

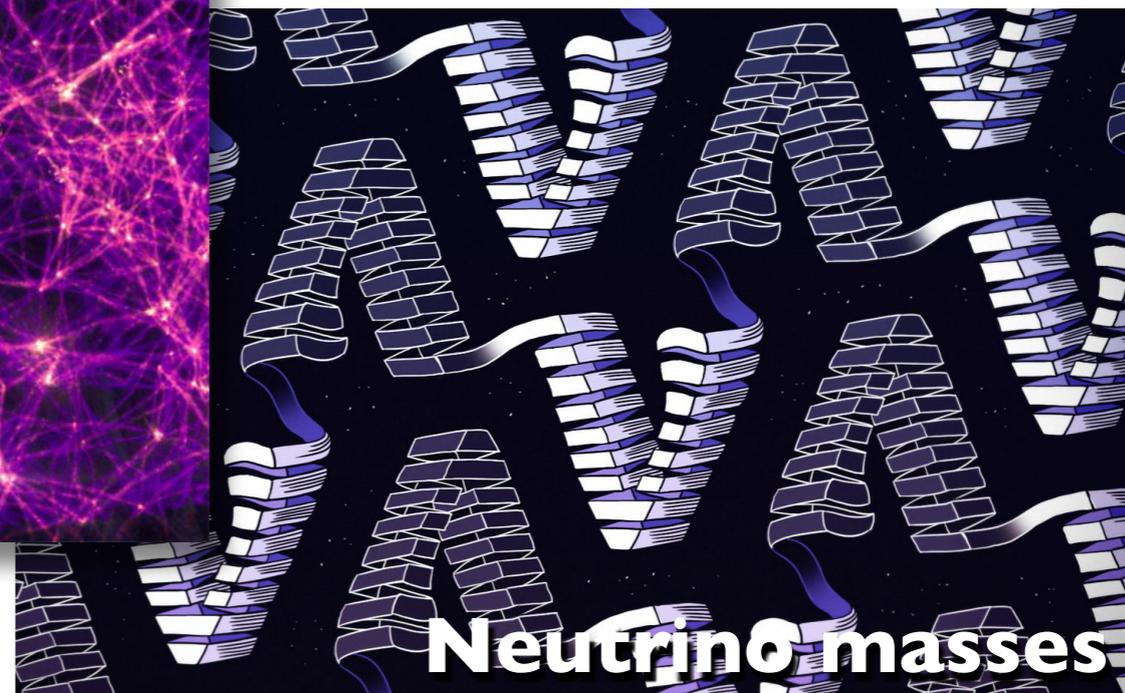
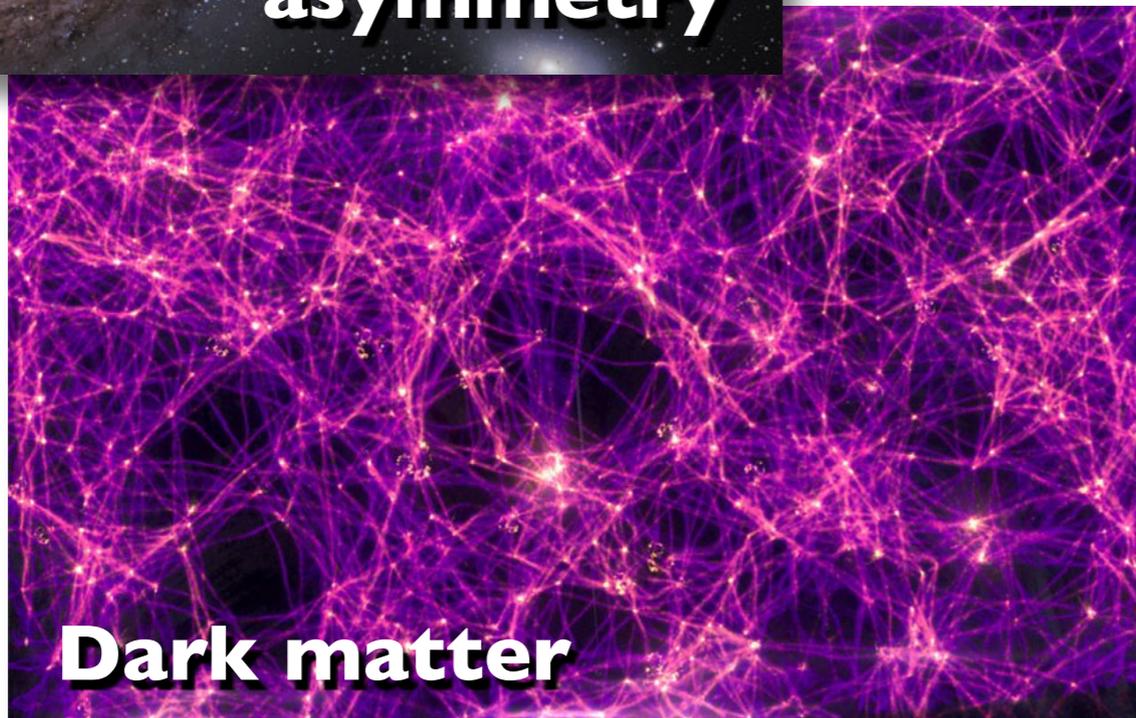
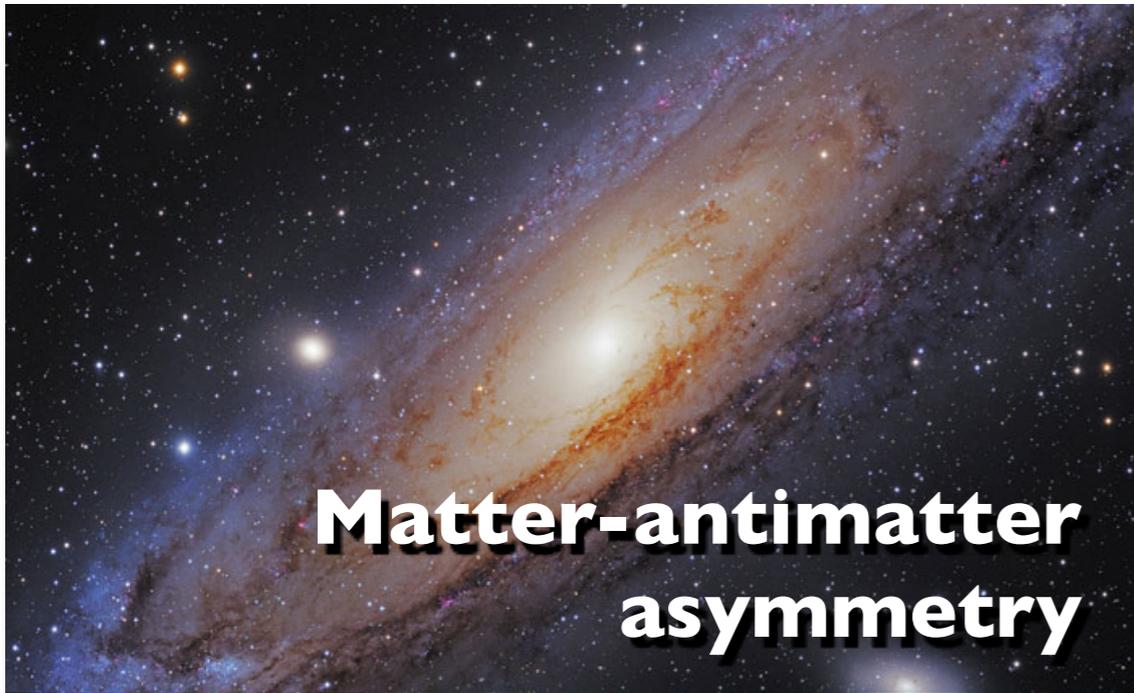
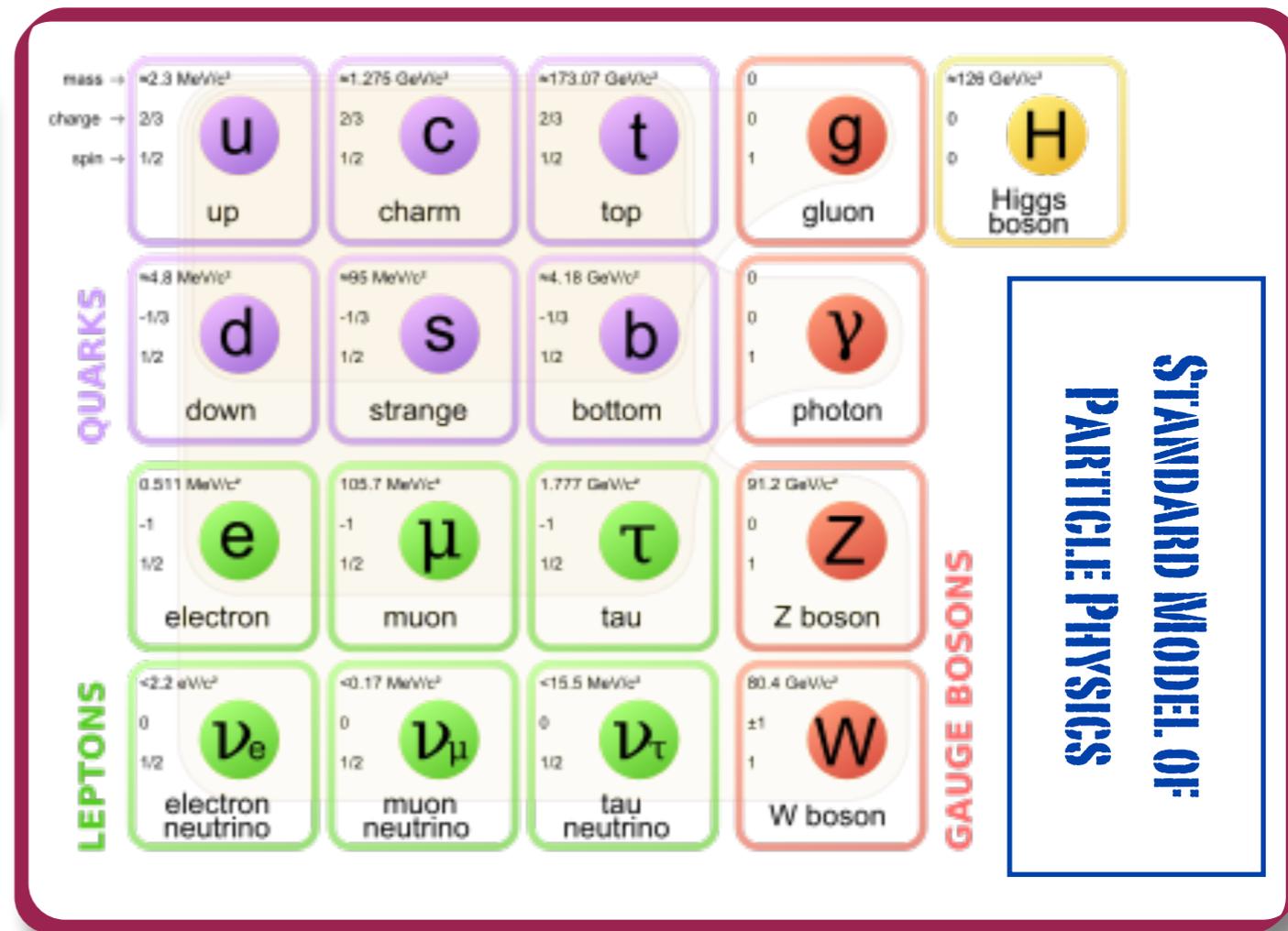
Symmetries and Interactions from Lattice QCD

Amy Nicholson
UNC, Chapel Hill

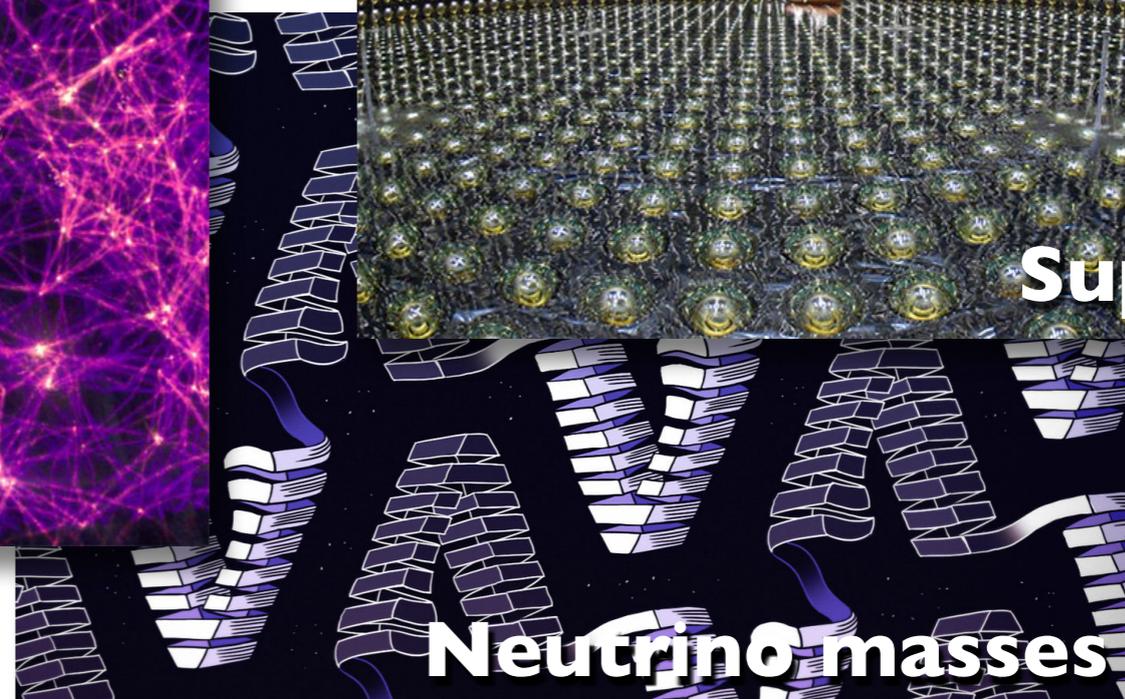
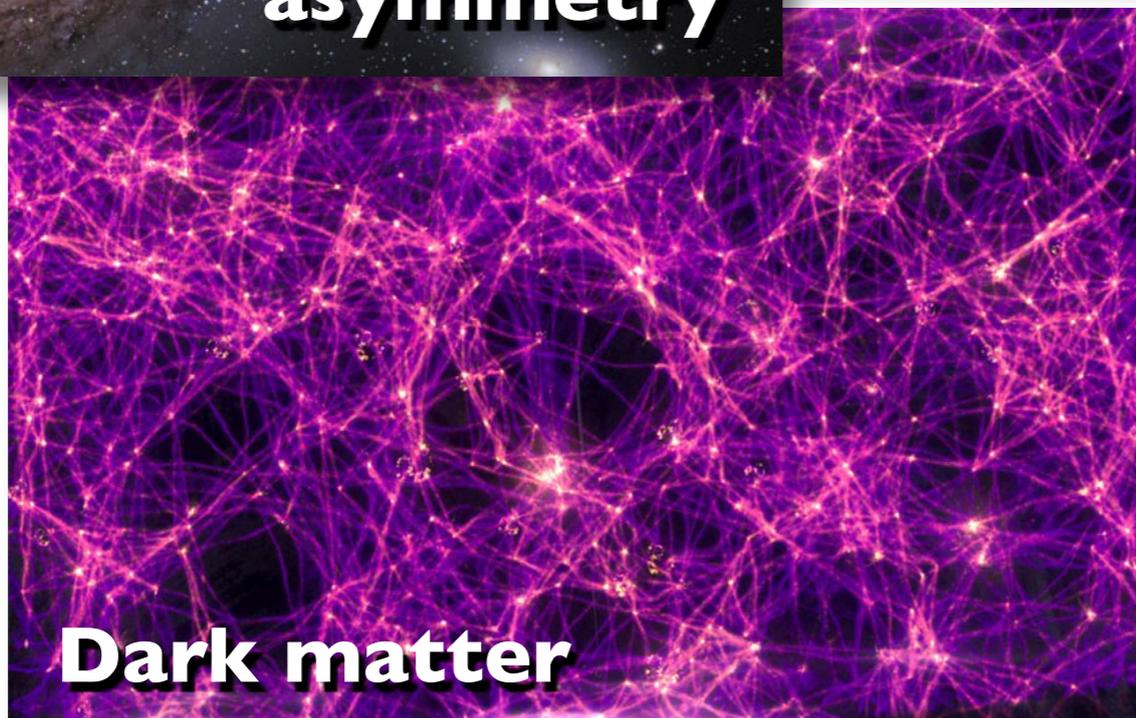
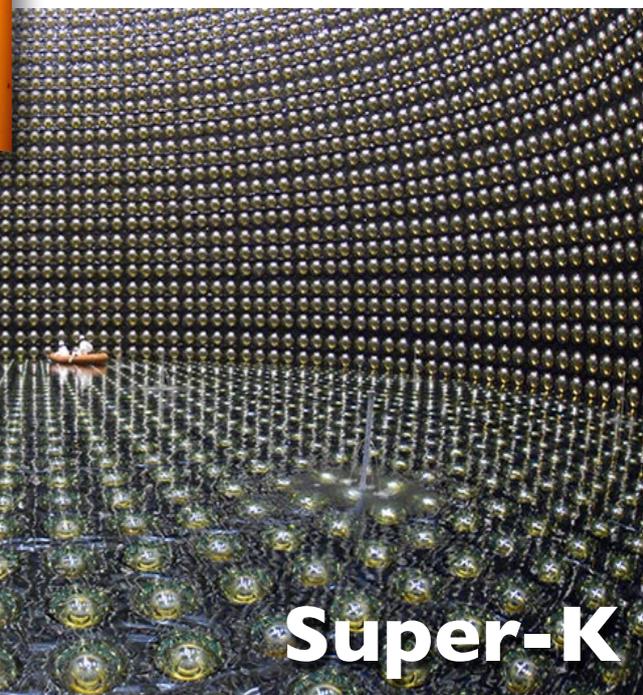
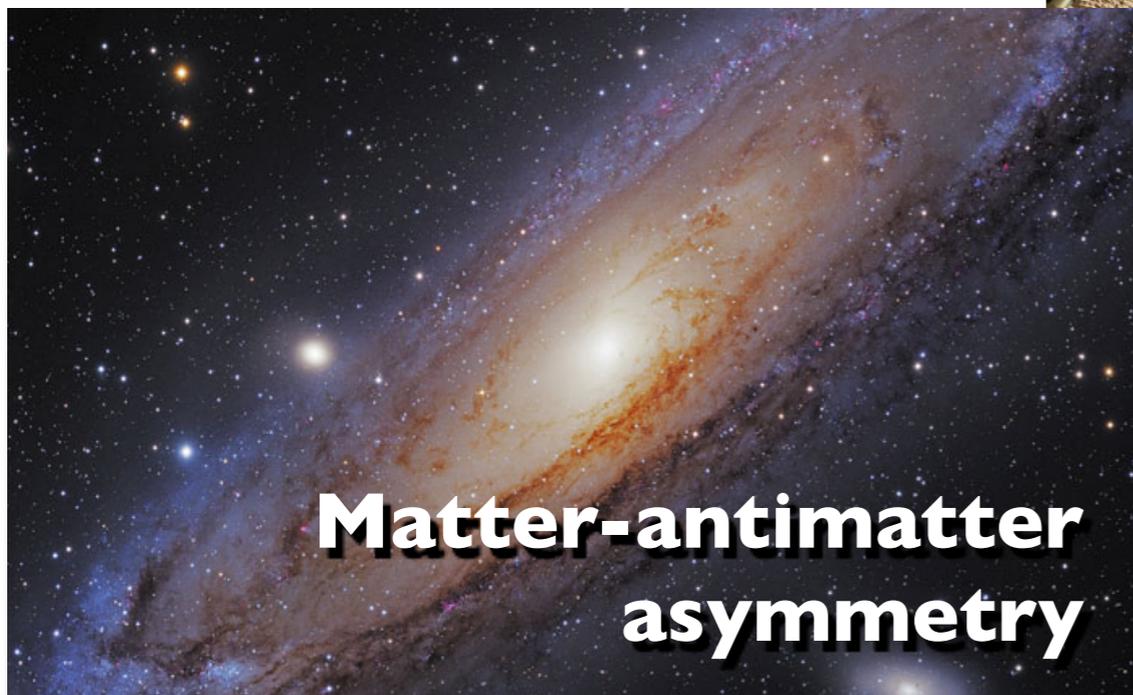
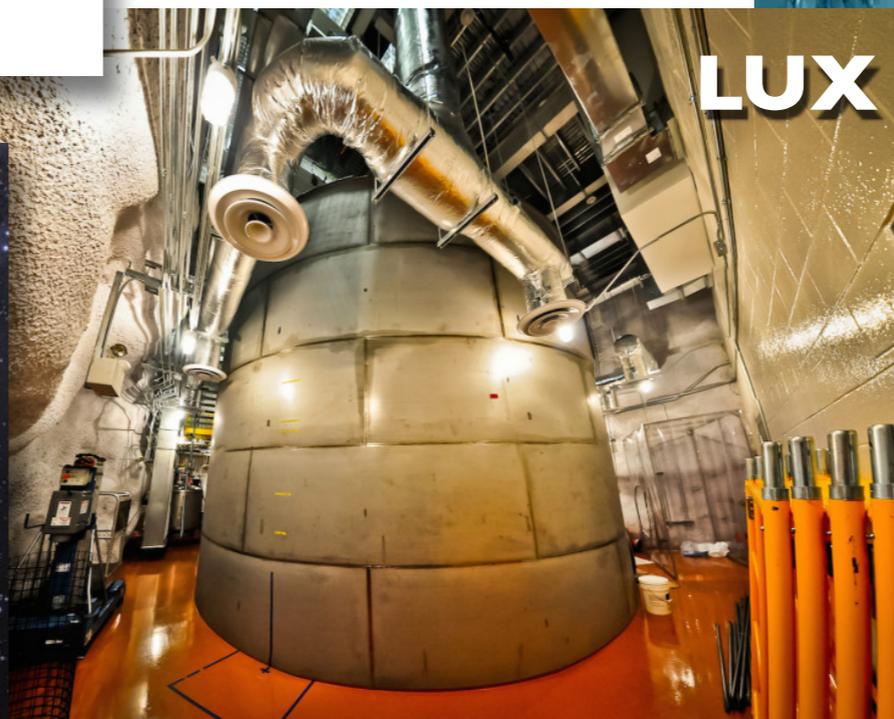
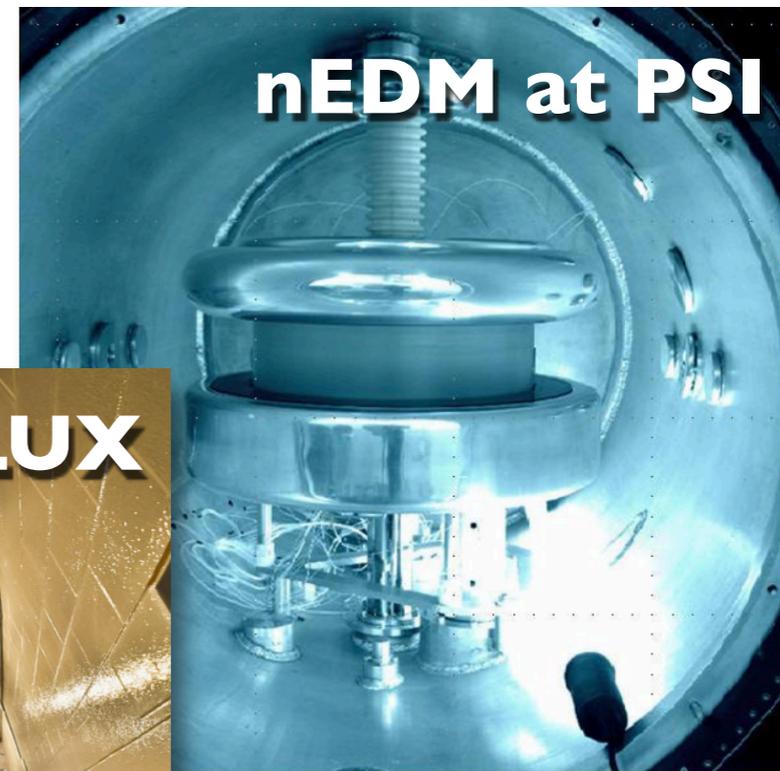
Quark Confinement 2018,
Maynooth, Ireland
August 6, 2018



The Standard Model and Beyond

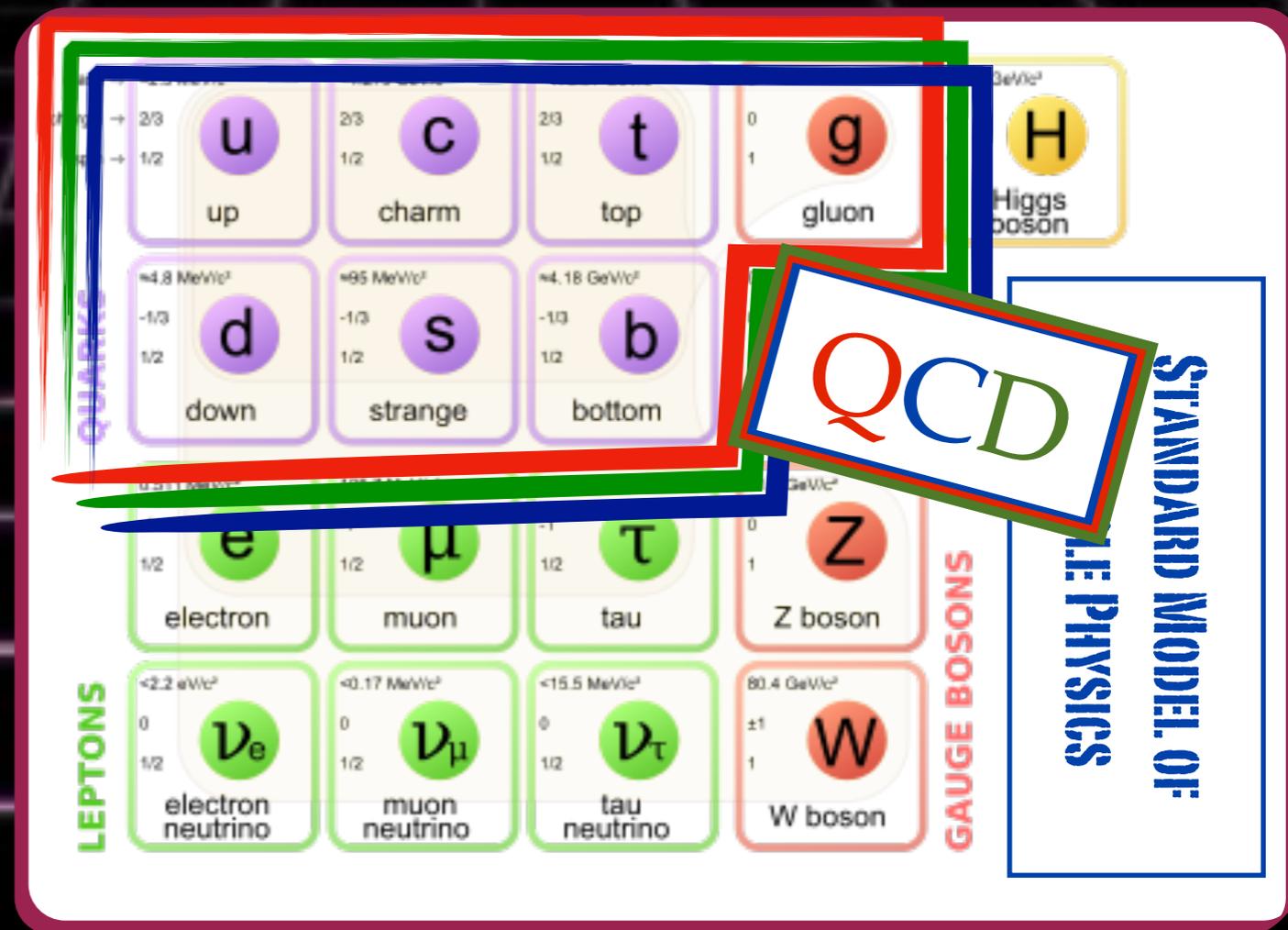


The Standard Model and Beyond



Lattice QCD

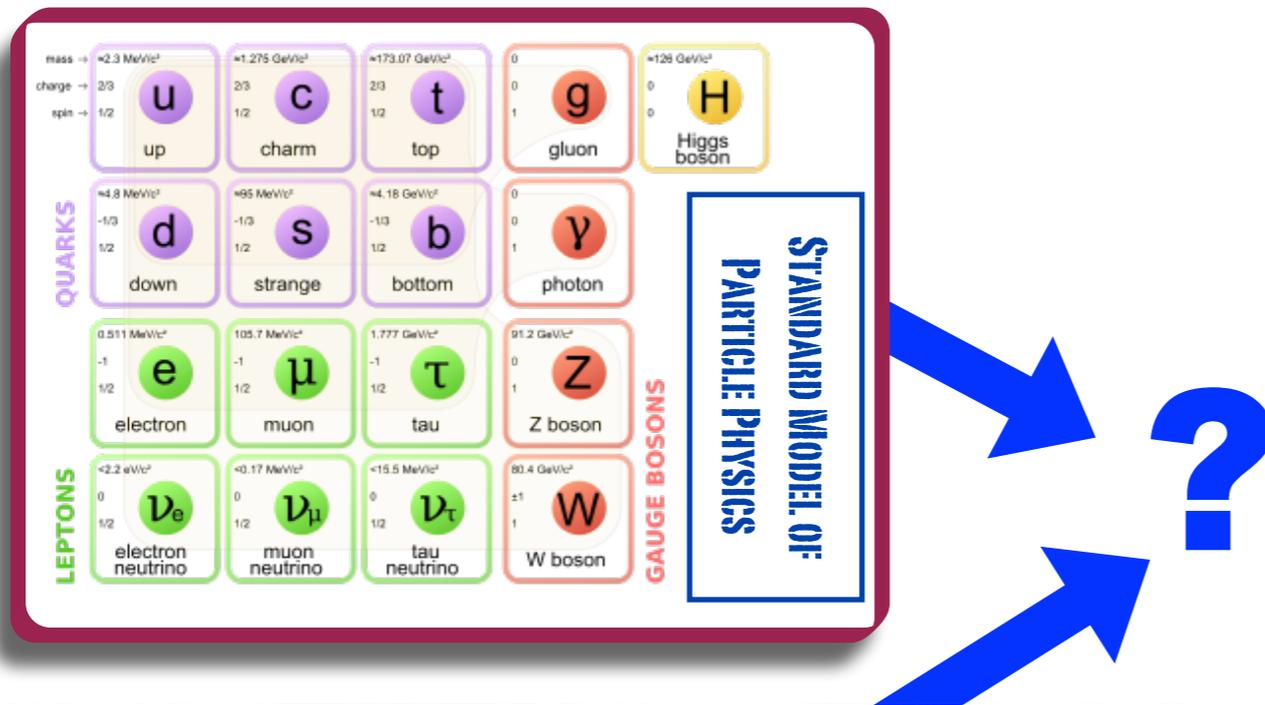
- Numerical solution to QCD:
 - Non-perturbative formulation of QCD in discretized, finite spacetime
 - Currently our only reliable technique for solving QCD at low energies
- All uncertainties are quantifiable and may be systematically removed
 - Extrapolations to continuum, infinite volume, physical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



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

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

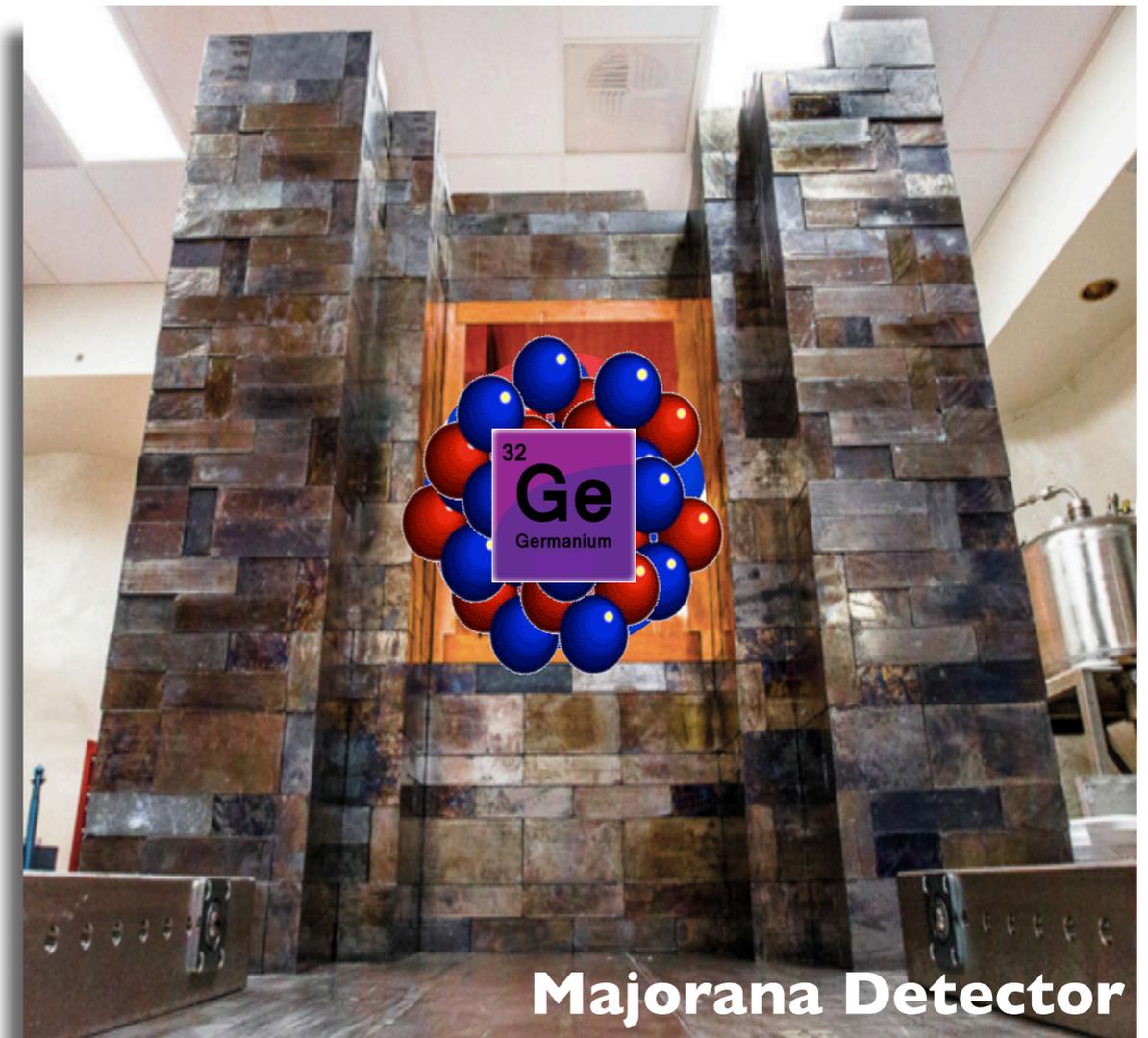
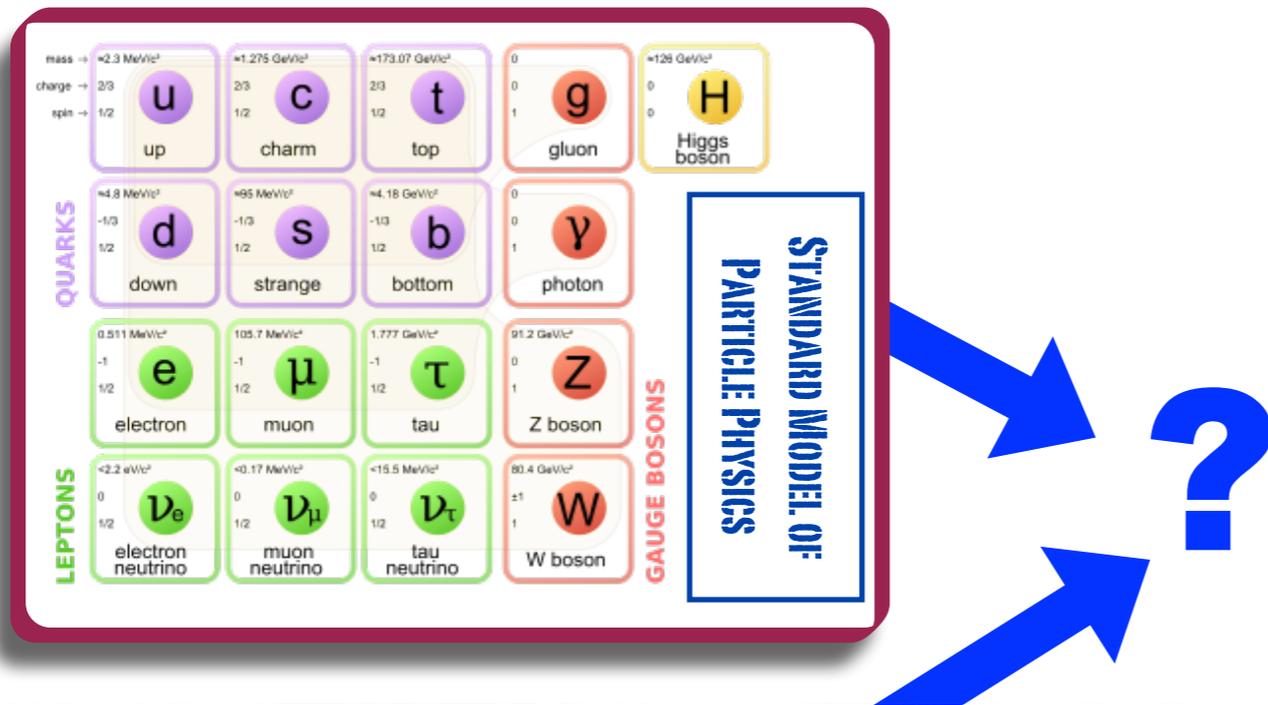
I. Look for discrepancies between the SM and experiment: neutron lifetime, proton radius, muon $g-2$

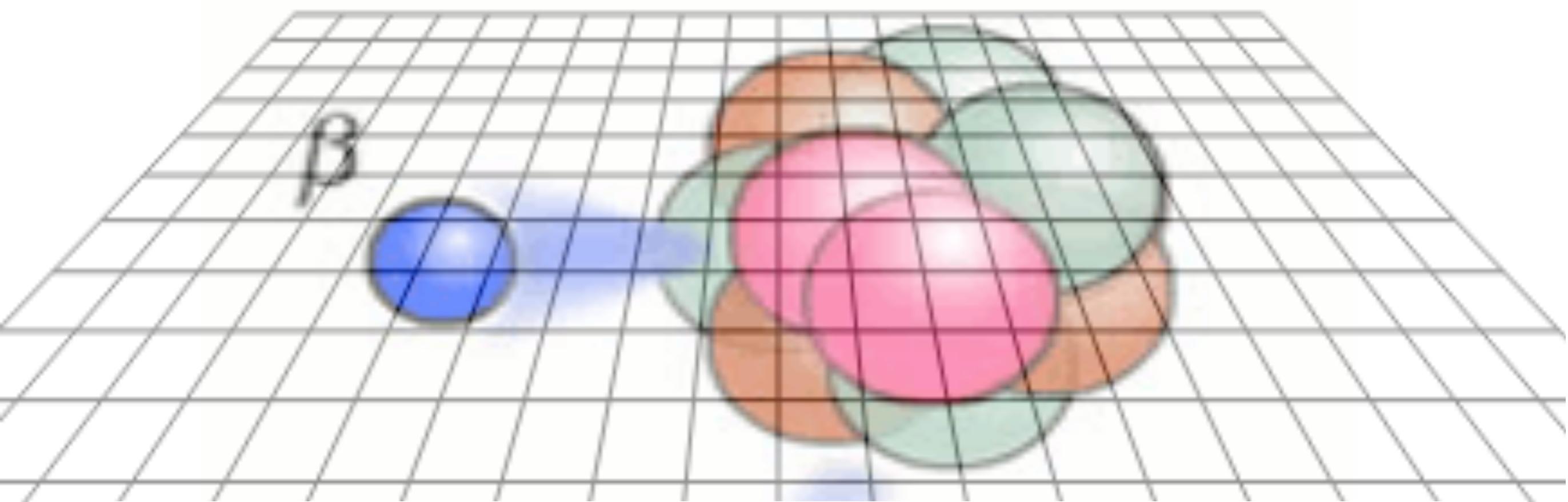


How can a solution of QCD teach us about new physics?

1. Look for discrepancies between the SM and experiment: neutron lifetime, proton radius, muon $g-2$

2. Match new physics model at high energies to low-energy, nuclear experiments: $0\nu\beta\beta$, nucleon/nuclear EDM, DM searches





Neutrinoless double beta decay



Neutrinos: Majorana or Dirac?

Neutrinos: Majorana or Dirac?

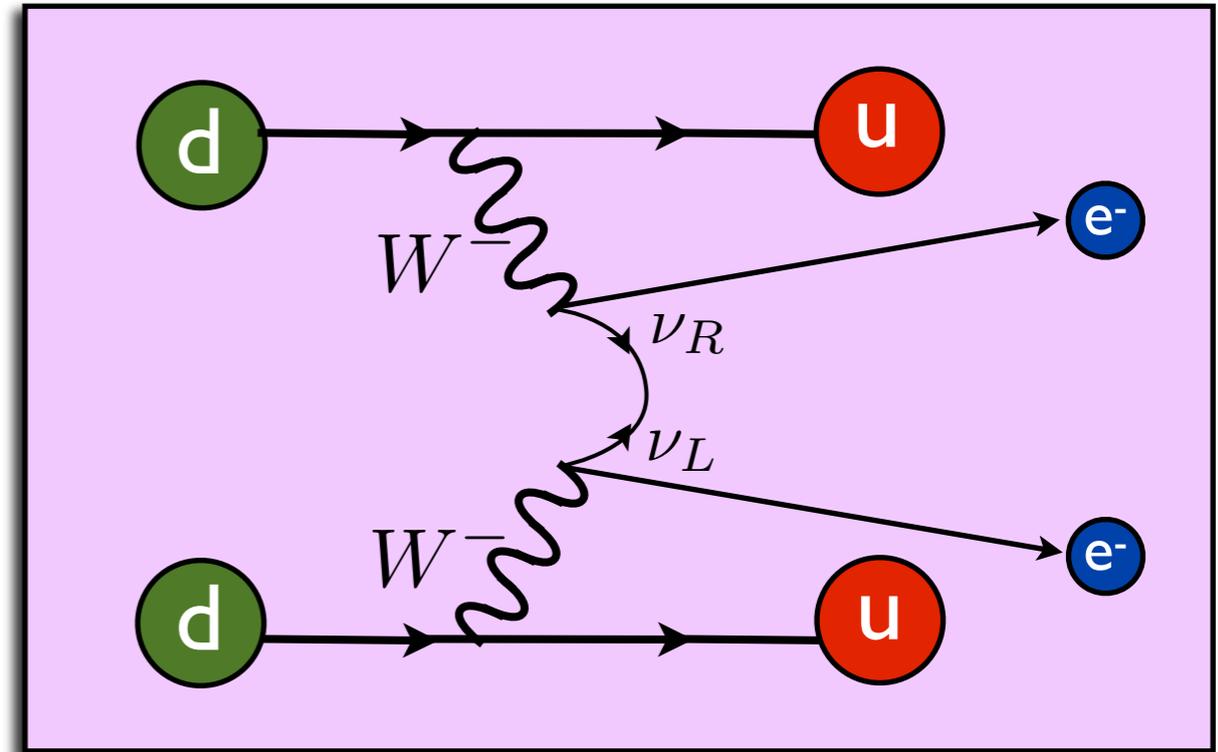
- Majorana: $\nu = \bar{\nu}$

Neutrinos: Majorana or Dirac?

- Majorana: $\nu = \bar{\nu}$
 - Dim-5 mass term leads to naturally light neutrinos (Seesaw mechanism)

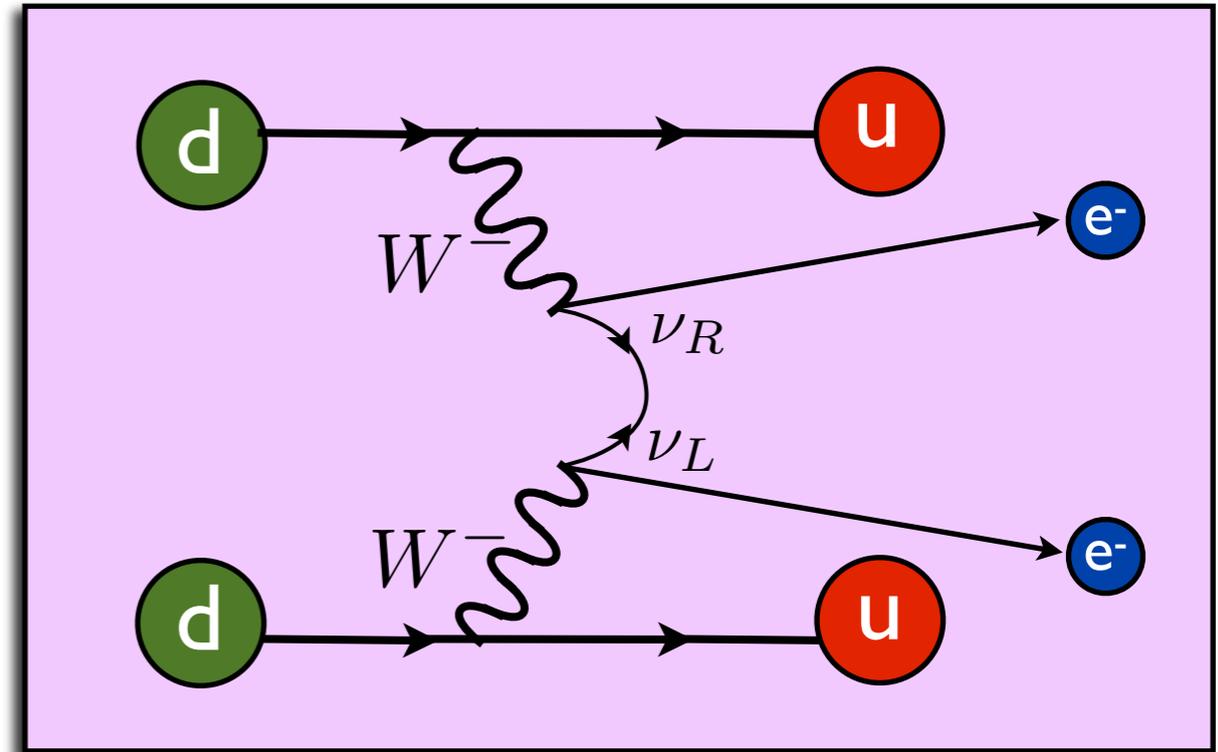
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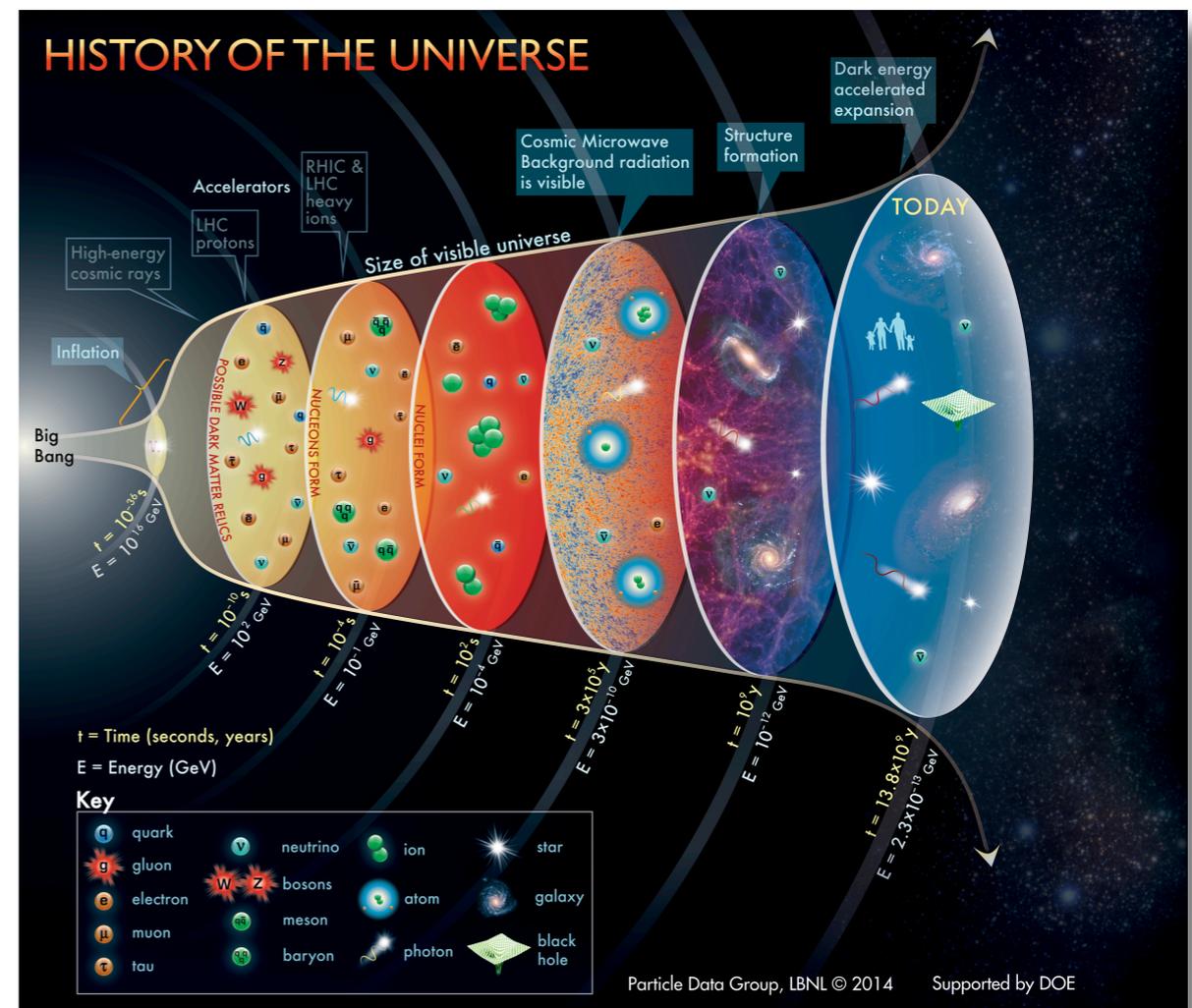
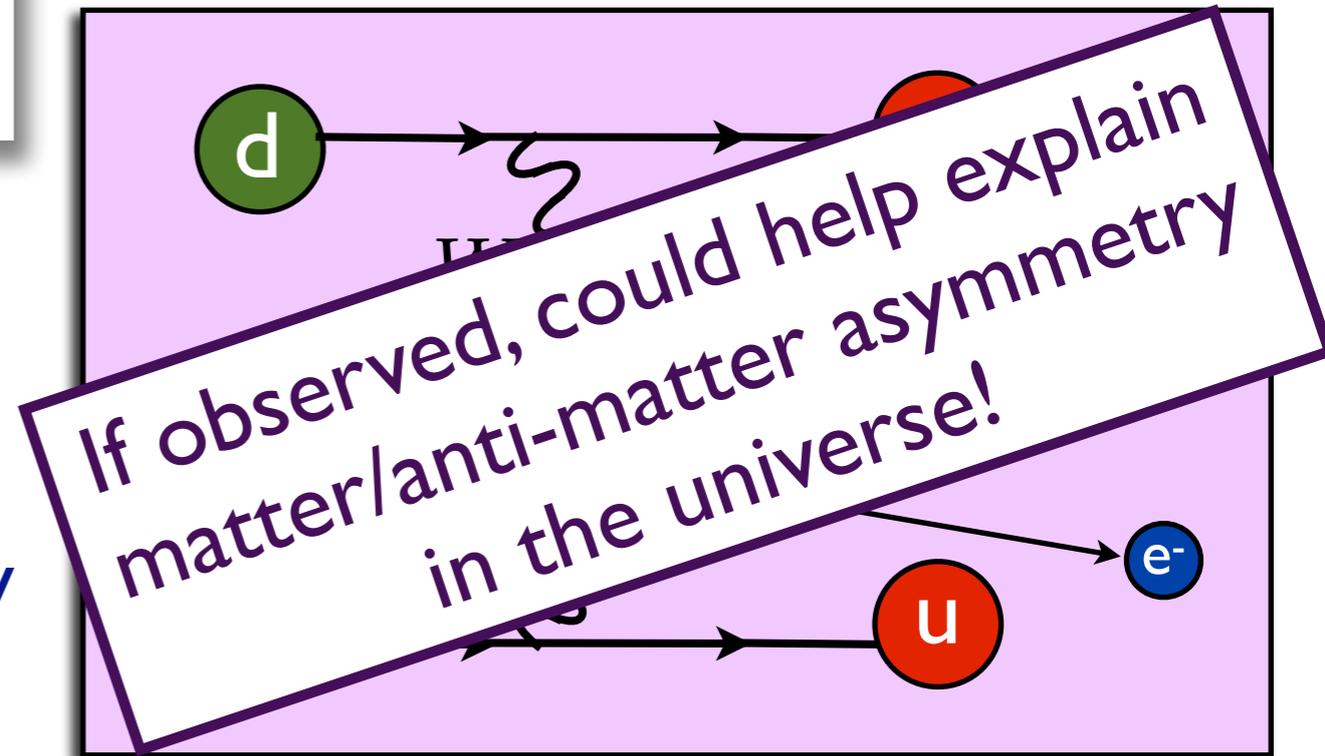
Neutrinos: Majorana or Dirac?

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 - Lepton number violating process



Neutrinos: Majorana or Dirac?

- Majorana: $\nu = \bar{\nu}$
 - Dim-5 mass term leads to naturally light neutrinos (Seesaw mechanism)
- 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





Cuore
 ^{130}Te

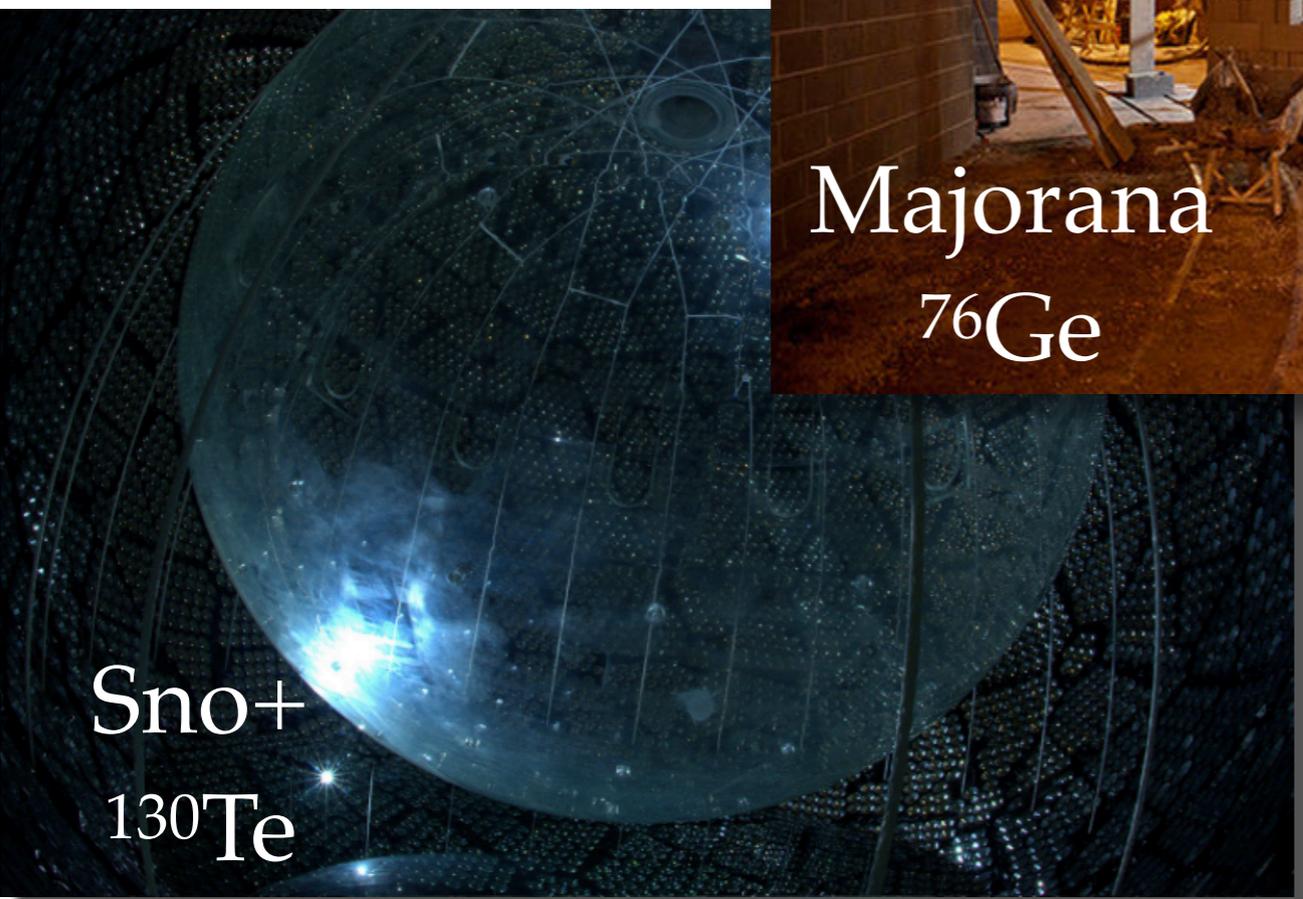


Gerda
 ^{76}Ge

Experiment



Majorana
 ^{76}Ge

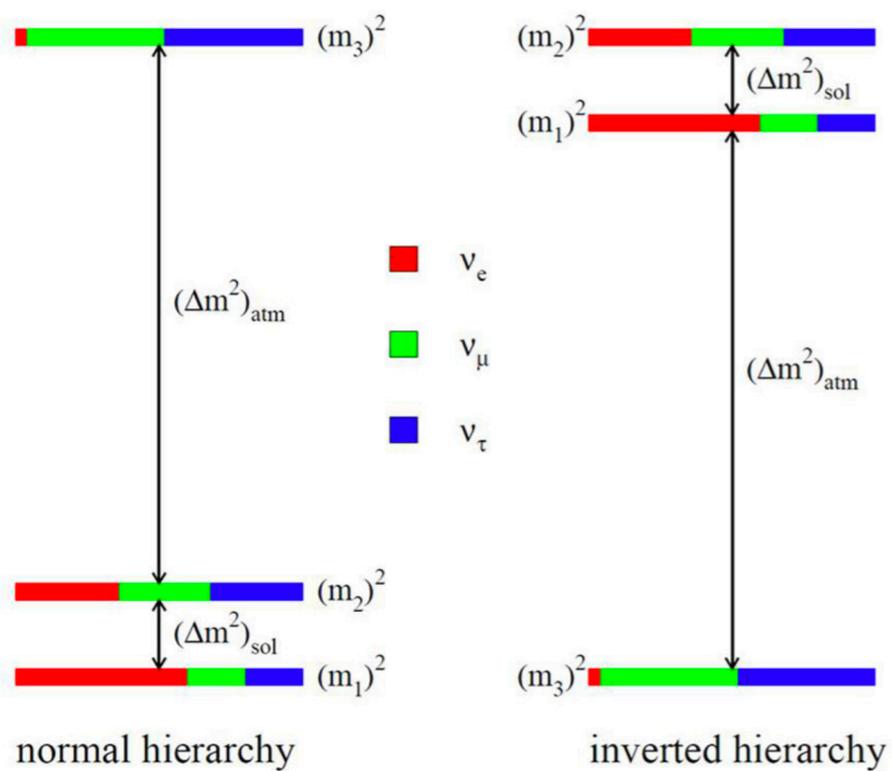
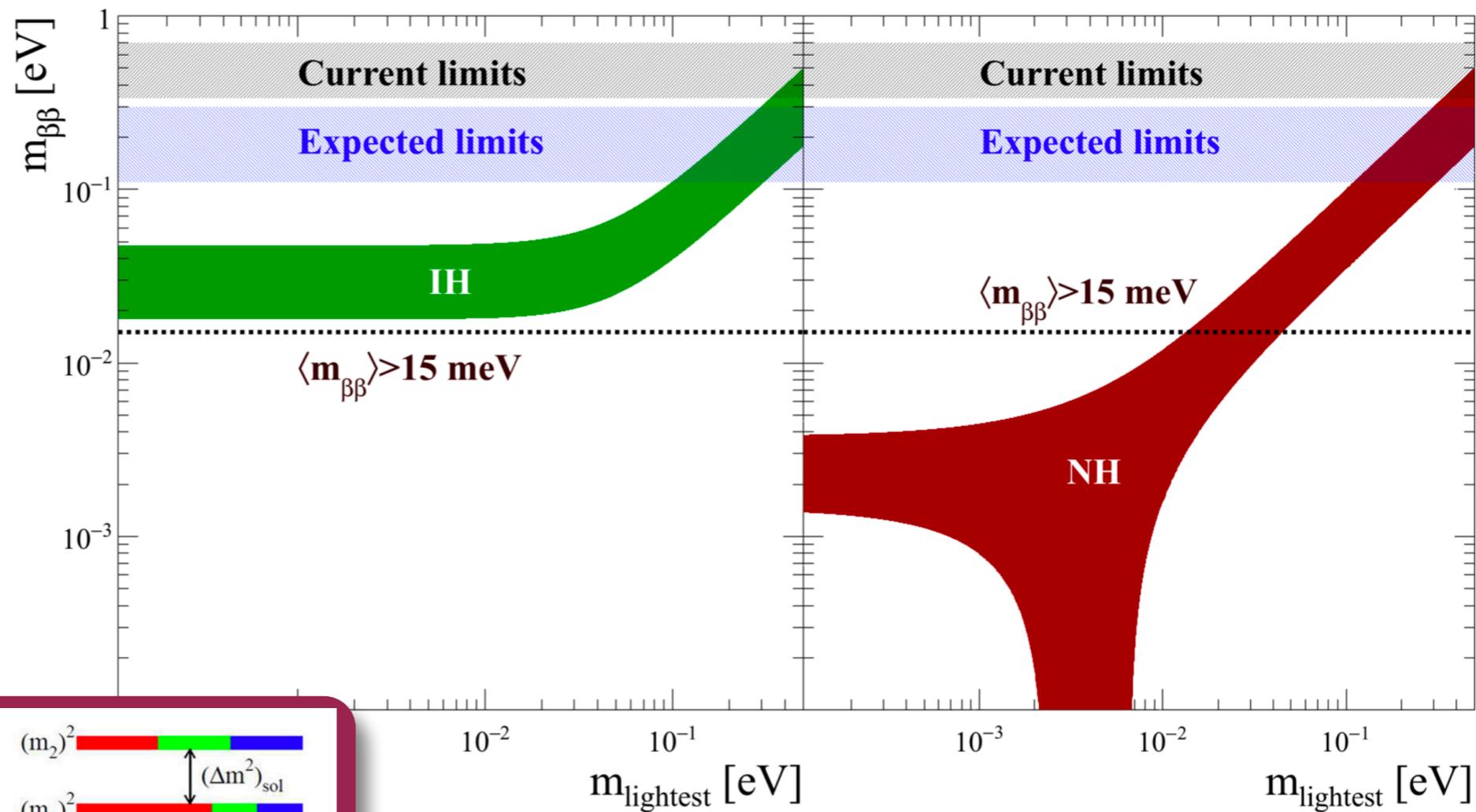


Sno+
 ^{130}Te

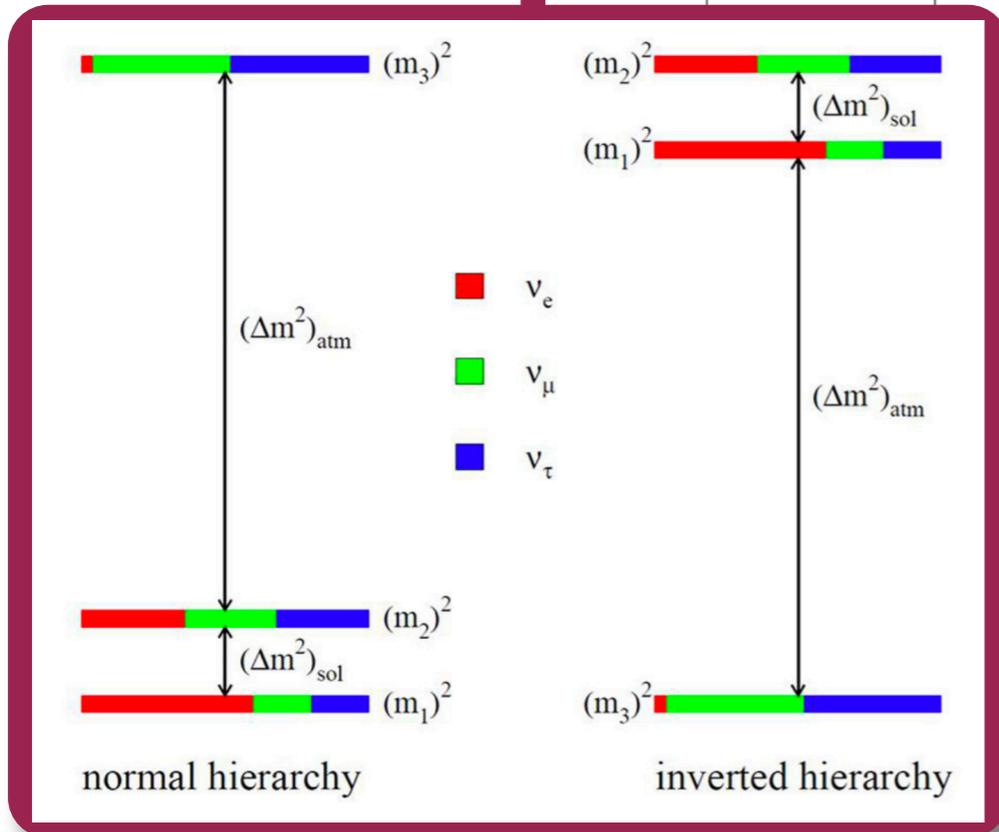
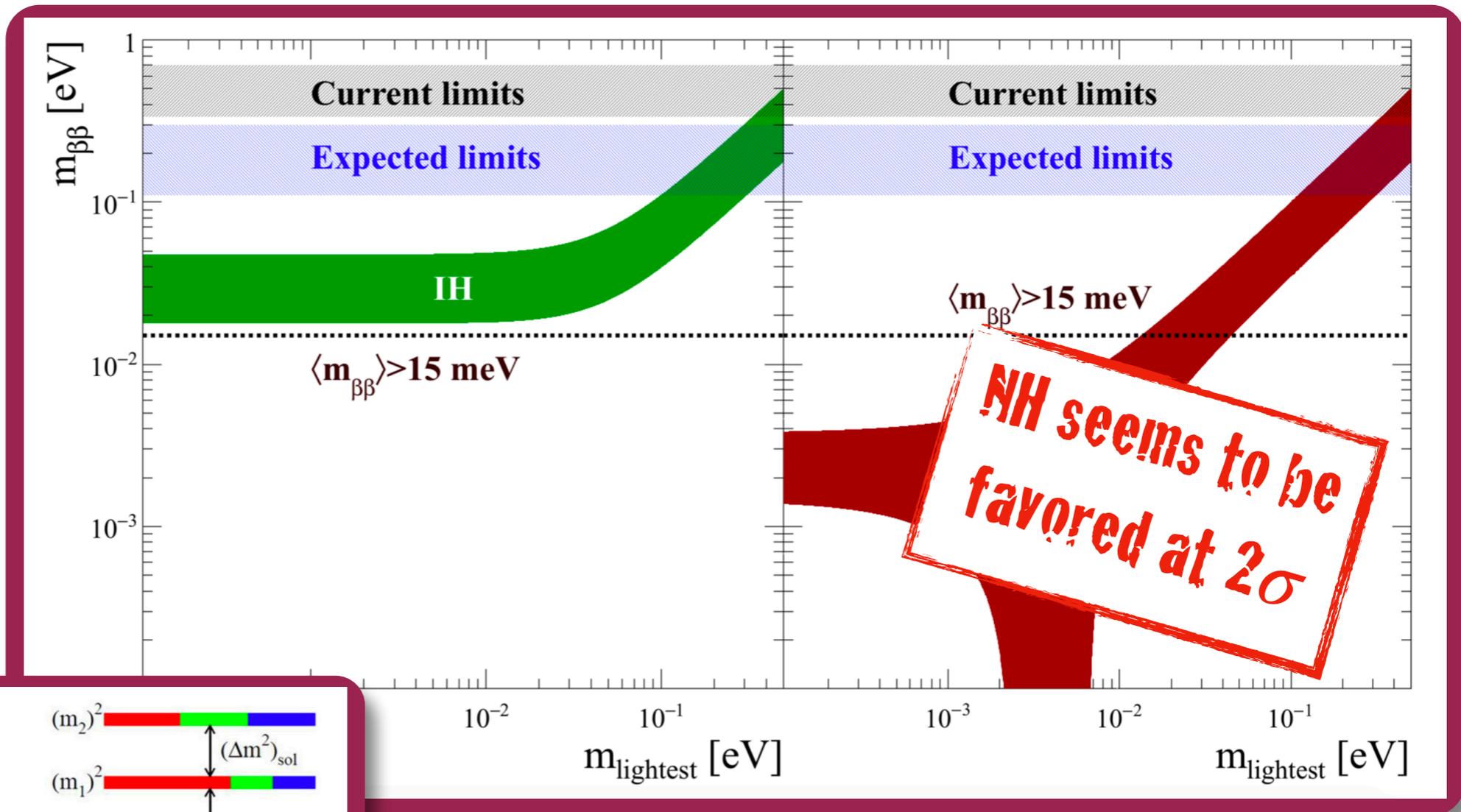


nEXO
 ^{136}Xe

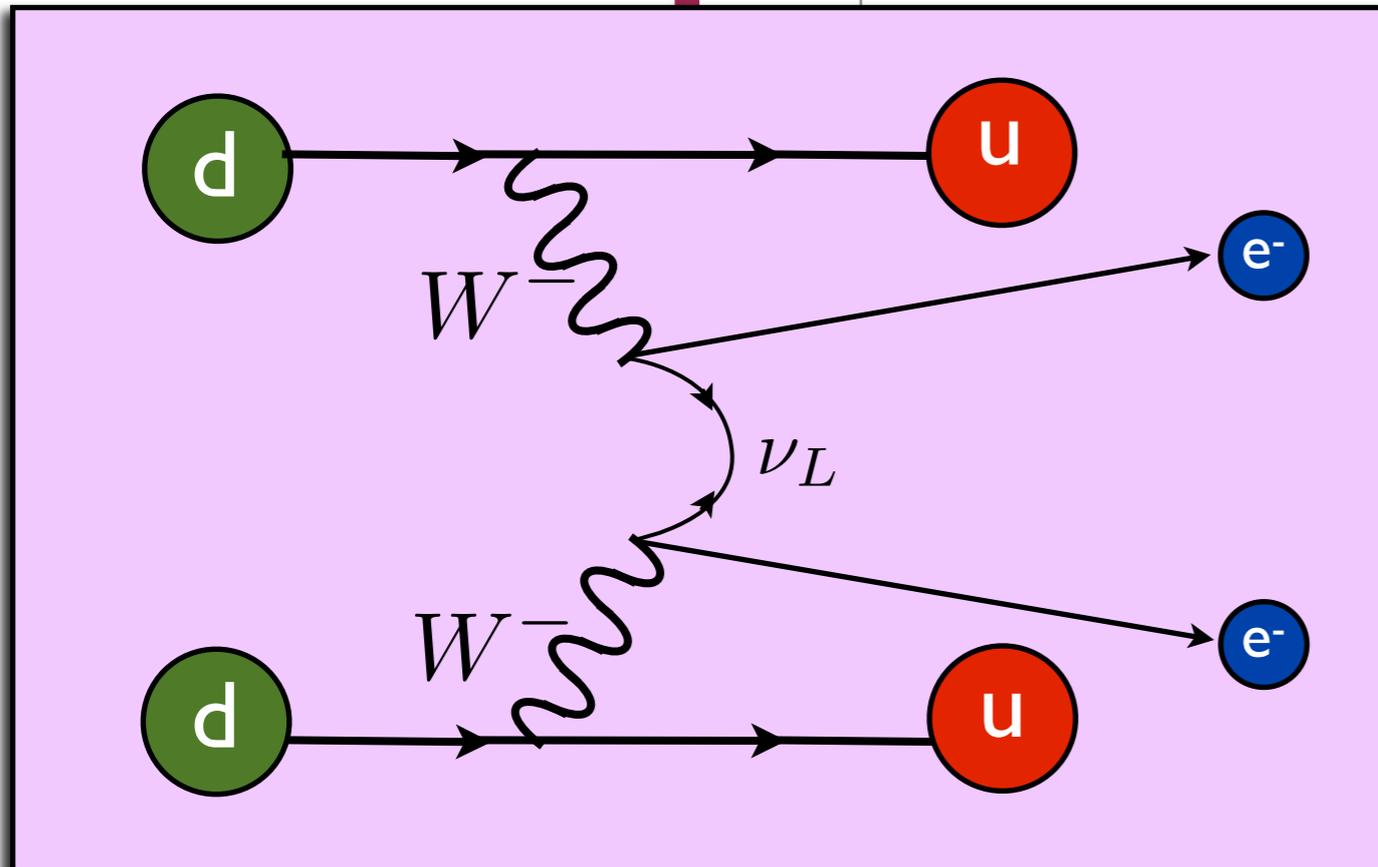
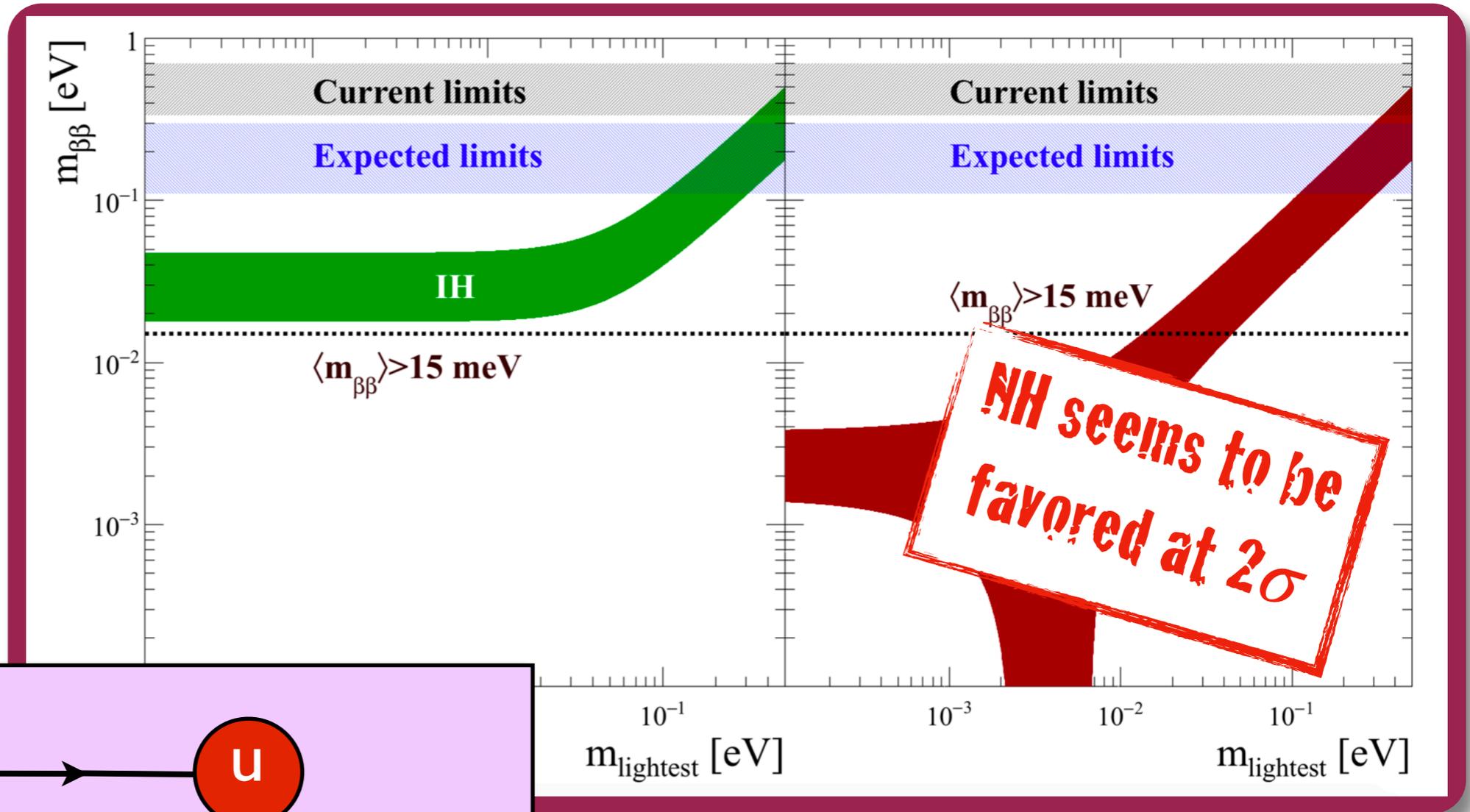
From NSAC Long Range Plan 2015



From NSAC
Long Range
Plan 2015

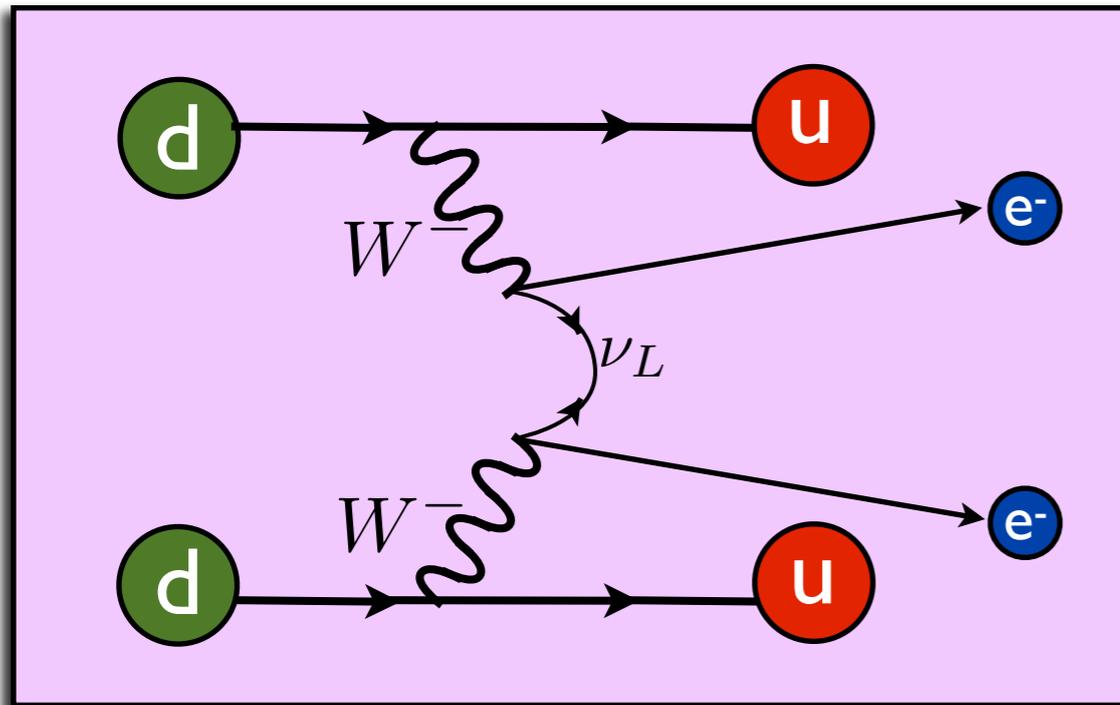


From NSAC
Long Range
Plan 2015

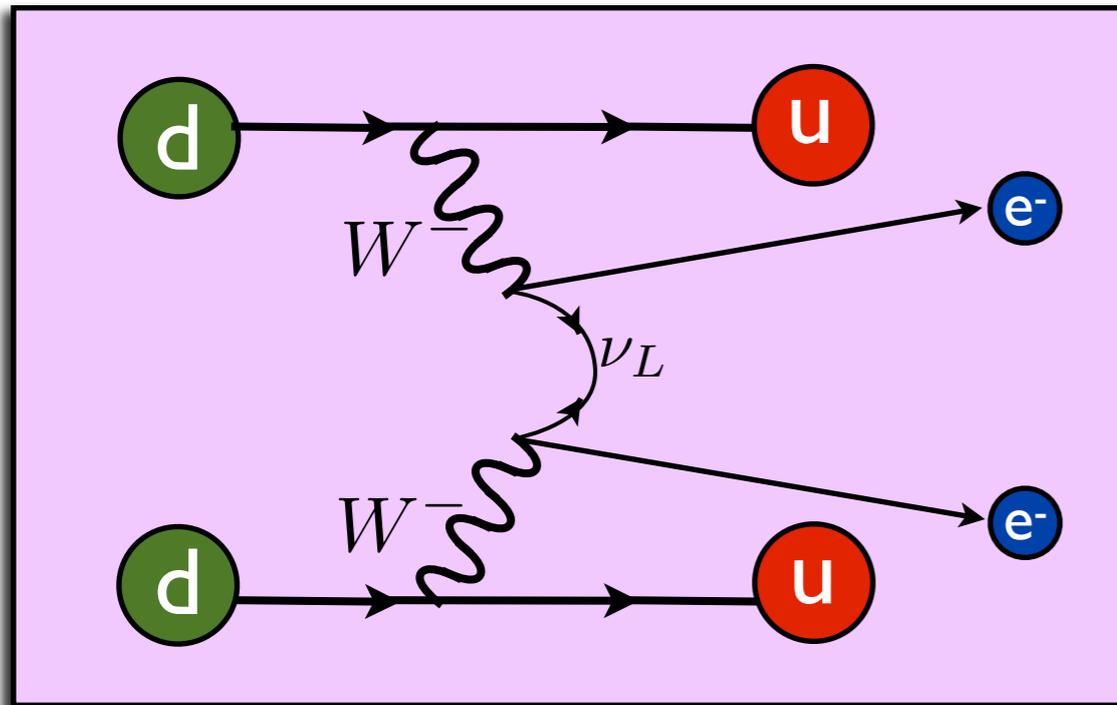


This picture assumes only long-range neutrino exchange. There's more to the story - maybe we're missing something important!

Short-range contributions



Short-range contributions



Seesaw Mechanism

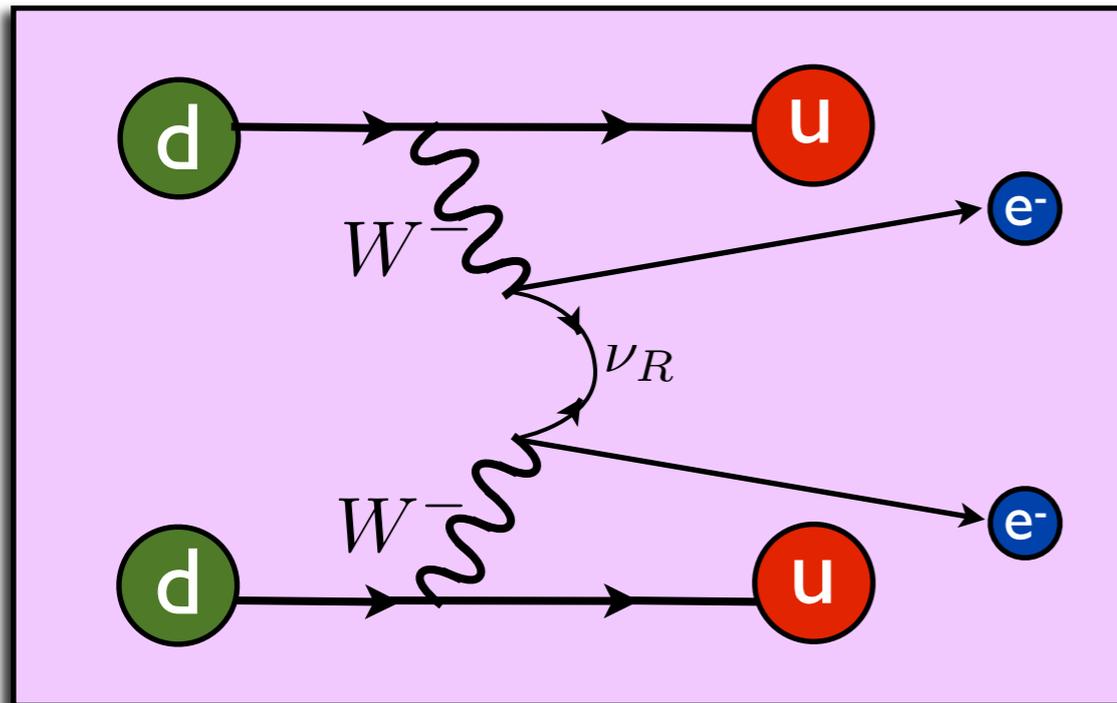
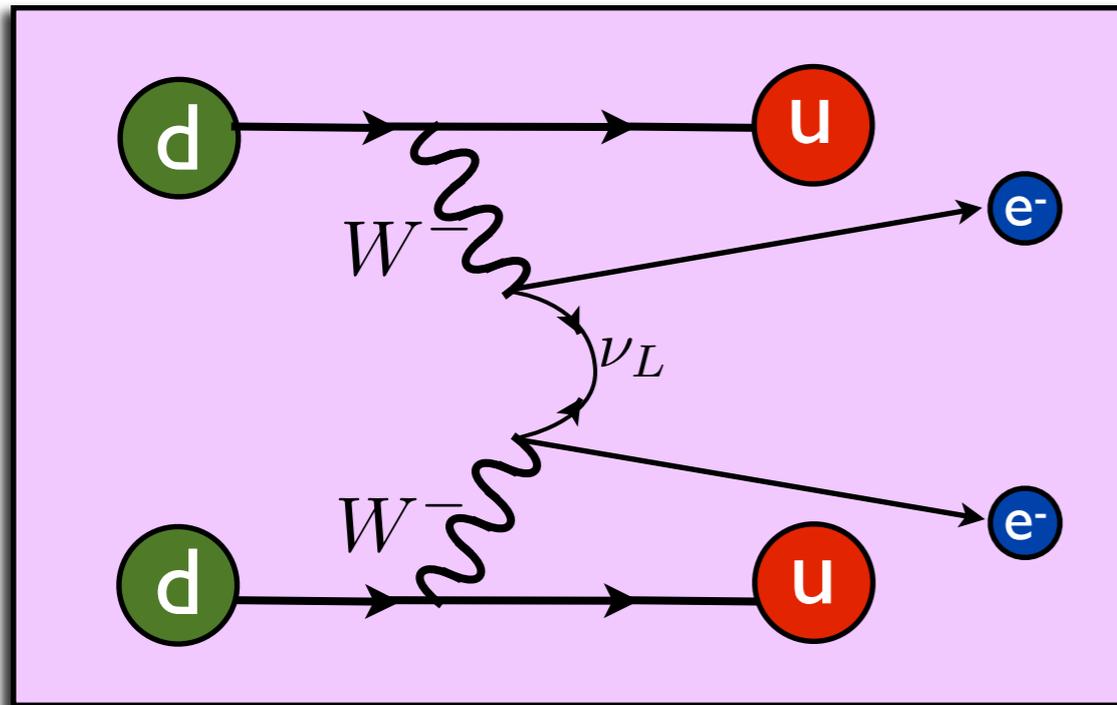


$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

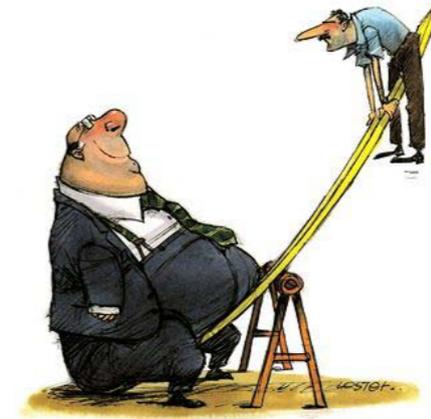
$$m_l \sim M_D^2 / M_R$$

$$m_h \sim M_R$$

Short-range contributions



Seesaw Mechanism

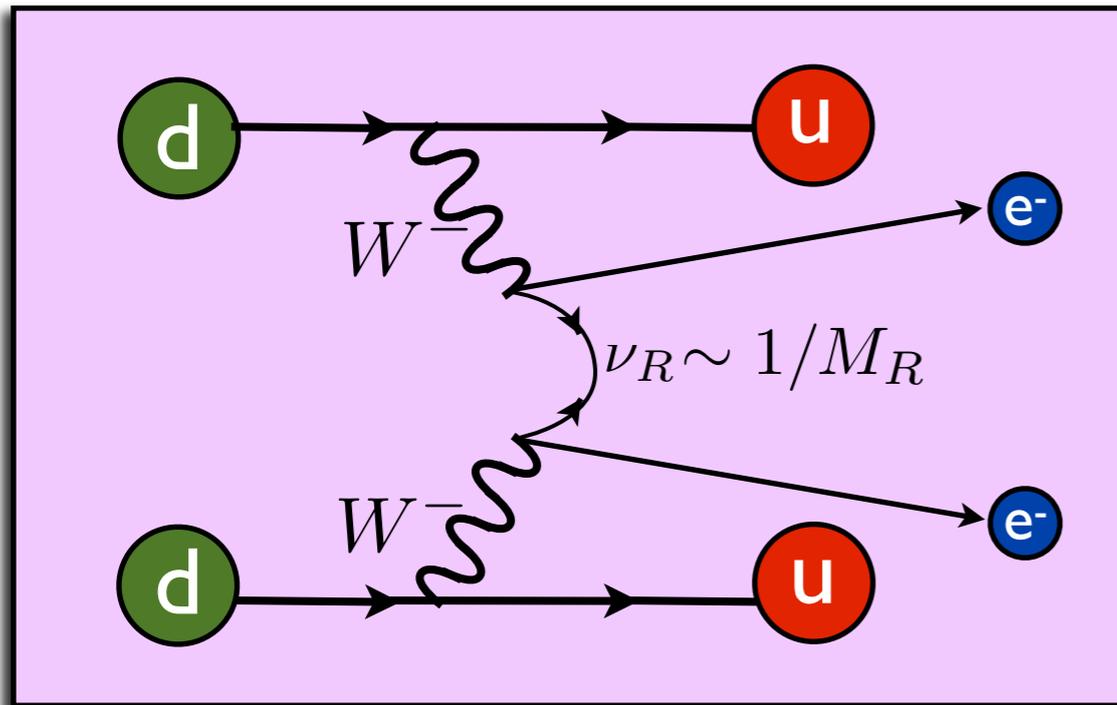
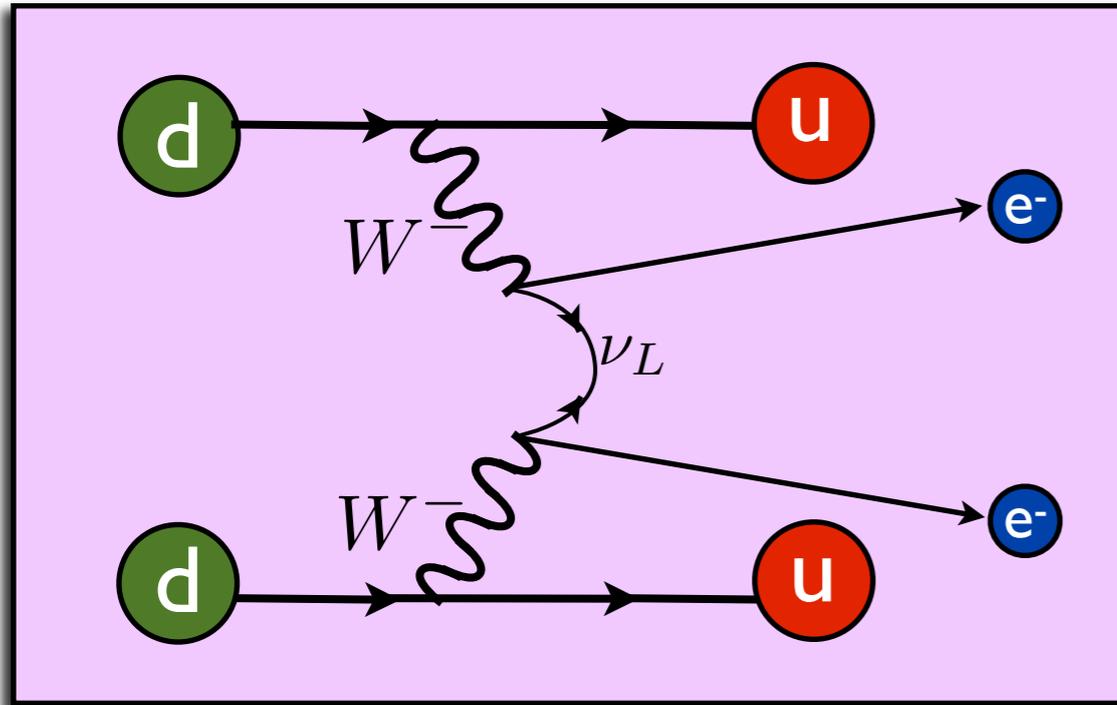


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Short-range contributions



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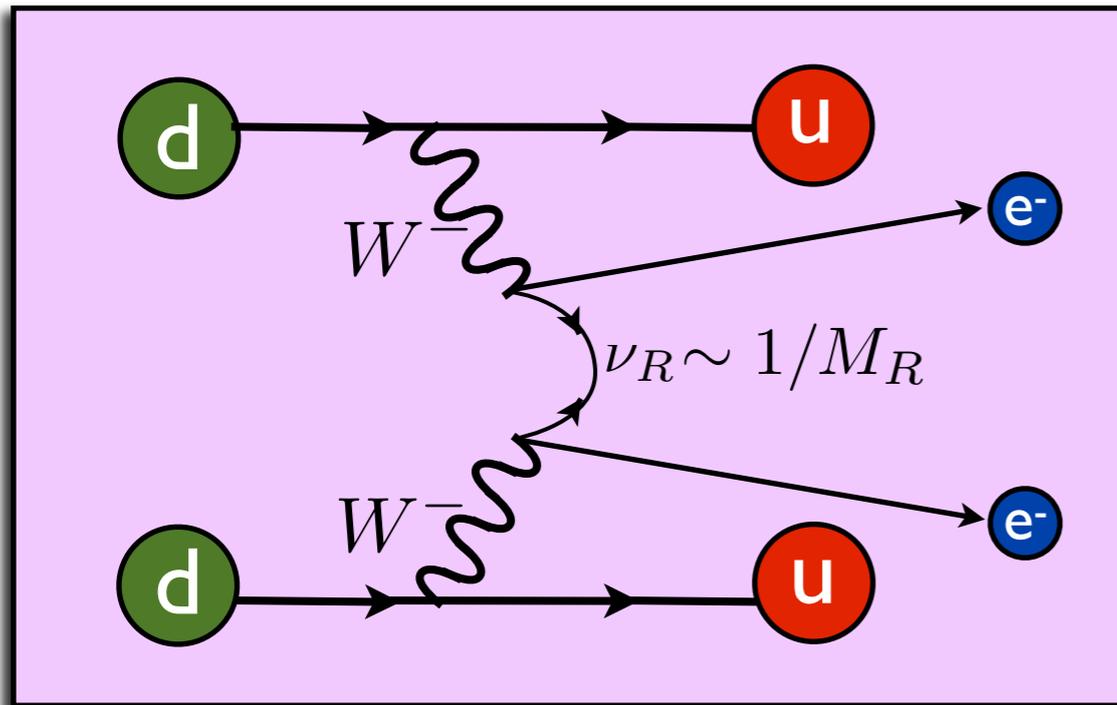
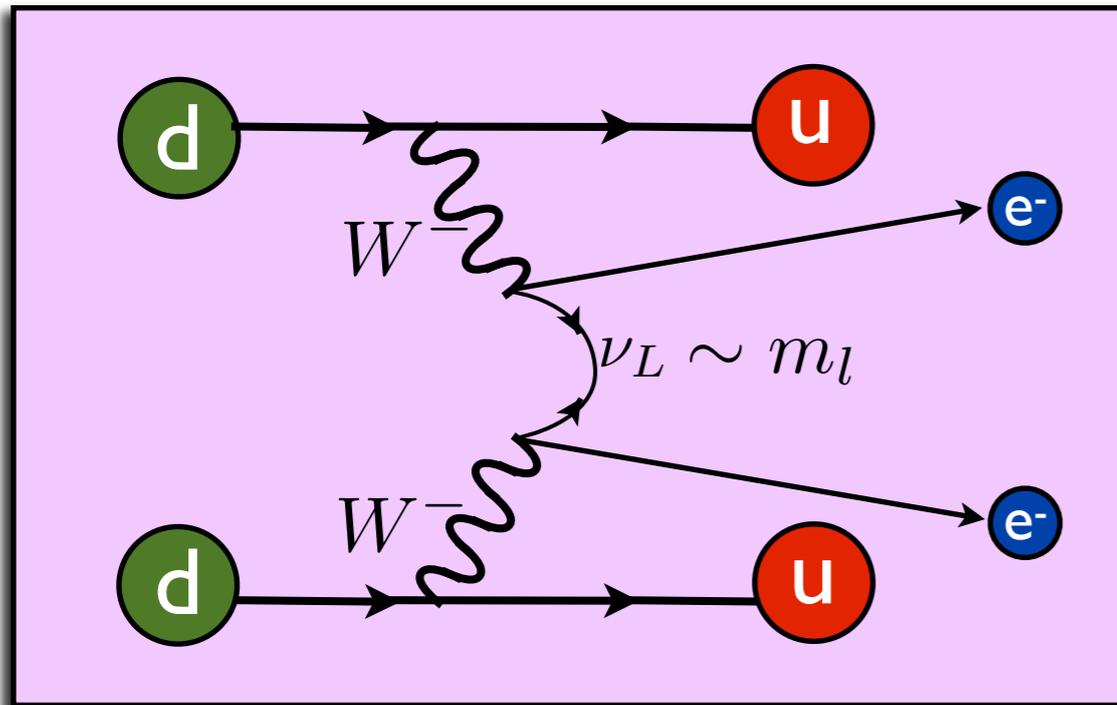


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Short-range contributions



Seesaw Mechanism

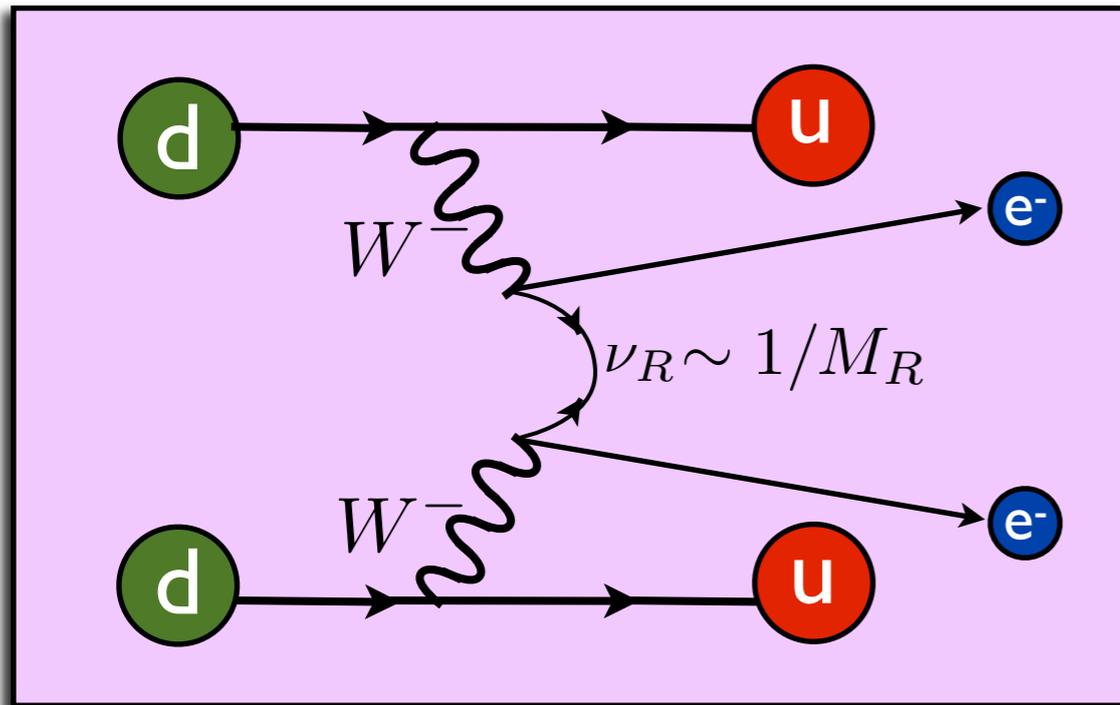
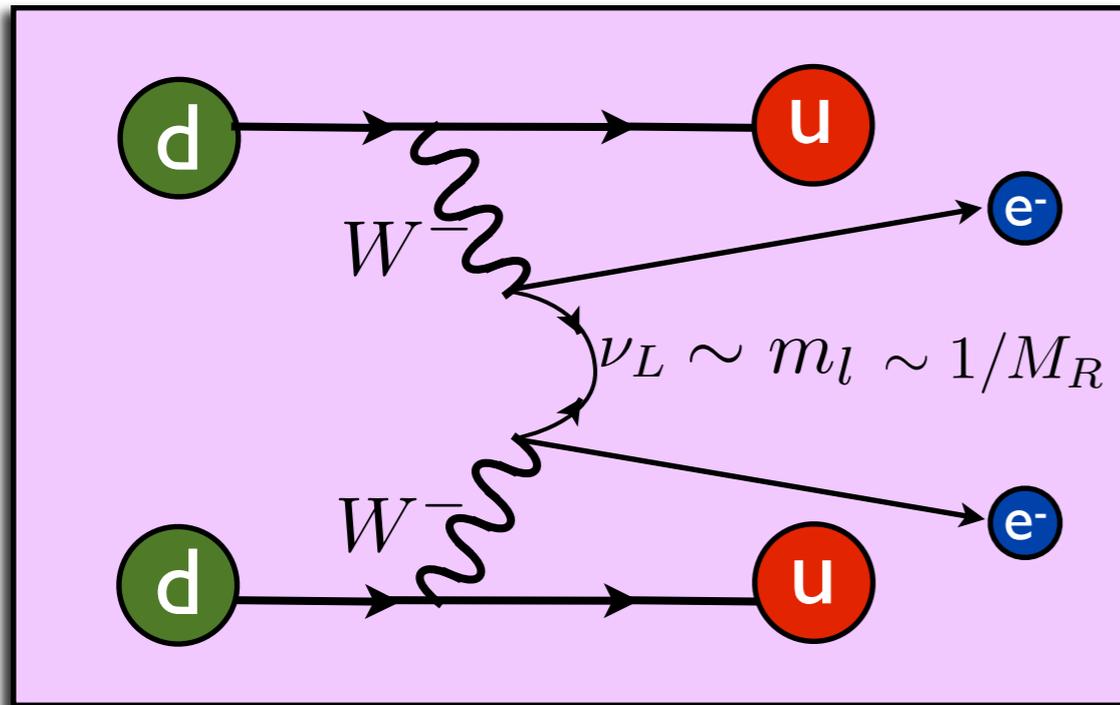


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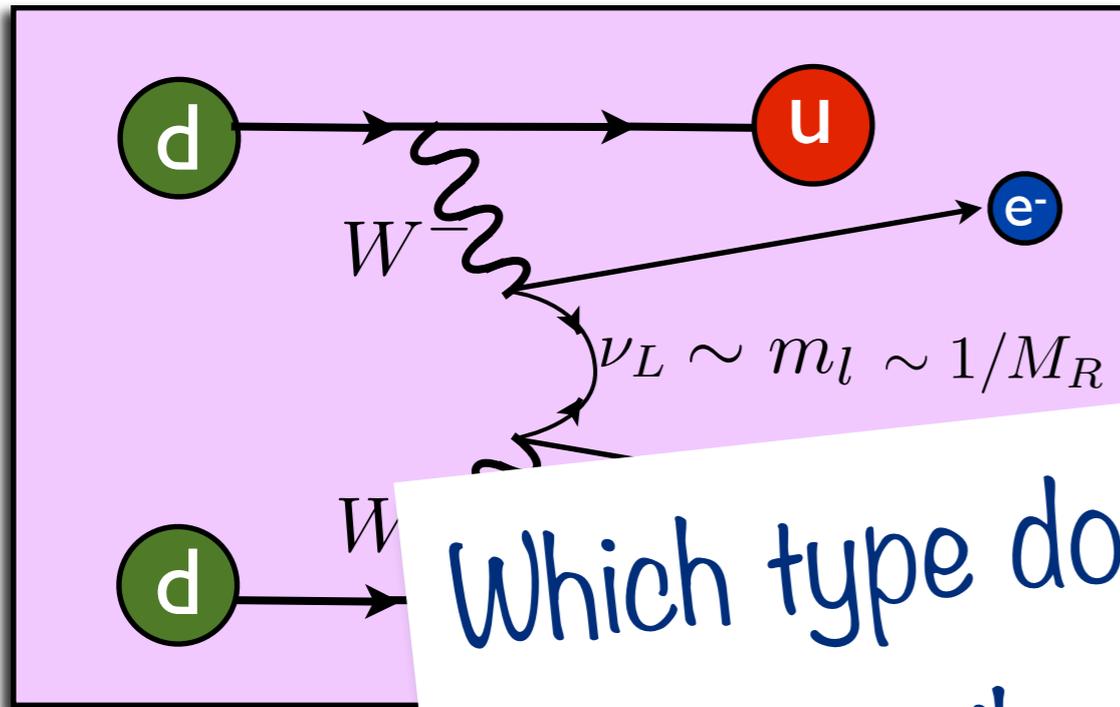


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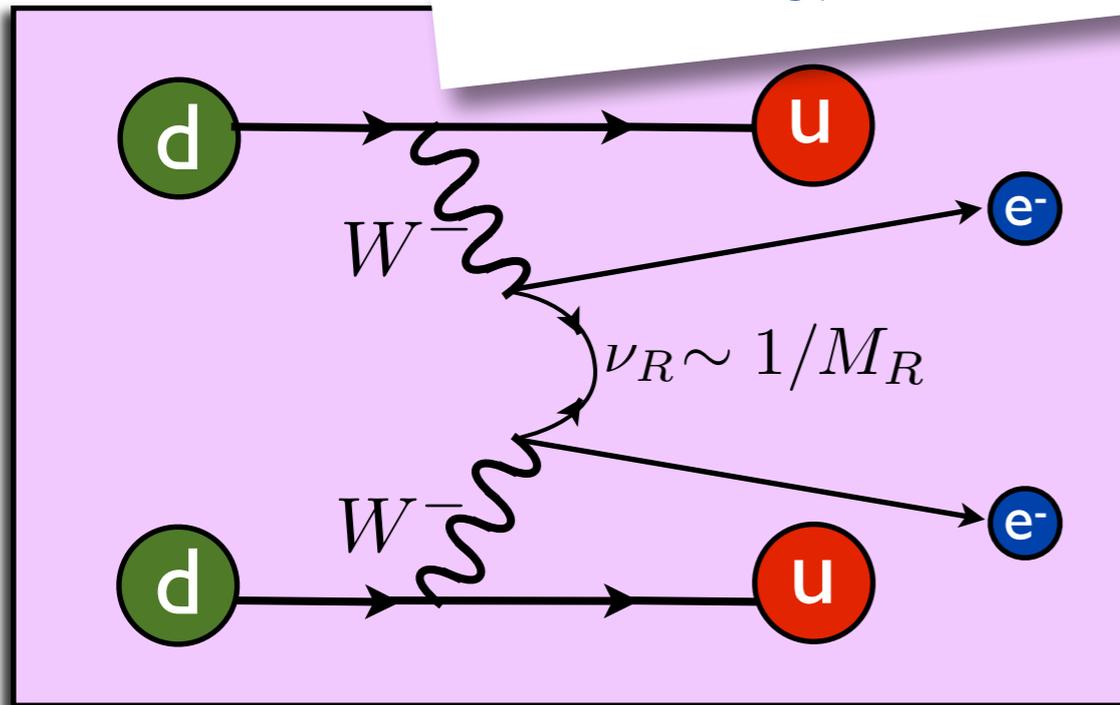
Short-range contributions



Seesaw Mechanism



Which type dominates depends on details of BSM model

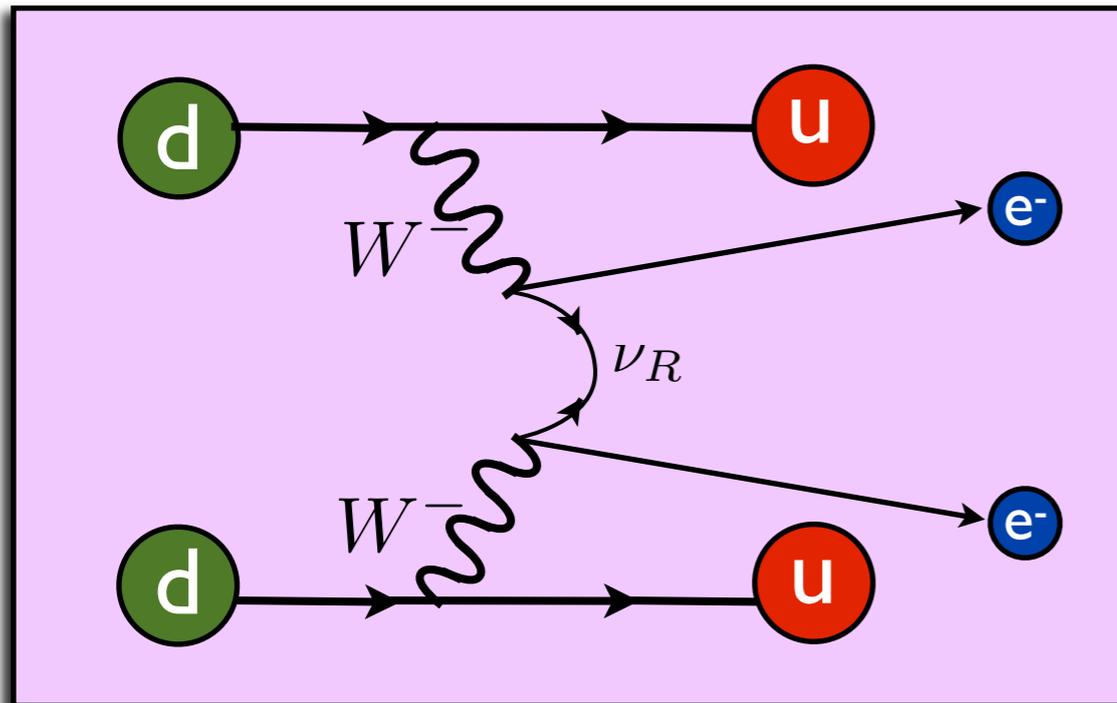


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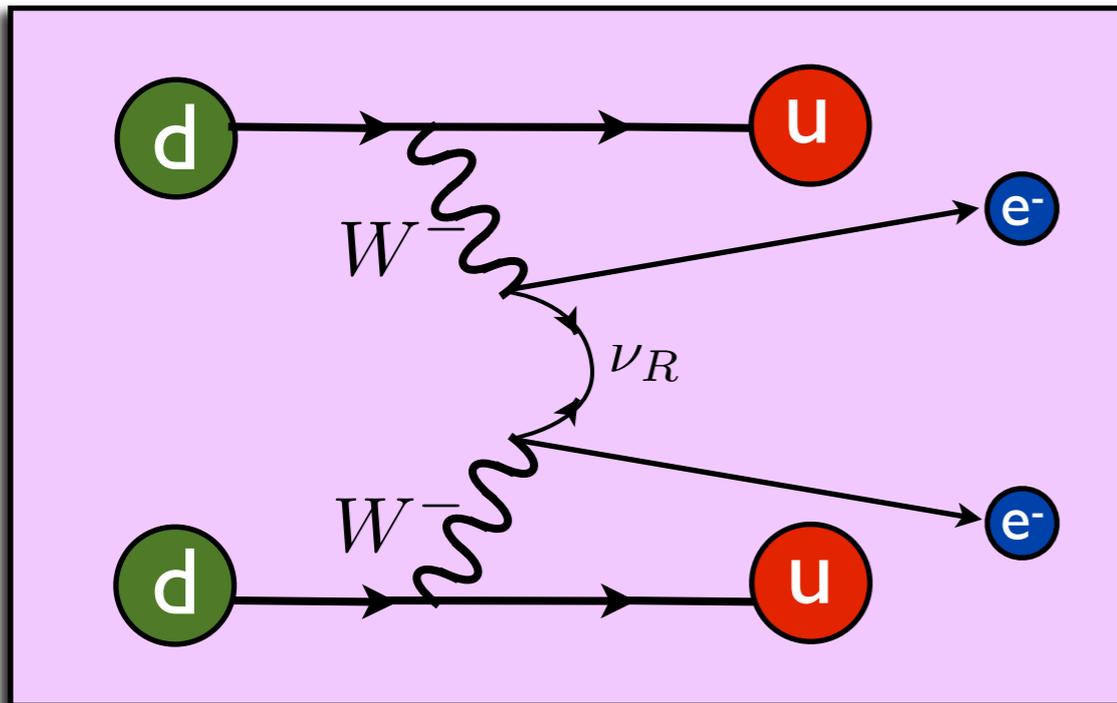
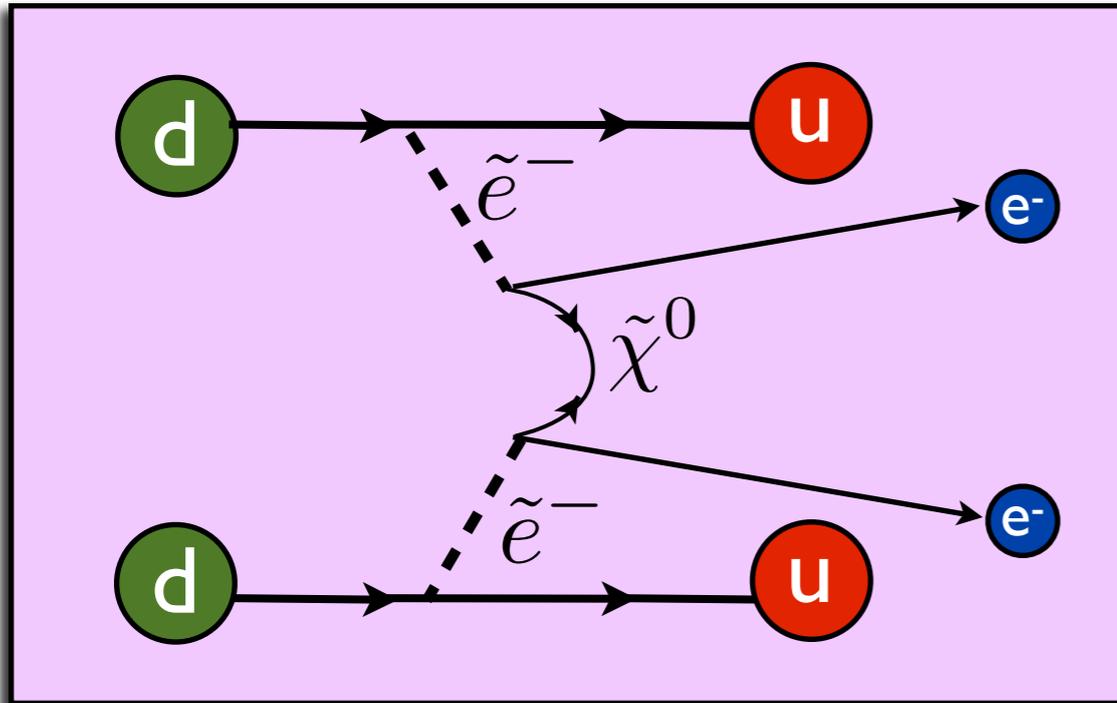
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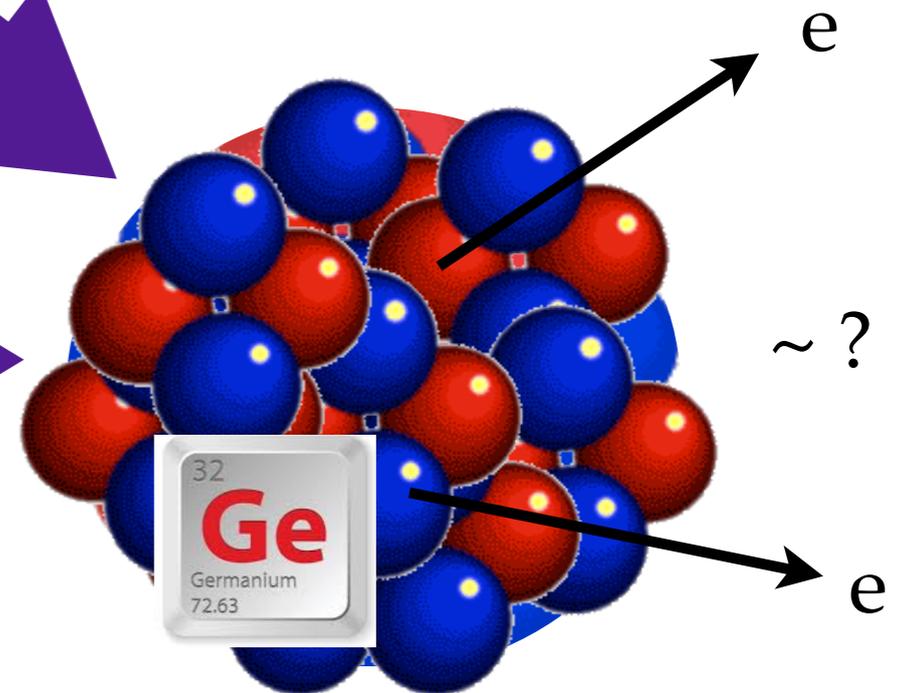
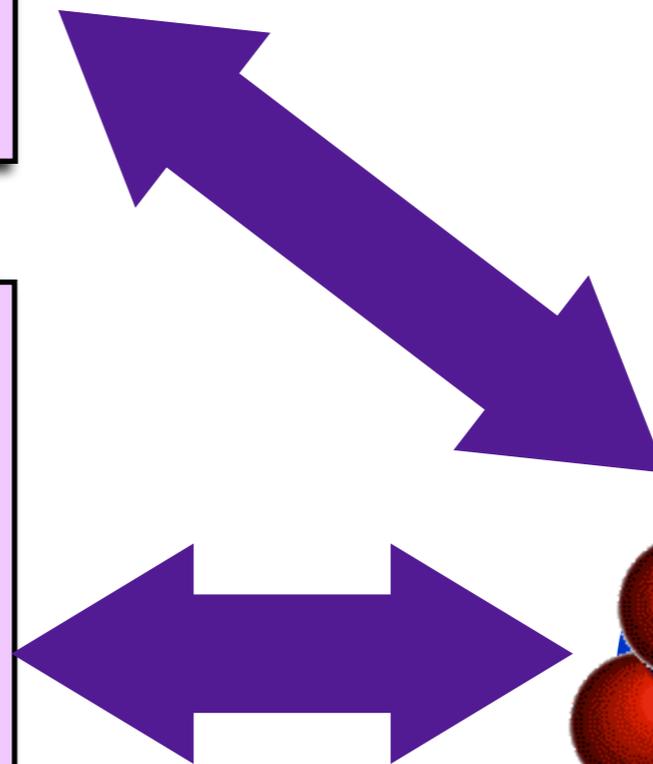
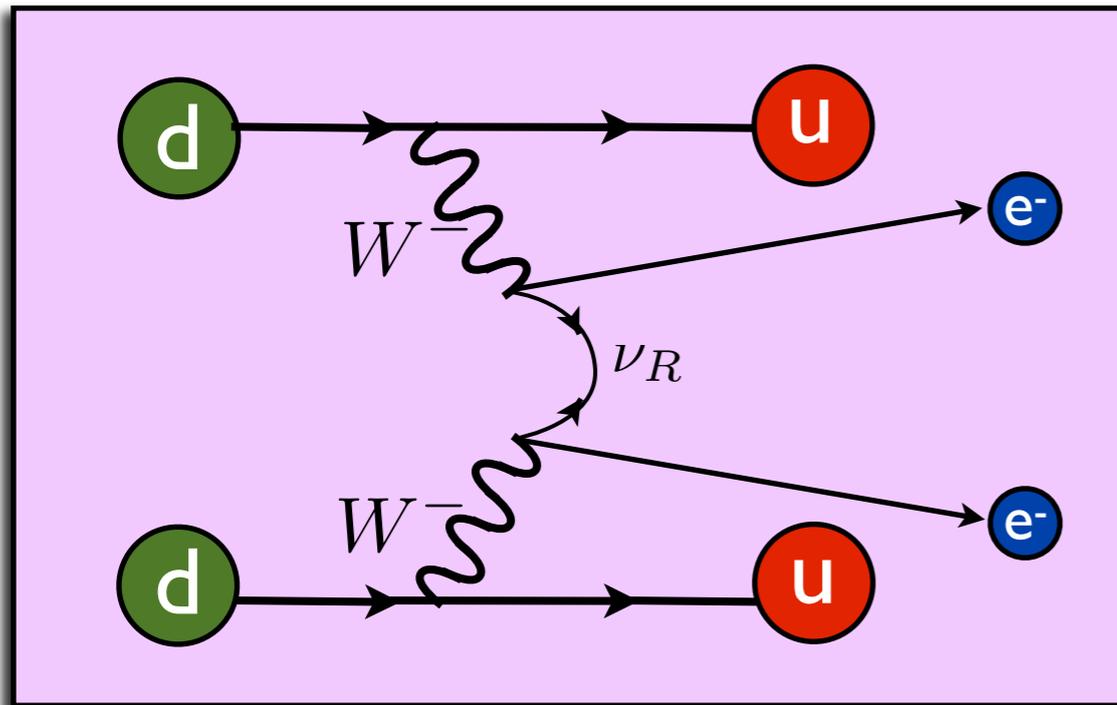
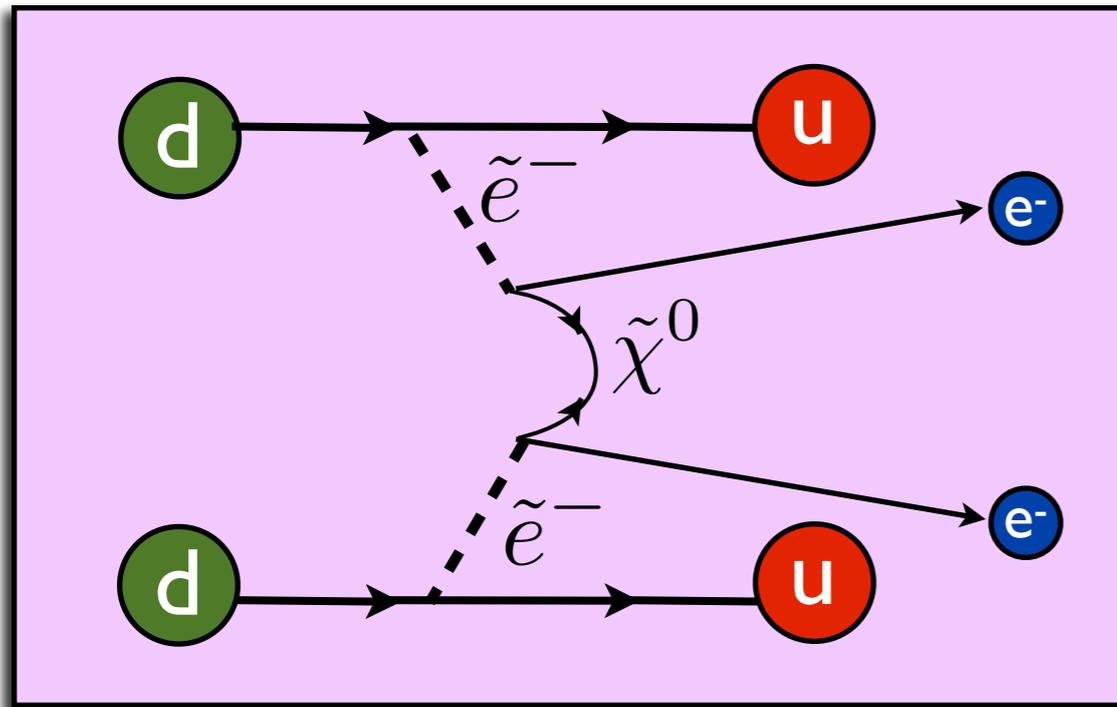
Short-range contributions



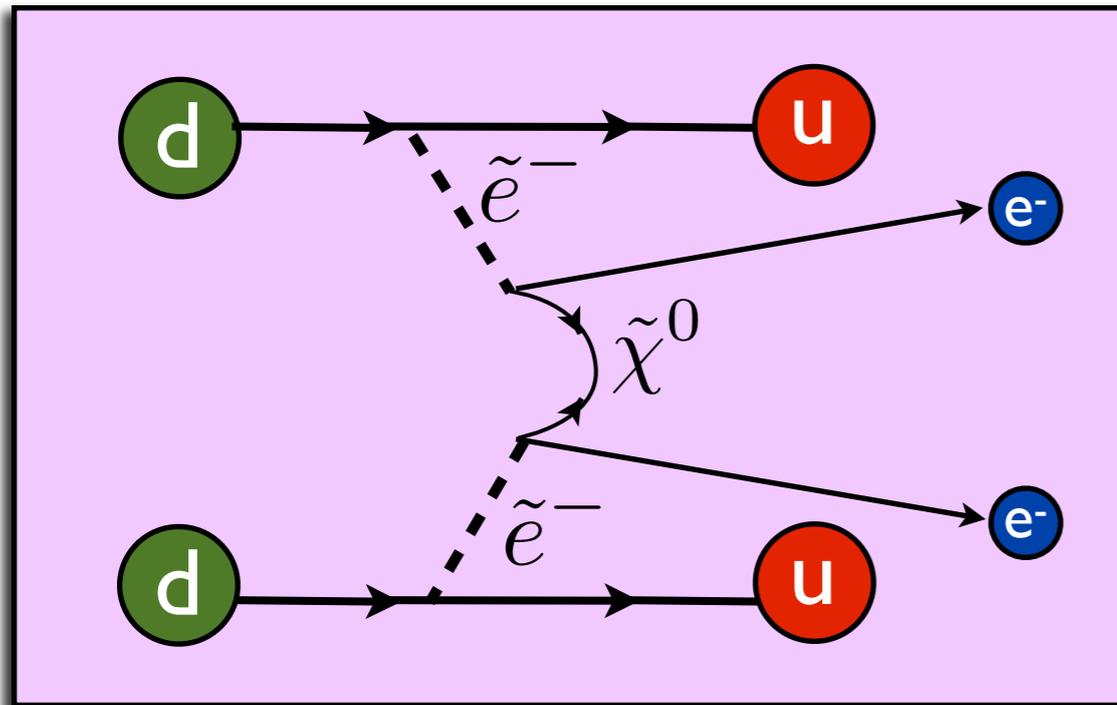
Short-range contributions



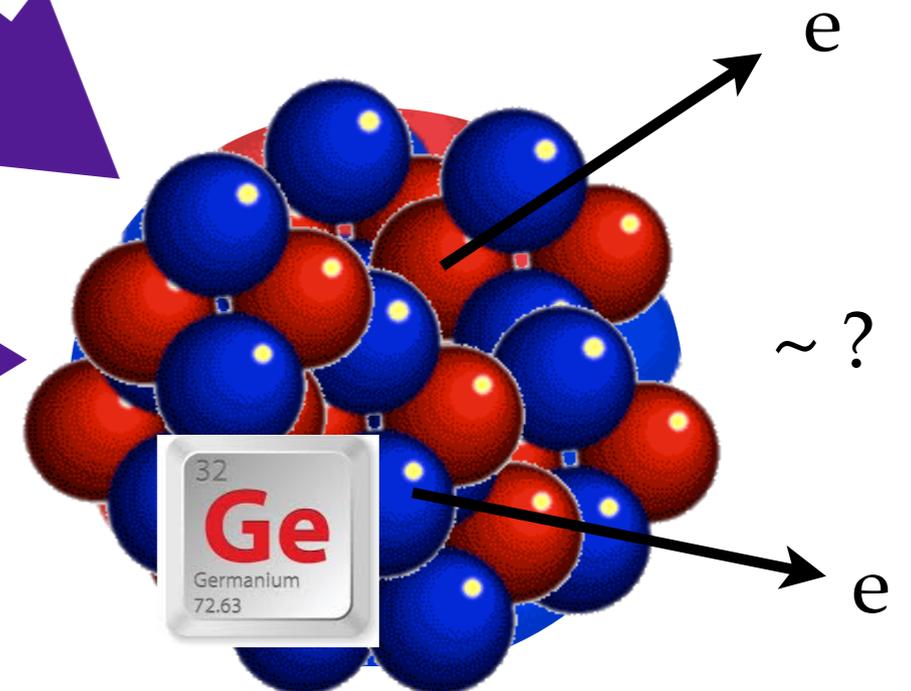
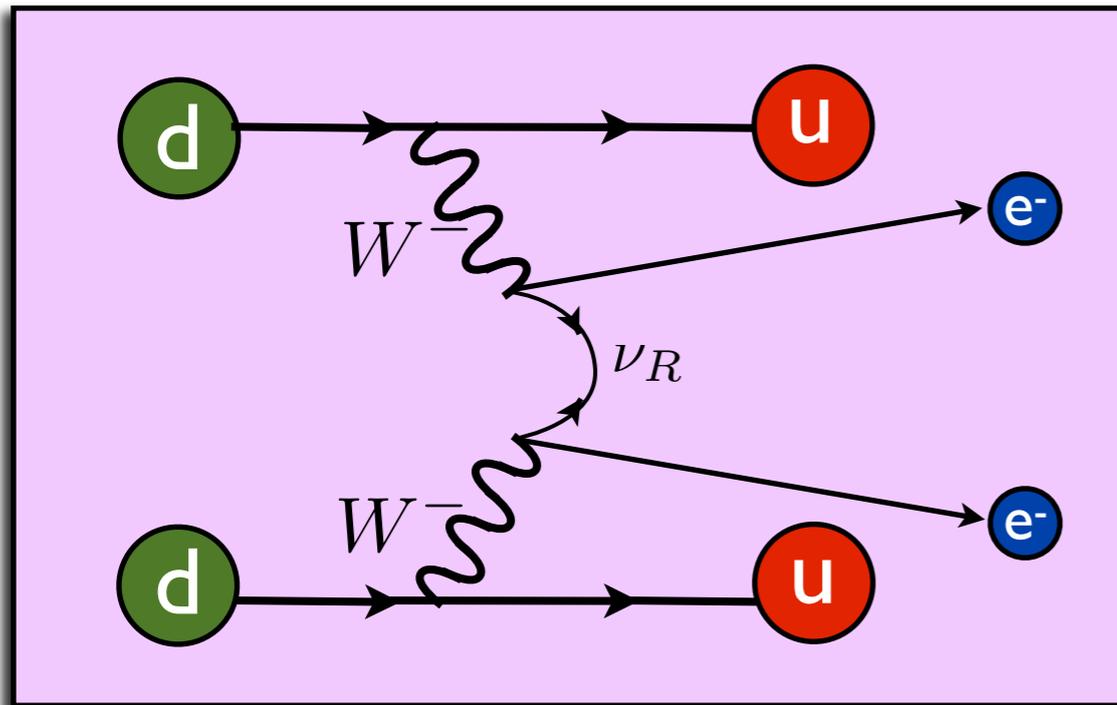
Short-range contributions



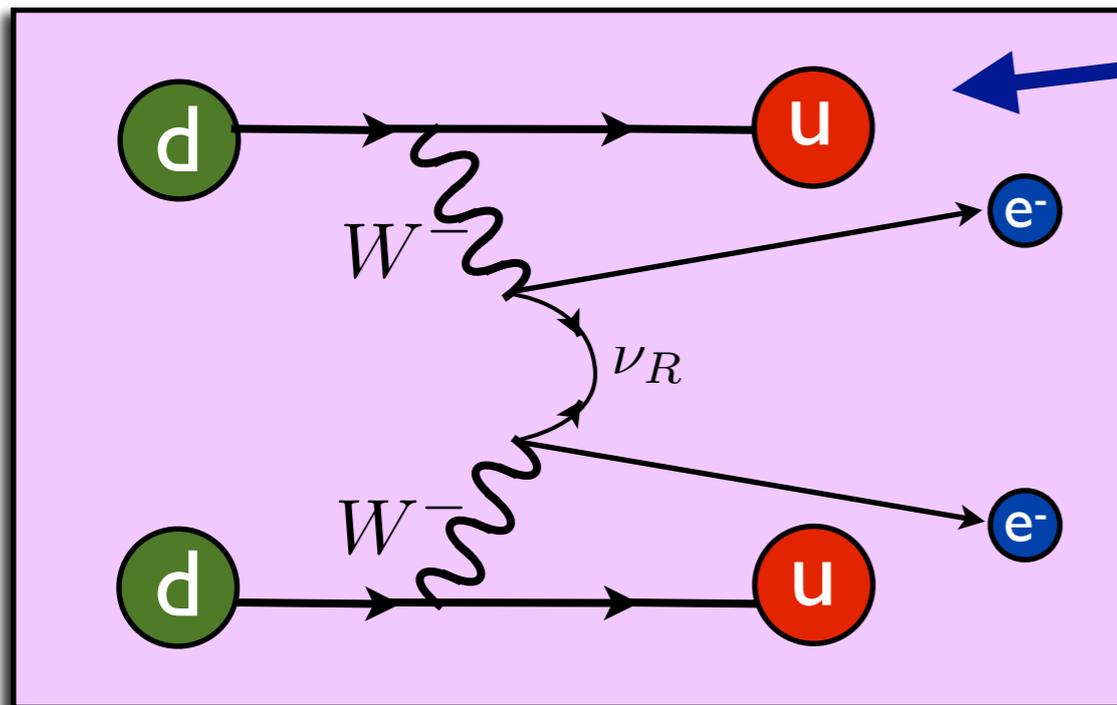
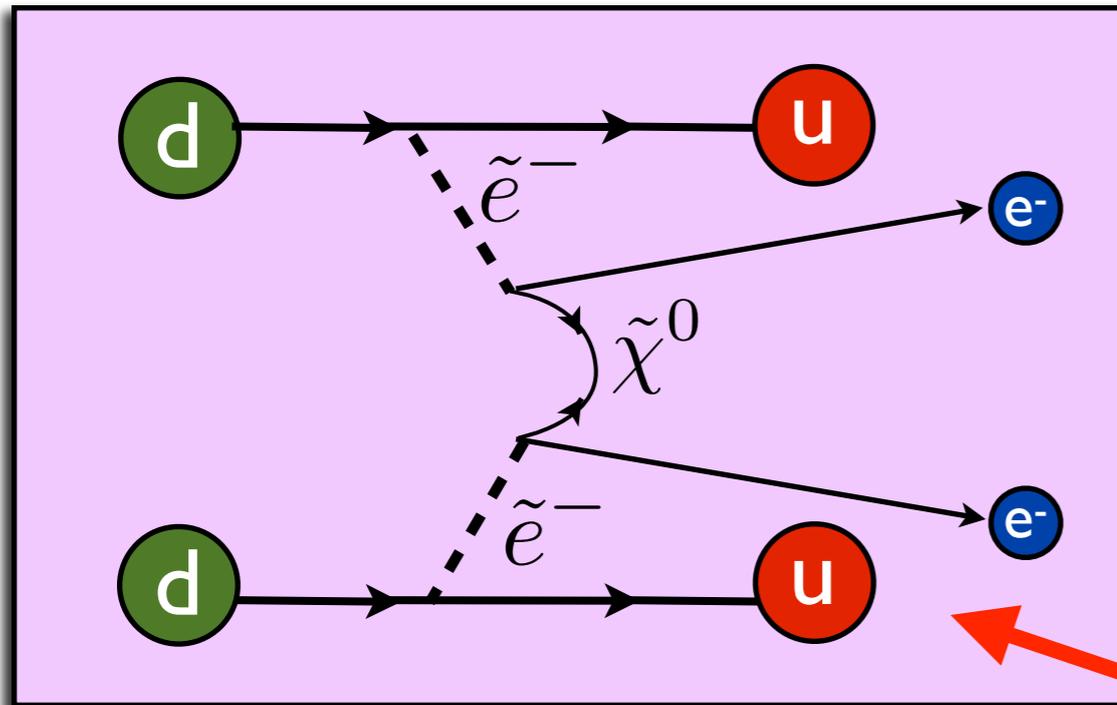
Short-range contributions



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



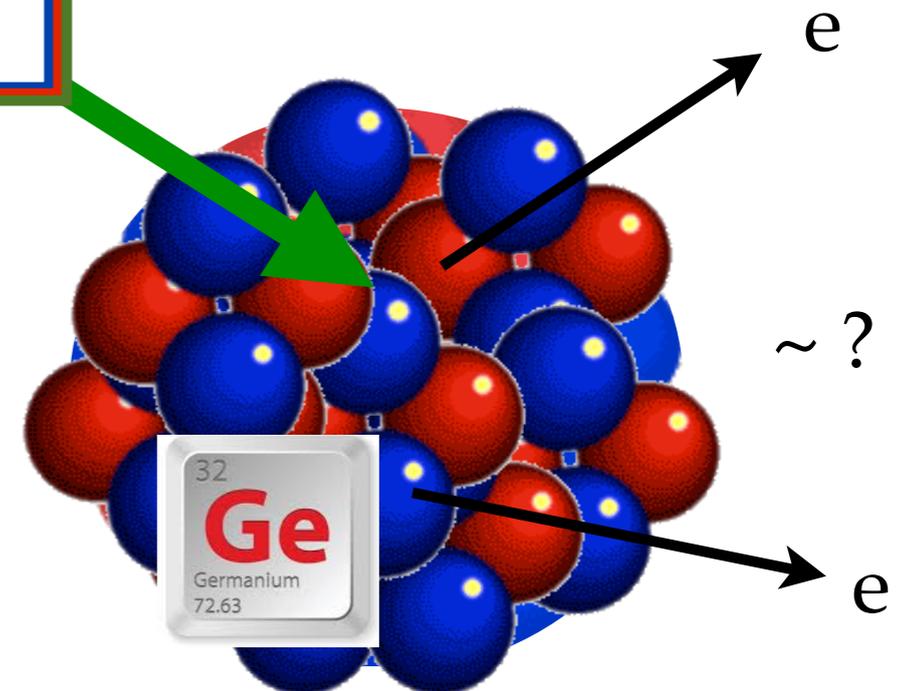
Relating Theory to Experiment



QCD

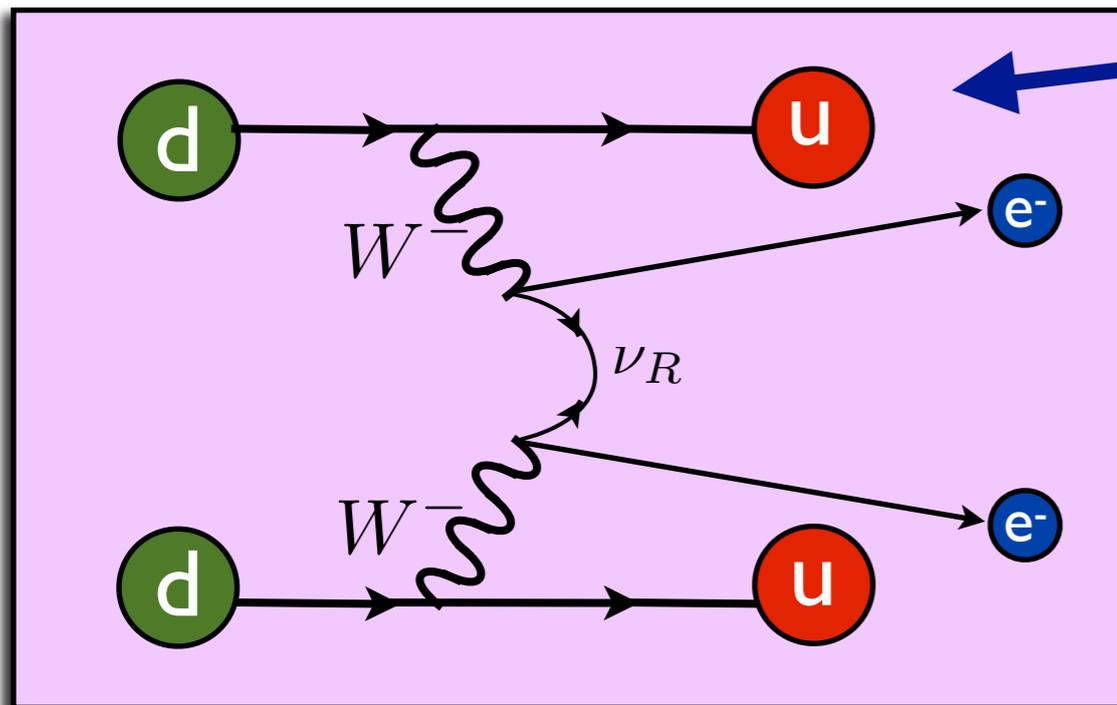
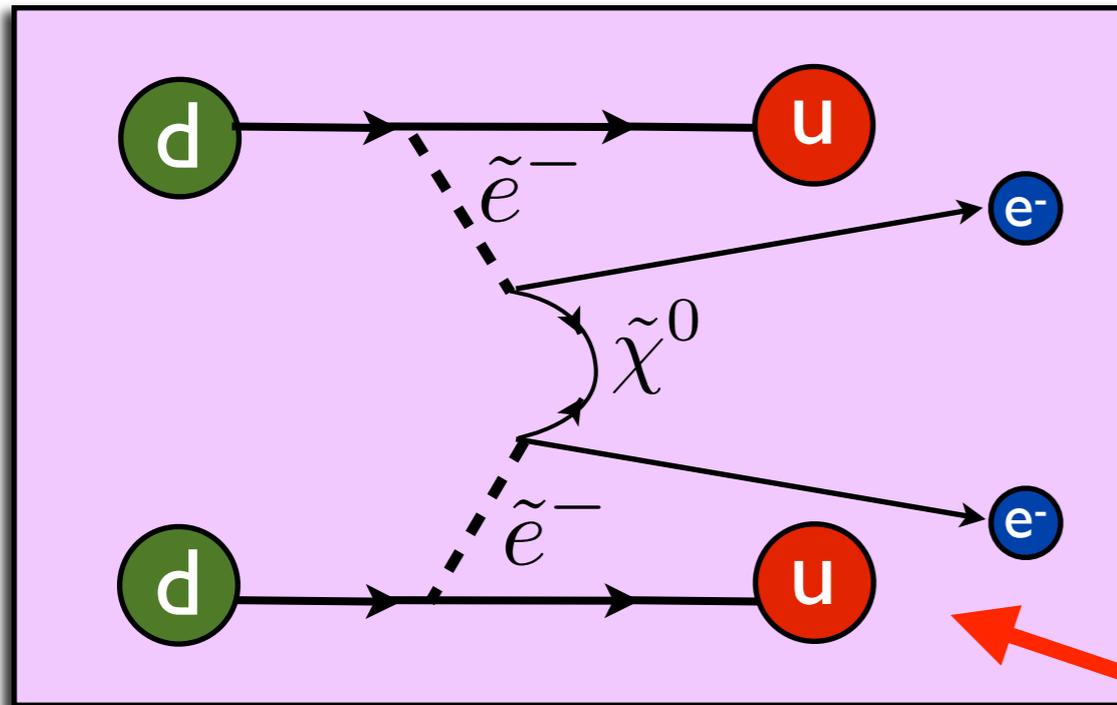
mass	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
LEPTONS				GAUGE BOSONS	

STANDARD MODEL OF PARTICLE PHYSICS



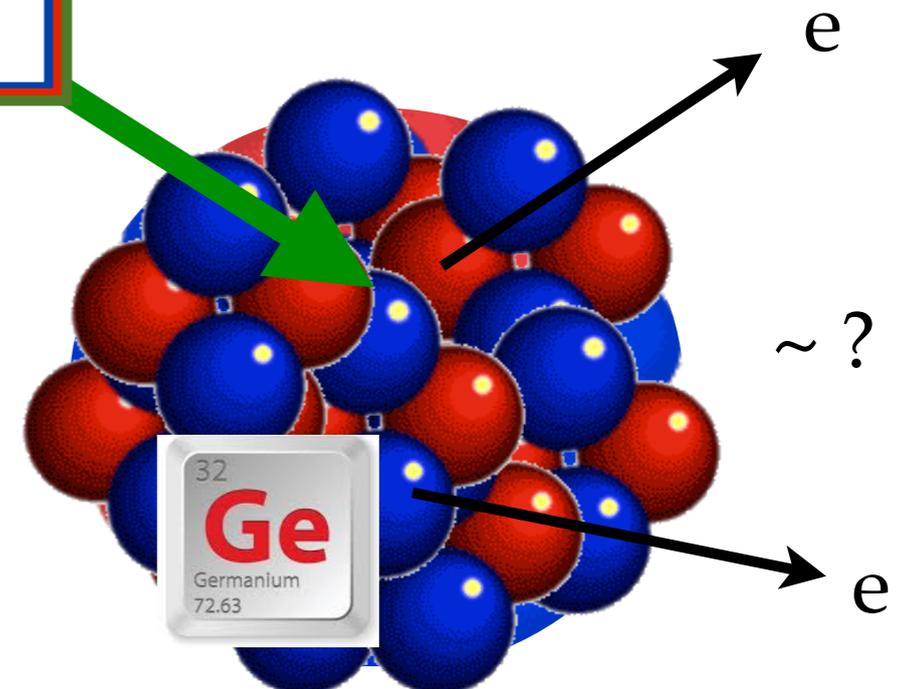
Relating Theory to Experiment

Need to solve QCD non-perturbatively to reach nuclear energy scales:
Only known method: Lattice QCD



QCD

mass	$\rightarrow 2.3 \text{ MeV}/c^2$	$\rightarrow 1.275 \text{ GeV}/c^2$	$\rightarrow 173.07 \text{ GeV}/c^2$	0	$\rightarrow 126 \text{ GeV}/c^2$
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QUARKS	u up	c charm	t top	g gluon	H Higgs boson
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	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
LEPTONS				GAUGE BOSONS	STANDARD MODEL OF PARTICLE PHYSICS



Precision era for (single nucleon) LQCD

Neutron-proton mass
difference: accurate to 300 KeV
(BMW 2015)

Axial charge of the nucleon:
 $g_A = 1.271(13)$
(CalLat 2018)

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1



Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi¹, S. Durr^{1,2}, Z. Fodor^{1,2,3,*}, C. Hoelbling¹, S. D. Katz^{3,4}, S. Krieg^{1,2}, L. Lellouch⁵, T. Lippert^{1,2}, A. Portelli^{5,6}, K. K. Szabo^{1,2}, B. C. Toth¹

¹Department of Physics, University of Wuppertal, D-42119 Wuppertal, Germany.

²Jülich Supercomputing Centre, Forschungszentrum Jülich, D-52428 Jülich, Germany.

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⁴Lendület Lattice Gauge Theory Research Group, Magyar Tudományos Akadémia–Eötvös Loránd University, H-1117 Budapest, Hungary.

⁵CNRS, Aix-Marseille Université, Université de Toulon, CPT UMR 7332, F-13288, Marseille, France.

⁶School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK.

*Corresponding author. E-mail: fodor@bodri.elte.hu

Science 27 Mar 2015:
Vol. 347, Issue 6229, pp. 1452-1455

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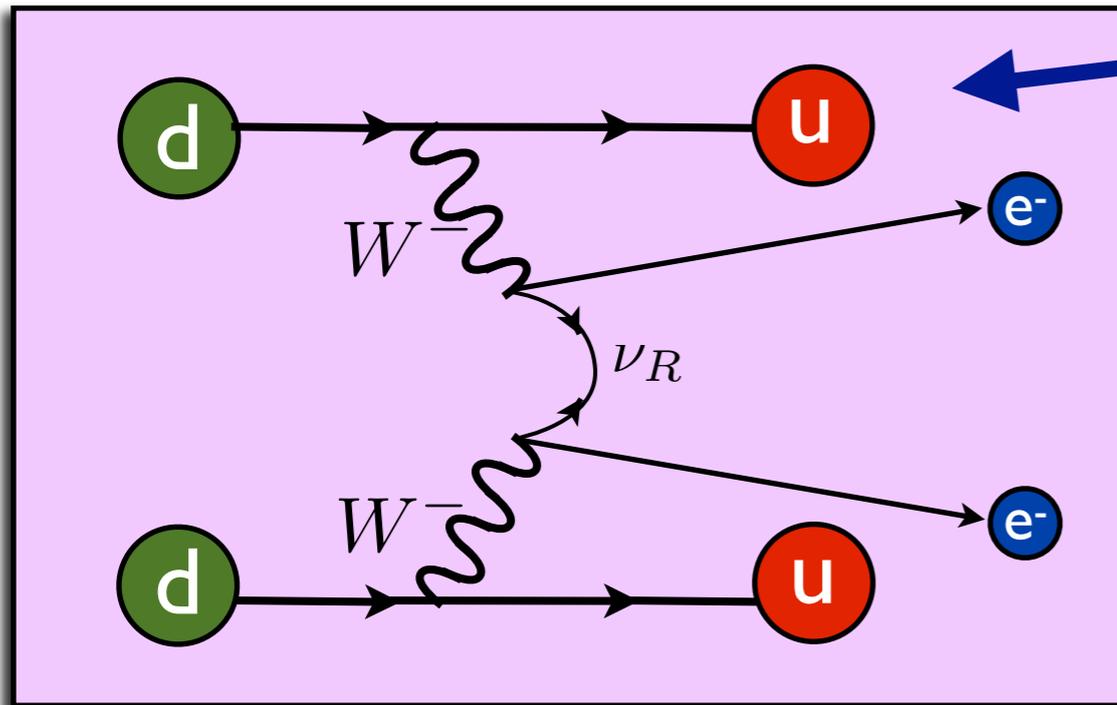
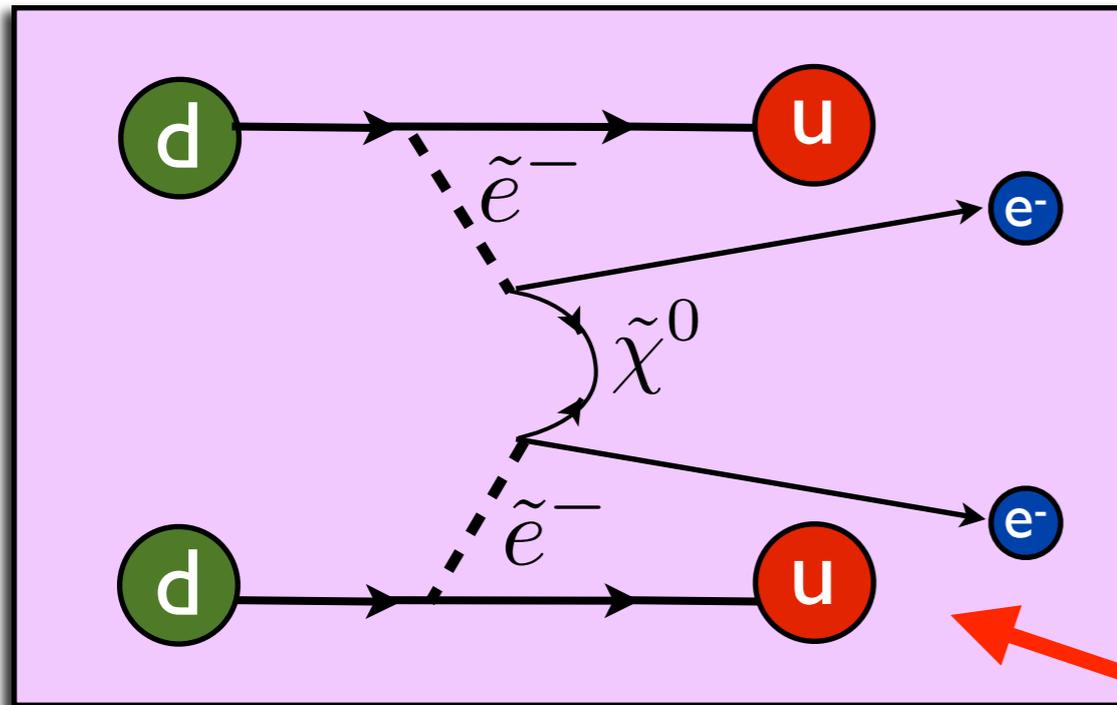
Letter | Published: 30 May 2018

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

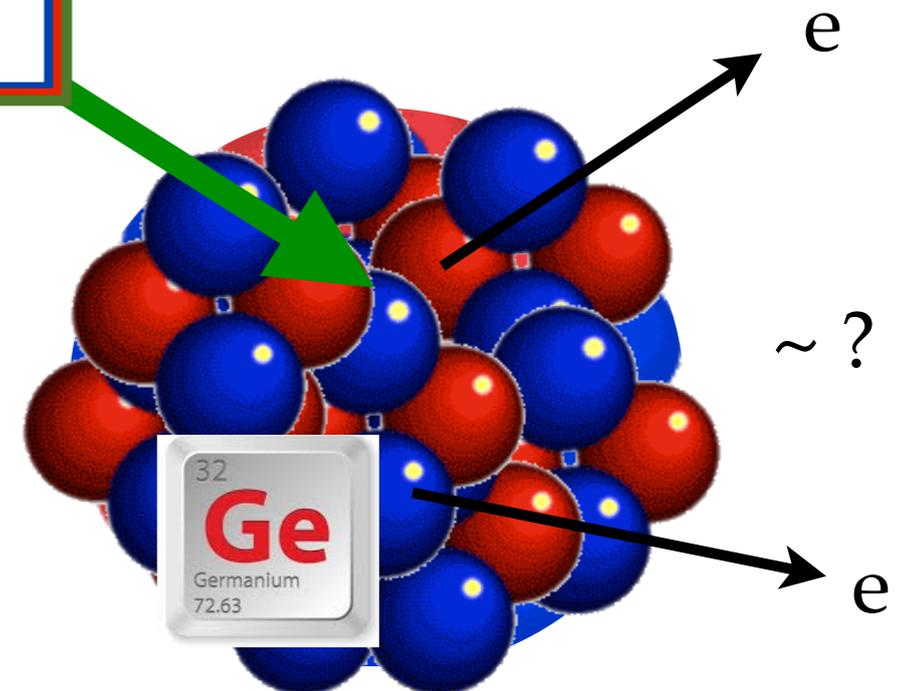
C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

Nature 558, 91–94 (2018) | [Download Citation](#)

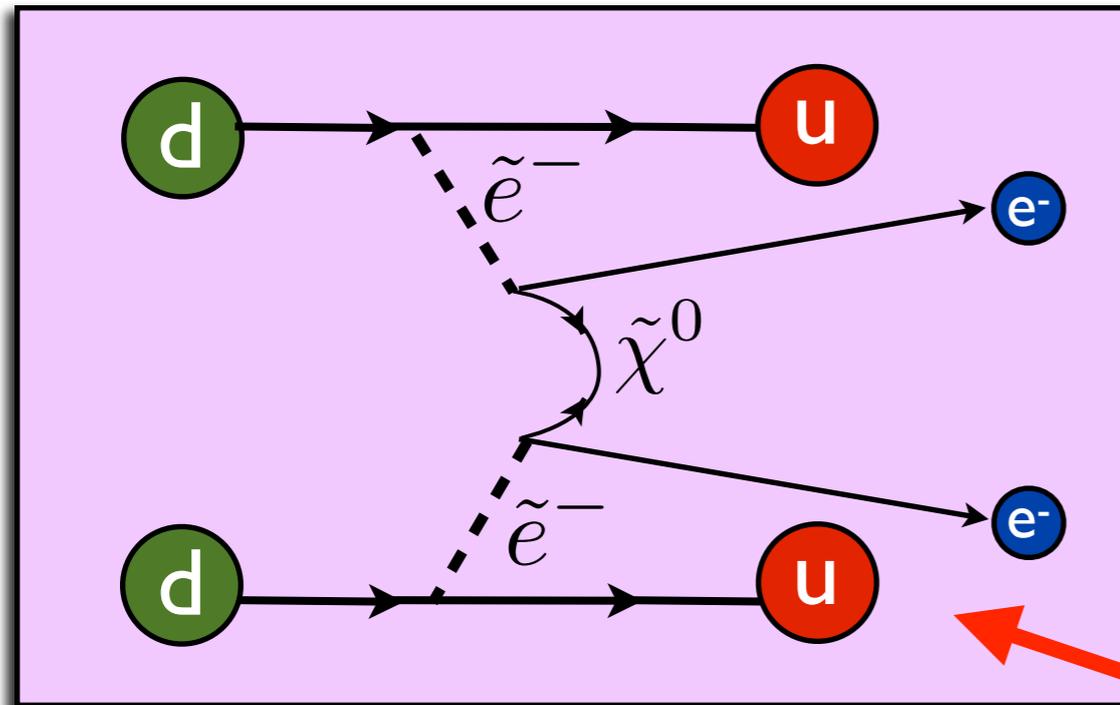
Relating Theory to Experiment



QCD

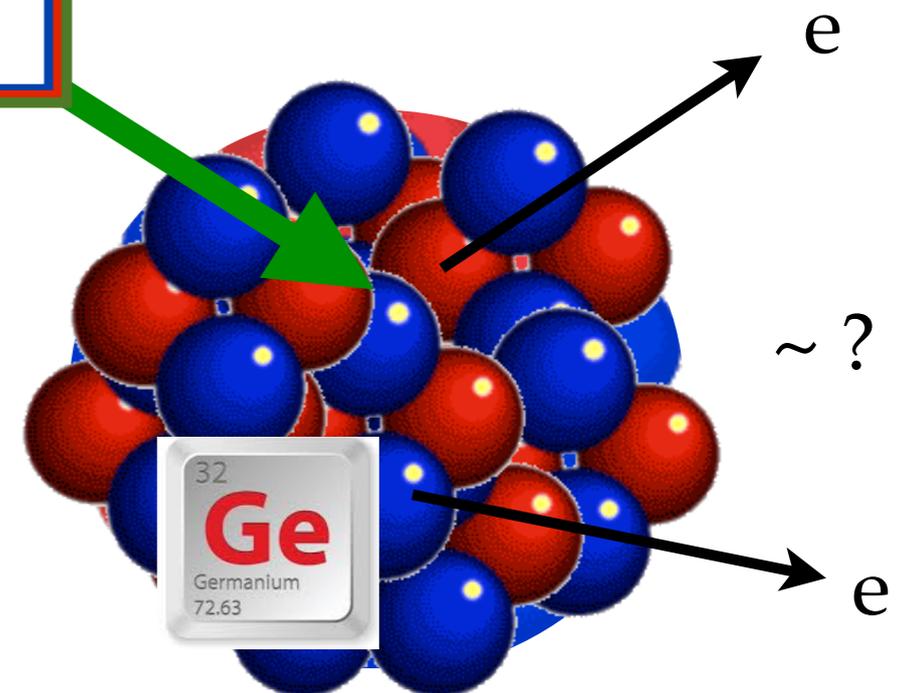
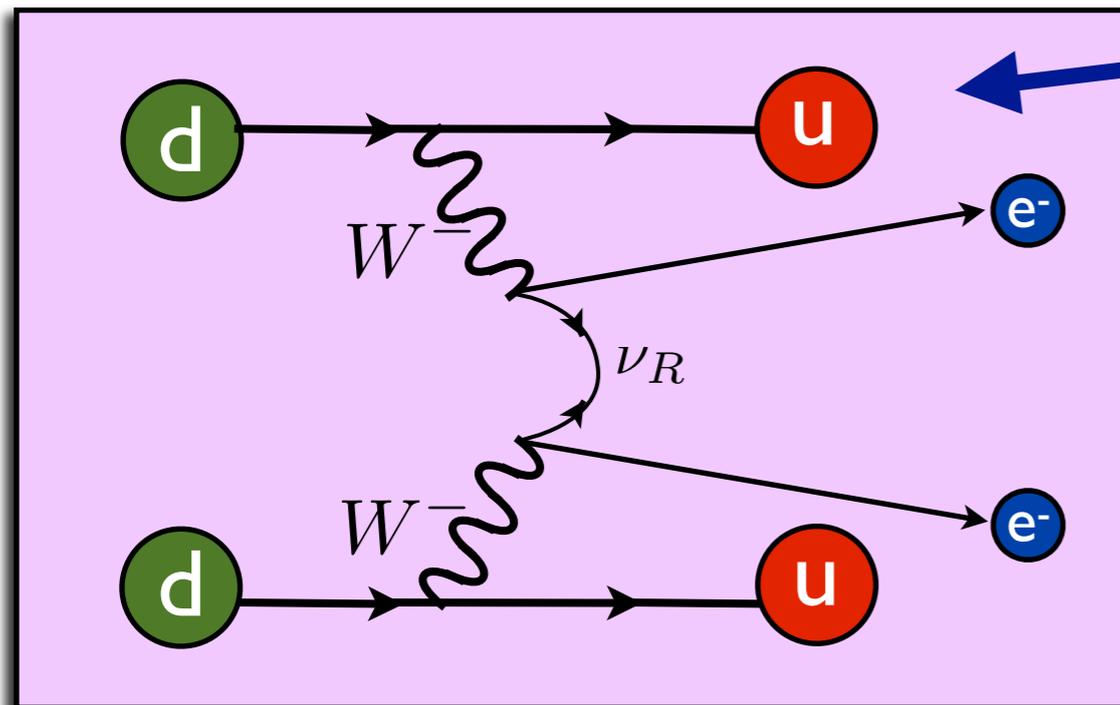


Relating Theory to Experiment

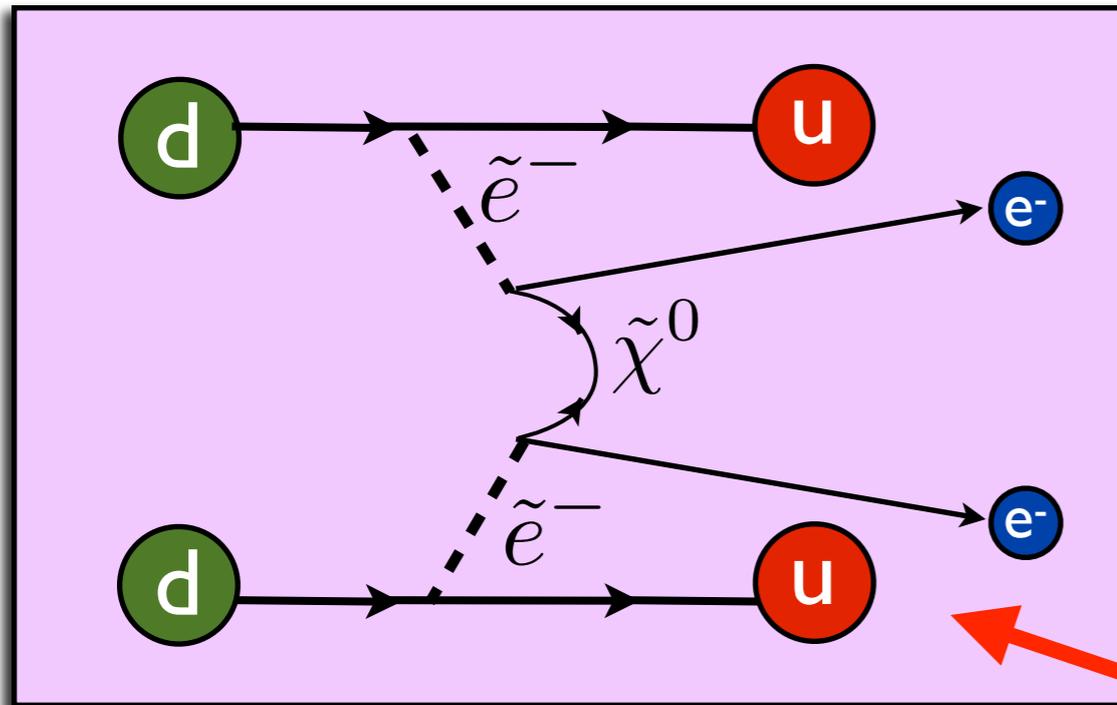


LQCD will never directly calculate your favorite $0\nu\beta\beta$ isotope:

QCD



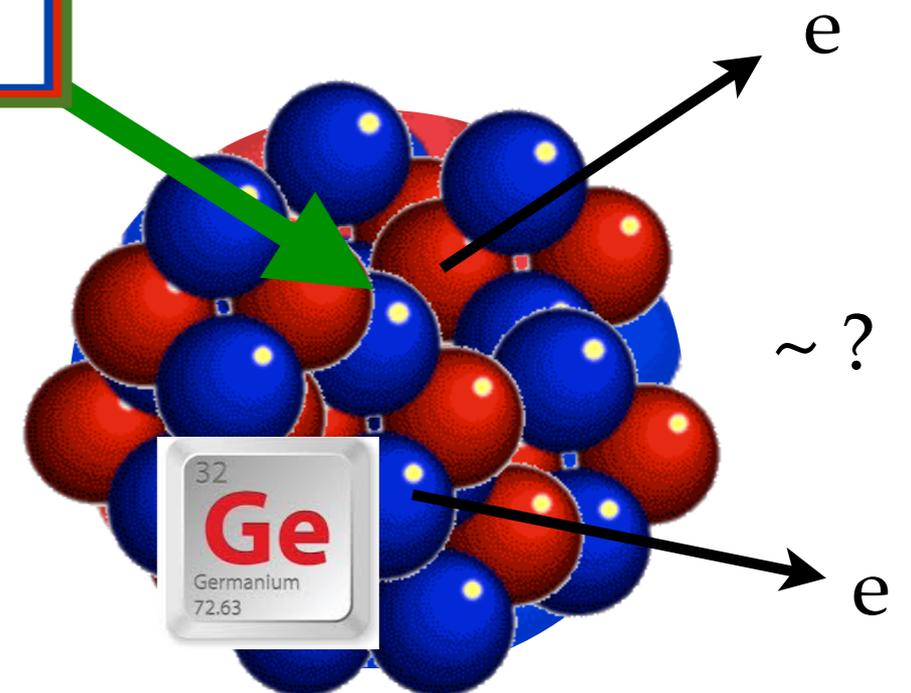
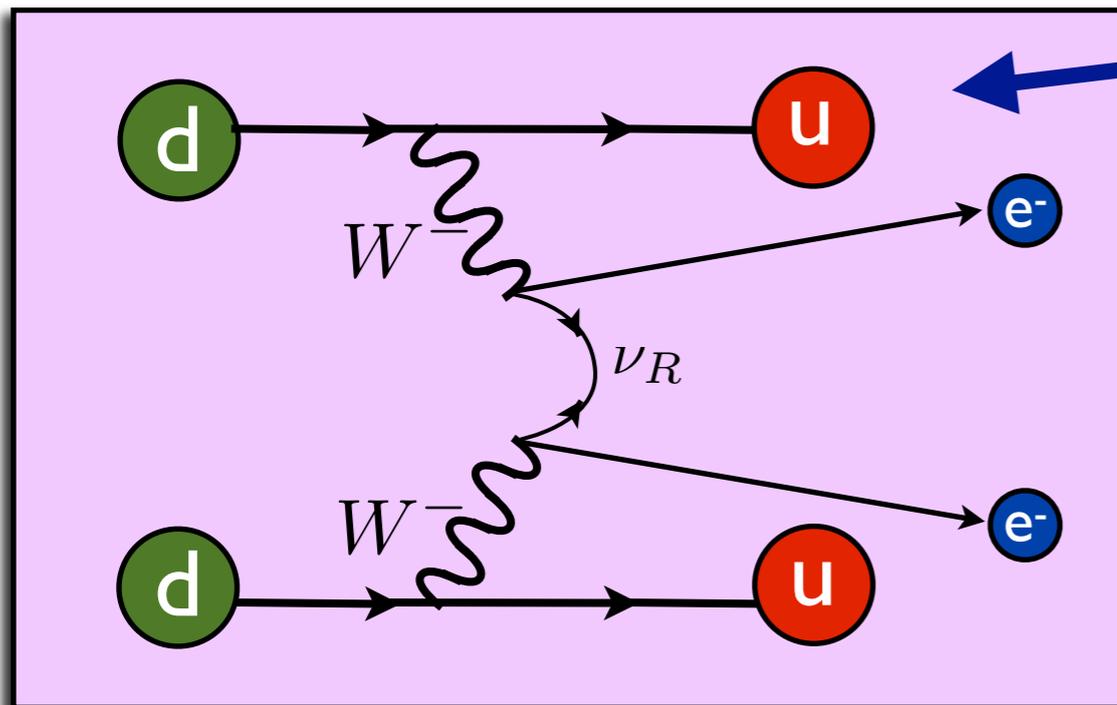
Relating Theory to Experiment



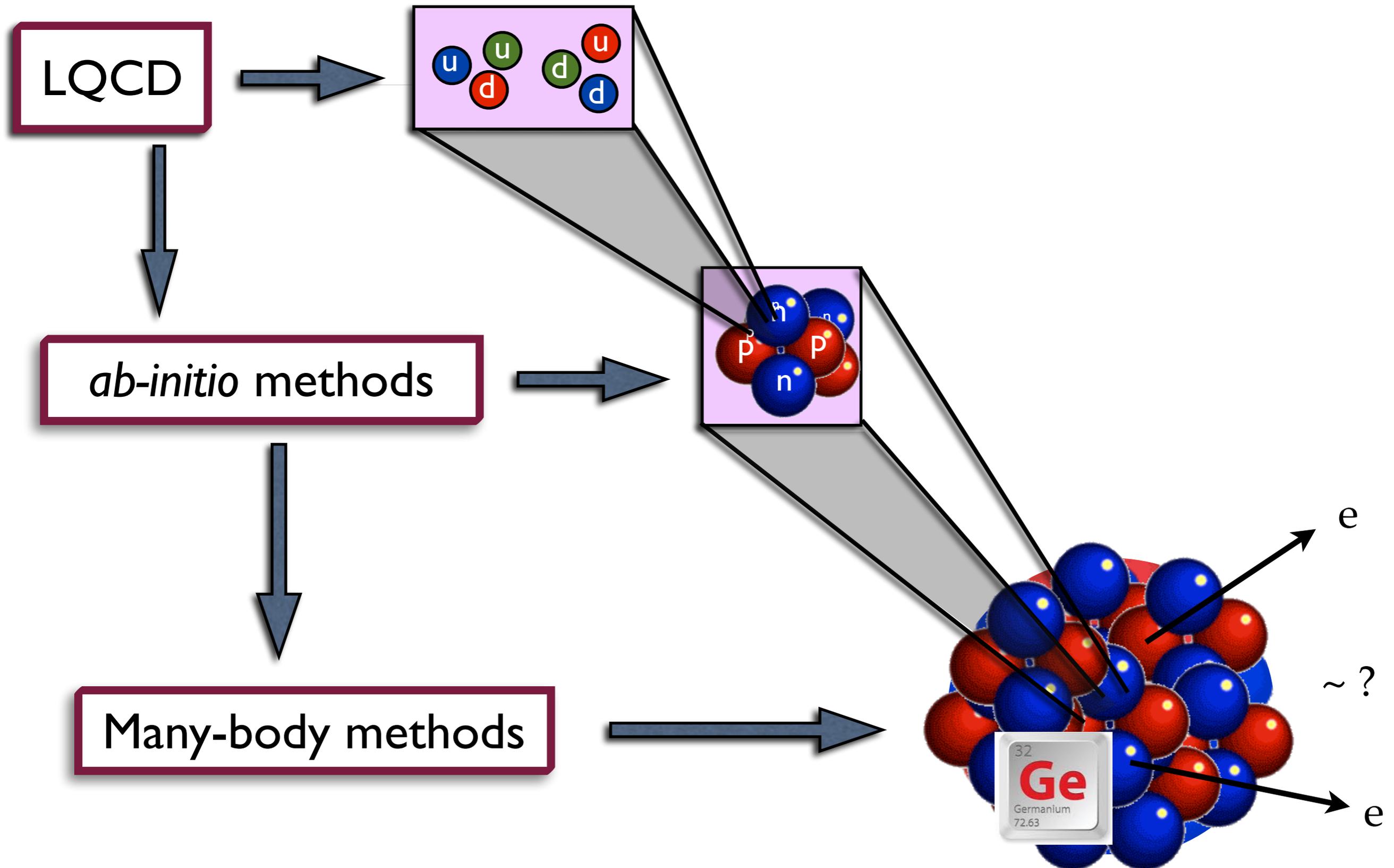
LQCD will never directly calculate your favorite $0\nu\beta\beta$ isotope:

Monte Carlo noise (sign) problem, too many quark degrees of freedom, large range of scales,....

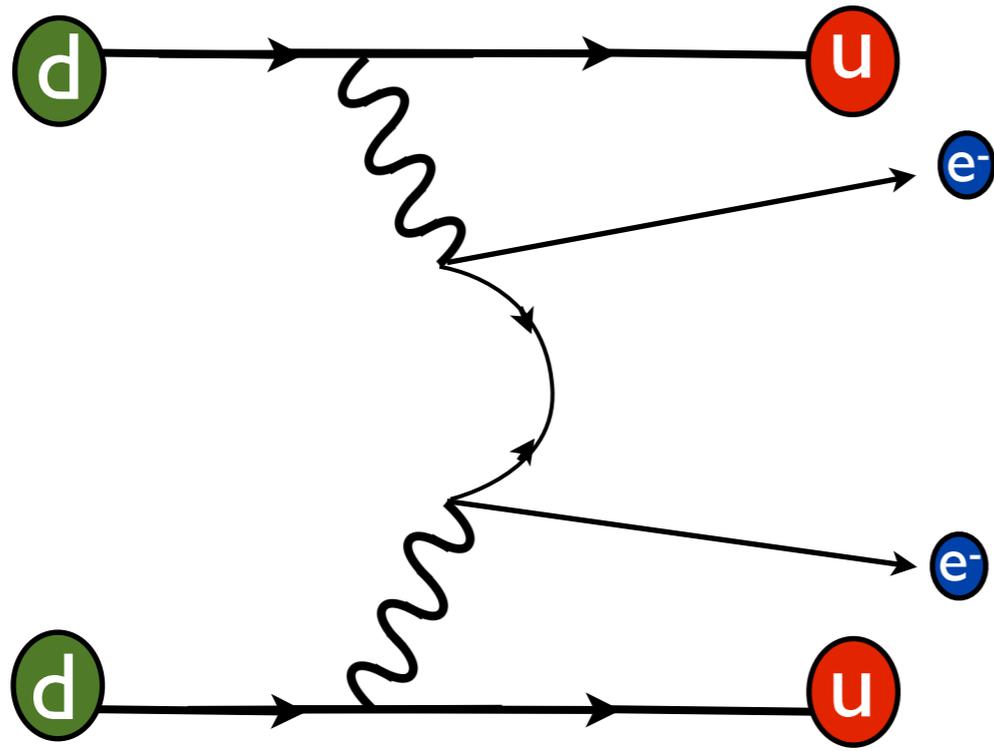
QCD



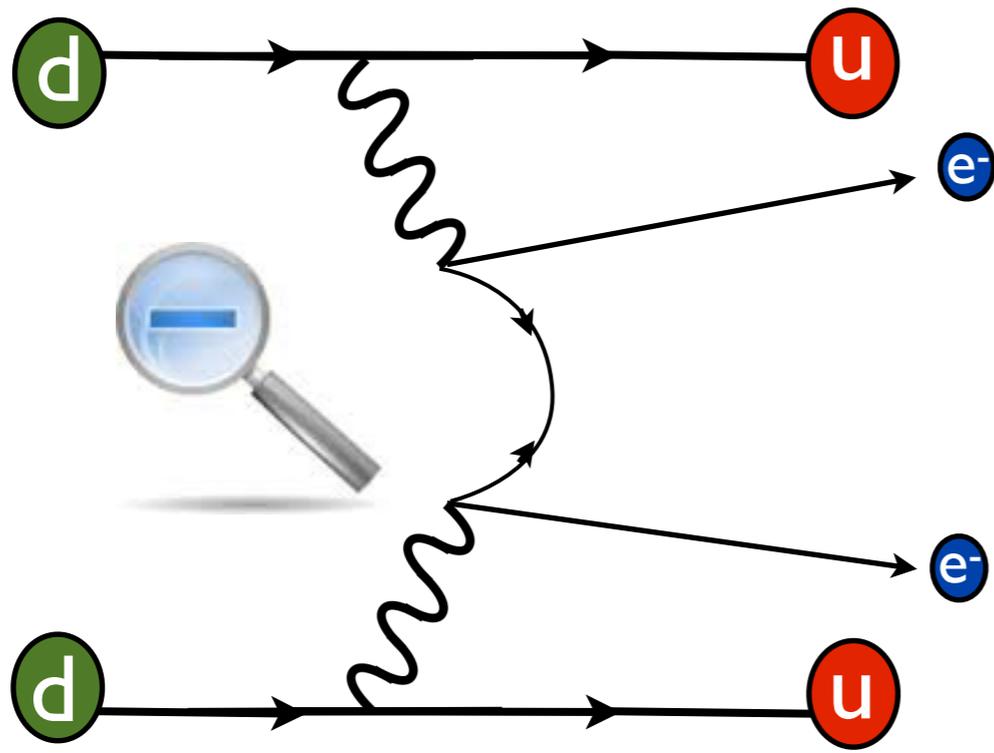
Relating Theory to Experiment



From quarks to hadrons

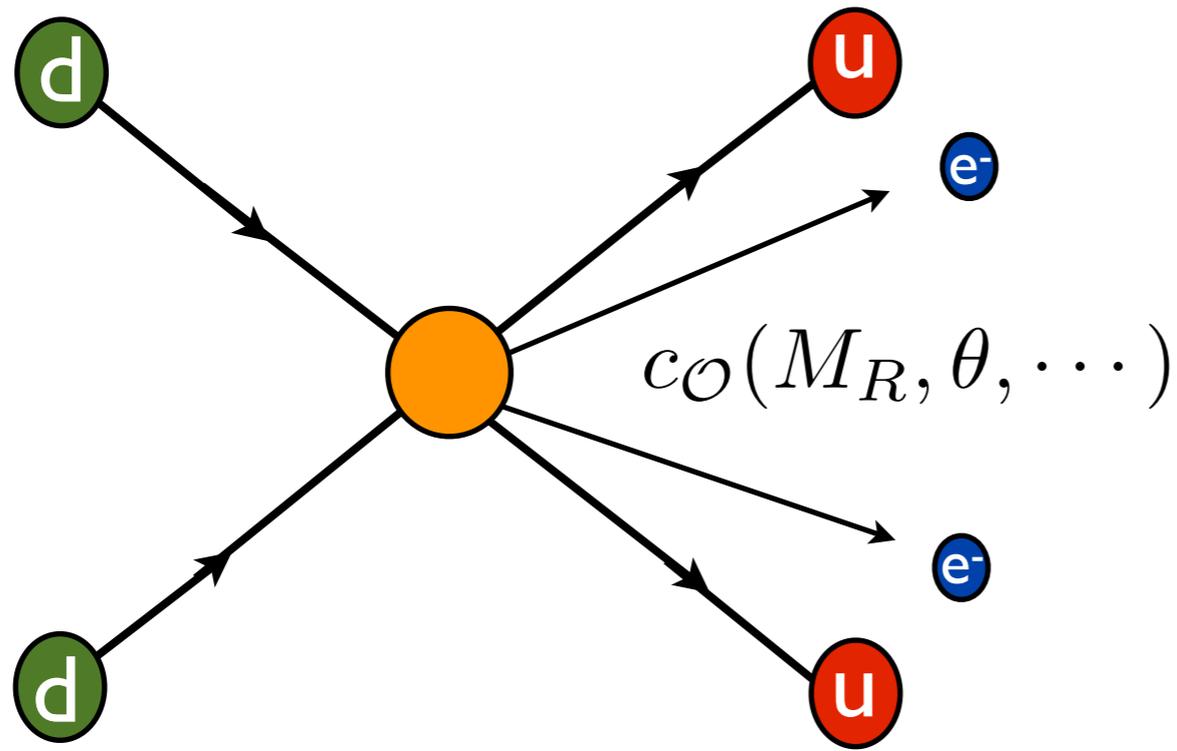


From quarks to hadrons



$$\Lambda \ll M_W$$

From quarks to hadrons



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

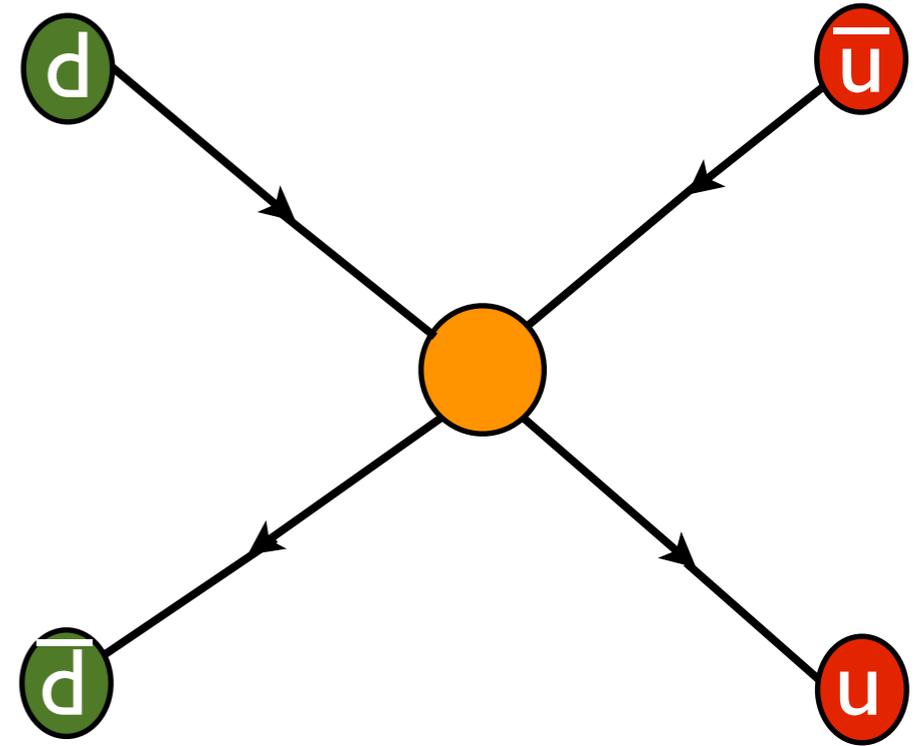
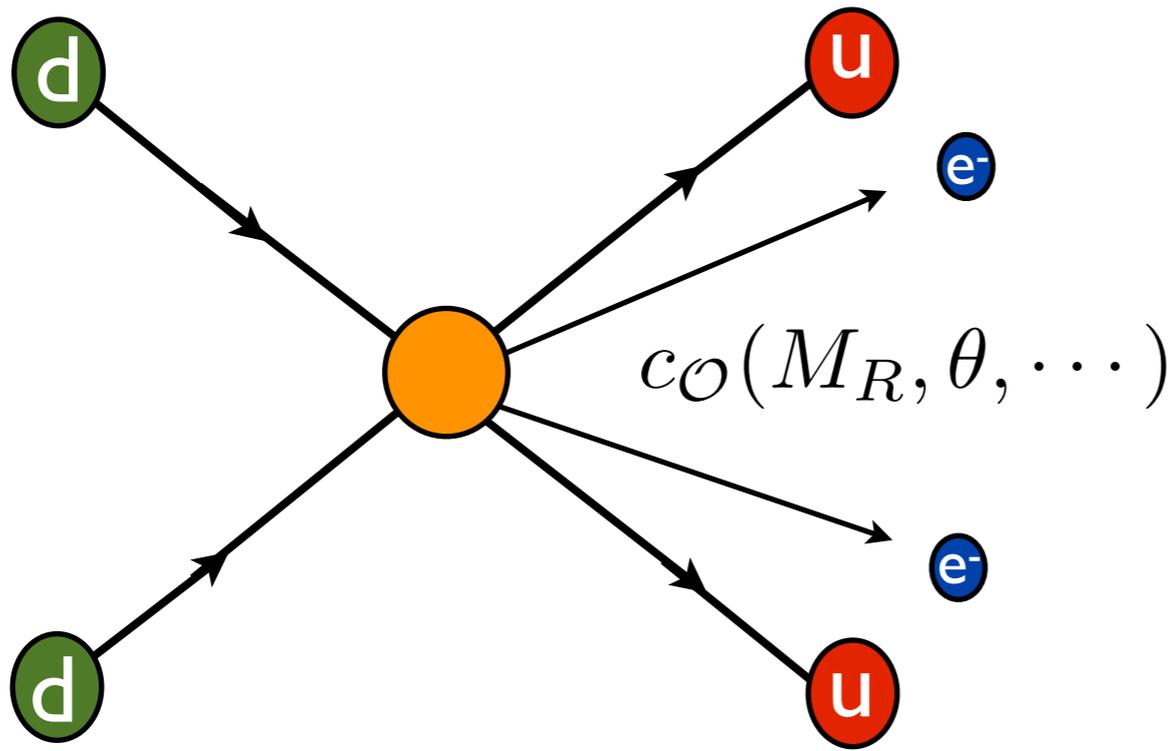
$$\mathcal{O}_{2\pm}^{ab} = (\bar{q}_R \tau^a q_L)(\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R)(\bar{q}_L \tau^b q_R),$$

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

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

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

From quarks to hadrons



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

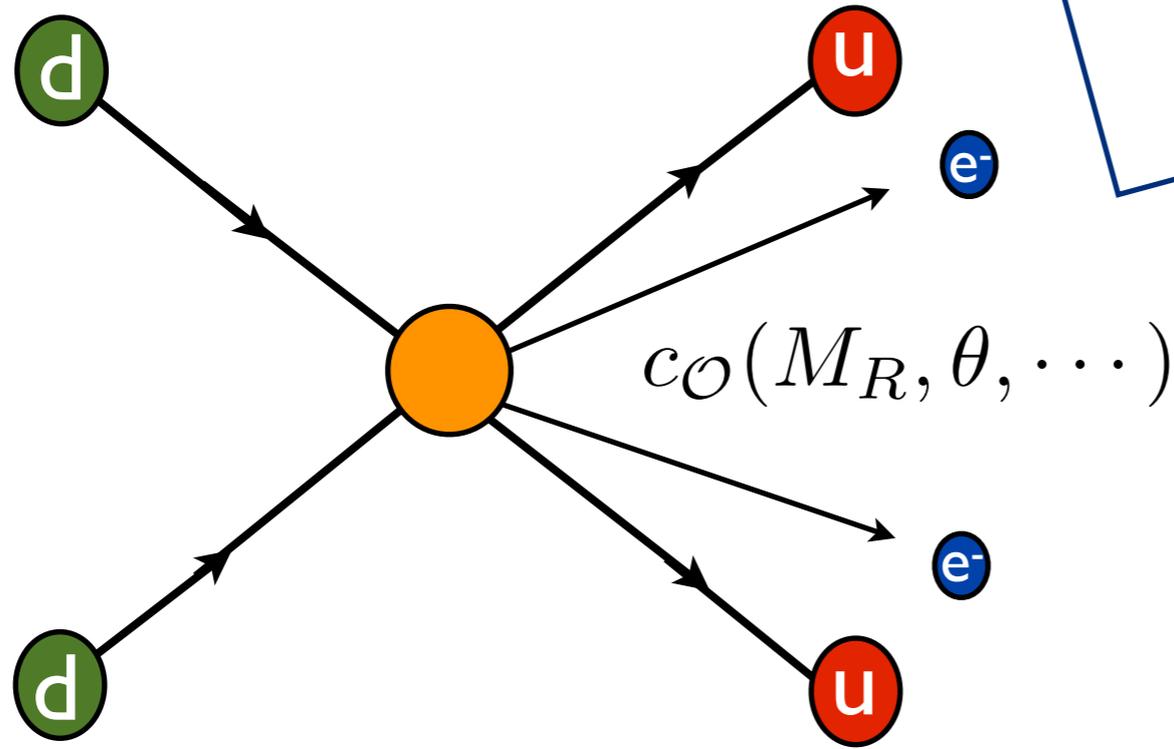
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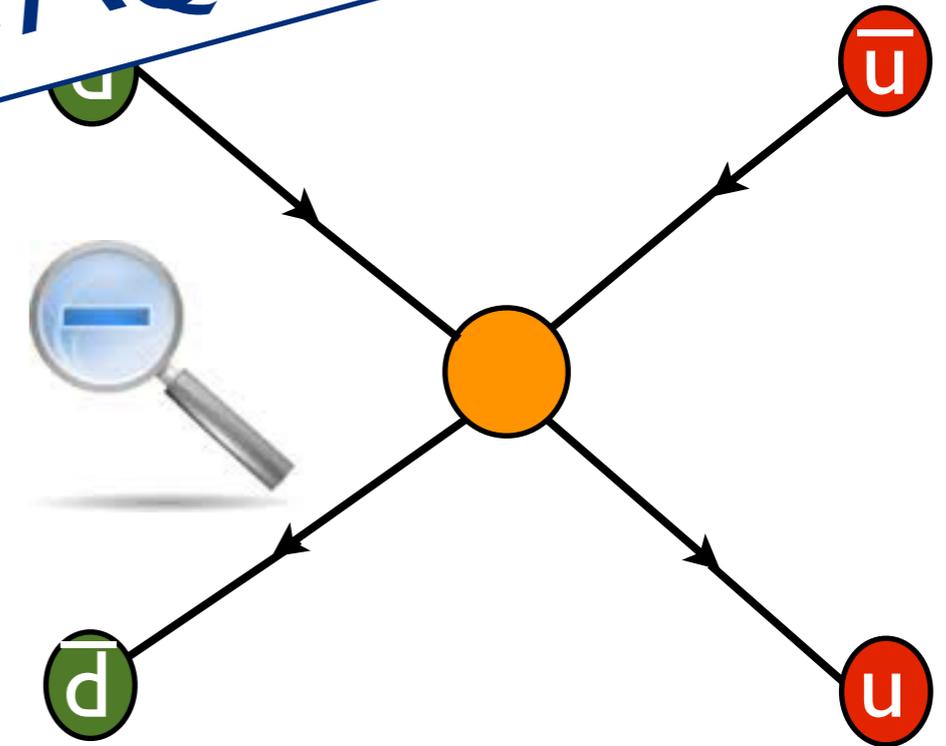
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From quarks to hadrons



$\Lambda \ll \Lambda_{\text{QCD}}$



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

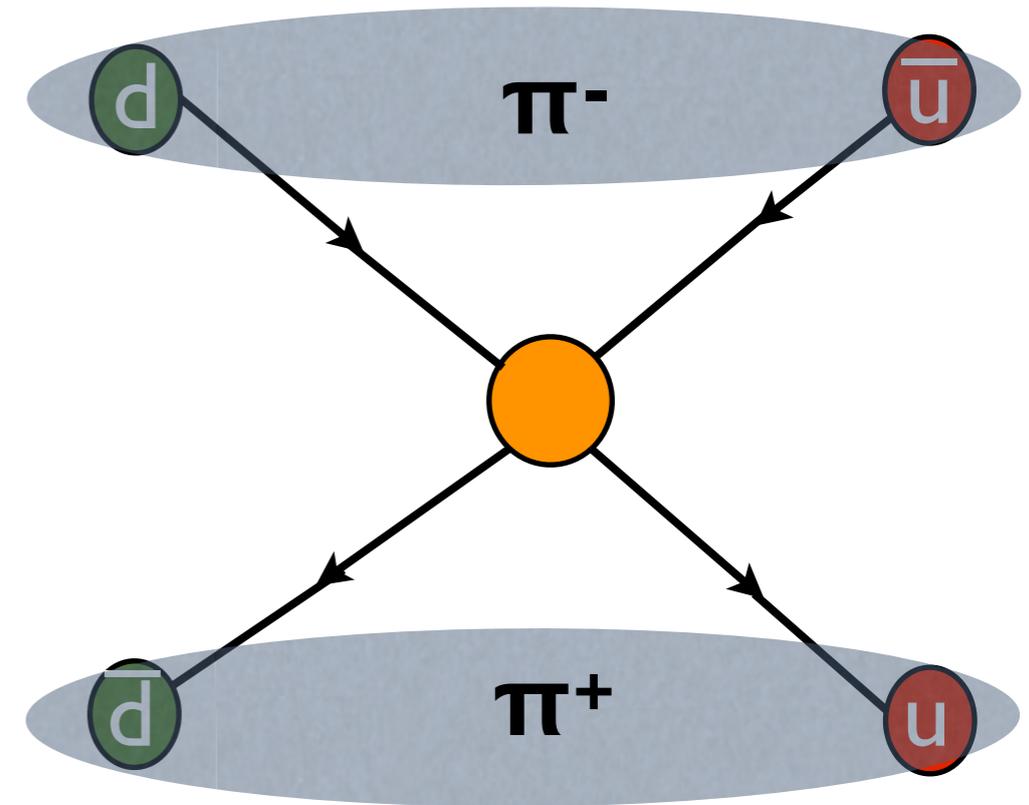
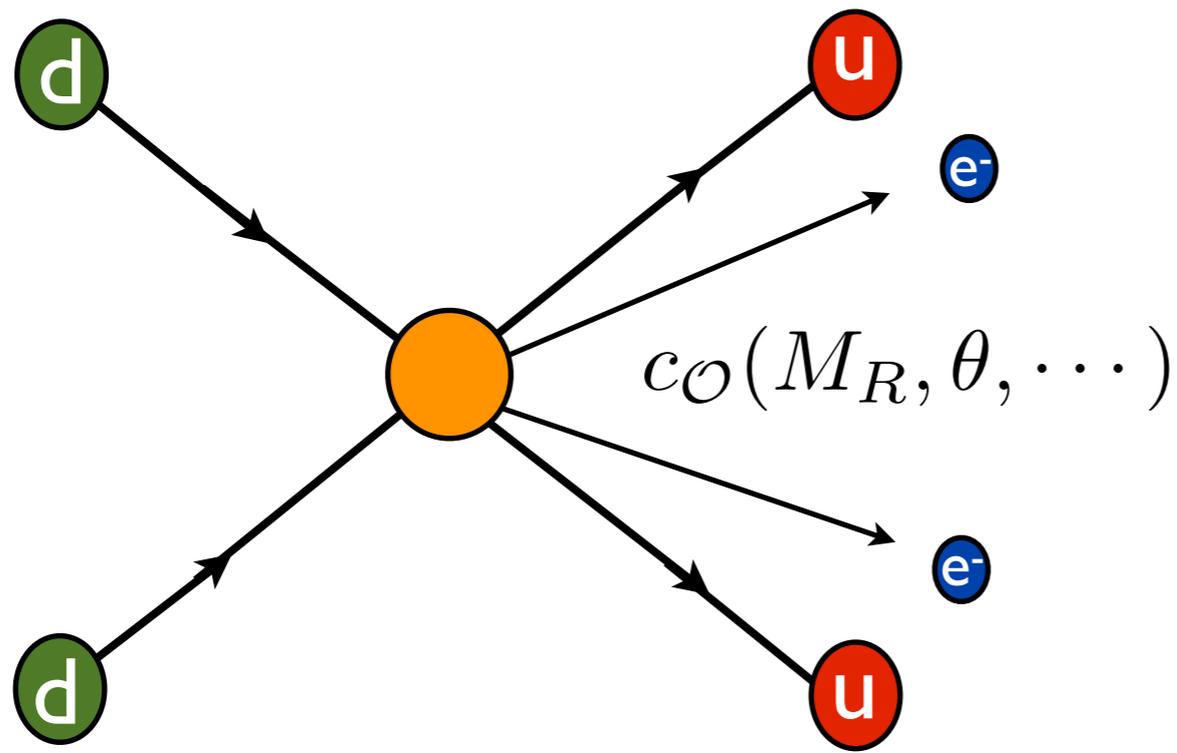
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From quarks to hadrons



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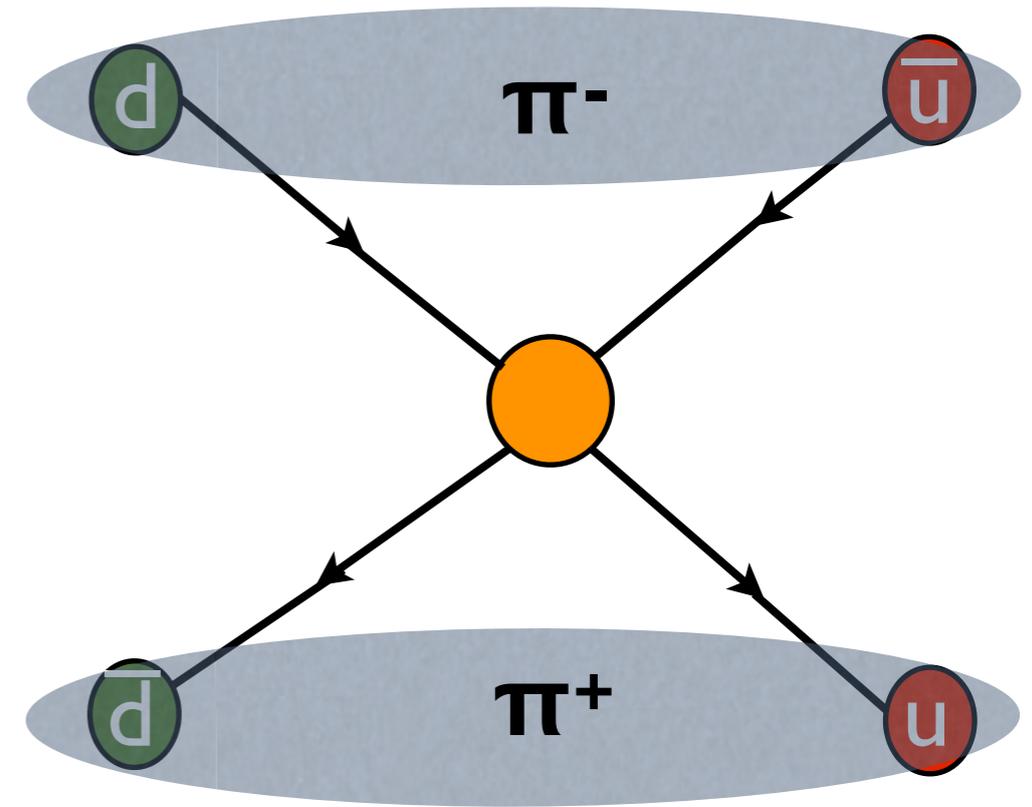
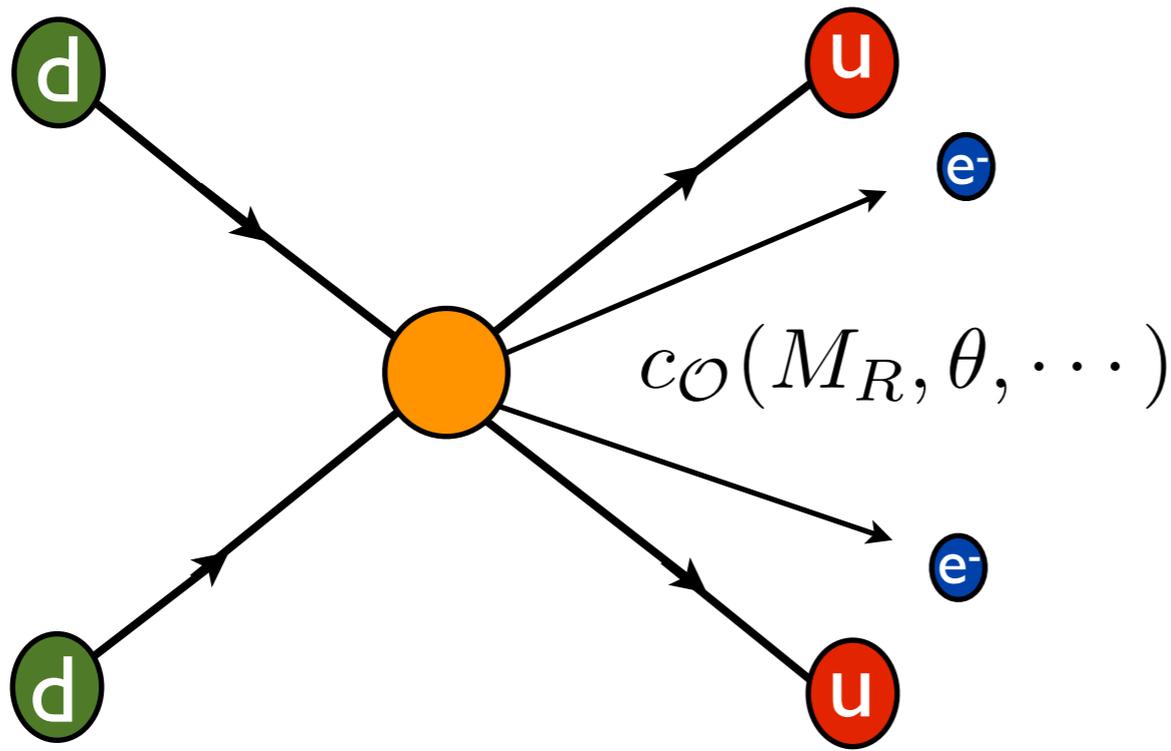
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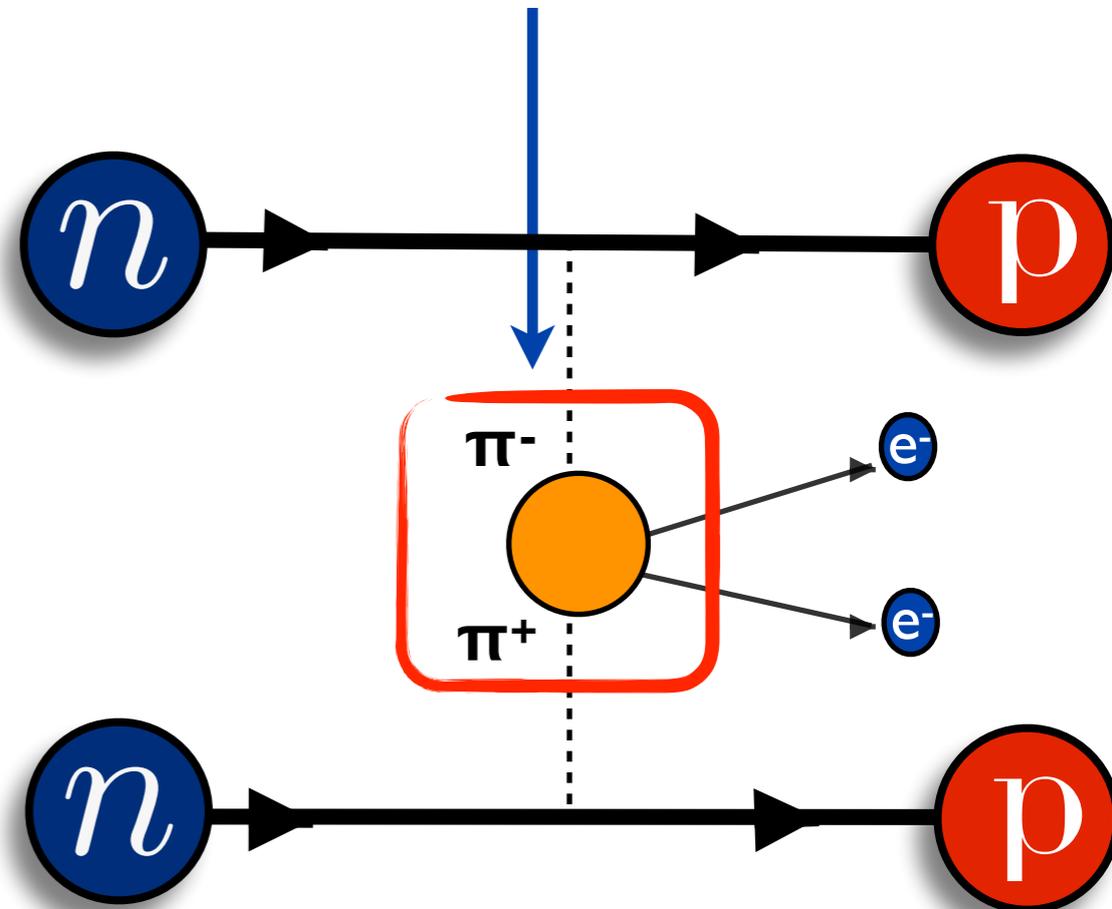
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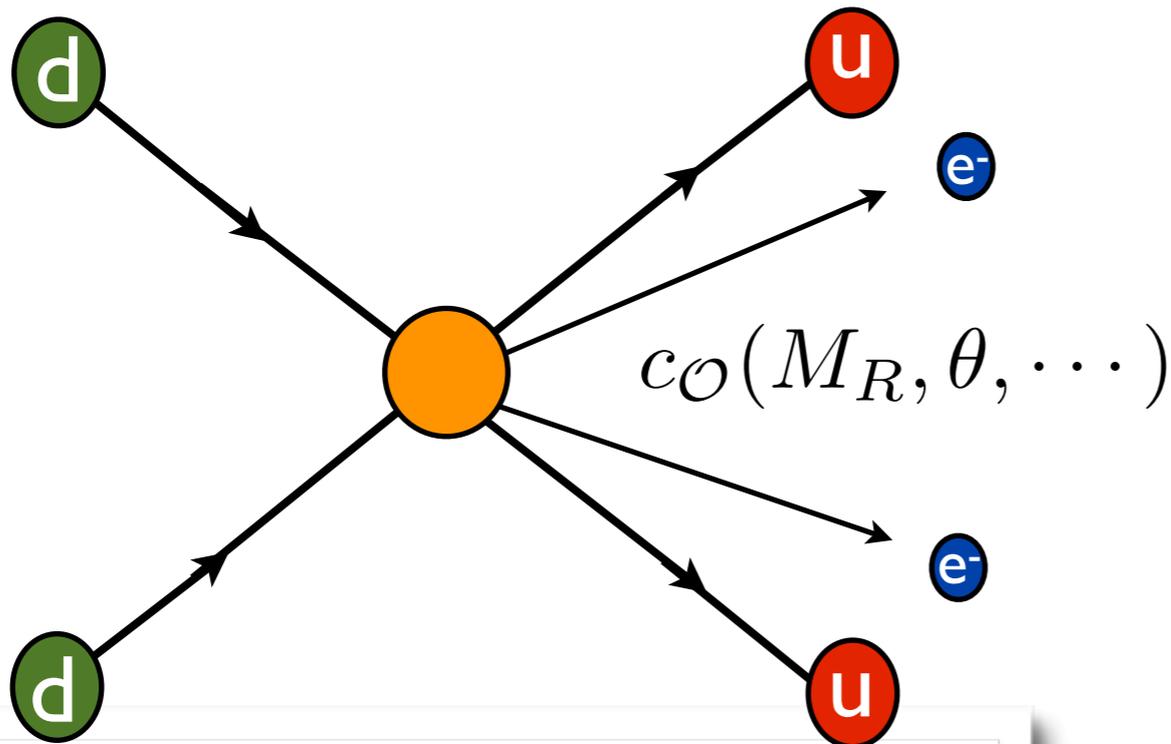
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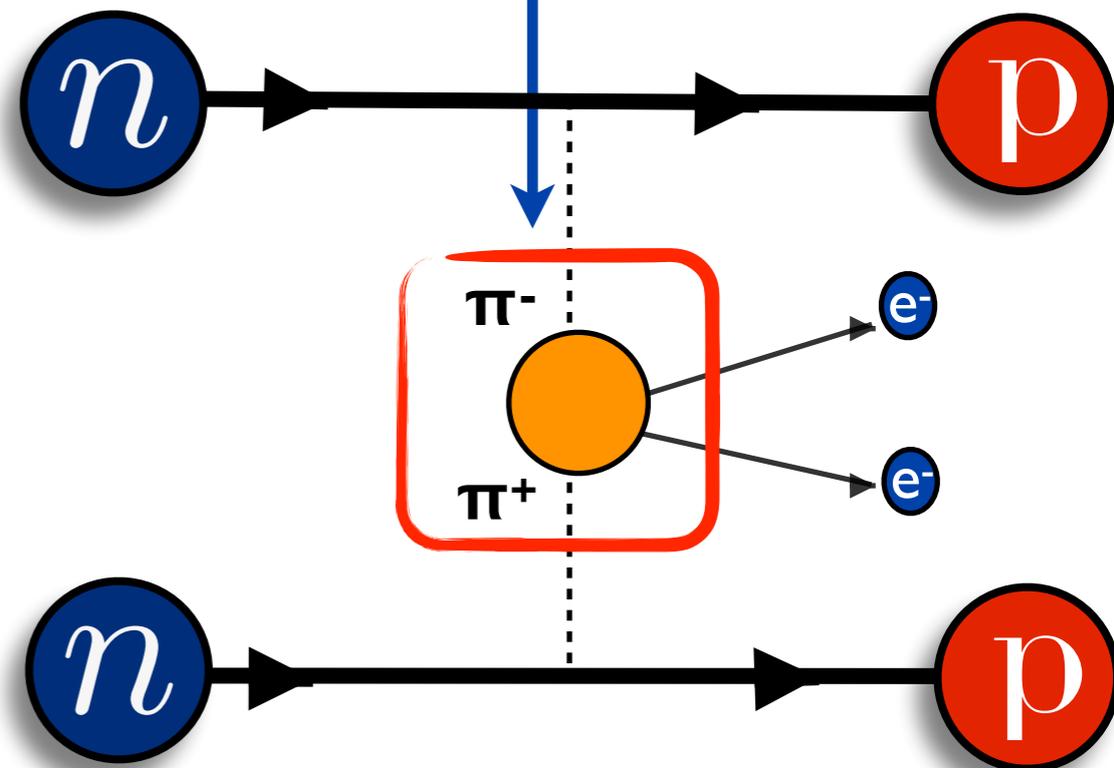
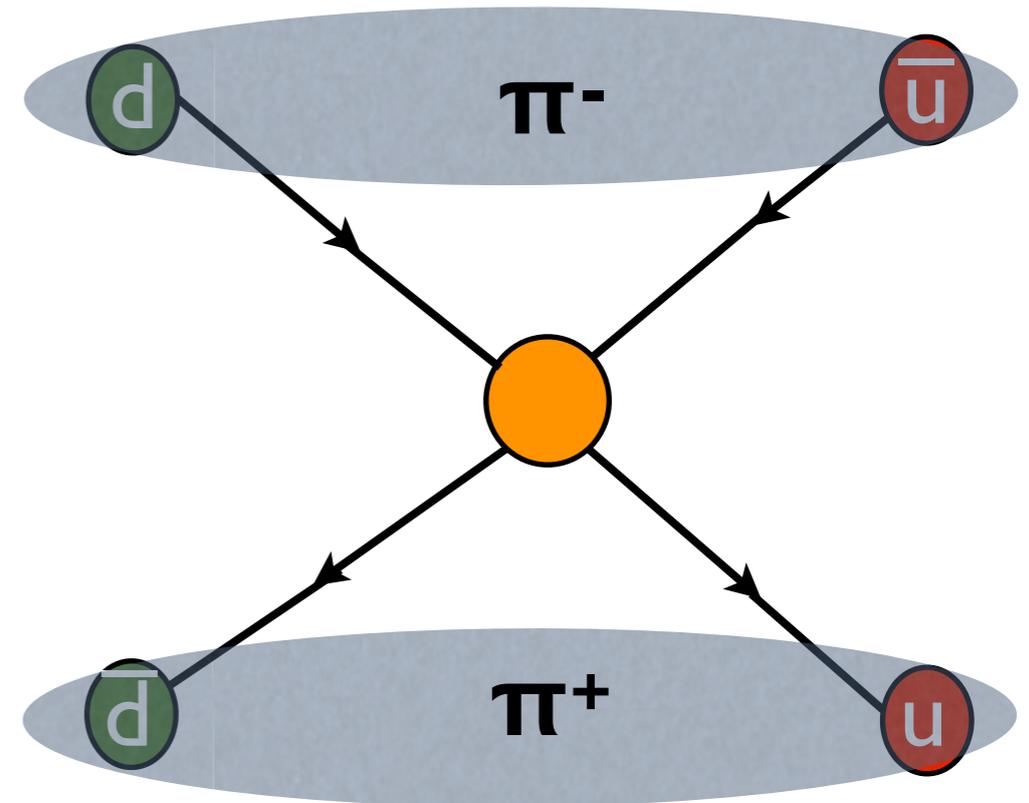
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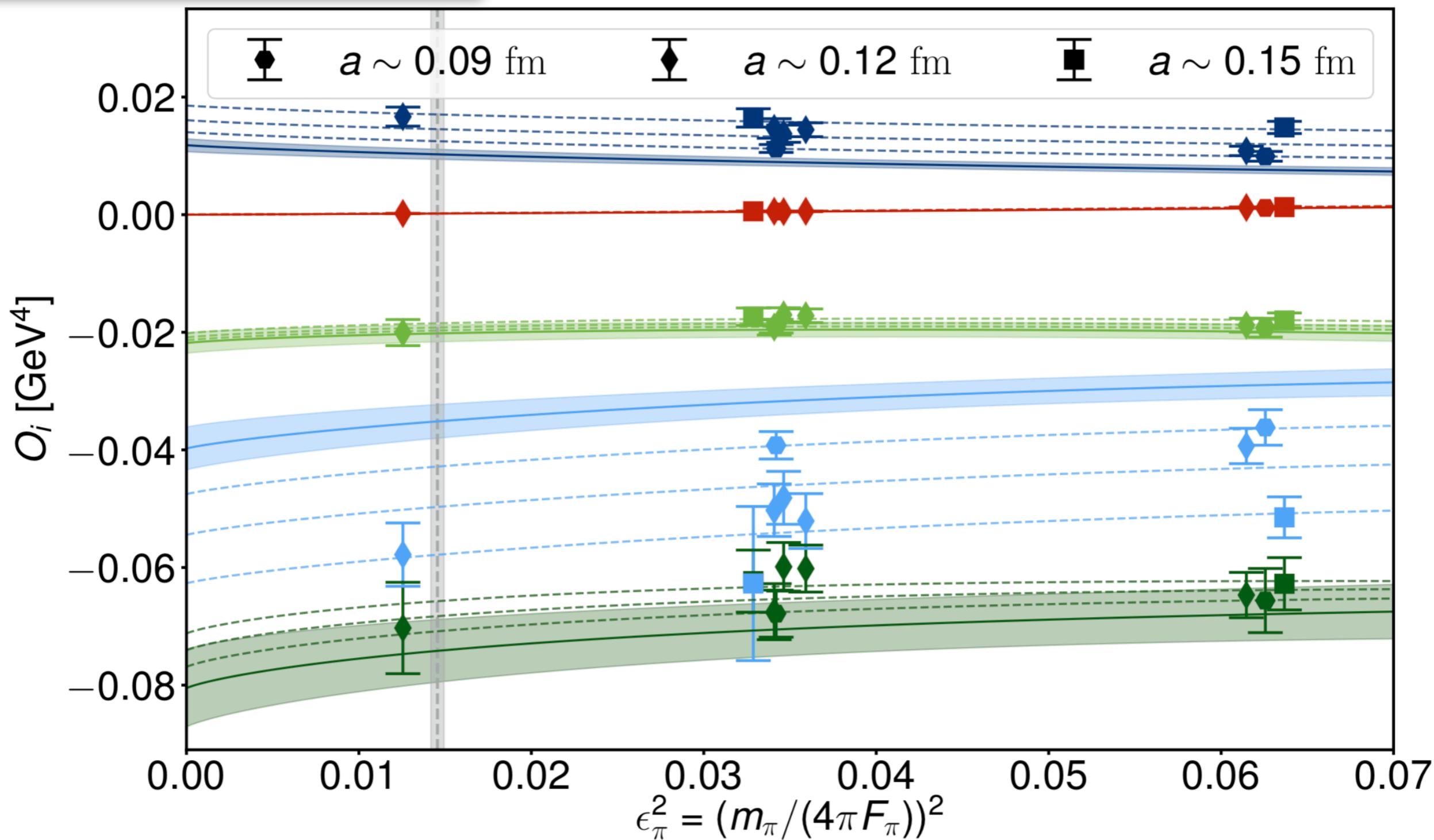
Leading order short-range:

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

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

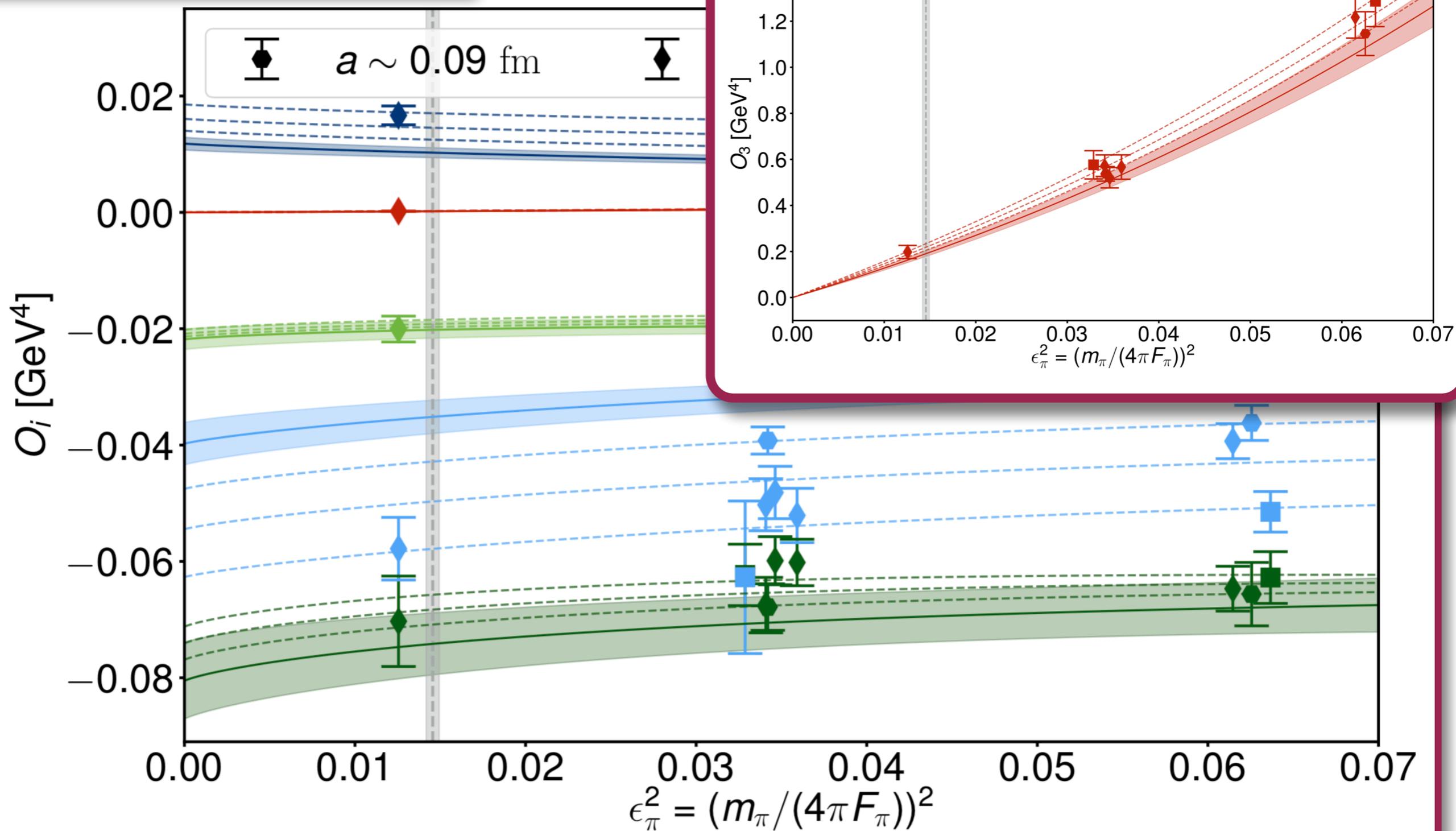


Lattice results



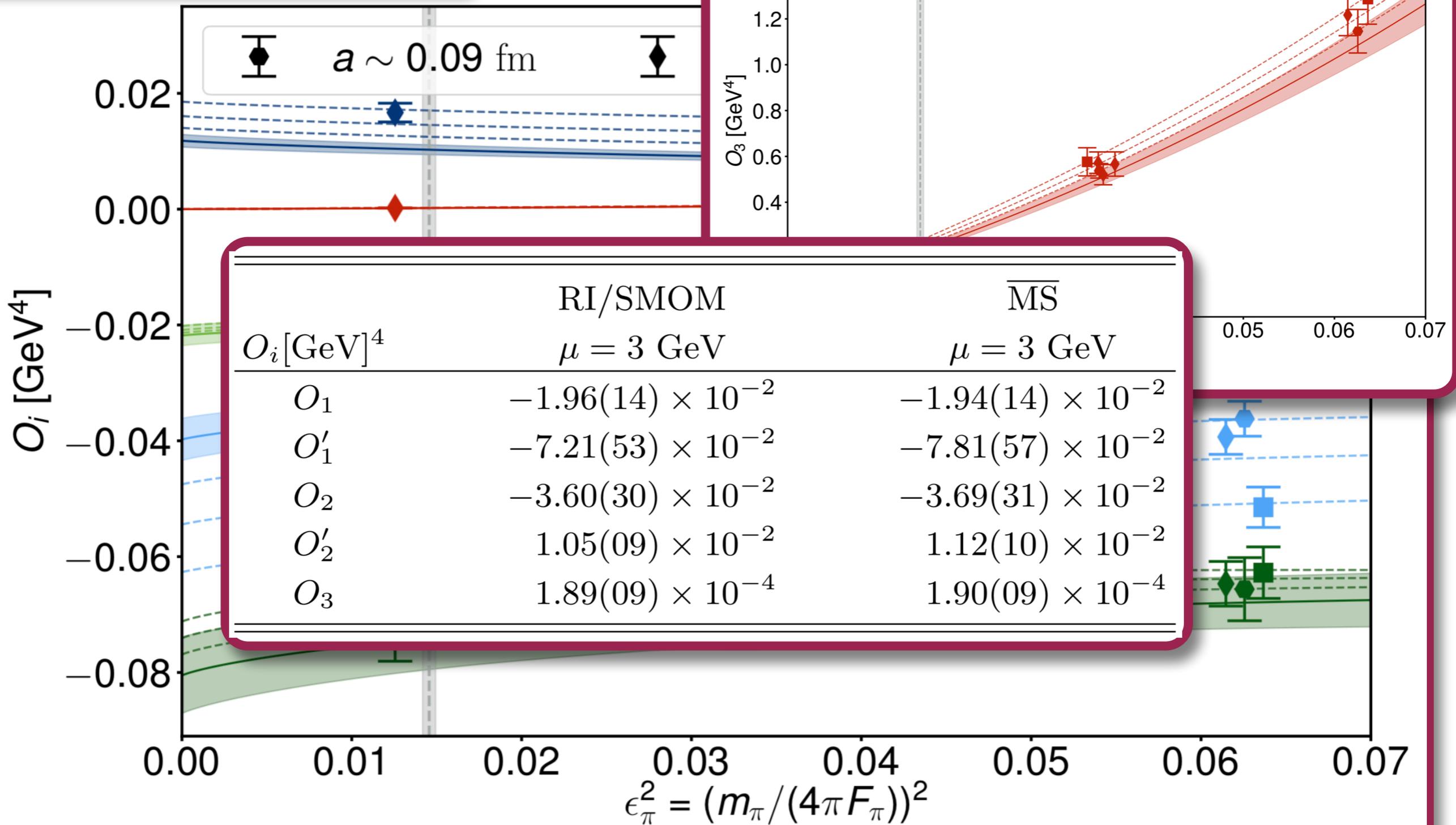
arXiv:1805.02634 (2018)
using MILC HISQ ensembles

Lattice results



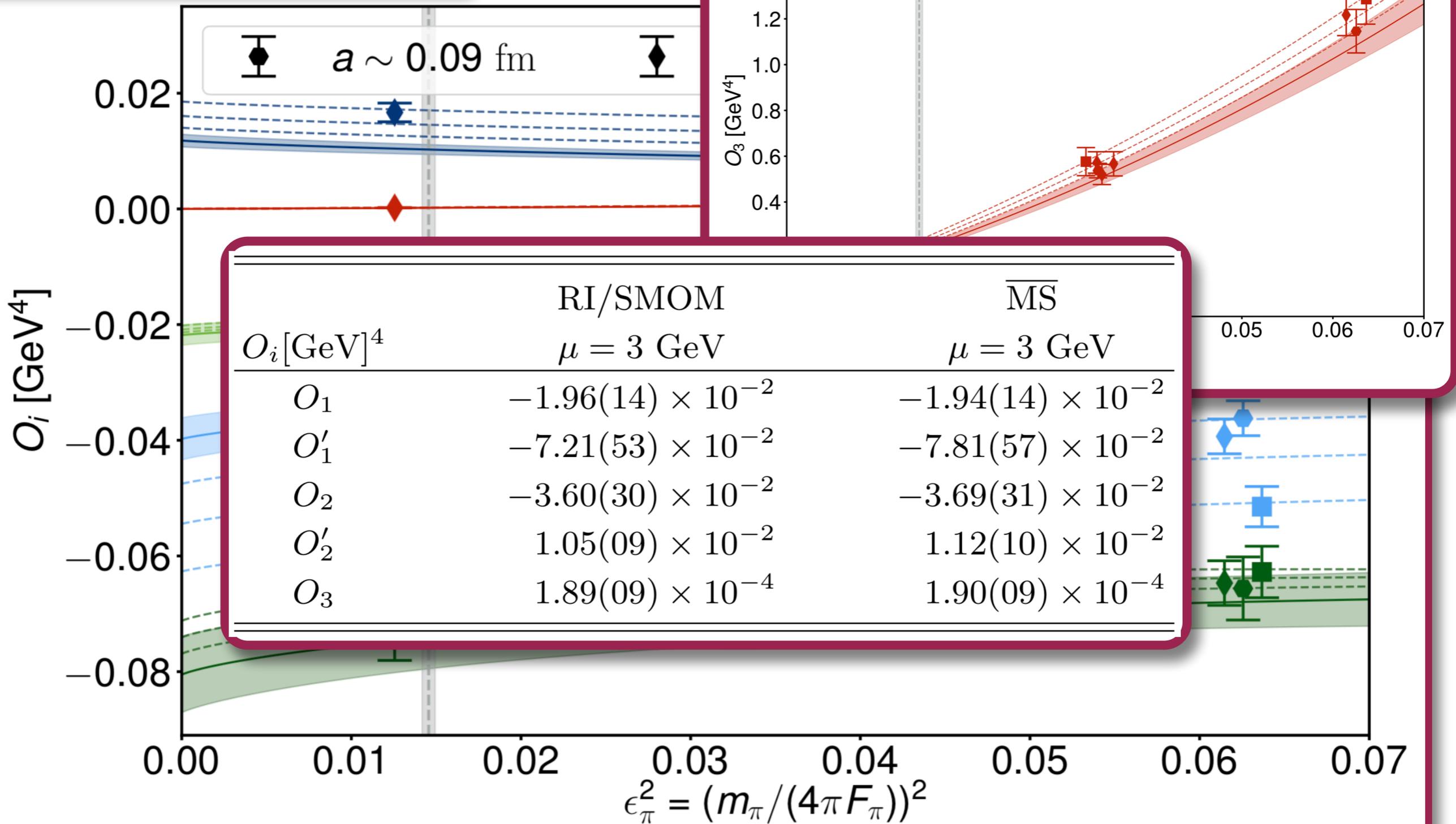
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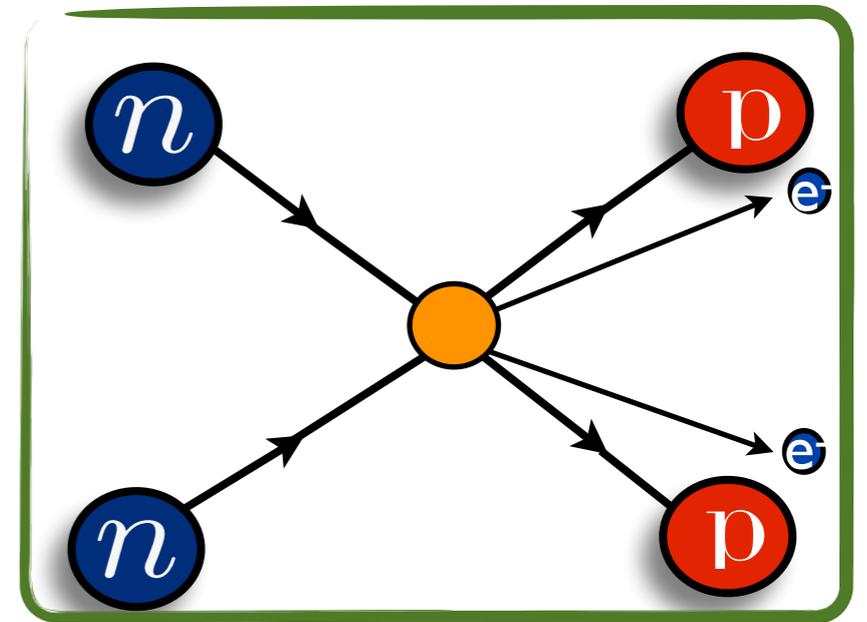
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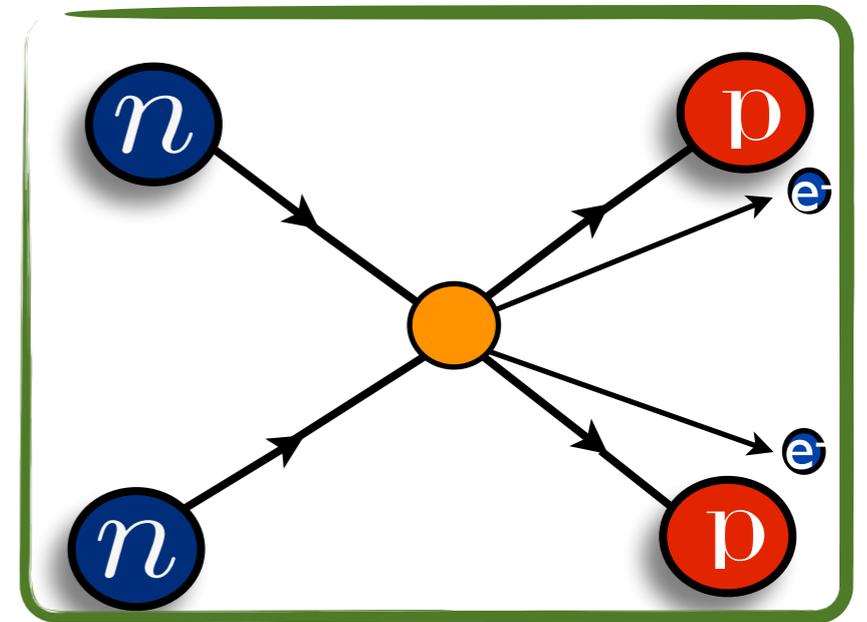
Agrees to 2σ with:
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti
Phys.Lett. B769 (2017) 460-464

Two-nucleon contact

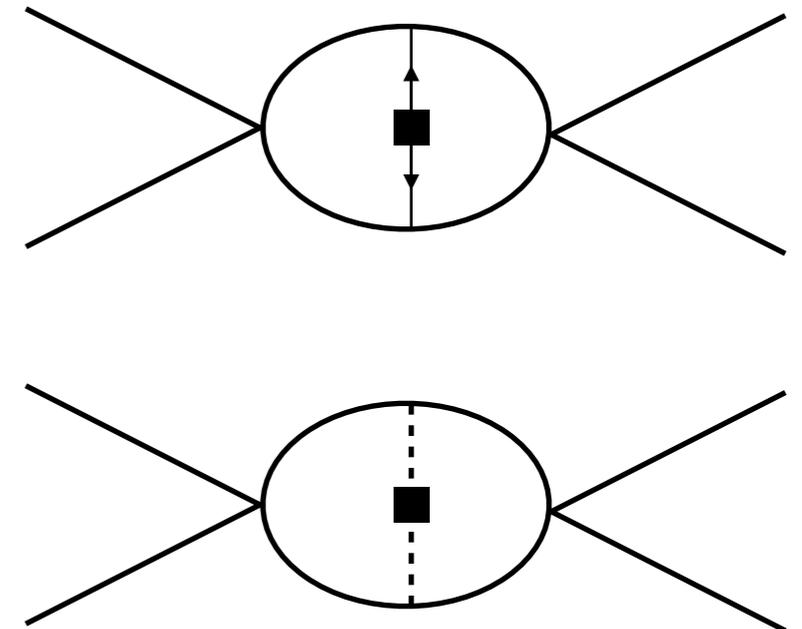


Two-nucleon contact

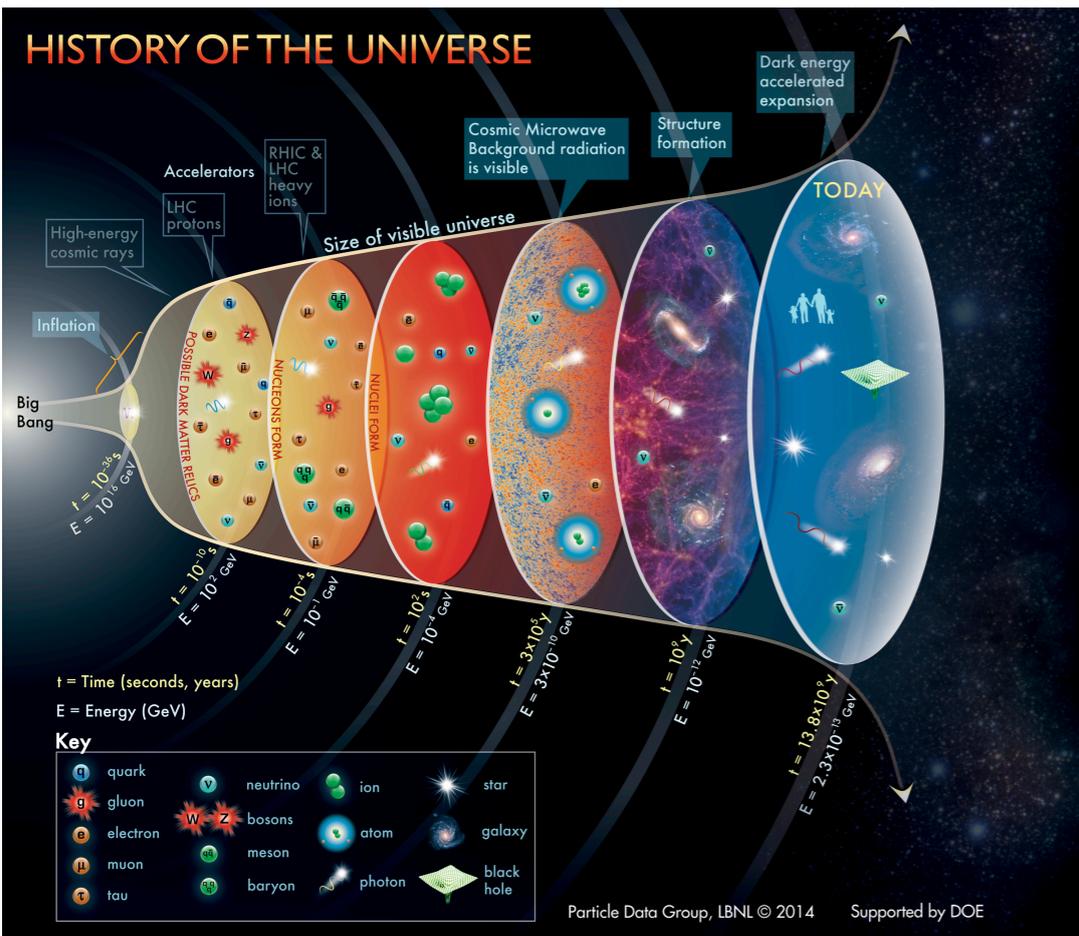
- Why calculate it?
 - Formally NNLO (Weinberg counting)
 - Weinberg often doesn't converge well, particularly in the spin singlet channel
 - LO contribution vanishes for some BSM models
- Contact operator for standard double beta decay found to be important at heavy pion mass (NPLQCD '17)
- New techniques for calculating contact op from light neutrino exchange (see talk by D. Murphy, ICHEP 2018)



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

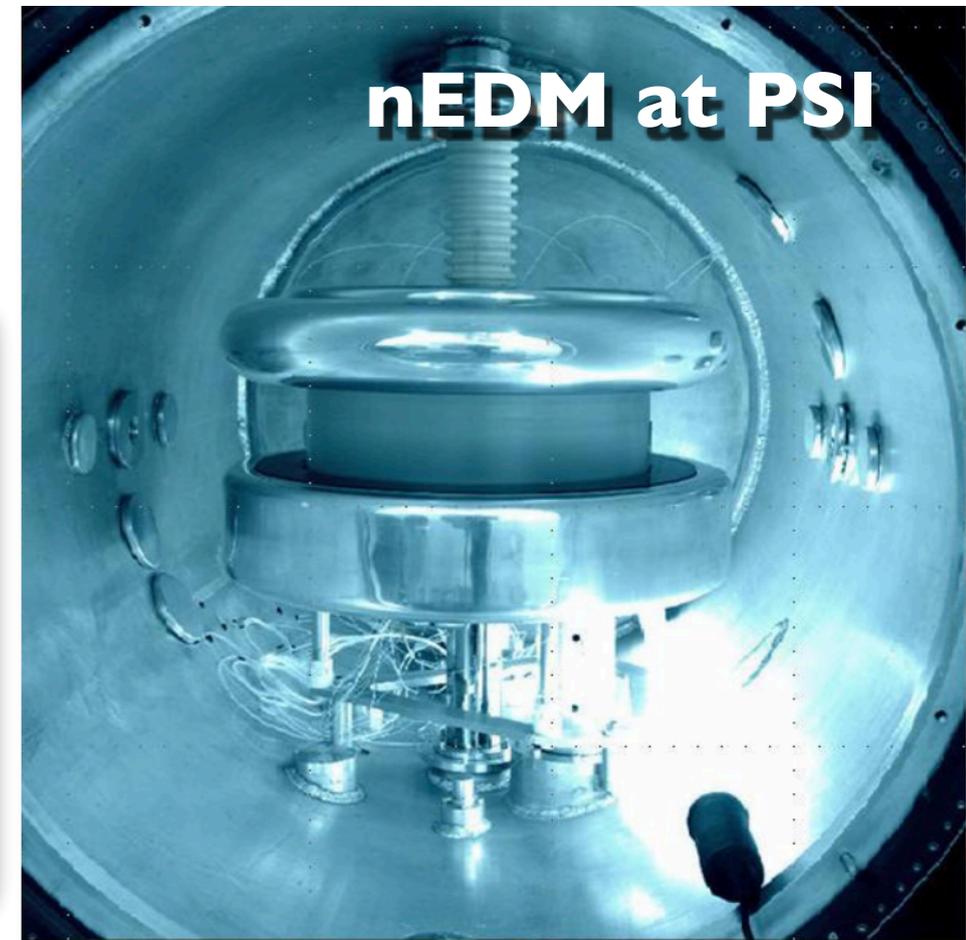


Baryogenesis: CP violation

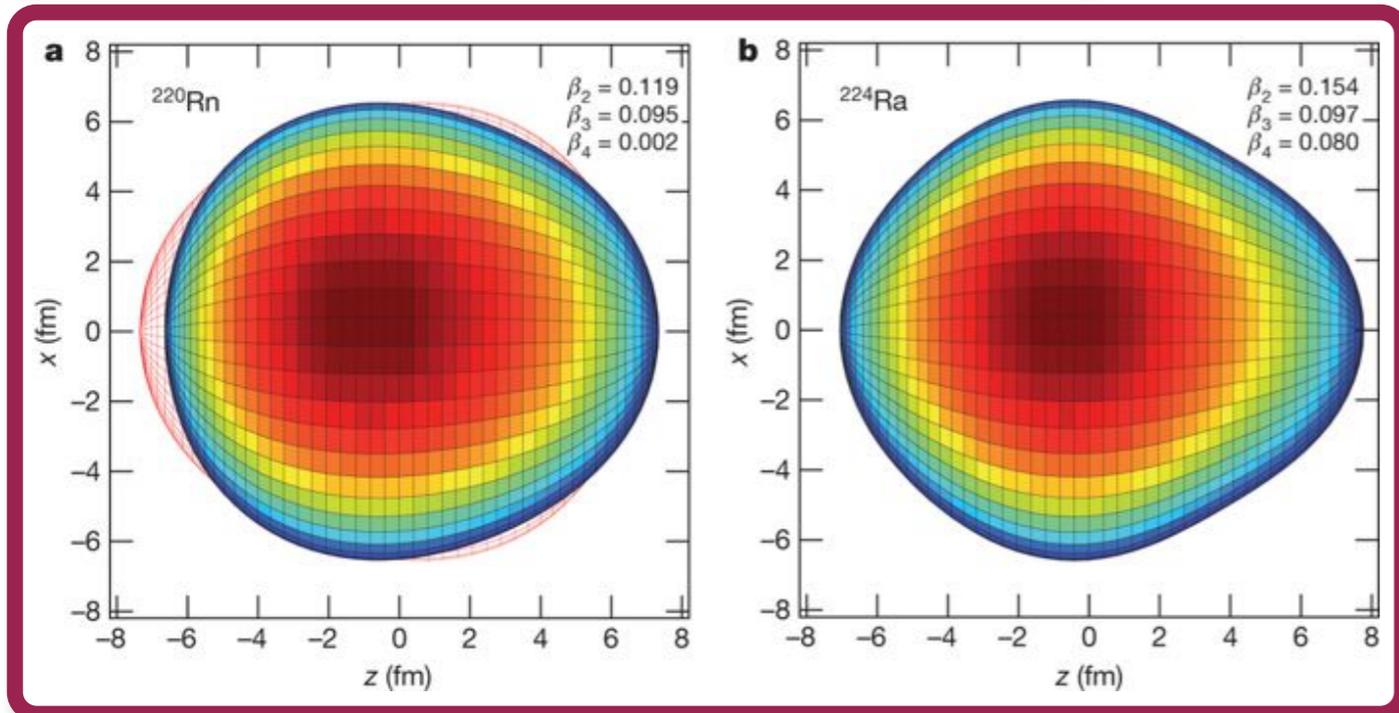
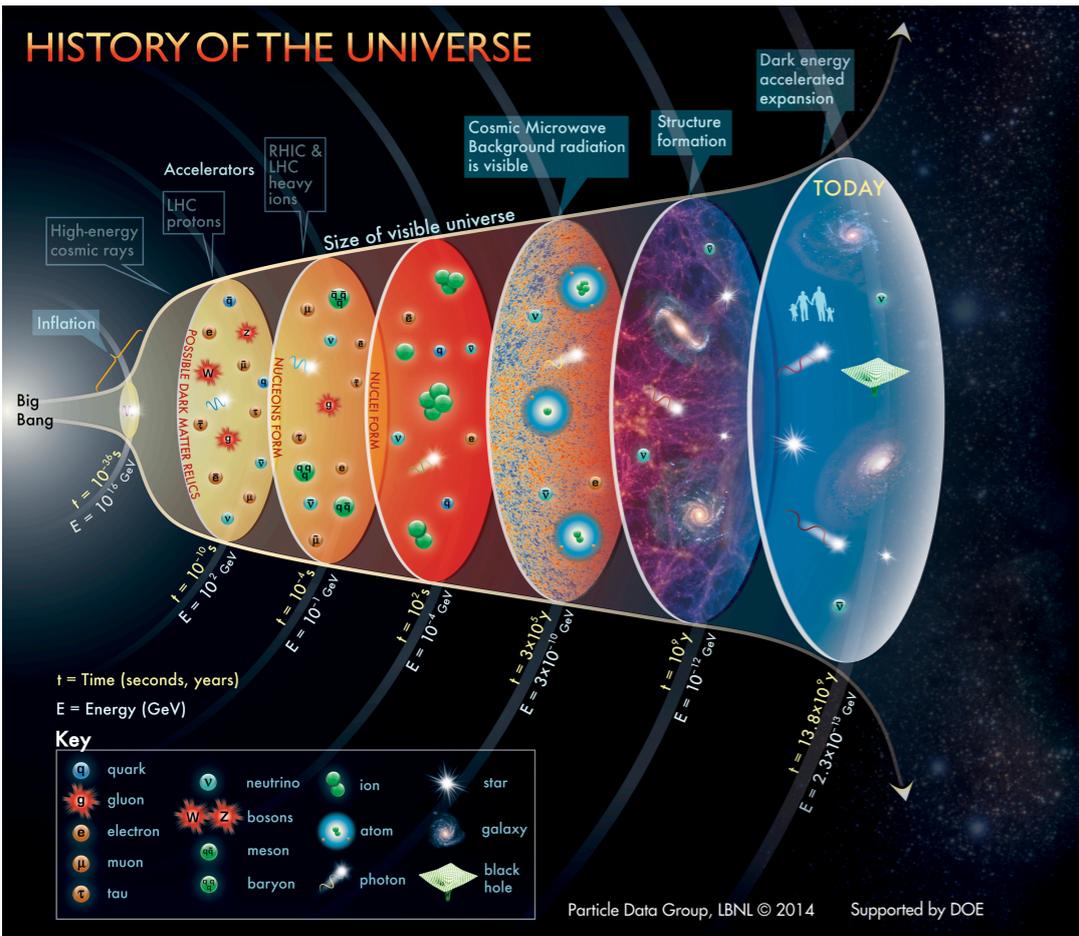


Time-reversal violation:
permanent electric dipole moments in fermions

Baryogenesis: CP violation

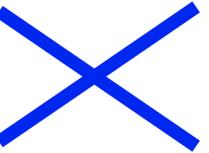
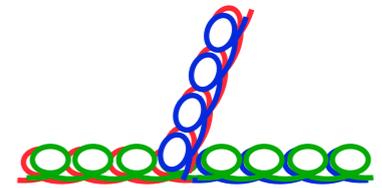
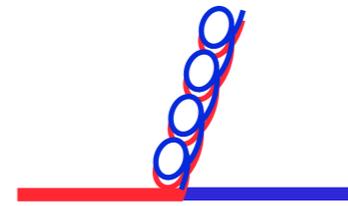
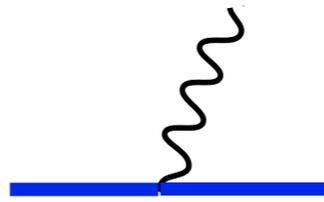
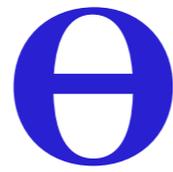


Time-reversal violation:
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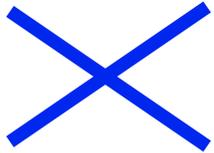
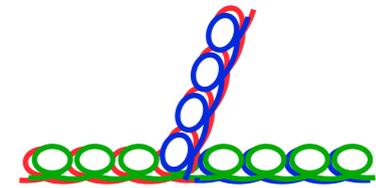
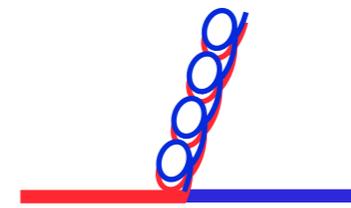
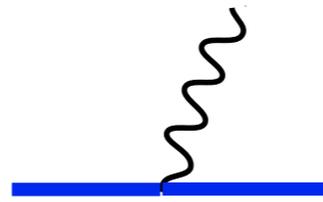


Gaffney et al. Nature 497 (2013)

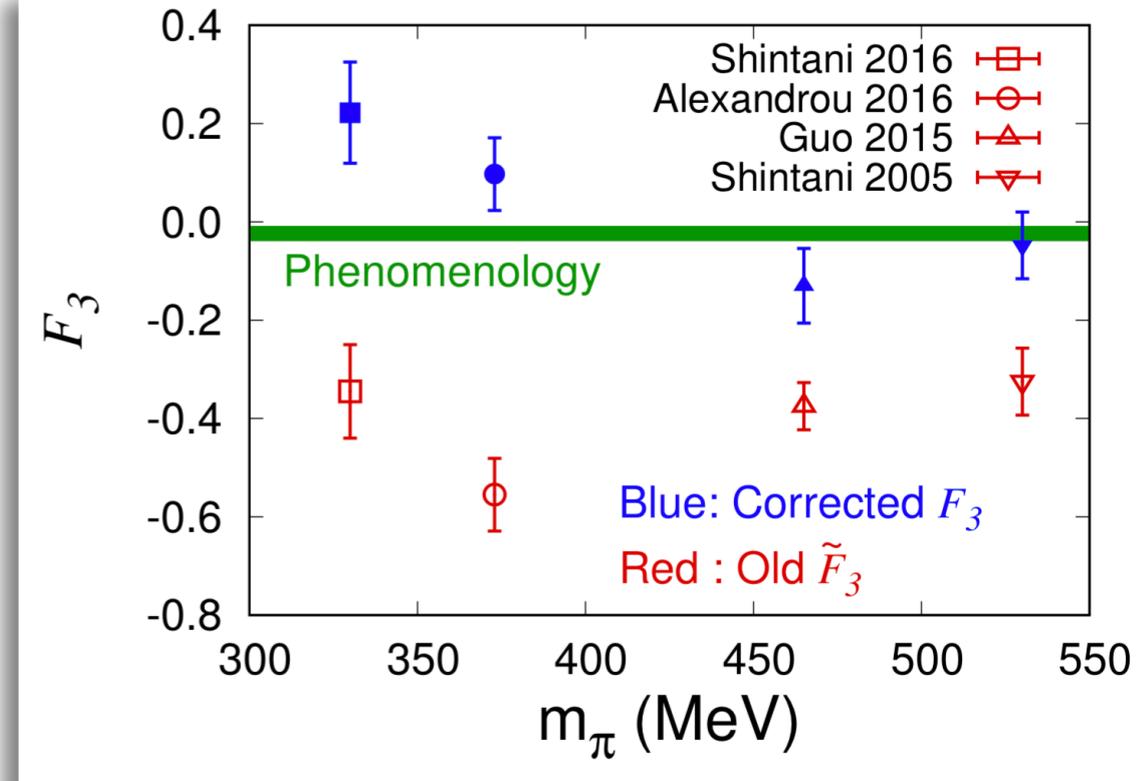
Lattice Results



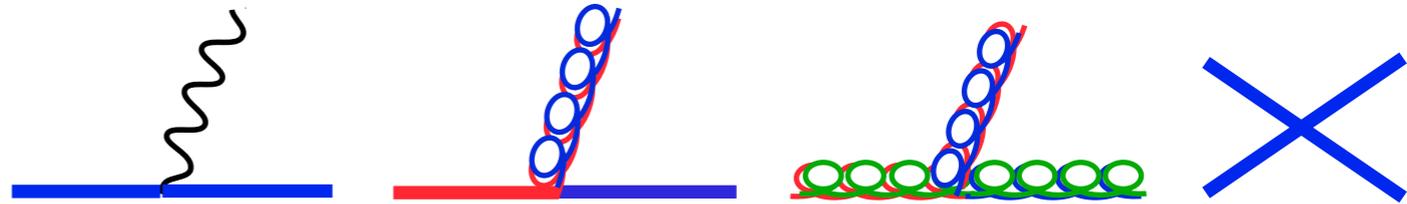
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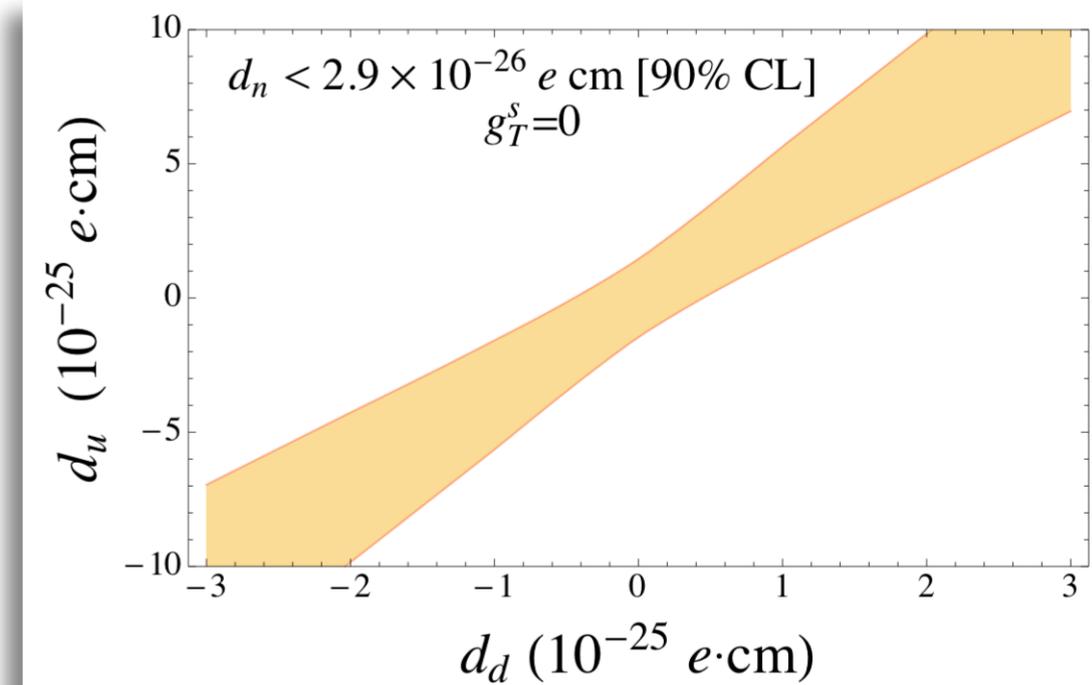
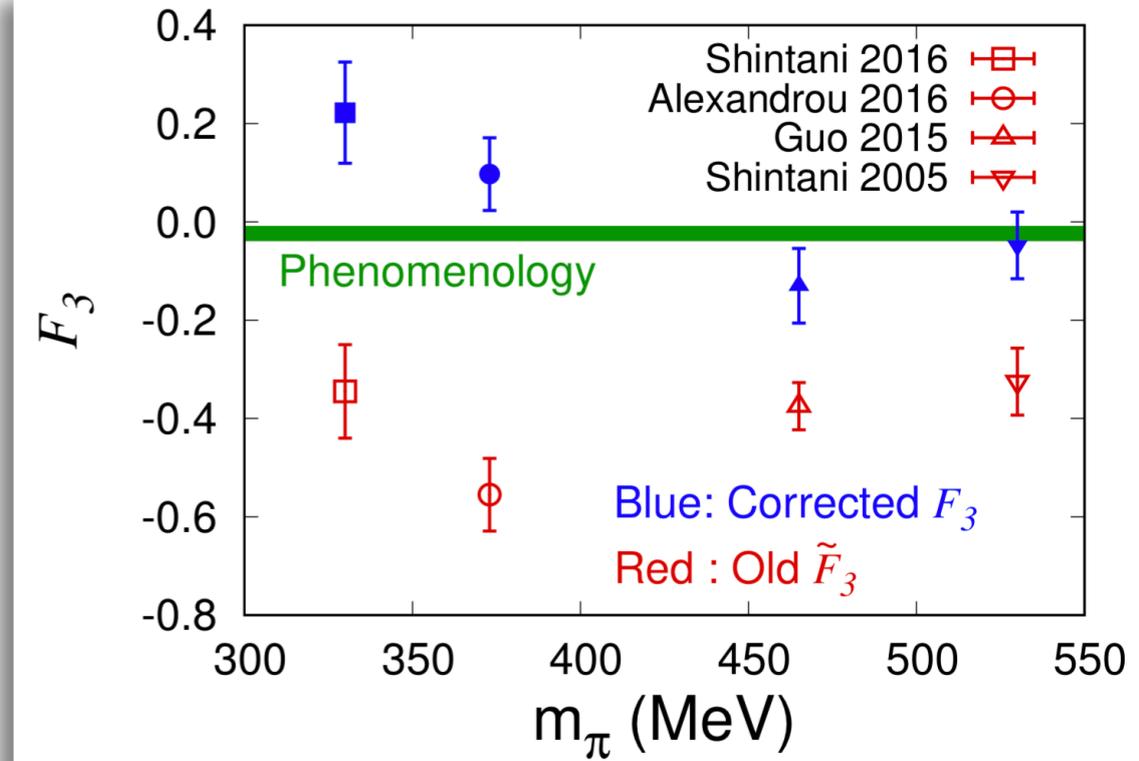
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 - all results now consistent with zero
Abramczyk et al, Phys. Rev. D 96, 014501 (2017)
 - promising new non-zero results at $m_\pi \sim 330$ MeV (see talk by S. Syritsyn)



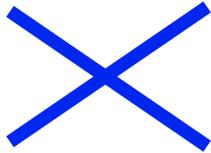
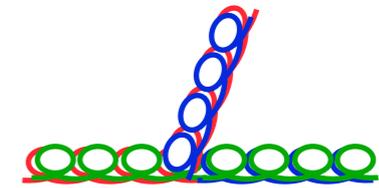
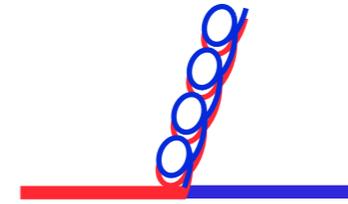
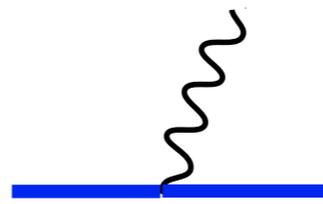
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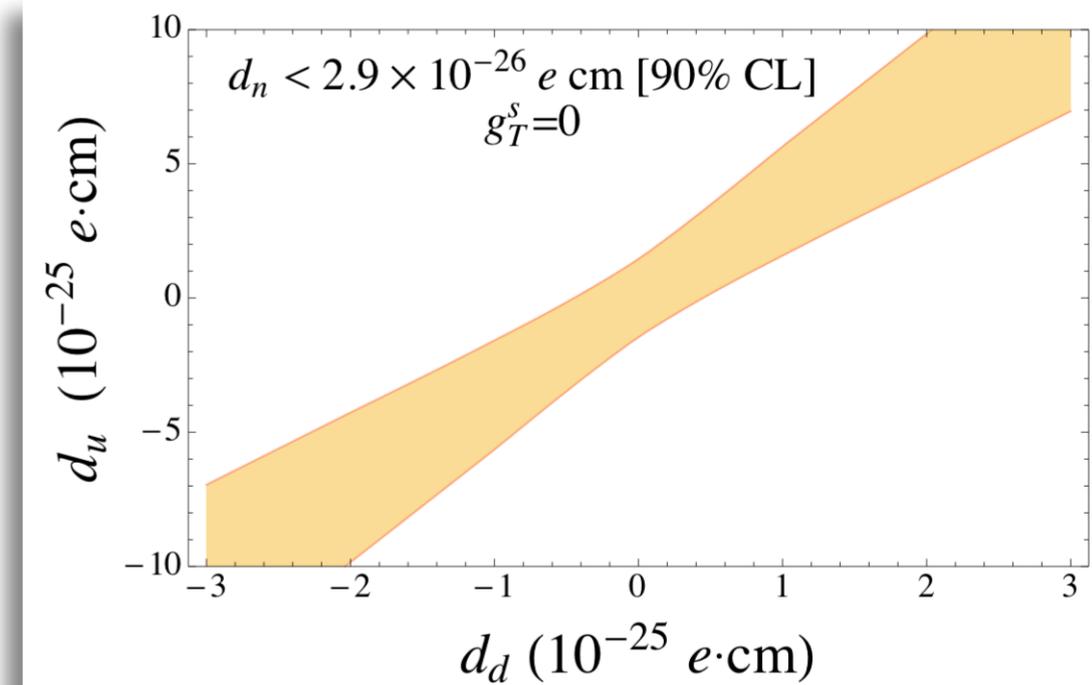
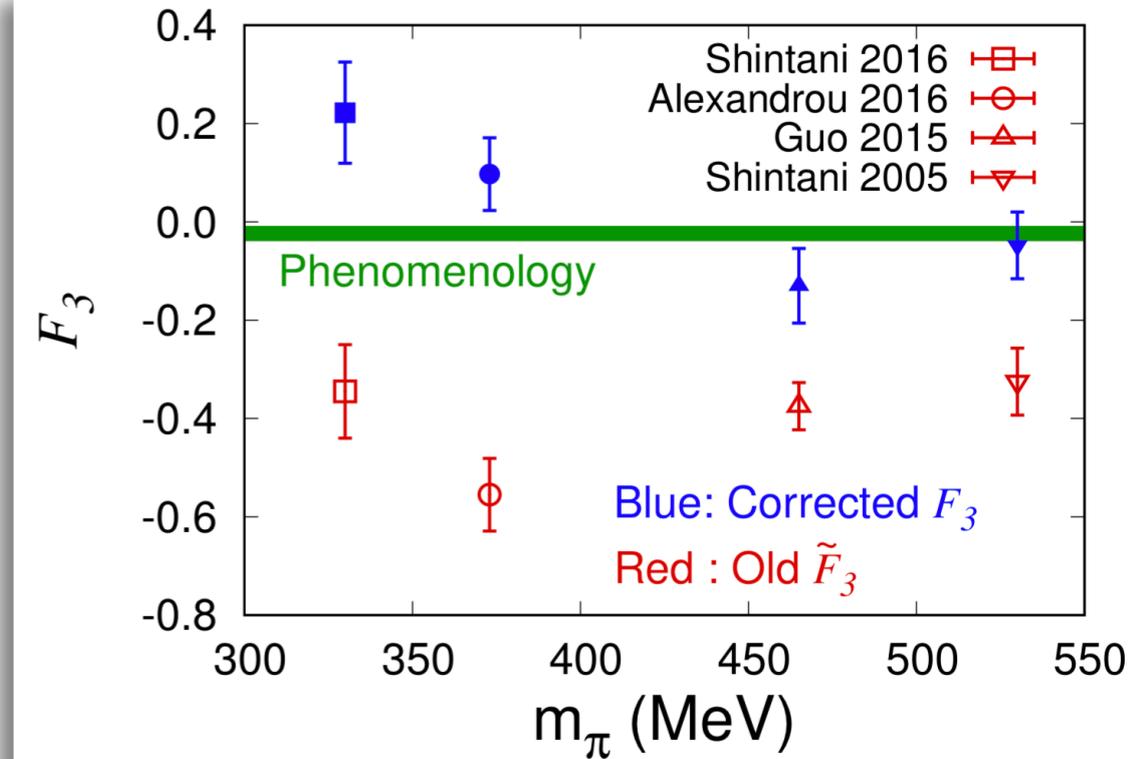
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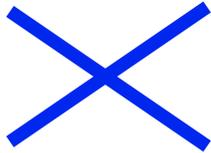
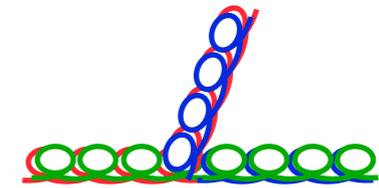
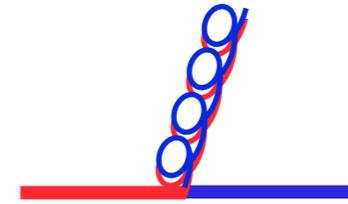
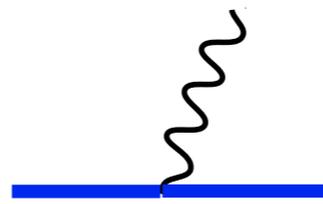
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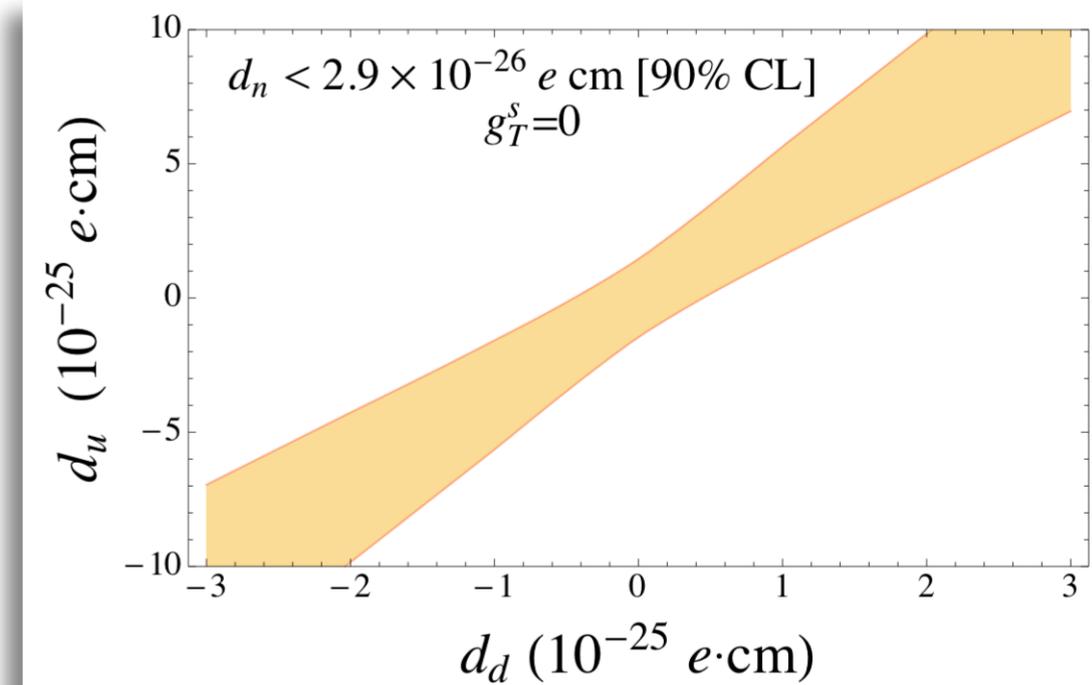
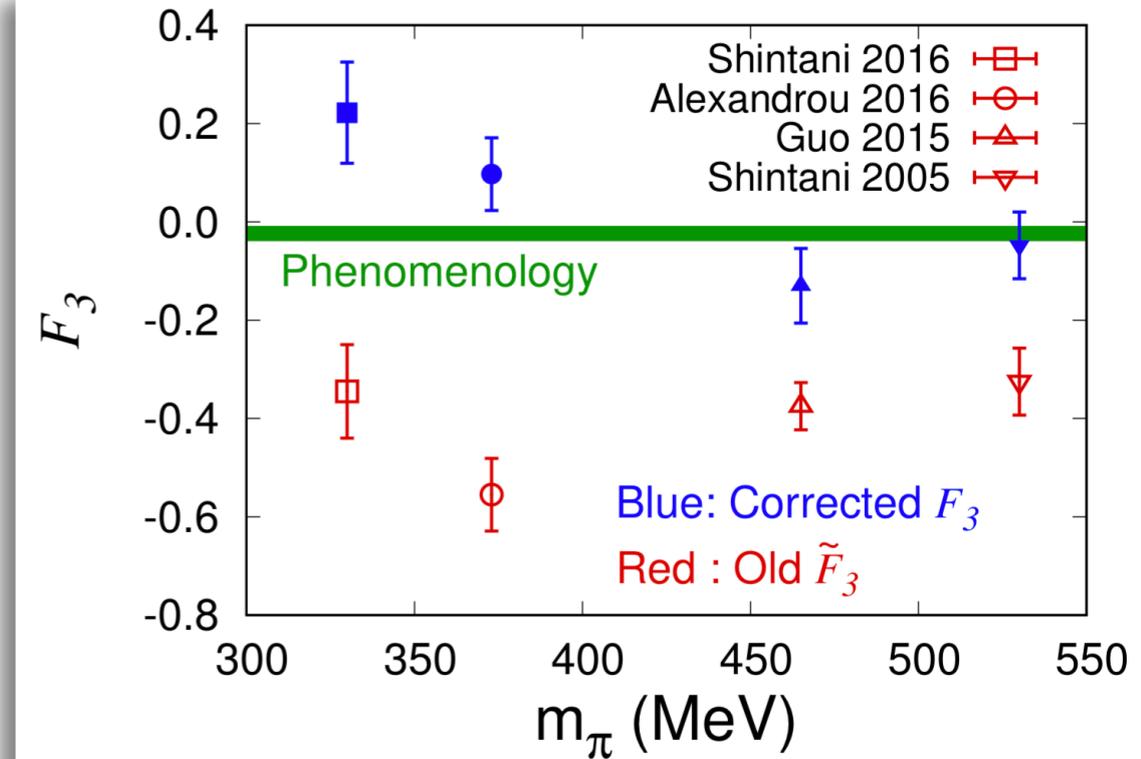
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T. Bhattacharya et al ('15, '16), Izubuchi et al ('17)



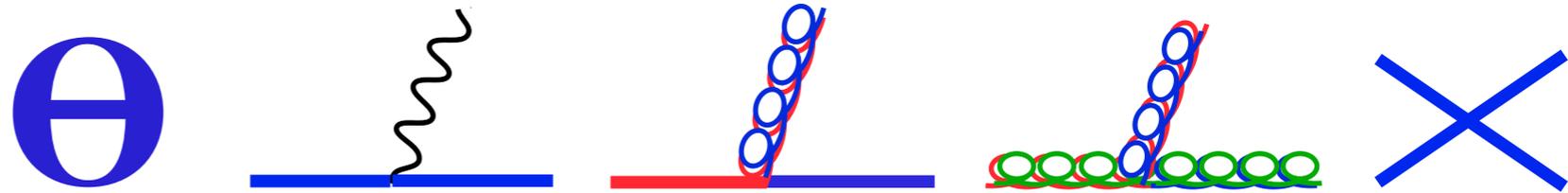
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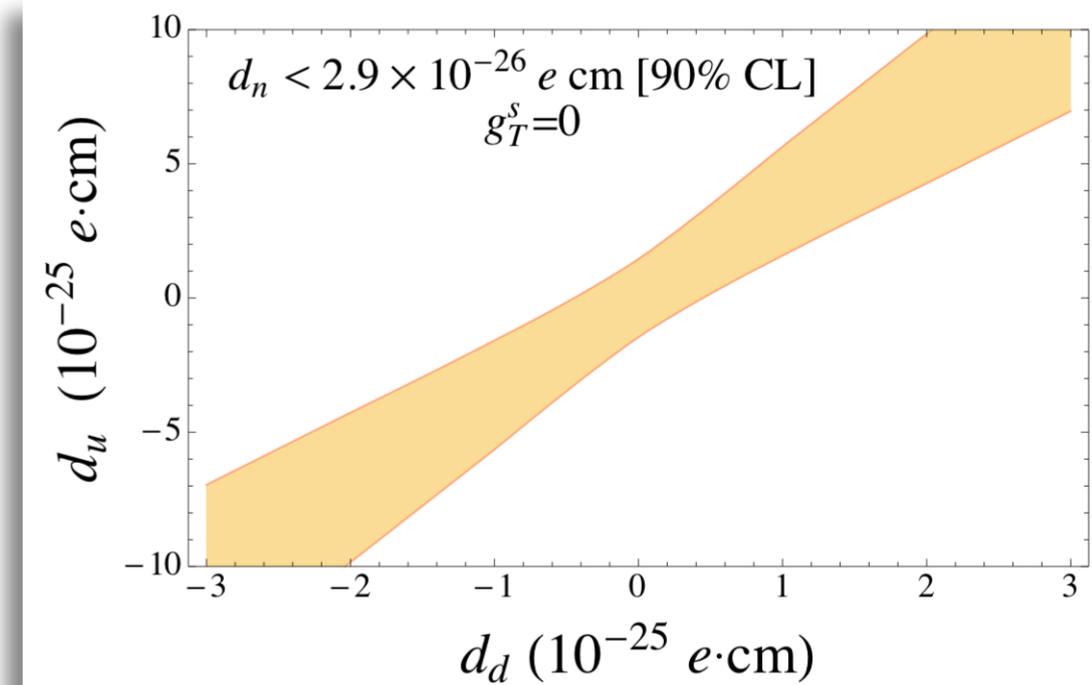
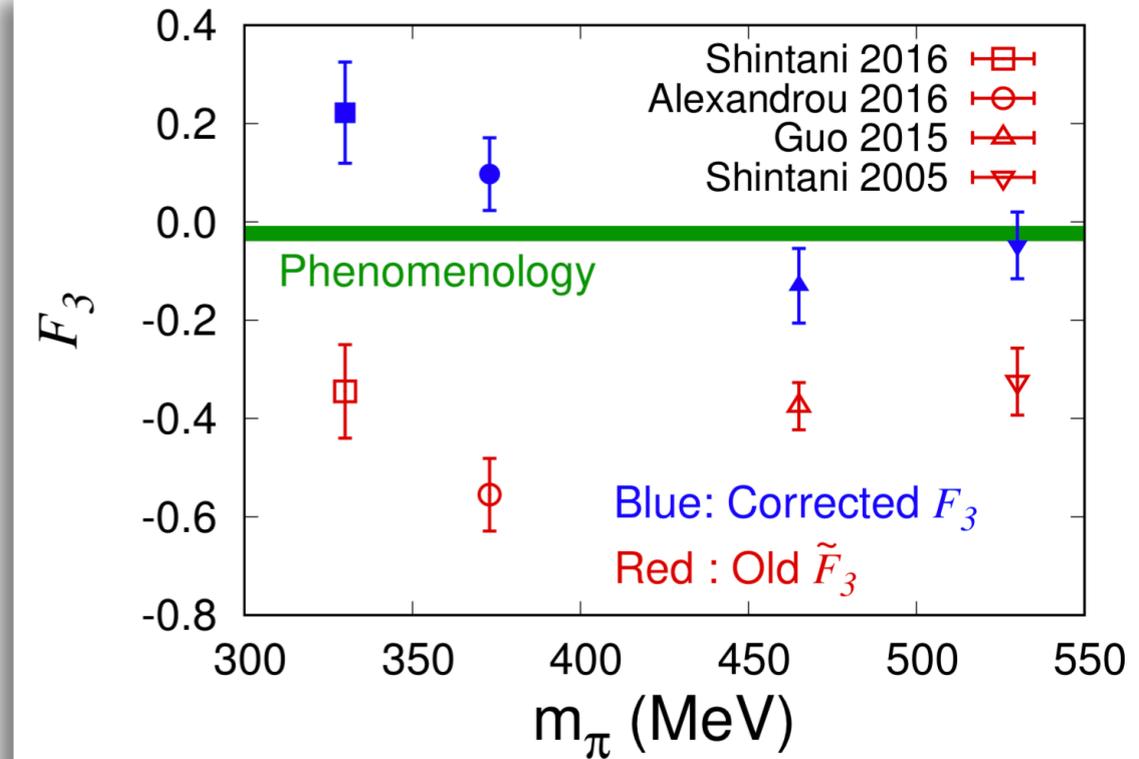
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T. Bhattacharya et al ('15, '16), Izubuchi et al ('17)
- Weinberg operator: A. Shindler, et al ('15)



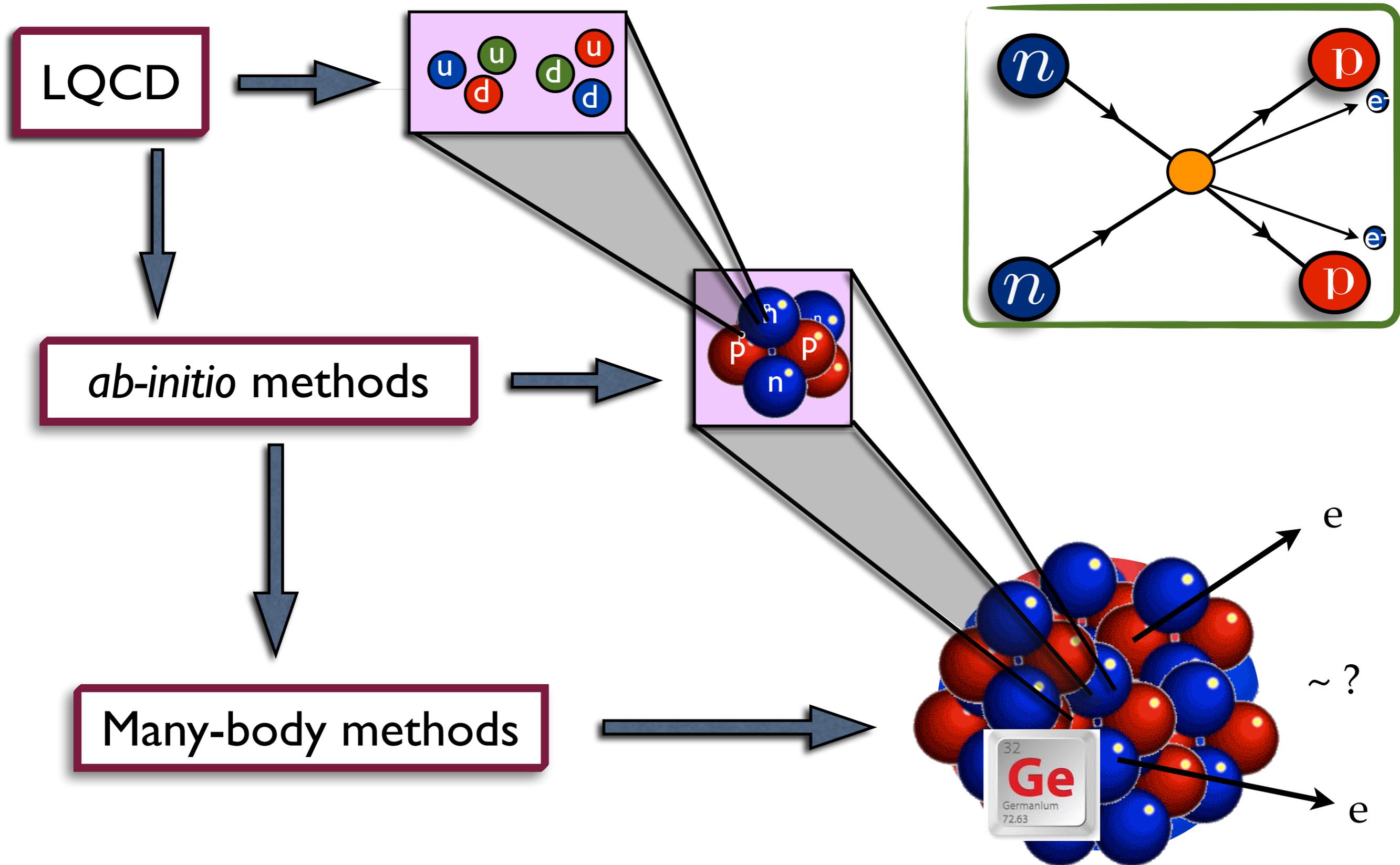
Lattice Results



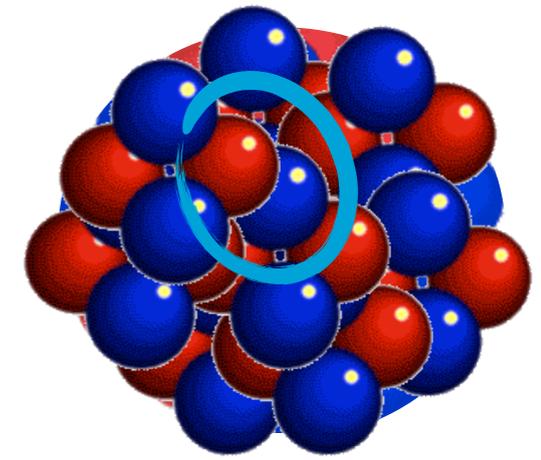
- Theta term:
 - S.Aoki et al ('89, '05), F. Berruto et al ('05), A. Shindler et al ('15), C. Alexandrou et al ('15), E. Shintani et al ('05, '06, '07, '15, '16), R. Horsley et al ('08), F.K. Guo et al ('15)
 - all results now consistent with zero
Abramczyk et al, Phys. Rev. D 96, 014501 (2017)
 - promising new non-zero results at $m_\pi \sim 330$ MeV (see talk by S. Syritsyn)
- quark EDM (Bhattacharya '16)
- quark chromo-EDM
 - non-zero signal, renormalization is difficult
T. Bhattacharya et al ('15, '16), Izubuchi et al ('17)
- Weinberg operator: A. Shindler, et al ('15)
- CPV pion-nucleon couplings: D. Brantley et al ('16), see also A. Walker-Loud Lattice '18



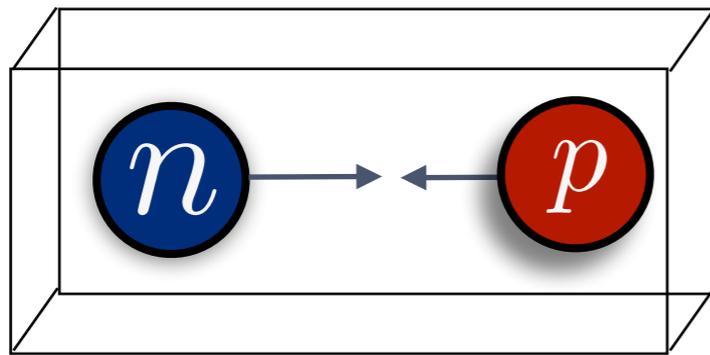
Multi-nucleon interactions



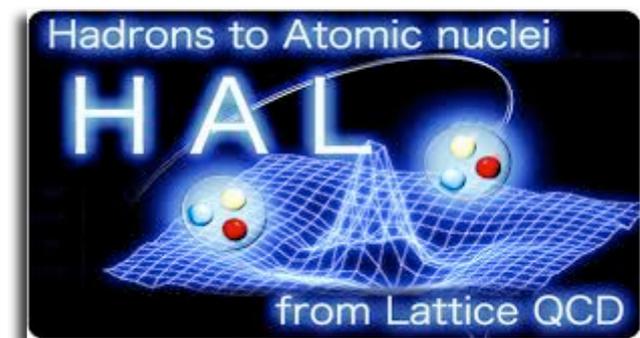
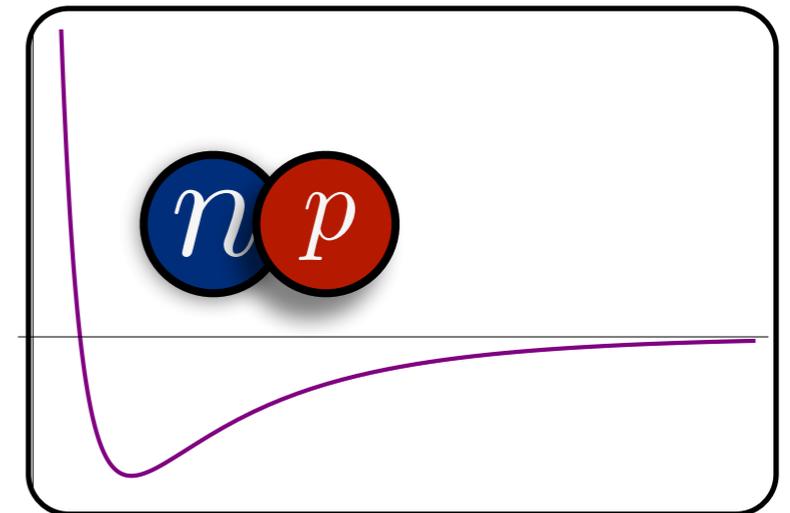
Two methods for calculating few-nucleon interactions from LQCD:



Spectroscopy + Lüscher Method

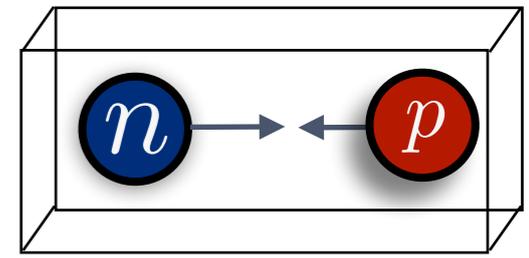


Potential Method



Yamazaki, et. al.

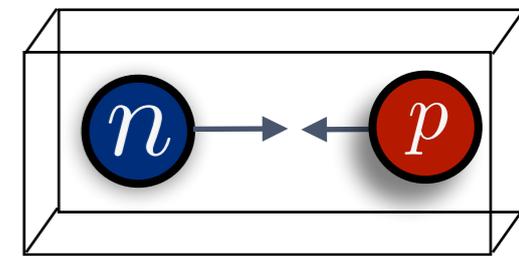
Lüscher



- Direct scattering “experiments” not possible in finite volume/Euclidean time
- Lüscher: measure discrete spectra of interacting particles in a box, and infer the interaction (scattering phase shift)

Lüscher

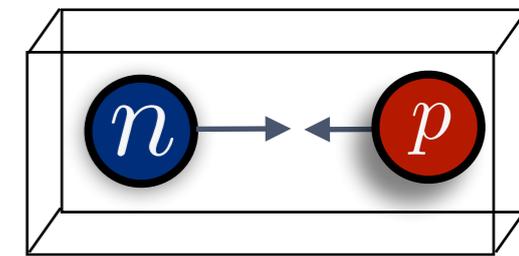
See talk by M.
Hansen



- Direct scattering “experiments” not possible in finite volume/Euclidean time
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Lüscher

See talk by M. Hansen

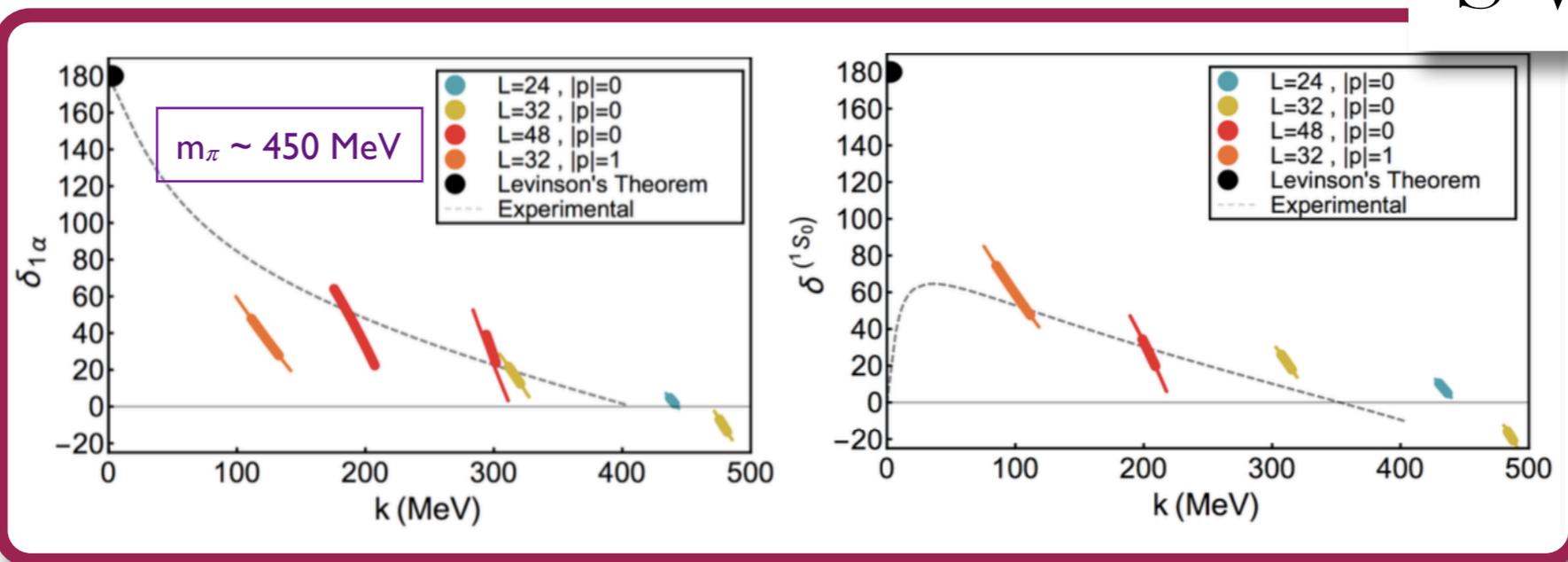


- Direct scattering “experiments” not possible in finite volume/Euclidean time
- Lüscher: measure discrete spectra of interacting particles in a box, and infer the interaction (scattering phase shift)

S-wave

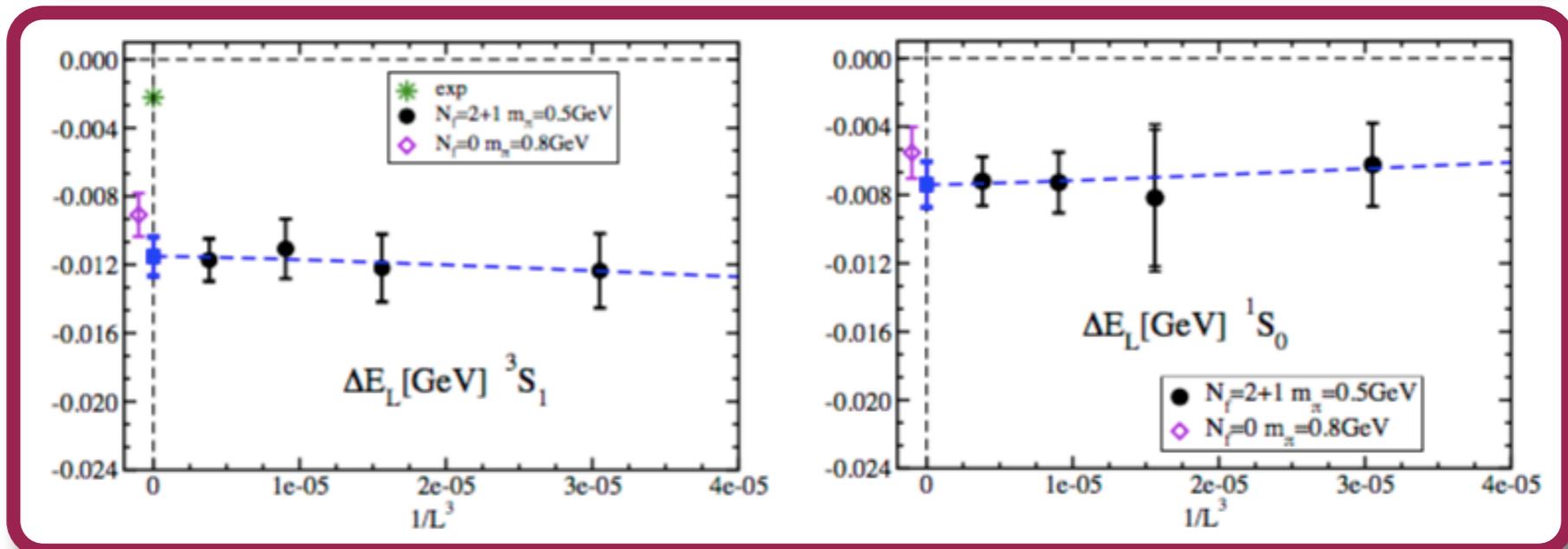
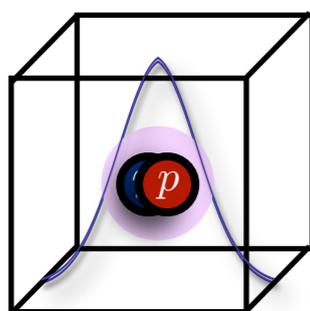


Phys.Rev. D92 (2015) no.11, 114512



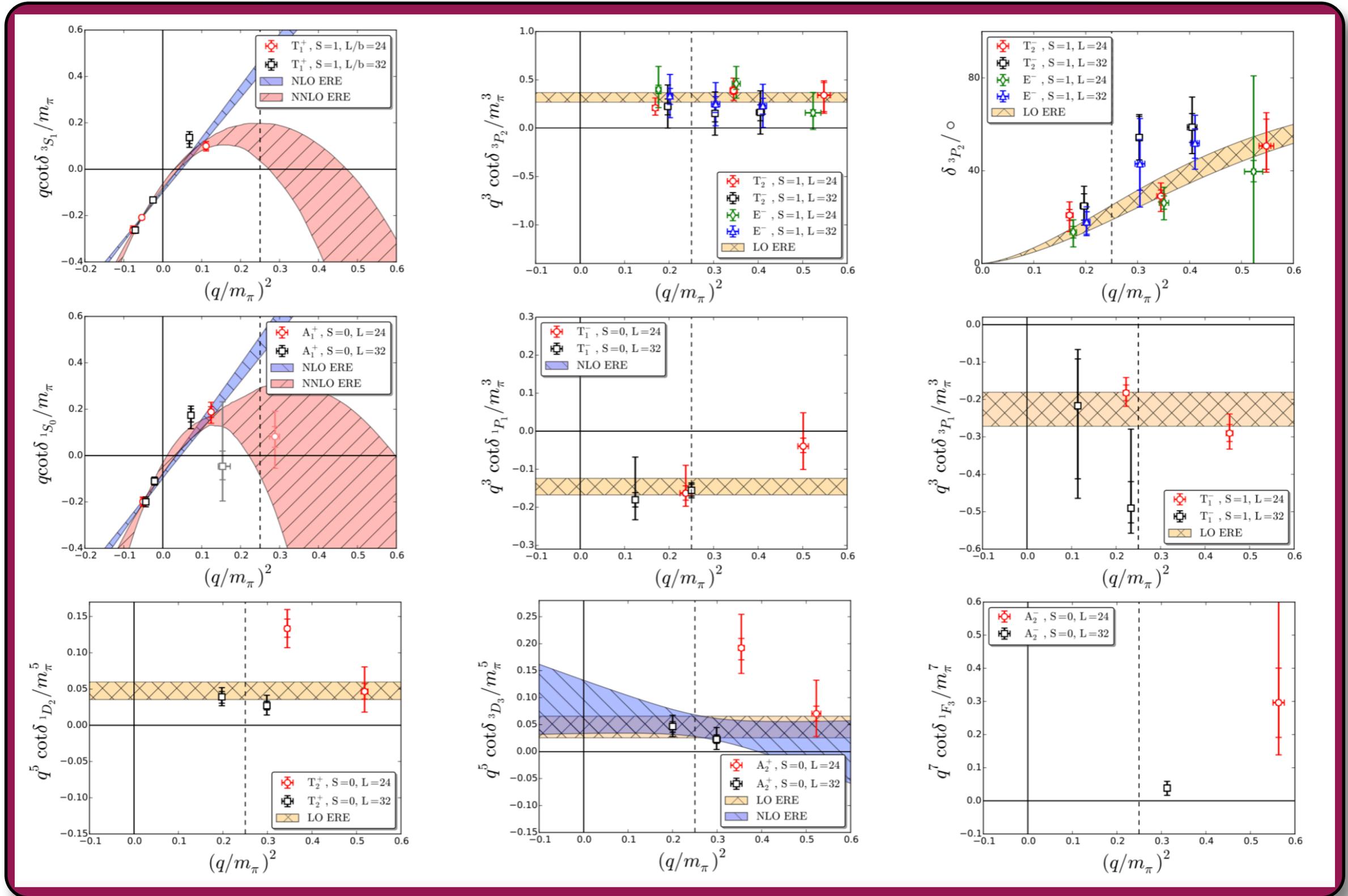
Yamazaki, et. al.

PoS LATTICE2013 (2014) 230



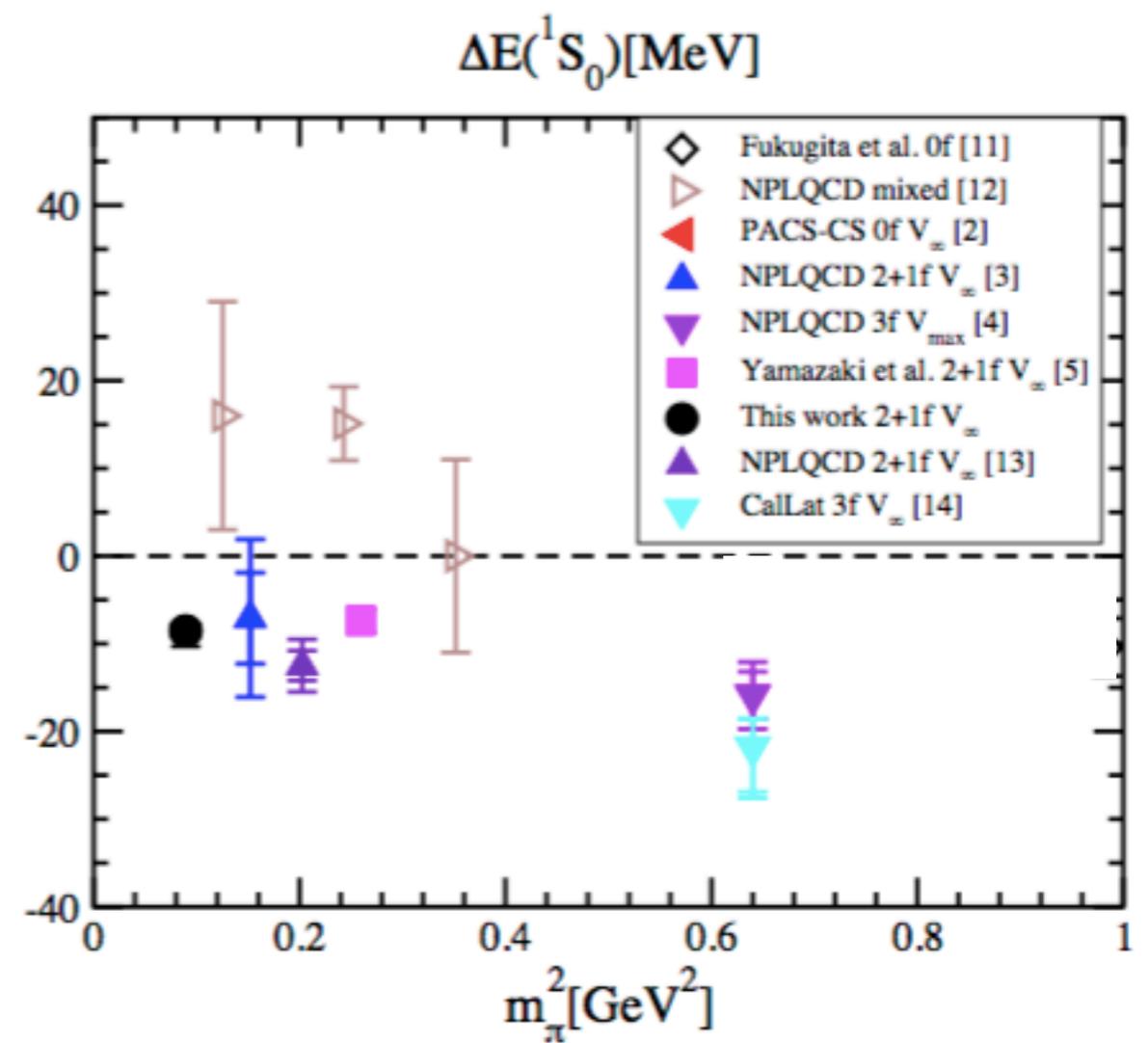
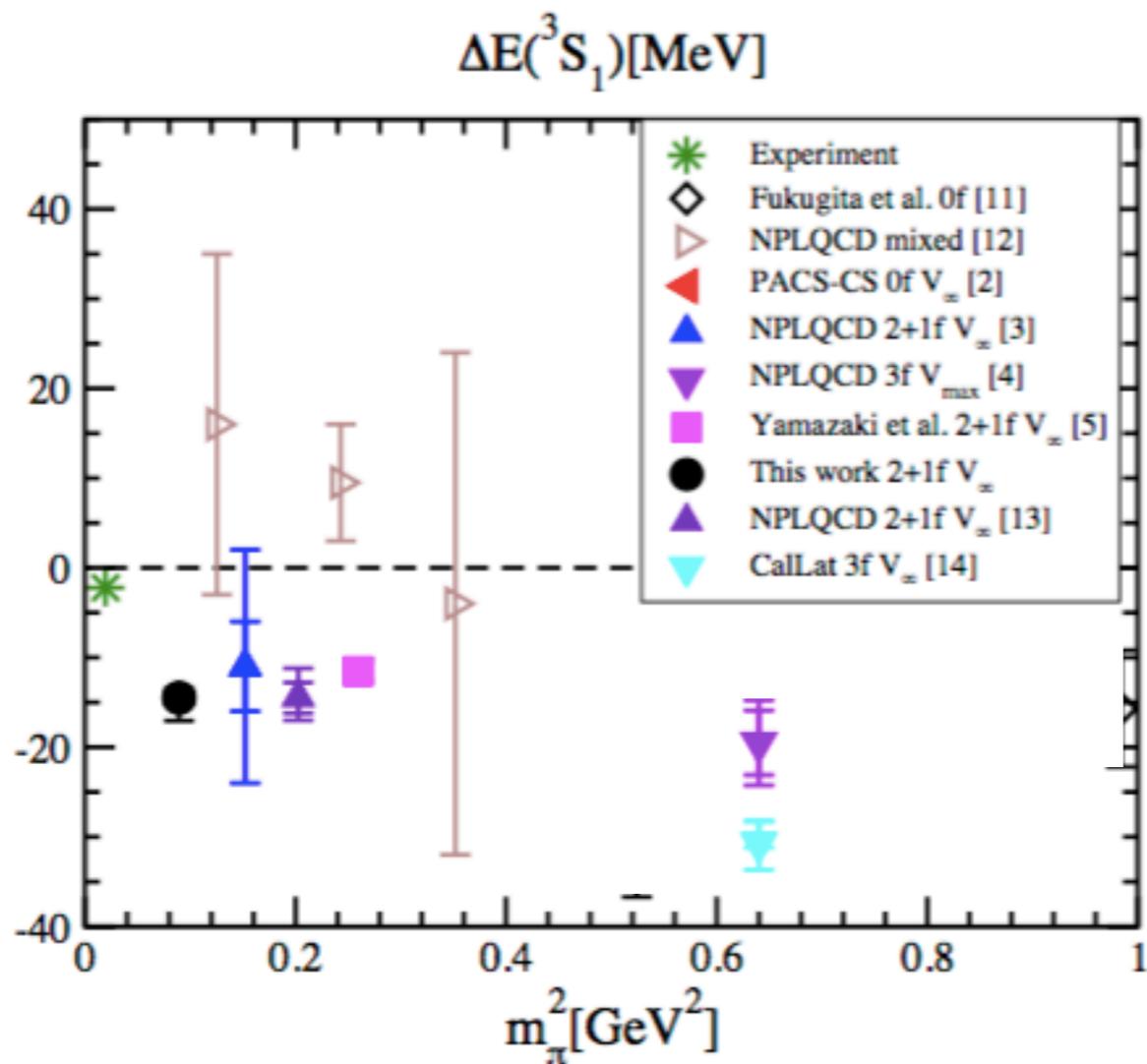
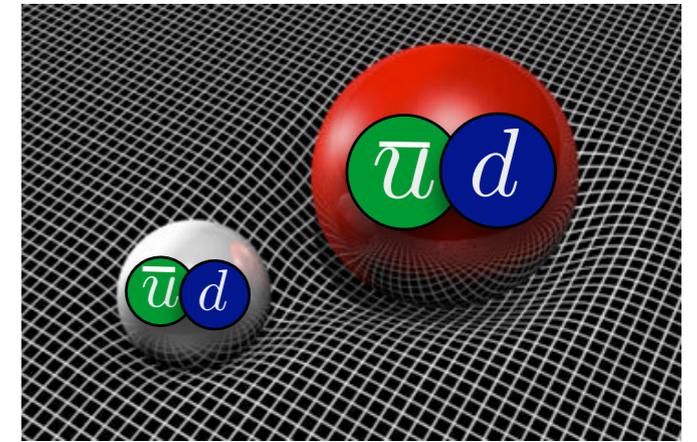
$m_\pi \sim 800$ MeV

Higher partial waves

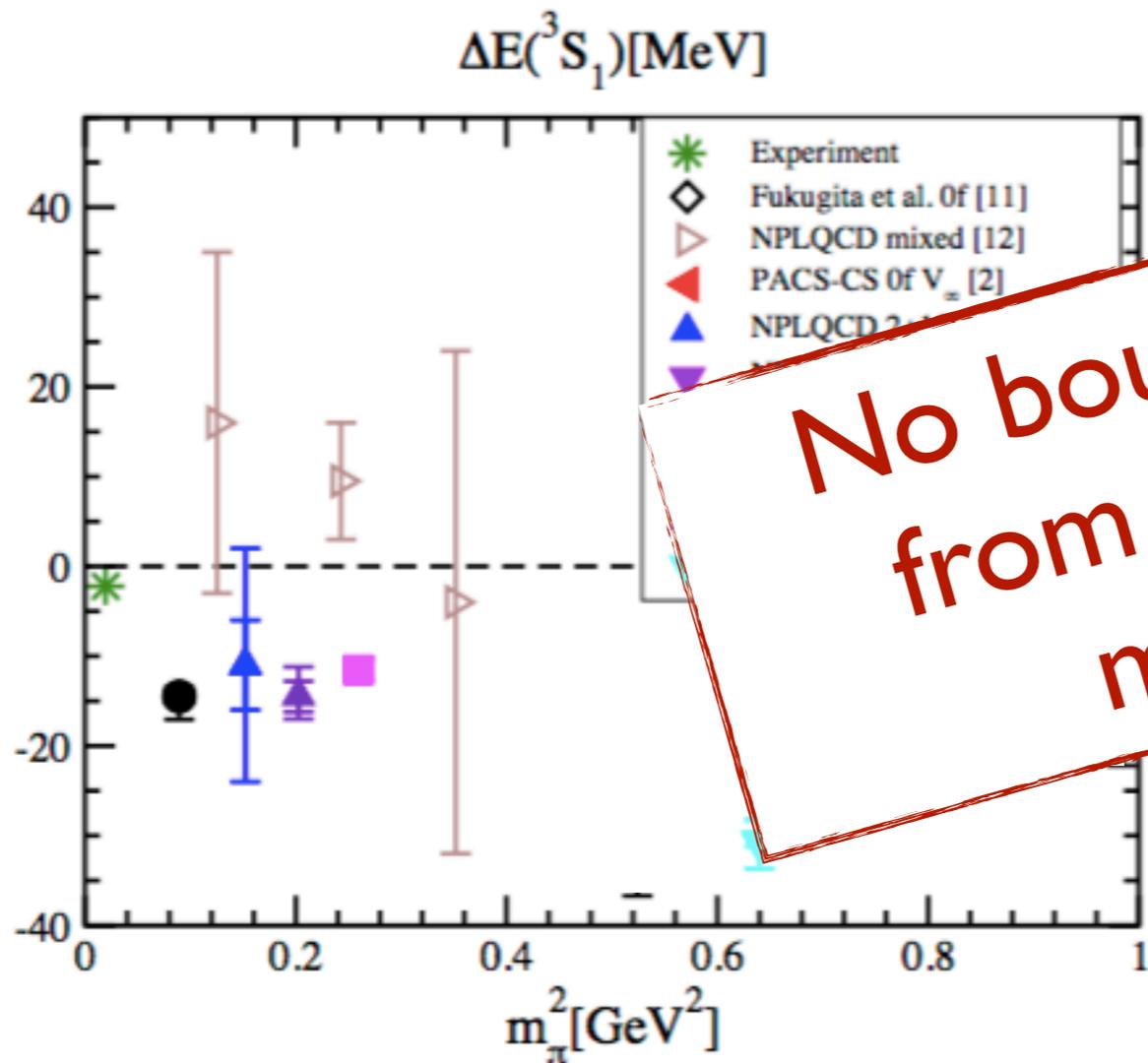
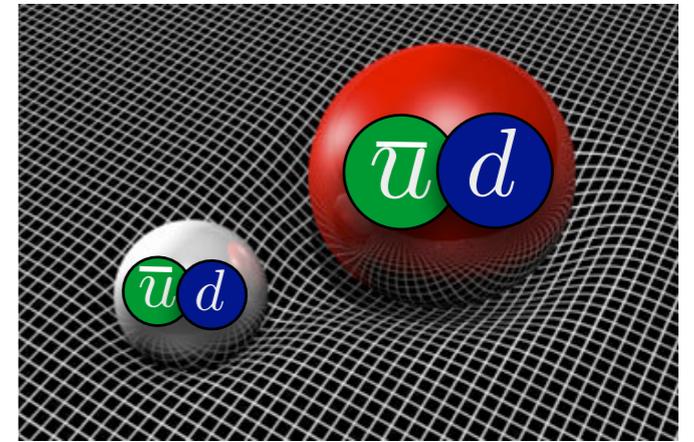


Berkowitz, et al, Phys.Lett. B765 (2017) 285-292, using JLab isotropic clover configs

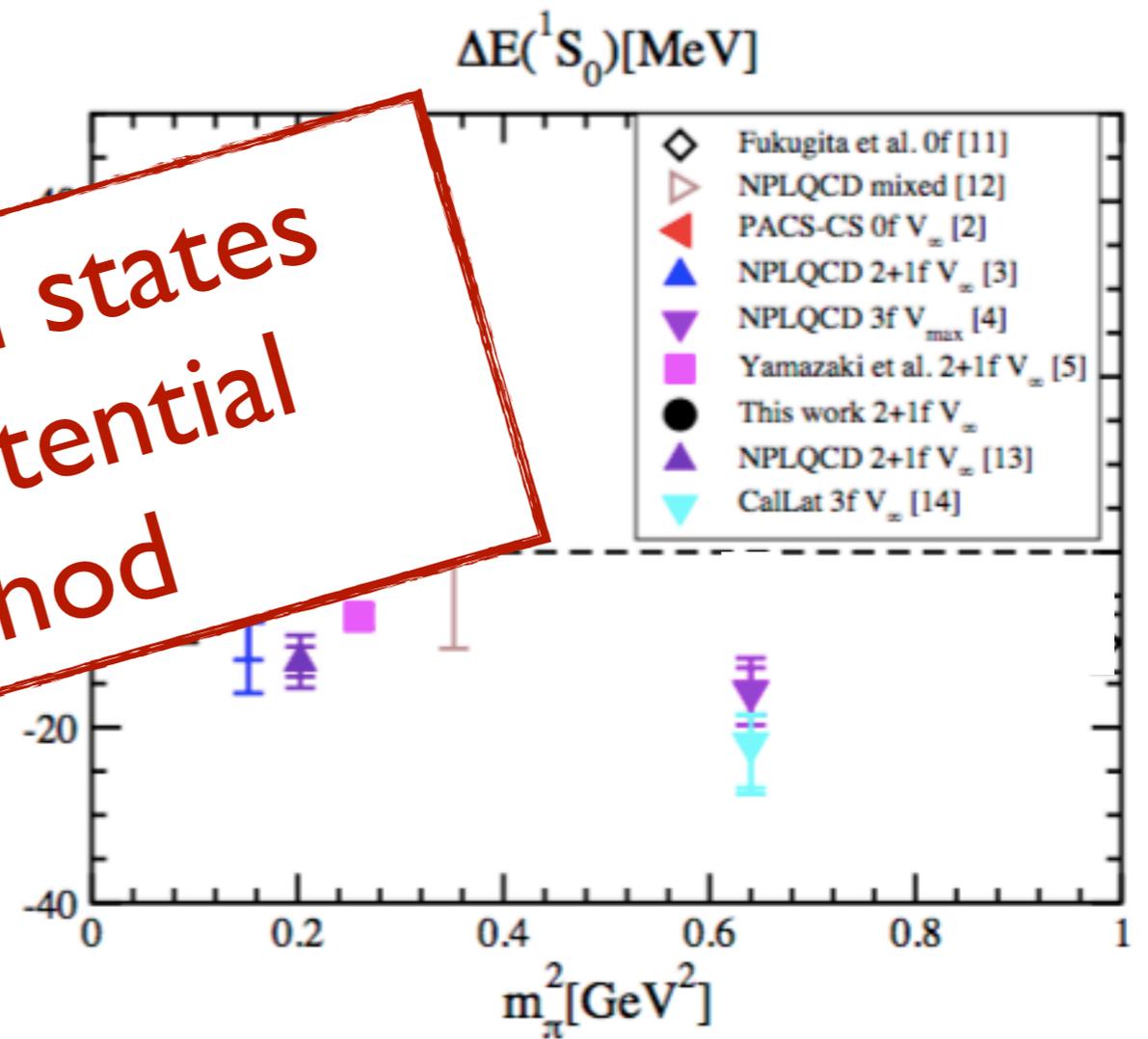
NN Binding energies



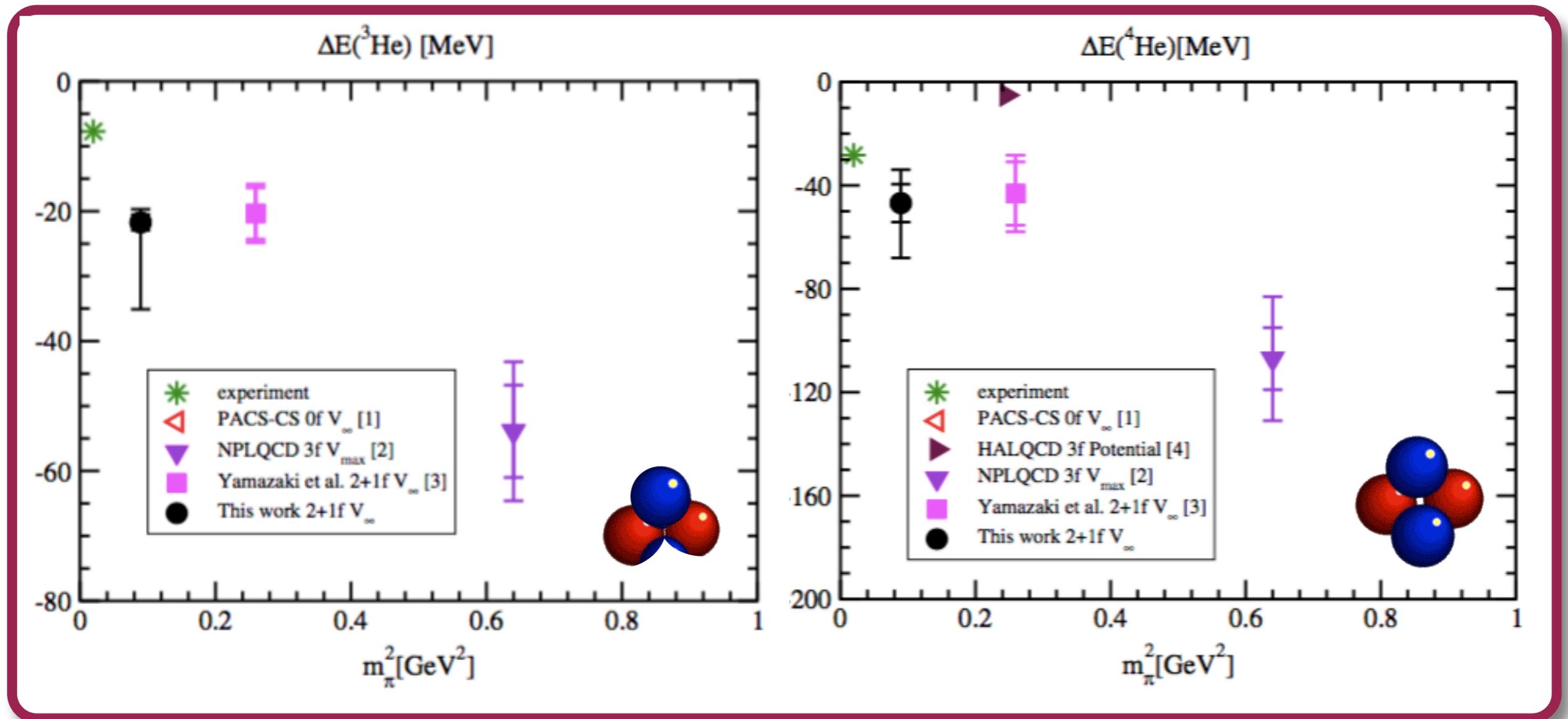
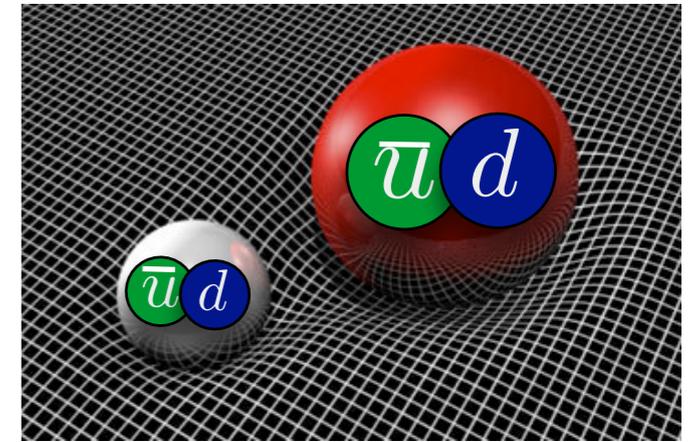
NN Binding energies



No bound states
from potential
method



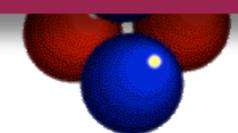
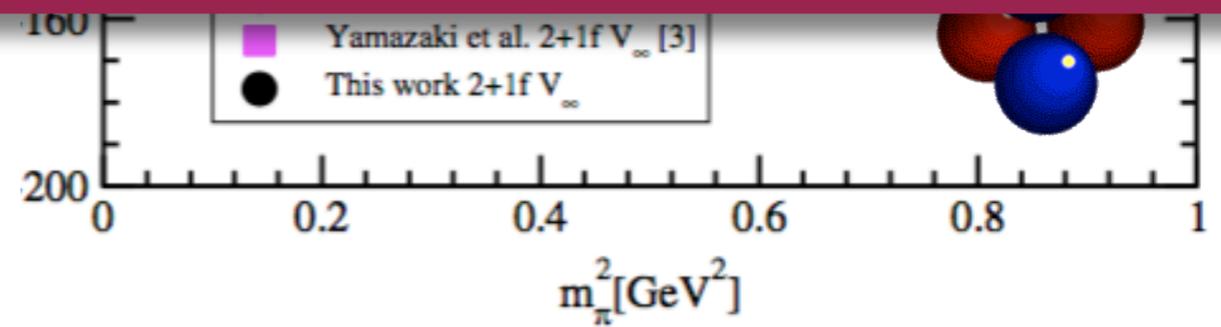
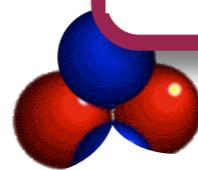
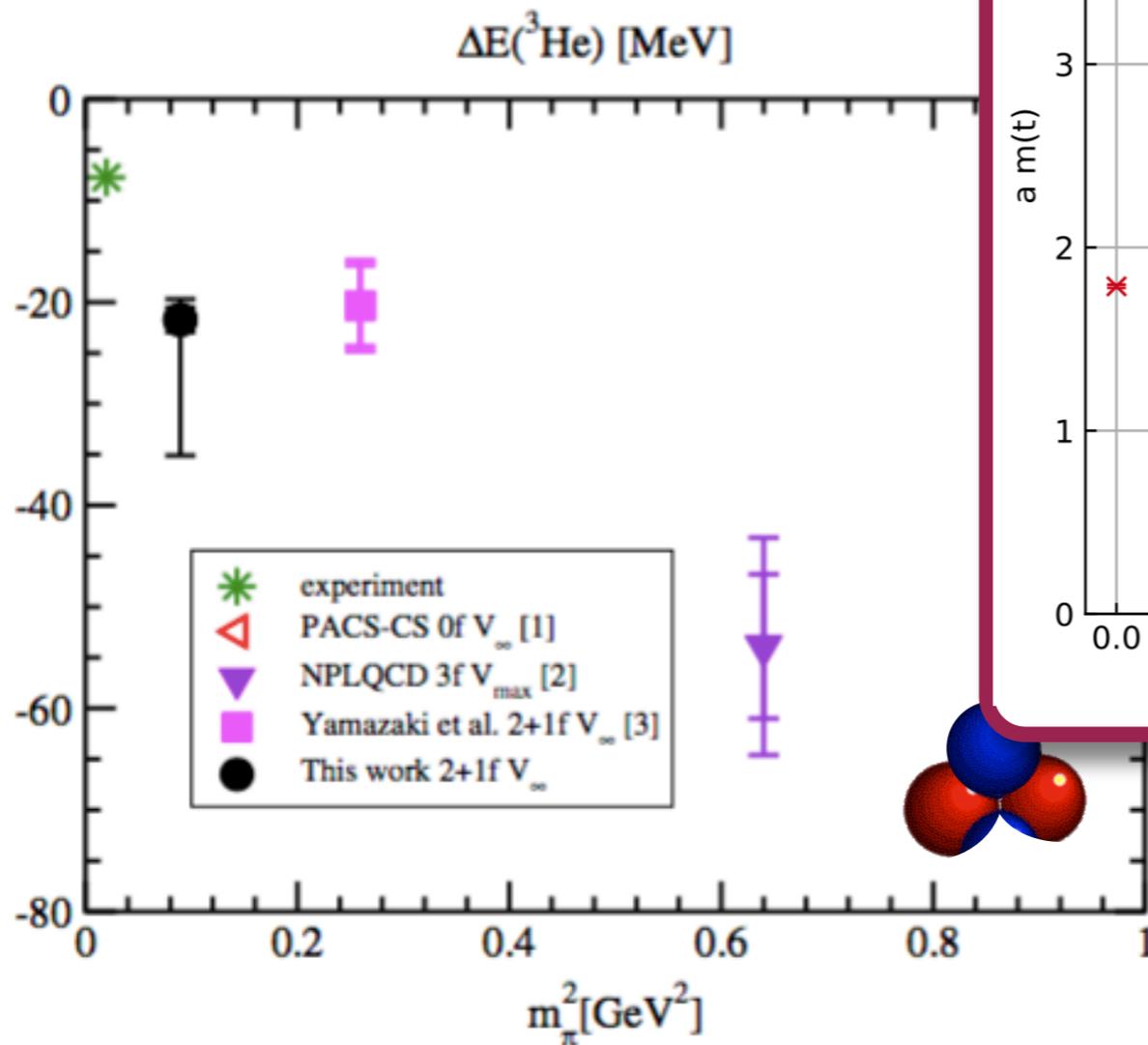
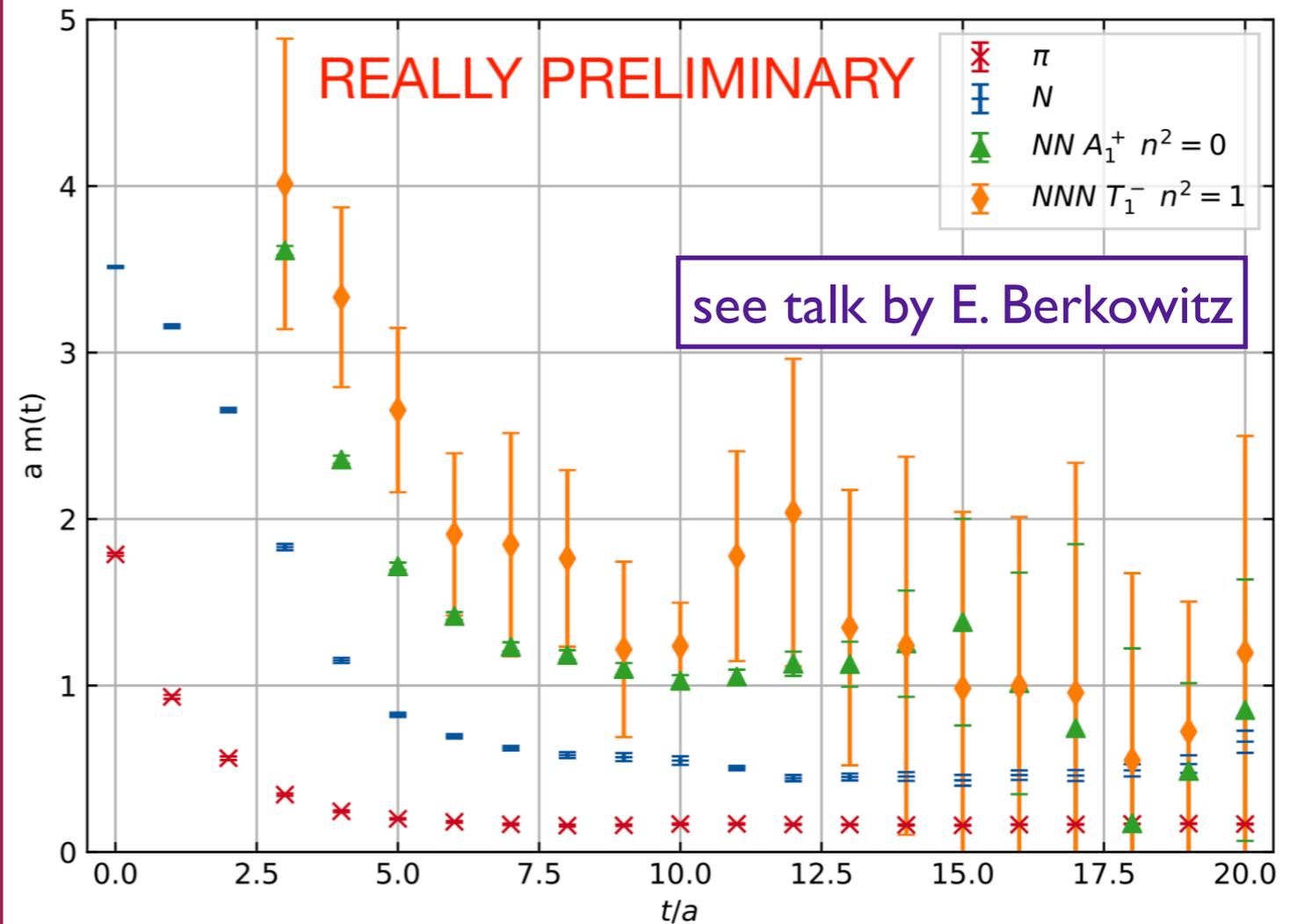
Few-body systems



Few-body syst

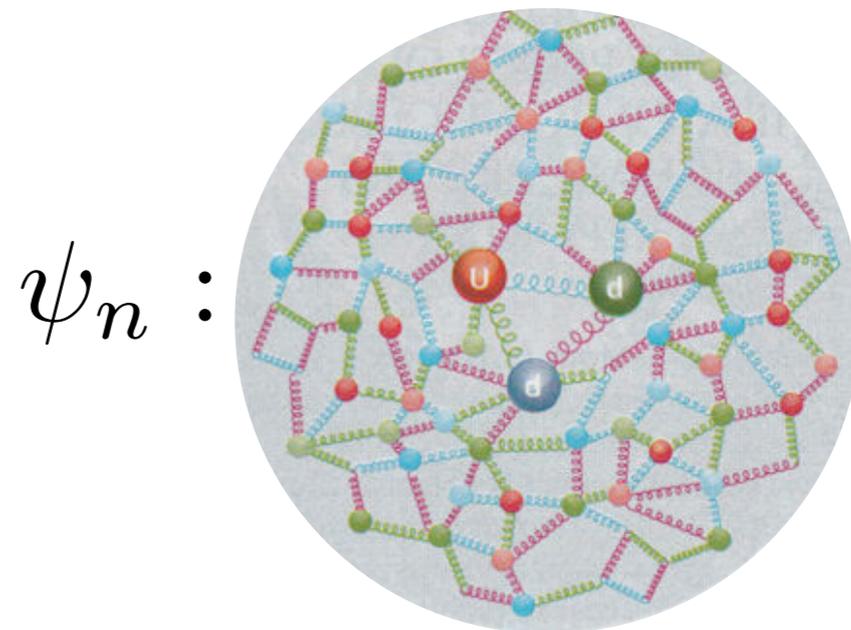
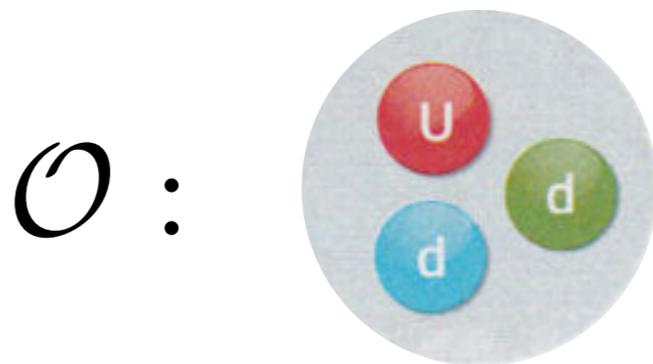
Three Neutrons In A Box

Jan-Lukas Wynen, EB, Tom Luu, Andrea Schindler, John Bulava



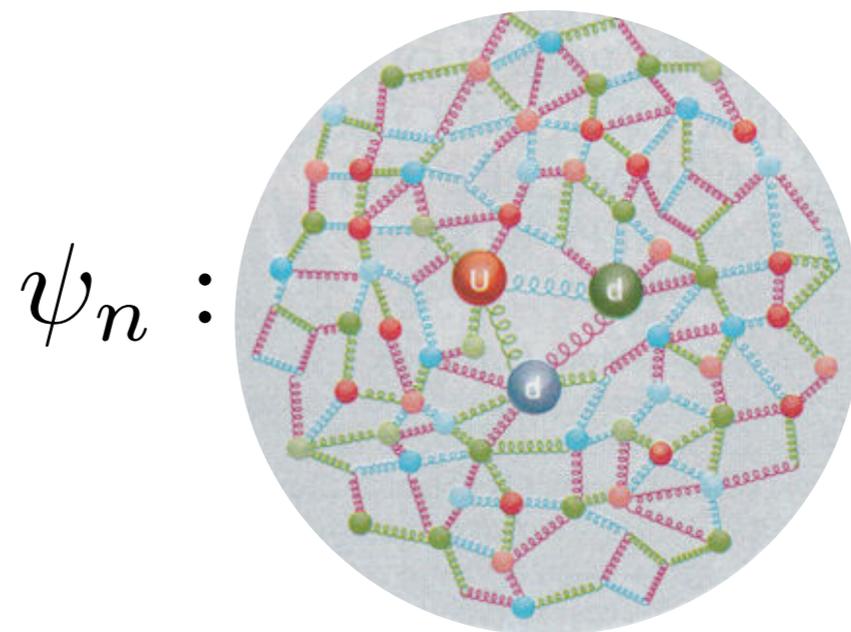
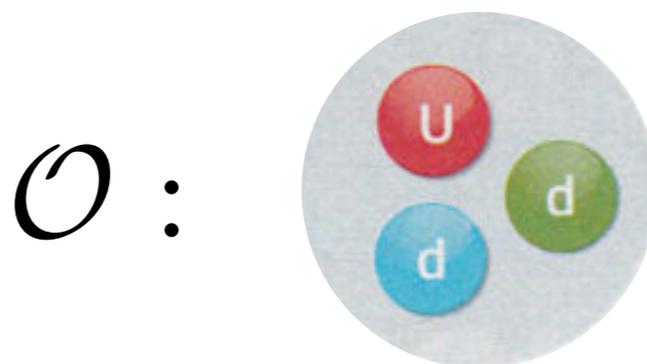
Lower pion mass?
Difficulty lies in
spectroscopy

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



Lower pion mass?
Difficulty lies in spectroscopy

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

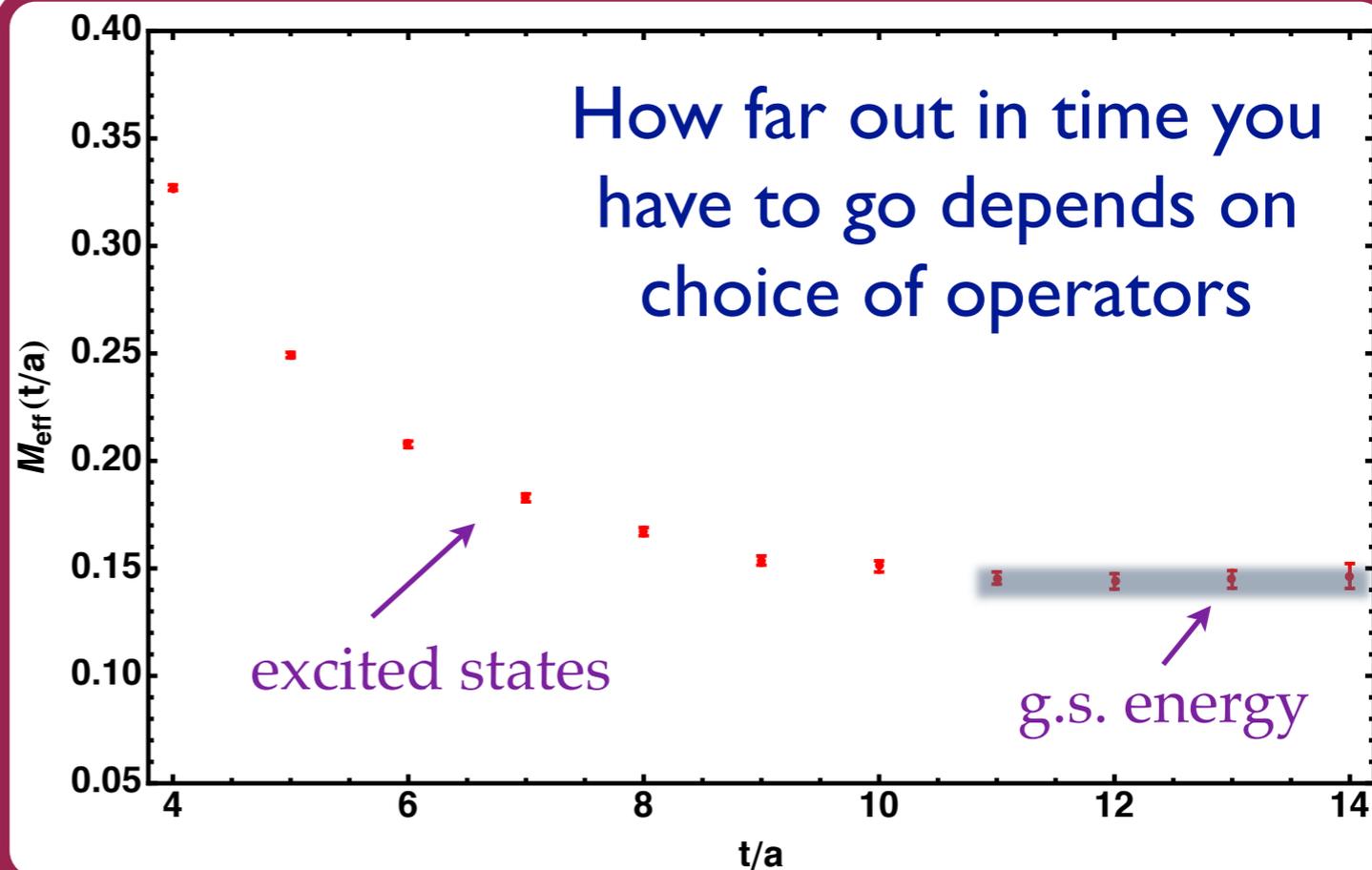


Effective mass

plot:

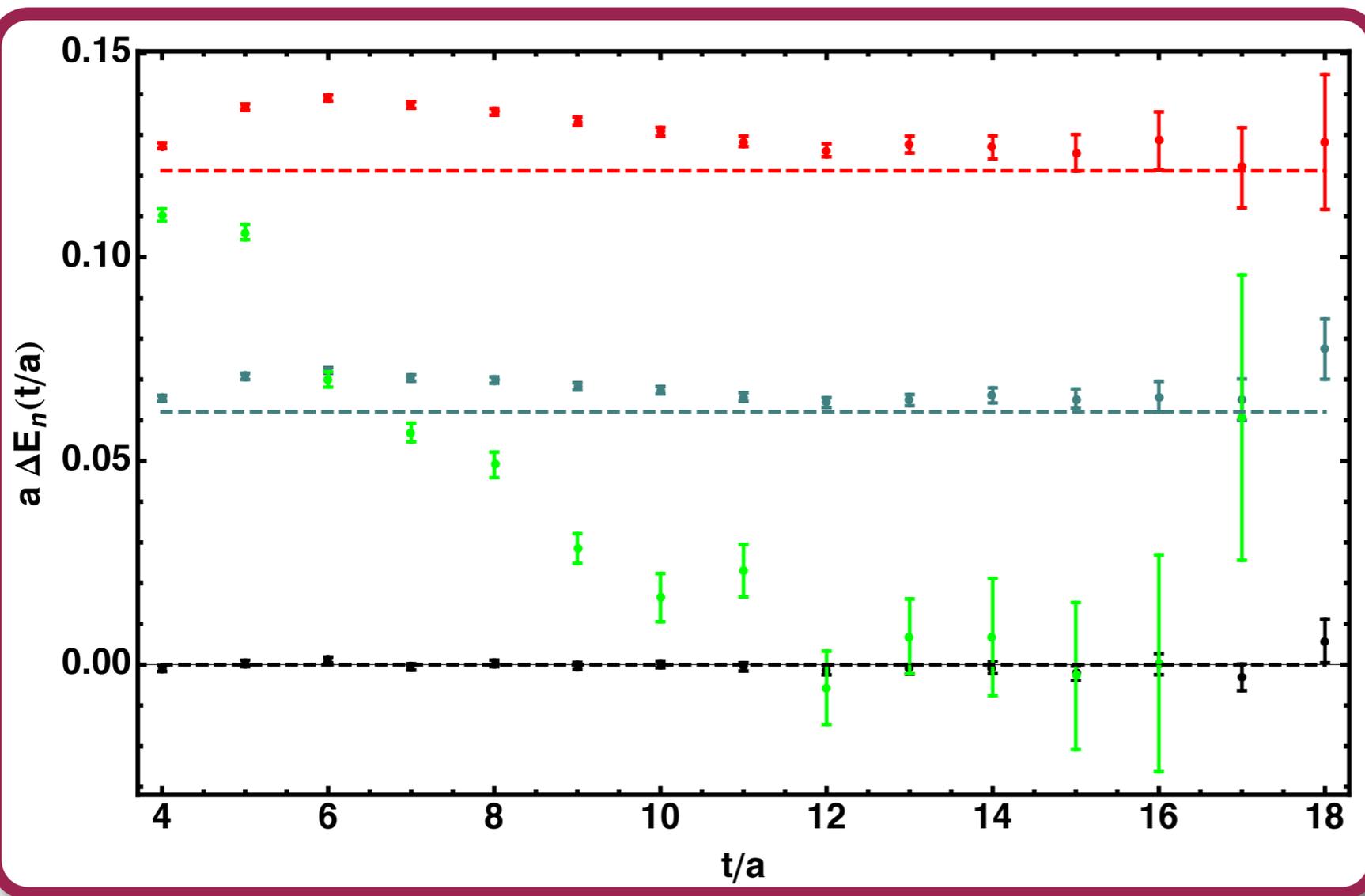
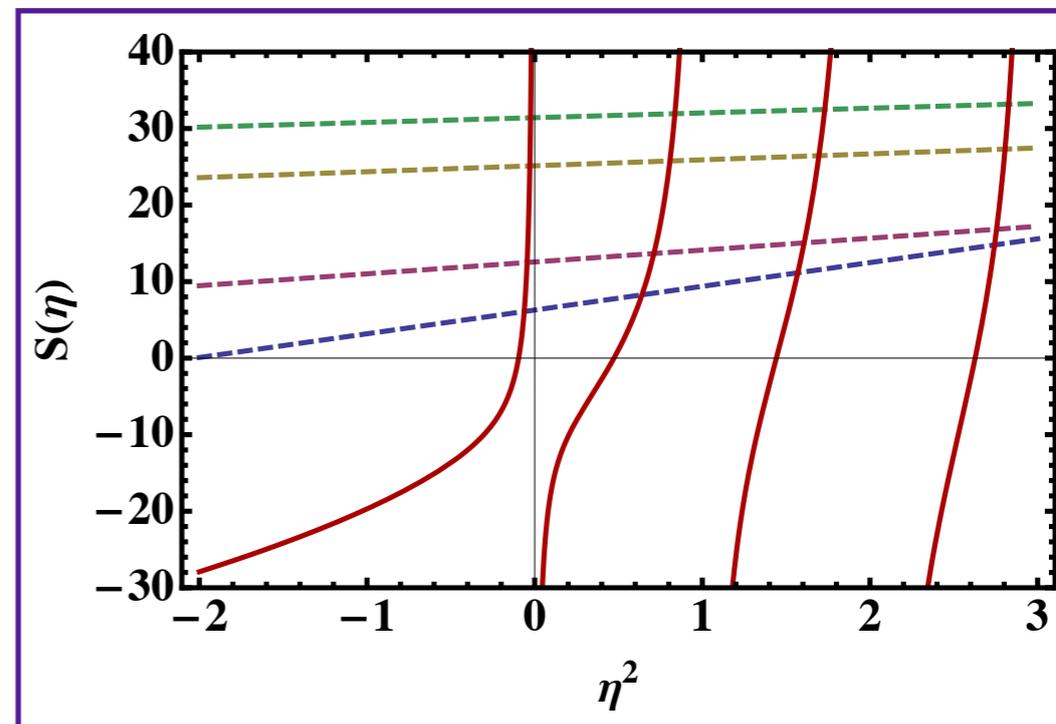
$$M_{\text{eff}} \equiv \ln \frac{C(t)}{C(t+1)}$$

$$\xrightarrow[t \rightarrow \infty]{} E_0$$



Trying to pull off small correction due to interactions:

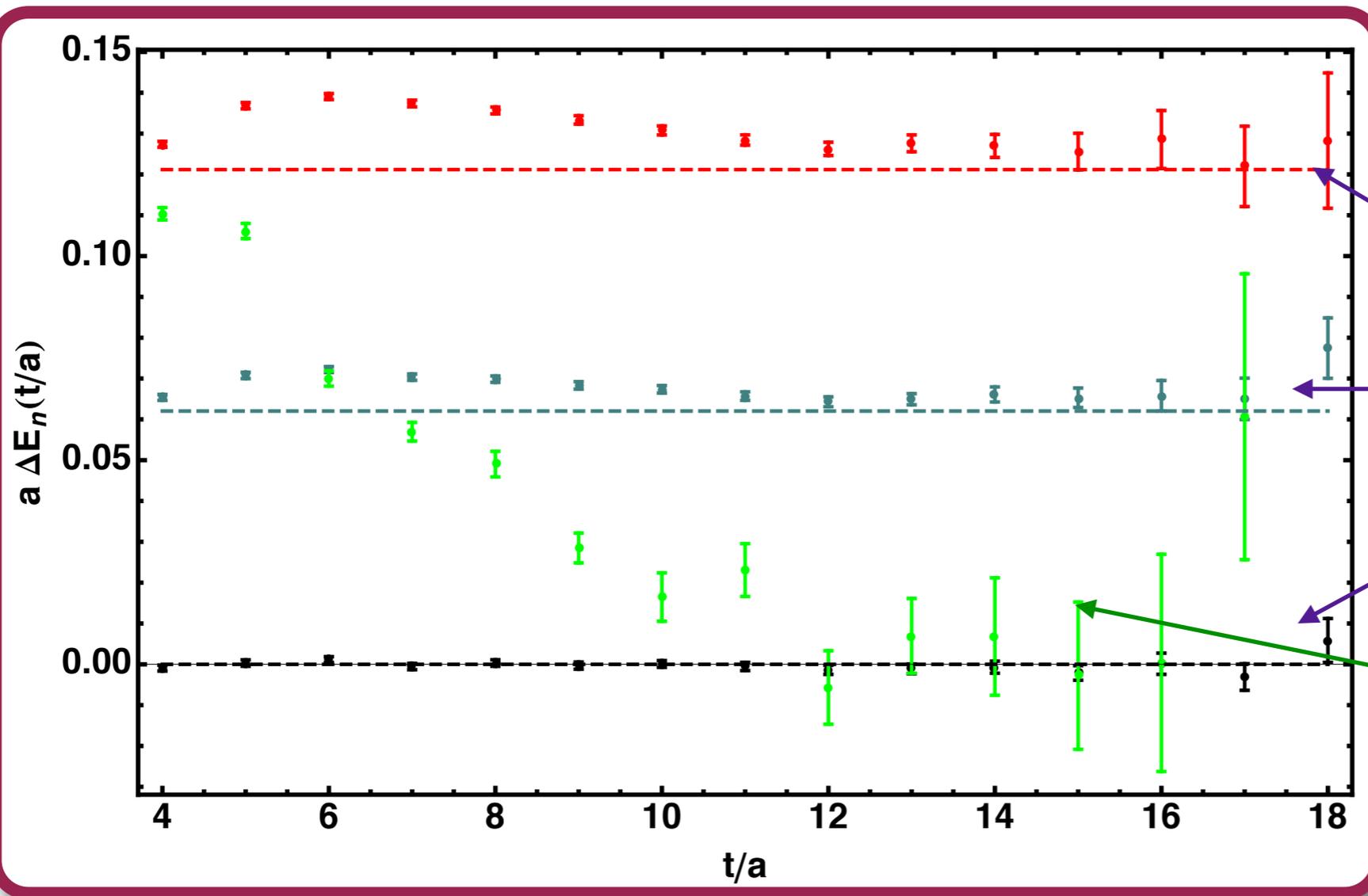
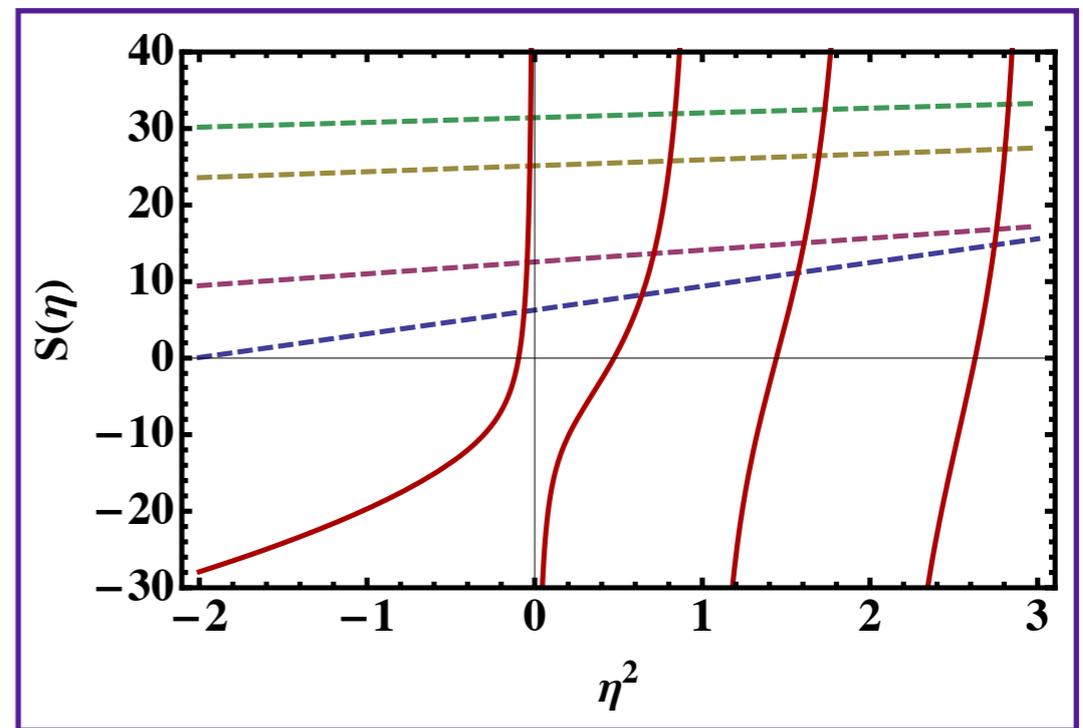
$$\Delta E = E_{NN} - 2E_N$$



$$p \cot \delta(p) = \frac{1}{\pi L} S[(pL/2\pi)^2]$$

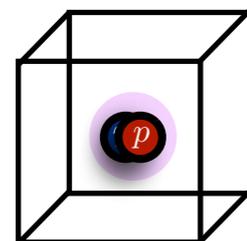
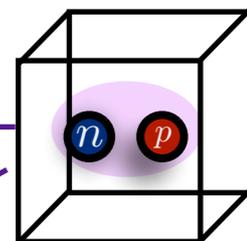
Lüscher (1986)

Trying to pull off small correction due to interactions:
 $\Delta E = E_{NN} - 2E_N$

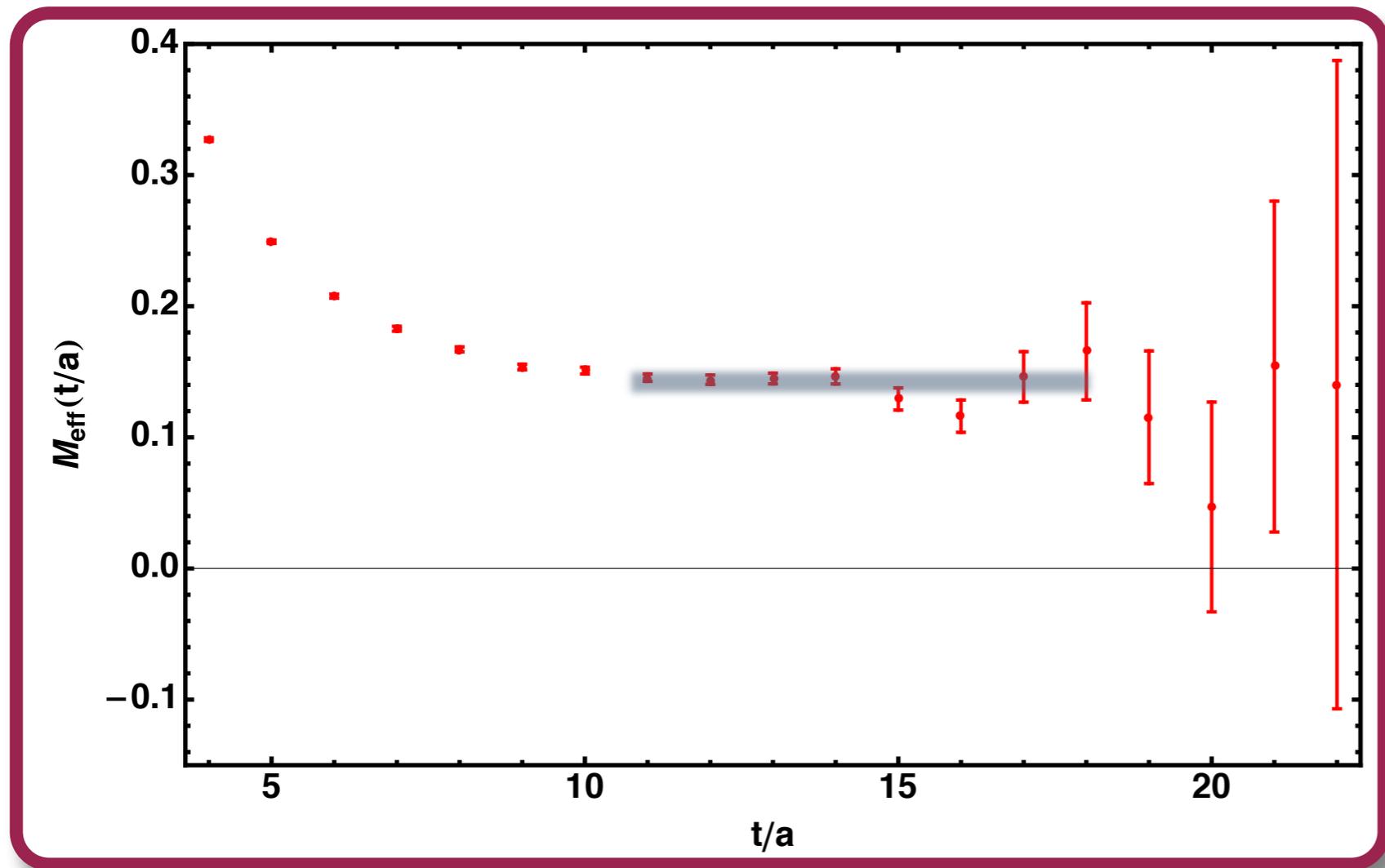


$$p \cot \delta(p) = \frac{1}{\pi L} S[(pL/2\pi)^2]$$

Lüscher (1986)

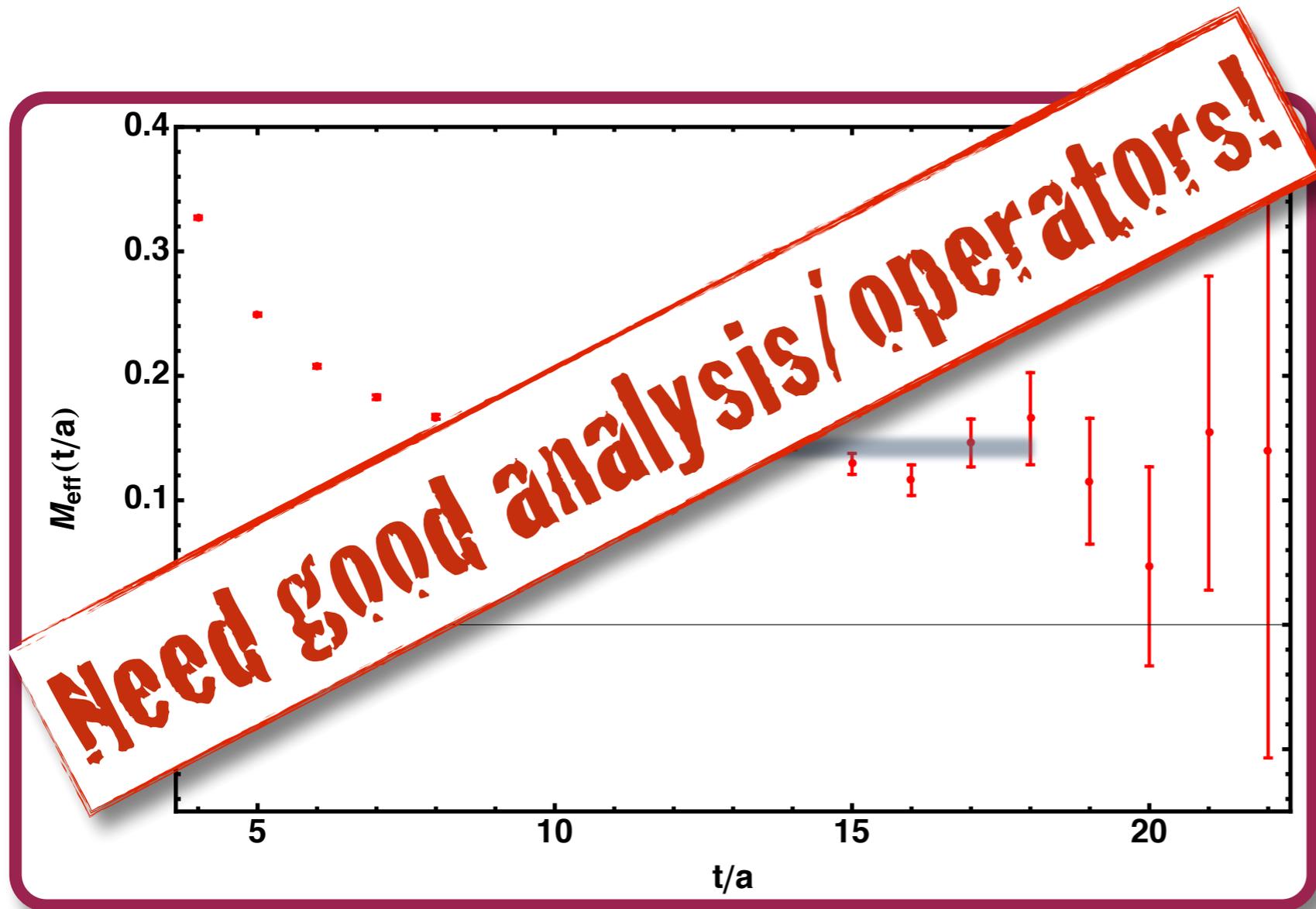


Nucleons: Signal-to-noise



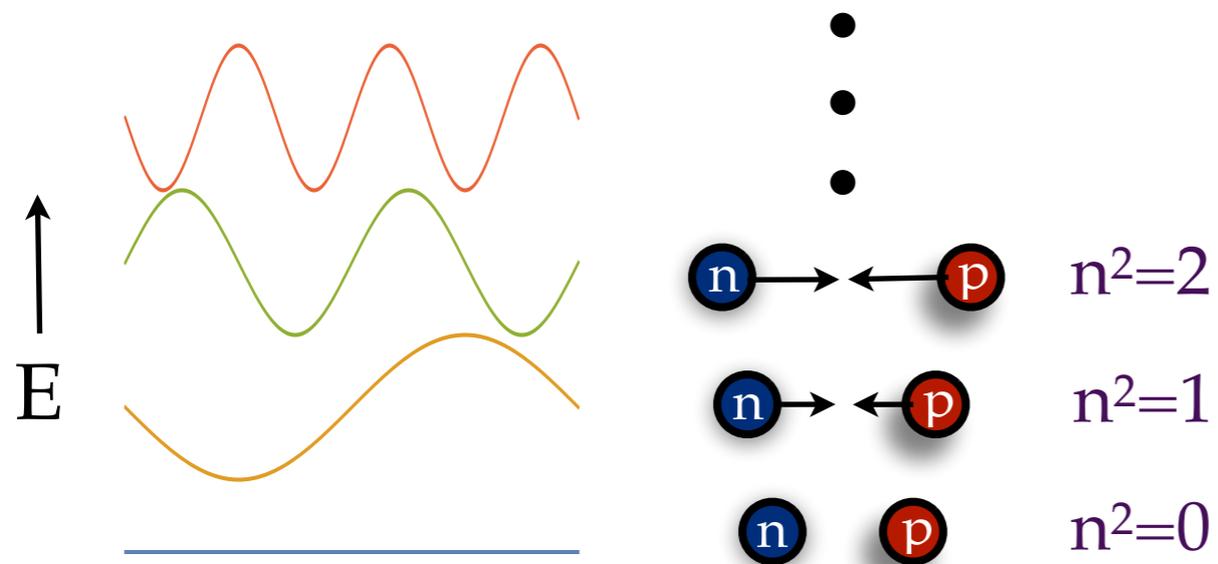
$$\left. \vphantom{\int} \right\} \sim e^{A(M_n - 3/2m_\pi)t}$$

Nucleons: Signal-to-noise



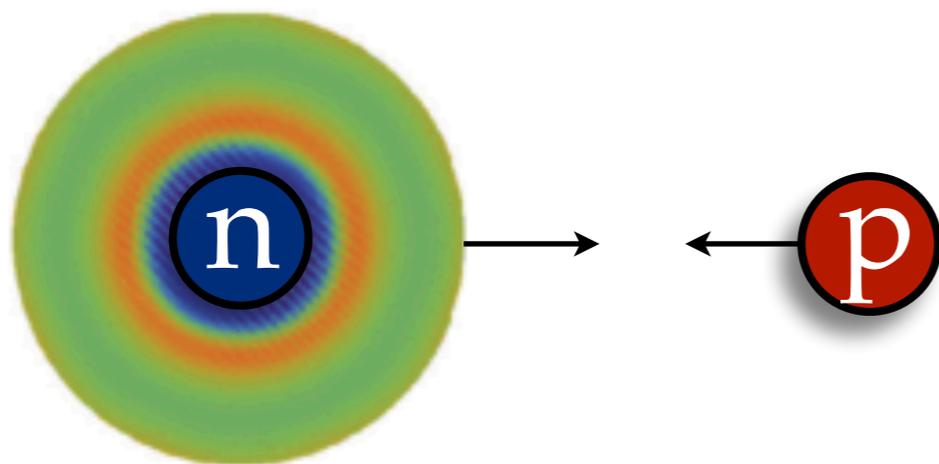
$$\sim e^{A(M_n - 3/2m_\pi)t}$$

Excited state contamination



Elastic scattering
(2-body)

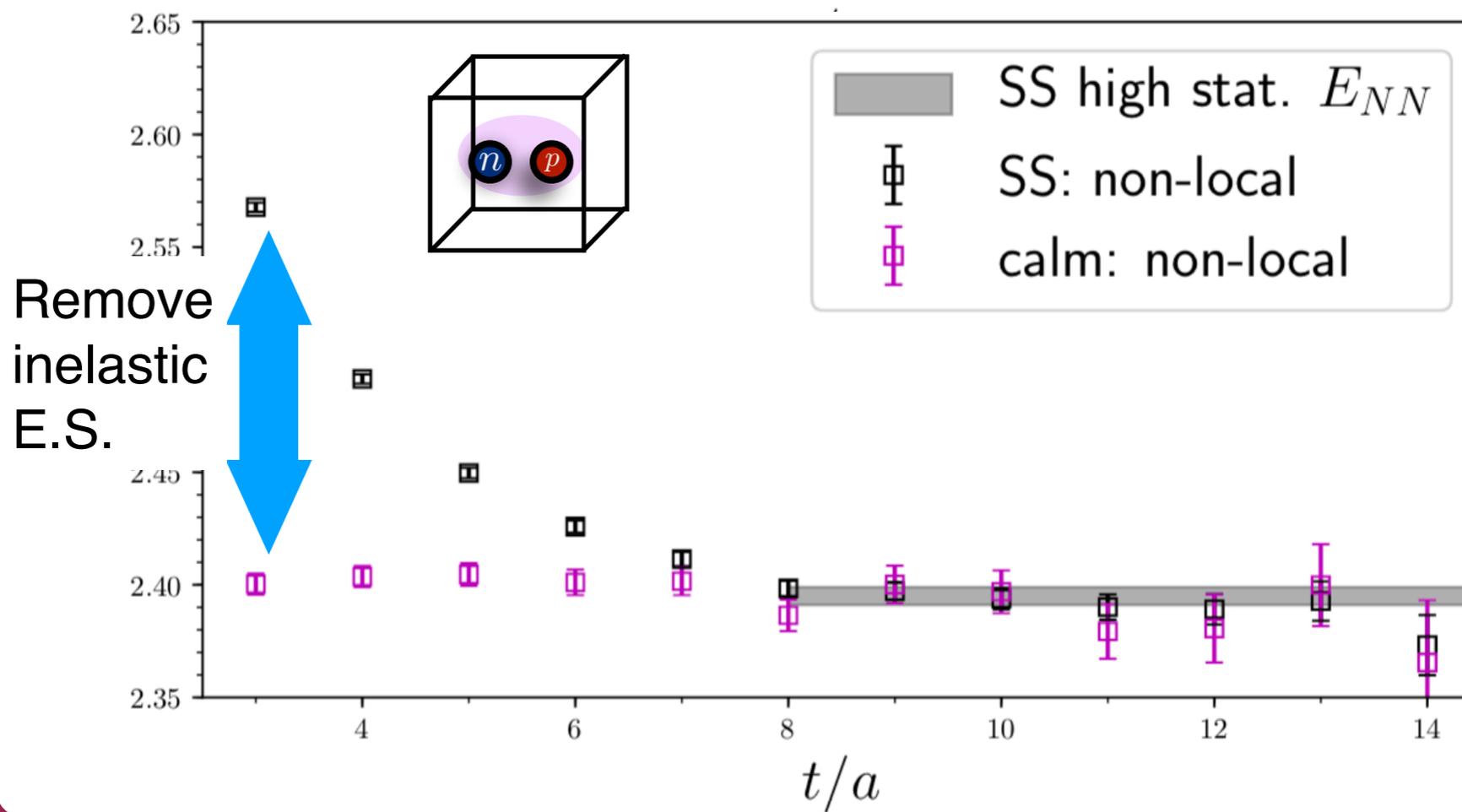
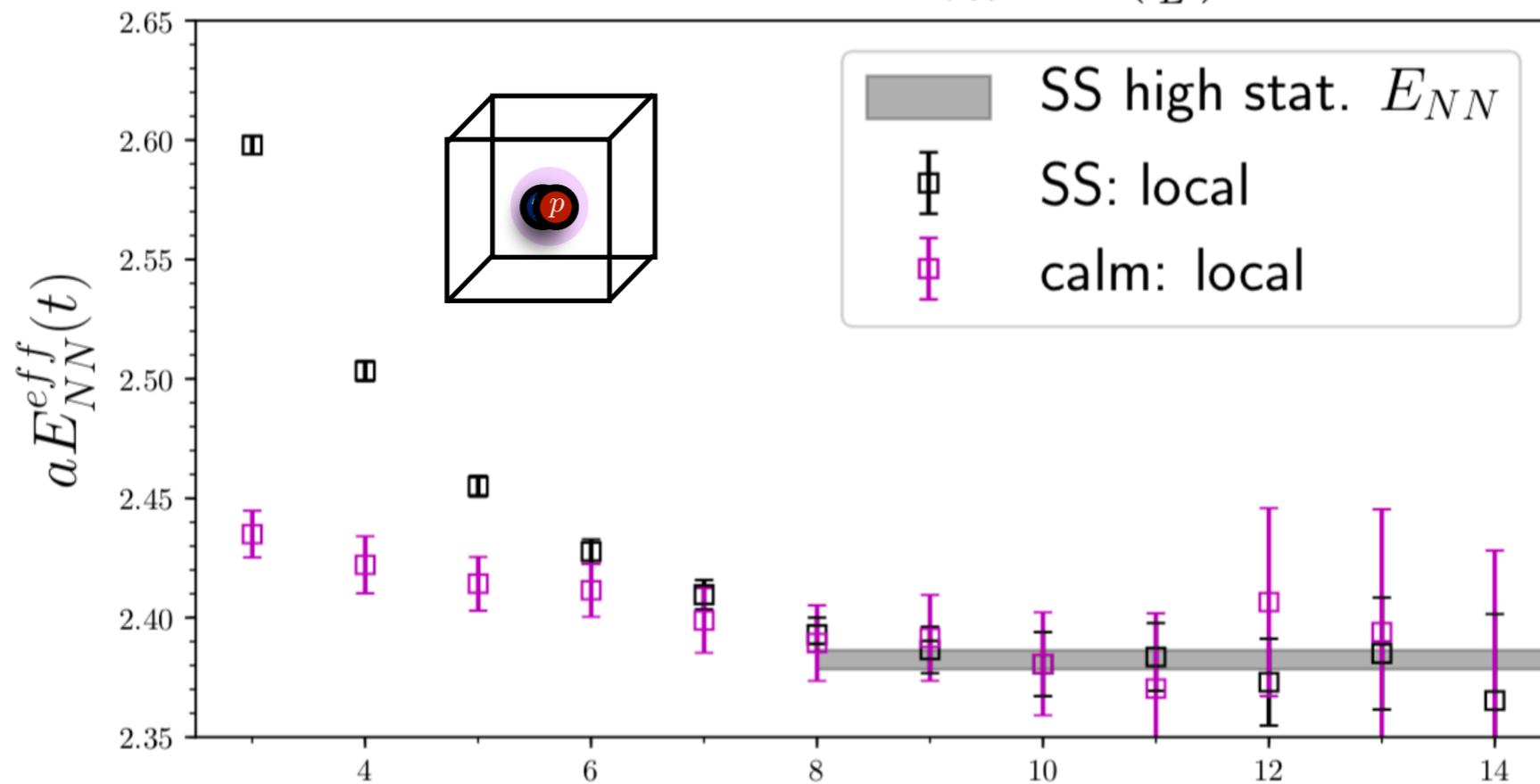
$$\Delta E \sim 50 \text{ MeV}$$



Inelastic single body

$$\Delta E \sim m_{\pi}$$

$$NN : T_1^+ : {}^3S_1 : p_{rel}^2 = 0 \left(\frac{2\pi}{L}\right)^2$$

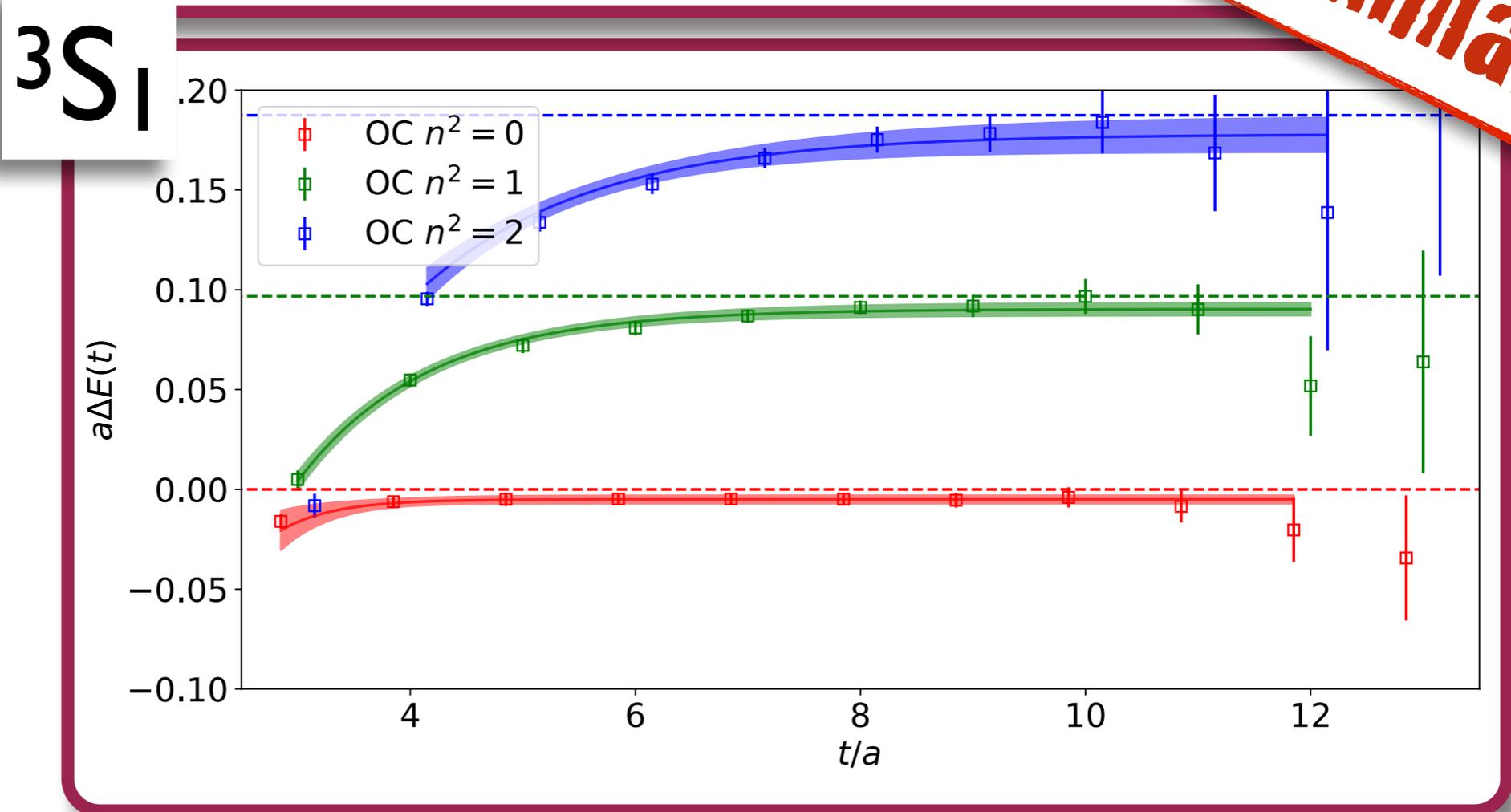
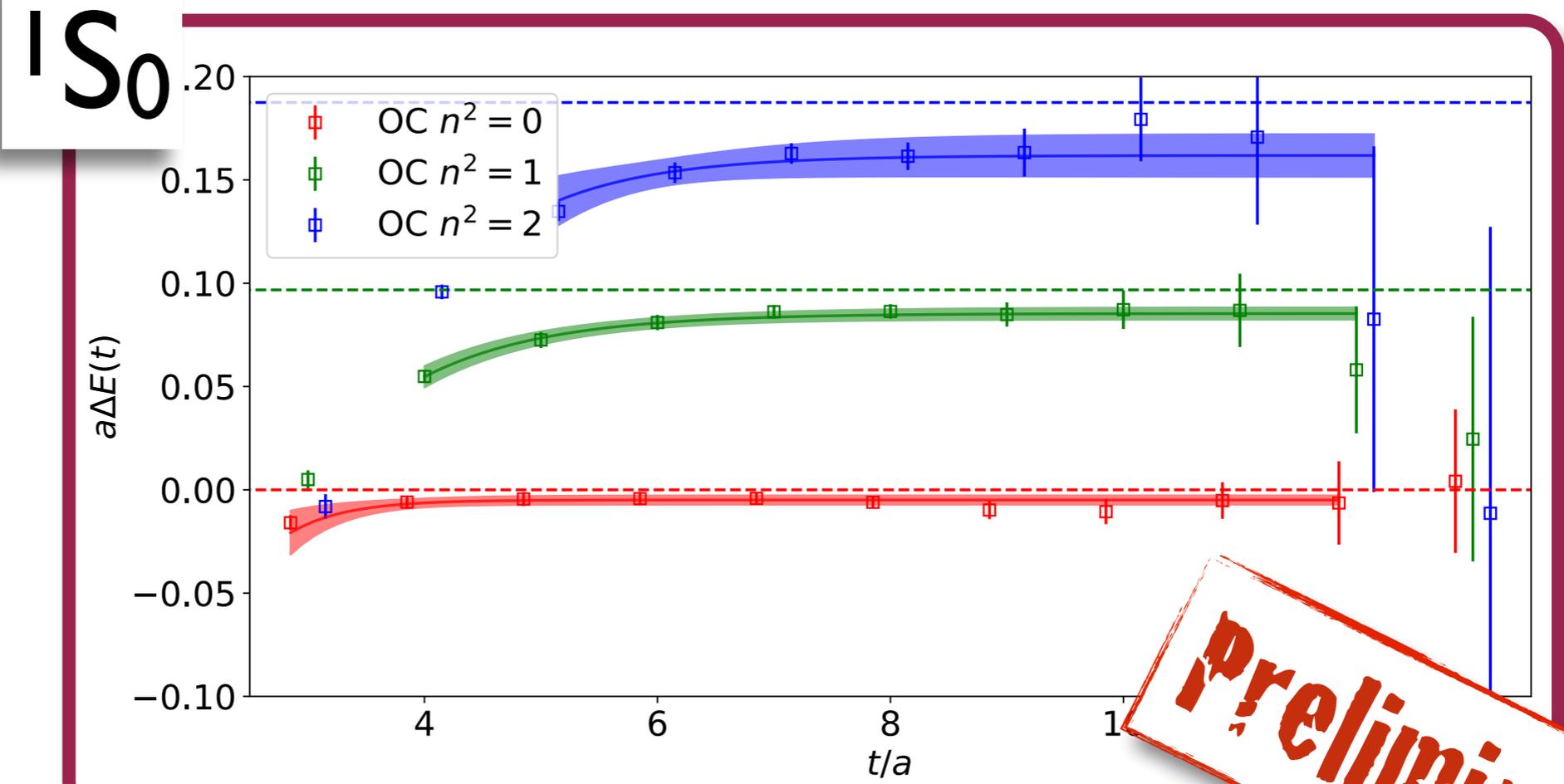


Remove elastic E.S.

Remove inelastic E.S.

CallLat (2017)
Matrix Prony:
NPLQCD (2009)

Energy levels:
 $m_\pi \sim 350$ MeV
 (DWF on MILC
 HISQ ensembles)

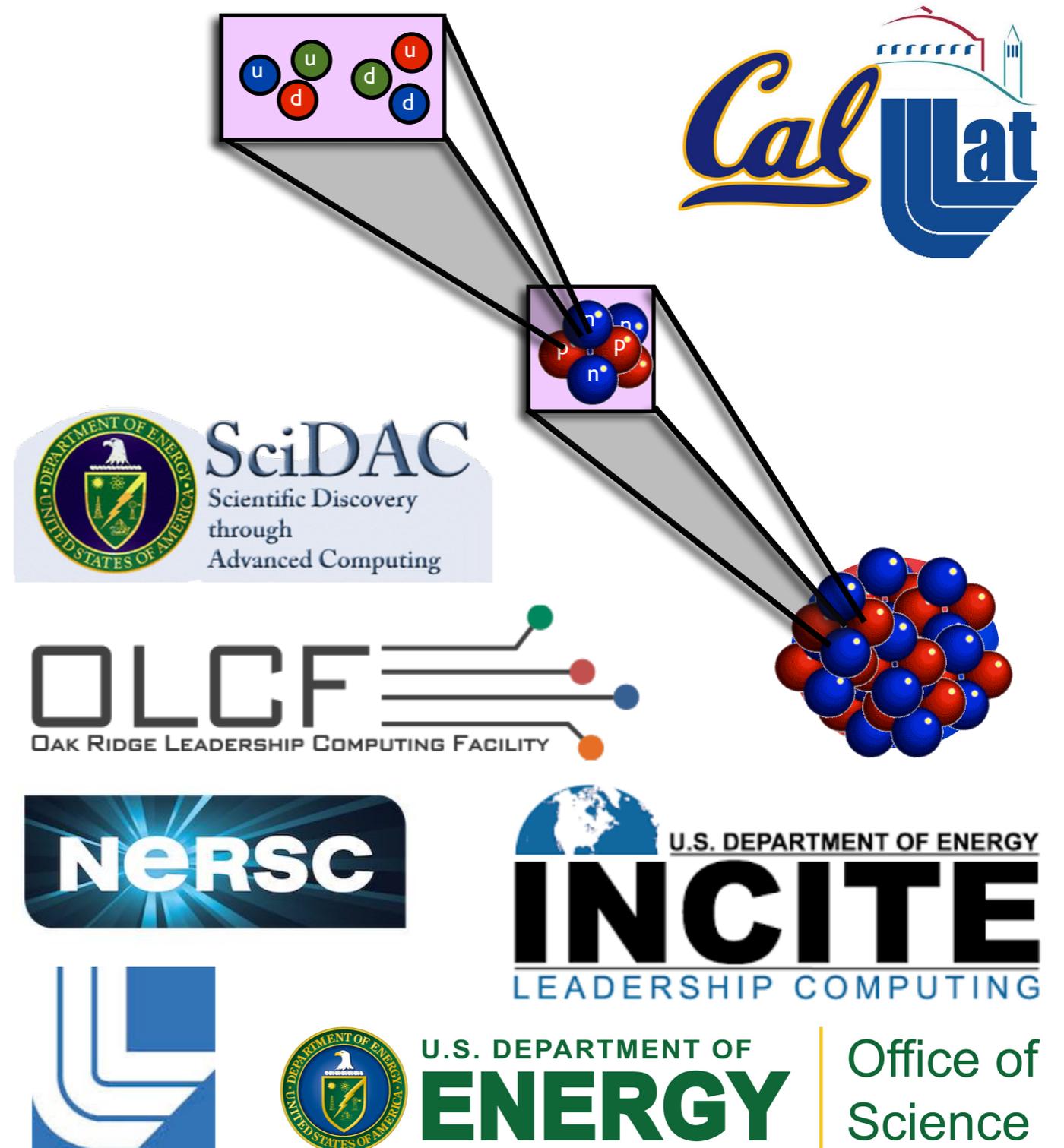


Summary

- LQCD is a necessary step toward reliably connecting experimental signals to the SM/BSM
- 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!
- Nucleon/nuclear EDMs
 - Lattice calculations of θ_{QCD} -induced nucleon EDM consistent with zero at the physical point
 - Promising calculations for cEDM, pion-nucleon coupling
- Multi-nucleon calculations
 - Results from several groups at heavier than physical pion mass
 - Physical pion mass will require excellent operators
 - Variational methods?
 - Francis et al. 1805.03966 (H-dibaryon)
 - Andersen, Bulava, Hörz, Morningstar, CalLat

- 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: A. Gambhir, P. Vranas

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



$$\begin{aligned}
\langle \pi^+ | \mathcal{O}^{V+} | \pi^- \rangle &= \frac{m_\pi^2}{f^2} C^{V+} \left[1 - \frac{16}{3} \frac{m_\pi^2}{(4\pi f)^2} \left(\frac{1}{4} \log \frac{m_\pi^2}{\mu^2} + \frac{3}{4} \frac{m_{vs}^2}{m_\pi^2} \log \frac{m_{vs}^2}{\mu^2} + c^{V+}(\mu) \right) \right], \\
\langle \pi^+ | \mathcal{O}^{LR} | \pi^- \rangle &= C^{LR} \left[1 - \frac{10}{3} \frac{m_\pi^2}{(4\pi f)^2} \left(-\frac{1}{5} \log \frac{m_\pi^2}{\mu^2} + \frac{6}{5} \frac{m_{vs}^2}{m_\pi^2} \log \frac{m_{vs}^2}{\mu^2} + c^{LR}(\mu) \right) \right], \\
\langle \pi^+ | \mathcal{O}^{S+} | \pi^- \rangle &= C^{S+} \left[1 - \frac{10}{3} \frac{m_\pi^2}{(4\pi f)^2} \left(-\frac{1}{5} \log \frac{m_\pi^2}{\mu^2} + \frac{6}{5} \frac{m_{vs}^2}{m_\pi^2} \log \frac{m_{vs}^2}{\mu^2} + \frac{6}{5} \frac{a^2 \Delta_I}{m_\pi^2} \left[\log \frac{m_\pi^2}{\mu^2} + 1 \right] + c^{S+}(\mu) \right) \right]
\end{aligned}$$

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

$$a^2 \Delta_I \left[\log \frac{m_\pi^2}{\mu^2} + 1 \right] \longrightarrow a^2 \Delta_I \frac{\partial}{\partial m_\pi^2} \left[4m_\pi^2 \sum_{\vec{v} \neq \vec{0}} \frac{K_1(m_\pi L |\vec{v}|)}{m_\pi L |\vec{v}|} \right] = -2a^2 \Delta_I \sum_{\vec{v} \neq \vec{0}} K_0(m_\pi L |\vec{v}|).$$

Contractions

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

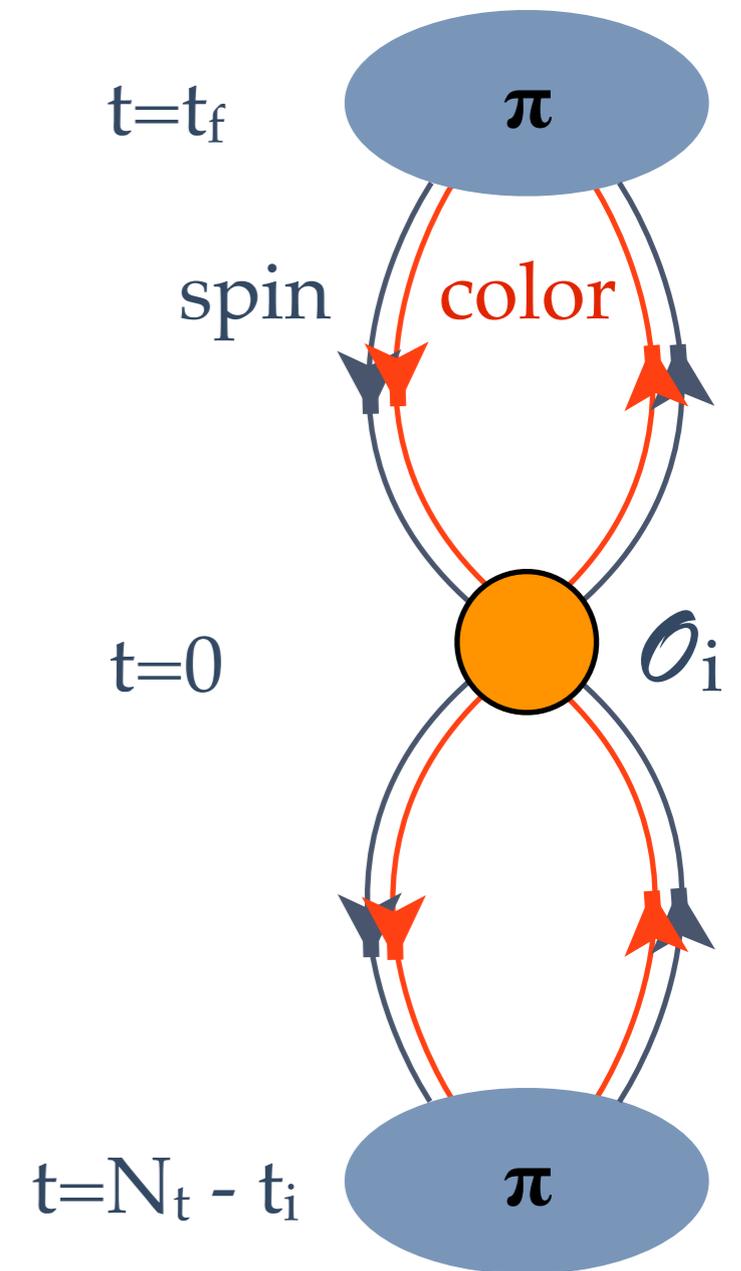
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L) [\bar{q}_R \tau^- \gamma_\mu q_R]$$

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

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

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

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



Contractions

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

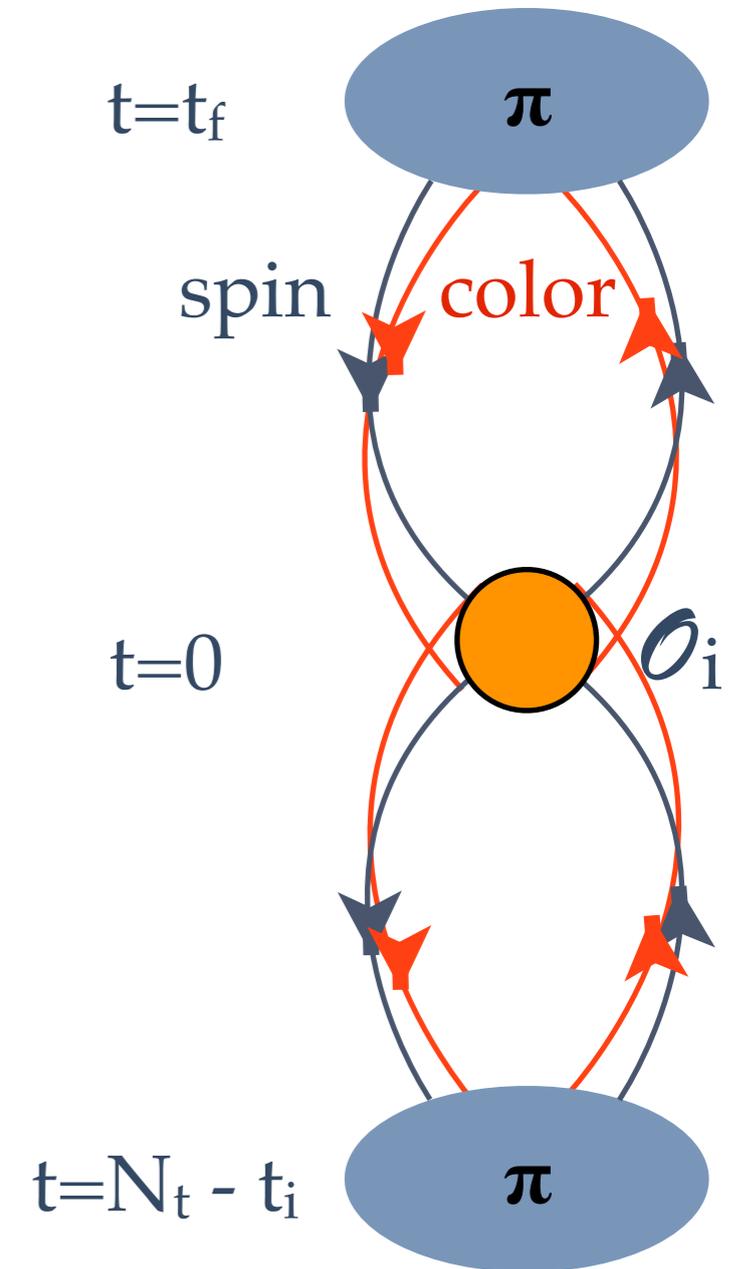
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L) [\bar{q}_R \tau^- \gamma_\mu q_R]$$

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

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

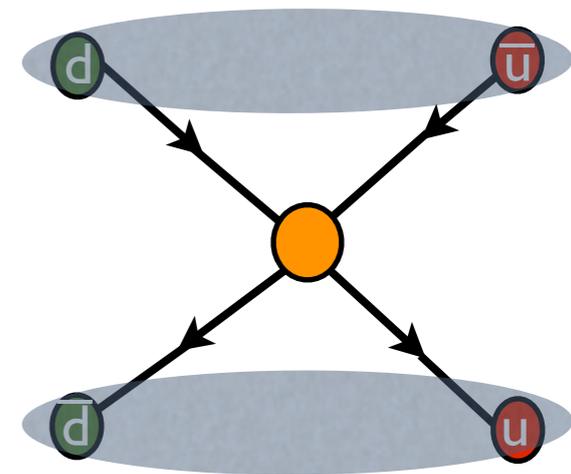
$$\mathcal{O}'_{2+}{}^{++} = (\bar{q}_R \tau^- q_L) [\bar{q}_R \tau^- q_L] + (\bar{q}_L \tau^- q_R) [\bar{q}_L \tau^- q_R]$$

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



XPT:

π -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	✓	✓	✓	✓
$NNN\pi ee$ LO	✓	✓	X	✓	X	✓	✓	✓	✓



- Nine operators:

- $\pi \rightarrow \pi$: only need parity even

- Vector operators suppressed

by m_e

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

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

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

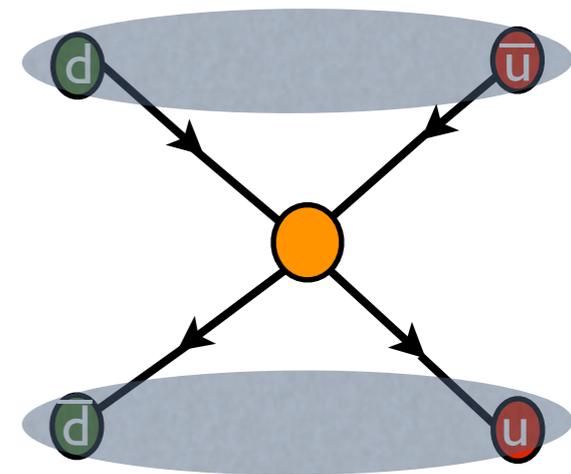
$$\mathcal{O}_{3\pm}^{ab} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L \tau^b \gamma_\mu q_L) \pm (\bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_R \tau^b \gamma_\mu q_R),$$

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

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

XPT:

π -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	✓	✓	✓	✓
$NNN\pi ee$ LO	✓	✓	X	✓	X	✓	✓	✓	✓



- Nine operators:

- $\pi \rightarrow \pi$: only need parity even

- Vector operators suppressed

by m_e

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

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

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

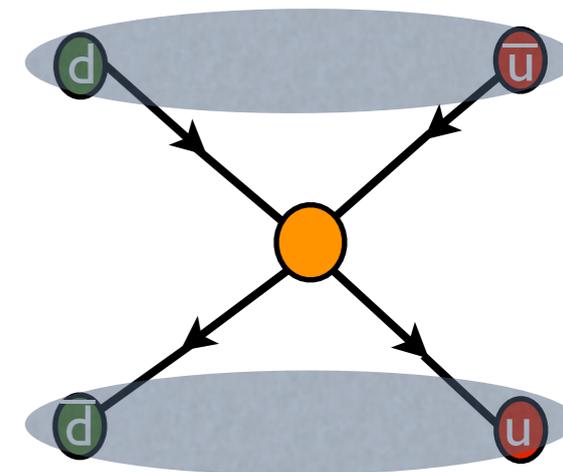
$$\mathcal{O}_{3\pm}^{ab} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L \tau^b \gamma_\mu q_L) \pm (\bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_R \tau^b \gamma_\mu q_R),$$

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

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

XPT:

π -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	✓	✓	✓	✓
$NNNNe e$ LO	✓	✓	X	✓	X	✓	✓	✓	✓



Left-right symmetric models

