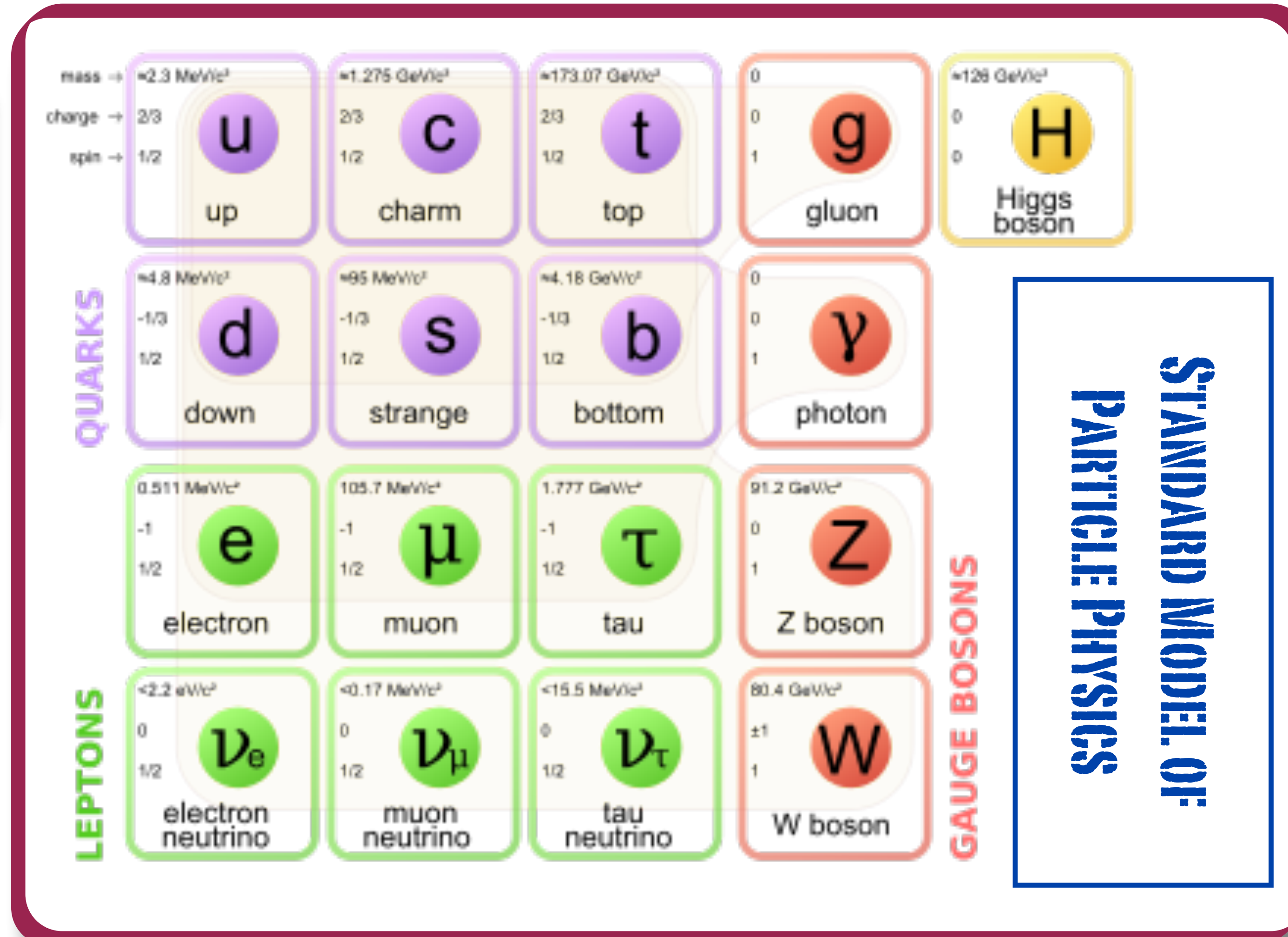
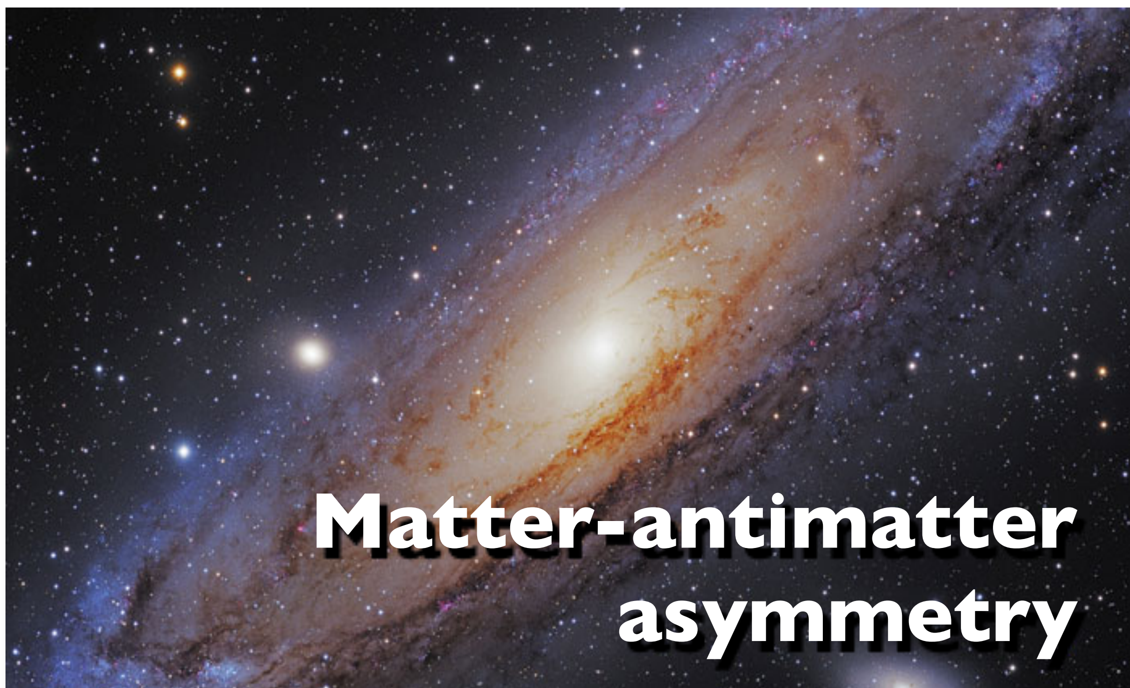
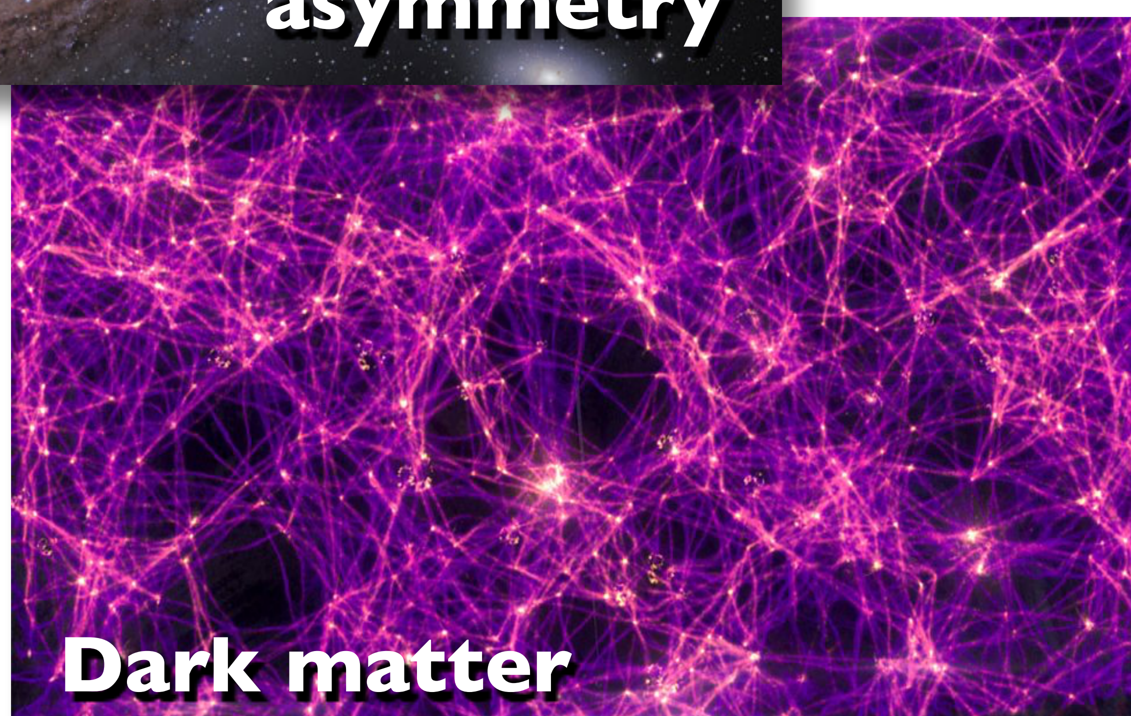
Neutrinoless double beta decay:
what can lattice QCD teach us beyond the Standard Model

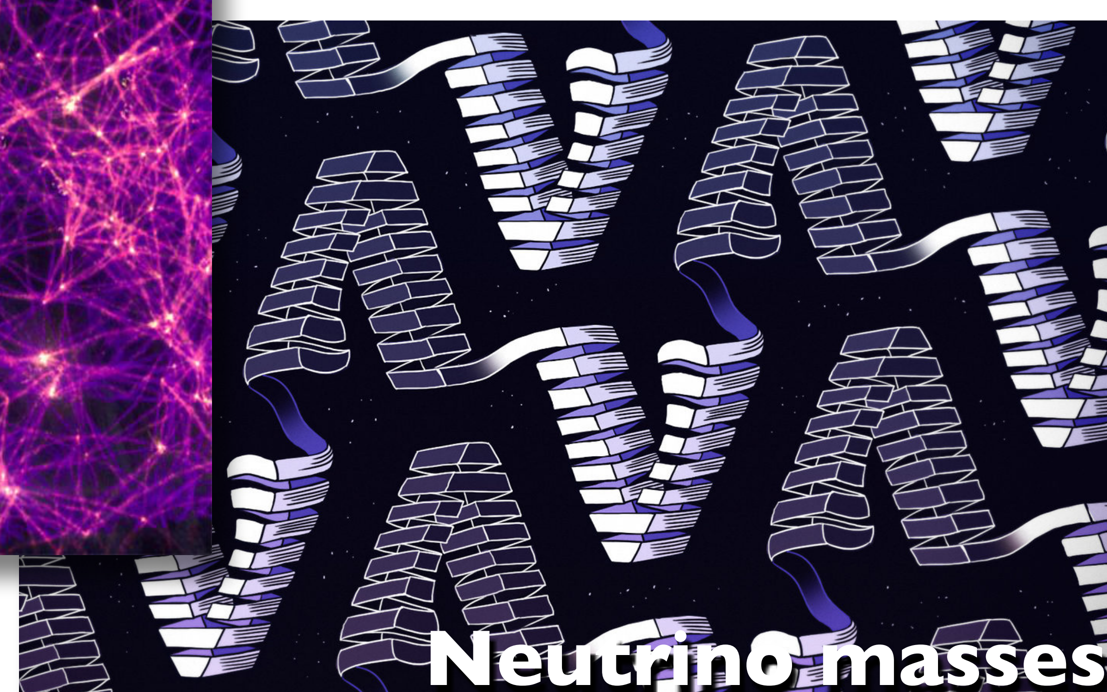
Amy Nicholson
UNC, Chapel Hill
Summer School on
"Frontiers in Lattice QCD"
Peking University, July 8, 2019

The Standard Model and Beyond









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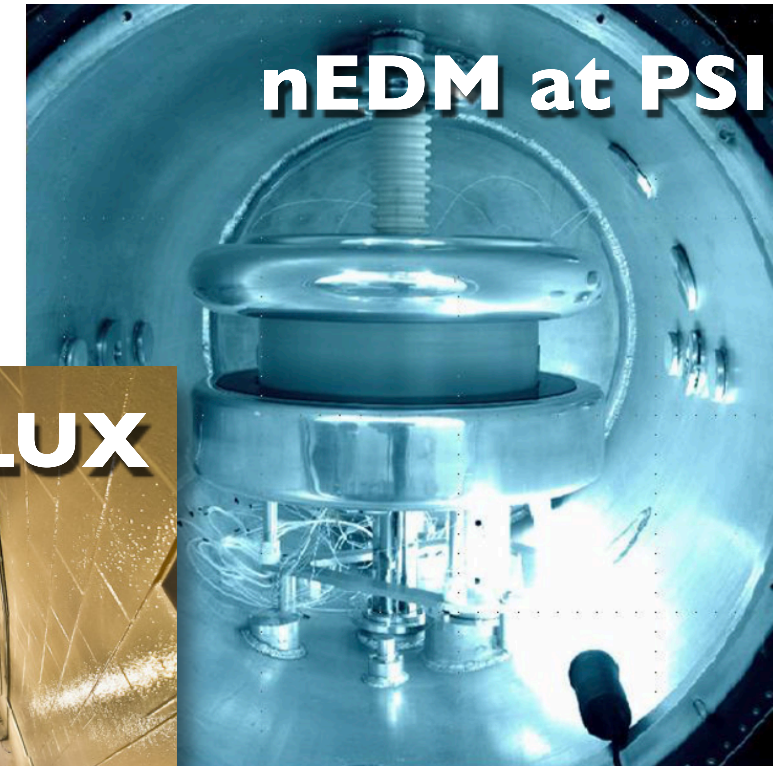

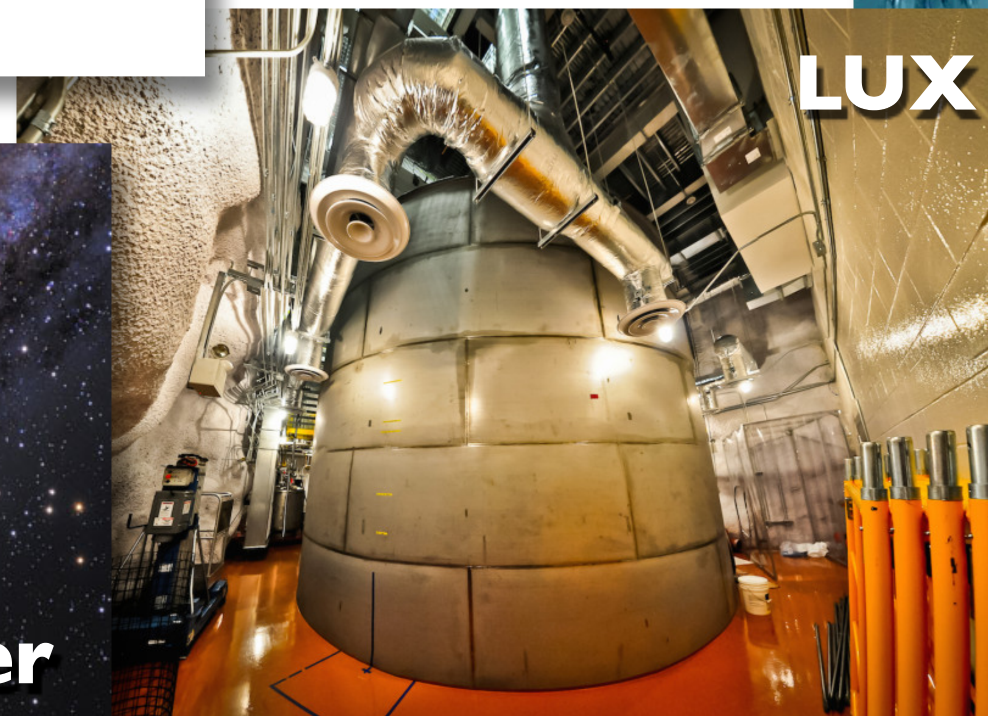

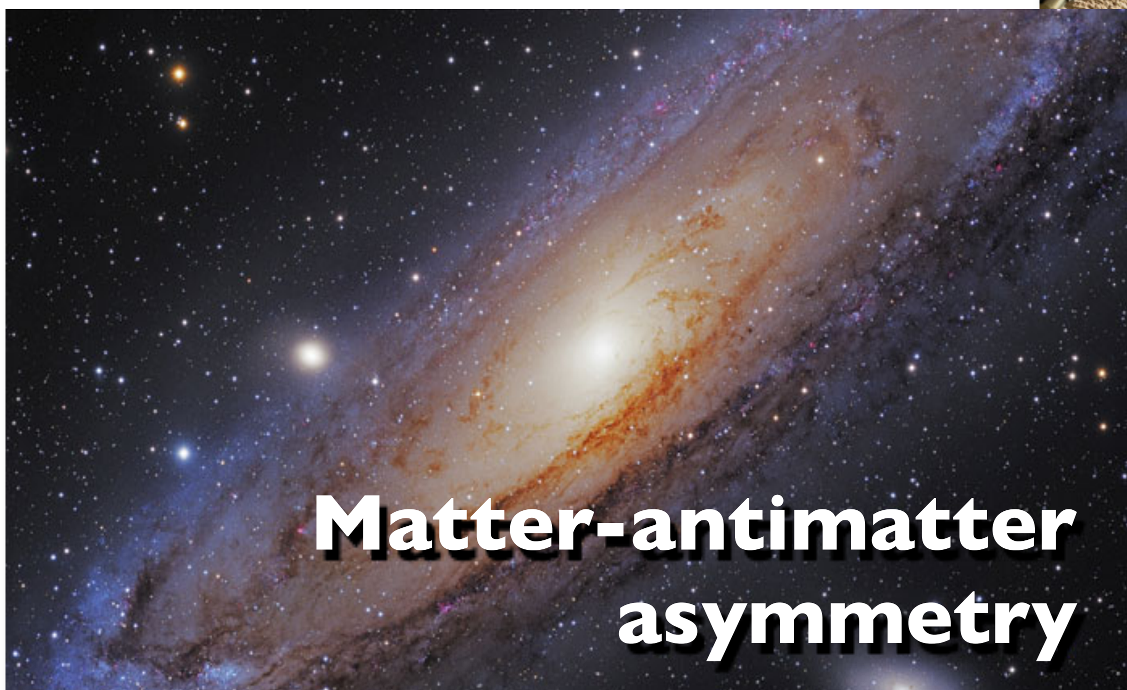

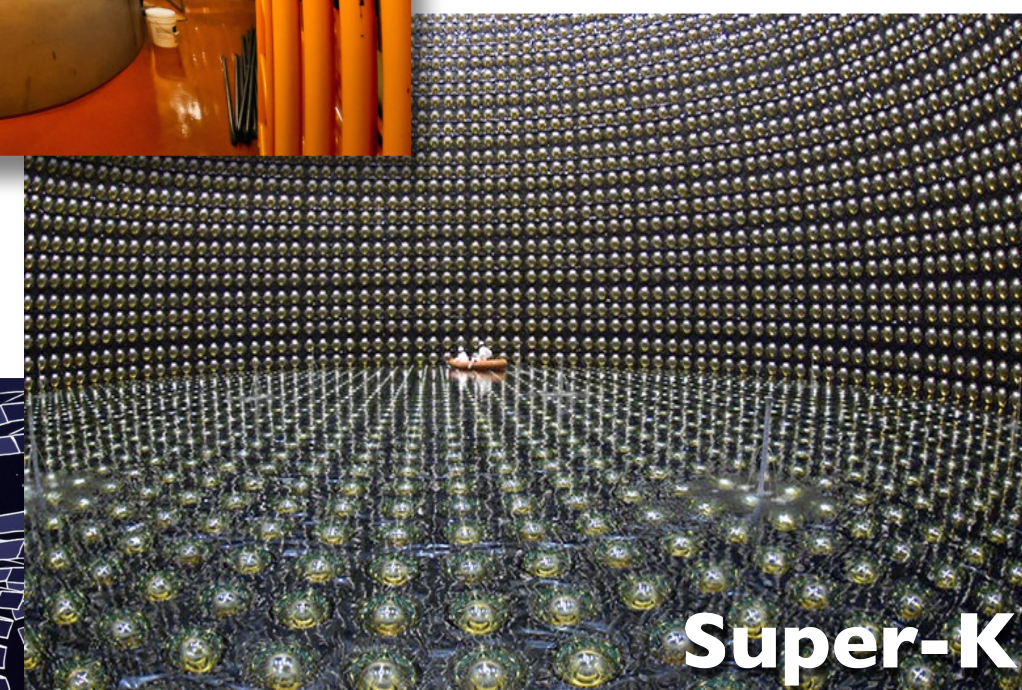

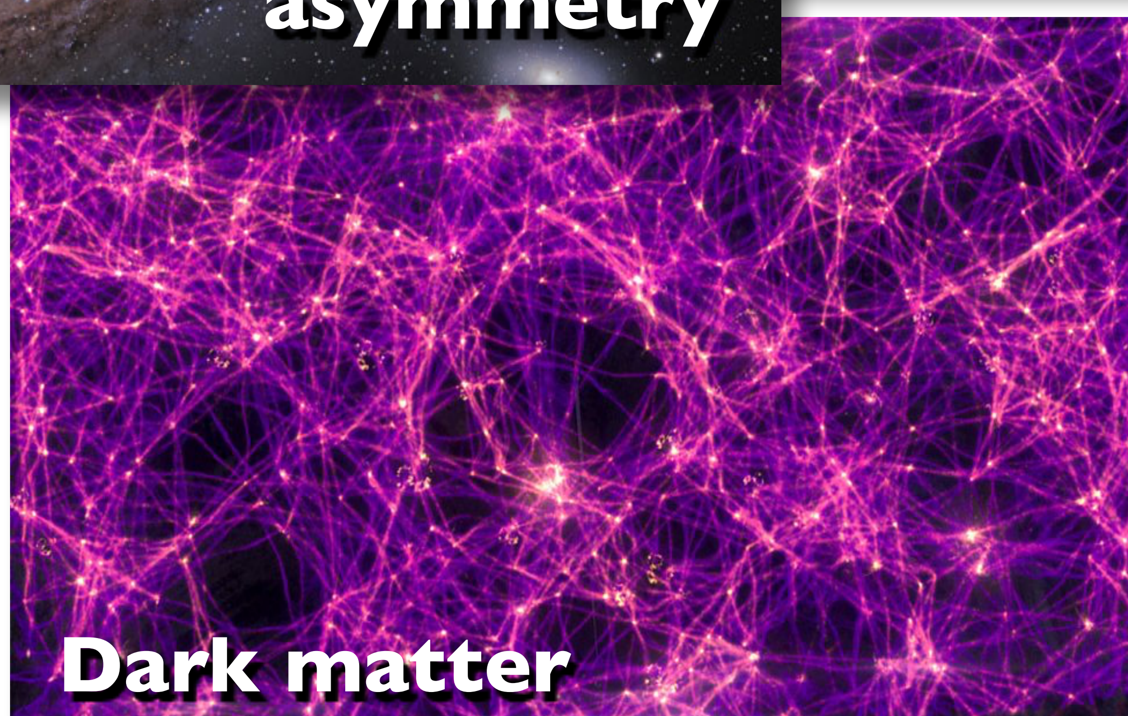

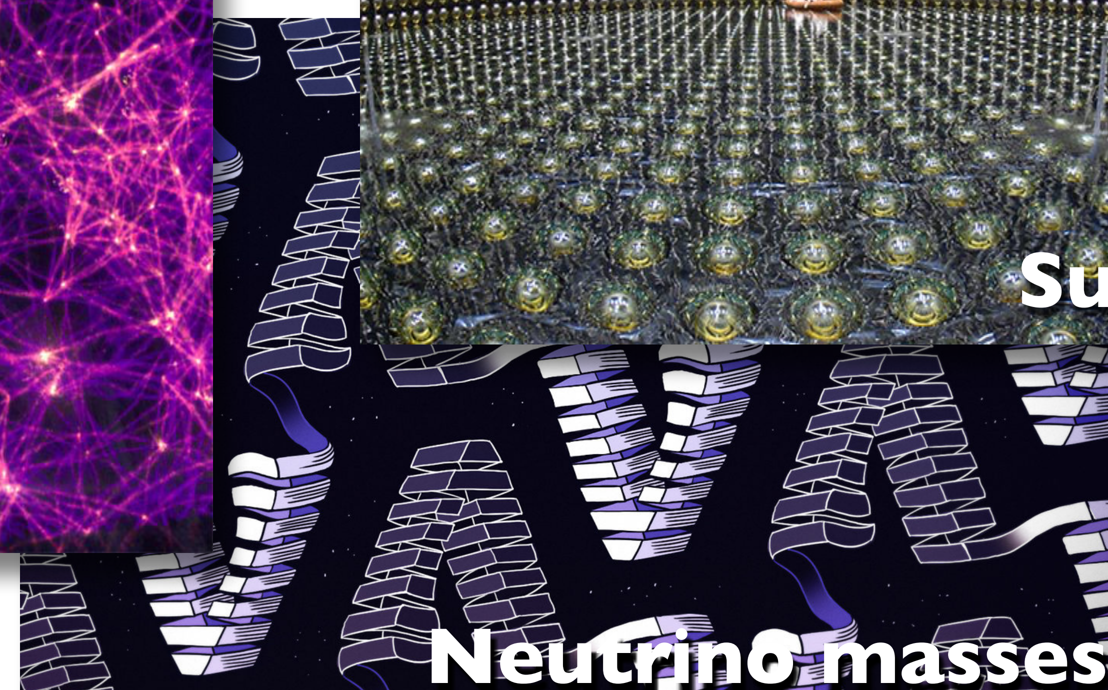

How can a solution of QCD teach us about new physics?

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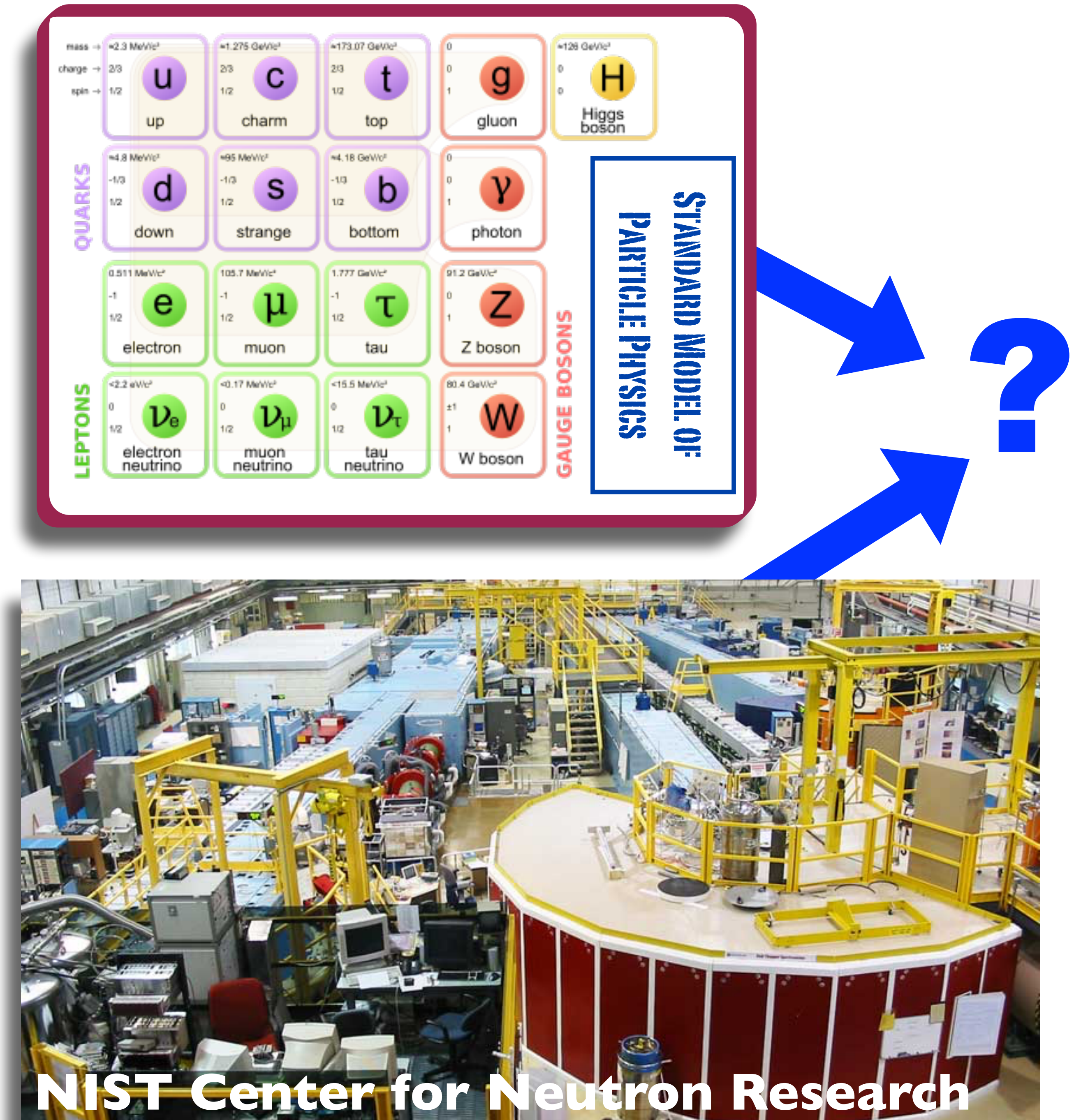

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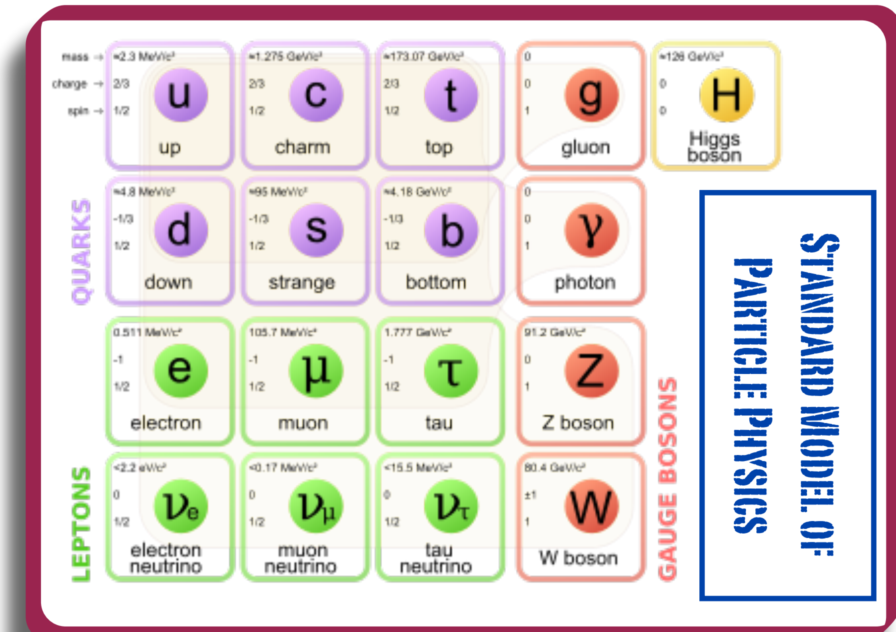

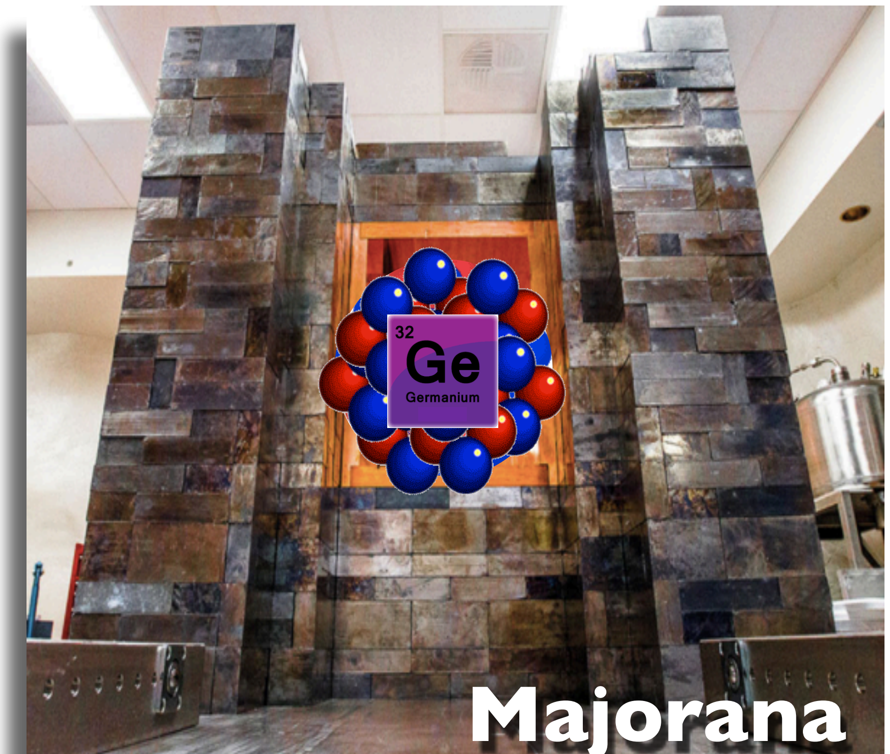

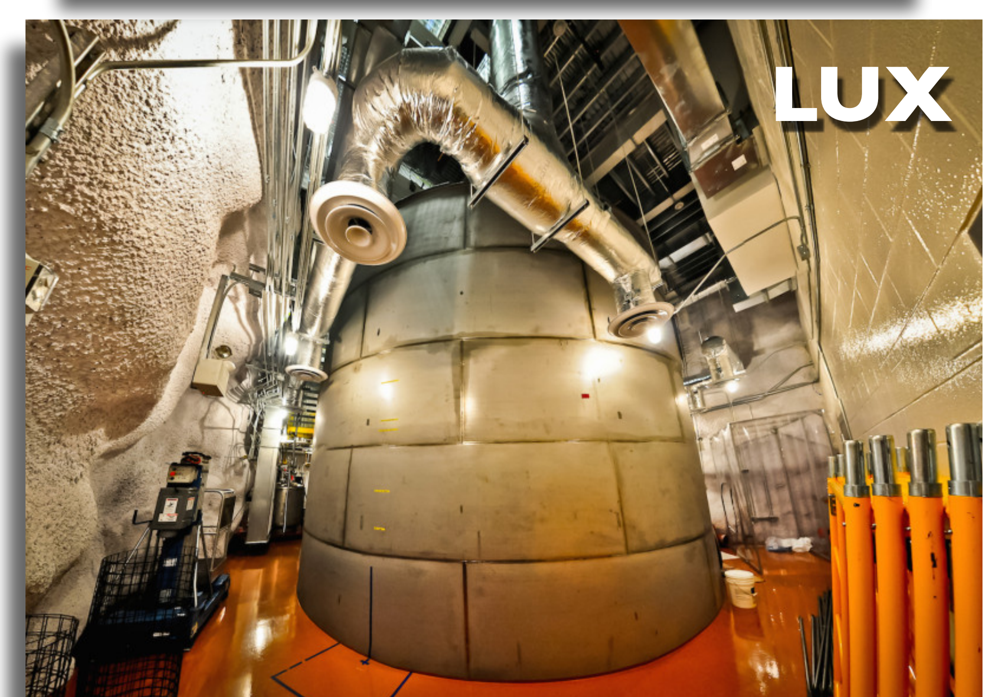

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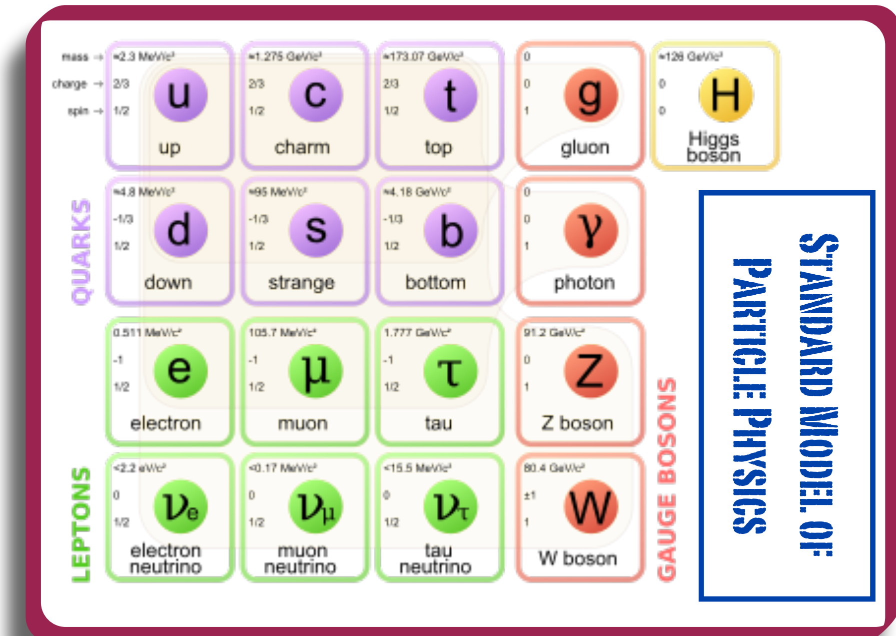
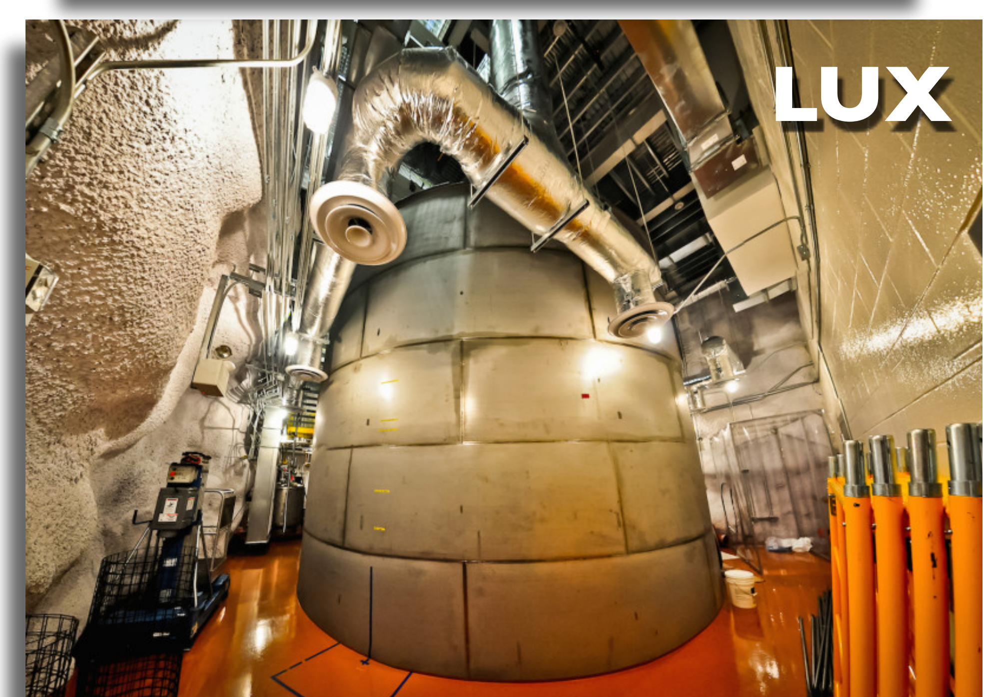
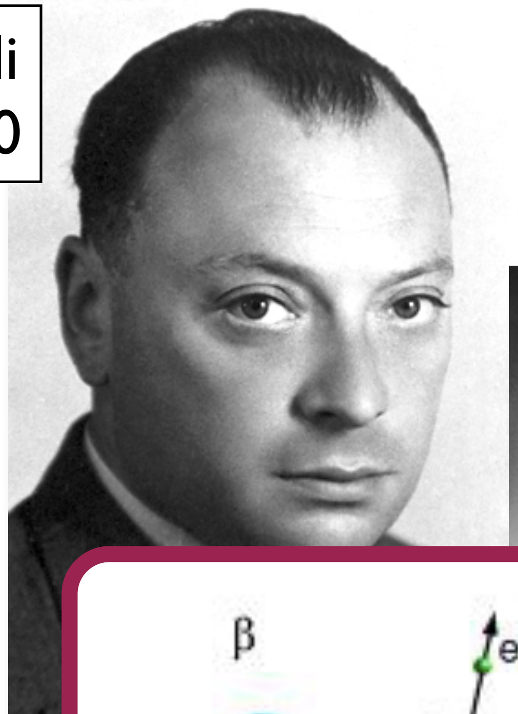
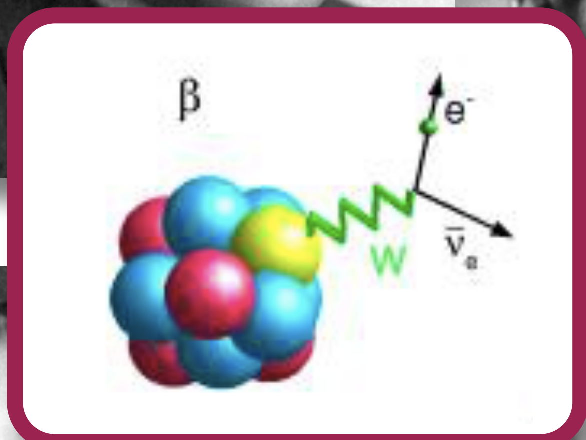


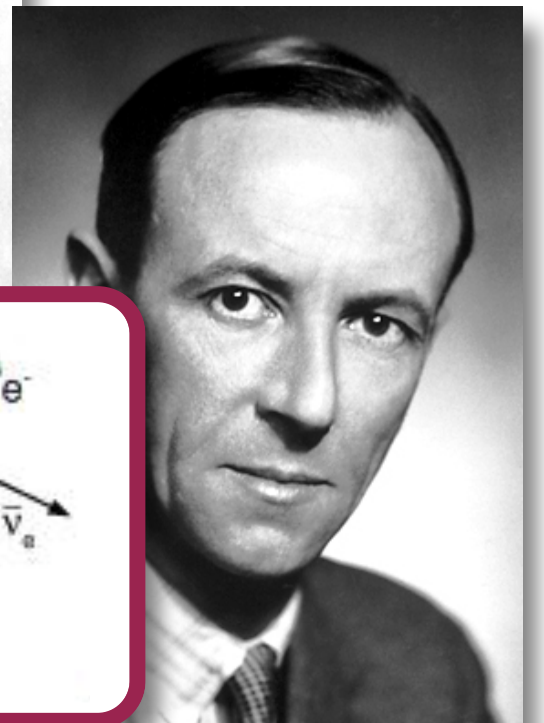


Neutrinoless Double Beta Decay

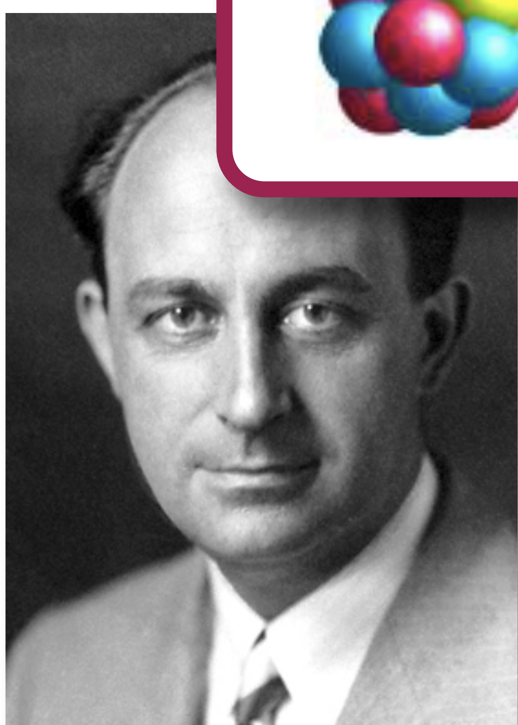
Pauli
1930



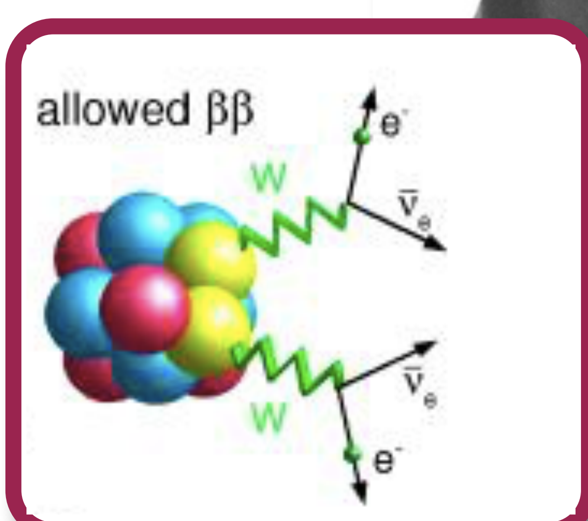




Chadwick
1932



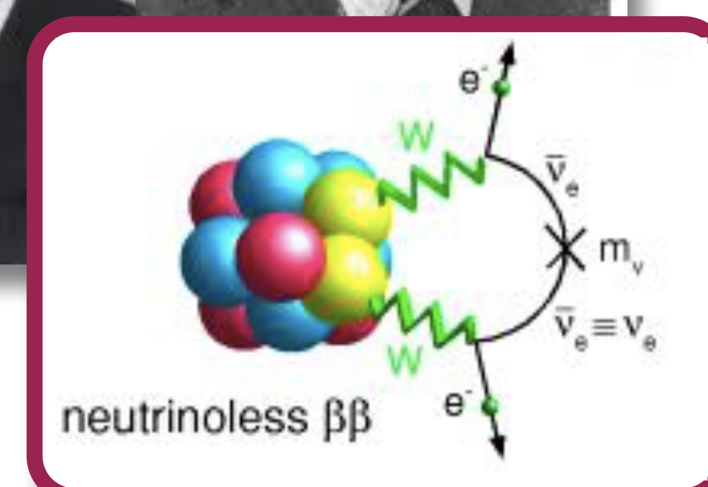
Fermi
1934



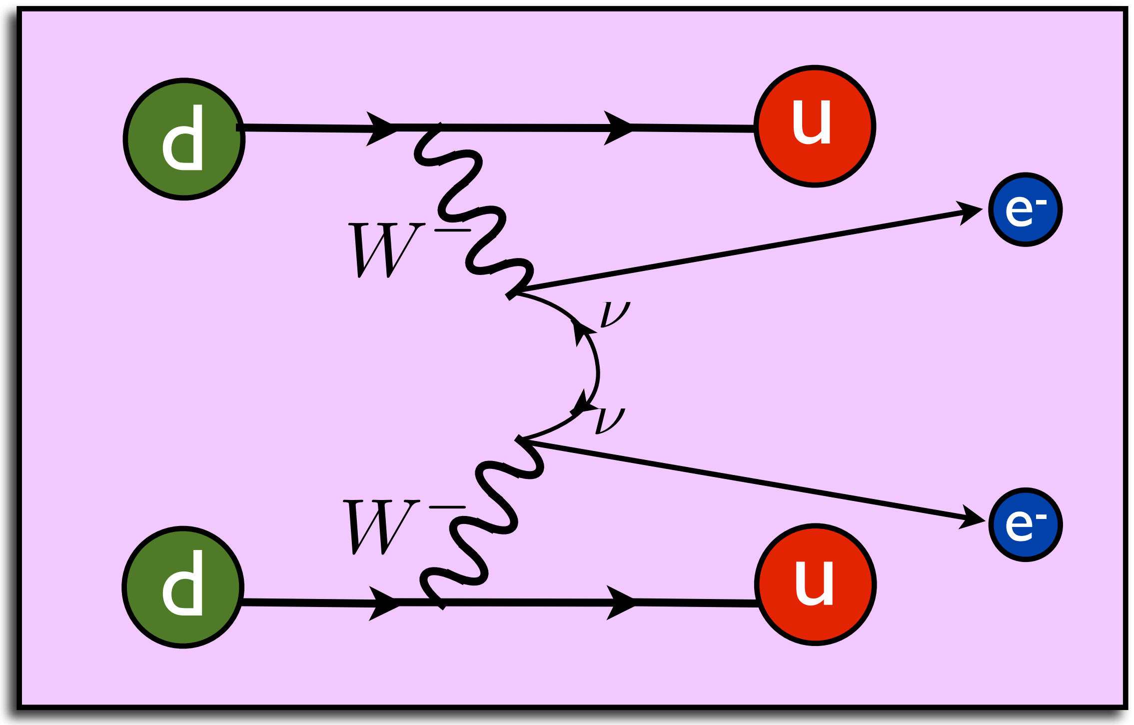
Goppert-Mayer
1935

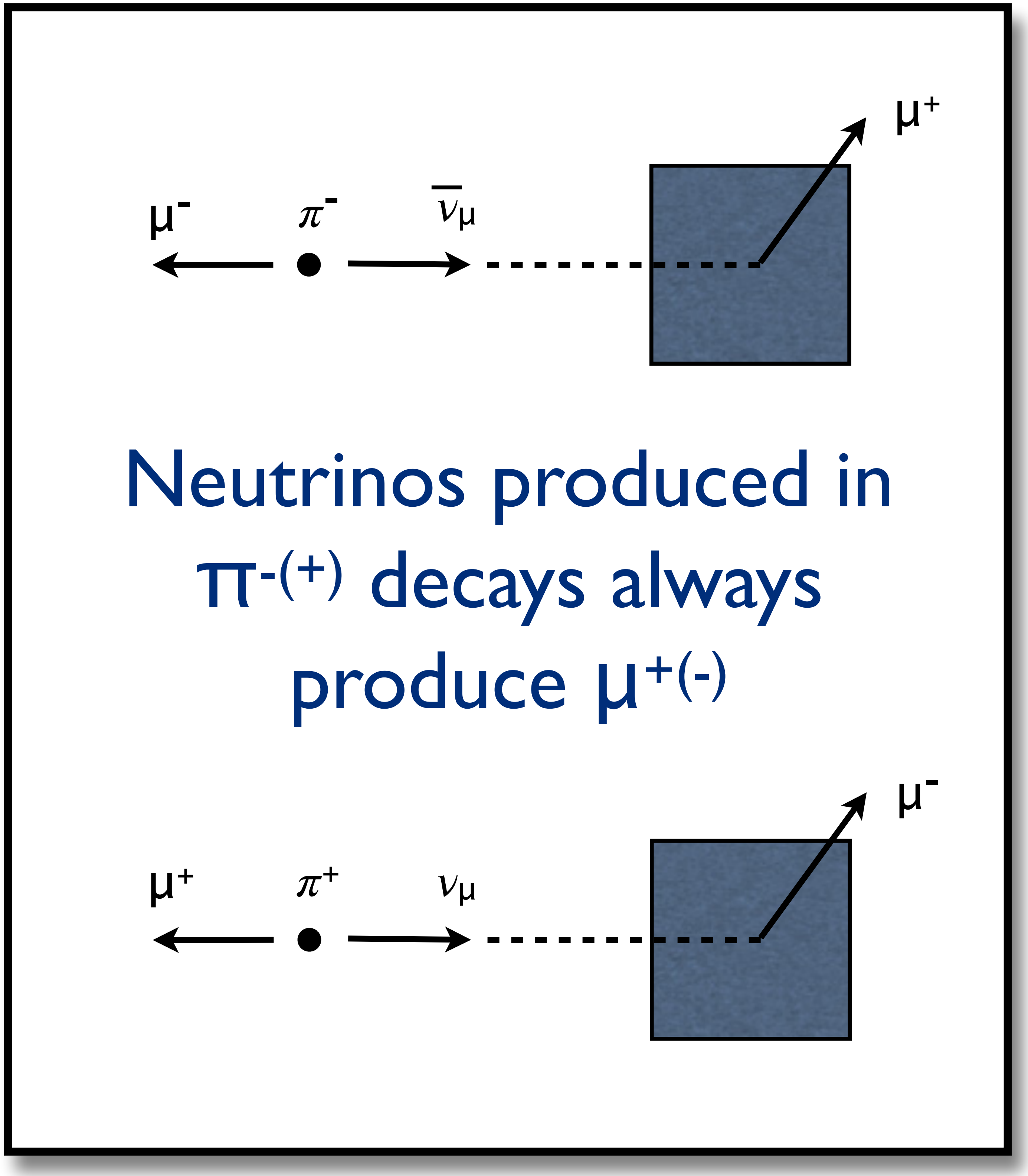
Majorana
1937

Racah
1937



Neutrinos & Symmetries





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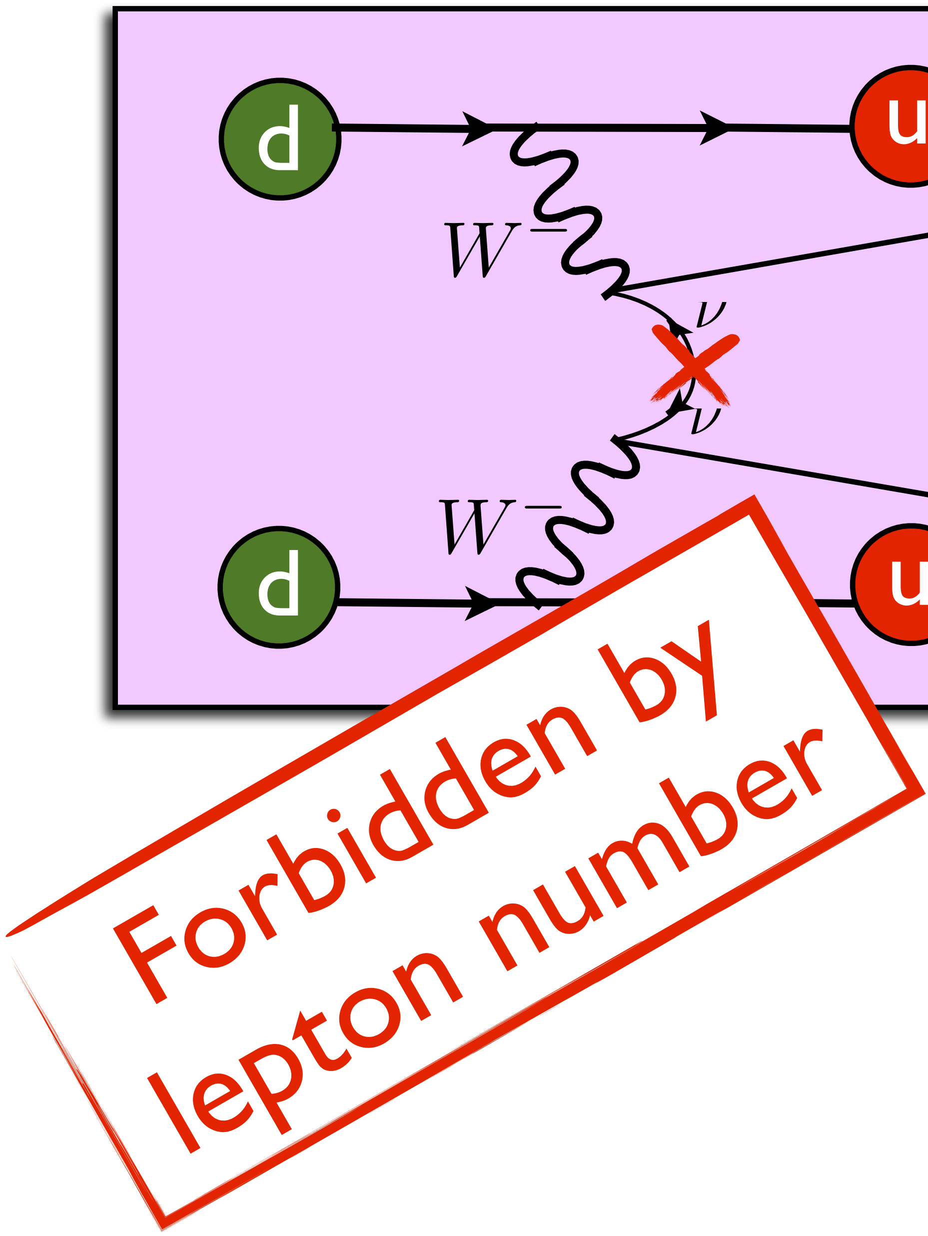

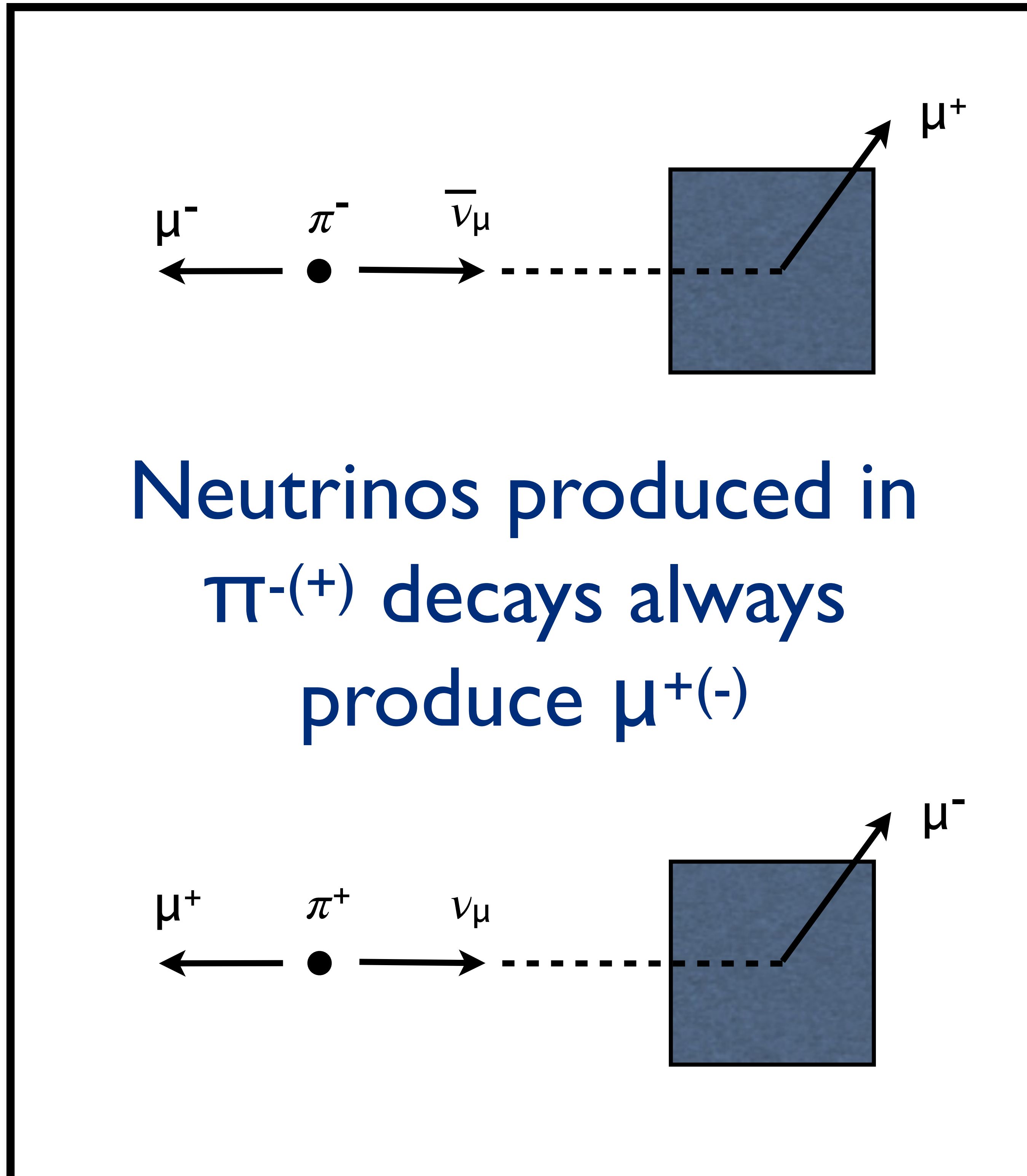

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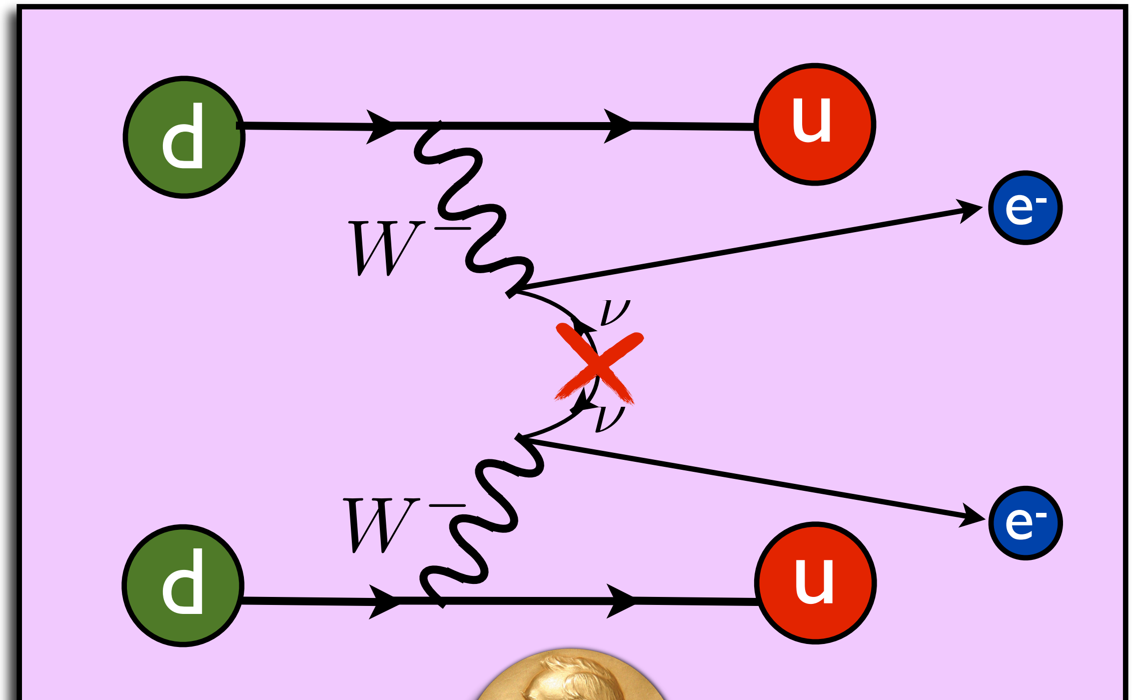
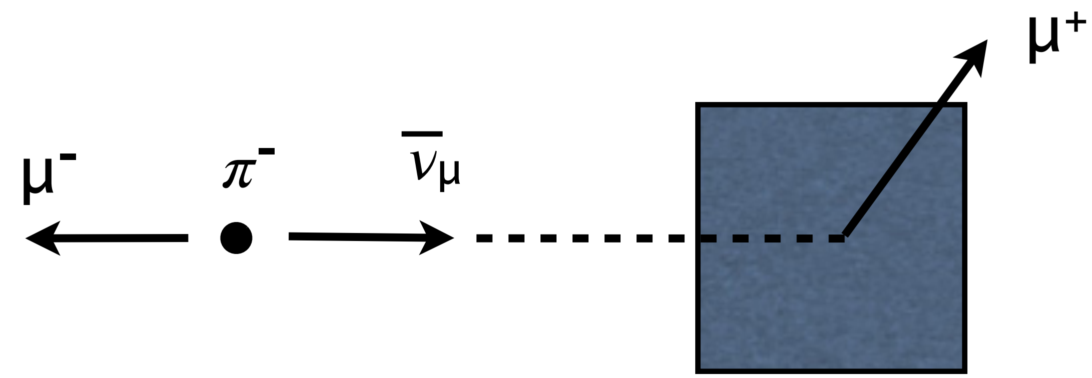
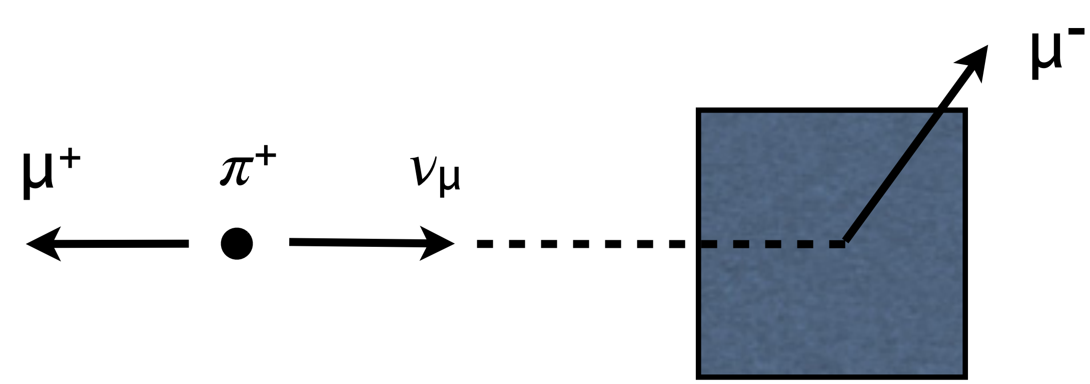


1950's: Neutrinos are produced with a specific helicity (parity violating)



Neutrinos produced in $\pi^{-(+)}$ decays always produce $\mu^{+(-)}$



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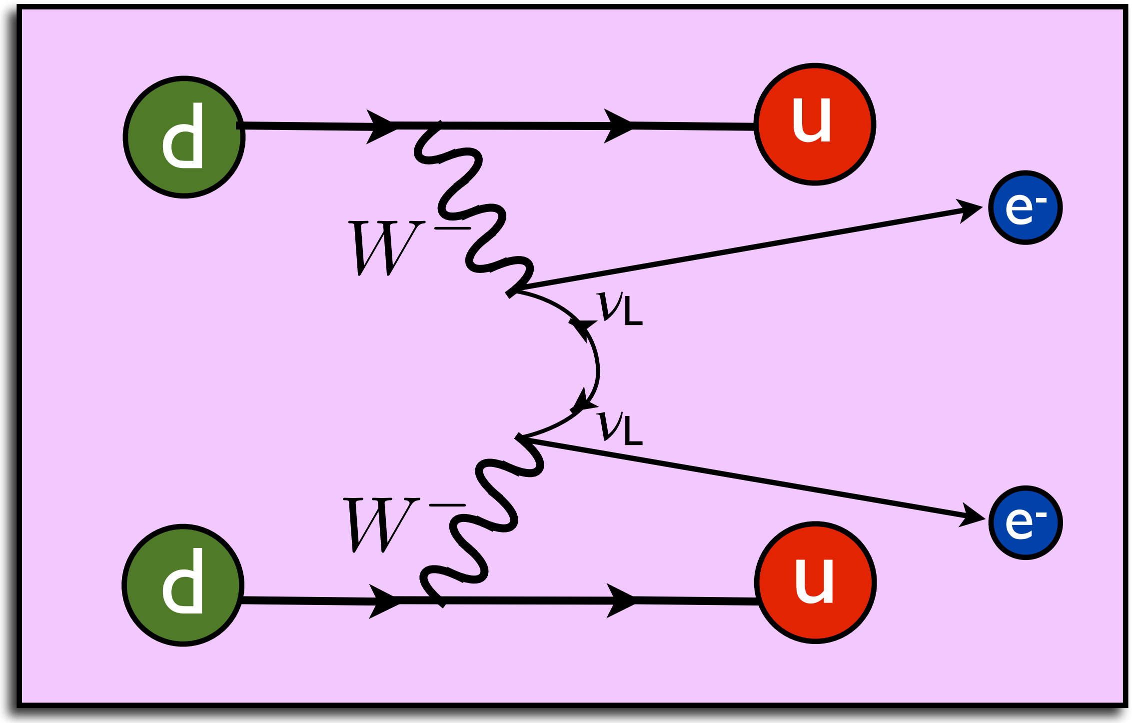

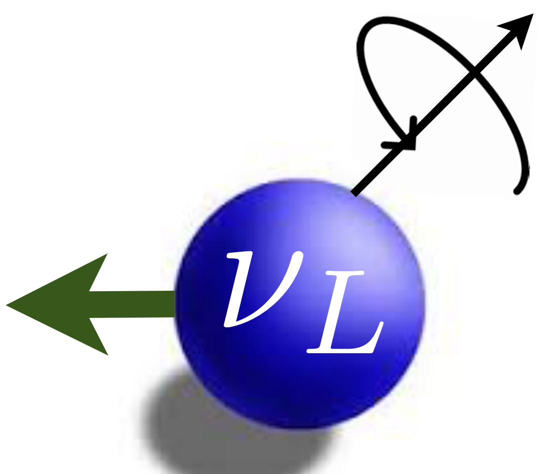

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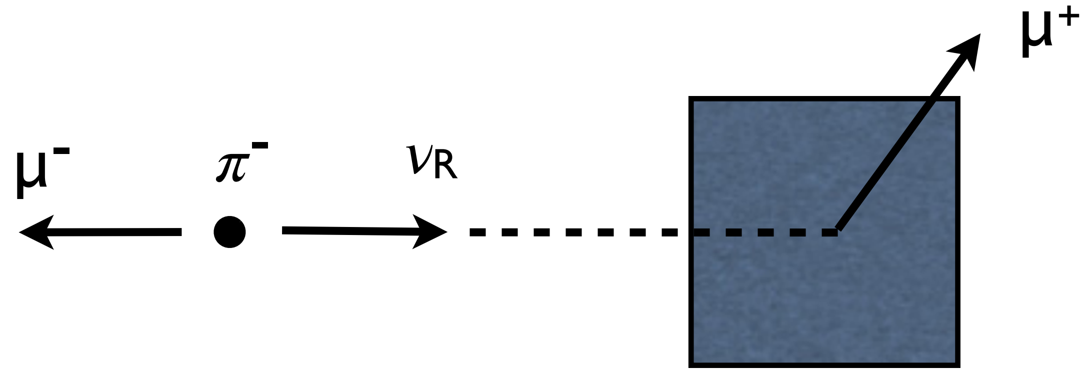
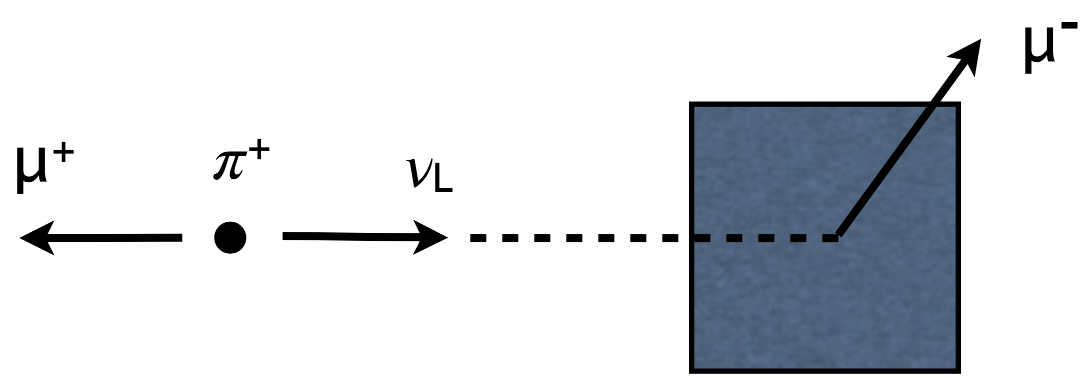
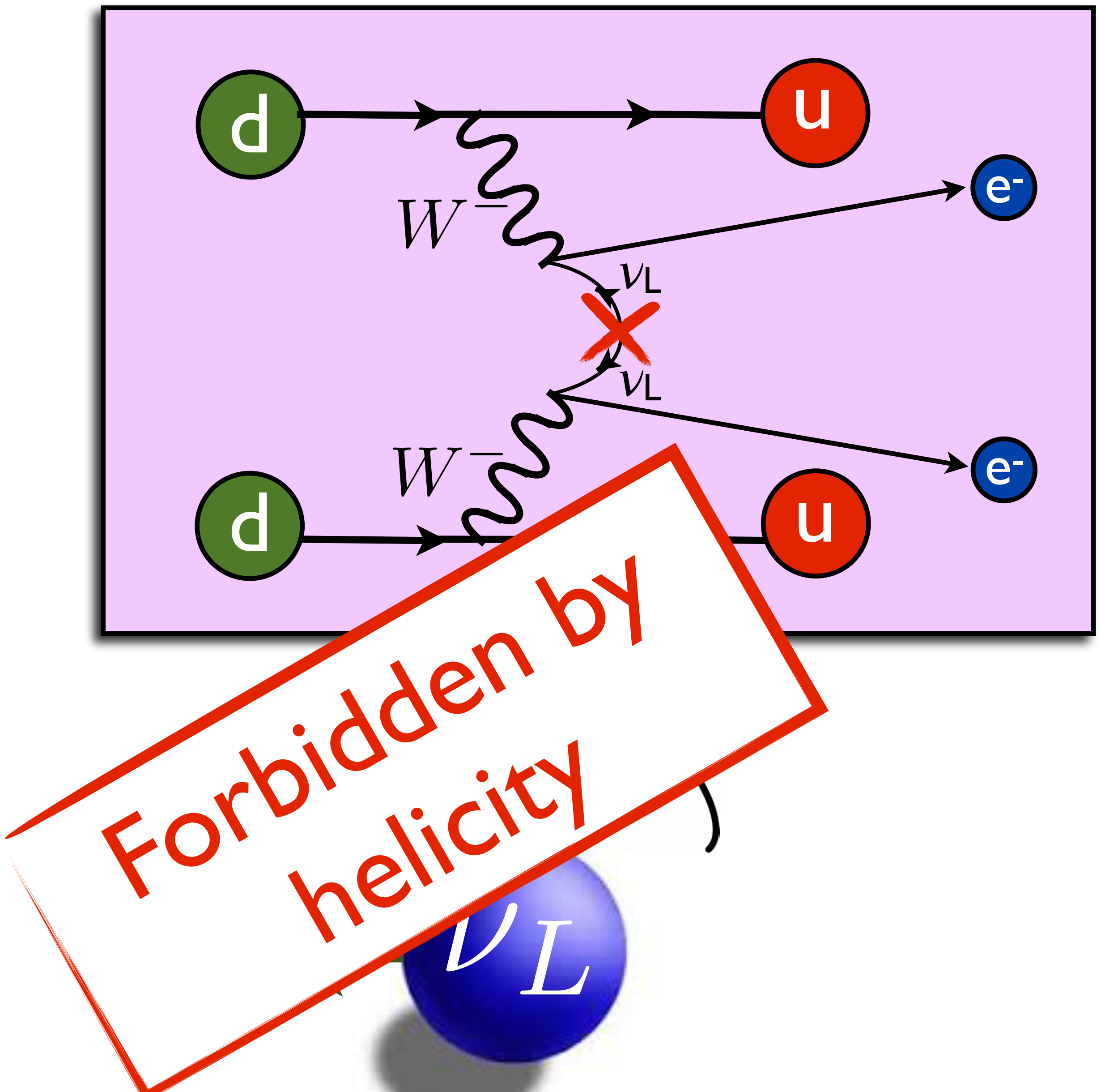


Neutrinos produced in π-(+) decays always produce μ+(-)



Neutrinos & Symmetries



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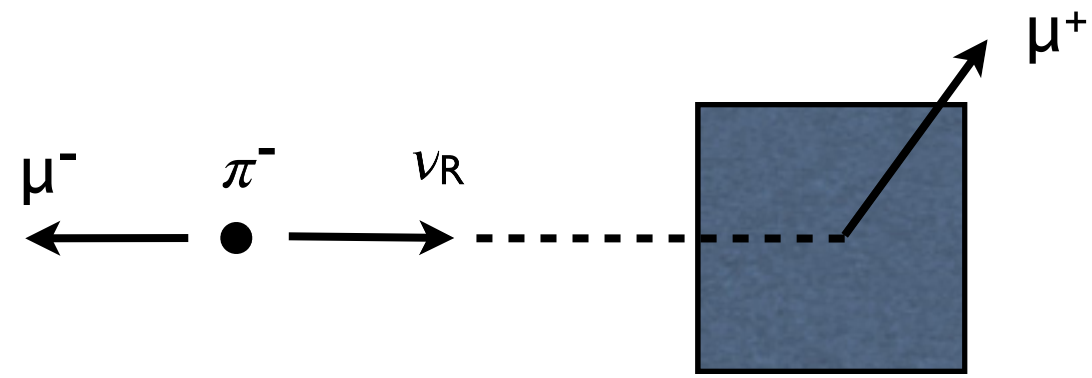

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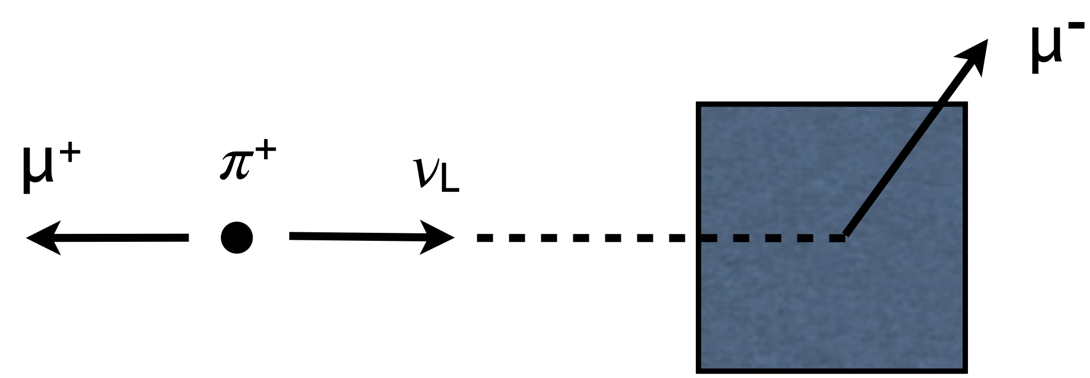
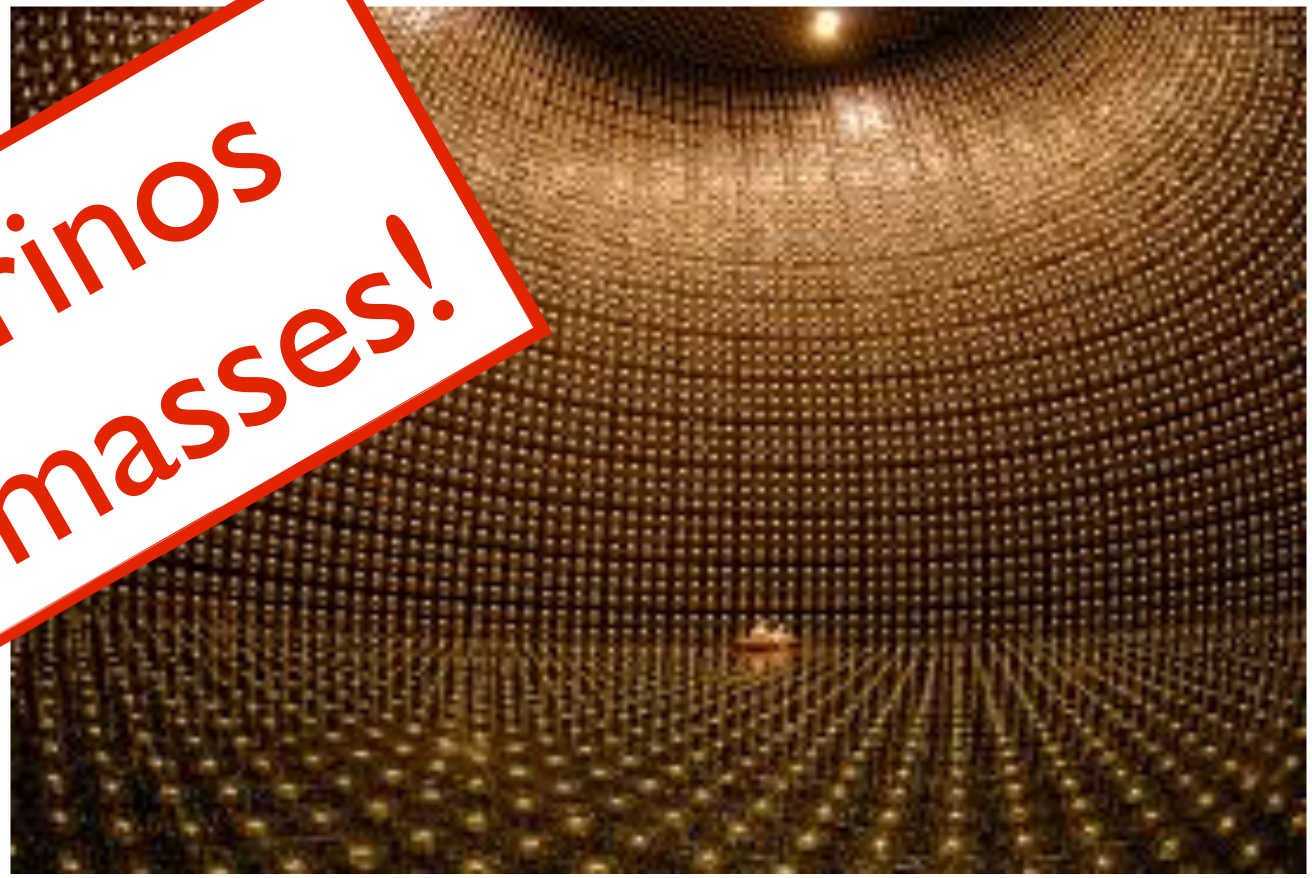
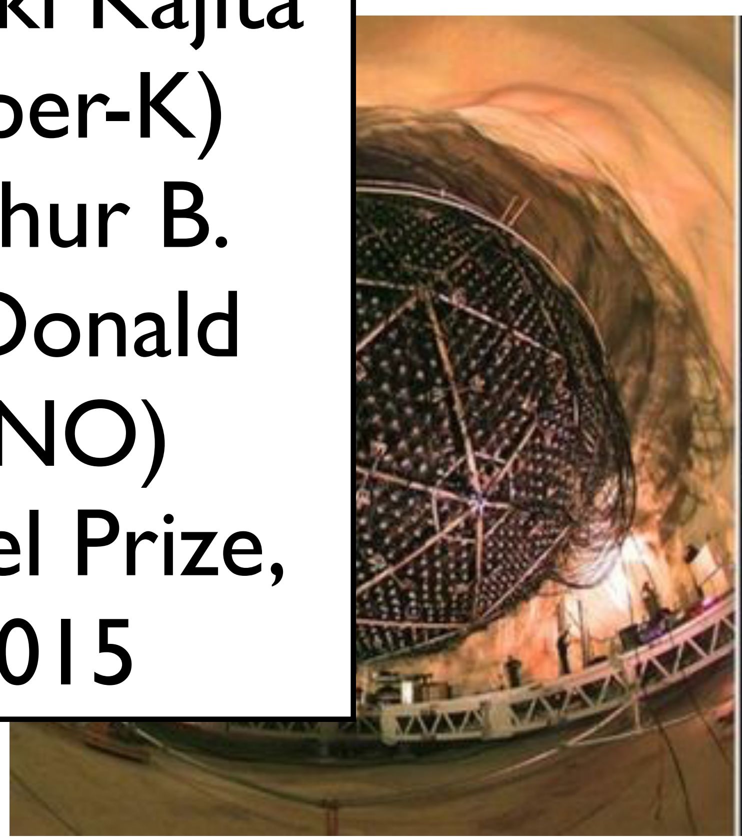
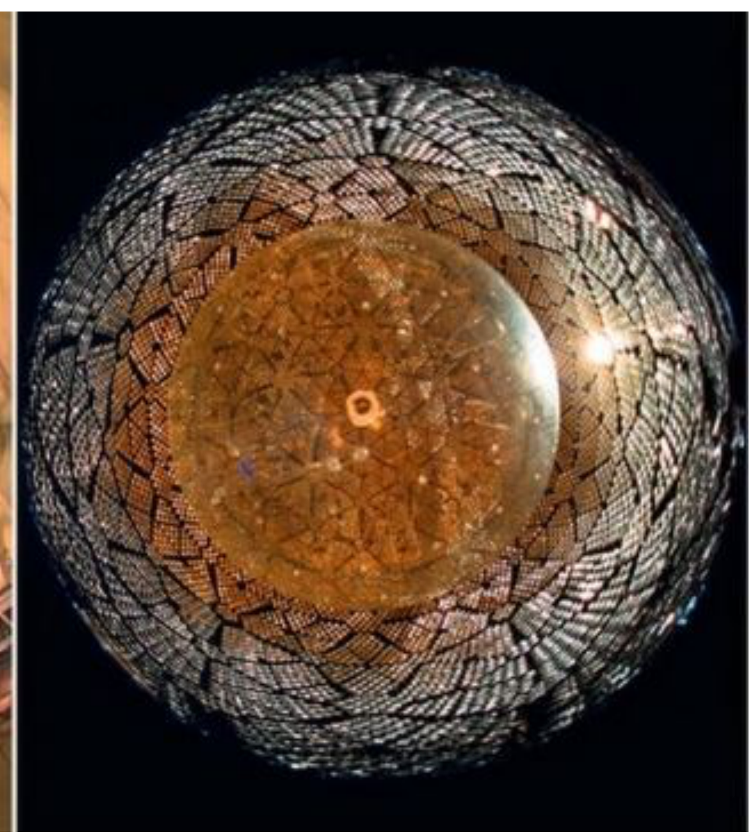


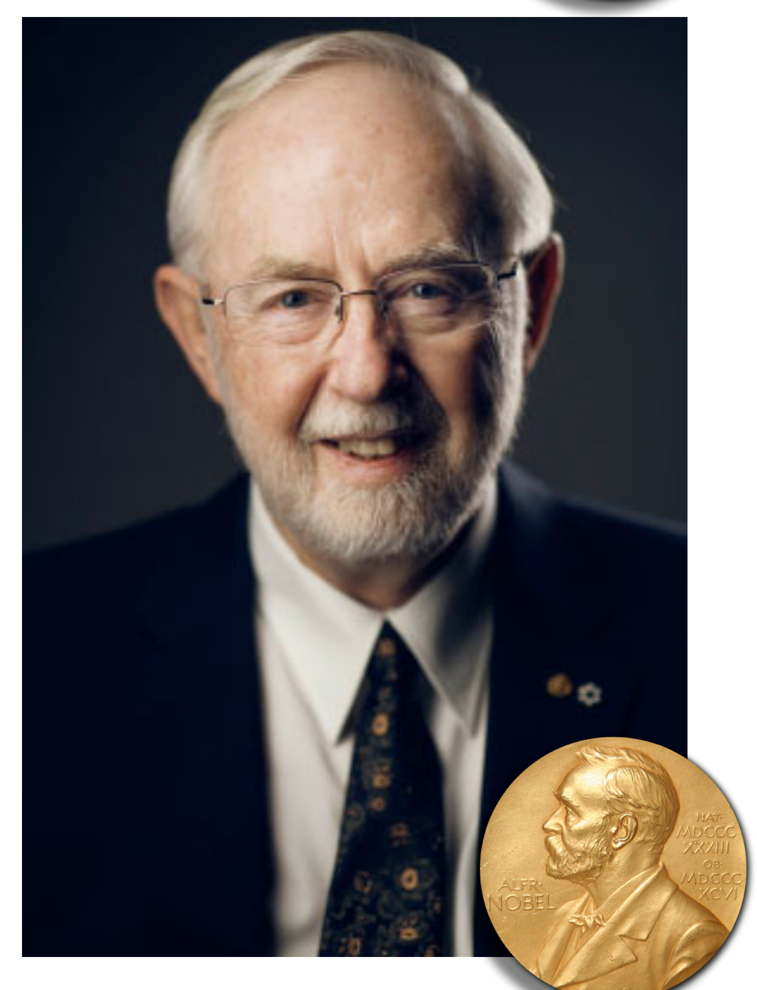
Neutrinos have masses!



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







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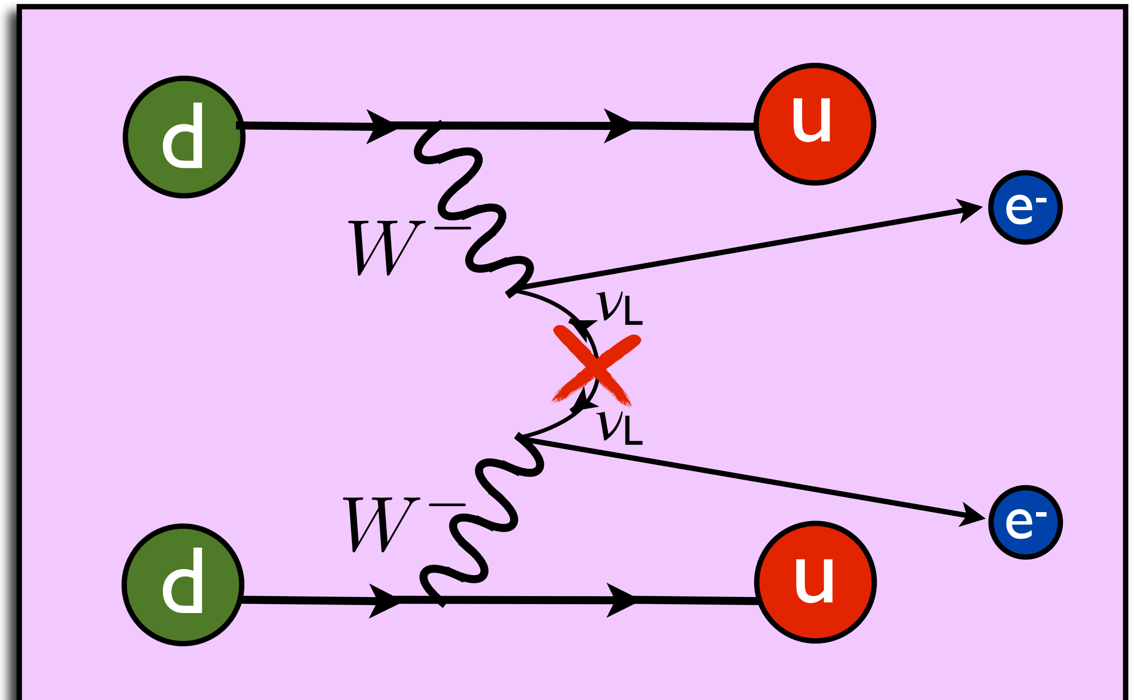

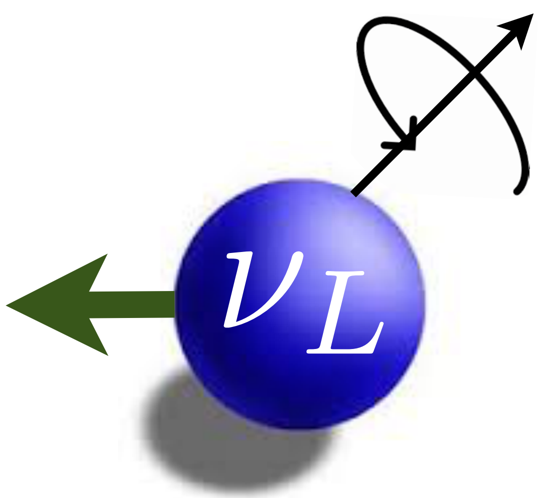

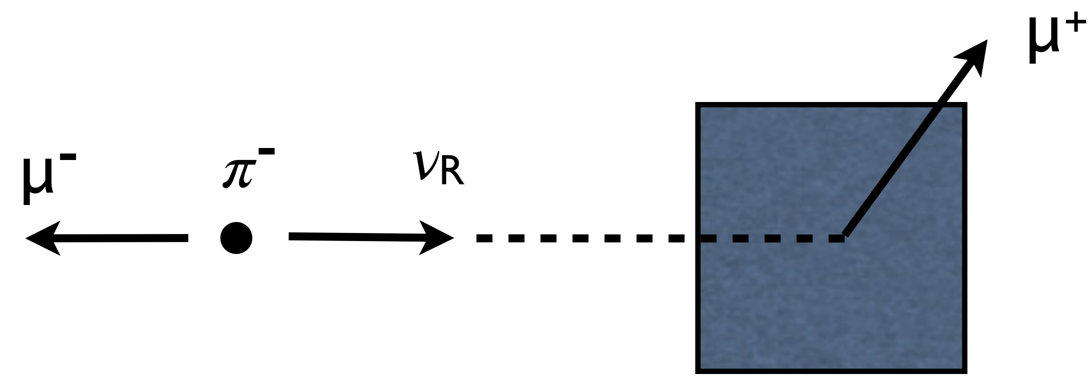

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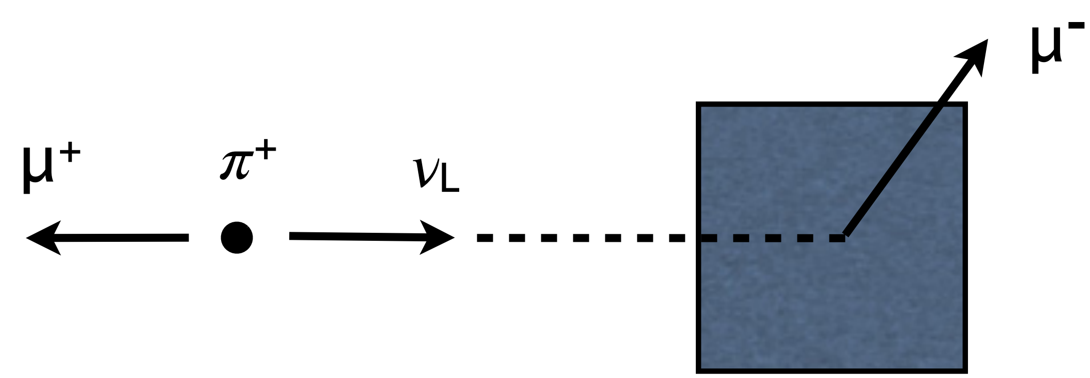
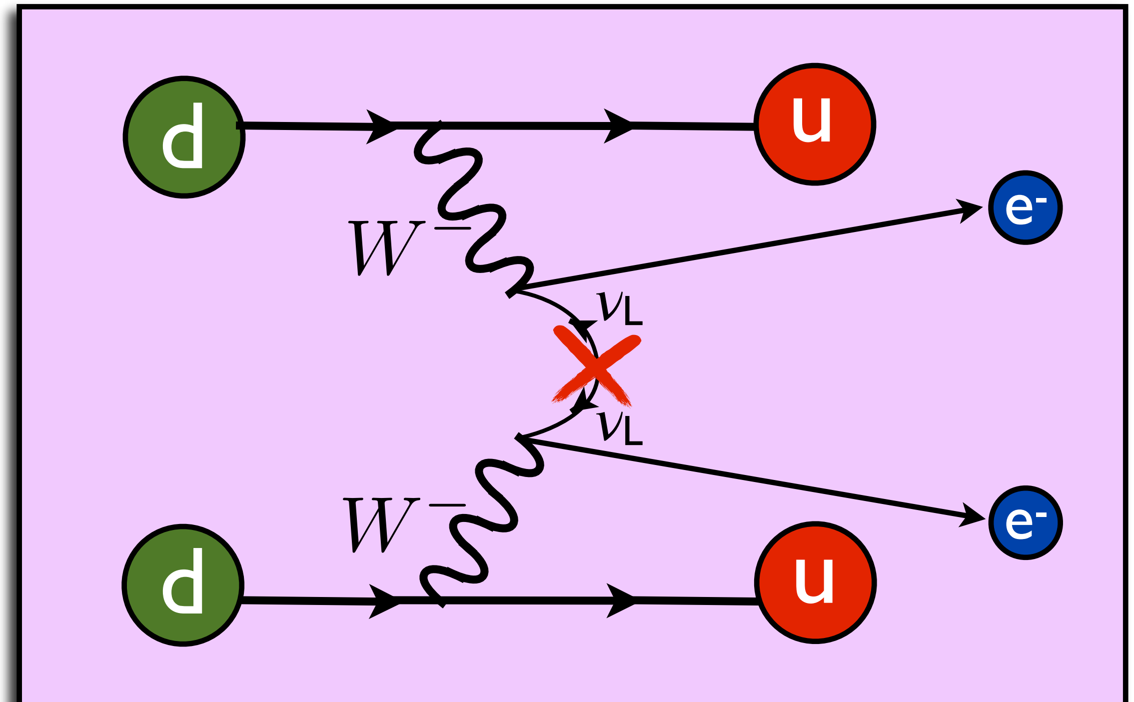
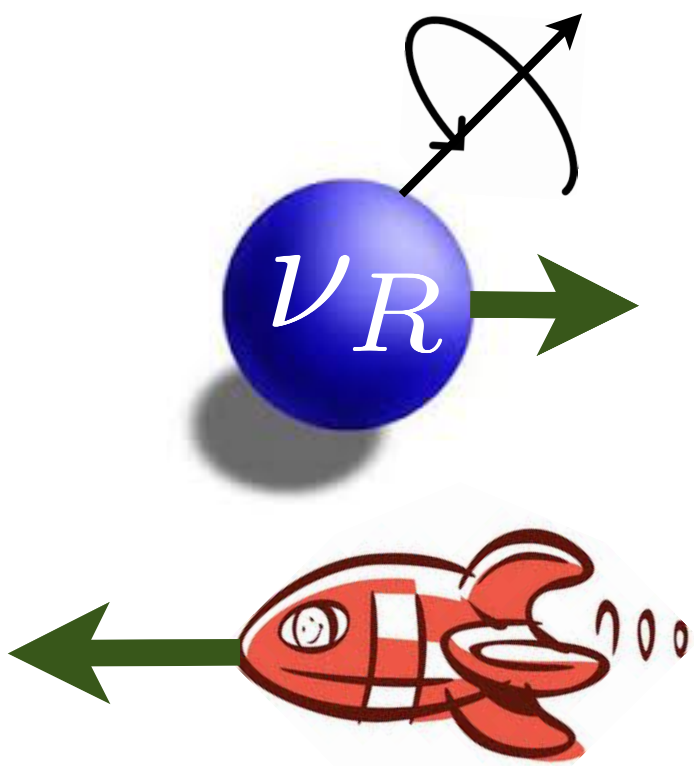
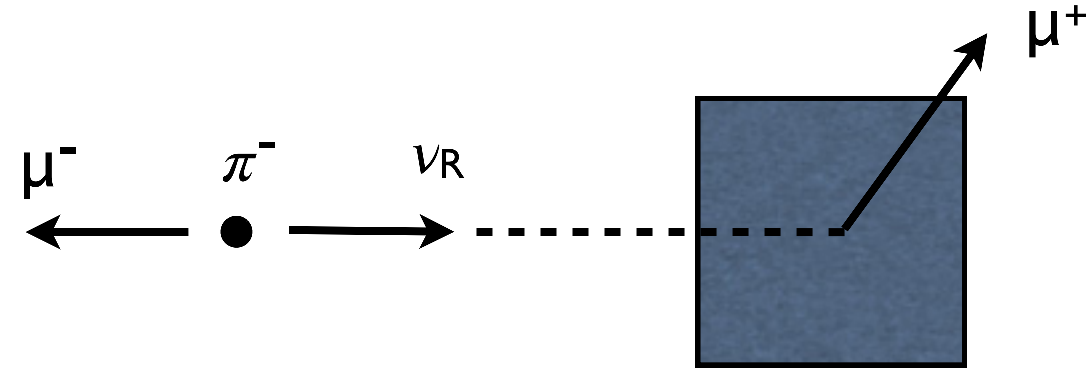


Neutrinos & Symmetries







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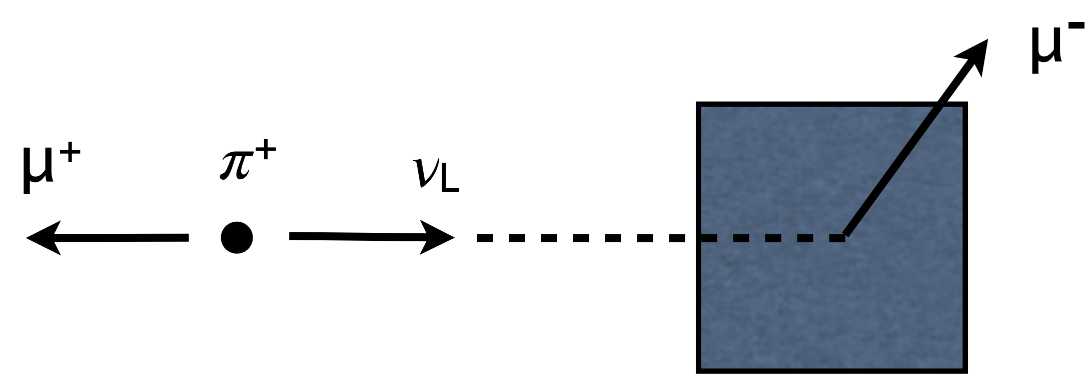

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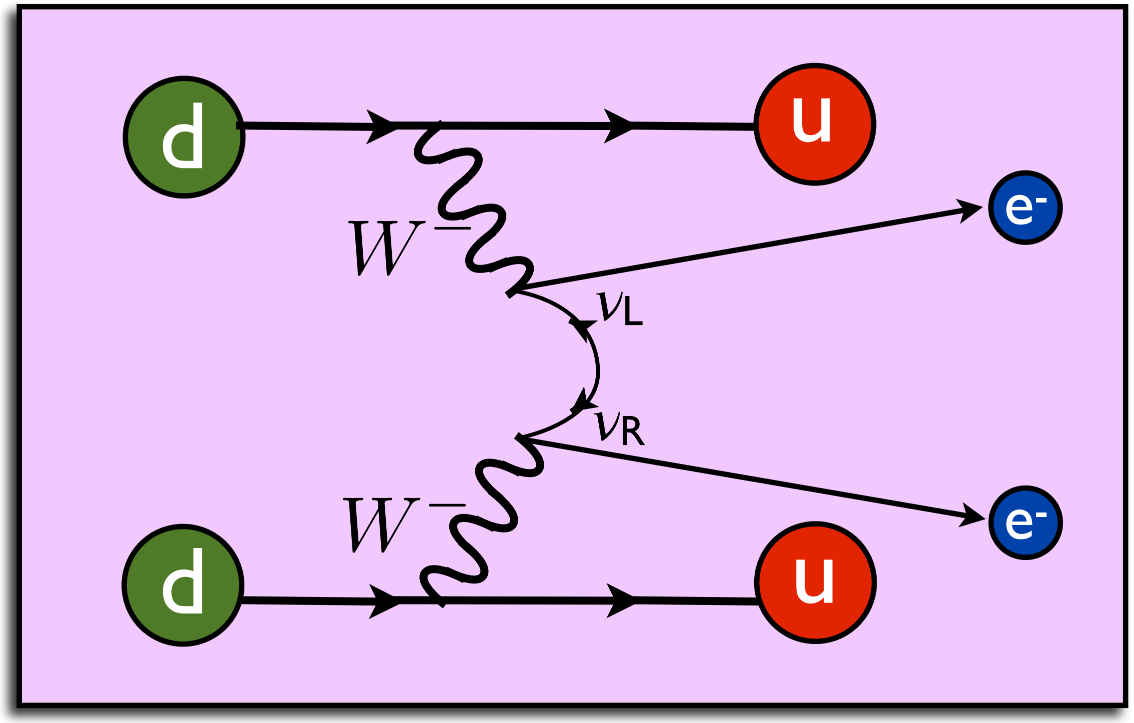

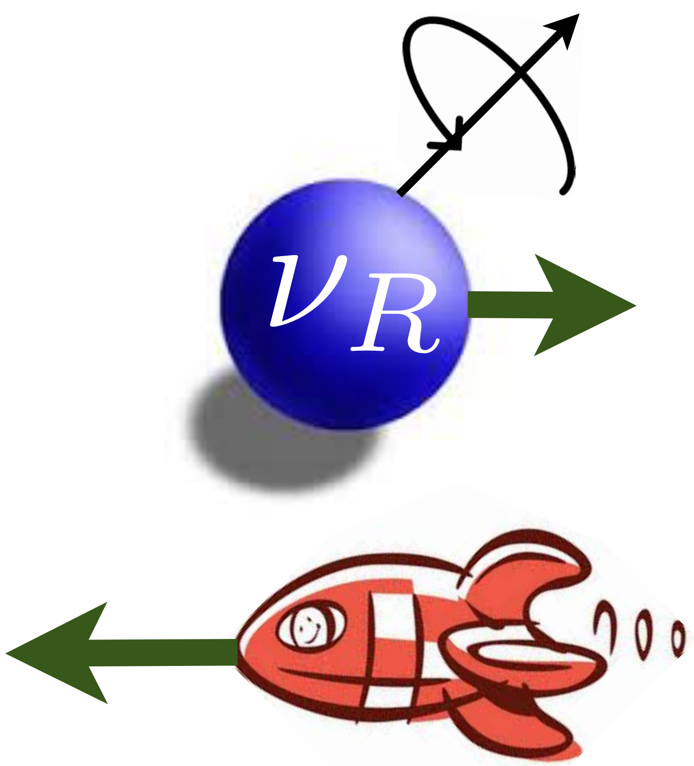

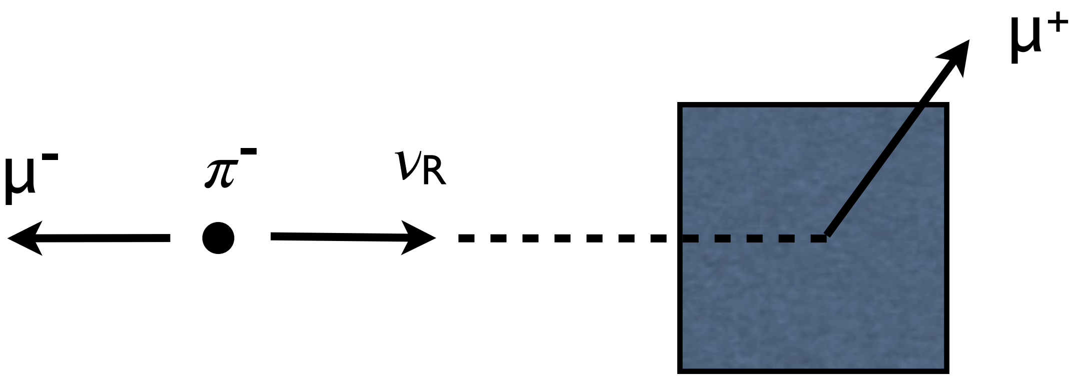

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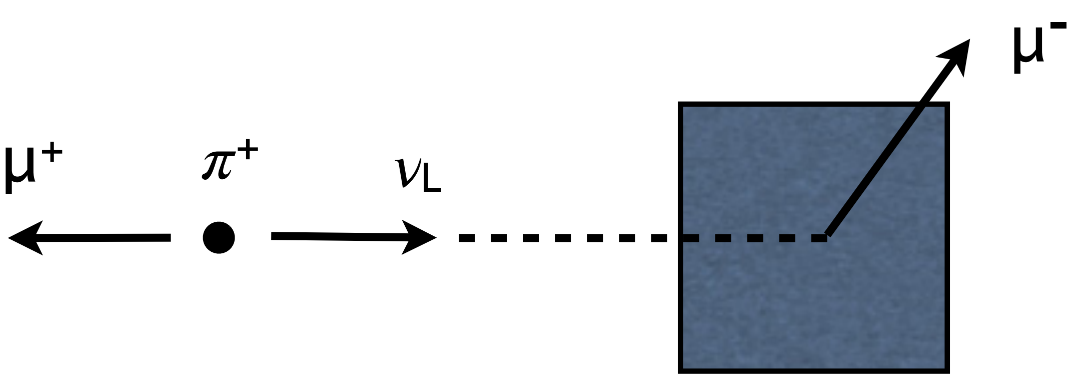

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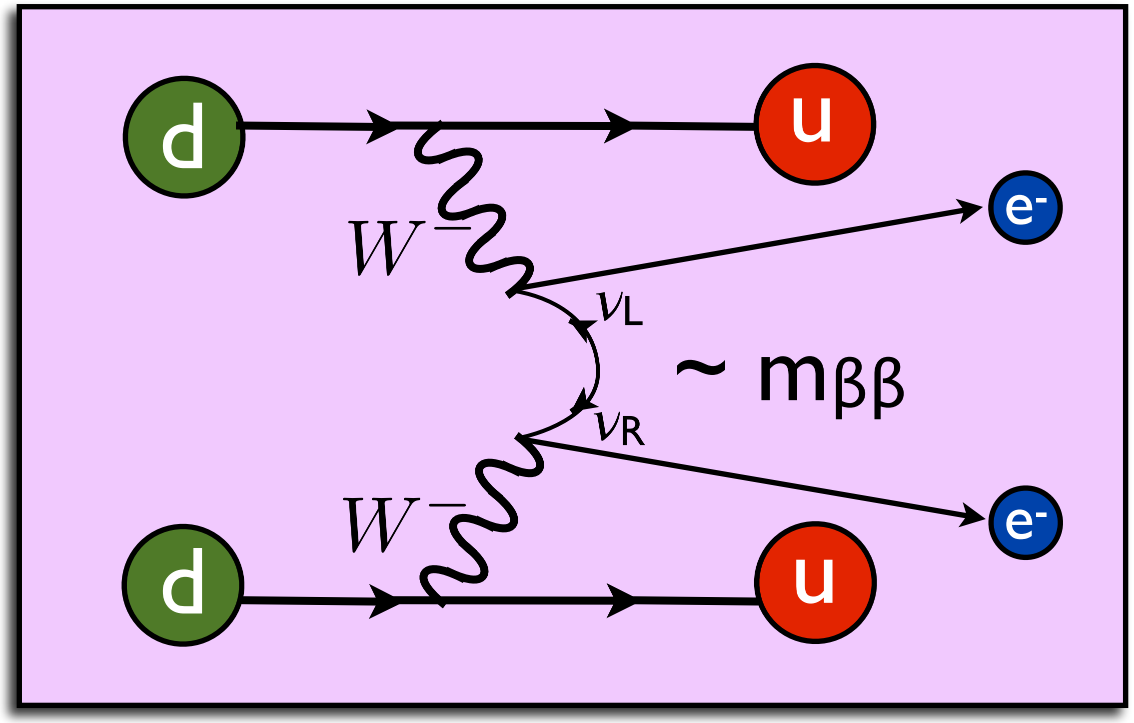

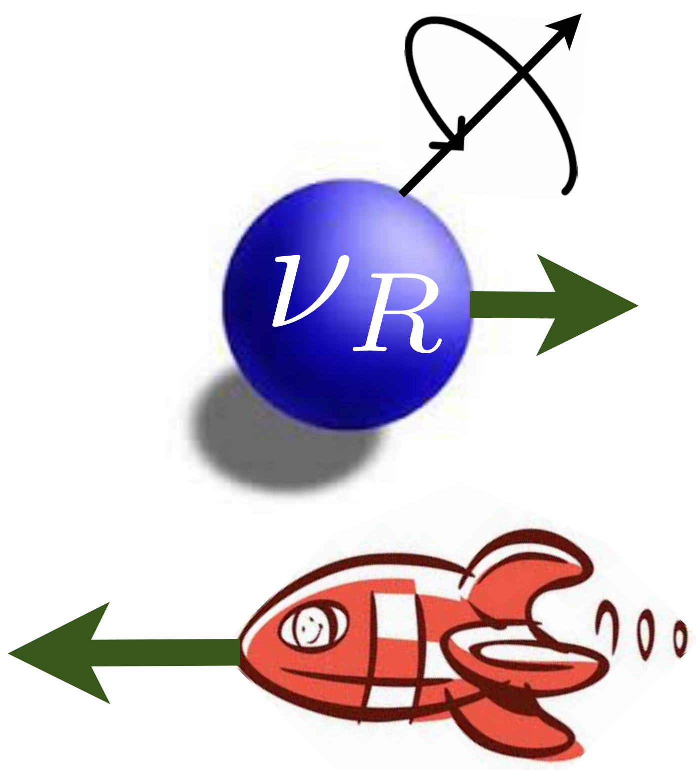

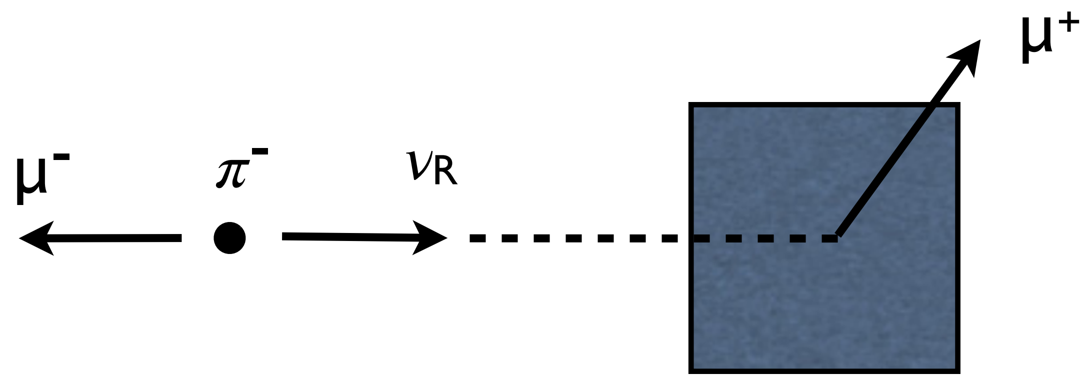

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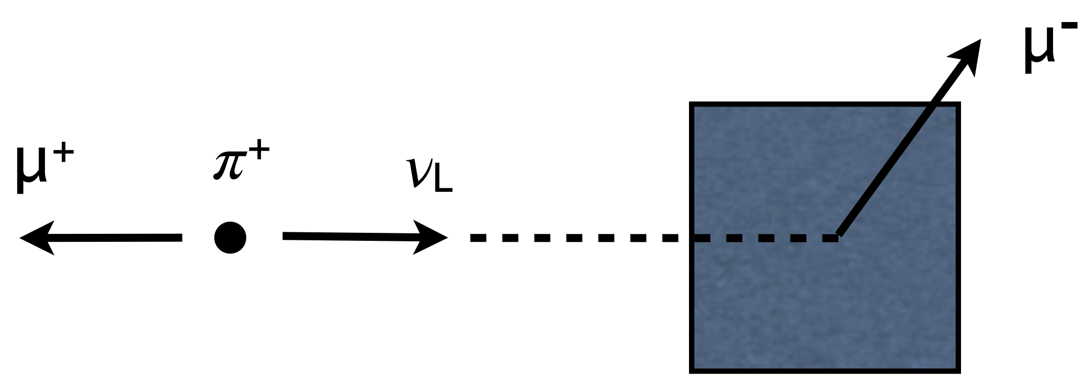

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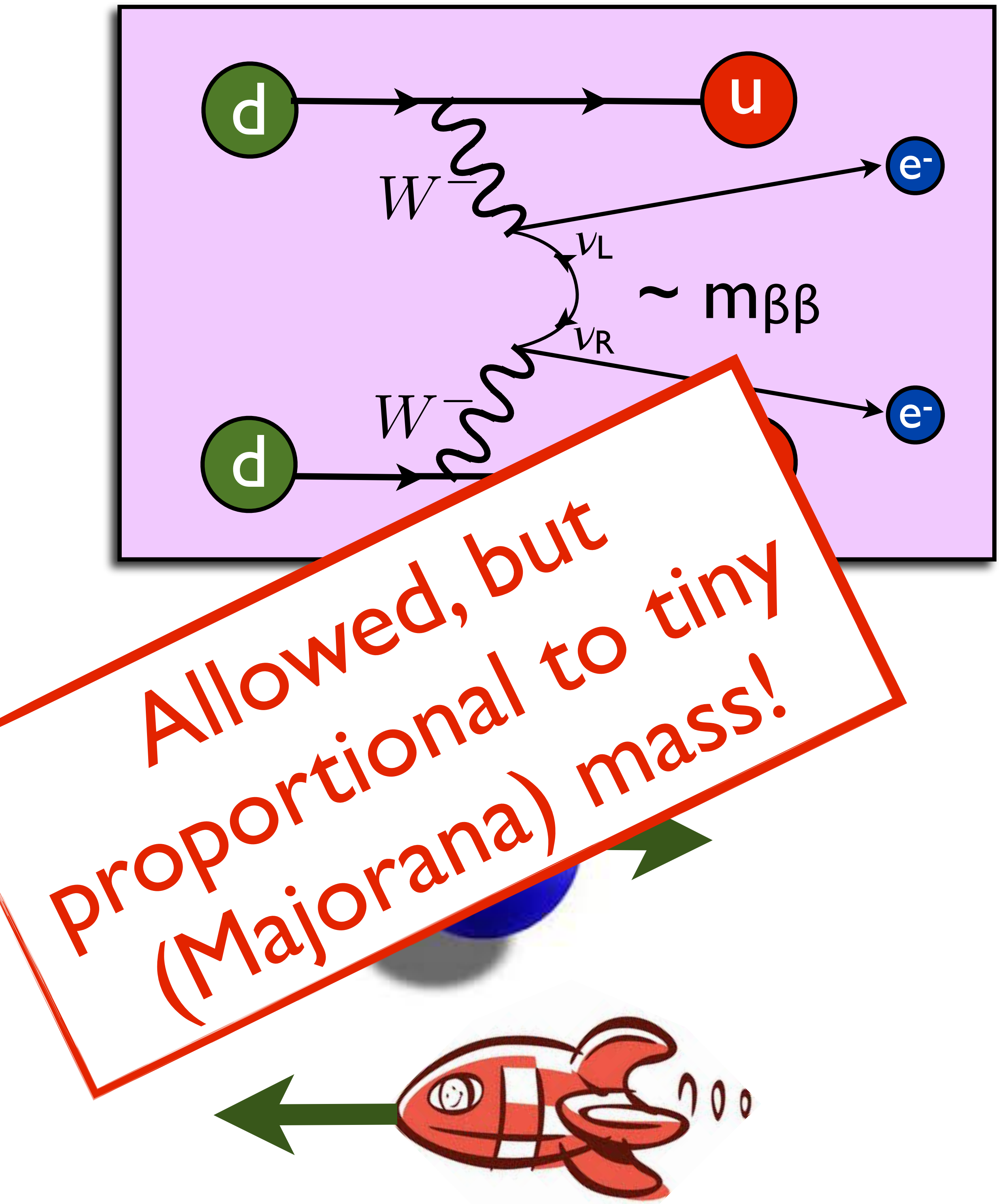

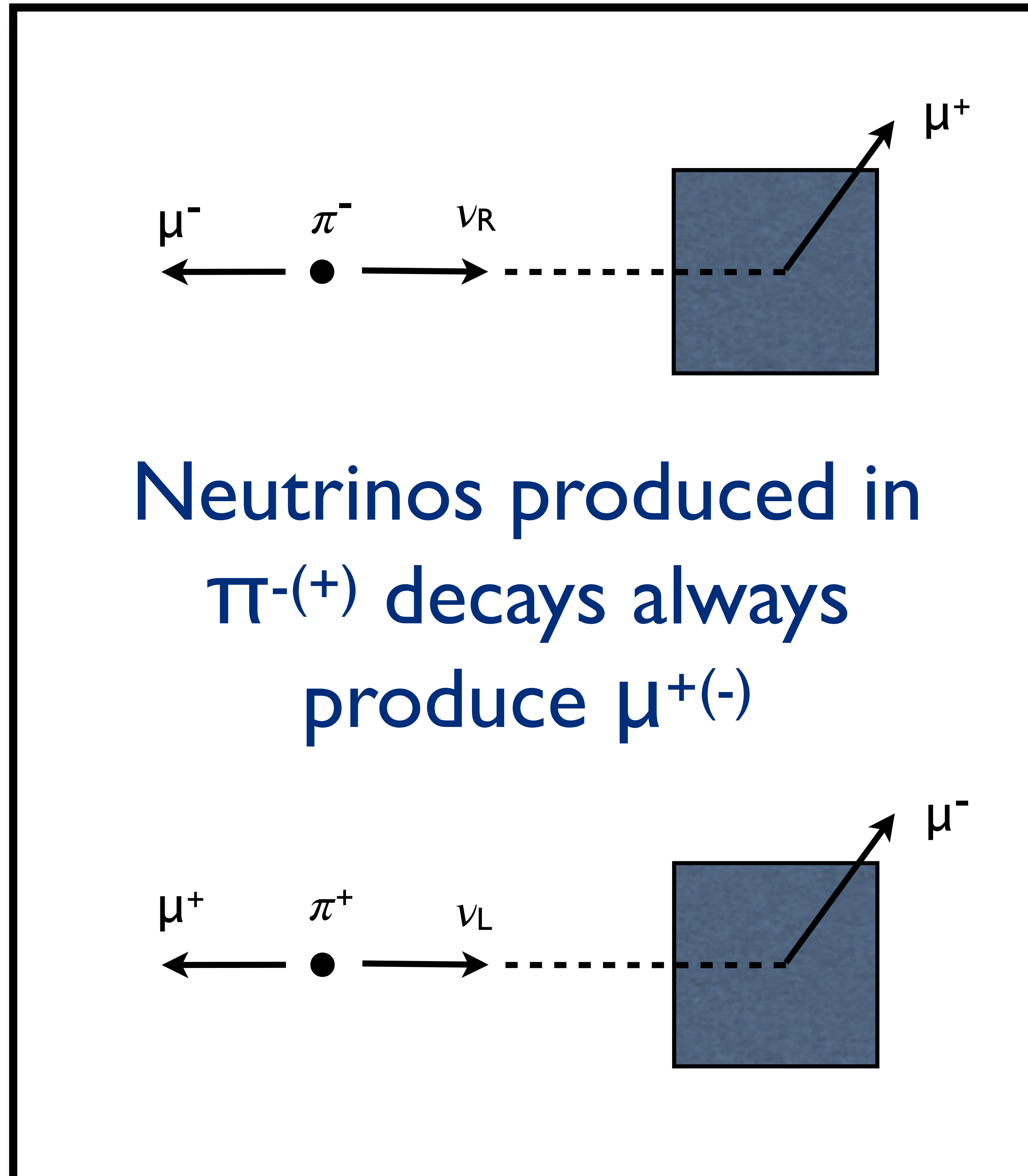

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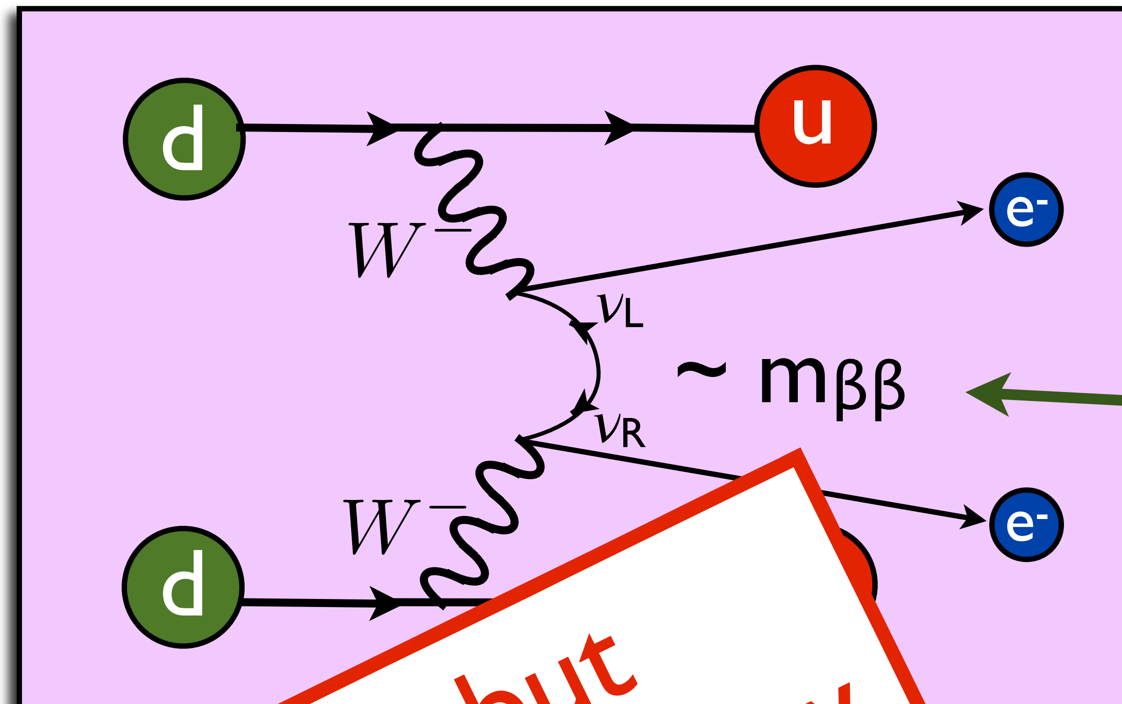
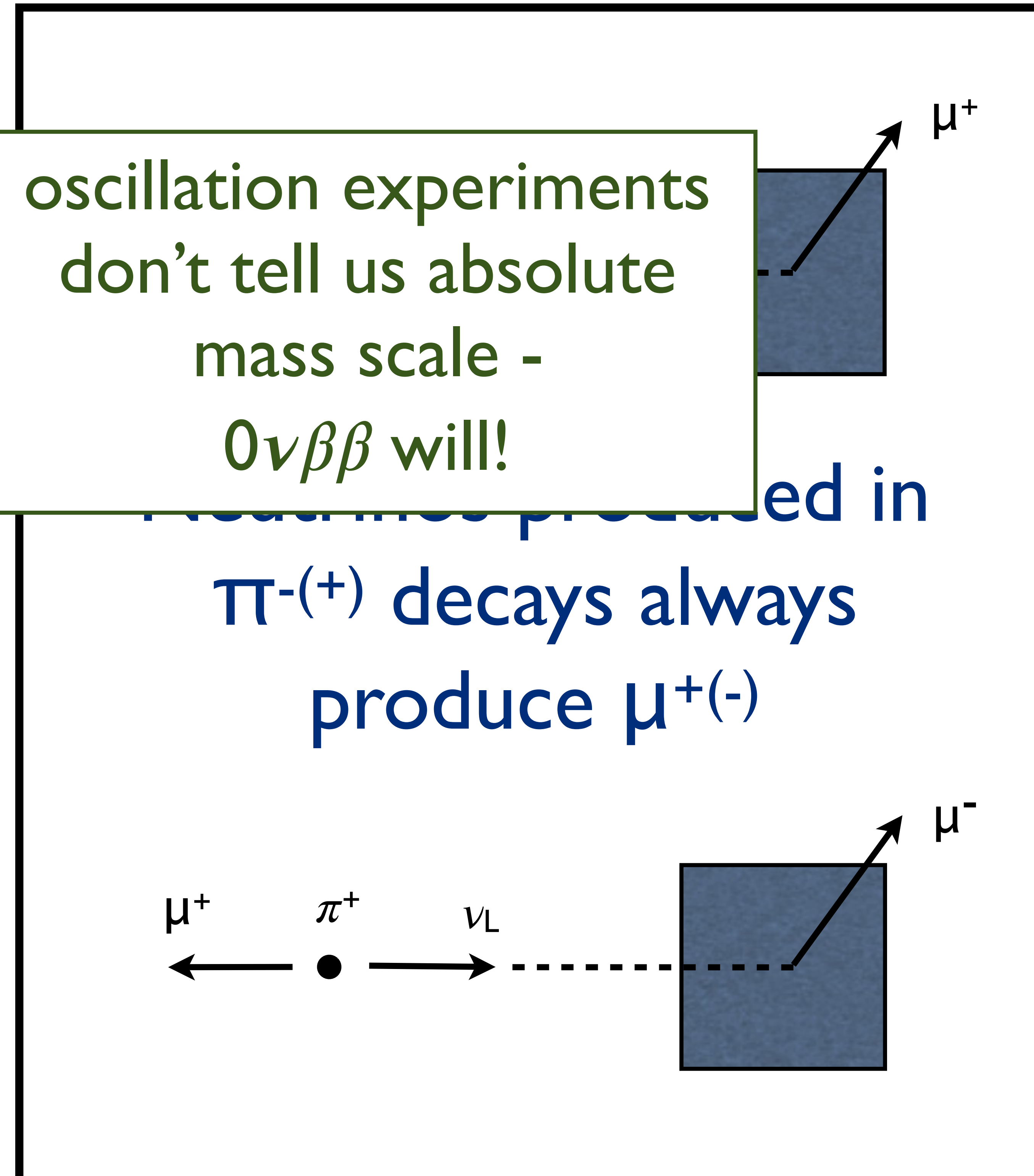


oscillation experiments don't tell us absolute mass scale - $0\nu\beta\beta$ will!

Allowed, but proportional to tiny (Majorana) mass!



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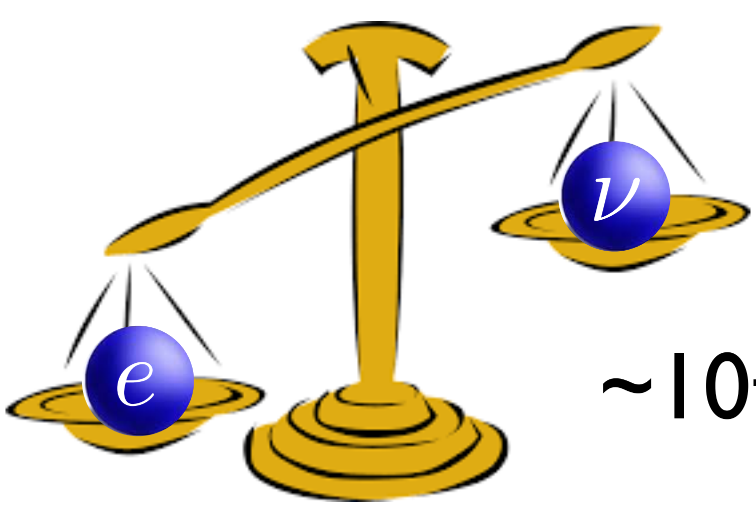
Why Majorana?

- Anything not forbidden by symmetry should occur in nature

$$\mathcal{L}_5 = \frac{c}{\Lambda}\left(\bar{L}\tilde{H}\right)\left(\tilde{H}L\right)^\dagger$$

- Why are neutrinos so light?



~10^{-7} m_e?

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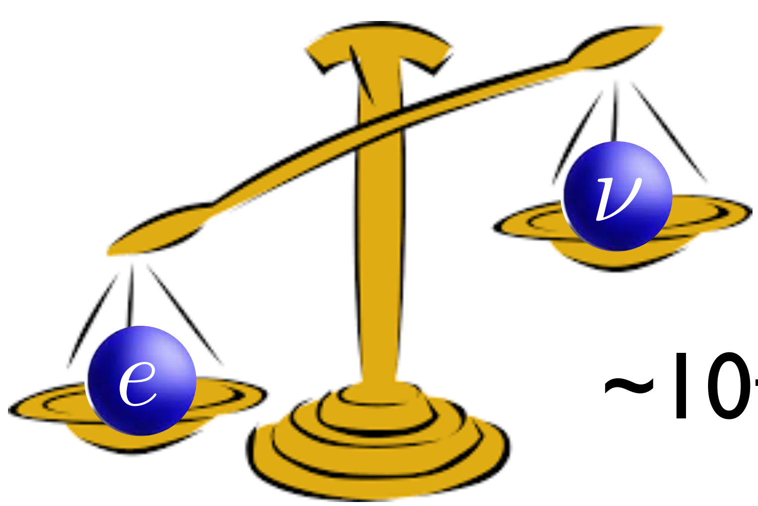

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Seesaw Mechanism

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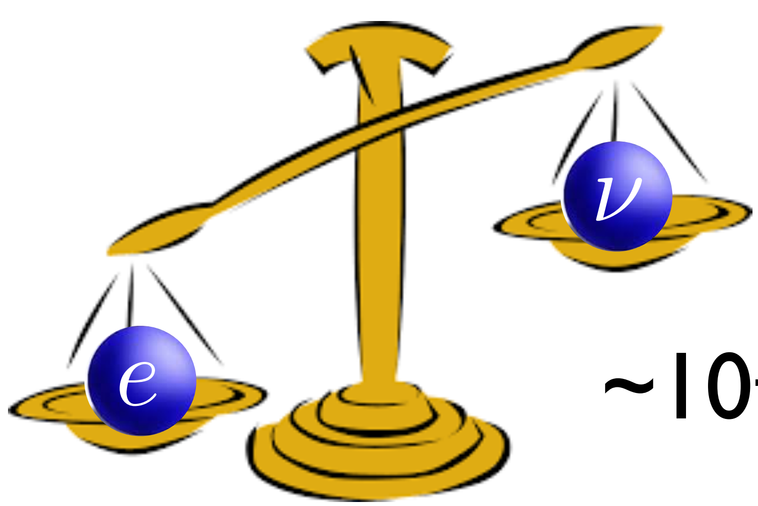

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Seesaw Mechanism

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

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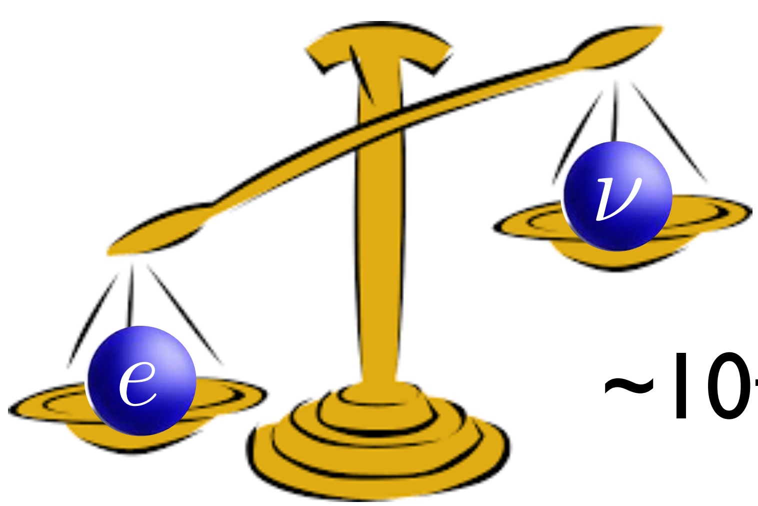

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<u>Seesaw Mechanism</u>

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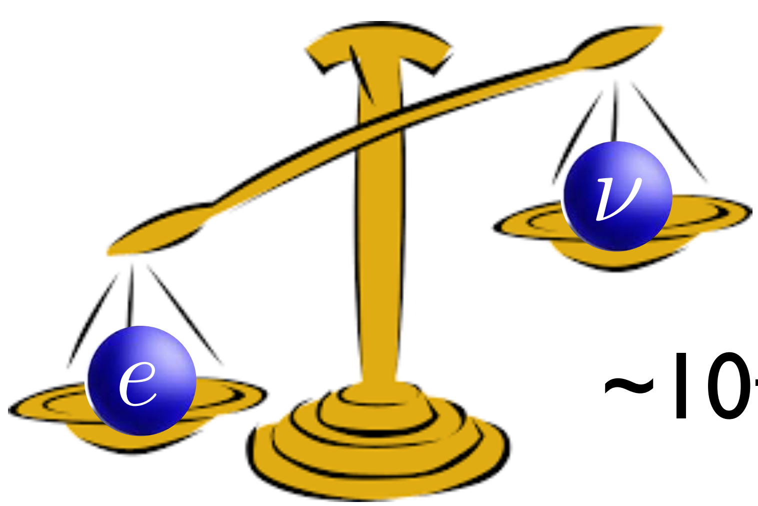

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<u>Seesaw Mechanism</u>

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

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

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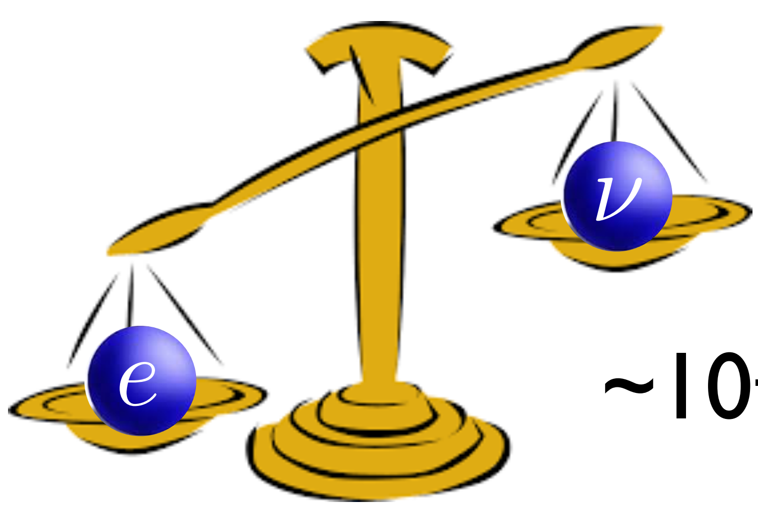


~10^{-7} m_e?

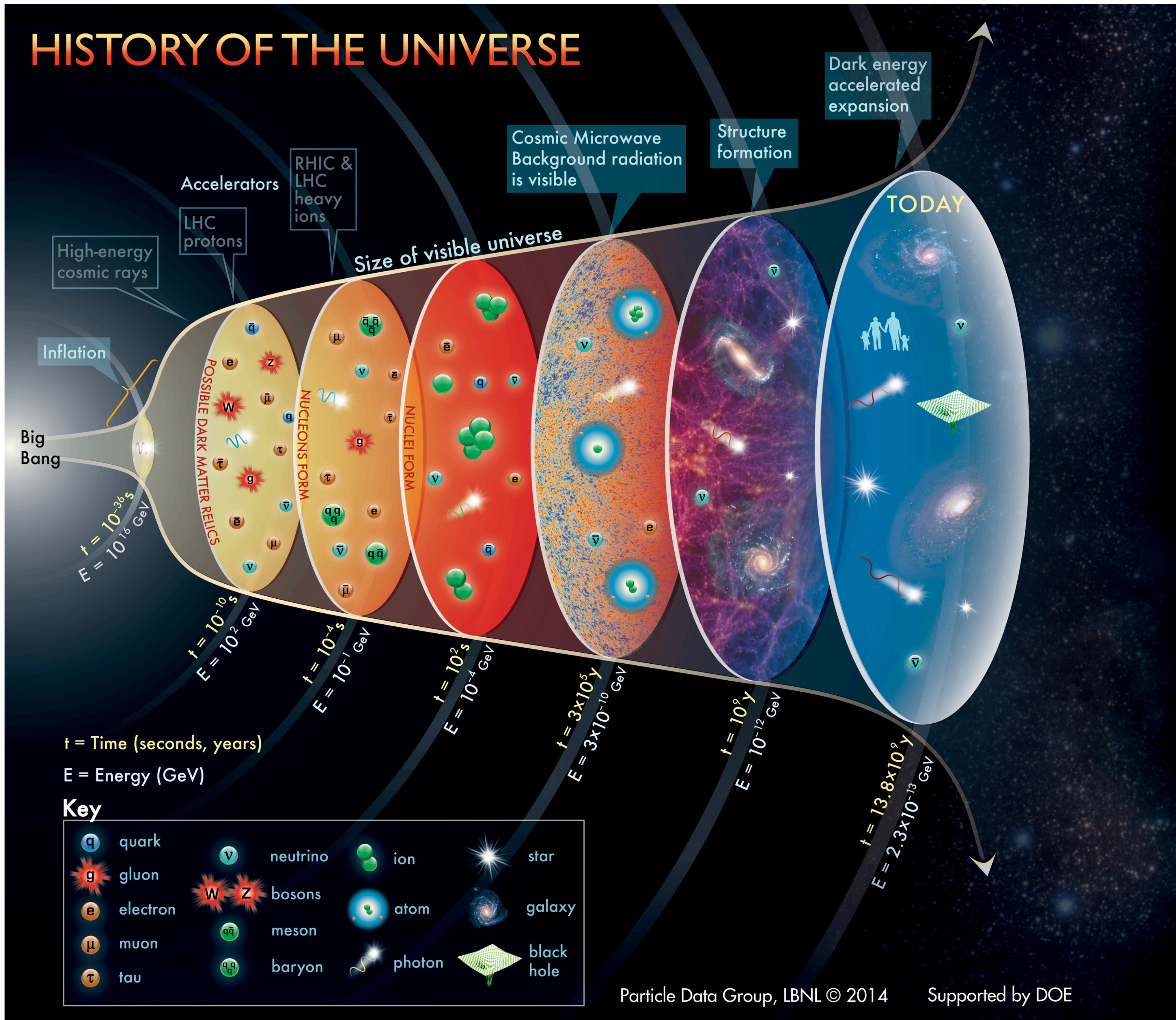
Seesaw Mechanism

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

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

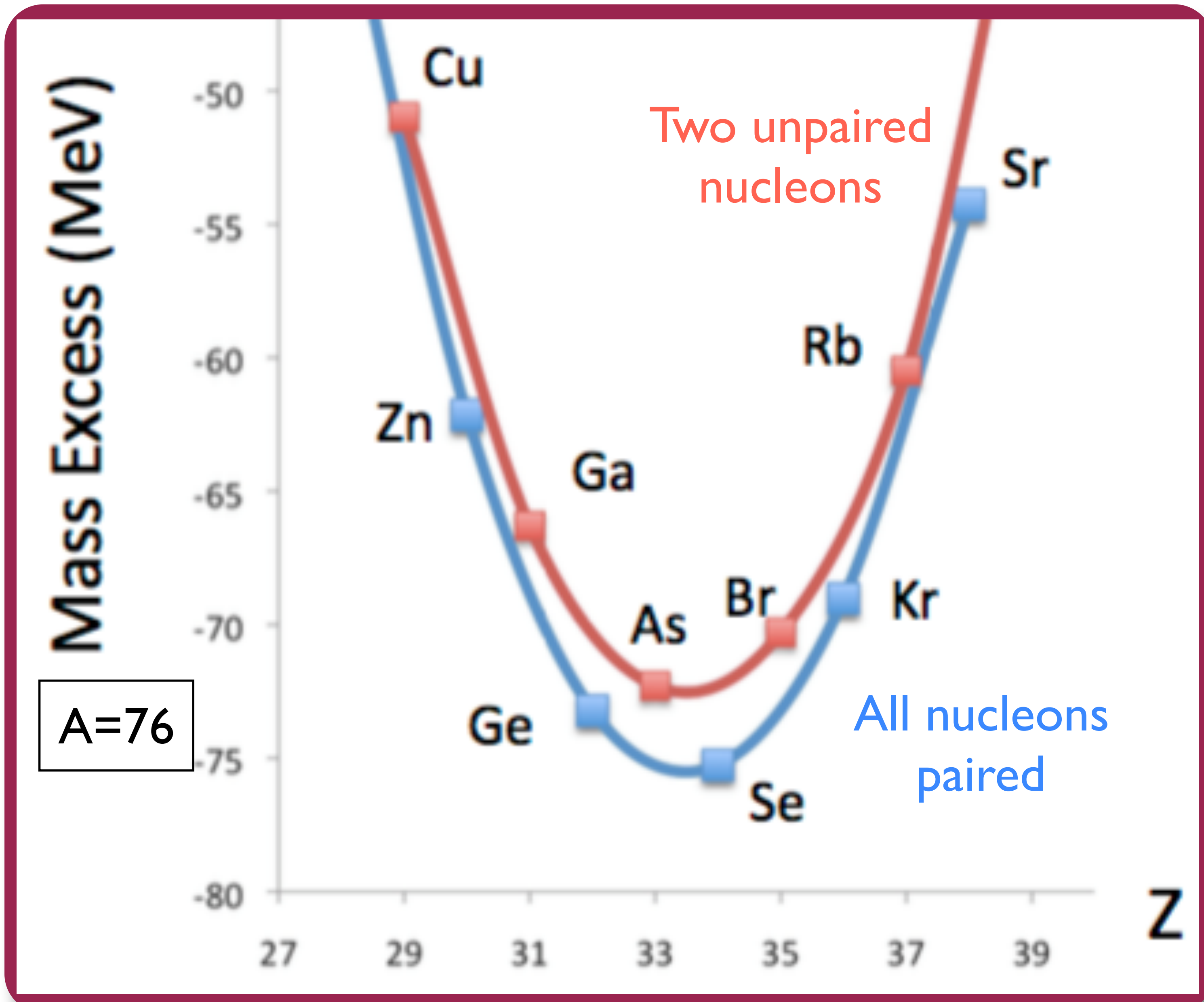
$$m_h \sim M_R$$

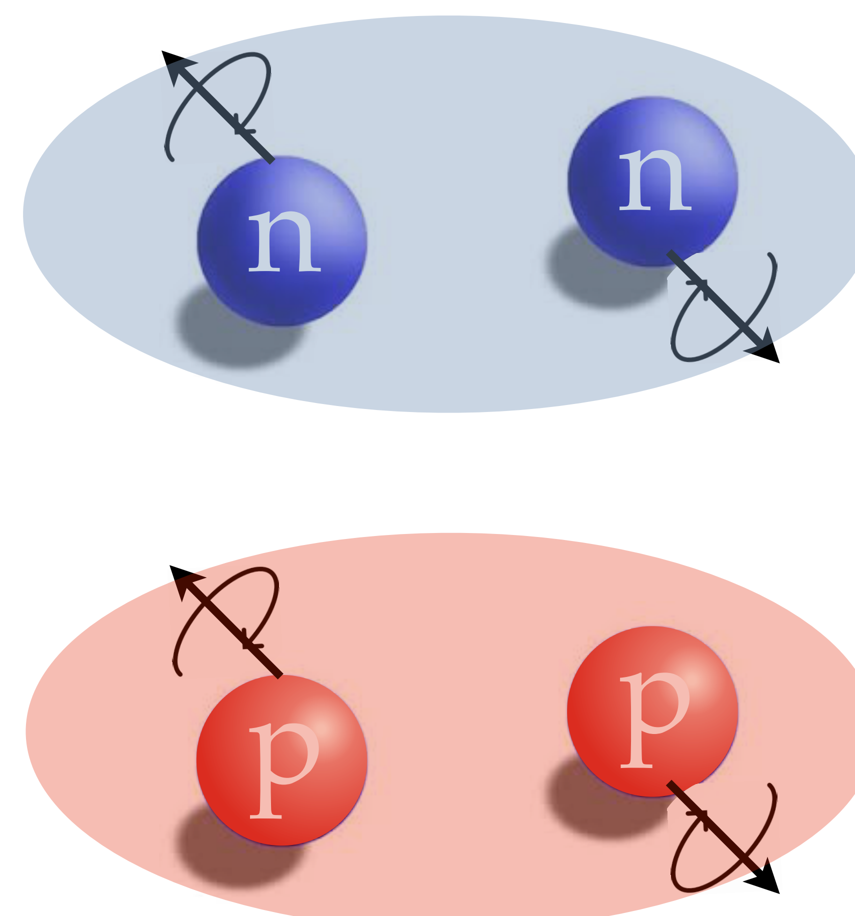
If observed, could help explain matter/anti-matter asymmetry in the universe!



Experiment

Nuclear physics gives us a natural filter for the process





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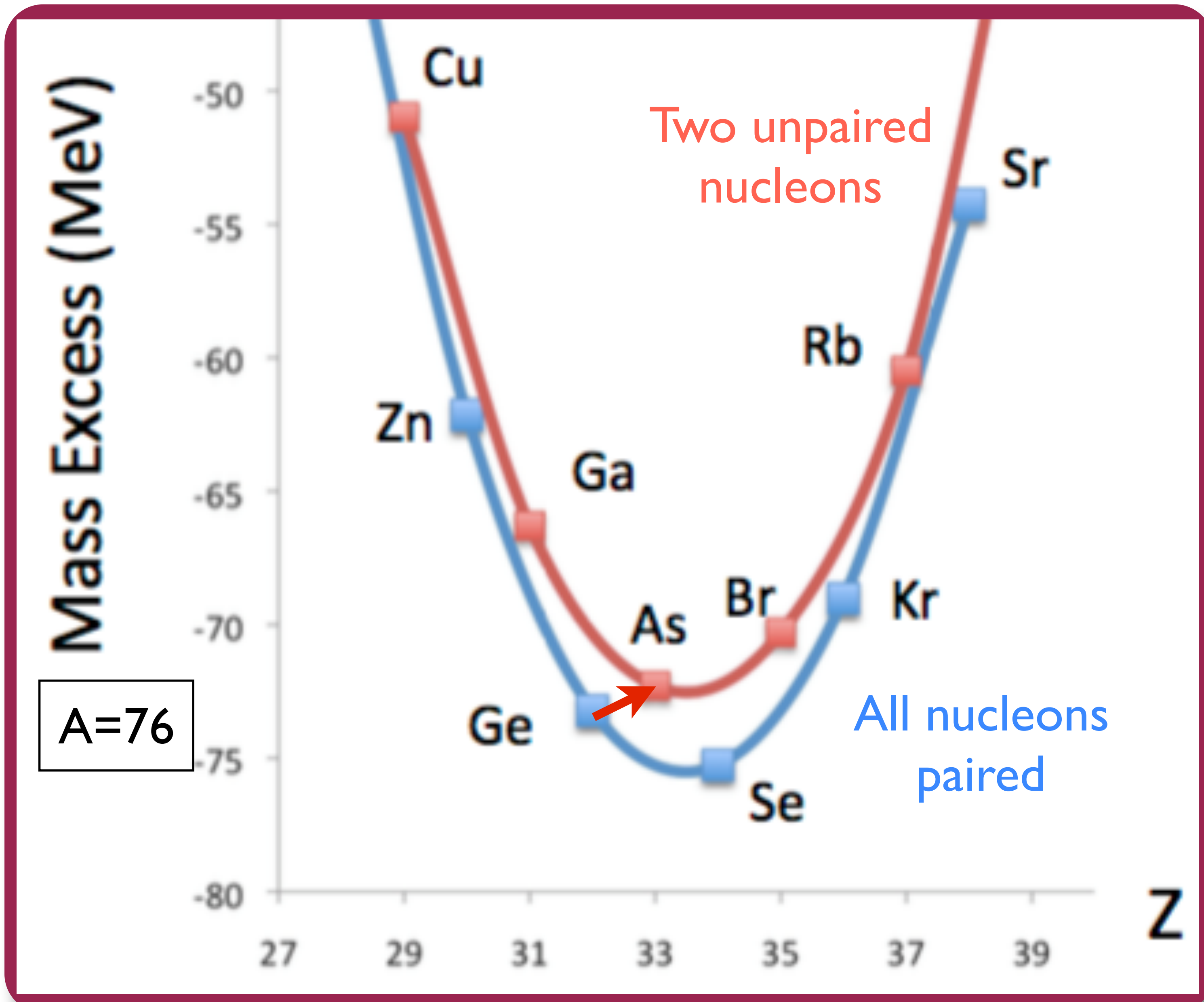

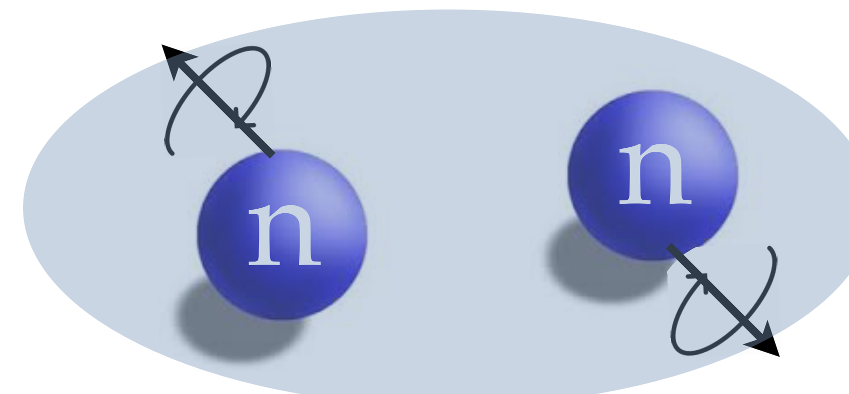

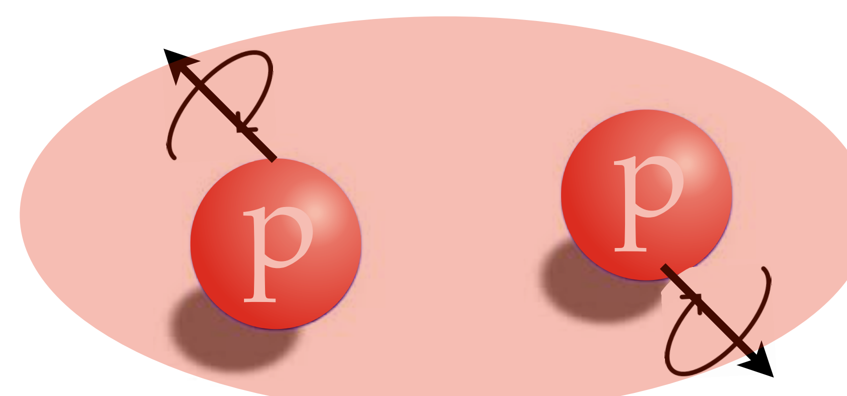

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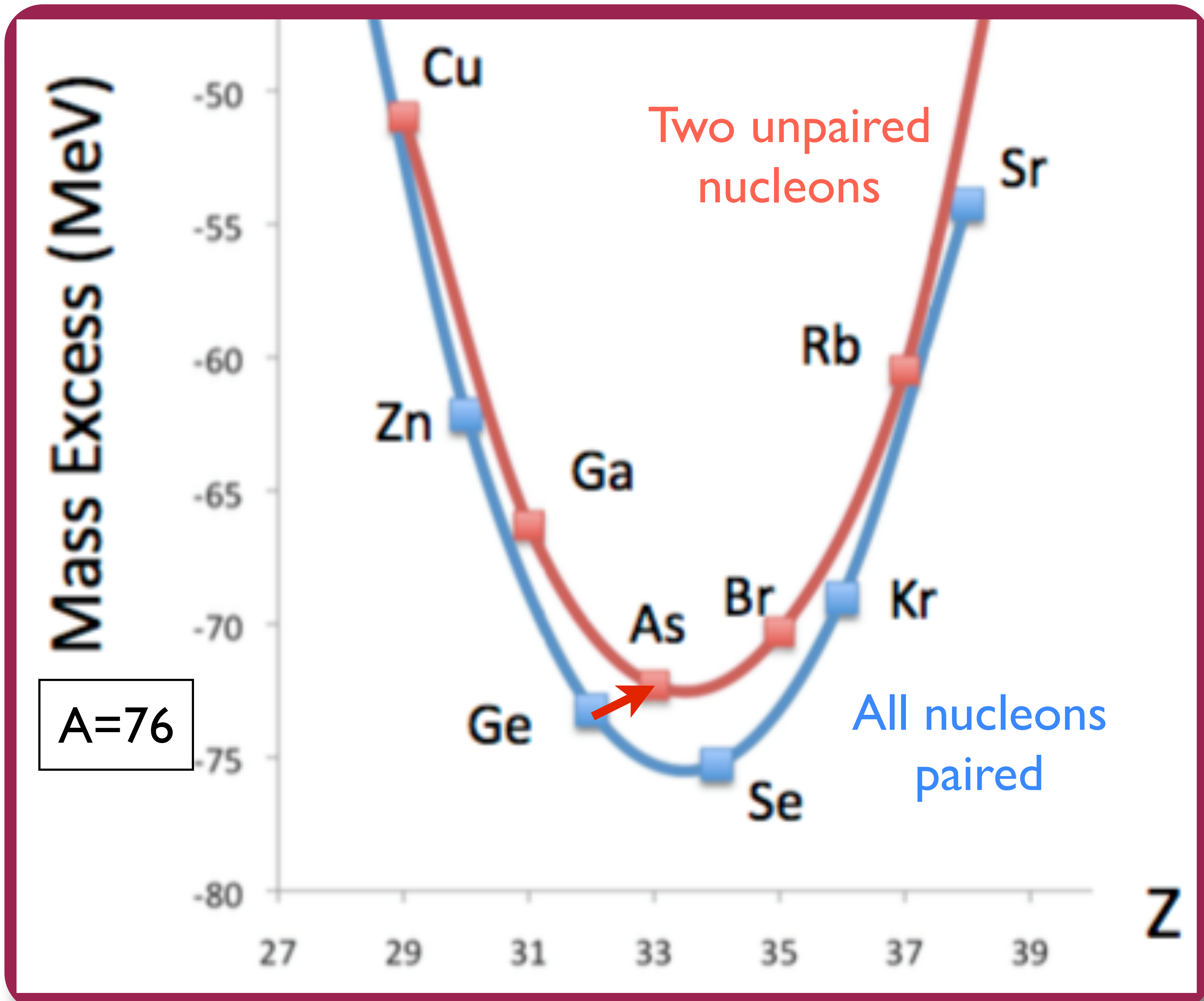

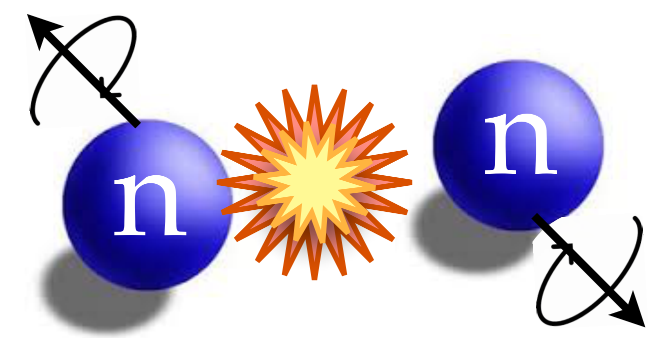

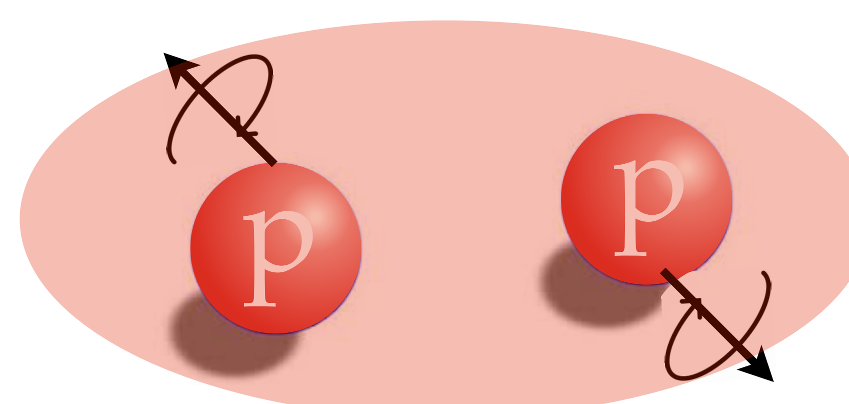

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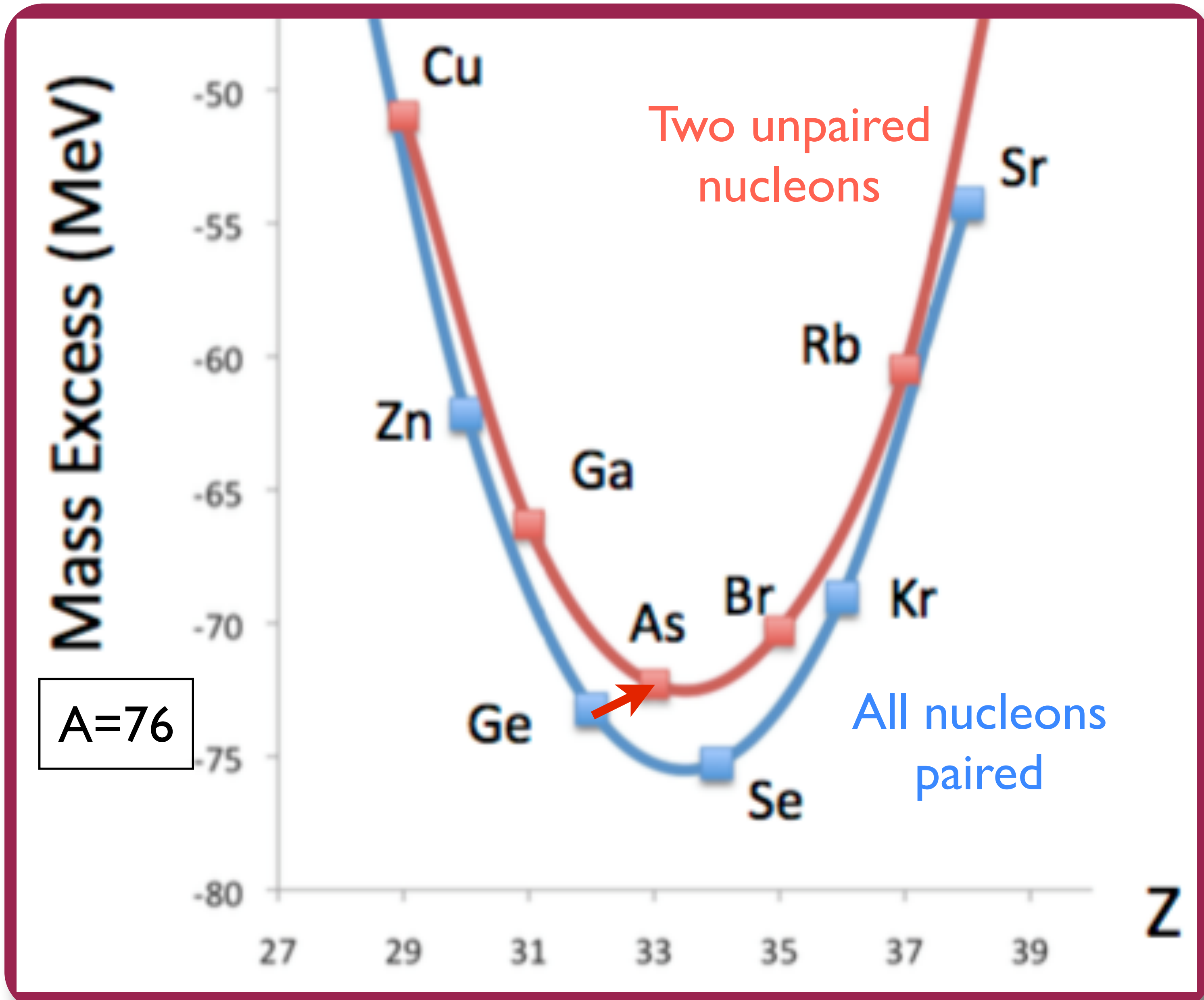

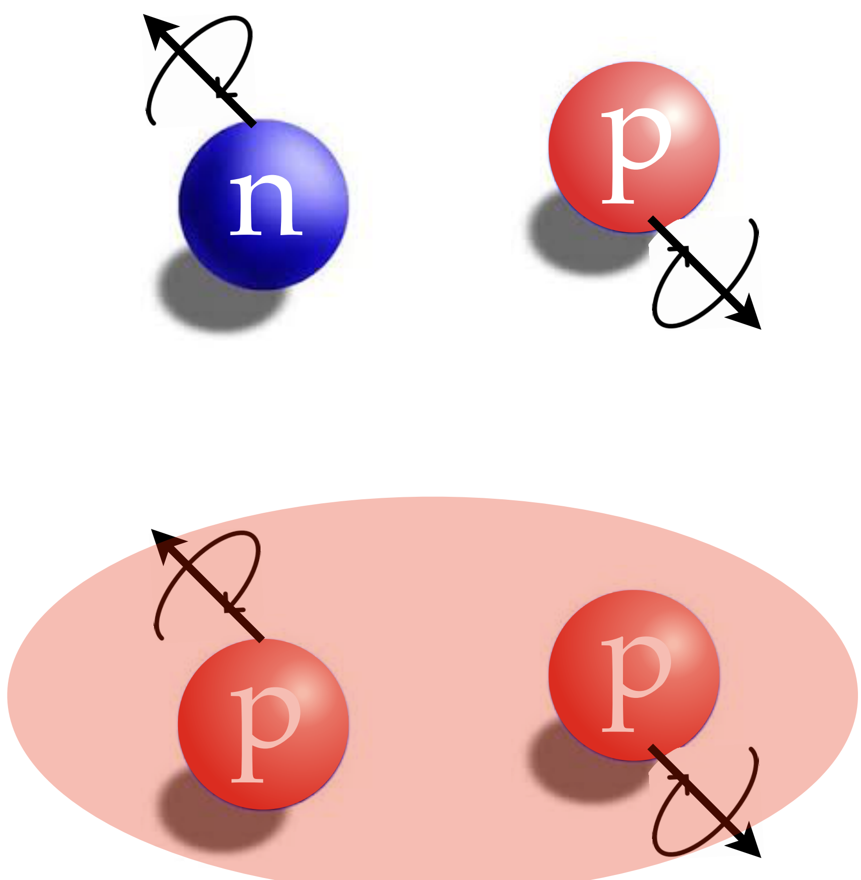

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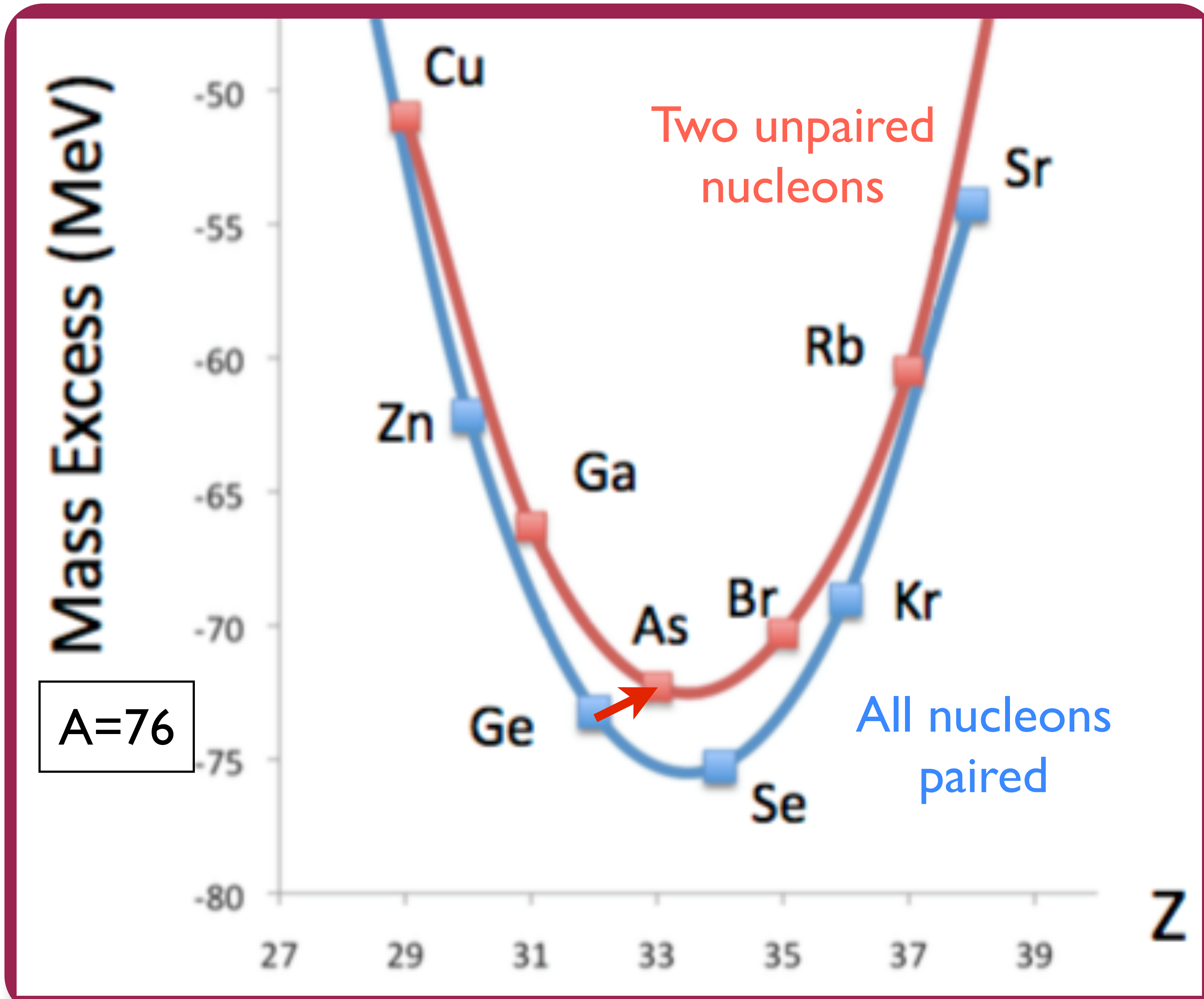
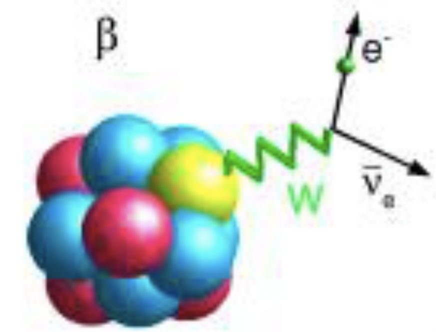
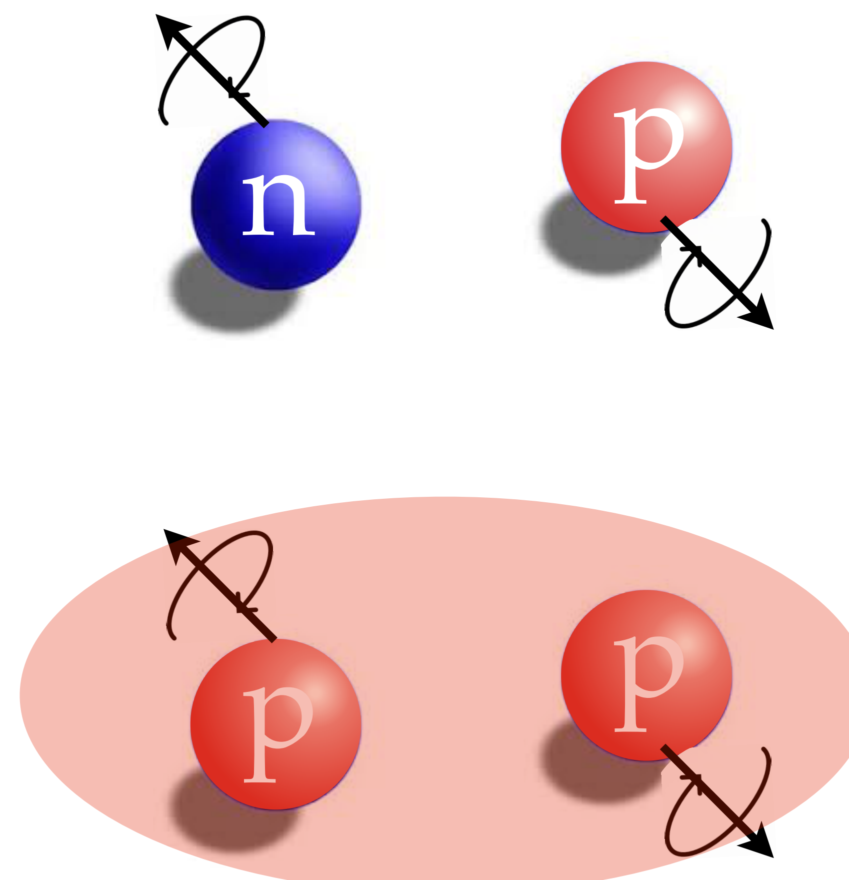


Energetically forbidden





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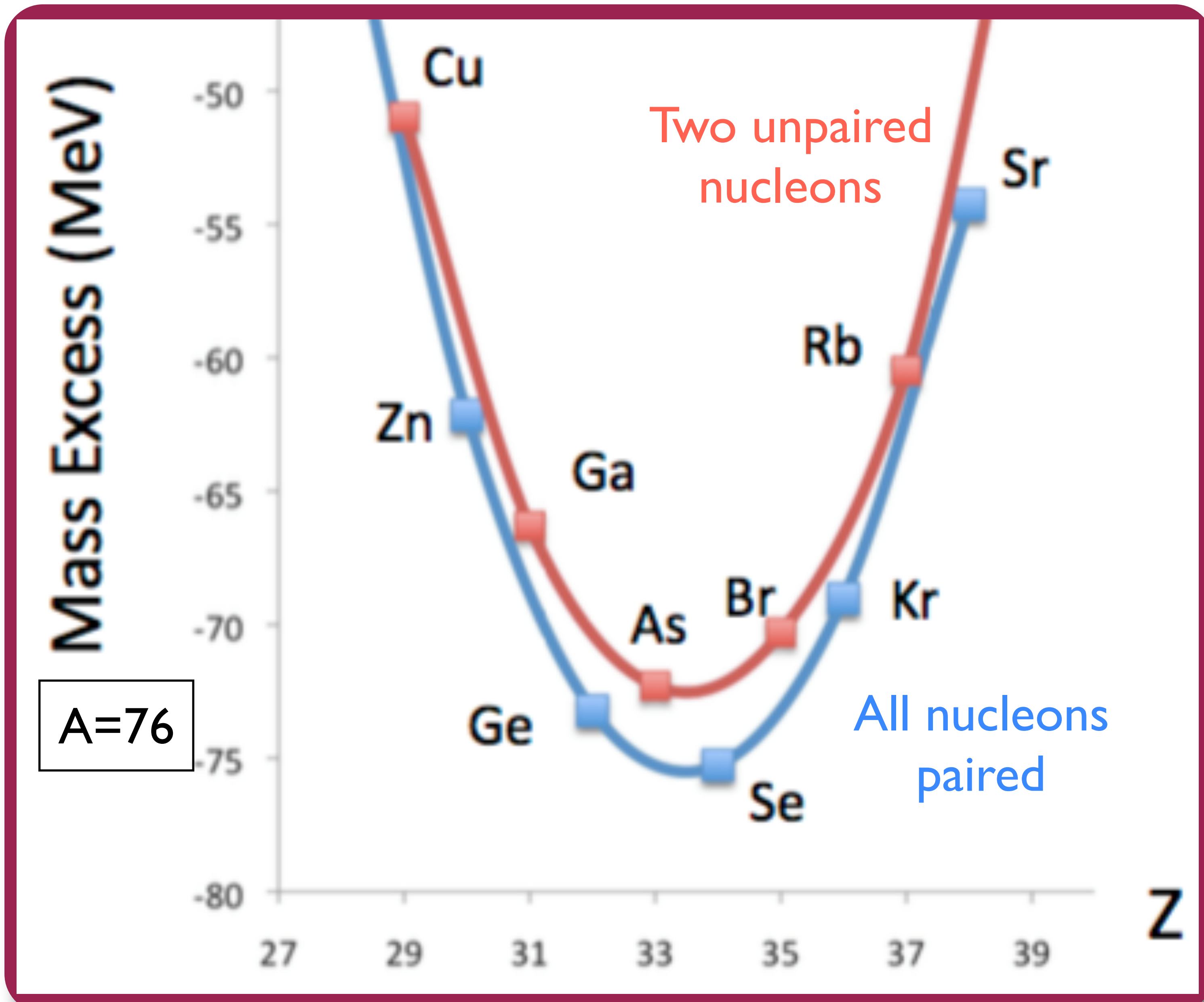

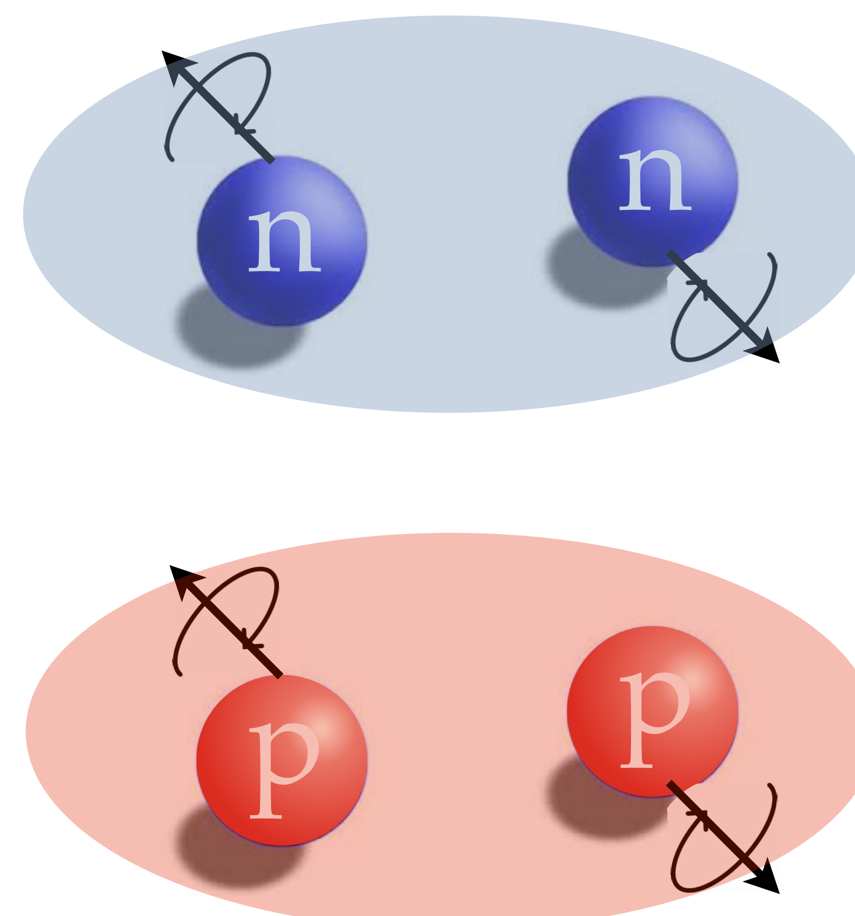

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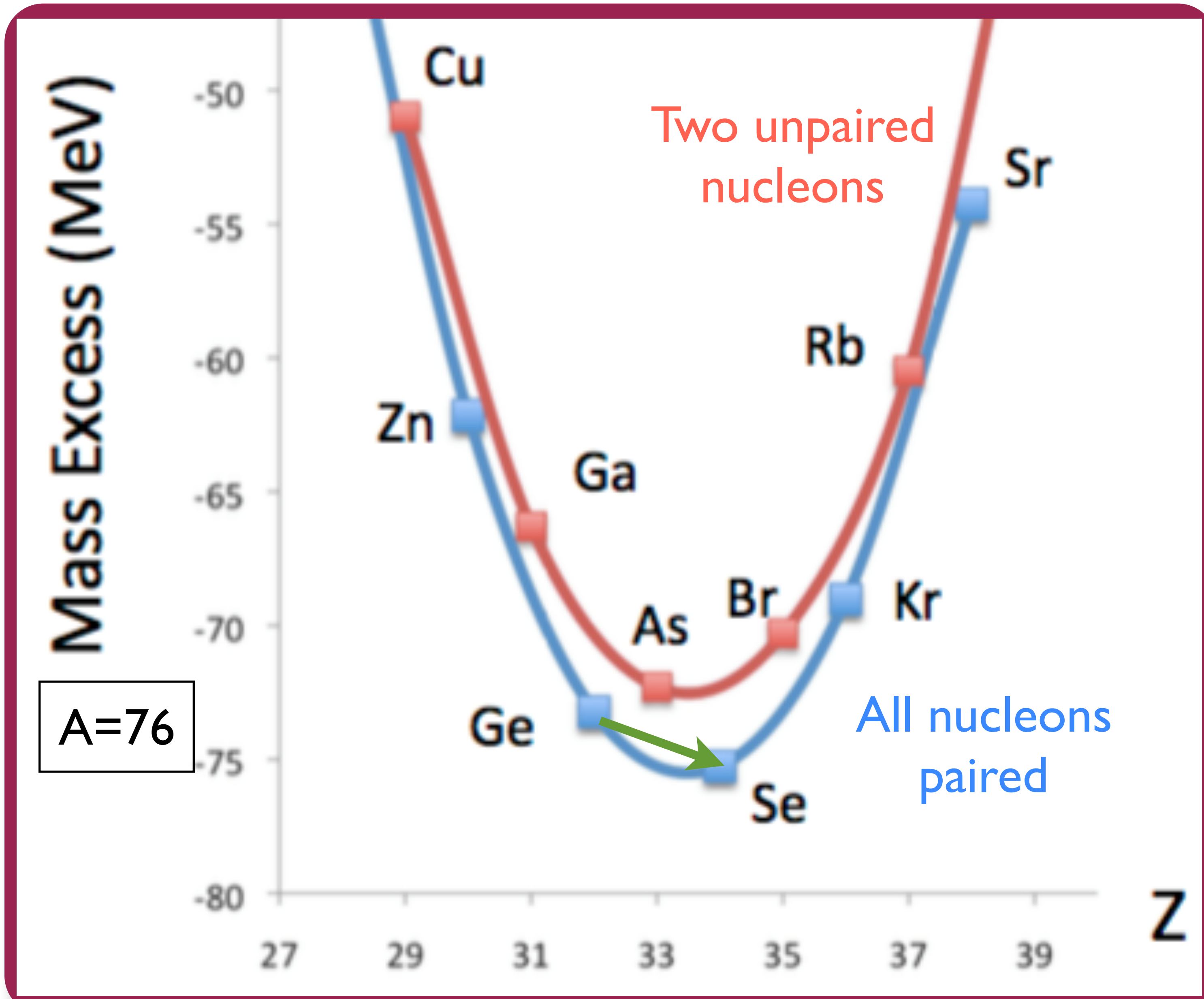

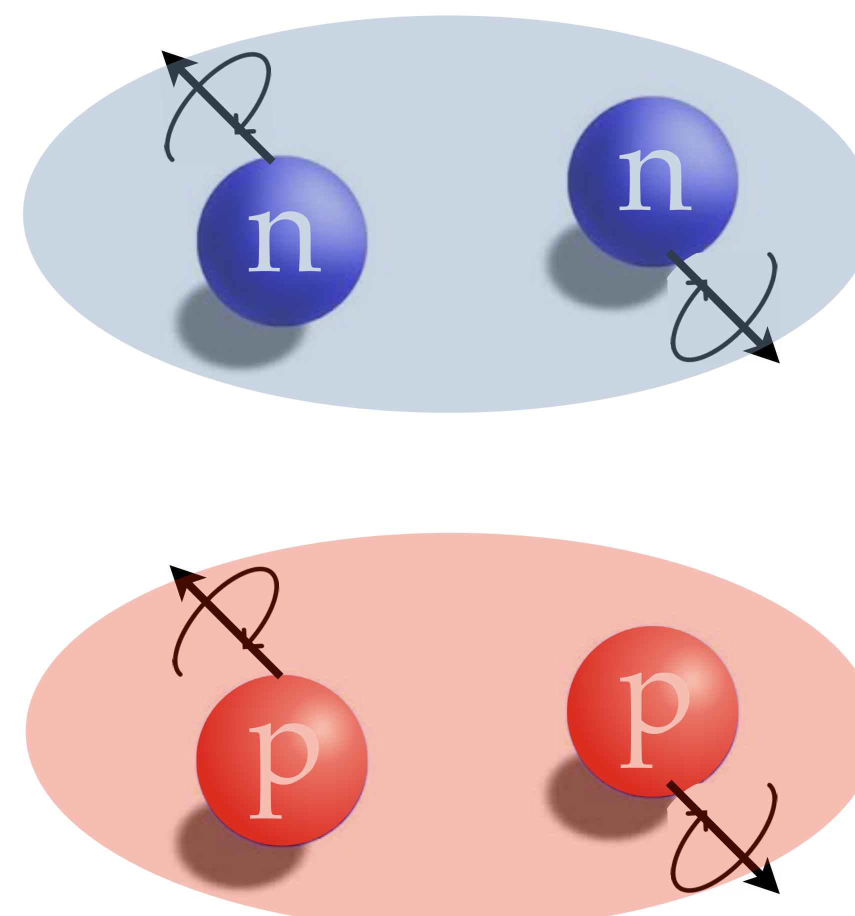

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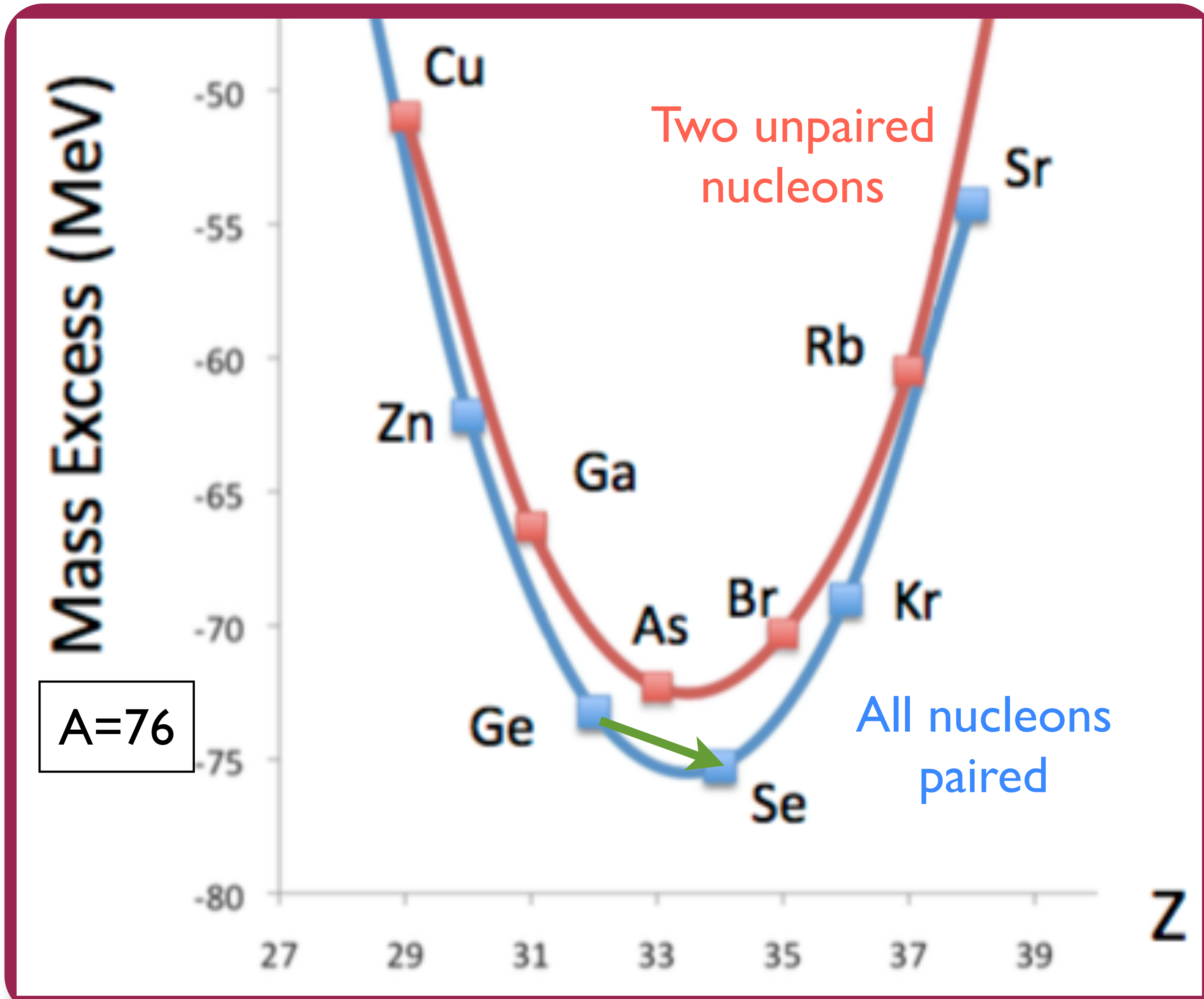
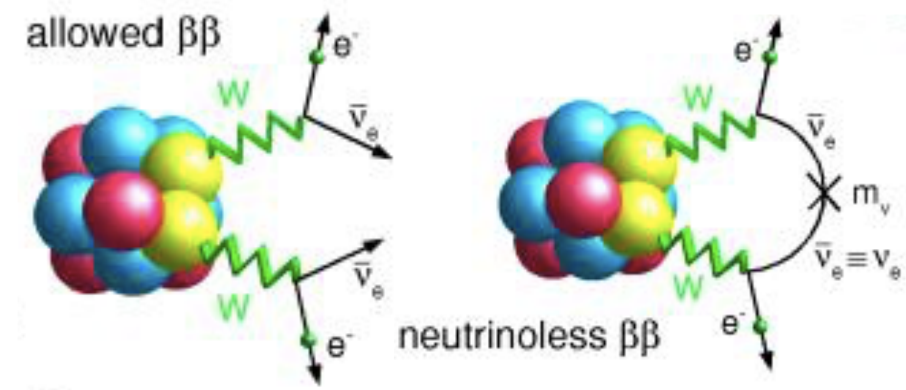
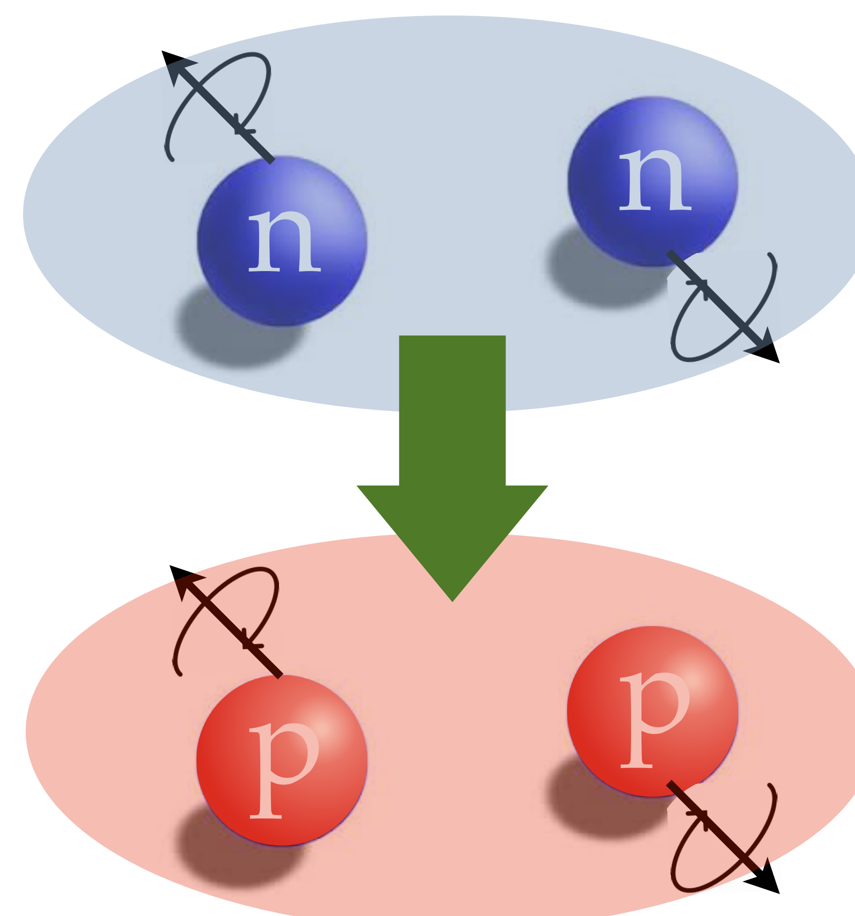


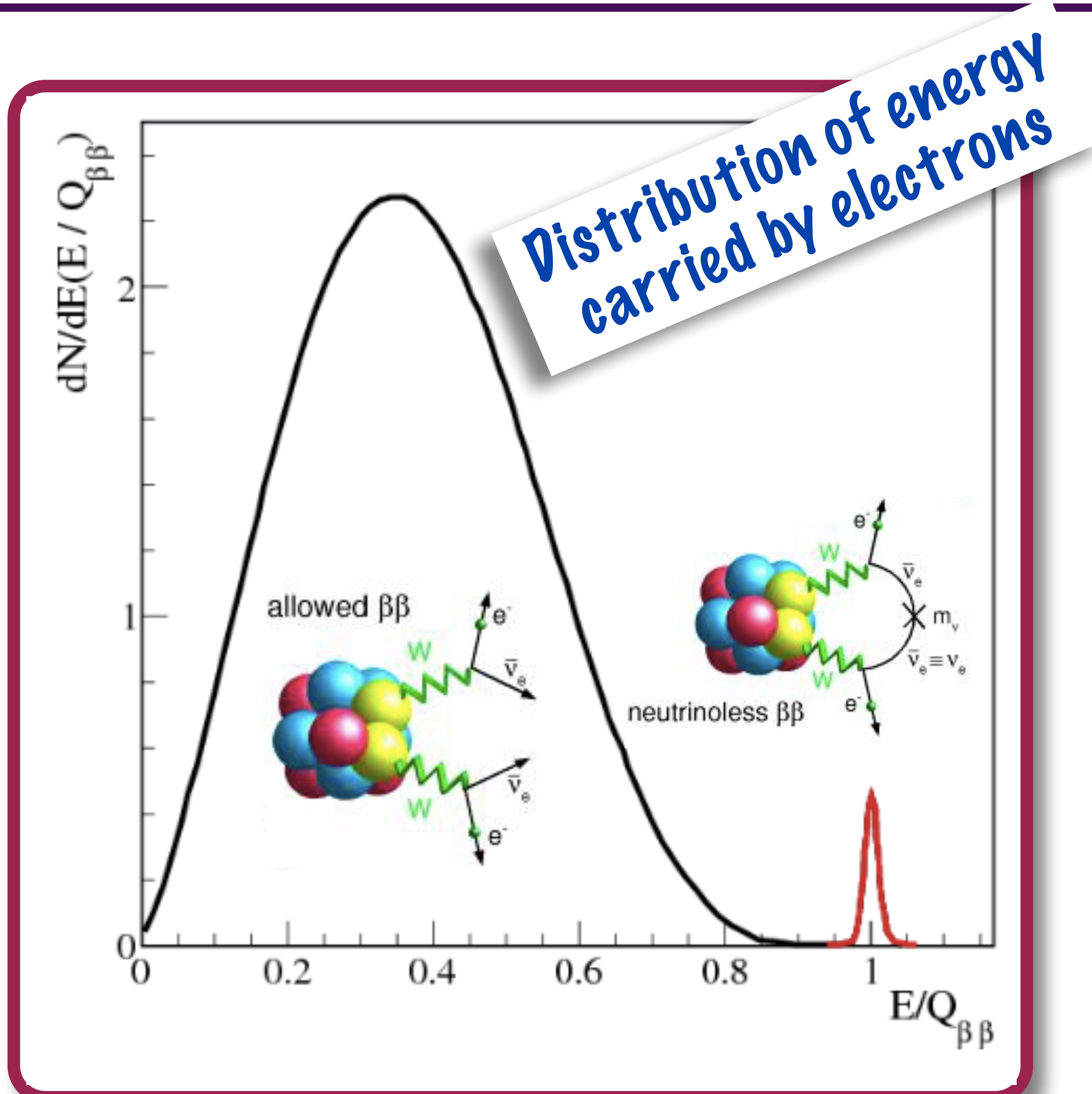
Second order, allowed



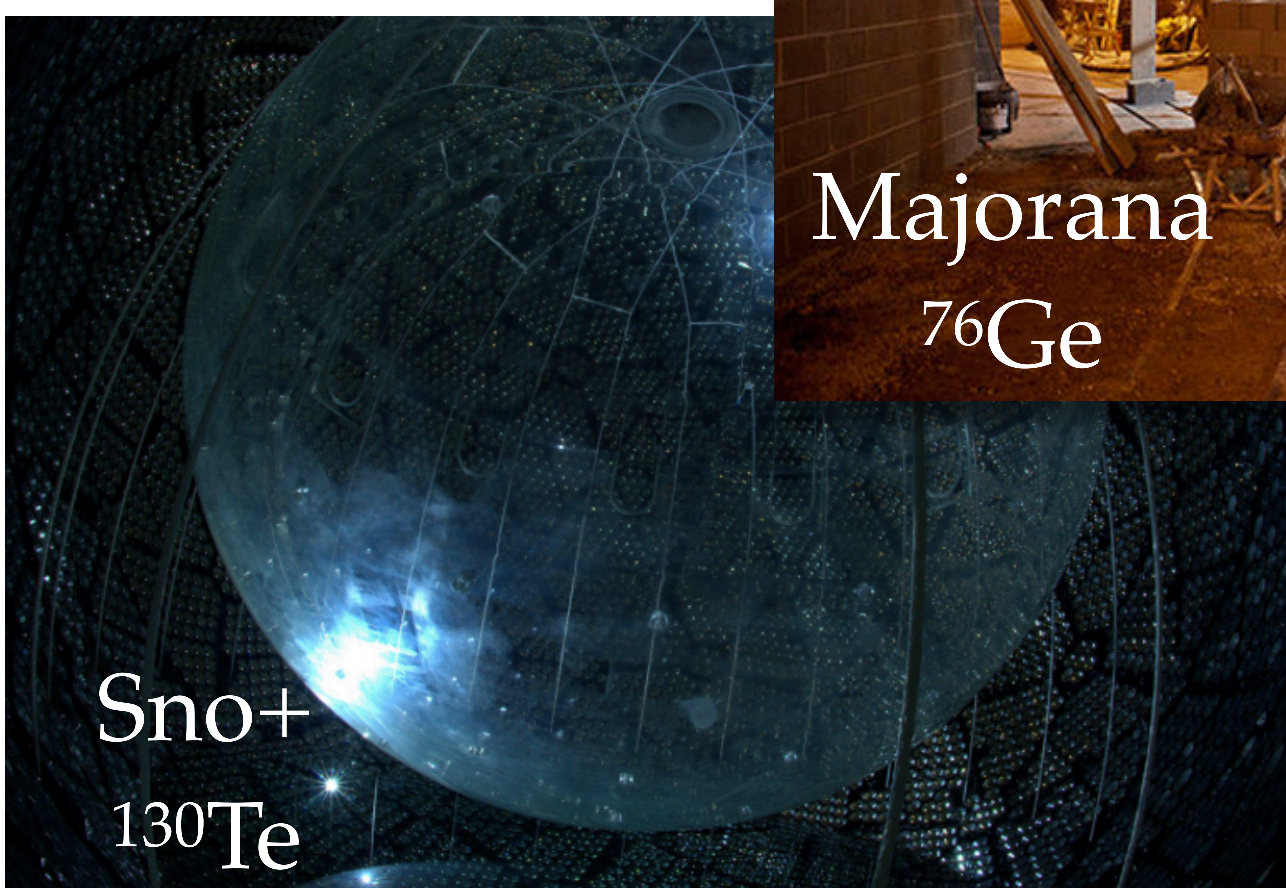


Experiment

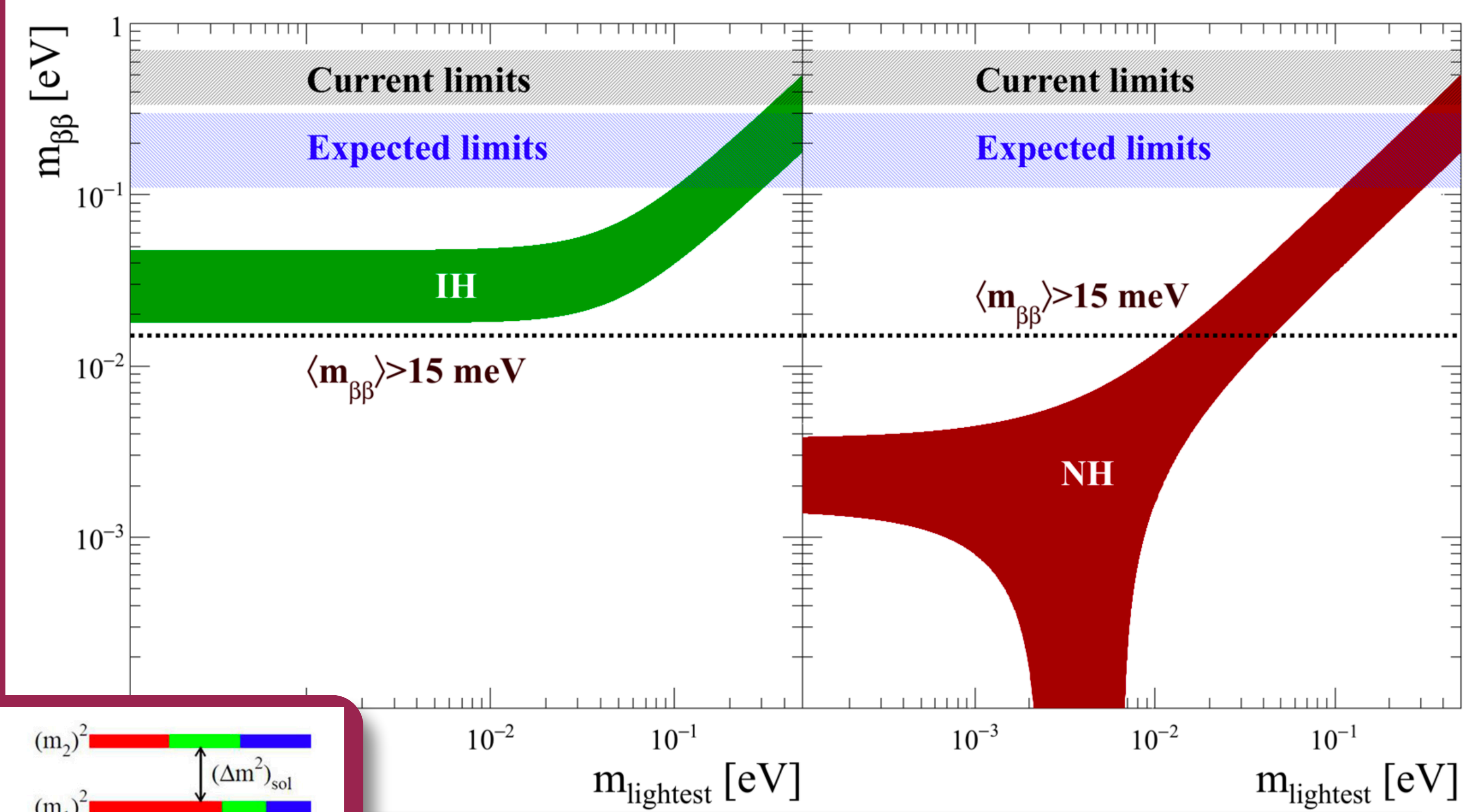
Neutrinoless mode can be isolated using spectroscopic methods

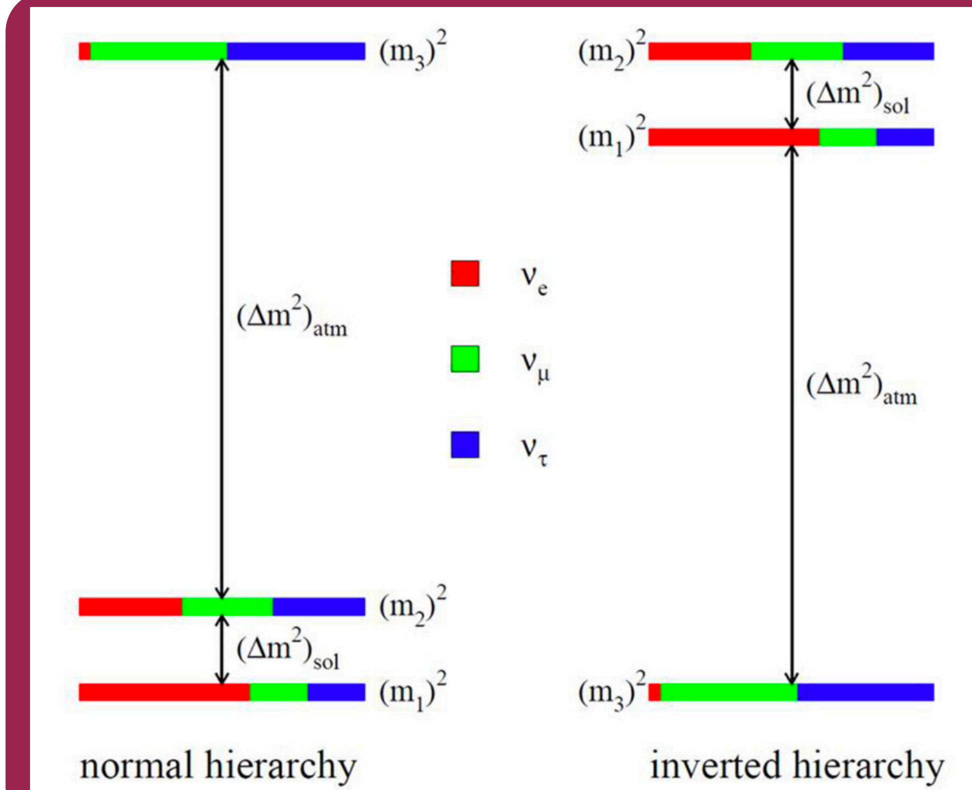


Experiment



From NSAC Long Range Plan 2015





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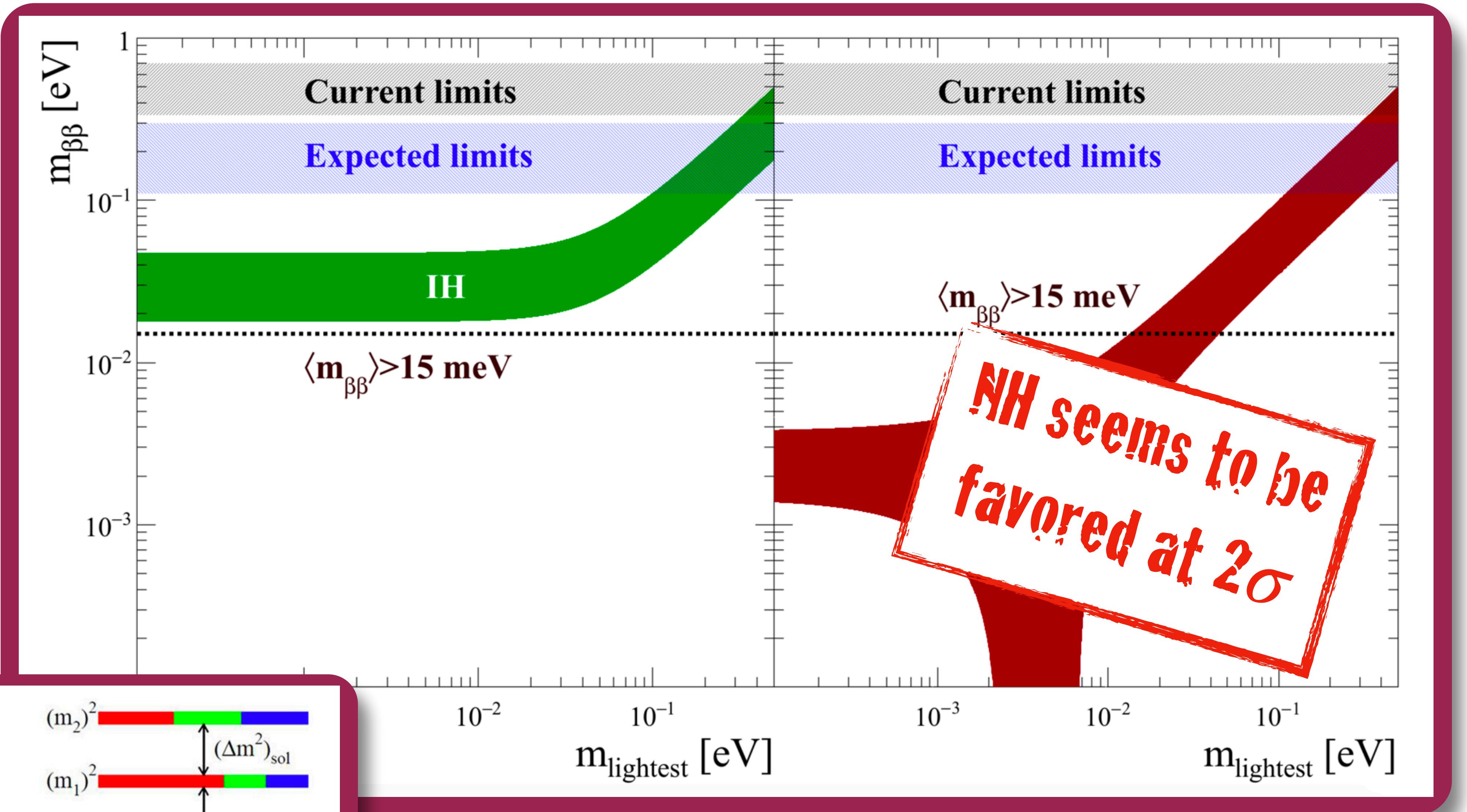
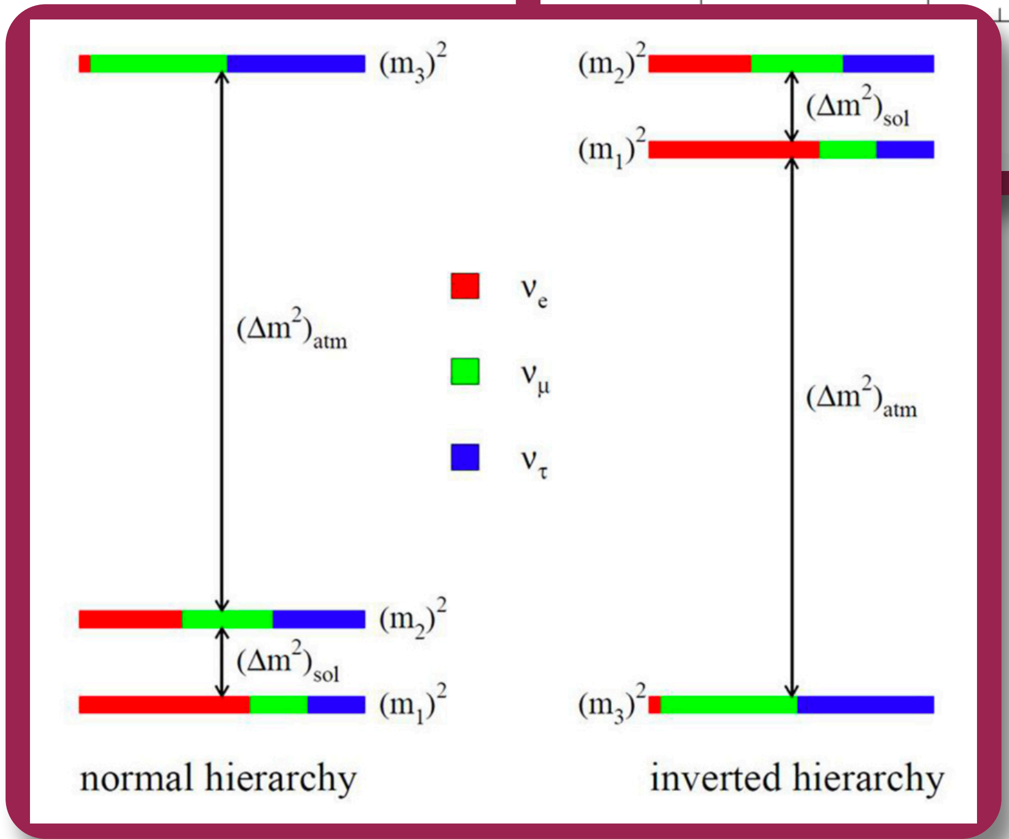
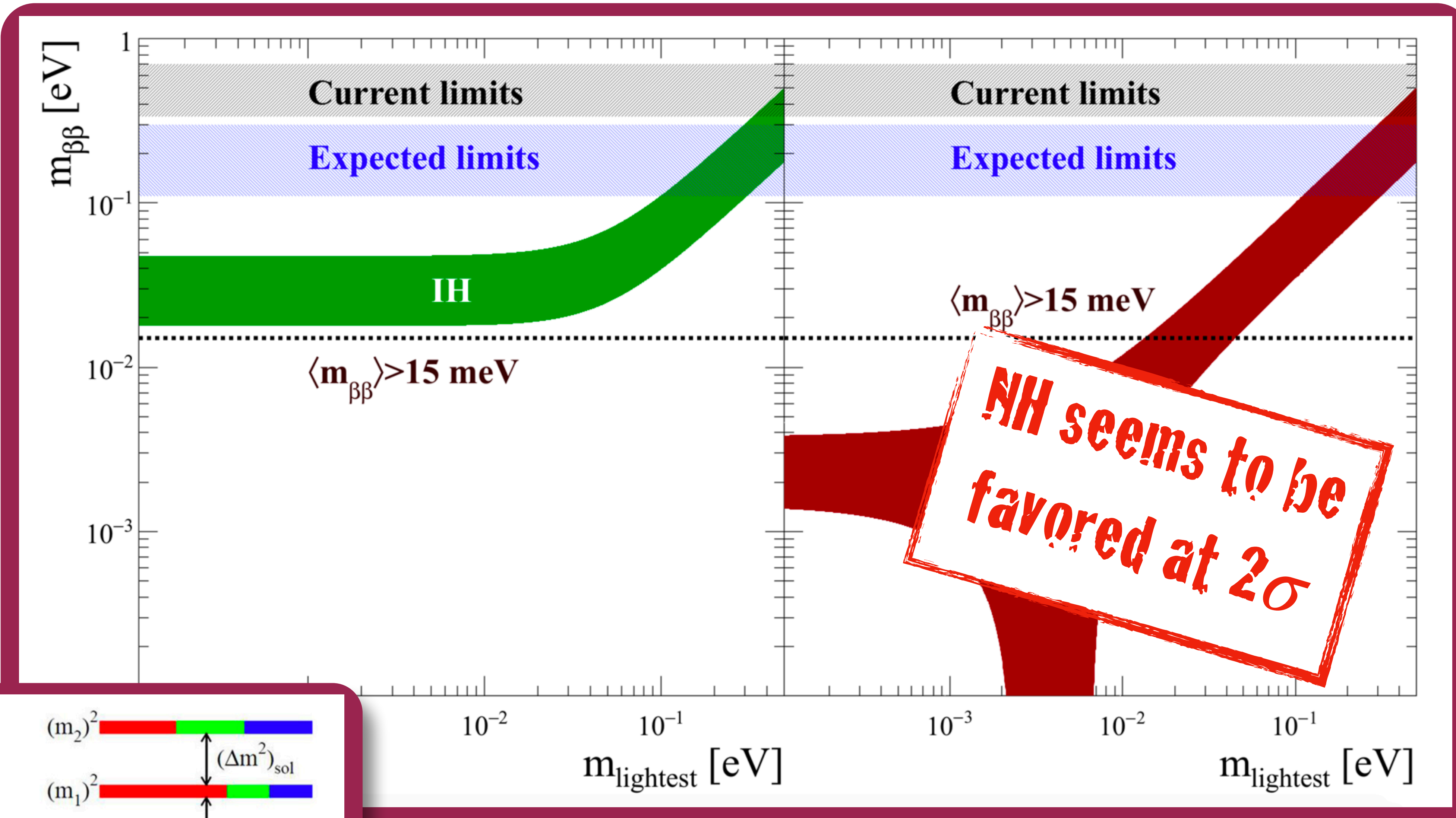
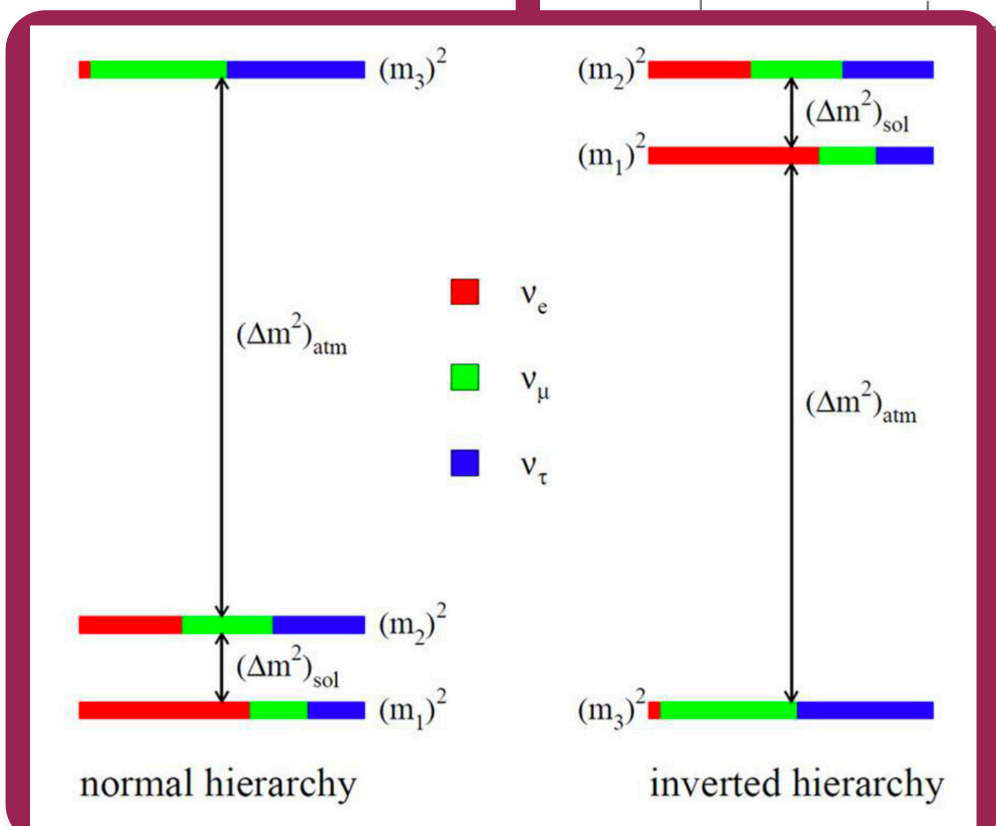




Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo
Phys.Rev. D95 (2017) no.9, 096014

From NSAC Long Range Plan 2015





1. NME's currently have large, uncontrolled theoretical uncertainties - can we improve this?

Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo
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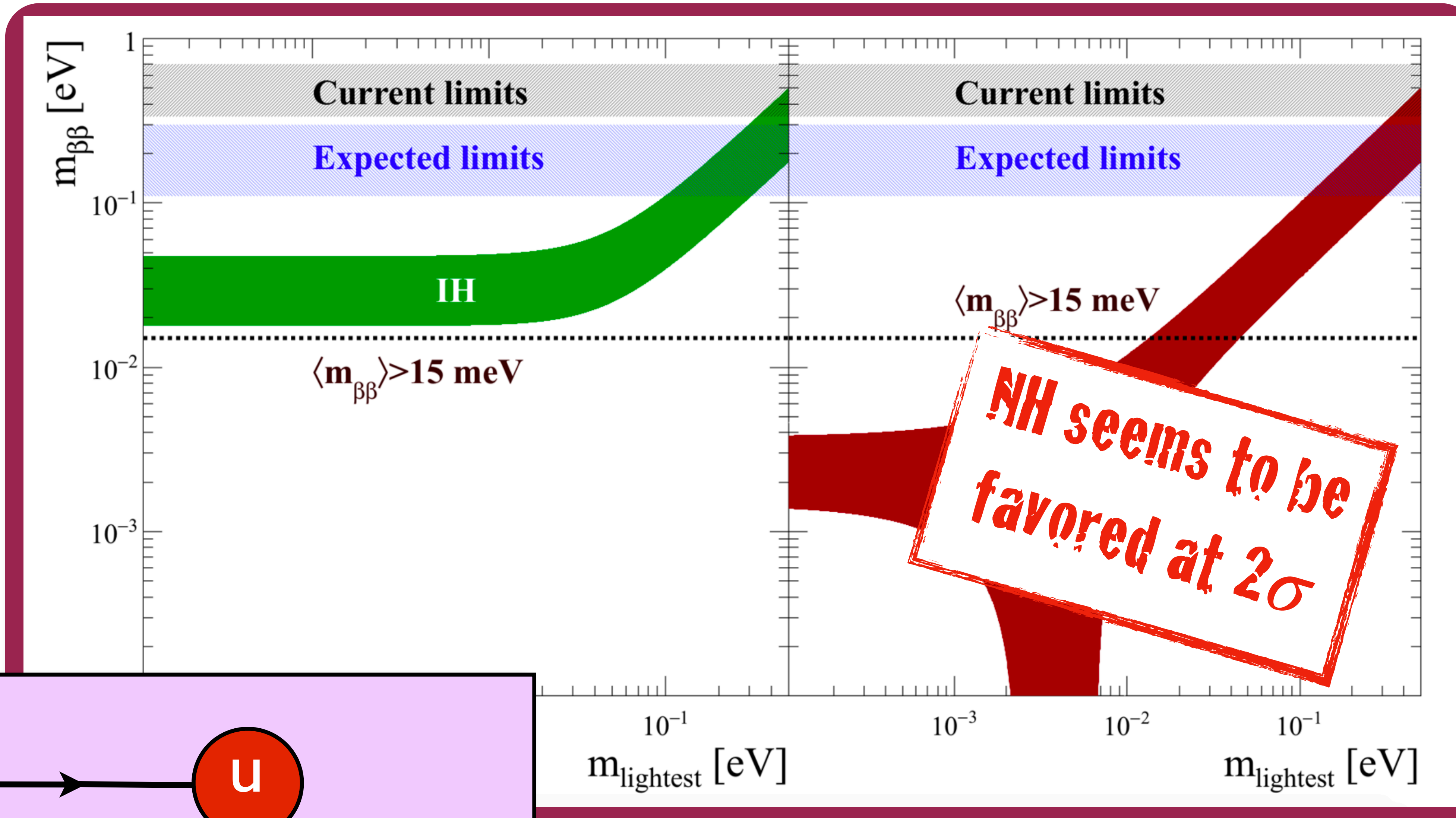

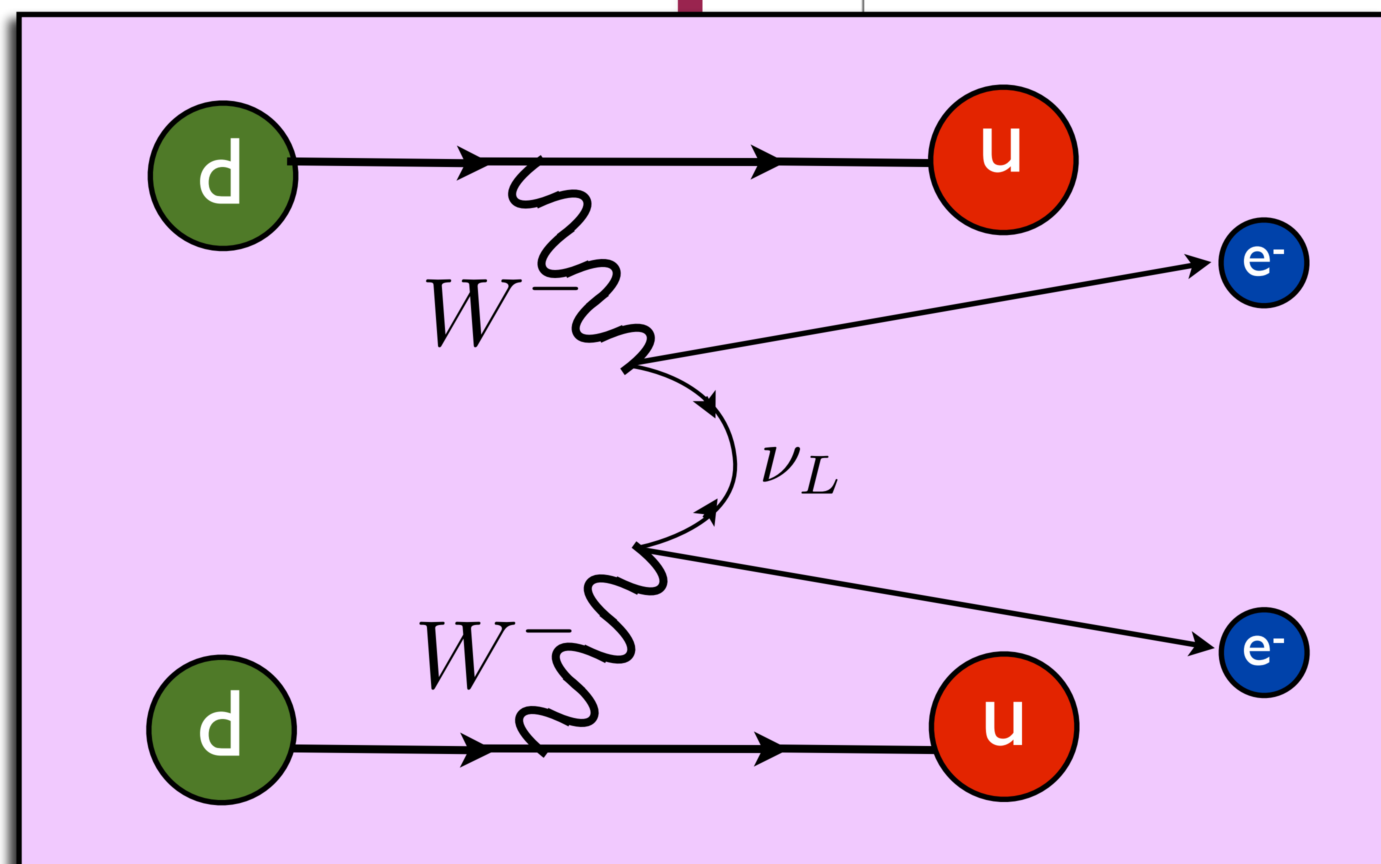

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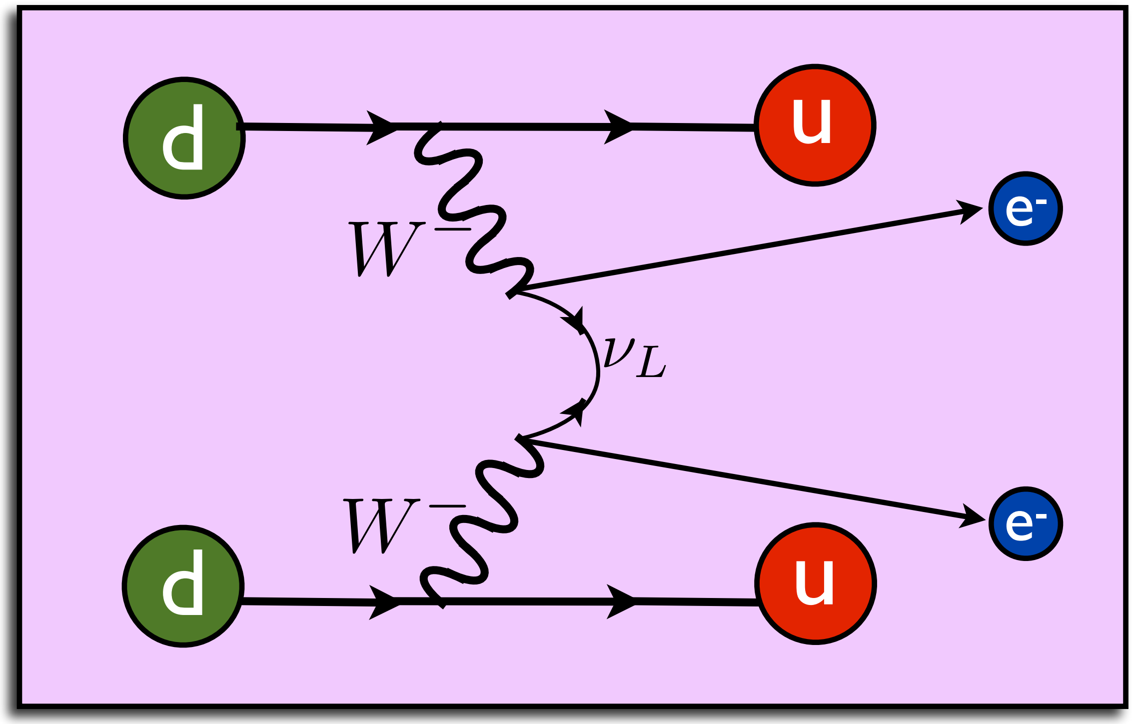
1. NME's currently have large, uncontrolled theoretical uncertainties - can we improve this?
2. This picture assumes only (perturbative) long-range neutrino exchange. There's more to the story - maybe we're missing something important!

Short-range contributions



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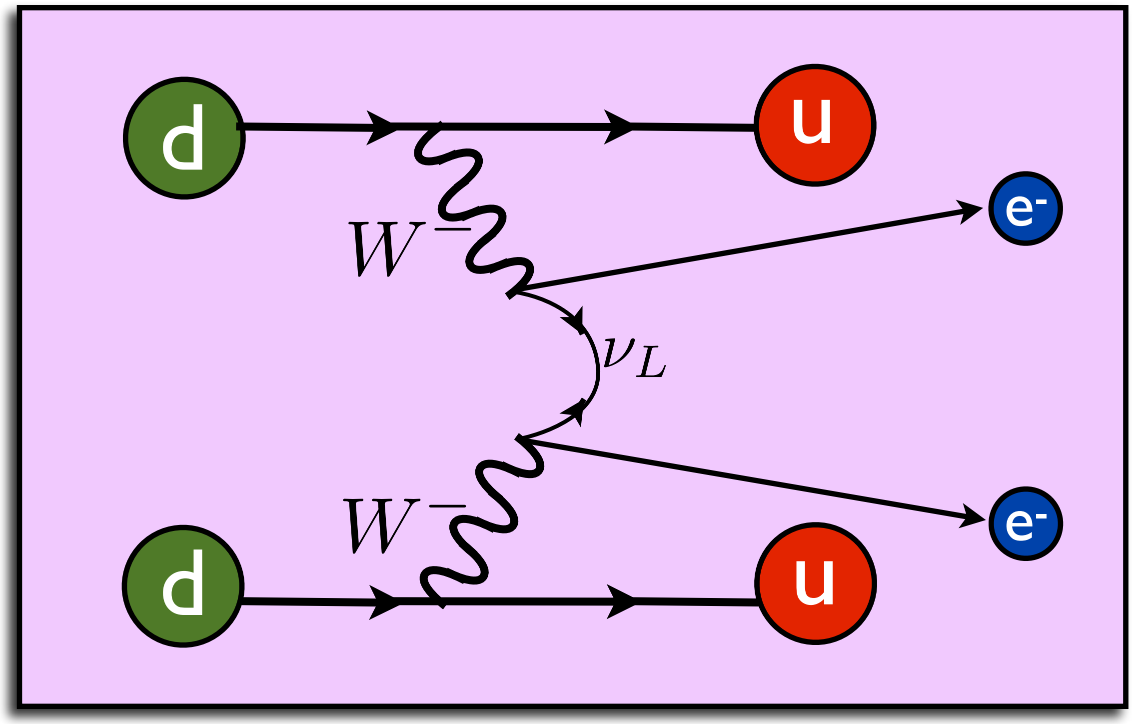

Seesaw Mechanism

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

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

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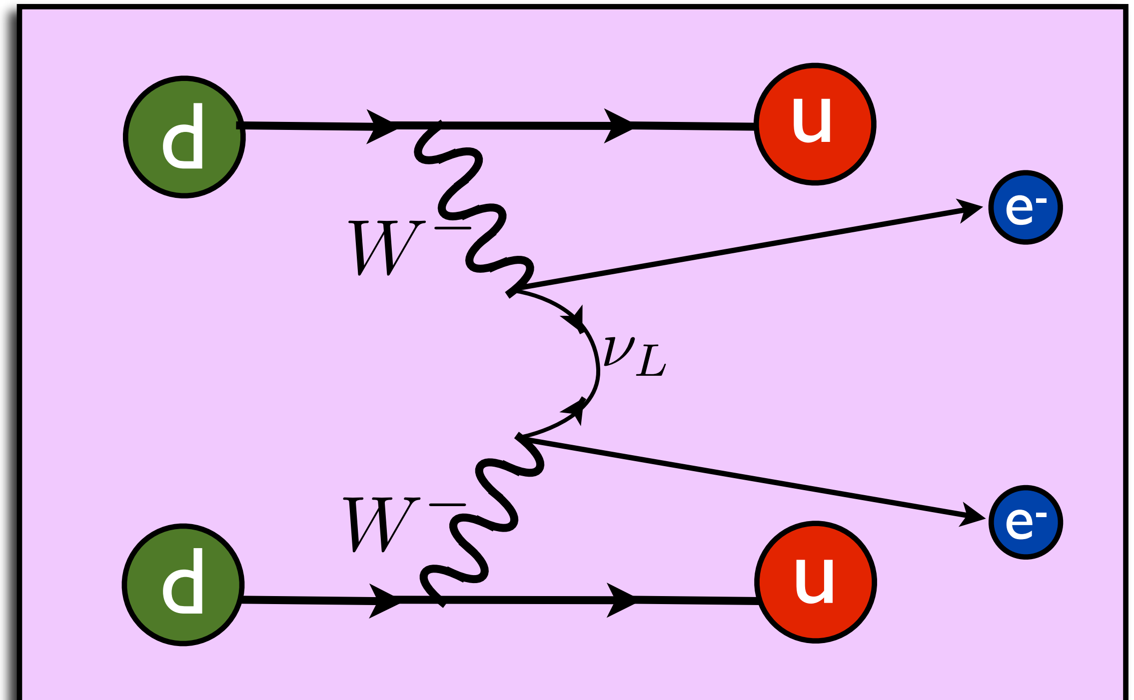

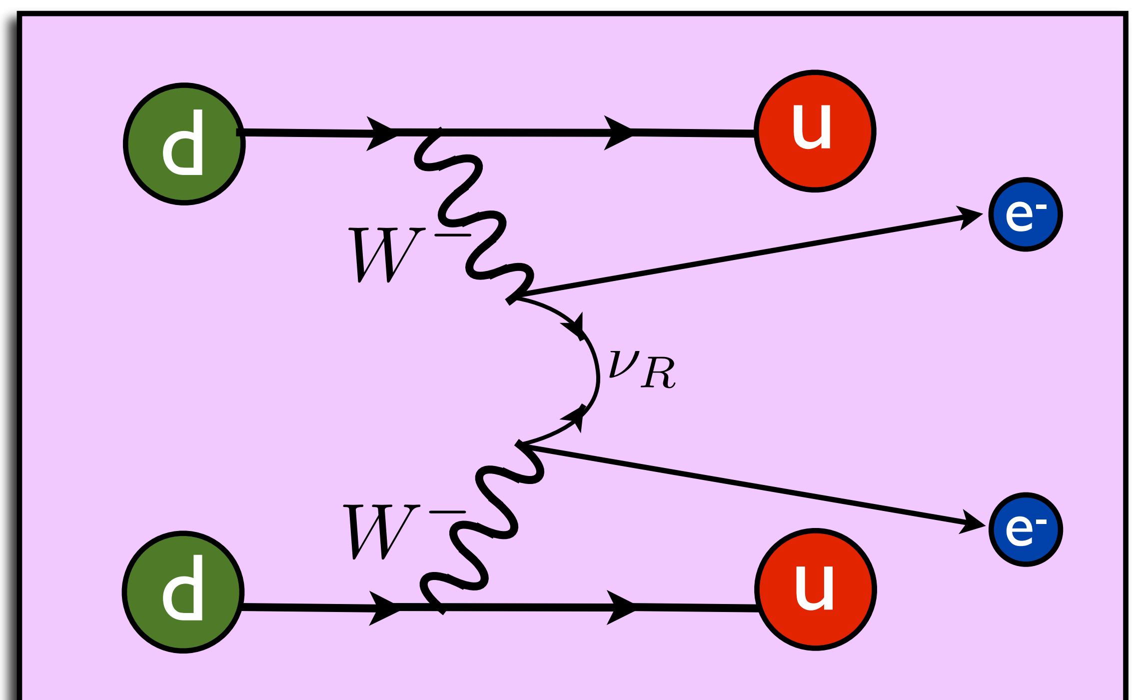

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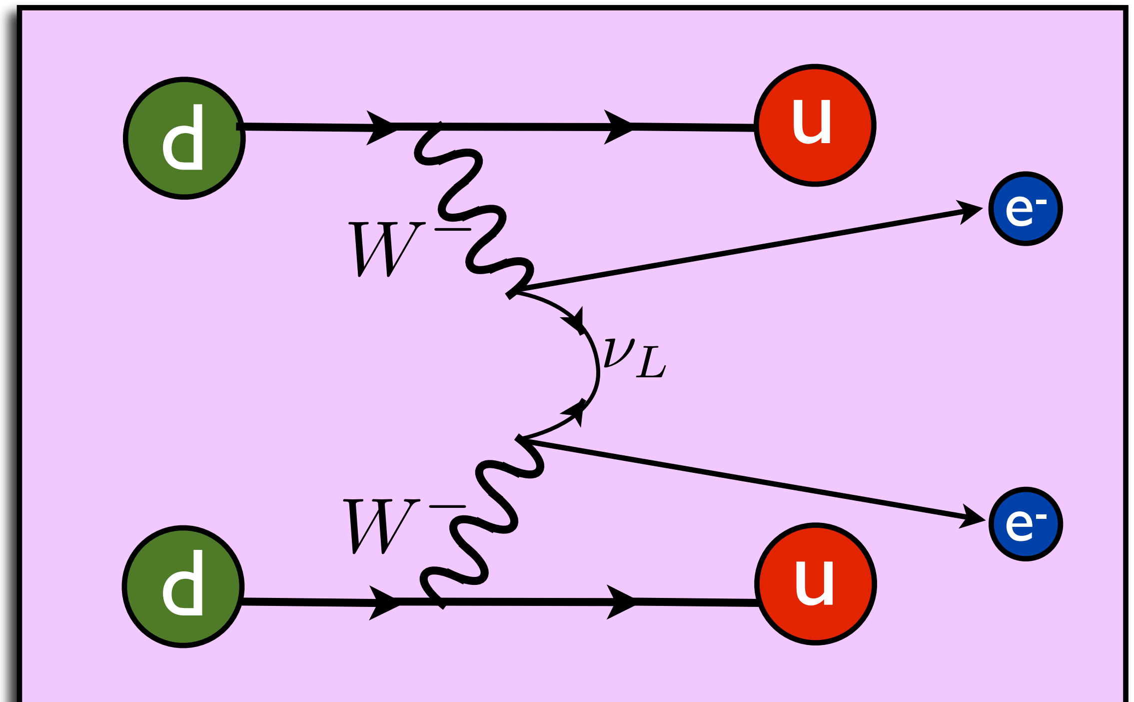

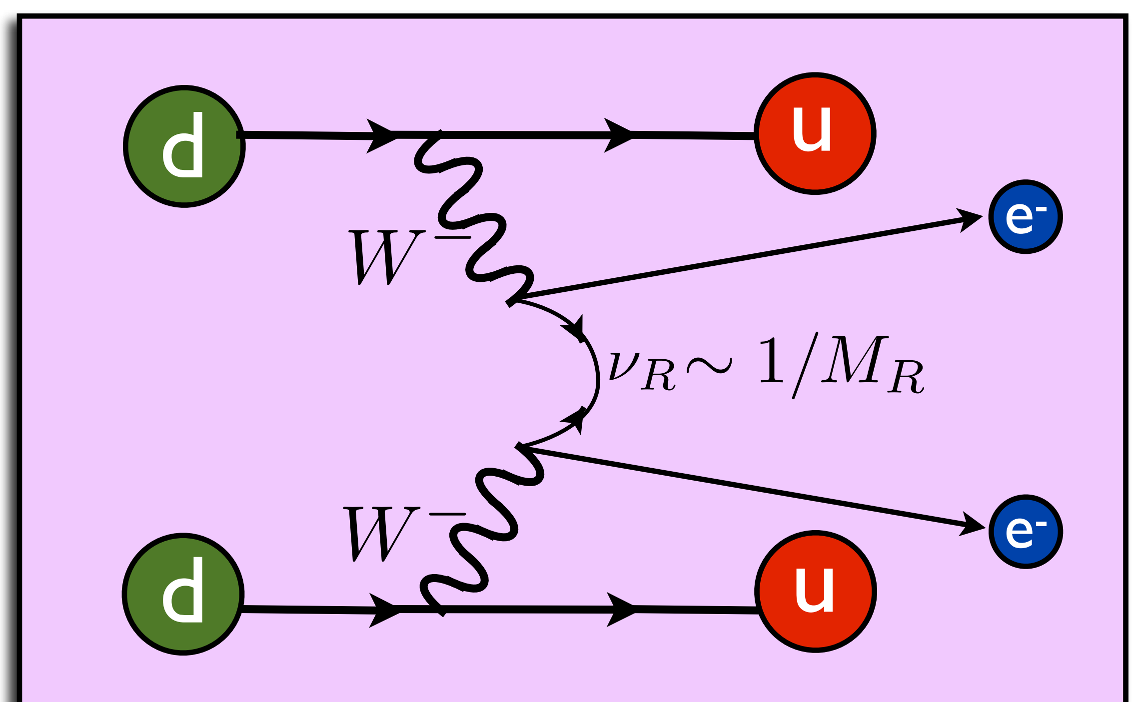

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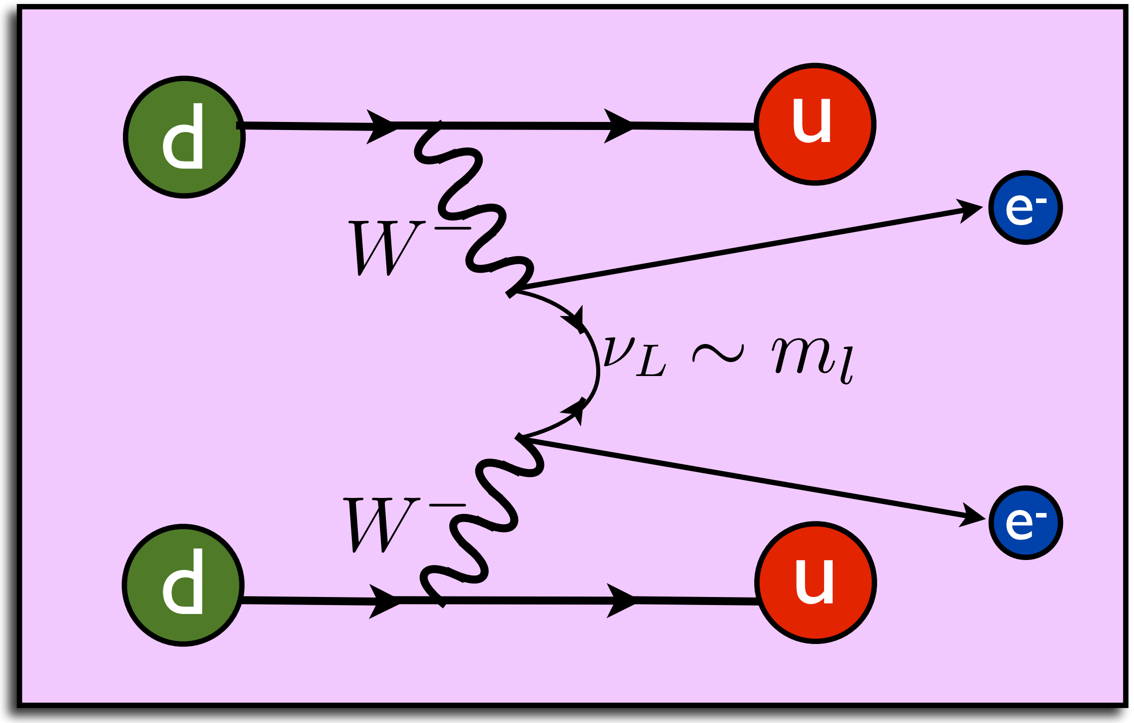

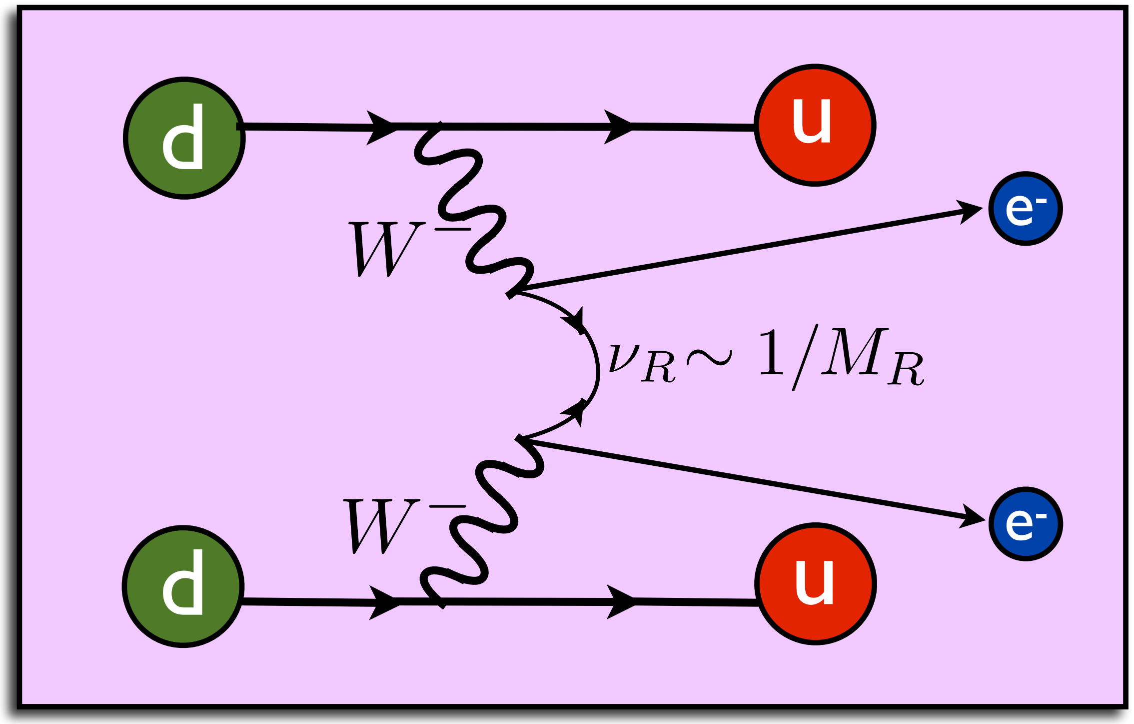

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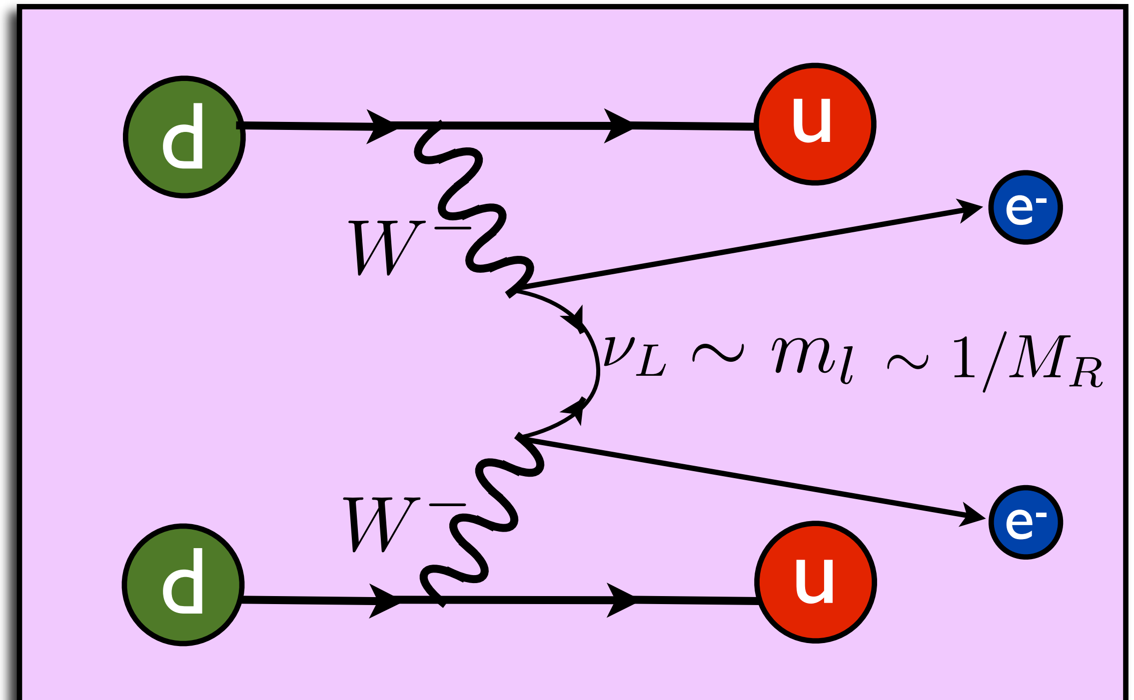

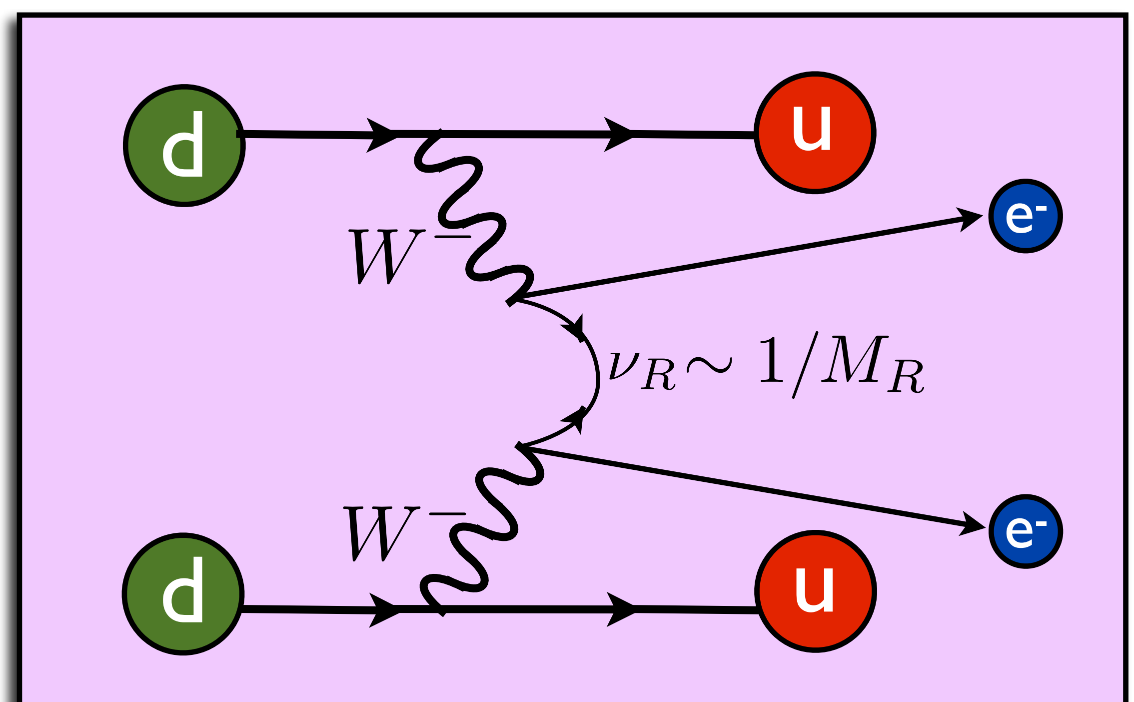

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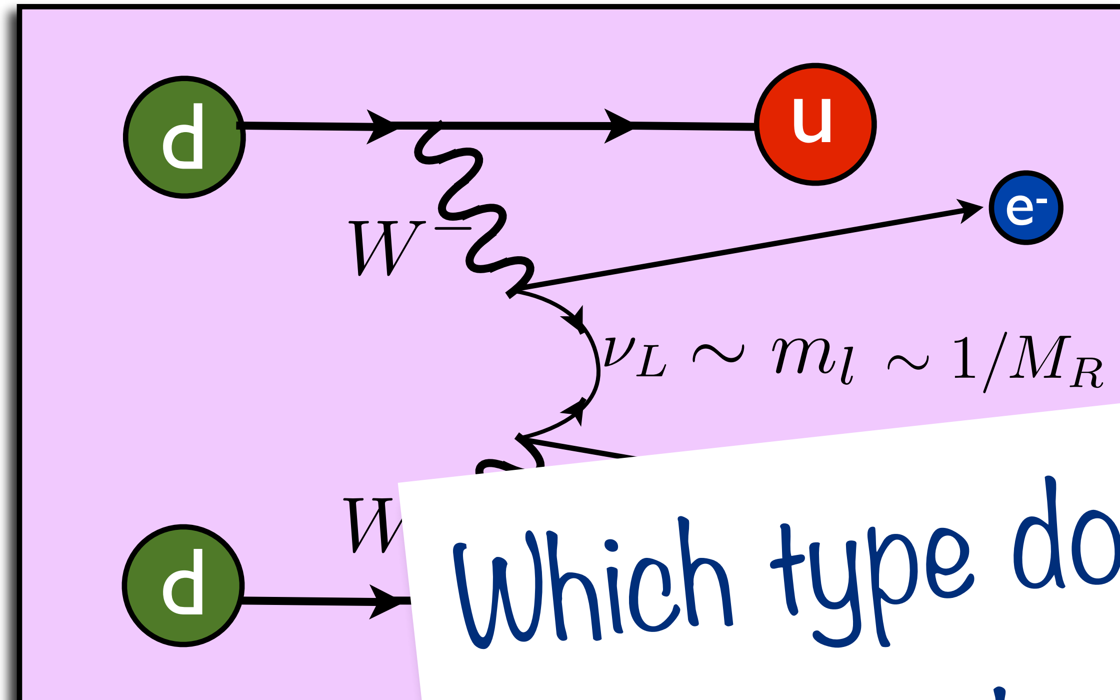
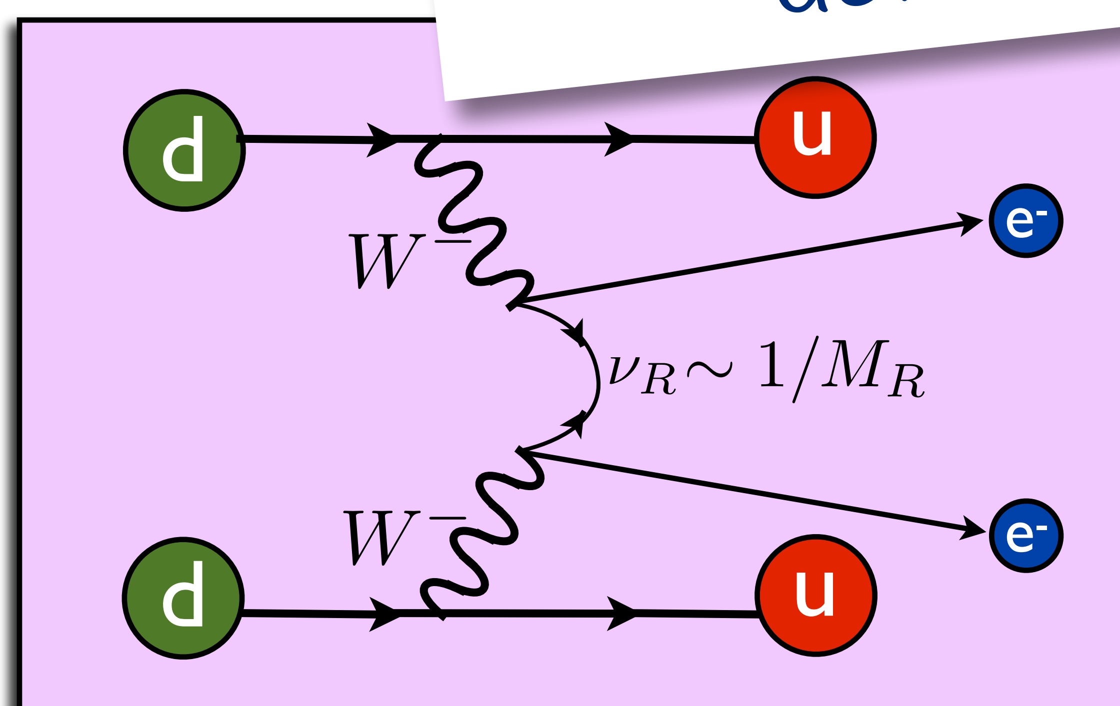


Seesaw Mechanism

Which type dominates depends on details of BSM model



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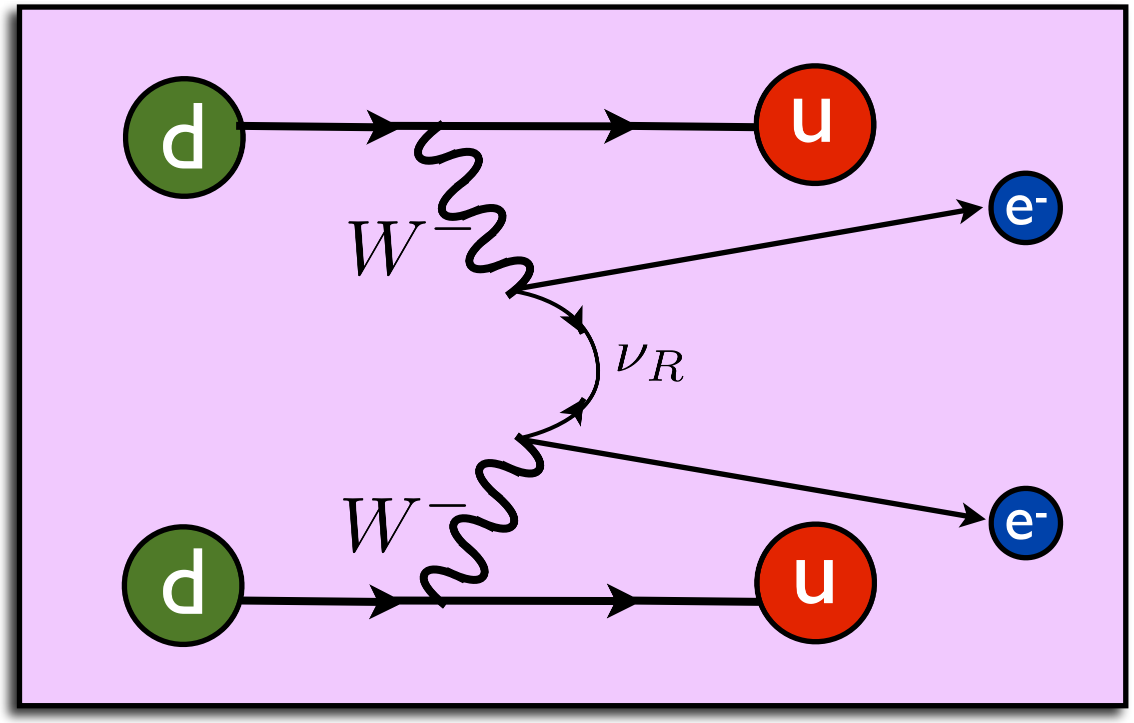
Short-range contributions

$$\mathcal{L}_5 = \frac{c}{\Lambda}\left(\bar{L}\tilde{H}\right)\left(\tilde{H}L\right)^{\dagger}$$



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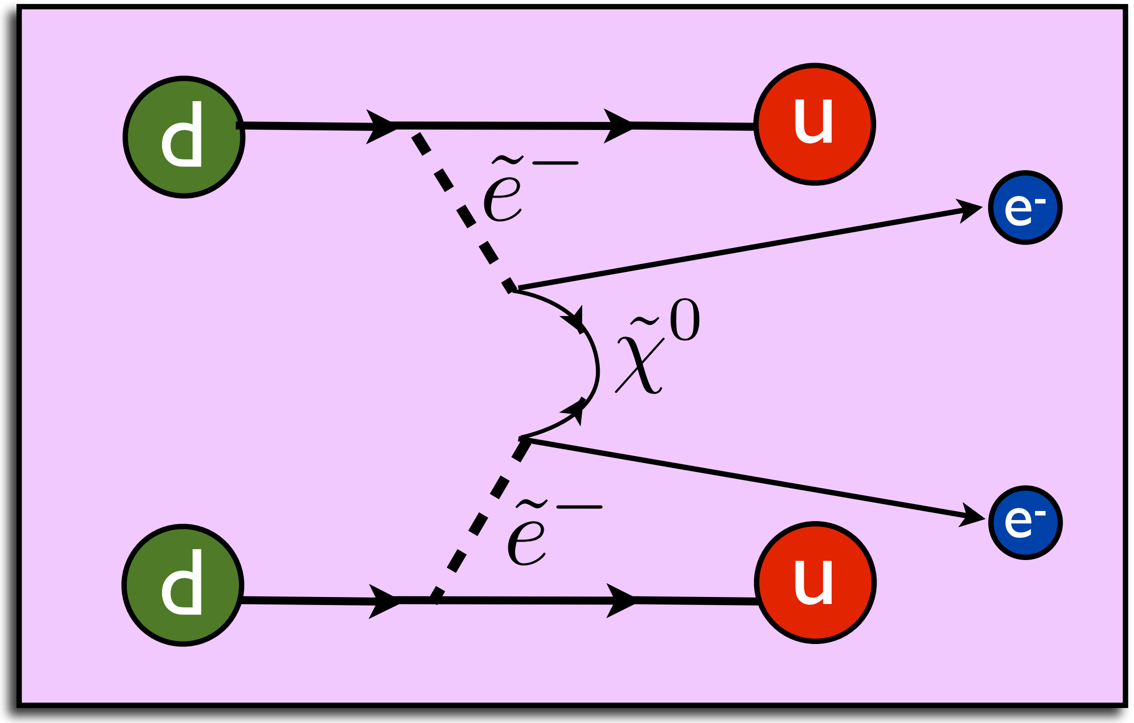

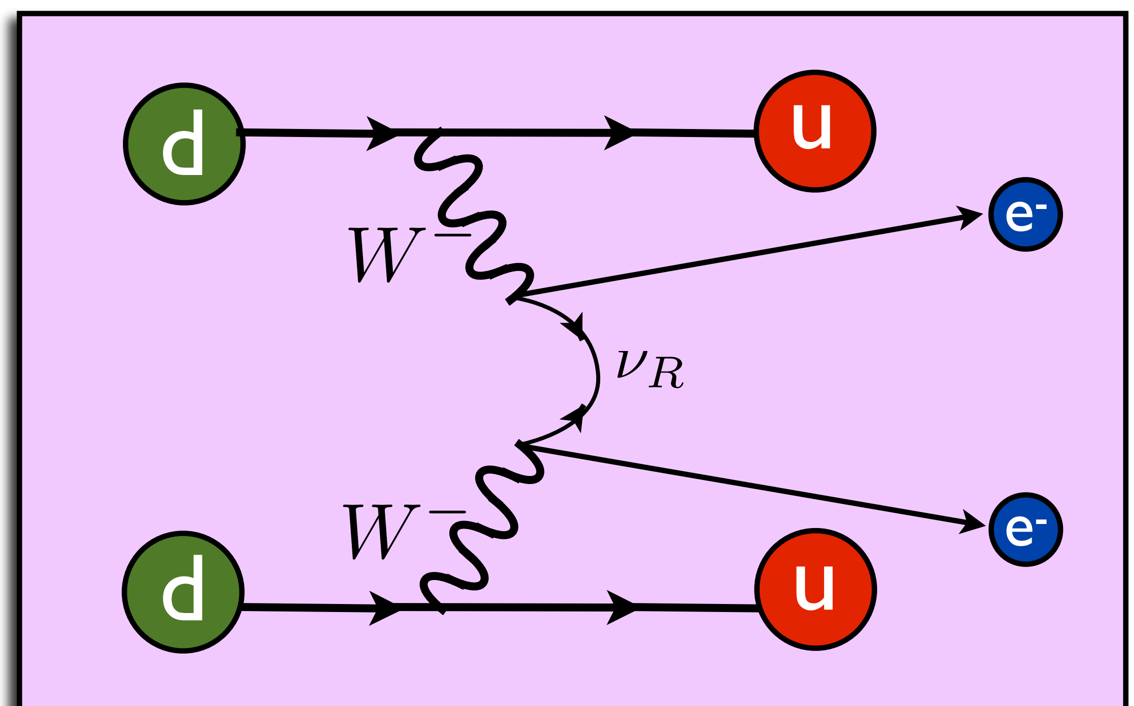

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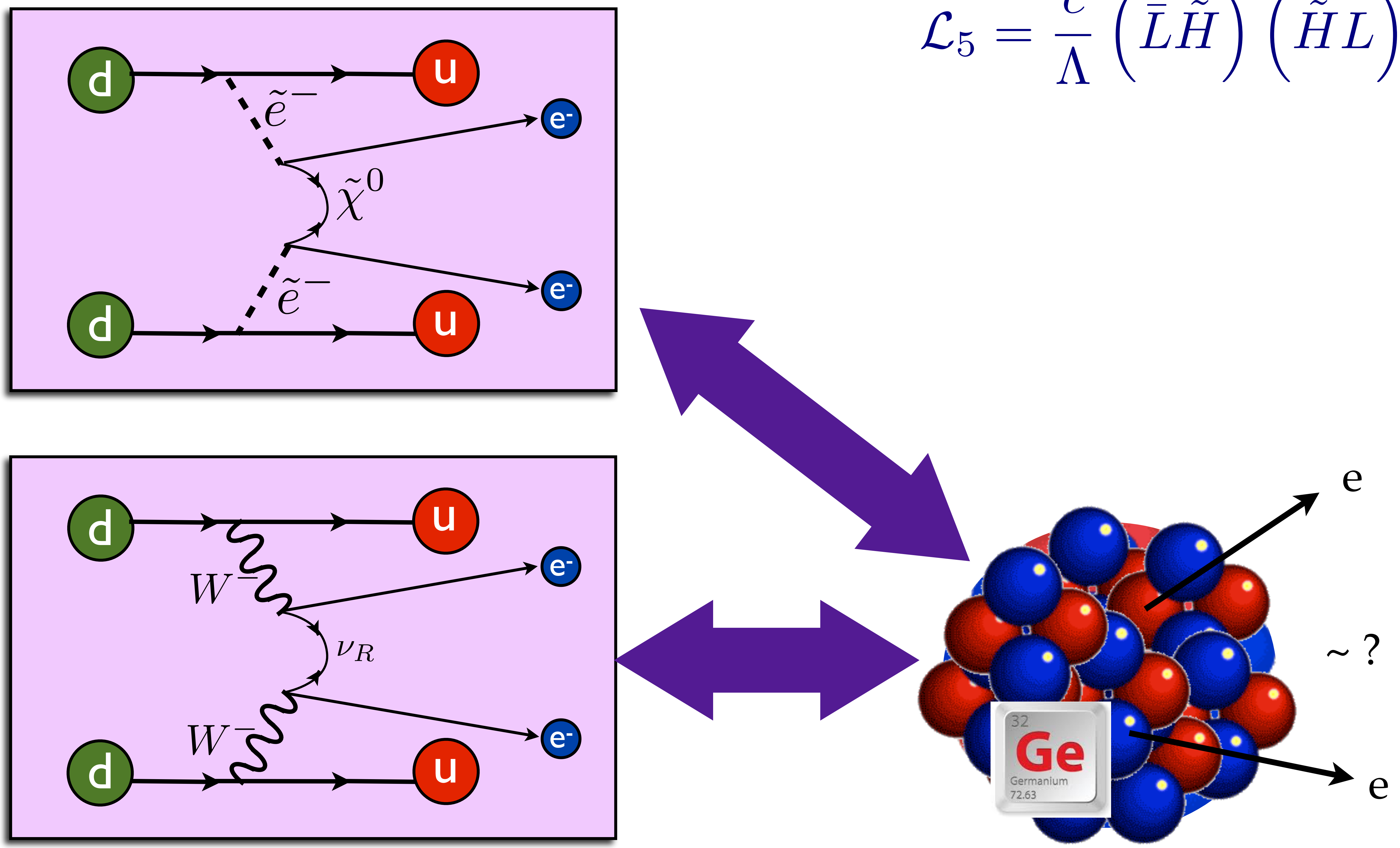

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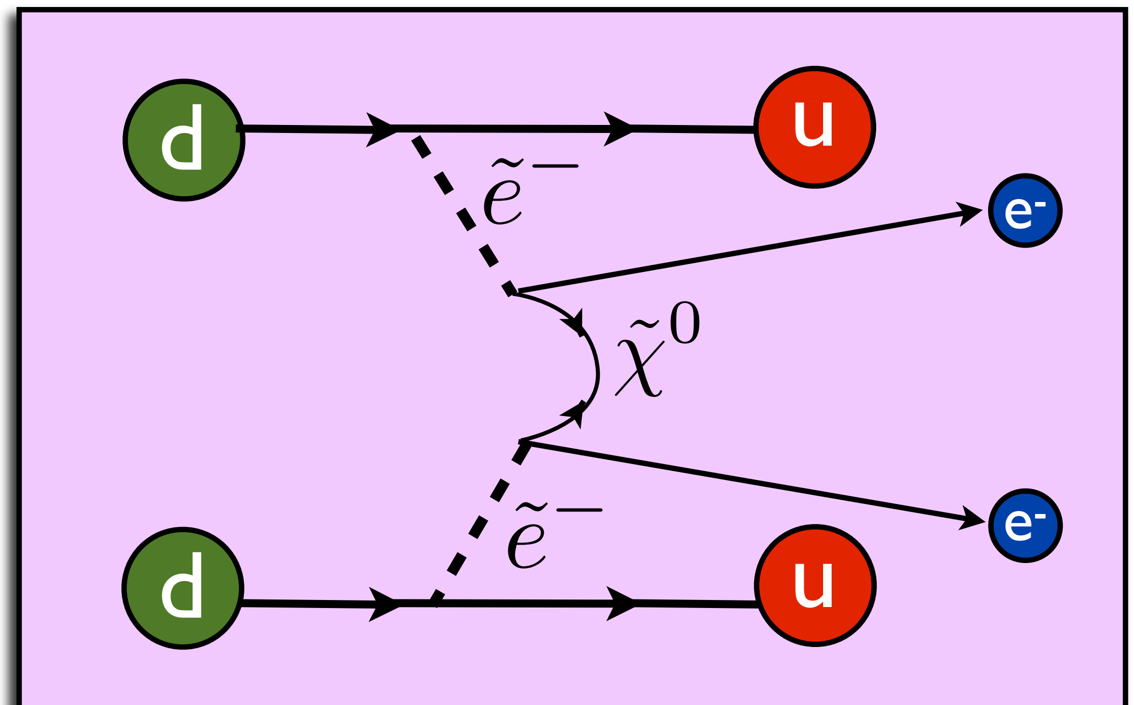
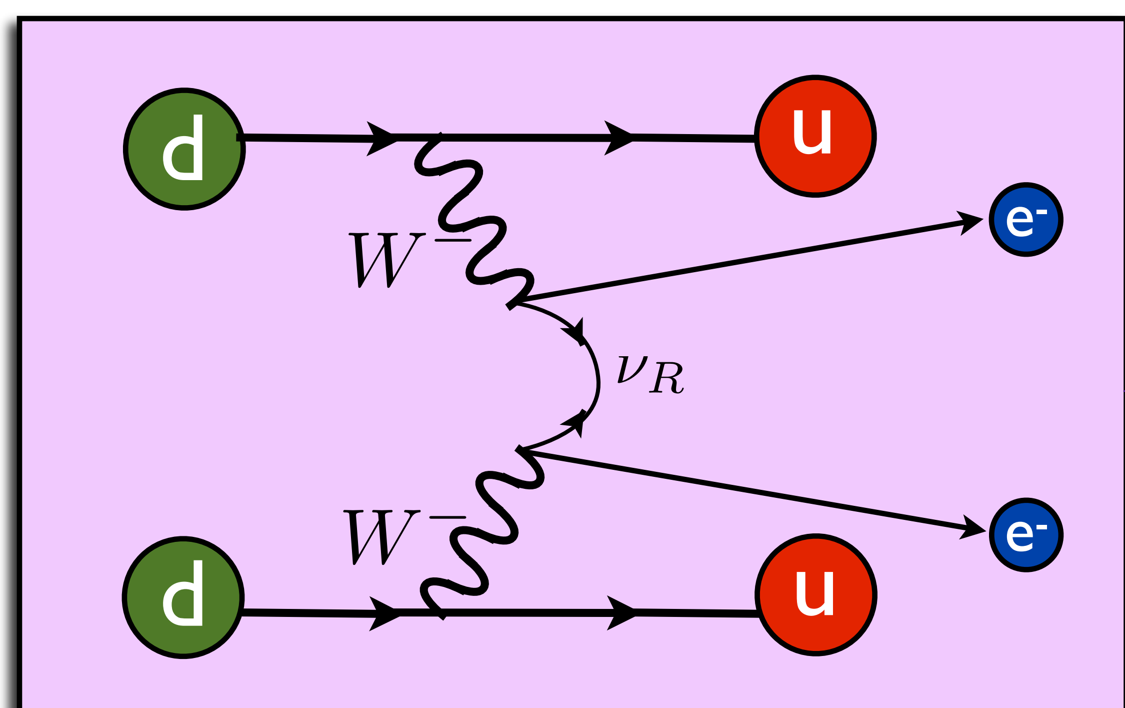
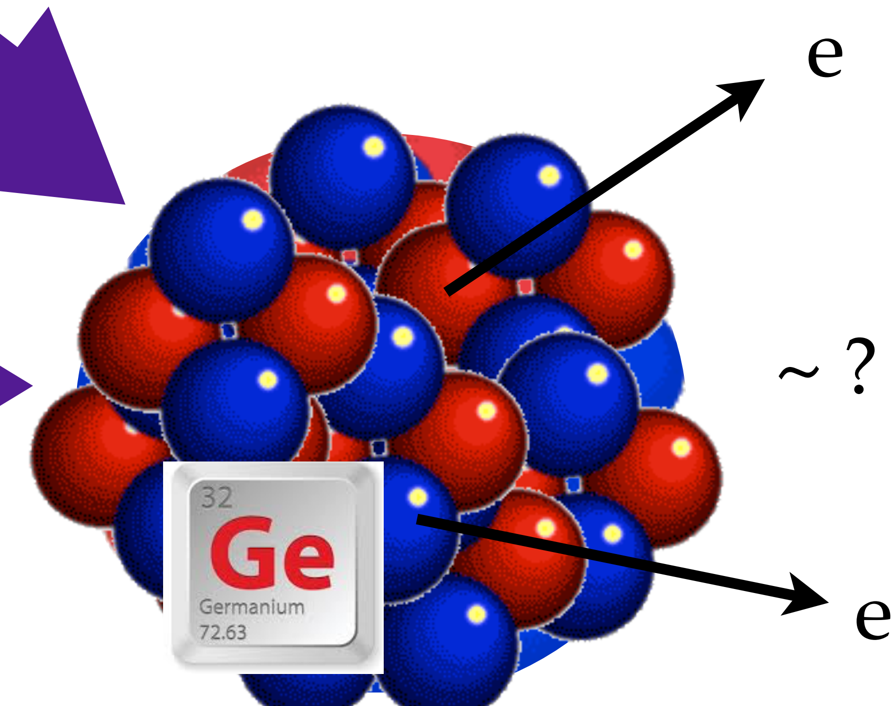
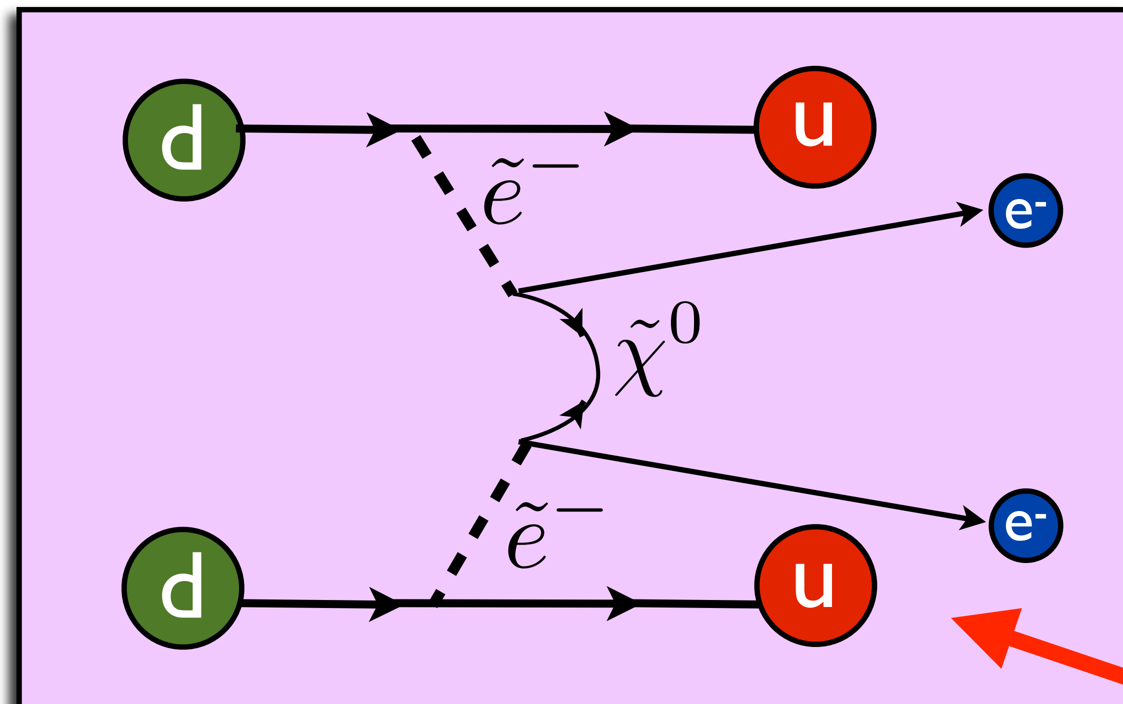


$0\nu\beta\beta$ bounds could help constrain R-parity violating coefficients



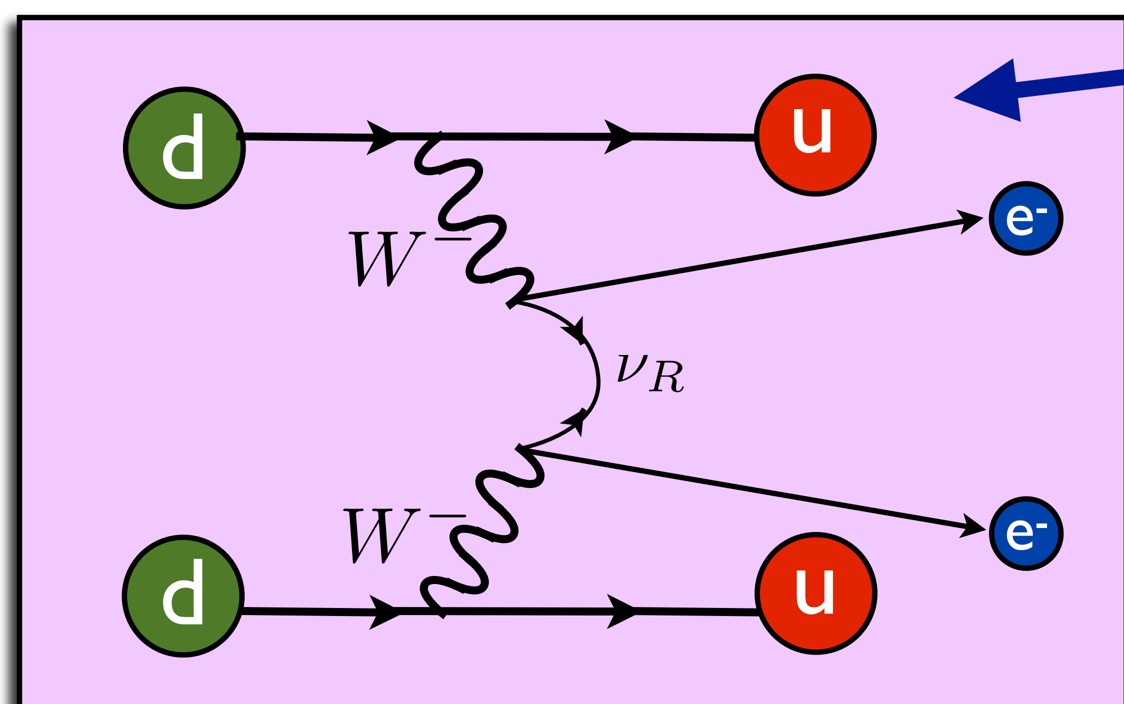


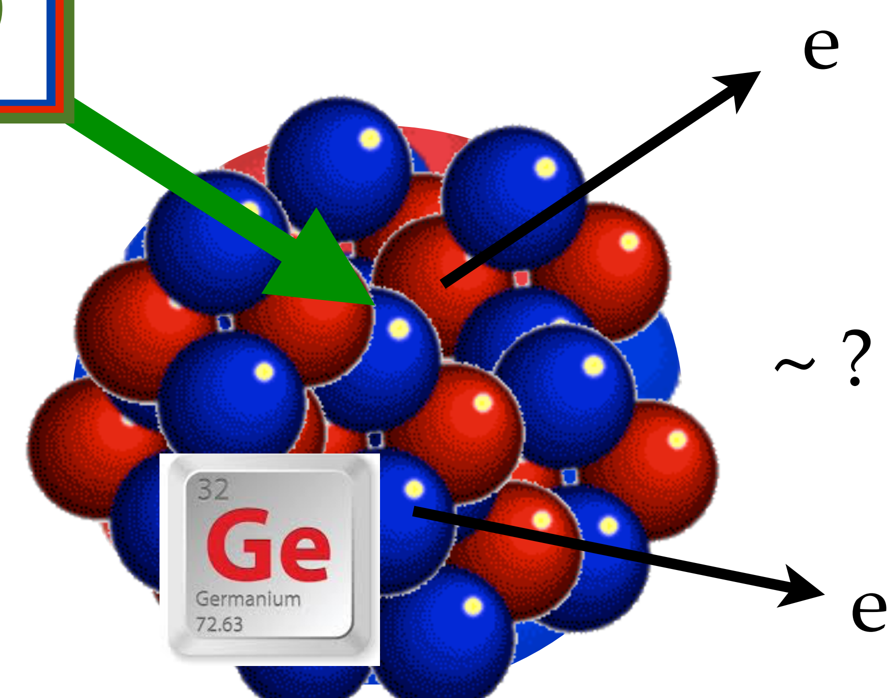
Relating Theory to Experiment



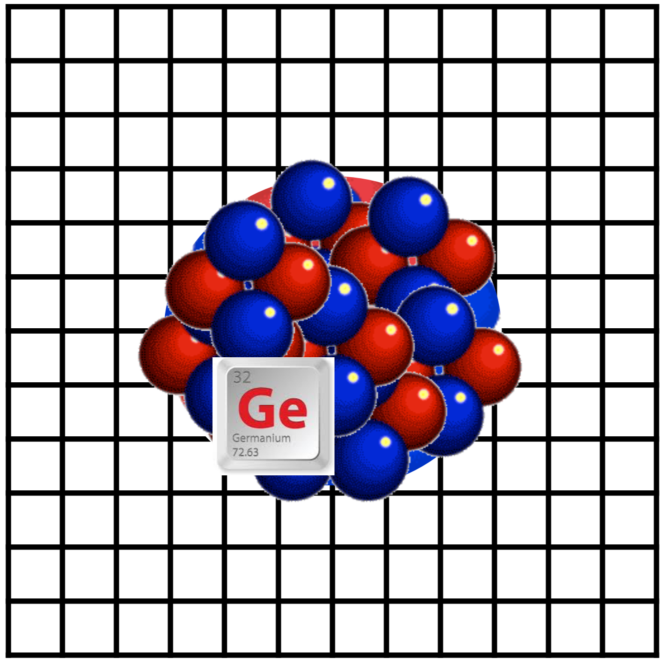
LQCD will never calculate your favorite $0\nu\beta\beta$ isotope

QCD



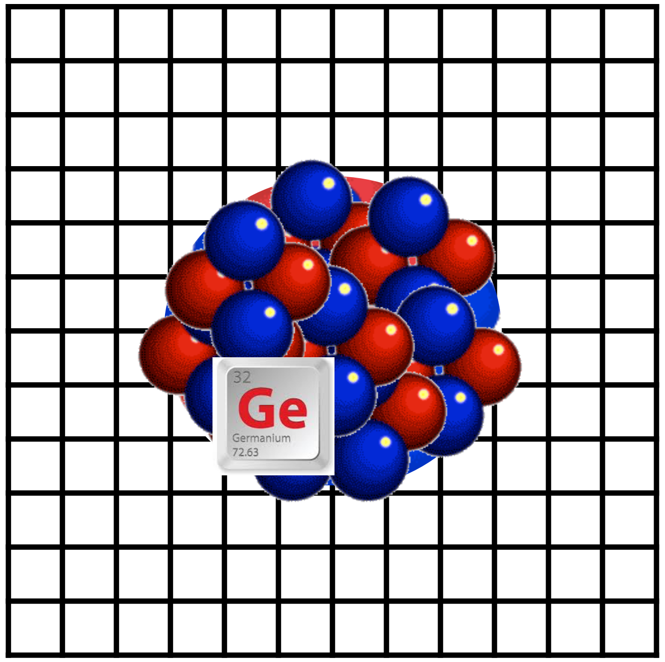


LQCD will never directly calculate your favorite experimental isotope



Why?

LQCD will never directly calculate your favorite experimental isotope



- Need extremely large lattices
  - Large range of scales
  - Tiny energy splittings

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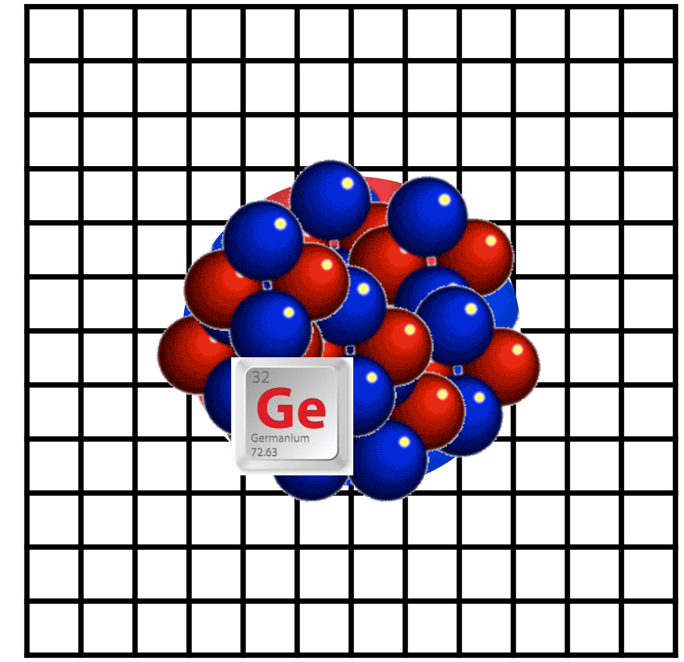

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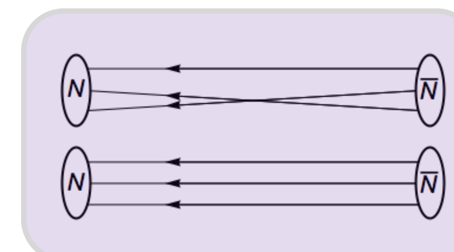
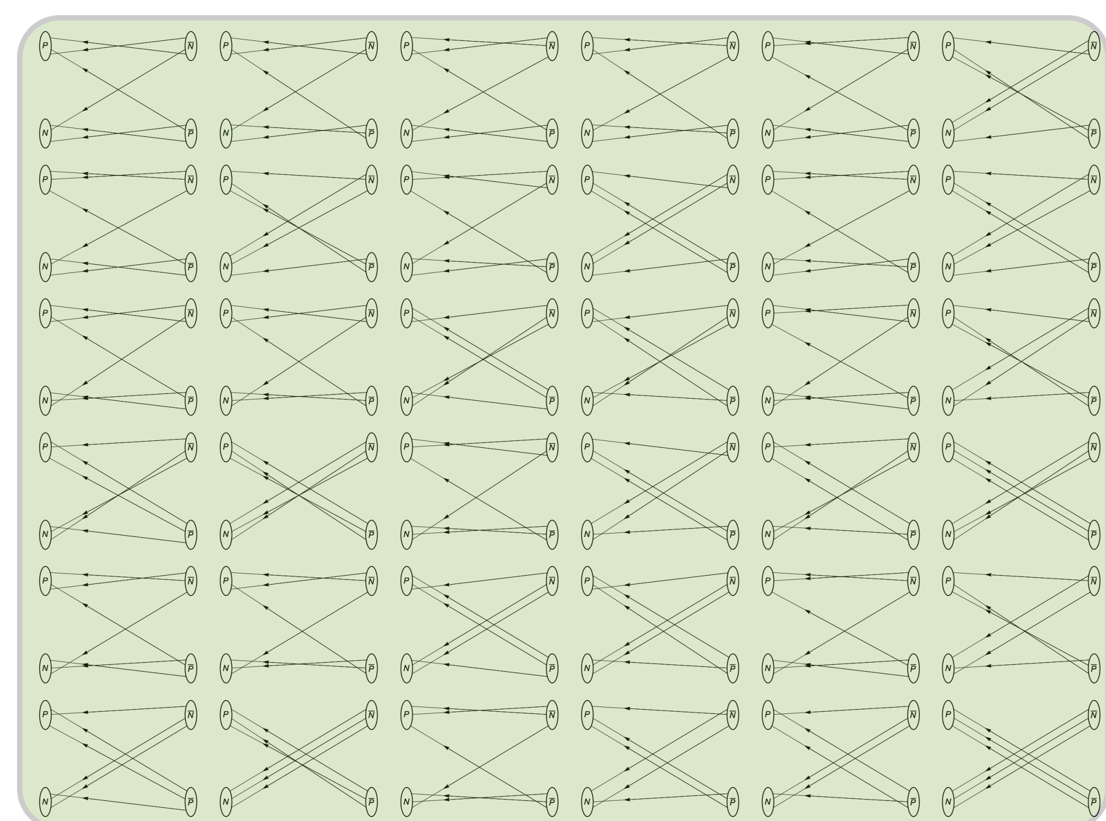
- Wick contractions: (A+Z)!x(2A-Z)!

He^4 : 518400

Nucleon:



Deuteron:



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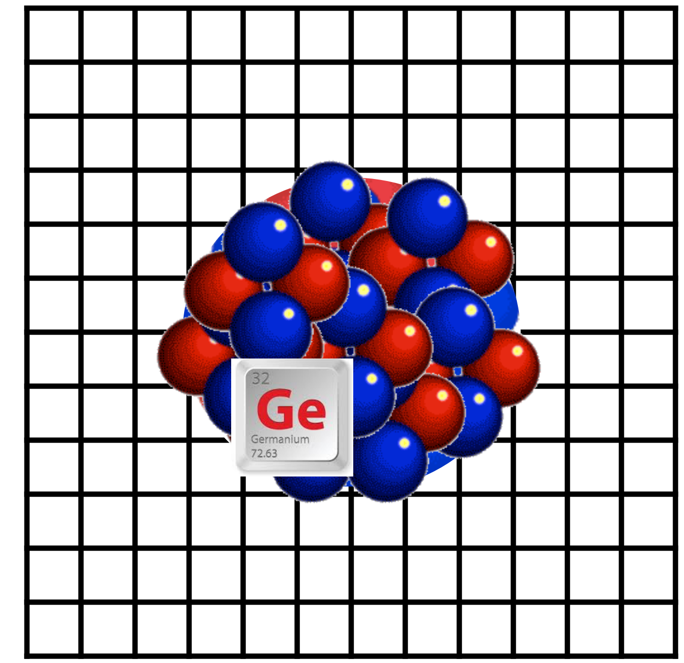

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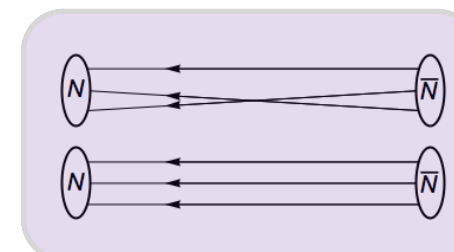
He^4 : 518400

- Nucleon noise/sign problem

  signal/noise

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

Nucleon:



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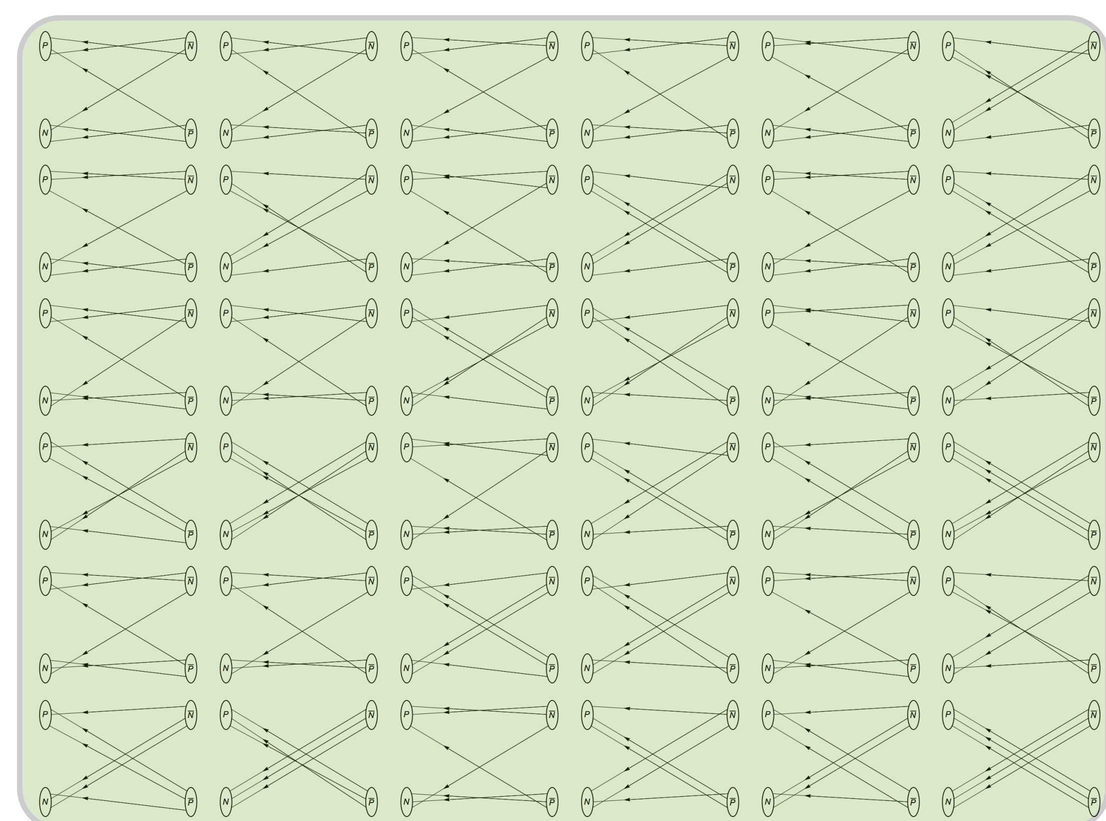
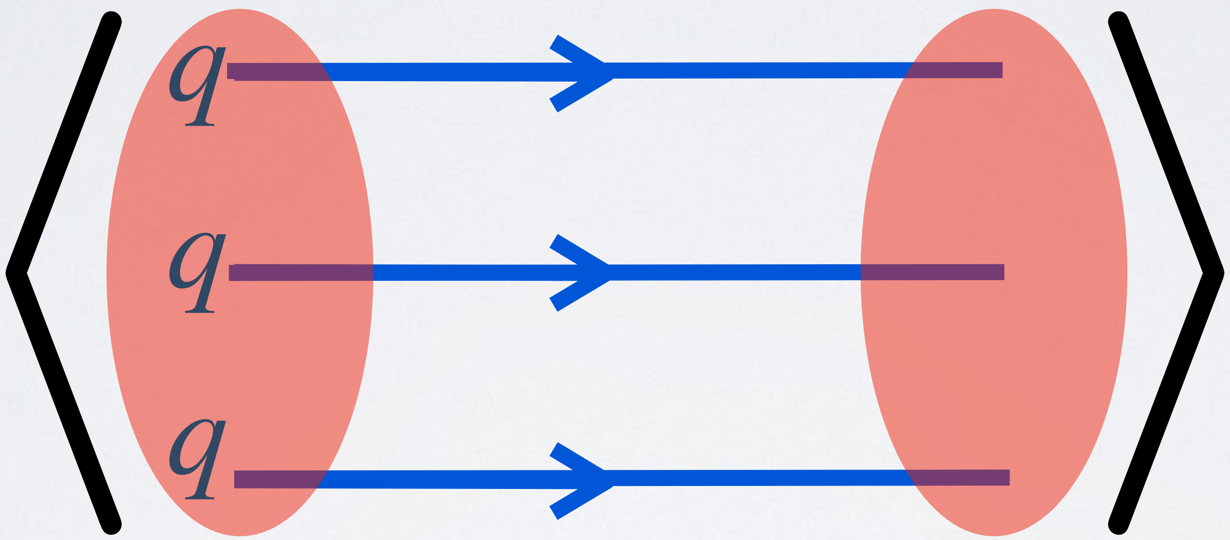


BARYON SNR

$$C_N(\tau) = $$

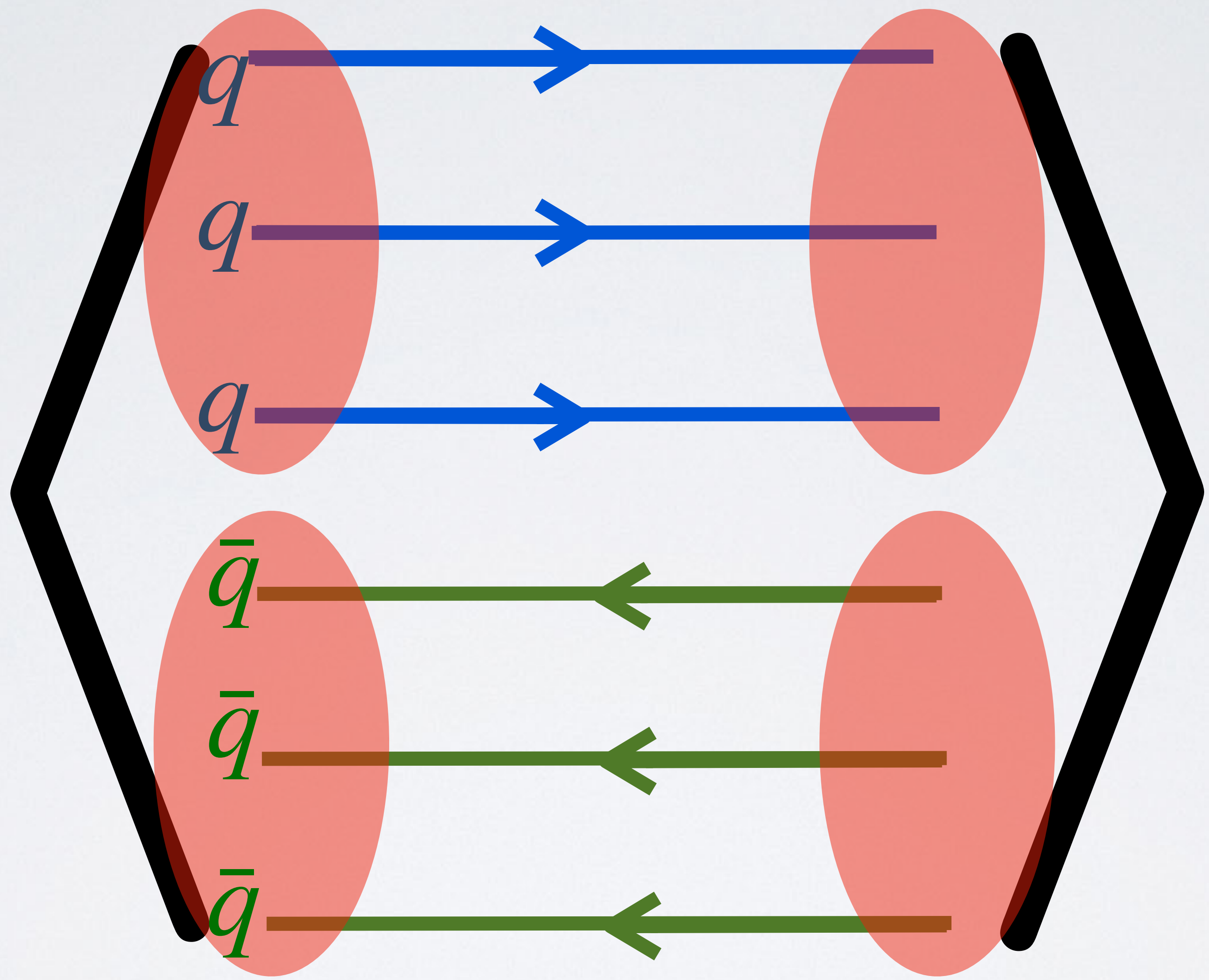


$$\xrightarrow[\tau \to \infty]{} e^{-M_N \tau}$$

Lepage (1989)

BARYON SNR

$C_{N^\dagger N}(\tau) =$

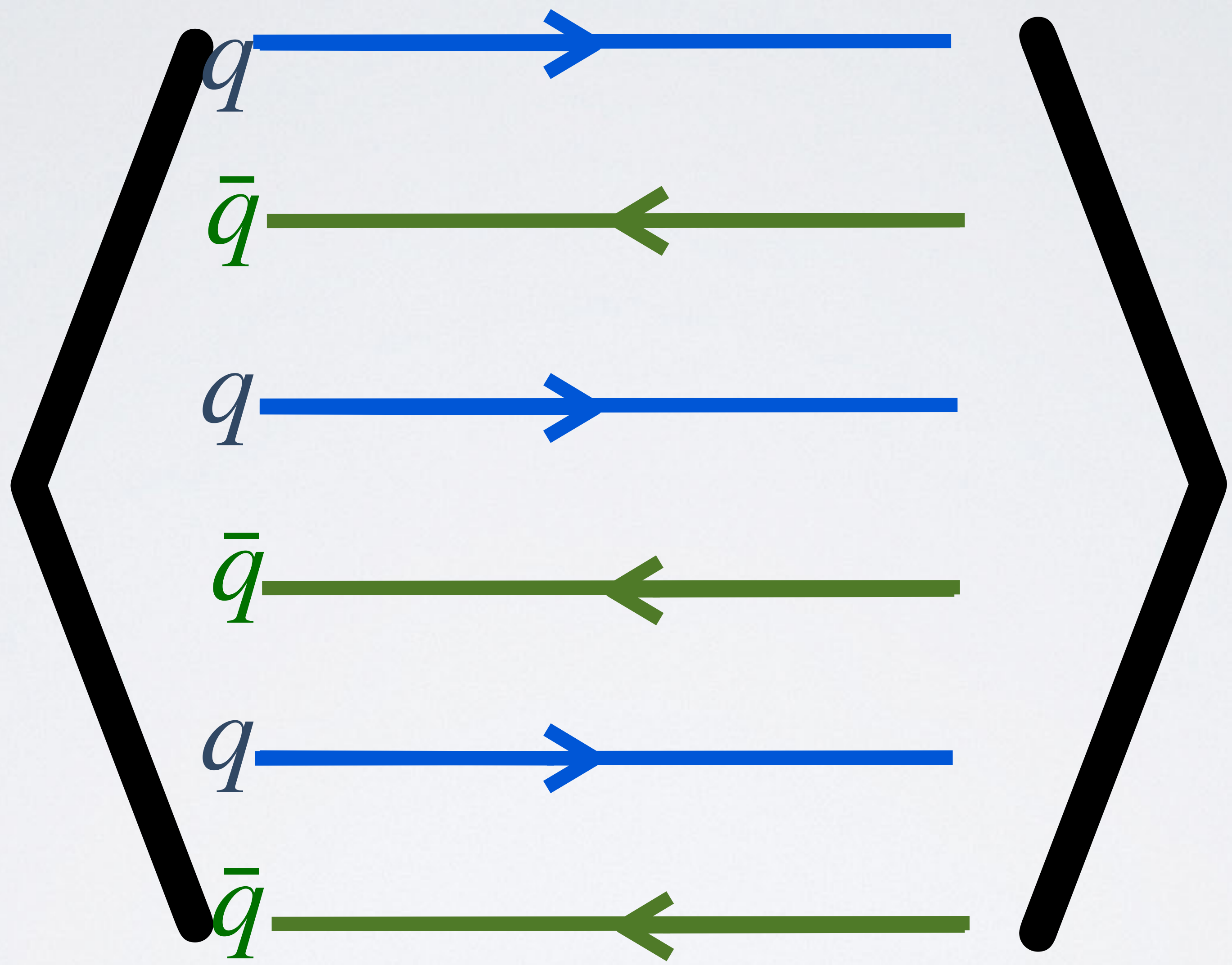


$\xrightarrow[\tau\to\infty]{} e^{-2M_N\tau}$

Lepage (1989)

BARYON SNR

$C_{N^\dagger N}(\tau) =$

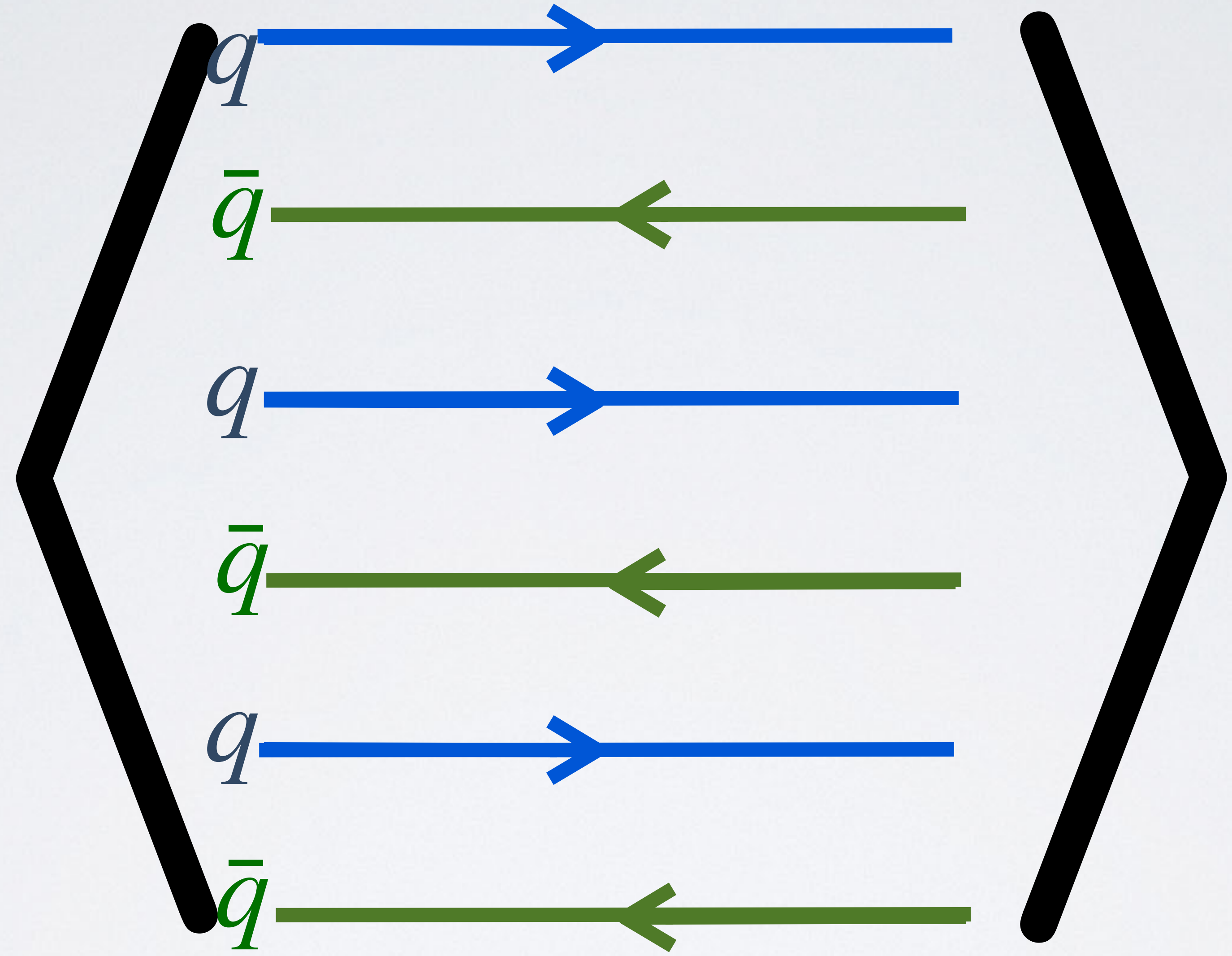


$\xrightarrow[\tau\to\infty]{} e^{-2M_N\tau}$

Lepage (1989)

BARYON SNR

$C_{N^\dagger N}(\tau) =$

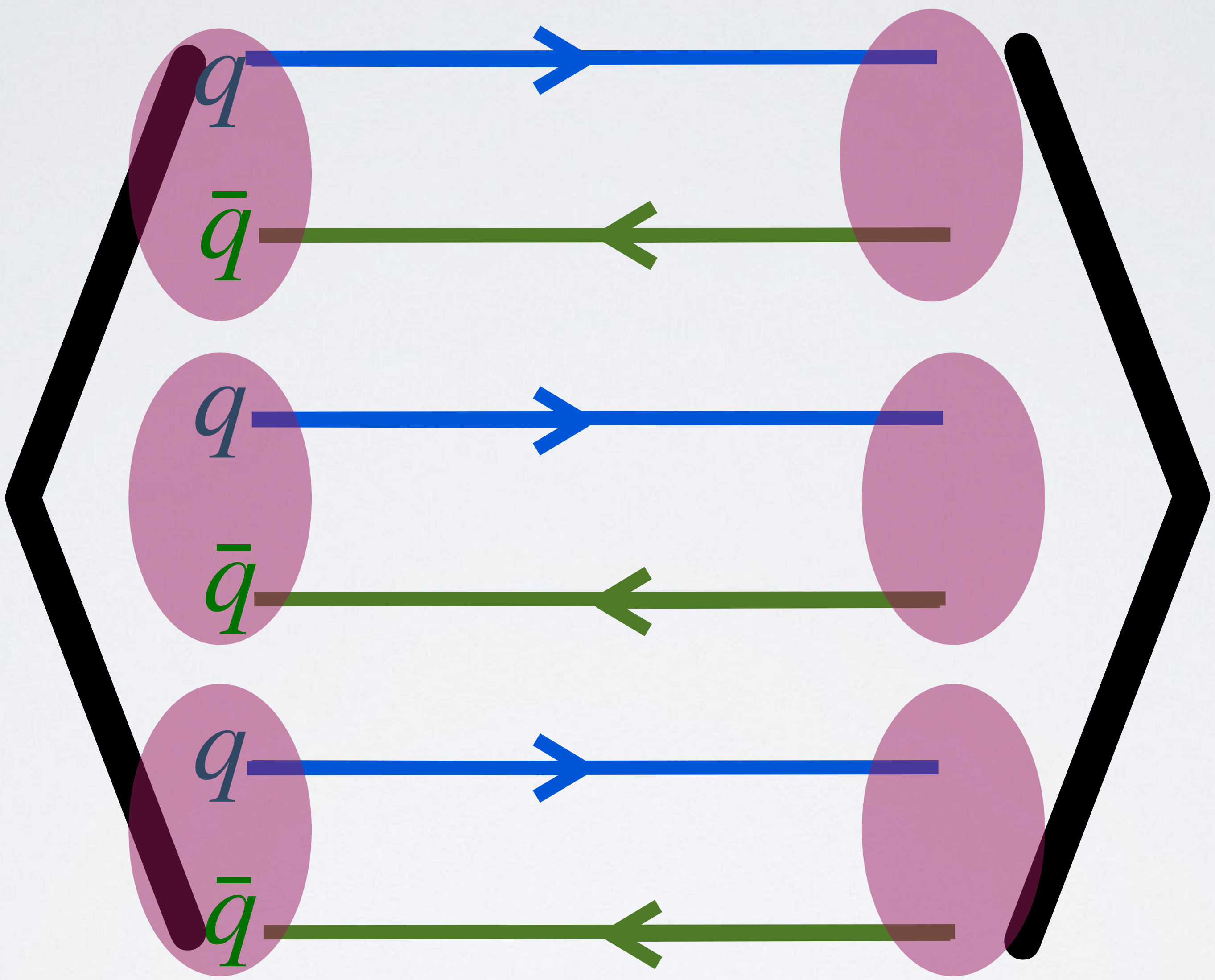


$\xrightarrow[\tau \to \infty]{} e^{-2M_N \tau}$

Lepage (1989)

BARYON SNR

$$C_{N^\dagger N}(\tau) =$$



$$\xrightarrow[\tau\to\infty]{} e^{-3m_\pi \tau}$$

Lepage (1989)

BARYON SNR

Signal-to-noise ratio:

$$\frac{C_N(\tau)}{\sigma(\tau)} \underset{\tau\to\infty}{\longrightarrow} \sqrt{N_{cfg}}e^{-(M_N-3/2m_\pi)\tau}$$

Need an exponential number of measurements to see a signal

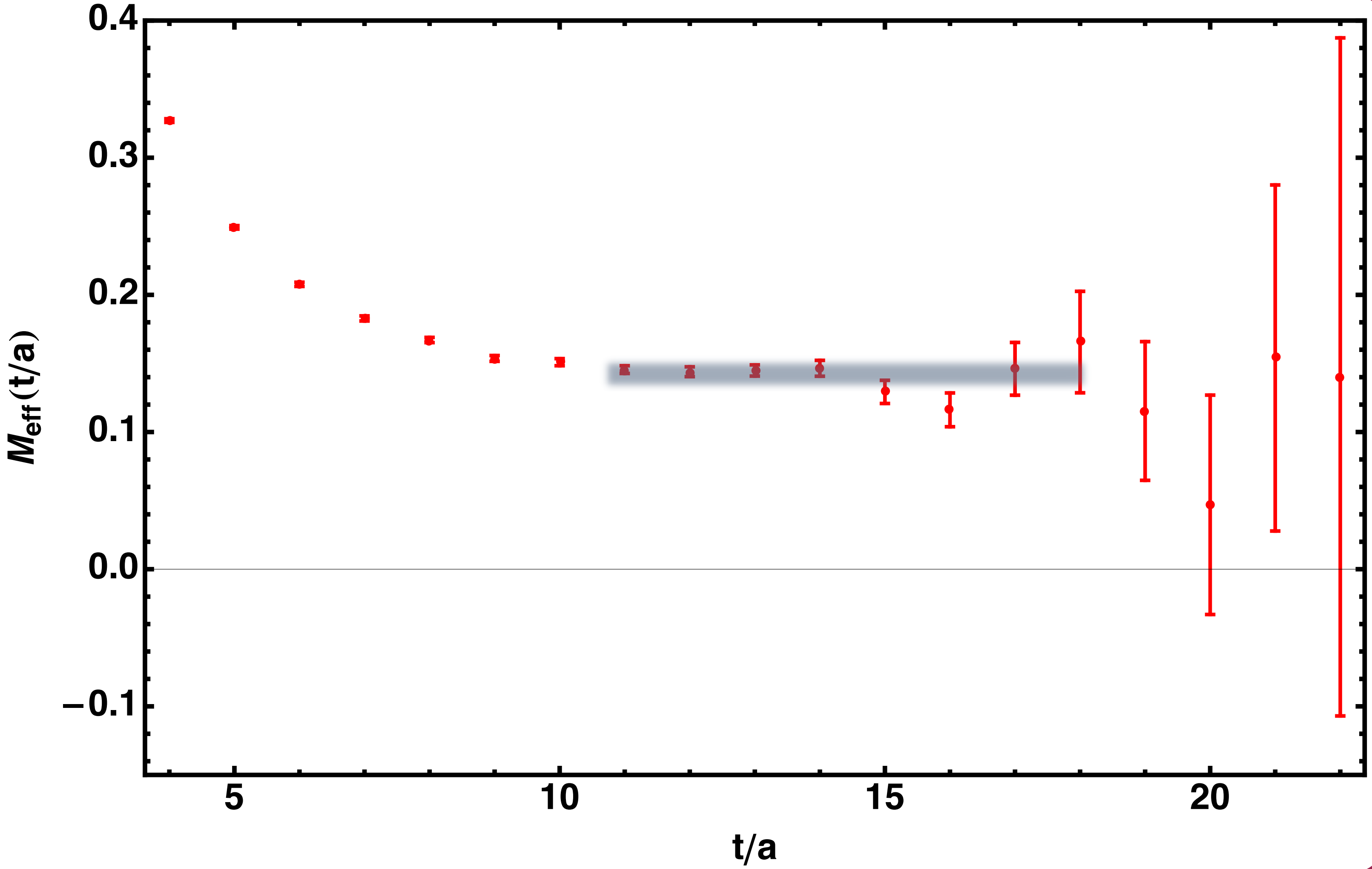
BARYON SNR

Signal-to-noise ratio:

$$\frac{C_{N^A}(\tau)}{\sigma(\tau)} \xrightarrow[\tau\to\infty]{} \sqrt{N_{cfg}}e^{-A(M_N-3/2m_\pi)\tau}$$

Need an exponential number of measurements to see a signal

BARYON SNR

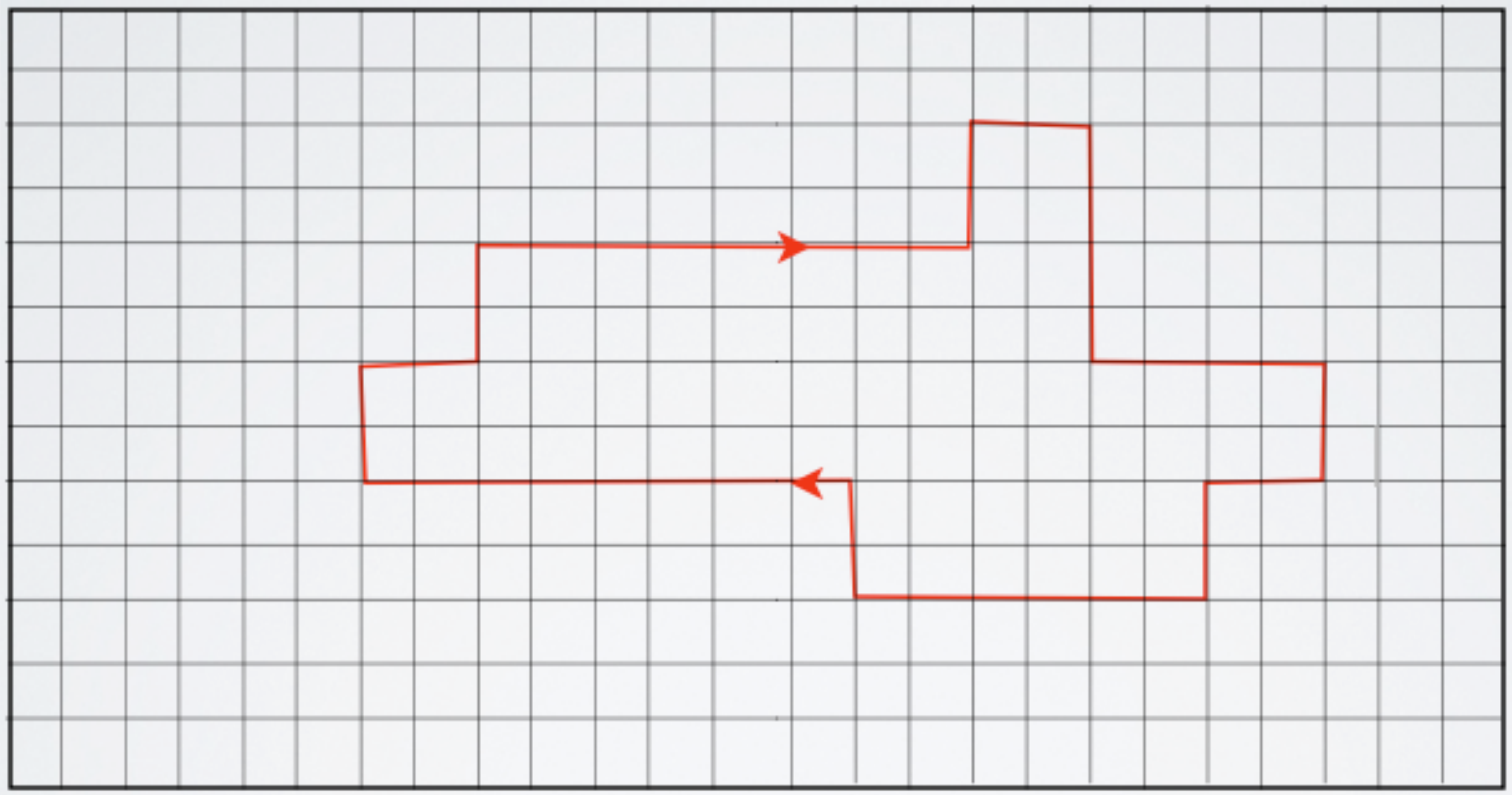


$$\sim e^{A(M_n - 3/2 m_\pi)t}$$

OVERLAP PROBLEM

Kaplan (sometime back when I was a student)

$$Z_A = \int \mathcal{D}A \det M_F(A) e^{-S_{YM}}$$



OVERLAP PROBLEM

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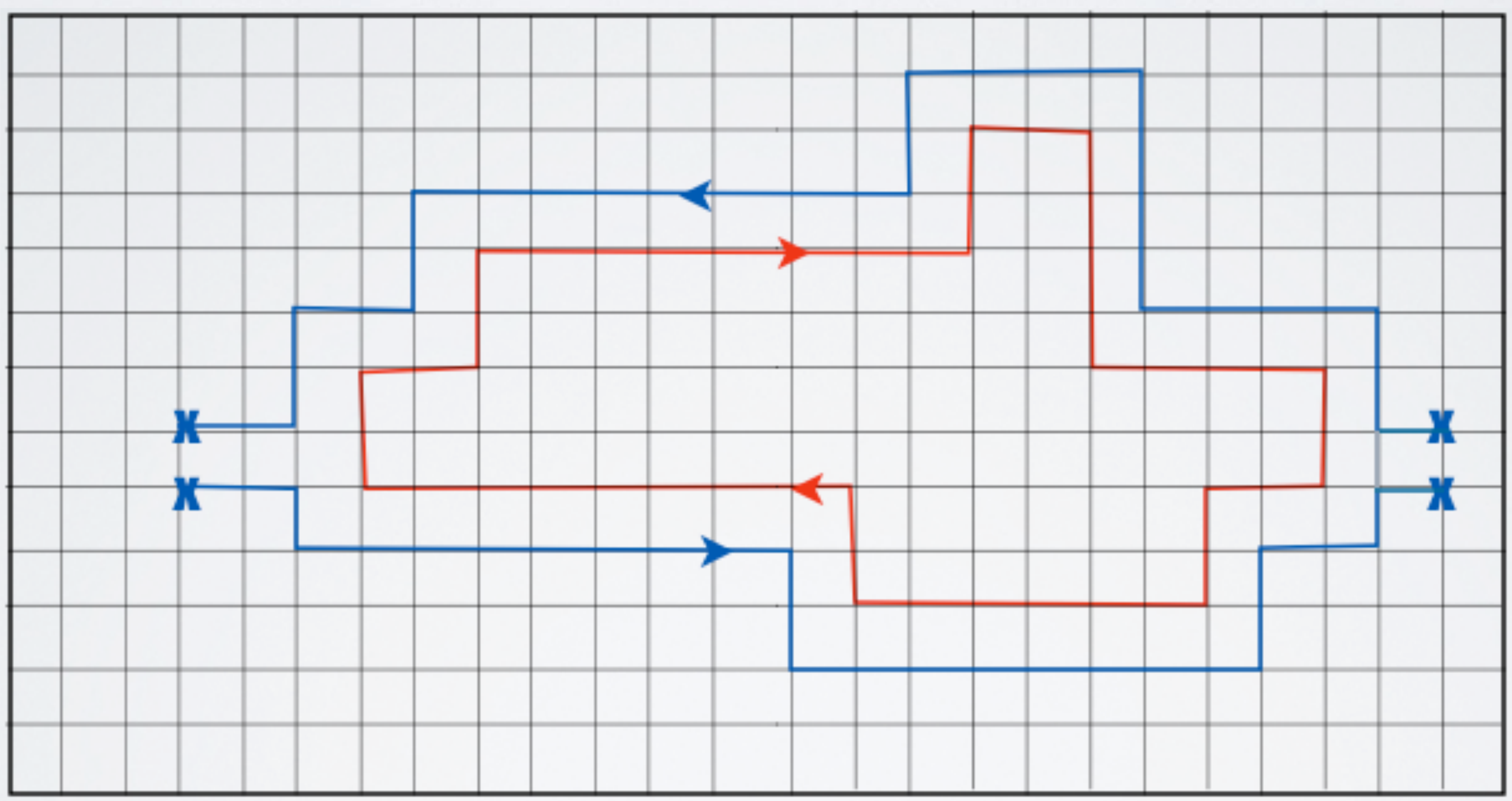
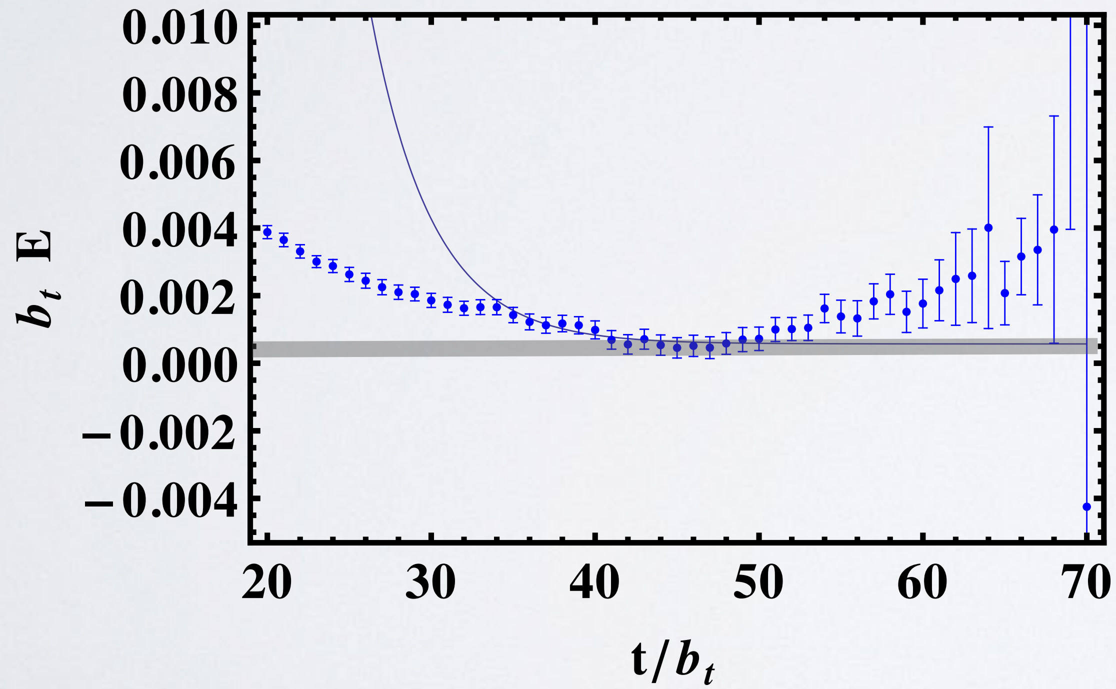
$$Z_A = \int \mathcal{D}A \det M_F(A) e^{-S_{YM}}$$



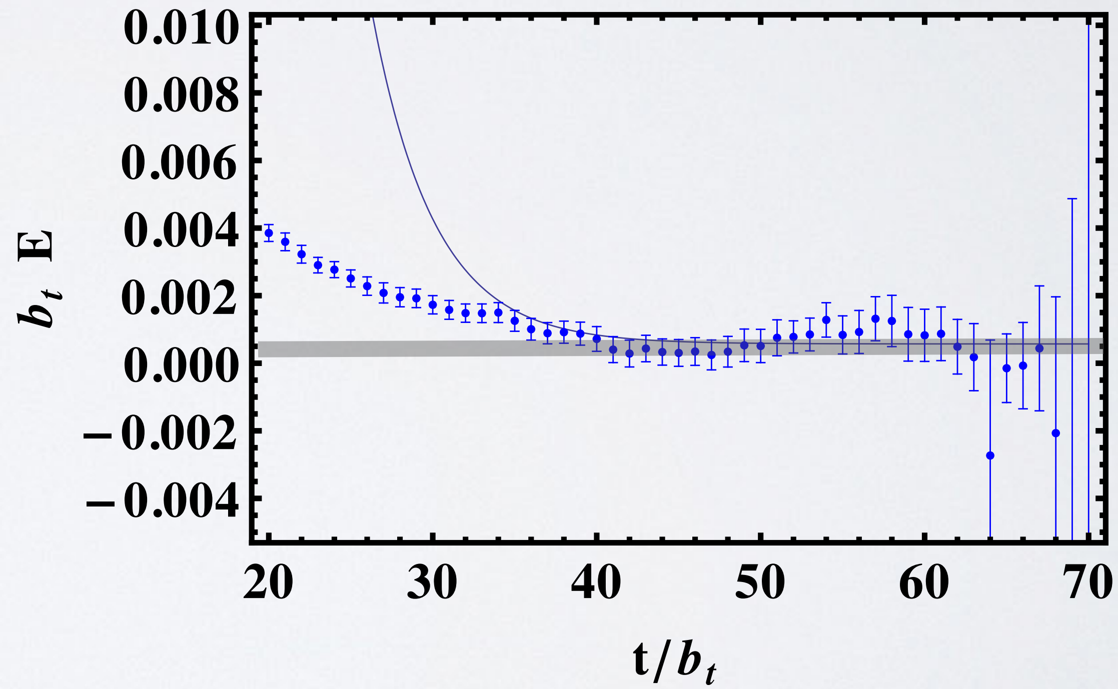
OVERLAP PROBLEM

Kaplan, Endres, Lee, A.N. (2011)

Correlator distributions

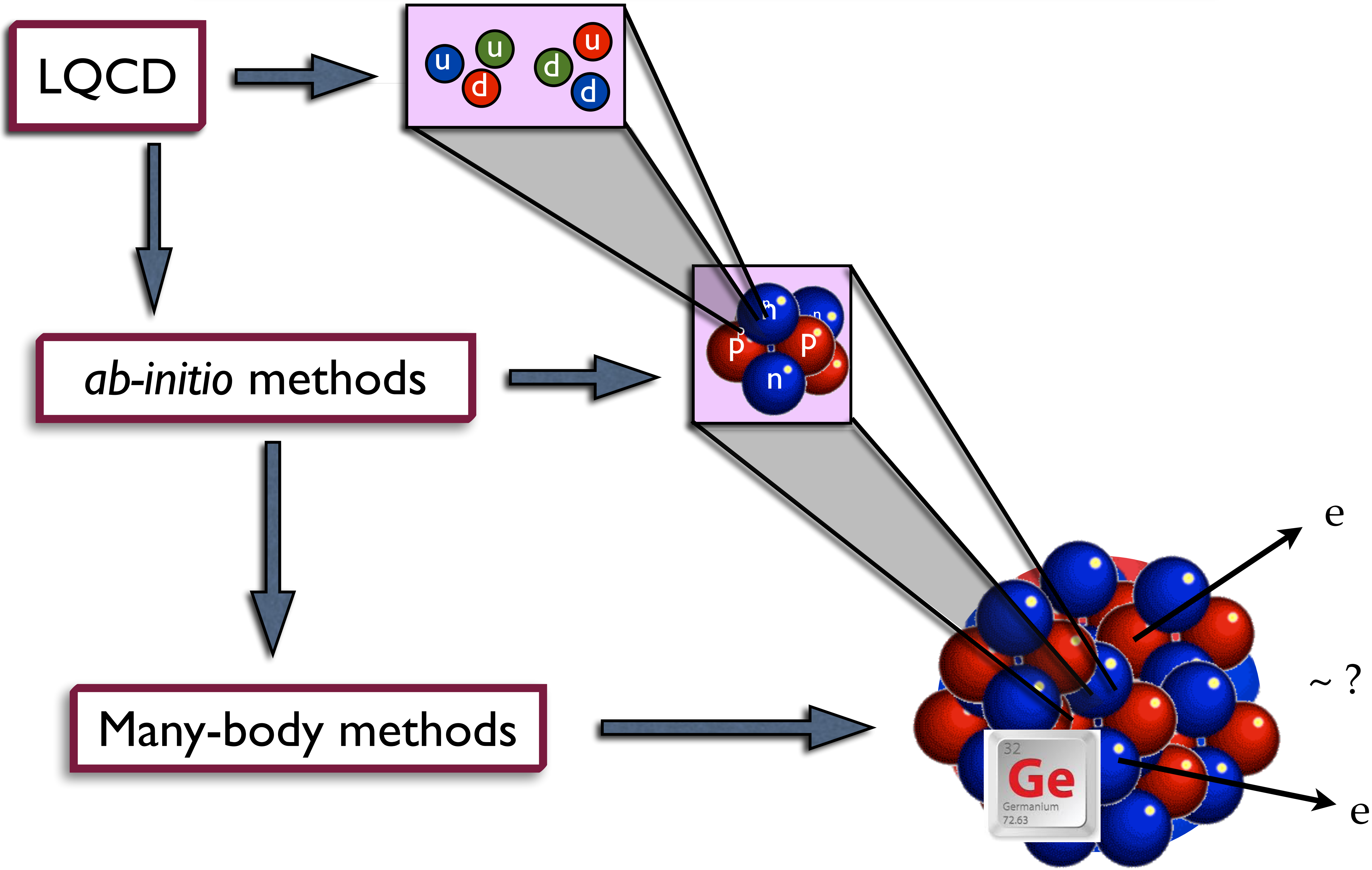


Standard

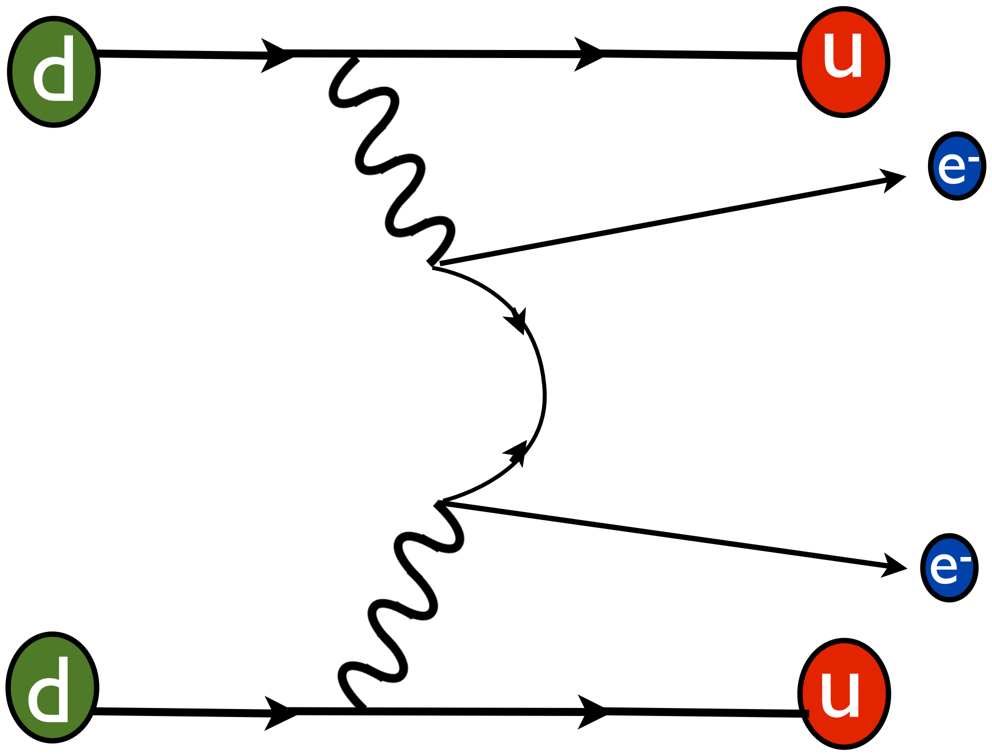


Cumulant Expansion

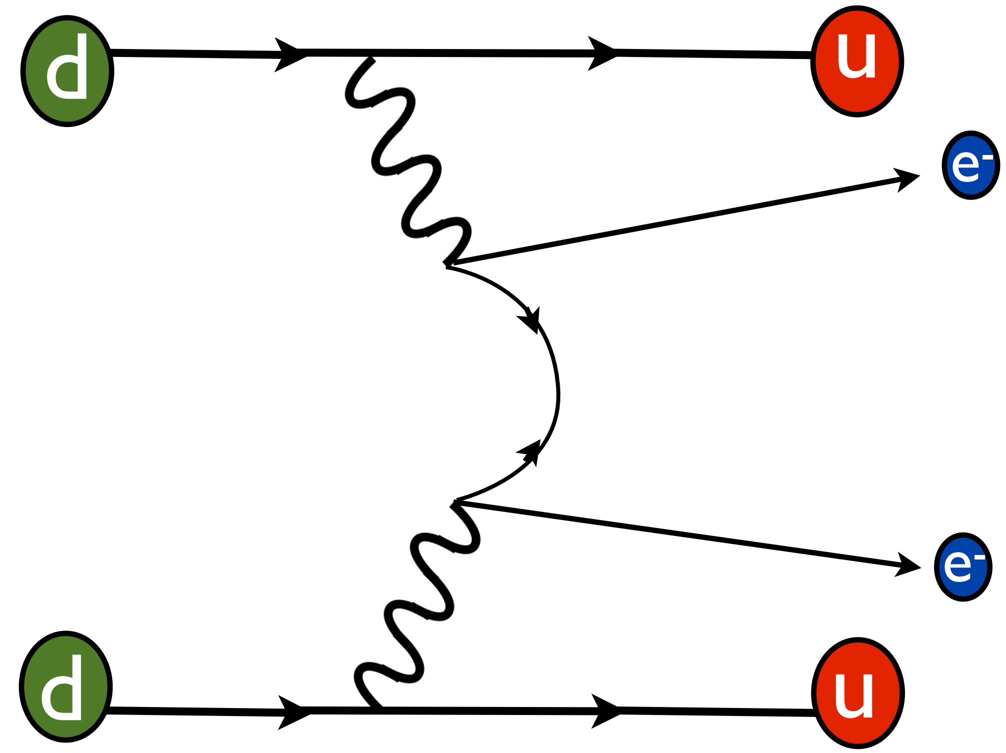
Relating Theory to Experiment



From quark to hadronic scales

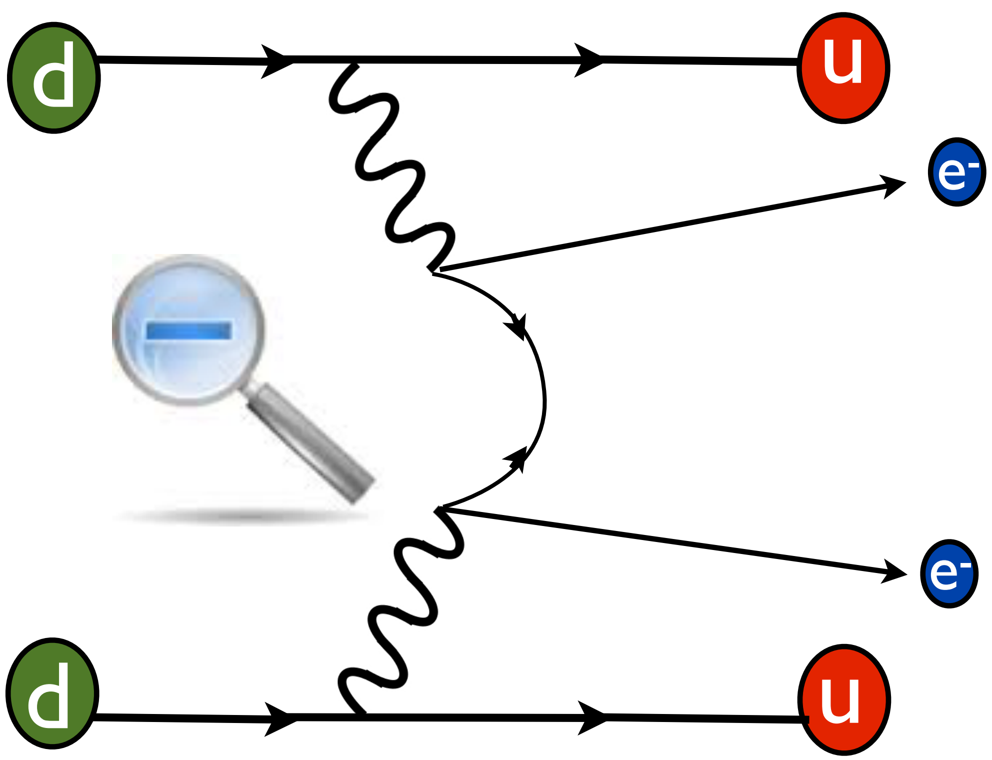


Long-range

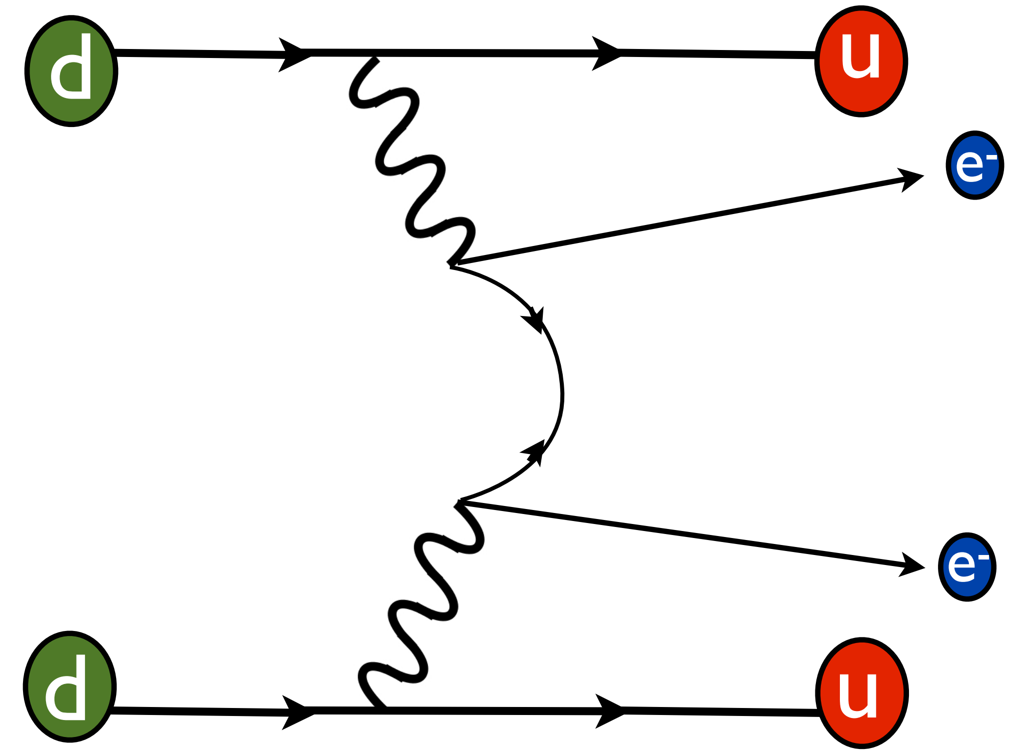


Short-range

From quark to hadronic scales



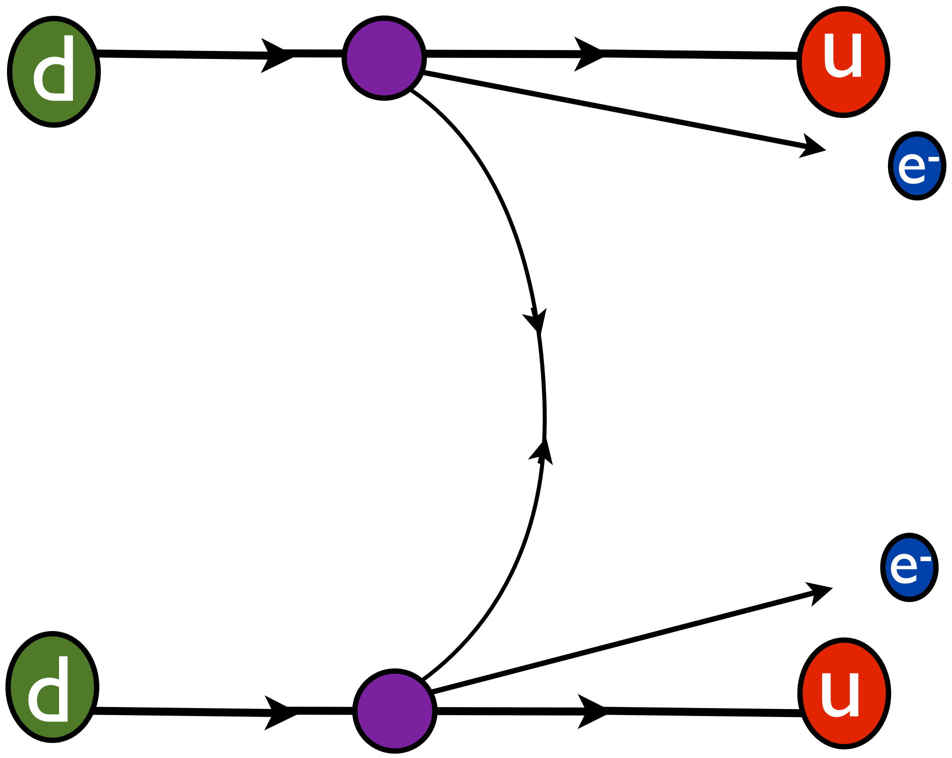
Long-range



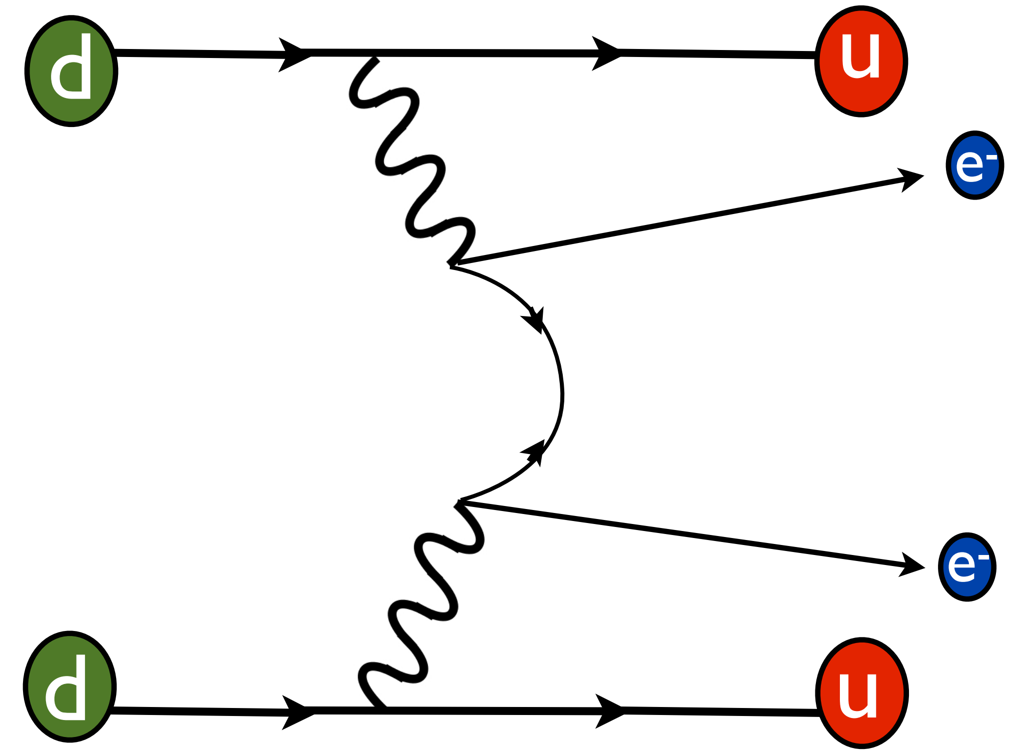
Short-range

$\Lambda \ll M_W$

From quark to hadronic scales

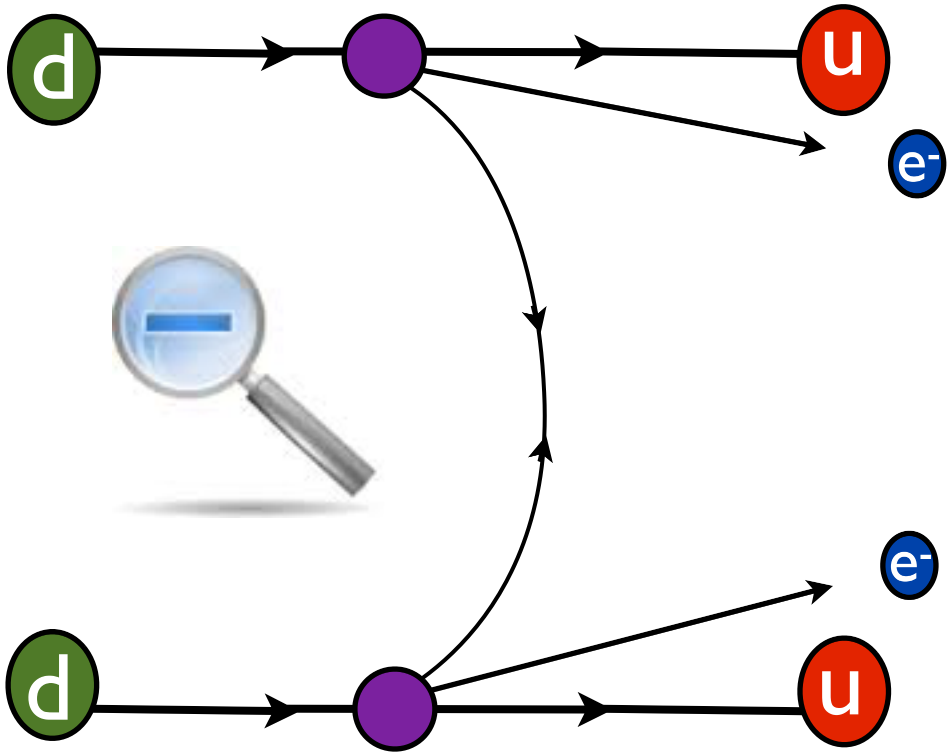


Long-range



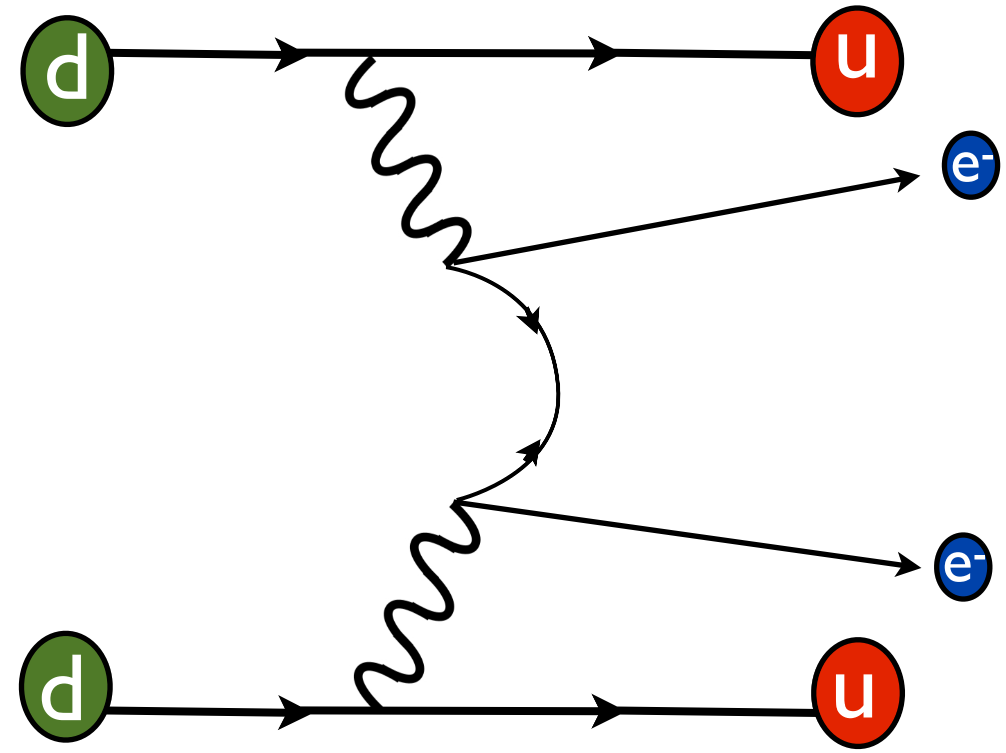
Short-range

From quark to hadronic scales



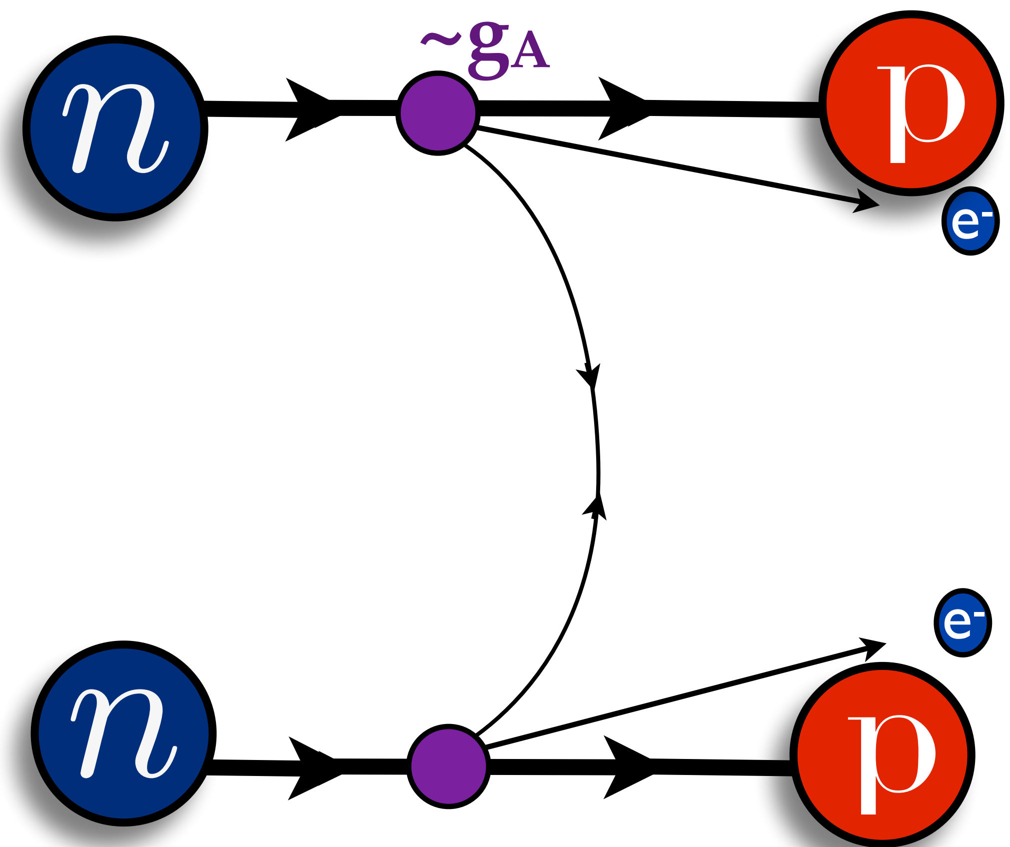
Long-range

$\Lambda \ll \Lambda_{QCD}$

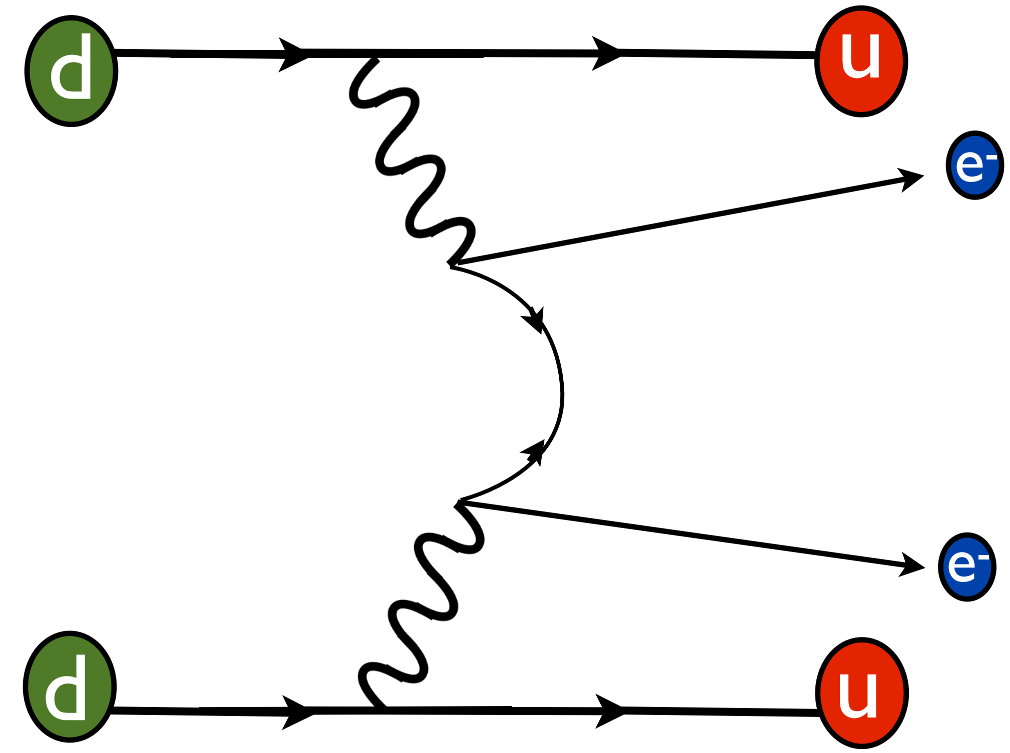


Short-range

From quark to hadronic scales

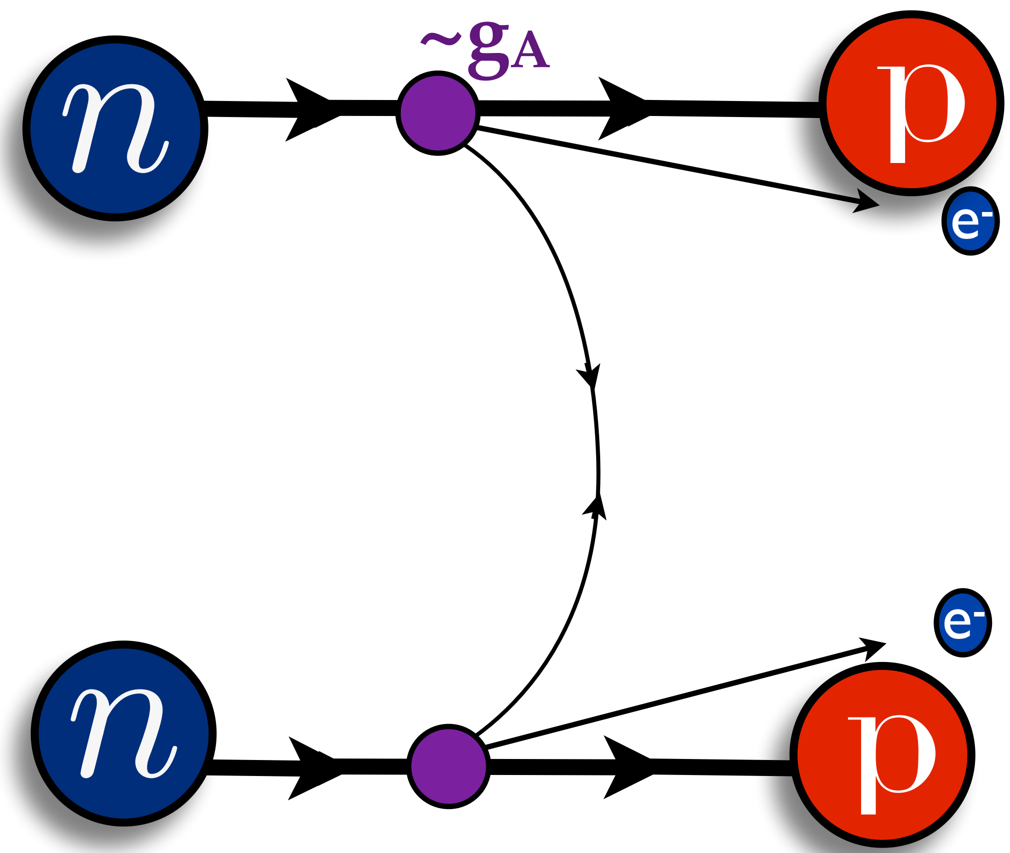


Long-range

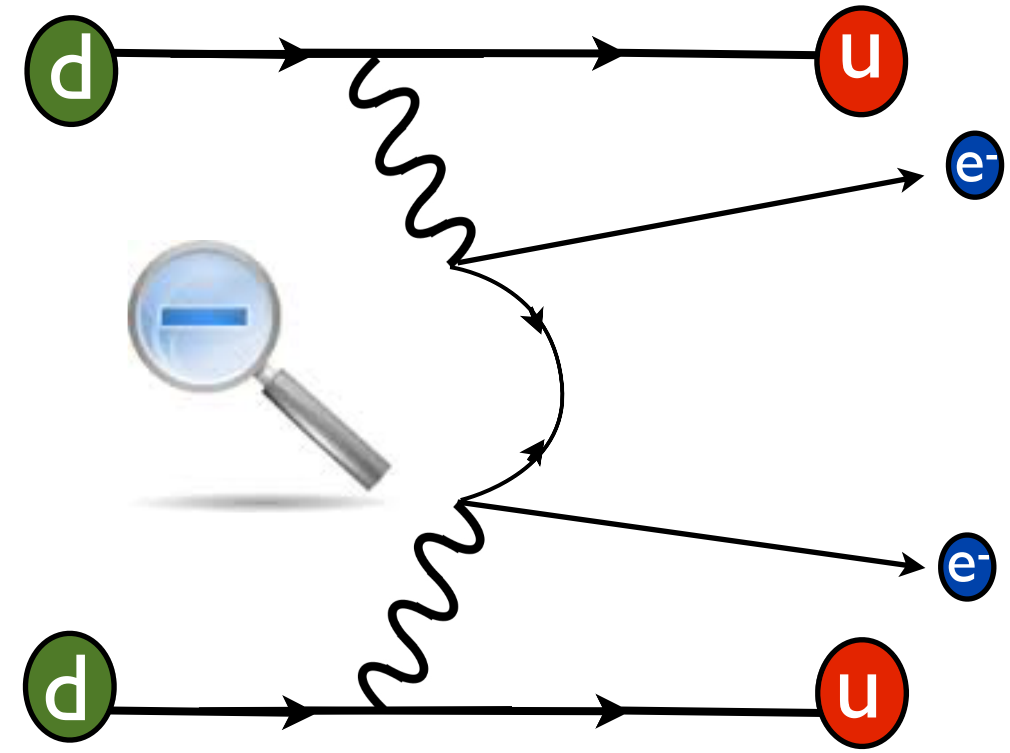


Short-range

From quark to hadronic scales



Long-range

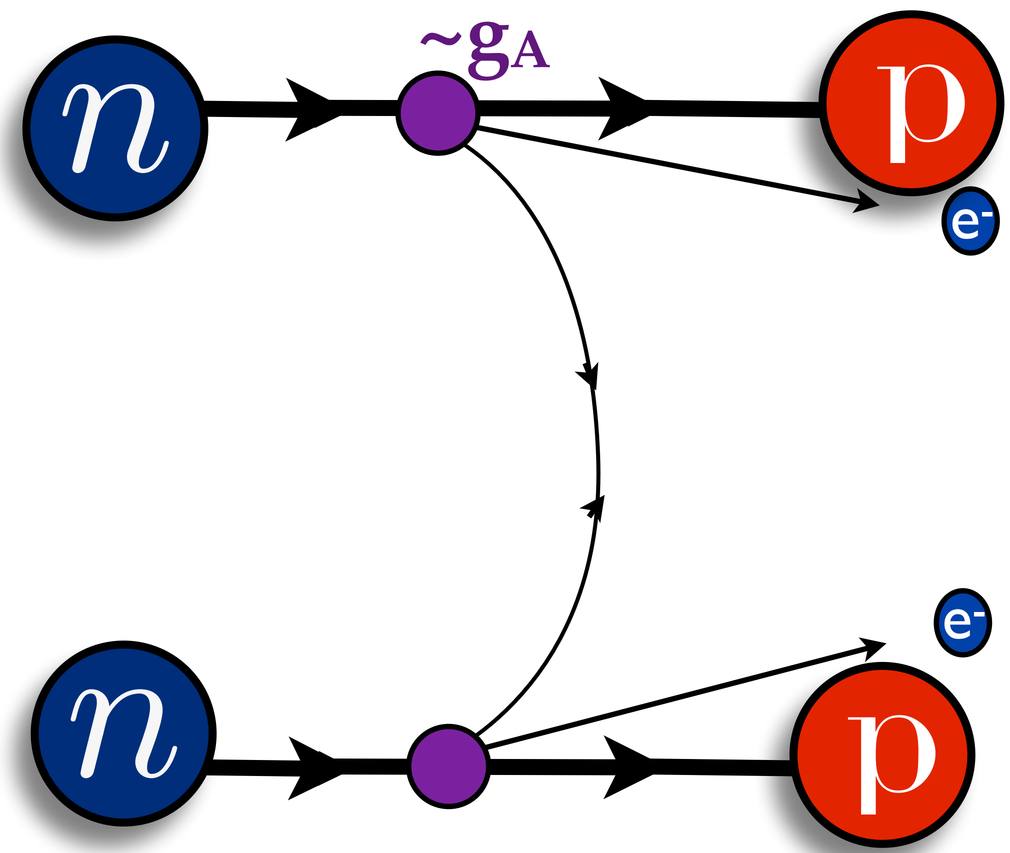


Short-range

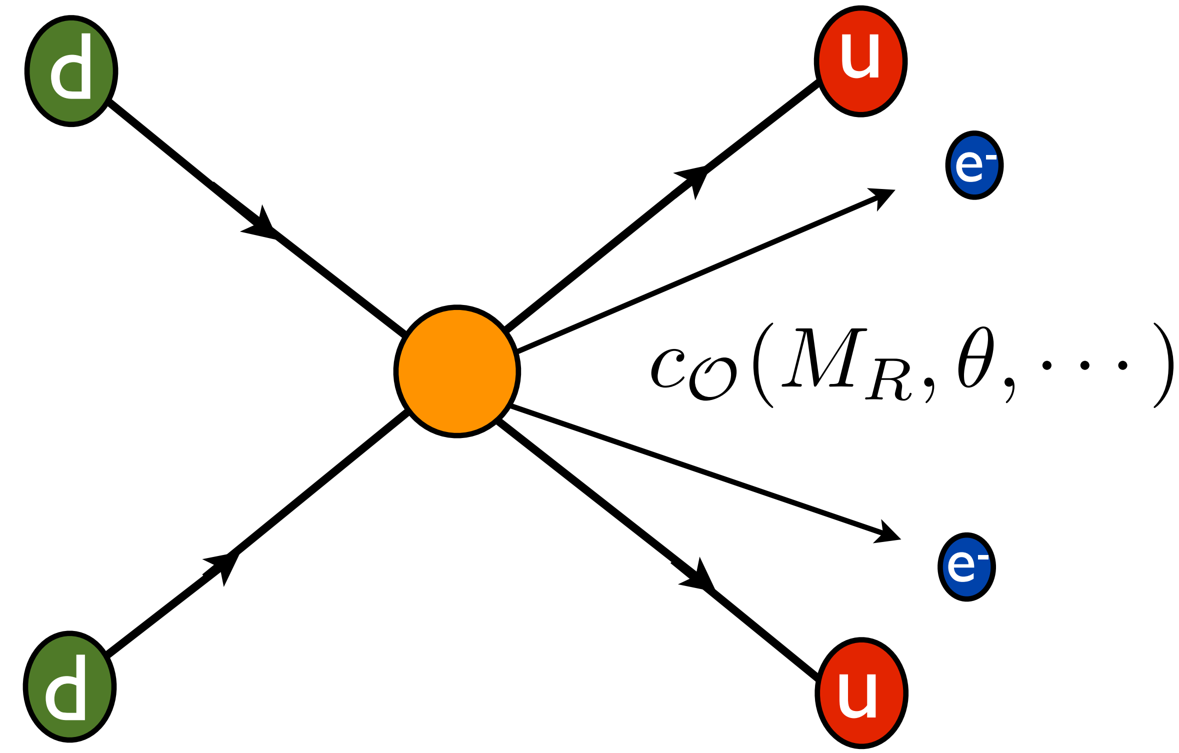
$\Lambda \ll M_W$

From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



Long-range



Short-range

$$\mathcal{O}^{ab}_{1+} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L})(\bar{q}_{\rm R}\tau^b\gamma_\mu q_{\rm R}),$$

$$\mathcal{O}^{ab}_{2\pm} = (\bar{q}_{\rm R}\tau^a q_{\rm L})(\bar{q}_{\rm R}\tau^b q_{\rm L}) \pm (\bar{q}_{\rm L}\tau^a q_{\rm R})(\bar{q}_{\rm L}\tau^b q_{\rm R}),$$

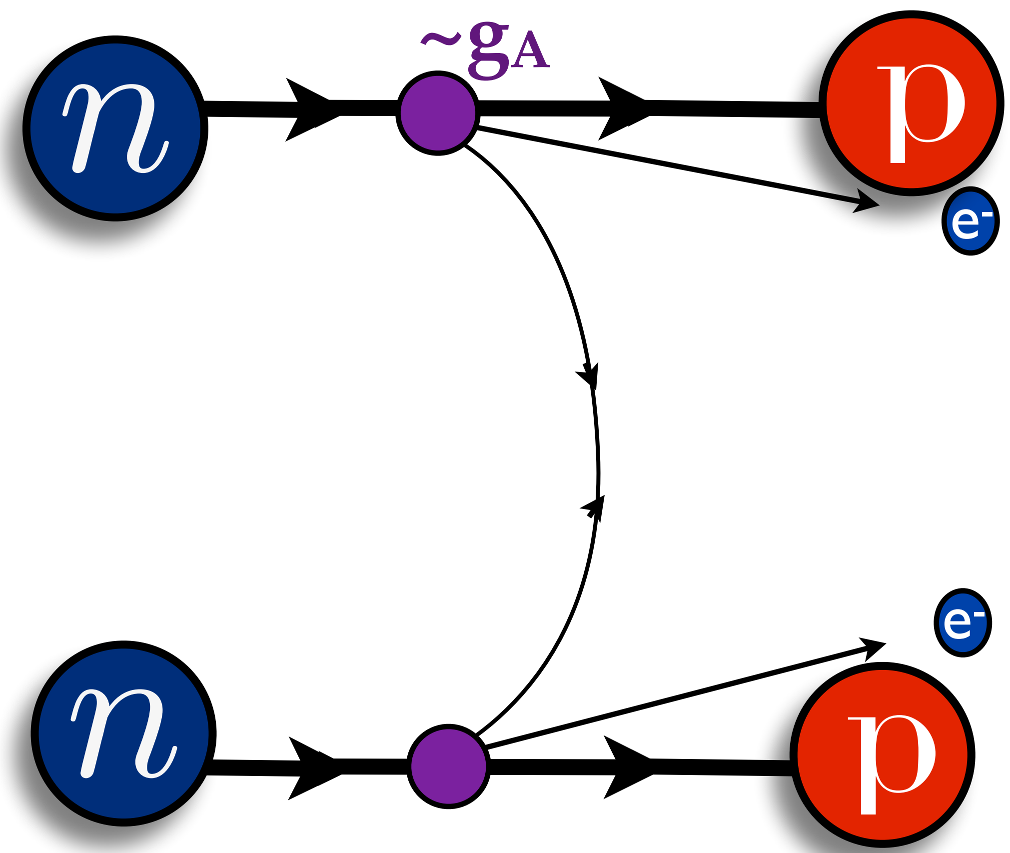
$$\mathcal{O}^{ab}_{3\pm} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L})(\bar{q}_{\rm L}\tau^b\gamma_\mu q_{\rm L}) \pm (\bar{q}_{\rm R}\tau^a\gamma^\mu q_{\rm R})(\bar{q}_{\rm R}\tau^b\gamma_\mu q_{\rm R}),$$

$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L} \mp \bar{q}_{\rm R}\tau^a\gamma^\mu q_{\rm R})(\bar{q}_{\rm L}\tau^b q_{\rm R} - \bar{q}_{\rm R}\tau^b q_{\rm L}),$$

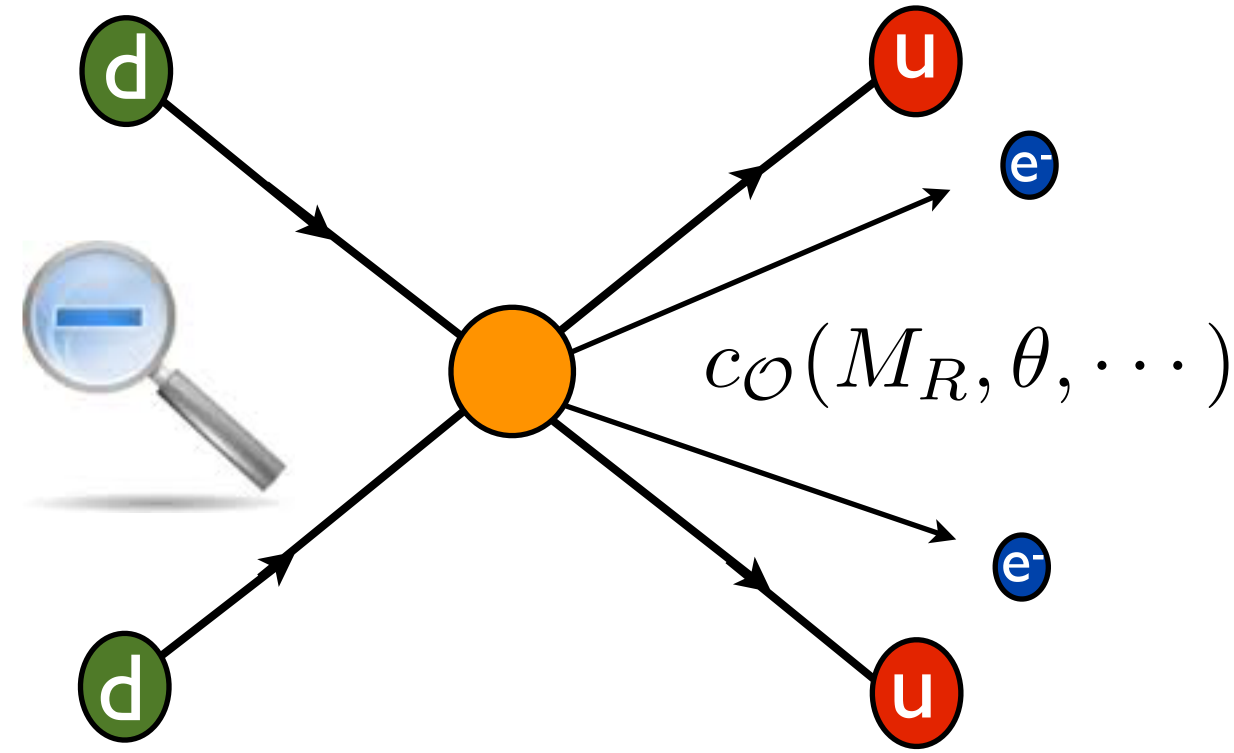
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L} \pm \bar{q}_{\rm R}\tau^a\gamma^\mu q_{\rm R})(\bar{q}_{\rm L}\tau^b q_{\rm R} + \bar{q}_{\rm R}\tau^b q_{\rm L}).$$

From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



Long-range

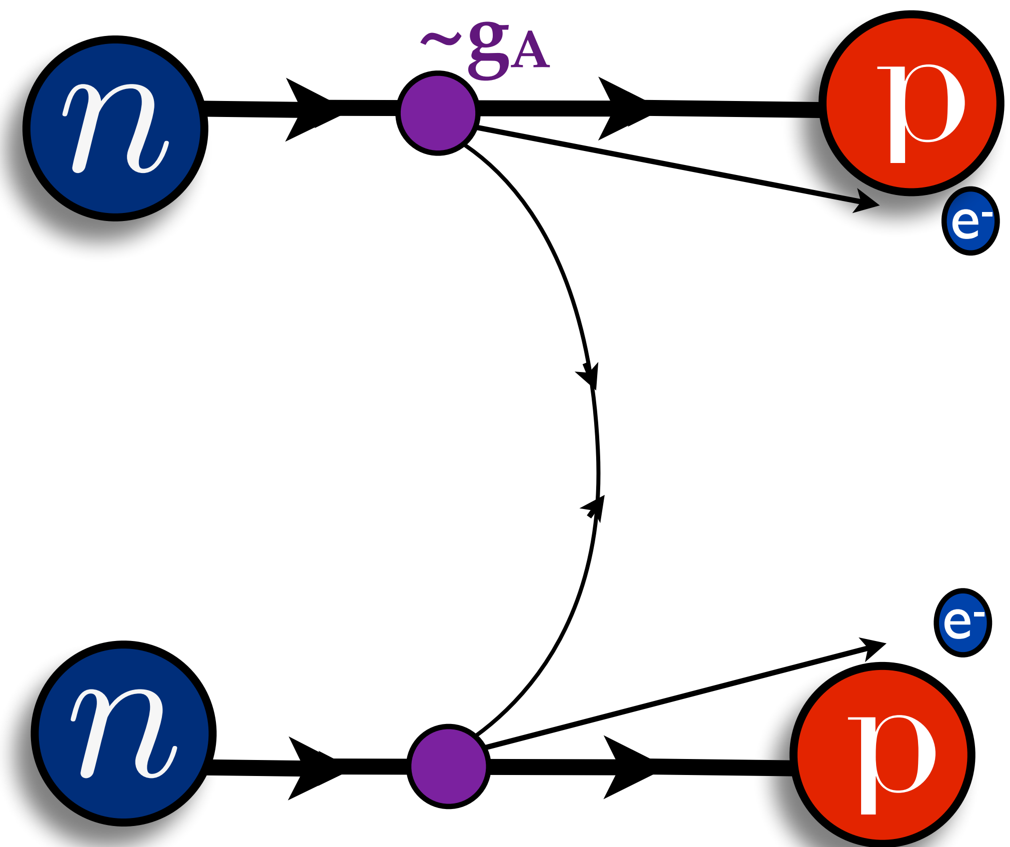


Short-range

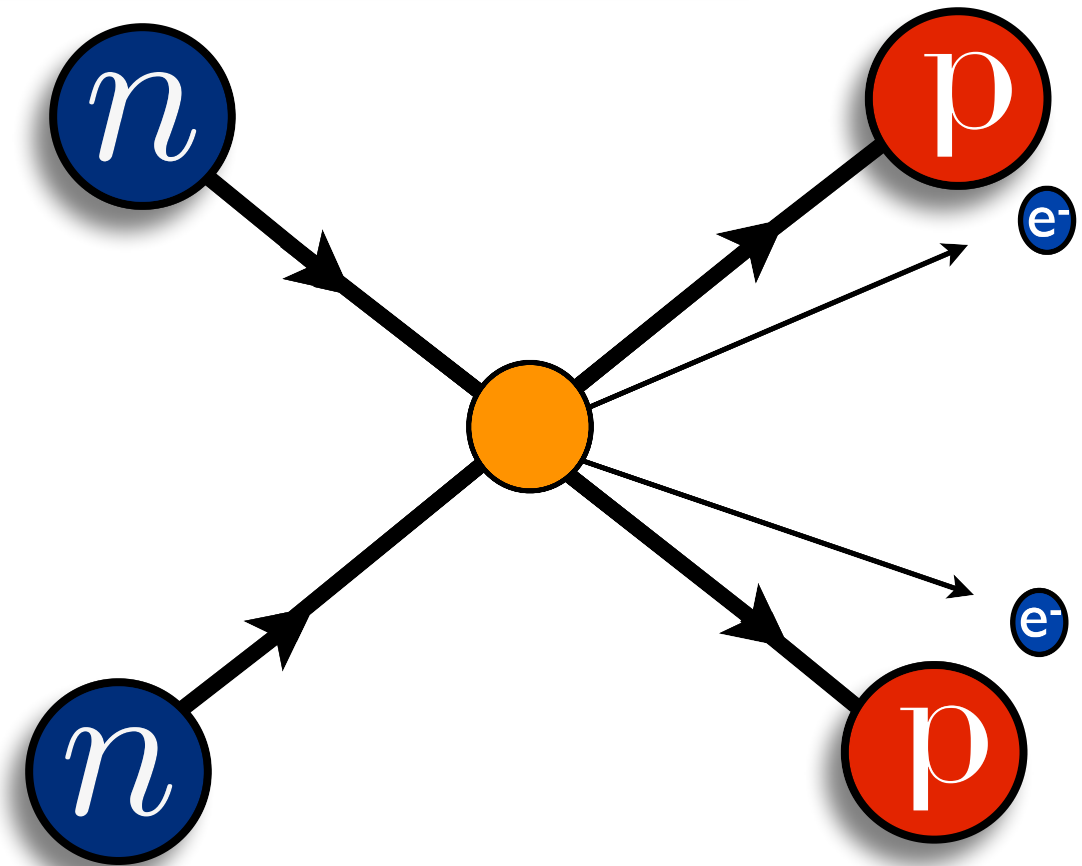
$\Lambda \ll \Lambda_{QCD}$

From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



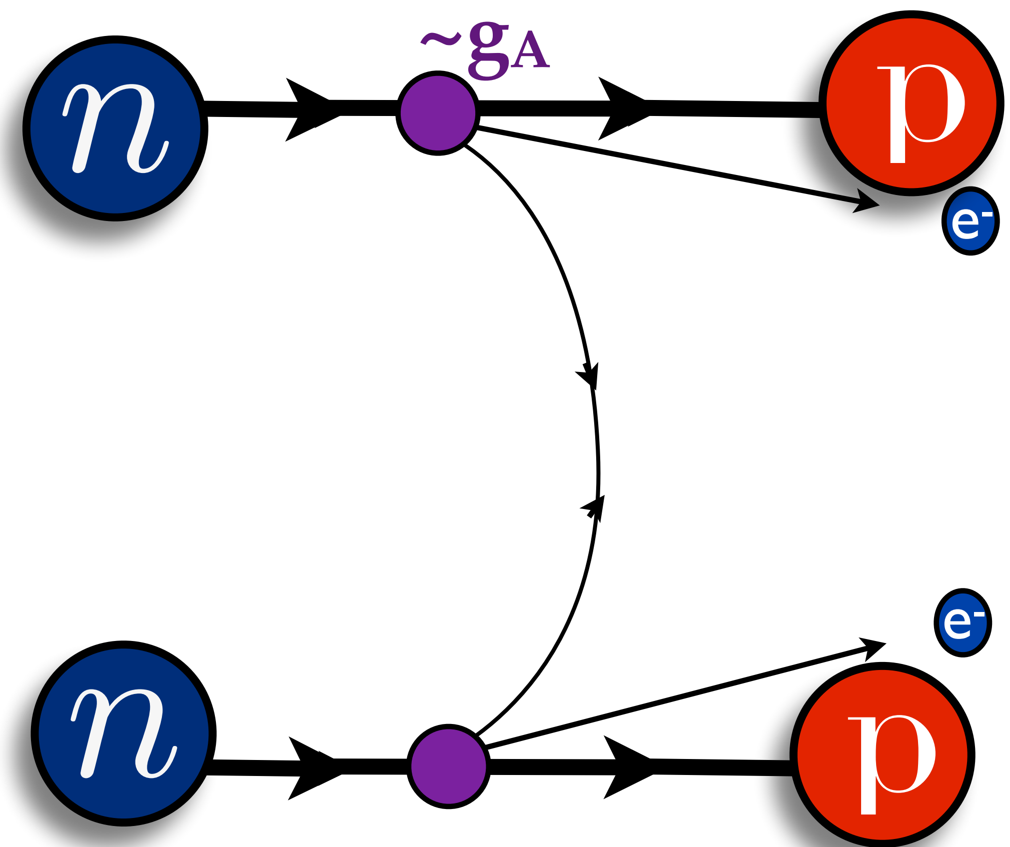
Long-range



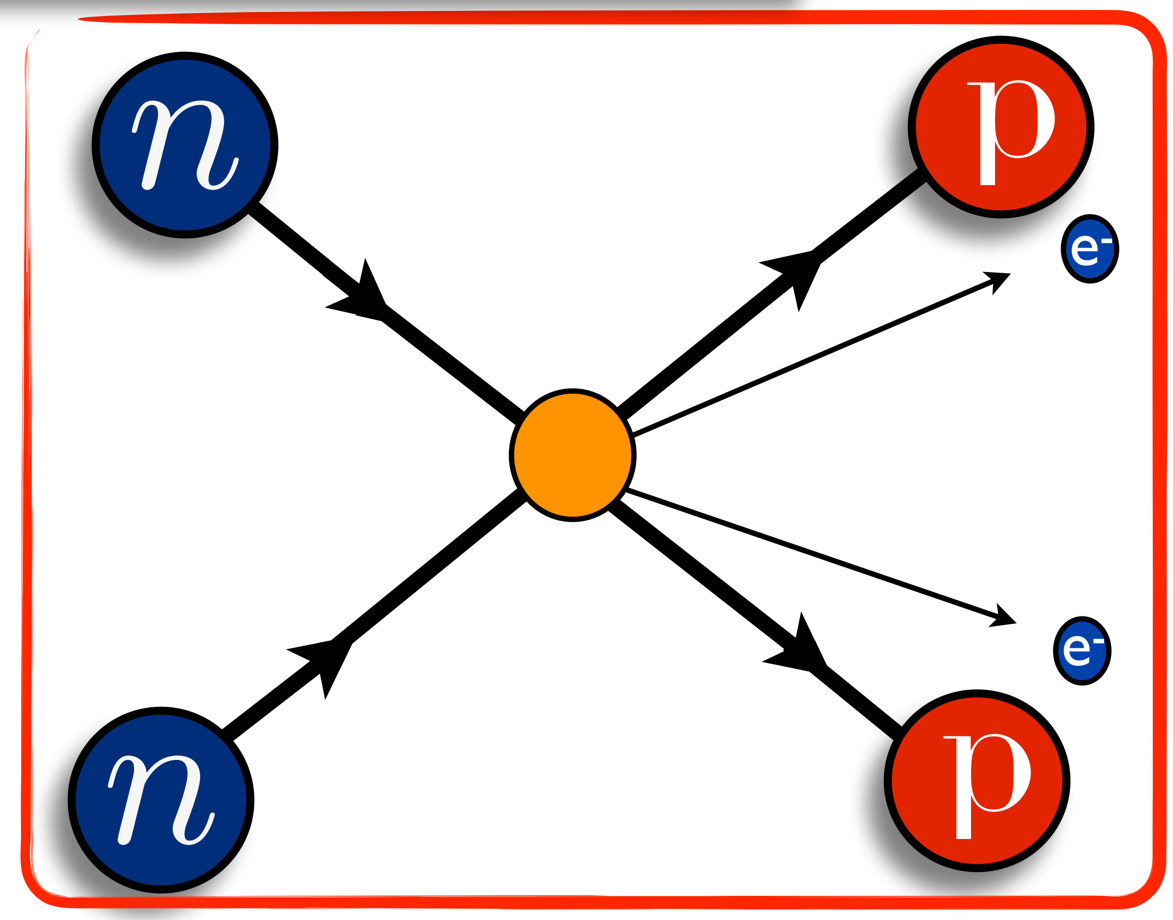
Short-range

From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



Long-range

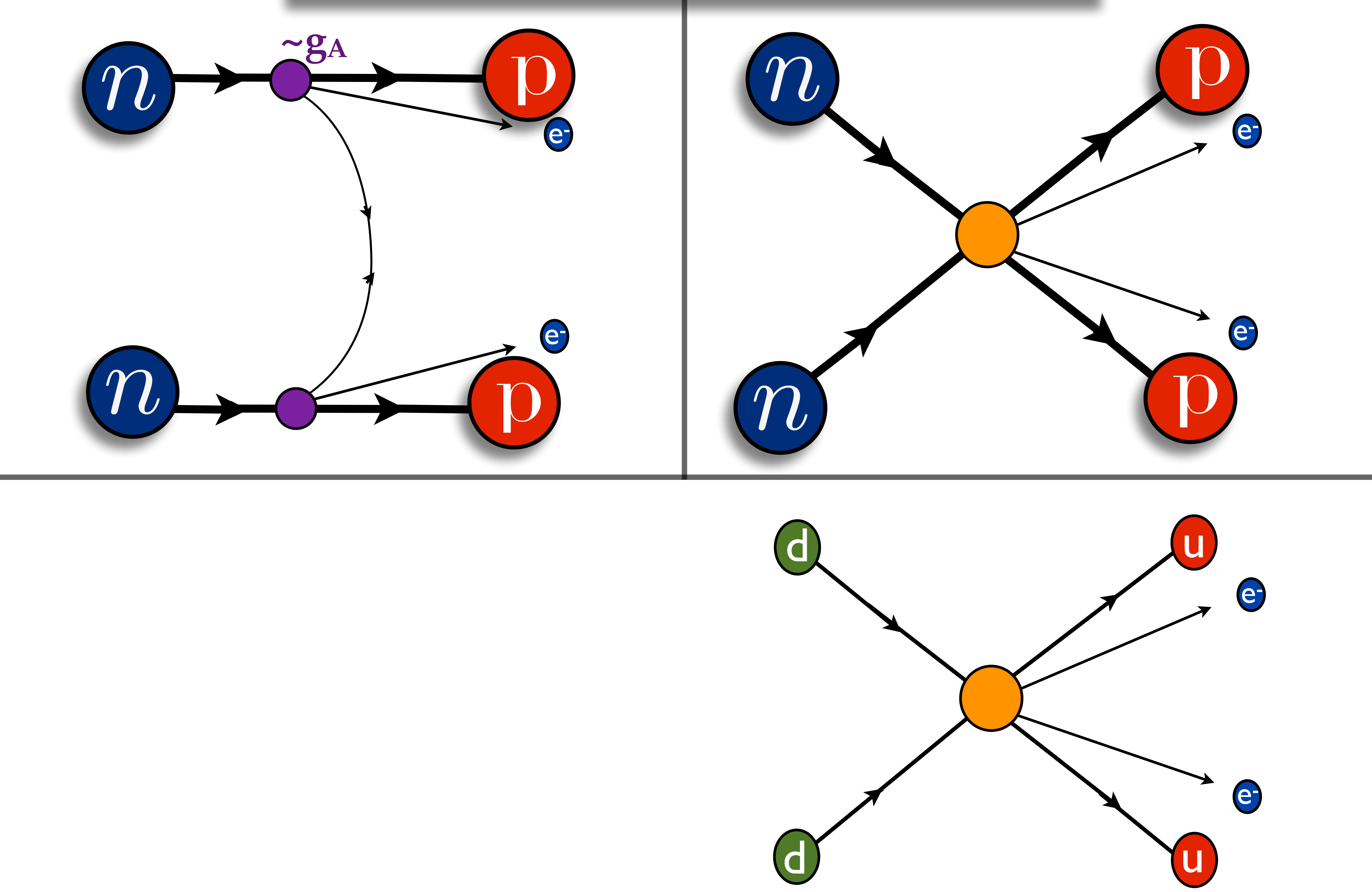


Short-range

Unknown from experiment

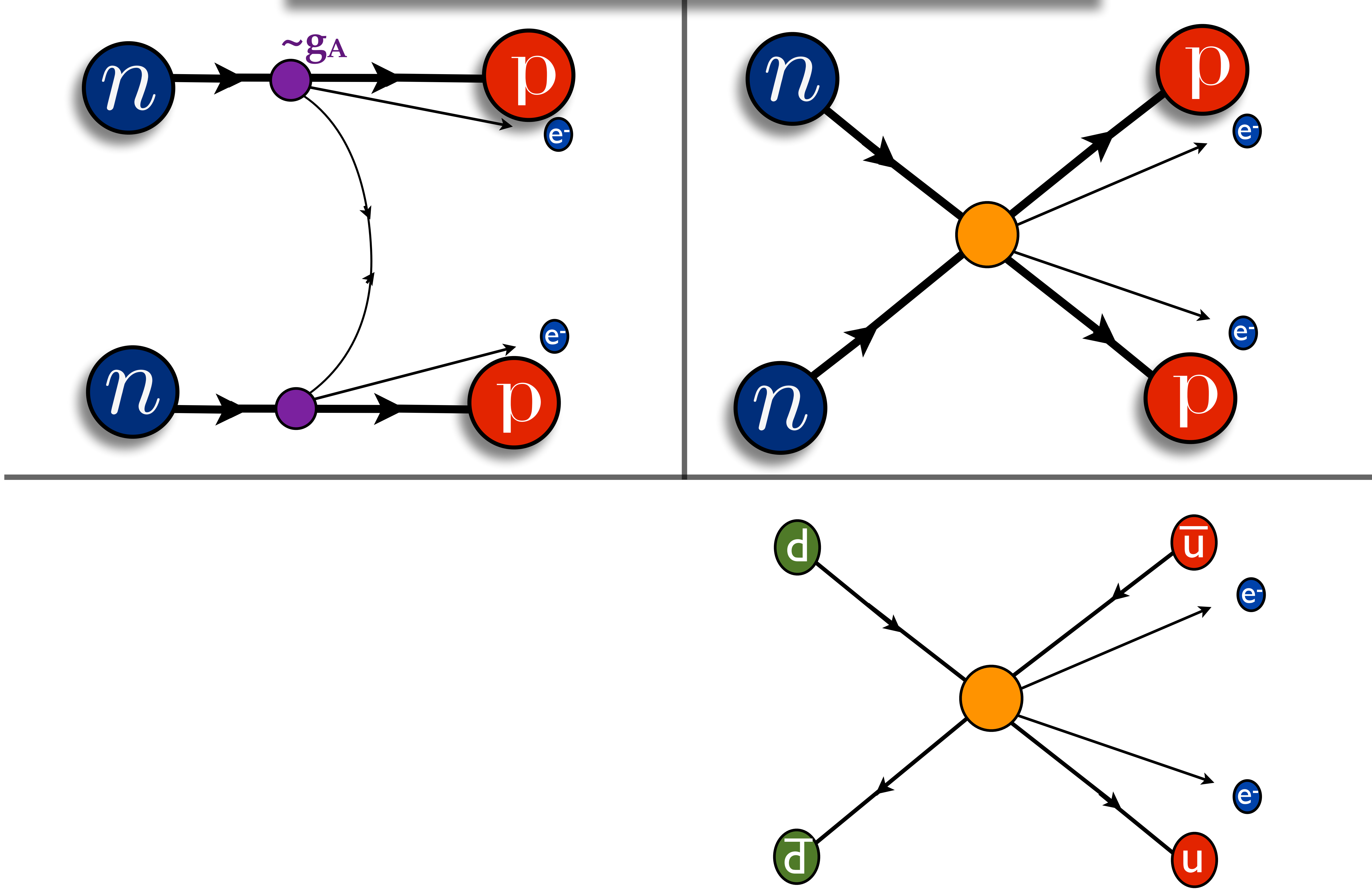
From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



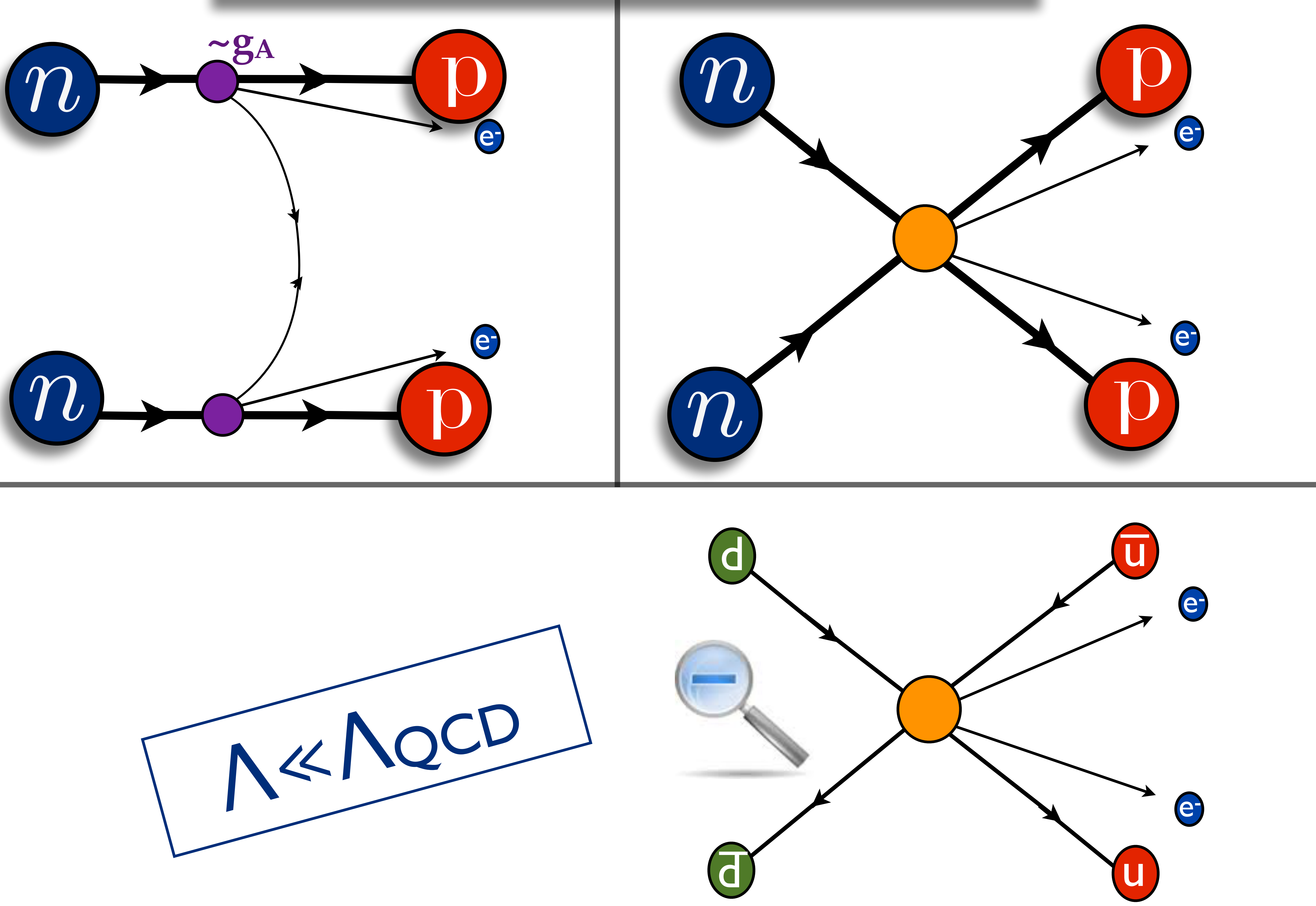
From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



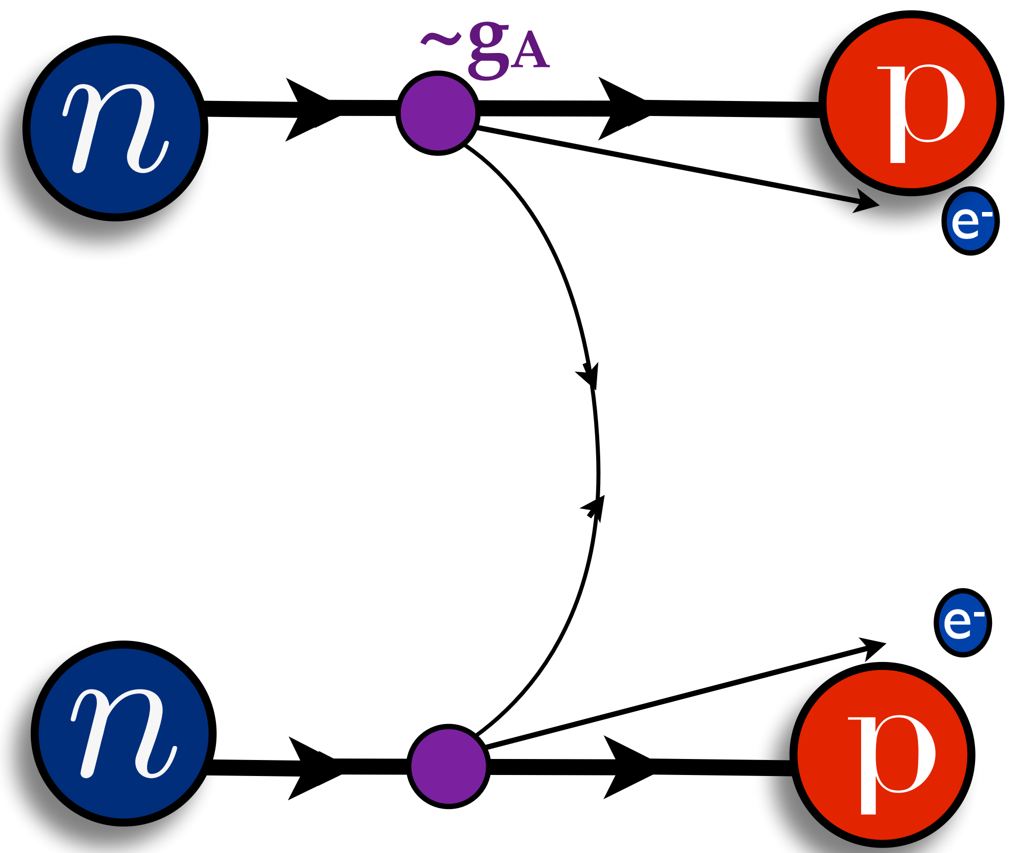
From quark to hadronic scales

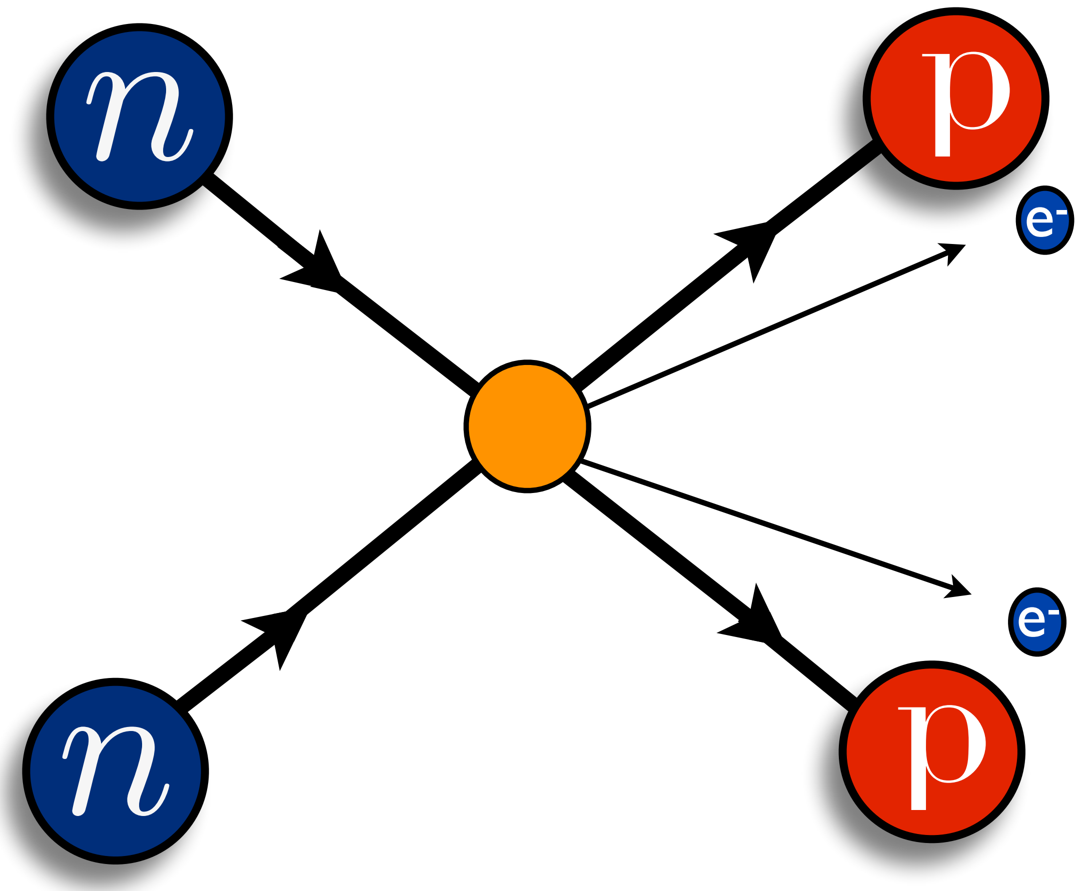
Prezeau, Ramsey-Musolf, Vogel (2003)

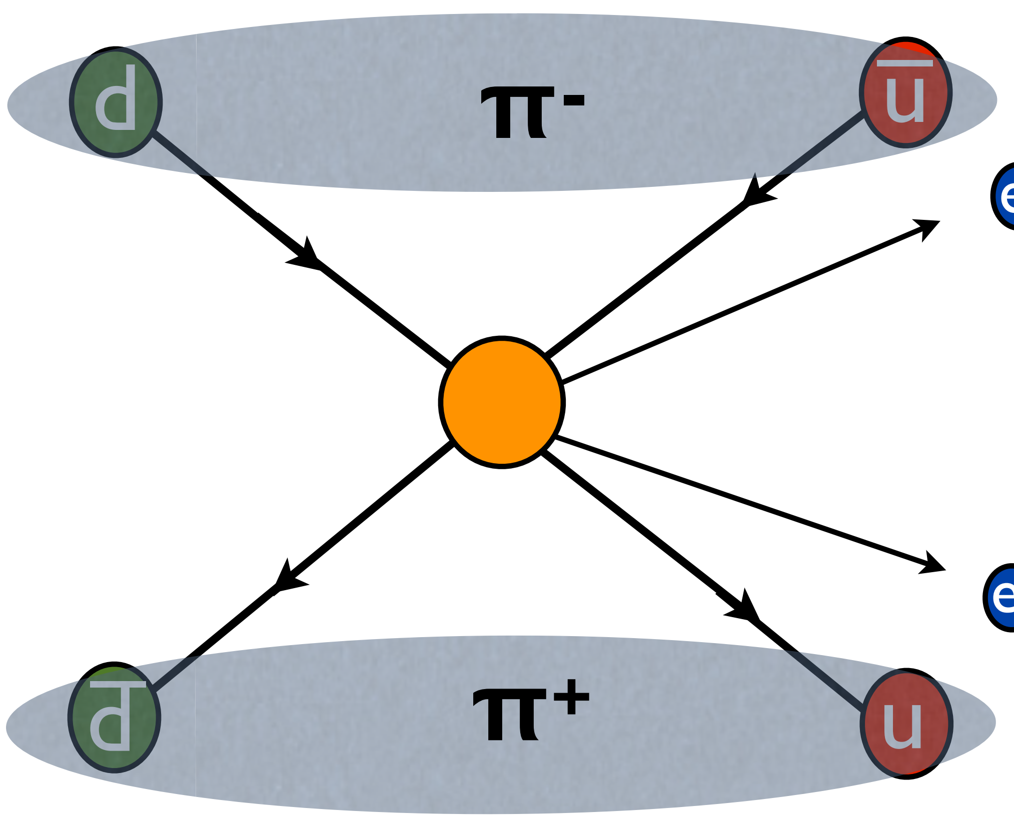


From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)

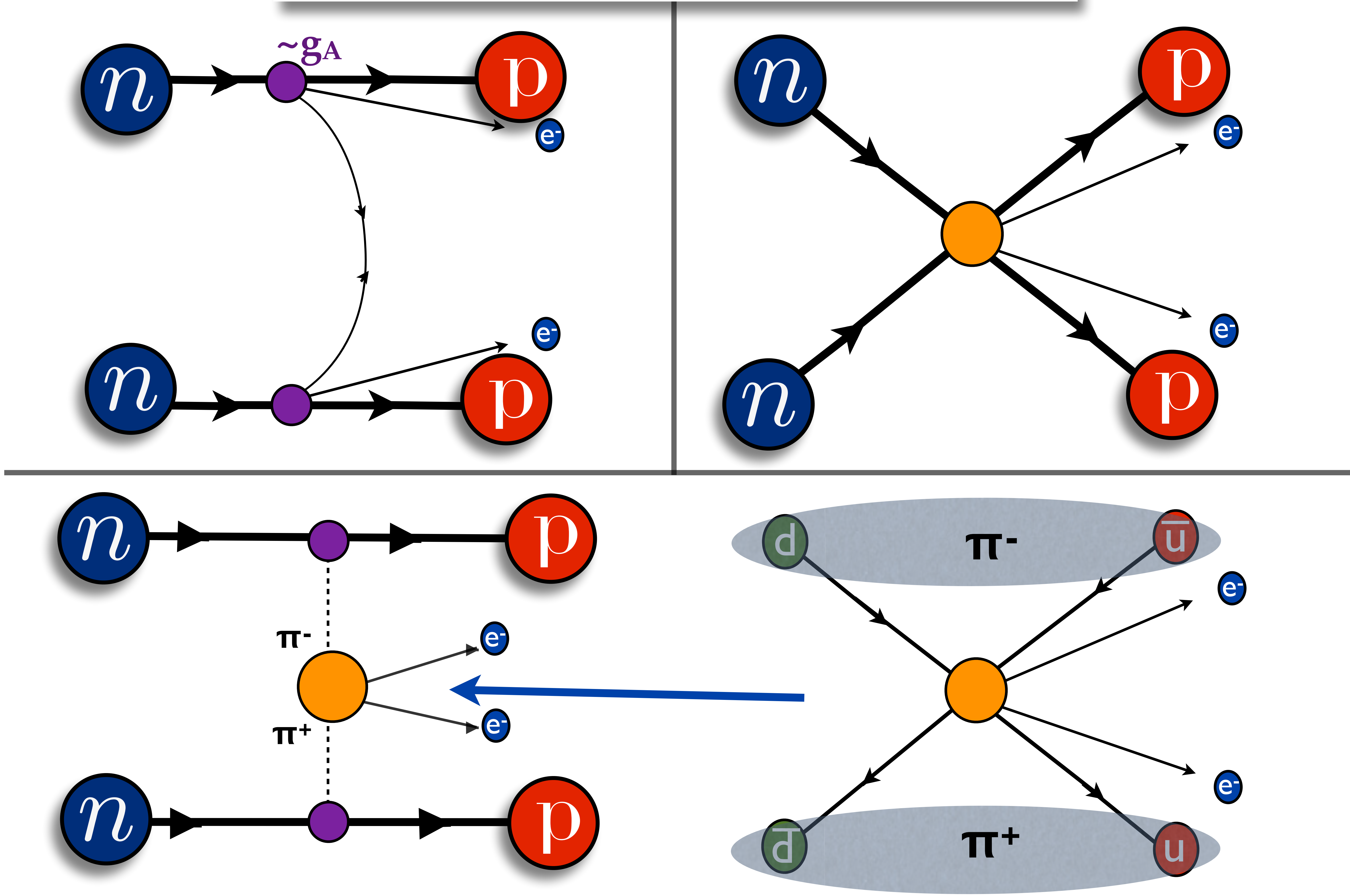






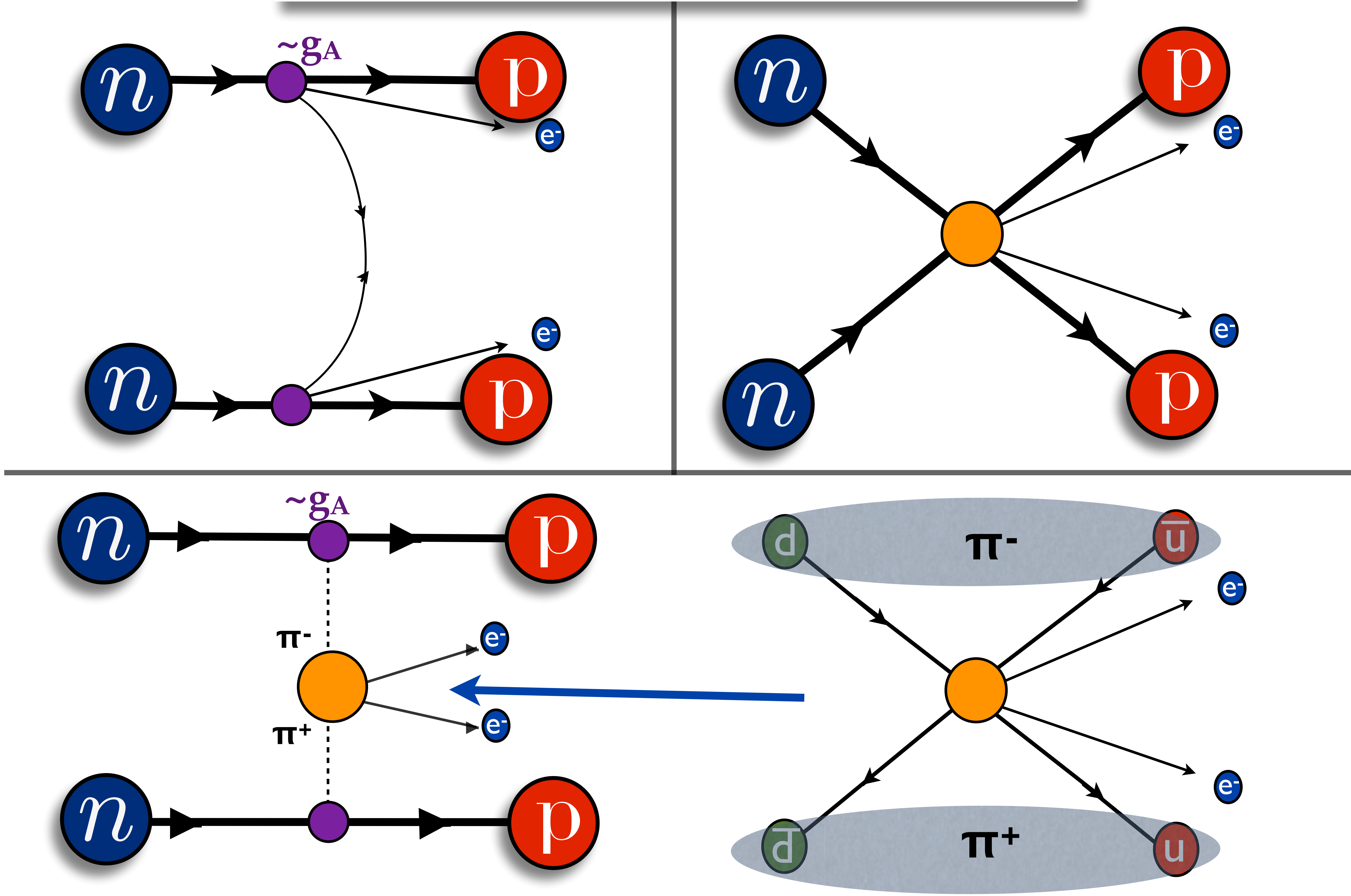
From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



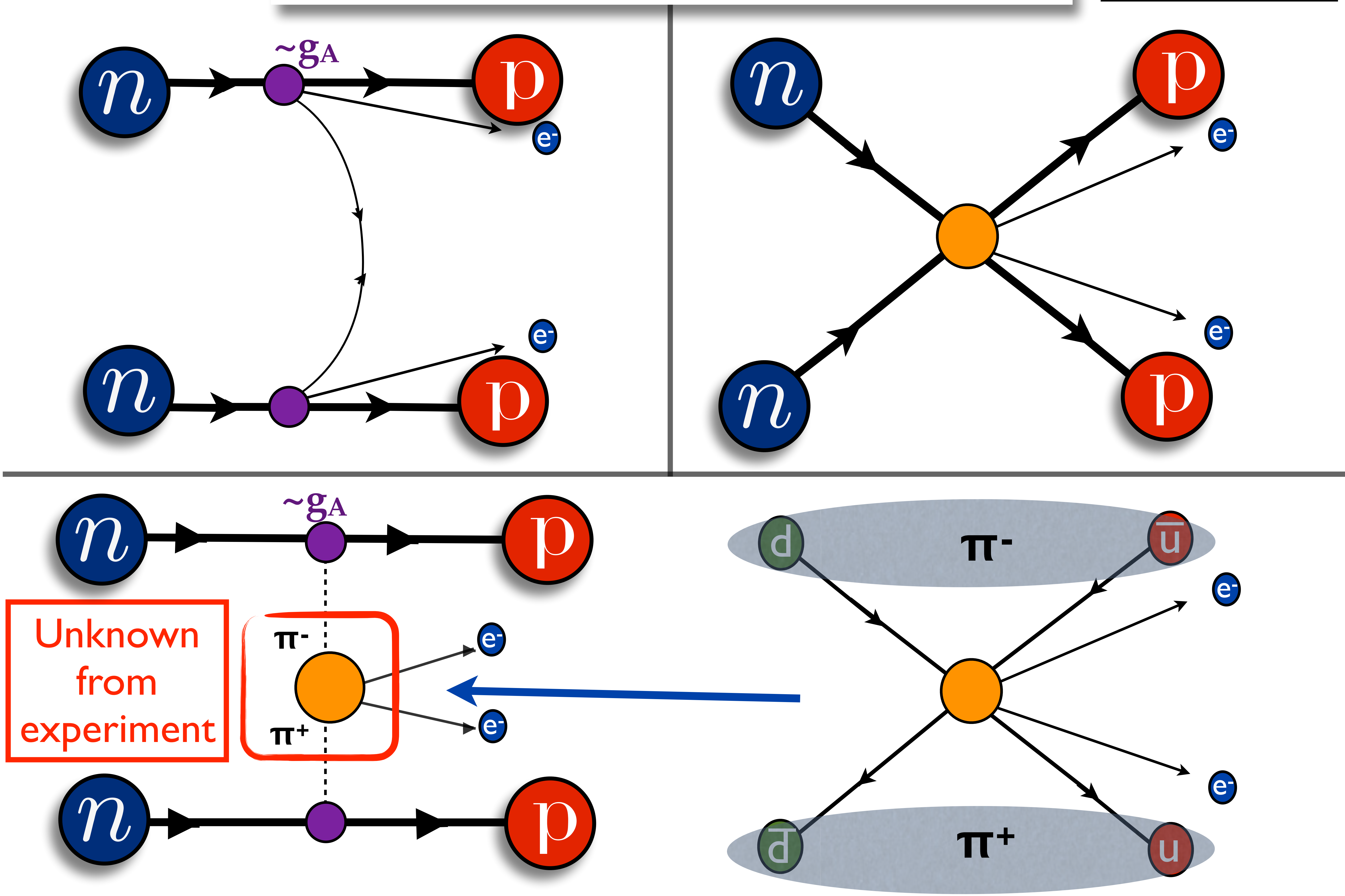
From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)

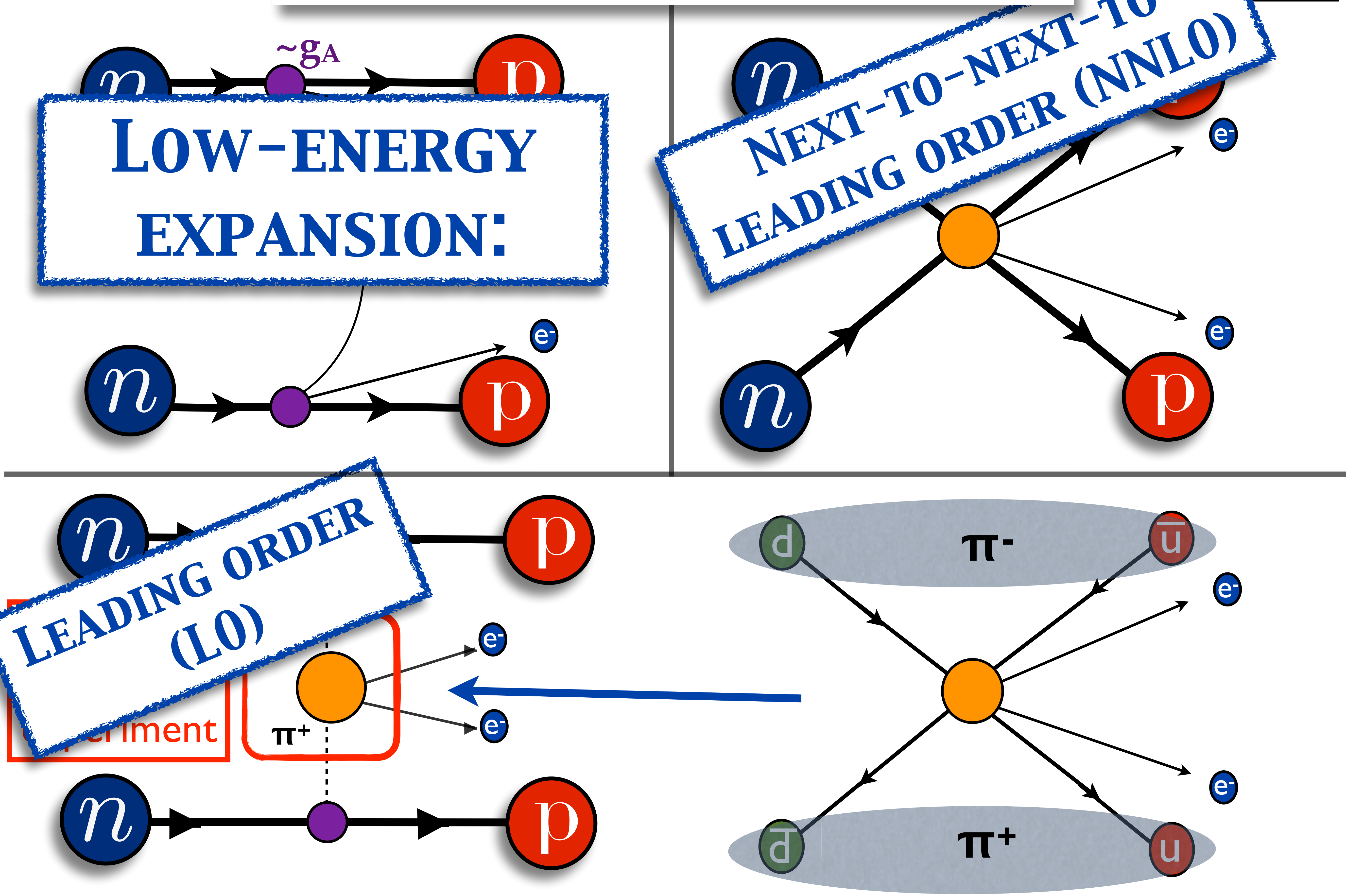


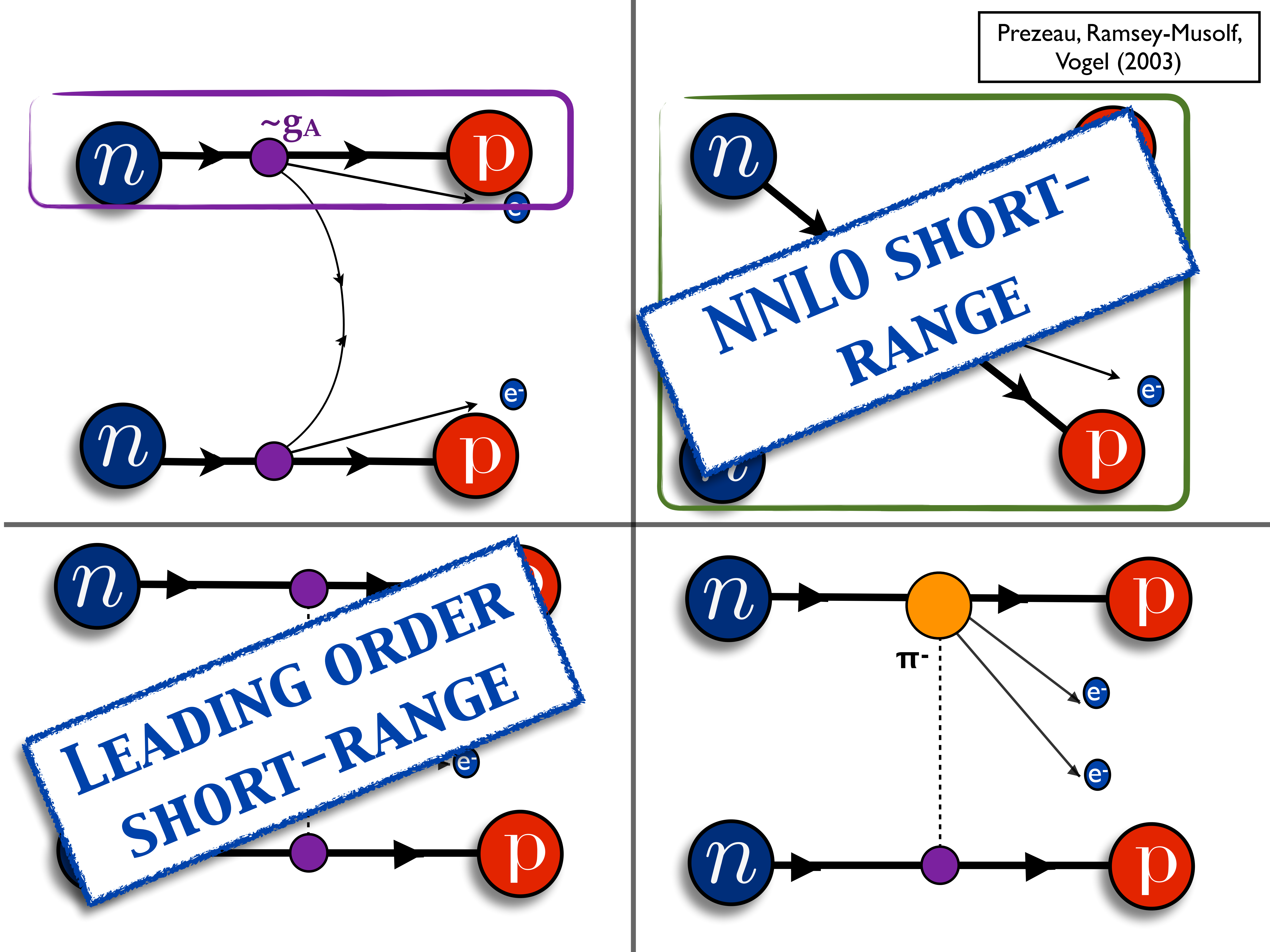
From quark to hadronic scales

Prezeau, Ramsey-Musolf, Vogel (2003)



From quark to hadronic scales





Prezeau, Ramsey-Musolf, Vogel (2003)
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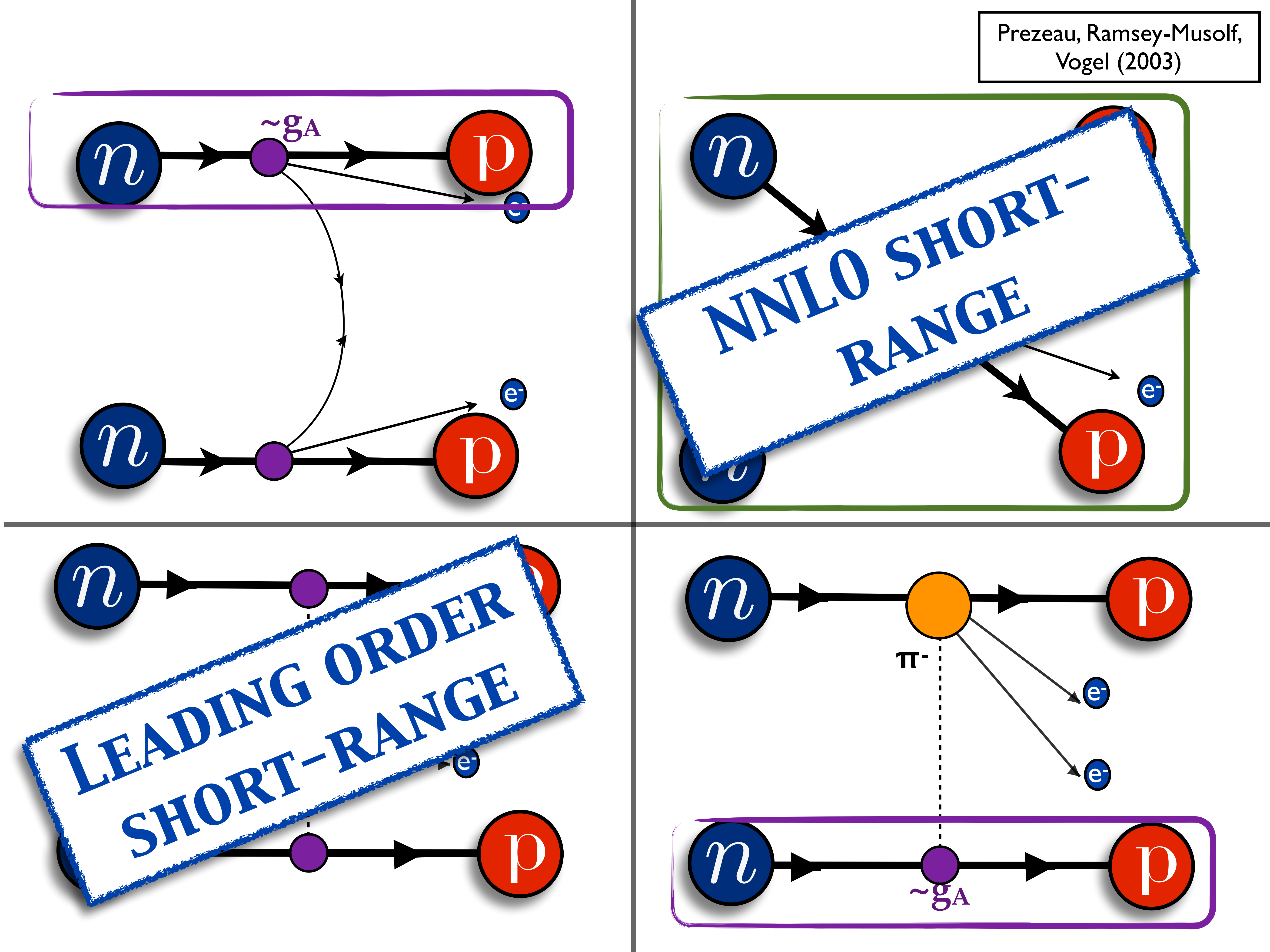
LEADING ORDER SHORT-RANGE
π-



Prezeau, Ramsey-Musolf, Vogel (2003)
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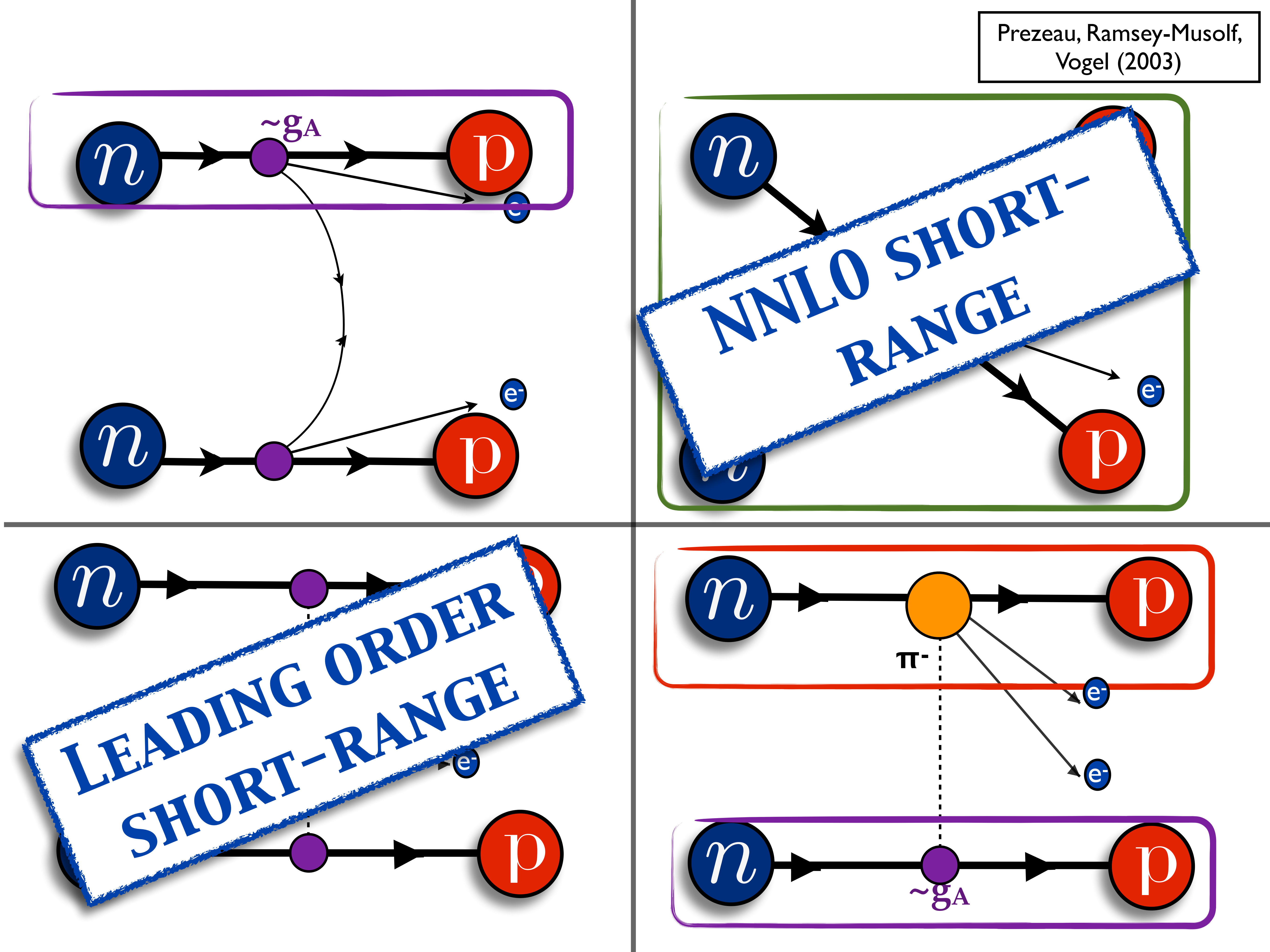
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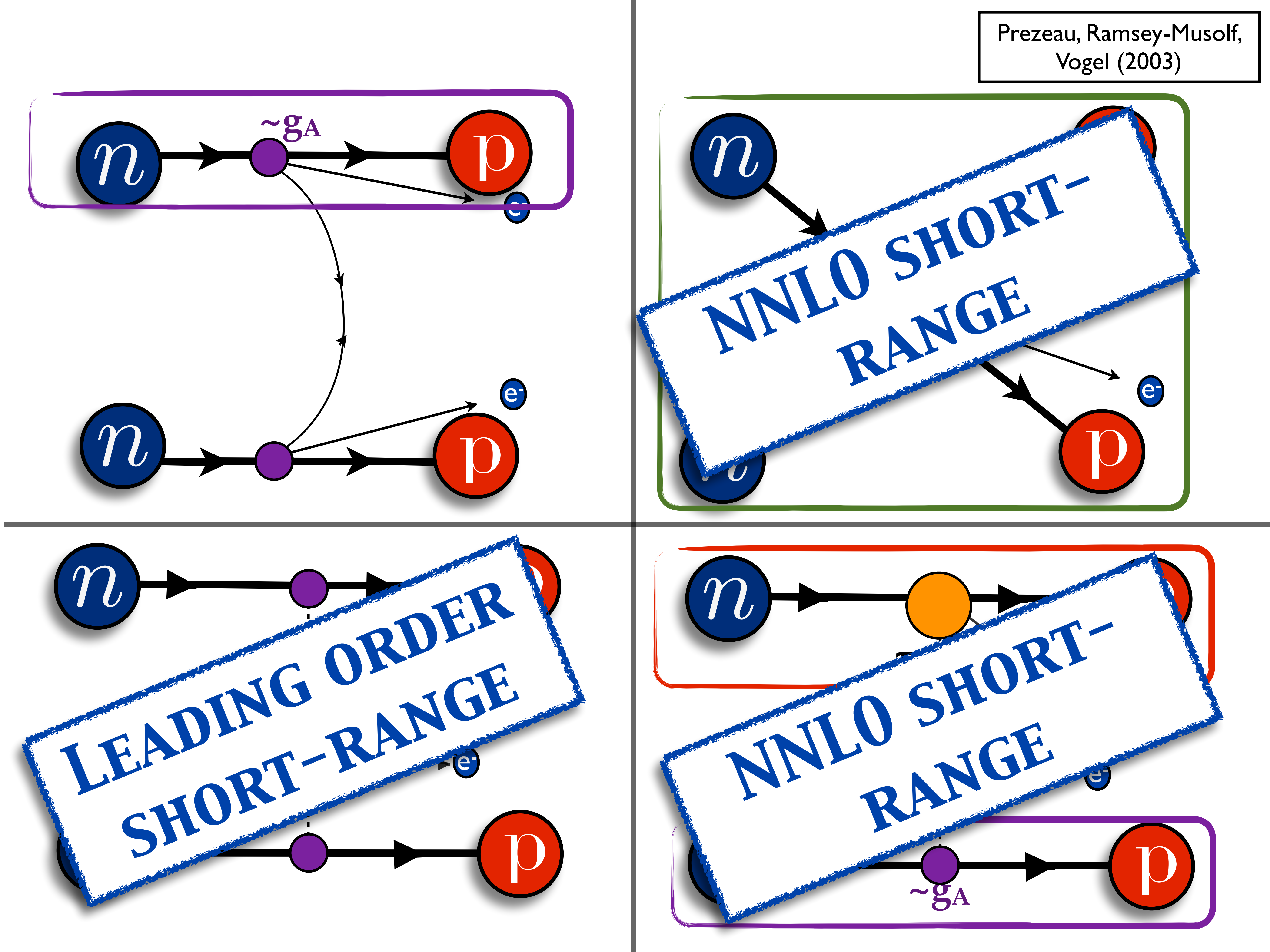

Prezeau, Ramsey-Musolf, Vogel (2003)
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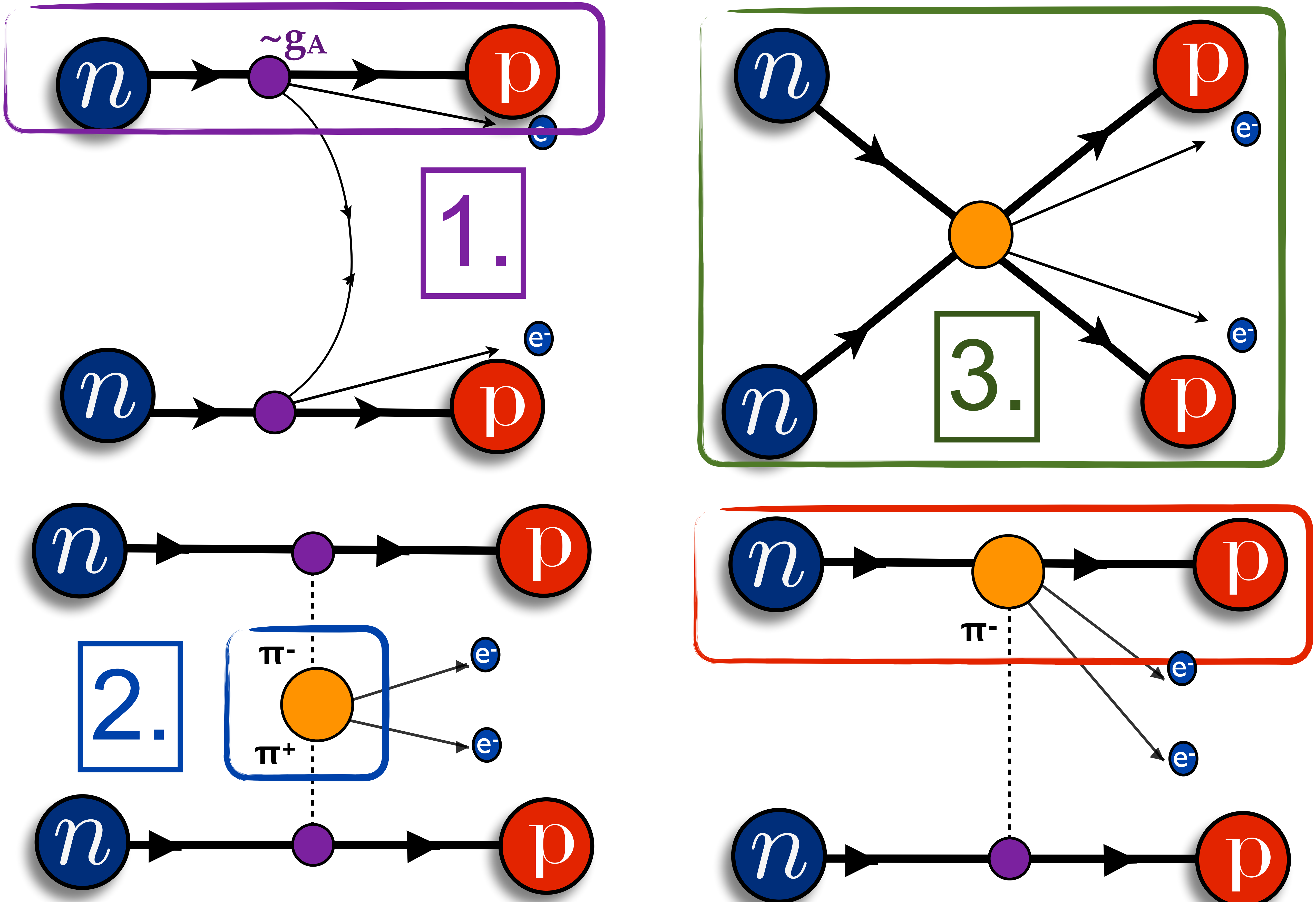
~gA

Prezeau, Ramsey-Musolf, Vogel (2003)



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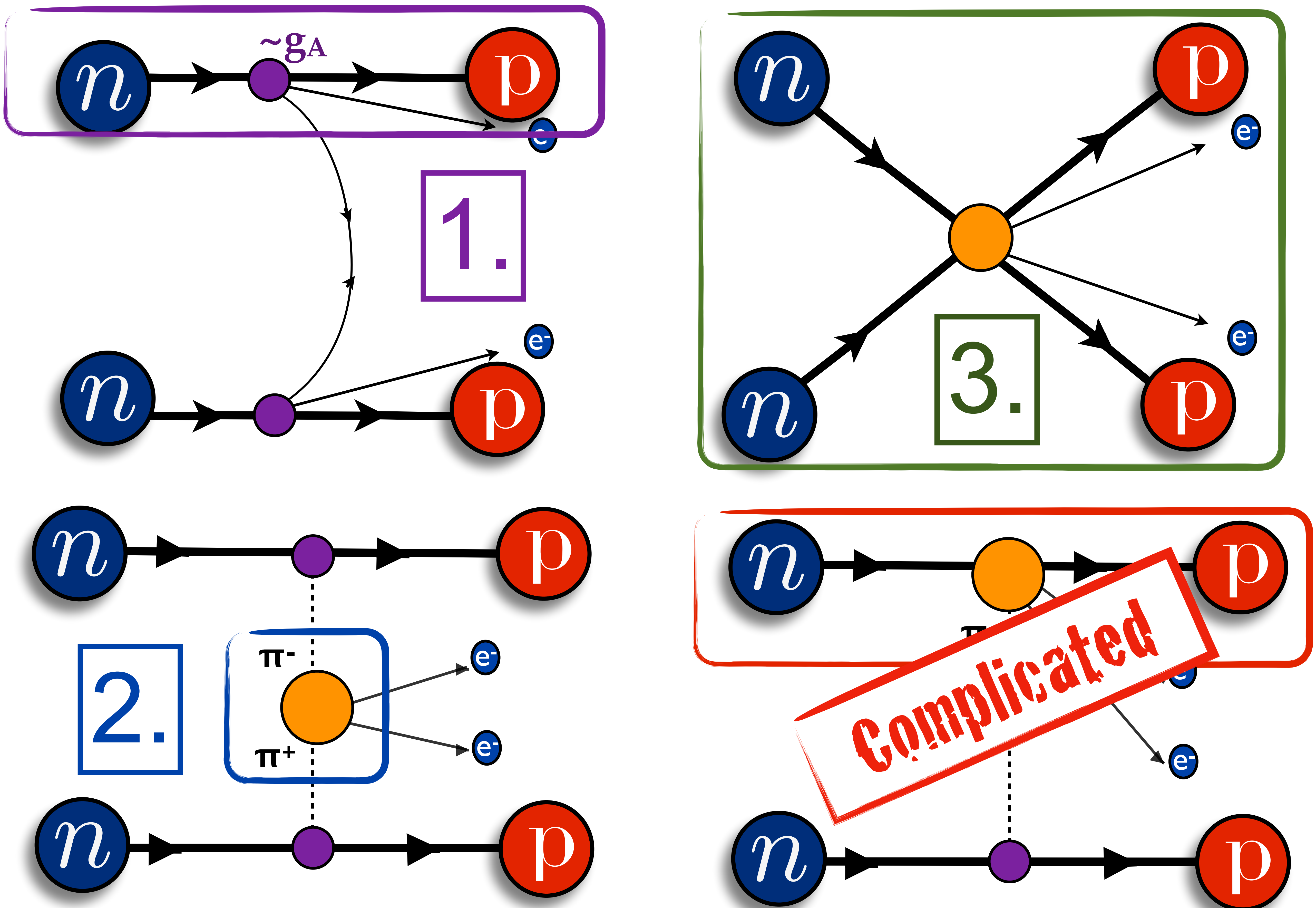
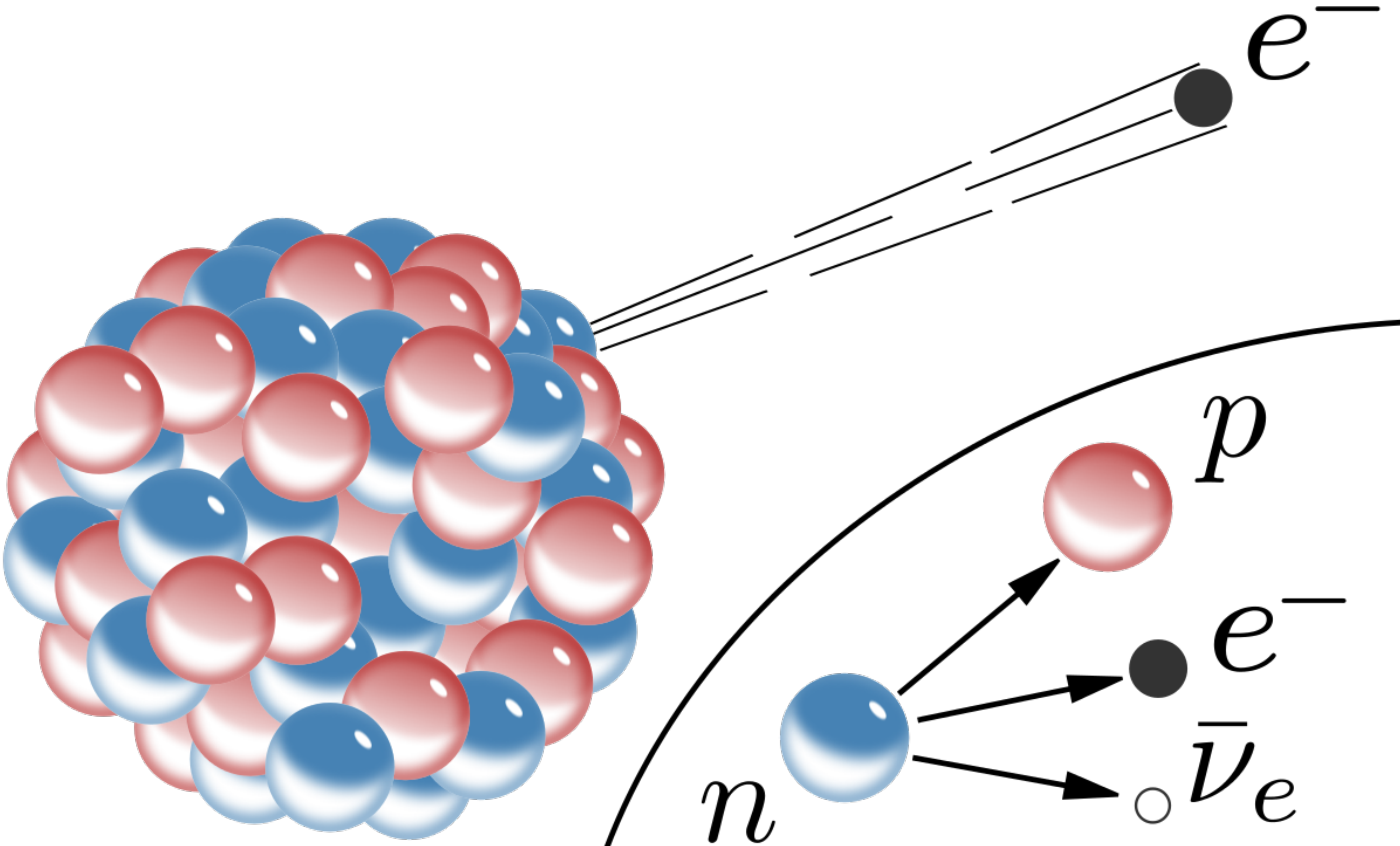


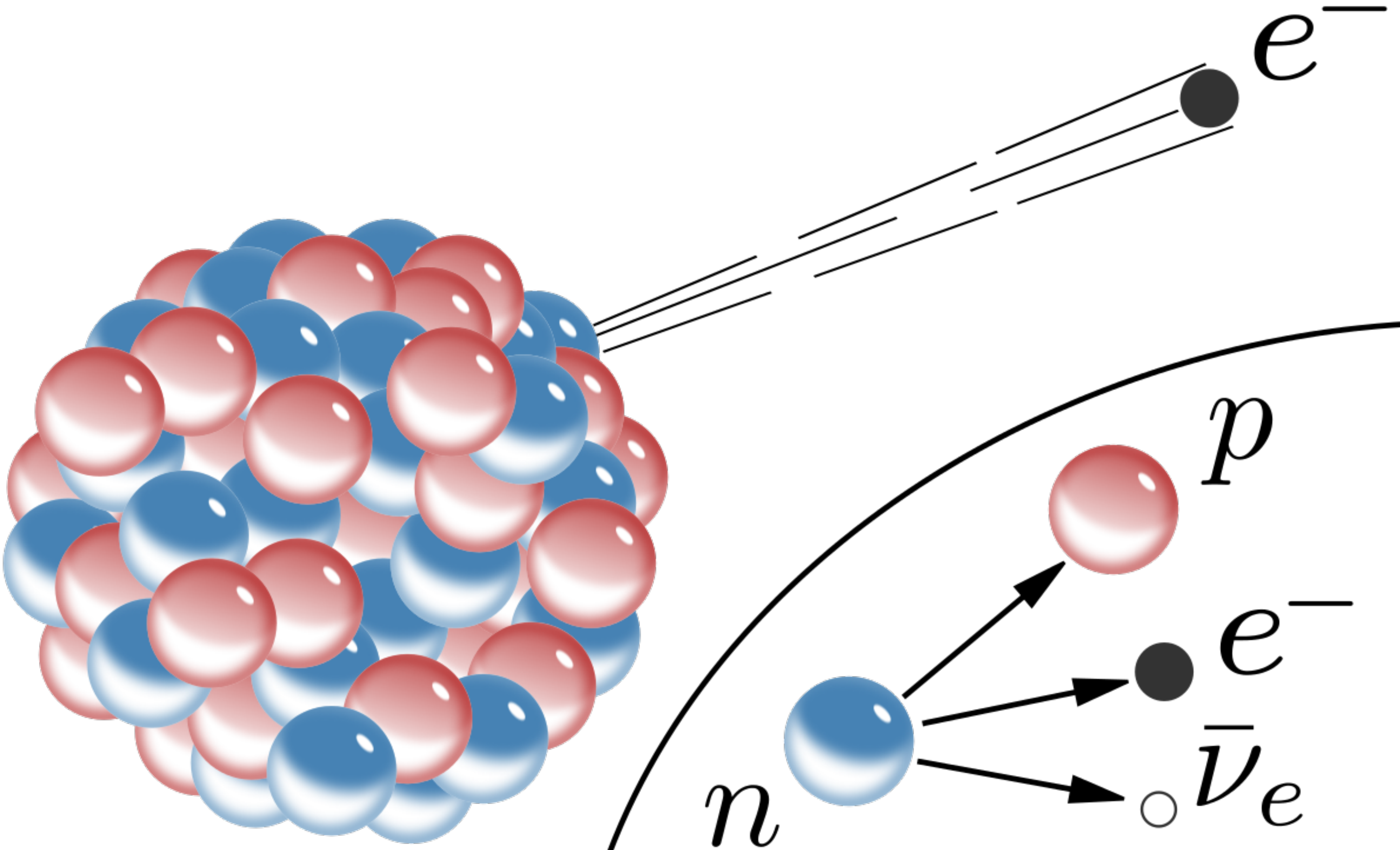
1. Nucleon axial charge, g_A

What depends on g_A?



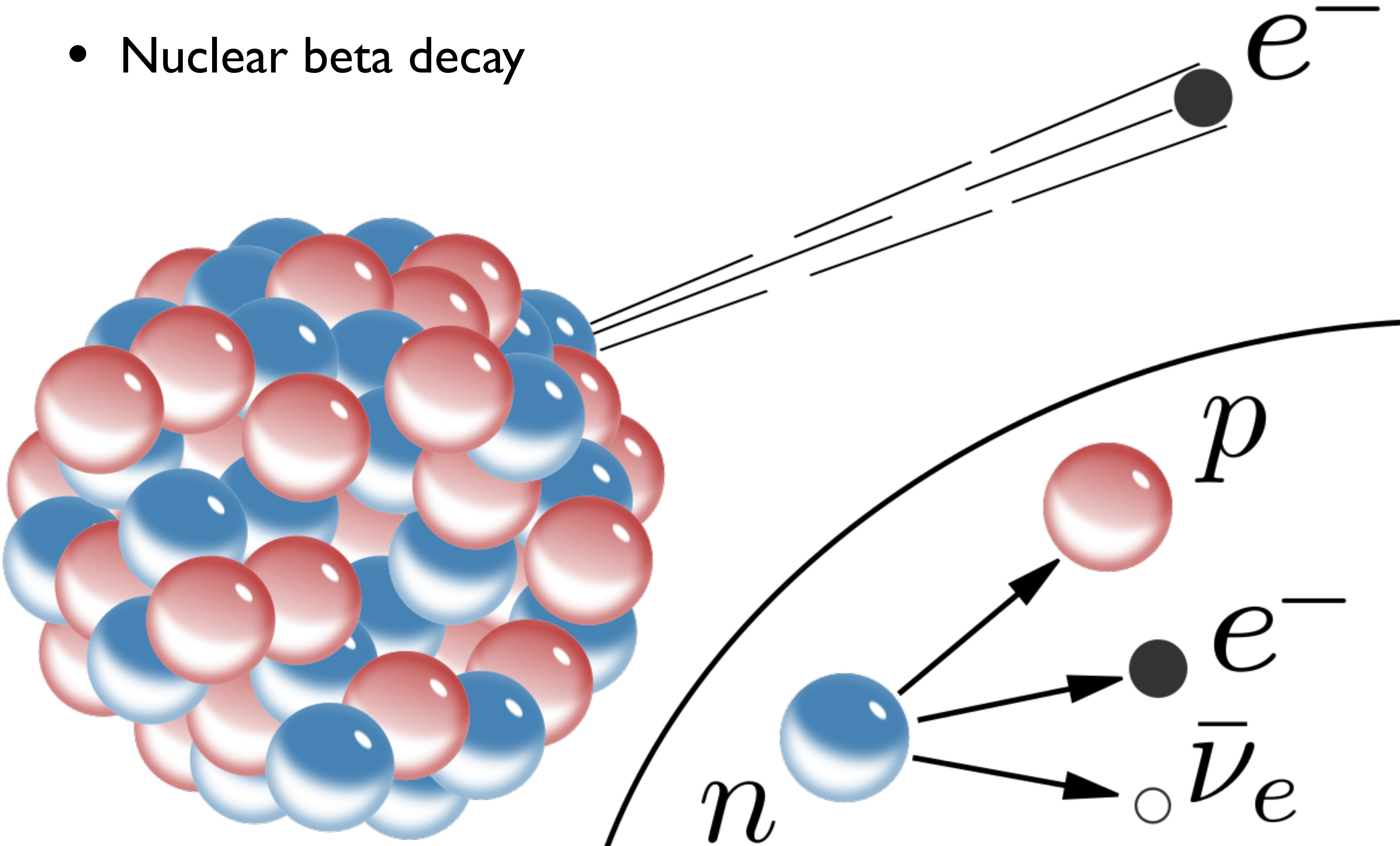
What depends on g_A?

- Free neutron lifetime



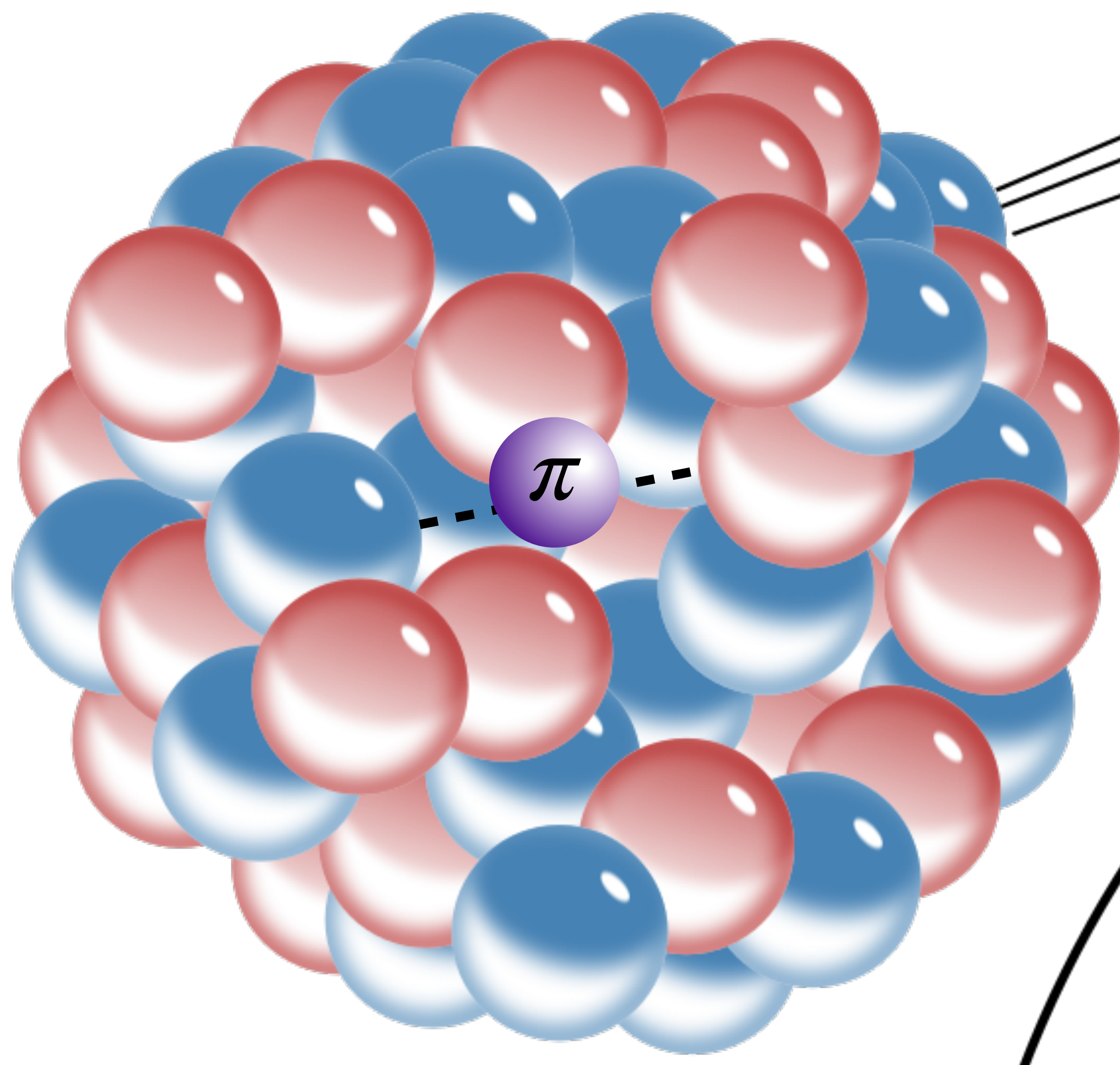
What depends on g_A?

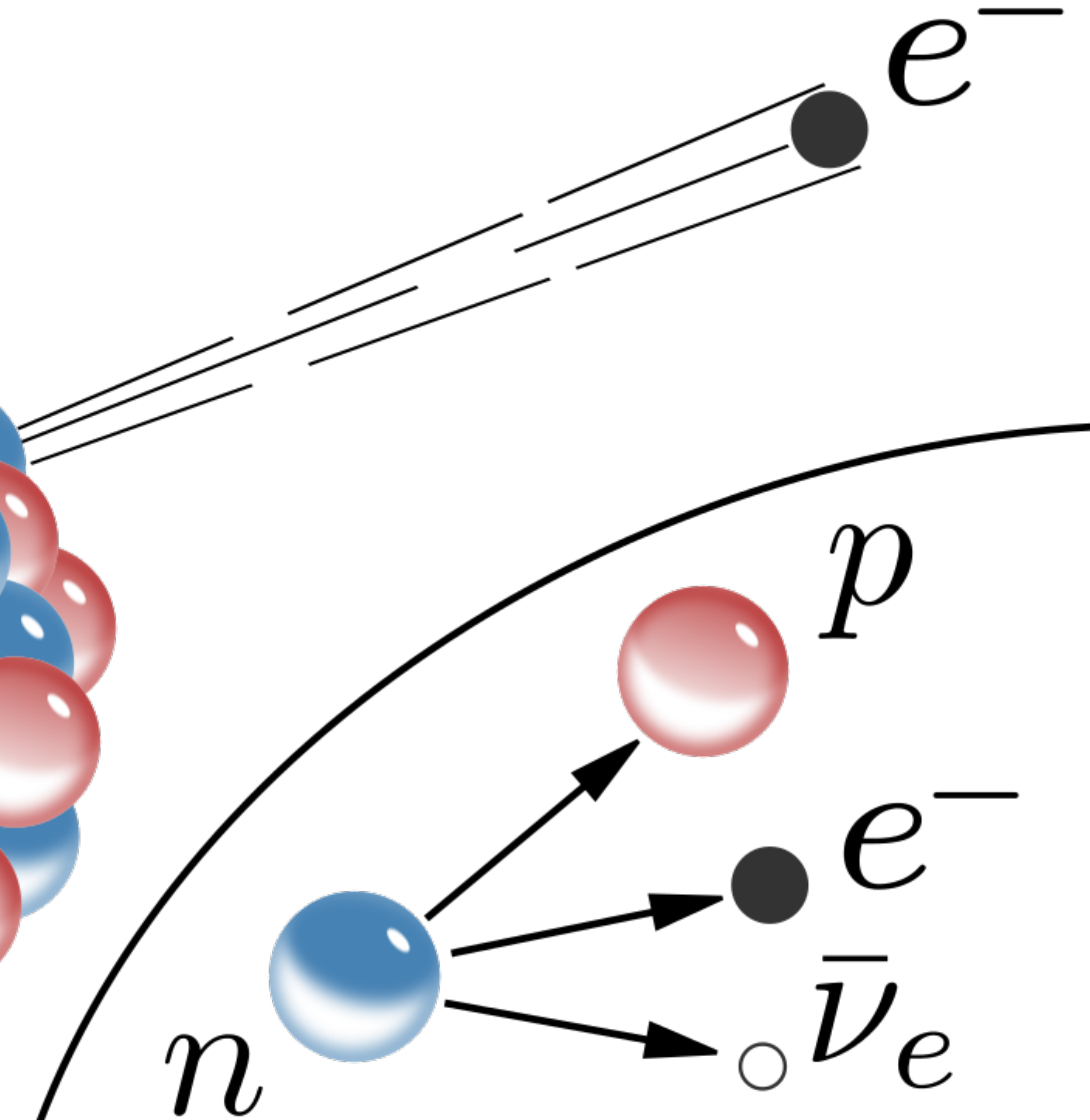
- Free neutron lifetime
- Nuclear beta decay



What depends on g_A?

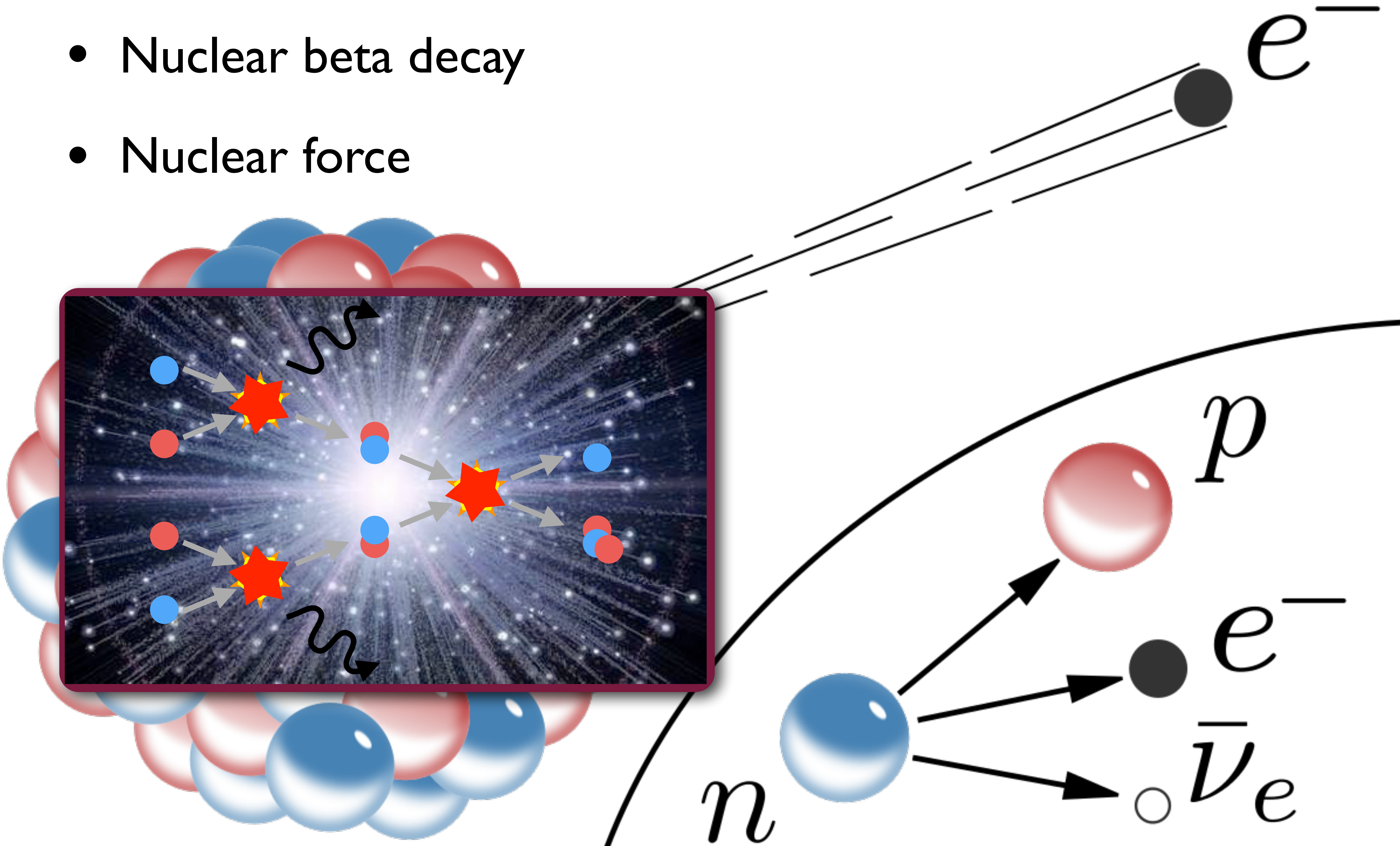
- Free neutron lifetime
- Nuclear beta decay
- Nuclear force





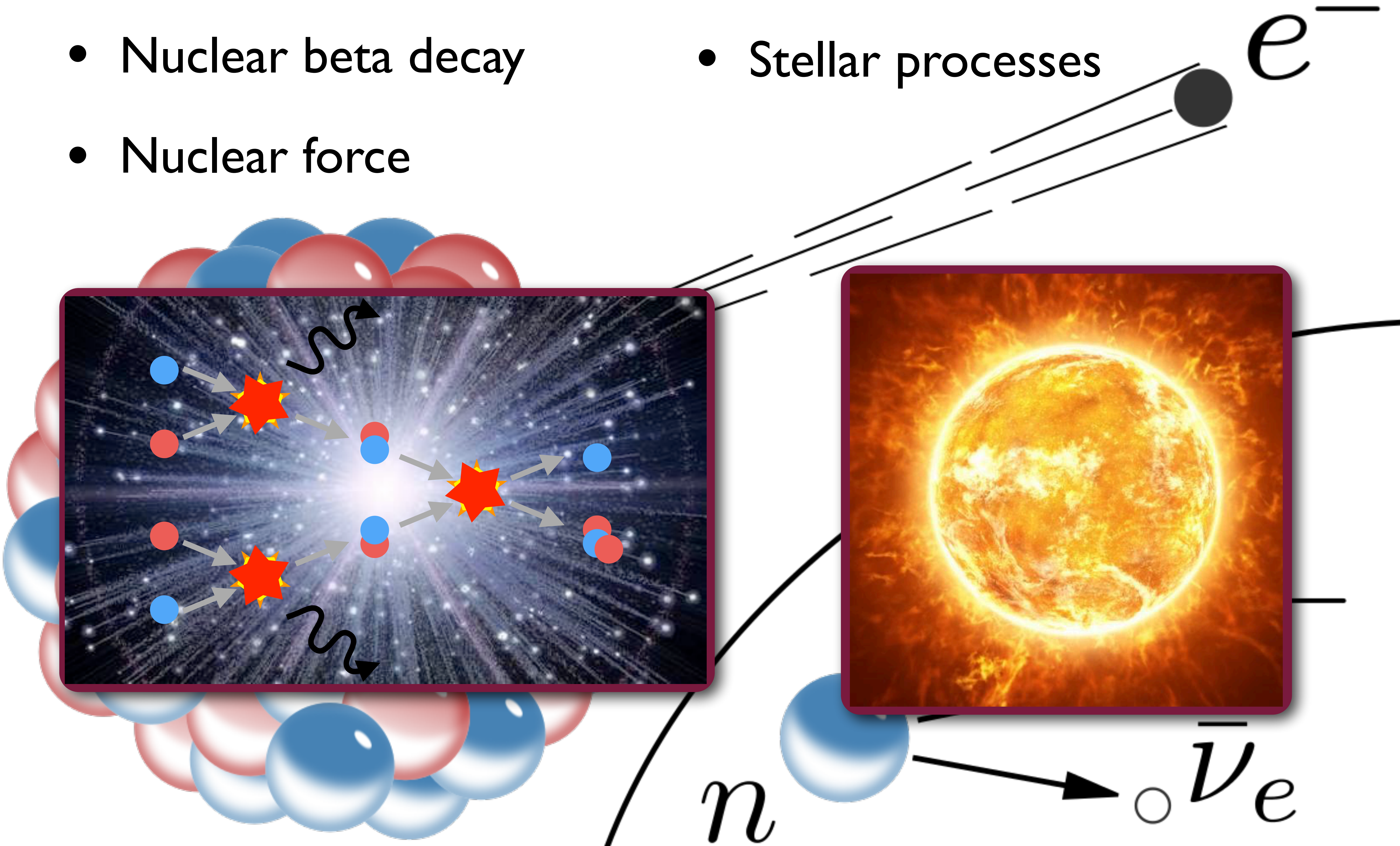
What depends on g_A?

- Free neutron lifetime
- Nuclear beta decay
- Nuclear force
- Big Bang nucleosynthesis



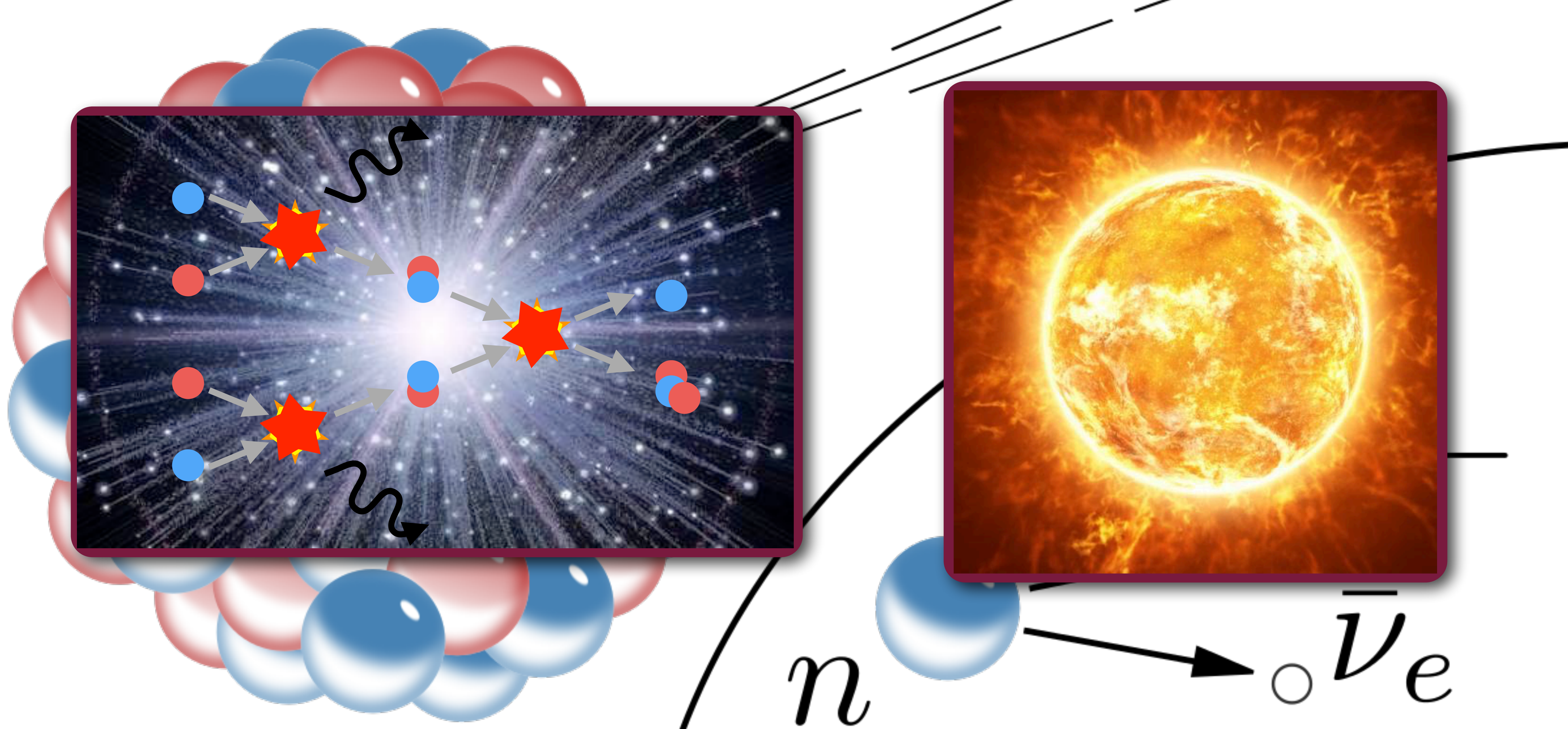
What depends on g_A?

- Free neutron lifetime
- Nuclear beta decay
- Nuclear force
- Big Bang nucleosynthesis
- Stellar processes

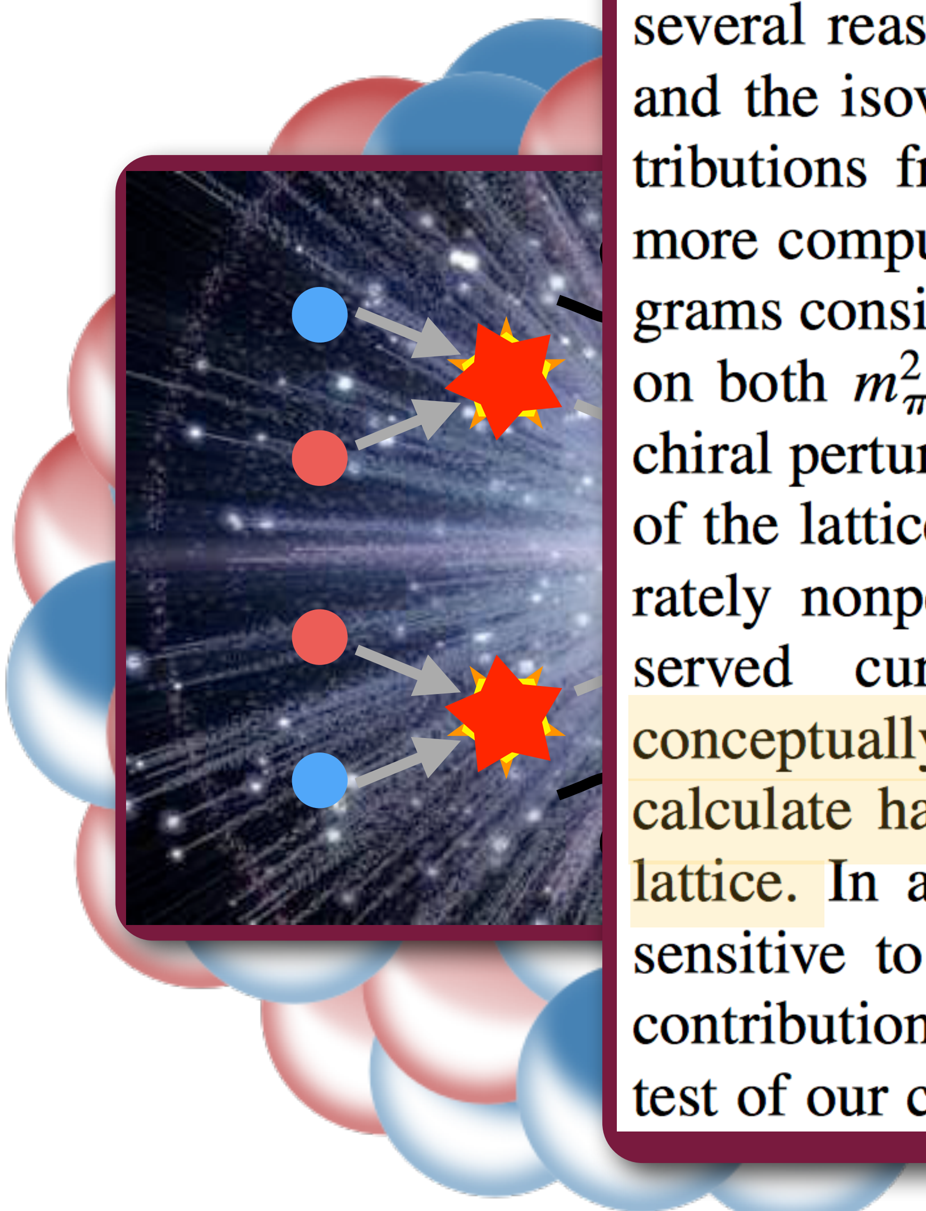


What depends on g_A?

- Free neutron lifetime
- Nuclear beta decay
- Nuclear force
- Big Bang nucleosynthesis
- Stellar processes
- ….



- Free neut… synthesis
- Nuclear … s
- Nuclear f…



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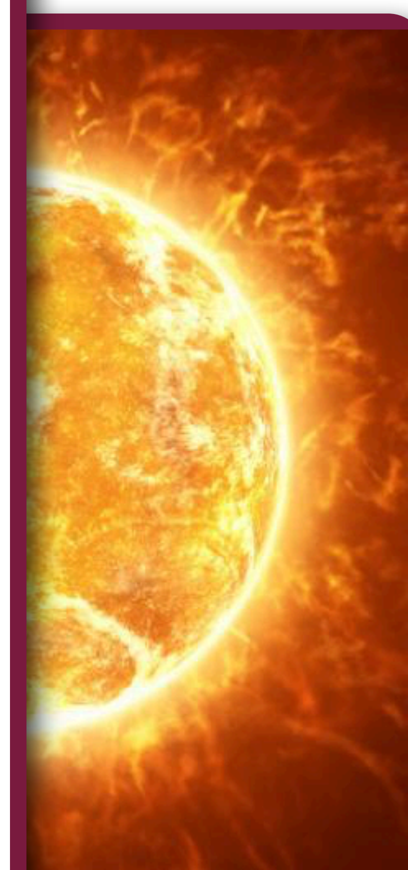
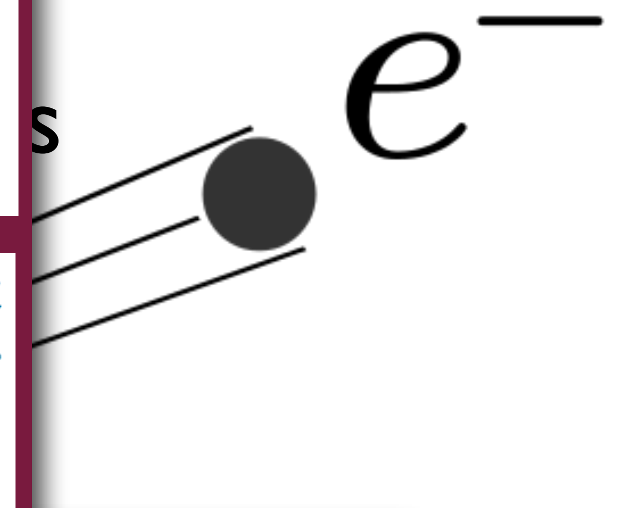
Nucleon Axial Charge in Full Lattice QCD

R. G. Edwards, G. T. Fleming, Ph. Hägler, J. W. Negele, K. Orginos, A. V. Pochinsky, D. B. Renner, D. G. Richards, and W. Schroers (LHPC Collaboration)

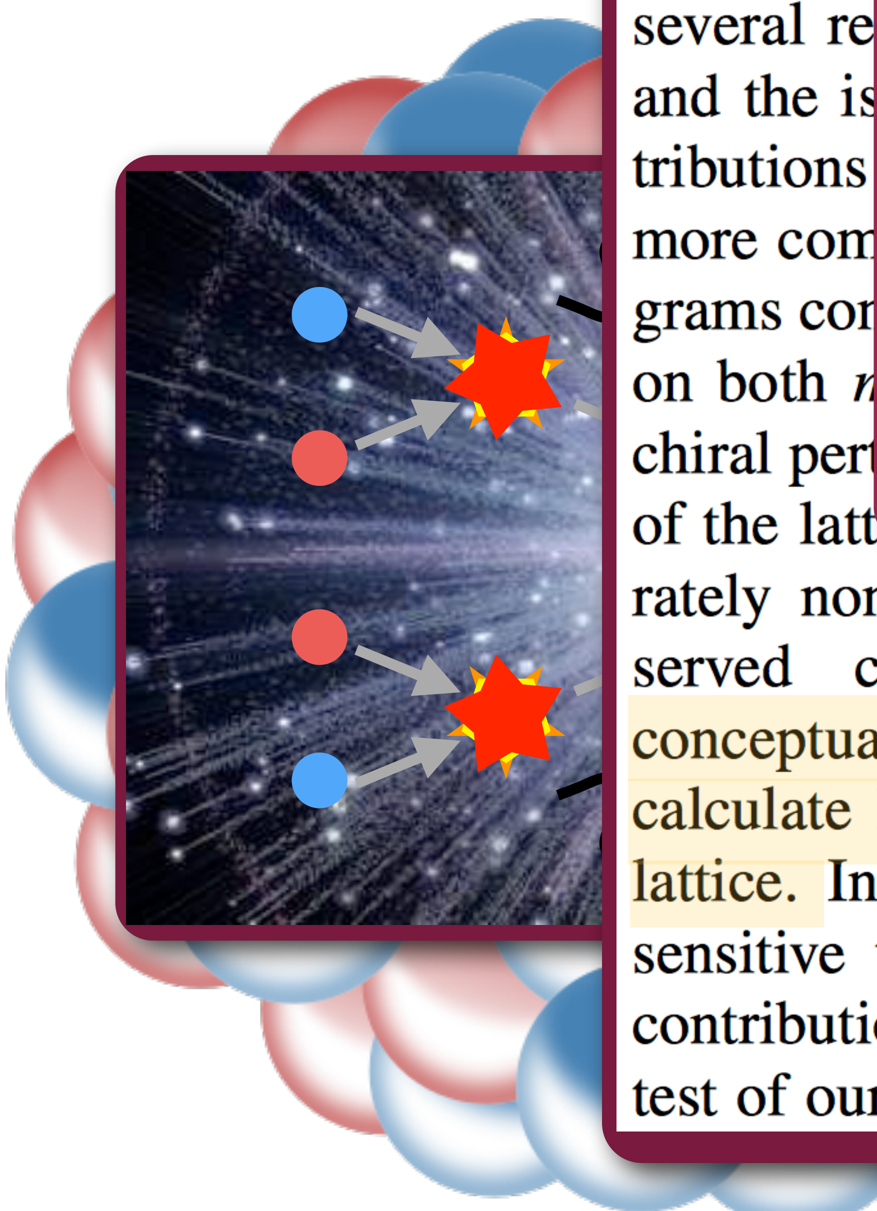
Phys. Rev. Lett. **96**, 052001 – Published 7 February 2006

The axial charge is the ideal starting point in the quest for precision lattice calculation of hadron structure for several reasons. It is accurately measured experimentally and the isovector combination $\langle 1 \rangle_{\Delta u} - \langle 1 \rangle_{\Delta d}$ has no contributions from disconnected diagrams, which are much more computationally demanding than the connected diagrams considered in this work. The functional dependence on both m_π^2 and volume is known at small masses from chiral perturbation theory (χPT) [5,6] and renormalization of the lattice axial vector current can be performed accurately nonperturbatively using the five-dimensional conserved current for domain wall fermions. Thus, conceptually, it is a "gold plated" test of our ability to calculate hadron observables from first principles on the lattice. In addition, since it is known to be particularly sensitive to finite lattice volume effects that reduce the contributions of the pion cloud [7,8], it is also a stringent test of our control of finite volume artifacts.





- Free neut… synthesis
- Nuclear …s
- Nuclear f…



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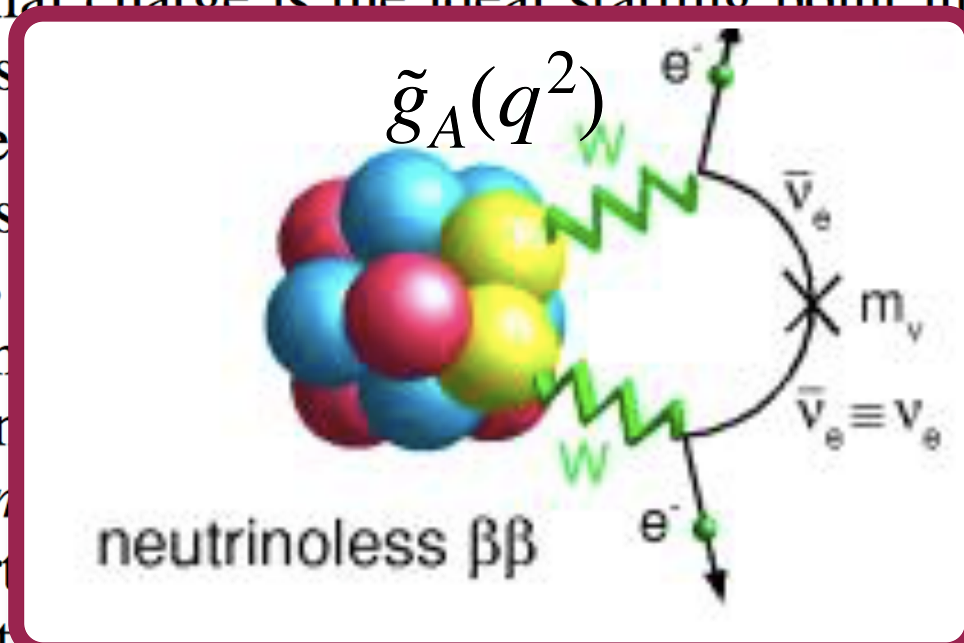
Access b…

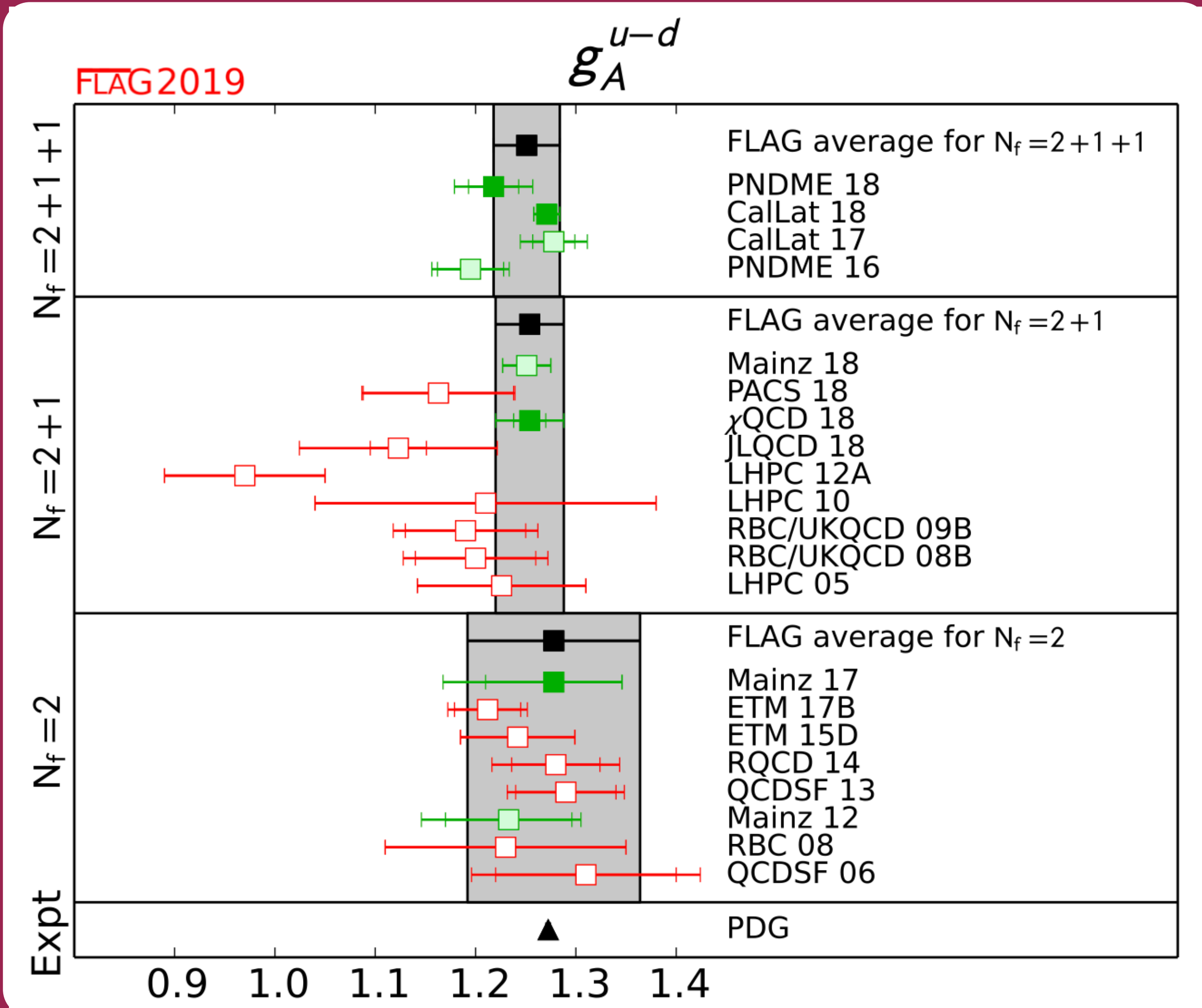
Nucleon Axial Charge in Full Lattice QCD

R. G. Edwards, G. T. Fleming, Ph. Hägler, J. W. Negele, K. Orginos, A. V. Pochinsky, D. B. Renner, D. G. Richards, and W. Schroers (LHPC Collaboration)

Phys. Rev. Lett. **96**, 052001 – Published 7 February 2006

The axial charge is the ideal starting point in the quest for precis… …ucture for several re… …imentally and the is… …s no contributions … …are much more com… …ected diagrams co… …pendence on both *n*… …sses from chiral pert… …nalization of the latt… …ned accurately nonperturbatively using the five-dimensional conserved current for domain wall fermions. Thus, conceptually, it is a “gold plated” test of our ability to calculate hadron observables from first principles on the lattice. In addition, since it is known to be particularly sensitive to finite lattice volume effects that reduce the contributions of the pion cloud [7,8], it is also a stringent test of our control of finite volume artifacts.



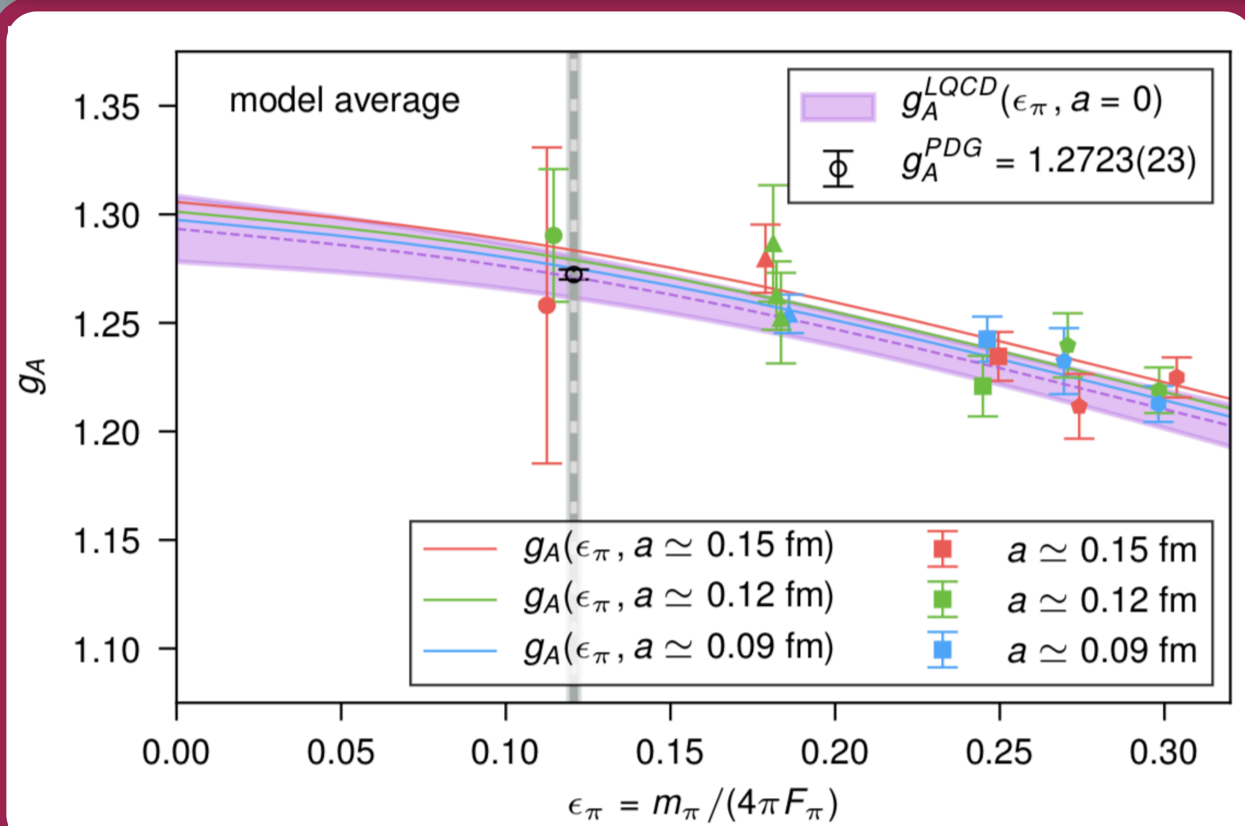


nature
International journal of science

Letter | Published: 30 May 2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

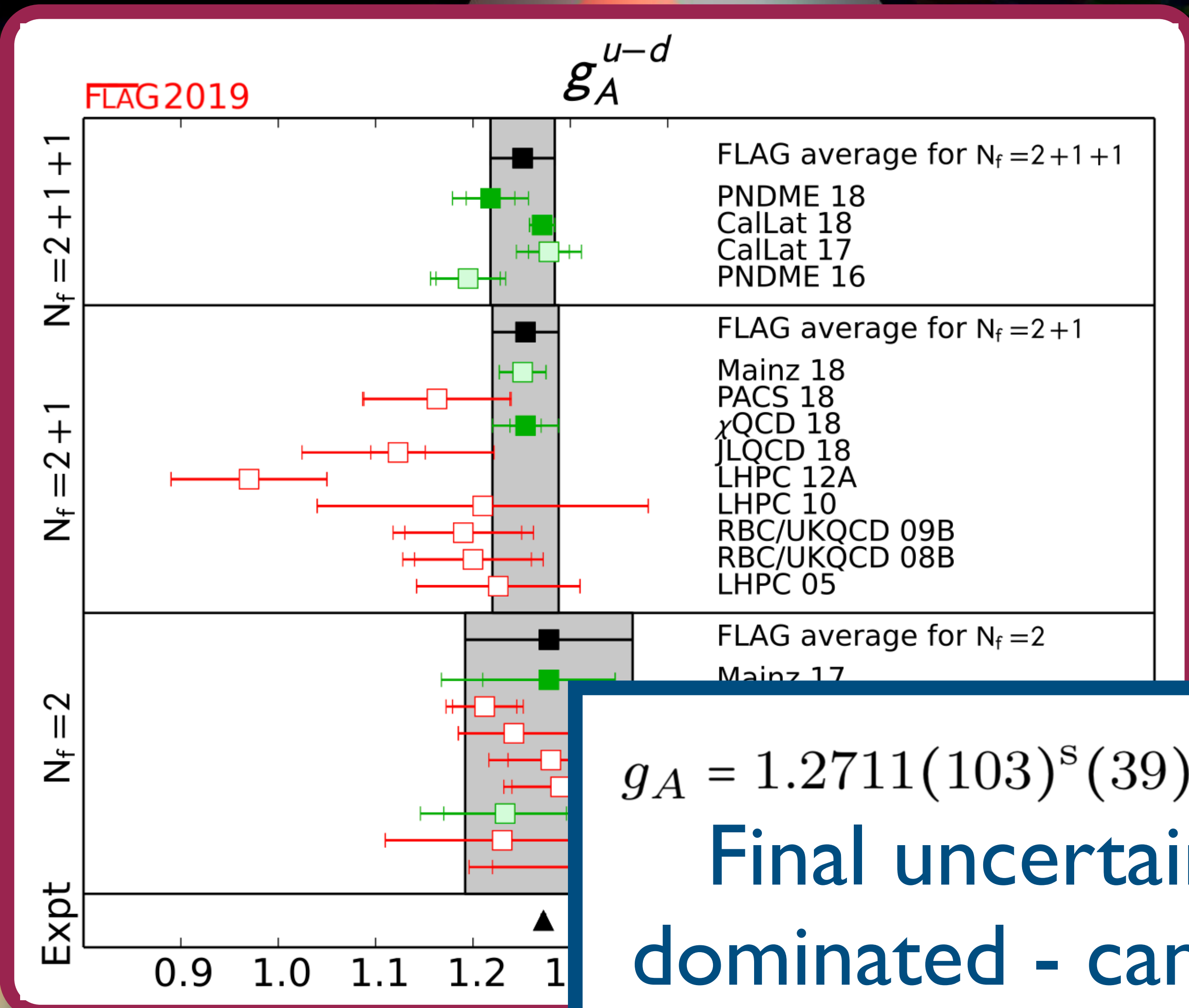


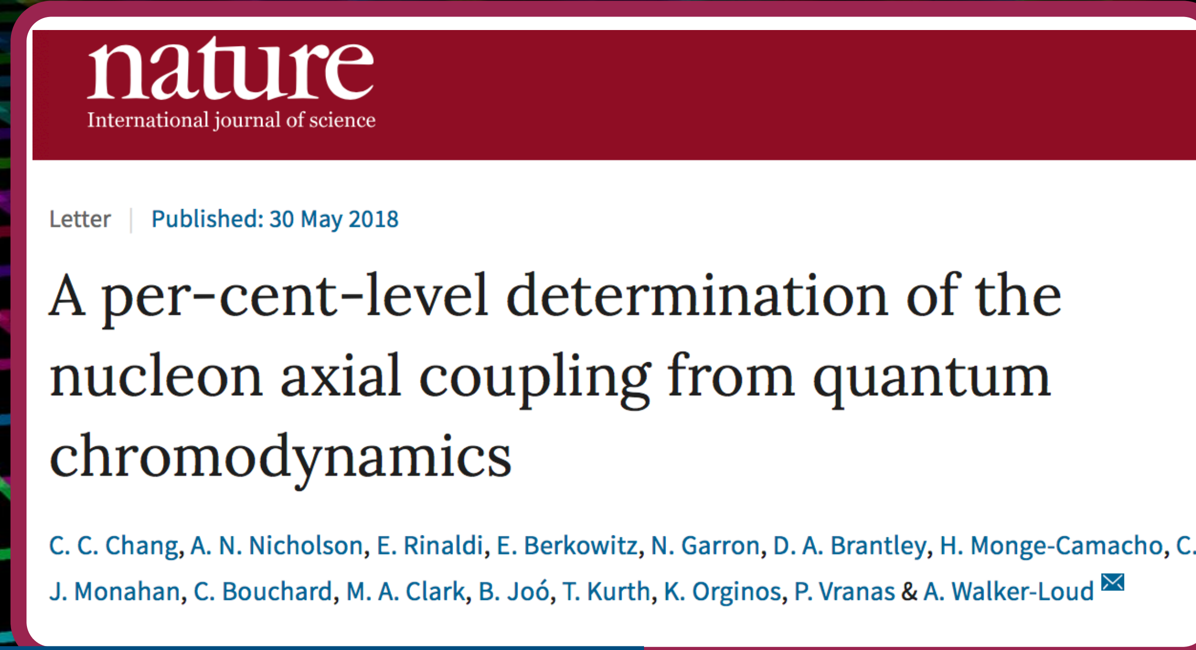
Simulating the *weak* death of the neutron in a femtoscale universe with near-Exascale computing

Evan Berkowitz*, M.A. Clark†, Arjun Gambhir‡§¶, Ken McElvain¶§, Amy Nicholson‖,
Enrico Rinaldi**§, Pavlos Vranas ‡§ André Walker-Loud §‡¶,
and Chia Cheng Chang§, Bálint Joó††, Thorsten Kurth‡‡§, Kostas Orginos×xi,

* Institut für Kernphysik and Institute for Advanced Simulation, Forschungszentrum Jülich, 54245 Jülich Germany
† NVIDIA Corporation, Santa Clara, California, 95051, USA
‡ Physical Sciences Directorate, Lawrence Livermore National Laboratory, Livermore, California 94550, USA
§ Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
¶ Department of Physics, University of California, Berkeley, CA 94720, USA
‖ Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27516-3255, USA
** RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA
†† Scientific Computing Group, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
‡‡ NERSC, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
× Department of Physics, The College of William & Mary, Williamsburg, VA 23187, USA
xi Theory Center, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

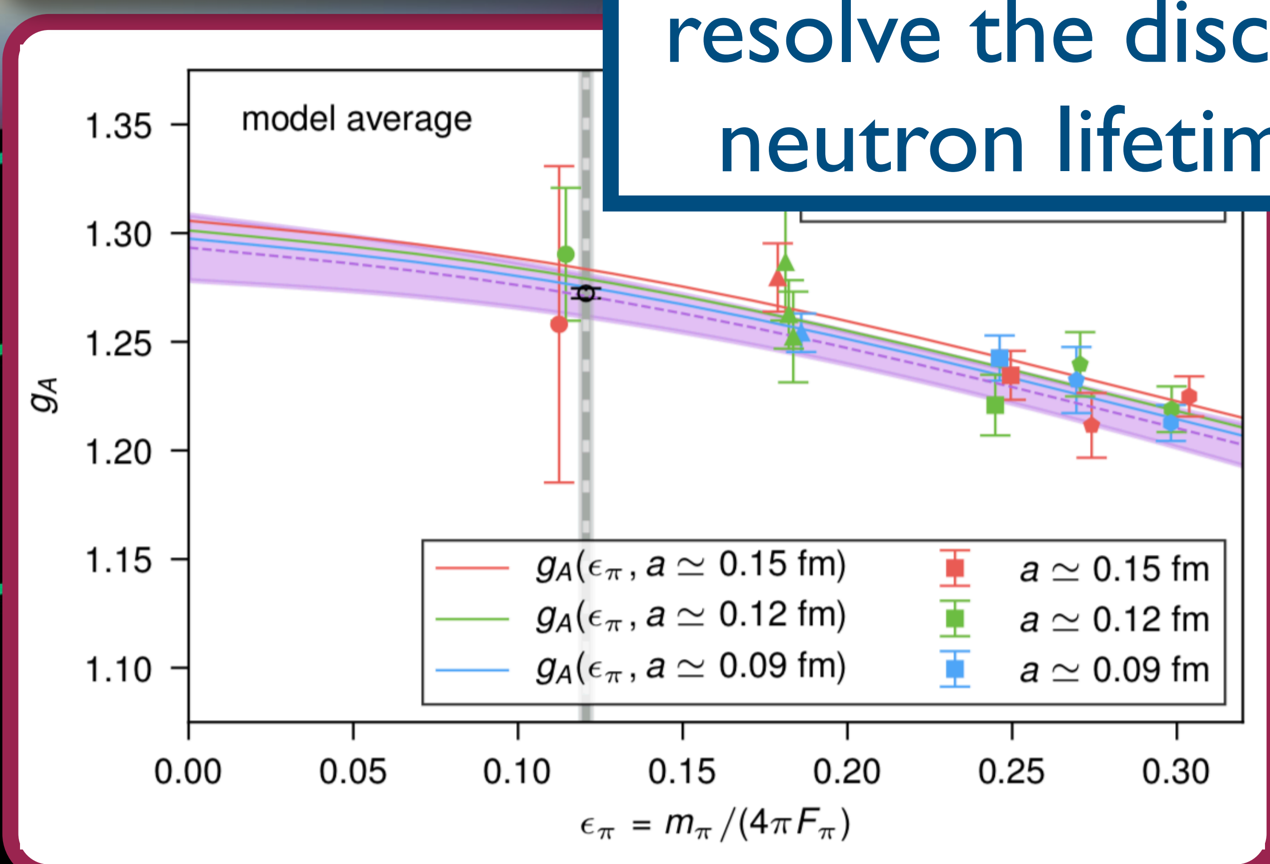
ACM AWARDS
Gordon Bell Prize
Finalist
SC18
Dallas, TX | hpc inspires.





$$g_A = 1.2711(103)^{s}(39)^{\chi}(15)^{a}(19)^{v}(04)^{I}(55)^{M}$$

Final uncertainty is statistics dominated - can we push this to resolve the discrepancy between neutron lifetime experiments?



New physics? Neutron lifetime puzzle

New physics? Neutron lifetime puzzle

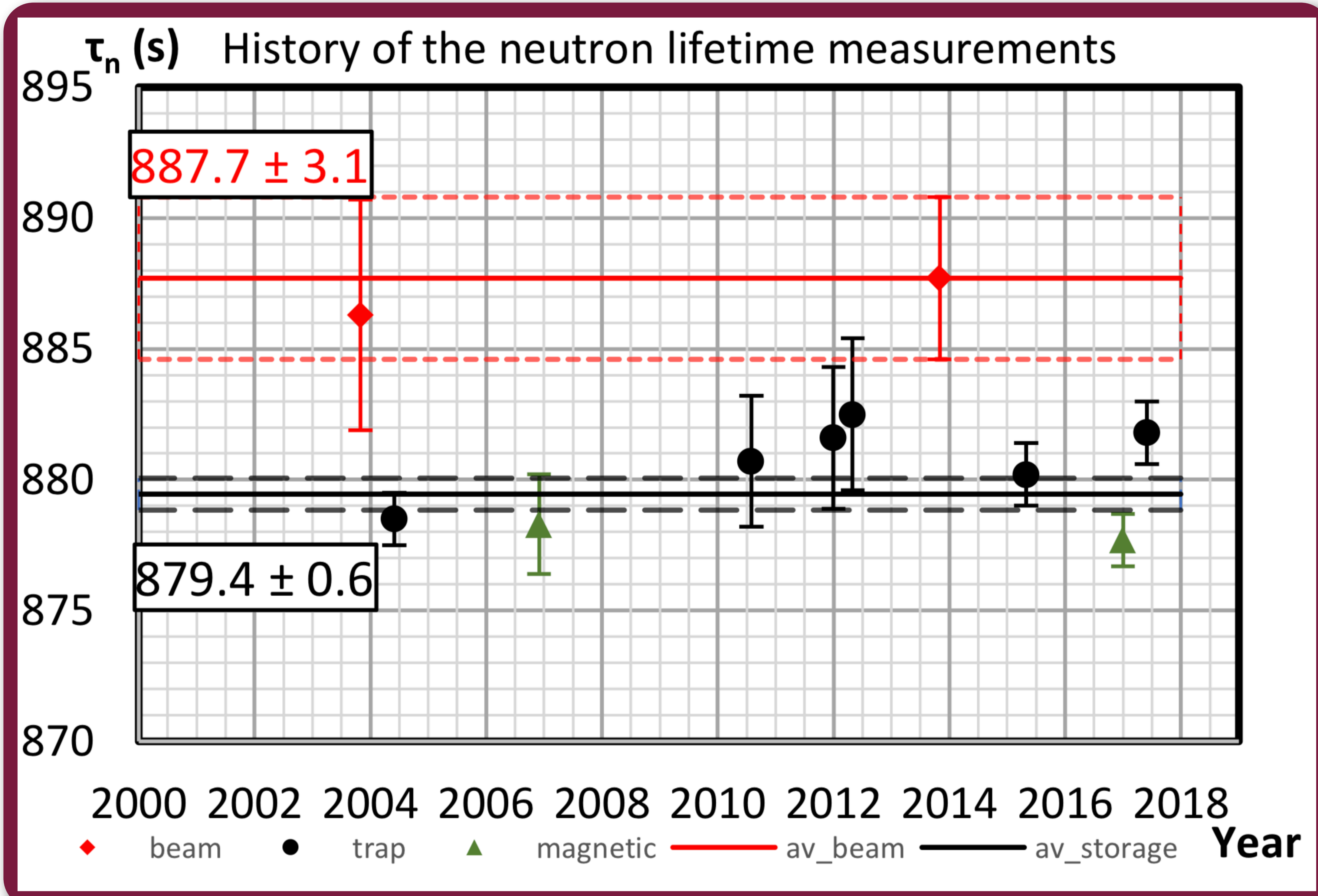
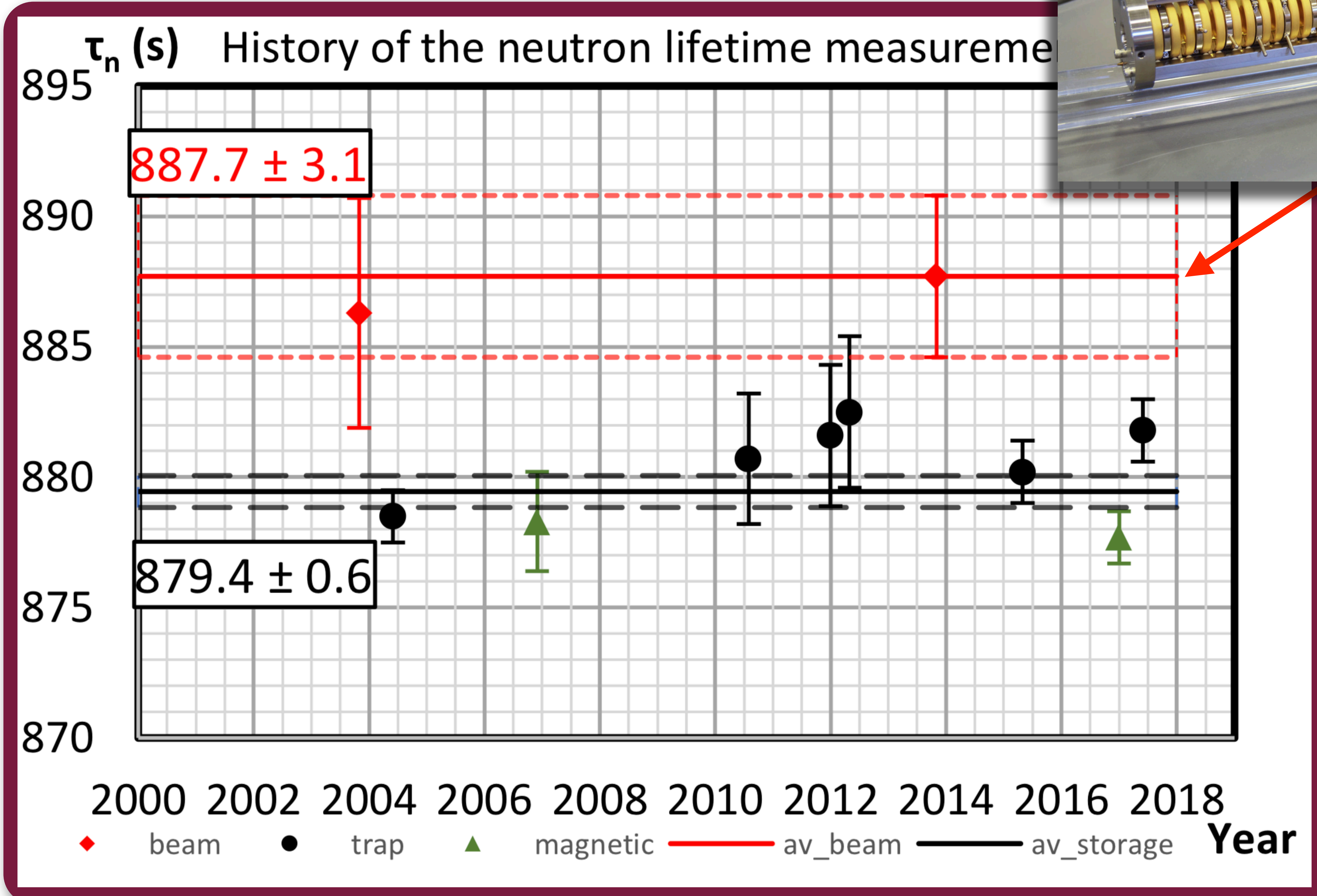
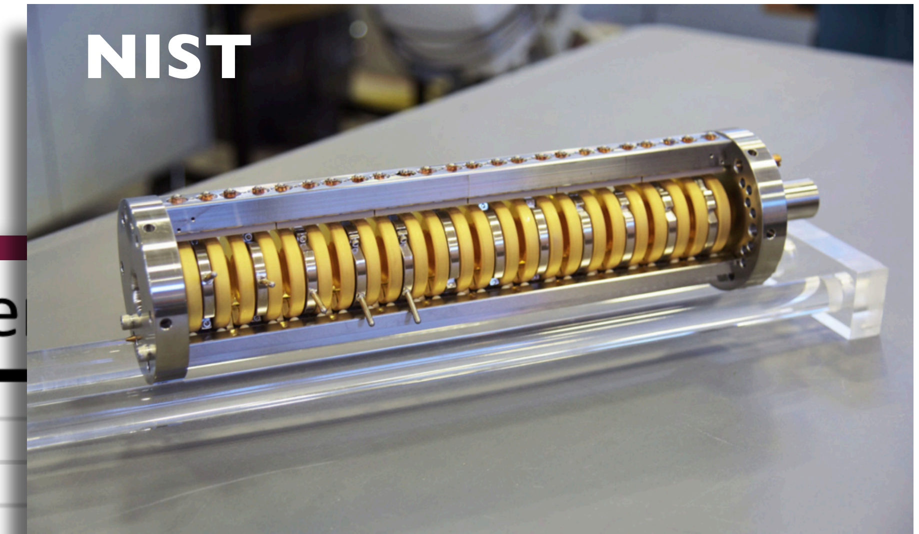


Figure: A. P. Serebrov, E .A. Kolomensky, A. K. Fomin, I. A. Krasnoschekova, A. V. Vassiljev, D. M. Prudnikov, I. V. Shoka, A. V. Chechkin, M. E. Chaikovskiy, V. E. Varlamov, S. N. Ivanov, A. N. Pirozhkov, P. Geltenbort, O. Zimmer, T. Jenke, M. Van der Grinten, M. Tucker, arXiv:1712.05663

New physics? Neutron lifetime puzzle





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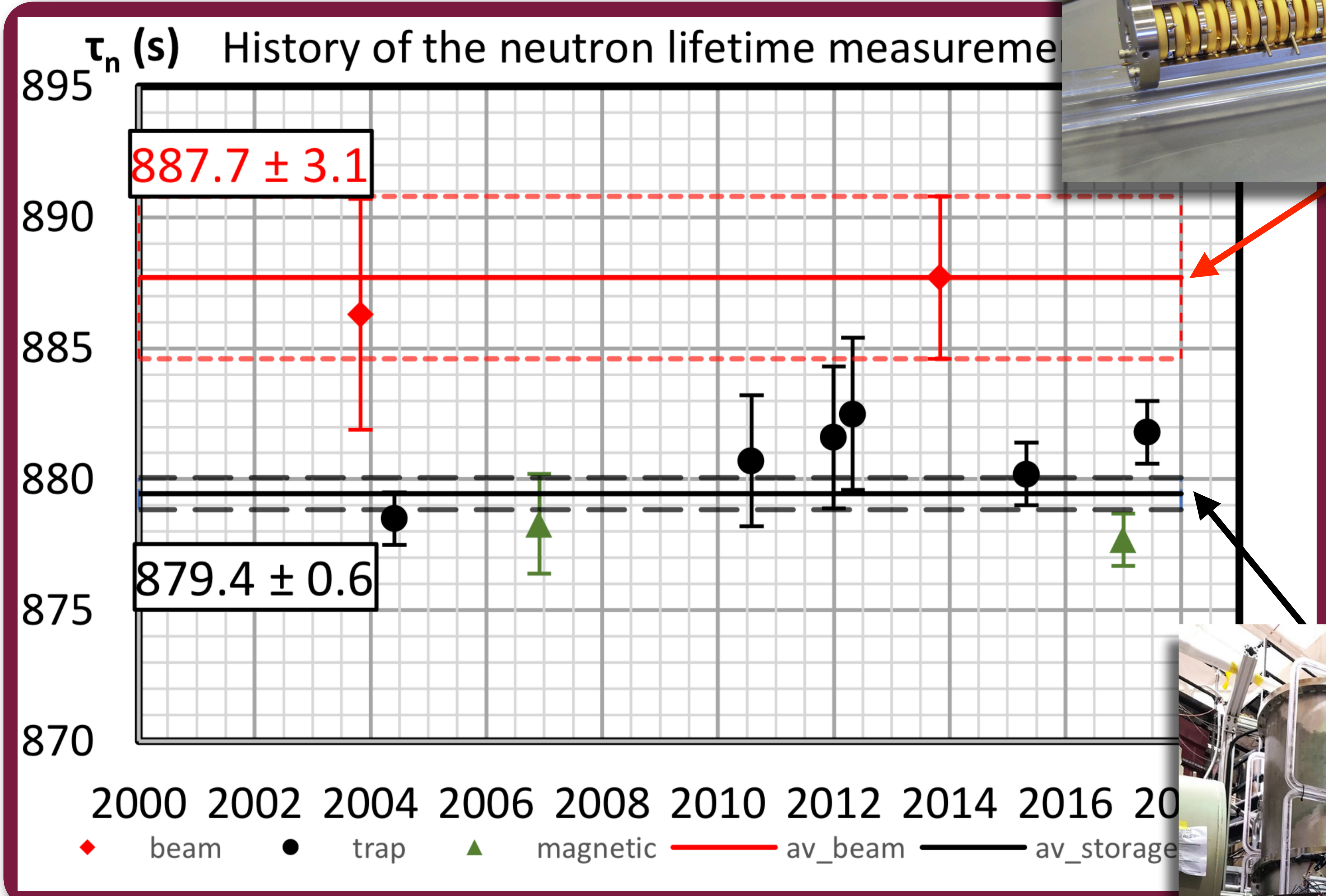


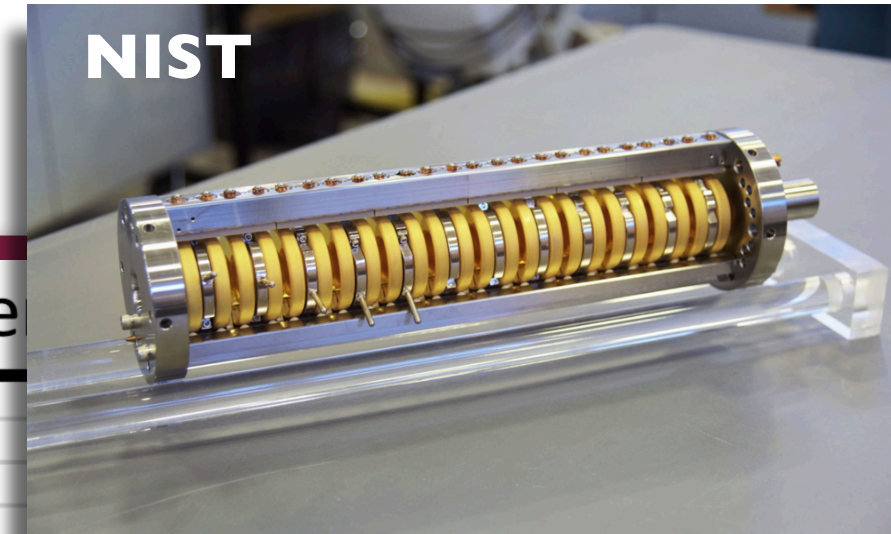
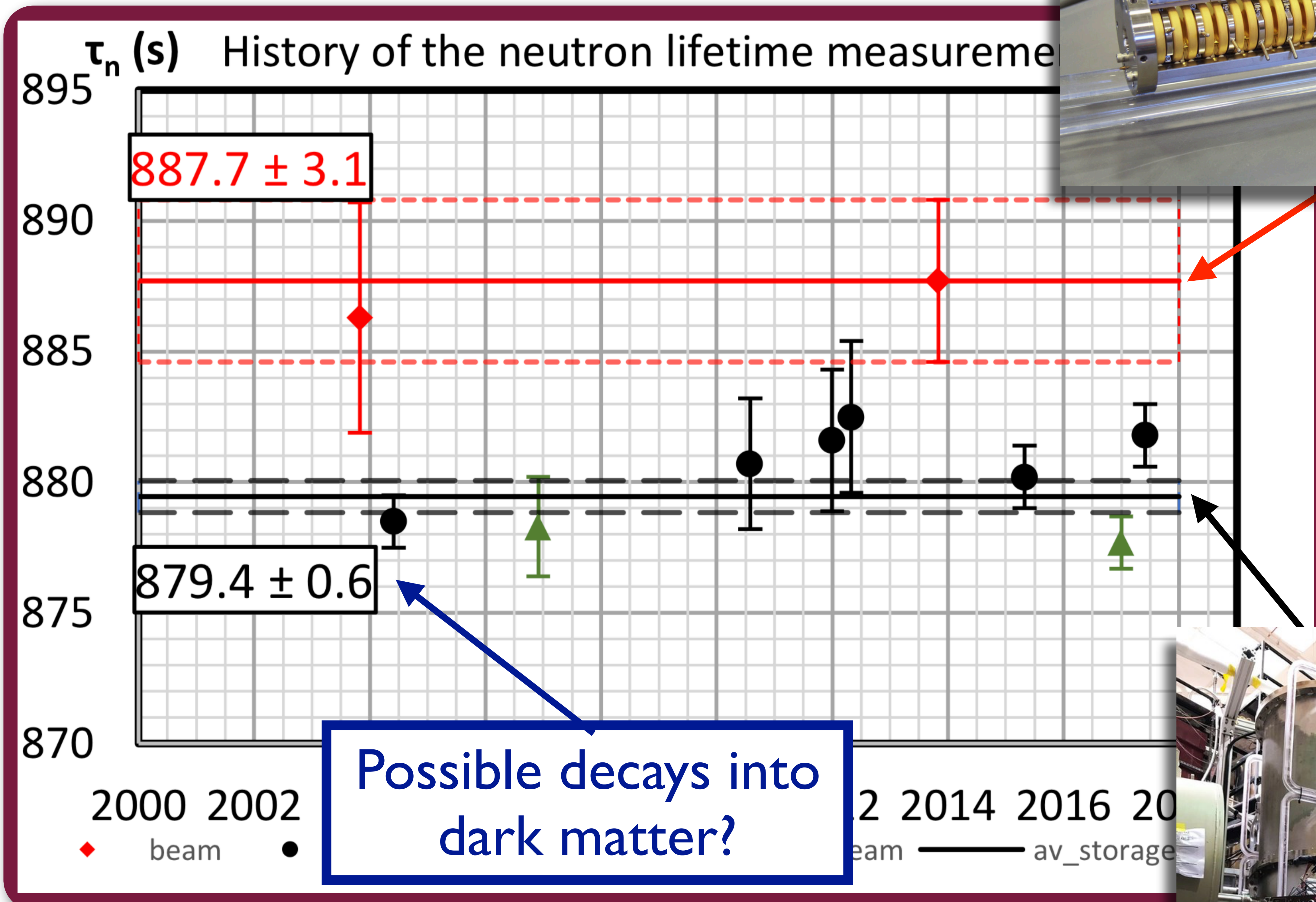
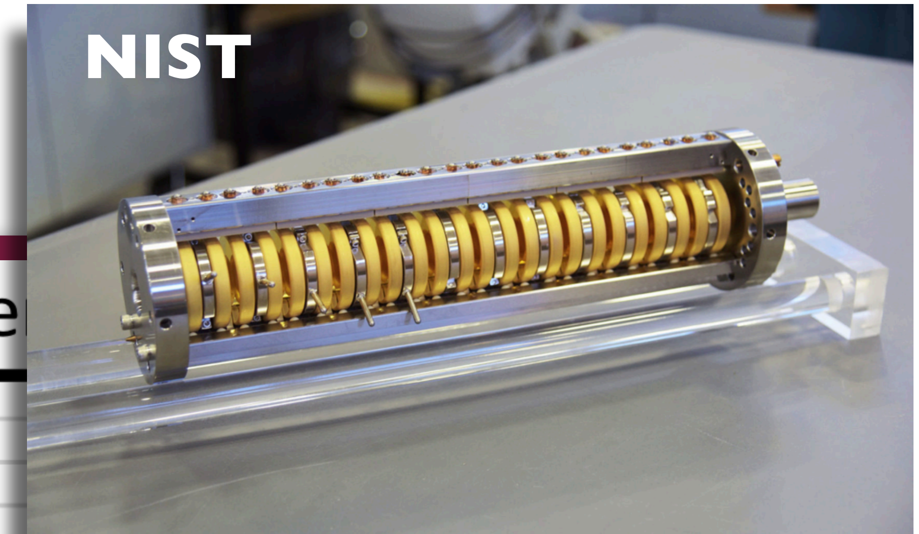
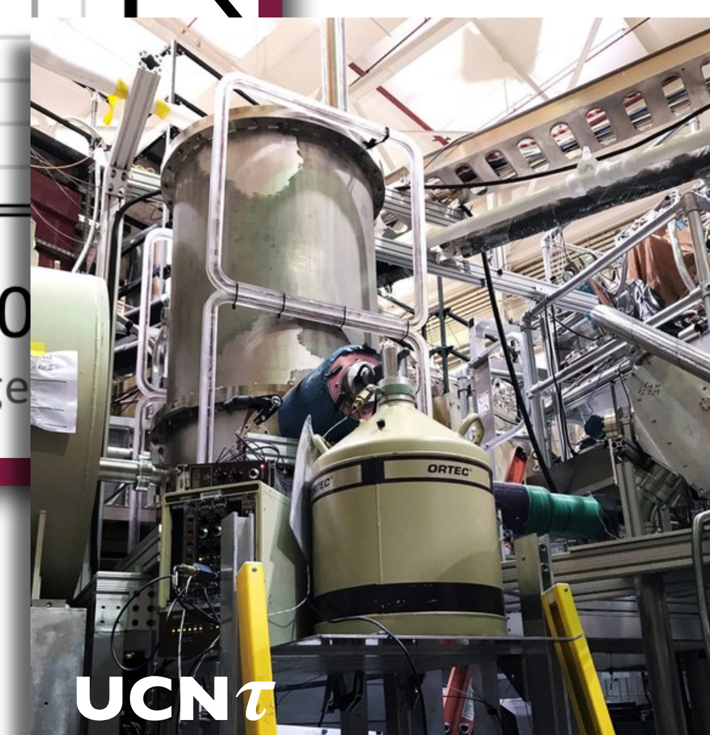


Figure: A. P. Serebrov, E .A. Kolomensky, A. K. Fomin, I. A. Krasnoschekova, A. V. Vassiljev, D. M. Prudnikov, I. V. Shoka, A. V. Chechkin, M. E. Chaikovskiy, V. E. Varlamov, S. N. Ivanov, A. N. Pirozhkov, P. Geltenbort, O. Zimmer, T. Jenke, M. Van der Grinten, M. Tucker, arXiv:1712.05663

New physics? Neutron lifetime puzzle







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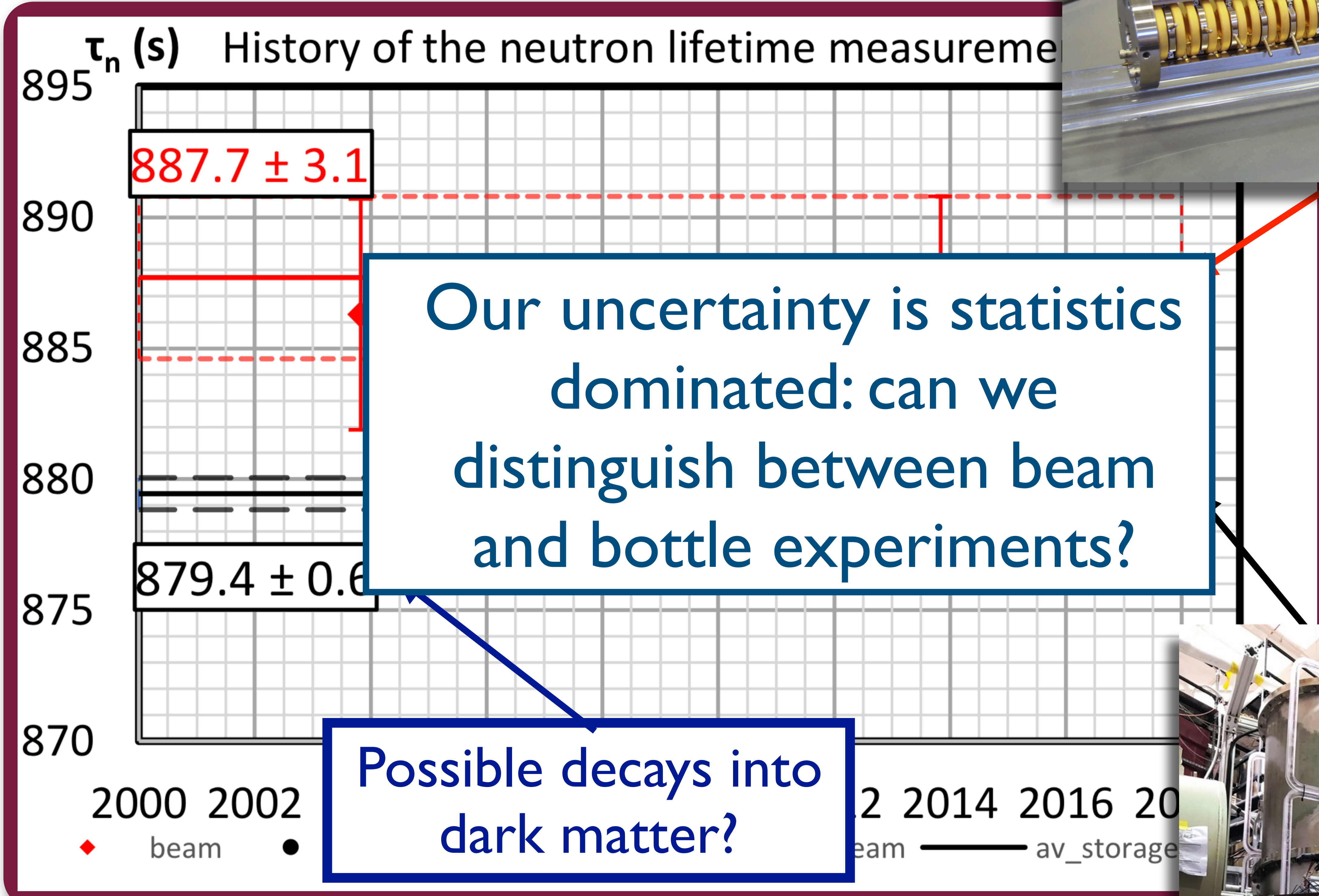
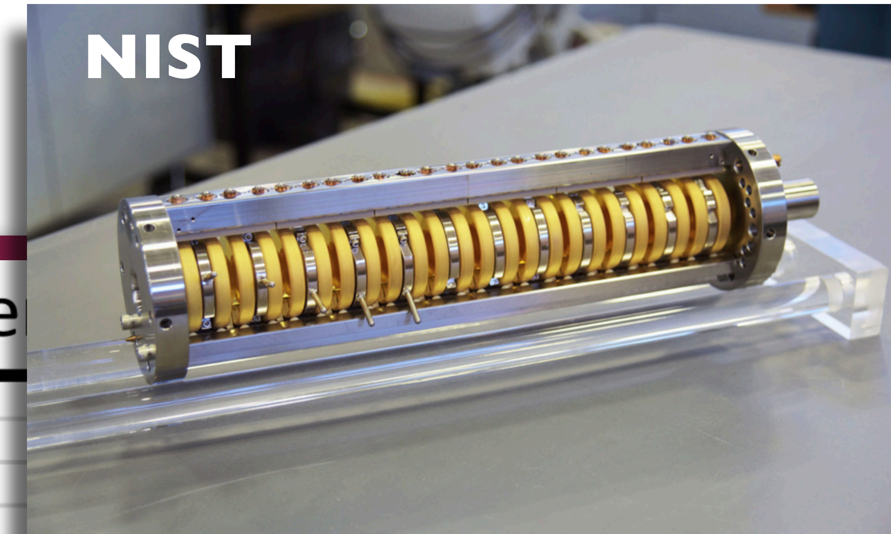
New physics? Neutron lifetime puzzle



Our uncertainty is statistics dominated: can we distinguish between beam and bottle experiments?

Possible decays into dark matter?



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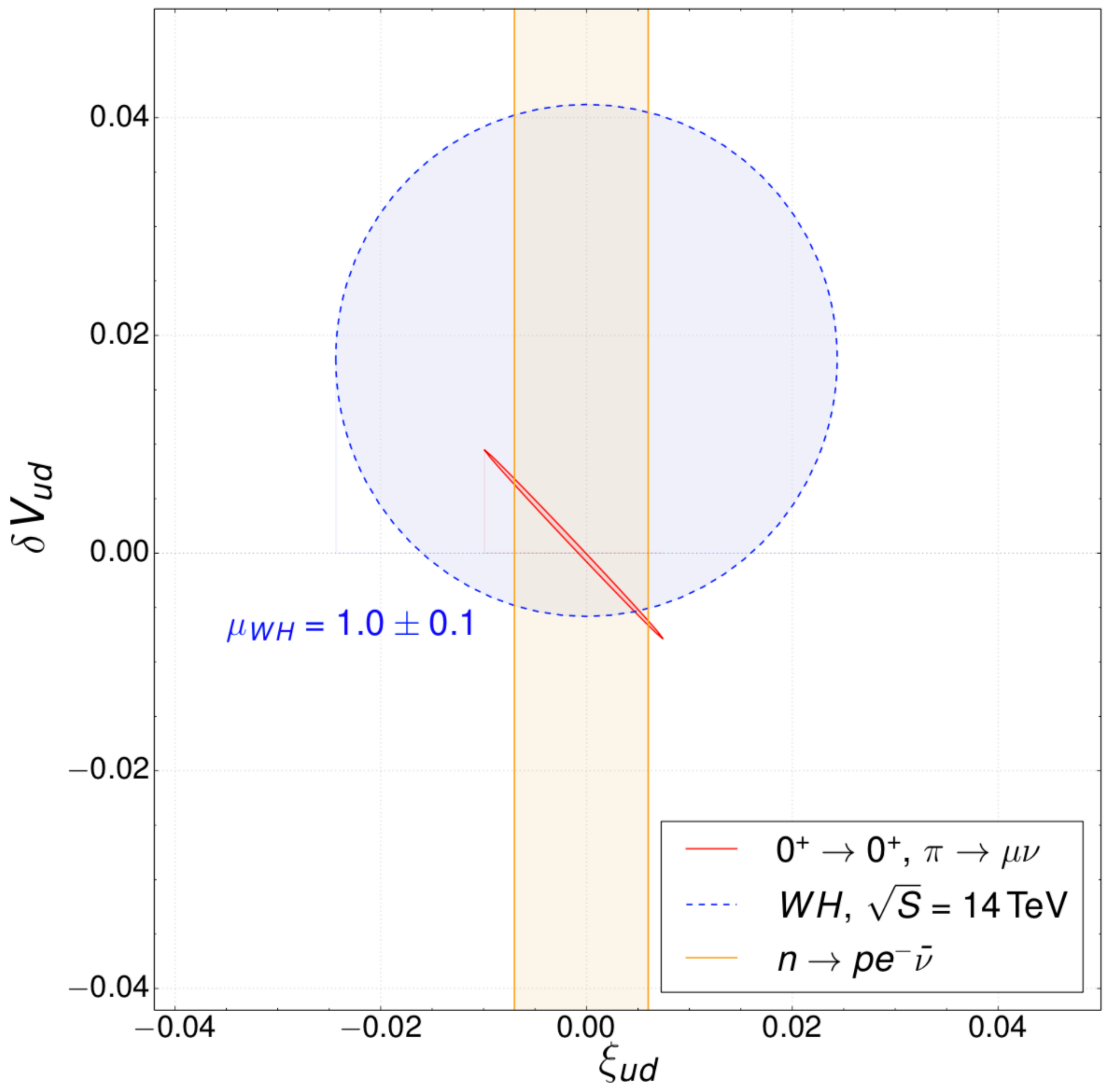
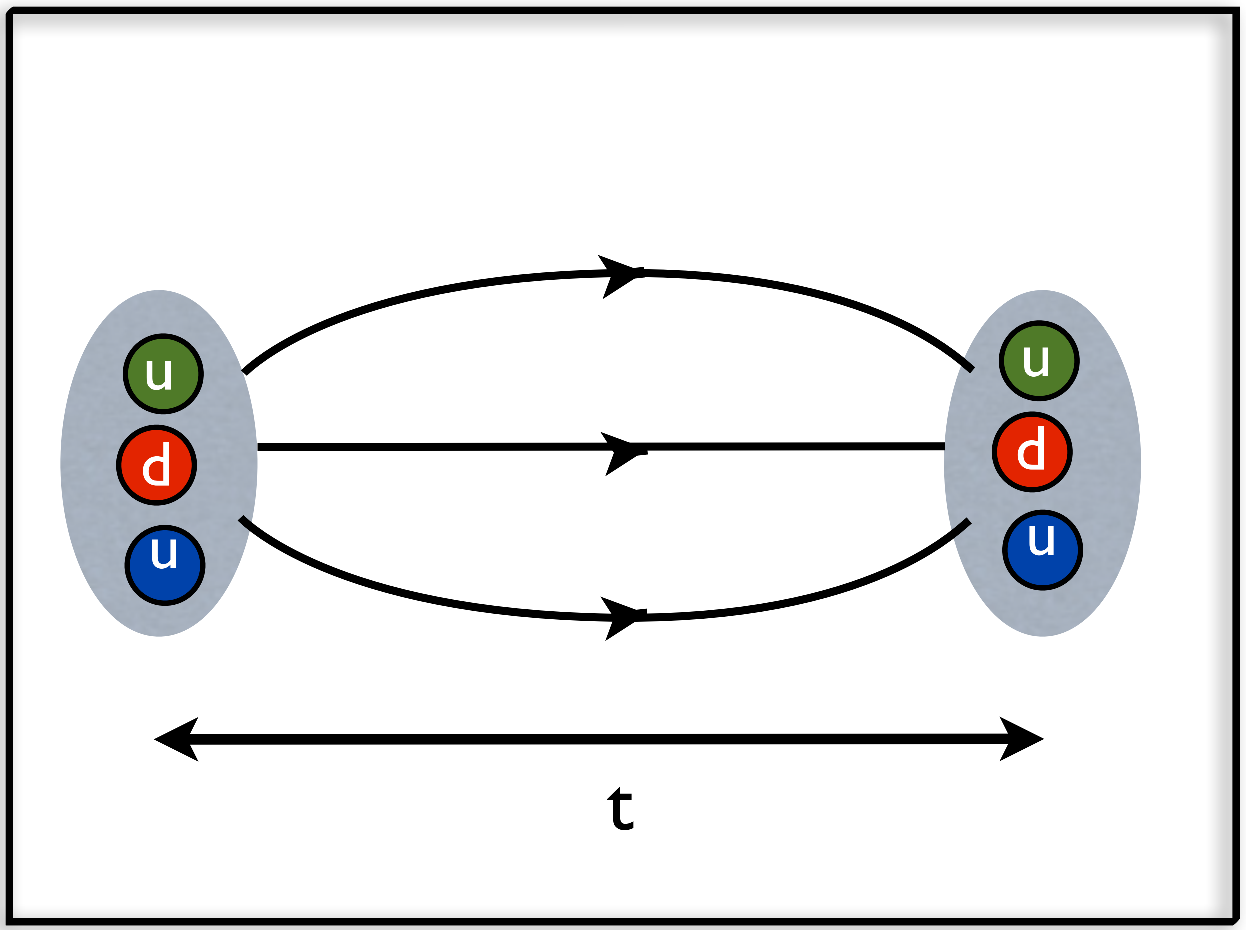


Can already place stronger constraints on right-handed BSM currents than collider experiments

Alioli, S., Cirigliano, V., Dekens, W., de Vries, J., and Mereghetti, E. JHEP 05, 086 (2017)

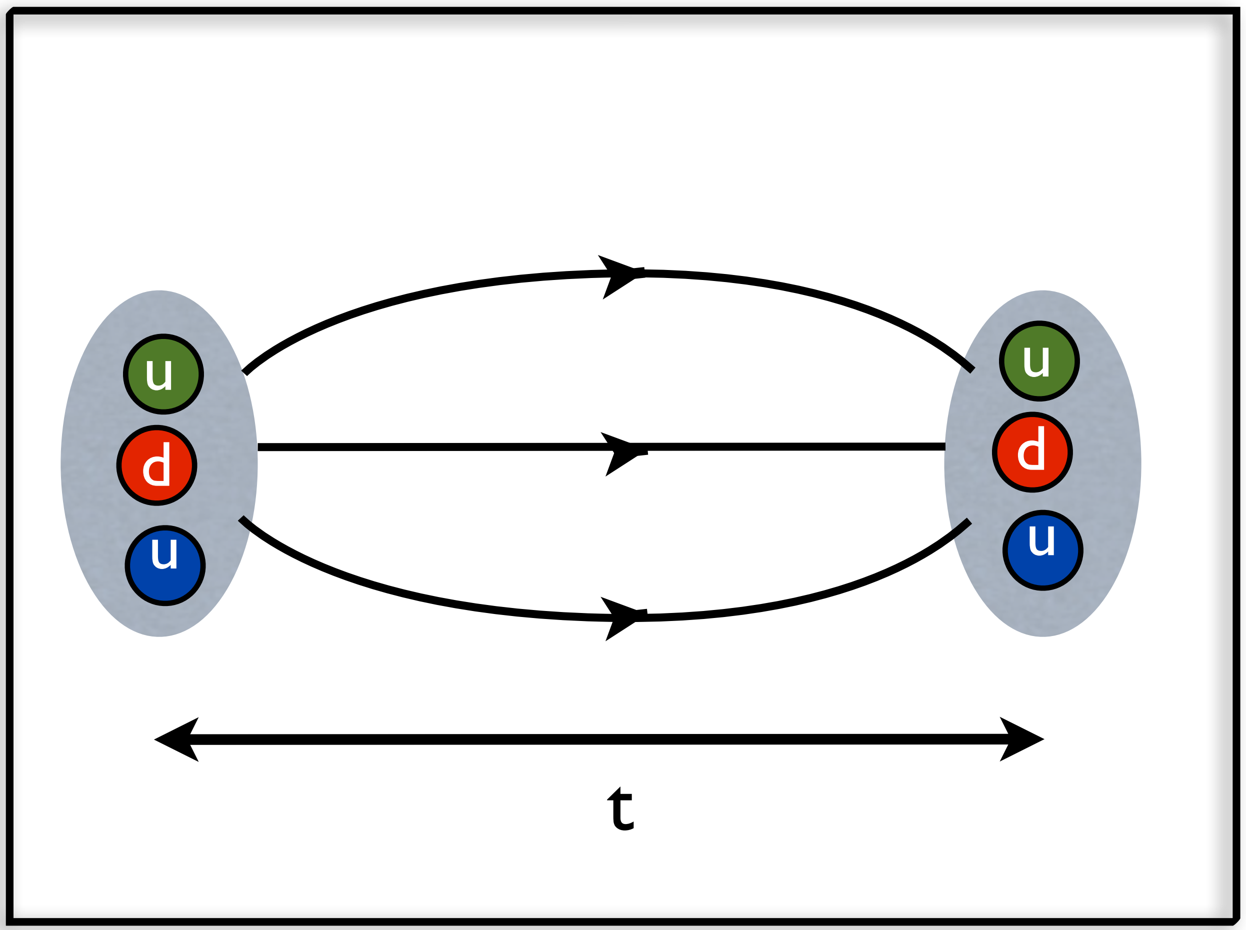
Matrix Elements

2-point function

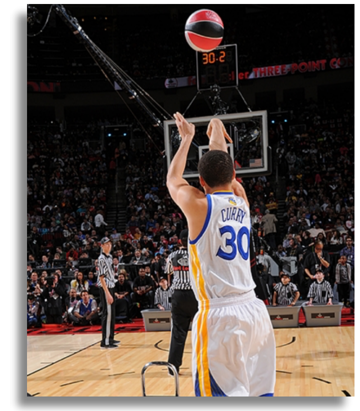


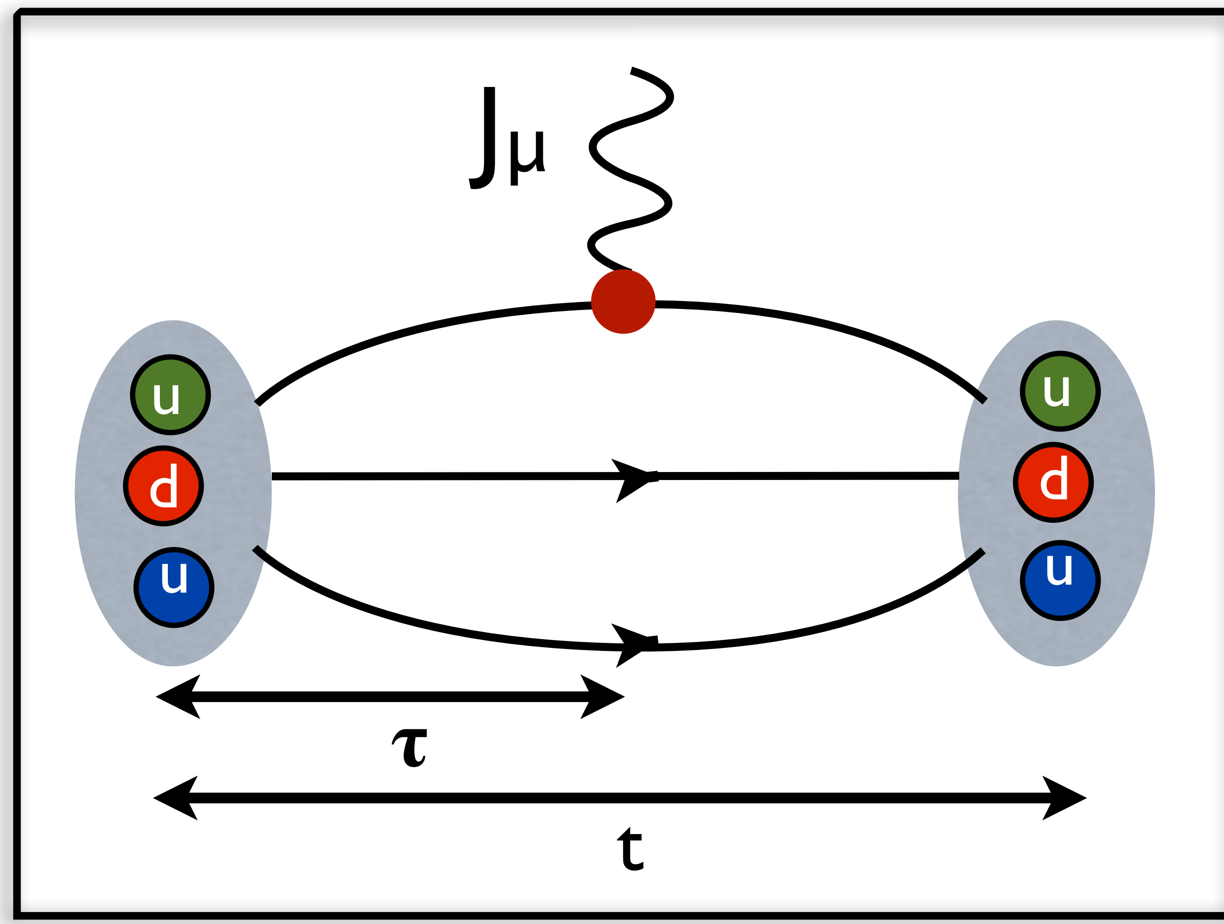
Matrix Elements

2-point function



3-point function

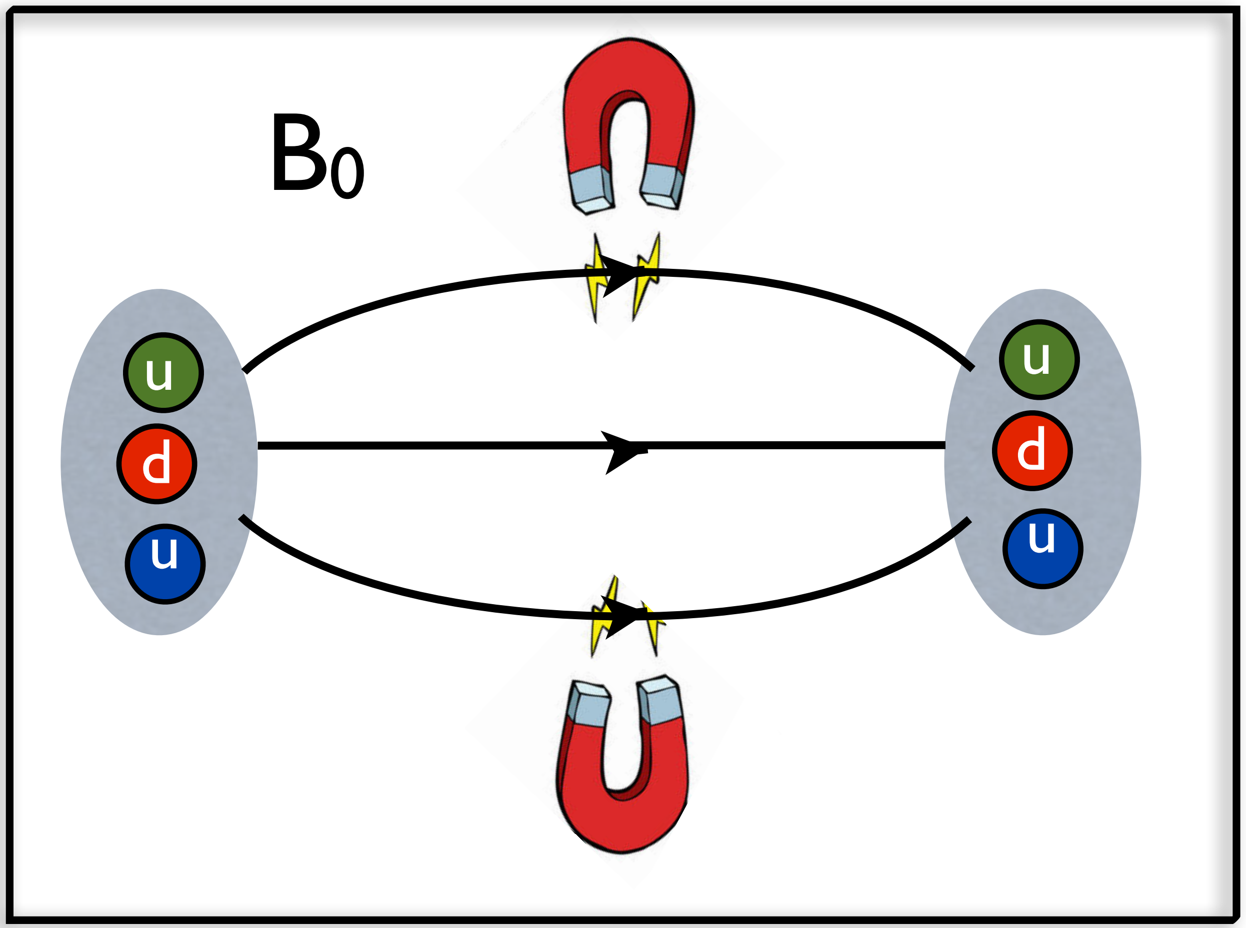


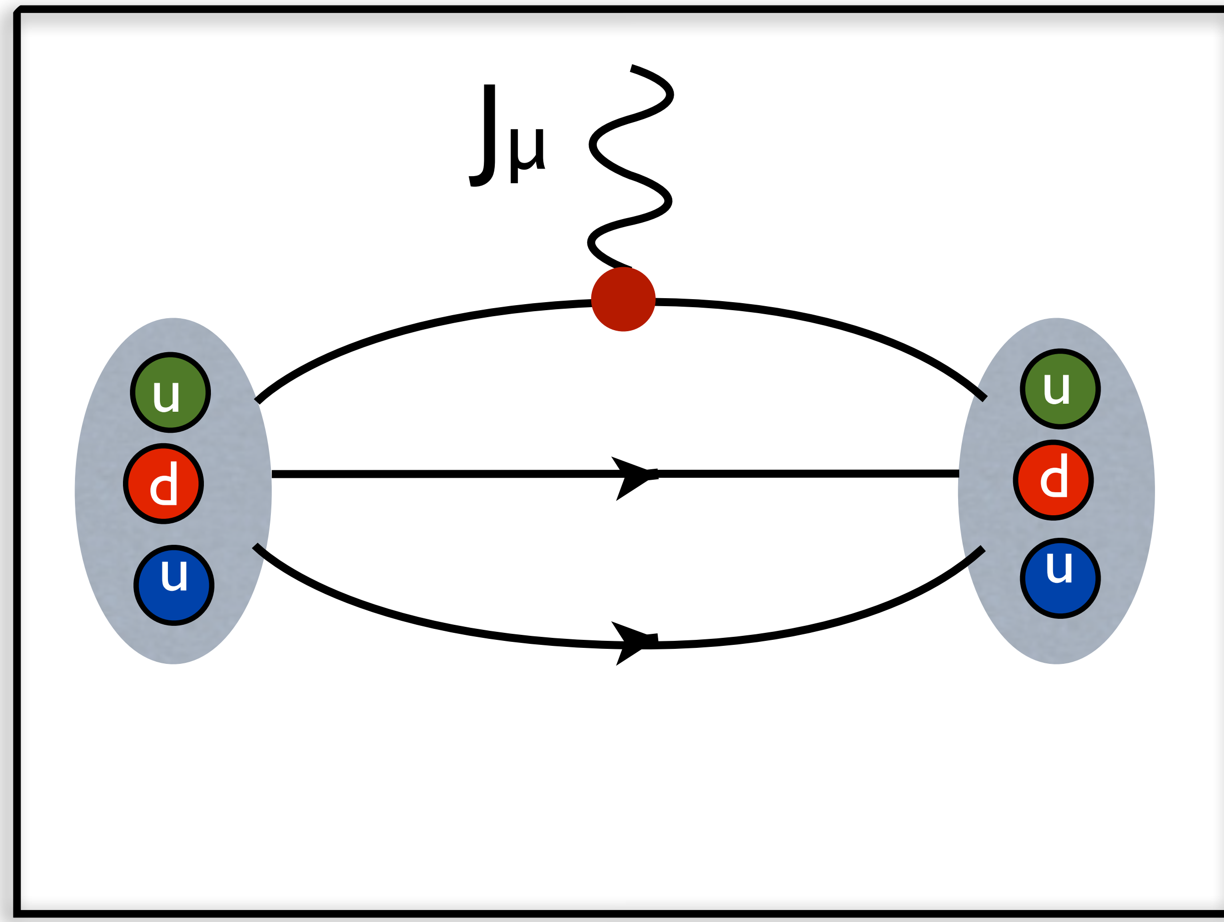


Matrix Elements

Background field

3-point function





FH Theorem: $H = H_0 + \lambda J$

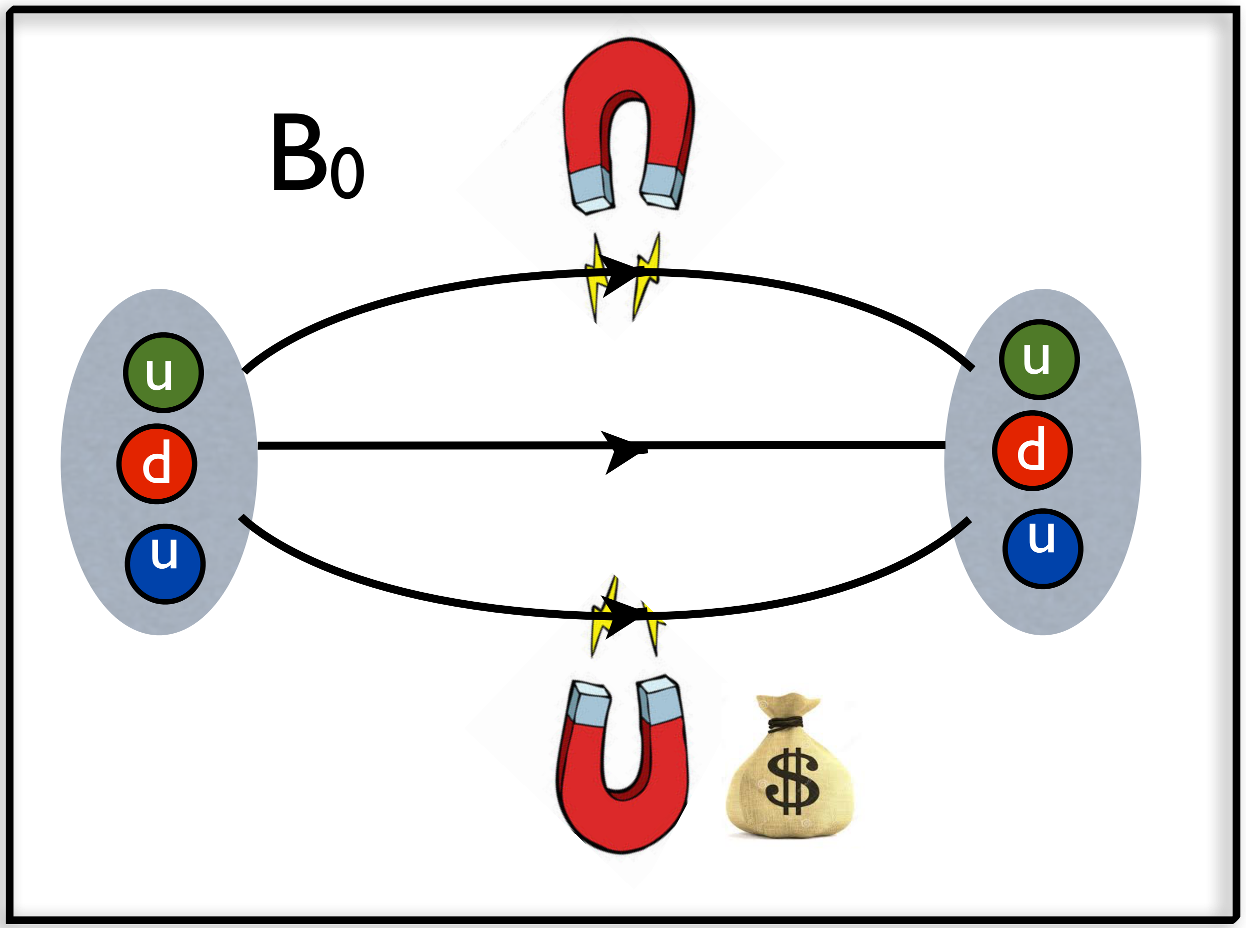
$$\frac{dE}{d\lambda} = \langle \psi | J | \psi \rangle$$

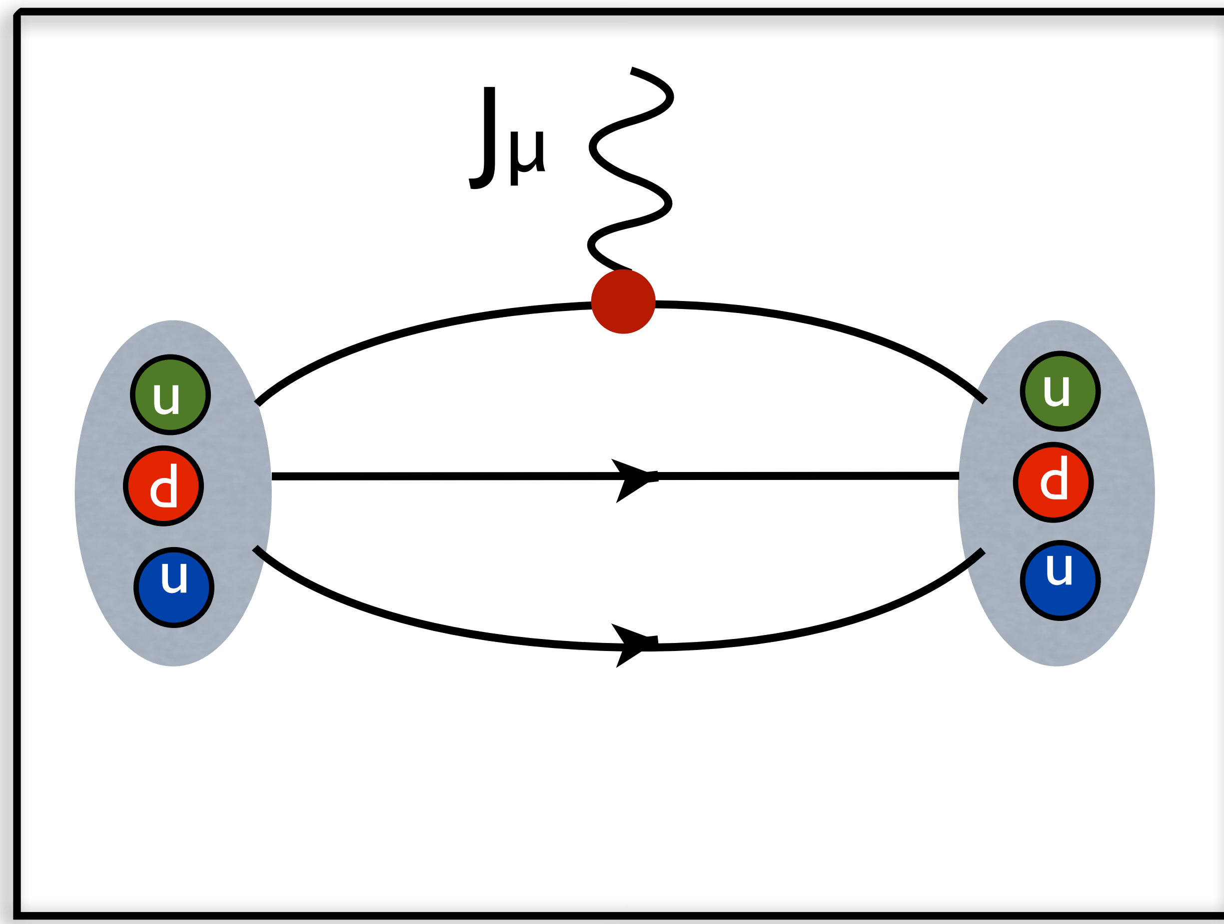
FH turns a 3-pt calc into a 2-pt calc

Matrix Elements

Background field

3-point function





FH Theorem: $H = H_0 + \lambda J$

$$\frac{dE}{d\lambda} = \langle \psi | J | \psi \rangle$$

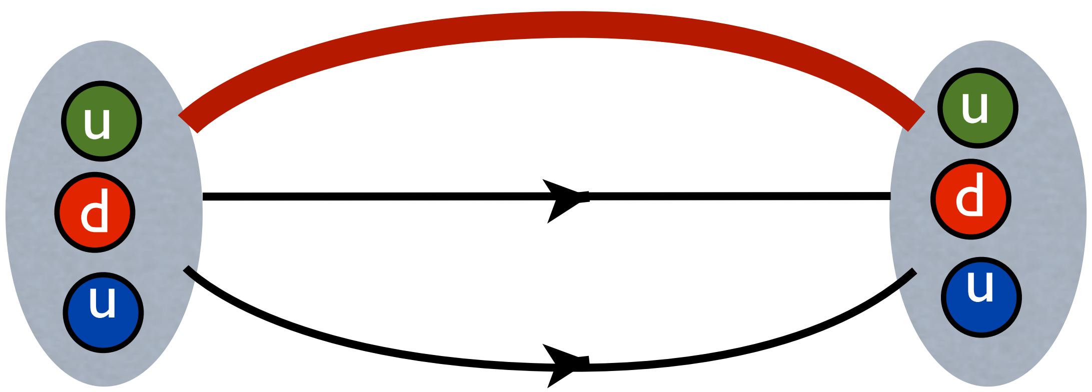
Must calculate field configurations at several λ to extract linear response

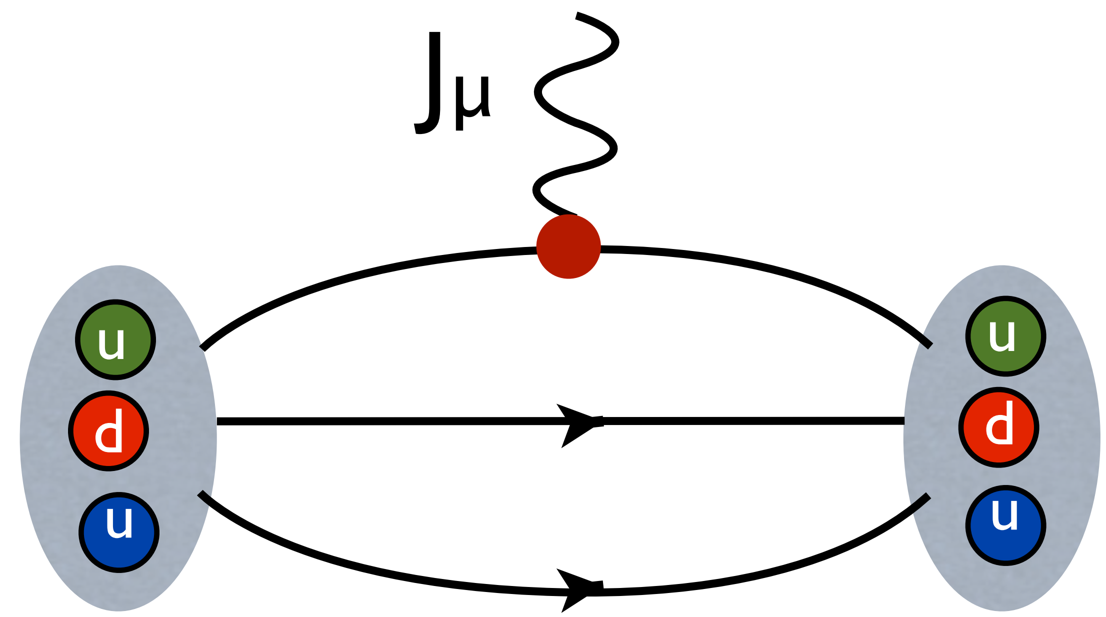
Matrix Elements

Feynman-Hellmann

3-point function

Chris Bouchard, Chia Cheng Chang, Thorsten Kurth, Kostas Orginos, Andre Walker-Loud arXiv:1612.06963
similar techniques used in:
A.J. Chambers et al. (2014,2015), M.J. Savage et al. (2016)





FH Theorem: $H = H_0 + \lambda J$

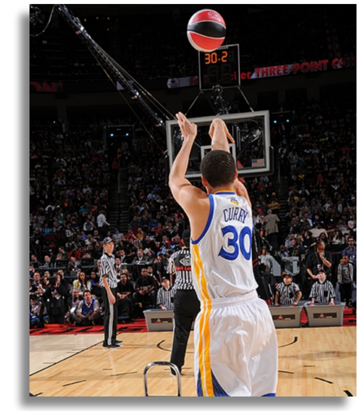
$$\frac{dE}{d\lambda} = \langle\psi|J|\psi\rangle$$

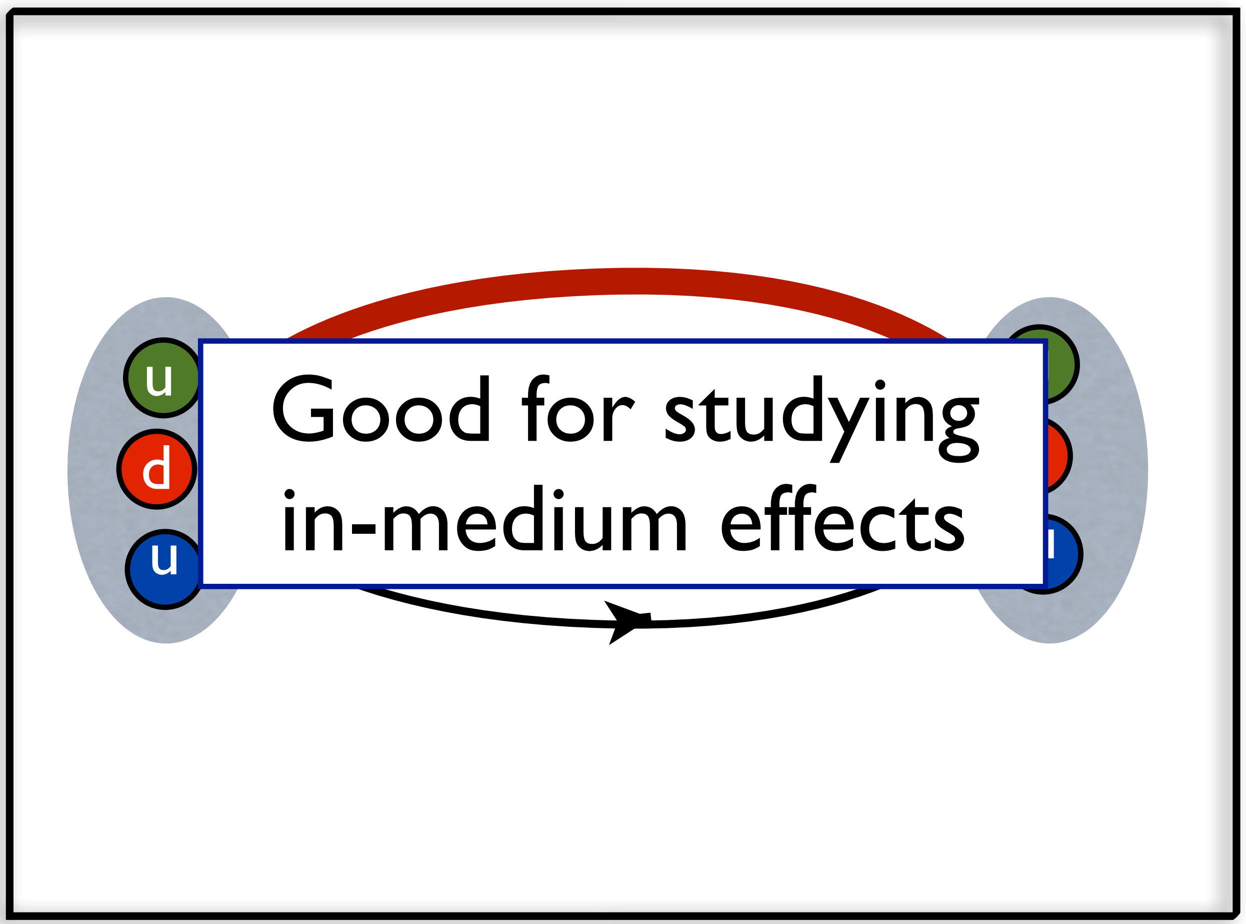
Get all time separations with a single calculation - found benefit in using earlier times where signal is more precise

Matrix Elements

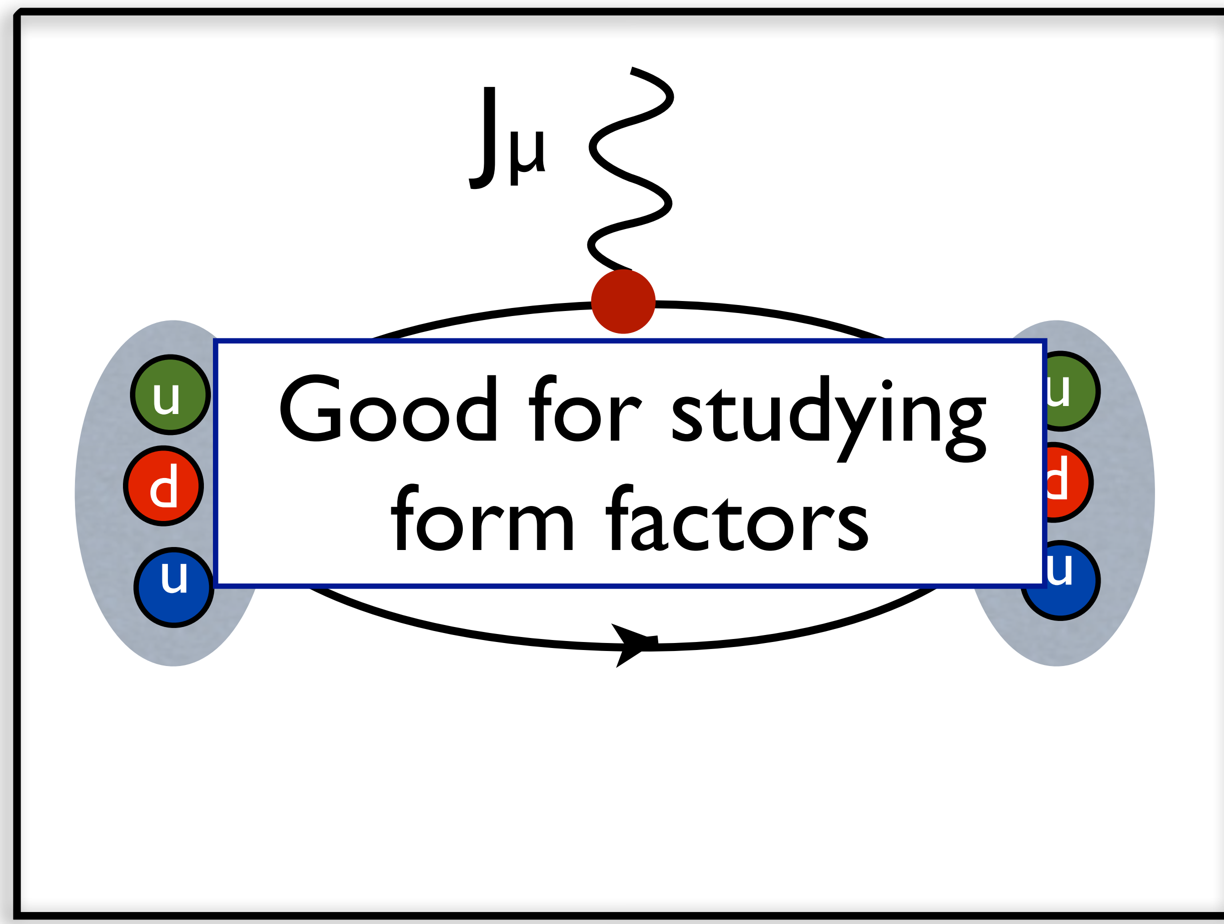
Feynman-Hellmann

3-point function





Good for studying in-medium effects



Good for studying form factors

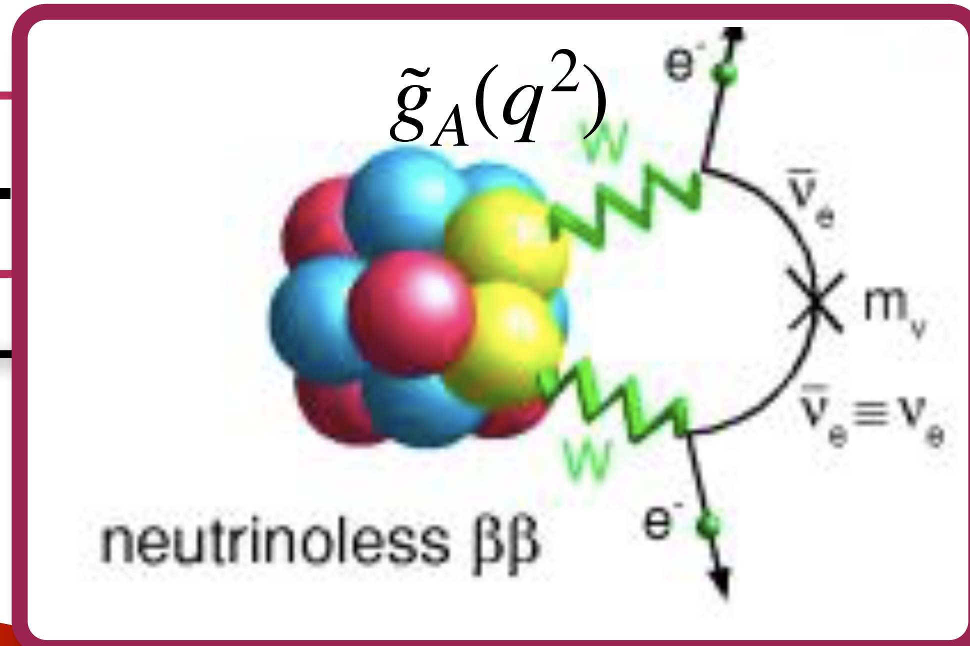
FH Theorem: $H = H_0 + \lambda J$

$$\frac{dE}{d\lambda} = \langle \psi | J | \psi \rangle$$

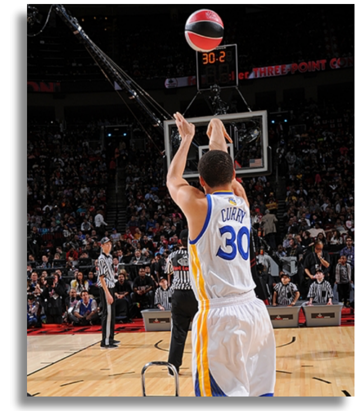
Get all time separations with a single calculation - found benefit in using earlier times where signal is more precise

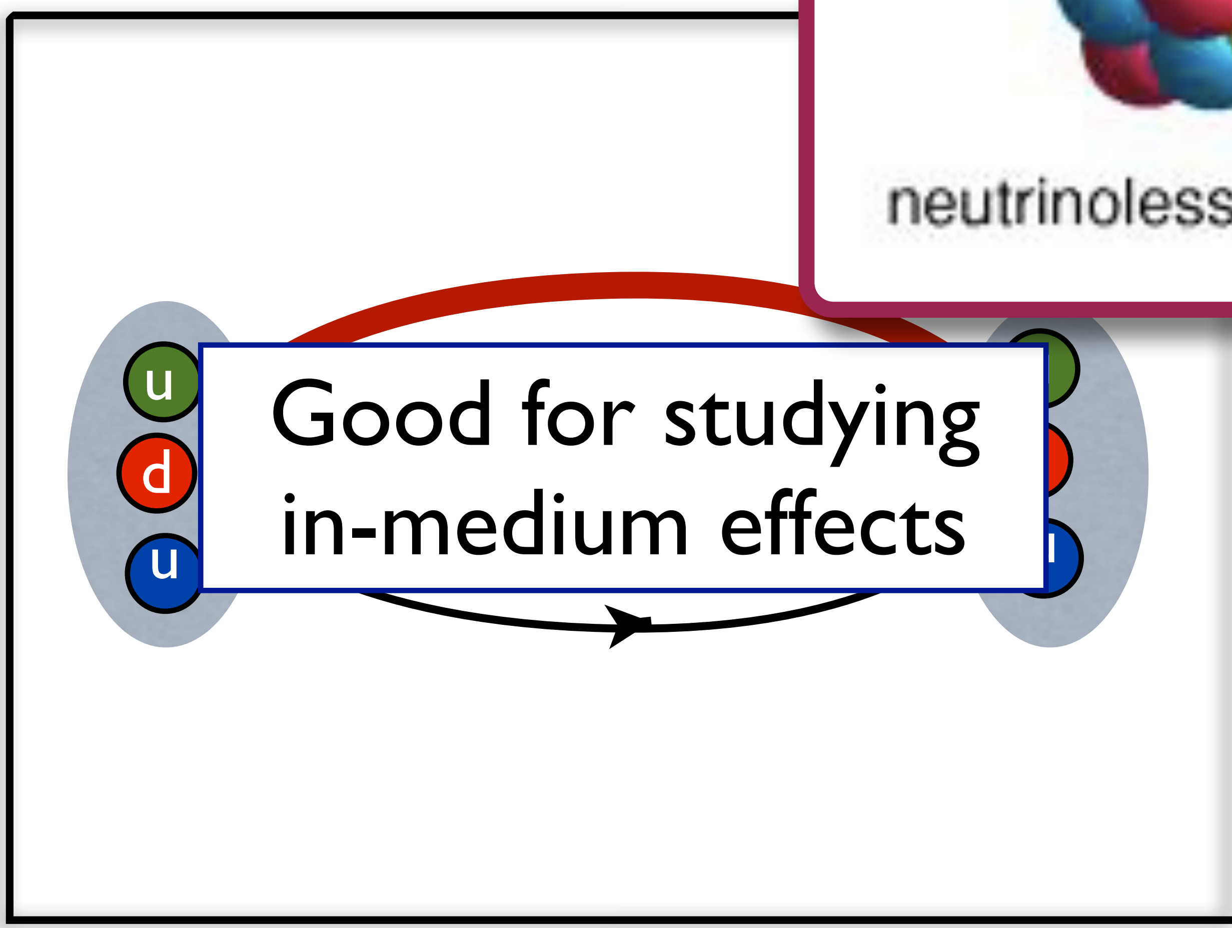
Matrix Elements

Feynman-



function





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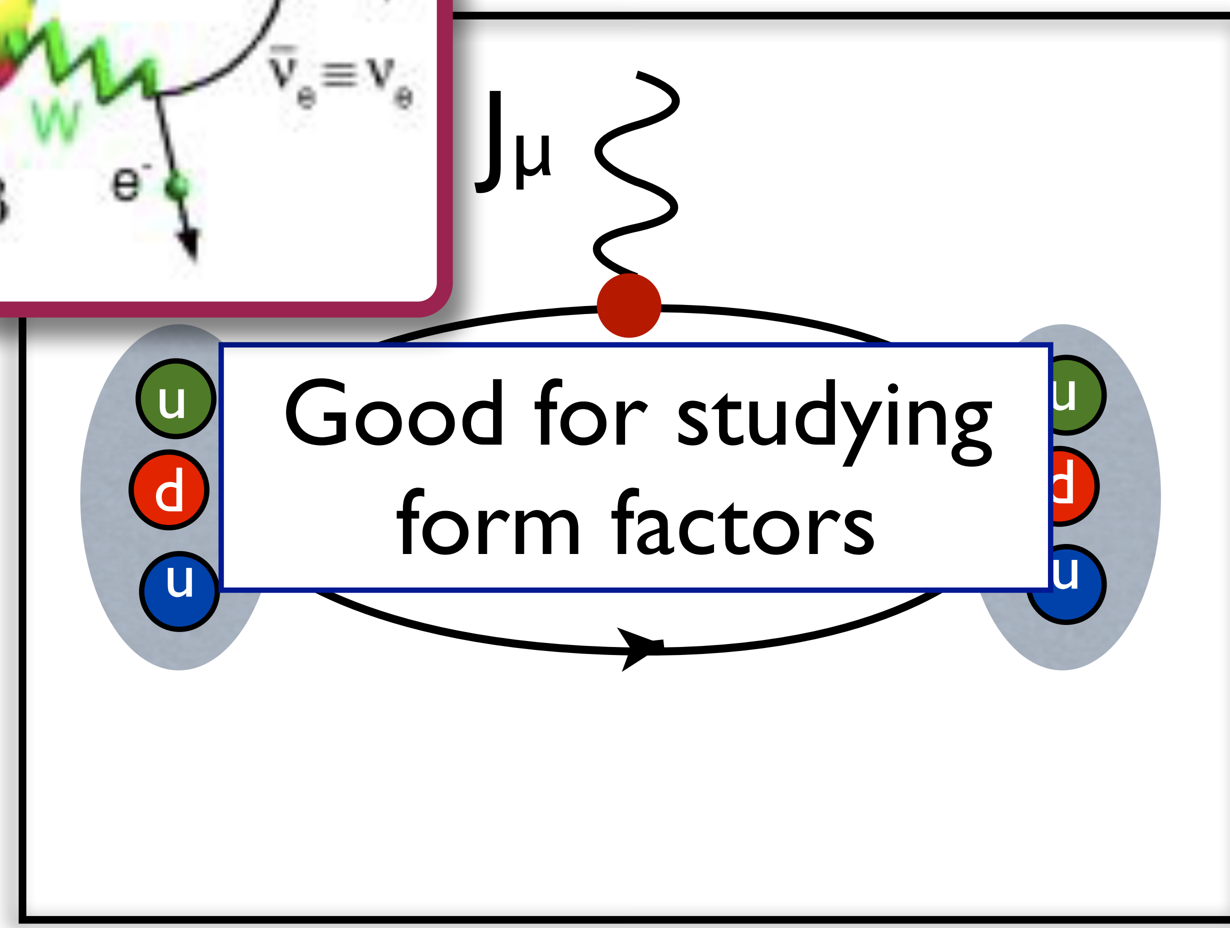

Good for studying form factors

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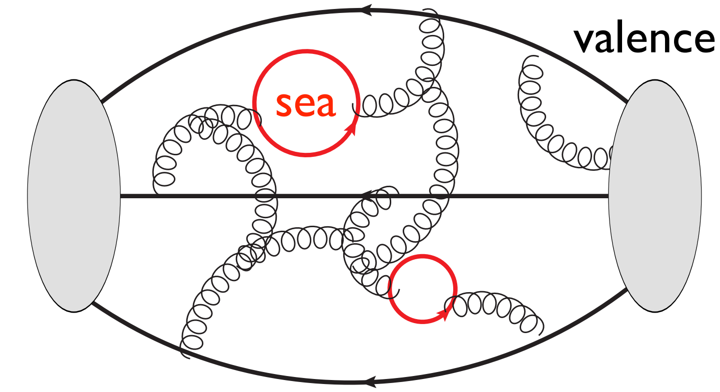
Get all time separations with a single calculation - found benefit in using earlier times where signal is more precise

Precision requires action with a well-behaved approach to the physical limit

CalLat, Phys.Rev. D96 (2017) no.5, 054513

Precision requires action with a well-behaved approach to the physical limit

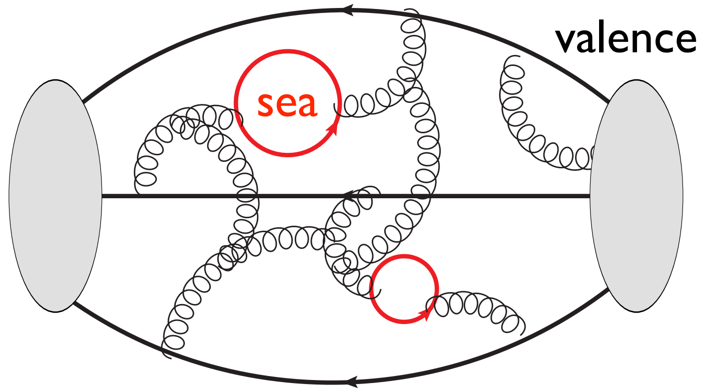


$a[\mathrm{fm}]$: $m_\pi[\mathrm{MeV}]$	400	350	310	220	130
0.15	$m_\pi L \sim 4.8$	$m_\pi L \sim 4.2$	$m_\pi L \sim 3.78$	$m_\pi L \sim 3.99$	$m_\pi L \sim 3.25$
				$m_\pi L \sim 3.22$	
0.12	$m_\pi L \sim 5.8$	$m_\pi L \sim 5.1$	$m_\pi L \sim 4.54$	$m_\pi L \sim 4.29$	$m_\pi L \sim 3.91$
				$m_\pi L \sim 5.36$	
0.09	$m_\pi L \sim 5.8$	$m_\pi L \sim 5.1$	$m_\pi L \sim 4.50$	$m_\pi L \sim 4.73$	

MILC Collaboration
Phys. Rev. D87 (2013)
054505

CalLat, Phys.Rev. D96
(2017) no.5, 054513

Precision requires action with a well-behaved approach to the physical limit



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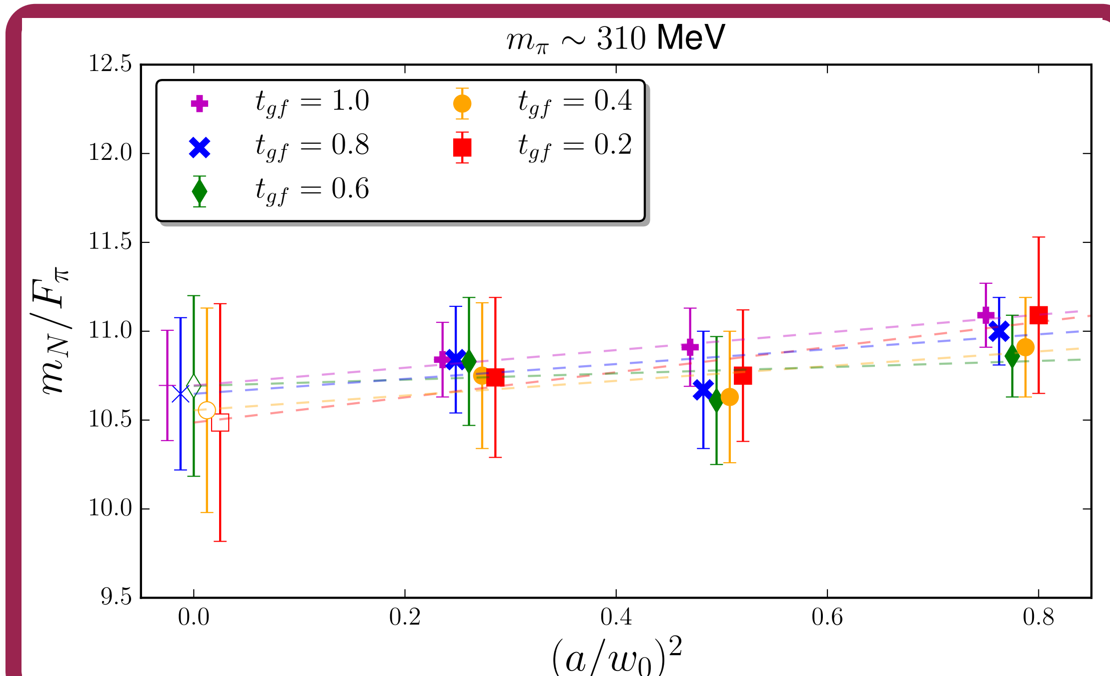
MILC Collaboration Phys. Rev. D87 (2013) 054505

- DWF:
- Chiral symmetry breaking exponentially suppressed
  - g_A/g_V is a quantitative measure of chiral symmetry breaking
  - Discretization effects come in at O(a^2)
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5
  - improved statistics

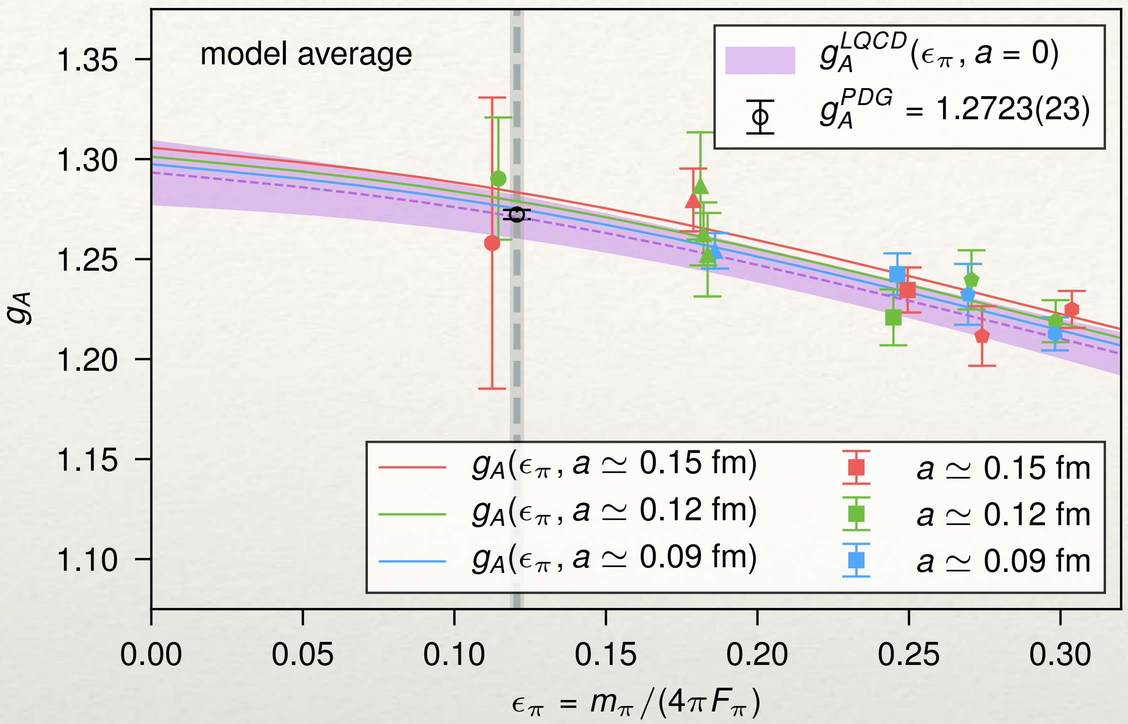
Narayanan, Neuberger (2006), Luscher (2010)



CalLat, Phys.Rev. D96 (2017) no.5, 054513

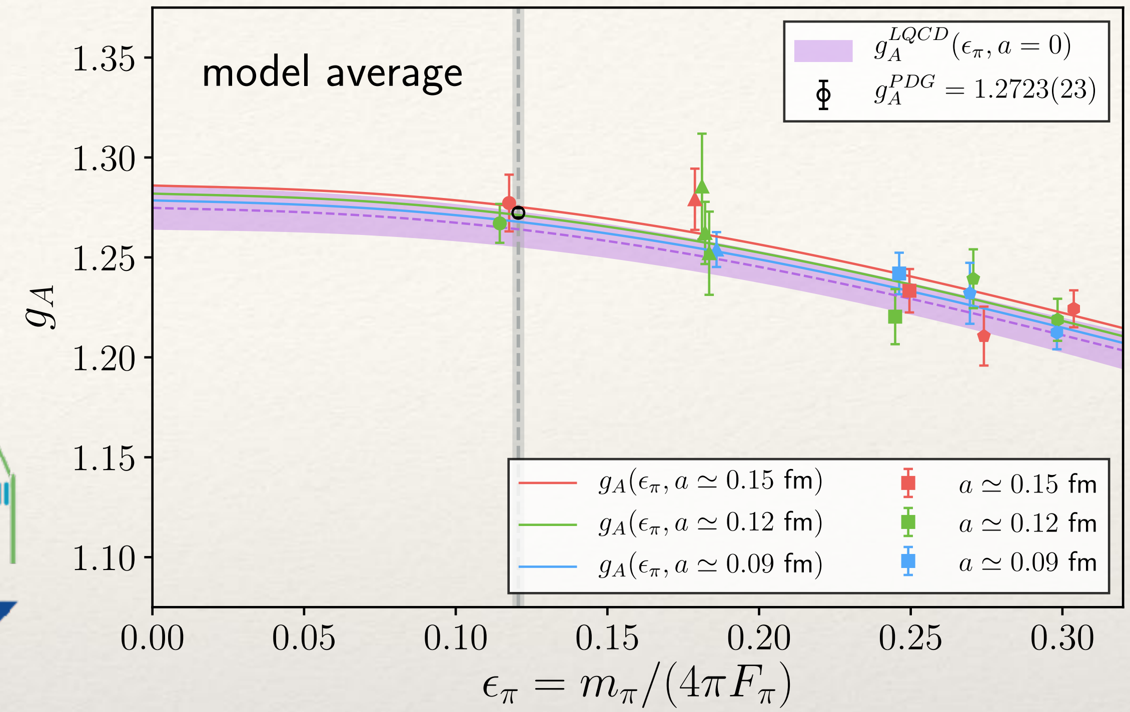
Nature 558 (2018) no. 7708, 91-94
Chang et al. [arXiv:1805.12130]

1 year on Titan (ORNL) + 2 years on GPU machines at LLNL



Sierra Early Science

PRELIMINARY

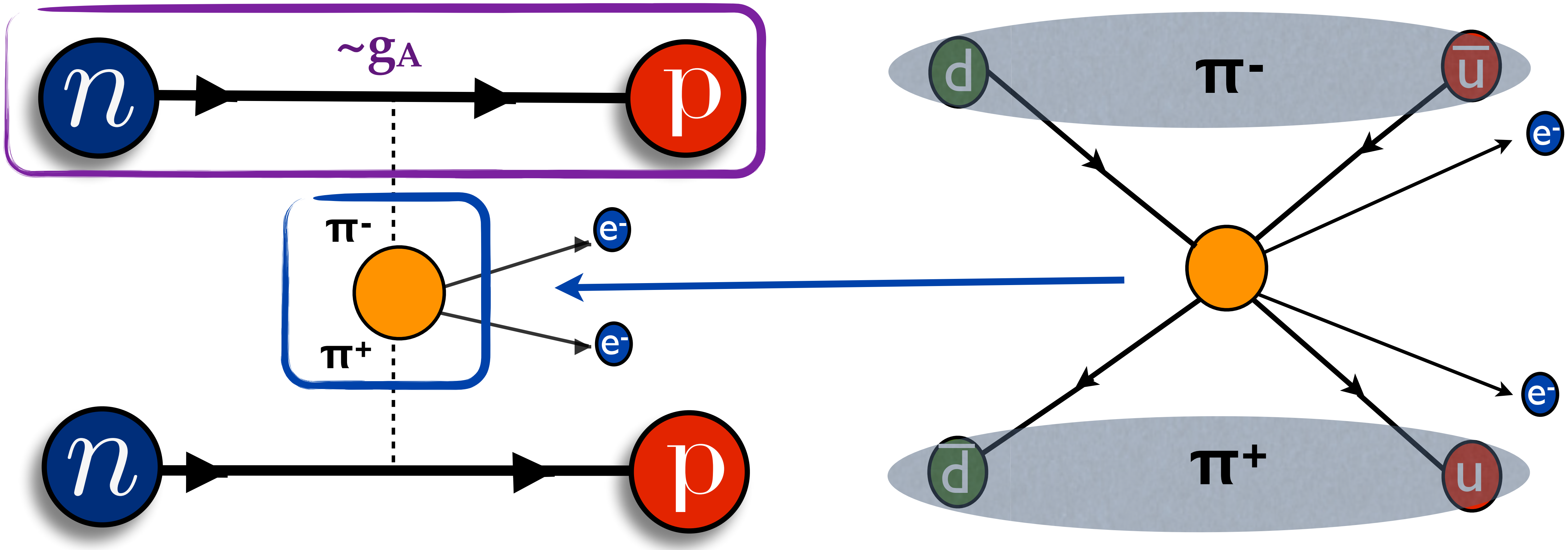


California Lattice Collaboration

- The a12m130 (48^3 x 64 x 20) with 3 sources cost as much as all other ensembles combined
  - 2.5 weekends on Sierra → 16 srcs
  - Now, 32 srcs (un-constrained, 3-state fit)
- We generated a new a15m135XL (48^3 x 64) ensemble (old a15m130 is 32^3 x 48)
  - $M_\pi L = 4.93$ (old $M_\pi L = 3.2$)
  - $L_5 = 24$, $N_{src} = 16$
- We are running $g_A(Q^2)$ on Summit this year (DOE INCITE)
  - We anticipate improving g_A to ~0.5%

$g_A = 1.2711(125) \rightarrow 1.2641(93)$ [0.74%]

Slides from A. Walker-Loud, Lattice 2019



2.

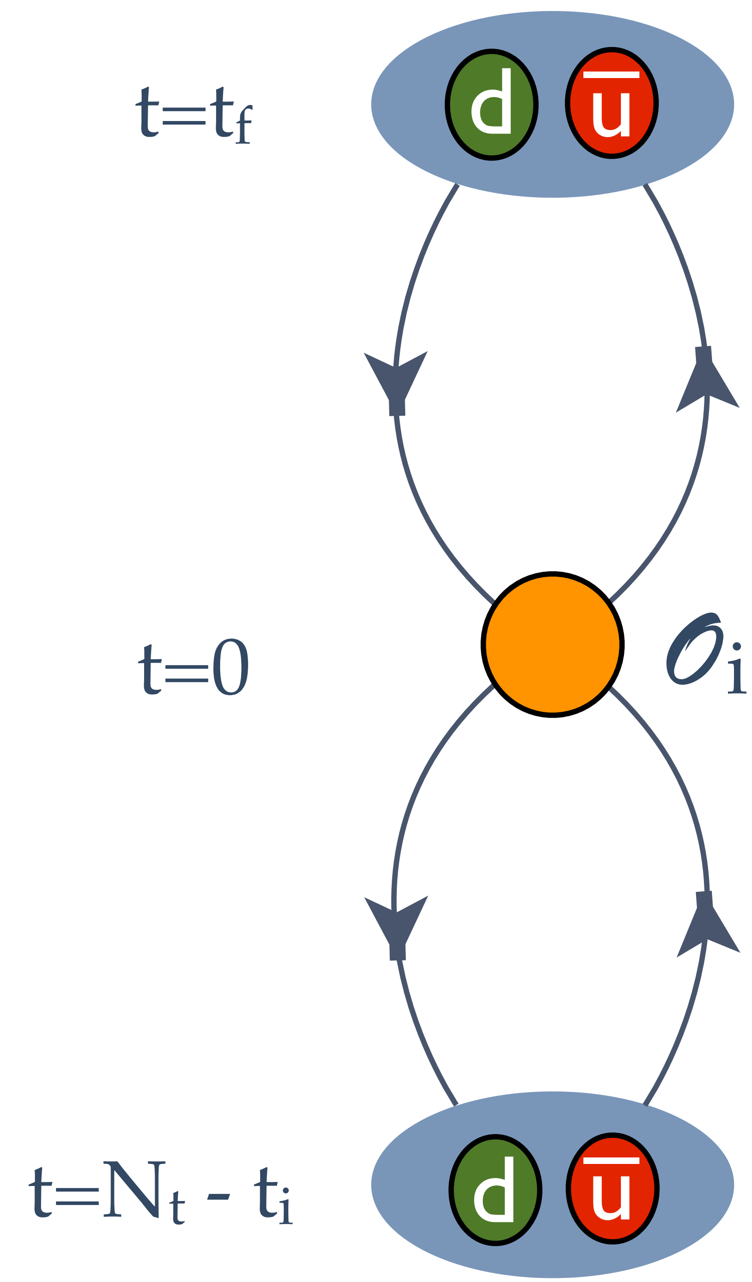
$\pi^{-} \rightarrow \pi^{+}$ Transition:

no direct experimental input

Long-range pion calculation

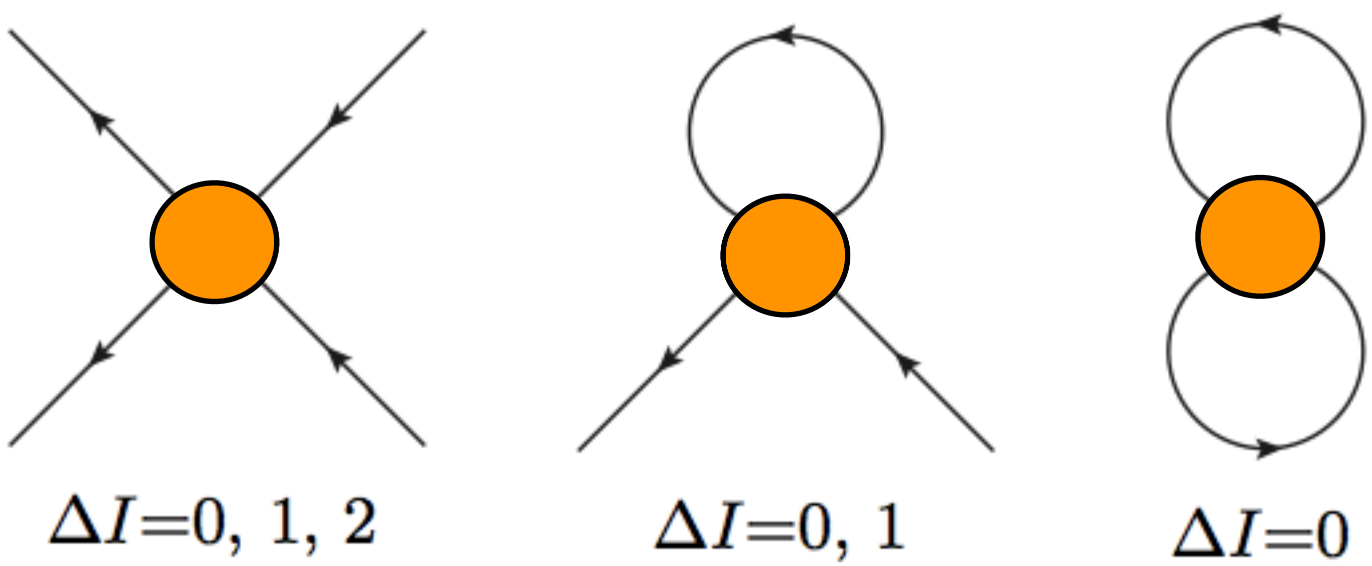
- Easy to compute pion physics on the lattice!
  - Clean signals
  - Single particle

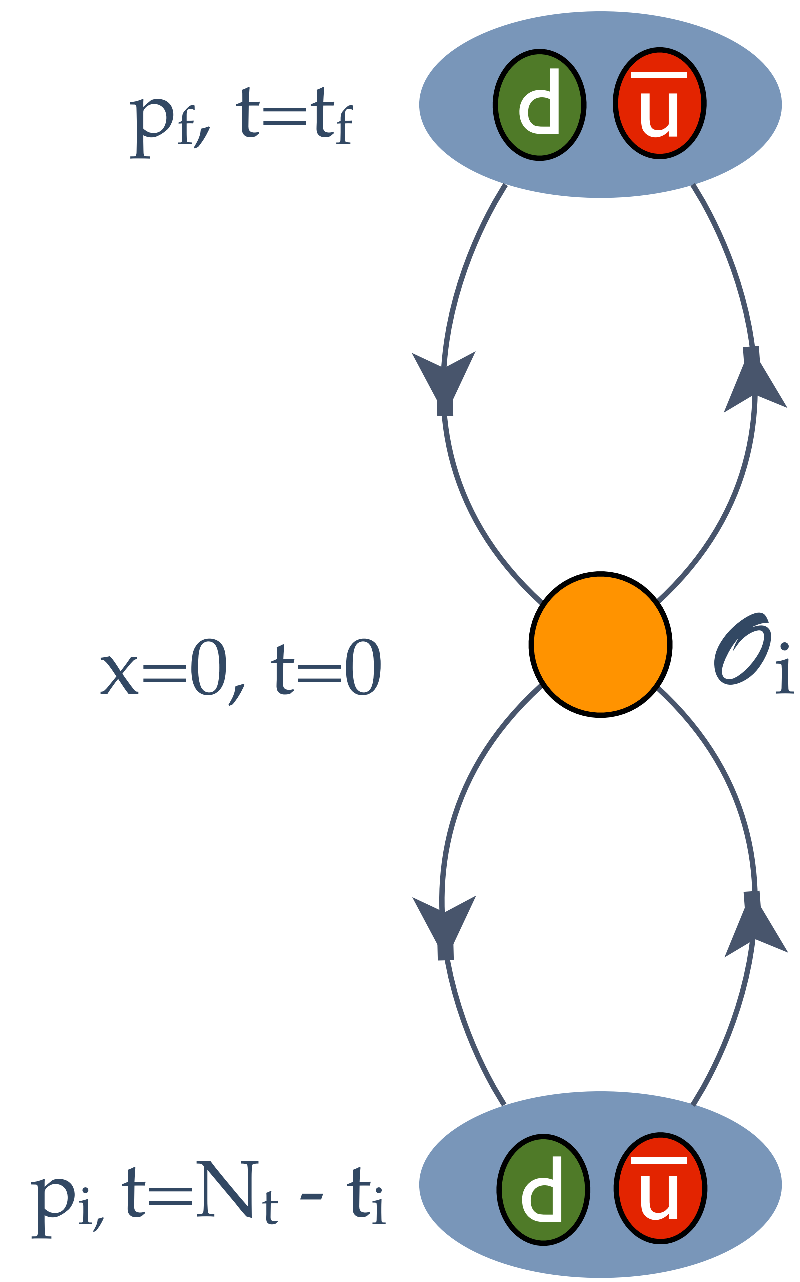
- No 4-quark FH (yet!), so we'll use standard 3-pt



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.	$\mathcal{O}_{1+}^{++}$	$\mathcal{O}_{2+}^{++}$	$\mathcal{O}_{2-}^{++}$	$\mathcal{O}_{3+}^{++}$	$\mathcal{O}_{3-}^{++}$	$\mathcal{O}_{4+}^{++,\mu}$	$\mathcal{O}_{4-}^{++,\mu}$	$\mathcal{O}_{5+}^{++,\mu}$	$\mathcal{O}_{5-}^{++,\mu}$
$\pi\pi ee$ 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	✓	✓	✓	✓

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

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

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	✓	✓	✓	✓

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

$$\mathcal{O}_{1+}^{ab} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L})(\bar{q}_{\rm R}\tau^b\gamma_\mu q_{\rm R}),$$

$$\mathcal{O}_{2\pm}^{ab} = (\bar{q}_{\rm R}\tau^a q_{\rm L})(\bar{q}_{\rm R}\tau^b q_{\rm L}) \pm (\bar{q}_{\rm L}\tau^a q_{\rm R})(\bar{q}_{\rm L}\tau^b q_{\rm R}),$$

$$\mathcal{O}_{3\pm}^{ab} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L})(\bar{q}_{\rm L}\tau^b\gamma_\mu q_{\rm L}) \pm (\bar{q}_{\rm R}\tau^a\gamma^\mu q_{\rm R})(\bar{q}_{\rm R}\tau^b\gamma_\mu q_{\rm R}),$$

$$\mathcal{O}_{4\pm}^{ab,\mu} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L} \pm \bar{q}_{\rm R}\tau^a\gamma^\mu q_{\rm R})(\bar{q}_{\rm L}\tau^b q_{\rm R} - \bar{q}_{\rm R}\tau^b q_{\rm L}),$$

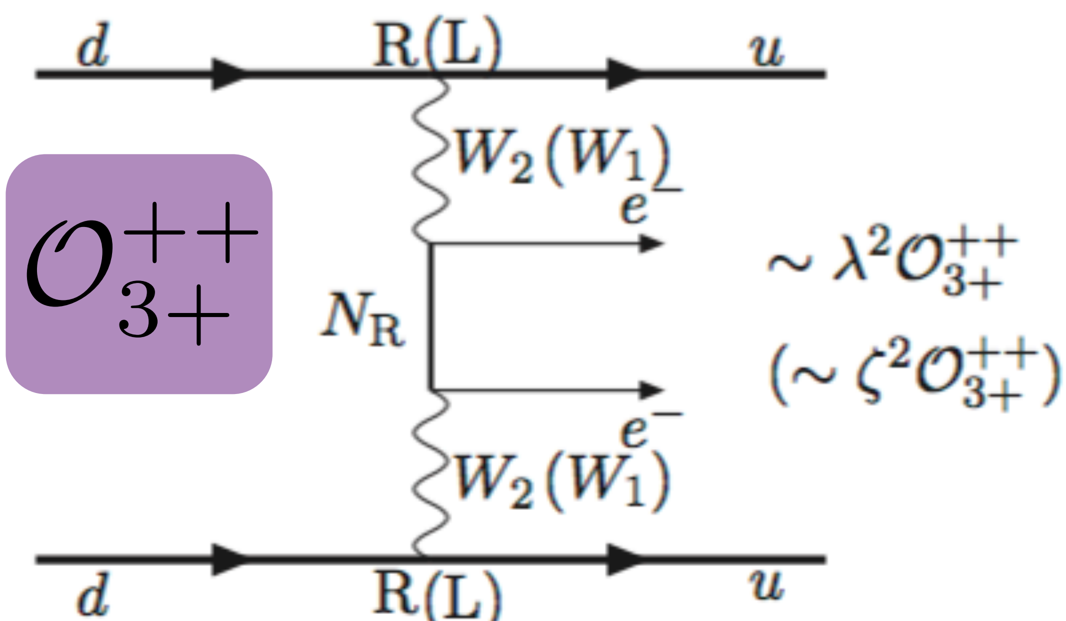
$$\mathcal{O}_{5\pm}^{ab,\mu} = (\bar{q}_{\rm L}\tau^a\gamma^\mu q_{\rm L} \pm \bar{q}_{\rm R}\tau^a\gamma^\mu q_{\rm R})(\bar{q}_{\rm L}\tau^b q_{\rm R} + \bar{q}_{\rm R}\tau^b q_{\rm L}).$$

Prezeau, Ramsey-Musolf, Vogel (2003)

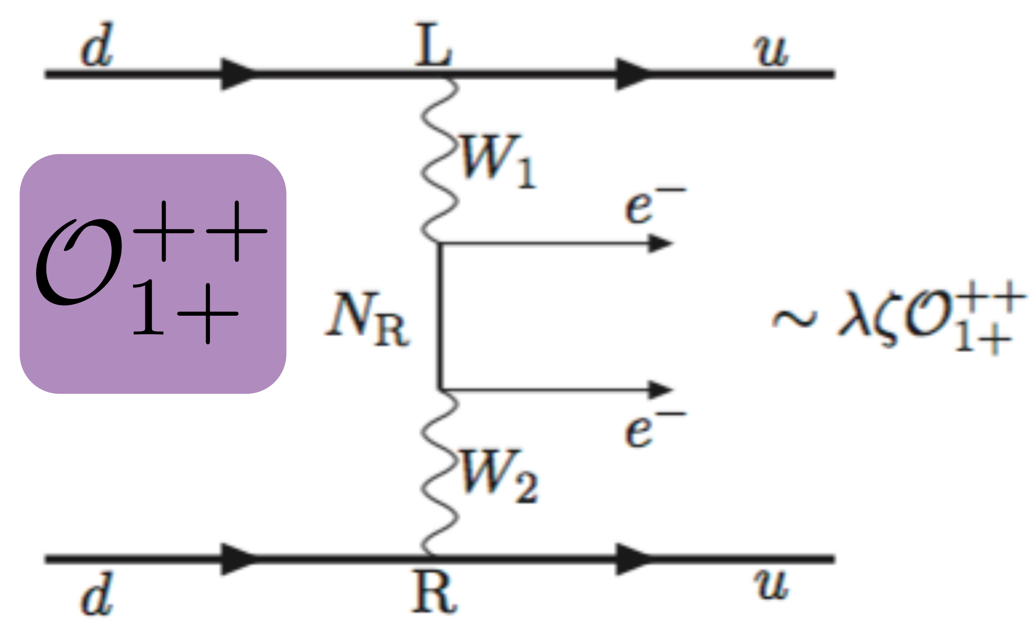
χPT:

$0\nu\beta\beta$-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



(a)



(b)

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

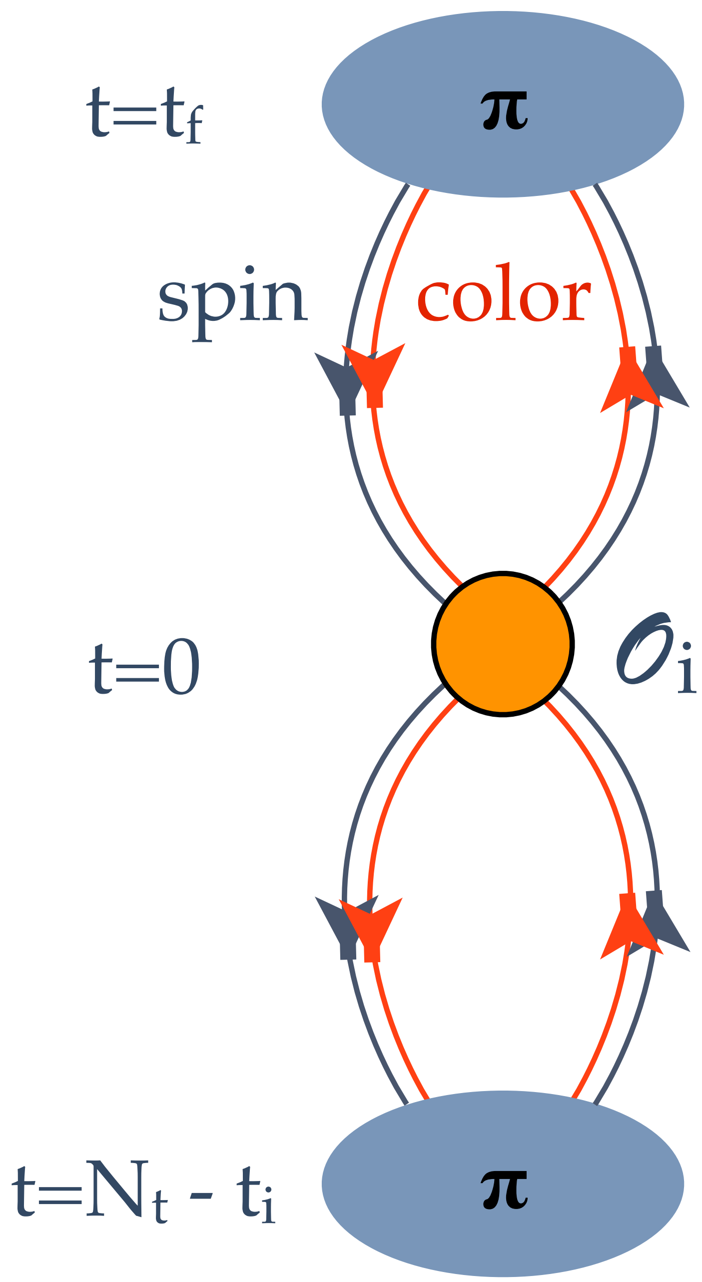
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L\tau^-\gamma^\mu q_L)\,[\bar{q}_R\tau^-\gamma_\mu q_R]$$

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

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

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

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



Contractions

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

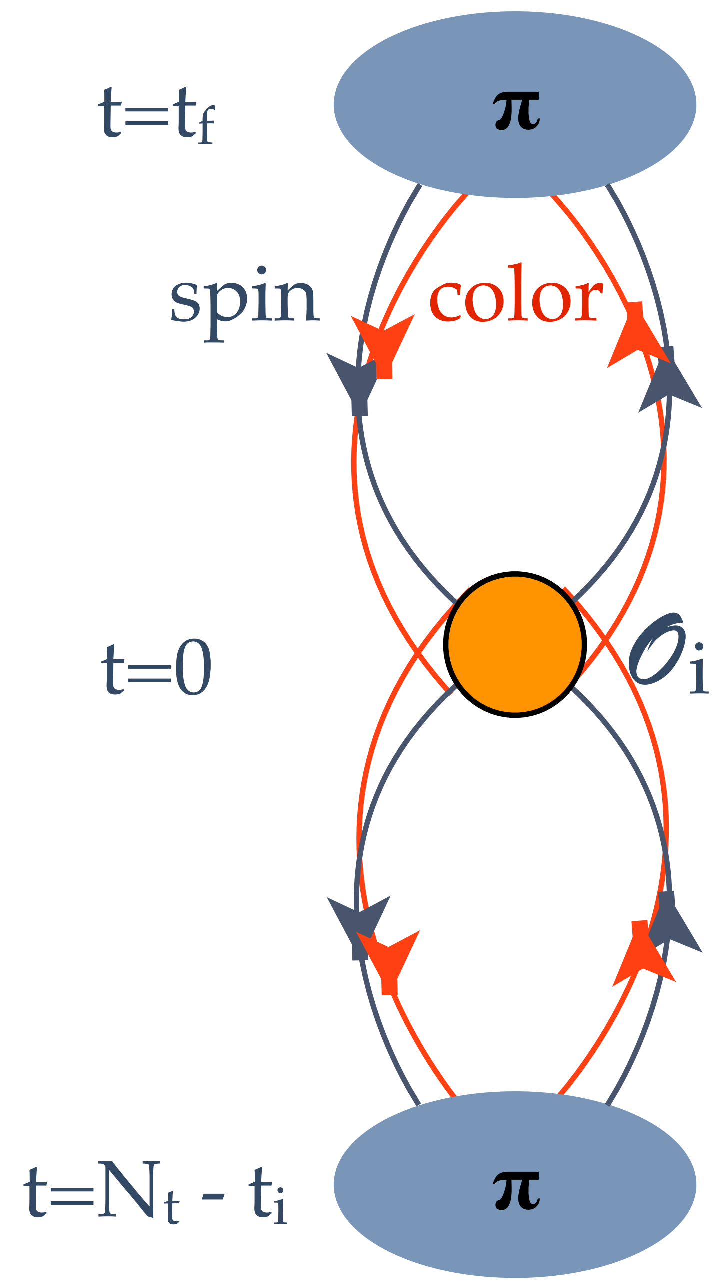
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L)\,[\bar{q}_R \tau^- \gamma_\mu q_R]$$

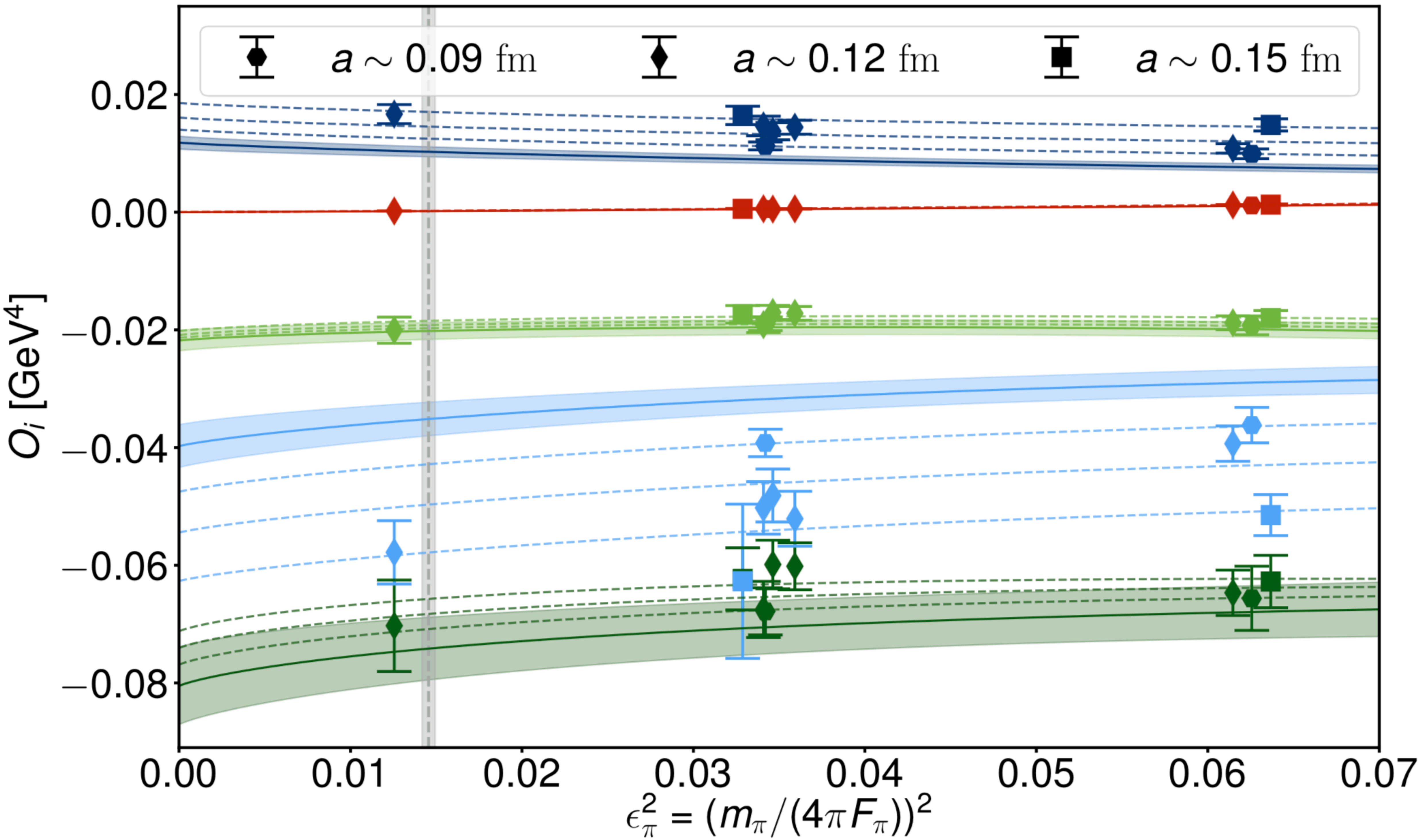
$$\mathcal{O}'^{++}_{1+} = (\bar{q}_L \tau^- \gamma^\mu q_L]\,[\bar{q}_R \tau^- \gamma_\mu q_R)$$

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

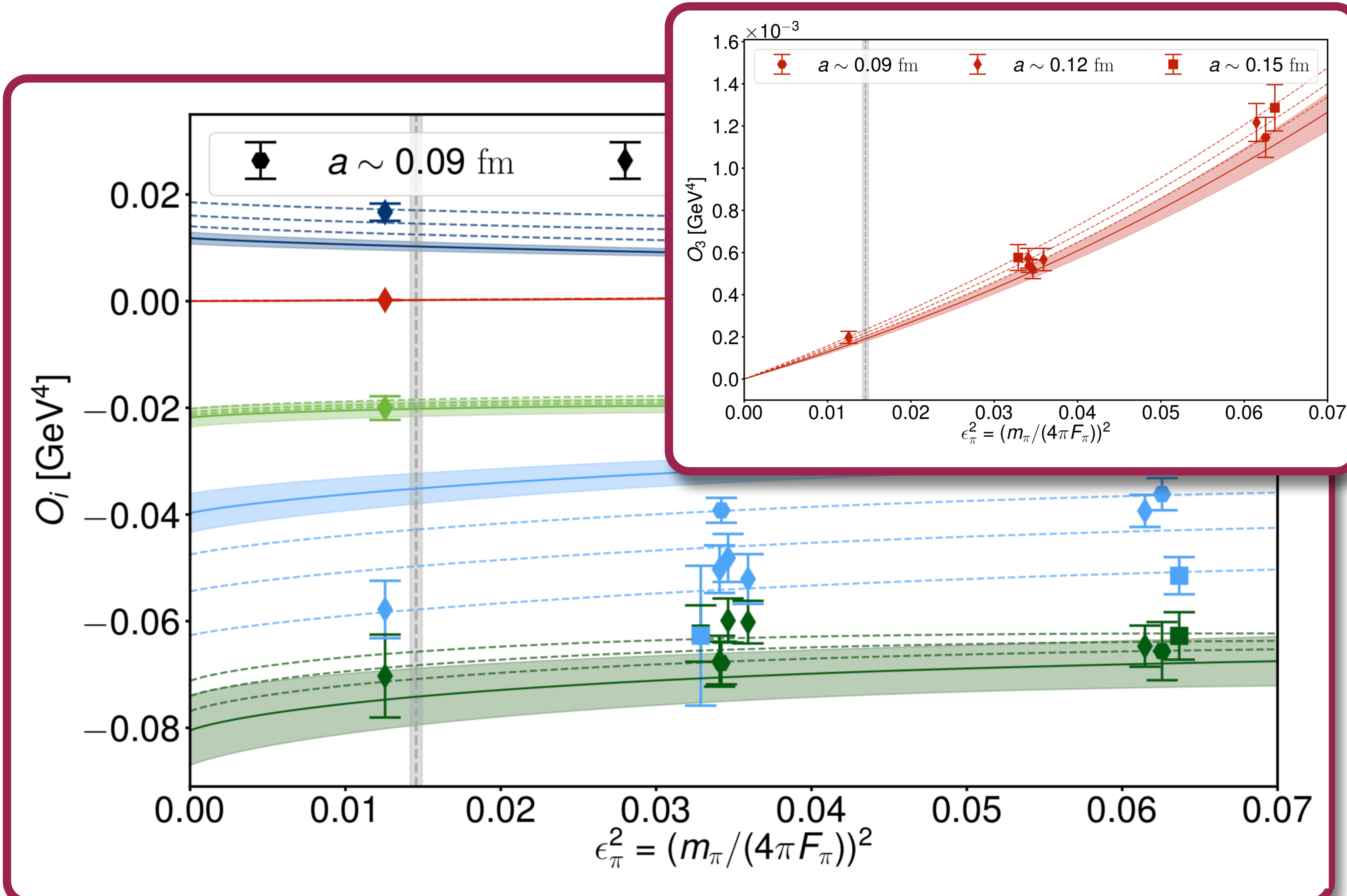
$$\mathcal{O}'^{++}_{2+} = (\bar{q}_R \tau^- q_L]\,[\bar{q}_R \tau^- q_L) + (\bar{q}_L \tau^- q_R]\,[\bar{q}_L \tau^- q_R)$$

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

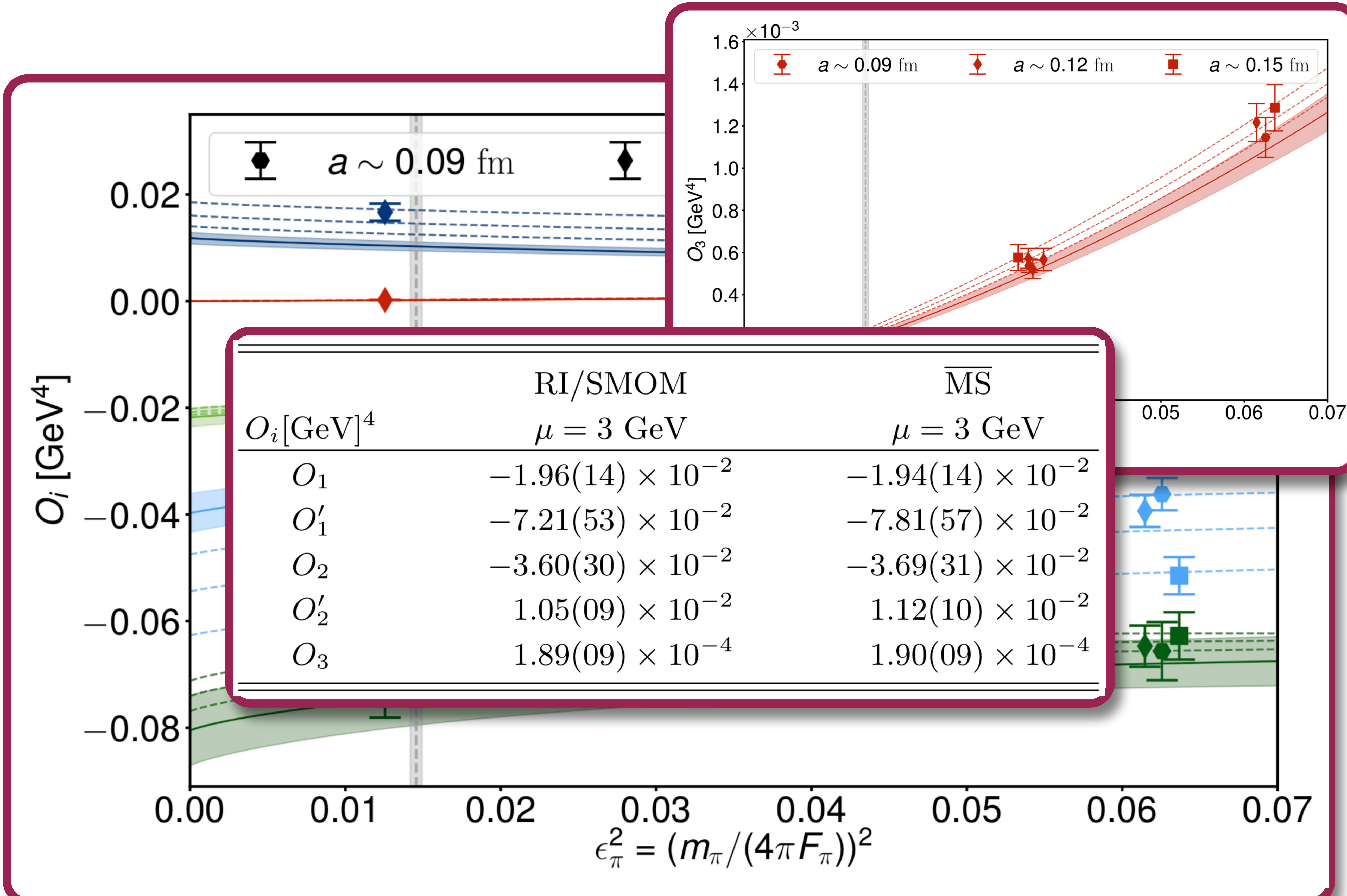




A.N., E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joo, T. Kurth, B. Tiburzi, P. Vranas, A. Walker-Loud, PRL 121 (2018) no.17, 172501

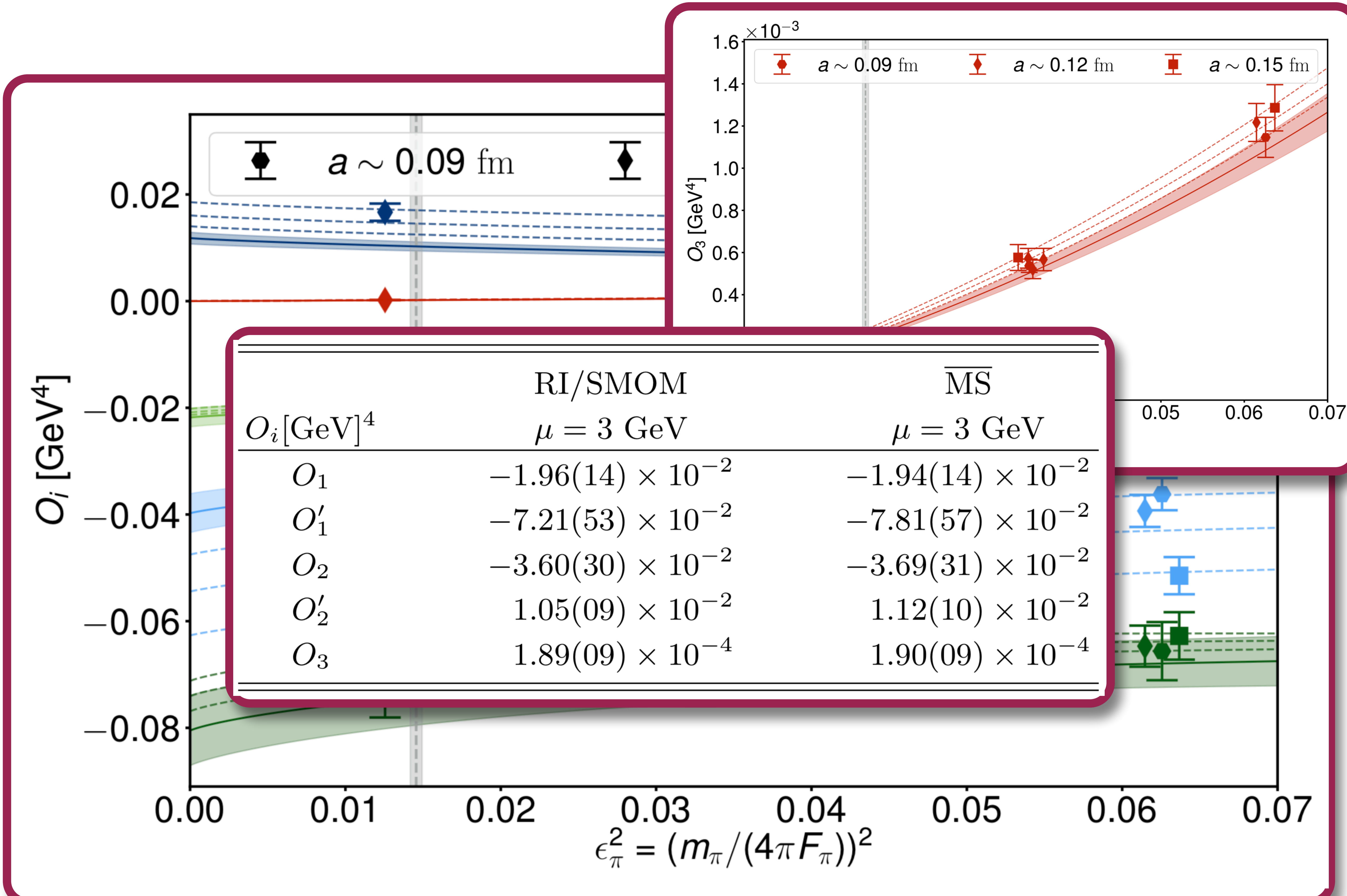


A.N., E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joo, T. Kurth, B. Tiburzi, P. Vranas, A. Walker-Loud, PRL 121 (2018) no.17, 172501



$O_i[\mathrm{GeV}]^4$	RI/SMOM $\mu = 3$ GeV	$\overline{\mathrm{MS}}$ $\mu = 3$ GeV
O_1	$-1.96(14) \times 10^{-2}$	$-1.94(14) \times 10^{-2}$
O_1'	$-7.21(53) \times 10^{-2}$	$-7.81(57) \times 10^{-2}$
O_2	$-3.60(30) \times 10^{-2}$	$-3.69(31) \times 10^{-2}$
O_2'	$1.05(09) \times 10^{-2}$	$1.12(10) \times 10^{-2}$
O_3	$1.89(09) \times 10^{-4}$	$1.90(09) \times 10^{-4}$

A.N., E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joo, T. Kurth, B. Tiburzi, P. Vranas, A. Walker-Loud, PRL 121 (2018) no.17, 172501



$O_i[\mathrm{GeV}]^4$	RI/SMOM $\mu = 3$ GeV	$\overline{\mathrm{MS}}$ $\mu = 3$ GeV
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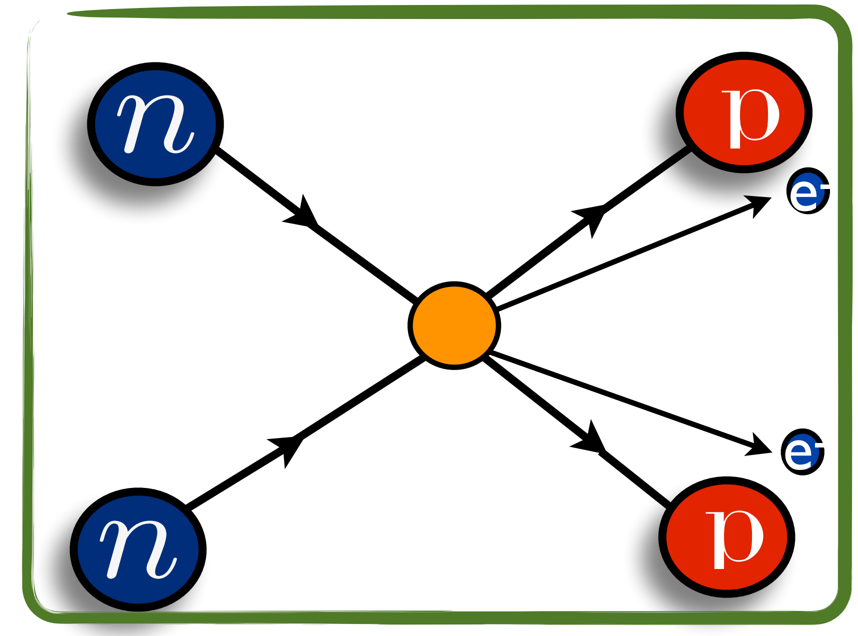
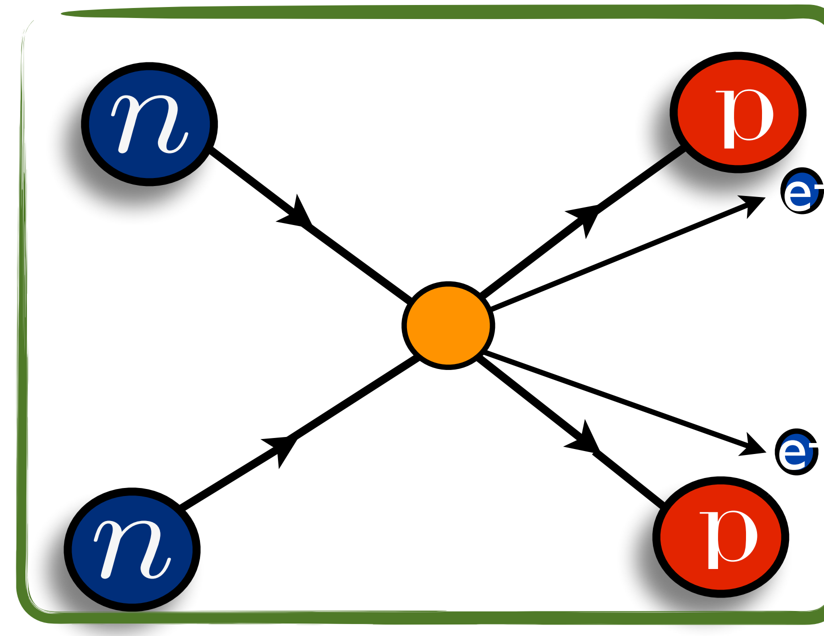
Agrees to 2σ with:
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti
Phys.Lett. B769 (2017) 460-464

Full $nn \to pp$ transition

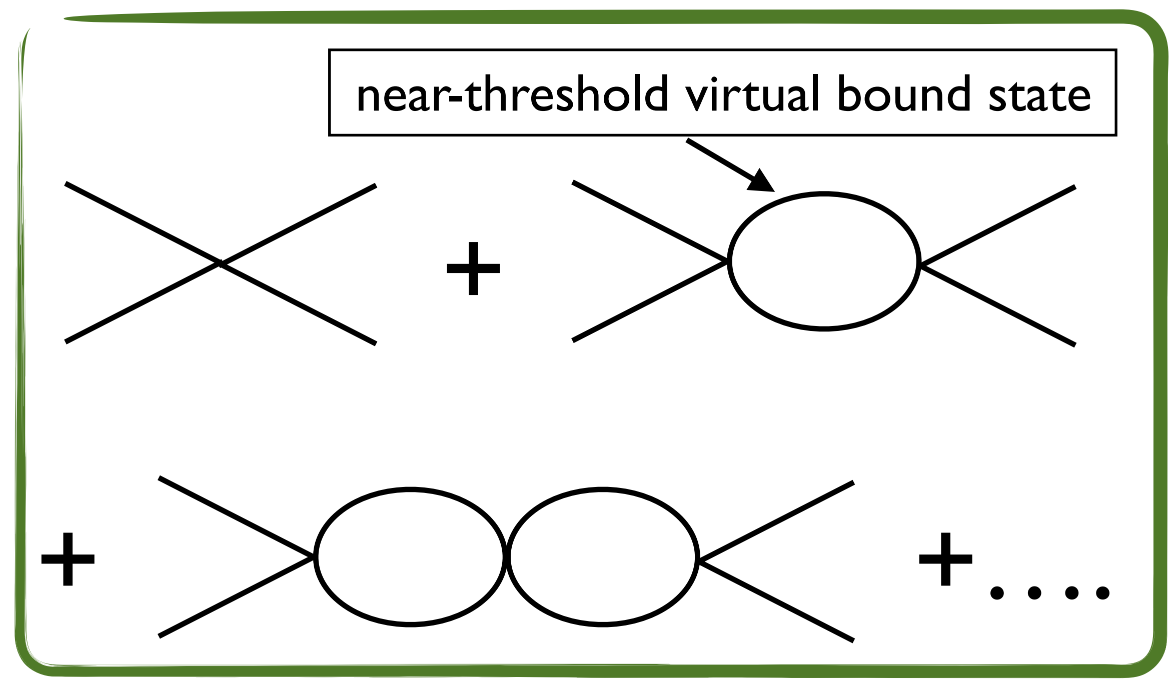


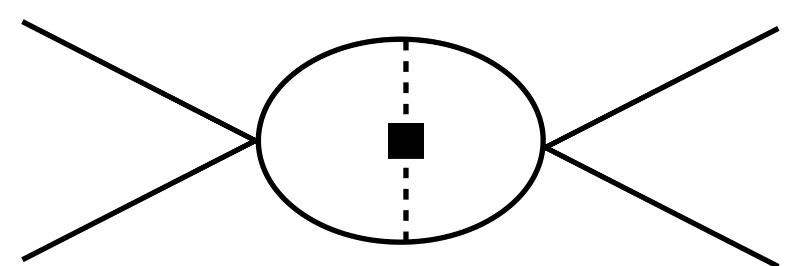
Full $nn \to pp$ transition

- Why calculate it?
  - Higher contributions formally NNLO (Weinberg counting)
  - Nuclear matrix elements currently have ~100% uncertainties
- The spin singlet channel is finely-tuned, leading to issues with Weinberg counting
- LO contribution vanishes for some BSM models
- Contact operator for standard double beta decay found to be important at heavy pion mass (NPLQCD '17)



Cirigliano, V., Dekens, W., de Vries, J., Mereghetti, E., Graesser, M., Pastore, S., van Kolck, U
arXiv:1802.10097

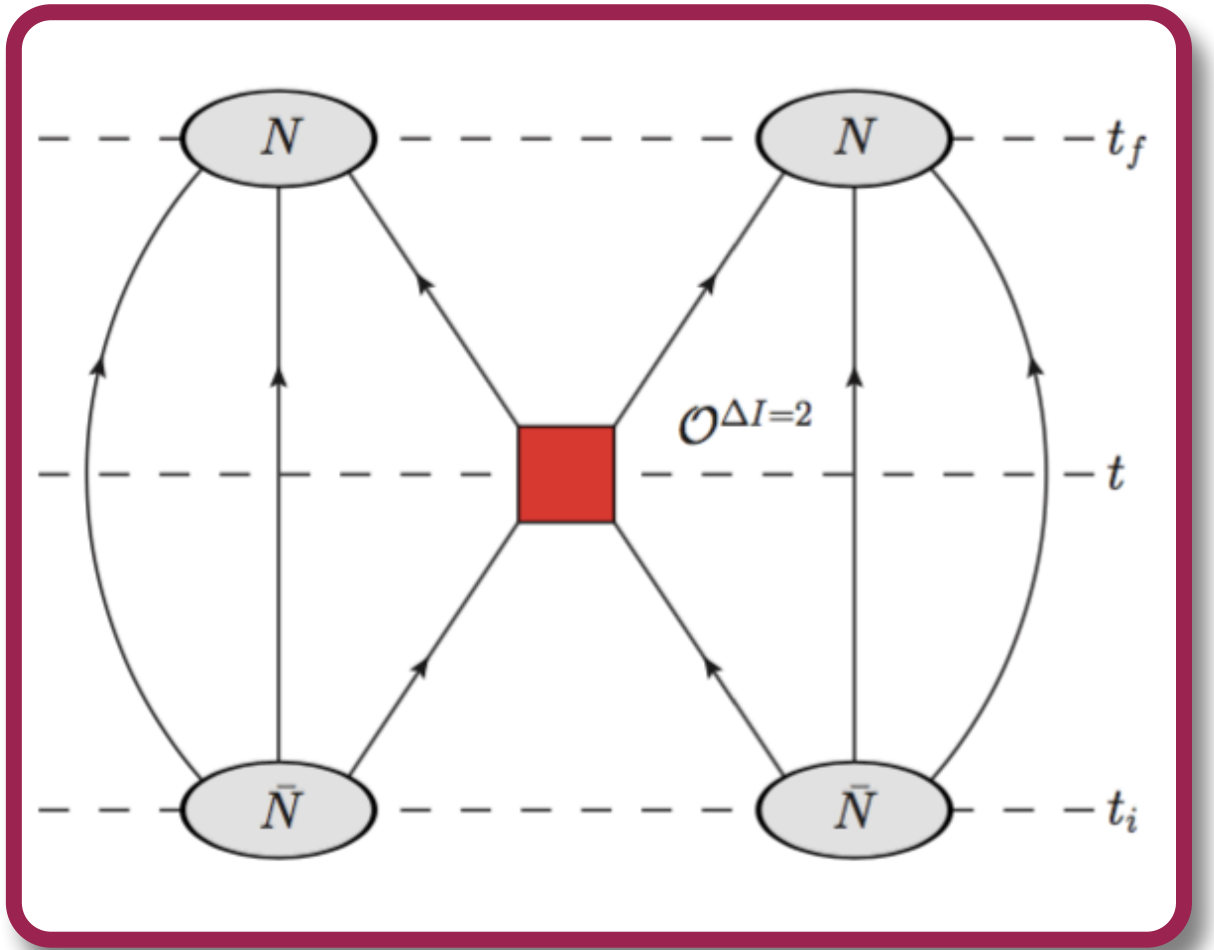




Full $nn \to pp$ transition

- Isospin limit: 576 contractions
  Doi & Endres, Originos et. al., Günther et. al.
- Baryon signal-to-noise problem, small excited state energy splittings, ...
- Cannot fix all momenta
  - otherwise all-to-all propagators connect to 4-quark operator
  - stochastically project onto zero total momentum
- Need phase shifts to connect to infinite volume

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

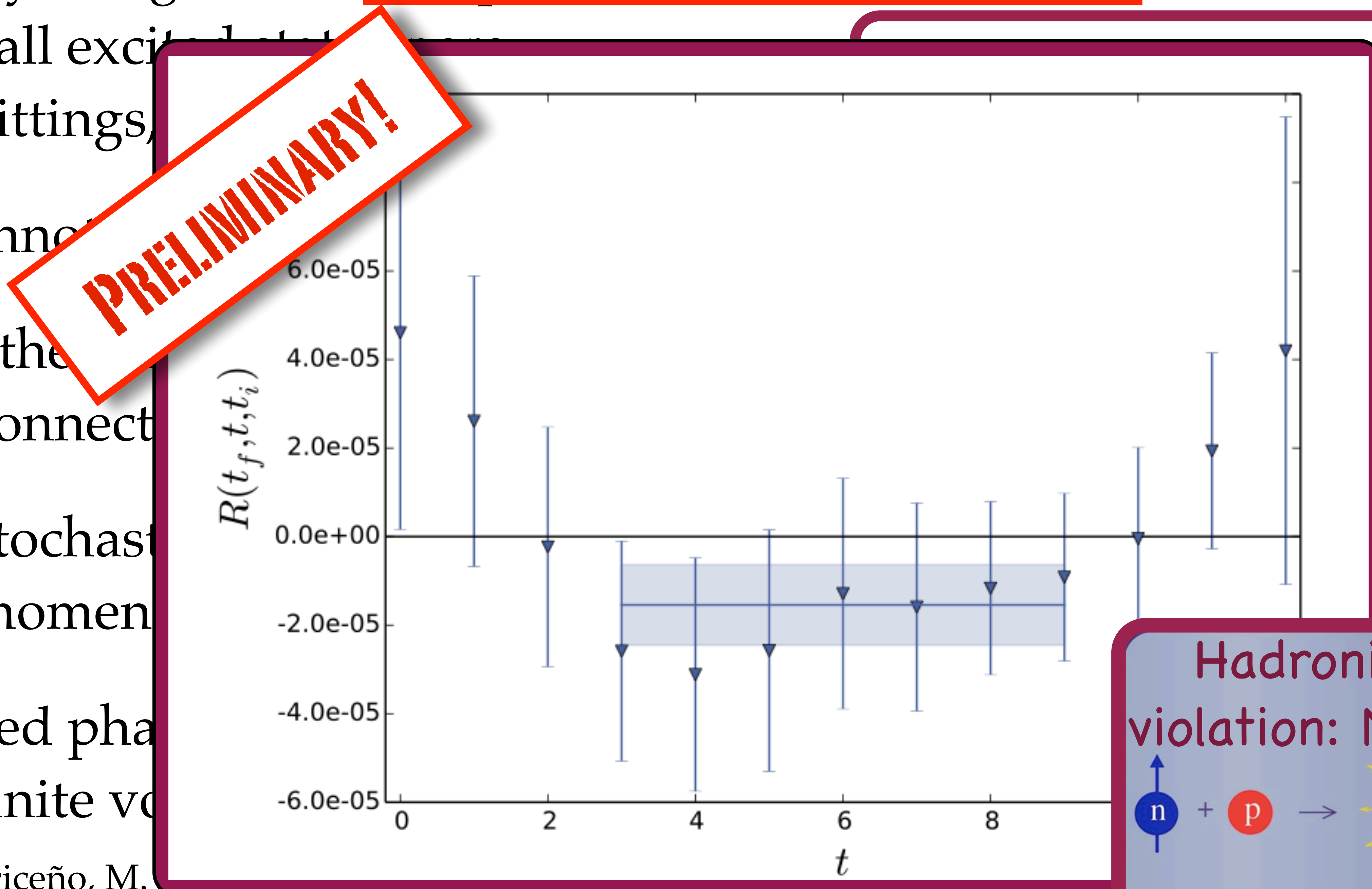


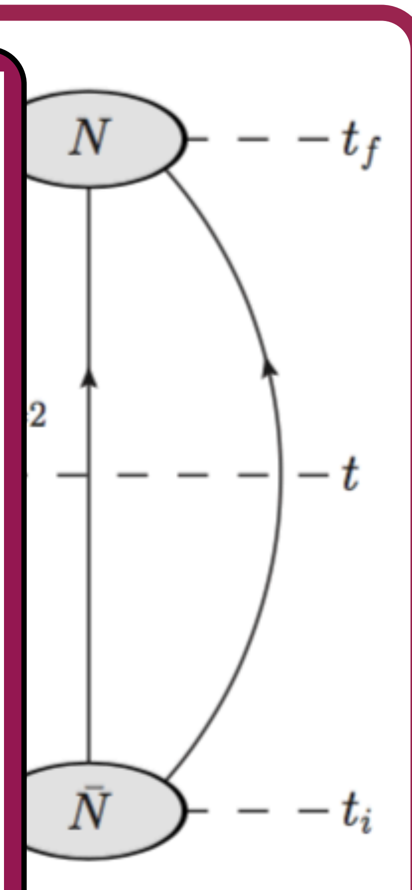
Full $nn \rightarrow p$

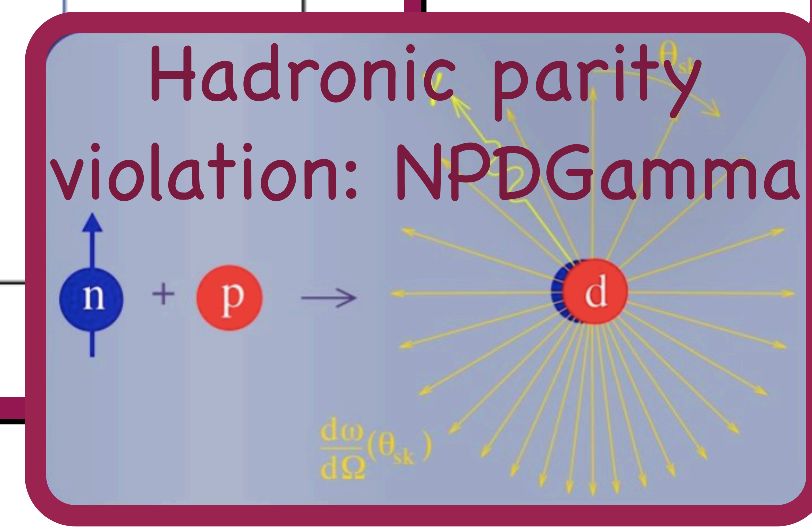
Difficult, but not impossible!

- Isospin limit: 576 c
  Doi & Endres, Originos et. a
- Baryon signal-to-n
  small excit
  splittings,
- Canno
  - othe
    connect
  - stochast
    momen
- Need pha
  infinite vo

R. Briceño, M.





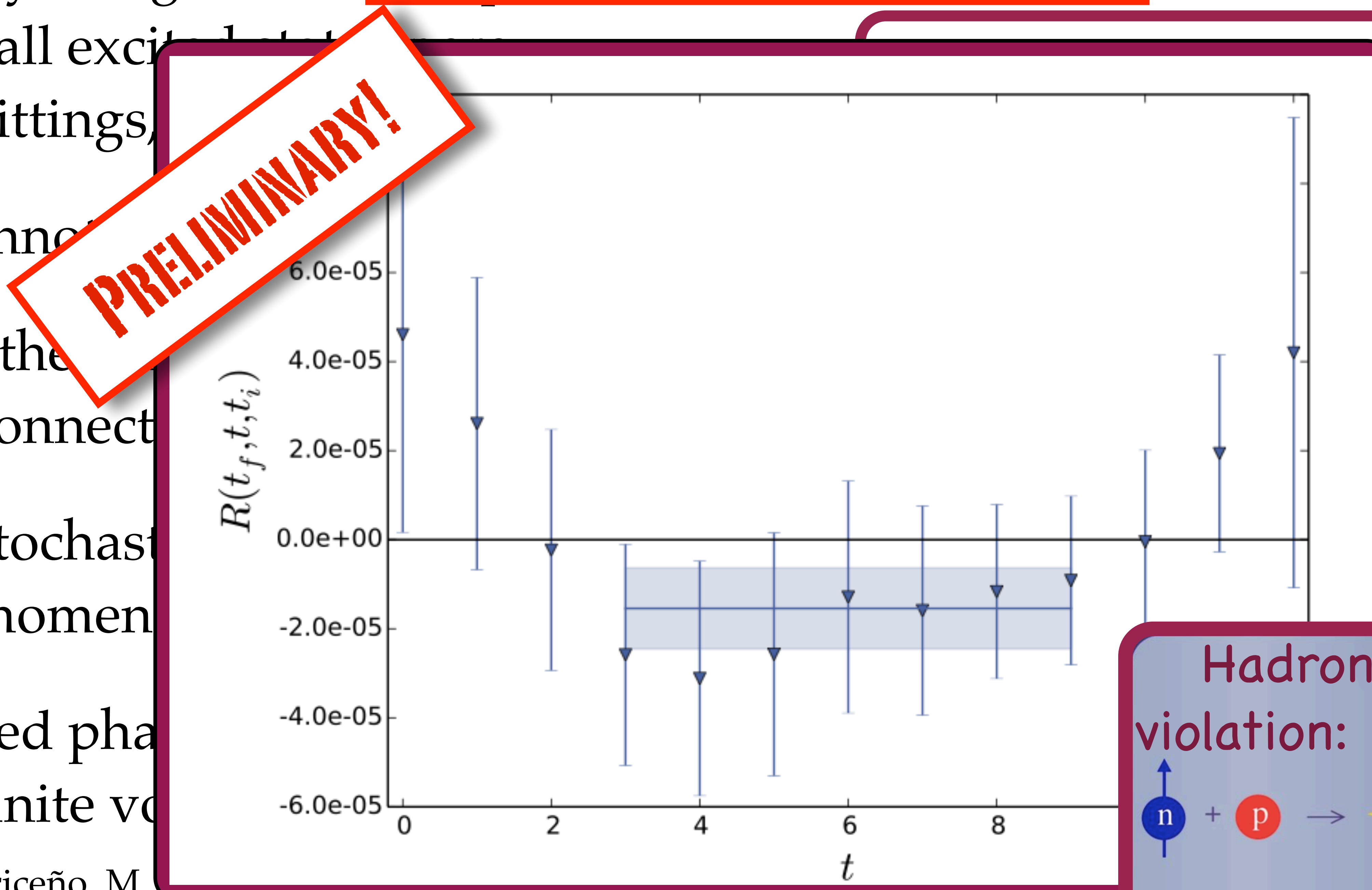


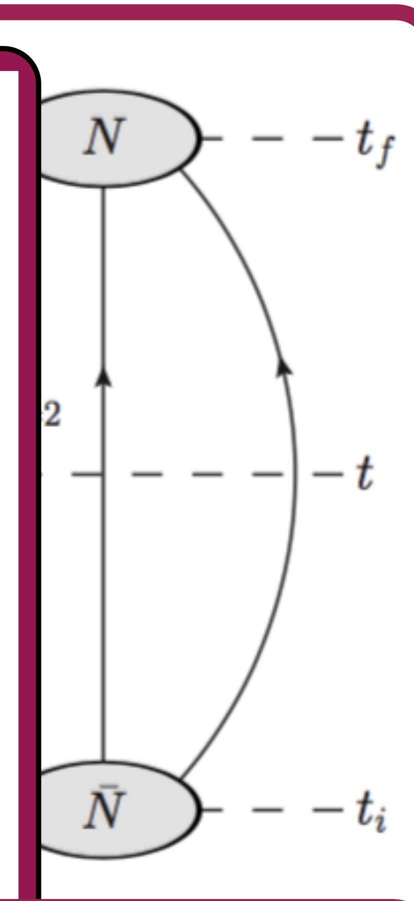
Full $nn \to p$ ... transition

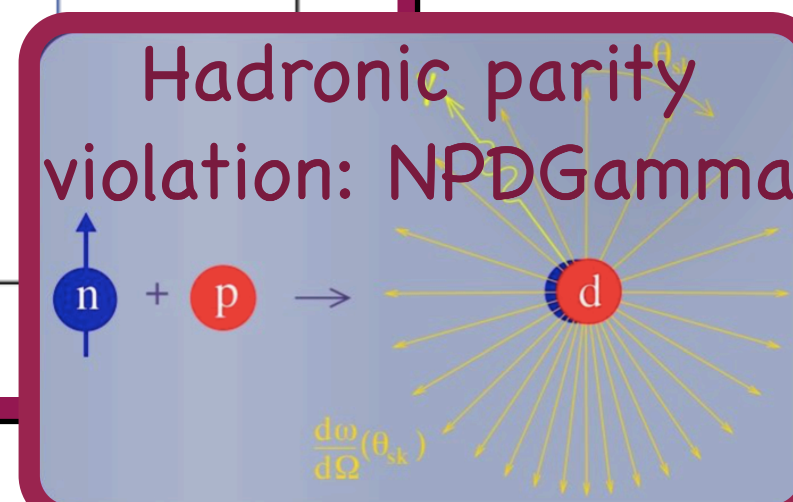
- Isospin limit: 576 c...
  Doi & Endres, Originos et. a...
- Baryon signal-to-n...
  small excited state ...
  splittings, ...
- Canno...
  - othe...
    connect...
  - stochast...
    momen...
- Need pha...
  infinite vo...

R. Briceño, M. ...

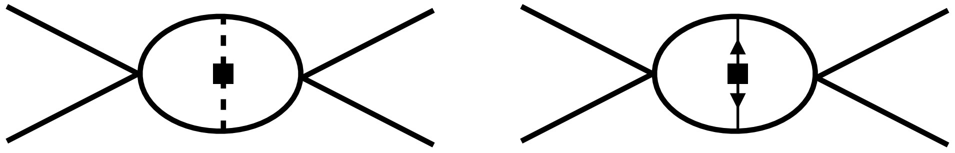
Difficult, but not impossible!
4-quark FH?
(Monge-Camacho Lattice 2018)



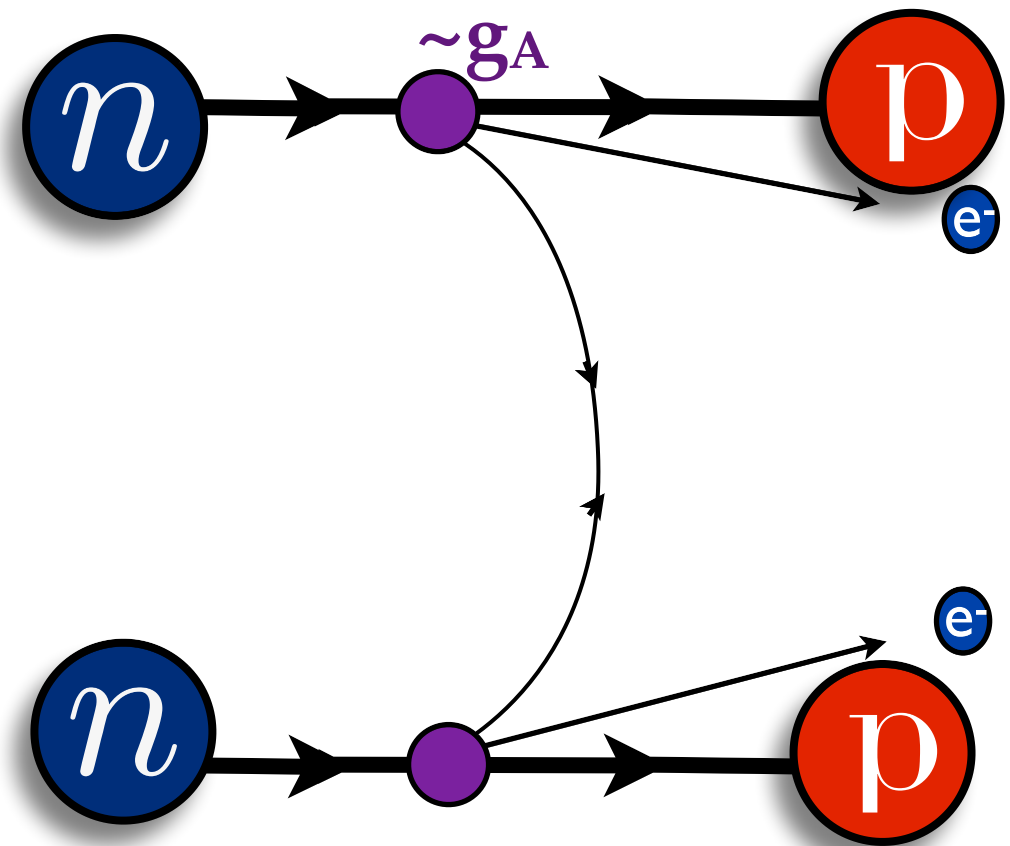




Full $nn \rightarrow pp$ transition

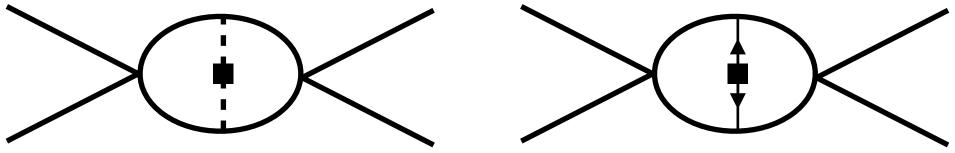


Cirigliano, V., Dekens, W., de Vries, J., Mereghetti, E., Graesser, M., Pastore, S., van Kolck, U
arXiv:1802.10097



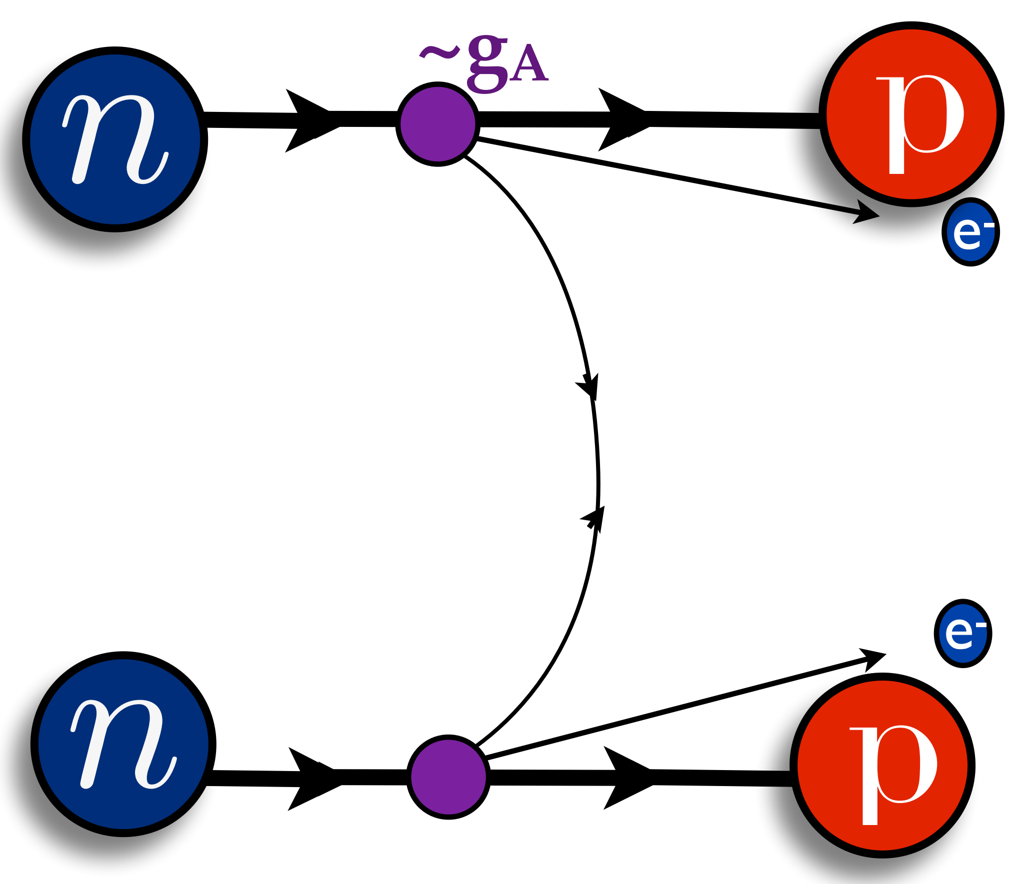
Long-range

Full $nn \to pp$ transition



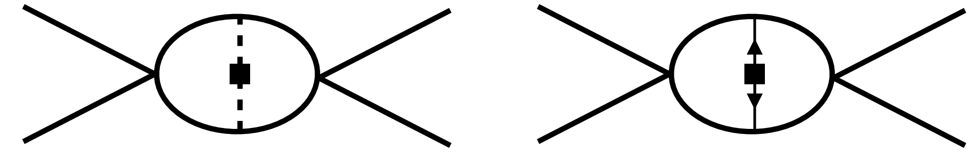
Cirigliano, V., Dekens, W., de Vries, J., Mereghetti, E., Graesser, M., Pastore, S., van Kolck, U
arXiv:1802.10097

- Work has begun to calculate full transition for light neutrino mechanism
  - Why? Just as in short-range operator case, EFT may not be reliable



Long-range

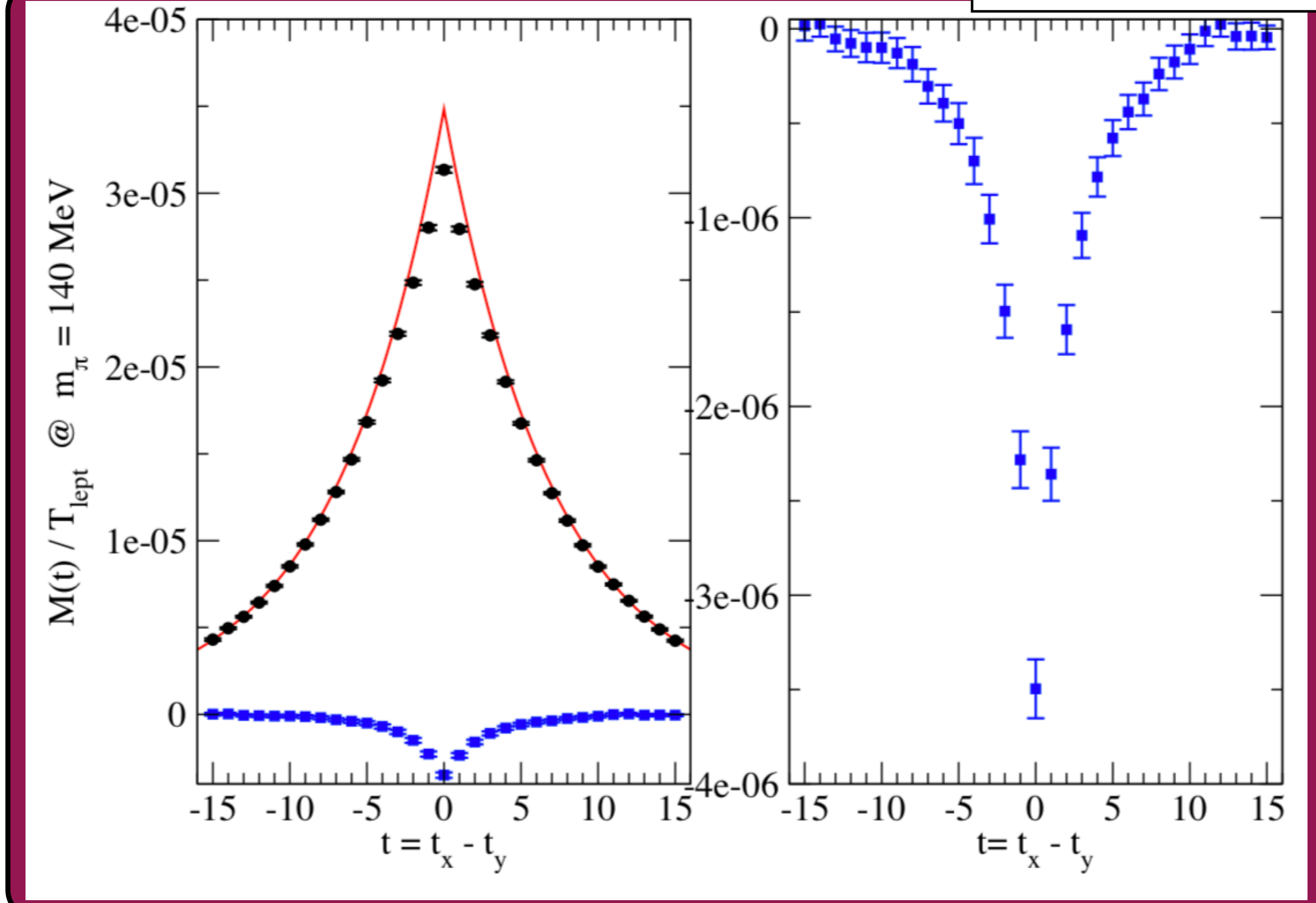
Full $nn \to pp$ transition

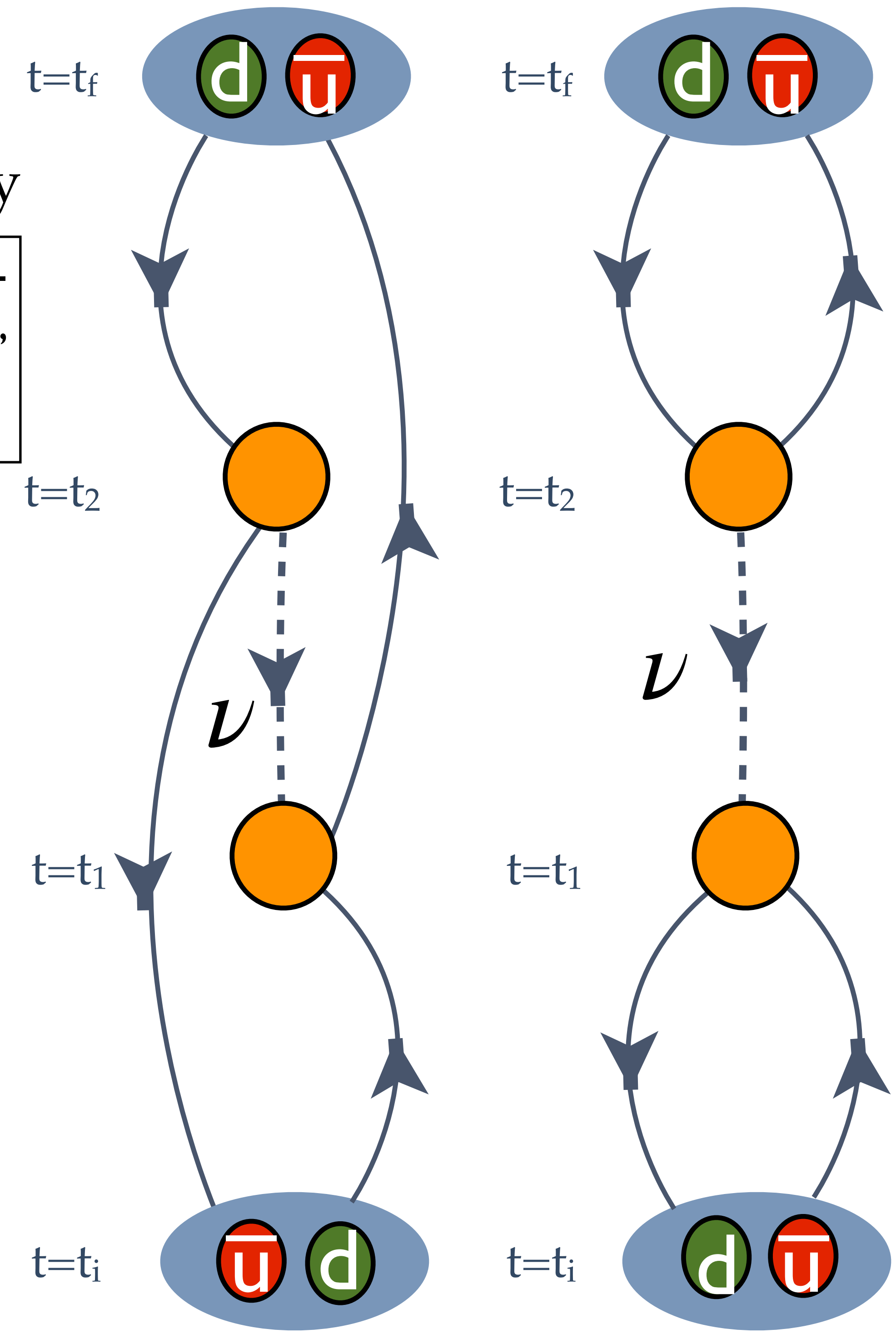


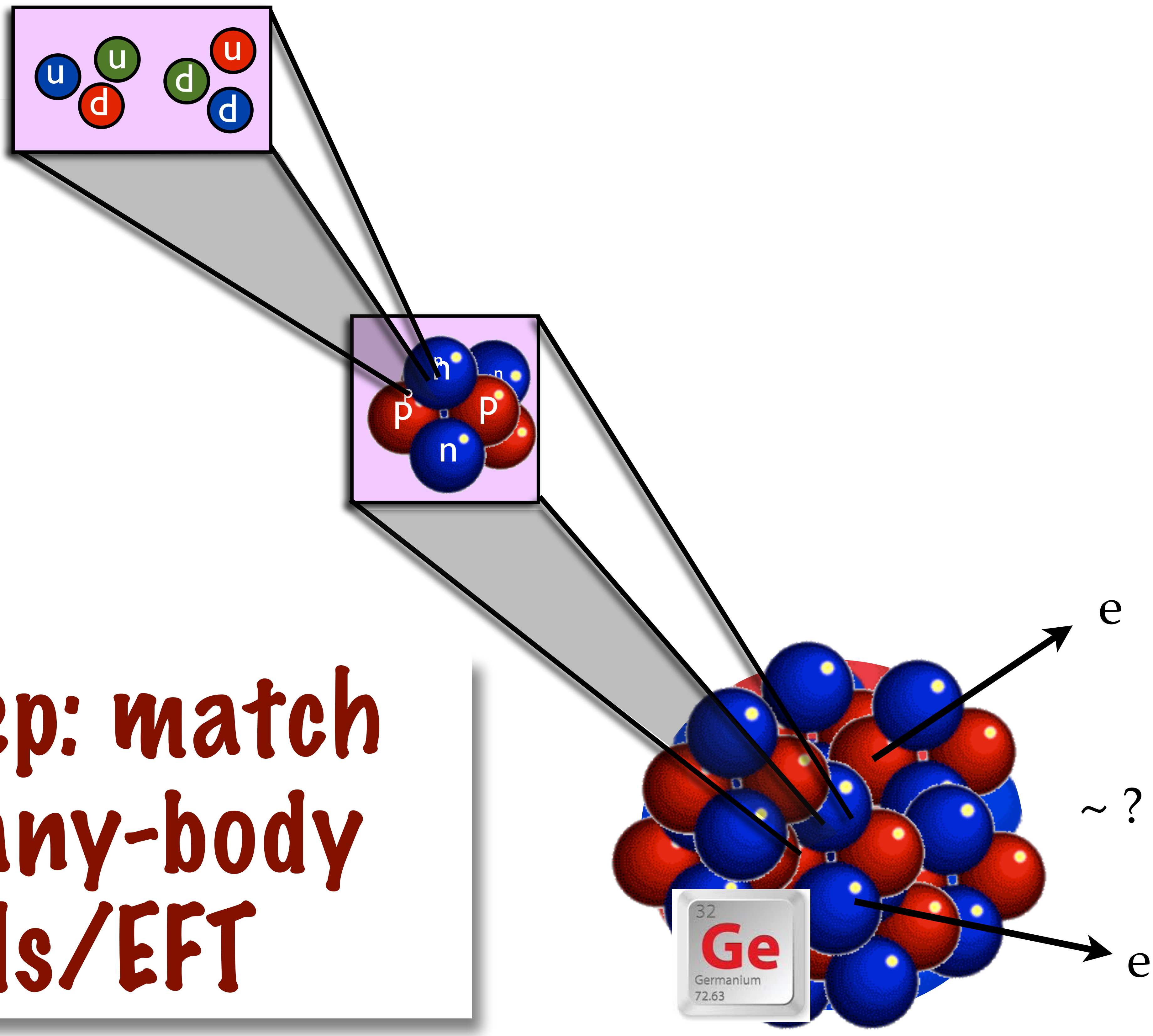
Cirigliano, V., Dekens, W., de Vries, J., Mereghetti, E., Graesser, M., Pastore, S., van Kolck, U
arXiv:1802.10097

- Work has begun to calculate full transition for light neutrino mechanism
  - Why? Just as in short-range operator case, EFT may not be reliable
  - Very difficult! both computationally and theoretically
  - Start with $\pi^- \to \pi^+$ as a test
    (see also Detmold & Murphy, Lattice 2018)

Xu Feng, Lu-Chang Jin, Xin-Yu Tuo, Shi-Cheng Xia, Phys. Rev. Lett. 122, 022001 (2019)

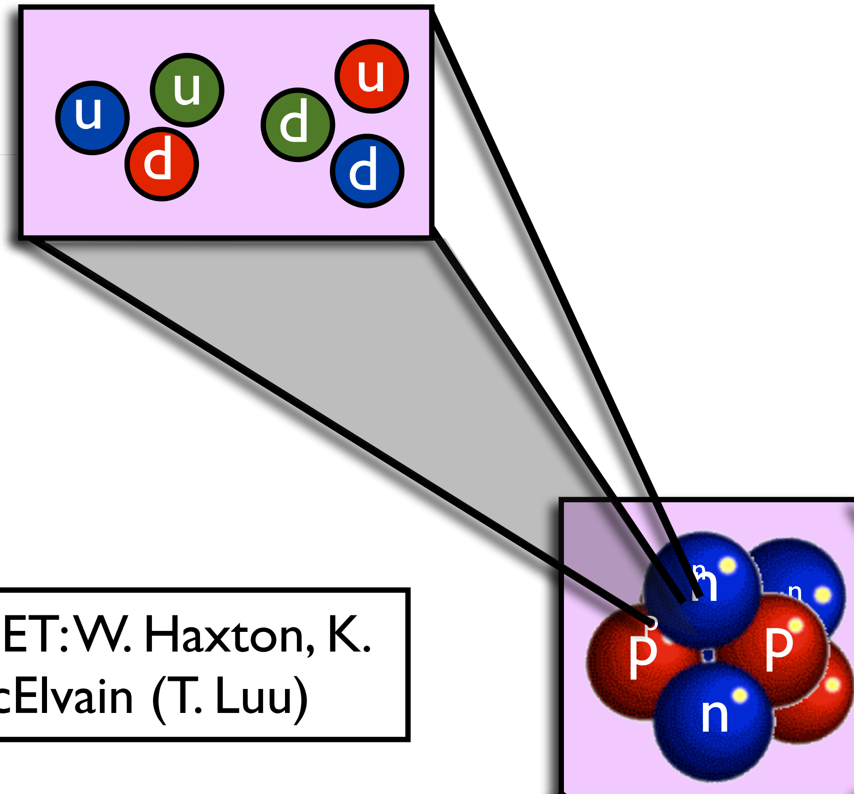


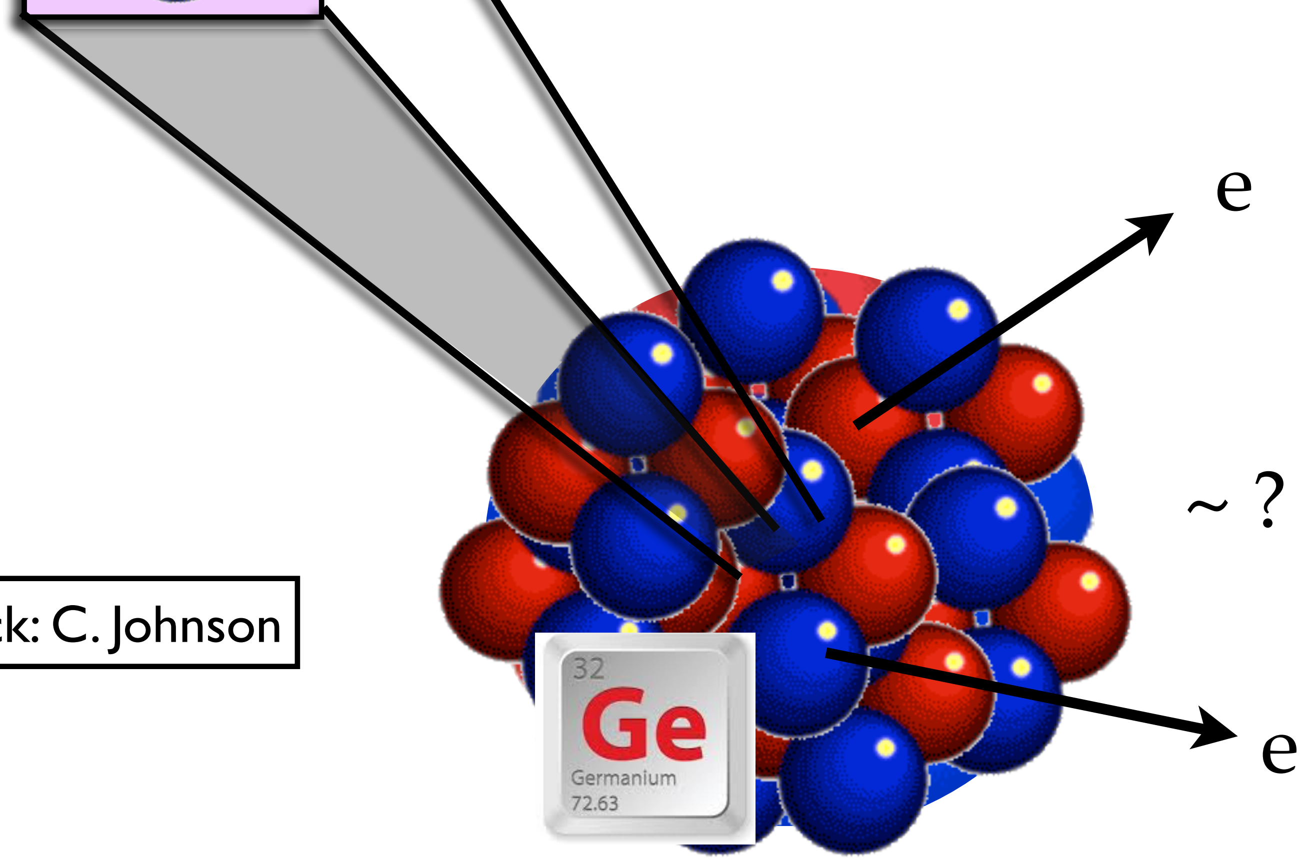




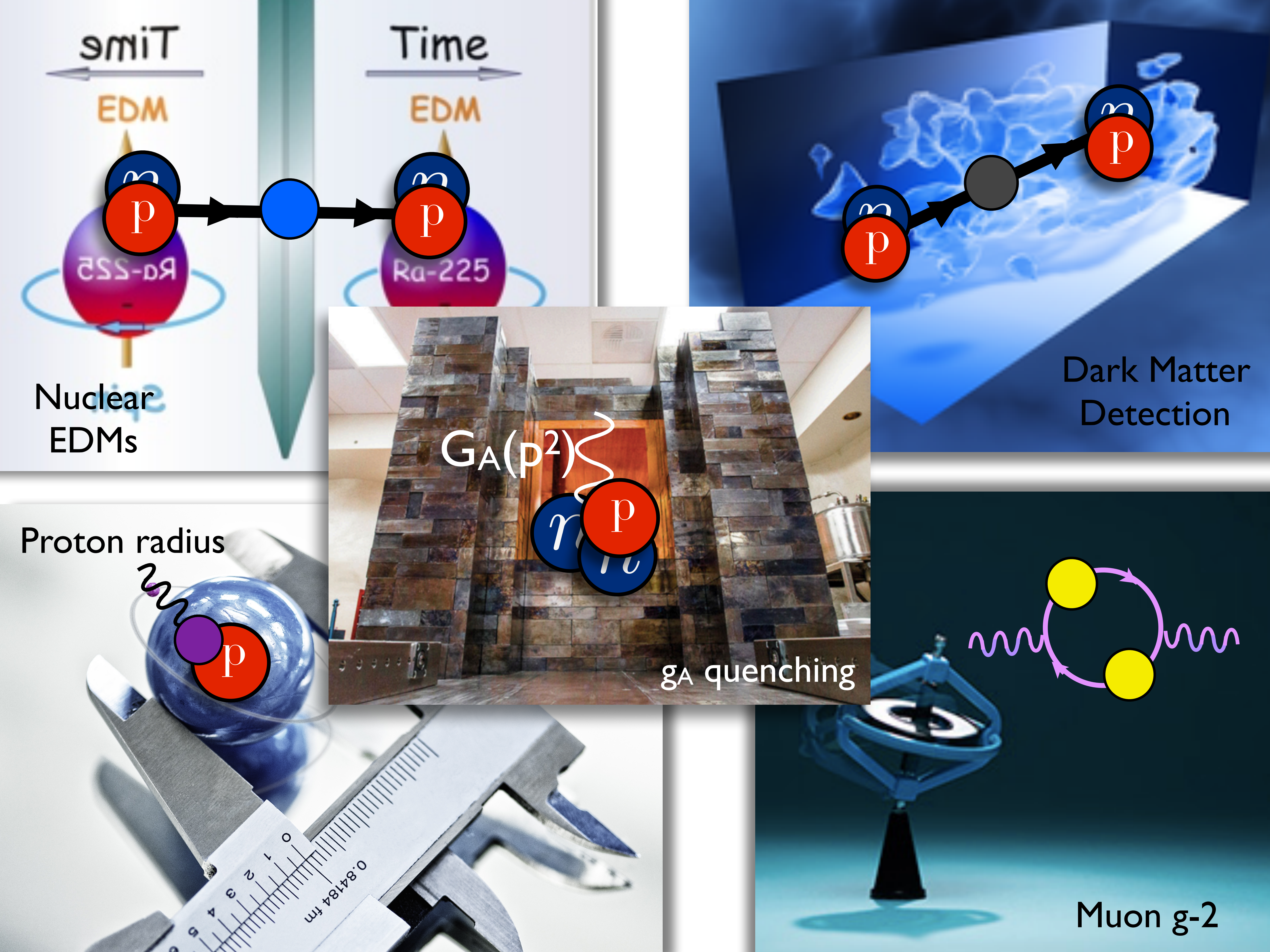
Final step: match onto many-body models/EFT

HOBET: W. Haxton, K. McElvain (T. Luu)





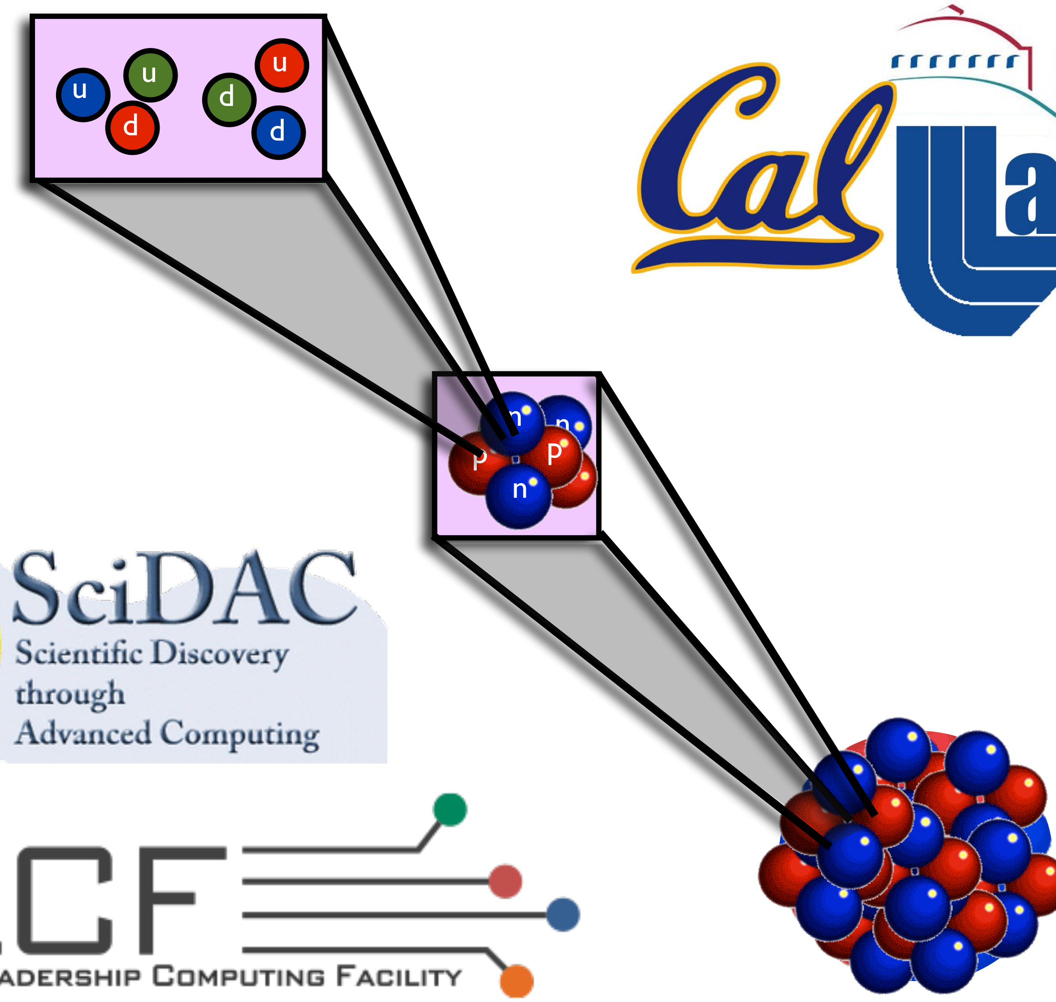
Bigstick: C. Johnson



Time
EDM
EDM
Ra-225
Nuclear EDMs
Dark Matter Detection
$G_A(p^2)$
g_A quenching
Proton radius
0.84184 fm
Muon g-2


Time
EDM
EDM
p
p
Ra-225
Nuclear
EDMs
p
p
Dark Matter
Detection
Stay Tuned!
gA quenching
Proton radius
p
0.84184 fm
Muon g-2

- RIKEN/LBL: C.C. Chang
- RIKEN/BNL: E. Rinaldi
- NERSC: T. Kurth
- Liverpool: N. Garron
- UW/INT C. Monahan
- nVidia: M.A. Clark
- JLab: B. Joo
- WM/JLab: K. Orginos
- CCNY: B. Tiburzi
- LBL/UCB: A. Walker-Loud
- Glasgow: C. Bouchard
- UNC: H. Monge-Camacho
- Jülich: E. Berkowitz
- LLNL: P. Vranas, A. Gambhir, D. Brantley



CalLat

SciDAC Scientific Discovery through Advanced Computing

OLCF Oak Ridge Leadership Computing Facility

NERSC

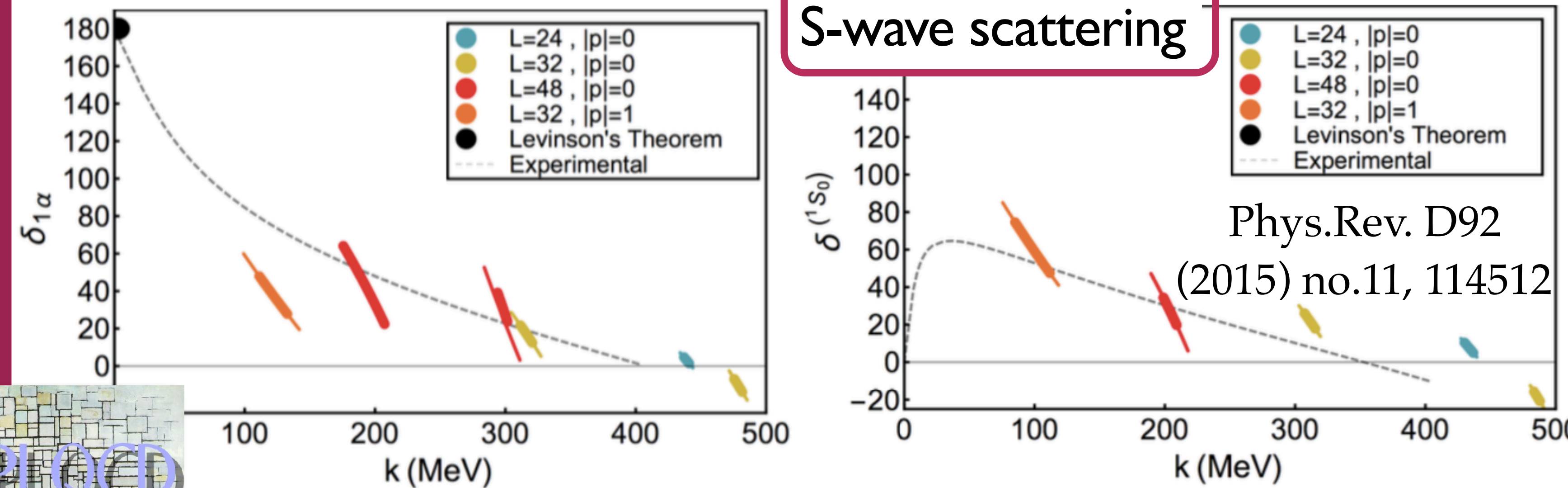
U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

U.S. DEPARTMENT OF ENERGY | Office of Science

NN: status

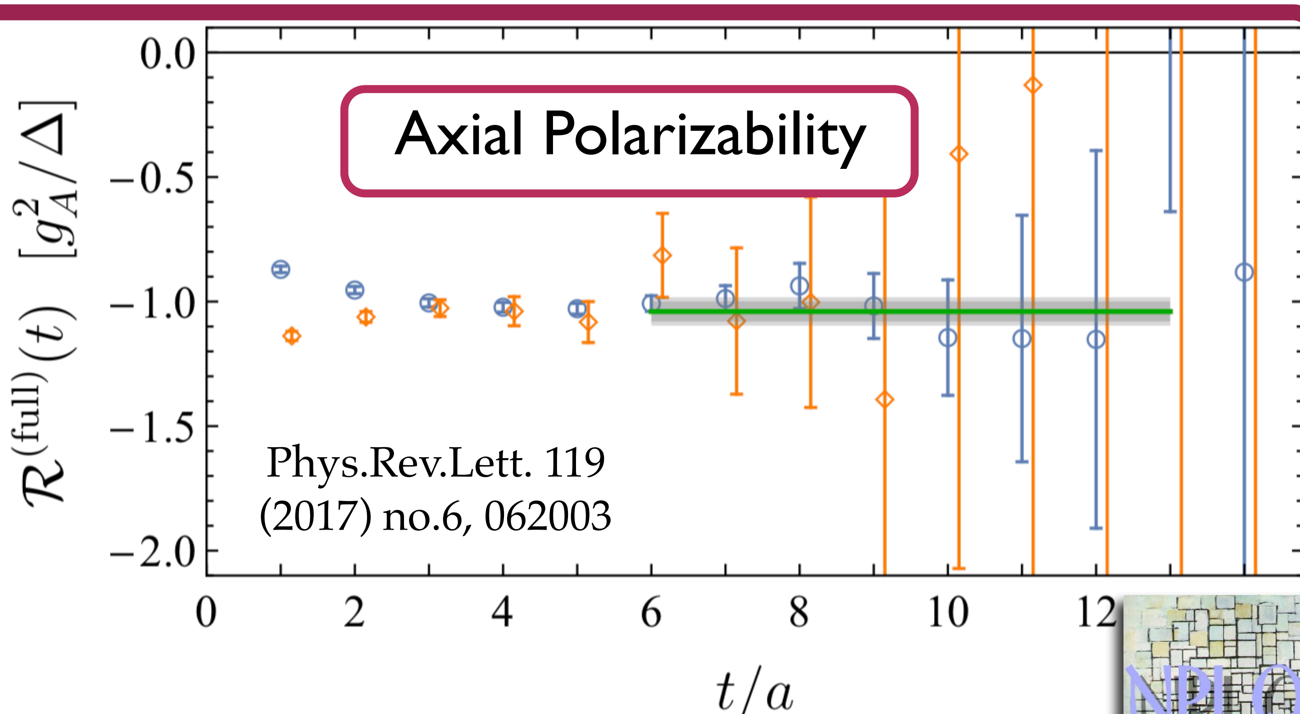
$m_\pi \sim 450$ MeV

S-wave scattering



Phys.Rev. D92 (2015) no.11, 114512

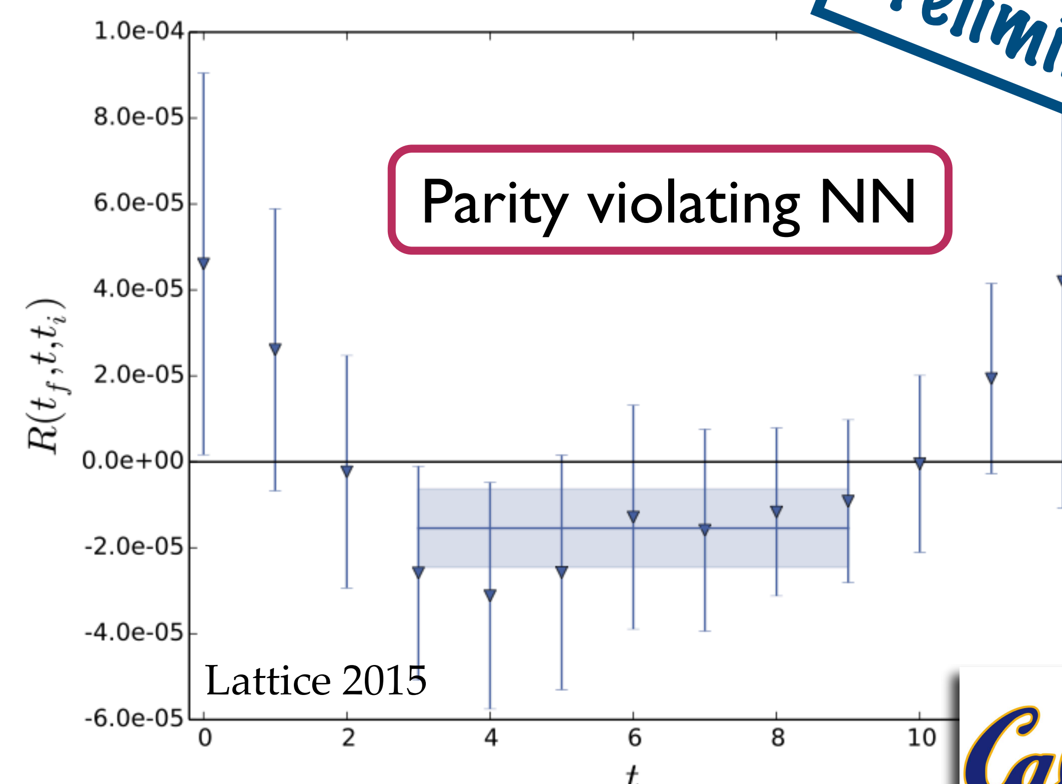
Axial Polarizability



Phys.Rev.Lett. 119 (2017) no.6, 062003

Preliminary

Parity violating NN

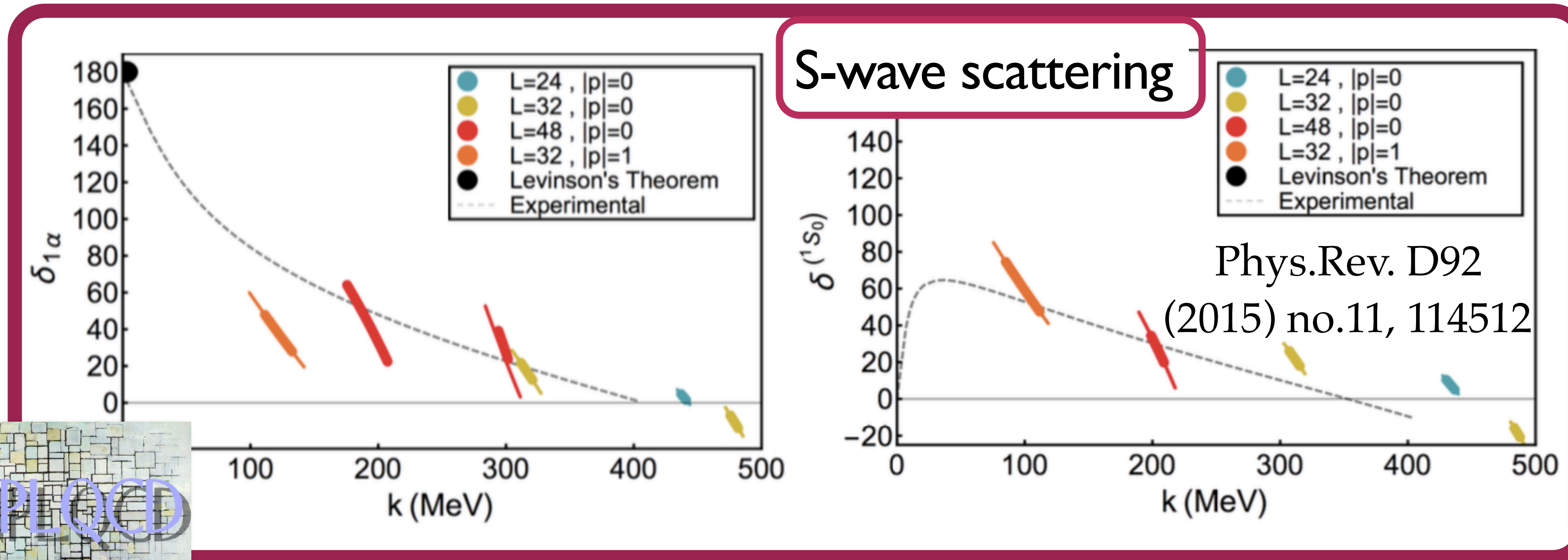


Lattice 2015

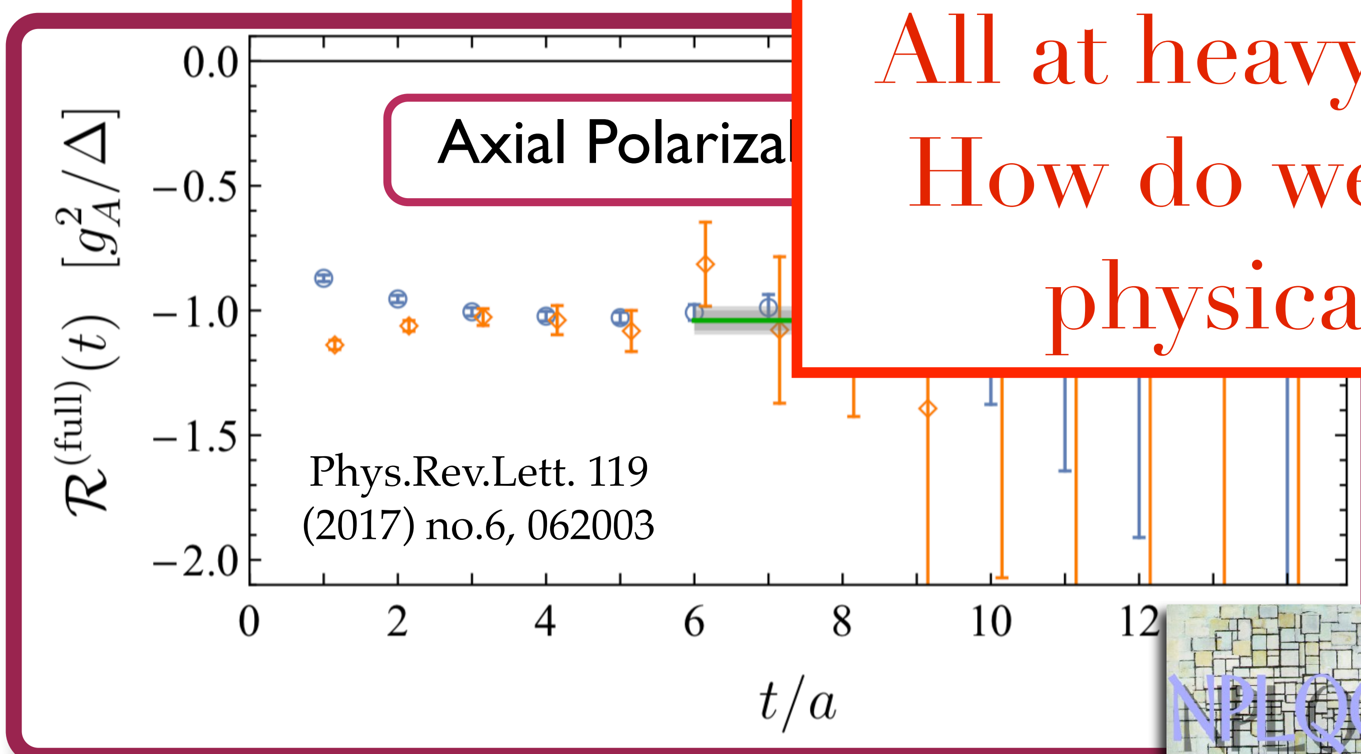
$m_\pi \sim 800$ MeV

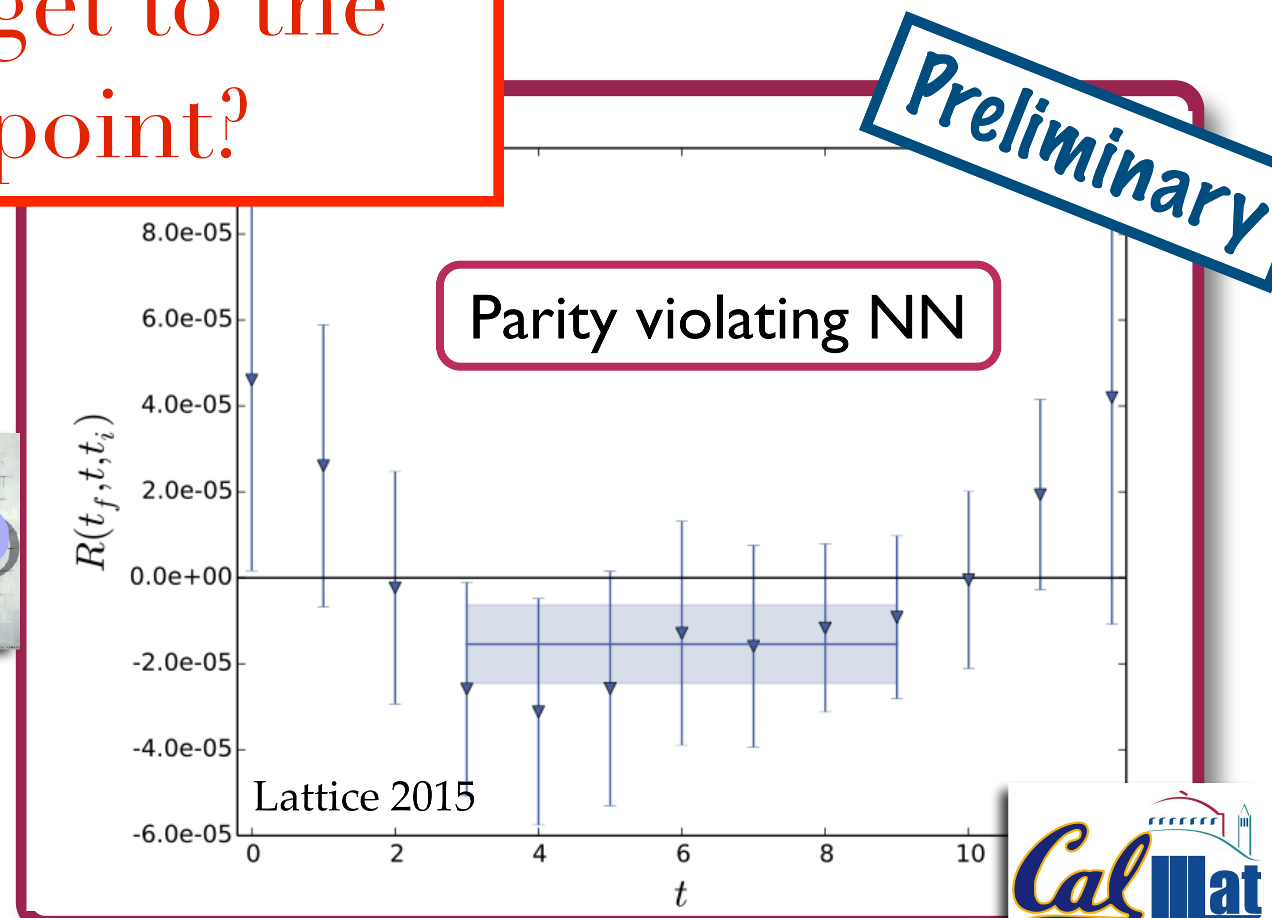
NN: status

$m_\pi \sim 450$ MeV



All at heavy pion mass. How do we get to the physical point?





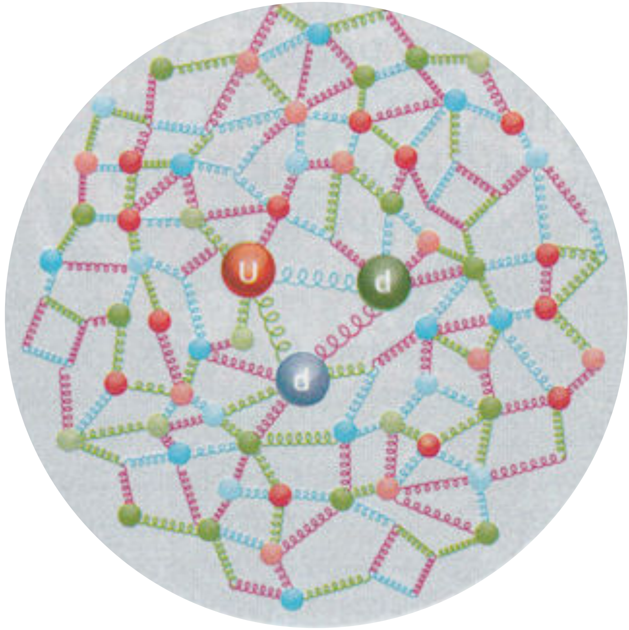
$m_\pi \sim 800$ MeV

Lower pion mass? Difficulty lies in spectroscopy

$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t}$$

$\mathcal{O}$:

ψ_n :



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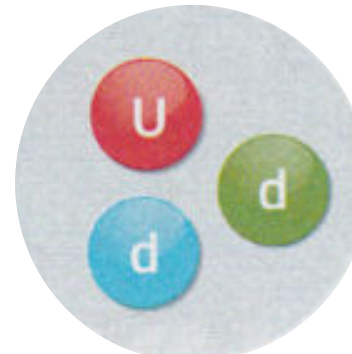
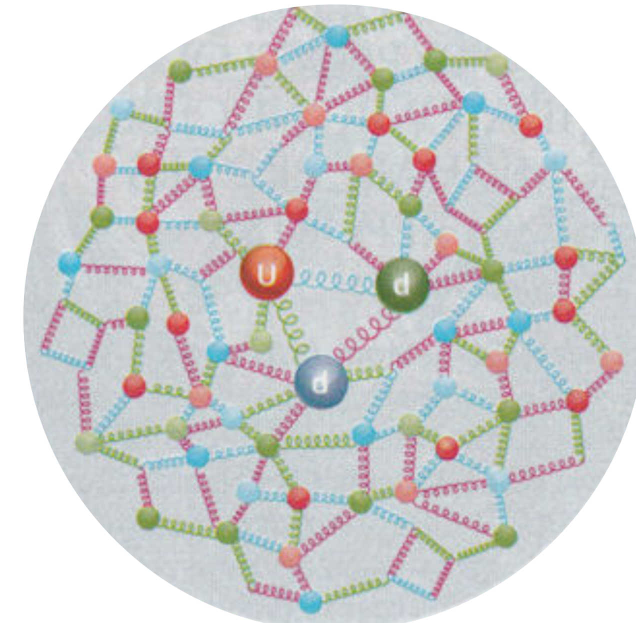
$\mathcal{O}$:

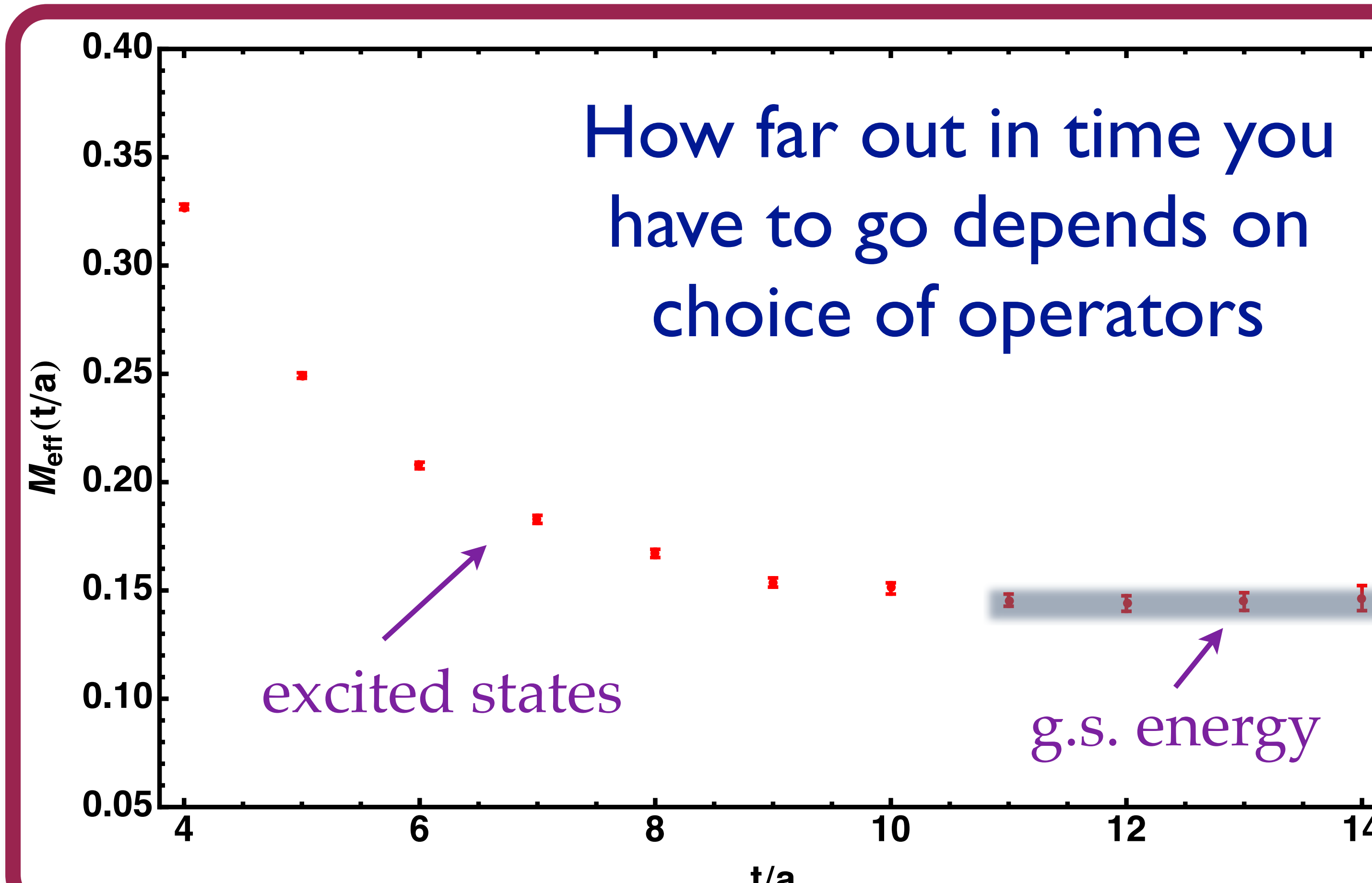


ψ_n :

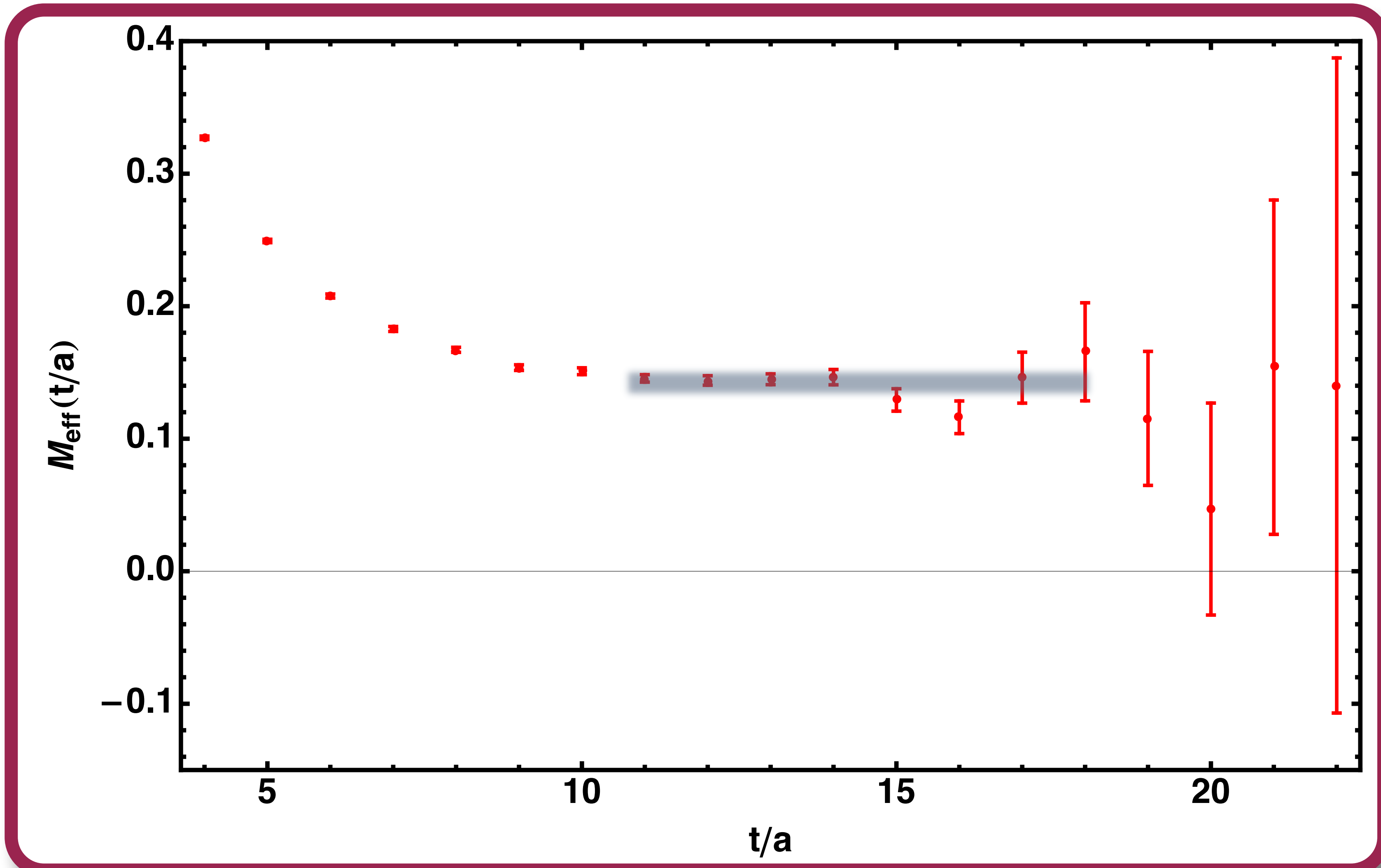


Effective mass plot:

$$M_{\rm eff} \equiv \ln \frac{C(t)}{C(t+1)} \underset{t\to\infty}{\longrightarrow} E_0$$

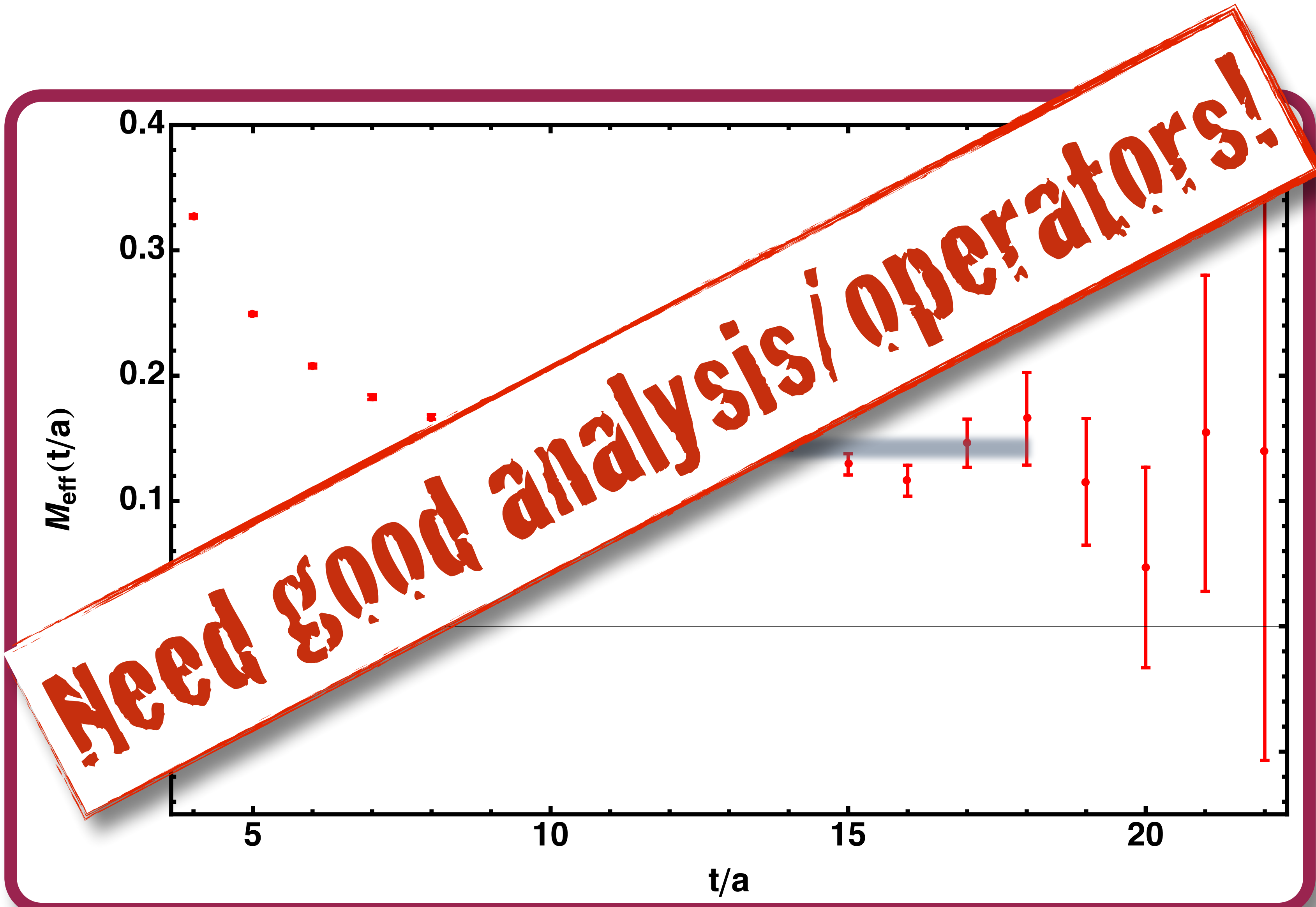


Nucleons: limited by signal-to-noise



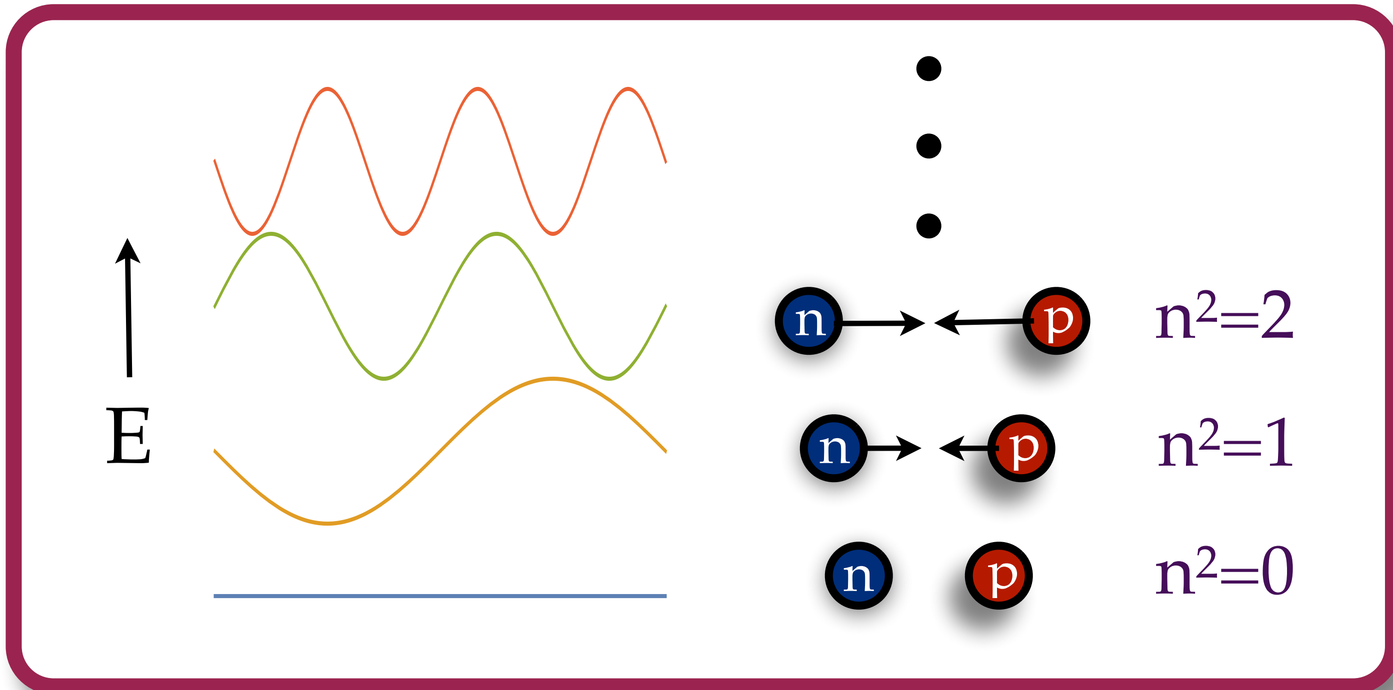
$$\sim e^{A(M_n - 3/2 m_\pi)t}$$

Nucleons: limited by signal-to-noise



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

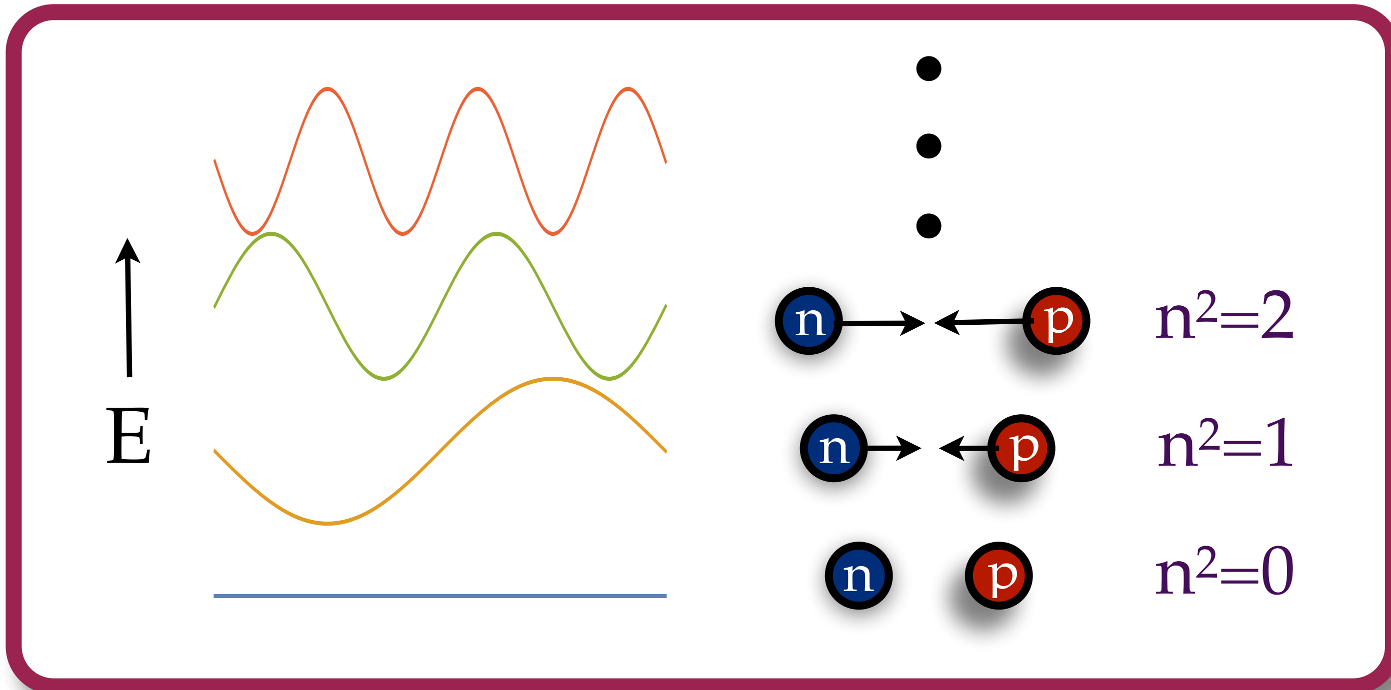
Excited state contamination



Elastic 2-body

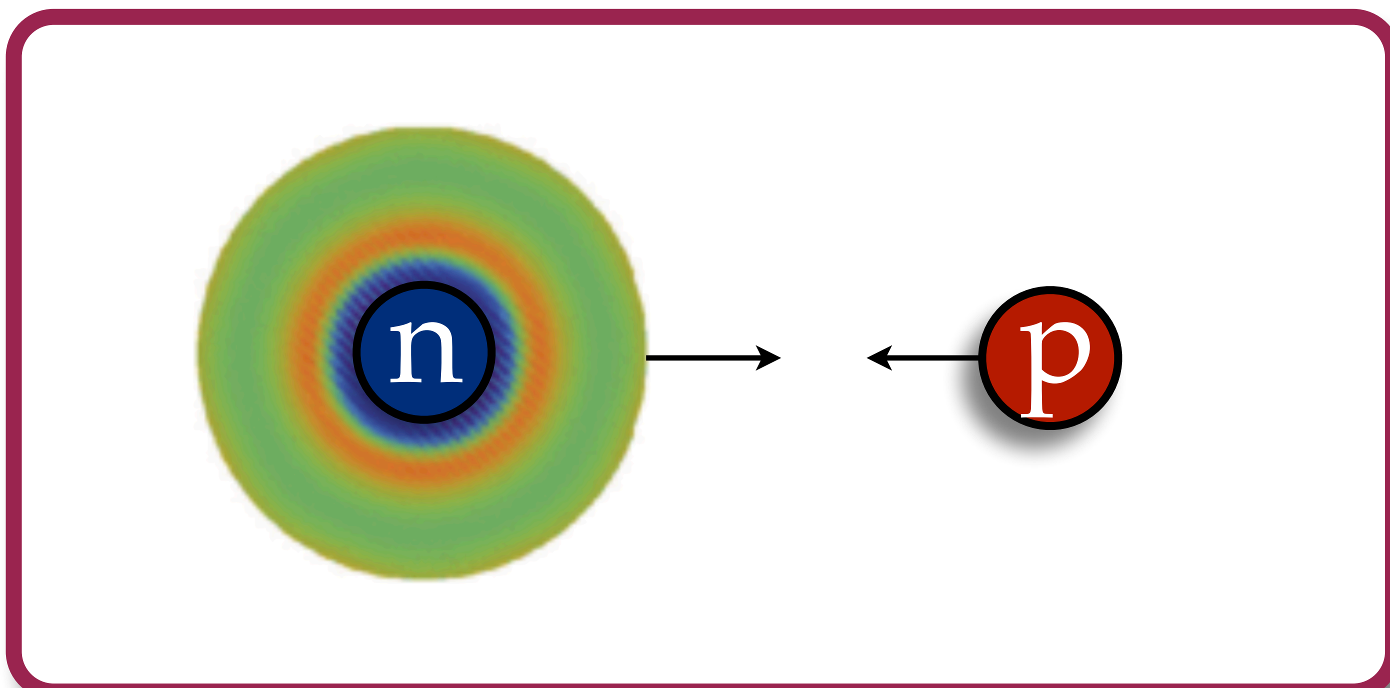
$\Delta E \sim 50$ MeV

Excited state contamination



Elastic 2-body

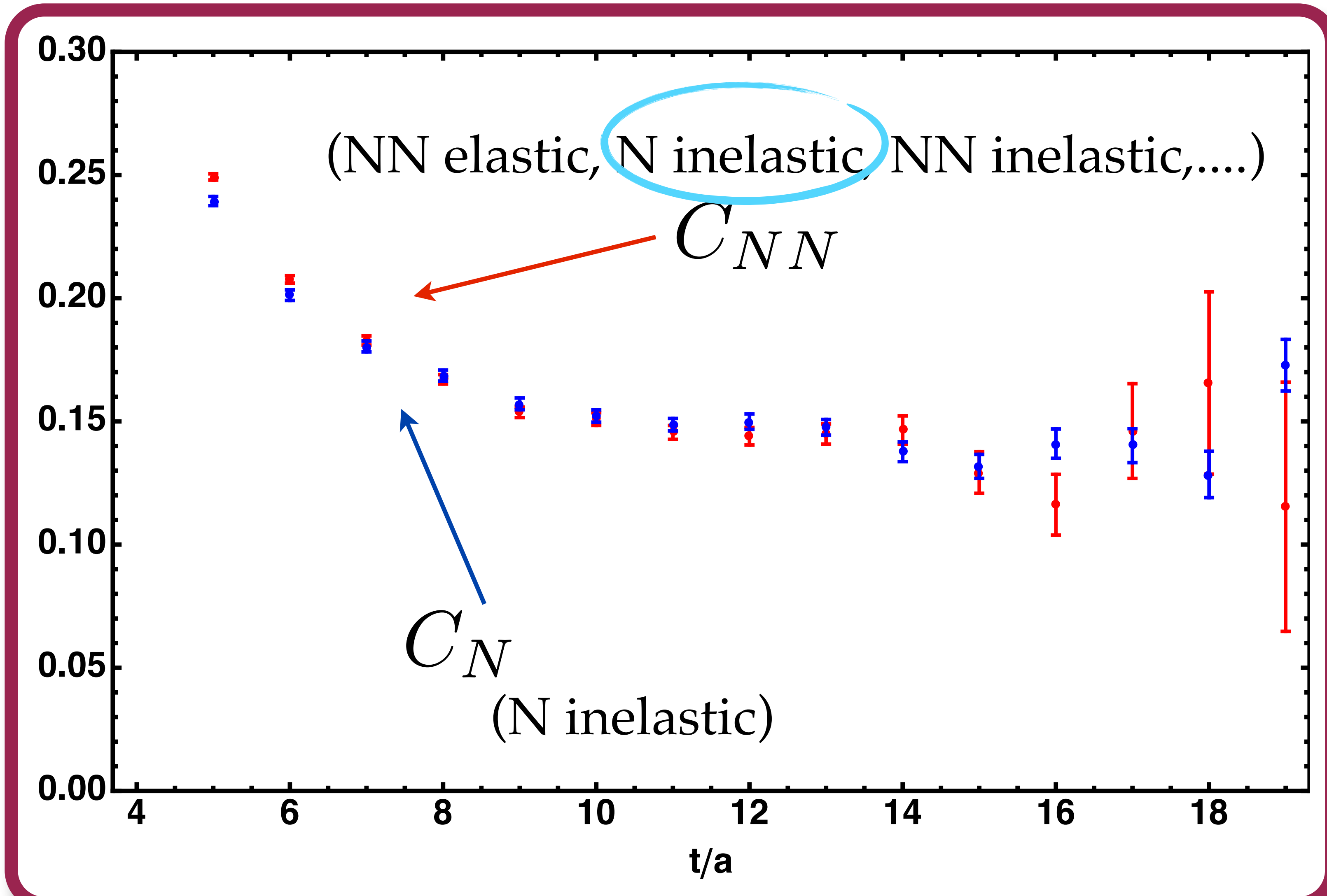
$\Delta E \sim 50$ MeV



Inelastic single body

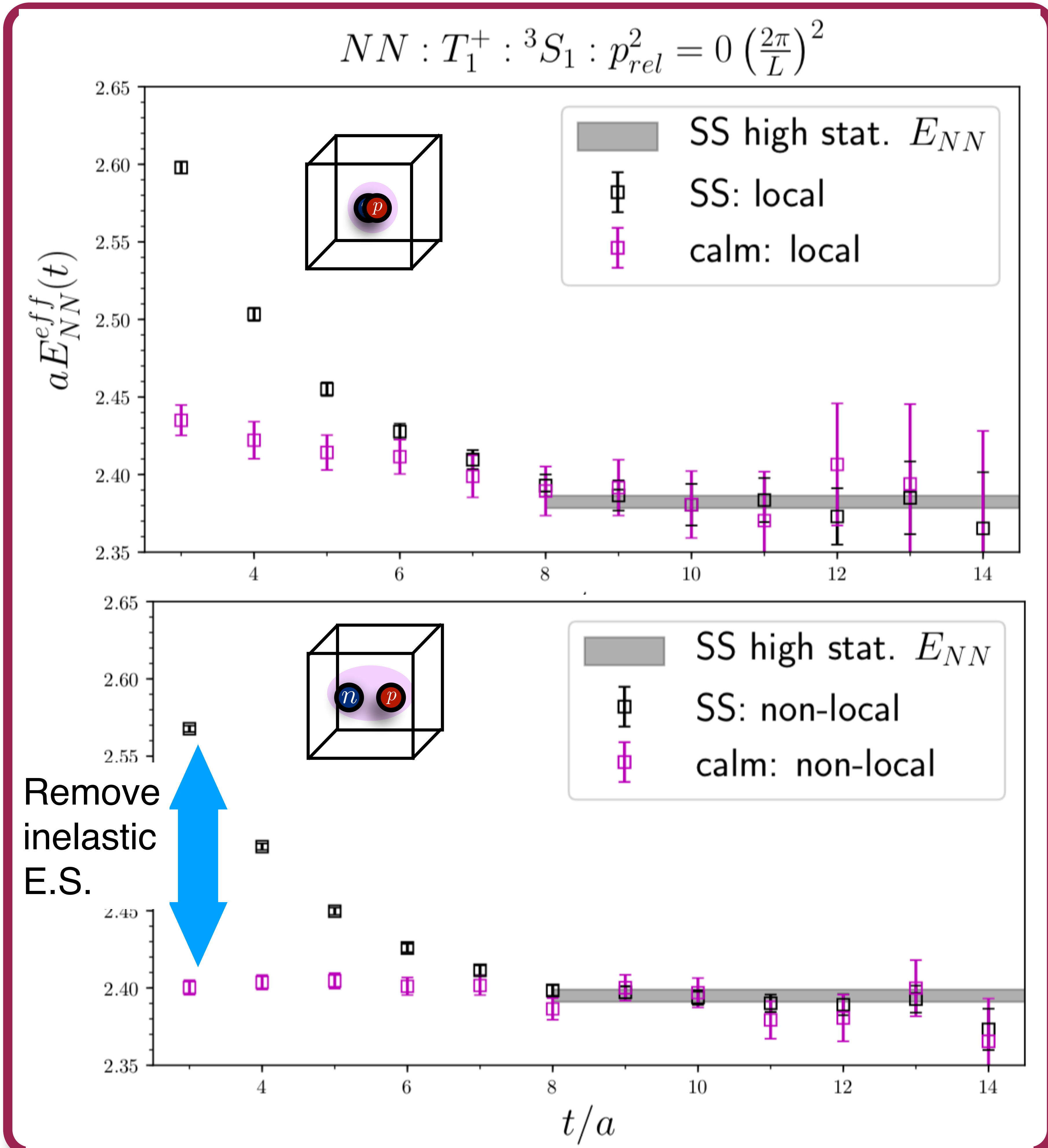
$\Delta E \sim m_\pi$

Improved NN



Long time behavior of NN correlator dominated by inelastic single nucleon excited state

→ Need to improve single nucleon interpolating operator for earlier plateaus

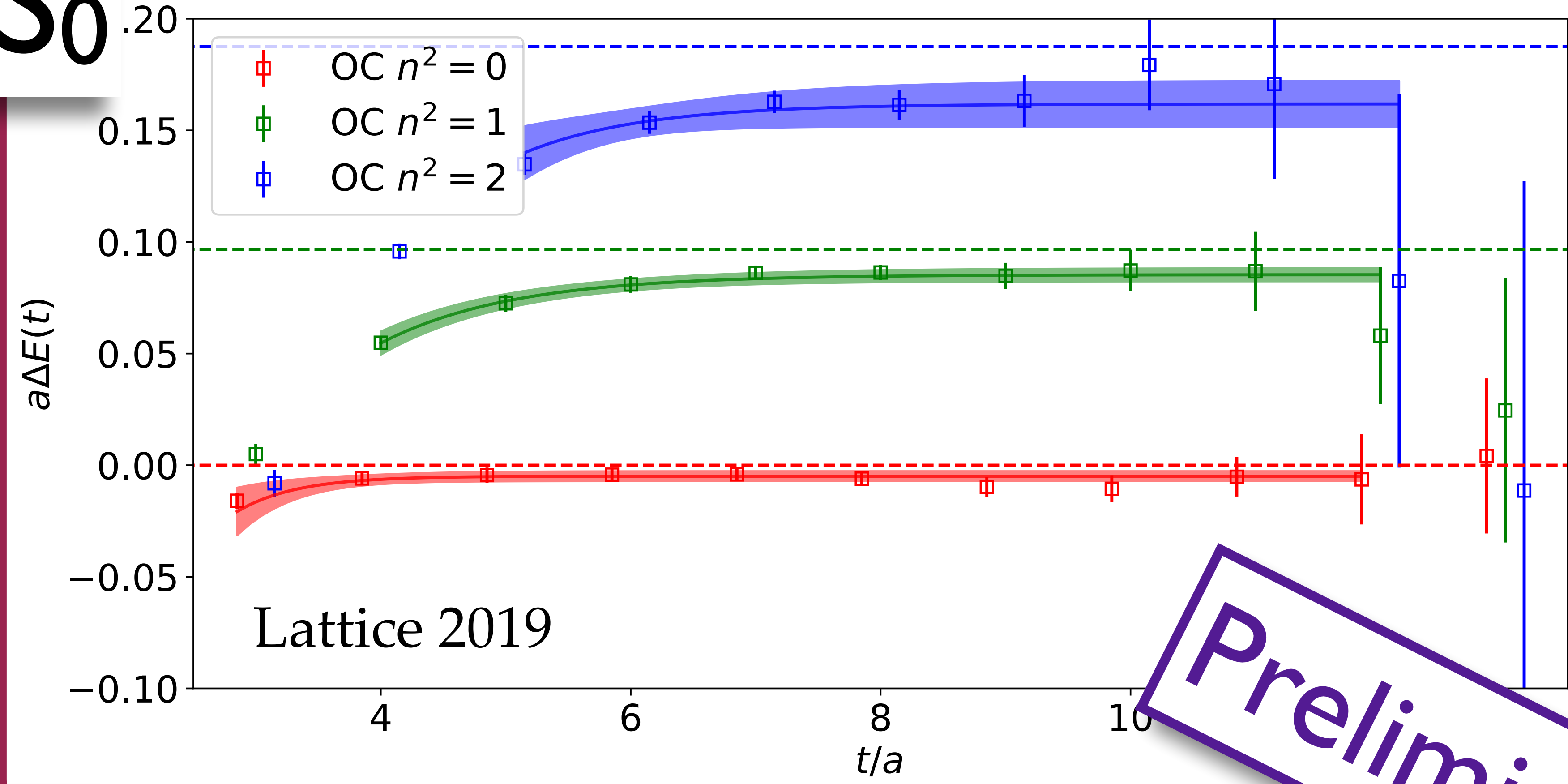


Remove
elastic E.S.

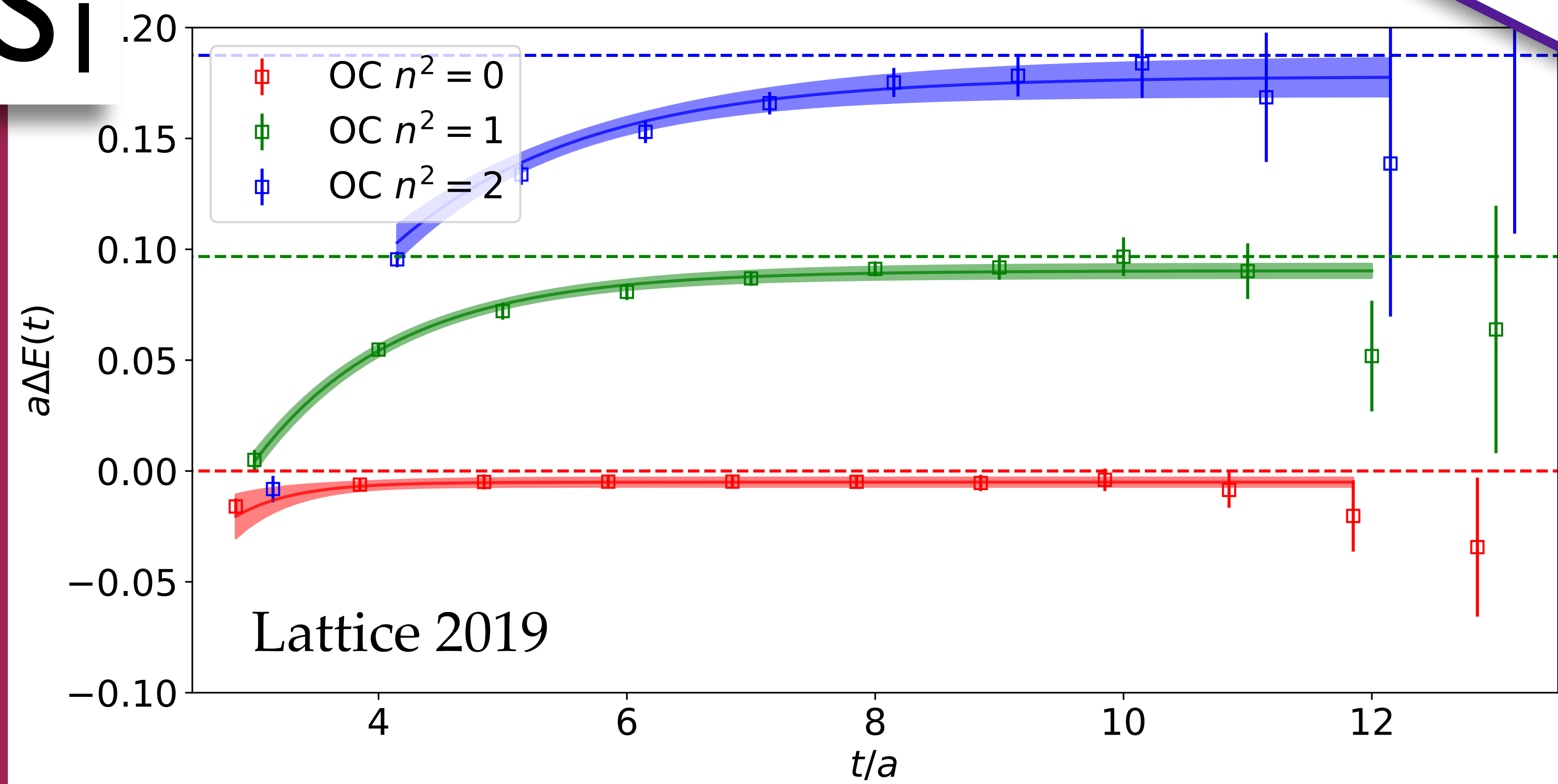
CalLat (2017)
Matrix Prony:
NPLQCD (2009)

Energy levels:
m_π ~ 350 MeV
(DWF on MILC HISQ ensembles)

$^1S_0$

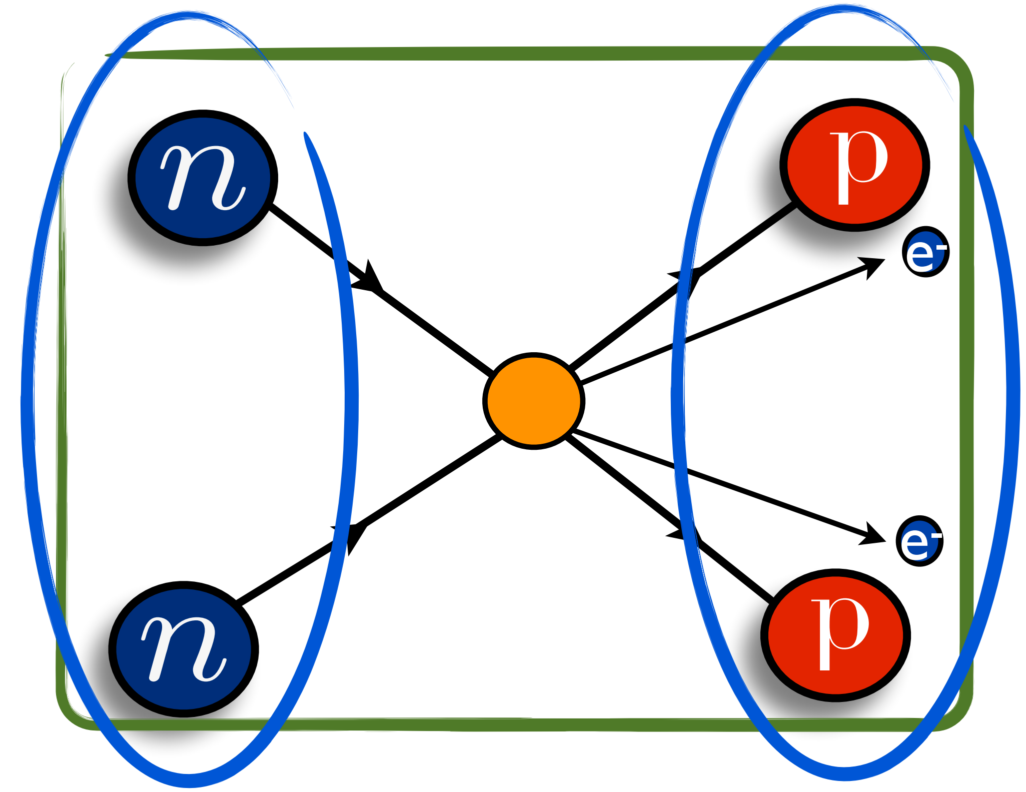


$^3S_1$



Preliminary

3. Two-nucleon contact



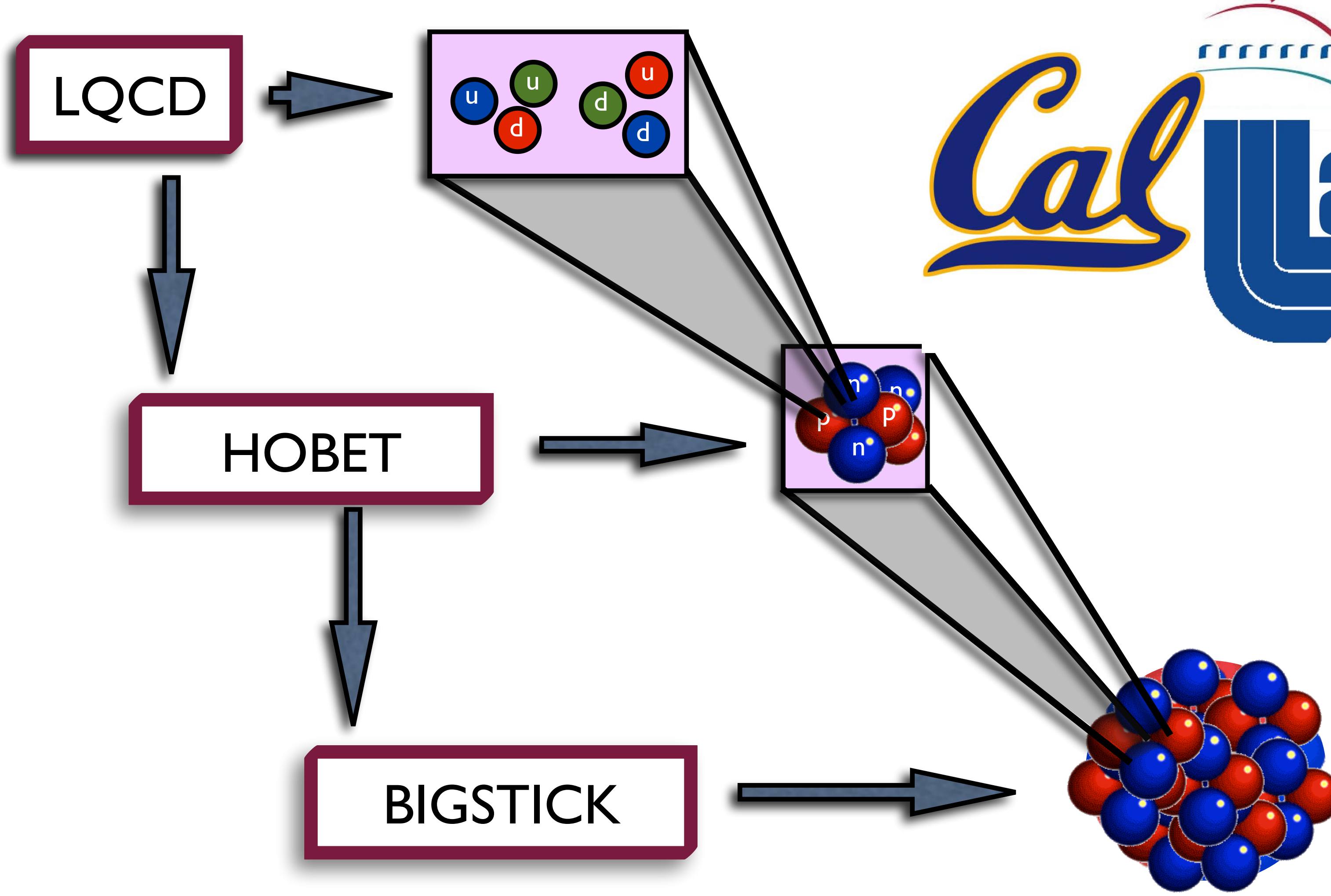
- Some new developments:
  - Exponentially improved NN operators will allow us to lower the pion mass
  - HOBET in a periodic box
    - more direct path from finite volume lattice results to nuclear many-body techniques (with W. Haxton and K. McElvain)
- Results to come!

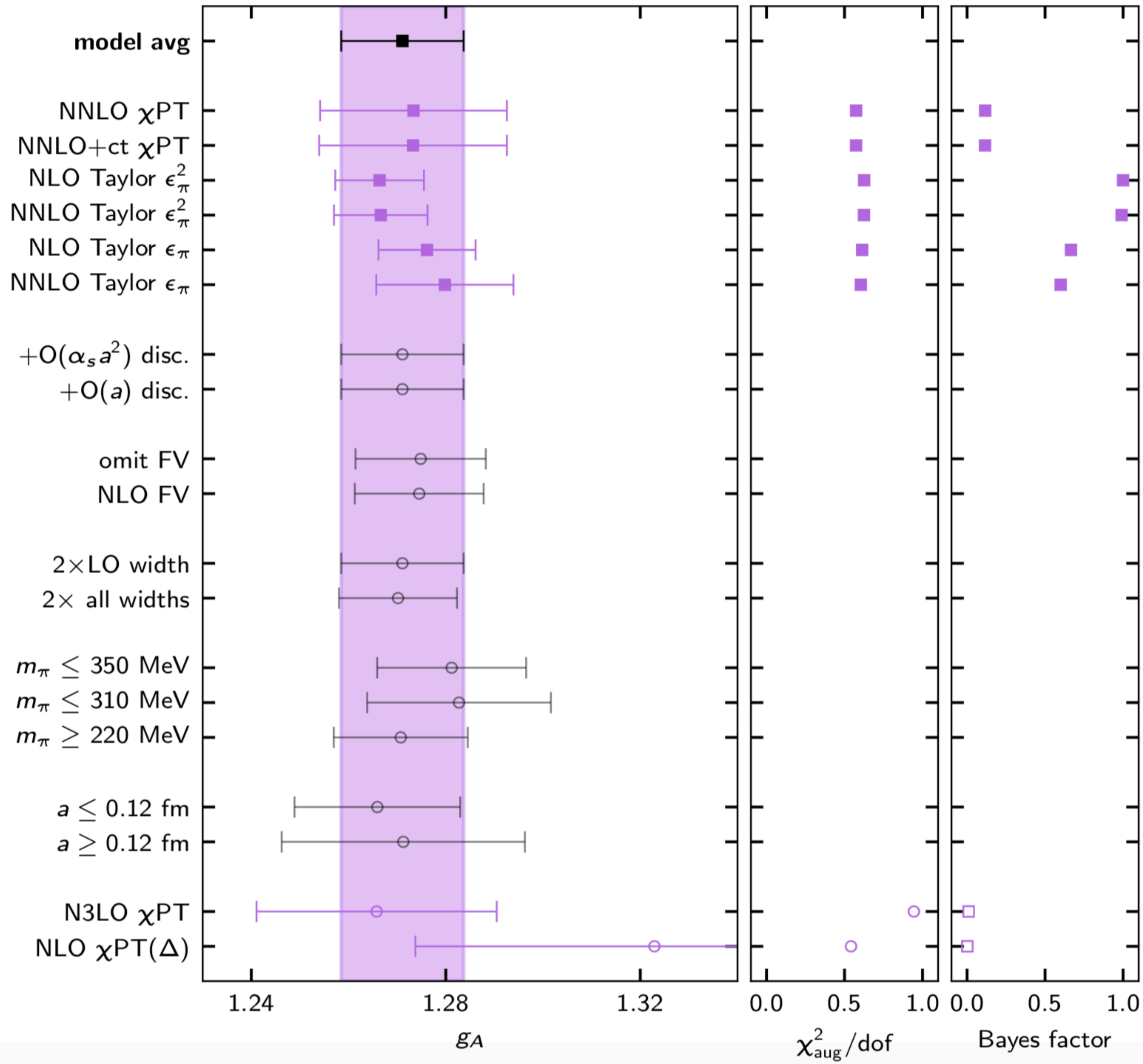
Summary

- LQCD can be used as a step toward connecting experimental signals to BSM models
- Nucleon axial charge
  - LQCD calculations are becoming reliably accurate and precise
  - Can be extended to calculate g_A quenching effects
- $\pi^- \rightarrow \pi^+$ $0\nu\beta\beta$ matrix element
  - Complete LQCD calculation at the physical point of leading short-range contribution
  - To do: Plug the results into your favorite many-body calculation!
- Two-nucleon contact
  - Testing new method for two nucleon operators
  - Machinery in place for calculating 3-point function
  - Advances in calculating light neutrino contributions may lead to calculation of non-perturbative NN ampitudes

W. Detmold, D.J. Murphy, Lattice 2019
X. Feng, et al, Phys. Rev. Lett. 122, 022001 (2019)

- 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





model avg
NNLO χPT
NNLO+ct χPT
NLO Taylor ϵ_π^2
NNLO Taylor ϵ_π^2
NLO Taylor ϵ_π
NNLO Taylor ϵ_π
$+O(\alpha_s a^2)$ disc.
$+O(a)$ disc.
omit FV
NLO FV
2×LO width
2× all widths
$m_\pi \leq 350$ MeV
$m_\pi \leq 310$ MeV
$m_\pi \geq 220$ MeV
$a \leq 0.12$ fm
$a \geq 0.12$ fm
N3LO χPT
NLO χPT(Δ)
1.24
1.28
1.32
g_A
0.0
0.5
1.0
χ^2_{aug}/dof
0.0
0.5
1.0
Bayes factor