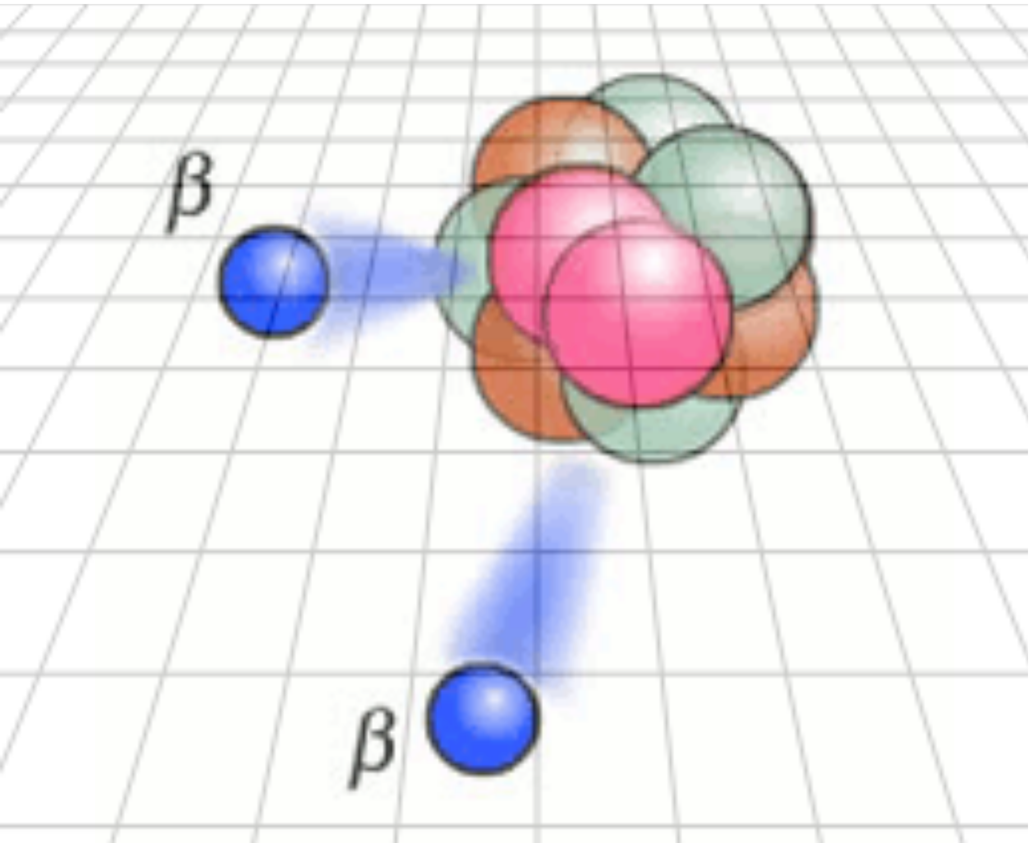
Neutrinoless Double Beta Decay from Lattice QCD

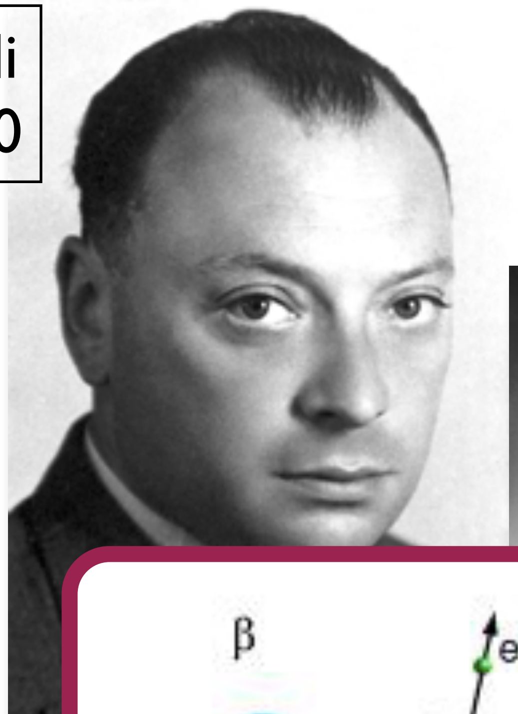


Amy Nicholson
UC Berkeley

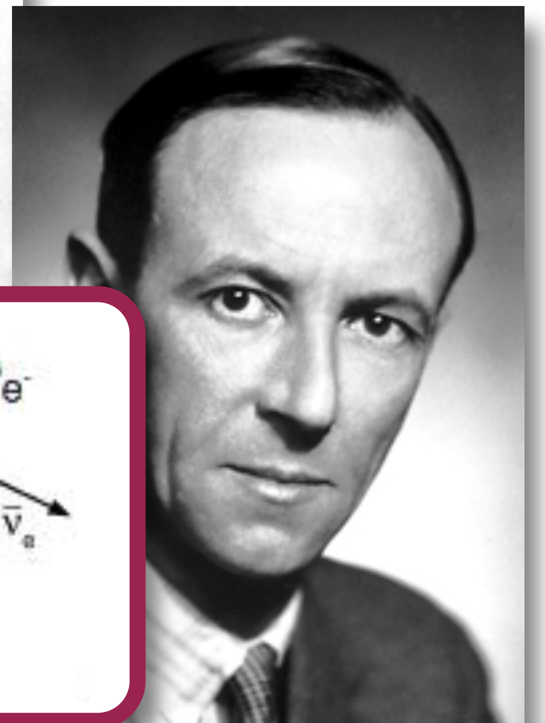
Lattice 2016
Southampton, UK

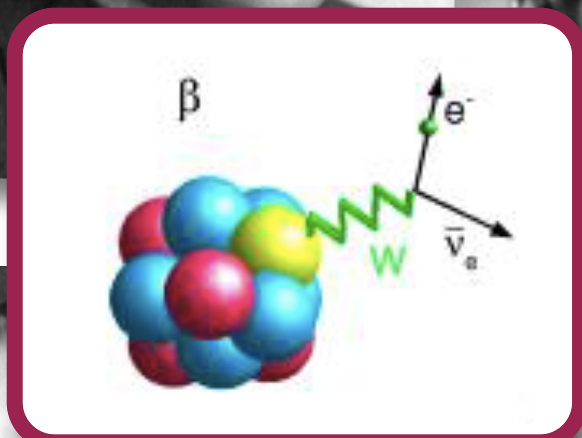
History

Pauli
1930

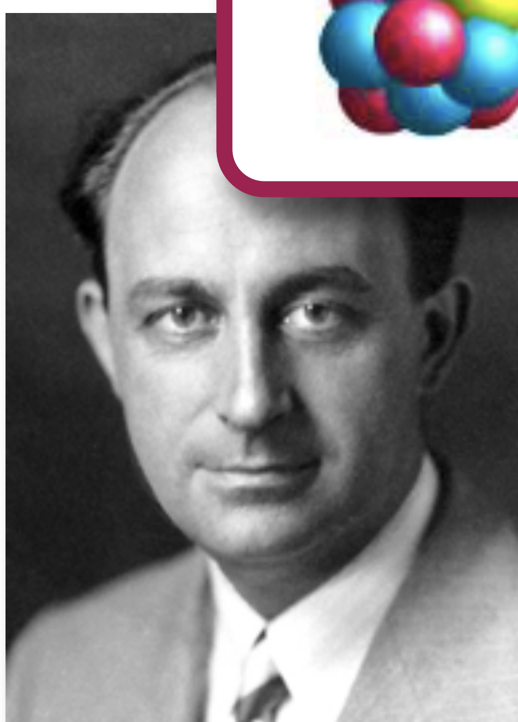


Chadwick
1932

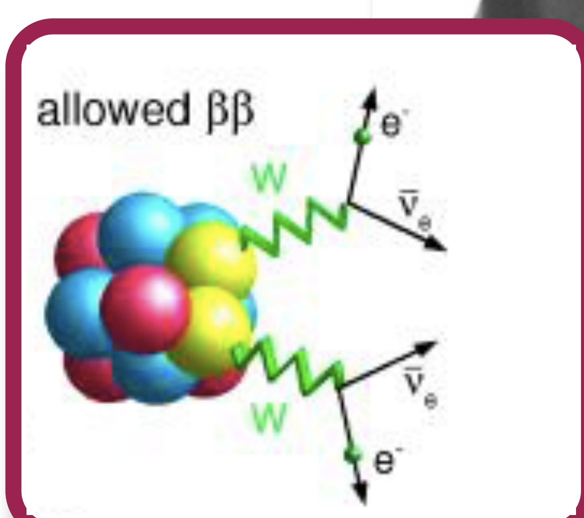




Fermi
1934

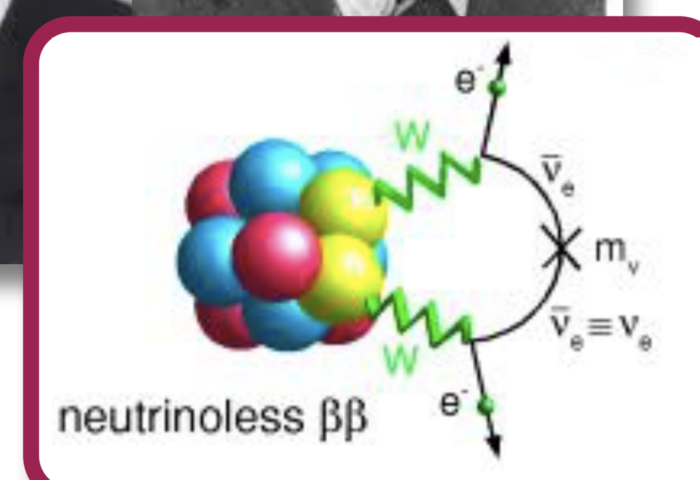


Goppert-Mayer
1935



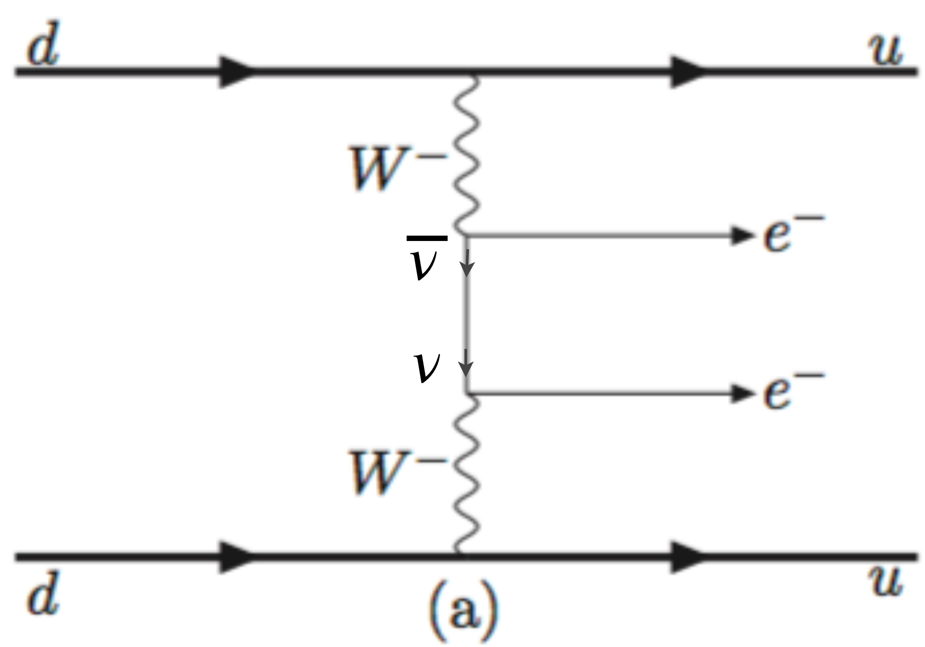
Majorana
1937

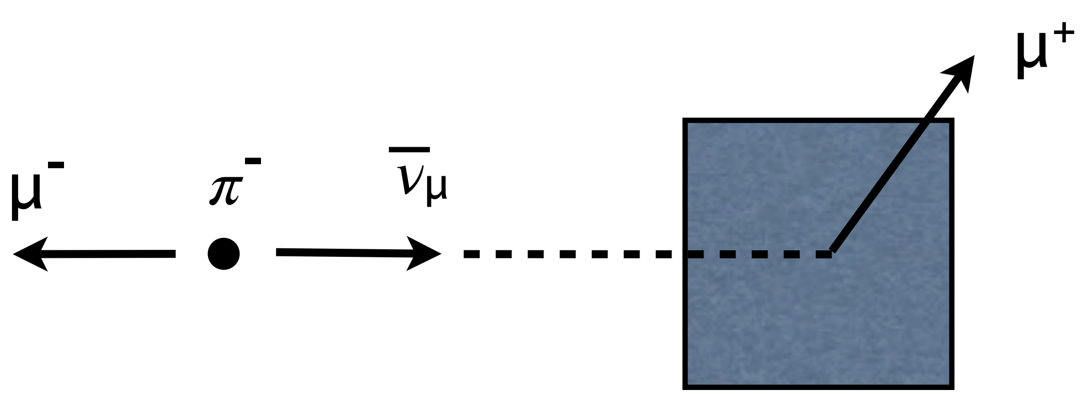
Racah
1937

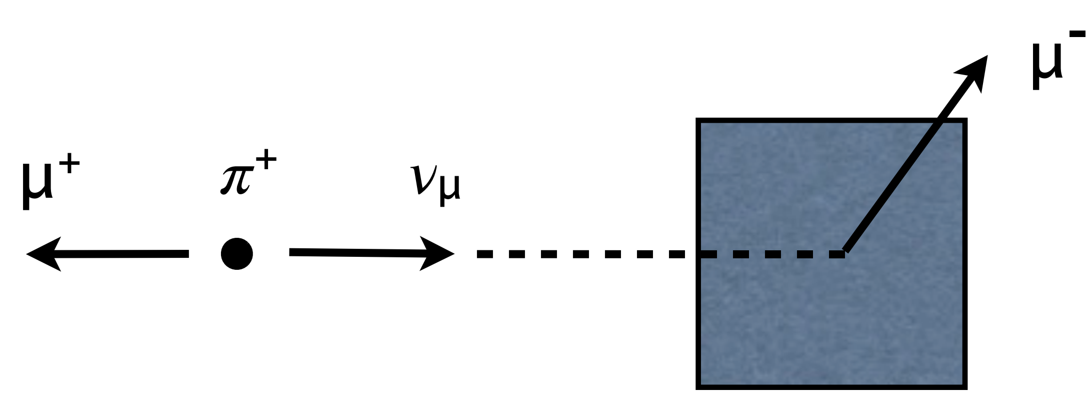


Lepton Number

Neutrinos have no known charge or other additively conserved quantum number







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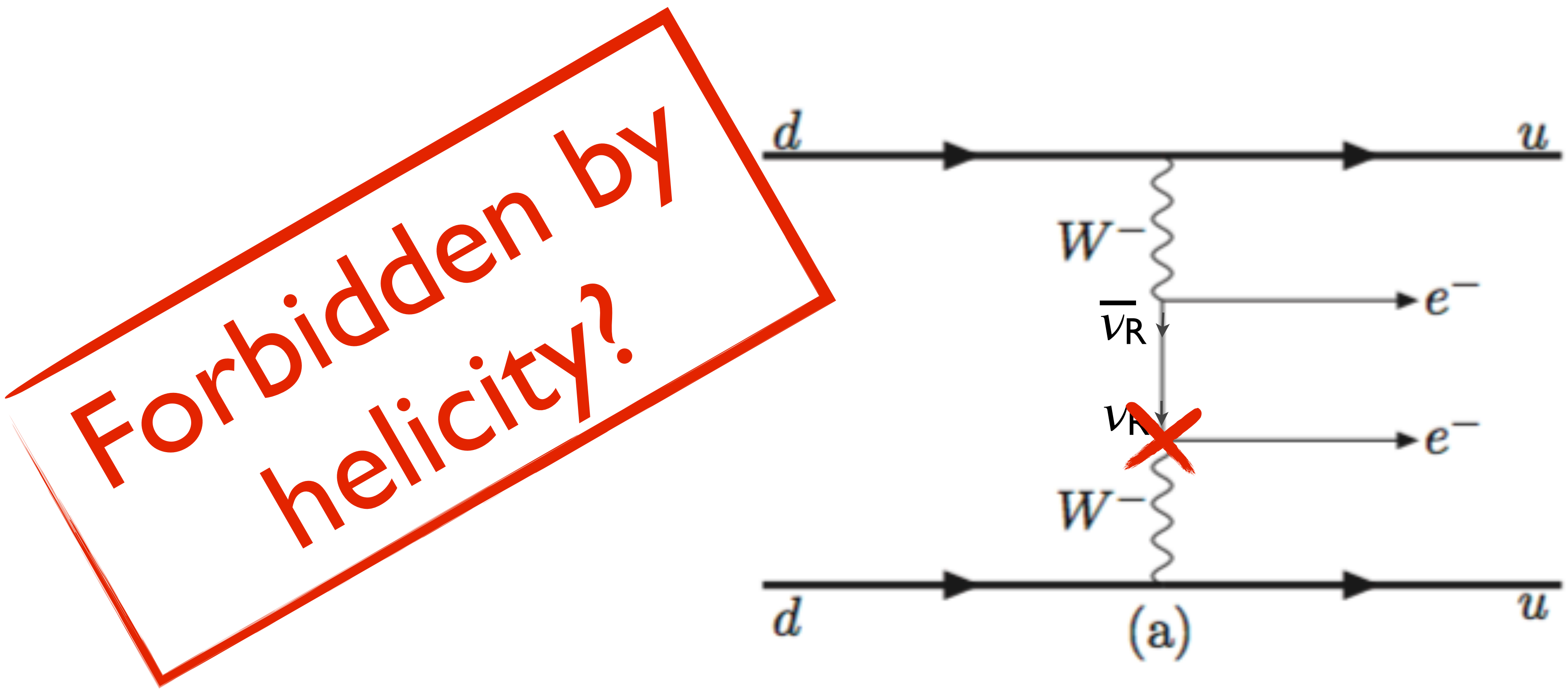
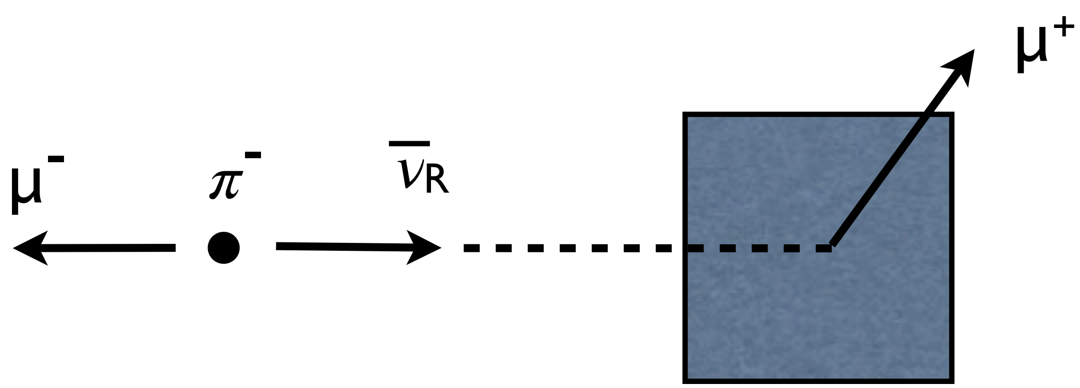
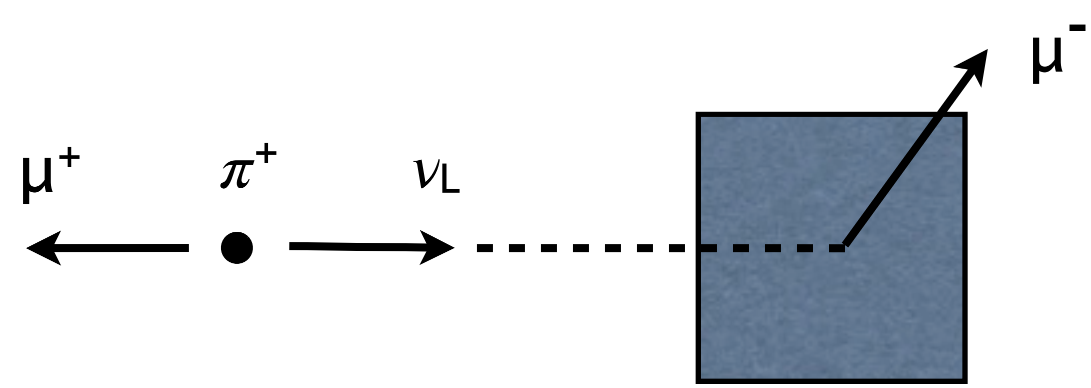
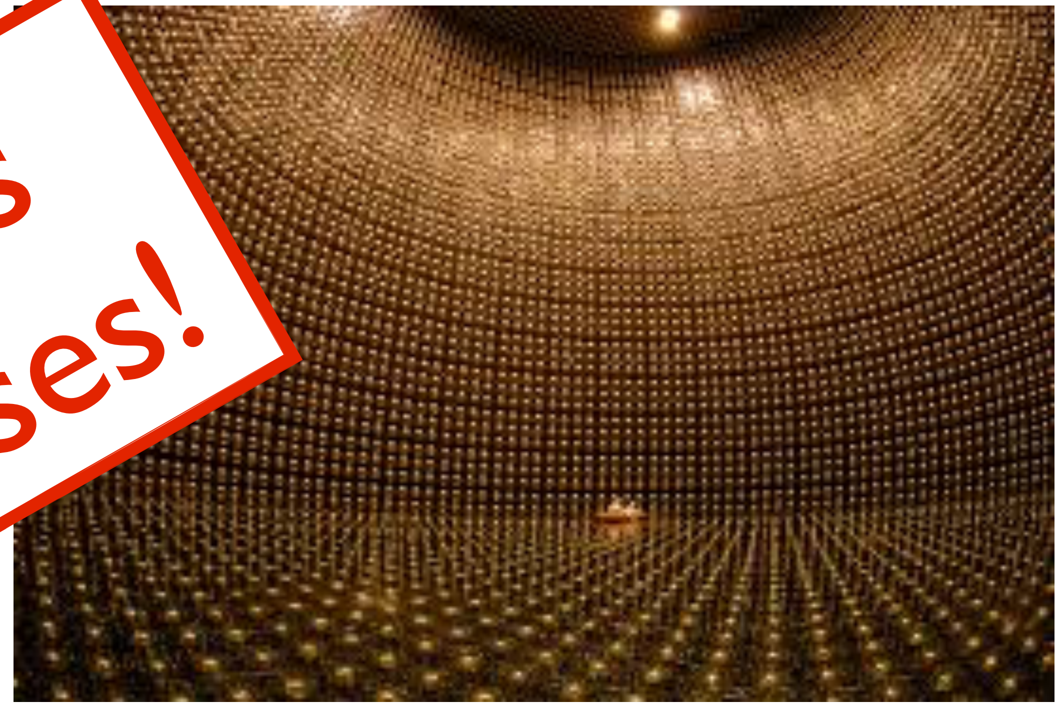
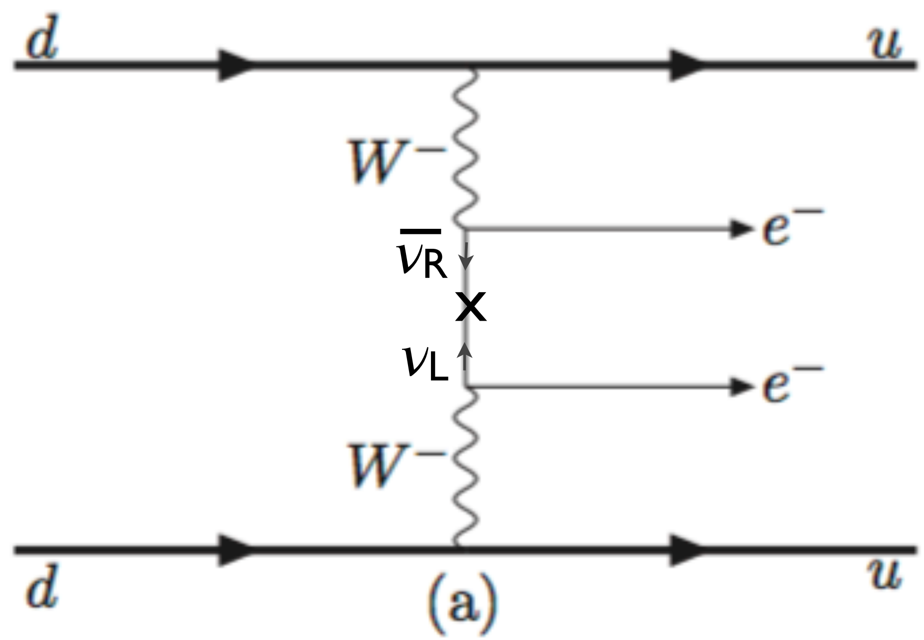


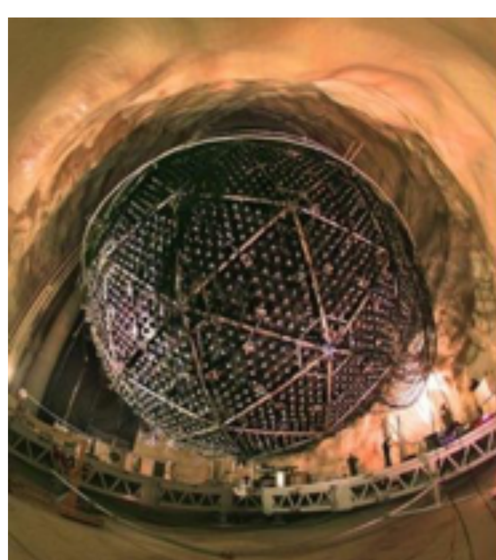


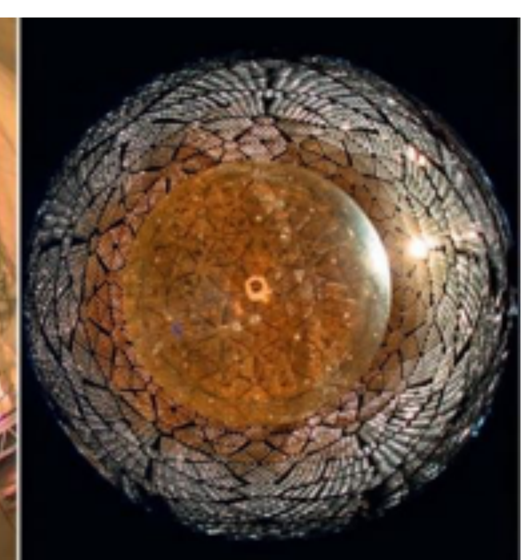


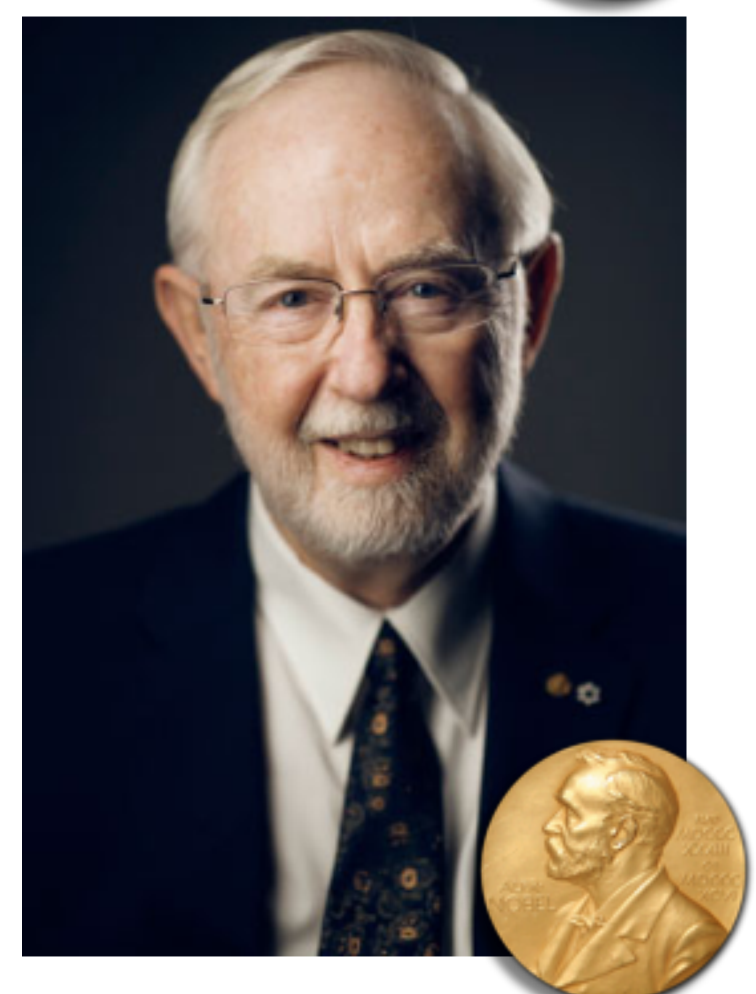
Neutrinos have masses!









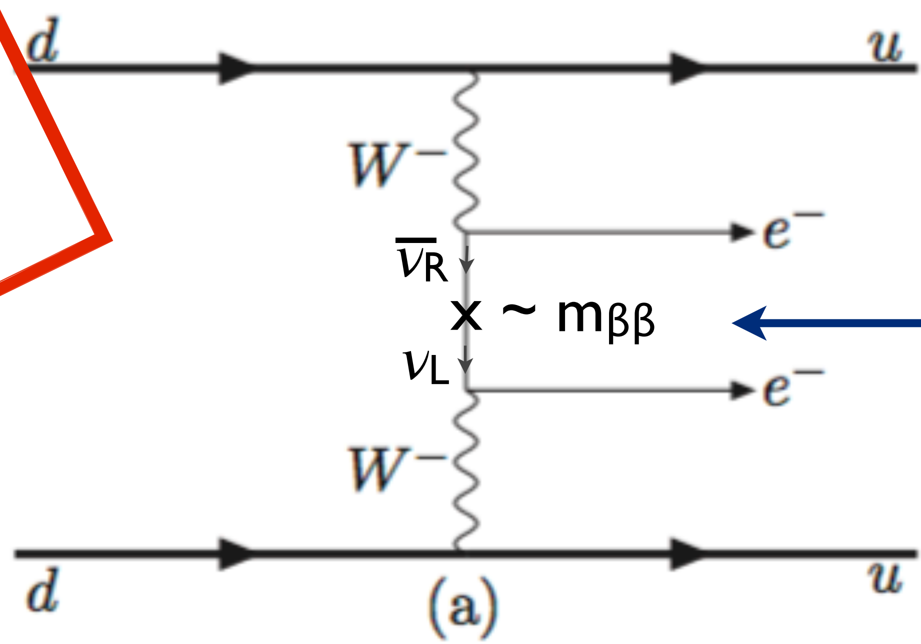


Takaaki Kajita (Super-K)
Arthur B. McDonald (SNO)
Nobel Prize, 2015

Lepton Number

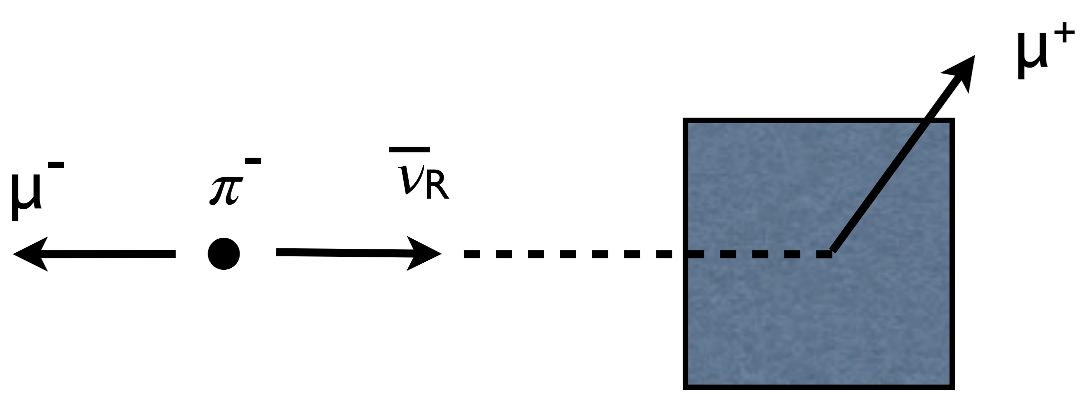
Neutrinos have no known charge or other additively conserved quantum number

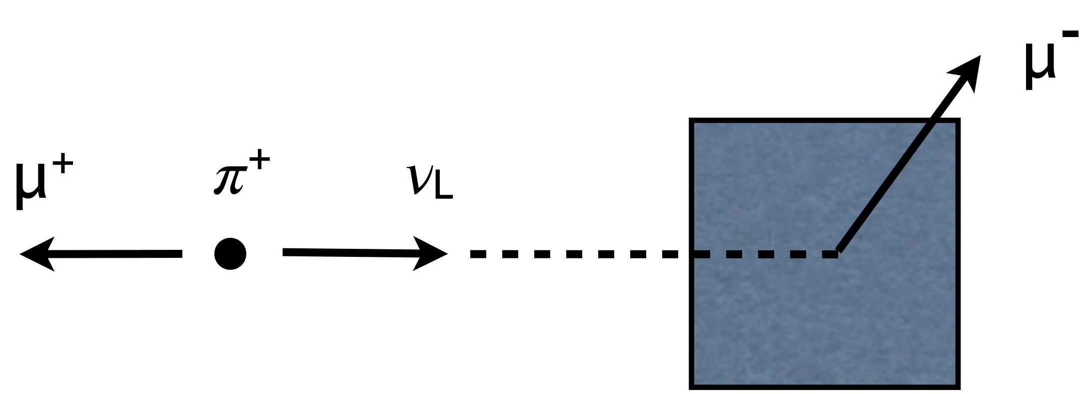
But they're tiny!



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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dim-4 operator not allowed

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

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

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

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

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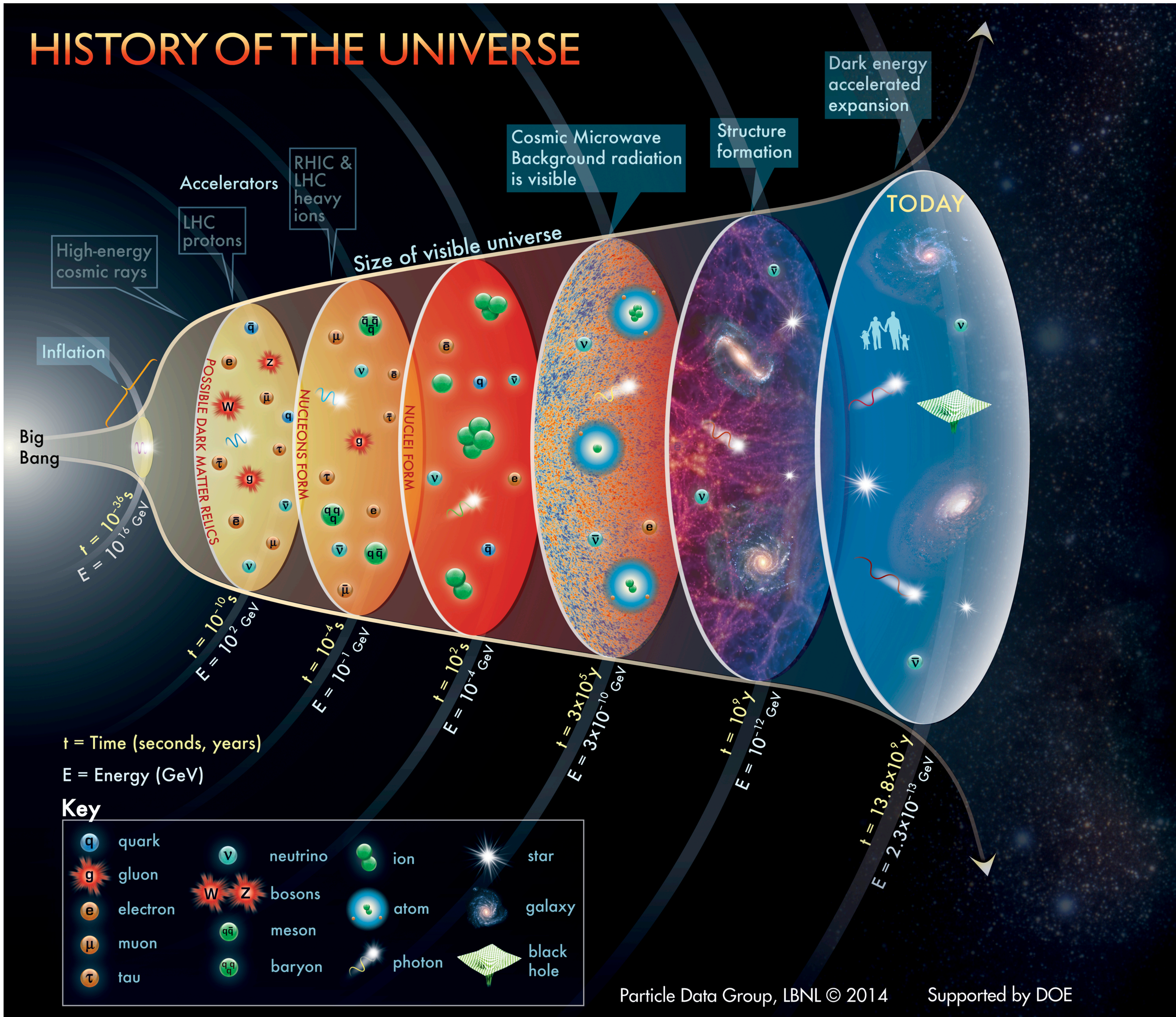
$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

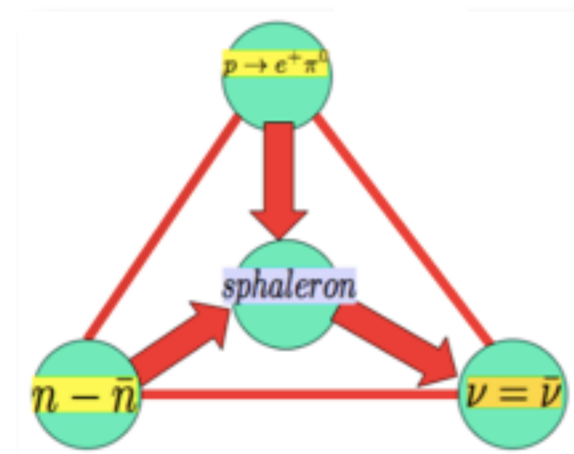
$$m_l \sim M_D^2/M_R \quad m_h \sim M_R$$

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

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

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

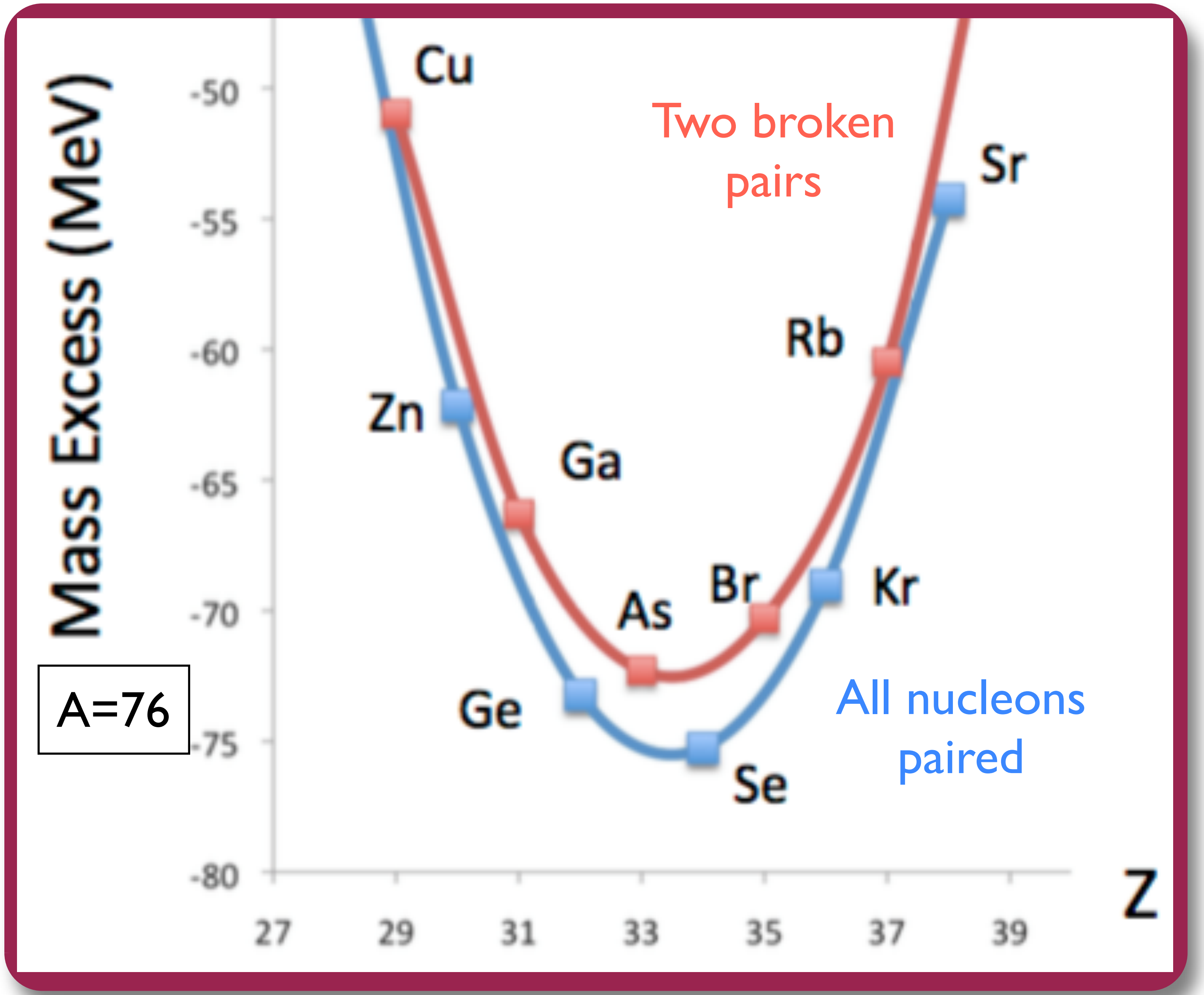




Jansen (1996)
Bödeker, Moore, Rummukainen (2000)
Fodor (2000)

Experiment

Nuclear physics gives us a natural filter for the process



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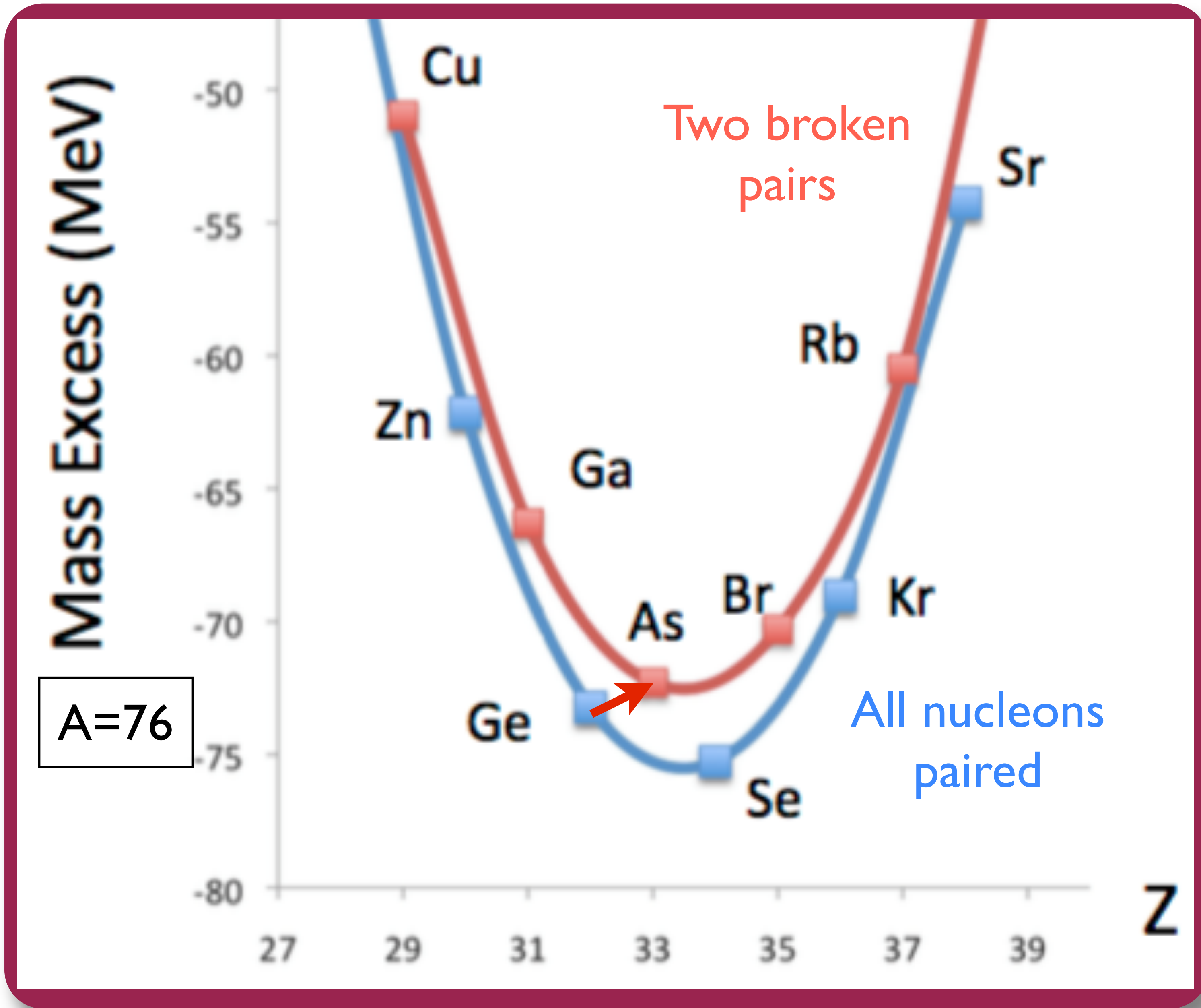
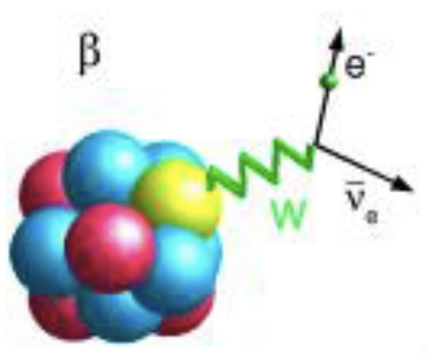


Energetically forbidden



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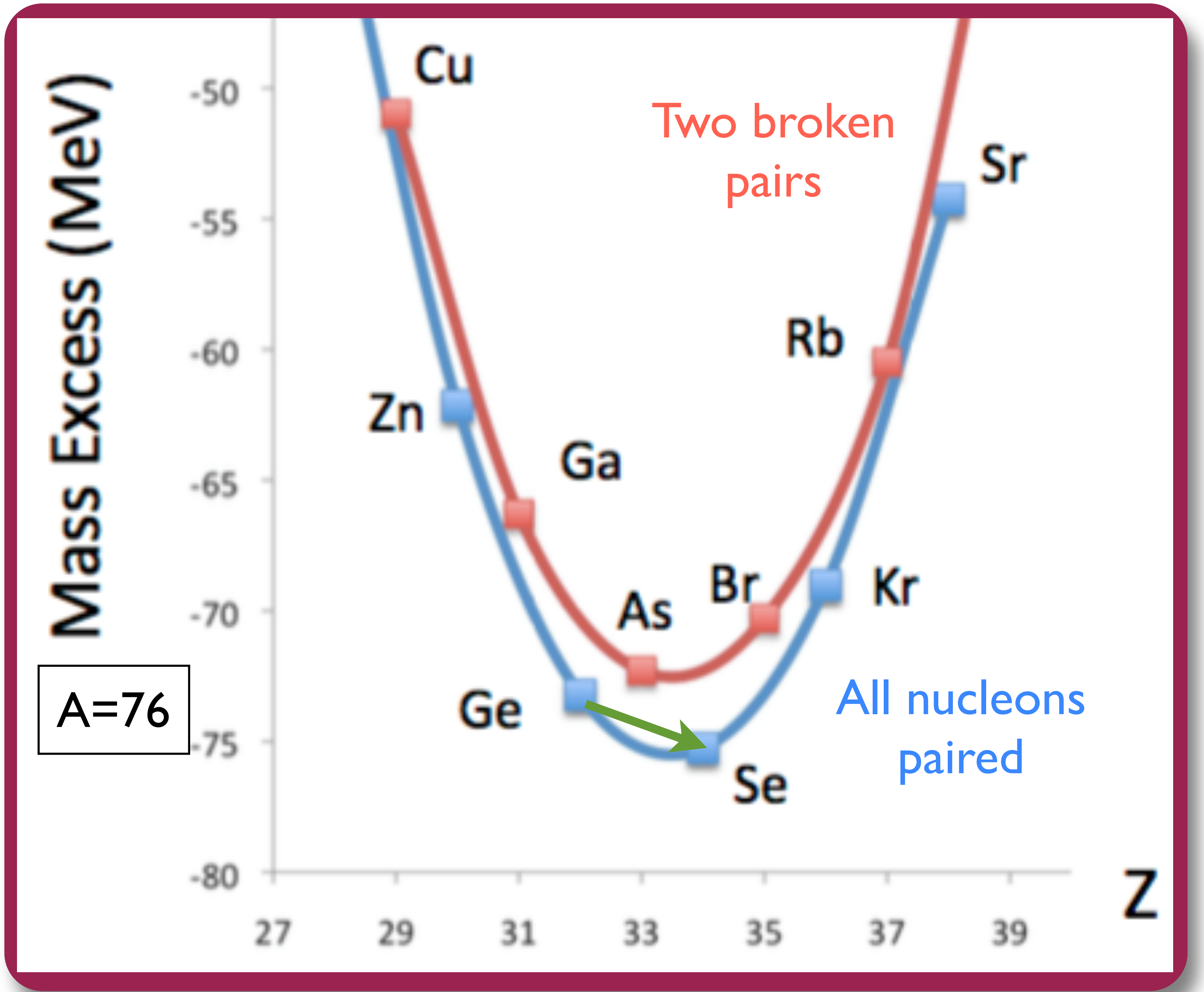
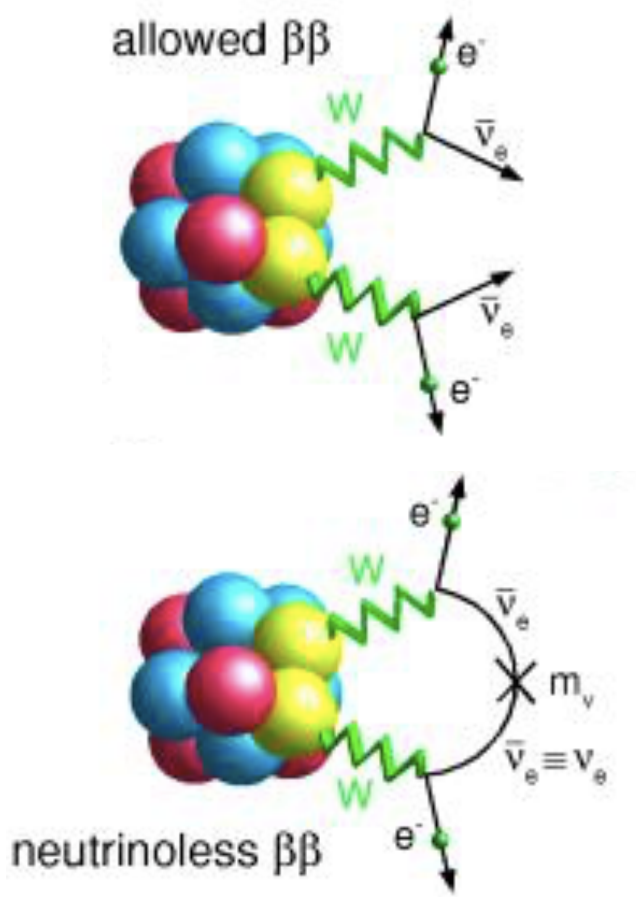
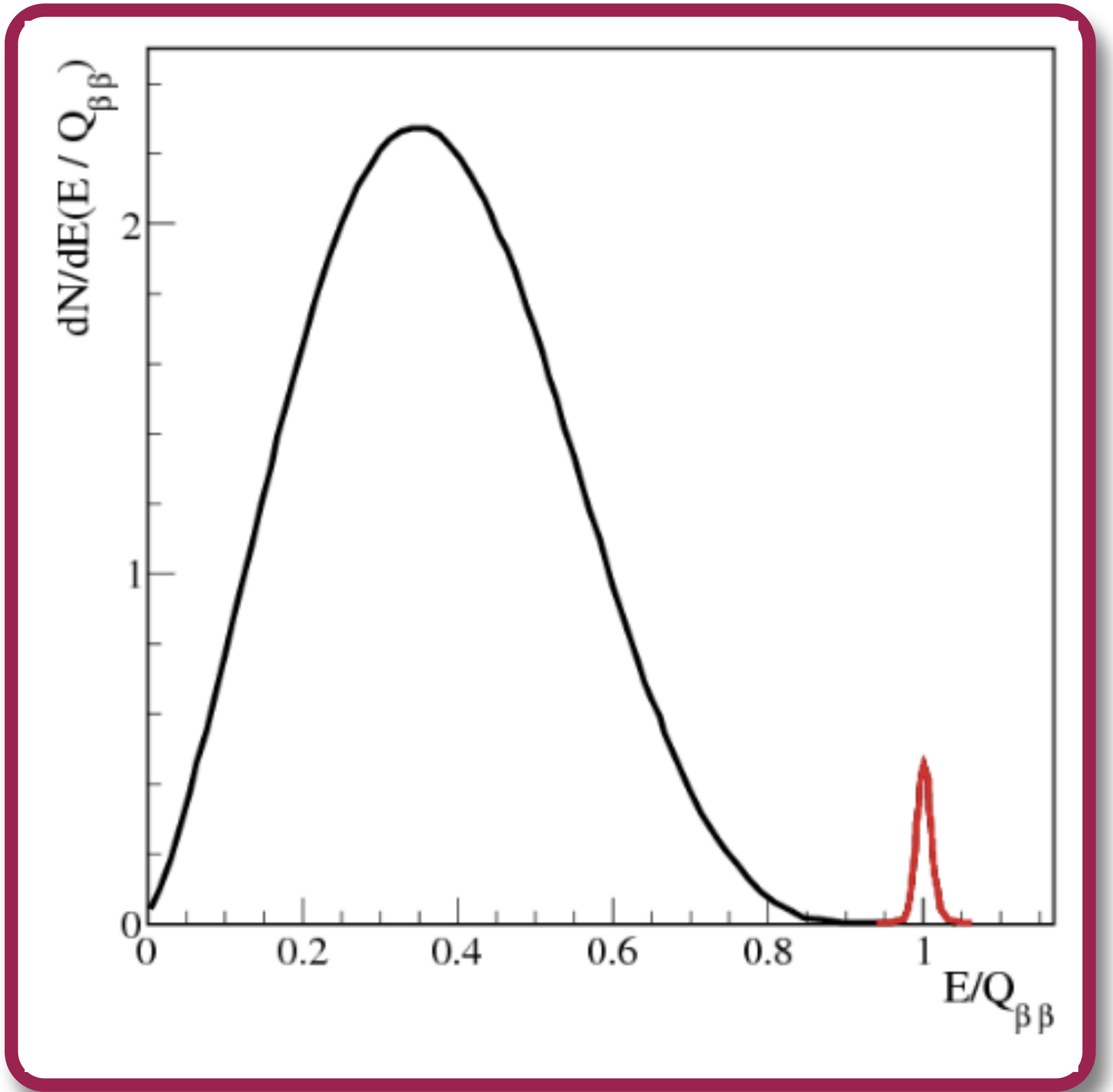


Second order, allowed



Experiment

Neutrinoless mode can be isolated using spectroscopic methods



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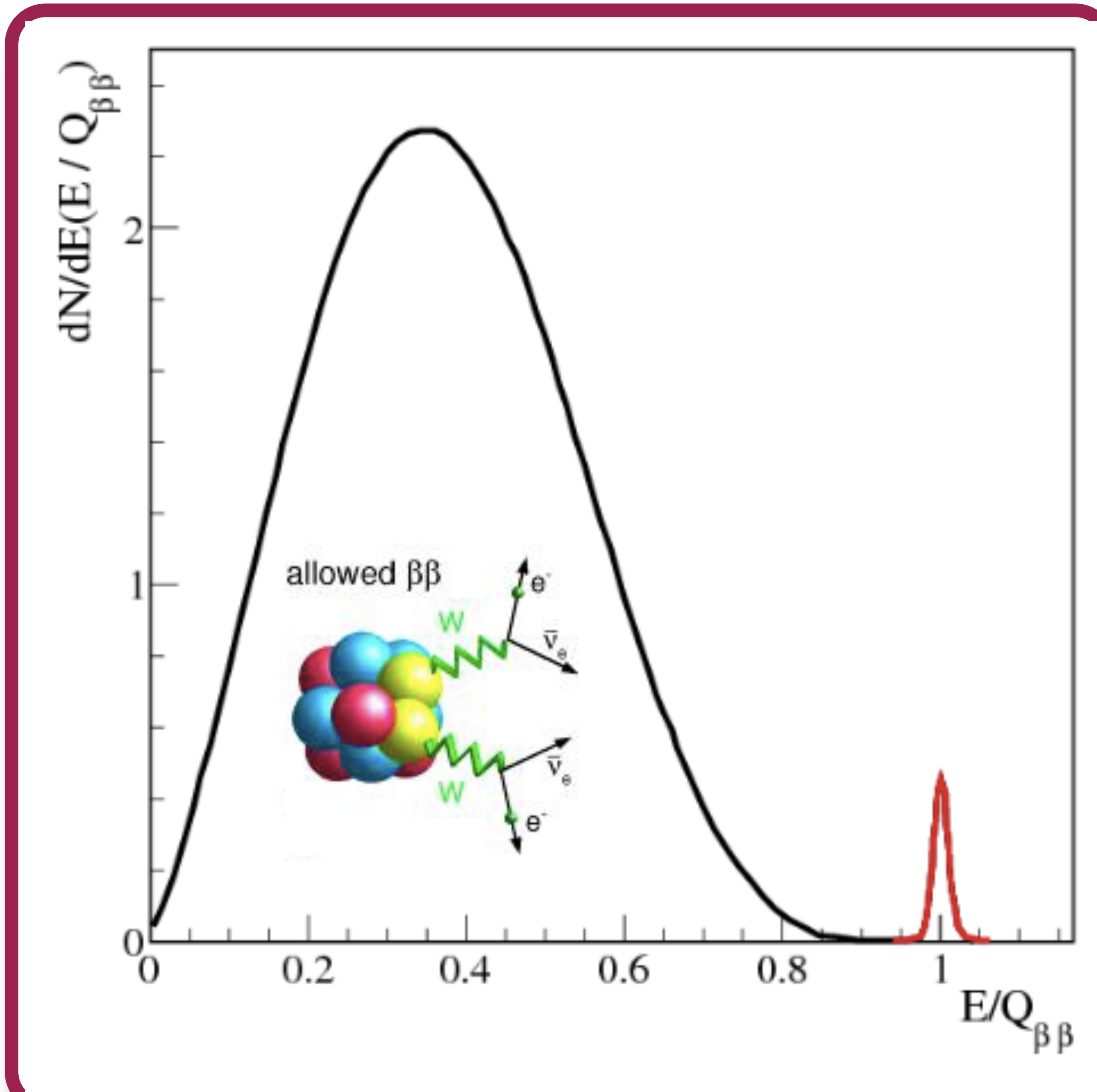

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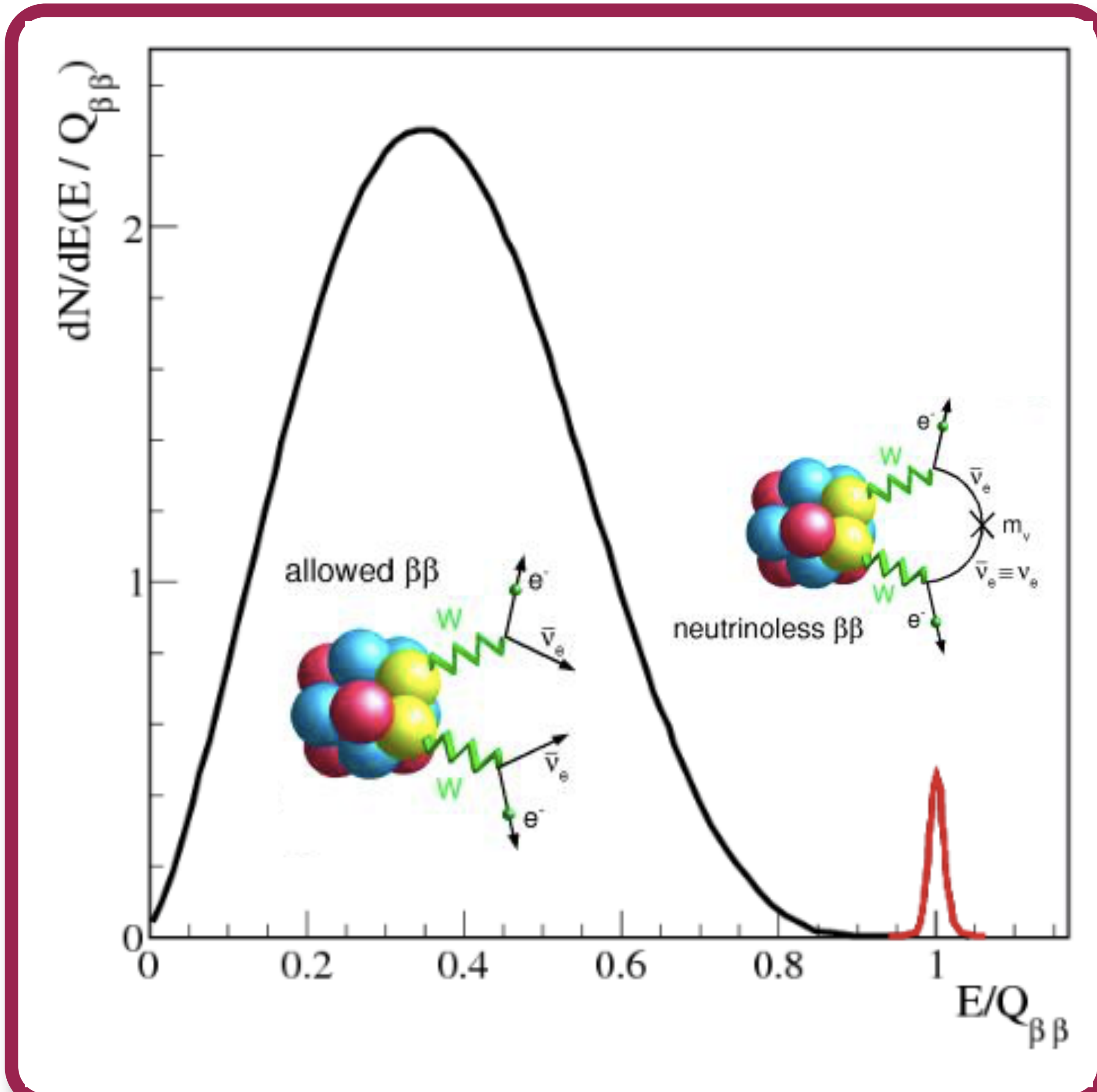
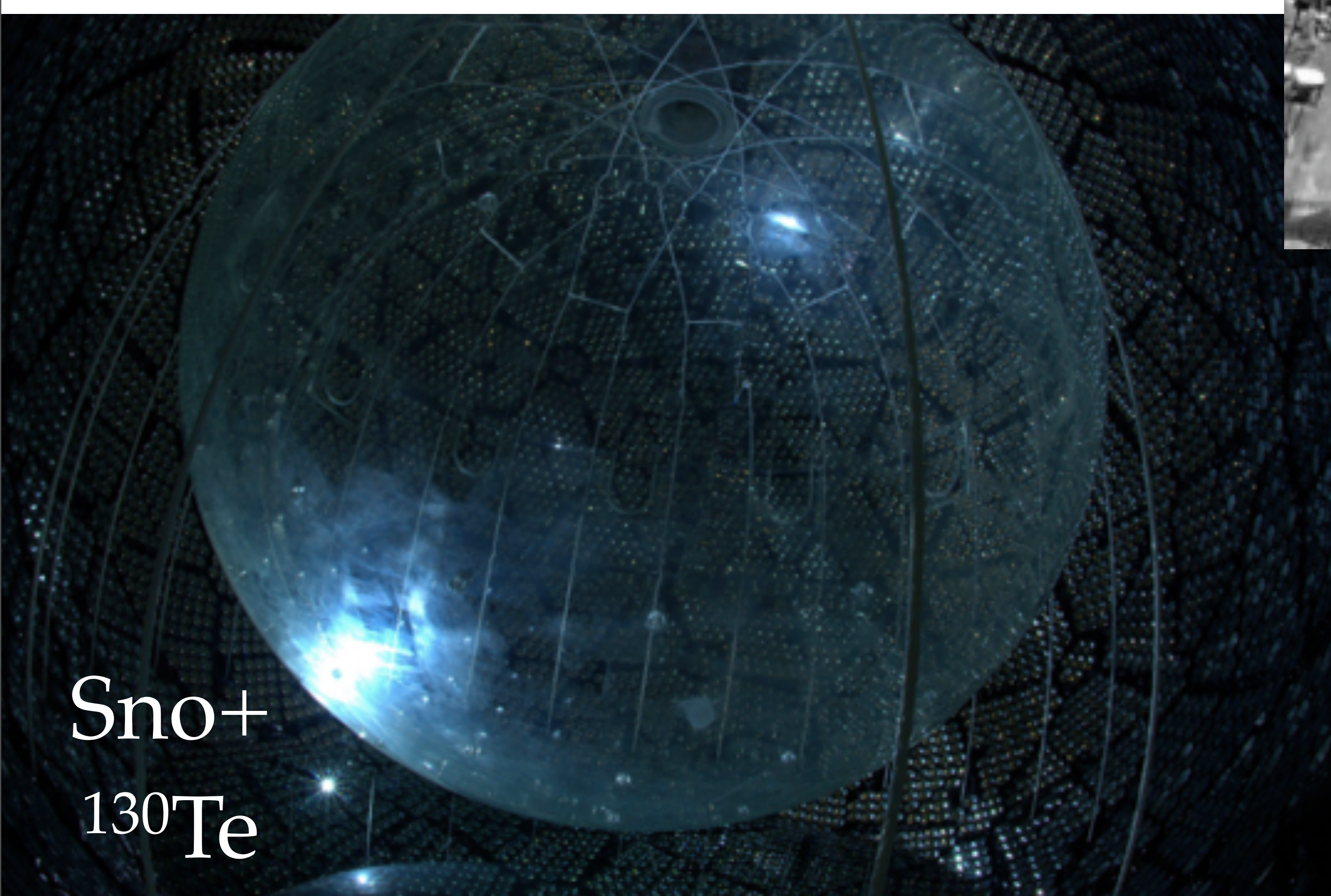
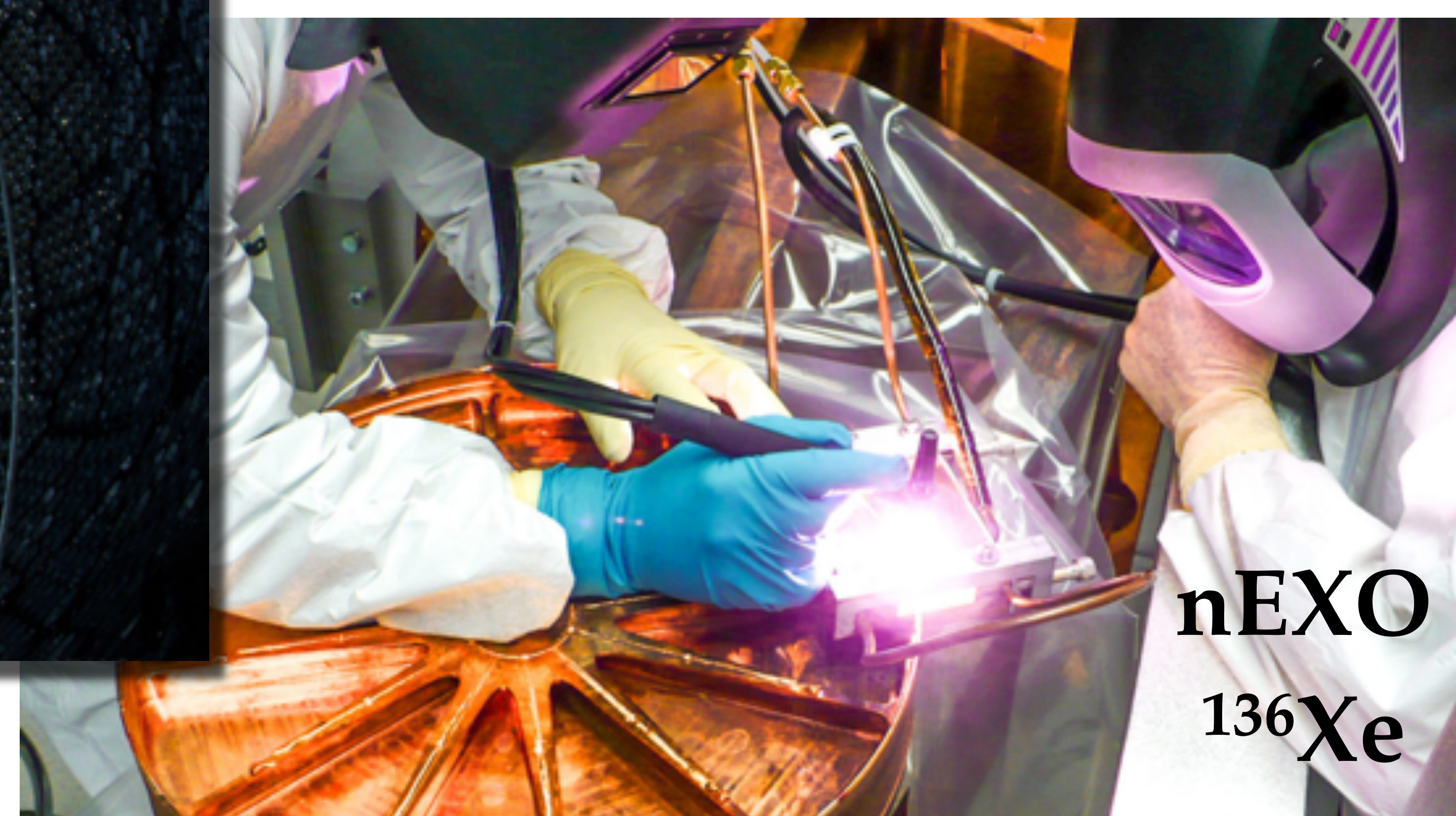


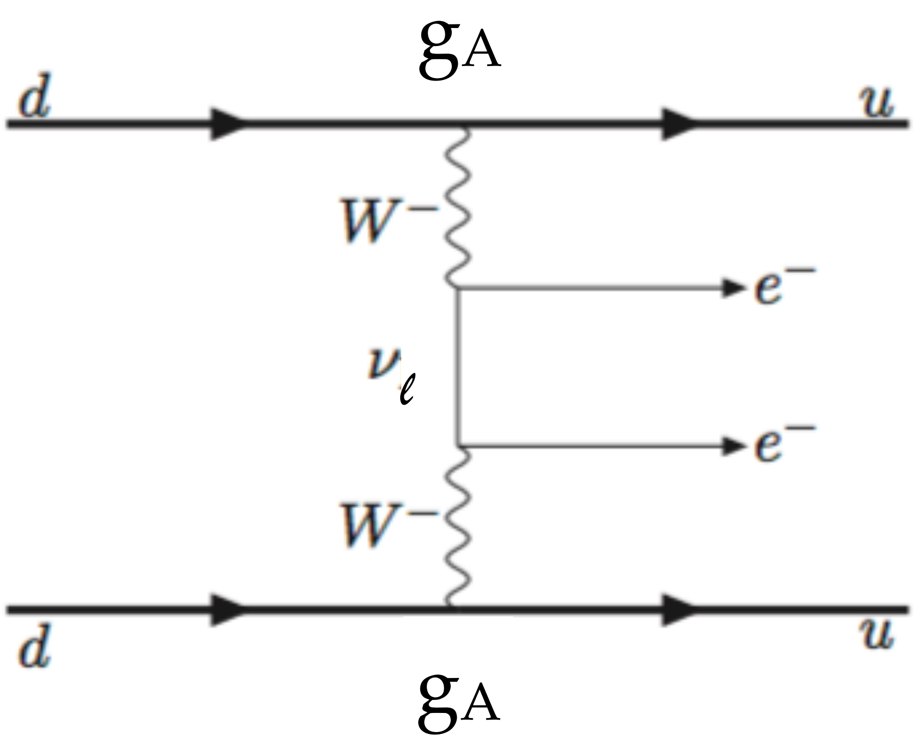
Experiment

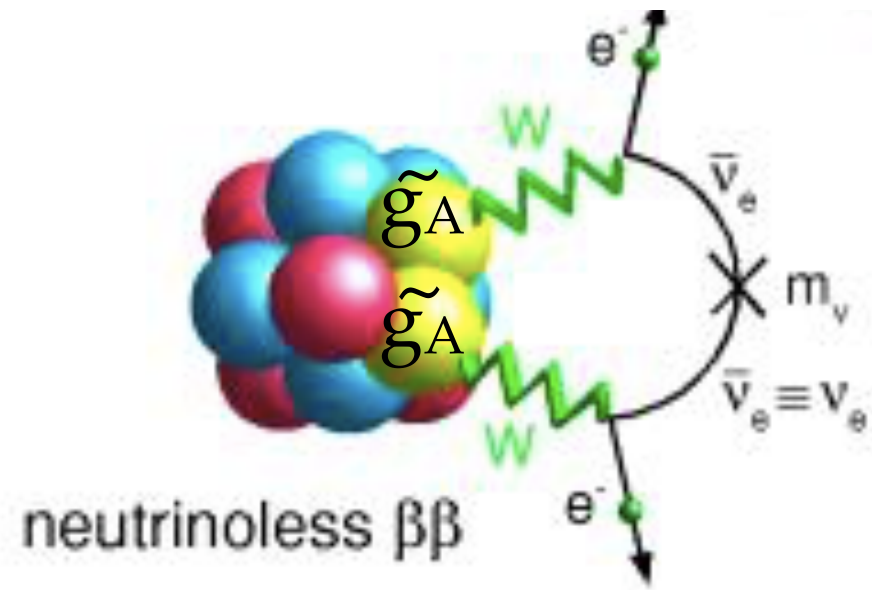


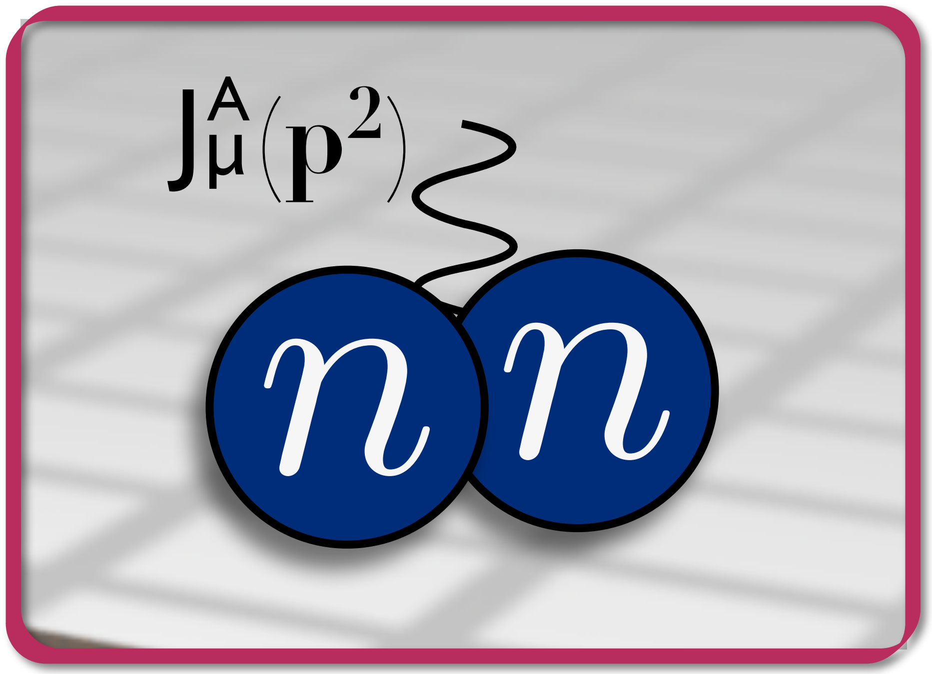


How can LQCD contribute?

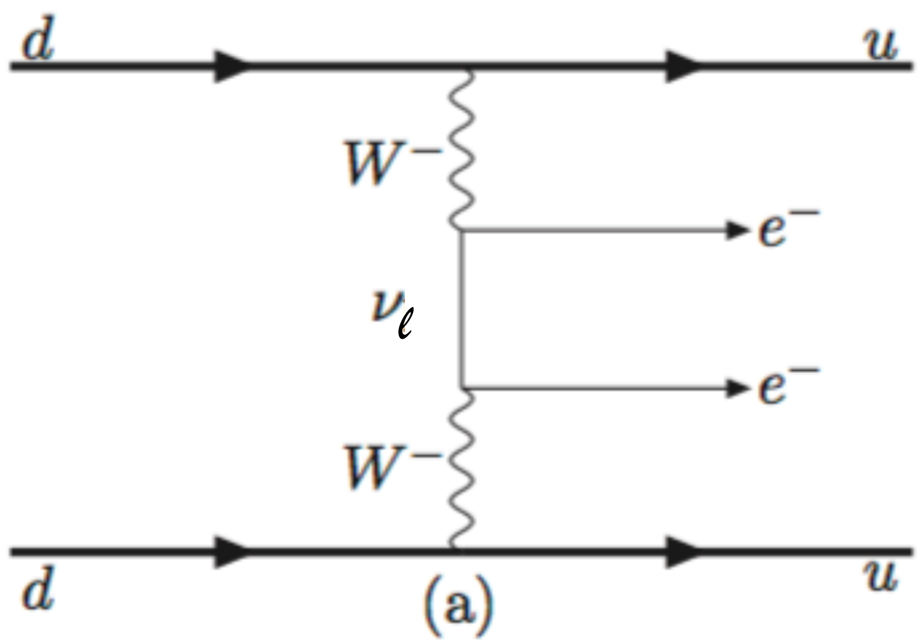
Standard picture: long-range contribution

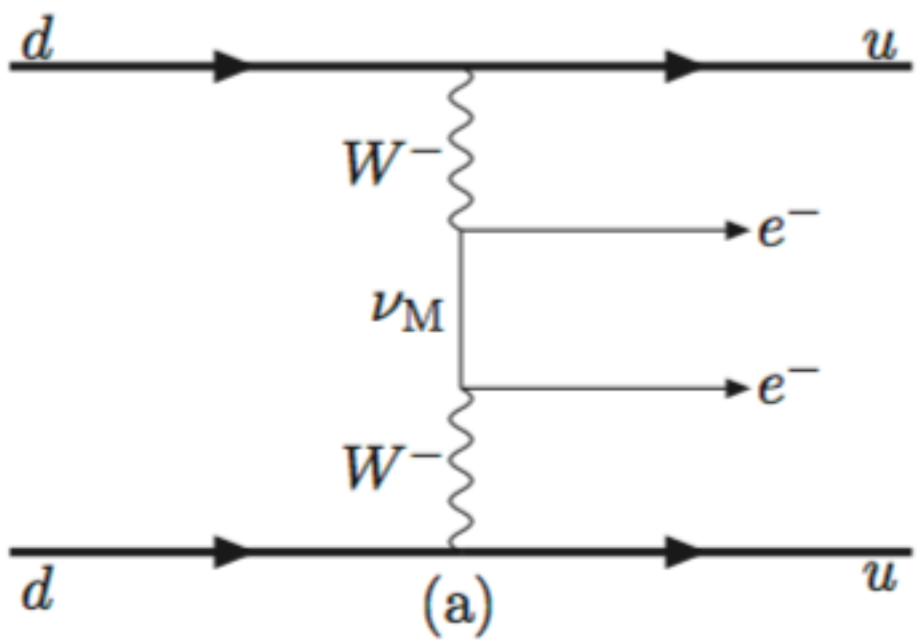


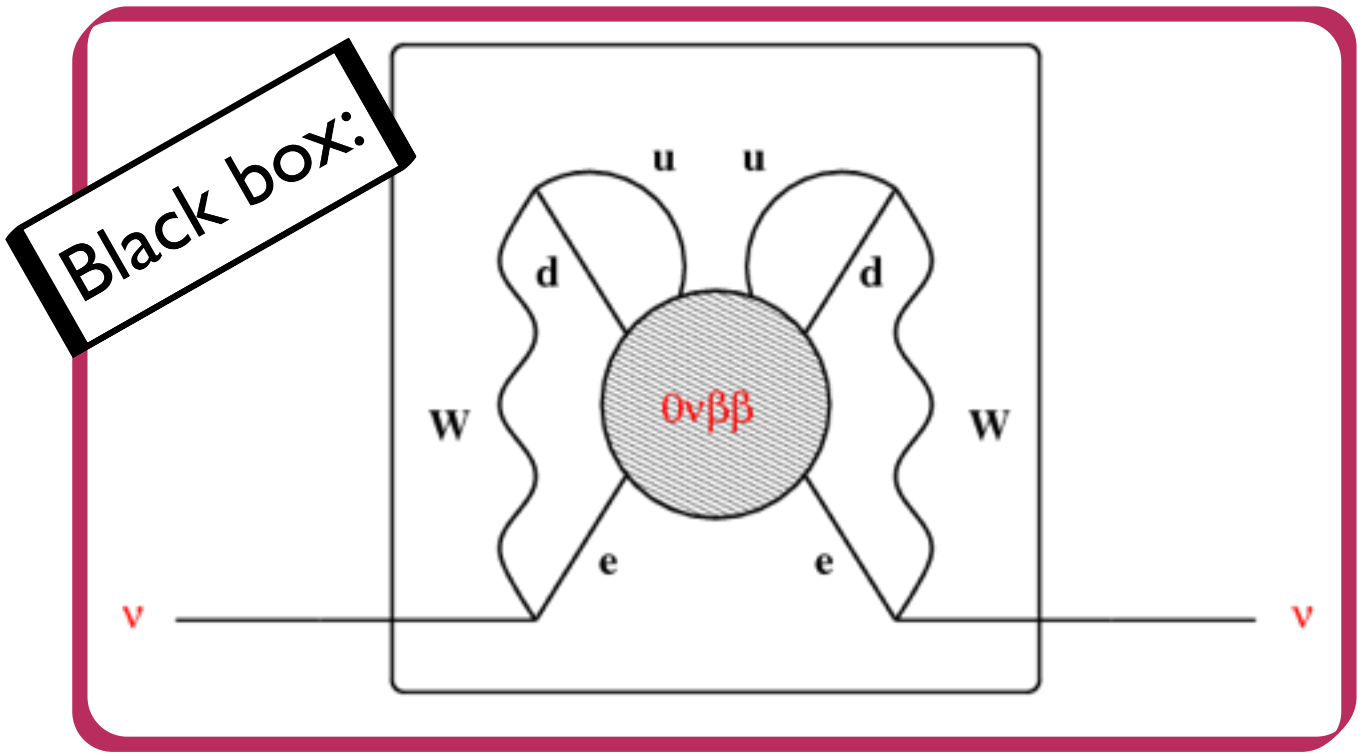




Short-range contribution: probe for heavy physics







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

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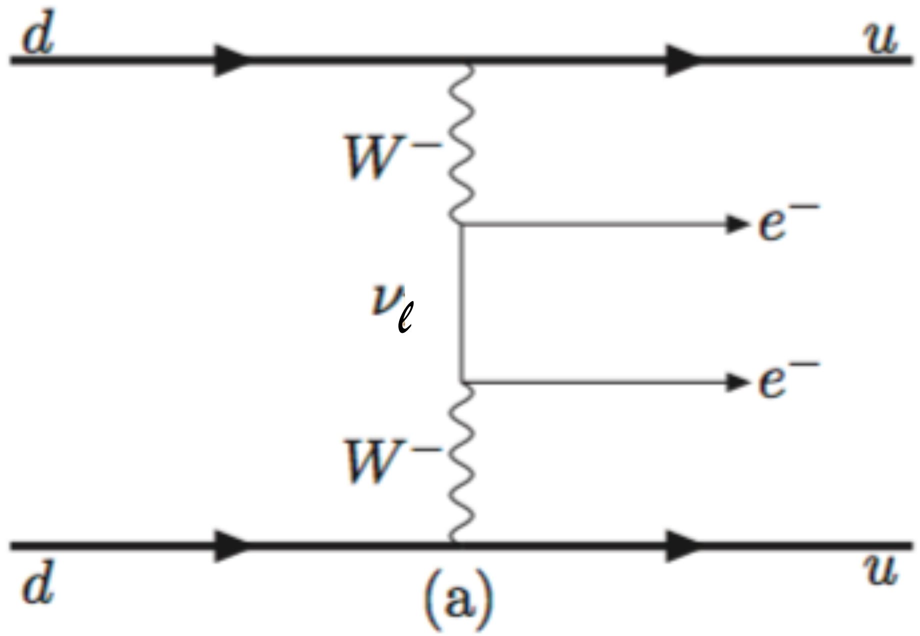

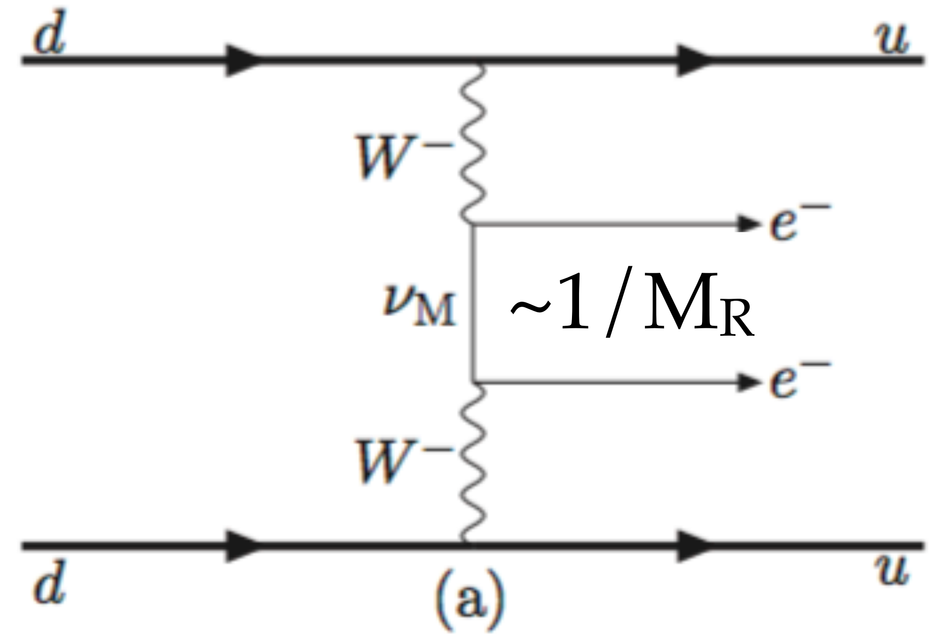

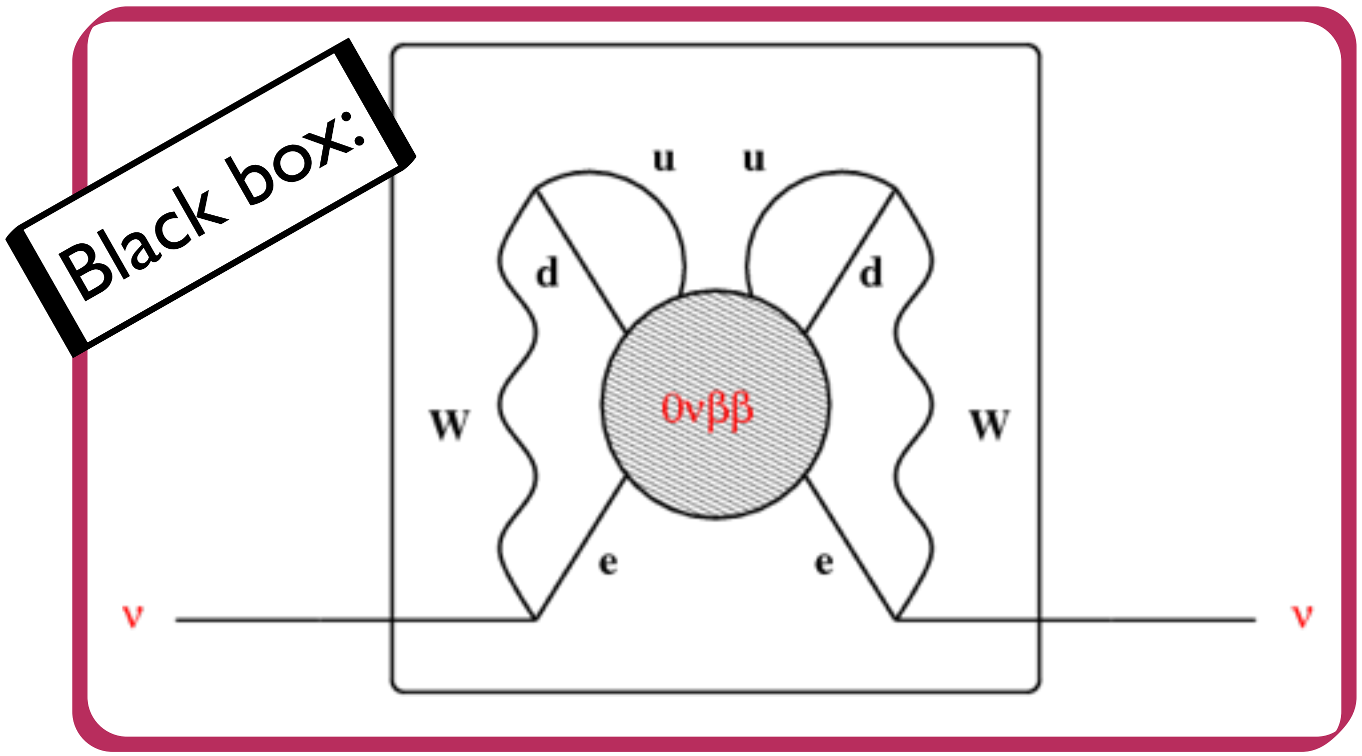

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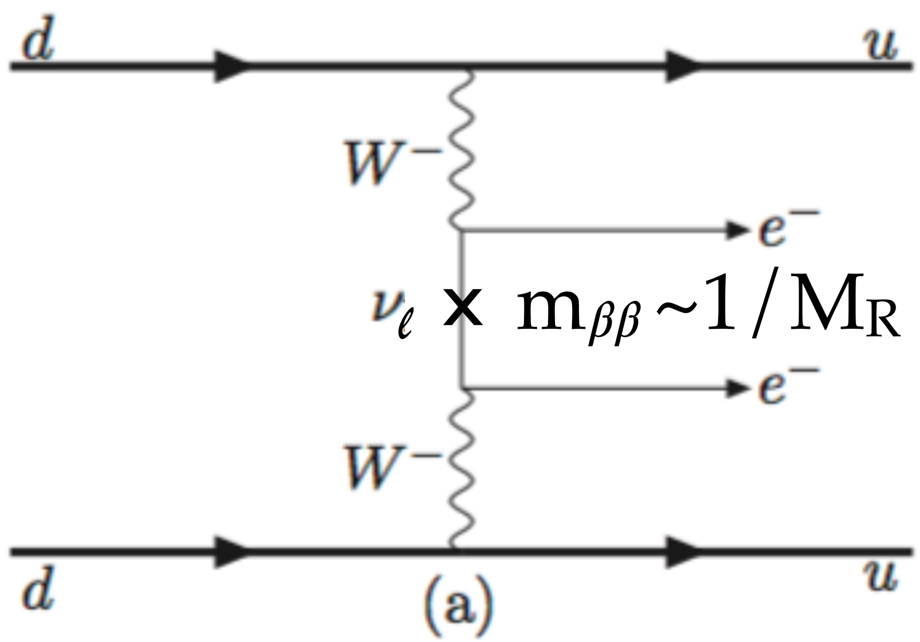

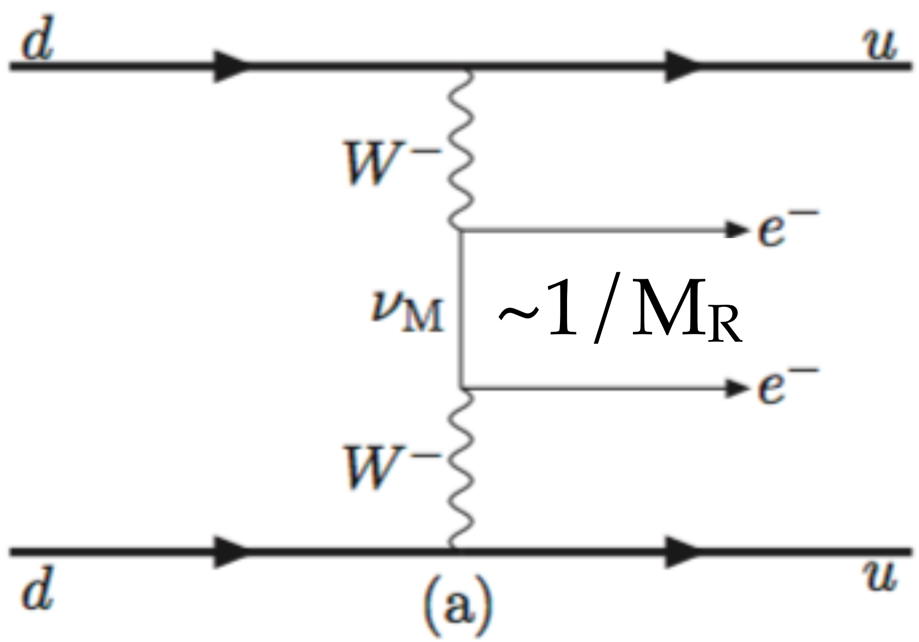

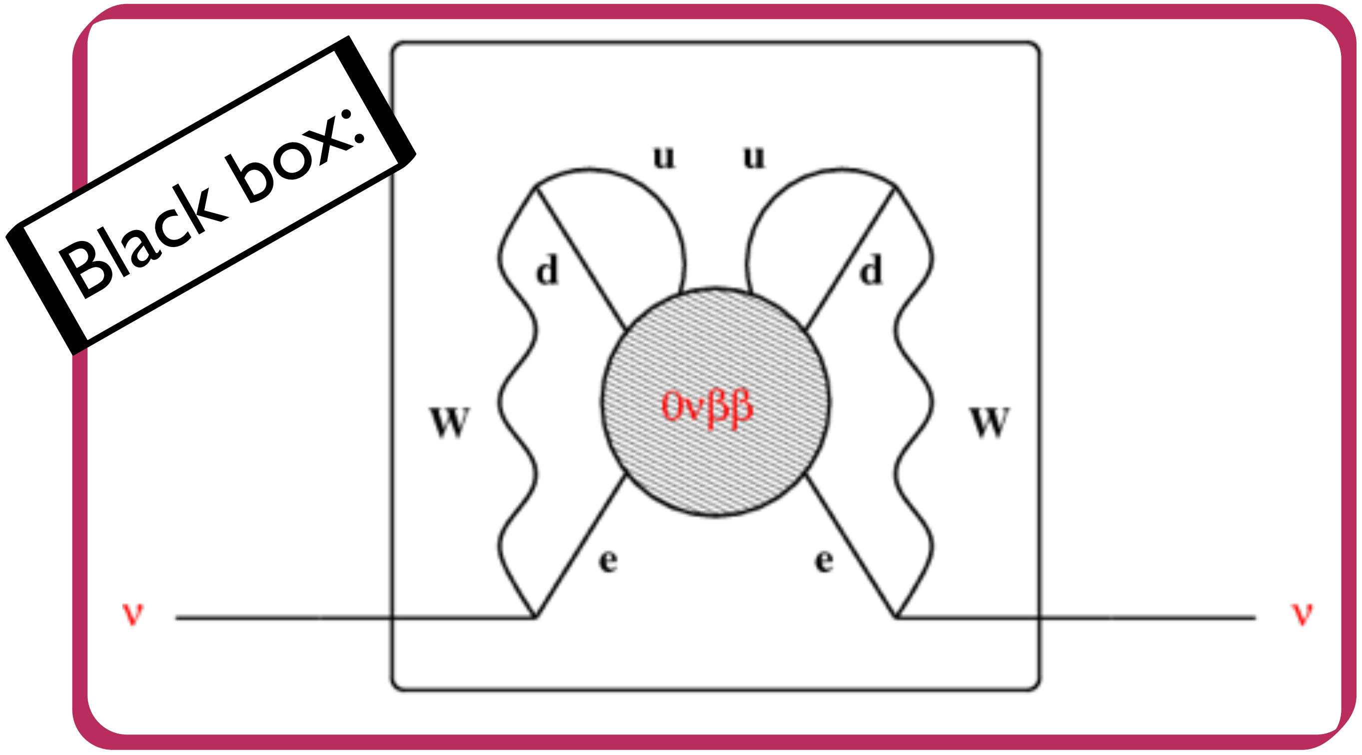

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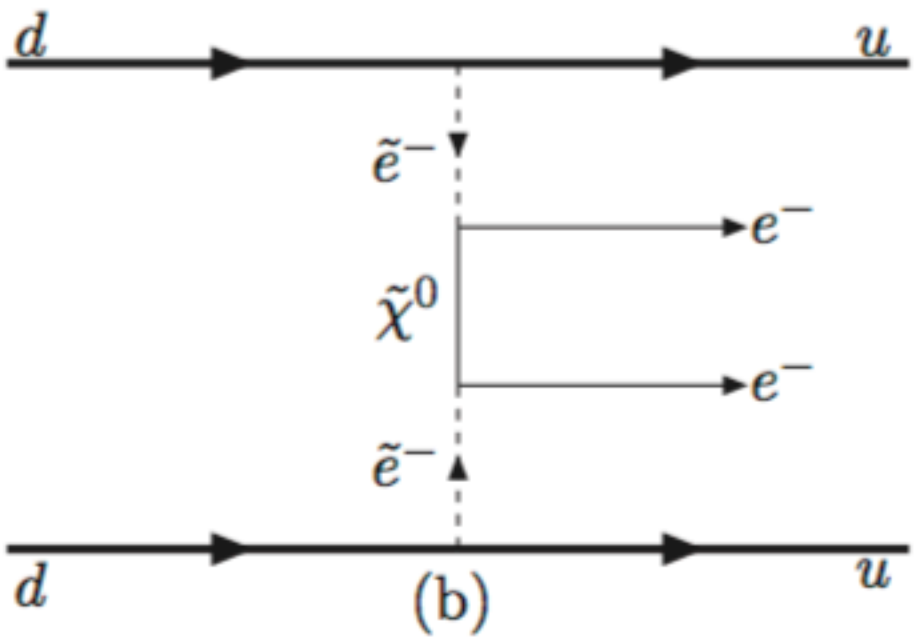
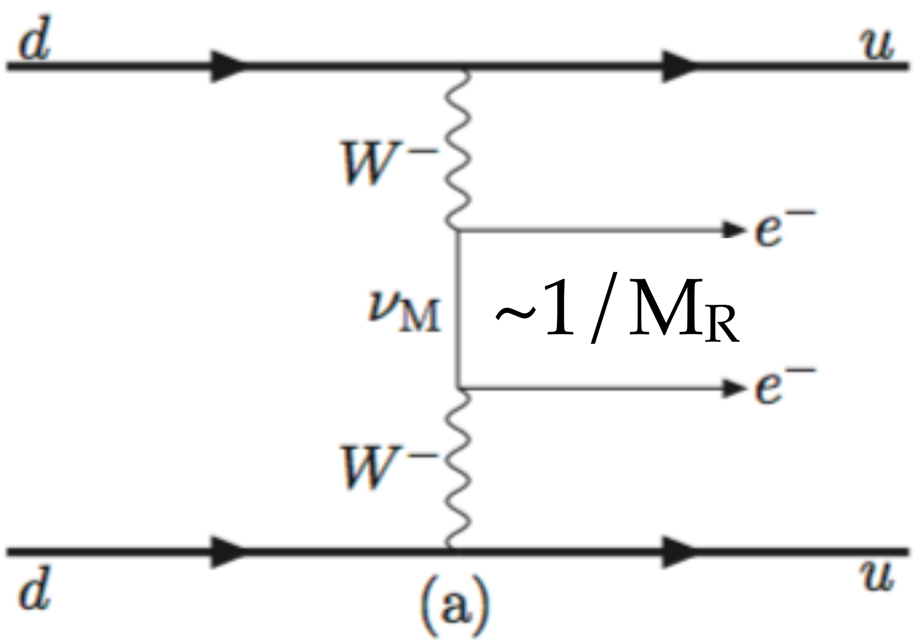
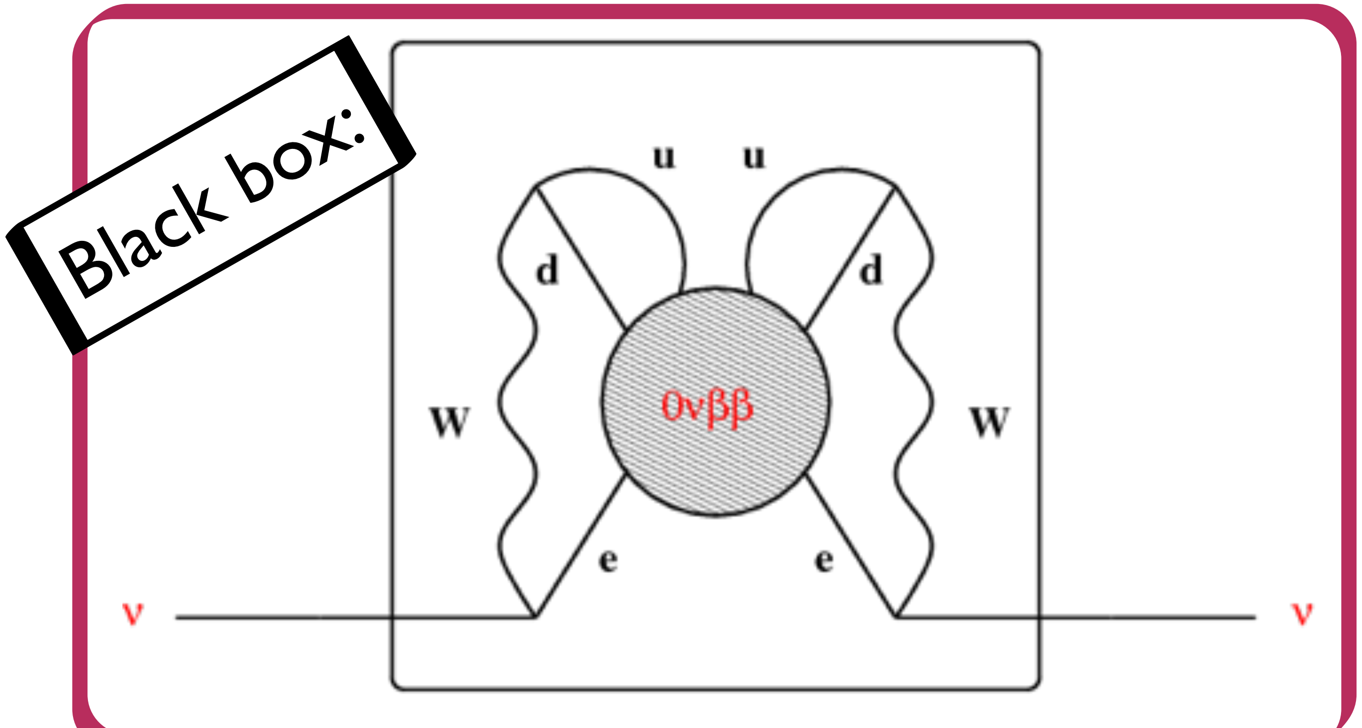


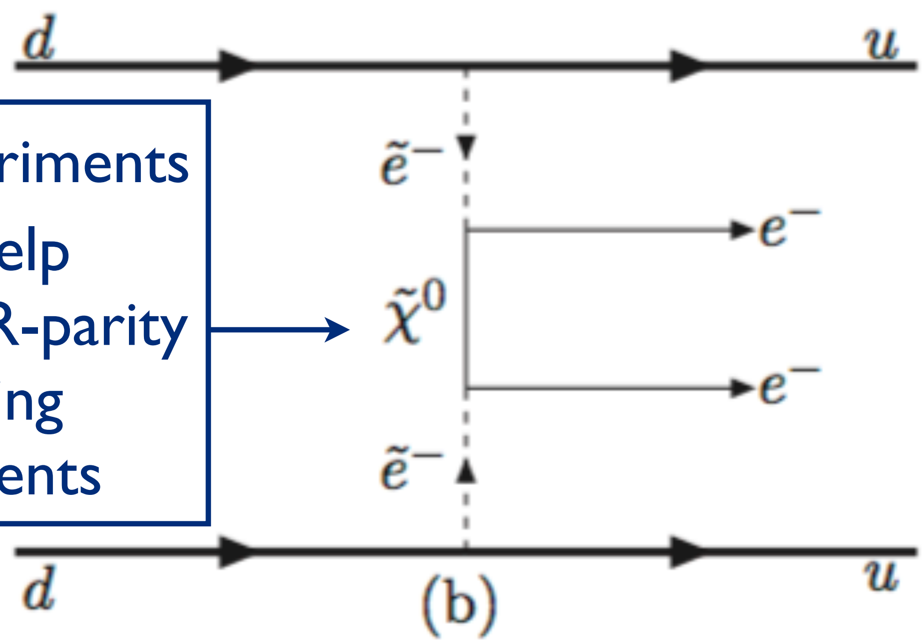


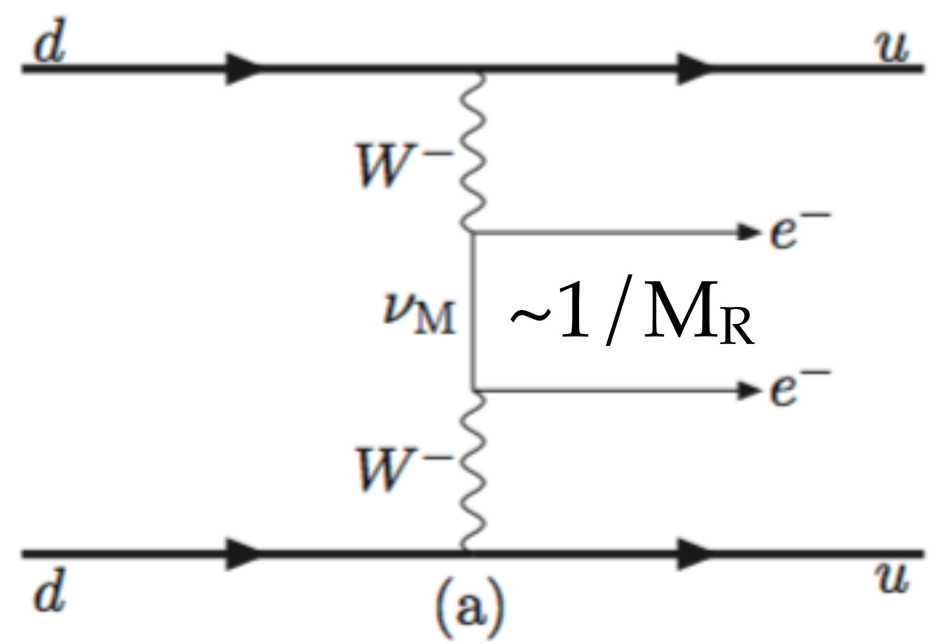


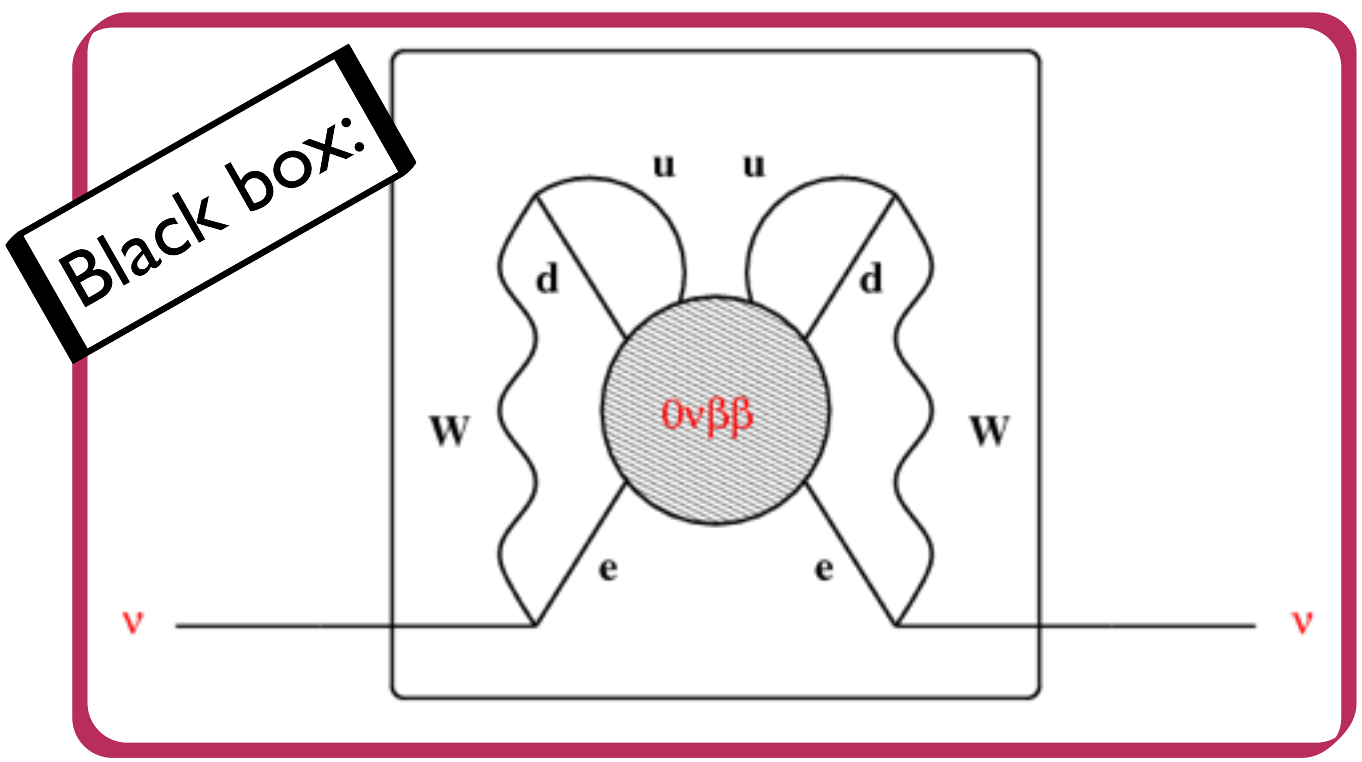
Valle & Schecter, Fig.: H. Päs, W. Rodejohann New J.Phys. 17 (2015) no.11, 115010

Short-range contribution: probe for heavy physics

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







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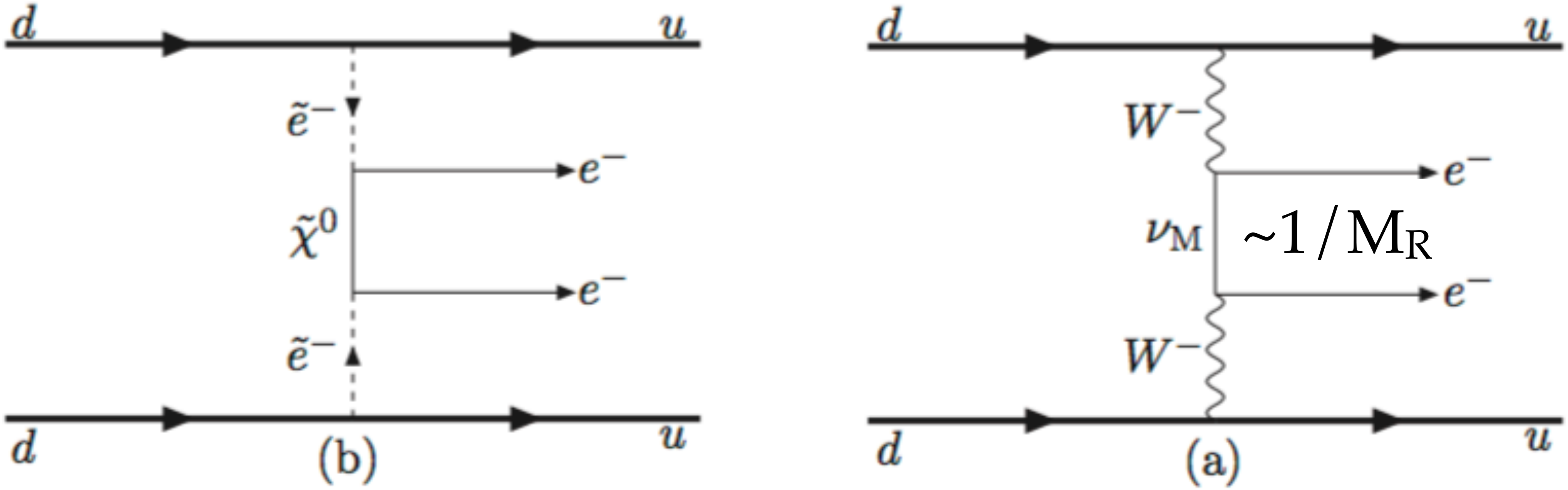
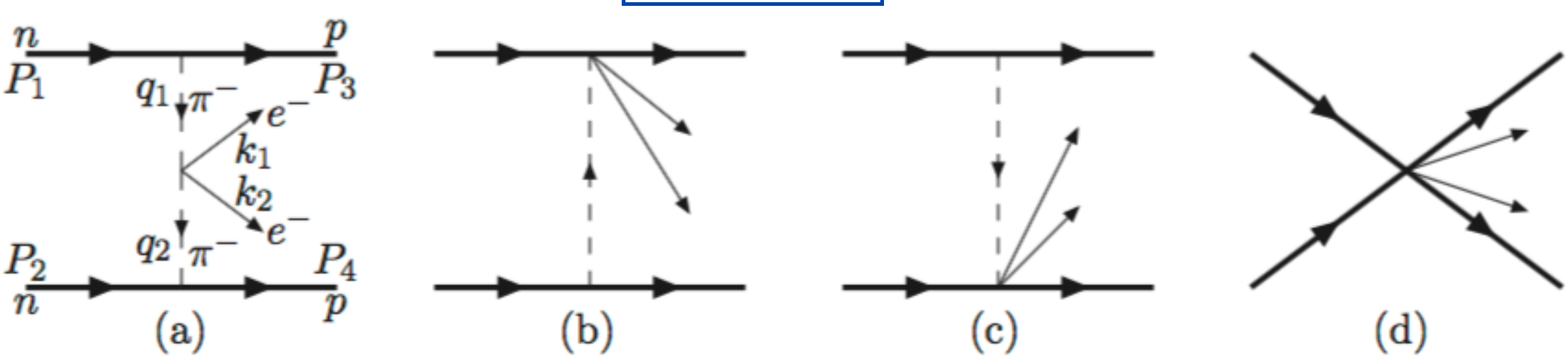


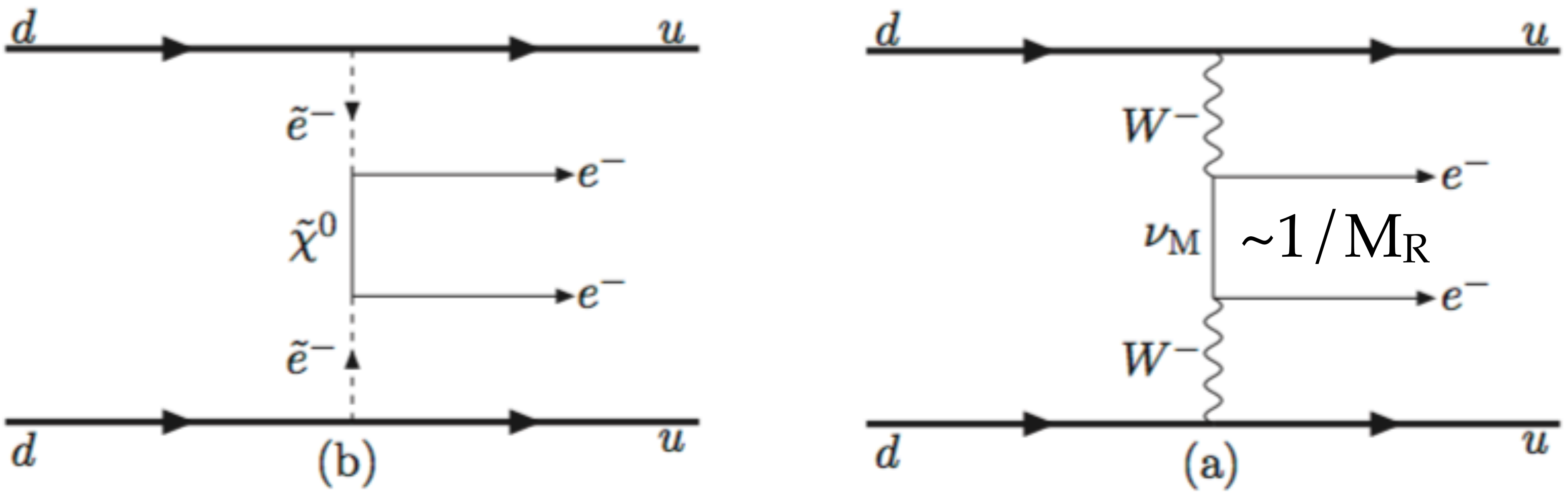
Chiral EFT



$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^{0})$ $\mathcal{O}(p^{0})$ $\mathcal{O}(p^{2})$

Prezeau, Ramsey-Musolf, Vogel (2003)

Short-range contribution: probe for heavy physics



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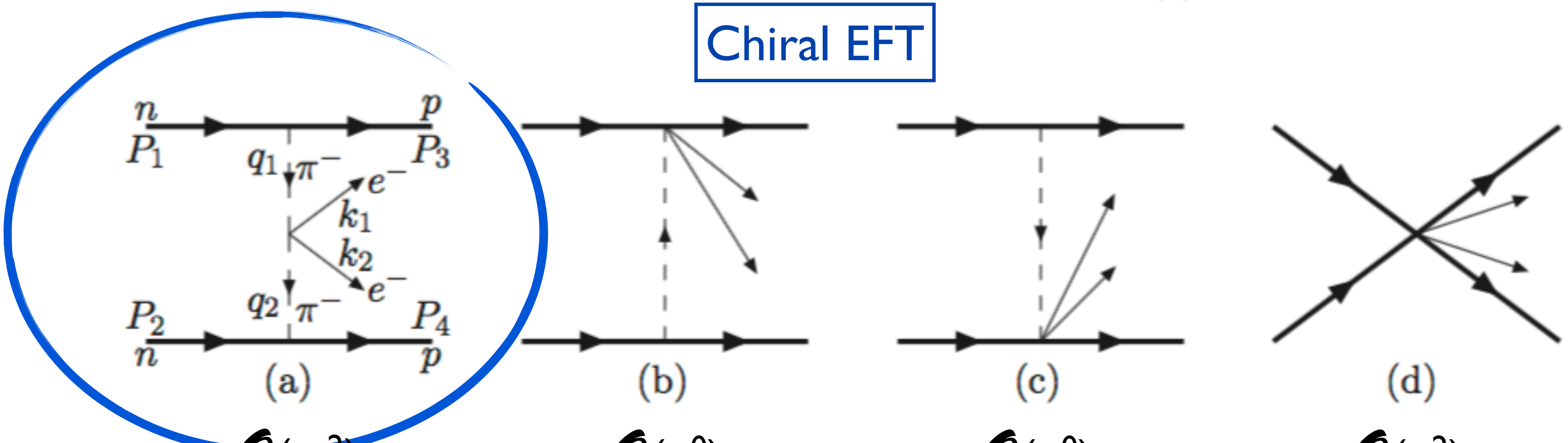

$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^{0})$ $\mathcal{O}(p^{0})$ $\mathcal{O}(p^{2})$

Prezeau, Ramsey-Musolf, Vogel (2003)

Effective Lagrangian

$$\mathcal{L}^q_{0\nu\beta\beta} = \frac{G_F^2}{\Lambda_{\beta\beta}} \{ \left(o_1 \mathcal{O}^{++}_{1+} + o_2 \mathcal{O}^{++}_{2+} + o_3 \mathcal{O}^{++}_{2-} + o_4 \mathcal{O}^{++}_{3+} + o_5 \mathcal{O}^{++}_{3-} \right) \bar{e} e^c$$

$$+ \left(o_6 \mathcal{O}^{++}_{1+} + o_7 \mathcal{O}^{++}_{2+} + o_8 \mathcal{O}^{++}_{2-} + o_9 \mathcal{O}^{++}_{3+} + o_{10} \mathcal{O}^{++}_{3-} \right) \bar{e} \gamma^5 e^c$$

$$+ \left(o_{11} \mathcal{O}^{++,\mu}_{4+} + o_{12} \mathcal{O}^{++,\mu}_{4-} + o_{13} \mathcal{O}^{++,\mu}_{5+} + o_{14} \mathcal{O}^{++,\mu}_{5-} \right) \bar{e} \gamma_\mu \gamma^5 e^c + \text{h.c.} \}$$

Prezeau, Ramsey-Musolf, Vogel (2003)

- Nine operators:
  - $\pi \to \pi$: only need parity even
  - Vector operators suppressed by m_e

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

Effective Lagrangian

$$\mathcal{L}^q_{0\nu\beta\beta} = \frac{G_F^2}{\Lambda_{\beta\beta}}\{(o_1\mathcal{O}^{++}_{1+} + o_2\mathcal{O}^{++}_{2+} + o_3\mathcal{O}^{++}_{2-} + o_4\mathcal{O}^{++}_{3+} + o_5\mathcal{O}^{++}_{3-})\,\bar{e}e^c$$
$$+ (o_6\mathcal{O}^{++}_{1+} + o_7\mathcal{O}^{++}_{2+} + o_8\mathcal{O}^{++}_{2-} + o_9\mathcal{O}^{++}_{3+} + o_{10}\mathcal{O}^{++}_{3-})\,\bar{e}\gamma^5 e^c$$
$$+ (o_{11}\mathcal{O}^{++,\mu}_{4+} + o_{12}\mathcal{O}^{++,\mu}_{4-} + o_{13}\mathcal{O}^{++,\mu}_{5+} + o_{14}\mathcal{O}^{++,\mu}_{5-})\,\bar{e}\gamma_\mu\gamma^5 e^c + \text{h.c.}\}$$

Prezeau, Ramsey-Musolf, Vogel (2003)

- Nine operators:
  - $\pi \to \pi$: only need parity even
  - Vector operators suppressed by m_e

$$\mathcal{O}^{ab}_{1+} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_R\tau^b\gamma_\mu q_R),$$
$$\mathcal{O}^{ab}_{2\pm} = (\bar{q}_R\tau^a q_L)(\bar{q}_R\tau^b q_L) \pm (\bar{q}_L\tau^a q_R)(\bar{q}_L\tau^b q_R),$$
$$\mathcal{O}^{ab}_{3\pm} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_L\tau^b\gamma_\mu q_L) \pm (\bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_R\tau^b\gamma_\mu q_R),$$
$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_L\tau^a\gamma^\mu q_L \mp \bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_L\tau^b q_R - \bar{q}_R\tau^b q_L),$$
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_L\tau^a\gamma^\mu q_L \pm \bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_L\tau^b q_R + \bar{q}_R\tau^b q_L).$$

Effective Lagrangian

$$\mathcal{L}^q_{0\nu\beta\beta} = \frac{G_F^2}{\Lambda_{\beta\beta}}\{(o_1\mathcal{O}^{++}_{1+} + o_2\mathcal{O}^{++}_{2+} + o_3\mathcal{O}^{++}_{2-} + o_4\mathcal{O}^{++}_{3+} + o_5\mathcal{O}^{++}_{3-})\,\bar{e}e^c$$
$$+ (o_6\mathcal{O}^{++}_{1+} + o_7\mathcal{O}^{++}_{2+} + o_8\mathcal{O}^{++}_{2-} + o_9\mathcal{O}^{++}_{3+} + o_{10}\mathcal{O}^{++}_{3-})\,\bar{e}\gamma^5 e^c$$
$$+ (o_{11}\mathcal{O}^{++,\mu}_{4+} + o_{12}\mathcal{O}^{++,\mu}_{4-} + o_{13}\mathcal{O}^{++,\mu}_{5+} + o_{14}\mathcal{O}^{++,\mu}_{5-})\,\bar{e}\gamma_\mu\gamma^5 e^c + \text{h.c.}\}$$

Prezeau, Ramsey-Musolf, Vogel (2003)

- Nine operators:
  - $\pi \to \pi$: only need parity even
  - Vector operators suppressed by m_e

$$\mathcal{O}^{ab}_{1+} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_R\tau^b\gamma_\mu q_R),$$
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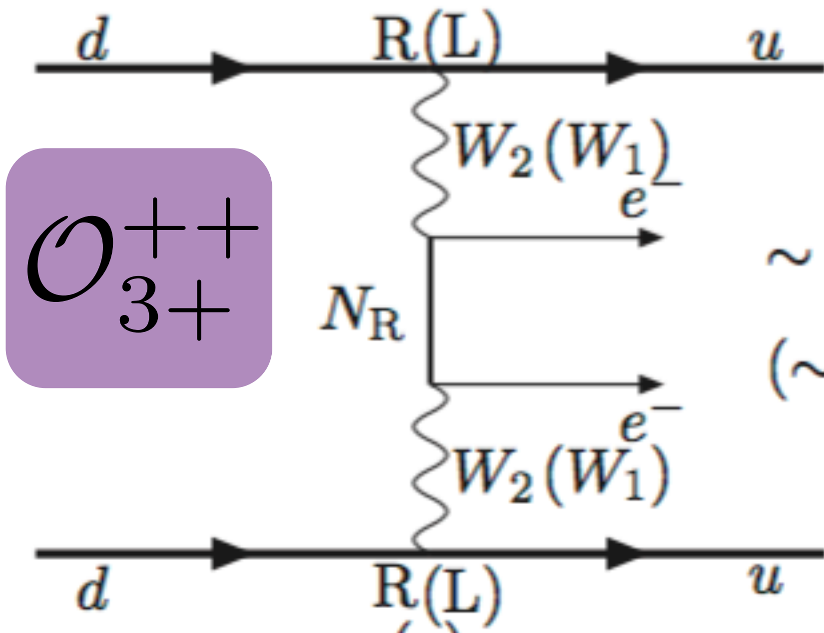
$$\mathcal{O}^{ab}_{3\pm} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_L\tau^b\gamma_\mu q_L) \pm (\bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_R\tau^b\gamma_\mu q_R),$$
$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_L\tau^a\gamma^\mu q_L + \bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_L\tau^b q_R - \bar{q}_R\tau^b q_L),$$
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_L\tau^a\gamma^\mu q_L \pm \bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_L\tau^b q_R + \bar{q}_R\tau^b q_L).$$

Calculate LECs; EFT then determines nn → pp transition via pion exchange diagram

$0\nu\beta\beta$-decay ops.	$\mathcal{O}_{1+}^{\pm\pm}$	$\mathcal{O}_{2+}^{\pm\pm}$	$\mathcal{O}_{2-}^{\pm\pm}$	$\mathcal{O}_{3+}^{\pm\pm}$	$\mathcal{O}_{3-}^{\pm\pm}$	$\mathcal{O}_{4+}^{\pm\pm,\mu}$	$\mathcal{O}_{4-}^{\pm\pm,\mu}$	$\mathcal{O}_{5+}^{\pm\pm,\mu}$	$\mathcal{O}_{5-}^{\pm\pm,\mu}$
$\pi\pi ee$ 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

$\mathcal{O}_{3+}^{++}$

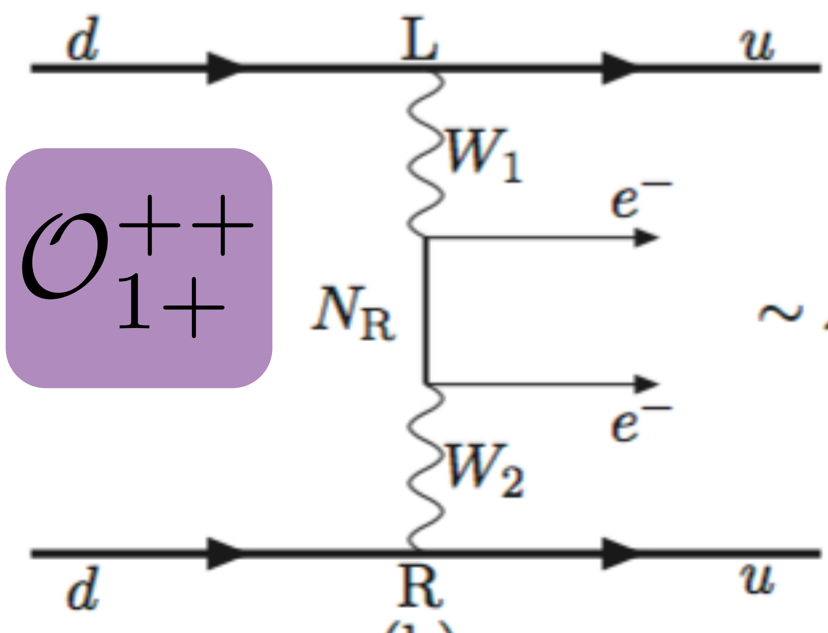


(a)

$\sim \lambda^2 \mathcal{O}_{3+}^{++}$

$(\sim \zeta^2 \mathcal{O}_{3+}^{++})$

$\mathcal{O}_{1+}^{++}$



(b)

$\sim \lambda\zeta \mathcal{O}_{1+}^{++}$

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

Contractions

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

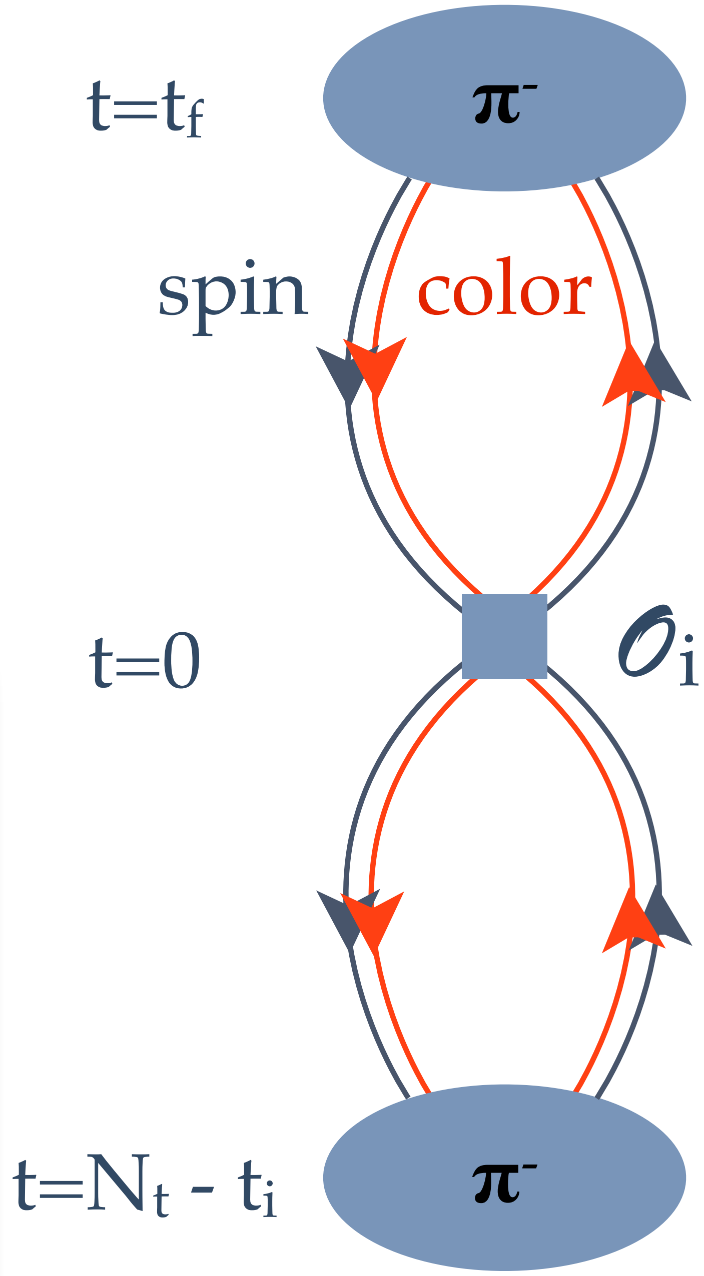
$$\mathcal{O}_{1+}^{++} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

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

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

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

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



Contractions

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

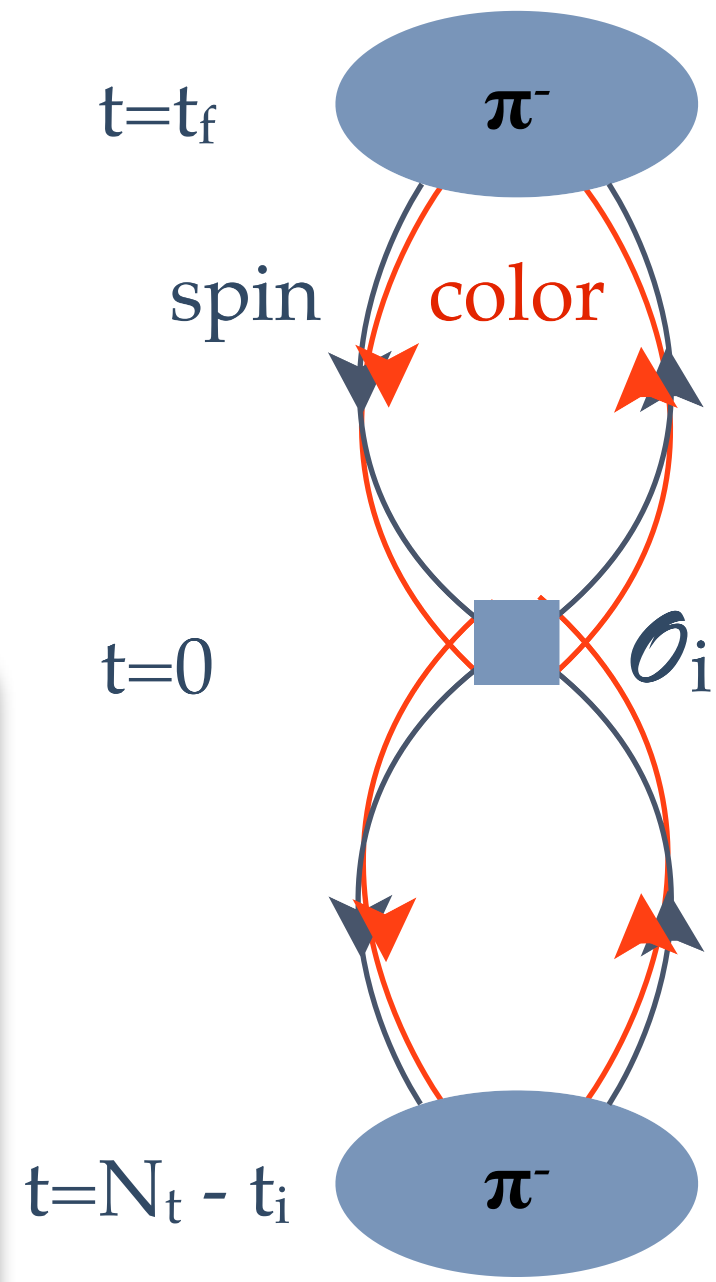
$$\mathcal{O}_{1+}^{++} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

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

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

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

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



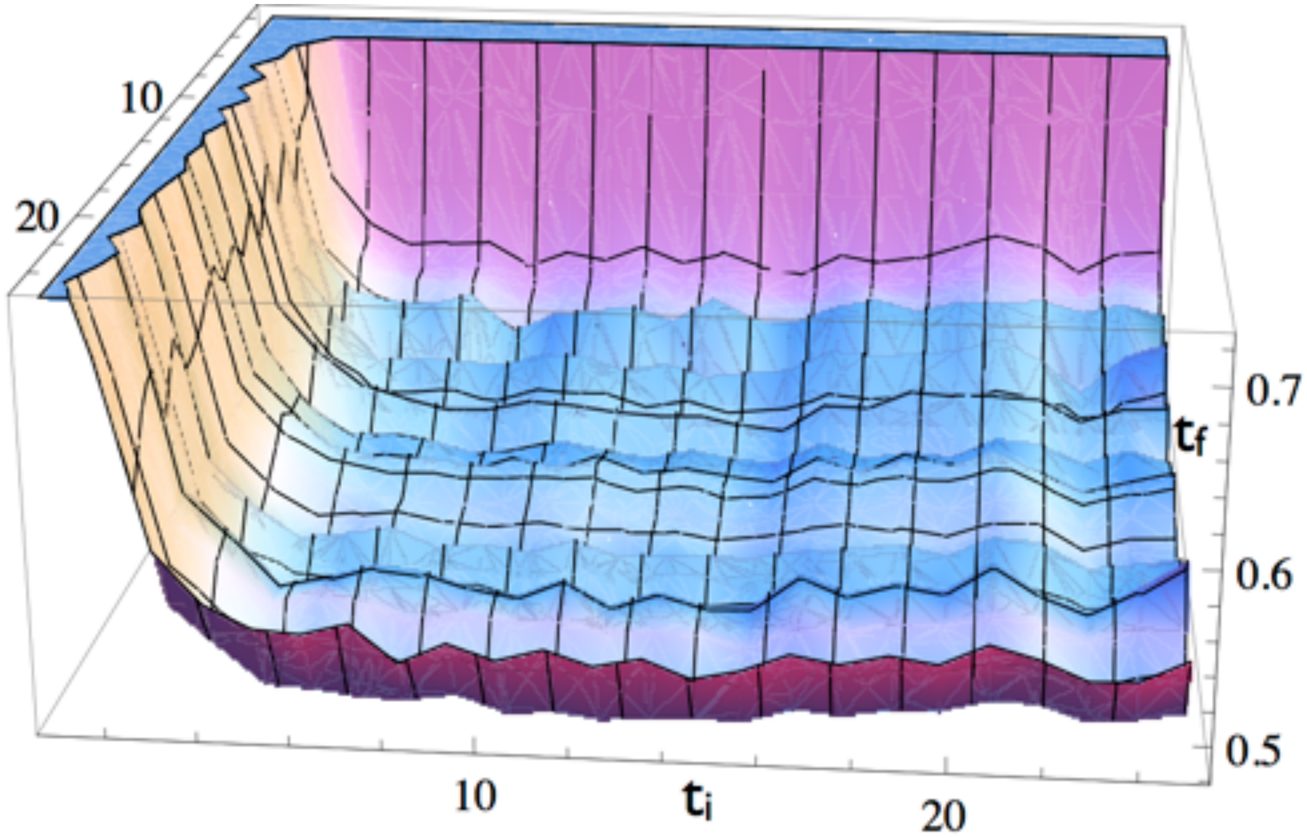
HISQ ensembles

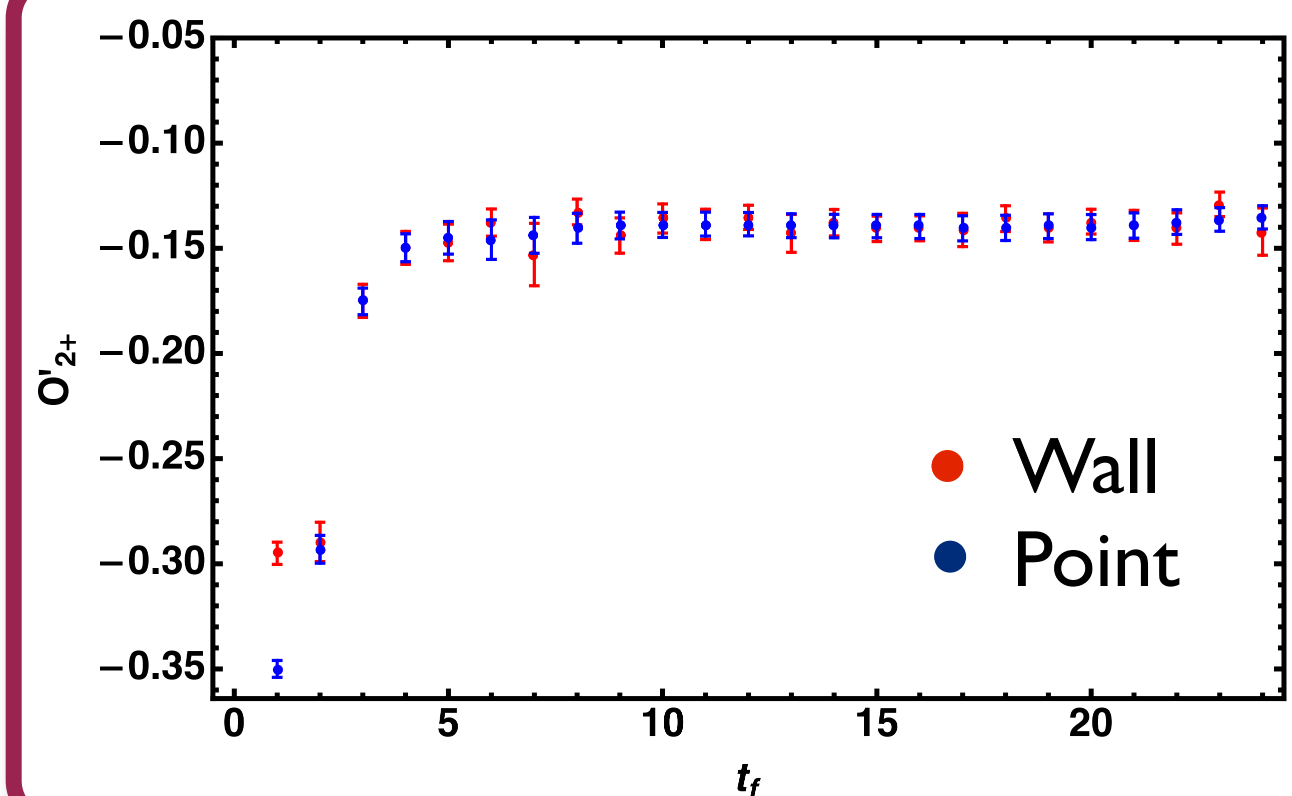
$a[fm] : m_\pi[MeV]$	310	220	135
0.15	$16^3 \times 48, m_\pi L \sim 3.78$	$24^3 \times 48, m_\pi L \sim 3.99$	$32^3 \times 48, m_\pi L \sim 3.25$
0.12		$24^3 \times 64, m_\pi L \sim 3.22$	
0.12	$24^3 \times 64, m_\pi L \sim 4.54$	$32^3 \times 64, m_\pi L \sim 4.29$	$48^3 \times 64, m_\pi L \sim 3.91$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

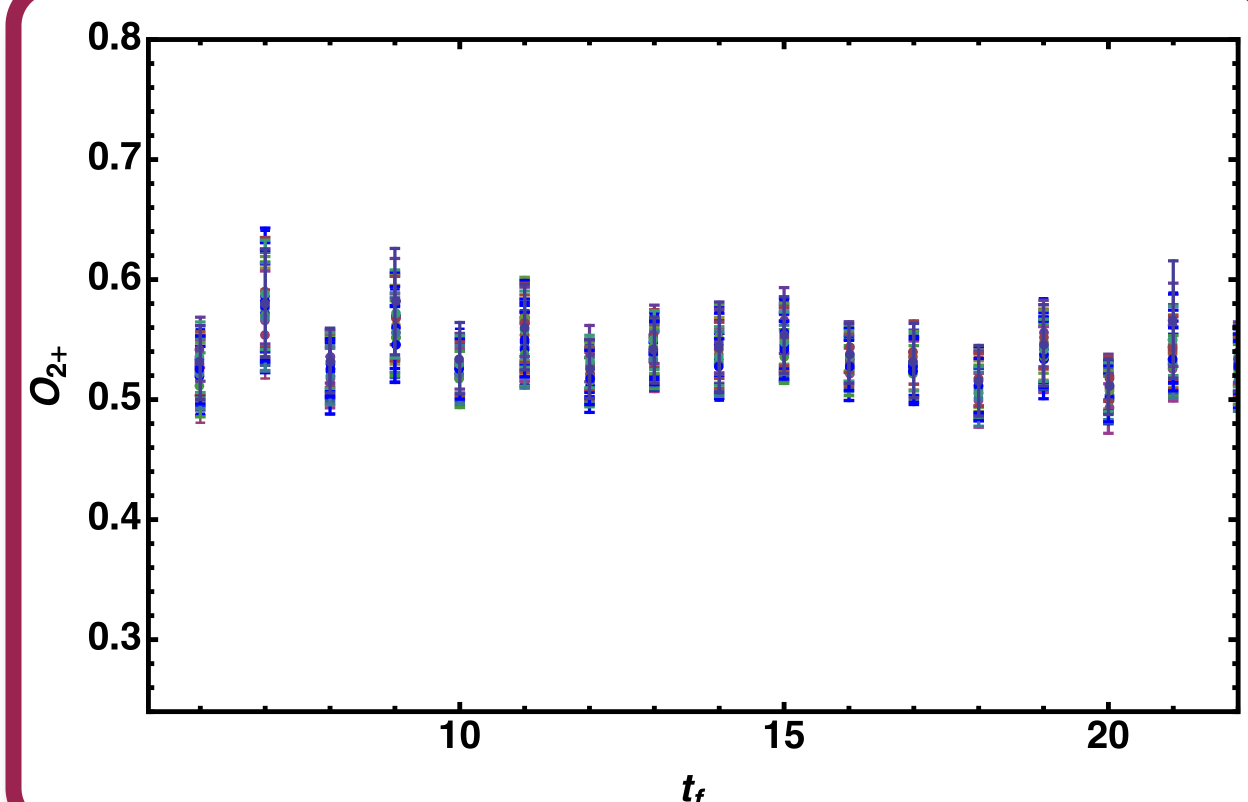
- Möbius DWF on HISQ
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5
- Wall + point sources for pions
- ~ 1000 cfgs, 1 source/cfg

MILC Collaboration Phys. Rev. D87 (2013) 054505
Narayanan, Neuberger (2006), Luscher (2010)
K. Orginos, C. Monahan (private communication)

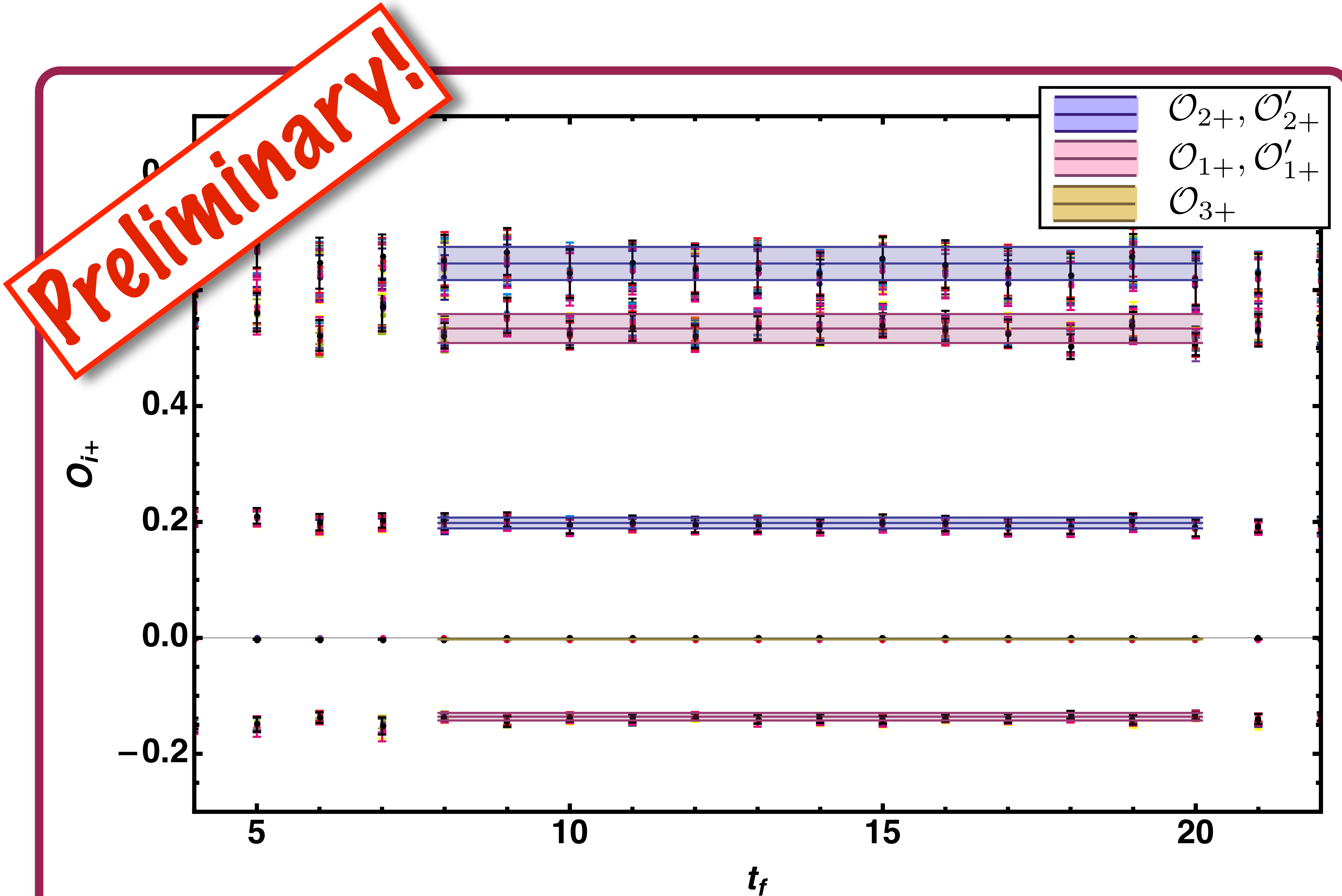
Signals



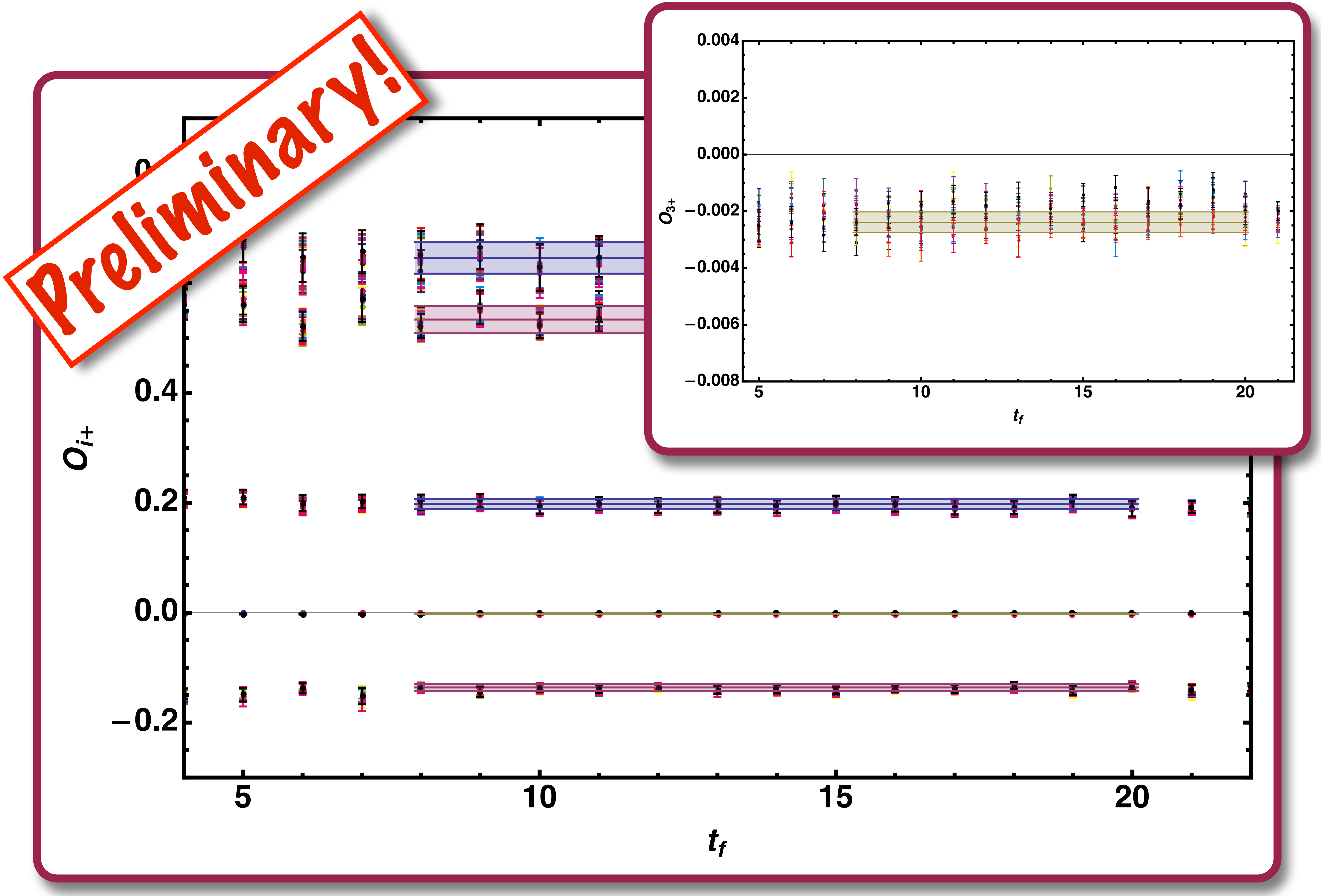




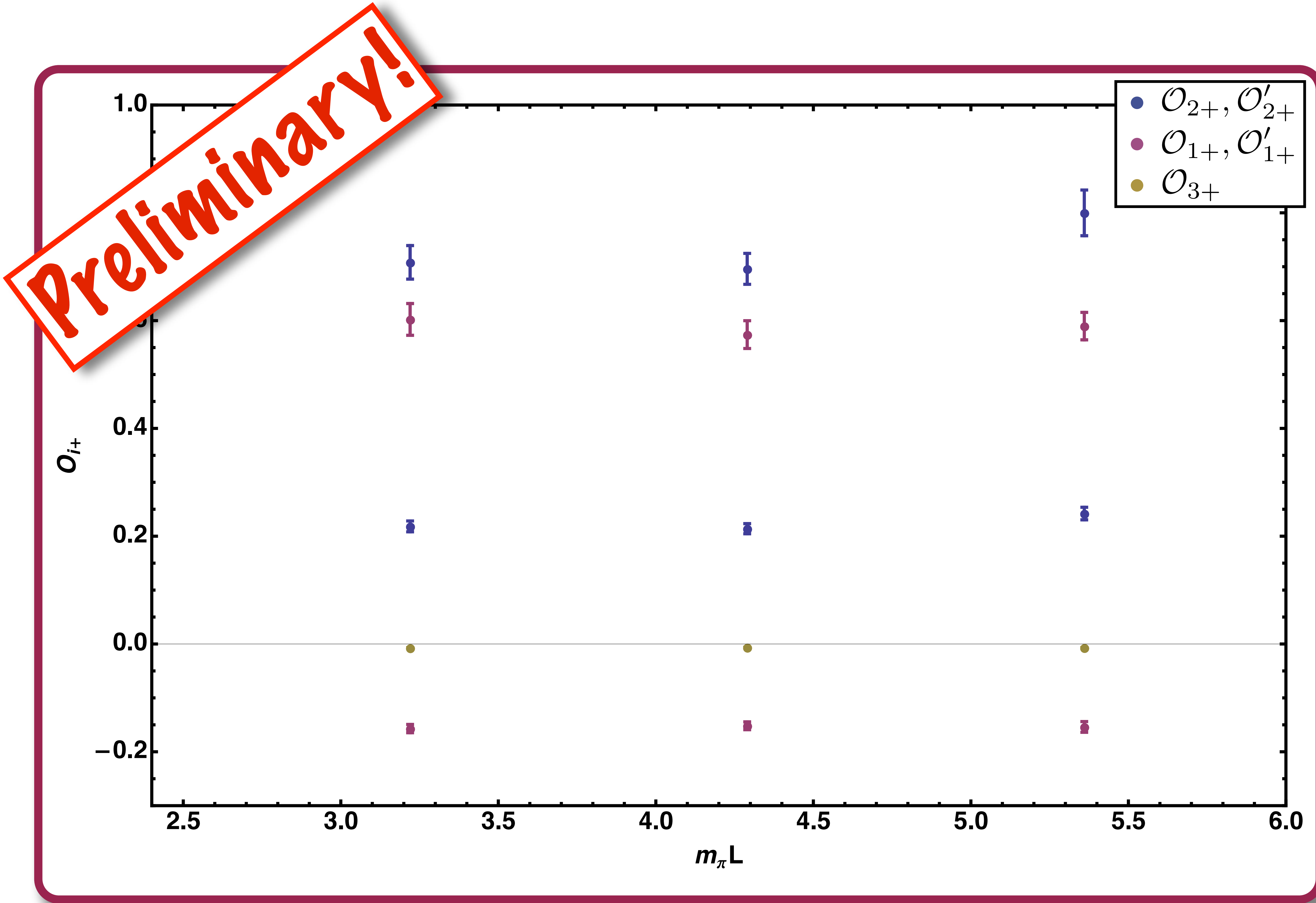
- $m_\pi \sim 135$ MeV
- L = 5.76 fm
- a = 0.12 fm



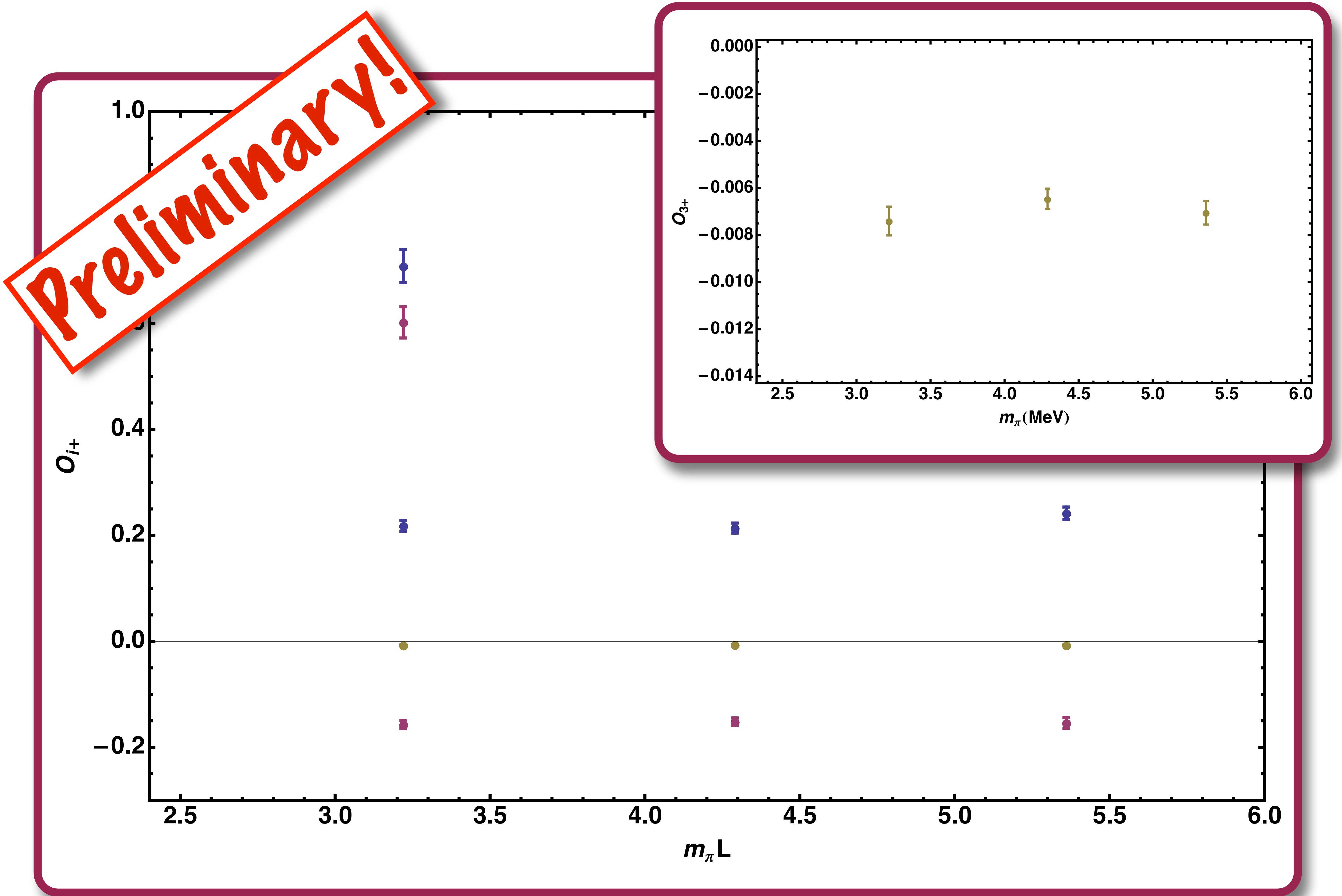
Preliminary!
$\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
$\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
$\mathcal{O}_{3+}$
O_{i+}
0.4
0.2
0.0
−0.2
5
10
15
20
t_f

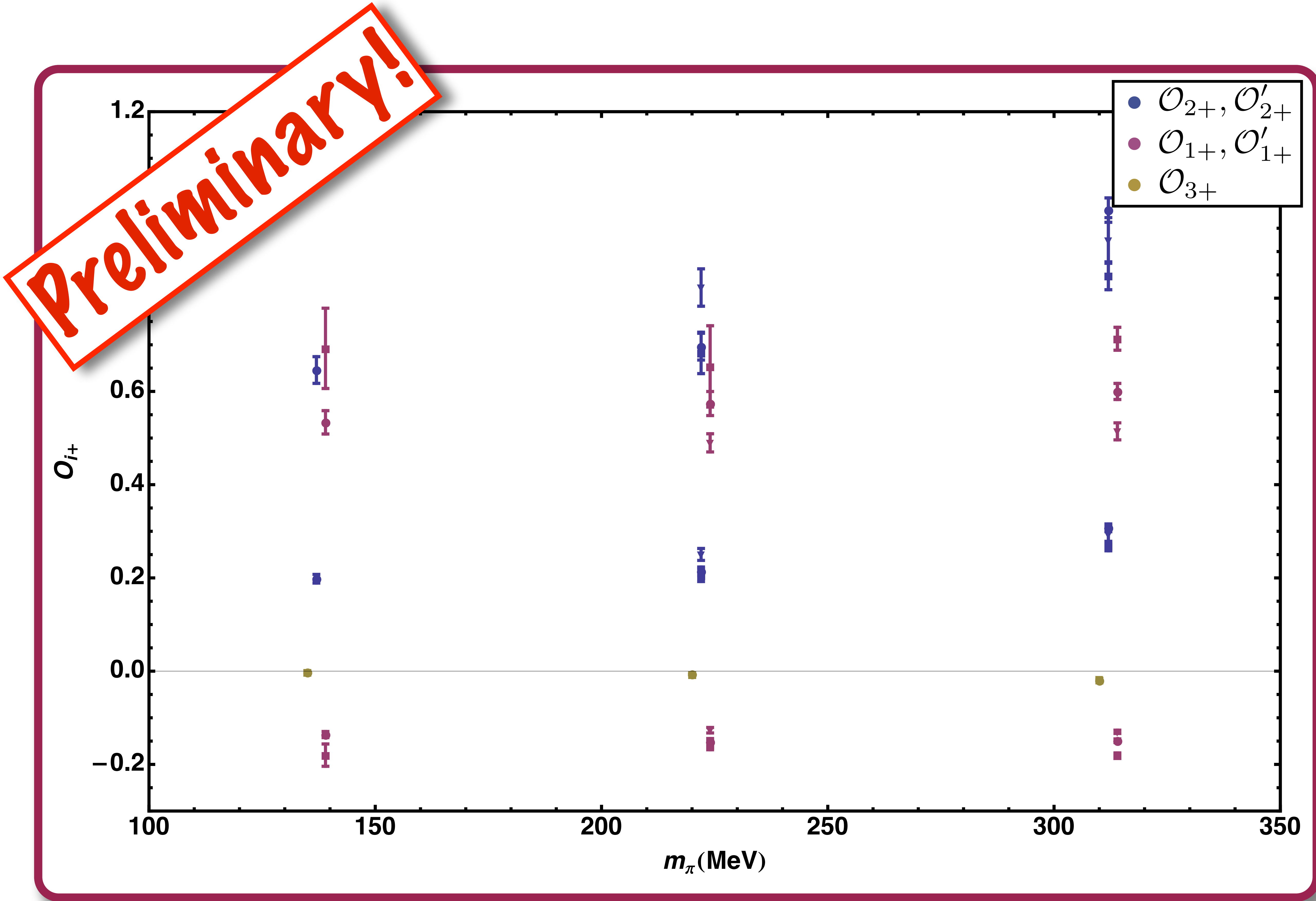


Preliminary!
0.4
0.2
0.0
−0.2
5
10
15
20
t_f
O_{i+}
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
O_{3+}

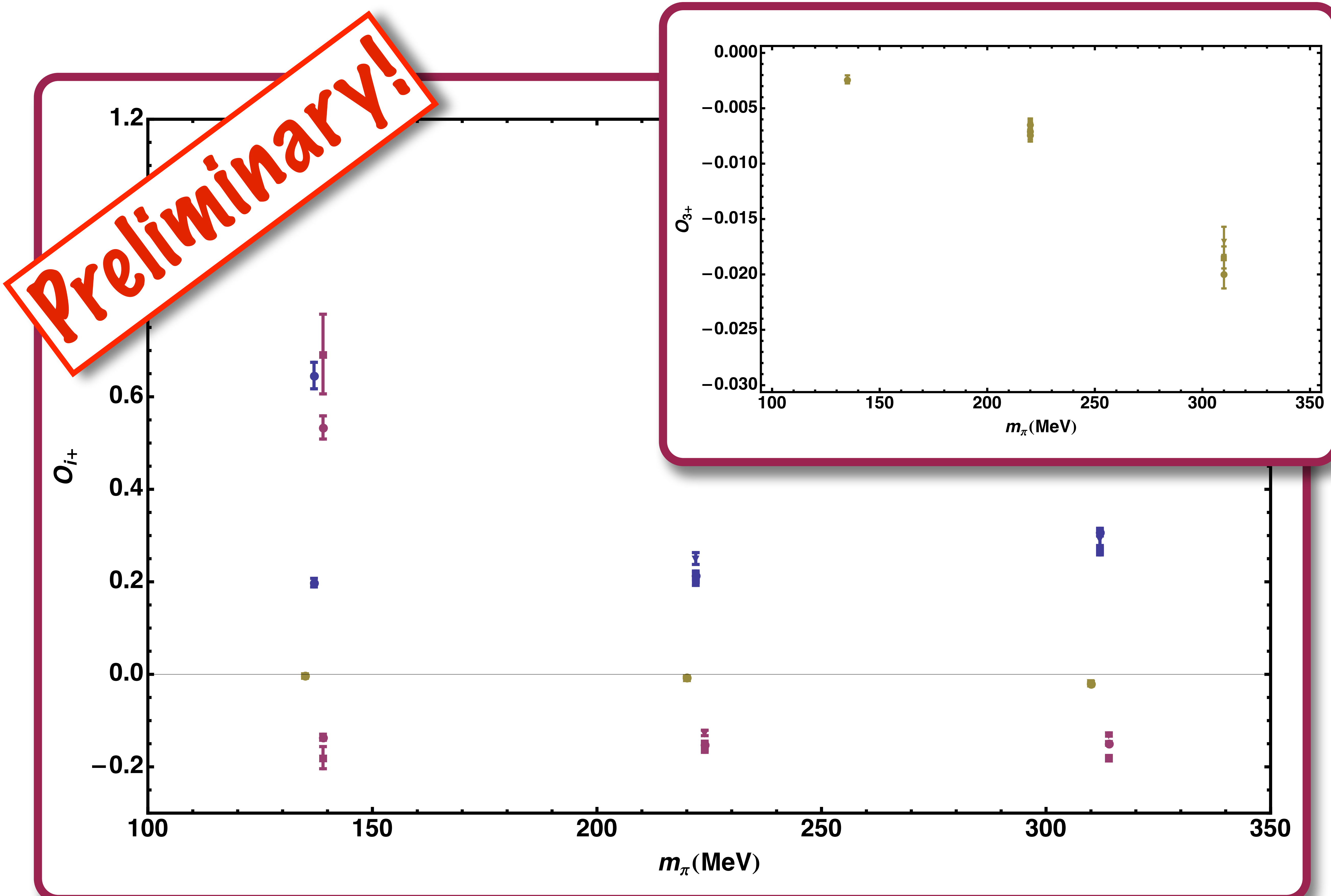


Preliminary!
$\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
$\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
$\mathcal{O}_{3+}$
O_{i+}
$m_\pi L$
1.0
0.4
0.2
0.0
−0.2
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

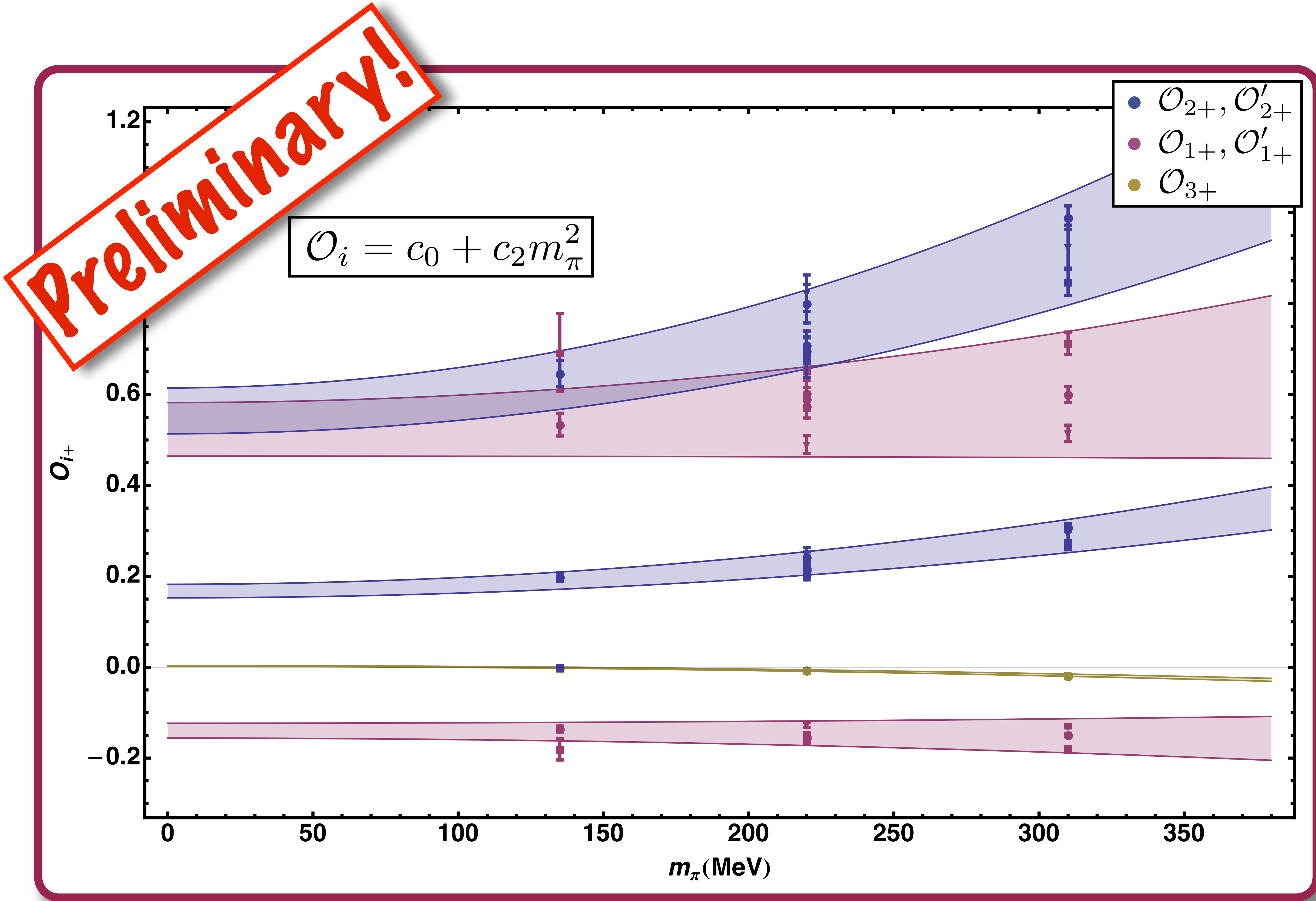

Preliminary!
1.0
0.4
0.2
0.0
−0.2
O_{i+}
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
m_πL
0.000
−0.002
−0.004
−0.006
−0.008
−0.010
−0.012
−0.014
O_{3+}
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
m_π(MeV)

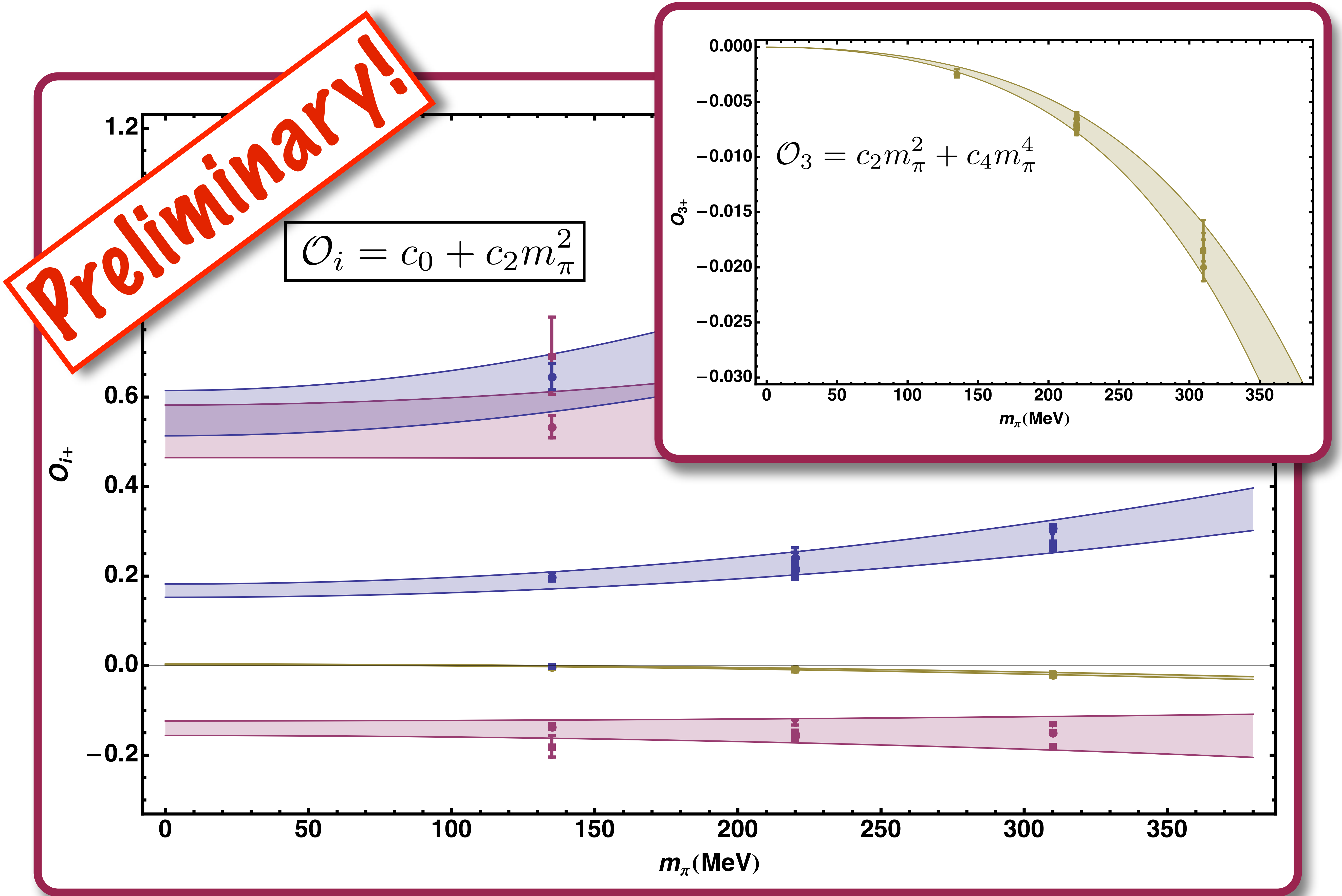


Preliminary!
$\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
$\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
$\mathcal{O}_{3+}$
o_{i+}
m_π(MeV)
1.2
0.6
0.4
0.2
0.0
−0.2
100
150
200
250
300
350



Preliminary!
1.2
0.6
0.4
0.2
0.0
−0.2
O_{i+}
100
150
200
250
300
350
m_π(MeV)
0.000
−0.005
−0.010
−0.015
−0.020
−0.025
−0.030
O_{3+}
100
150
200
250
300
350
m_π(MeV)

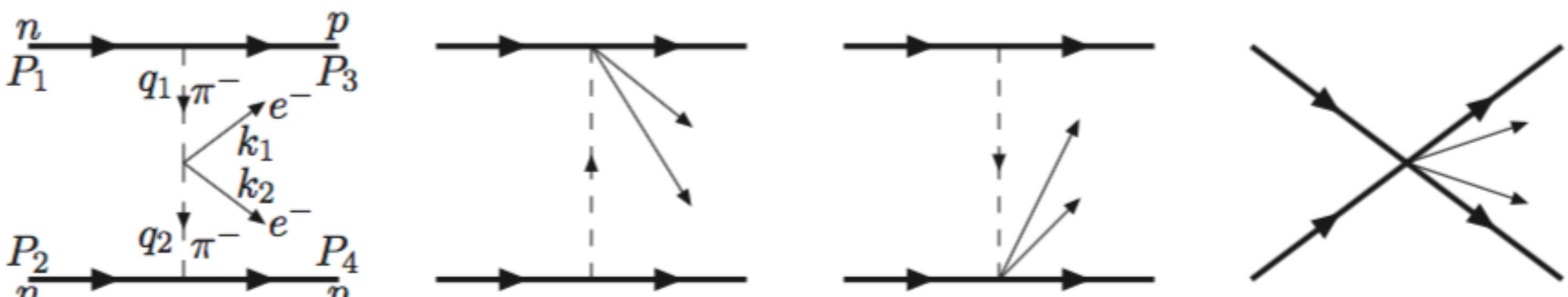

Preliminary!
$\mathcal{O}_i = c_0 + c_2 m_\pi^2$
$\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
$\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
$\mathcal{O}_{3+}$
O_{i+}
m_π(MeV)
1.2
0.6
0.4
0.2
0.0
−0.2
0
50
100
150
200
250
300
350


Preliminary!
$\mathcal{O}_i = c_0 + c_2 m_\pi^2$
O_{i+}
m_π(MeV)
1.2
0.6
0.4
0.2
0.0
−0.2
0
50
100
150
200
250
300
350
$\mathcal{O}_3 = c_2 m_\pi^2 + c_4 m_\pi^4$
O_{3+}
0.000
−0.005
−0.010
−0.015
−0.020
−0.025
−0.030
m_π(MeV)

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 $\pi^- \rightarrow \pi^+$ 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

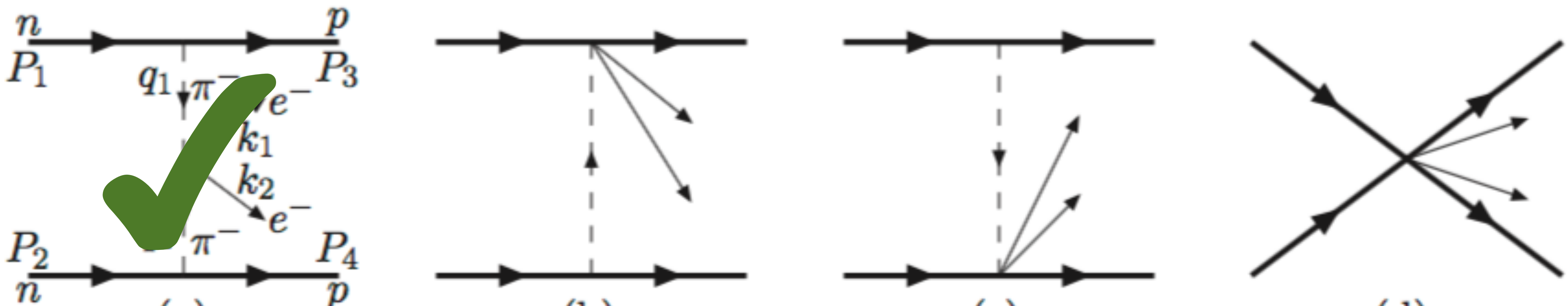


(a) (b) (c) (d)

$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^0)$ $\mathcal{O}(p^0)$ $\mathcal{O}(p^2)$

Contact operators

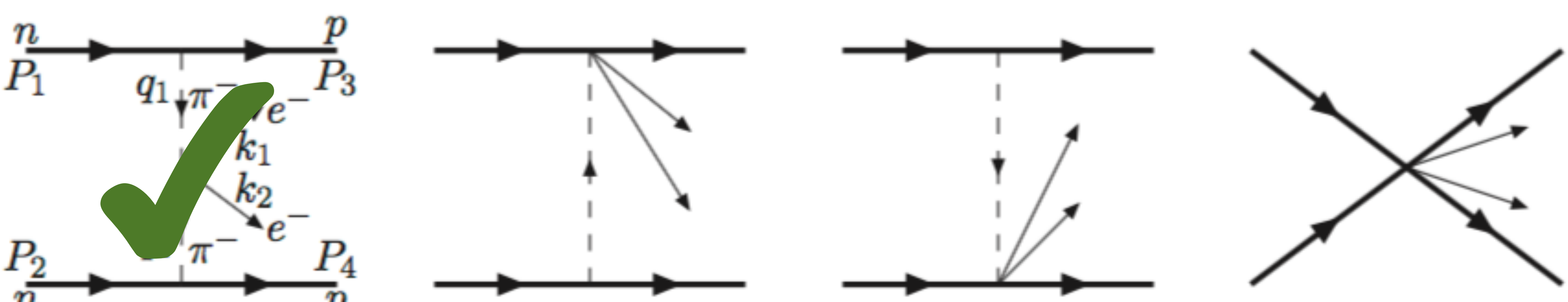
- LO almost complete!



(a) $\mathcal{O}(p^{-2})$ (b) $\mathcal{O}(p^0)$ (c) $\mathcal{O}(p^0)$ (d) $\mathcal{O}(p^2)$

Contact operators

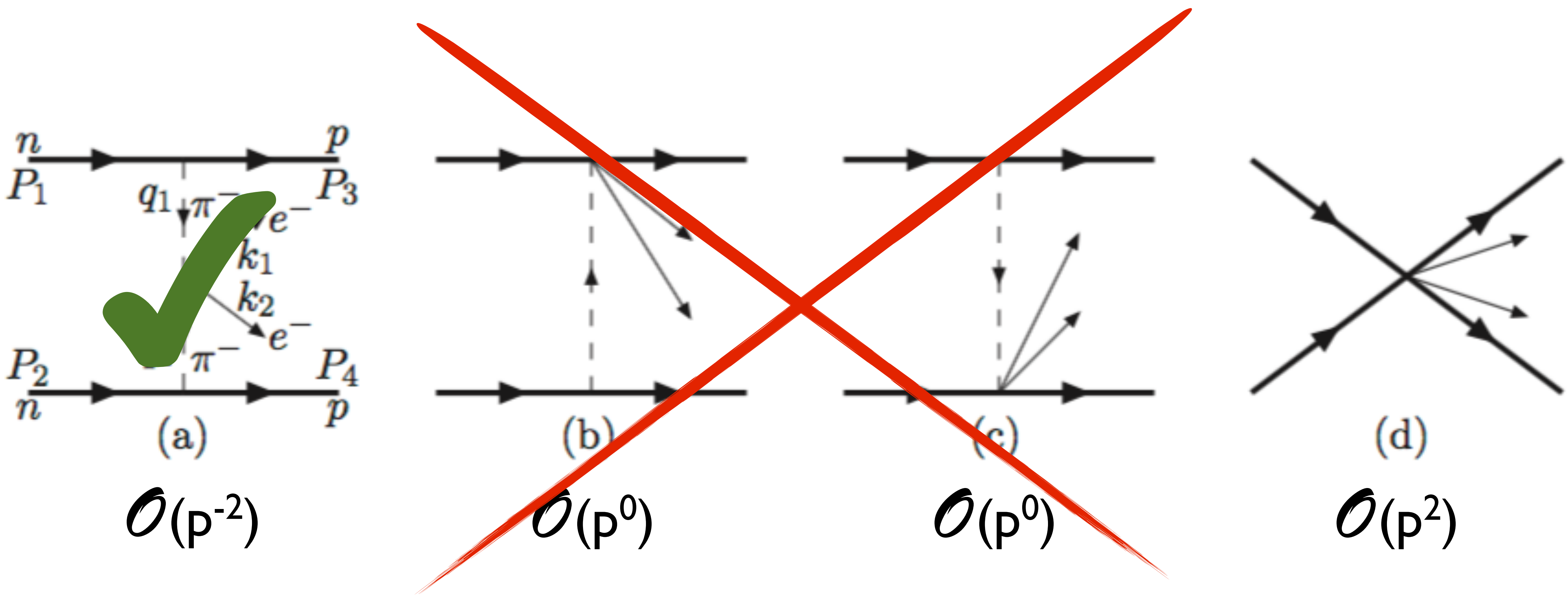
- LO almost complete!
- NLO: disconnected diagrams



(a) $\mathcal{O}(p^{-2})$ (b) $\mathcal{O}(p^{0})$ (c) $\mathcal{O}(p^{0})$ (d) $\mathcal{O}(p^{2})$

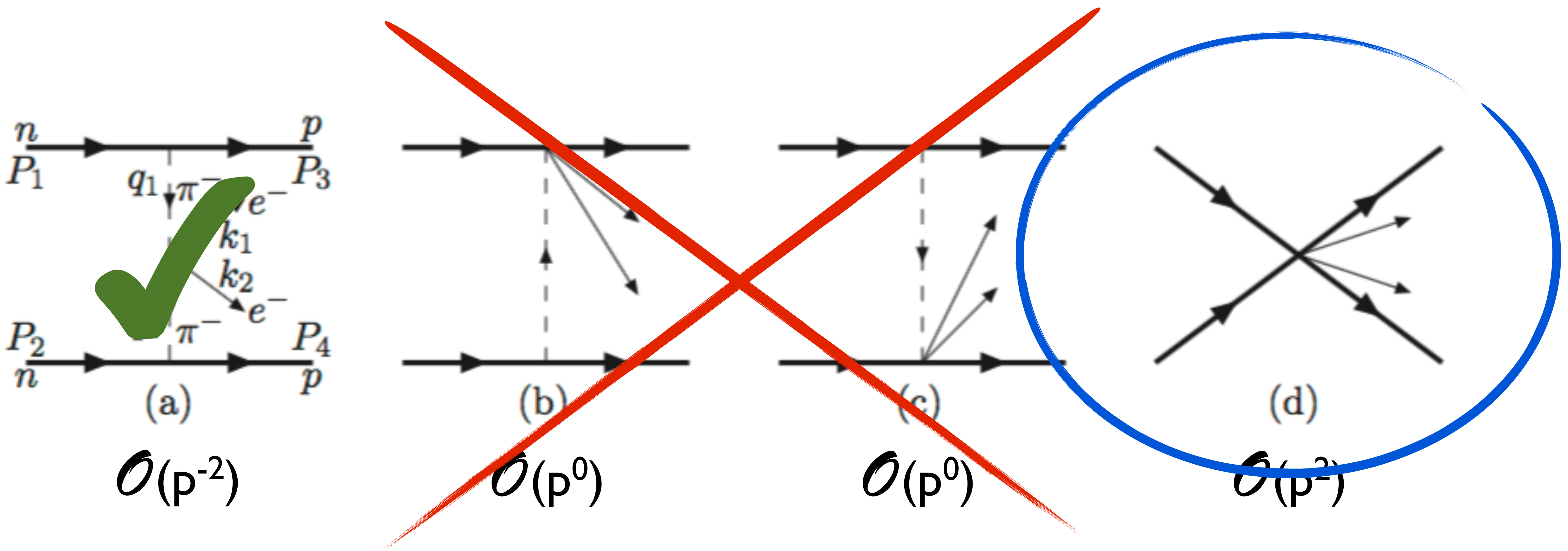
Contact operators

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



Contact operators

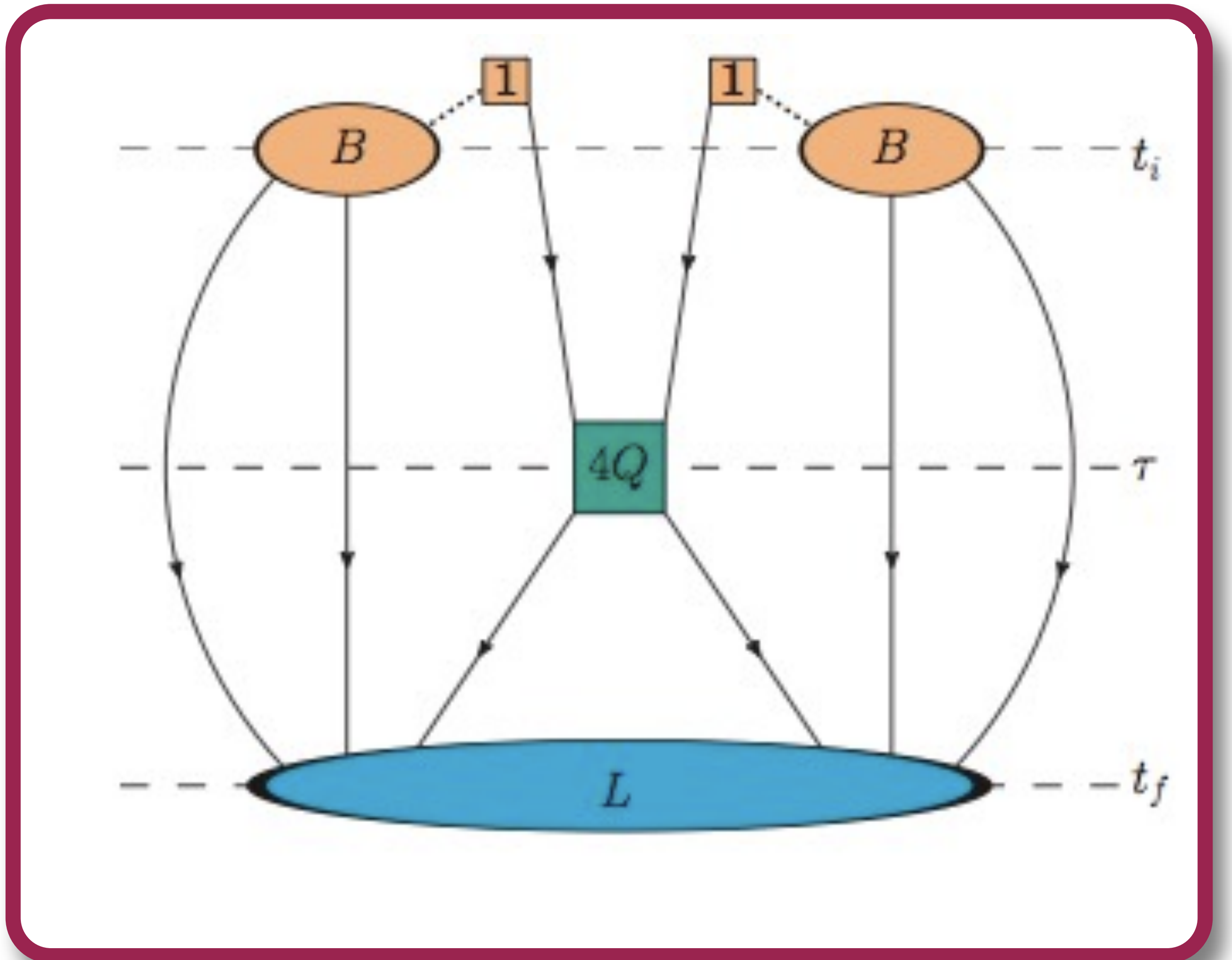
- LO almost complete!
- NLO: disconnected diagrams
  - Don't contribute to $0^+ \to 0^+$ nuclear transitions
- $nn \to pp$ contact operators

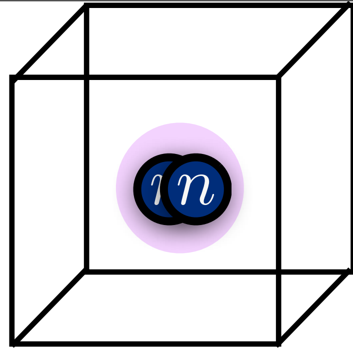


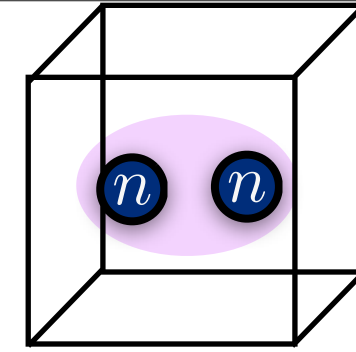
*Doi & Endres, Originos et. al., Günther et. al.

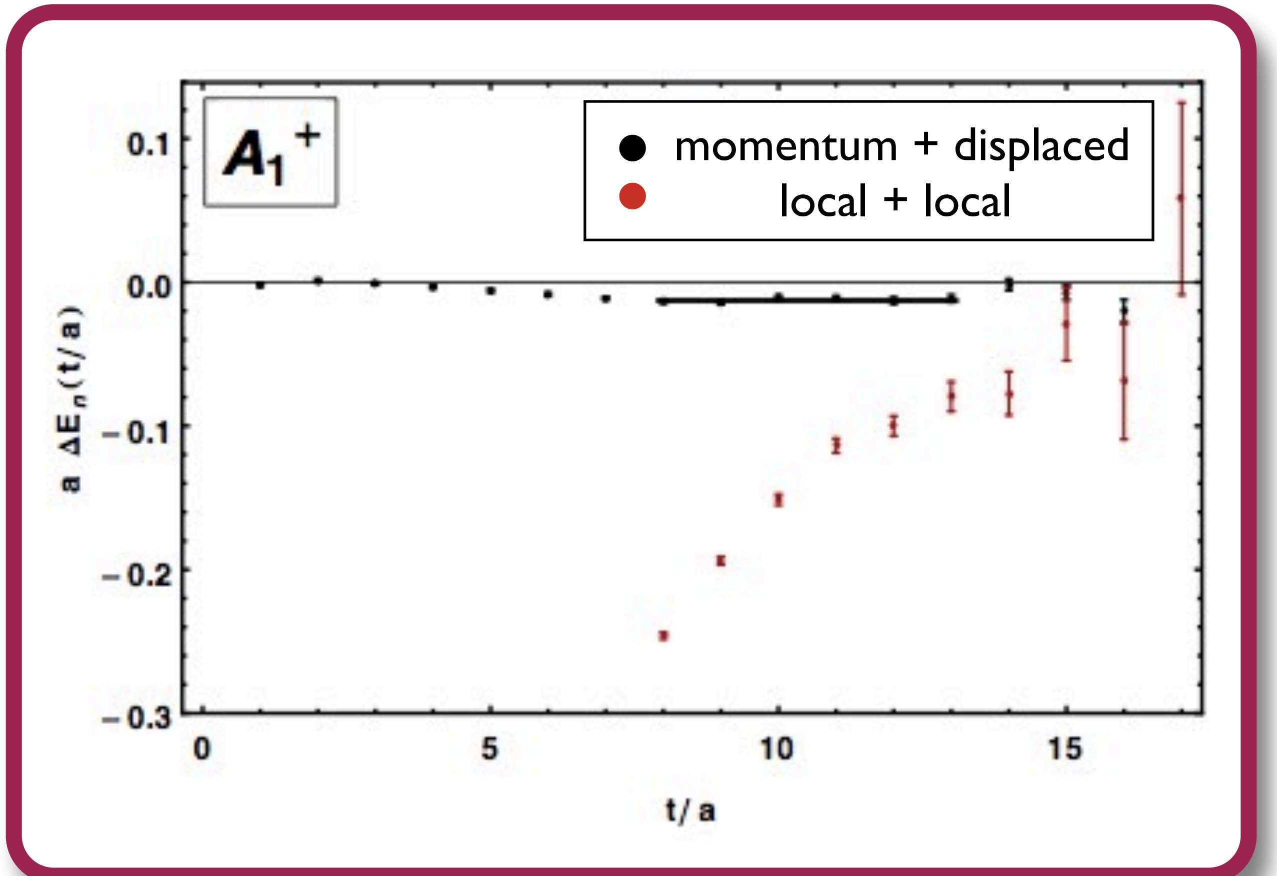
Contractions

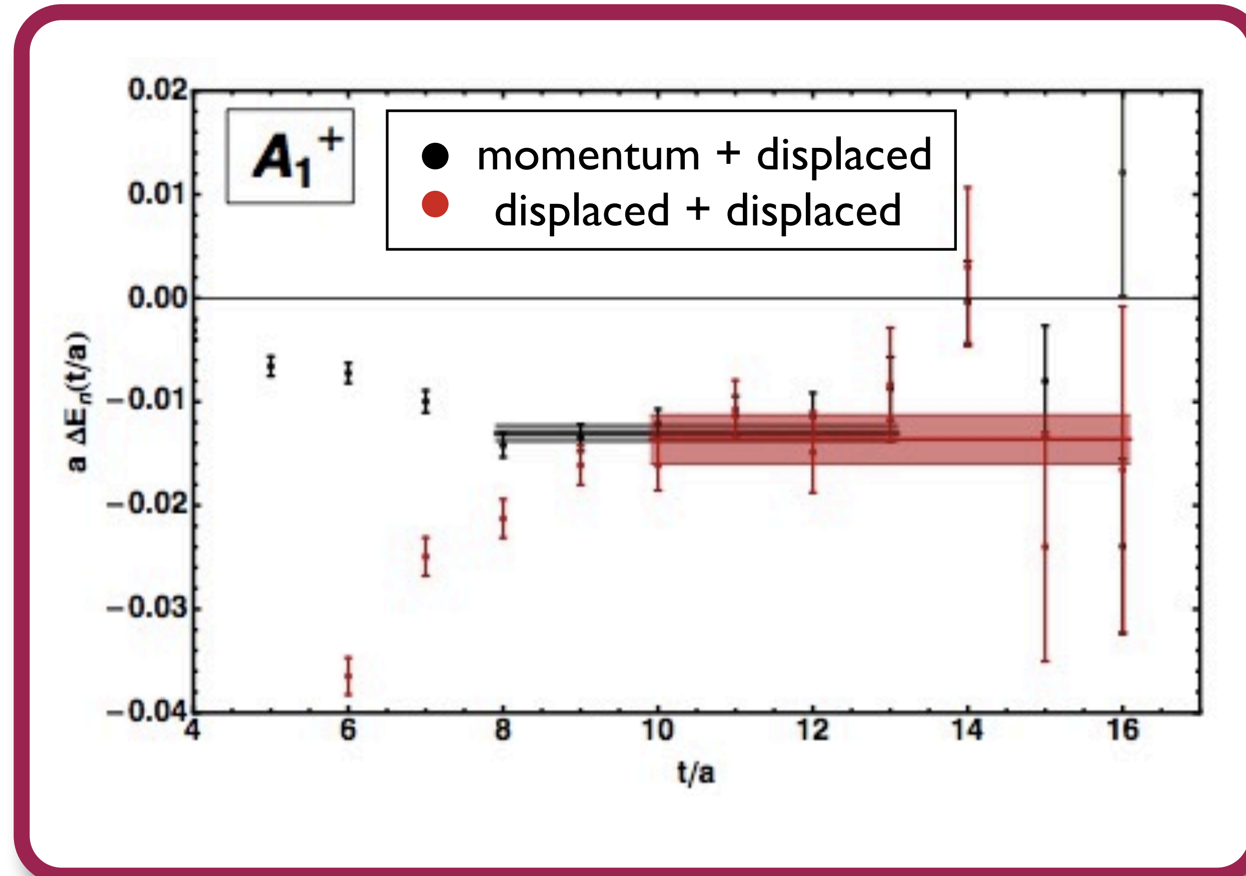
- Isospin limit: 576 contractions
- Extension of unified contraction method*
- Need position space source & sink
  - otherwise all-to-all propagators connect to 4-quark operator
  - stochastically project onto zero total momentum



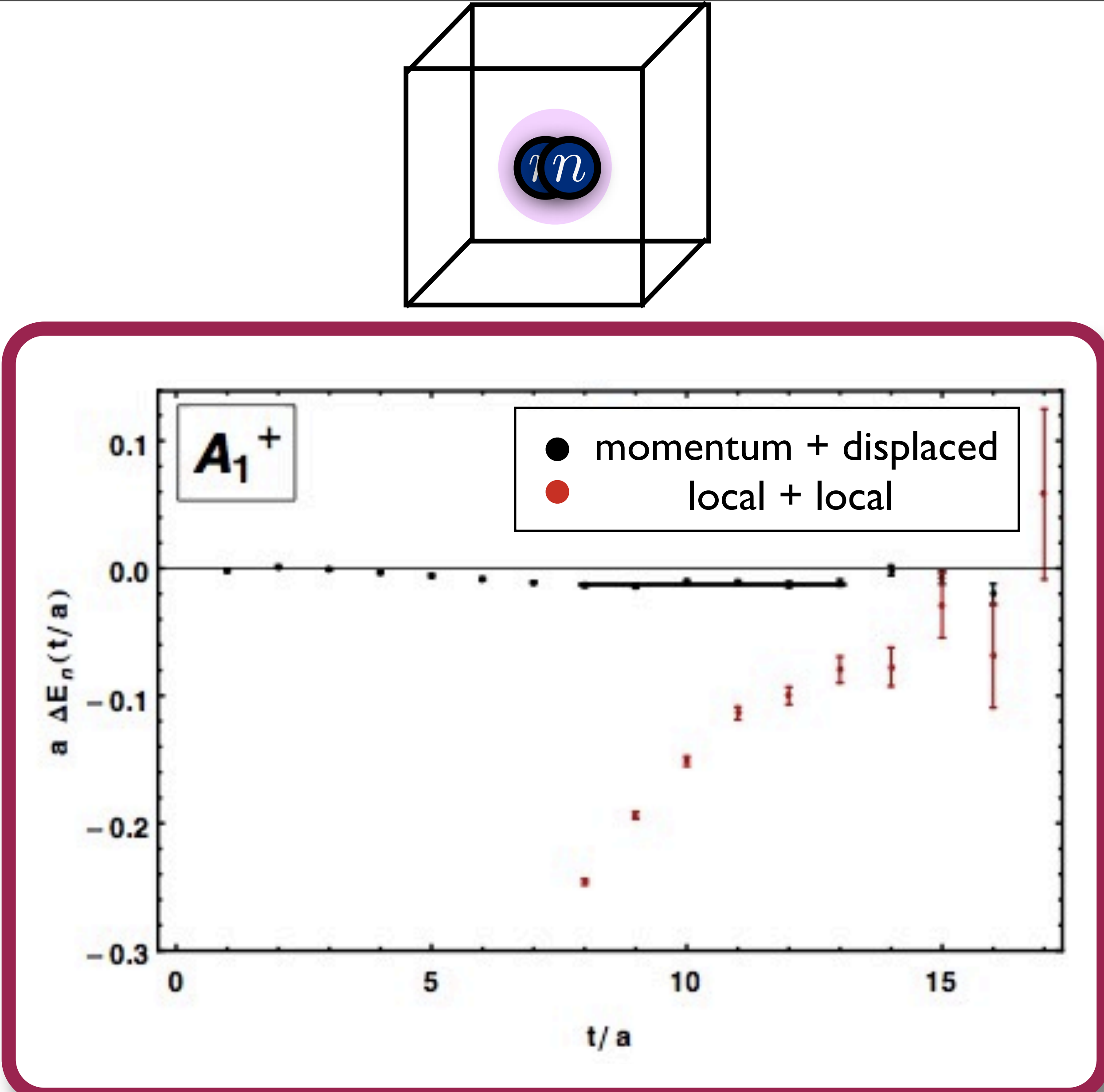


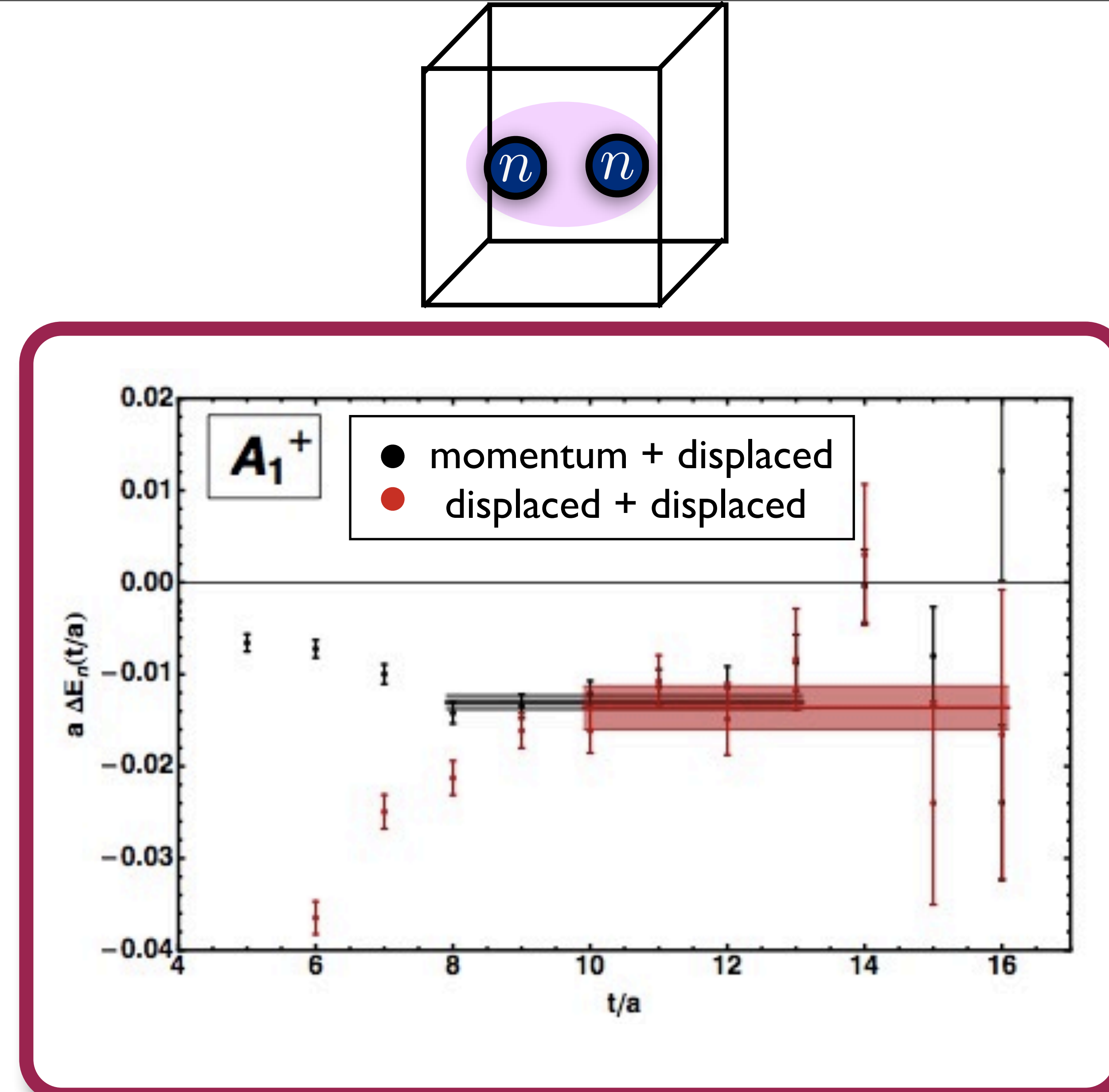






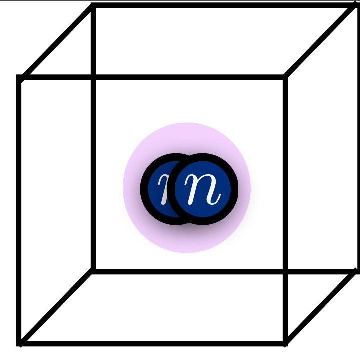
Iso-clover cfgs (W. Detmold, R.Edwards, D. Richards, K. Orginos)

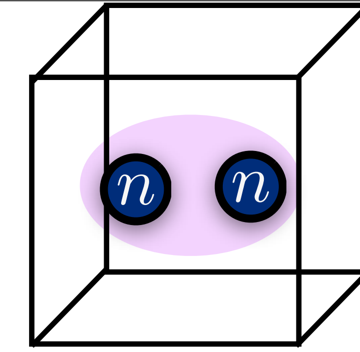


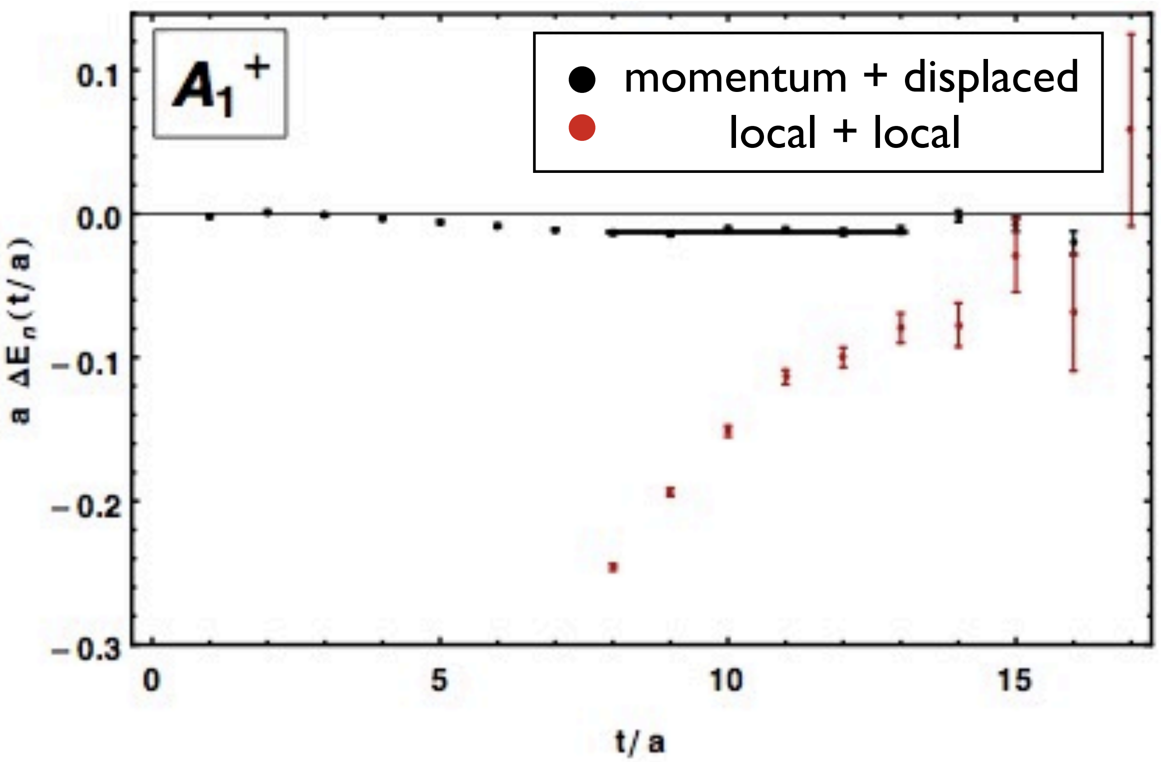


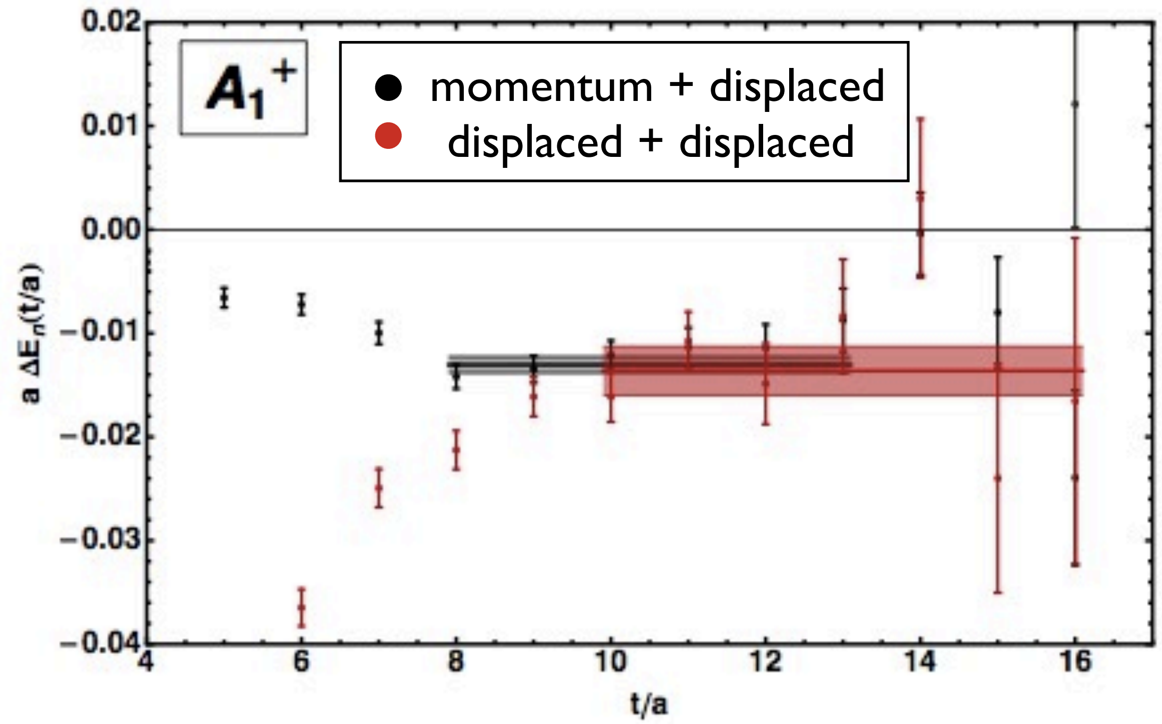
Need displaced operators!

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







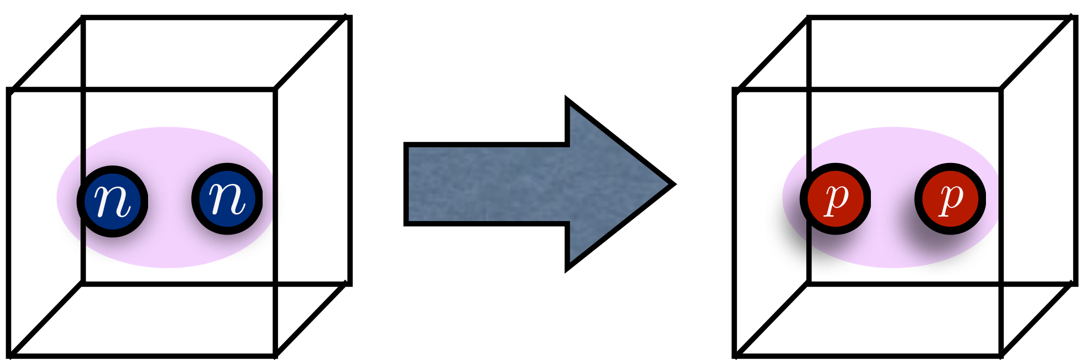


Finite volume formalism for 2 → 2 matrix elements completed:

R. Briceño, M. Hansen Phys.Rev. D94 (2016) no.1, 013008

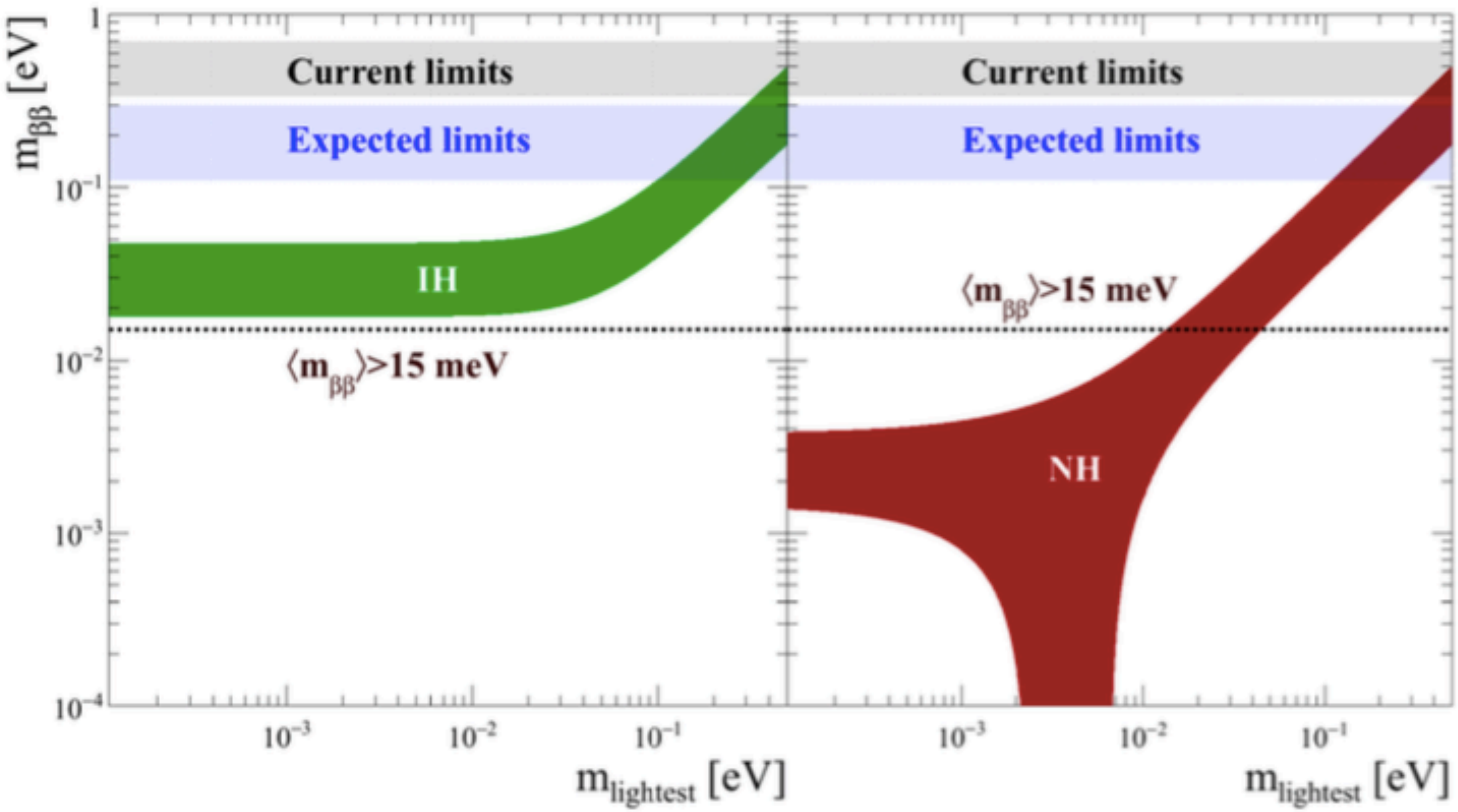
Renormalization known in $\overline{\text{MS}}$:

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



Current limits
Expected limits
IH
⟨m_ββ⟩>15 meV
Current limits
Expected limits
⟨m_ββ⟩>15 meV
NH
m_ββ [eV]
m_lightest [eV]
m_lightest [eV]

Ton-scale Neutrinoless Double Beta Decay (0νββ) - A Notional Timeline

Search for Lepton Number Violation