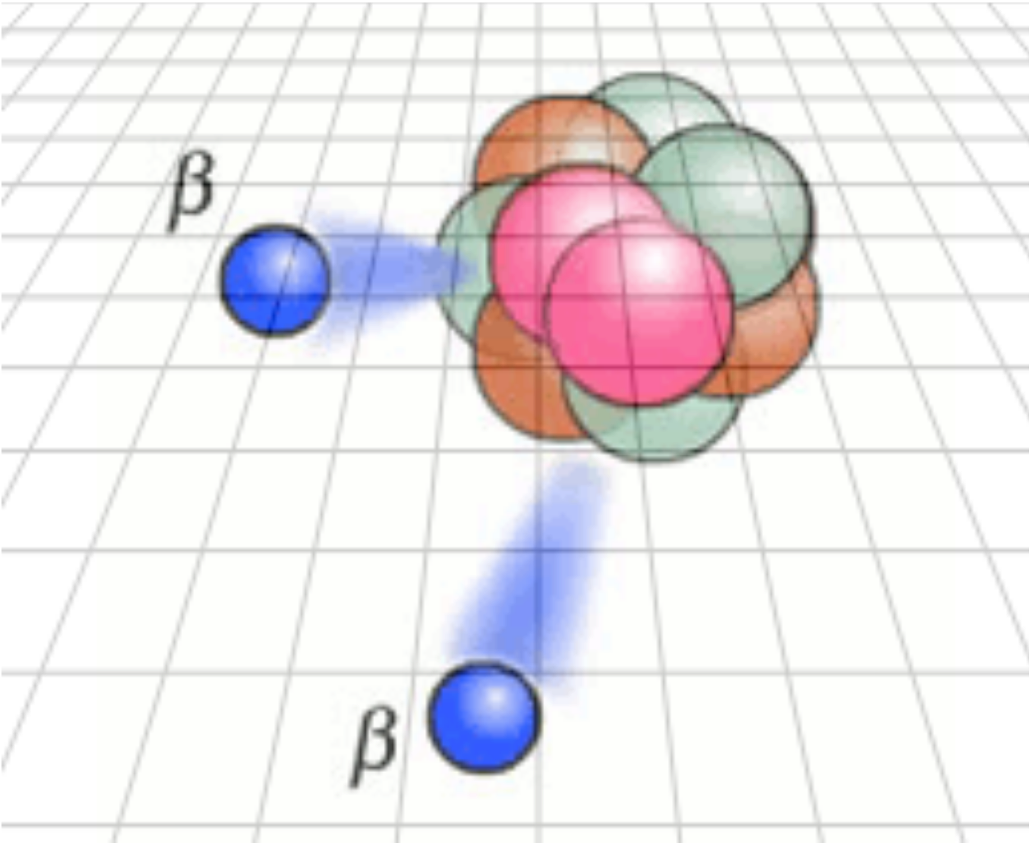
Status of LQCD calculations of double-beta decay operators



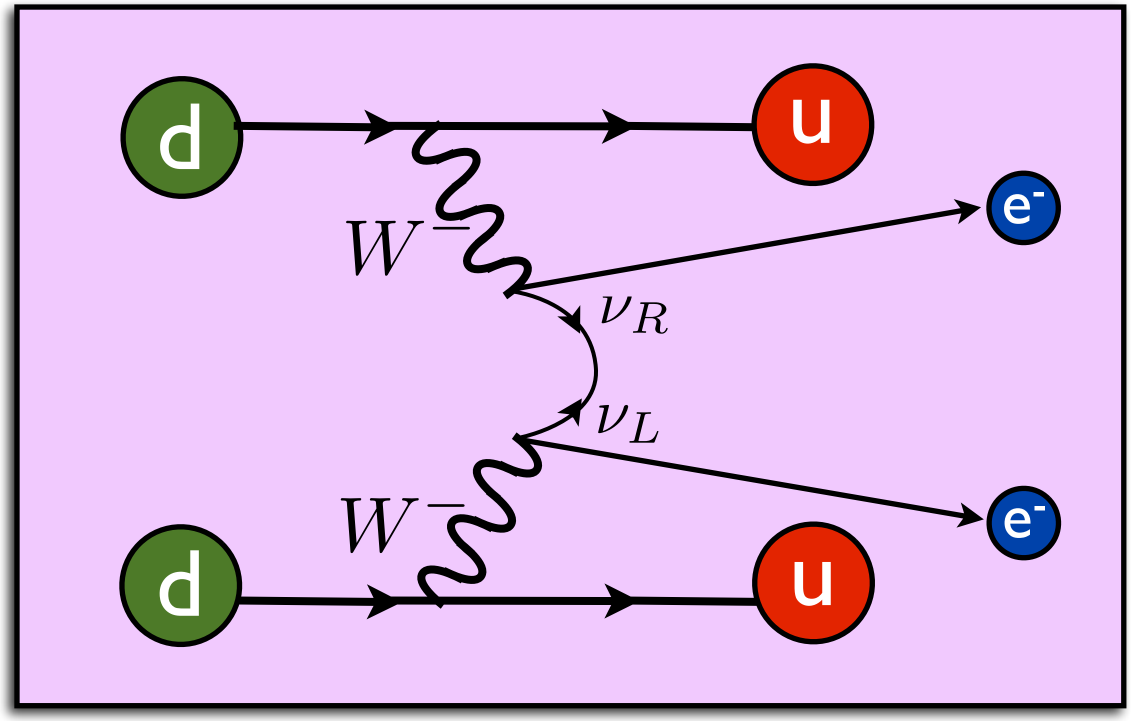
Amy Nicholson
UC Berkeley/UNC

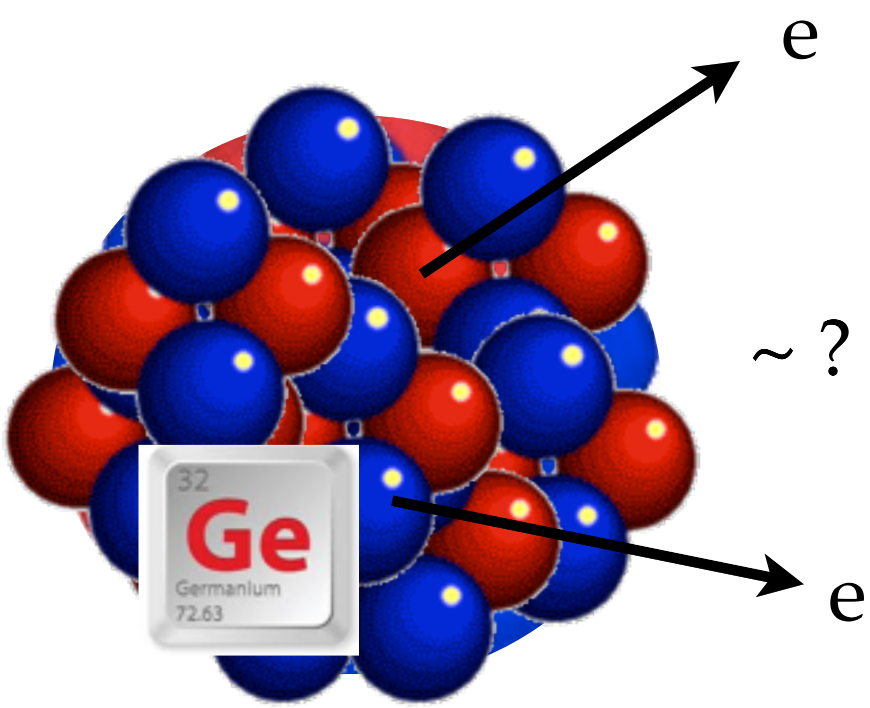
Institute for Nuclear Theory, Seattle, WA

Lattice QCD Input for Neutrinoless Double-Beta Decay

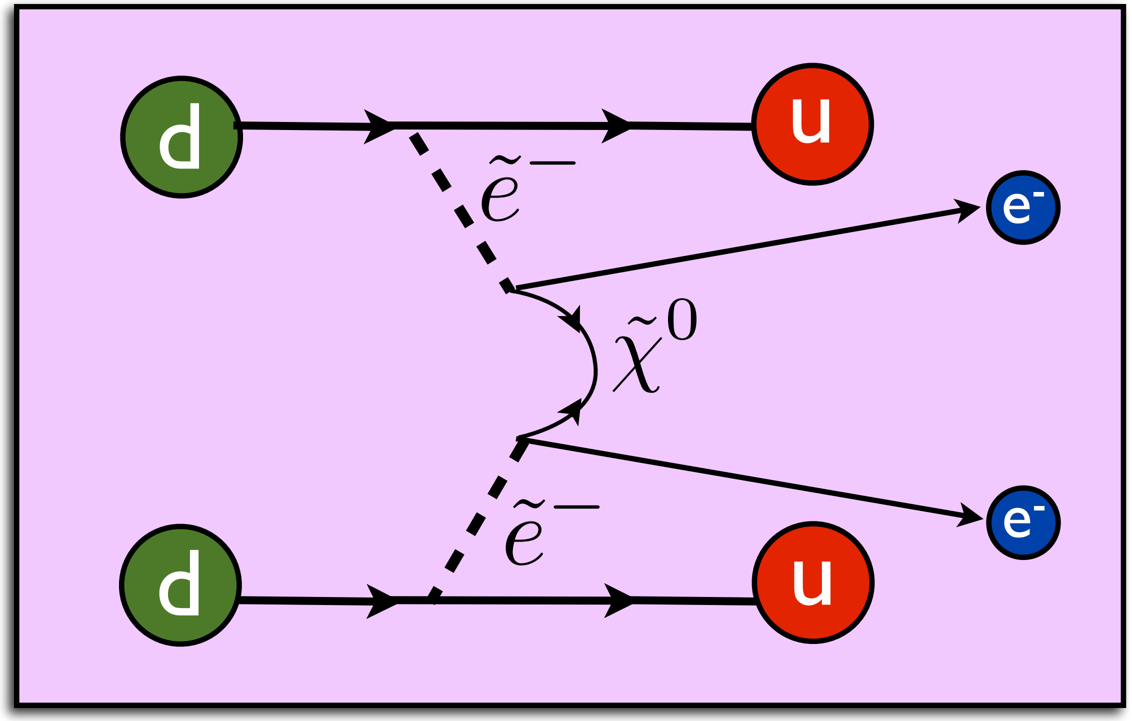
July 6, 2017

Relating Theory to Experiment

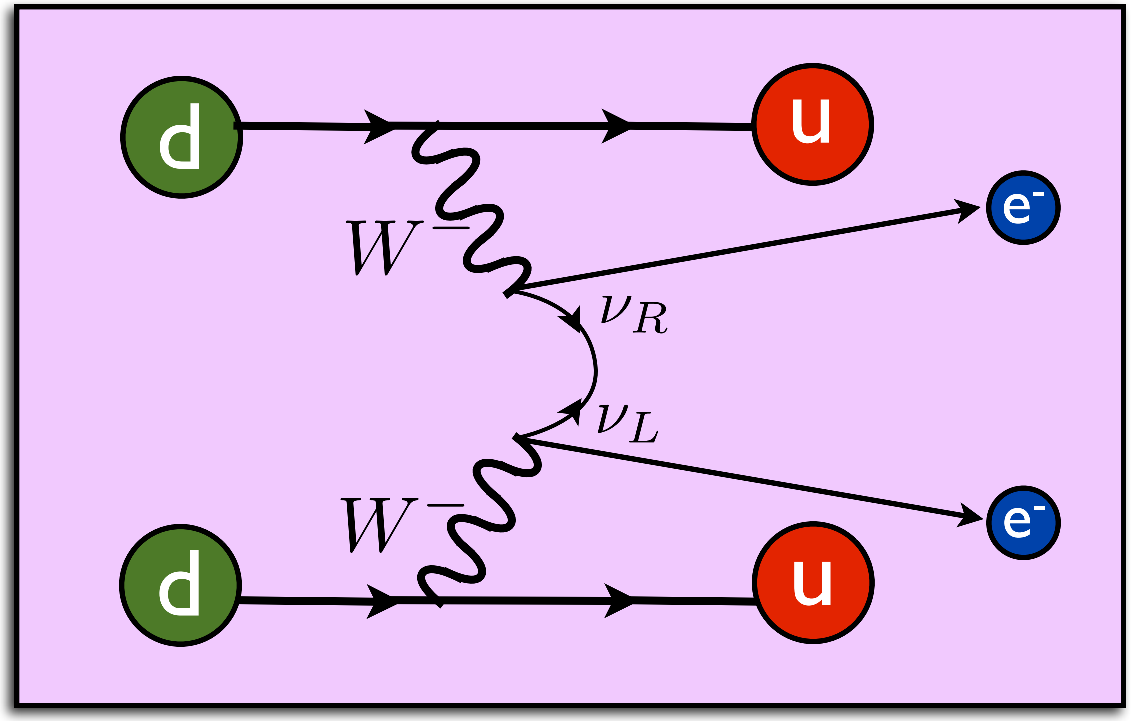


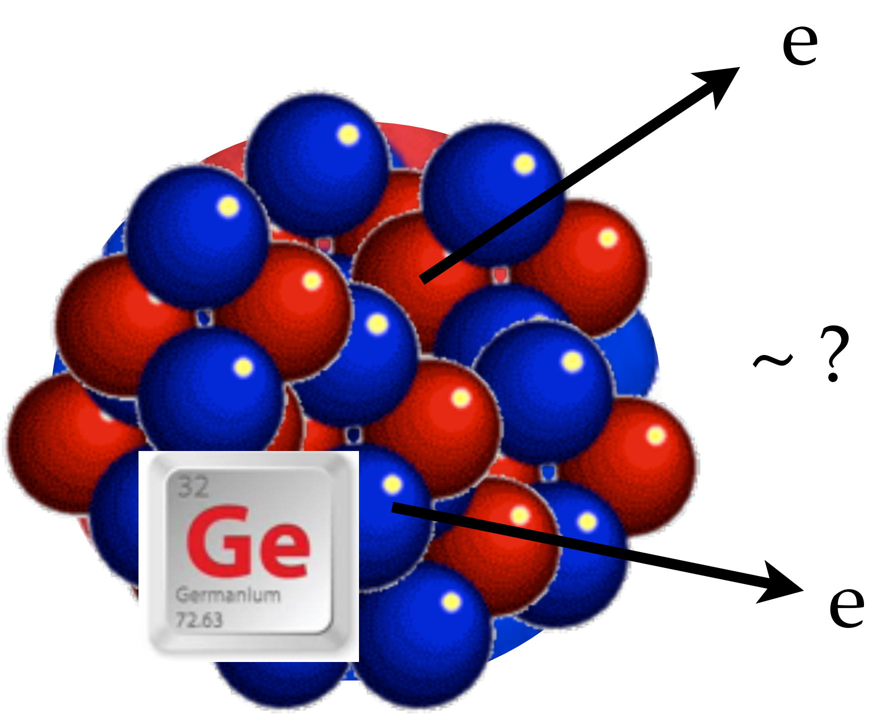


Relating Theory to Experiment



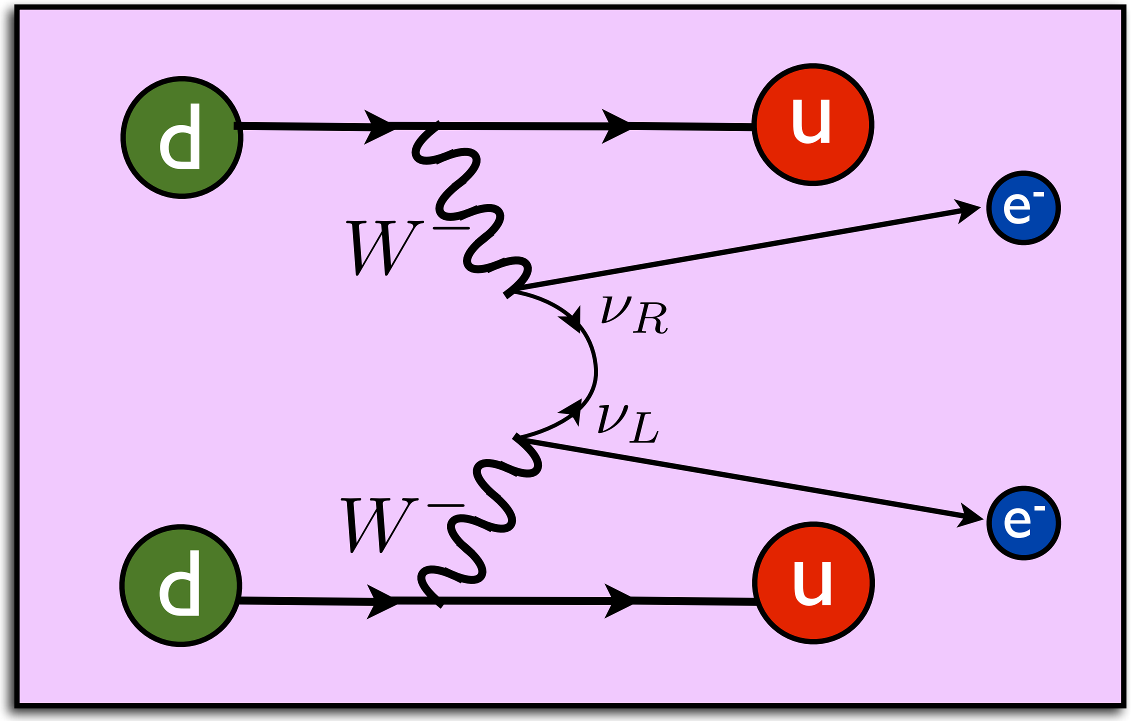
$0\nu\beta\beta$ experiments could help constrain R-parity violating coefficients

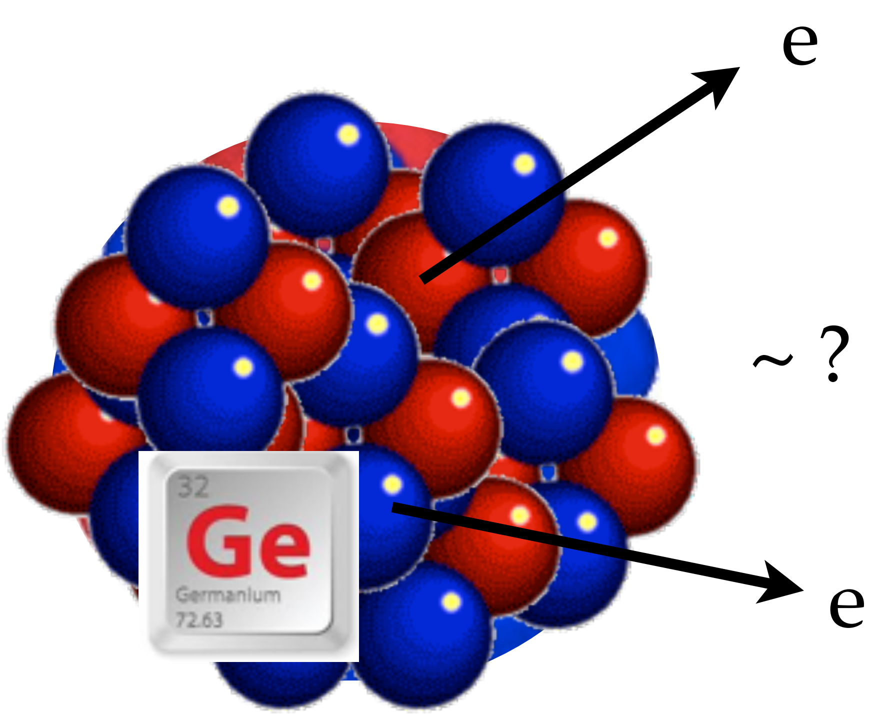




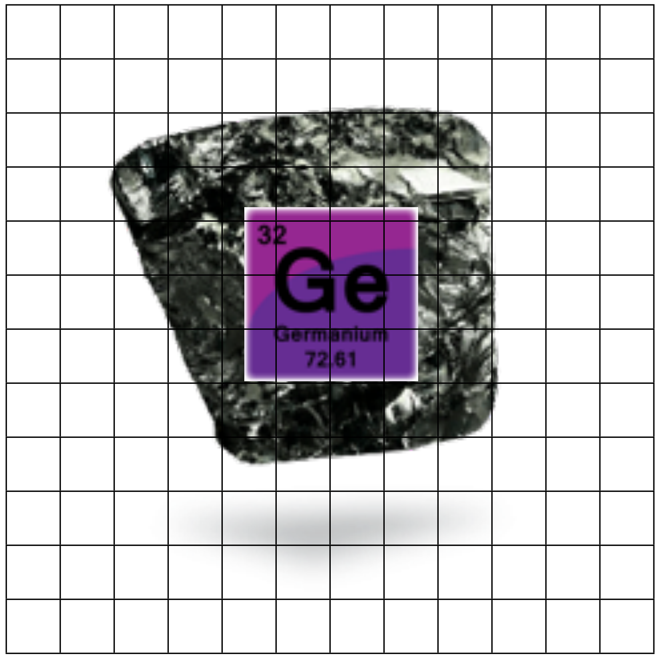
Relating Theory to Experiment

- 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 can't directly calculate your favorite $0\nu\beta\beta$ isotope!



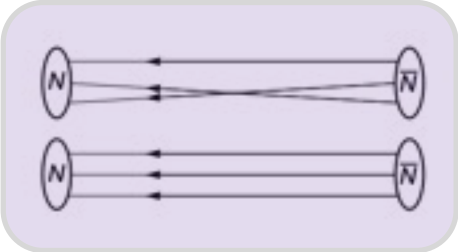


Why?

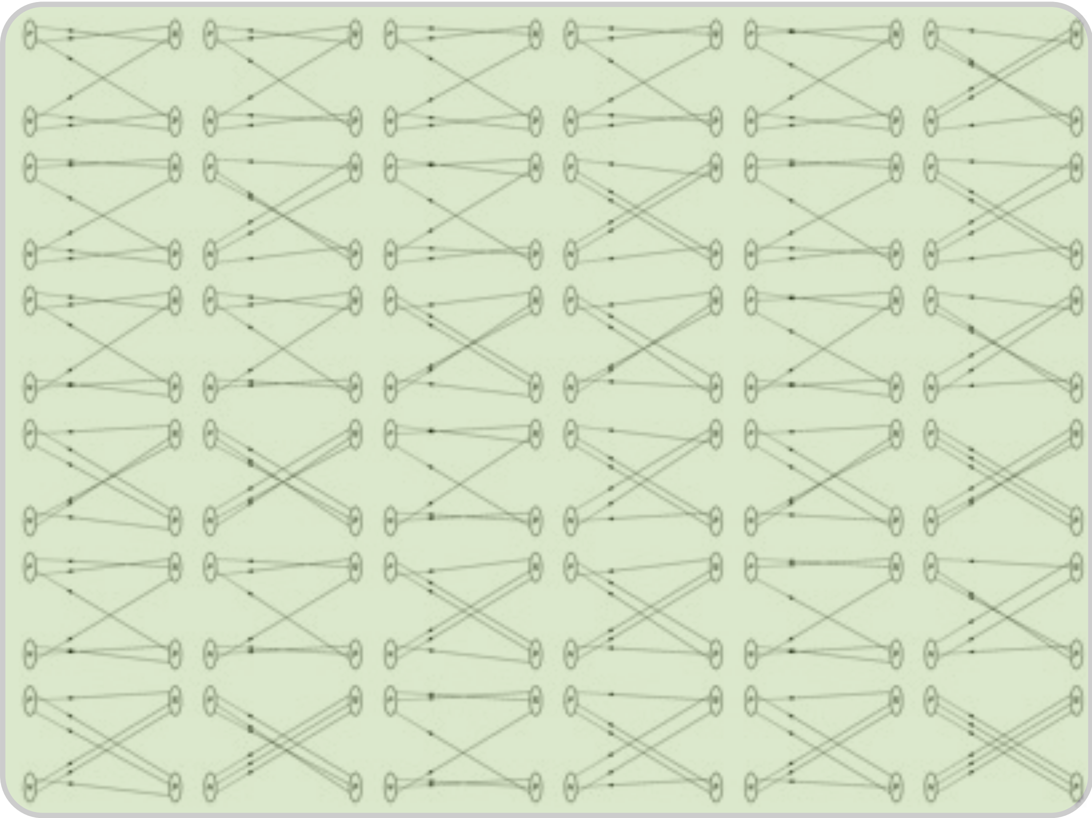


- Need enormous lattices
  - Tiny energy splittings
  - Large range of scales

Nucleon:



Deuteron:

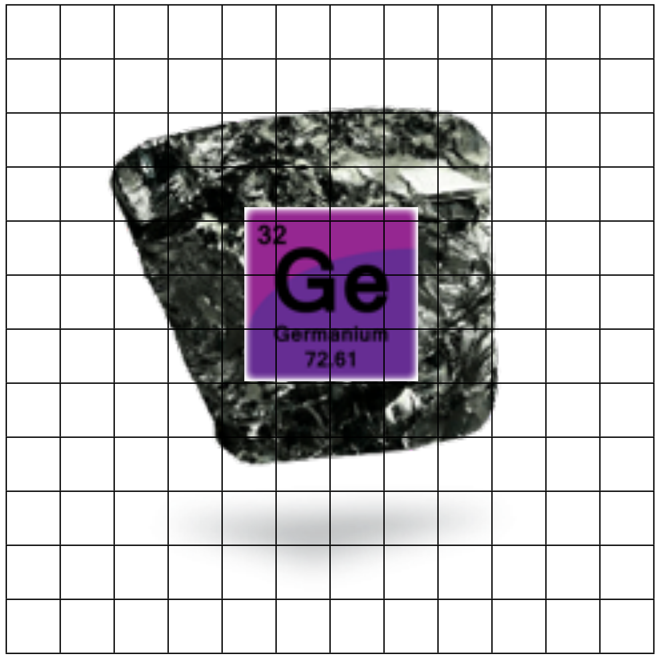


- Wick contractions: (A+Z)!x(2A-Z)! $He^4 : 518400$

- **Nucleon noise/sign problem**
  signal/noise ~

$$e^{-A(m_N - 3/2 m_\pi)t}$$

Why?



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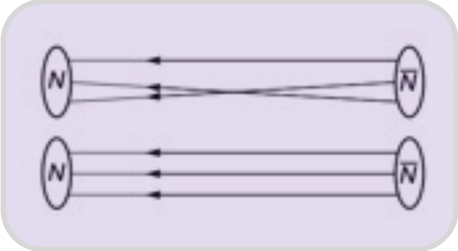
Nucleon:



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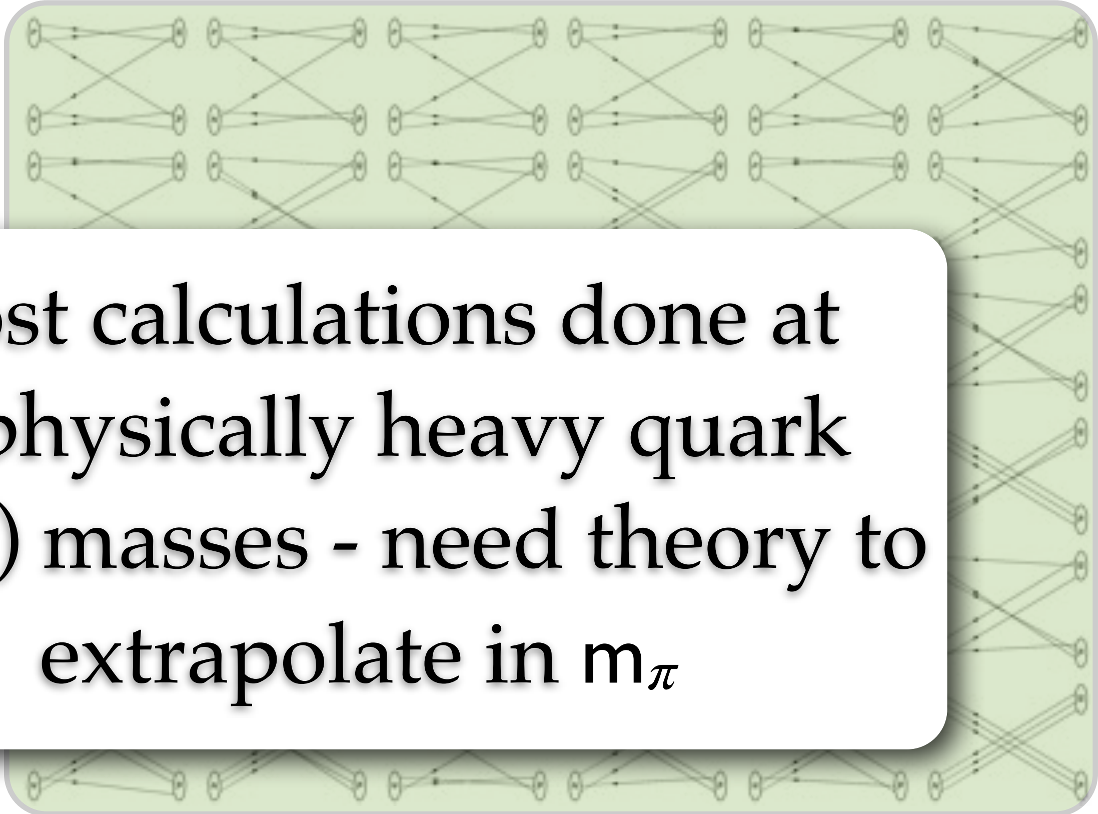
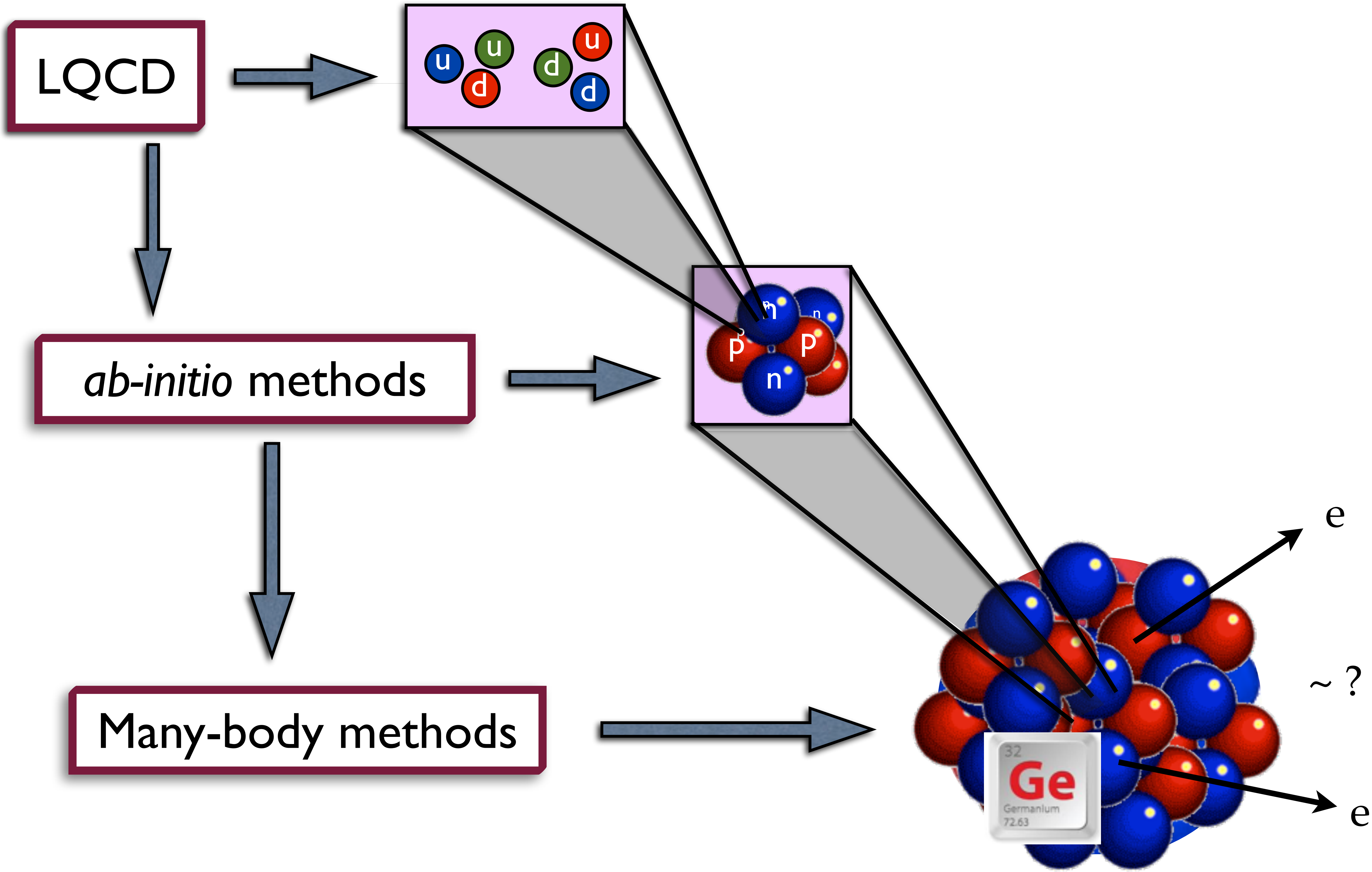


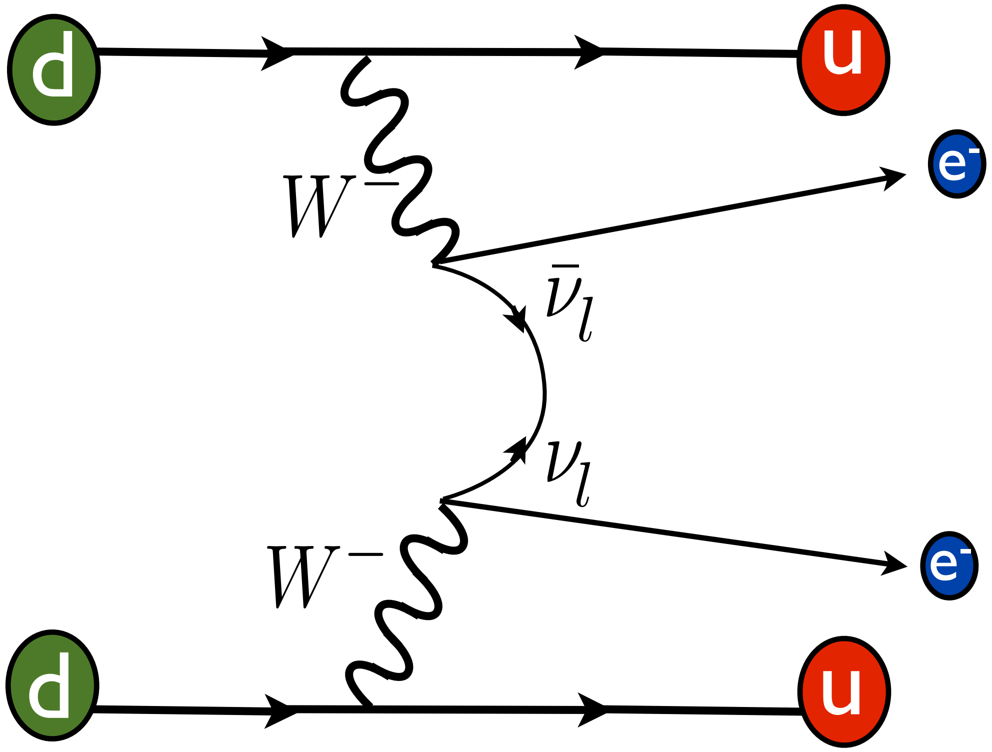
Most calculations done at unphysically heavy quark (pion) masses - need theory to extrapolate in m_π

Relating Theory to Experiment

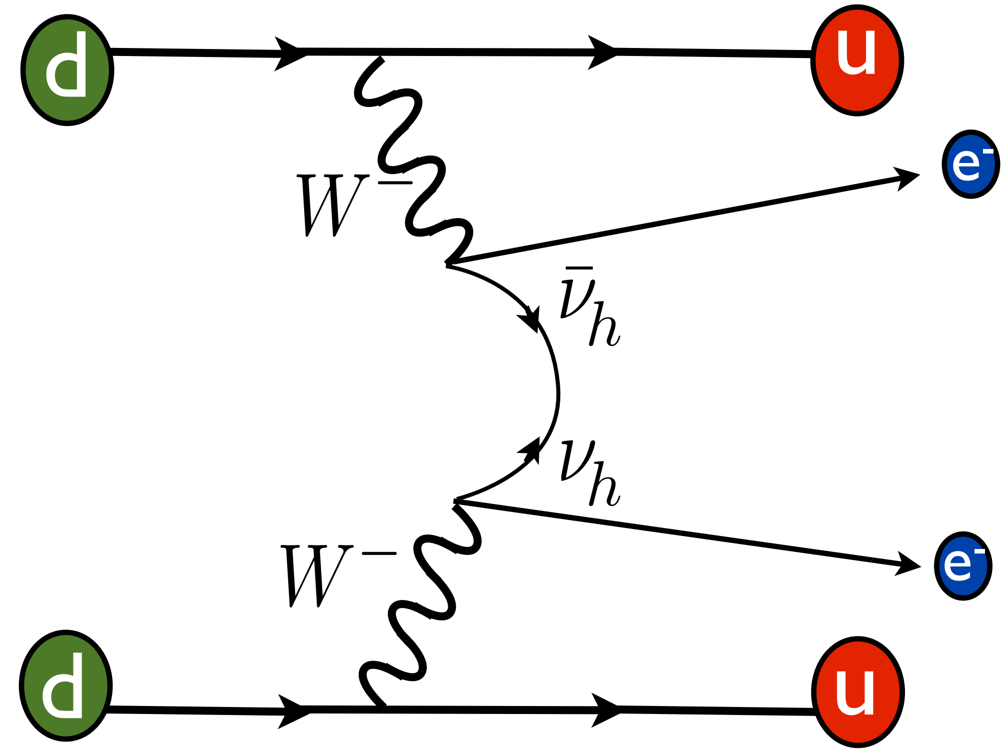


Lattice QCD contributions to $0\nu\beta\beta$

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



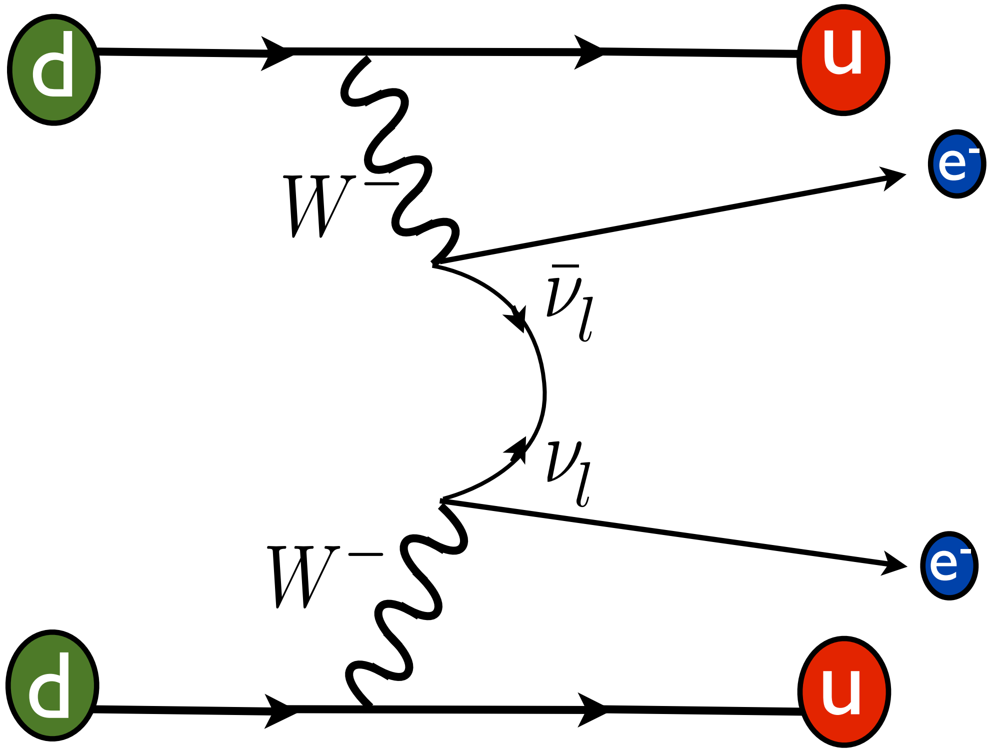
Long-range



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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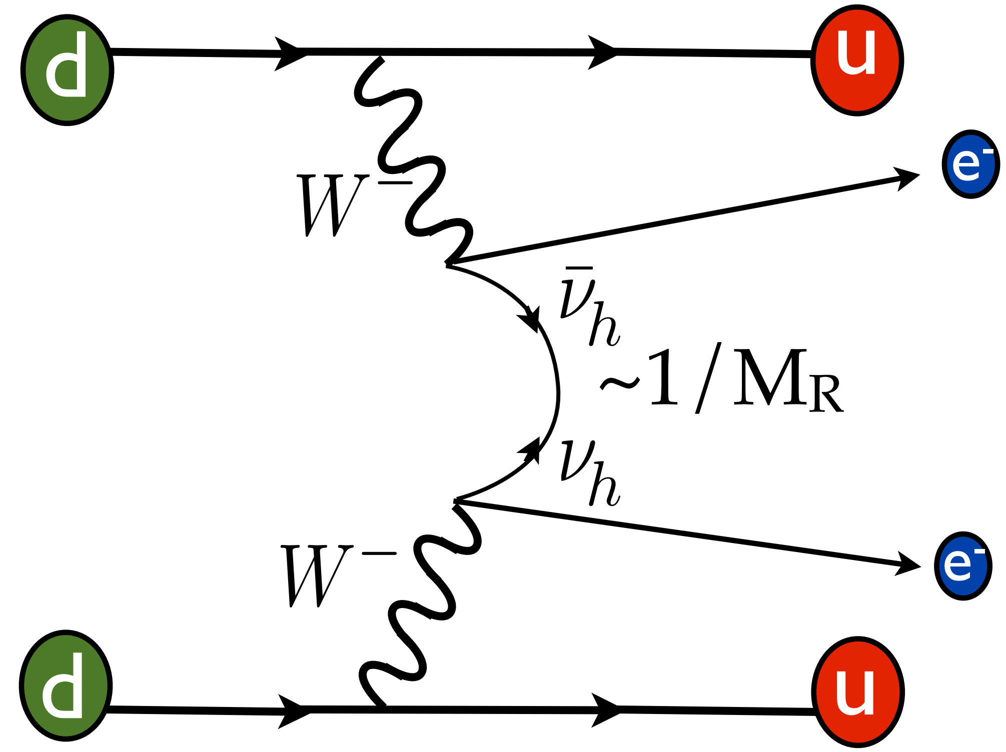

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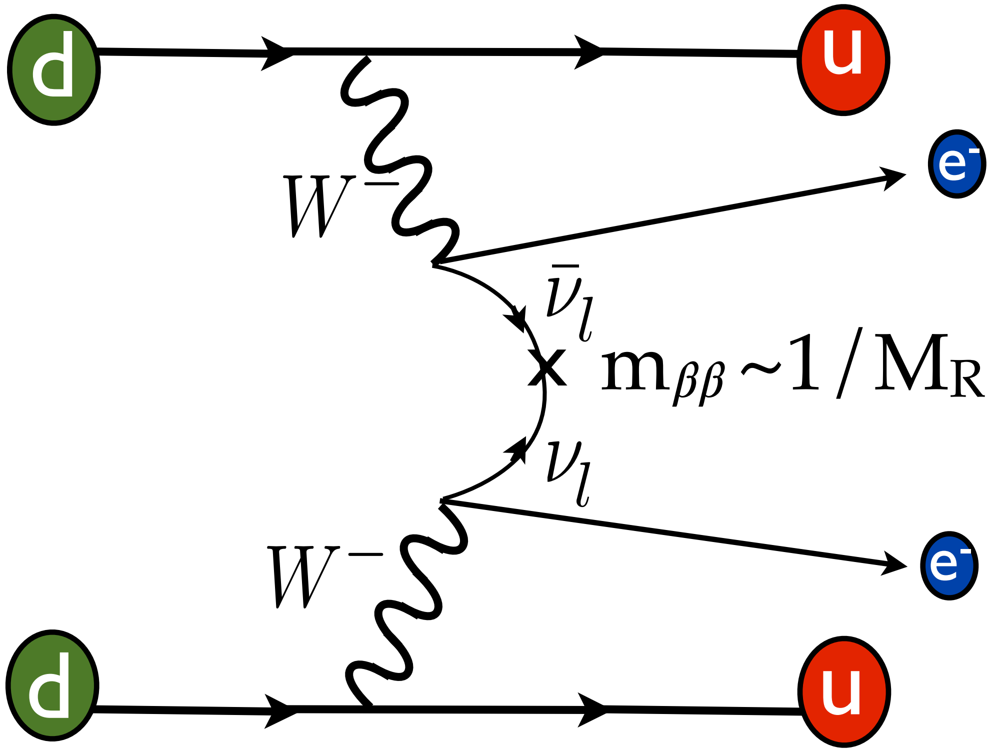

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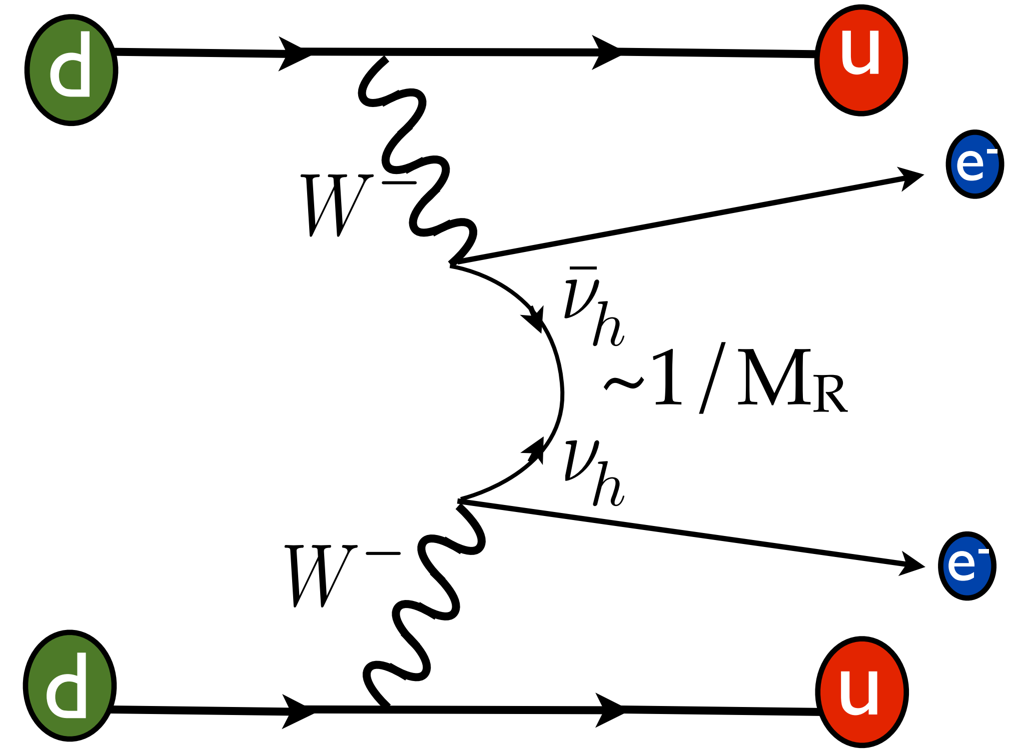

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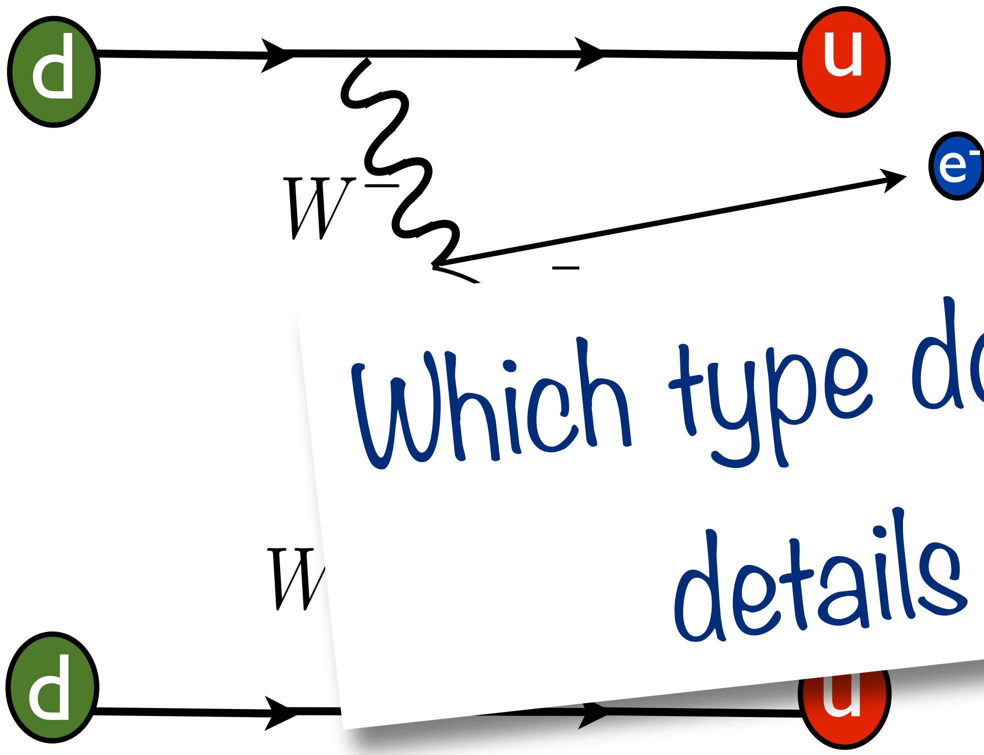

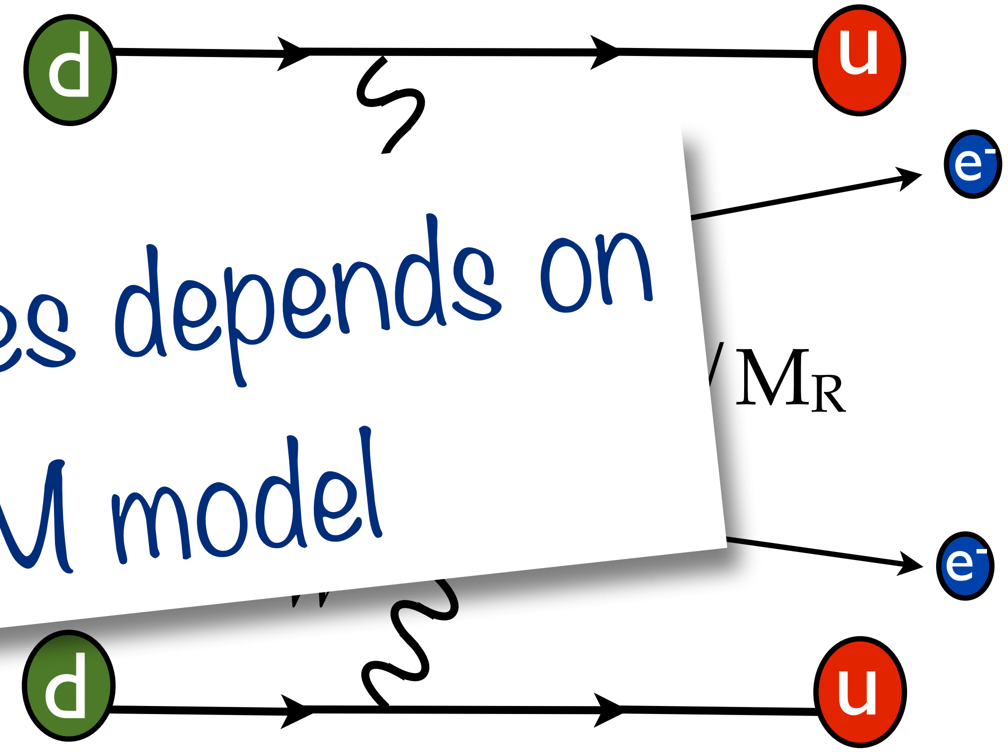

Which type dominates depends on details of BSM model

Long-range

Short-range

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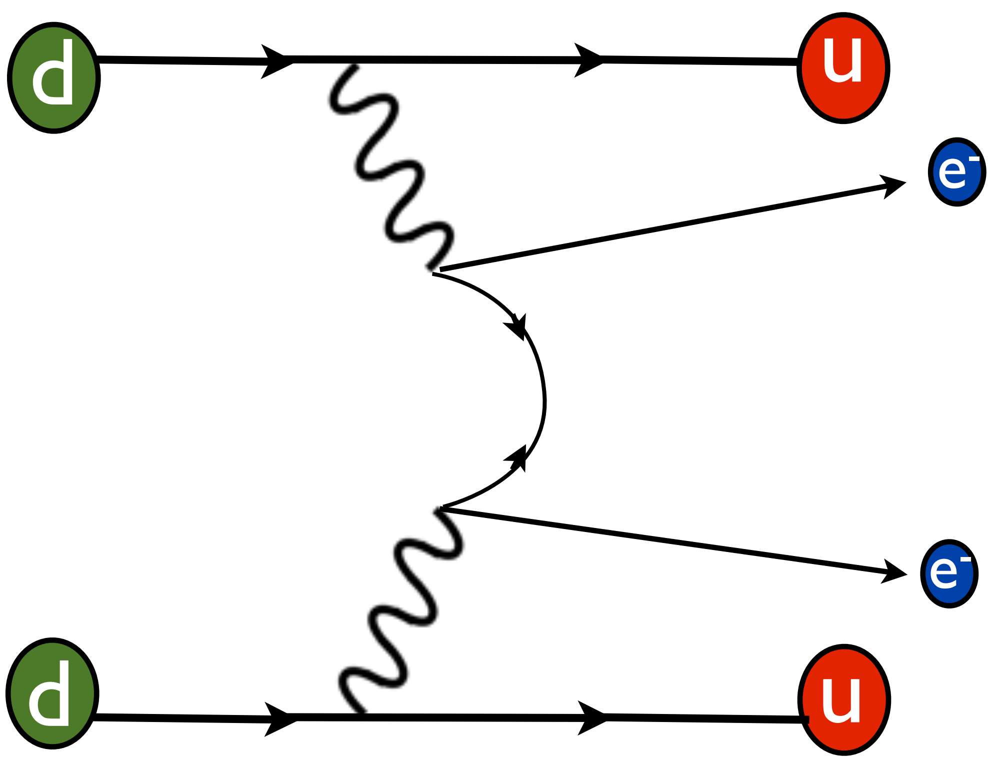
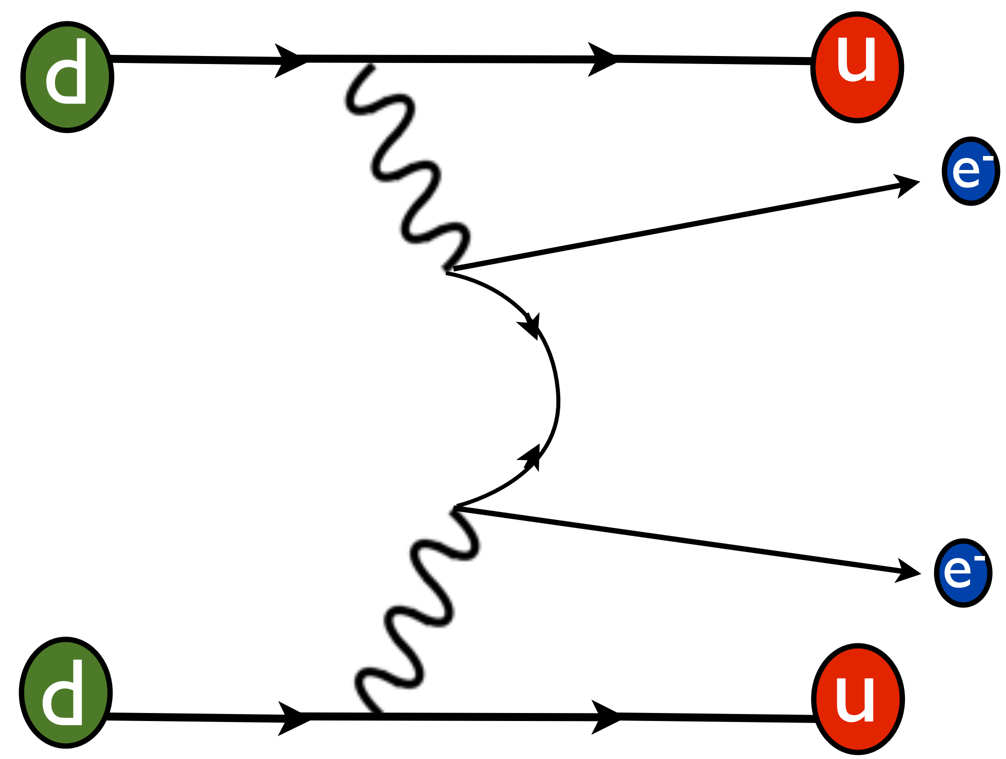


Long-range



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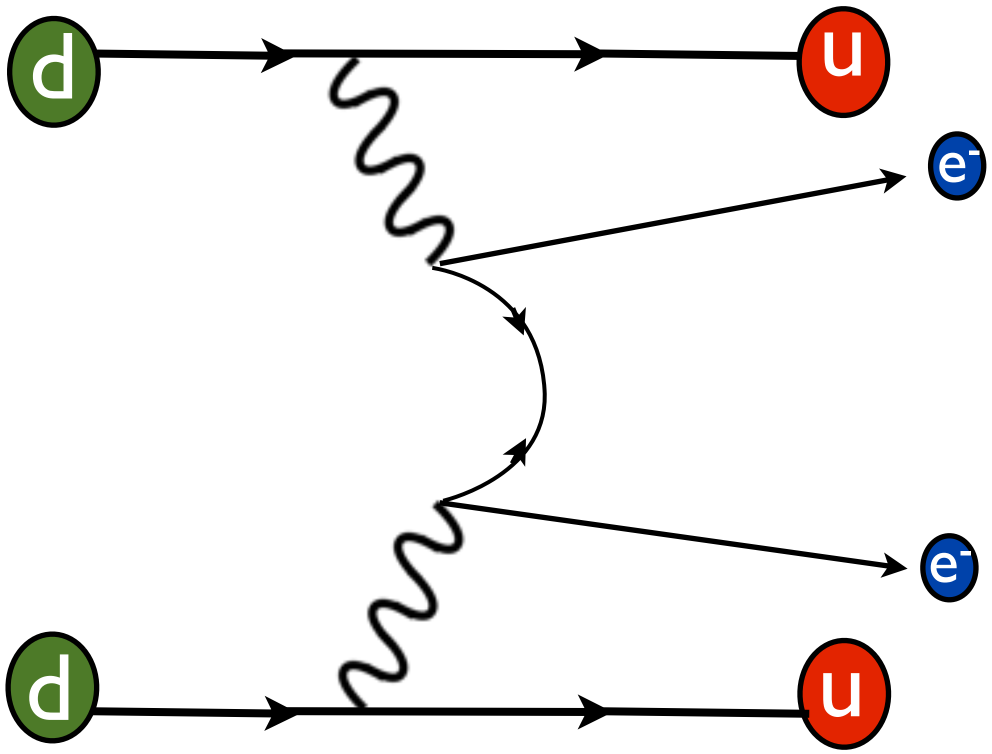
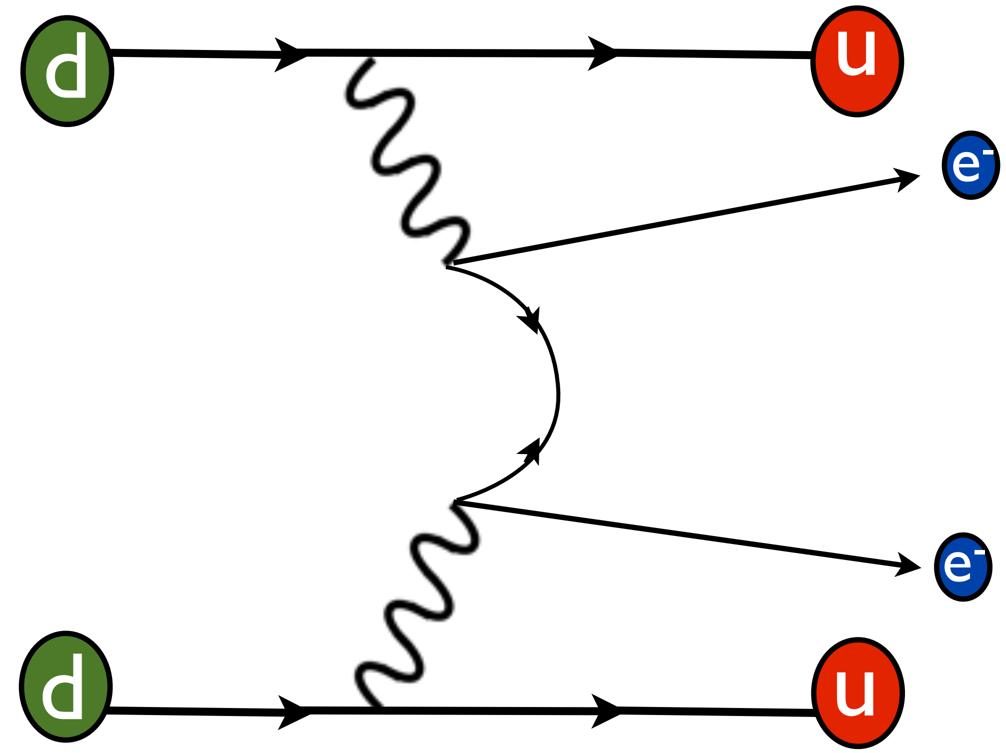


Long-range

$\Lambda \ll M_W$



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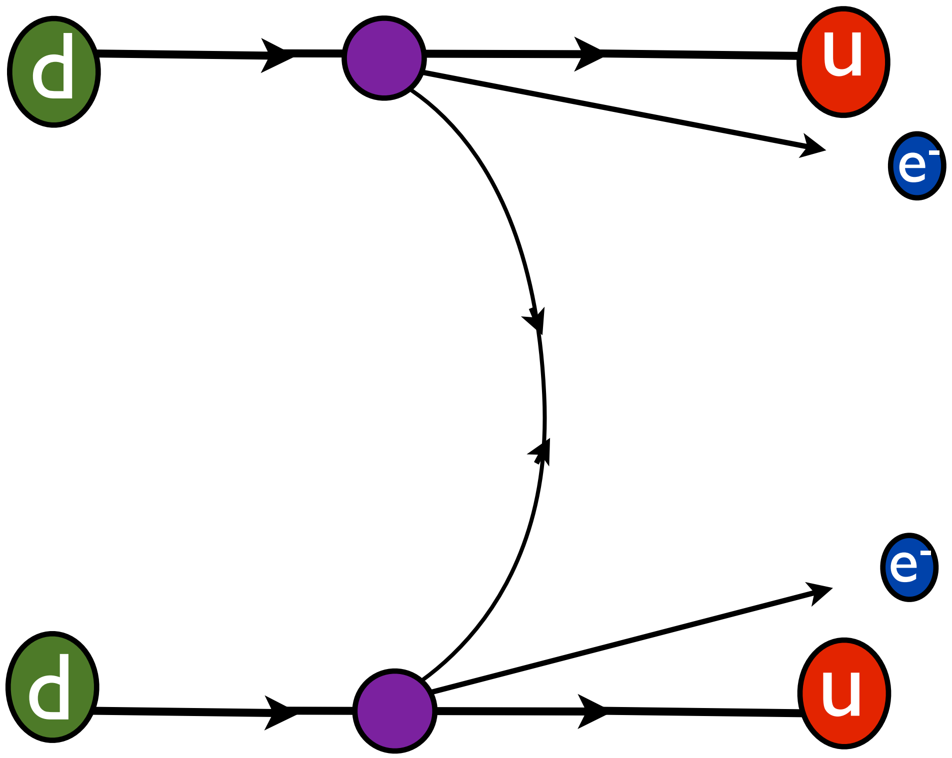

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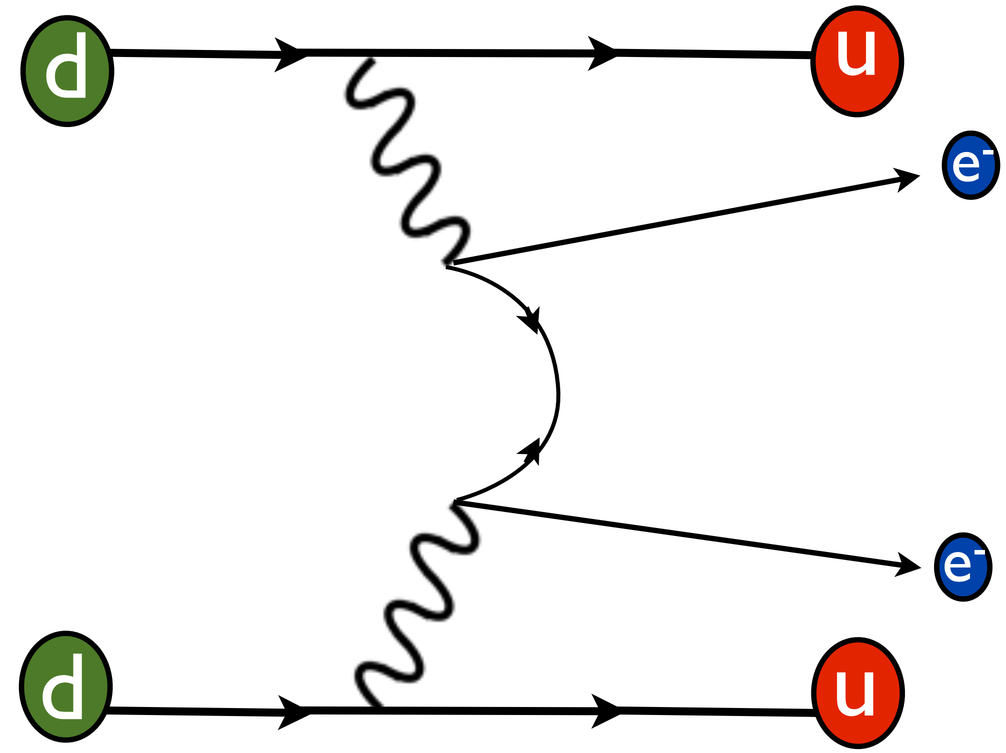

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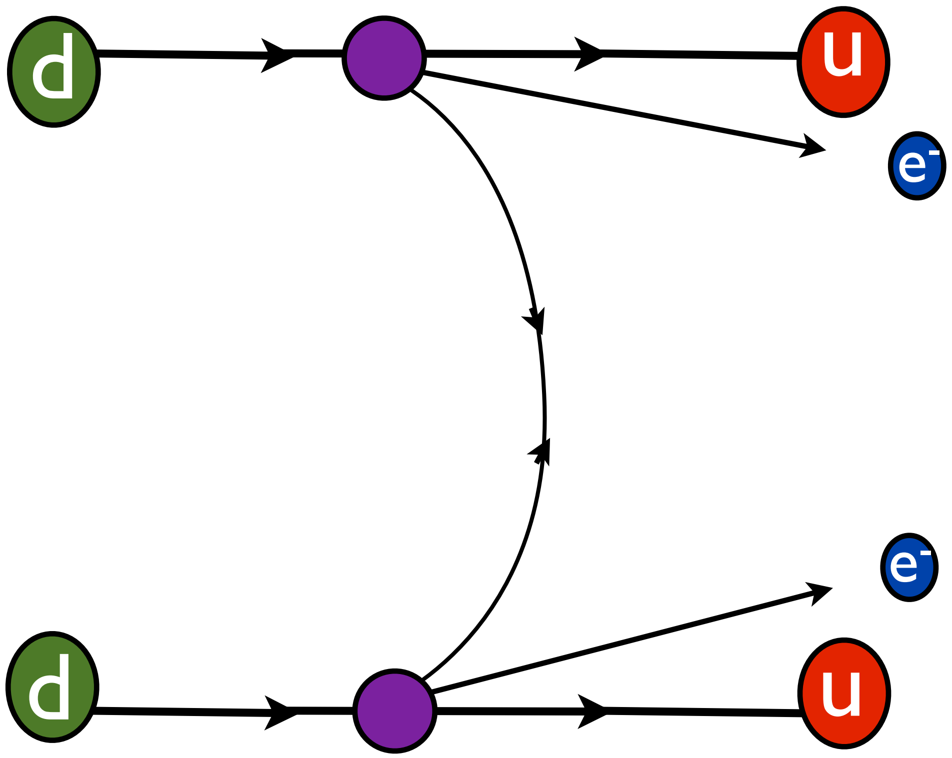
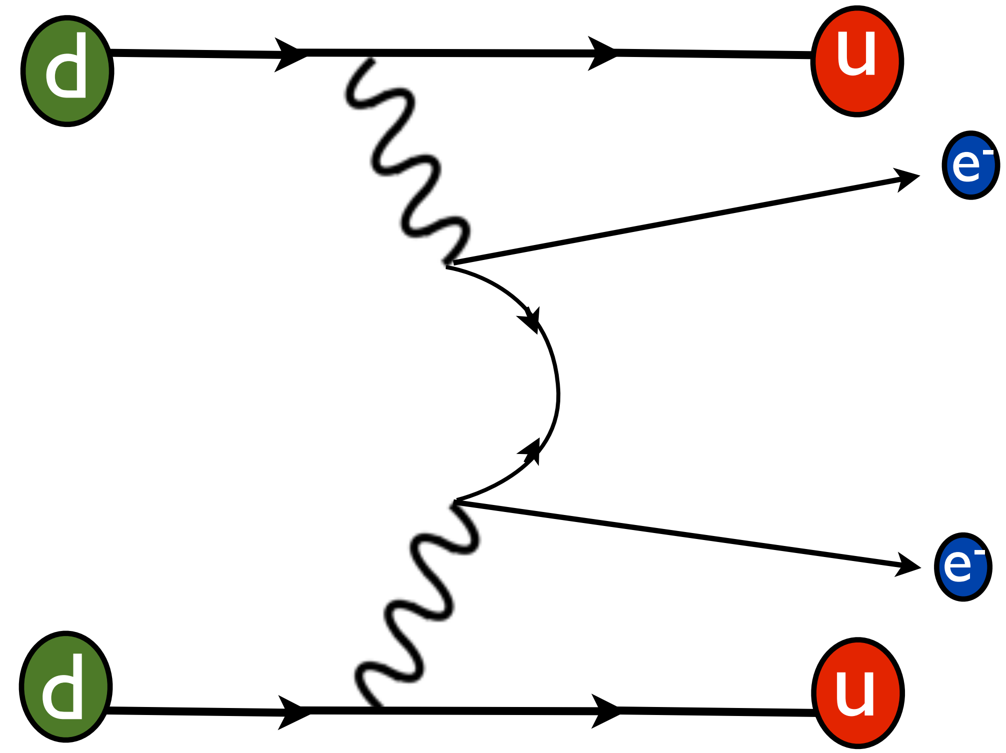


Long-range

$\Lambda \ll \Lambda_{QCD}$



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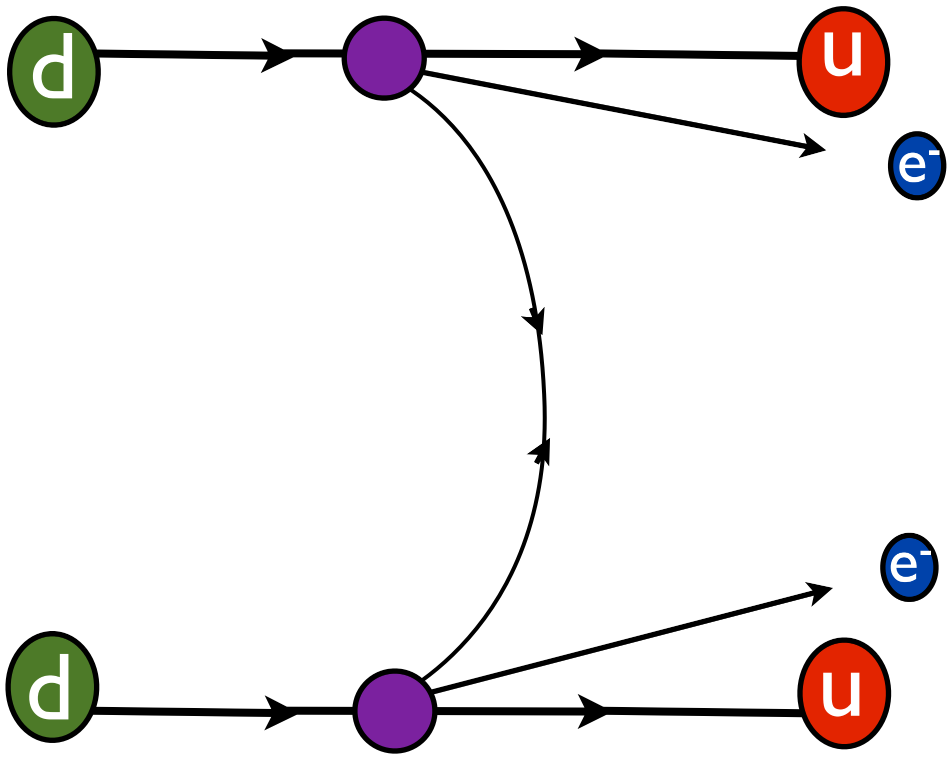

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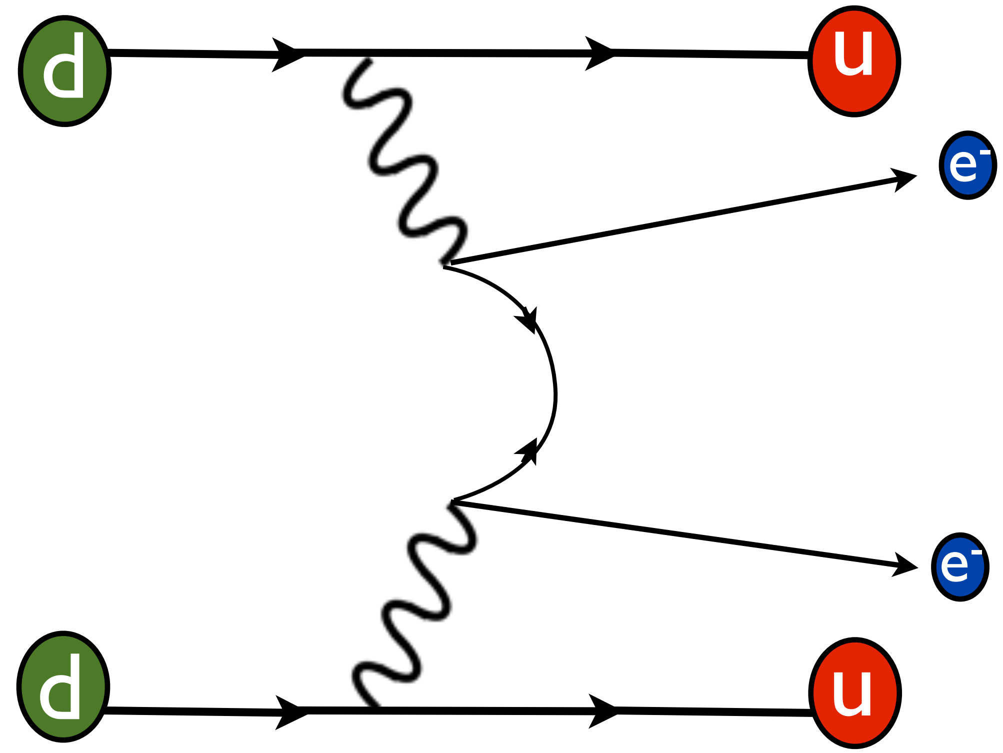

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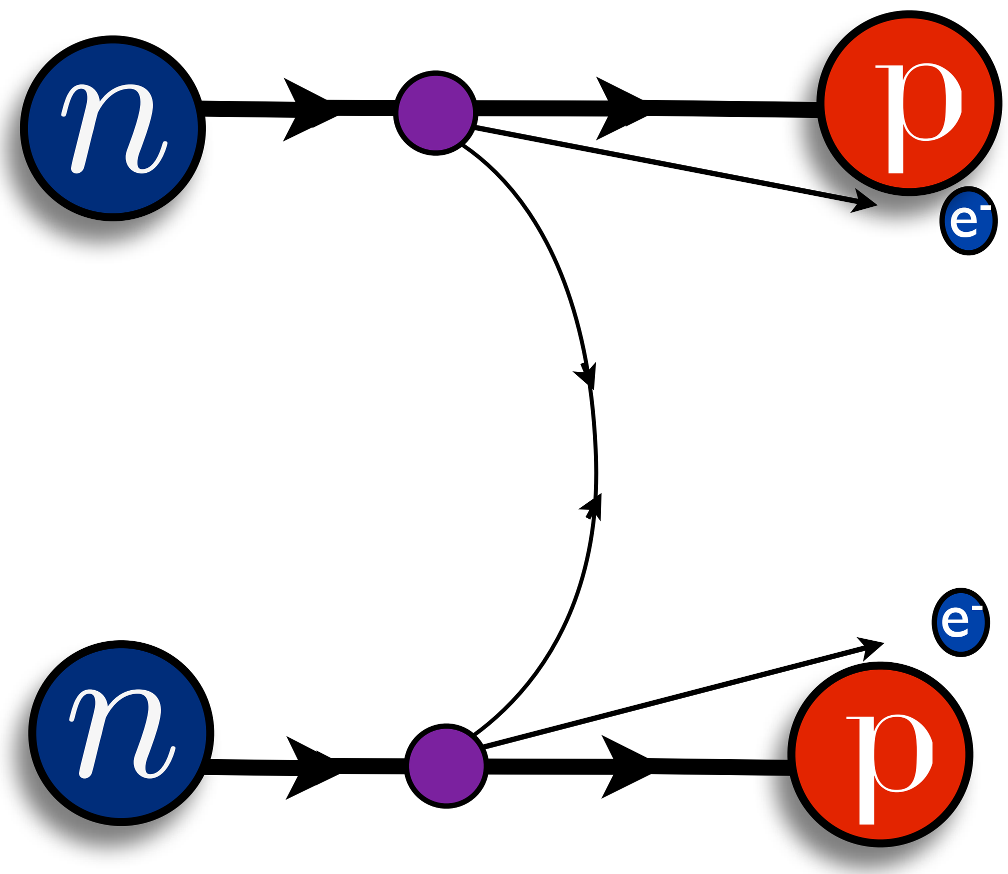

Long-range

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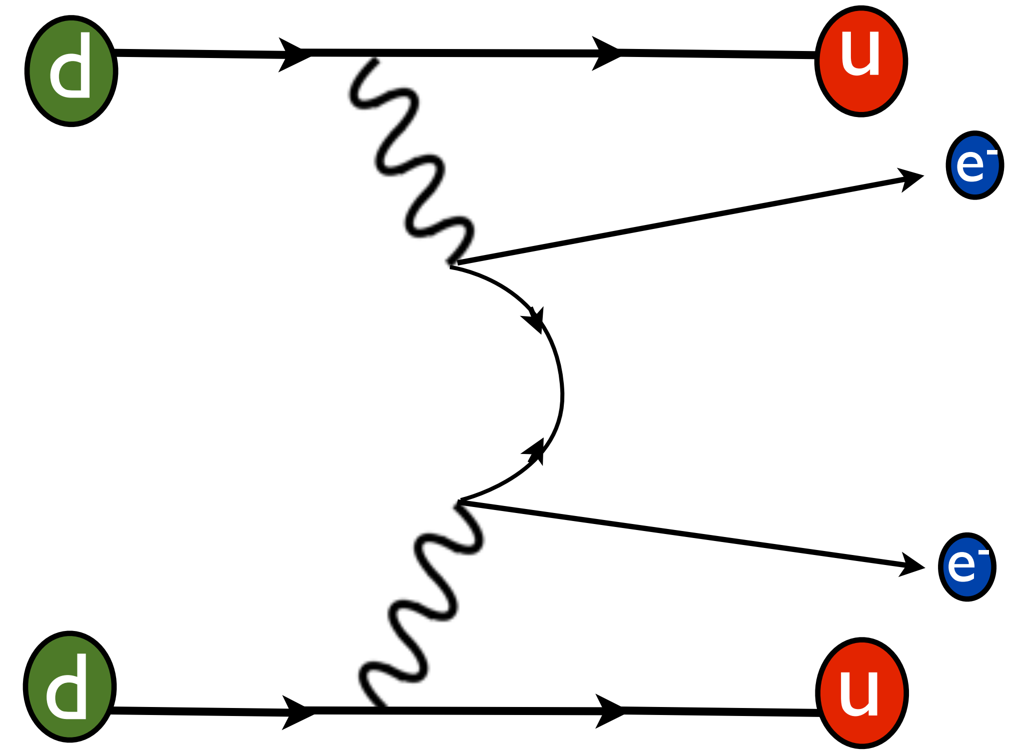

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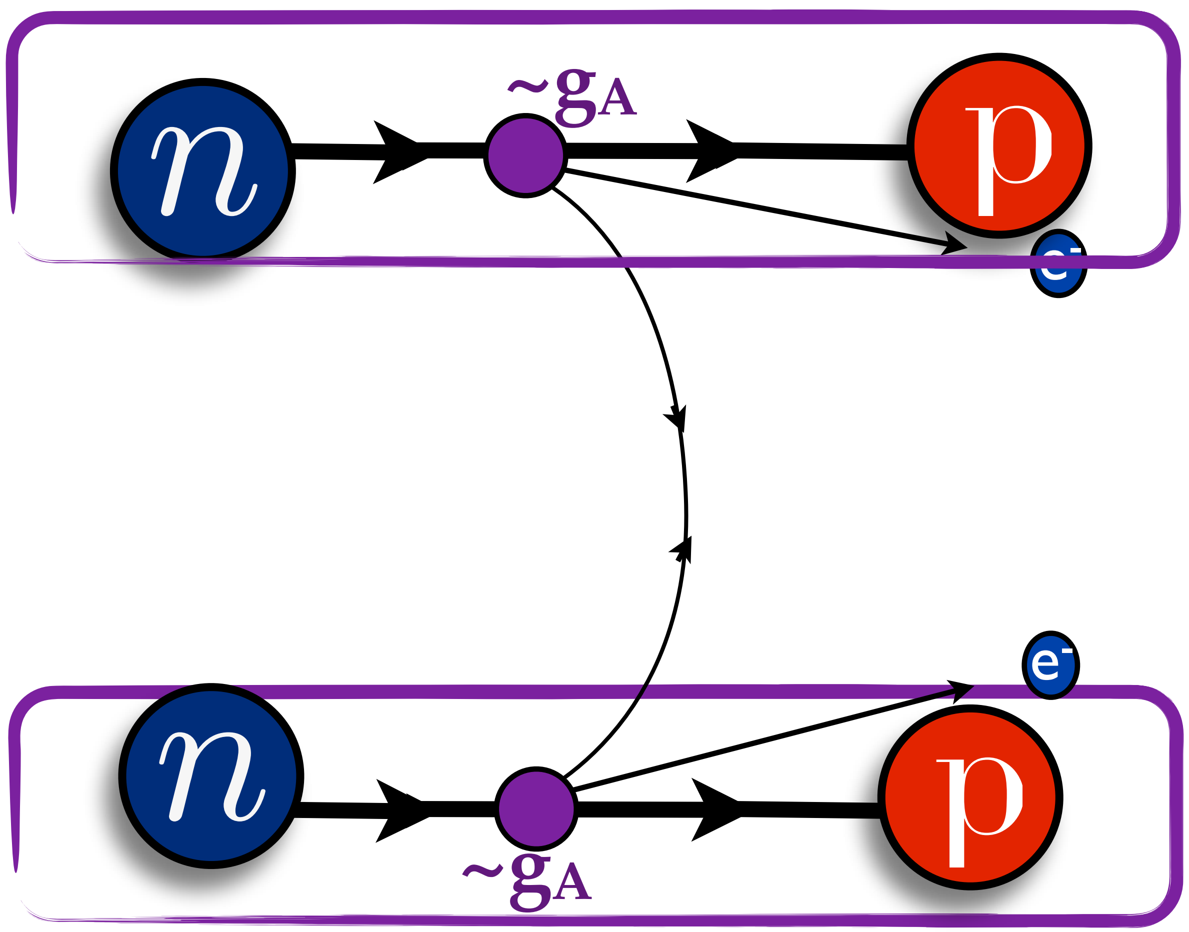

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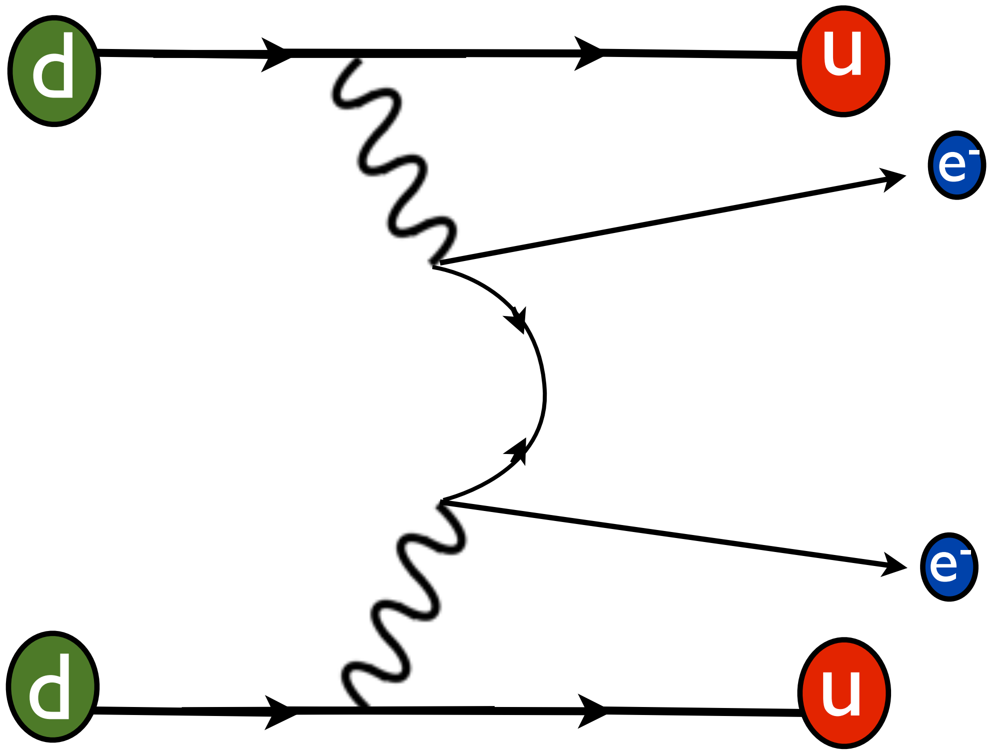

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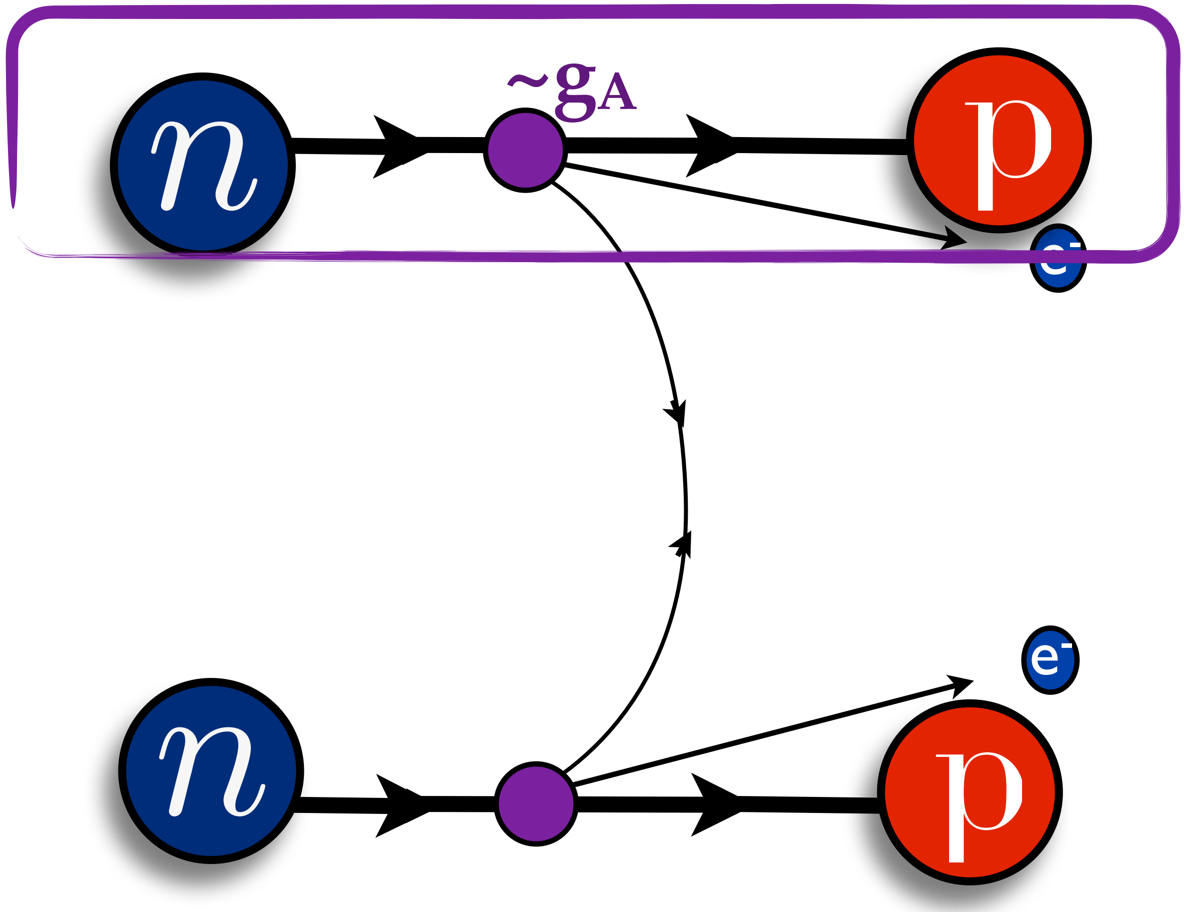

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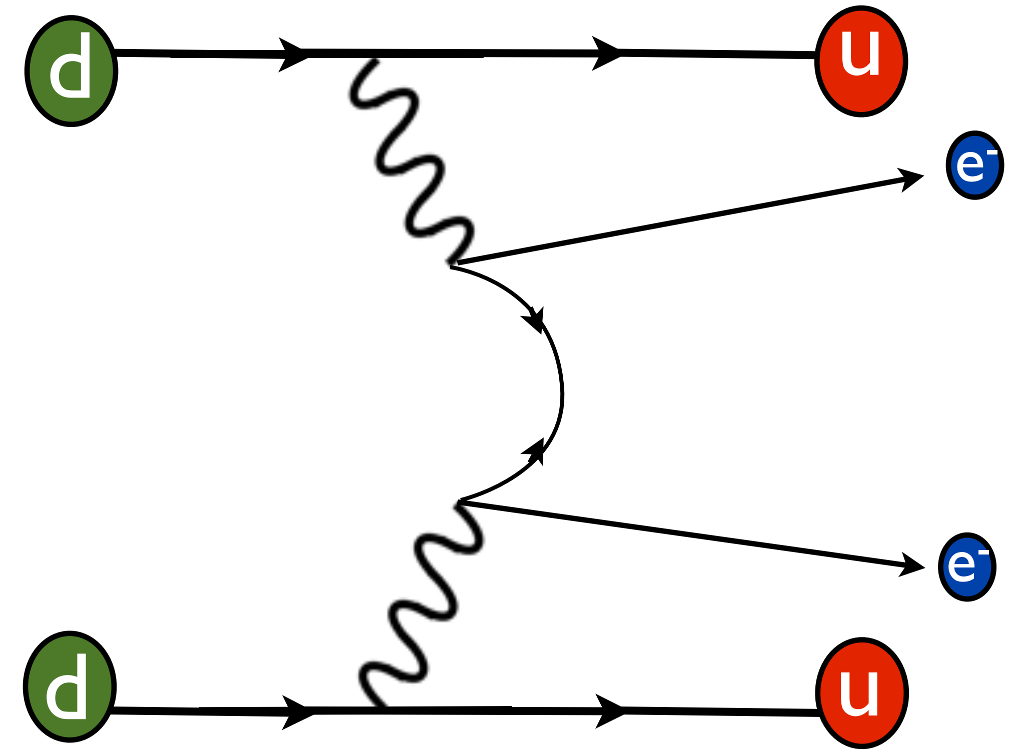
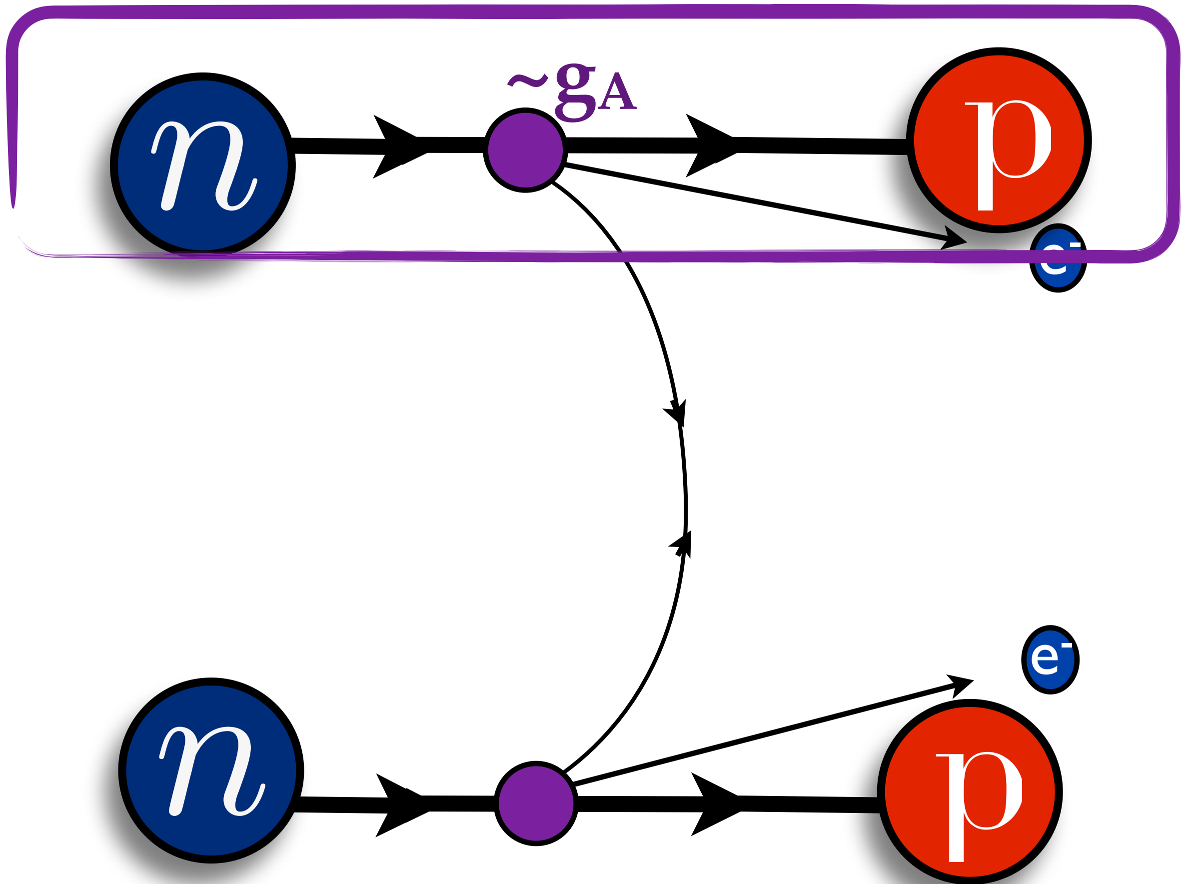


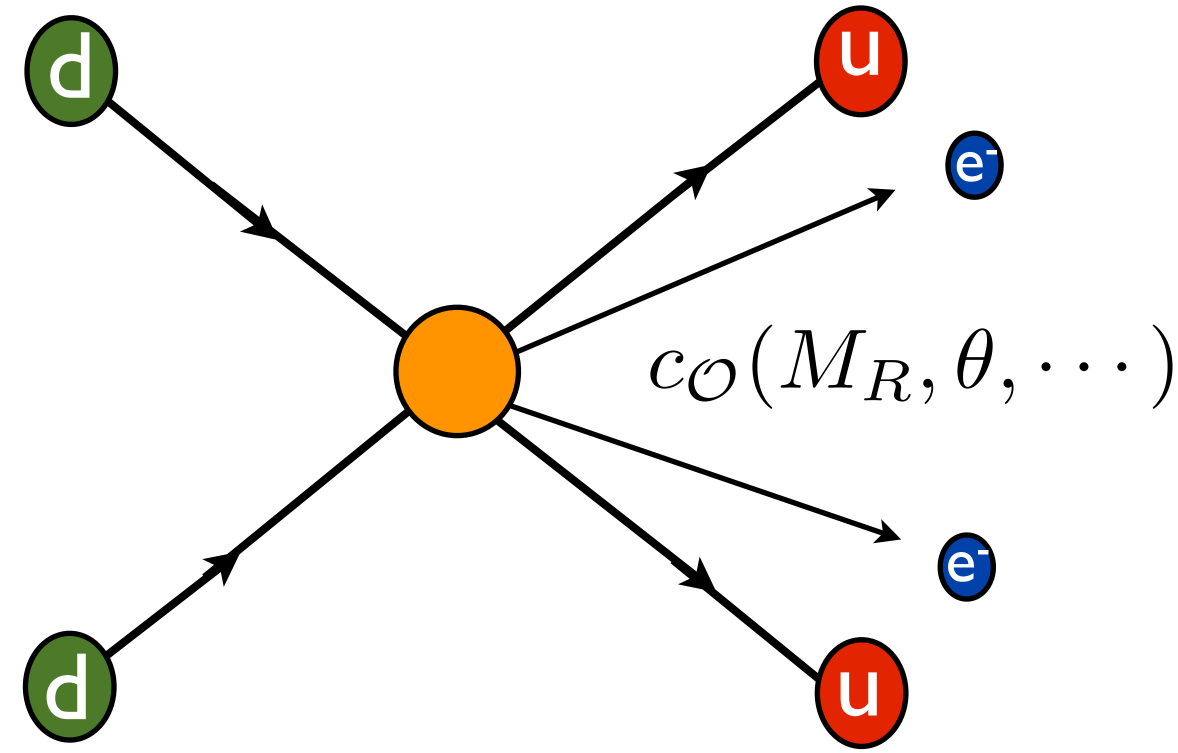
Short-range

$\Lambda \ll M_W$

Prezeau, Ramsey-Musolf, Vogel (2003)

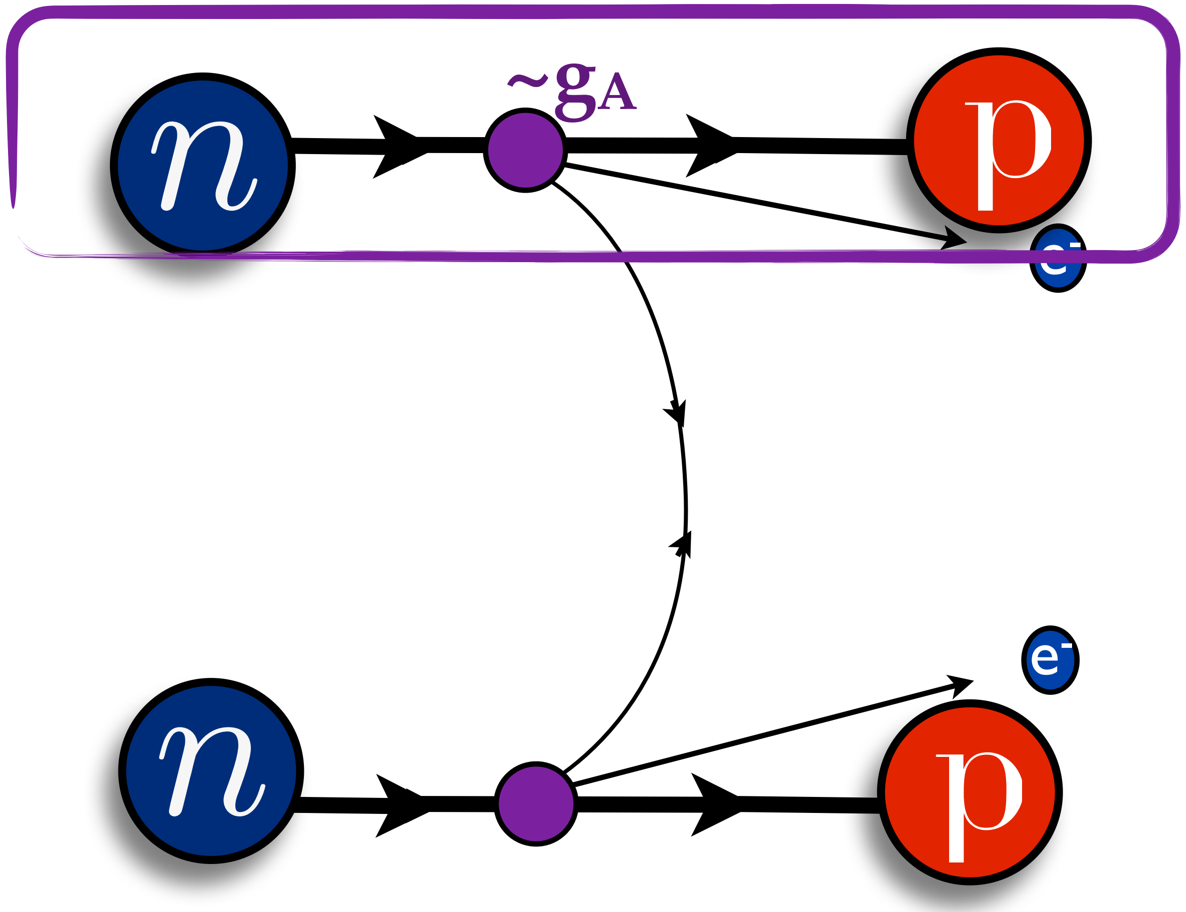


Long-range



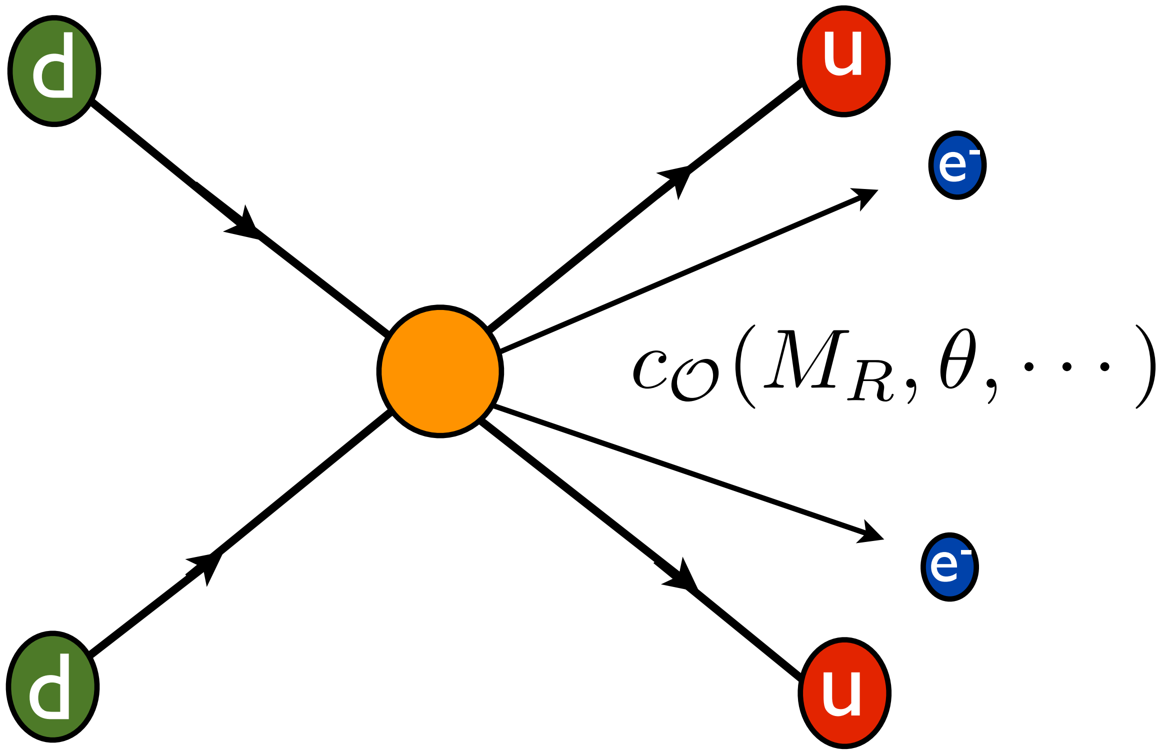
Short-range

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



Long-range

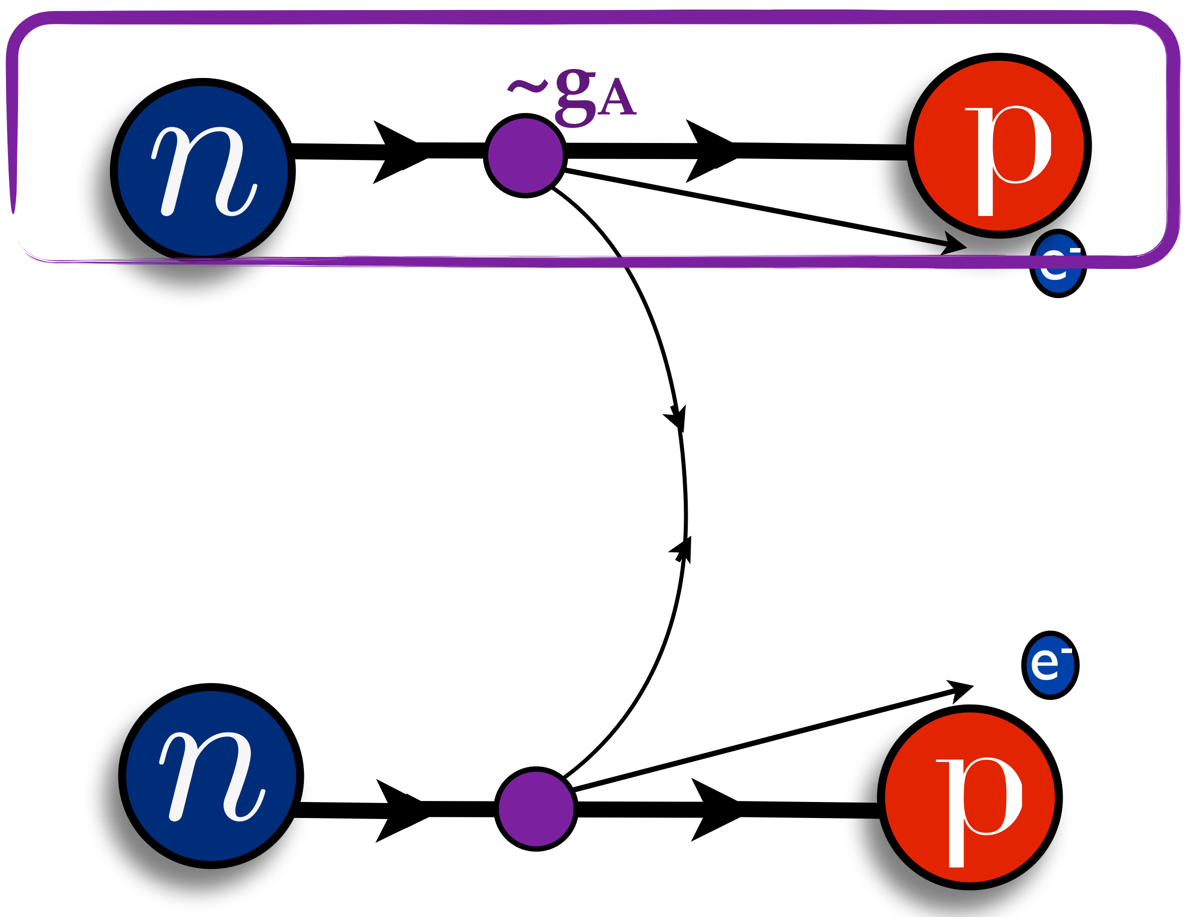
Prezeau, Ramsey-Musolf, Vogel (2003)



Short-range

$\Lambda \ll \Lambda_{QCD}$

Prezeau, Ramsey-Musolf, Vogel (2003)



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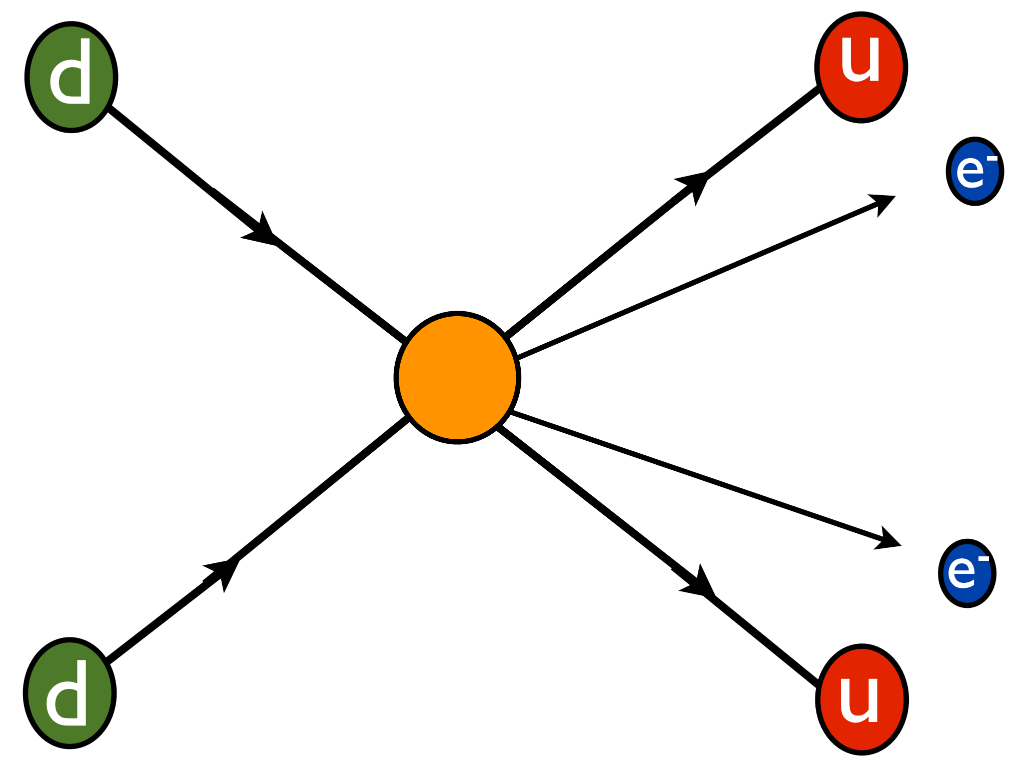
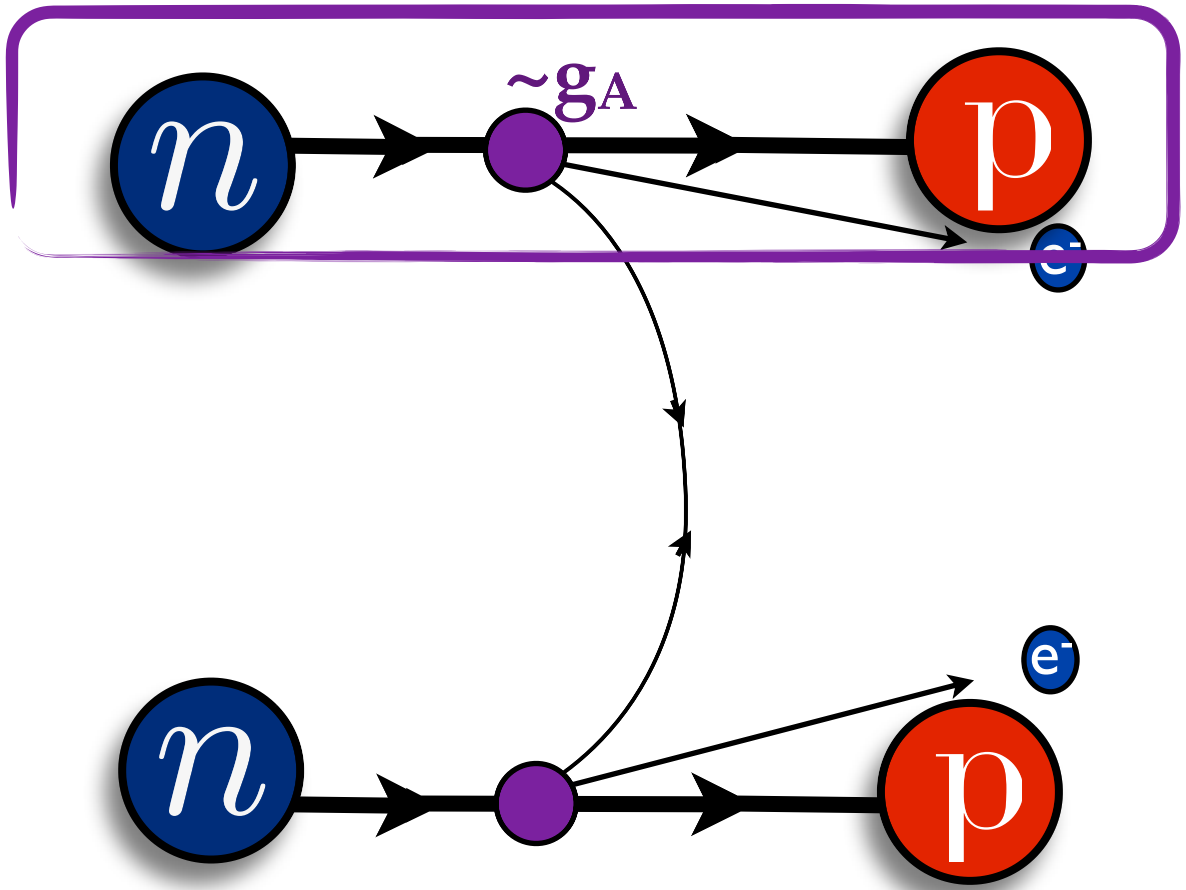


Short-range

Prezeau, Ramsey-Musolf, Vogel (2003)



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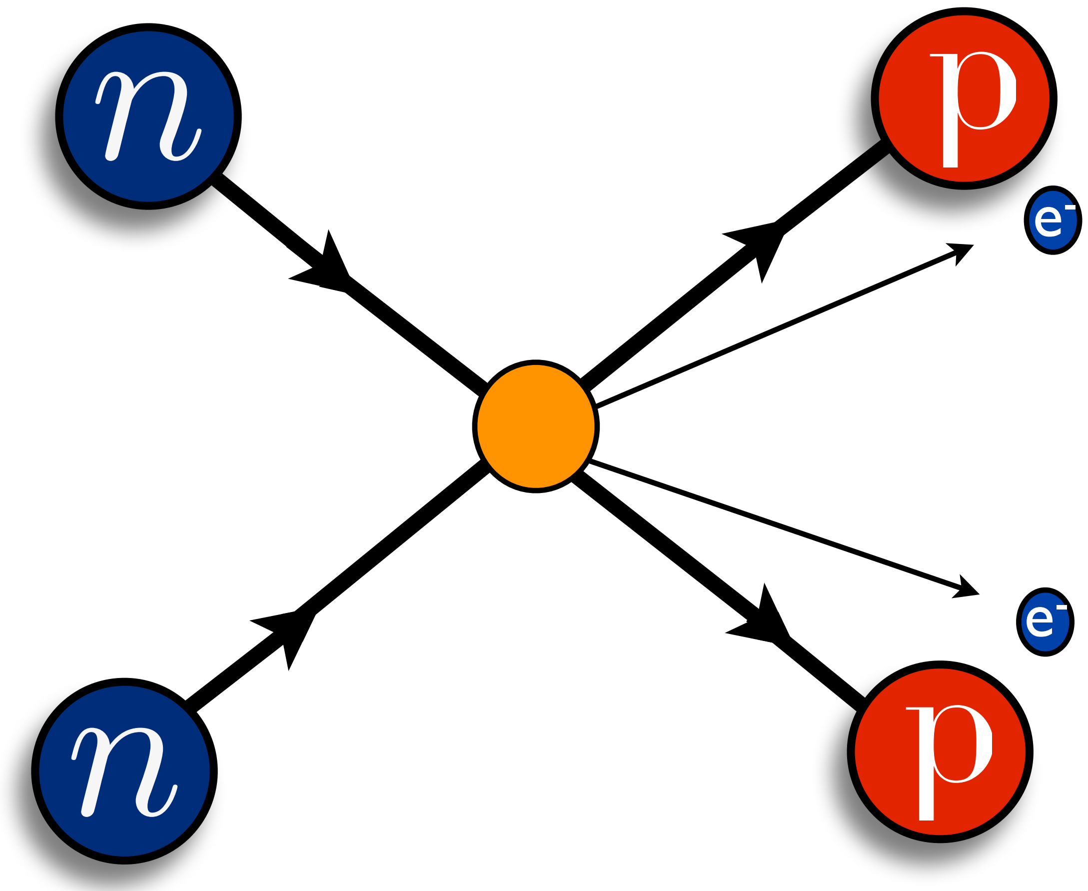
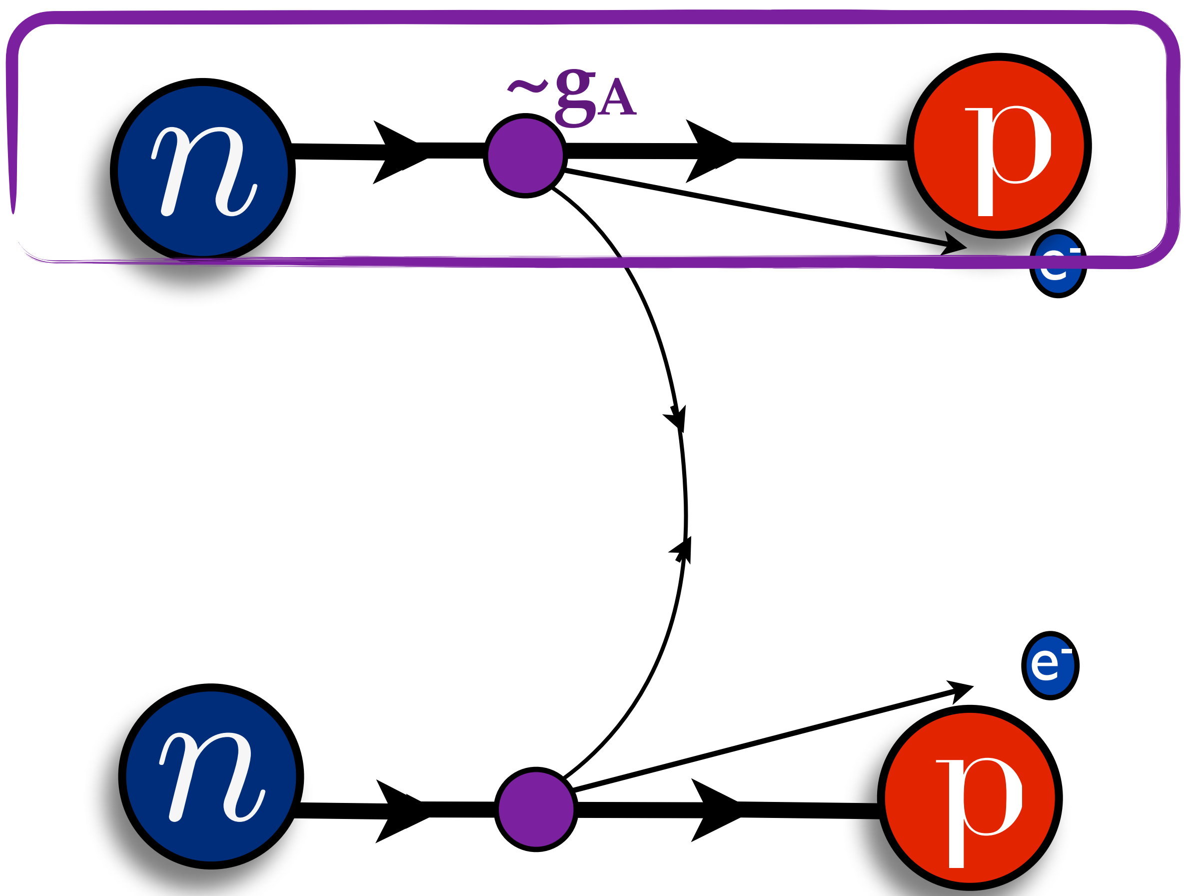


Short-range

Prezeau, Ramsey-Musolf, Vogel (2003)



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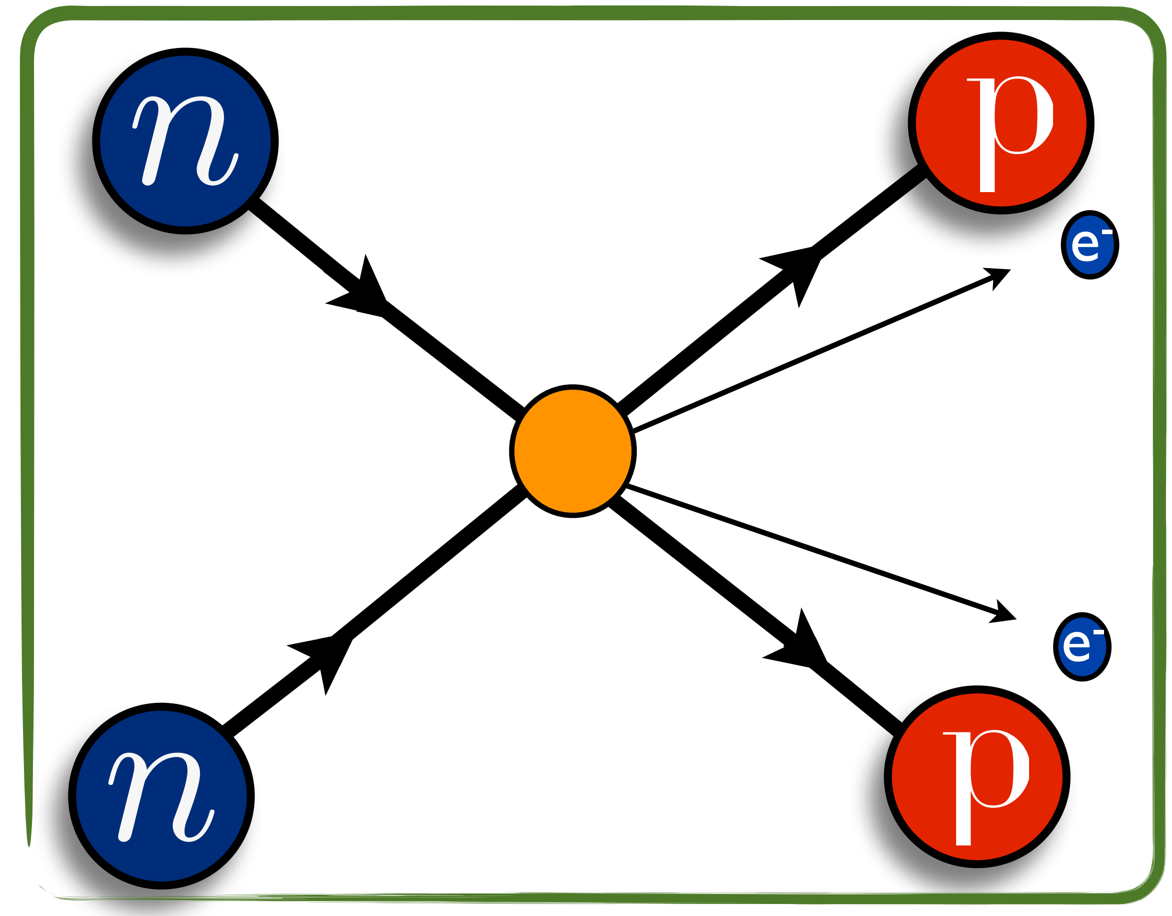
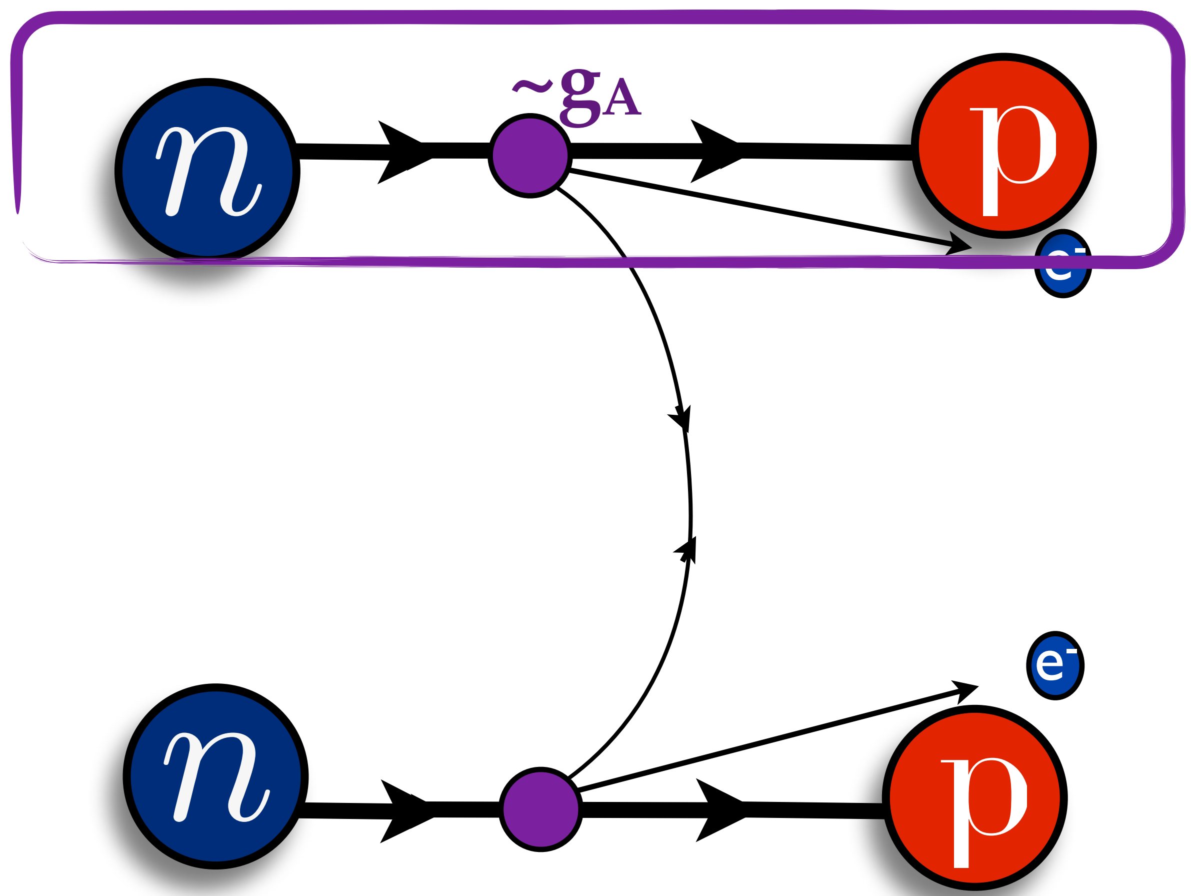
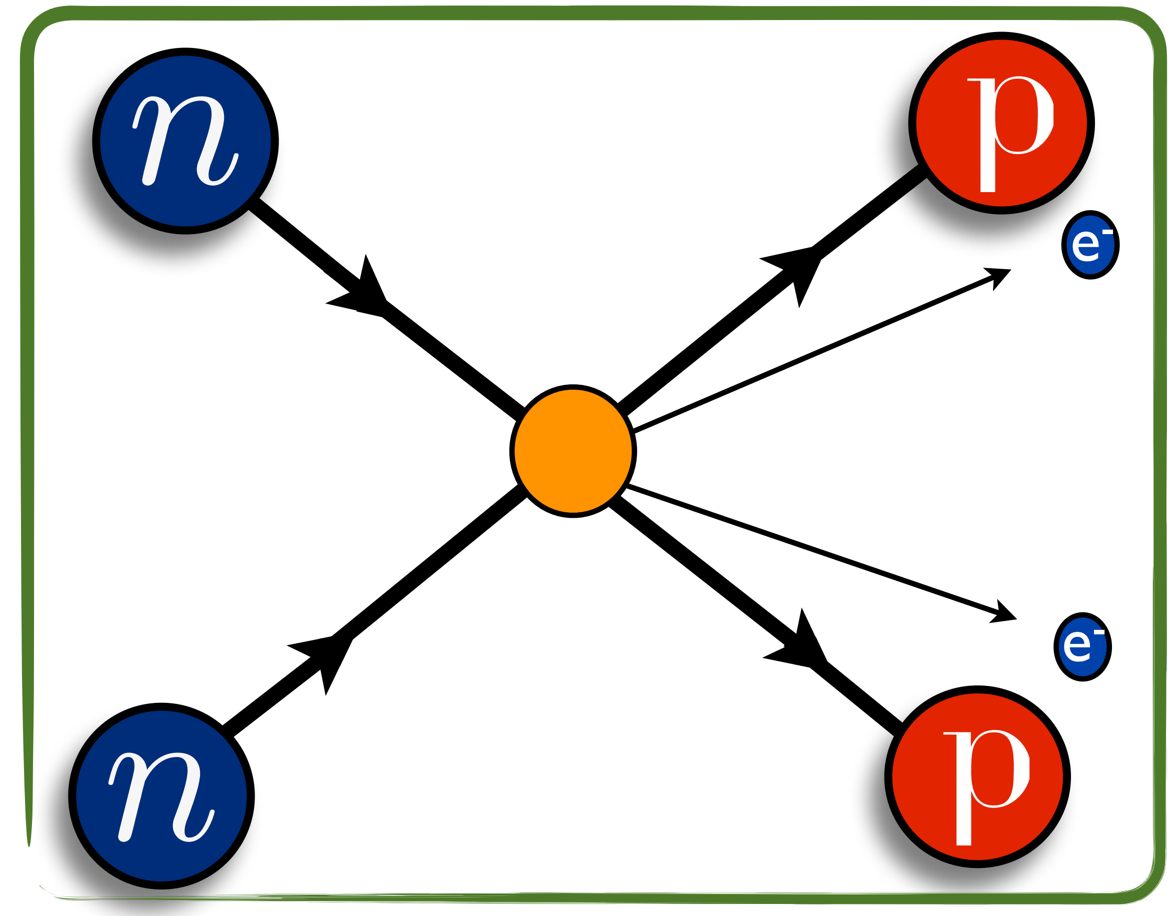
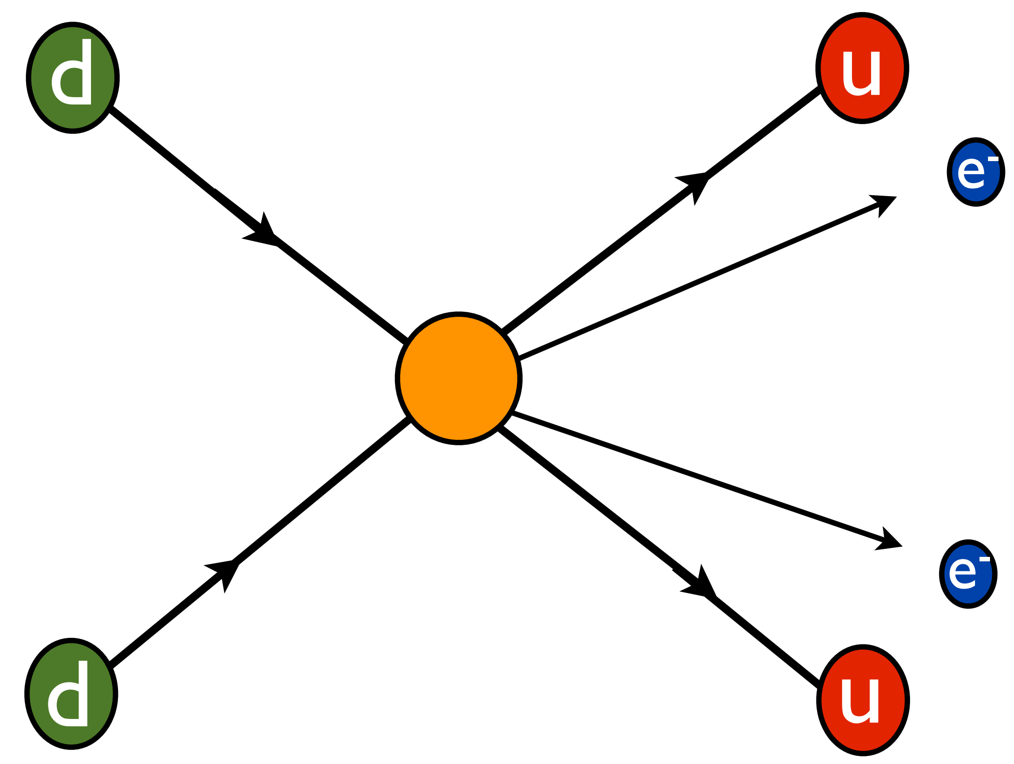


Short-range

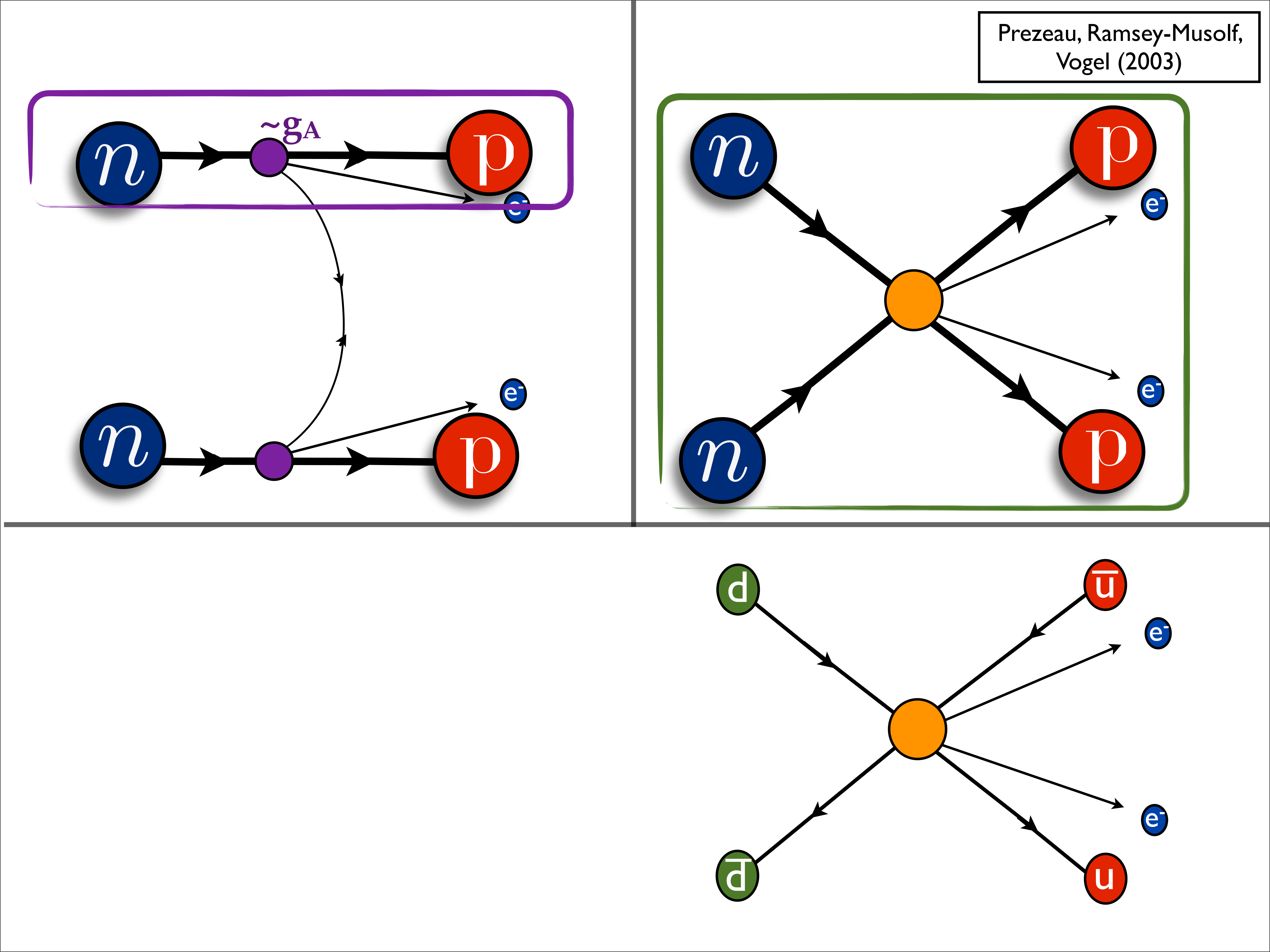
Prezeau, Ramsey-Musolf, Vogel (2003)

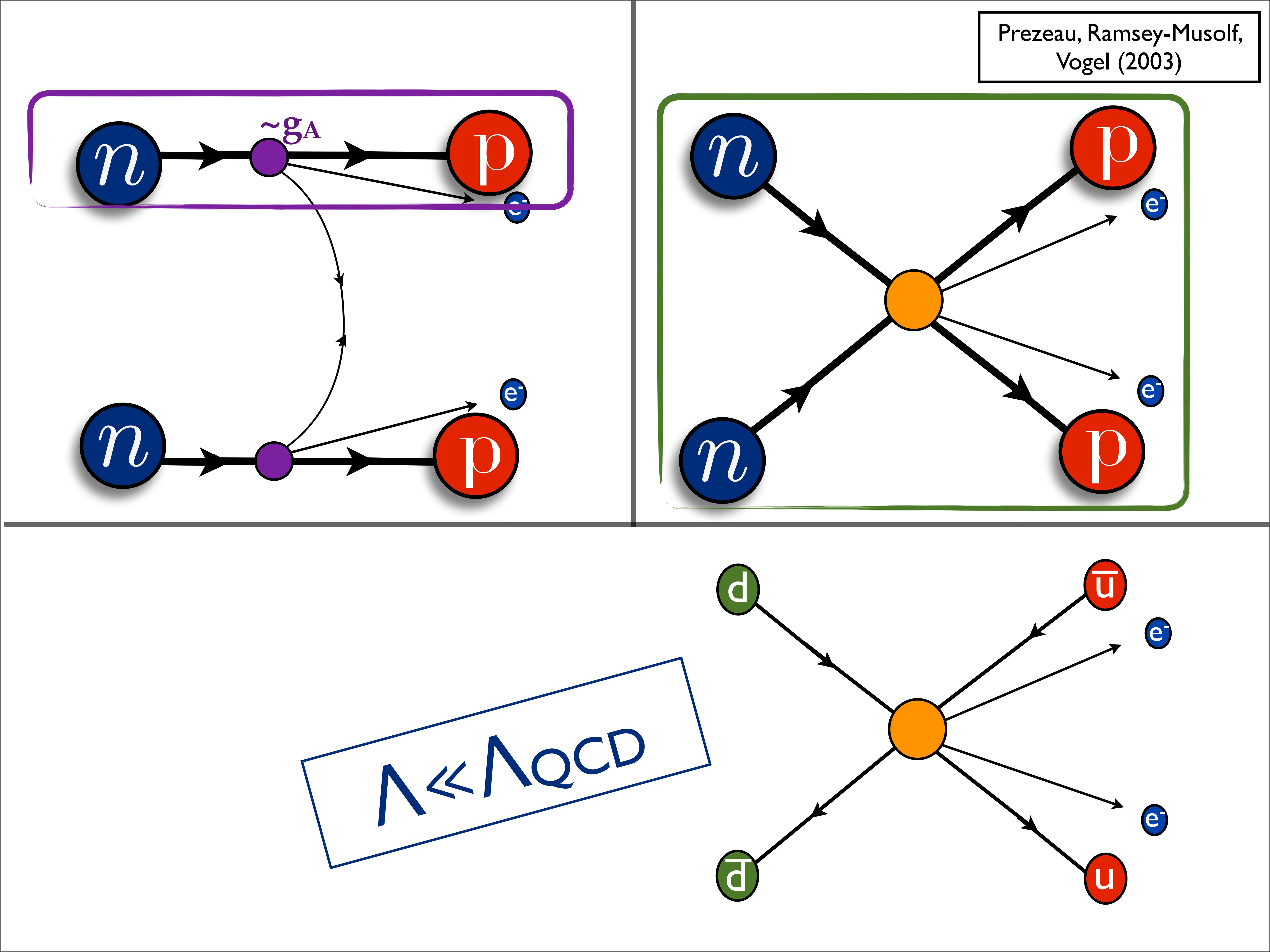






Prezeau, Ramsey-Musolf, Vogel (2003)




Prezeau, Ramsey-Musolf, Vogel (2003)
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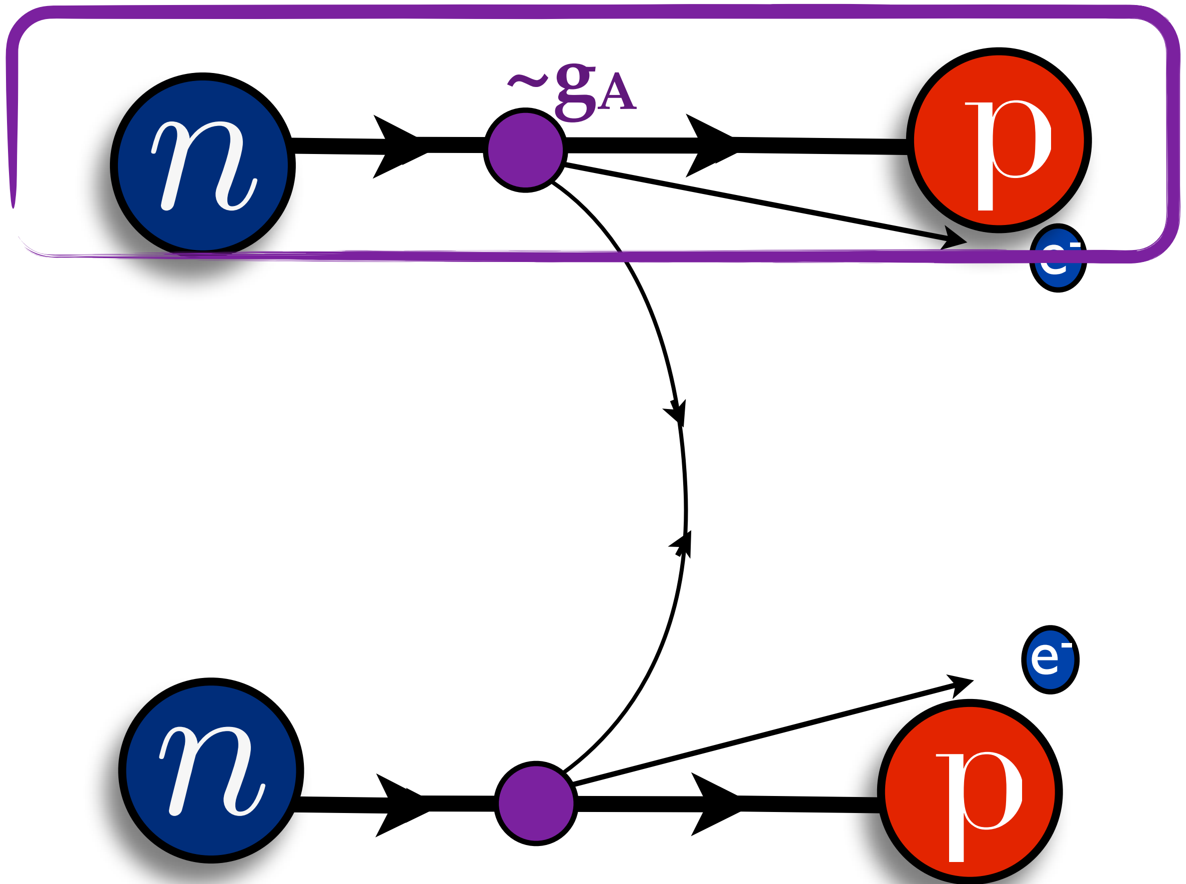

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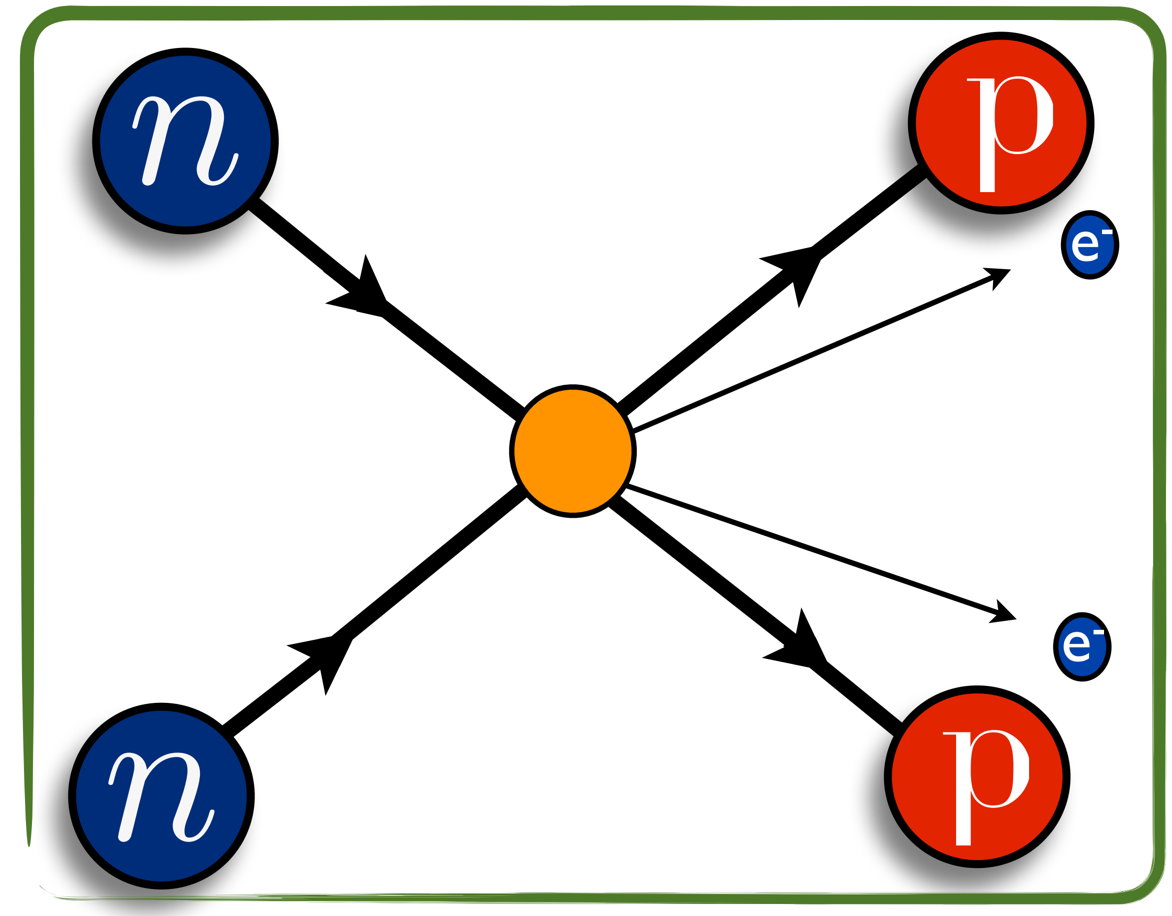
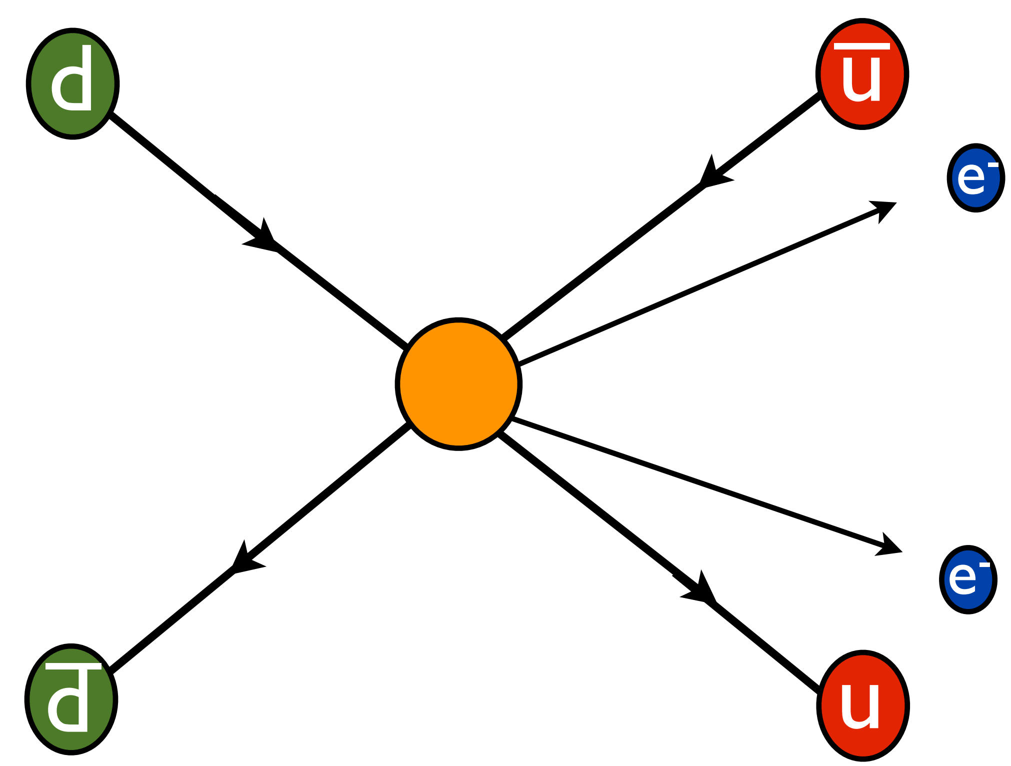
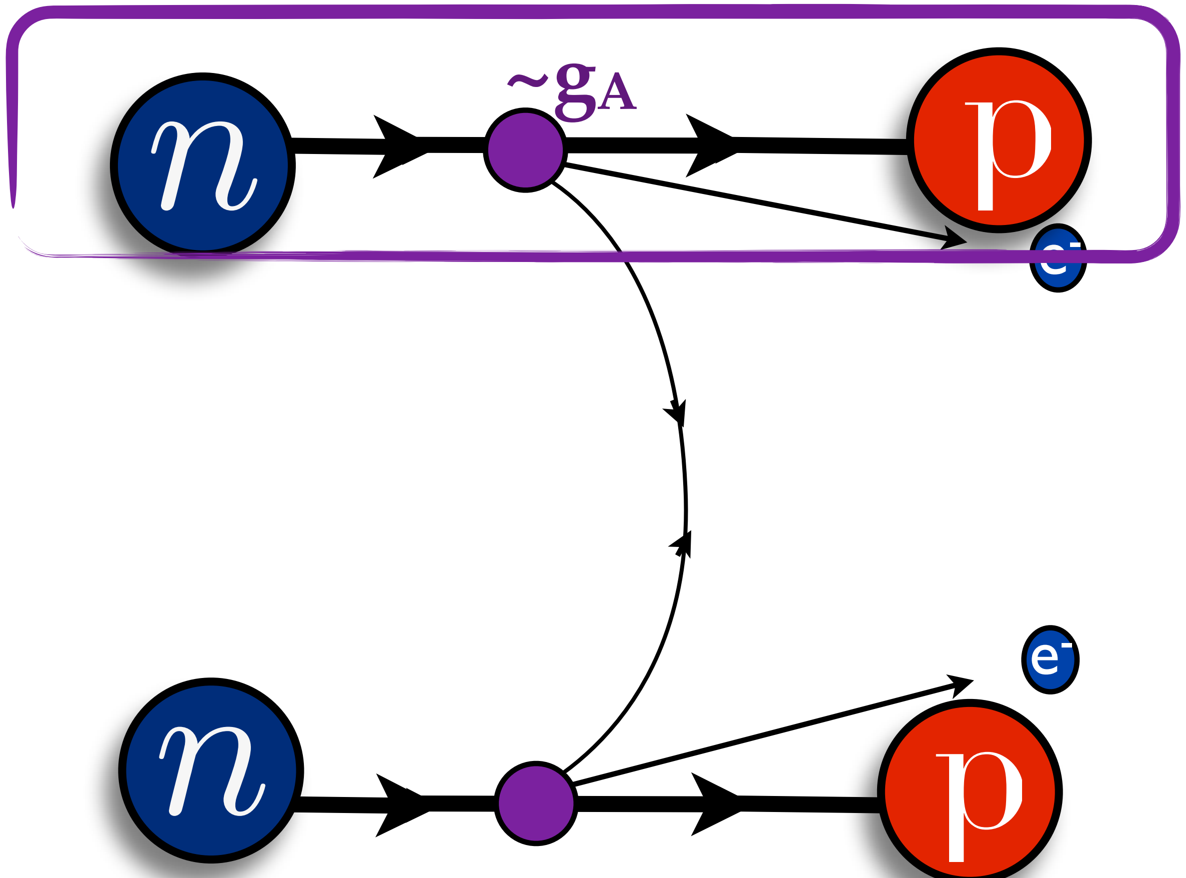
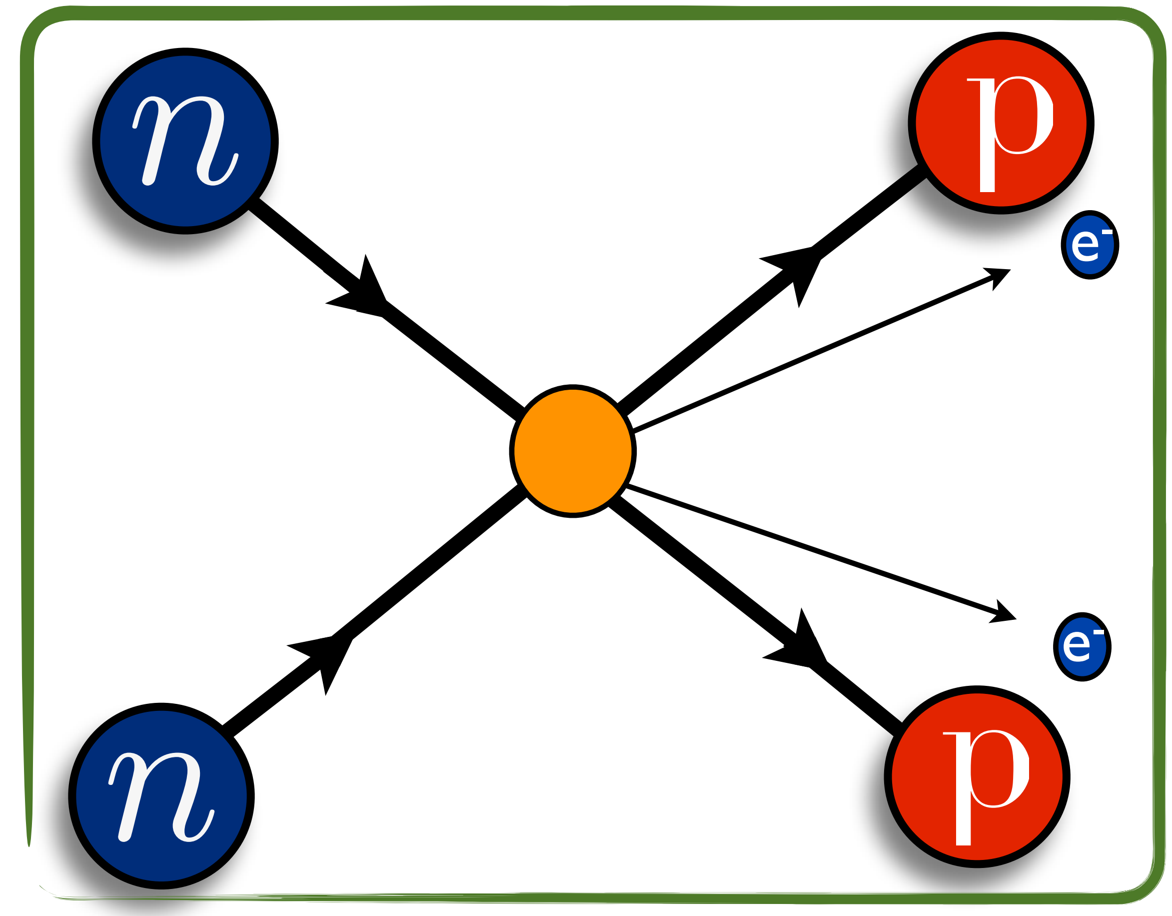
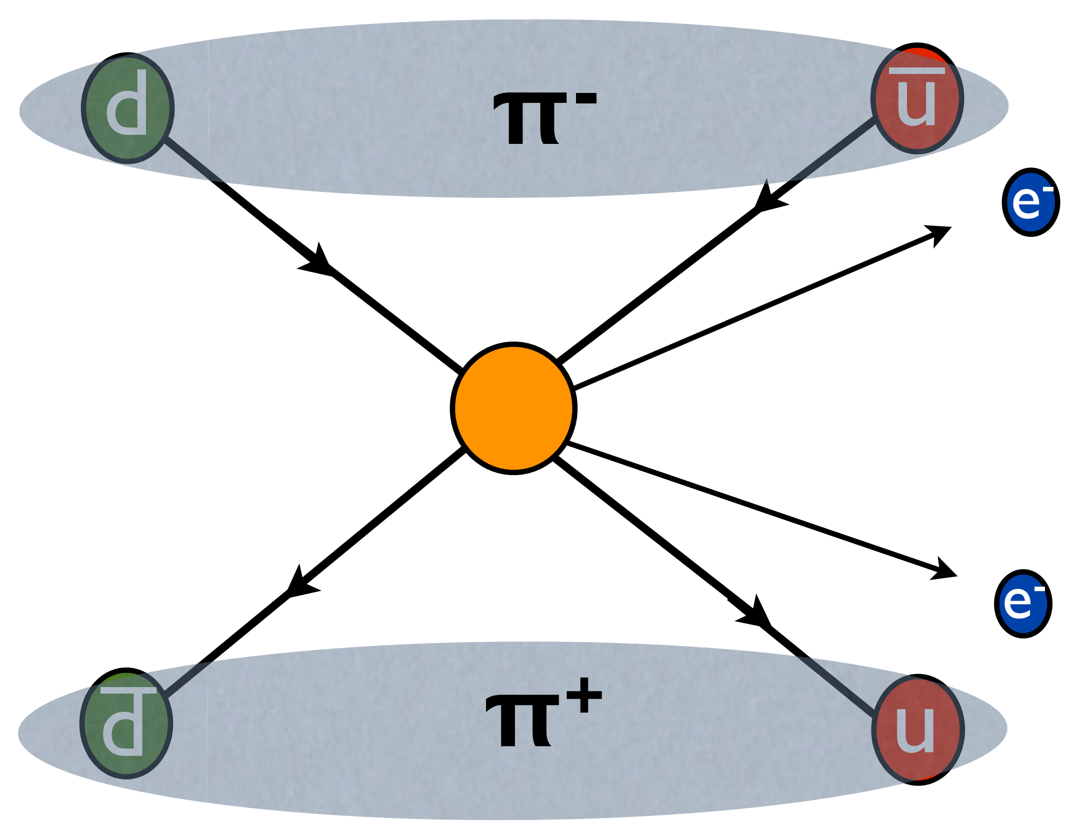




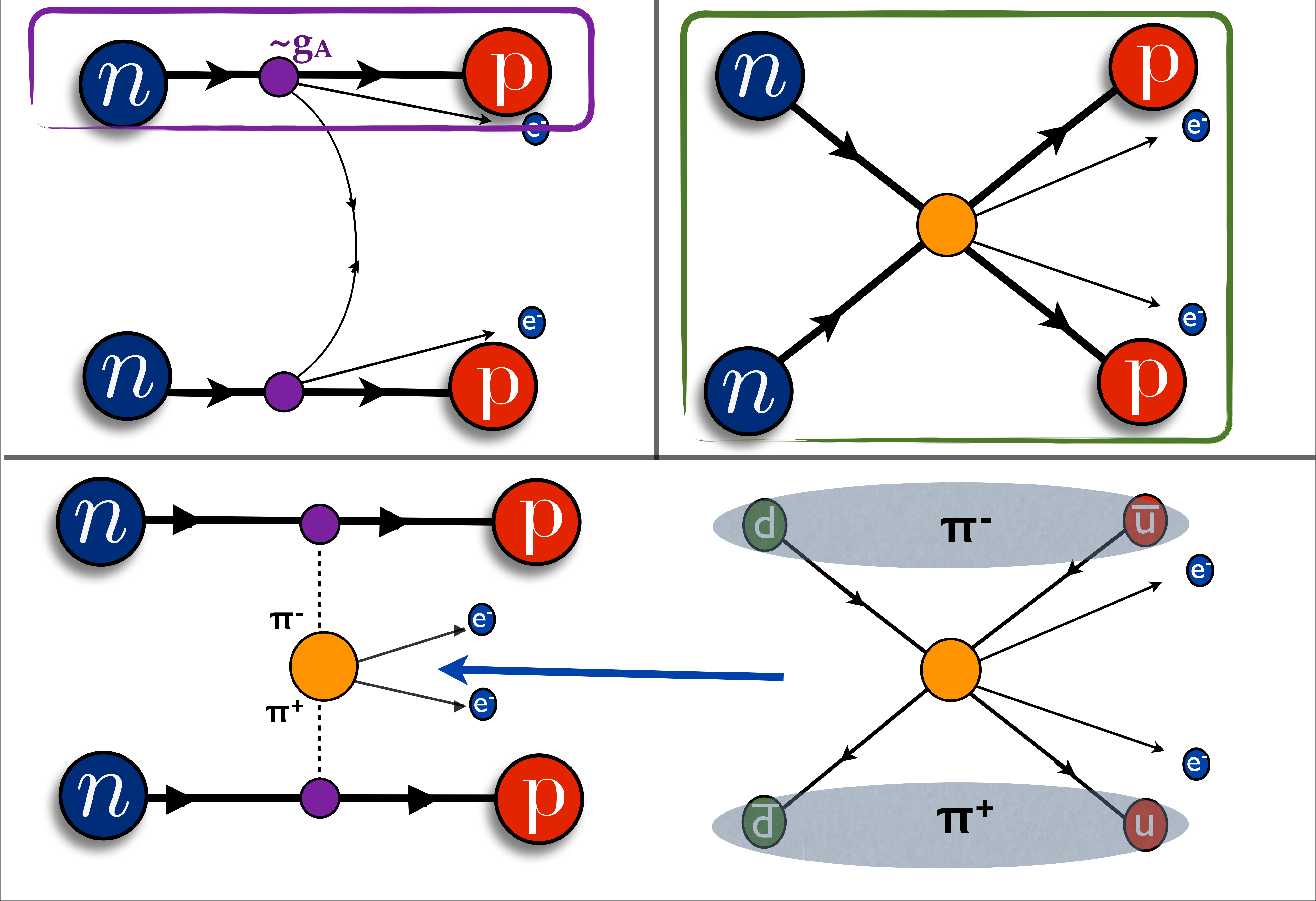
Prezeau, Ramsey-Musolf, Vogel (2003)

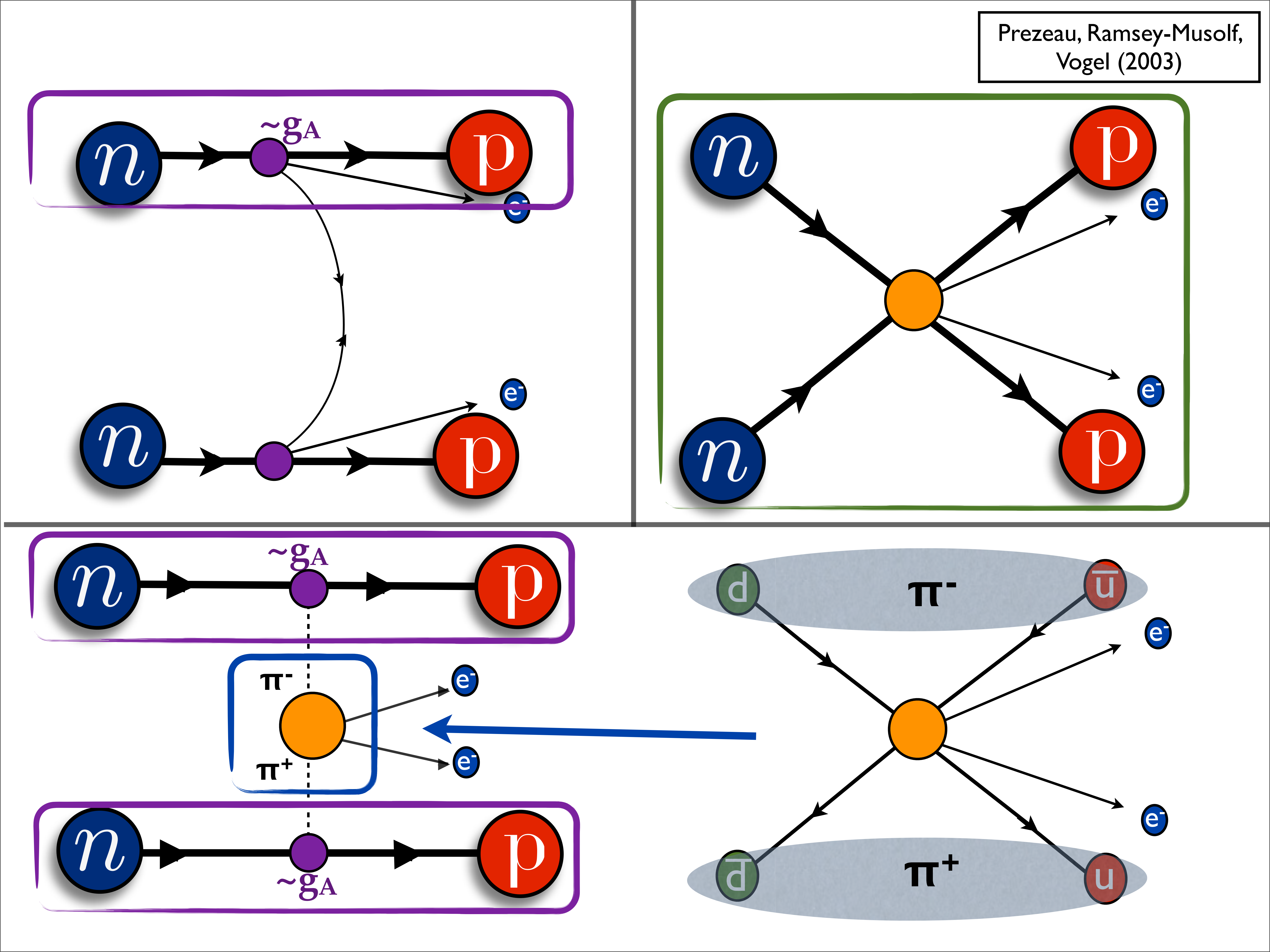






Prezeau, Ramsey-Musolf, Vogel (2003)





Prezeau, Ramsey-Musolf, Vogel (2003)
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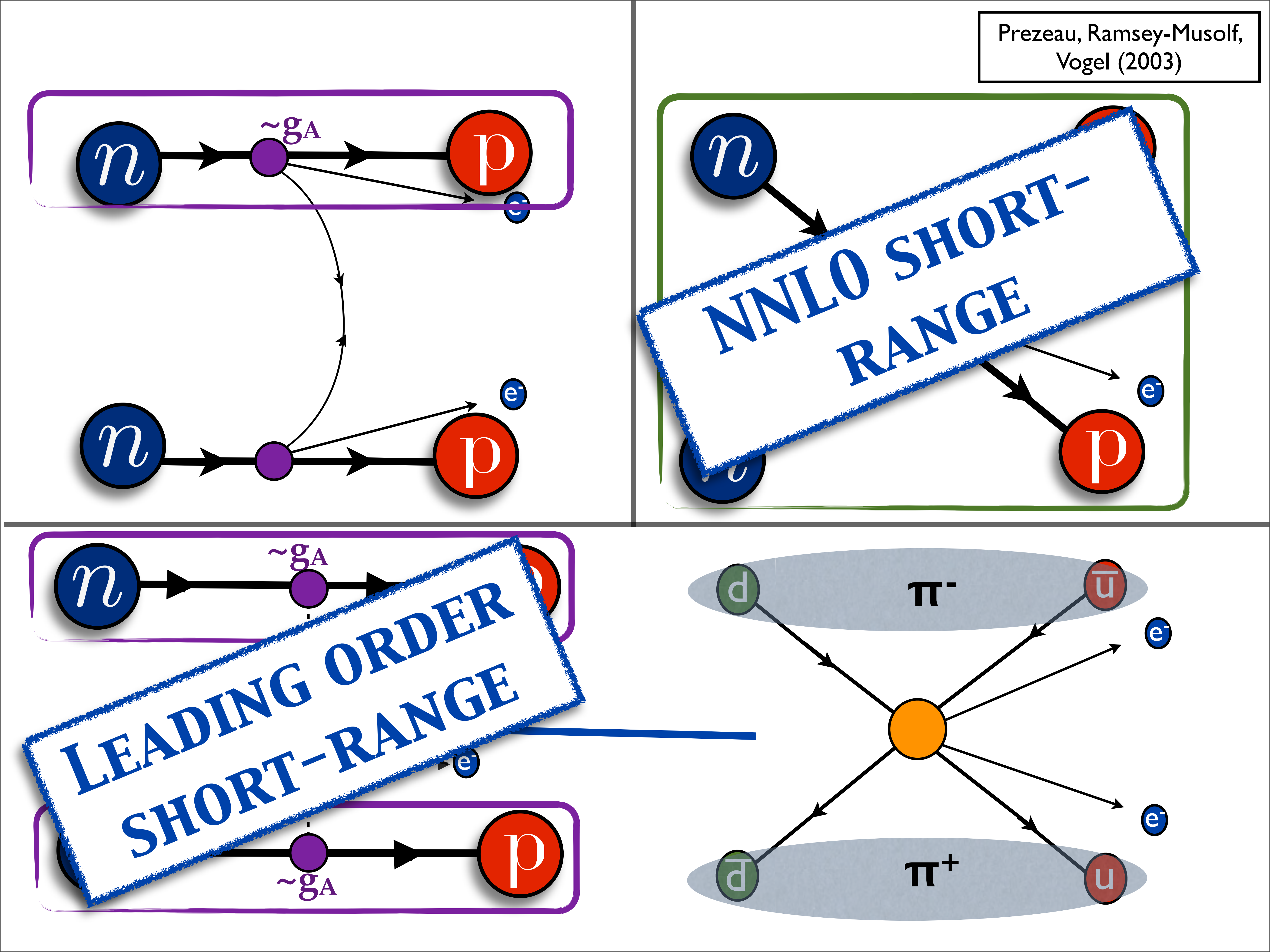
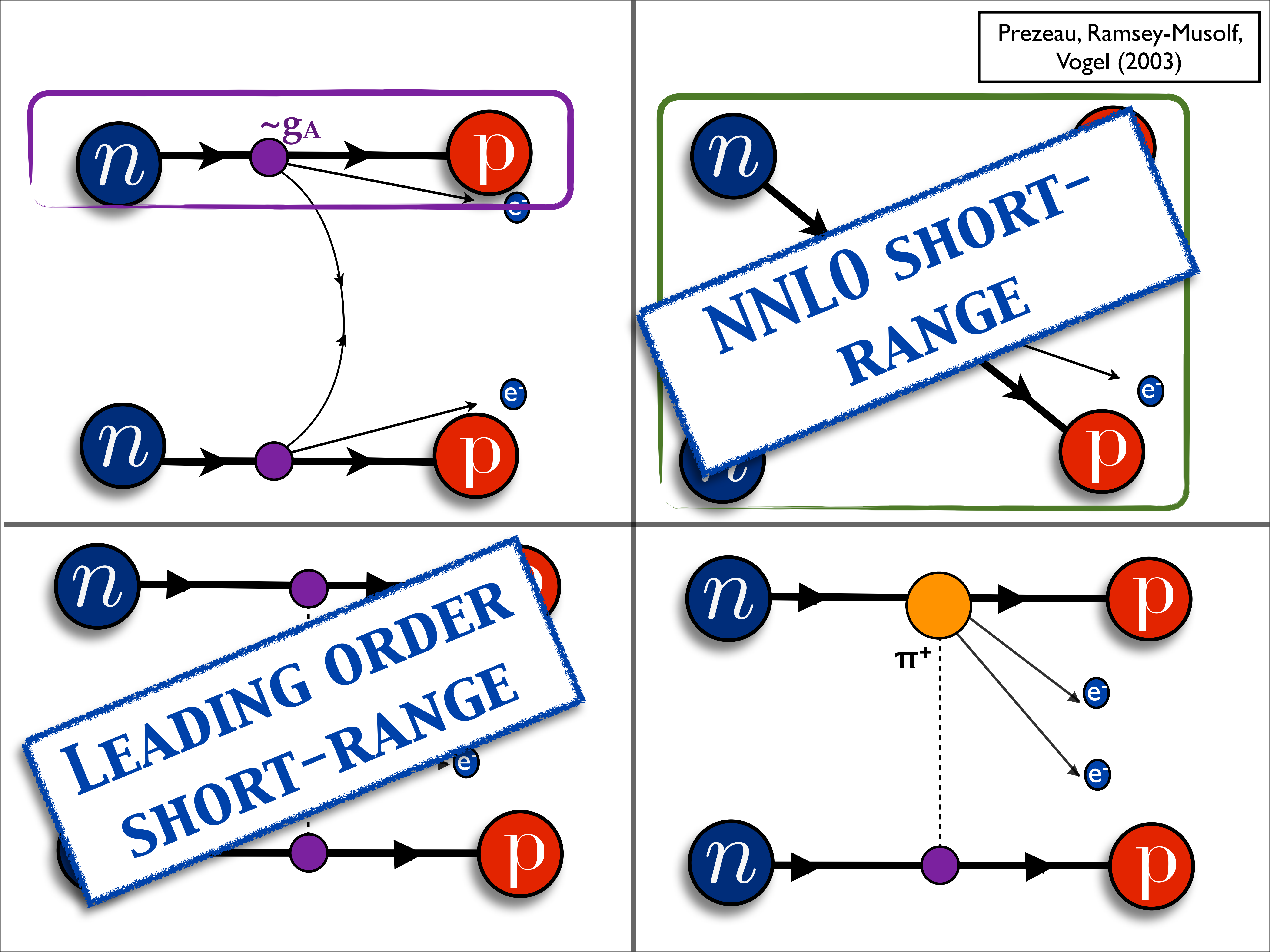
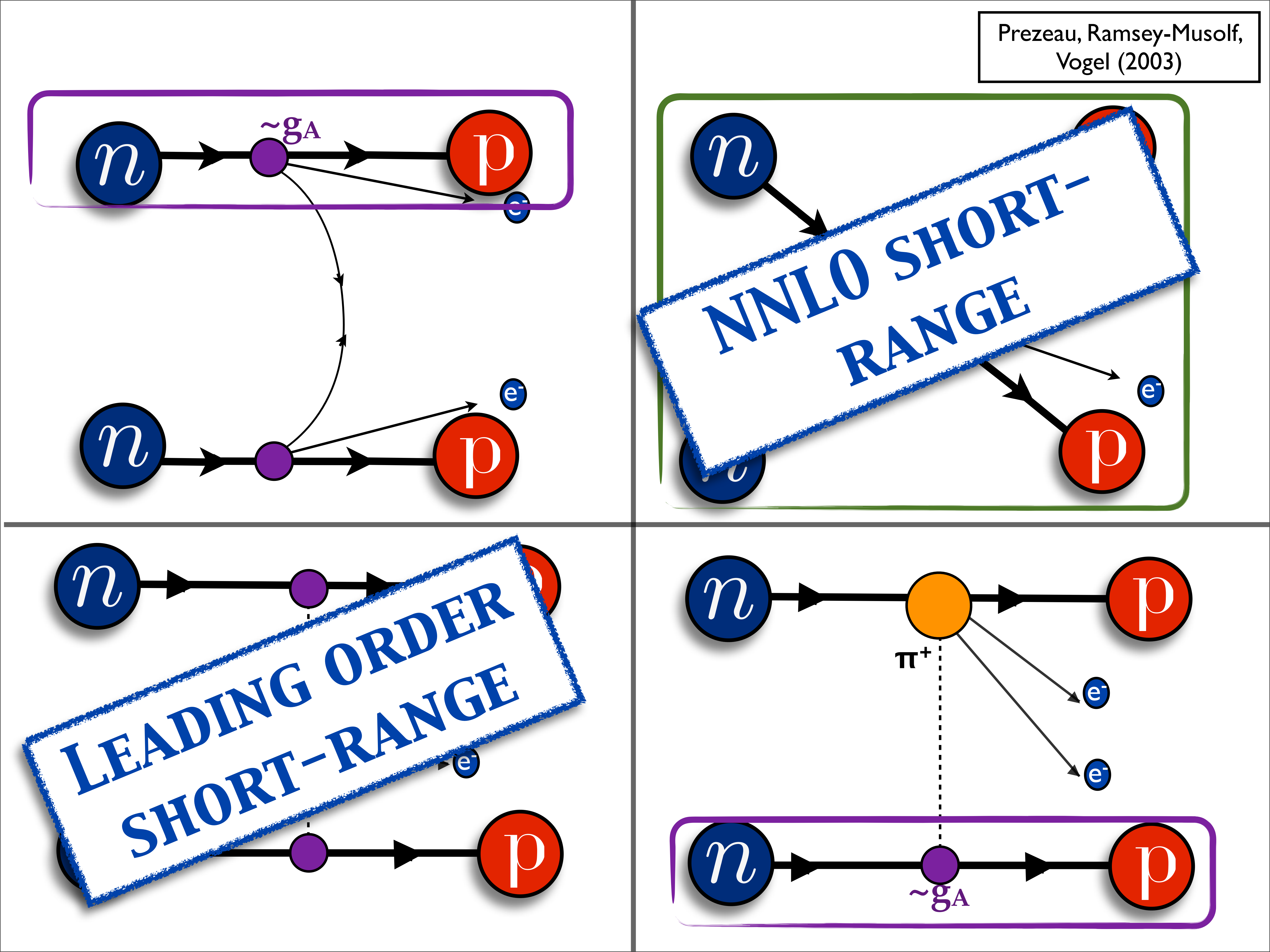
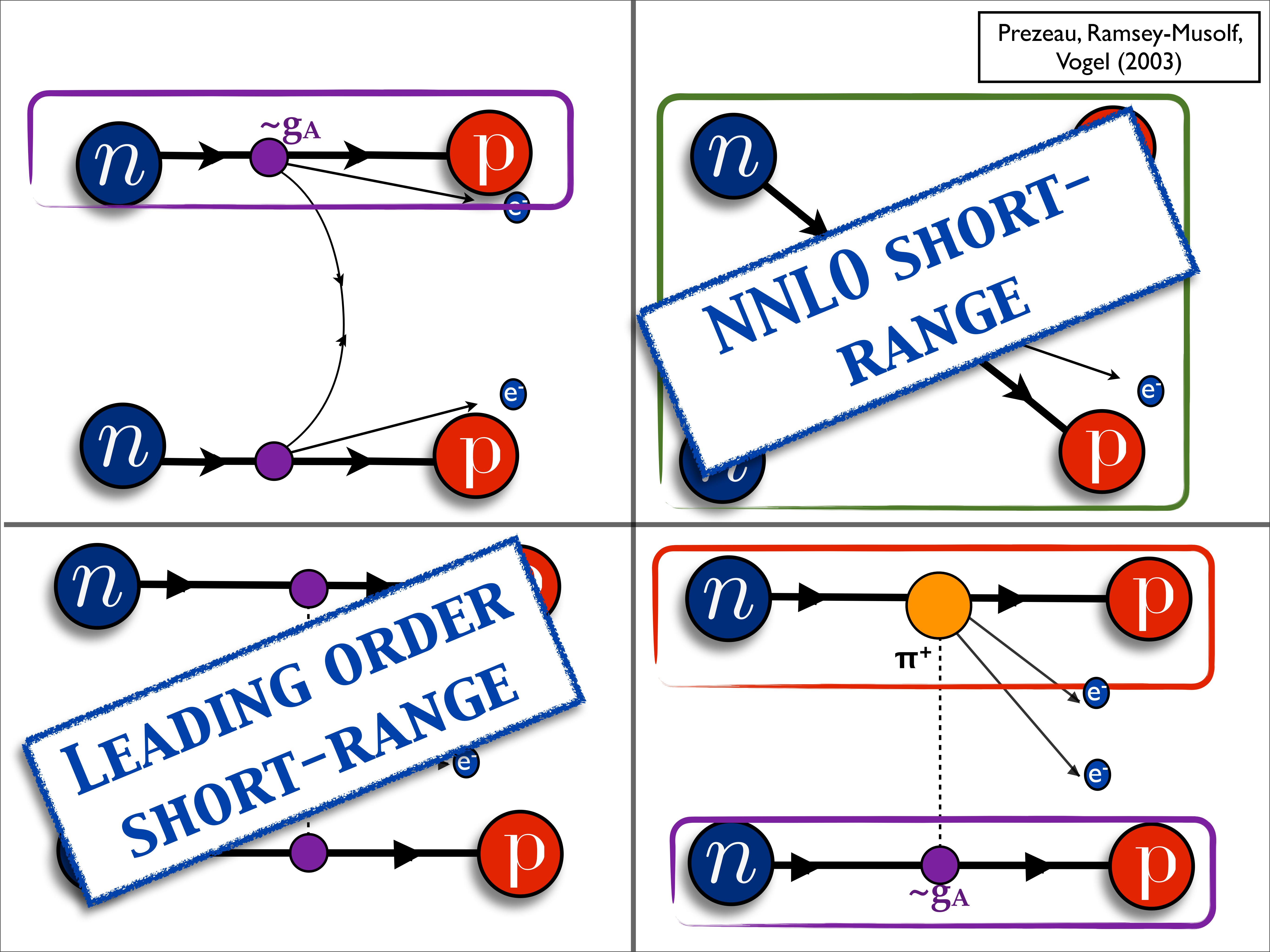

Prezeau, Ramsey-Musolf, Vogel (2003)
~gA
n
p
e-
NNLO SHORT-RANGE
LEADING ORDER SHORT-RANGE
π-
π+
d
u
e-

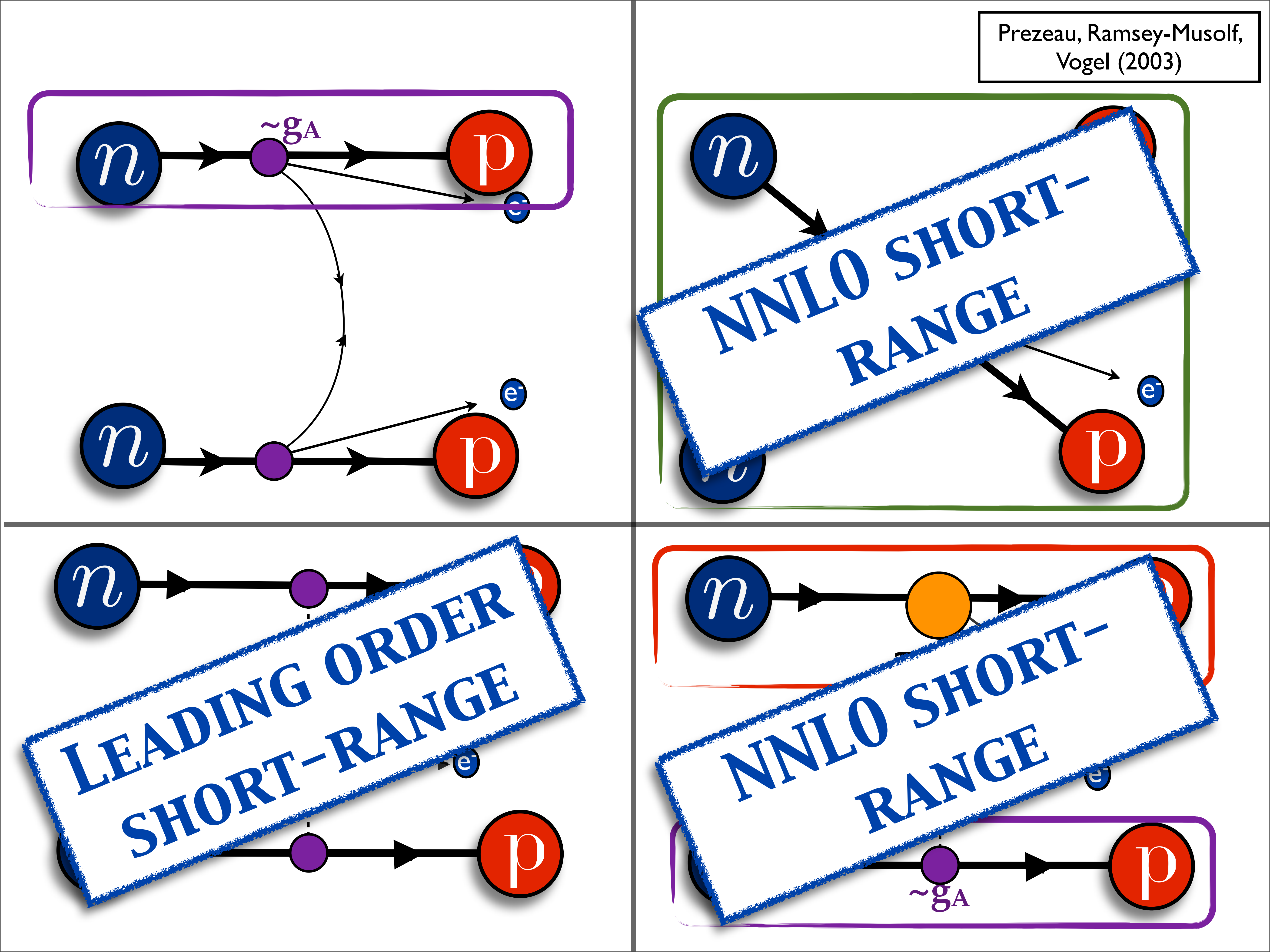

Prezeau, Ramsey-Musolf, Vogel (2003)
~gA
n
p
e-
NNLO SHORT-RANGE
LEADING ORDER SHORT-RANGE
π+



Prezeau, Ramsey-Musolf, Vogel (2003)
~gA
n
p
e-
NNLO SHORT-RANGE
LEADING ORDER SHORT-RANGE
π+

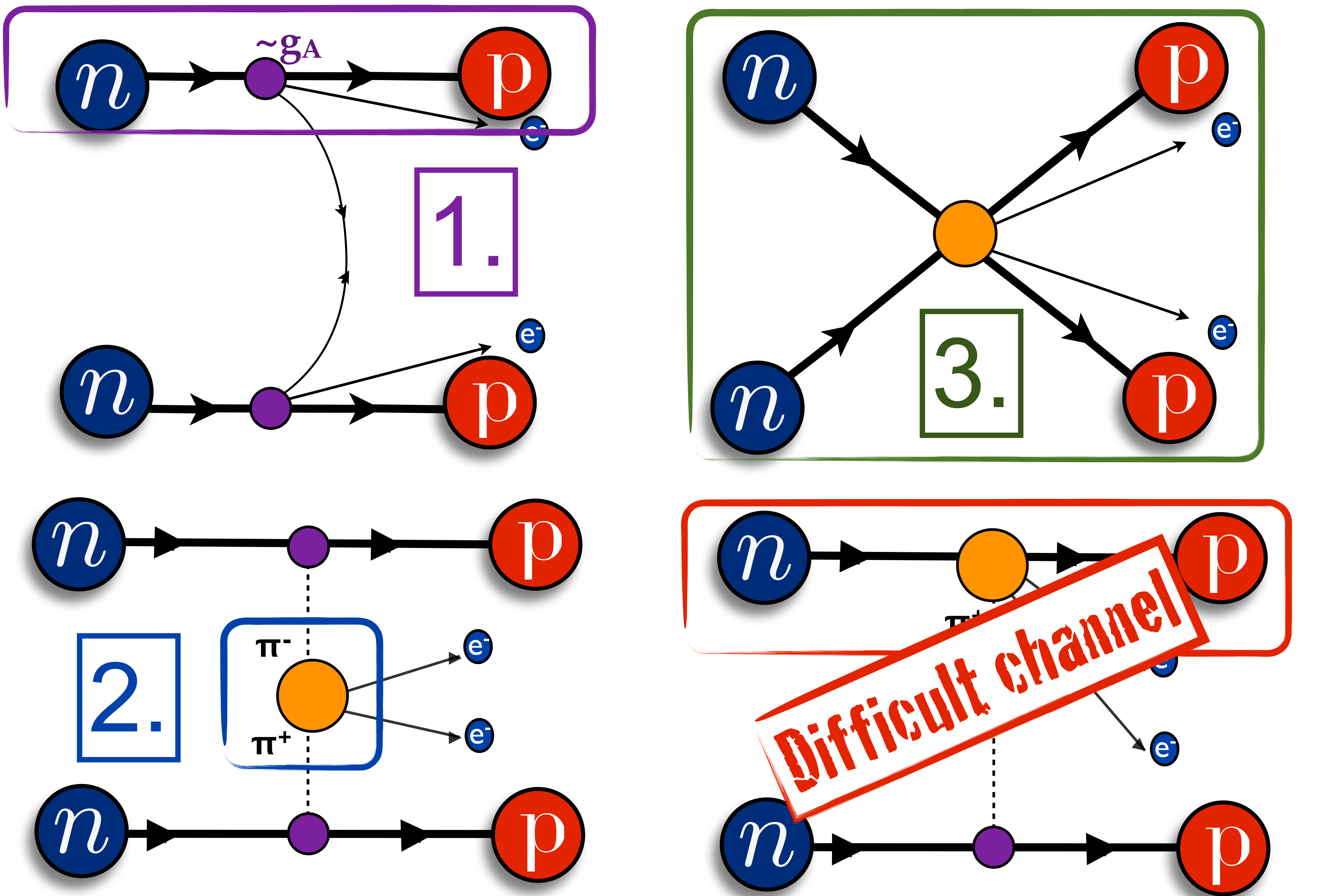


Prezeau, Ramsey-Musolf, Vogel (2003)
~gA
n
p
e-
NNLO SHORT-RANGE
LEADING ORDER SHORT-RANGE
π+

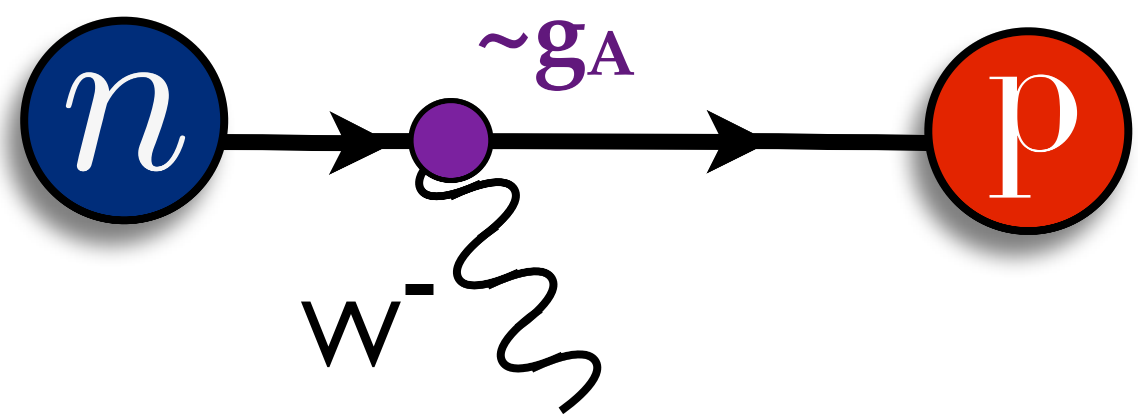


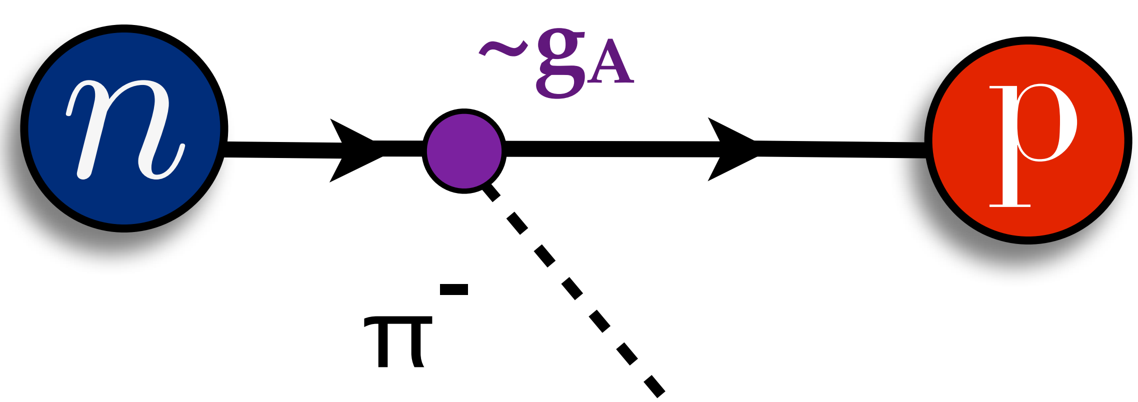
Prezeau, Ramsey-Musolf, Vogel (2003)
~gA
n
p
e-
NNLO SHORT-RANGE
LEADING ORDER SHORT-RANGE
NNLO SHORT-RANGE
~gA

Prezeau, Ramsey-Musolf, Vogel (2003)



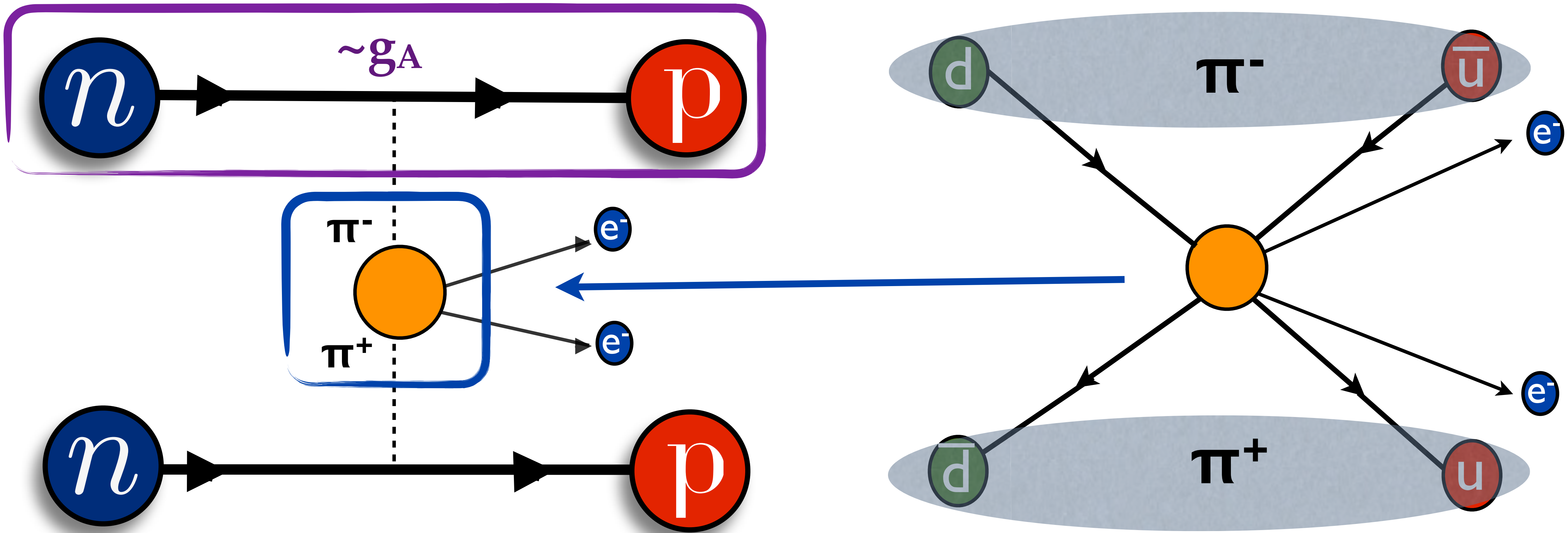
1. Nucleon axial charge, g_A





- Very well-tested experimentally
  - $g_A^{exp} = 1.2723(23)$
  - good place to look for BSM physics
- Benchmark for nuclear physics on the lattice
- Would like to understand medium modifications (Z. Davoudi, P. Shanahan)

See R. Gupta's talk for status



2.

π- → π+ Transition:

no direct experimental input

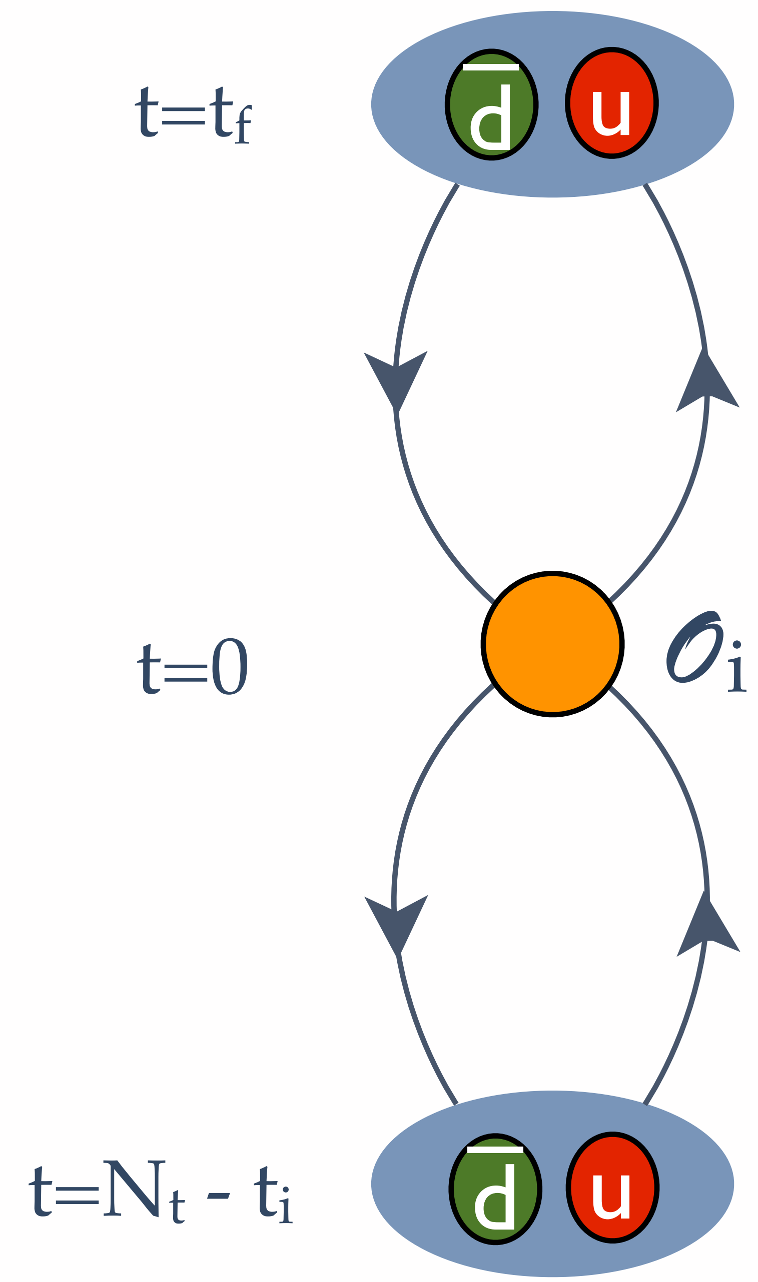
Long-range pion calculation

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

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

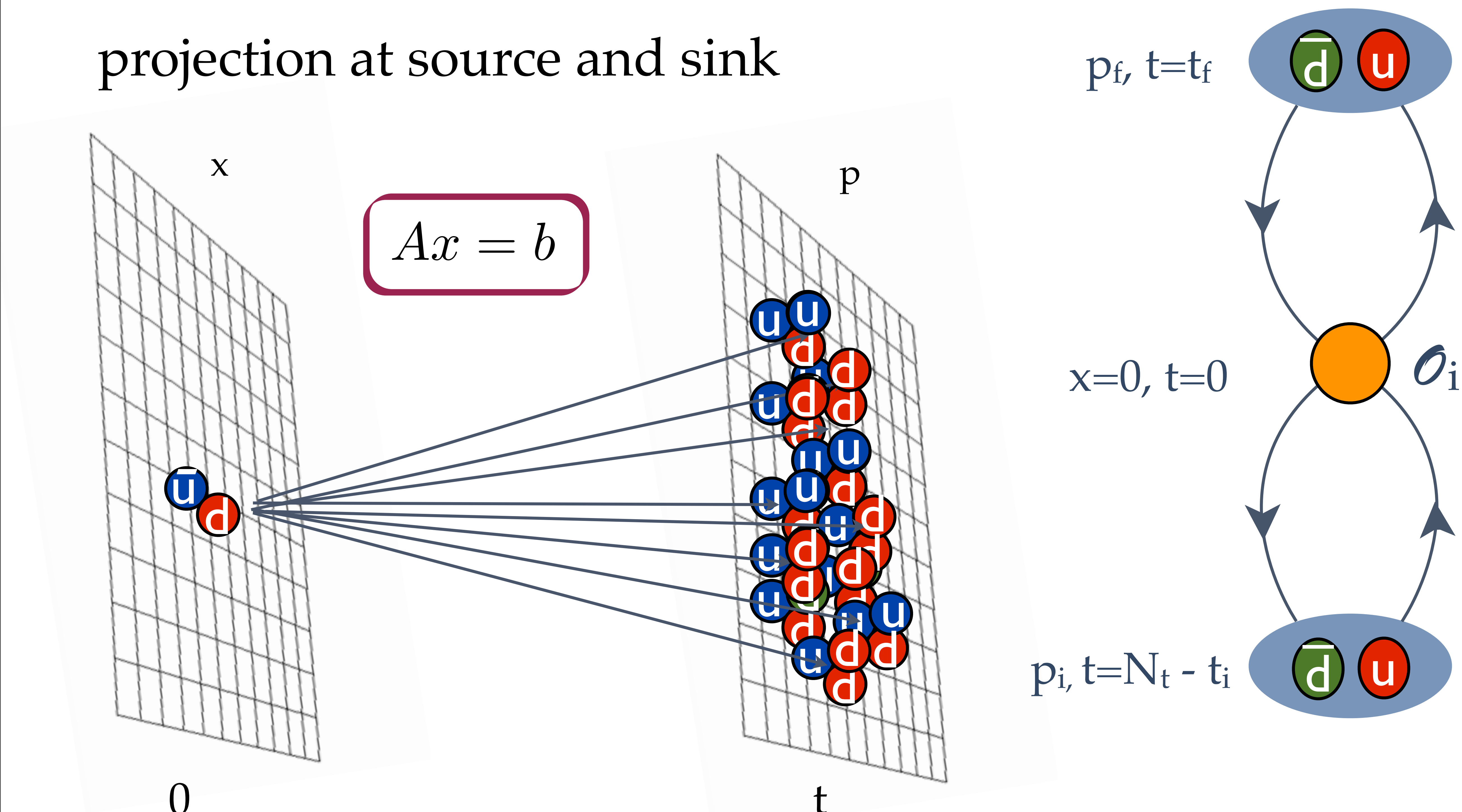
$$= \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t} \xrightarrow[t\to\infty]{} \langle 0|\mathcal{O}|0\rangle e^{-E_0 t}$$

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



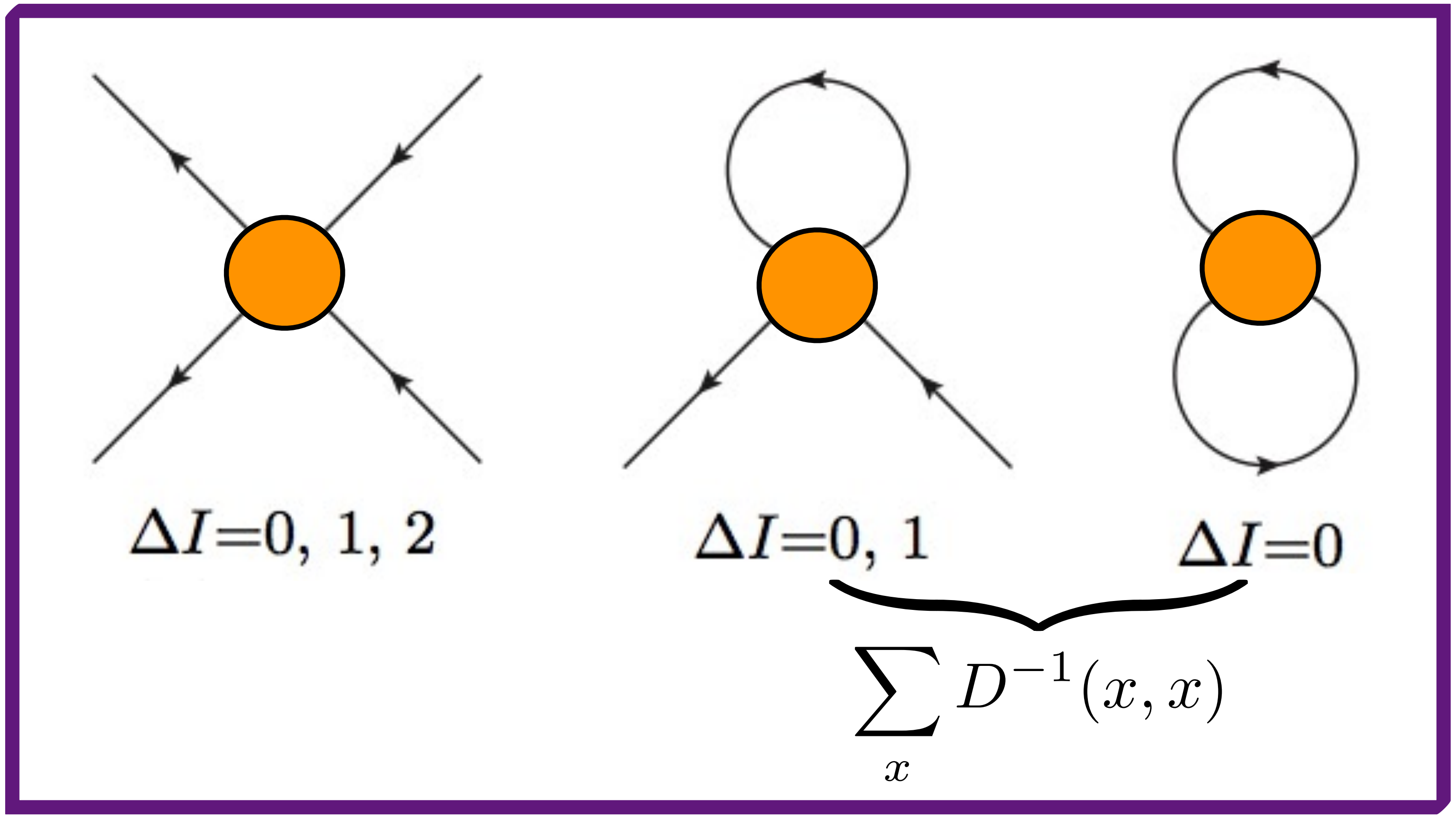
Long-range pion calculation

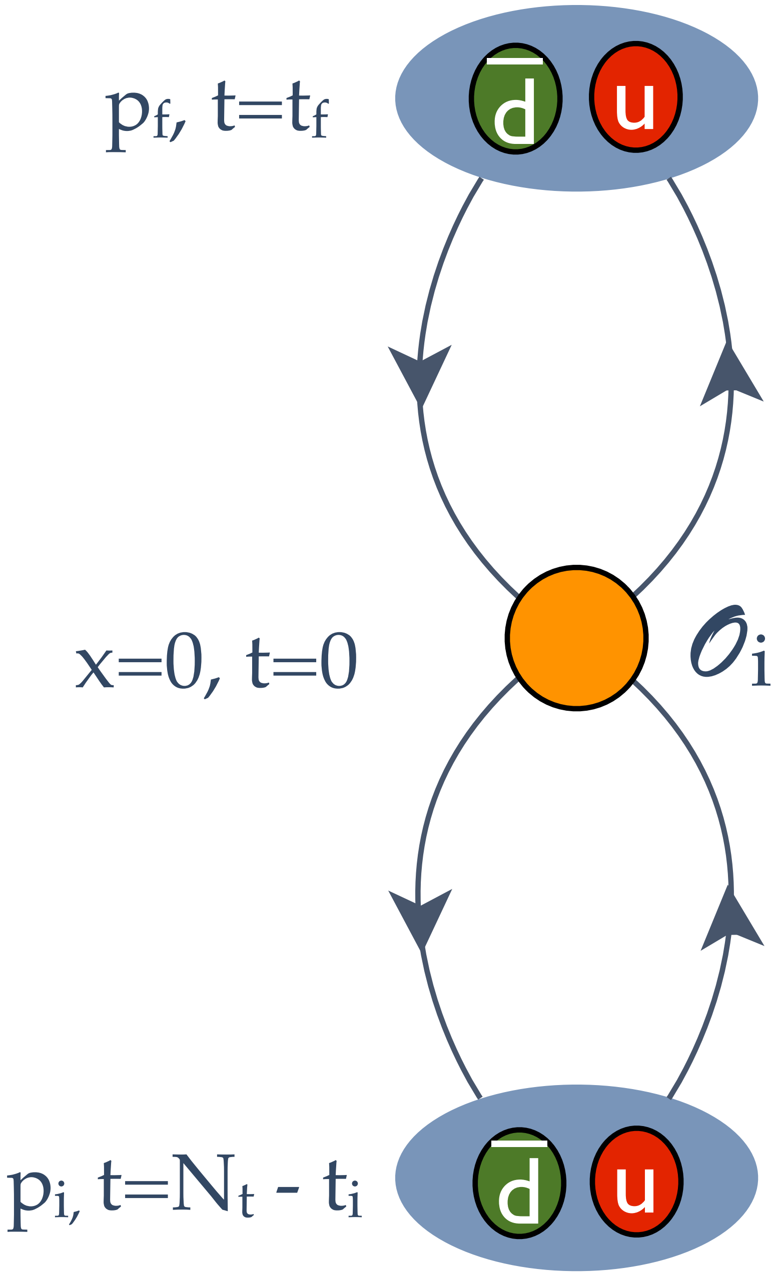
- Can perform exact momentum projection at source and sink



Long-range pion calculation

- Can perform exact momentum projection at source and sink
- ΔI = 2 no disconnected pieces from operators





XPT:

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

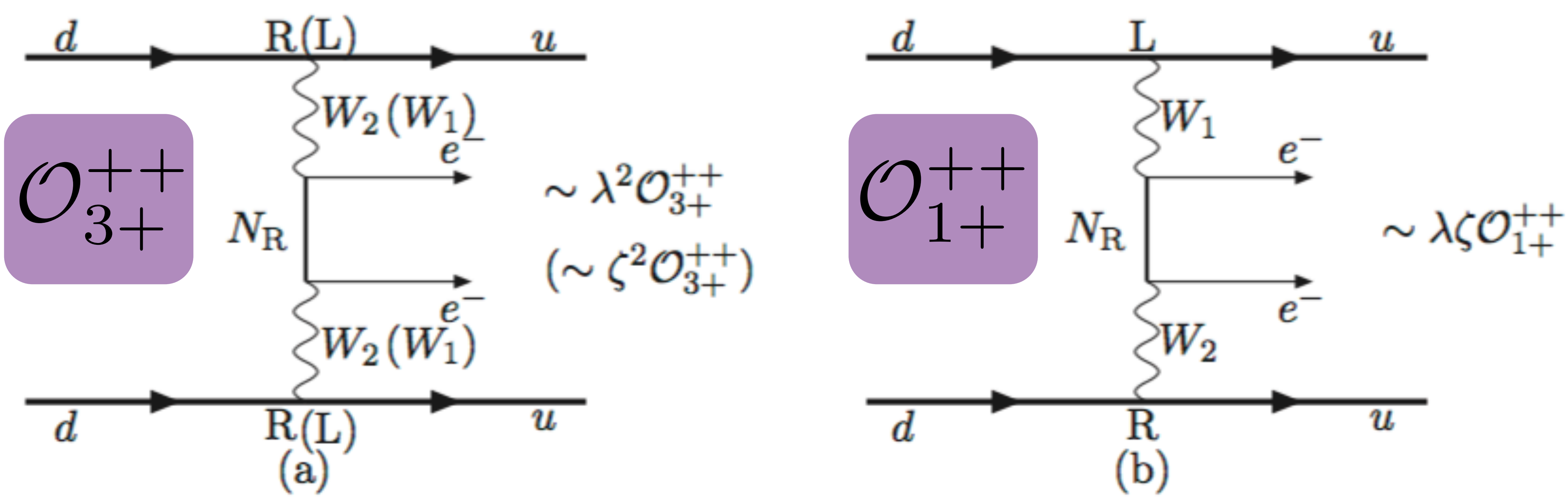
$$
\begin{aligned}
\mathcal{O}_{1+}^{ab} &= (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_R \tau^b \gamma_\mu q_R), \\
\mathcal{O}_{2\pm}^{ab} &= (\bar{q}_R \tau^a q_L)(\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R)(\bar{q}_L \tau^b q_R), \\
\mathcal{O}_{3\pm}^{ab} &= (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L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

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

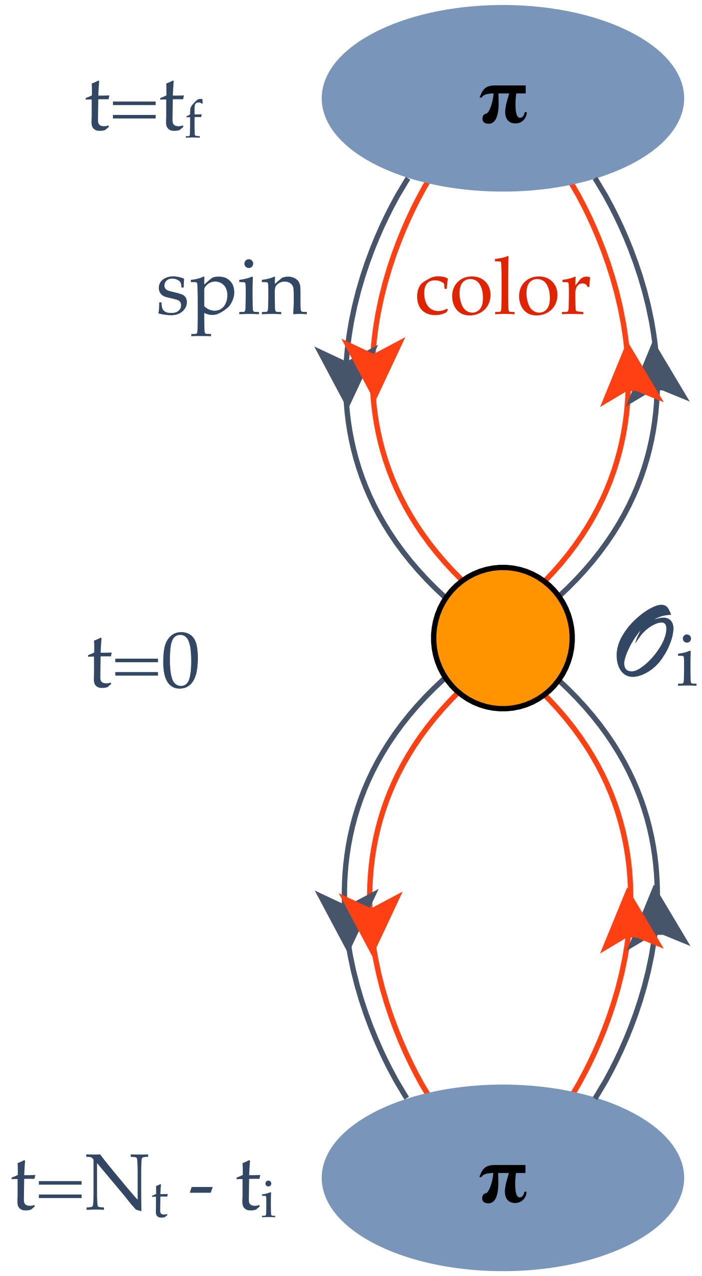
$$\mathcal{O}_{1+}^{++} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

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

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

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

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



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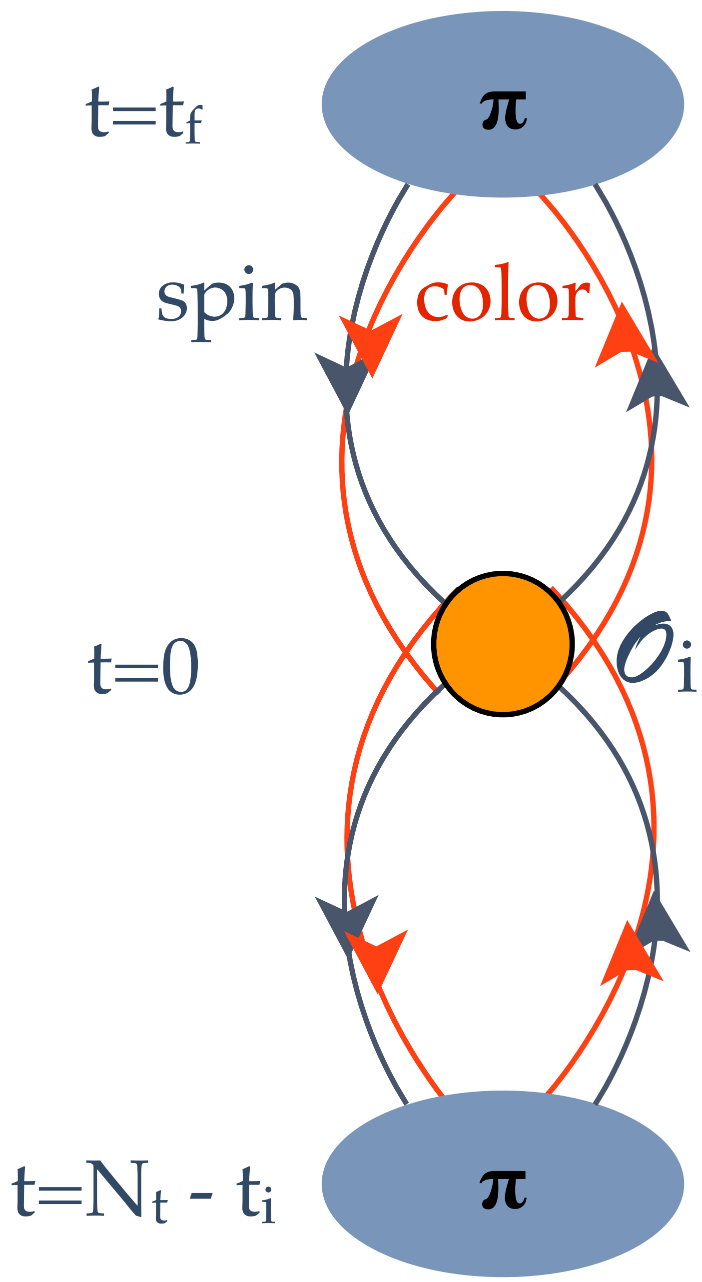
$$\mathcal{O}'^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right] \left[\bar{q}_R \tau^- \gamma_\mu q_R\right)$$

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

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

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



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

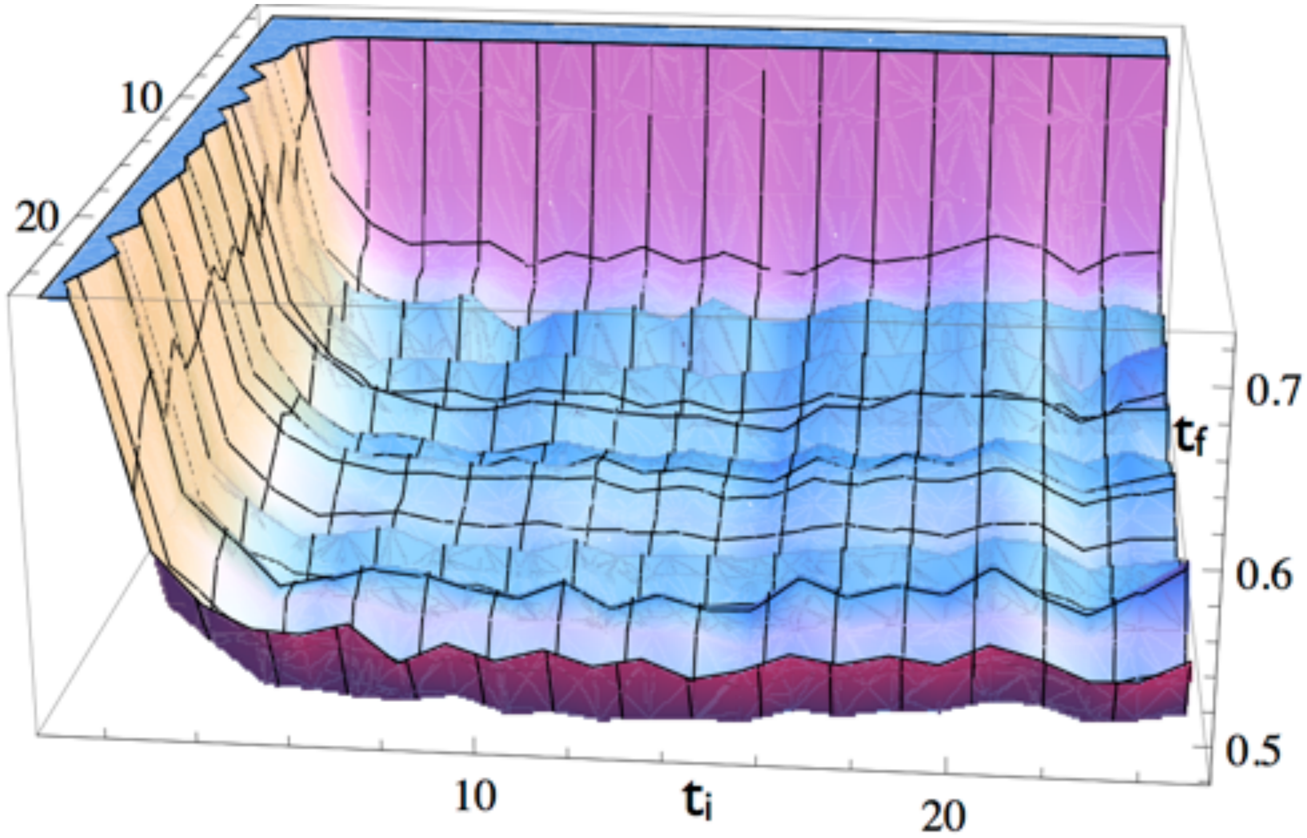
- Möbius DWF on HISQ
- Gradient flow method for smearing configs
    - $m_{res} < 0.1\ m_\ell$ for moderate L_5

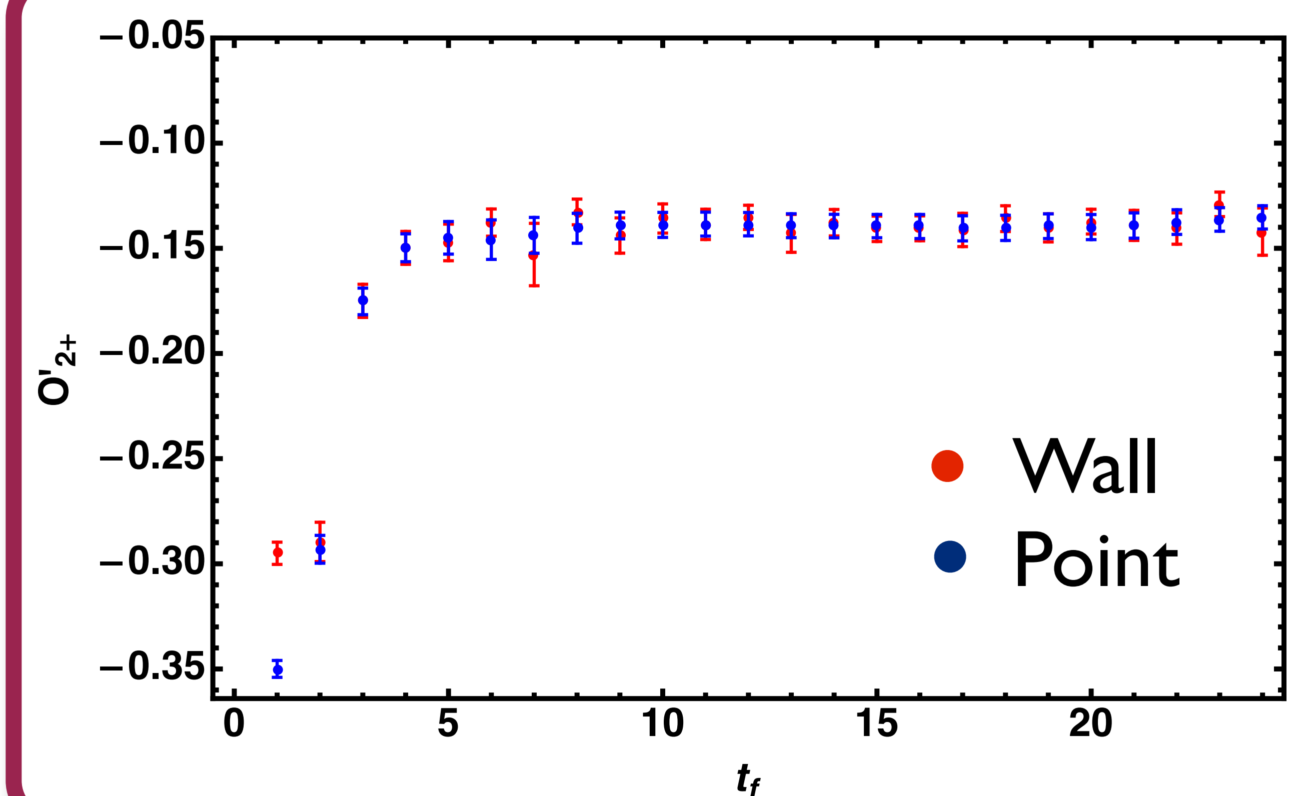
MILC Collaboration Phys. Rev. D87 (2013) 054505

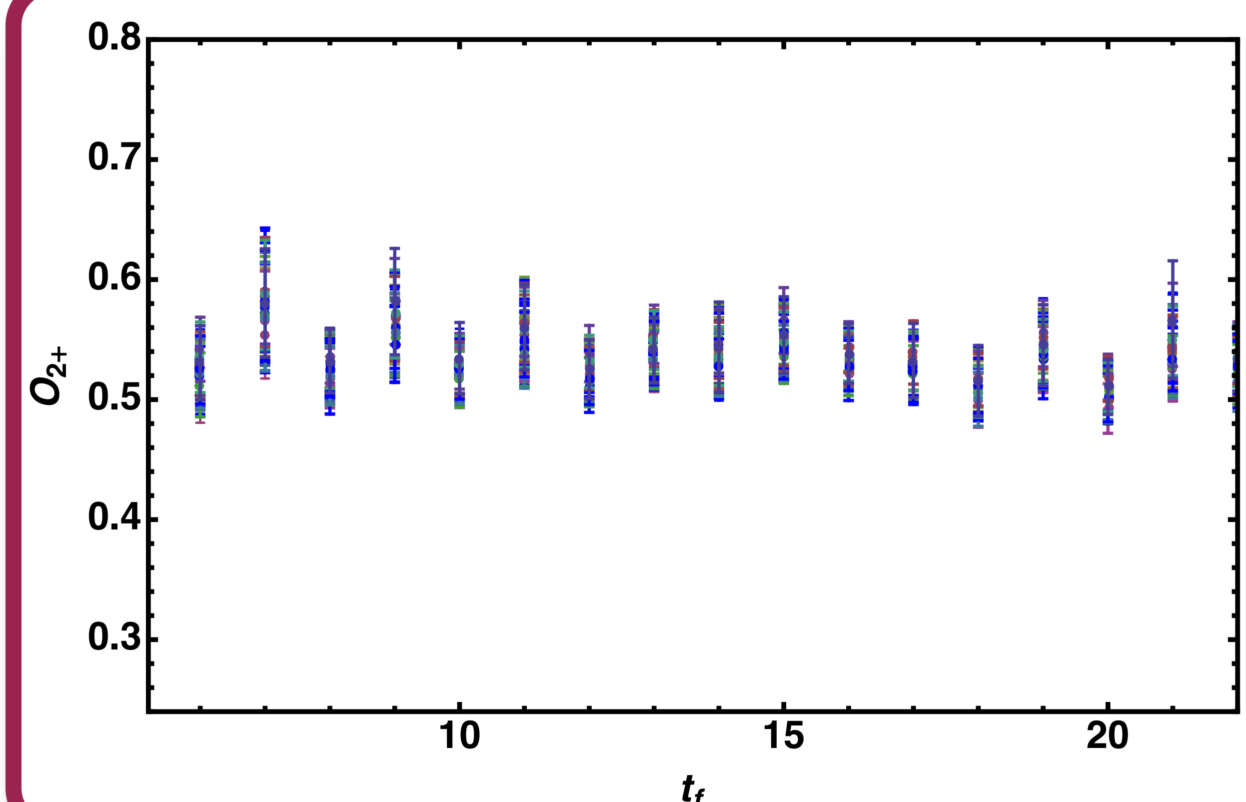
Narayanan, Neuberger (2006), Luscher (2010)

Callat arXiv:1701.07559

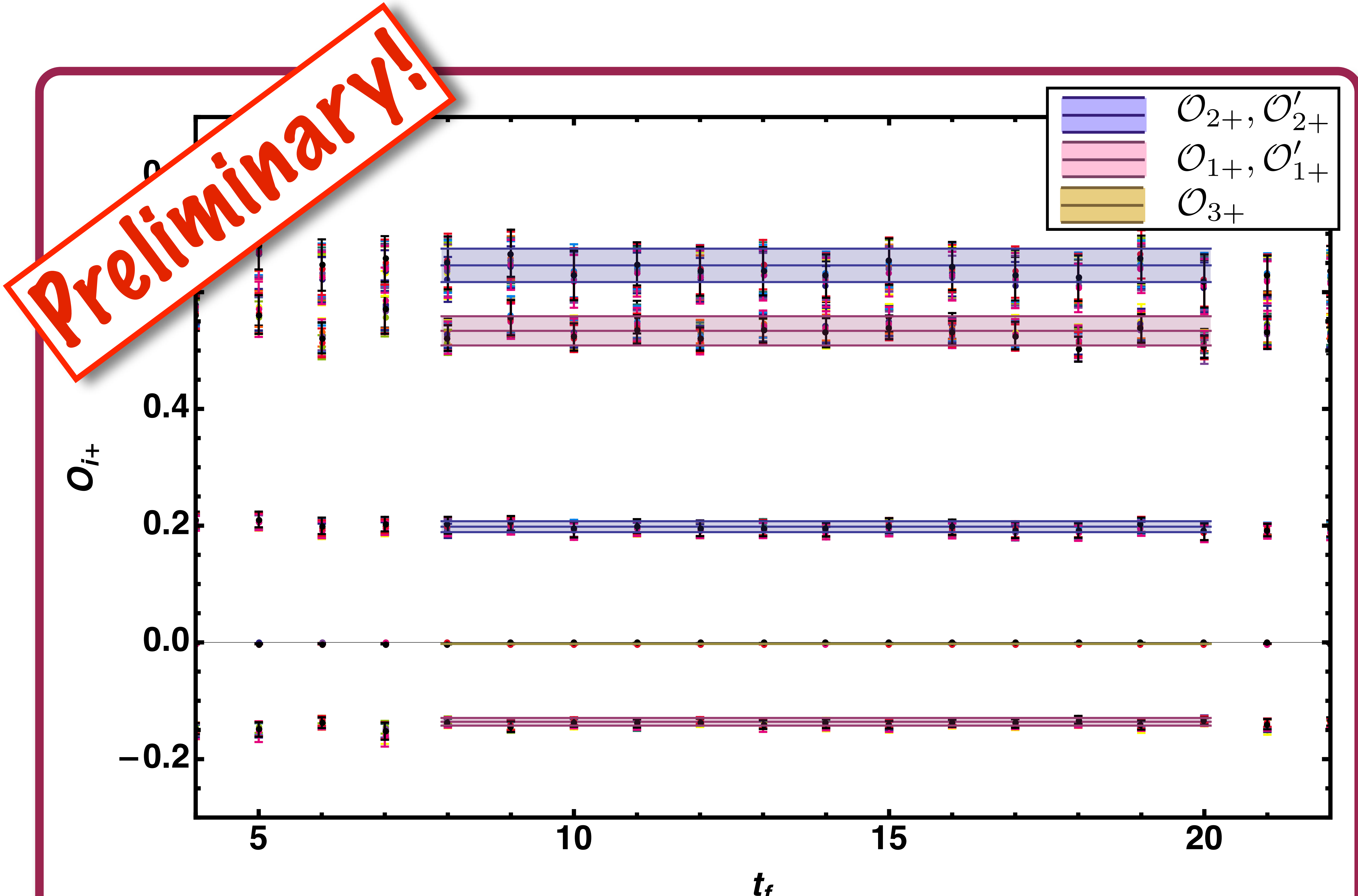
Signals



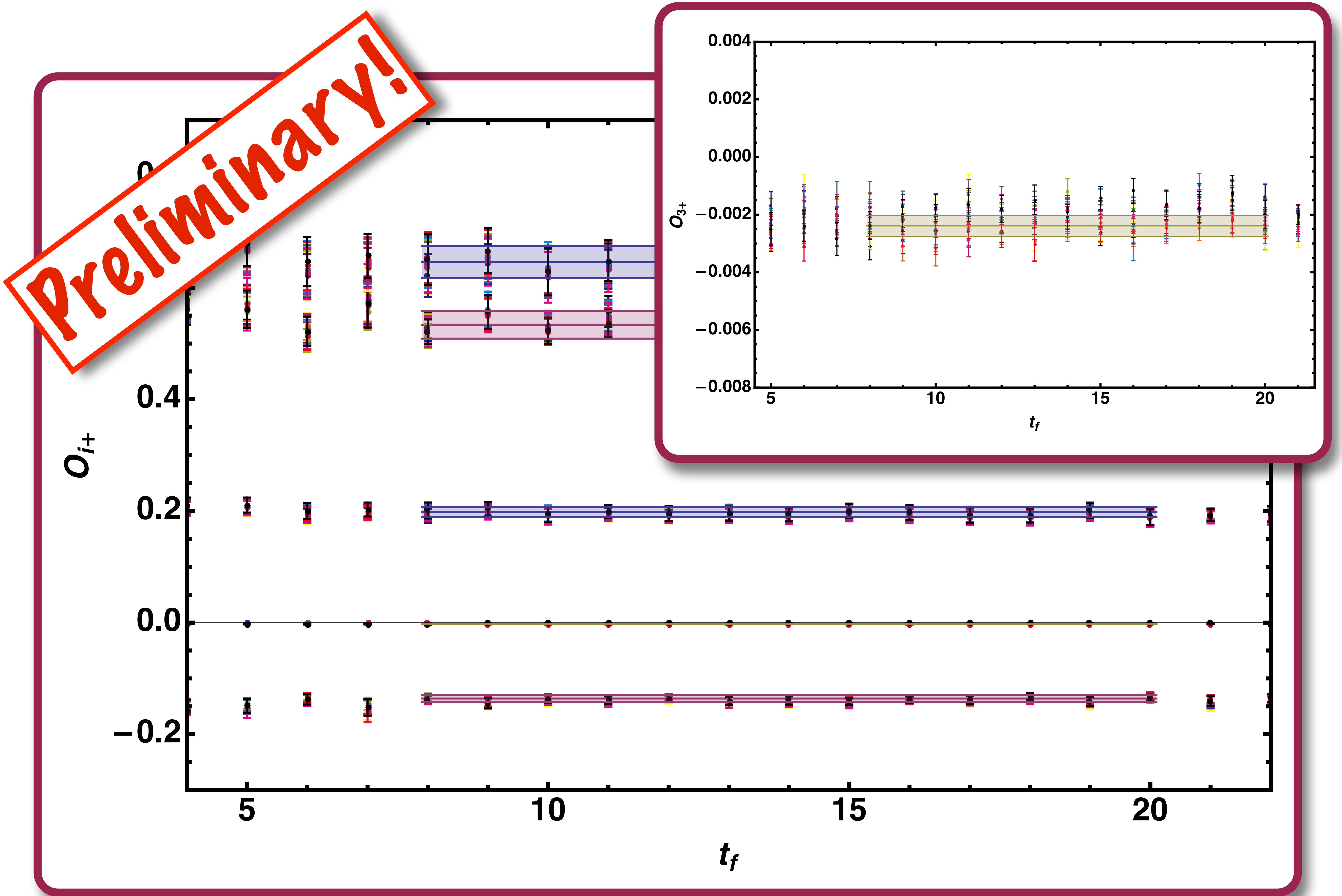




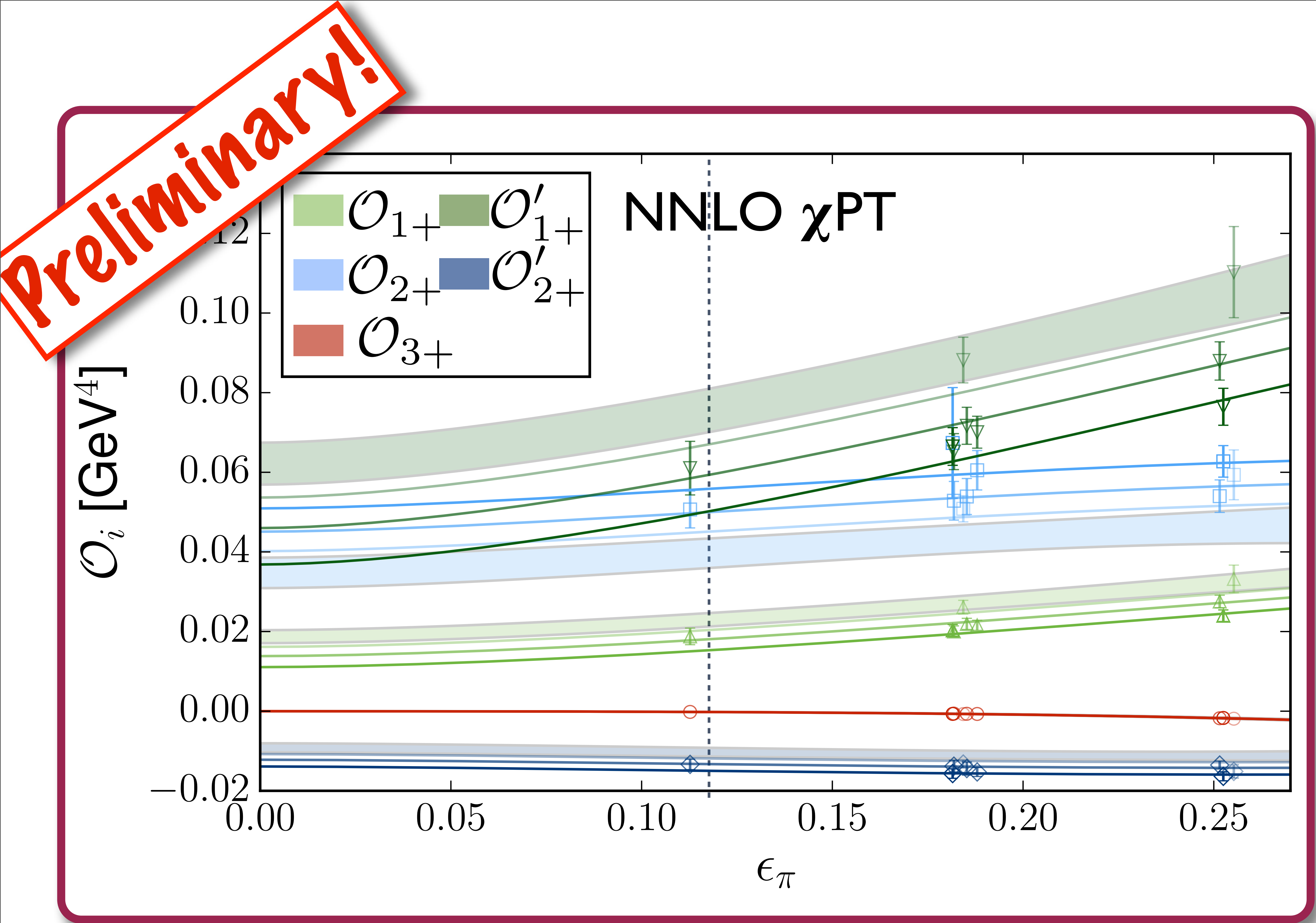
- $m_\pi \sim 135$ MeV
- L = 5.76 fm
- a = 0.12 fm

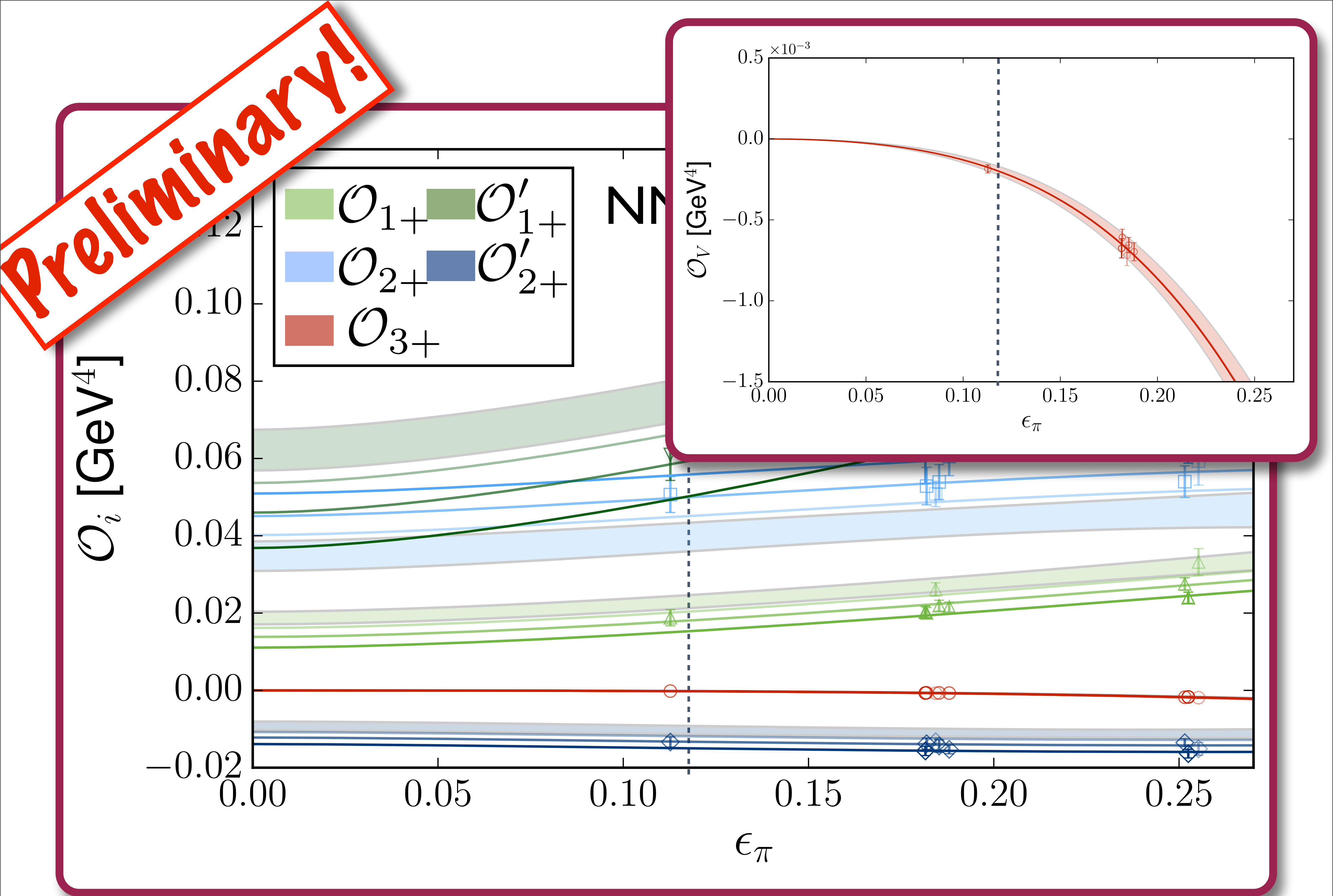


Preliminary!
$\mathcal{O}_{2+}, \mathcal{O}'_{2+}$
$\mathcal{O}_{1+}, \mathcal{O}'_{1+}$
$\mathcal{O}_{3+}$
o_{i+}
0.4
0.2
0.0
−0.2
5
10
15
20
t_f



Preliminary!
0.4
0.2
0.0
−0.2
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

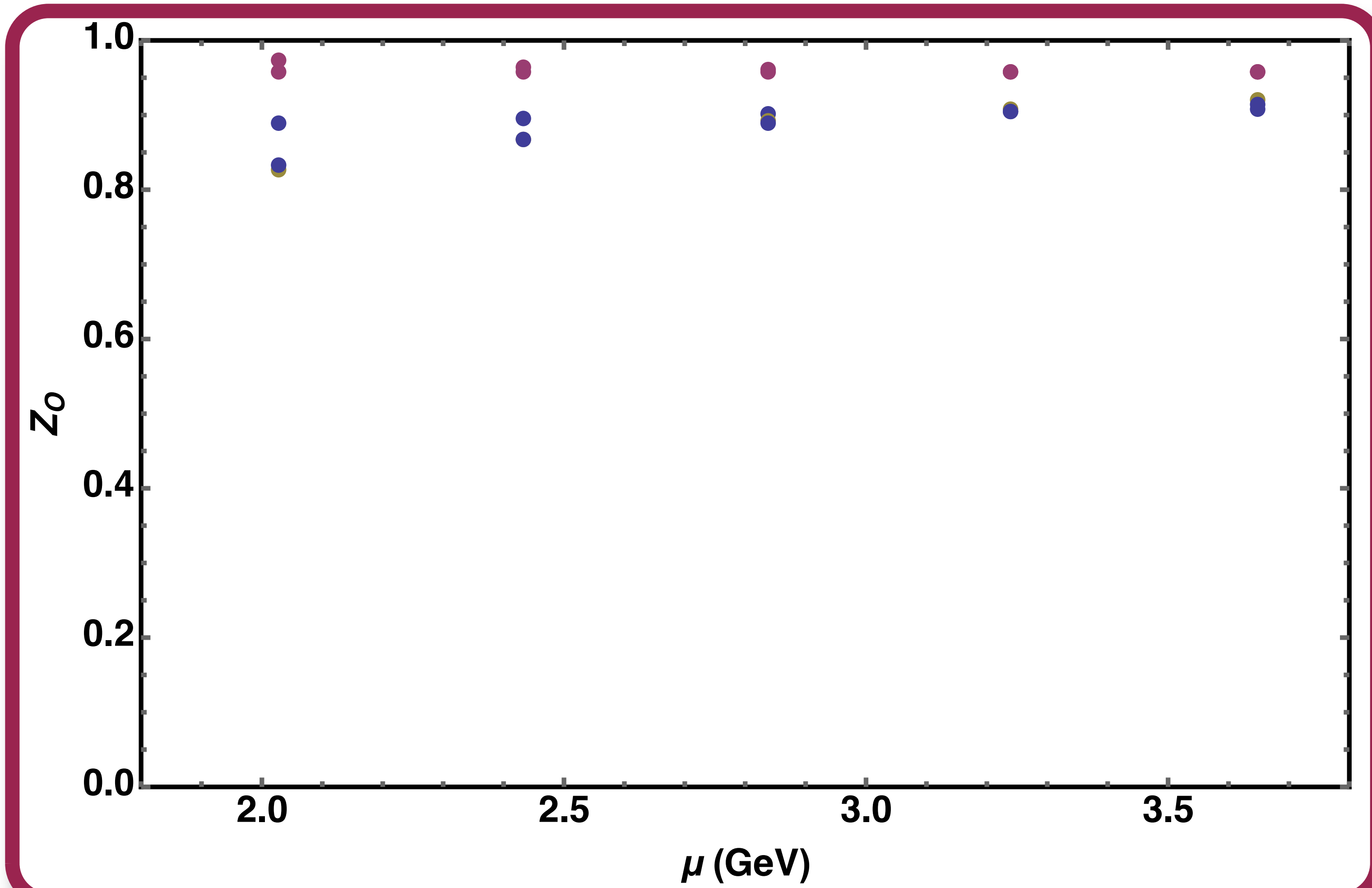

Preliminary!
NNLO χPT
$\mathcal{O}_{1+}$
$\mathcal{O}'_{1+}$
$\mathcal{O}_{2+}$
$\mathcal{O}'_{2+}$
$\mathcal{O}_{3+}$
$\mathcal{O}_i$ [GeV^4]
ϵ_π
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
0.00
0.05
0.10
0.15
0.20
0.25



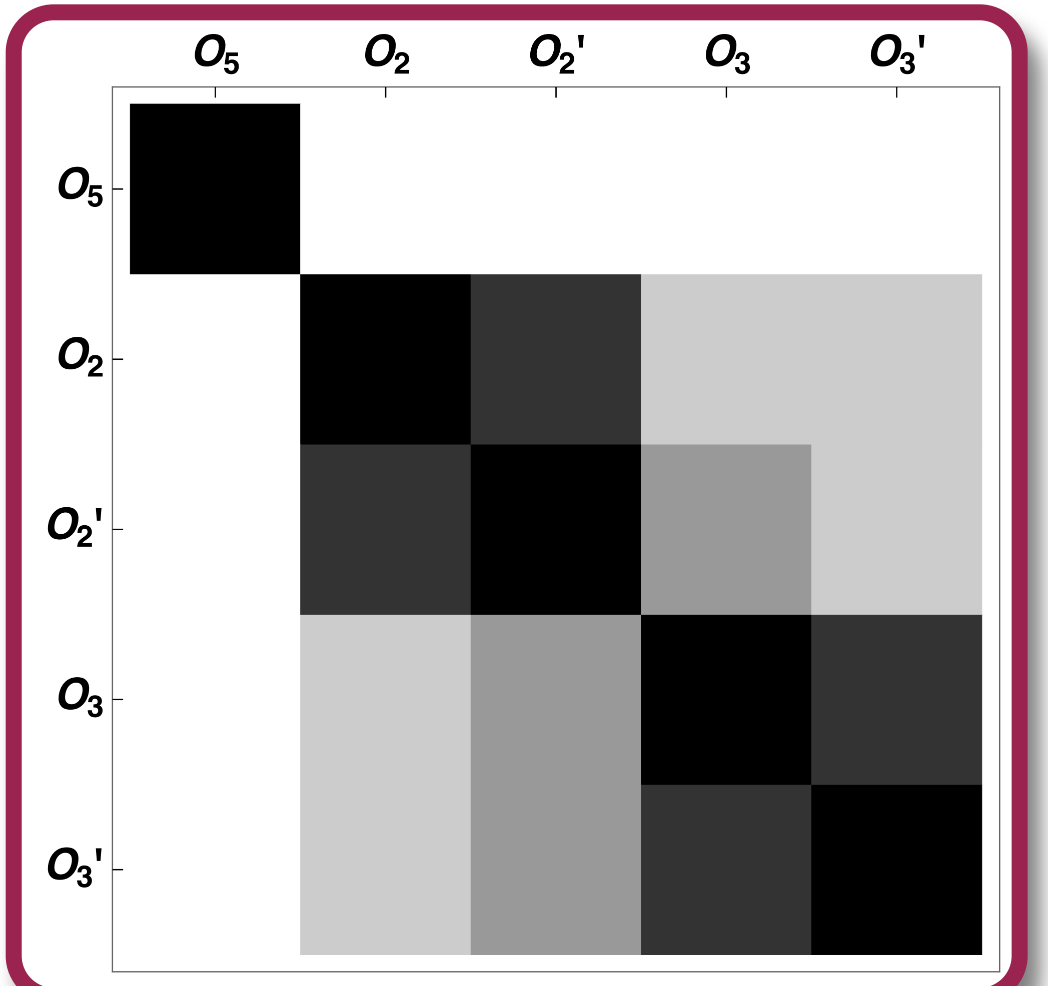
Preliminary!
$\mathcal{O}_{1+}$
$\mathcal{O}'_{1+}$
$\mathcal{O}_{2+}$
$\mathcal{O}'_{2+}$
$\mathcal{O}_{3+}$
NN
$\mathcal{O}_i$ [GeV^4]
ϵ_π
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
0.00
0.05
0.10
0.15
0.20
0.25
$\times 10^{-3}$
$\mathcal{O}_V$ [GeV^4]
0.5
0.0
−0.5
−1.0
−1.5

Renormalization

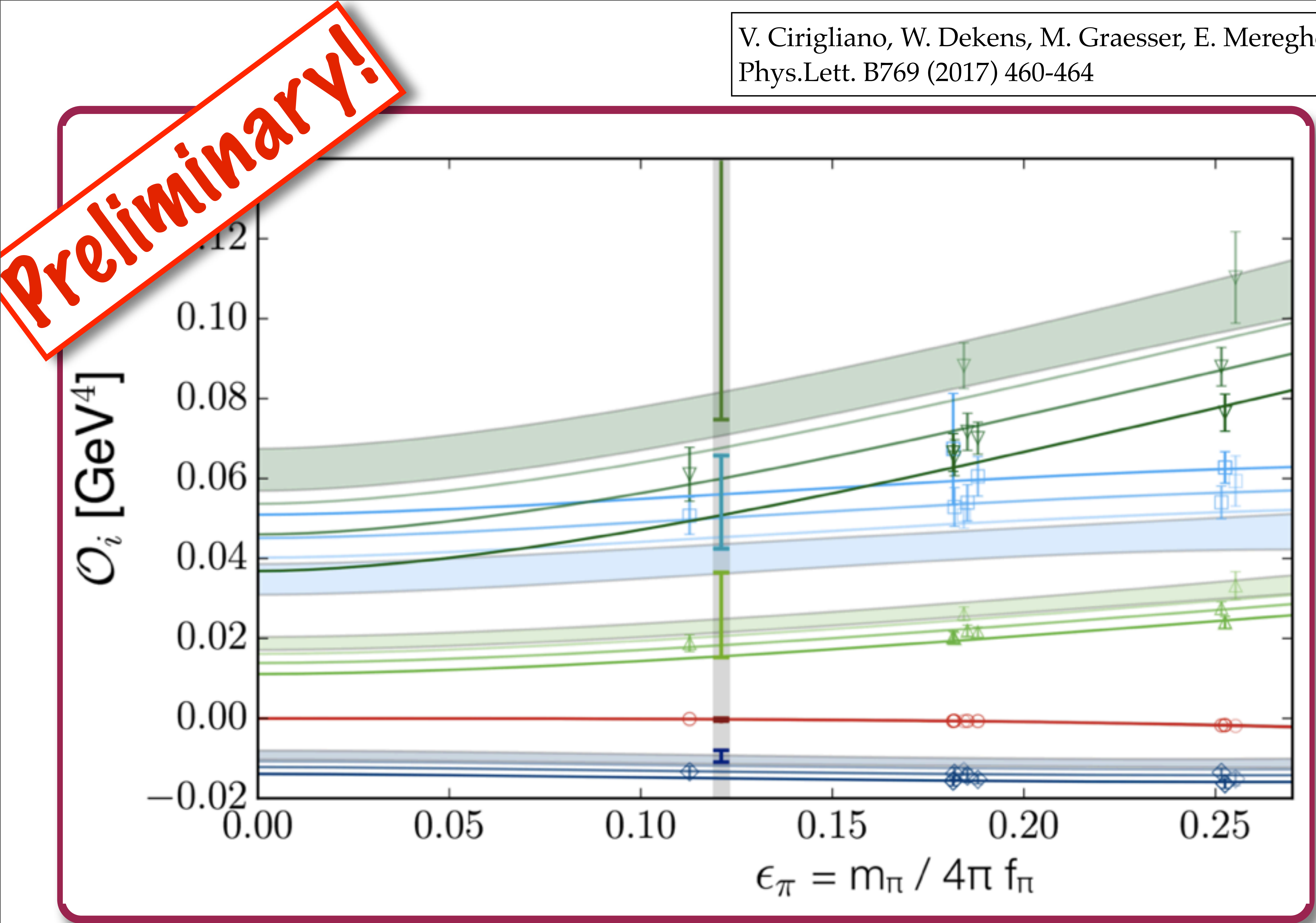
- Lattice perturbation theory is difficult and poorly convergent
- Nonperturbative running (RI-SMOM) to match onto $\overline{\text{MS}}$

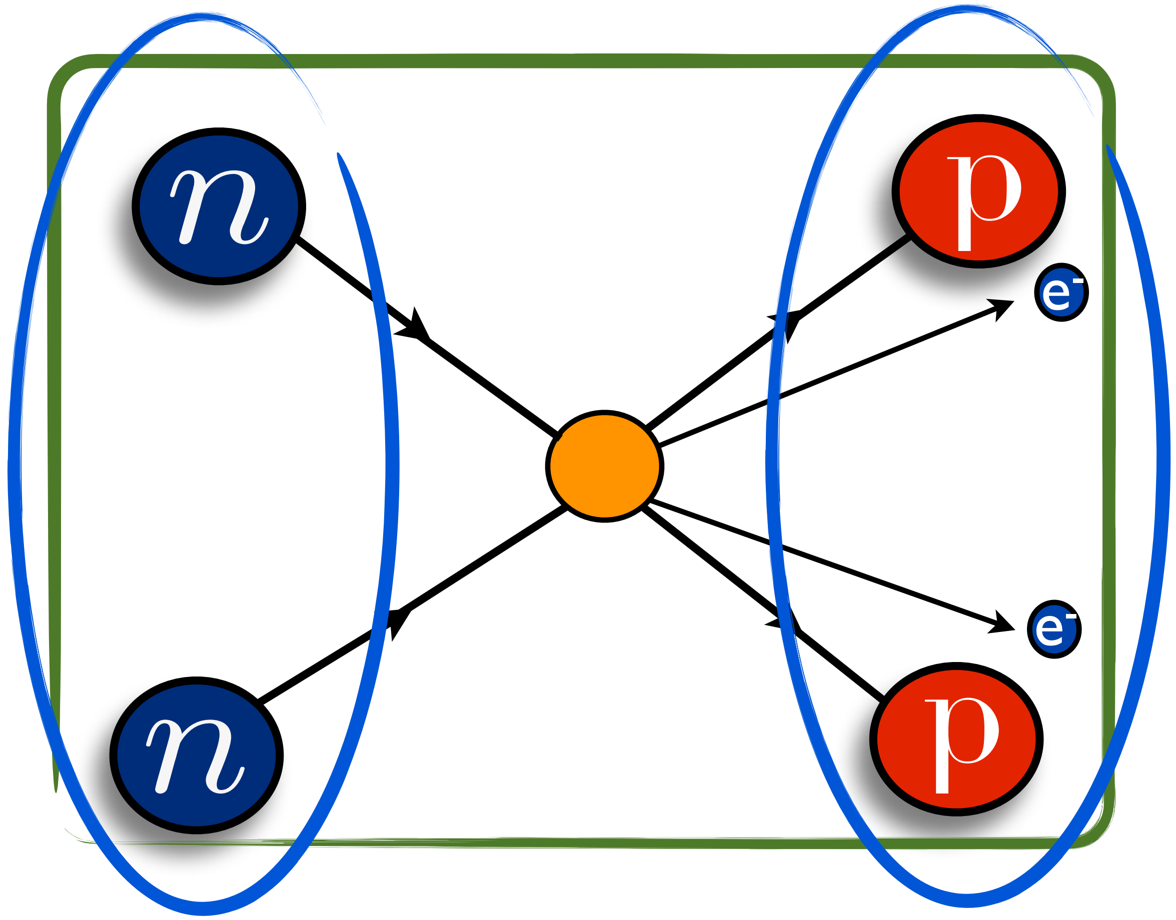


Mixing matrix



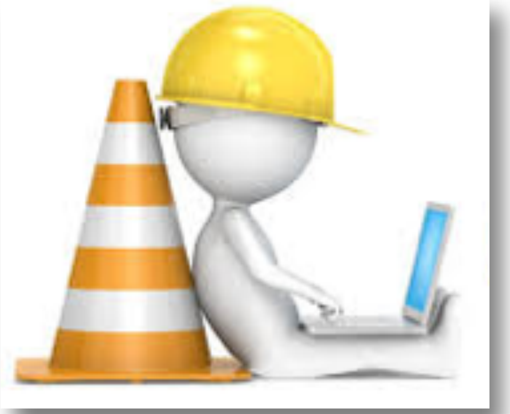
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti
Phys.Lett. B769 (2017) 460-464





3.

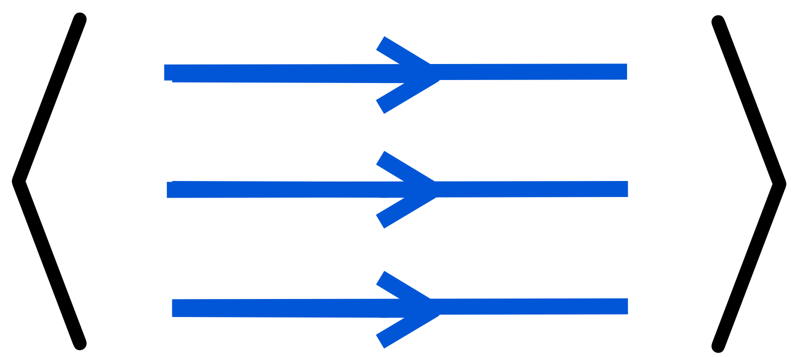
Two-nucleon contact



Two-nucleon contact

- Nucleons and multi-particle states are much more difficult!
  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...

Signal:

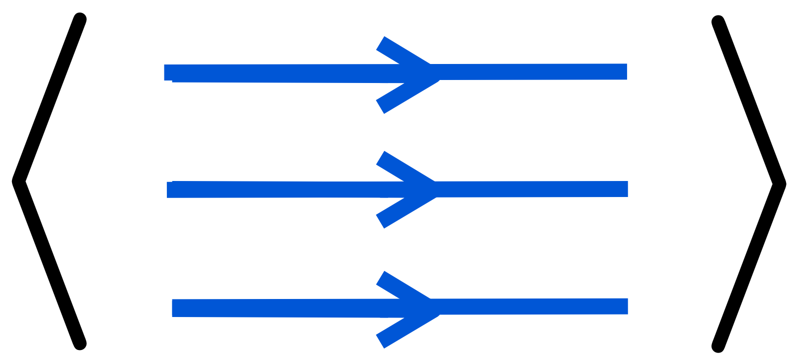


$$\xrightarrow[t\to\infty]{} Z_p e^{-M_p t}$$

Two-nucleon contact

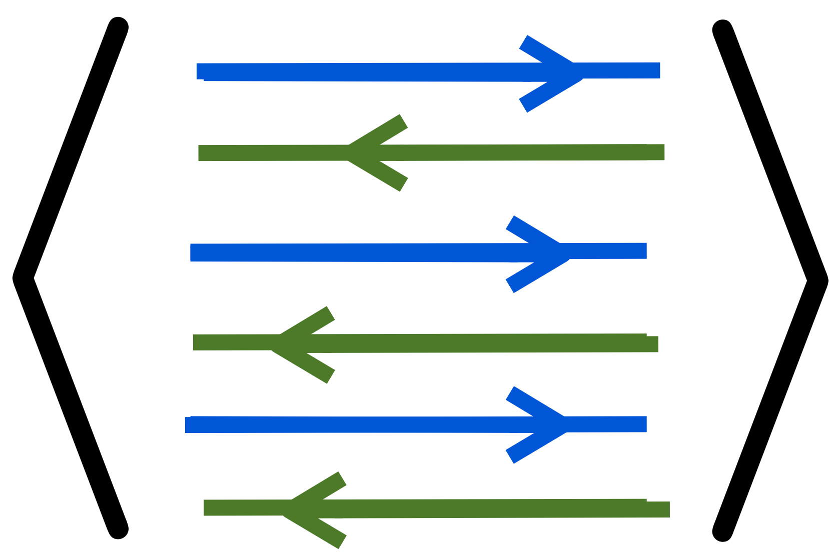
- Nucleons and multi-particle states are much more difficult!
  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...

Signal:



$$\xrightarrow[t\to\infty]{} Z_p e^{-M_p t}$$

Variance:



$$\xrightarrow[t\to\infty]{} Z_{3\pi} e^{-3M_\pi t}$$

Two-nucleon contact

- Nucleons and multi-particle states are much more difficult!
  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...

$$\frac{\text{Signal}}{\text{Noise}} \xrightarrow[t\to\infty]{} \sqrt{N_{\text{cfgs}}}\frac{Z_{Ap}}{\sqrt{Z_{3A\pi}}}e^{-A(M_p-3/2m_\pi)t}$$

Two-nucleon contact

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Exponentially large ensembles

Two-nucleon contact

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$$\frac{\text{Signal}}{\text{Noise}} \xrightarrow[t\to\infty]{} \sqrt{N_{\text{cfgs}}}\frac{Z_{Ap}}{\sqrt{Z_{3A\pi}}}e^{-A(M_p-3/2m_\pi)t}$$

Exponentially large ensembles

Heavy quark mass

Two-nucleon contact

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  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...

$$\frac{\text{Signal}}{\text{Noise}} \xrightarrow[t\to\infty]{} \sqrt{N_{\text{cfgs}}}\,\frac{Z_{Ap}}{\sqrt{Z_{3A\pi}}}\,e^{-A(M_p-3/2m_\pi)t}$$

Exponentially large ensembles

Maximize overlap

Heavy quark mass

Two-nucleon contact

- Nucleons and multi-particle states are much more difficult!
  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...

$$\frac{\text{Signal}}{\text{Noise}} \xrightarrow[t\to\infty]{} \sqrt{N_{\text{cfgs}}}\frac{Z_{Ap}}{\sqrt{Z_{3A\pi}}}e^{-A(M_p-3/2m_\pi)t}$$

Exponentially large ensembles

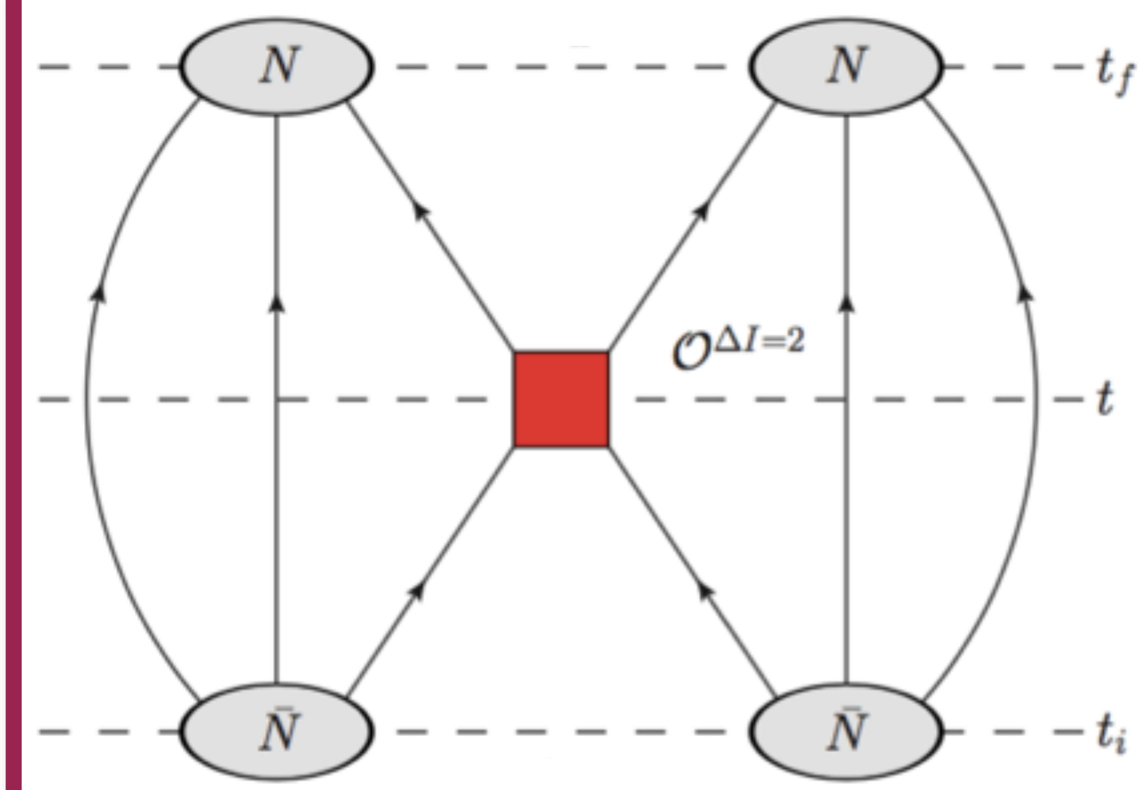
Maximize overlap

Heavy quark mass

M. Wagman, M. Savage arXiv:1704.07356

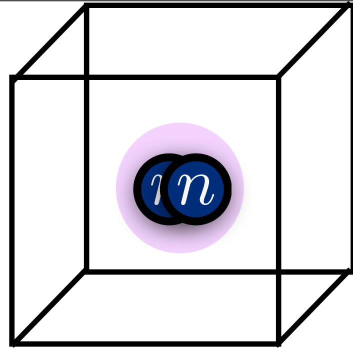
Two-nucleon contact

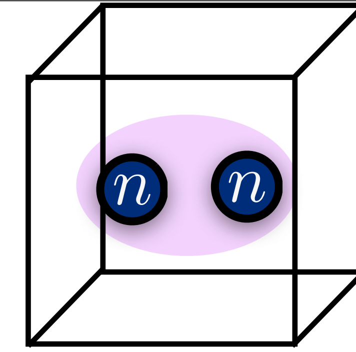
- Nucleons and multi-particle states are much more difficult!
  - exponentially poor signal-to-noise problem, small excited state energy splittings, ...
- Isospin limit: 576 contractions*
- Must deal with multi-particle states in a finite volume✱
- Ops must be in position space
  - otherwise all-to-all propagators connect to 4-quark operator

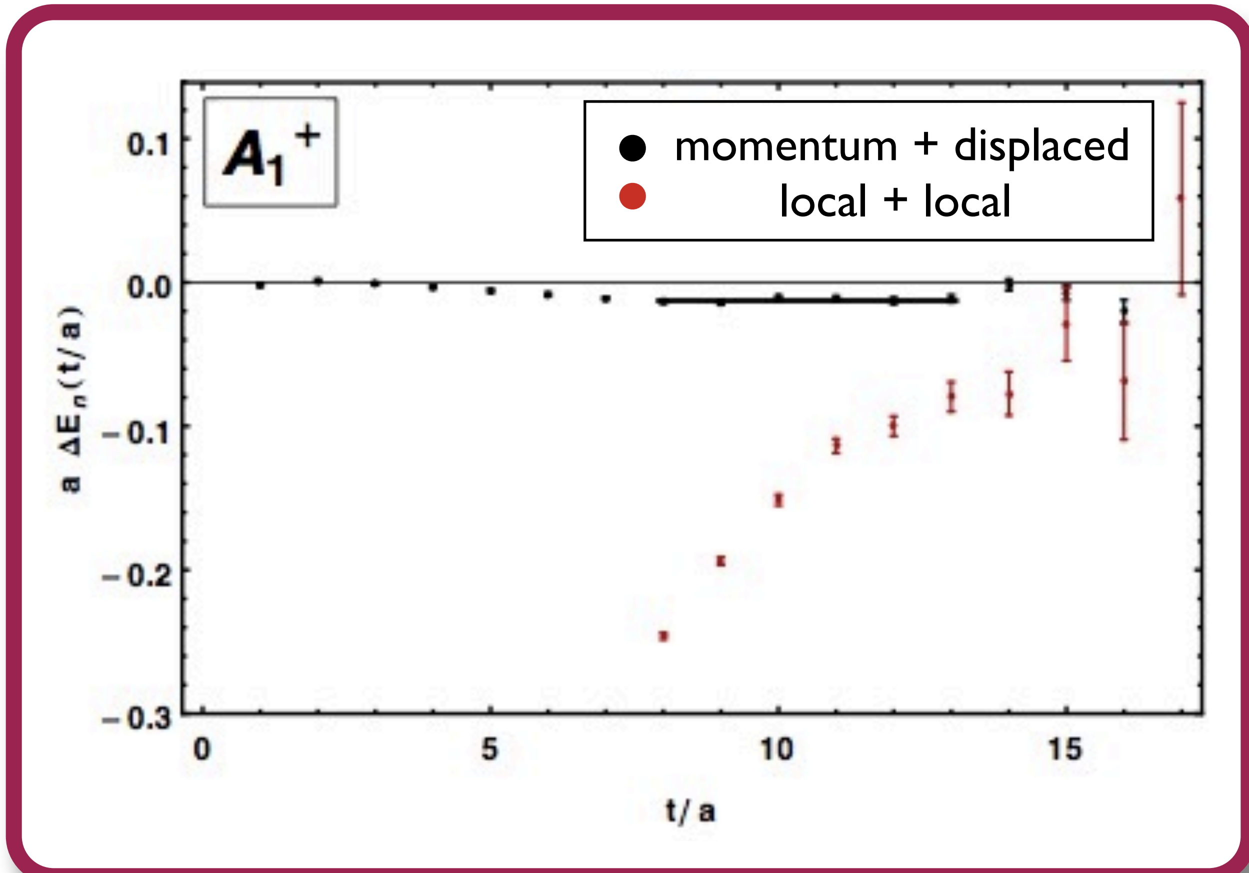


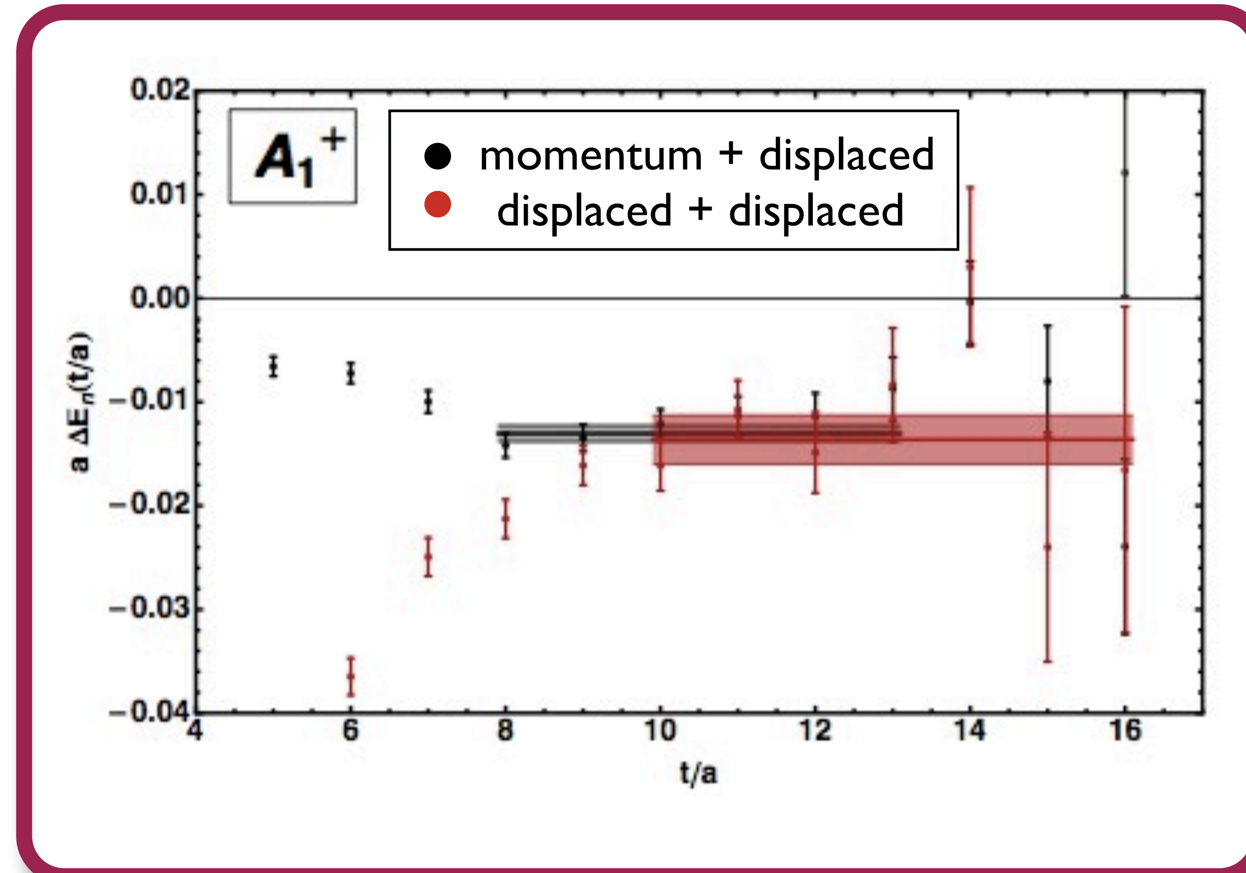
*Doi & Endres, Originos et. al., Günther et. al.

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





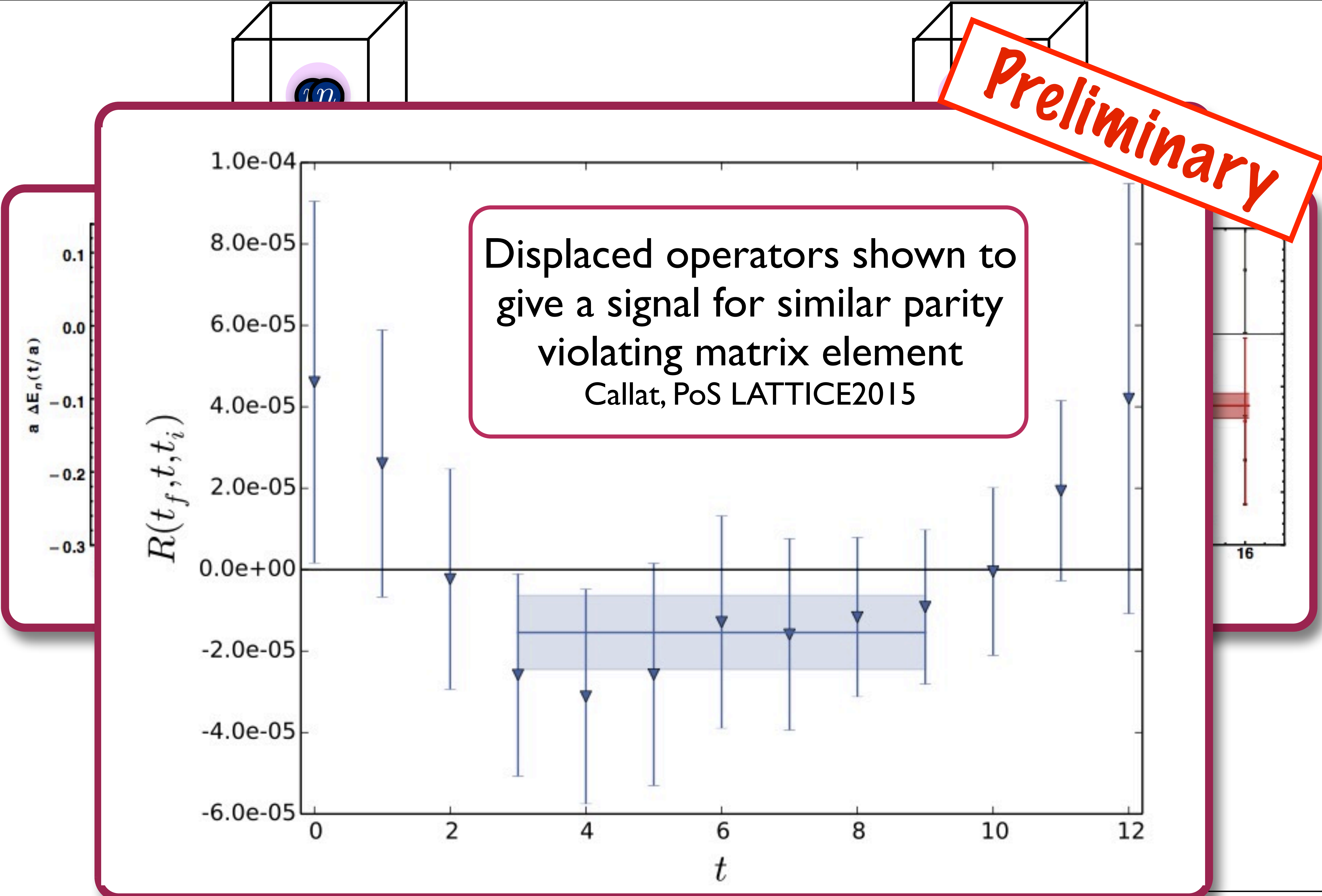




Need displaced operators

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

Callat arXiv:1508.00886 (2015)

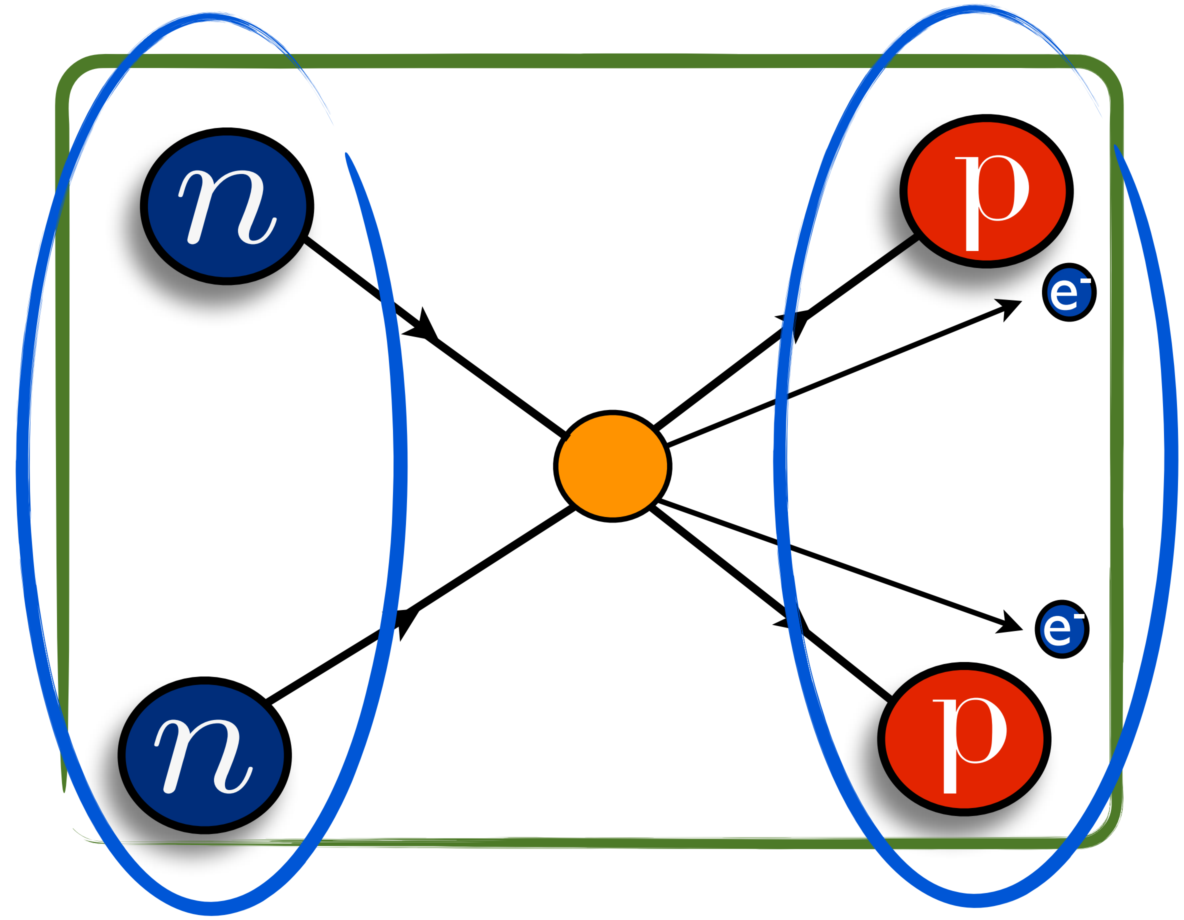


Iso-clover cfgs, m_π~800 MeV (W. Detmold, R.Edwards, D. Richards, K. Orginos)

Callat arXiv:1508.00886 (2015)

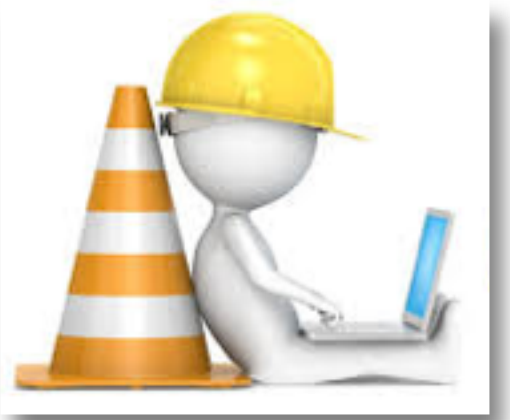
3.

Two-nucleon contact

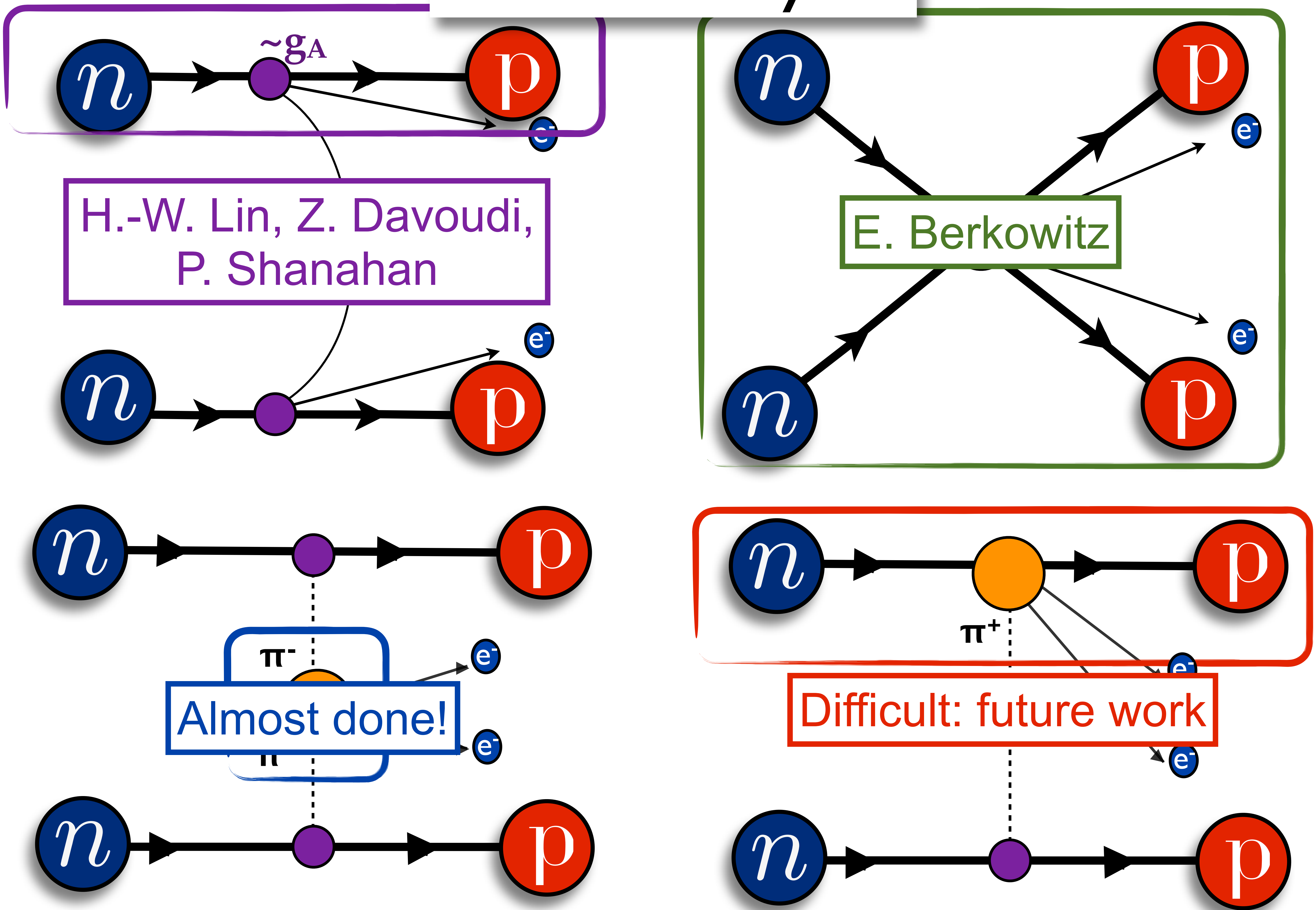


- Some new developments:
  - Exponentially improved NN operators
    - will allow us to lower the pion mass
  - HOBET in a periodic box
    - more direct path from finite volume lattice results to nuclear many-body techniques (W. Haxton & K. McElvain)

See E. Berkowitz's talk for updates



Summary



~gA
n
p
e-
H.-W. Lin, Z. Davoudi,
P. Shanahan
E. Berkowitz
π-
π+
Almost done!
Difficult: future work

- 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
- CCNY: B. Tiburzi