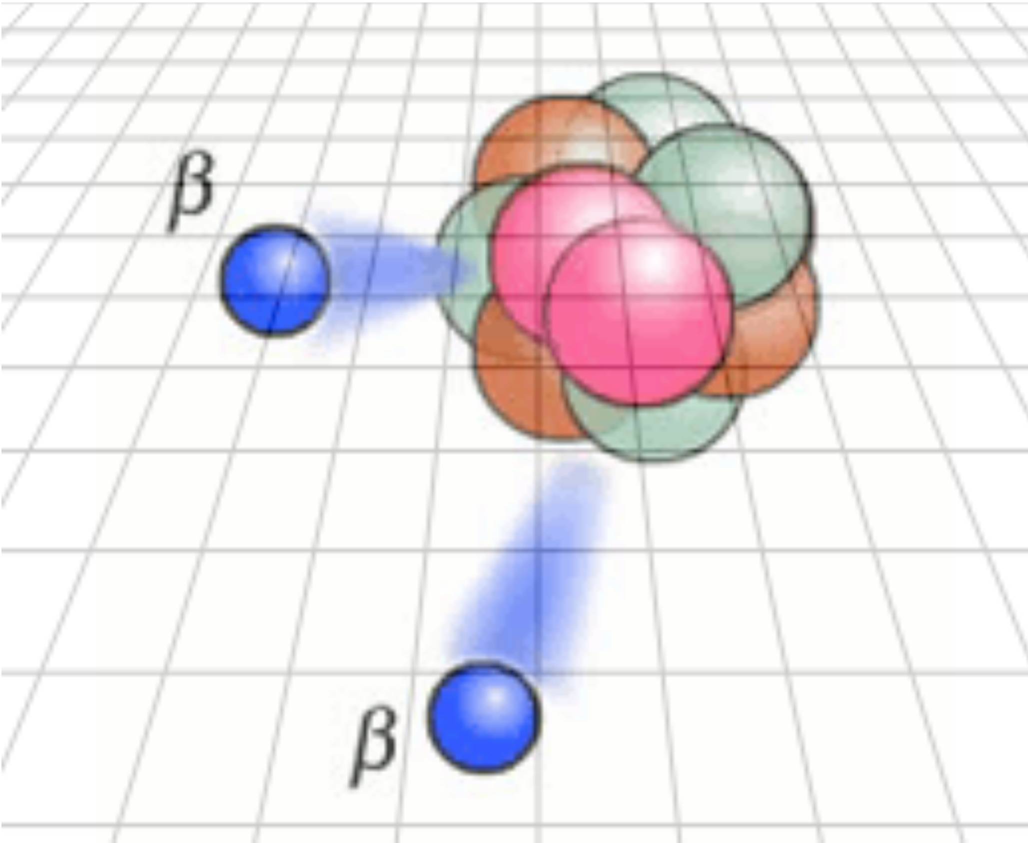
Neutrinoless Double Beta Decay from Lattice QCD



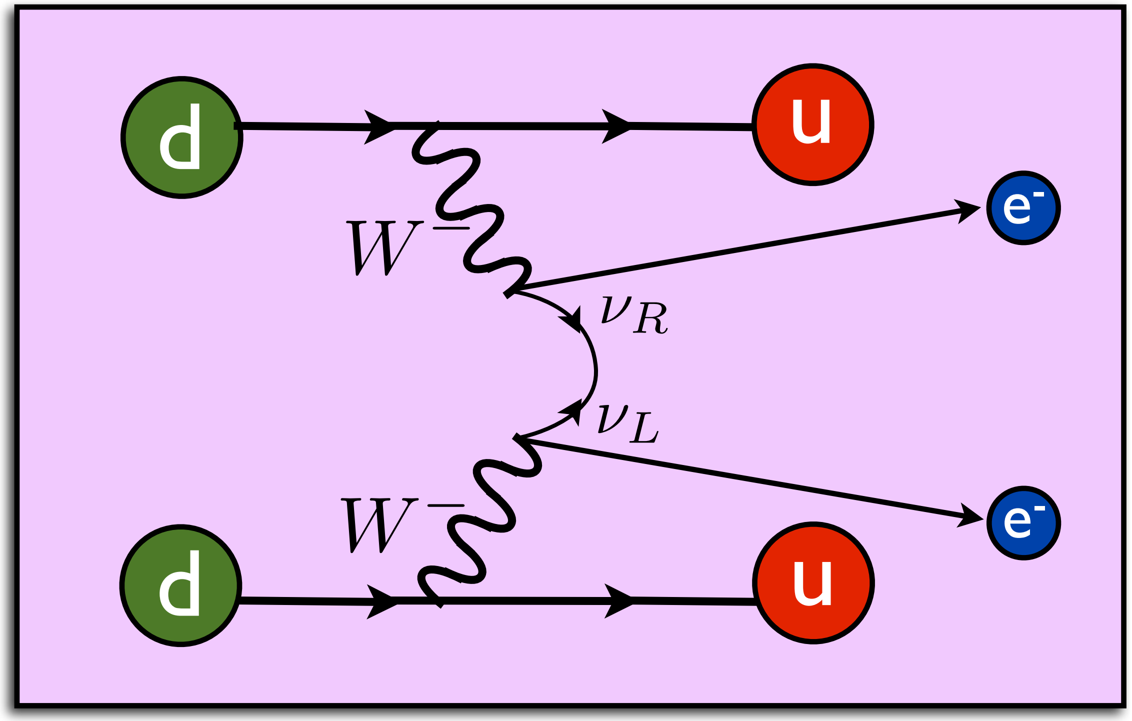
Amy Nicholson
UC Berkeley/UNC

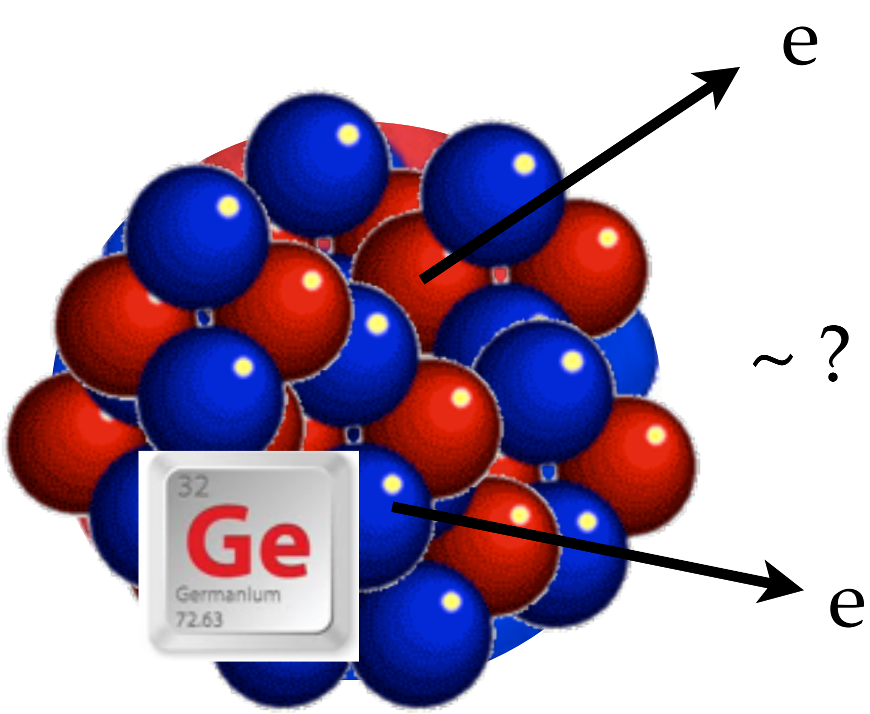
Institute for Nuclear Theory, Seattle, WA

Neutrinoless Double-beta Decay Opening Workshop

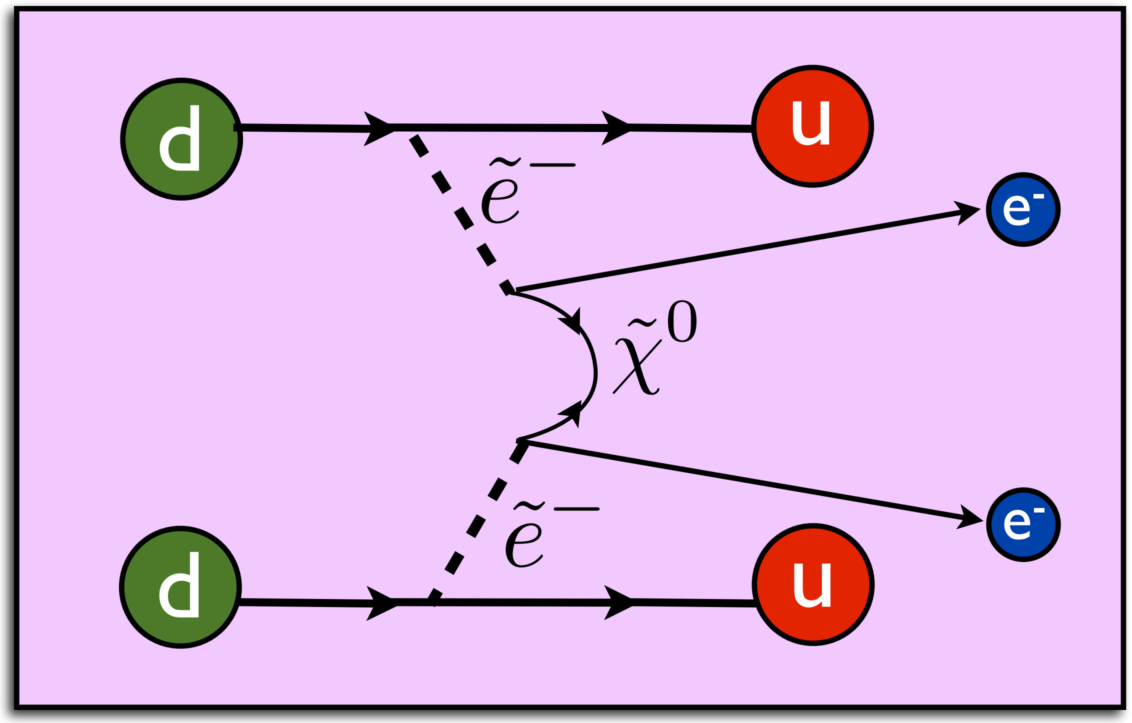
June 14, 2017

Relating Theory to Experiment

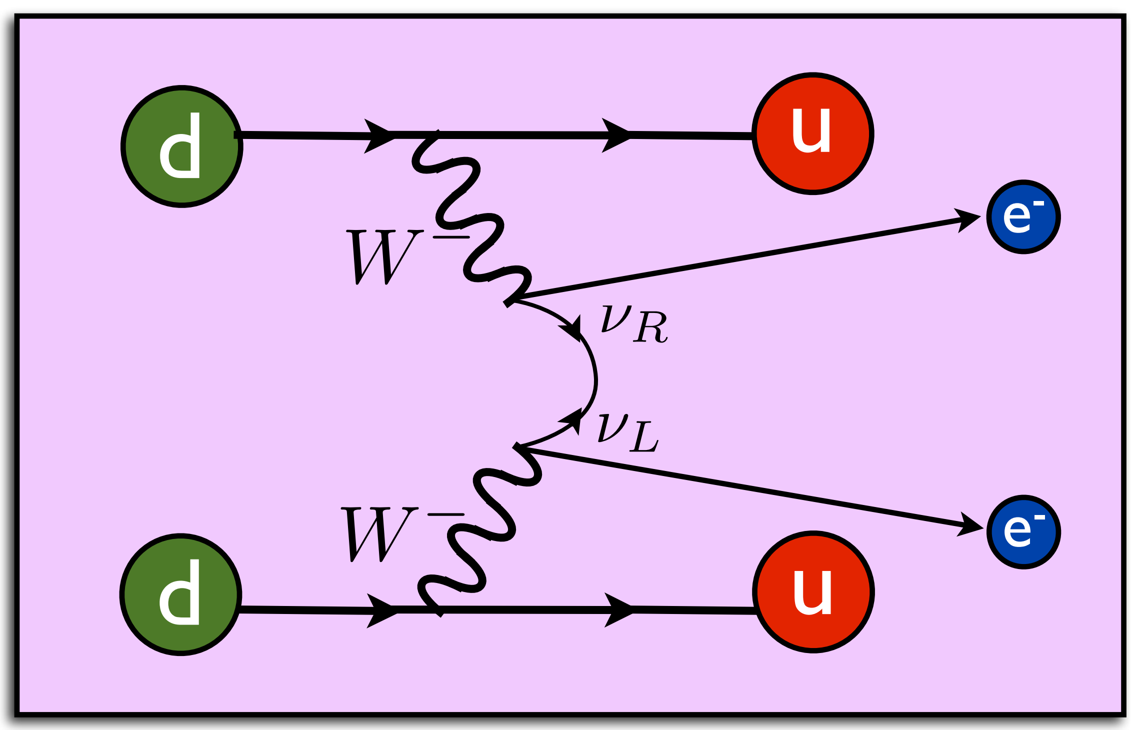


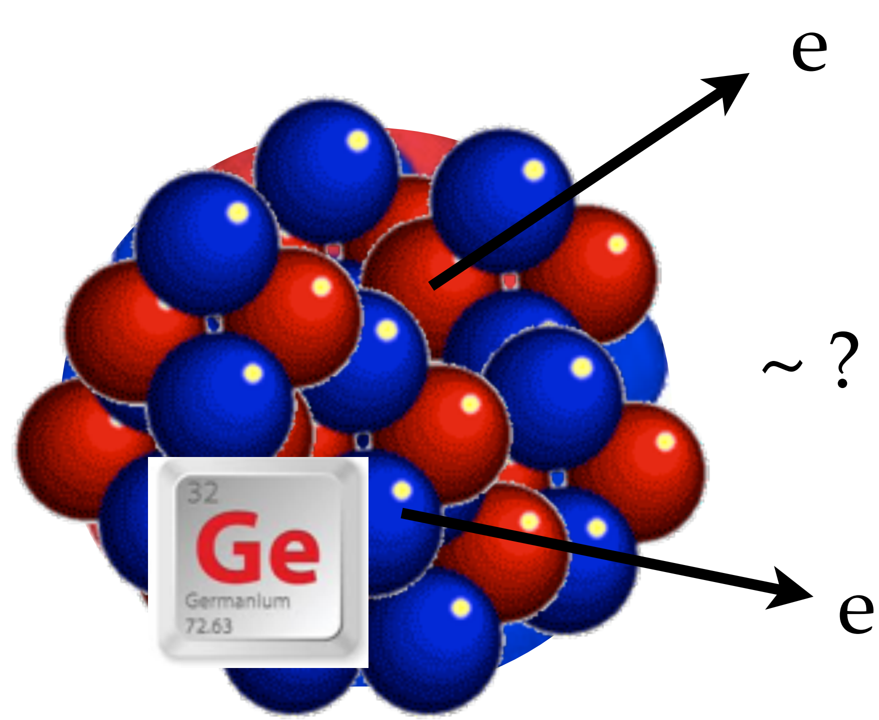


Relating Theory to Experiment



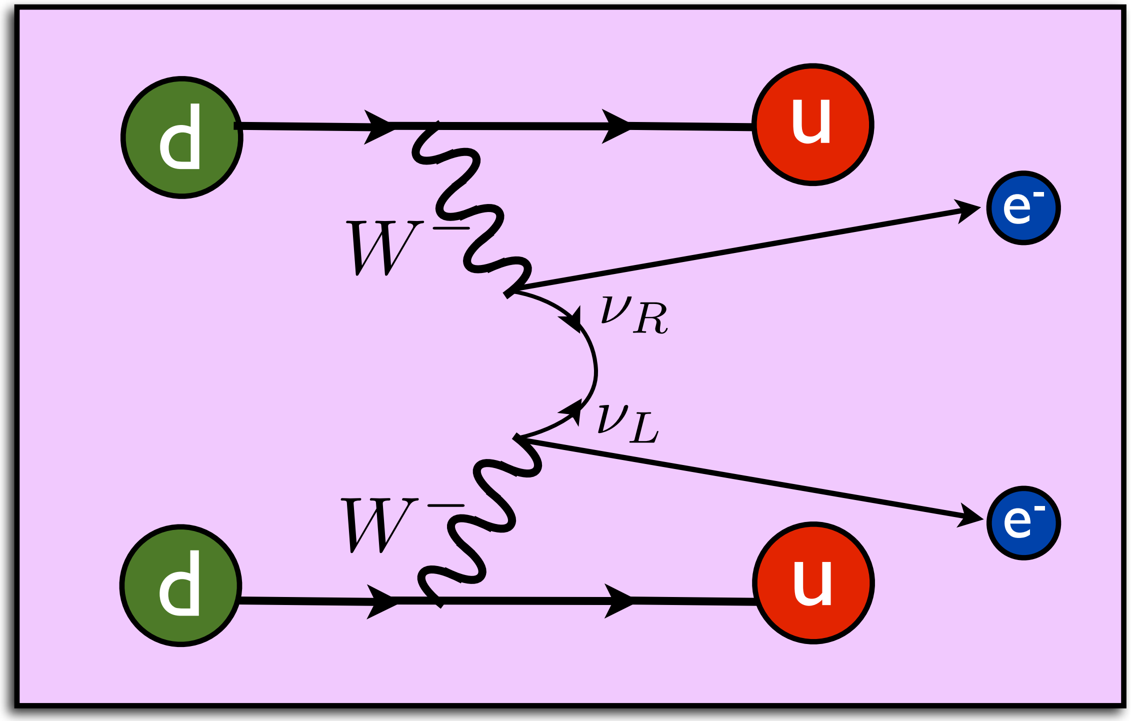
$0\nu\beta\beta$ experiments could help constrain R-parity violating coefficients

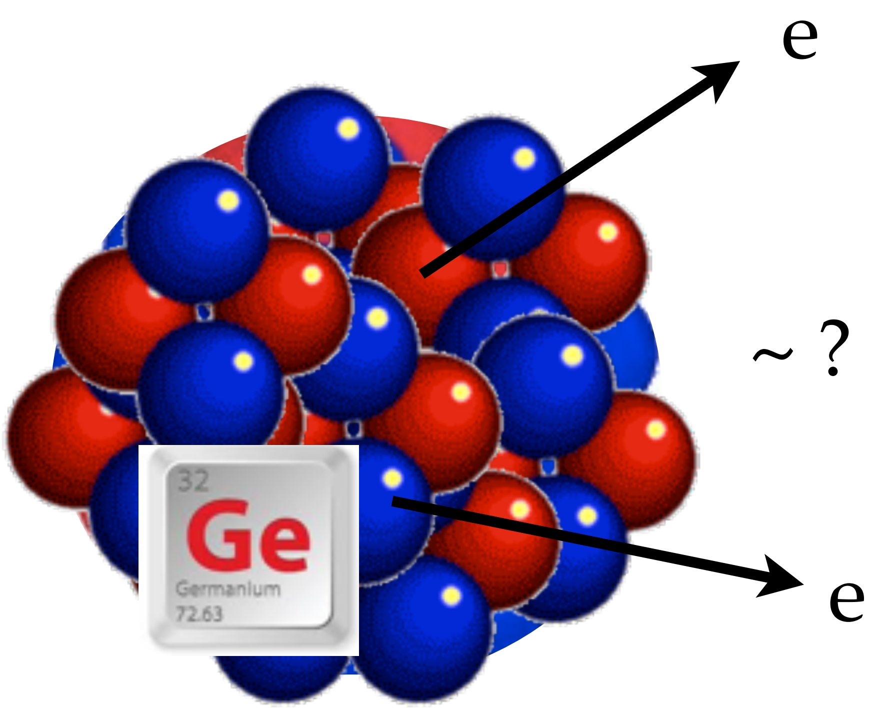




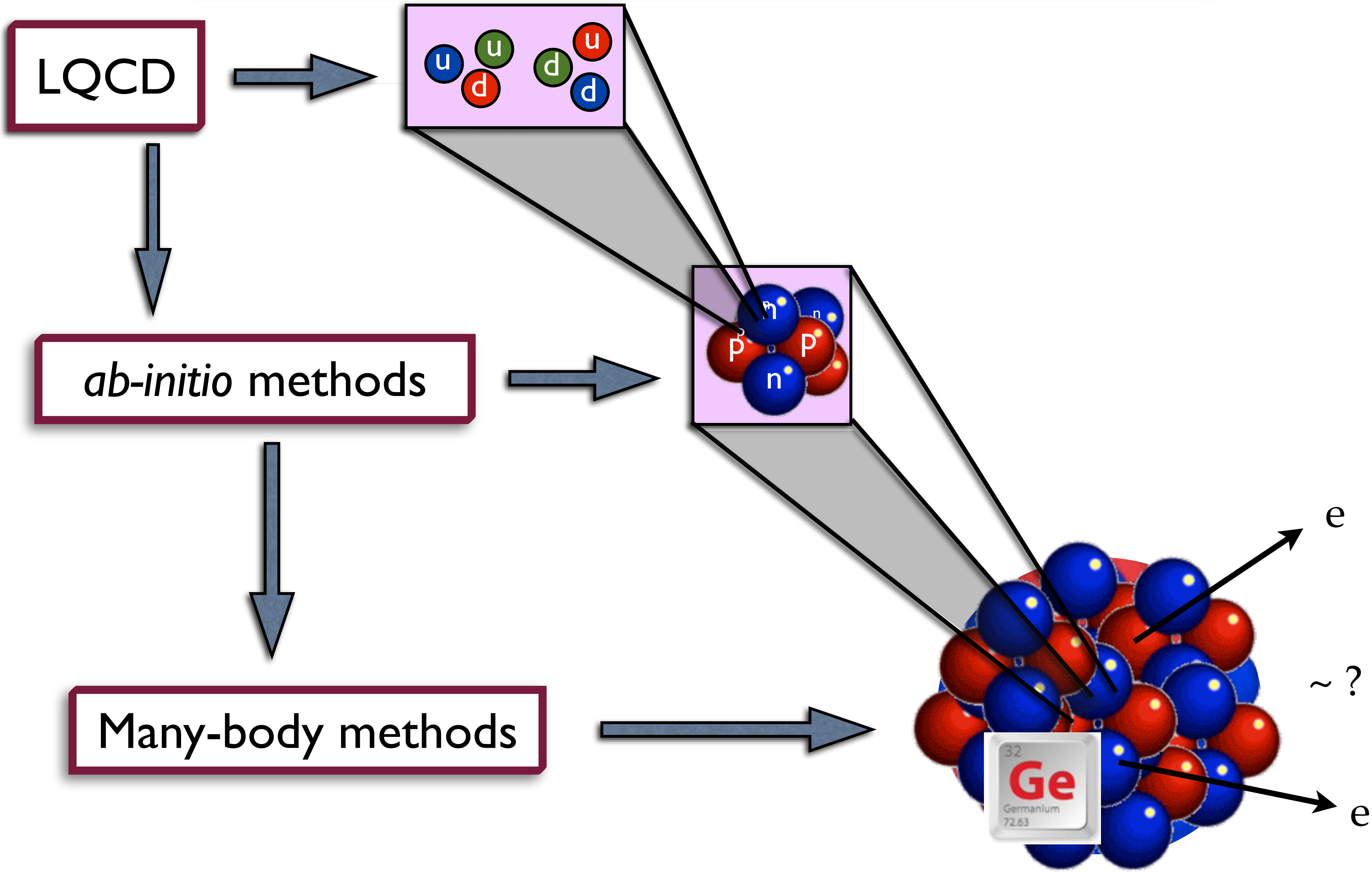
Relating Theory to Experiment

- LQCD: formulation of QCD in discretized, finite spacetime
- All errors are quantifiable and may be systematically removed
  - Extrapolations to continuum, infinite volume, physical quark mass
- LQCD will never calculate your favorite $0\nu\beta\beta$ isotope
  - Monte Carlo noise (sign) problem, quark contractions, large range of scales,....



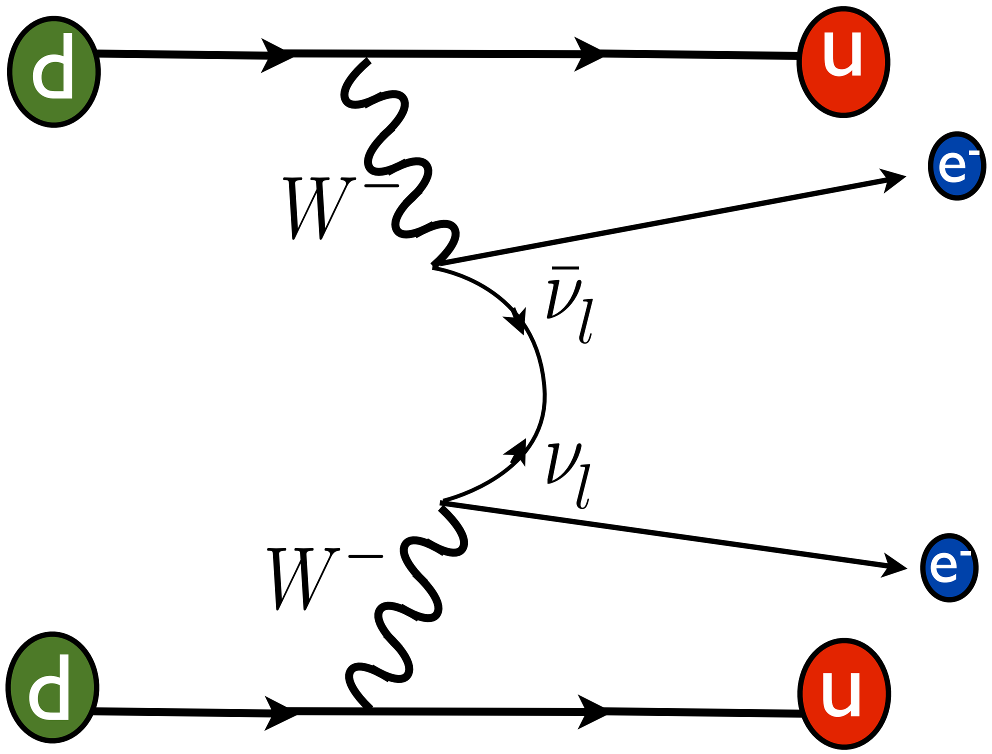


Relating Theory to Experiment

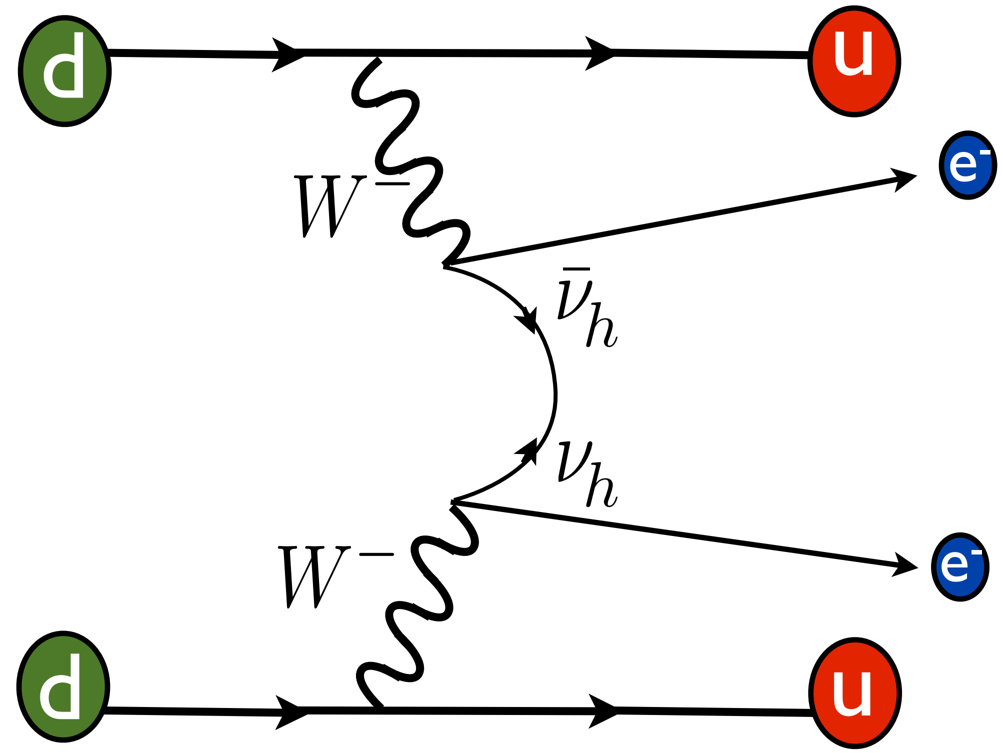


Lattice QCD contributions to $0\nu\beta\beta$

- Long-range
  - Axial charge of the nucleon
- Short-range
  - Leading order single pion exchange contribution
  - Two-nucleon matrix elements



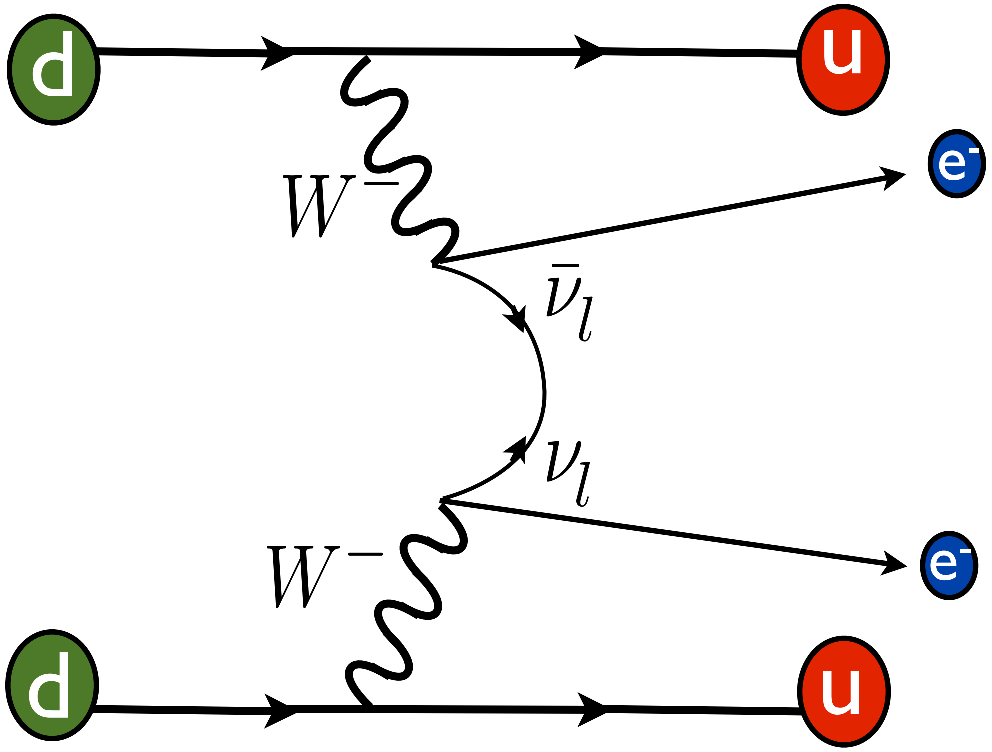
Long-range



Short-range

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

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



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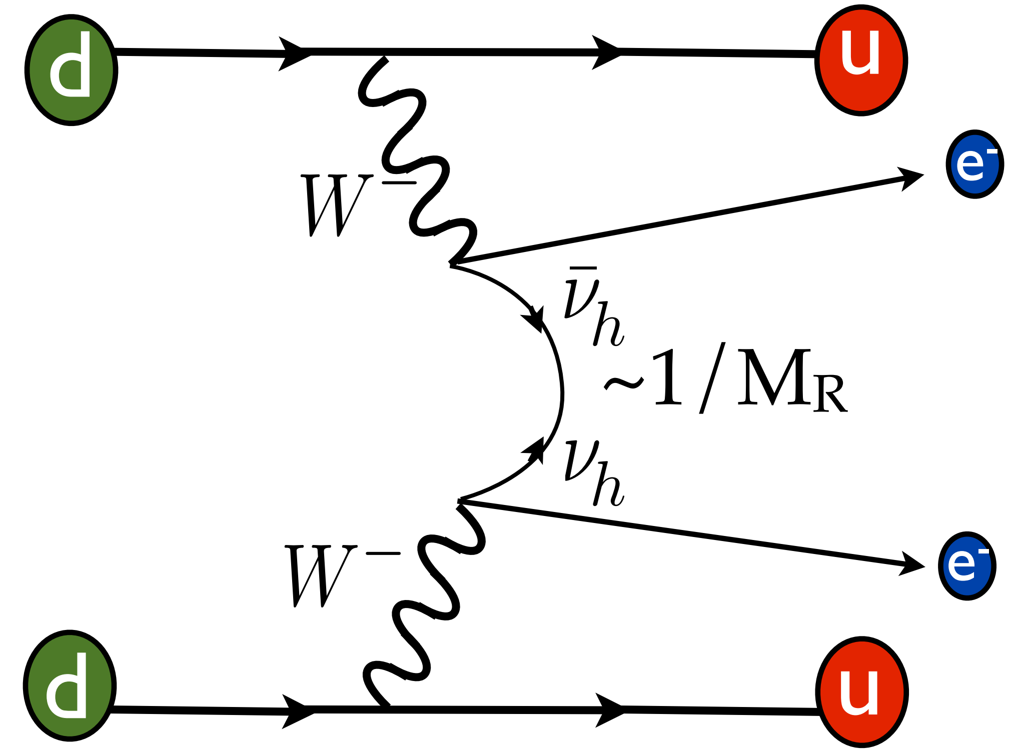

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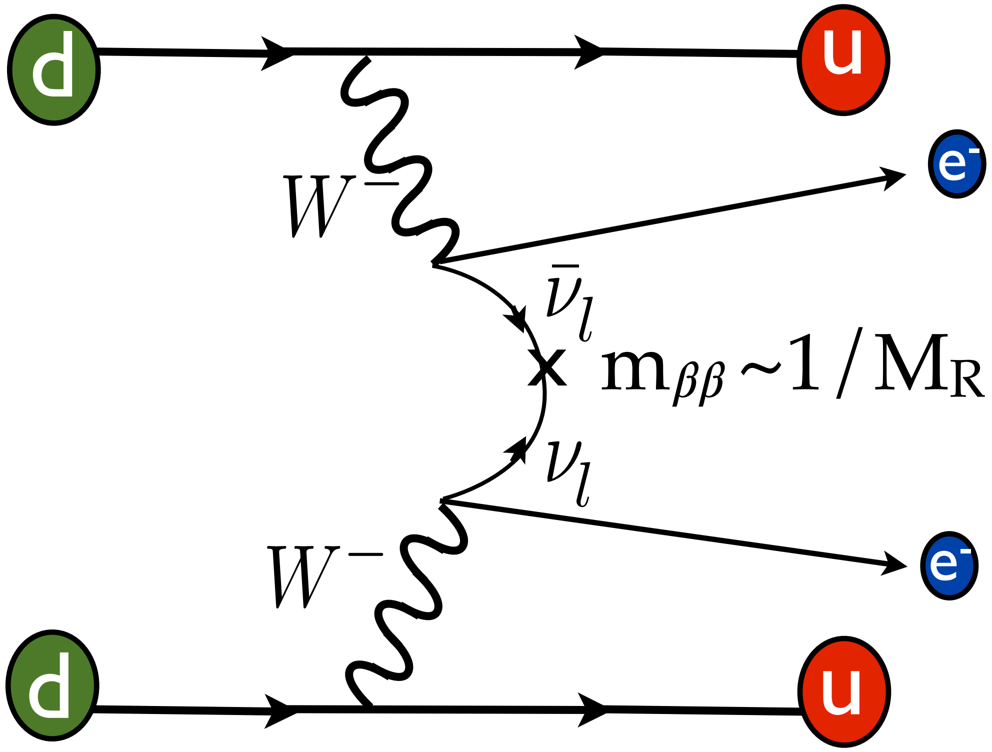

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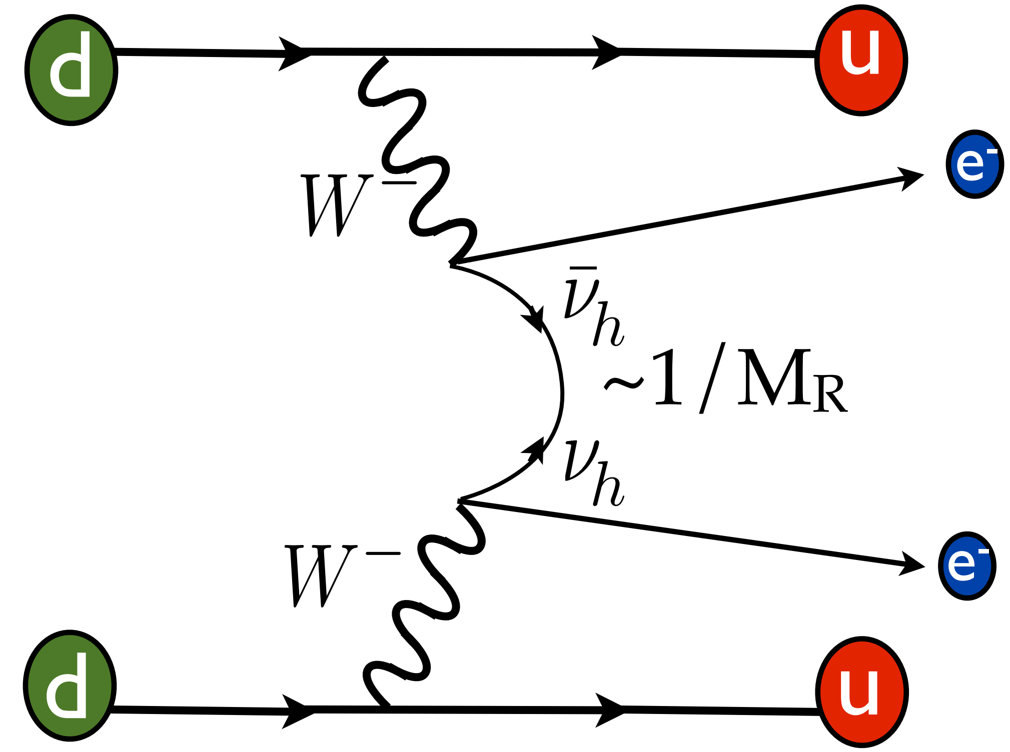

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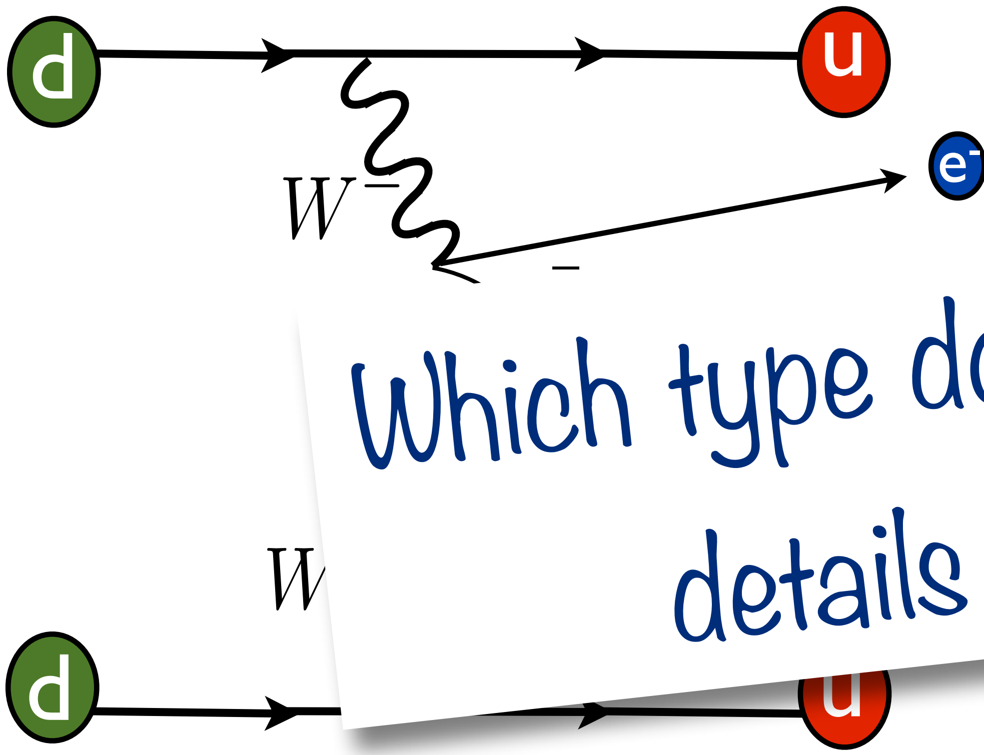

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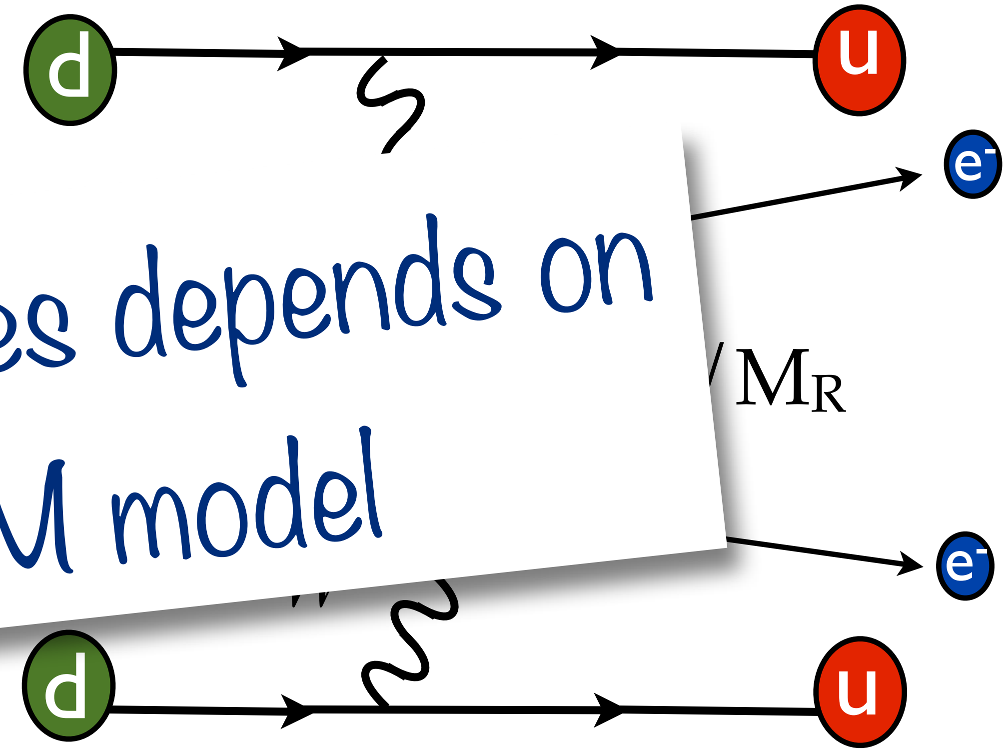
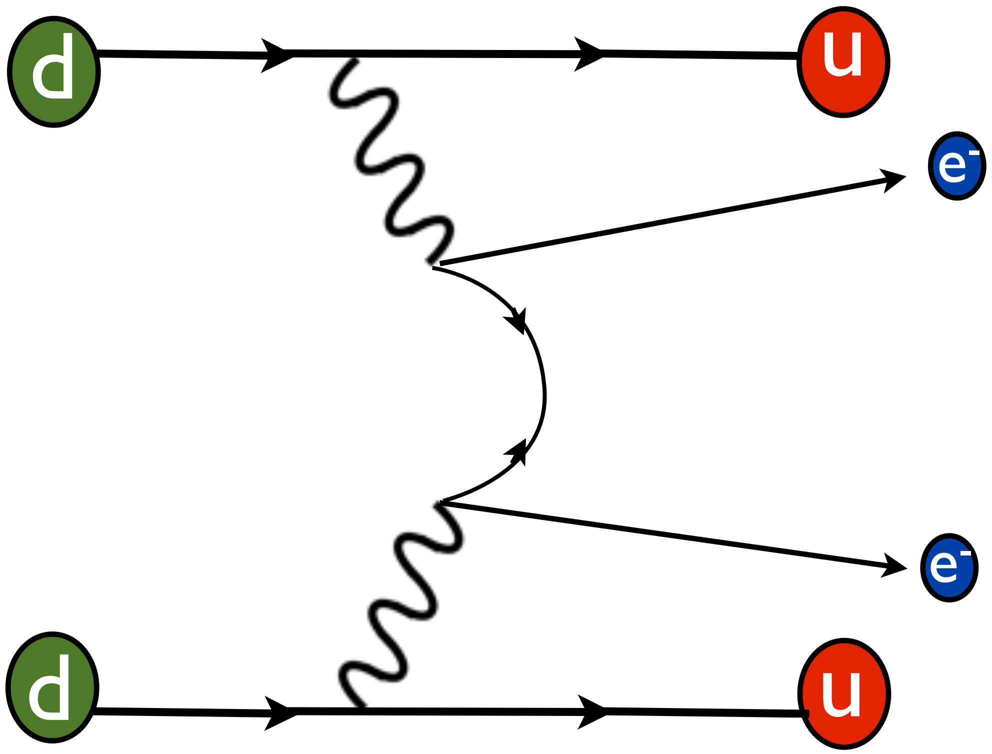


Short-range

Which type dominates depends on details of BSM model

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

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



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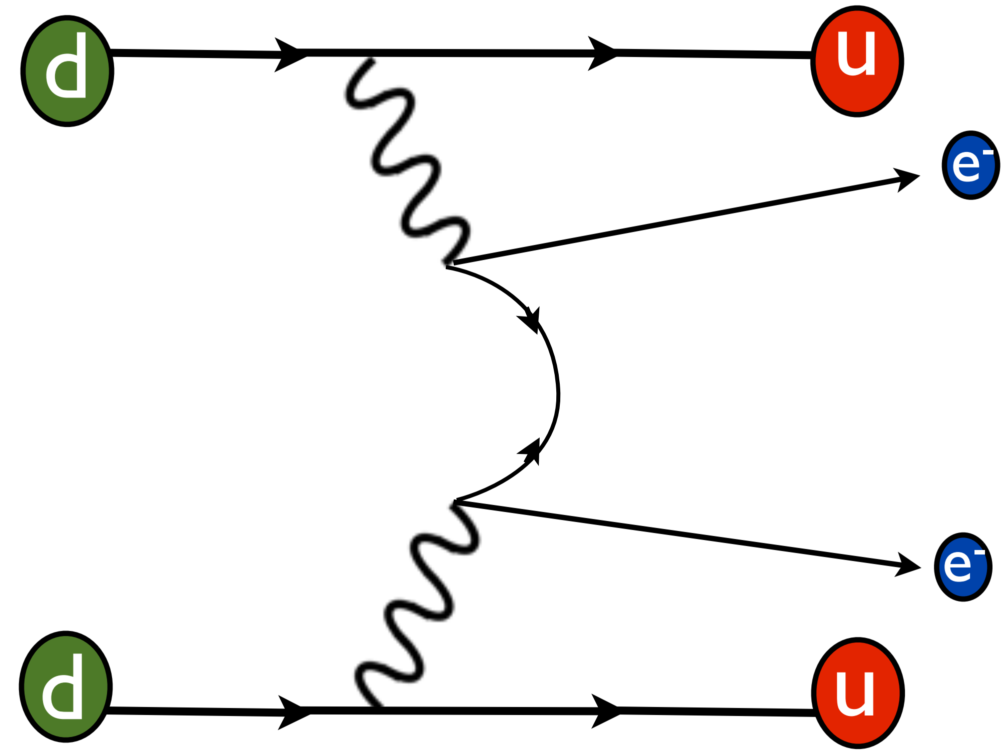

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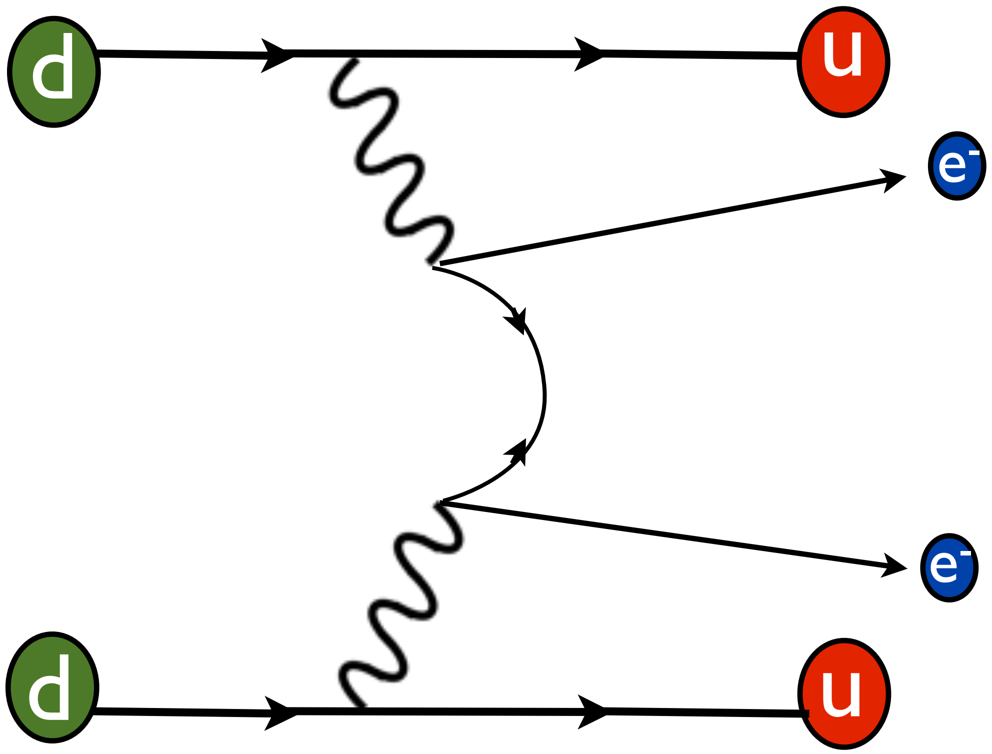
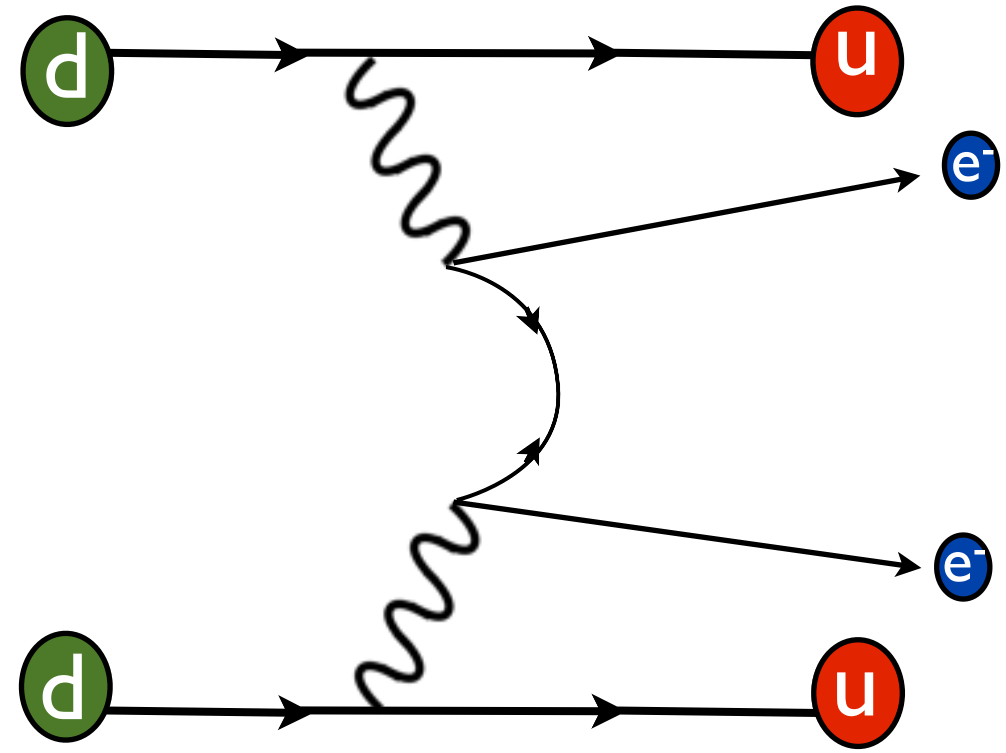


Long-range

$\Lambda \ll M_W$



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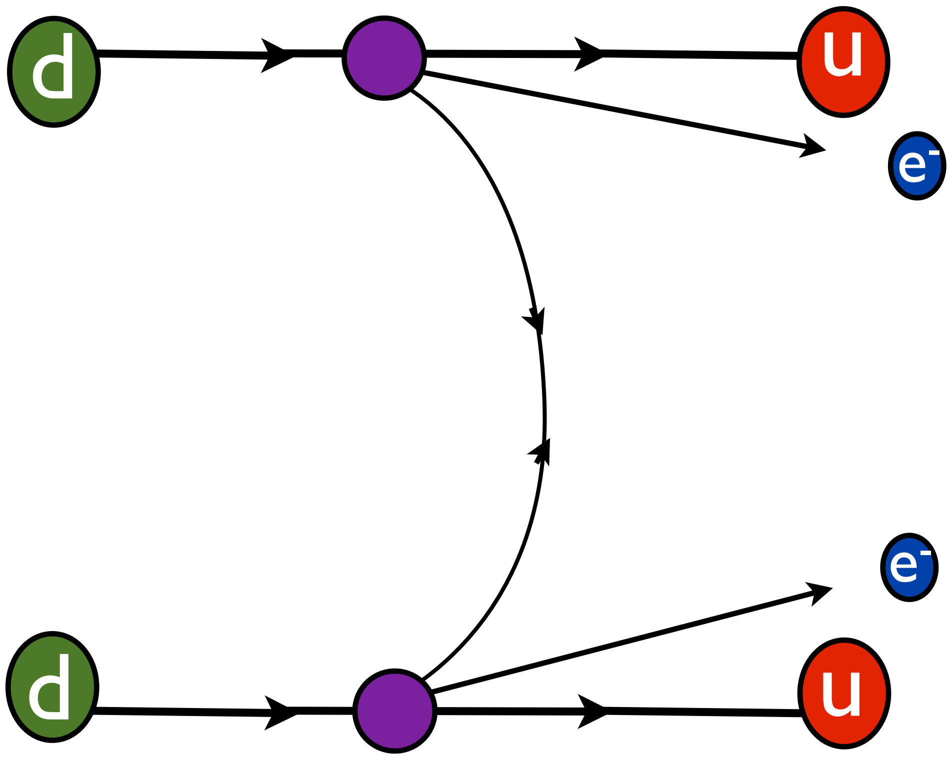

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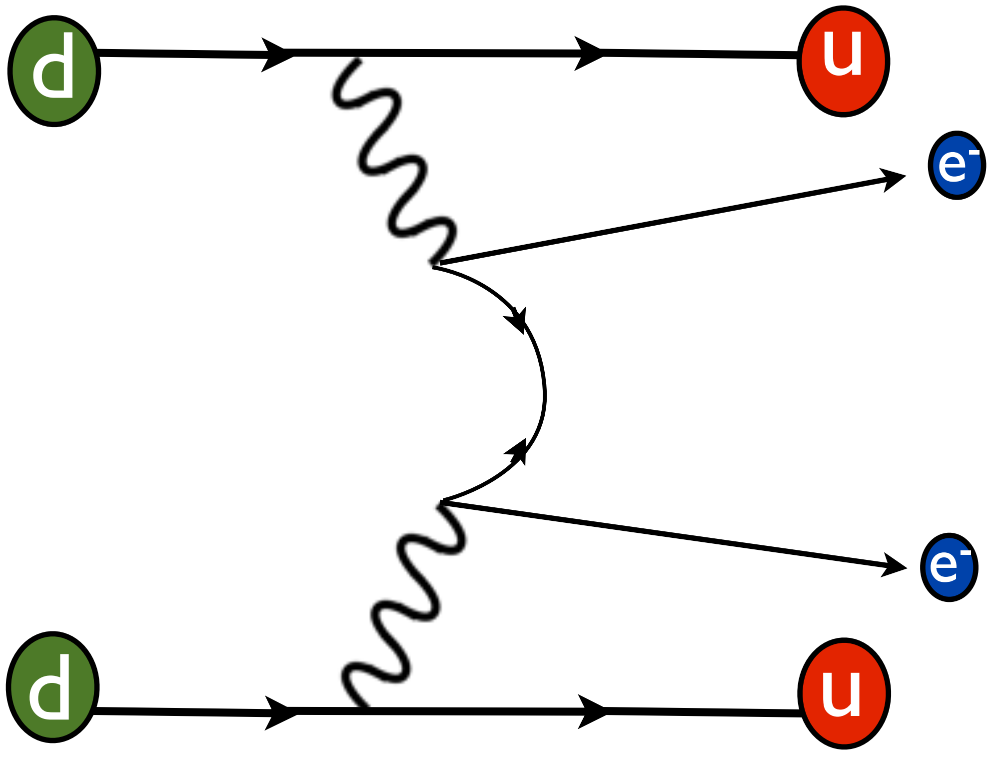

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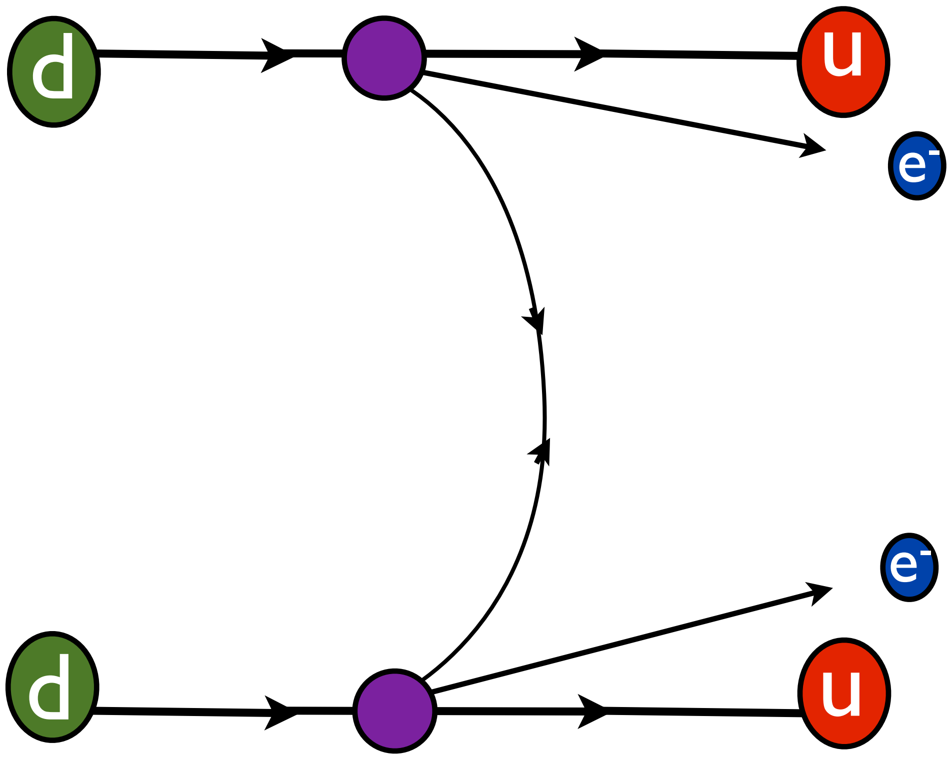
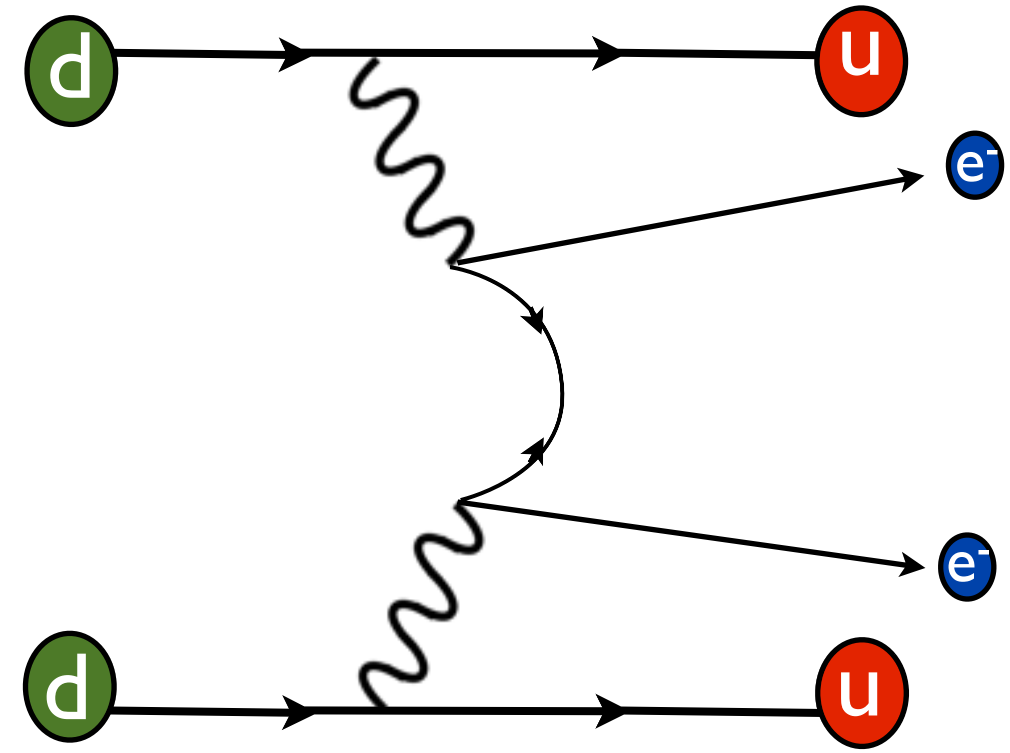


Long-range

$\Lambda \ll \Lambda_{QCD}$



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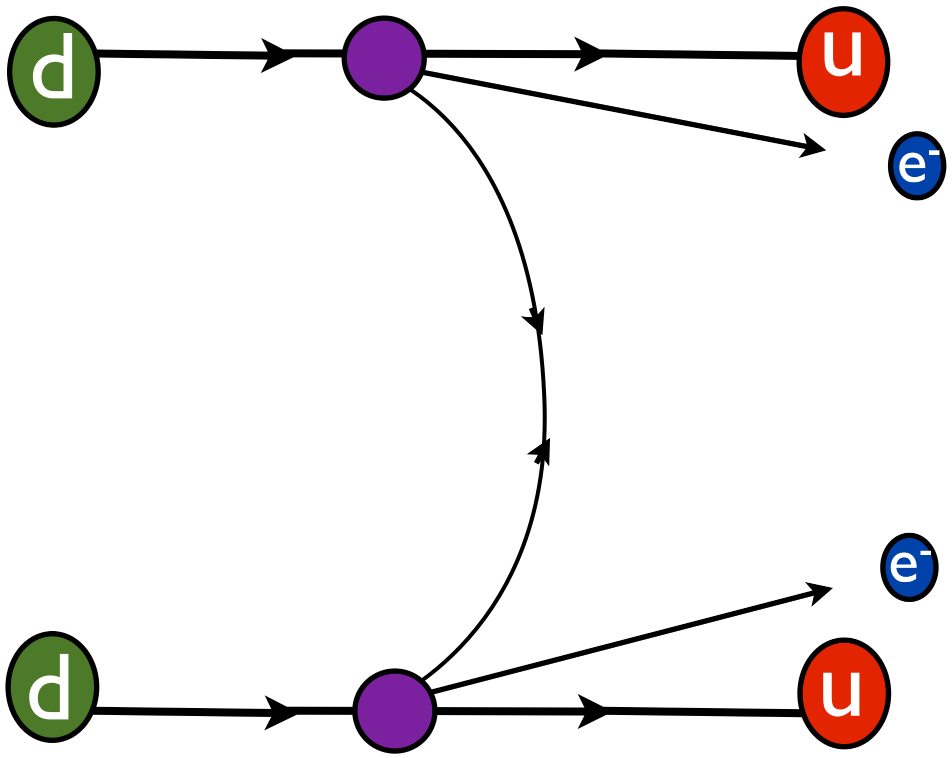

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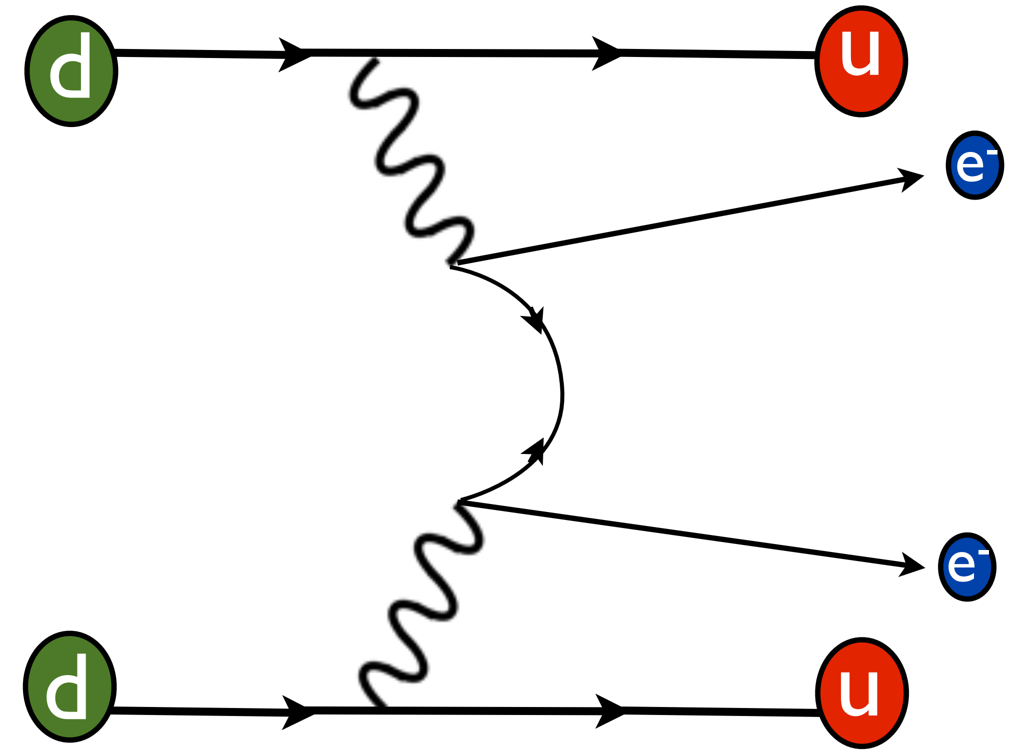

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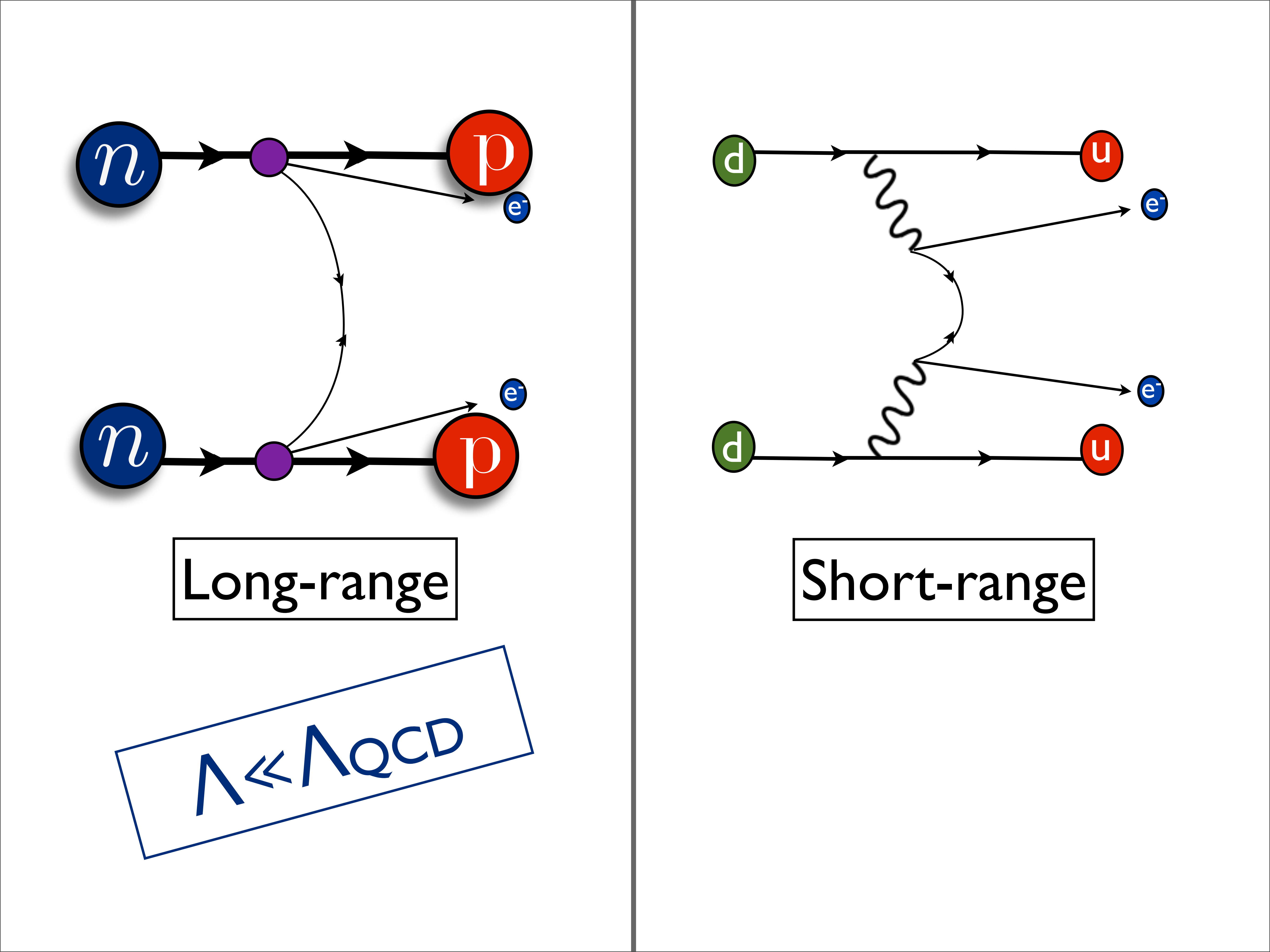

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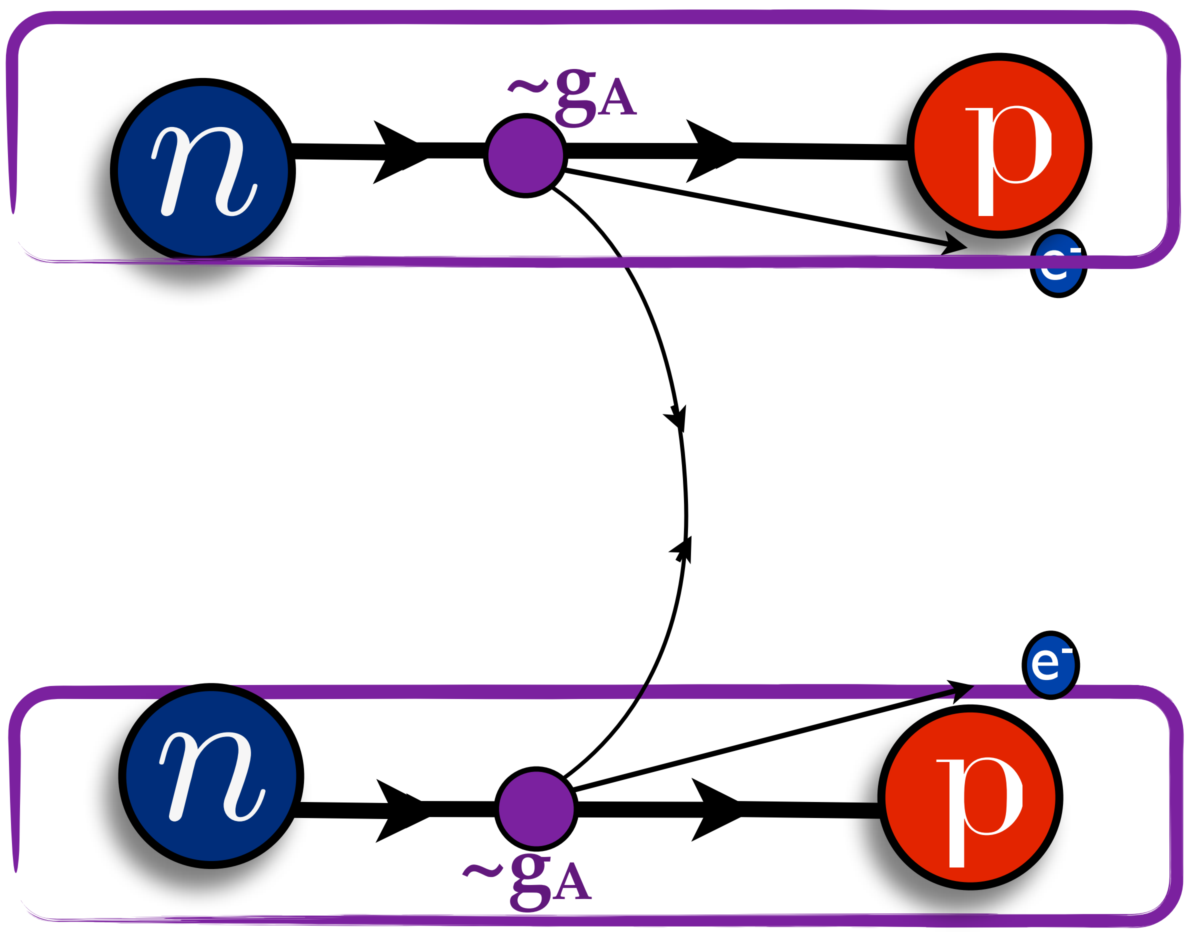

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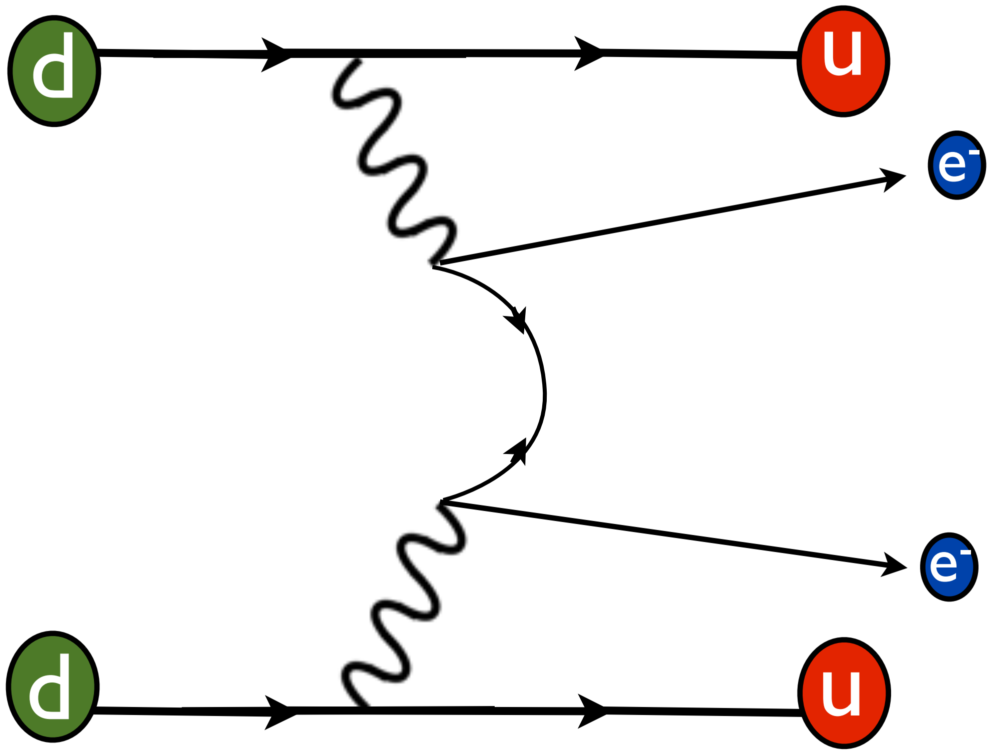

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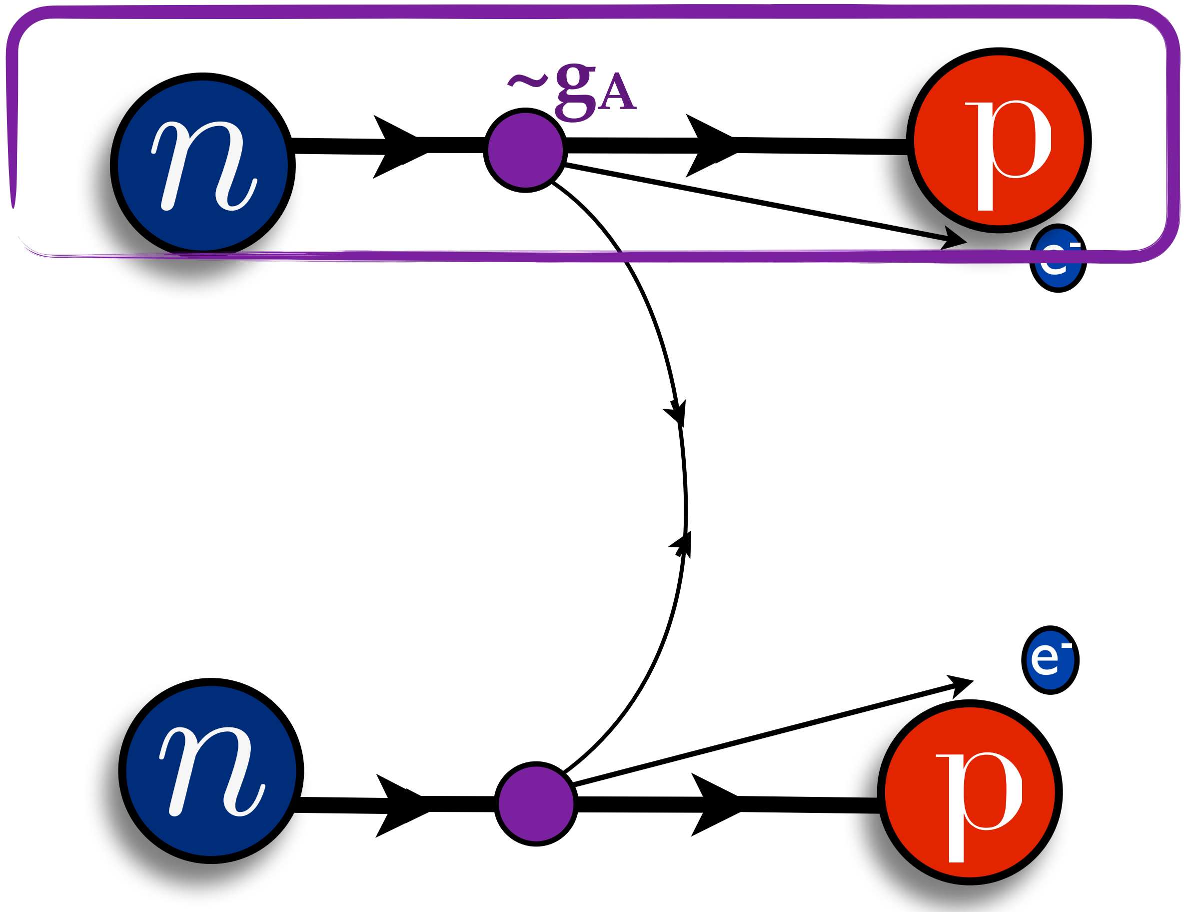

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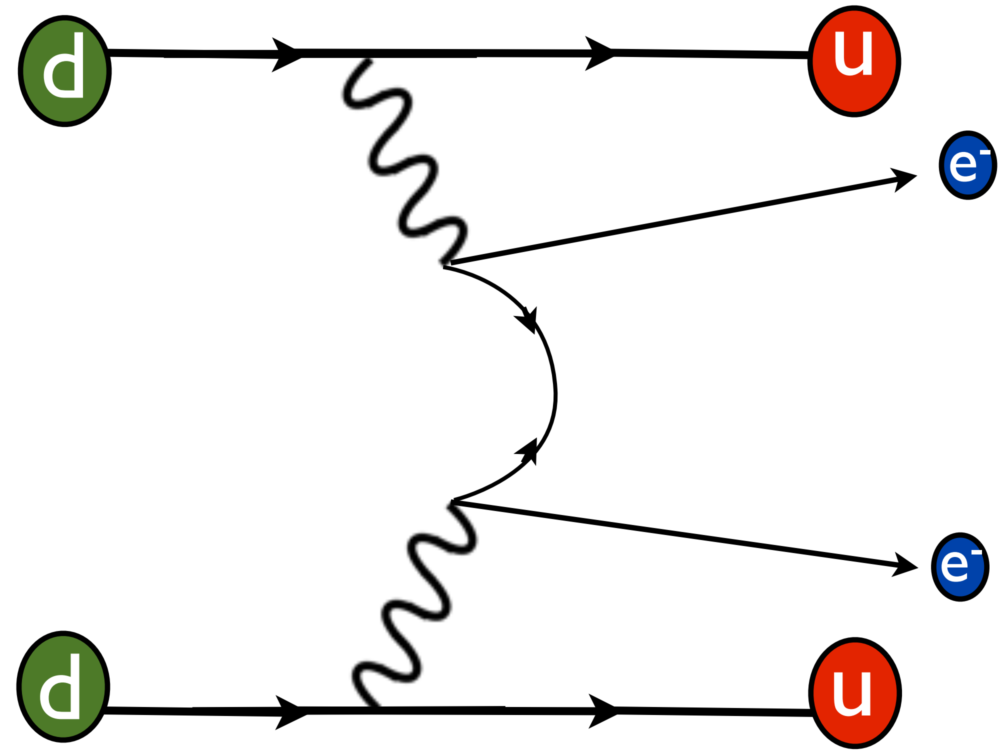
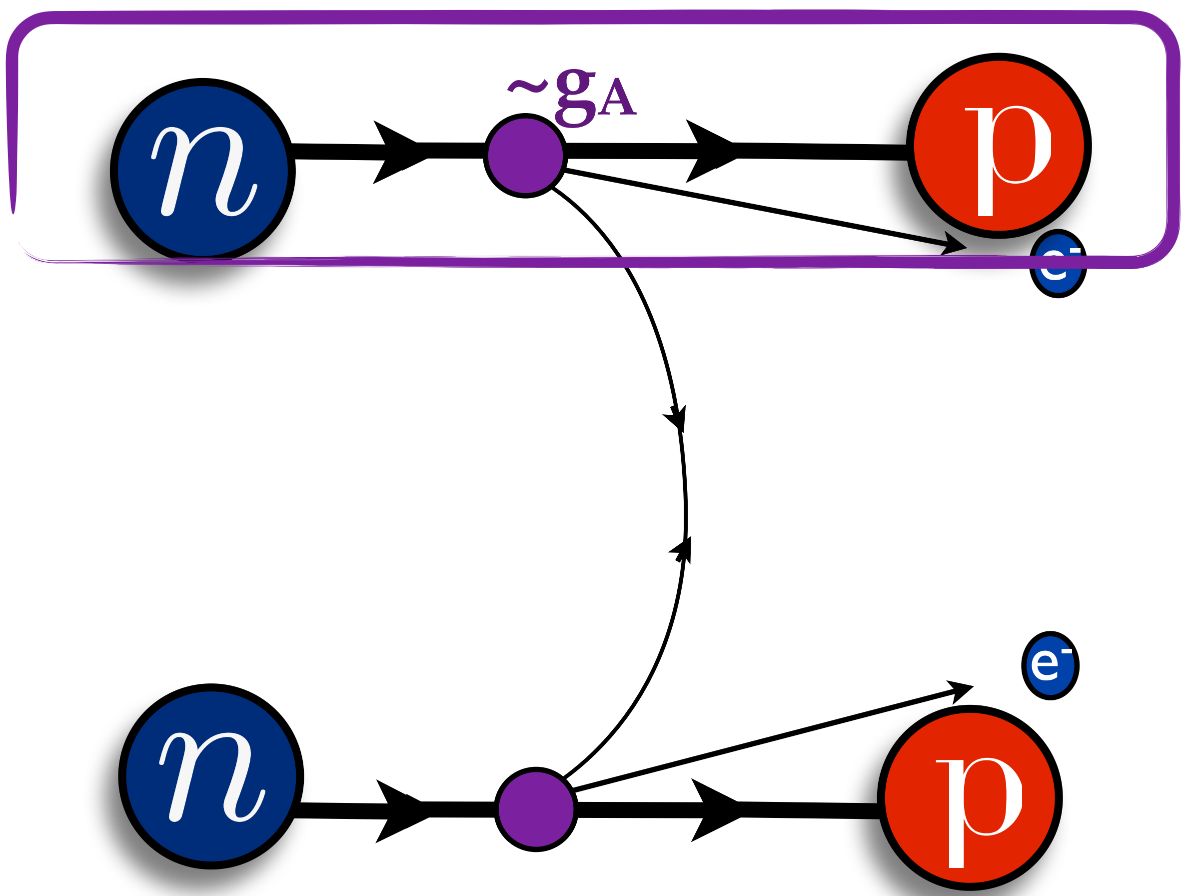


Short-range

$\Lambda \ll M_W$

Prezeau, Ramsey-Musolf, Vogel (2003)



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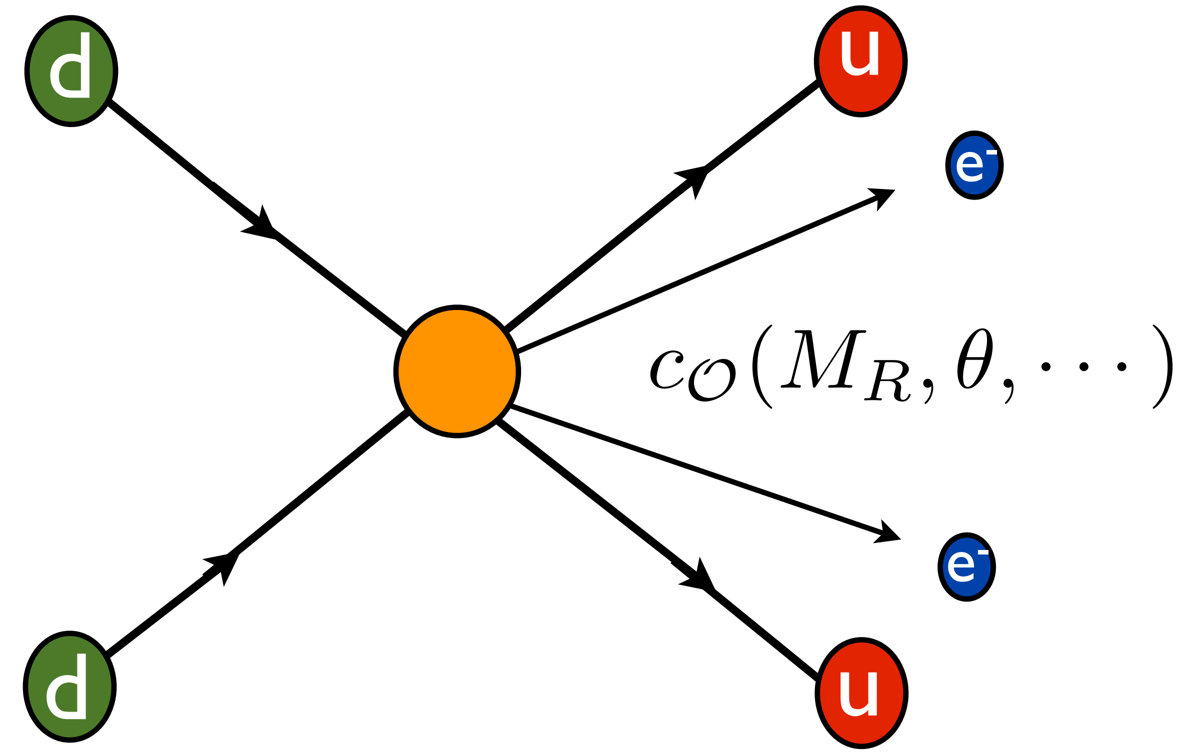
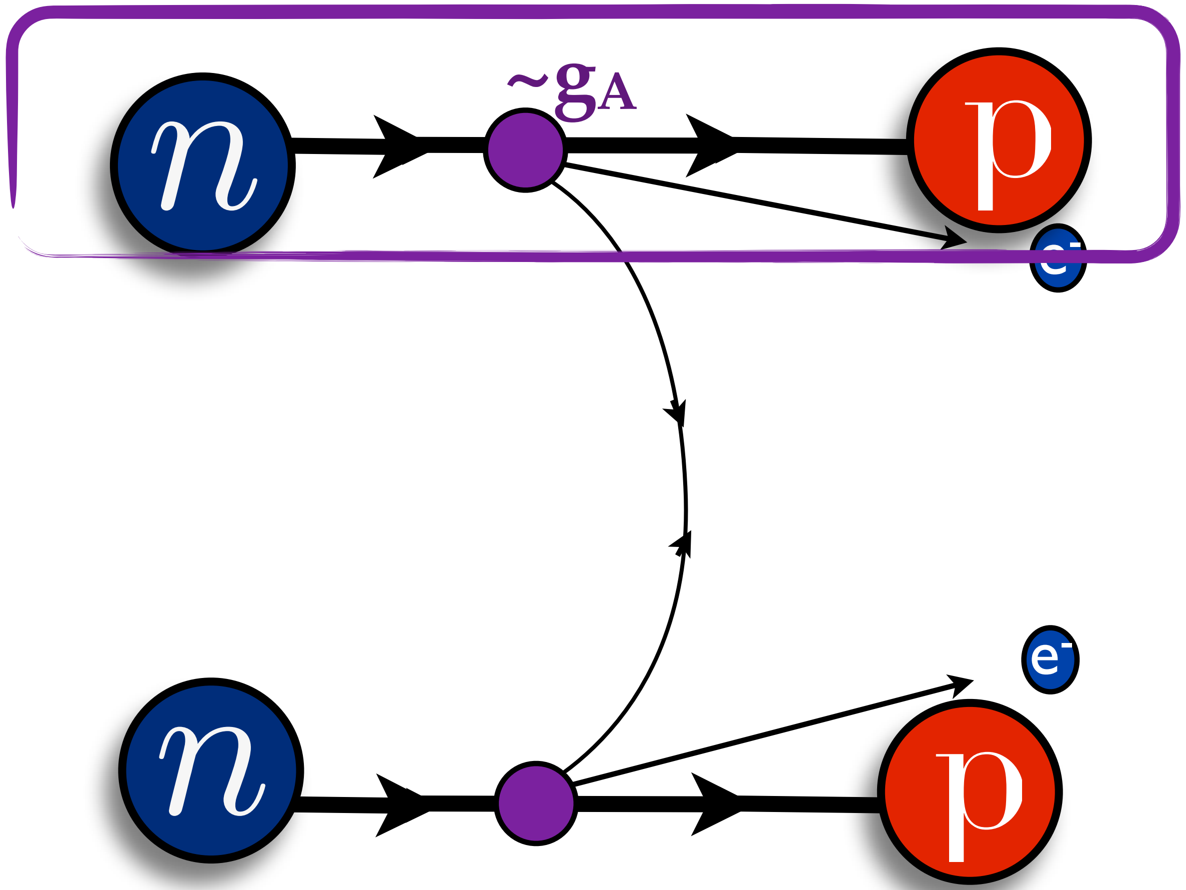
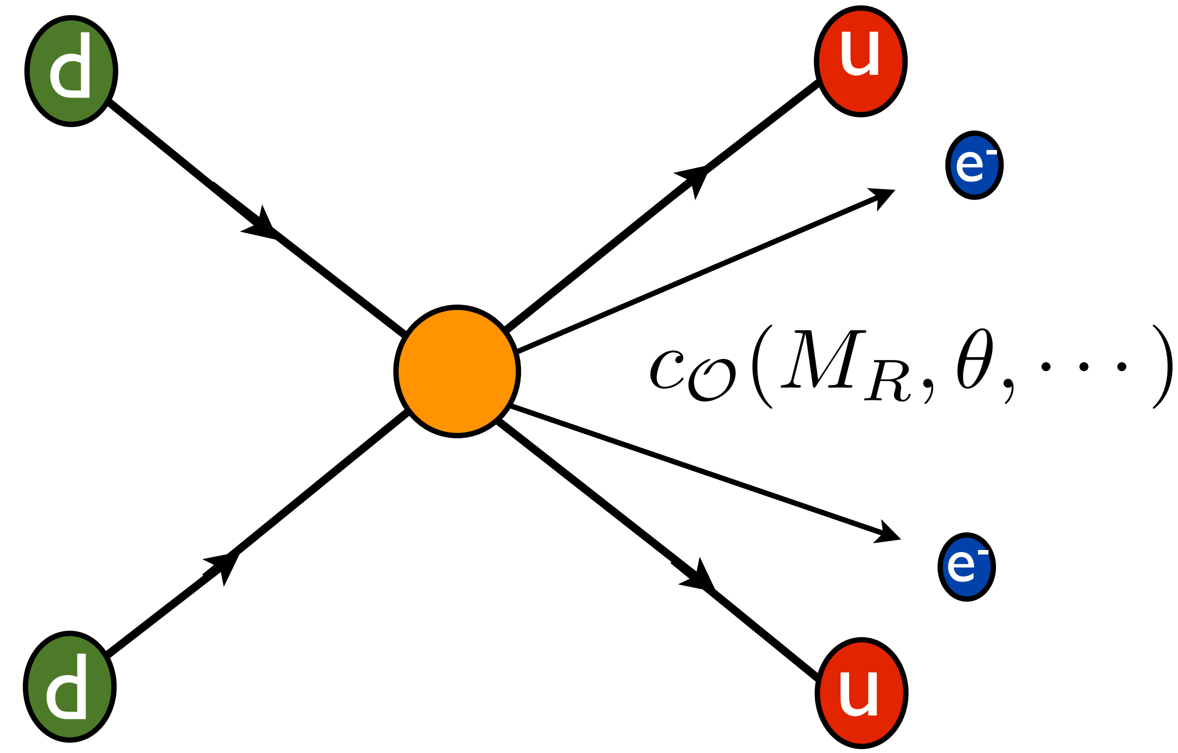


Short-range

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

Prezeau, Ramsey-Musolf, Vogel (2003)





Long-range

Short-range

$\Lambda \ll \Lambda_{QCD}$

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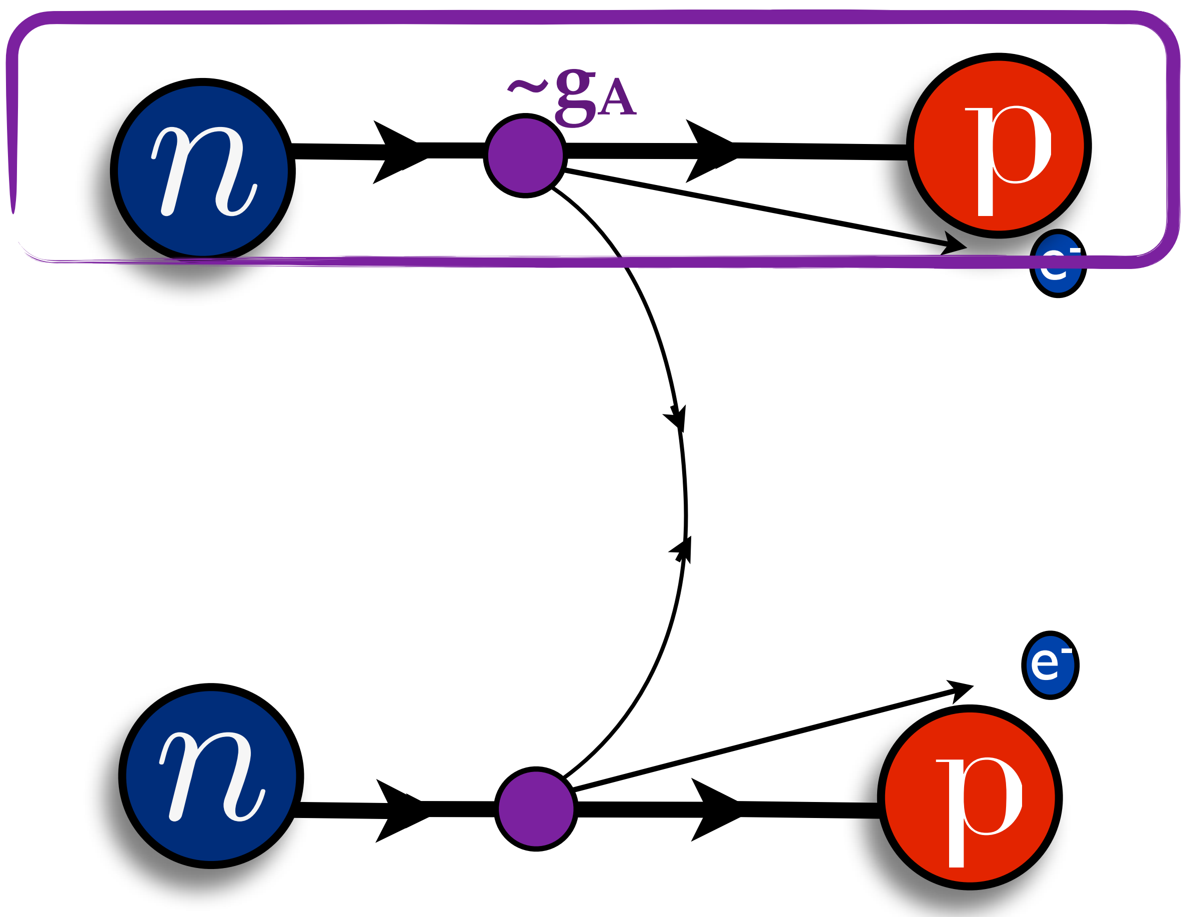

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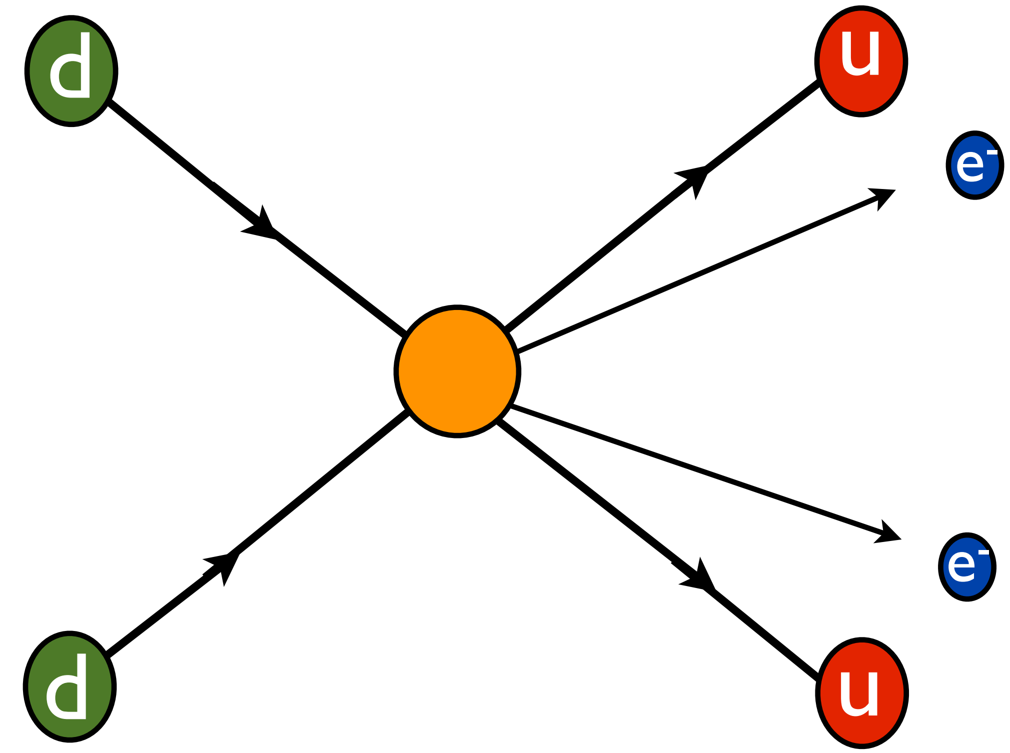
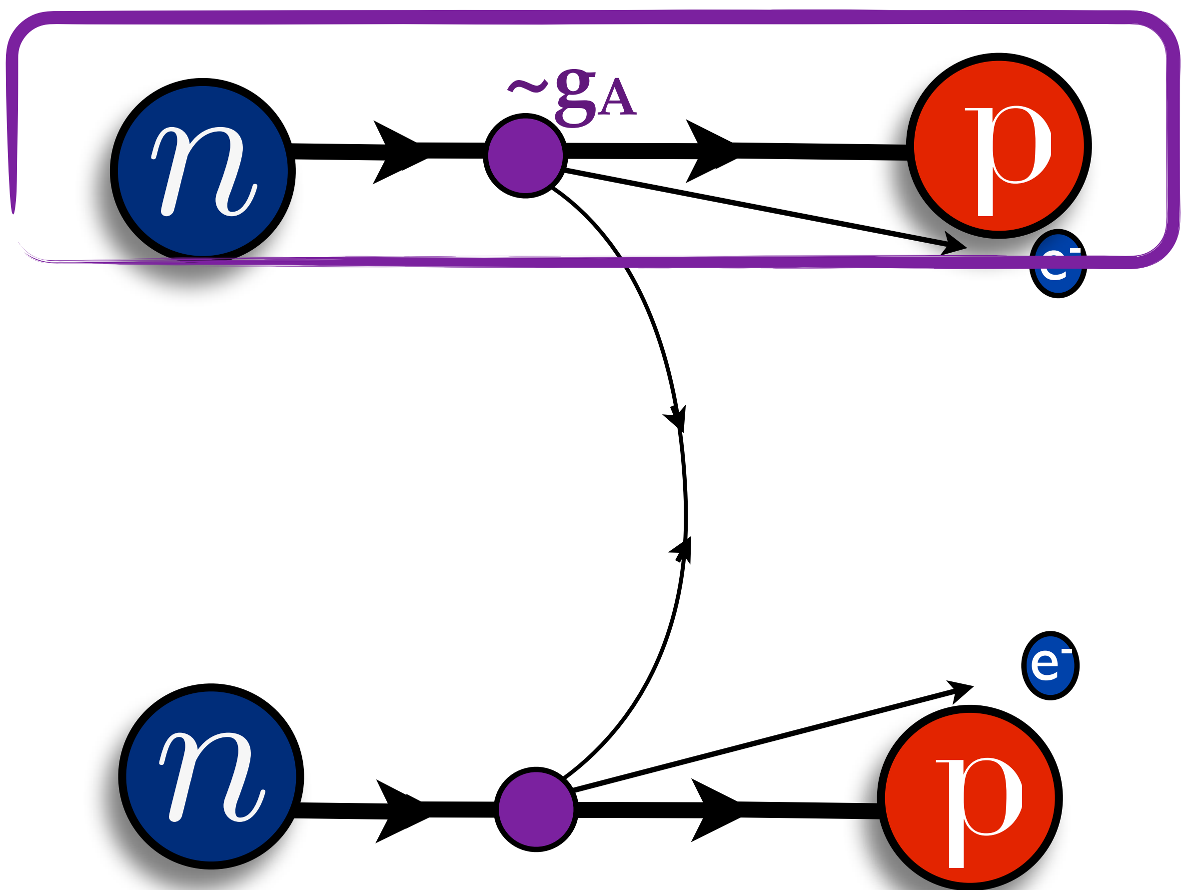


Short-range

Prezeau, Ramsey-Musolf, Vogel (2003)



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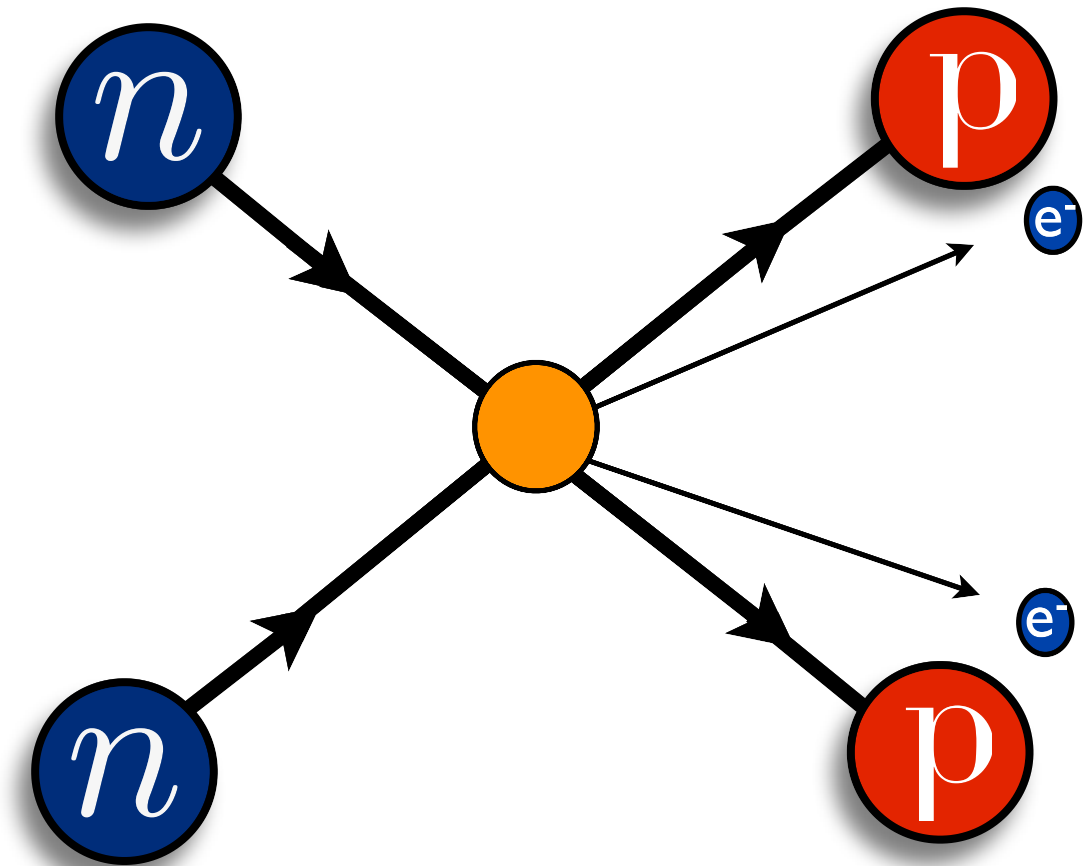

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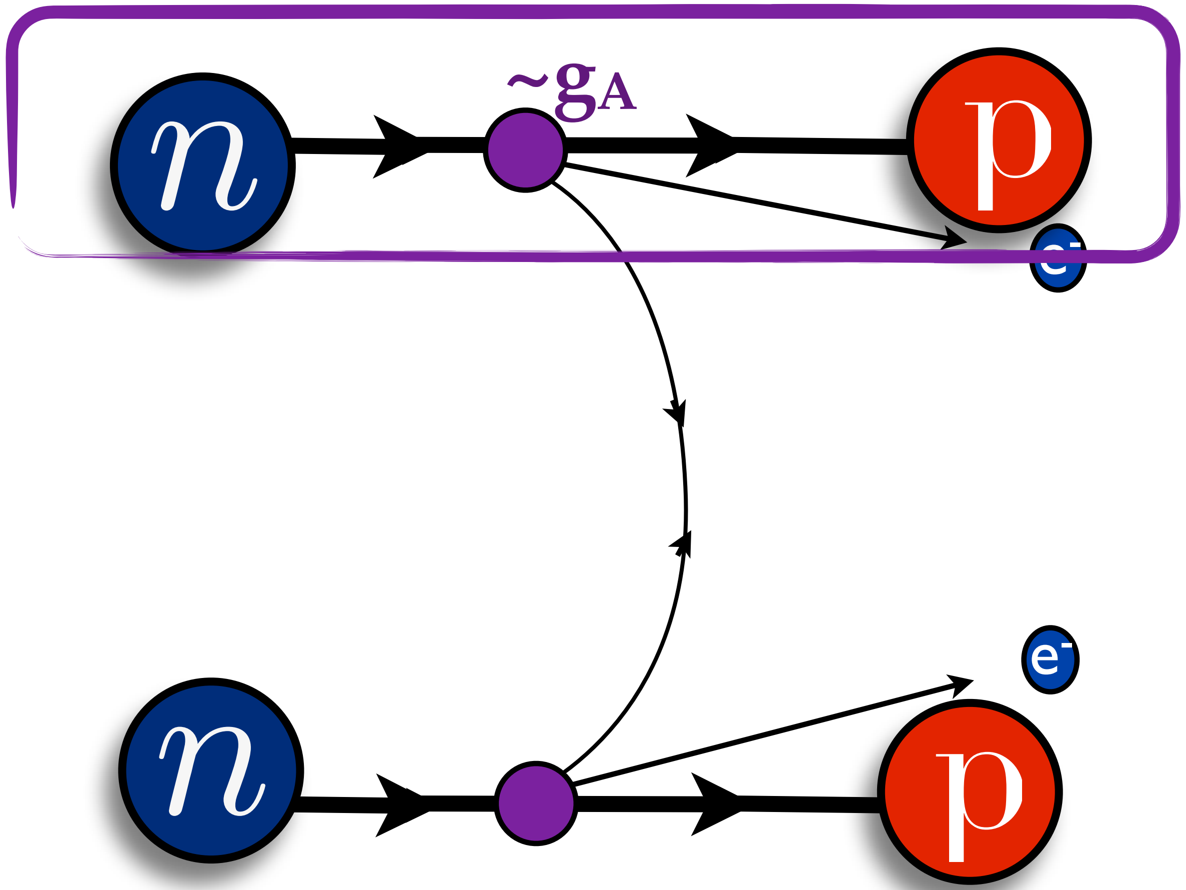

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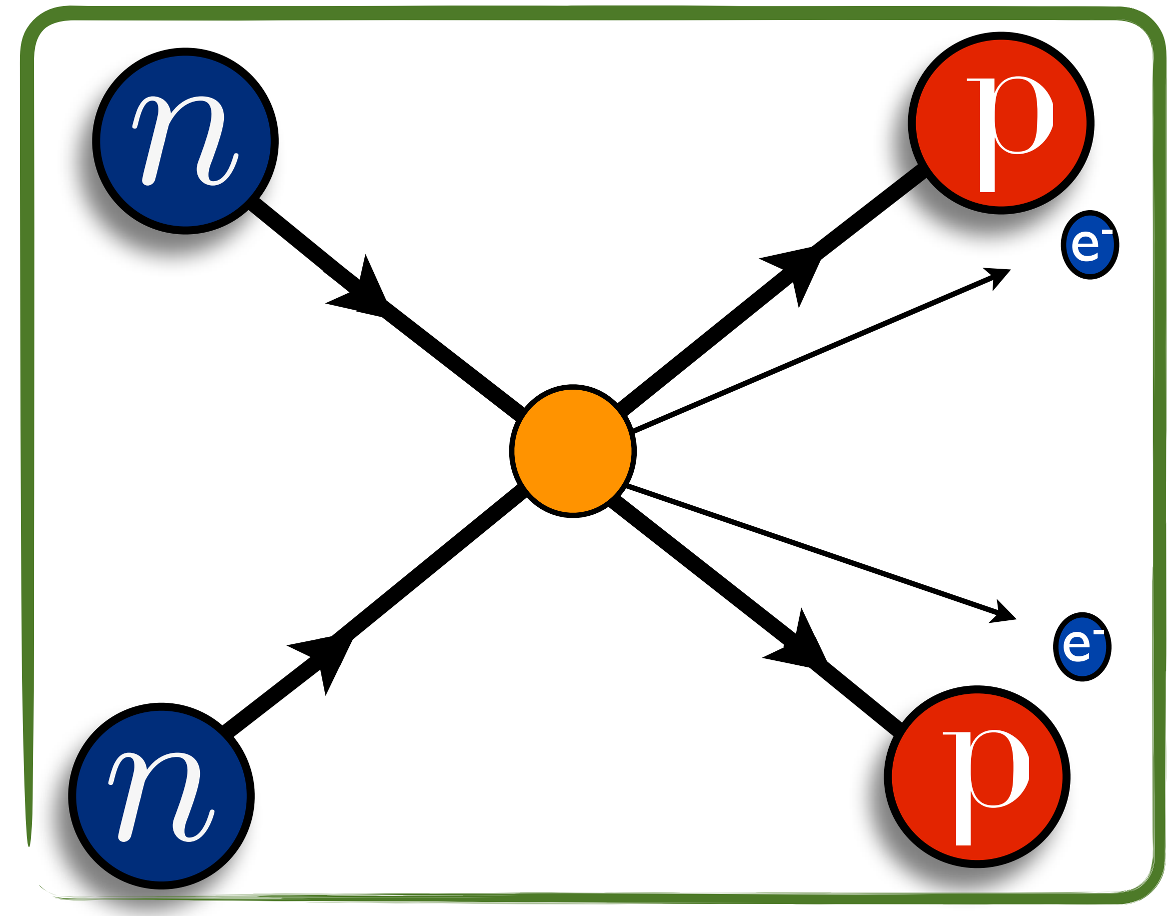

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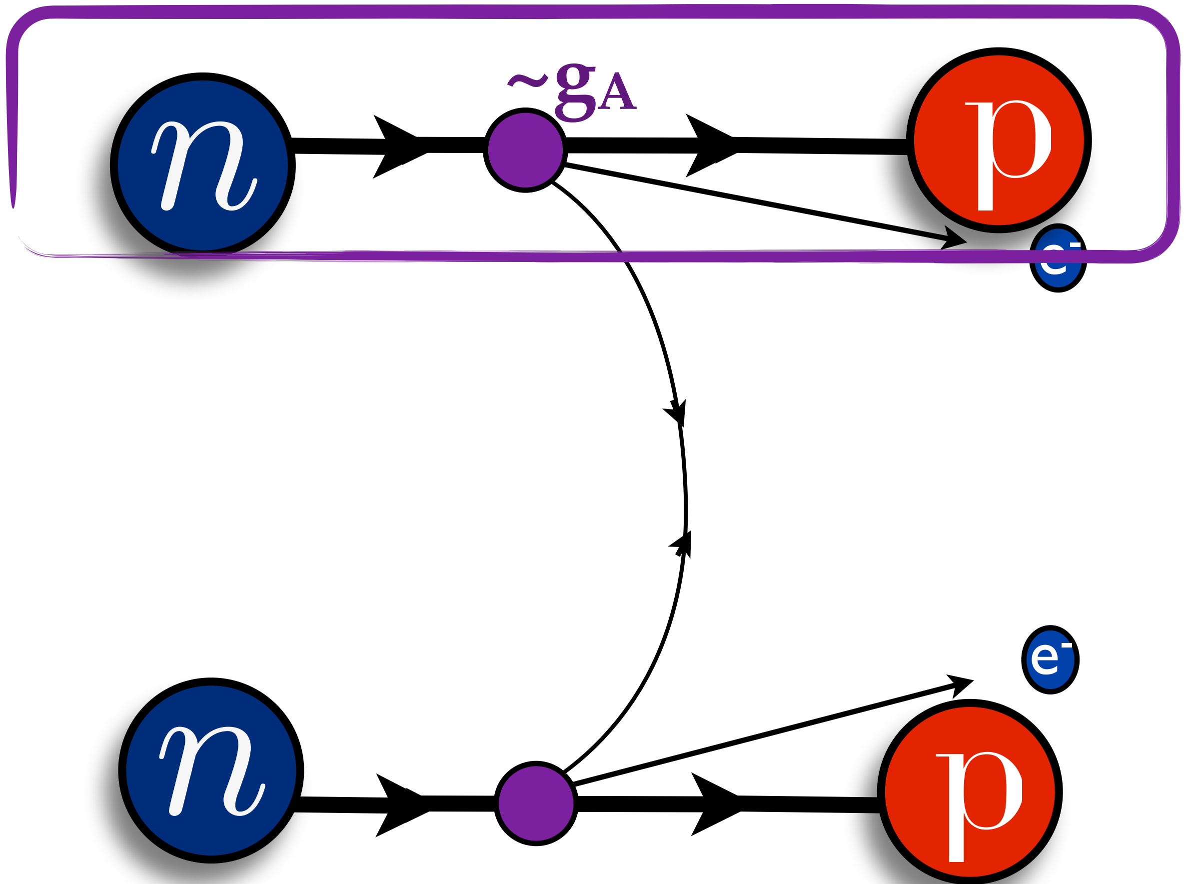

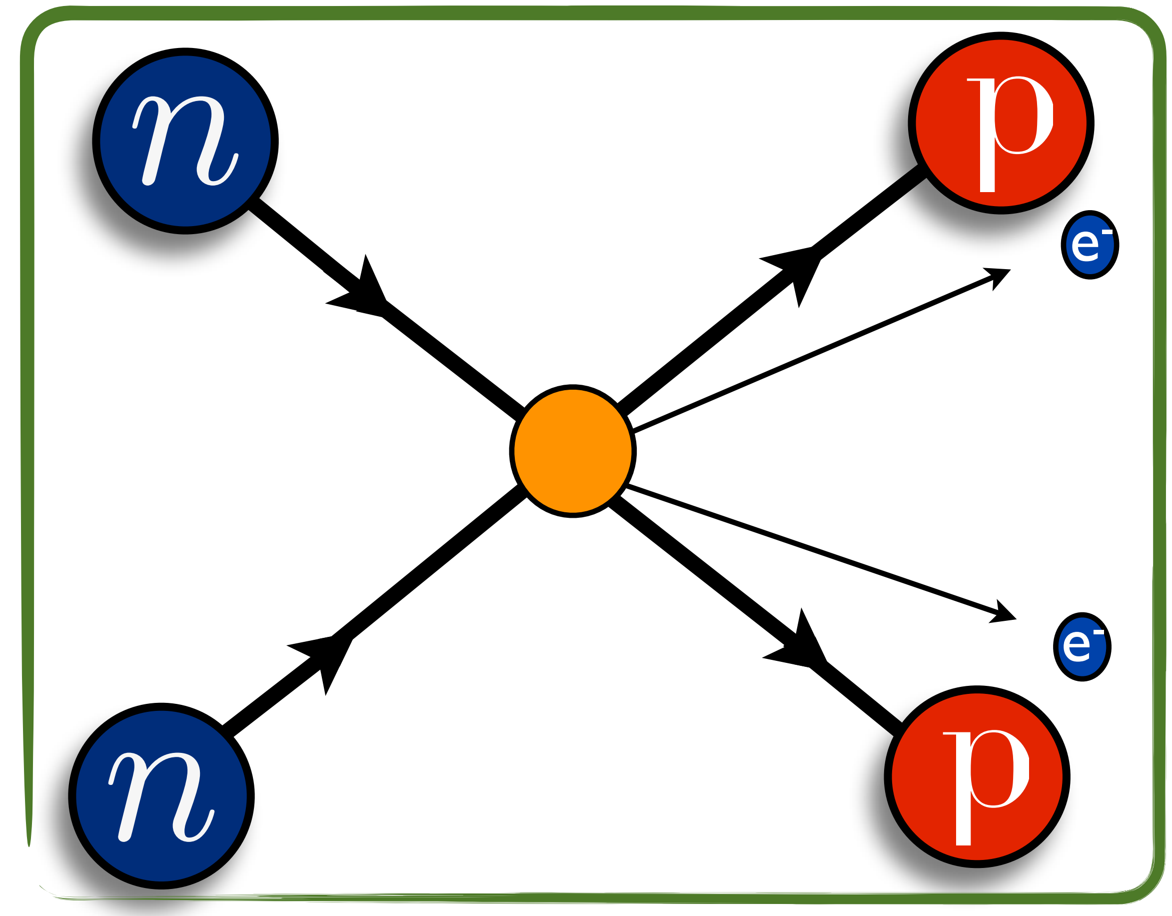

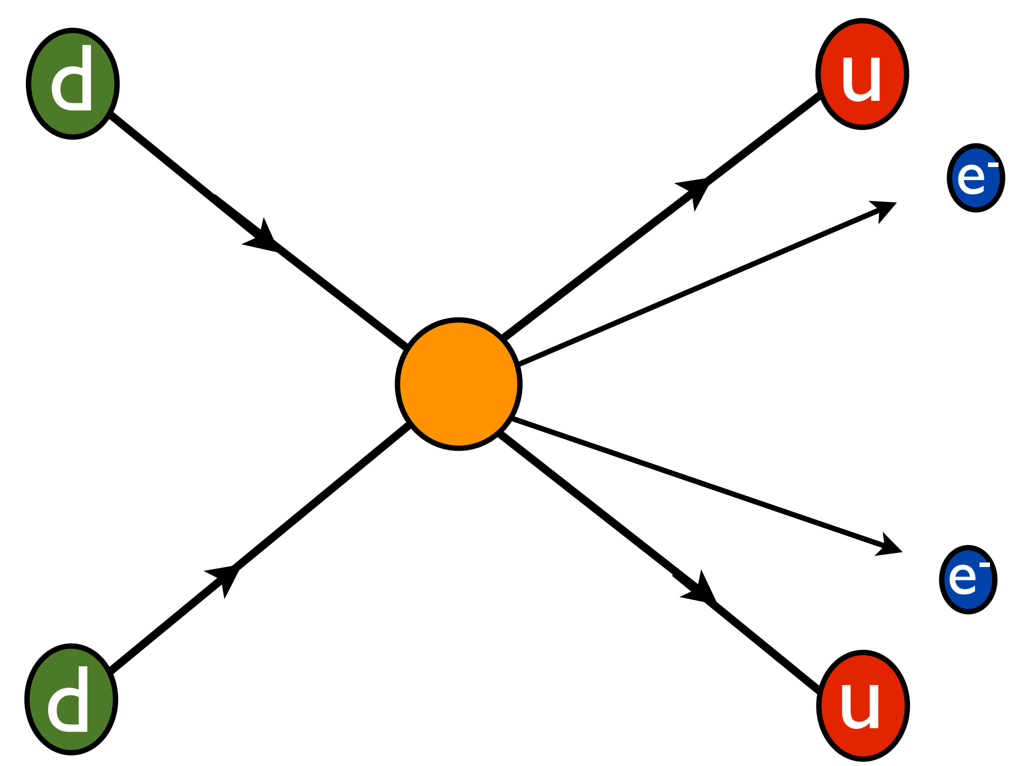

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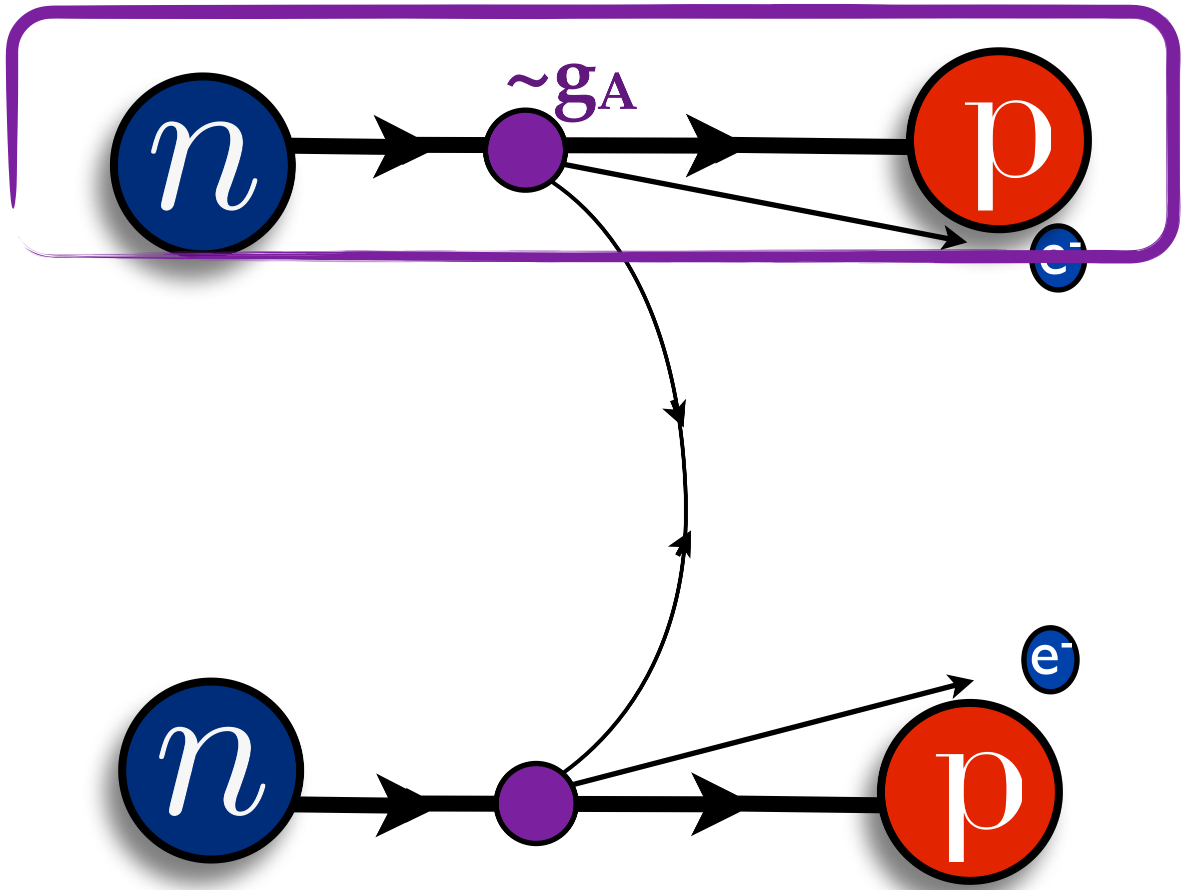

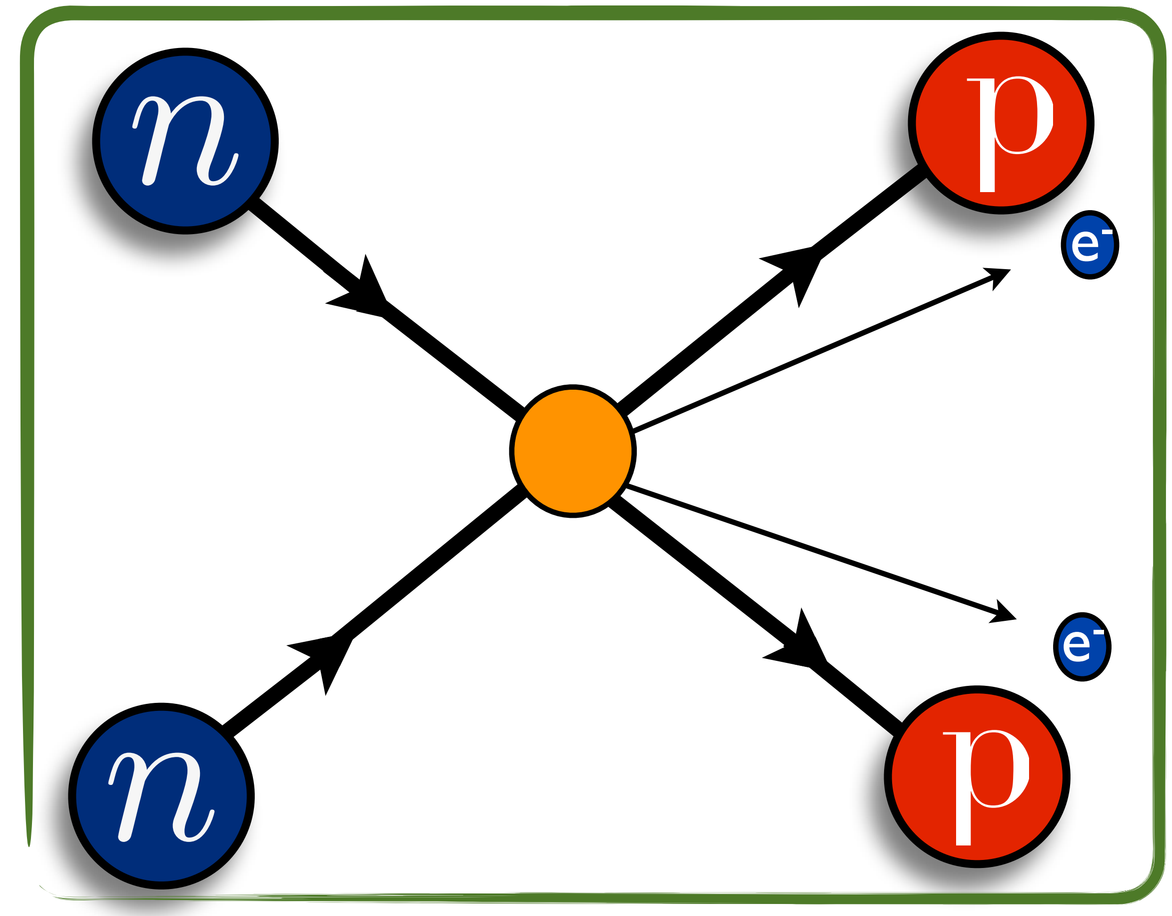

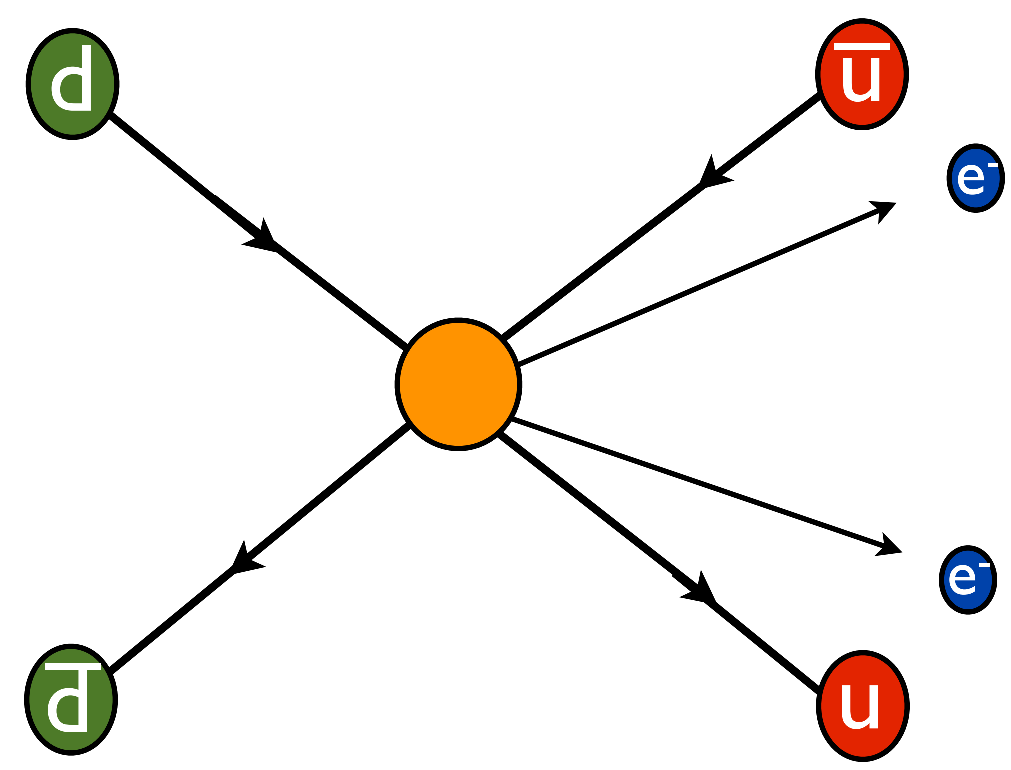

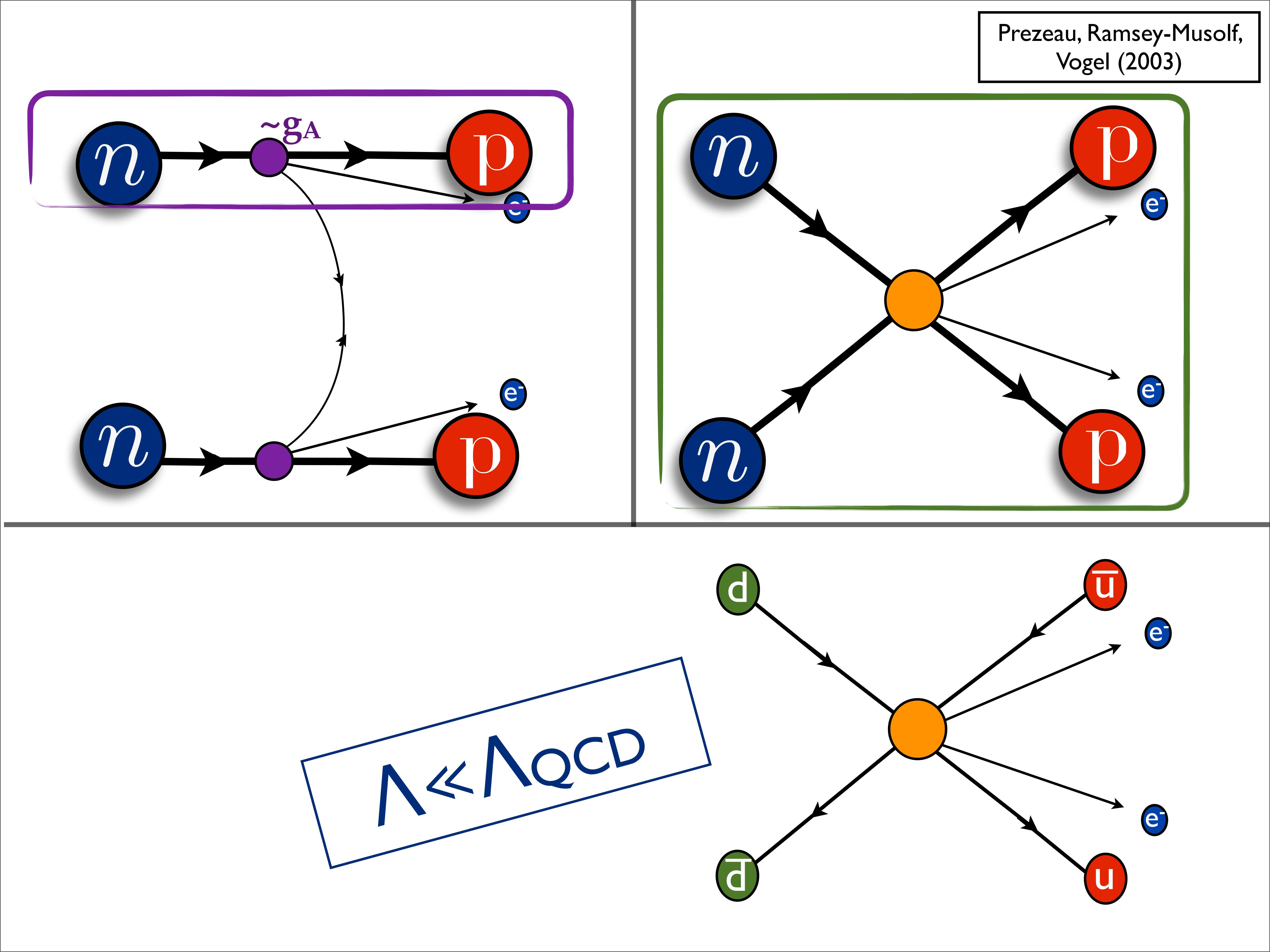

Prezeau, Ramsey-Musolf, Vogel (2003)
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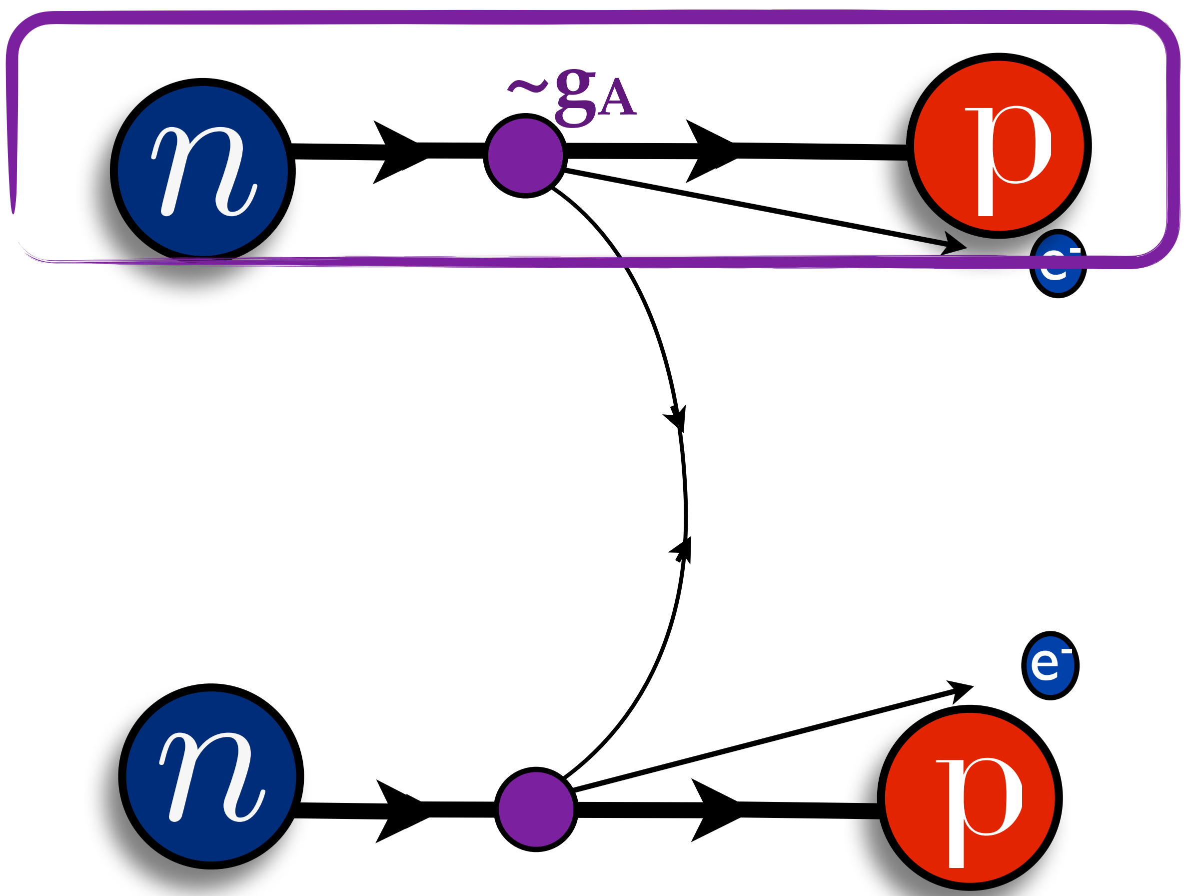

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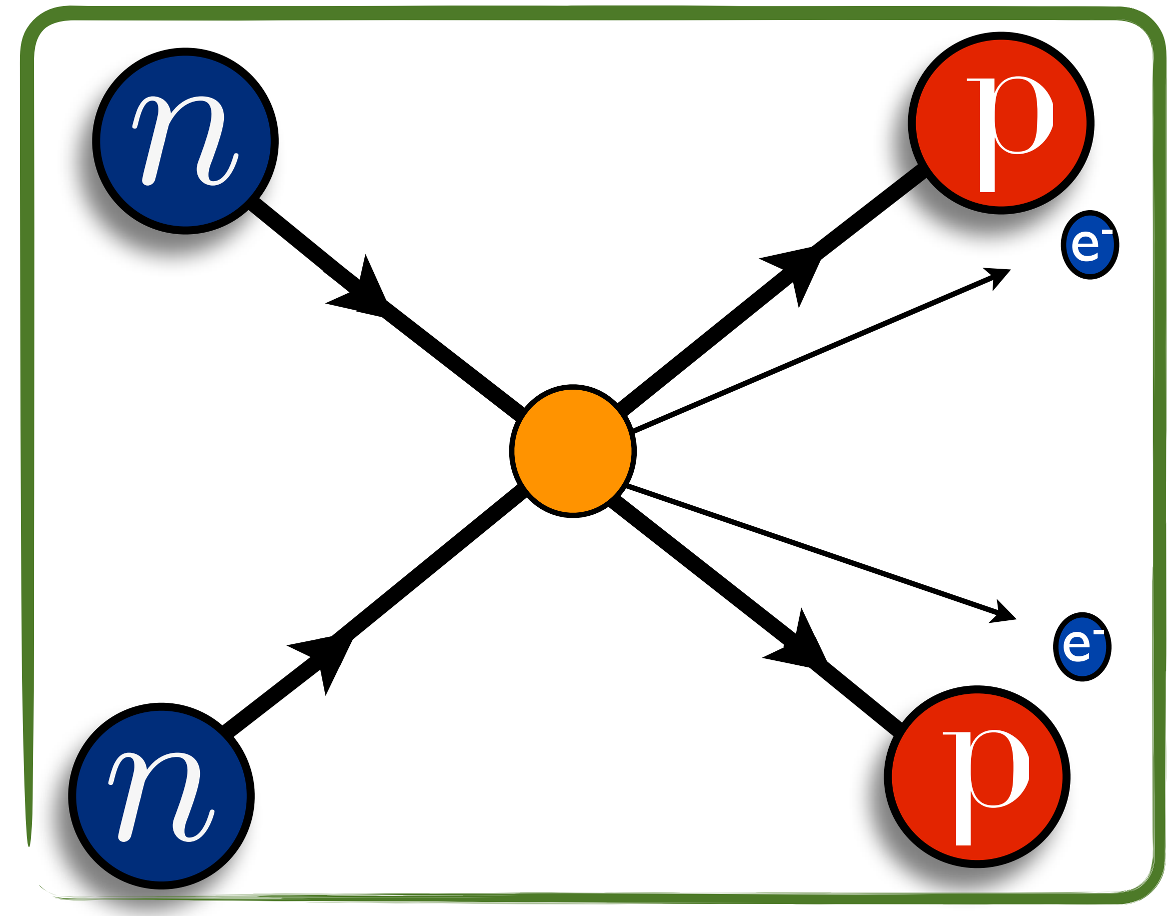
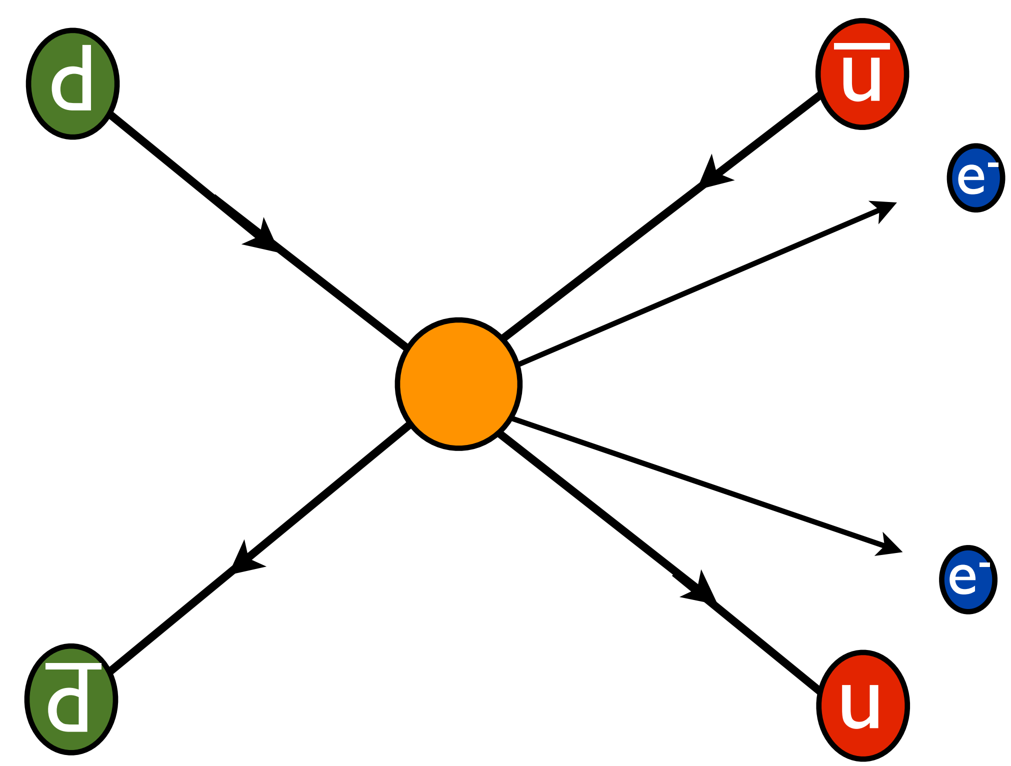
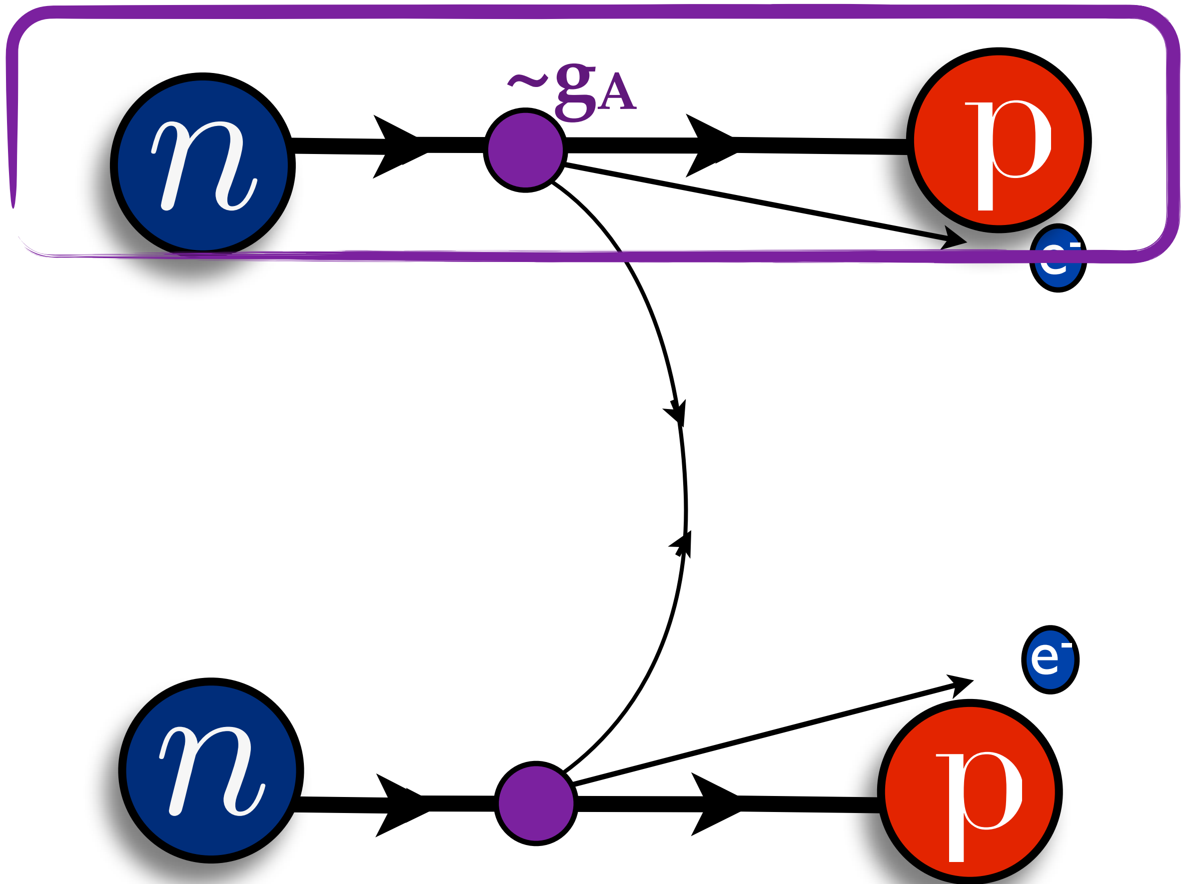
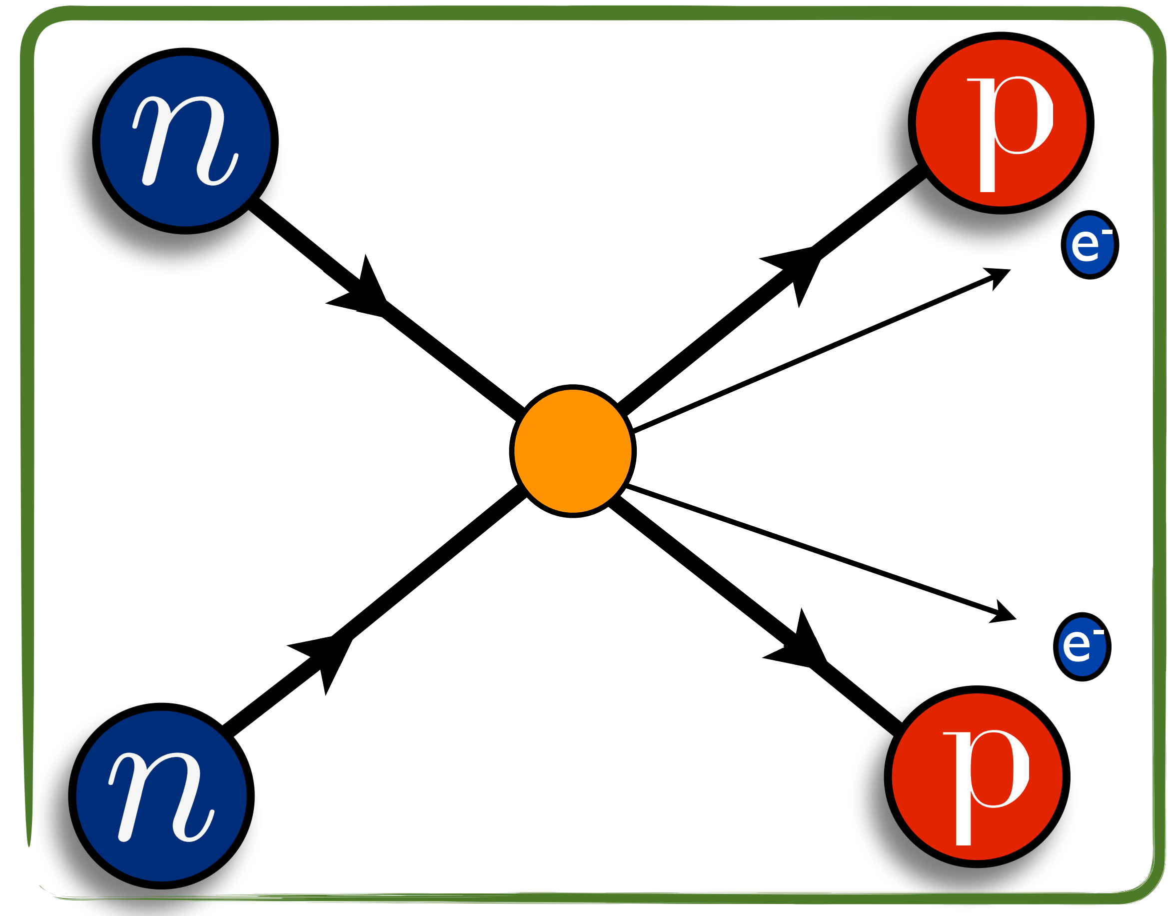
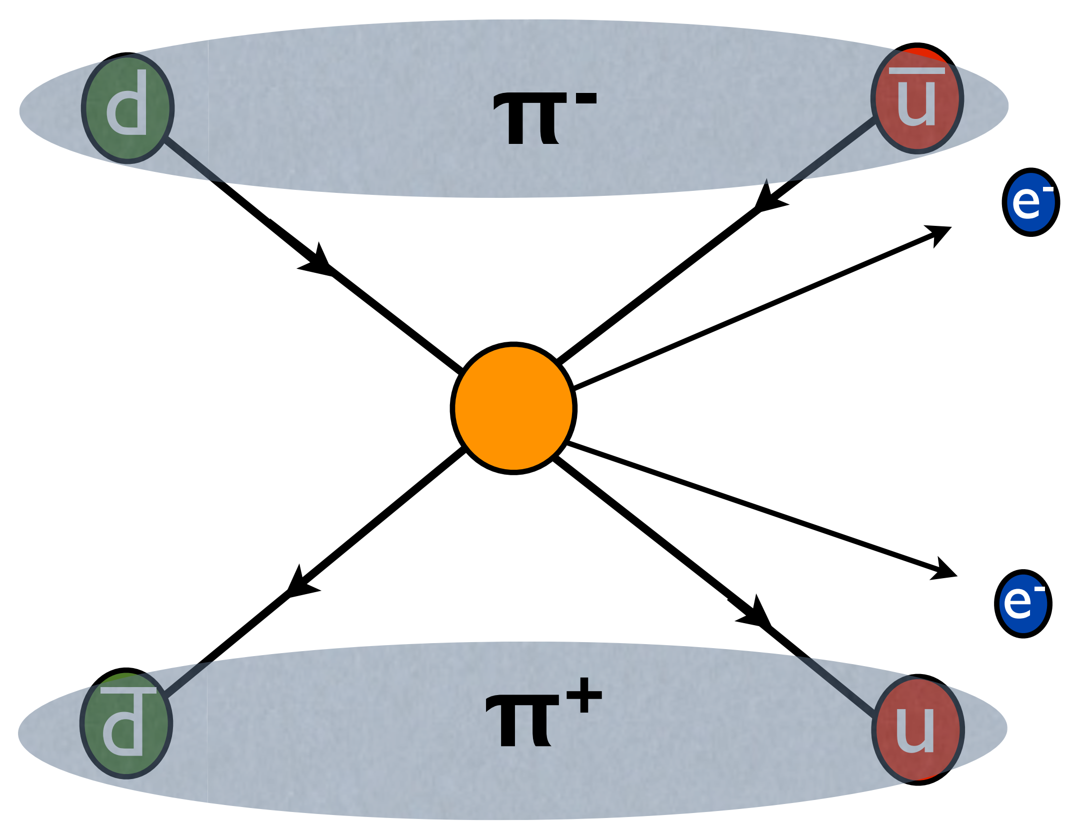


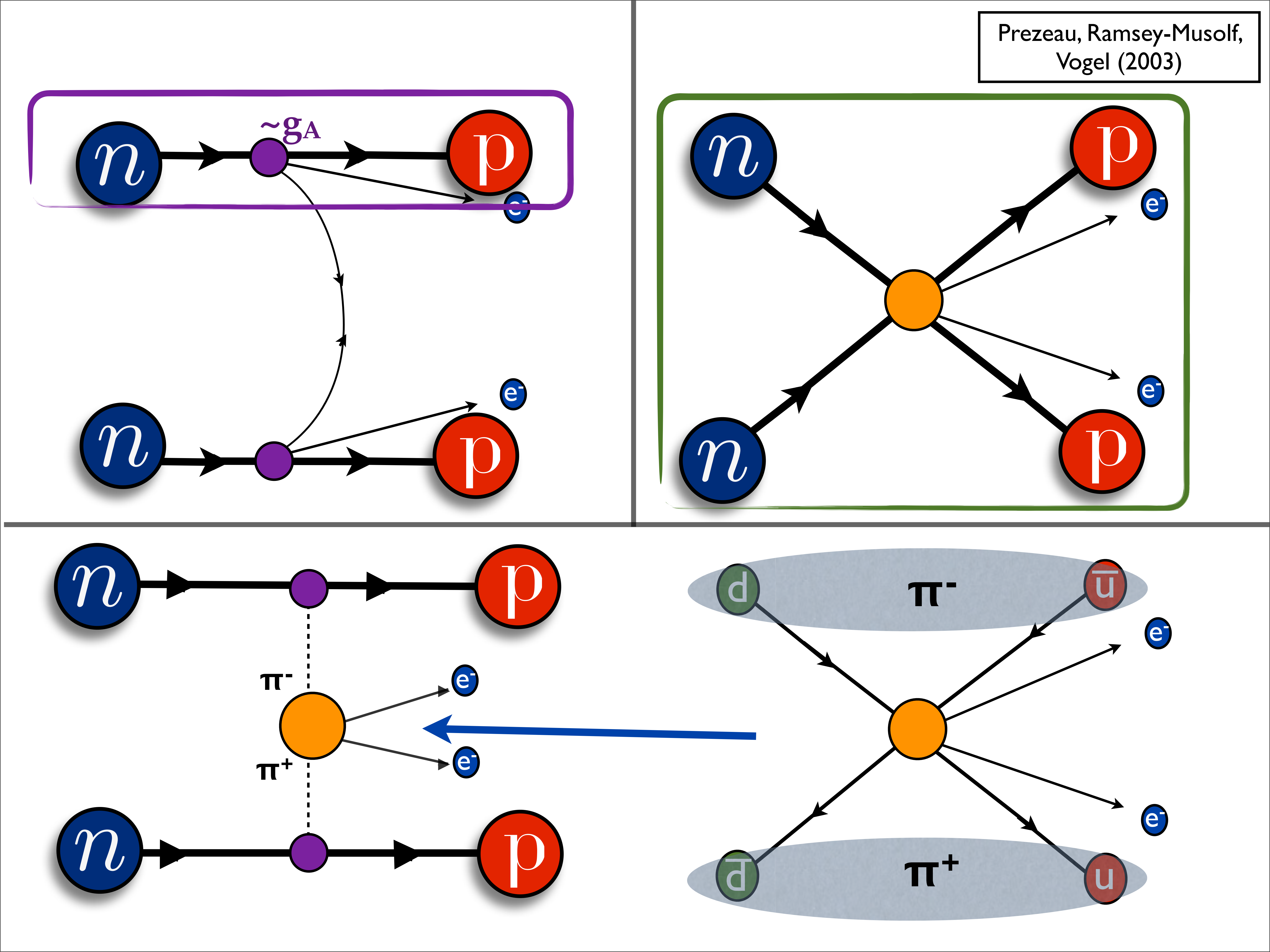


Prezeau, Ramsey-Musolf, Vogel (2003)









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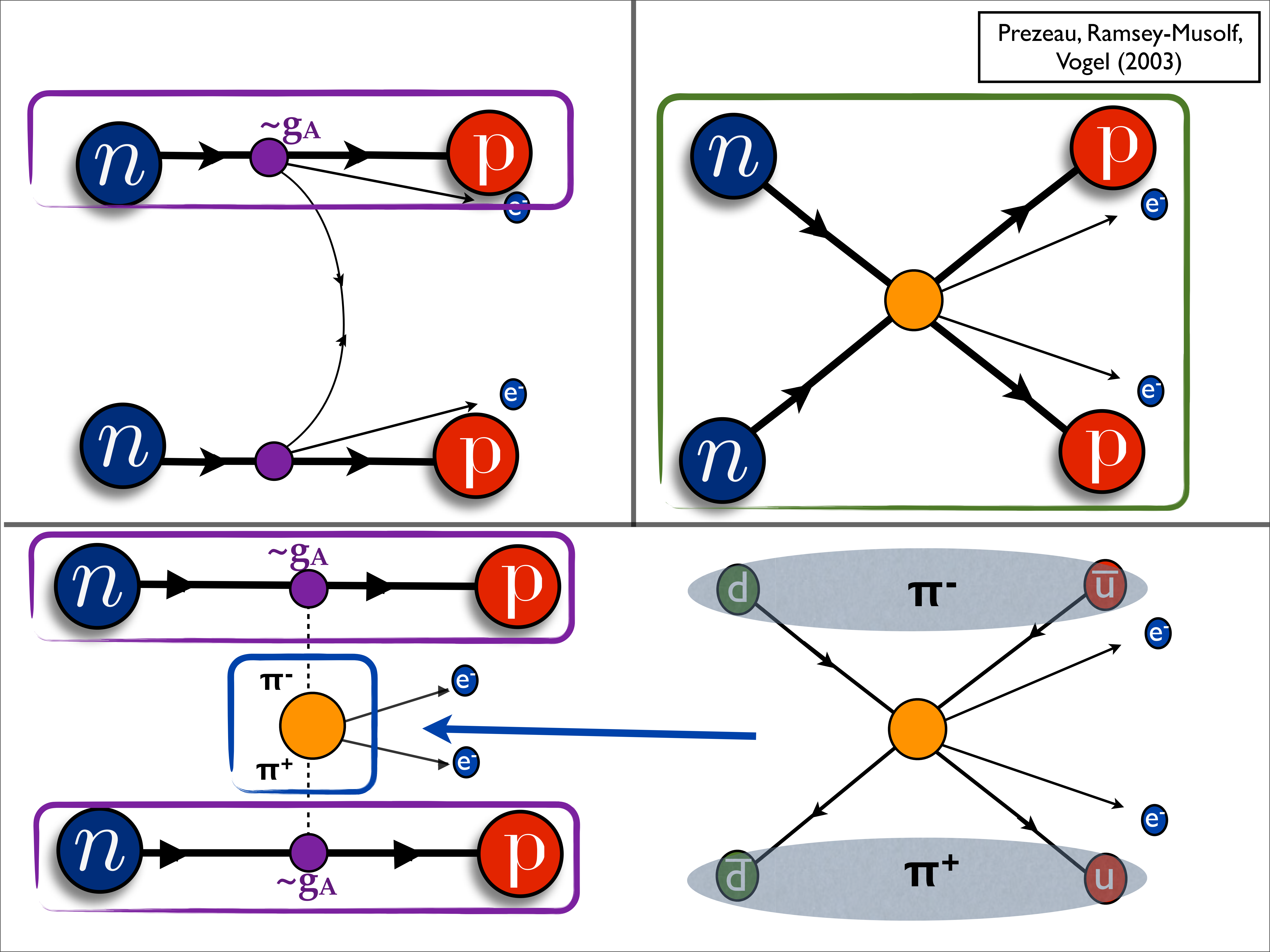
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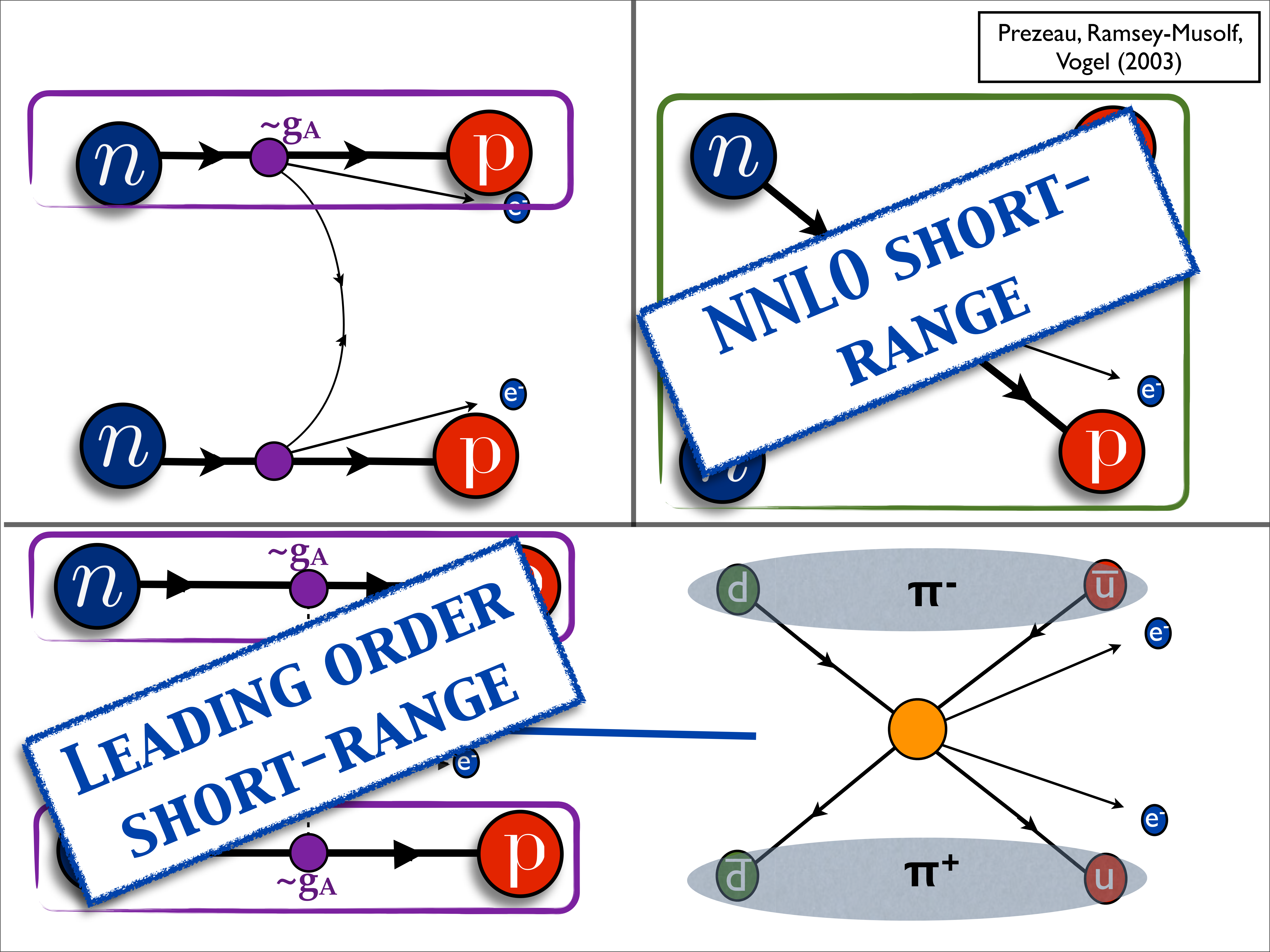

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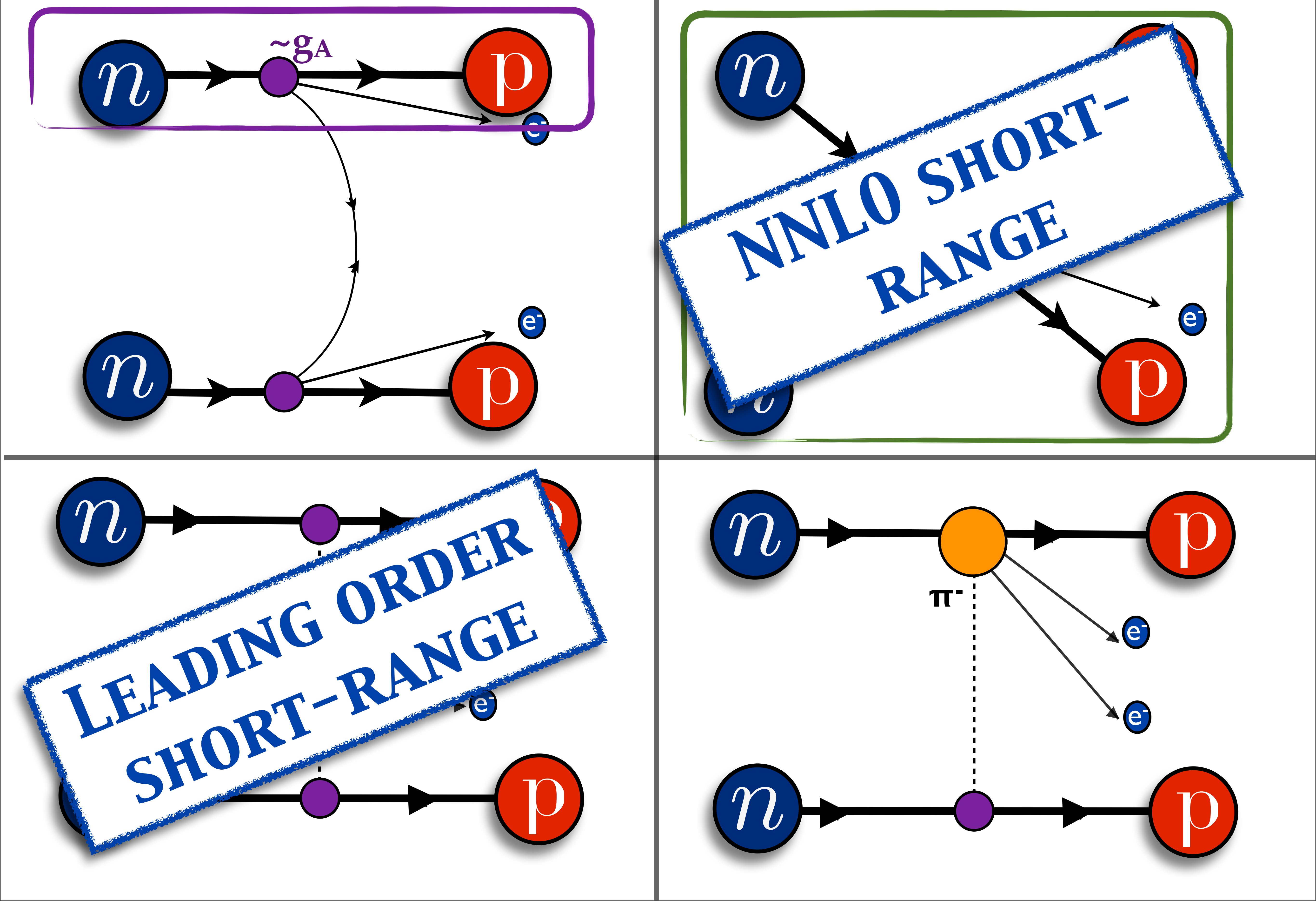
Prezeau, Ramsey-Musolf, Vogel (2003)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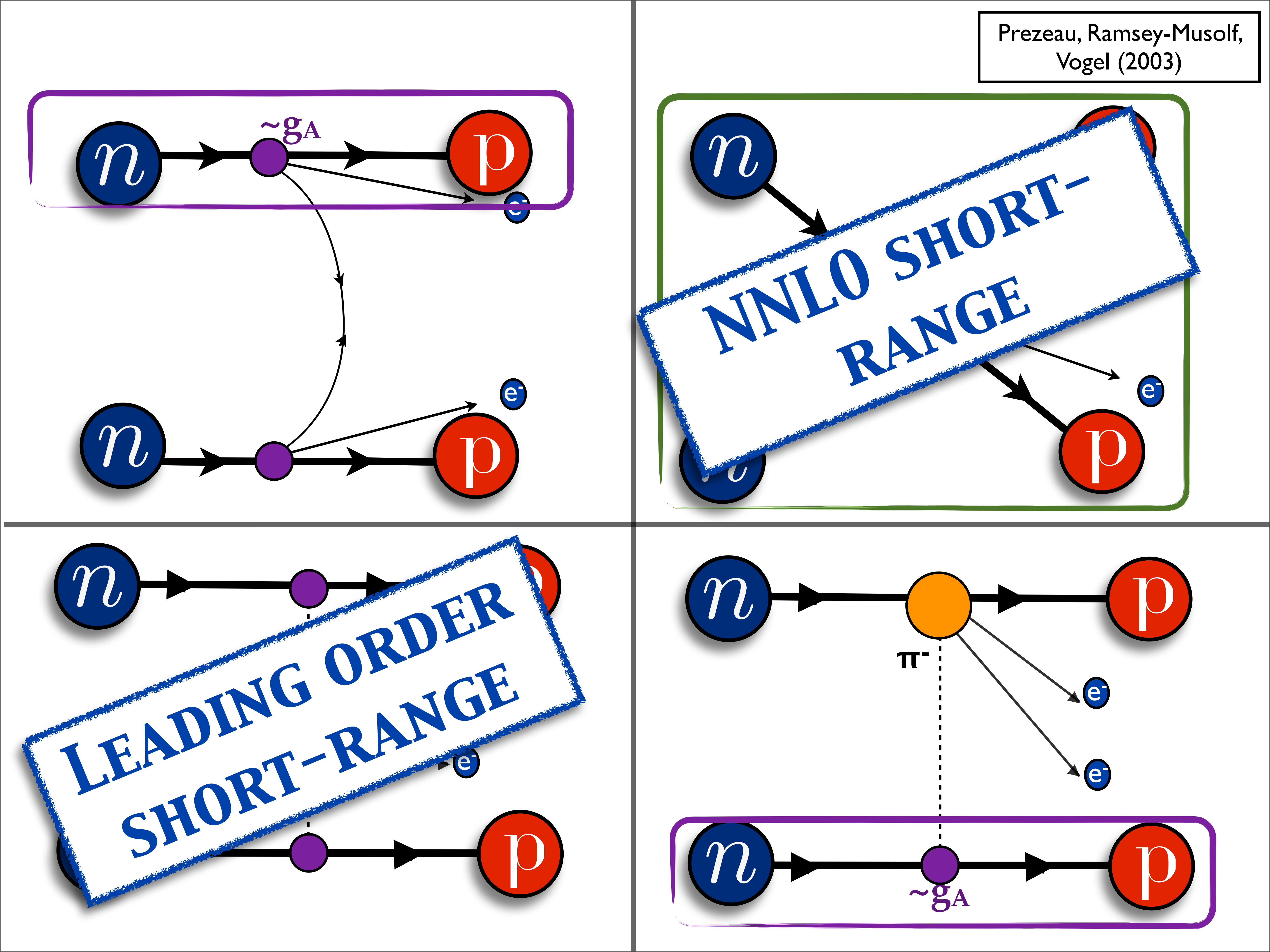

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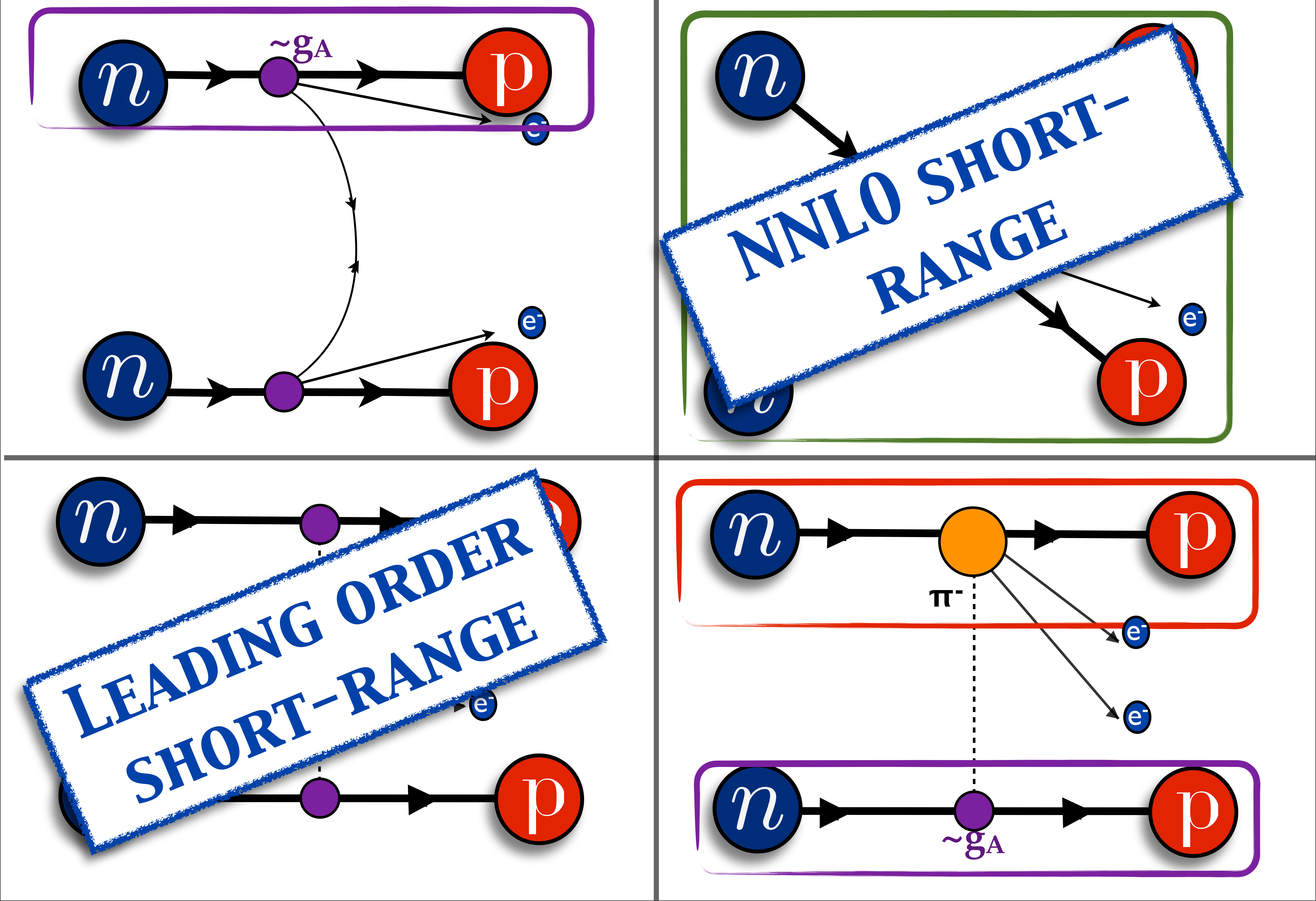
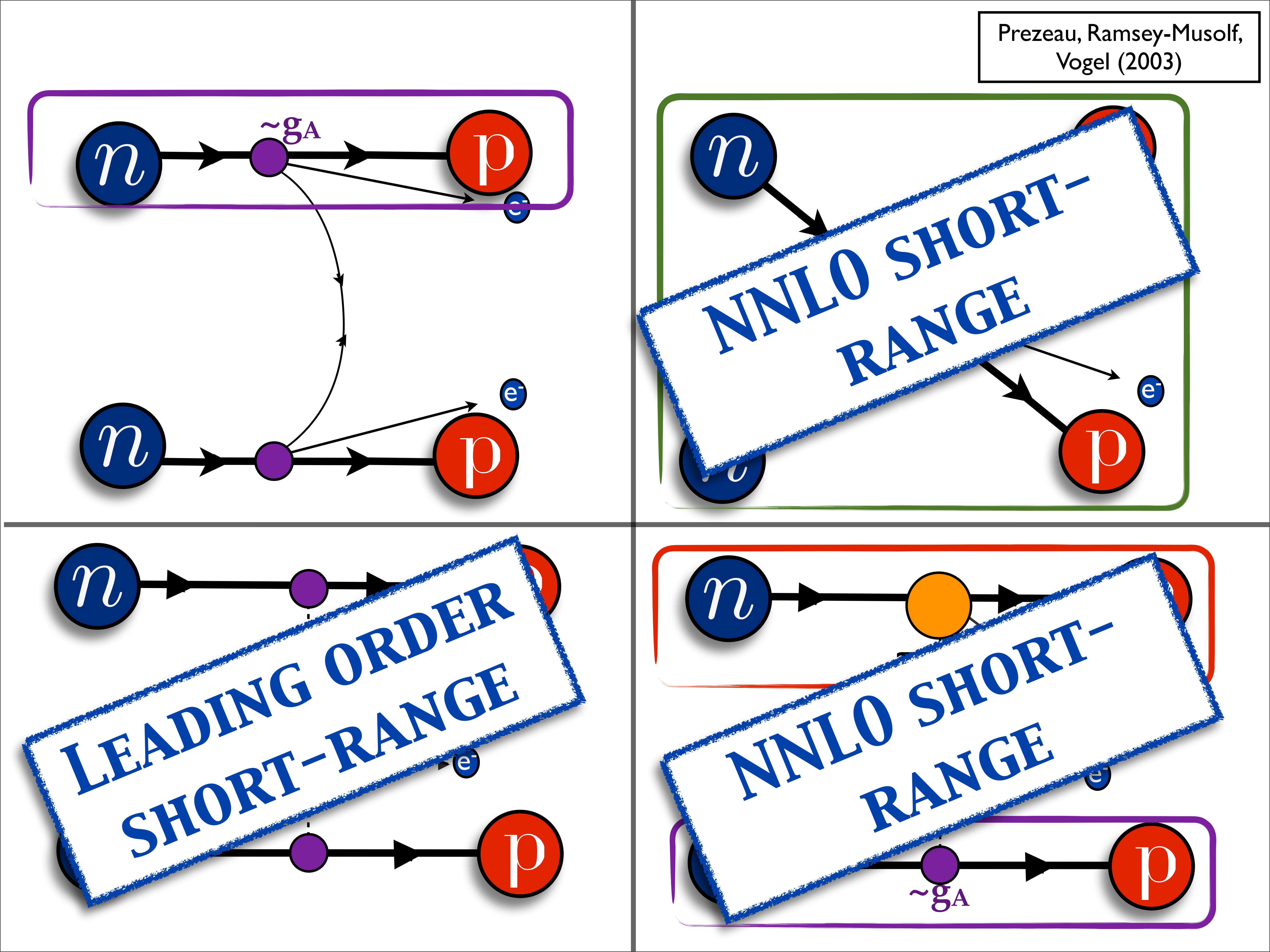
Prezeau, Ramsey-Musolf, Vogel (2003)

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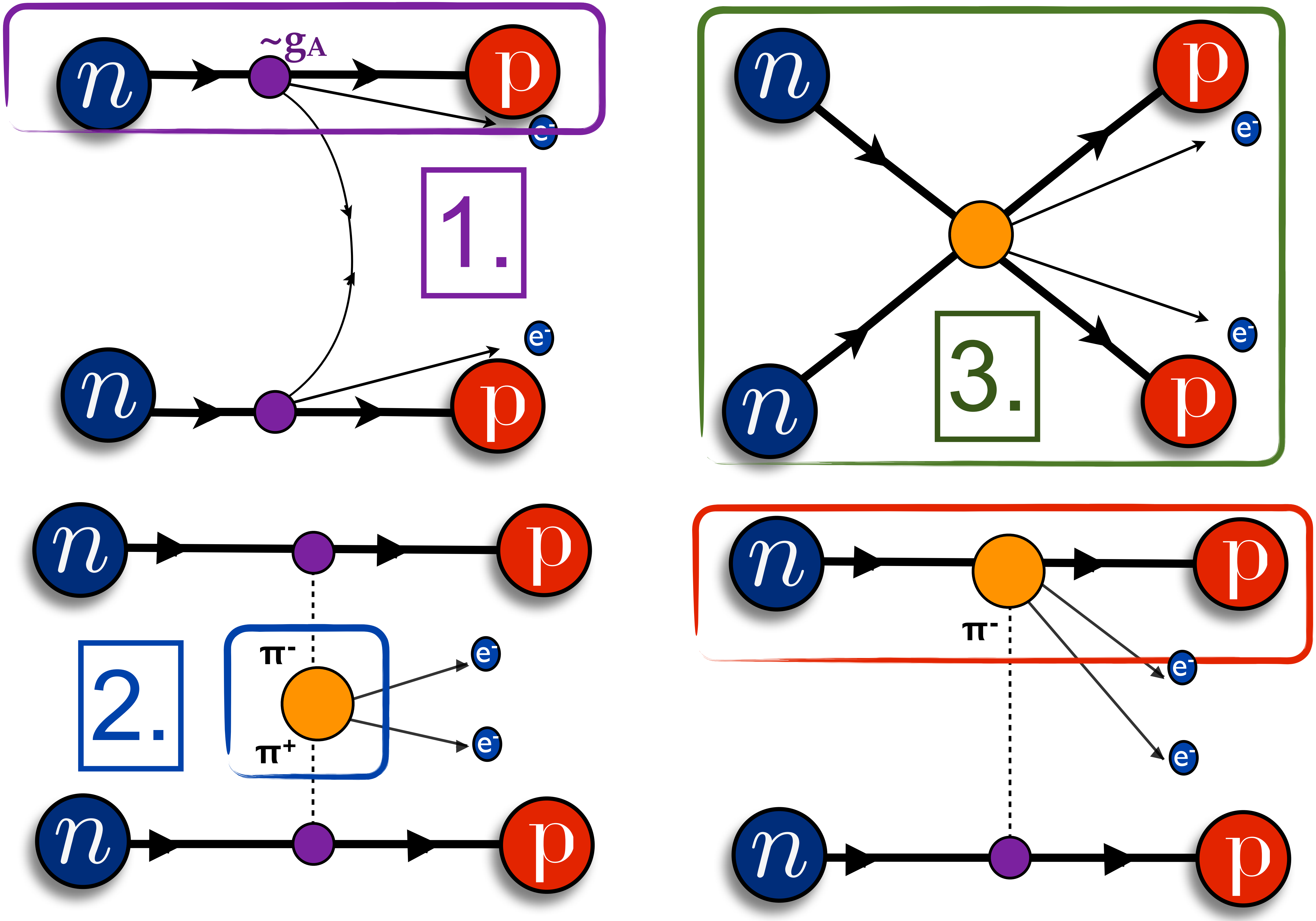
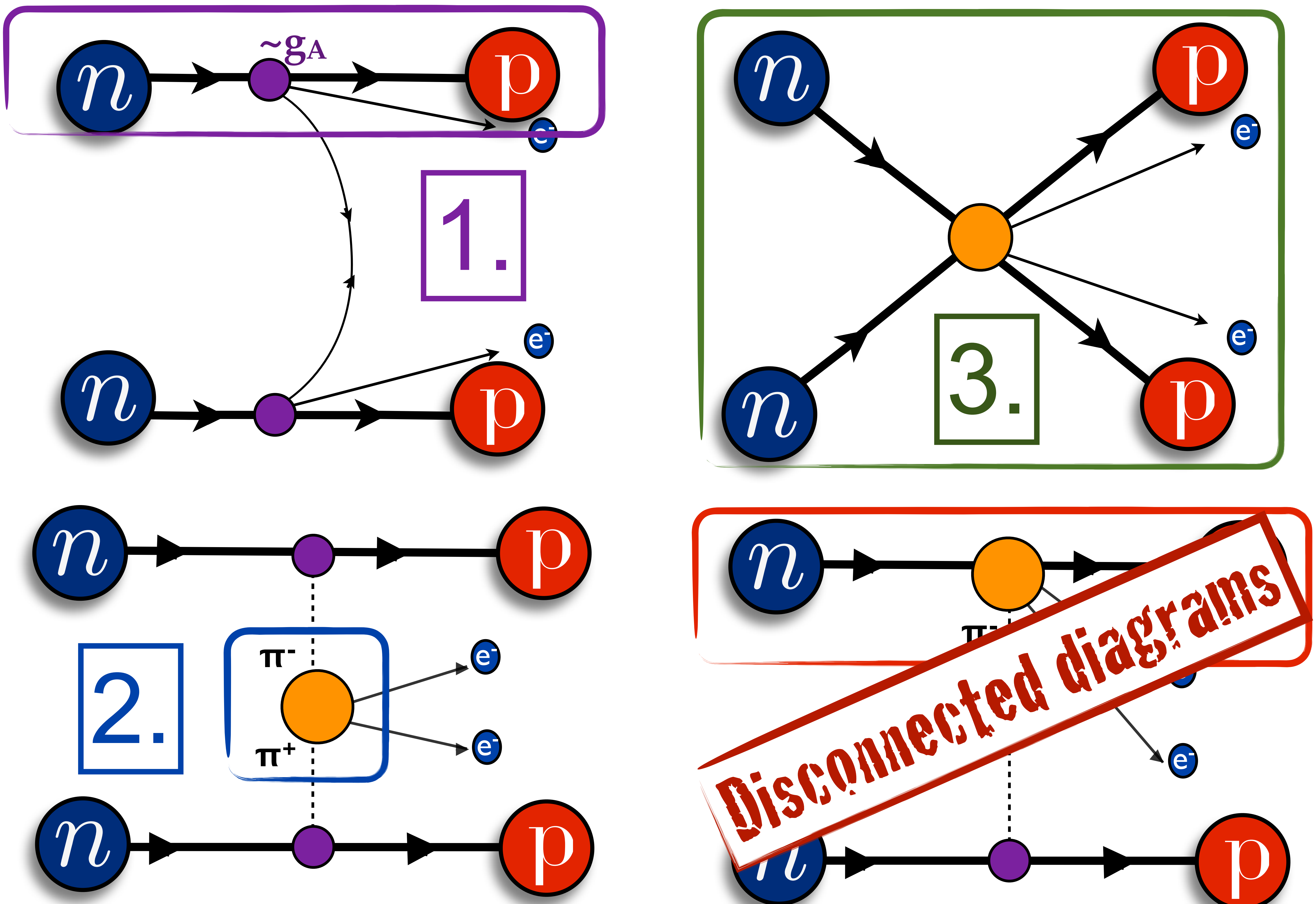
LEADING ORDER SHORT-RANGE
NNLO SHORT-RANGE
~gA

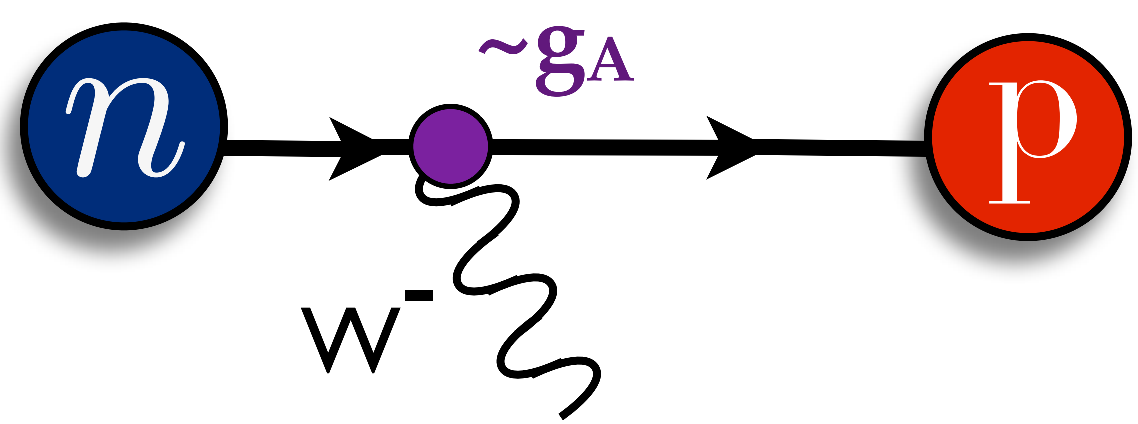
Prezeau, Ramsey-Musolf, Vogel (2003)

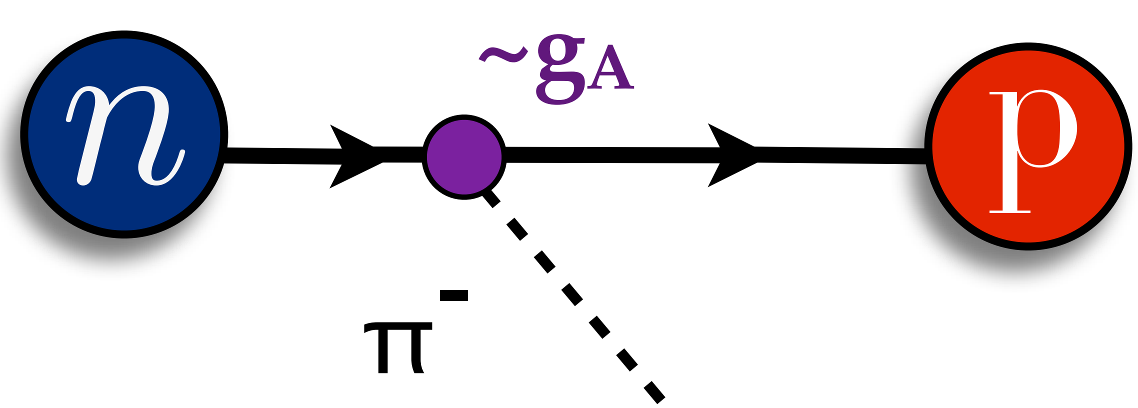


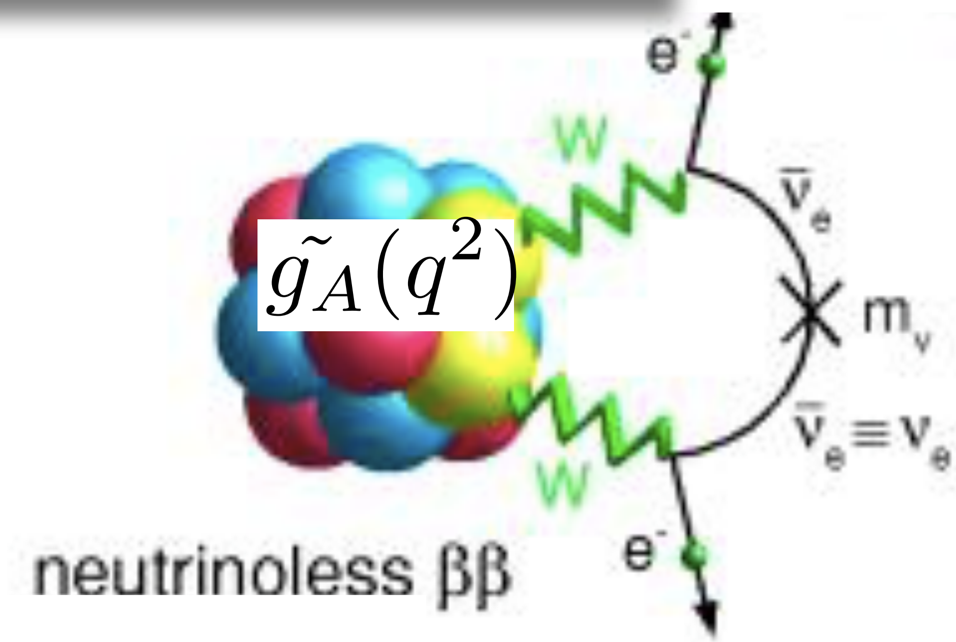
Prezeau, Ramsey-Musolf, Vogel (2003)



1. Nucleon axial charge, g_A





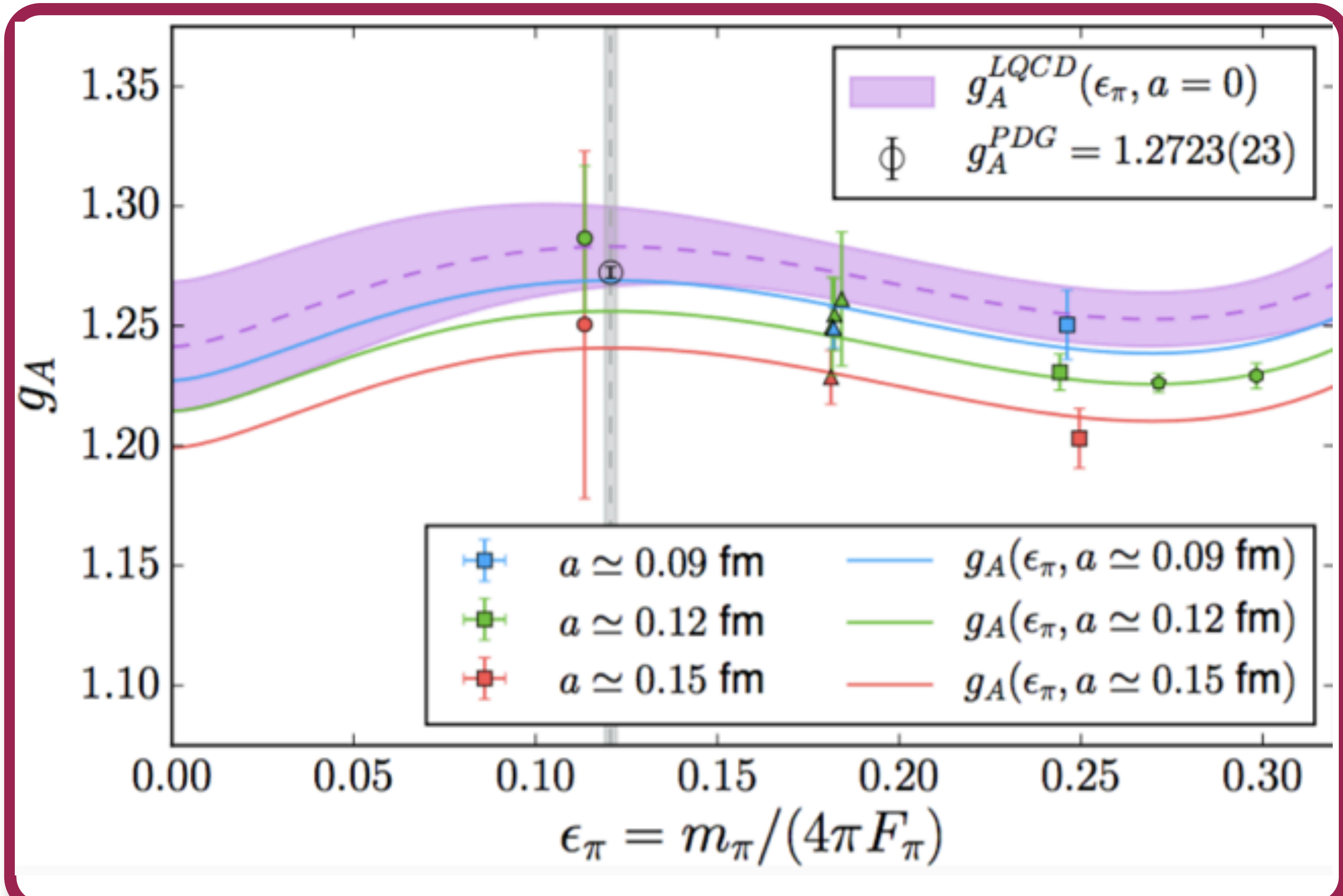


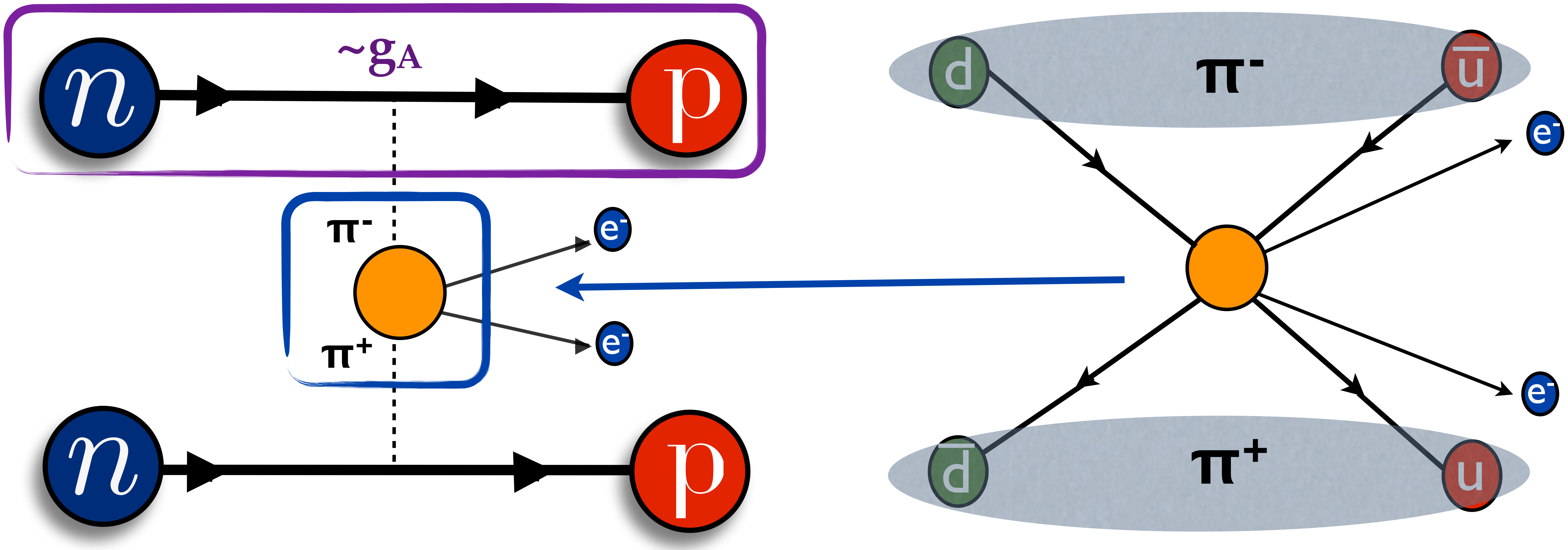
- $g_A^{exp} = 1.2723(23)$
- Less well known: in-medium modifications to g_A at relevant momentum scale NPLQCD (2017)
- Notoriously difficult "benchmark" for nuclear physics from LQCD!

Nucleon axial charge, g_A

arXiv:1704.01114
$g_A^{LQCD} = 1.283 \pm 0.017$

+ C. Bouchard, C. Monahan, K. Orginos





2. $\pi^- \rightarrow \pi^+$ Transition:

no direct experimental input

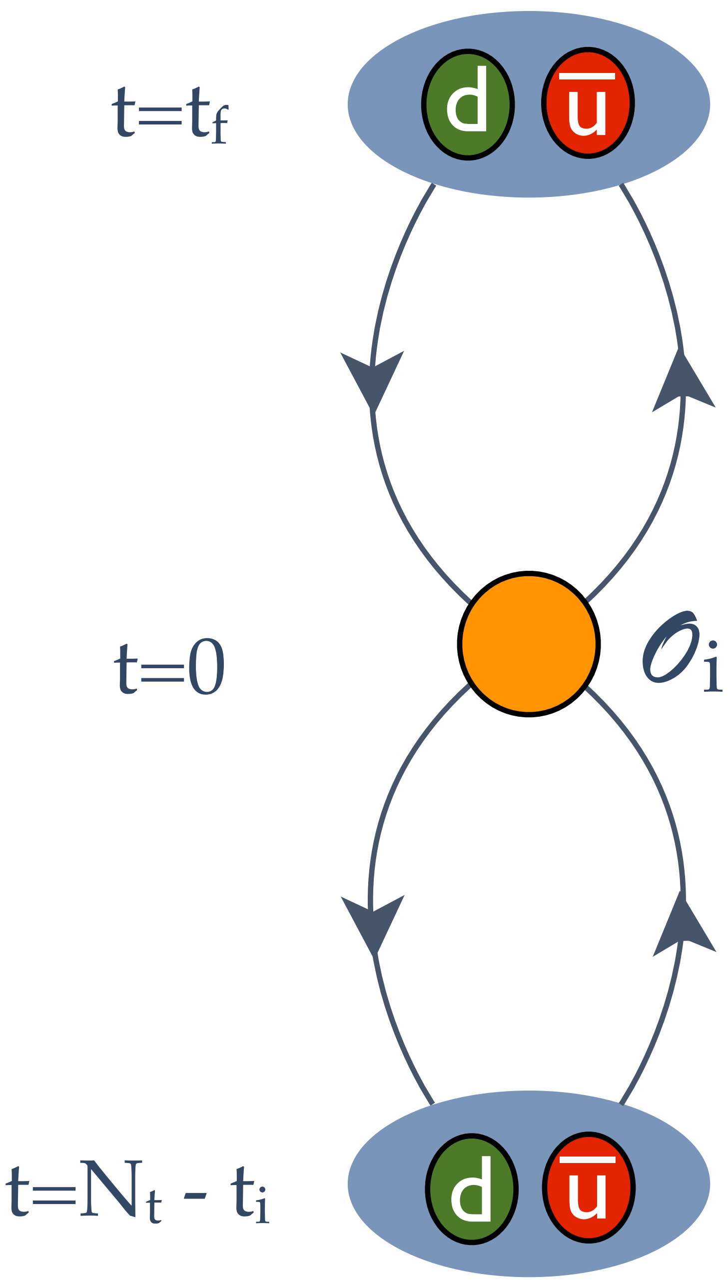
Long-range pion calculation

- Evolution in Euclidean time leads to exponential damping of excited states

- Easy to compute pion physics on the lattice!
  - Clean signals
  - Single particle

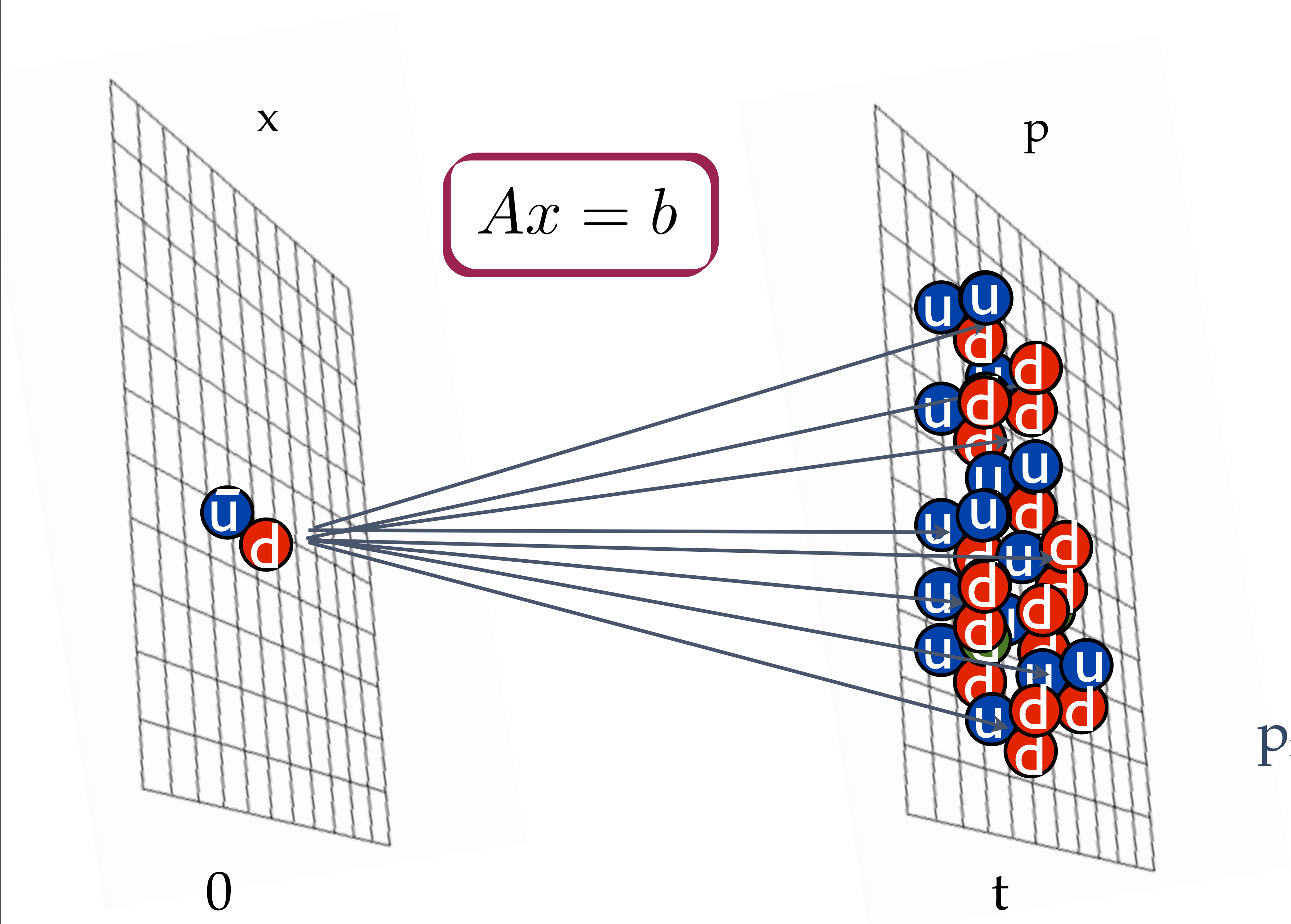
$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle$$

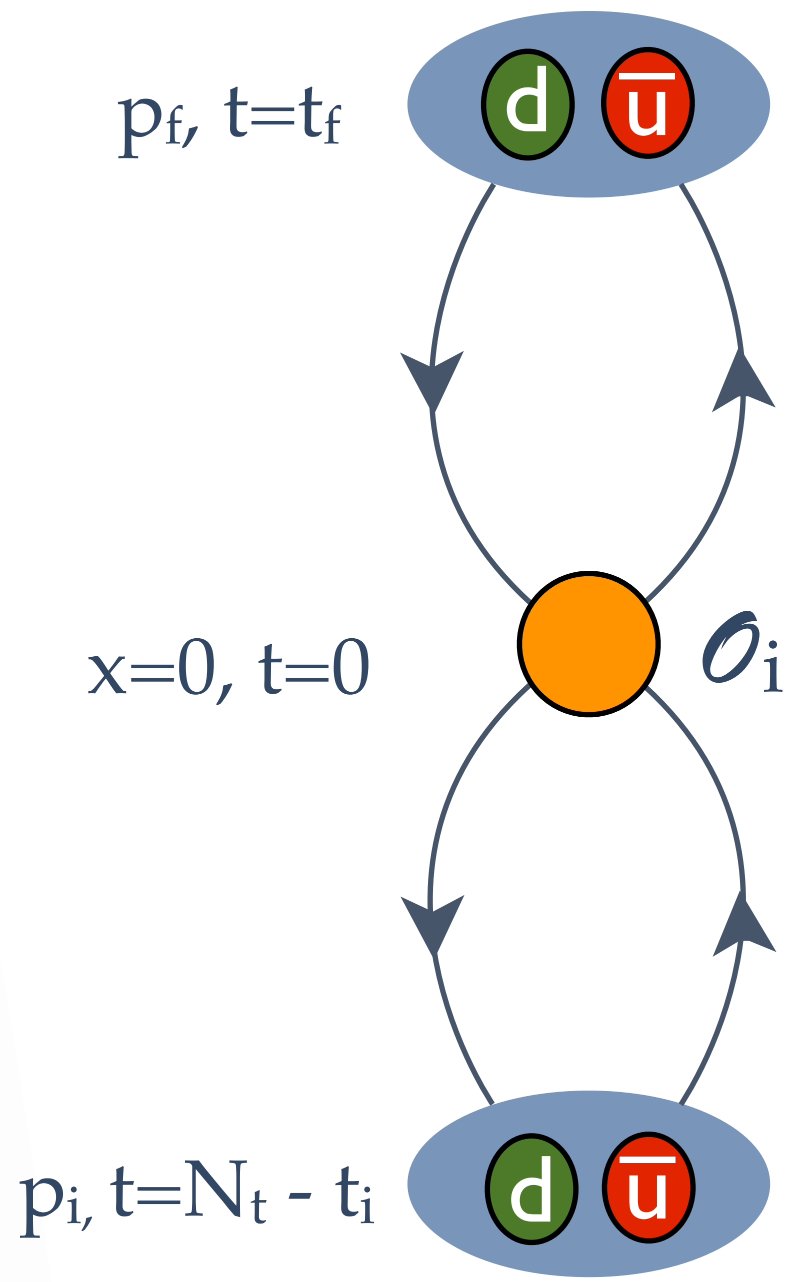
$$= \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t} \underset{t\to\infty}{\longrightarrow} \langle 0|\mathcal{O}|0\rangle e^{-E_0 t}$$



Long-range pion calculation

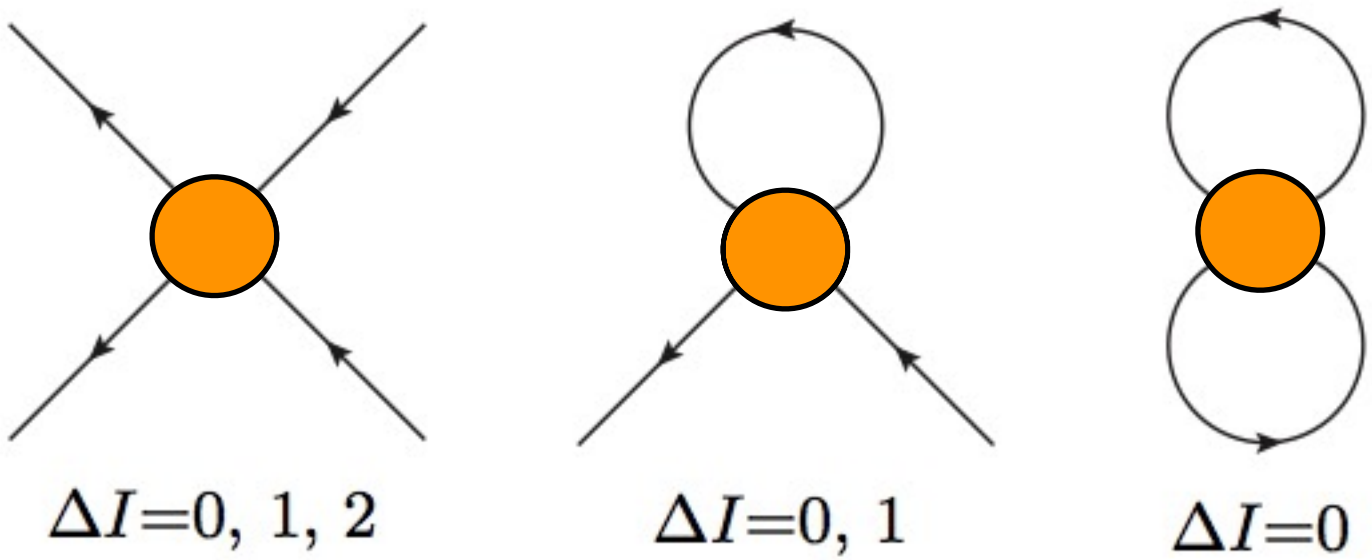
- Can perform exact momentum projection at source and sink

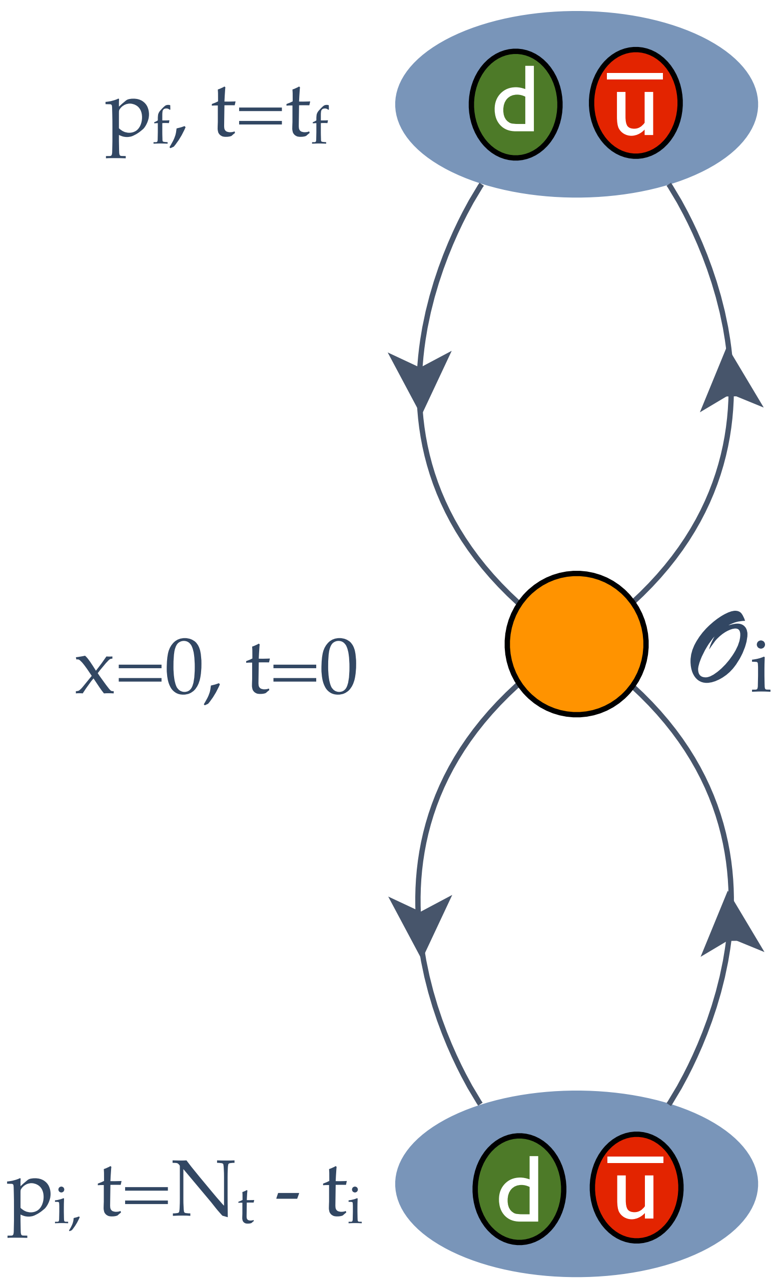




Long-range pion calculation

- Can perform exact momentum projection at source and sink
- $\Delta I = 2$ no disconnected pieces from operators





XPT:

$0\nu\beta\beta$-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	✓	✓	✓	✓

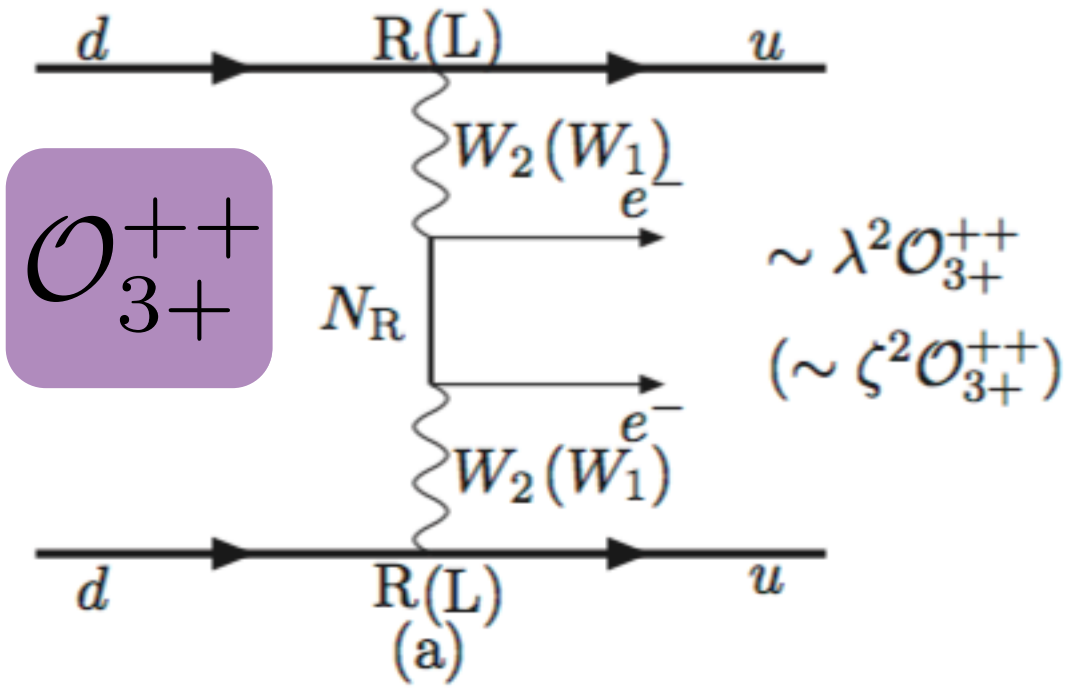
$$
\begin{aligned}
\mathcal{O}_{1+}^{ab} &= (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_R \tau^b \gamma_\mu q_R), \\
\mathcal{O}_{2\pm}^{ab} &= (\bar{q}_R \tau^a q_L)(\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R)(\bar{q}_L \tau^b q_R), \\
\mathcal{O}_{3\pm}^{ab} &= (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L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

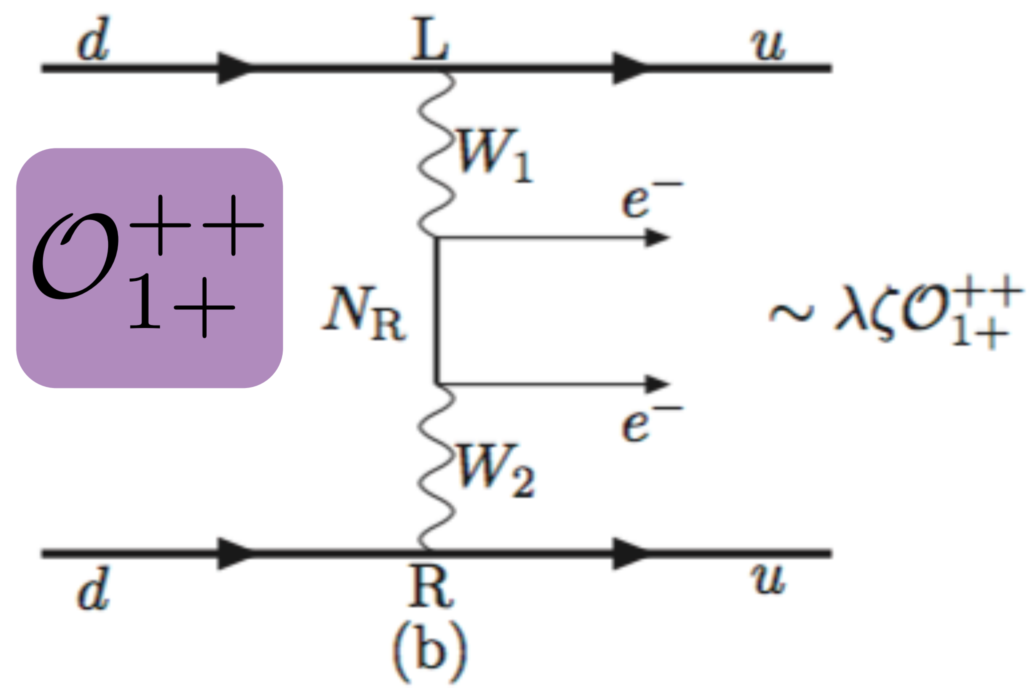
Prezeau, Ramsey-Musolf, Vogel (2003)

XPT:

$0\nu\beta\beta$-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





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

Contractions

- QCD interactions can mix colors below the electroweak scale
- Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2

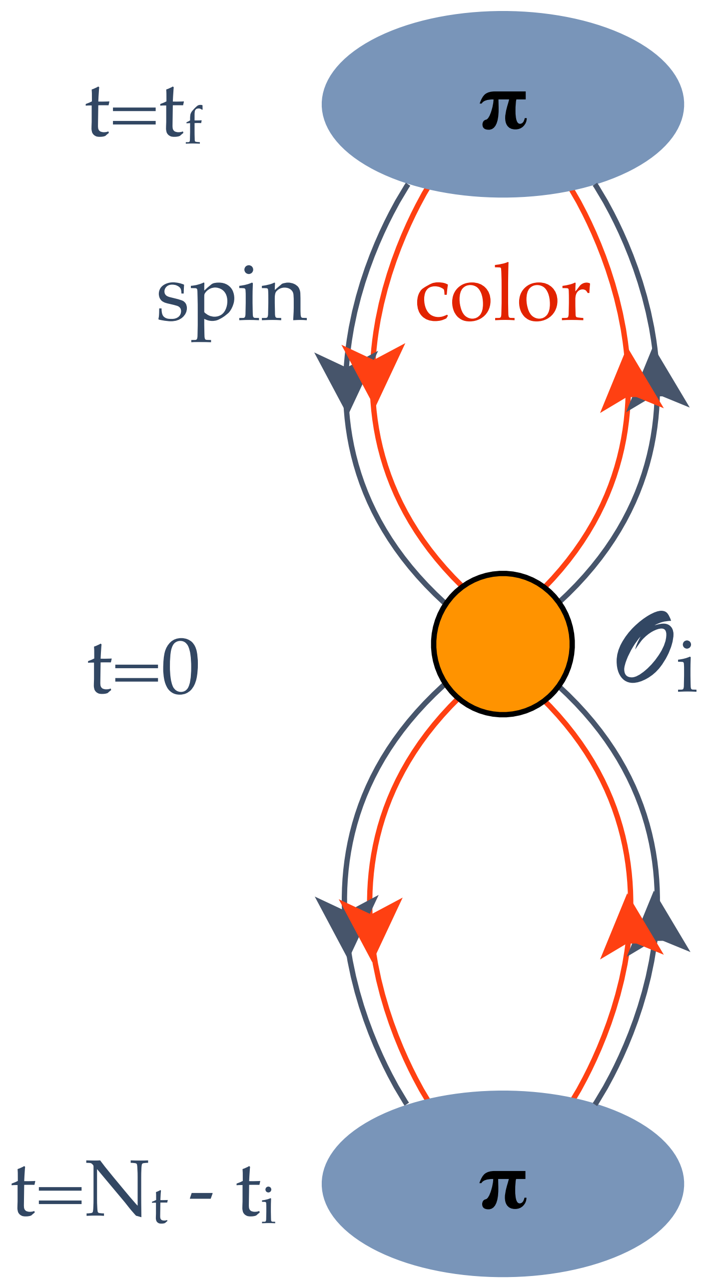
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L)\,[\bar{q}_R \tau^- \gamma_\mu q_R]$$

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

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

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

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



Contractions

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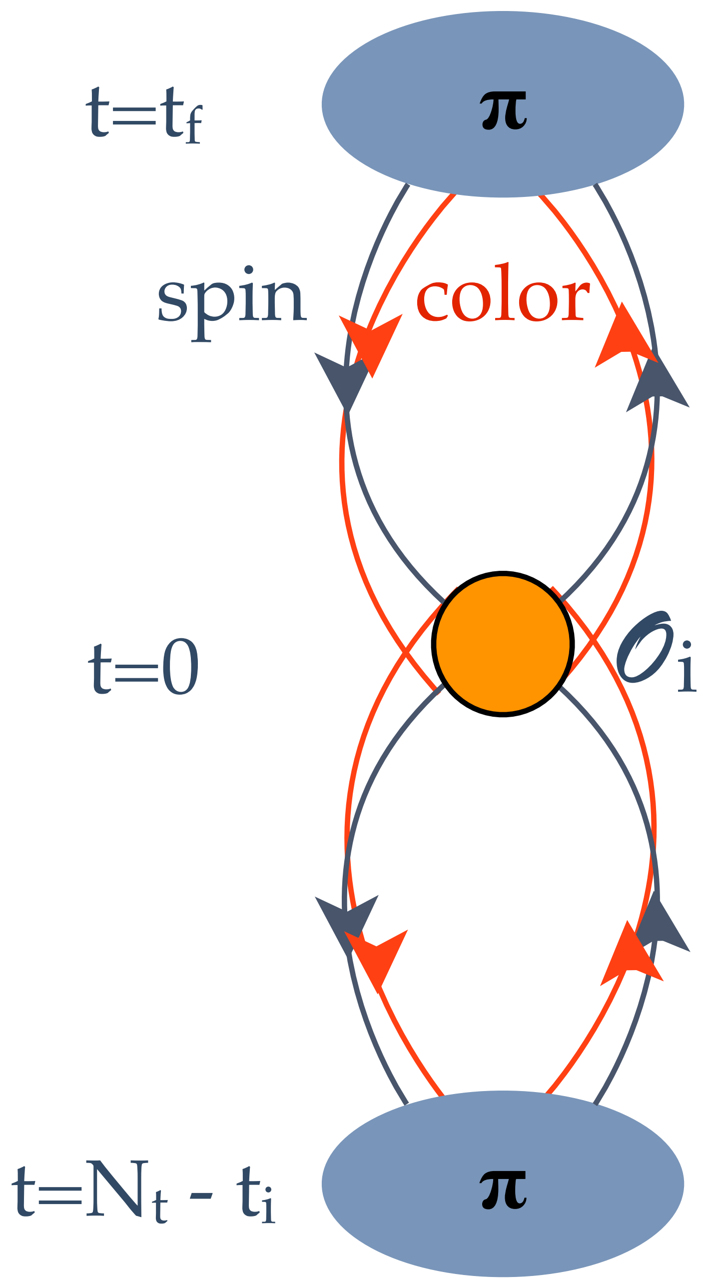
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L)\, [\bar{q}_R \tau^- \gamma_\mu q_R]$$

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

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

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

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



Lattice Ensembles

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	$32^3 \times 96, m_\pi L \sim 4.50$	$48^3 \times 96, m_\pi L \sim 4.73$	

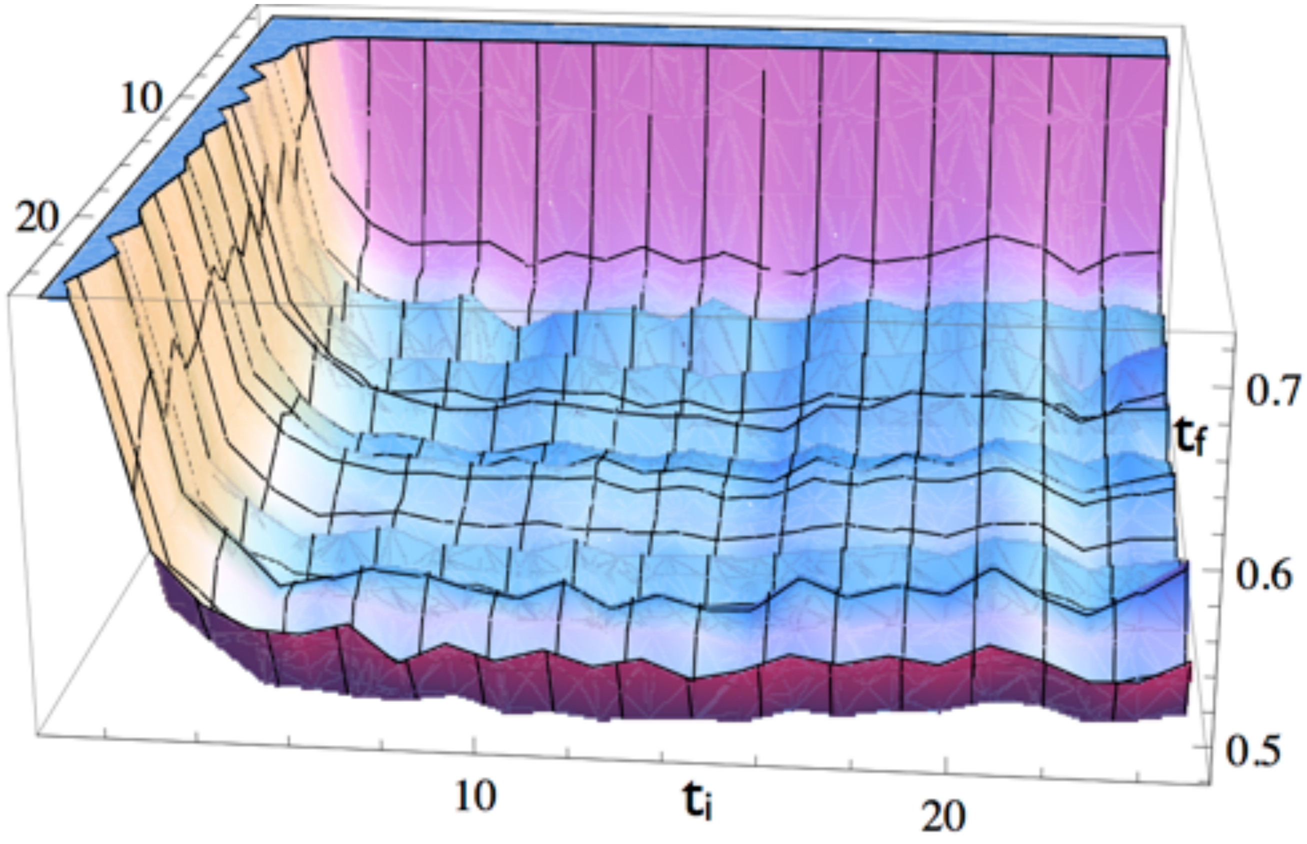
- Möbius DWF on HISQ
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5

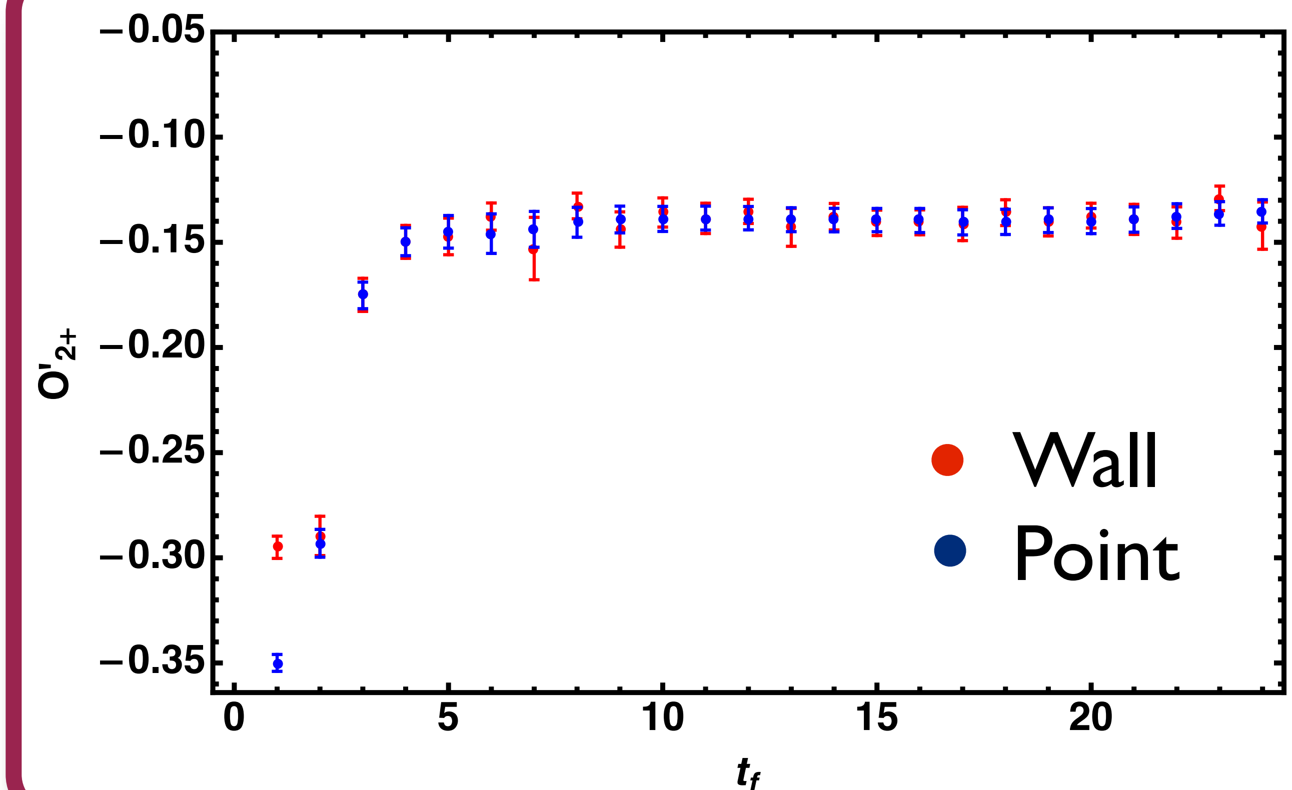
MILC Collaboration Phys. Rev. D87 (2013) 054505

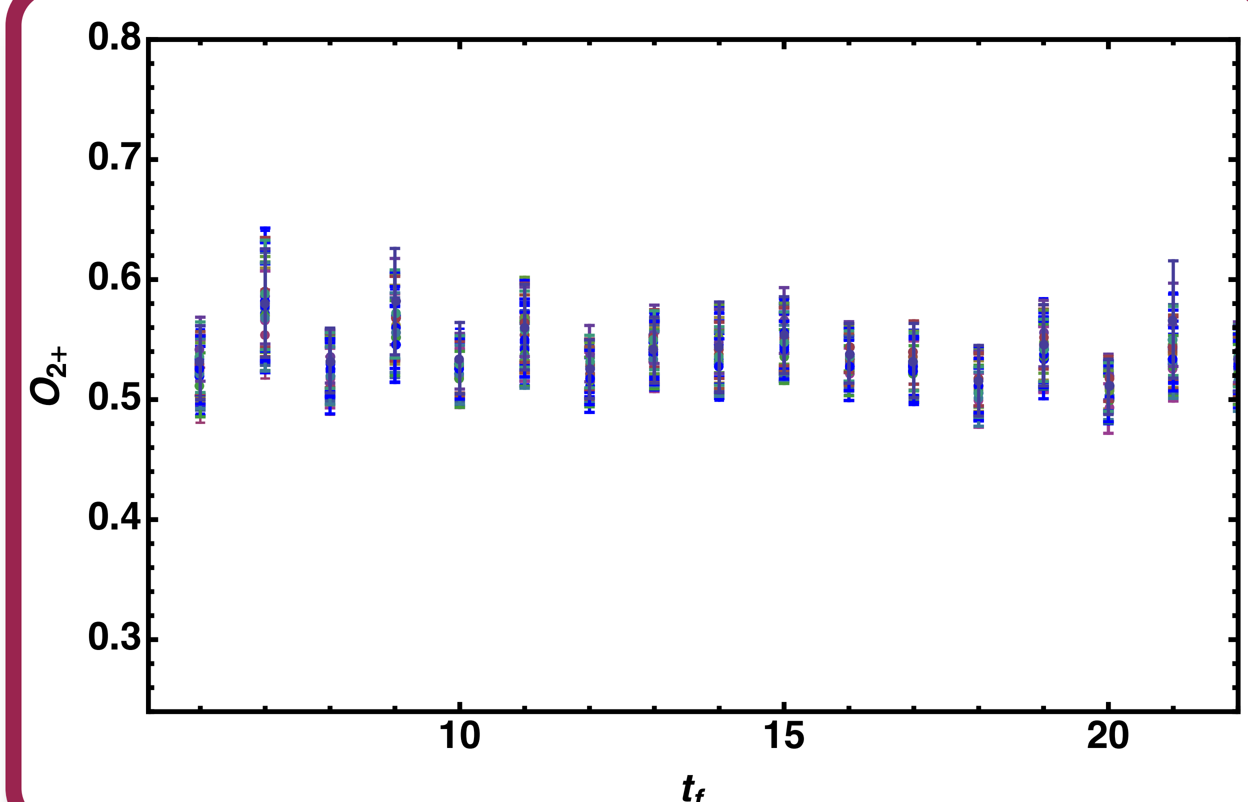
Narayanan, Neuberger (2006), Luscher (2010)

Callat arXiv:1701.07559

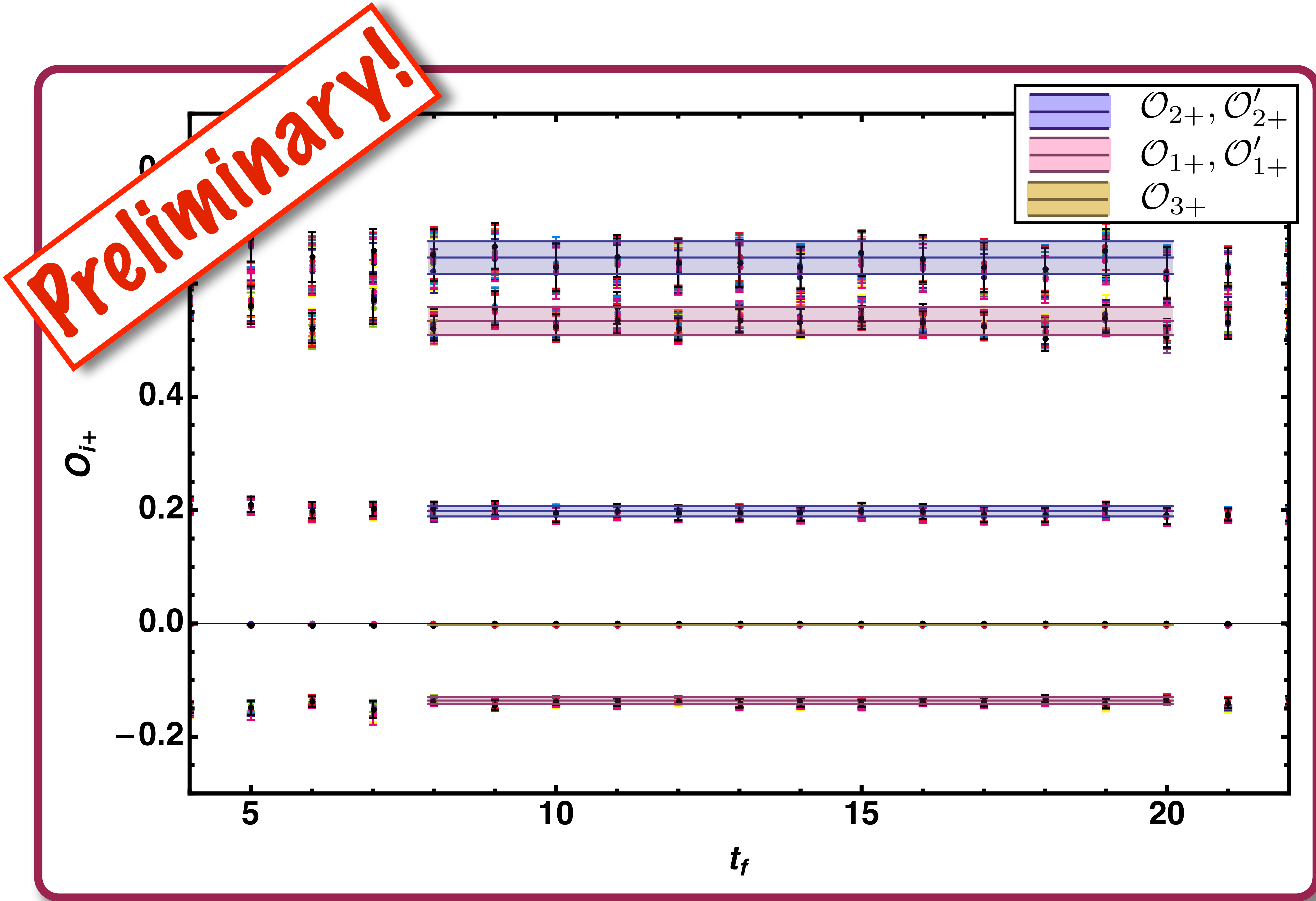
Signals



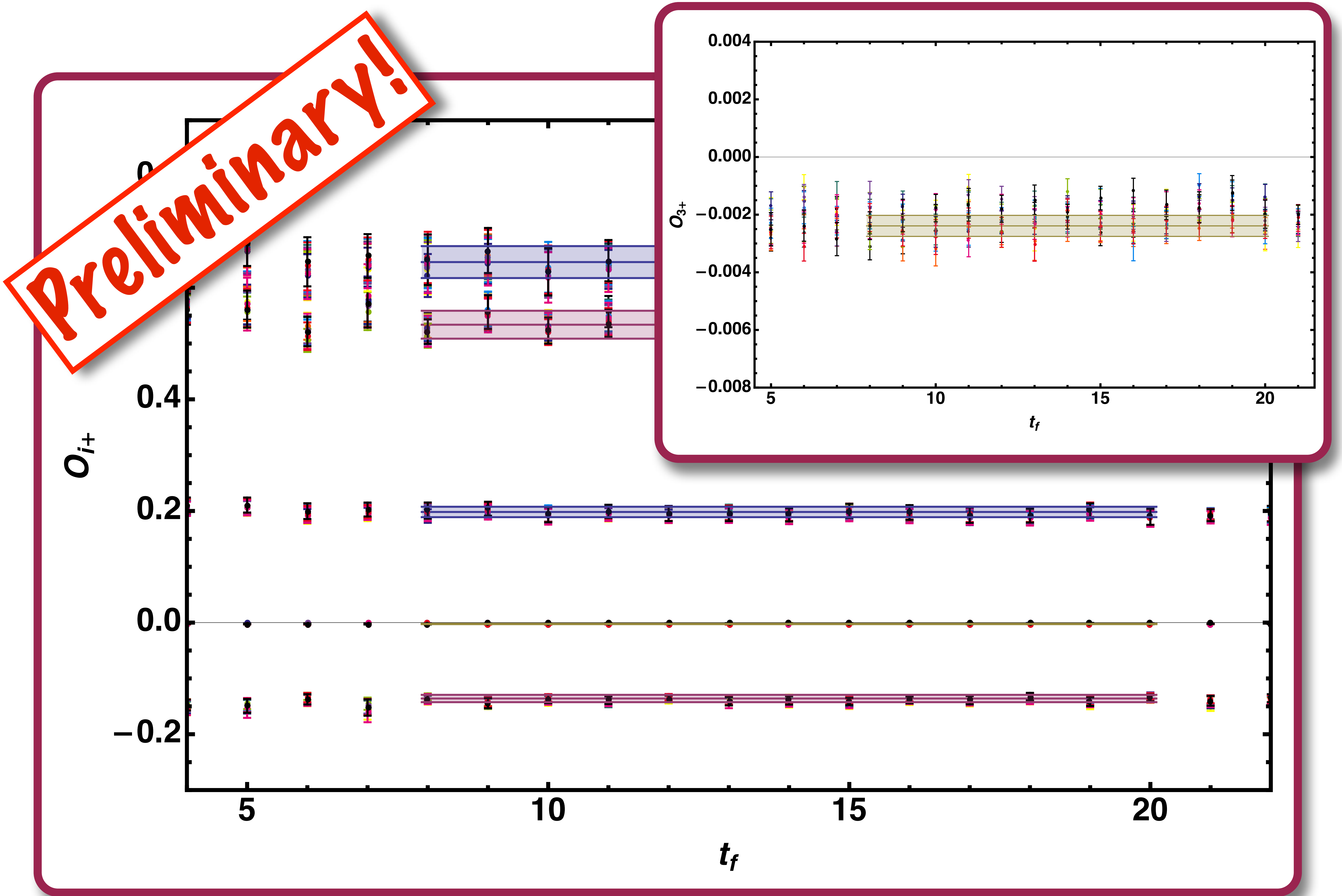




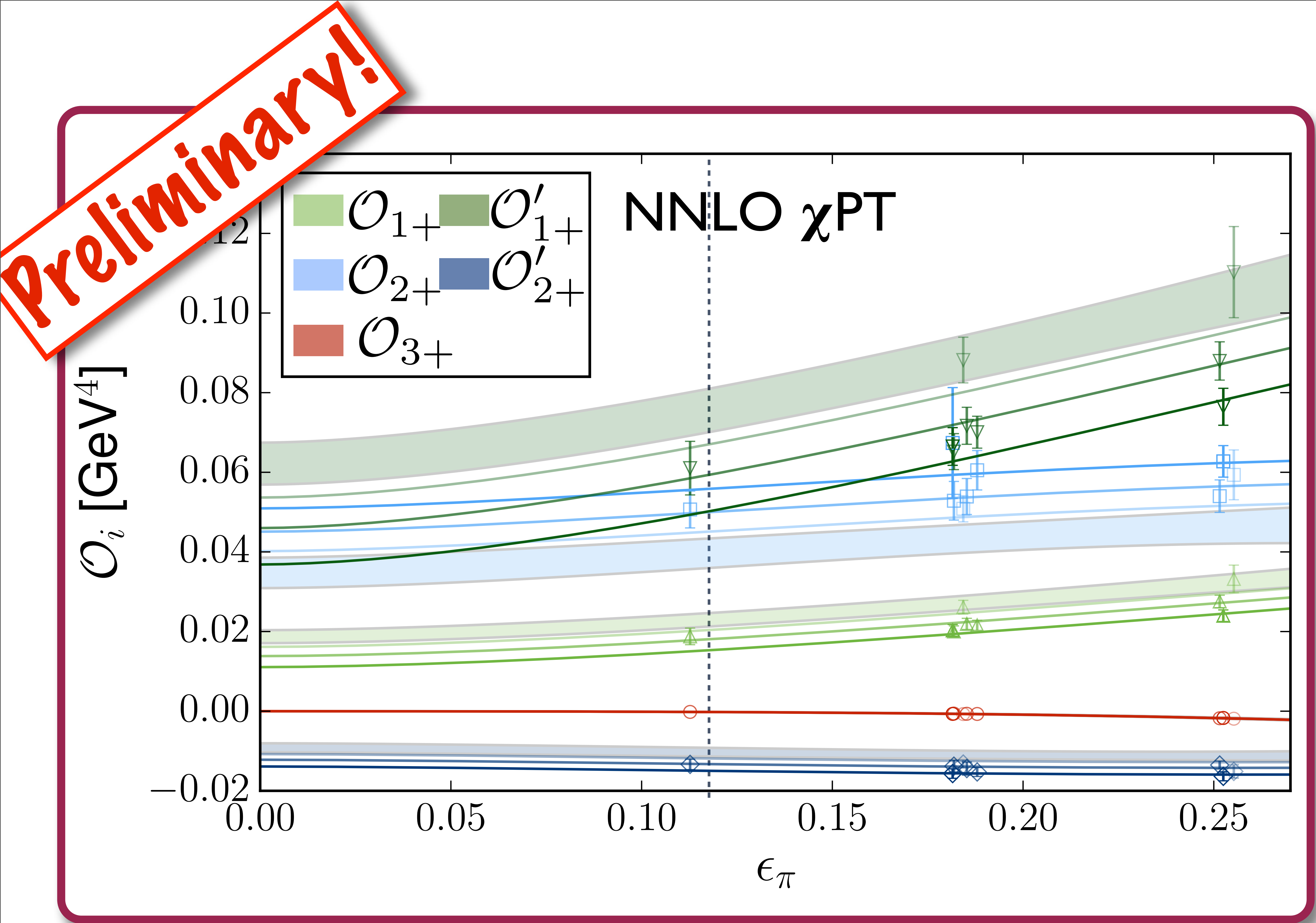
- $m_\pi \sim 135$ MeV
- L = 5.76 fm
- a = 0.12 fm



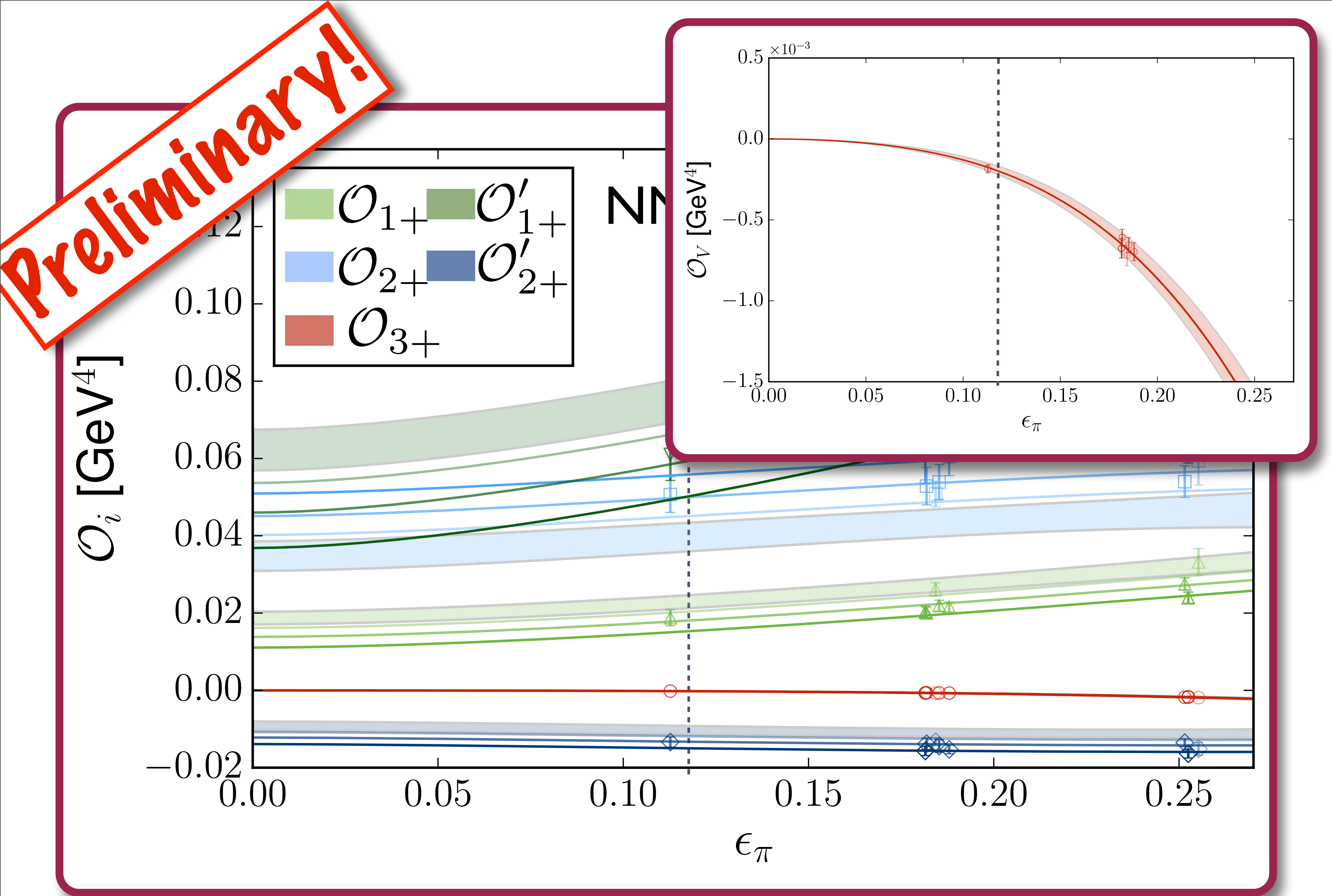
Preliminary!
$\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
$\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
$\mathcal{O}_{3+}$
0.4
0.2
0.0
−0.2
o_{i+}
5
10
15
20
t_f



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

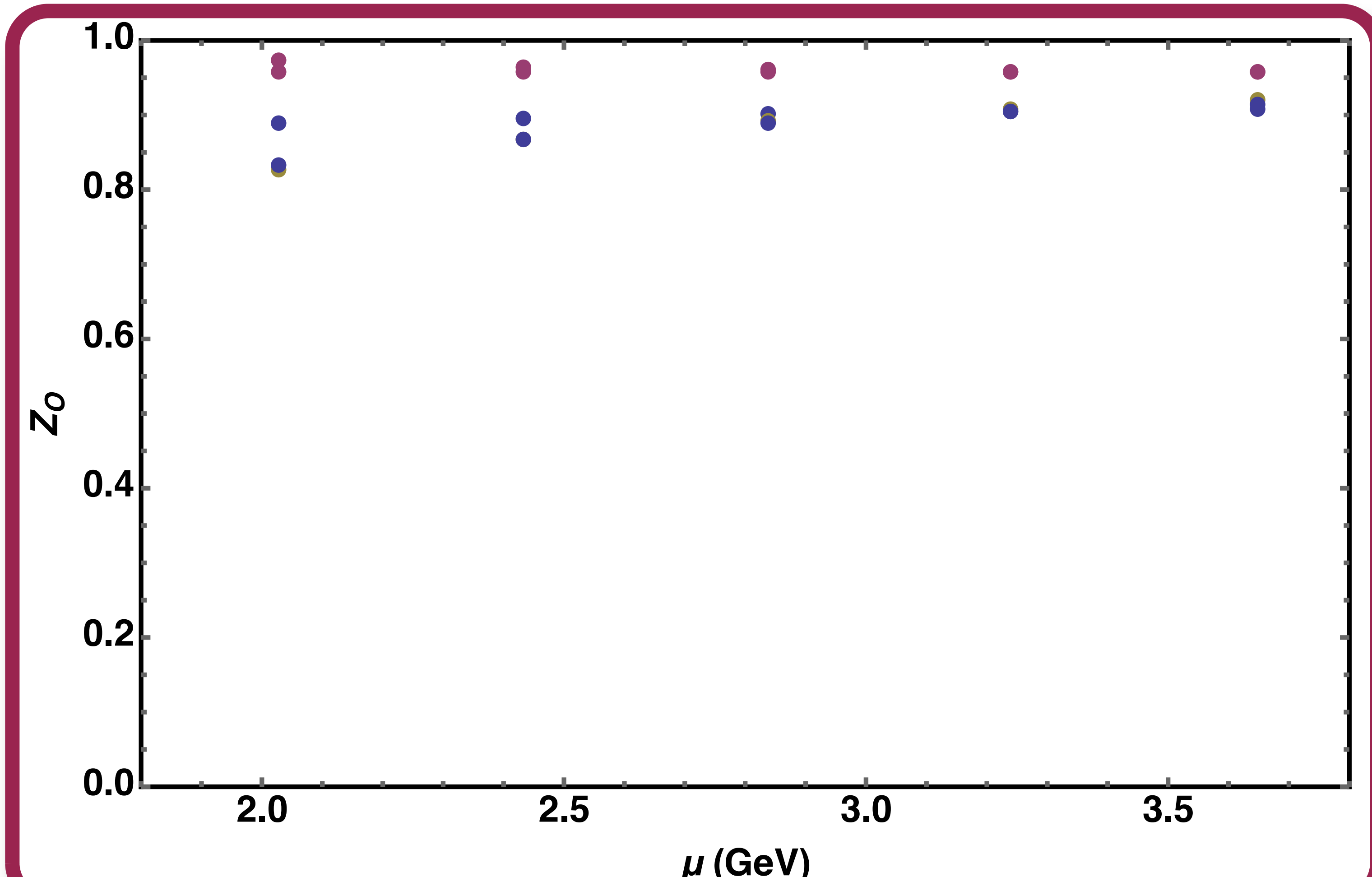


Preliminary!
NNLO χPT
$\mathcal{O}_{1+}$
$\mathcal{O}'_{1+}$
$\mathcal{O}_{2+}$
$\mathcal{O}'_{2+}$
$\mathcal{O}_{3+}$
$\mathcal{O}_i$ [GeV^4]
ϵ_π
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
0.00
0.05
0.10
0.15
0.20
0.25

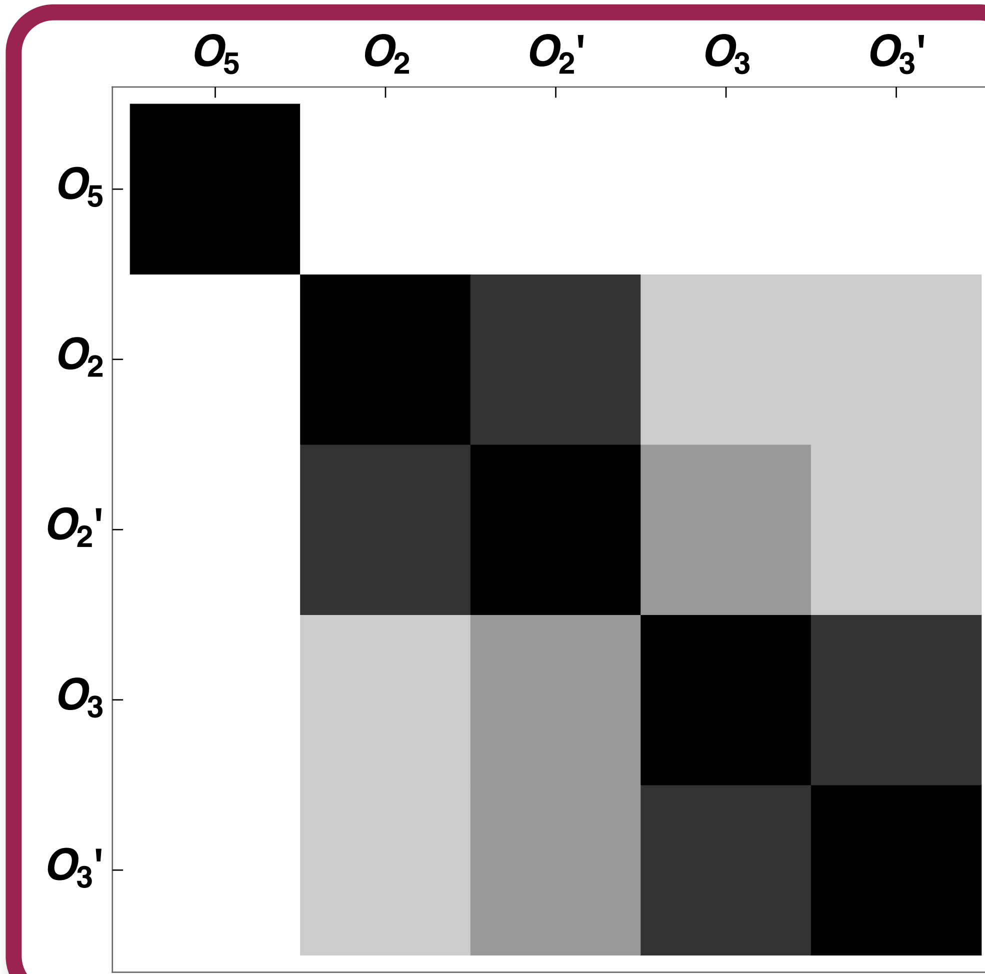

Preliminary!
$\mathcal{O}_{1+}$
$\mathcal{O}'_{1+}$
$\mathcal{O}_{2+}$
$\mathcal{O}'_{2+}$
$\mathcal{O}_{3+}$
NN
$\mathcal{O}_i$ [GeV^4]
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
0.00
0.05
0.10
0.15
0.20
0.25
ϵ_π
$\times 10^{-3}$
0.5
0.0
−0.5
−1.0
−1.5
$\mathcal{O}_V$ [GeV^4]
0.00
0.05
0.10
0.15
0.20
0.25
ϵ_π

Renormalization

- Lattice perturbation theory is difficult and poorly convergent
- Nonperturbative running (RI-SMOM) to match onto $\overline{\text{MS}}$

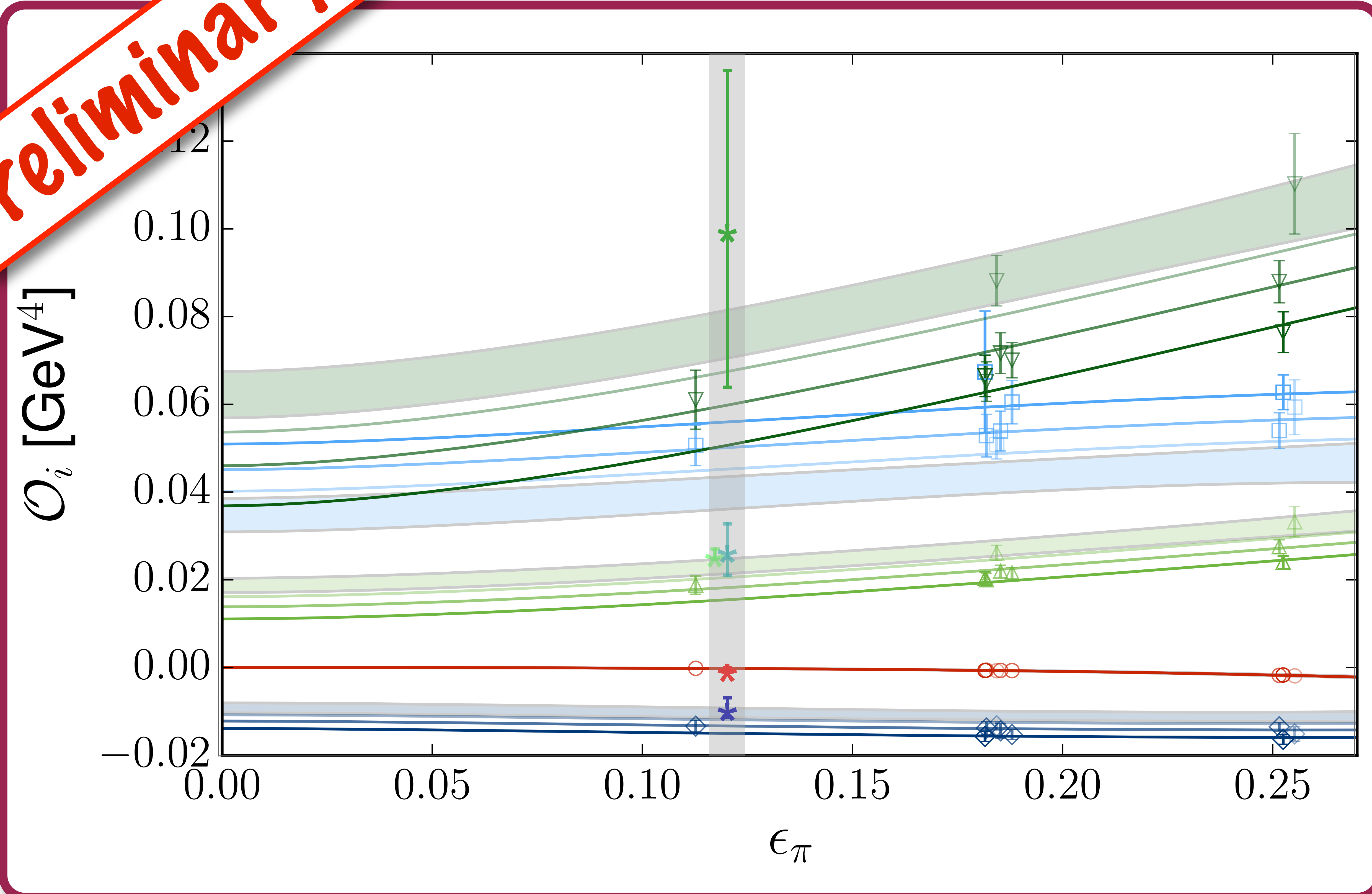


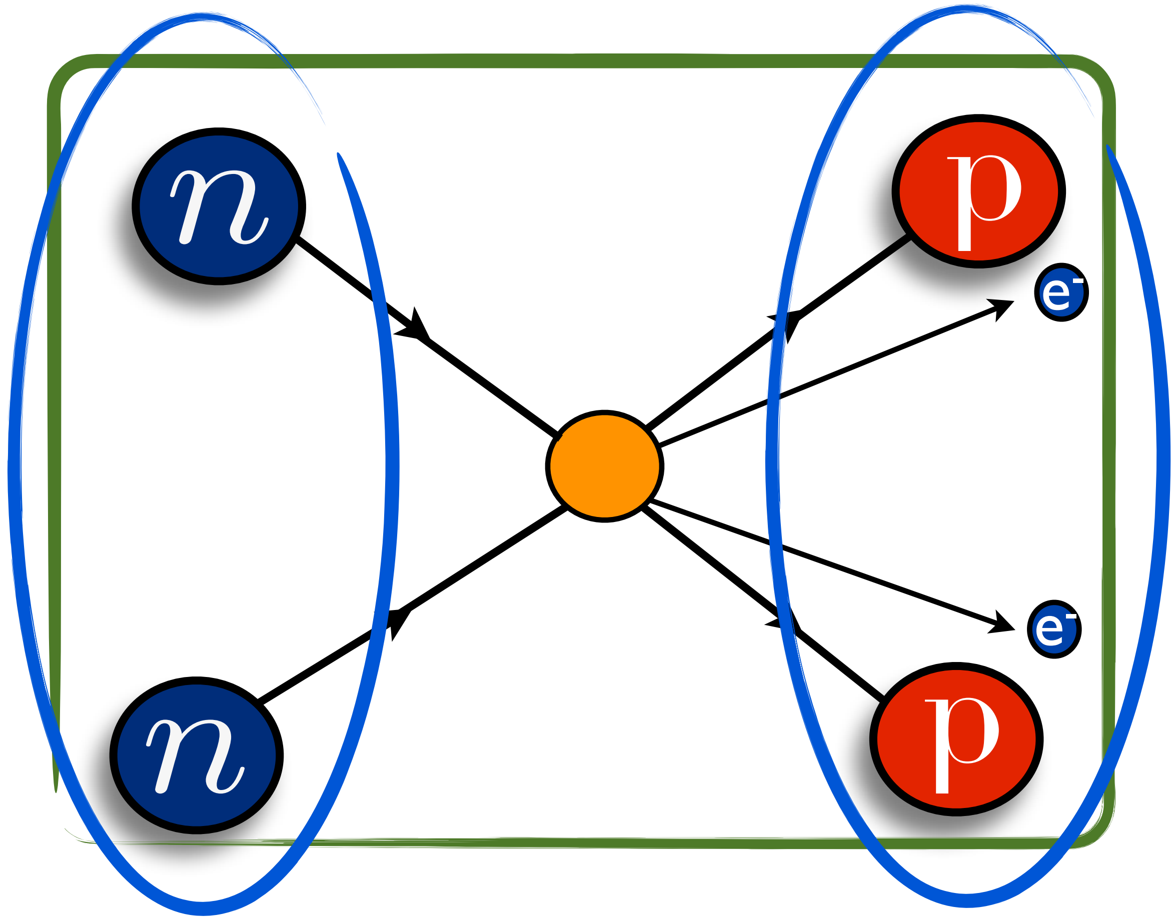
Mixing matrix



V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti
Phys.Lett. B769 (2017) 460-464

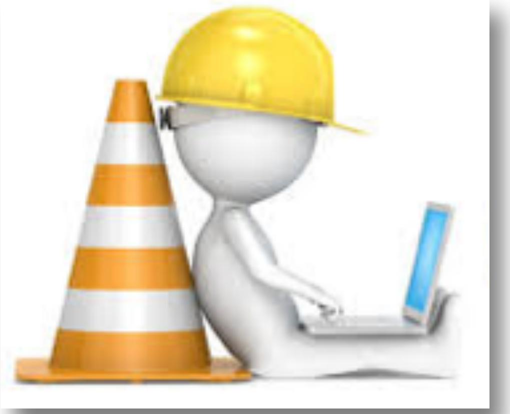
Preliminary!





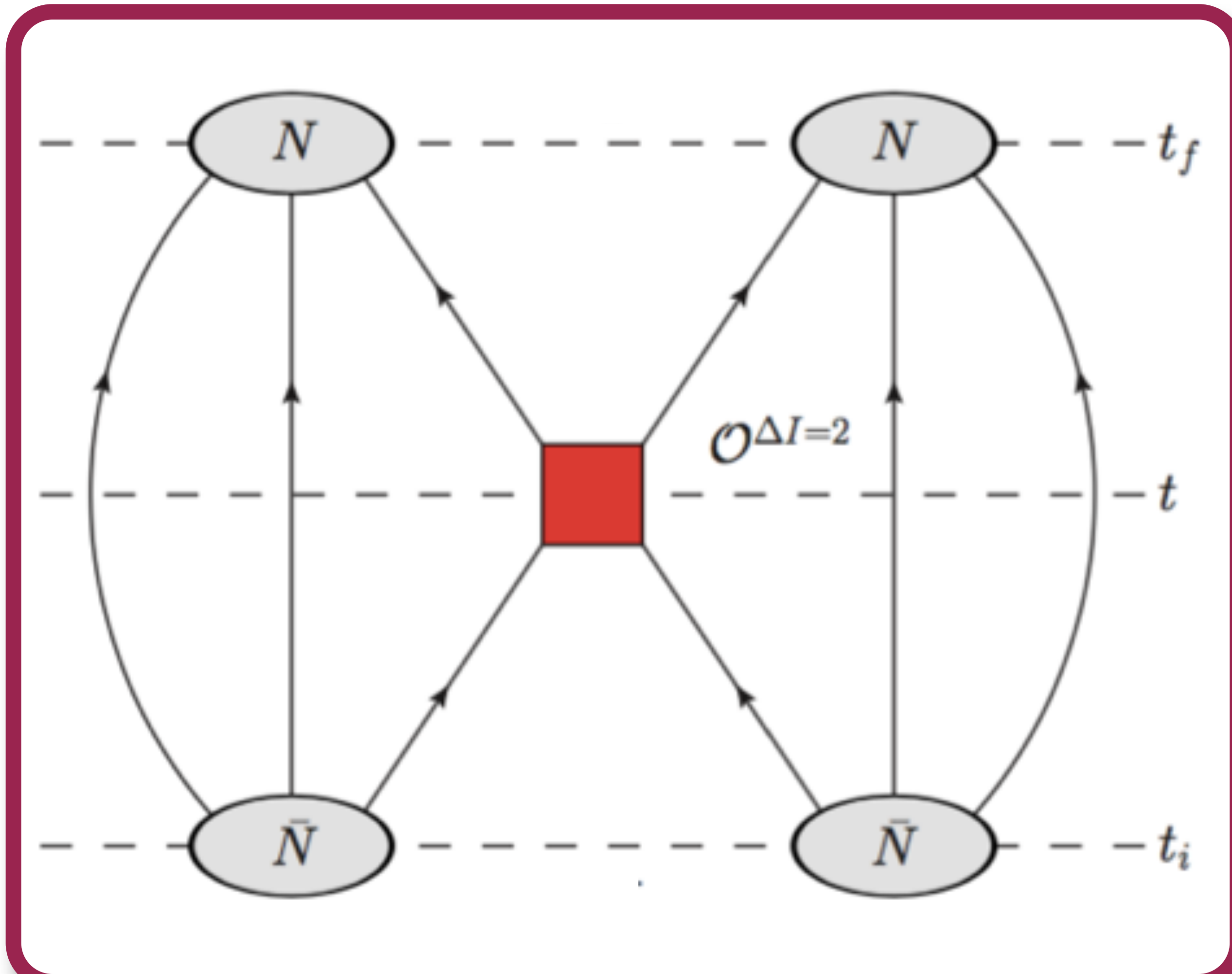
3.

Two-nucleon contact

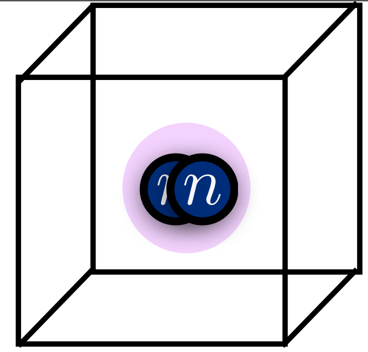


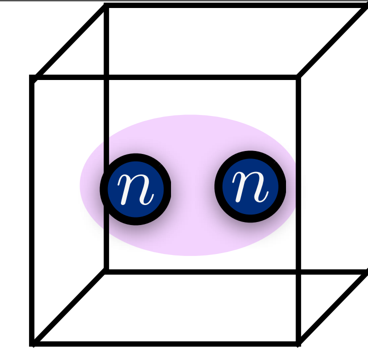
Two-nucleon contact

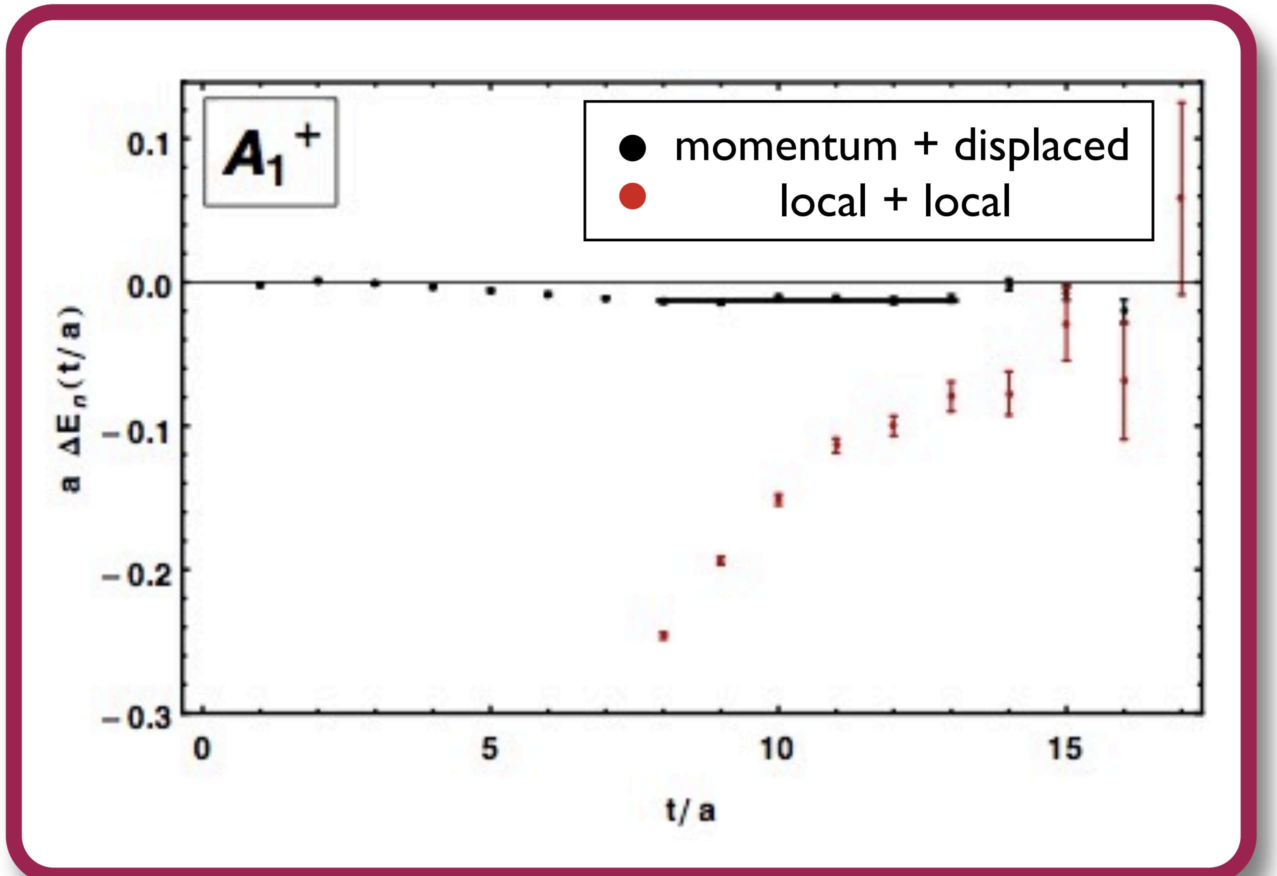
- Nucleons and multi-particle states are much more difficult!
  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...
- Isospin limit: 576 contractions*
- Must deal with multi-particle states in a finite volume
- Ops must be in position space
  - otherwise all-to-all propagators connect to quark operator

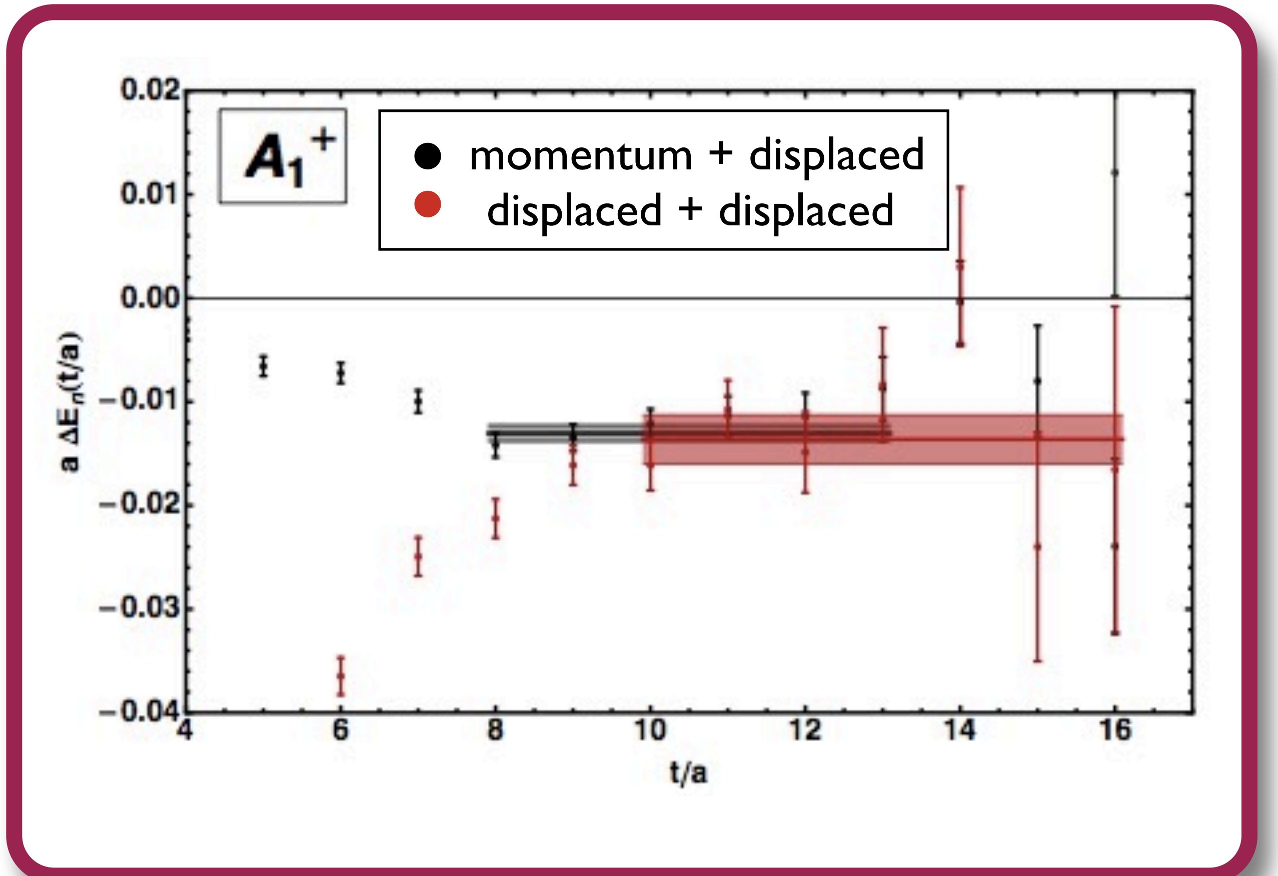


*Doi & Endres, Originos et. al., Günther et. al.





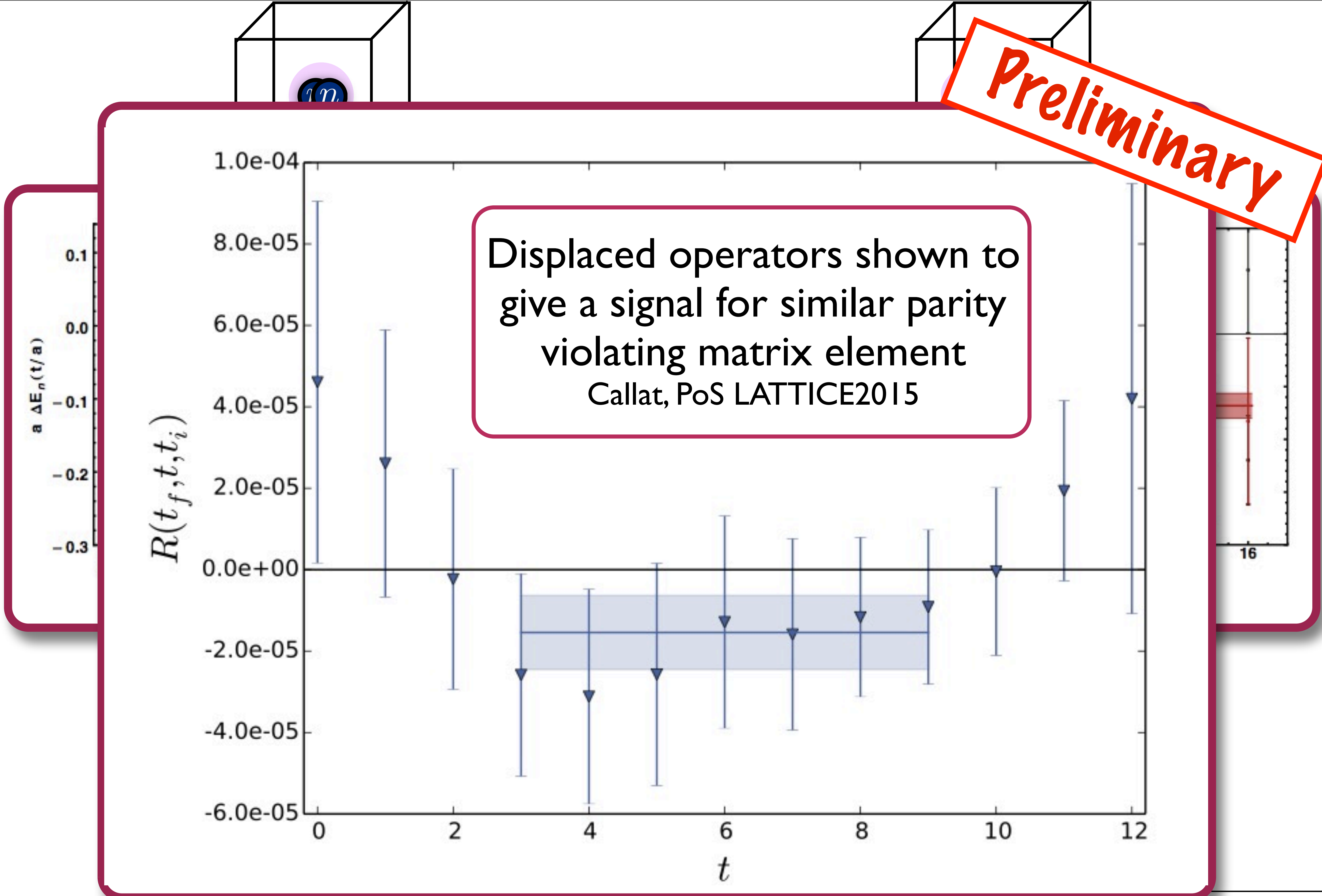




Need displaced operators

Callat arXiv:1508.00886 (2015)

Iso-clover cfgs, m_π~800 MeV (W. Detmold, R.Edwards, D. Richards, K. Orginos)



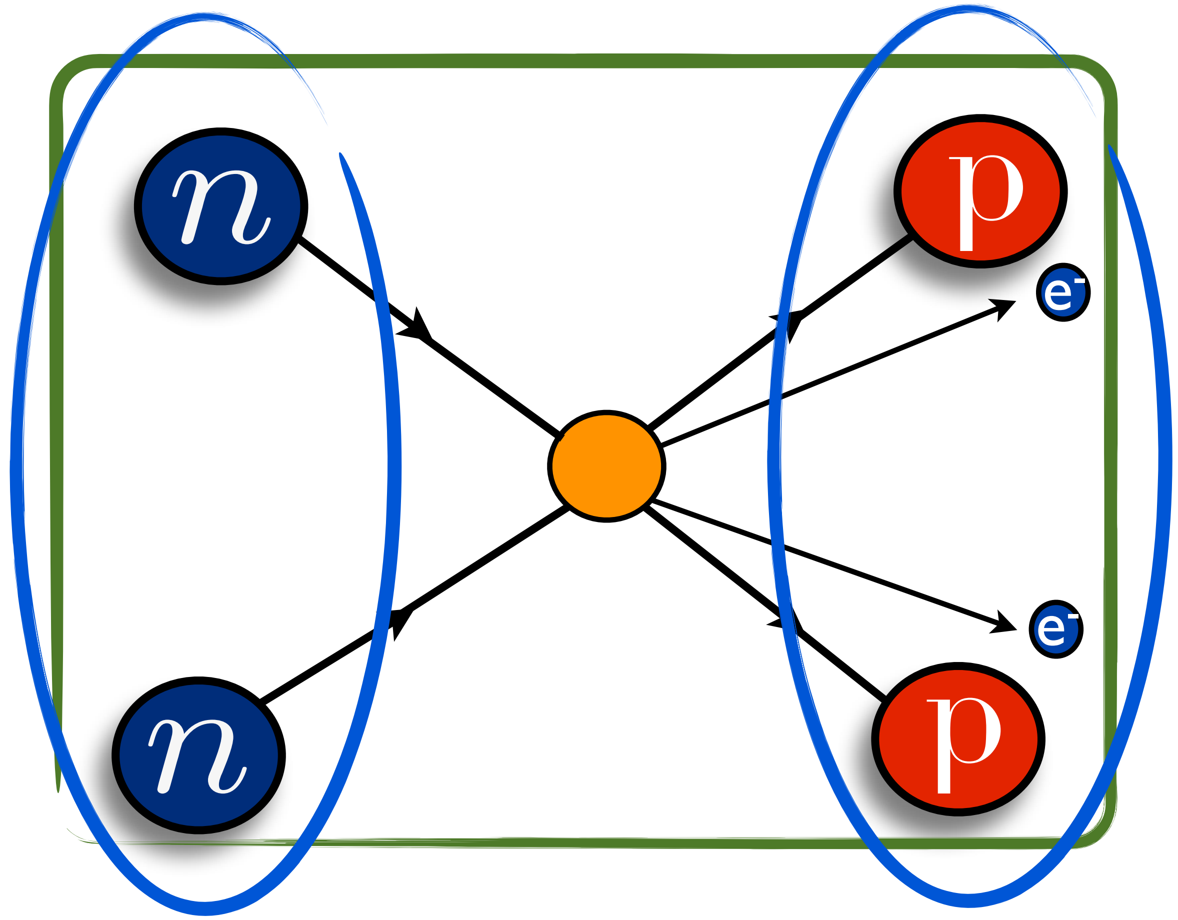
Displaced operators shown to give a signal for similar parity violating matrix element
Callat, PoS LATTICE2015

Iso-clover cfgs, m_π~800 MeV (W. Detmold, R.Edwards, D. Richards, K. Orginos)

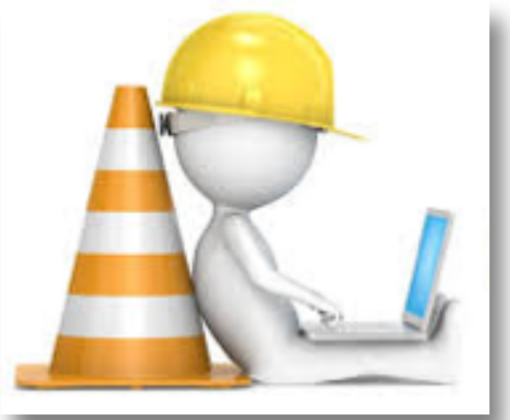
Callat arXiv:1508.00886 (2015)

3.

Two-nucleon contact



- Some new developments:
  - Exponentially improved NN operators
    - will allow us to lower the pion mass
  - HOBET in a periodic box
    - more direct path from finite volume lattice results to nuclear many-body techniques (talk by W. Haxton)



Summary

- LQCD can be used as a step toward connecting experimental signals to BSM models
- Nucleon axial charge
  - Finally achieved accuracy with LQCD!
- $\pi^- \rightarrow \pi^+$ matrix element
  - Leading short-range contribution
  - To do: complete renormalization
- Two-nucleon contact
  - Testing new method for two nucleon operators
  - Machinery in place for calculating 3-point function

- LBL/UCB: C.C. Chang, AN, A. Walker-Loud
- LLNL: P. Vranas
- NERSC: T. Kurth
- Jülich: E. Berkowitz
- BNL: E. Rinaldi
- nVidia: M.A. Clark
- JLab: B. Joo
- Plymouth: N. Garron
- WM/LBL: D. Brantley, H. Monge-Comacho