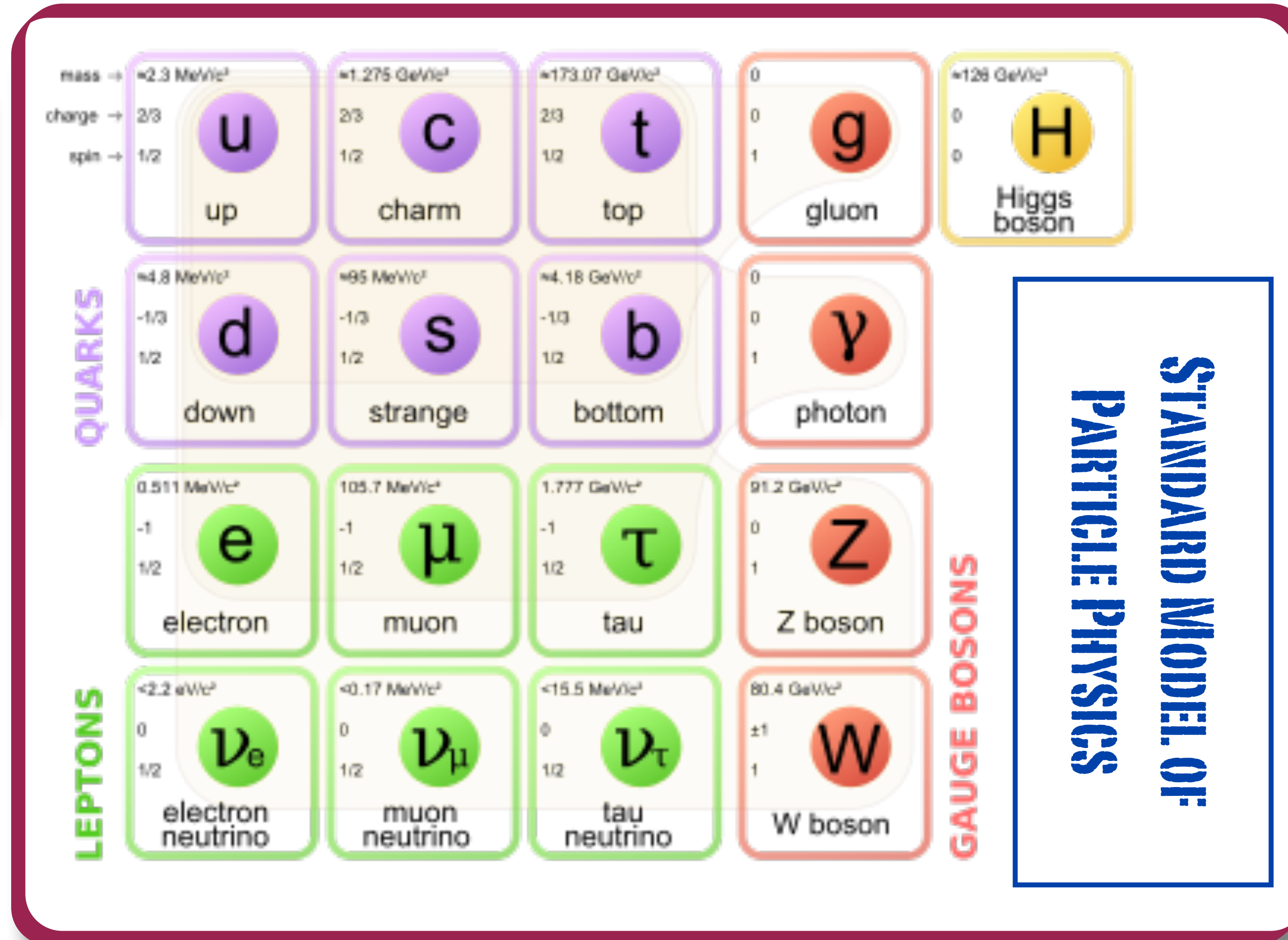
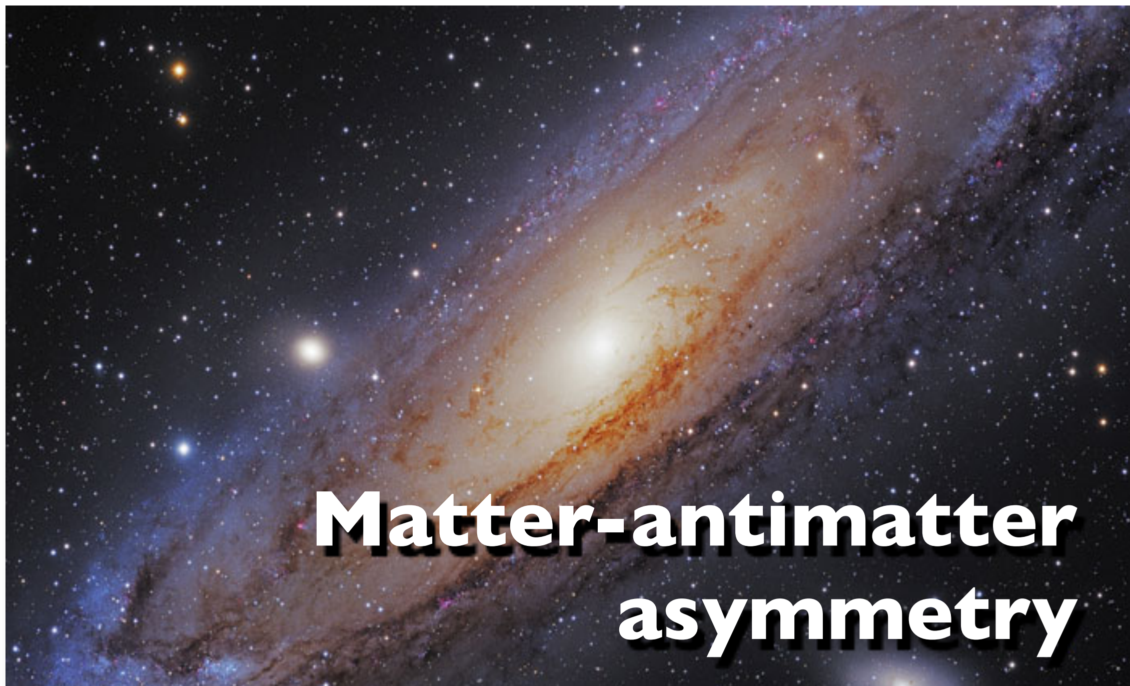
Symmetries and Interactions from Lattice QCD

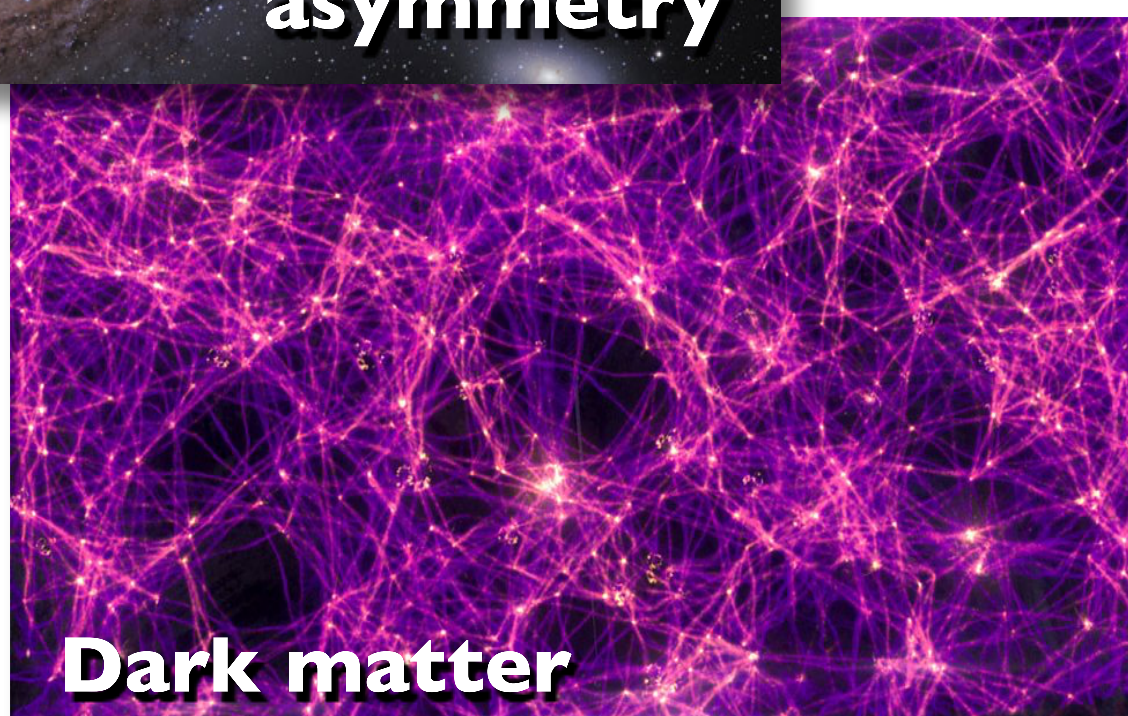
Amy Nicholson
UNC, Chapel Hill

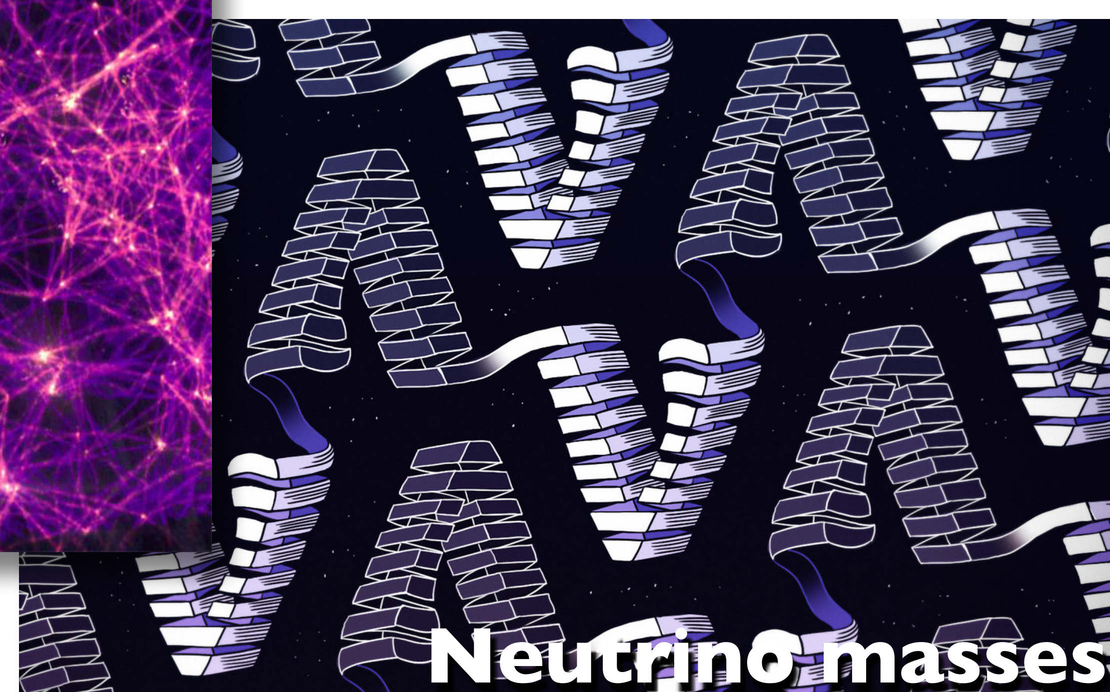
CIPANP18, Palm Springs, CA
May 30, 2018

The Standard Model and Beyond









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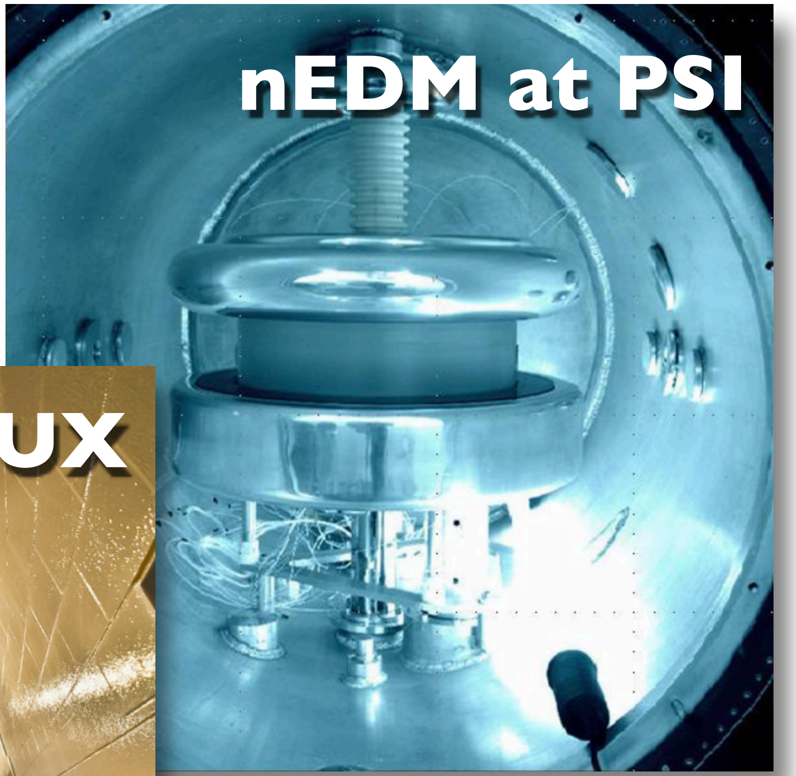
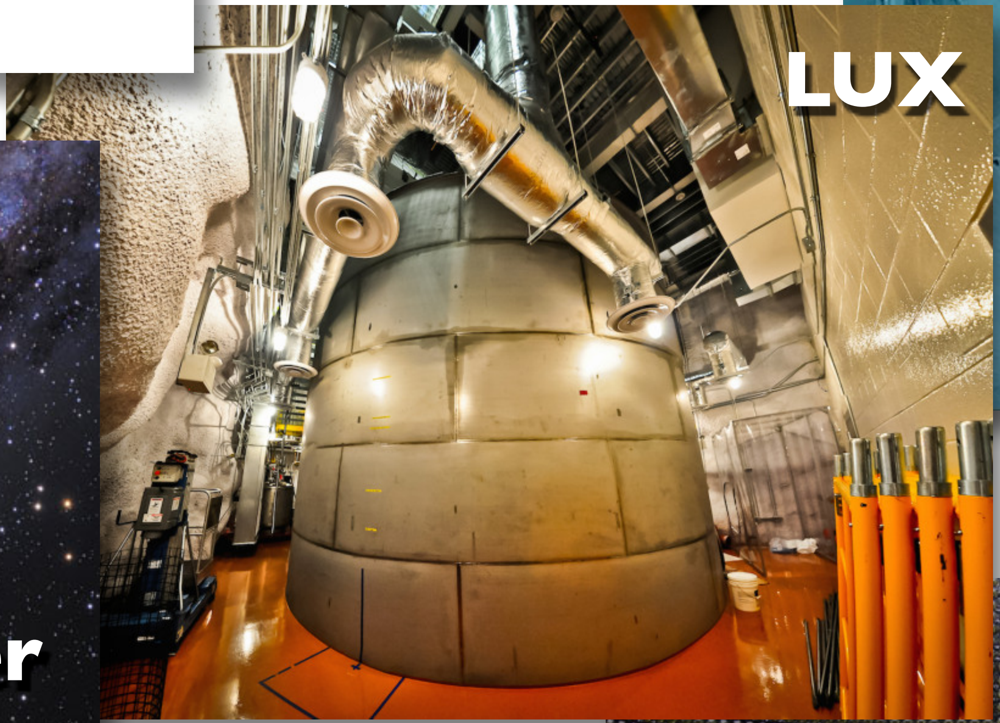
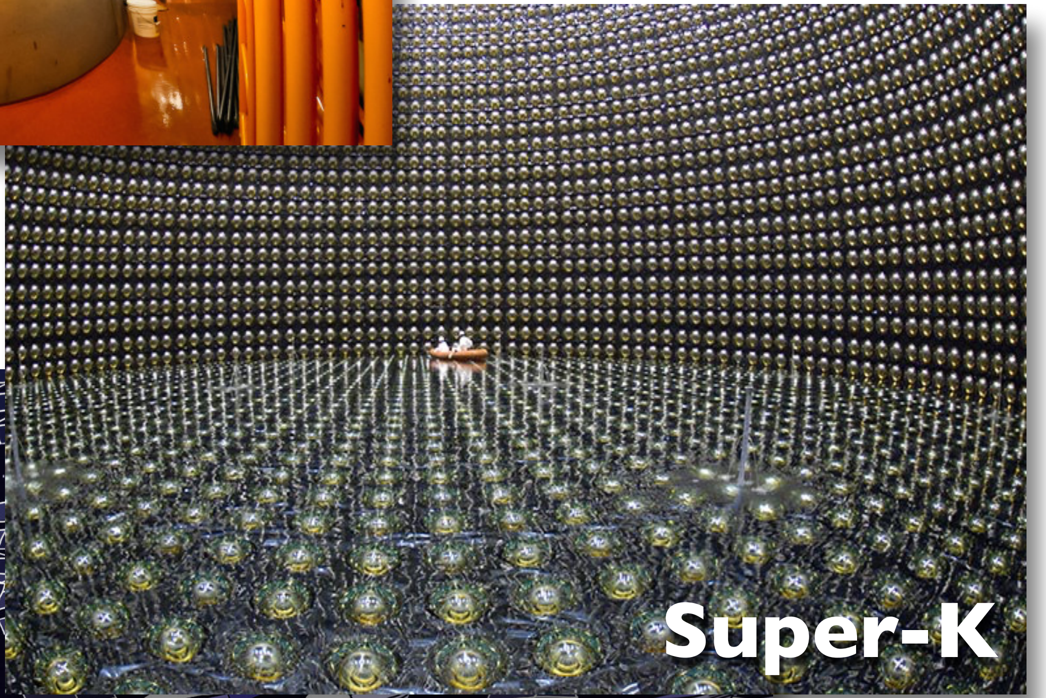
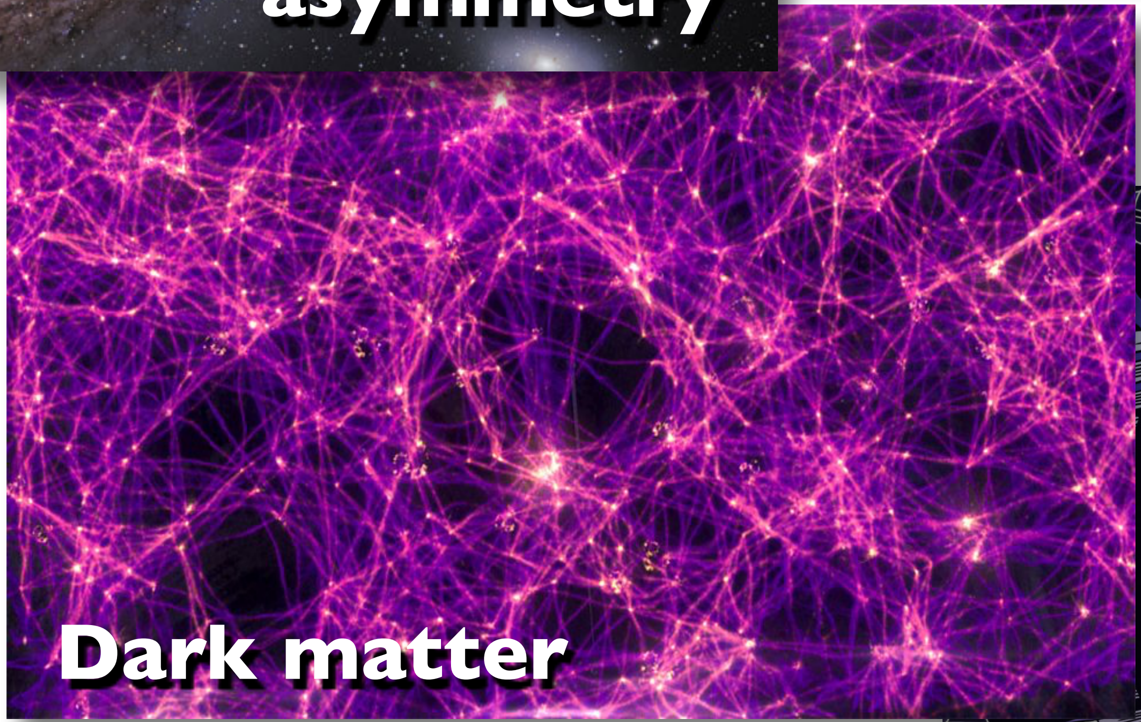
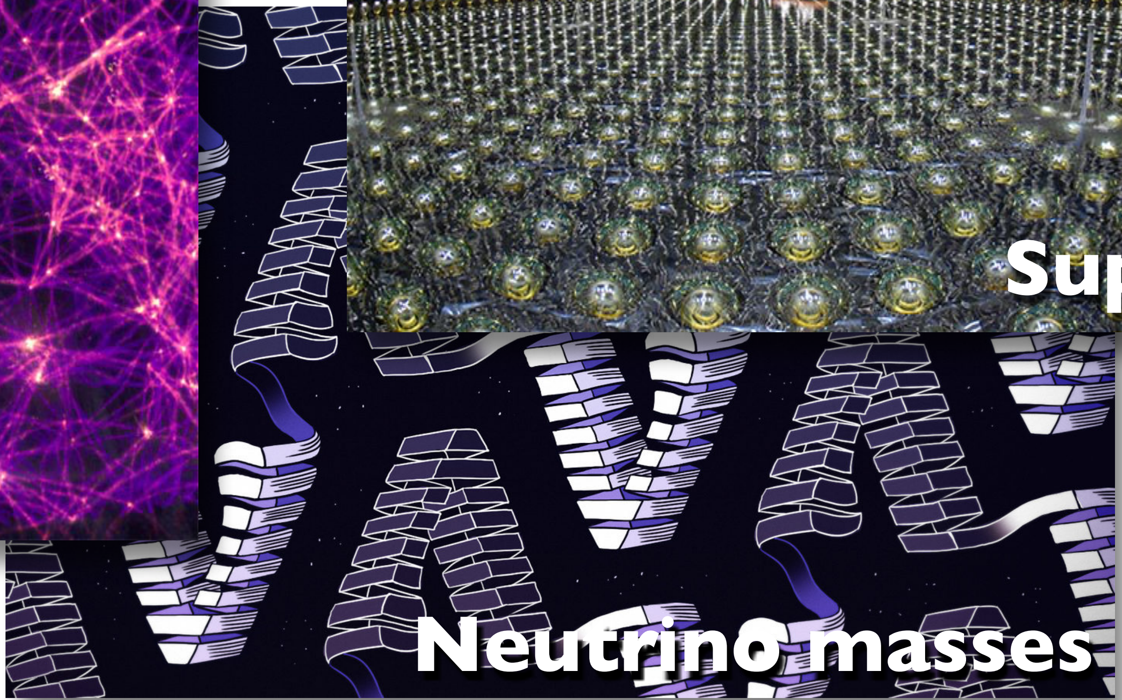




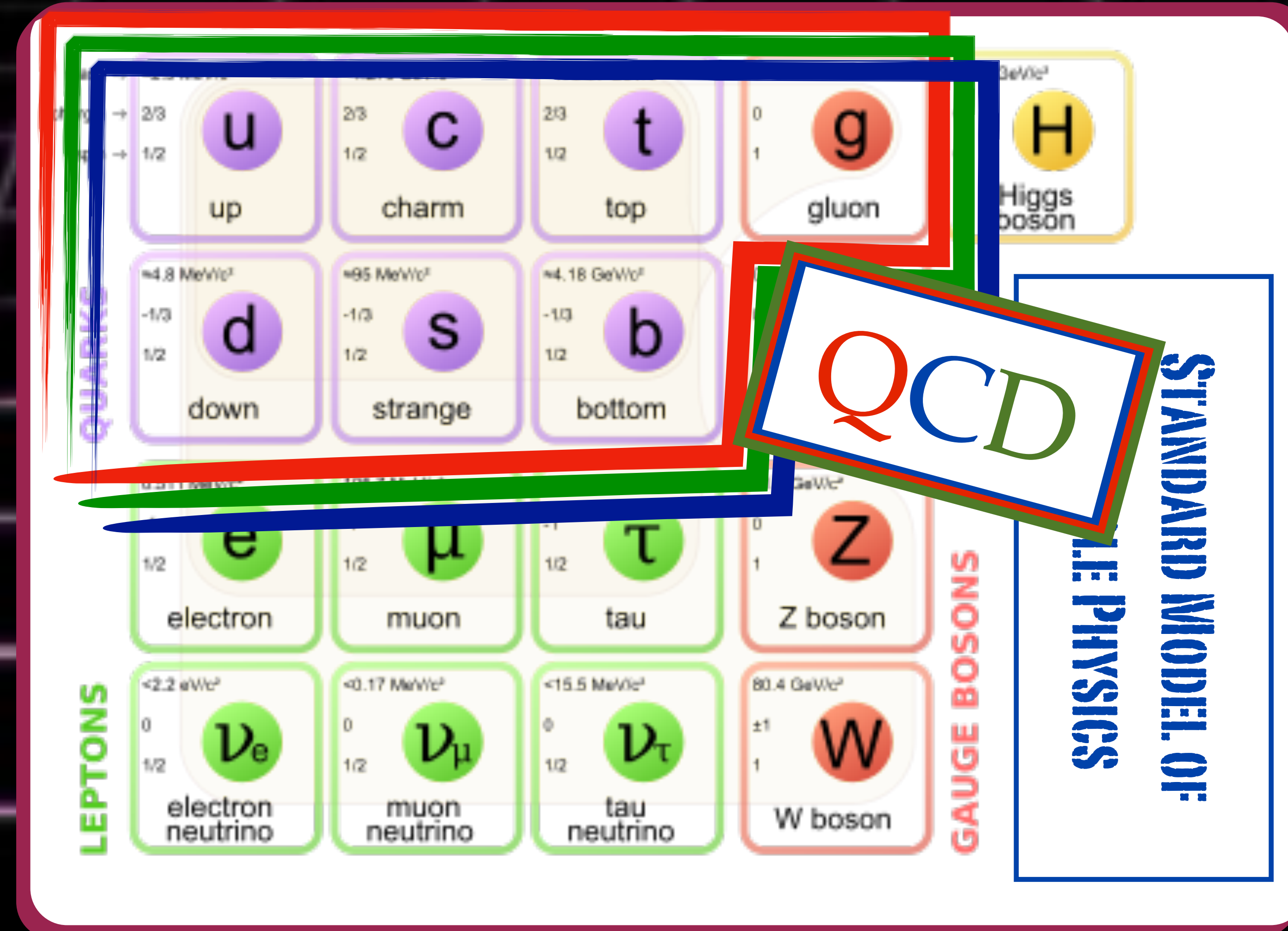






Lattice QCD

- Numerical solution to QCD:
  - Non-perturbative formulation of QCD in discretized, finite spacetime
  - Currently our only reliable technique for solving QCD at low energies
- All uncertainties are quantifiable and may be systematically removed
  - Extrapolations to continuum, infinite volume, physical pion mass



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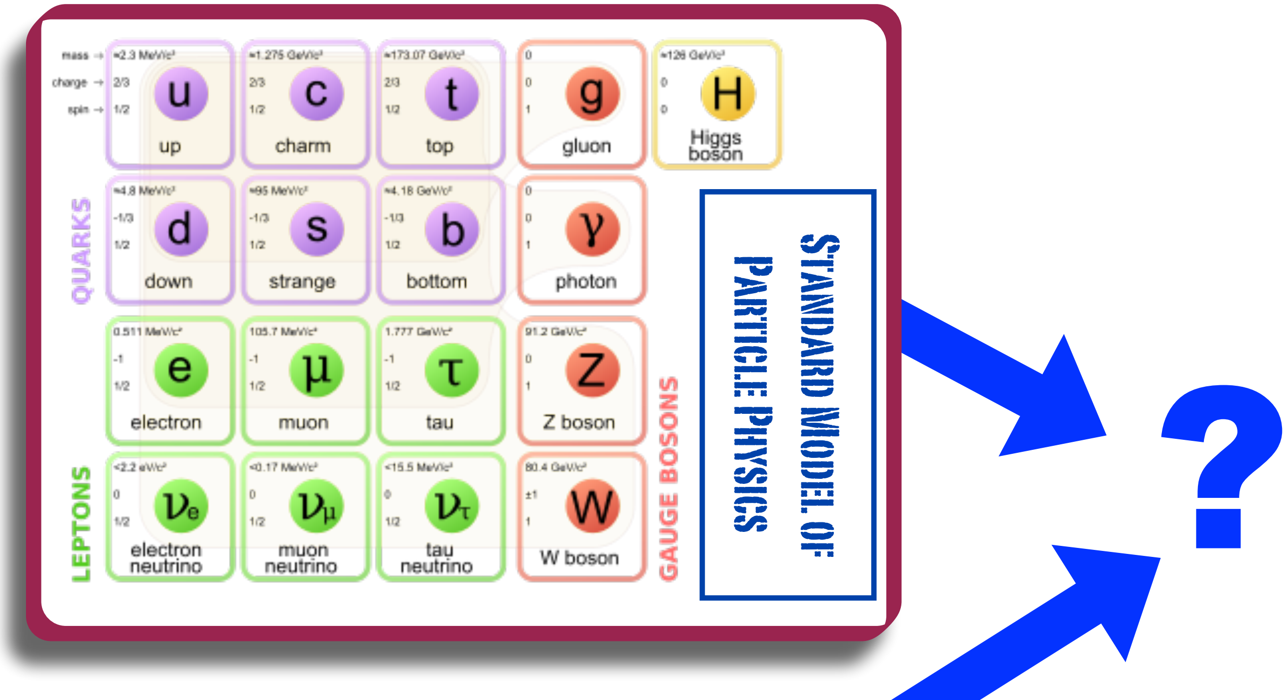

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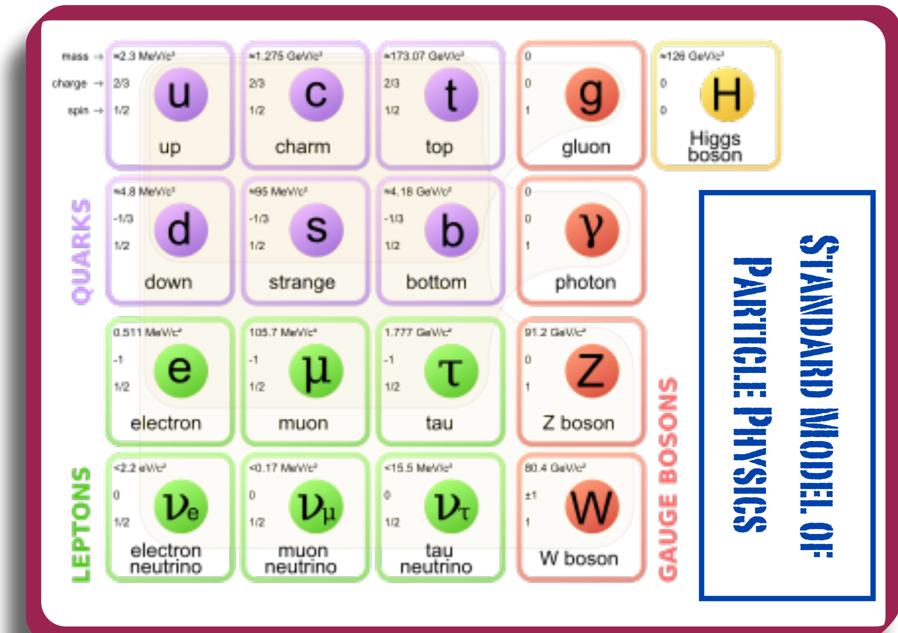
2. Match new physics model at high energies to nuclear experiments: $0\nu\beta\beta$, nucleon/nuclear EDM (see talk by S. Syritsyn, Tues. 17:50), DM searches (see talk by E. Rinaldi, Tues. 15:00)



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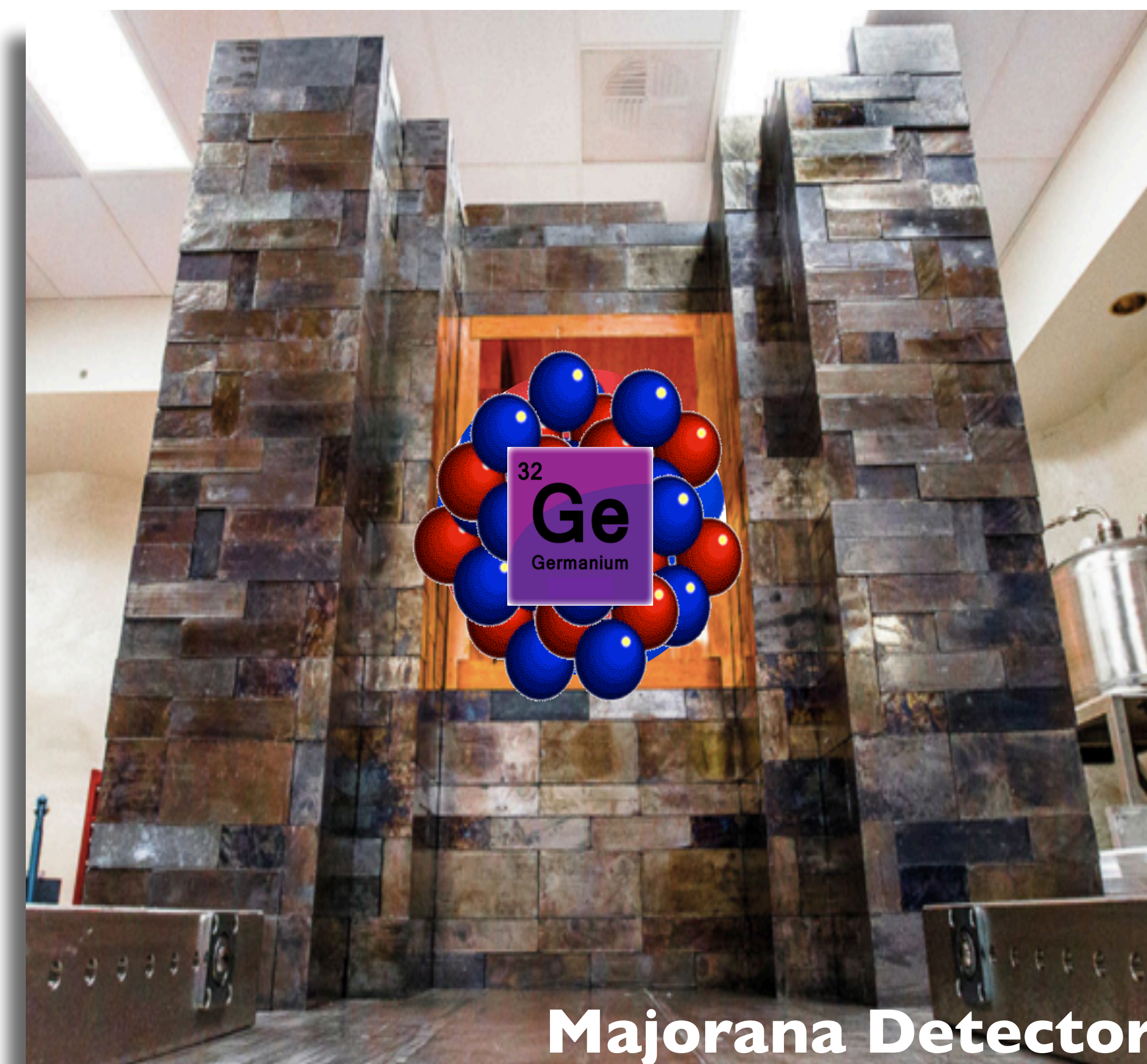
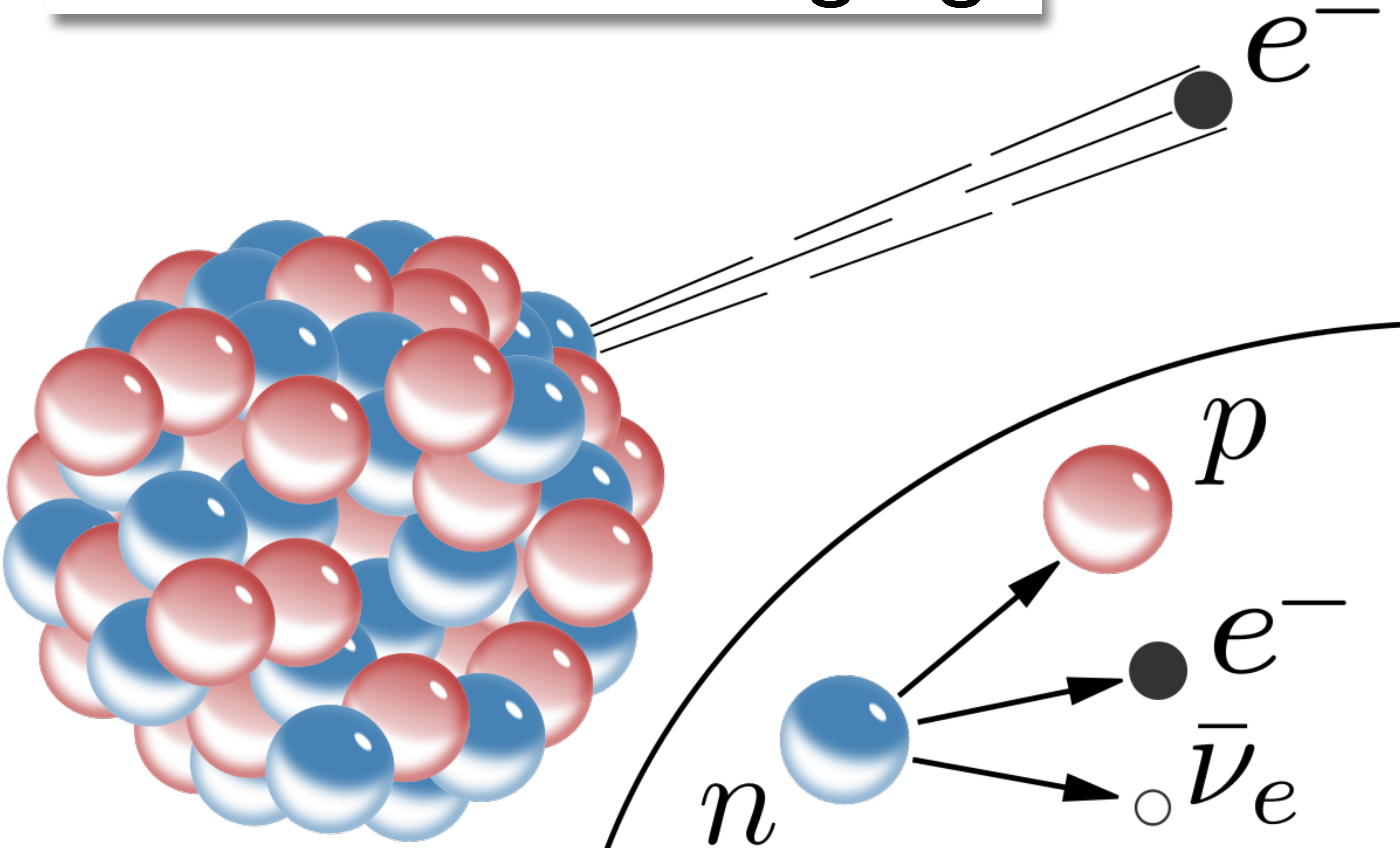
NIST Center for Neutron Research



Majorana Detector

Nucleon axial charge, g_A



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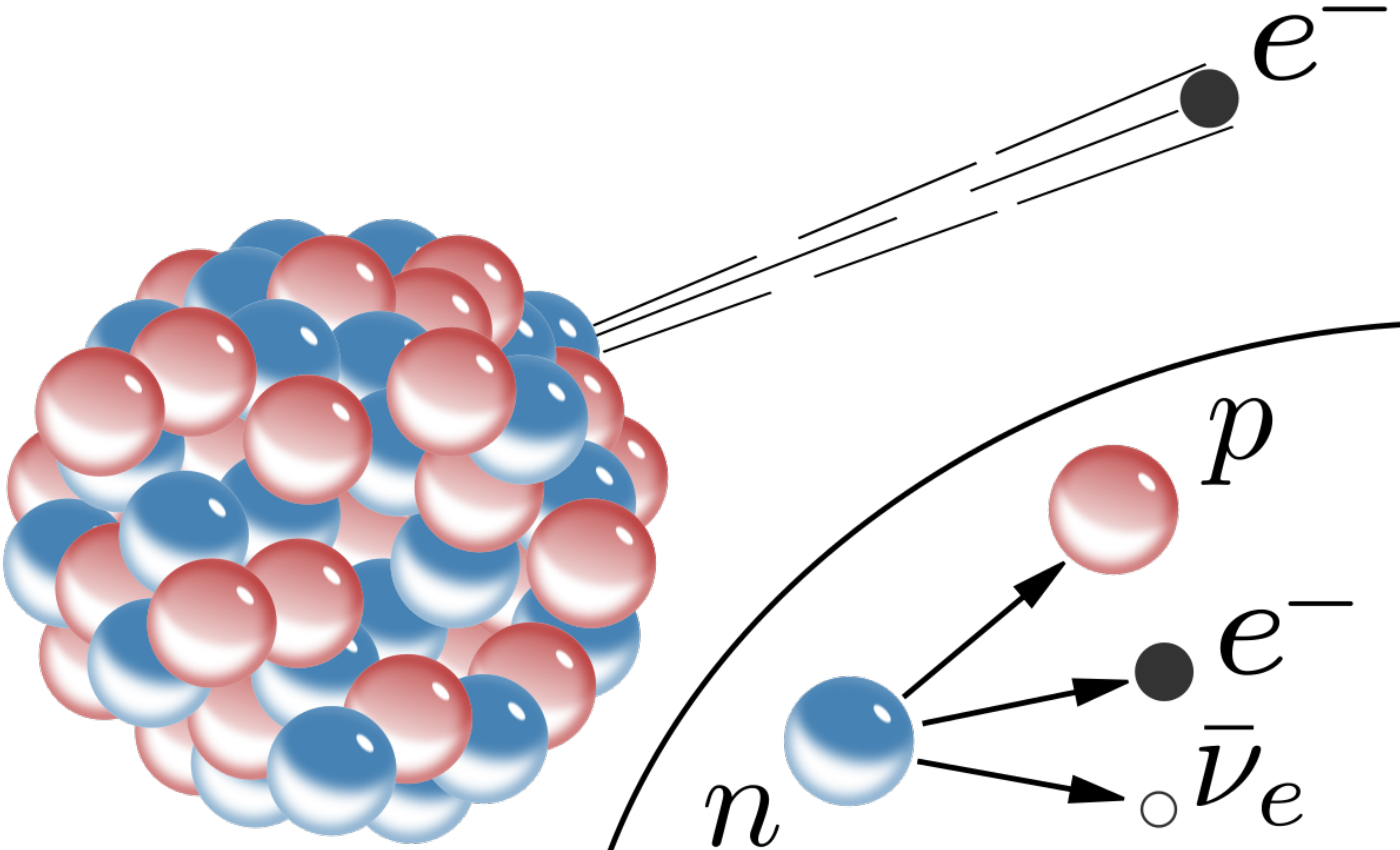

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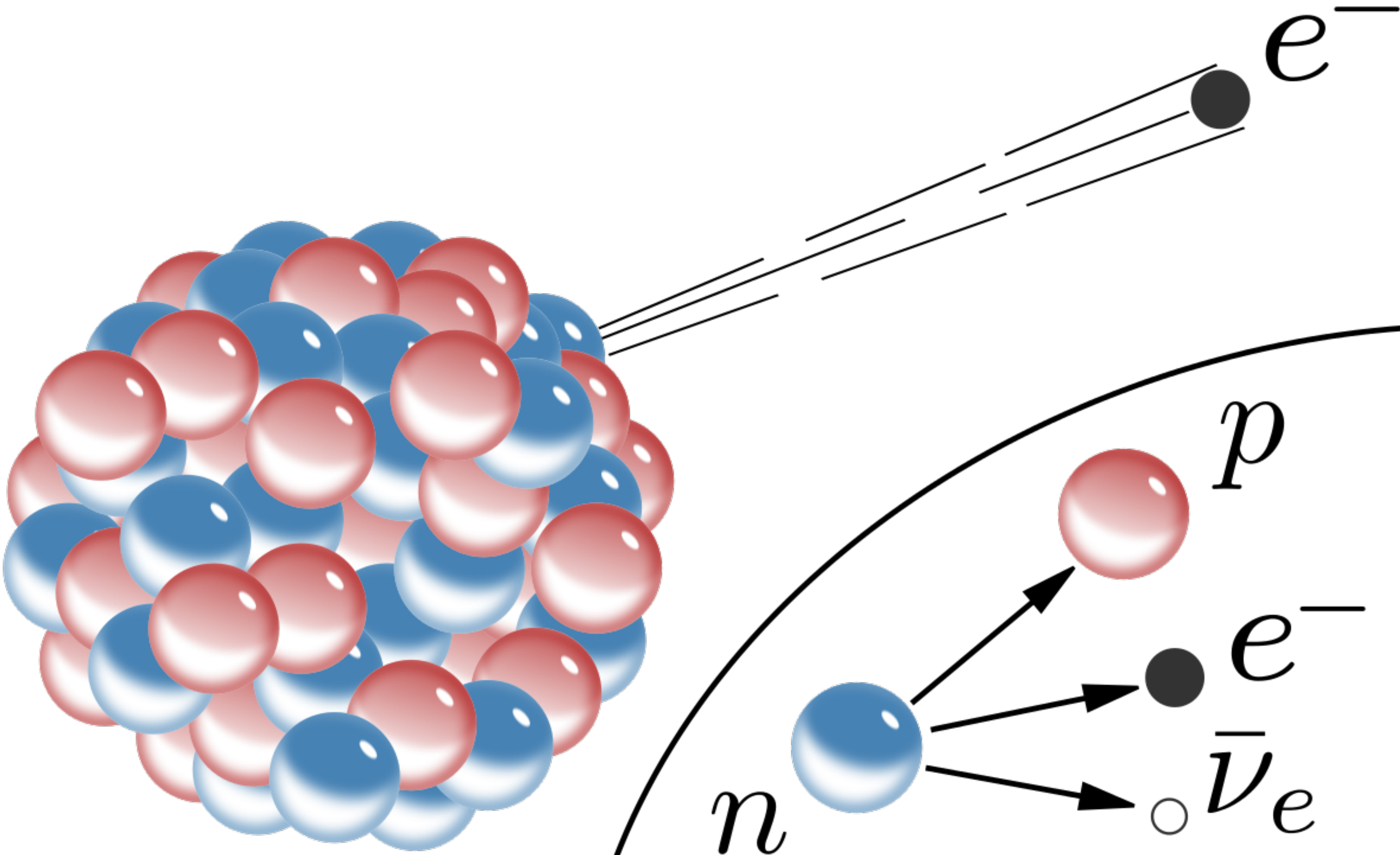
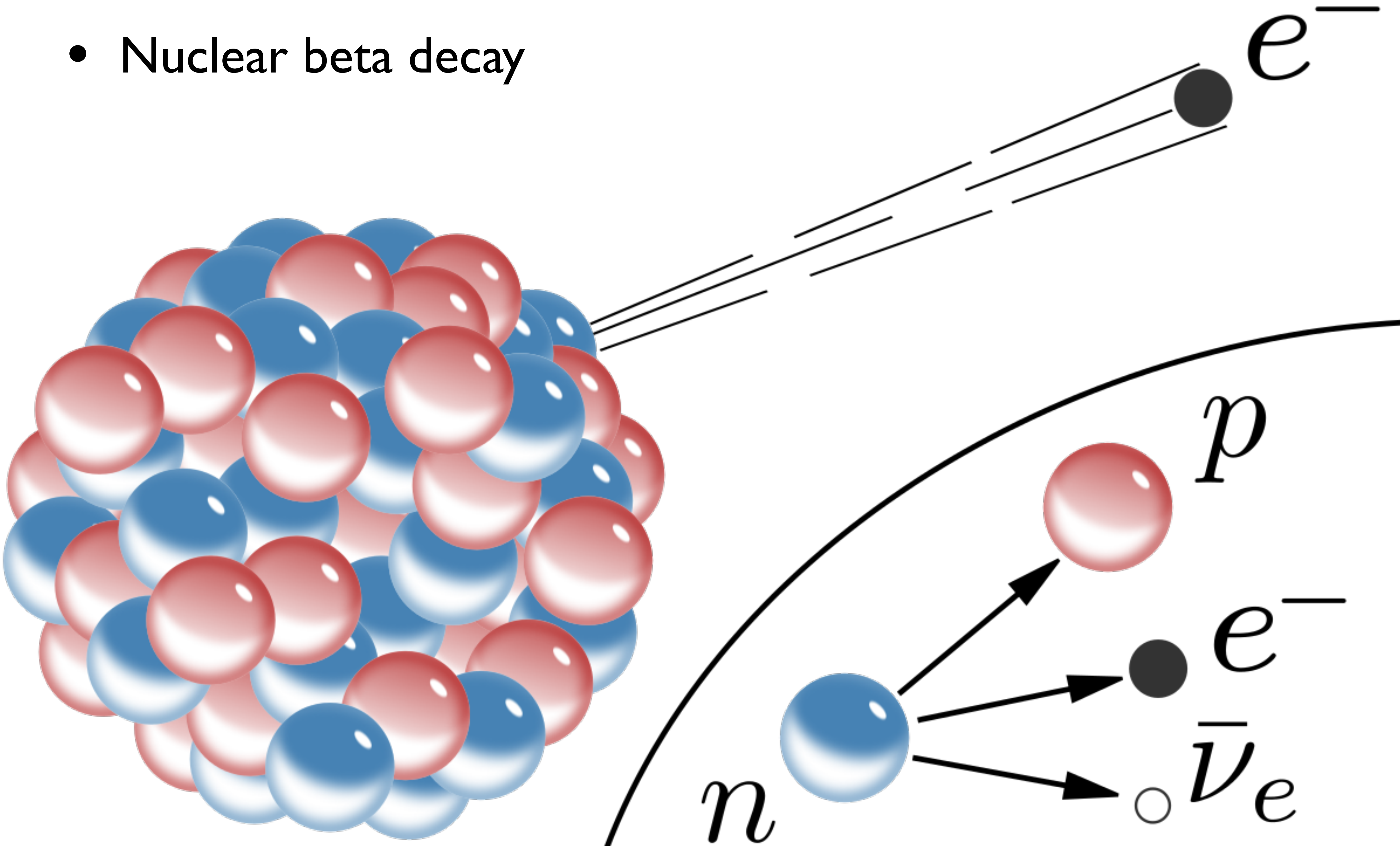


What depends on g_A?

- Free neutron lifetime
- Nuclear beta decay



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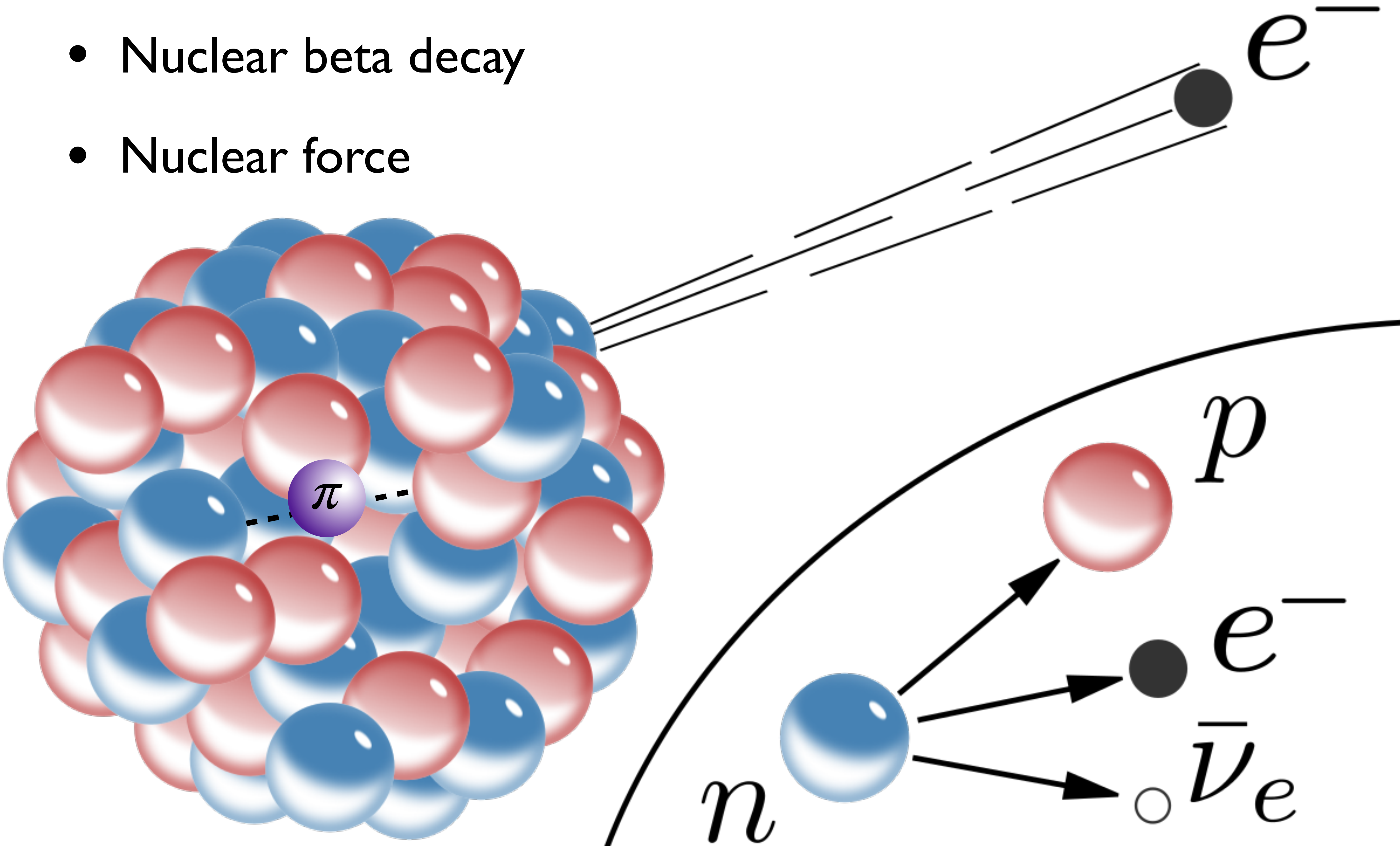

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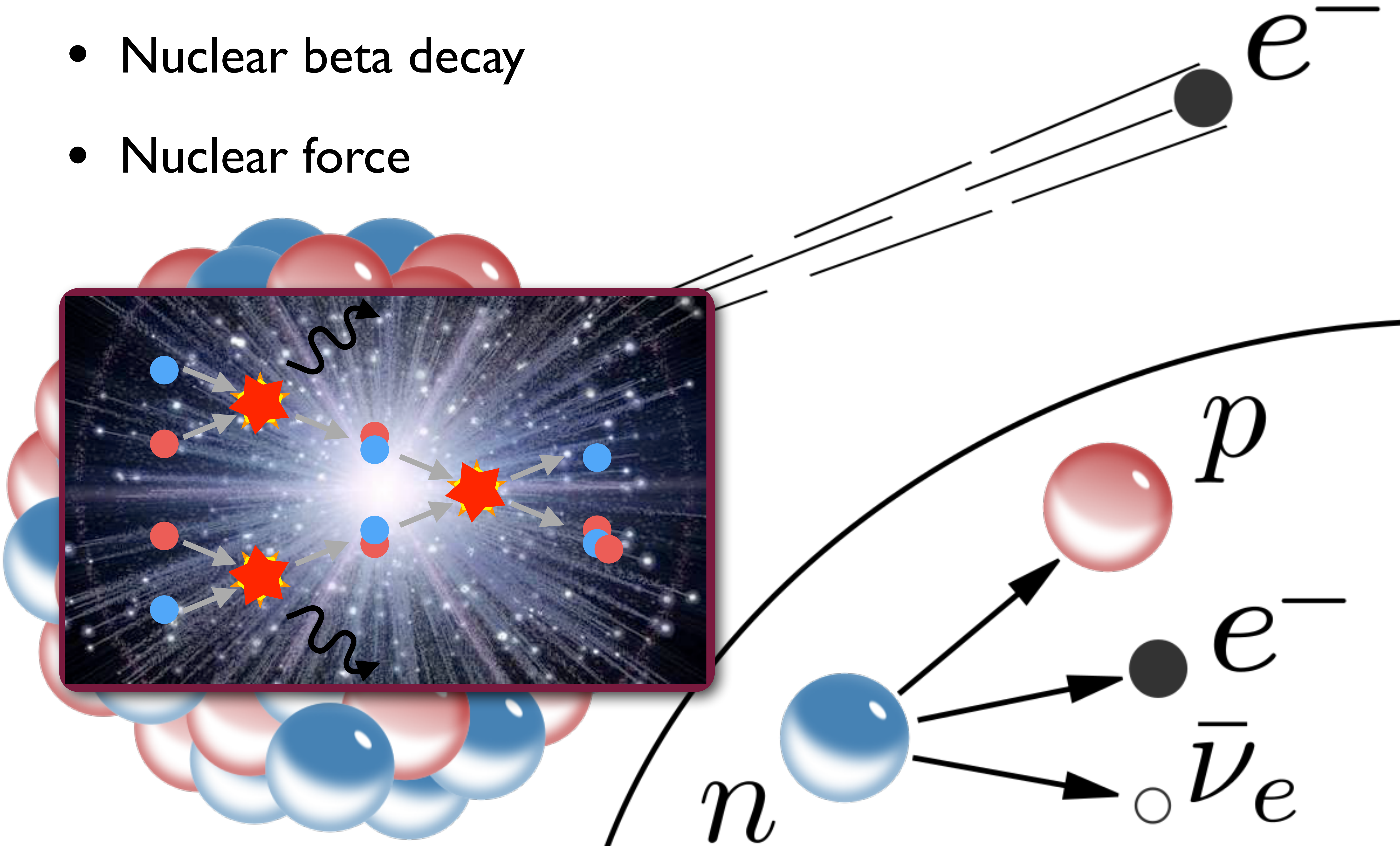

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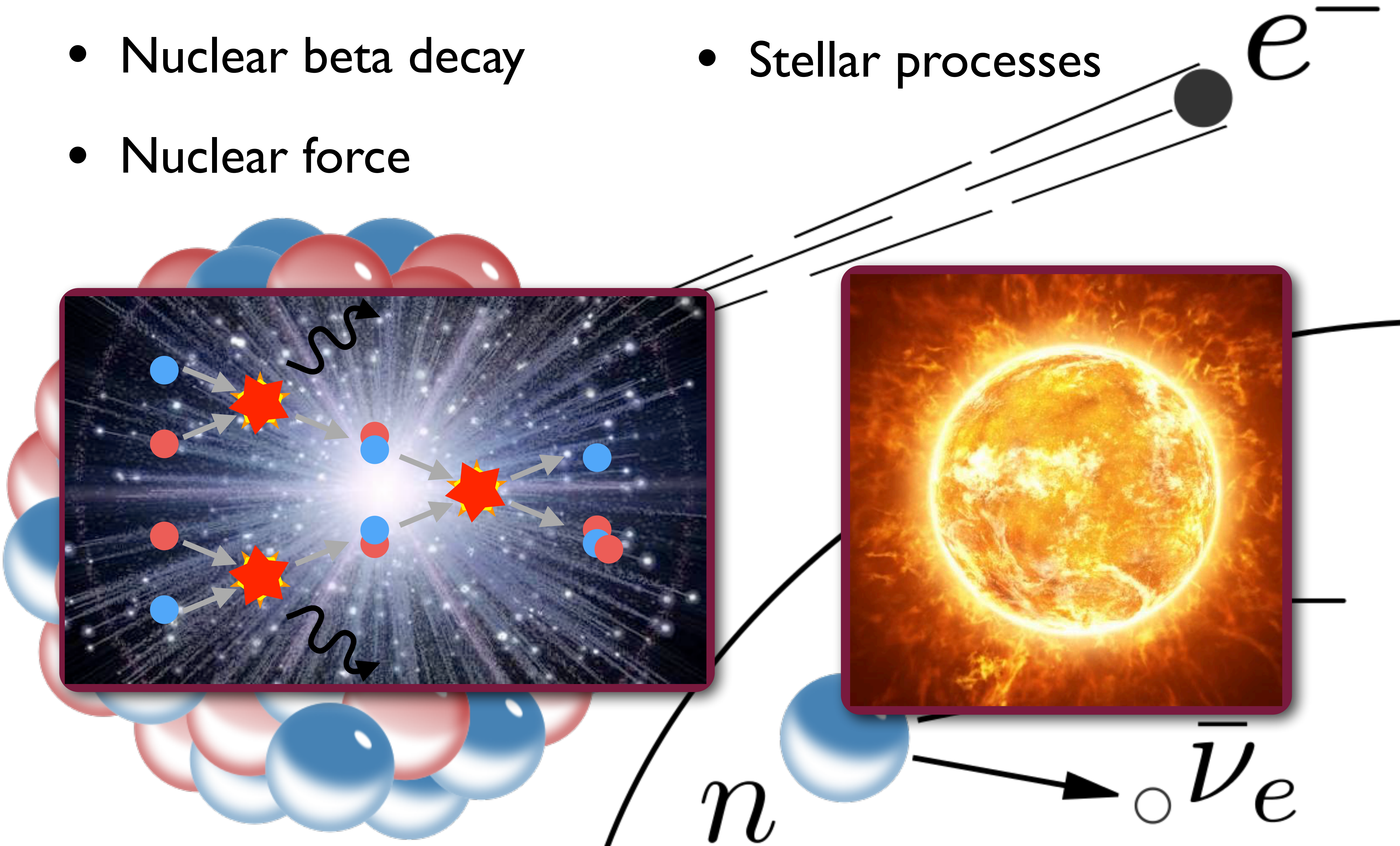

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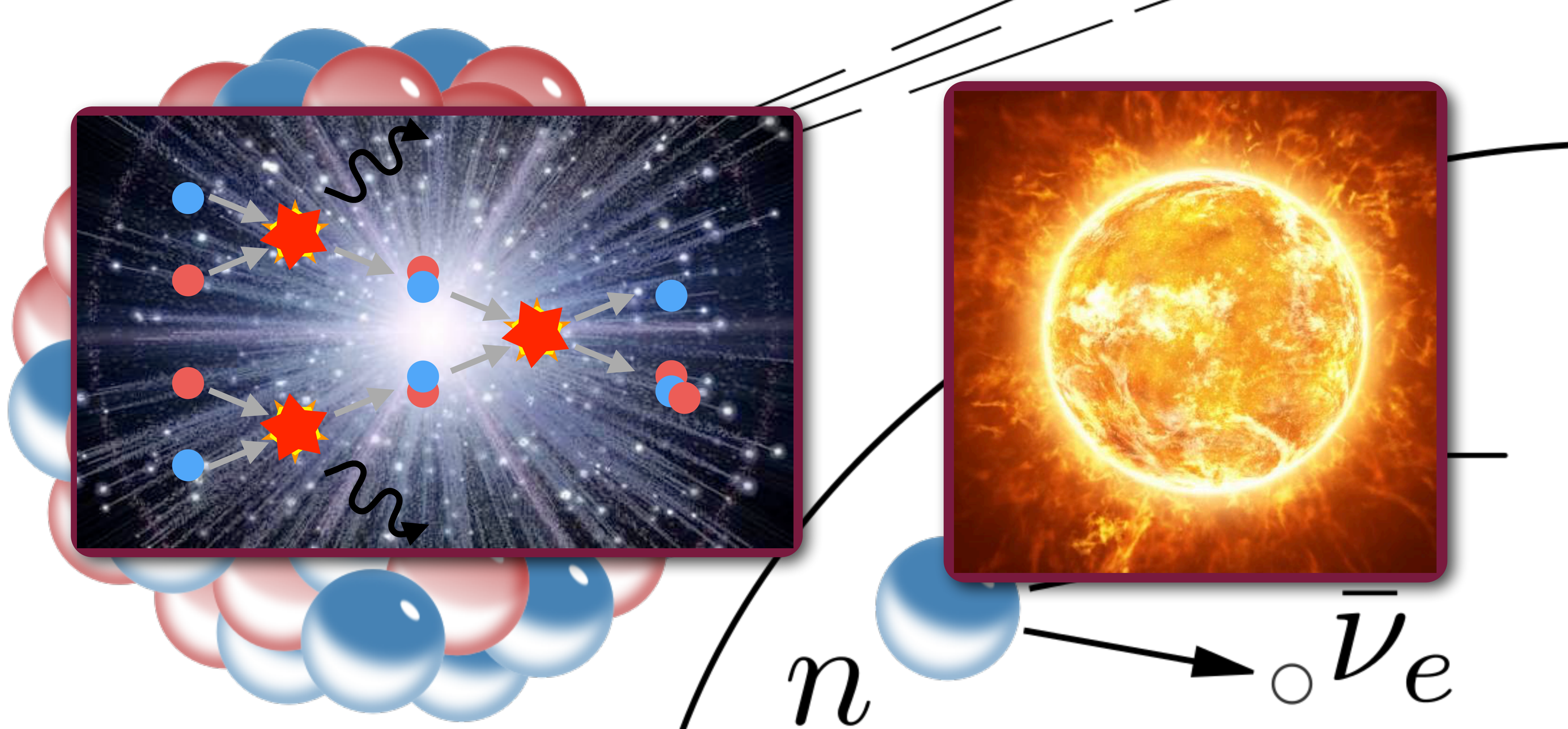
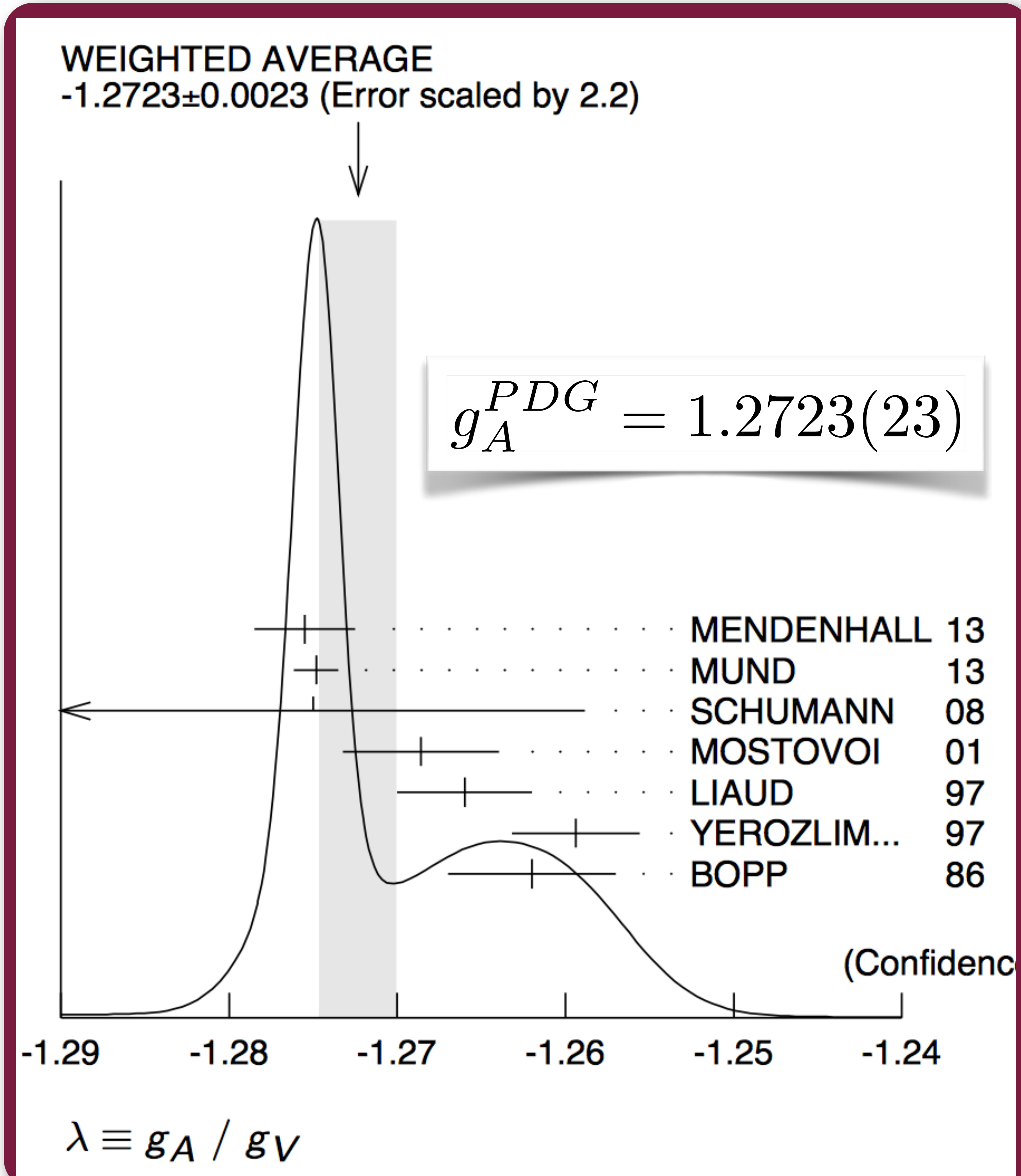


Very precisely measured experimentally



Neutron lifetime puzzle

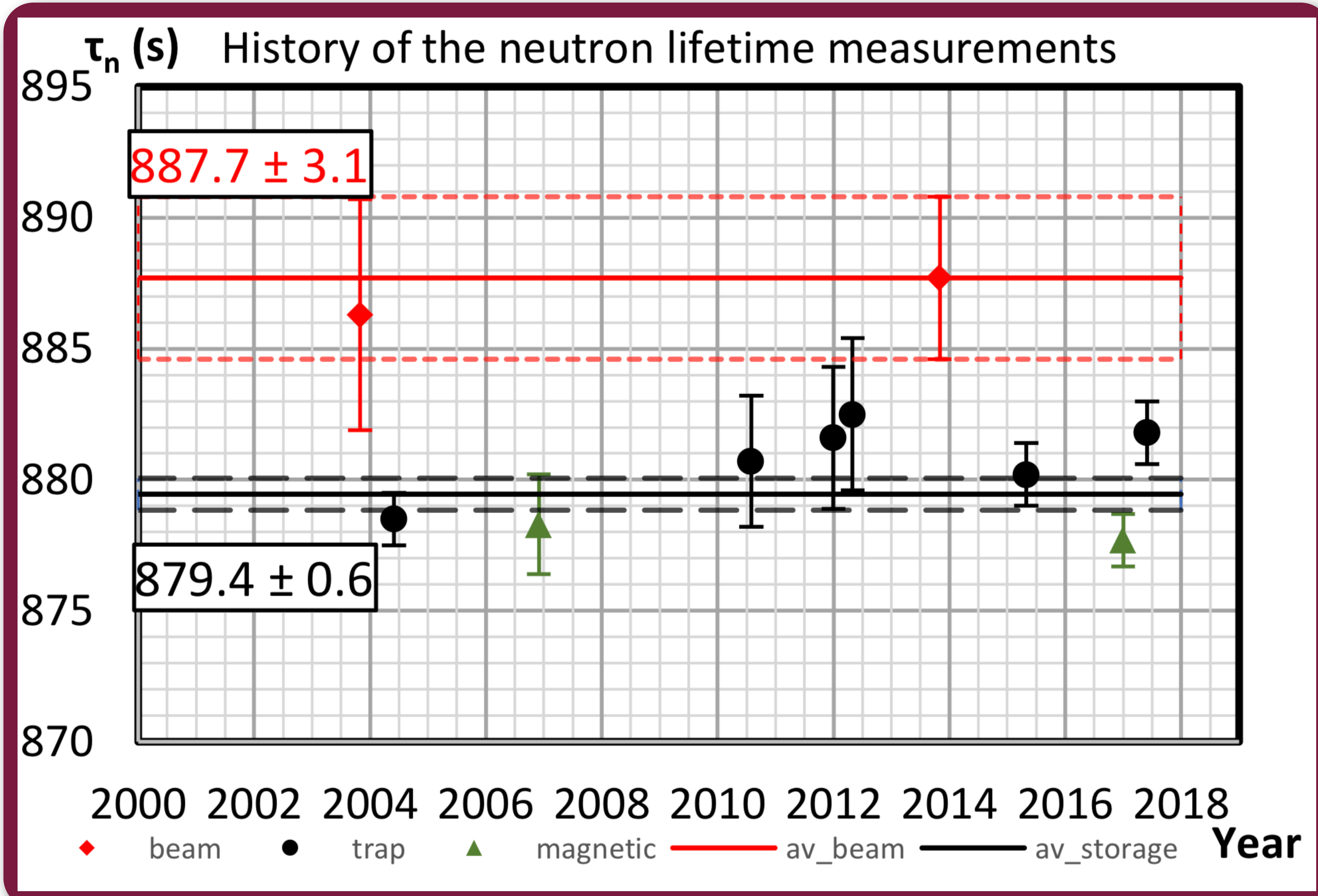


Figure: A. P. Serebrov, E .A. Kolomensky, A. K. Fomin, I. A. Krasnoschekova, A. V. Vassiljev, D. M. Prudnikov, I. V. Shoka, A. V. Chechkin, M. E. Chaikovskiy, V. E. Varlamov, S. N. Ivanov, A. N. Pirozhkov, P. Geltenbort, O. Zimmer, T. Jenke, M. Van der Grinten, M. Tucker, arXiv:1712.05663

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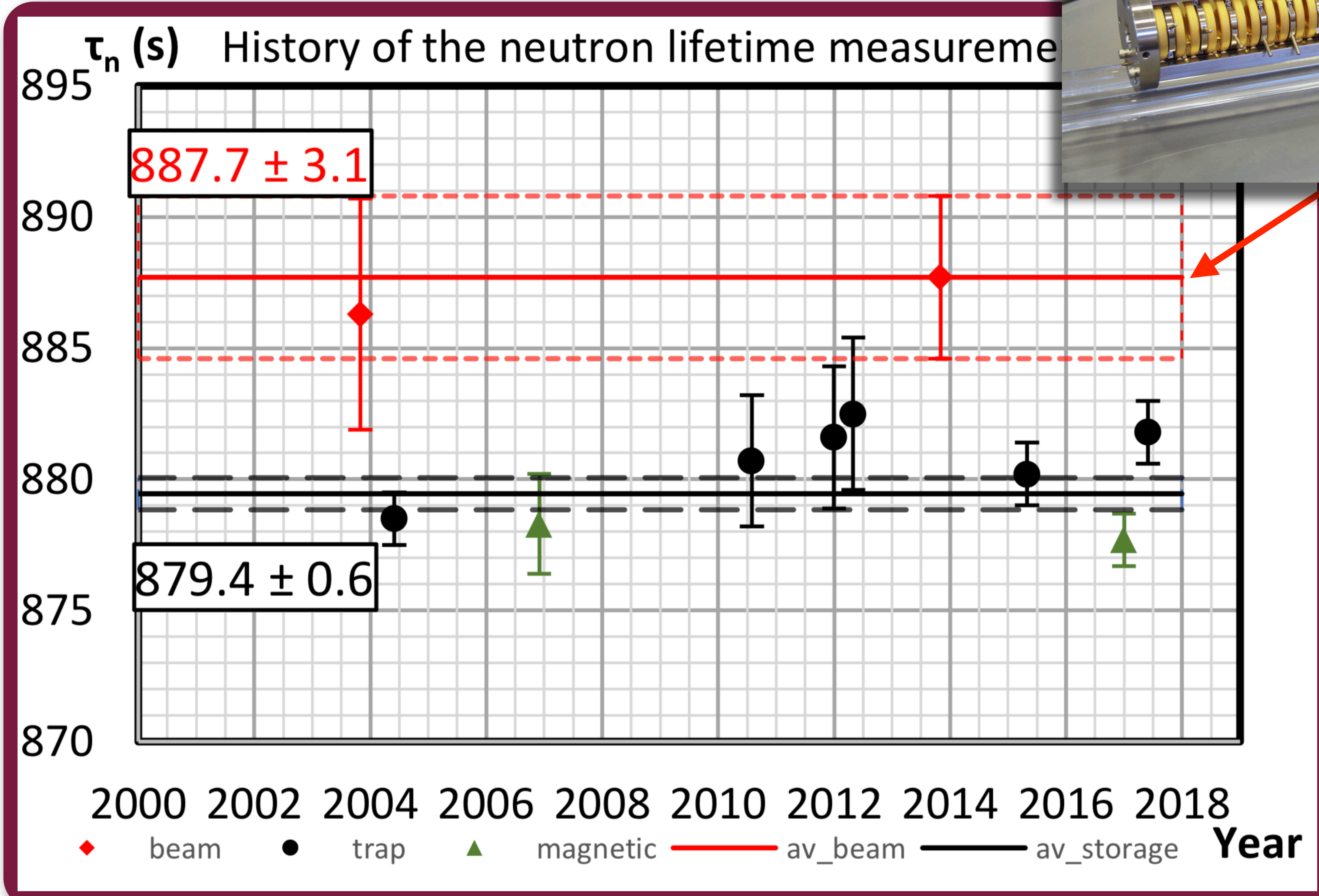

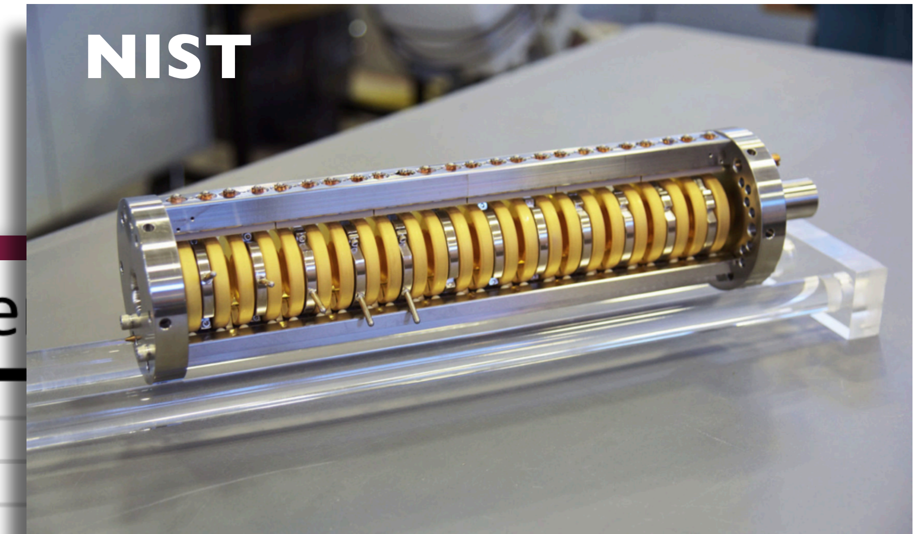

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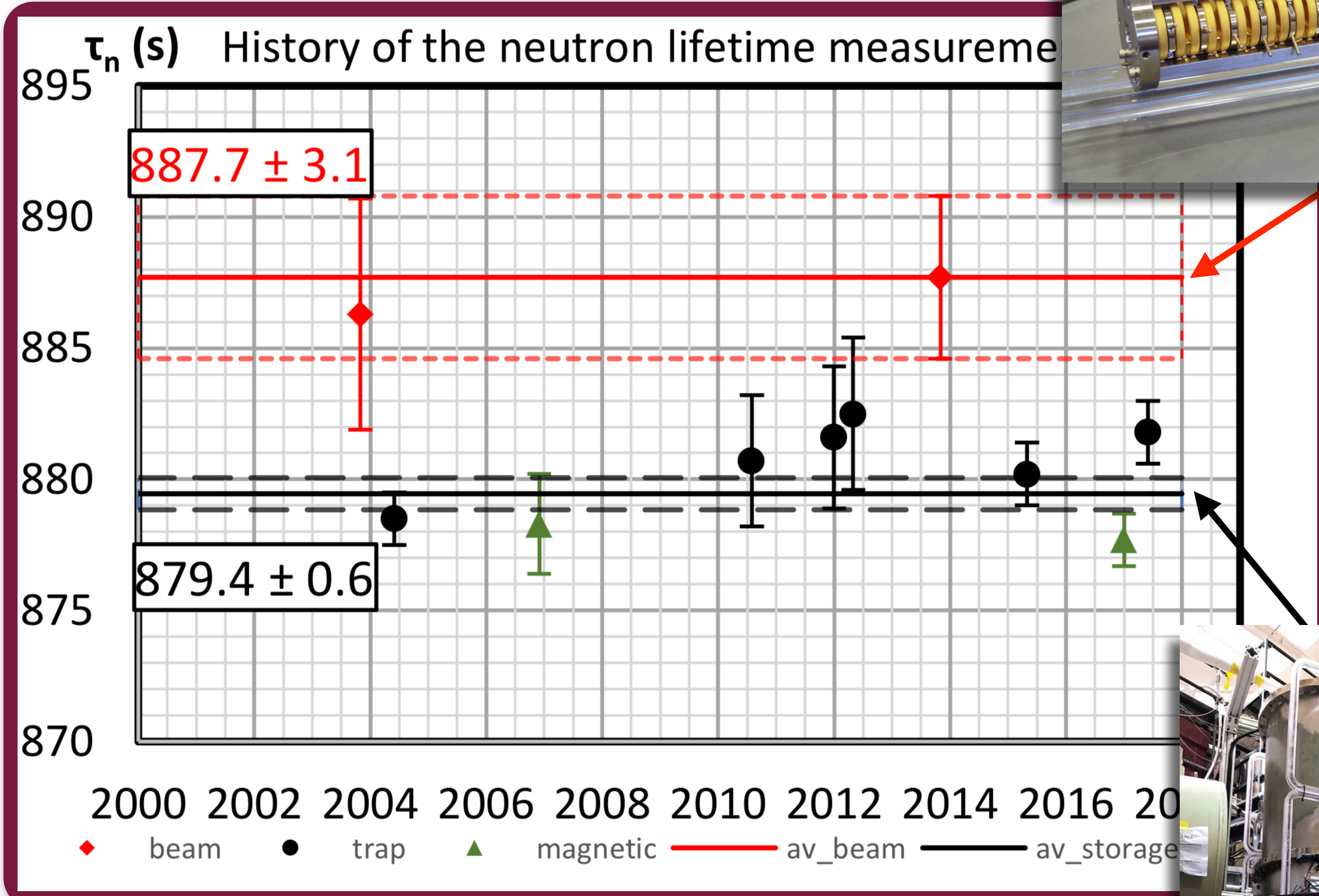

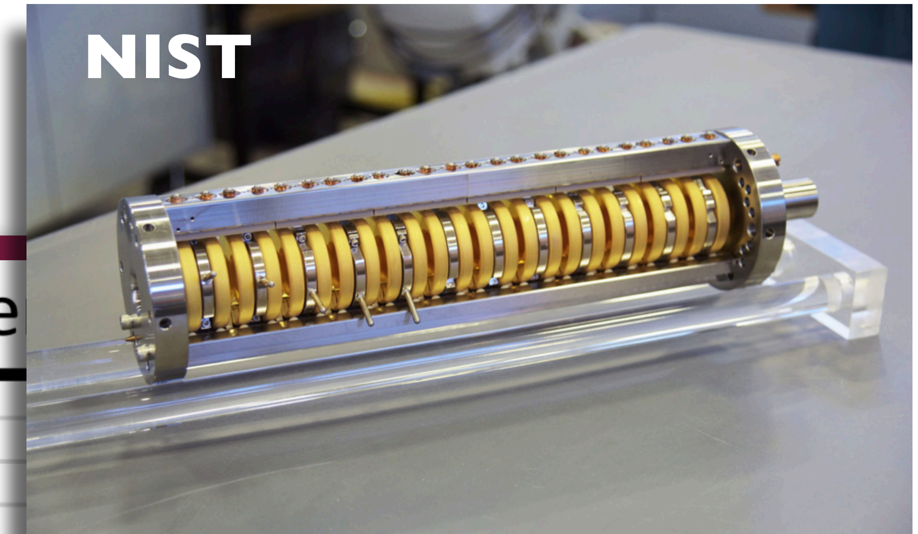

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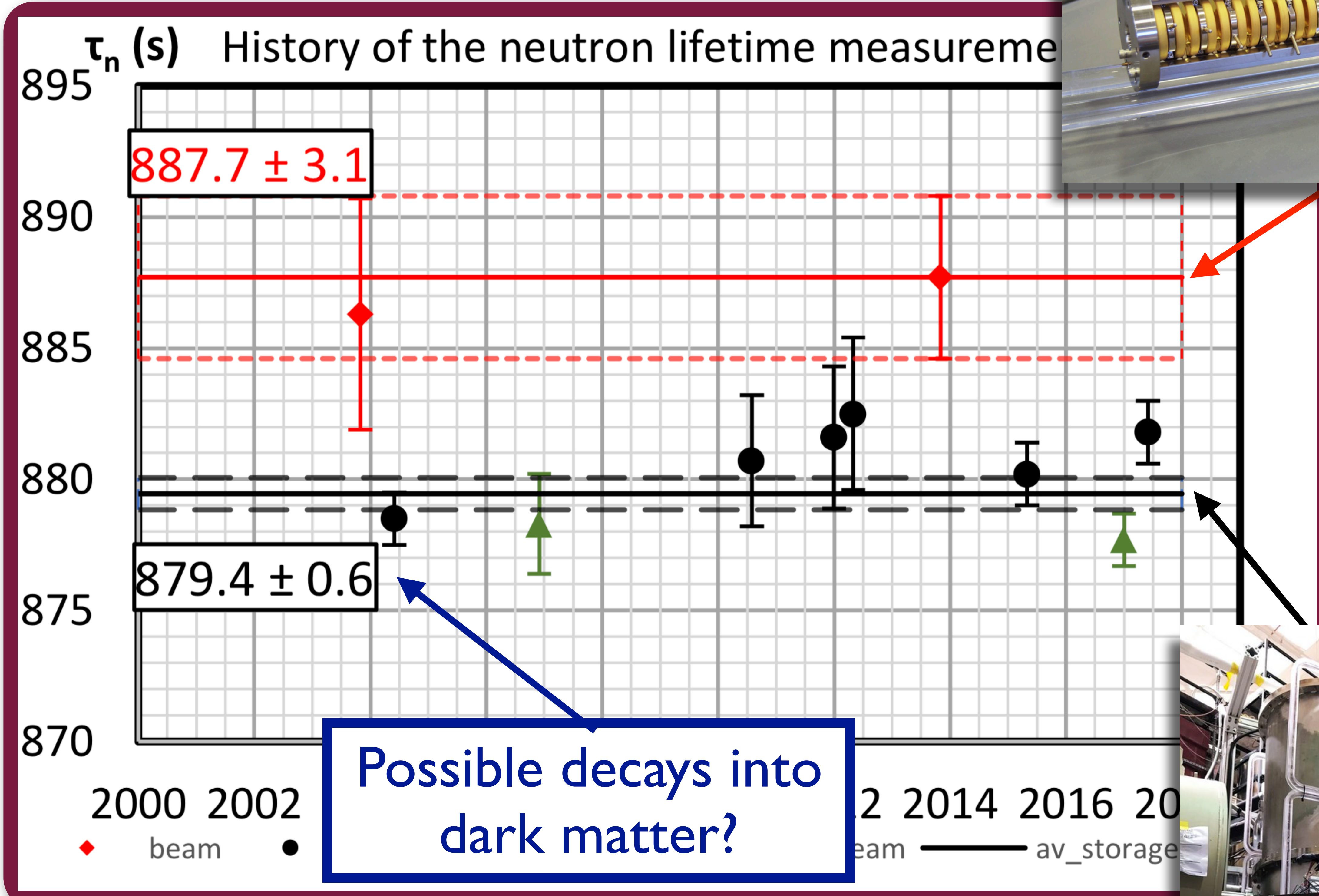

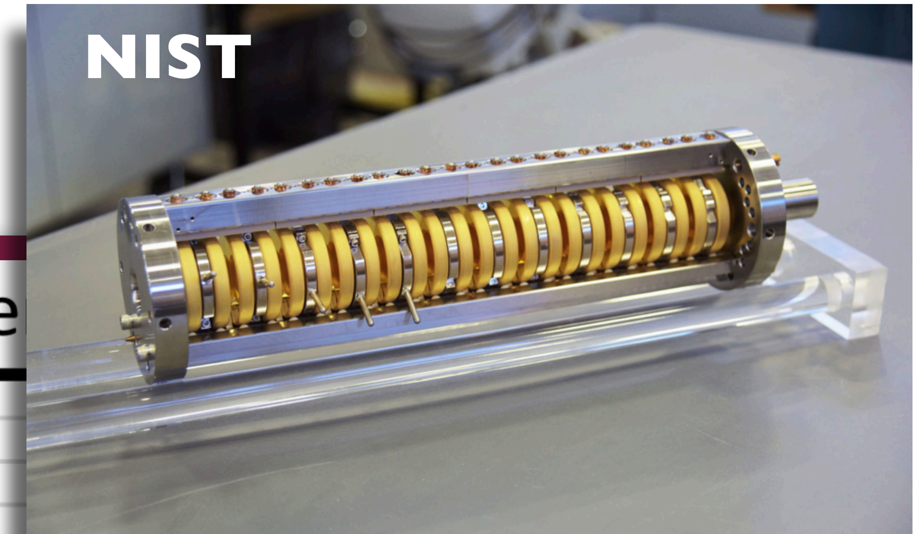

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Why calculate g_A from LQCD?

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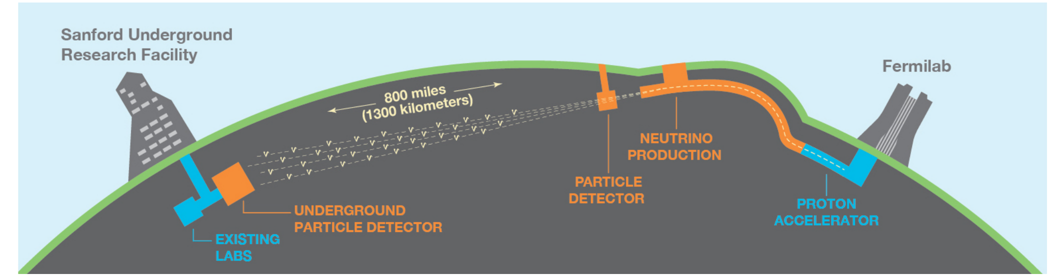

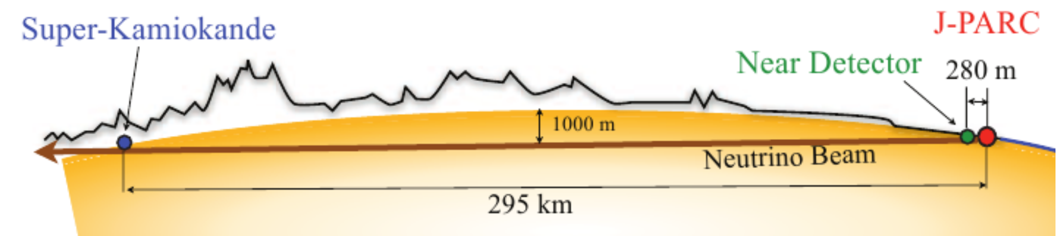

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- in-medium effects/axial form factors (see talk by R. Gupta, Thurs. 16:40)
  - neutrinoless double beta decay (see recent work by NPLQCD), long baseline neutrino experiments

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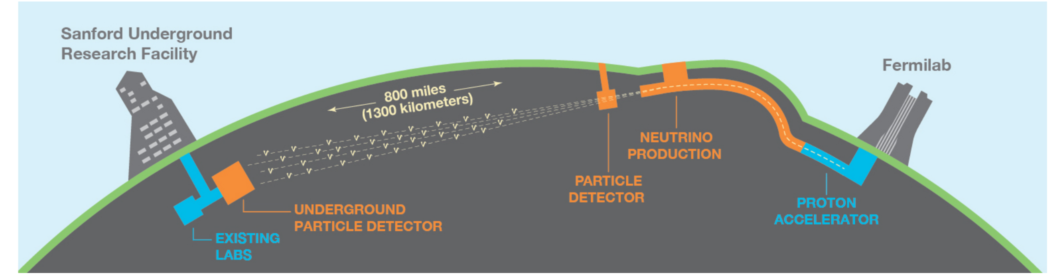
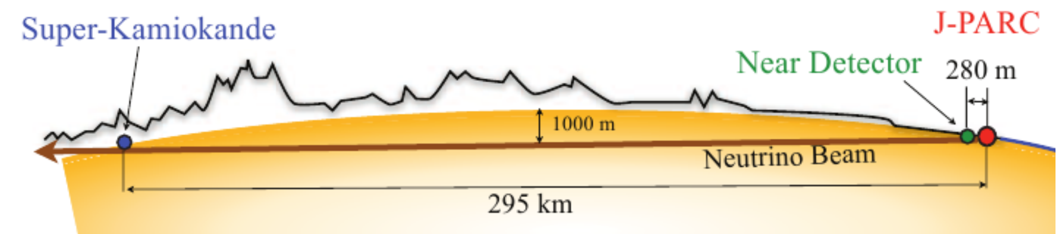
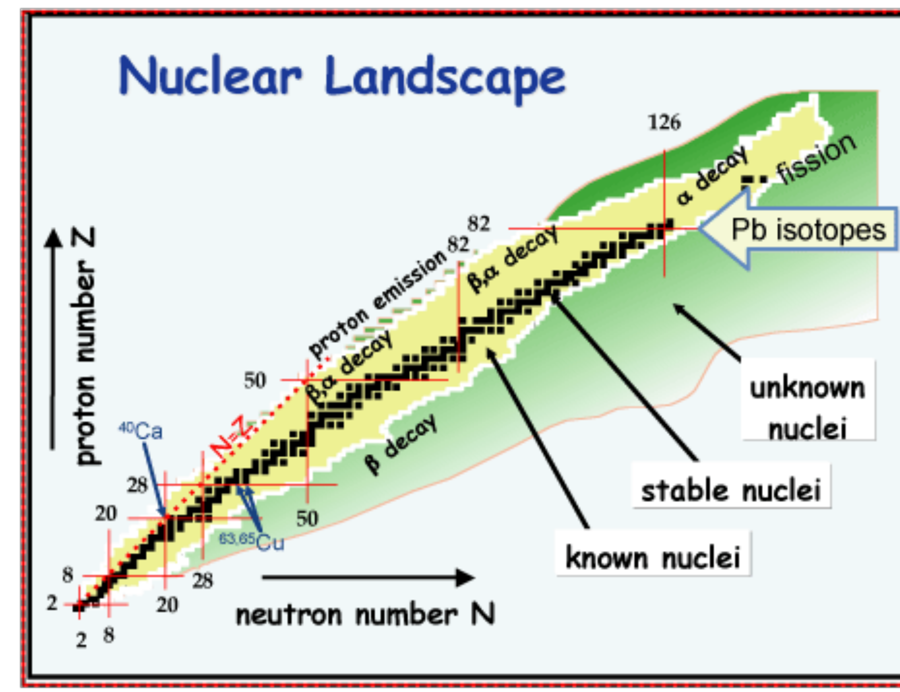
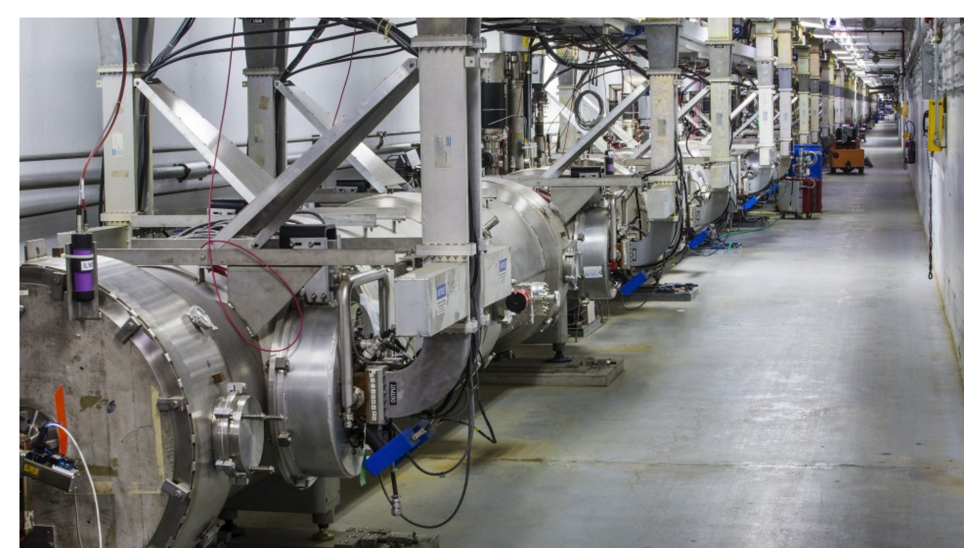
- in-medium effects/axial form factors (see talk by R. Gupta, Thurs. 16:40)
  - neutrinoless double beta decay (see recent work by NPLQCD), long baseline neutrino experiments
- Build quantitative connection between QCD & nuclear physics
  - g_A should be a benchmark
    - one of the simplest hadron structure matrix elements









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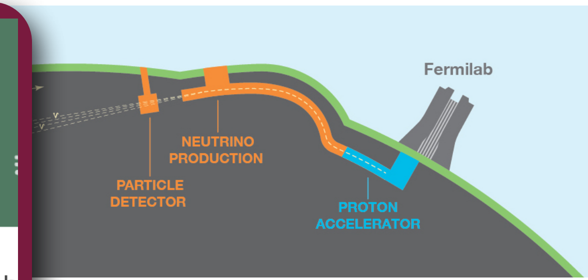
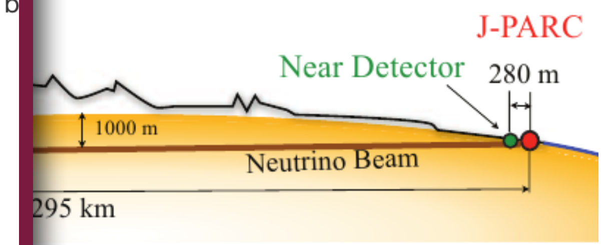
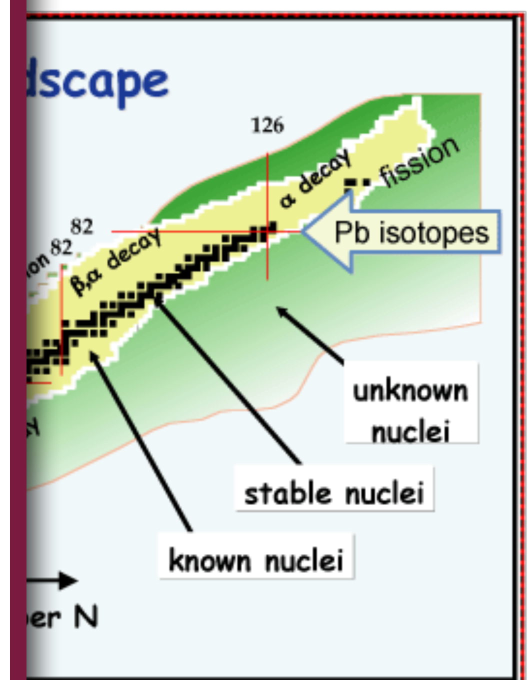
Nucleon Axial Charge in Full Lattice QCD

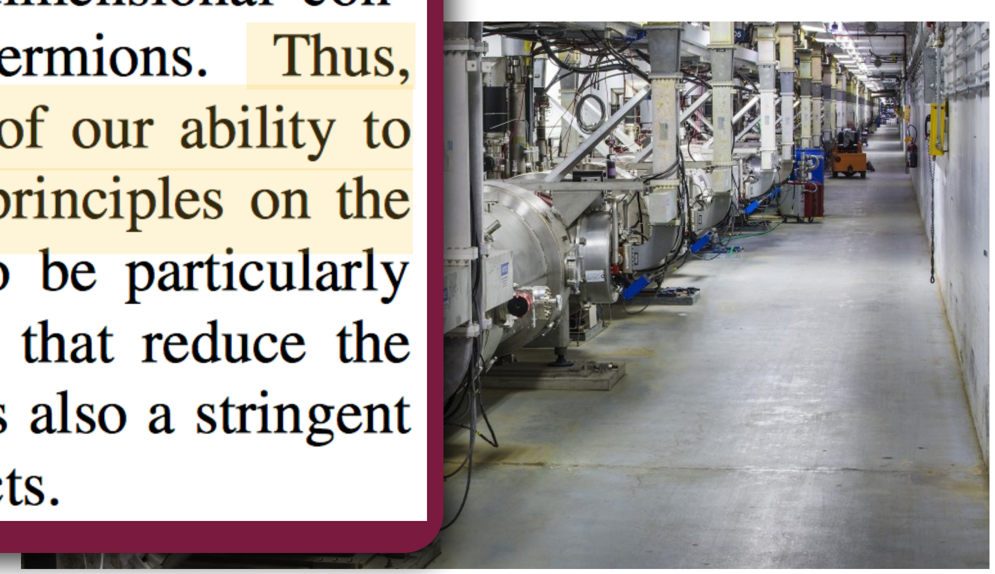
R. G. Edwards, G. T. Fleming, Ph. Hägler, J. W. Negele, K. Orginos, A. V. Pochinsky, D. B. Renner, D. G. Richards, and W. Schroers (LHPC Collaboration)
Phys. Rev. Lett. **96**, 052001 – Published 7 February 2006

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.

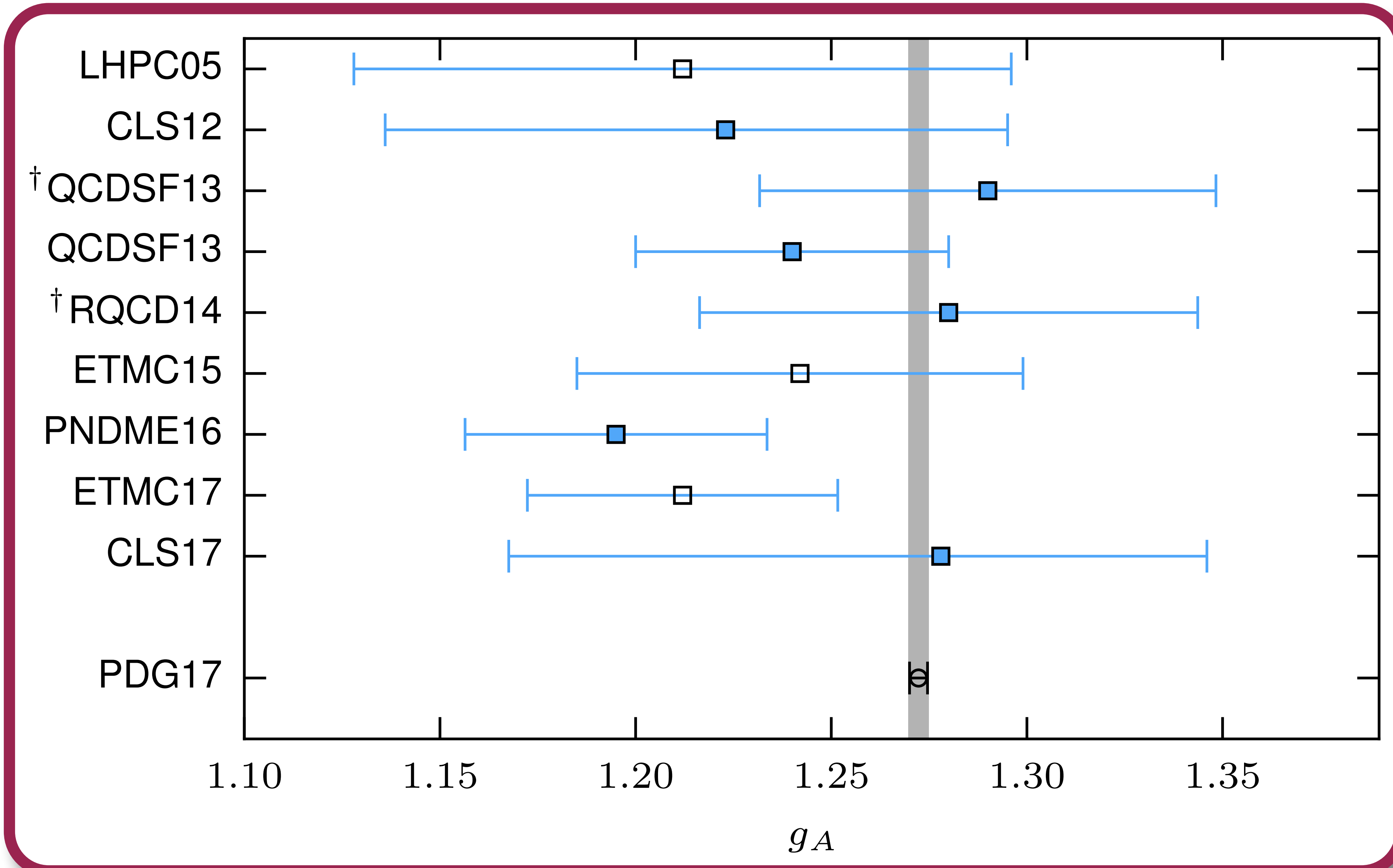








g_A : LQCD results



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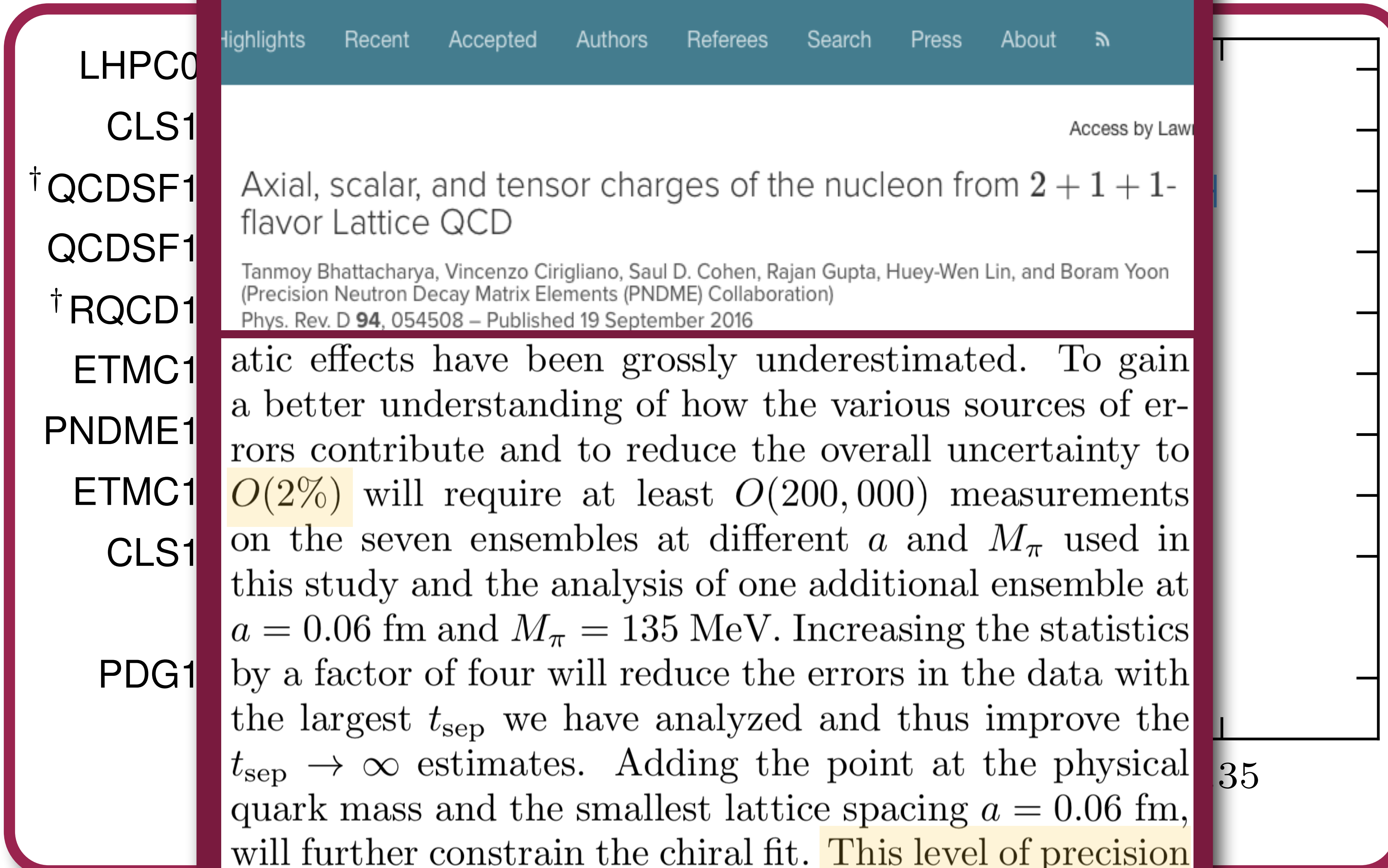

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Axial, scalar, and tensor charges of the nucleon from $2+1+1$-flavor Lattice QCD

Tanmoy Bhattacharya, Vincenzo Cirigliano, Saul D. Cohen, Rajan Gupta, Huey-Wen Lin, and Boram Yoon
(Precision Neutron Decay Matrix Elements (PNDME) Collaboration)

Phys. Rev. D **94**, 054508 – Published 19 September 2016

atic effects have been grossly underestimated. To gain a better understanding of how the various sources of errors contribute and to reduce the overall uncertainty to $O(2\%)$ will require at least $O(200,000)$ measurements on the seven ensembles at different a and M_π used in this study and the analysis of one additional ensemble at $a = 0.06$ fm and $M_\pi = 135$ MeV. Increasing the statistics by a factor of four will reduce the errors in the data with the largest $t_{\rm sep}$ we have analyzed and thus improve the $t_{\rm sep} \to \infty$ estimates. Adding the point at the physical quark mass and the smallest lattice spacing $a = 0.06$ fm, will further constrain the chiral fit. This level of precision is achievable with the next generation of leadership-class computing resources.

Challenges

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- Monte Carlo noise/sign problem (nucleons)
  signal/noise ~ $e^{-A(m_N - 3/2 m_\pi)t}$

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- New mixed action: DWF on HISQ (E. Berkowitz, et al 2017)
  - smaller discretization effects, better chiral symmetry
  - gradient flow: improved statistics

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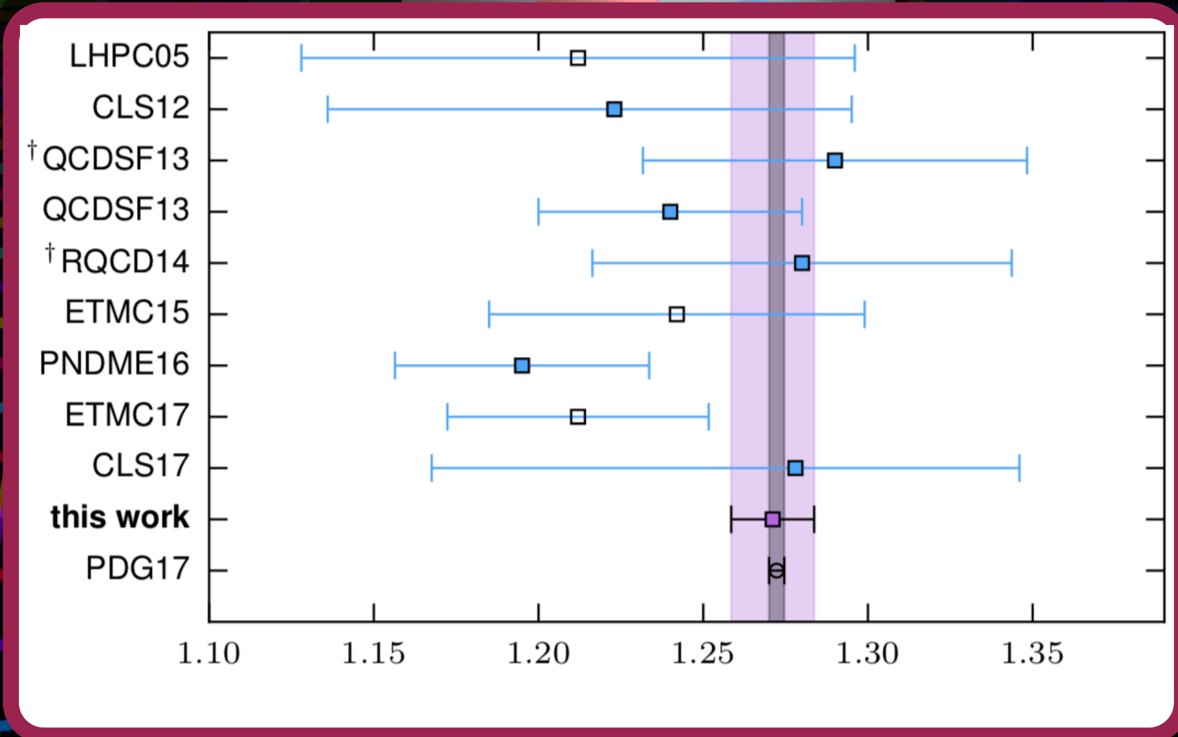
  - matrix elements states (g_A quenching)
  - WF on HISQ (E. Berkowitz, et al 2017)
  - smaller discretization effects, better chiral symmetry
  - gradient flow: improved statistics

See talk by C. C. Chang (Thurs. 16:10) for more details!

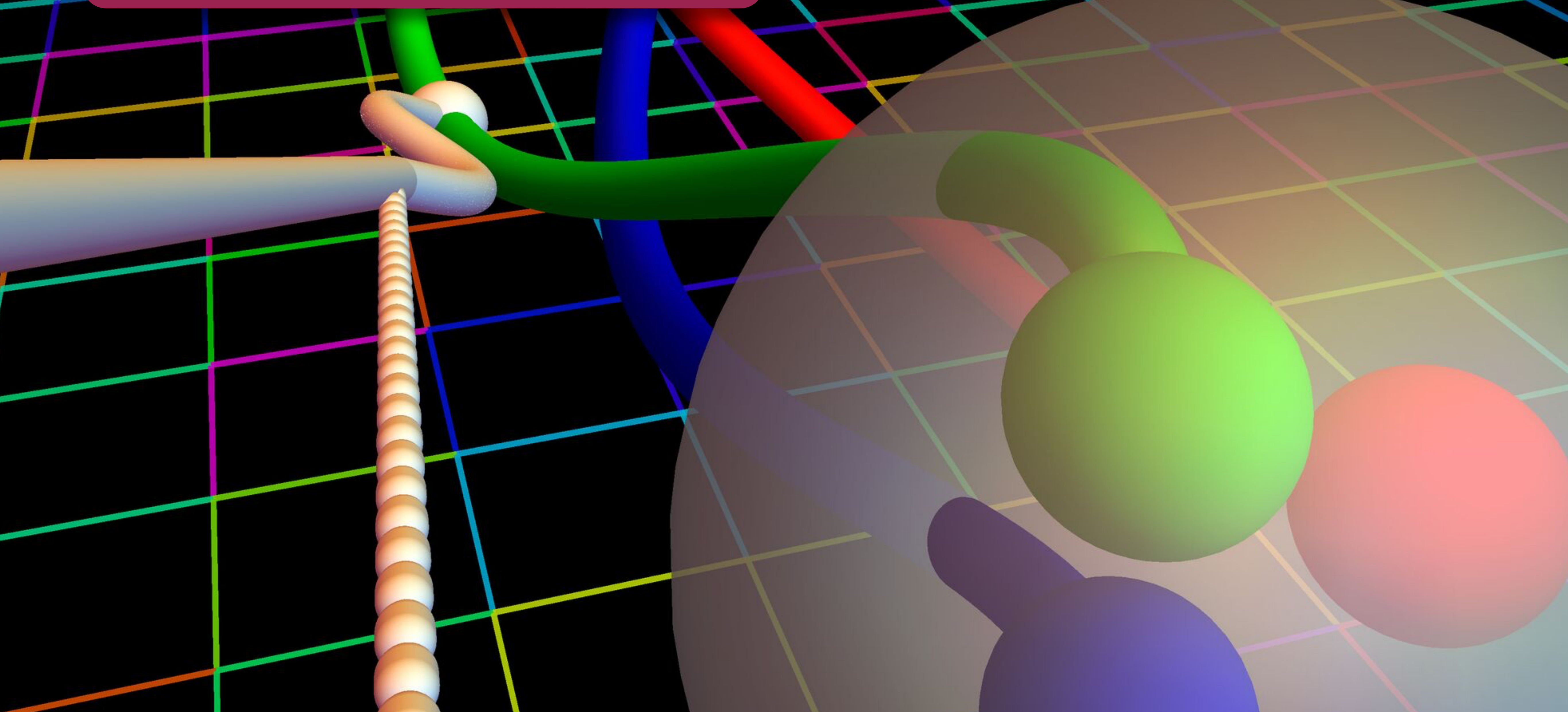
similar techniques used in:
A.J. Chambers et al. (2014,2015)
M.J. Savage et al. (2016)

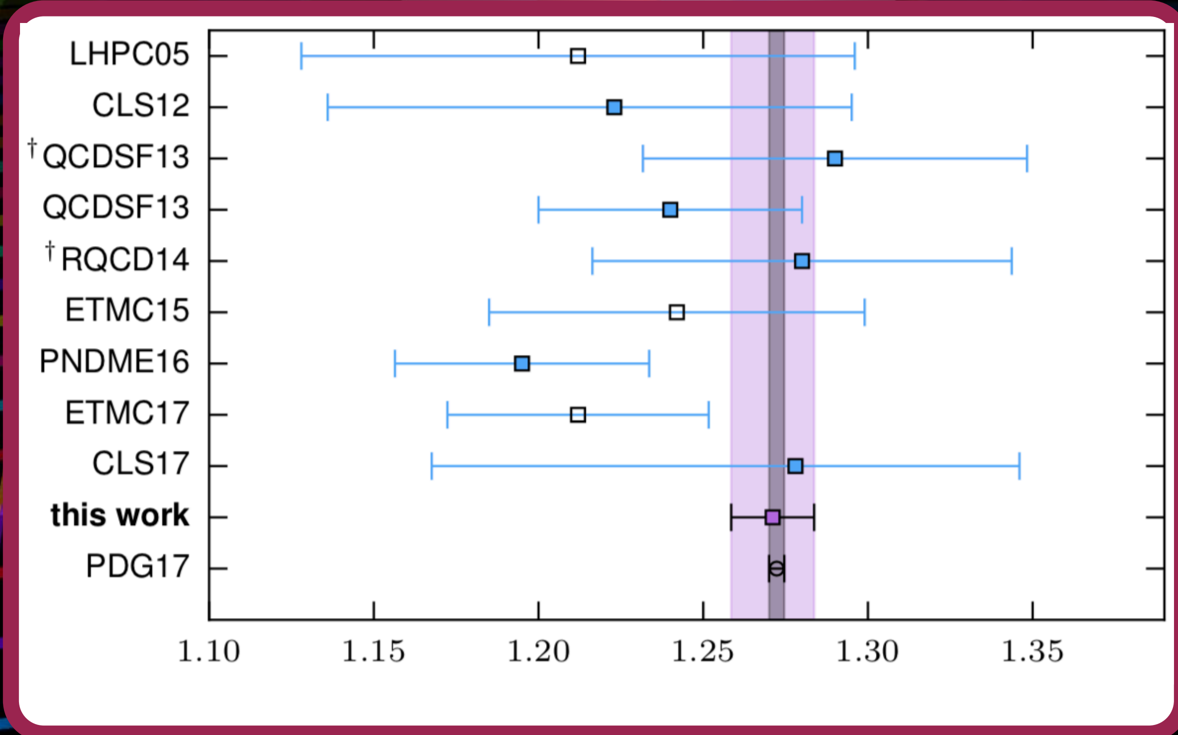


$g_A^{LQCD} = 1.271 \pm 0.013$

Nature, May 30, 2018

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





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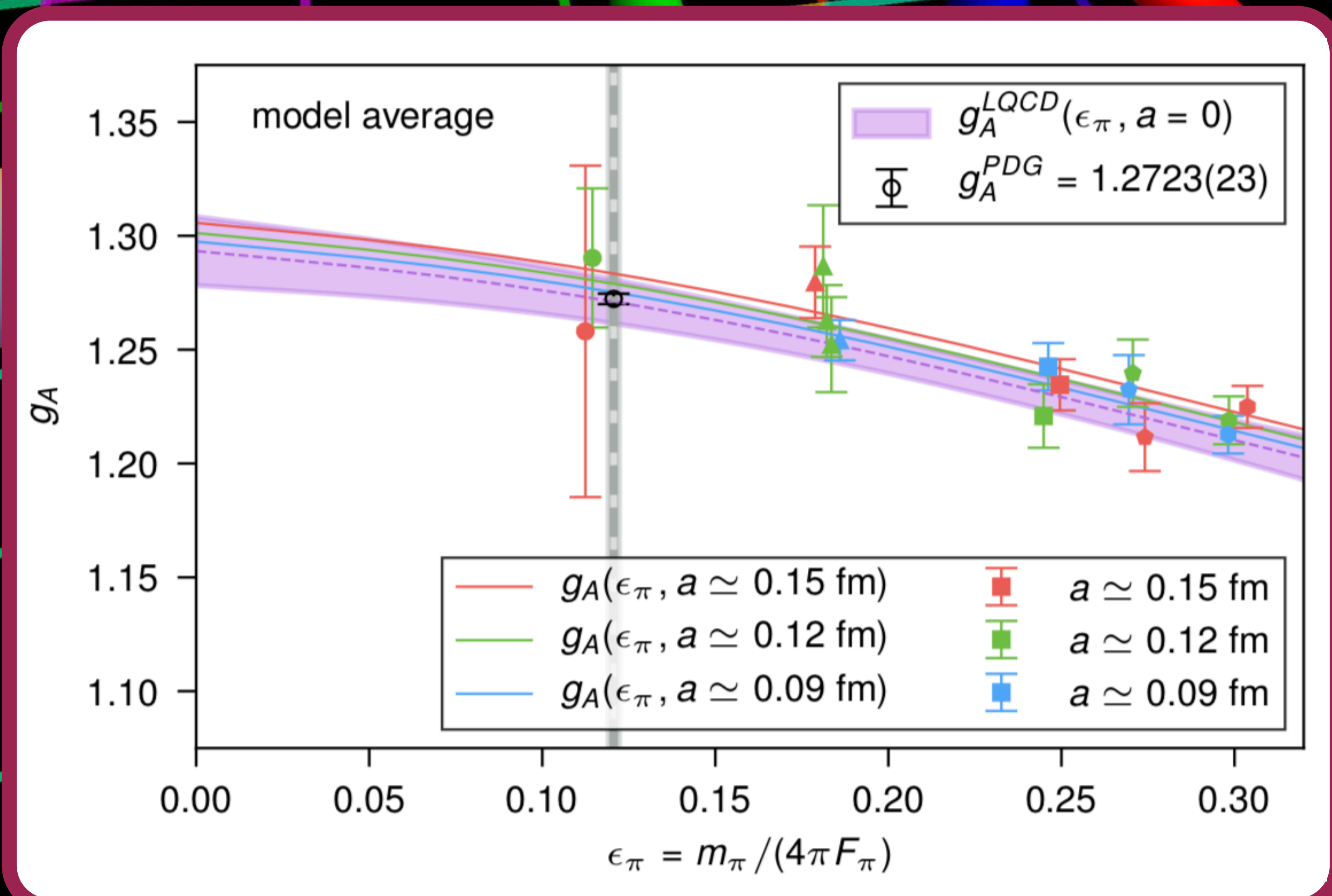

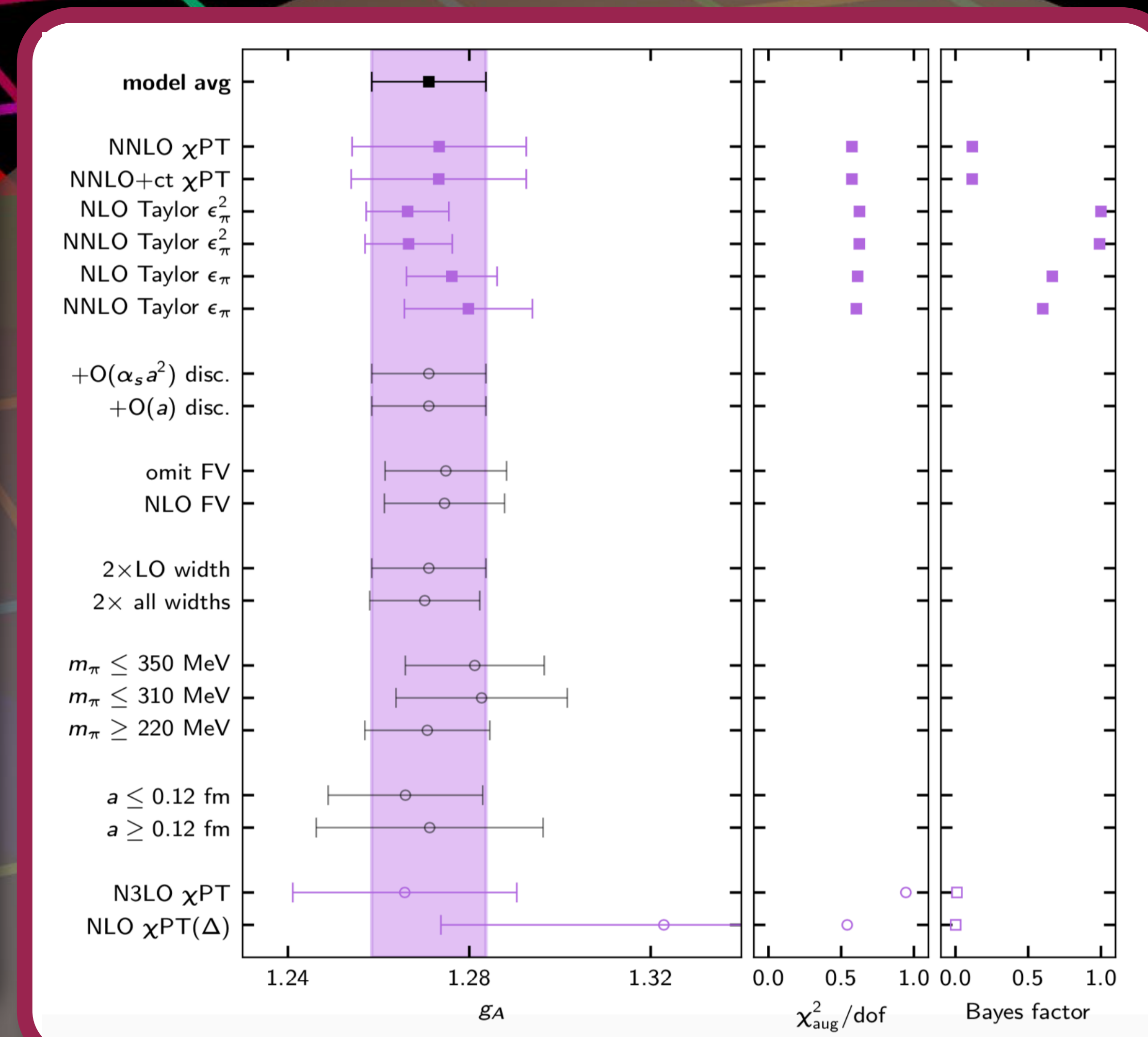

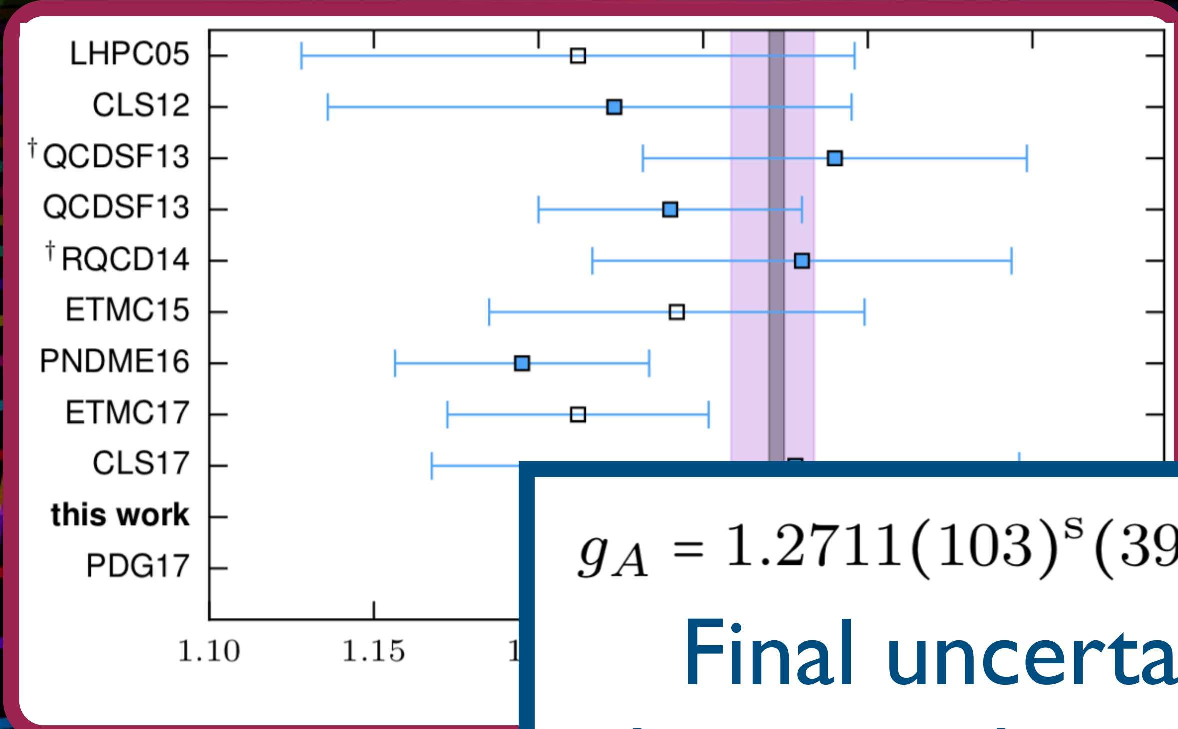

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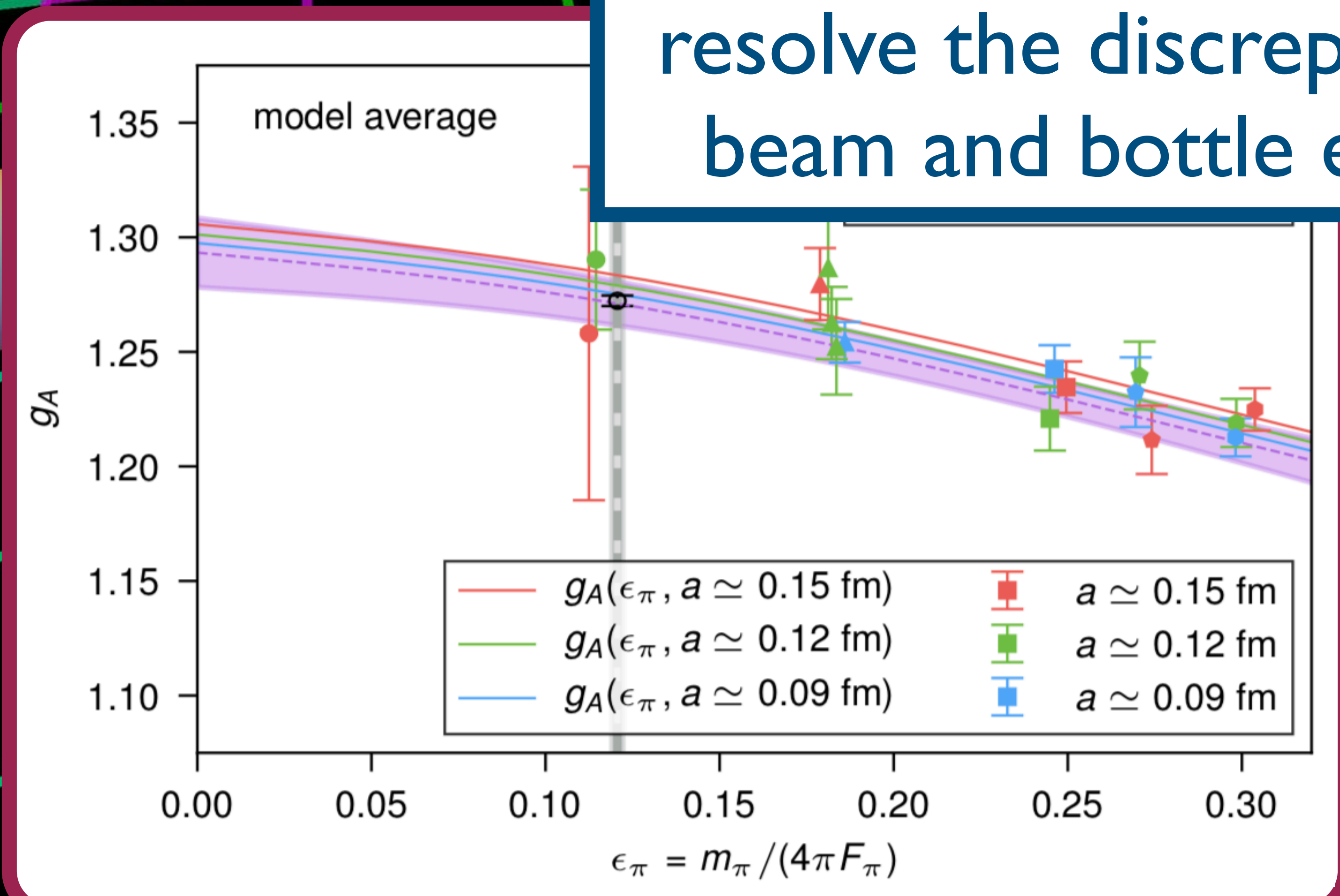
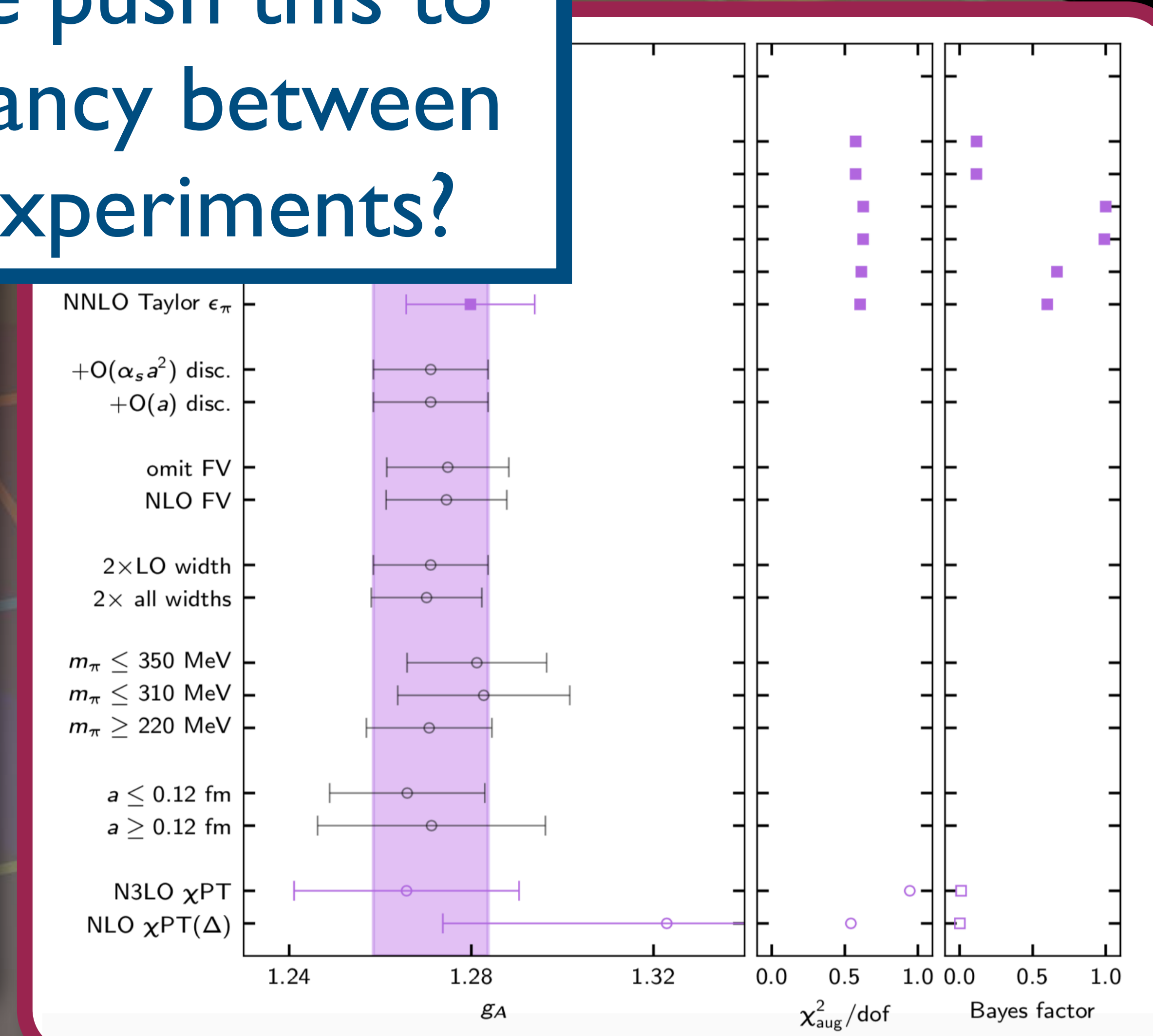
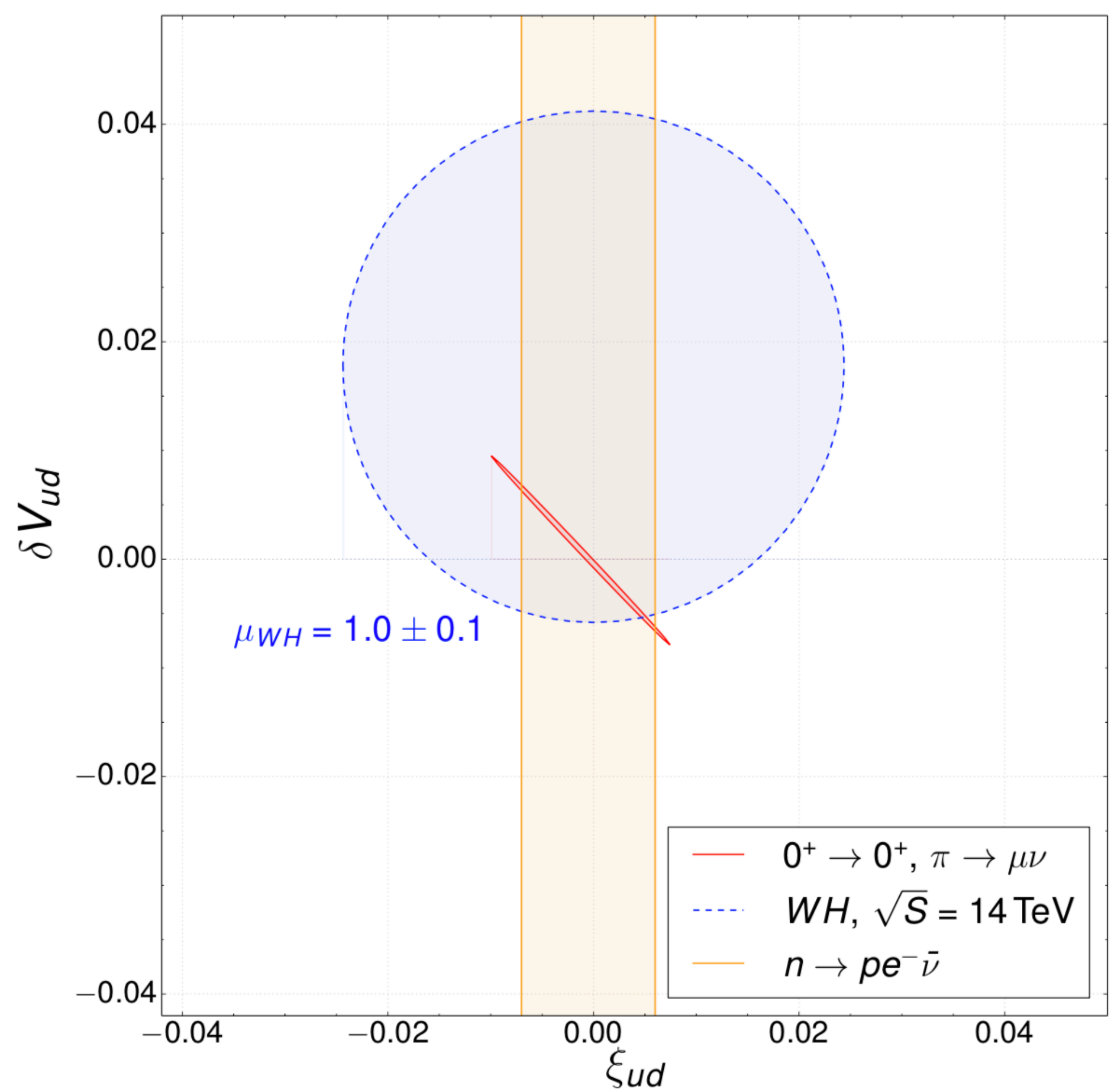
$$g_A = 1.2711(103)^{\mathrm{s}}(39)^{\chi}(15)^{\mathrm{a}}(19)^{\mathrm{v}}(04)^{\mathrm{I}}(55)^{\mathrm{M}}$$

Final uncertainty is statistics dominated - can we push this to resolve the discrepancy between beam and bottle experiments?

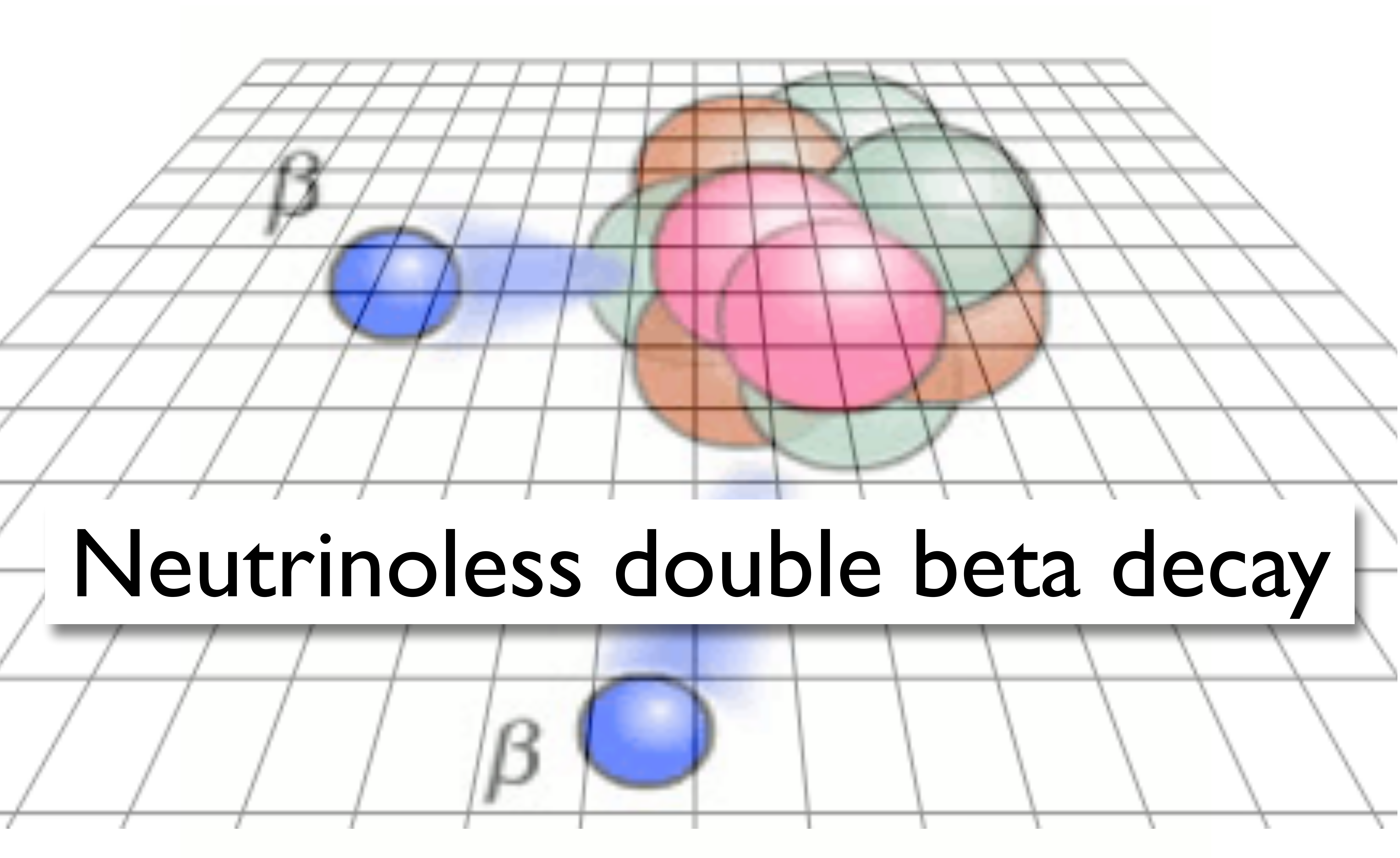






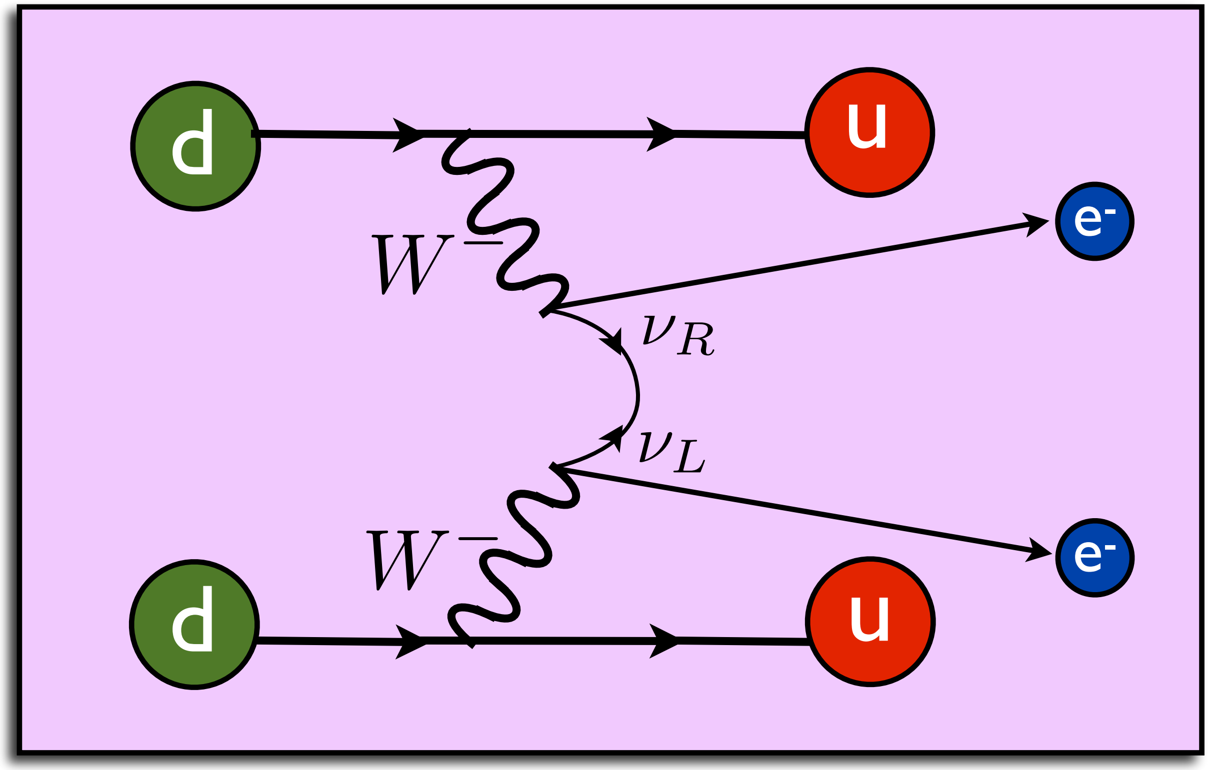
Can already place stronger constraints on right-handed BSM currents than collider experiments

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



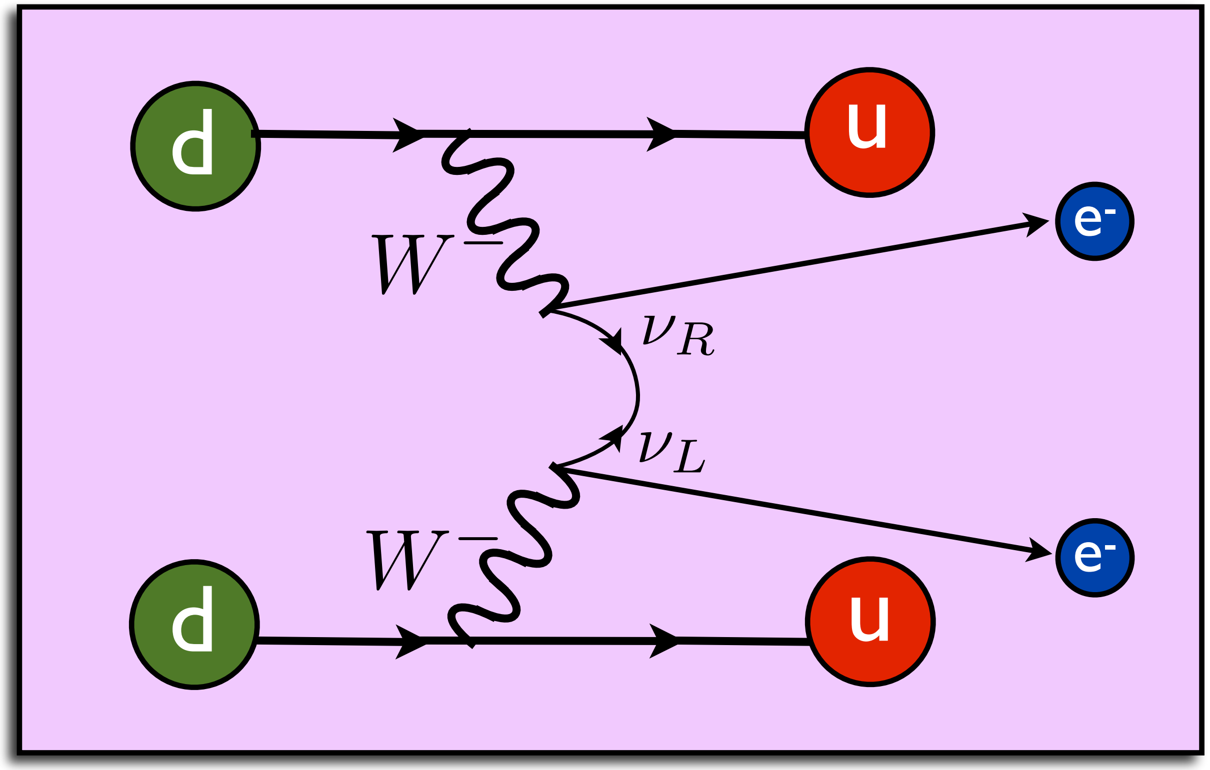
Neutrinoless double beta decay

Neutrinos: Majorana or Dirac?



Neutrinos: Majorana or Dirac?

- Majorana: $\nu = \bar{\nu}$



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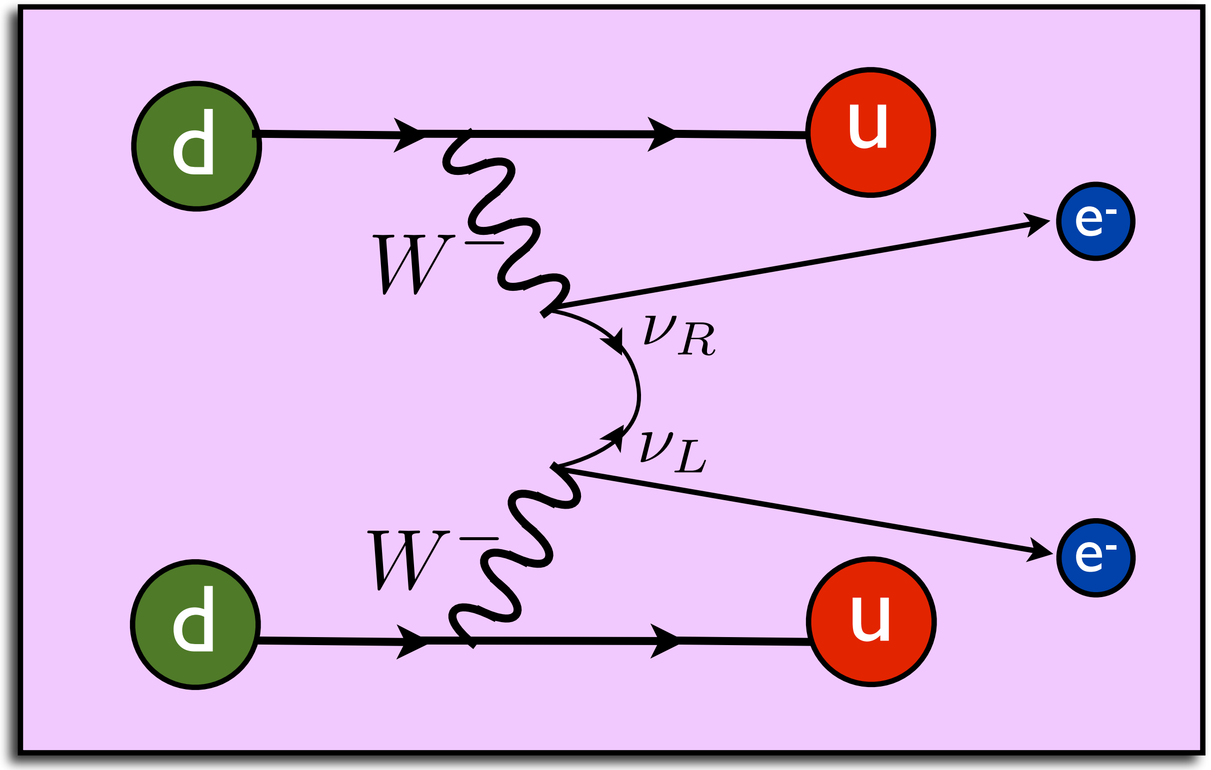
- Could be verified through observation of simultaneous double beta decay with no neutrino emission



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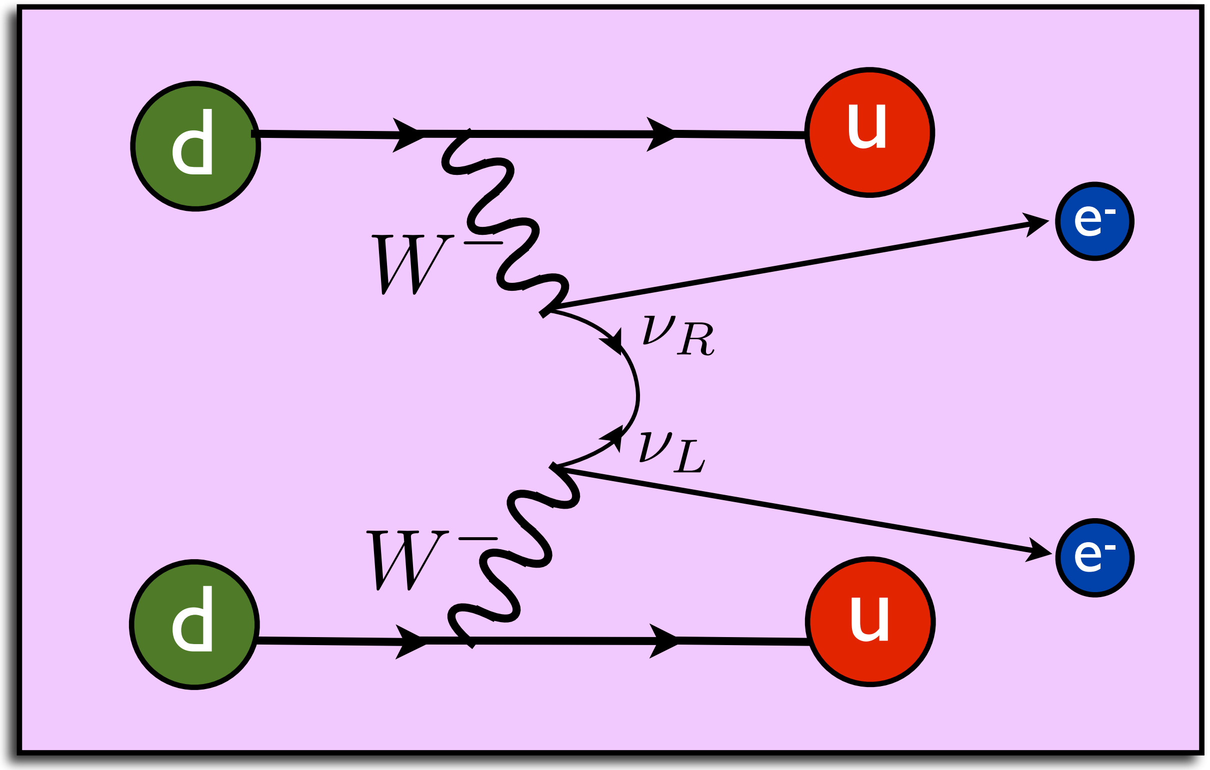
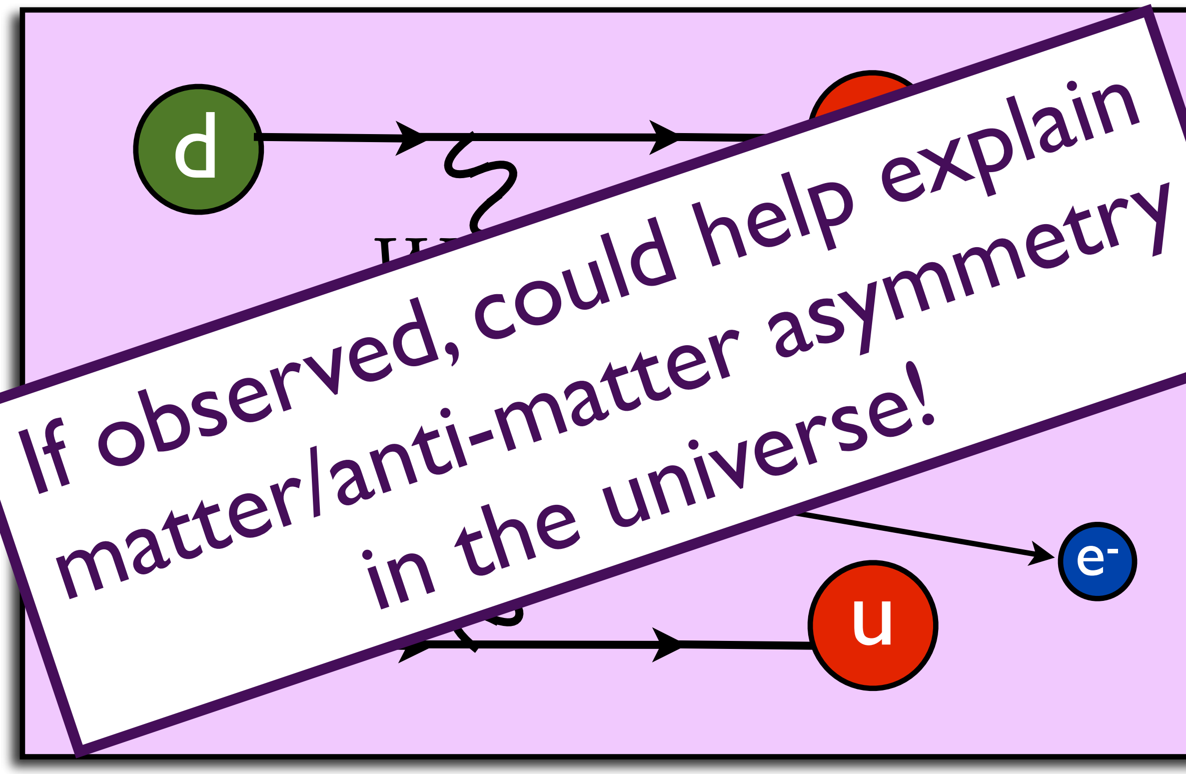
  - Lepton number violating process

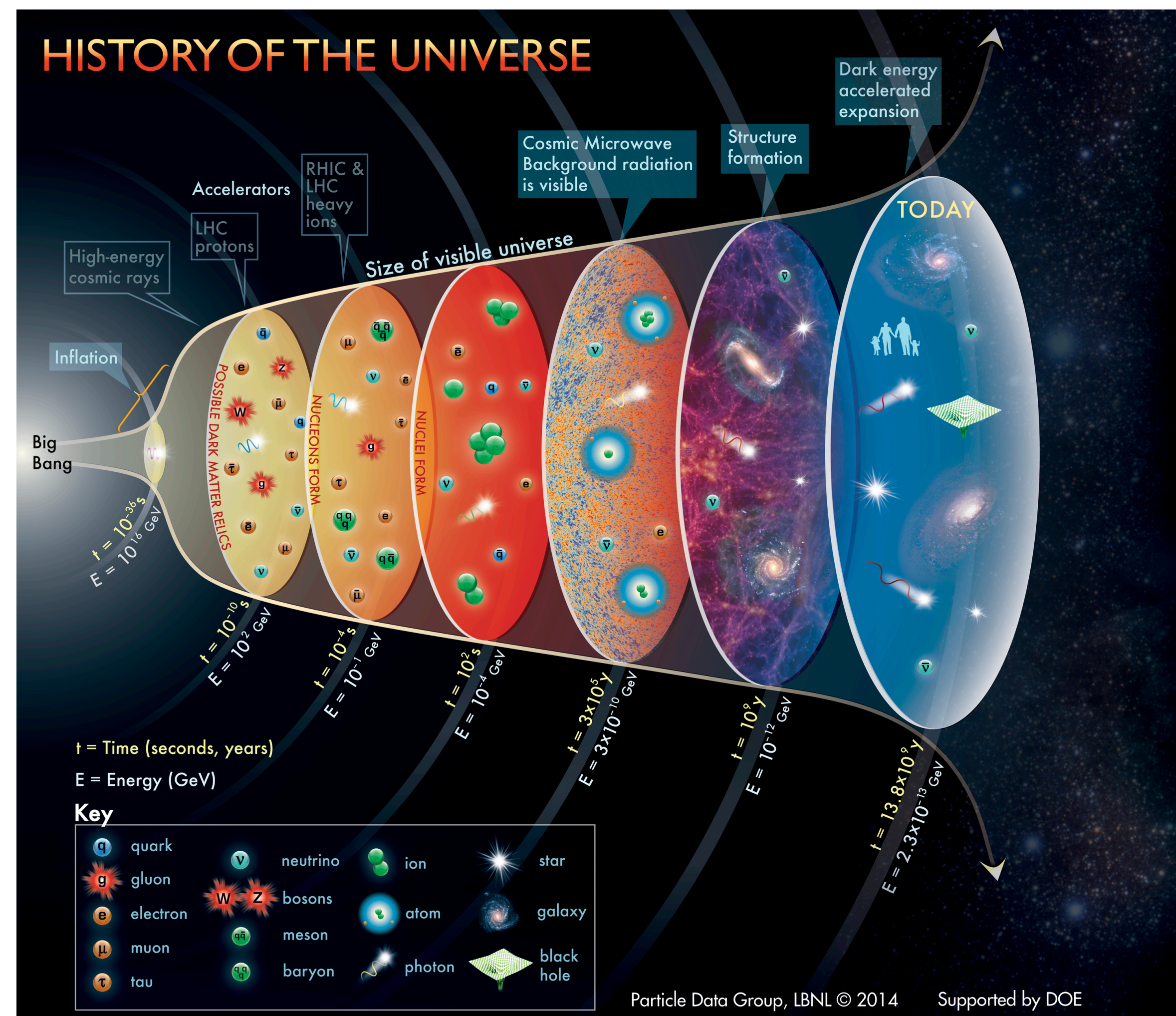


Neutrinos: Majorana or Dirac?

- Majorana: $\nu = \bar{\nu}$
- Could be verified through observation of simultaneous double beta decay with no neutrino emission
    - Lepton number violating process
    - Lepton number asymmetry (in early Universe) can be converted to baryon number asymmetry

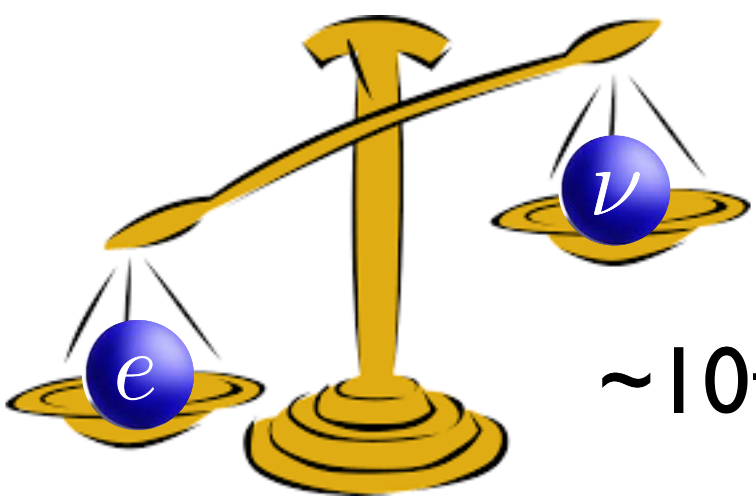


If observed, could help explain matter/anti-matter asymmetry in the universe!



Why Majorana?

- Anything not forbidden by symmetry should occur in nature
- Why are neutrinos so light?



$\sim 10^{-7}\ m_e$?

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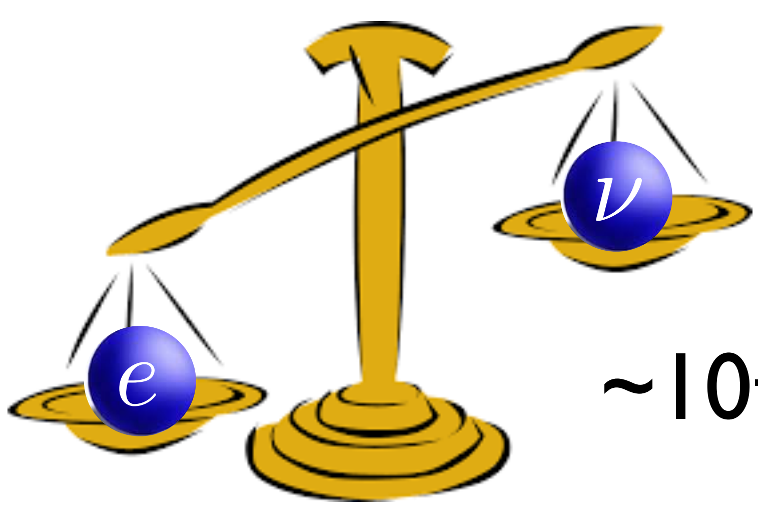

$\sim 10^{-7}\, m_e$?

<u>Seesaw Mechanism</u>

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

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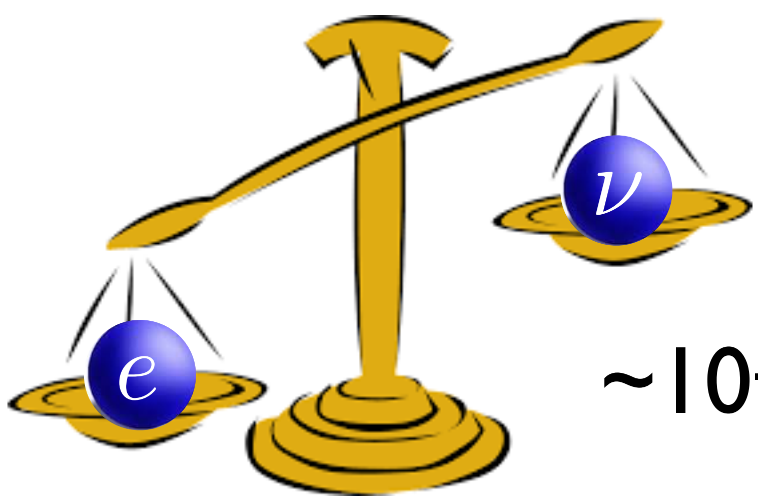

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<u>Seesaw Mechanism</u>

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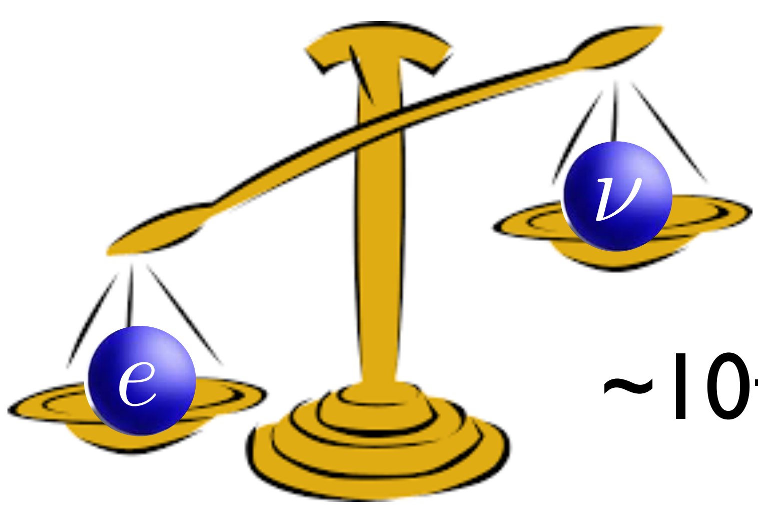

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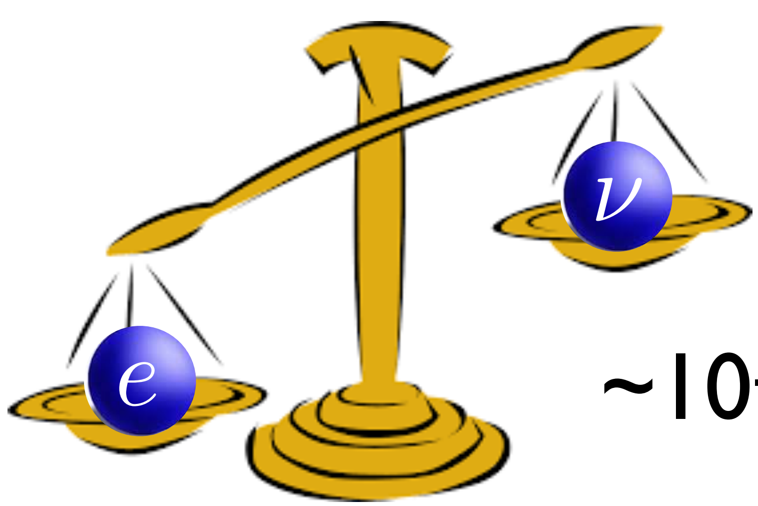


~10^{-7} m_e?

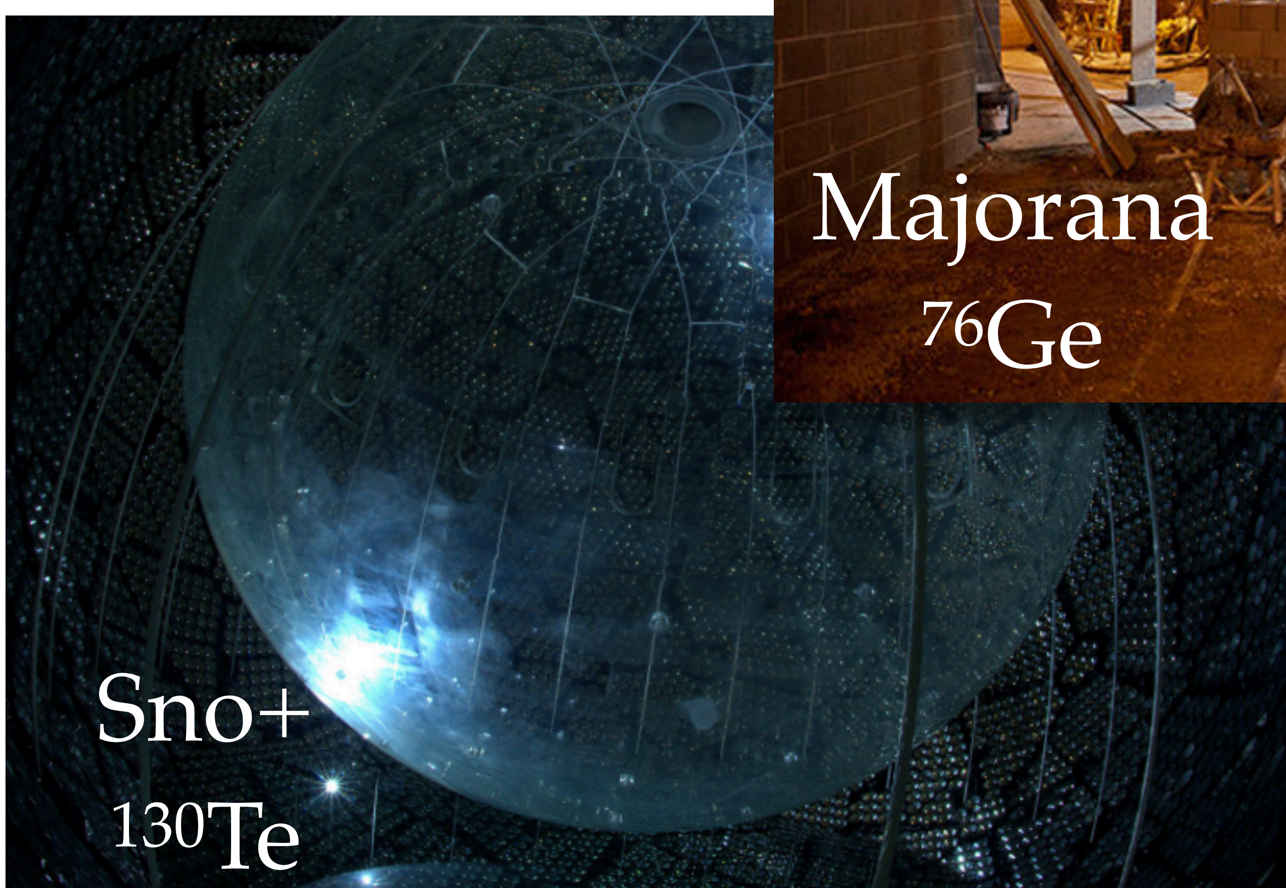
Seesaw Mechanism

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

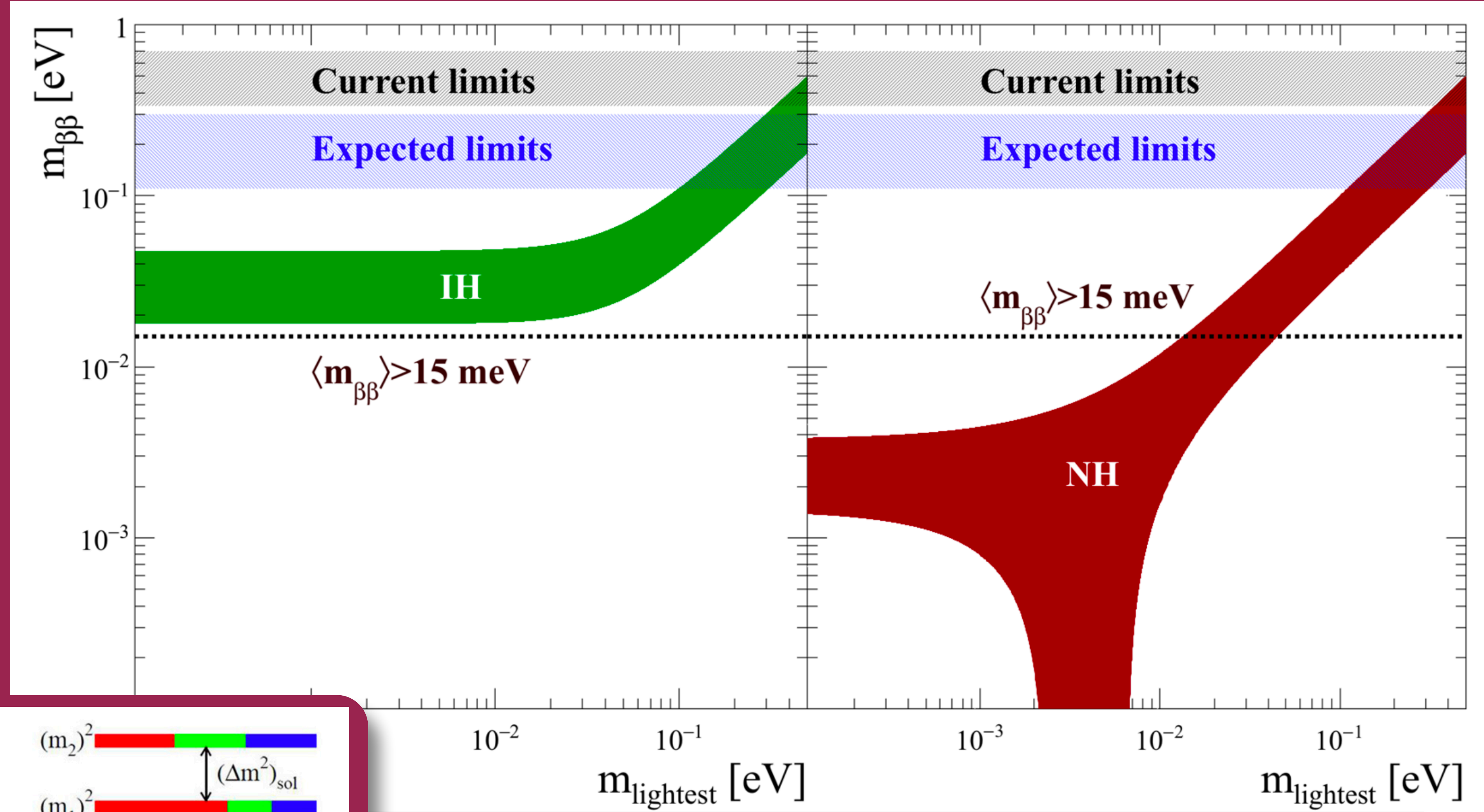
$$m_l \sim M_D^2/M_R$$

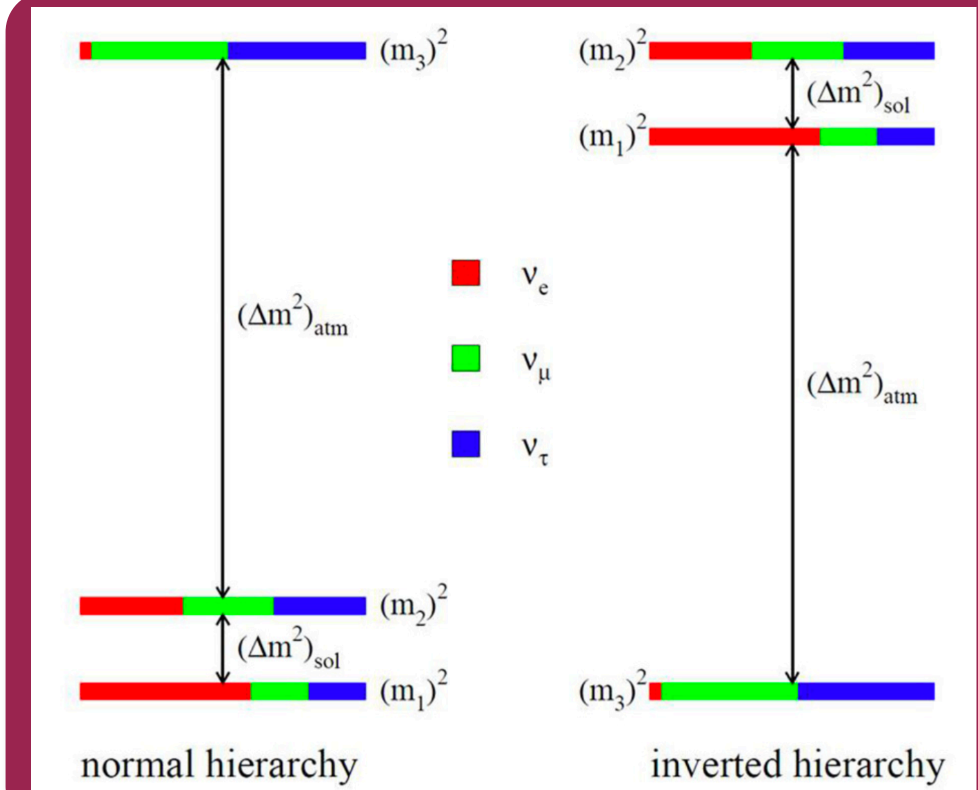
$$m_h \sim M_R$$

Experiment



From NSAC Long Range Plan 2015





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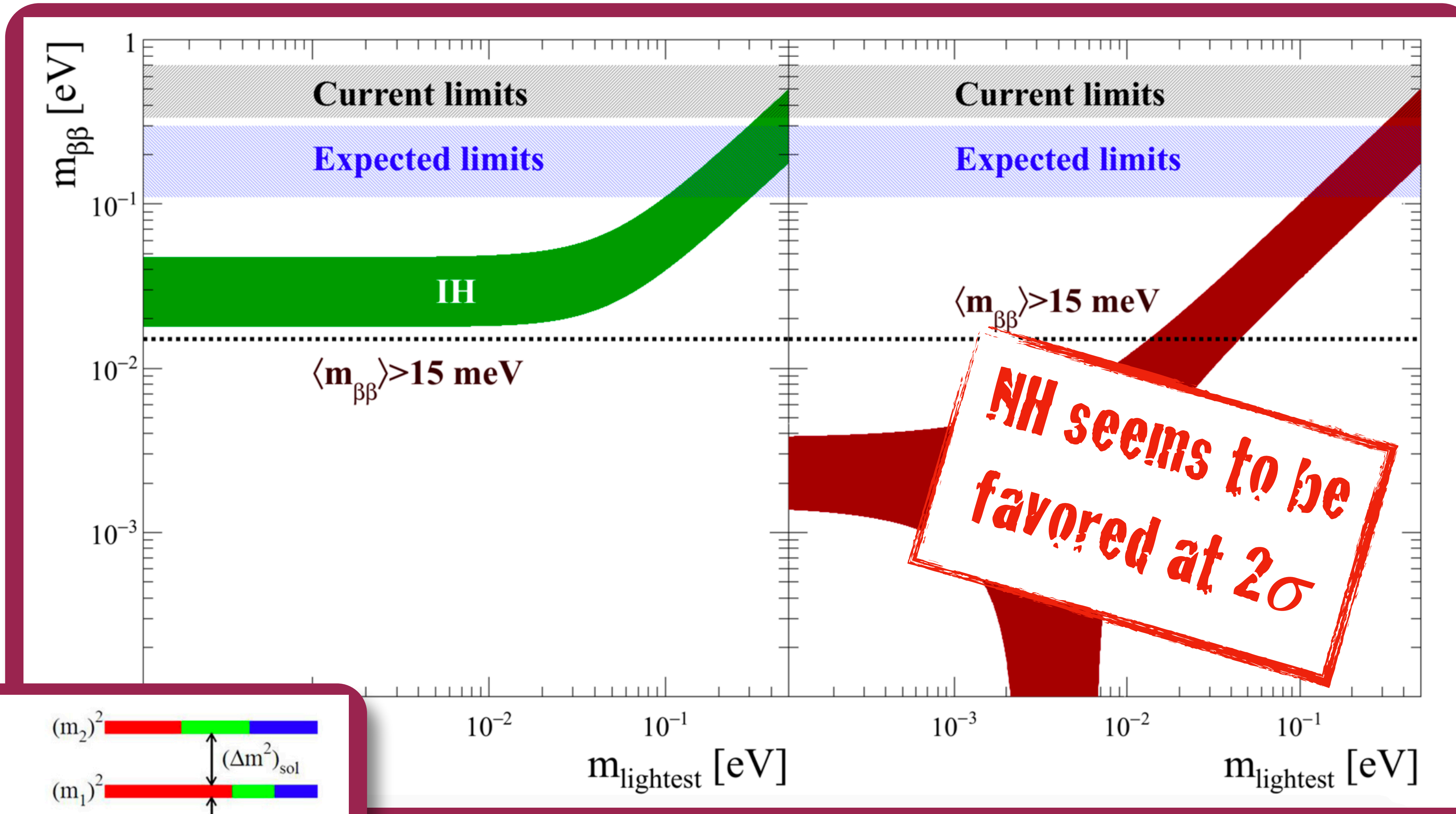
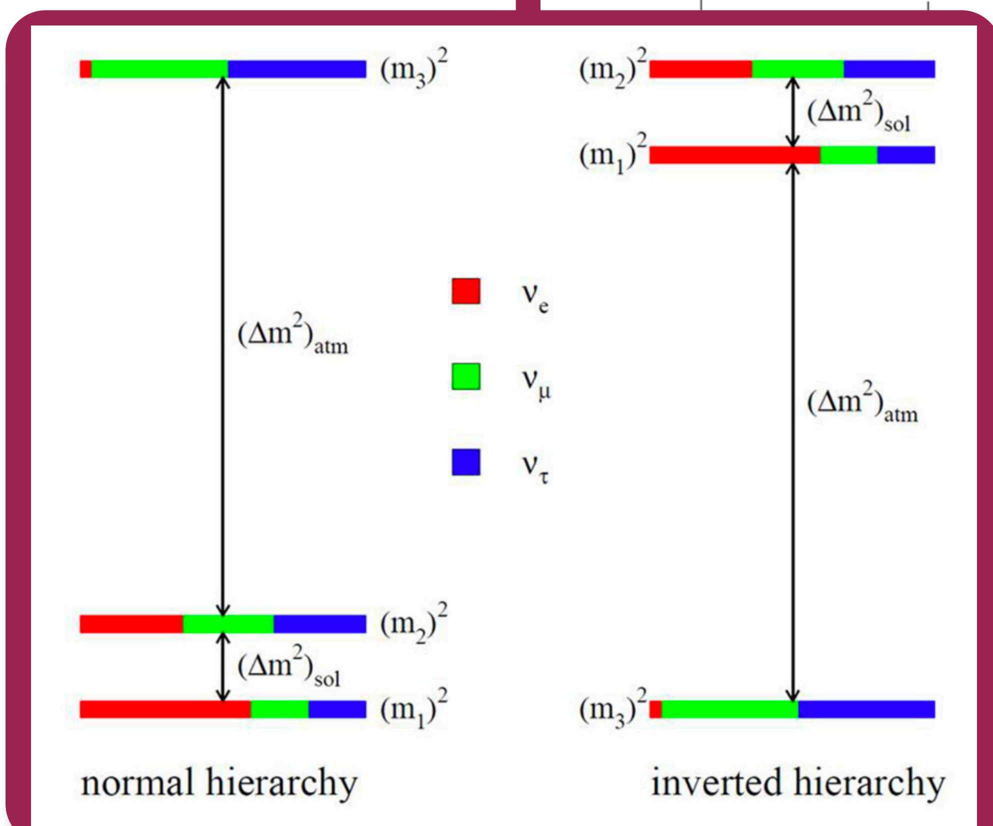
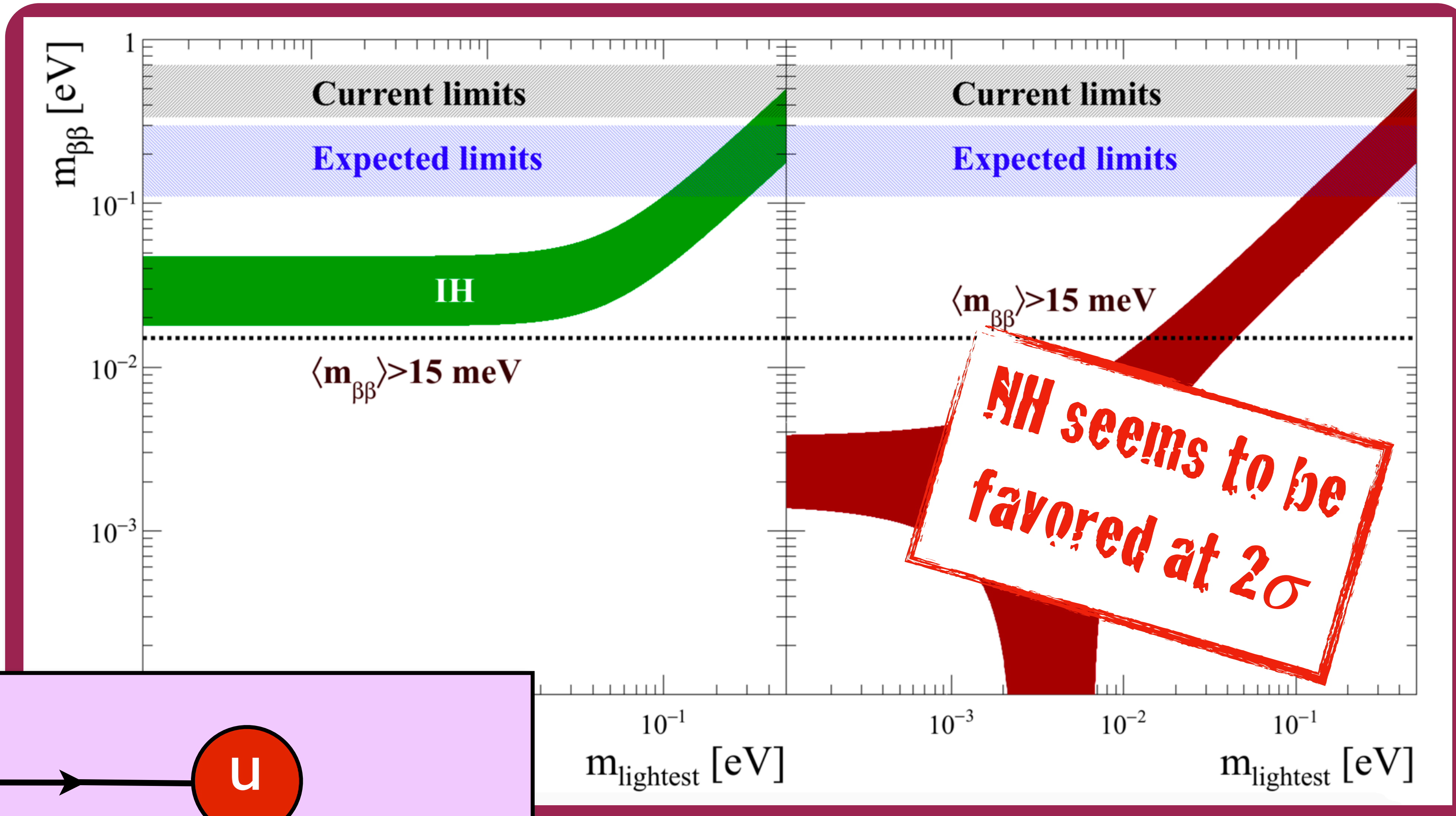
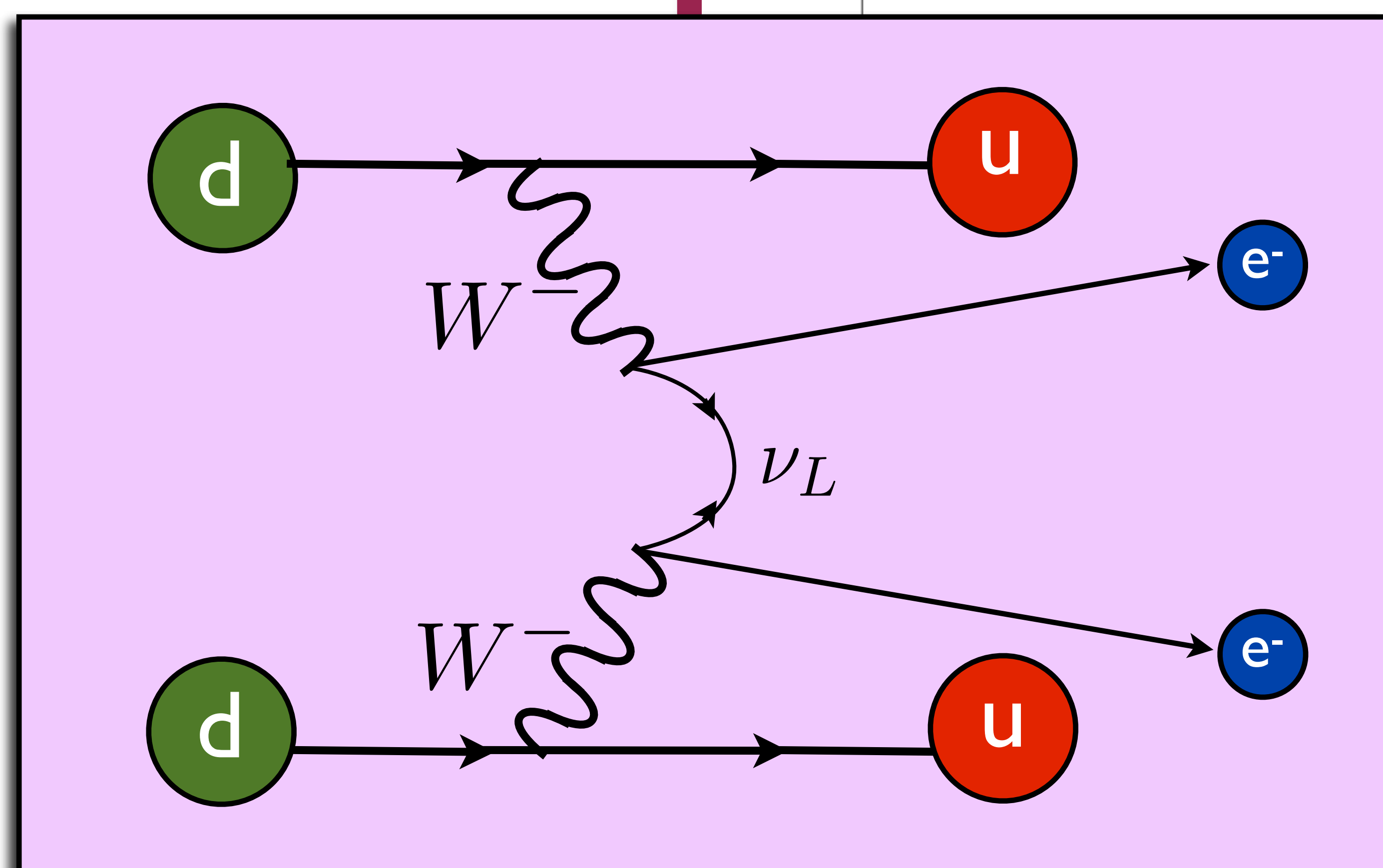




Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo
Phys.Rev. D95 (2017) no.9, 096014

From NSAC Long Range Plan 2015

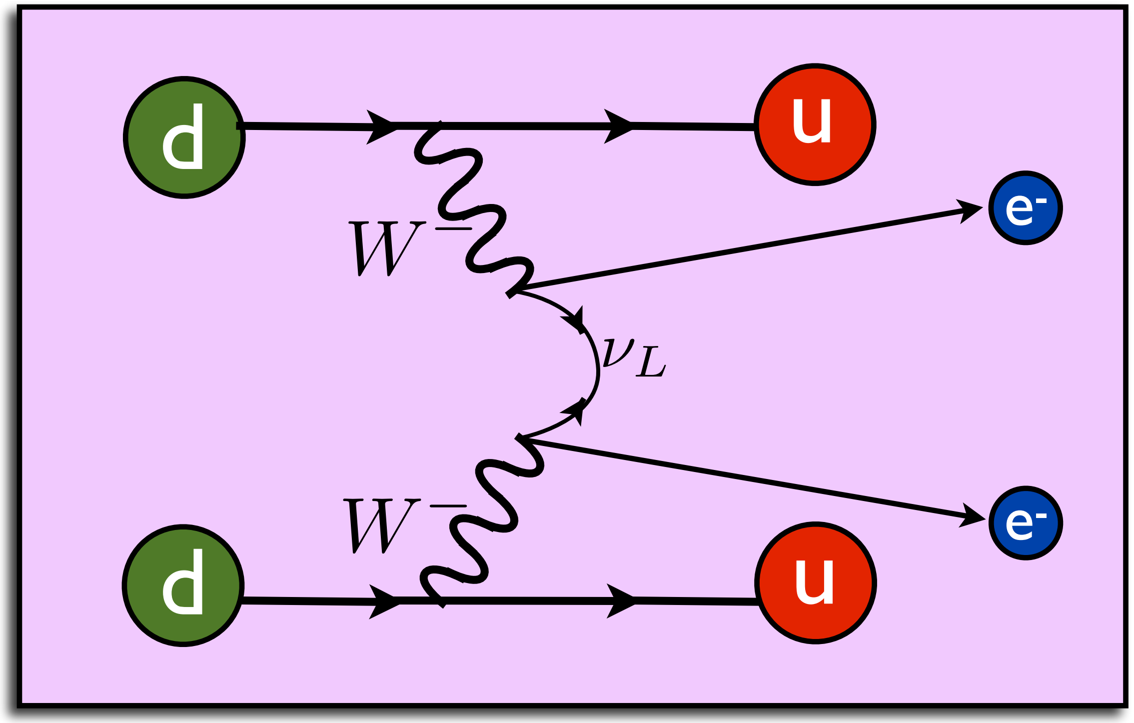




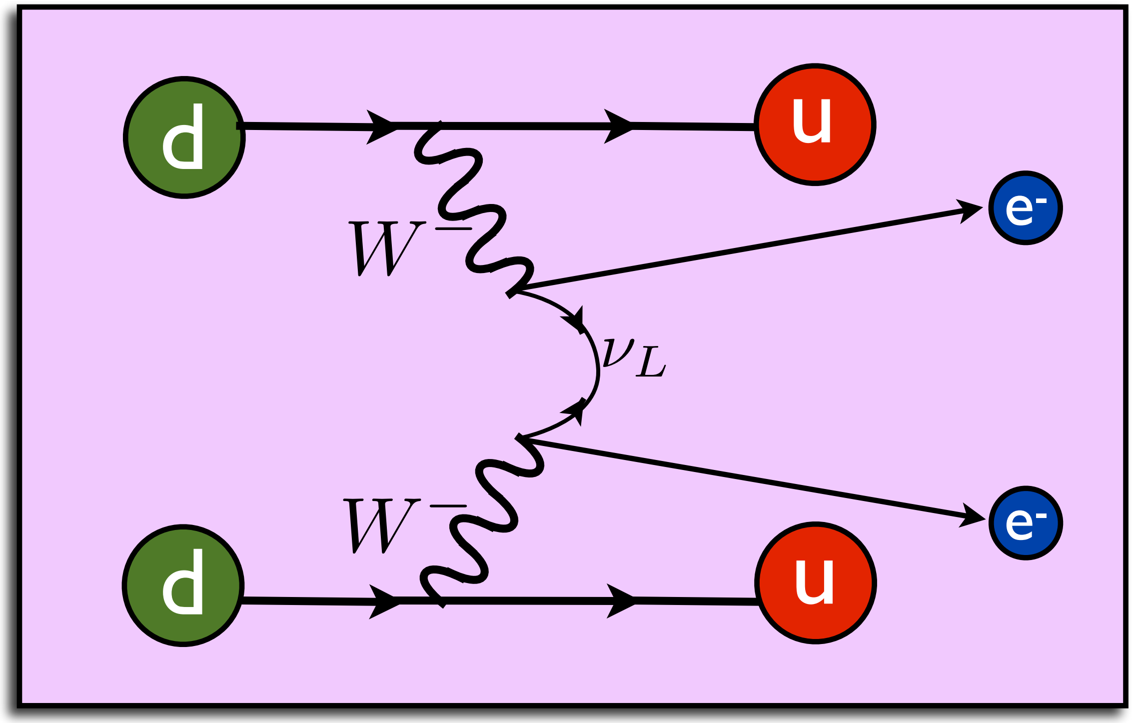
This picture assumes only long-range neutrino exchange - maybe we're missing something!

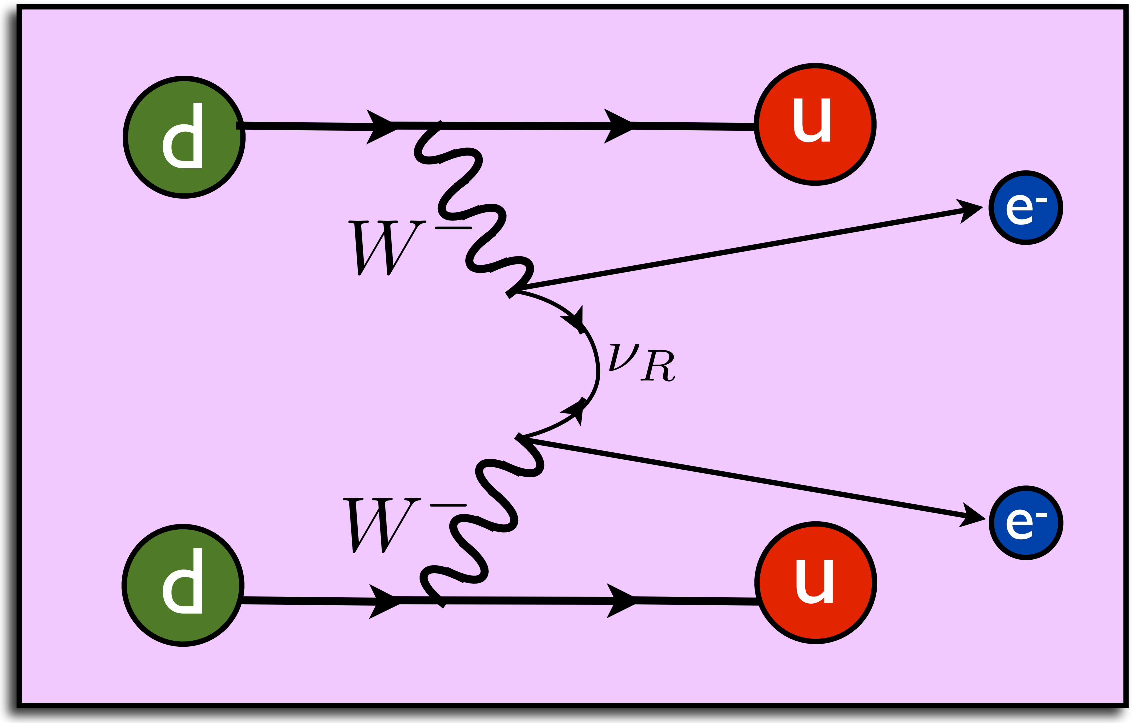
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo
Phys.Rev. D95 (2017) no.9, 096014

Short-range contributions



Short-range contributions





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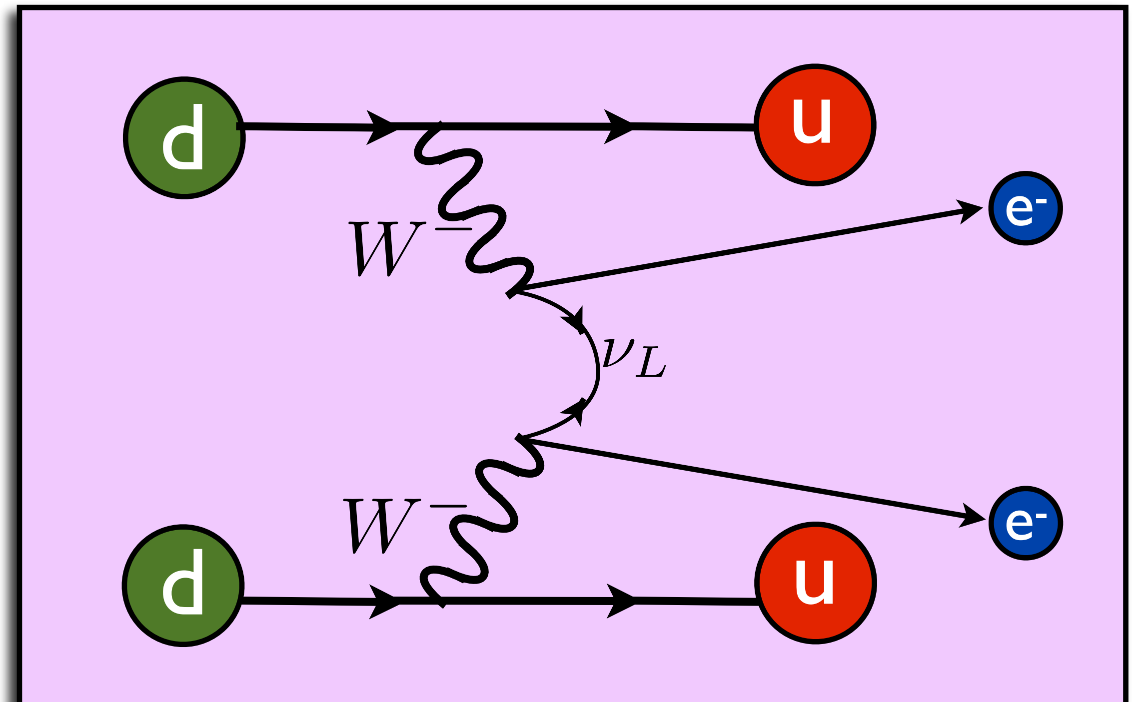

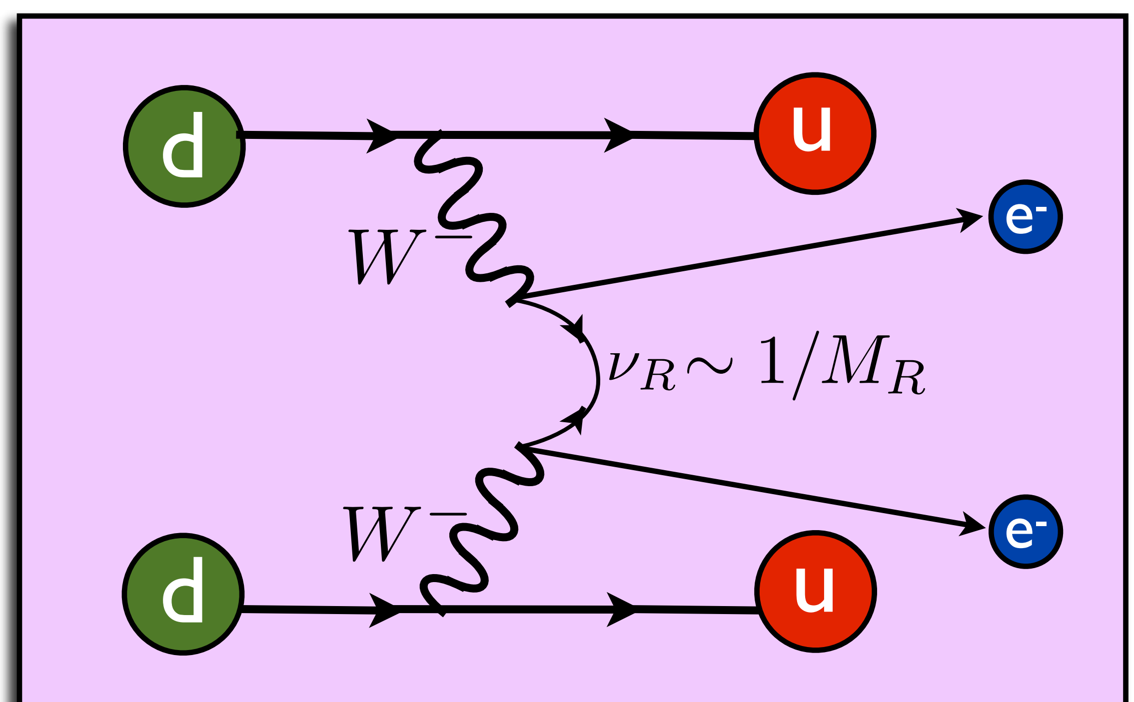

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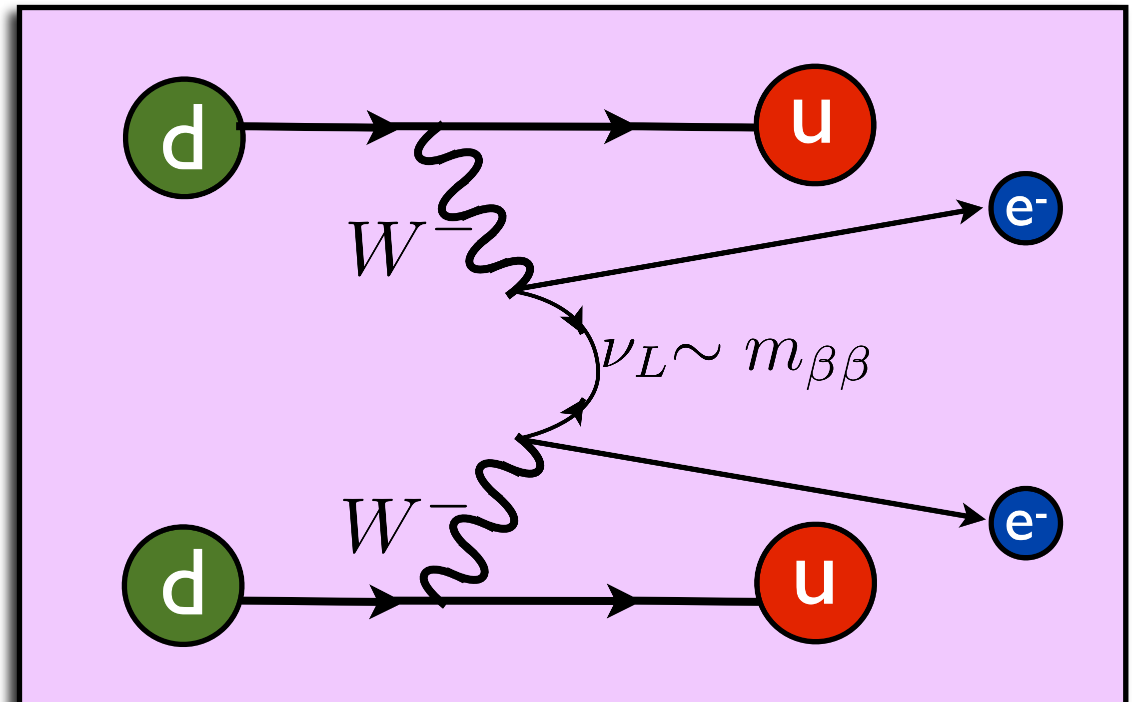

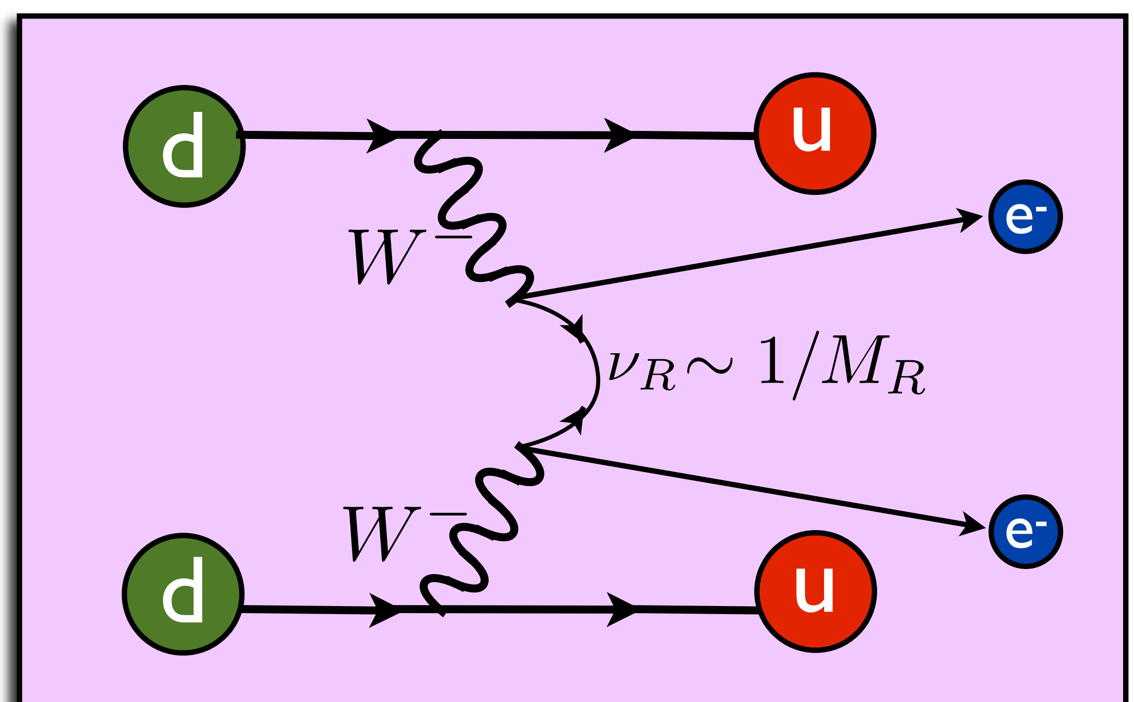

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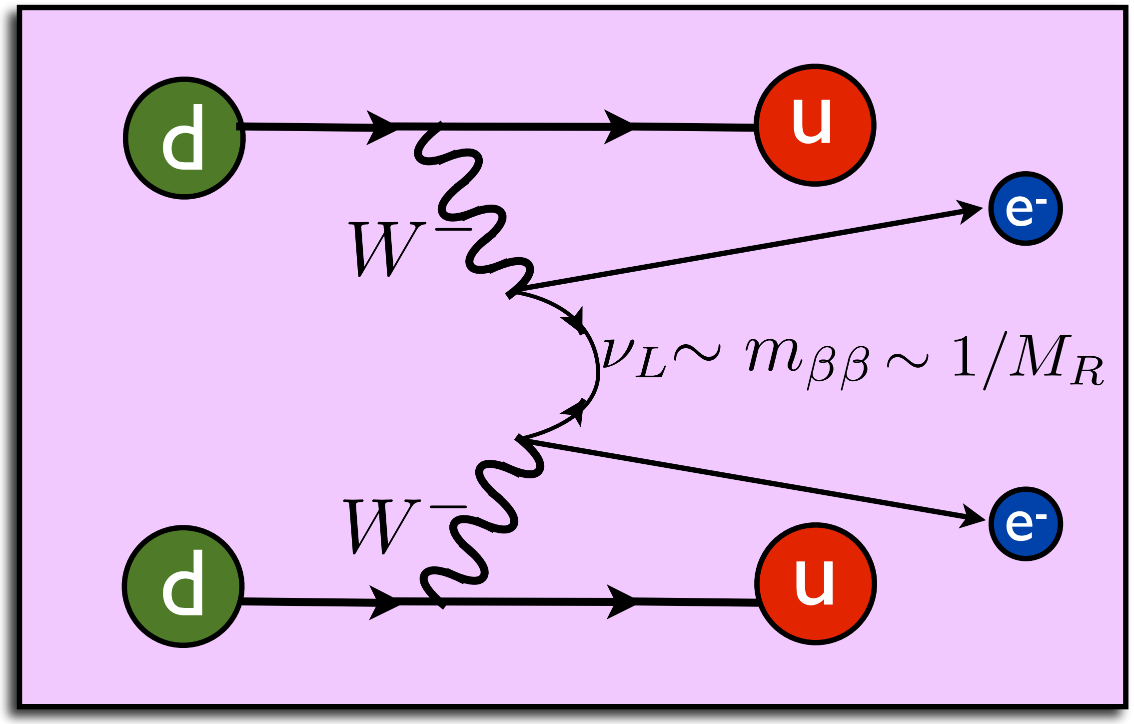

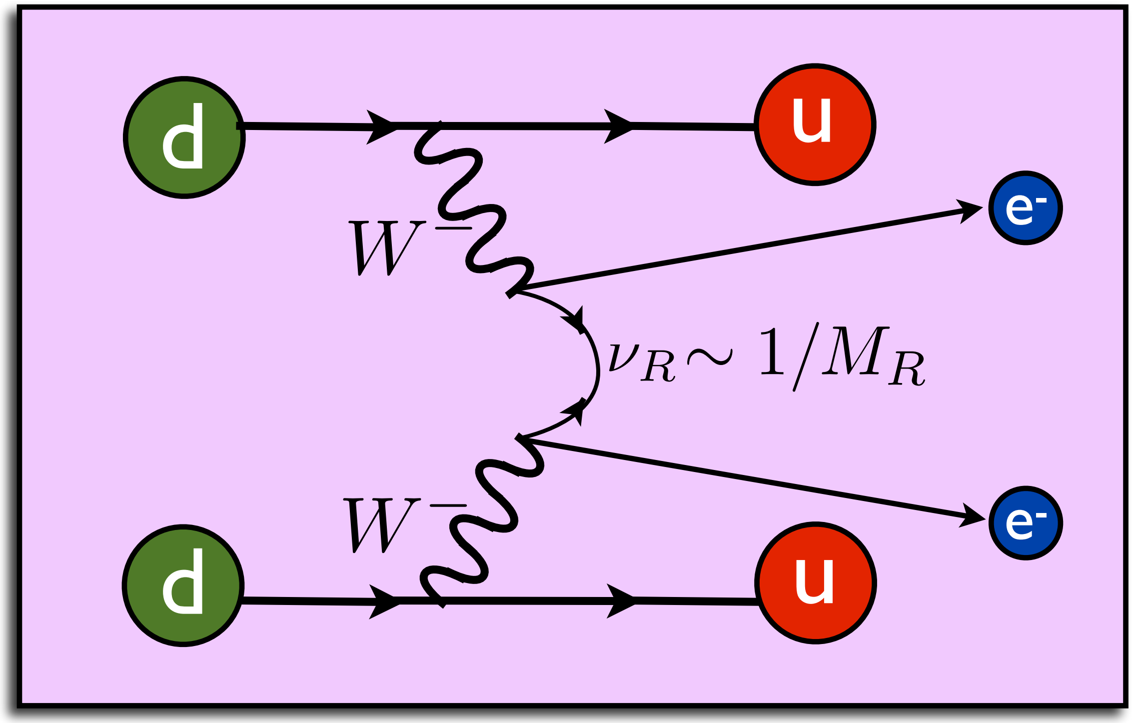

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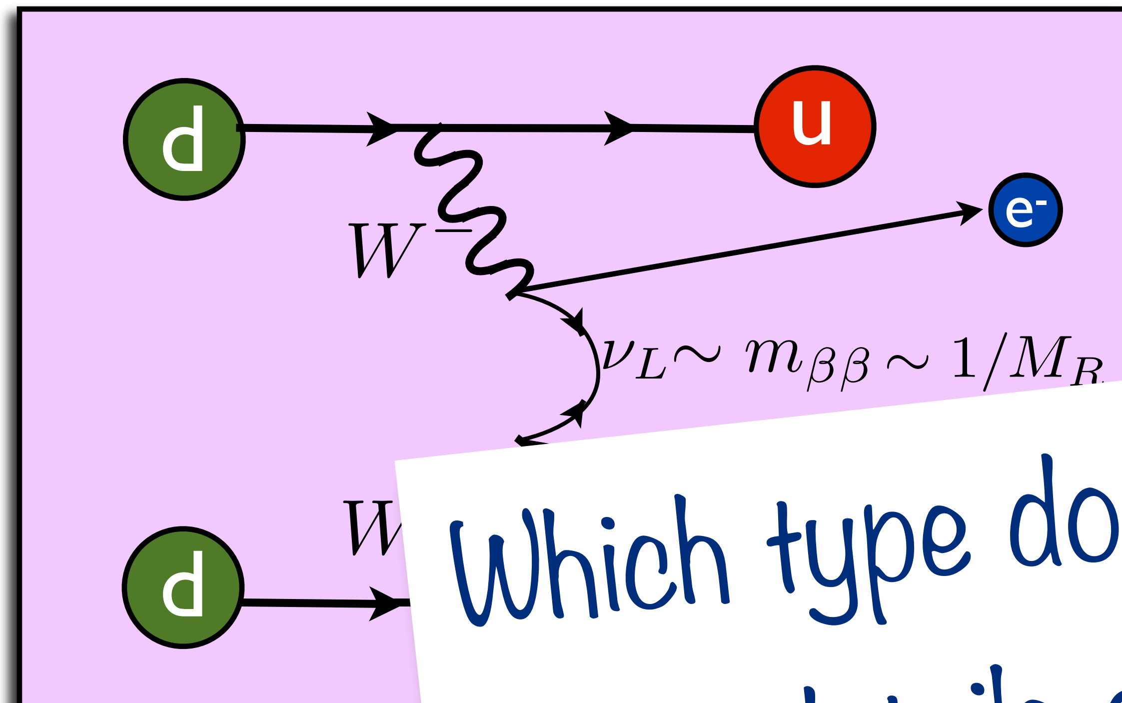
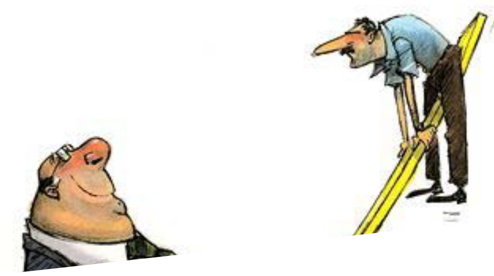
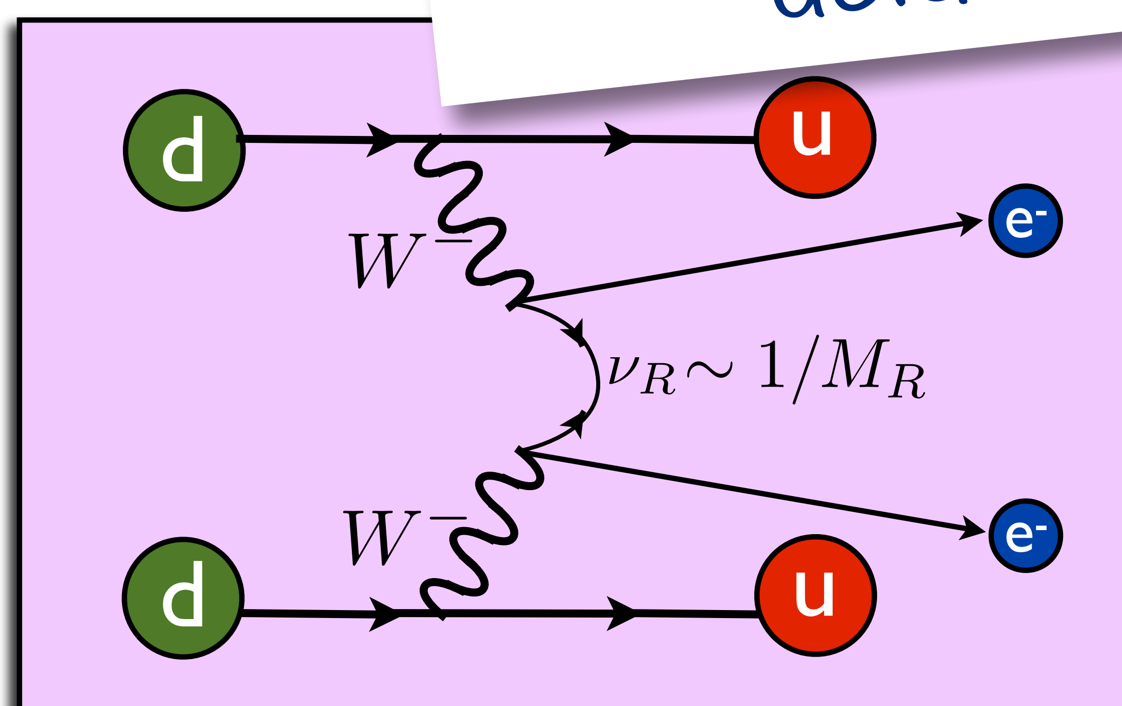




Which type dominates depends on details of BSM model



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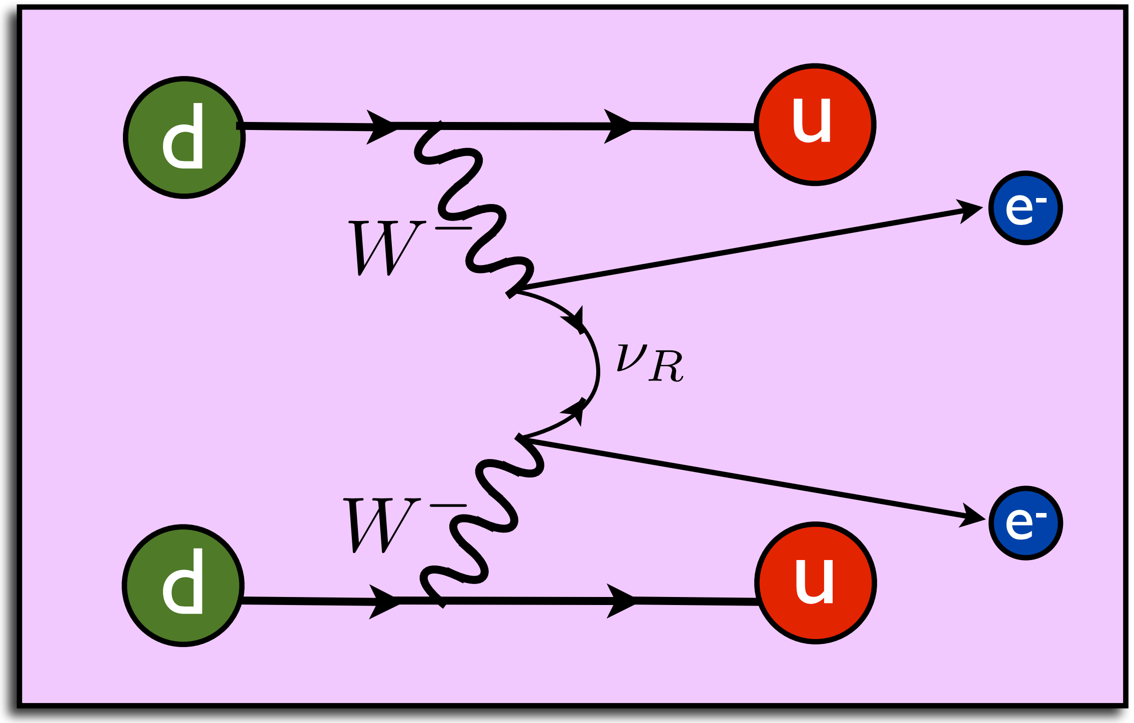

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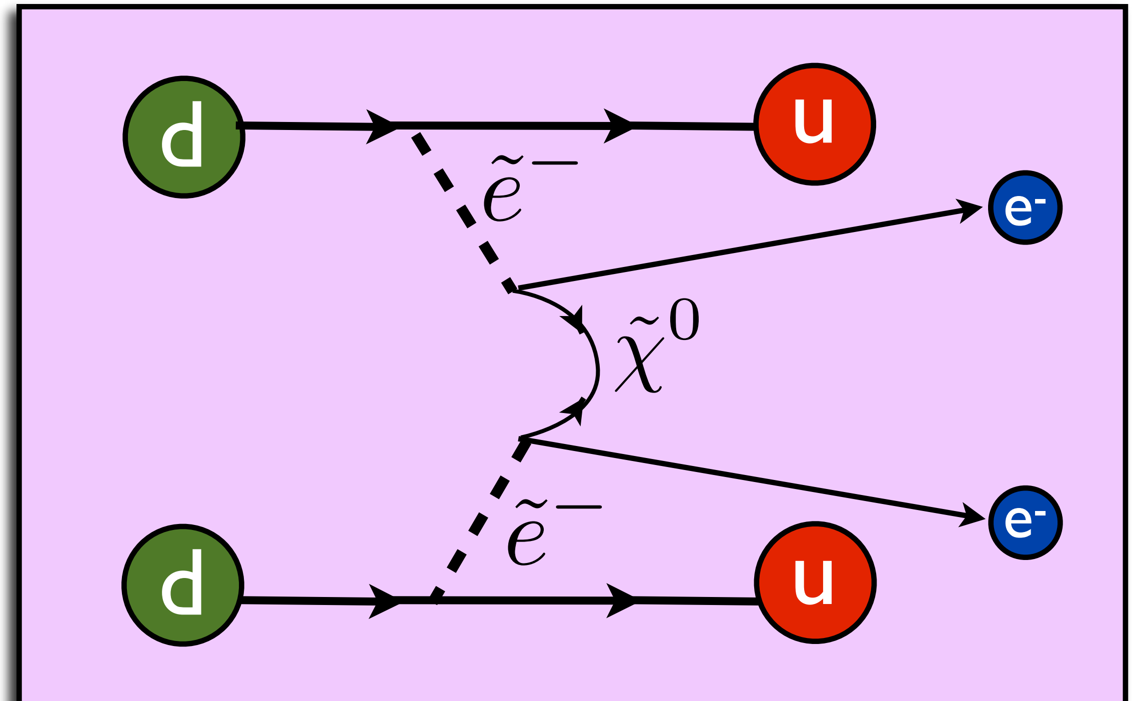

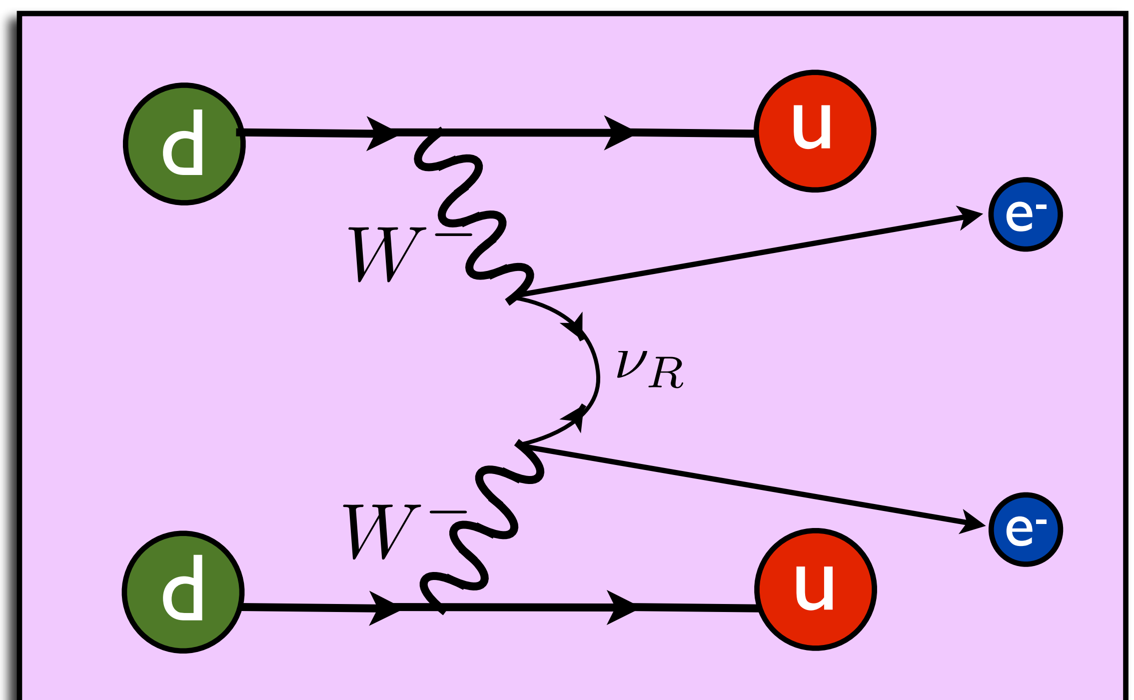

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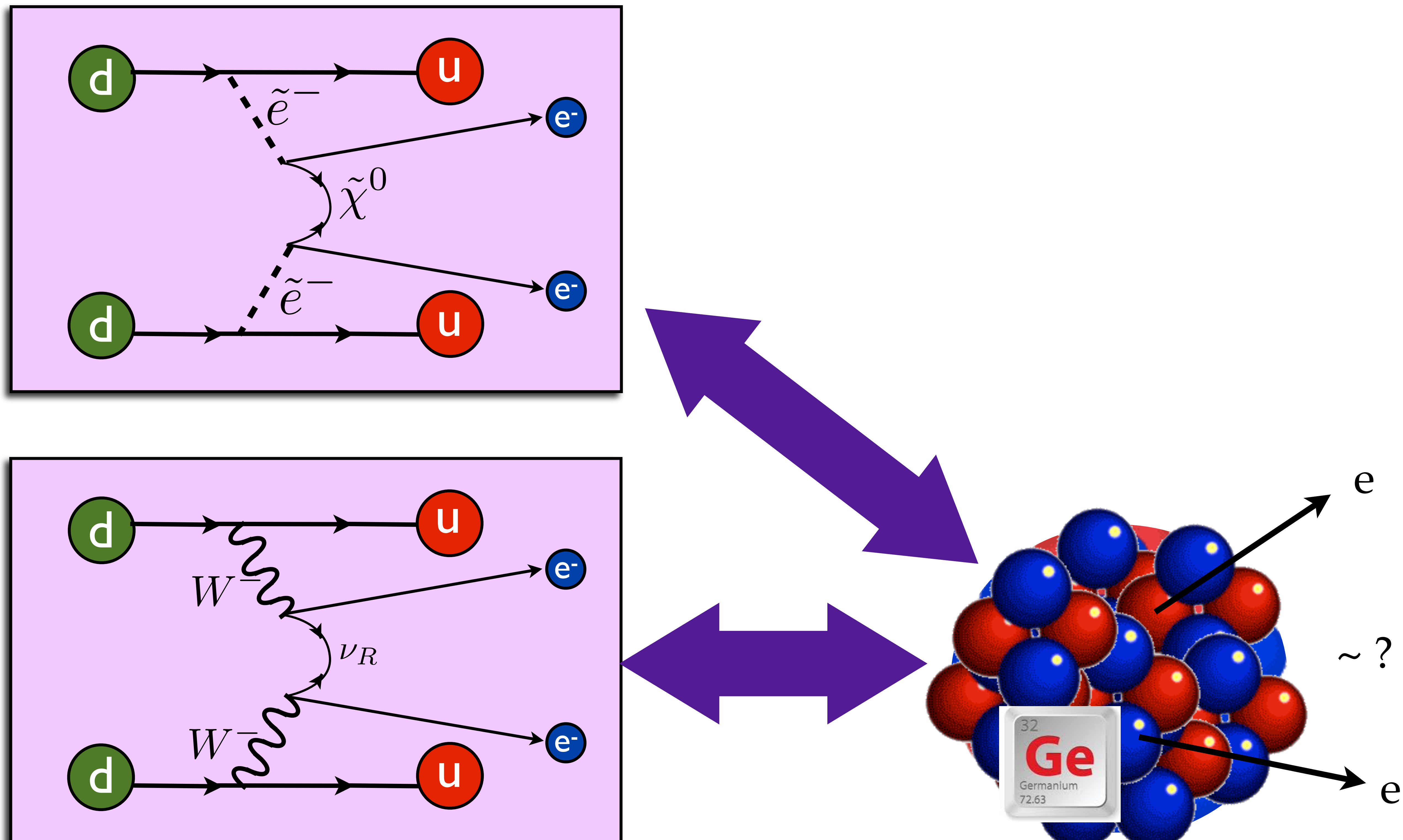

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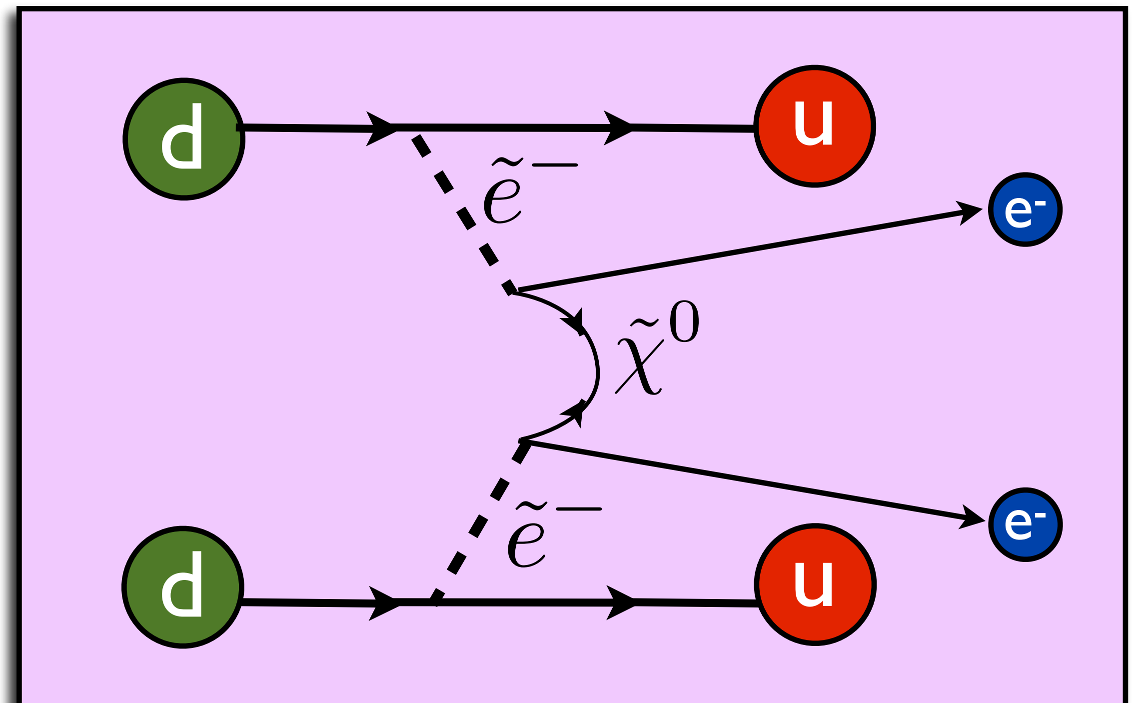
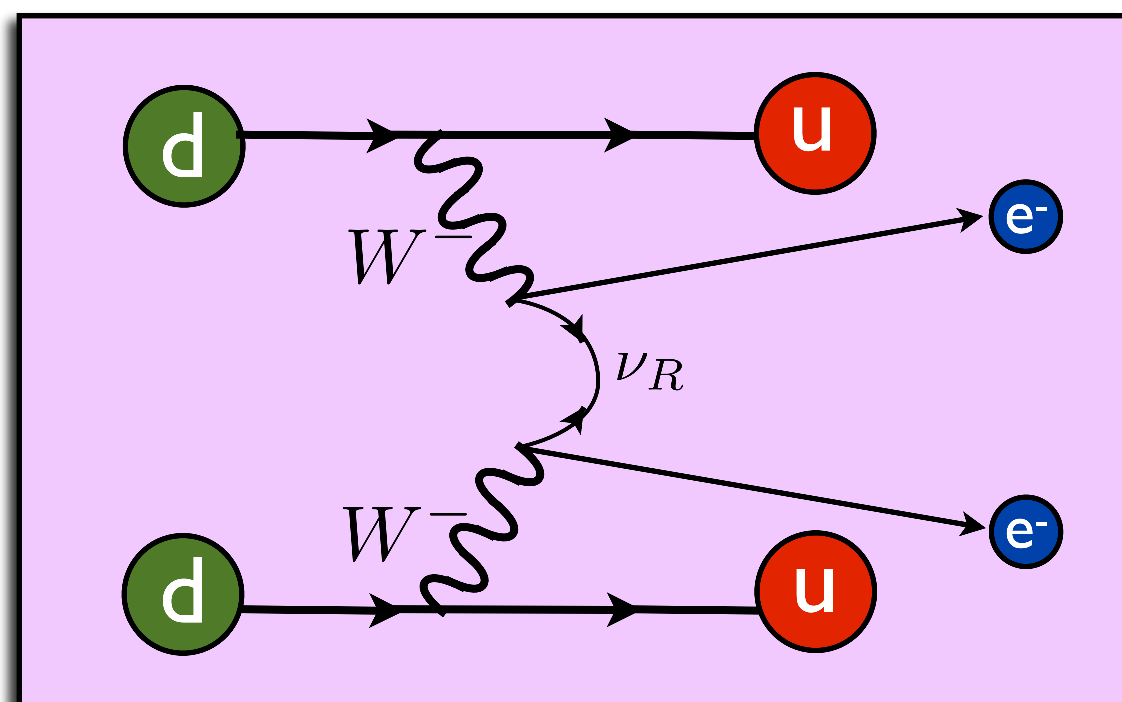
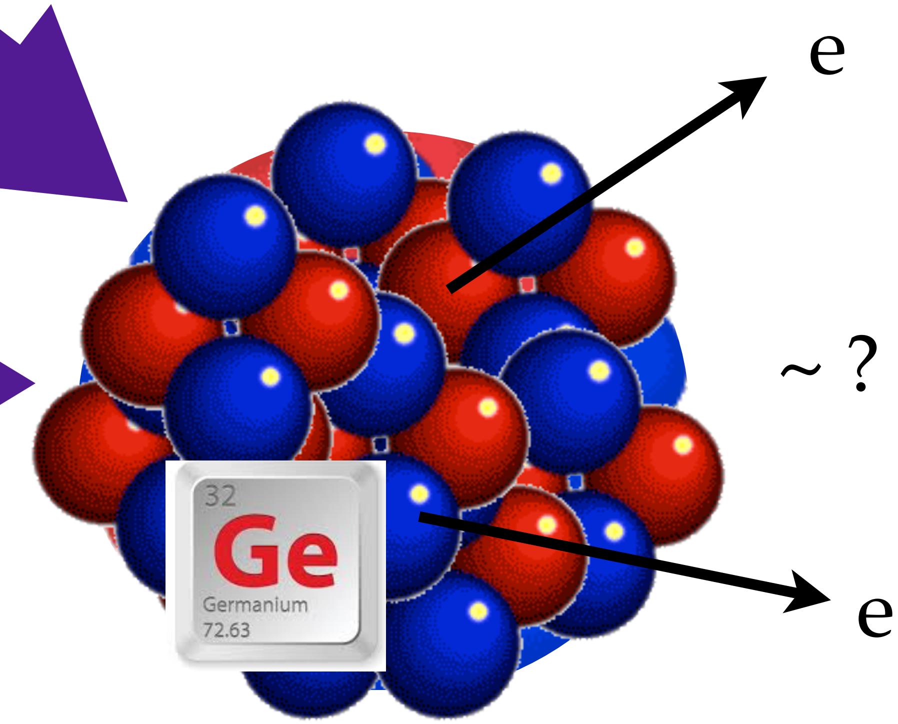
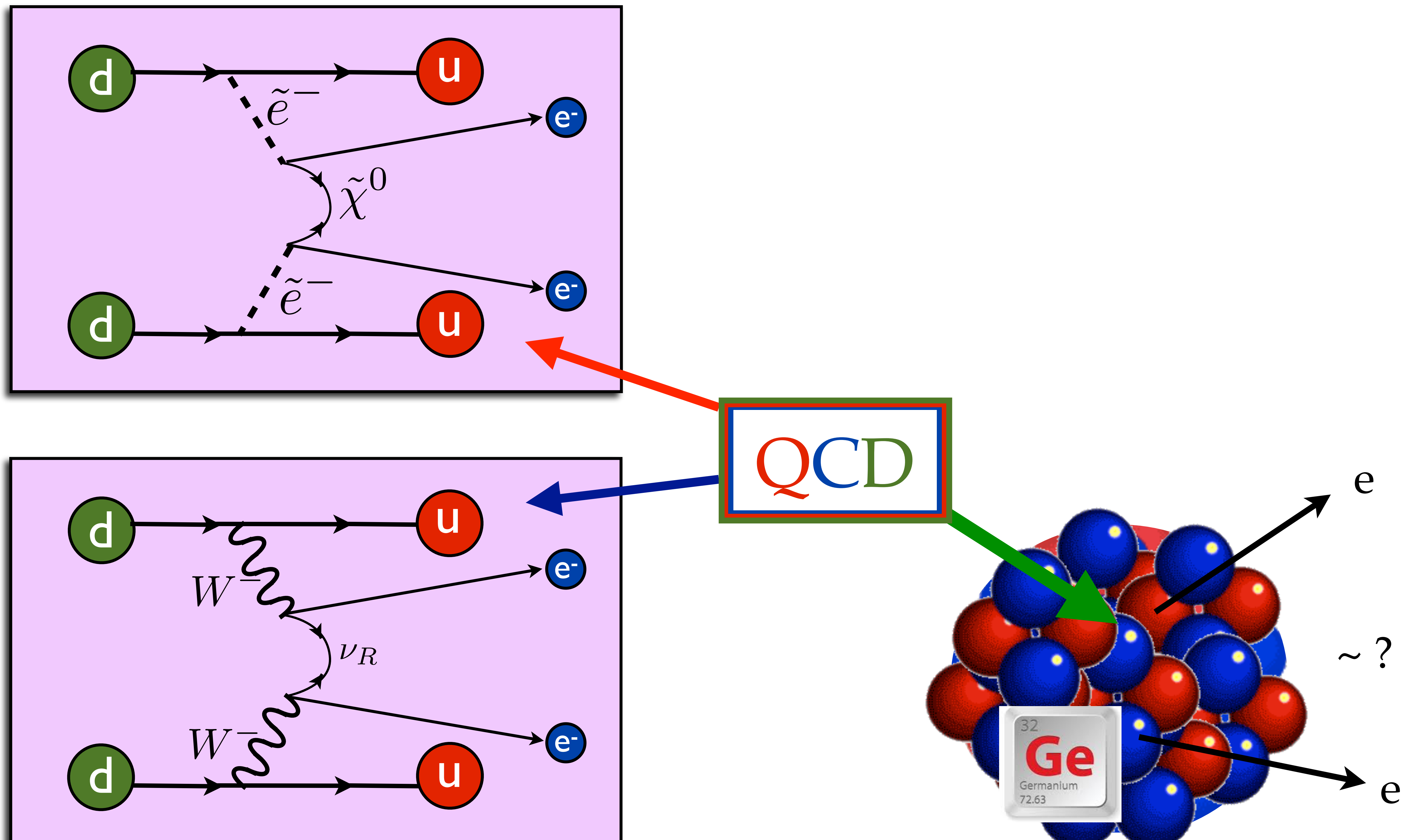


$0\nu\beta\beta$ bounds could help constrain R-parity violating coefficients



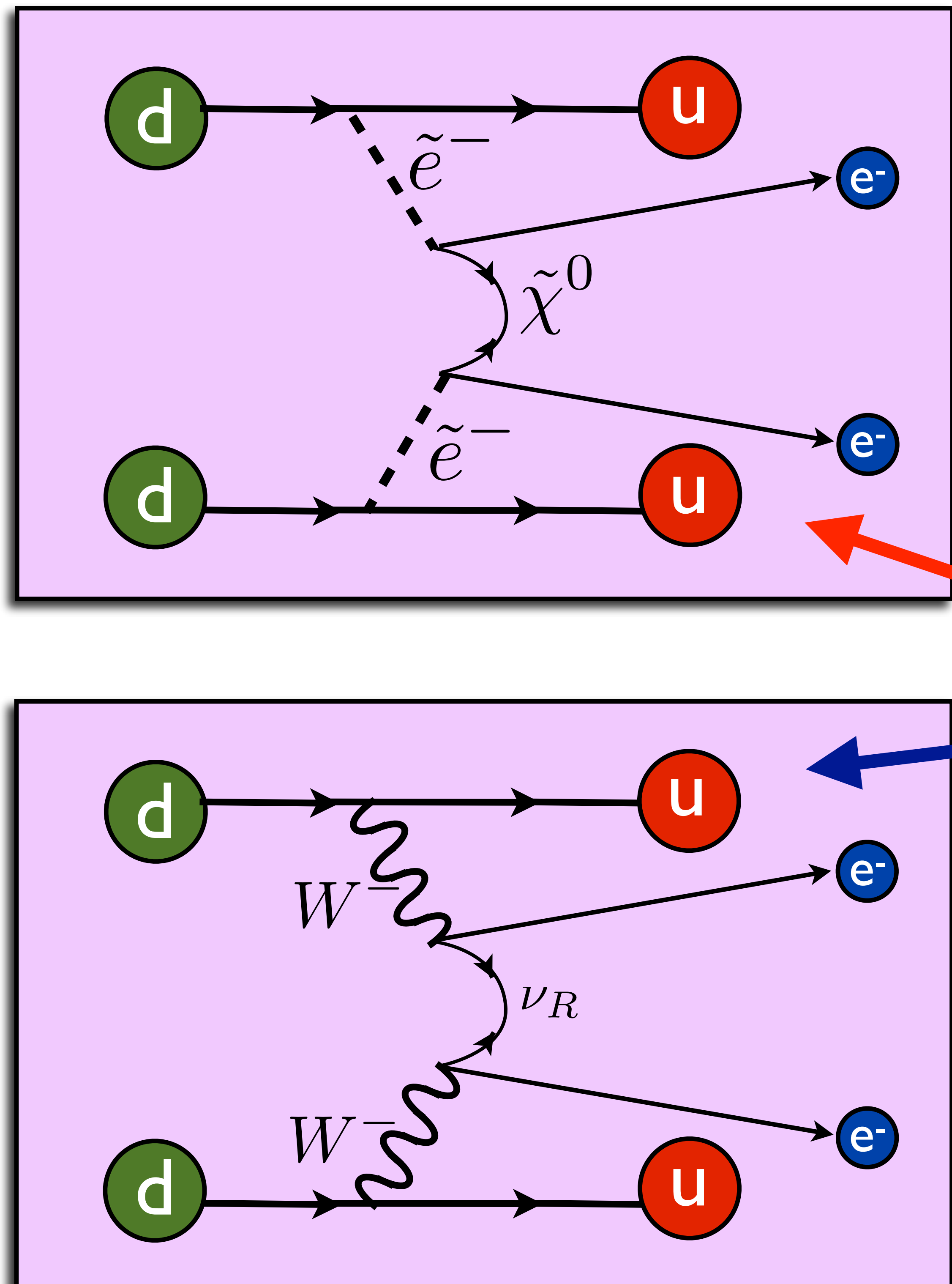


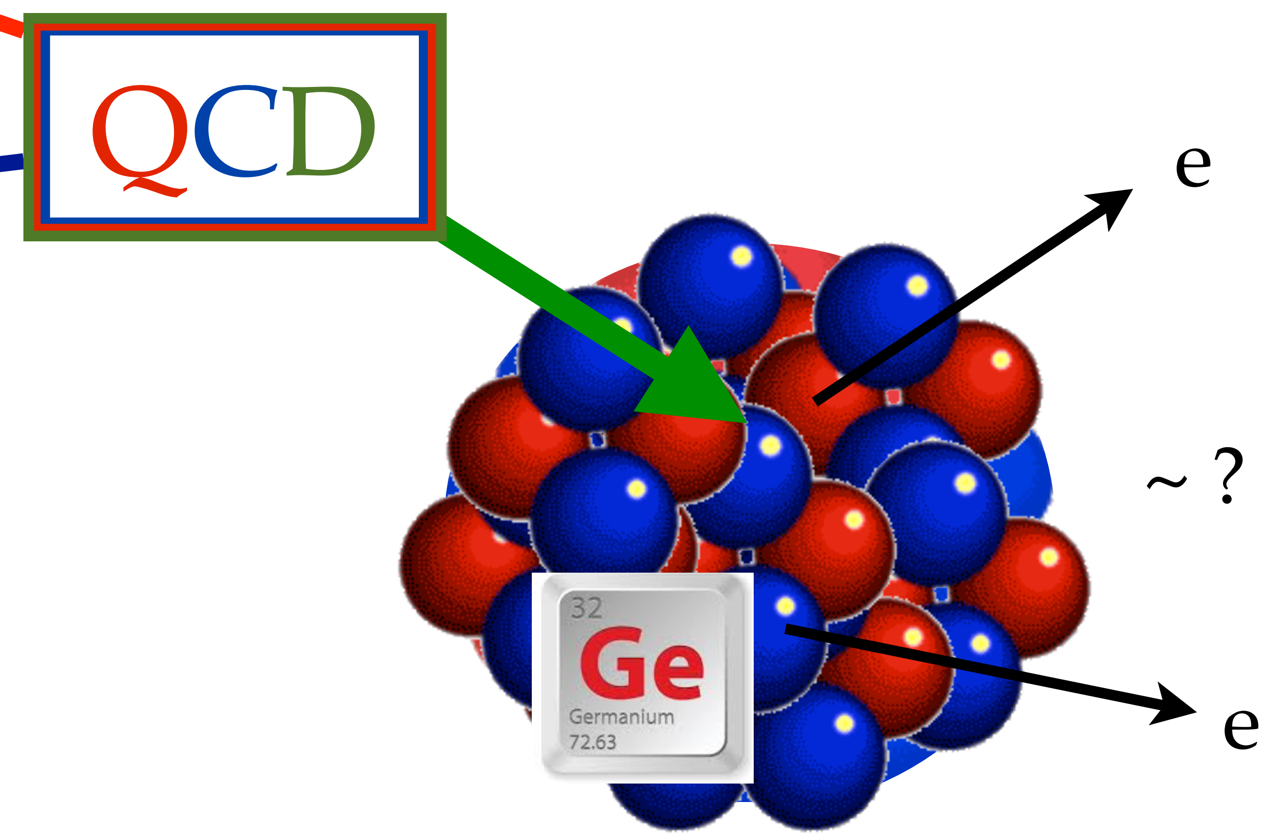
Relating Theory to Experiment



Relating Theory to Experiment

Need to solve QCD non-perturbatively:
LQCD!





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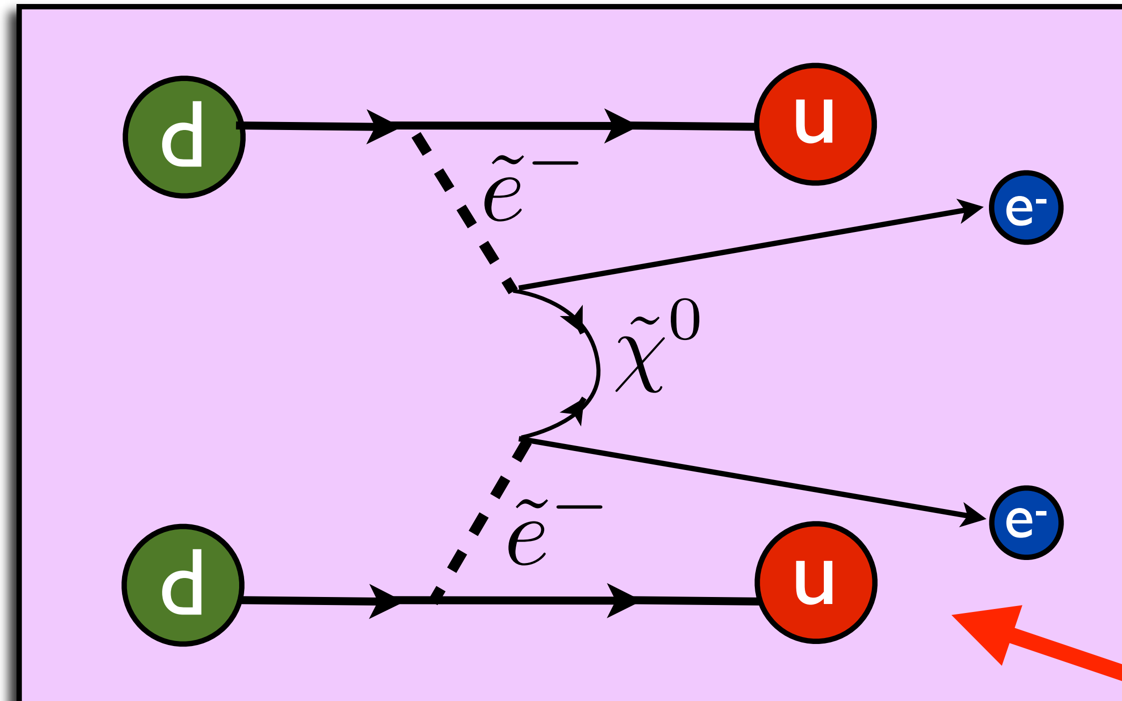
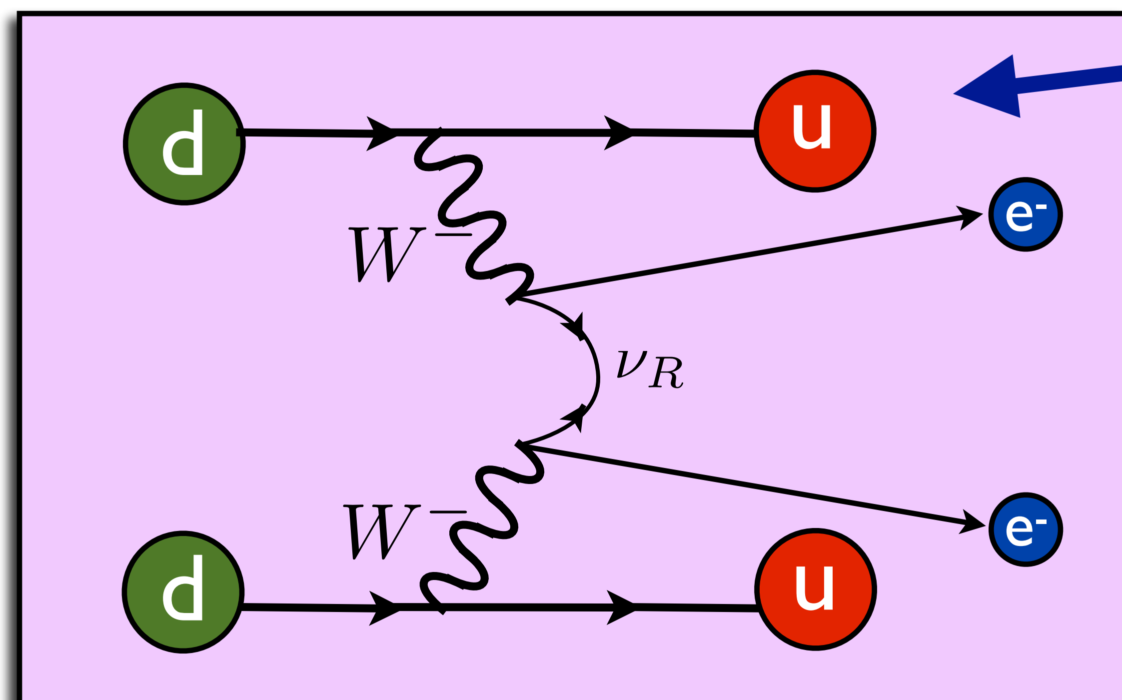


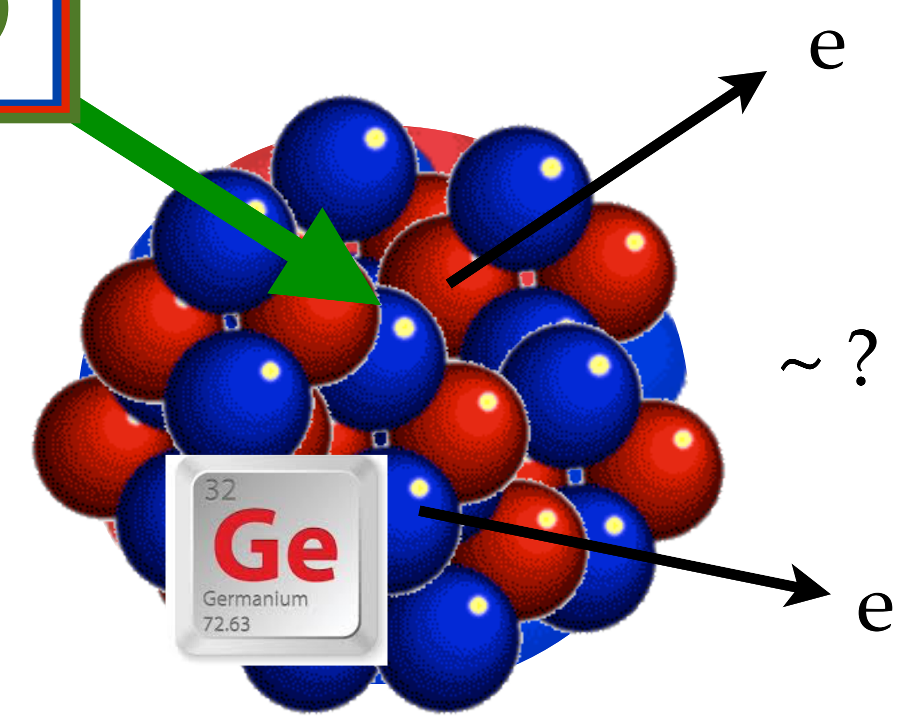


Need to solve QCD non-perturbatively: LQCD!

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

Monte Carlo noise (sign) problem, quark contractions, large range of scales,....

QCD



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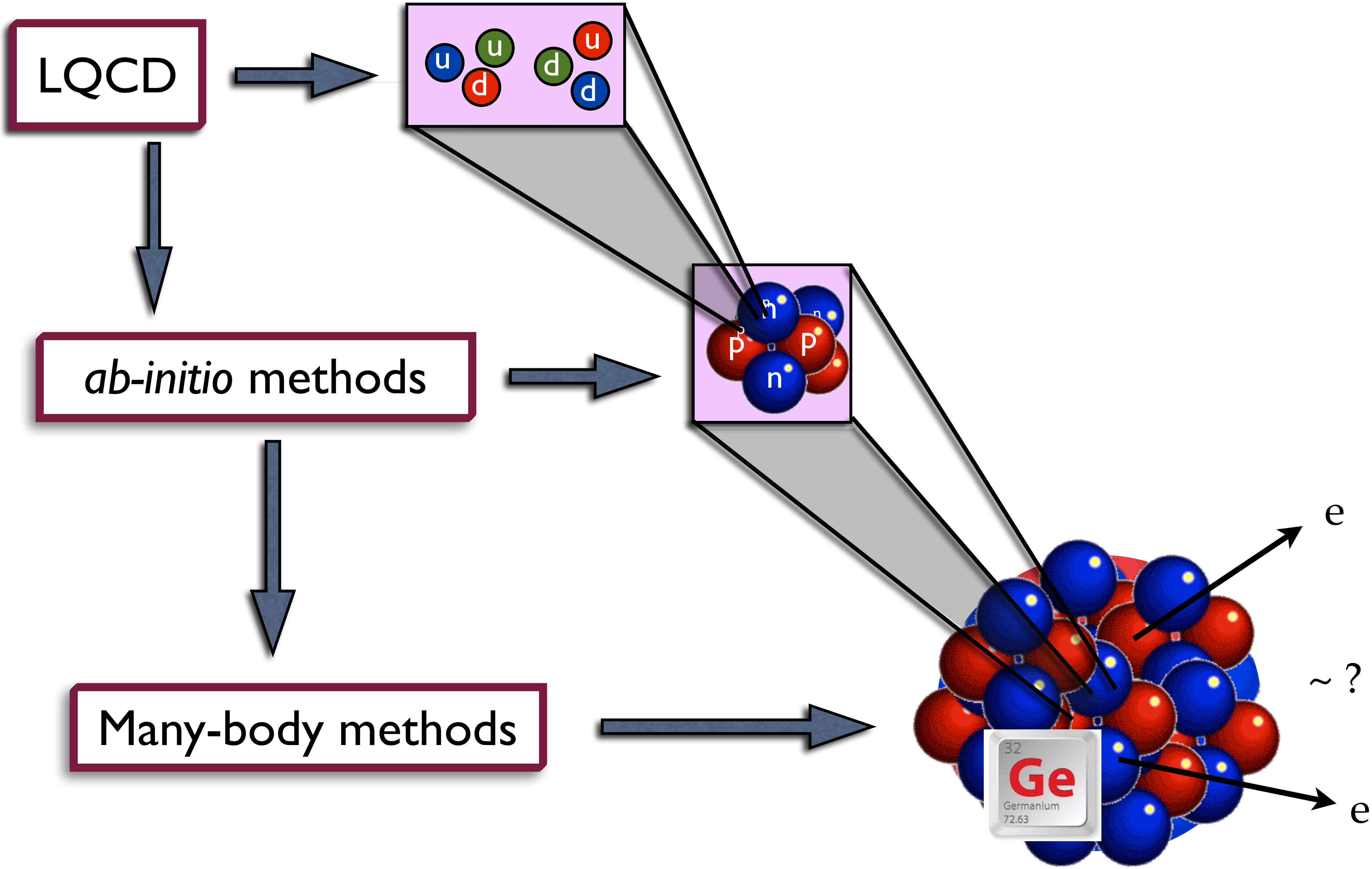
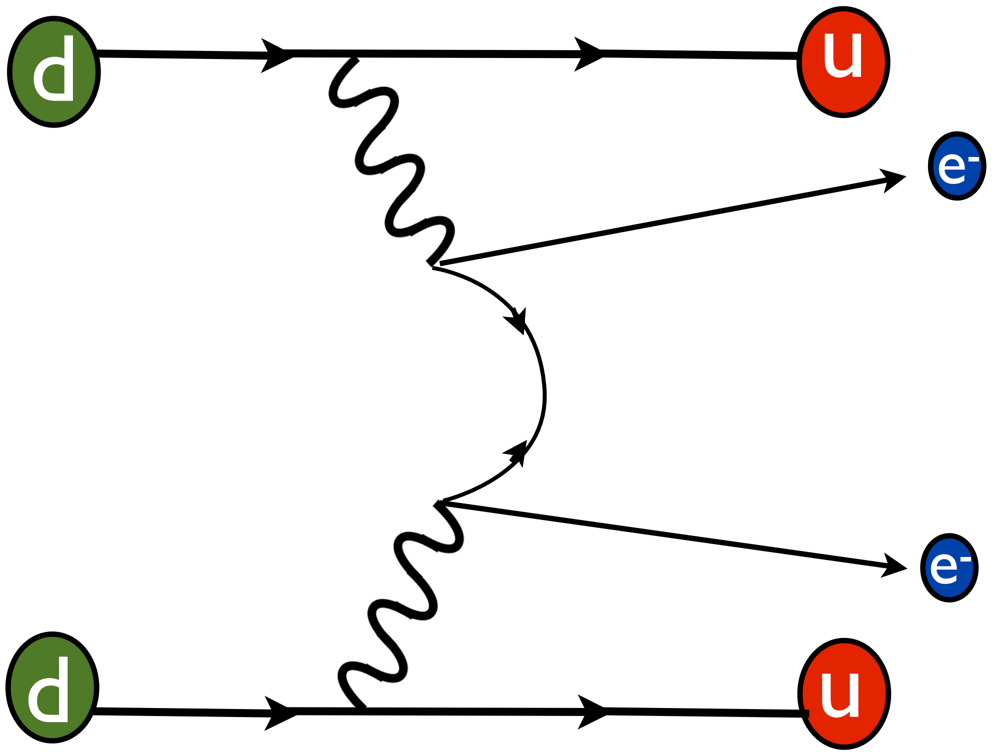
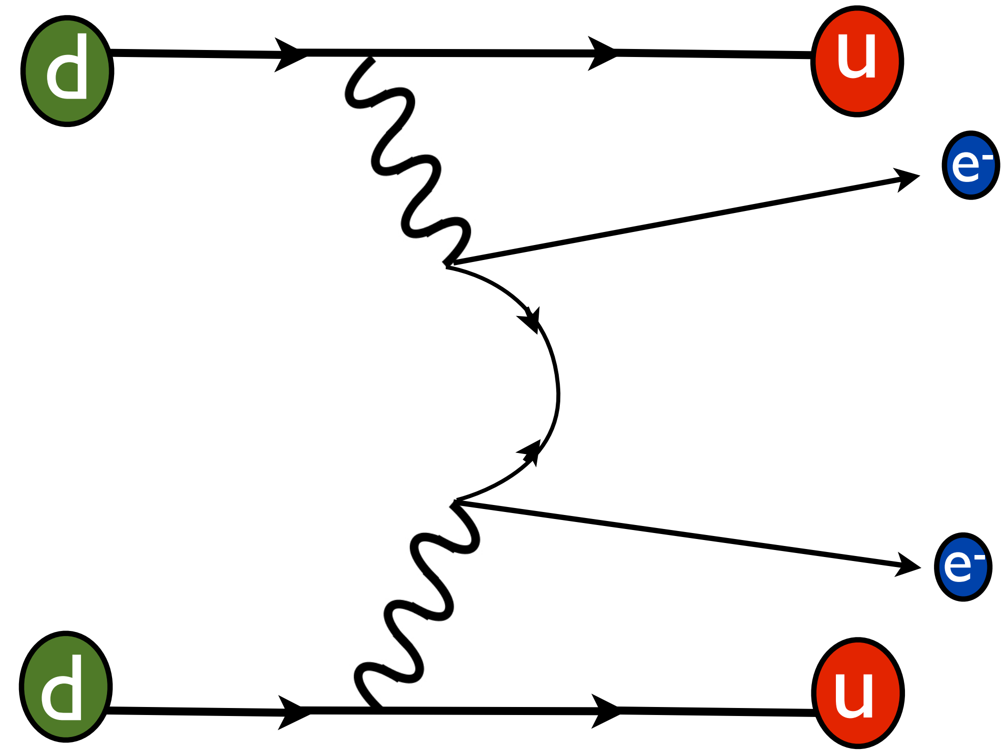
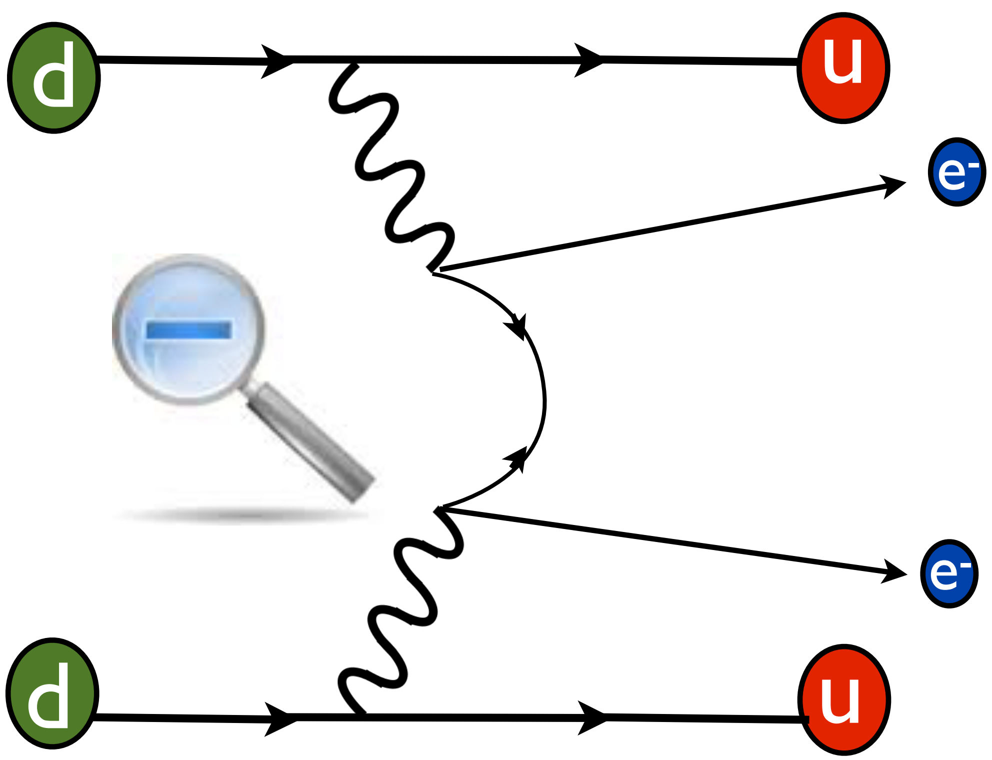




Long-range

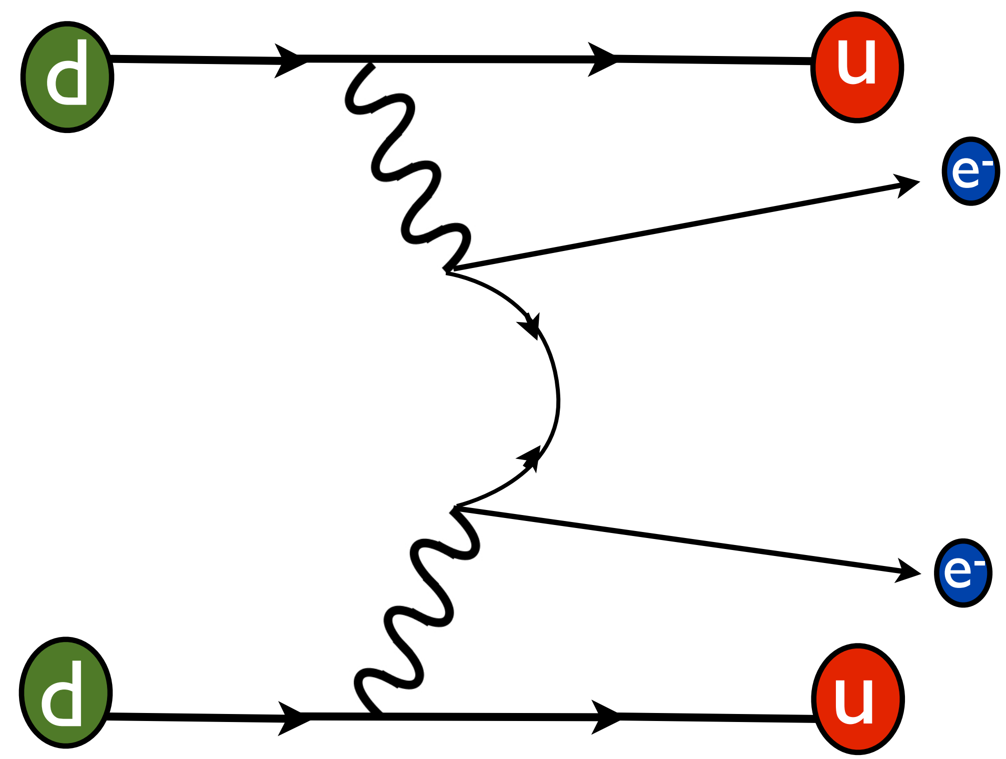


Short-range



Long-range

$\Lambda \ll M_W$



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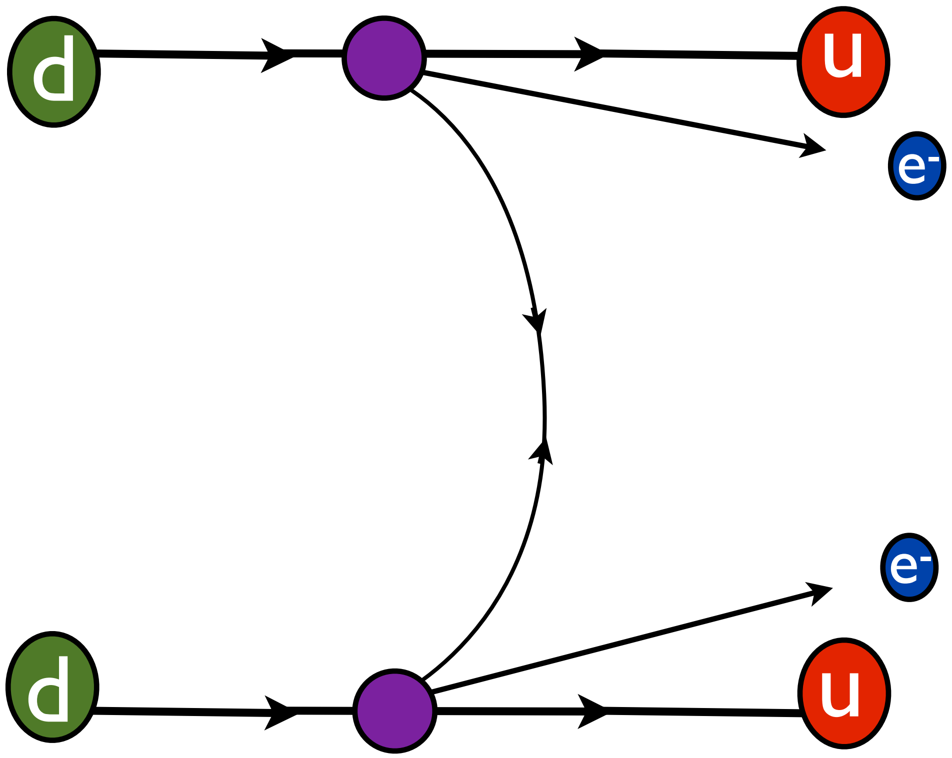
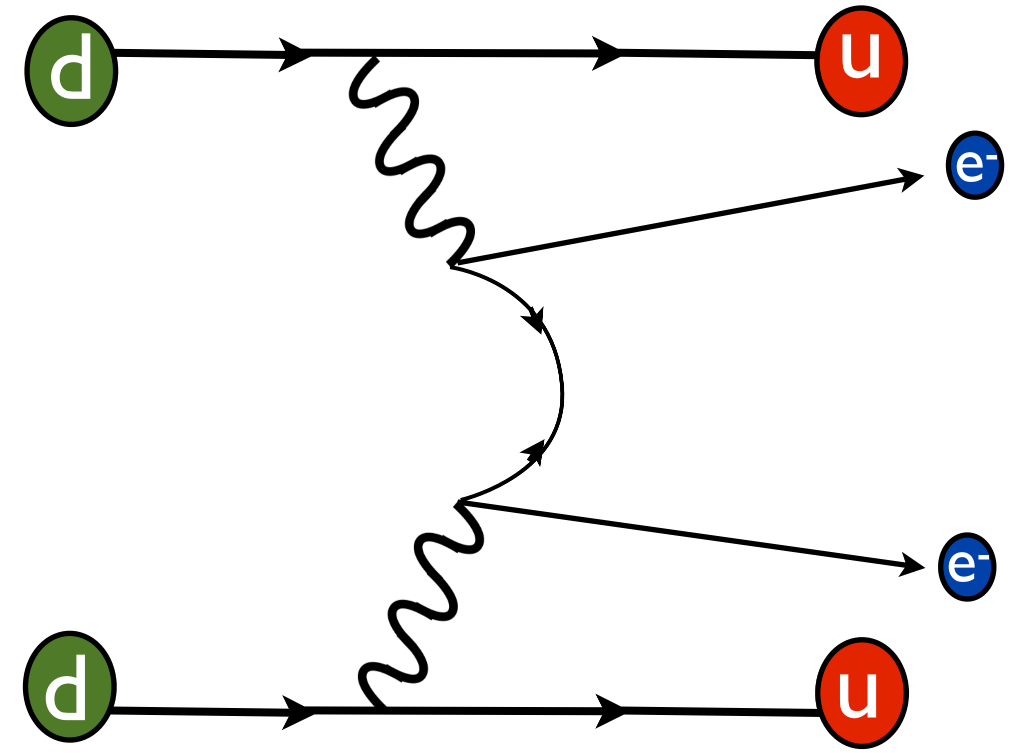
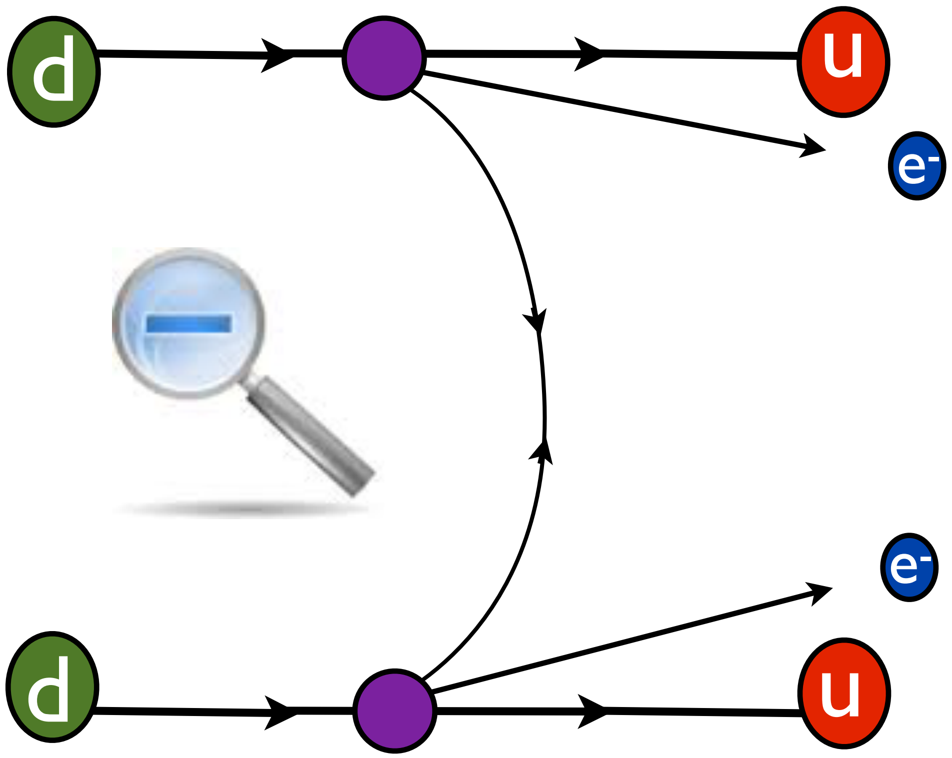


Long-range

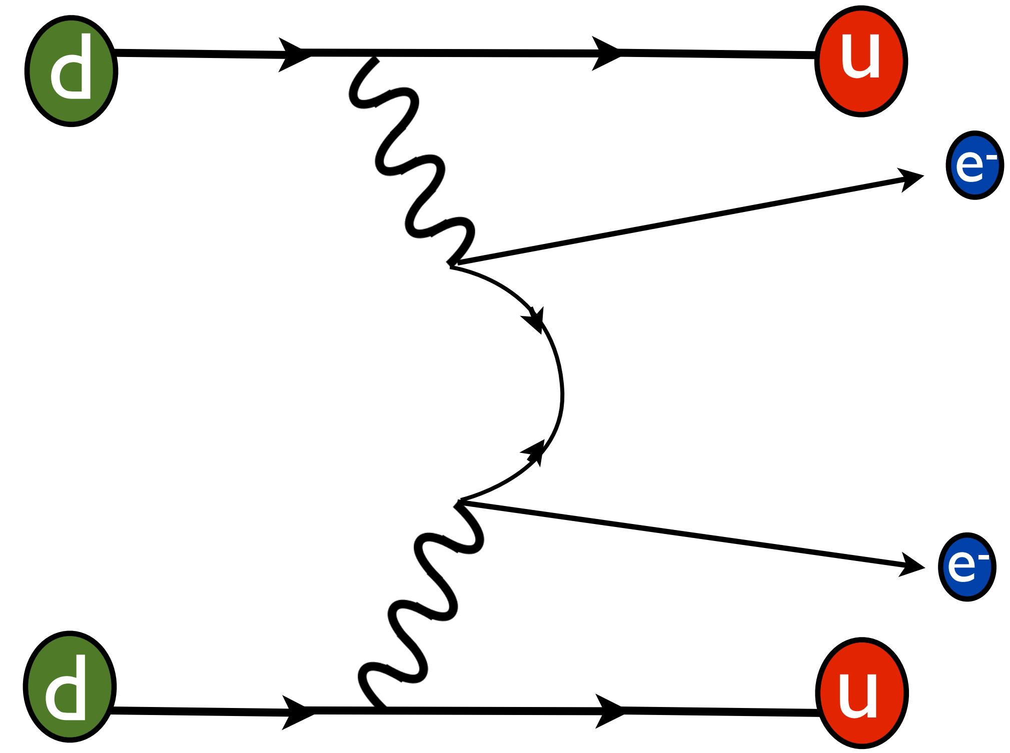


Short-range

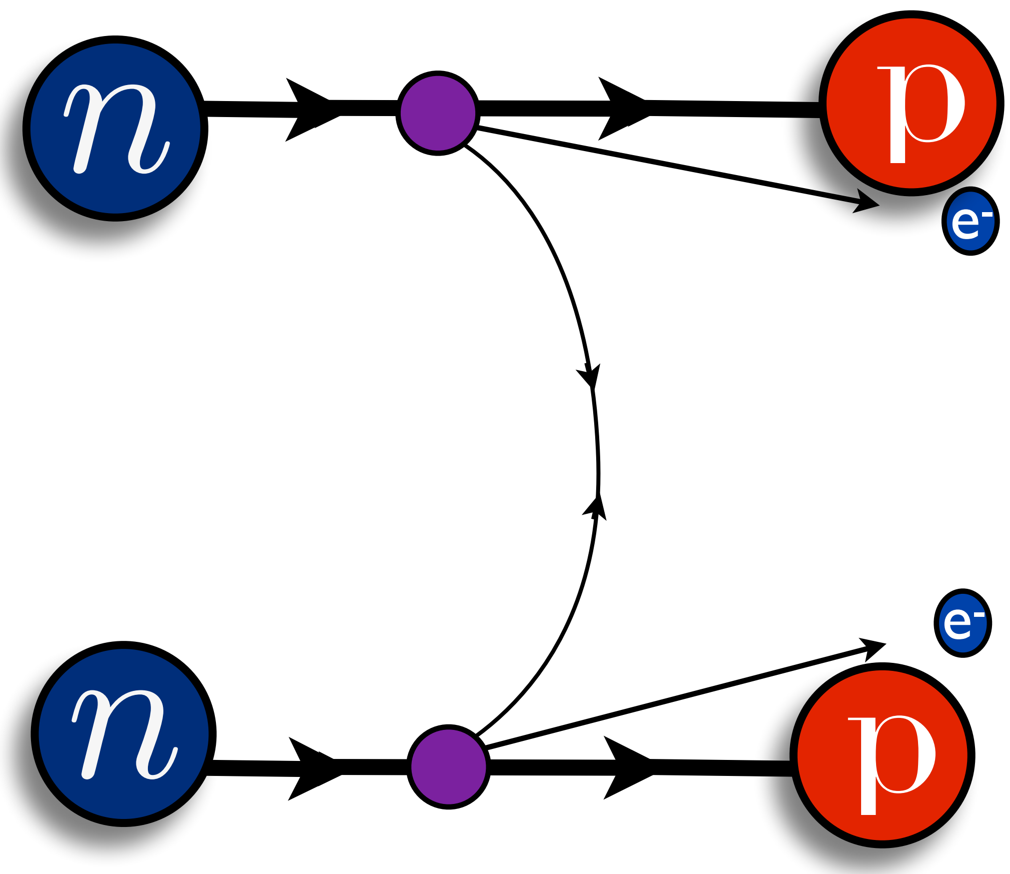


Long-range

$\Lambda \ll \Lambda_{QCD}$

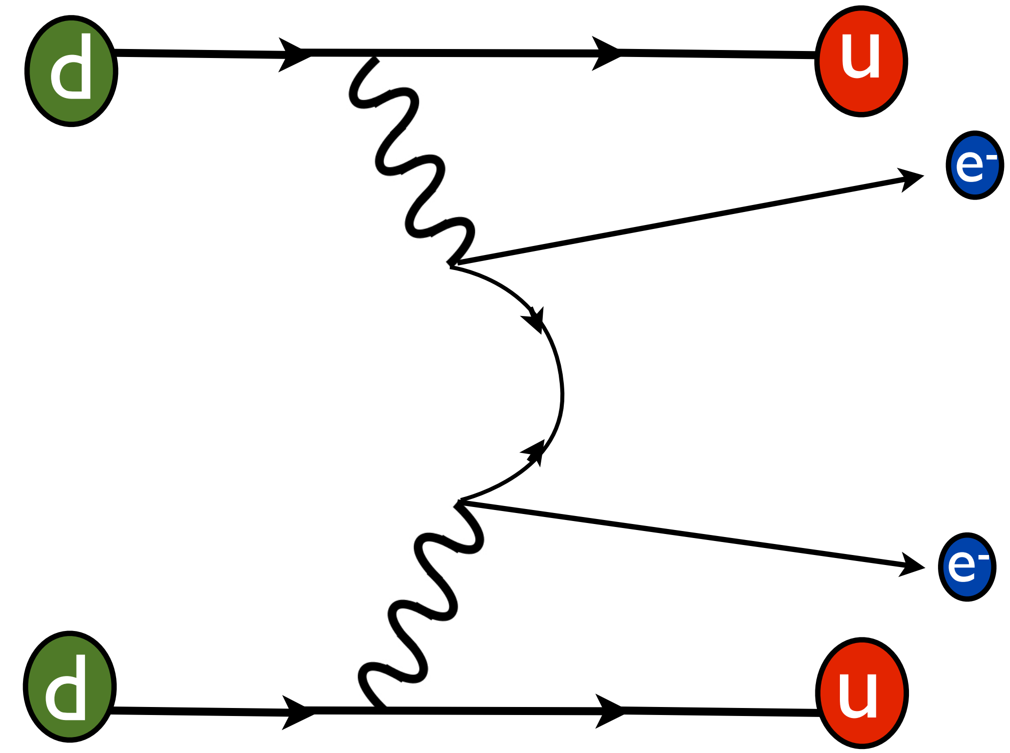


Short-range

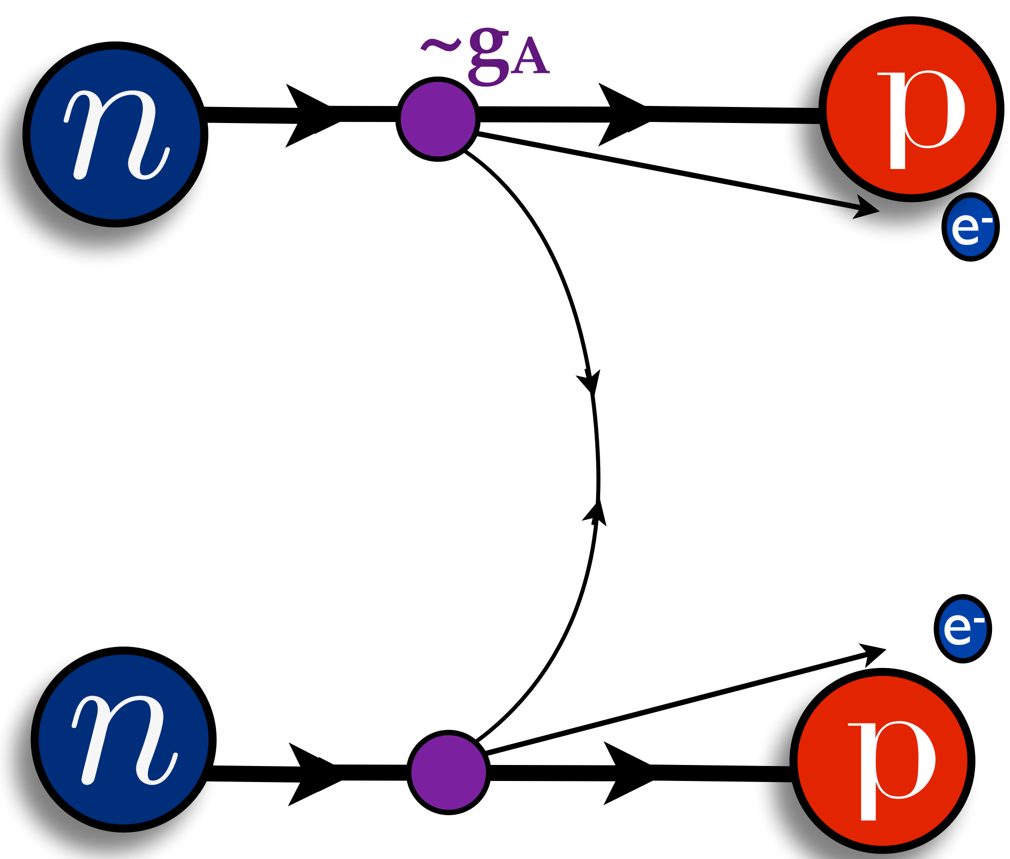


Long-range

$\Lambda \ll \Lambda_{QCD}$

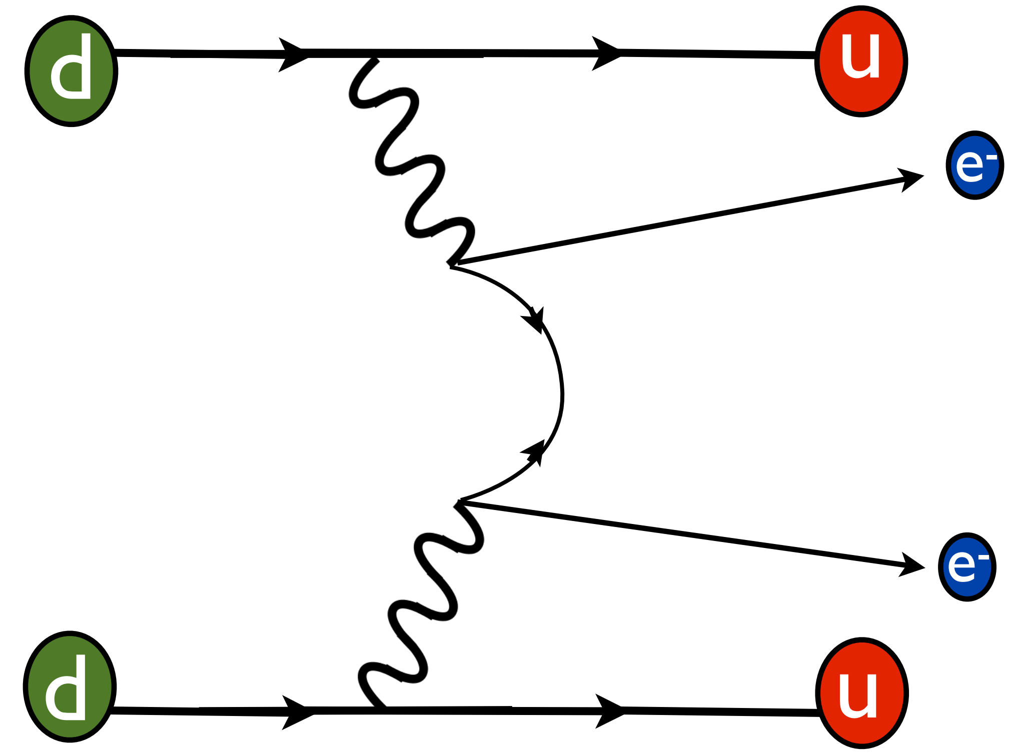


Short-range

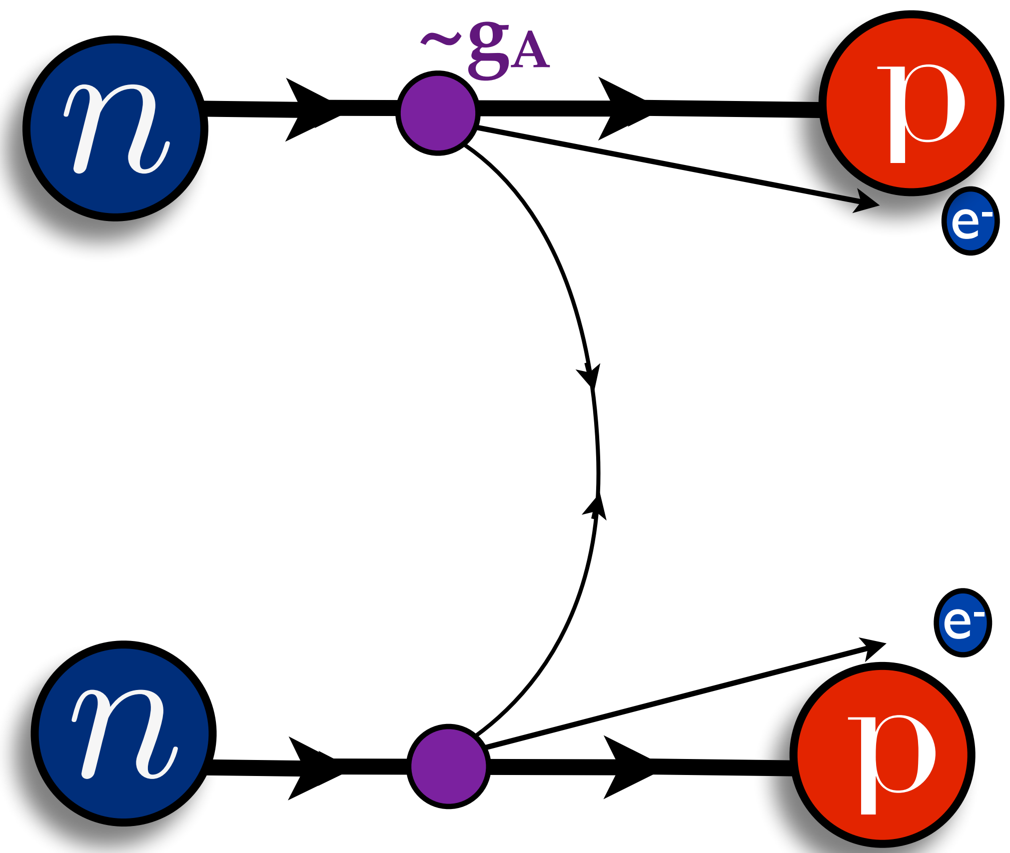


Long-range

No unknowns here!

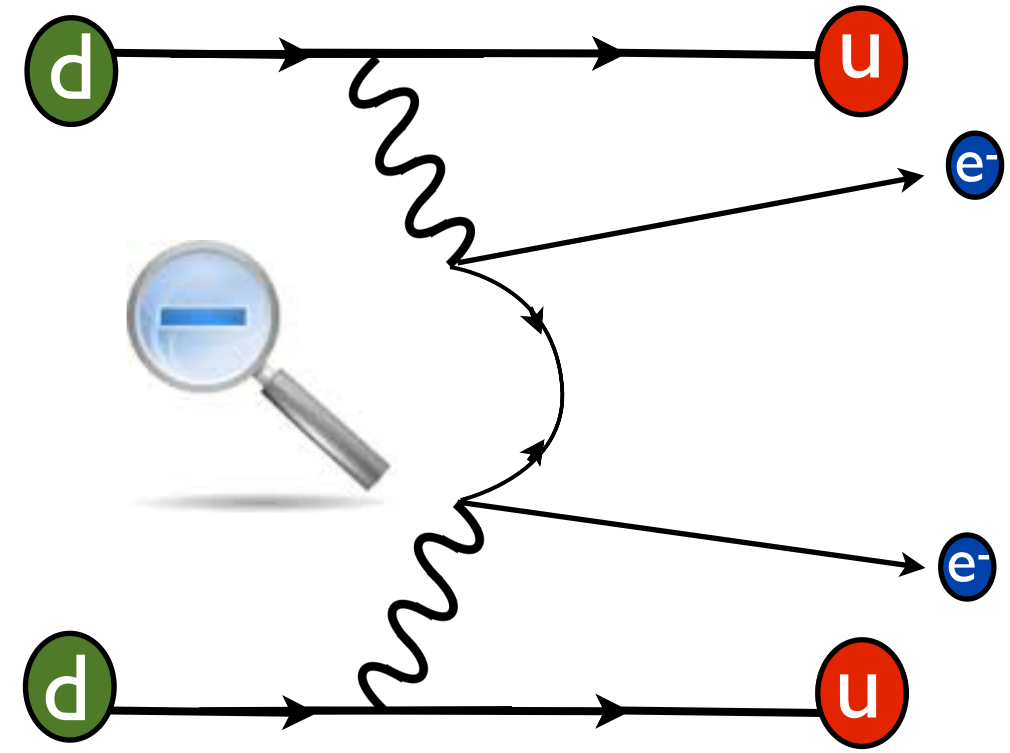


Short-range



Long-range

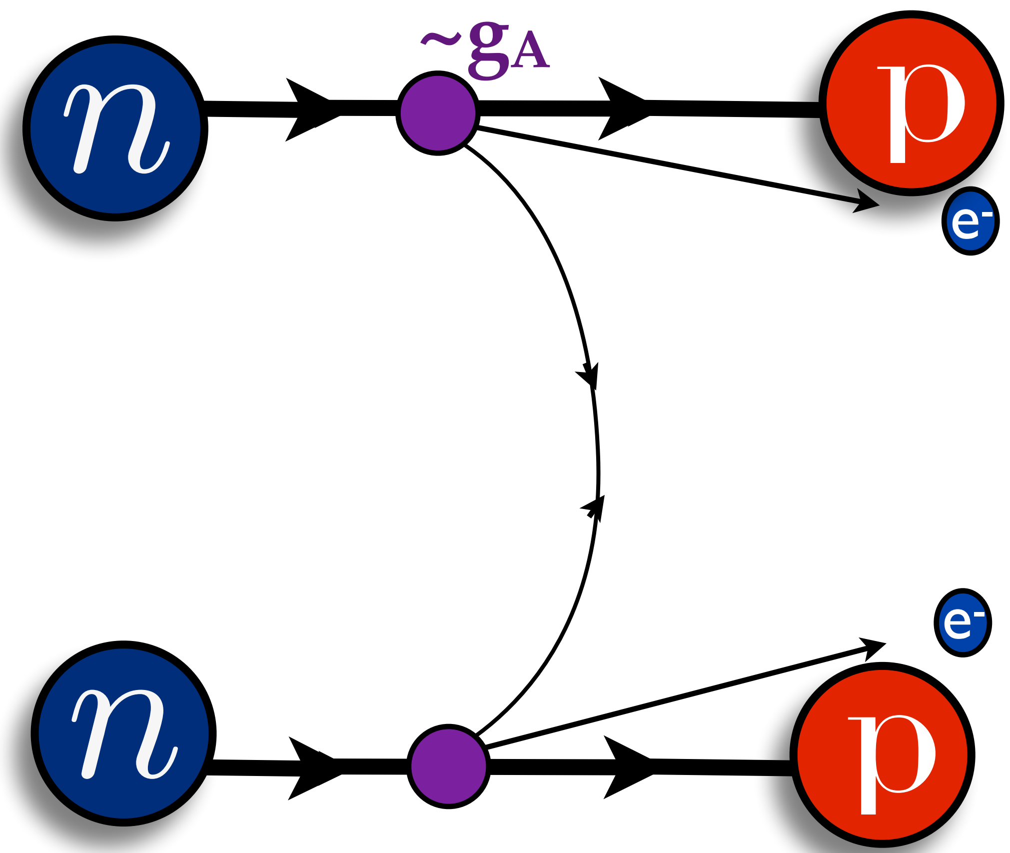
No unknowns here!



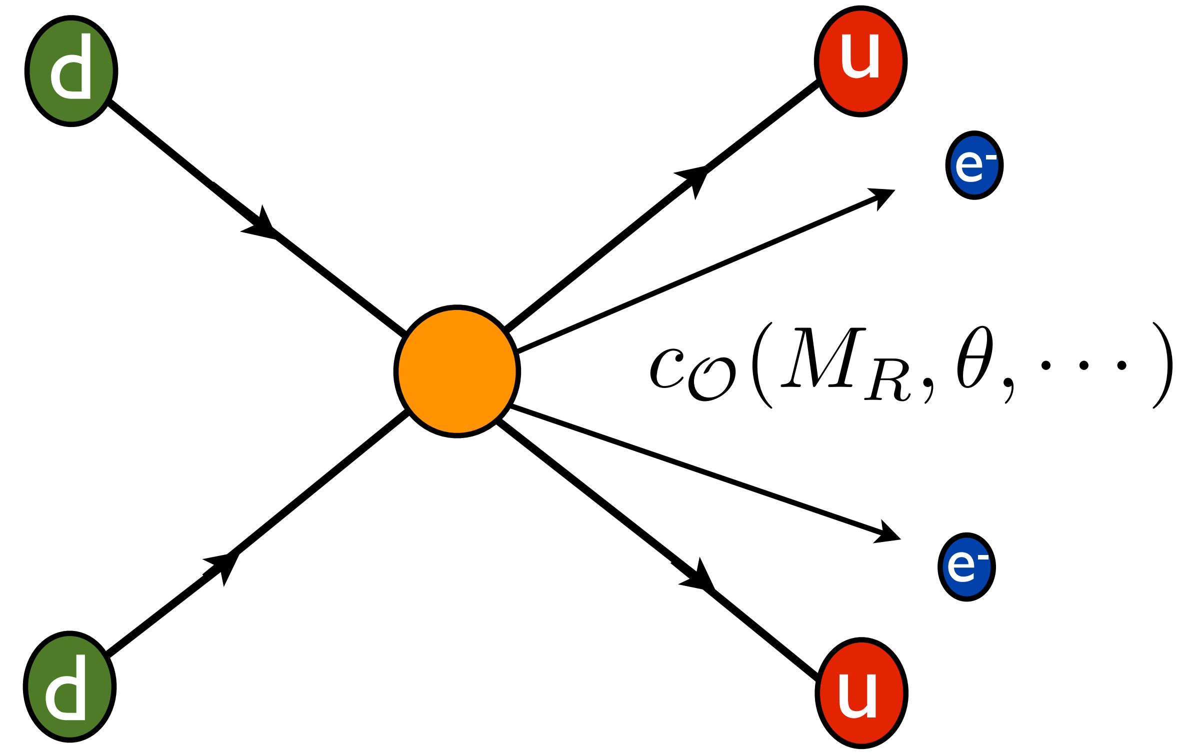
Short-range

$\Lambda \ll M_W$

Prezeau, Ramsey-Musolf, Vogel (2003)



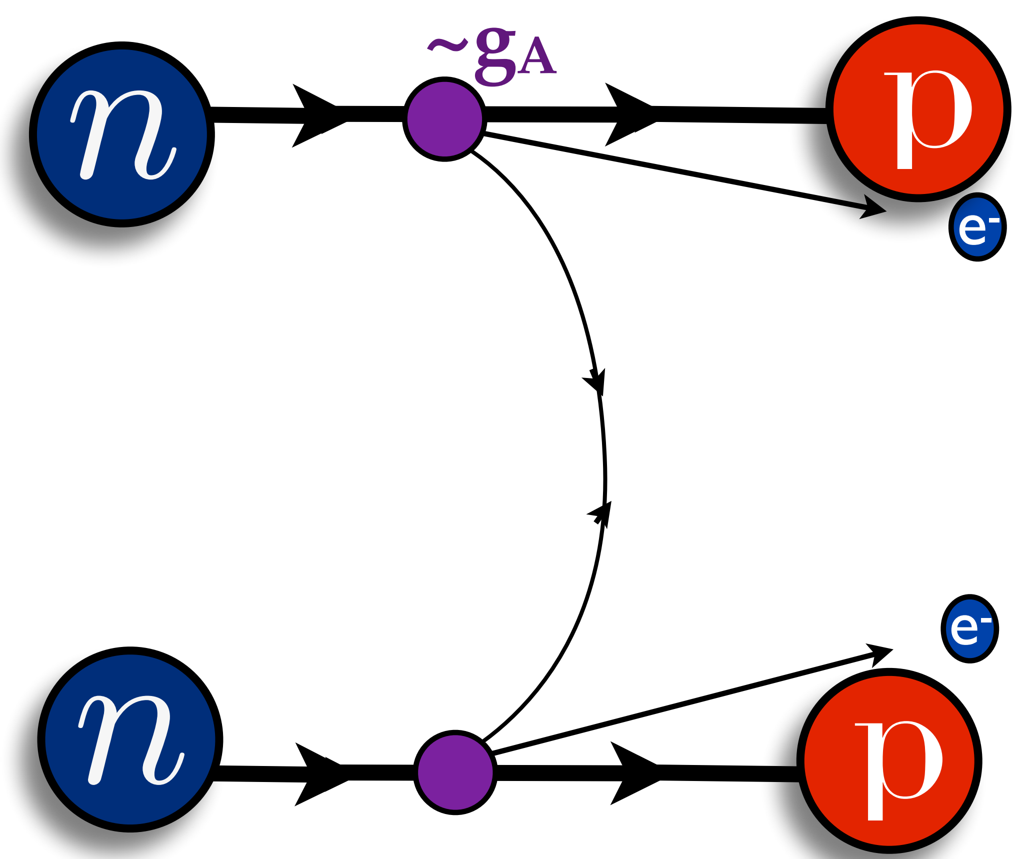
Long-range



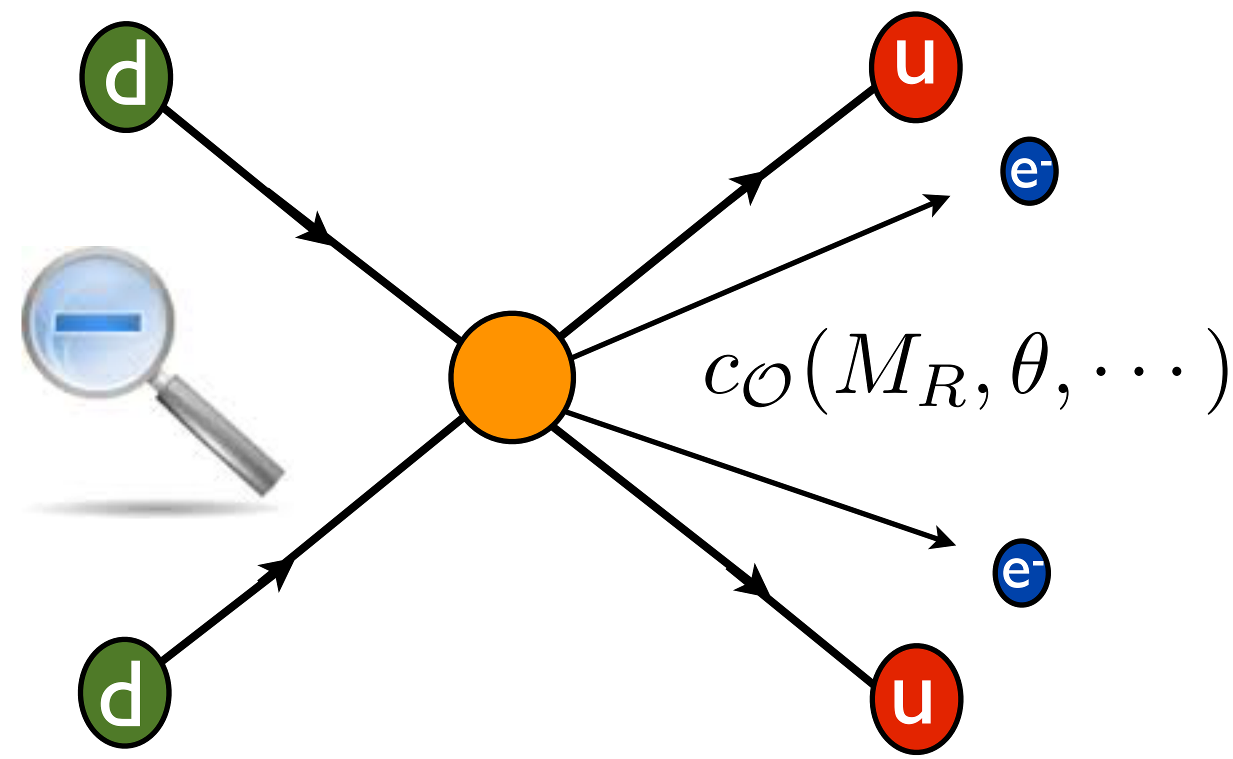
Short-range

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

Prezeau, Ramsey-Musolf, Vogel (2003)



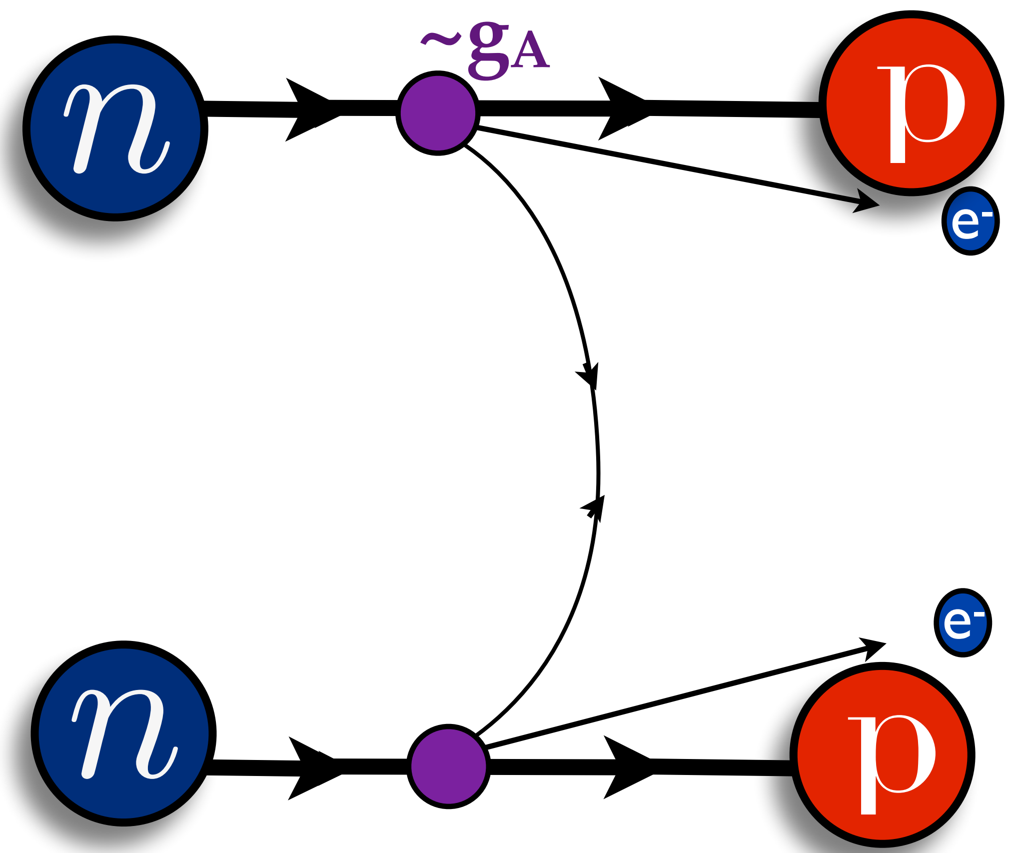
Long-range



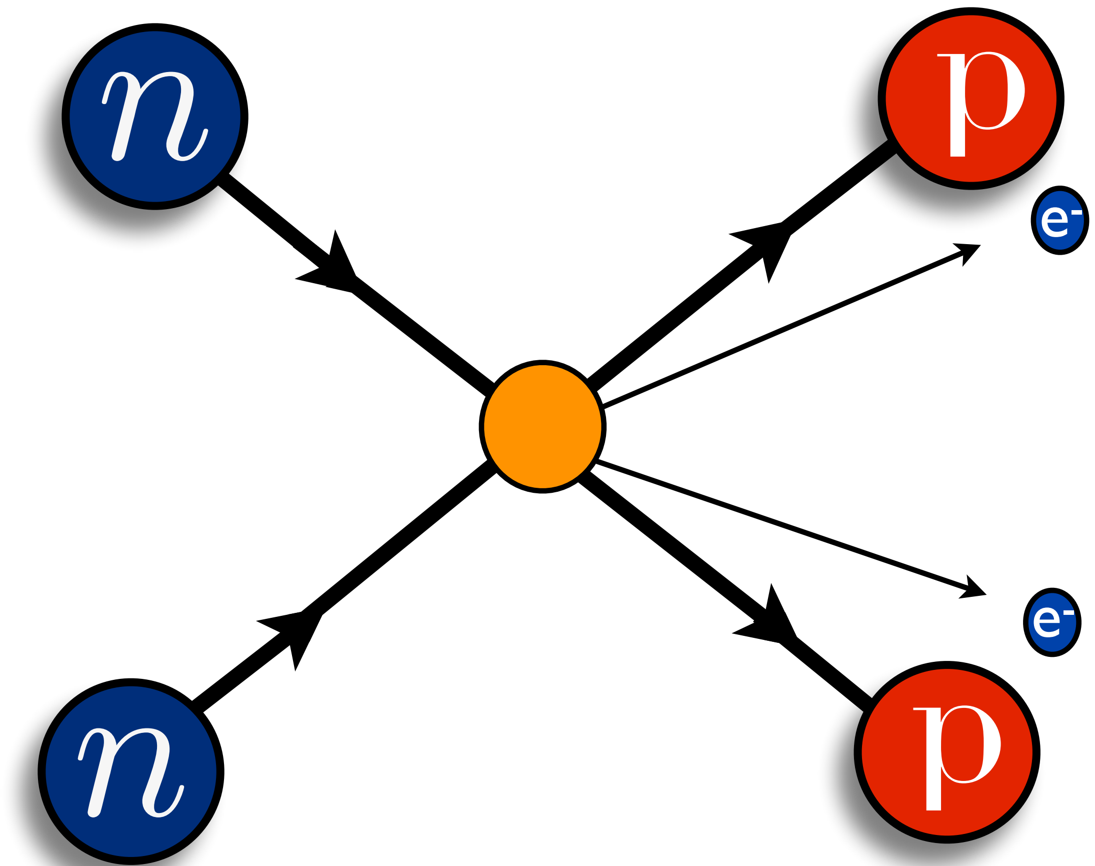
Short-range

$\Lambda \ll \Lambda_{QCD}$

Prezeau, Ramsey-Musolf, Vogel (2003)

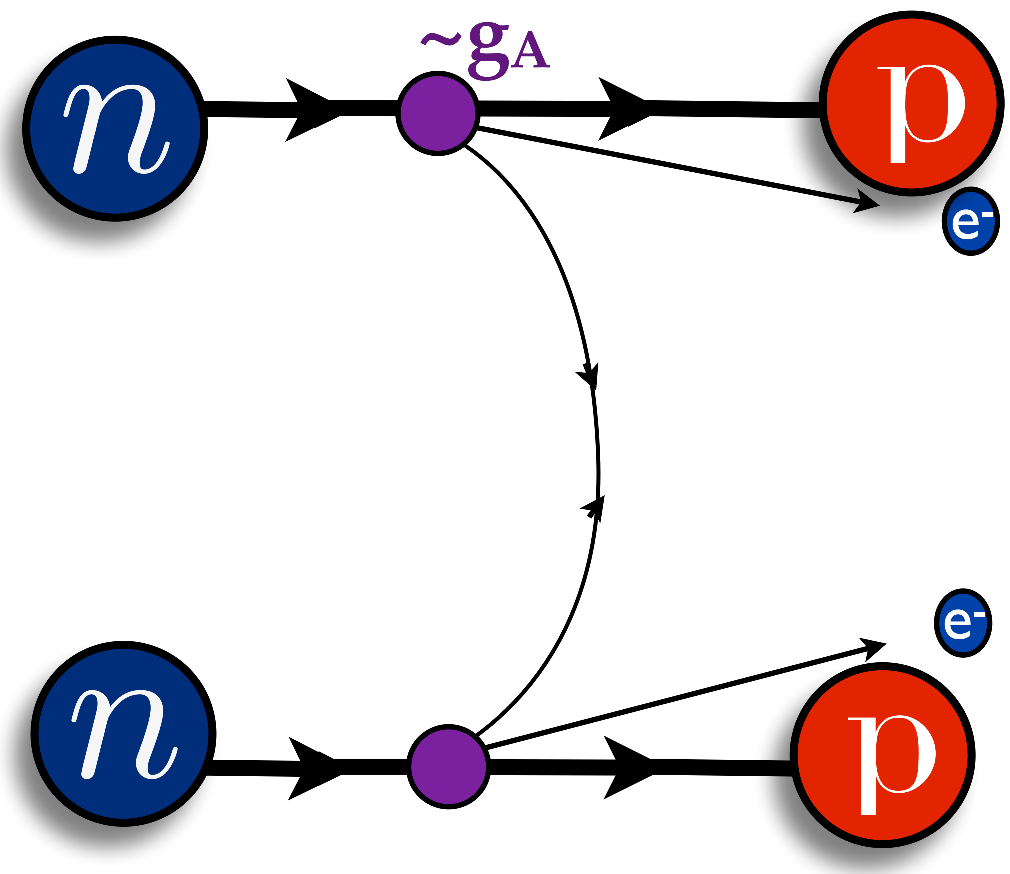


Long-range



Short-range

Prezeau, Ramsey-Musolf, Vogel (2003)



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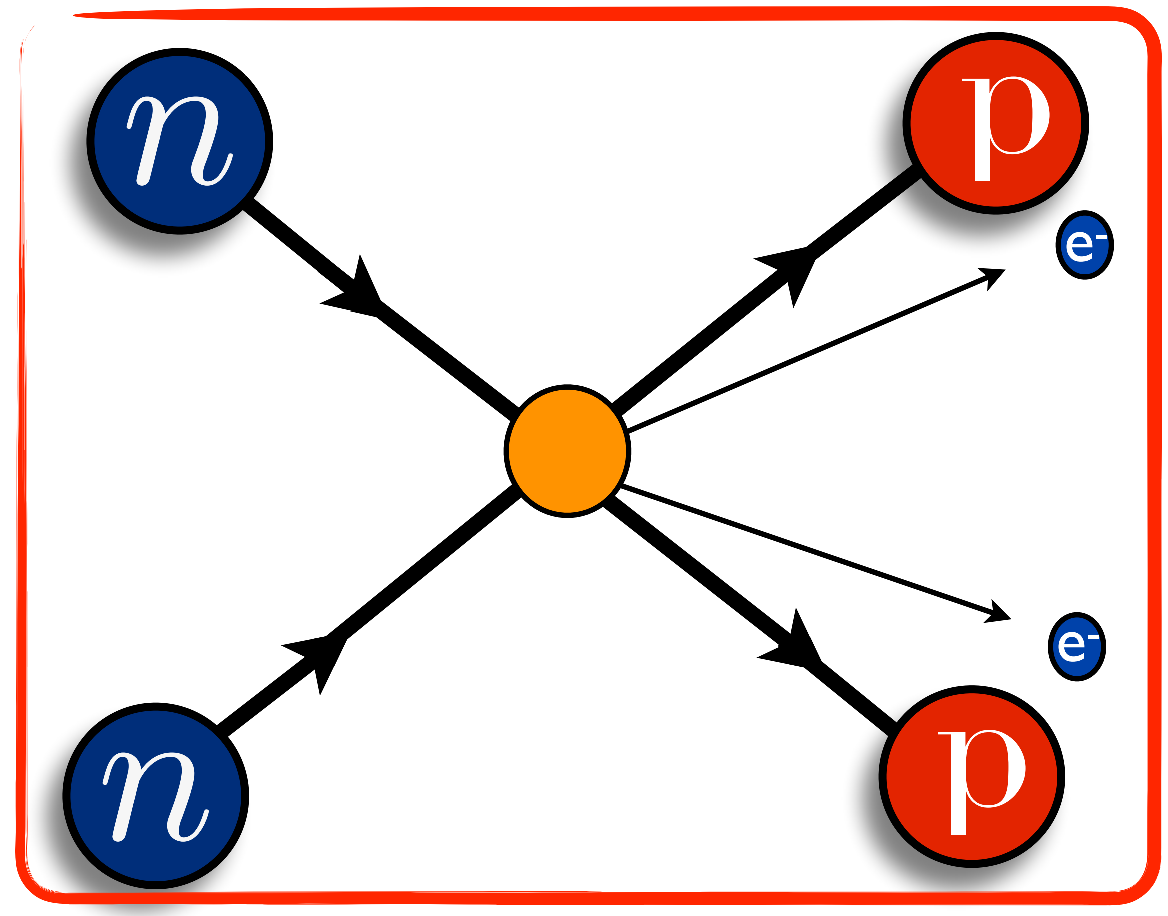
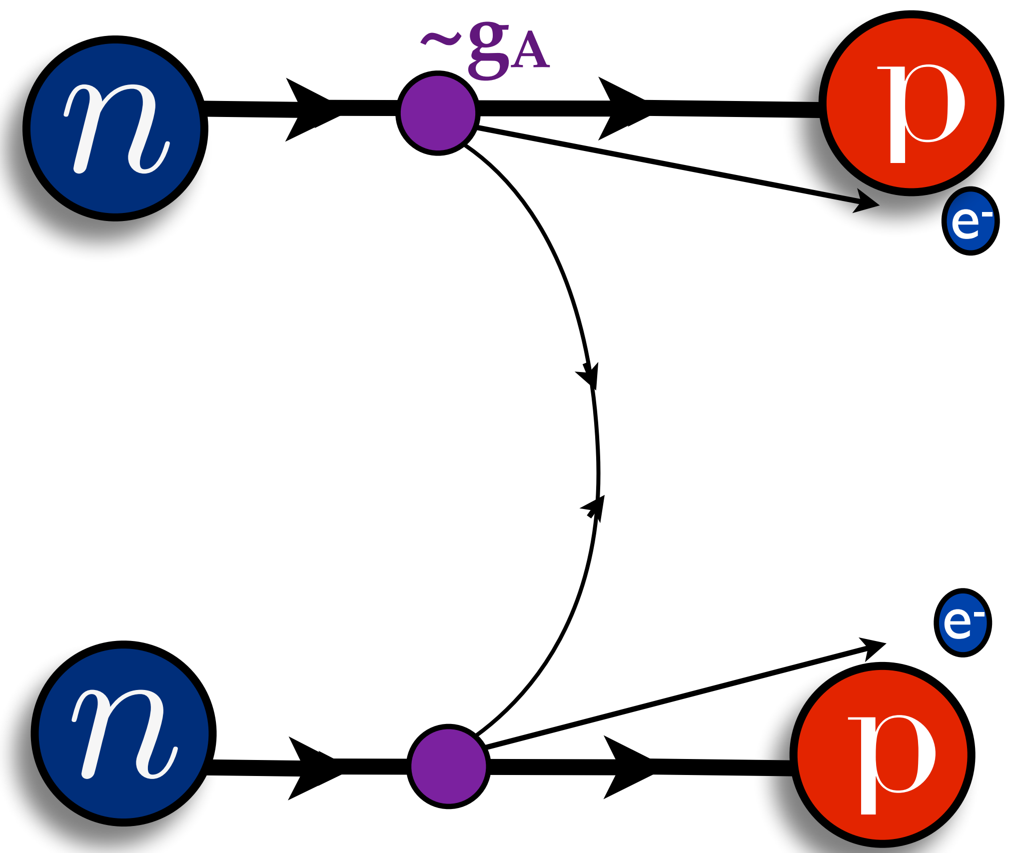
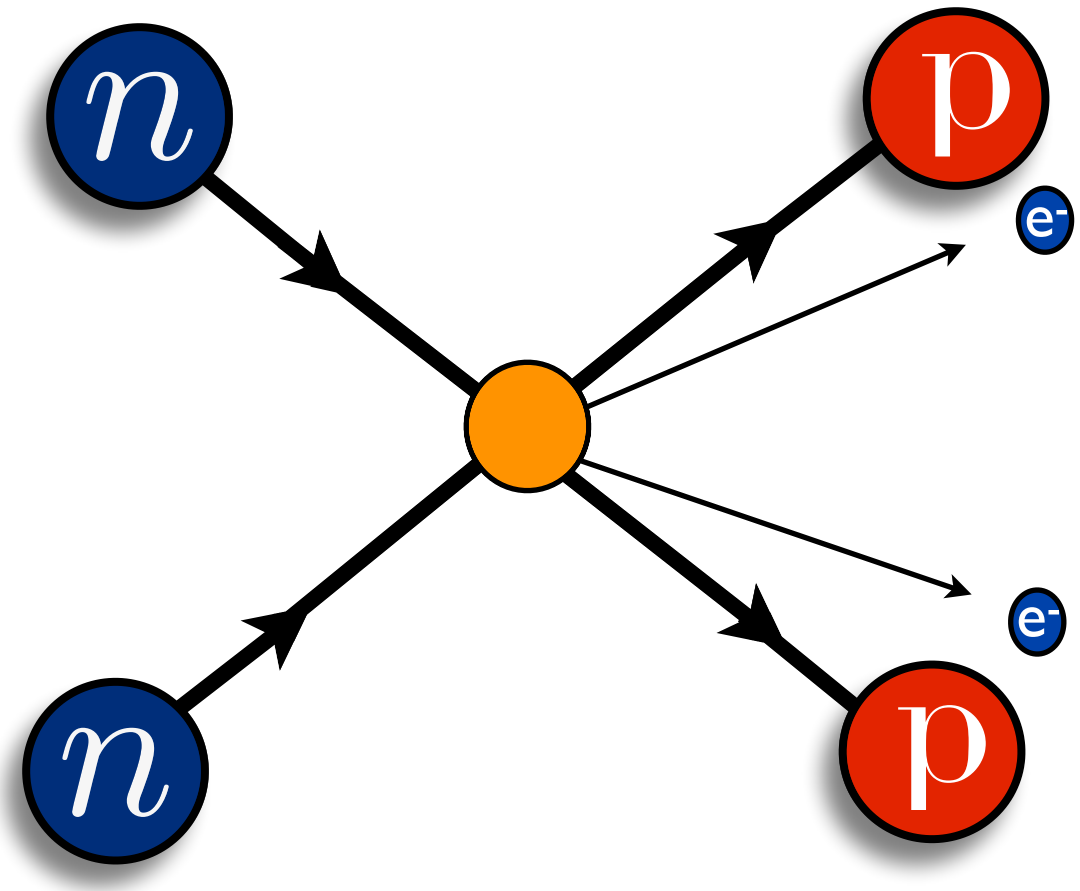


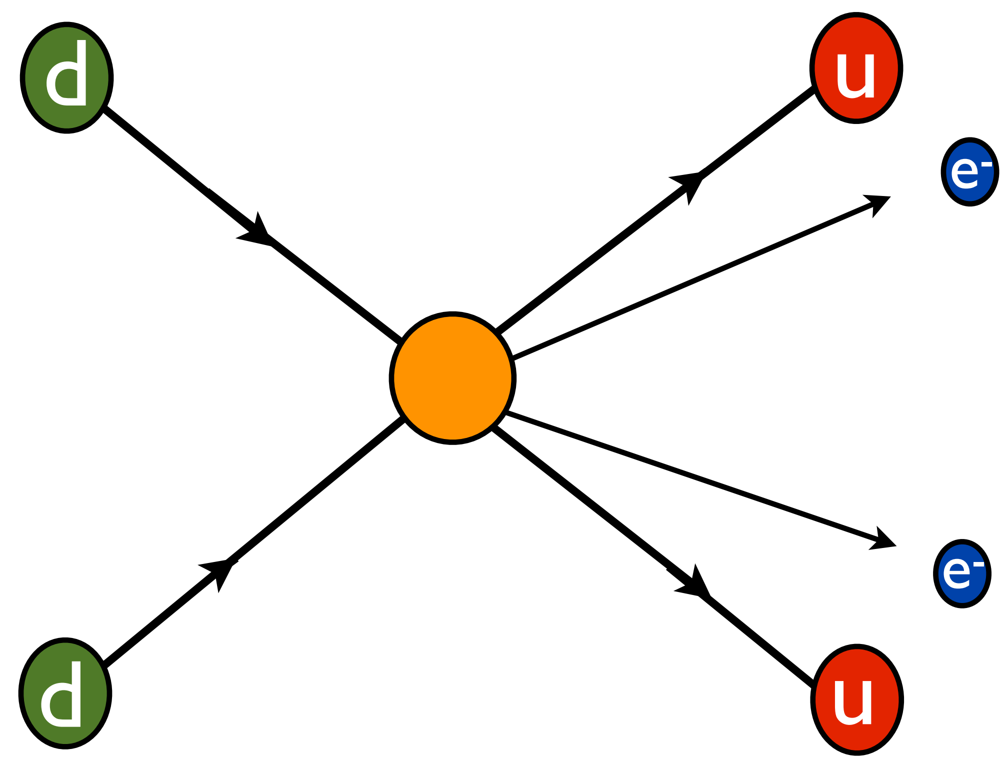
Short-range

Unknown!

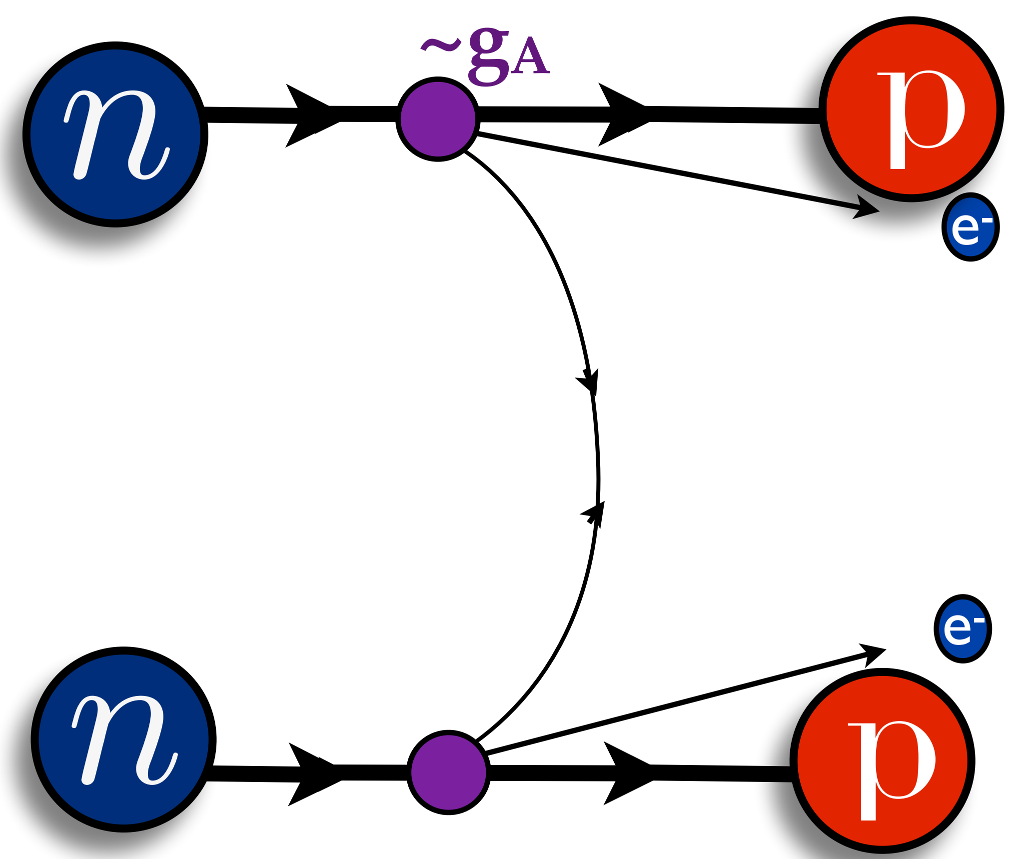
Prezeau, Ramsey-Musolf, Vogel (2003)

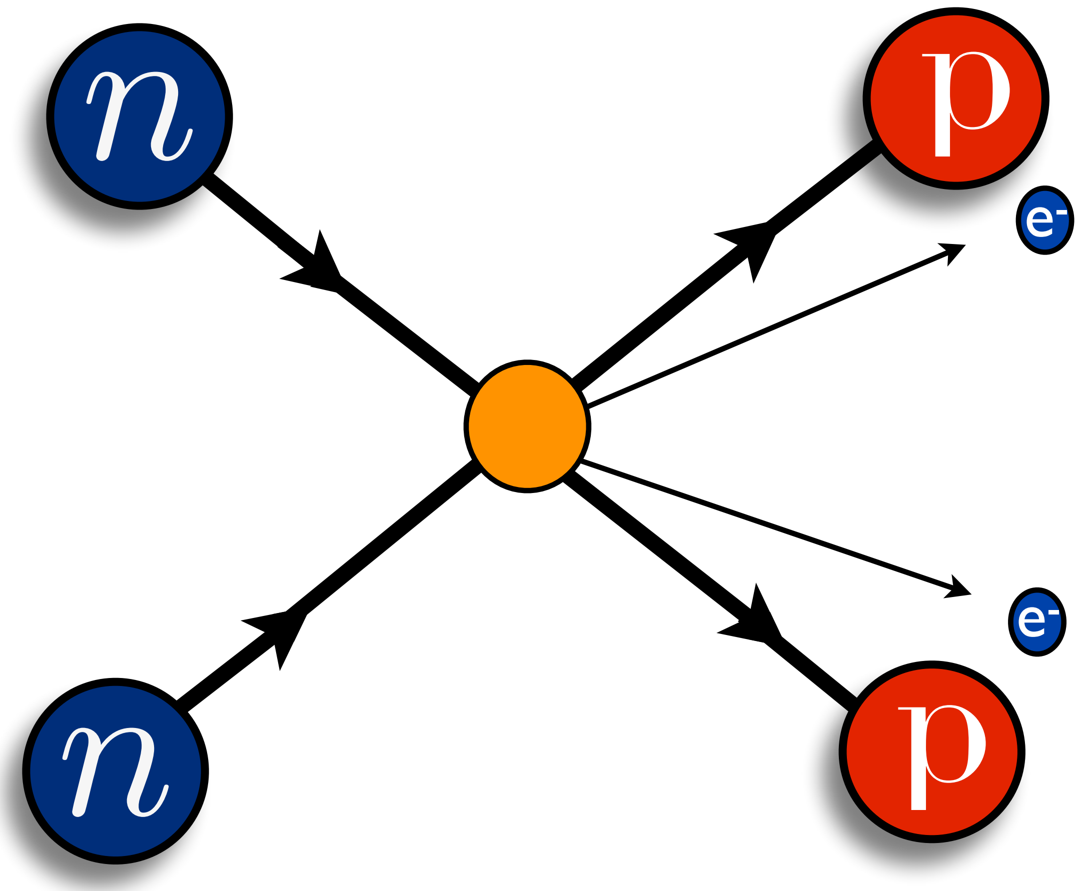


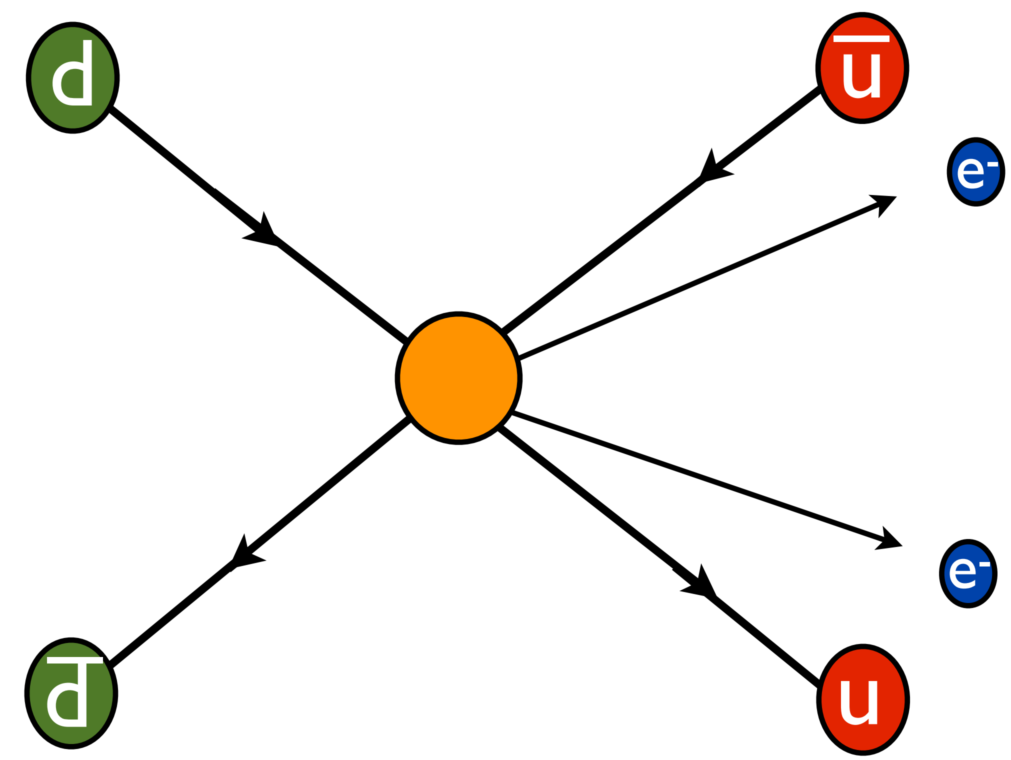




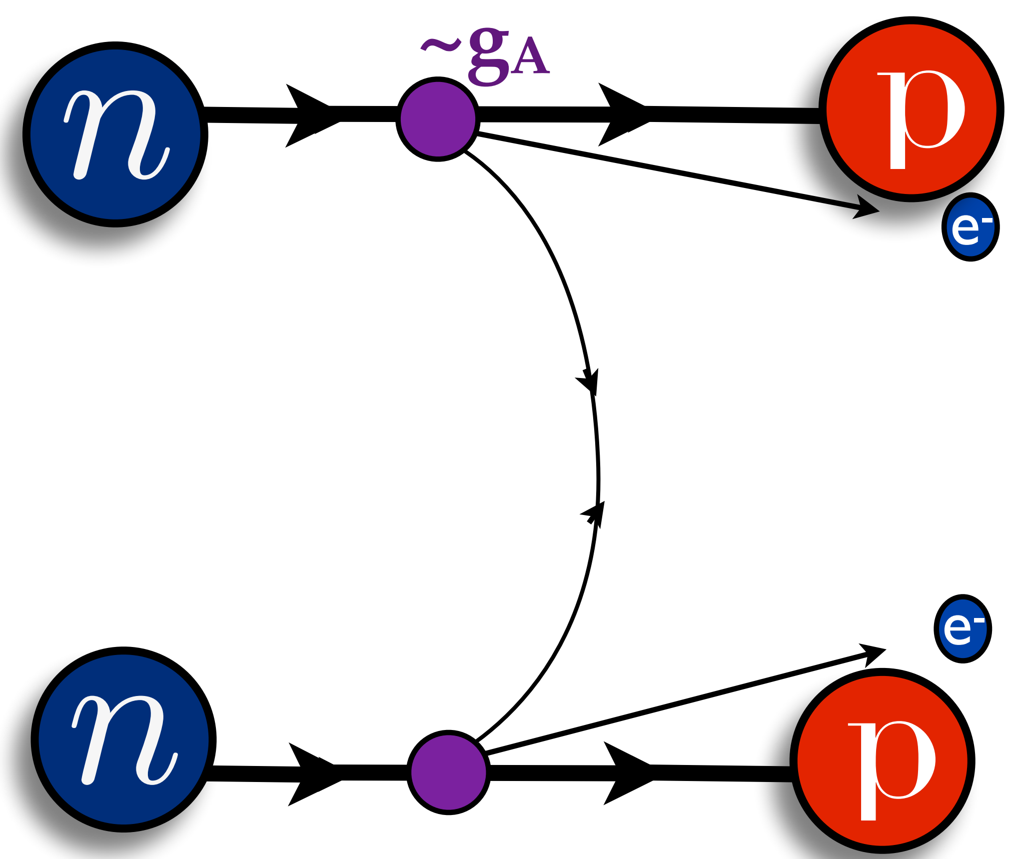
Prezeau, Ramsey-Musolf, Vogel (2003)

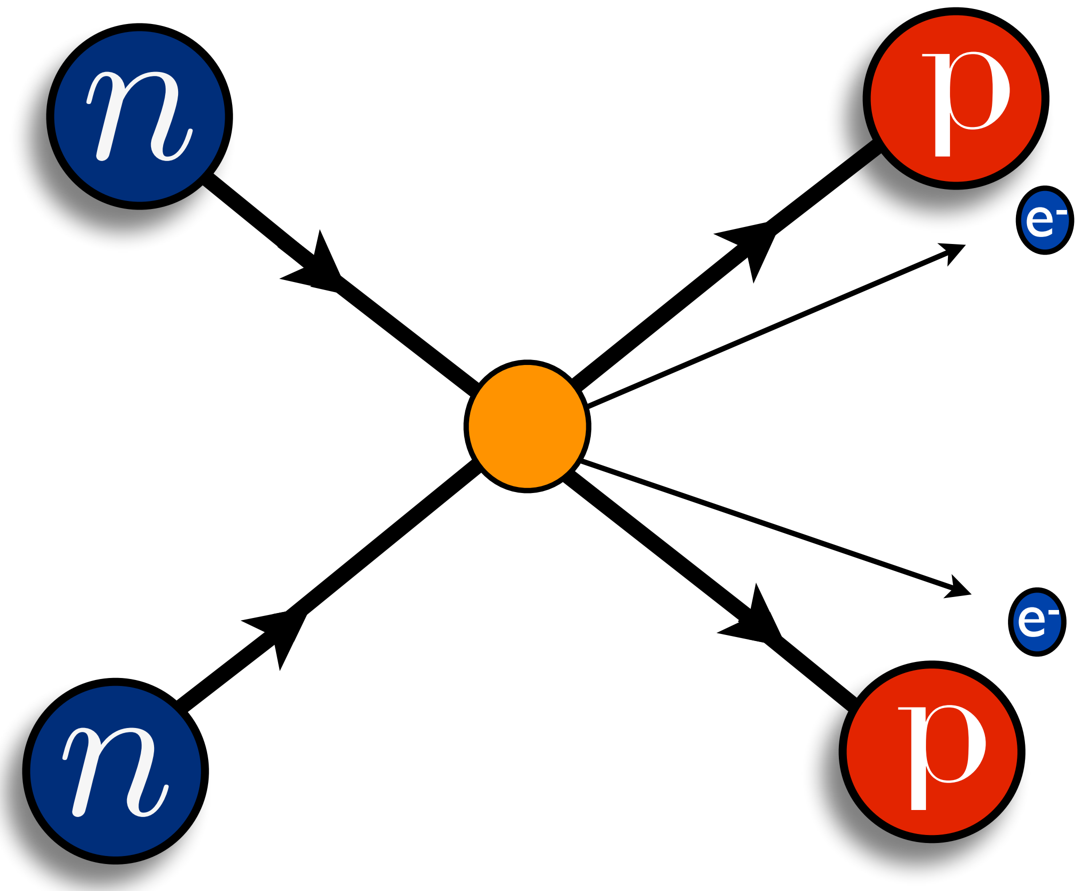




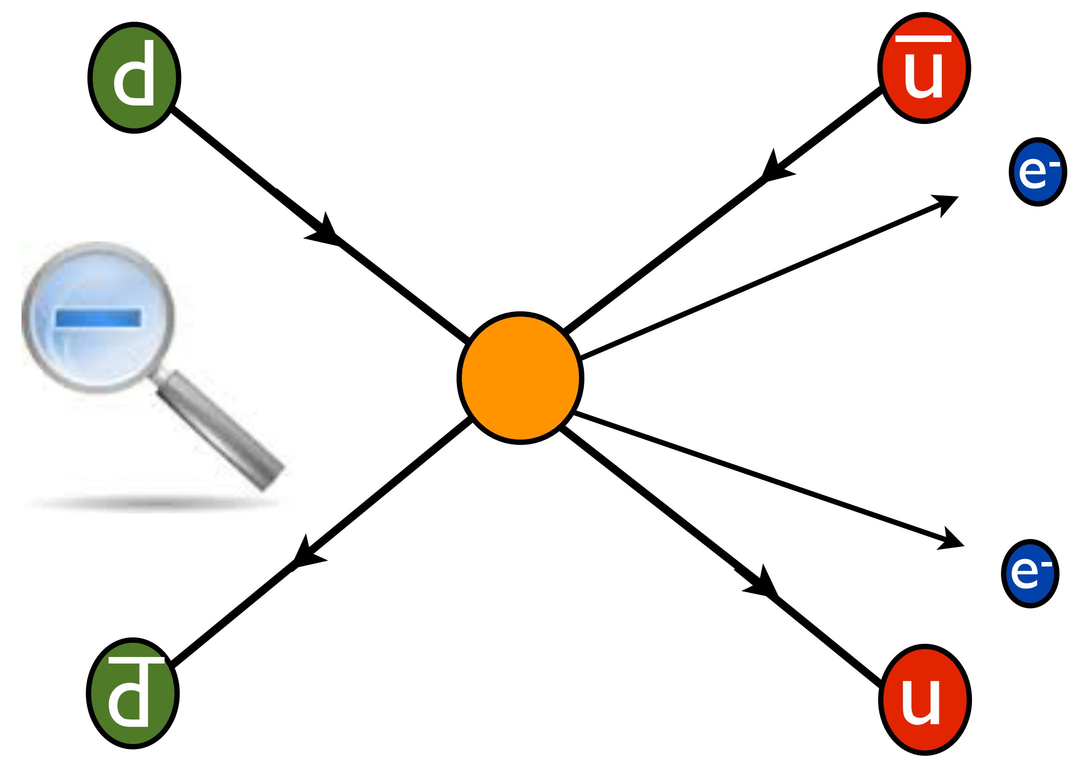


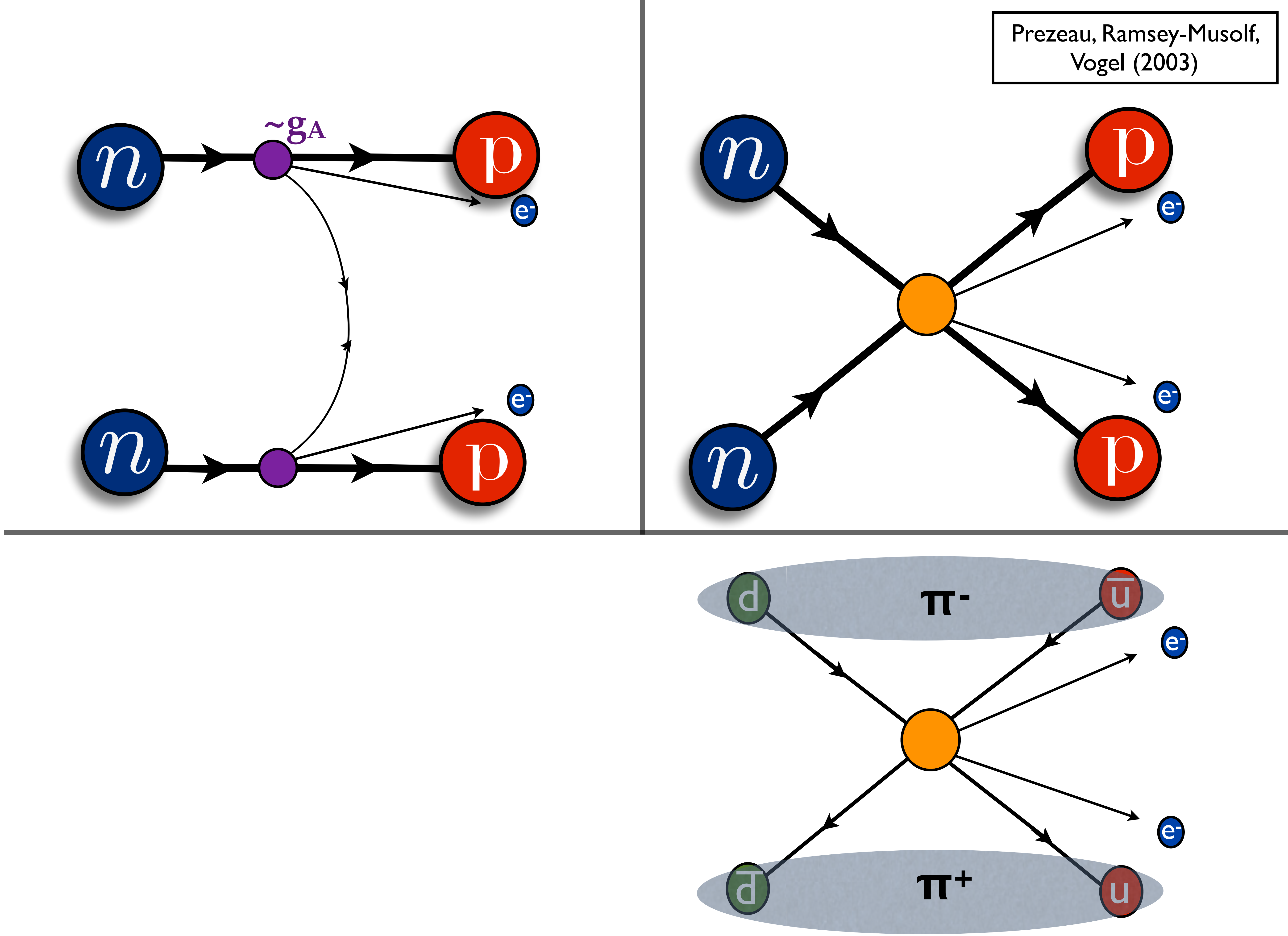
Prezeau, Ramsey-Musolf, Vogel (2003)





$\Lambda \ll \Lambda_{QCD}$





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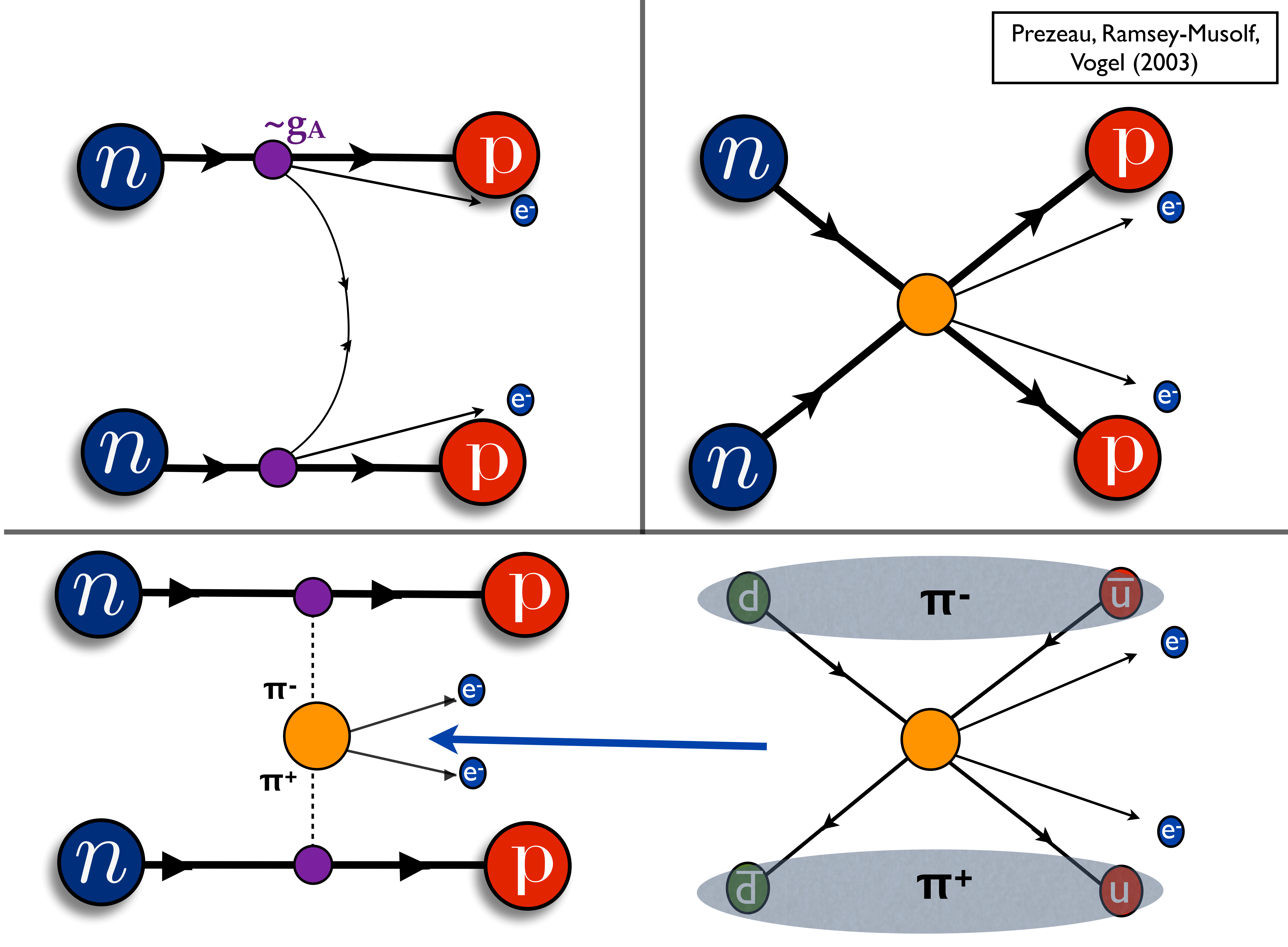
Prezeau, Ramsey-Musolf, Vogel (2003)
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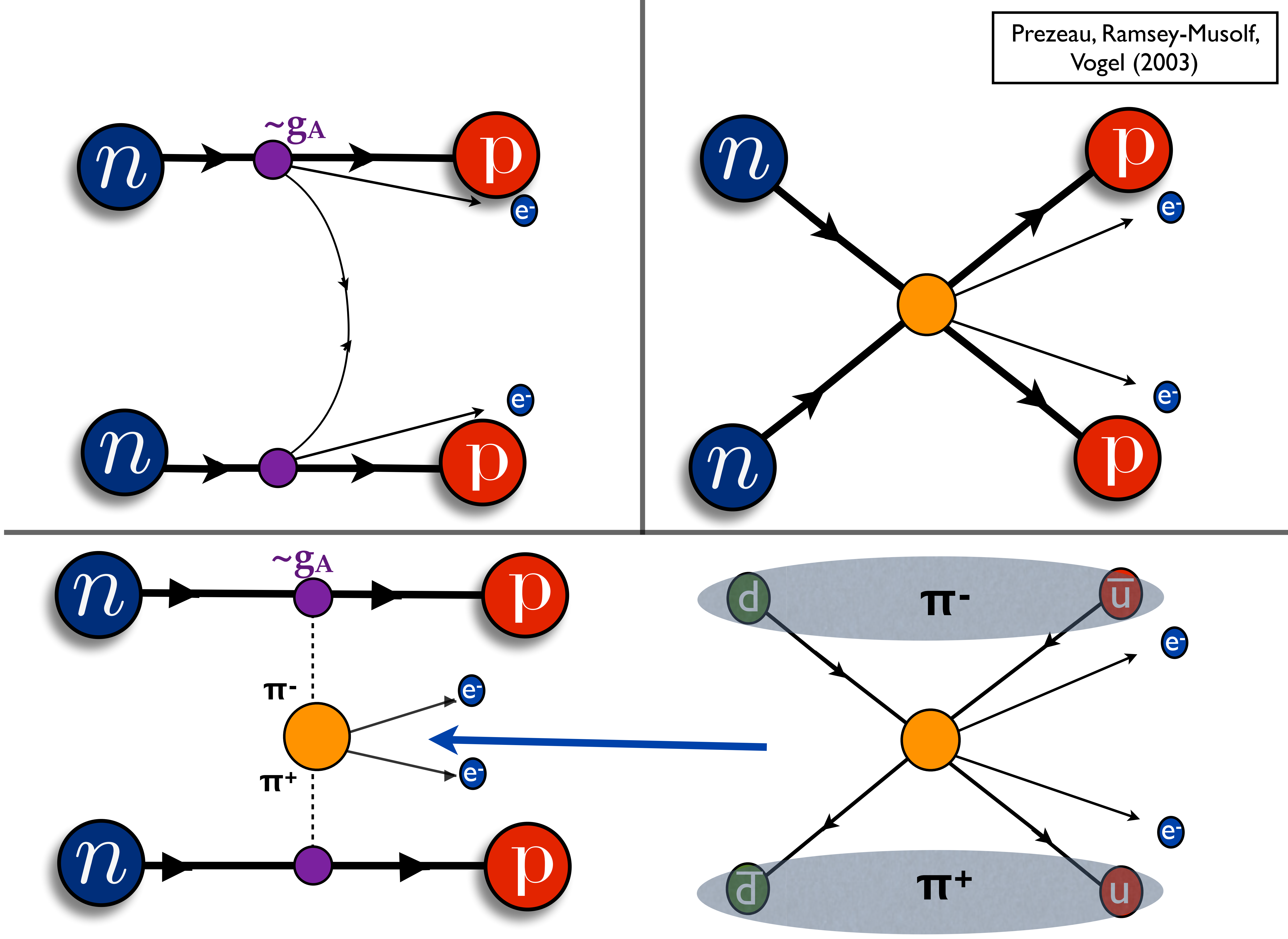

Prezeau, Ramsey-Musolf, Vogel (2003)
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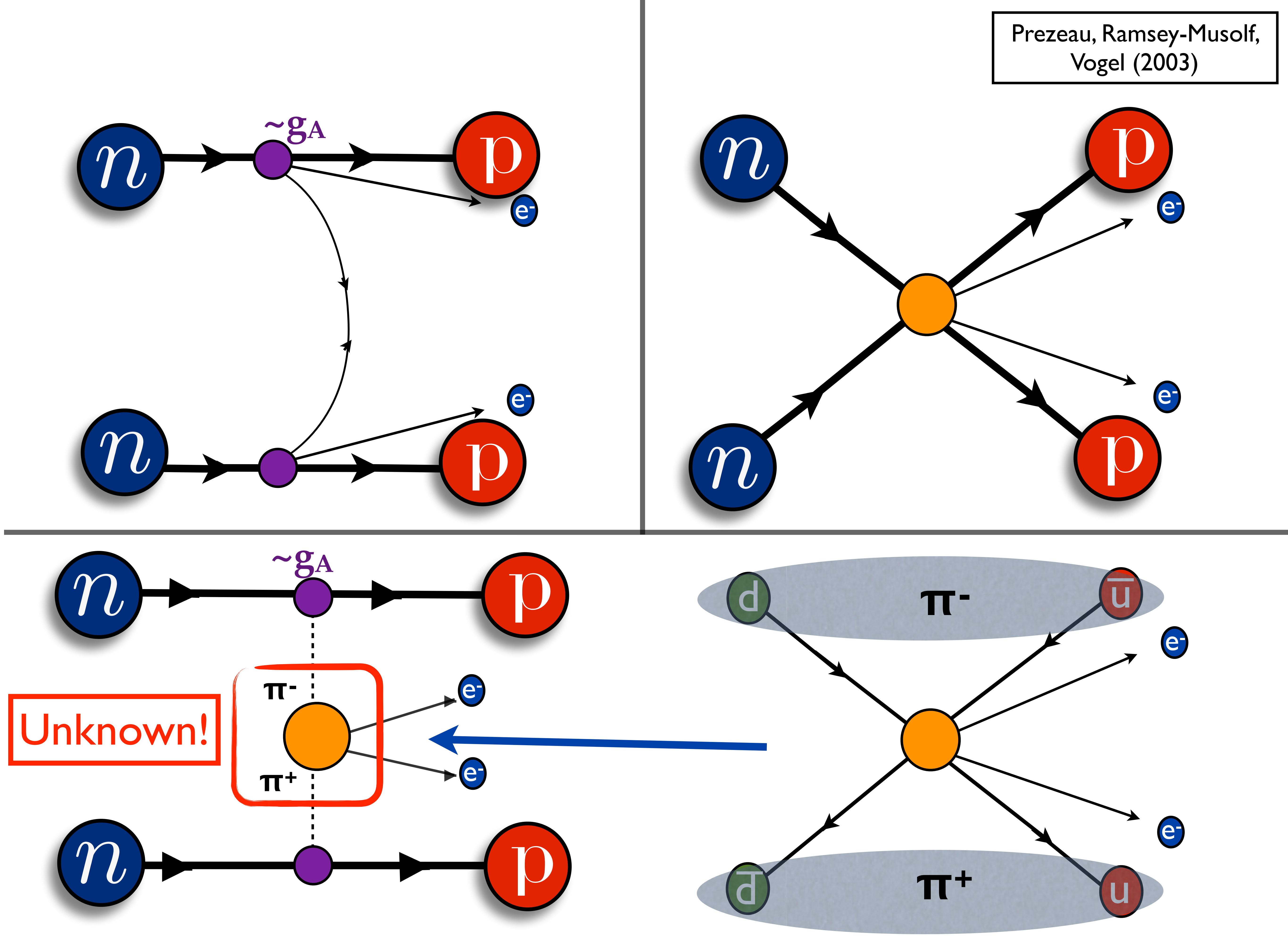

Prezeau, Ramsey-Musolf, Vogel (2003)
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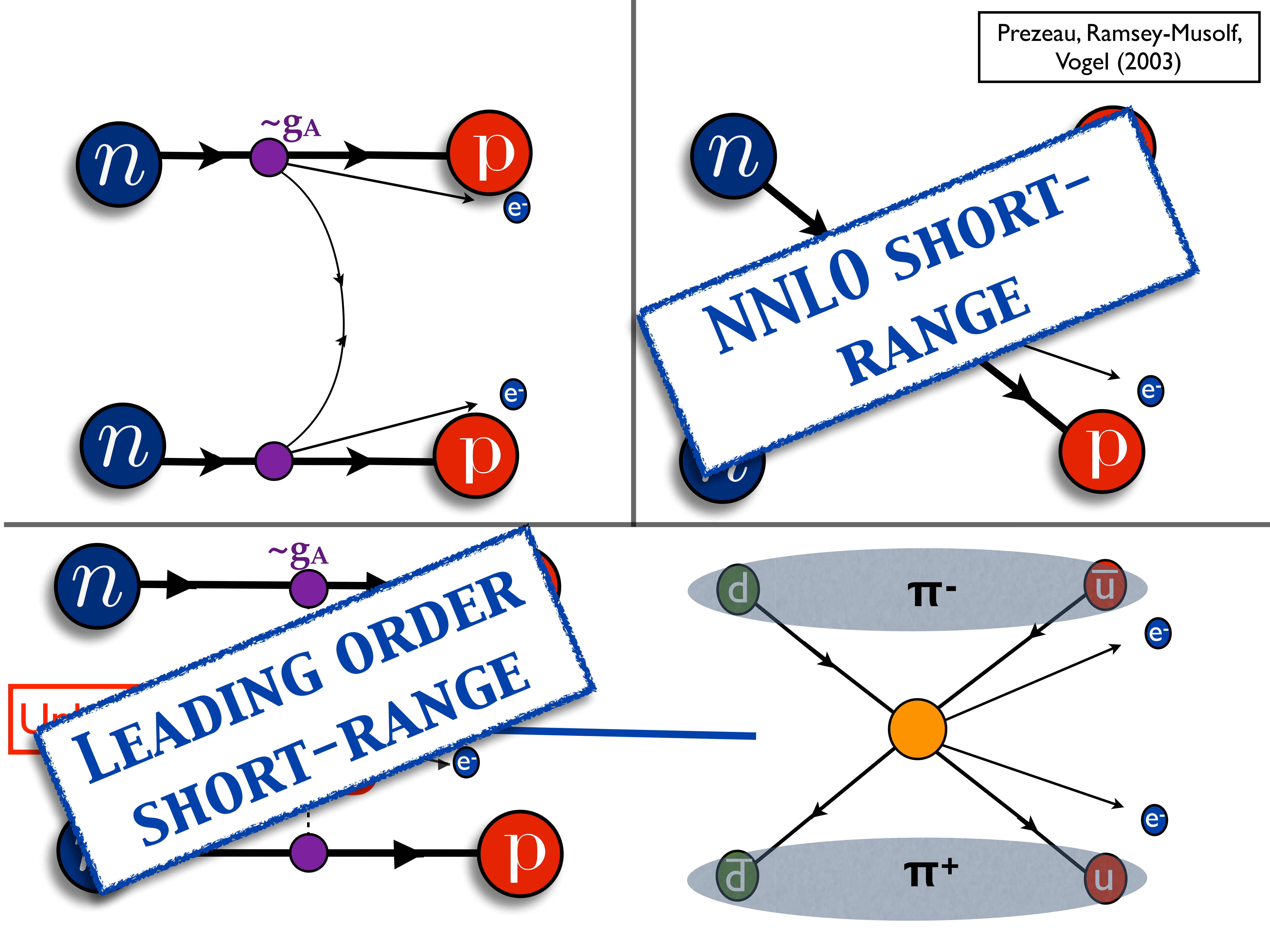
Prezeau, Ramsey-Musolf, Vogel (2003)
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NNLO SHORT-RANGE
LEADING ORDER SHORT-RANGE
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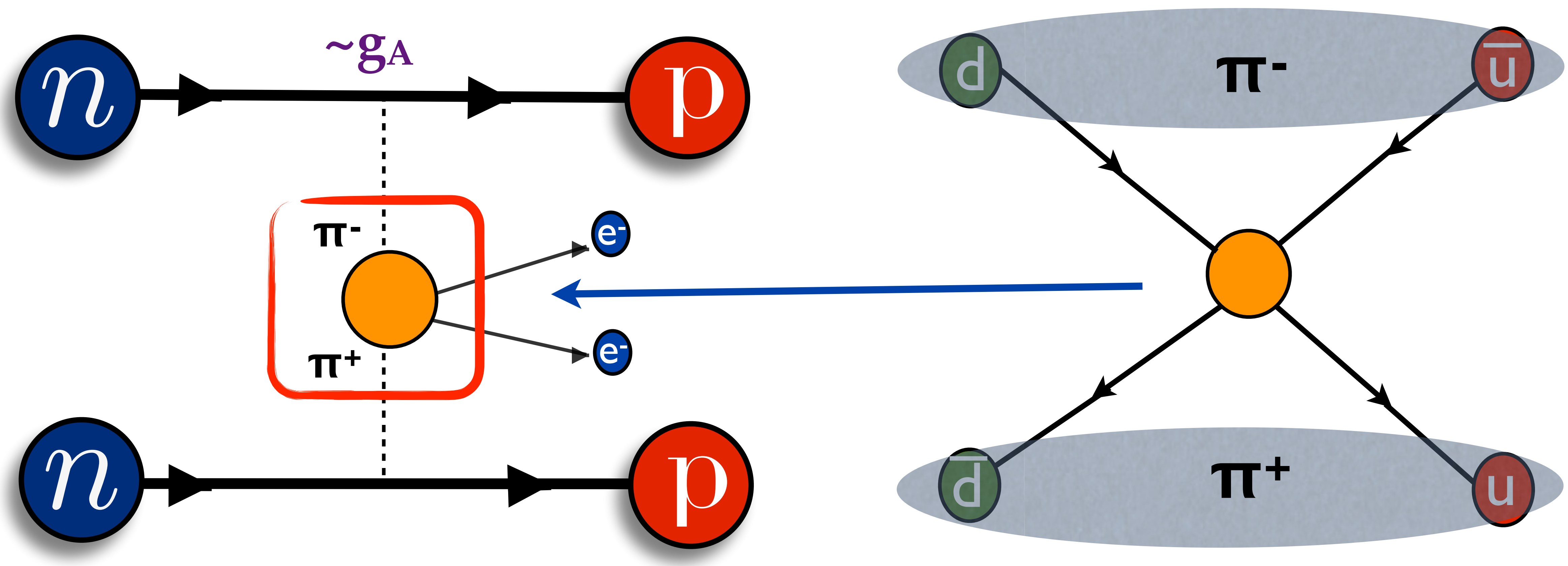
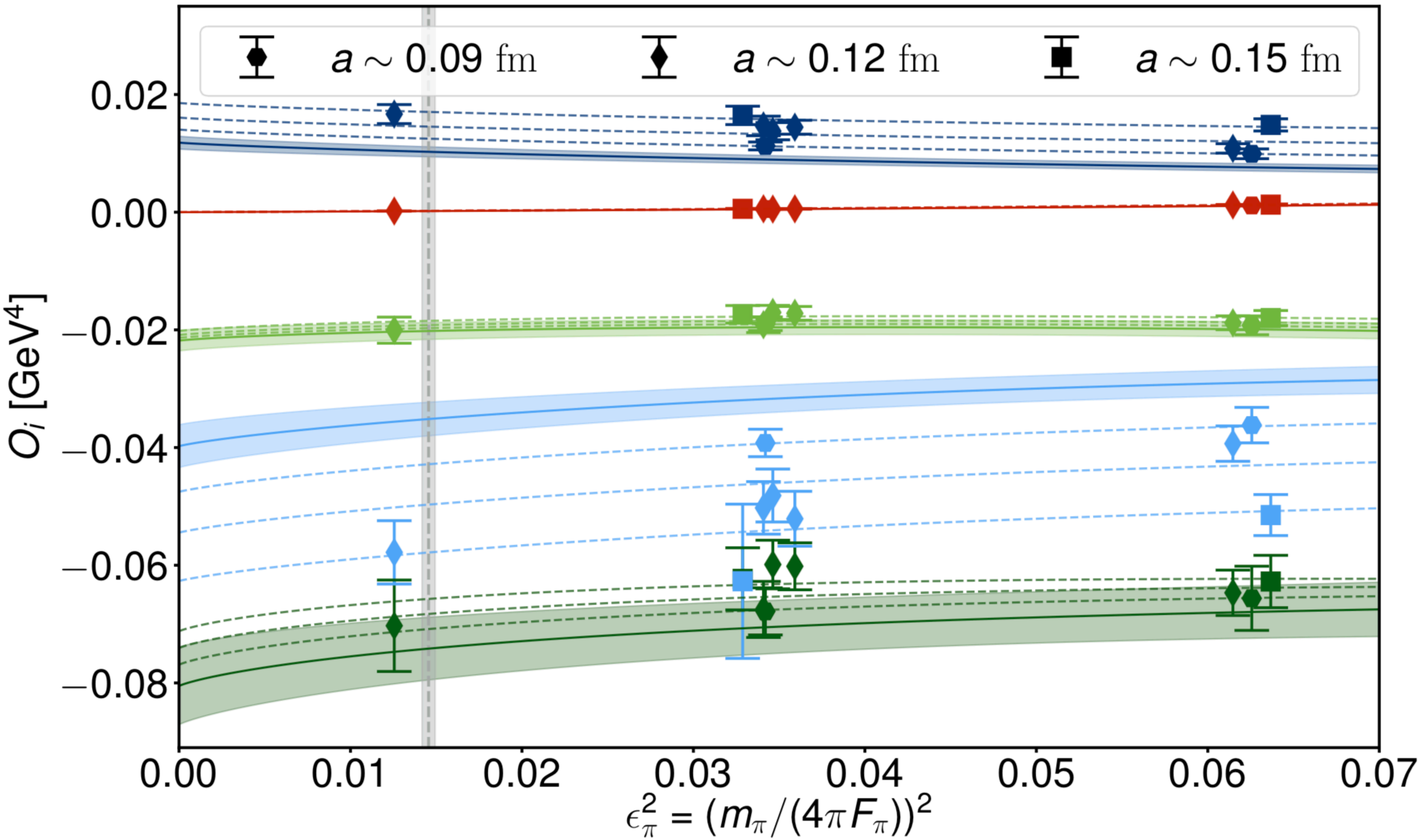


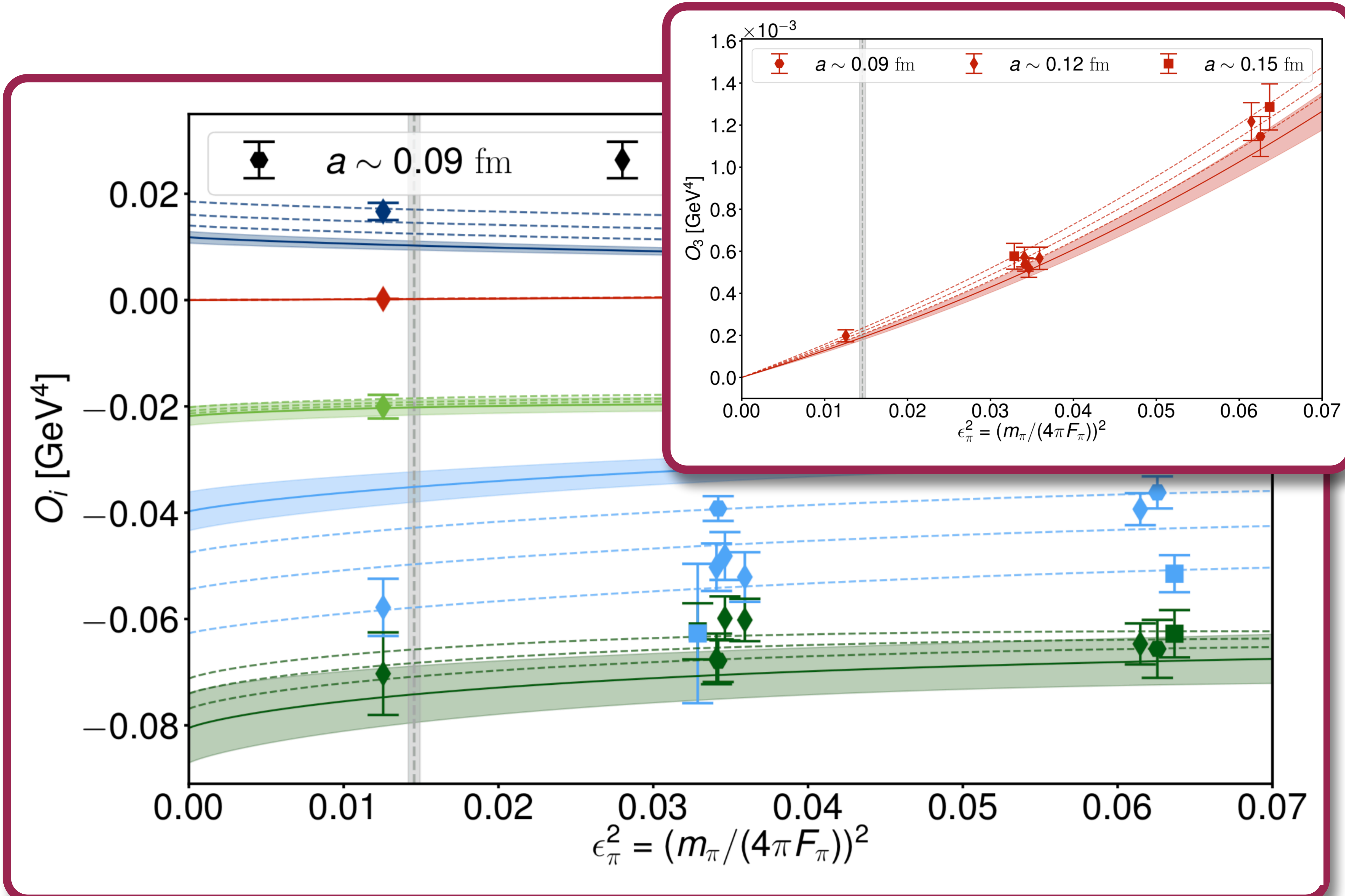
Leading order short-range:

Don't need to calculate full nn→pp transition from LQCD (difficult)!

1. With LQCD, calculate $\pi^- \rightarrow \pi^+$ transition
2. Use EFT to determine nn→pp matrix element



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, arXiv:1805.02634 (2018)



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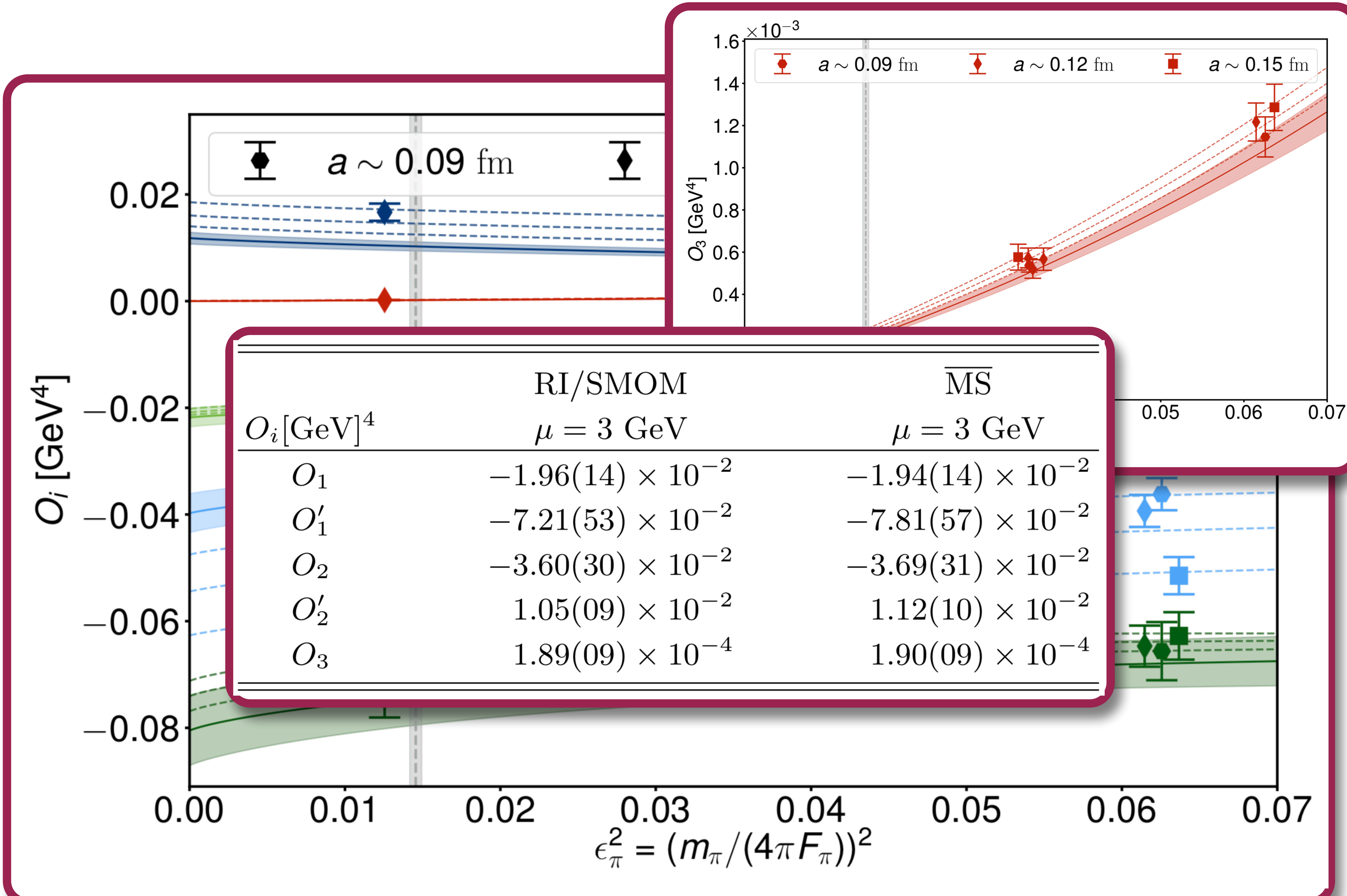
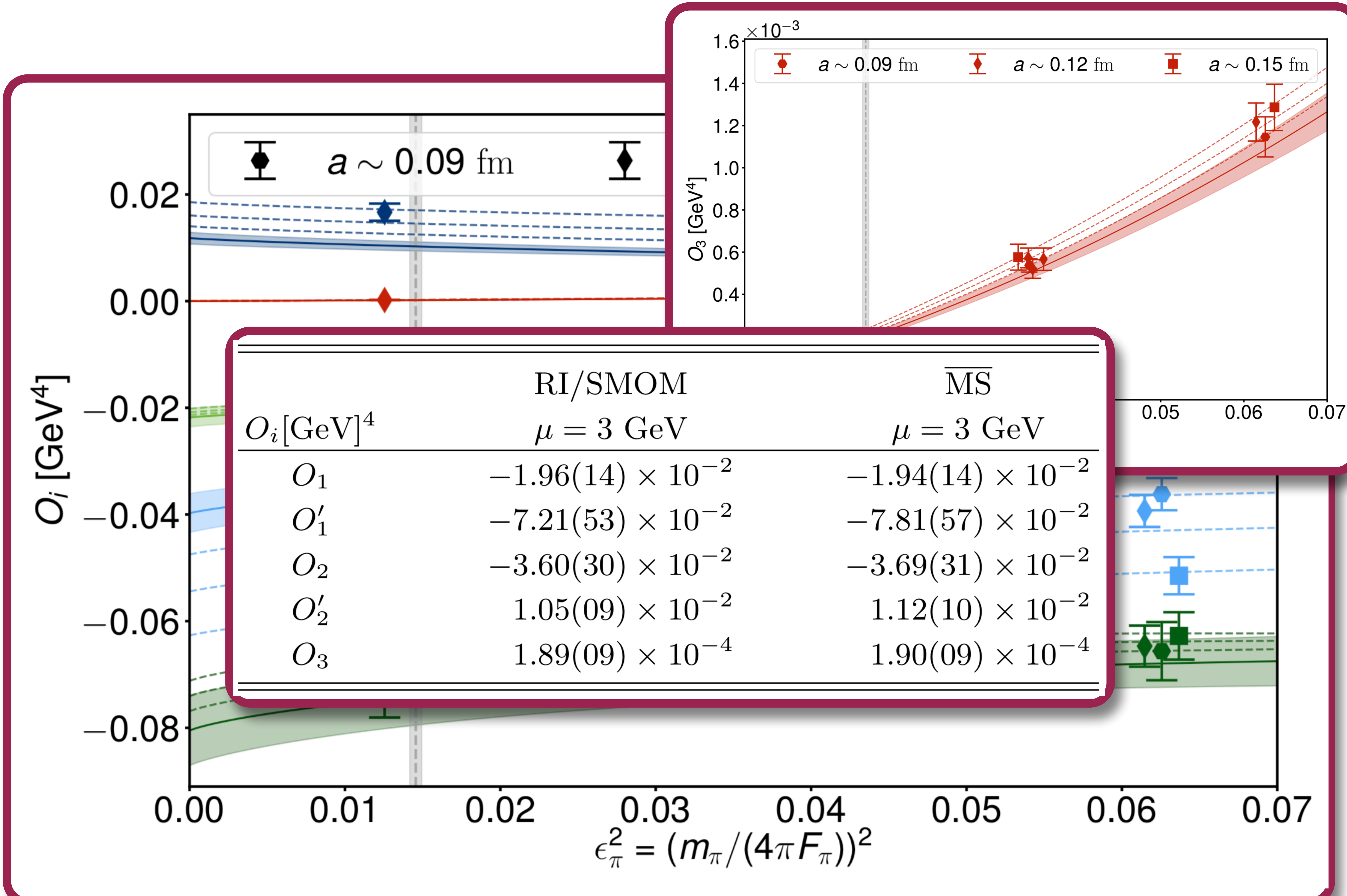


$O_i[\mathrm{GeV}]^4$	RI/SMOM $\mu = 3$ GeV	$\overline{\mathrm{MS}}$ $\mu = 3$ GeV
O_1	$-1.96(14) \times 10^{-2}$	$-1.94(14) \times 10^{-2}$
O'_1	$-7.21(53) \times 10^{-2}$	$-7.81(57) \times 10^{-2}$
O_2	$-3.60(30) \times 10^{-2}$	$-3.69(31) \times 10^{-2}$
O'_2	$1.05(09) \times 10^{-2}$	$1.12(10) \times 10^{-2}$
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, arXiv:1805.02634 (2018)



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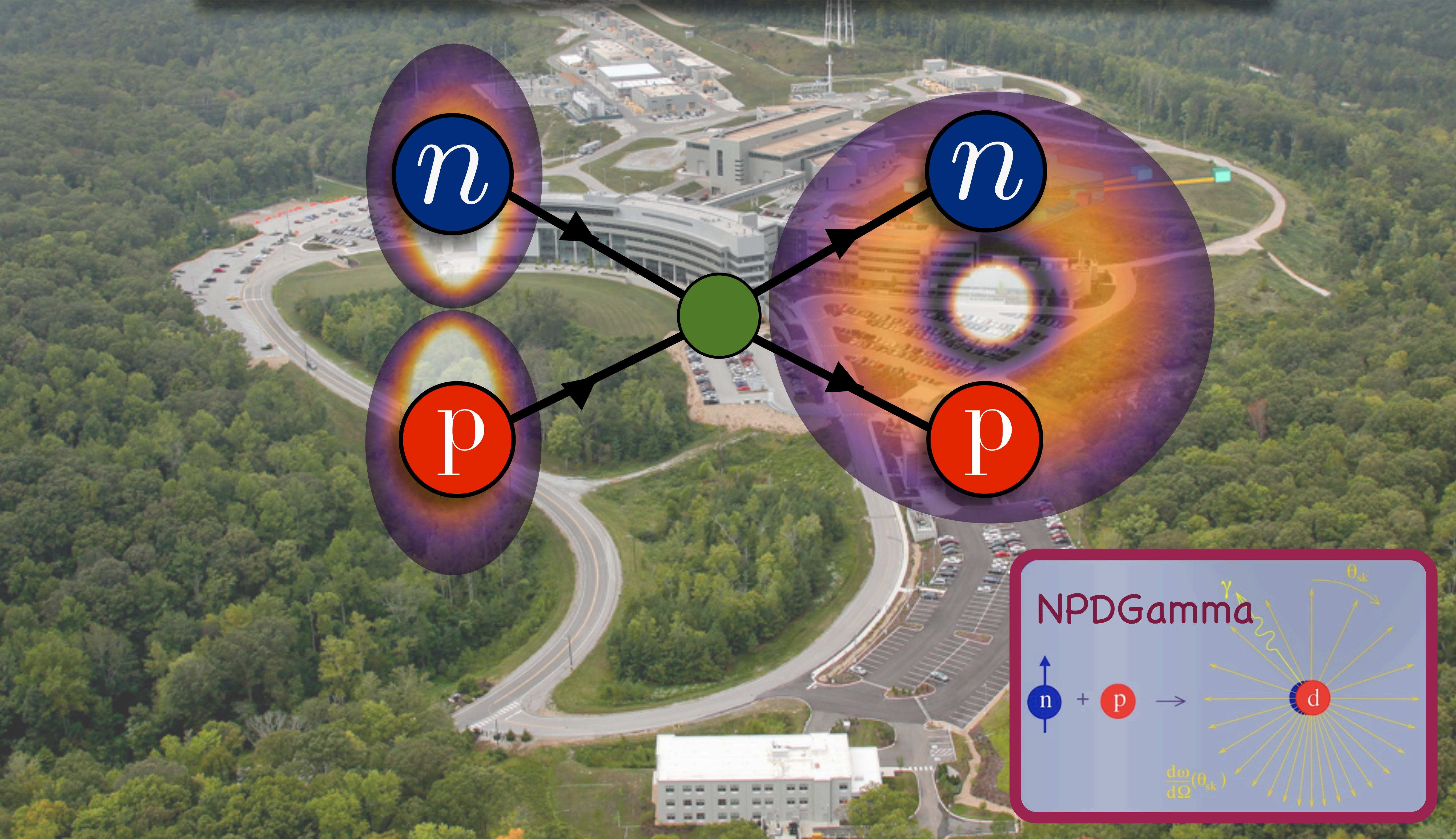
A.N., E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joo, T. Kurth, B. Tiburzi, P. Vranas, A. Walker-Loud, arXiv:1805.02634 (2018)

Agrees to 2σ with:
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti
Phys.Lett. B769 (2017) 460-464

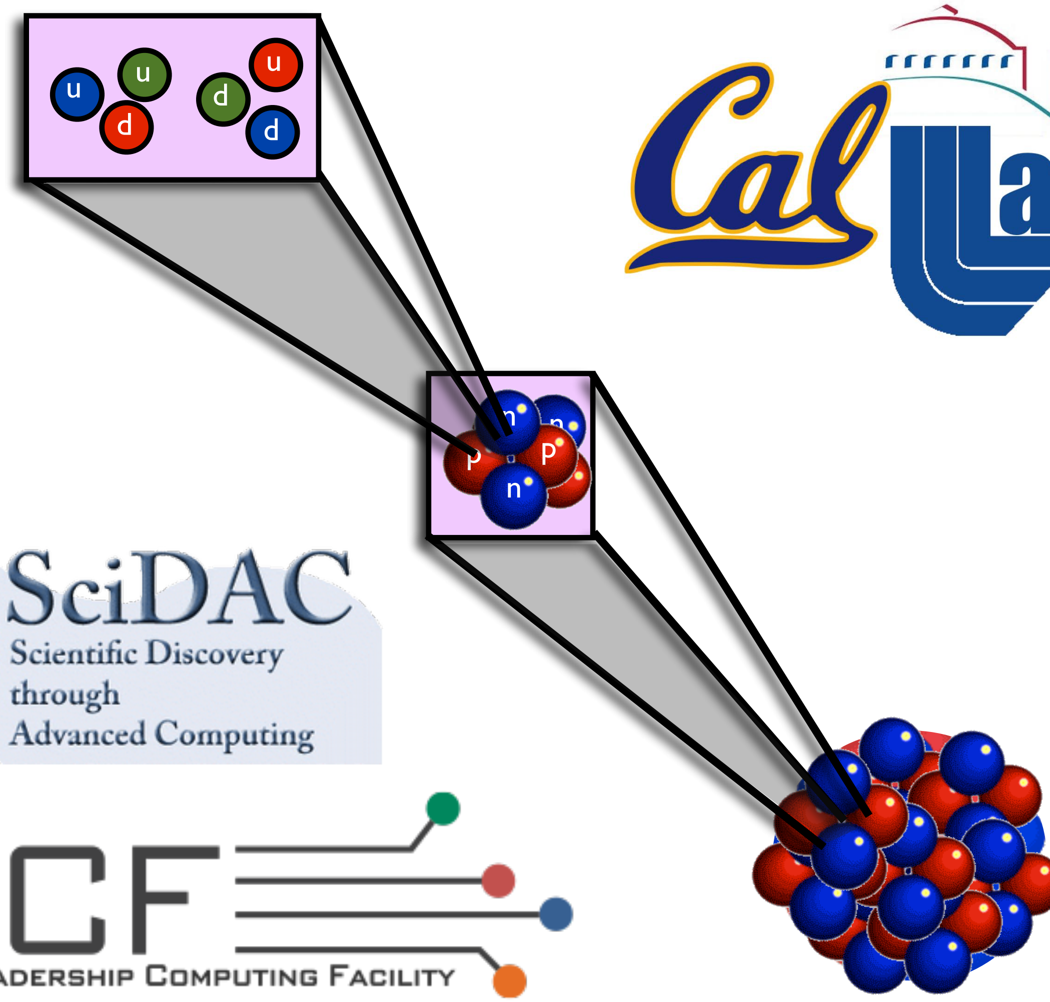
Summary

- LQCD is a necessary step toward reliably connecting experimental signals to the SM/BSM
- Nucleon axial charge
  - Finally achieved 1% precision with LQCD!
  - Statistics dominated: can we resolve neutron lifetime puzzle?
- Leading short-range contribution to $0\nu\beta\beta$
  - Complete LQCD calculation at the physical point
  - To do: Plug the results into your favorite many-body calculation!
  - Future: full NNLO calculation including two-nucleon contact

Very similar to calculation of hadronic parity violation (see talk by A. Walker-Loud Sat. 17:30)



- 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
- LLNL: P. Vranas
- Jülich: E. Berkowitz
- WM/LBL: D. Brantley, H. Monge-Camacho



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

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

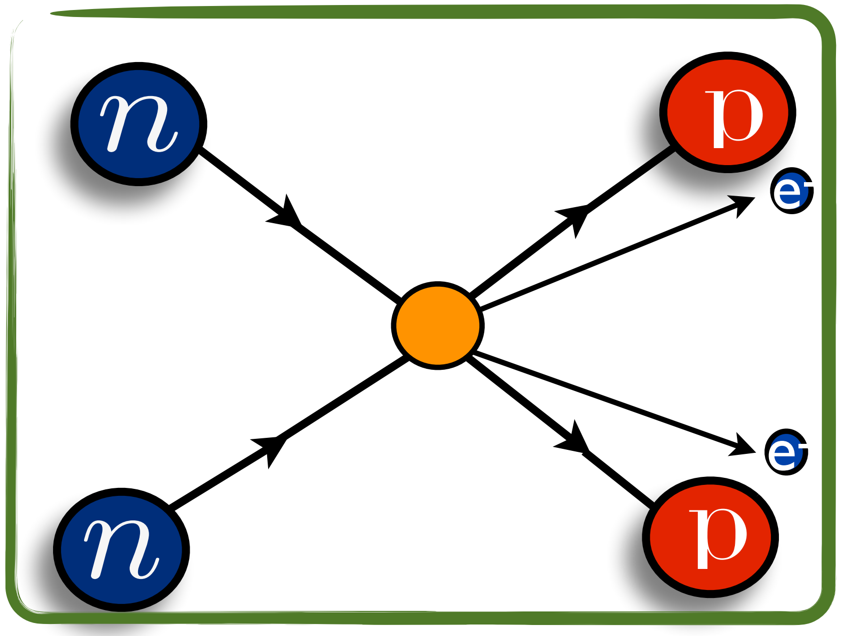
- DWF on HISQ
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5
  - dampens unphysical oscillations
  - noise reduction

MILC Collaboration Phys. Rev. D87 (2013) 054505

Narayanan, Neuberger (2006), Luscher (2010)

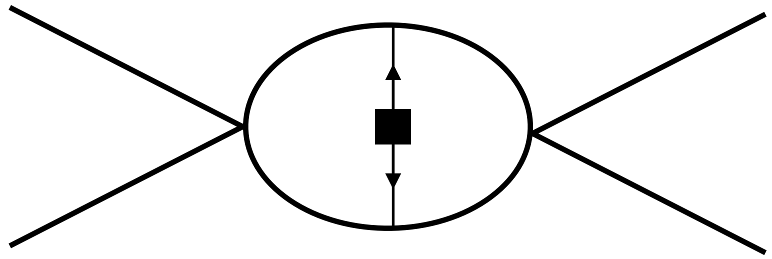
Callat arXiv:1701.07559

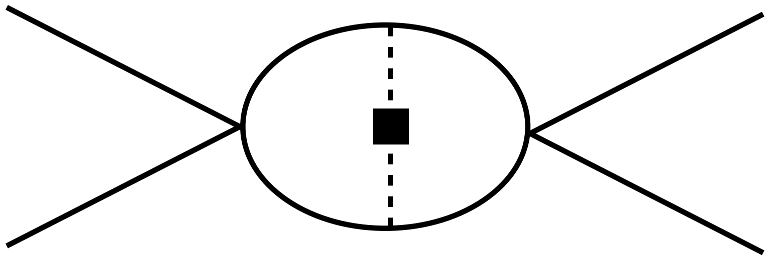
Future: two-nucleon contact



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

- Why calculate it?
  - Formally NNLO (Weinberg counting)
  - Weinberg often doesn't converge well, particularly in the $^1S_0$ channel (see talk by V. Cirigliano)
  - LO contribution vanishes for some BSM models
- Two nucleon LQCD calculations much more difficult (see talks by S. Beane, J. Bulava?)





$$\langle\pi^+|\mathcal{O}^{V+}|\pi^-\rangle = \frac{m_\pi^2}{f^2}C^{V+}\left[1-\frac{16}{3}\frac{m_\pi^2}{(4\pi f)^2}\left(\ \frac{1}{4}\log\frac{m_\pi^2}{\mu^2}+\frac{3}{4}\frac{m_{vs}^2}{m_\pi^2}\log\frac{m_{vs}^2}{\mu^2}+c^{V^+}(\mu)\right)\right],$$

$$\langle\pi^+|\mathcal{O}^{LR}|\pi^-\rangle = \qquad C^{LR}\left[1-\frac{10}{3}\frac{m_\pi^2}{(4\pi f)^2}\left(-\frac{1}{5}\log\frac{m_\pi^2}{\mu^2}+\frac{6}{5}\frac{m_{vs}^2}{m_\pi^2}\log\frac{m_{vs}^2}{\mu^2}+c^{LR}(\mu)\right)\right],$$

$$\langle\pi^+|\mathcal{O}^{S+}|\pi^-\rangle = \qquad C^{S+}\left[1-\frac{10}{3}\frac{m_\pi^2}{(4\pi f)^2}\left(-\frac{1}{5}\log\frac{m_\pi^2}{\mu^2}+\frac{6}{5}\frac{m_{vs}^2}{m_\pi^2}\log\frac{m_{vs}^2}{\mu^2}+\frac{6}{5}\frac{a^2\Delta_I}{m_\pi^2}\big[\log\frac{m_\pi^2}{\mu^2}+1\big]+c^{S+}(\mu)\right)\right]$$

e hairpin only seems to infect the last matrix element. There is a corresponding enhancement of the finite vo ect, which can be obtained by the replacement

$$a^2\Delta_I\big[\log\frac{m_\pi^2}{\mu^2}+1\big] \longrightarrow a^2\Delta_I\frac{\partial}{\partial m_\pi^2}\left[4m_\pi^2\sum_{\vec{\nu}\neq\vec{0}}\frac{\mathtt{K}_1(m_\pi L|\vec{\nu}|)}{m_\pi L|\vec{\nu}|}\right] = -2a^2\Delta_I\sum_{\vec{\nu}\neq\vec{0}}\mathtt{K}_0(m_\pi L|\vec{\nu}|).$$

Contractions

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

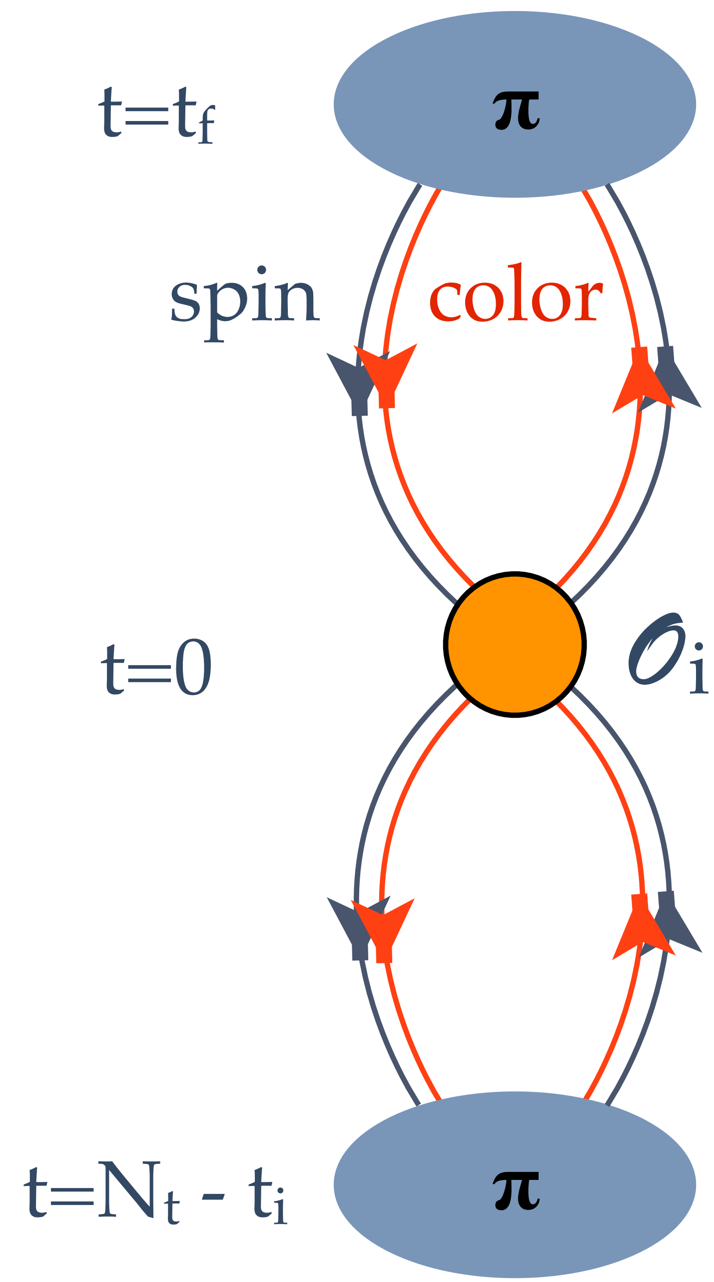
$$\mathcal{O}_{1+}^{++} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

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

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

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

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



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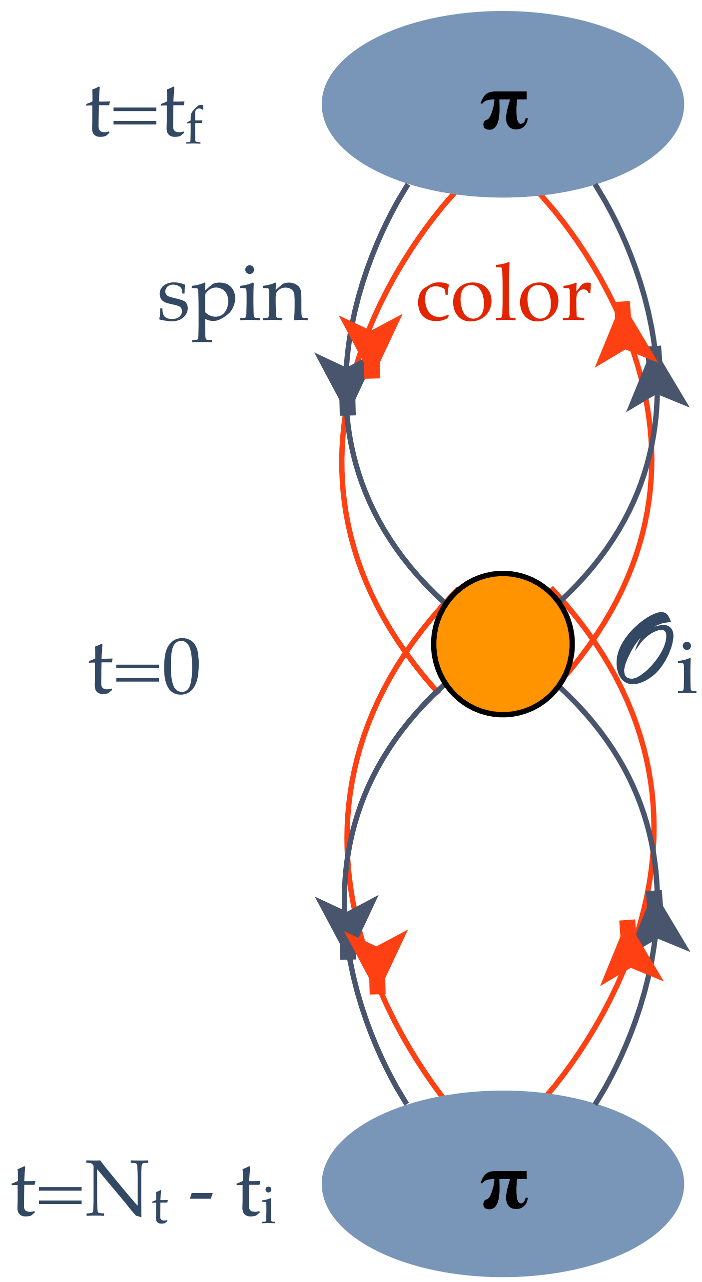
$$\mathcal{O}_{2+}^{++} = \left(\bar{q}_R \tau^- q_L\right) \left[\bar{q}_R \tau^- q_L\right] + \left(\bar{q}_L \tau^- q_R\right) \left[\bar{q}_L \tau^- q_R\right]$$

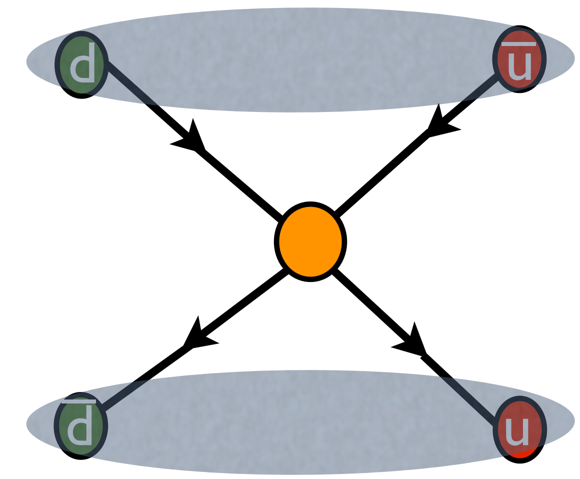
$$\mathcal{O'}_{2+}^{++} = \left(\bar{q}_R \tau^- q_L\right] \left[\bar{q}_R \tau^- q_L\right) + \left(\bar{q}_L \tau^- q_R\right] \left[\bar{q}_L \tau^- q_R\right)$$

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



XPT:

-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

  - QCD interactions can mix

colors below the electroweak

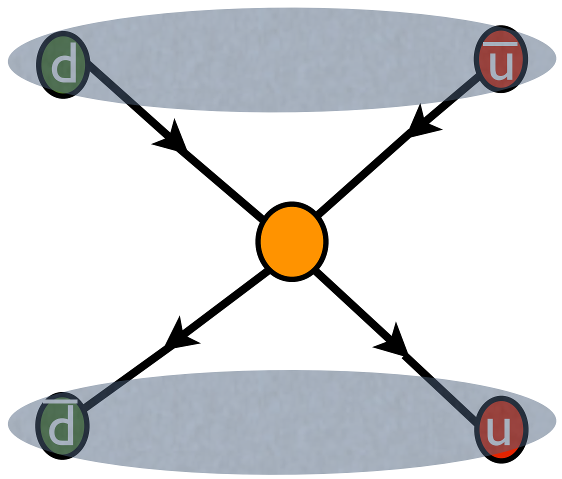
scale: +2 ops

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

Prezeau, Ramsey-Musolf, Vogel (2003)

XPT:

-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
  - QCD interactions can mix colors below the electroweak scale: +2 ops

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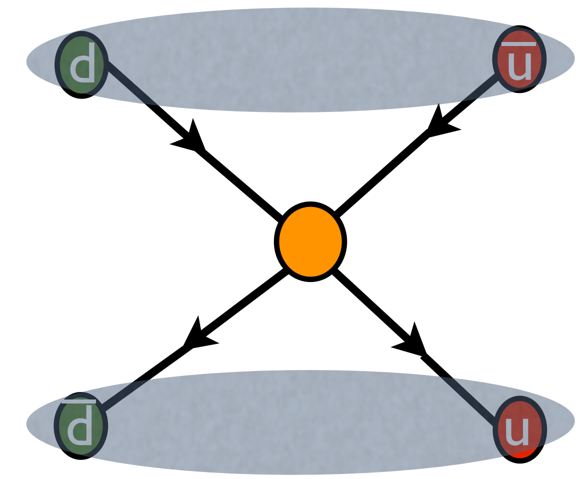
\mathcal{O}_{3\pm}^{ab} &= (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L \tau^b \gamma_\mu q_L) \pm (\bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_R \tau^b \gamma_\mu q_R), \\
\mathcal{O}_{4\pm}^{ab,\mu} &= (\bar{q}_L \tau^a \gamma^\mu q_L \mp \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R - \bar{q}_R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

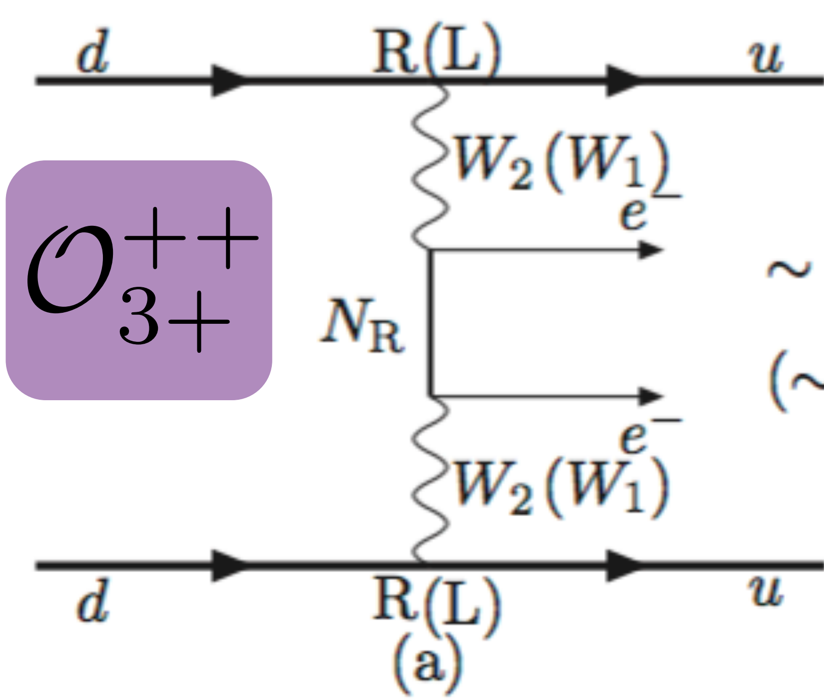
XPT:

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



Left-right symmetric models

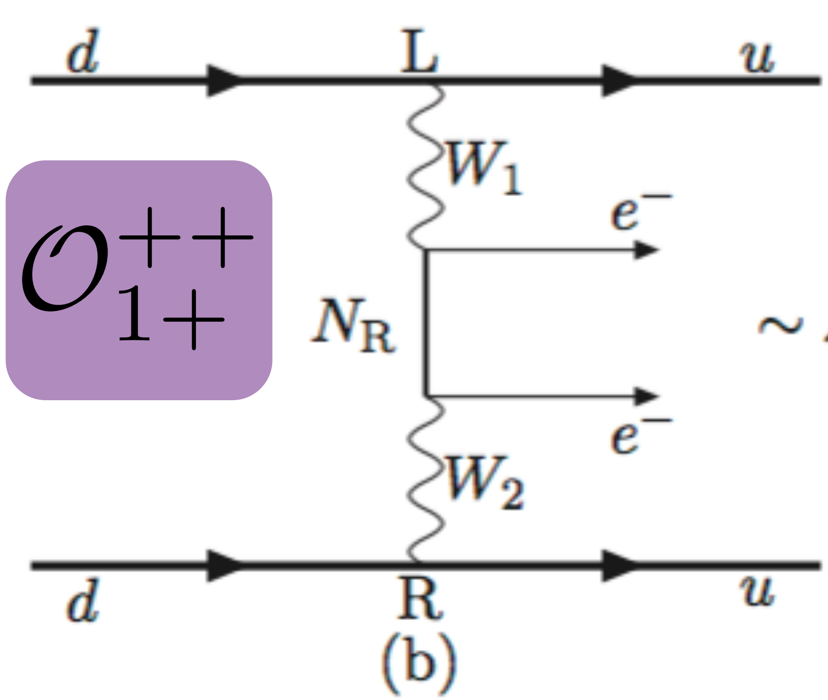
$\mathcal{O}_{3+}^{++}$



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

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

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



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

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