Mechanisms of $0\nu\beta\beta$ Decay

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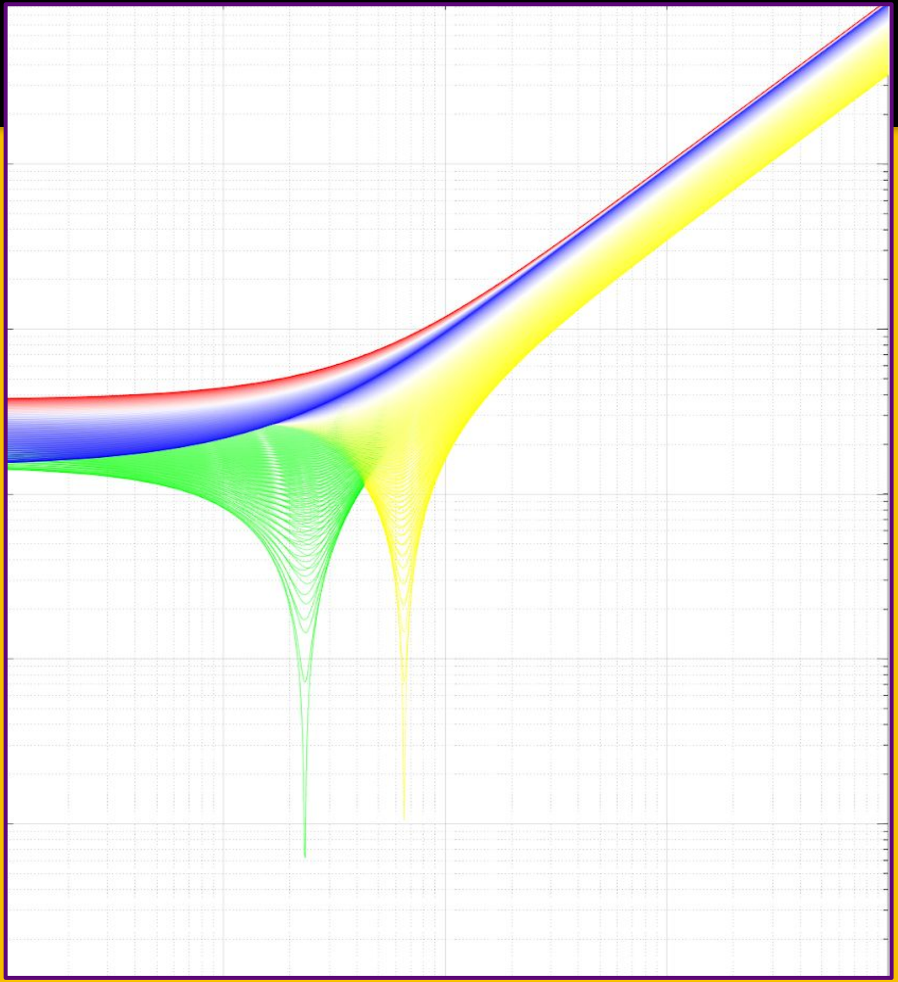
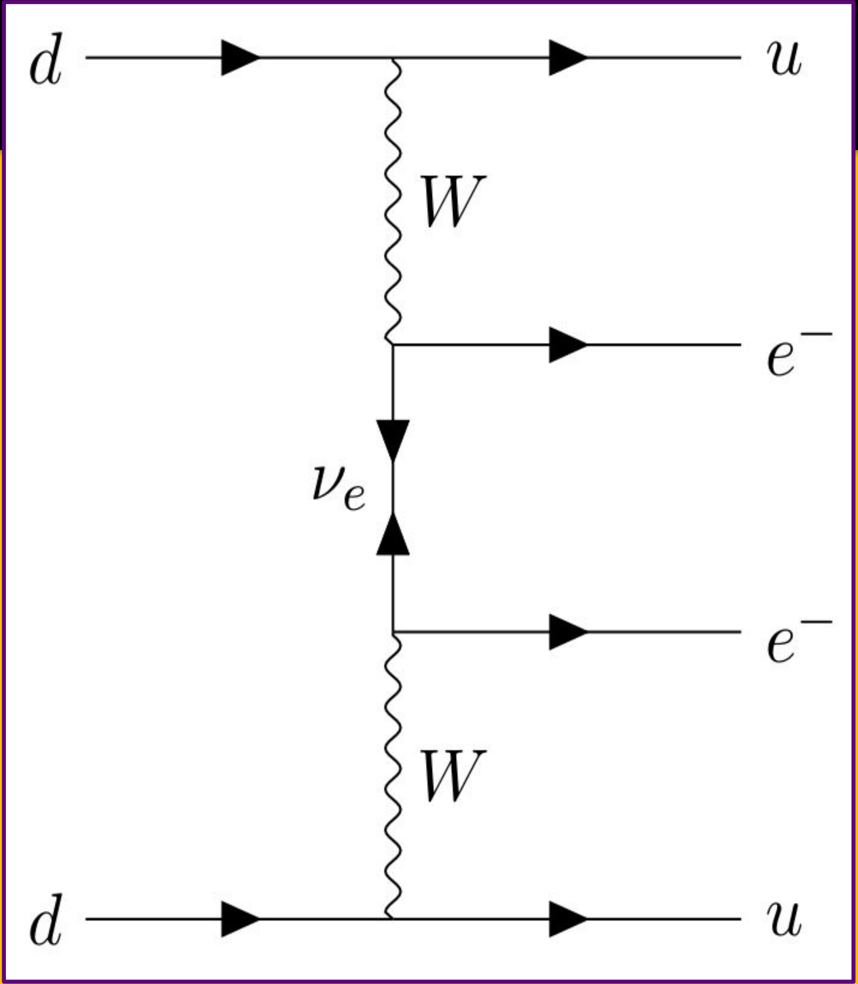


Neutrinos and $0\nu\beta\beta$

- **Flavour oscillation ⇒ massive neutrinos**
- Cosmology, oscillations, β-decay provide partial answers and constraints.
- $0\nu\beta\beta$ -- just another probe? No!
  - Sensitive to LNV
  - May differentiate mass mechanisms
- Current bounds (@90%)
  - GERDA: $T_{1/2} > 1.8 \cdot 10^{26}$ y [1]
  - KamLAND-Zen: $T_{1/2} > 1.1 \cdot 10^{26}$ y [2]

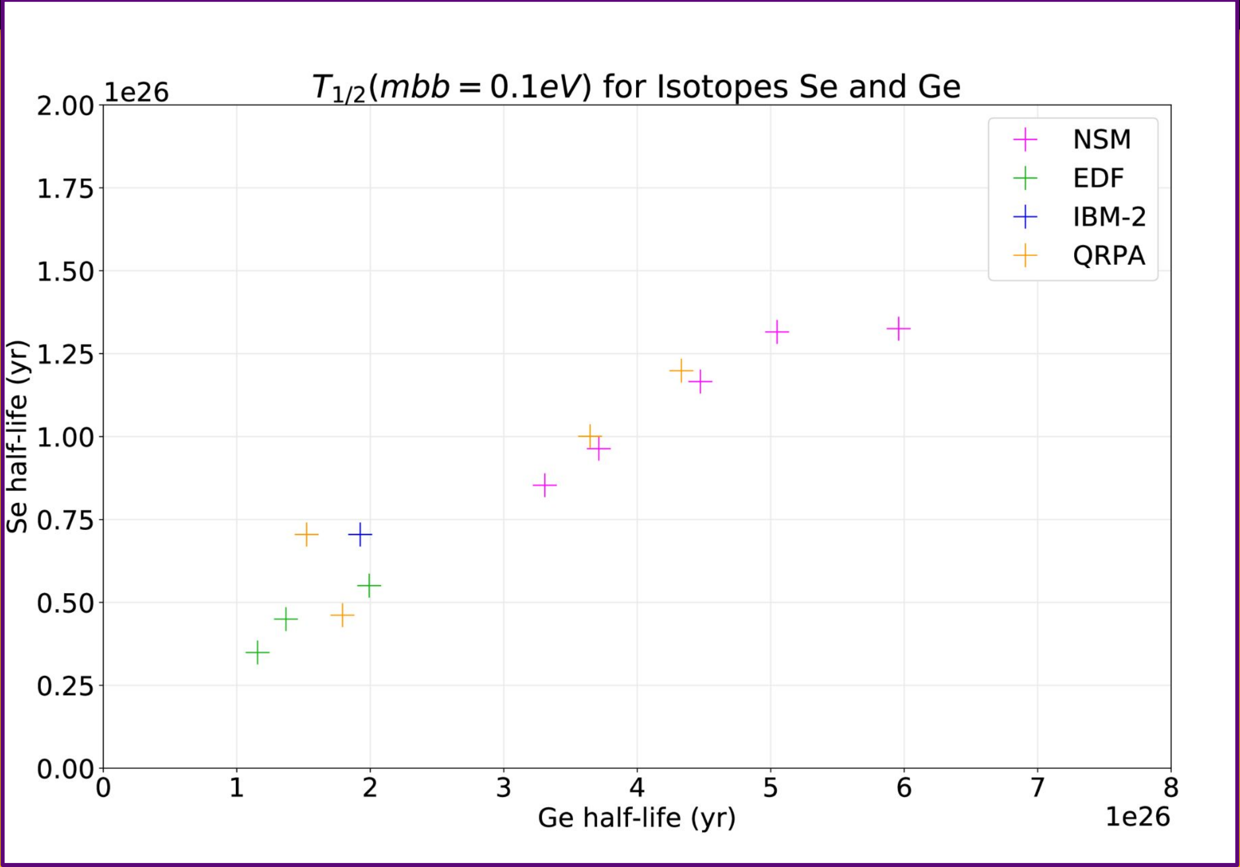


Nuclear Matrix Elements (NMEs)

- Observable $m_{\beta\beta}$ related to decay half-life: [3]

$$T_{1/2}^{-1} = G_{0\nu}|\mathbb{M}|^2 m_{\beta\beta}^2$$

- NMEs are key source of error for $0\nu\beta\beta$ theory.
- However, discrepancies are correlated for (some) pairs of isotopes.



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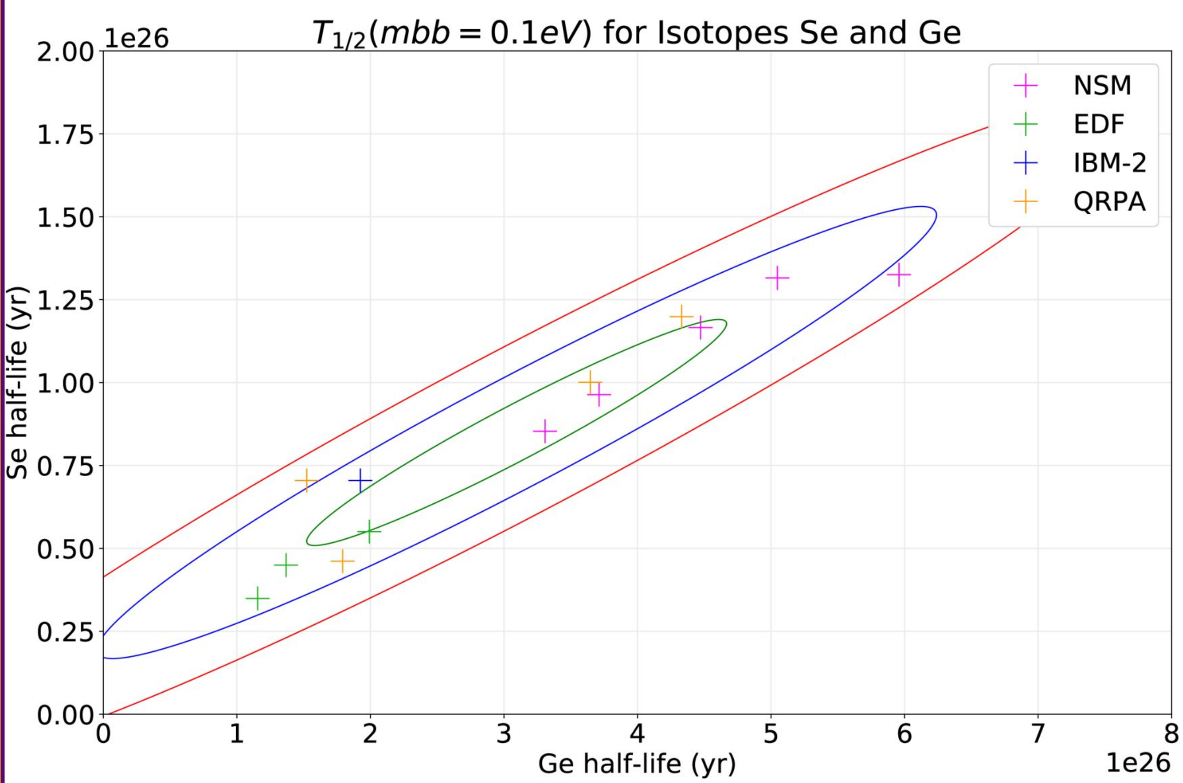


Research Directions

Strand 1 – Computational	Strand 2 – Analytical
• How will correlated NME errors impact inference from future $0\nu\beta\beta$ searches? • Bayesian (MCMC) methods	• How much do short-range $0\nu\beta\beta$ mechanisms contribute to NME discrepancies? • EFT-inspired approaches

Strand 1:
Inference with NMEs

Searching for Short-Range Mechanisms

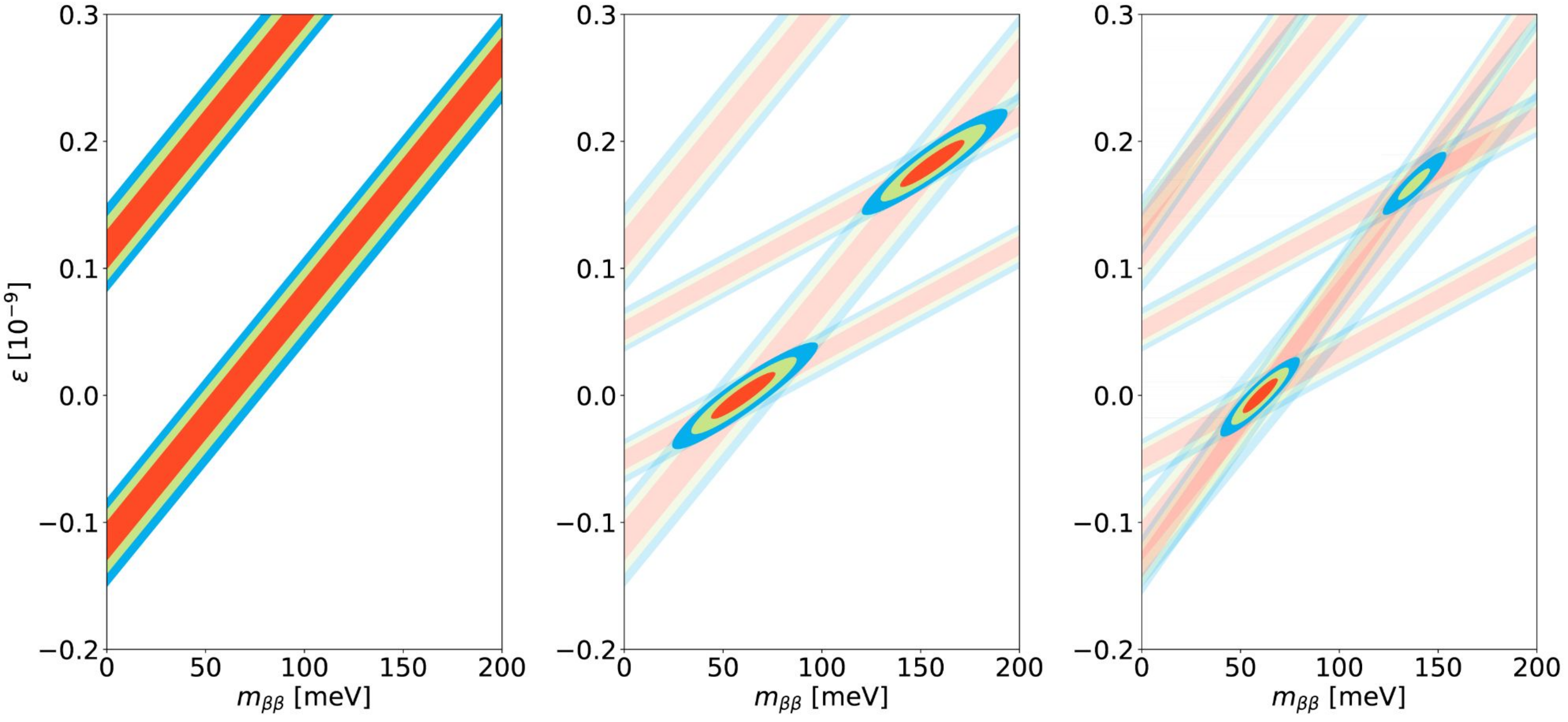
- Numerous mechanisms have been parameterised [Deppisch et al. arXiv:2009.10119]
- We consider a single exotic $0\nu\beta\beta$ mechanism with its own compound "heavy NME":

$$T_{1/2}^{-1} = G_{iso} \left| \frac{m_{\beta\beta}}{m_e} M_{\nu,iso} + \epsilon M_{H,iso} \right|^2$$

- Any fixed $0\nu\beta\beta$ half-life corresponds to two parallel-line solutions in $\{m_{\beta\beta}, \varepsilon\}$
  - Slope and intercept of these lines are isotope-dependent.

- Multi-isotope observations can constrain both $m_{\beta\beta}$ and ε.

Likelihoods for Ge, Ge/Mo, Ge/Mo/Xe



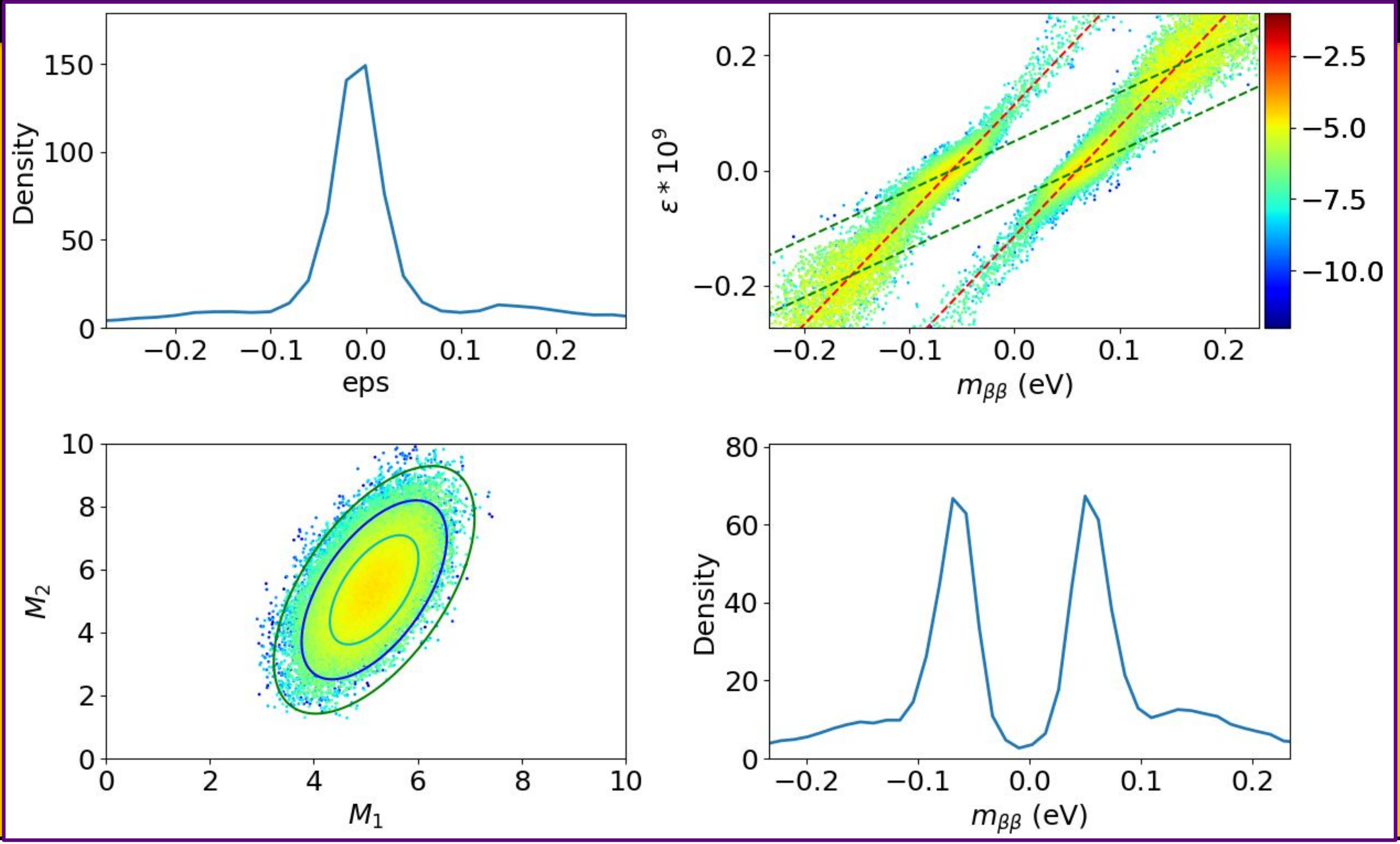
Bayesian Inference

- Update prior knowledge $\pi(\boldsymbol{\theta})$ with likelihood $\mathbf{L_X(\boldsymbol{\theta})}$ to obtain posterior knowledge $\mathbf{p(\boldsymbol{\theta})}$.

$$p(\boldsymbol{\theta}) = \frac{L_X(\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\int L_{\mathbf{X}}(\boldsymbol{\theta}')\pi(\boldsymbol{\theta}')d\boldsymbol{\theta}'_H} \equiv \frac{L_{\mathbf{X}}(\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{M^H_{\mathbf{X}}}$$

- Markov Chain Monte Carlo (MCMC) samples $\mathbf{p(\boldsymbol{\theta})}$ using only local distributions.
  - Locality helps to combat MC rejection problems at high-dimensionalities.
- Our parameter space: $\{m_{\beta\beta}, \varepsilon\}$ + $\{M_\nu, M_H\}$ for each isotope
  - Flat priors on $m_{\beta\beta}$, ε – see [Deppisch, Van Goffrier arXiv:2103.06660]
  - Careful tuning of the proposal width needed for d≥6.

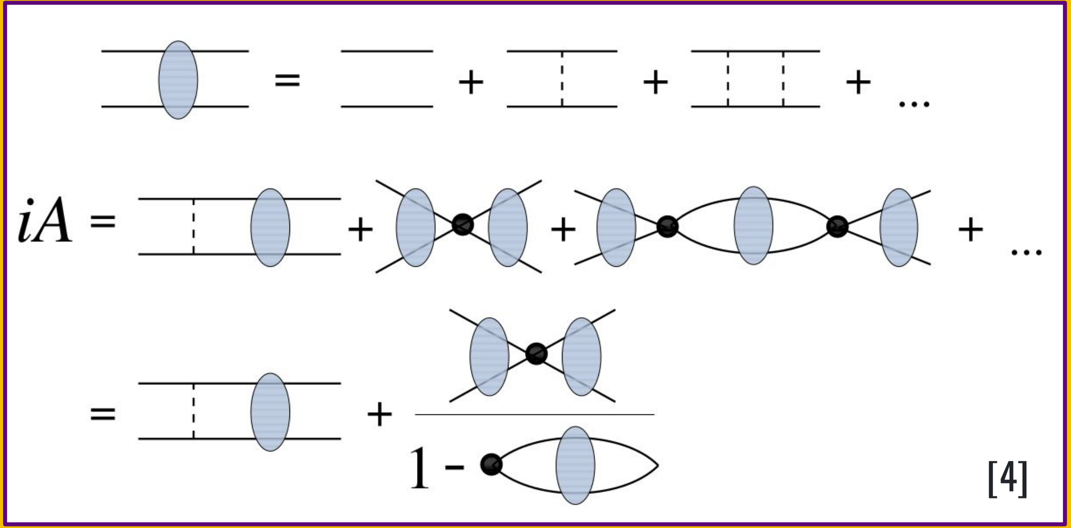
Correlated Likelihood, Ge/Mo



Strand 2:
Corrections to NMEs

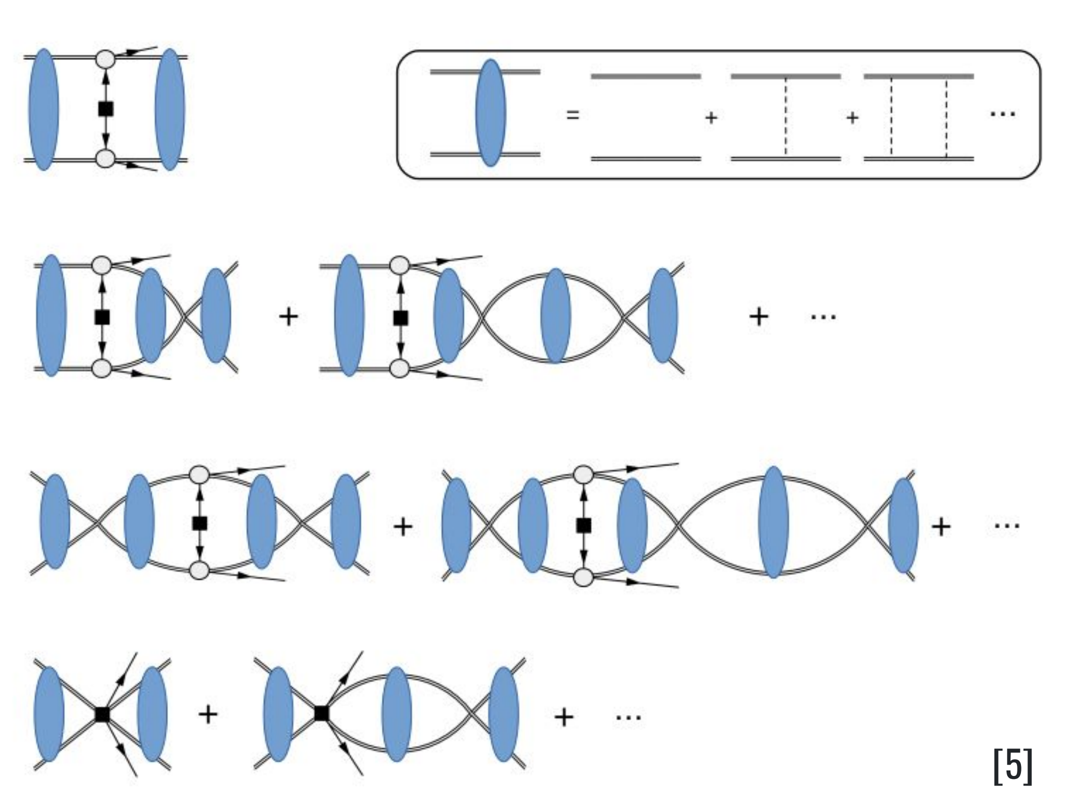
Background: Nuclear Effective Theory

- Approximate chiral symmetry of QCD facilitates construction of Chiral EFTs for p << Λ
  - At their simplest, only include nucleon (-) and Goldstone pion (--) fields.
  - Perturbative expansion made possible by a consistent power-counting scheme. [4]
- NN scattering is non-perturbative
  - Bound states
  - Large scattering lengths
- Novel subtraction scheme and "KSW" power-counting prove necessary - [Kaplan et al., 1996]



Background: Promoted $0\nu\beta\beta$ Contact Operator

- In LO ChEFT, including only a long-range LNV operator leads to a regulator-dependent amplitude.
- Renormalization requires a contact counterterm at distance scale $R \lesssim \Lambda_{\square}$, with unknown LEC. [Cirigliano et al., 2018]
- Divergence only arises from “double-contact” LNV diagrams.



[5]

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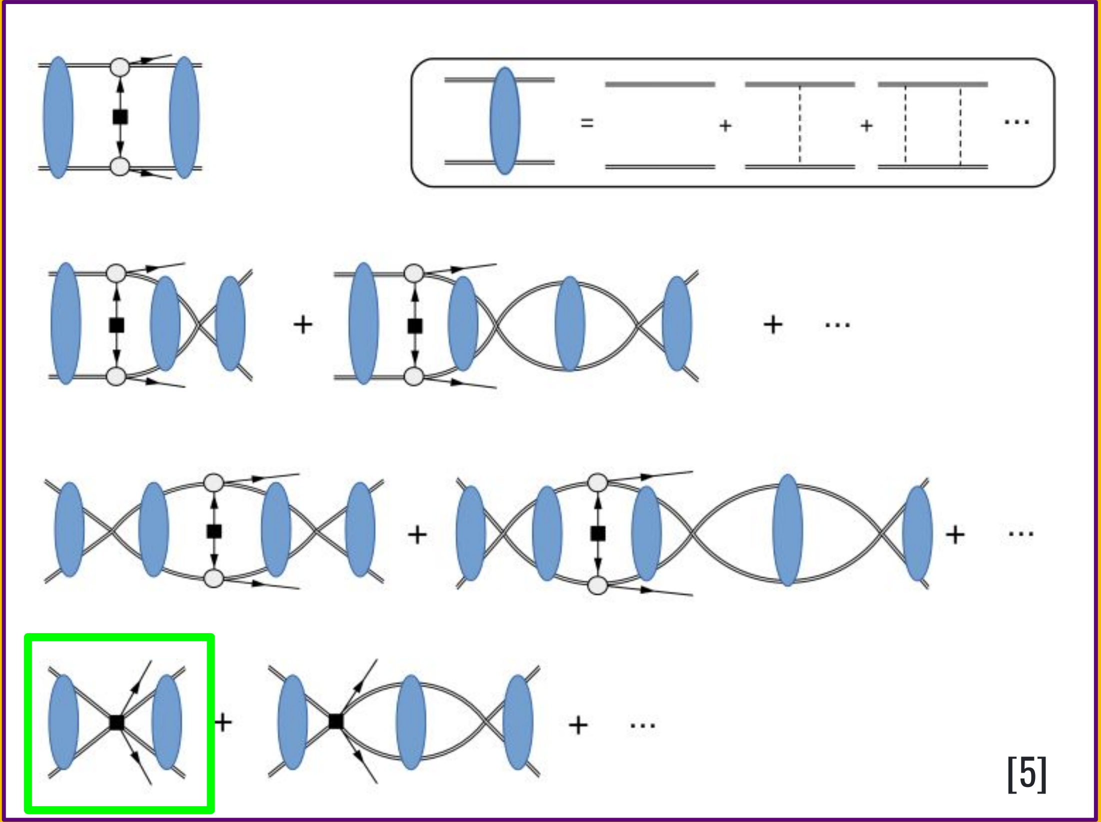

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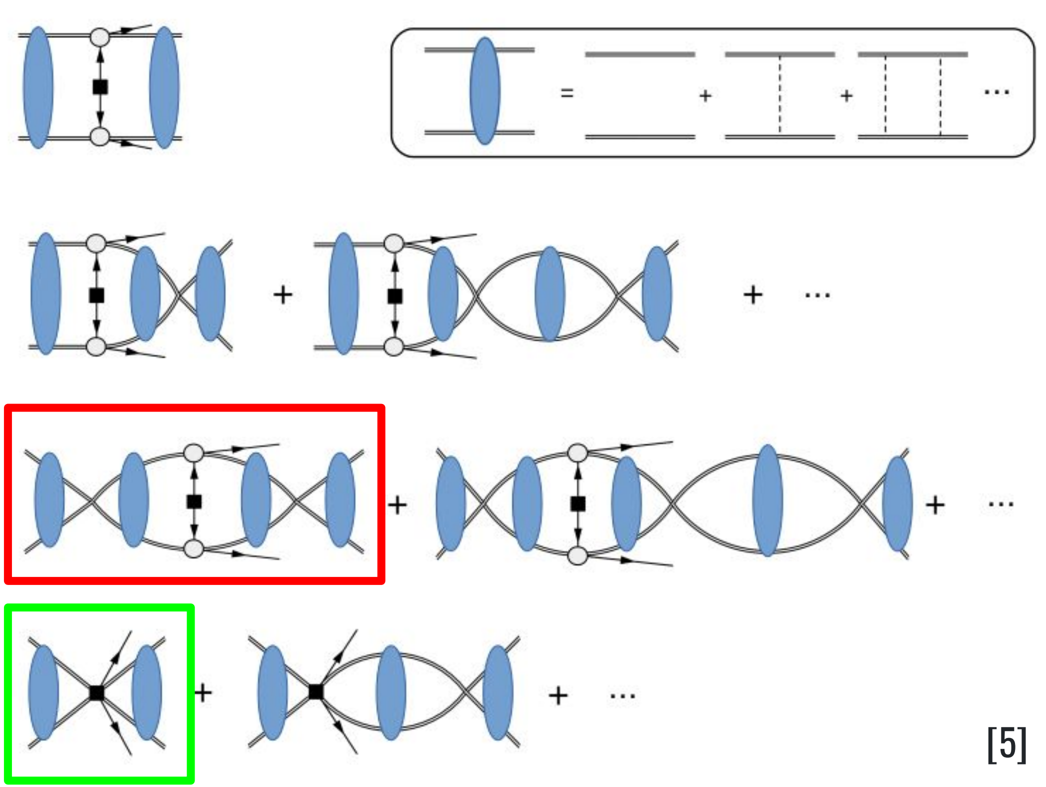
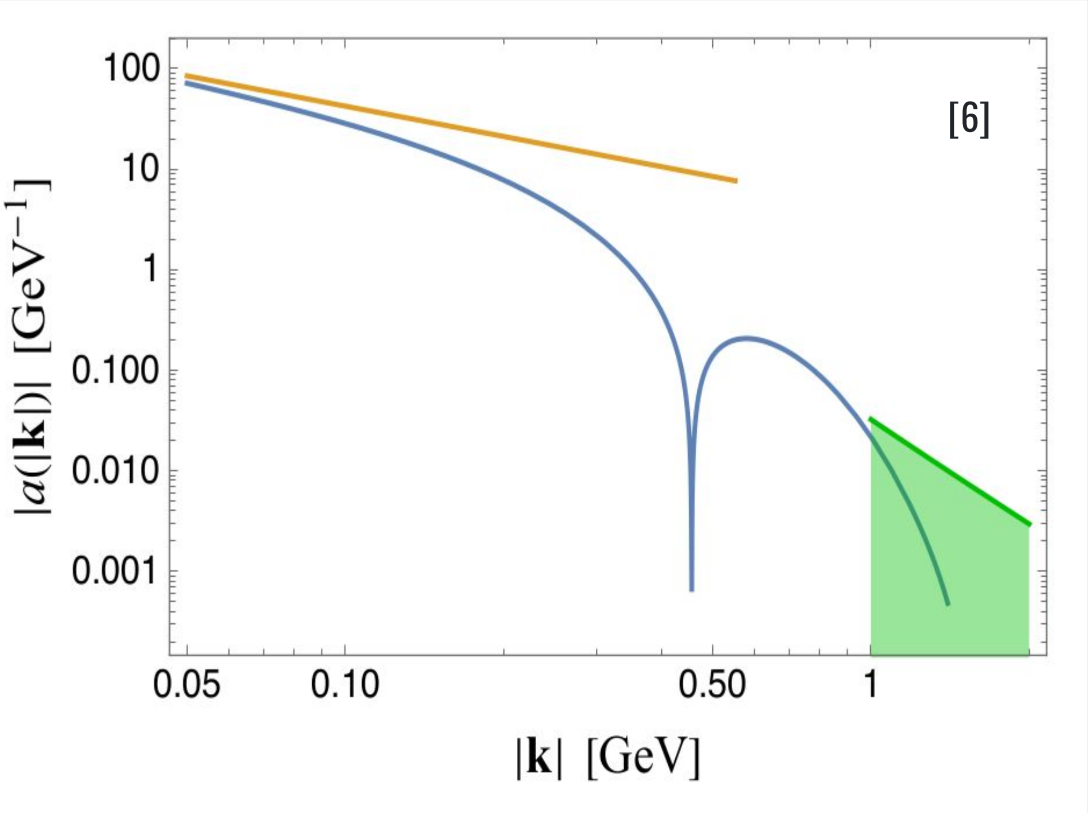


[5]

Matching Estimate of Contact LEC

- Can decompose hadronic $0\nu\beta\beta$ amplitude into regions of low-med-high virtual momentum.
- Anchor to ChEFT in the low region, QCD operator product expansion in the high region. [Cirigliano et al., 2021]
- The result is an estimate of the contact counterterm LEC.

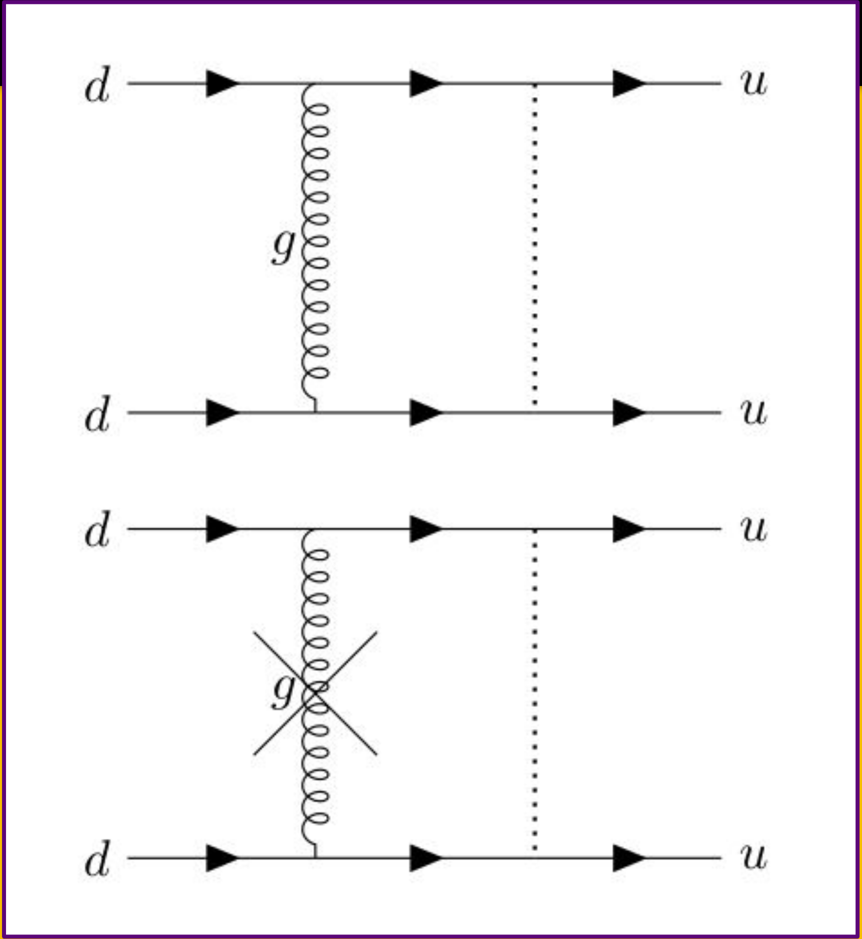


Matching Corrections

- OPE takes advantage of perturbative QCD above cutoff Λ.
  - Non-perturbative effects absorbed into coefficients, including vacuum effects.

- We expect gluon vacuum condensates to give the leading correction to the $0\nu\beta\beta$ OPE.

- Making use of external field approximations to compute these corrections. [7]
  - Compton scattering results indicate size of spin-0, spin-2 gluon contributions. [8]



Next Steps

- Complete calculation of gluon condensate OPE terms, as well as NLO pQCD terms
  - Draw conclusion about range of validity of OPE in matching below Λ.

- Address other dominant systematic uncertainties in ChEFT matching
  - Inelastic intermediate states (e.g. NNπ) may be responsible for ~20% error.
  - Could elucidate relationship with forward Compton scattering. [6]

THANK YOU FOR LISTENING!

Works Cited

[1] G. collaboration, M. Agostini, G. R. Araujo, A. M. Bakalyarov, M. Balata, I. Barabanov et al., Final results of gerda on the search for neutrinoless double-β decay , 2020.

[2] KamLAND-Zen Collaboration, A. Gando, Y. Gando, T. Hachiya, A. Hayashi, S. Hayashida, H. Ikeda et al., Search for majorana neutrinos near the inverted mass hierarchy region with kamland-zen , Phys. Rev. Lett. 117 (Aug, 2016) 082503.

[3] M. Agostini, G. Benato and J. Detwiler, Discovery probability of next-generation neutrinoless double-beta decay experiments , Phys. Rev. D96 (2017) 053001, [1705.02996].

[4] Kaplan, David B., Martin J. Savage, and Mark B. Wise. "Nucleon-nucleon scattering from effective field theory." Nuclear Physics B 478.3 (1996): 629-659.

[5] Cirigliano, Vincenzo, et al. "New leading contribution to neutrinoless double-β decay." Physical review letters 120.20 (2018): 202001.

[6] Cirigliano, Vincenzo, et al. "Determining the leading-order contact term in neutrinoless double β decay." Journal of High Energy Physics 2021.5 (2021): 1-68.

[7] Novikov, V. A., et al. "Calculations in external fields in quantum chromodynamics. Technical review." Fortschritte der Physik32.11 (1984): 585-622.

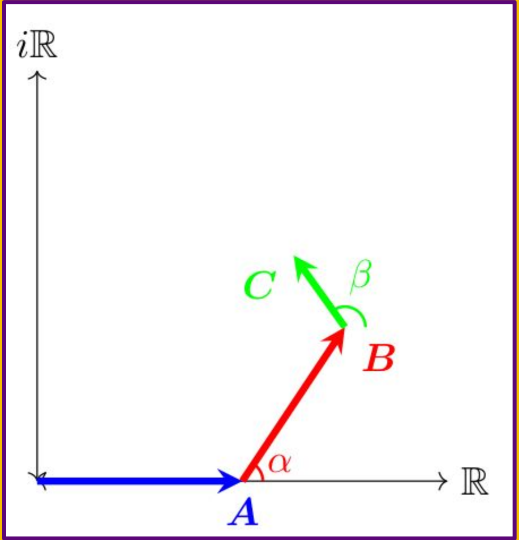
[8] Hill, Richard J., and Gil Paz. "Nucleon spin-averaged forward virtual Compton tensor at large Q 2." Physical Review D 95.9 (2017): 094017.

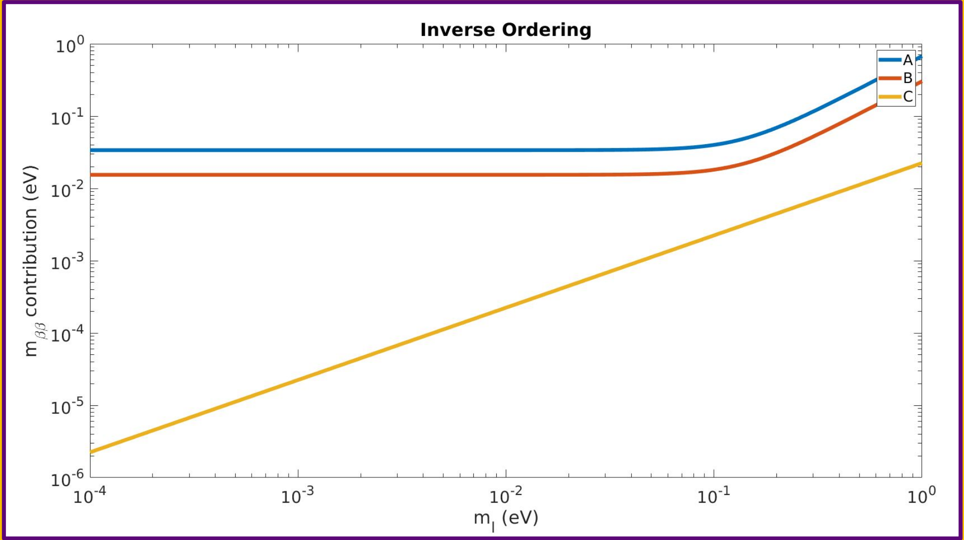
Backup I: Neutrinos and $0\nu\beta\beta$

- $m_{\beta\beta}$ dependent on neutrino masses and two Majorana phases α and β:

$$m_{\beta\beta} = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta} \right| = \left| A + Be^{i\alpha} + Ce^{i\beta} \right|$$

- With IO hierarchy, small m_3 causes C << A, B.





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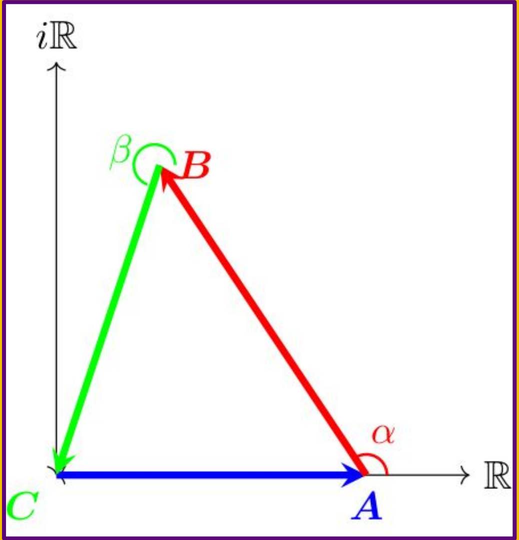
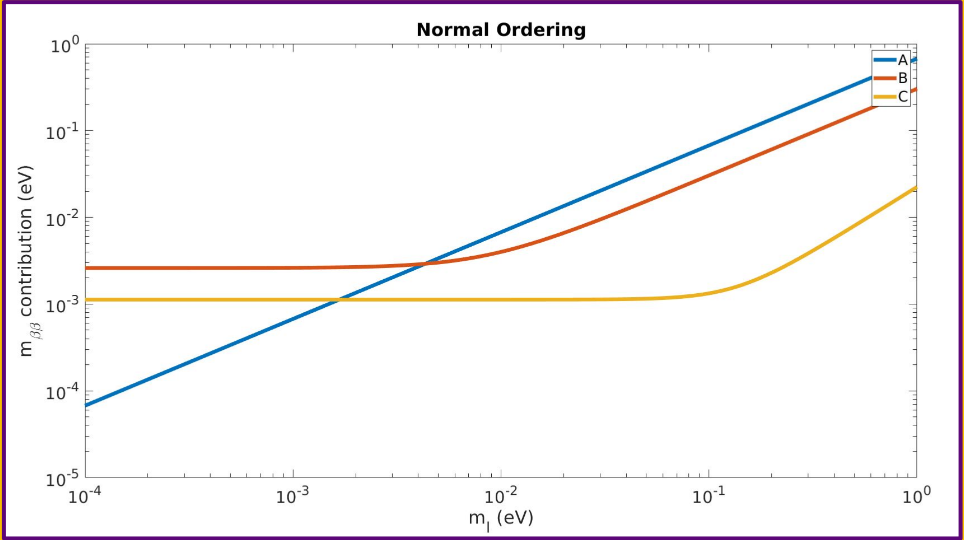
- With NO hierarchy, possible to tune parameters and drive $m_{\beta\beta} \rightarrow 0$.





Backup II: Least-Informative Priors

- **Information theory:** we want posterior to arise from experiment, not our prior biases.
- Information gain from prior to posterior captured in the Kullback-Leibler divergence.
- Define Least-Informative Prior (LIP) as prior which maximises expected information gain.

$$\langle D_{KL}(p|\pi)\rangle_{data} = \int dX \int d\theta\ p(\theta|X)\log\left(\frac{p(\theta|X)}{\pi(\theta)}\right)$$

- No prior is bias-free, but the LIP can serve as a reference with which to compare others.