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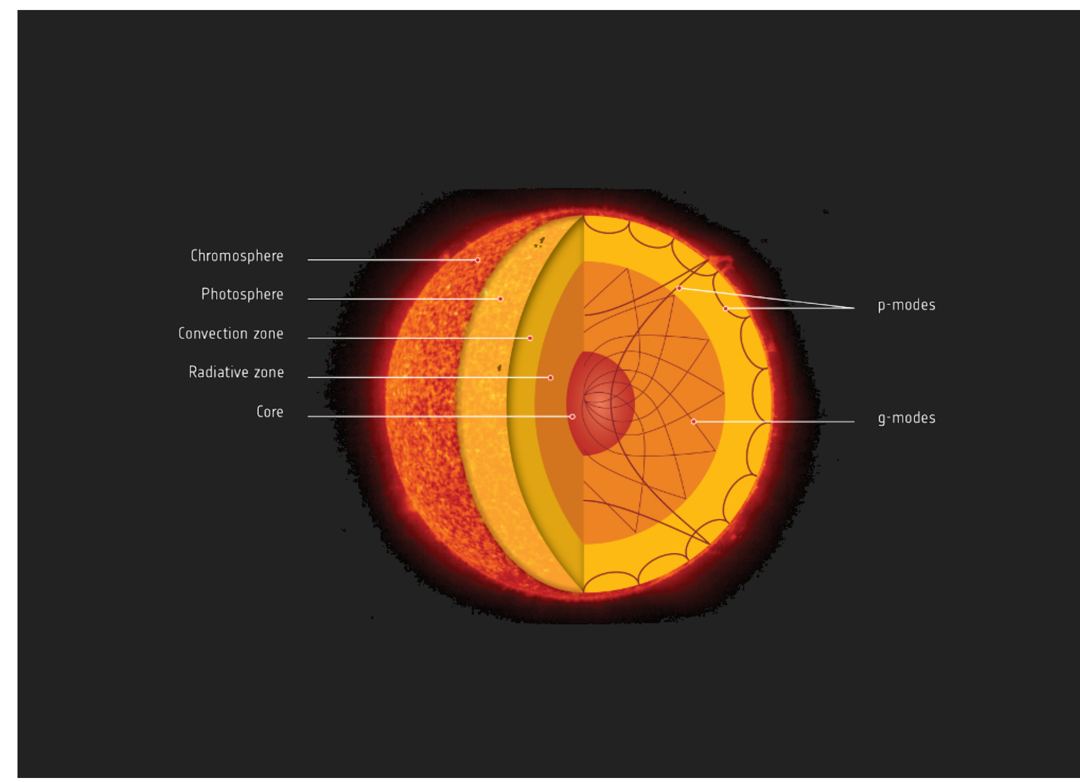
FROM SOLAR COMPOSITION PROBLEM TO NEW SOLAR NEUTRINO PROBLEM –
THE ELECTROWEAK PROPERTIES OF A=2, 3 PERSPECTIVE

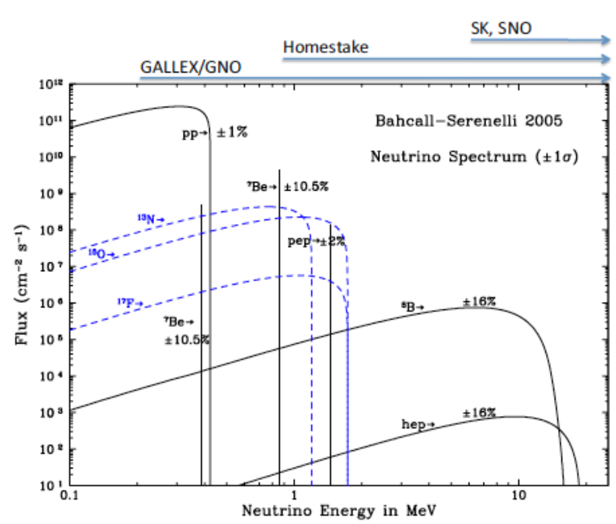
THE SUN AS A LABORATORY

- The interior of the Sun is an extreme environment, not found in terrestrial laboratories, and thus a natural scenario to search for new physics signatures.
- i.e., building a ***Solar Model*** and comparing with experiment allows viewing the Sun as a laboratory.



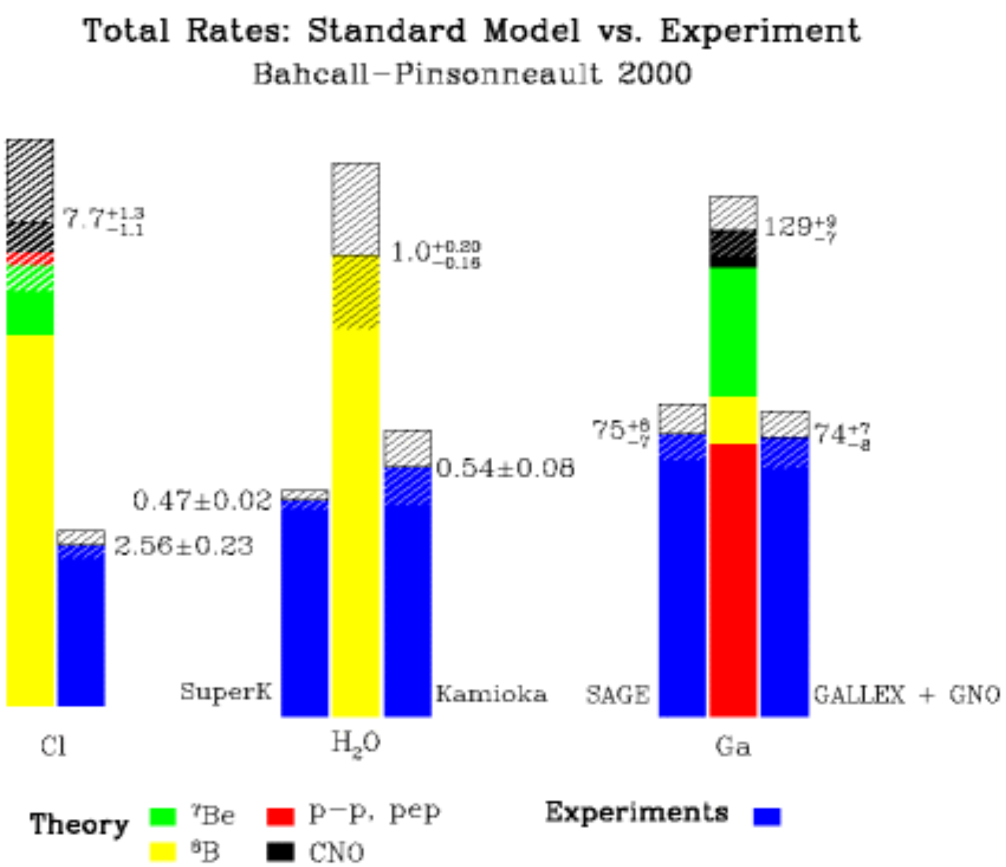
Helioseismology – "sun-quakes" on the surface which can tell us about the structure to the core.

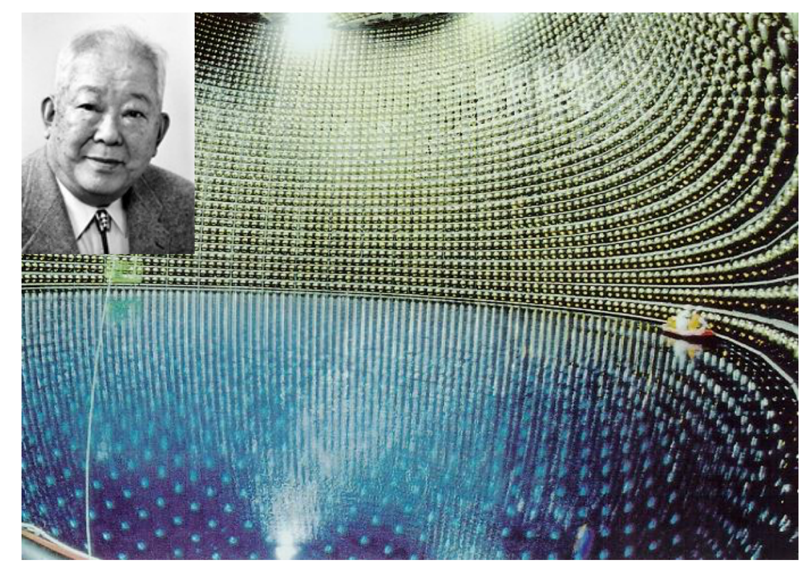
Neutrinos– probe the temperature of the core.



Basu 2009, Villante 2010, Serenelli (2013)

THE SUN AS A LABORATORY

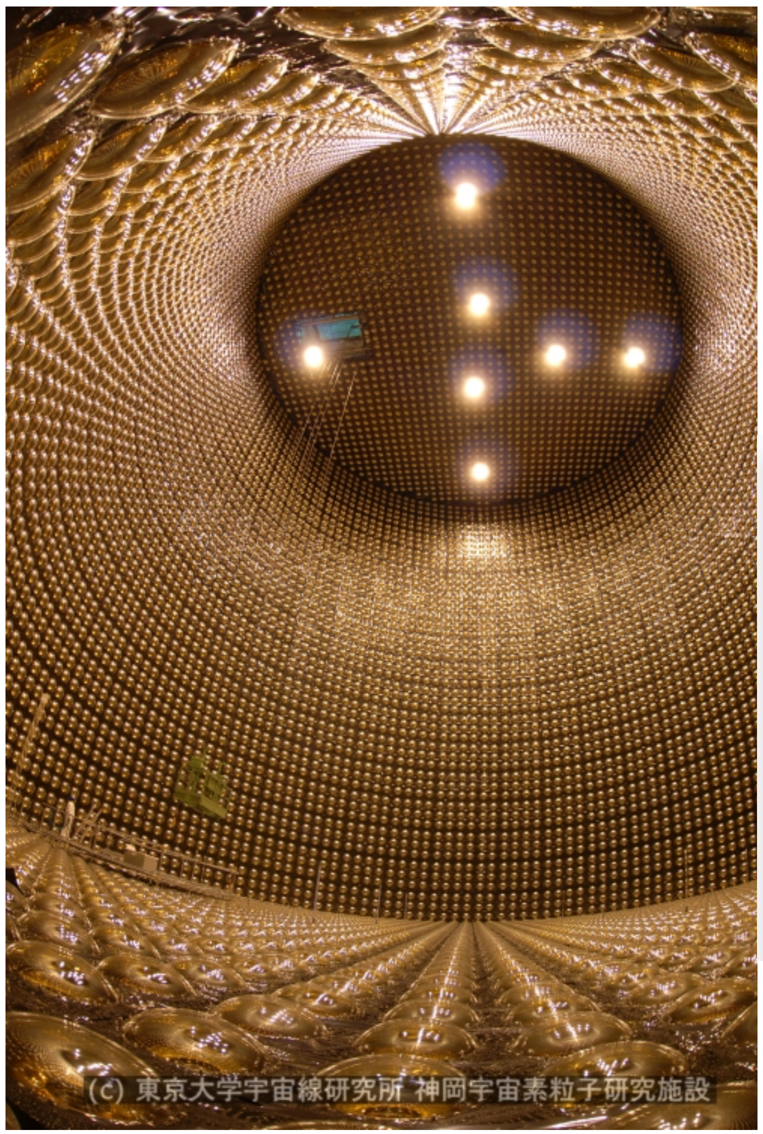


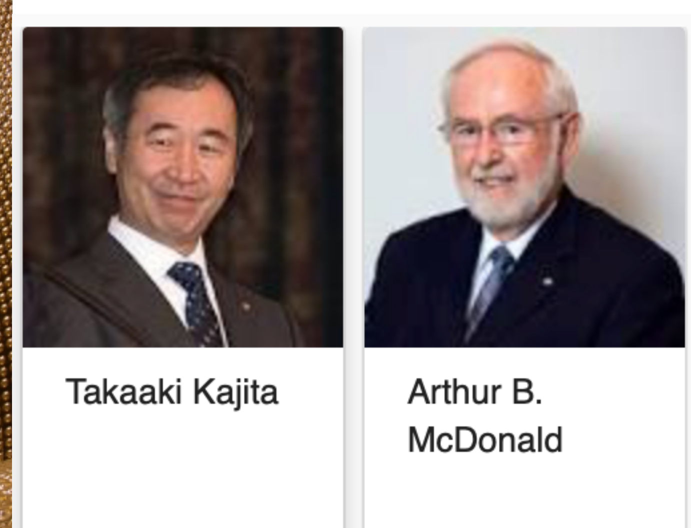


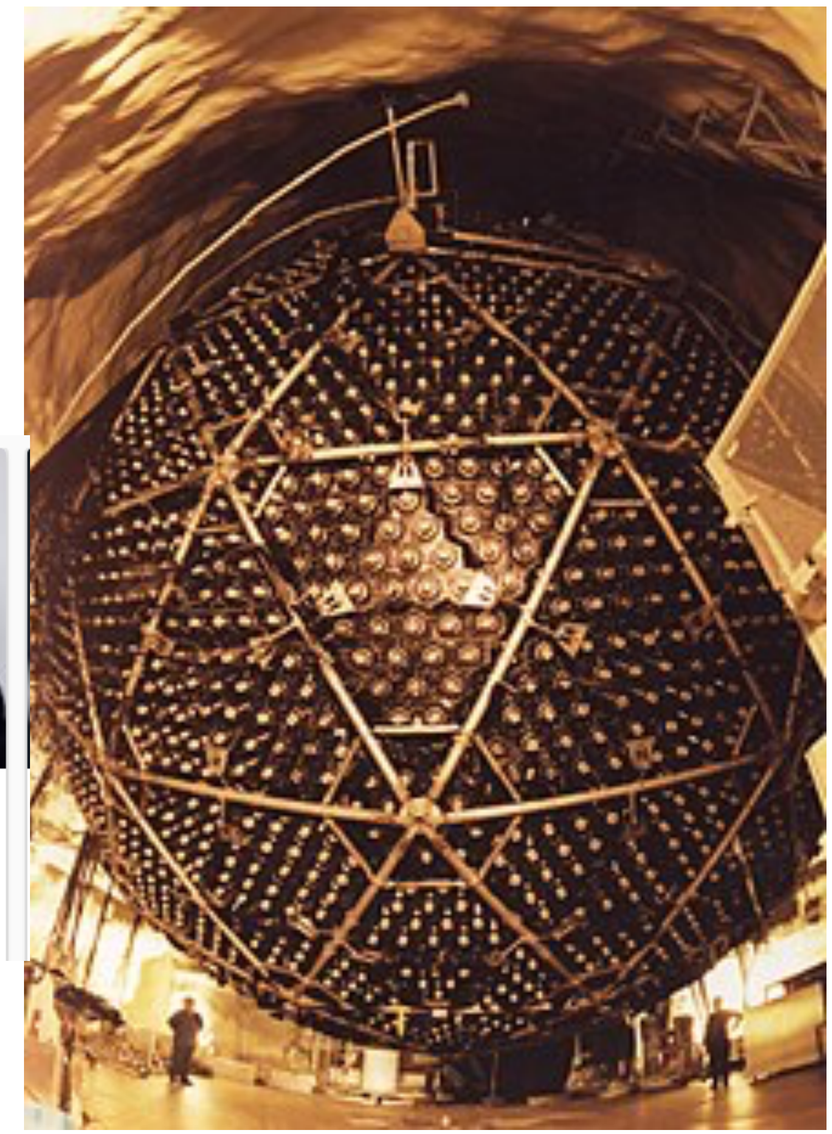
Nobel prize 2002: the solar neutrino problem

Predicted Solar neutrino flux can not match measured solar neutrino flux

THE SUN AS A LABORATORY







Solution – neutrino masses and oscillations

Hinted from solar measurements, proven terrestrially

STANDARD SOLAR MODELS

input

Mass, Luminocity, Age, ***Composition***

→

Equations and data bases

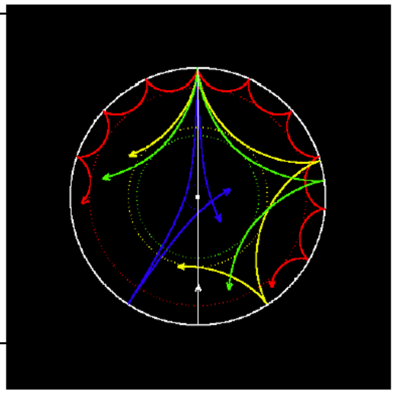
Standard Solar Model (SSM)

- Rad-hyd
- 1d mixing.
- Opacities
- Eqs. of state (EOS)
- Nuclear rates
- …..

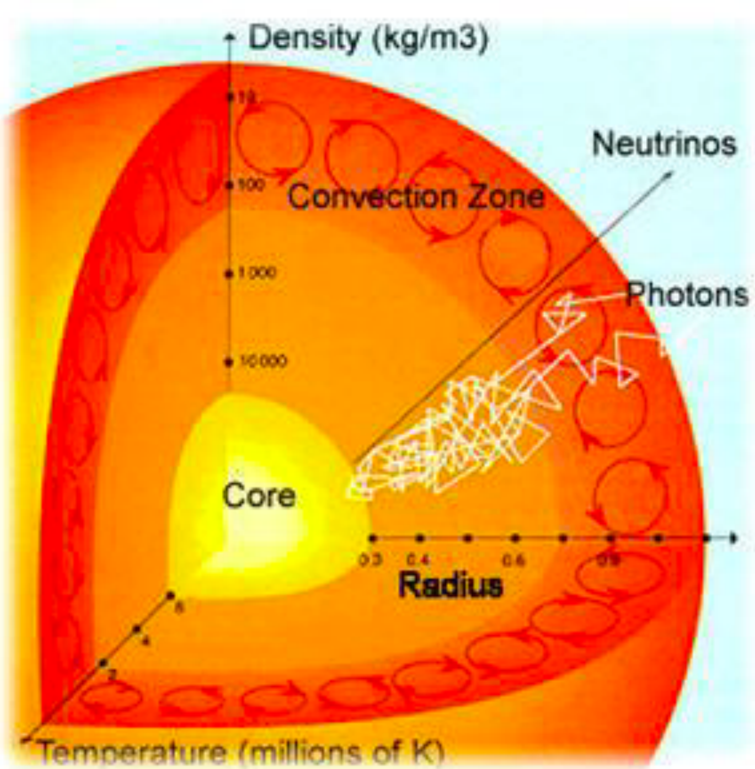
→

Output verified vs. Helioseismology & neutrinos

- Rcz – convection zone
- Ycz – Helium abundance
- Sound vel. profile
- Neutrino fluxes



differential probing of solar structur



ASPLUND ET AL. (2009) SOLAR COMPOSITION REEVALUATION

- A *downward* revision in the abundance of some of the elements in the solar mixture, due to better solar atmosphere simulations, as well as meteorite data.

Element	GS98	AGSS09	δz_i
C	8.52 ± 0.06	8.43 ± 0.05	0.23
N	7.92 ± 0.06	7.83 ± 0.05	0.23
O	8.83 ± 0.06	8.69 ± 0.05	0.38
Ne	8.08 ± 0.06	7.93 ± 0.10	0.41
Mg	7.58 ± 0.01	7.53 ± 0.01	0.12
Si	7.56 ± 0.01	7.51 ± 0.01	0.12
S	7.20 ± 0.06	7.15 ± 0.02	0.12
Fe	7.50 ± 0.01	7.45 ± 0.01	0.12
Z/X	0.0229	0.0178	0.29

$$[I/H] \equiv \log(N_I/N_H) + 12$$

THE SOLAR COMPOSITION PROBLEM

input

Mass, Luminocity, Age, ***Composition***

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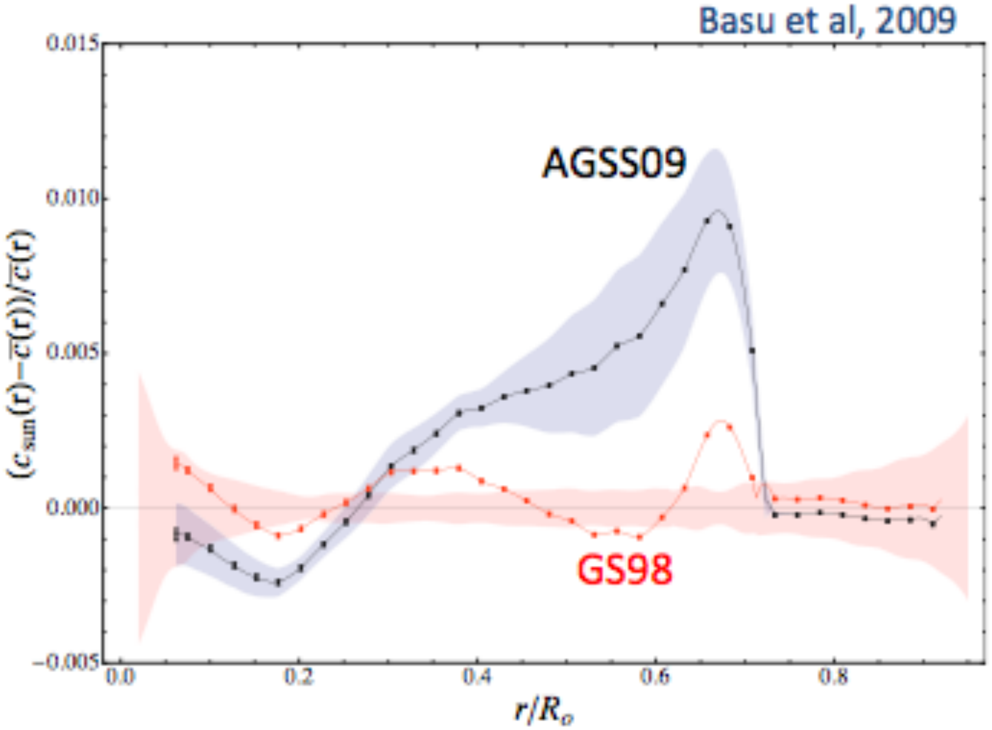
Basu et al, 2009



	AGSS09	GS98	Obs.
Y_b	$0.2319\,(1 \pm 0.013)$	$0.2429\,(1 \pm 0.013)$	0.2485 ± 0.0035
$R_b/R_\odot$	$0.7231\,(1 \pm 0.0033)$	$0.7124\,(1 \pm 0.0033)$	0.713 ± 0.001

$\sim 3 - 4\sigma$ discrepancy!

Serenelli et al 2013
Bailey, J. E., et al. 2009

THE SOLAR COMPOSITION PROBLEM

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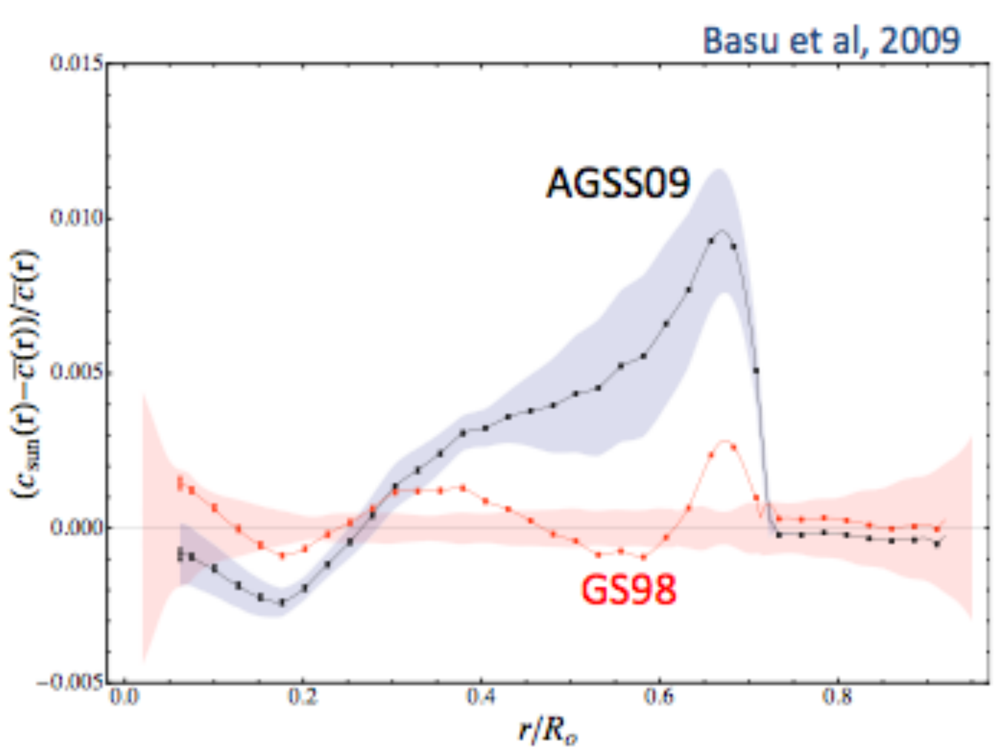

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$\sim 3 - 4\sigma$ discrepancy!

Note: 4σ deviation is just 1.5%…

A precision type of problem demands assessing uncertainties

Serenelli et al 2013
Bailey, J. E., et al. 2009

WE TRY TO ANSWER THE FOLLOWING QUESTIONS

HOW WELL DO WE UNDERSTAND MICROSCOPIC PHENOMENA IN THE SUN?

WHAT IS THE ORIGIN OF CURRENT UNCERTAINTY ESTIMATES?

CAN WE IMPROVE ON THESE?

THE SOLAR COMPOSITION PROBLEM

input

Mass, Luminocity, Age, ***Composition***

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Equations and data bases

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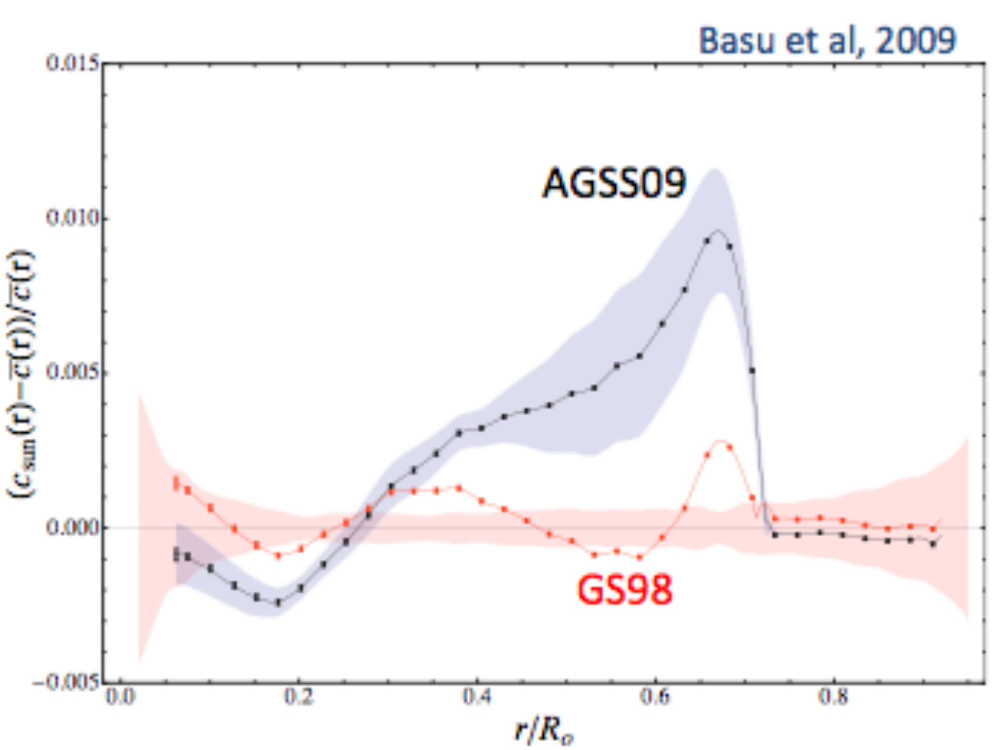

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"IN THE NEWS"

Krief, Feigel, DG, ApJ (2016a,b).

Krief, Feigel, Kurzweil, DG, ApJ (2017).

Segev, DG, Physica A (2018).

Krief, Segev, DG, in preparation.

MAJOR UNNOTICED UNCERTAINTIES IN SOLAR OPACITIES

THE SOLAR COMPOSITION PROBLEM

input

Mass, Luminocity, Age, ***Composition***

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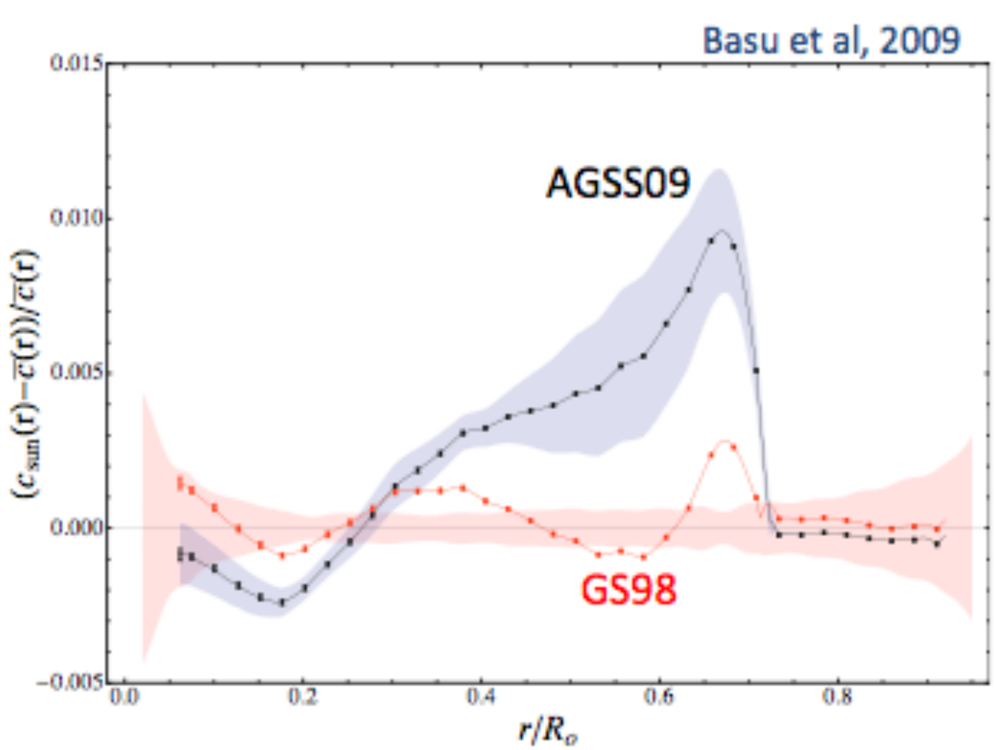

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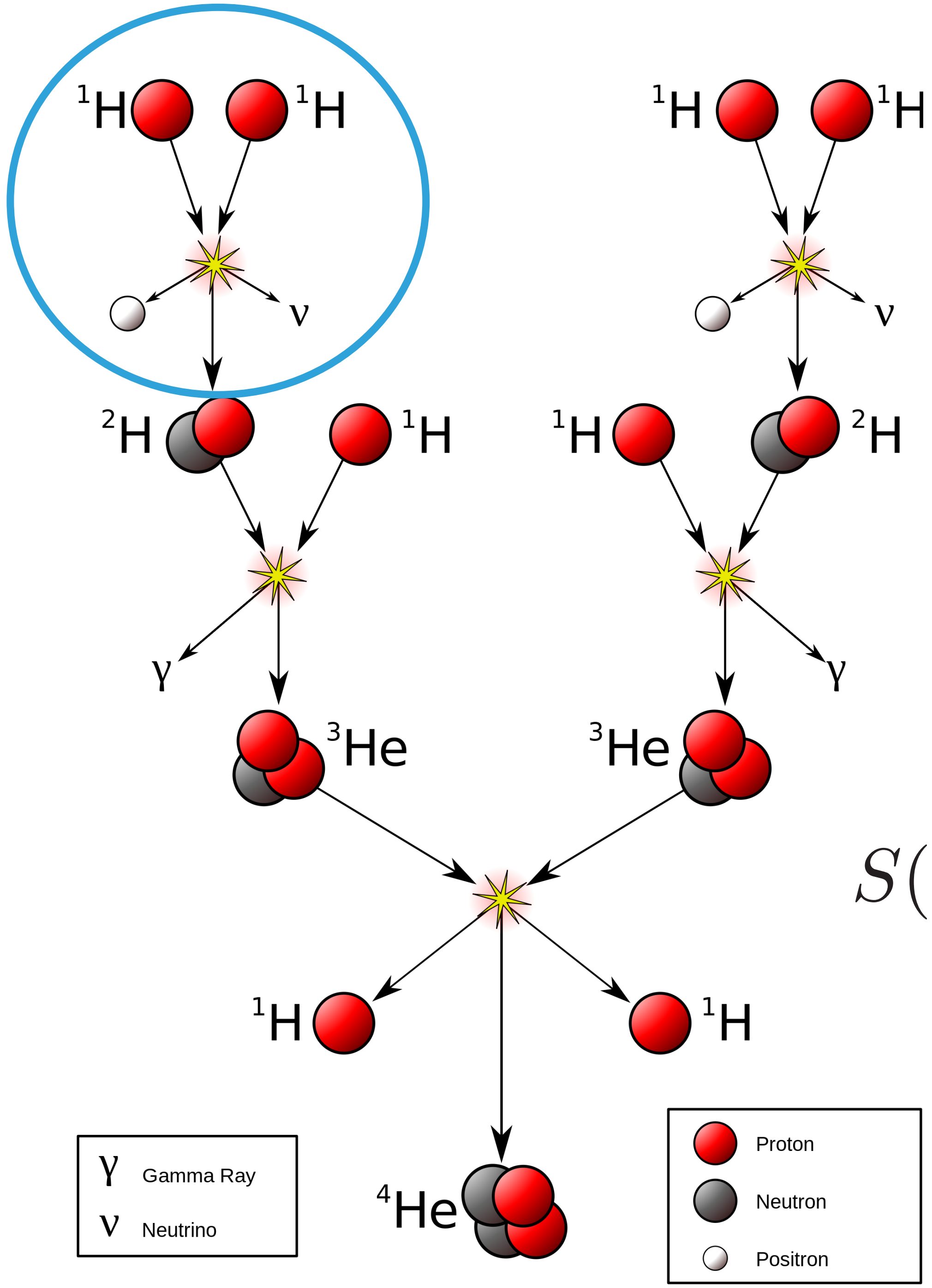
PROTON-PROTON FUSION IN THE SUN

Deleon, Platter, DG (2016, 2019).

Deleon, DG (2019,2020a,b)

MOTIVATION: WEAK PROTON-PROTON FUSION IN THE SUN



Cannot be measured terrestrially – depends on theory

Very low proton-proton relative momentum (E_{rel}~6 keV).

Needed accuracy: ~1%.

$$\sigma(E) = \frac{S(E)}{E} \exp[-2\pi\eta(E)]$$

$$S(E) = S(0) + S'(0)E + S''(0)E^2/2 + \cdots$$

Theory challenge: accuracy and precision

WEAK PROTON-PROTON FUSION IN THE SUN – THEORY STANDARDS

SFII – Adelberger et al., Rev. Mod. Phys. 83, 195 (2011)

$$4.01(1 \pm 0.009) \times 10^{-25}\ \text{MeV b} \quad \text{potential models,}$$
$$4.01(1 \pm 0.009) \times 10^{-25}\ \text{MeV b} \quad \text{EFT}^*,$$
$$3.99(1 \pm 0.030) \times 10^{-25}\ \text{MeV b} \quad \text{pionless EFT.}$$

2011

SFII recommended value (2011): $S_{11}(0) = 4.01(1 \pm 0.009) \times 10^{-25}\ \text{MeV b}.$

Marcucci et al. χEFT: $S(0) = (4.030 \pm 0.006) \times 10^{-23}\ \text{MeV fm}^2$ **2013**

Archaya et al (1603.01593) *χEFT:* $S(0) = (4.081^{+0.024}_{-0.032}) \times 10^{-23}\ \text{MeV fm}^2$ **2016**

WEAK PROTON-PROTON FUSION IN THE SUN – THEORY STANDARDS

SFII – Adelberger et al., Rev. Mod. Phys. 83, 195 (2011)

$$4.01(1 \pm 0.009) \times 10^{-25}\ \mathrm{MeV\,b} \quad \text{potential models,}$$
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2011

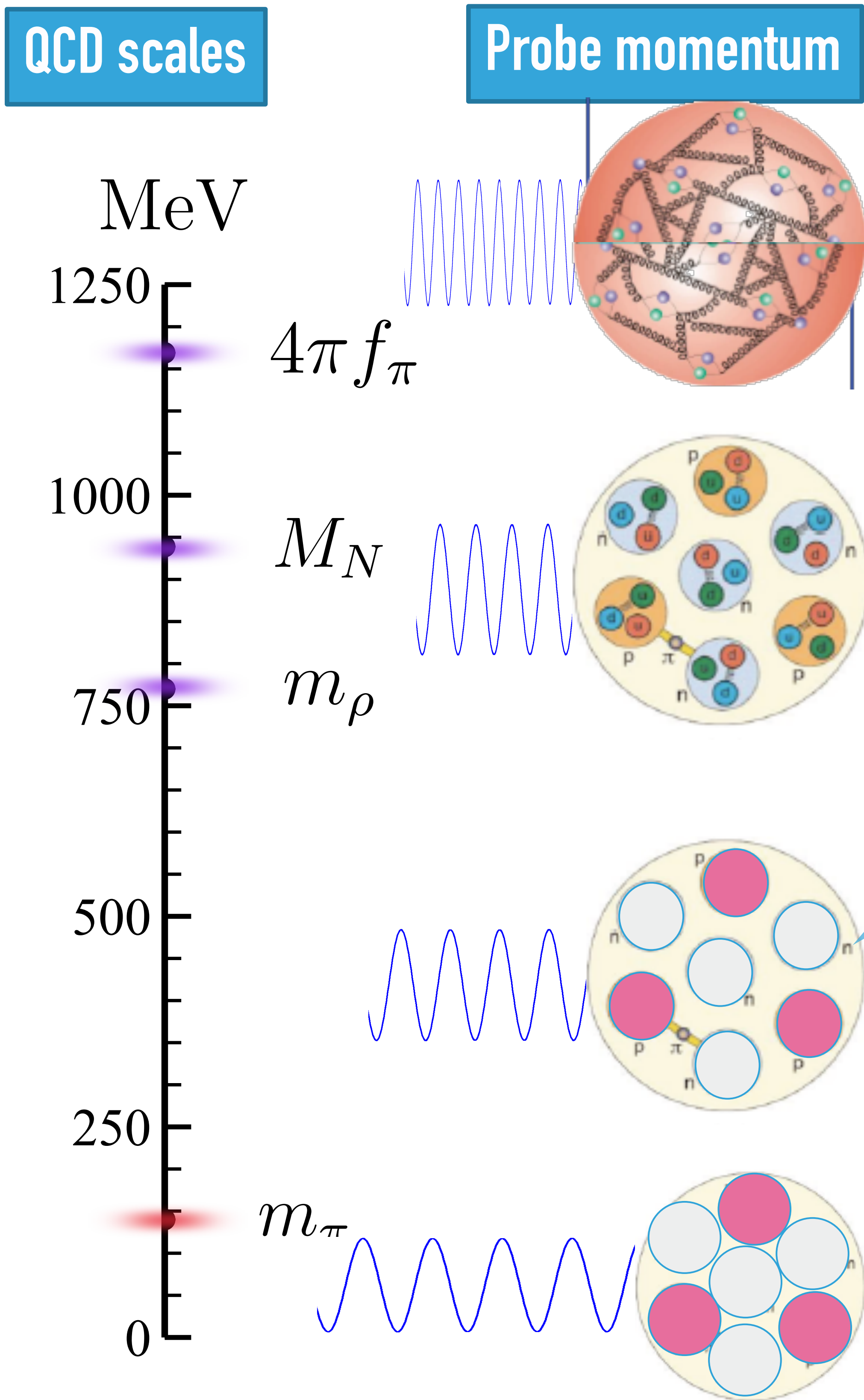
SFII recommended value (2011): $S_{11}(0) = 4.01(1 \pm 0.009) \times 10^{-25}\ \mathrm{MeV\,b}.$

Marcucci et al. χEFT: $S(0) = (4.001 \pm 0.006) \times 10^{-23}\mathrm{MeV} \cdot \mathrm{fm}^2$ **2013/19**

Corrected down by 0.034, due to erroneous p-wave contribution assessment. (Acharya, Platter, Rupak, 2019)

Archaya et al (1603.01593) *χEFT:* $S(0) = (4.047^{+0.024}_{-0.032}) \times 10^{-23}\mathrm{MeV} \cdot \mathrm{fm}^2$ **2016/19**

Plagued by my mistake, though… ;-)



χEFT: Acharya et al, Marcucci et al, calculations:

Many parameters ~ 25-40 (pions, nucleons, contacts).

Non-renormalizable – theory depends on the cutoff, questionable order by order convergence.

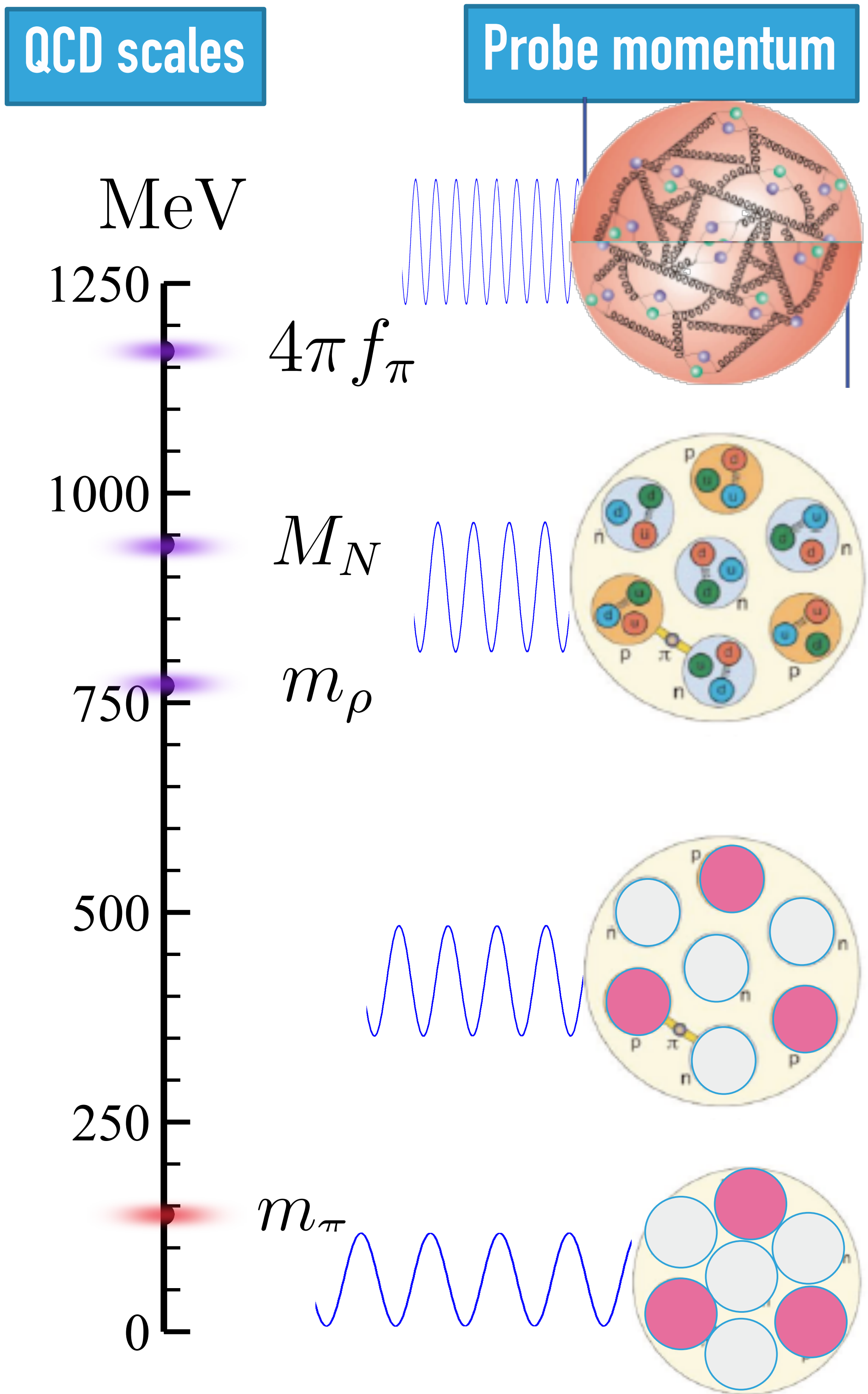
Challenging to assess systematic uncertainties.

Weinberg (1991), van-Kolck (1992), Kaplan (1996)…

CAN WE VALIDATE AND VERIFY THESE RESULTS?

CAN WE ESTIMATE "SYSTEMATIC" UNCERTAINTIES?

Use pion-less EFT



Pion-less EFT at NLO

Natural for description of A=2, 3 bound states.

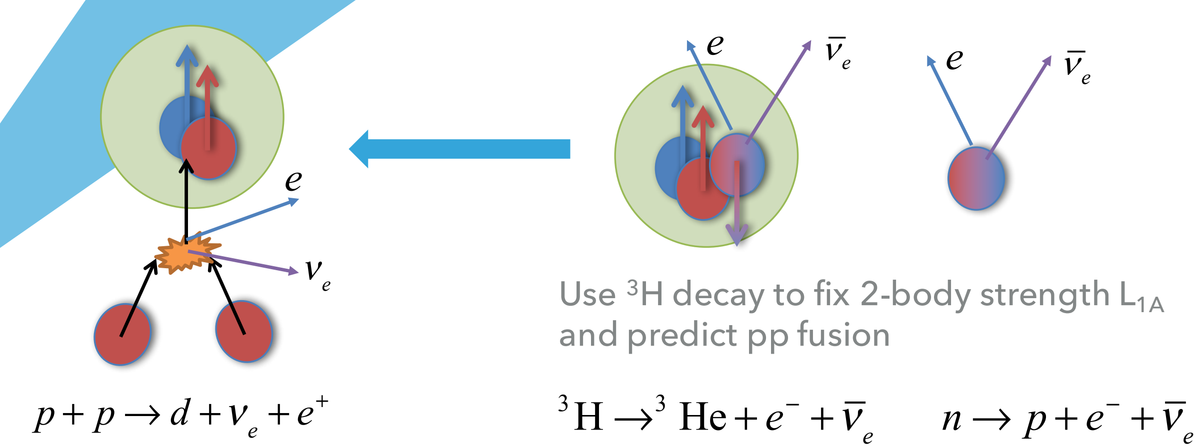
Natural for the energy regime of pp fusion and triton decay

Small number of parameters

Renormalizable

NLO/LO ratio will be used to assess uncertainties.

A different model than χEFT – good for V&V!



Weinberg (1991), van-Kolck (1992), Kaplan (1996)…

A FULLY PERTURBATIVE PIONLESS EFT A=2, 3 CALCULATION @NLO

- 5 Leading Order Parameters
  - nn and 2-np Scattering lengths: $^3S_1$, $^1S_0$
  - pp scattering length.
  - Three body force strength to prevent Thomas collapse.
- 5 Next-to Leading Order parameters:

  $A_S \equiv \sqrt{2\gamma_t Z_d}$, and $Z_d = \frac{1}{1-\gamma_t\rho_t} \approx 1 + \gamma_t\rho_t$

  ER -PARAMETERIZTION

  $$\rho_{\substack{s\\t}} = \underbrace{0}_{\text{LO}} + \underbrace{\rho_{\substack{s\\t}}^{\text{exp}}}_{\text{NLO}},$$

  "Z"-PARAMETERIZTION

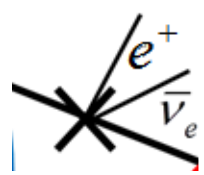
  $$\rho_t^Z \approx \underbrace{0}_{\text{LO}} + \underbrace{\frac{Z_d^{\text{exp}} - 1}{\gamma_t}}_{\text{NLO}}$$

  - effective ranges:
  - Renormalizations of pp scattering length and 3NF.
  - isospin dependent 3NF to prevent logarithmic divergence in the binding energy of ^{3}He.
- Only ^{3}H and ^{3}He binding energies are "many-body" parameters. All the rest- very well experimentally known scattering parameters.

ADDING THE WEAK INTERACTION

- **5+1** LO Parameters

One body



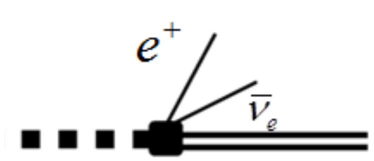
g_A

$$\mathrm{GT}_n = \langle n \| \mathrm{GT}^{(-)} \| p \rangle = \sqrt{3} \cdot (\frac{1}{g_A})$$

axial coupling constant, "known" from neutron β decay.

- **5+1** NLO parameters:

Two body

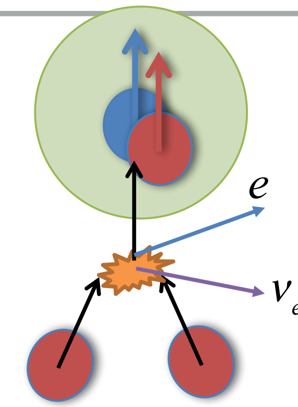


L_{1A}

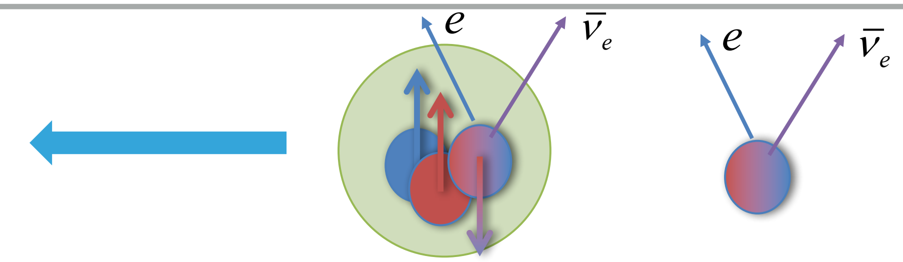
$$\mathrm{GT}^{emp}_{^3\mathrm{H}} = \langle {}^3\mathrm{H} \| \mathrm{GT}^{(-)} \| {}^3\mathrm{He} \rangle = \sqrt{3} \cdot (\frac{1.213 \pm 0.002}{g_A})$$

2-body analogue of g_A, we fix it from ^{3}H decay rate.

ADDING THE WEAK INTERACTION



$p + p \to d + \nu_e + e^+$

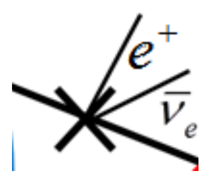


Use ^{3}H decay to fix 2-body strength L_{1A} and predict pp fusion

$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$ $\quad n \to p + e^- + \bar{\nu}_e$

- **5+1** LO Parameters

One body



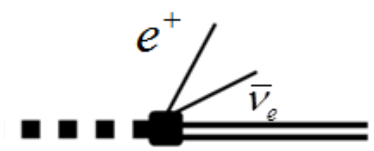
g_A

$$\mathrm{GT}_n = \langle n \| \mathrm{GT}^{(-)} \| p \rangle = \sqrt{3} \cdot \left(\frac{1}{g_A}\right)$$

axial coupling constant, "known" from neutron β decay.

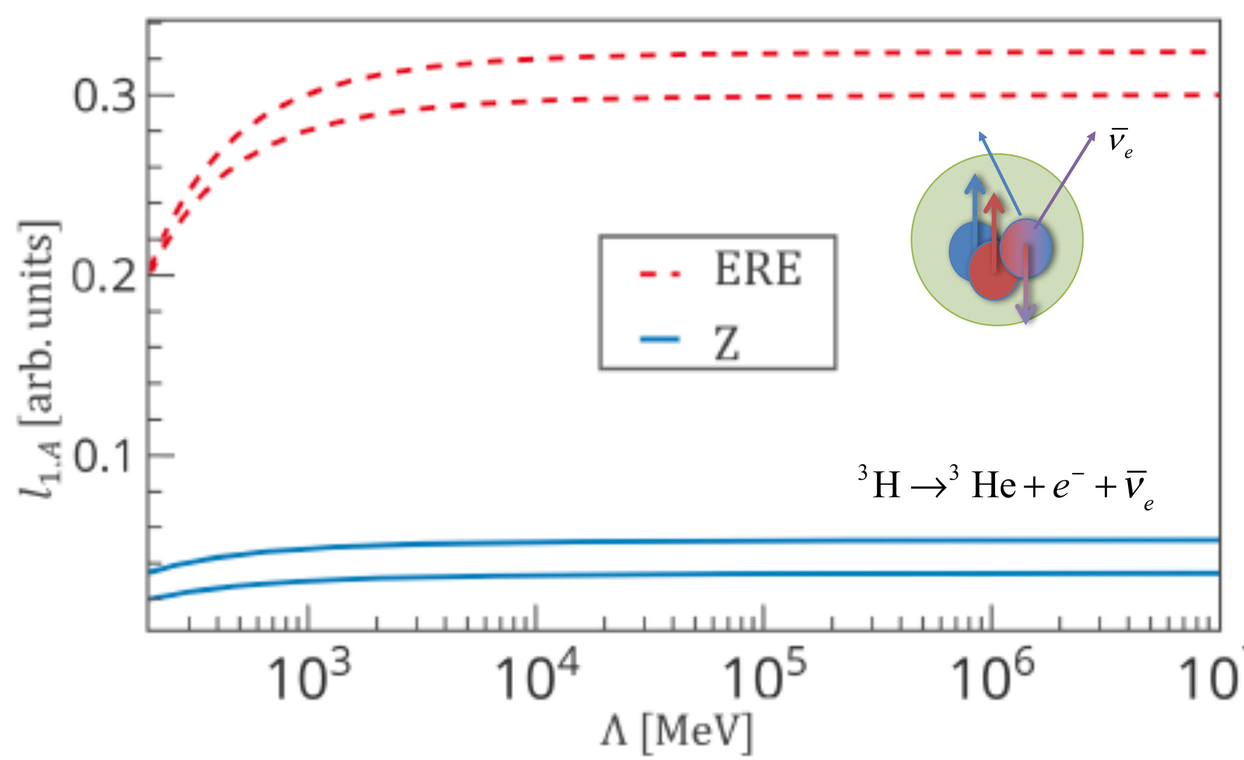
- **5+1** NLO parameters:

Two body



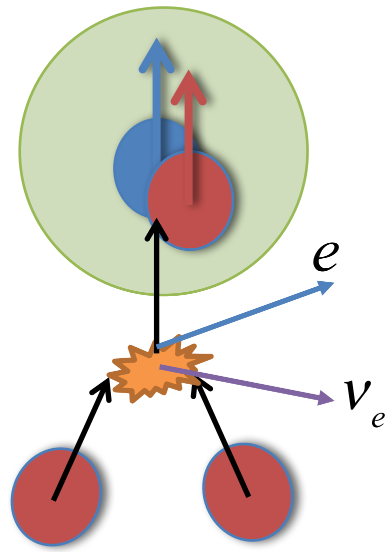
L_{1A}

G' … 2)

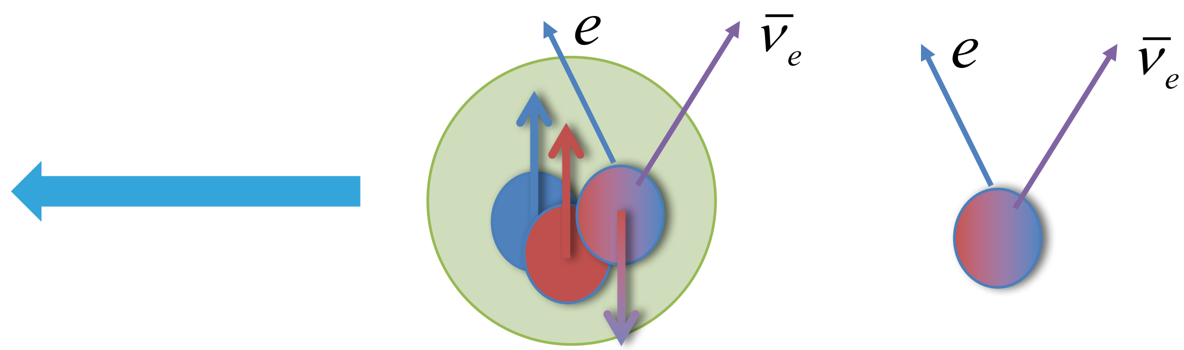


$$L_{1,A}(\mu) = -\frac{\rho_t + \rho_s}{2\sqrt{\rho_s \rho_t}} + \frac{L'_{1,A}}{2\pi g_A} \frac{1}{\sqrt{\rho_s \rho_t}} (\mu - \gamma_t) \left(\mu - \frac{1}{a_s}\right)$$

A FULLY PERTURBATIVE PIONLESS EFT A=2, 3 CALCULATION @NLO



$p + p \to d + \nu_e + e^+$



Weak observables

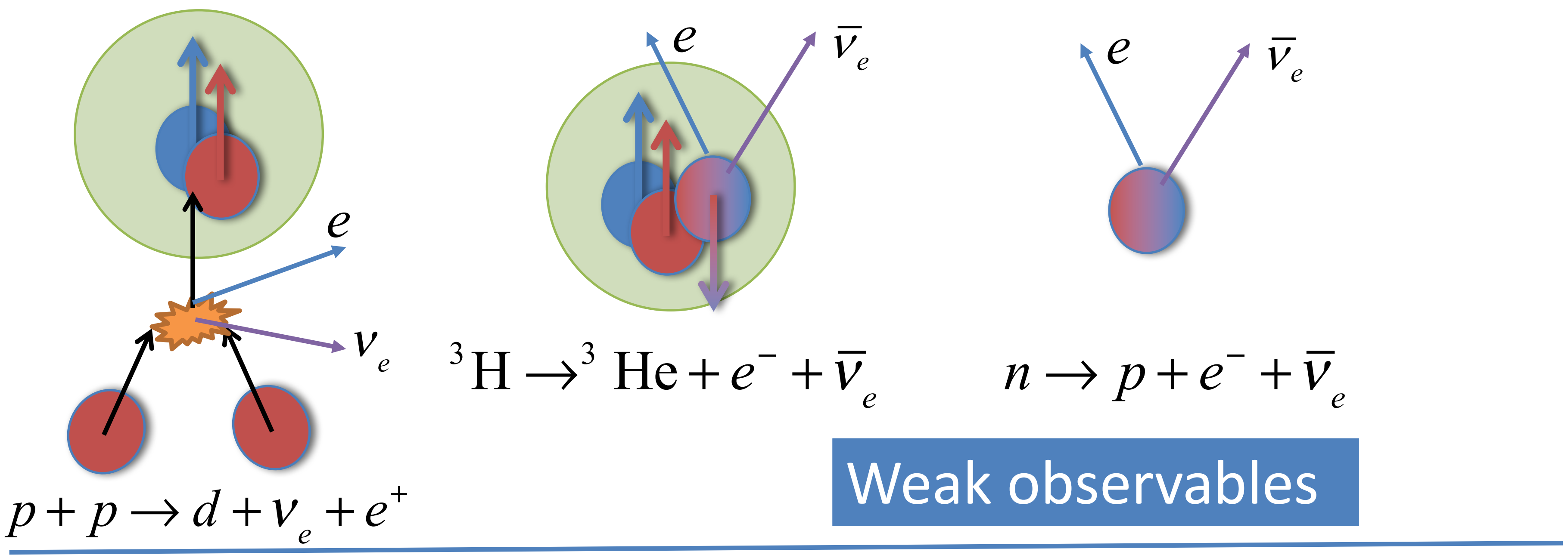
Use ^{3}H decay to fix 2-body strength L_{1A} and predict pp fusion

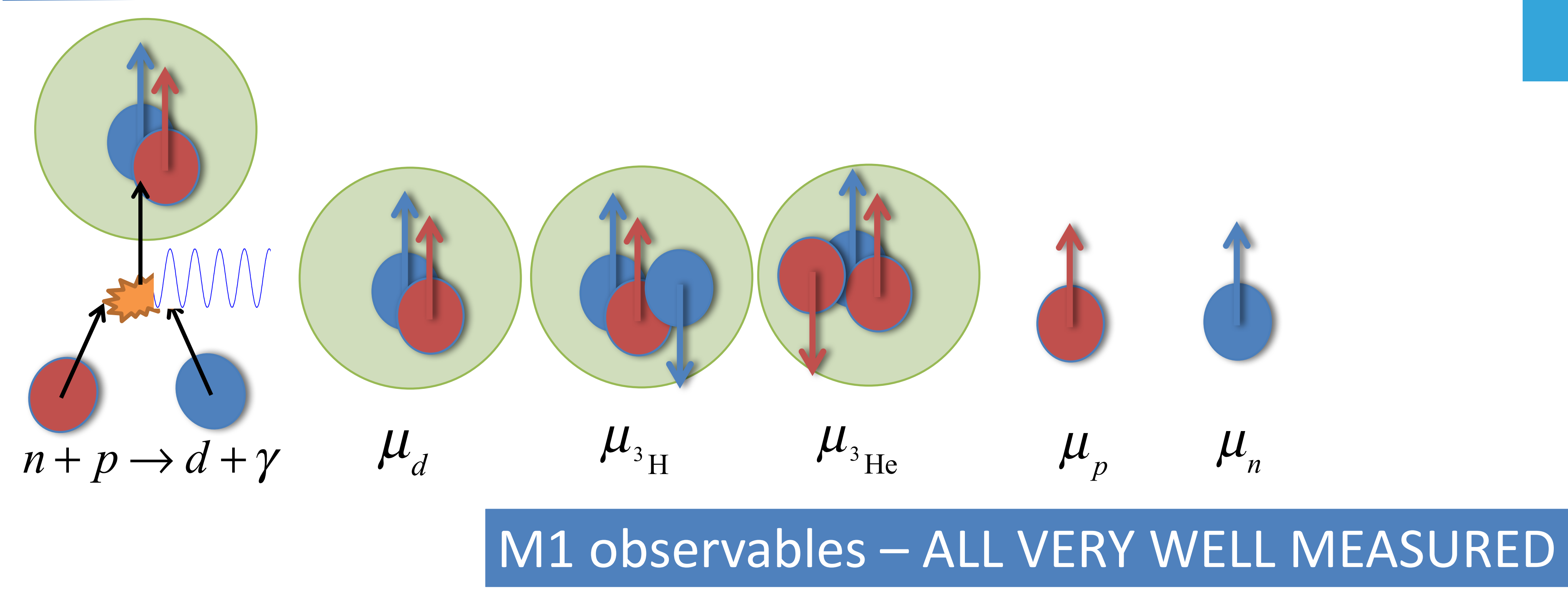
$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e \qquad n \to p + e^- + \bar{\nu}_e$

For both observables: $T = T_{LO} \times \left(1 + \underbrace{\frac{T_{NLO}(L_{1A})}{T_{LO}}}_{c \cdot \delta} + O\left(\delta^2\right) \right)$ *use to estimate theoretical uncertainty*

- ✓ However, we find small NLO contribution $\approx 4\%$...
  - ✓ How do we know if c is unnaturally small or δ? Is this unique for GT?
  - ✓ How do assess expansion parameter and uncertainty?
  - ✓ How do we know if this is valid?

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

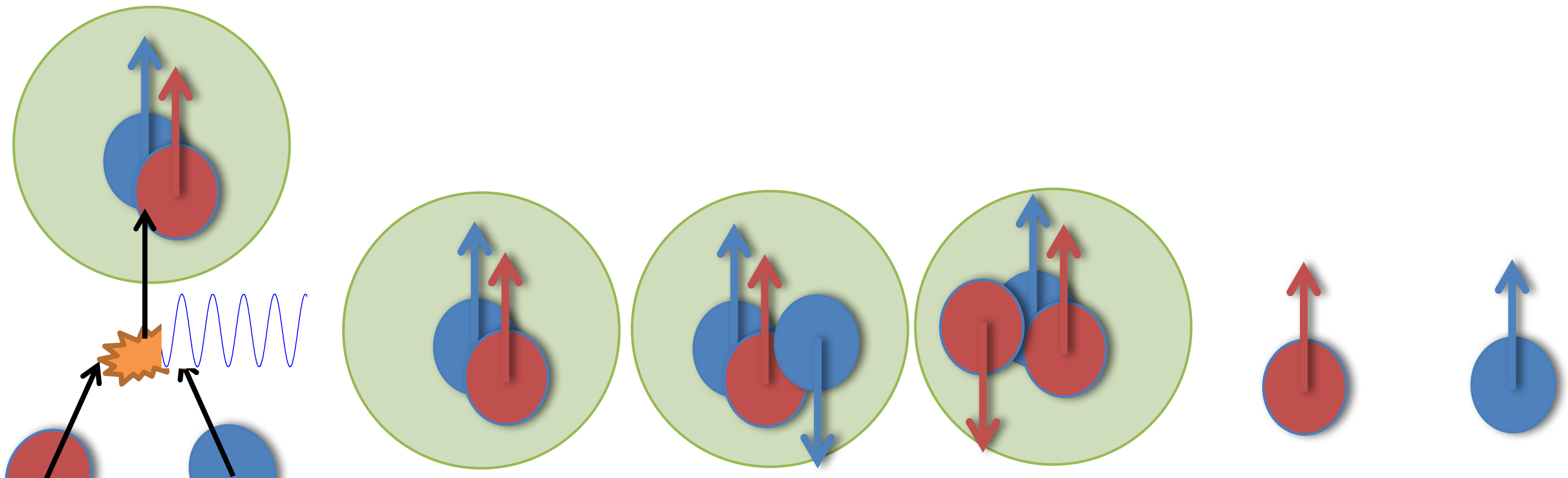




WHAT CAN WE SAY ABOUT THIS ANALOGY?

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

M1 observables – ALL VERY WELL MEASURED

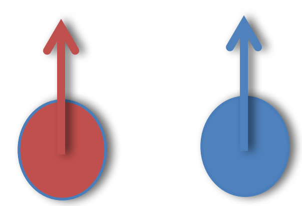


$n + p \rightarrow d + \gamma$ μ_d $\mu_{^3\mathrm{H}}$ $\mu_{^3\mathrm{He}}$ μ_p μ_n

$$\hat{\mu} = -\frac{i}{2}\vec{\nabla}_q \times \hat{\mathcal{J}}(\vec{q})\big|_{q=0}$$

LO interaction Lagrangian

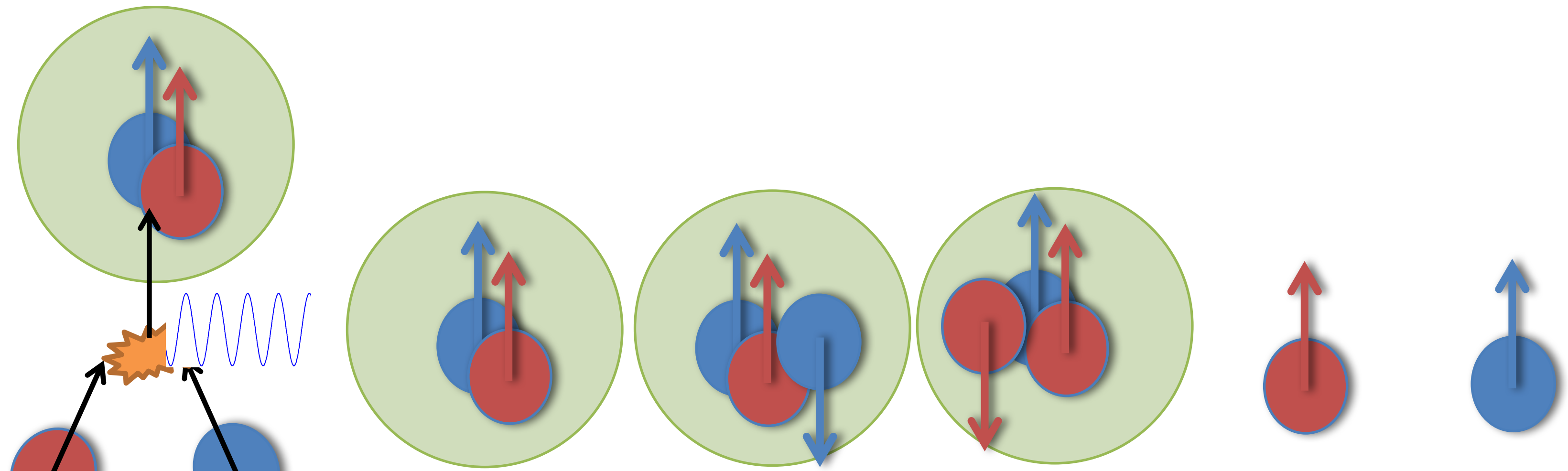
$$\mathcal{L}^{\text{1-B}}_{\text{magnetic}} = \frac{e}{2M} N^\dagger \left(\kappa_0 + \kappa_1 \tau_3\right) \vec{\sigma} \cdot \vec{B} N$$



$\mu_p \pm \mu_n$

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

M1 observables – ALL VERY WELL MEASURED



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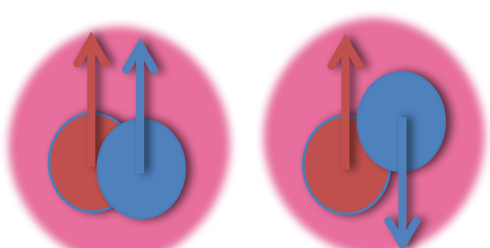
$$\hat{\mu} = -\frac{i}{2}\vec{\nabla}_q \times \hat{\mathcal{J}}(\vec{q})\big|_{q=0}$$

NLO interaction Lagrangian



t s

$$\mathcal{L}^{\text{2-B}}_{\text{magnetic}} = \frac{e}{2M}\left[\kappa_1 L_1 (t^\dagger s + s^\dagger t)\cdot \vec{B} - i\epsilon^{ijk}\kappa_0 L_2((t^i)^\dagger t^j)\cdot B_k\right]$$

$$L_1(\mu) = \underbrace{-\frac{\rho_t + \rho_s}{\sqrt{\rho_t \rho_s}}}_{\text{LO}} + \frac{4}{\gamma_t \sqrt{\rho_t \rho_s}}\underbrace{l_1'(\mu)}_{\text{NLO}}$$

$$L_2(\mu) = -\underbrace{2}_{\text{LO}} + \frac{2}{\gamma_t \rho_t}\underbrace{l_2'(\mu)}_{\text{NLO}} .$$

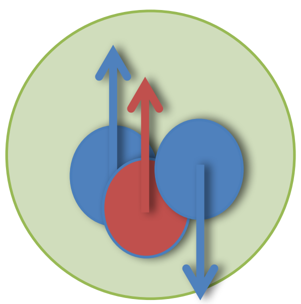
$$l_1'(\mu) = \frac{M\gamma_t}{4\pi}\frac{L_1'}{\kappa_1}(\mu - \gamma_t)\left(\mu - \frac{1}{a_s}\right)$$

$$l_2'(\mu) = \frac{M\gamma_t}{\pi}\frac{L_2'}{\kappa_0}(\mu - \gamma_t)^2 \ ,$$

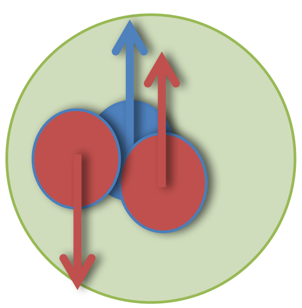
ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

M1 observables – ALL VERY WELL MEASURED

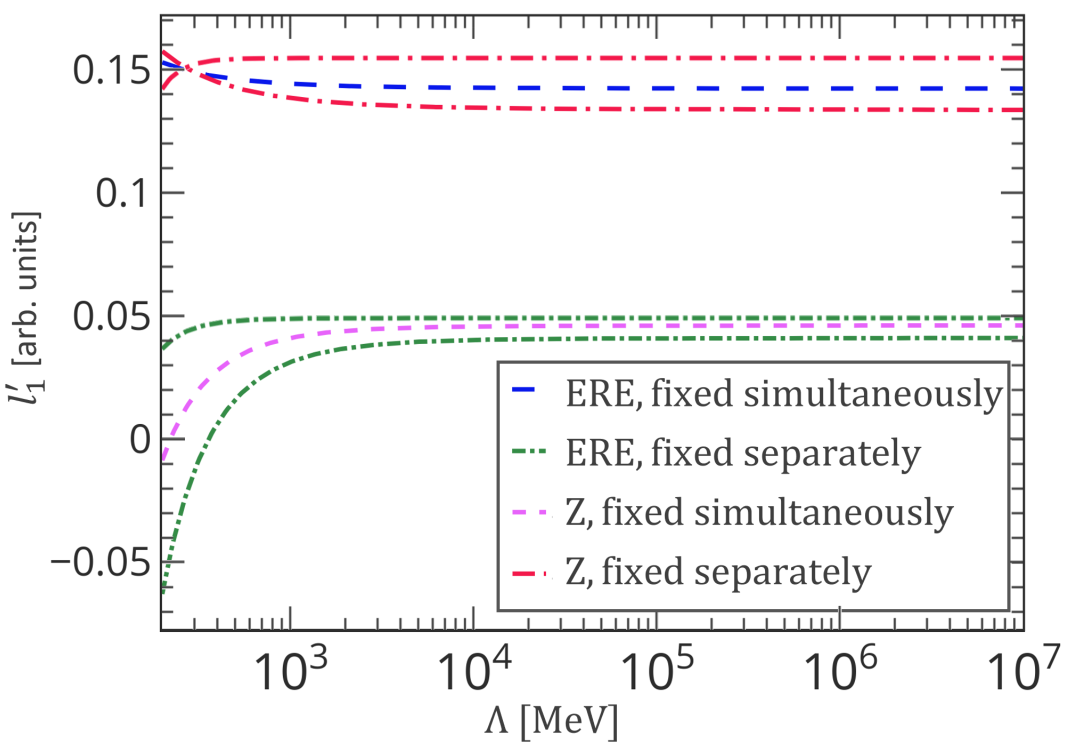
RG invariant results – take same cutoff in LS eq. and in L_1, L_2

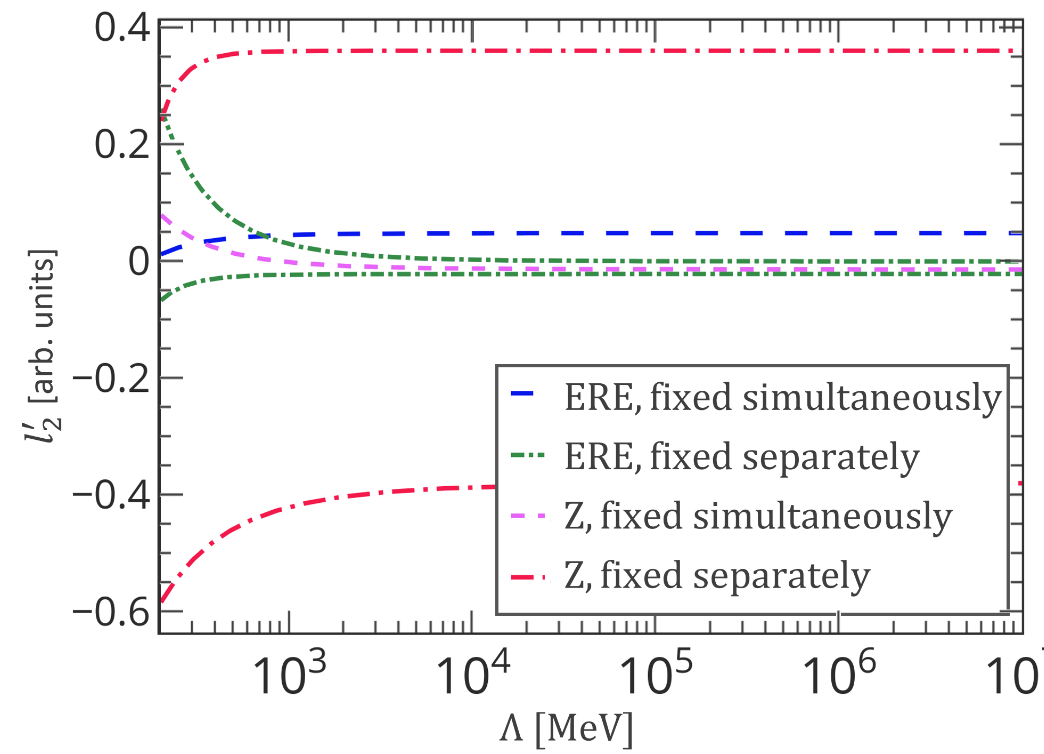


$\mu_{^3\mathrm{H}}$

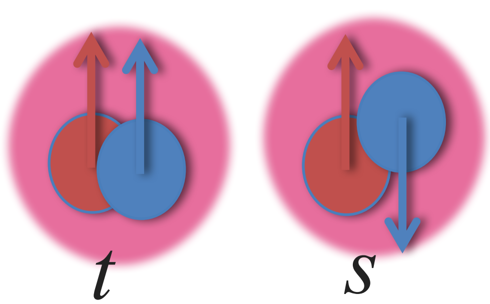


$\mu_{^3\mathrm{He}}$





NLO interaction Lagrangian



$$\mathcal{L}^{\text{2-B}}_{\text{magnetic}} = \frac{e}{2M}\left[\kappa_1 L_1 (t^\dagger s + s^\dagger t)\cdot\vec{B} - i\epsilon^{ijk}\kappa_0 L_2((t^i)^\dagger t^j)\cdot B_k\right]$$

$$L_1(\mu) = -\underbrace{\frac{\rho_t+\rho_s}{\sqrt{\rho_t\rho_s}}}_{\text{LO}} + \frac{4}{\gamma_t\sqrt{\rho_t\rho_s}}\underbrace{l'_1(\mu)}_{\text{NLO}}$$

$$L_2(\mu) = -\underbrace{2}_{\text{LO}} + \frac{2}{\gamma_t\rho_t}\underbrace{l'_2(\mu)}_{\text{NLO}} .$$

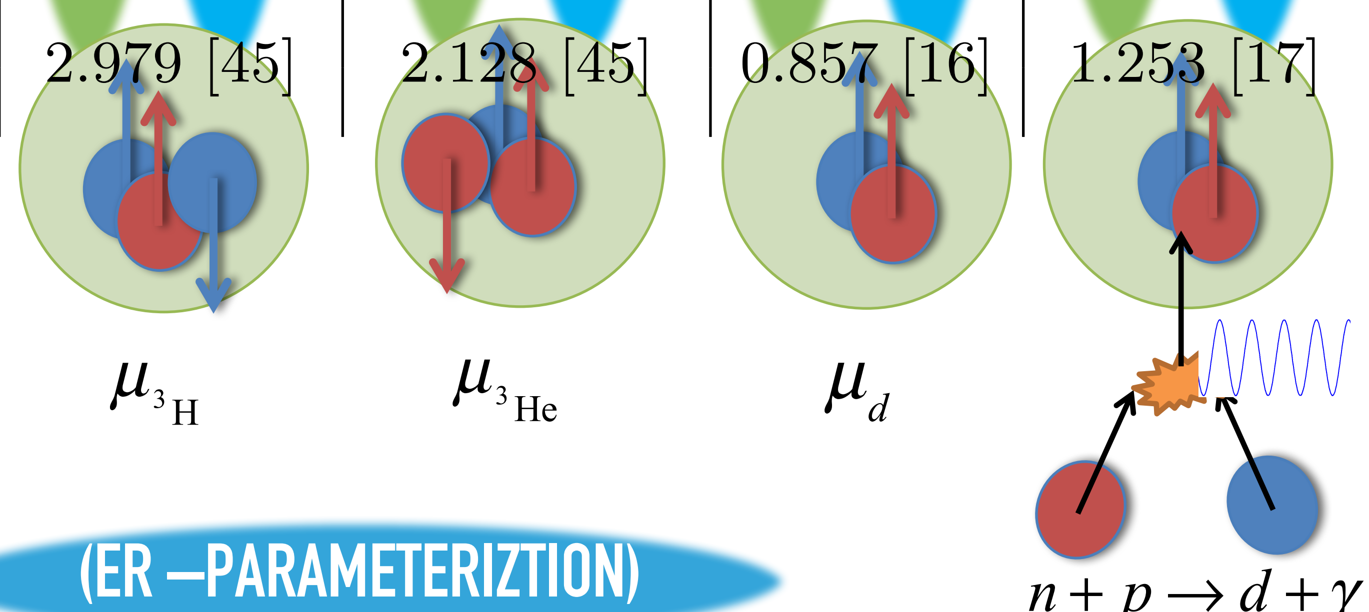
$$l'_1(\mu) = \frac{M\gamma_t}{4\pi}\frac{L'_1}{\kappa_1}(\mu-\gamma_t)\left(\mu-\frac{1}{a_s}\right)$$

$$l'_2(\mu) = \frac{M\gamma_t}{\pi}\frac{L'_2}{\kappa_0}(\mu-\gamma_t)^2 ,$$

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

For each row, take two M1 observables as input, and predict the other two

	$l_1'^{\infty}/10^{-2}$	$l_2'^{\infty}/10^{-2}$	$\langle\hat{\mu}_{^3\mathrm{H}}\rangle$[NM]	$\lvert\langle\hat{\mu}_{^3\mathrm{He}}\rangle\rvert$[NM]	$\langle\hat{\mu}_d\rangle$[NM]	Y'_{np}
LO	0 (0)	0 (0)	2.76 (2.78)	1.84 (1.84)	0.88 (0.88)	1.18 (1.18)
NLO	4.72 (14.2)	-1.6 (4.1)	⋆	⋆	0.87 (0.92)	1.253 (1.31)
	4.66 (9.0)	-2.6 (-2.6)	2.978 (2.76)	2.145 (1.89)	⋆	⋆
	4.66 (9.0)	-2.4 (29)	⋆	2.144 (1.66)	0.86 (1.17)	⋆
	4.66 (9.0)	-0.13 (-31)	2.996 (2.59)	⋆	0.88 (0.61)	⋆
	4.92 (15.2)	-2.6 (-2.6)	⋆	2.143 (2.23)	⋆	1.255 (1.32)
	4.60 (13.4)	-2.6 (-2.6)	2.967 (2.91)	⋆	⋆	1.253 (1.30)
Mean	4.73 (13.0)	-1.7 (-0.04)	2.98 (2.75)	2.144 (1.93)	0.87 (0.89)	1.253 (1.31)
std	0.2 (2.8)	1.1 (25)	0.015 (0.16)	0.001 (0.28)	0.01 (0.26)	0.001 (0.01)
Exp data			2.979 [45]	2.128 [45]	0.857 [16]	1.253 [17]



"Z"-PARAMETERIZTION (ER –PARAMETERIZTION)

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

For each row, take two M1 observables as input, and predict the other two

$$\langle\hat{\mu}\rangle = \langle\hat{\mu}\rangle^{\text{1-B}}_{\text{LO}} \times \left(\underbrace{1}_{\mathcal{O}(0)} + \underbrace{\delta\langle\hat{\mu}\rangle^{\text{1-B}}_{\text{ERE}} + \delta\langle\hat{\mu}\rangle^{\text{2-B}}_{\text{ERE}}}_{\mathcal{O}(Q/\Lambda_b)} + \underbrace{\delta\langle\hat{\mu}\rangle^{\text{2-B}}}_{\mathcal{O}(Q/\Lambda_b)} \right)$$

LO magntic opert. NLO storng inter. — NLO magntic opert. LO storng inter.

M_1	$\delta\langle\hat{\mu}\rangle_{\text{total}}$	$\delta\langle\hat{\mu}\rangle$ NLO strong inter.	$\delta\langle\hat{\mu}\rangle^{\text{2-B}}$ NLO magnetic opert.
$\langle\hat{\mu}_{^3\text{H}}\rangle$	7% (1%)	3% (11%)	5% (10%)
$\langle\hat{\mu}_{^3\text{He}}\rangle$	13% (4%)	3% (25%)	10% (29%)
$\langle\hat{\mu}_d\rangle$	1% (1%)	0% (0%)	1% (1%)
Y'_{np}	6% (9%)	2% (2%)	4% (12%)

“Z”-PARAMETERIZTION (ER –PARAMETERIZTION)

- ✓ What do we see here?
  - ✓ The NLO contribution is about $\epsilon \approx 5-10\%$ - We “expected” $\epsilon \approx \frac{1}{3}$
  - ✓ ER parameterization seems more precise; **However, fluctuations within contributions are significantly bigger than total one**.
- ✓ We focus on Z paramterization only!

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

For each row, take two M1 observables as input, and predict the other two

$$\langle\hat{\mu}\rangle = \langle\hat{\mu}\rangle_{\text{LO}}^{\text{1-B}}\times\left(\underbrace{1}_{\mathcal{O}(0)} + \underbrace{\delta\langle\hat{\mu}\rangle_{\text{ERE}}^{\text{1-B}} + \delta\langle\hat{\mu}\rangle_{\text{ERE}}^{\text{2-B}}}_{\substack{\mathcal{O}(Q/\Lambda_b)\\ \text{LO magntic opert.}\\ \text{NLO storng inter.}}} + \underbrace{\delta\langle\hat{\mu}\rangle^{\text{2-B}}}_{\substack{\mathcal{O}(Q/\Lambda_b)\\ \text{NLO magntic opert.}\\ \text{LO storng inter.}}}\right)$$

M_1	$\delta\langle\hat{\mu}\rangle_{\text{total}}$	$\delta\langle\hat{\mu}\rangle$ NLO strong inter.	$\delta\langle\hat{\mu}\rangle^{\text{2-B}}$ NLO magnetic opert.
$\langle\hat{\mu}_{^3\text{H}}\rangle$	7% (1%)	3% (11%)	5% (10%)
$\langle\hat{\mu}_{^3\text{He}}\rangle$	13% (4%)	3% (25%)	10% (29%)
$\langle\hat{\mu}_d\rangle$	1% (1%)	0% (0%)	1% (1%)
Y'_{np}	6% (9%)	2% (2%)	4% (12%)

- ✓ What do we see here?
  - ✓ The deuteron magnetic moment receives unnaturally small contribution

$$\langle\hat{\mu}_d\rangle = \kappa_0\left\{2Z_d^{\text{NLO}} + Z_d^{\text{LO}}\left[\gamma_t\rho_t L_2(\mu)\right]\right\}$$

$$= 2\kappa_0\left[1 + \underbrace{0}_{\text{NLO storng inter.}} + \underbrace{l_2'(\mu)}_{\text{NLO magnetic opert.}}\right]$$

"Z"-PARAMETERIZTION (ER –PARAMETERIZTION)

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

For each row, take two M1 observables as input, and predict the other two

		$l_1'^{\infty}/10^{-2}$	$l_2'^{\infty}/10^{-2}$
LO		0 (0)	0 (0)
NLO		4.72 (14.2)	-1.6 (4.1)
		4.66 (9.0)	-2.6 (-2.6)
		4.66 (9.0)	-2.4 (29)
		4.66 (9.0)	-0.13 (-31)
		4.92 (15.2)	-2.6 (-2.6)
		4.60 (13.4)	-2.6 (-2.6)
Mean		4.73 (13.0)	-1.7 (-0.04)
std		0.2 (2.8)	1.1 (25)
Exp data			

M_1	$\delta\langle\hat{\mu}\rangle_{\text{total}}$	$\delta\langle\hat{\mu}\rangle$ NLO strong inter.	$\delta\langle\hat{\mu}\rangle^{\text{2-B}}$ NLO magnetic opert.
$\langle\hat{\mu}_{^3\text{H}}\rangle$	7% (1%)	3% (11%)	5% (10%)
$\langle\hat{\mu}_{^3\text{He}}\rangle$	13% (4%)	3% (25%)	10% (29%)
$\langle\hat{\mu}_d\rangle$	1% (1%)	0% (0%)	1% (1%)
Y'_{np}	6% (9%)	2% (2%)	4% (12%)

- ✓ What do we see here?
  - ✓ The deuteron magnetic moment receives unnaturally small contribution
  - ✓ The statistical analysis shows that $l_2'^{\infty}$ is consistent with 0.

$$\Delta l_1'^{\infty}/l_1' \approx 3\% \qquad \Delta l_2'^{\infty}/l_2'^{\infty} \approx 70\%$$

"Z"-PARAMETERIZTION (ER –PARAMETERIZTION)

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

For each row, take two M1 observables as input, and predict the other two

	$l_1'^{\infty}/10^{-2}$	$l_2'^{\infty}/10^{-2}$
LO	0 (0)	0 (0)
NLO	4.72 (14.2)	-1.6 (4.1)
	4.66 (9.0)	-2.6 (-2.6)
	4.66 (9.0)	-2.4 (29)
	4.66 (9.0)	-0.13 (-31)
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Mean	4.73 (13.0)	-1.7 (-0.04)
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Exp data		

M_1	$\delta\langle\hat{\mu}\rangle_{\text{total}}$	$\delta\langle\hat{\mu}\rangle_{\text{NLO strong inter.}}$	$\delta\langle\hat{\mu}\rangle^{\text{2-B}}_{\text{NLO magnetic opert.}}$
$\langle\hat{\mu}_{^3\text{H}}\rangle$	7% (1%)	3% (11%)	5% (10%)
$\langle\hat{\mu}_{^3\text{He}}\rangle$	13% (4%)	3% (25%)	10% (29%)
$\langle\hat{\mu}_d\rangle$	1% (1%)	0% (0%)	1% (1%)
Y'_{np}	6% (9%)	2% (2%)	4% (12%)

- ✓ What do we see here?
  - ✓ The deuteron magnetic moment receives unnaturally small contribution
  - ✓ **The statistical analysis shows that $l_2'^{\infty}$ is consistent with 0.**

$$\Delta l_1'^{\infty}/l_1' \approx 3\% \qquad \Delta l_2'^{\infty}/l_2'^{\infty} \approx 70\%$$

  - ✓ Surprising! (different physics than pion-less expansion?)

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

Conjecture $l_2'^{\infty} = 0, i.e.,$ 2-body isoscalar interaction is at least N²LO

$$\mathcal{L}^{\text{2-B}}_{\text{magnetic}} = \frac{e}{2M}\left[\kappa_1 L_1 (t^\dagger s + s^\dagger t)\cdot \vec{B} - i\epsilon^{ijk}\kappa_0 L_2 ((t^i)^\dagger t^j)\cdot B_k\right]$$

$$L_1(\mu) = \underbrace{-\frac{\rho_t+\rho_s}{\sqrt{\rho_t\rho_s}}}_{\text{LO}} + \frac{4}{\gamma_t\sqrt{\rho_t\rho_s}}\underbrace{l_1'(\mu)}_{\text{NLO}}$$

$$L_2(\mu) = -\underbrace{2}_{\text{LO}} + \frac{2}{\gamma_t\rho_t}\underbrace{l_2'(\mu)}_{\text{N}^2\text{LO}} .$$

$$l_1'(\mu) = \frac{M\gamma_t}{4\pi}\frac{L_1'}{\kappa_1}(\mu-\gamma_t)\left(\mu - \frac{1}{a_s}\right)$$

$$l_2'(\mu) = 0 ,$$

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

For each row, take ***one*** M1 observables as input, and predict the other two

Conjecture $l_2'^{\infty} = 0, i.e.,$ 2-body isoscalar interaction is at least N²LO

	$l_1'^{\infty}/10^{-2}$	$\langle\hat{\mu}_{^3\mathrm{H}}\rangle$[NM]	$\langle\hat{\mu}_{^3\mathrm{He}}\rangle$[NM]	Y'_{np}
	4.36	$\star$	-2.10	1.250
	4.97	3.00	$\star$	1.256
	4.66	2.99	-2.11	$\star$
Mean	4.7	2.99	-2.11	1.253
std	0.6	0.01	0.01	0.006
%NLO/LO		8%	13%	6%
Exp. data		2.979	-2.128	1.253

- What do we see here?
  - Everything still works even if $l_2'^{\infty} = 0$:
    - natural convergence,
    - same order of magnitude of expansion parameter $\epsilon \approx 6 - 13\%$
    - Small STD on predictions and $\frac{\Delta l_1'^{\infty}}{l_1'^{\infty}} \approx \epsilon^2 \approx 10\%$

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

"Our theory": pion-less EFT at NLO based on Z-parameterization

Operators:

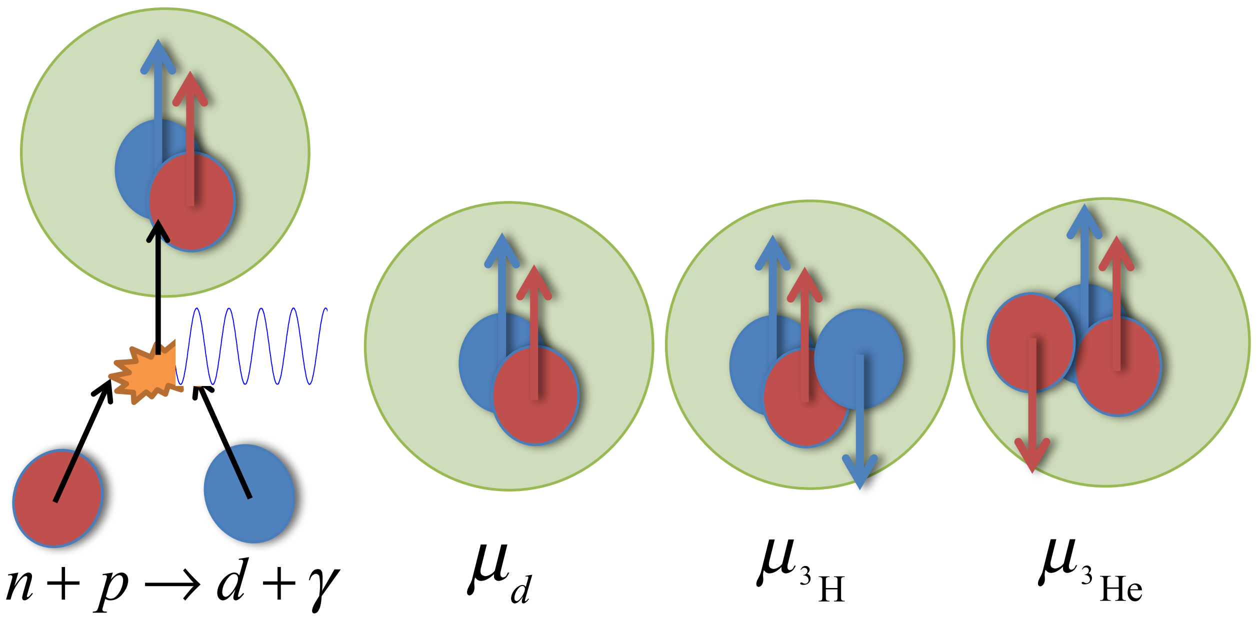
	M1
1-b	$(\mu_{n,p})\ \sigma, \sigma\tau^0$
2-b	$L_1 s^\dagger d$, ~~$L_2 d^\dagger d$~~

N^2LO

***Still need to assess theoretical uncertainty*:**

🙁 RG invariant – no cutoff dependence as a guide

😀 *Natural convergence: order by order*



ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

"Our theory": pion-less EFT at NLO based on Z-parameterization

Assessing theoretical uncertainties:

Take a generic observable: $\langle M_1 \rangle = \langle M_1 \rangle_{\mathrm{LO}} \cdot \left(1 + c_{M_1}^{\mathrm{NLO}} \cdot \delta + \mathcal{O}(\delta^2)\right)$

- ✓ $c_{M_1}^{\mathrm{NLO}}$ should be natural.
- ✓ "Usually", we would take δ from a Naïve estimate of the theory:
  - ✓ In pionless EFT The Naïve estimate is $\delta \approx \frac{\gamma_t}{m_\pi} \approx \frac{1}{3}$
  - ✓ We got $\delta \approx 6 - 13\%$
  - ✓ Surprising! (different physics than pion-less expansion?)
- ✓ Let us estimate δ from the results!

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

"Our theory": pion-less EFT at NLO based on Z-parameterization

Assessing theoretical uncertainties:

Take a generic observable: $\langle M_1 \rangle = \langle M_1 \rangle_{\mathrm{LO}} \cdot \left(1 + c^{\mathrm{NLO}}_{M_1} \cdot \delta + \mathcal{O}(\delta^2)\right)$

$a^{NLO}_{M_1^k}$

- ✓ Let us estimate δ from the results!
  - ✓ We take 3 measurements of $a^{NLO}_{M_1^k} \approx 6, 8, 13\%$ from the NLO observables
  - ✓ From $< \mu_d >$ ➔ $(\mathrm{N^2LO/LO}) \approx (\mathrm{NLO/LO})^2 \sim \delta^2_{\hat{\mu}_d}$
    Thus $(\mathrm{NLO/LO}) \approx 0.1$
  - ✓ And fluctuations in $l_2'^{\infty}$ ➔ $(\mathrm{N^2LO/NLO}) \approx 0.04 - 0.1$
  - ✓ We use information theory to show that ratios of orders should be distributed log-normally to maximize information entropy.
  - ✓ We use the "measurements" of $a^{NLO}_{M_1^k}$ to assess the size of δ and its standard deviations. The finite number of measurements ➔ t-student

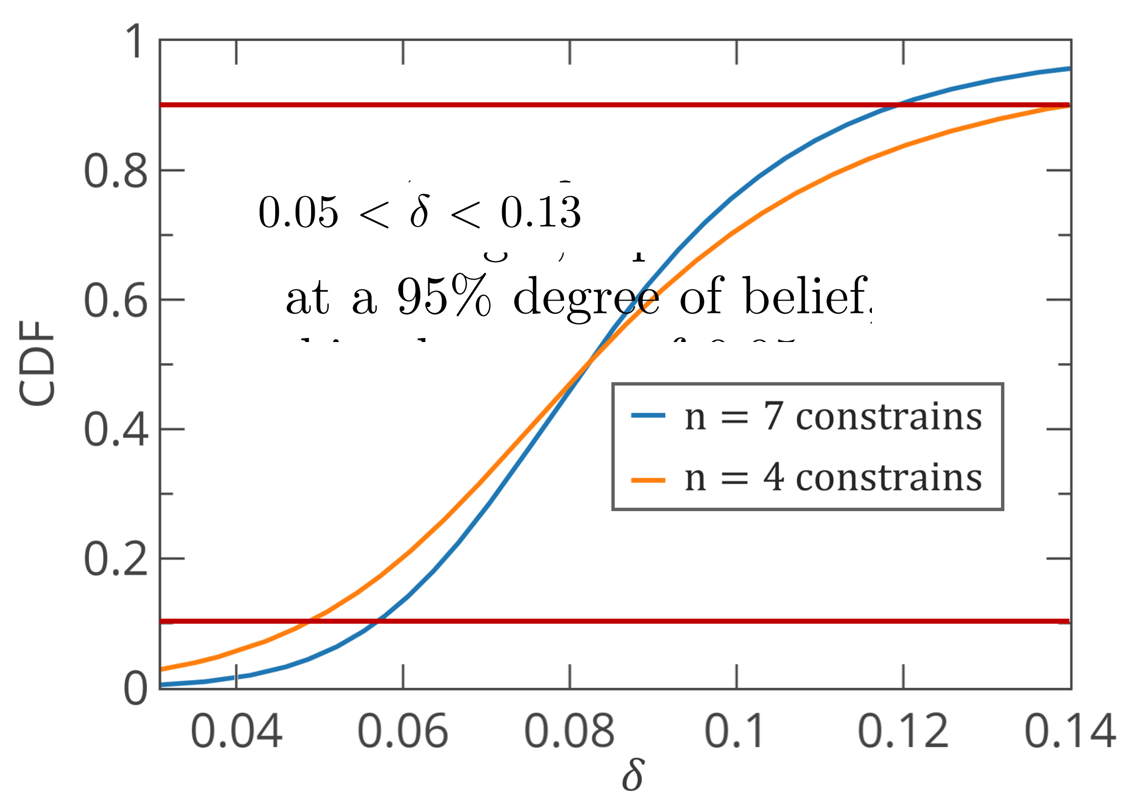
ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

"Our theory": pion-less EFT at NLO based on Z-parameterization

Assessing theoretical uncertainties:

Take a generic observable: $\langle M_1 \rangle = \langle M_1 \rangle_{\mathrm{LO}} \cdot \left(1 + c_{M_1}^{\mathrm{NLO}} \cdot \delta + \mathcal{O}(\delta^2)\right)$

✓ Let us estimate δ from the results!



$pr\left(\delta \middle| \left\{a_{M_1^k}^{NLO}\right\}_{k=1}^{n}\right)$

ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES

"Our theory": pion-less EFT at NLO based on Z-parameterization

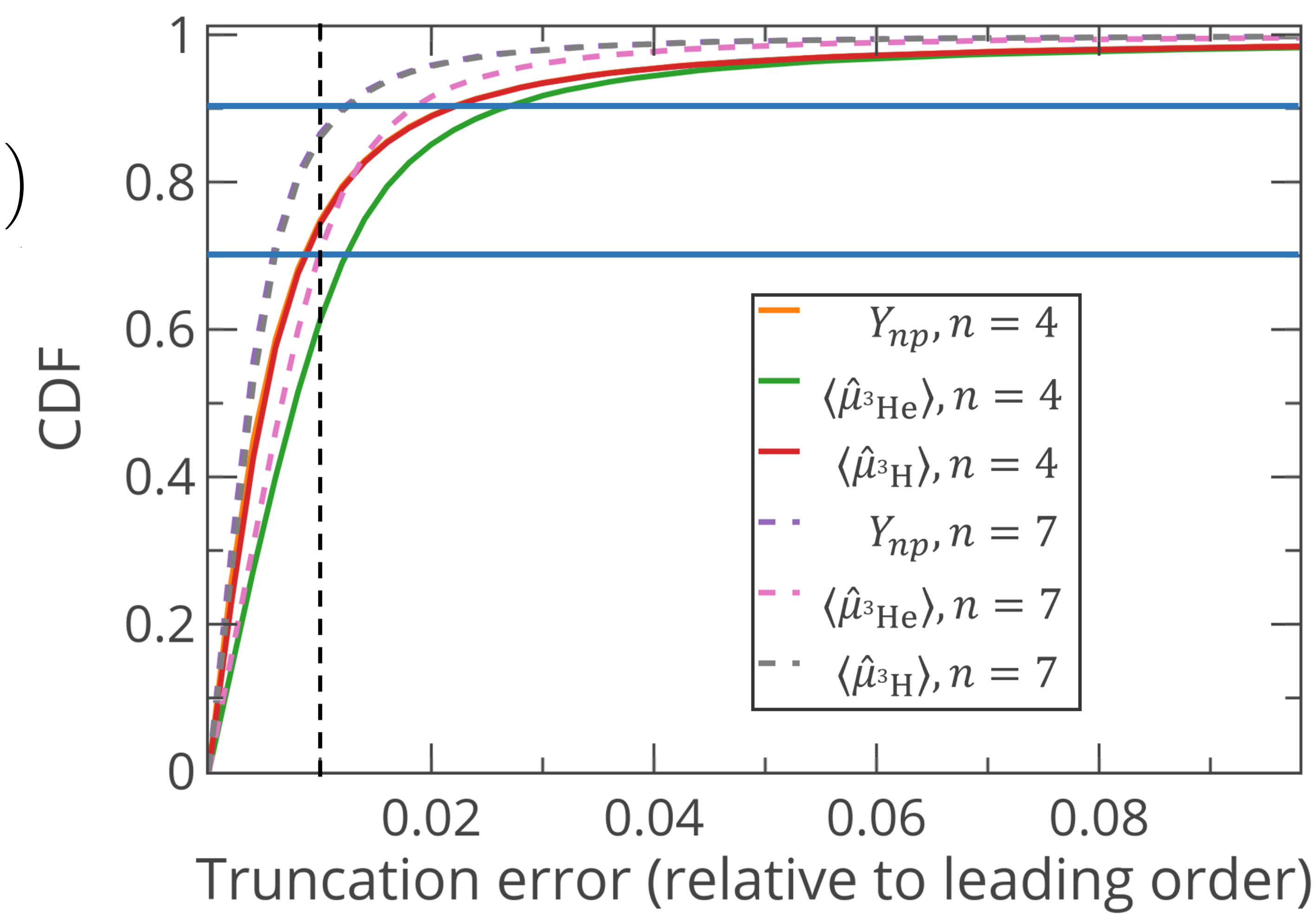
Assessing theoretical uncertainties:

Take a generic observable: $\langle M_1 \rangle = \langle M_1 \rangle_{\mathrm{LO}} \cdot \left(1 + c_{M_1}^{\mathrm{NLO}} \cdot \delta + \mathcal{O}(\delta^2)\right)$

$$pr\left(\Delta \middle| \left\{a_{M_1^k}^{NLO}\right\}_{k=1}^{n}\right) = \int d\delta\, pr\left(\Delta \middle| \left\{c_{M_1^k}^{NLO}\right\}_{k=1}^{n}, \delta\right) \cdot pr\left(\delta \middle| \left\{a_{M_1^k}^{NLO}\right\}_{k=1}^{n}\right)$$

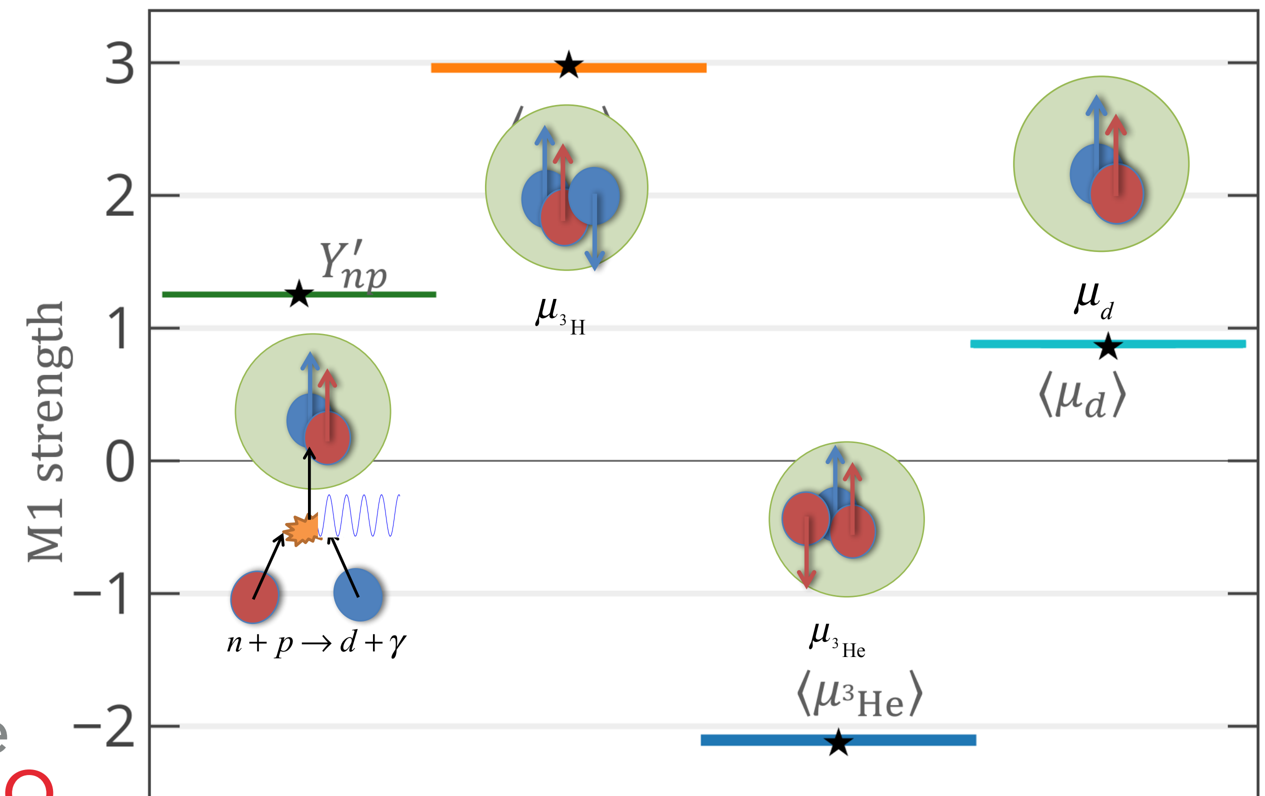
This is the CDF of the truncation error Δ

The theoretical uncertainty of M_1 observables in our theory is about 1% at 70% DOB



ELECTROMAGENTIC OBSERVABLES OF A=2, 3 NUCLEI

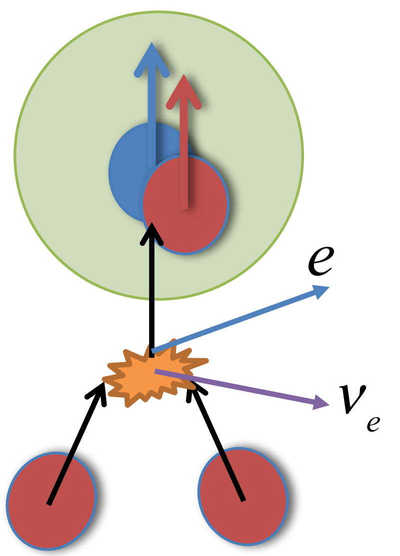
- Perfect post-diction,
  within 1% theoretical uncertainty!
- Amazing precision and accuracy.
- Surprising:
  - Changes in Naïve pion-less EFT counting, by $l_2'^{\infty} = 0$.
    - Is this a result of the flow to very low energies of ***chiral EFT***, where iso-vector pion leads to $l_1'^{\infty}$ at NLO, while $l_2'^{\infty}$ comes at N[3]LO?



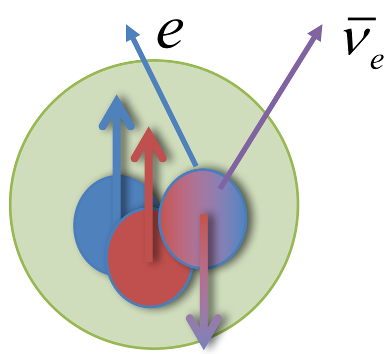
- Unnaturally small expansion parameter, $\delta \approx 5 - 10\% << \frac{\gamma_t}{m_\pi} \approx \frac{1}{3}$!
  - Hinting different physics than pionless? Unitary expansion (van Kolck, König)? Wigner symmetry (Phillips, Vanasse)?
  - This is the origin of the "shell model" like behavior of these magnetic moments, while the wave functions are very far from shell model – Can this be extended to heavier nuclei?

"Our theory": pion-less EFT at NLO based on Z-parameterization

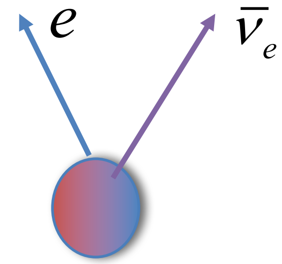
ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES



$p + p \rightarrow d + \nu_e + e^+$



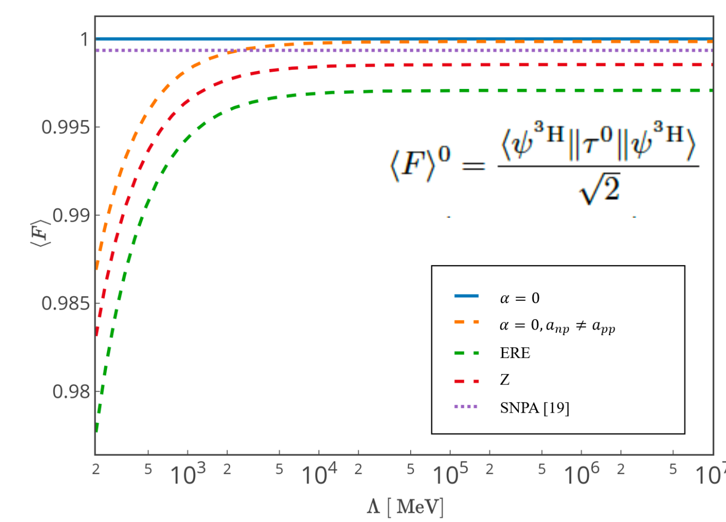
$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$

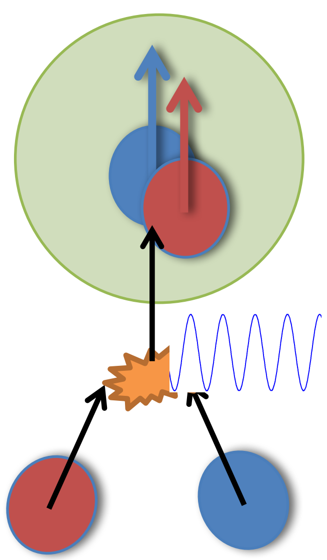


$n \rightarrow p + e^- + \bar{\nu}_e$

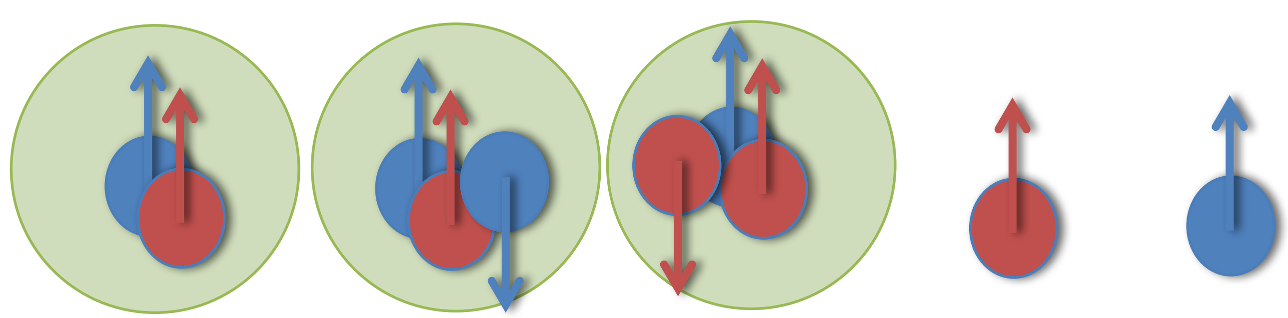
Weak observables

^{3}H and ^{3}He have almost the same wave function :





$n + p \rightarrow d + \gamma$



μ_d $\mu_{^3\mathrm{H}}$ $\mu_{^3\mathrm{He}}$ μ_p μ_n

M1 observables – ALL VERY WELL MEASURED

Operators:

	M1	Weak
1-b	$(\mu_{n,p})\ \sigma, \sigma\tau^0$	$g_A\ \sigma\tau^{+,-}$
2-b	$L_1 s^\dagger d$, ~~$L_2 d^\dagger d$~~	$L_{1A} s^\dagger d$

N^{2}LO

Take expansion parameter CDF from M1 analysis!

A PREDICTIVE AND VERIFIED THEORY, A CHECKLIST:

$$S_{11}(g_A = 1.275) = 4.16 \pm 0.08 \pm_{g_A} 0.03 \pm 0.02 \cdot 10^{-23}\text{MeV} \cdot \text{fm}^2$$

theoretical uncertainty

g_A stat.+syst unc.

^3H halflife syst. unc.

A predicted increase of 2–6% over SFII

NEUTRINO FLUXES WITH PREVIOUS S_{11} VALUE

Flux	Old composition SSM	New composition SSM	Solar[a]
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

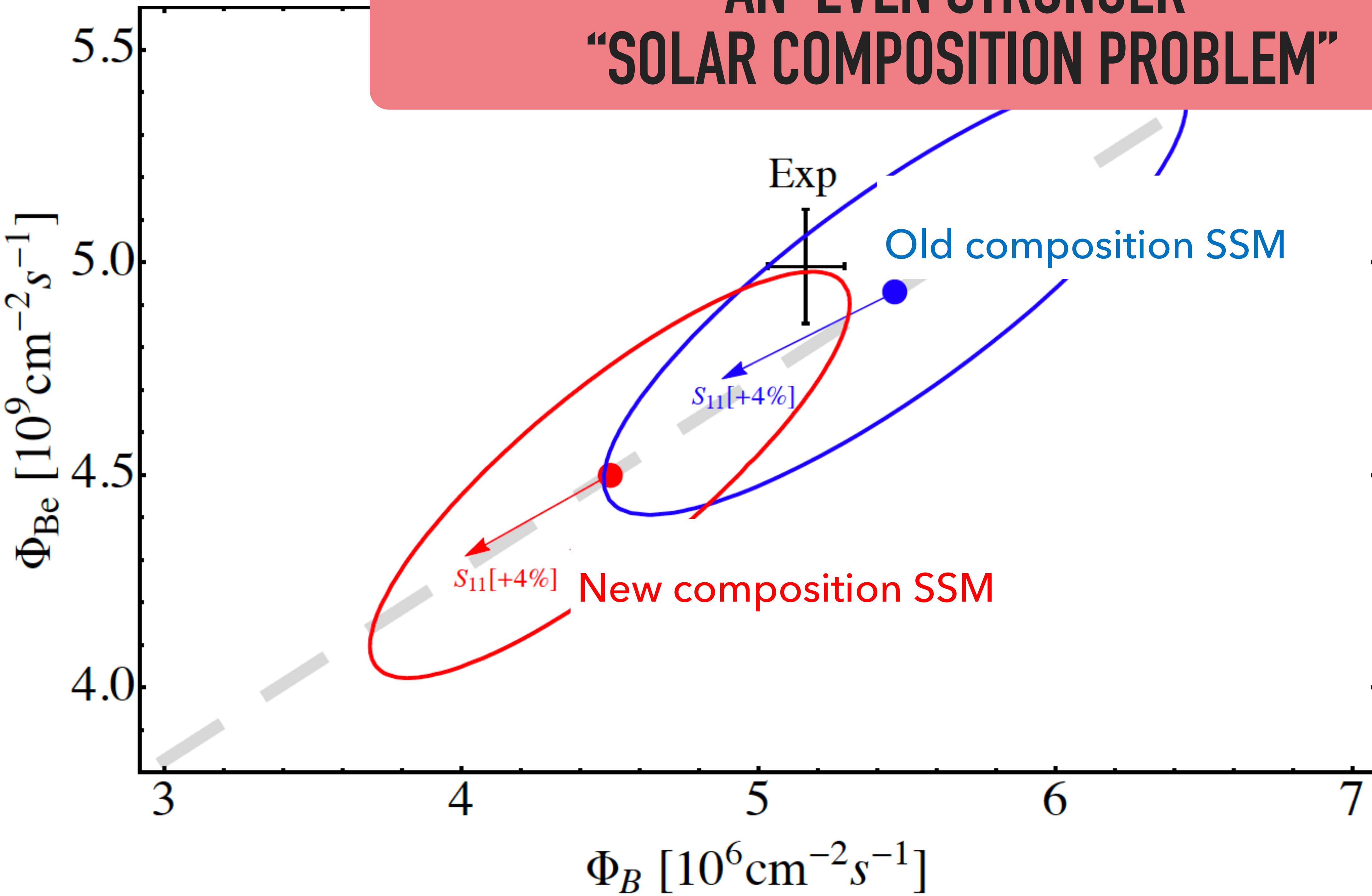
EFFECT OF NEW S_{11} ON NEUTRINO FLUXES

Flux	Old composition SSM	New composition SSM	Solar[a]
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.72(1 \pm 0.08)$	$4.31(1 \pm 0.08)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8B)$	$4.91(1 \pm 0.15)$	$4.05(1 \pm 0.15)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}N)$	[illegible]	[illegible]	≤ 13.7
$\Phi(^{15}O)$	[illegible]	[illegible]	[illegible].8
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

BETTER AGREEMENT USING OLD SSM
WORSE AGREEMENT USING NEW SSM

EFFECT OF NEW S_{11} ON NEUTRINO FLUXES

AN 'EVEN STRONGER' "SOLAR COMPOSITION PROBLEM"



SUMMARY

- *SOLAR PP-FUSION*:
  - Controlled, perturbative calculations, with reliable order by order convergence, indicate an increase of 2-6% over the current standard!
  - Predicted neutrino fluxes dis-favor new solar composition assessments.
    - A new perspective on the solar composition problem, or a new solar neutrino problem?
  - Disagreement with χEFT calculations (at the 90% level), though they are still plagued by my mistake ☺
- Perfect post-diction of A=2, 3 magnetic M1 observables, within 1% theoretical uncertainty!
- Surprises hint that something is weird in the pionless EFT description of these reactions:
  - Deviation from the naïve pion-less EFT counting of the magnetic interaction, by $l_2'^{\infty} = 0$.
  - Unnaturally small expansion parameter, $\delta \approx 5 - 10\% << \frac{\gamma_t}{m_\pi} \approx \frac{1}{3}$ is the source of shell model behavior of M1 observables in A=2, 3 systems!