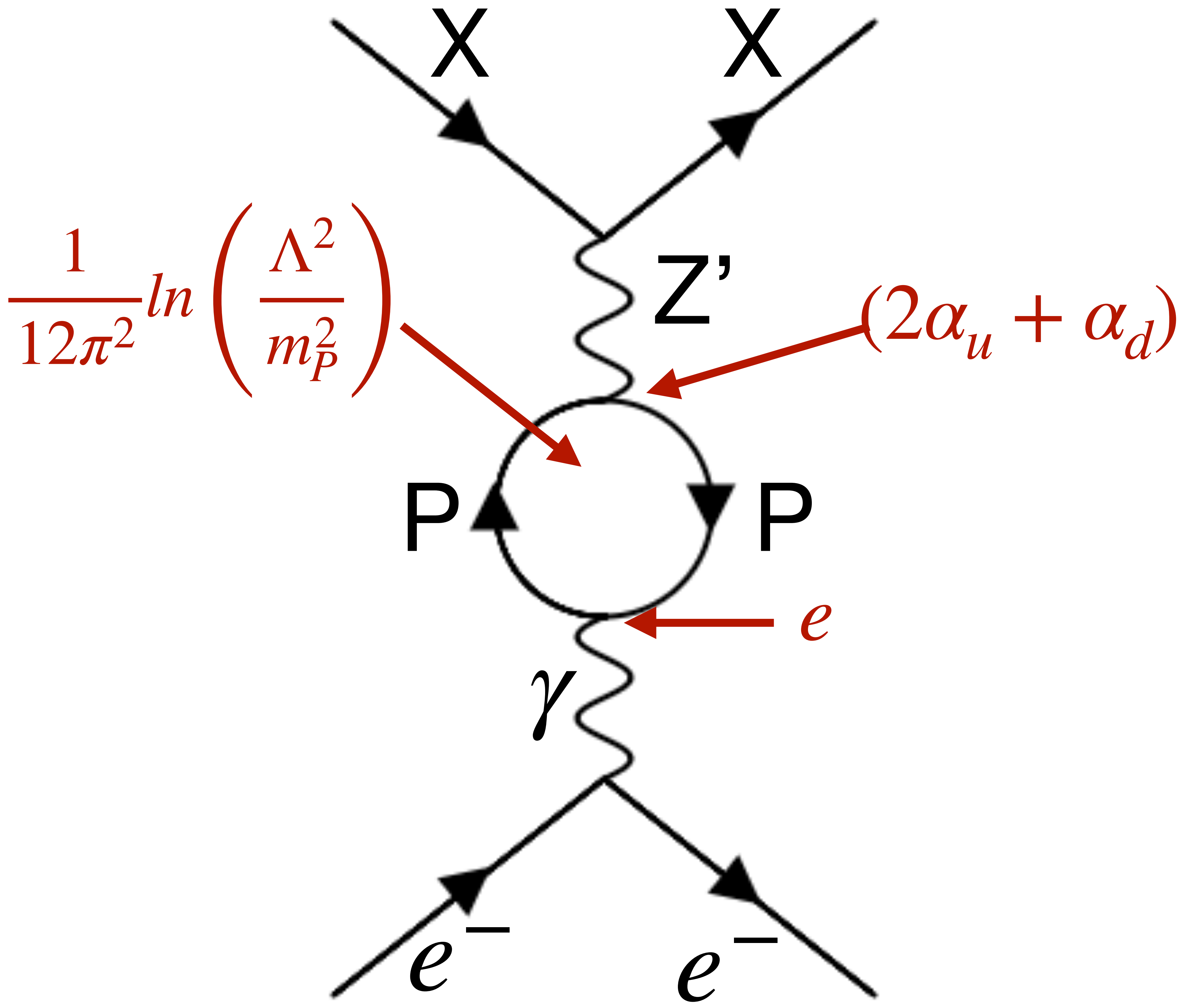

Electron scattering through Proton loop

$$\mathscr{L} \supset \Sigma_q\ \alpha_q Z'_\mu q \gamma^\mu \bar{q}$$

Effective Electron Cross Section

$$\sigma_{Xe} = \frac{\sigma_{Xp}}{(2\alpha_u + \alpha_d)^2} \frac{e^2}{2304\ \pi^4} \left(4(2\alpha_u + \alpha_d) ln \left(\frac{\Lambda^2}{m_p^2} \right) + (\alpha_u - \alpha_d) ln \left(\frac{\Lambda^2}{m_\pi^2} \right) \right)^2 e^2 \left(\frac{\mu_{eX}}{\mu_{pX}} \right)^2$$

Proton tree
level interaction

Effective Electron Cross Section

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Proton tree
level interaction

Loop
Contribution

Effective Electron Cross Section

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Proton tree
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Proton Loop

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Proton tree
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Proton Loop

Pion Loop

Effective Electron Cross Section

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Proton tree level interaction

Proton Loop

Pion Loop

Electron Coupling and reduced mass

Effective Electron Cross Section

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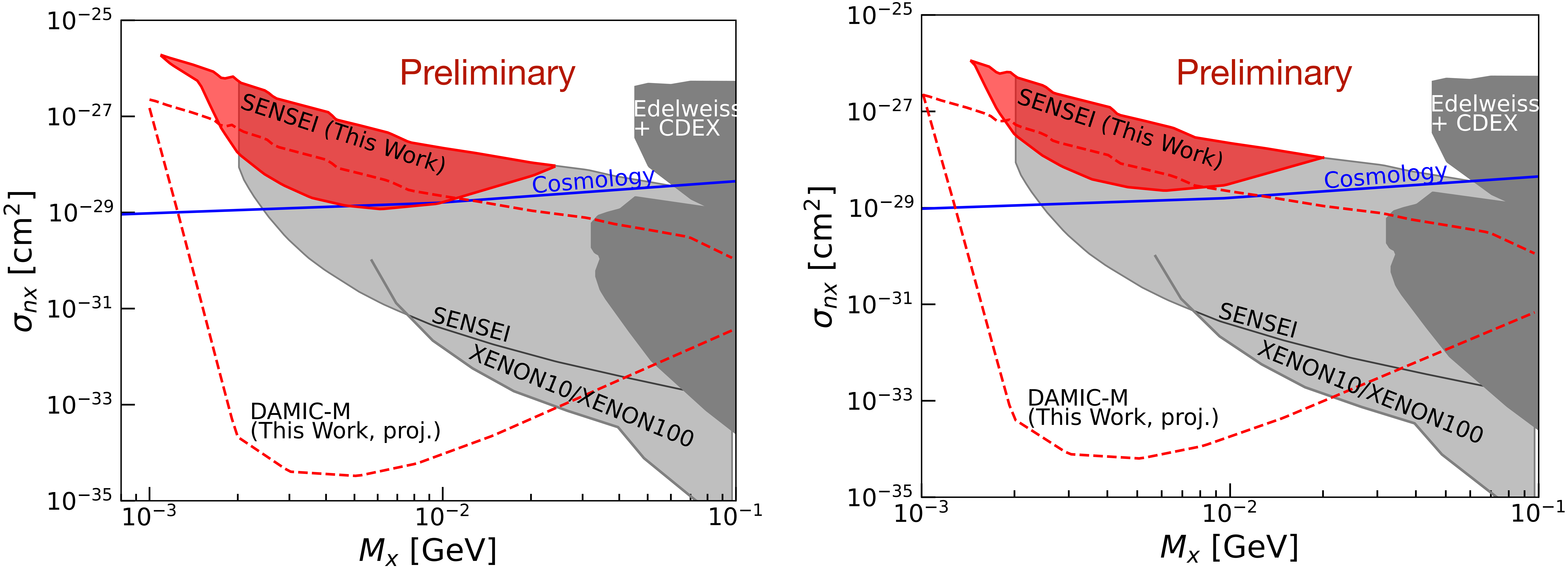
$$\sigma_{Xe} \simeq 10^{-14}\frac{\sigma_{Xp}}{(2\alpha_u + \alpha_d)^2}\left(4(2\alpha_u + \alpha_d)ln\left(\frac{\Lambda^2}{m_p^2}\right) + (\alpha_u - \alpha_d)ln\left(\frac{\Lambda^2}{m_\pi^2}\right)\right)^2\left(\frac{m_X + m_p}{m_e + m_X}\right)^2$$

Probe Hadrophilic DM with a Heavy Mediator using Electron Recoil Detectors



$\alpha_u = -\alpha_d \, , \alpha_s = 0$

Pion Contribution only

$\alpha_u = \alpha_d = \alpha_s$

Proton Contribution only

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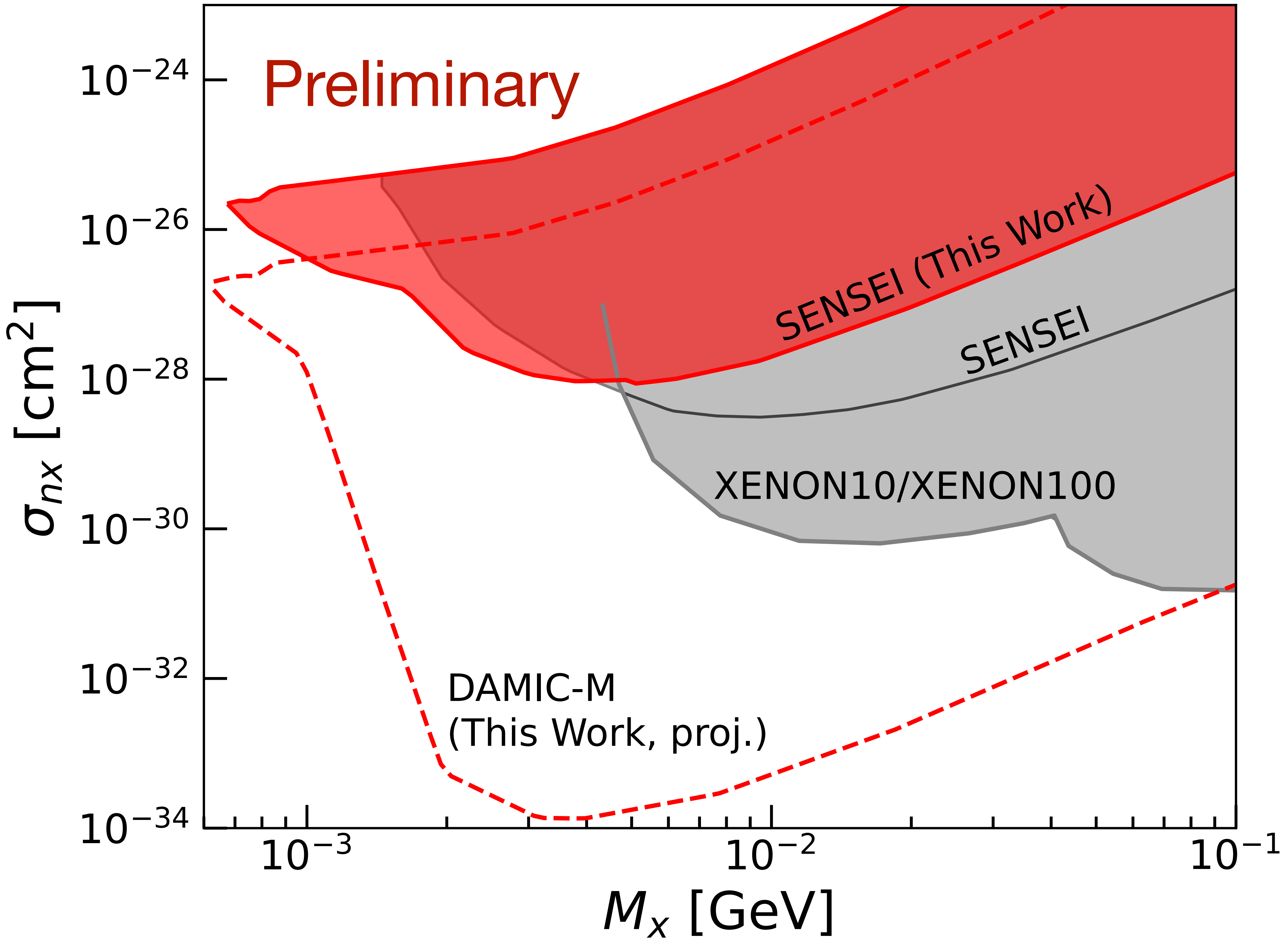

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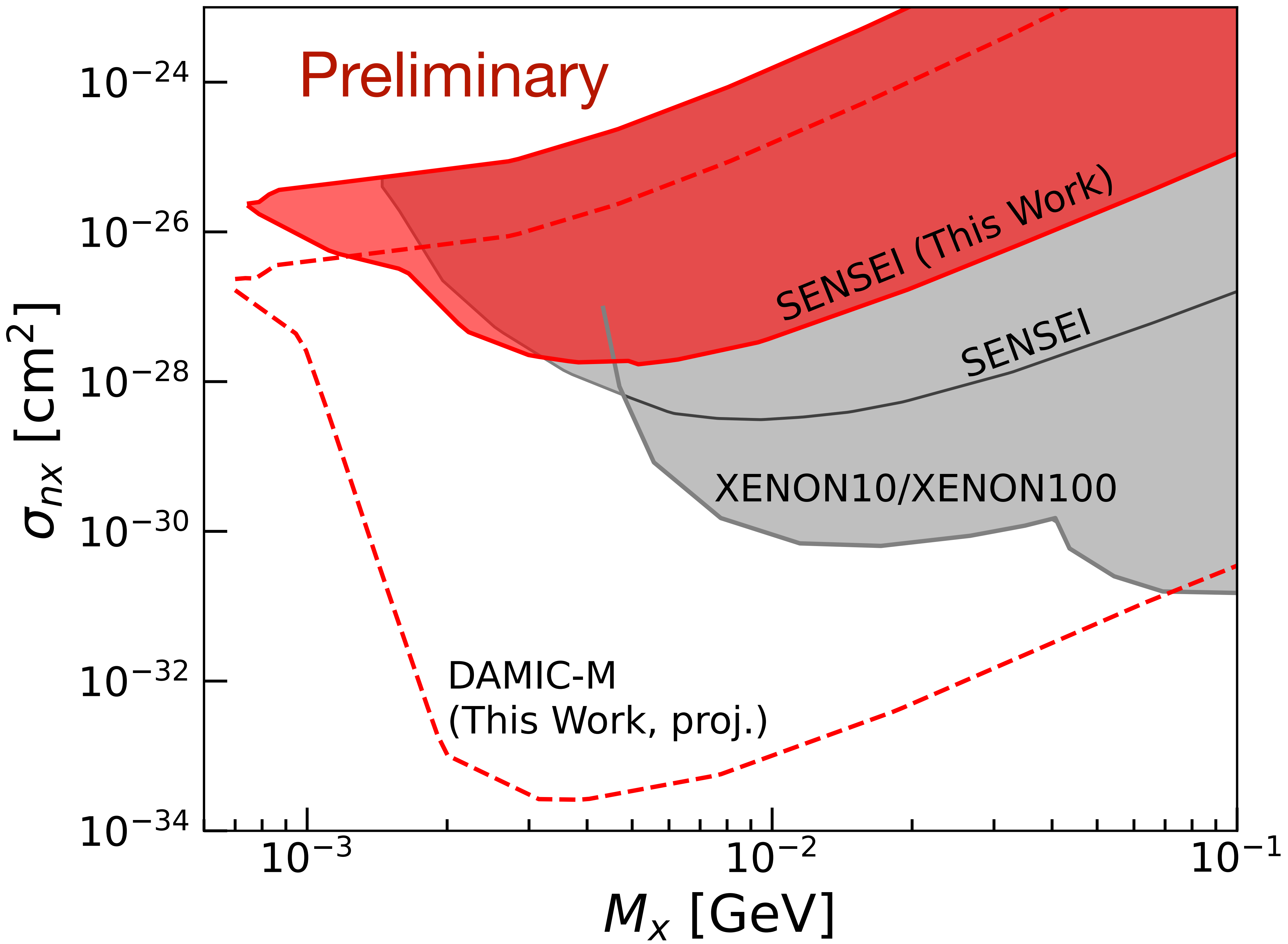

$$\alpha_u = \alpha_d = \alpha_s$$

Proton Contribution only

Conclusions

- Loop interactions cause dark matter that interacts with one part of the Standard model to interact with many other parts of it
- We can use existing constraints and detectors to probe multiple different DM interactions
- Low energy hadronic loops mean
  - New constraints on DM-nucleon couplings from SENSEI
  - Damic-M will be sensitive to DM-nucleon couplings that other direct detectors cannot probe

Thank You!