Precision extraction of a_{nn} from $\pi^- d \to nn\gamma$

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Relevant publications

In collaboration with Daniel Phillips (Ohio University):

- A.G. and D.R. Phillips
  Phys. Rev. C **73**, 014002 (2006)
  `arXiv.org/abs/nucl-th/0501049`
- A.G. and D.R. Phillips
  Phys. Rev. Lett. **96**, 232301 (2006)
  `arXiv.org/abs/nucl-th/0603045`
- A.G.
  Phys. Rev. C **74**, 017001 (2006)
  `arXiv.org/abs/nucl-th/0604035`

Supported by DOE and NSF

Charge Symmetry Breaking

QCD Lagrangian almost symmetric under $u \leftrightarrow d$ exchange
(Charge Symmetry, CS), $P_{CS} = \exp(i\pi\tau_2/2)$
broken by $m_u \neq m_d$ (and EM effects)
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Special case of isospin violation

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Special case of isospin violation

For hadrons and nuclei CS implies

$p \leftrightarrow n$
$d \leftrightarrow d$
$\alpha \leftrightarrow \alpha$

$\pi^0 \leftrightarrow -\pi^0$

Experimental evidence

n-p mass difference
ρ^0-ω mixing ($e^+e^- \to \pi^+\pi^-$)
mirror nuclei (e.g. $^3\mathrm{He}$-$^3\mathrm{H}$) binding energy, N-S anomaly
$np \to np$: $A_n(\theta_n) \neq A_p(\theta_p)$ analyzing powers

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$a_{nn}^{\mathrm{str}} \neq a_{pp}^{\mathrm{str}}$

CSB reviews: [Miller, Nefkens, and Šlaus, PRt**194**, 1 (1990); Miller and van Oers, nucl-th/9409013; Miller, Opper, and Stephenson, ARNPS56, 293 (2006), nucl-ex/0602021]

Effective range expansion

At low energies NN s-wave phase shifts can be written as

$$p\cot\delta = -\frac{1}{a^{\rm str}} + \frac{1}{2}r_0 p^2, \quad \text{CSB} \;\Rightarrow\; a^{\rm str}_{nn} \neq a^{\rm str}_{pp}$$

Calcs of $B(^3\mathrm{H}) - B(^3\mathrm{He})$ rely on $|a^{\rm str}_{pp}| < |a^{\rm str}_{nn}|$, fails if $|a^{\rm str}_{pp}| > |a^{\rm str}_{nn}|$!

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$a_{nn}^{\rm str} = -18.9 \pm 0.4$ fm, $a_{pp}^{\rm str} = -17.3 \pm 0.4$ fm

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WHAT TO DO?

Solutions

Direct measurements:

Wild idea #1: Simultaneous underground nuclear explosions

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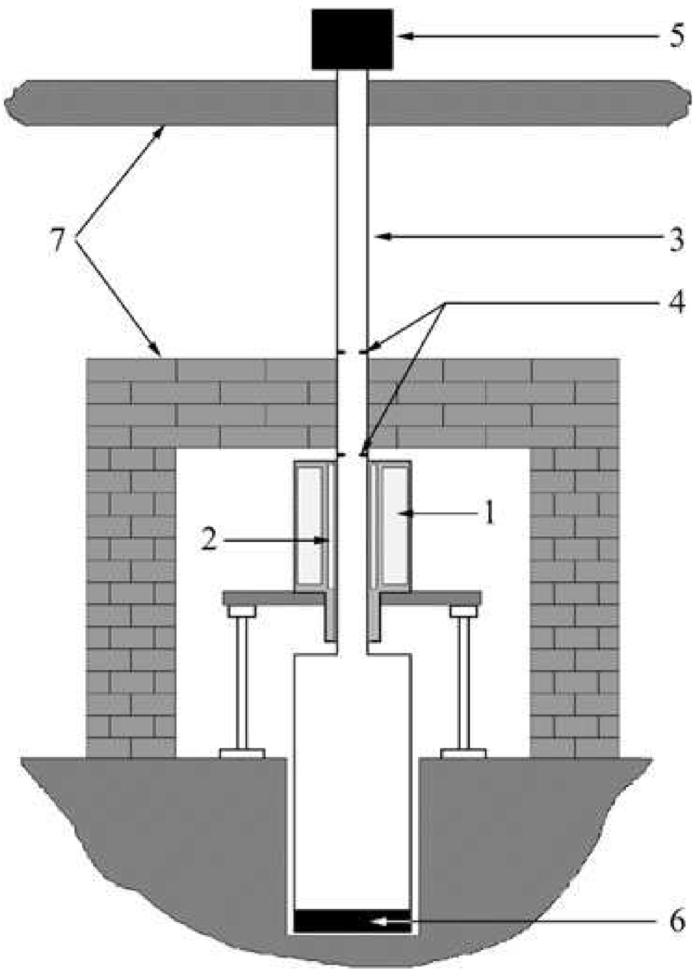
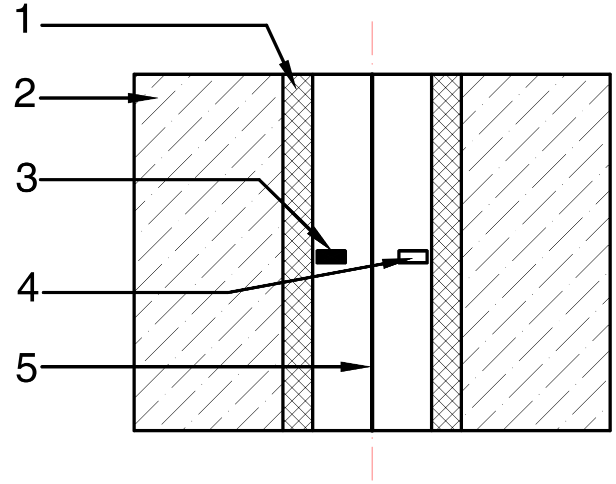
Recent idea: Pulsed reactor YAGUAR in Snezhinsk, Russia





[Furman et al., JPG **28**, 2627 (2002)]

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Indirect nn experiments:
Implemented idea: Reactions giving nn with small rel. energy

- $nd \to nnp$: 3-body forces needed, expts differ:
  $a_{nn} = -16.1 \pm 0.4$ fm (n, np) [Huhn et al., PRL**85**, 1190 (2000)] and
  $a_{nn} = -16.5 \pm 0.9$ fm (n, p) [von Witsch et al., PRC**74**, 014001 (2006)] vs
  $a_{nn} = -18.7 \pm 0.7$ fm (n, nnp) [González Trotter et al., PRC**73**, 034001 ('06)]
- $\pi^- d \to nn\gamma$: -18.59 ± 0.40 fm $(\pi^-, n\gamma)$ $\Rightarrow$ standard value (PSI and LAMPF) [Machleidt and Slaus, JPG:NPP**27**, R69 (2001)]

Need accurate theoretical input for extraction!

LAMPF set-up

Stopped pions captured on d in atomic s-wave orbitals

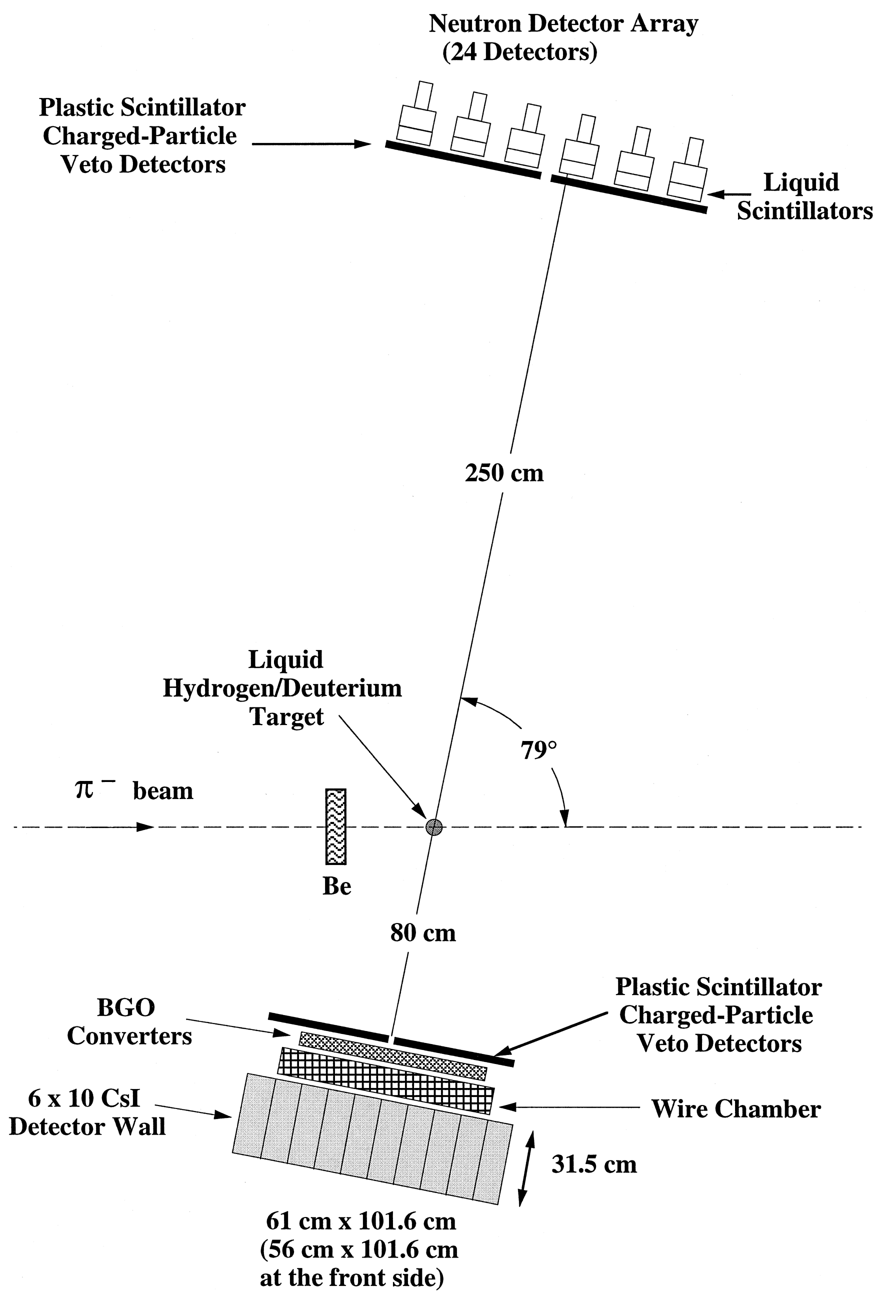
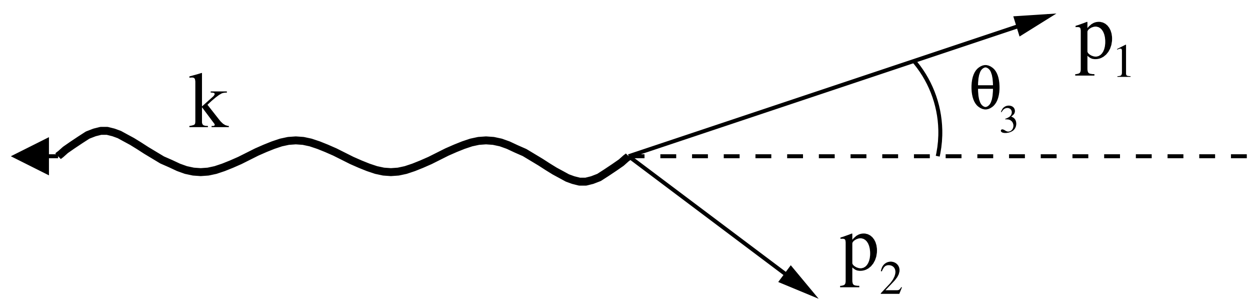


Fig. 1. Schematic of the mid-level cut-away view of the experimental layout.

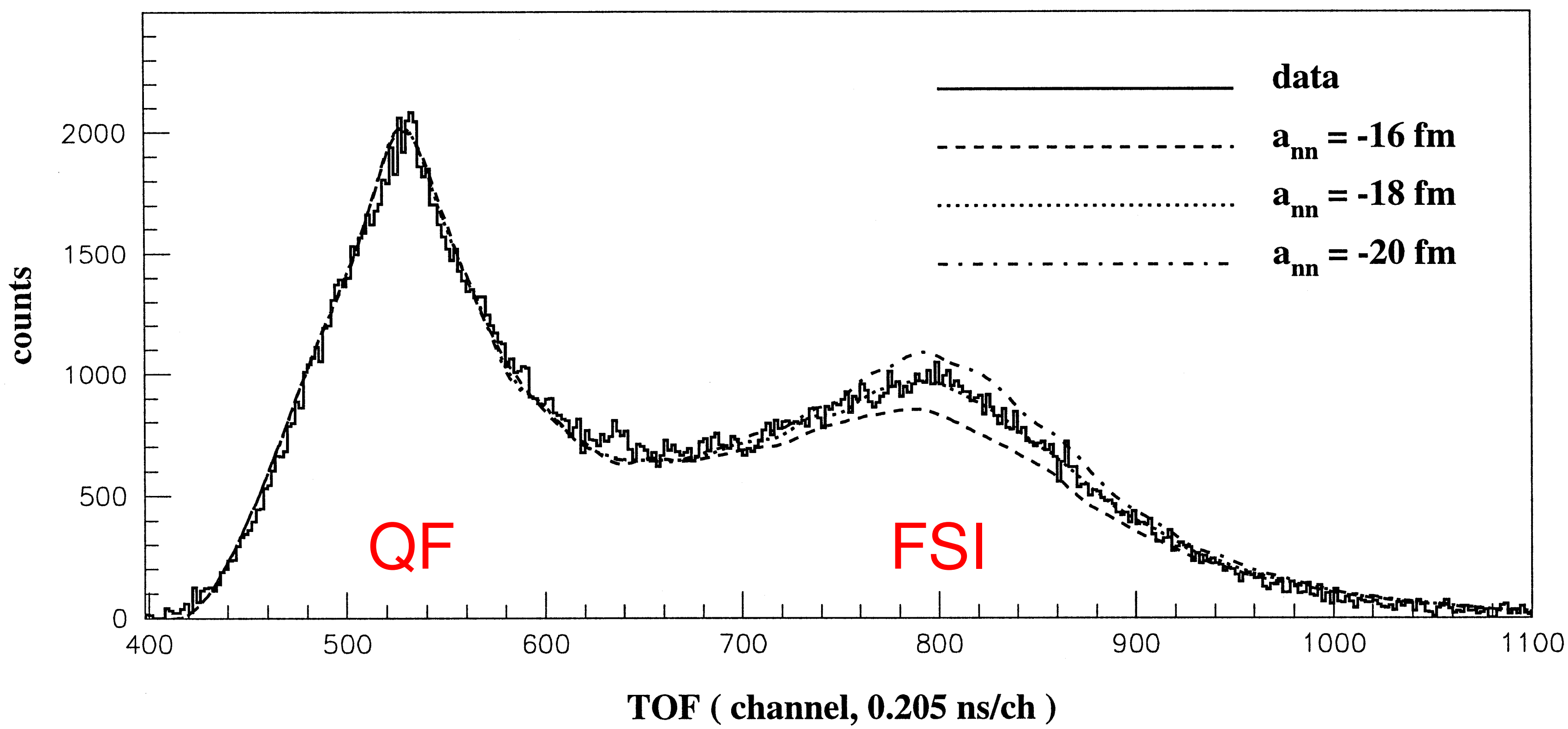
Lab = cm

γ and n detected in coincidence

$\pi^- d \to nn\gamma$ data (LAMPF)



γ and n_1 detected at $0.05 < \theta_3 < 0.1$ (rad) [Howell et al., PLB**444**, 252 (1998)]



Unnormalized, but shape fitted to give a_{nn}!

Old theory for $\pi^- d \to nn\gamma$

Gibbs, Gibson, and Stephenson (GGS) [PRC**11**, 90 (1975)]:

- $\pi^- p \to \gamma n$, rel corr up to $O(p/M)$
- estimated pion rescattering
- tried different wave functions
- theoretical error (mainly SD): $\Delta a_{nn} = \pm 0.3$ fm
- Only accurate at the FSI peak!

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Can chiral perturbation theory (χPT) do better?

EFT credo

Advantages of an effective field theory like χPT:

- Consistent amplitudes and wave functions
- Recipe to estimate theoretical error
- Systematic improvement possible
- χPT = low-energy limit of QCD, retains chiral symmetry of QCD

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Expansion in $\alpha_S \sim 1$ not possible.
Power counting gives hierarchy of amplitudes. Here:

- $Q \sim m_\pi$ small momentum/energy of problem
- $\Lambda_\chi \sim M \sim 4\pi f_\pi \sim$ 1 GeV energy scale where χPT breaks down
- Expand in Q/Λ_χ

χPT for $\pi^- d \to nn\gamma$

For $\pi^- d \to nn\gamma$ we get

- $O(Q^3)$ = GGS + π loops + 2-body
- $O(Q^3)$ $\pi N \to \gamma N$ fitted to data $\Rightarrow$ no free parameters

For capture on d: $q_\pi = 0$, only one CGLN amplitude (F_1) survives

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$\Rightarrow$ High precision possible

CGLN amplitudes

Spin decomposition

$$\mathcal{A}_{\rm I}(\gamma N \to \pi N) = F_1(E_\pi, x) i\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}_\gamma + F_2(E_\pi, x)\boldsymbol{\sigma}\cdot\widehat{\mathbf{q}}\,\boldsymbol{\sigma}\cdot(\widehat{\mathbf{k}}\times\boldsymbol{\epsilon}_\gamma) + F_3(E_\pi, x) i\boldsymbol{\sigma}\cdot\widehat{\mathbf{k}}\,\widehat{\mathbf{q}}\cdot\boldsymbol{\epsilon}_\gamma + F_4(E_\pi, x) i\boldsymbol{\sigma}\cdot\widehat{\mathbf{q}}\,\widehat{\mathbf{q}}\cdot\boldsymbol{\epsilon}_\gamma$$

Isospin

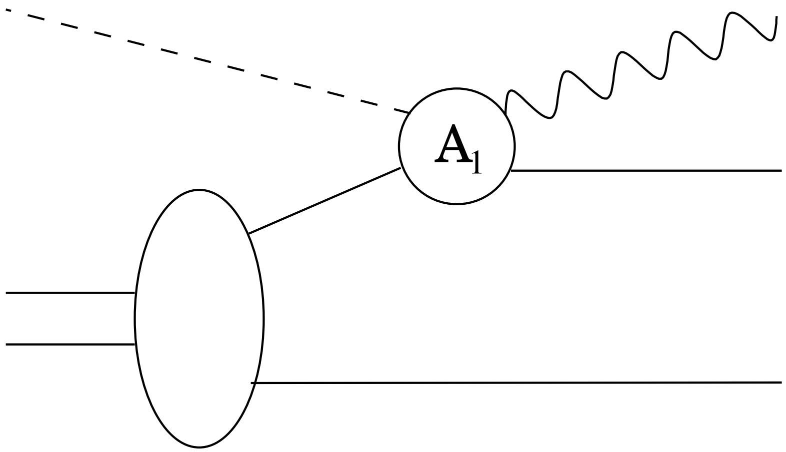
$$F_i^a(E_\pi, x) = F_i^{(-)}(E_\pi, x) i\epsilon^{a3b}\tau^b + F_i^{(0)}(E_\pi, x)\tau^a + F_i^{(+)}(E_\pi, x)\delta^{a3}$$

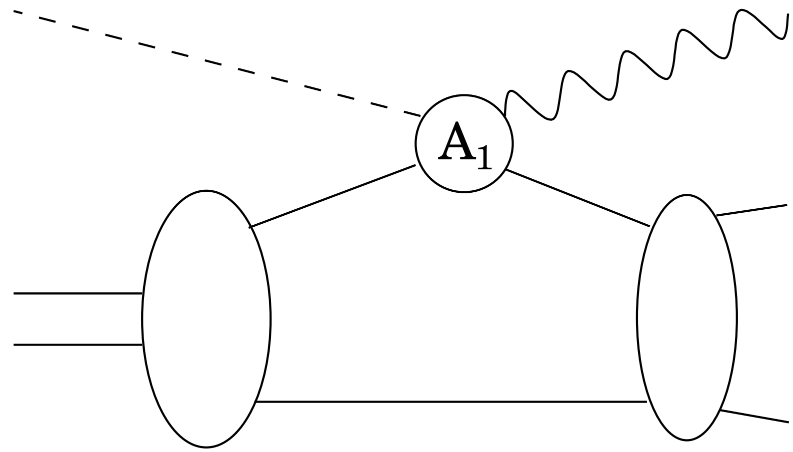
and for $\gamma n \to \pi^- p$

$$F_i(\gamma n \to \pi^- p) = \sqrt{2}[F_i^{(0)} - F_i^{(-)}]$$

$\boldsymbol{q} = \mathbf{0} \Rightarrow$ only F_1, dominated by KR for charged pions

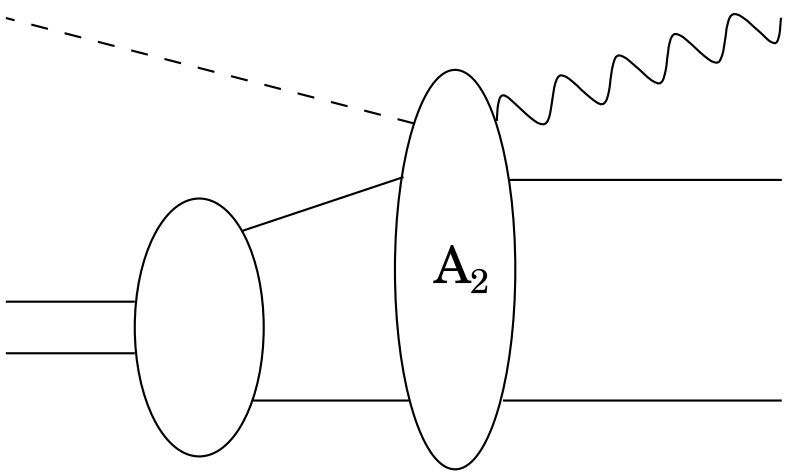
Generic diagrams

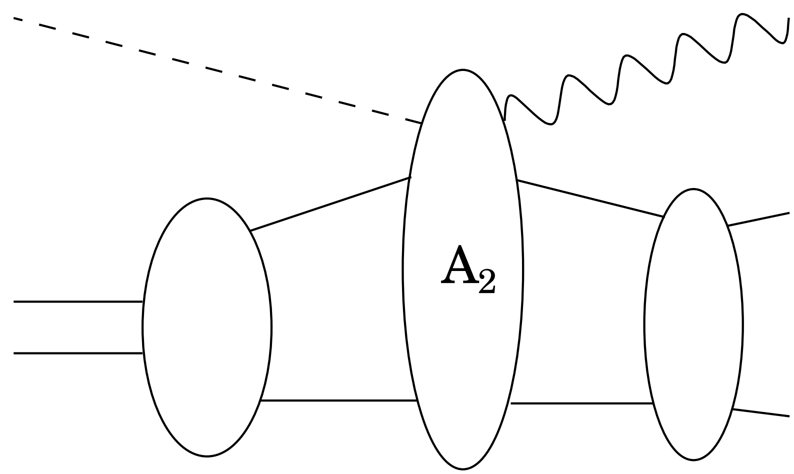




Quasifree (QF)

Final State Interaction (FSI)





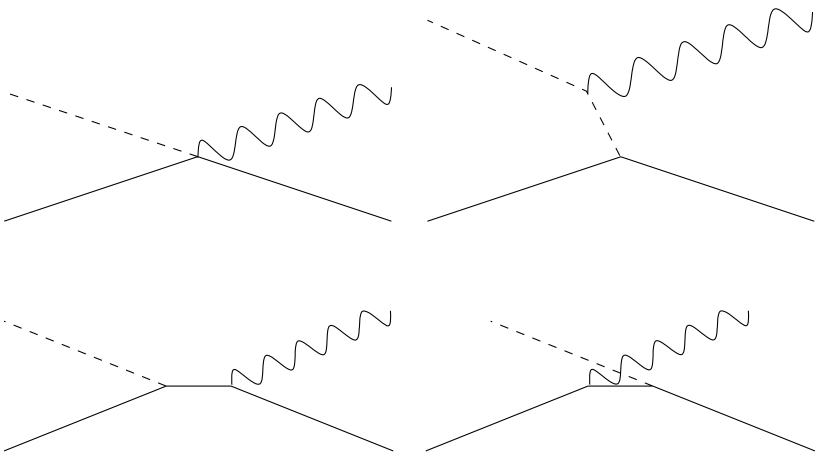
Two-body effects (2)

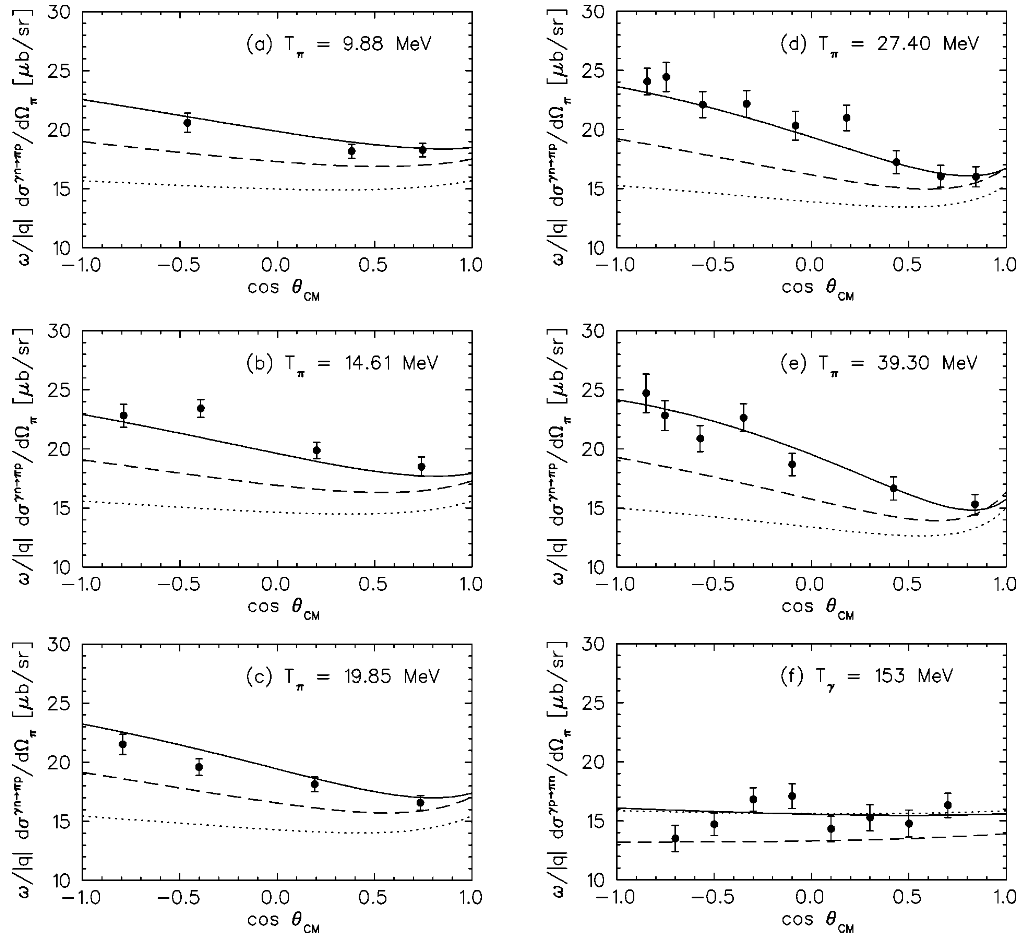
$$\Gamma \propto |\mathcal{M}_{\rm QF} + \mathcal{M}_{\rm FSI} + \mathcal{M}_2|^2$$

One-body amplitudes

EFT to $O(Q^3)$

[Fearing et al., PRC**62**, 054006 (2000)]:





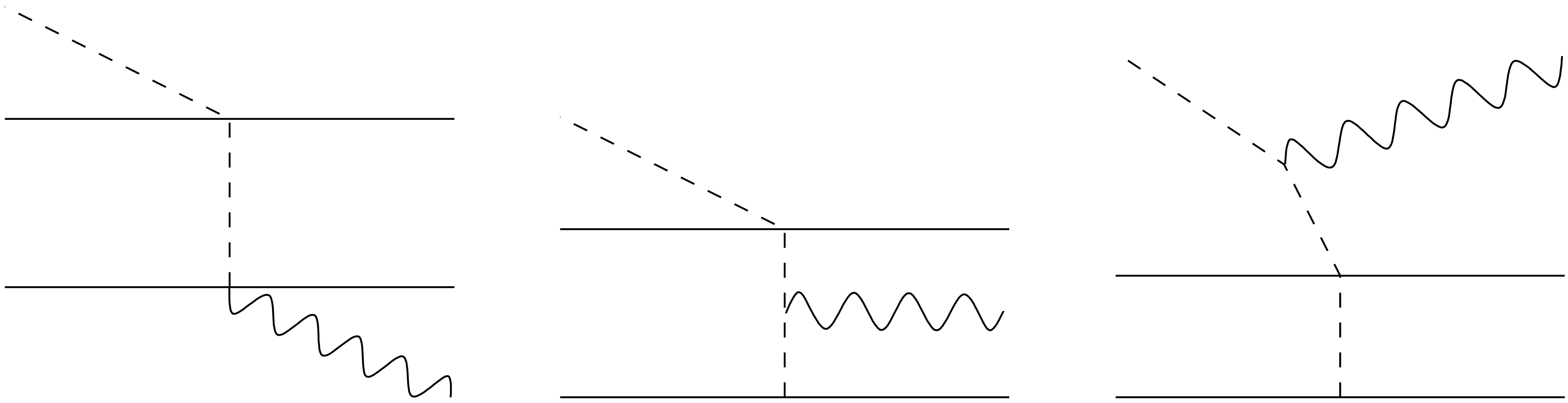
+pion loops at $O(Q^3) \Rightarrow \mathcal{A}_1$

all parameters fitted to data

Fitted parameters (LECs) unnaturally large (~ 10) $\Rightarrow \Delta$?

Two-body amplitudes $O(Q^3)$

In order of importance:



$\Rightarrow \mathcal{A}_2$

Reasons for pecking order:

First diagram has a Coulomb-like propagator, $1/\vec{q}^{\,2}$
Second diagram has $1/\vec{q}^{\,2}$ and also an off-shell pion prop
Third diagram (2 off-shell props) vanishes in Coulomb gauge

Chirally inspired wave functions

Start from asymptotic wave functions
Schrödinger eq integrated in from $r = \infty$ with OPEP

[Phillips & Cohen, NPA**668**, 45 (2000)]:

- Coupled integral equations for d $(^3S_1–^3D_1)$
- Single integral equation for nn $(^1S_0)$

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Match with spherical well solution at $r = R =$ 1.4 to 3.0 fm
(Regulates unknown short-distance physics)

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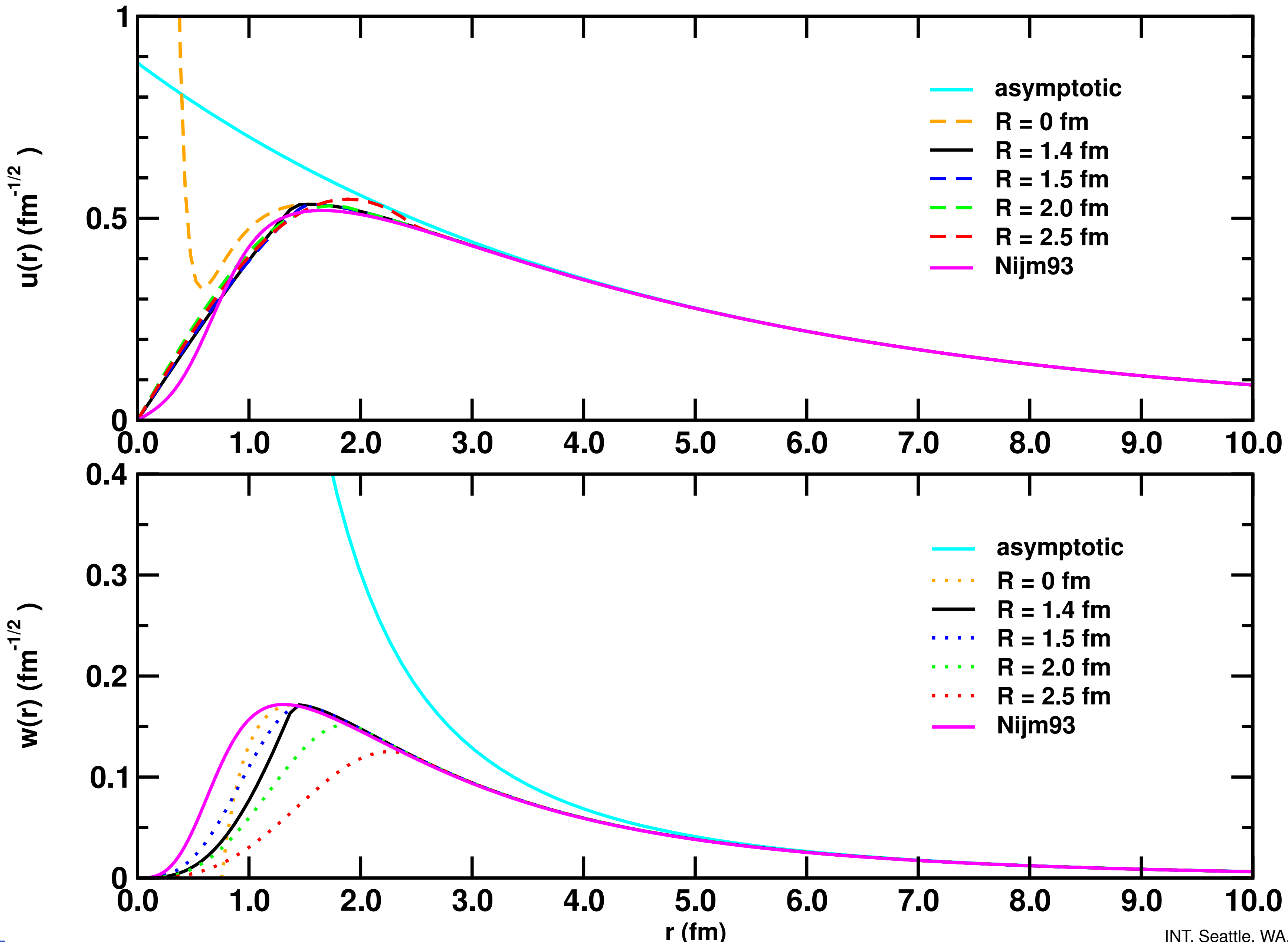
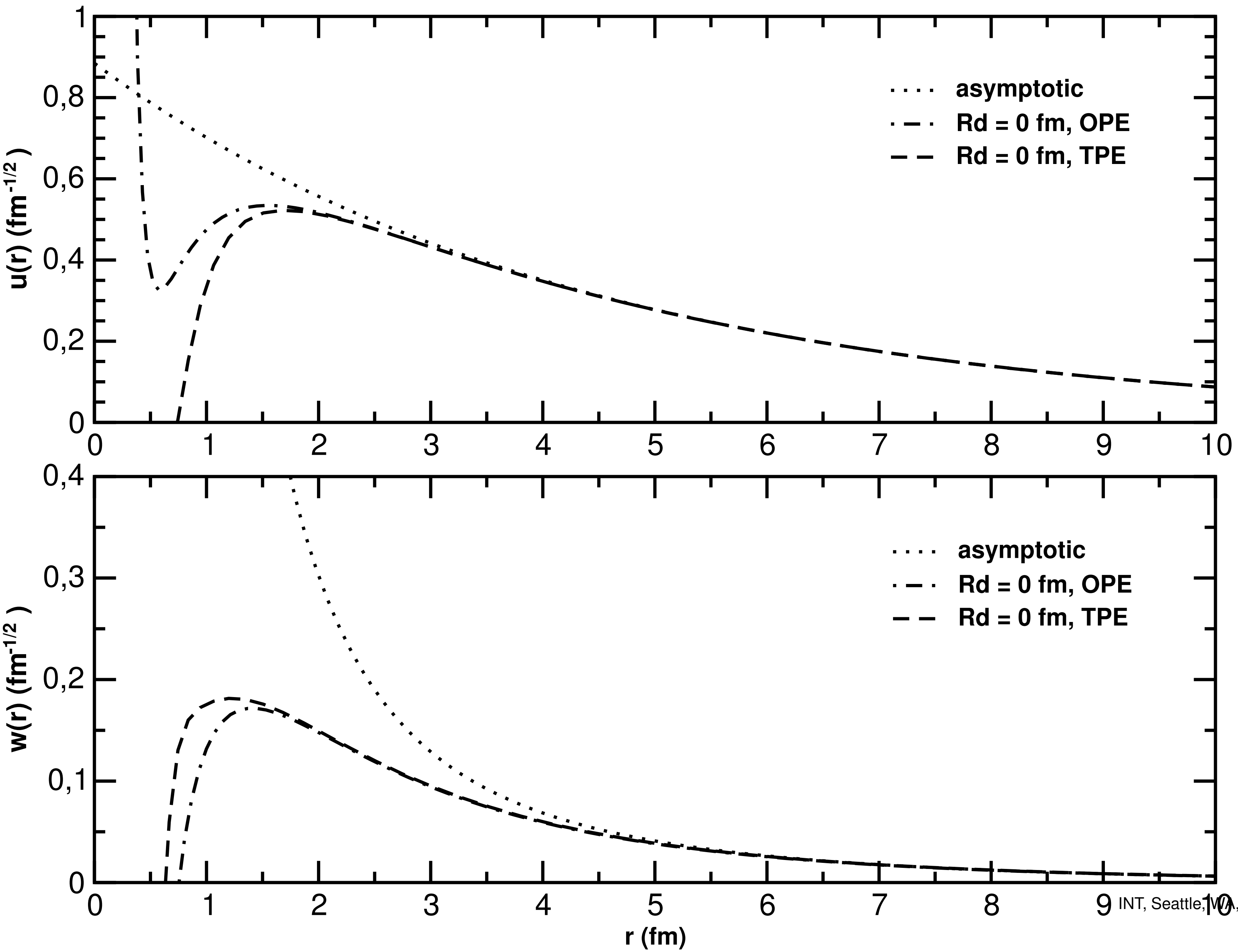
Chiral TPEP now implemented

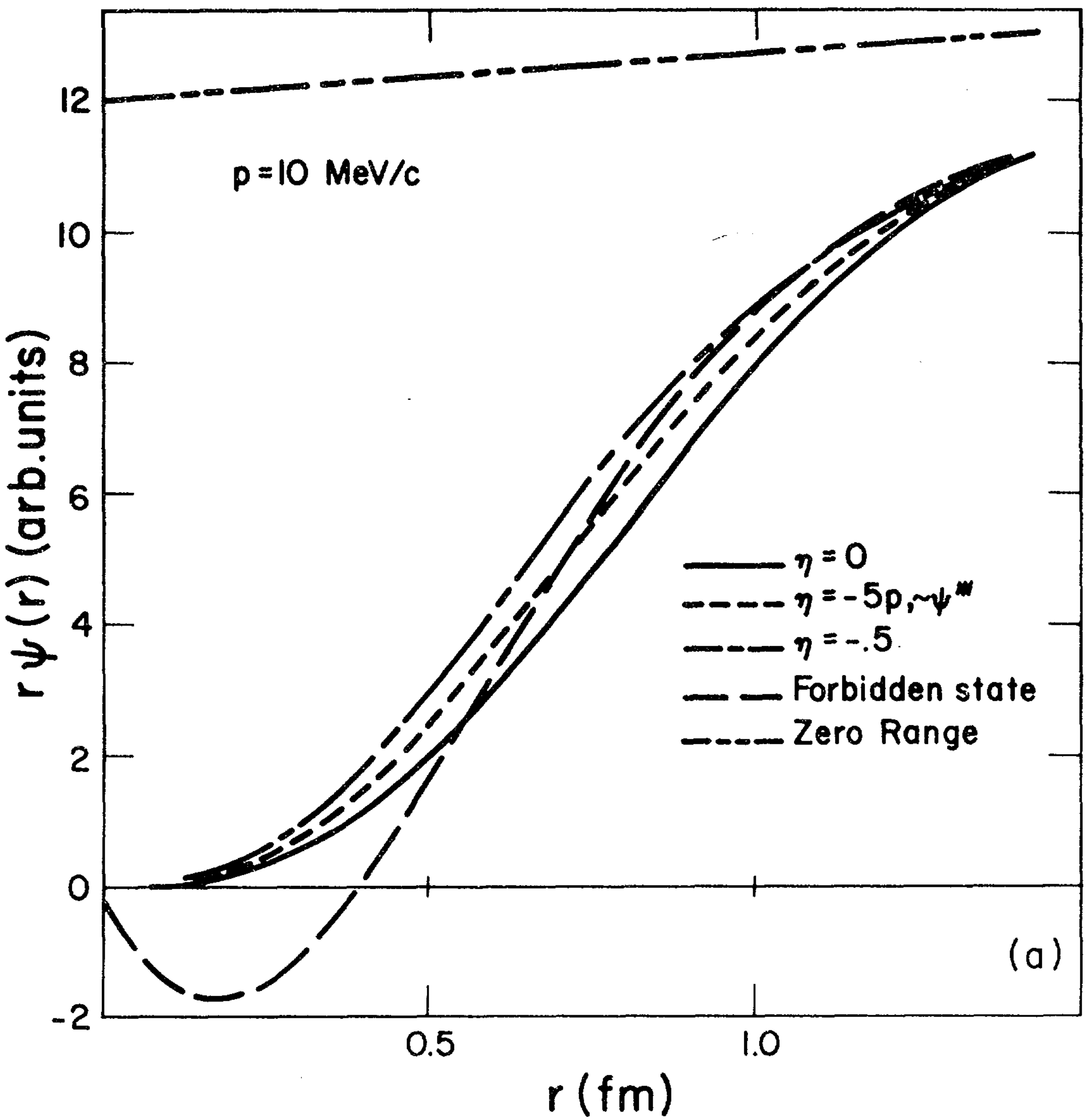
Deuteron wave functions (OPE)



Deuteron wave functions (TPE)

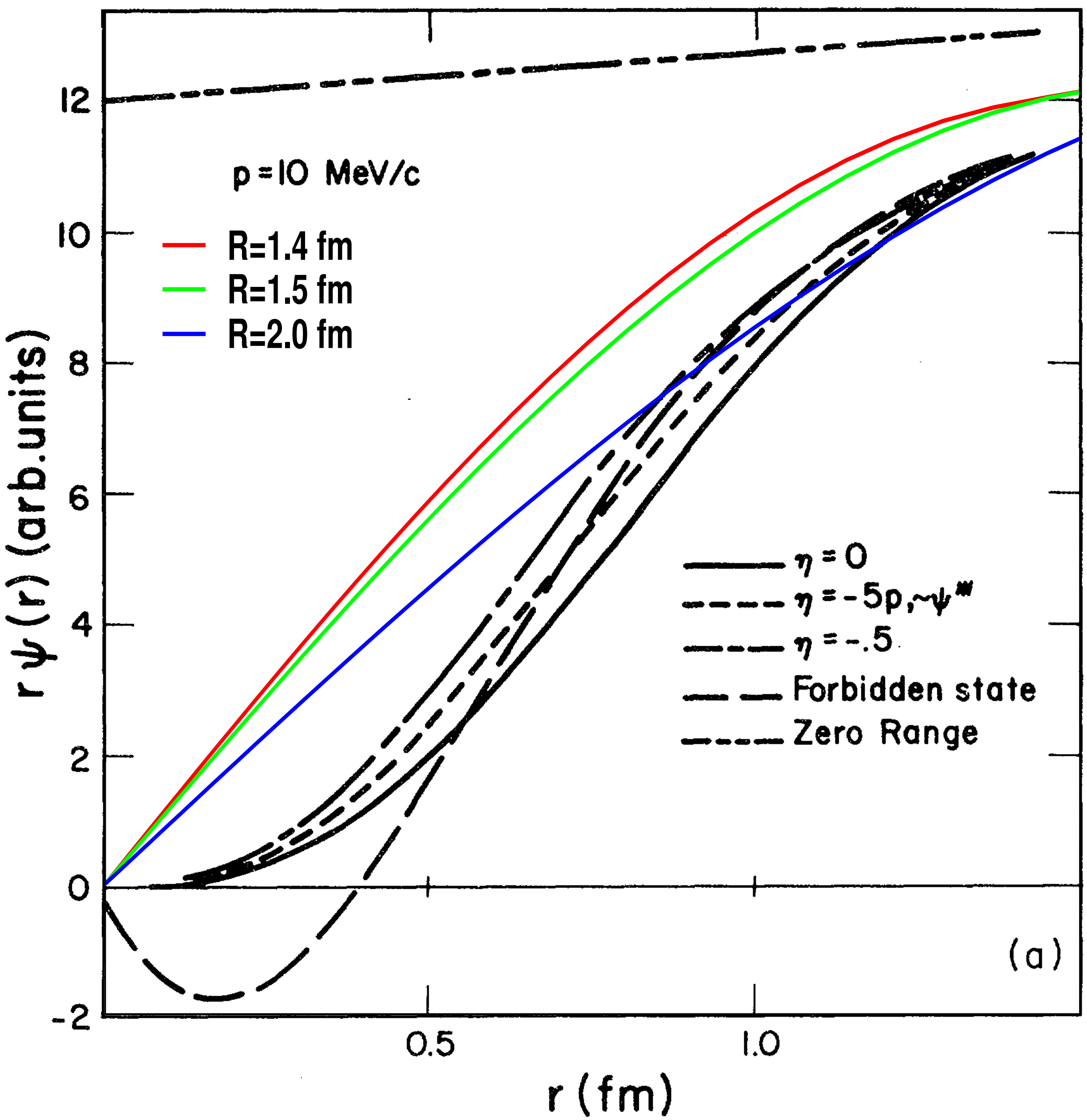


nn scattering wfs, GGS



GGS use $P_5(r)$
$R = 1.4$ fm
RSC

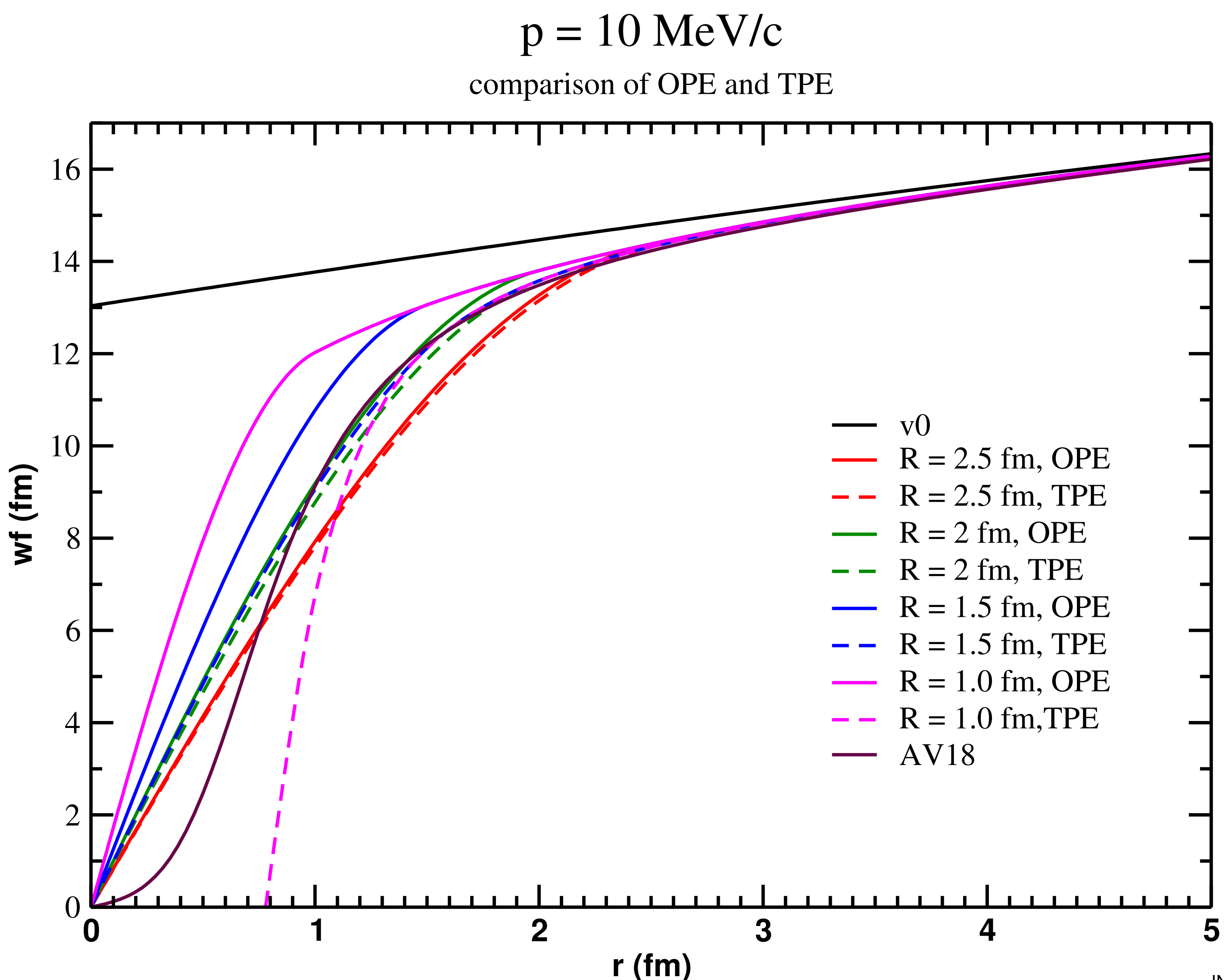
nn scattering wfs, GGS vs GP



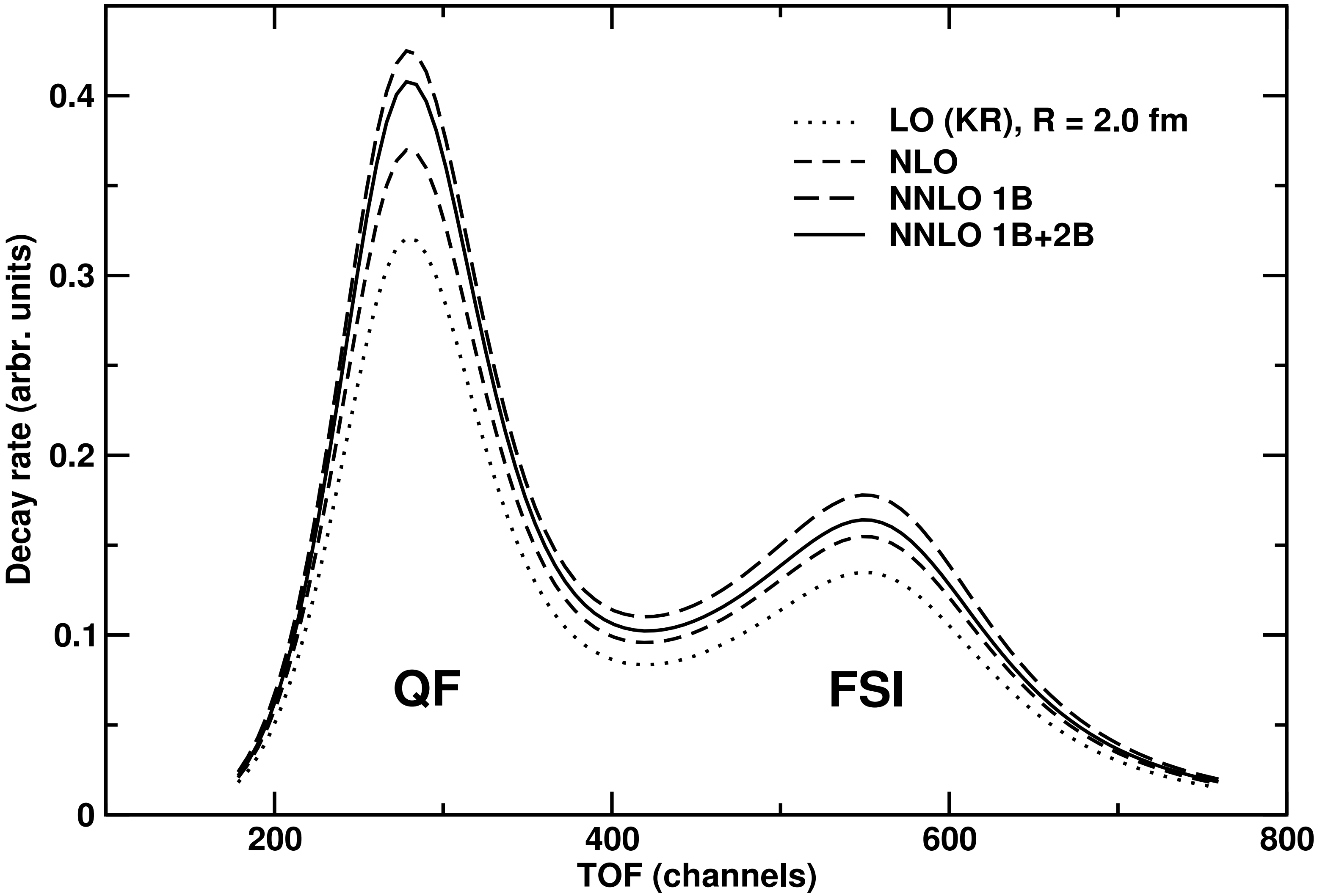
GGS use $P_5(r)$
$R = 1.4$ fm
RSC

GP use sph well
varying R
OPEP

nn scattering wfs OPE vs TPE

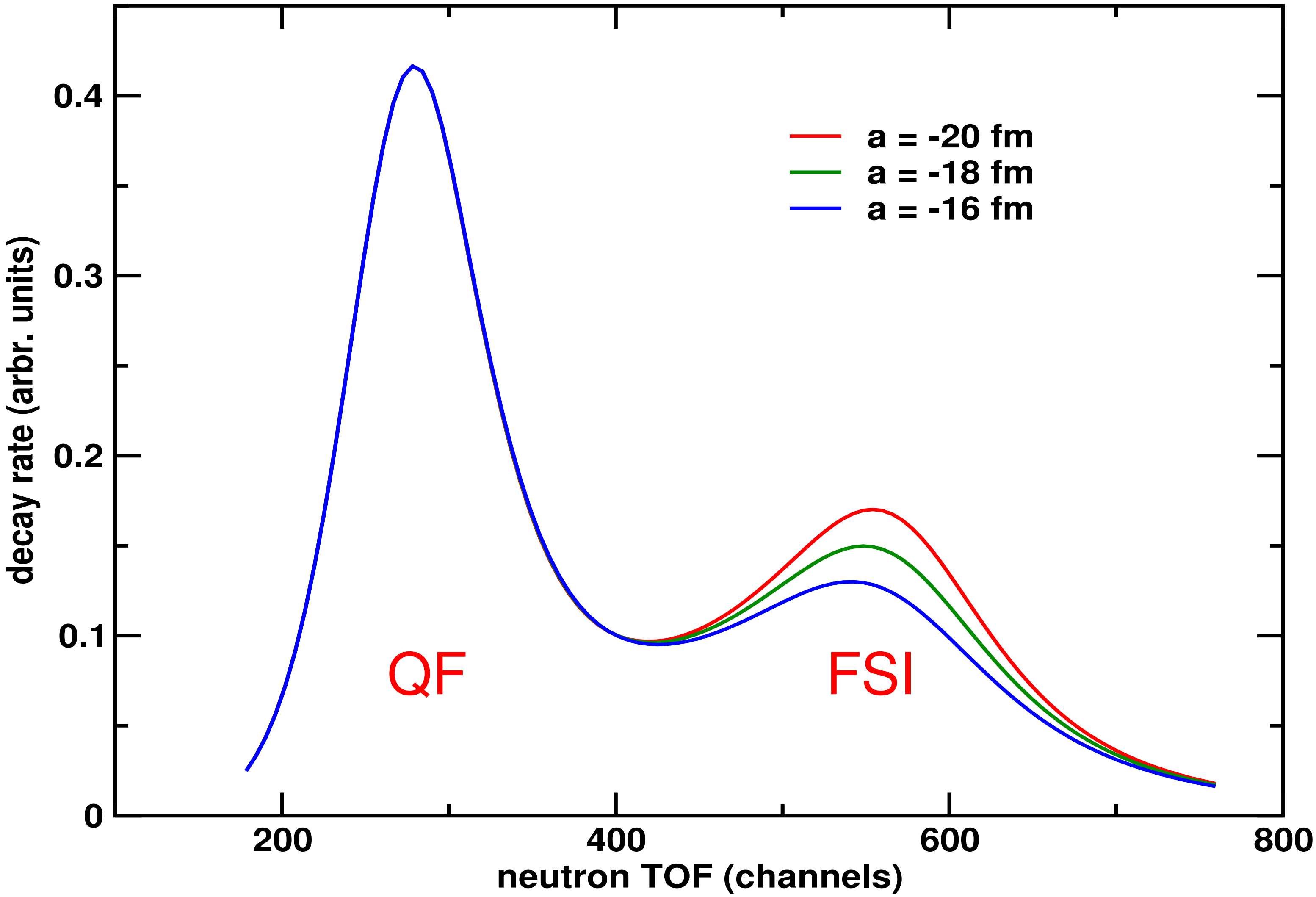


Convergence



$$\frac{\Gamma_{\mathrm{QF}}}{\Gamma_{\mathrm{FSI}}} = (2.379 + 0.011 - 0.001 + 0.097)$$

Sensitivity to a_{nn}



Neutron TOF spectrum at $\theta_3 = 0.075$ rad $\Rightarrow \frac{\Delta a_{nn}}{a_{nn}} = 0.83 \frac{\Delta \Gamma}{\Gamma}$

Fine details (fitting both peaks)

Boost corrections: $<$ 0.11% or 0.02 fm

'Off-shell' nucleon: 0.12% or 0.02 fm

Subthreshold extrapolation:
Error of order $(\omega^3 - \omega_0^3)/\Delta^3 \sim$ 3%–4%
QF and FSI change in the same way $\Rightarrow$ 0.96% $\leftrightarrow$ 0.17 fm

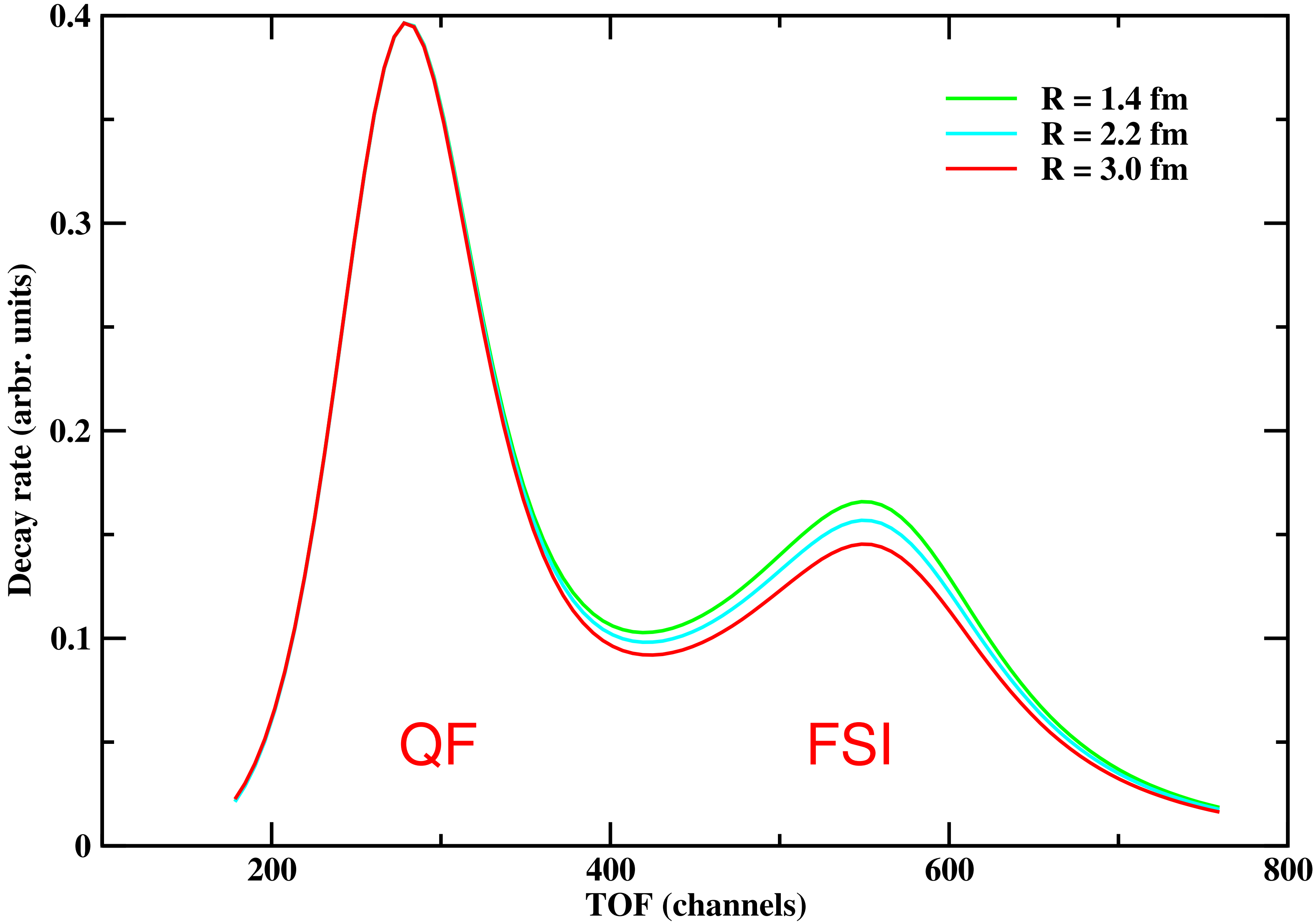
$O(Q^4)$ 2B: $\frac{p}{\Lambda_\chi} \sim$ 20% of $O(Q^3)$ 2B $\Rightarrow \sim$ 0.7%, 0.13 fm

Deuteron wave function: $\Delta a_{nn} \sim$ 0.10 fm
negligible R dep., Bonn B indistinguishable

Sensitivity to r_0: ± 0.25 fm $\Rightarrow <$ 1.2% or 0.21 fm
Expt. error in r_0: ± 0.11 fm $\Rightarrow <$ 0.5% or 0.09 fm

Higher partial waves in FSI: $<$ 0.43 fm

Results at $\mathcal{O}(Q^3)$



Neutron time-of-flight spectrum at $\theta_3 = 0.075$ rad

How to reduce SD error?

Possible constraints of SD physics?

Can we borrow the unknown SD physics from some other observable?

Axial isovector ${}^3S_1 \leftrightarrow {}^1S_0$ transitions common in NN systems:

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Calculated by [Park *et al.*, PRC**67**, 055206 (2003)]
constrained by tritium beta decay

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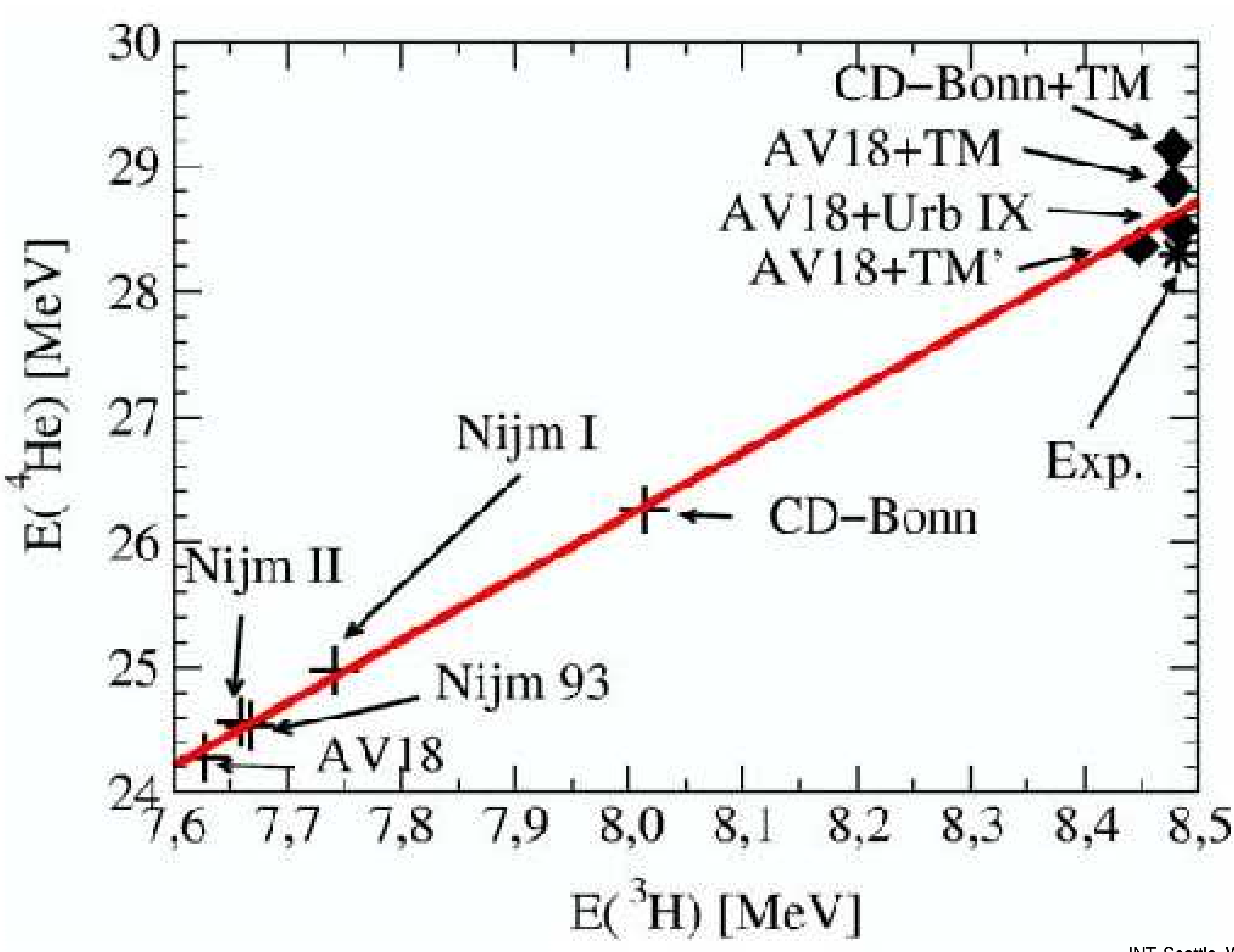
Let's do a numerical experiment!

Remember:

Tjon line: $B(^4\mathrm{He})$ vs $B(^3\mathrm{H})$
Phillips line: $^2a_{nd}$ vs $B(^3\mathrm{H})$

Tjon line



CD−Bonn+TM
AV18+TM
AV18+Urb IX
AV18+TM'
Exp.
Nijm I
CD−Bonn
Nijm II
Nijm 93
AV18
E(⁴He) [MeV]
E(³H) [MeV]
30
29
28
27
26
25
24
7,6
7,7
7,8
7,9
8,0
8,1
8,2
8,3
8,4
8,5

Phillips line [Witała et al., PRC68, 034002 (2003)]

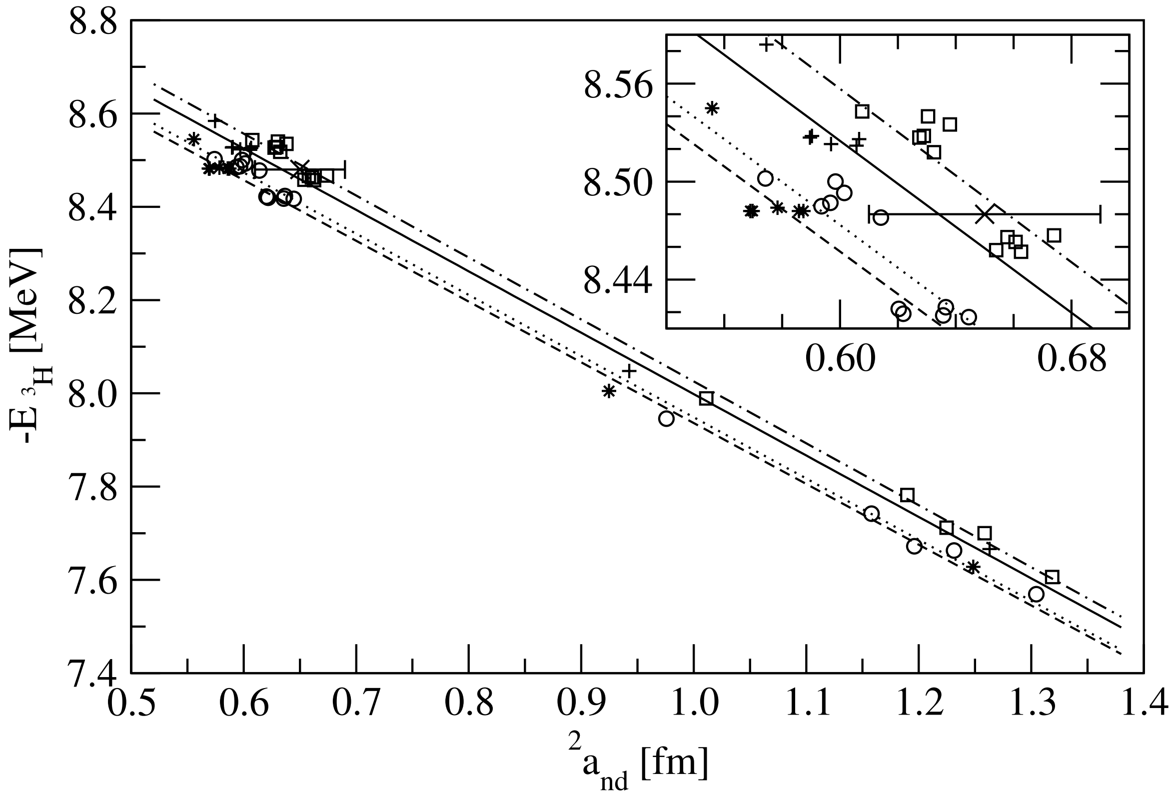
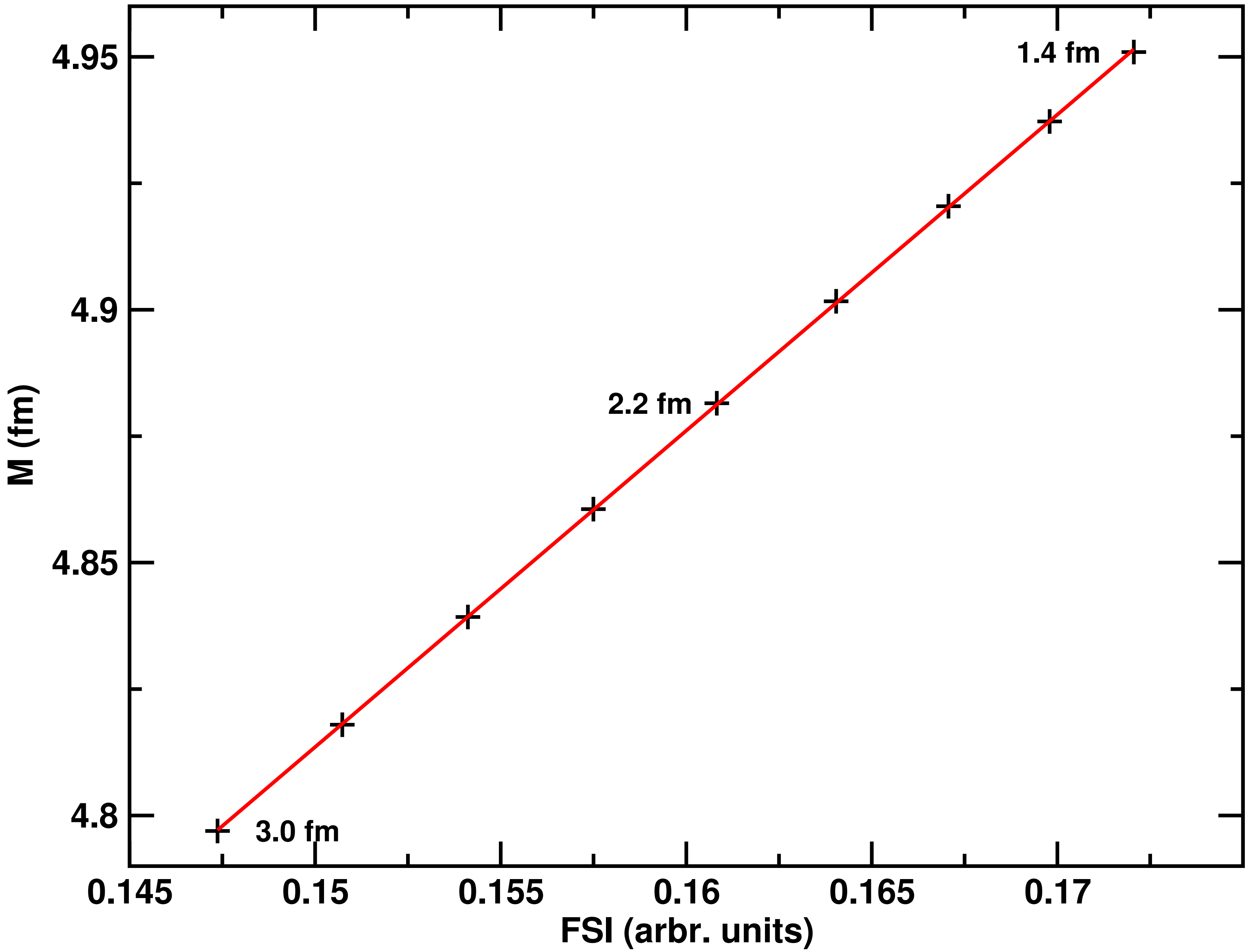


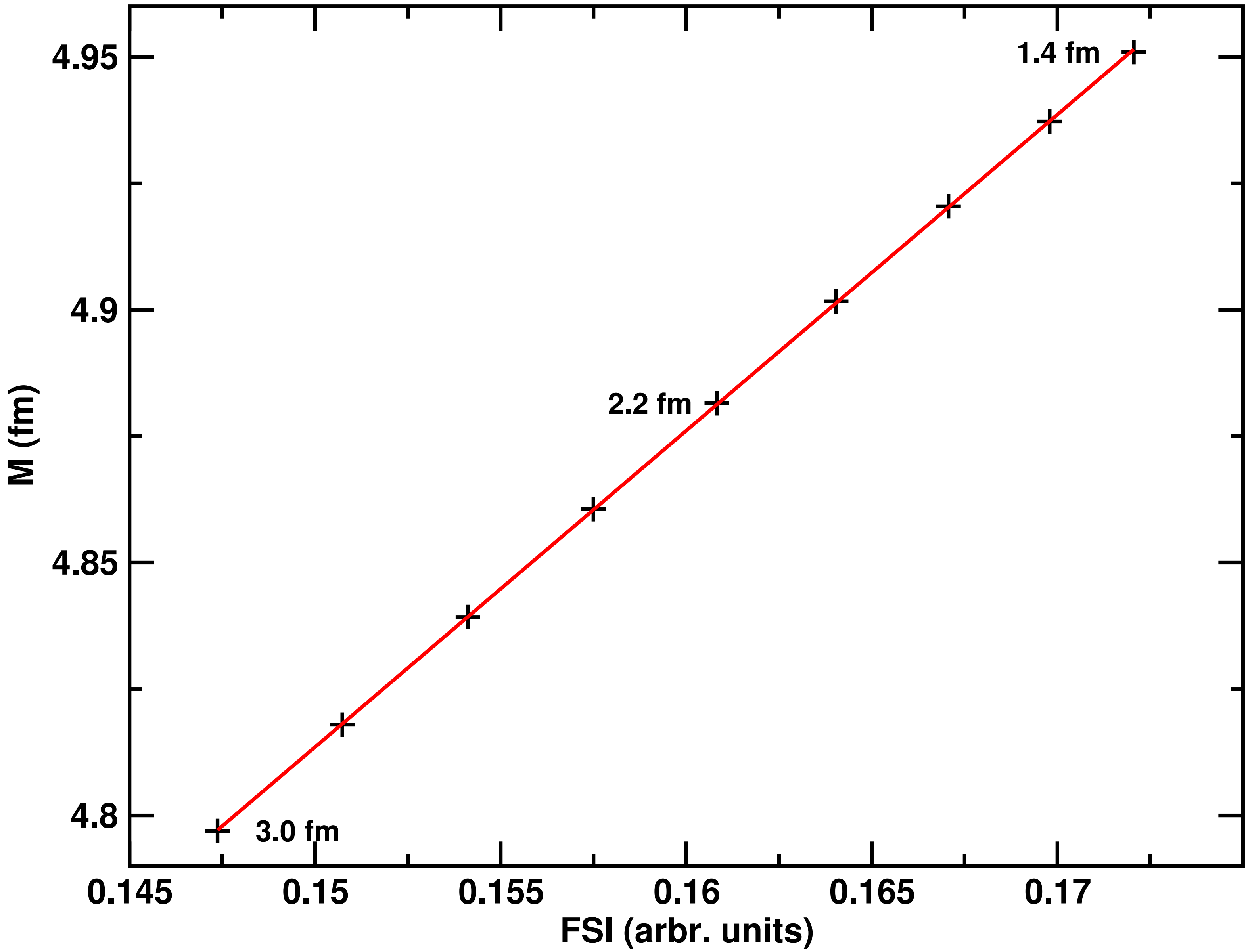
FIG. 4. The results for $^2a_{nd}$ and $E_{^3\mathrm{H}}$ from Table I: np-nn forces alone (pluses), np-pp forces alone (squares), and np-nn and np-pp forces plus electromagnetic interactions (stars and circles, respectively). The four straight lines (Phillips lines) are χ^2 fits (np-nn, solid; np-pp, dashed-dotted; np-nn with EMI's, dashed; np-pp with EMI's, dotted). The lines with EMI's miss the experimental error bar for $^2a_{nd}$ [33]. The physically interesting domain around the experimental values is shown in the inset.

Gamow-Teller vs FSI



Gamow-Teller ME of pp fusion vs FSI peak height

Gårdestig-Phillips line



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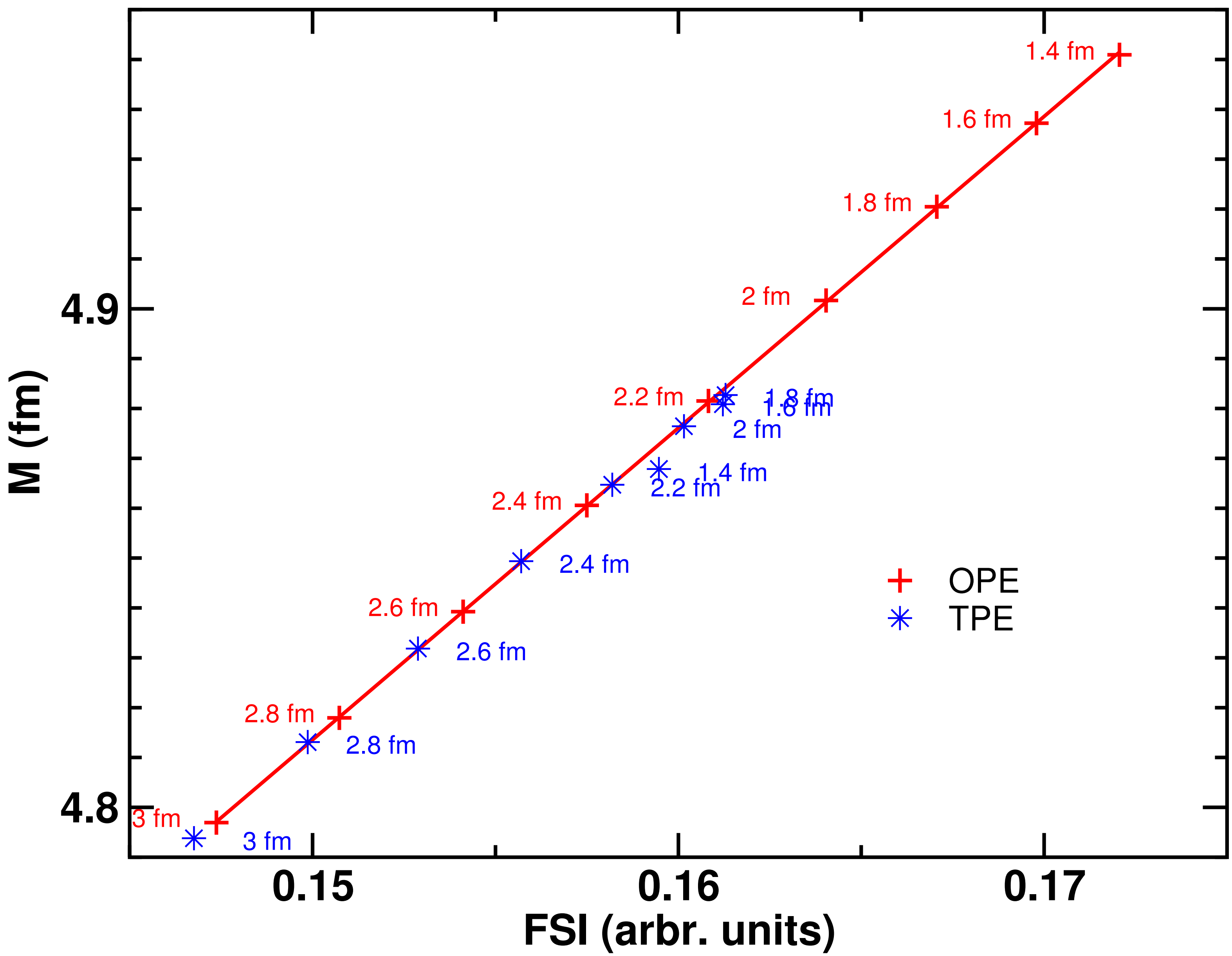

Gamow-Teller ME of pp fusion vs FSI peak height

Chiral explanation I

Chiral $1N$ Lagrangian:

$$\mathcal{L} = N^\dagger (iv \cdot D + g_{\mathrm{A}} S \cdot u) N$$

where

$$f_\pi u_\mu = -\tau^a \partial_\mu \pi^a - \epsilon^{3ba} V_\mu \pi^b \tau^a + f_\pi A_\mu + \mathcal{O}(\pi^3)$$

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Goldberger-Treiman and Kroll-Ruderman relations (1N)

$$\frac{g_A}{f_\pi} = \frac{g_{\pi NN}}{M} \qquad |\mathcal{A}_{KR}| = \frac{e g_A}{f_\pi}$$

relate axial coupling to πN coupling and $\gamma\pi N$ coupling.

Chiral explanation II

Axial isovector coupling to NN $(^3S_1 \leftrightarrow {}^1S_0) \Rightarrow$
Two-nucleon version of GT and KR relations?

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Two-nucleon version of GT and KR relations?

2N HBχPT Lagrangian contains contact terms:

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$$f_\pi u_\mu = -\tau^a \partial_\mu \pi^a - \epsilon^{3ba} V_\mu \pi^b \tau^a + f_\pi A_\mu + \mathcal{O}(\pi^3)$$

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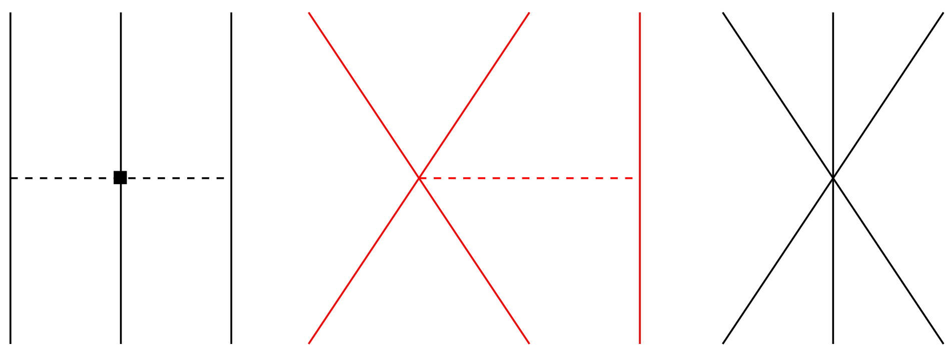
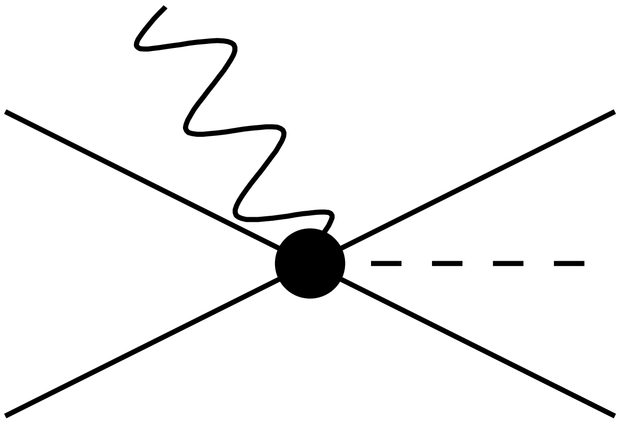
Connects π (photo)prod to EW reactions and chiral 3NF!



$\mathcal{O}(Q^4)$ axial isovector contact term



For ${}^3S_1 \leftrightarrow {}^1S_0$ one single LEC:

$$\hat{d} \equiv \hat{d}_1 + 2\hat{d}_2 + \frac{\hat{c}_3}{3} + \frac{2\hat{c}_4}{3} + \frac{1}{6}$$

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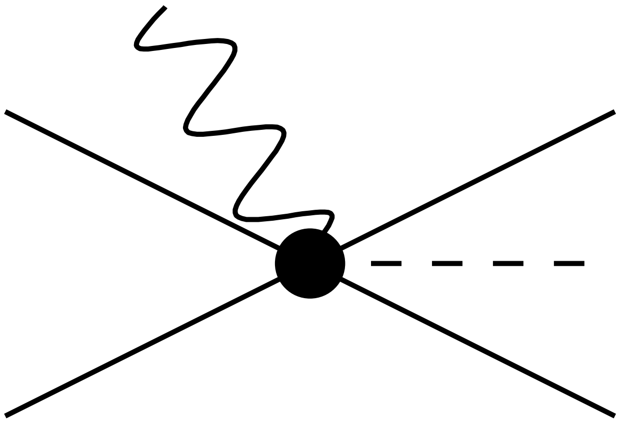

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Relates SD physics of

pp fusion, ${}^3\mathrm{H} \to {}^3\mathrm{He}\, e^- \bar{\nu}_e$ (not EFT): [Schiavilla *et al.*, PRC**58**, 1263 (1998)]

p-wave π prod+3NF: [Hanhart, van Kolck, Miller, PRL**85**, 2905 (2000)]

$\mu^- d \to nn\nu_\mu$: [Ando *et al.*, PLB**533**, 25 (2002)]

$\nu(\bar{\nu})d$ breakup: [Ando *et al.*, PLB**555**, 49 (2003)]

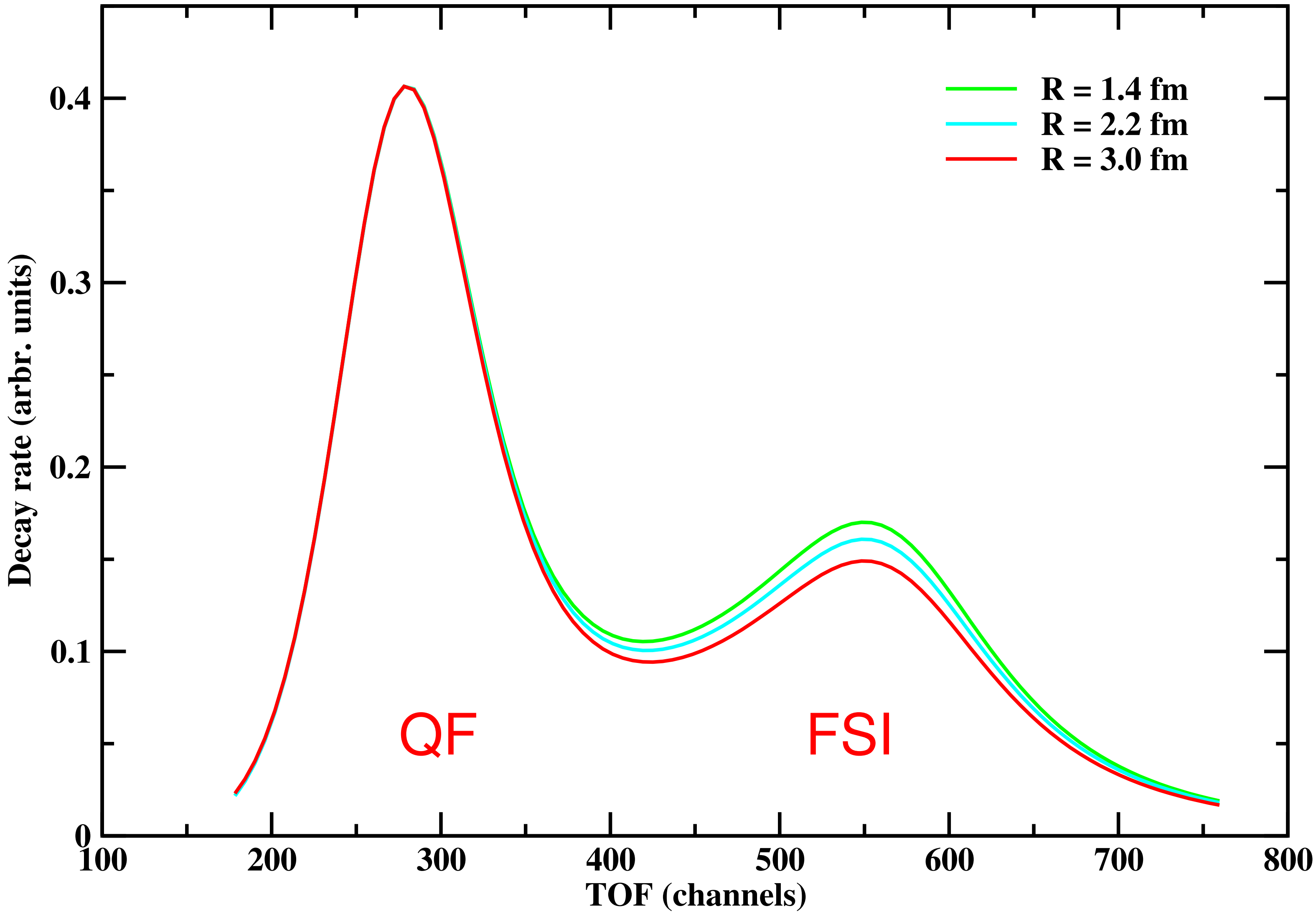
pp fusion, hep, ${}^3\mathrm{H} \to {}^3\mathrm{He}\, e^- \bar{\nu}_e$: [Park *et al.*, PRC**67**, 055206 (2003)]

pp fusion, $\pi^- d \to nn\gamma$, $\gamma d \to nn\pi^+$: [AG+DRP, PRL **96**, 232301 (2006); AG, PRC **74**, 017001 (2006)]

pp fusion, $\nu(\bar{\nu})d$, $\mu^- d \to nn\nu_\mu$: [Butler *et al.*, PLB**520**, 97 (2001);

EFT($\not\pi$): $\hat{d} \leftrightarrow L_{1,A}$ Chen *et al.*, PRC**72**, 061001(R) (2005)]

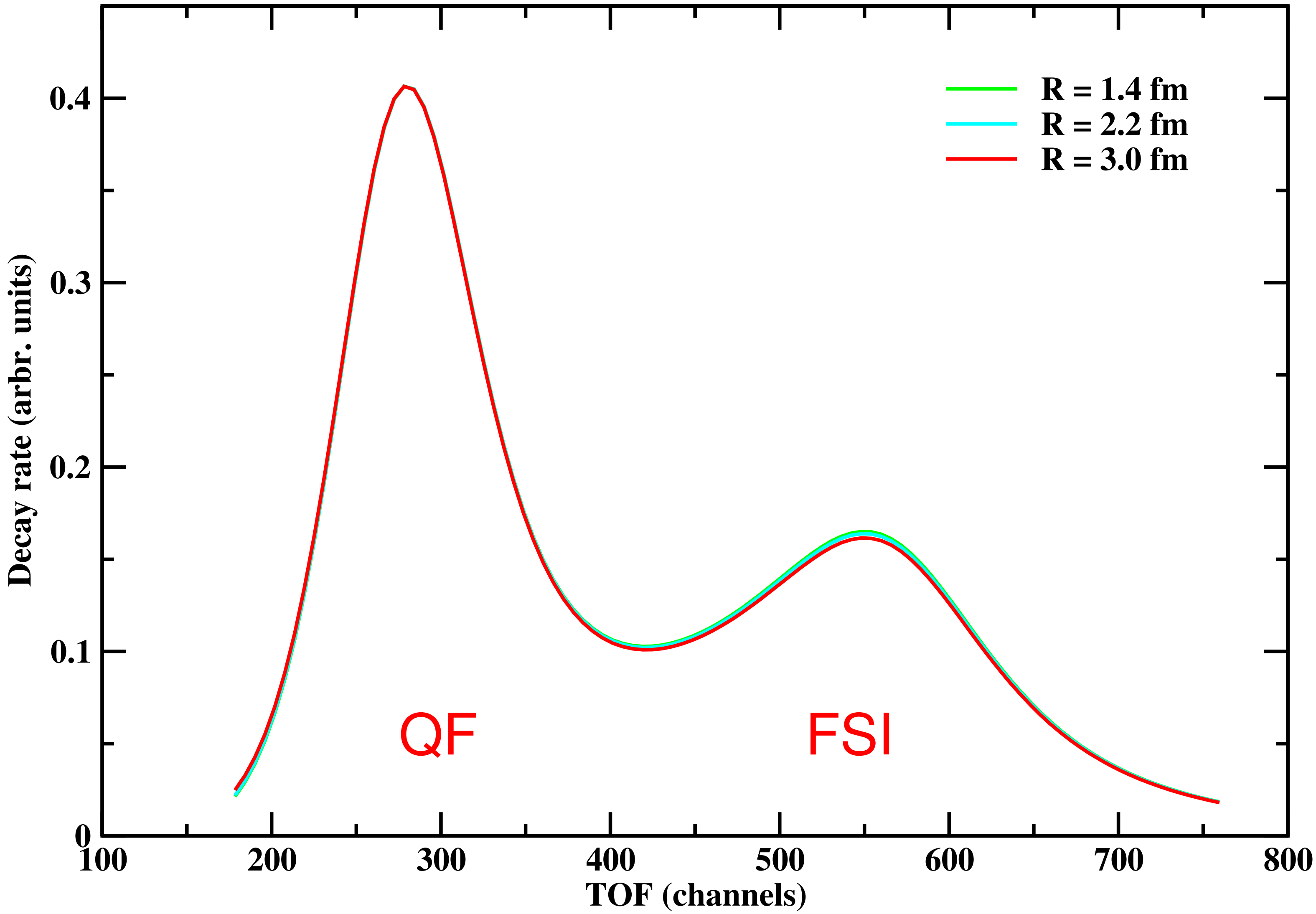
Error before renormalization



Δa_{nn}(theory) $= \pm 0.2$ fm (FSI only)

Δa_{nn}(theory) $= \pm 1$ fm (full spectrum)

Error after renormalization



Δa_{nn}(theory) $= \pm 0.05$ fm (FSI only)

Δa_{nn}(theory) $= \pm 0.3$ fm (full spectrum)

Summary and Conclusions

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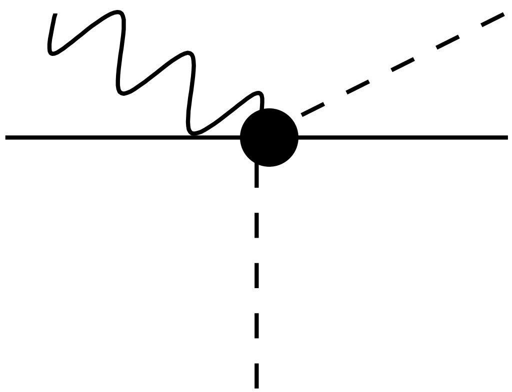
- Better input possible from $\gamma d \to nn\pi^+$ or $\mu^- d \to nn\nu_\mu$?
  $\mu^- d \to nn\nu_\mu$ (1%) at PSI? calculation under way

Feynman rule for $\gamma\pi\pi NN$

$\hat{d}$ can only be established if new FR derived:



$$\left(c_4 + \frac{1}{4M}\right)\frac{2ie}{f_\pi^2}\left[\left(\delta^{ab}\tau^3 - \delta^{a3}\tau^b\right)[S\cdot q_1, S\cdot\epsilon_\gamma] - \left(\delta^{ab}\tau^3 - \delta^{b3}\tau^a\right)[S\cdot q_2, S\cdot\epsilon_\gamma]\right]$$

Not published before (not in [Bernard, Kaiser, Meißner, IJMPE **4**, 193 (1995)])

[AG, PRC **74**, 017001 (2006)]

Boost corrections

Corrections to CGLN

$$\Delta F_1^{(0)}(E_\pi) = \frac{eg_A}{2f_\pi}\frac{-(E_\pi \mathbf{p}_n \cdot \widehat{\mathbf{k}} + E_\pi^2)}{2M^2}(\mu_p + \mu_n)$$

$$\Delta F_1^{(-)}(E_\pi) = \frac{eg_A}{2f_\pi}\frac{E_\pi \mathbf{p}_n \cdot \widehat{\mathbf{k}} + E_\pi^2}{M^2}$$

New spin-momentum structures

$$G^{(0)}(E_\pi) = \frac{eg_A}{2f_\pi}\frac{iE_\pi \mathbf{p}_n \cdot \boldsymbol{\epsilon}_\gamma \boldsymbol{\sigma} \cdot \widehat{\mathbf{k}}}{2M^2}(\mu_p + \mu_n - 1)$$

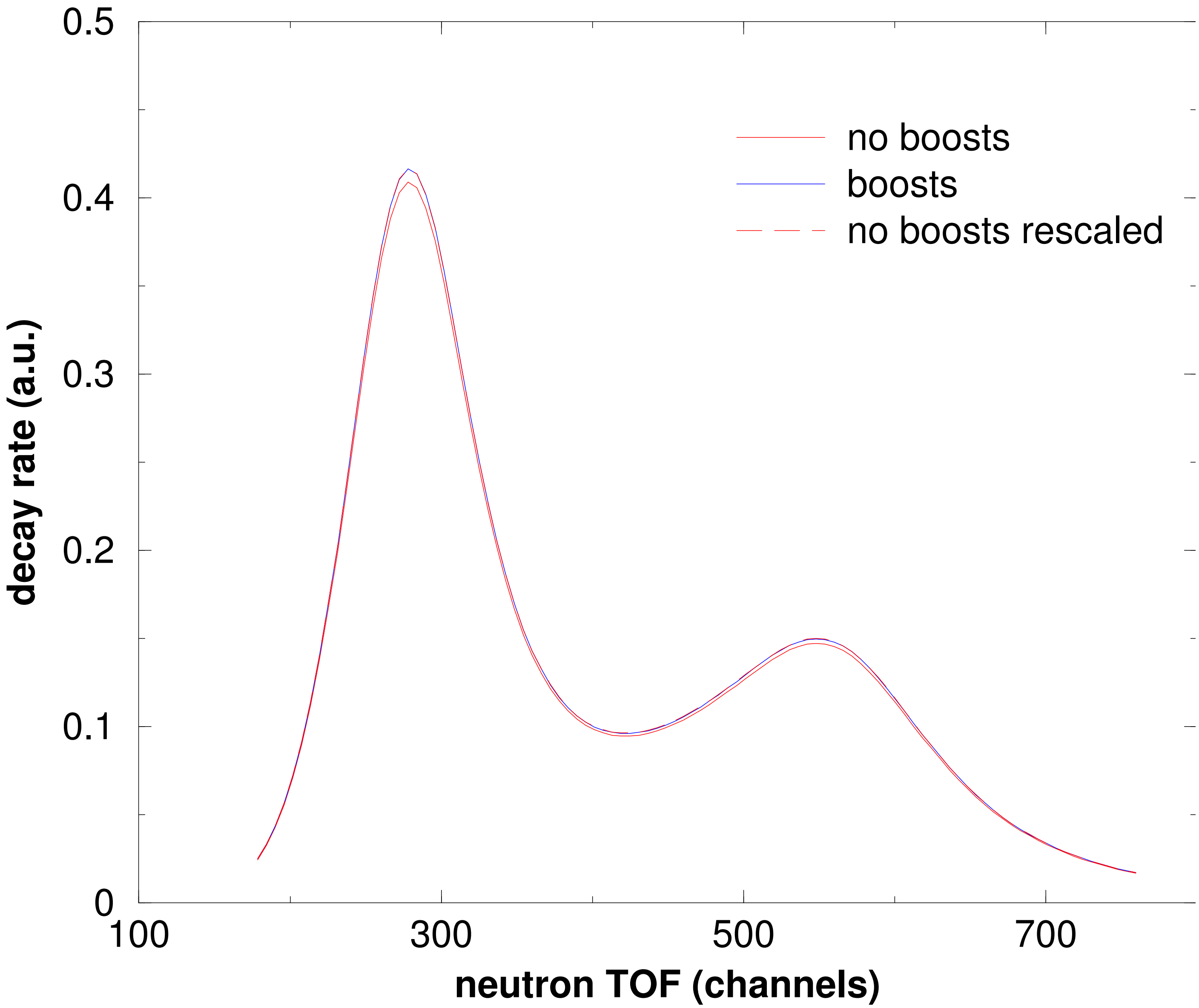
$$G^{(-)}(E_\pi) = \frac{eg_A}{2f_\pi}\left(\frac{E_\pi \mathbf{p}_n \cdot (\widehat{\mathbf{k}} \times \boldsymbol{\epsilon}_\gamma)}{2M^2}(\mu_p - \mu_n + \frac{1}{2}) - \frac{i\mathbf{p}_n \cdot \boldsymbol{\epsilon}_\gamma \boldsymbol{\sigma} \cdot (2\mathbf{p}_n + E_\pi \widehat{\mathbf{k}})}{M^2}\right)$$

$\mu_p - \mu_n + \frac{1}{2} = 5.2$, but $\mathbf{p}_n \cdot (\widehat{\mathbf{k}} \times \boldsymbol{\epsilon}_\gamma) \approx E_\pi^2 \sin\theta_3$ with $\theta_3 = 0.075$ rad

similarly $\mathbf{p}_n \cdot \boldsymbol{\epsilon}_\gamma \approx E_\pi \sin\theta_3$

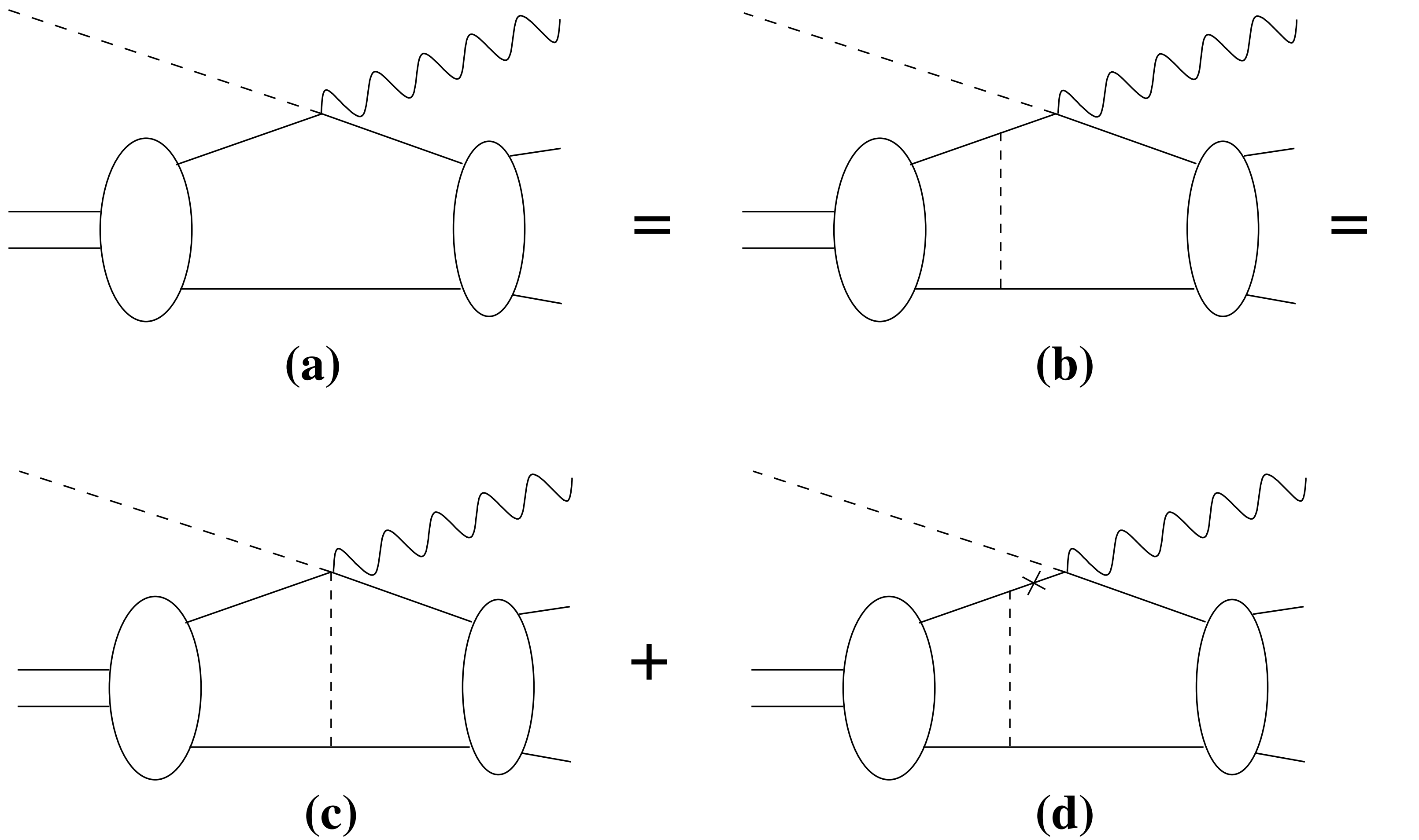
Thus only CGLN corr's important, $O(\mu^2/2M^2) \sim 1\%$

To boost or not to boost?



Both peaks scale the same way $\Rightarrow 0.10\%$ for a_{nn}

‘Off-shellness’

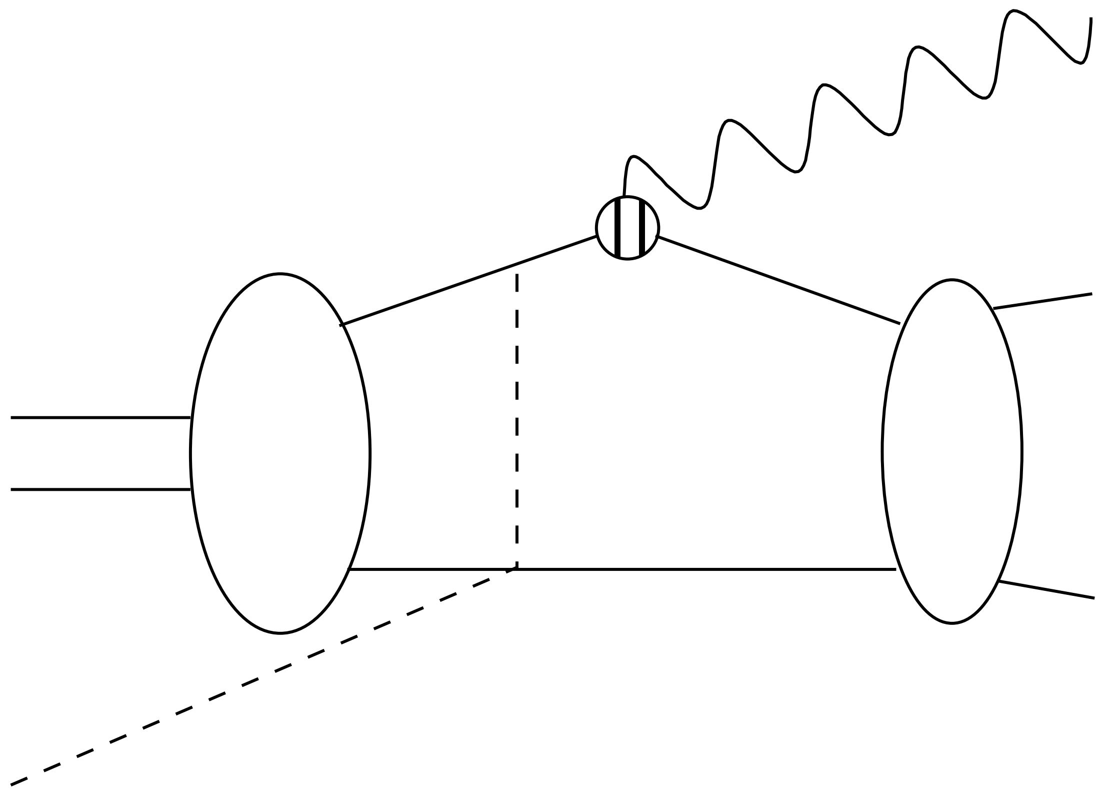


Off-shell nucleon transformed into 2B and on-shell 1B

New 2B $O(Q^5) \Leftrightarrow p^2/M^2 \sim \mu^2/M^2 \sim 2\%$ of $O(Q^3)$ 2B

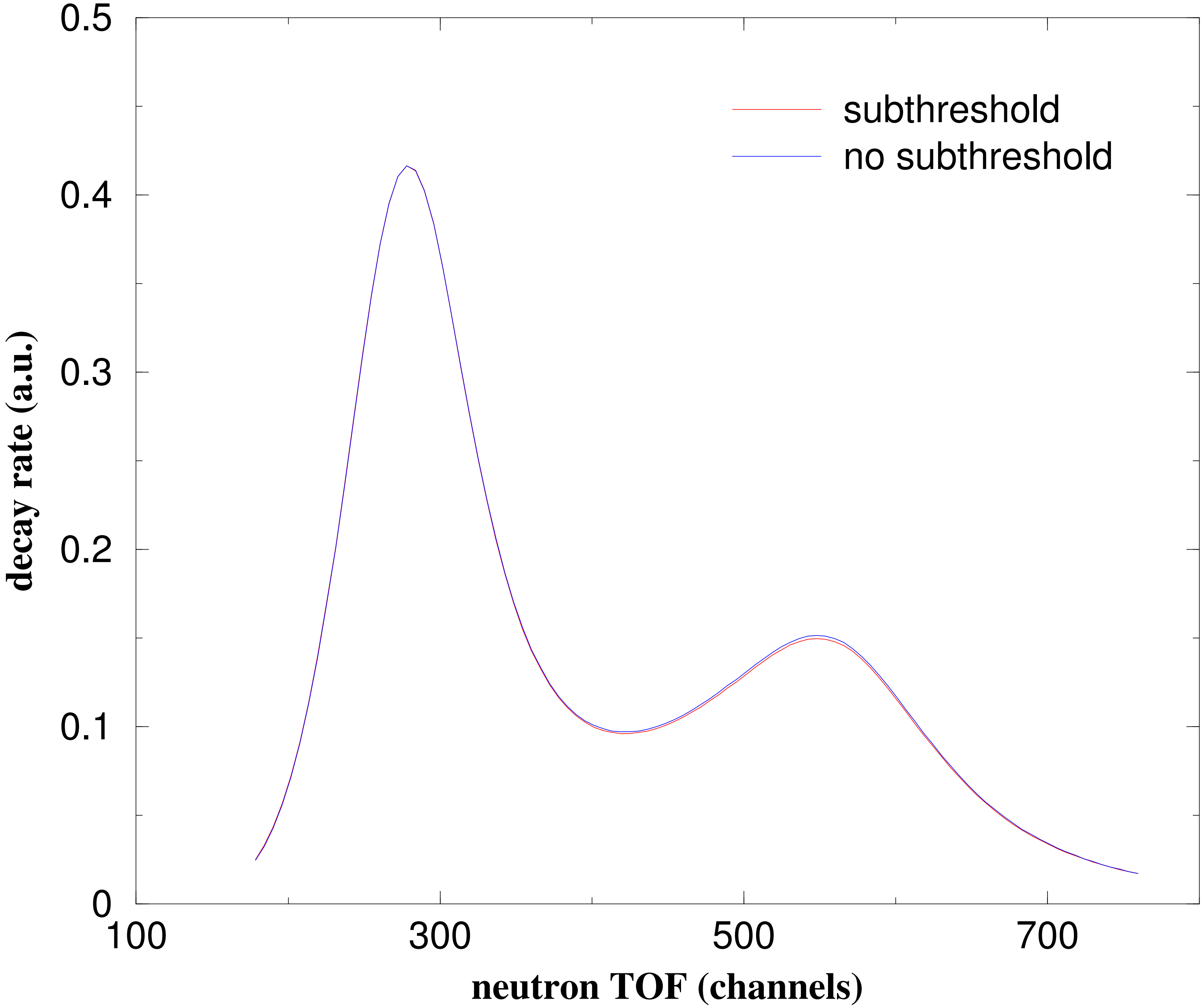
$\Rightarrow \Delta a_{nn} = 0.02$ fm

$O(Q^4)$ two-body operators



$O(Q^4)$ 2B operator $\sim p/\Lambda_\chi \sim 20\%$ of $O(Q^3)$ 2B $\Rightarrow \sim 0.7\%$ in a_{nn}

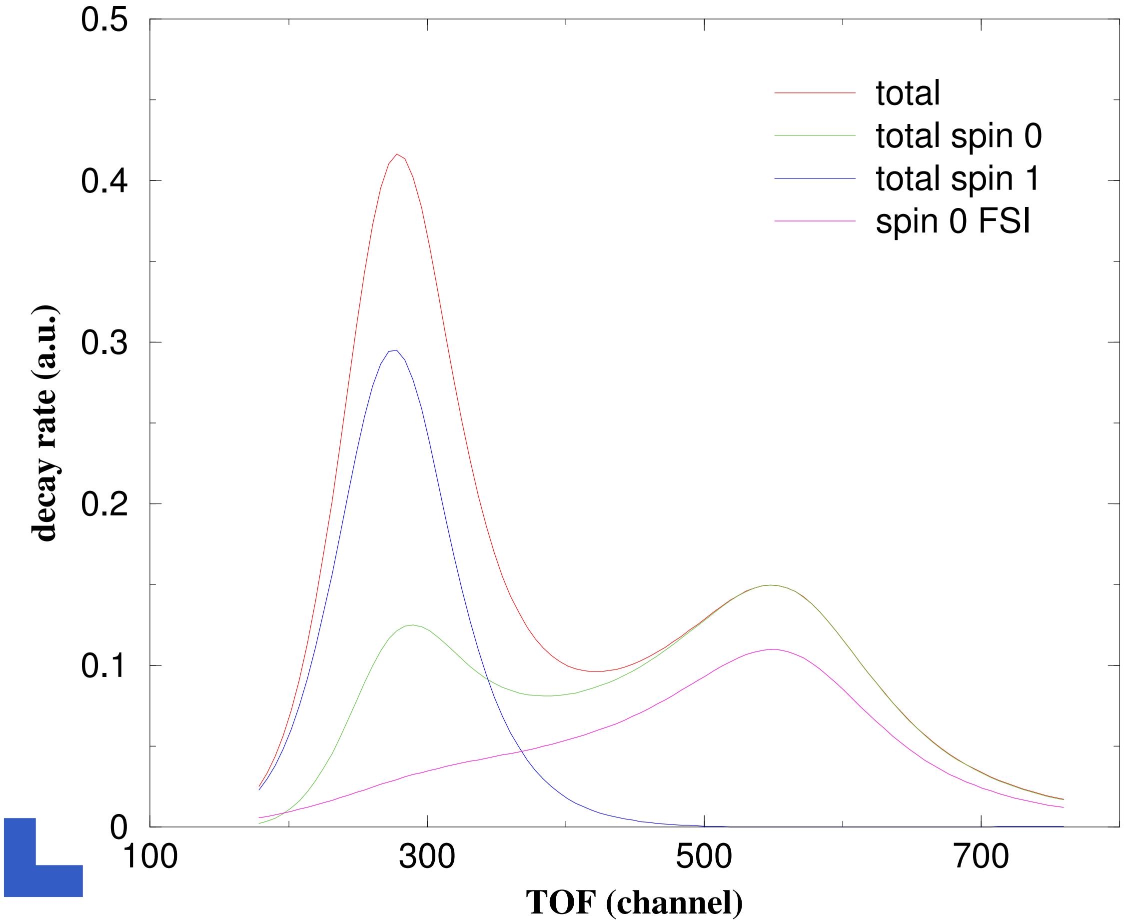
Subthreshold extrapolation



Higher partial waves in FSI

Typical phase shifts in QF region, p-waves small at FSI peak (low rel mom):

$$\delta_0 = 60^\circ,\ \delta_1 = 5^\circ \ \Rightarrow \ \frac{A_{\rm FSI,p}}{A_{\rm FSI,s}} \sim \frac{\sin\delta_1}{\sin\delta_0} = 0.1$$

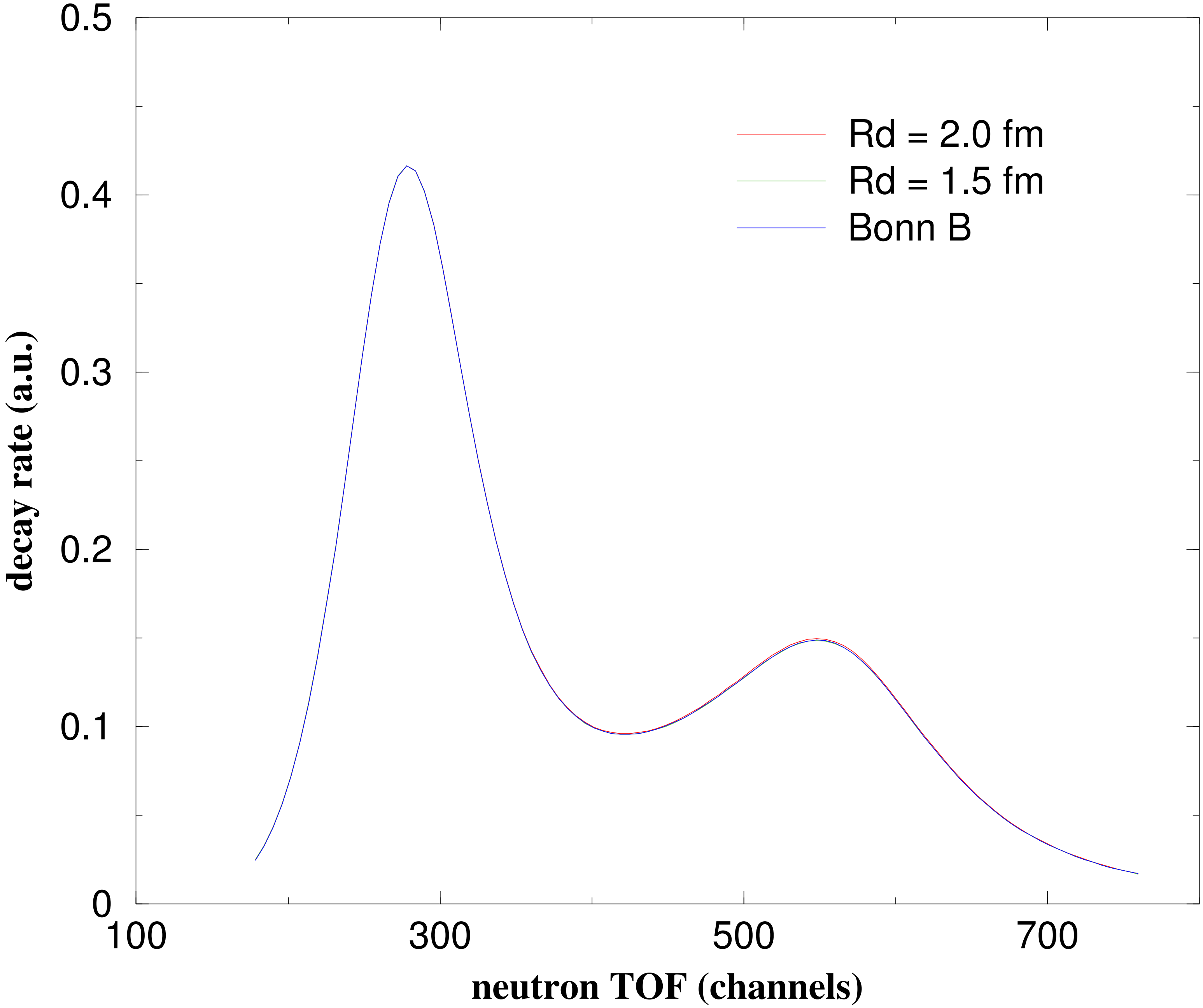


spin-0 and spin-1 orthogonal $\Rightarrow$

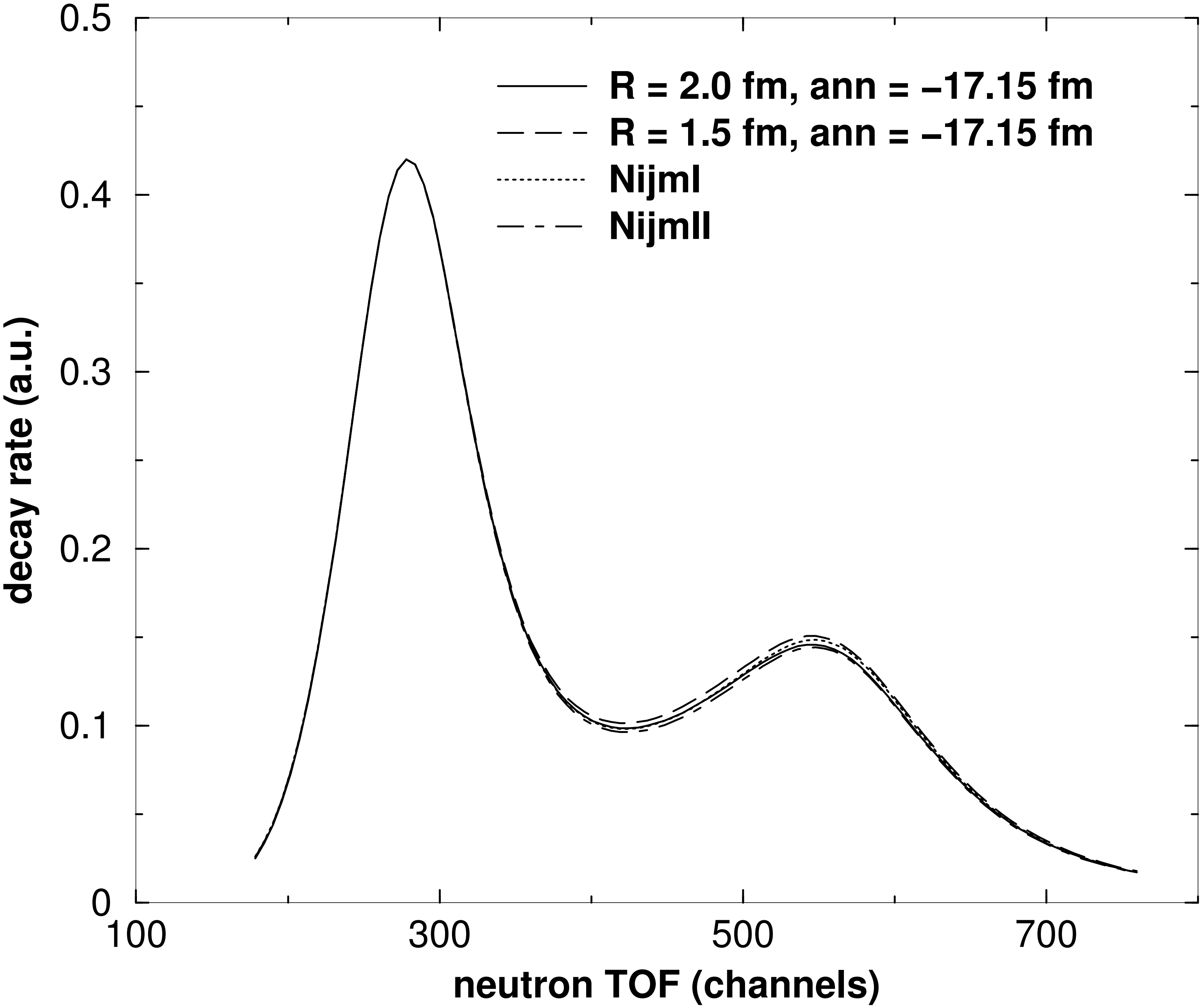
FSI,p fraction of spin-1 QF: 2.9% in Γ $\Rightarrow$

2.4% in a_{nn} $\leftrightarrow$ 0.43 fm

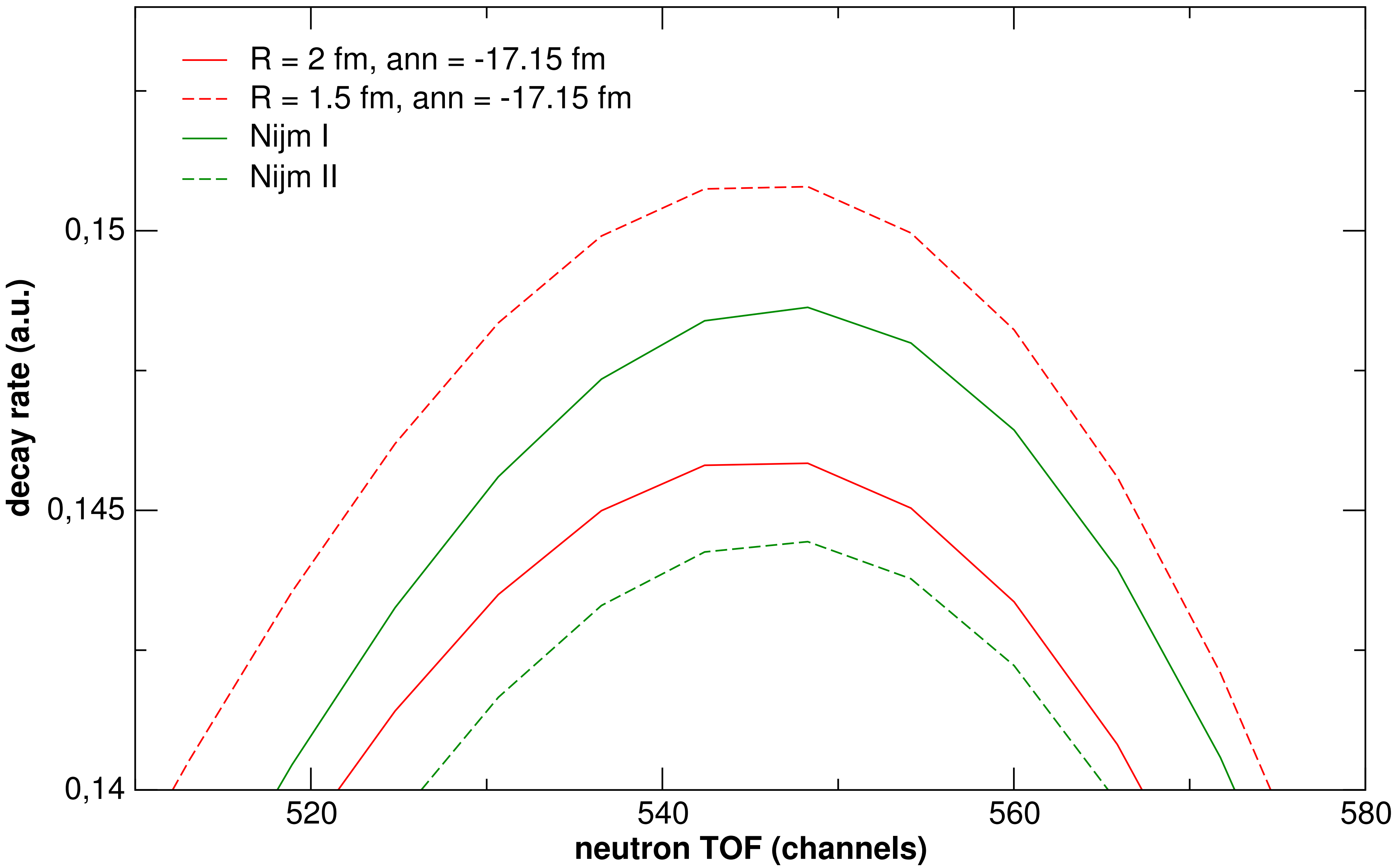
Error from *d* wfs



Error from nn wfs



FSI only



R = 2 fm, ann = -17.15 fm
R = 1.5 fm, ann = -17.15 fm
Nijm I
Nijm II
decay rate (a.u.)
0,15
0,145
0,14
520
540
560
580
neutron TOF (channels)

Error budget for extr. of a_{nn}

Source	Relative error (%)	Absolute error (fm)
Off-shell	0.07	0.02
Boost	<0.11	<0.02
Subthreshold	0.95	0.17
$O(Q^4)$ 2B	0.7	0.12
Dep. on R_d	0.5	0.09
r_0	0.55	0.10
p-wave in FSI	<2.4	<0.43
Dep. on R_{nn}	<3.3	<0.60
total	<4.3	<0.78

$1.5 < R_{nn} < 2.0$ fm

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Fitting FSI only: ± 0.2 fm!