Neutrinoless double-beta decay from Lattice QCD

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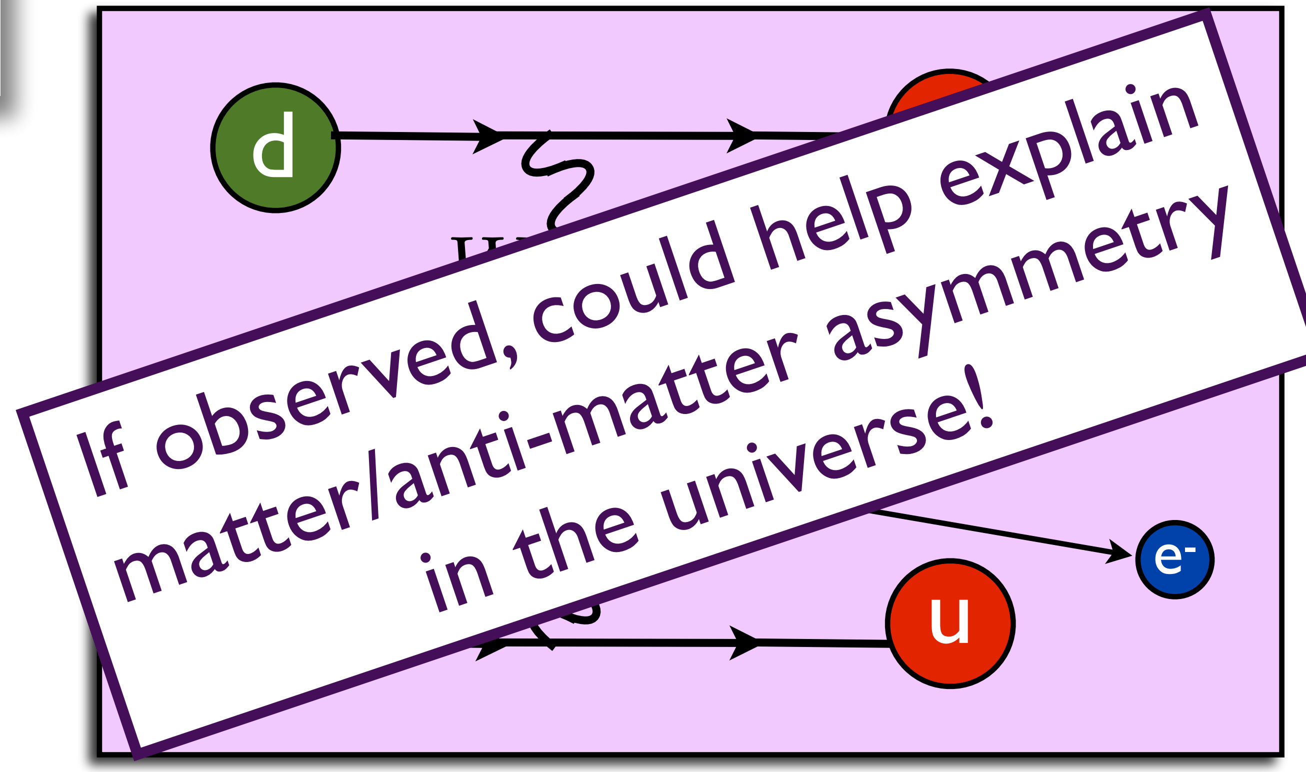
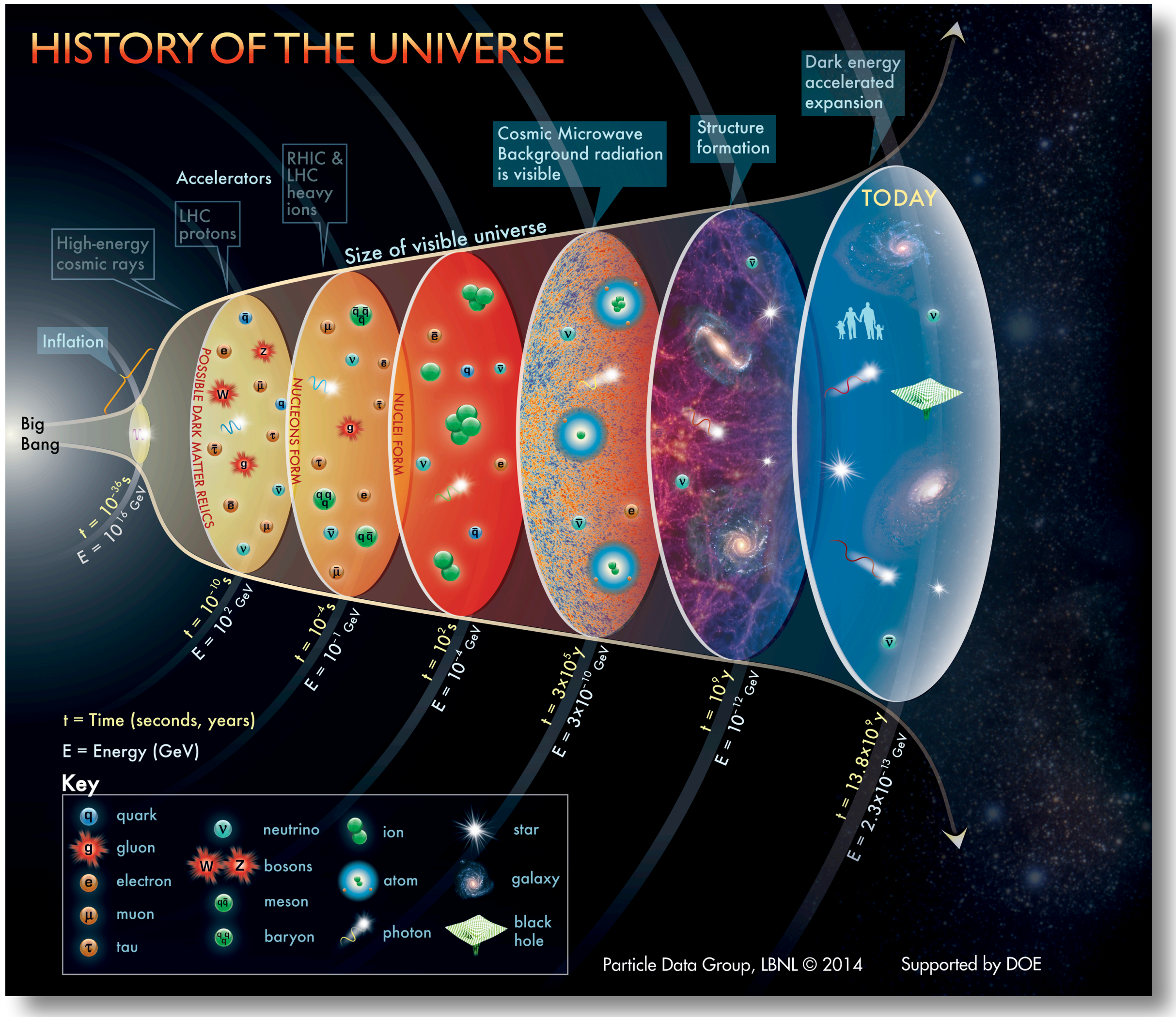
UNC, Chapel Hill

BNL-HET & RBRC Joint Workshop
DWQ@25
Dec. 16, 2021

Neutrinos: Majorana or Dirac?

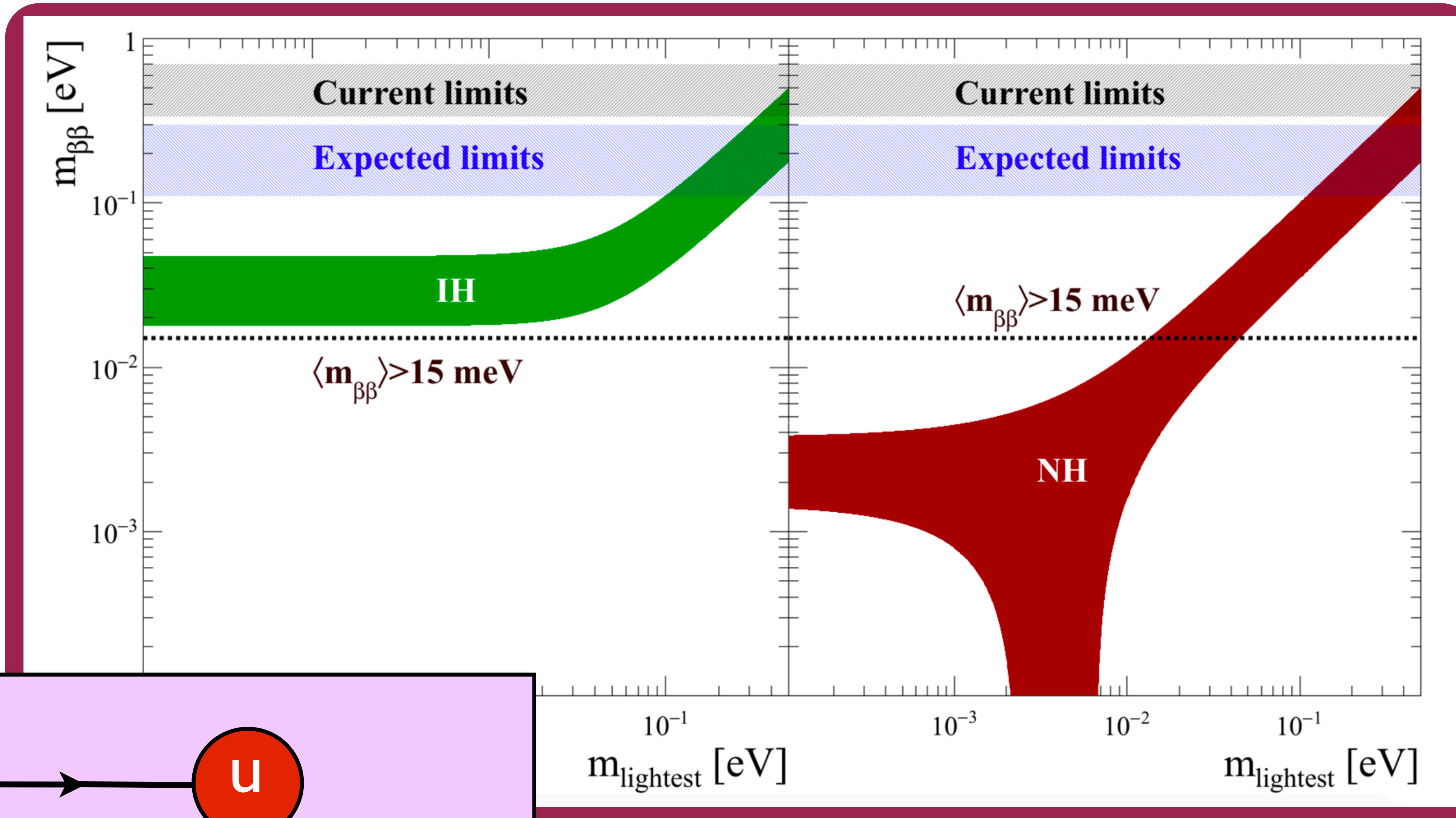
- Majorana: $\nu = \bar{\nu}$
  - Dim-5 mass term leads to naturally light neutrinos (Seesaw mechanism)
- Could be verified through observation of simultaneous double beta decay with no neutrino emission
  - Proportional to effective absolute neutrino mass
  - Lepton number violating process
  - Lepton number asymmetry (in early Universe) can be converted to baryon number asymmetry
  - Enormous international experimental efforts underway!

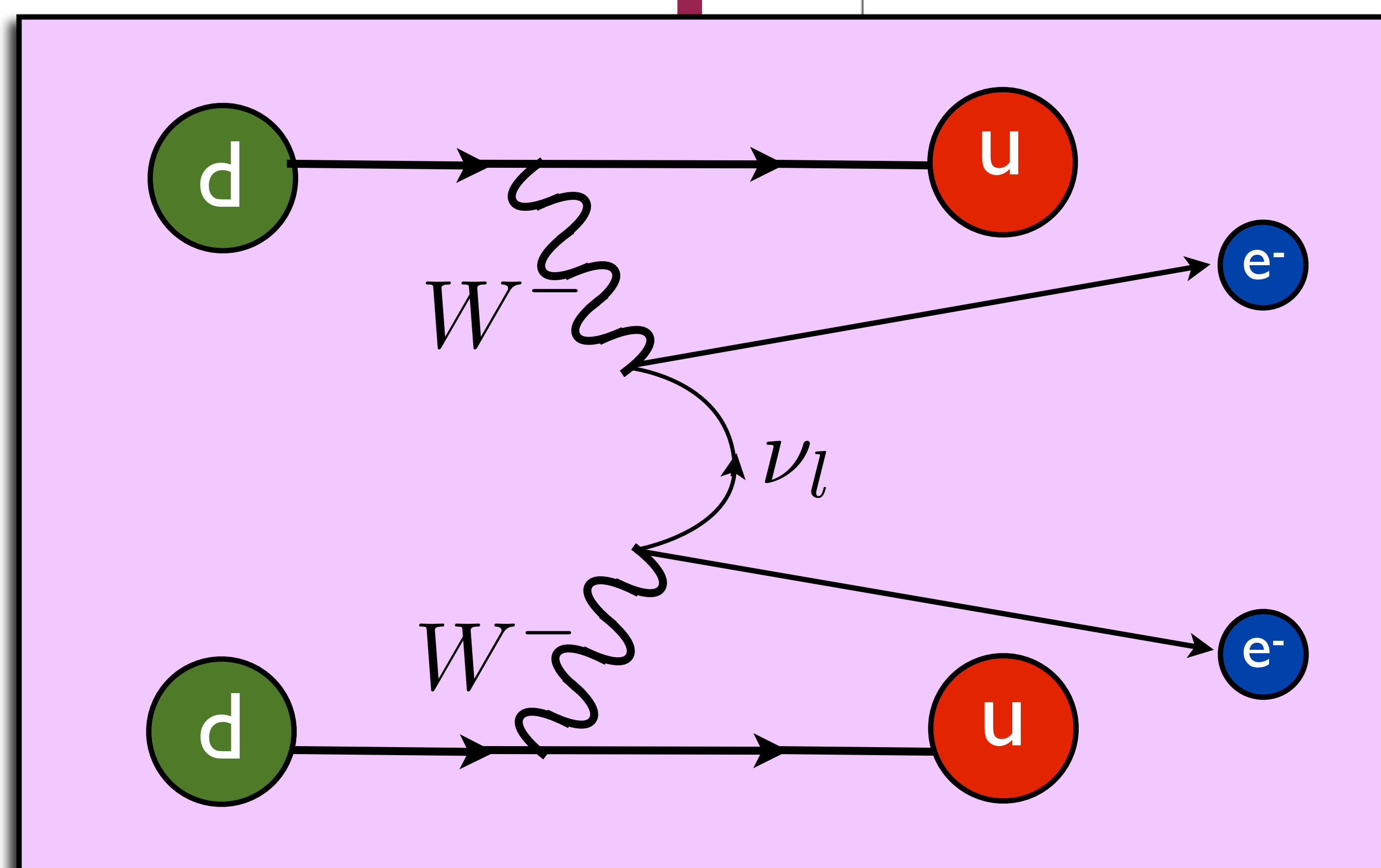




Theory?

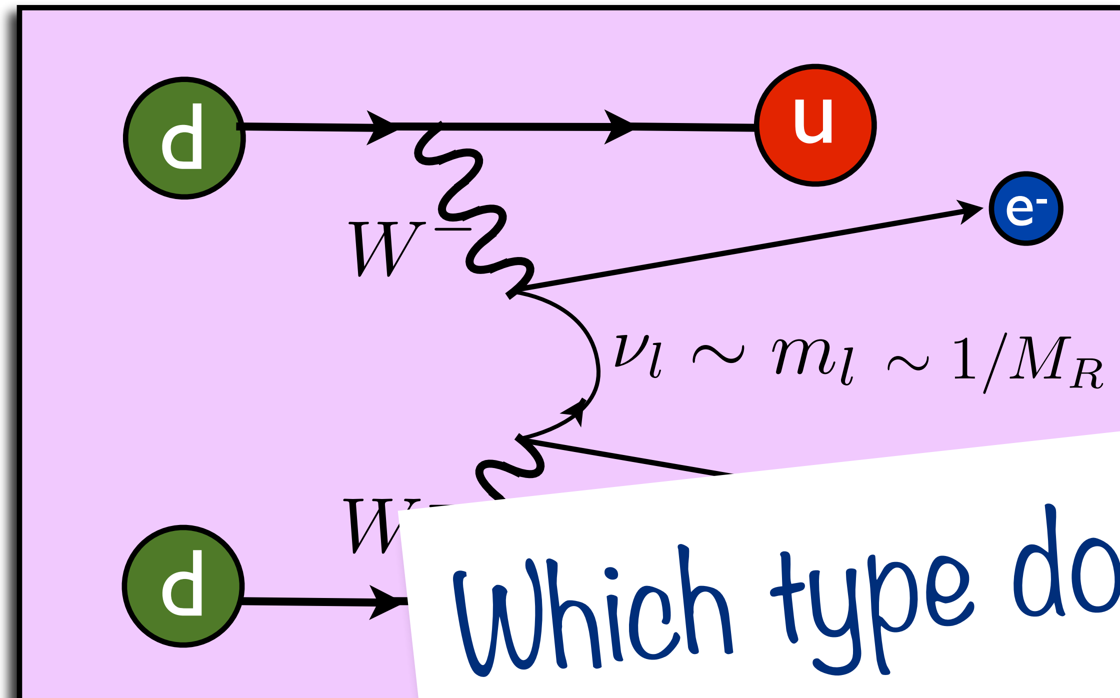
From NSAC Long Range Plan 2015

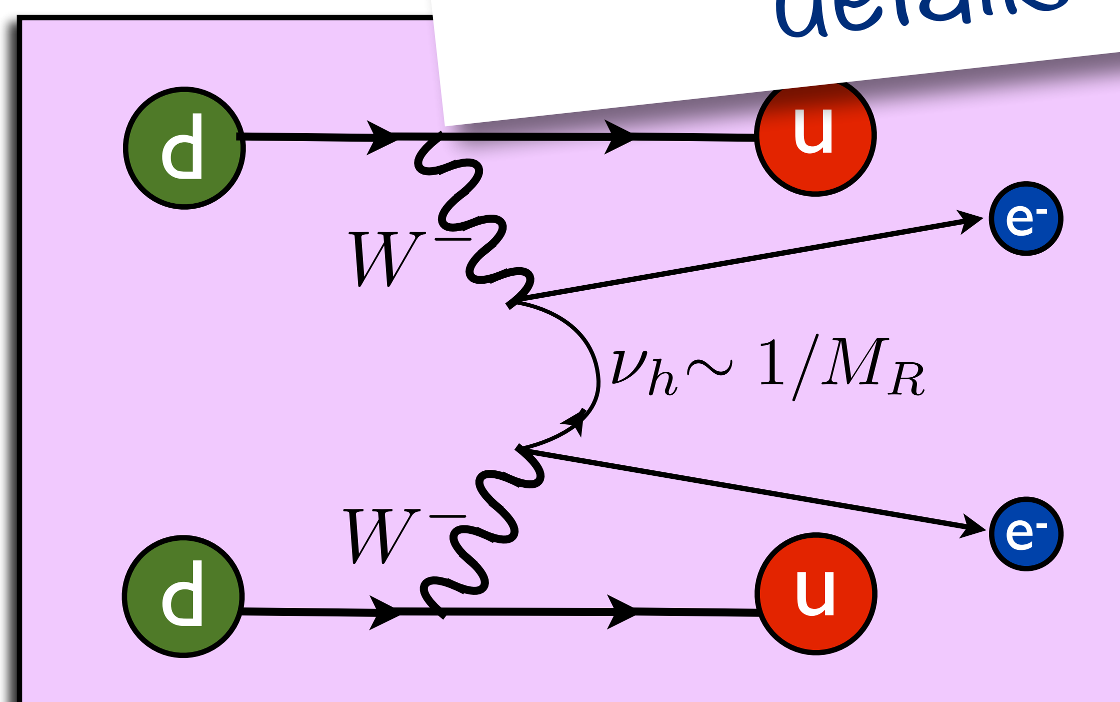




This picture assumes only light neutrino exchange, and uncertainties from many-body calcs are large and poorly understood. There's more to the story - maybe we're missing something important!

Short-range contributions





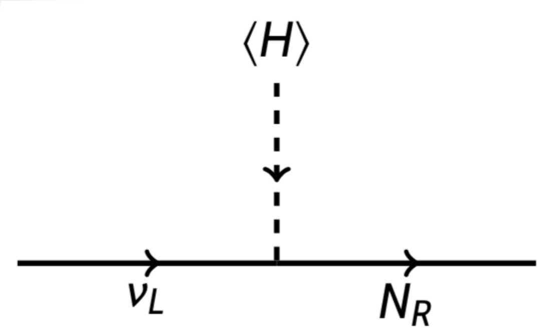
Seesaw Mechanism

$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

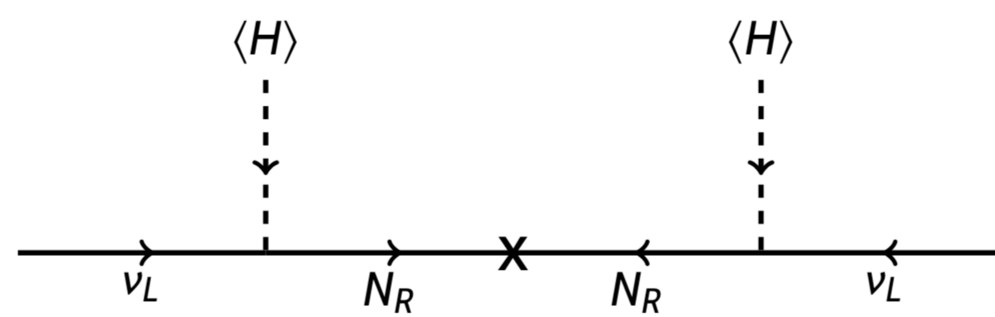
M_D^2/M_R

$\sim M_R$

Which type dominates depends on details of BSM model

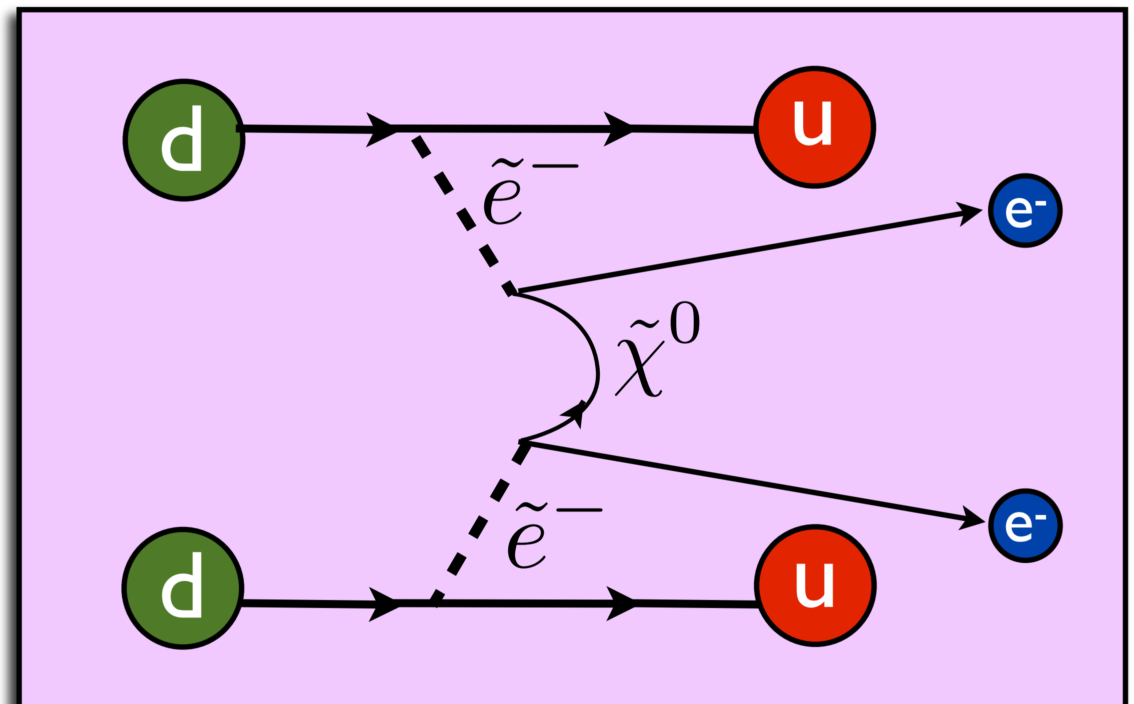


$\sim M_D$

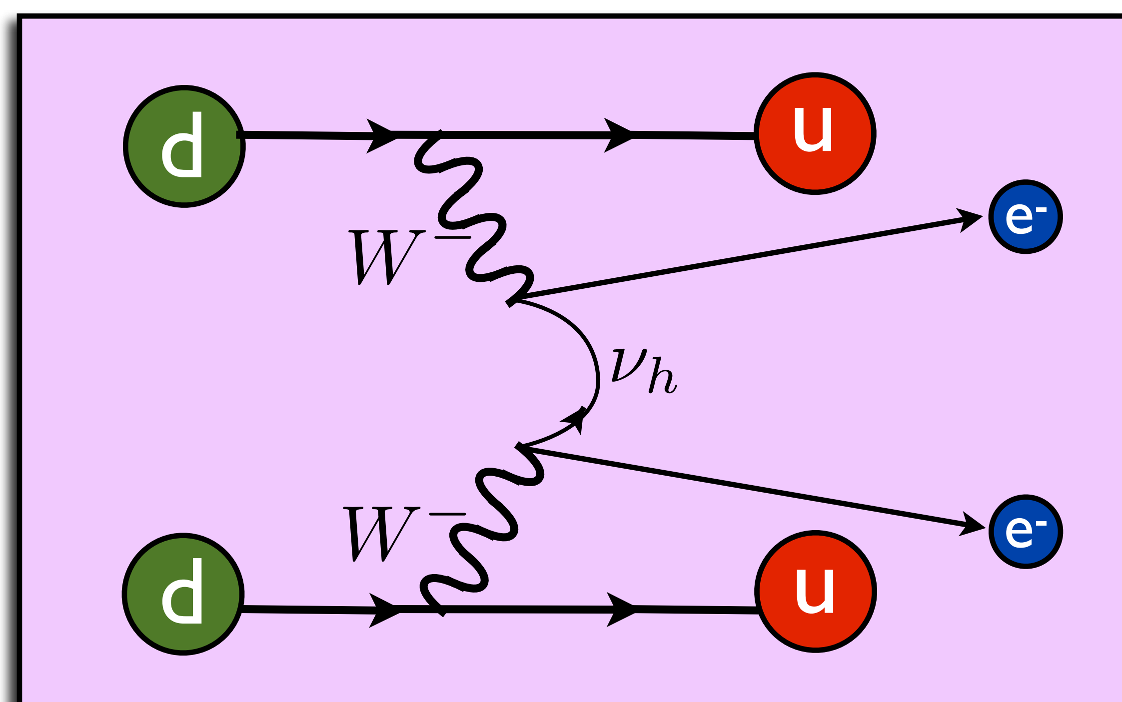


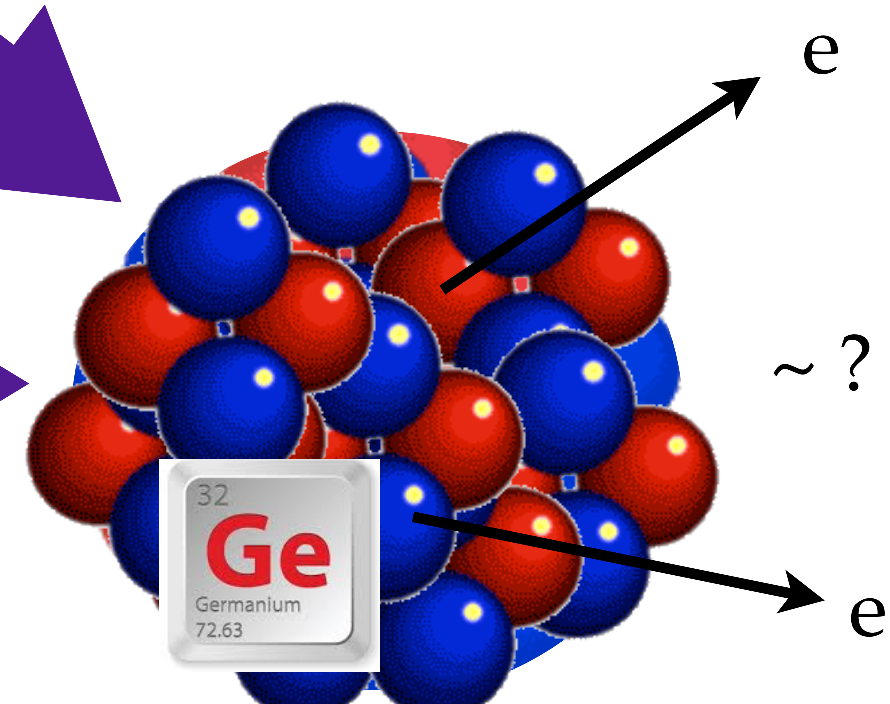
$\sim M_D^2/M_R$

Short-range contributions



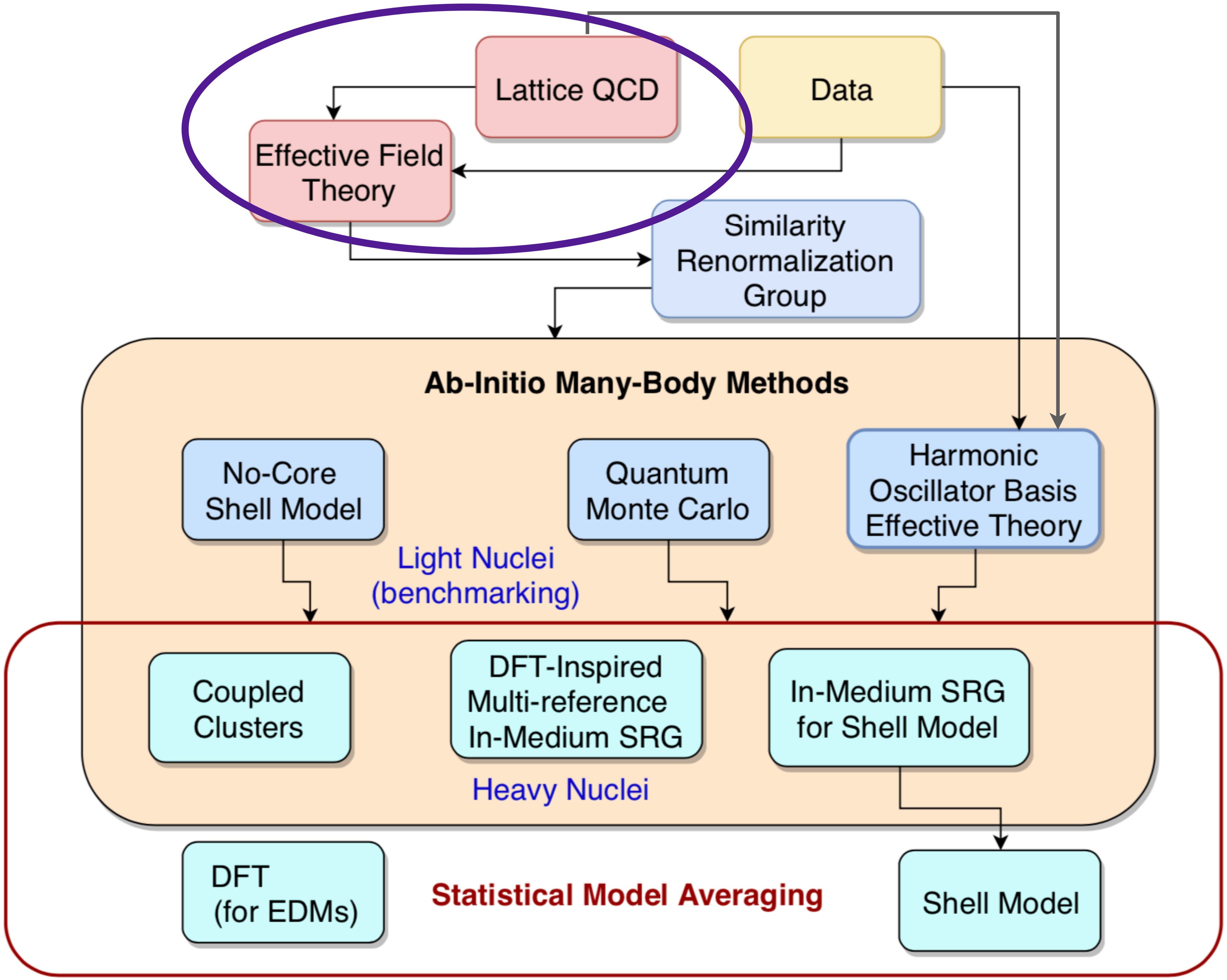
$0\nu\beta\beta$ bounds could help constrain R-parity violating coefficients





Integrated approach:
DOE DBD Topical Collaboration

https://c51.lbl.gov/~walkloud/0nubb



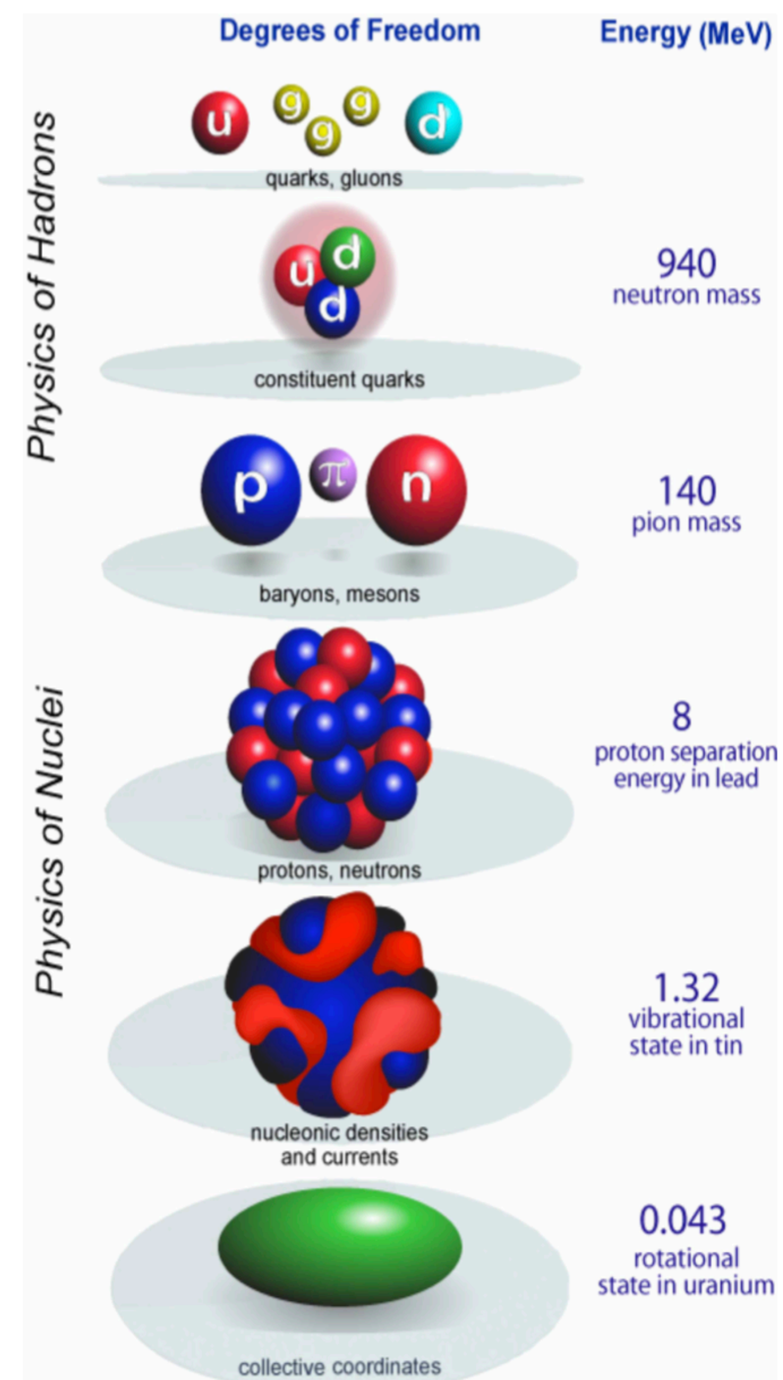
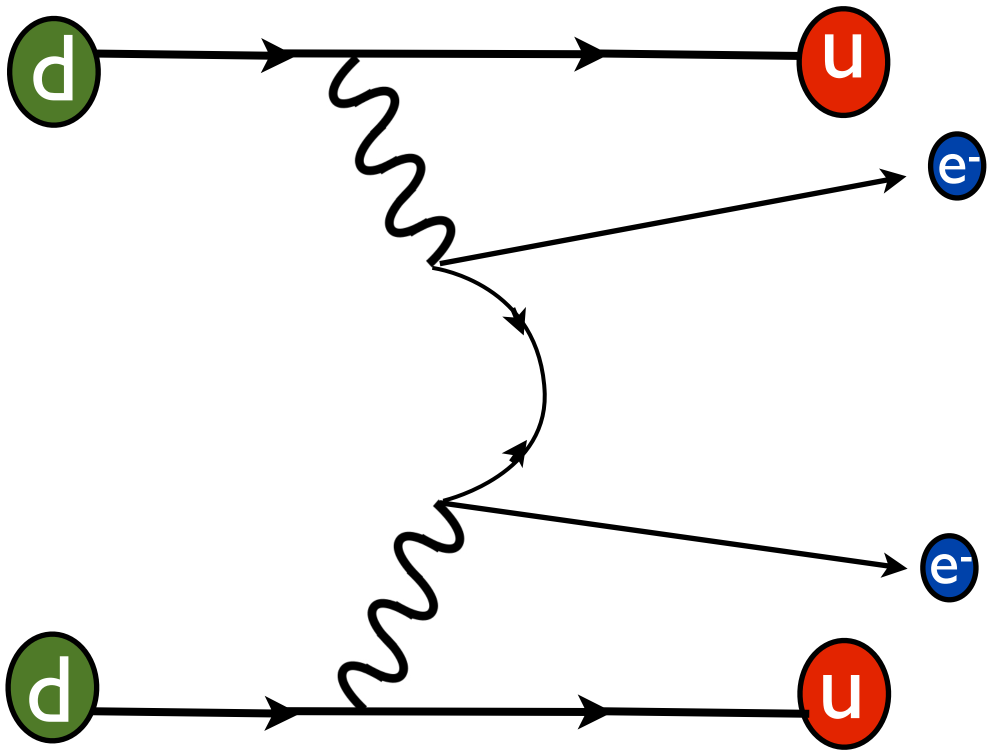


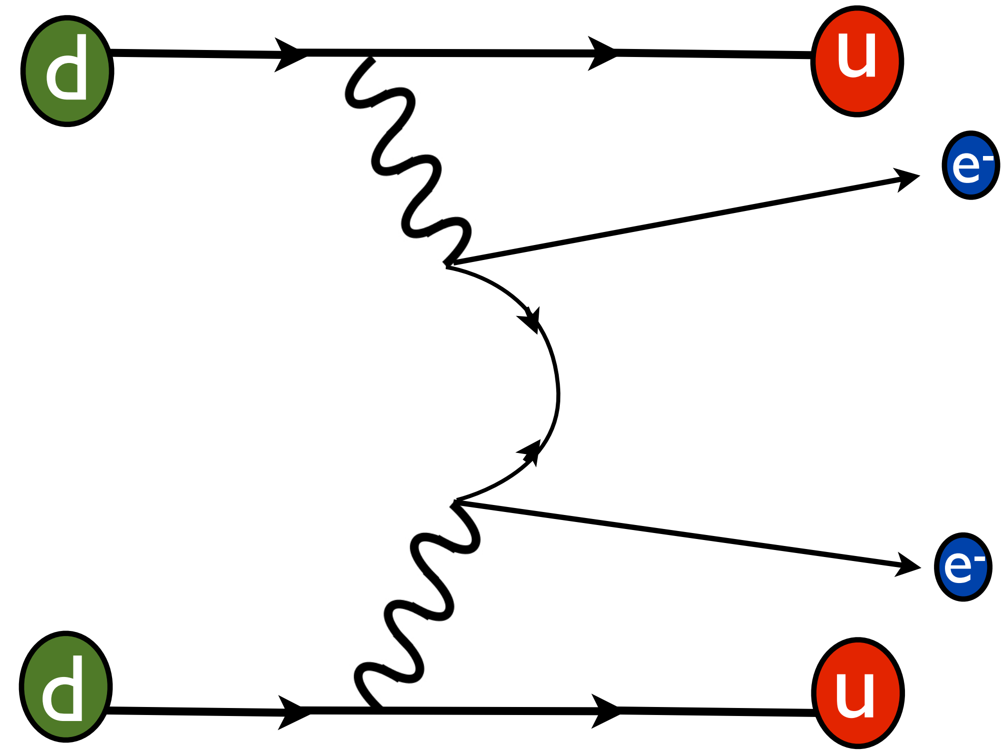
Image courtesy Jon Engel

From high energy to nuclear EFT



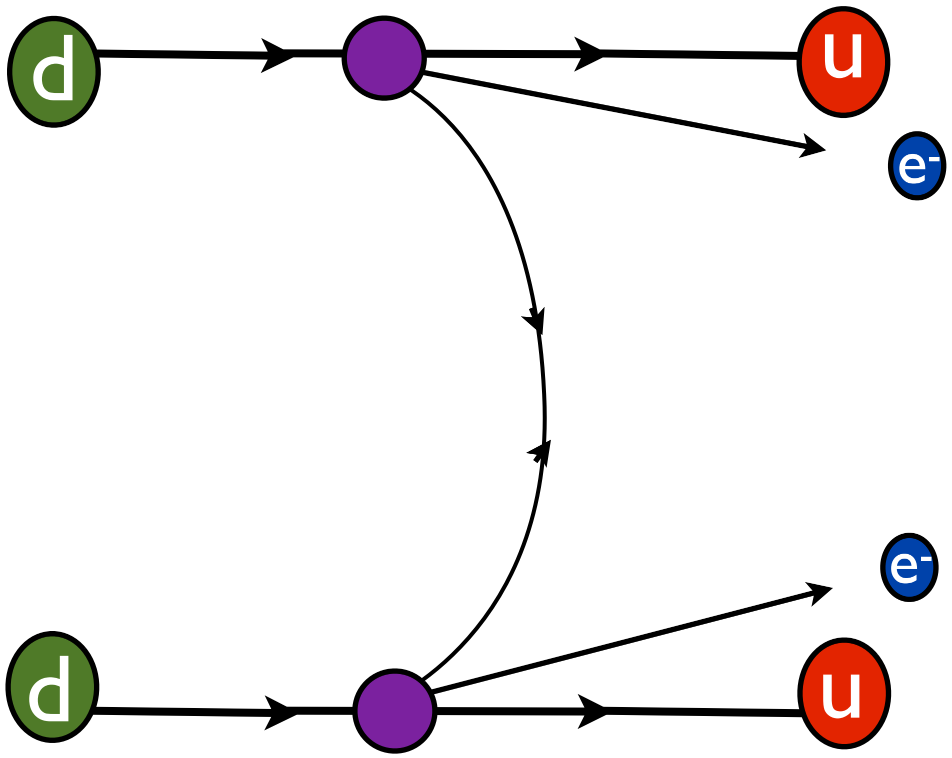
Long-range

$\Lambda \ll M_W$



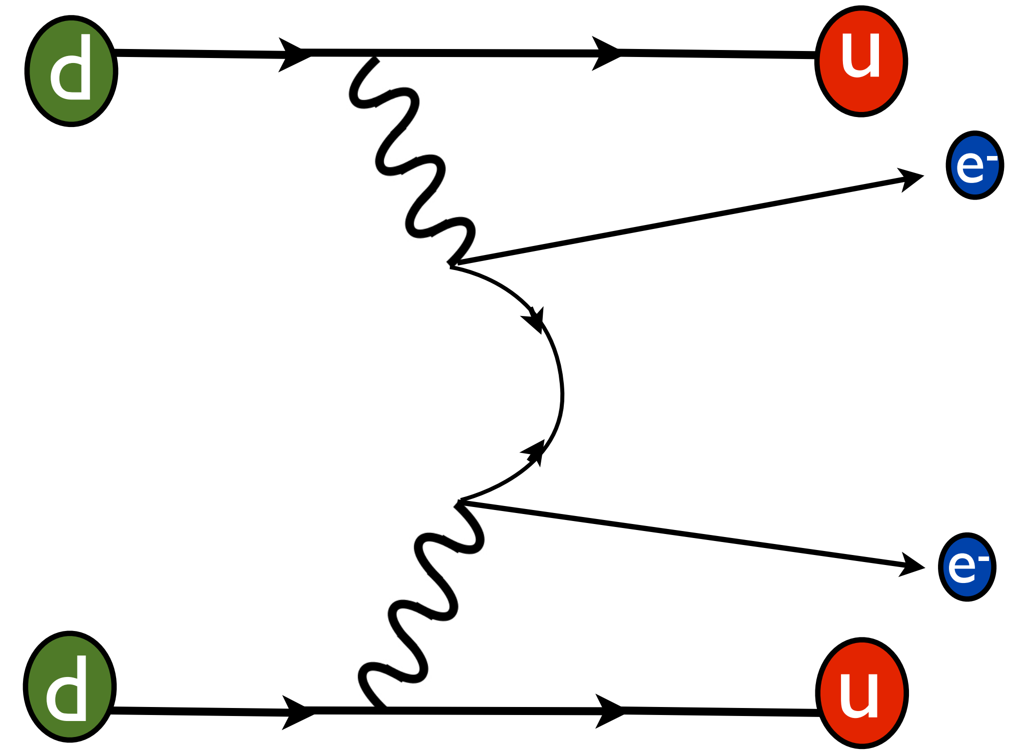
Short-range

From high energy to nuclear EFT



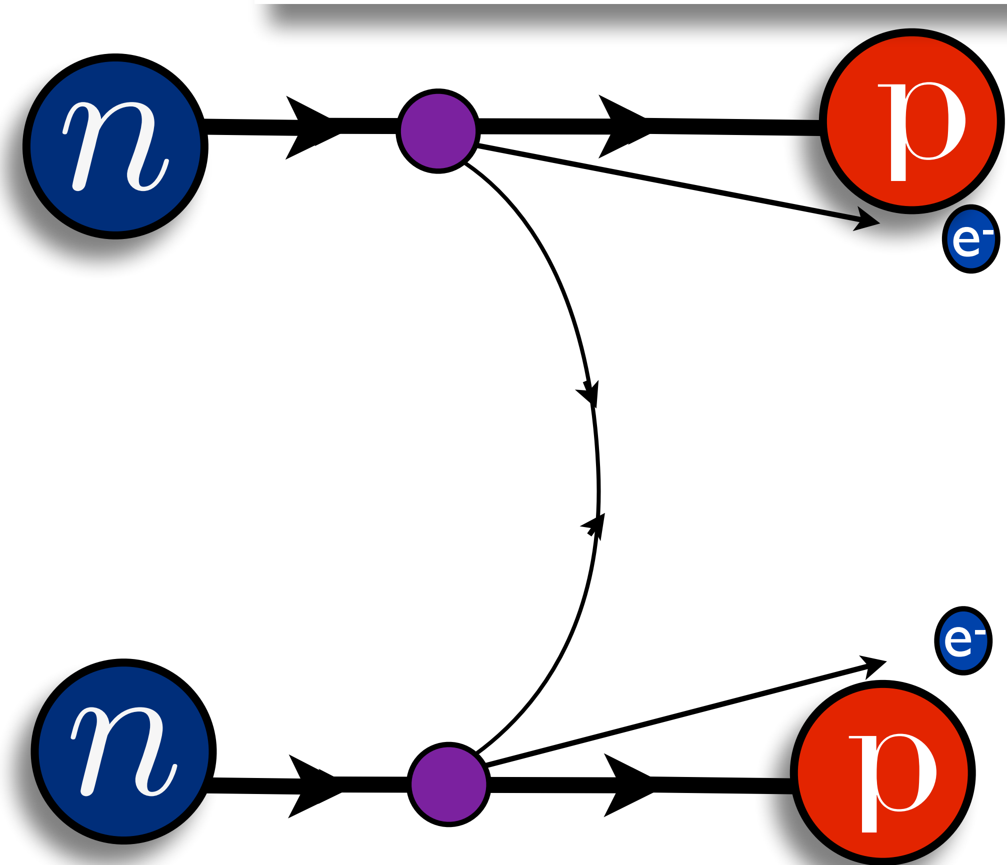
Long-range

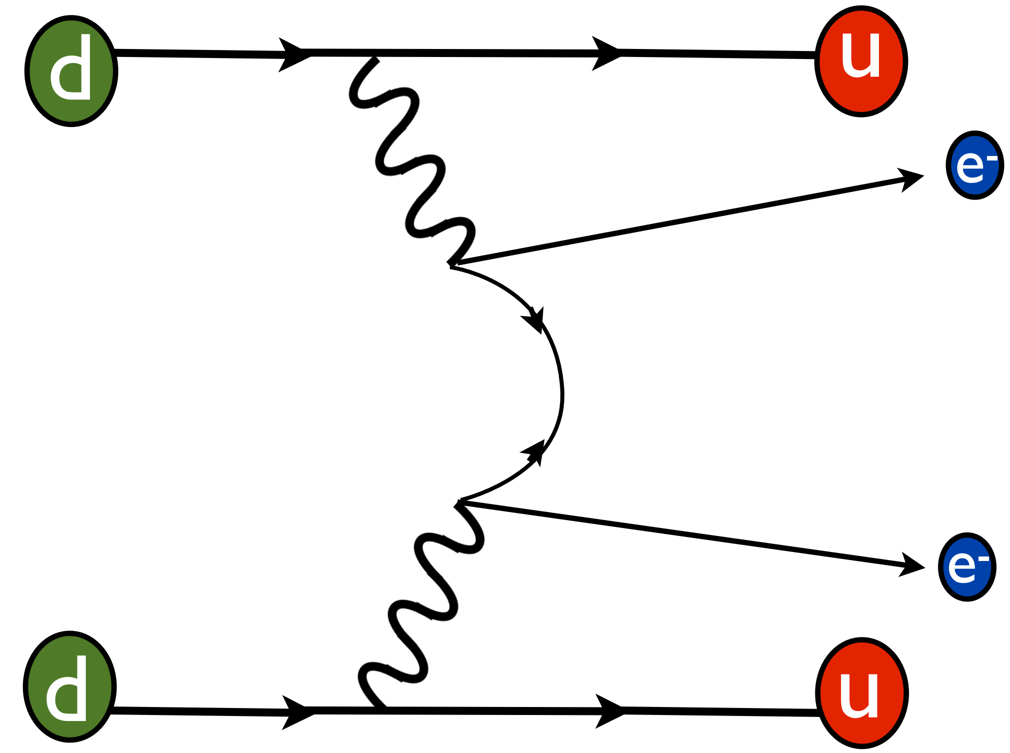
$\Lambda \ll \Lambda_{QCD}$



Short-range

From high energy to nuclear EFT

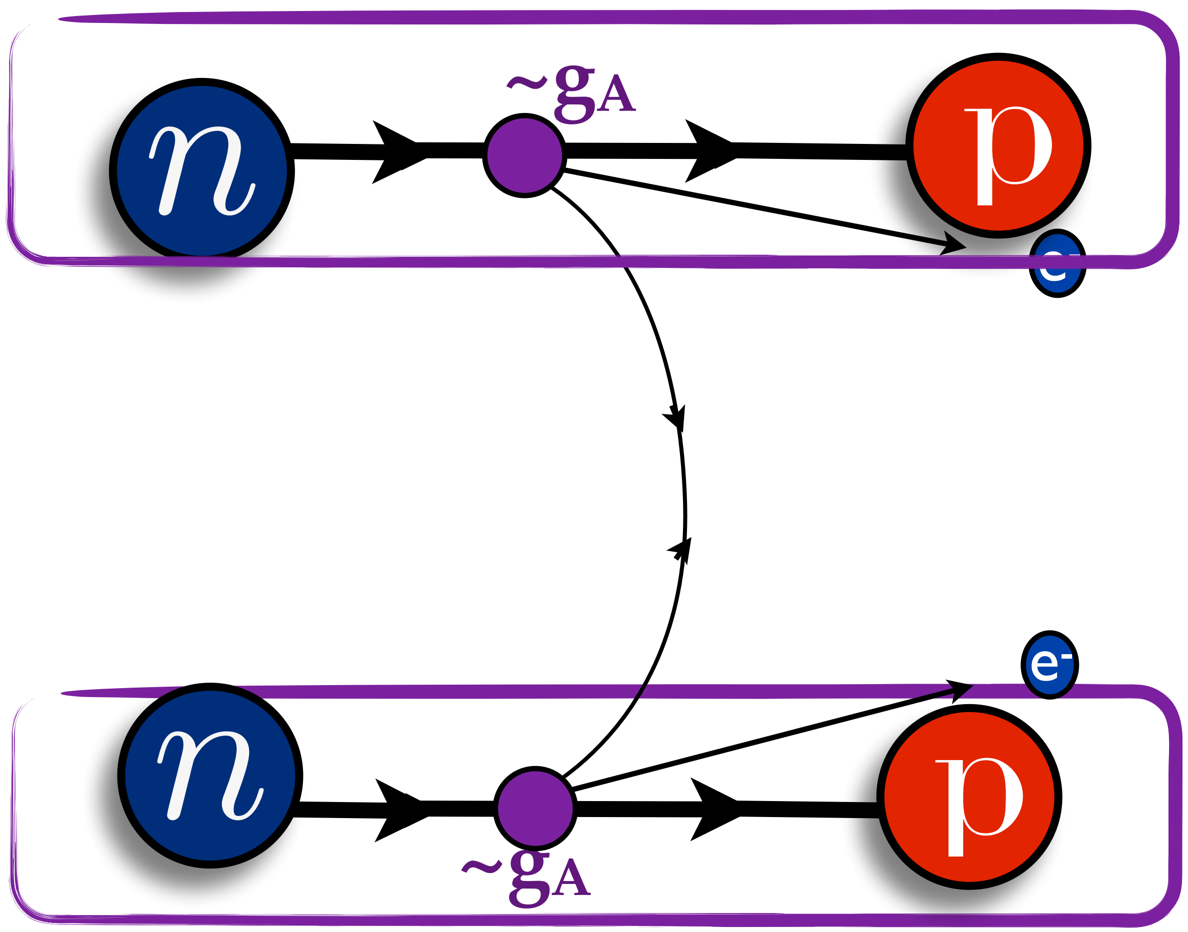




Long-range

Short-range

$\Lambda \ll \Lambda_{QCD}$



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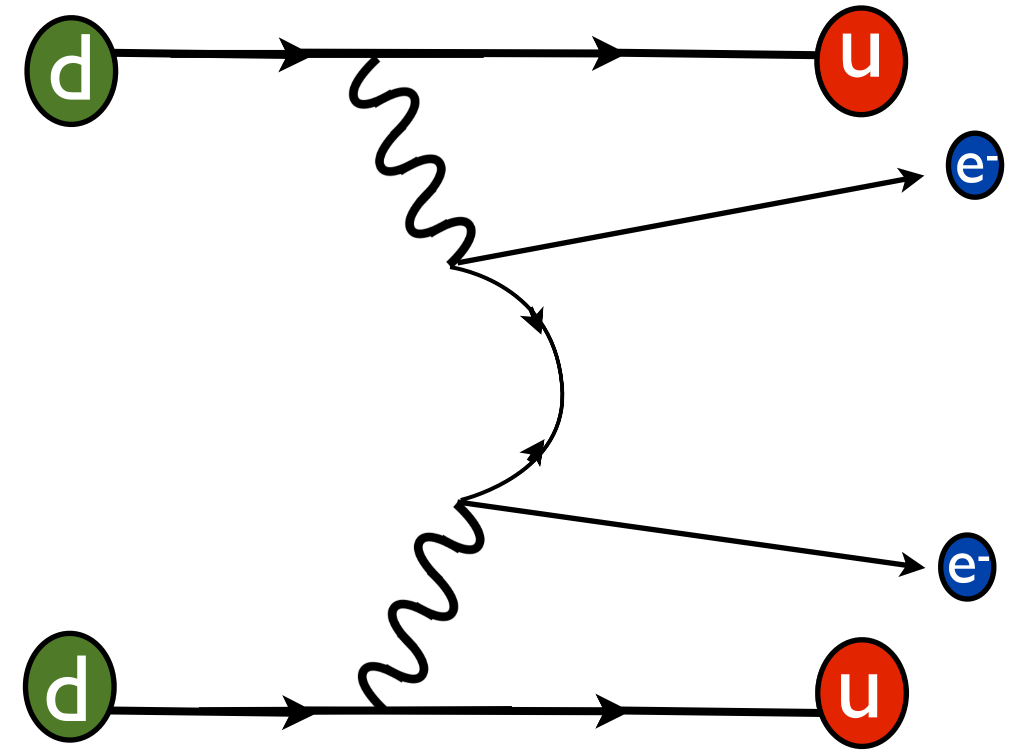
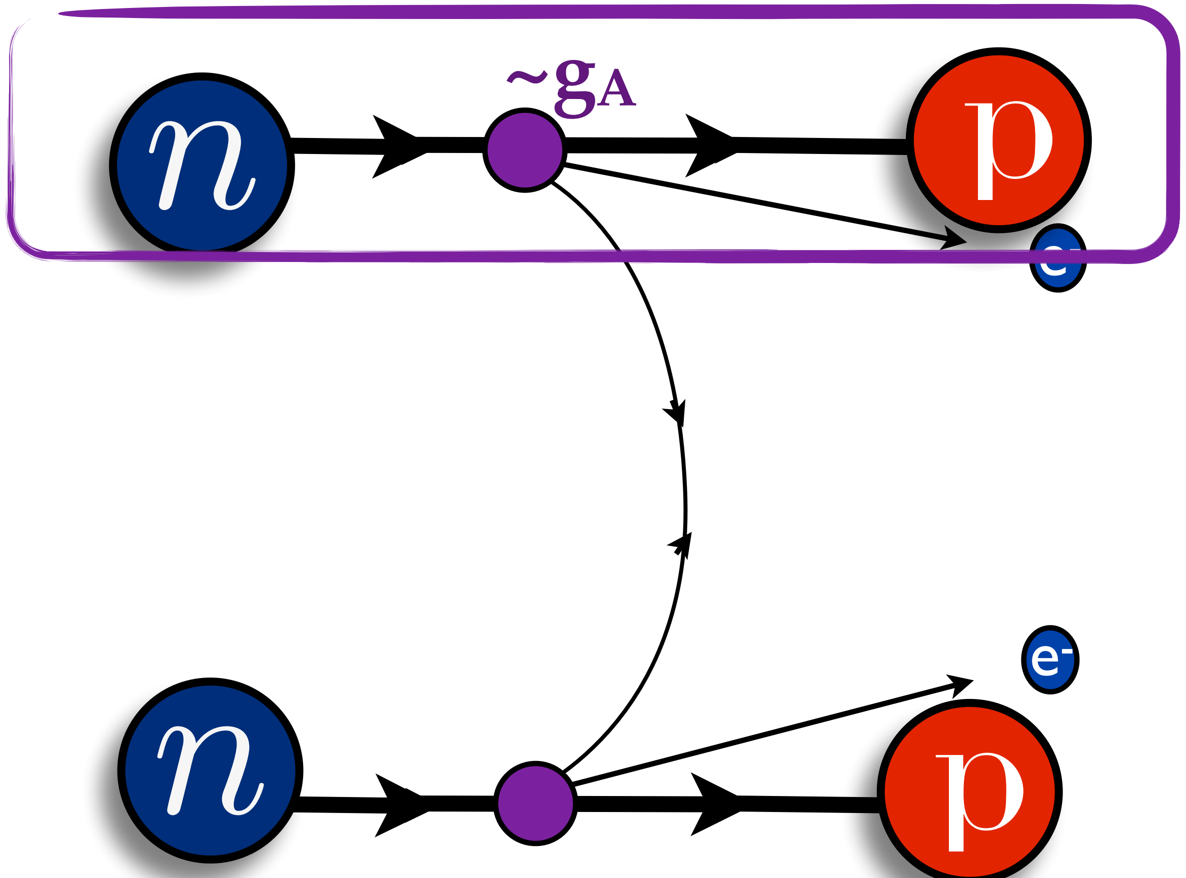


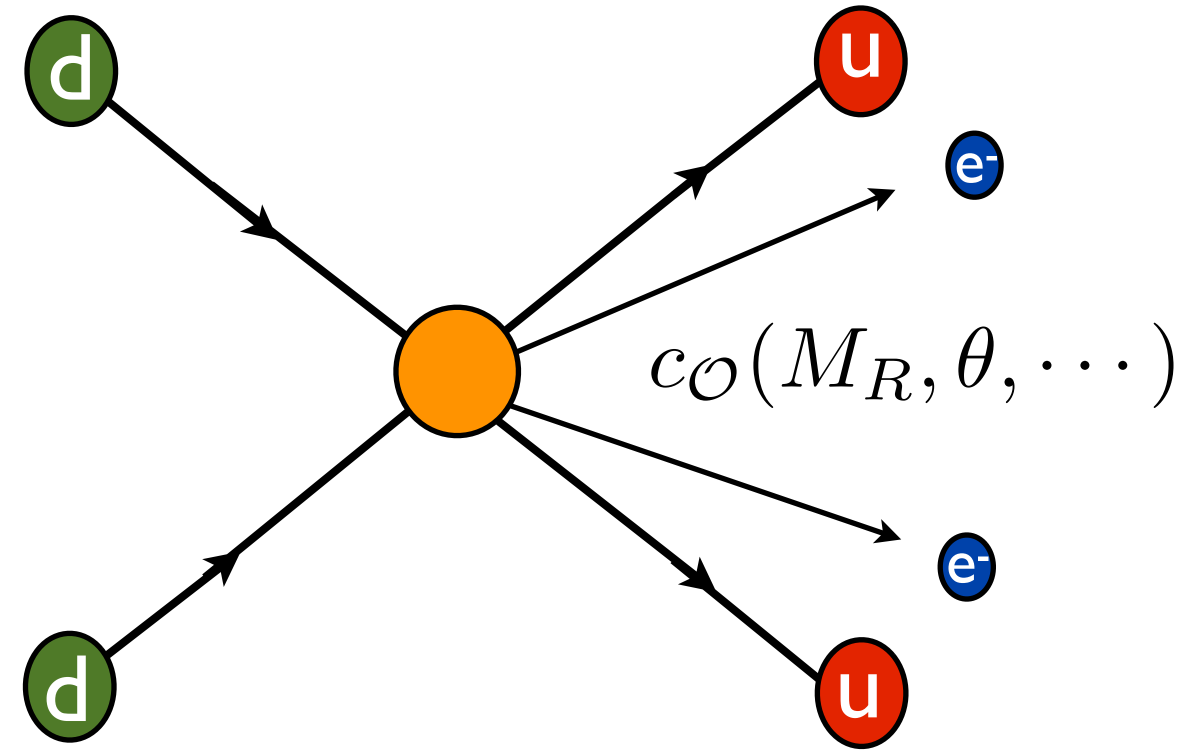
Short-range

$\boxed{\Lambda \ll M_W}$

Prezeau, Ramsey-Musolf, Vogel (2003)
Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)



Long-range



Short-range

$$
\begin{aligned}
\mathcal{O}^{ab}_{1+} &= (\bar{q}_{\mathrm{L}}\tau^a\gamma^\mu q_{\mathrm{L}})(\bar{q}_{\mathrm{R}}\tau^b\gamma_\mu q_{\mathrm{R}}),\\
\mathcal{O}^{ab}_{2\pm} &= (\bar{q}_{\mathrm{R}}\tau^a q_{\mathrm{L}})(\bar{q}_{\mathrm{R}}\tau^b q_{\mathrm{L}}) \pm (\bar{q}_{\mathrm{L}}\tau^a q_{\mathrm{R}})(\bar{q}_{\mathrm{L}}\tau^b q_{\mathrm{R}}),\\
\mathcal{O}^{ab}_{3\pm} &= (\bar{q}_{\mathrm{L}}\tau^a\gamma^\mu q_{\mathrm{L}})(\bar{q}_{\mathrm{L}}\tau^b\gamma_\mu q_{\mathrm{L}}) \pm (\bar{q}_{\mathrm{R}}\tau^a\gamma^\mu q_{\mathrm{R}})(\bar{q}_{\mathrm{R}}\tau^b\gamma_\mu q_{\mathrm{R}}),\\
\mathcal{O}^{ab,\mu}_{4\pm} &= (\bar{q}_{\mathrm{L}}\tau^a\gamma^\mu q_{\mathrm{L}} \mp \bar{q}_{\mathrm{R}}\tau^a\gamma^\mu q_{\mathrm{R}})(\bar{q}_{\mathrm{L}}\tau^b q_{\mathrm{R}} - \bar{q}_{\mathrm{R}}\tau^b q_{\mathrm{L}}),\\
\mathcal{O}^{ab,\mu}_{5\pm} &= (\bar{q}_{\mathrm{L}}\tau^a\gamma^\mu q_{\mathrm{L}} \pm \bar{q}_{\mathrm{R}}\tau^a\gamma^\mu q_{\mathrm{R}})(\bar{q}_{\mathrm{L}}\tau^b q_{\mathrm{R}} + \bar{q}_{\mathrm{R}}\tau^b q_{\mathrm{L}}).
\end{aligned}
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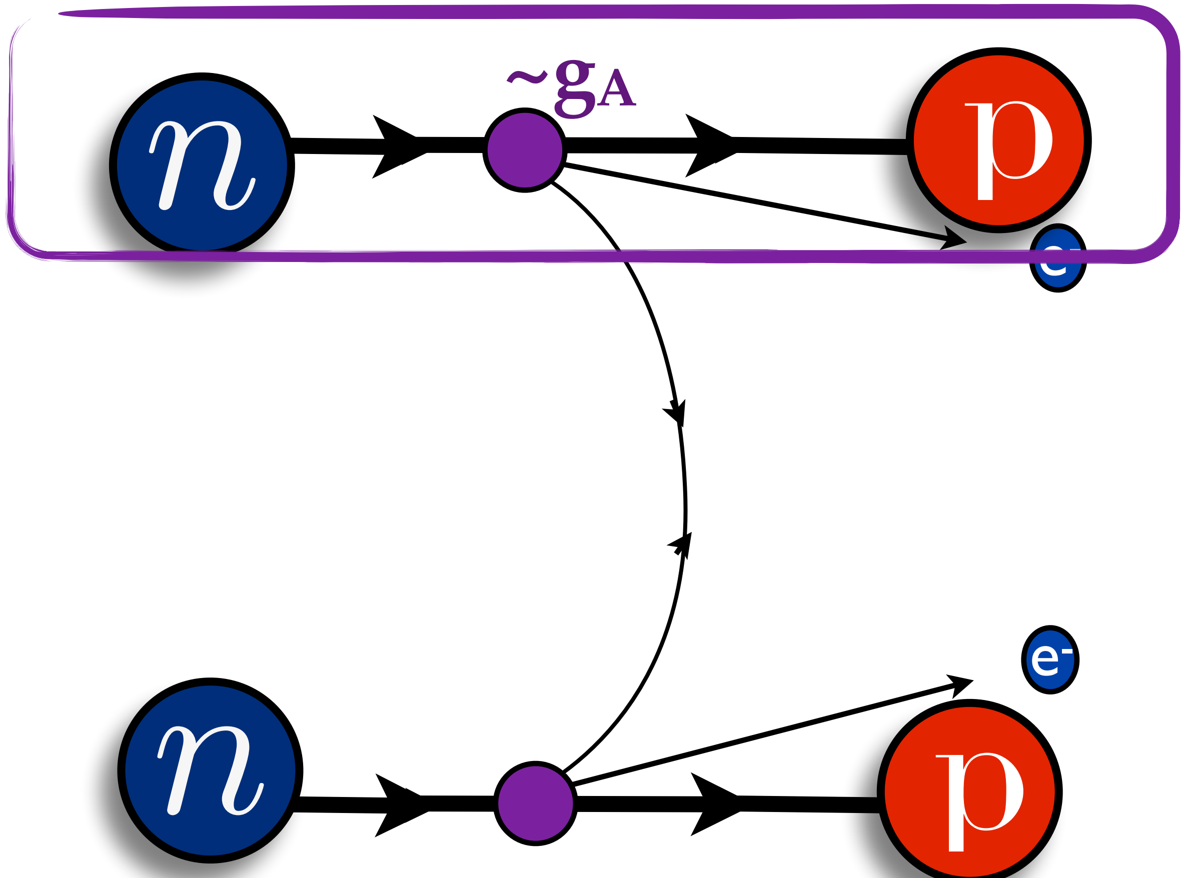
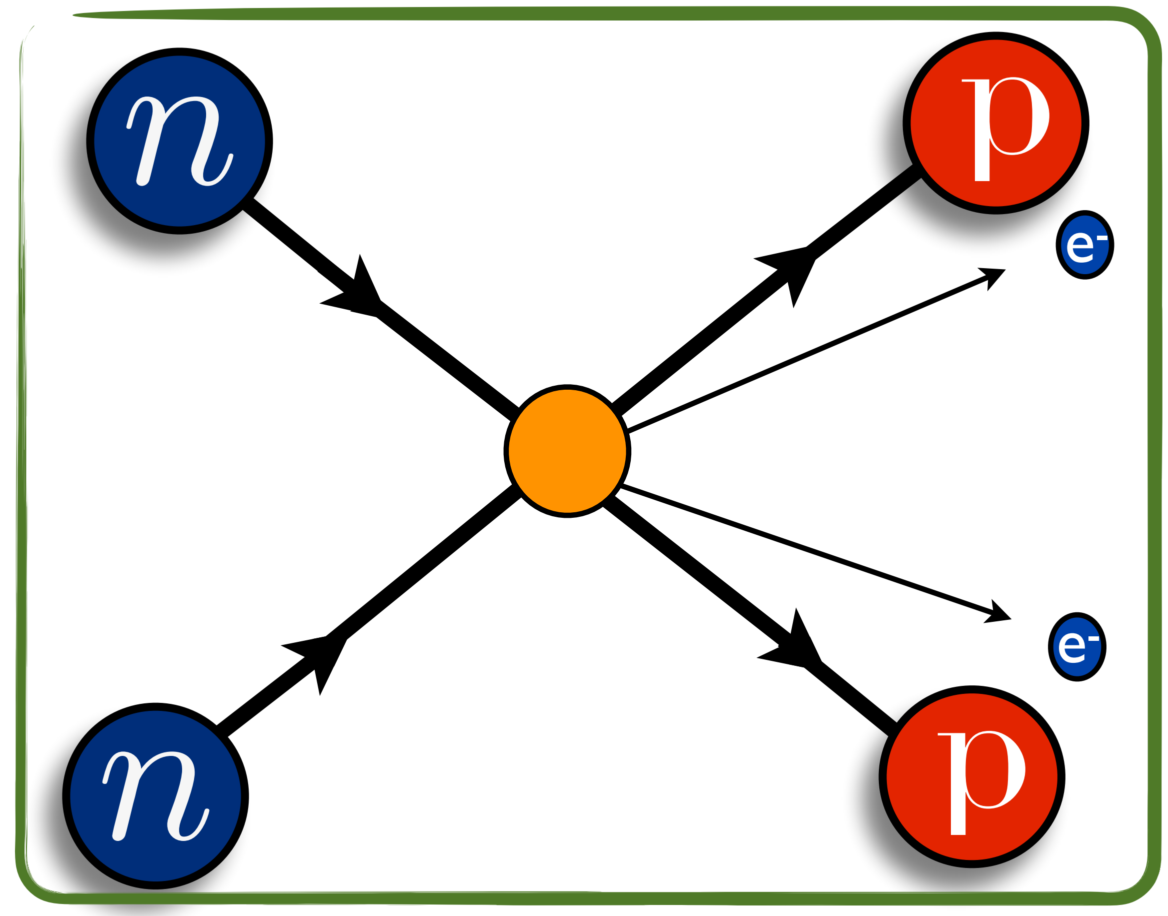


Long-range



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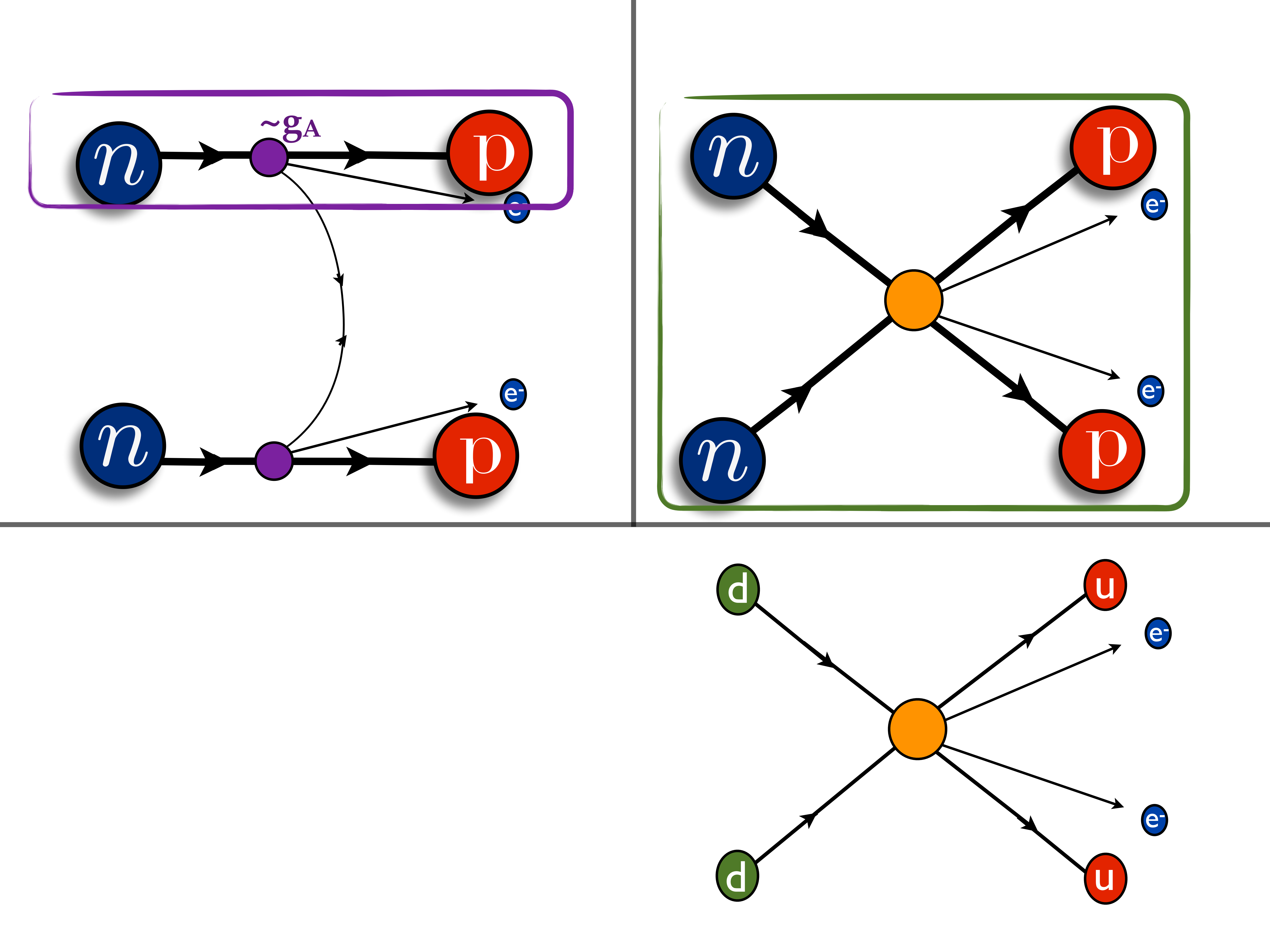

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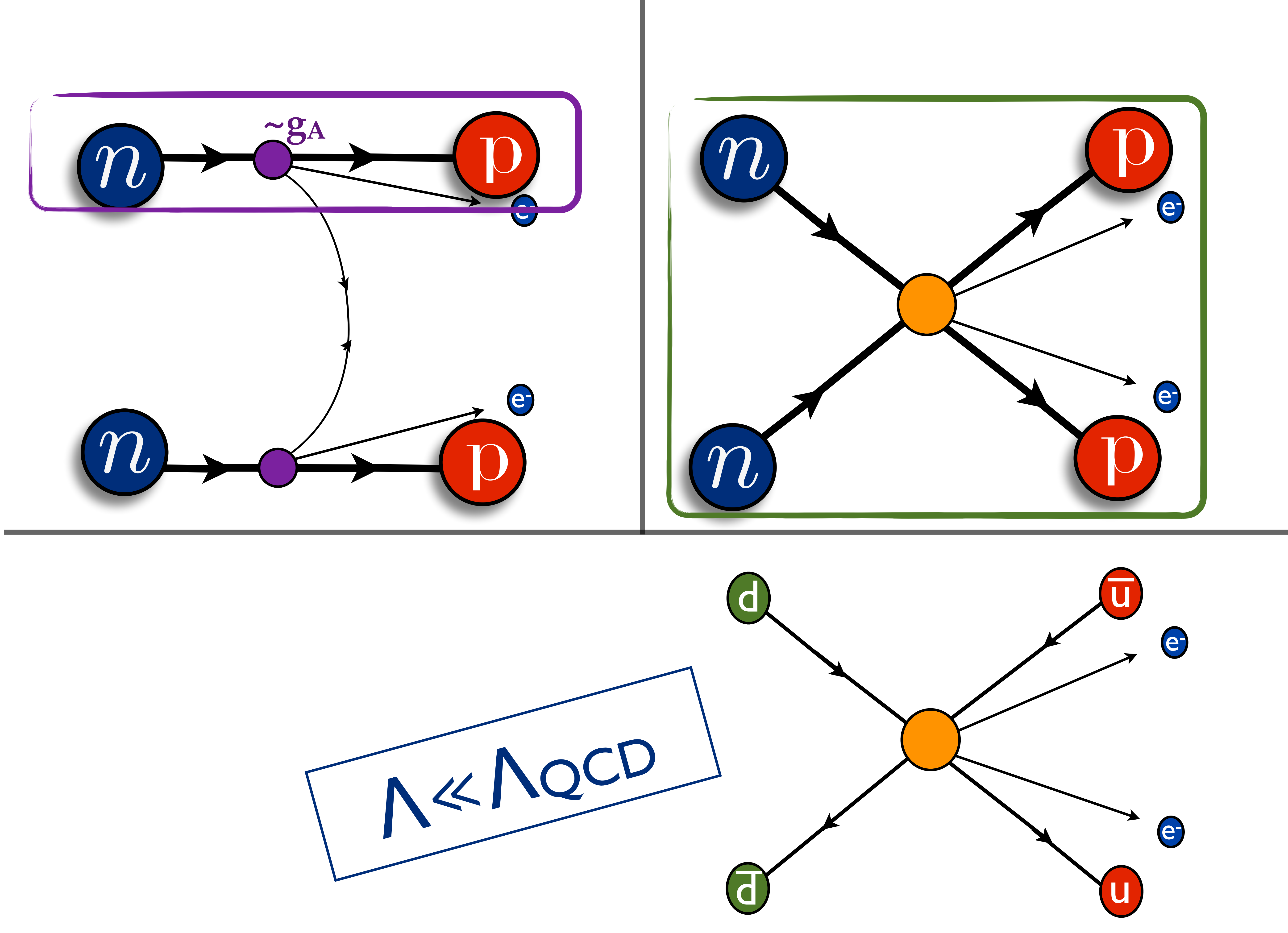
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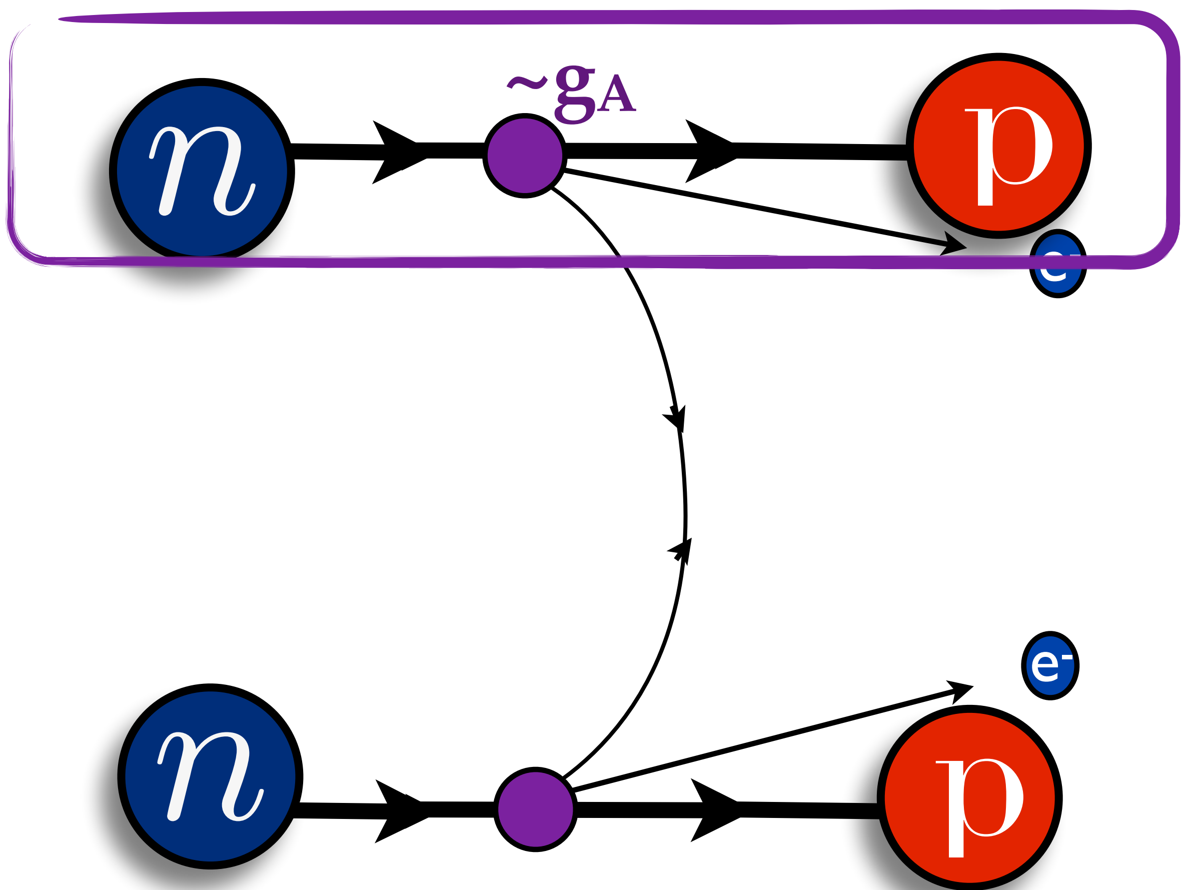
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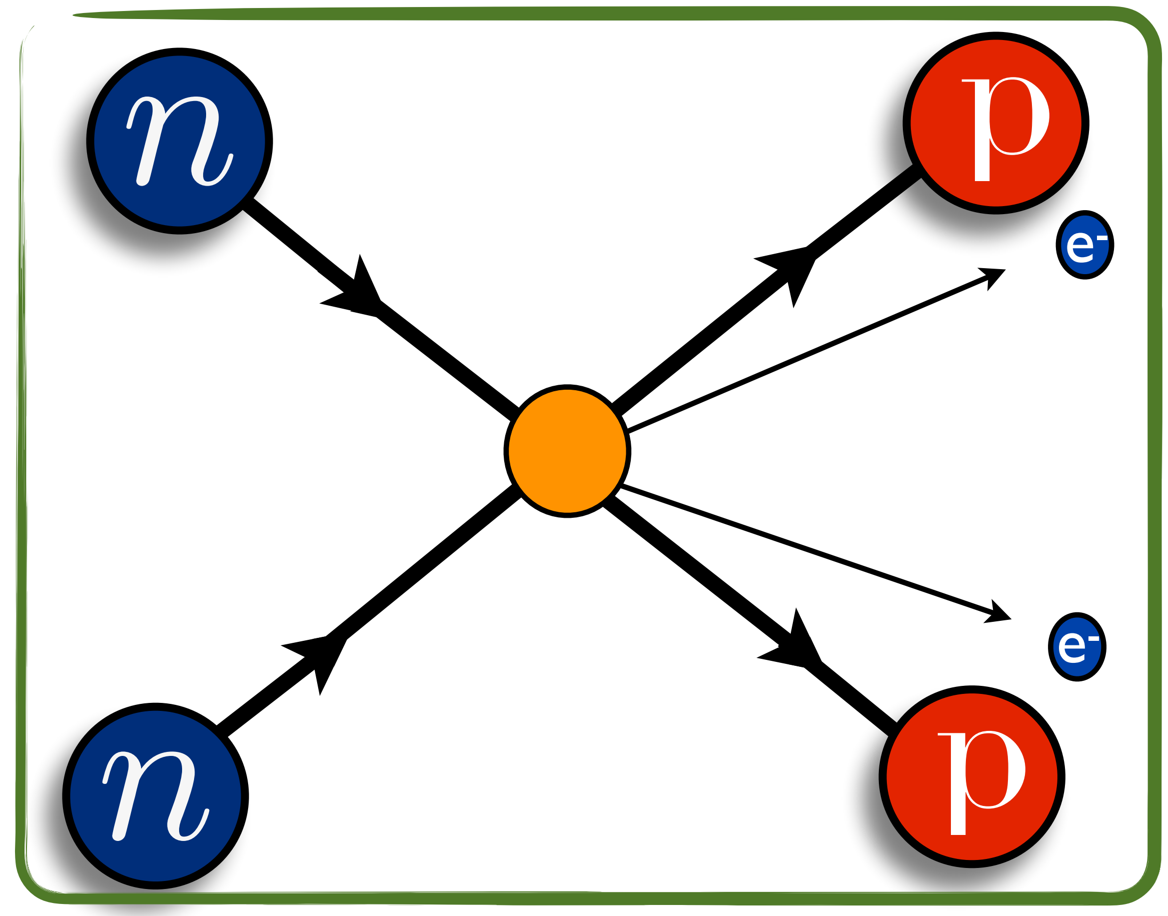
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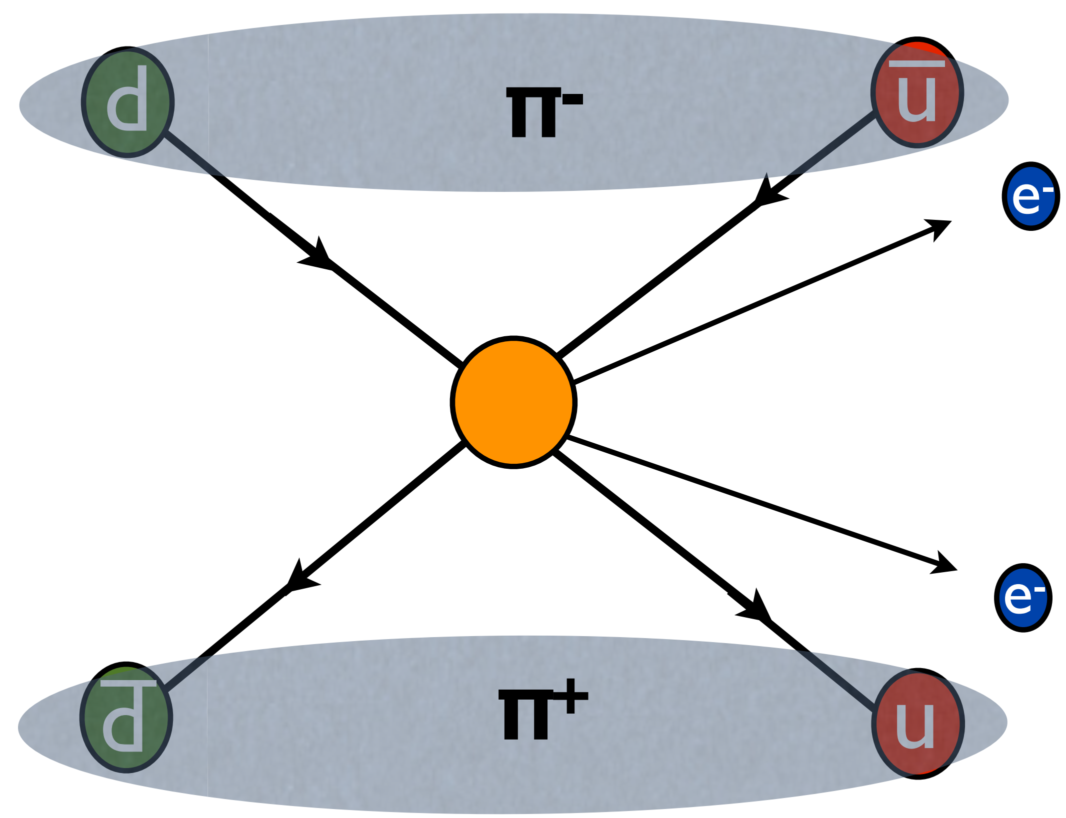
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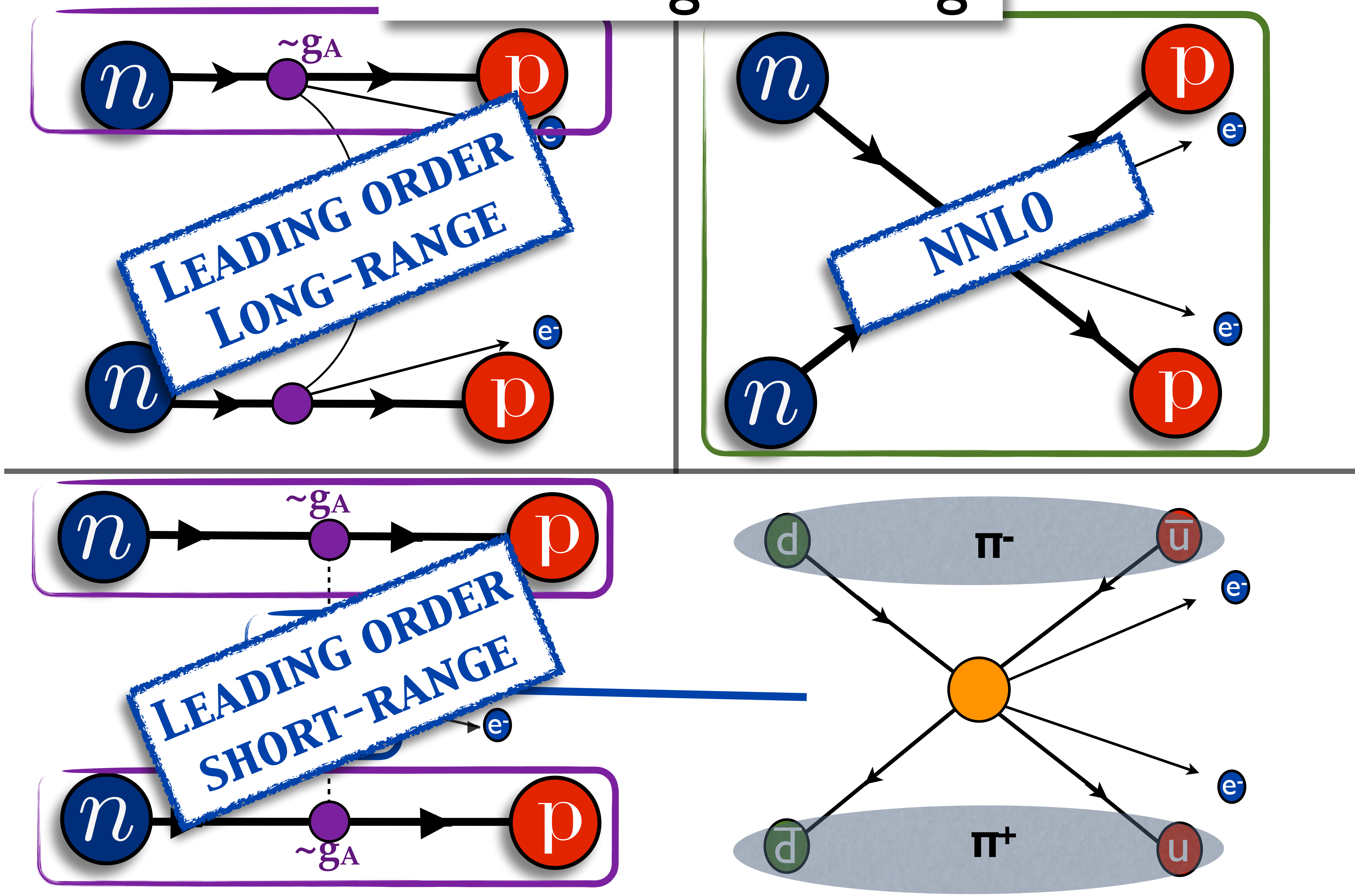
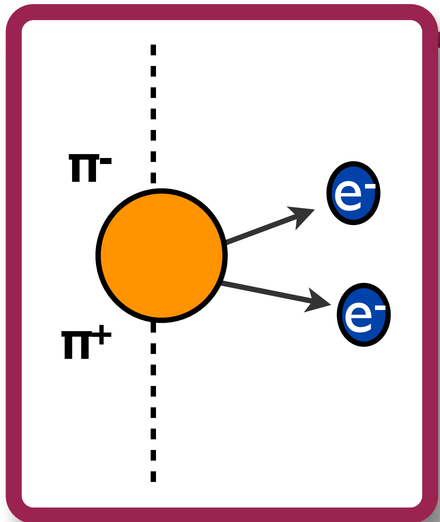
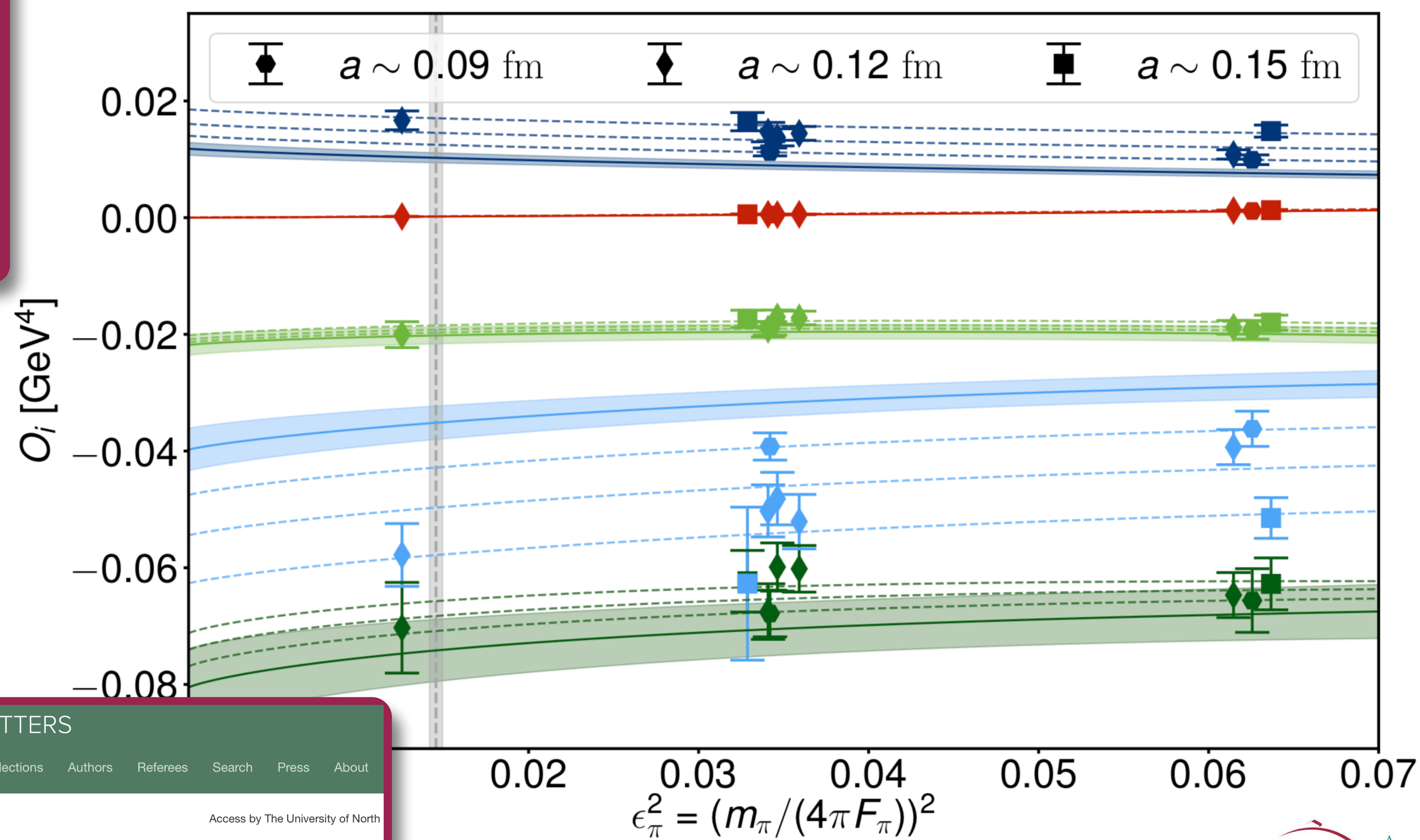
Weinberg counting

Prezeau, Ramsey-Musolf, Vogel (2003)







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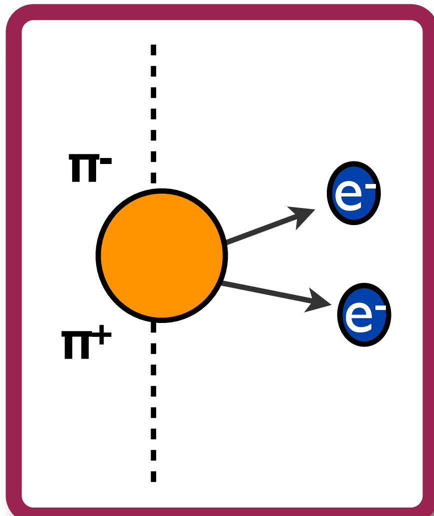
Heavy Physics Contributions to Neutrinoless Double Beta Decay from QCD

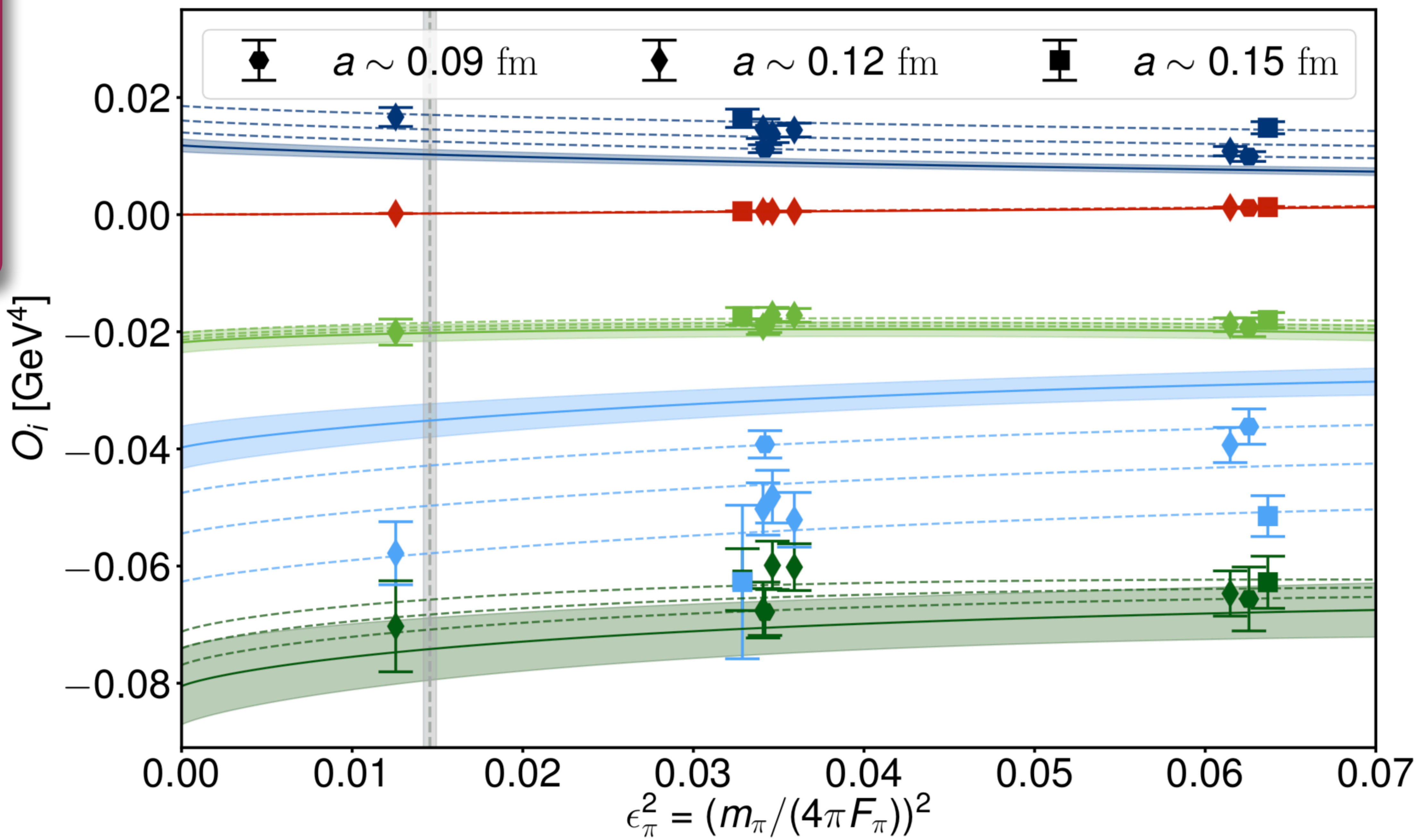
A. Nicholson, E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joó, T. Kurth, B. C. Tiburzi, P. Vranas, and A. Walker-Loud

Phys. Rev. Lett. **121**, 172501 – Published 25 October 2018

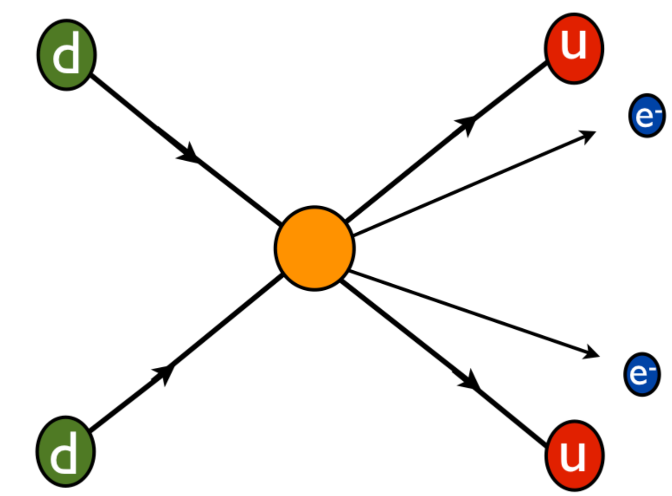
	RI/SMOM	$\overline{\text{MS}}$
$O_i[\text{GeV}]^4$	$\mu = 3$ GeV	$\mu = 3$ GeV
O_1	$-1.96(14)\times10^{-2}$	$-1.94(14)\times10^{-2}$
O_1'	$-7.21(53)\times10^{-2}$	$-7.81(57)\times10^{-2}$
O_2	$-3.60(30)\times10^{-2}$	$-3.69(31)\times10^{-2}$
O_2'	$1.05(09)\times10^{-2}$	$1.12(10)\times10^{-2}$
O_3	$1.89(09)\times10^{-4}$	$1.90(09)\times10^{-4}$

Möbius DWQ on HISQ ensembles (MILC)



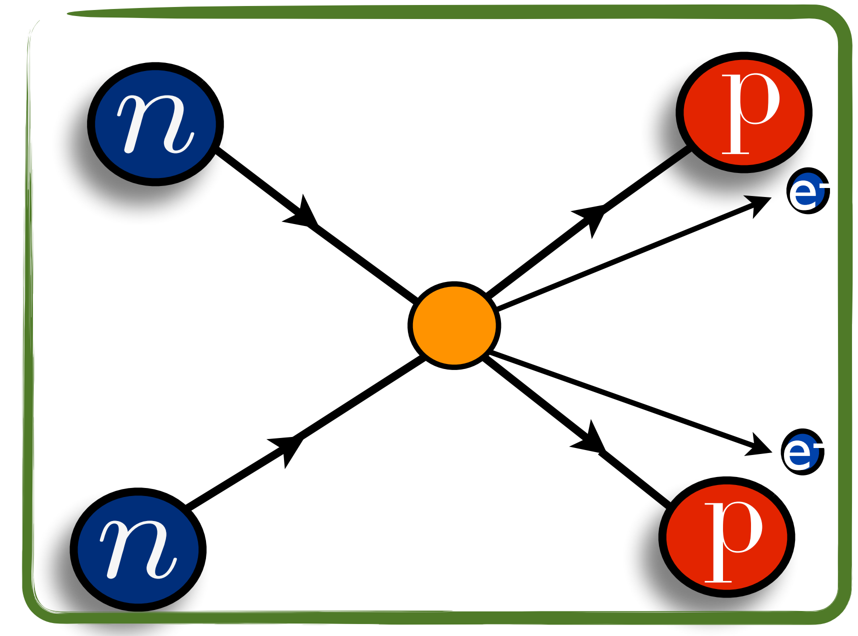


Non-perturbative operator renormalization complete: can be reused for any 0νββ matrix element calculation



D. Brantley, N. Garron, H. Monge-Camacho, AN, A. Walker-Loud, *in preparation*

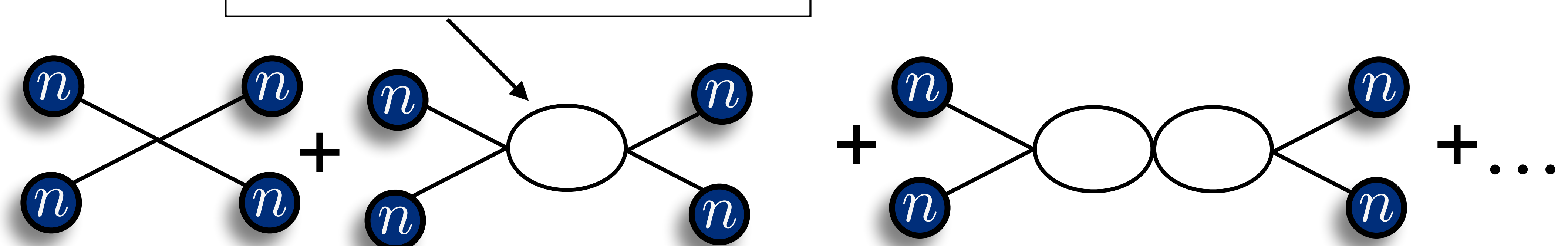
Two-nucleon transitions



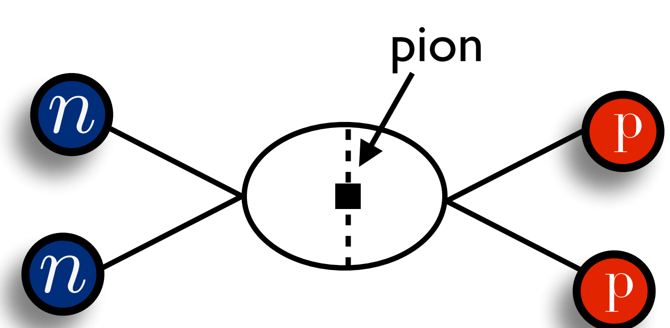
- Why calculate them? Leading contributions known (Weinberg counting)
  - LO contribution vanishes for some BSM models
  - The spin singlet channel is finely-tuned, leading to issues with Weinberg counting

Kaplan, Savage, Wise Phys.Lett. B424 (1998) 390-396

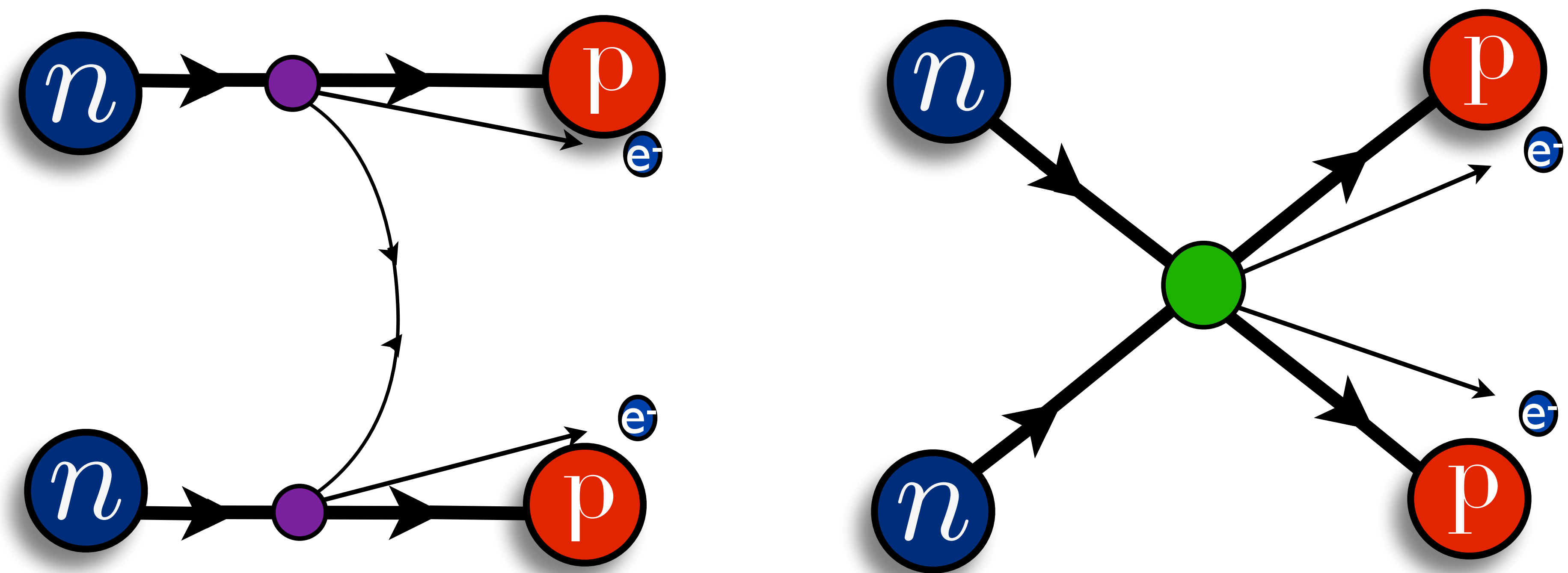
near-threshold virtual bound state



Cirigliano, et al, Phys. Rev. Lett. 120, 202001 (2018)



Beyond Weinberg: light neutrino exchange

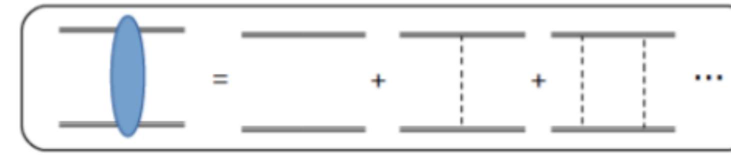


- Symmetries allow one to write down a contact term

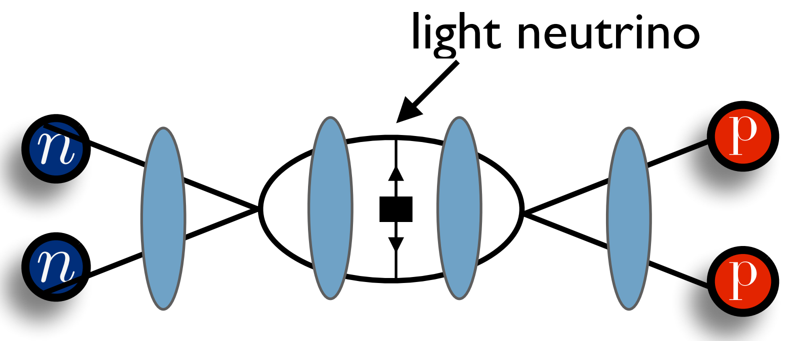
$$\boxed{V_{\nu,CT}^{(a,b)} = -2\, g_\nu\, \tau^{(a)+}\tau^{(b)+}}$$

$g_\nu \sim 1/(4\pi F_\pi)^2$ in NDA /
Weinberg counting
(and hence sub-leading)
But is it?

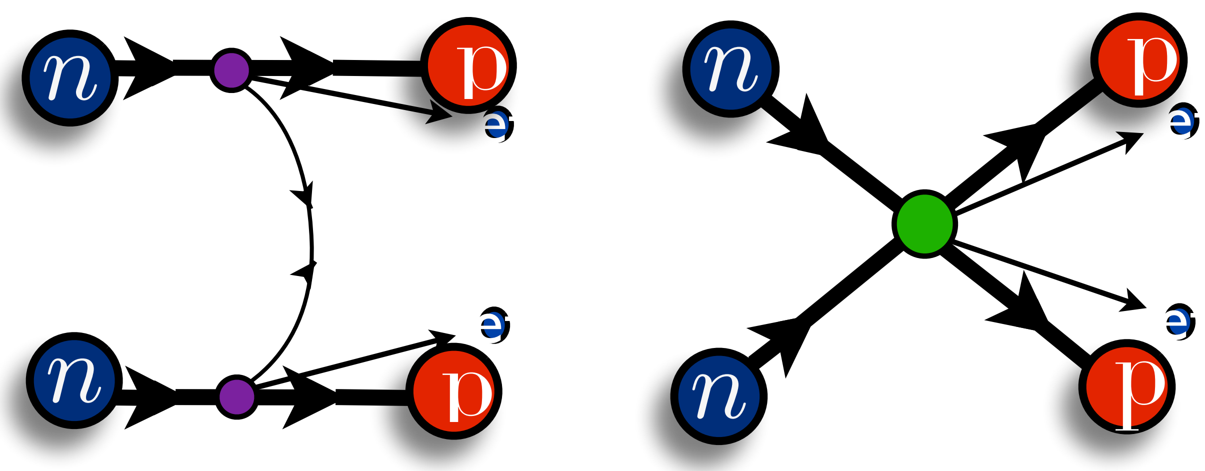
Fine-tuning



- Neutrinoless double-beta decay:



- Divergence in loops requires contact operator at leading order for renormalization



$g_\nu \sim 1/F_\pi^2 \gg 1/(4\pi F_\pi)^2$

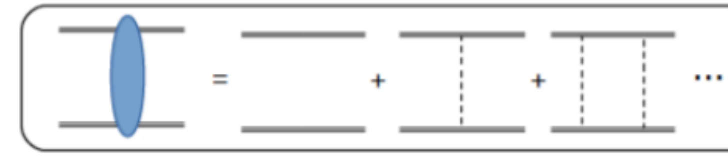
PHYSICAL REVIEW LETTERS **120**, 202001 (2018)

Editors' Suggestion | Featured in Physics

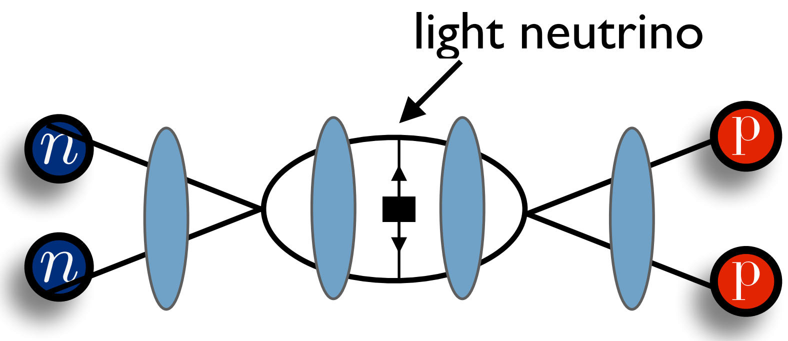
New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2] Michael L. Graesser,[1]
Emanuele Mereghetti,[1] Saori Pastore,[1] and Ubirajara van Kolck[3,4]

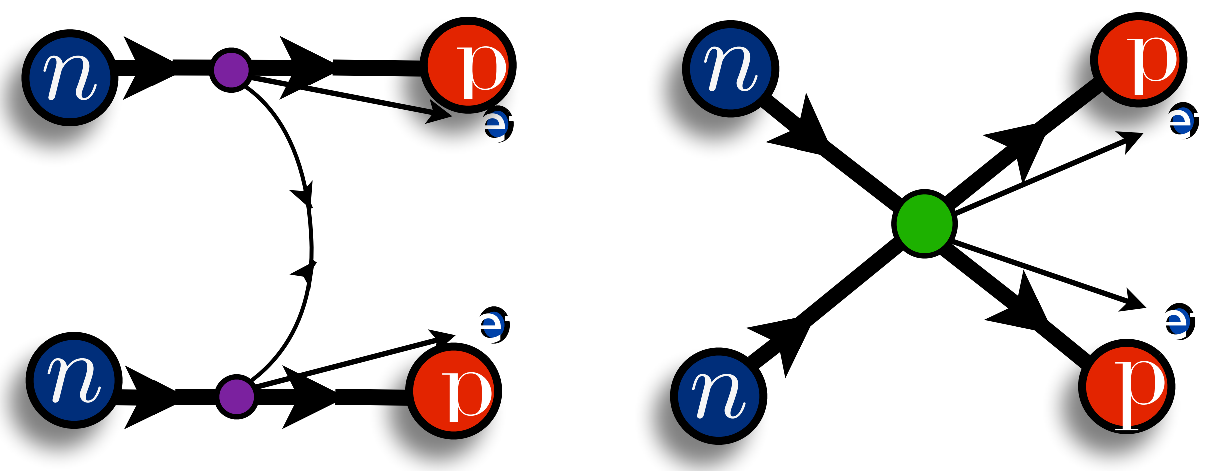
Fine-tuning



- Neutrinoless double-beta decay:

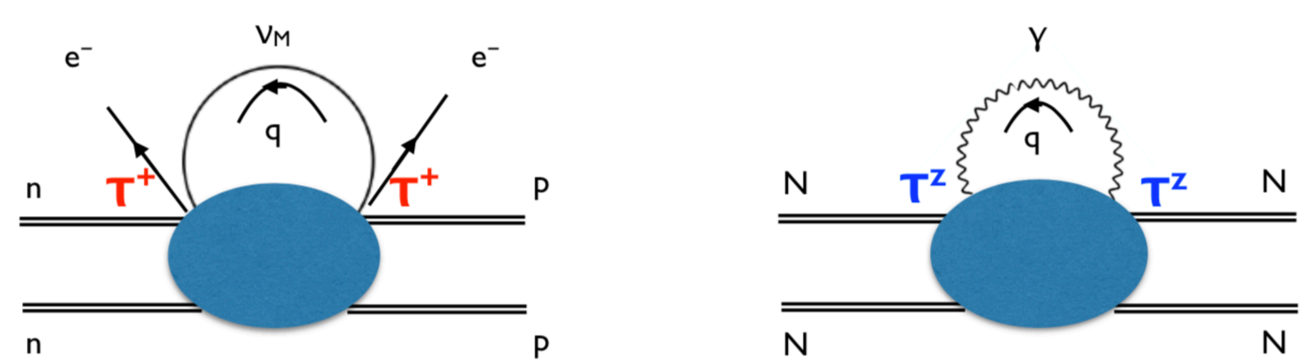


- Divergence in loops requires contact operator at leading order for renormalization



- We don't know the numerical value of g_ν
- Can it be estimated?

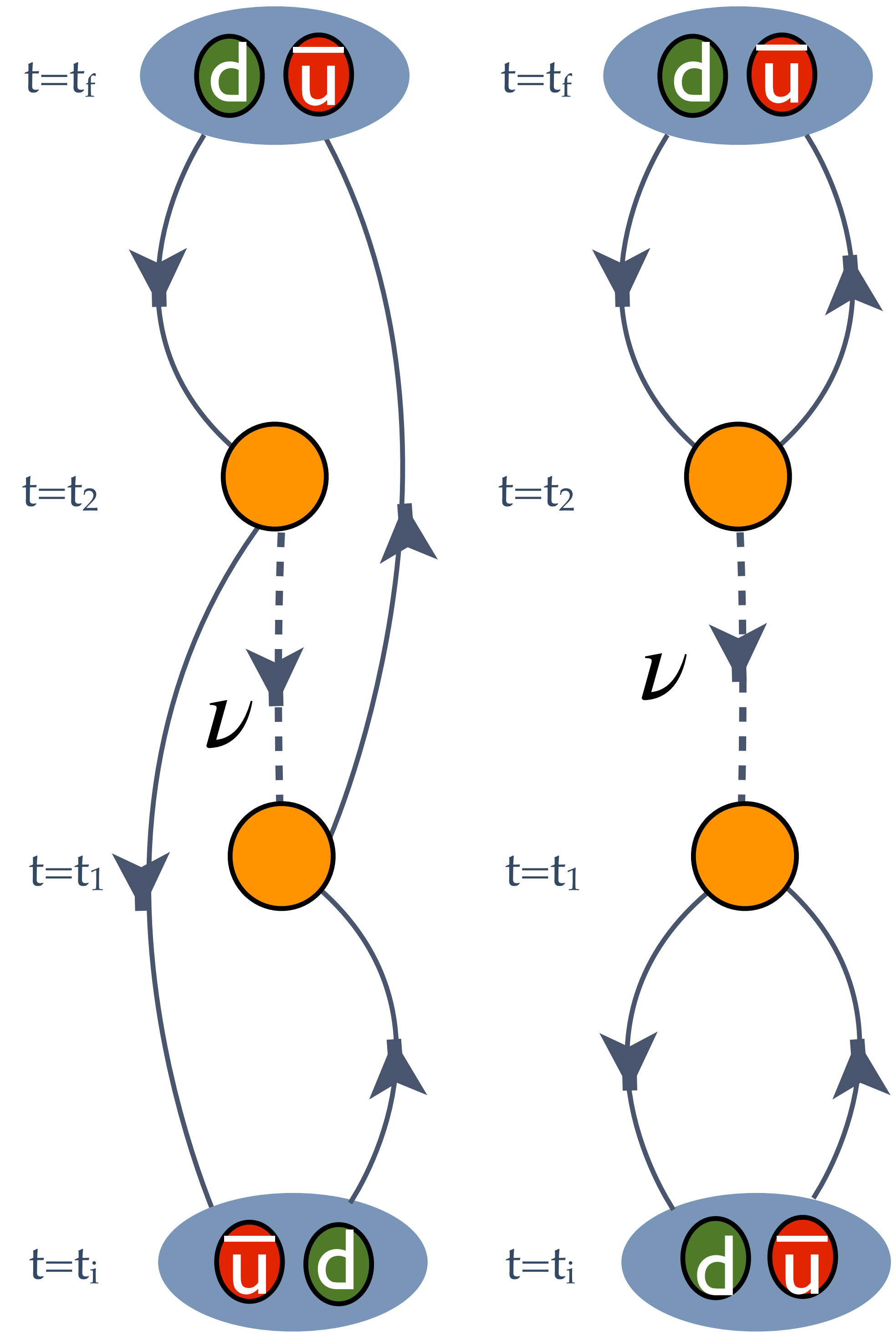
Chiral symmetry relates g_ν to one of two I=2 EM LECs (hard γ's vs ν's)



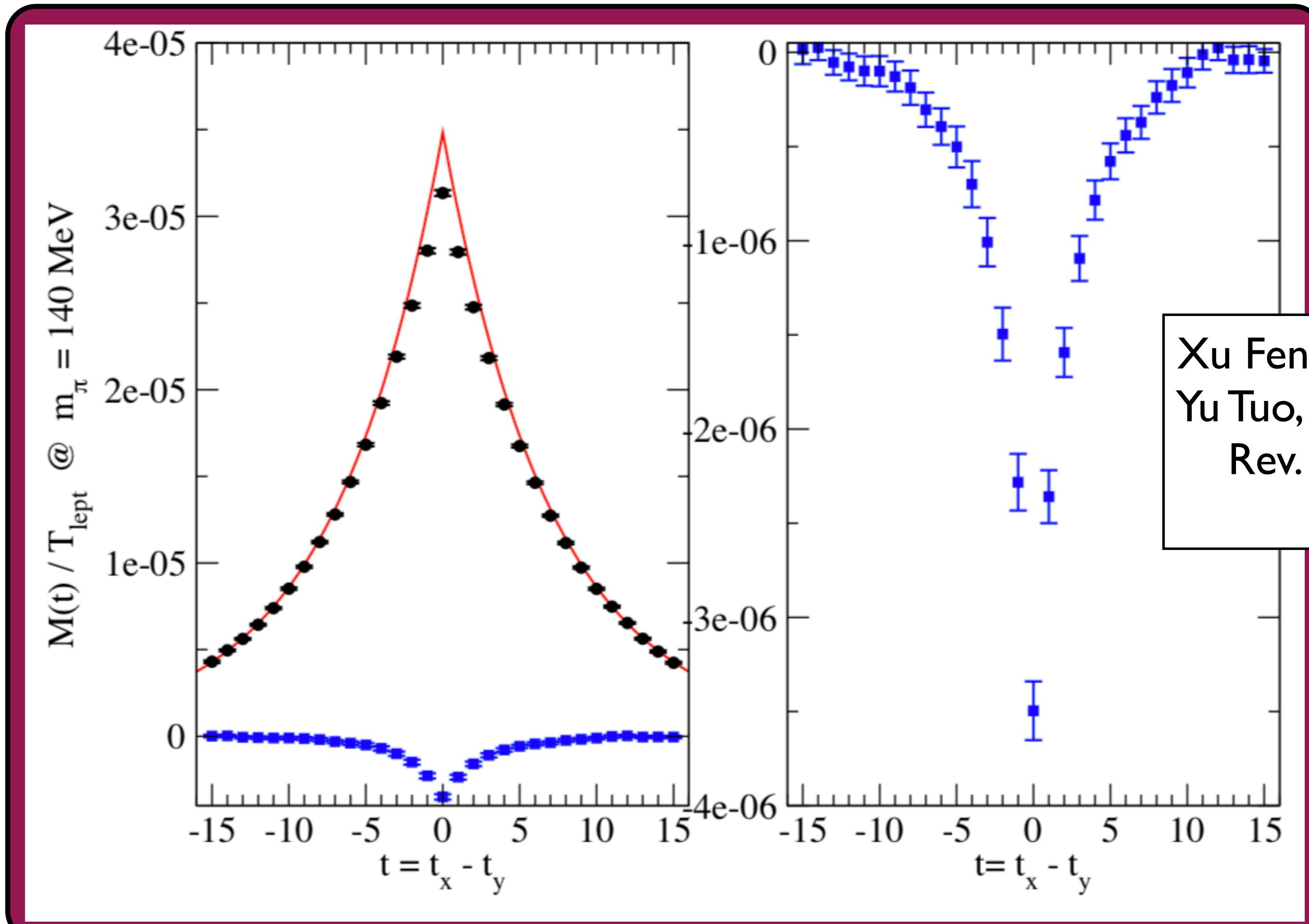
Cirigliano, et al, Phys. Rev. C 100, 055504 (2019)

Beyond Weinberg: light neutrino mechanism

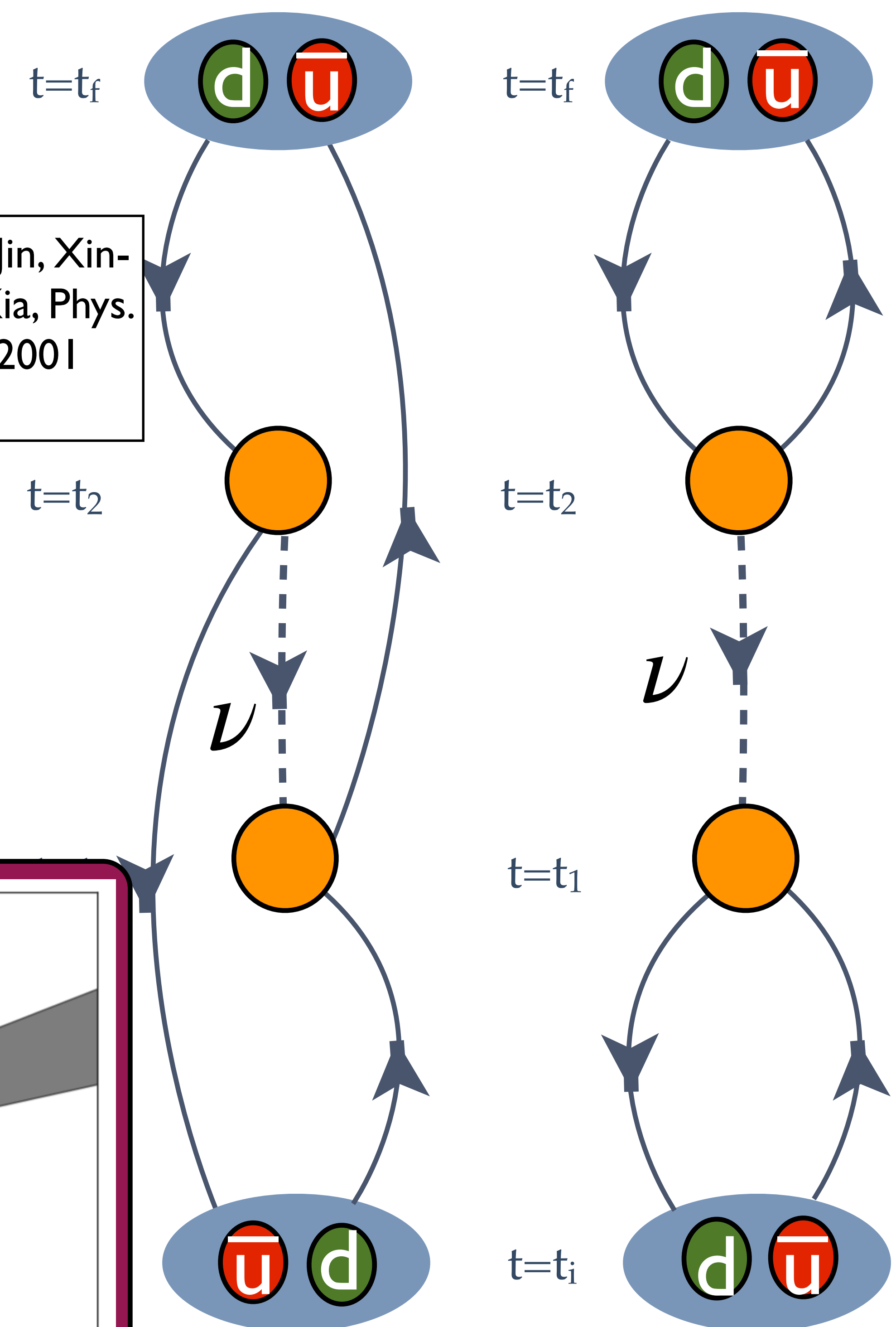
- Work has begun to calculate fully non-perturbative nn —> pp transition for light neutrino mechanism
  - Very difficult! both computationally and theoretically
  - Start with $\pi^- \to \pi^+$ as a test

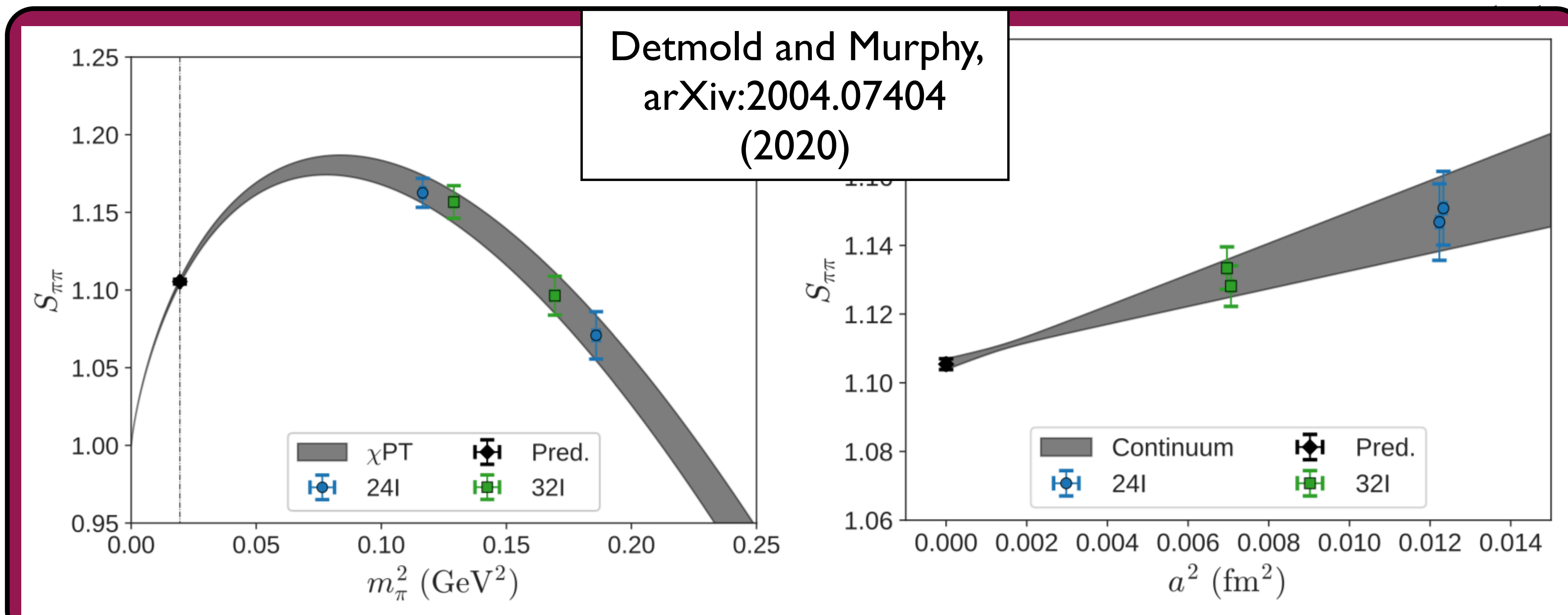


Beyond Weinberg: light neutrino mechanism

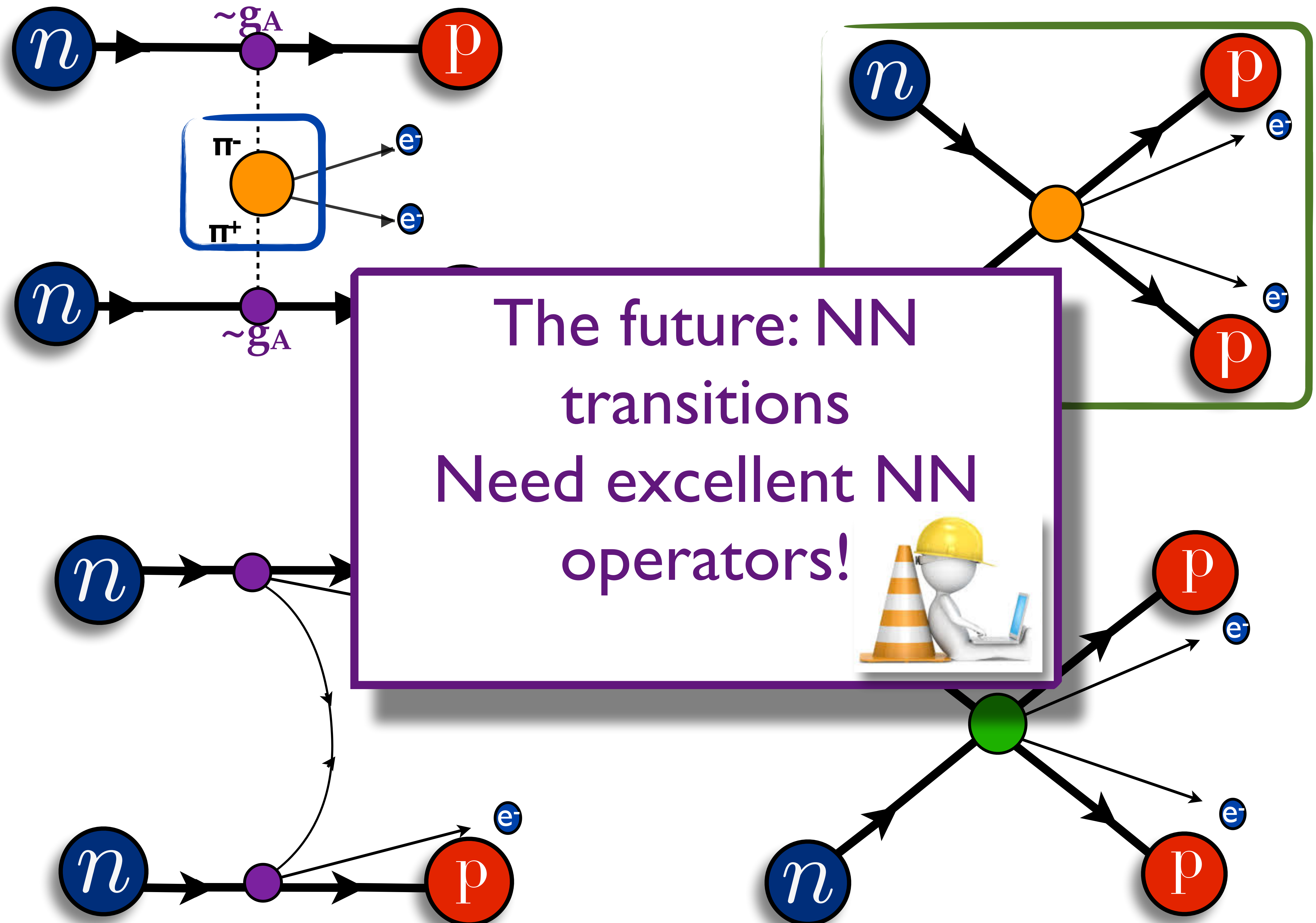


Xu Feng, Lu-Chang Jin, Xin-Yu Tuo, Shi-Cheng Xia, Phys. Rev. Lett. 122, 022001 (2019)





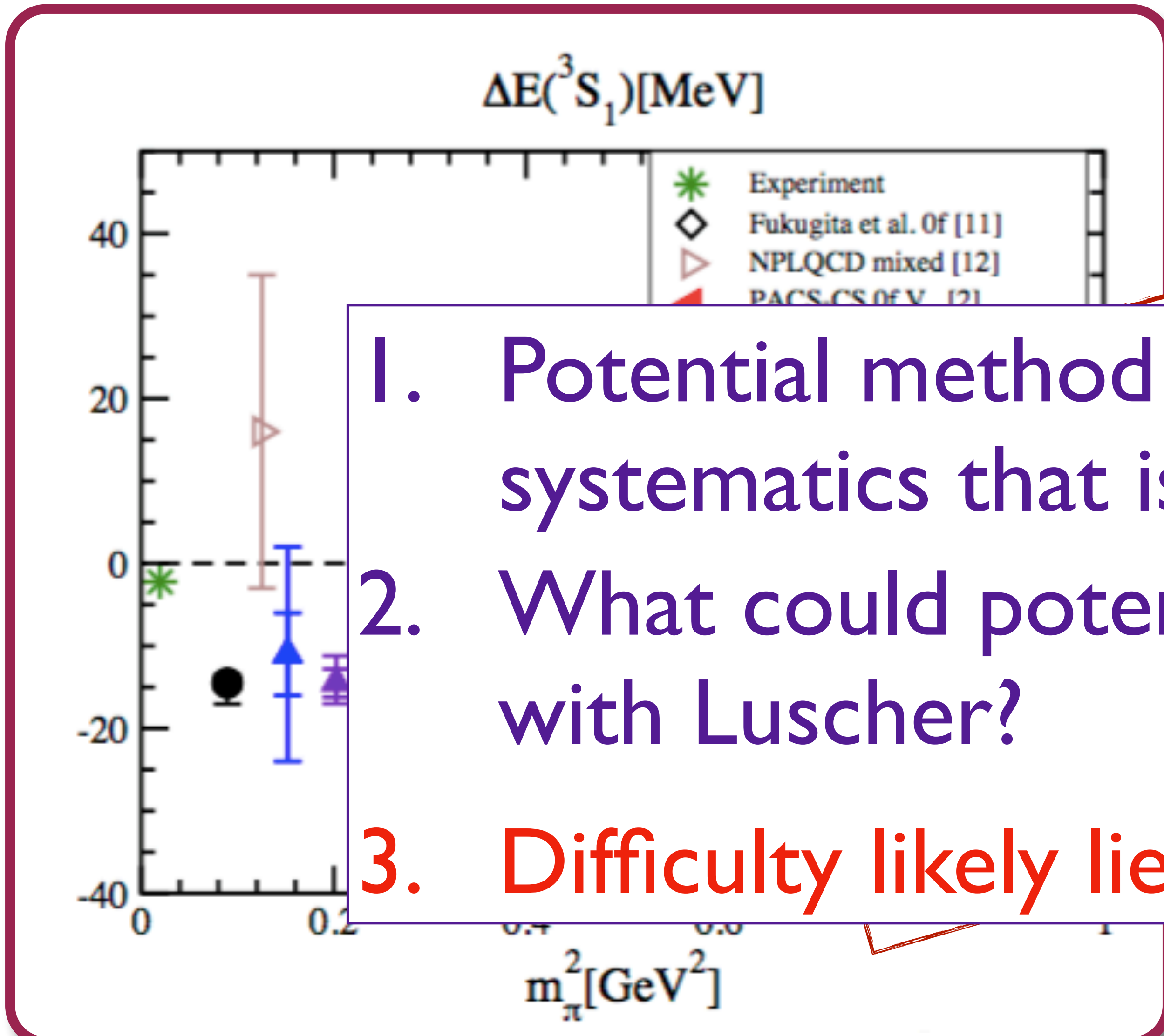
Detmold and Murphy, arXiv:2004.07404 (2020)

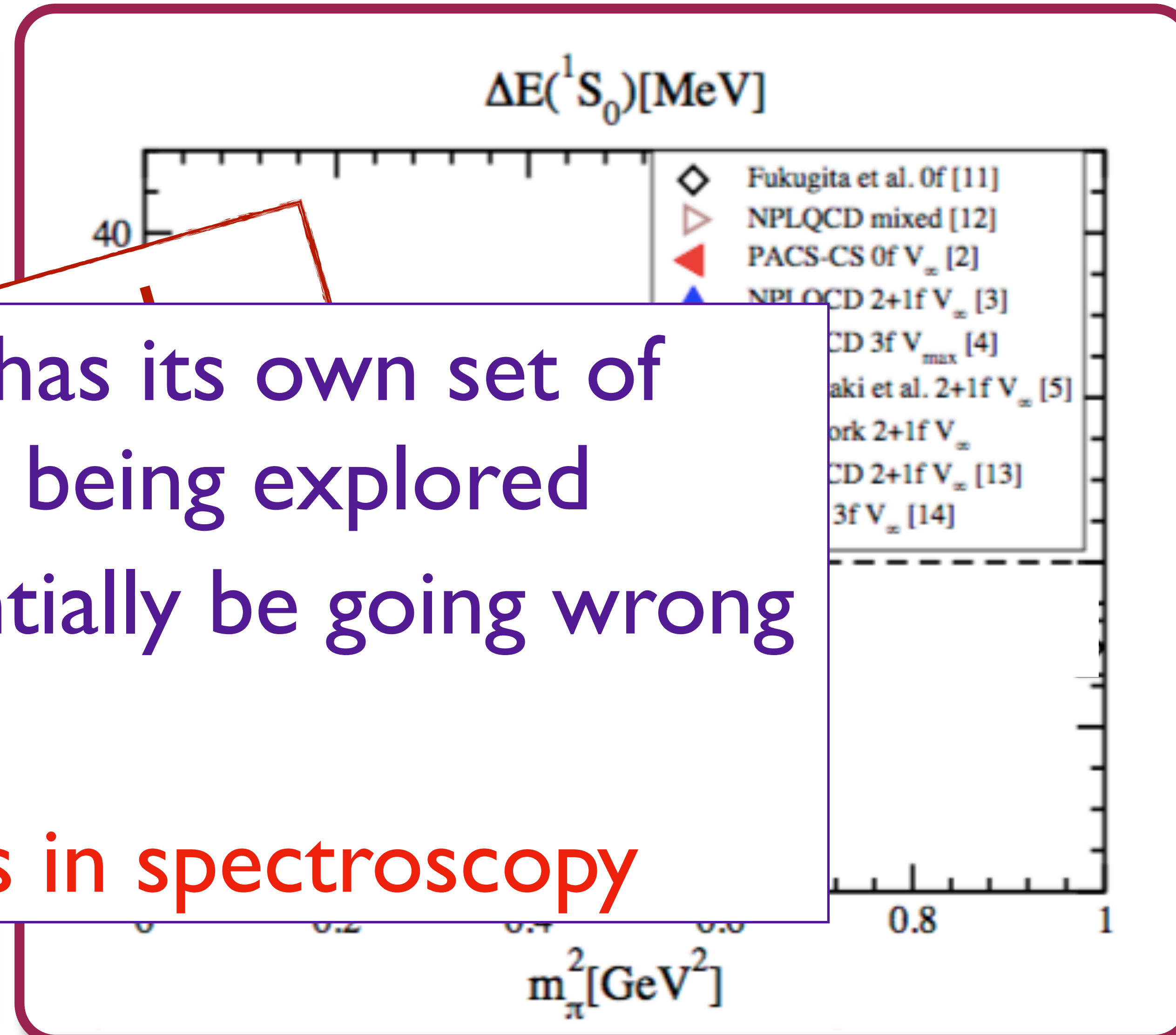


The future: NN transitions

Need excellent NN operators!

NN Binding energies: history



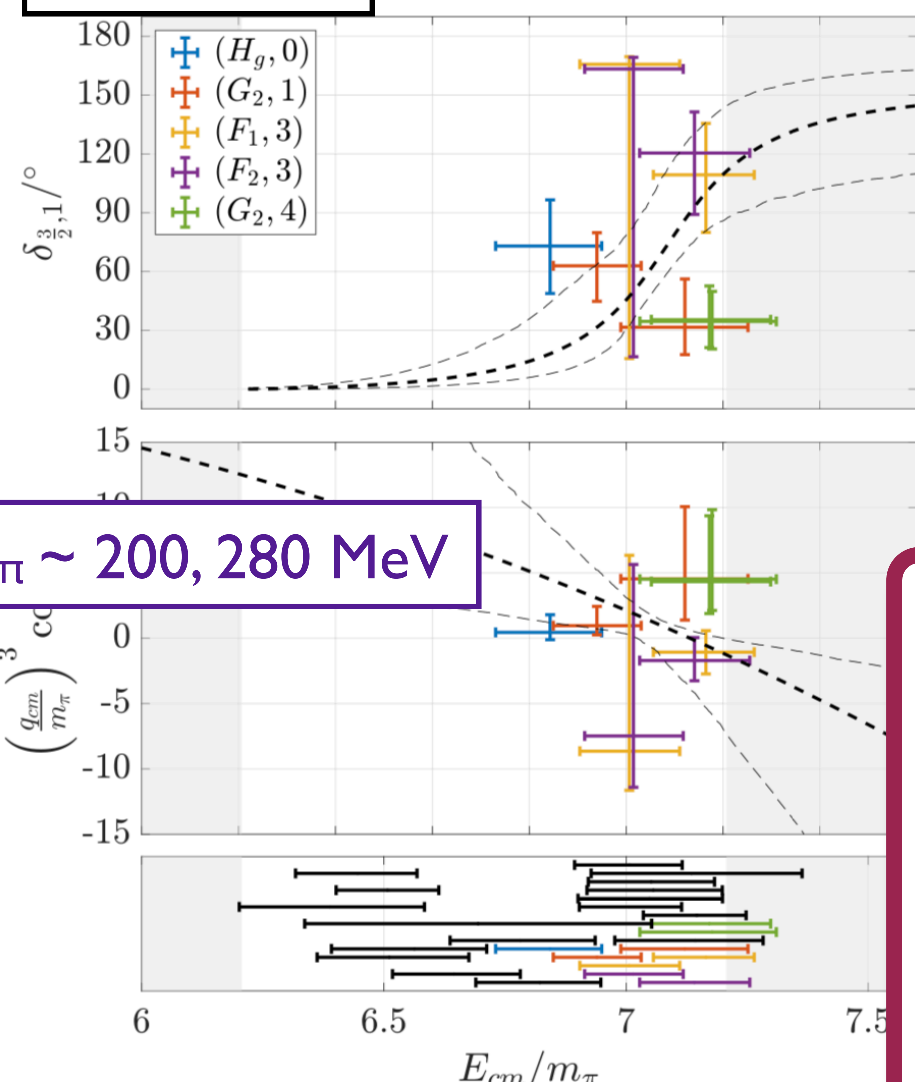


1. Potential method has its own set of systematics that is being explored
2. What could potentially be going wrong with Luscher?
3. Difficulty likely lies in spectroscopy

T. Yamazaki, arXiv:1511.09179

The future?
GEVP approaches

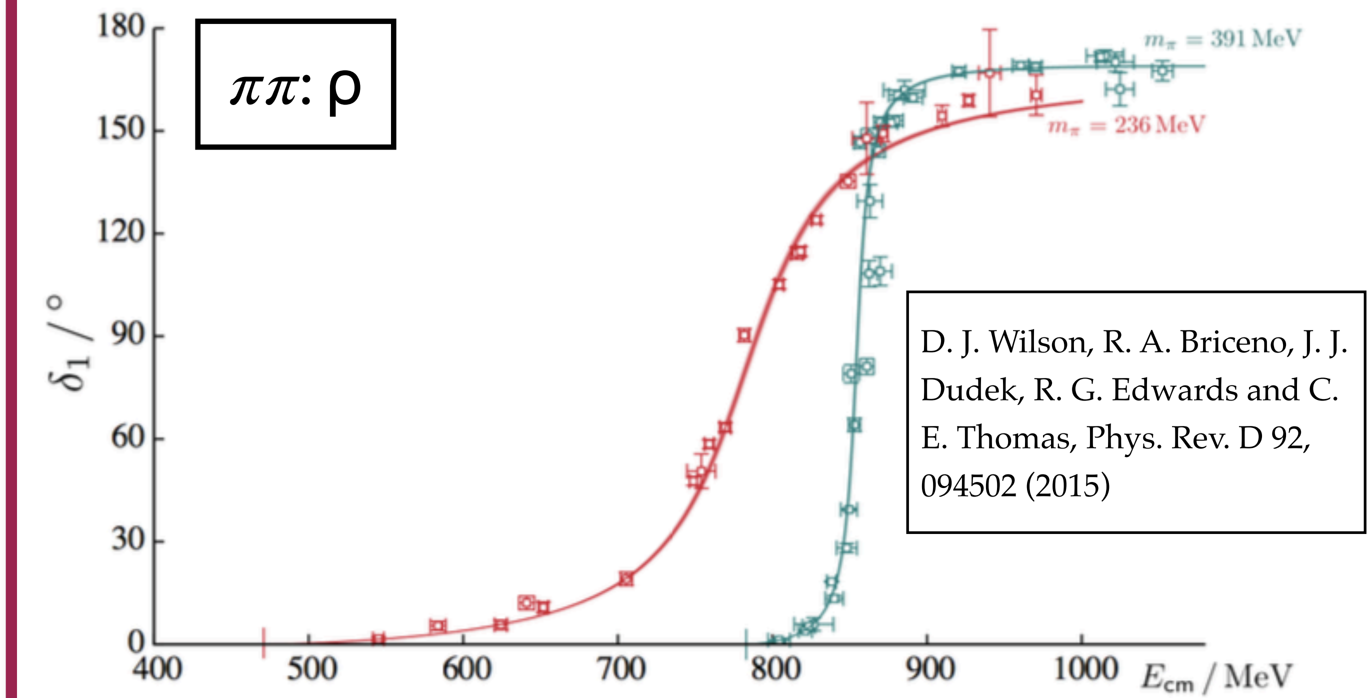
$N\pi$: Δ



m_π ~ 200, 280 MeV

Andersen, Bulava, Horz, Morningstar (2019)

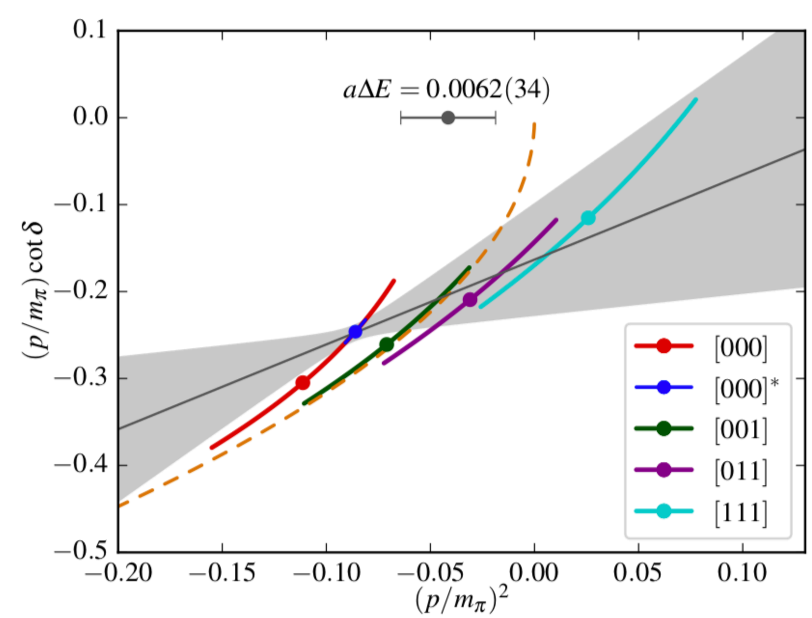
$\pi\pi$: ρ

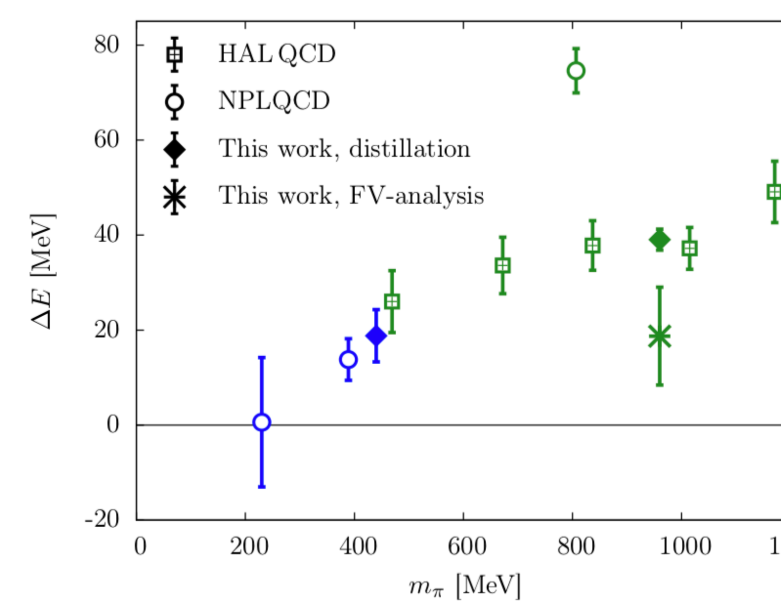


D. J. Wilson, R. A. Briceno, J. J. Dudek, R. G. Edwards and C. E. Thomas, Phys. Rev. D 92, 094502 (2015)

$\Lambda\Lambda$: H-dibaryon

m_π ~ 900 MeV
(strange quark quenched)

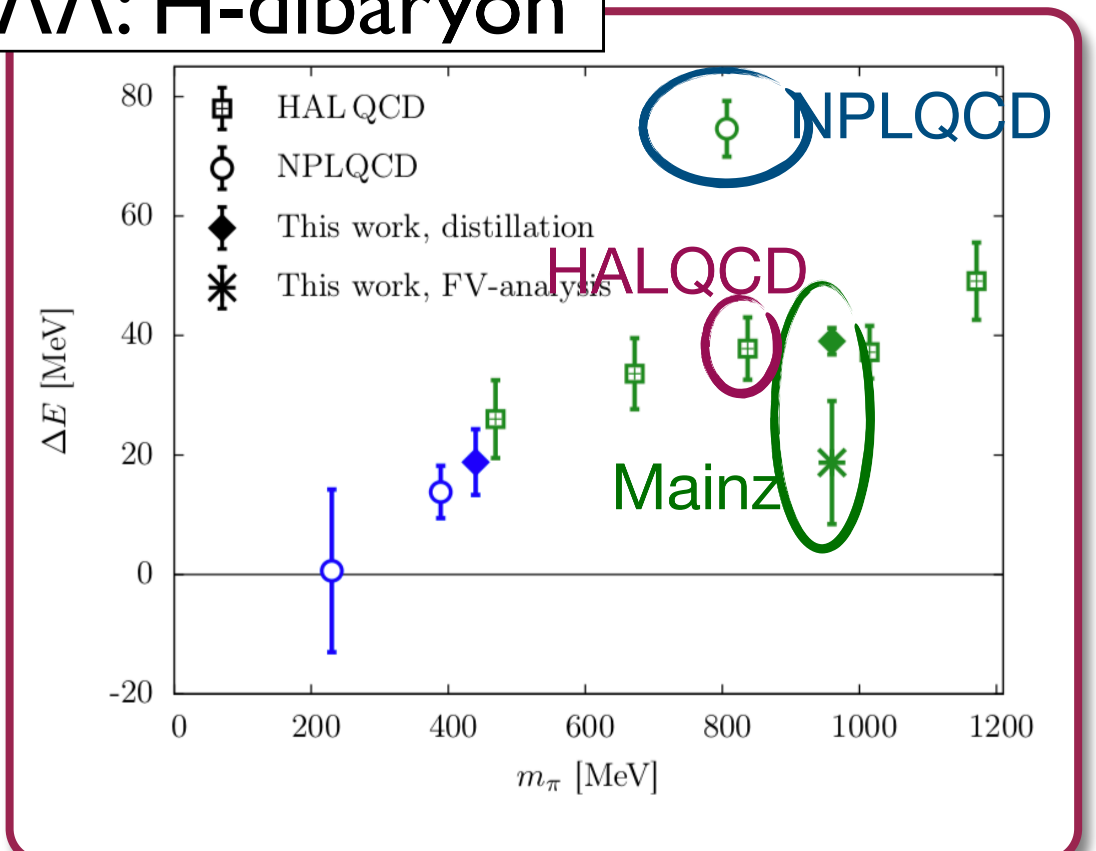




Hanlon, Francis, Green, Junnarkar, Wittig (2018)

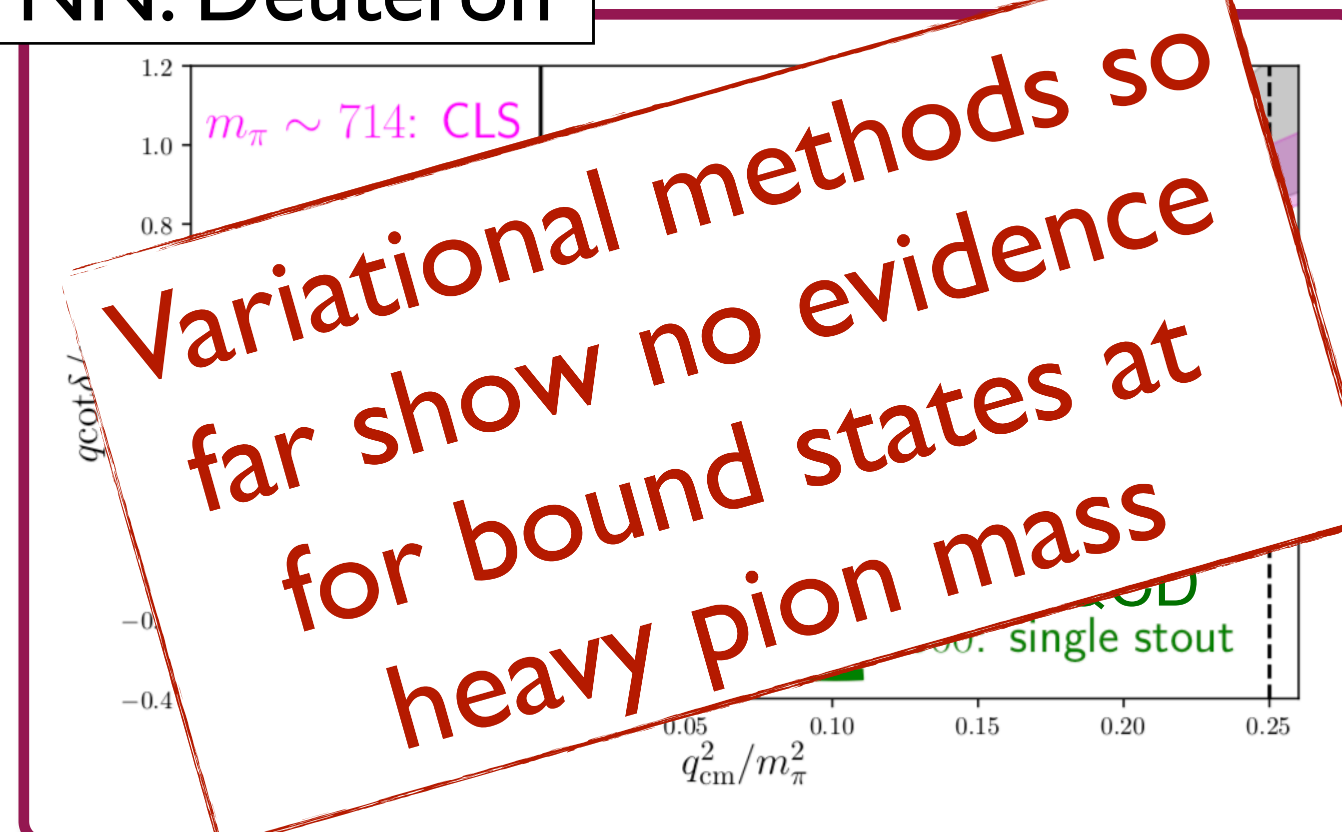
Variational calculations

ΛΛ: H-dibaryon



Francis, Green, Junnarkar, Miao, Rae, Wittig (2018)

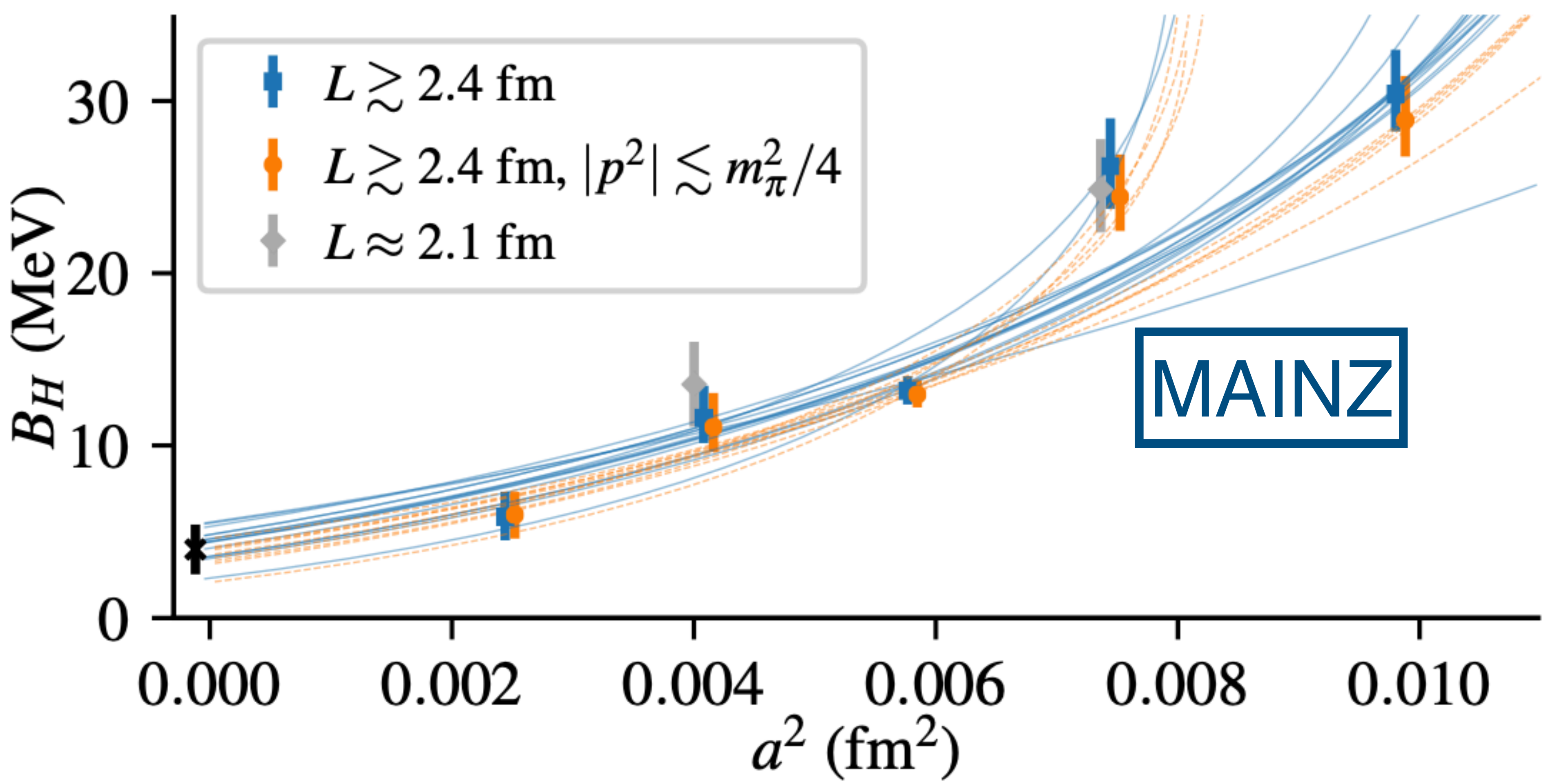
NN: Deuteron



Variational methods so far show no evidence for bound states at heavy pion mass

sLapHnn (2021)

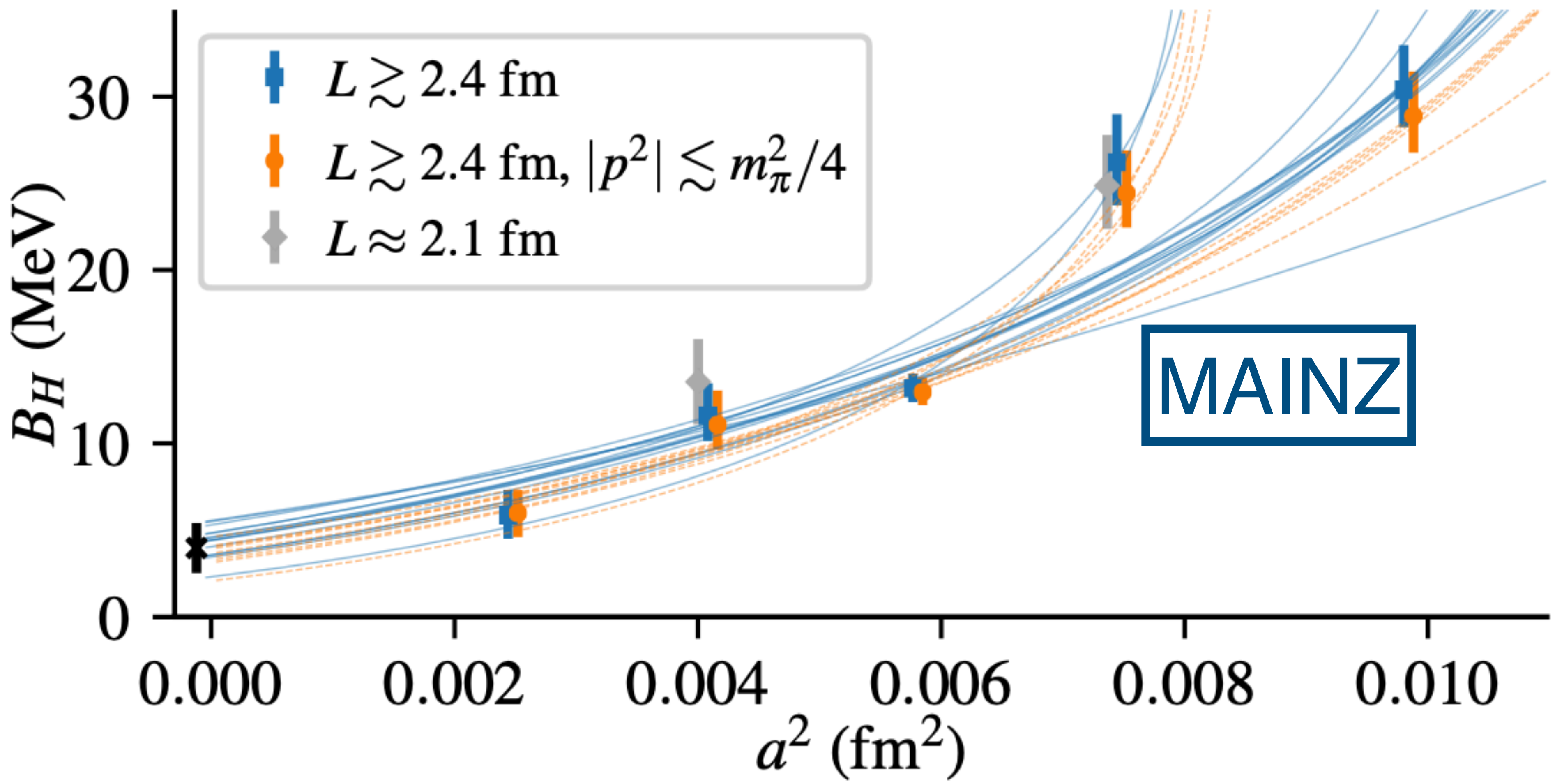
What about lattice artifacts?



Need to perform all methods on a single ensemble to fully resolve the controversy

Green, Hanlon, Junnarkar, Wittig (2021)

What about lattice artifacts?

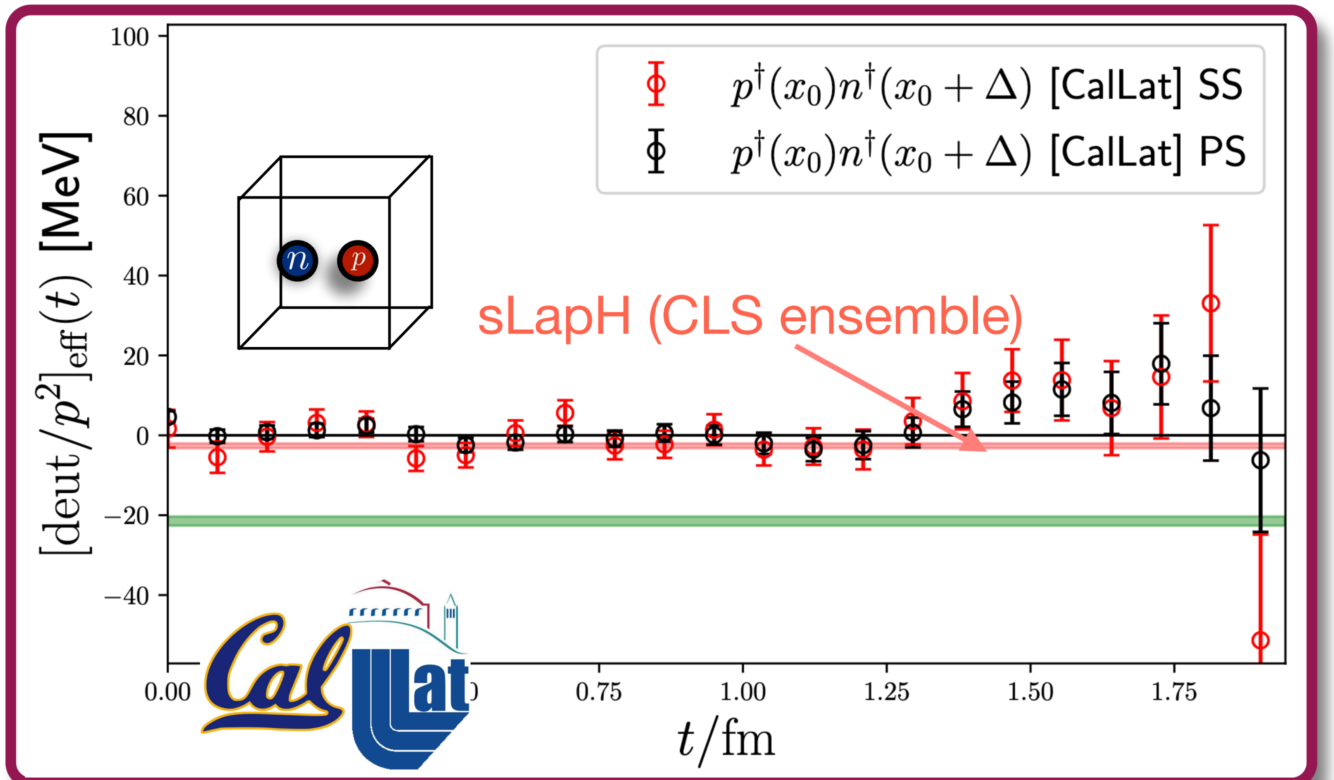


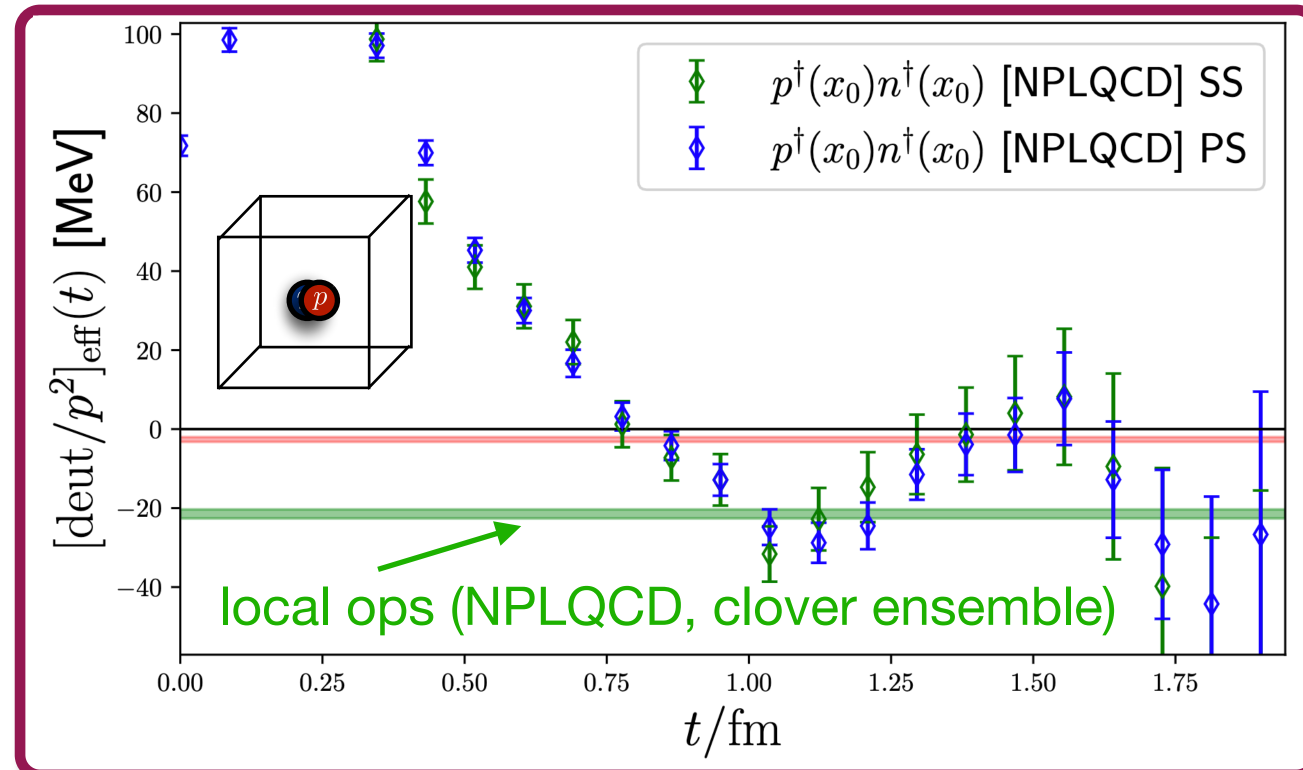
NPLQCD (2021): variational vs local vs quasi-local show clear discrepancies in extracted spectra

Preliminary

Displaced (CalLat) vs local (NPLQCD) vs sLapH + GEVP

CLS ensemble: $m_\pi \sim 714$ MeV, $a \approx 0.086$ fm, $L = 48$





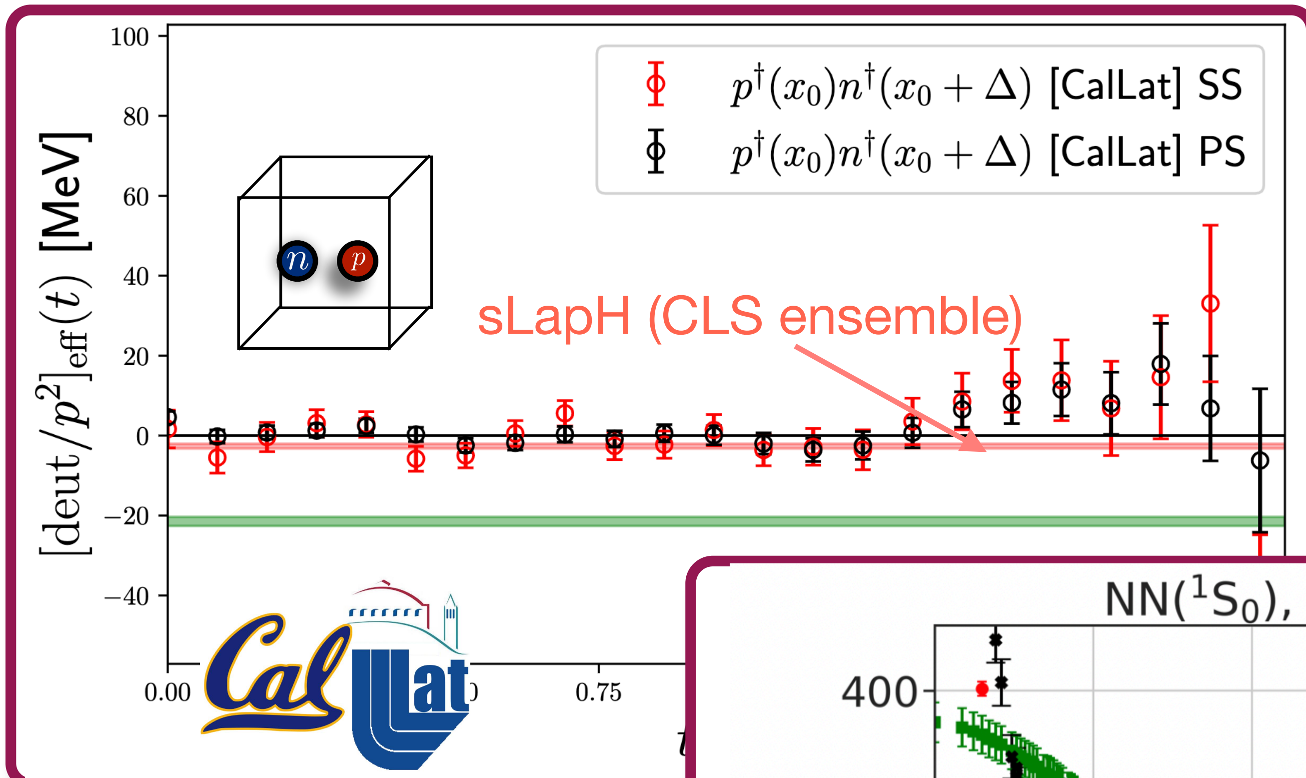
Lattice EFT indicates that local operators can distort the spectrum and do not couple at all to scattering states

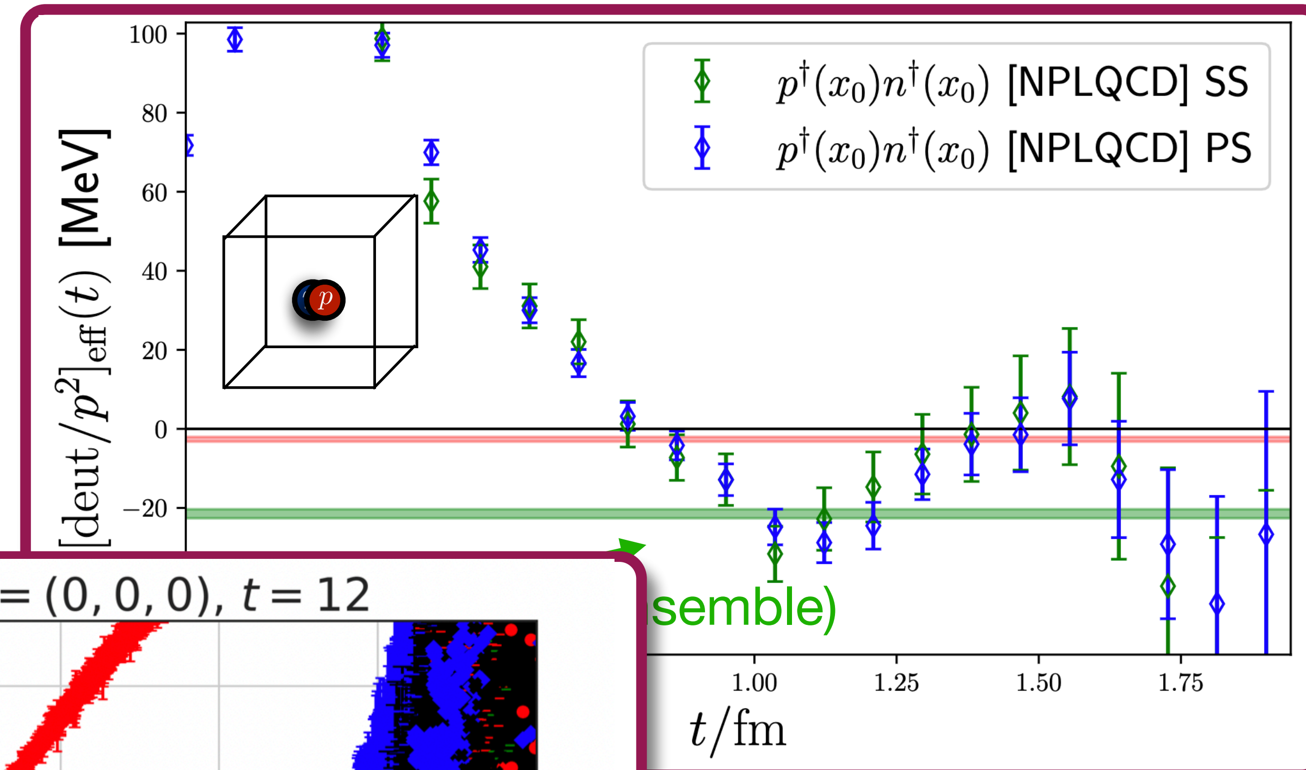
A. Nicholson, Lattice 2021

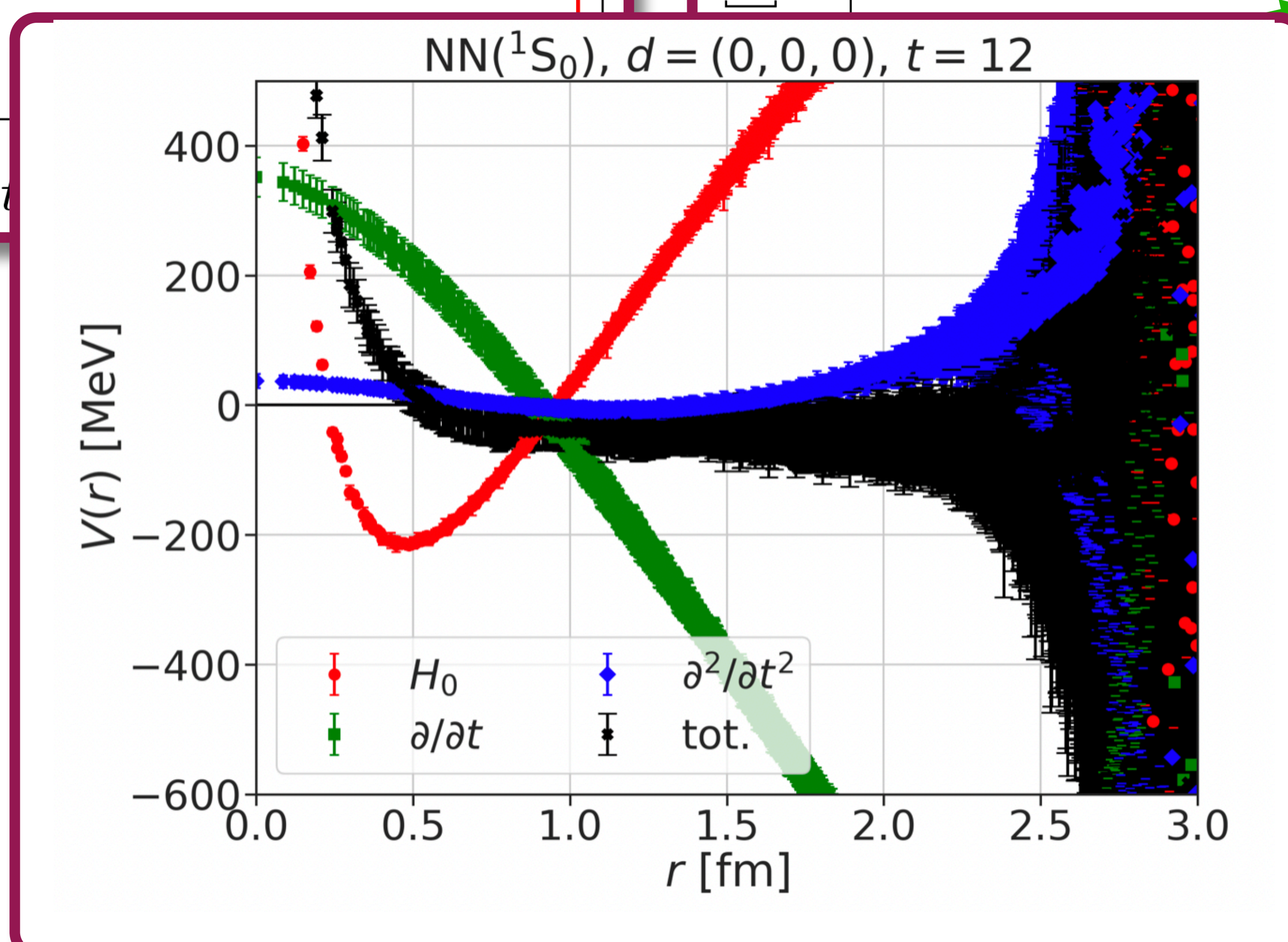
Preliminary

Displaced (CalLat) vs local (NPLQCD) vs sLapH + GEVP

CLS ensemble: $m_\pi \sim 714$ MeV, $a \approx 0.086$ fm, $L = 48$







HALQCD method:

Current statistics insufficient to extract physics

Summary

- Integrated approach to nuclear theory is necessary for understanding low-energy new physics searches
- Lattice QCD has been used to calculate short-range contributions to neutrinoless double-beta decay that cannot be directly measured by experiment
- Effective field theory calculations have shown the need to determine the impact of a new leading order contact operator
    - Efforts underway to use Lattice QCD to calculate
- Future calculations will necessitate improvements in two-nucleon calculations

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