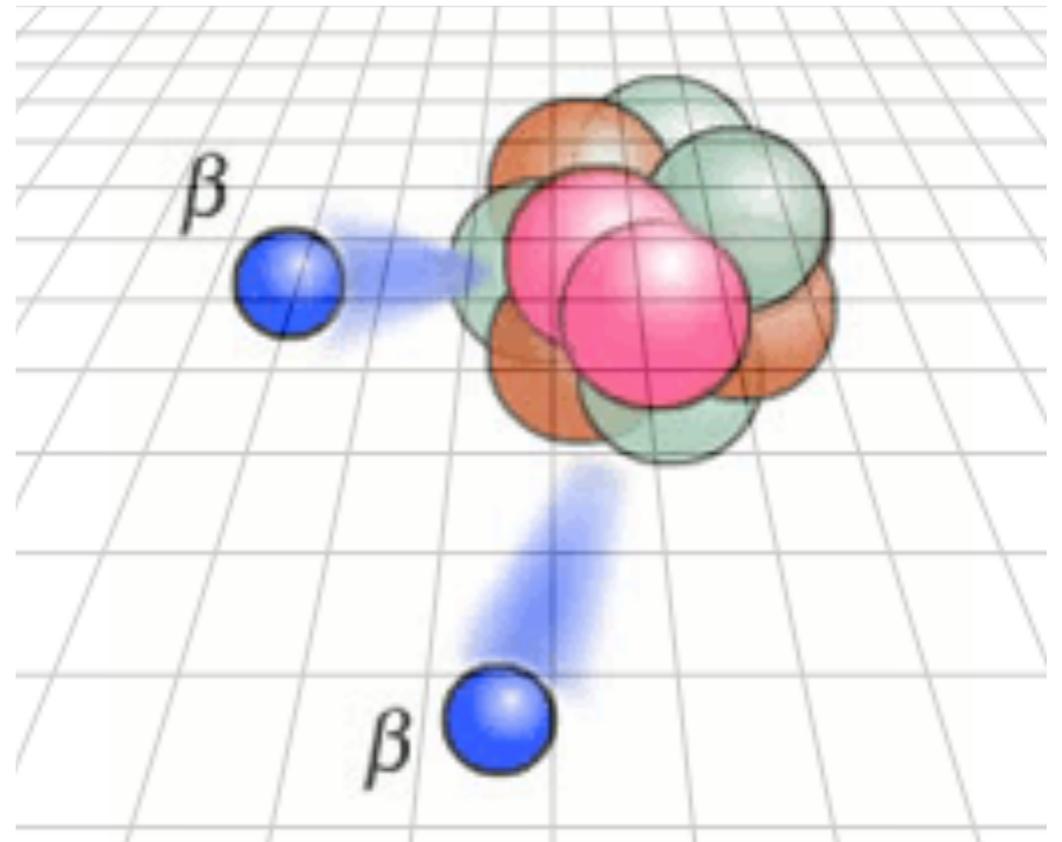


# Neutrinoless Double Beta Decay from Lattice QCD



Evan Berkowitz  
LLNL  
KITP NUCLEAR16

And soon: Amy Nicholson  
UC Berkeley  
KITP NUCLEAR16  
CONFERENCE



~~Amy Nicholson  
UC Berkeley  
Lattice 2016  
Southampton, UK~~

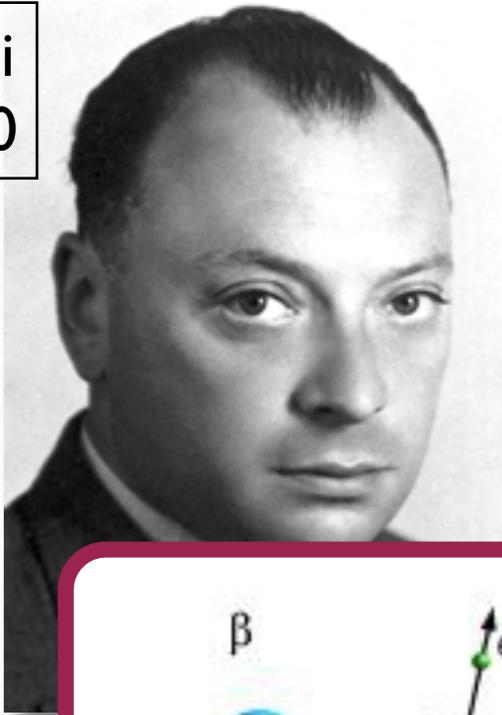




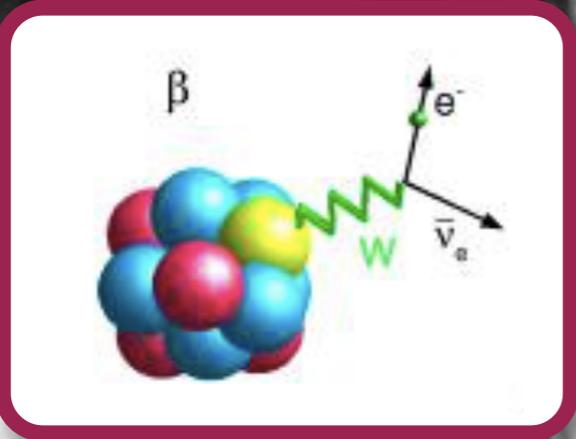
- LBL/UCB: Chia Cheng Chang, Amy Nicholson, André Walker-Loud
- LLNL: EB, Enrico Rinaldi, Pavlos Vranas
- NERSC: Thorsten Kurth
- JLab: Balint Joo
- CCNY: Brian Tiburzi
- nVidia: Kate Clark



Pauli  
1930



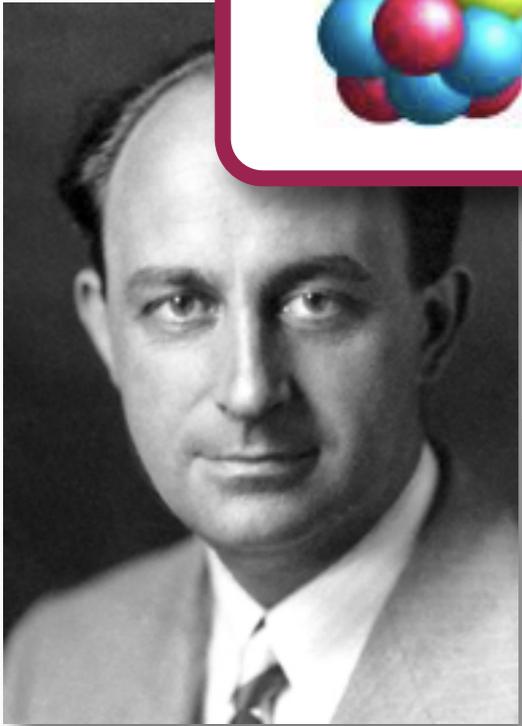
# History



Chadwick  
1932

Racah  
1937

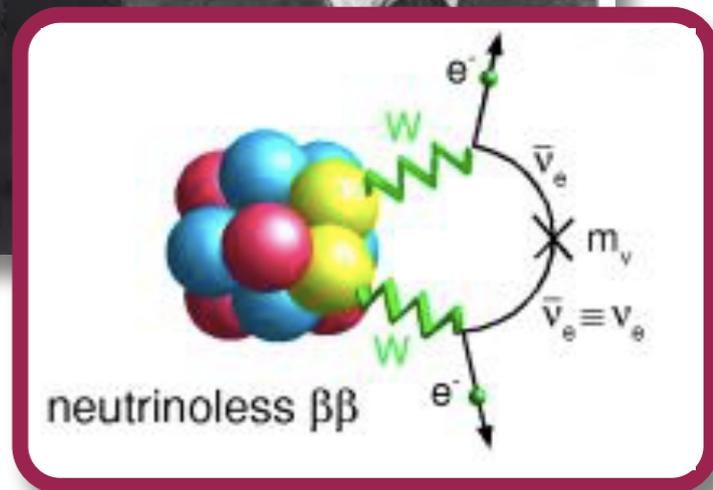
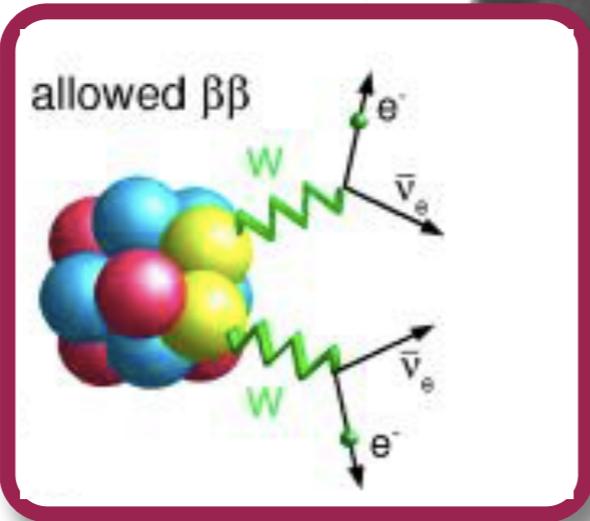
Majorana  
1937



Fermi  
1934

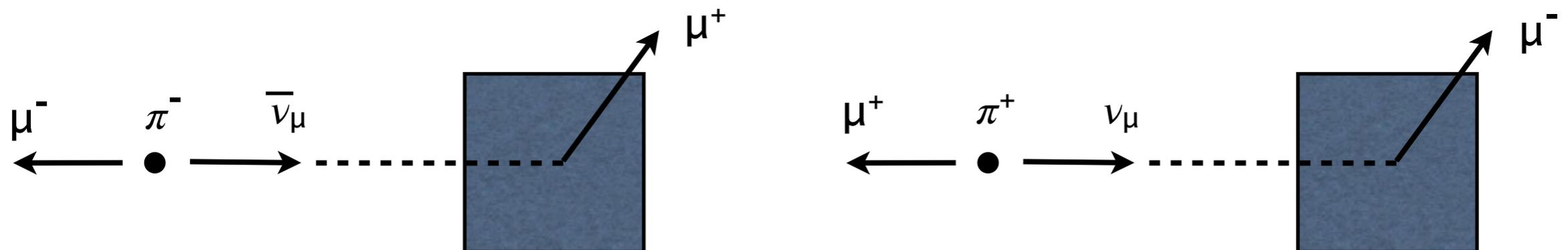
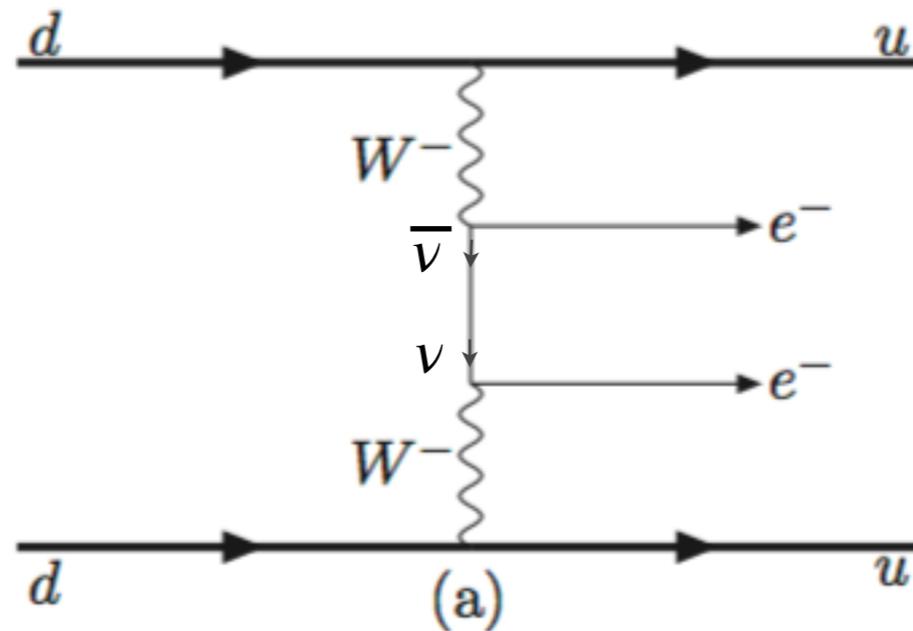


Goppert-Mayer  
1935



# Lepton Number

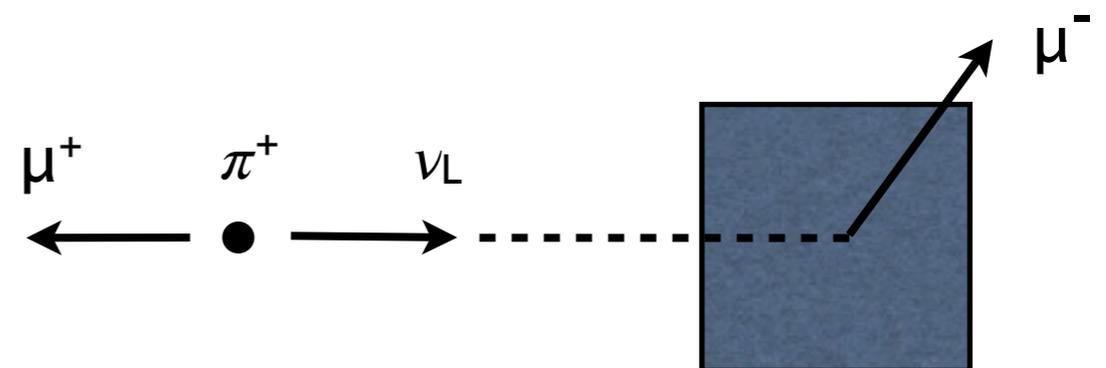
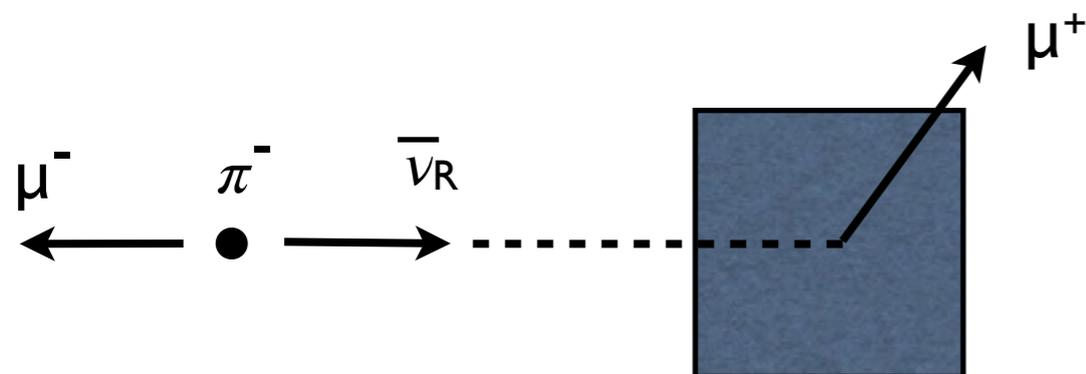
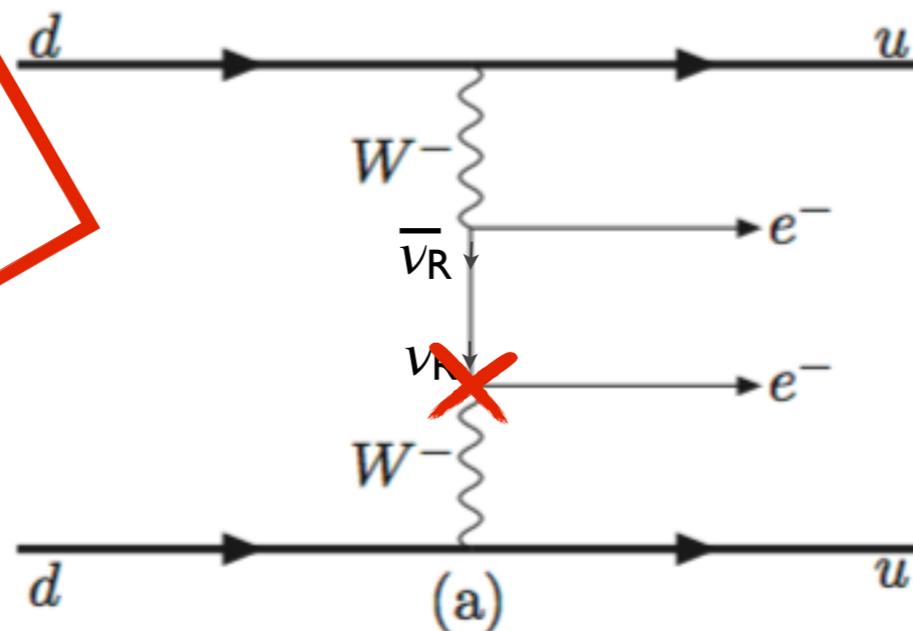
Neutrinos have no known charge or other additively conserved quantum number



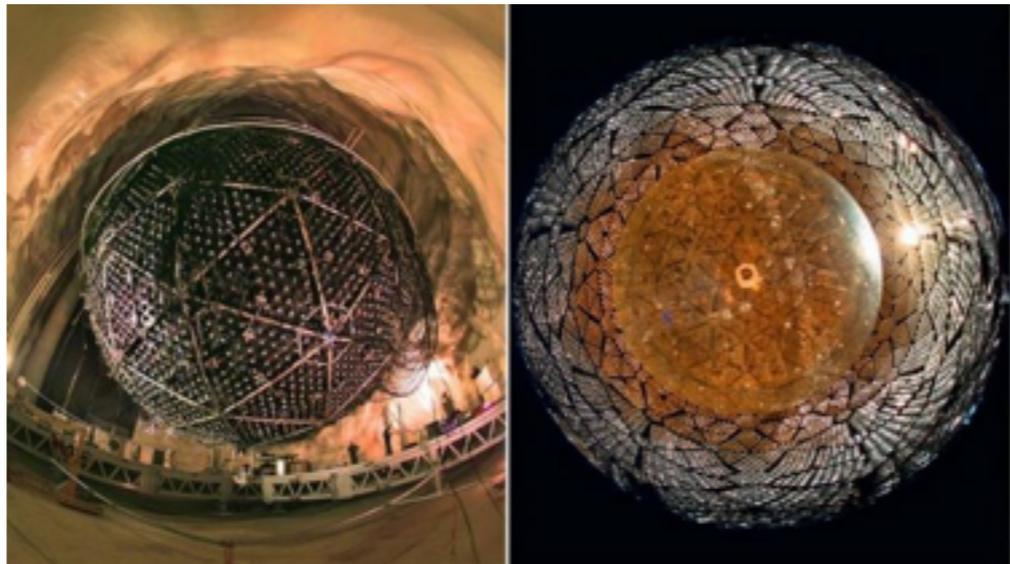
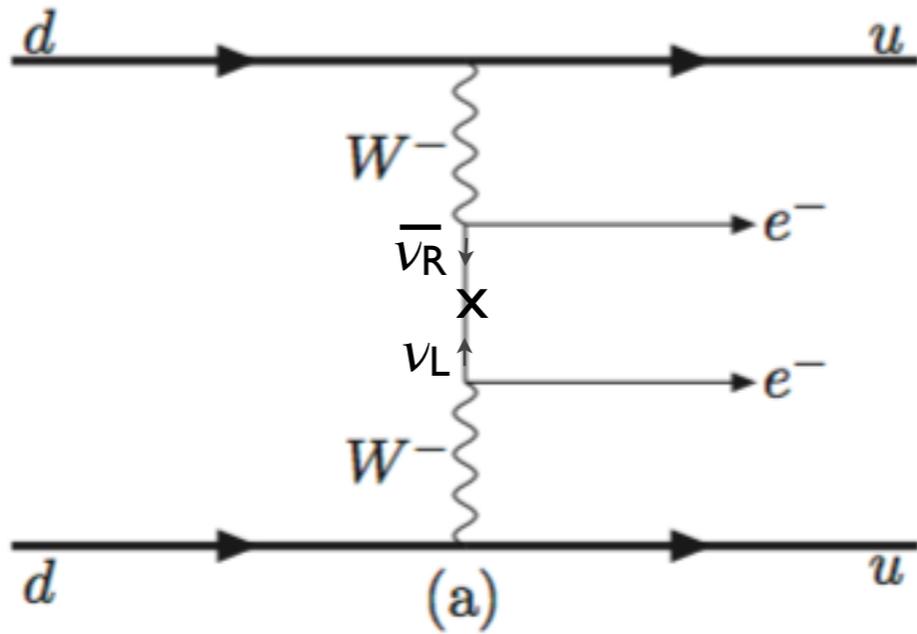
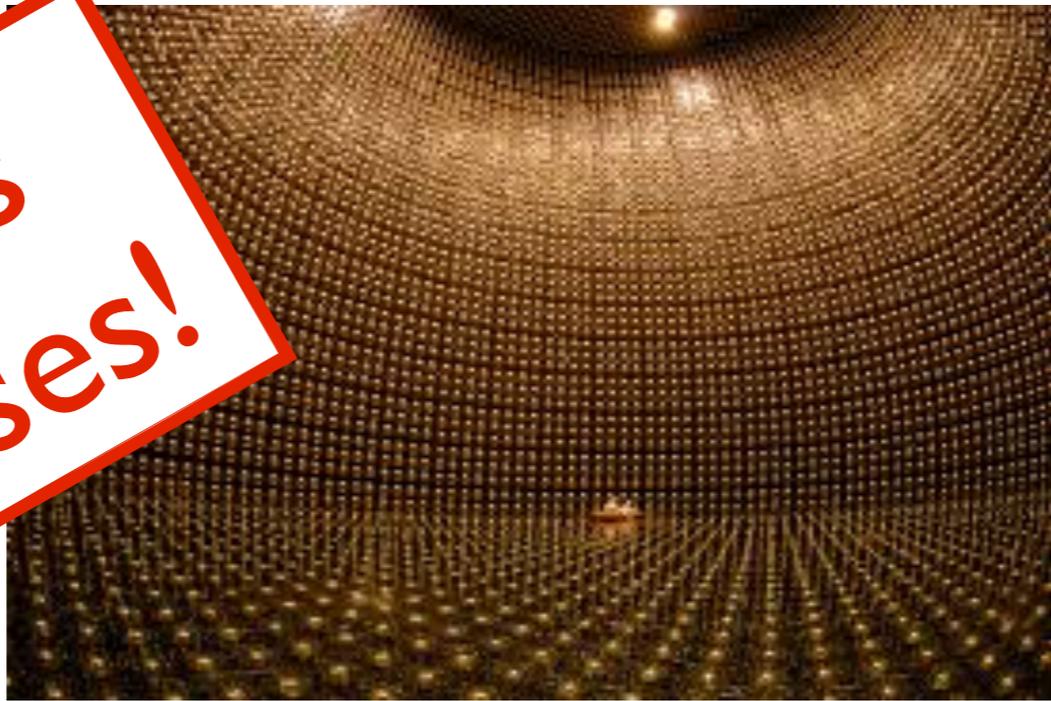
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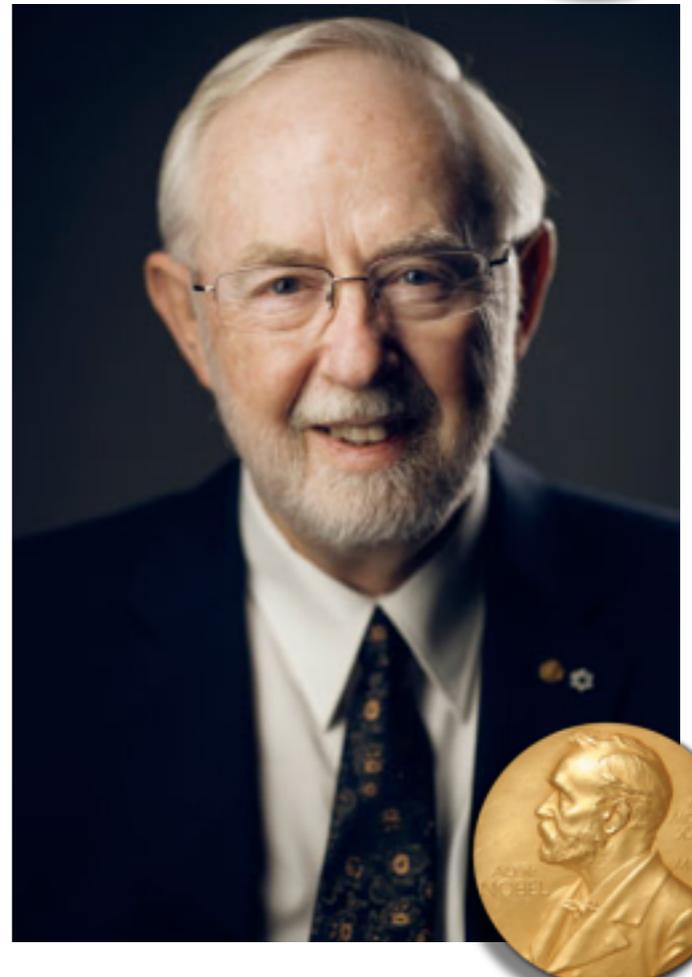
Forbidden by helicity?



Neutrinos  
have masses!



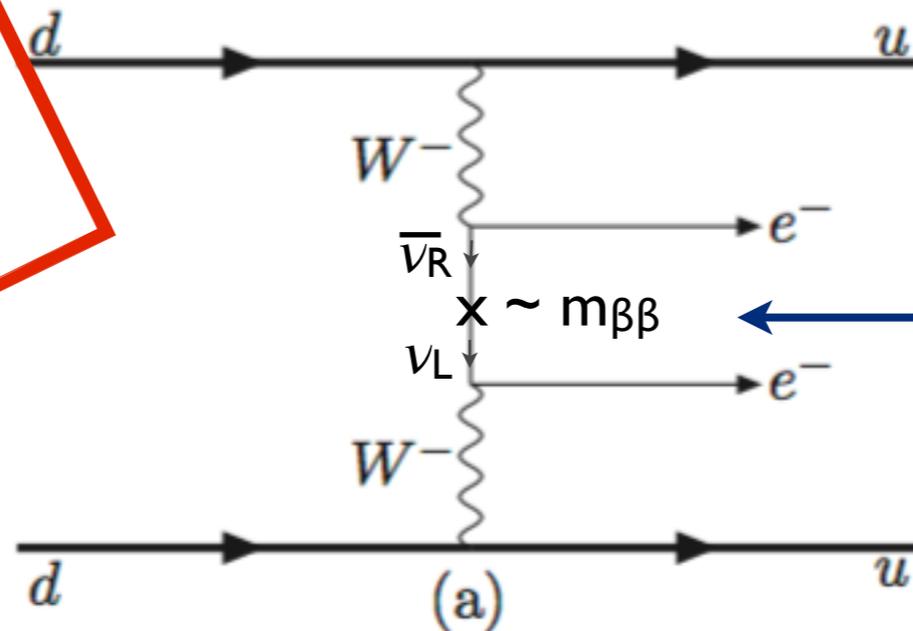
Takaaki Kajita  
(Super-K)  
Arthur B.  
McDonald  
(SNO)  
Nobel Prize,  
2015



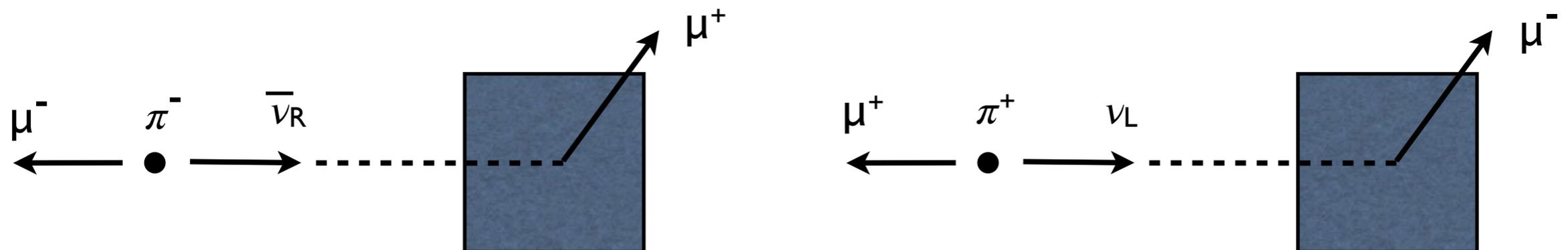
# Lepton Number

Neutrinos have no known charge or other additively conserved quantum number

But they're tiny!



oscillation experiments don't tell us absolute mass scale, but  $0\nu\beta\beta$  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



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

# Majorana or Dirac?

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

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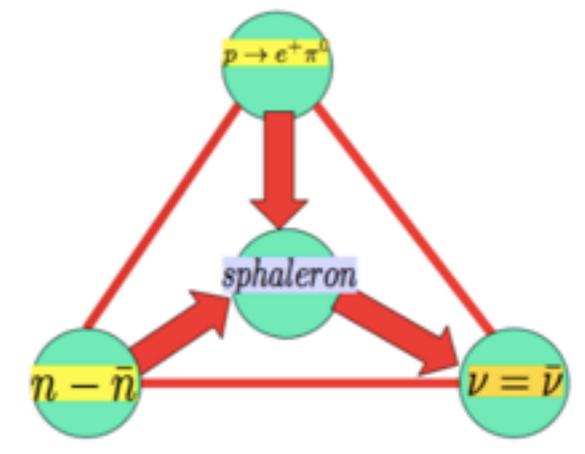
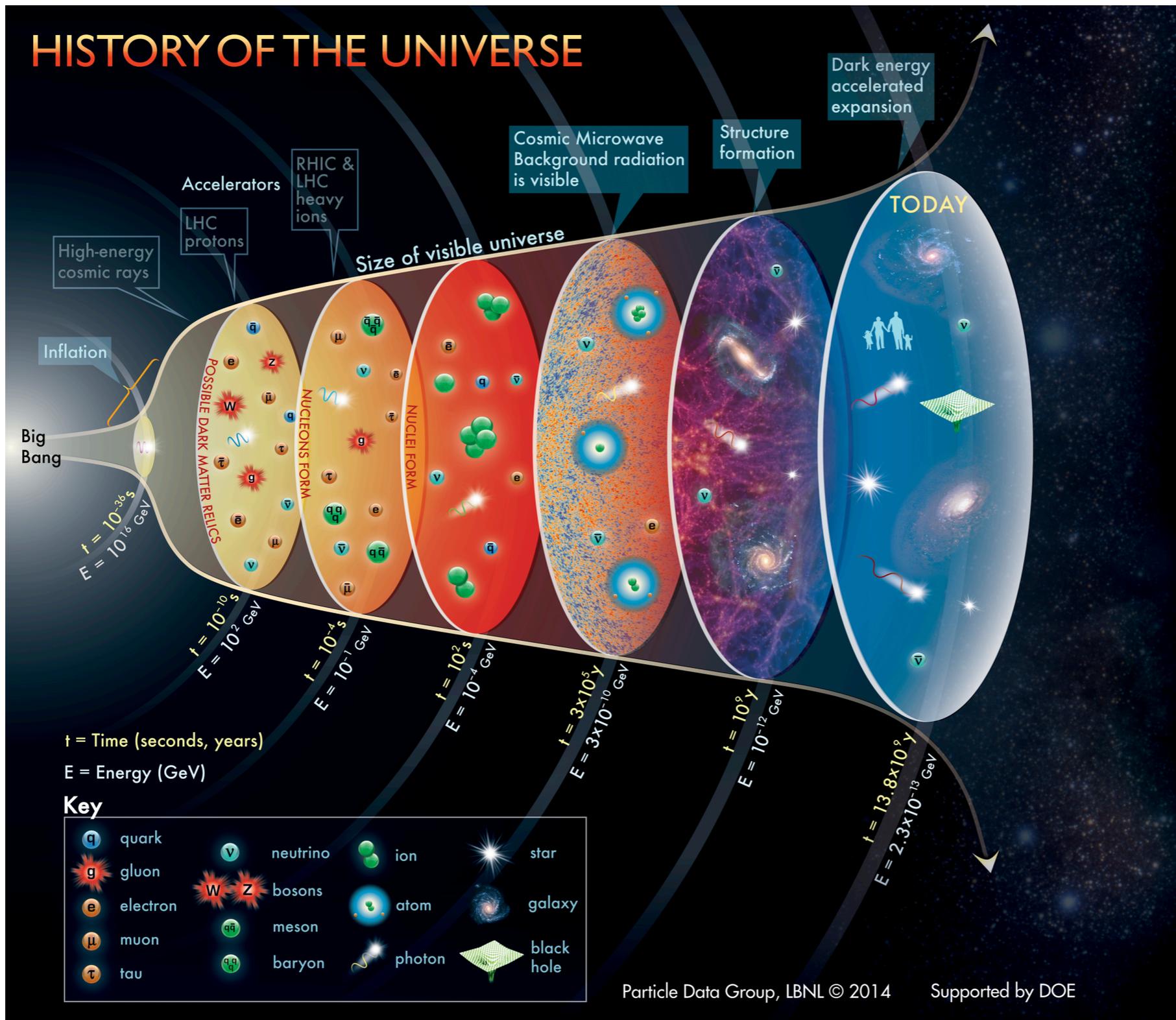
$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

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

$$M_D \sim 200 \text{ GeV} \quad m_l \sim 0.05 \text{ eV}$$

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

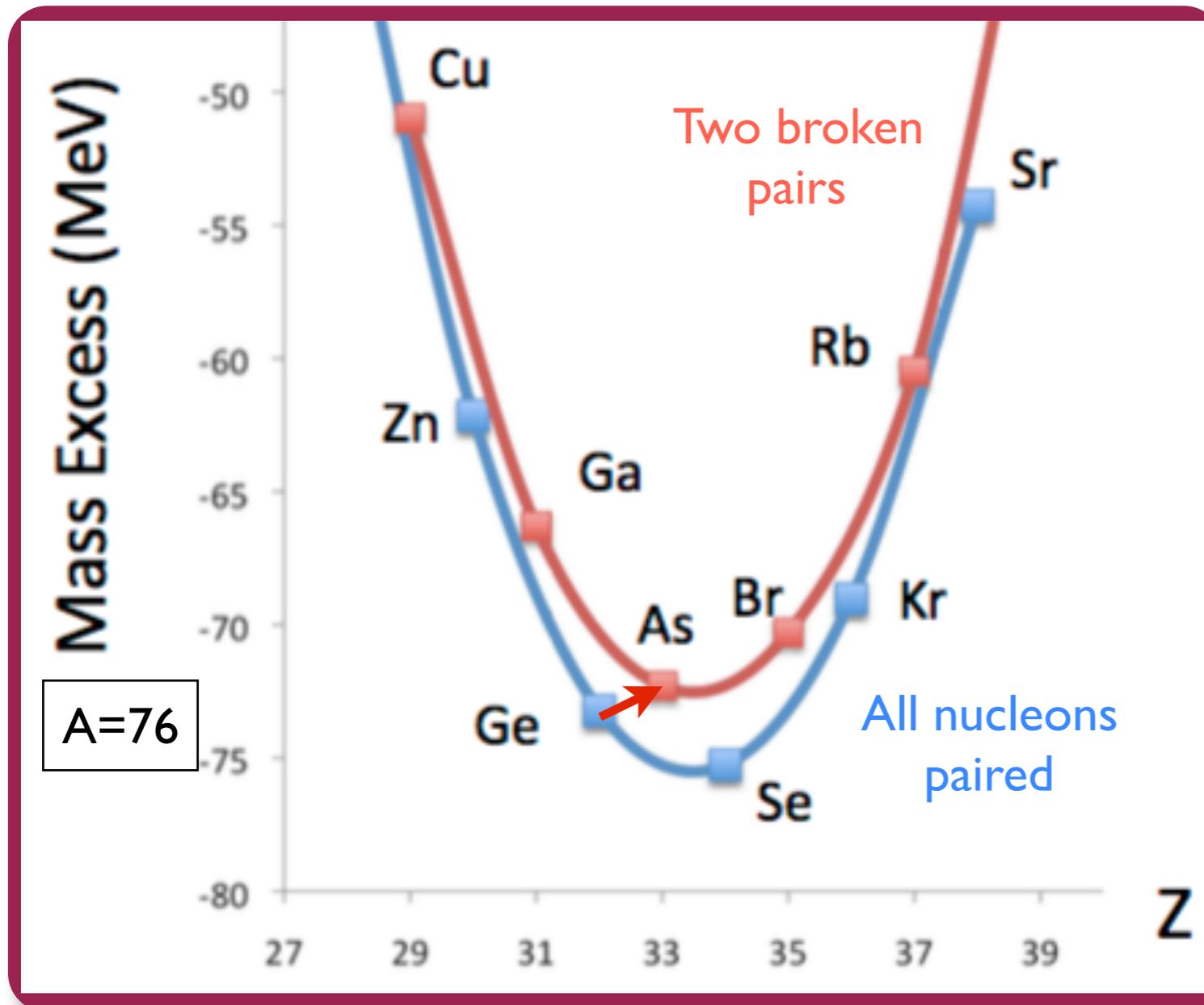
If observed, could help explain matter/anti-matter asymmetry in the universe!



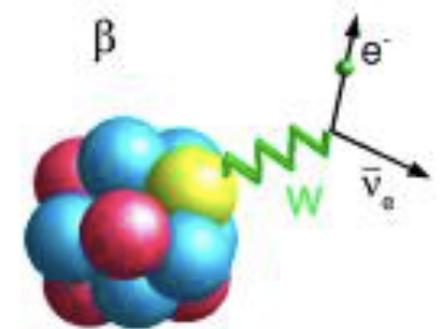
Jansen (1996)  
 Bödeker,  
 Moore,  
 Rummukainen  
 (2000)  
 Fodor (2000)

# Experiment

Nuclear physics gives us a natural filter for the process

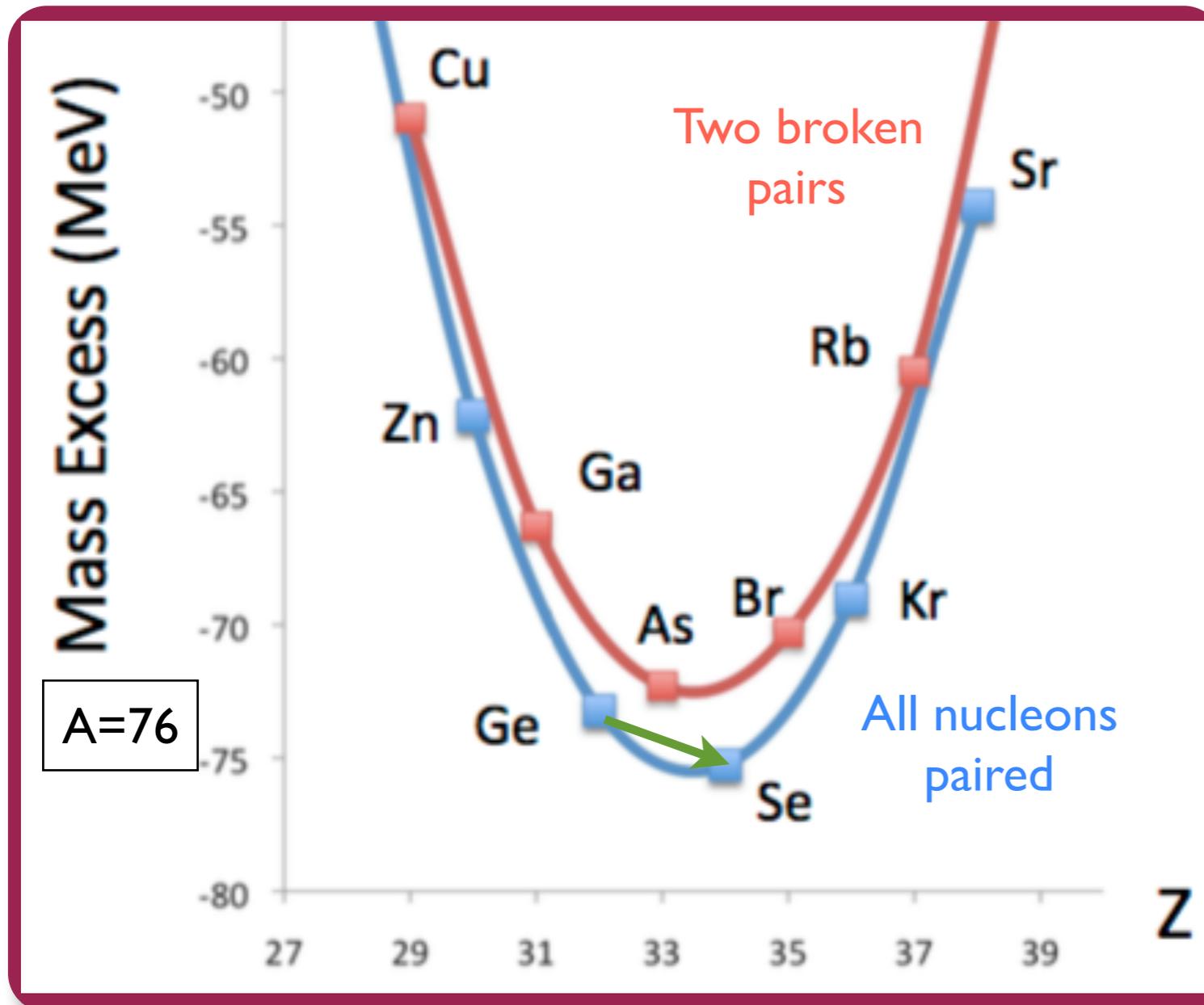


**Energetically forbidden**

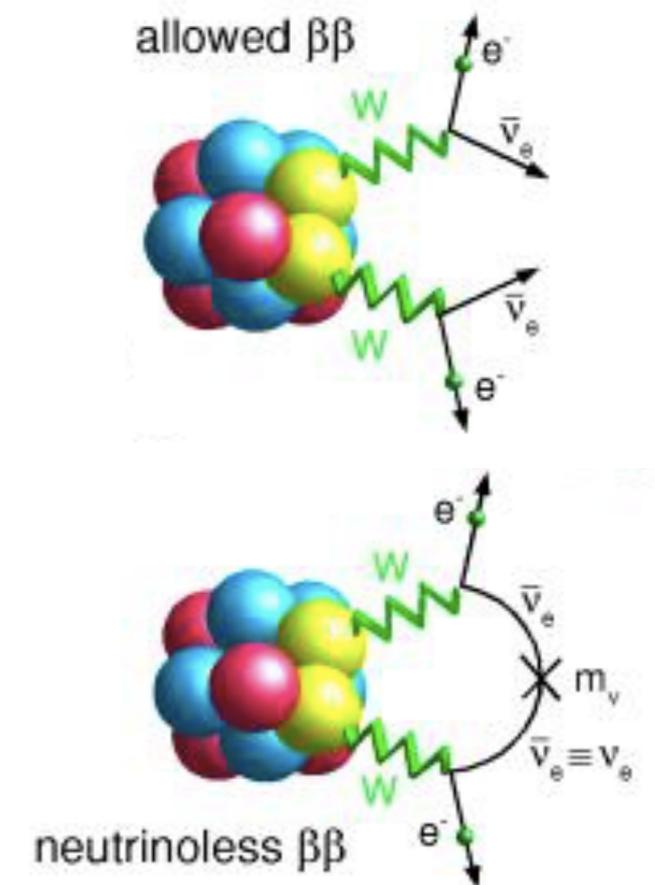


# Experiment

Nuclear physics gives us a natural filter for the process

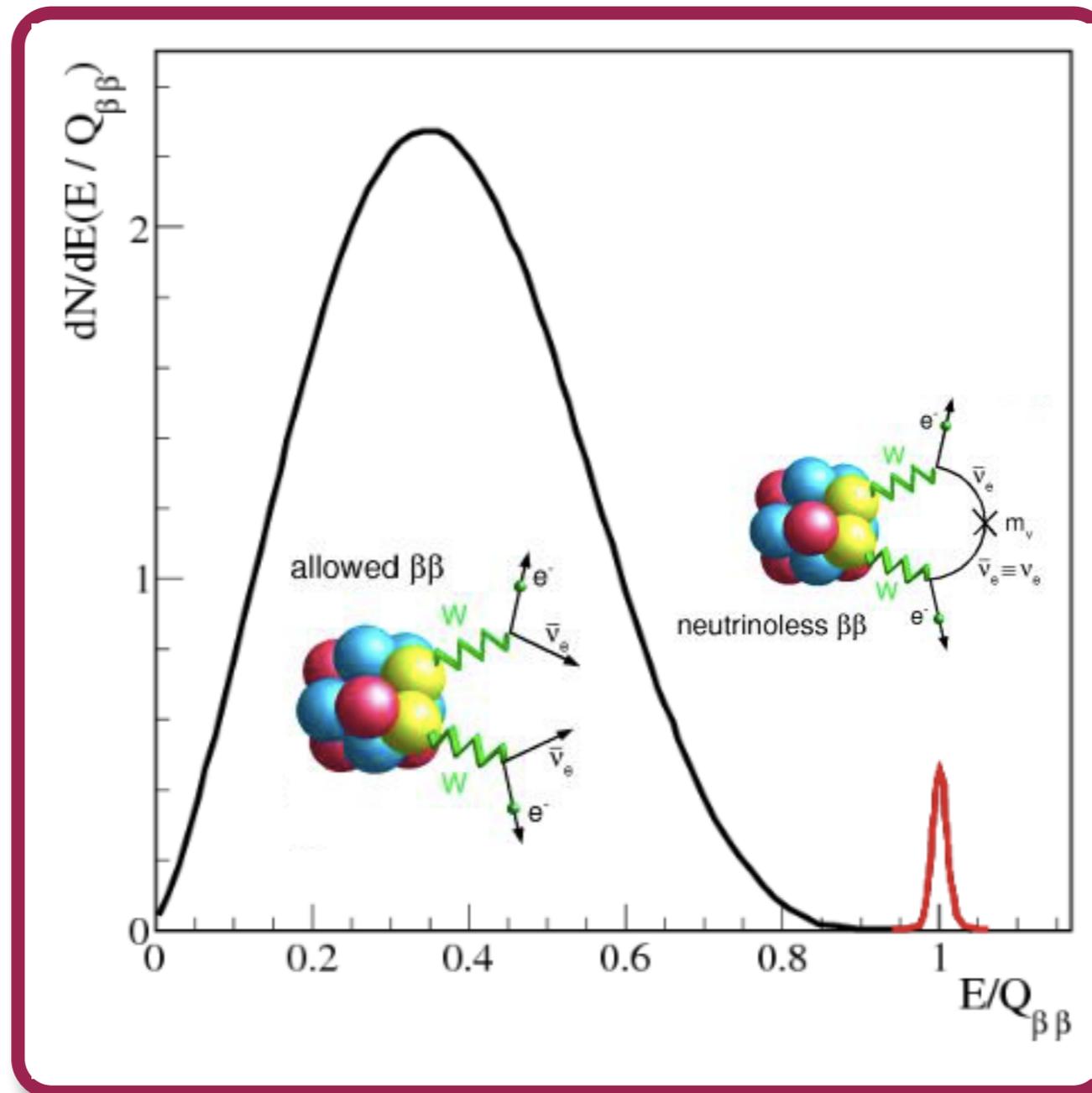


Second order, allowed



# Experiment

Neutrinoless mode can be isolated using spectroscopic methods



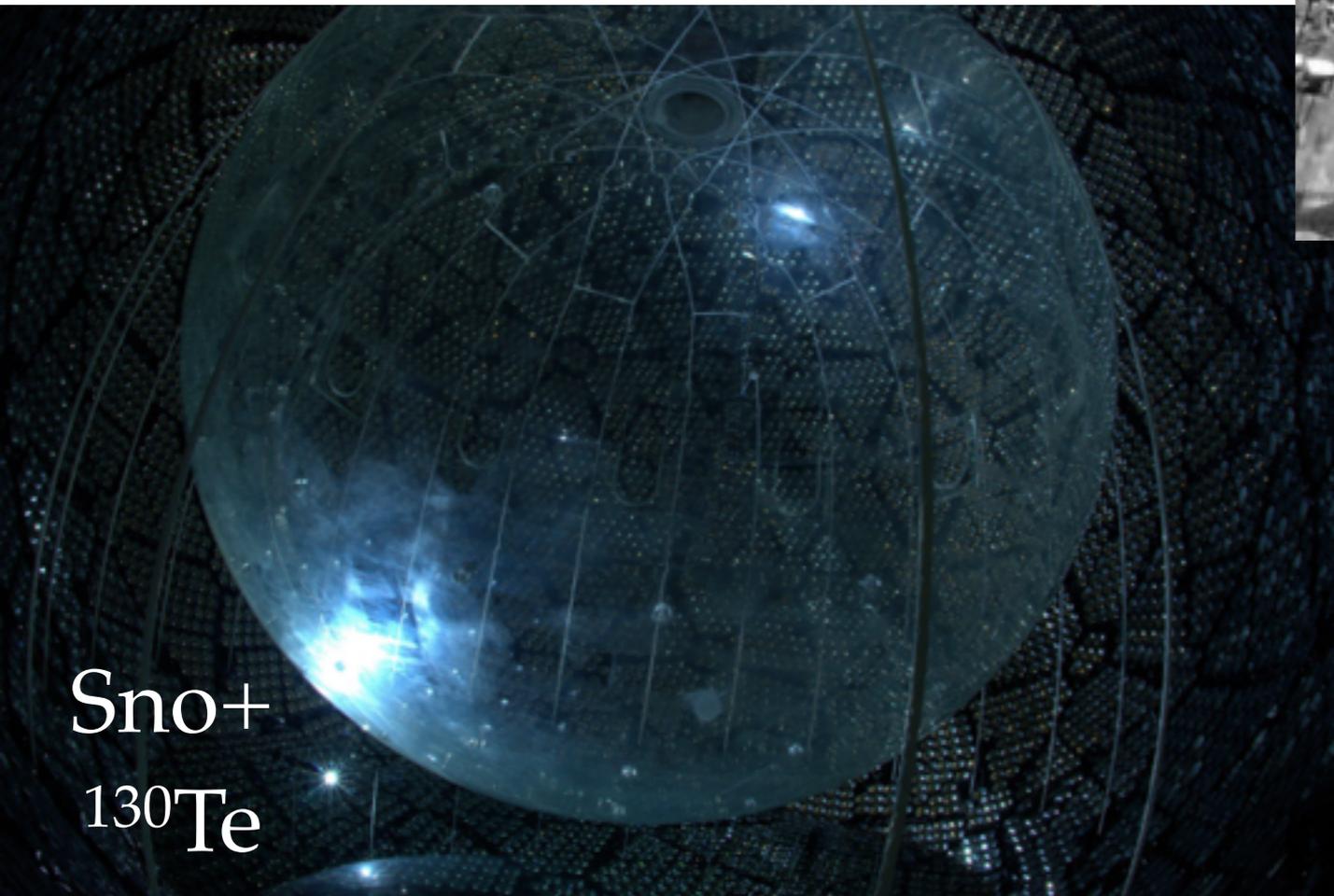
# Experiment



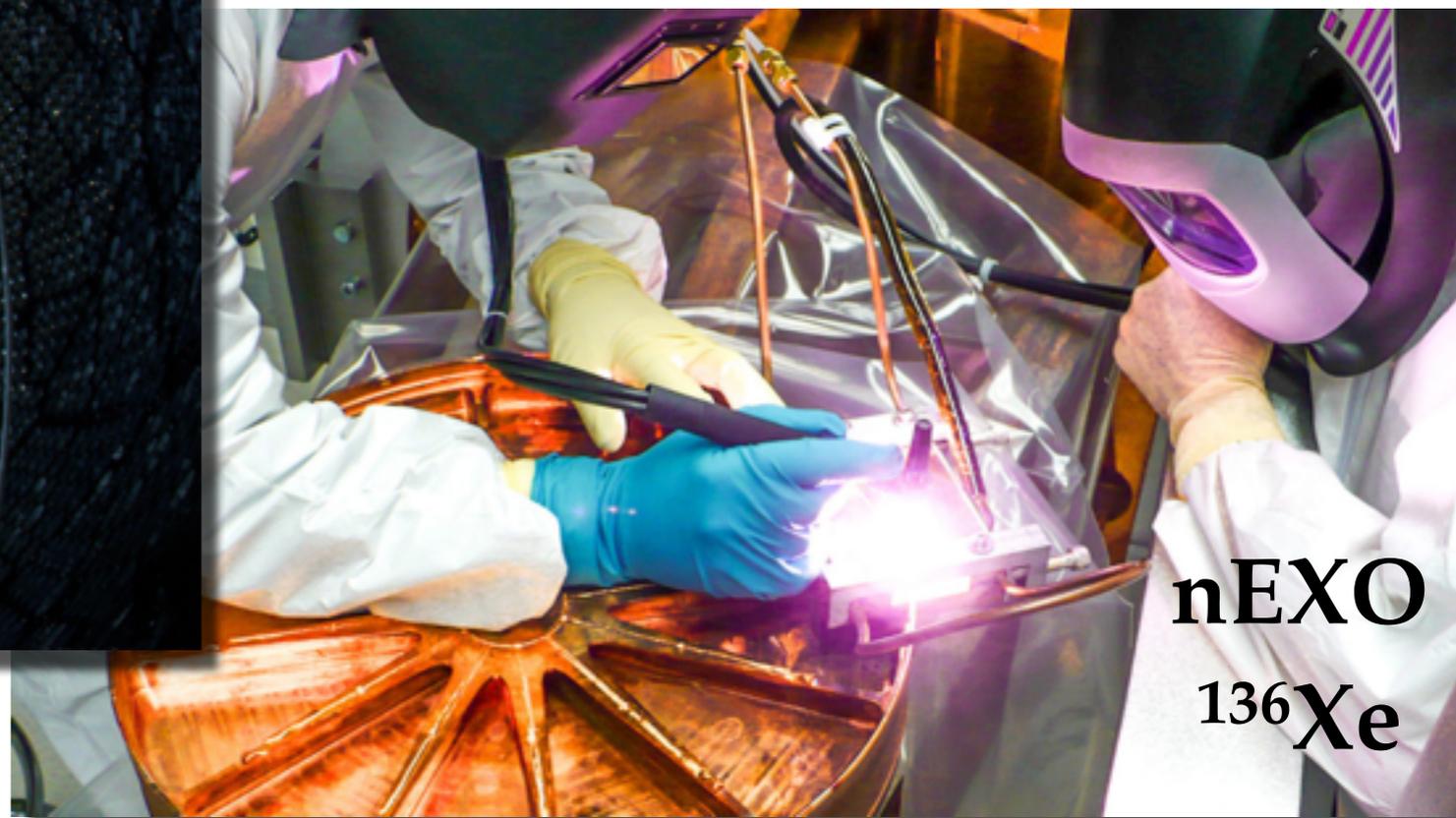
Cuore  
 $^{130}\text{Te}$



Gerda  
 $^{76}\text{Ge}$



Sno+  
 $^{130}\text{Te}$

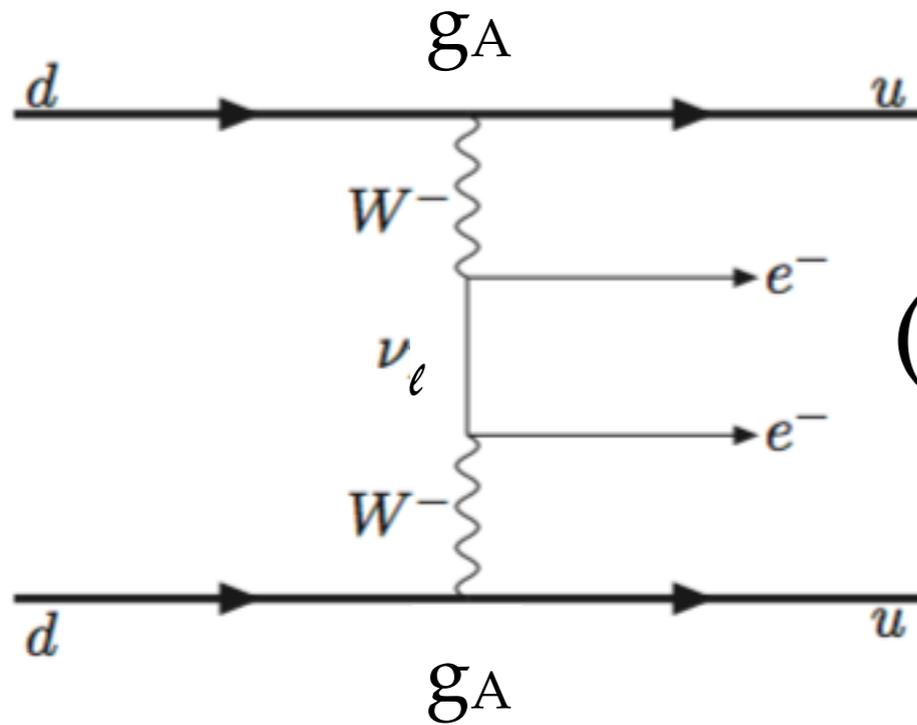


nEXO  
 $^{136}\text{Xe}$

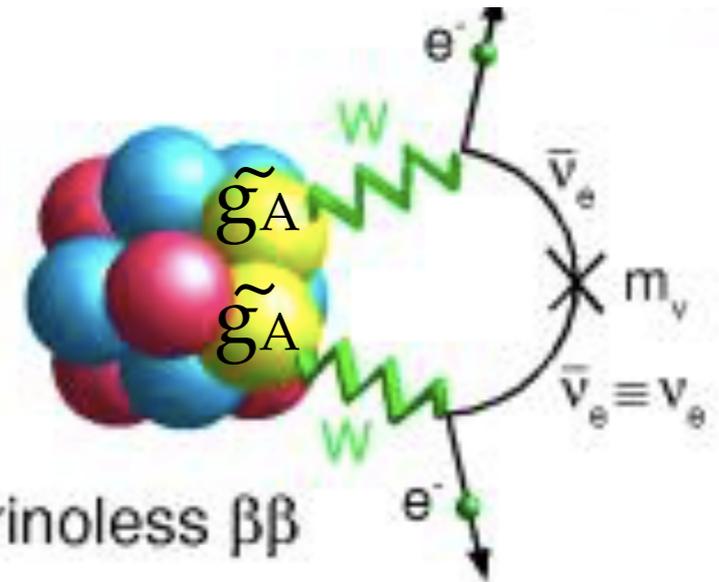


How can LQCD  
contribute?

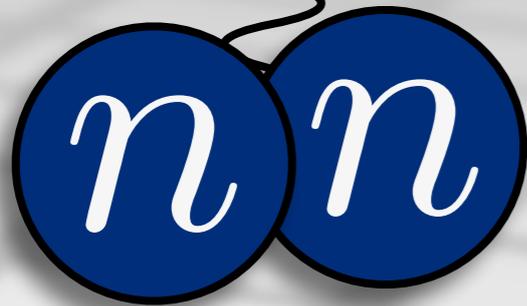
# Standard picture: long-range contribution



$g_A$   
 (see Sergey's talk)

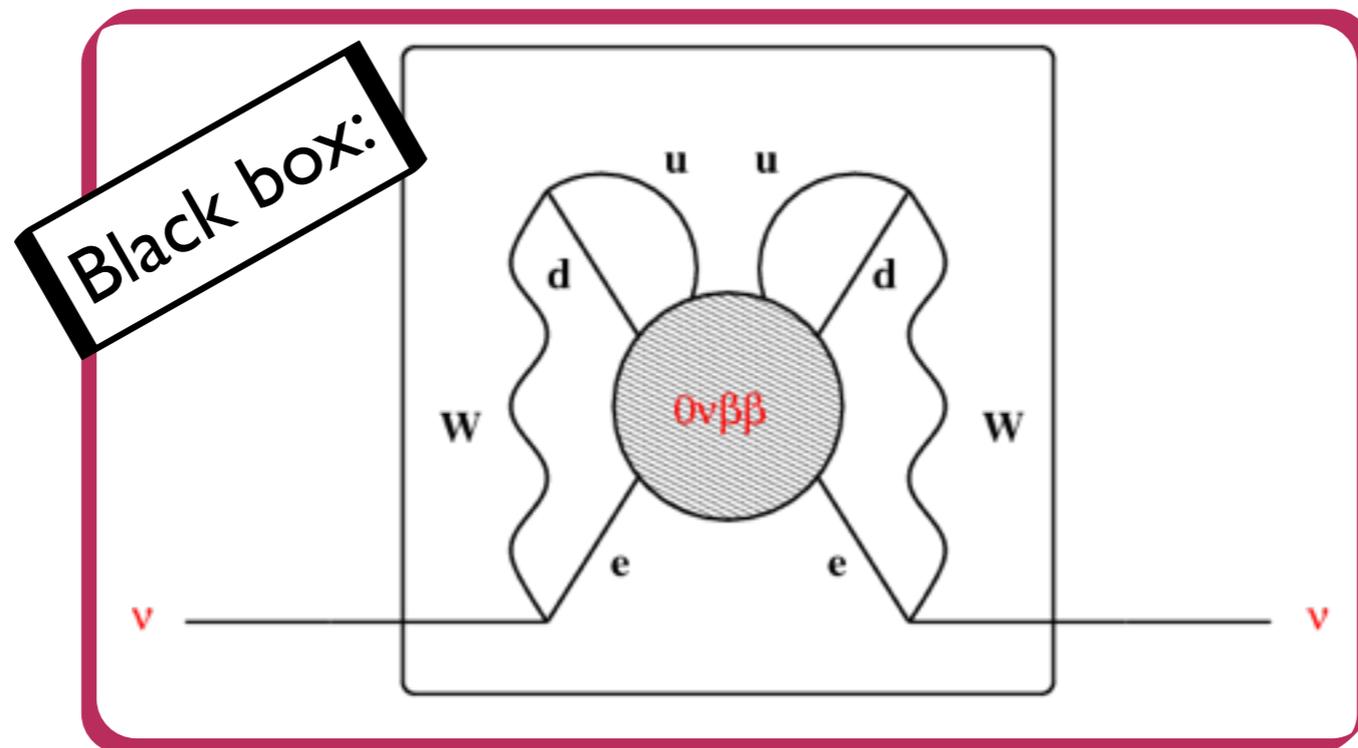
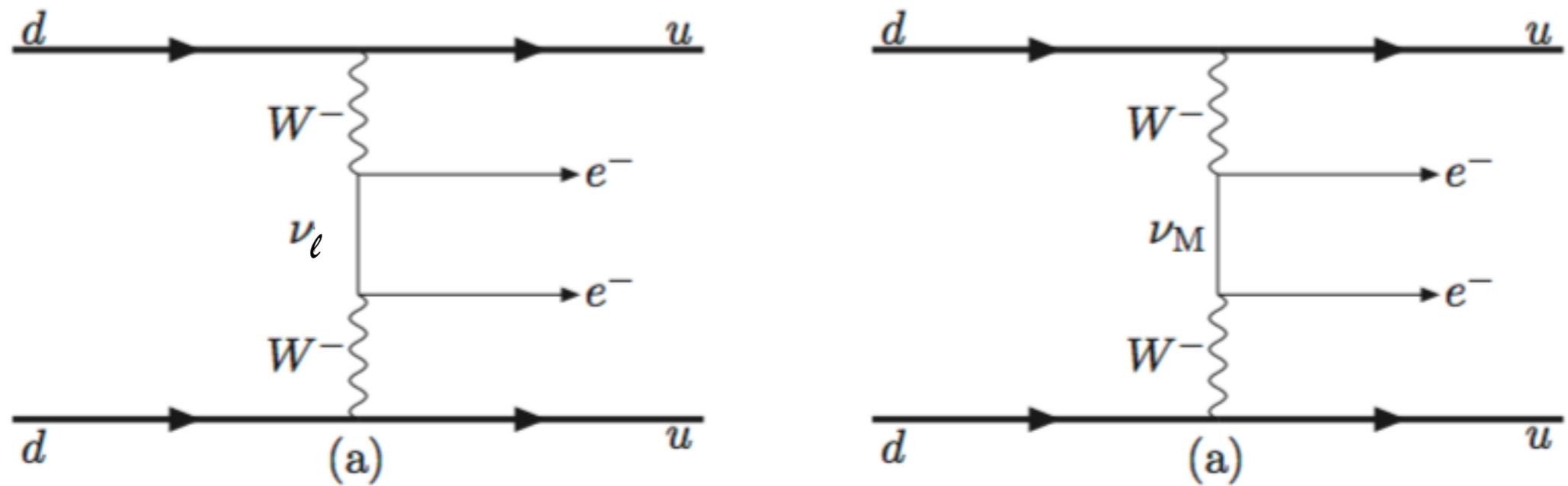


$$J_\mu^A(p^2)$$

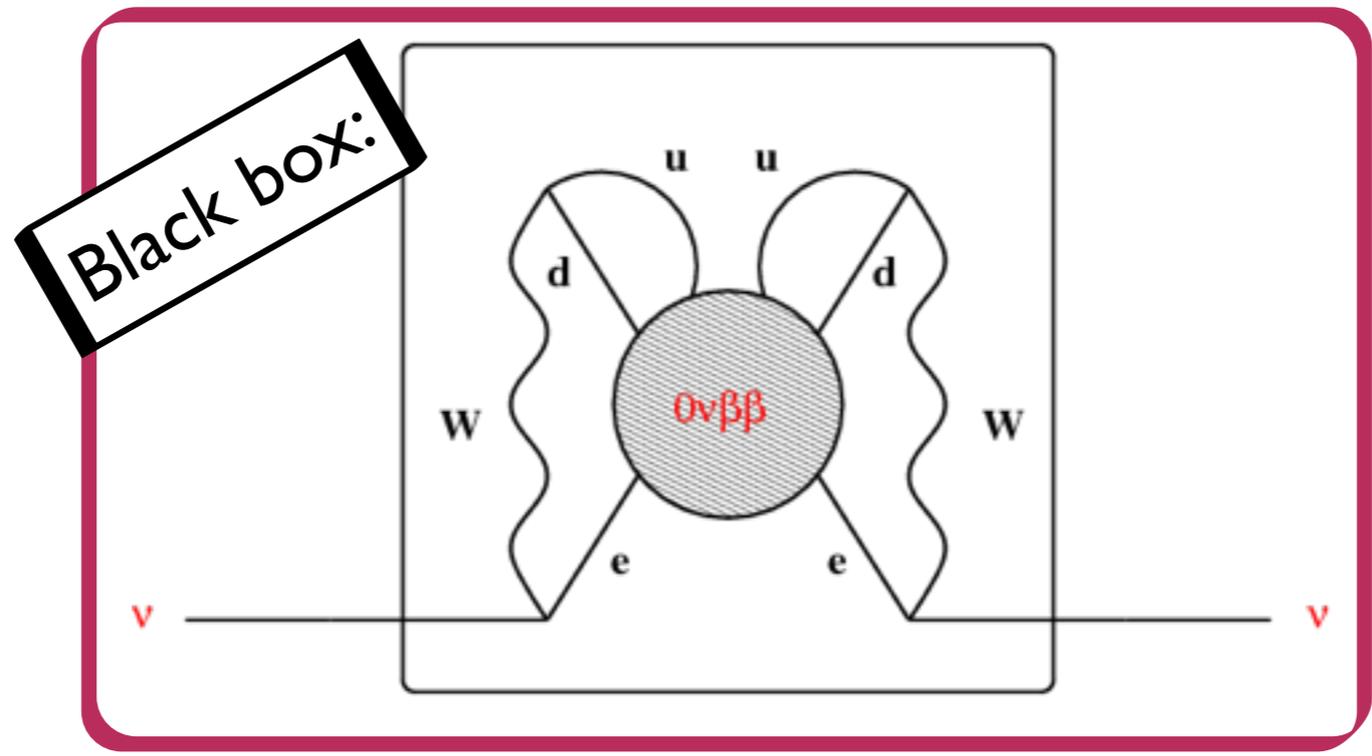
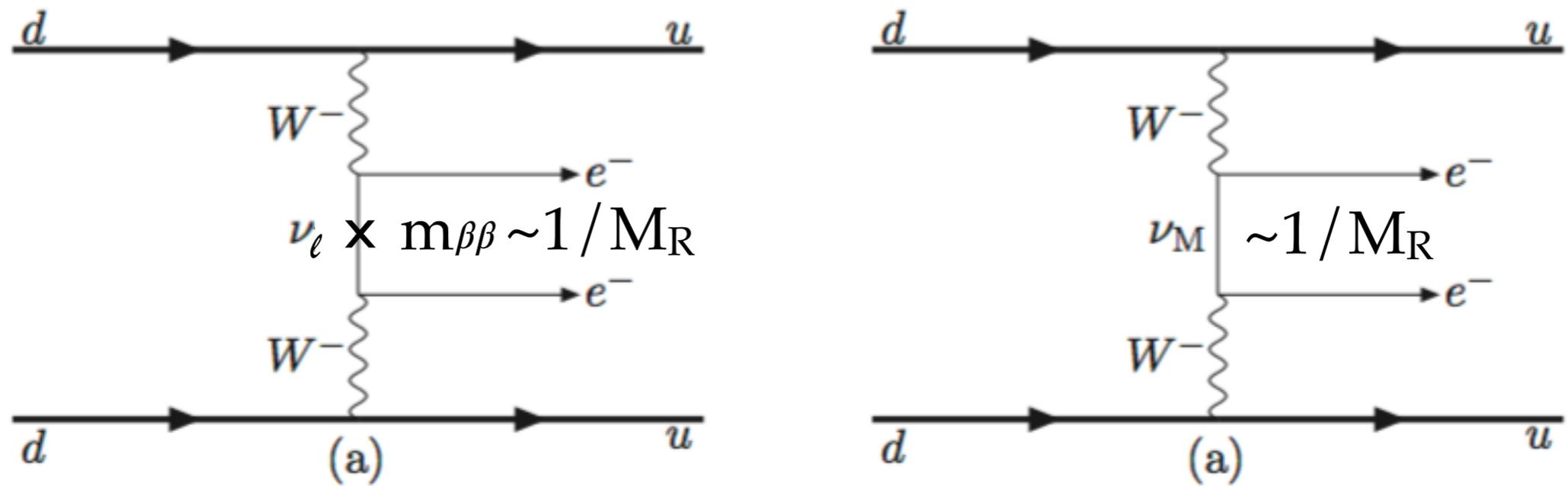


$g_A$  quenching  
 (see Martin's talk)

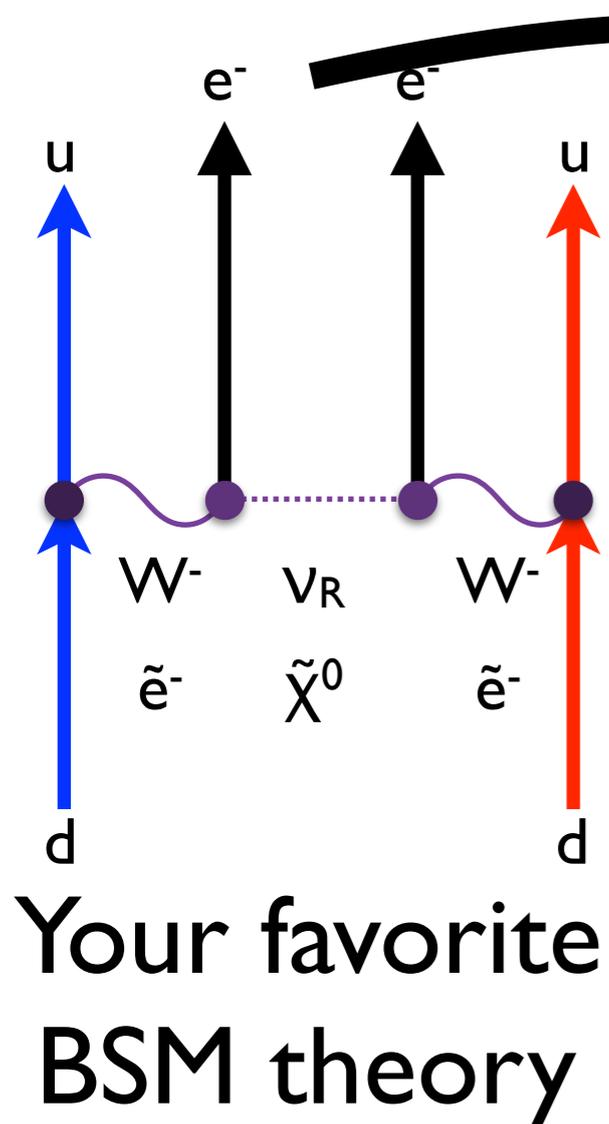
# Short-range contribution: probe for heavy physics



# Short-range contribution: probe for heavy physics

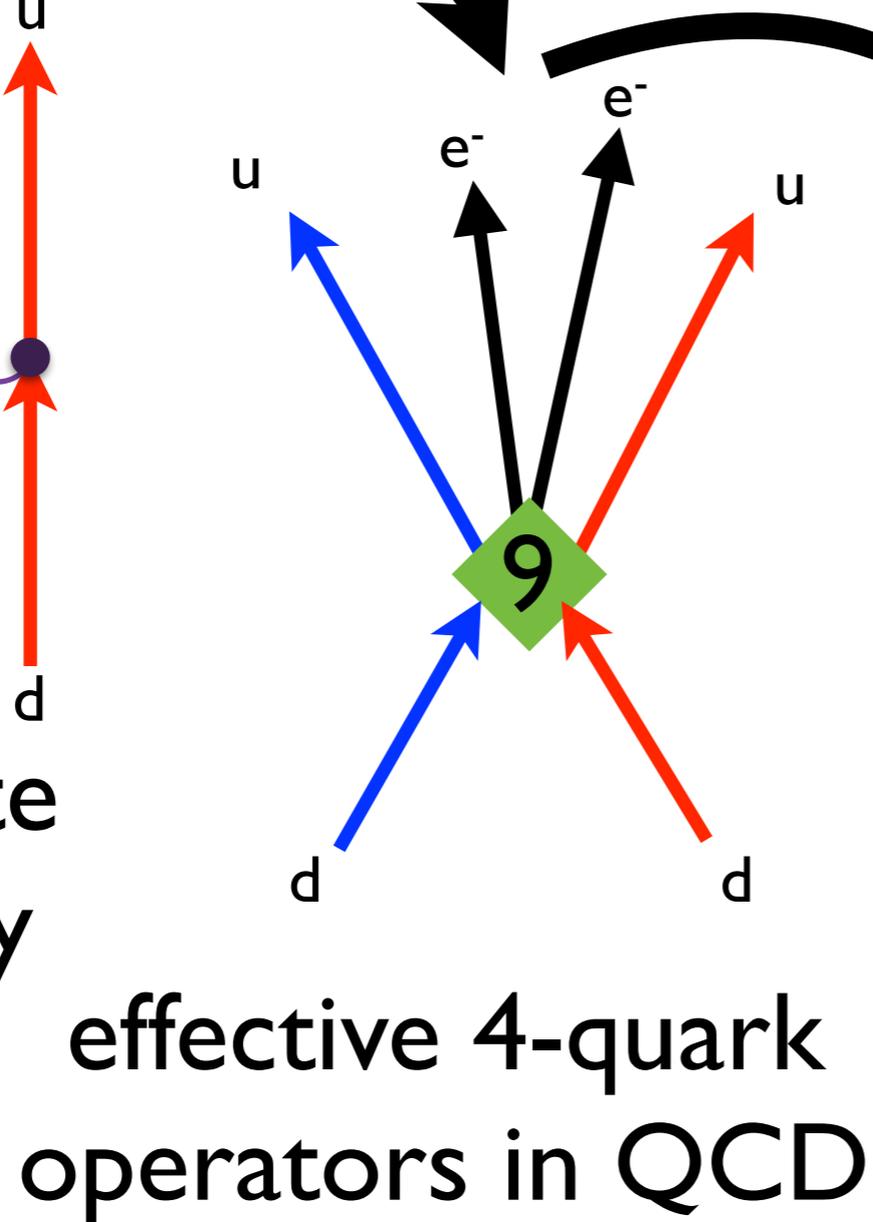


# Pen & Paper



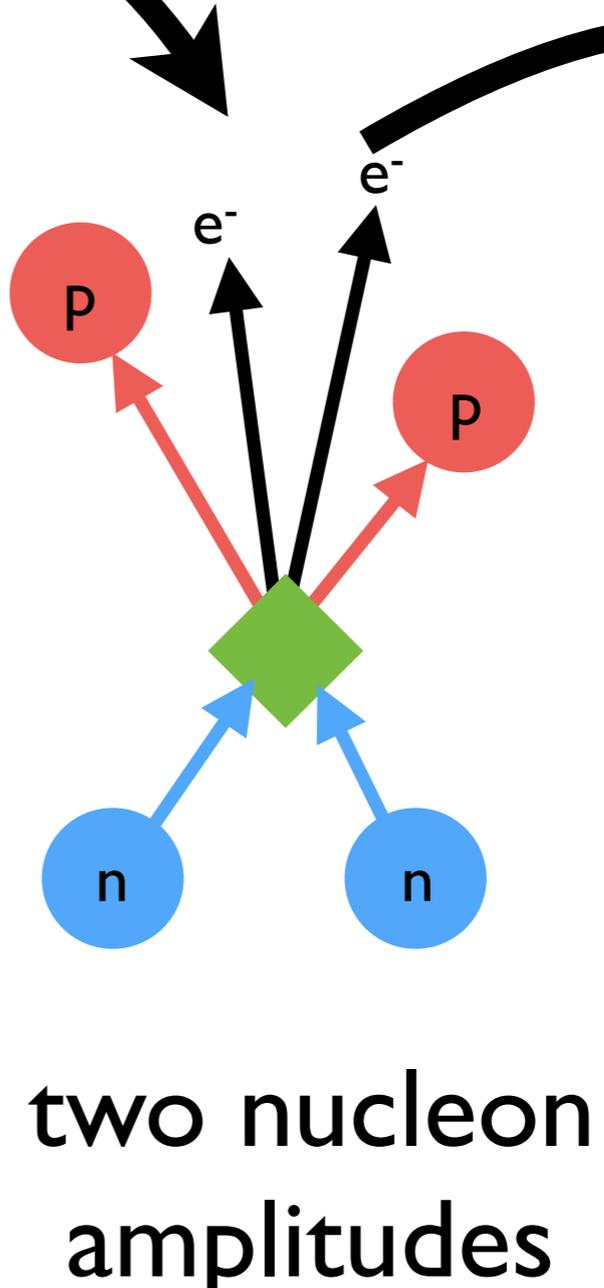
Your favorite  
BSM theory

# LQCD

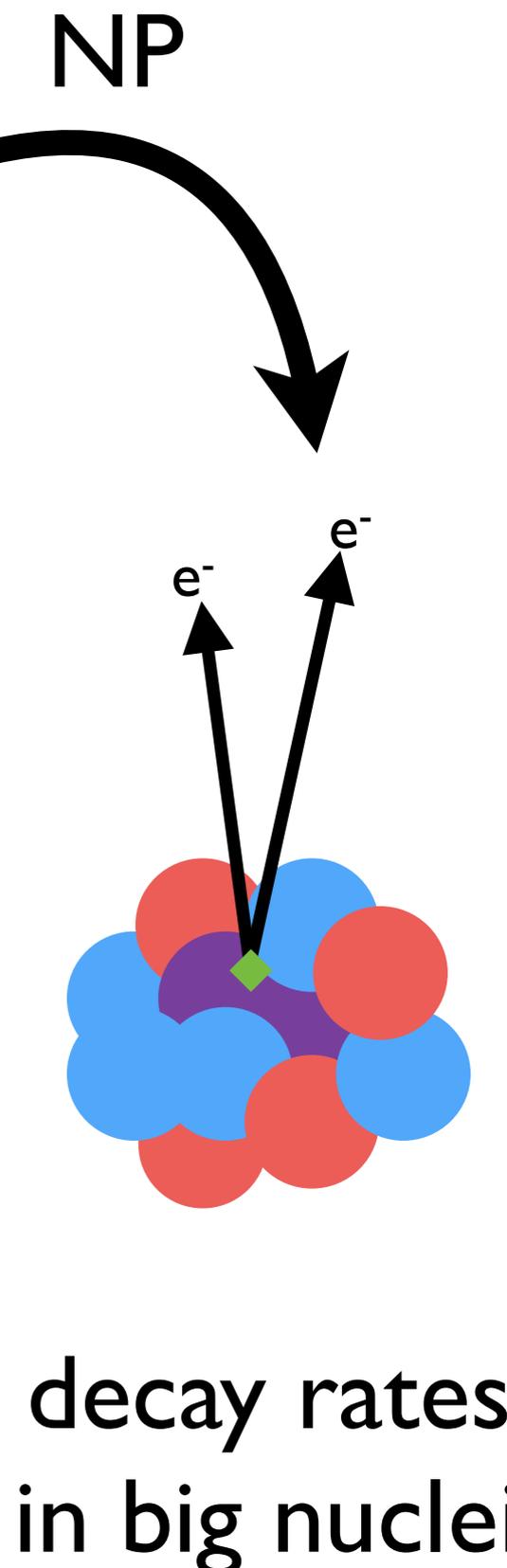


effective 4-quark  
operators in QCD

# NP

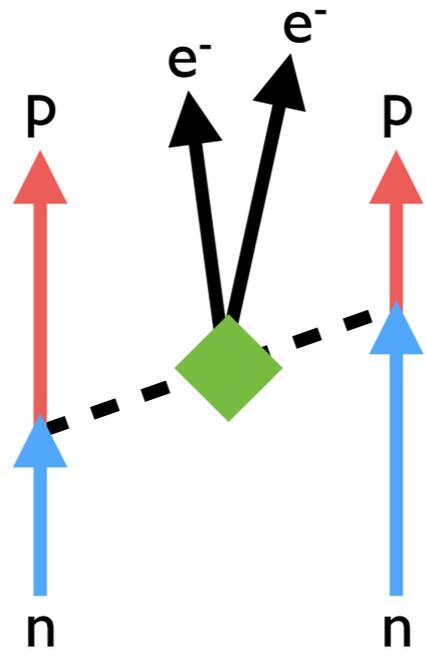
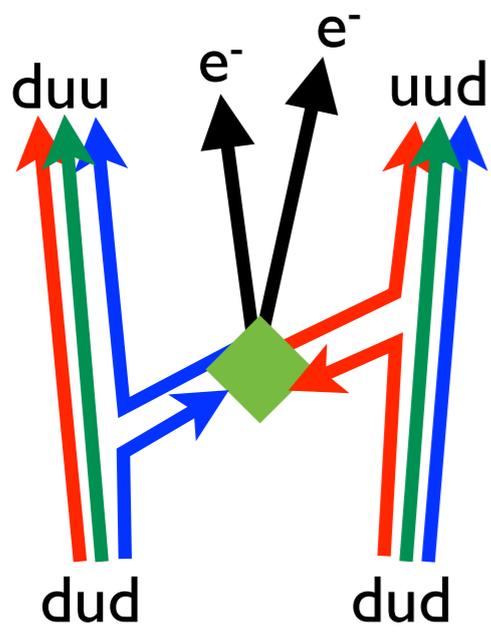


two nucleon  
amplitudes



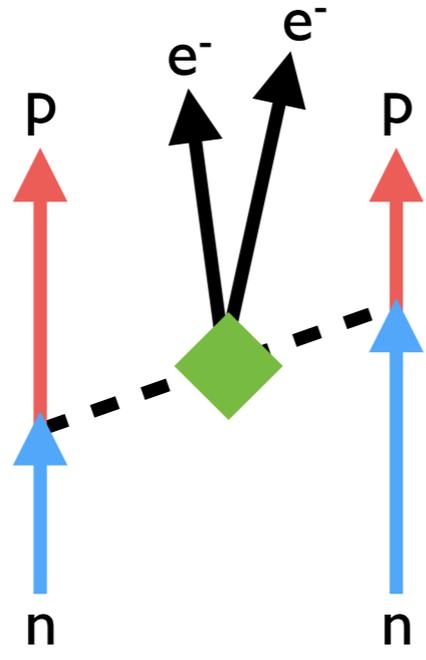
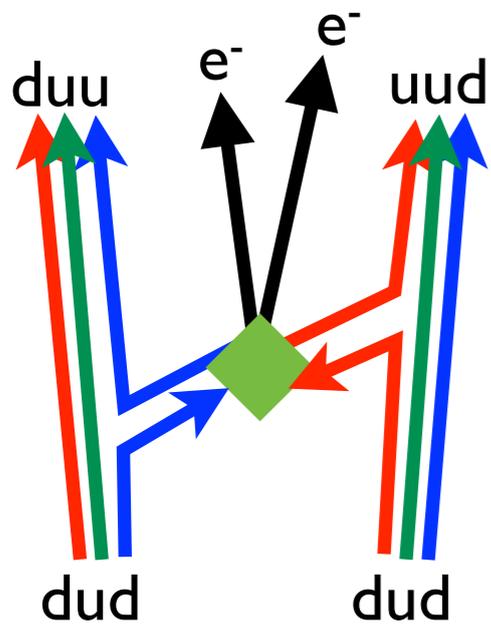
decay rates  
in big nuclei

In  $\chi$ PT



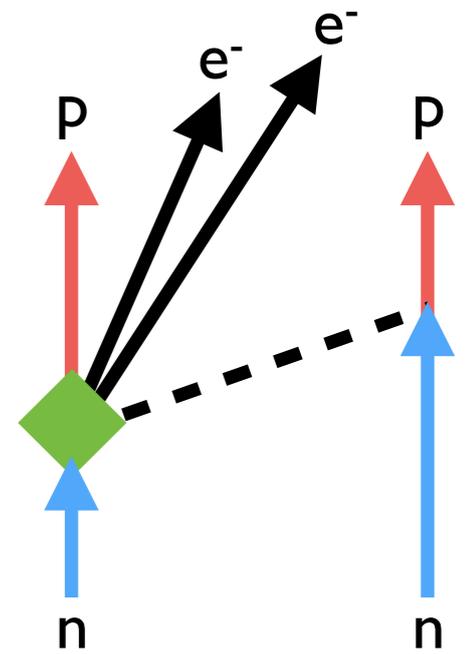
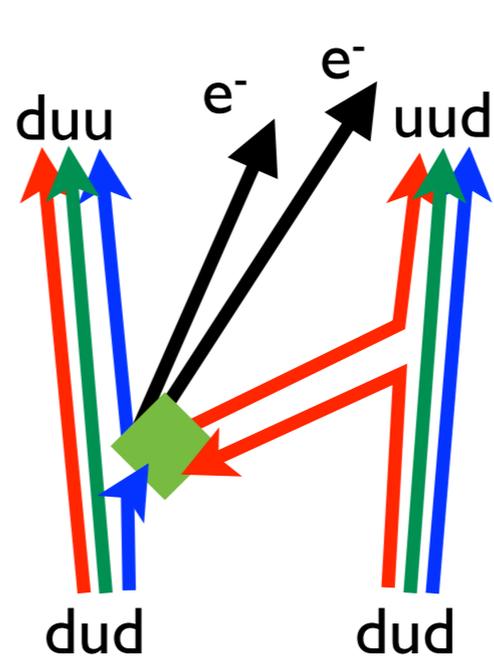
$\mathcal{O}(p^{-2})$  long-range  $\pi$  exchange

In  $\chi$ PT

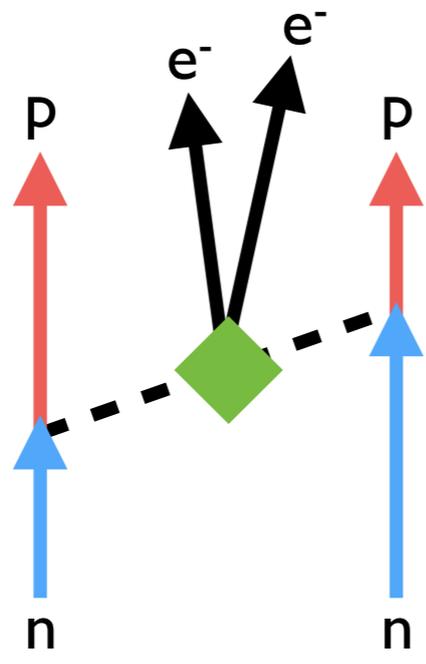
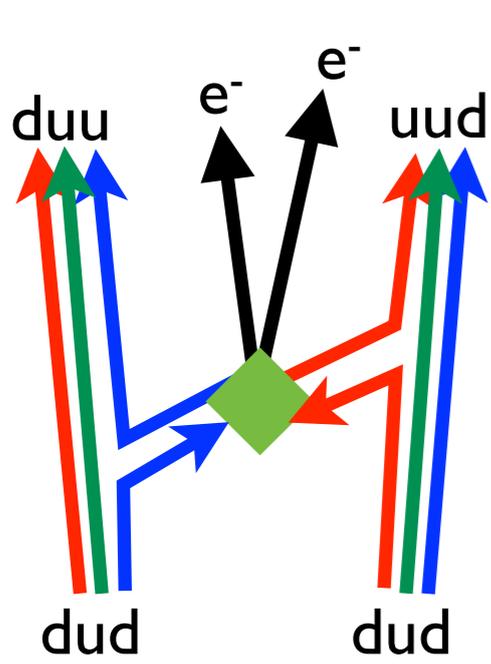


$\mathcal{O}(p^{-2})$  long-range  $\pi$  exchange

$\mathcal{O}(p^{-1})$  new  $\pi$ N vertex

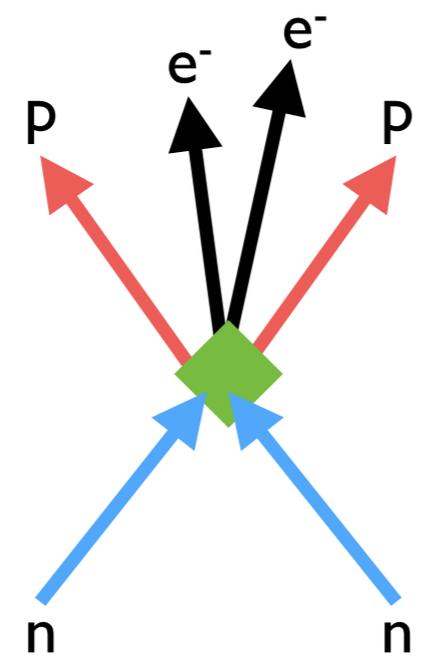
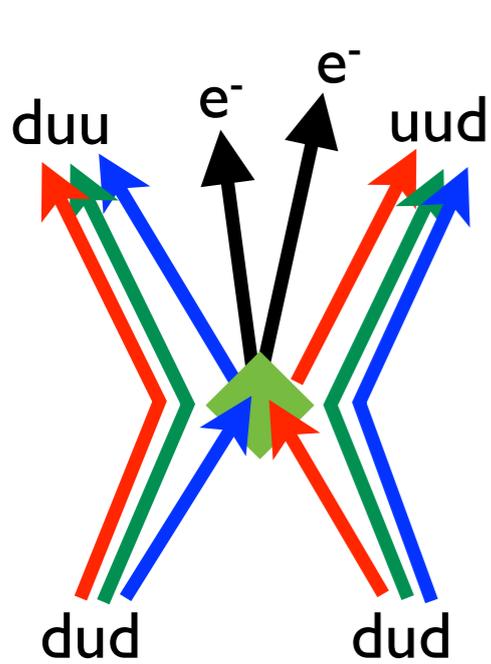
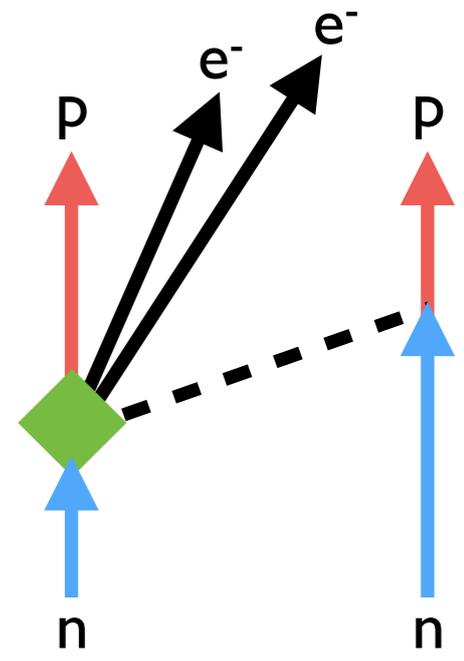
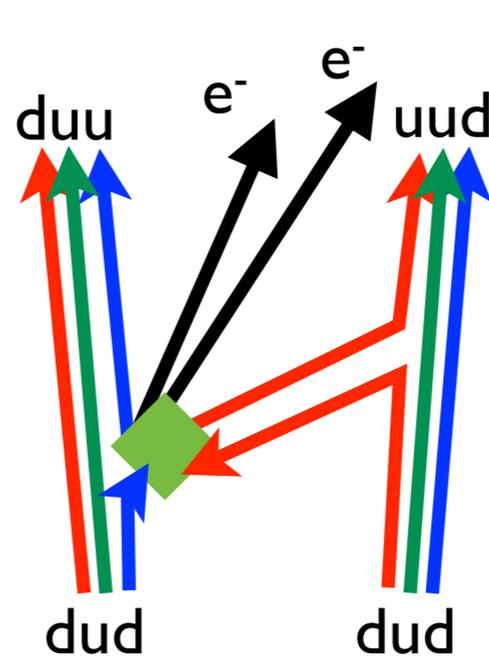


In  $\chi$ PT



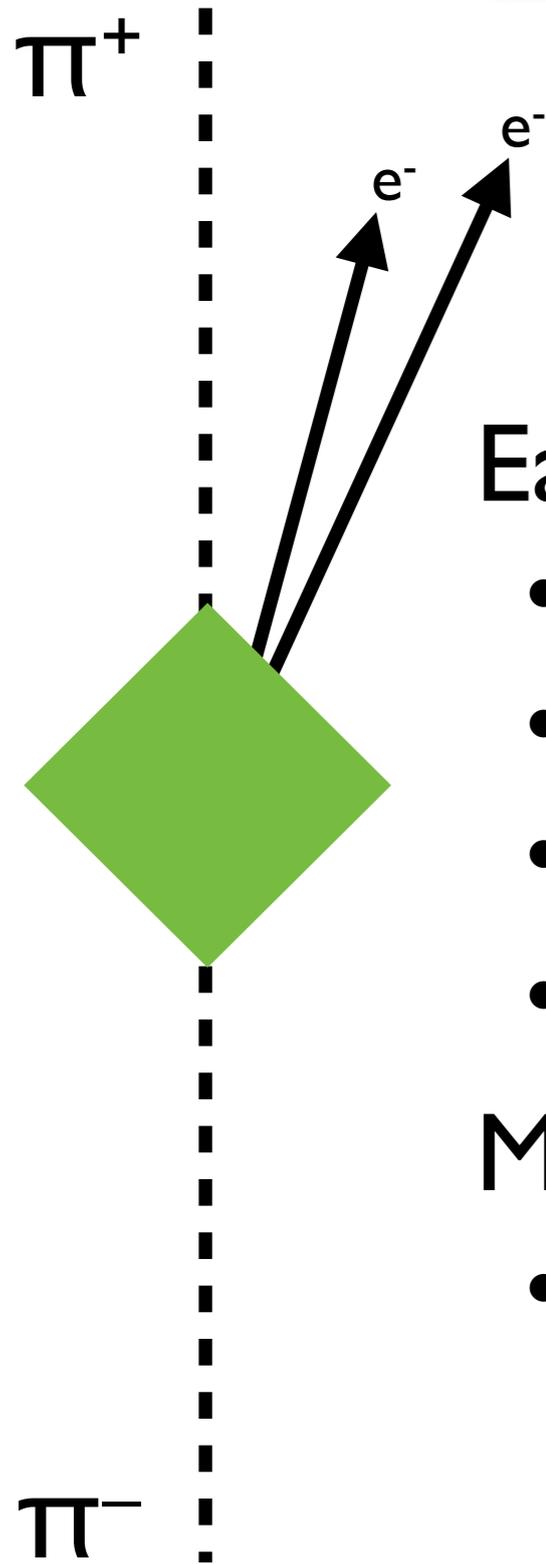
$\mathcal{O}(p^{-2})$  long-range  $\pi$  exchange

$\mathcal{O}(p^{-1})$  new  $\pi N$  vertex



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

# Long Range $\pi$ physics



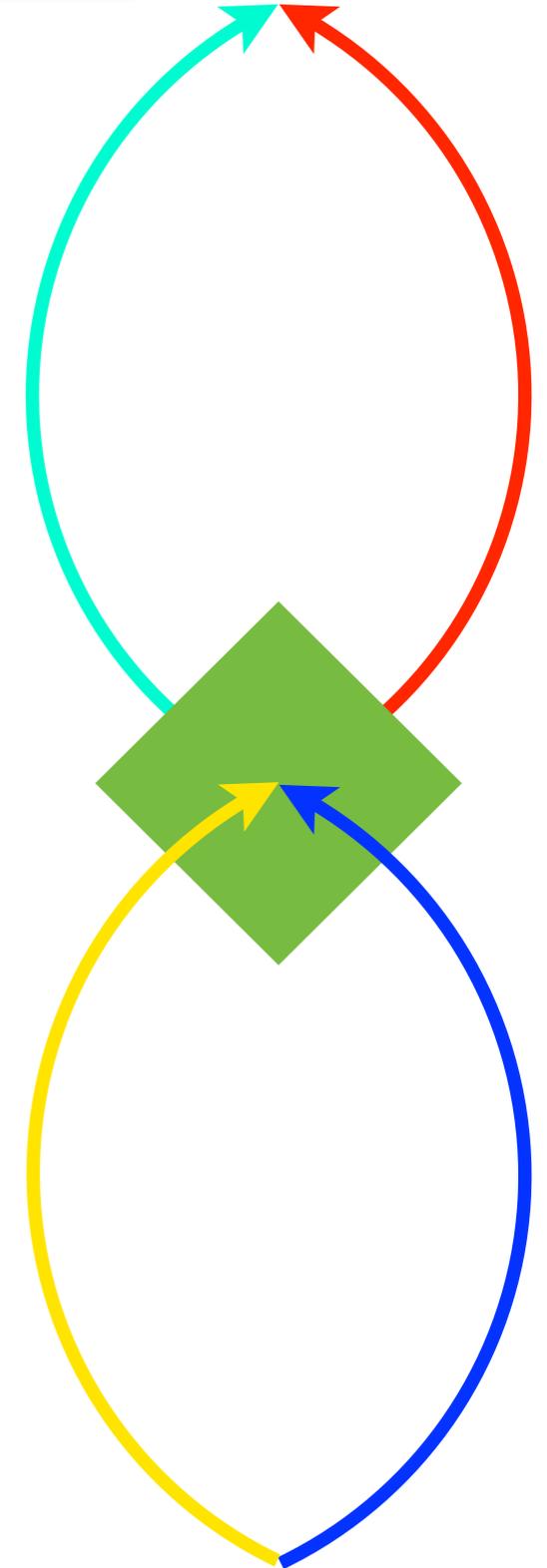
$\pi$  exchange operators  
also give  $\pi^-$  to  $\pi^+$  transition

Easy to compute on the lattice

- Cheap
- Clean signals
- Mild systematics
- $I=2$ : no disconnected pieces

Most important piece

- Assuming naive  $\chi$ PT counting



# Effective Lagrangian

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

Prezeau, Ramsey-Musolf, Vogel (2003)

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

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

$$\mathcal{O}_{2\pm}^{ab} = (\bar{q}_R \tau^a q_L) (\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R) (\bar{q}_L \tau^b q_R),$$

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

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

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

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

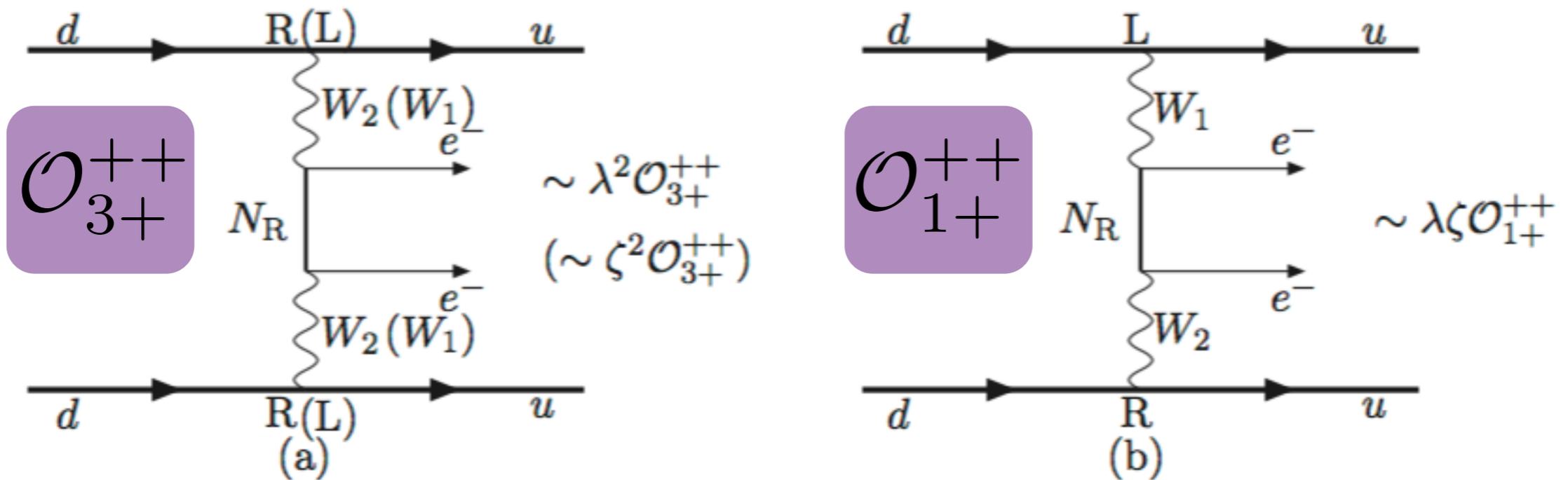
$$\mathcal{O}_{4\pm}^{ab,\mu} = (\bar{q}_L \tau^a \gamma^\mu q_L + \bar{q}_R \tau^a \gamma^\mu q_R)(q_L \tau^b q_R - \bar{q}_R \tau^b q_L),$$

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

Calculate LECs; EFT then determines  $nn \rightarrow pp$  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



# Contractions

- Exact momentum projection at source and sink, just 1 inversion
  - Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2
- [Graesser (1606.04549)]

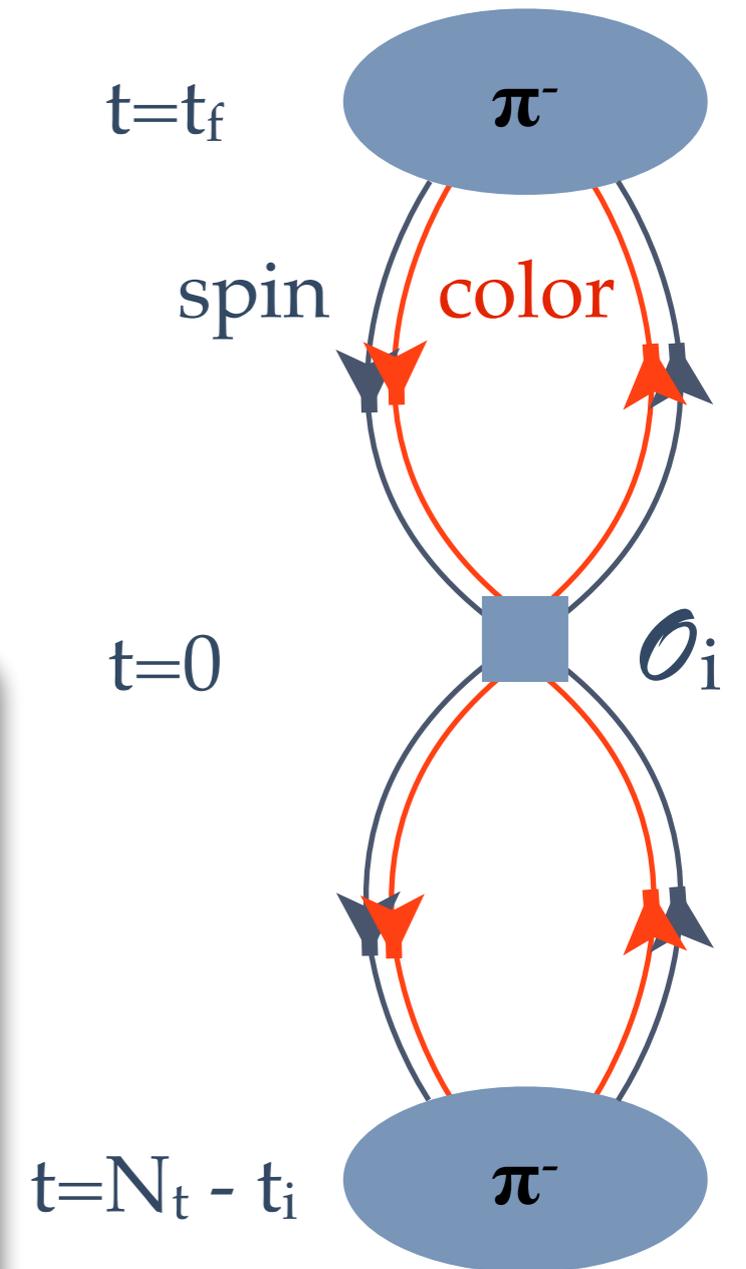
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L) [\bar{q}_R \tau^- \gamma_\mu q_R]$$

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

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

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

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



# Contractions

- Exact momentum projection at source and sink, just 1 inversion
- Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2 [Graesser (1606.04549)]

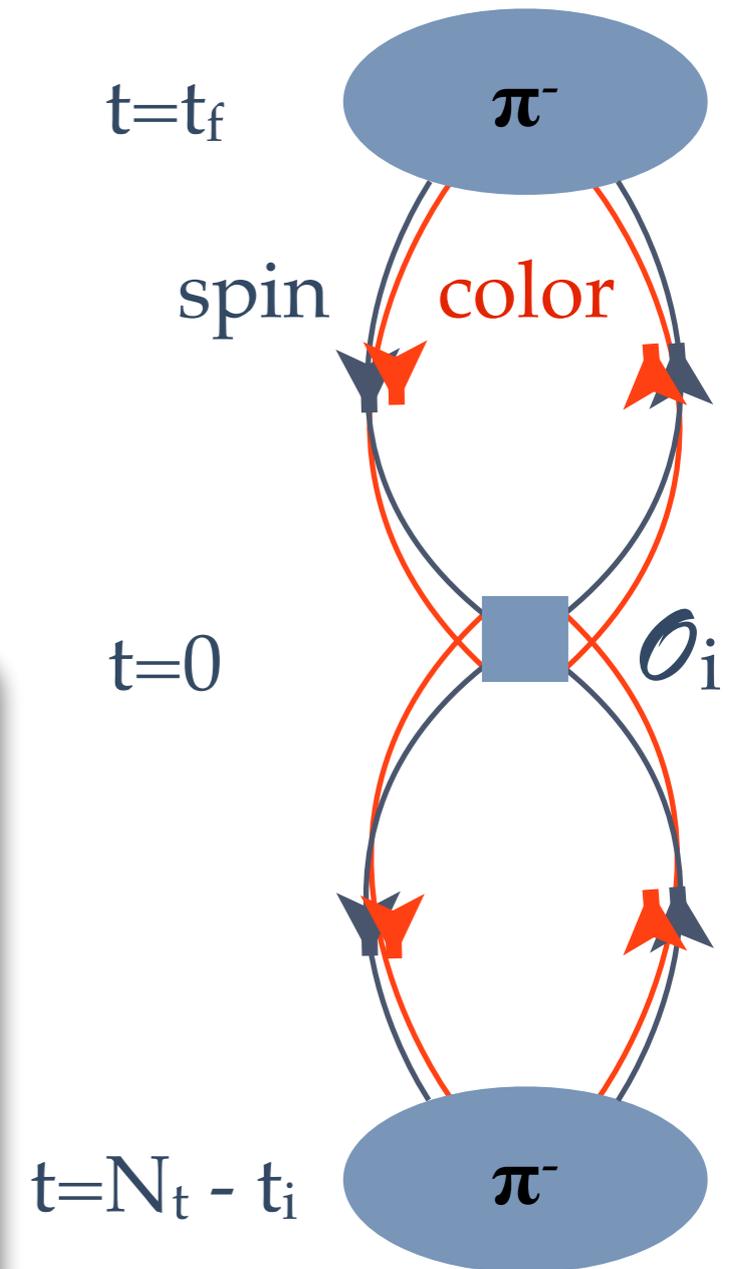
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L) [\bar{q}_R \tau^- \gamma_\mu q_R]$$

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

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

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

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



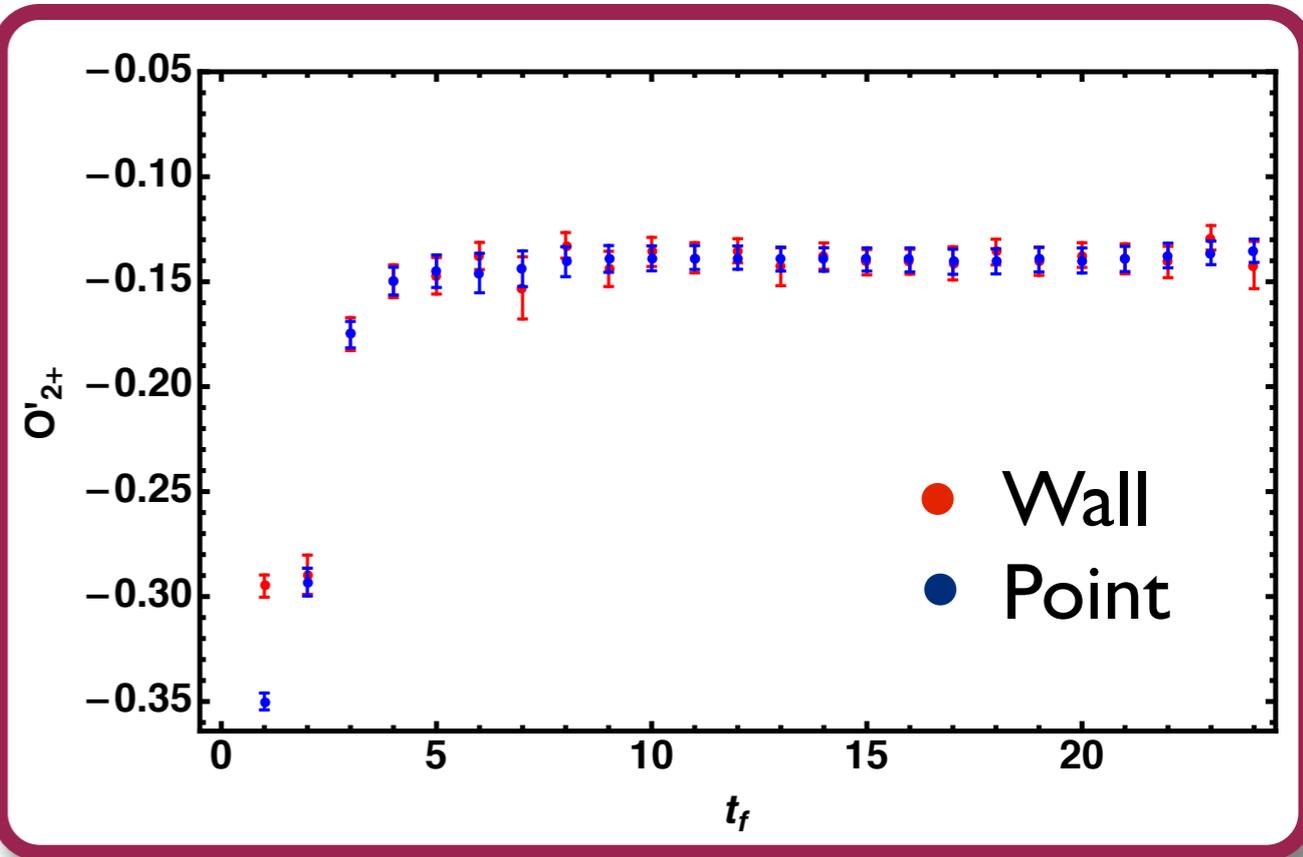
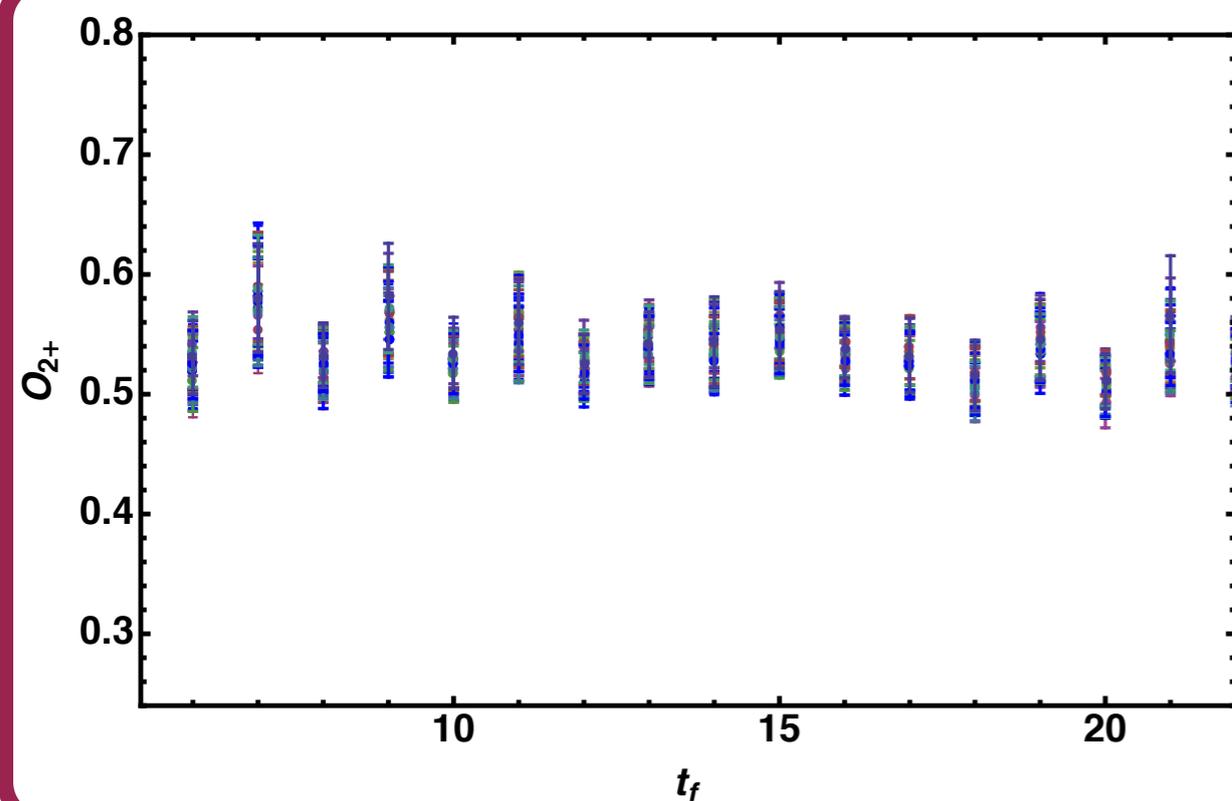
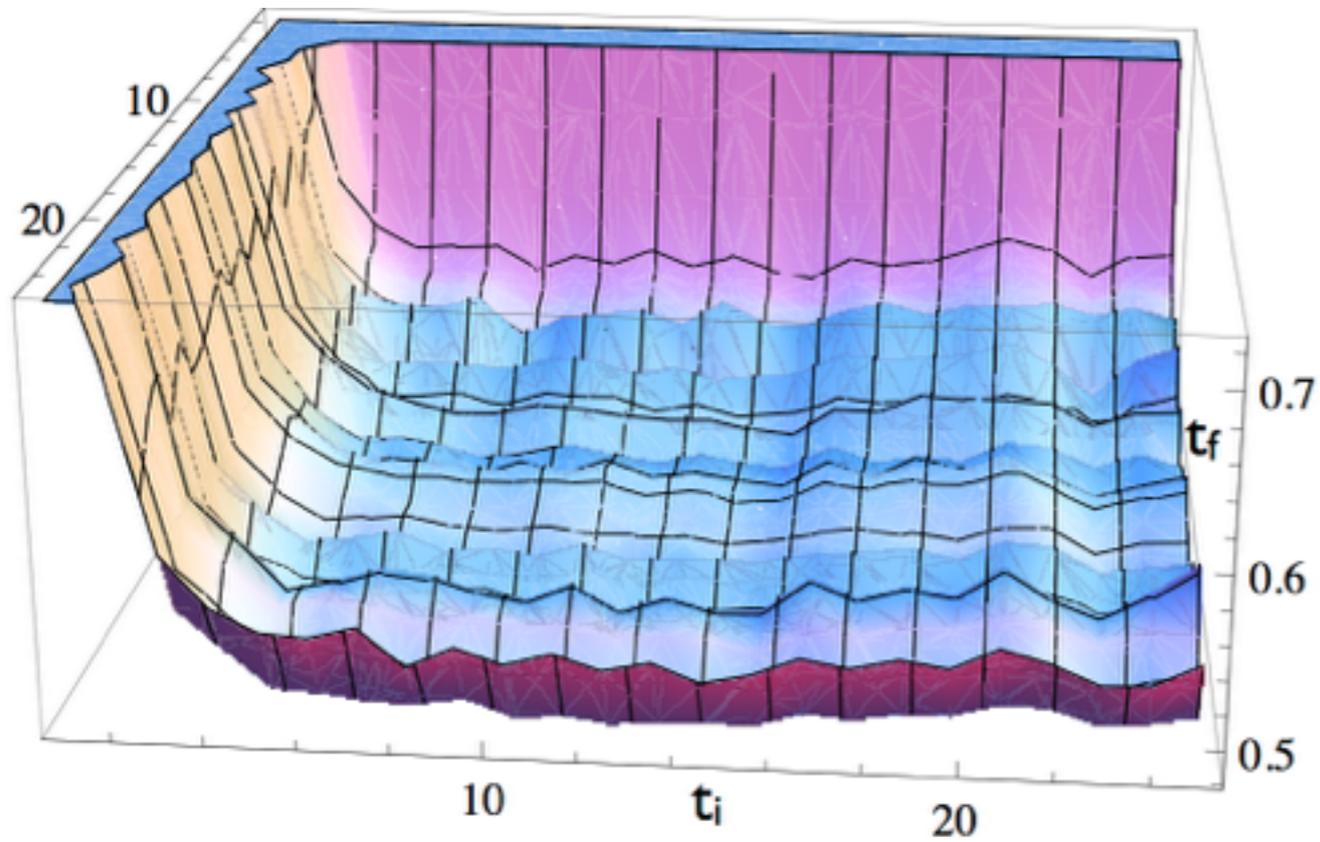
## HISQ ensembles

$a[fm] : m_\pi[MeV]$	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
  - $m_{\text{res}} < 0.1 m_\ell$  for moderate  $L_5$
- Wall + point sources for pions
- $\sim 1000$  cfigs, 1 source/cfg

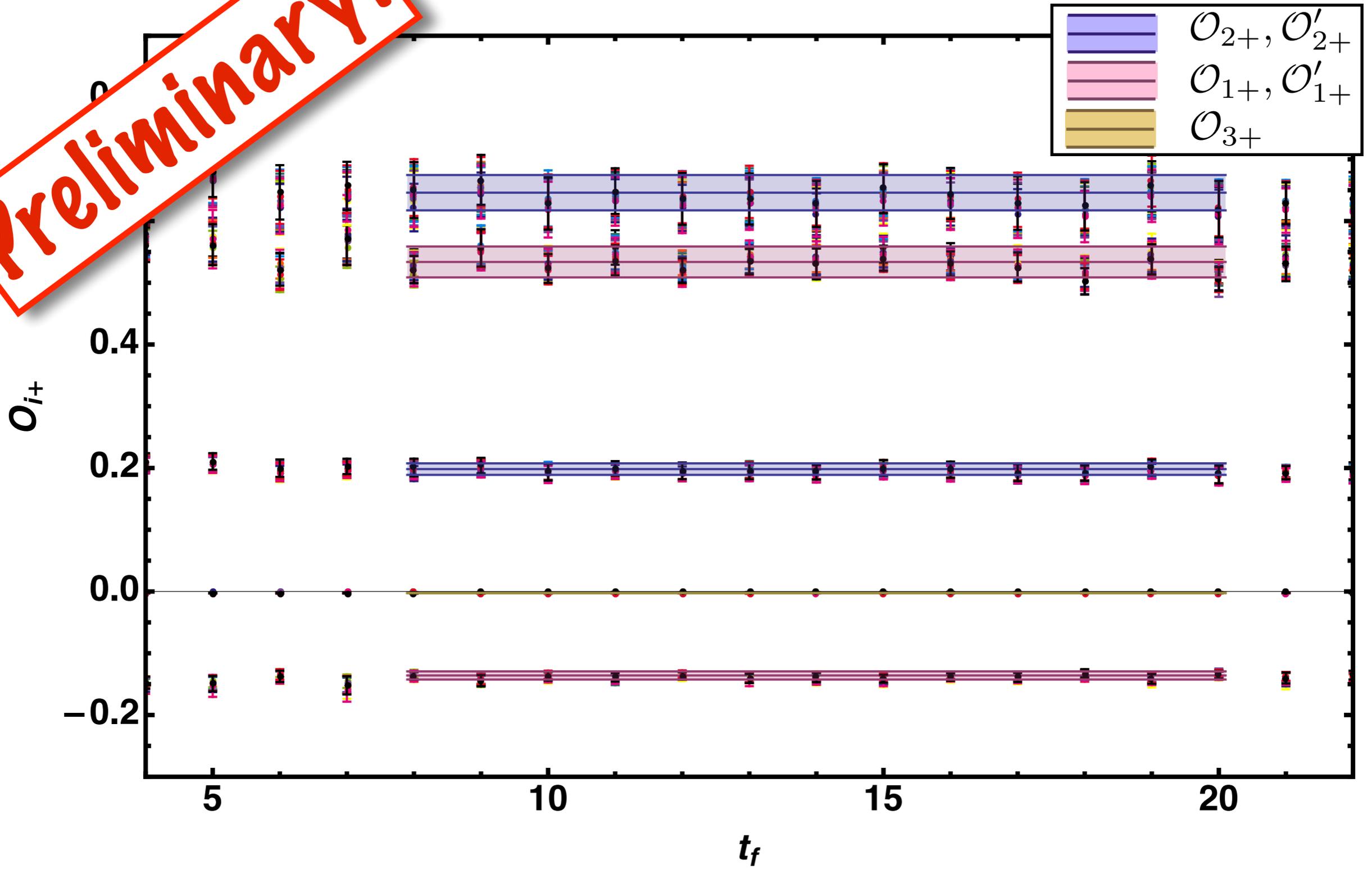
MILC Collaboration Phys. Rev. D87 (2013) 054505  
Narayanan, Neuberger (2006), Luscher (2010)  
K. Orginos, C. Monahan (private communication)

# Signals



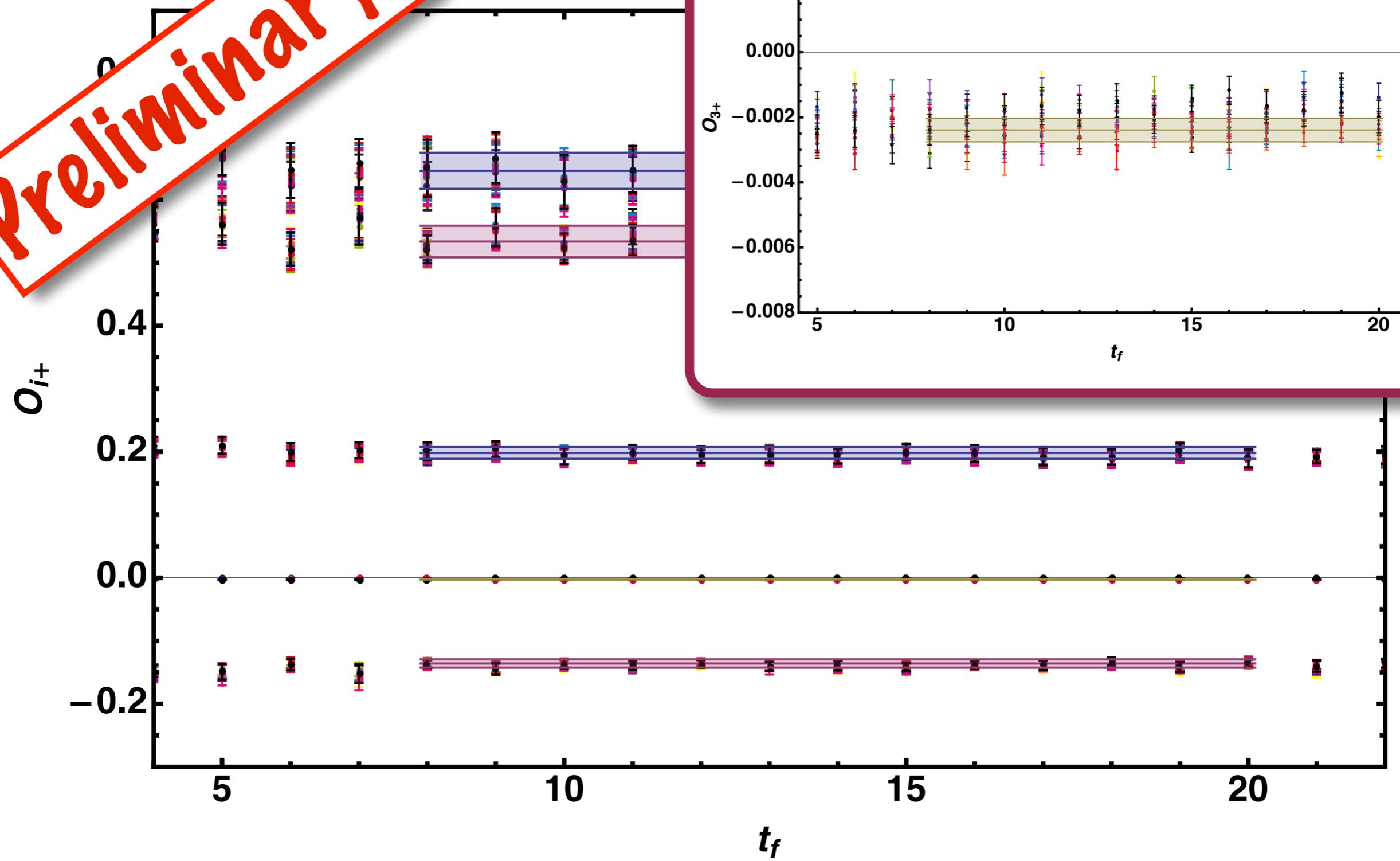
- $m_\pi \sim 135$  MeV
- $L = 5.76$  fm
- $a = 0.12$  fm

Preliminary!



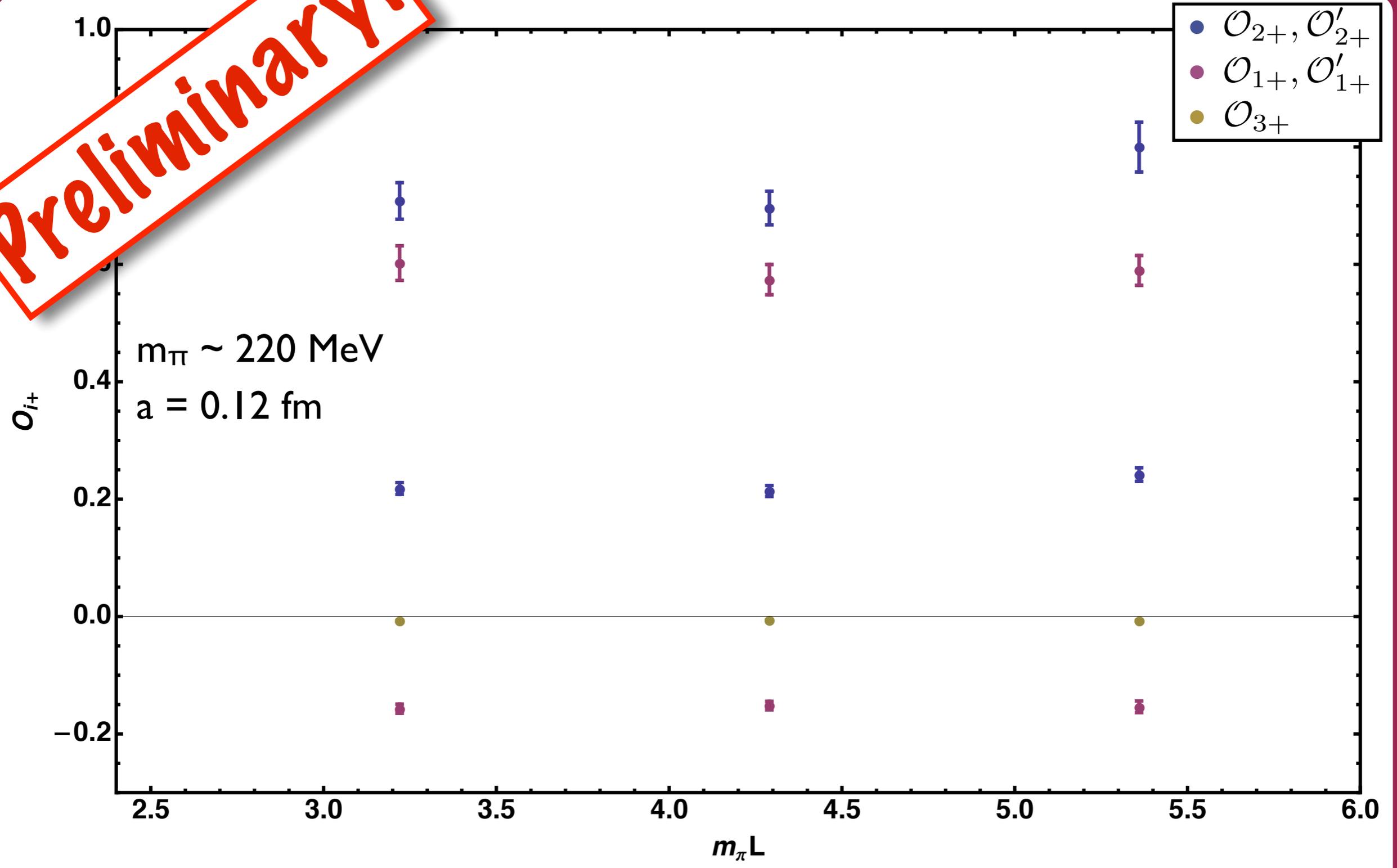
Signals are great

**Preliminary!**



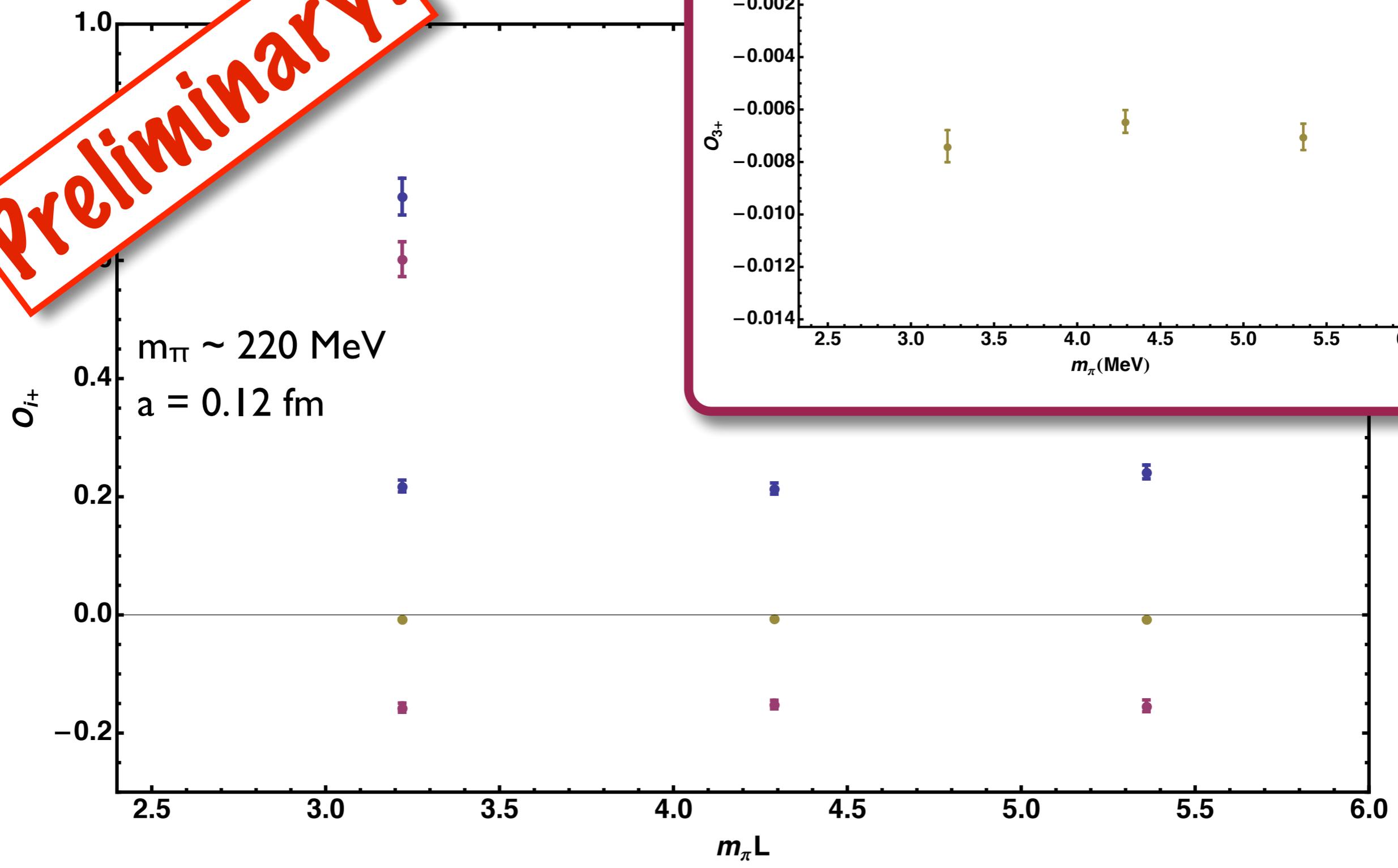
Signals are great

**Preliminary!**



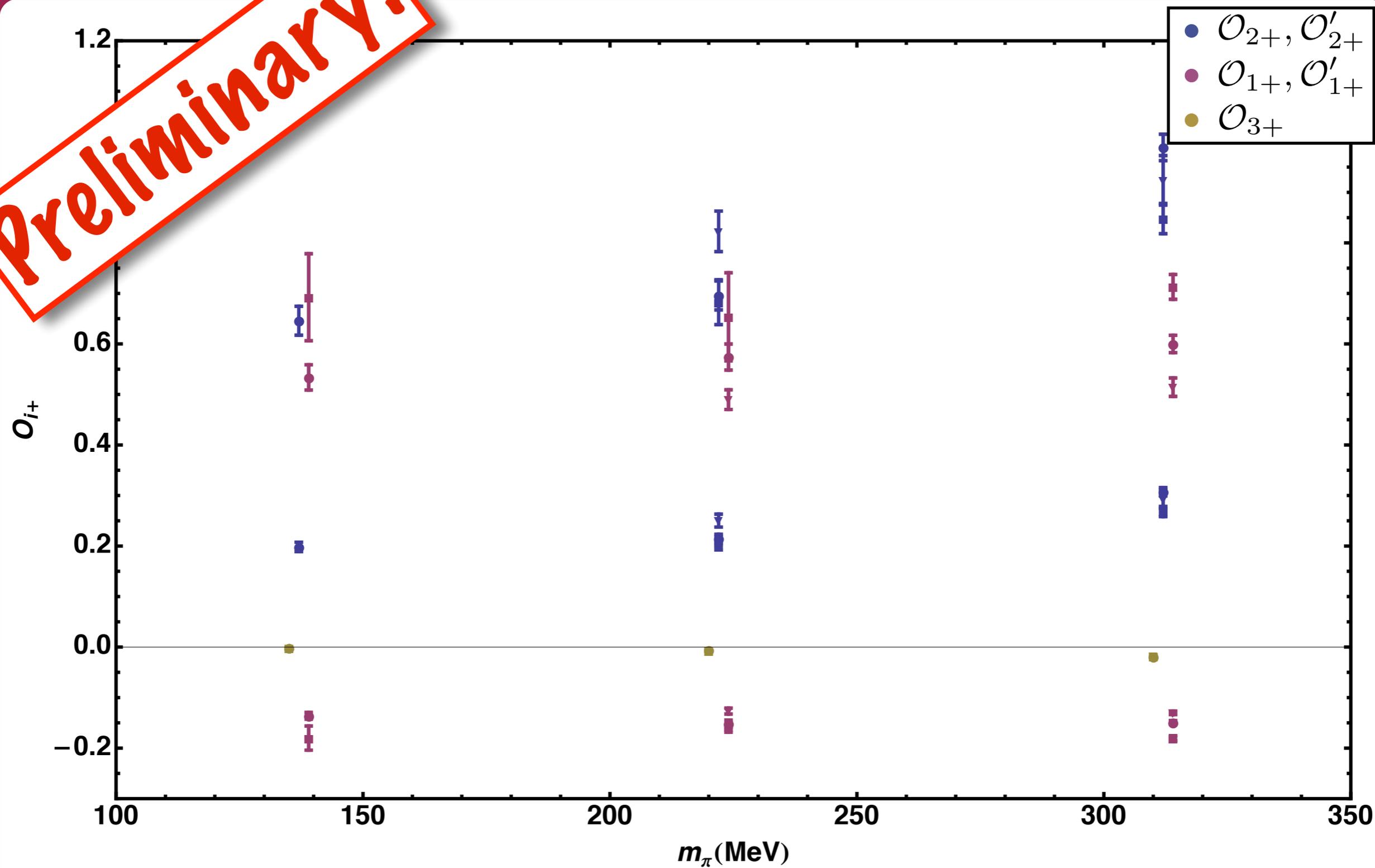
Volume study

**Preliminary!**



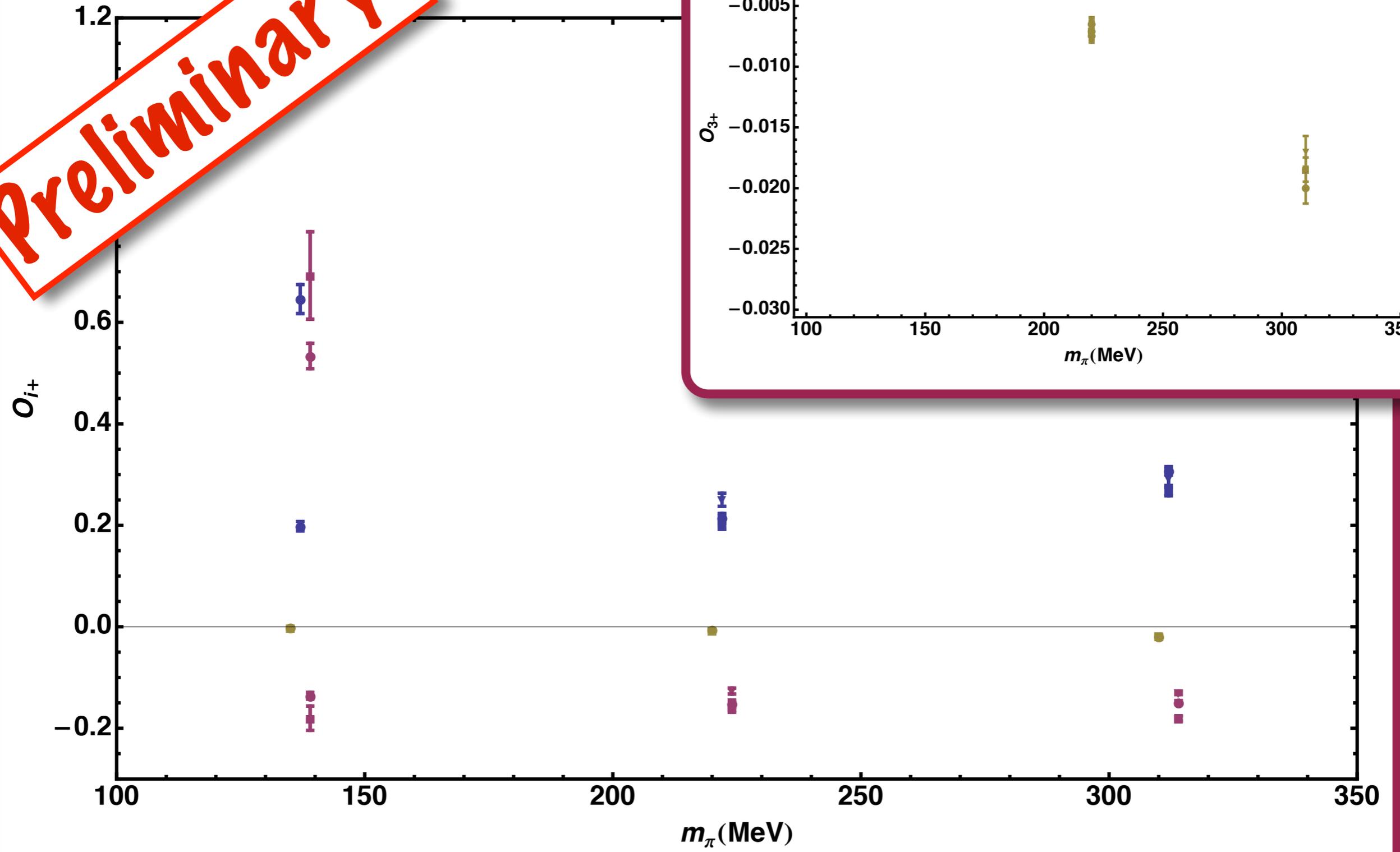
Volume study

Preliminary!



$m_{\pi}$  dependence

**Preliminary!**

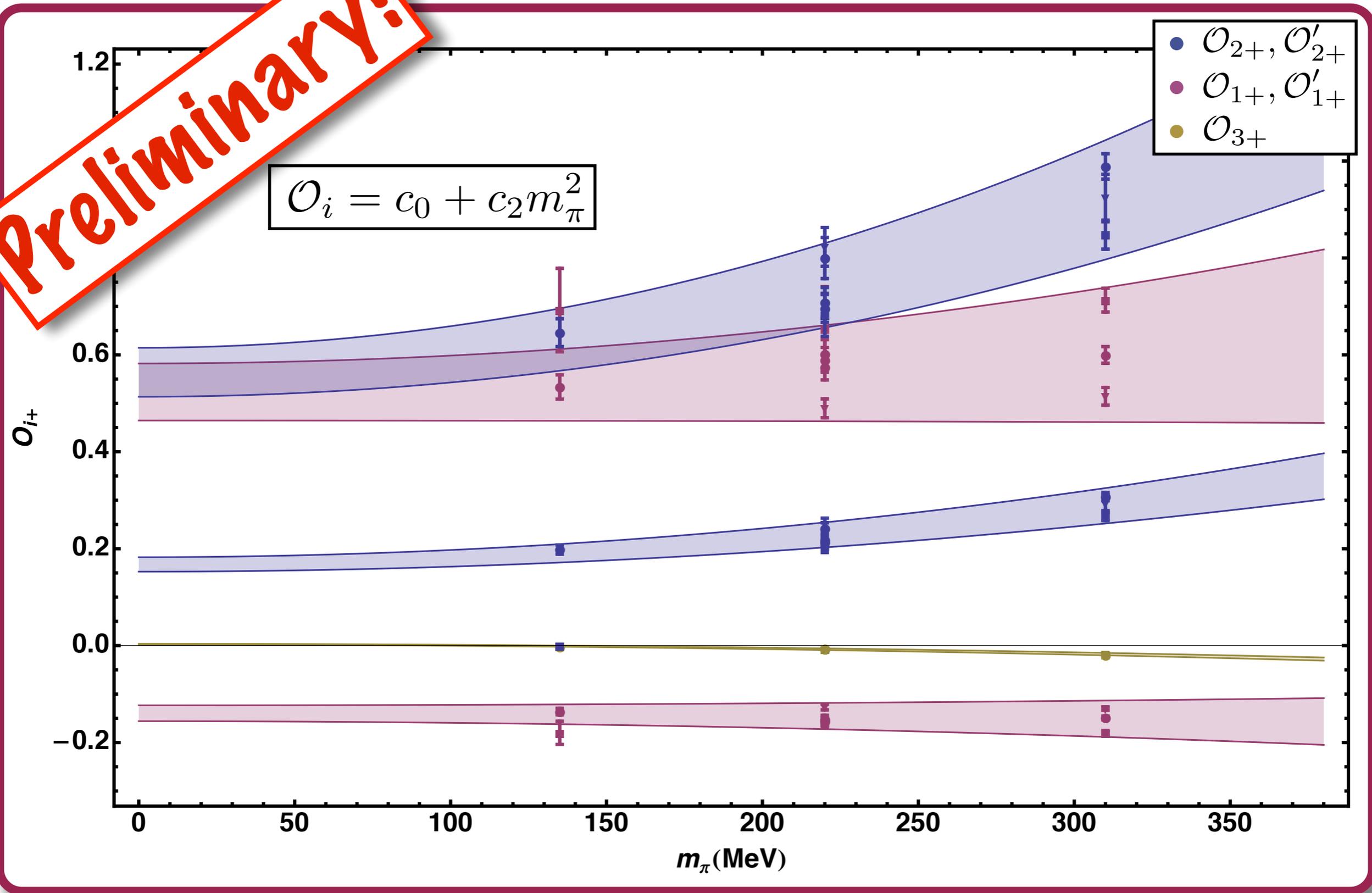


$m_\pi$  dependence

**Preliminary!**

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

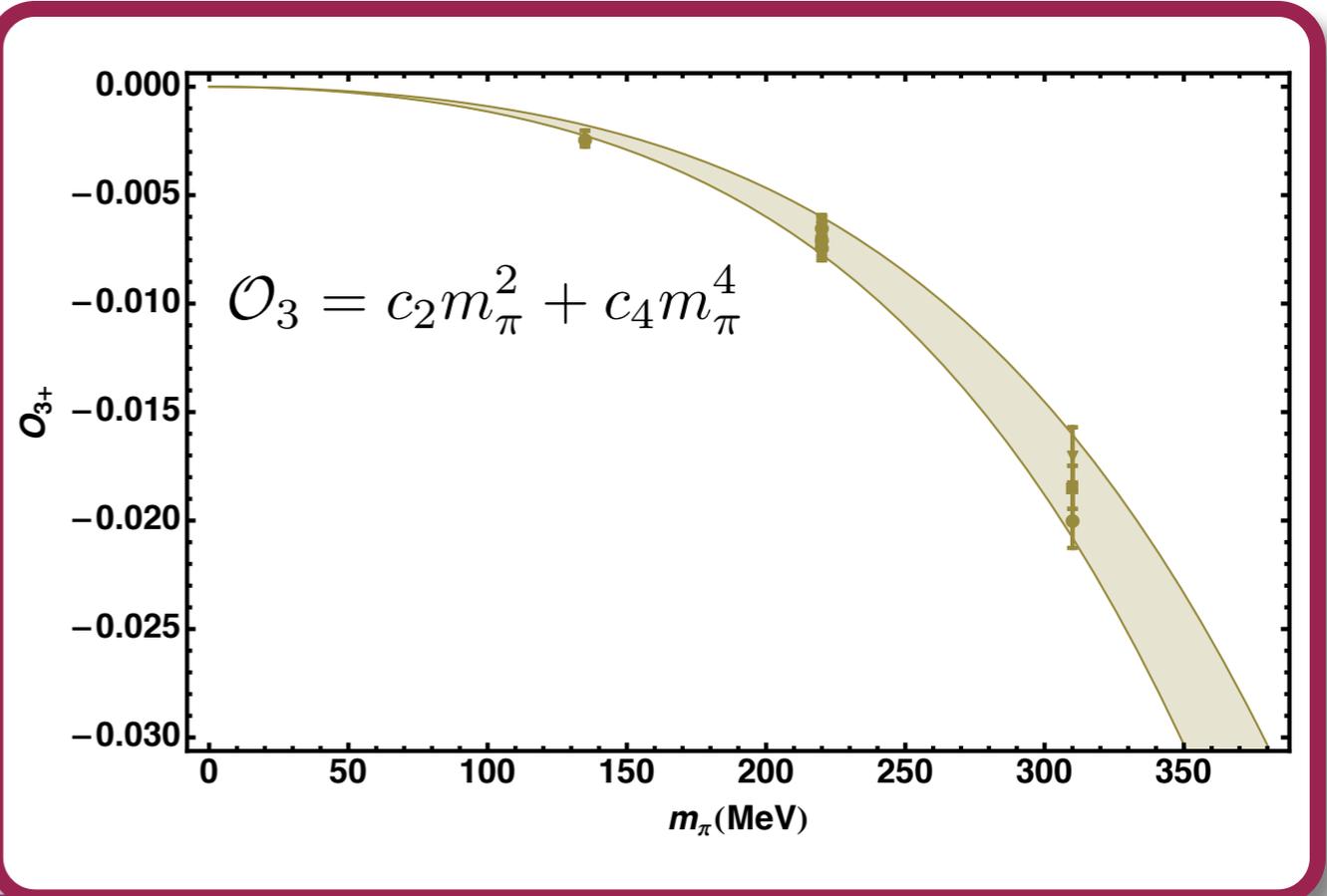
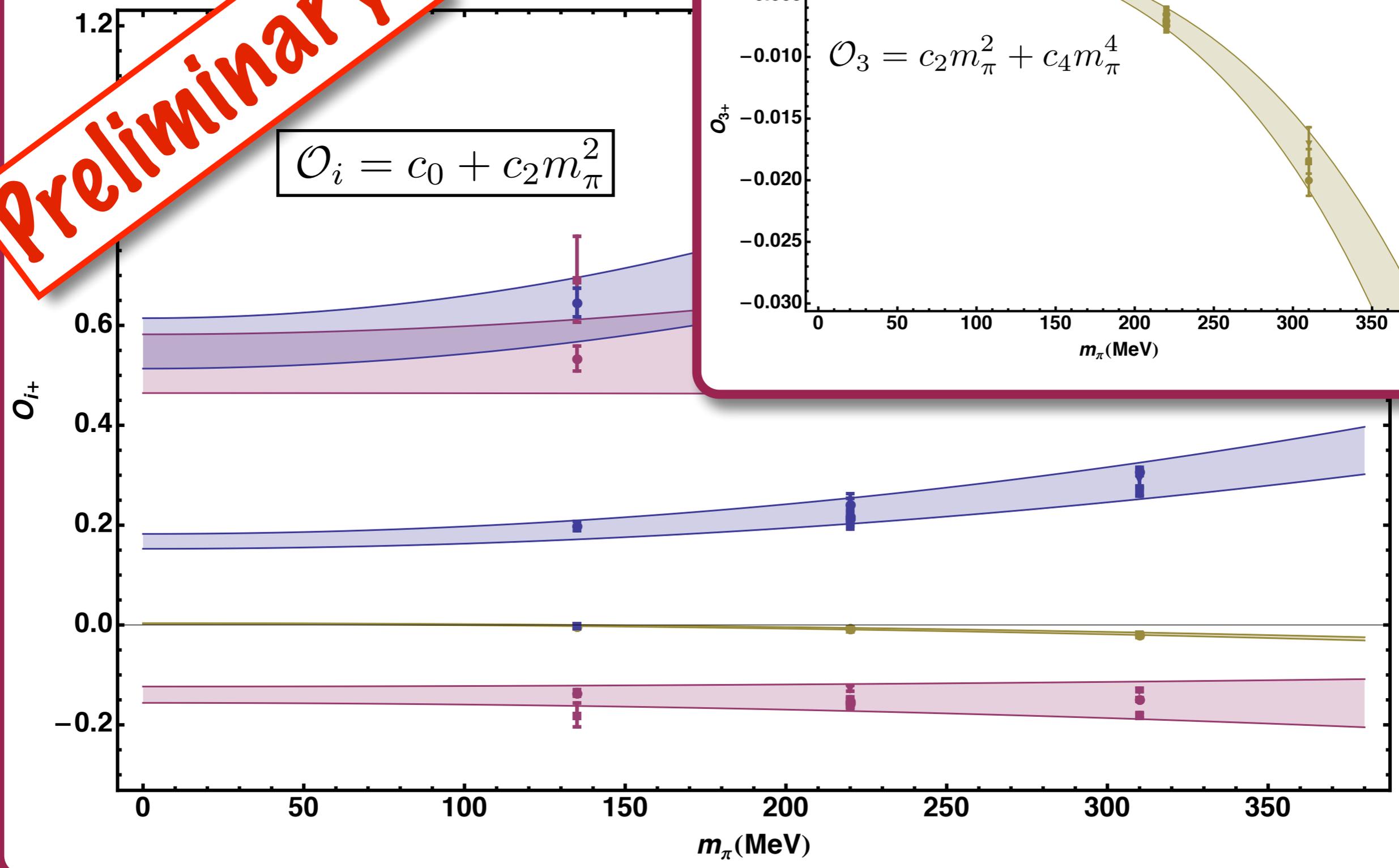
- $\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
- $\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
- $\mathcal{O}_{3+}$



naïve fits

**Preliminary!**

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



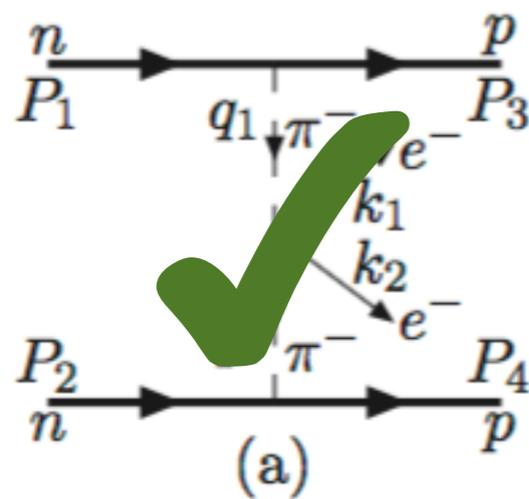
naïve fits

# Summary

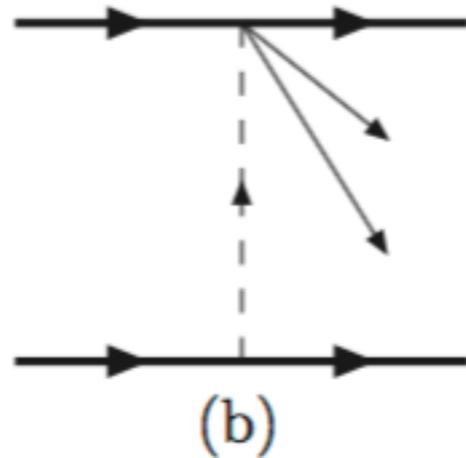
- $0\nu\beta\beta$ : search for Majorana mass signature
  - Lepton number violation could be source of matter / anti-matter asymmetry
  - Huge experimental efforts planned / underway
  - LQCD can make major impact on understanding of short-range operators
- Preliminary results for  $\pi^- \rightarrow \pi^+$  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....

# $\pi N \rightarrow \nu \beta \beta$ diagrams

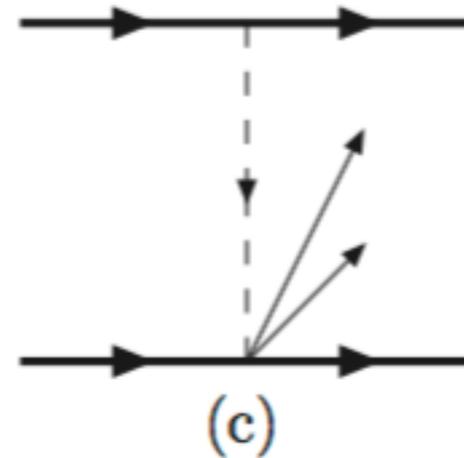
- LO almost complete!



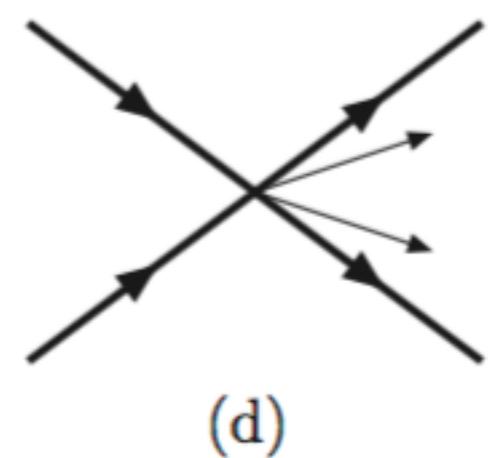
$\mathcal{O}(p^{-2})$



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



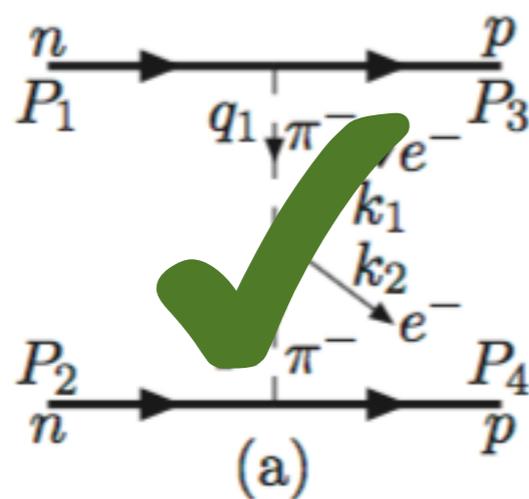
$\mathcal{O}(p^{-1})$



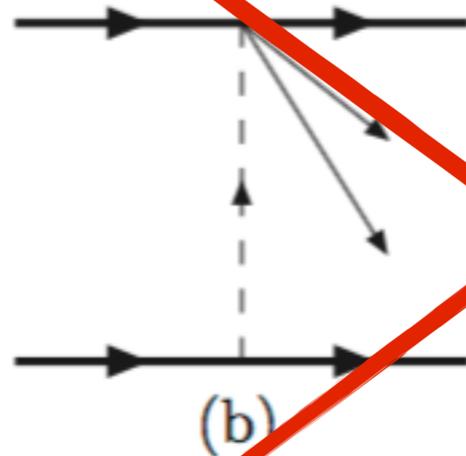
$\mathcal{O}(p^0)$

# $\pi N 0\nu\beta\beta$ diagrams

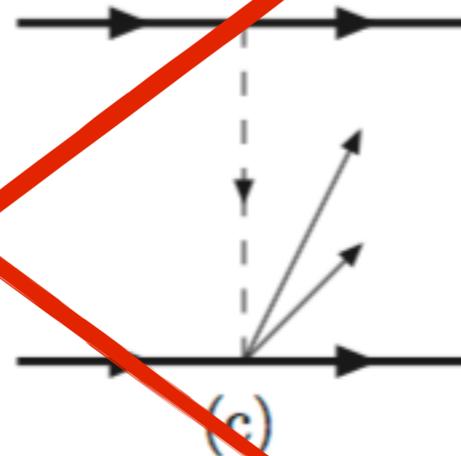
- LO almost complete!
- NLO: **disconnected diagrams**
  - Don't contribute to  $0^+ \rightarrow 0^+$  nuclear transitions



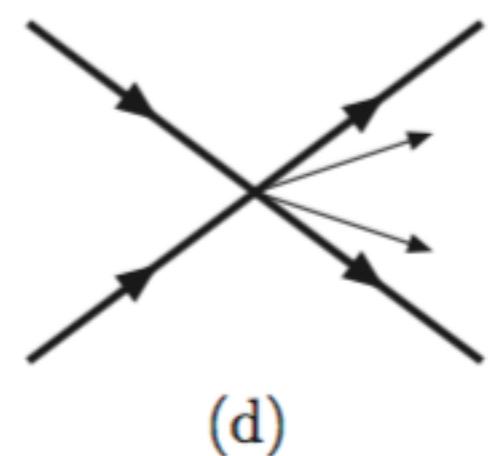
$\mathcal{O}(p^{-2})$



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



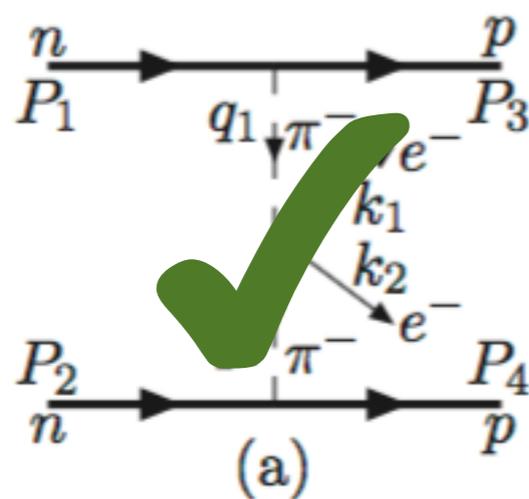
$\mathcal{O}(p^{-1})$



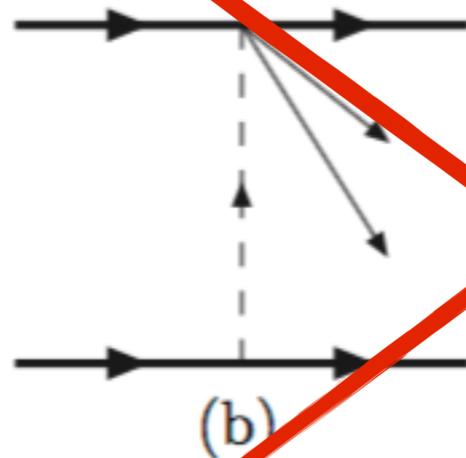
$\mathcal{O}(p^0)$

# $\pi N 0\nu\beta\beta$ diagrams

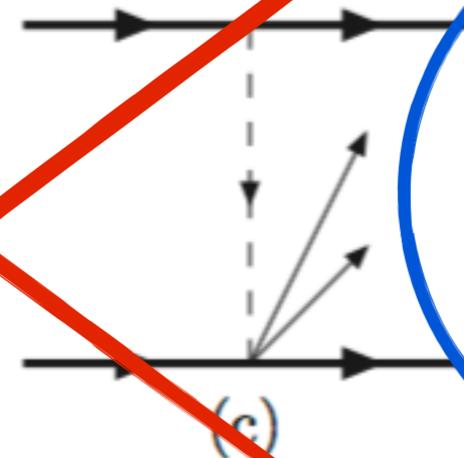
- LO almost complete!
- NLO: **disconnected diagrams**
  - Don't contribute to  $0^+ \rightarrow 0^+$  nuclear transitions
- $nn \rightarrow pp$  contact operators



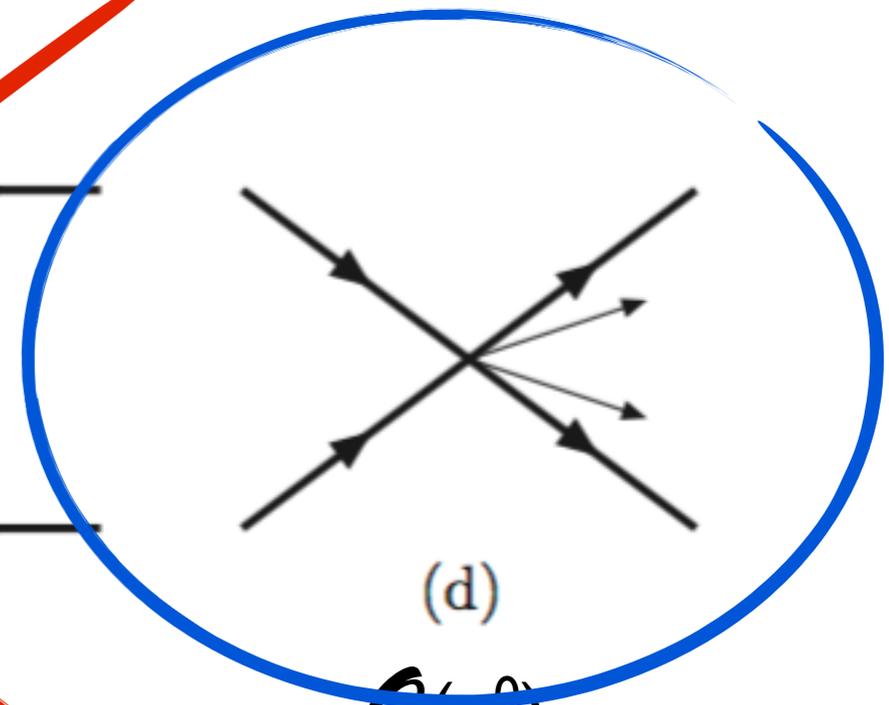
$\mathcal{O}(p^{-2})$



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



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



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

*Stay tuned!*