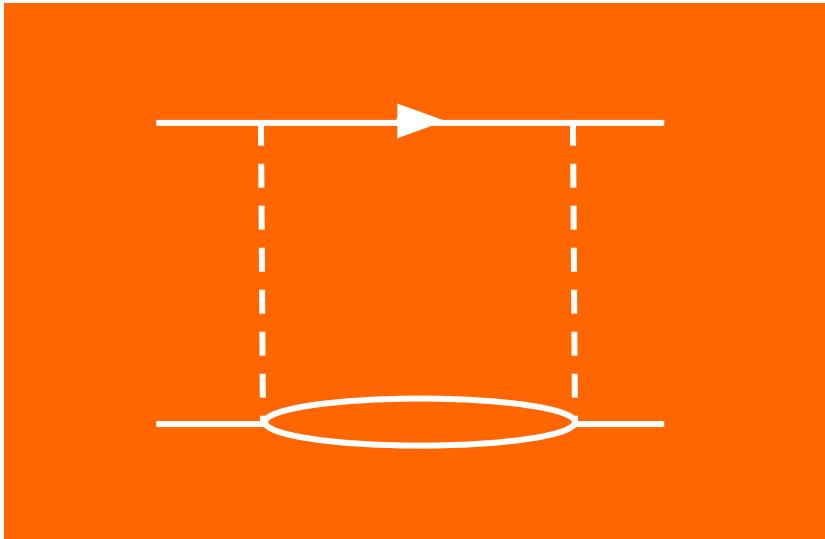


The deuteron-radius puzzle is alive: A new analysis of nuclear structure uncertainties



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Nir Nevo Dinur
Chen Ji
Sonia Bacca
Nir Barnea



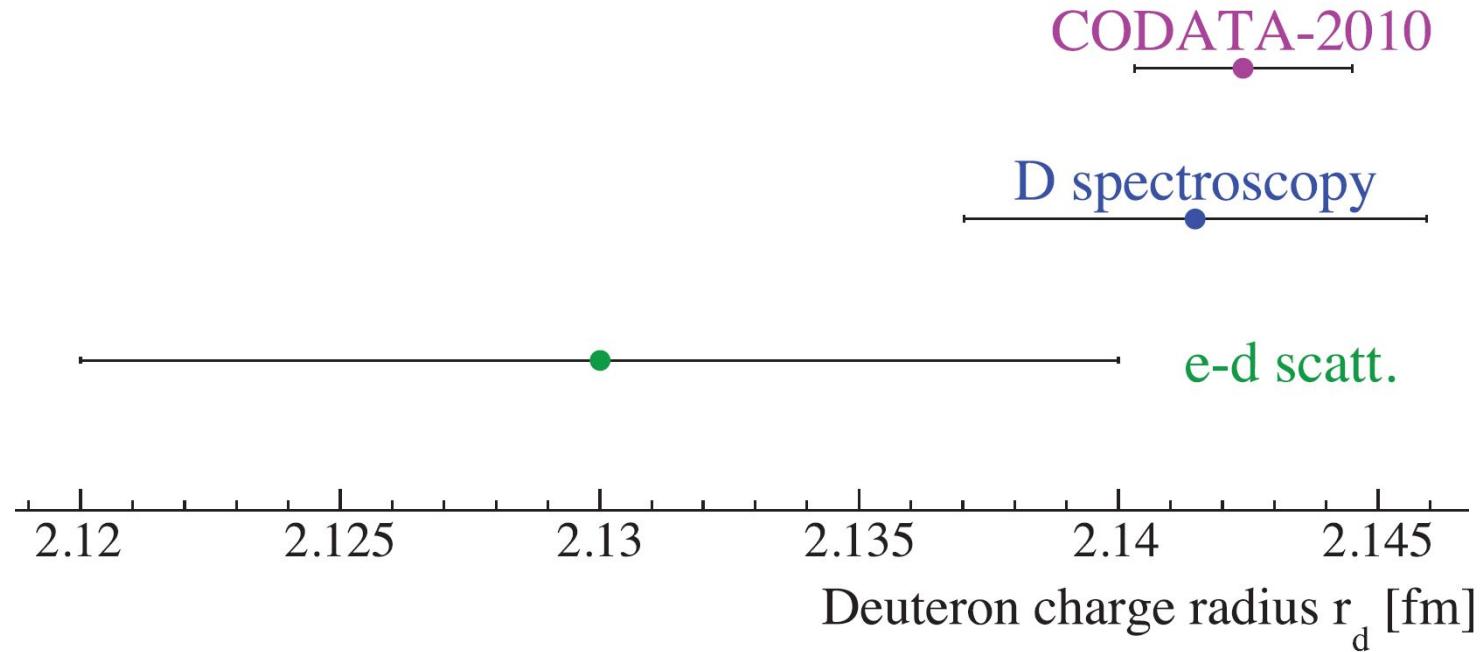
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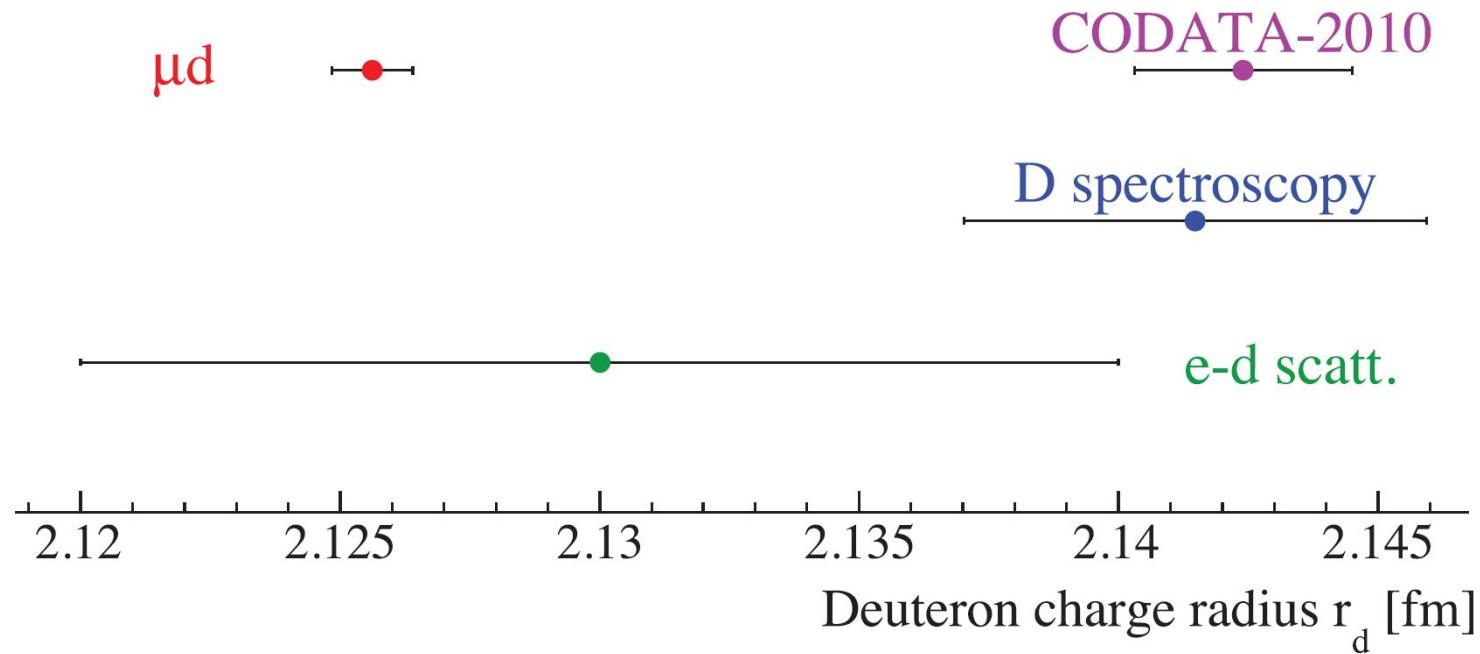
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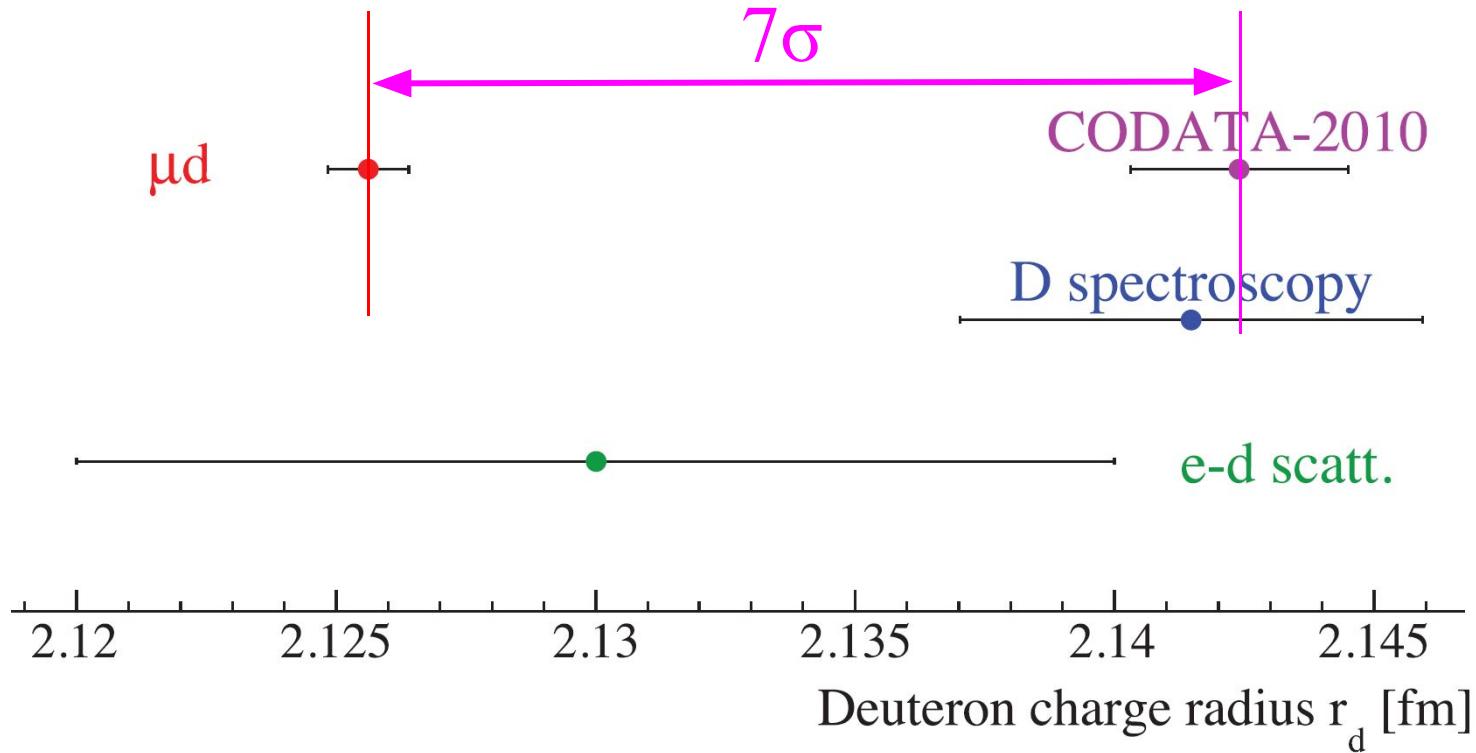
There is a discrepancy between eD and μ D data



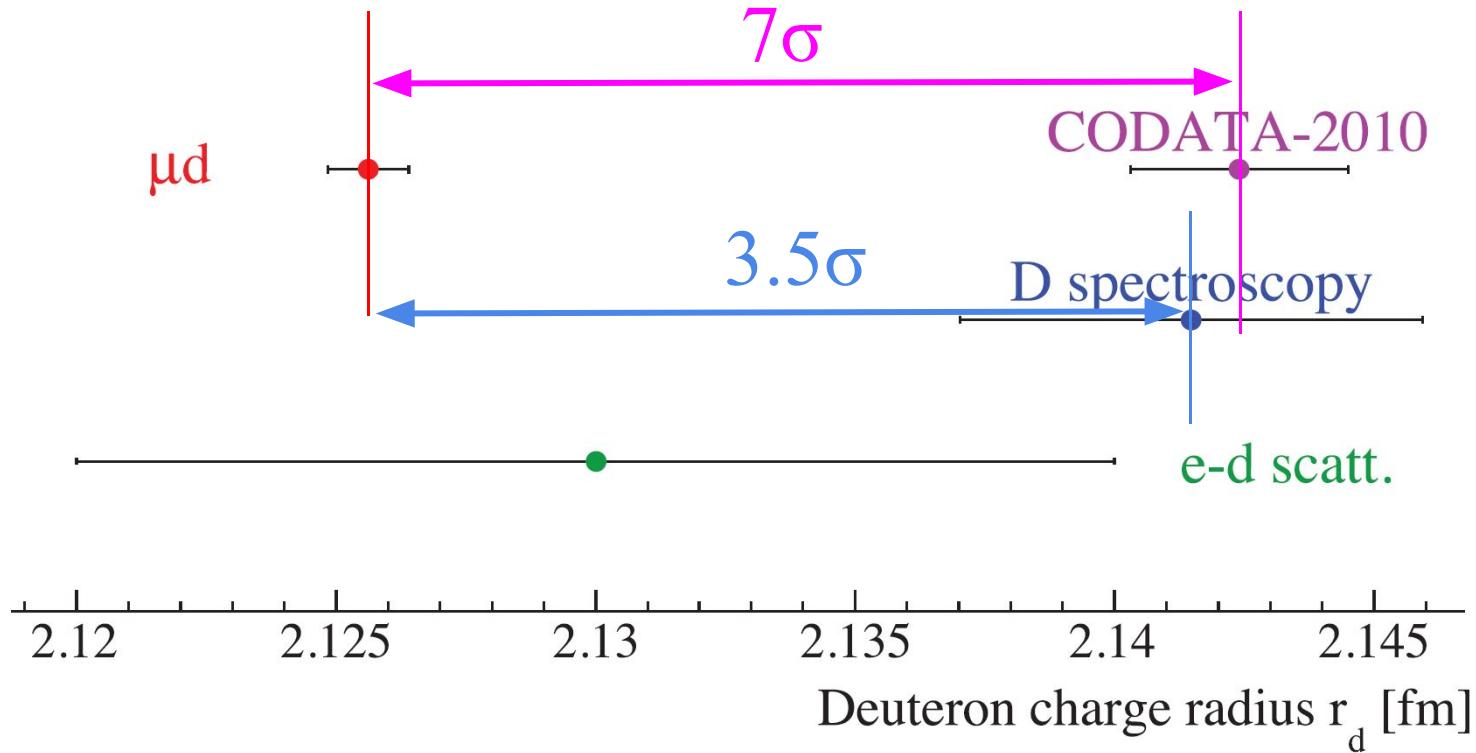
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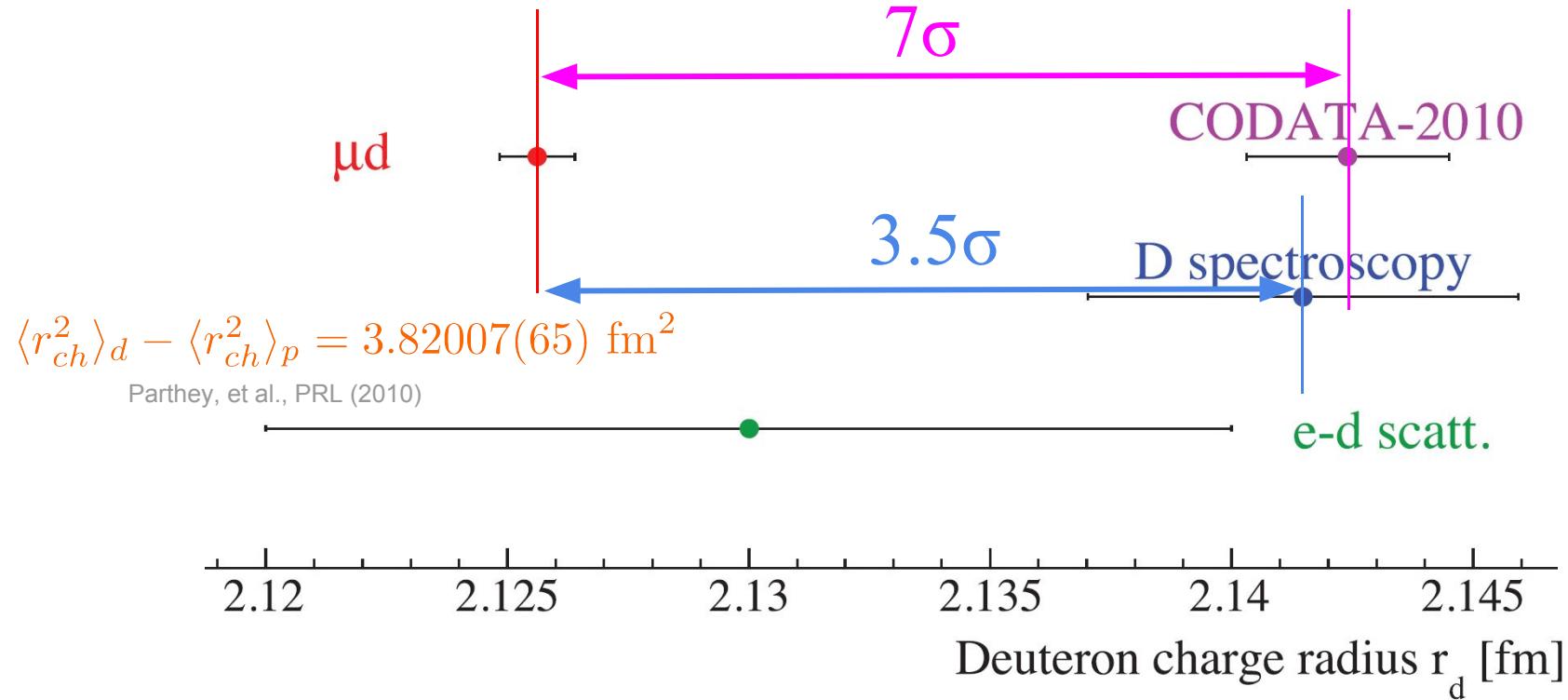
There is a discrepancy between eD and μ D data



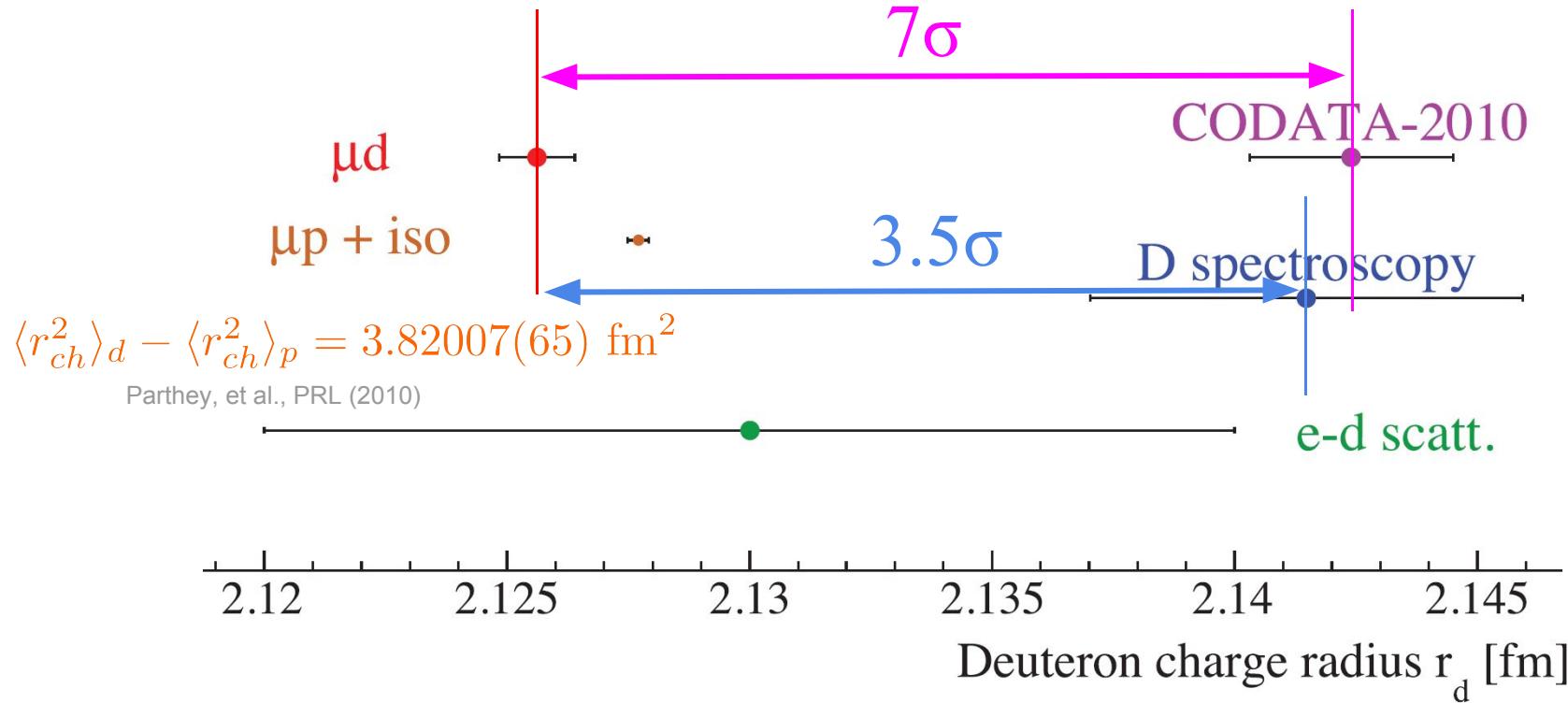
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There is a discrepancy between eD and μ D data

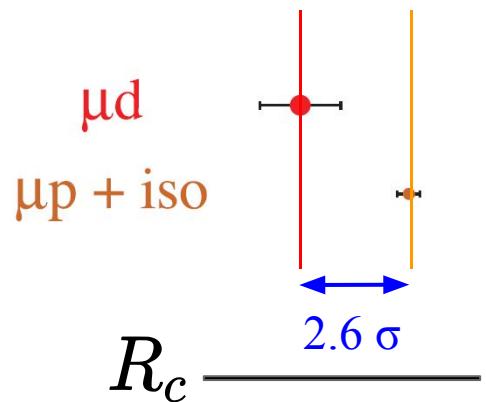


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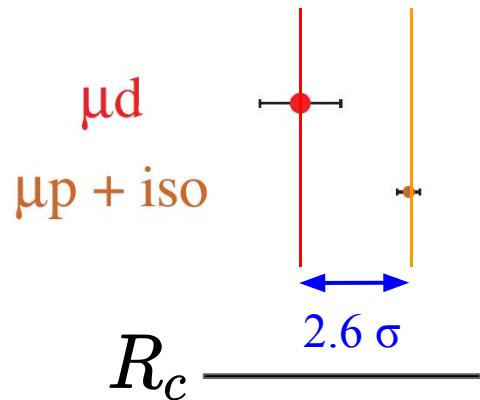


TPE discrepancy

$$\Delta E_{LS} = \delta_{QED} + \delta_{FS}(R_c) + \delta_{TPE}$$



TPE discrepancy



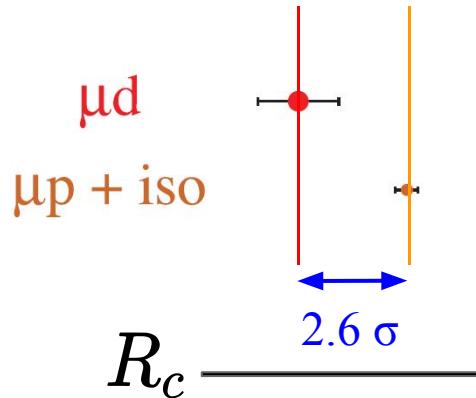
$$\Delta E_{LS} = \delta_{QED} + \delta_{FS}(R_c) + \delta_{TPE}$$

$$\delta_{TPE}(\text{Our Work}) = -1.718(22) \text{ meV}$$

$$\delta_{TPE}(\text{Pachucki}) = -1.717(20) \text{ meV}$$

$$\delta_{TPE}(\text{Krauth et al.}) = -1.710(20) \text{ meV}$$

TPE discrepancy



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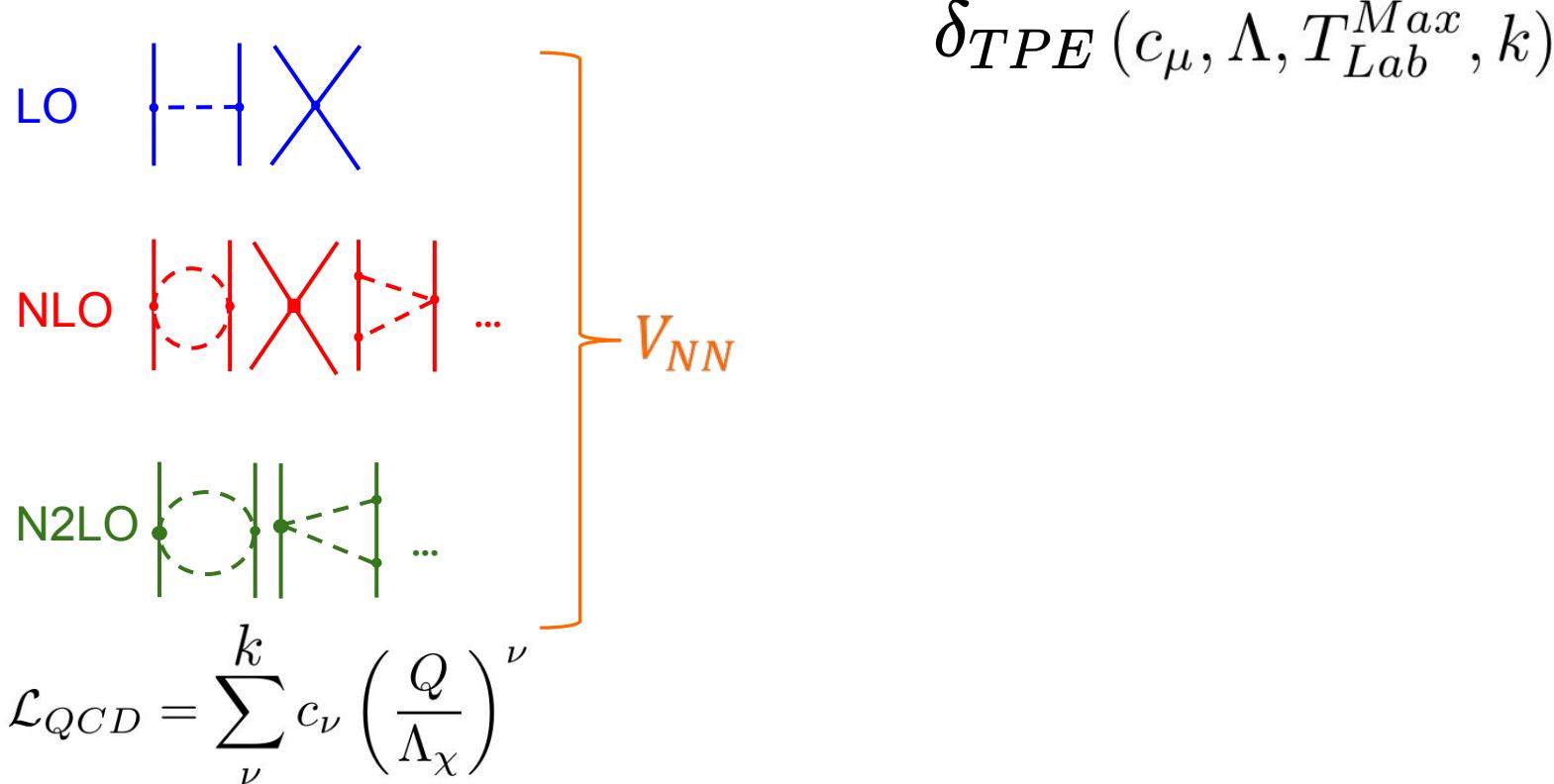
$$\delta_{TPE}(\text{Krauth et al.}) = -1.710(20) \text{ meV}$$

$$\delta_{TPE} = \delta_{QED} + \delta_{FS}(R_c) - \Delta E_{LS} \rightarrow \delta_{TPE}(\text{Exp.}) = -1.7638(68) \text{ meV}$$

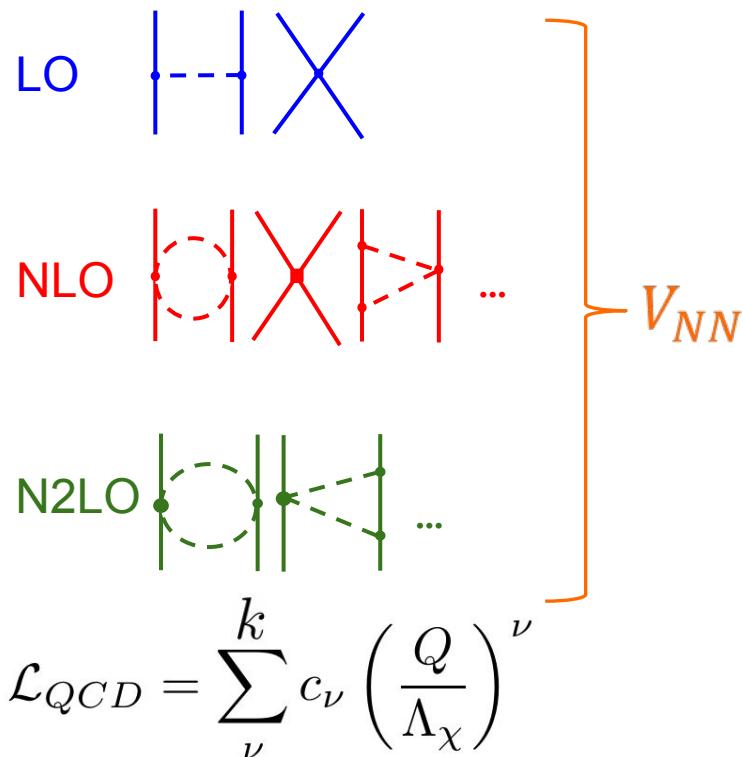
[Pohl et. al. Science, Vol 353, 6300, 2016]

- Theoretical TPE is 6 times larger than experimental uncertainty
- A thorough analysis may change our $\sim 1\%$ uncertainty and shed light on disagreement in δ_{TPE}

Improving the uncertainty estimates



Improving the uncertainty estimates

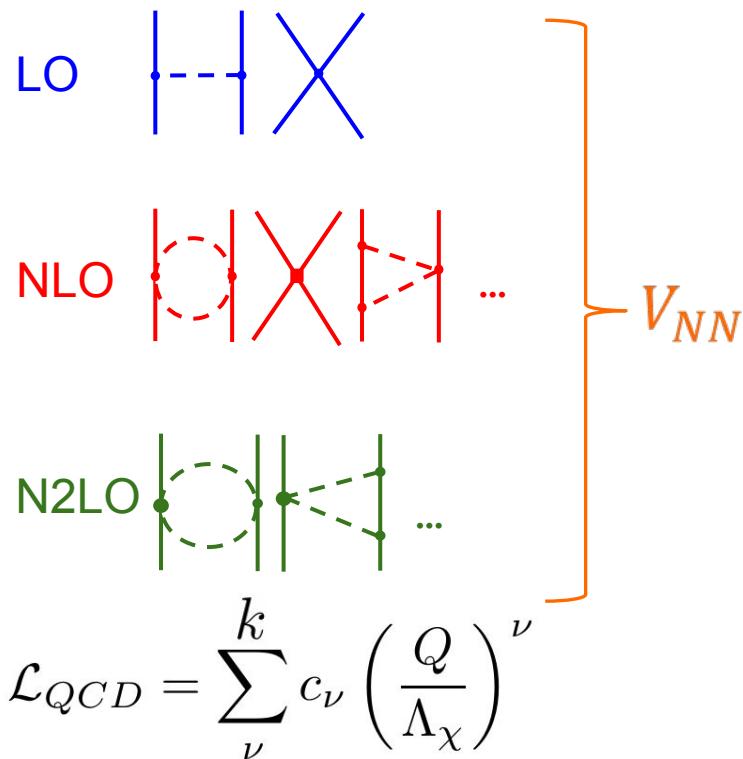


$$\delta_{TPE}(c_{\mu}, \Lambda, T_{Lab}^{Max}, k)$$

- Use N2LO potentials fit simultaneously to NN and πN data

Statistical uncertainties: c_{μ}

Improving the uncertainty estimates



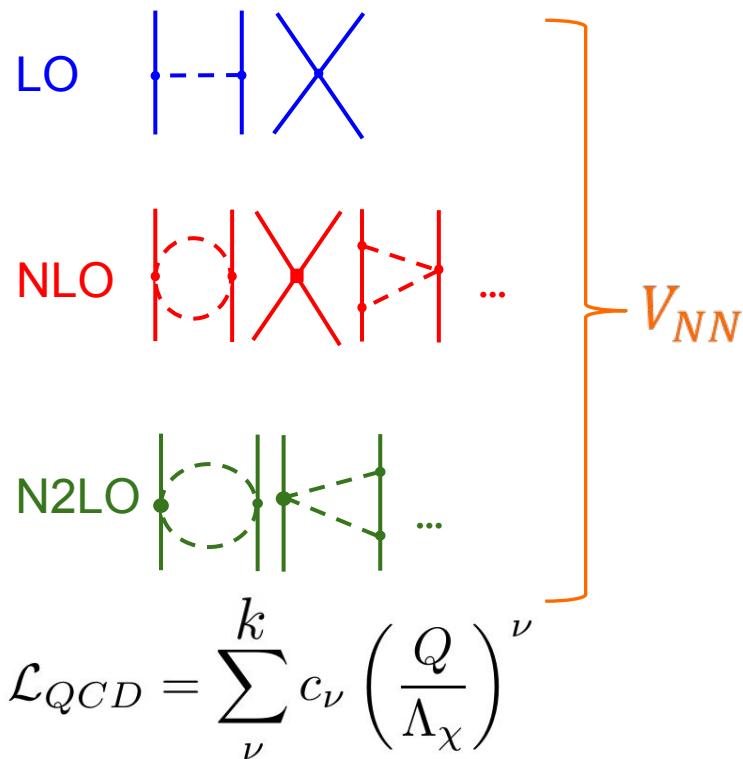
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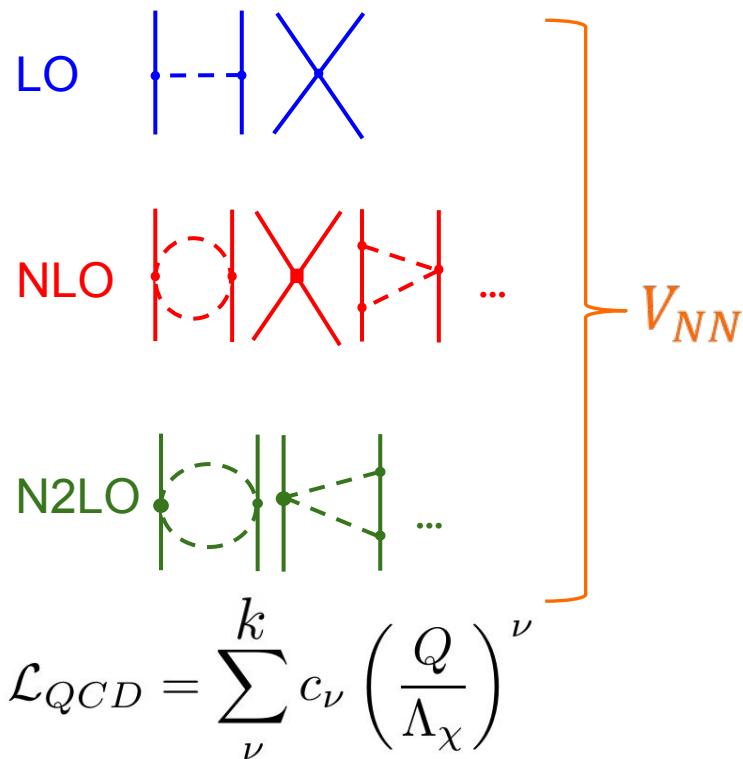
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η, ρ, \vec{j}

Improving the uncertainty estimates



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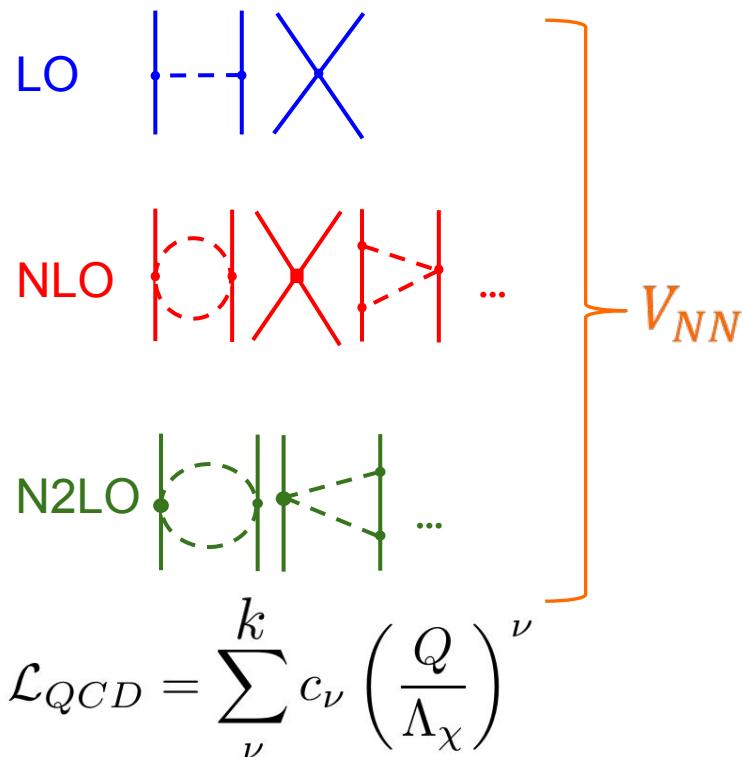
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η, ρ, \vec{j}

Single Nucleon: δ_{TPE}^N

Improving the uncertainty estimates



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- Use N2LO potentials fit simultaneously to NN and πN data

Statistical uncertainties: c_{μ}

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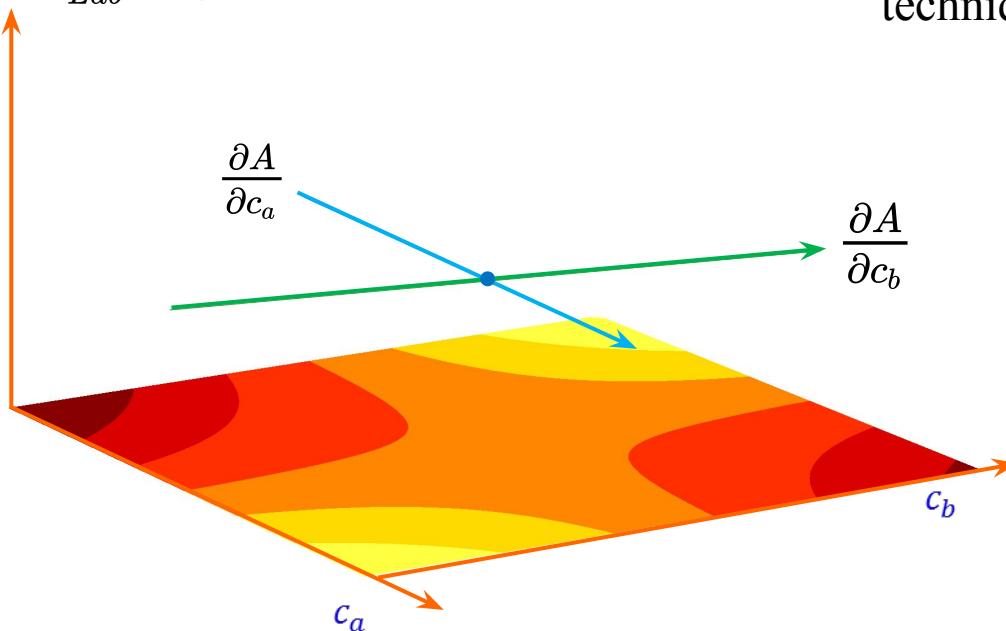
η, ρ, \vec{j}

Single Nucleon: δ_{TPE}^N

Higher Order Corrections: $O(\alpha^6)$

Statistical uncertainties

$$A(c_\mu, \Lambda, T_{Lab}^{Max}, k)$$



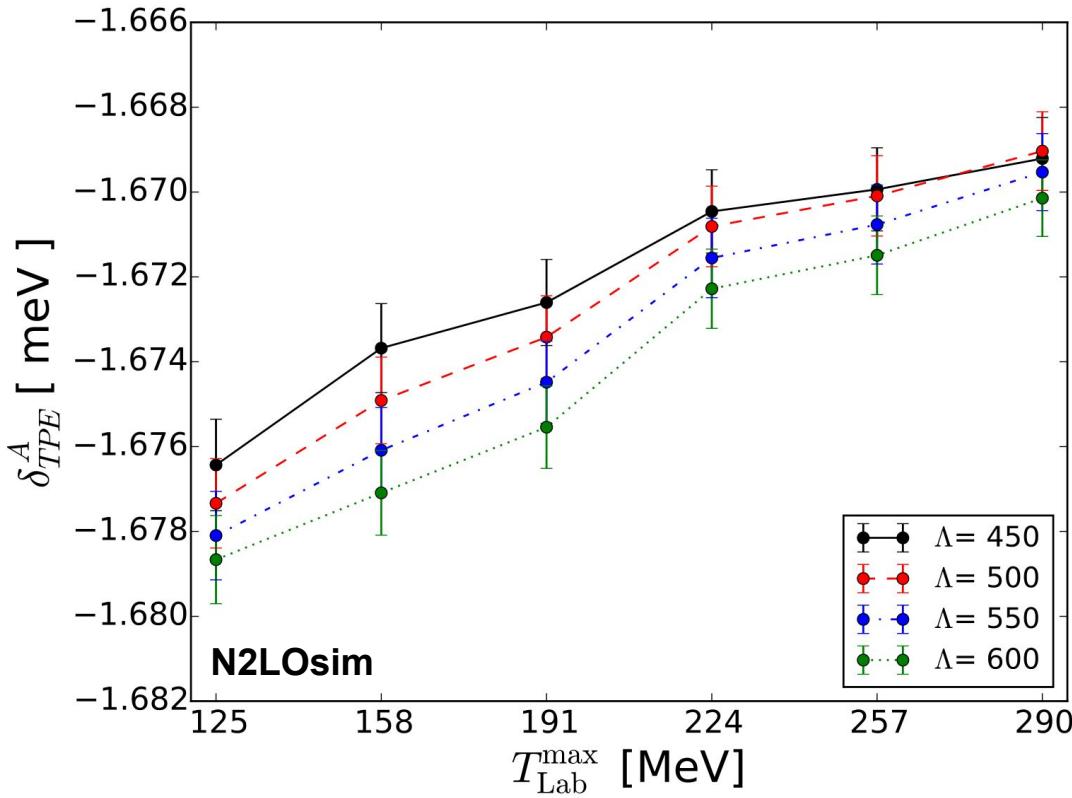
- Propagate uncertainty using standard techniques

$$J_{A,i} = \frac{\partial A}{\partial c_{\mu,i}}$$

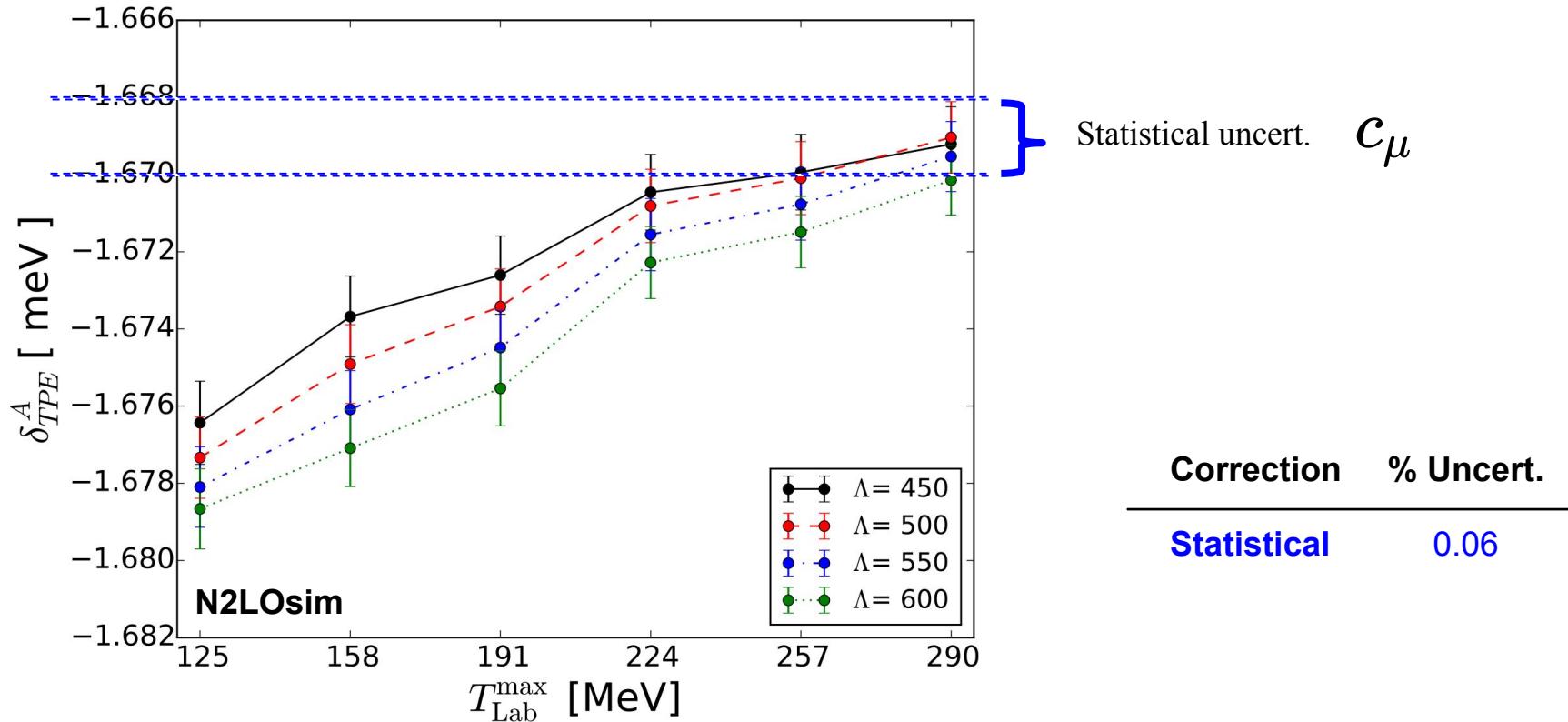
$$\text{Cov}(A, B) = \mathbf{J}_A \text{Cov}(c_\mu) \mathbf{J}_B^T$$

$$\sigma_{A,stat} = \sqrt{\text{Cov}(A, A)}$$

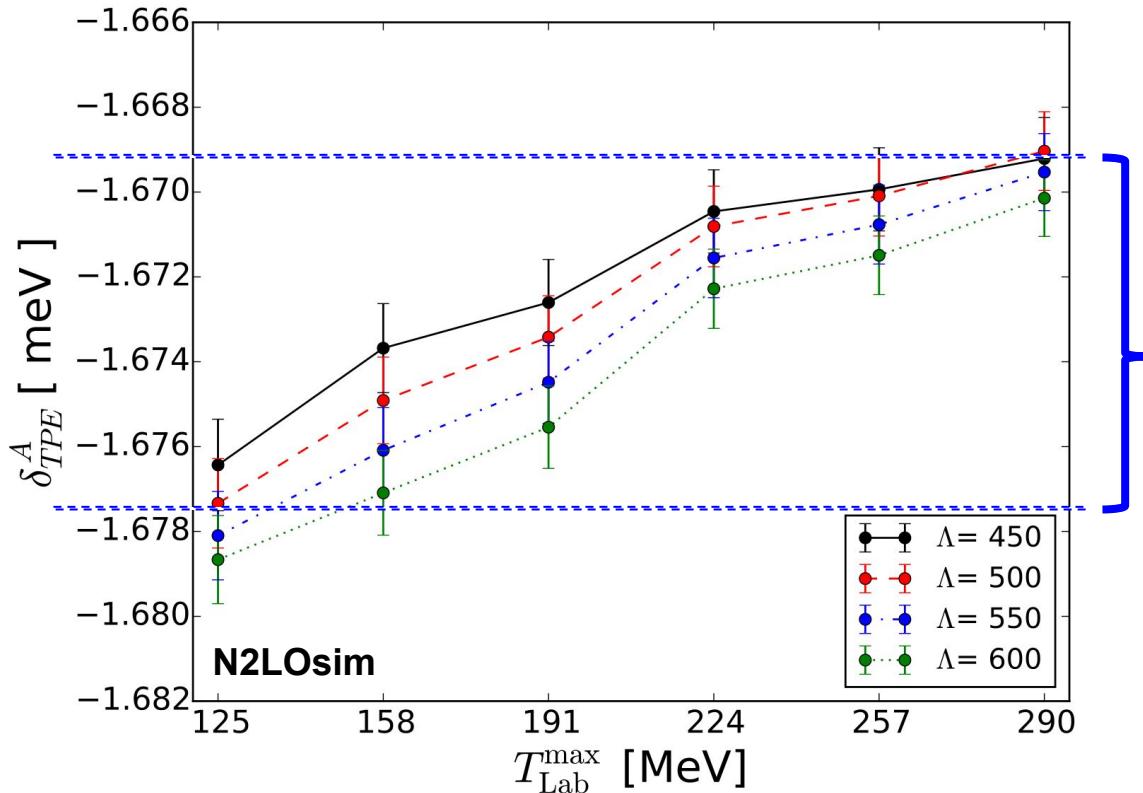
Statistical uncertainties



Statistical uncertainties



Sytematic Tlab Uncertainties



Correction	% Uncert.
Statistical	0.06
Tlab Sys.	0.2

Chiral truncation uncertainties

$$\mathcal{L}_{QCD} = \sum_{\nu}^k c_{\nu} \left(\frac{Q}{\Lambda_{\chi}} \right)^{\nu} = \text{LO} + \text{NLO} + \dots$$

The diagram illustrates the expansion of the QCD Lagrangian into Chiral EFT. It shows two terms: LO (Left) and NLO (Right). The LO term consists of two vertical blue lines connected by a horizontal dashed blue line, which then connects to a blue crossed line. The NLO term consists of two vertical red lines. The left one has a red circle with a dashed arc around it. The right one has a red cross with a red dot at its center. Dashed red lines connect the top and bottom of the red lines, and a dashed red line connects the two red lines horizontally. Ellipses indicate higher-order terms.

- Expand observable in the same Chiral EFT pattern,

$$A^{N^k LO}(p) = A_0 \sum_{\nu=0}^{k+1} \beta_{\nu}(p) Q^{\nu}$$

$$Q = \max \left\{ \frac{p}{\Lambda_b}, \frac{m_{\pi}}{\Lambda_b} \right\}$$

Chiral truncation uncertainties

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The equation shows the QCD Lagrangian as a sum of terms. The first term is the LO (Leading Order) contribution, shown as a diagram with two vertical blue lines connected by a horizontal dashed line, followed by a crossed blue line. The second term is the NLO (Next-to-Leading Order) contribution, shown as a diagram with two vertical red lines connected by a crossed red line, followed by a dashed red loop and a dashed red line. The ellipsis indicates higher-order terms.

- Expand observable in the same Chiral EFT pattern,

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- Truncation uncertainty can then be calculated according to

$$\sigma_{A,sys}^{N^k LO}(p) \approx Q \cdot |A_0 Q^{k+1} \beta_{k+1}|$$

$$\sigma_{A,sys}^{N^k LO}(p) = A_0 Q^{k+2} \max\{|\beta_0|, \dots, |\beta_{k+1}|\}$$

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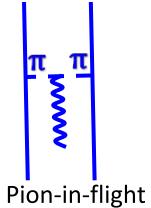
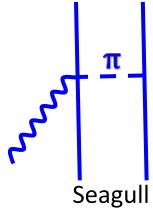
Correction	% Uncert.
Chiral Trunc.	0.4

Additional uncertainties

Two body currents + relativistic corr.

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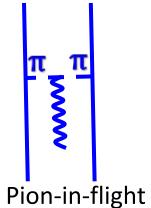
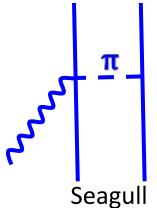


ρ, \vec{j}

Correction	% Uncert.
NLO MEC	0.05
Rel. Corr.	0.05

Additional uncertainties

Two body currents + relativistic corr.



ρ, \vec{j}

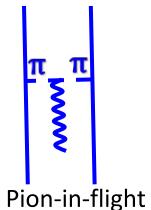
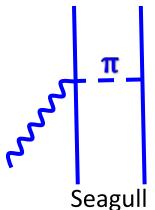
Eta Expansion η

$$\delta_{TPE}^A = \delta^{(0)} + \delta^{(1)} + \delta^{(2)} + O(\eta^3)$$

Correction	% Uncert.
NLO MEC	0.05
Rel. Corr.	0.05
Eta Exp.	0.3

Additional uncertainties

Two body currents + relativistic corr.

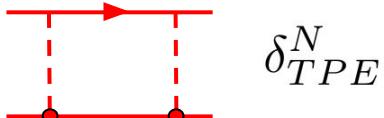


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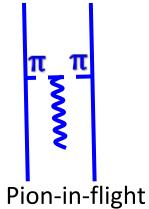
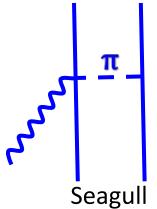
Single Nucleon Physics



Correction	% Uncert.
NLO MEC	0.05
Rel. Corr.	0.05
Eta Exp.	0.3
Nucleon	0.6
	1.15

Additional uncertainties

Two body currents + relativistic corr.

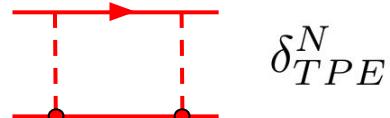


ρ, \vec{j}

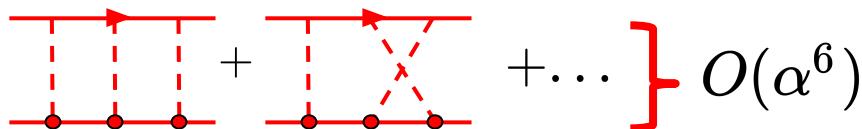
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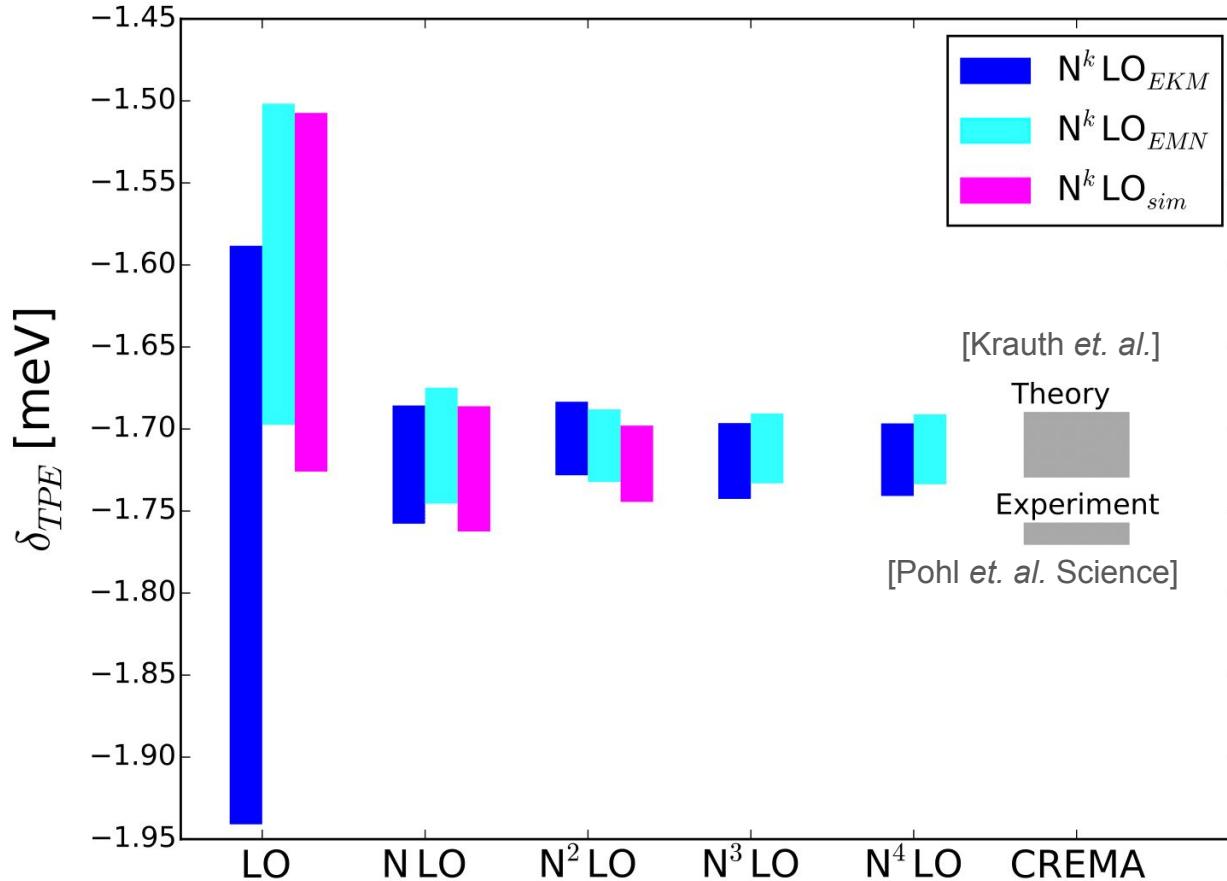


Atomic Physics uncert.



Correction	% Uncert.
NLO MEC	0.05
Rel. Corr.	0.05
Eta Exp.	0.3
Nucleon	0.6
Atomic Phys.	1.0

The total uncertainty



Summary

Krauth et. al. [2016]

$$\delta_{TPE}(\text{Krauth et al.}) = -1.710(20) \text{ meV}$$

Carlson et. al. [2016]

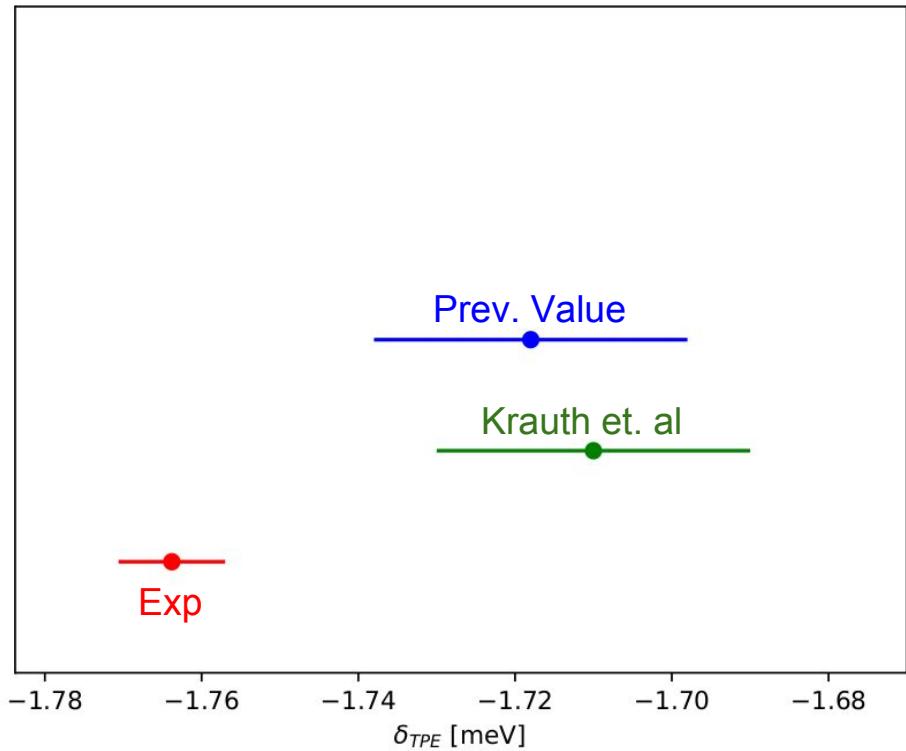
$$\delta_{TPE}(\text{Carlson et al.}) = -2.01(74) \text{ meV}$$

Previous Value [2014,2016]

$$\delta_{TPE}(\text{Prev Work}) = -1.718(22) \text{ meV}$$

Experimental

$$\delta_{TPE}(\text{Exp}) = -1.7638(68) \text{ meV}$$



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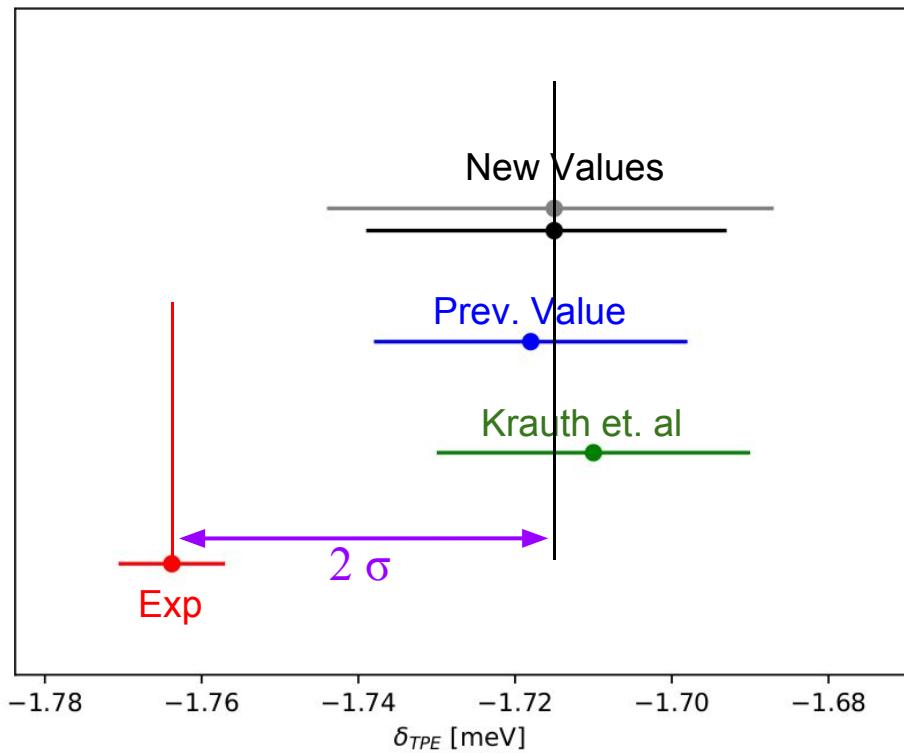
New values [2018]

$$\delta_{TPE} = -1.715^{+22}_{-24} \text{ meV}$$

$$\delta_{TPE} = \quad \quad \quad {}^{+28}_{-29} \text{ meV}$$

Experimental

$$\delta_{TPE}(\text{Exp}) = -1.7638(68) \text{ meV}$$



Outlook

Results:

- Experimental vs theory disagreement likely not due to the nuclear TPE uncertainty

Uncertainty Analysis:

- Reduce atomic physics uncert. $O(\alpha^6)$

Etaless Expansion

- Apply formalism to A=3 systems
- Extend formalism for HFS

Thank you!



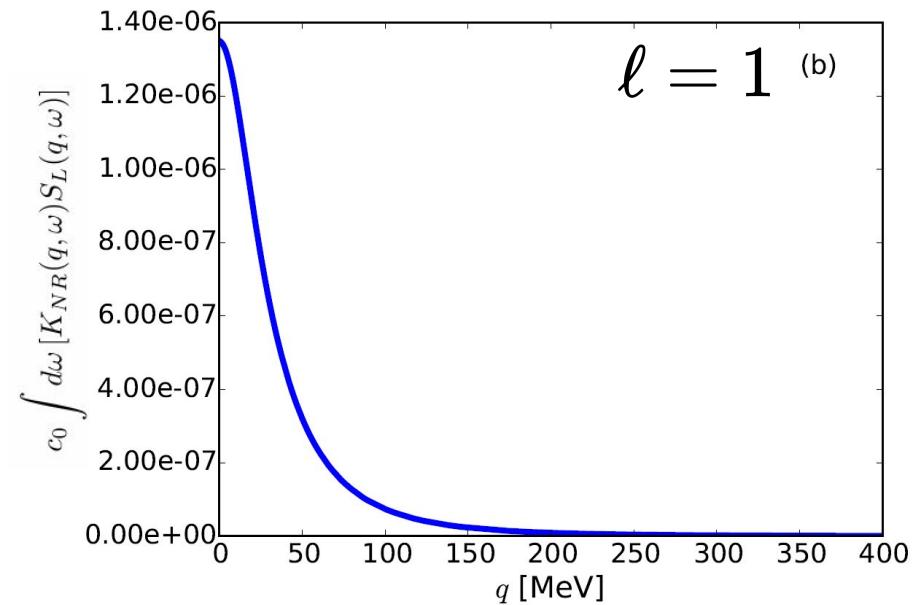
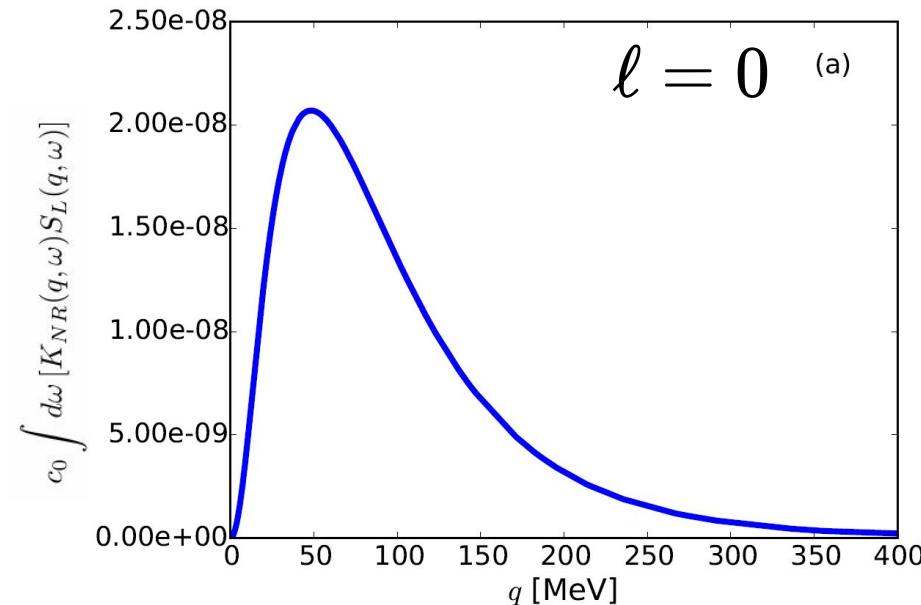
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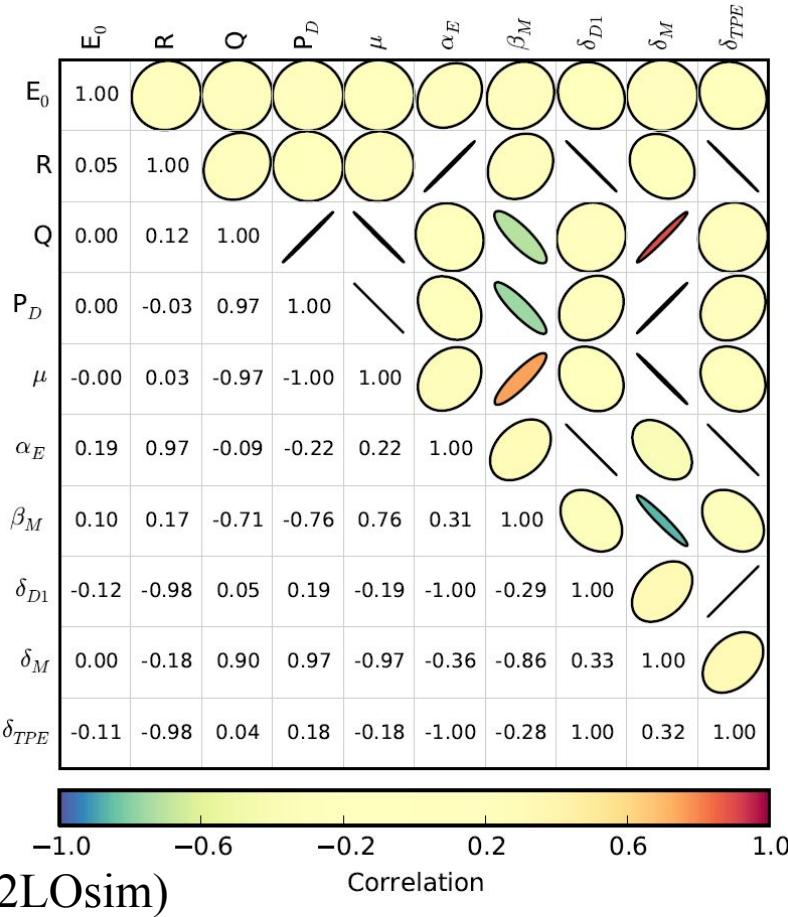


η -less expansion



$N^3\text{LO-EM}$	$\delta_{\ell=0}^{(0)}$	$\delta_{\ell=1}^{(0)}$	$\delta_{\ell=2}^{(0)}$	$\delta_{\ell=3}^{(0)}$	$\delta_{\ell=4}^{(0)}$	$\sum \delta_{\ell}^{(0)}$
[meV]	-0.069	-1.436	-0.064	-0.012	-0.004	-1.585
[meV]	[PLB 2014., Proc. H.H.I 2016]				-1.590	

Correlation analysis



- Serves as a check of the error propagation formalism

$$\rho(A, B) = \frac{Cov(A, B)}{\sigma_A \sigma_B}$$

- We observe strong correlations between
 - $\{P_d, \mu_d\}$
 - $\{R(^2\text{H}), \alpha_E\}$
 - $\{R(^2\text{H}), \delta_{TPE}\}$