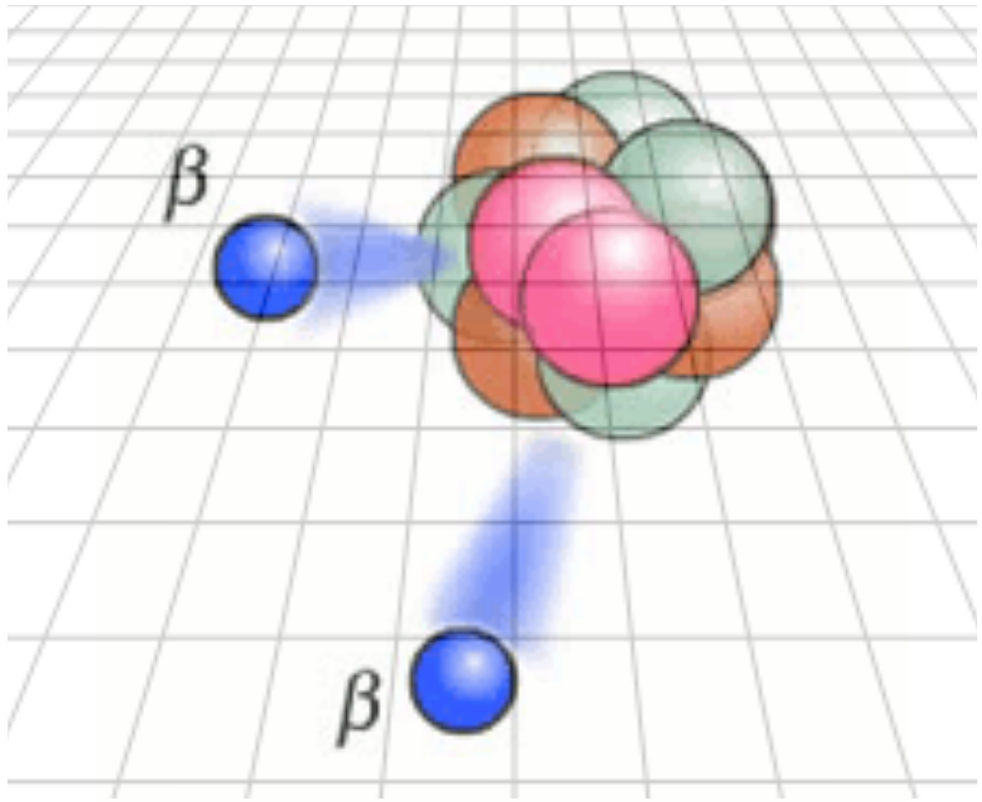
Neutrinoless Double Beta Decay from Lattice QCD

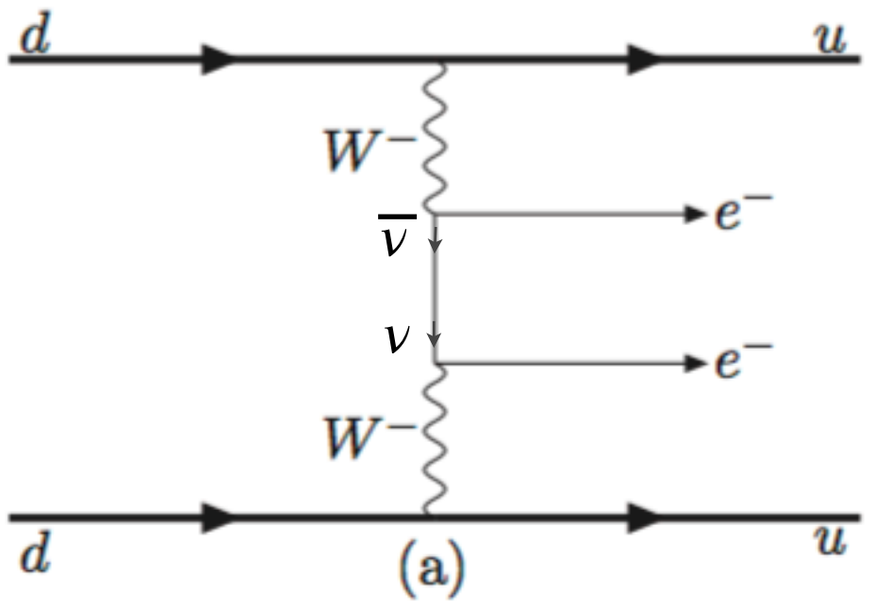


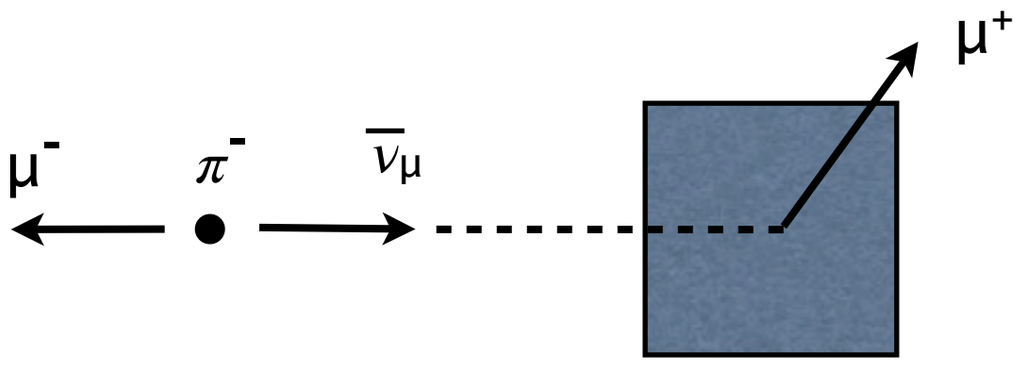
Amy Nicholson
UC Berkeley

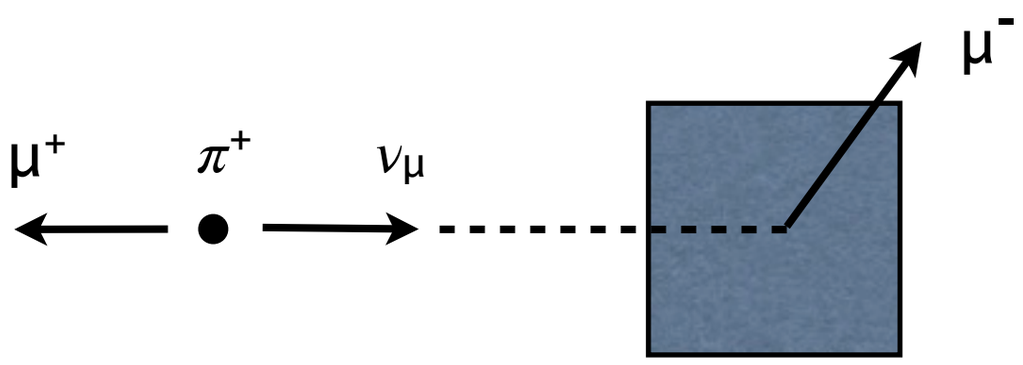
Symmetry Tests in Nuclei and Atoms
KITP, Sept. 22, 2016

0νββ and Lepton Number

Neutrinos have no known charge or other additively conserved quantum number







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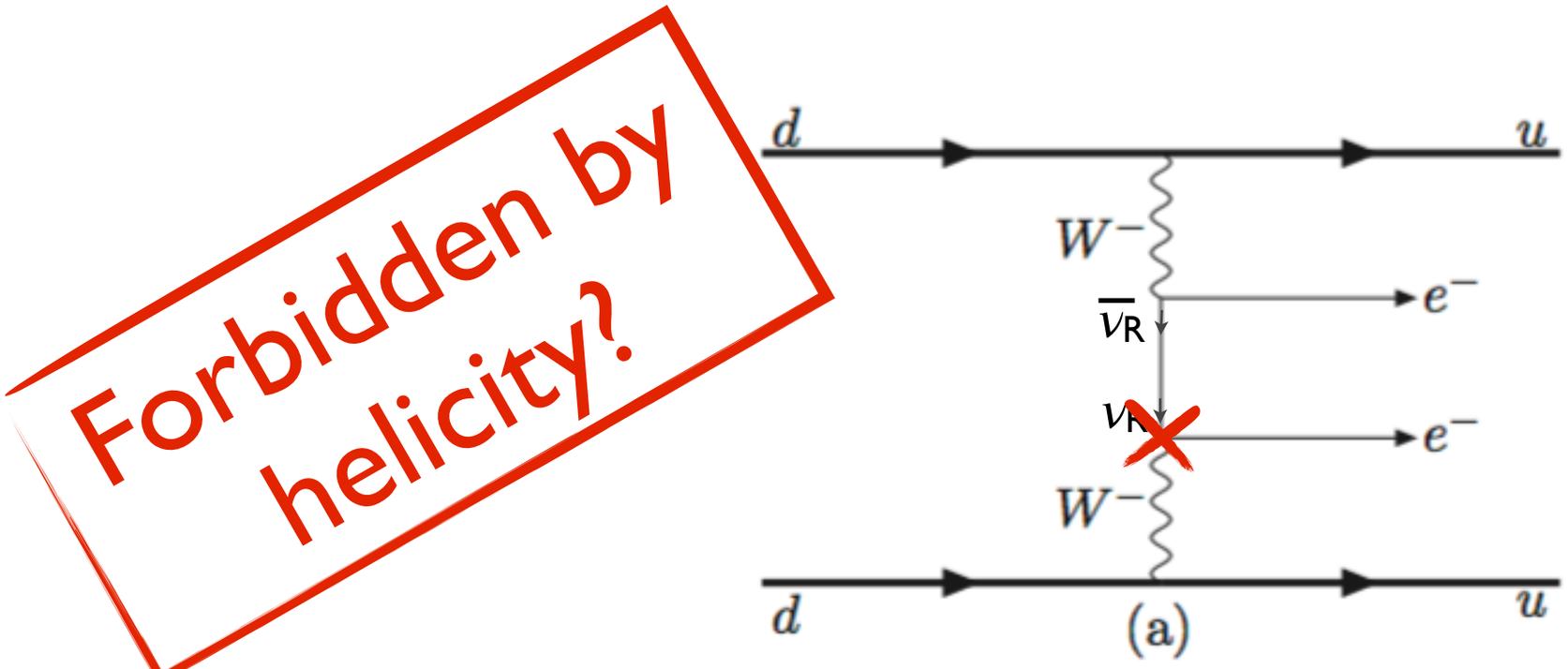
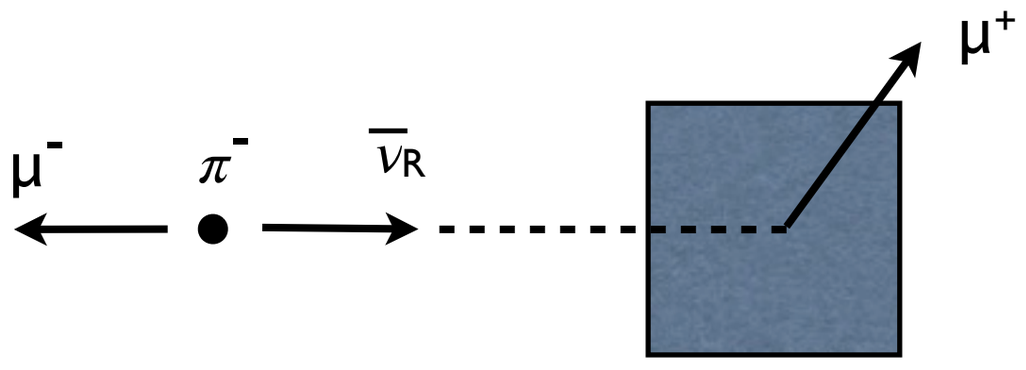
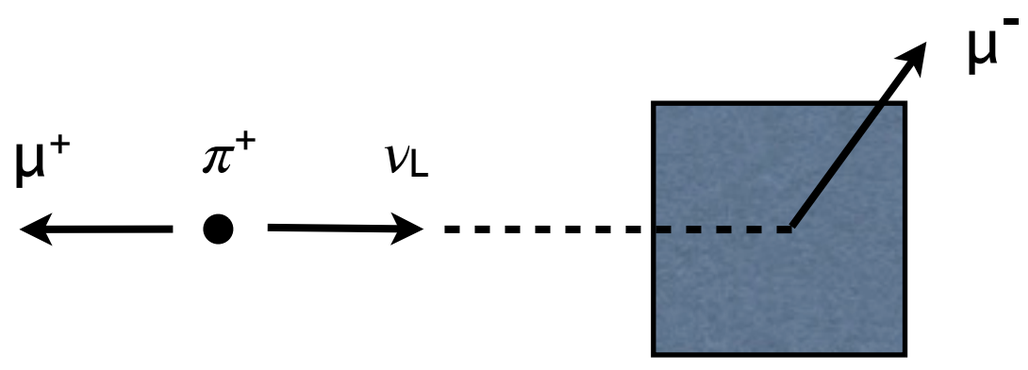
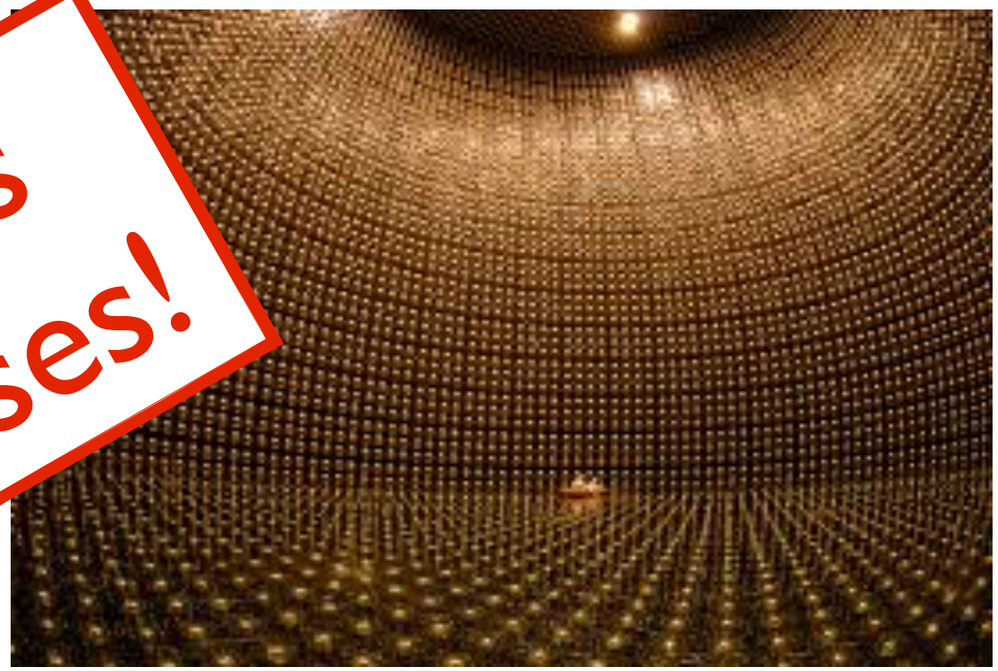
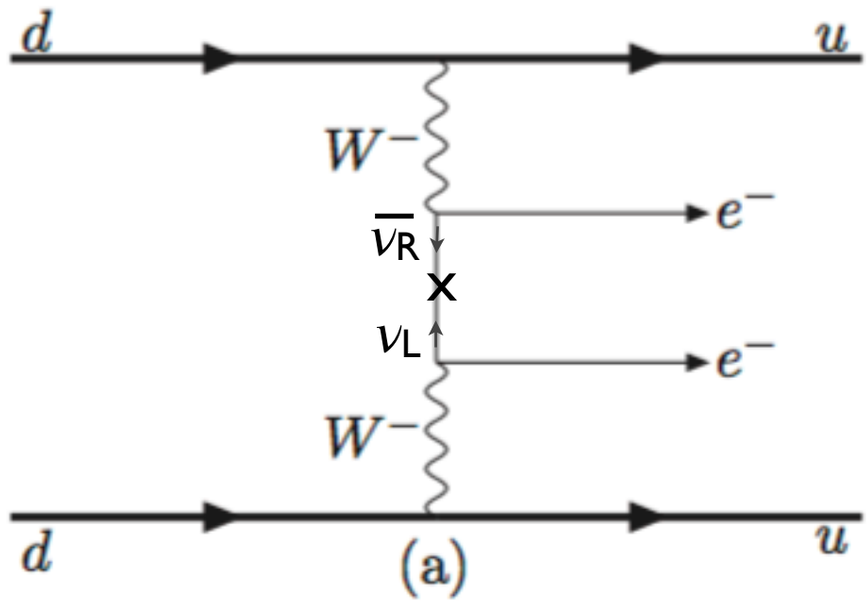




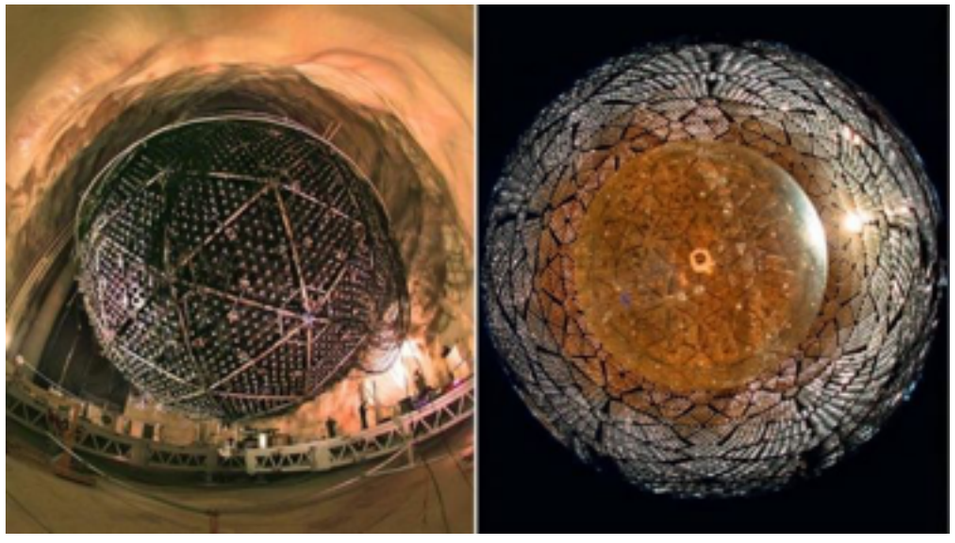


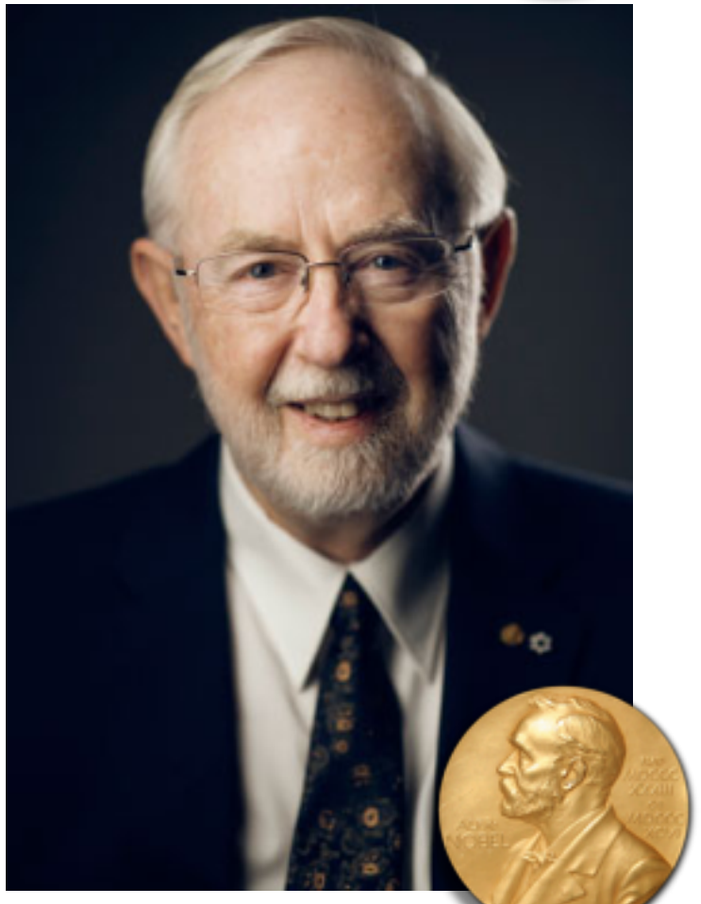
Neutrinos have masses!





Takaaki Kajita (Super-K)
Arthur B. McDonald (SNO)
Nobel Prize, 2015

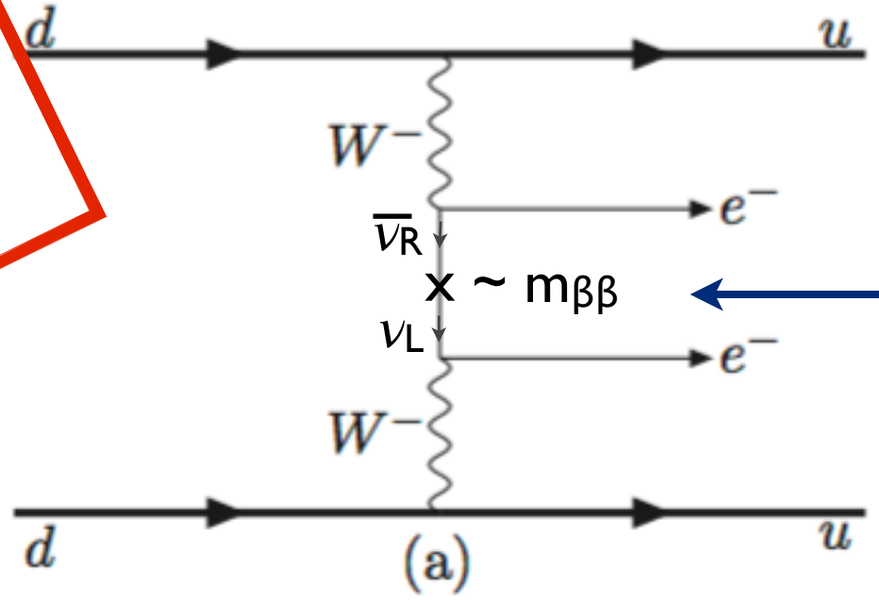




0νββ and Lepton Number

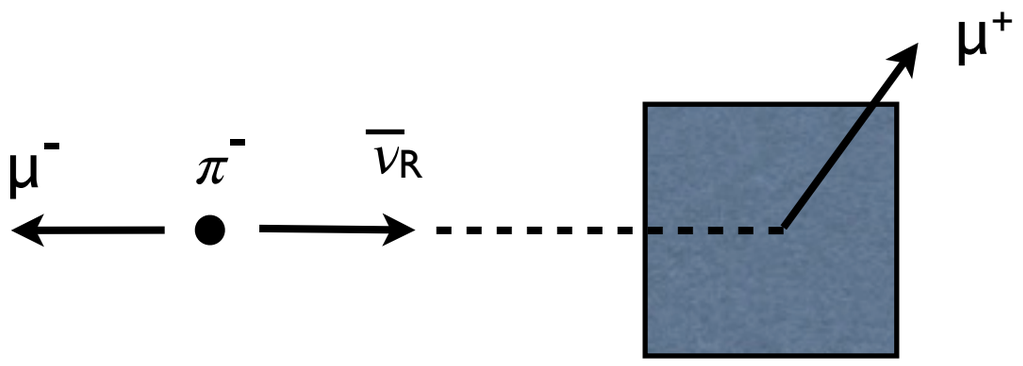
Neutrinos have no known charge or other additively conserved quantum number

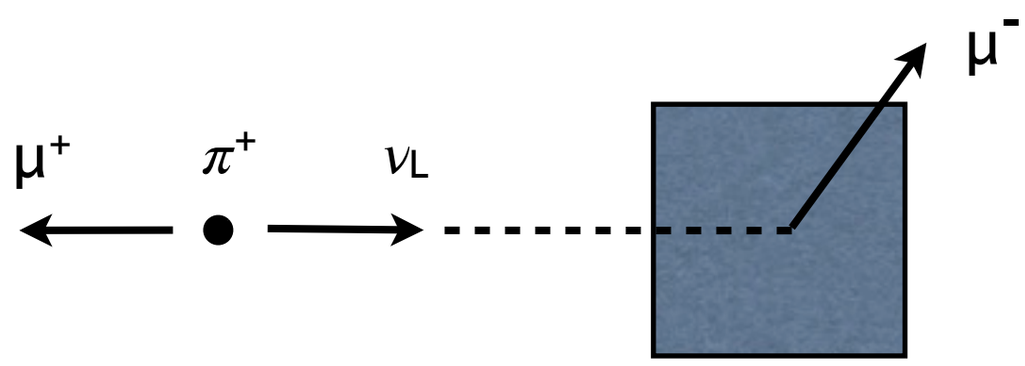
But they're tiny!



oscillation experiments don't tell us absolute mass scale

$0\nu\beta\beta$ will!





Majorana or Dirac?

- Anything not forbidden by symmetry should occur in nature

$$\mathcal{L}_5 = -m\left(\bar{L}\tilde{H}\right)\left(\tilde{H}L\right)^{\dagger}$$

- Why are neutrinos so light?
  - Dirac mass on its own requires fine-tuning

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

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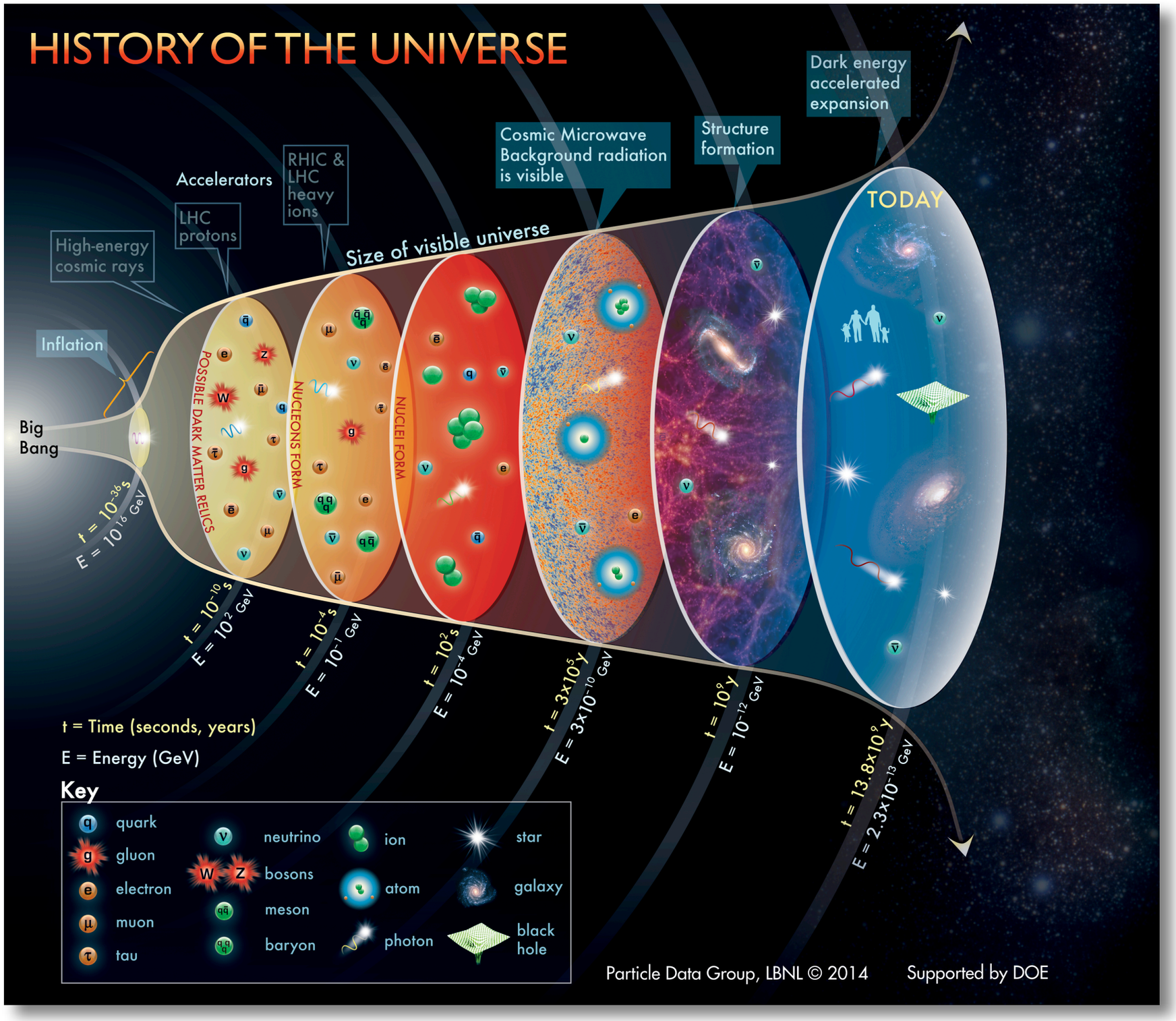
$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

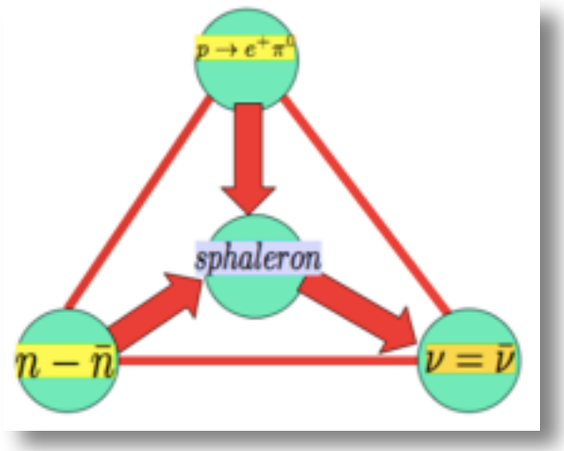
$$m_l \sim M_D^2/M_R \quad m_h \sim M_R$$

$$M_D \sim 200GeV \quad m_l \sim 0.05eV$$

$$M_R \sim 10^{15}GeV$$

If observed, could help explain matter/anti-matter asymmetry in the universe!

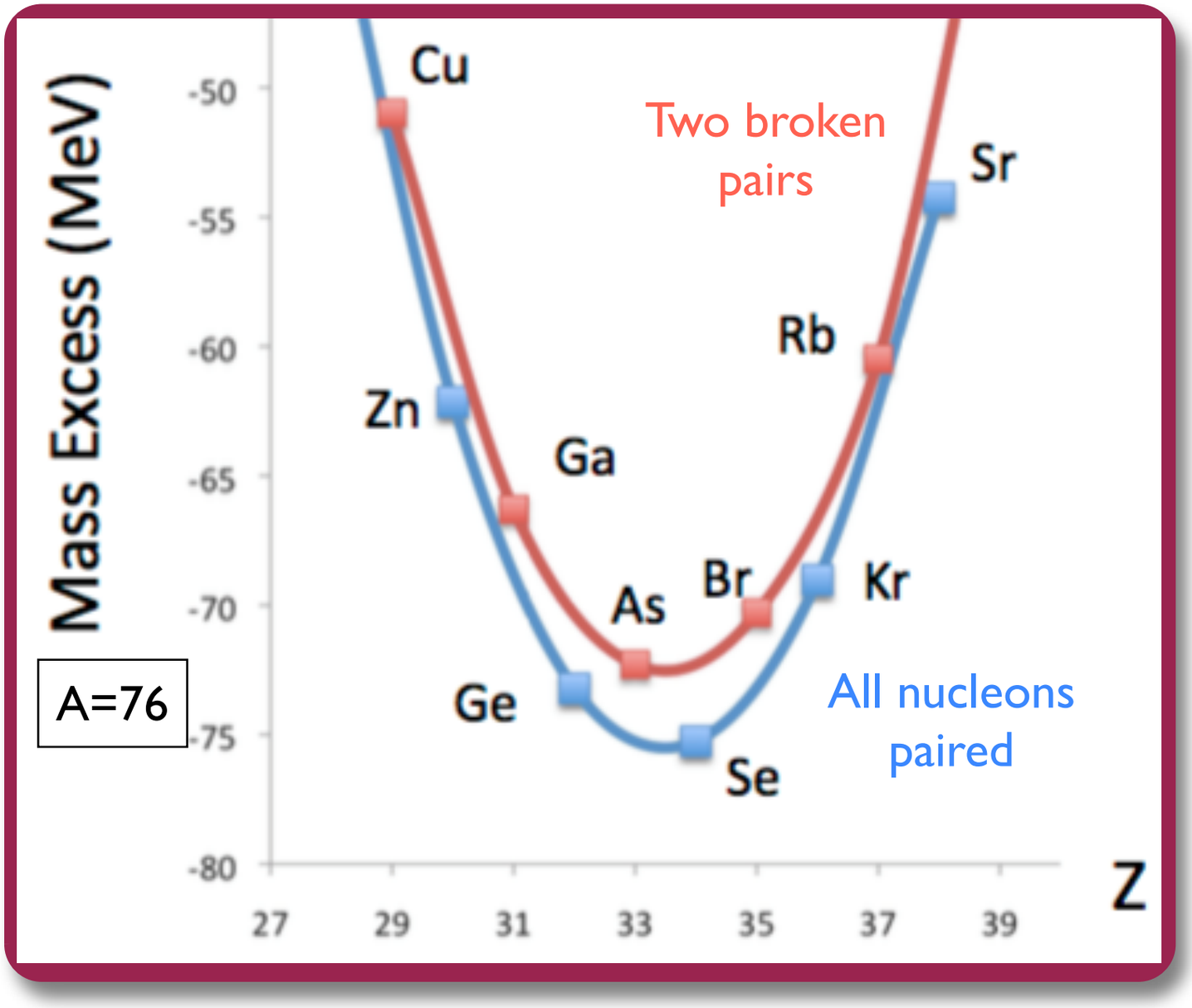




Jansen (1996)
Bödeker, Moore, Rummukainen (2000)
Fodor (2000)

Experiment

Nuclear physics gives us a natural filter for the process



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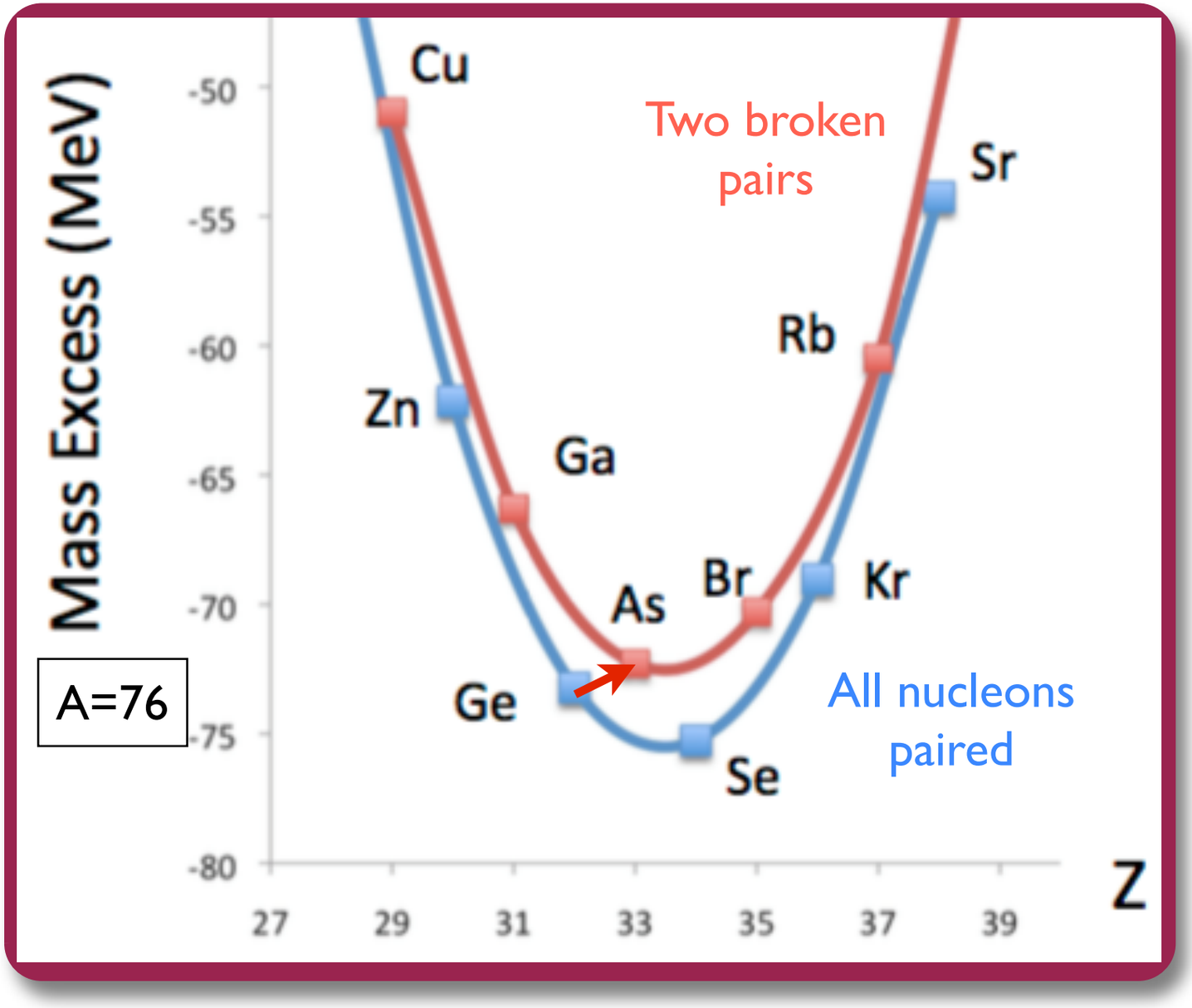
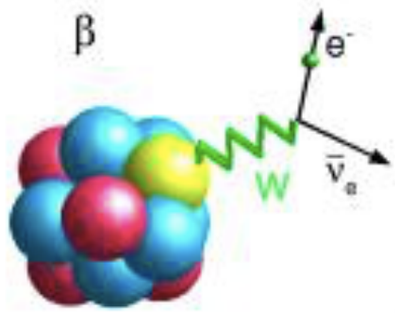


Energetically forbidden



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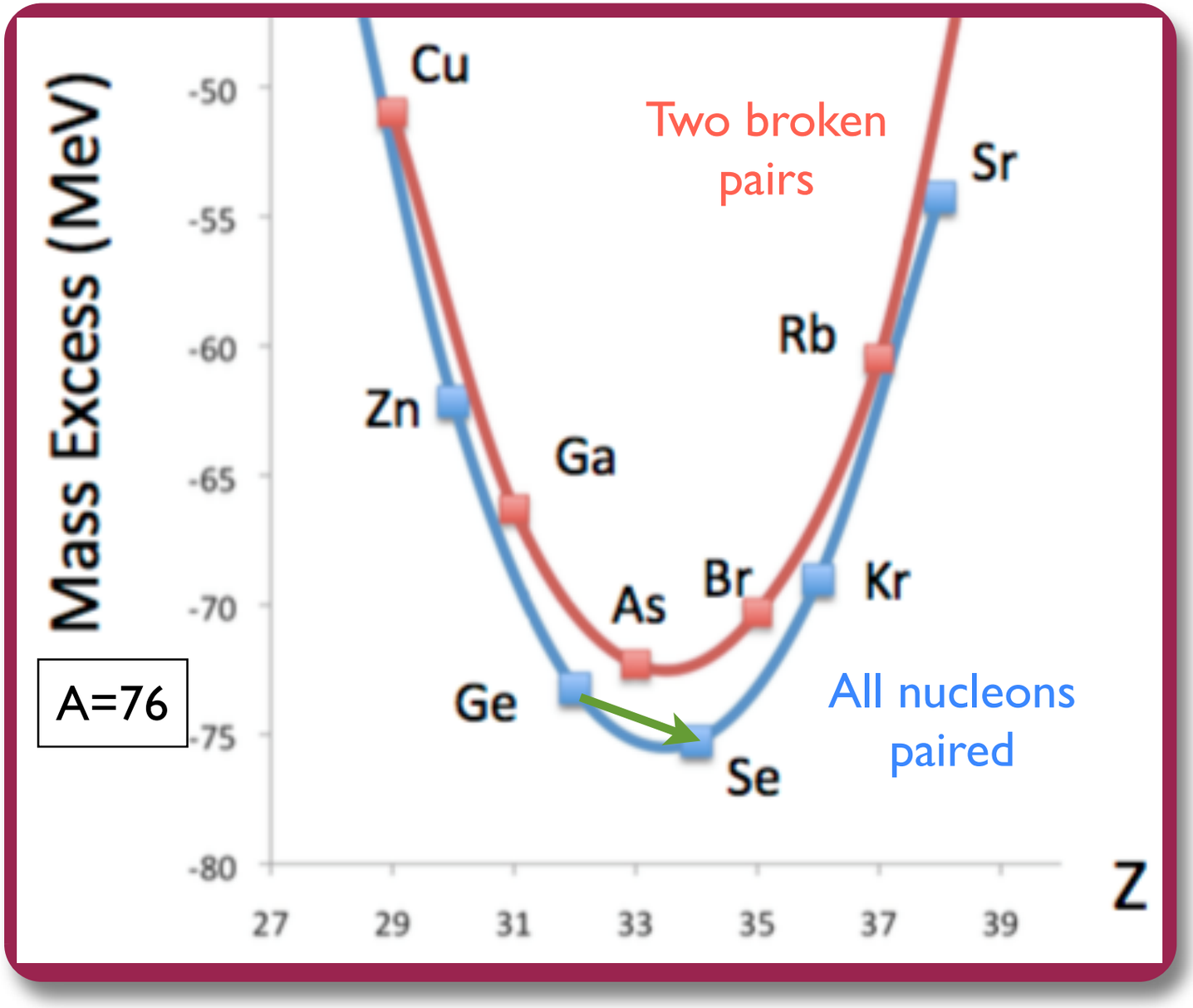
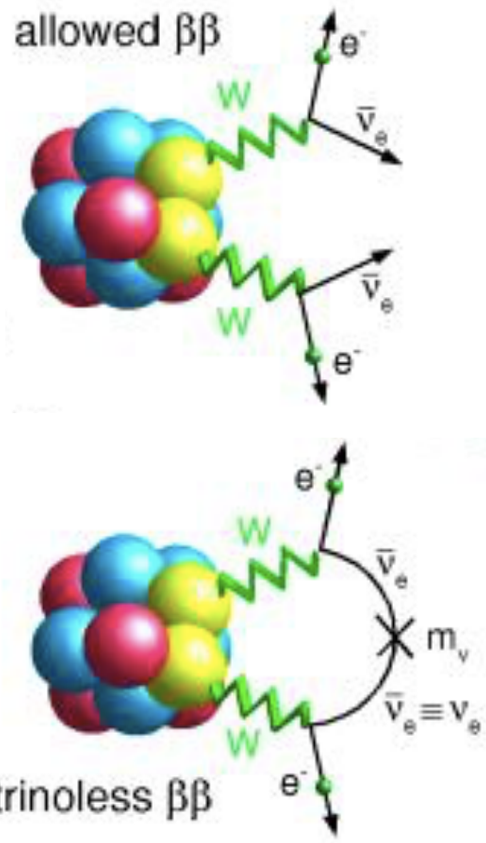
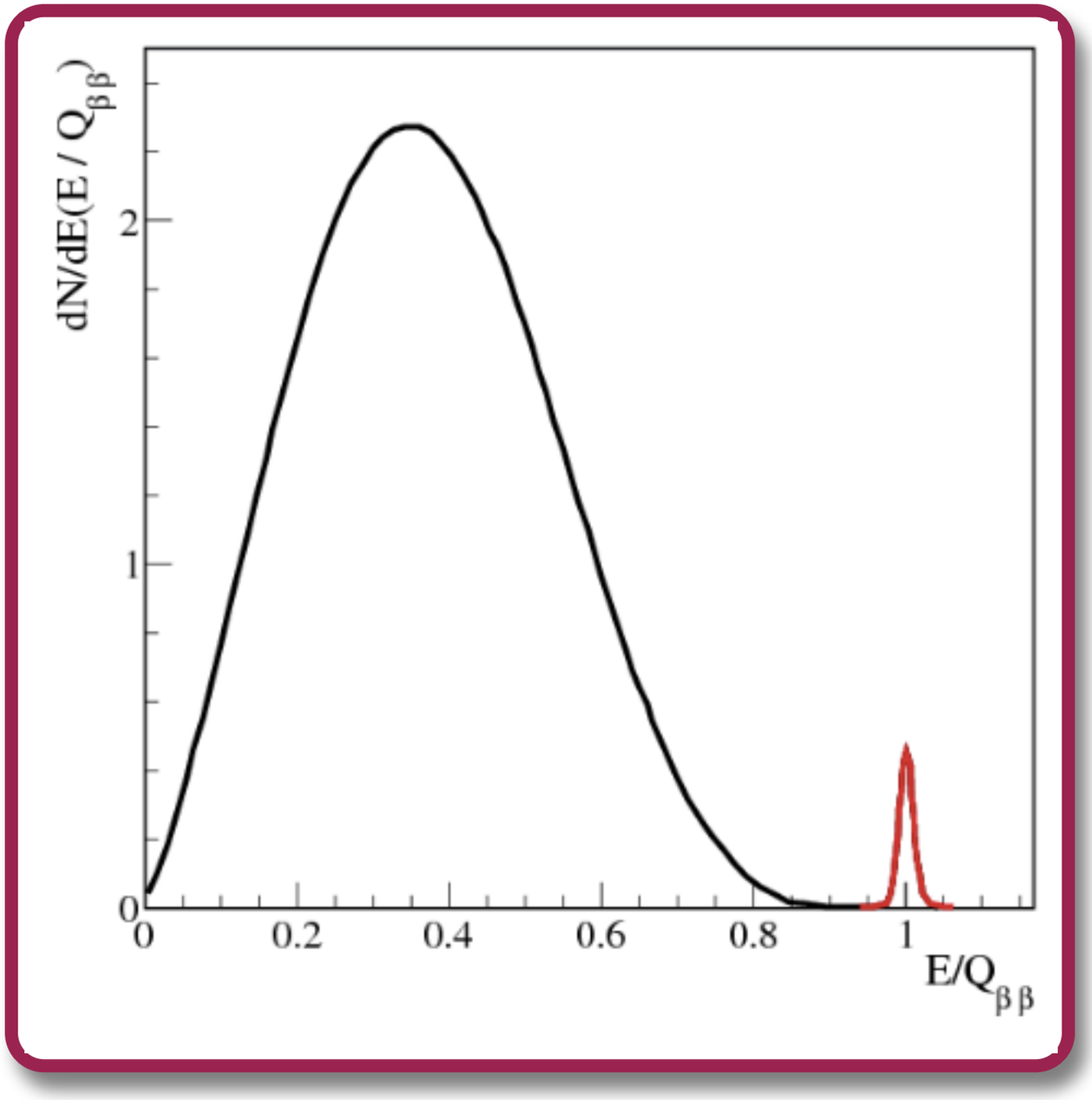


Second order, allowed



Experiment

Neutrinoless mode can be isolated using spectroscopic methods



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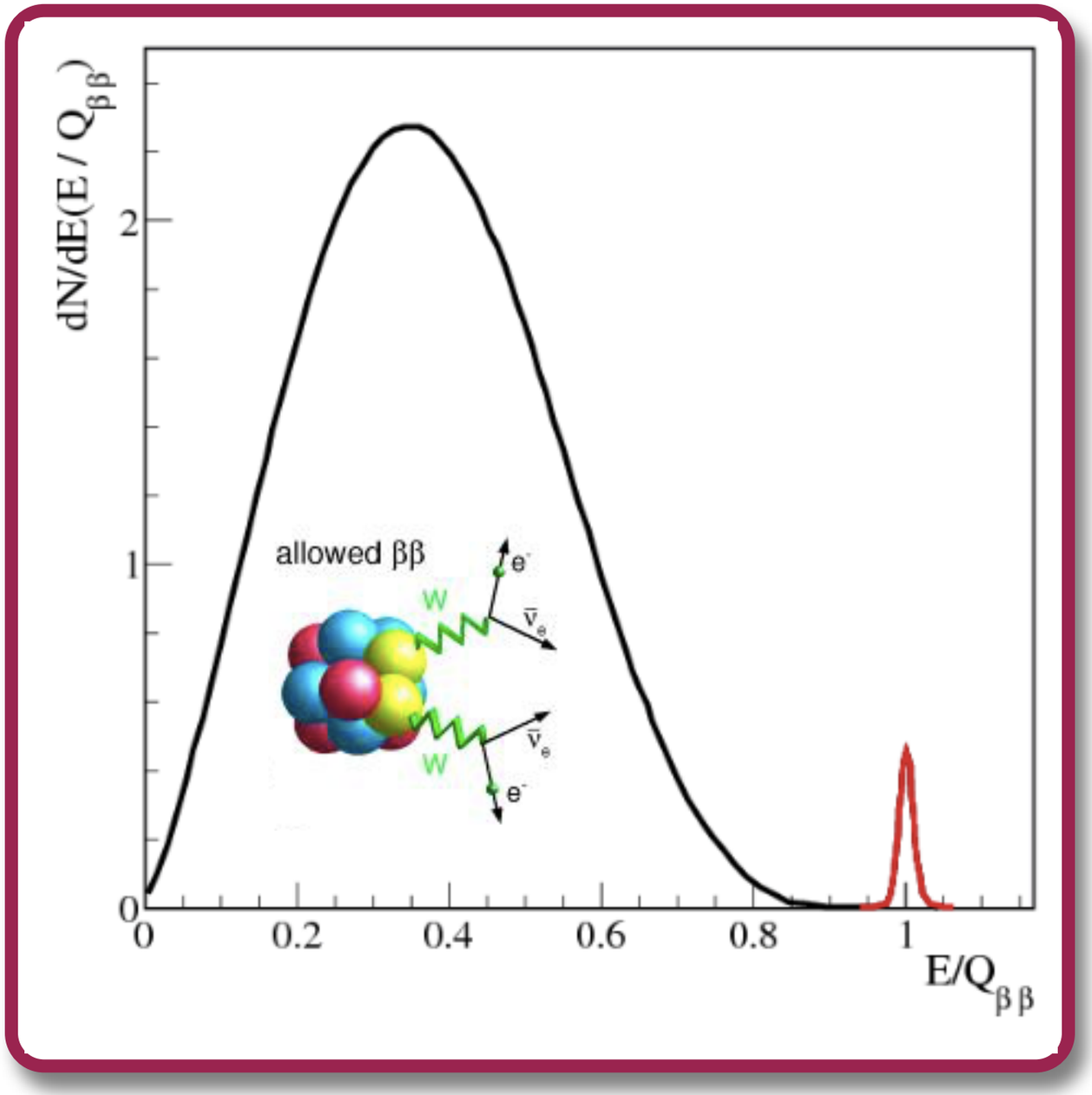

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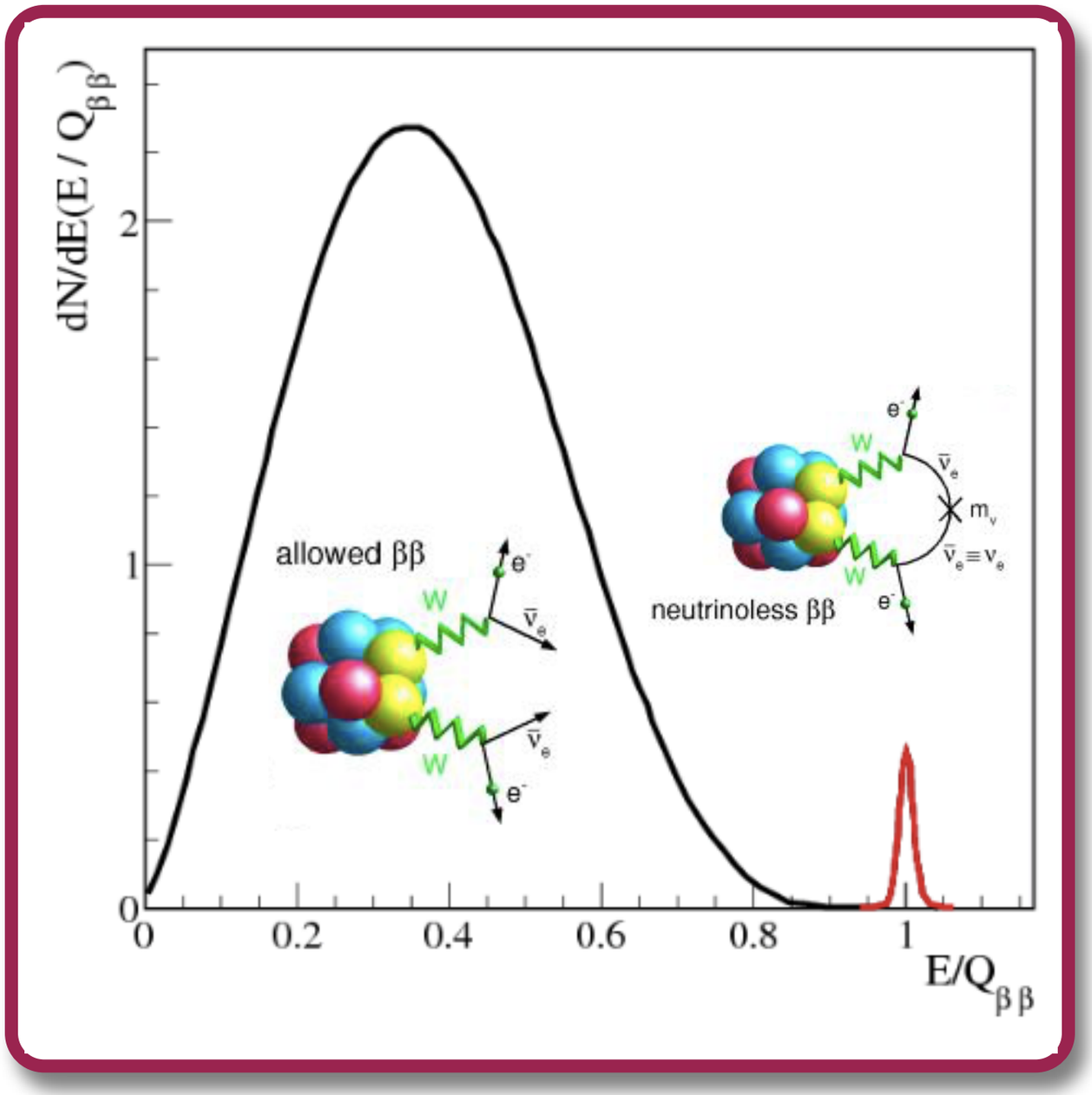

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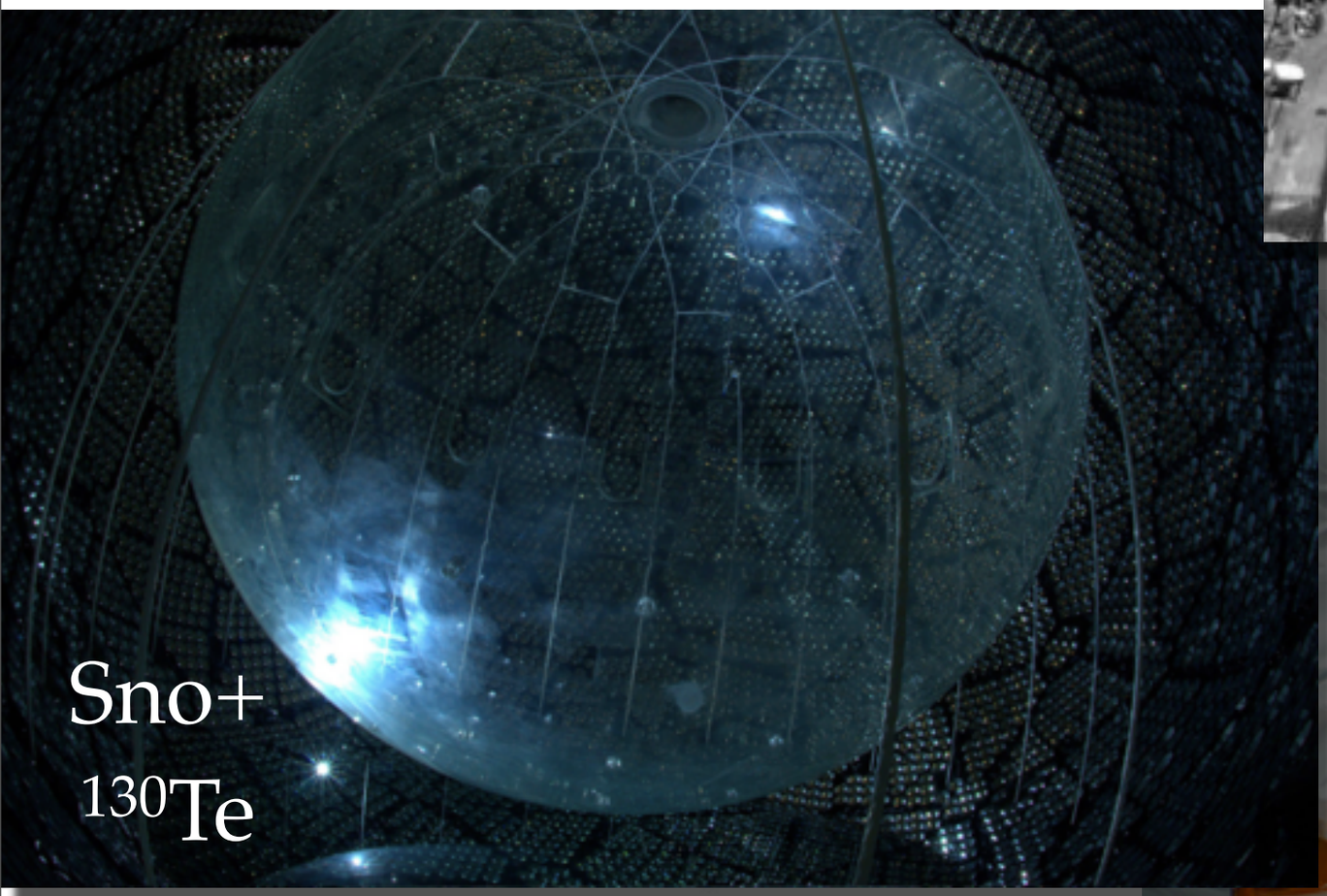
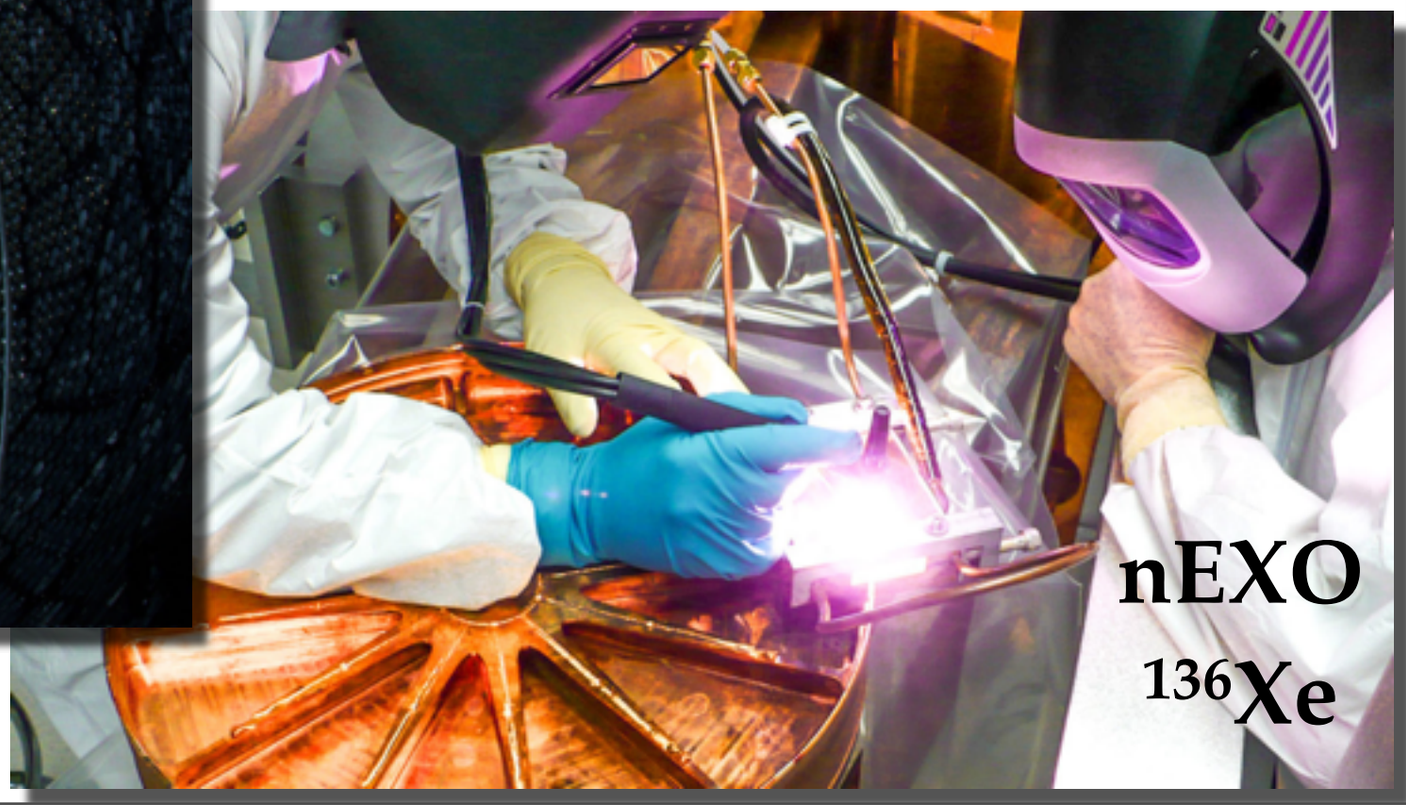




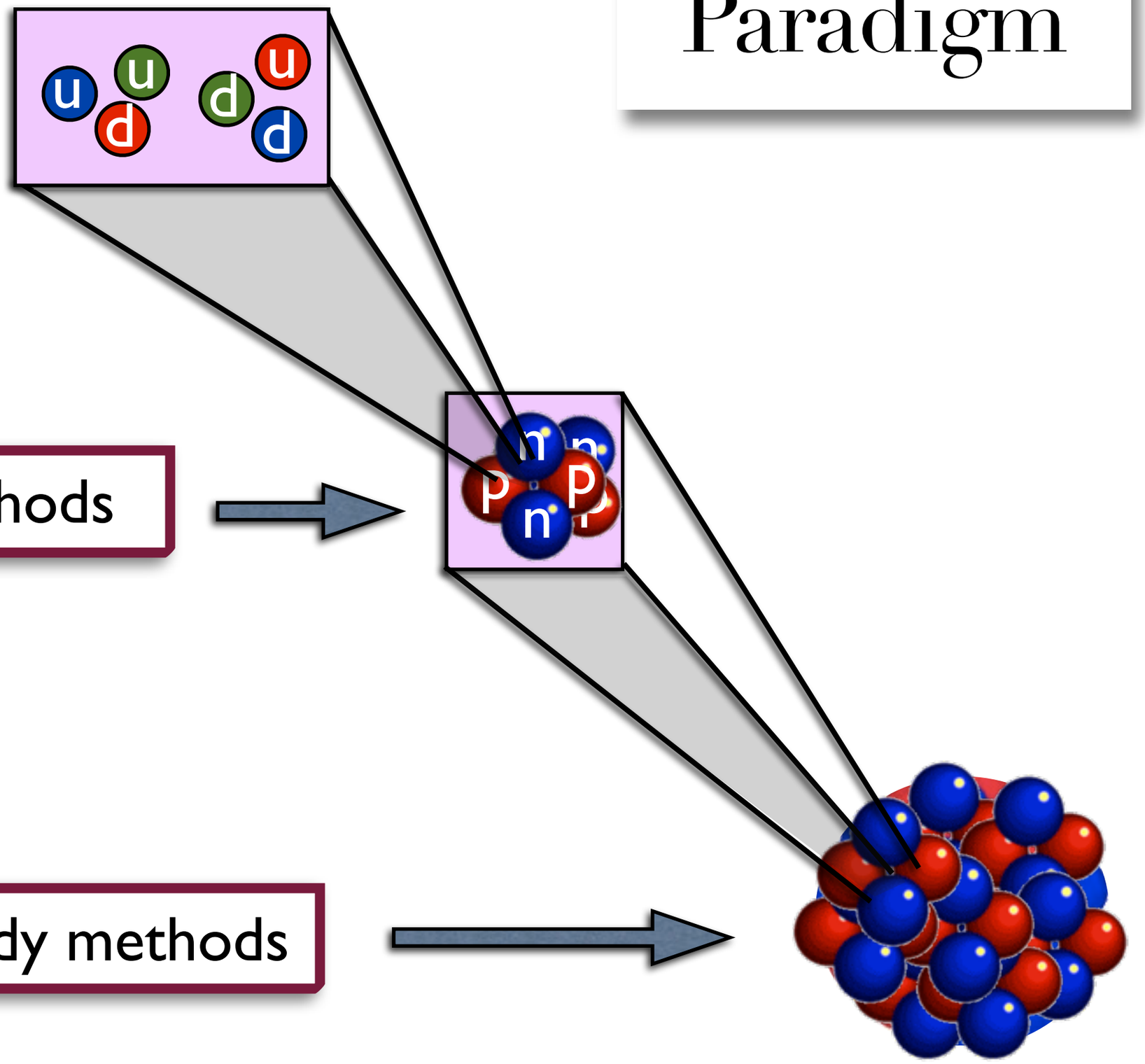
How can LQCD contribute?

Paradigm

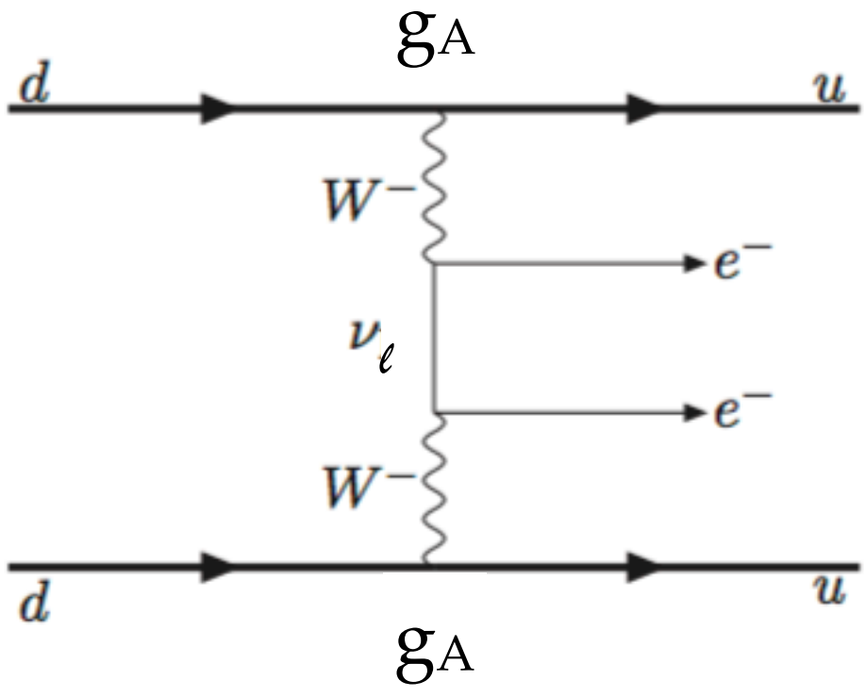
LQCD

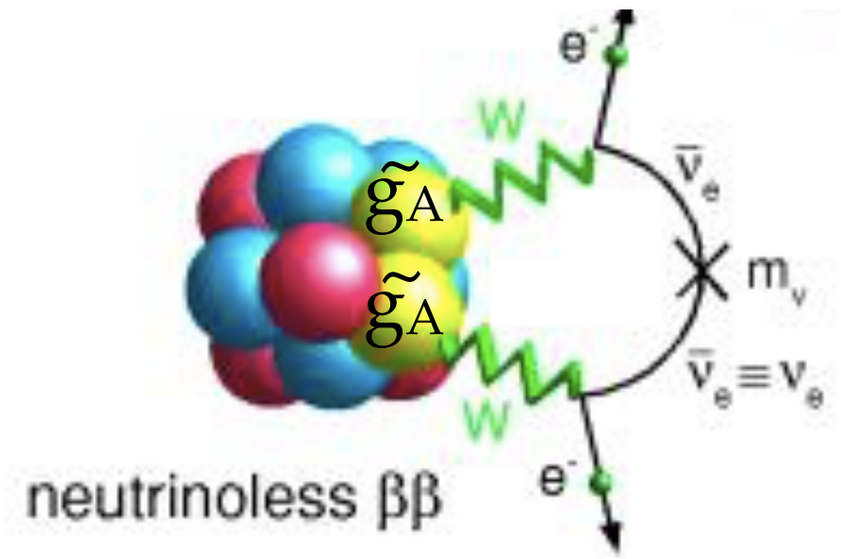
ab-initio methods

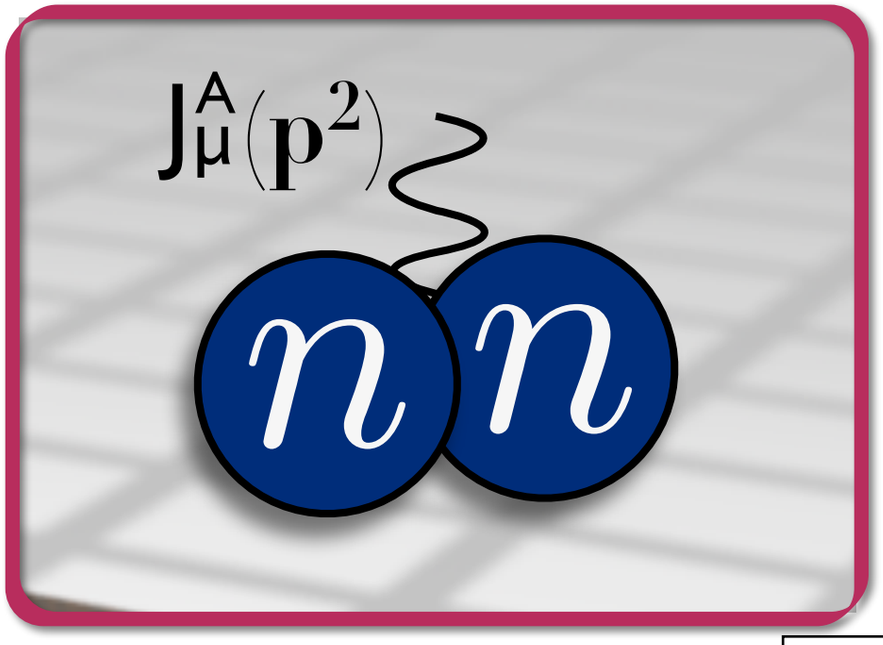
Many-body methods



Standard picture: long-range contribution

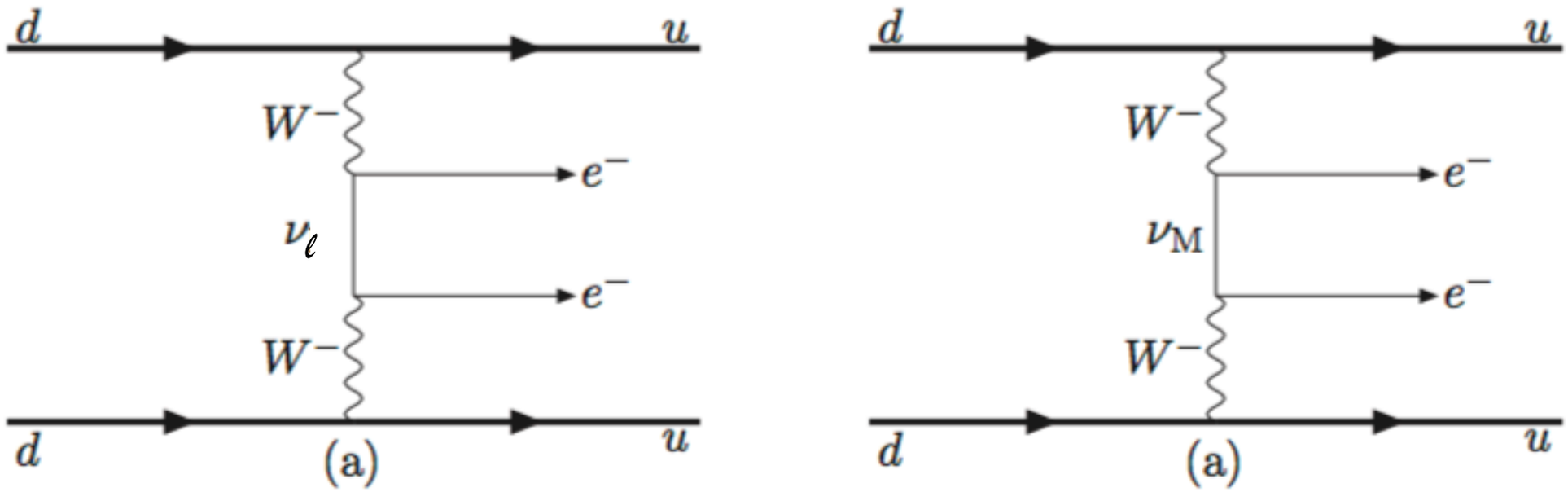


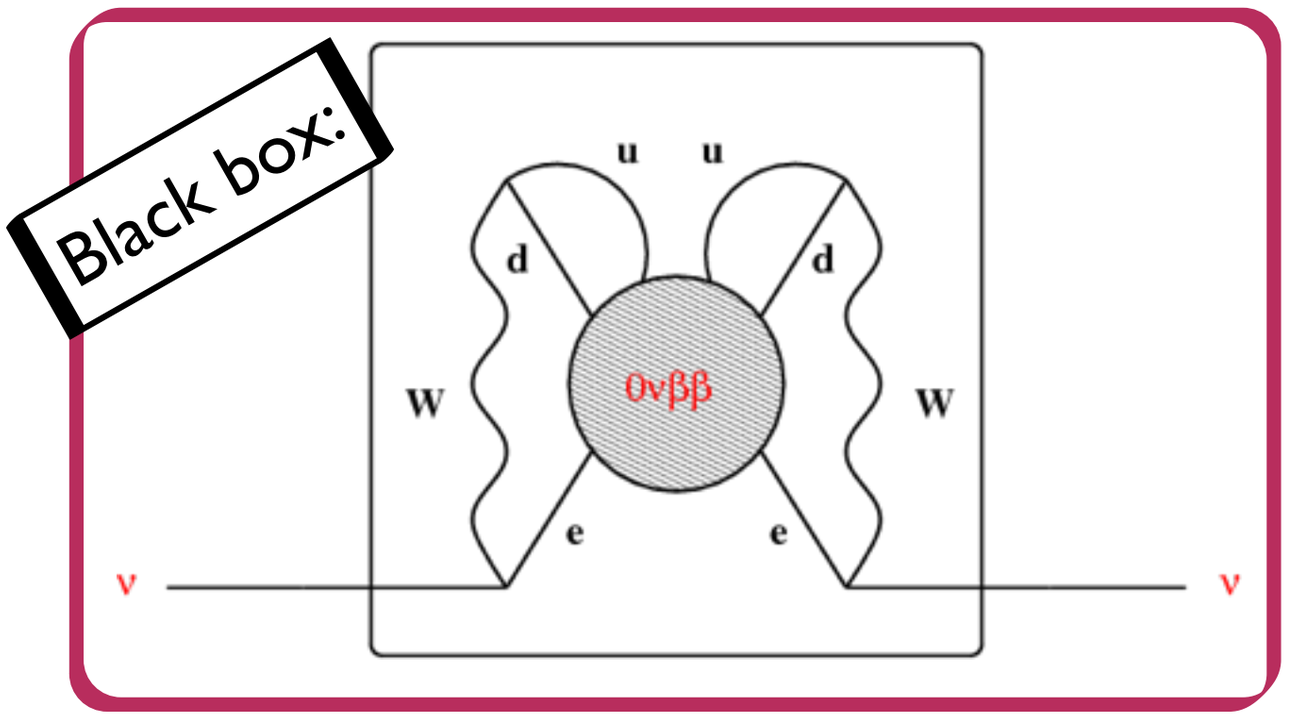




NPLQCD (M. Savage, ICHEP 2016)

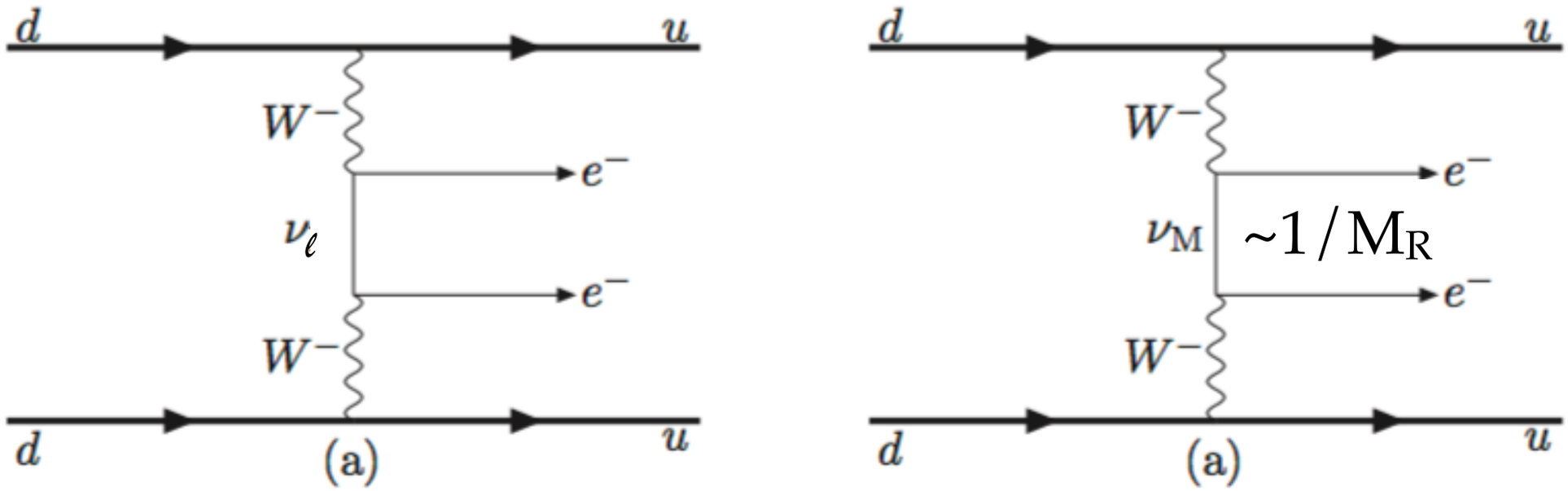
Short-range contribution: probe for heavy physics

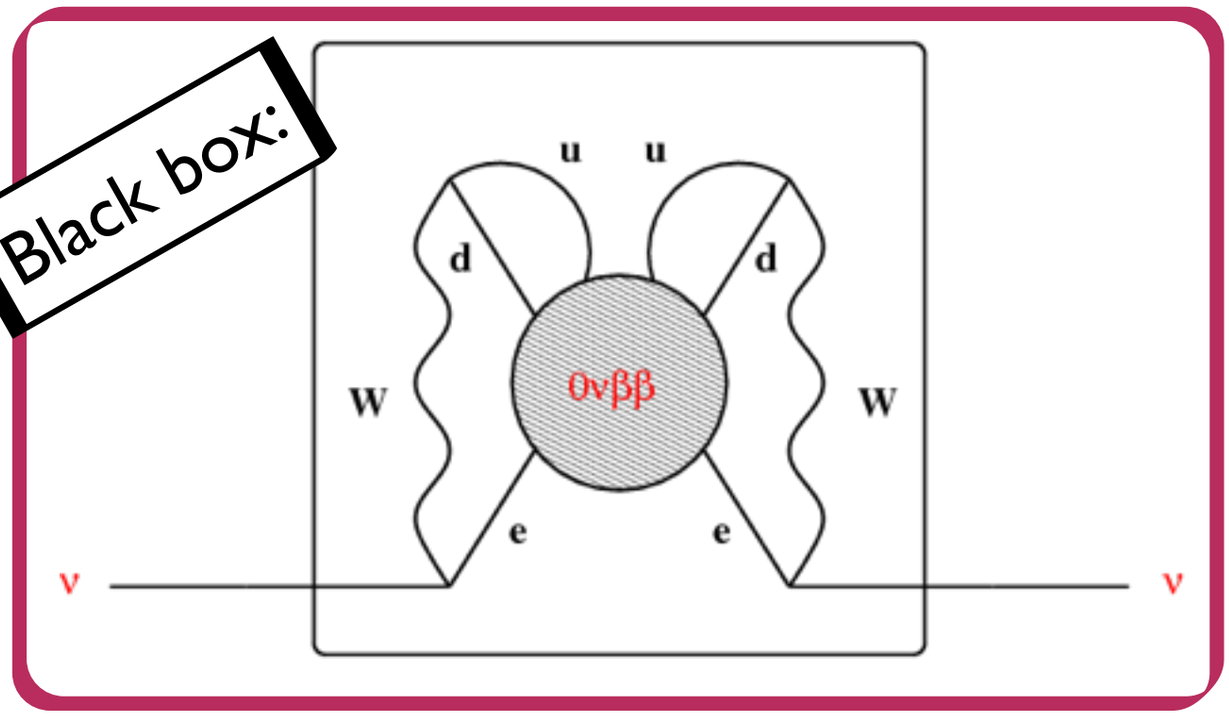




Valle & Schecter, Fig.: H. Päs, W. Rodejohann New J.Phys. 17 (2015) no.11, 115010

Short-range contribution: probe for heavy physics





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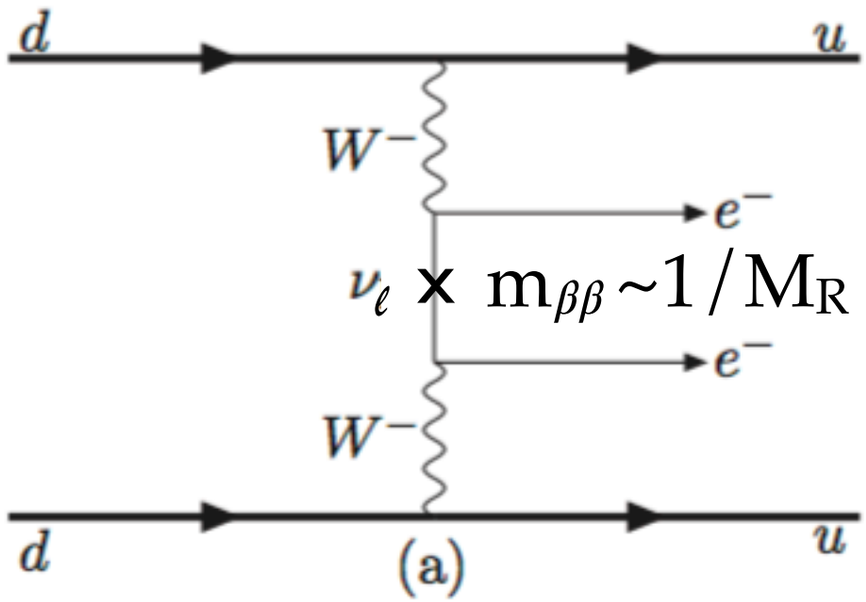

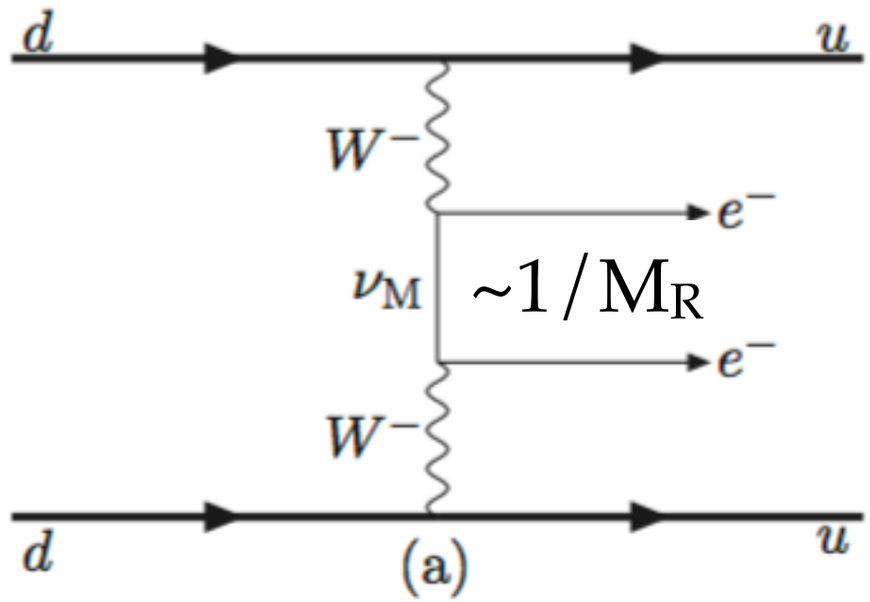

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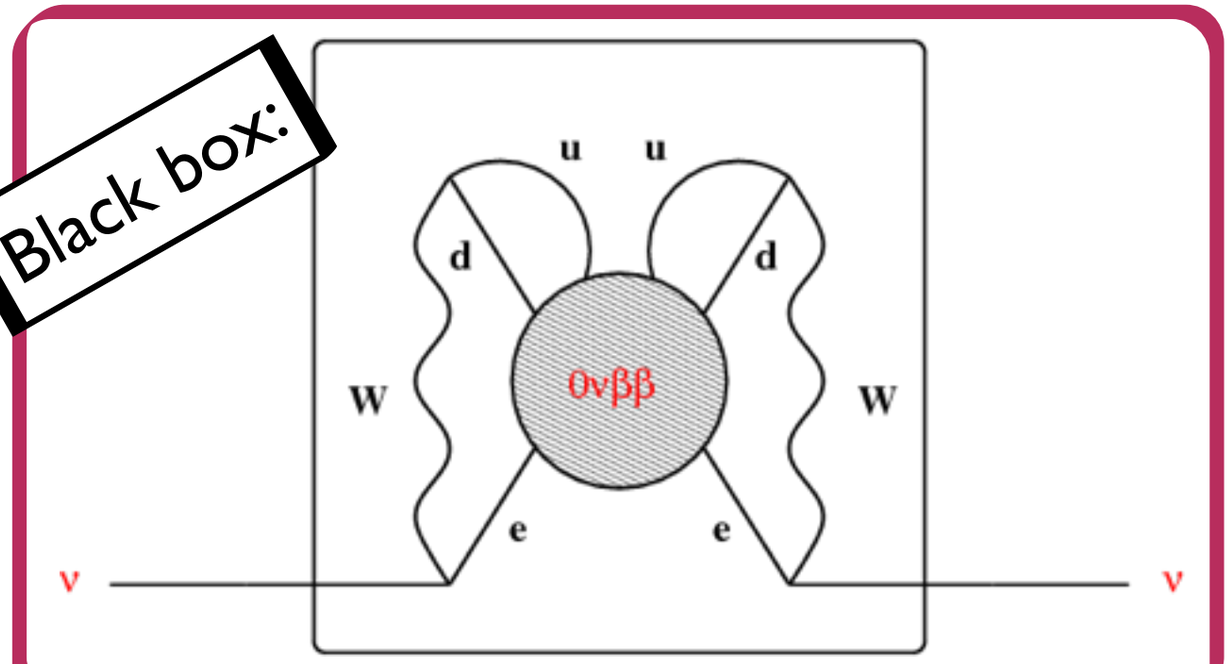

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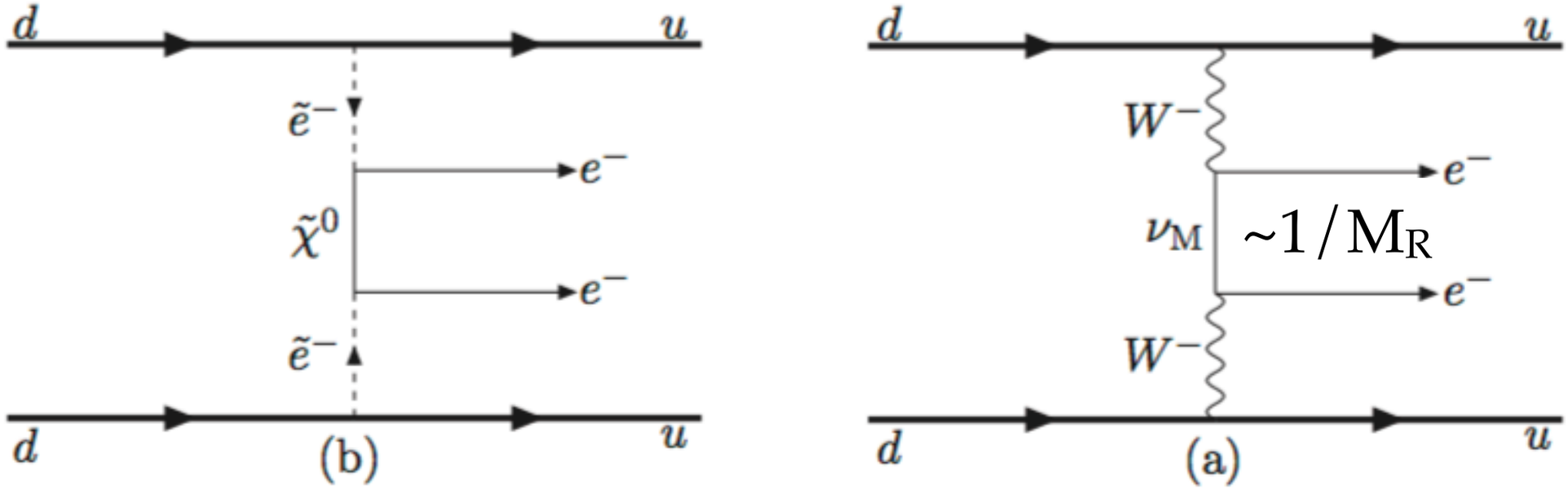
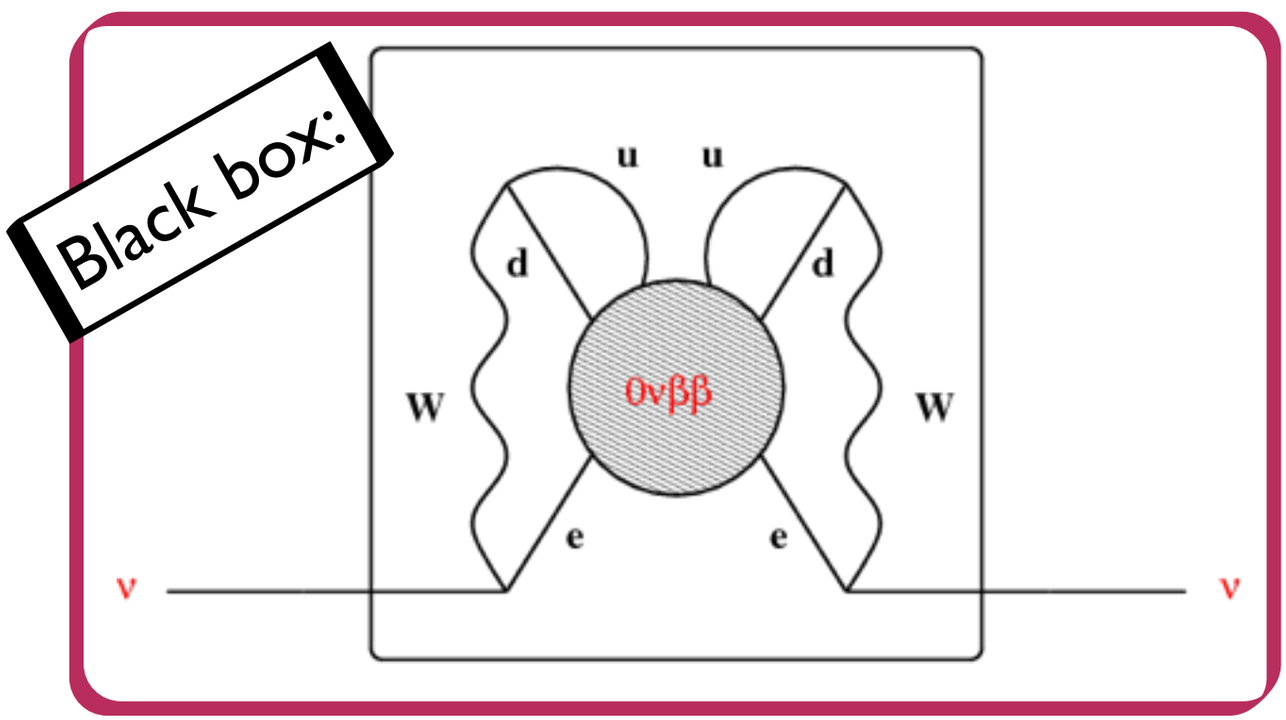
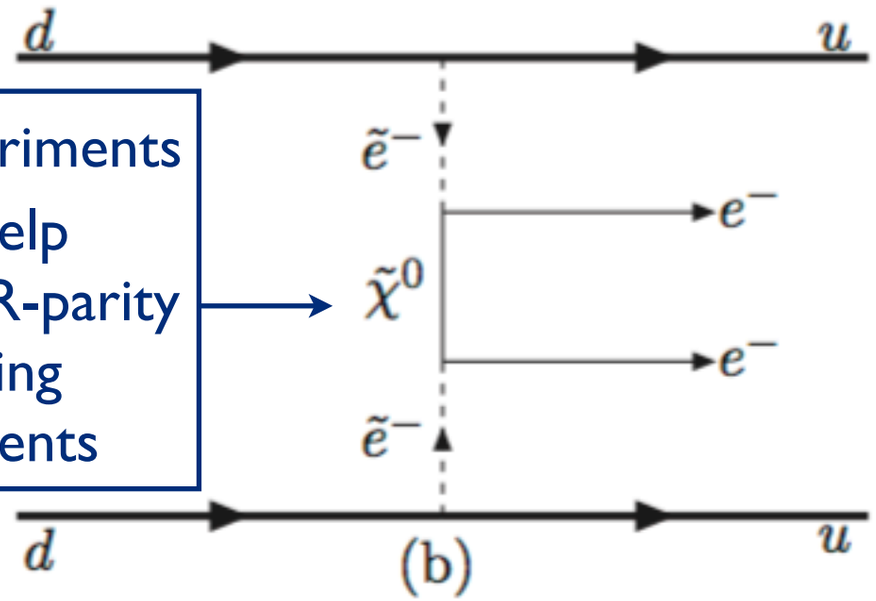


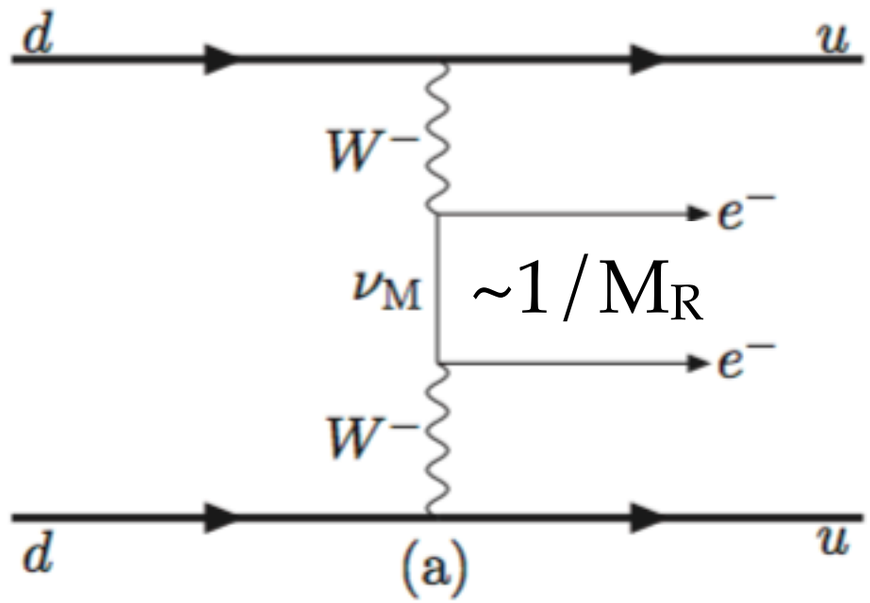


Valle & Schecter, Fig.: H. Päs, W. Rodejohann New J.Phys. 17 (2015) no.11, 115010

Short-range contribution: probe for heavy physics

$0\nu\beta\beta$ experiments may help constrain R-parity violating coefficients





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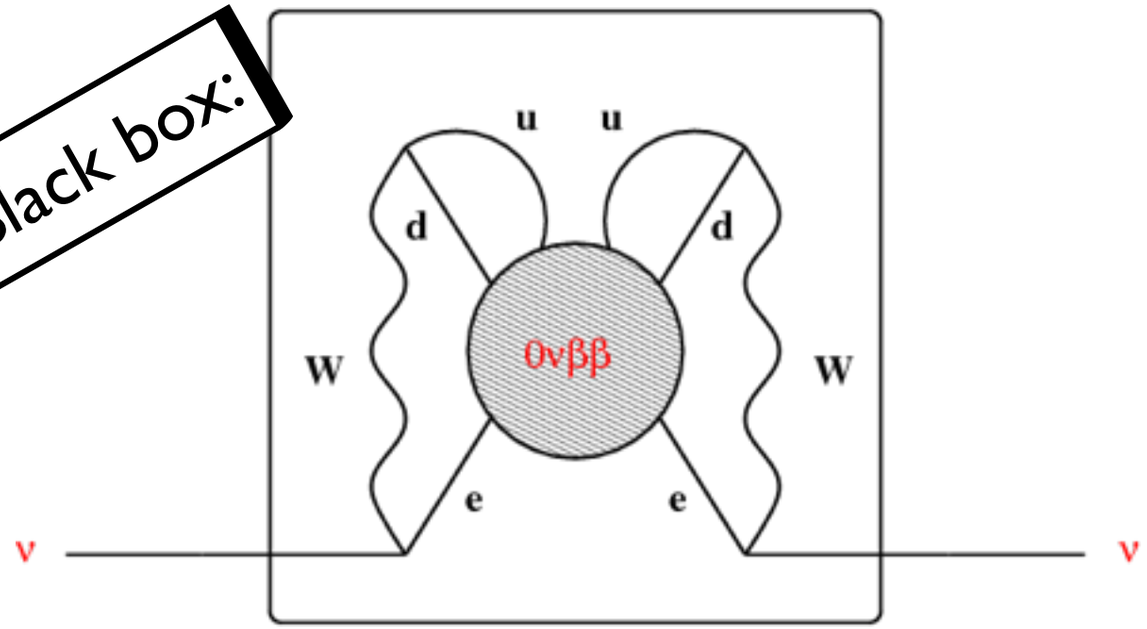

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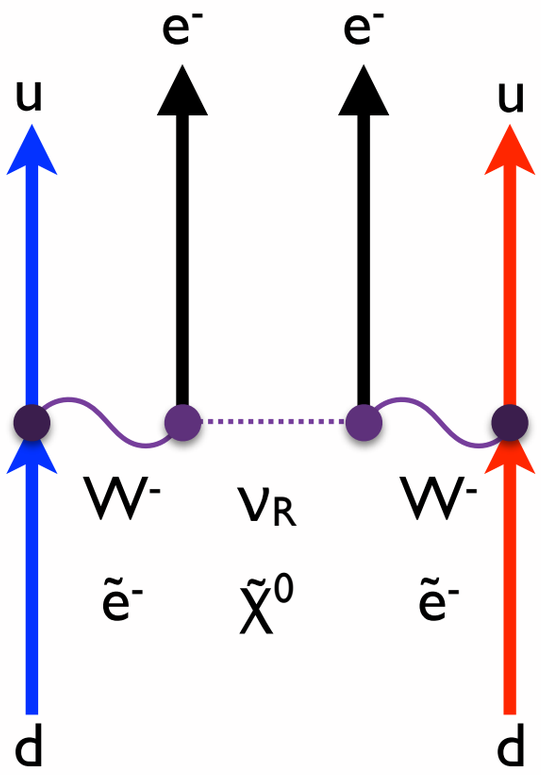
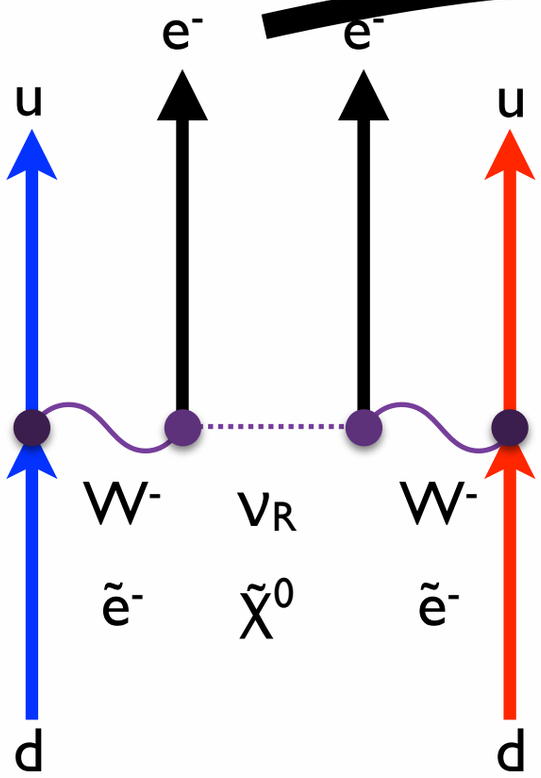


Your favorite BSM theory

Pen & Paper



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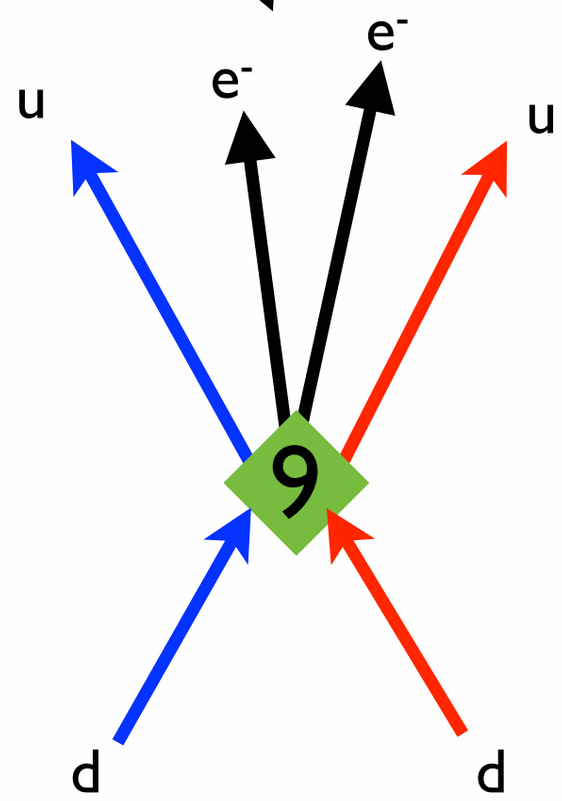
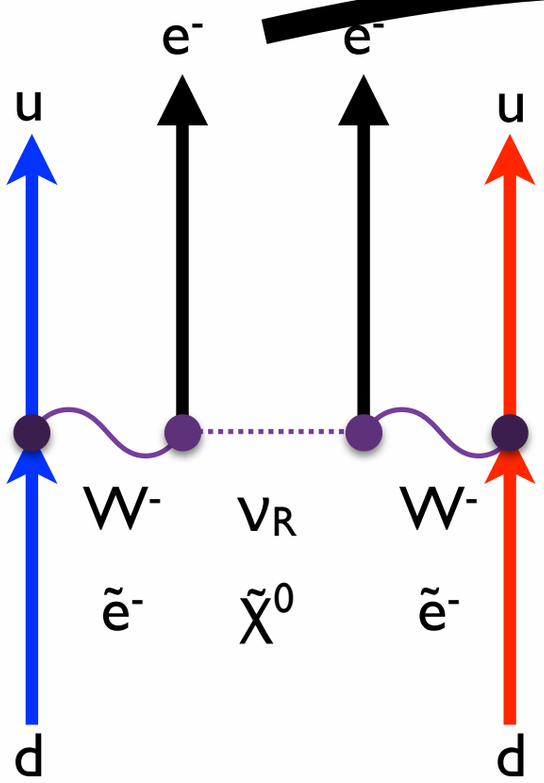
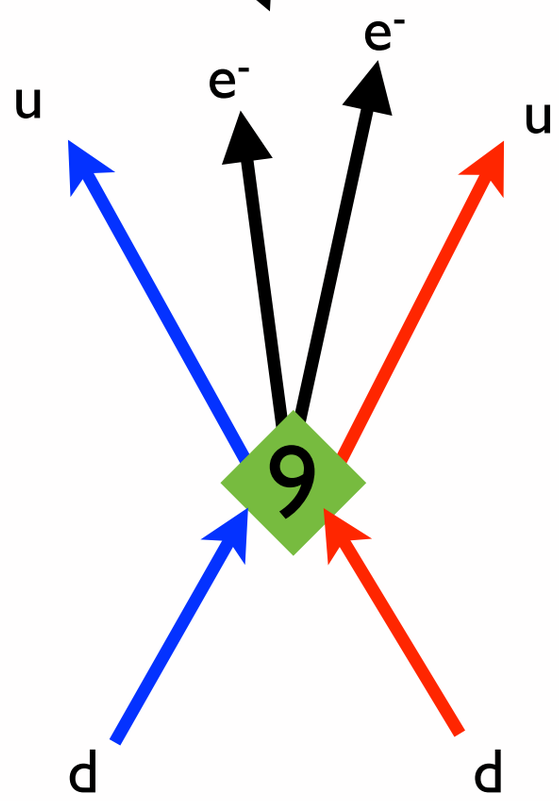


effective 4-quark
operators in QCD

Pen & Paper



Your favorite BSM theory



ef

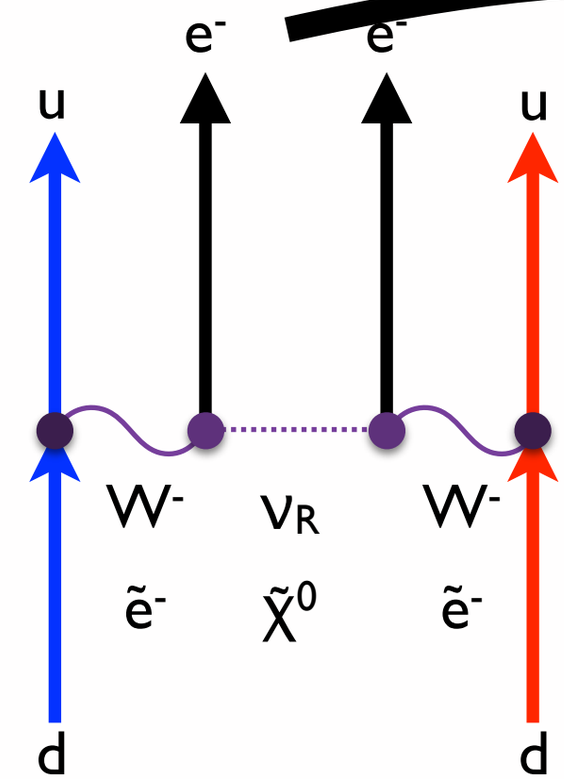
op

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

Prezeau, Ramsey-Musolf, Vogel (2003)

Pen & Paper

LQCD



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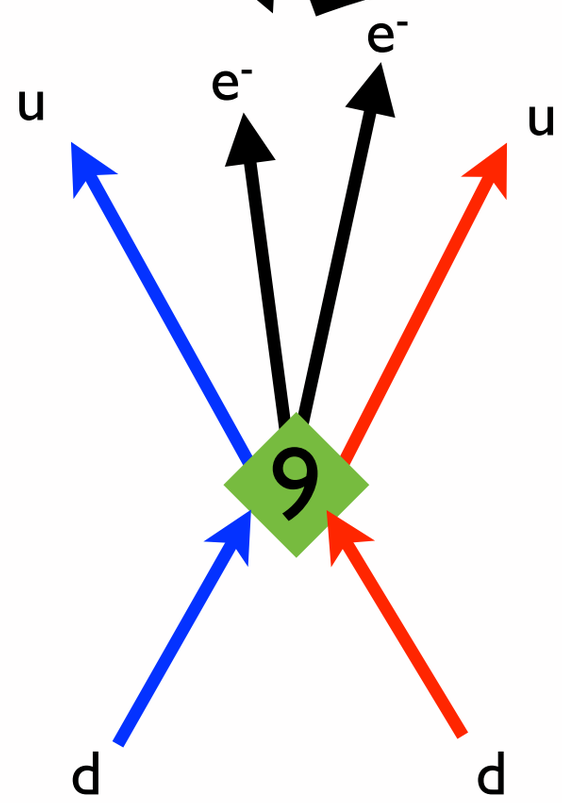
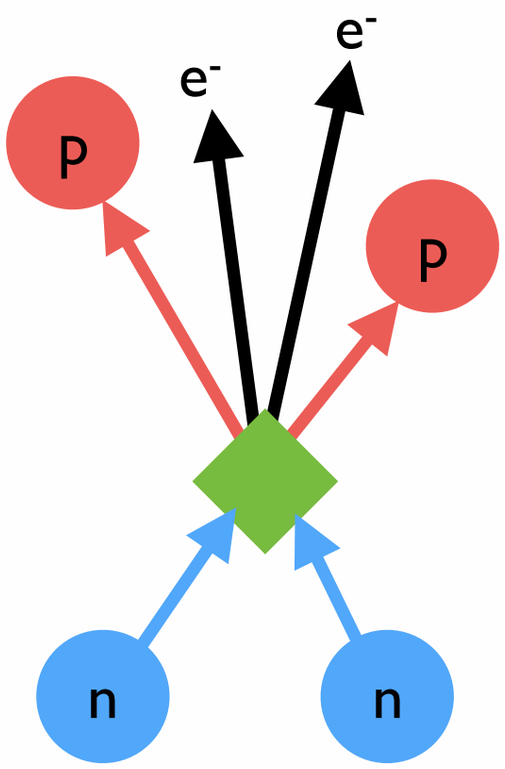
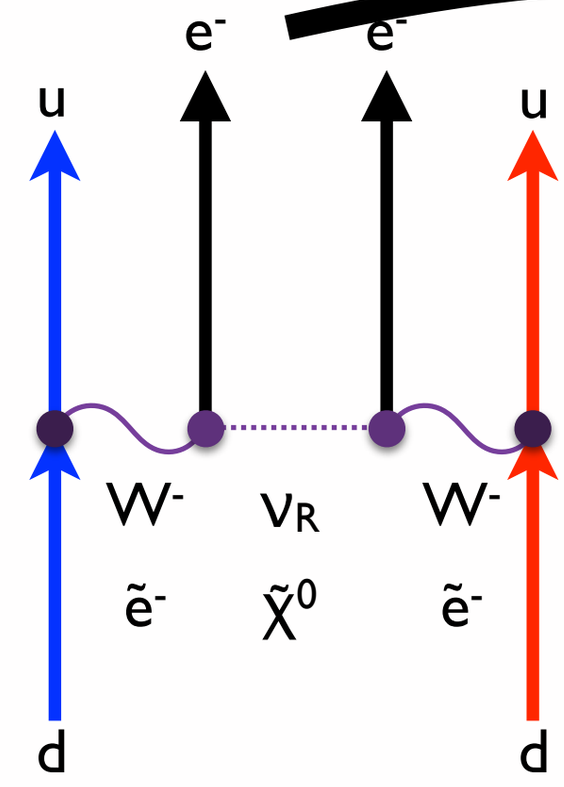


effective 4-quark operators in QCD



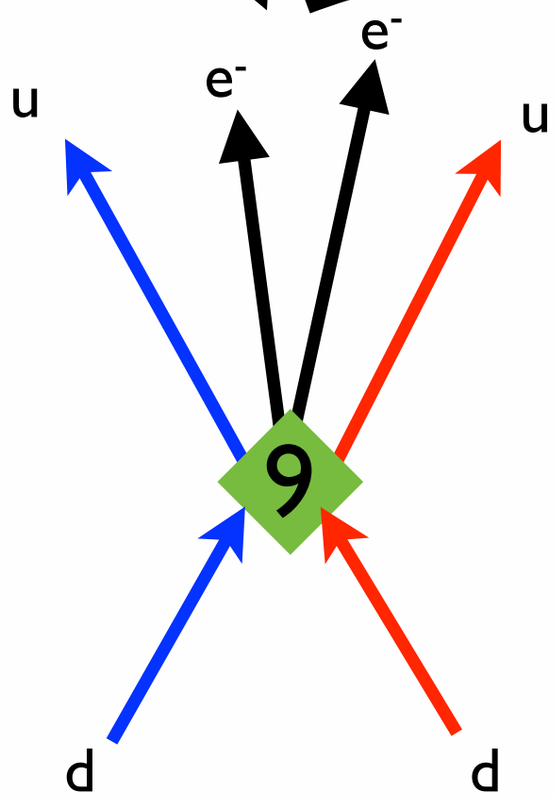
two nucleon amplitudes

Pen & Paper



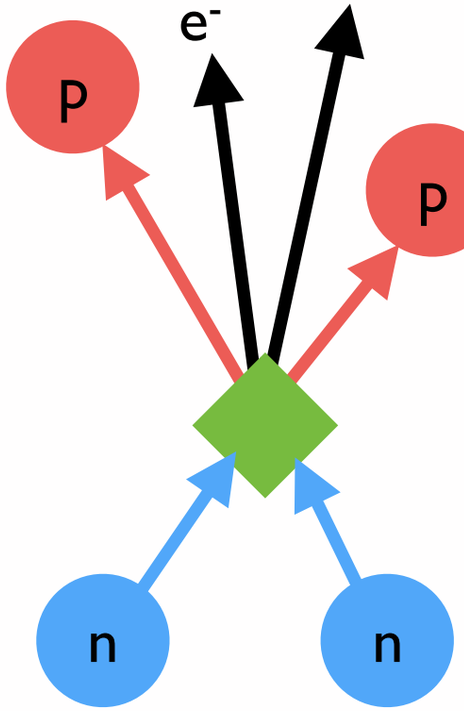
Your favorite
BSM theory

LQCD

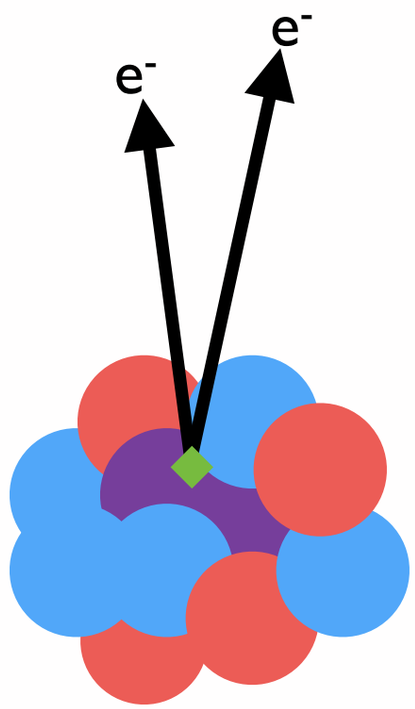


effective 4-quark
operators in QCD

NP



two nucleon
amplitudes

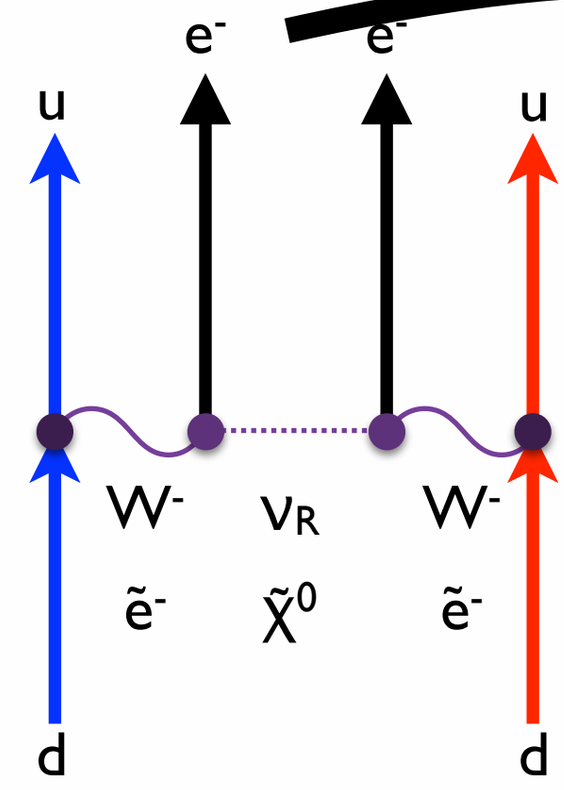


decay rates
in big nuclei

Pen & Paper

LQCD

NP



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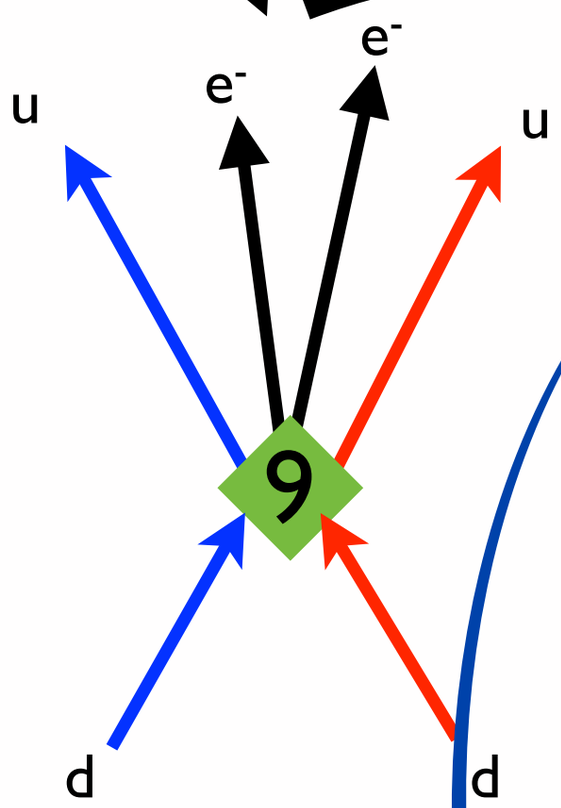
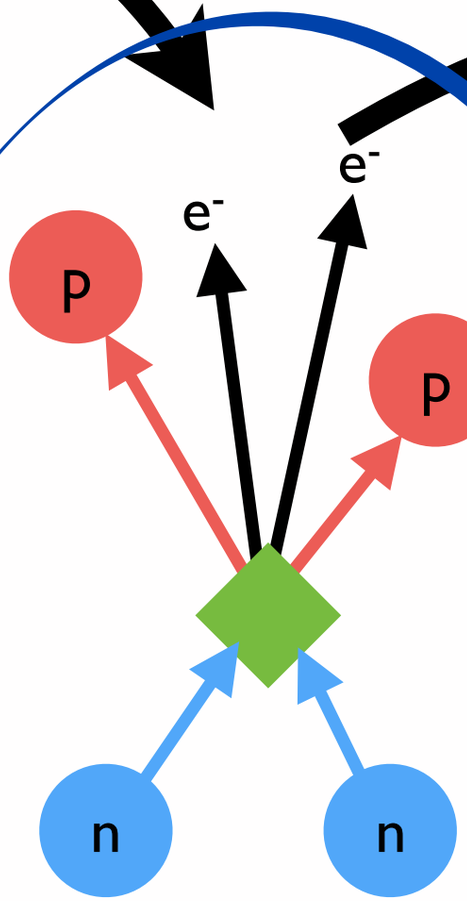


effective 4-quark operators in QCD



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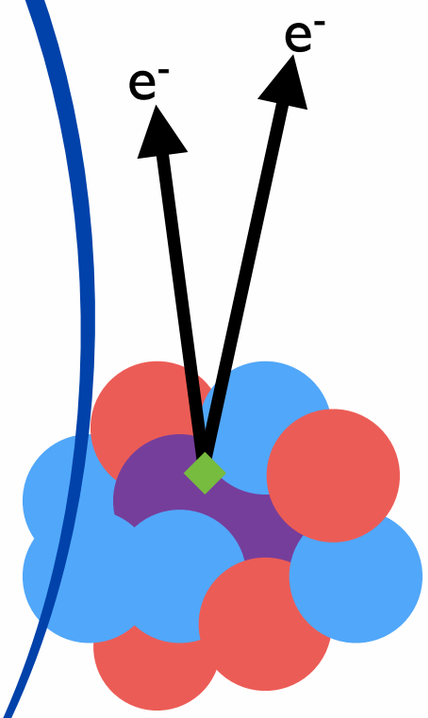
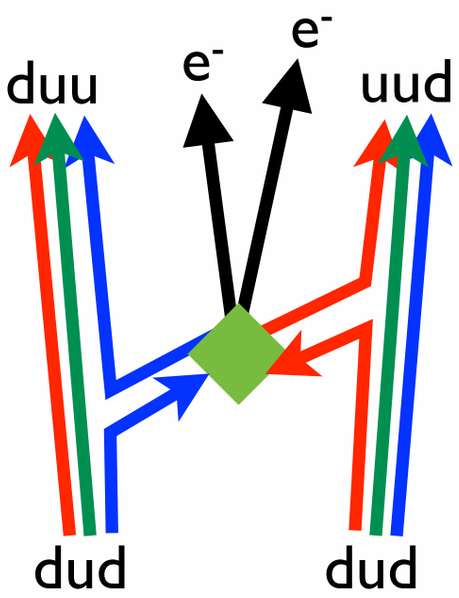
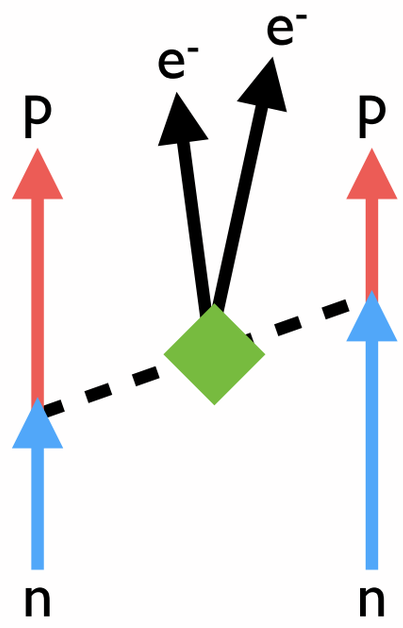


decay rates in big nuclei

Can determine power-counting of various contributions using chiral perturbation theory

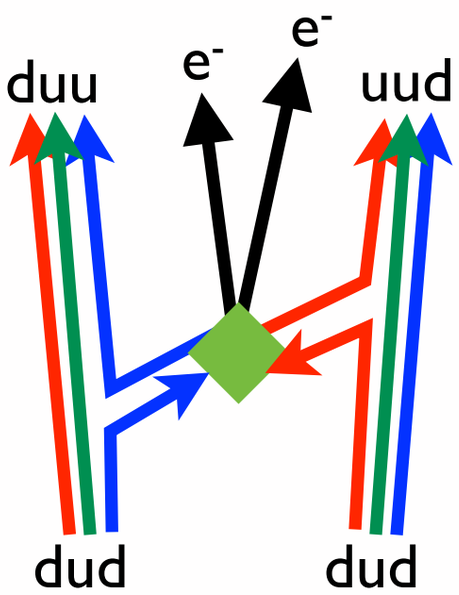


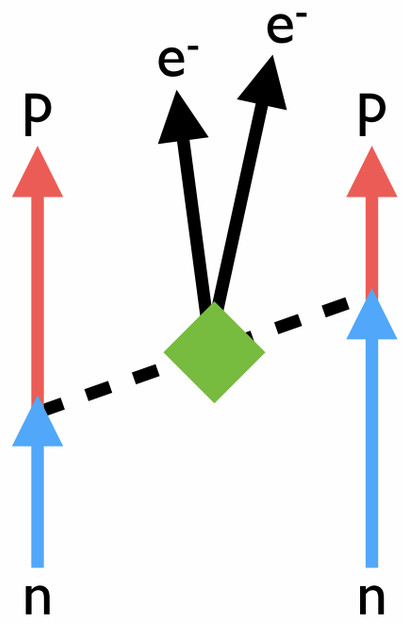


χPT power-counting of operators

$\mathcal{O}(p^{-2})$ long-range π exchange

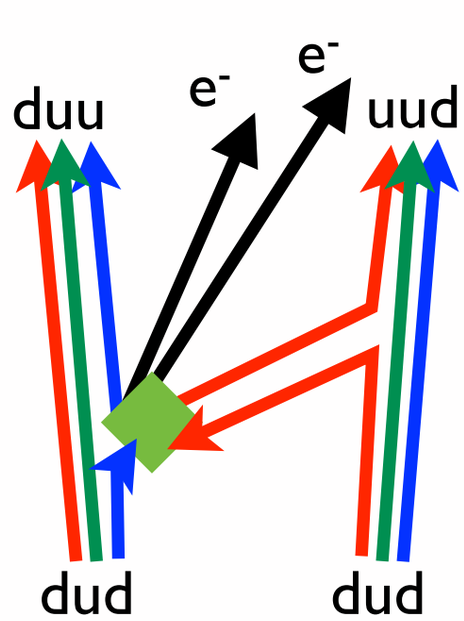
χPT power-counting of operators

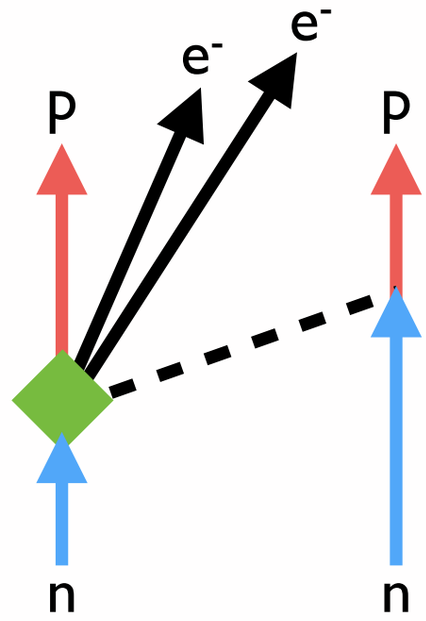




$\mathcal{O}(p^{-2})$ long-range π exchange

$\mathcal{O}(p^{-1})$ πN vertex





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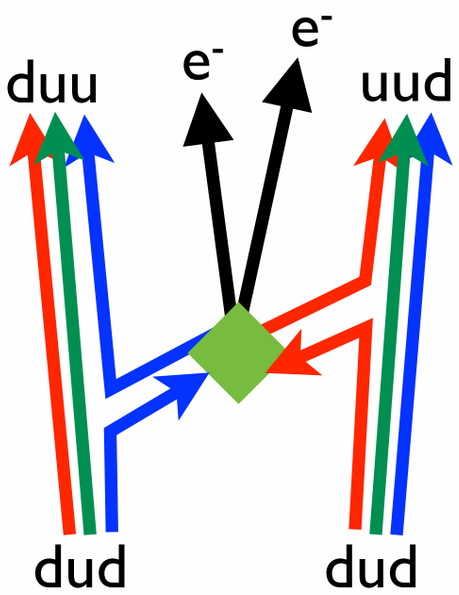

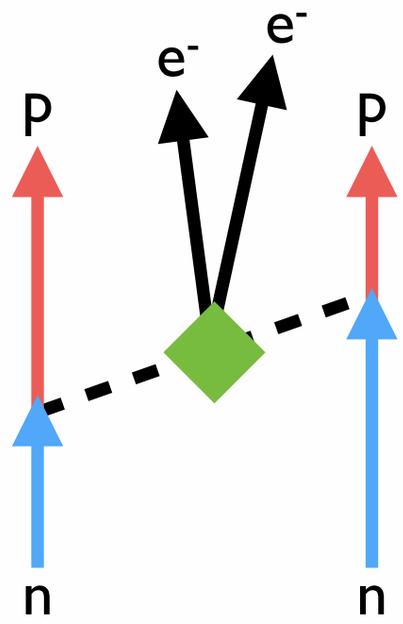

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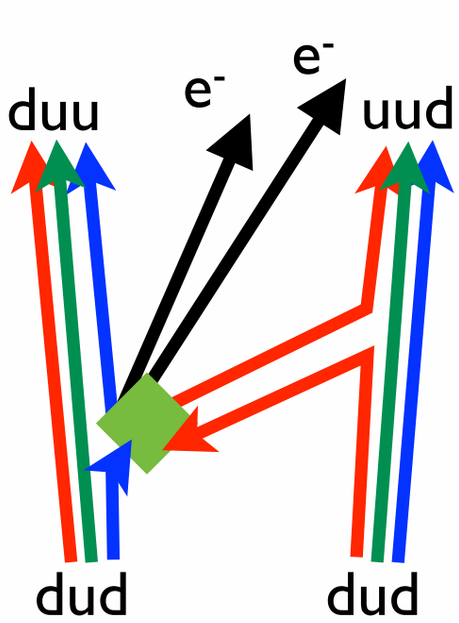
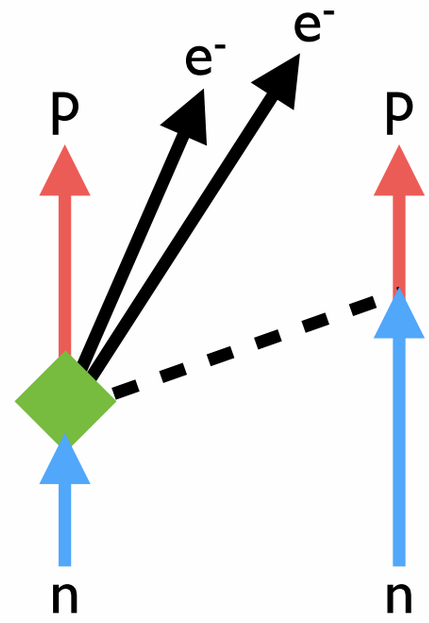
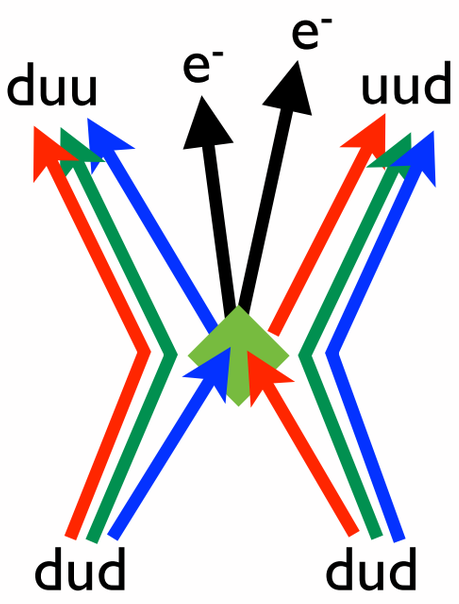
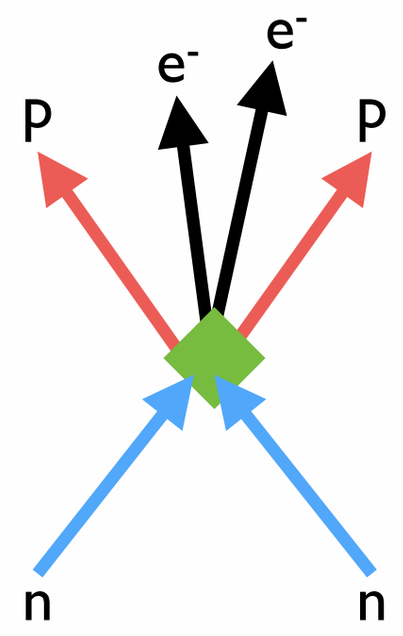




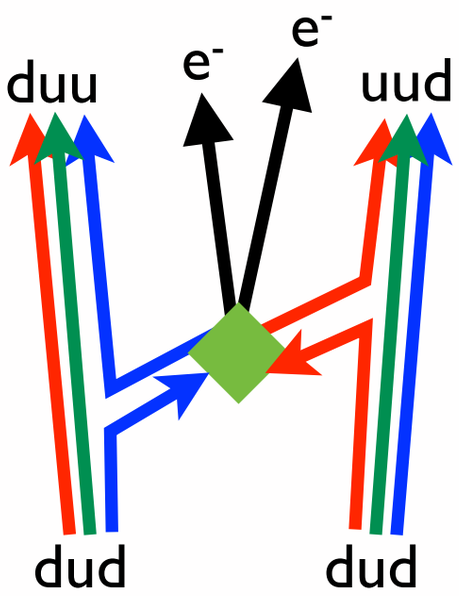
$\mathcal{O}(p^{-1})$ πN vertex

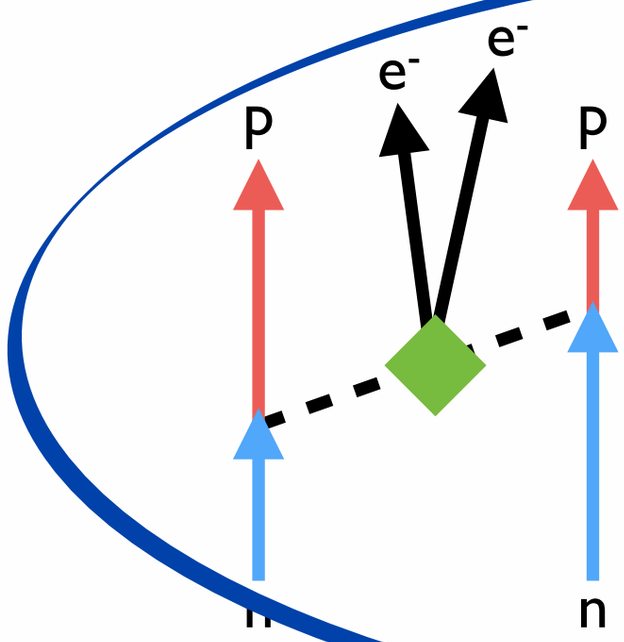




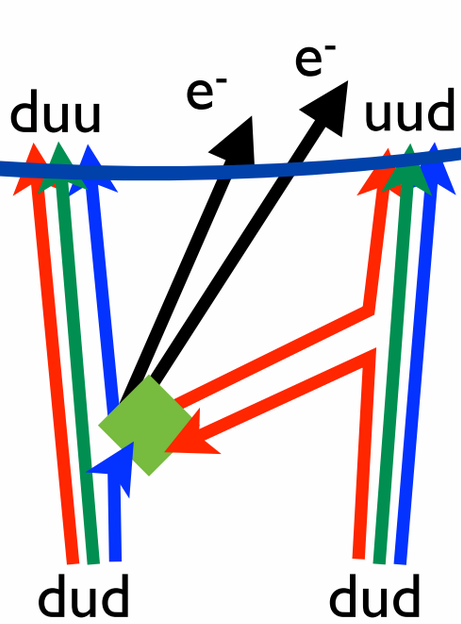
$\mathcal{O}(p^{0})$ NN contact operator

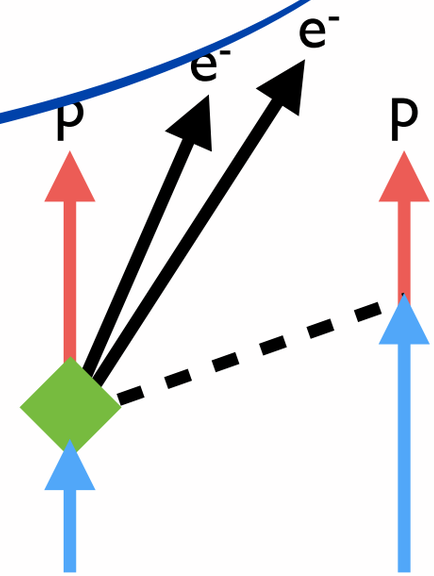
χPT power-counting of operators





$\mathcal{O}(p^{-2})$ long-range π exchange





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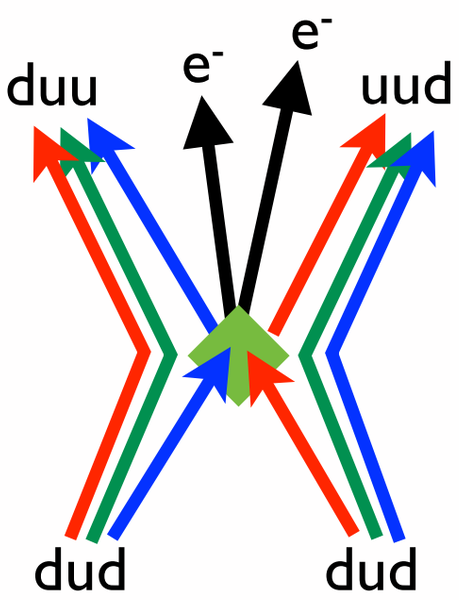
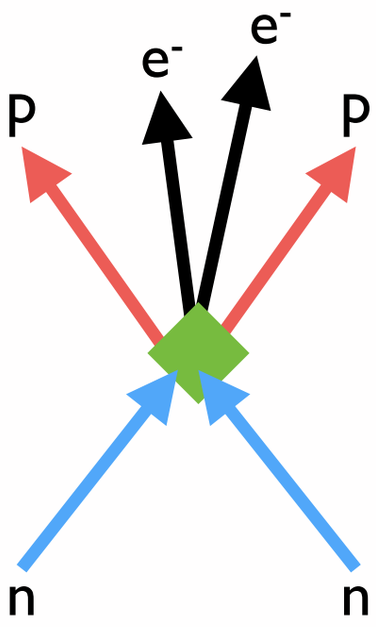
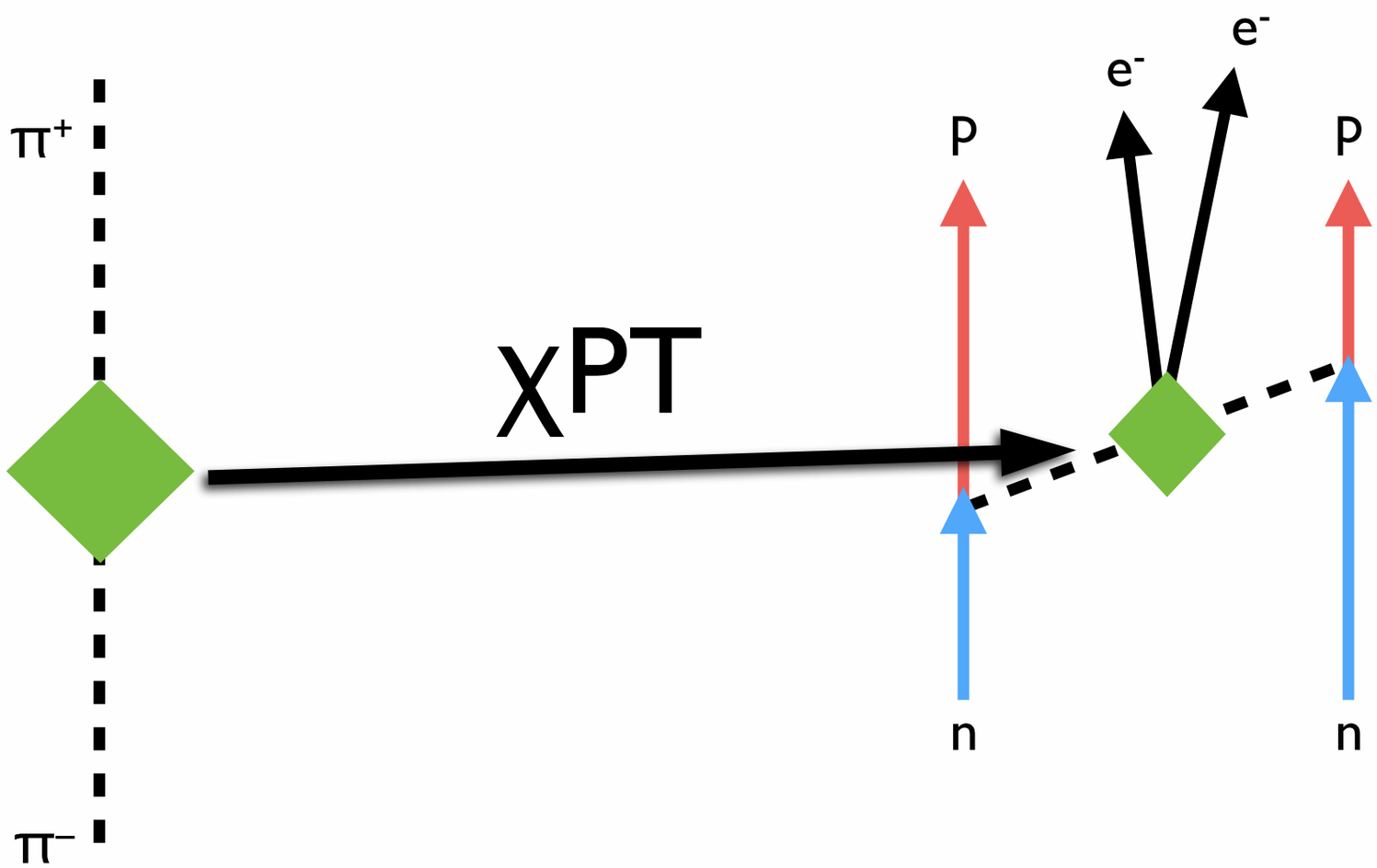




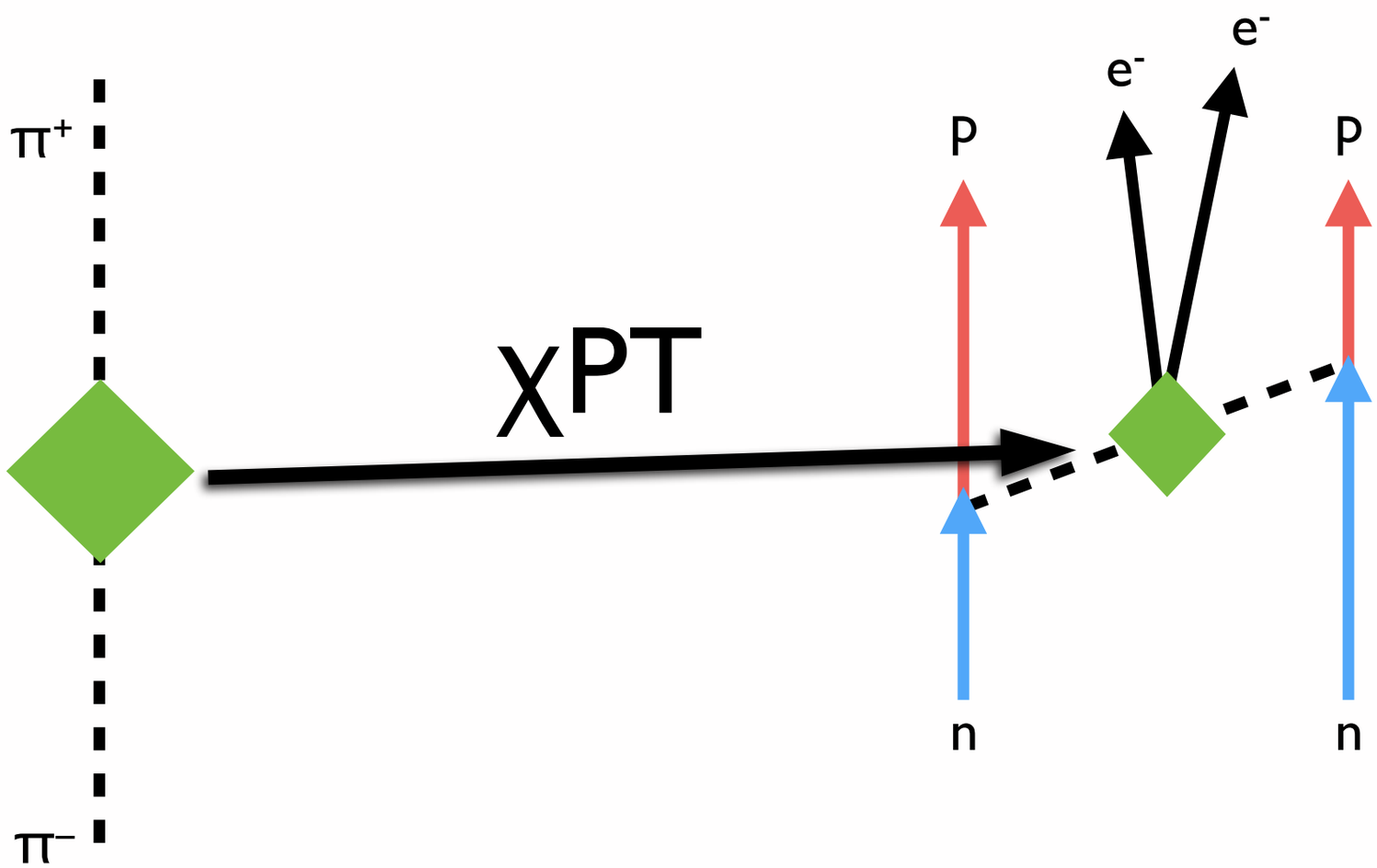
$\mathcal{O}(p^{0})$ NN contact operator

Long Range pion contribution



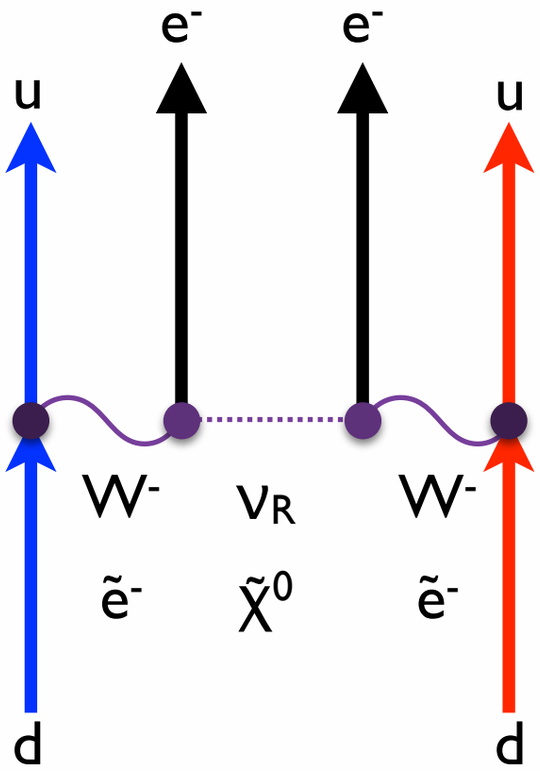
Unknown LEC is the same as for π^- to π^+ transition: don't have to explicitly calculate two nucleon amplitude in LQCD

Long Range pion contribution

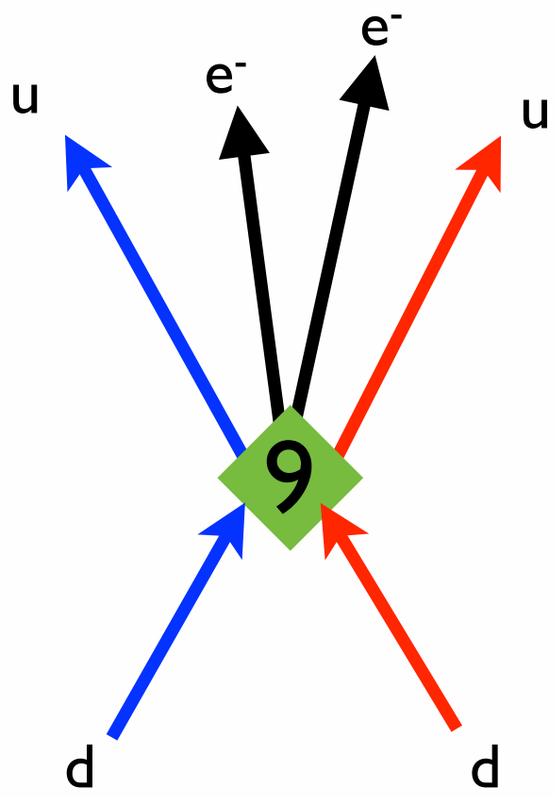


Easy to compute pion physics on the lattice!

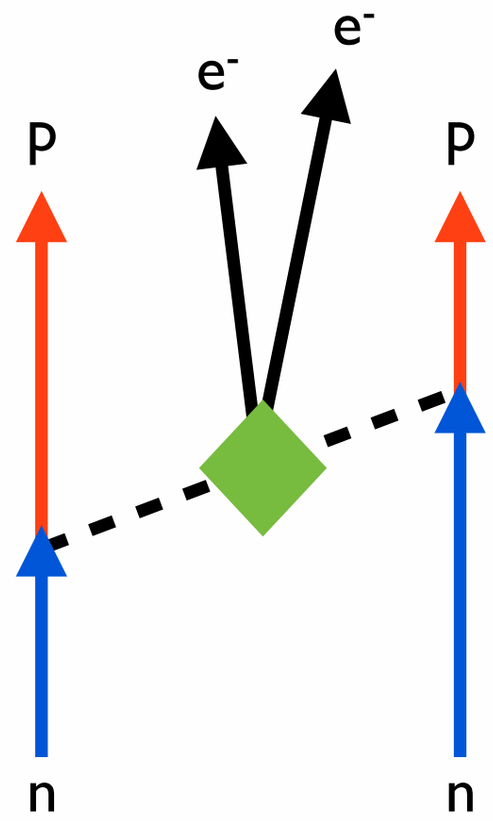
- Cheap
- Clean signals
- I=2: no disconnected pieces



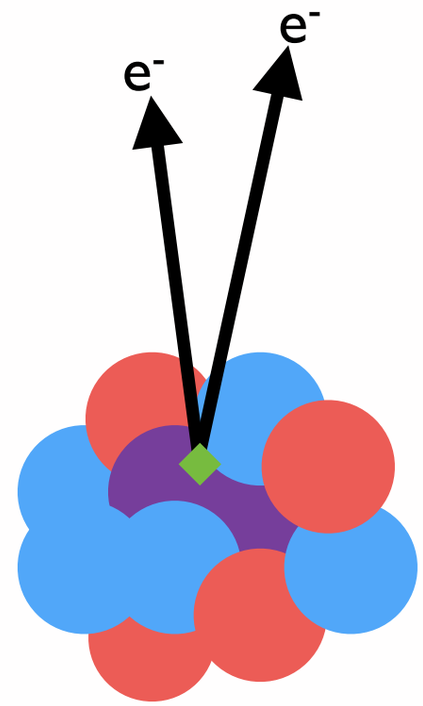
Your favorite BSM theory



effective 4-quark operators in QCD



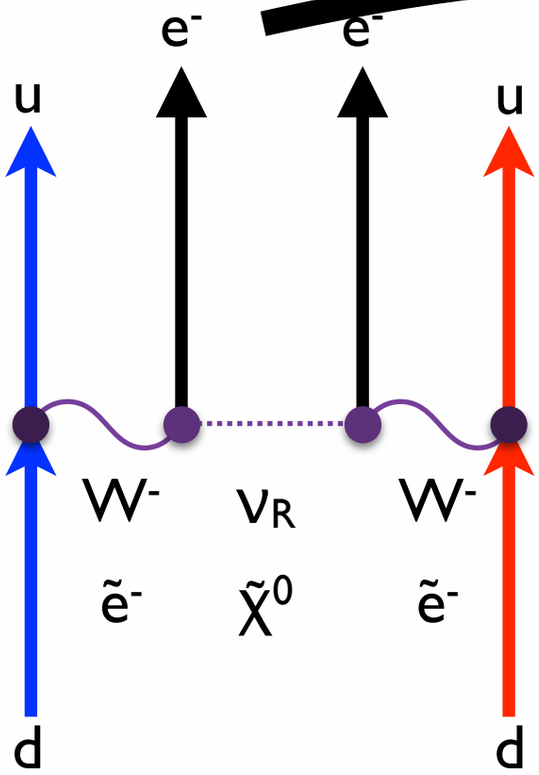
two nucleon amplitudes



decay rates in big nuclei

effective $\pi^- \to \pi^+$ vertex

Pen & Paper



Your favorite
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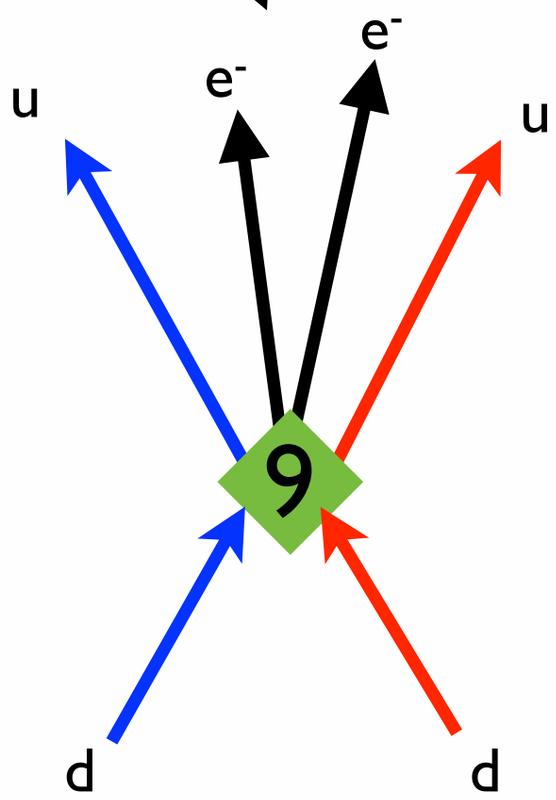
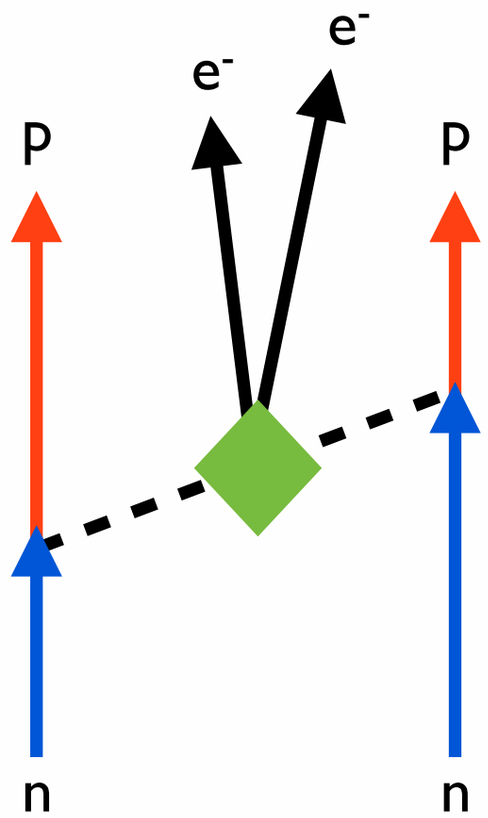
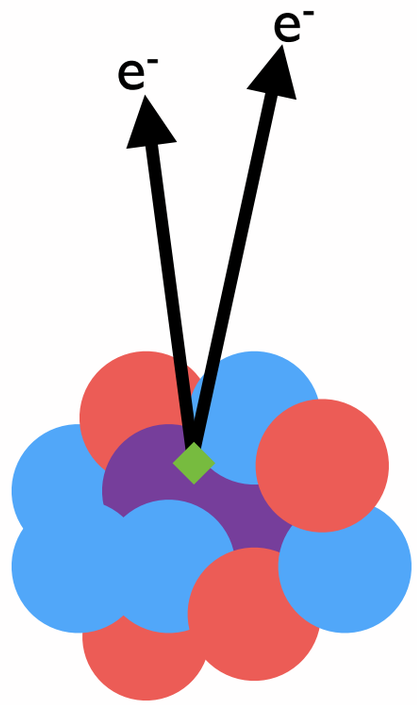


effective 4-quark
operators in QCD



two nucleon
amplitudes



decay rates
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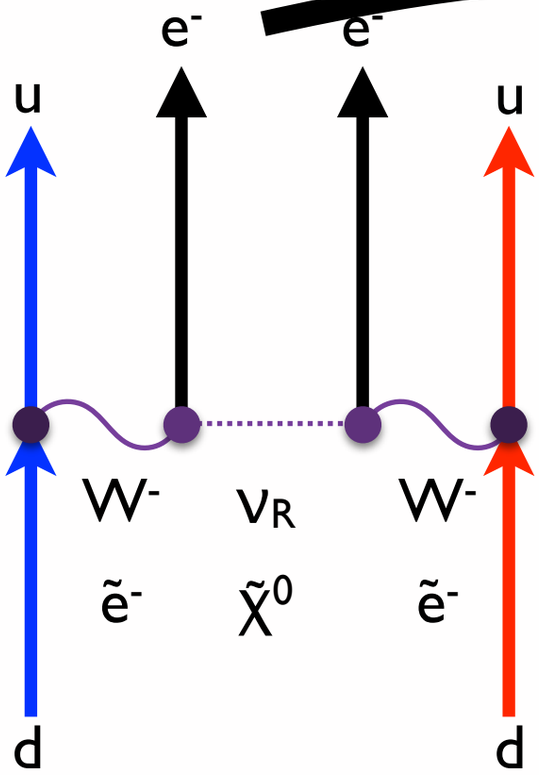
Pen & Paper



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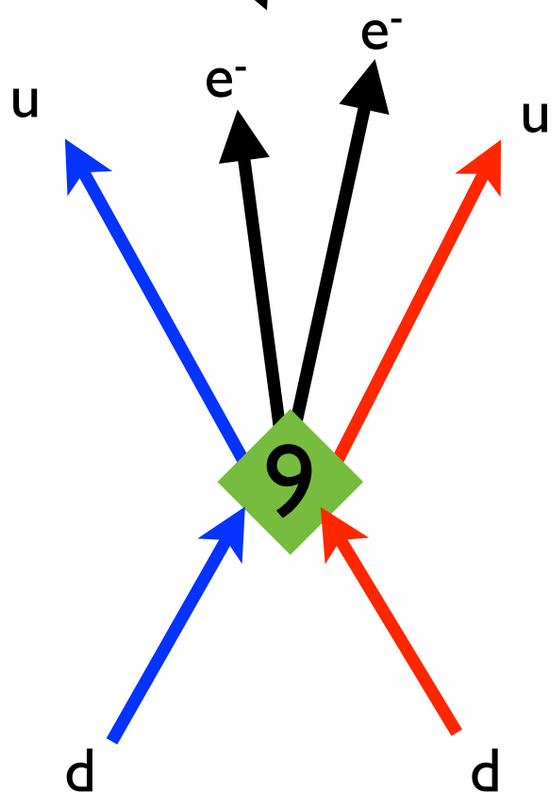

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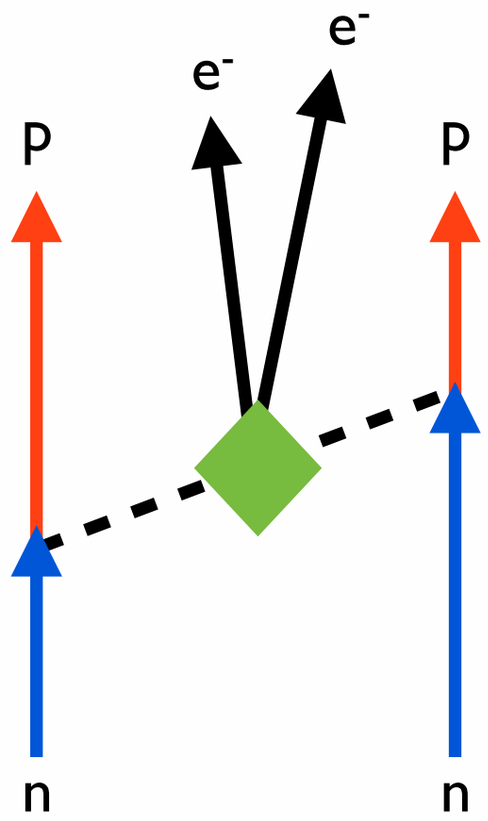

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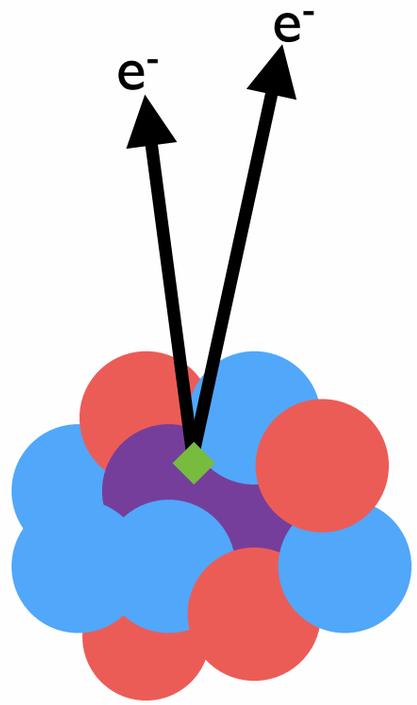
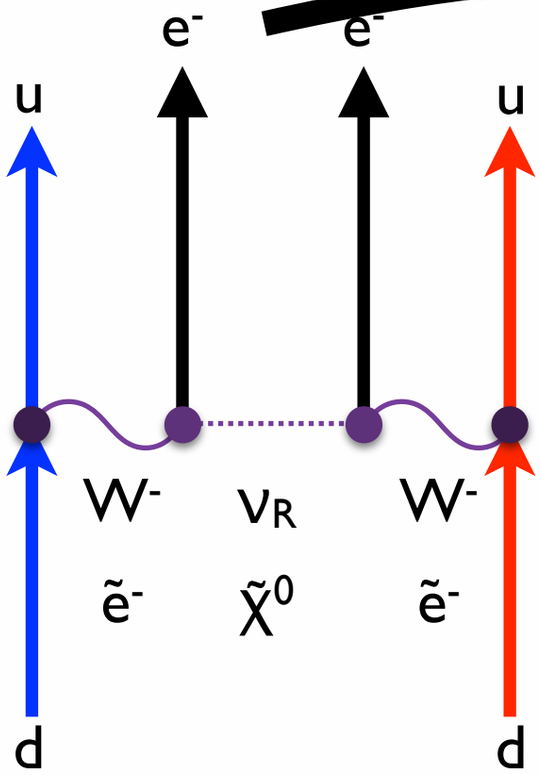


decay rates
in big nuclei

LQCD

effective $\pi^- \rightarrow \pi^+$
vertex

Pen & Paper



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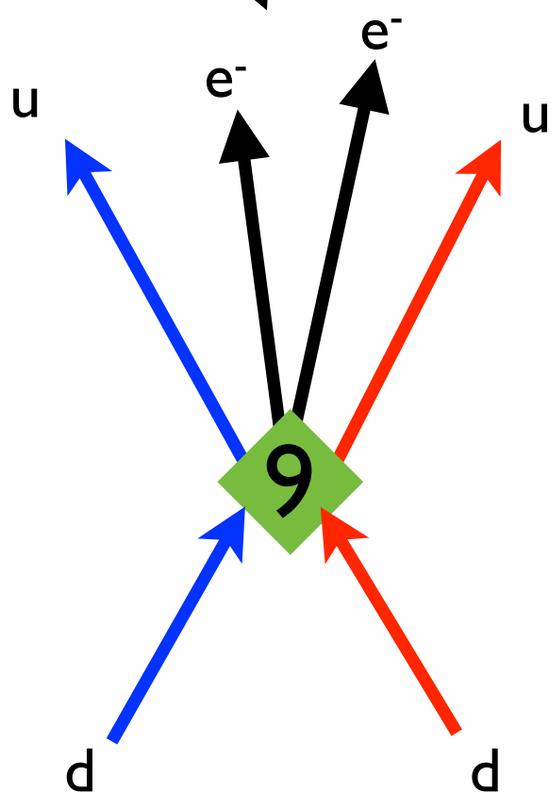

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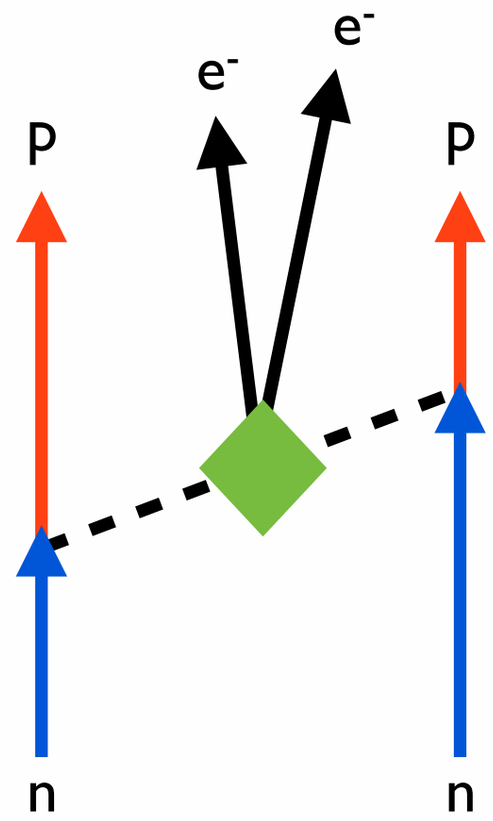

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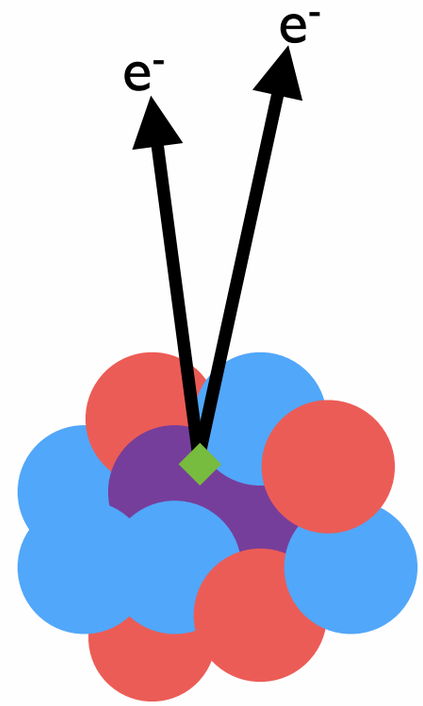

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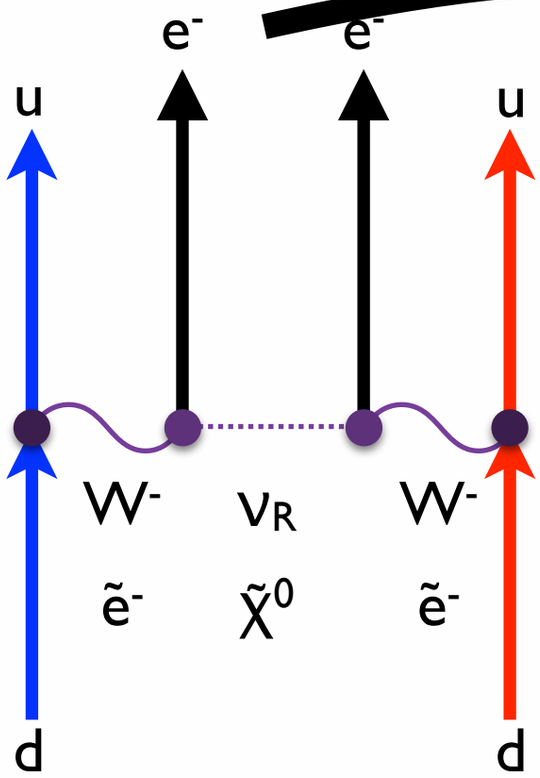
Pen & Paper



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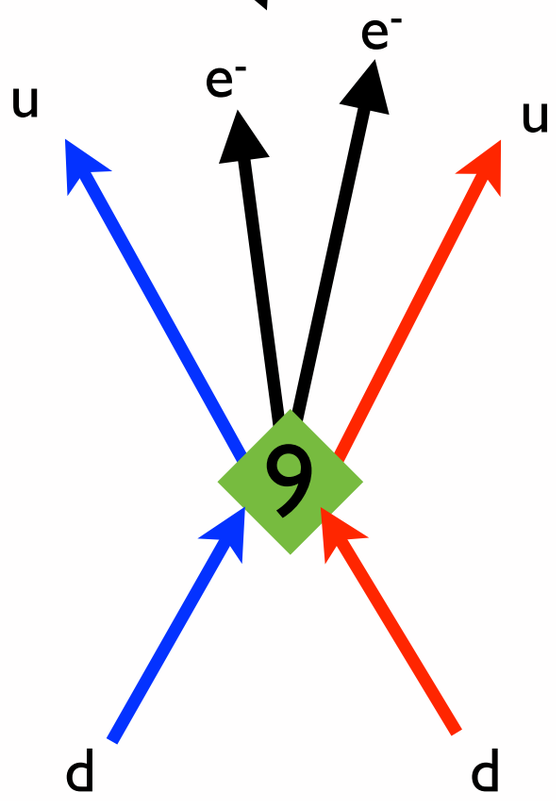

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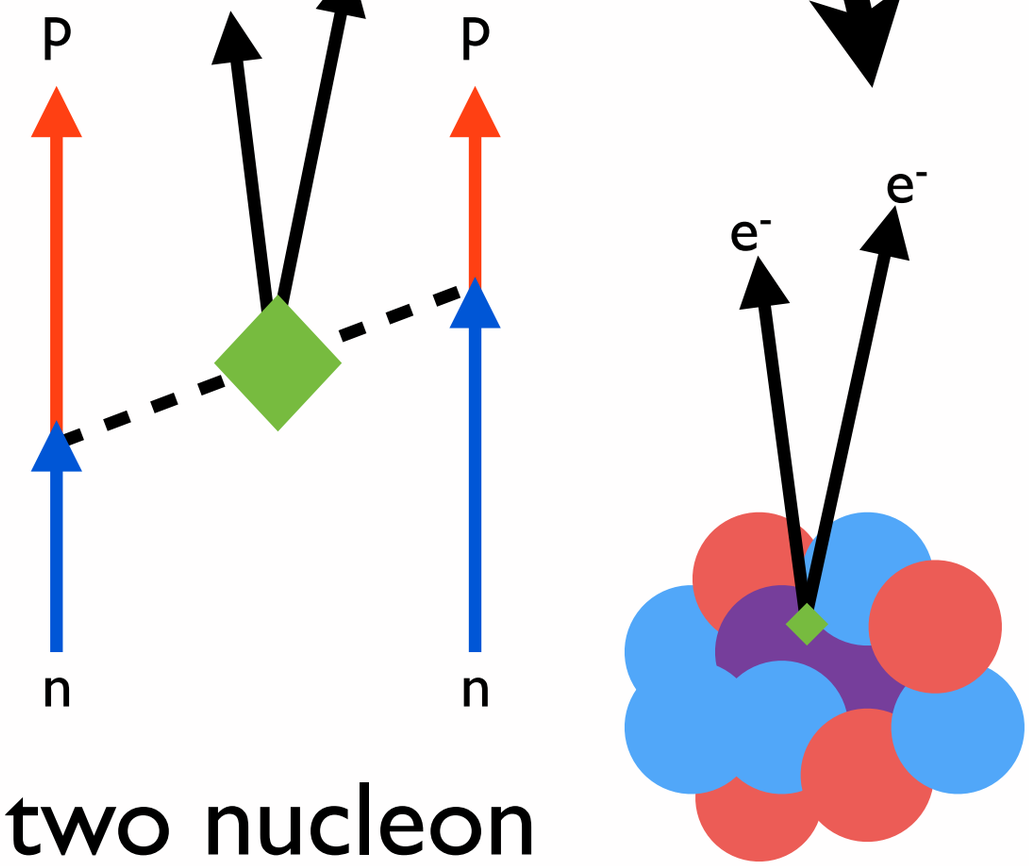
NP



two nucleon
amplitudes

LQCD

effective $\pi^- \to \pi^+$
vertex

XPT

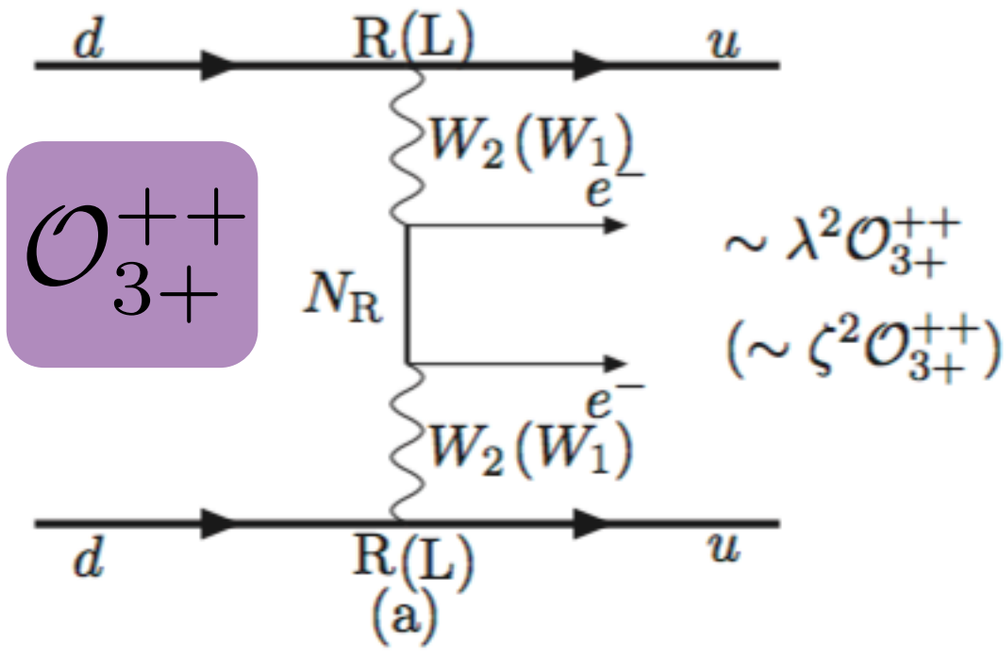
decay rates
in big nuclei

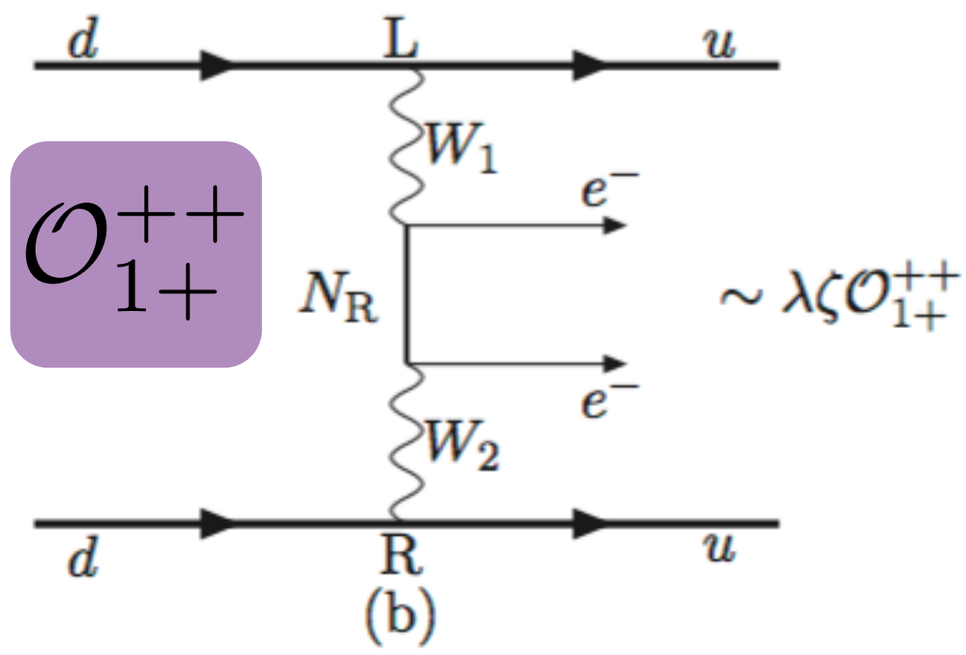
LQCD calculation: details/results

XPT:

$0\nu\beta\beta$-decay ops.	$\mathcal{O}_{1+}^{++}$	$\mathcal{O}_{2+}^{++}$	$\mathcal{O}_{2-}^{++}$	$\mathcal{O}_{3+}^{++}$	$\mathcal{O}_{3-}^{++}$	$\mathcal{O}_{4+}^{++,\mu}$	$\mathcal{O}_{4-}^{++,\mu}$	$\mathcal{O}_{5+}^{++,\mu}$	$\mathcal{O}_{5-}^{++,\mu}$
$\pi\pi ee$ LO	✓	✓	X	X	X	X	X	X	X
$\pi\pi ee$ NNLO	✓	✓	X	✓	X	X	X	X	X
$NN\pi ee$ LO	X	X	√	X	X	√	√	√	√
$NN\pi ee$ NLO	X	√	X	√	X	√	√	√	√
$NNNNee$ LO	√	√	X	√	X	√	√	√	√

Left-right symmetric models





Prezeau, Ramsey-Musolf, Vogel (2003), Savage (1999)

Contractions

- Can perform exact momentum projection at source and sink
- Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2

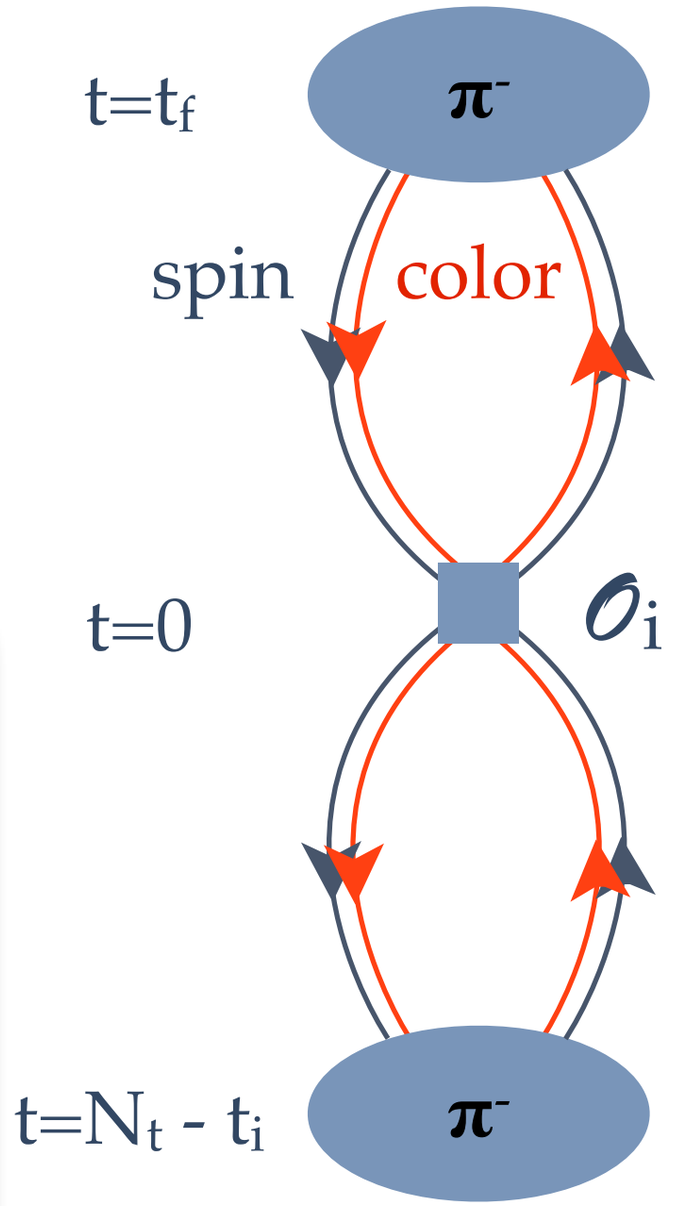
$$\mathcal{O}^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

$$\mathcal{O}'^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right] \left[\bar{q}_R \tau^- \gamma_\mu q_R\right)$$

$$\mathcal{O}^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right) \left[\bar{q}_R \tau^- q_L\right] + \left(\bar{q}_L \tau^- q_R\right) \left[\bar{q}_L \tau^- q_R\right]$$

$$\mathcal{O}'^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right] \left[\bar{q}_R \tau^- q_L\right) + \left(\bar{q}_L \tau^- q_R\right] \left[\bar{q}_L \tau^- q_R\right)$$

$$\mathcal{O}^{++}_{3+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_L \tau^- \gamma_\mu q_L\right] + \left(\bar{q}_R \tau^- \gamma^\mu q_R\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$



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- Can perform exact momentum projection at source and sink
- Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2

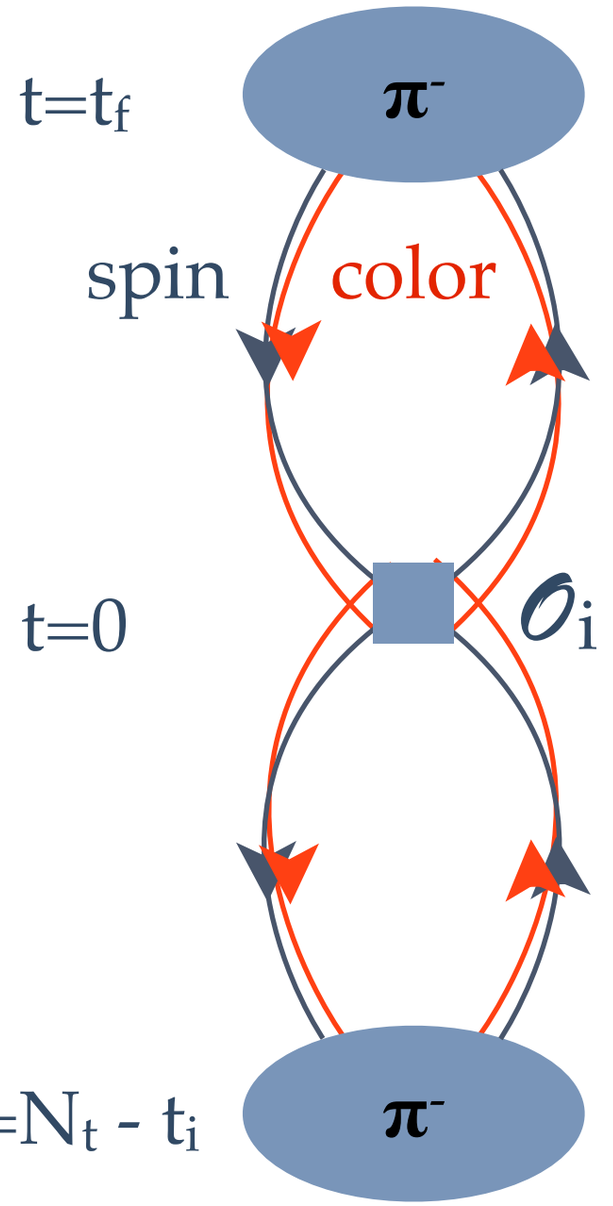
$$\mathcal{O}^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

$$\mathcal{O}'^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right] \left[\bar{q}_R \tau^- \gamma_\mu q_R\right)$$

$$\mathcal{O}^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right) \left[\bar{q}_R \tau^- q_L\right] + \left(\bar{q}_L \tau^- q_R\right) \left[\bar{q}_L \tau^- q_R\right]$$

$$\mathcal{O}'^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right] \left[\bar{q}_R \tau^- q_L\right) + \left(\bar{q}_L \tau^- q_R\right] \left[\bar{q}_L \tau^- q_R\right)$$

$$\mathcal{O}^{++}_{3+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_L \tau^- \gamma_\mu q_L\right] + \left(\bar{q}_R \tau^- \gamma^\mu q_R\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$



HISQ ensembles

$a[fm]$: $m_\pi[MeV]$	310	220	135
0.15	$16^3 \times 48, m_\pi L \sim 3.78$	$24^3 \times 48, m_\pi L \sim 3.99$	$32^3 \times 48, m_\pi L \sim 3.25$
0.12		$24^3 \times 64, m_\pi L \sim 3.22$	
0.12	$24^3 \times 64, m_\pi L \sim 4.54$	$32^3 \times 64, m_\pi L \sim 4.29$	$48^3 \times 64, m_\pi L \sim 3.91$
0.12		$40^3 \times 64, m_\pi L \sim 5.36$	
0.09	$32^3 \times 96, m_\pi L \sim 4.50$	$48^3 \times 96, m_\pi L \sim 4.73$	

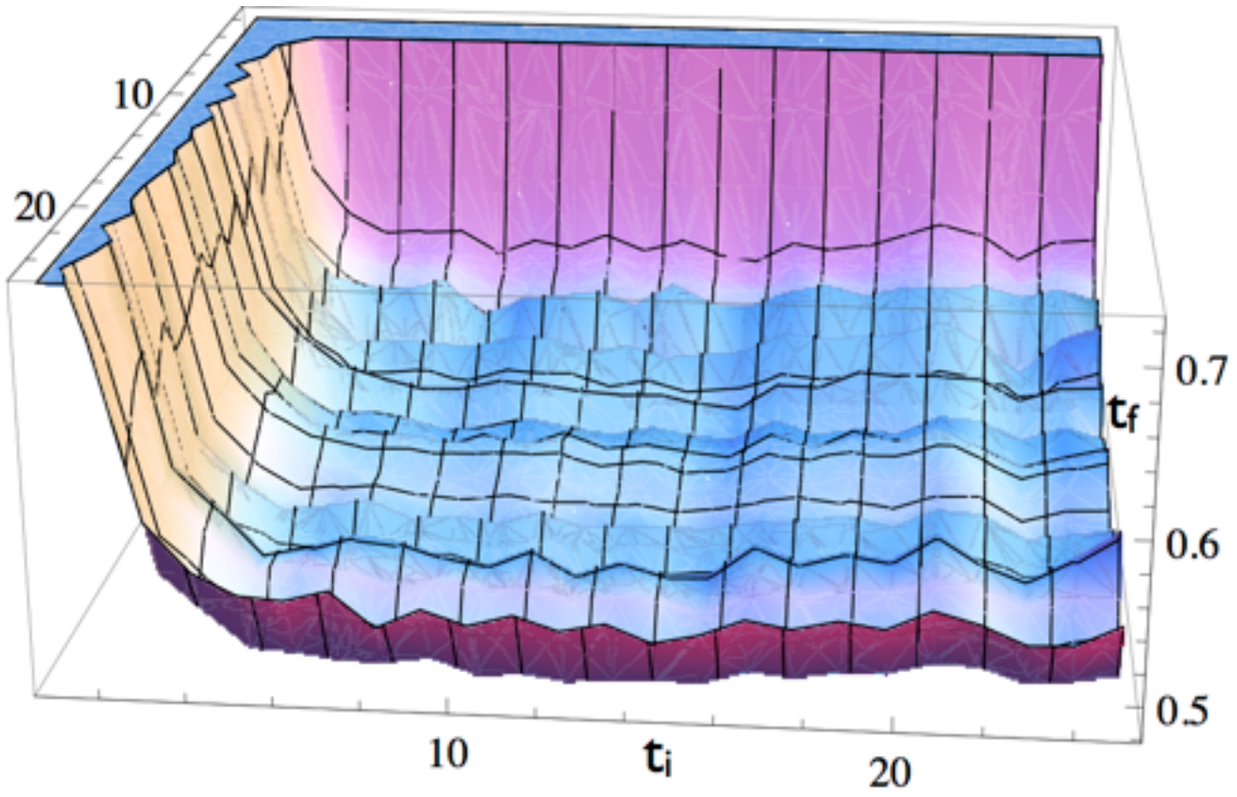
- Möbius DWF on HISQ
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5
- Wall + point sources for pions
- ~ 1000 cfgs, 1 source/cfg

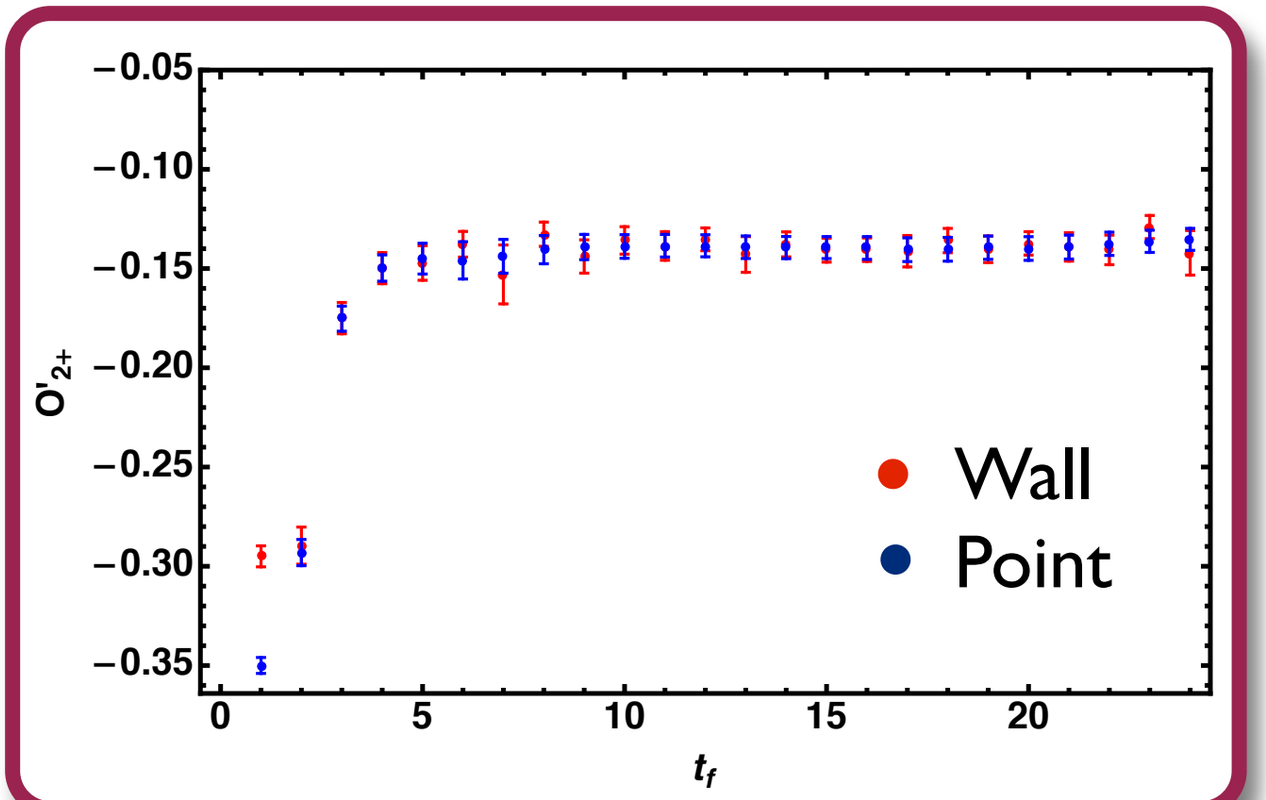
MILC Collaboration Phys. Rev. D87 (2013) 054505

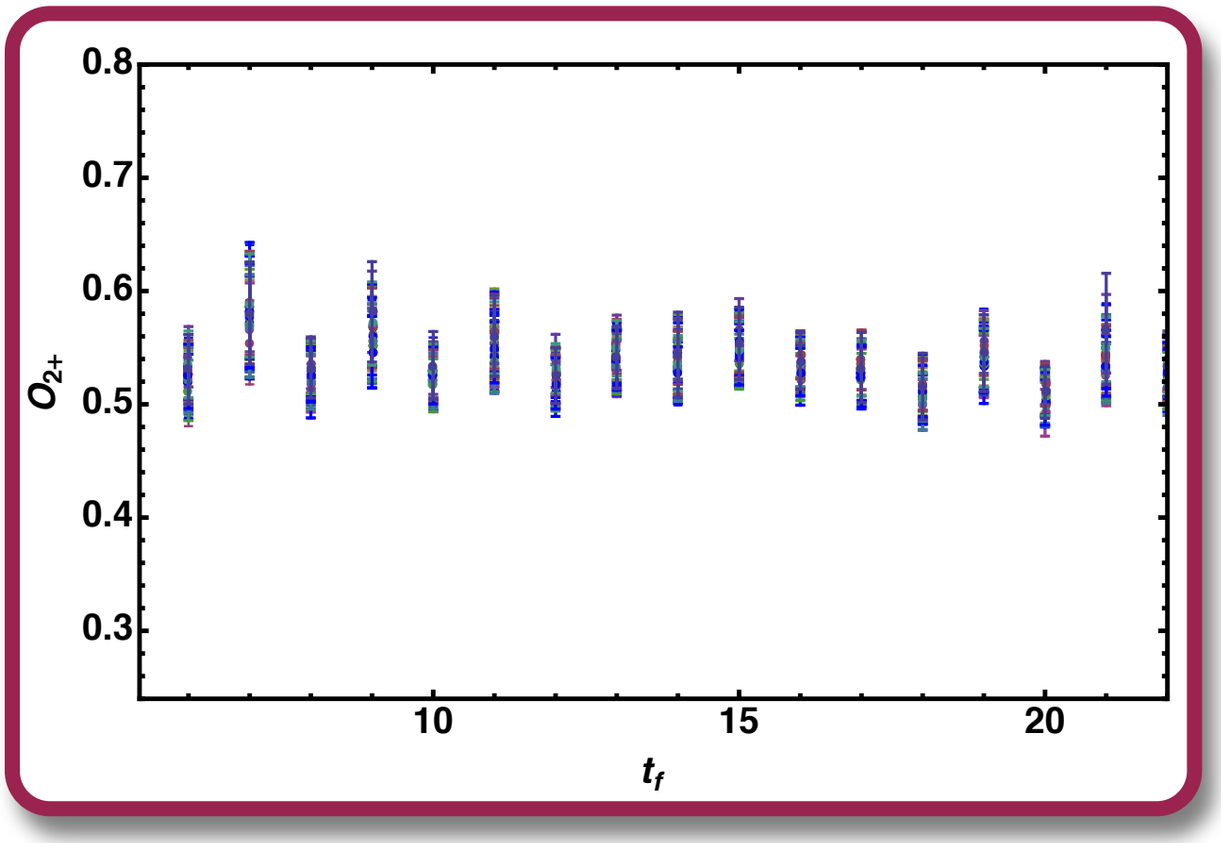
Narayanan, Neuberger (2006), Luscher (2010)

K. Orginos, C. Monahan (private communication)

Signals

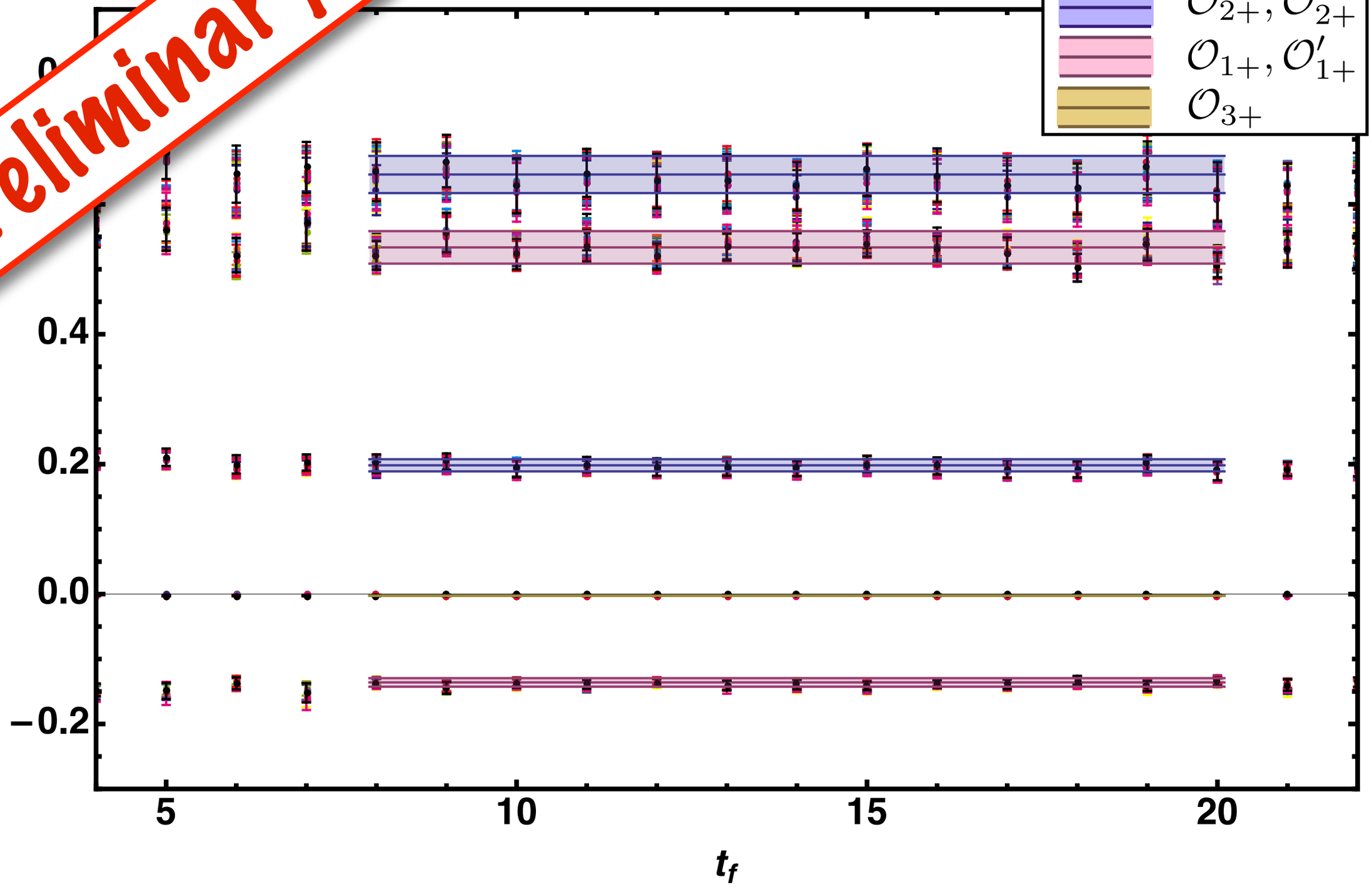






- m_π ~ 135 MeV
- L = 5.76 fm
- a = 0.12 fm

Preliminary!



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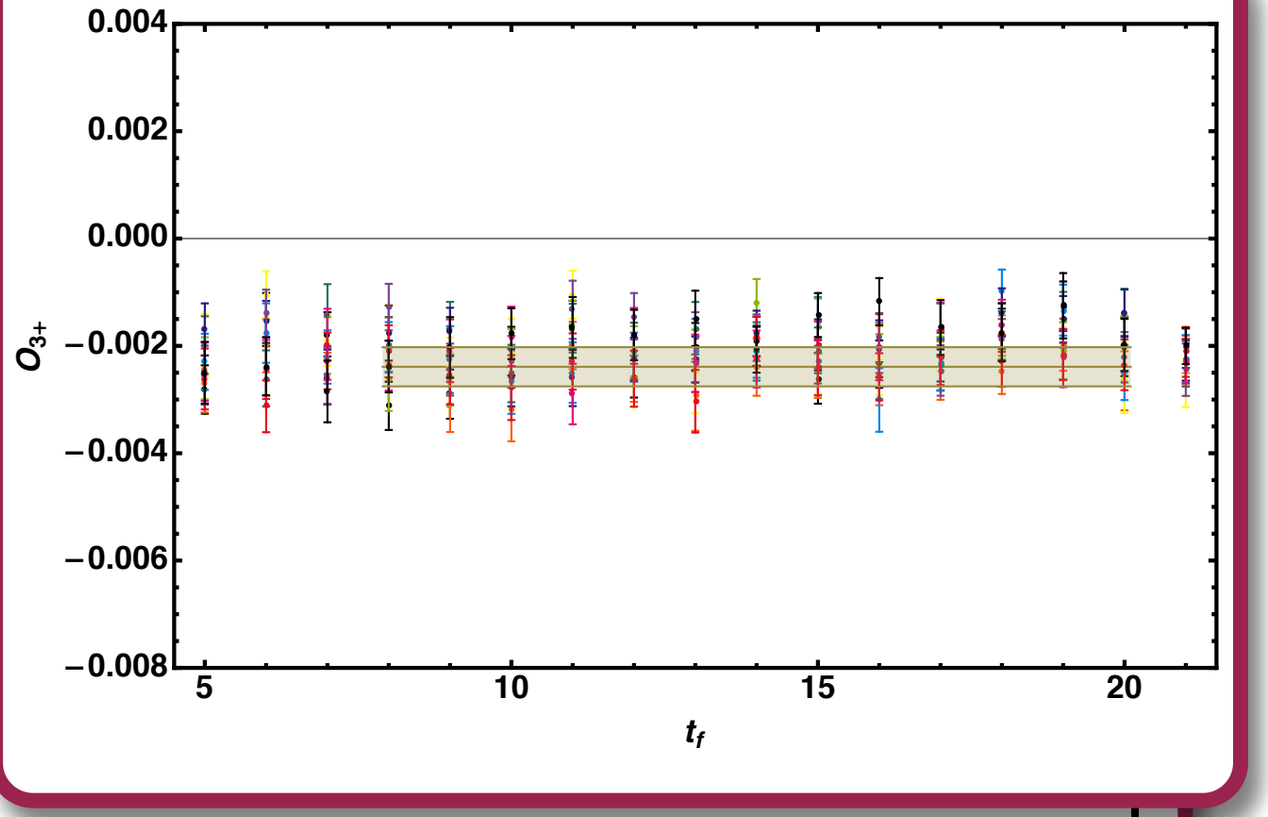

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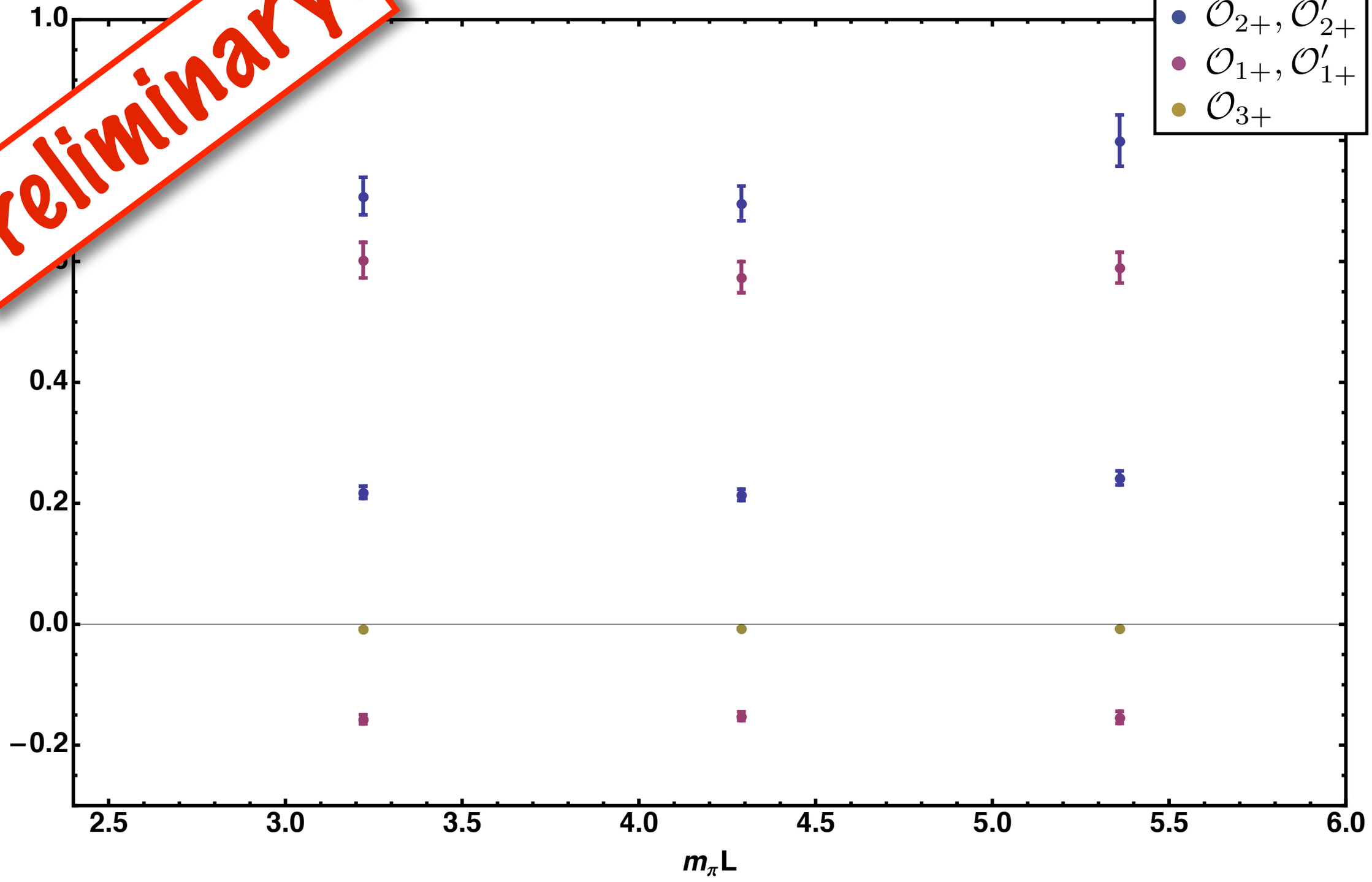
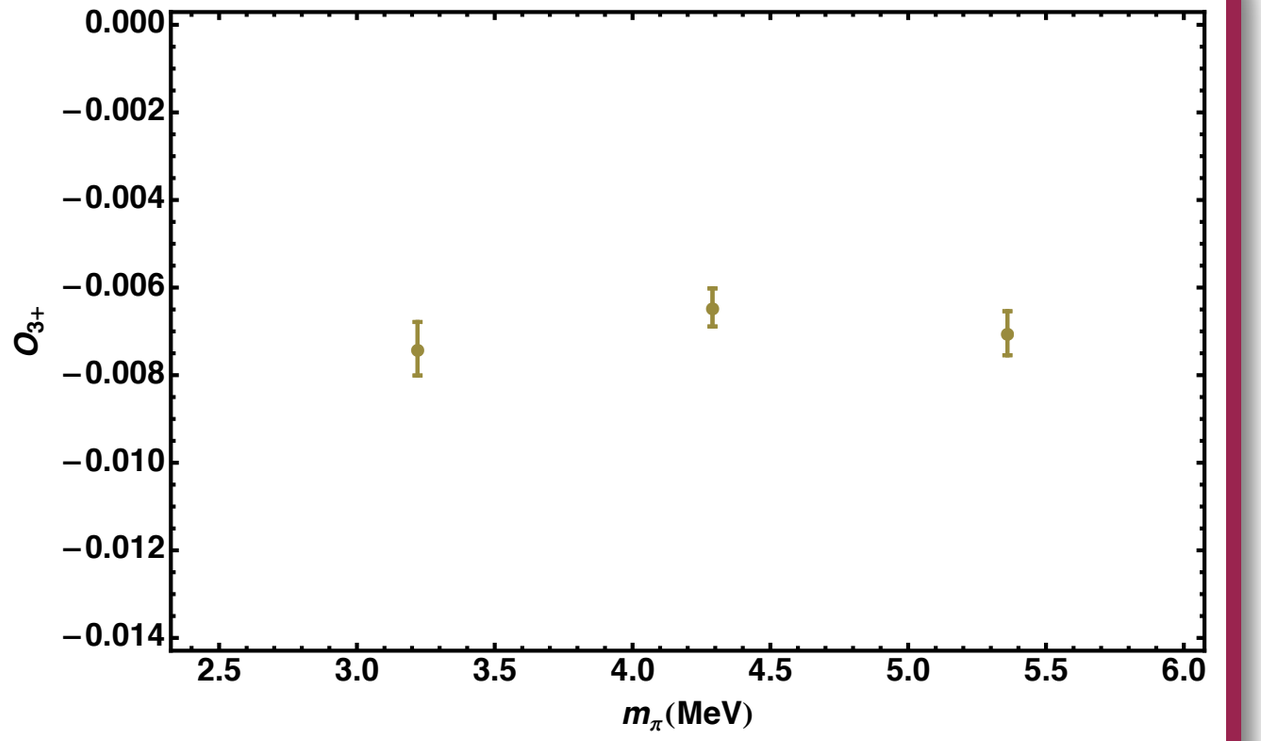


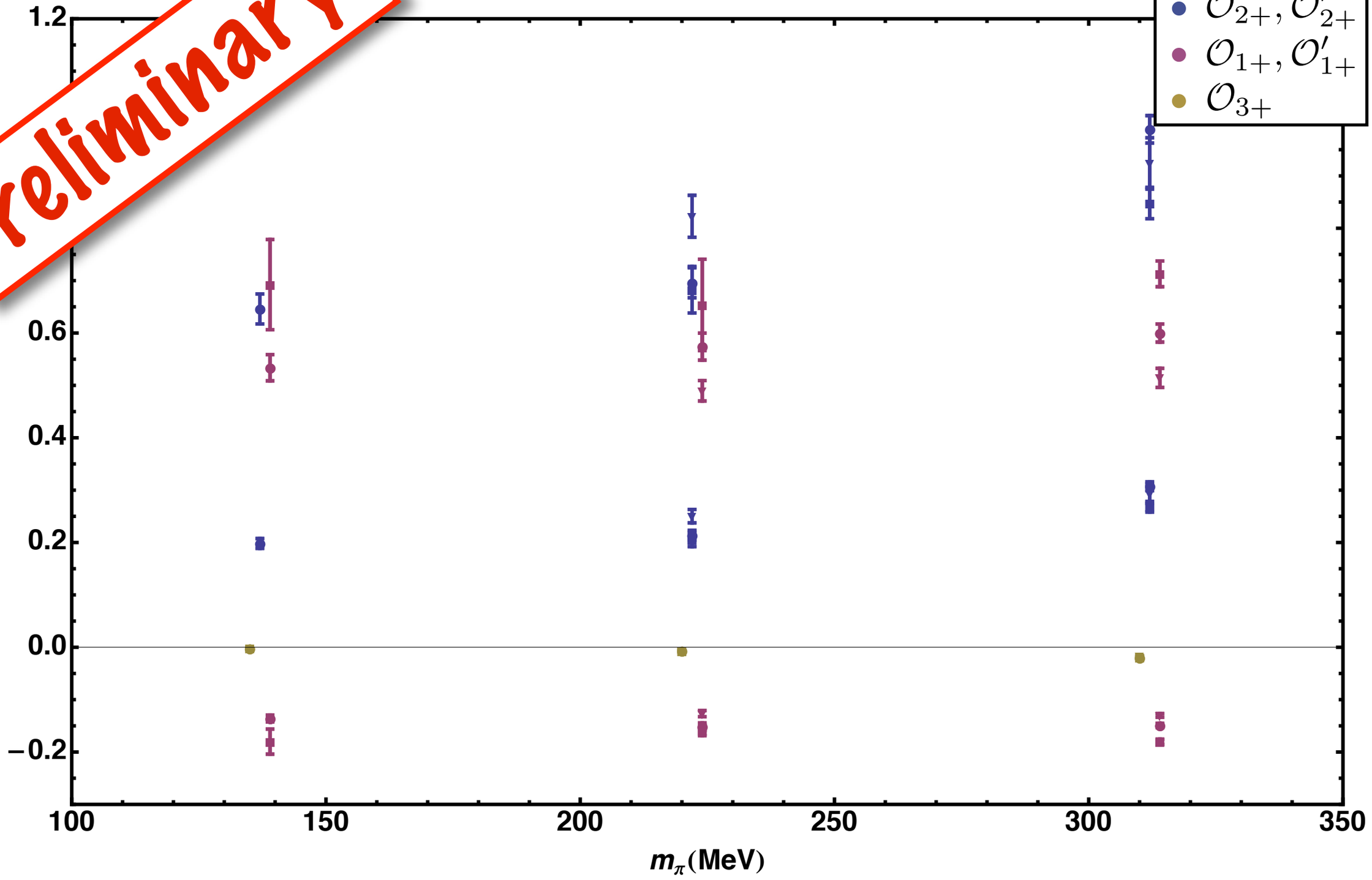
$m_\pi \sim 220$ MeV, $a = 0.12$ fm

Preliminary!

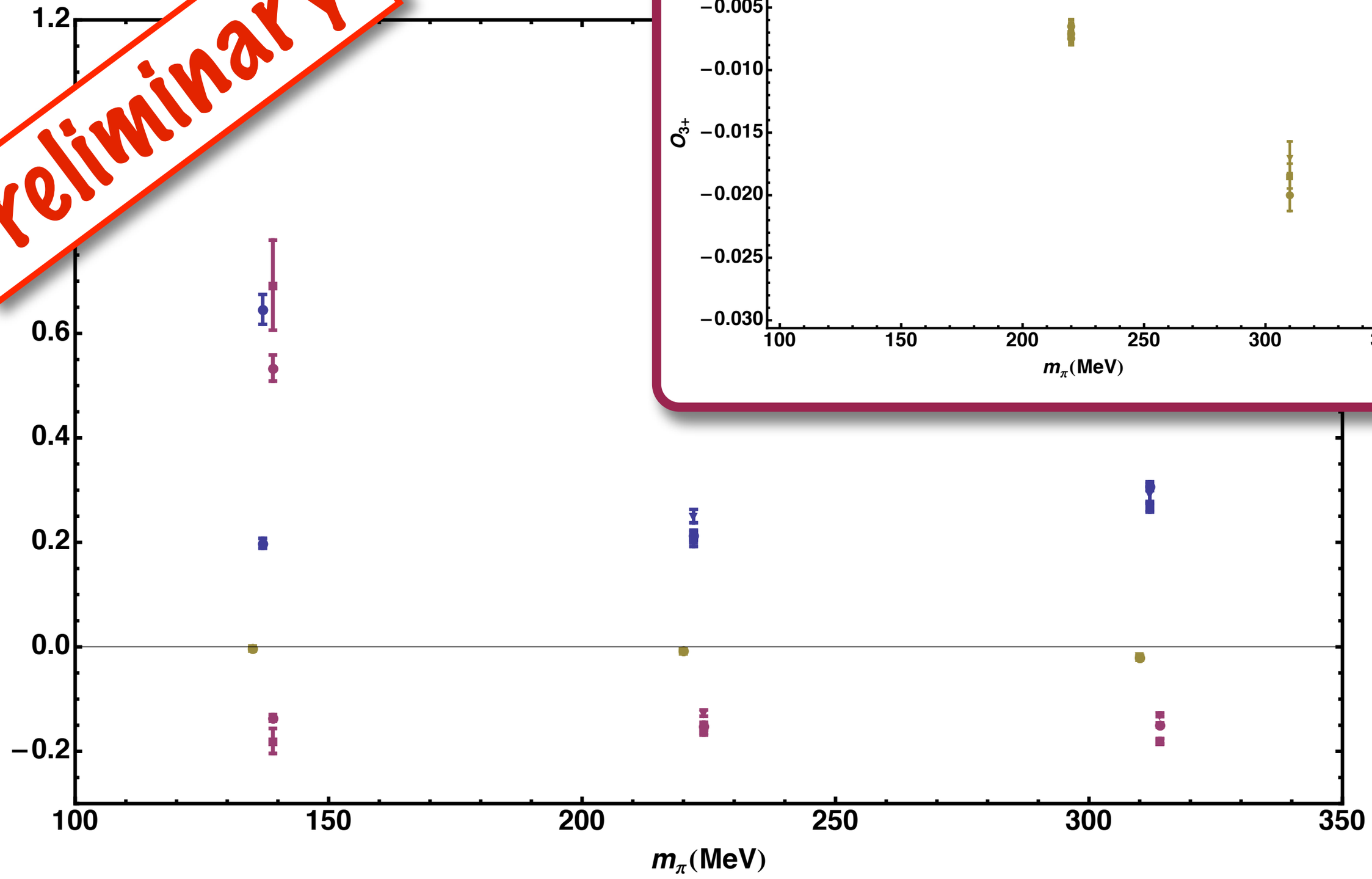


$m_\pi \sim 220$ MeV, $a = 0.12$ fm

Preliminary!

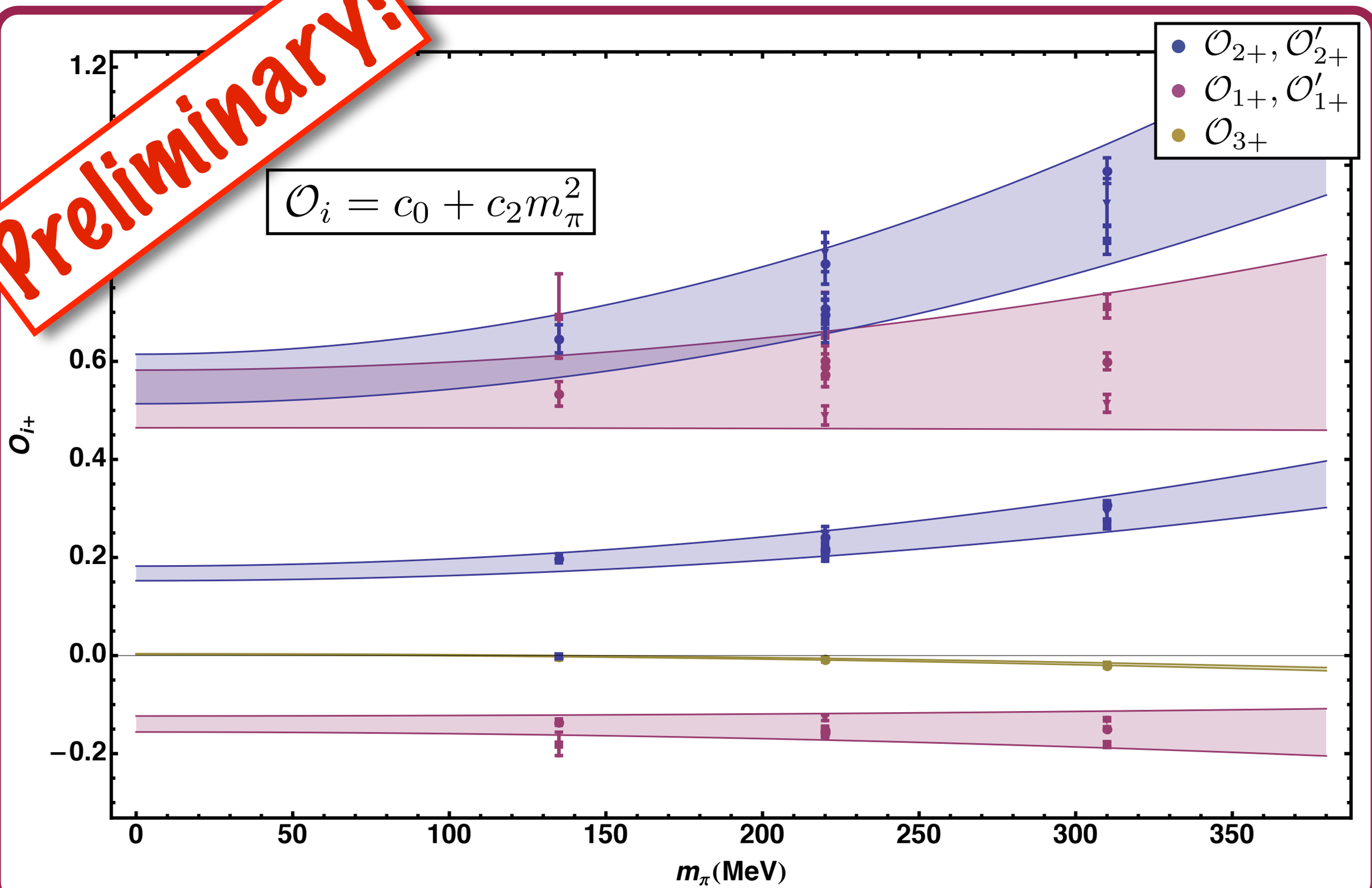


Preliminary!



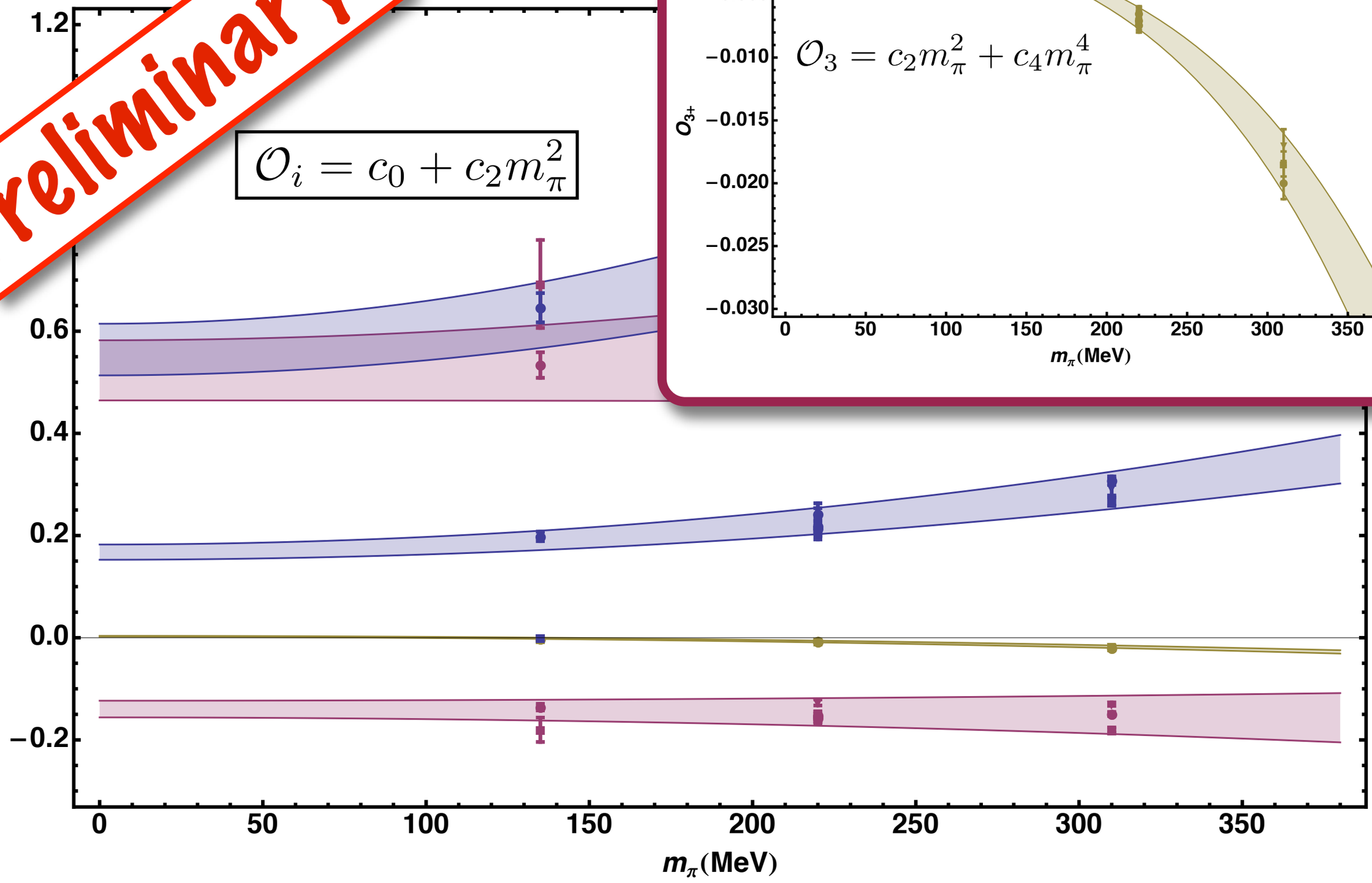
Preliminary!

$$\mathcal{O}_i = c_0 + c_2 m_\pi^2$$



Preliminary!

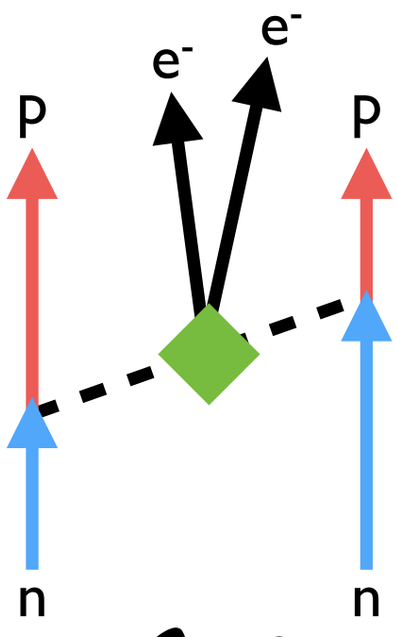
$$\mathcal{O}_i = c_0 + c_2 m_\pi^2$$



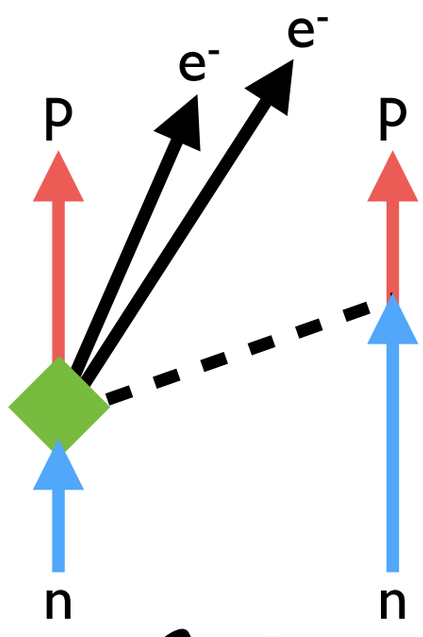
Summary

- $0\nu\beta\beta$: search for Majorana mass signature
  - Lepton number violation could be source of matter/anti-matter asymmetry
  - Huge experimental efforts planned/underway
  - LQCD can make major impact on understanding of short-range operators
- Preliminary results for $\pi^- \to \pi^+$ matrix element
  - Multiple pion masses, lattice spacings, volumes
  - Pion mass dependence as expected from chiral EFT counting
- To do:
  - Renormalization Buras, Misiak, Urban (2000), Tiburzi (2012)
  - Extrapolations in pion mass/lattice spacing
  - Other contact operators....

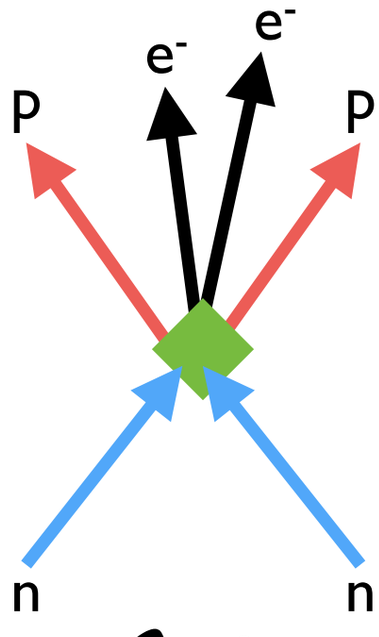
Contact operators



$\mathcal{O}(p^{-2})$



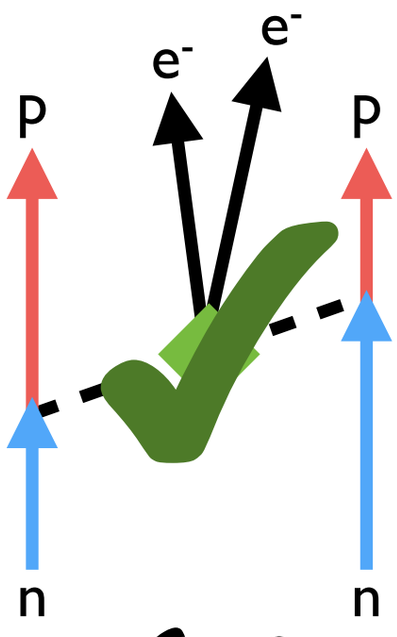
$\mathcal{O}(p^{1})$



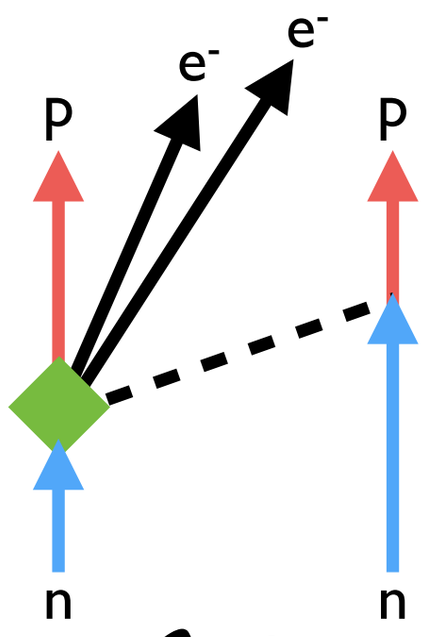
$\mathcal{O}(p^{0})$

Contact operators

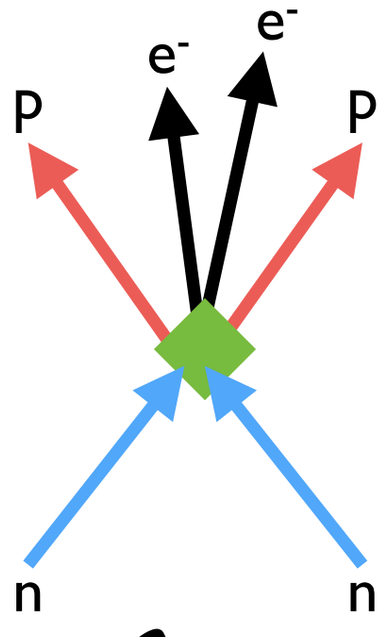
- LO almost complete!



$\mathcal{O}(p^{-2})$



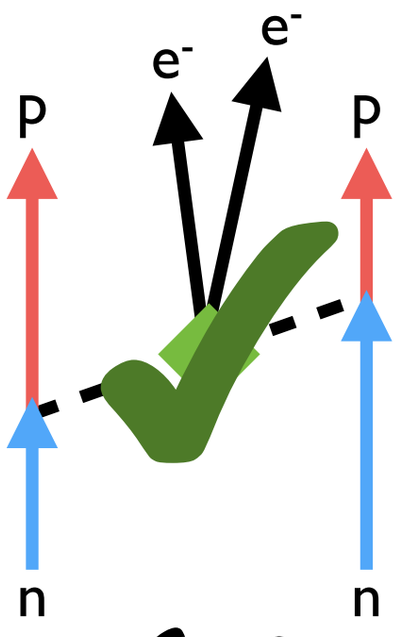
$\mathcal{O}(p^{1})$



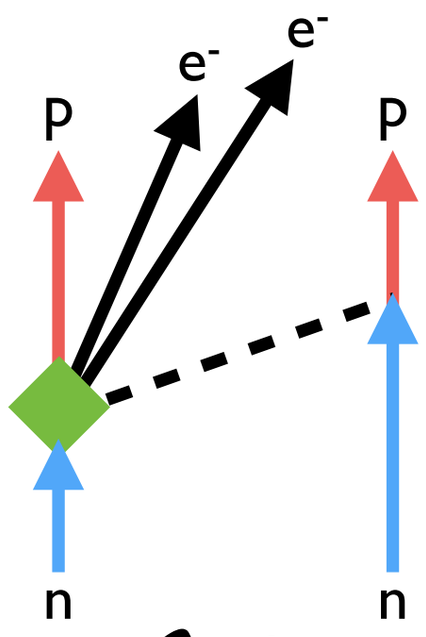
$\mathcal{O}(p^{0})$

Contact operators

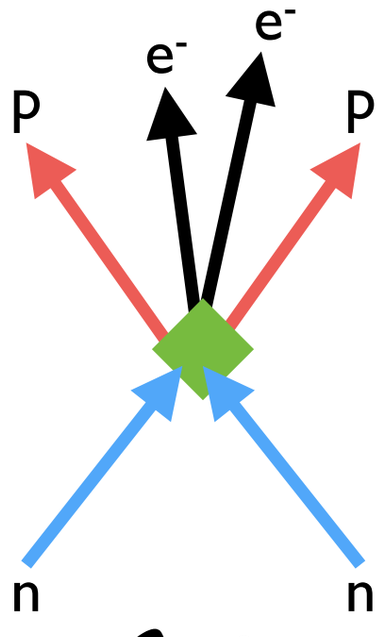
- LO almost complete!
- NLO: disconnected diagrams



$\mathcal{O}(p^{-2})$



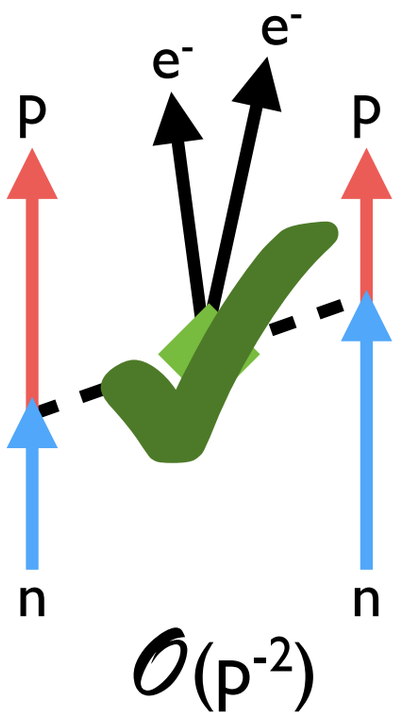
$\mathcal{O}(p^{1})$



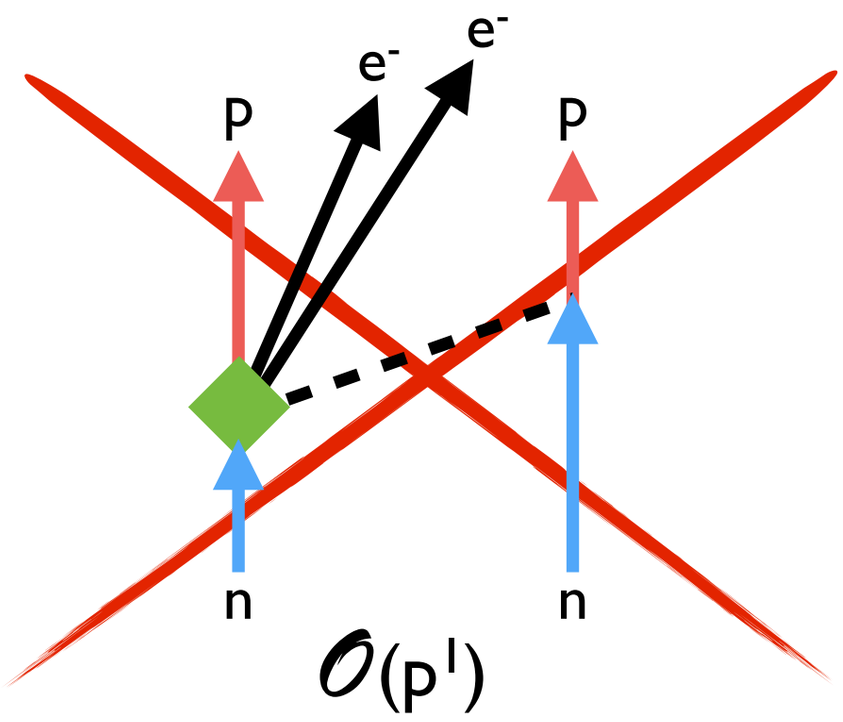
$\mathcal{O}(p^{0})$

Contact operators

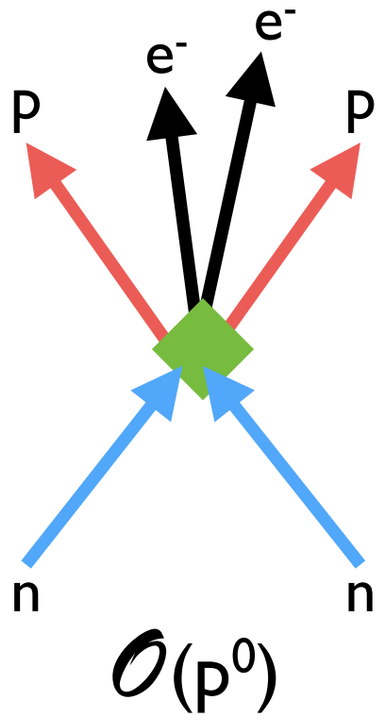
- LO almost complete!
- NLO: disconnected diagrams
  - Don't contribute to $0^+ \rightarrow 0^+$ nuclear transitions



$\mathcal{O}(p^{-2})$



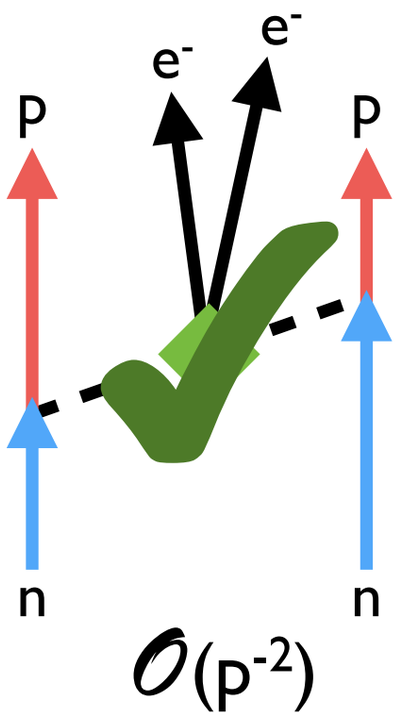
$\mathcal{O}(p^{1})$



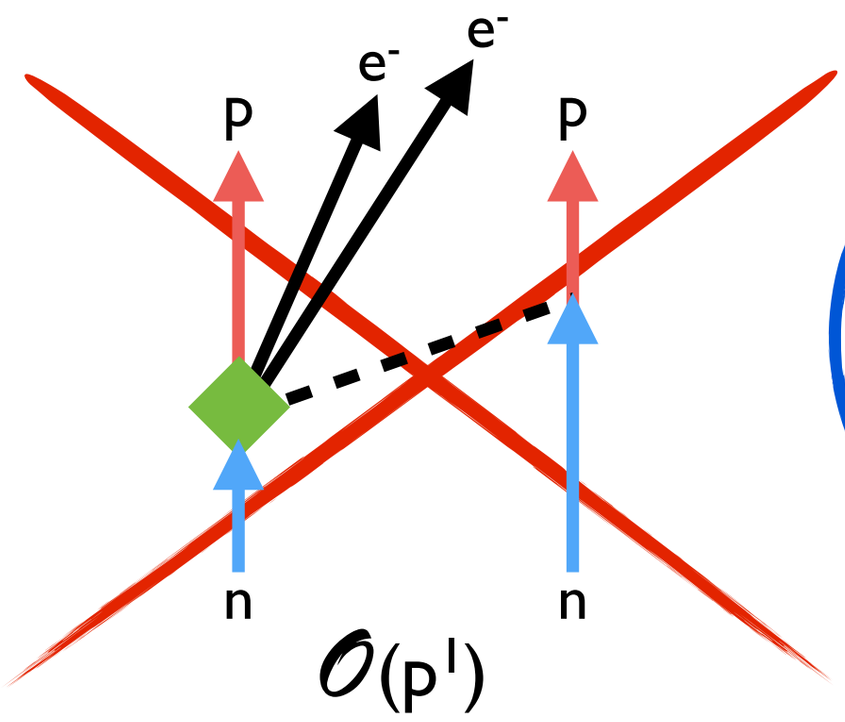
$\mathcal{O}(p^{0})$

Contact operators

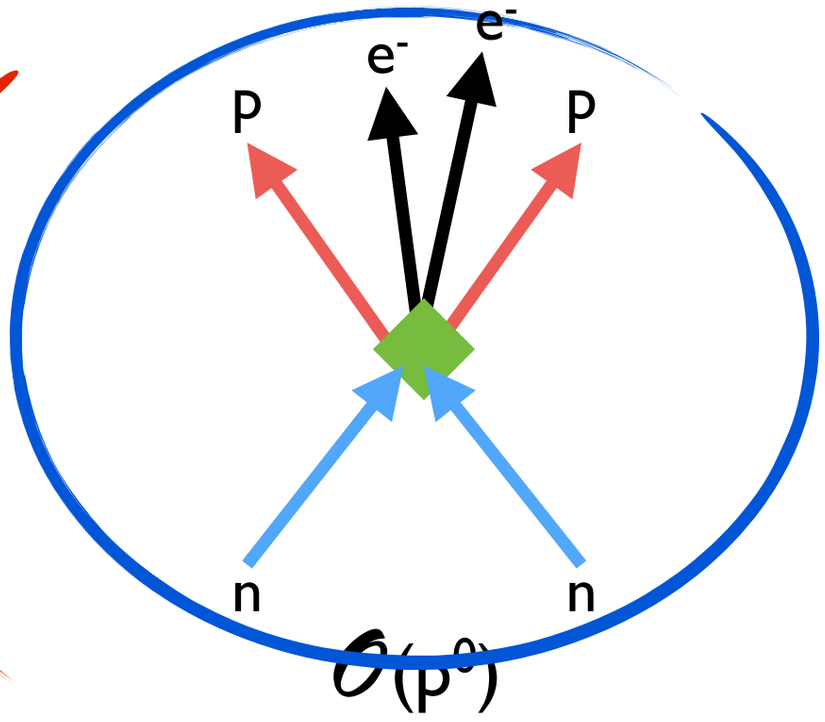
- LO almost complete!
- NLO: disconnected diagrams
  - Don't contribute to $0^+ \rightarrow 0^+$ nuclear transitions
- nn → pp contact operators



$\mathcal{O}(p^{-2})$



$\mathcal{O}(p^{1})$

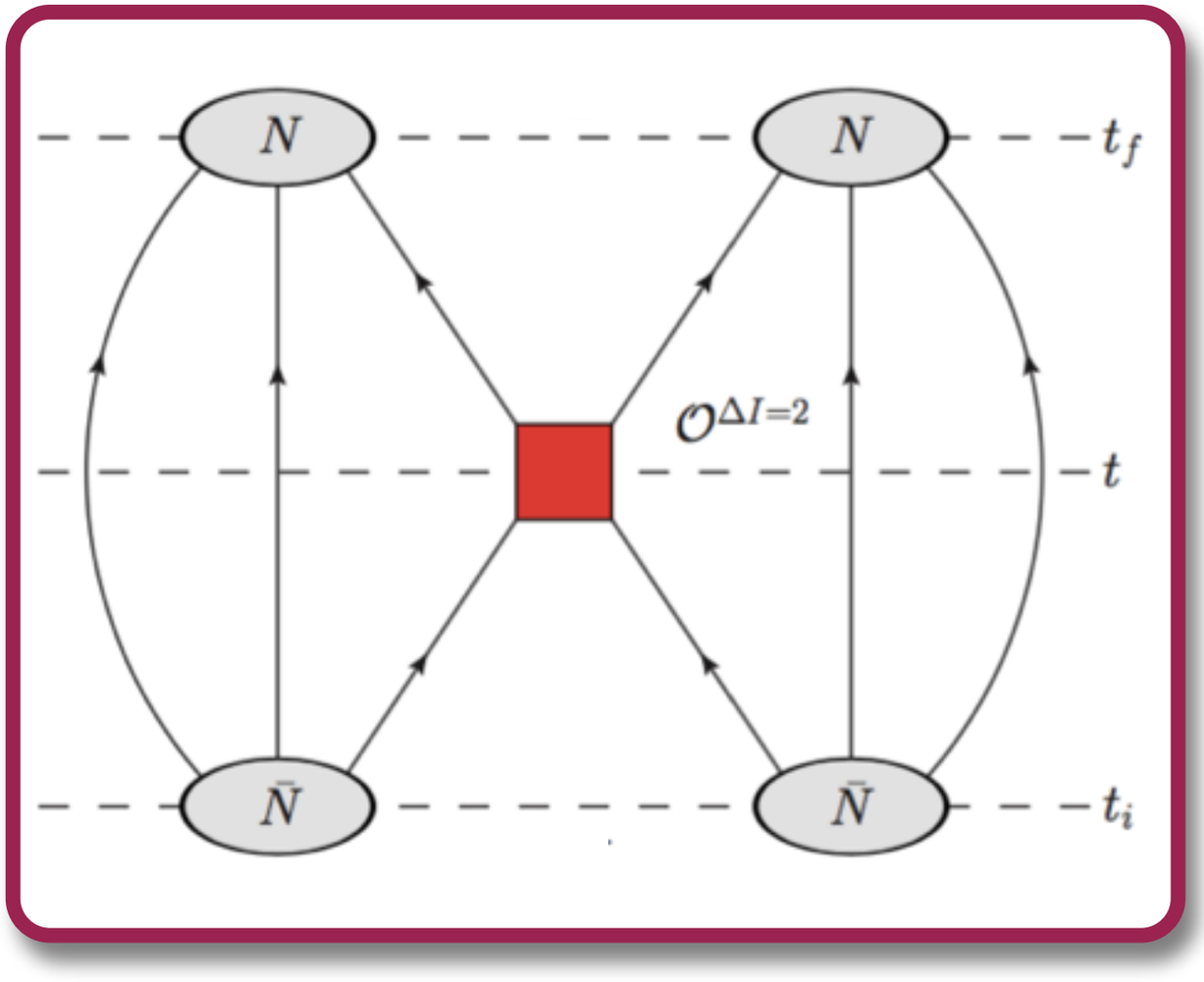


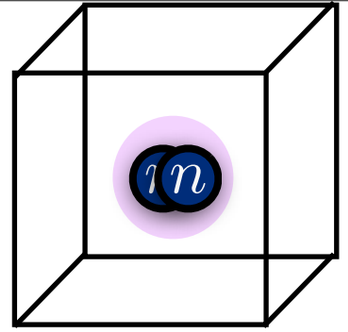
$\mathcal{O}(p^{0})$

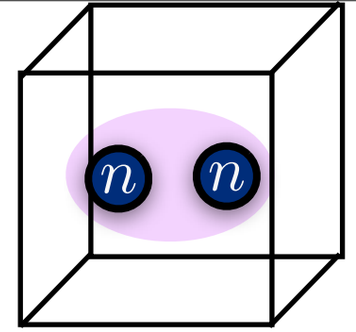
*Doi & Endres, Originos et. al., Günther et. al.

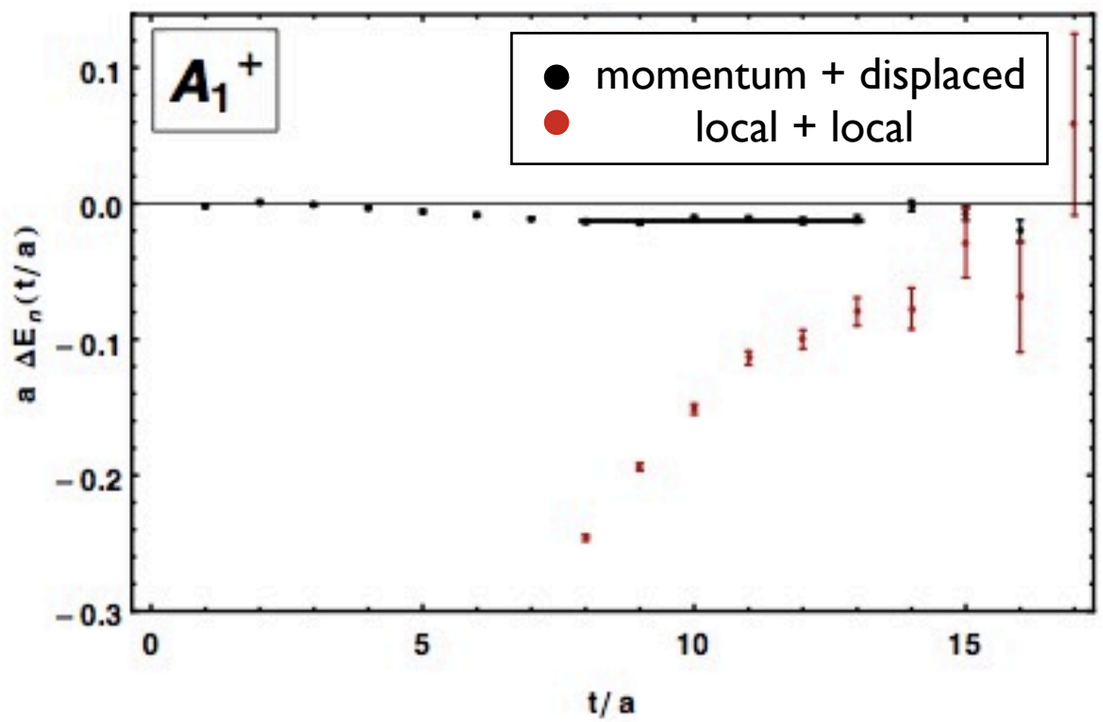
Contractions

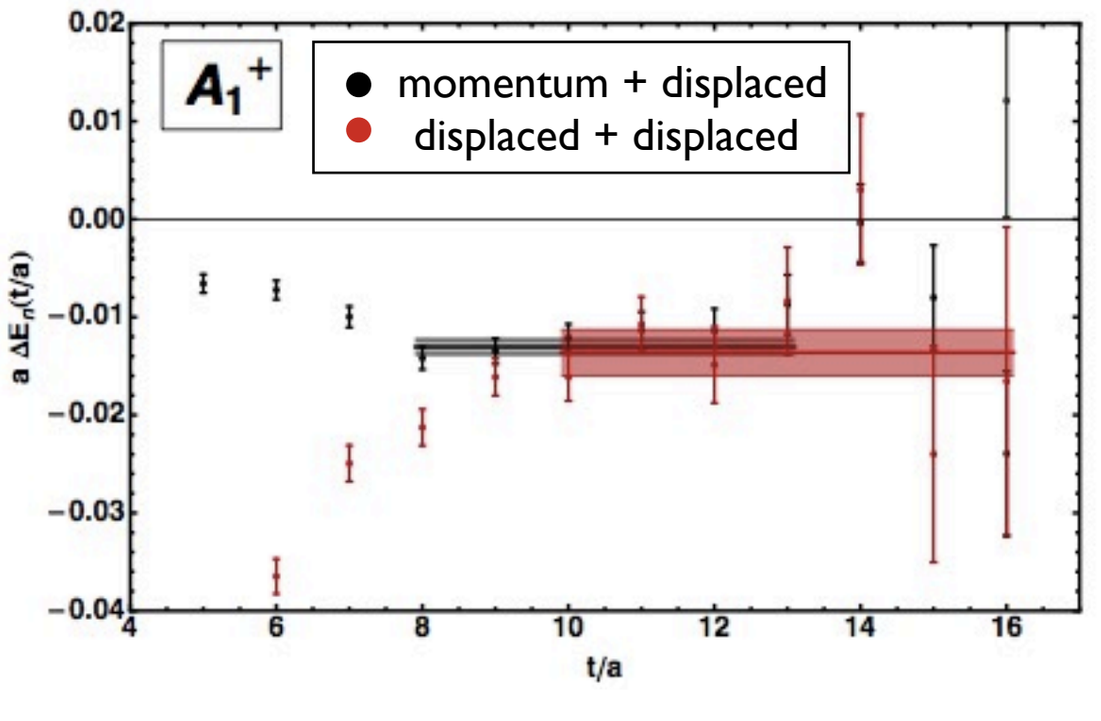
- Isospin limit: 576 contractions*
- Baryon signal-to-noise problem, small excited state energy splittings, ...
- Need position space source & sink
  - otherwise all-to-all propagators connect to 4-quark operator
  - stochastically project onto zero total momentum



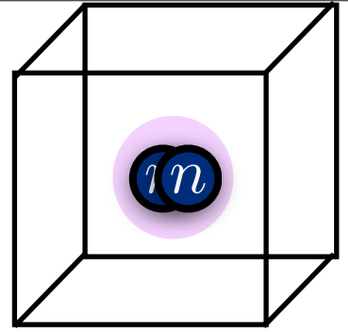


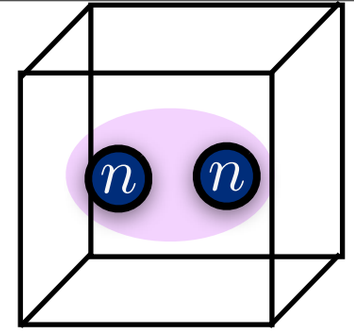


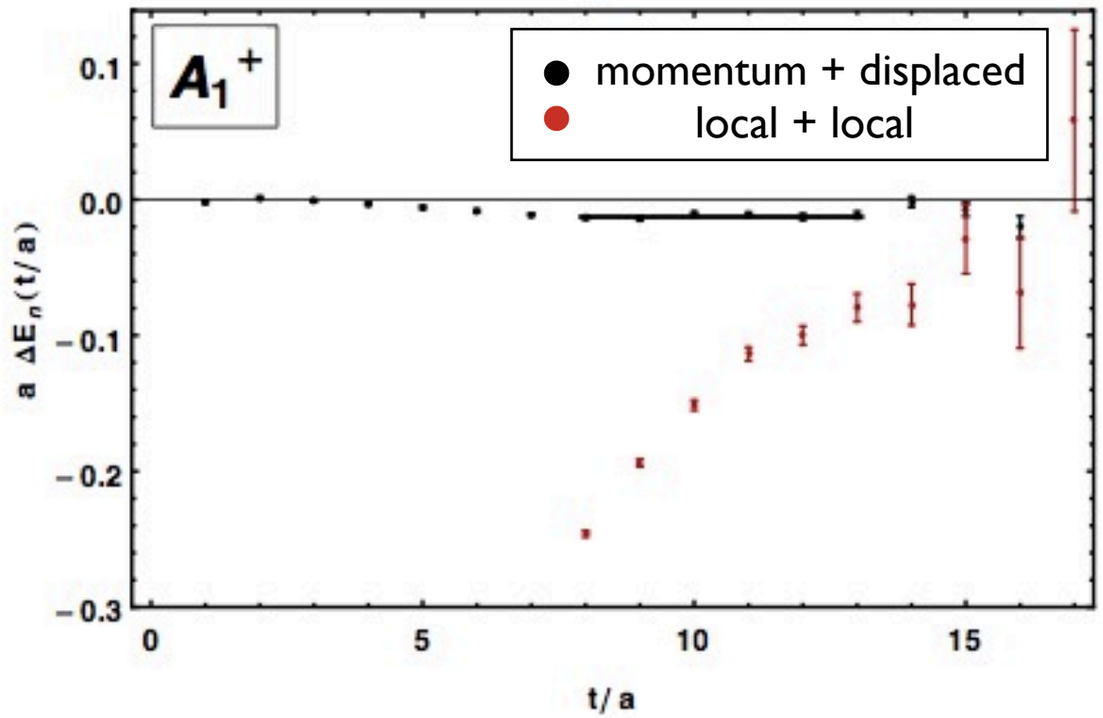


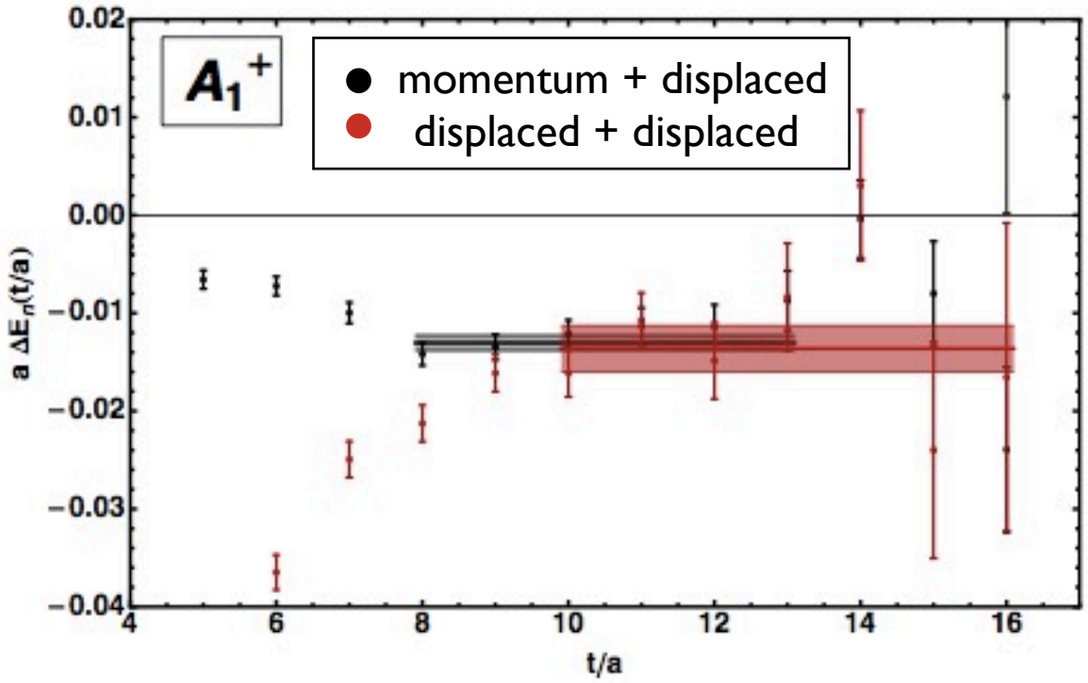


Iso-clover cfgs (W. Detmold, R.Edwards, D. Richards, K. Orginos)





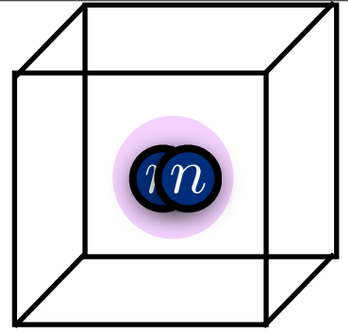


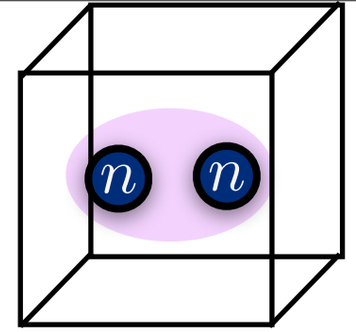


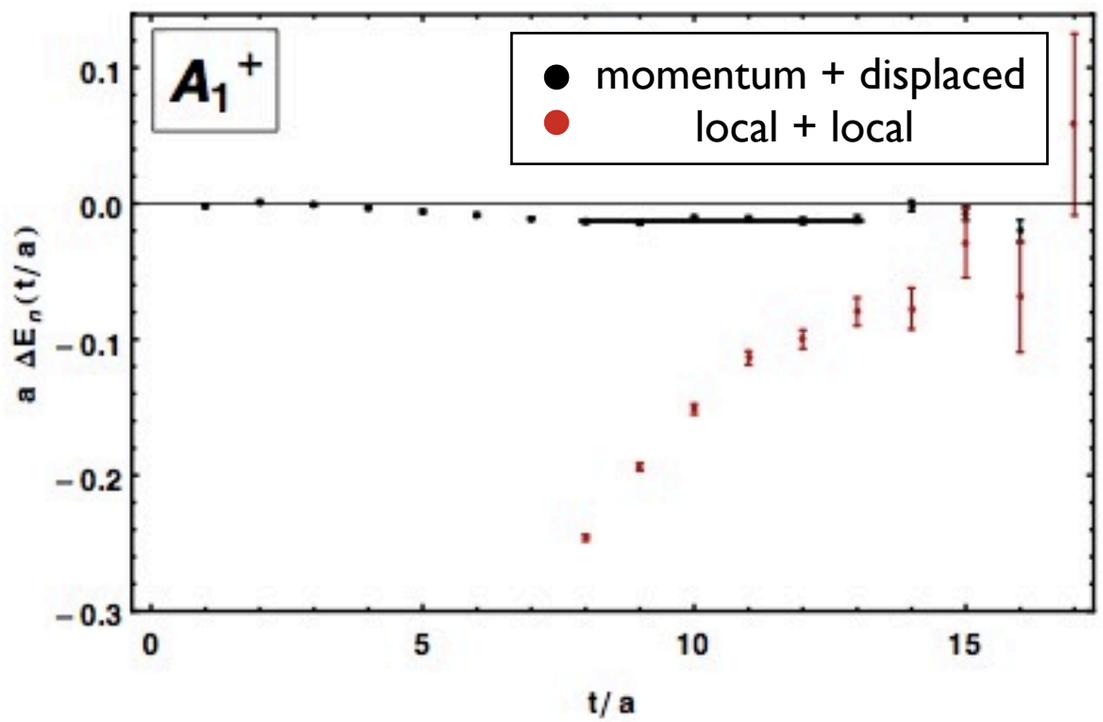
Need displaced operators!

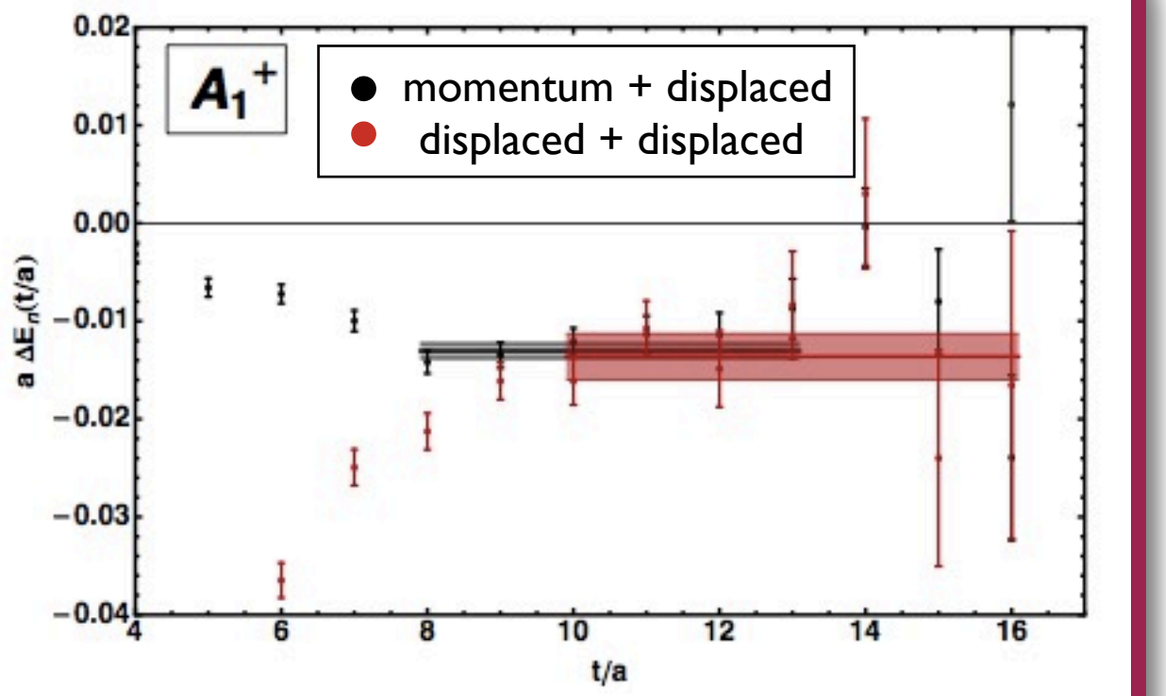
E. Berkowitz, T. Kurth, A.N., B. Joo, E. Rinaldi, M. Strother, P.Vranas, A. Walker-Loud arXiv:1508.00886 (2015)

Iso-clover cfgs (W. Detmold, R.Edwards, D. Richards, K. Orginos)

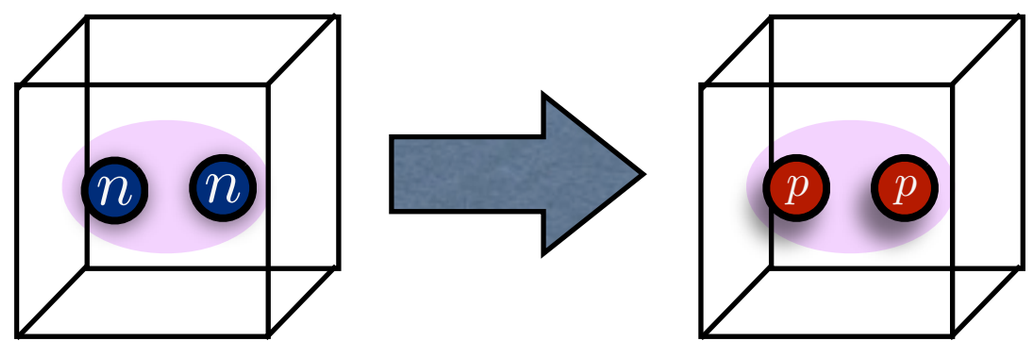








Finite volume formalism for 2 → 2 matrix elements completed:
R. Briceño, M. Hansen Phys.Rev. D94 (2016) no.1, 013008
Renormalization known in $\overline{\text{MS}}$:
B. Tiburzi Phys.Rev. D86 (2012) 097501



Stay tuned!

- LBL/UCB: Chia Cheng Chang, AN, André Walker-Loud,
- LLNL: Evan Berkowitz, Enrico Rinaldi, Pavlos Vranas
- NERSC: Thorsten Kurth
- JLab: Balint Jóo
- CCNY: Brian Tiburzi
- nVidia: Kate Clark