Electroweak processes in nuclei

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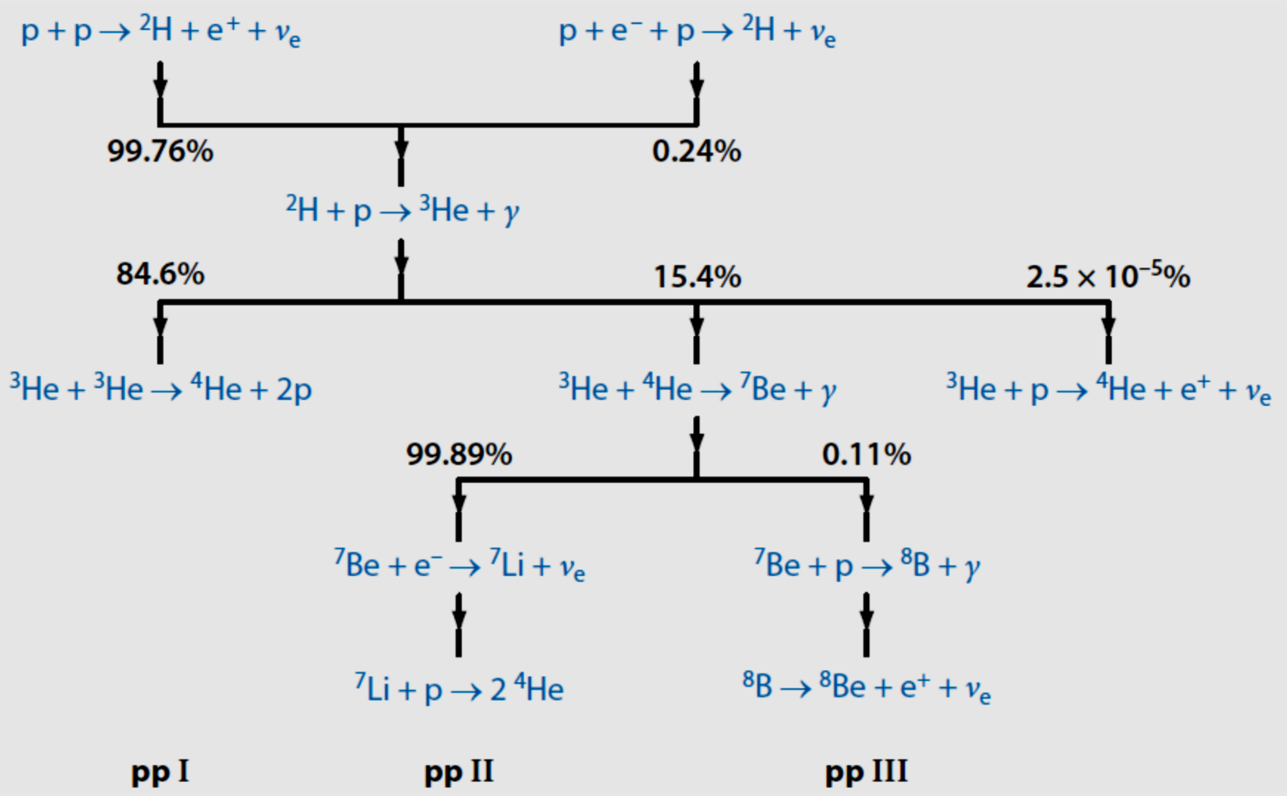
"From nucleons to nuclei: enabling discovery for neutrinos, dark matter and more", INT workshop, Seattle, WA, June 2018

Outline

- Low-energy nuclear physics for solar neutrino generation: radiative capture reactions
- GeV-neutrino—nucleus reactions for base-line neutrino experiment: neutral-current induced photon production
- Hadronic physics for base-line neutrino experiment: weak-Compton scattering and nucleon form factors
- Dark-photon explanation in Be-8 anomaly
- Summary

Solar neutrinos: radiative capture reactions

Motivations



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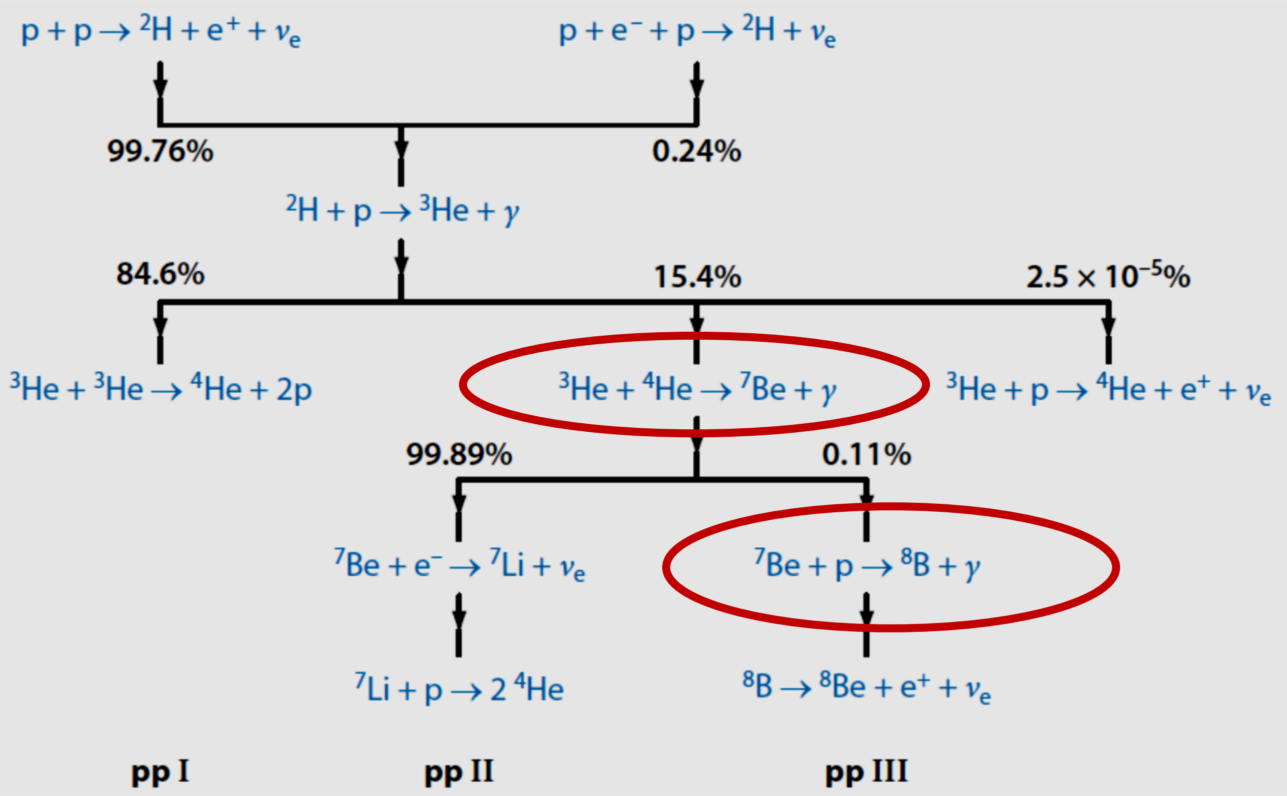

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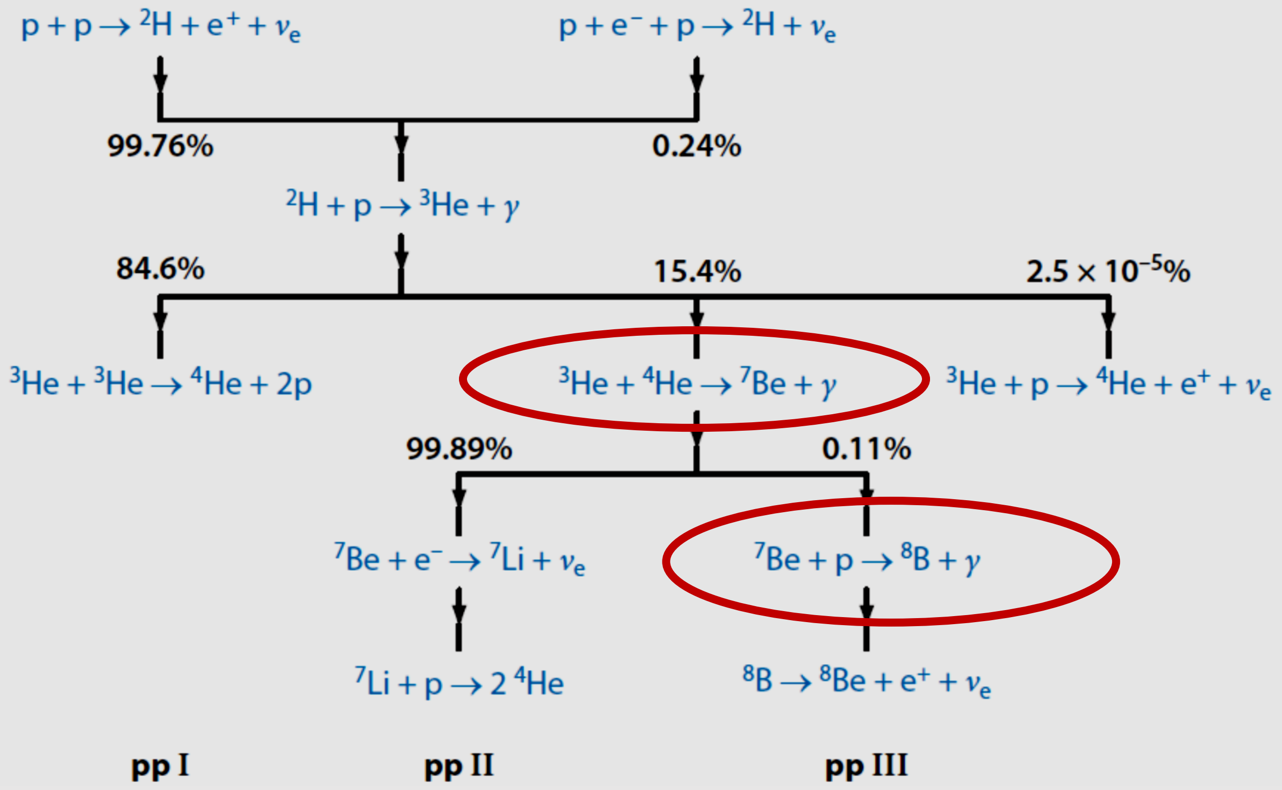

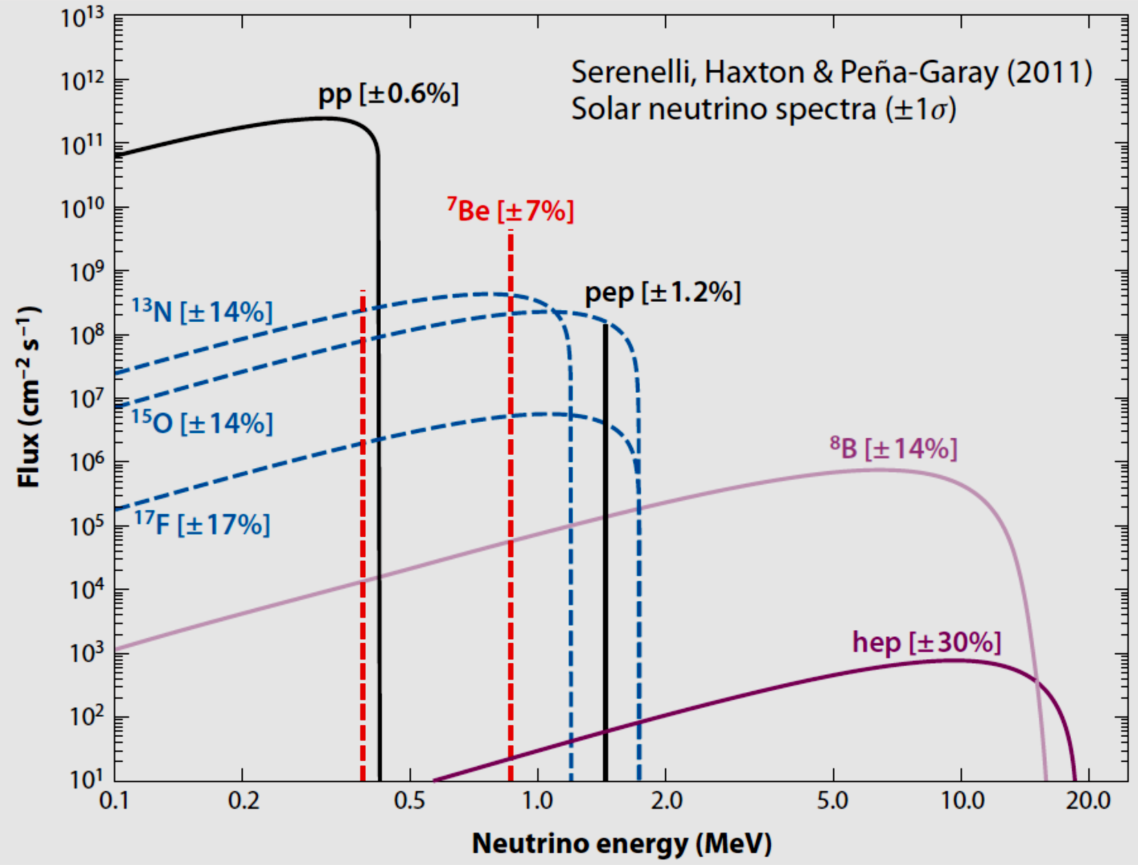

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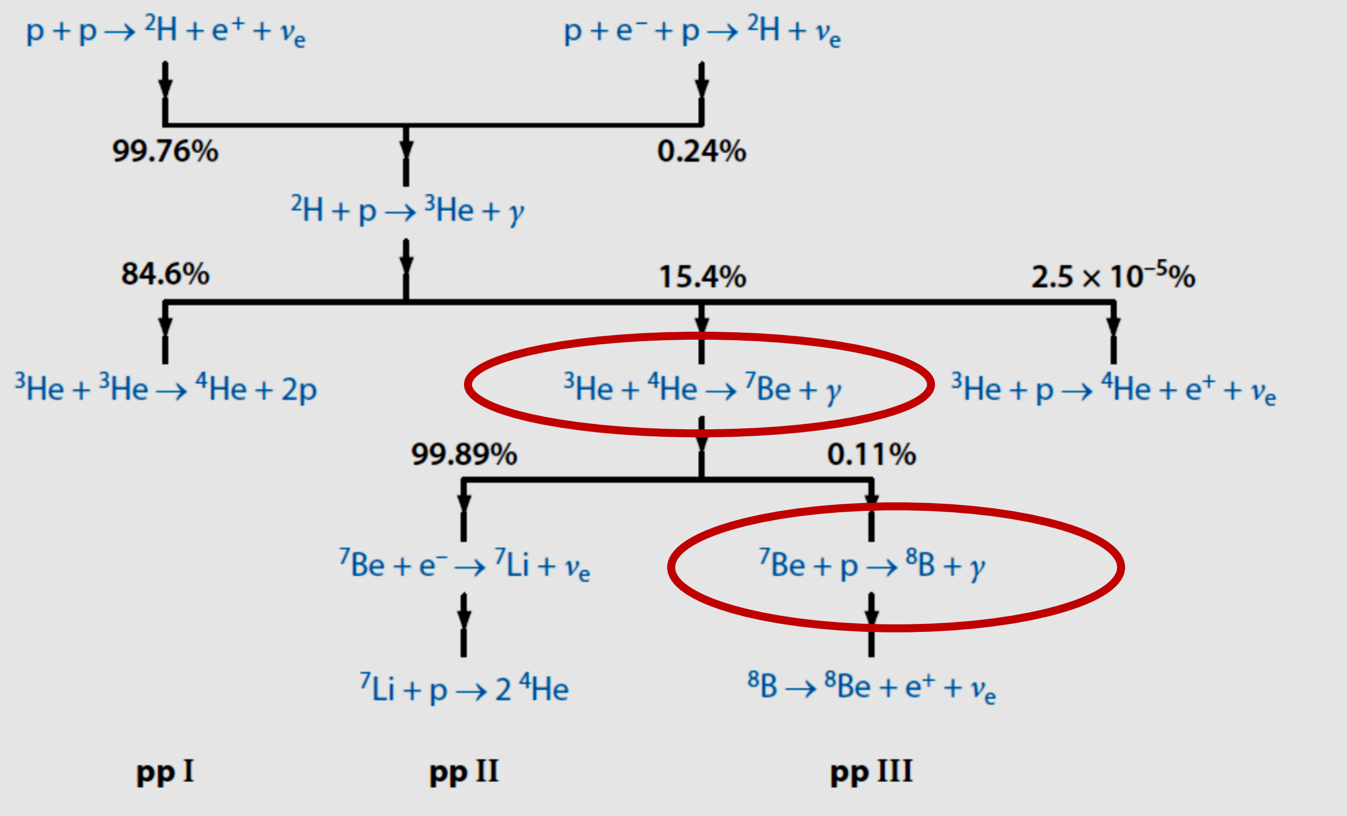
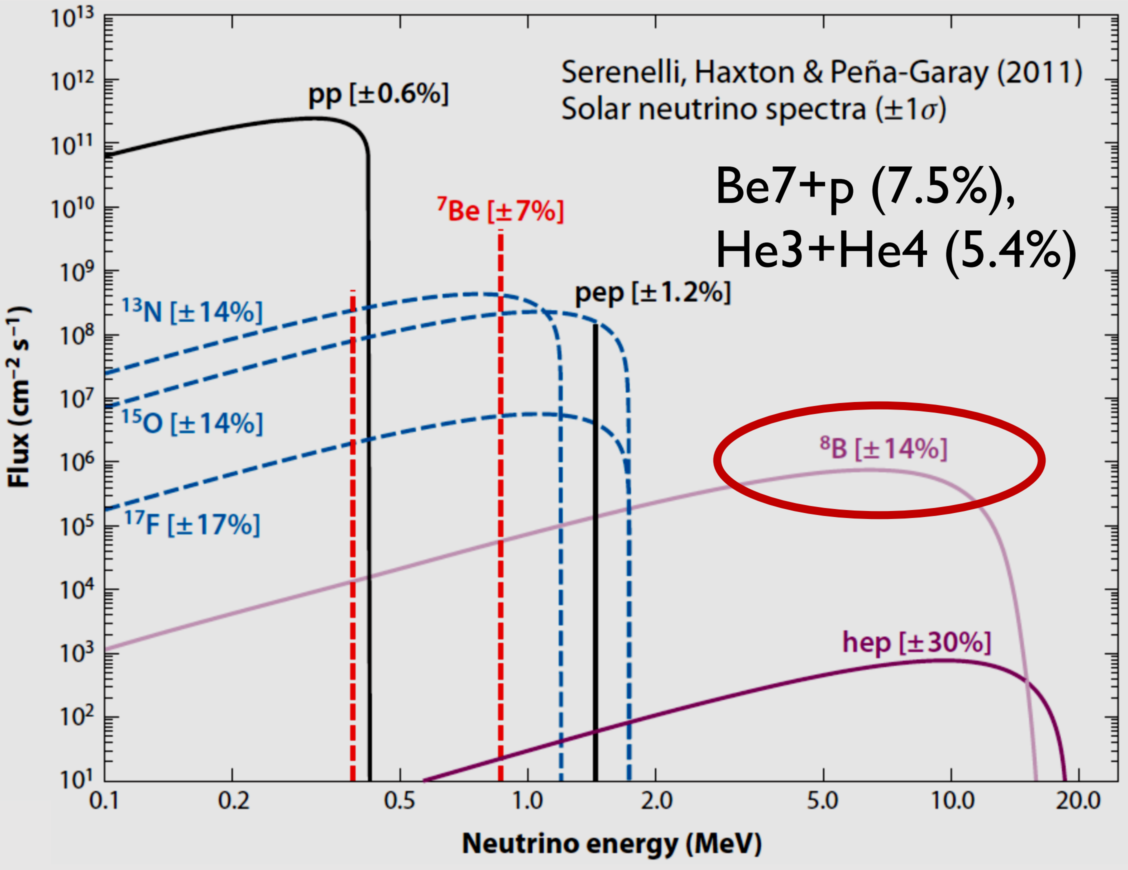
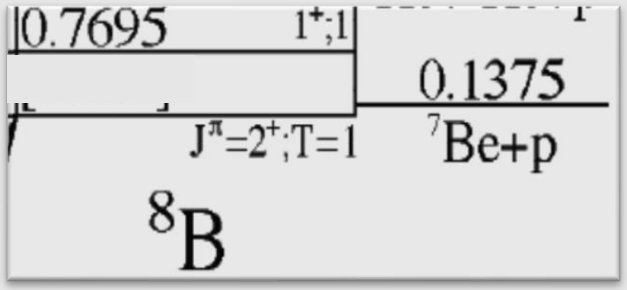


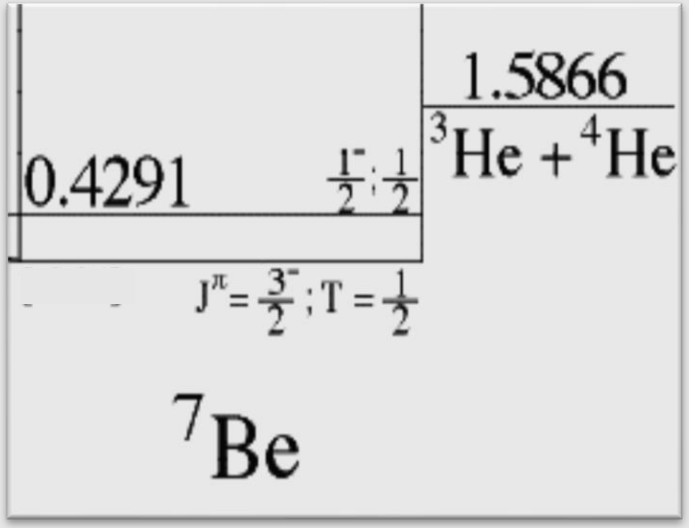


Be7+p (7.5%), He3+He4 (5.4%)

Not experimentally accessible (20 keV CM energy)

${}^{7}_{4}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$: basics





- B8: a p-wave **shallow** bound state
- Proton-Be s-wave has large scattering lengths
- Strong Coulomb effect

$$\frac{Q_{low}}{\Lambda} \approx 0.2$$

$$\eta = \frac{Z_c Z_N \alpha_{EM} M_R}{Q_{low}} \approx 1$$

${}^{7}_{4}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$: picture

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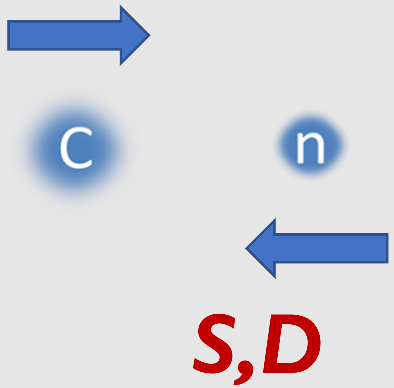
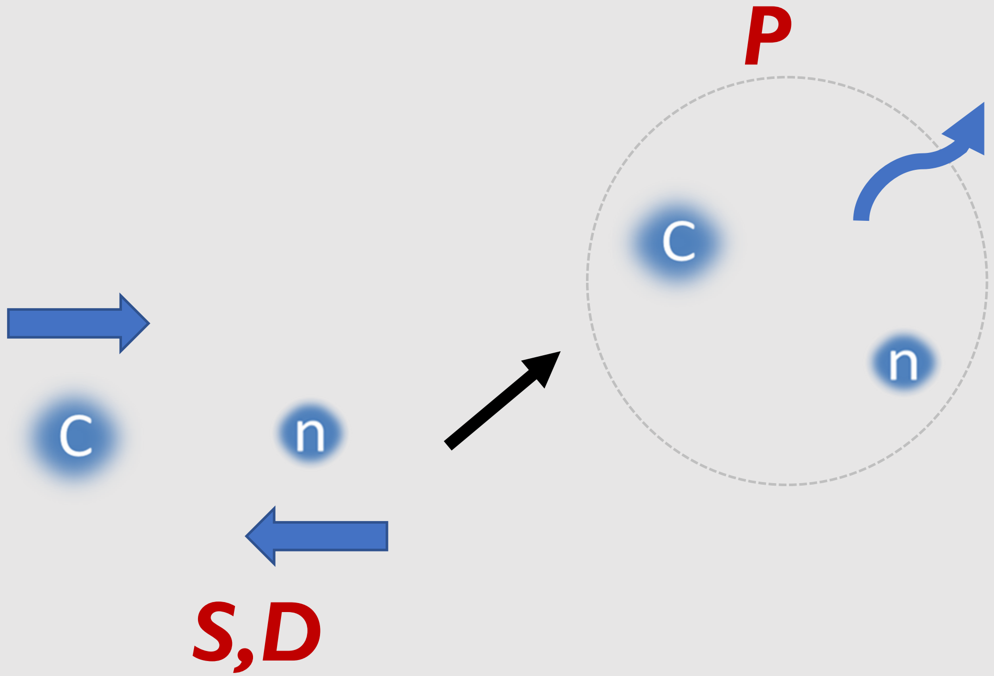


${}_{4}^{7}\mathrm{Be} + \mathrm{p} \rightarrow {}_{5}^{8}\mathrm{B} + \gamma$: picture



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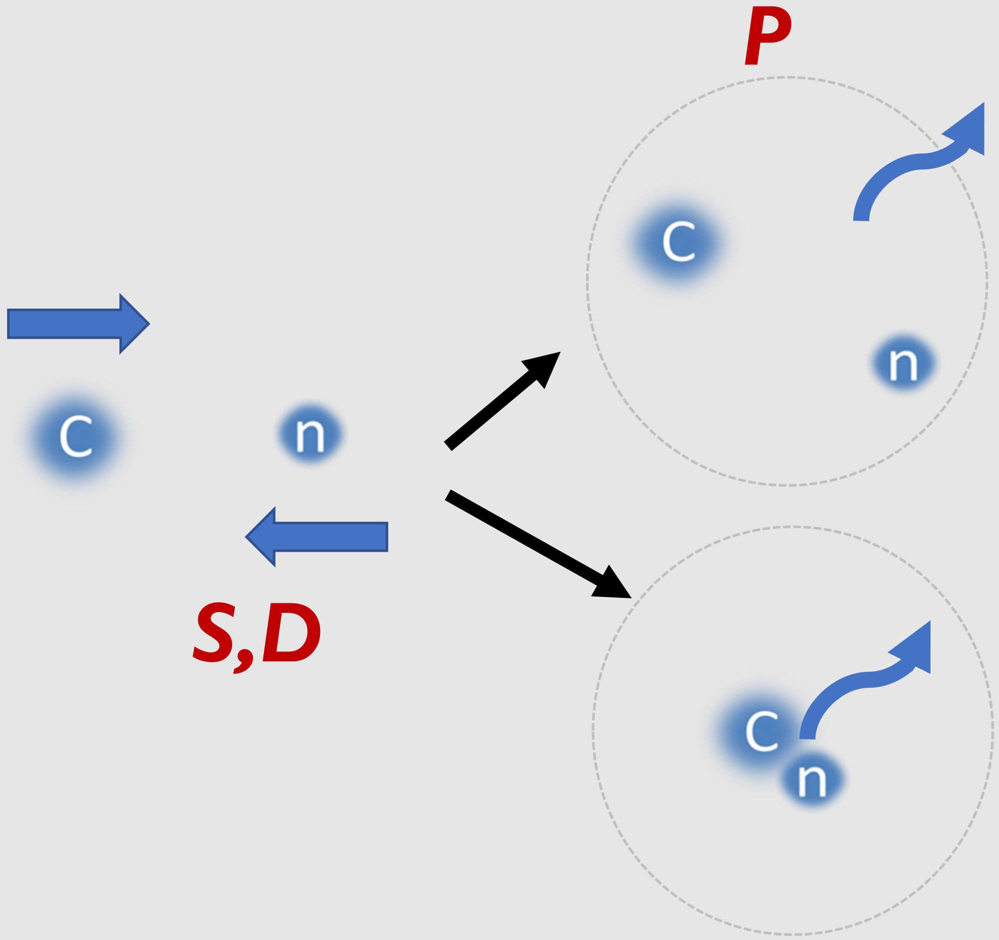
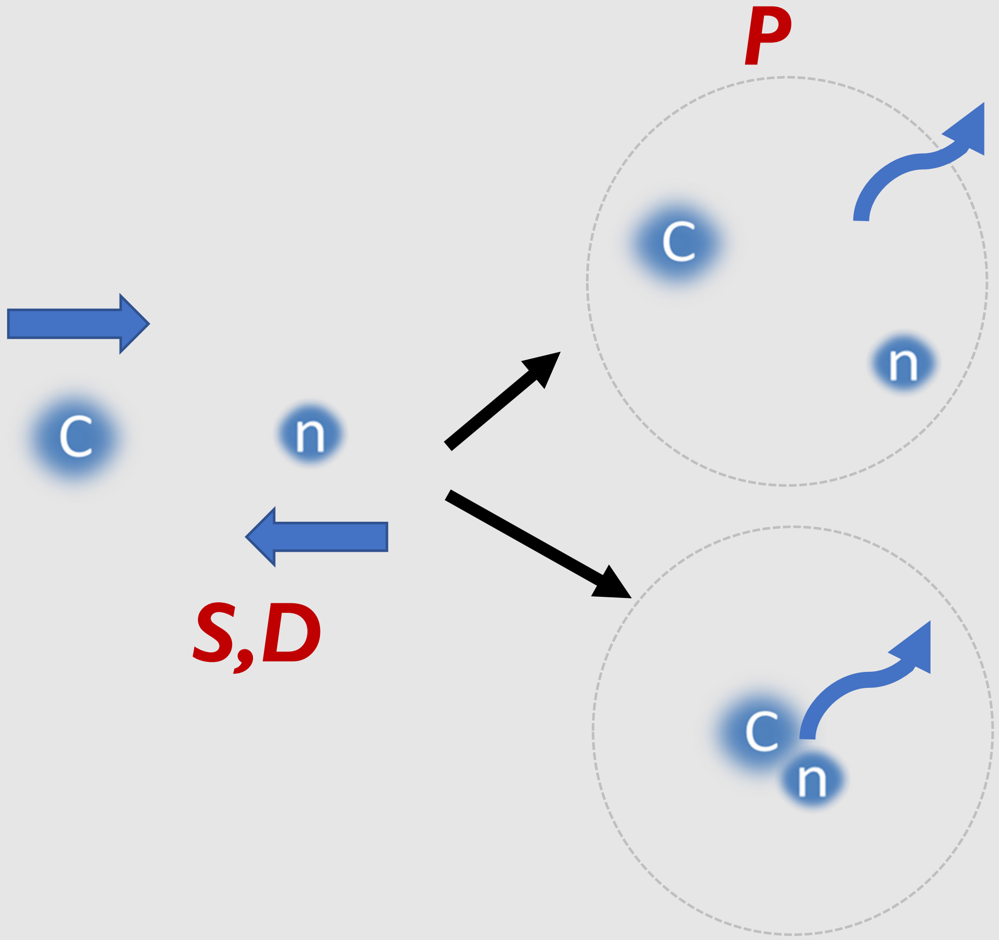


${}^{7}_{4}\mathrm{Be} + \mathrm{p} \to {}^{8}_{5}\mathrm{B} + \gamma$: picture

$$AMP \sim \int_{>\Lambda^{-1}}^{+\infty} dr\ \psi_f(r) r \psi_i(r) + \int_0^{\Lambda^{-1}} dr\, \psi_f(r) r \psi_i(r)$$



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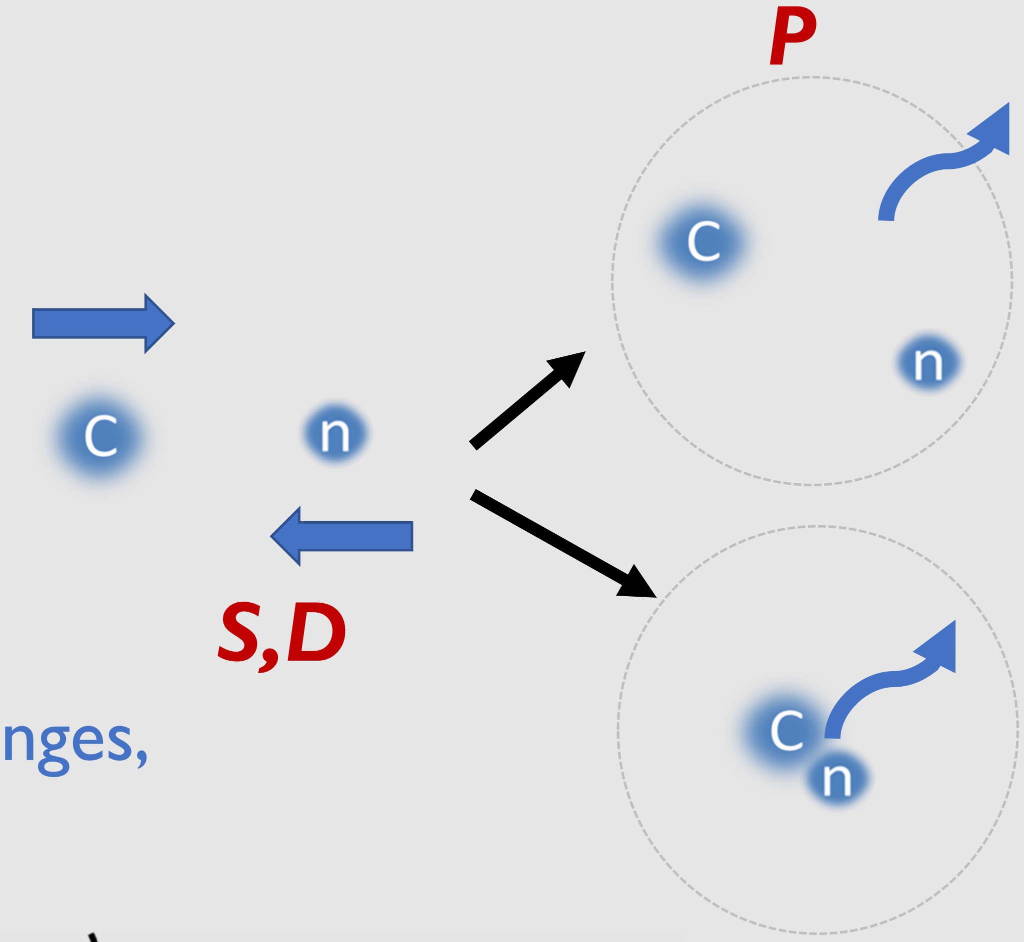
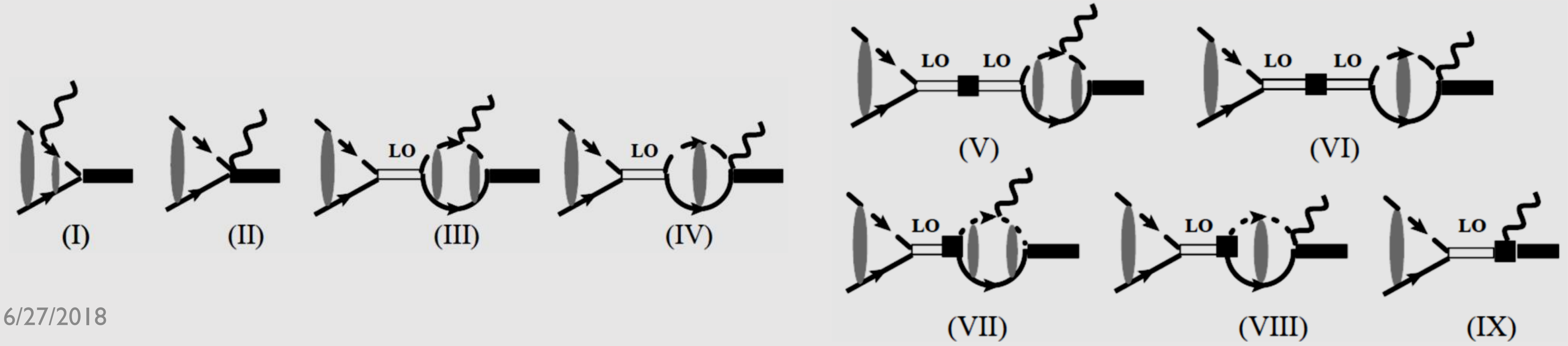


9 parameters: scattering lengths, effective ranges, ANCs, and short-distance contact terms



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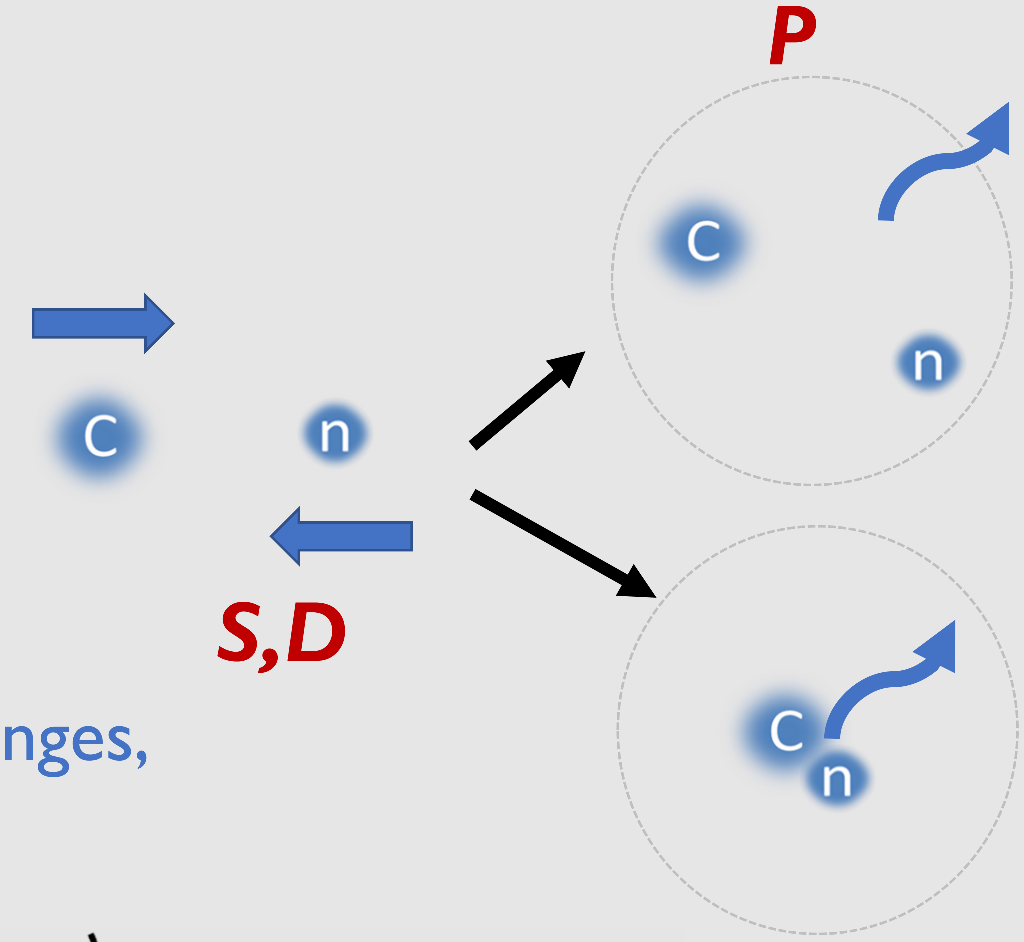
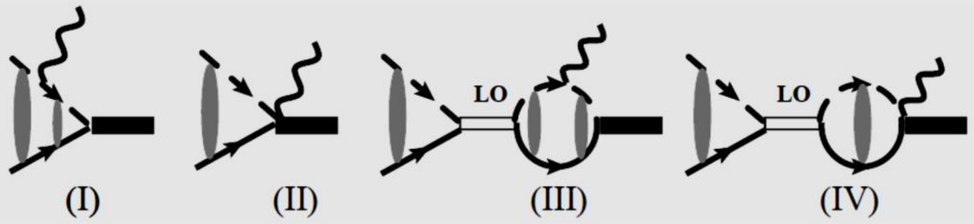
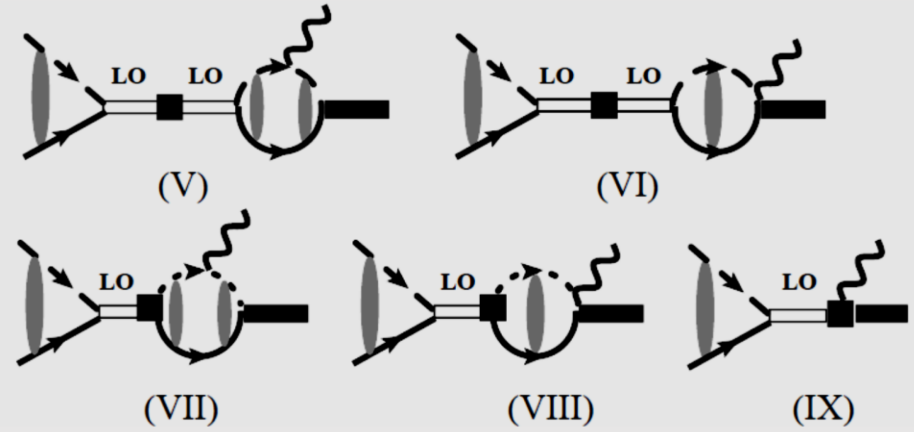


9 parameters: scattering lengths, effective ranges, ANCs, and short-distance contact terms

Initial state interaction is similar to the final state interaction in neutrino—nucleus reaction





${}^{7}_{4}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$: picture

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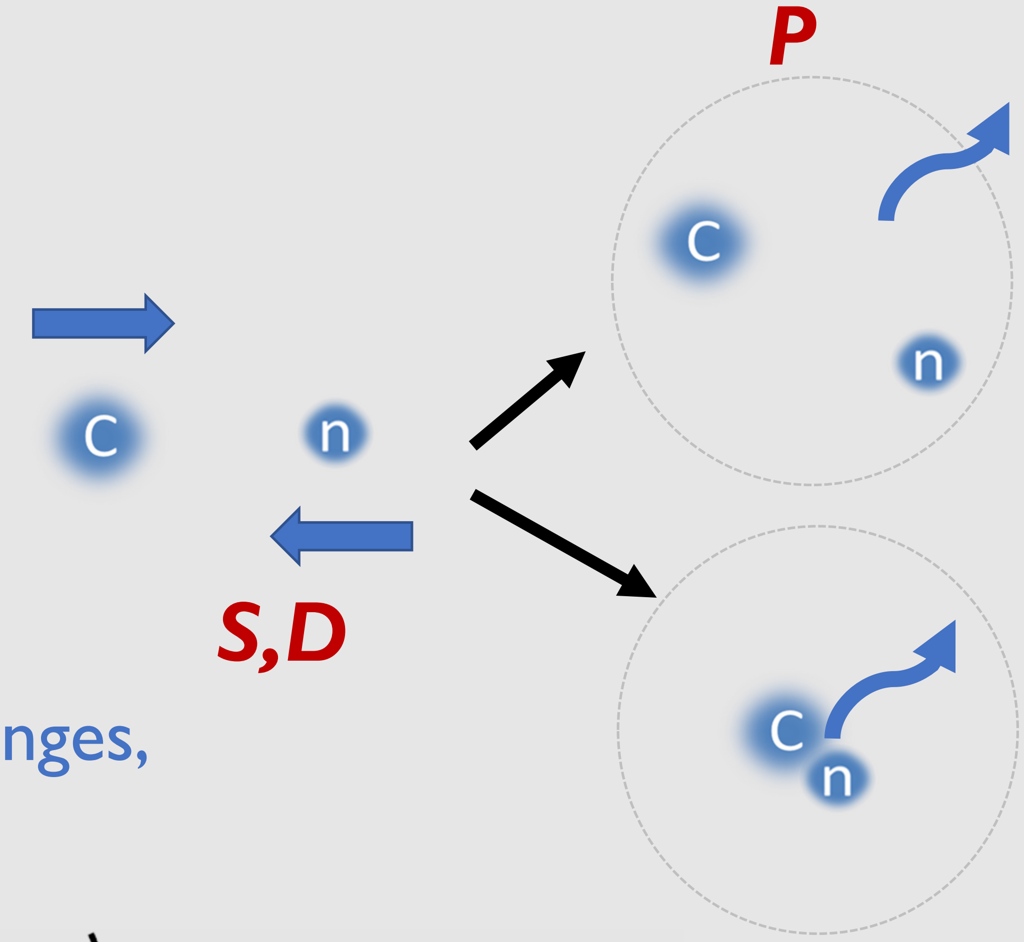

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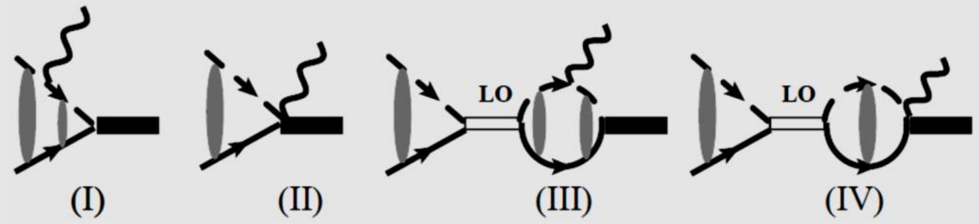
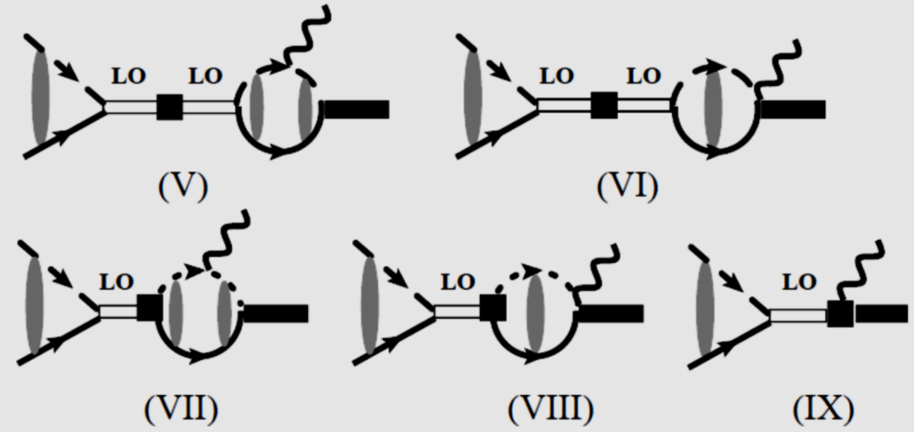
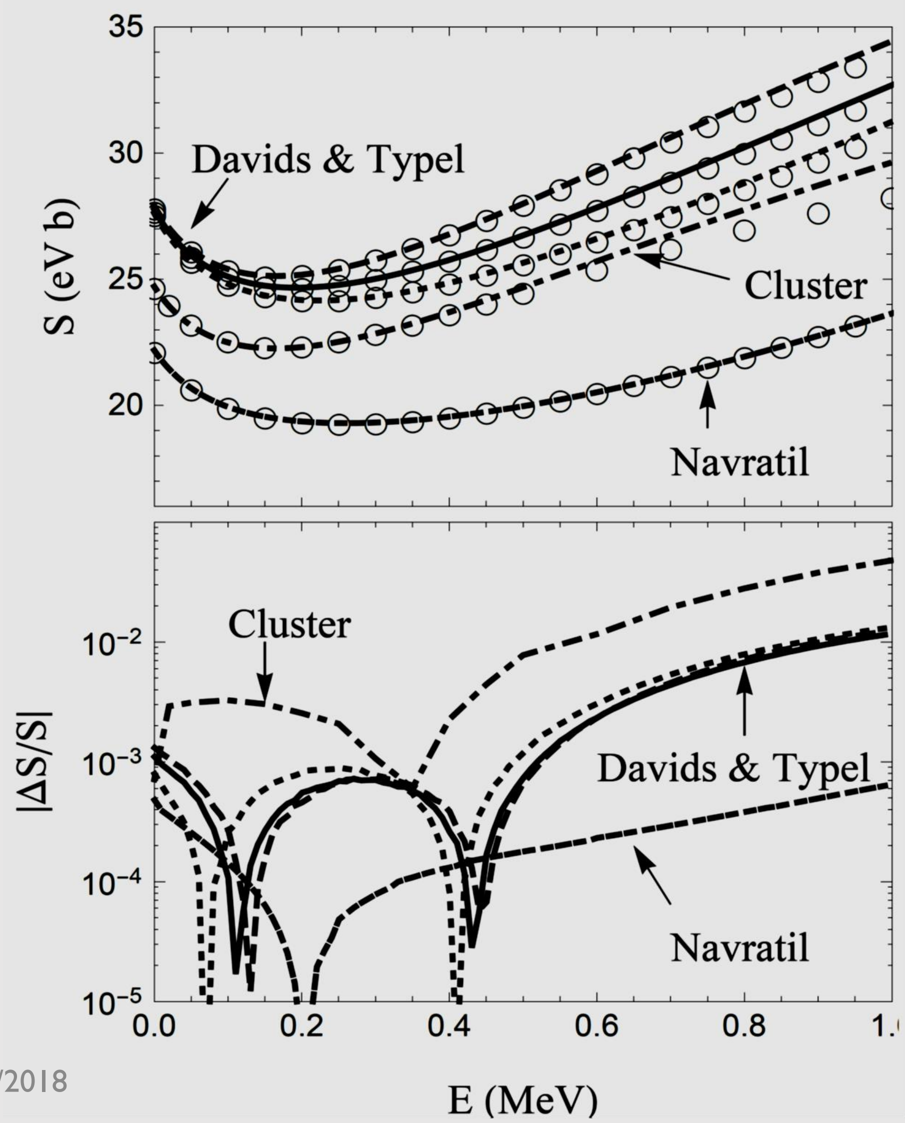




${}^{7}_{4}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$: comparisons



- The EFT at NLO reproduces other models by 1% below 1 MeV
- **Other models can be “projected” into EFT parameter space.**

X.Z., K. Nollett, and D. Phillips, 2018

${}^{7}_{4}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$: uncertainty analysis

Bayesian inference:

$$\mathrm{pr}\left(\boldsymbol{g}, \{\xi_i\} | D; T; I\right) = \mathrm{pr}\left(D | \boldsymbol{g}, \{\xi_i\}; T; I\right) \mathrm{pr}\left(\boldsymbol{g}, \{\xi_i\} | I\right)$$

6/27/2018

X.Z., K. Nollett, and D. Phillips, PLB (2015)

${}^{7}_{4}\mathrm{Be} + \mathrm{p} \to {}^{8}_{5}\mathrm{B} + \gamma$: uncertainty analysis

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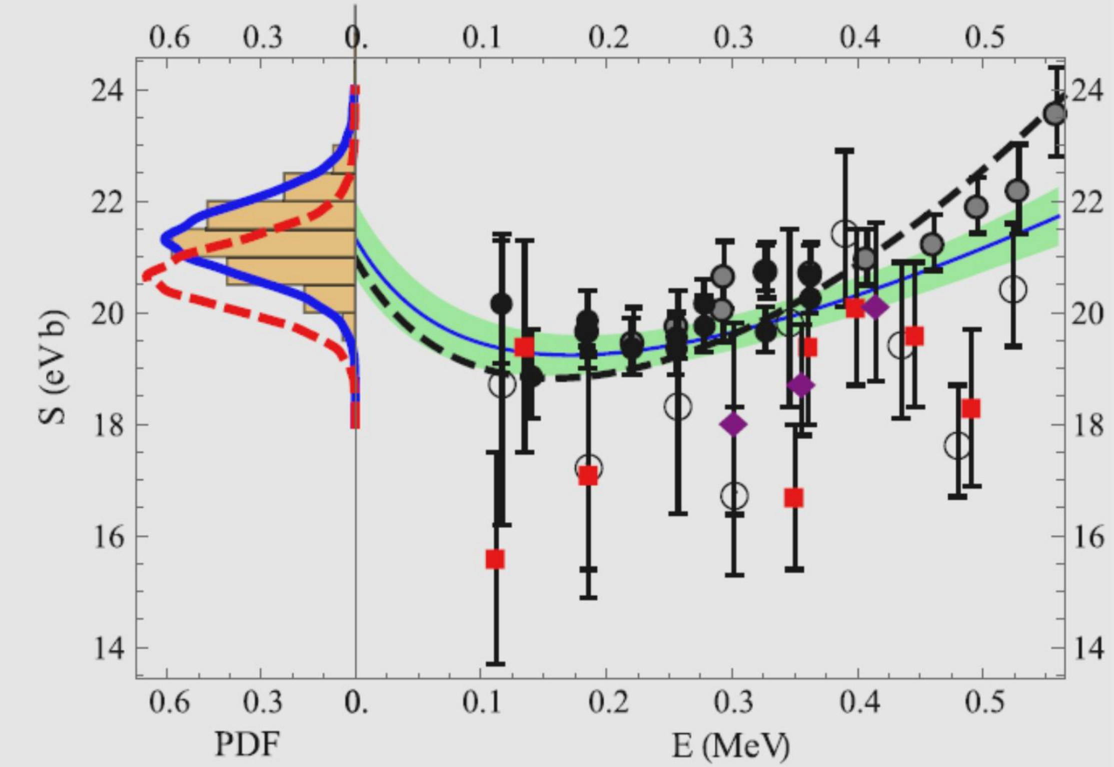

X.Z., K. Nollett, and D. Phillips, PLB (2015)

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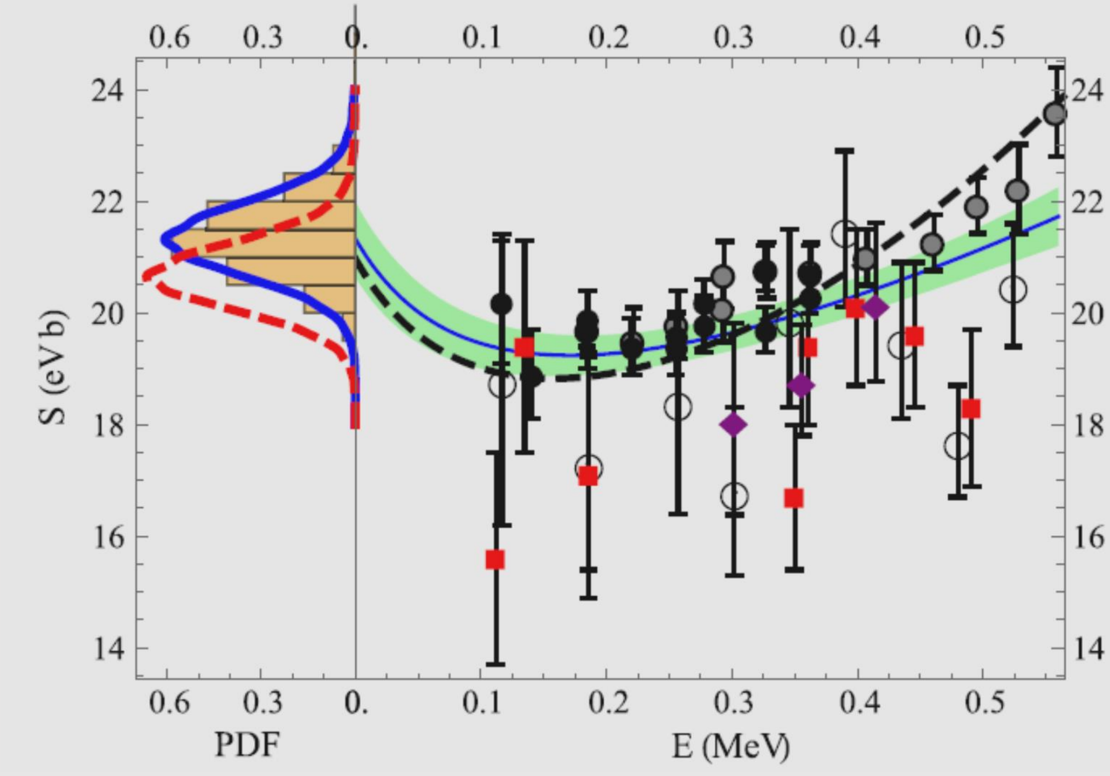
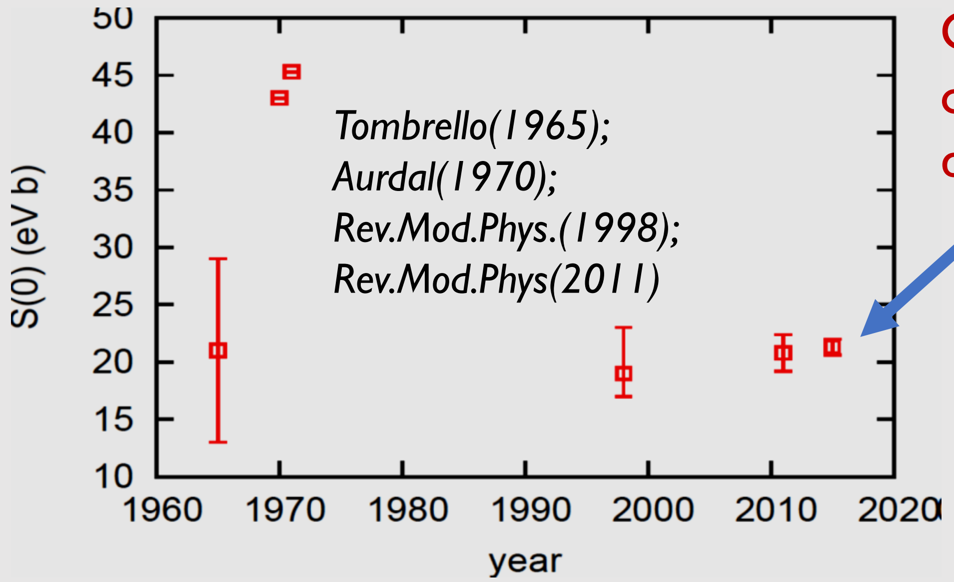




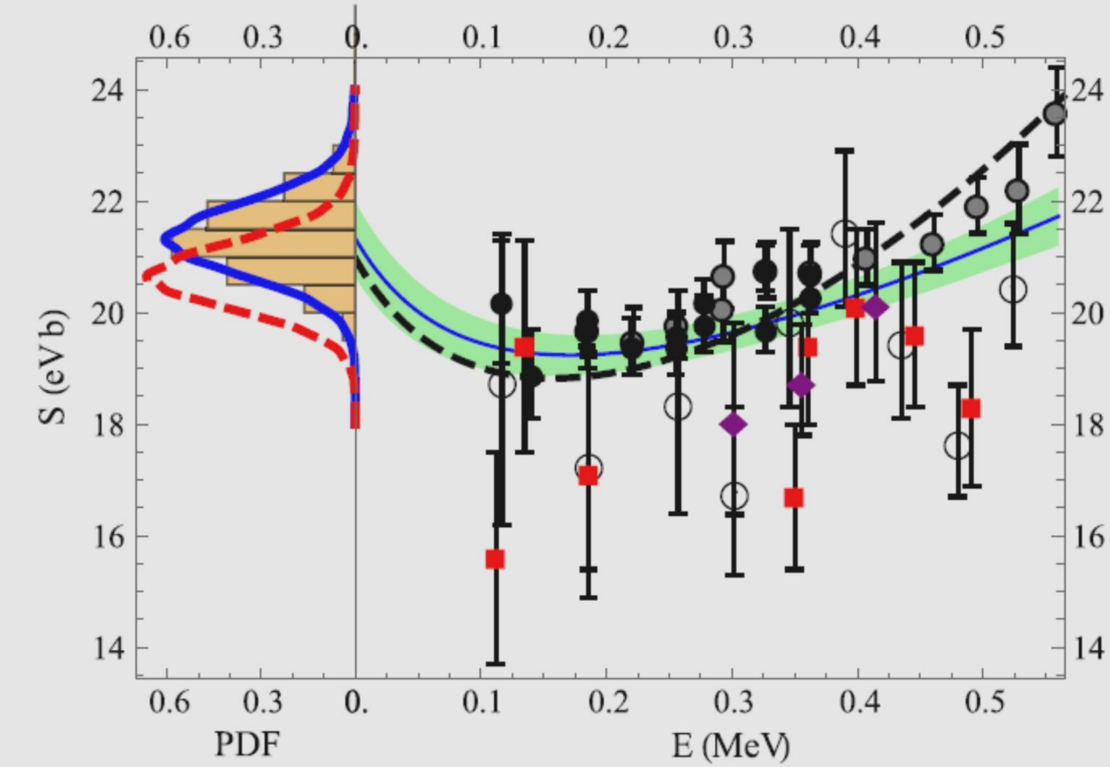
Ours based on the same data

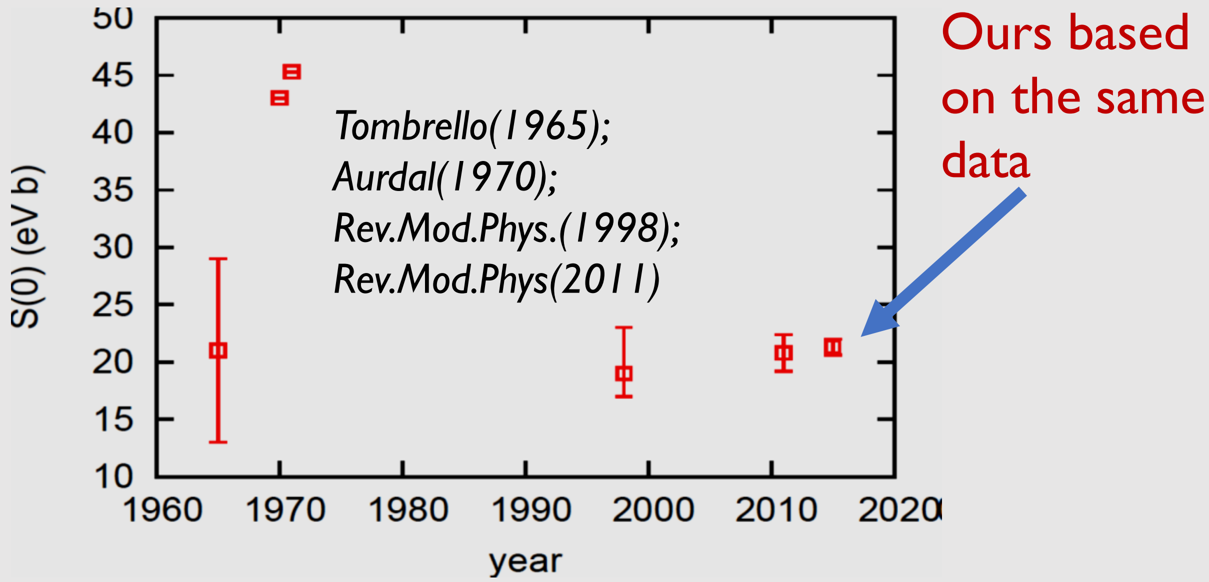
X.Z., K. Nollett, and D. Phillips, PLB (2015)

${}^{7}_{4}Be + p \rightarrow {}^{8}_{5}B + \gamma$: uncertainty analysis

Bayesian inference:

$$\mathrm{pr}\left(\boldsymbol{g}, \{\xi_i\} | D; T; I\right) = \mathrm{pr}\left(D | \boldsymbol{g}, \{\xi_i\}; T; I\right) \mathrm{pr}\left(\boldsymbol{g}, \{\xi_i\} | I\right)$$



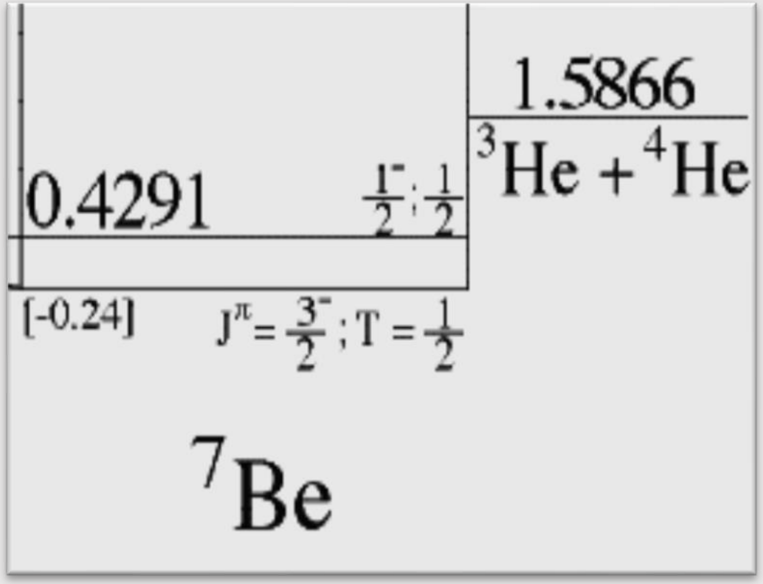


EFT+Bayesian is a natural tool for evaluating uncertainties

X.Z., K. Nollett, and D. Phillips, PLB (2015)

X.Z., K. Nollett, and D. Phillips
(in preparation)

$$^{3}_{2}\text{He} + ^{4}_{2}\text{He} \rightarrow ^{7}_{4}\text{Be} + \gamma$$

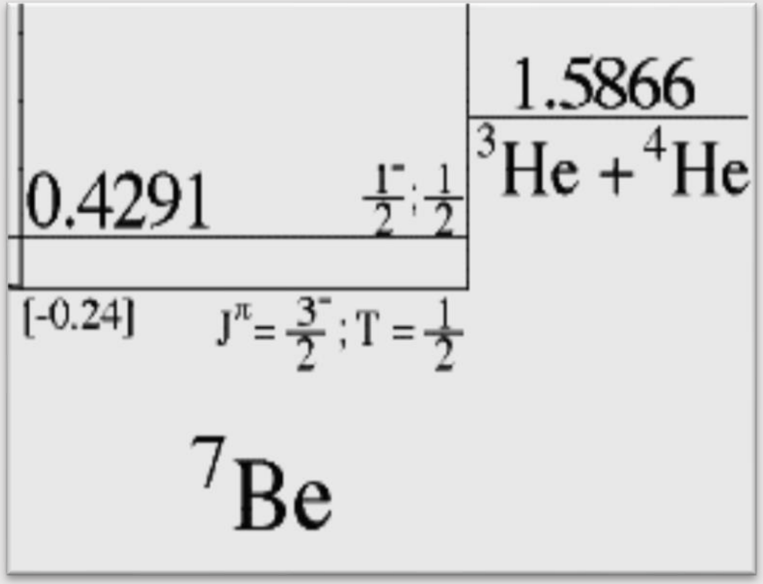


$$\frac{Q_{low}}{\Lambda} \approx 0.4$$

$$\eta = \frac{Z_3 Z_4 \alpha_{EM} M_R}{Q_{low}} \approx 0.7$$

X.Z., K. Nollett, and D. Phillips
(in preparation)

${}^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma$



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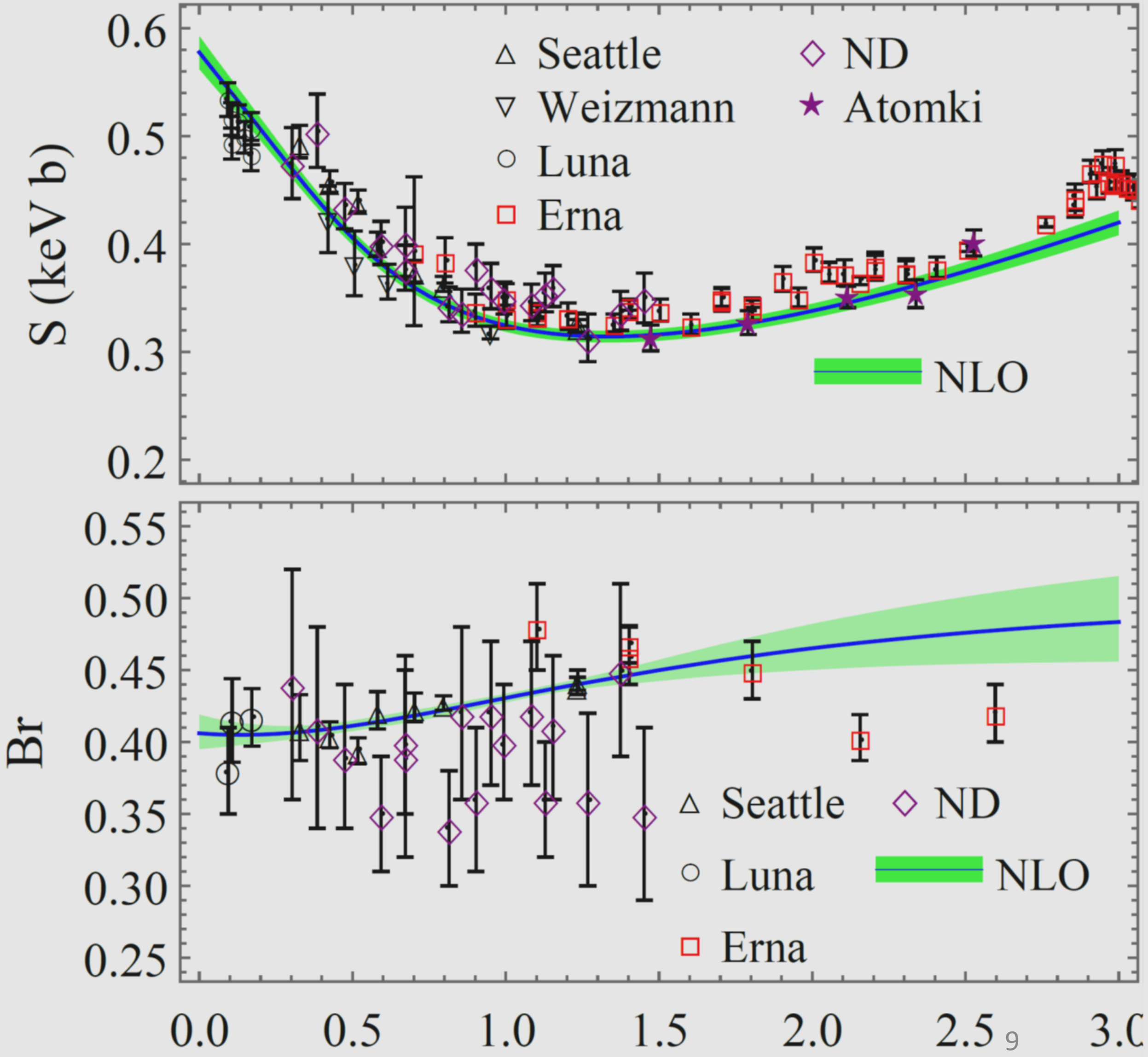
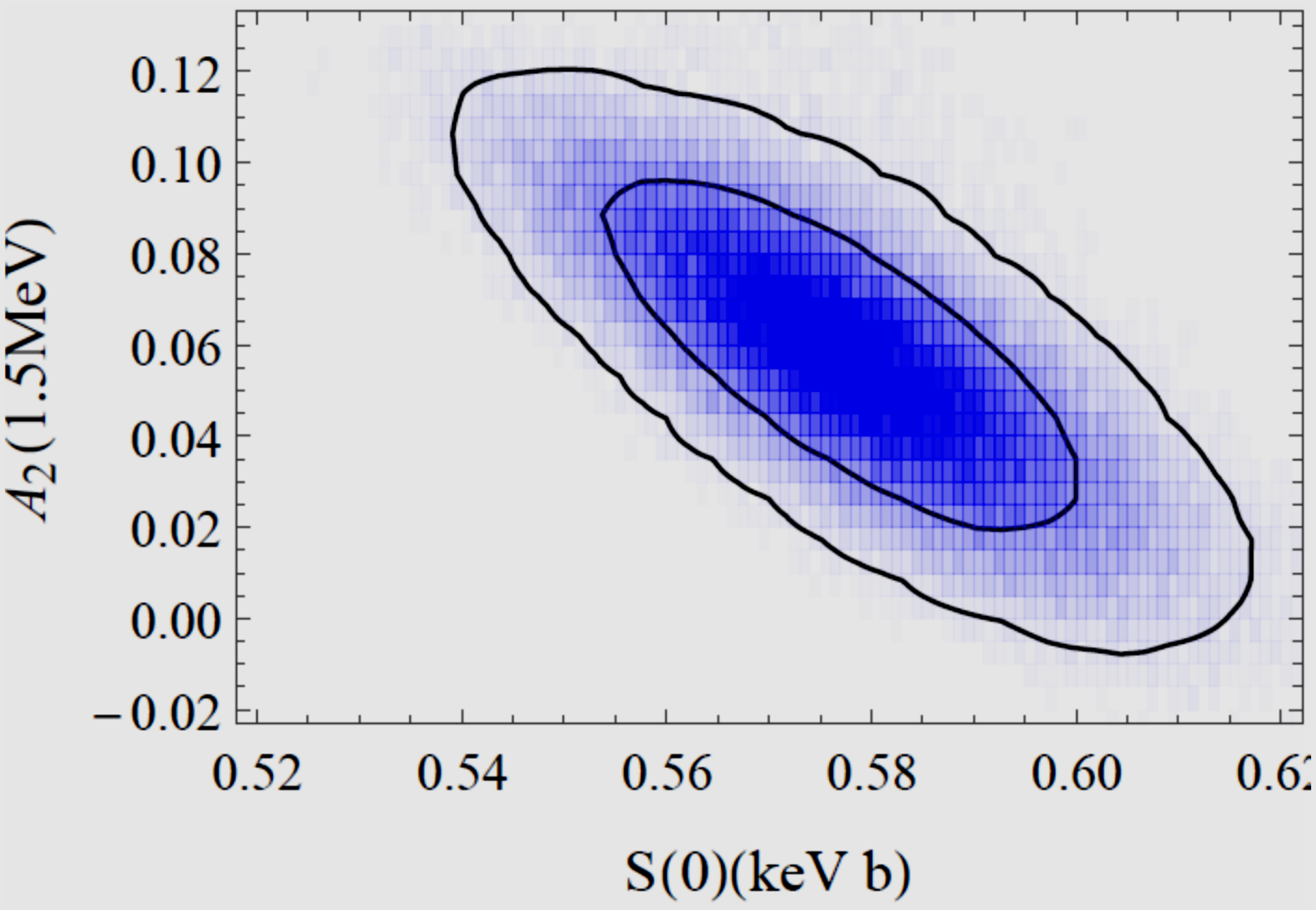
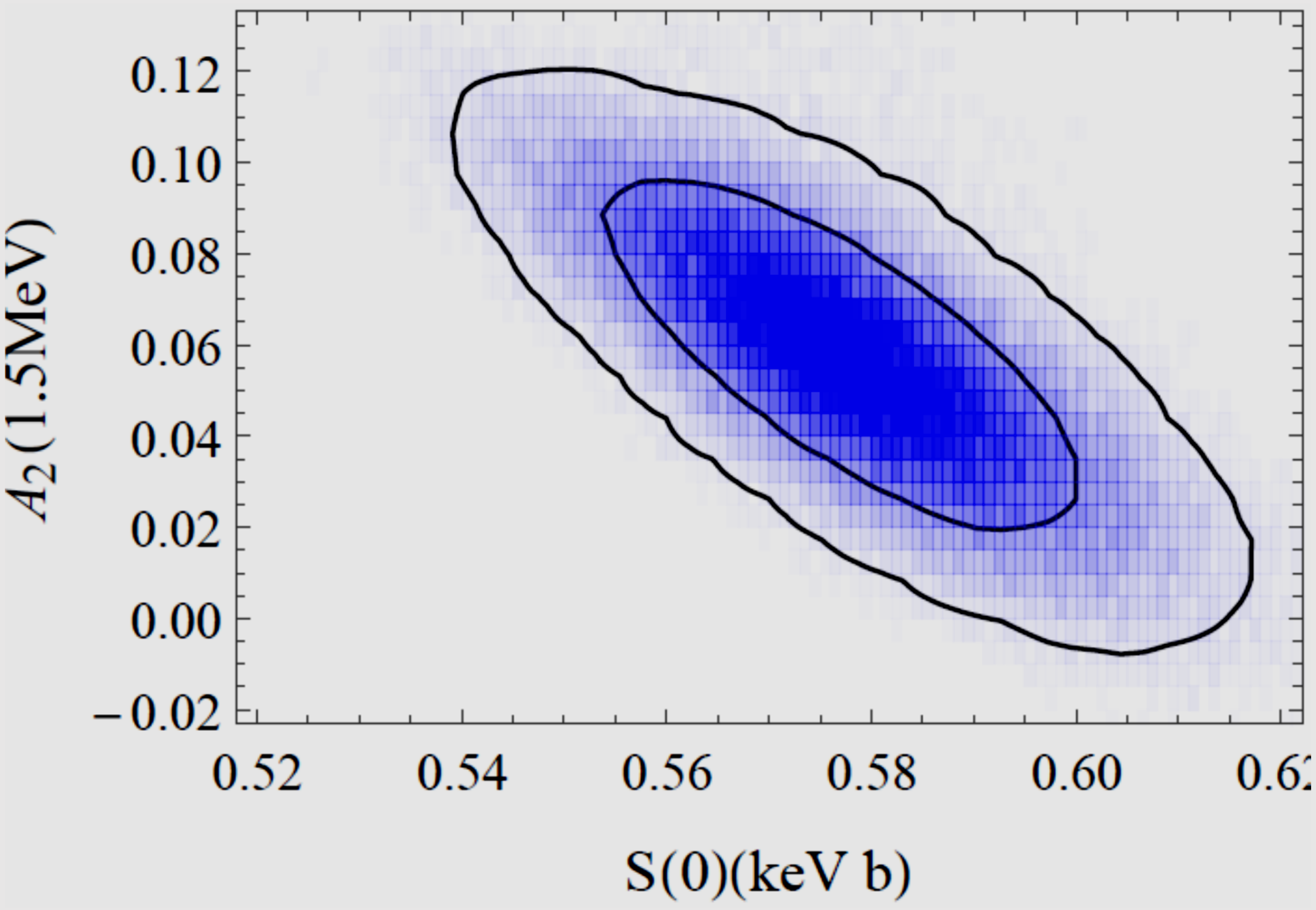


${}_2^3He + {}_2^4He \rightarrow {}_4^7Be + \gamma$: new avenue to constrain S(0)



$$\frac{d\sigma}{d\Omega} \propto 1 + A_2\, cos^2\theta$$

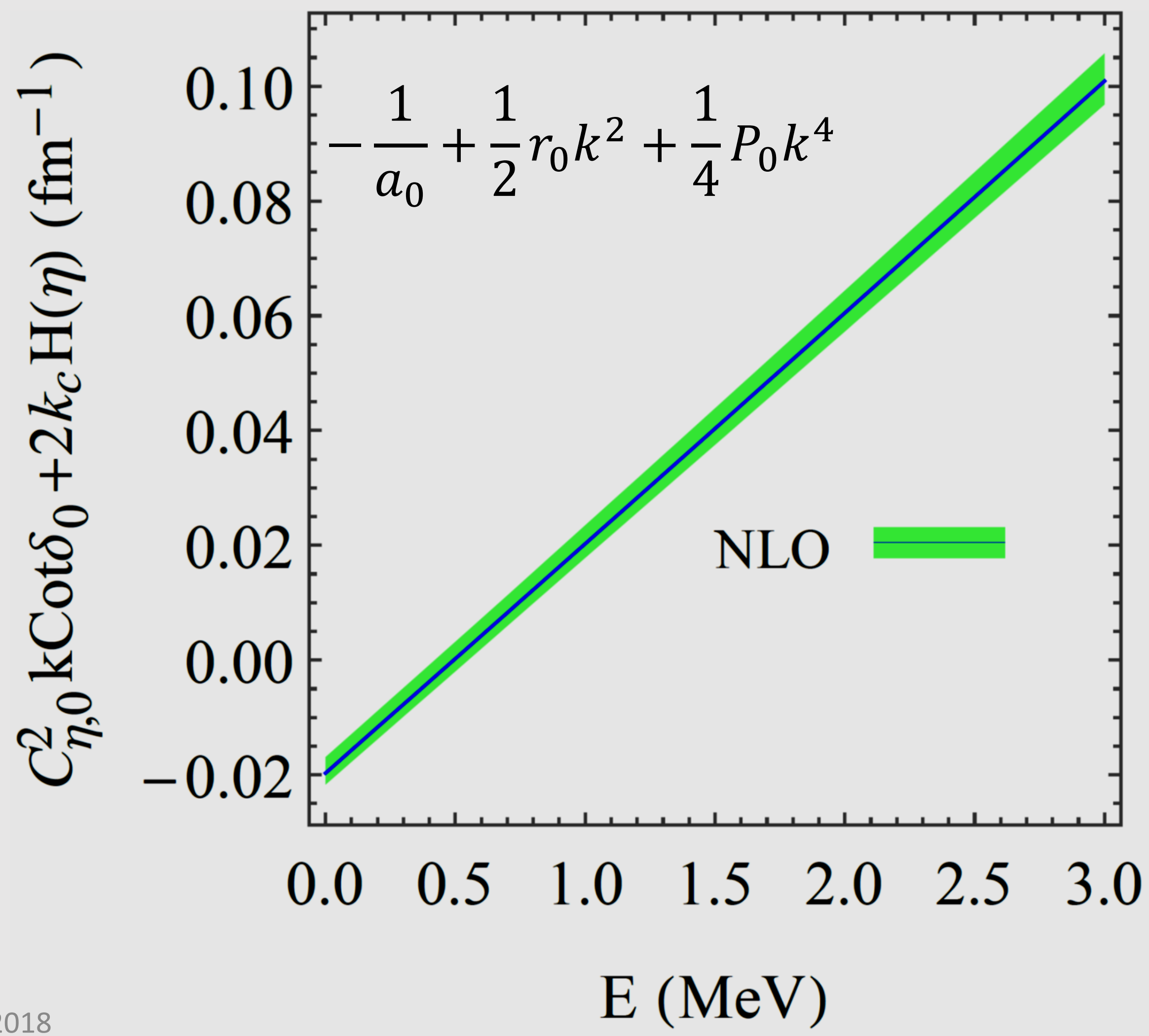
${}^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma$: new avenue to constrain S(0)



$$\frac{d\sigma}{d\Omega} \propto 1 + A_2\, cos^2\theta$$

Halo-EFT+Bayesian inference can find valuable correlations to guide experiments

${}^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \to {}^{7}_{4}\mathrm{Be} + \gamma$: unexpected



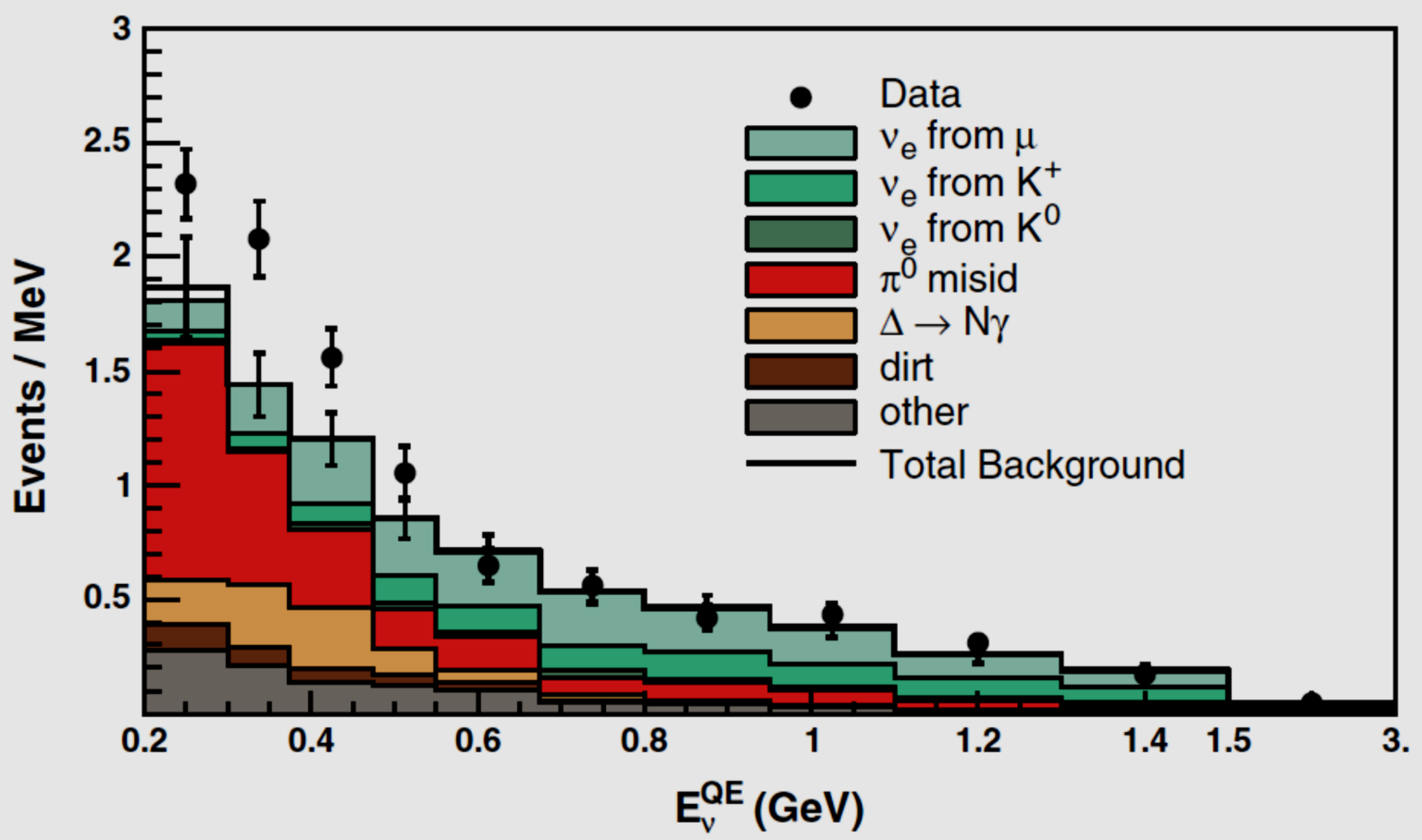
Capture data constrains scattering parameters

Base-line neutrino experiment: neutral-current induced photon production

MiniBooNE event excess

MiniBooNE Collaboration (2009, 2018)

MiniBooNE event excess



MiniBooNE Collaboration (2009, 2018)

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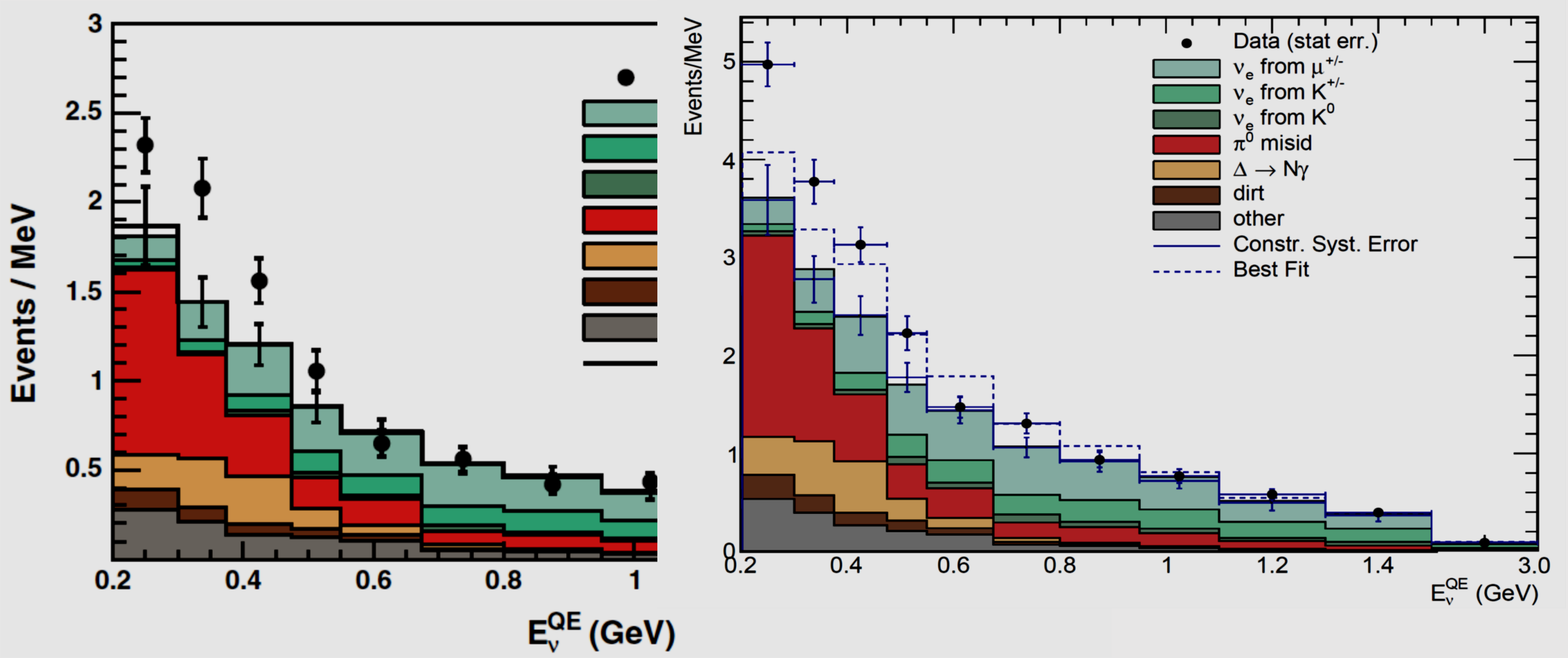
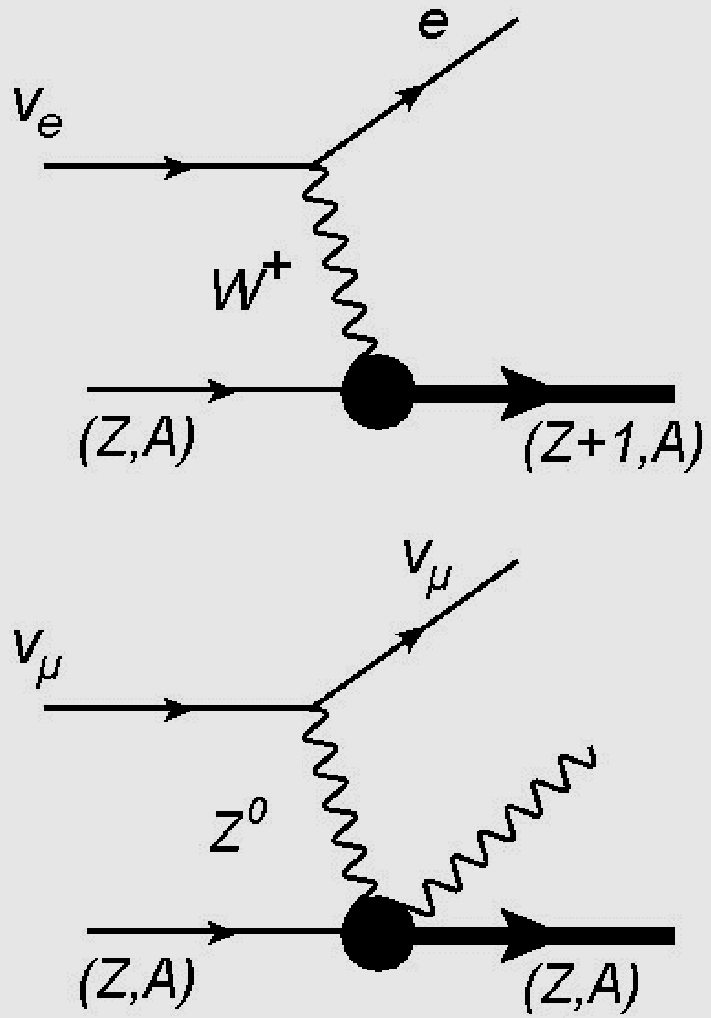


MiniBooNE Collaboration (2009, 2018)

NC photon production?



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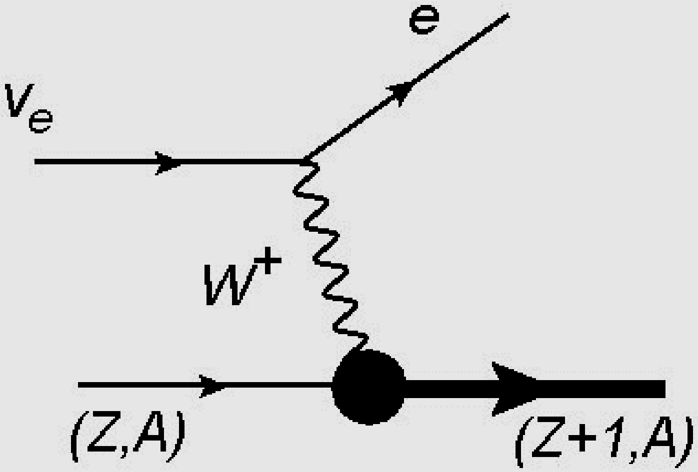

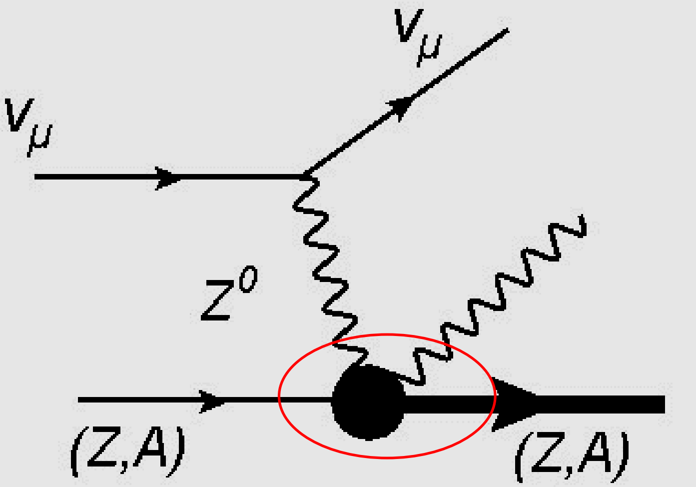

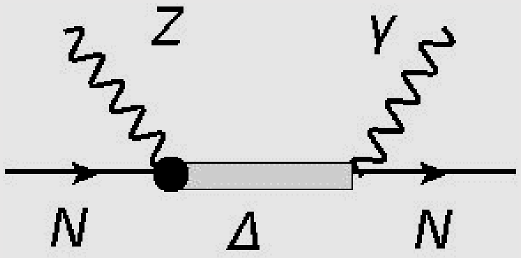

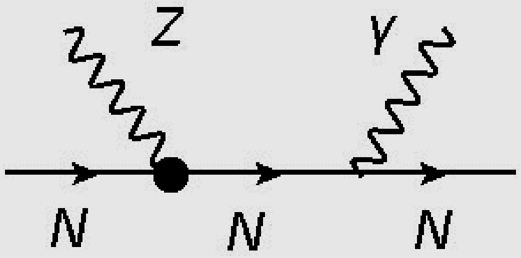

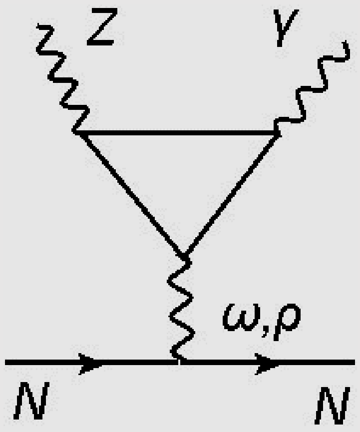

J.A. Harvey, C.T. Hill, R.J. Hill, 2007, 2008
R.J. Hill, 2010, 2011
J. L. Rosner, 2015

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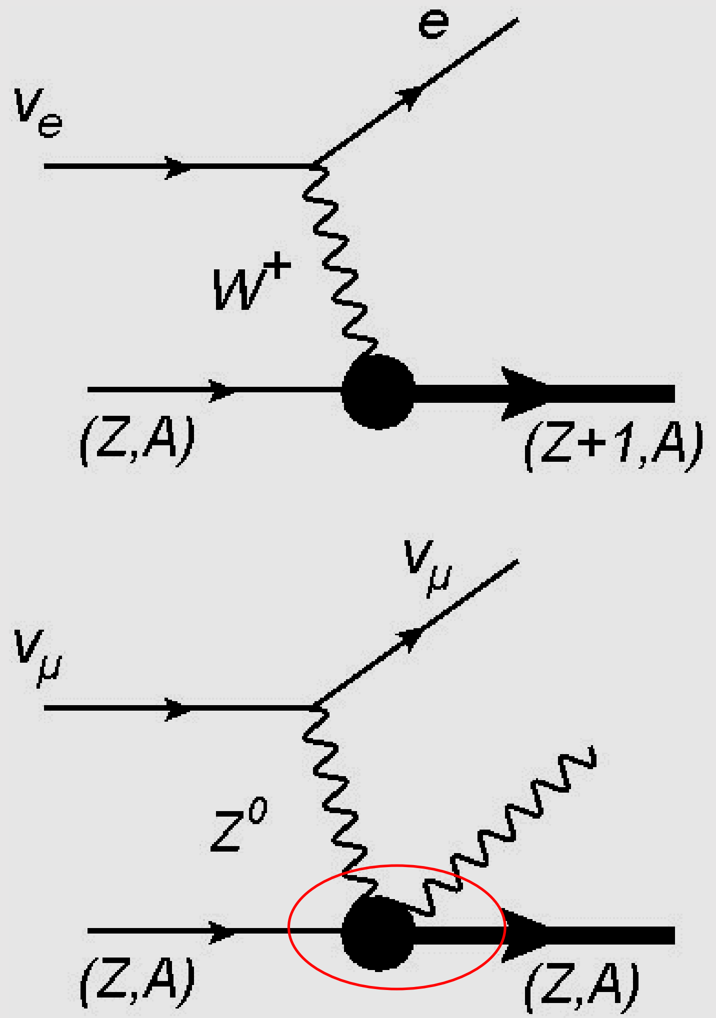
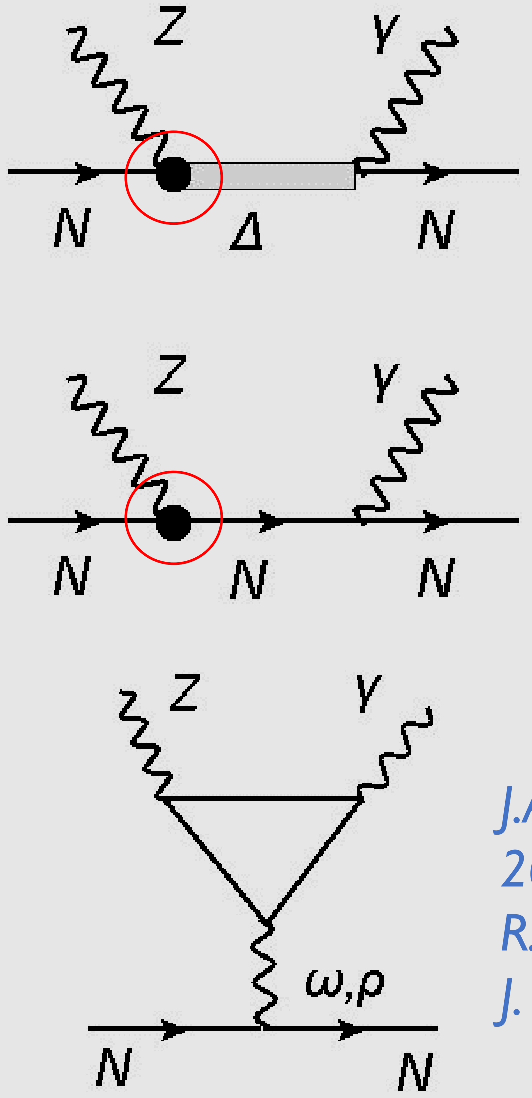




Form factors are poorly known

J.A. Harvey, C.T. Hill, R.J. Hill, 2007, 2008
R.J. Hill, 2010, 2011
J. L. Rosner, 2015

Production of single photons in the exclusive neutrino process $\nu N \to \nu\gamma N$

S. S. Gershteĭn, Yu. Ya. Komachenko, and M. Yu. Khlopov

Institute of High Energy Physics, Serpukhov
(Submitted 16 January 1981)
Yad. Fiz. 33, 1597–1604 (June 1981)

It is shown that the experimentally observed production of single photons in neutrino interactions involving neutral currents without visible accompaniment of other particles can be explained by the scattering of the neutrino by a virtual ω meson with small momentum transfer to a nucleon and subsequent coherent enhancement of the process in the nucleus.

PACS numbers: 13.15. + g, 14.80.Kx

1. INTRODUCTION

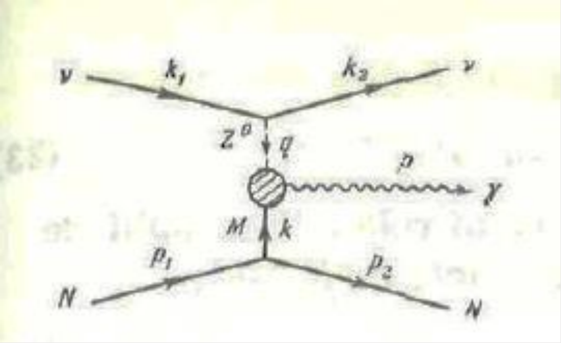
In neutrino experiments performed at CERN using the chamber Gargamelle, more than ten events were detected in which it was observed that single photons with energy 1–10 GeV were produced without visible tracks of any other particles.[1] It can be assumed that the observed events correspond to the weak–electromagnetic process of single-photon production in the reaction

$$\nu N \to \nu\gamma N, \tag{1}$$

$$H_{\mu\nu} = \sum_M T^{(M)} P^{(M)} J^{(M)}_{\mu\nu}, \tag{3}$$

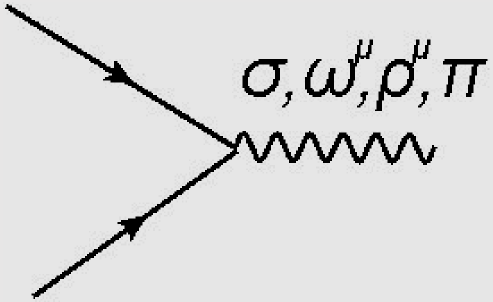
in which $T^{(M)}$ is the vertex for emission of a virtual meson (M) by the target nucleon, $P^{(M)}$ is the meson propagator, and $J^{(M)}_{\mu\nu} = \int \langle 0 | T(J^W_\mu(x), J^{EM}_\nu(y)) | M \rangle e^{iqx+ipy} d^4x d^4y$ is the weak-electromagnetic $Z^0 M\gamma$ vertex. The notation for the particle momenta is given in Fig. 2.

In accordance with the estimates of Ref. 3, we shall take into account the contributions to the diagram of Fig.



A systematic calculation

- The nucleon level physics (form factors)
- Benchmarked against electron-nucleus quasi-elastic and (in)coherent pion production reactions
- Many body effects: Fermi motion, resonance modification, final state interaction…
- A relativistic many body theory (quantum hadrondynamics, QHD) for studying GeV-lepton-nucleus reactions



- Dirac spinor
- Mean field approximation

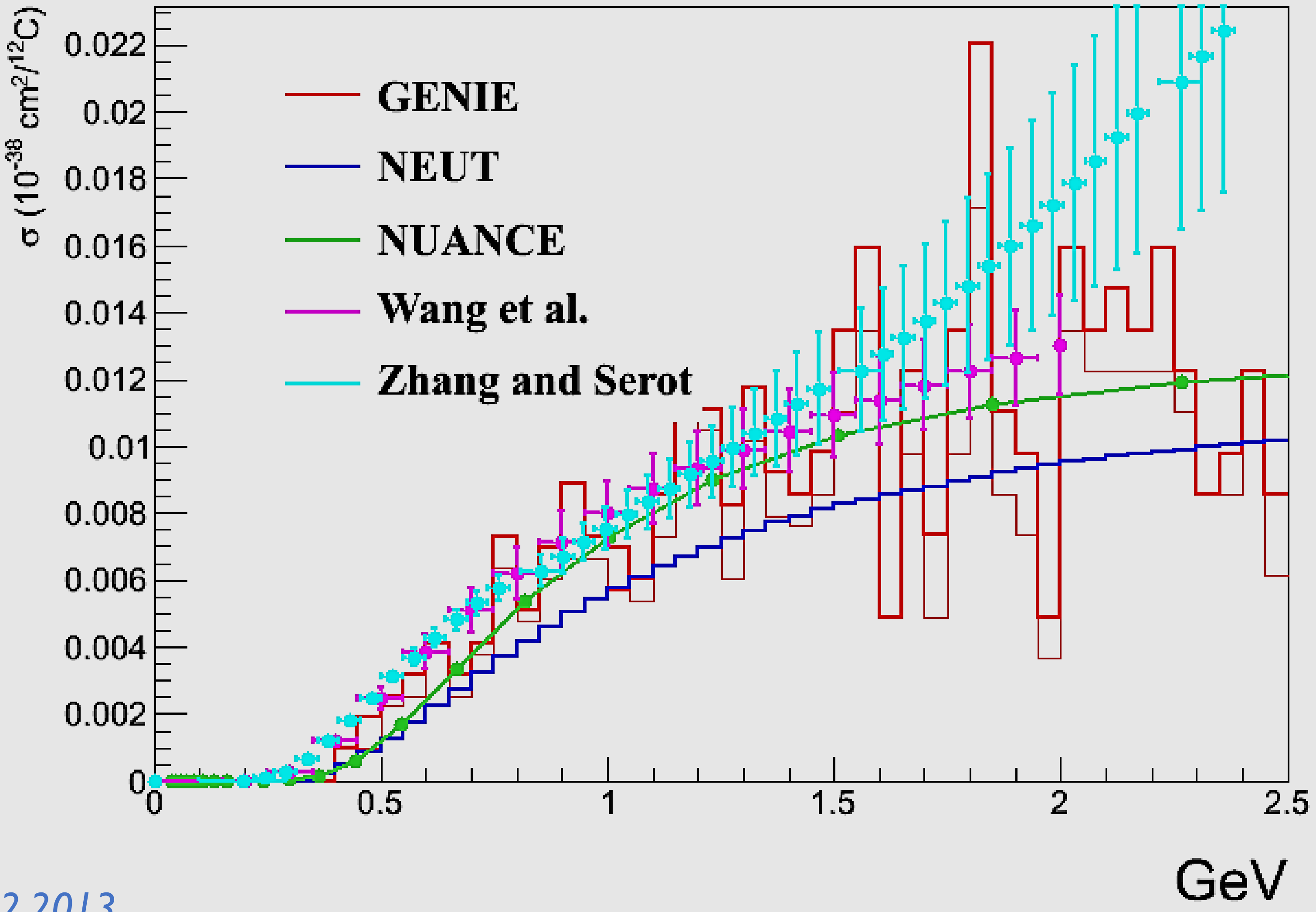
A systematic calculation

E_{QE}(GeV)	[0.2 , 0.3]	[0.3 , 0.475]	[0.475 , 1.25]
Mine	(17.6, 21.4)	(42.1, 51.9)	(19.3, 37.5)
MiniBN	19.5	47.3	19.4
Excess	42.6 ± 25.3	82.2 ± 23.3	21.5 ± 34.9

X.Z. and B.D.Serot (2012, 2013)

Cross section needs to be at least doubled

Report for INT neutrino-nucleus cross section workshop (2013)
G.T. Garvey, D.A. Harris, H.A.Tanaka, R.Tayloe, G. P. Zeller, arXiv: 1412.4294



R.J. Hill, 2010, 2011
X.Z. and B. Serot, 2012,2013,
E.Wang, J. Alvarez-Ruso , J. Nieves, 2015

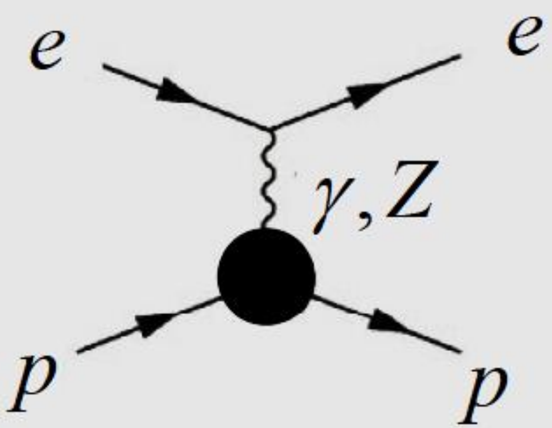
Base-line neutrino experiment: hadronic physics

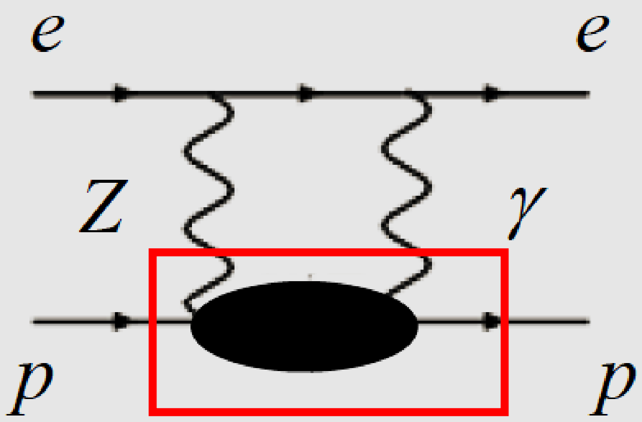
Qweak experiment at Jlab

$$A_{ep} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A_0\left[\underbrace{1 - 4\sin^2\theta_W}_{Q_W^p} + Q^2 B(Q^2, \theta)\right]$$

It probes high energy scale physics

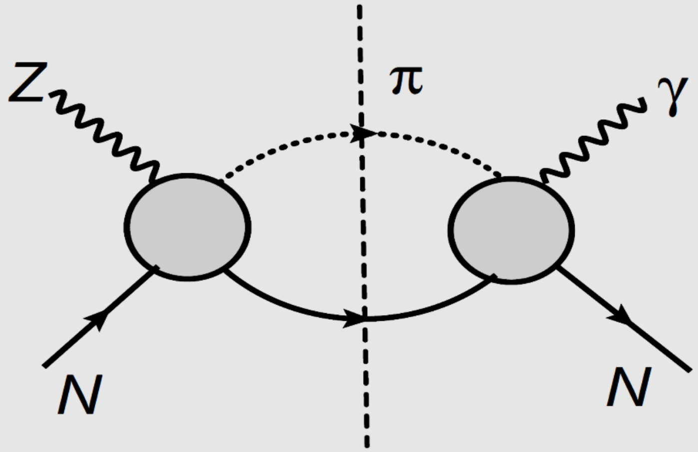
Radiative correction (gamma Z box)





M. Gorchtein and C.J. Horowitz, (2009);
M. Gorchtein, C.J. Horowitz, and M.J. Ramsey-Musolf, (2011);
B.C. Rislow and C.E. Carlson, (2013);
N.L. Hall, P.G. Blunden, W. Melnitchouk, A.W. Thomas and R.D. Young, (2013)

Dispersion analysis on weak-Compton scattering



Again form factors are poorly known

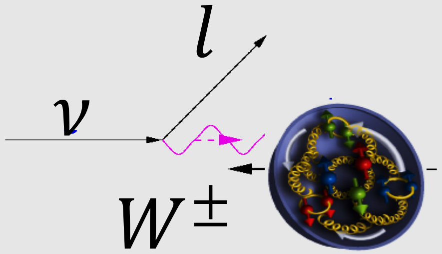
- The Z vertex is poorly known. Need neutrino measurement
- Our first work reduces the uncertainty in extracting Q_W^p

M. Gorchtein and X.Z. (2015)

Partially supported by Fermilab

Axial current form factors are important

- They are an important part of the systematic uncertainty in base-line neutrino oscillation experiments
- They impact calculations of neutrino-nucleus reactions and radiative corrections



$$\langle N\lambda'|J^{\mu}_{EM}|N\lambda\rangle = \overline{u}_{\lambda'}\left[F_1\gamma^{\mu} + F_2\frac{i\sigma^{\mu\nu}q_{\nu}}{2M_N}\right]u_{\lambda}$$

$$\langle N\lambda'|\boldsymbol{J}^{\mu}_{A}|N\lambda\rangle = \overline{u}_{\lambda'}\left[G_A\gamma^{\mu}\gamma_5 + G_P\frac{q^{\mu}\gamma_5}{2M_N}\right]\frac{\boldsymbol{\tau}}{2}u_{\lambda}$$

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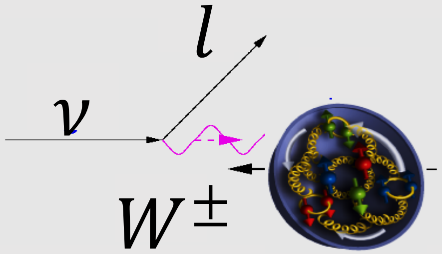

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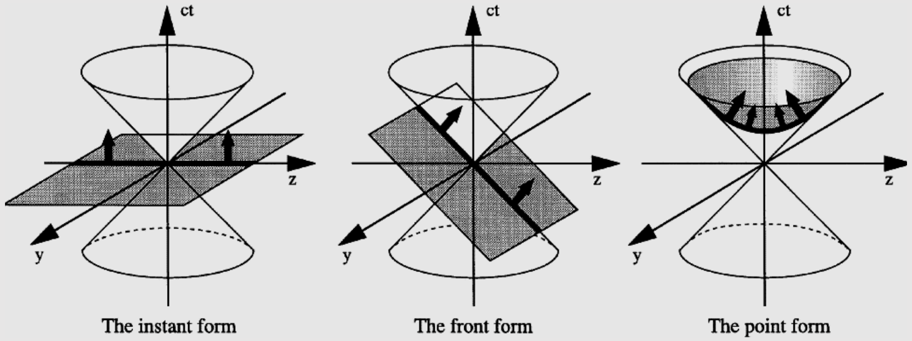
- Lattice QCD won't be the full answer: high Q^2 behavior, N→Resonance transition (inelastic) form factors
- We need a model/framework to cover elastic and inelastic form factors at Q^2 from zero to a few GeV^2.
- Other approaches: "meson-dominance" model (see Emilie Passemar's talk), Z-expansion (by R. Hill et.al.,), and Bayesian analysis on data (Luis Alveriz-Ruso et.al.,)

Light front quark model (LFQM) with pion cloud (in collaboration with G. Miller and T. Hobbs)



S. J. Brodsky et.al., Phys. Rept., ***301****, 299 (1998)*

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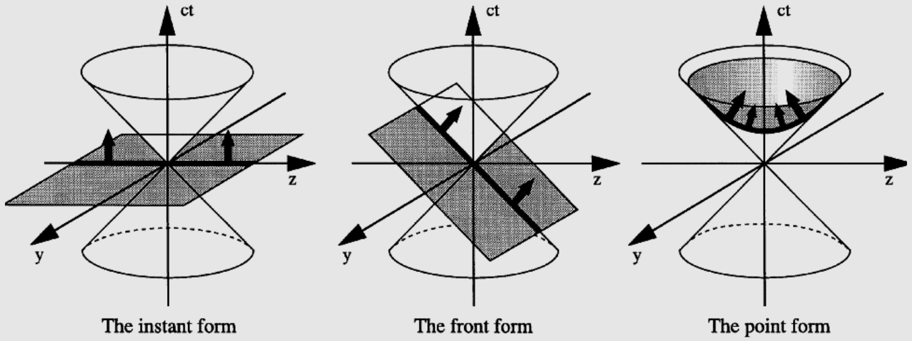

S. J. Brodsky et.al., Phys. Rept., ***301****, 299 (1998)*

$$
\begin{aligned}
|N,\lambda,P^+,\mathbf{0}\rangle &= \sqrt{Z}|N,\lambda\rangle_{Bare} + \sum_{N'=N}^{\Delta}\sum_{x,\boldsymbol{k}^\perp}\sum_{\lambda'}\Phi^{\lambda}_{N',\lambda'}(x,\boldsymbol{k}^\perp)|N',\lambda',xP^+,\boldsymbol{k}^\perp\rangle\otimes|\pi,(1-x)P^+,-\boldsymbol{k}^\perp\rangle \\
|N,\lambda\rangle_{Bare} &= |qqq\rangle \\
&= \sum_{D=S}^{A}\sum_{x,\boldsymbol{k}^\perp}\sum_{\lambda_D\lambda_q}\Psi^{\lambda}_{D,\lambda_D,\lambda_q}(x,\boldsymbol{k}^\perp)|q,\lambda_q,xP^+,\boldsymbol{k}^\perp\rangle\otimes|D,\lambda_D,(1-x)P^+,-\boldsymbol{k}^\perp\rangle
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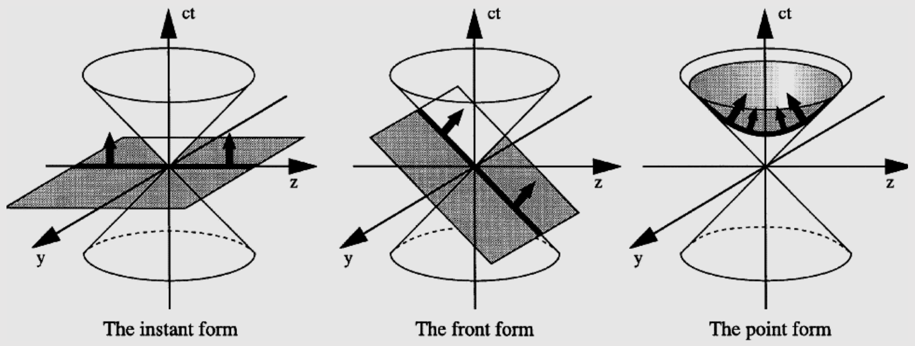

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R.L. Jaffe, Phys. Rept., ***409****, 1 (2005)*

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Scalar & axial-vector diquarks

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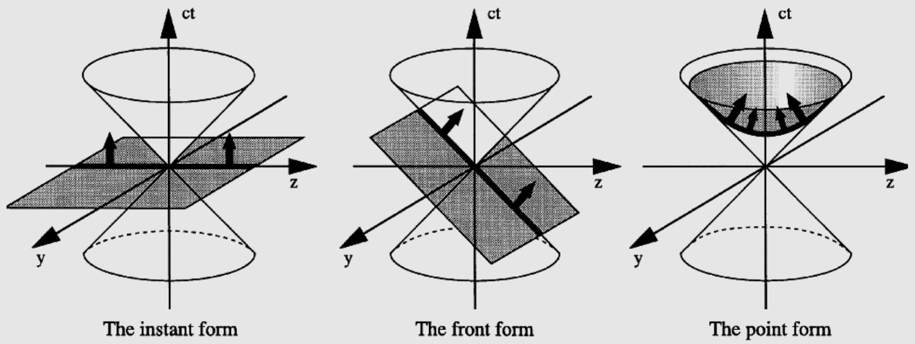

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*R.L. Jaffe, Phys. Rept., **409**, 1 (2005)*

*I. Cloet and G. Miller, Phys.Rev.C, **86**, 015208 (2012)*

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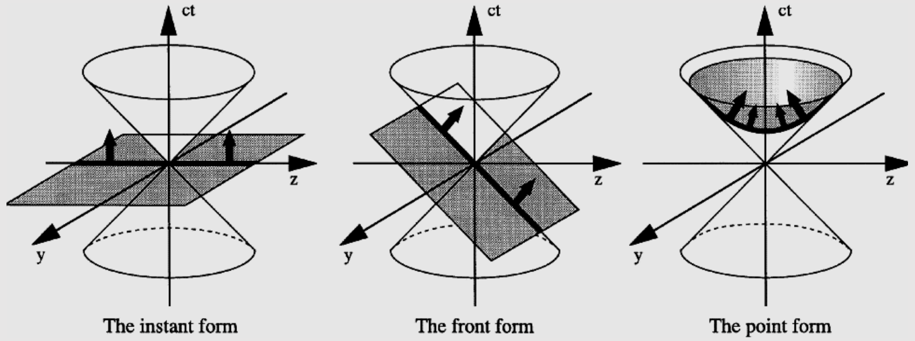

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Delta resonance included in our work

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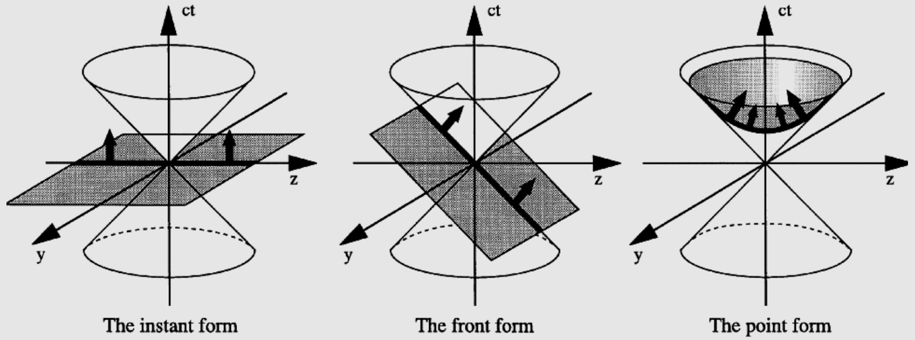

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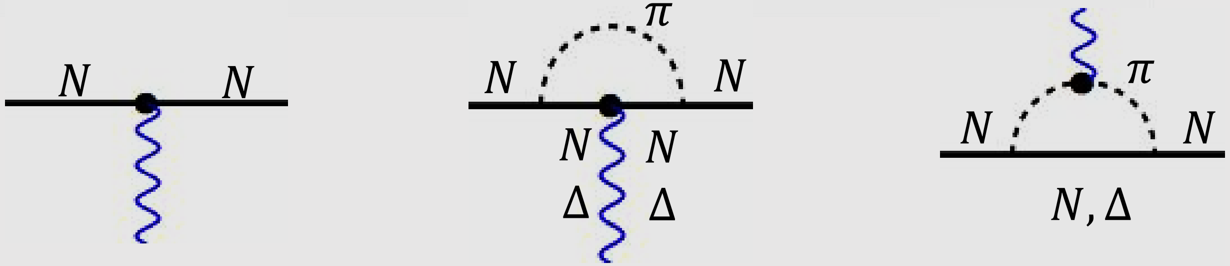
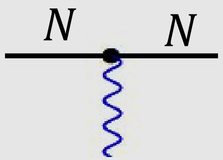


LFQM: EM and Axial form factors

- The bare-quark contribution to $F_{1,2}$ is directly related to the overlap of quark wave functions:

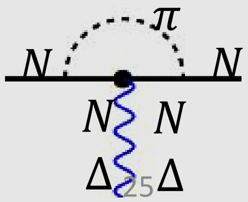
$$F_1^{Bare}(Q^2) = \sum_{D=S}^{A} \sum_{x,\boldsymbol{k}^{\perp}} \sum_{\lambda_D \lambda_q} \left[\Psi^{\lambda=+1/2}_{D,\lambda_D,\lambda_q}(x, \boldsymbol{k}^{\perp\prime}) \right]^* \Psi^{\lambda=+1/2}_{D,\lambda_D,\lambda_q}(x, \boldsymbol{k}^{\perp})$$



- The bare-quark contribution to G_A, is also related to the wave function overlap, but has different component-weights from $F_{1,2}$:

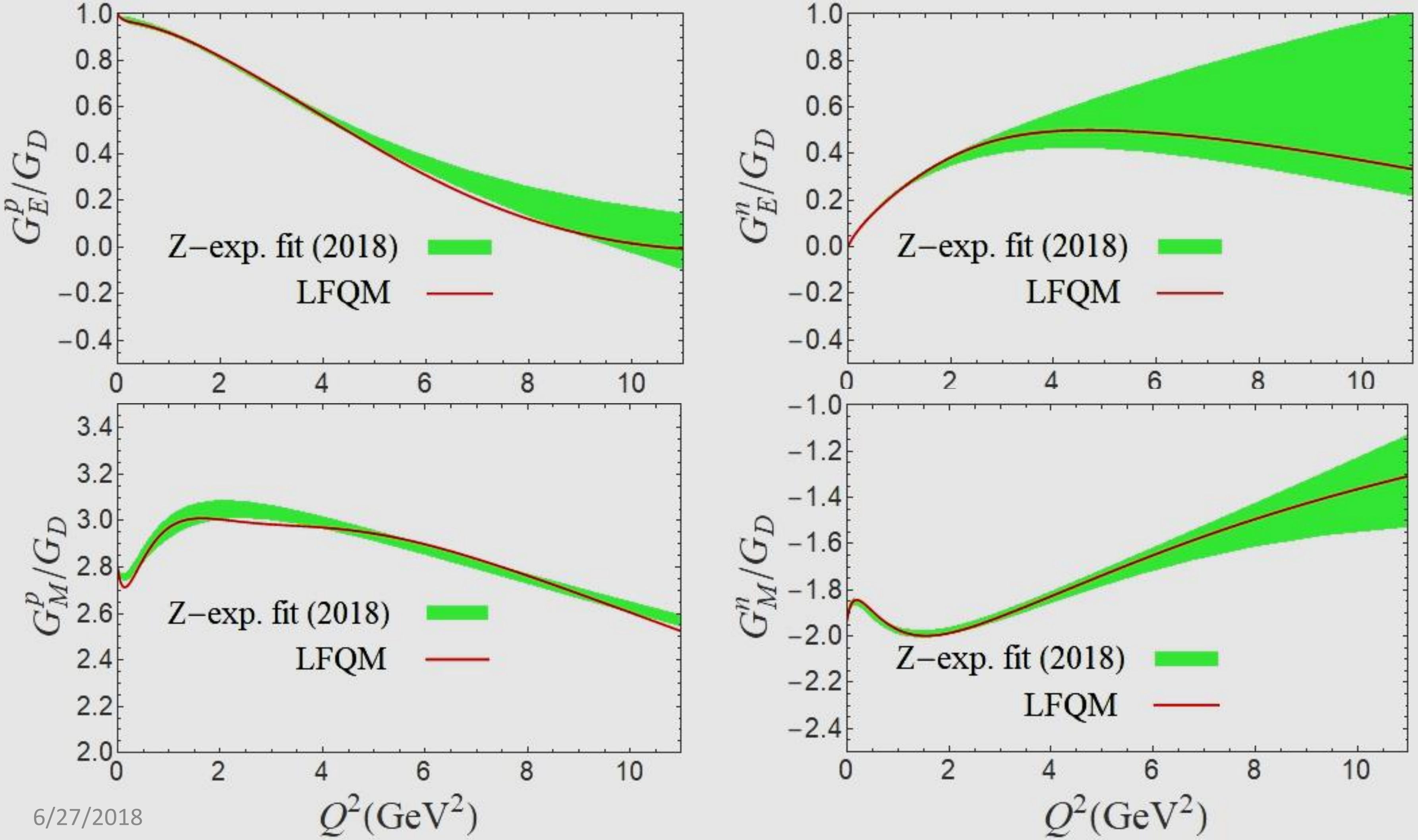
$$G_A^{Bare}(Q^2) = \sum_{D=S}^{A} \sum_{x,\boldsymbol{k}^{\perp}} \sum_{\lambda_D \lambda_q} \left[\Psi^{\lambda=+1/2}_{D,\lambda_D,\lambda_q}(x, \boldsymbol{k}^{\perp\prime}) \right]^* \Psi^{\lambda=+1/2}_{D,\lambda_D,\lambda_q}(x, \boldsymbol{k}^{\perp})(-1)^{\lambda_q - \frac{1}{2}}$$

- The pion cloud couples elastic form factor to the inelastic form factors



Fit EM FFs: preliminary results

$$G_E \equiv F_1 + \frac{Q^2}{4M_N} F_2$$
$$G_M \equiv F_1 + F_2$$
$$G_D \equiv \left(1 + \frac{Q^2}{0.71\text{GeV}^2}\right)^{-2}$$



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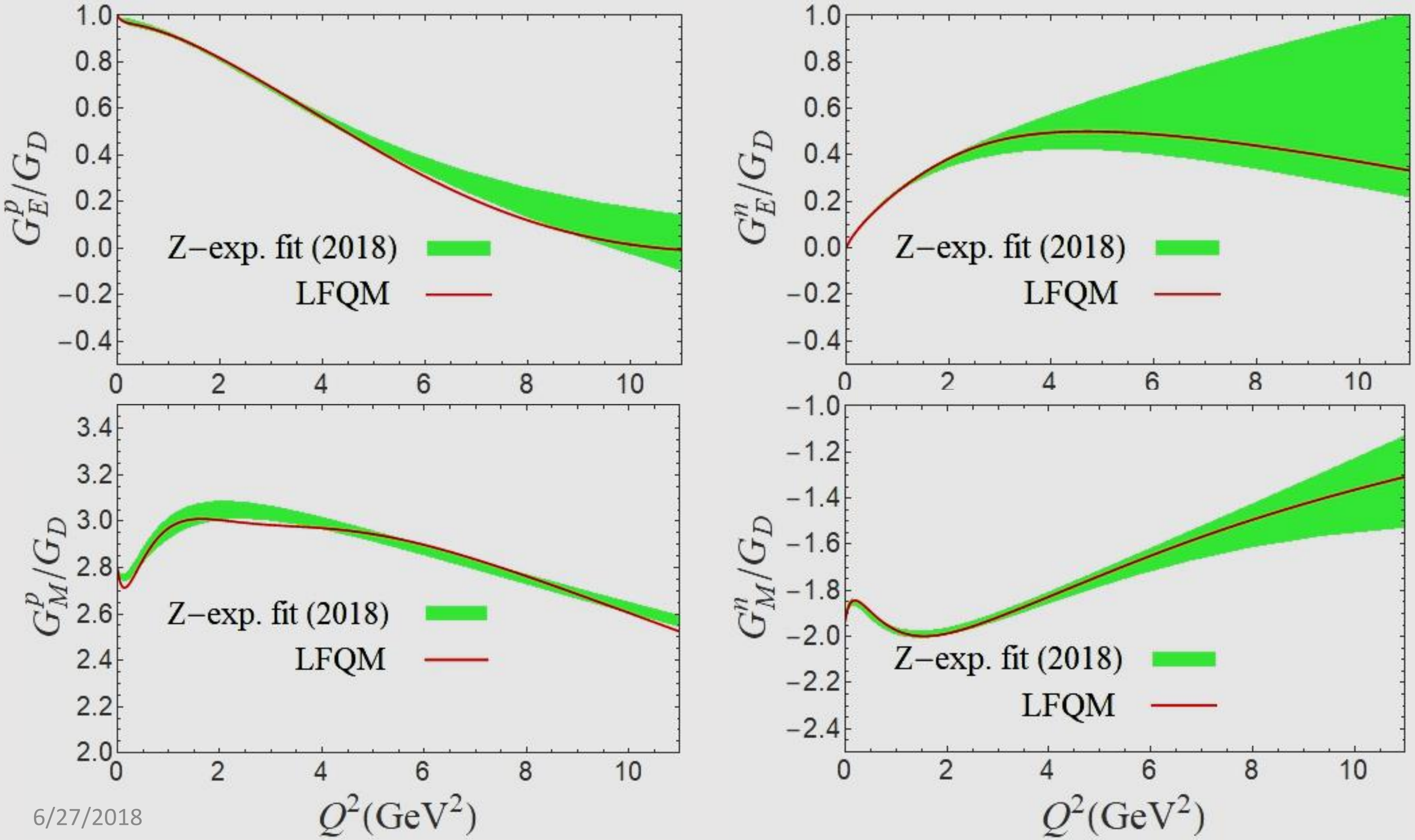

Zhihong Ye, John Arrington, Richard J.Hil, and Gabriel Lee, Phys. Lett. ***B, 777,*** *8 (2018)*

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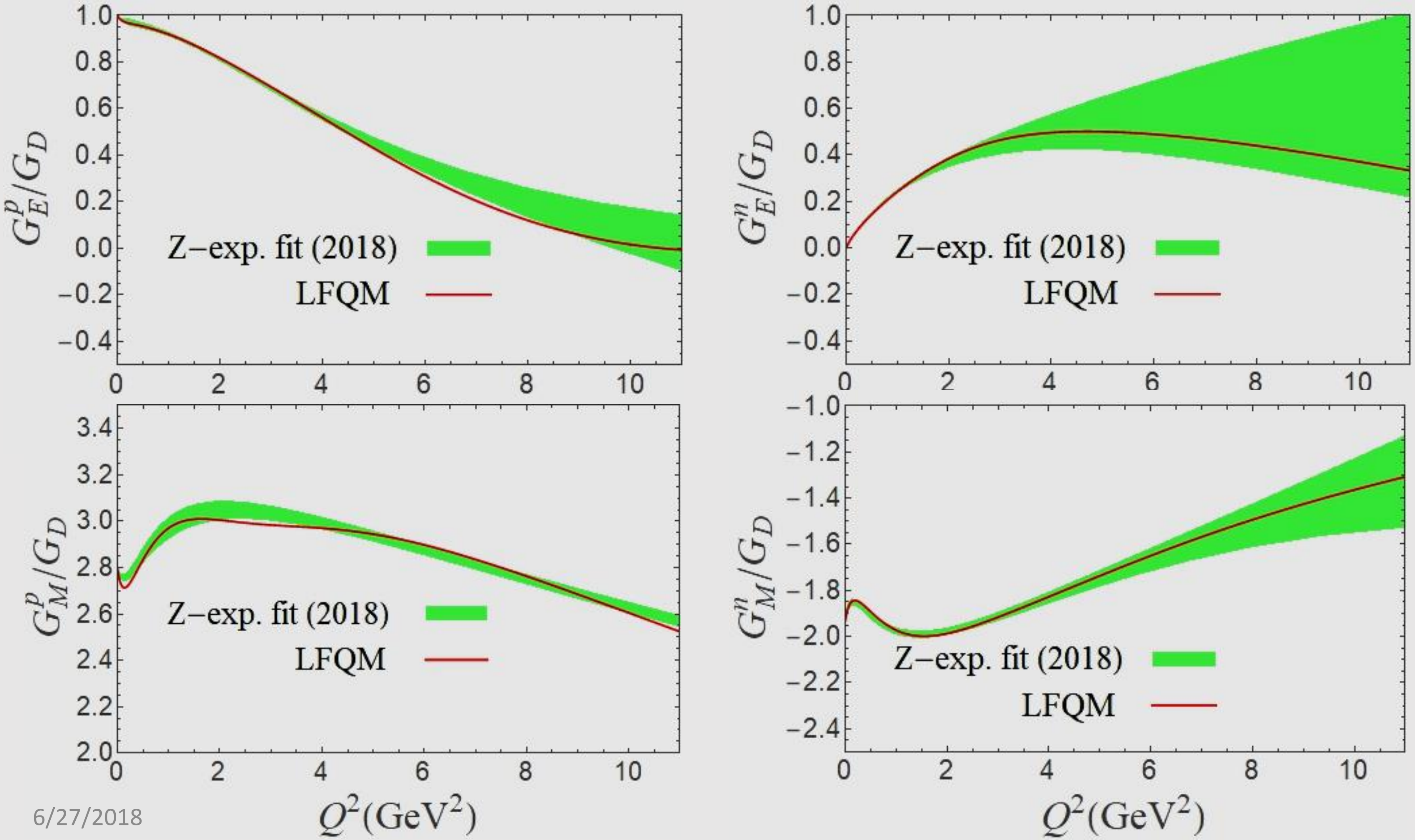

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Zhihong Ye, John Arrington, Richard J.Hil, and Gabriel Lee, Phys. Lett. ***B, 777,*** *8 (2018)*

- Just one-local minimum of χ^2minimization
- There are many local minima
- I am currently exploring the whole parameter space by using Bayesian inference approach

Dark photon: Be-8 anomaly

The anomaly

The anomaly

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

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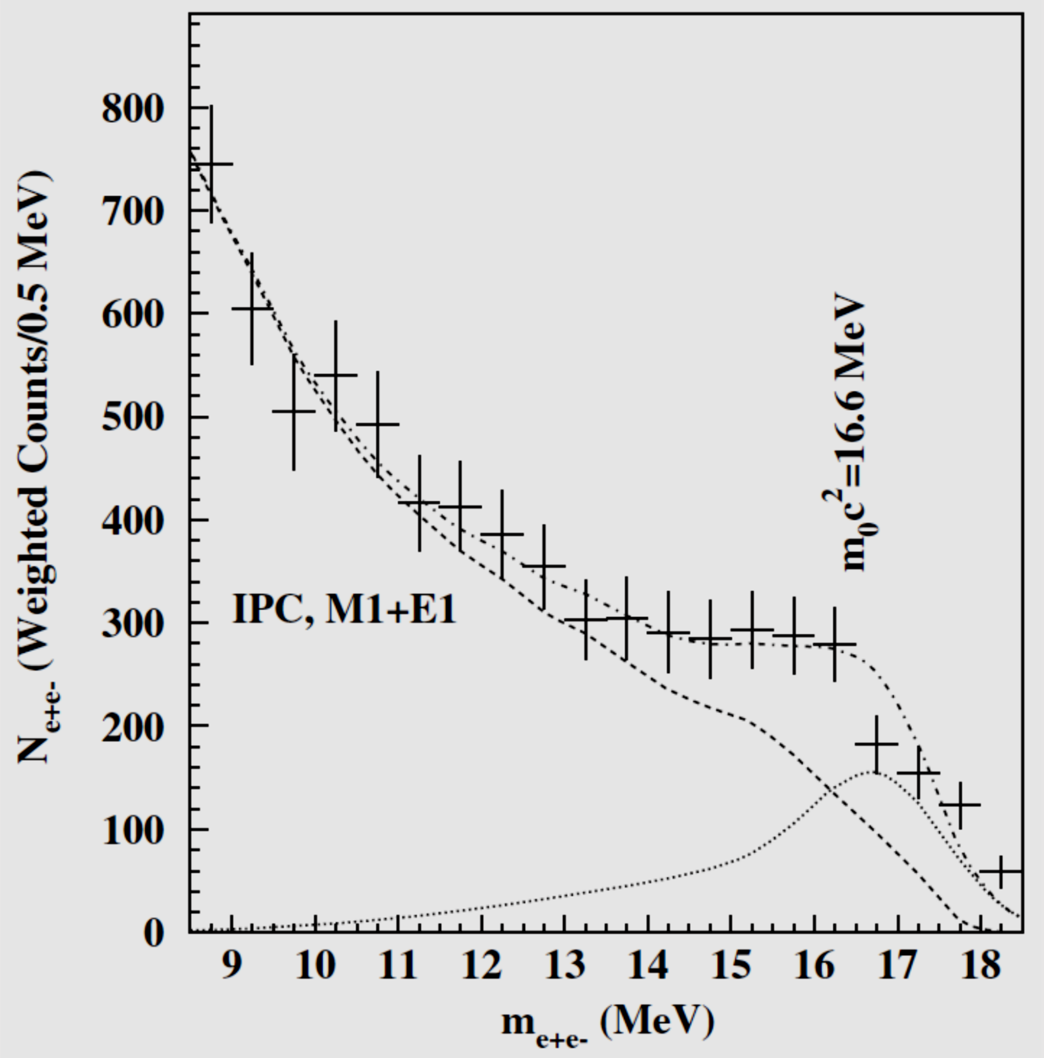
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

(Received 7 April 2015; published 26 January 2016)

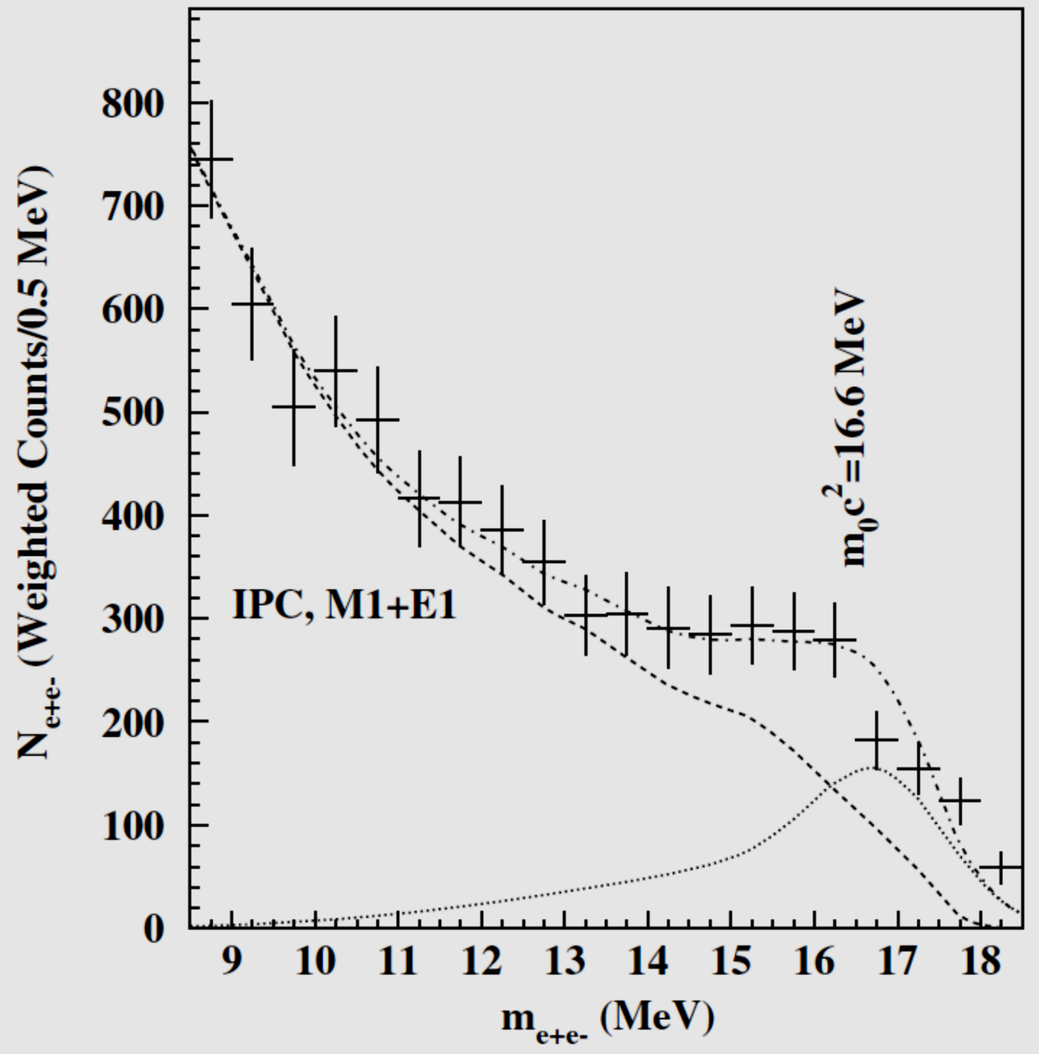
Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV$/c^2$ and $J^\pi = 1^+$ was created.

The anomaly



N_{e+e-} (Weighted Counts/0.5 MeV)
800
700
600
500
400
300
200
100
0
9
10
11
12
13
14
15
16
17
18
m_{e+e-} (MeV)
IPC, M1+E1
m_0c^2=16.6 MeV

The anomaly



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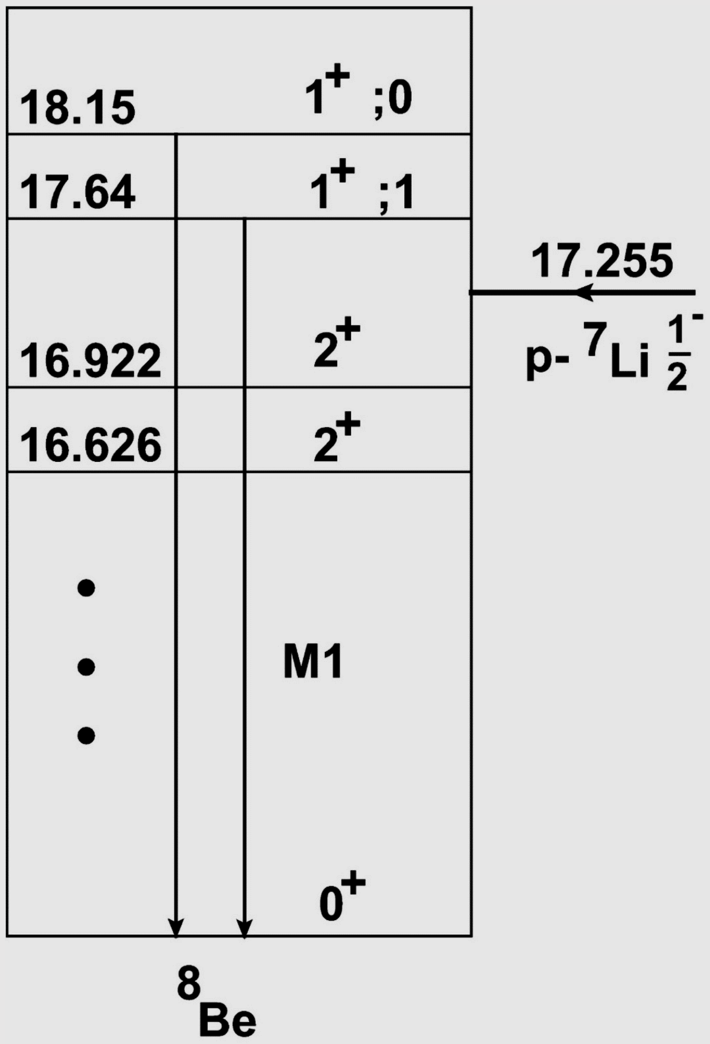
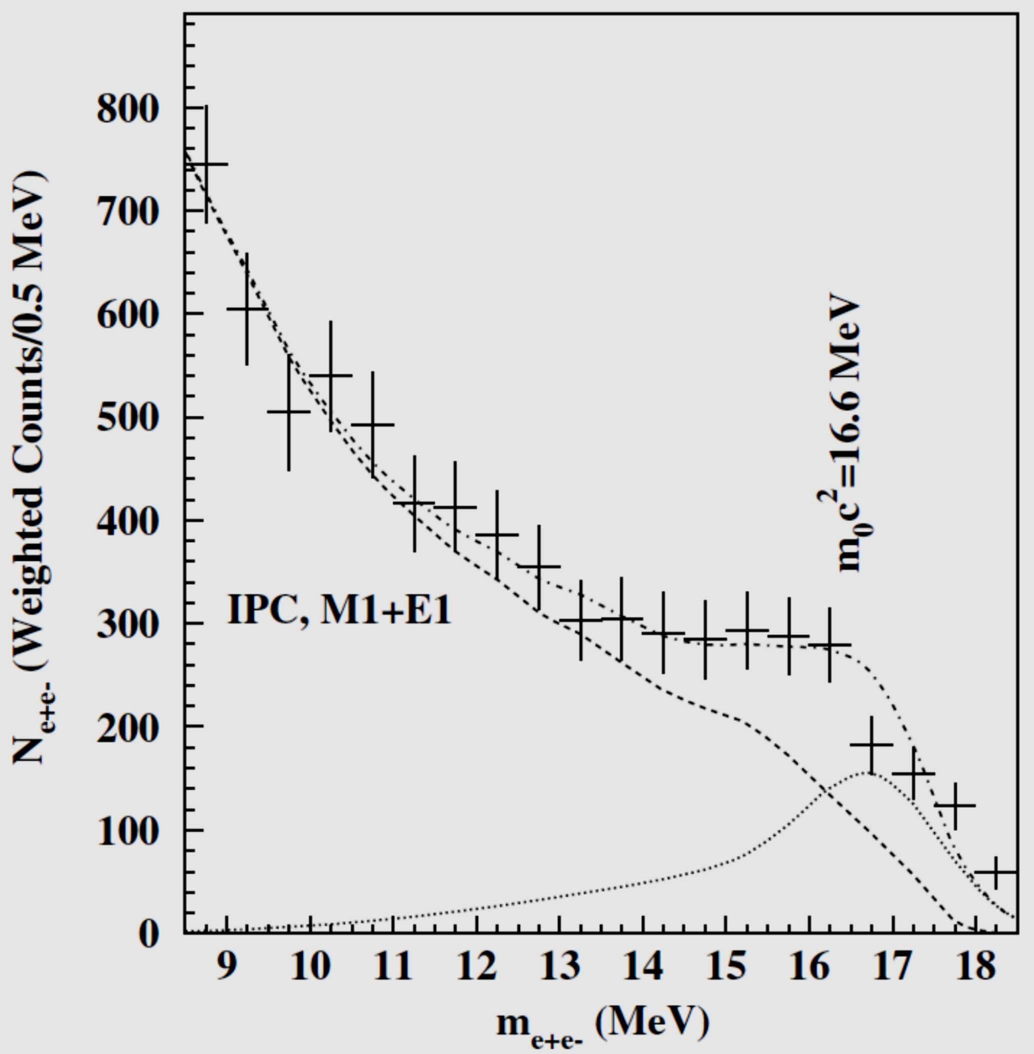


18.15
1^+ ;0
17.64
1^+ ;1
17.255
p- ^{7}Li $\frac{1}{2}^-$
16.922
2^+
16.626
2^+
M1
0^+
^{8}Be

The anomaly



800
700
600
500
400
300
200
100
0
9 10 11 12 13 14 15 16 17 18
N_{e+e-} (Weighted Counts/0.5 MeV)
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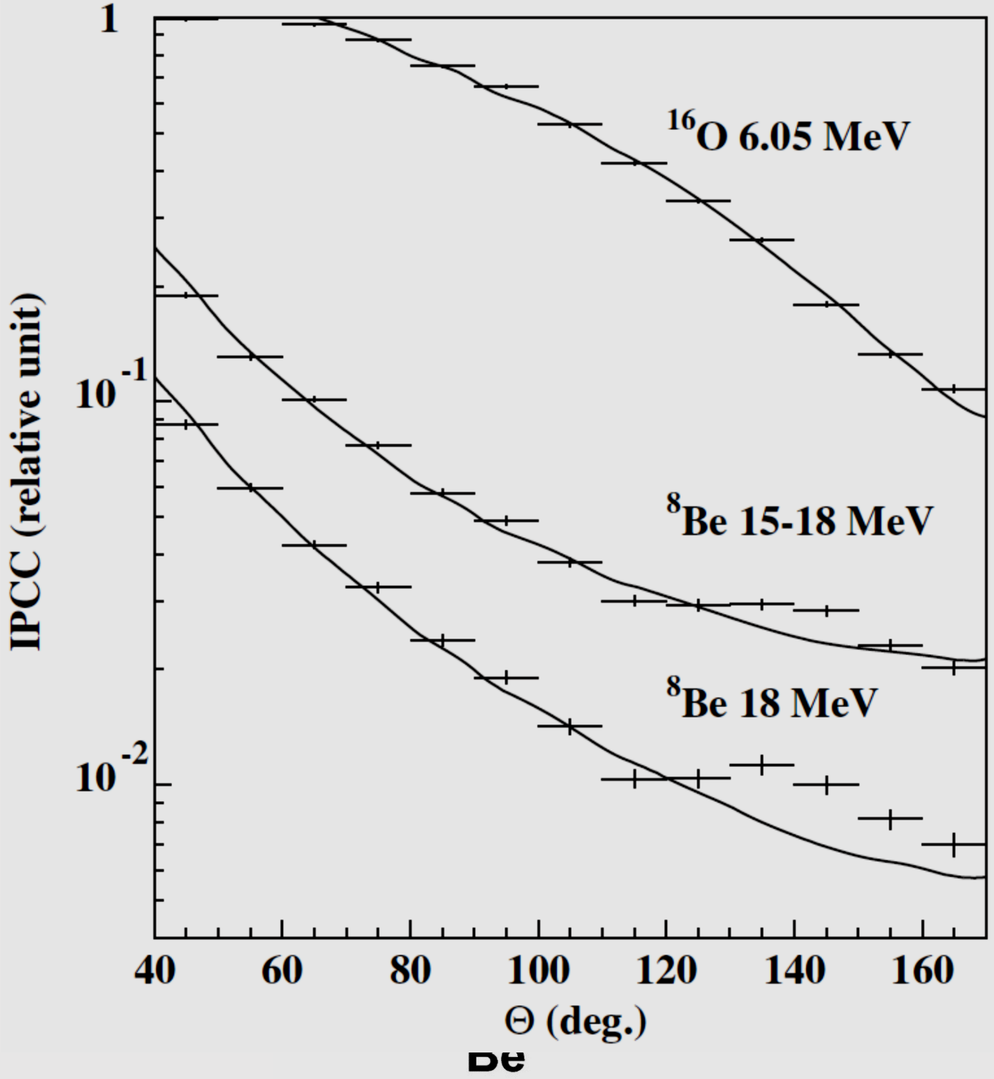
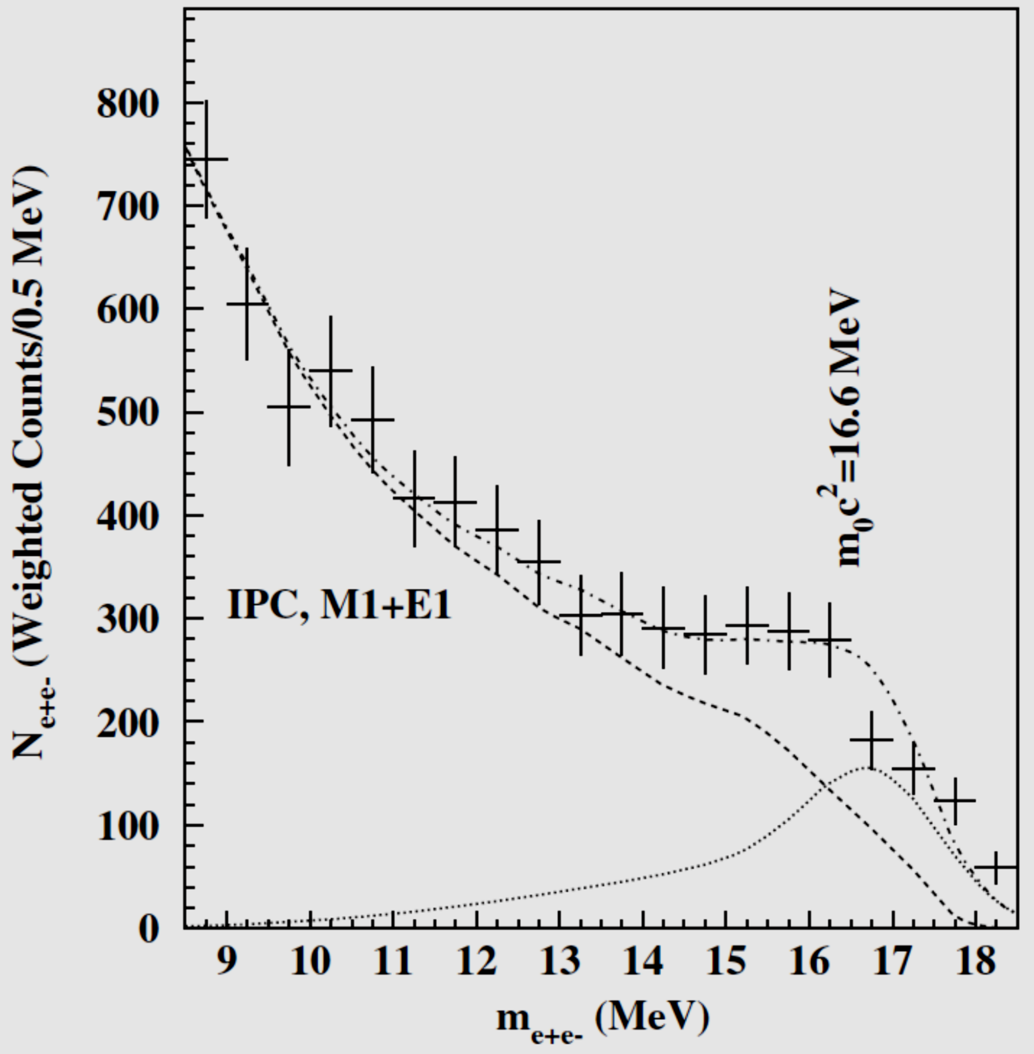
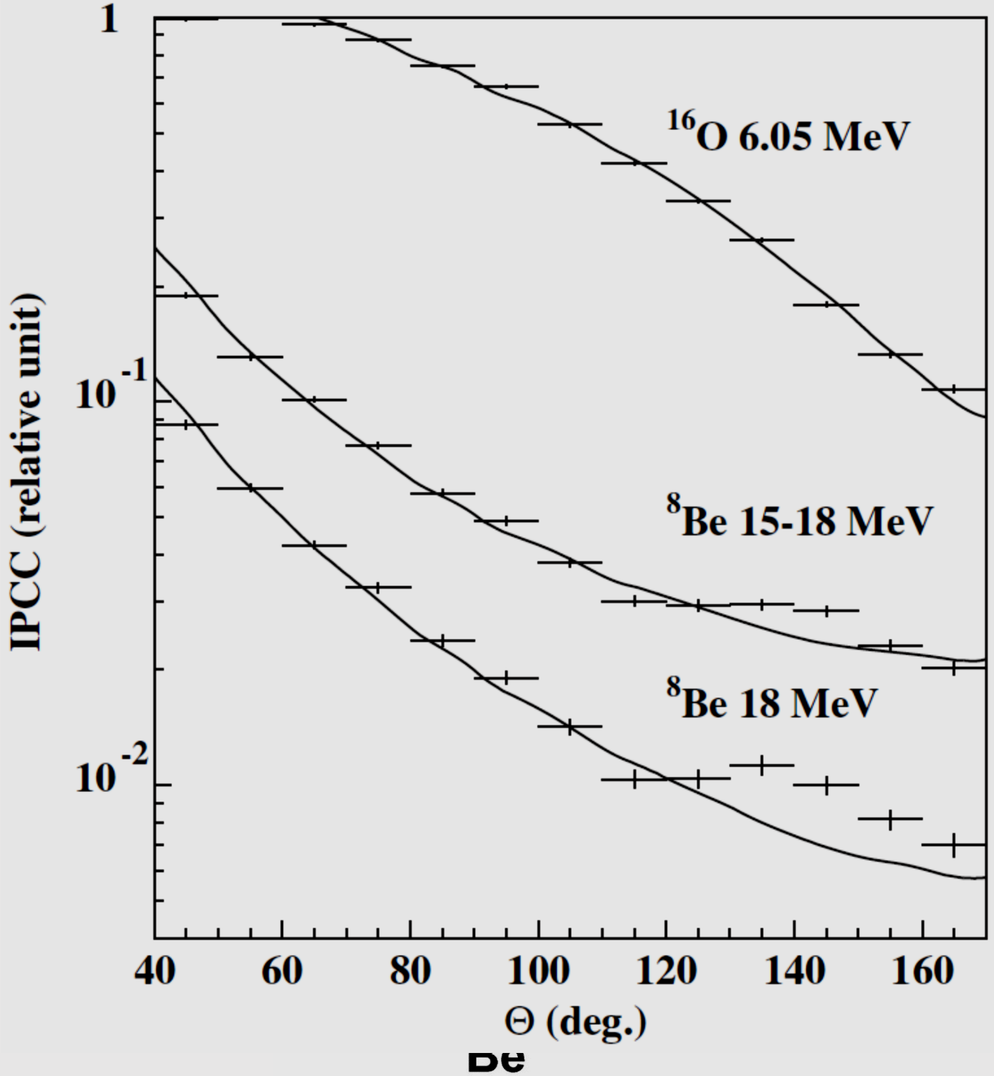


1
10^{-1}
10^{-2}
40 60 80 100 120 140 160
IPCC (relative unit)
Θ (deg.)
^{16}O 6.05 MeV
^{8}Be 15-18 MeV
^{8}Be 18 MeV

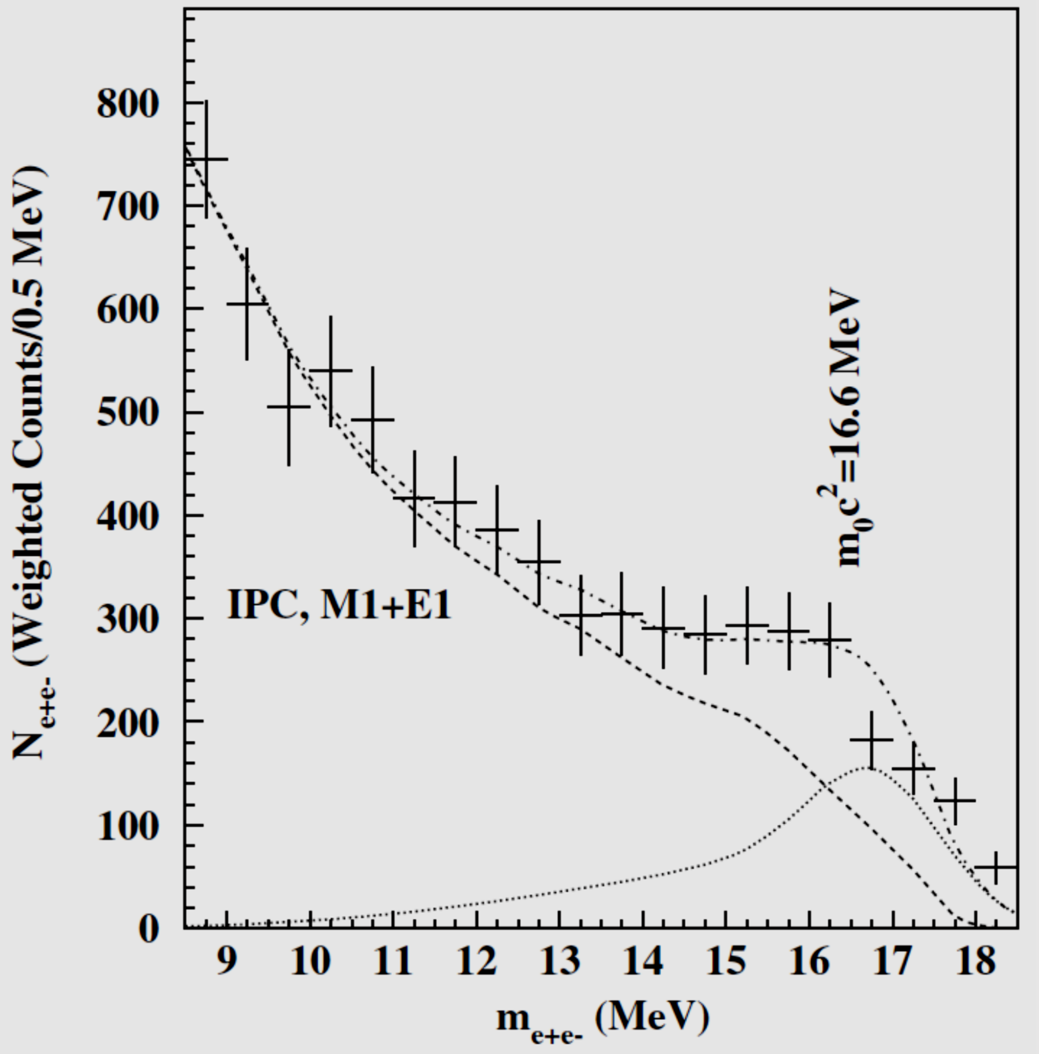
The anomaly

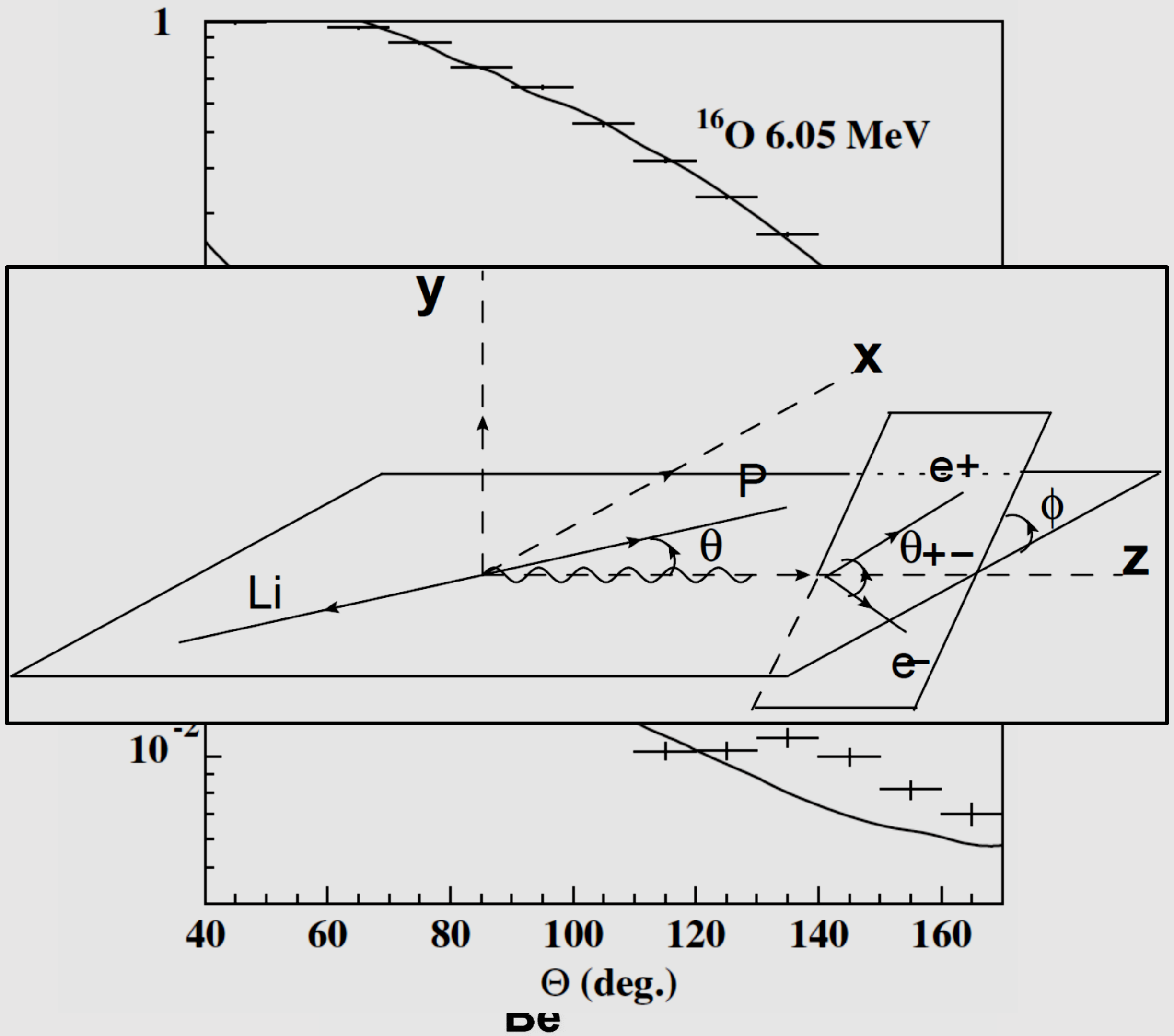




The theoretical model used is from M. E. Rose [PR 76, **678** (1949)]; No interference was studied.

The anomaly





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EM transitions

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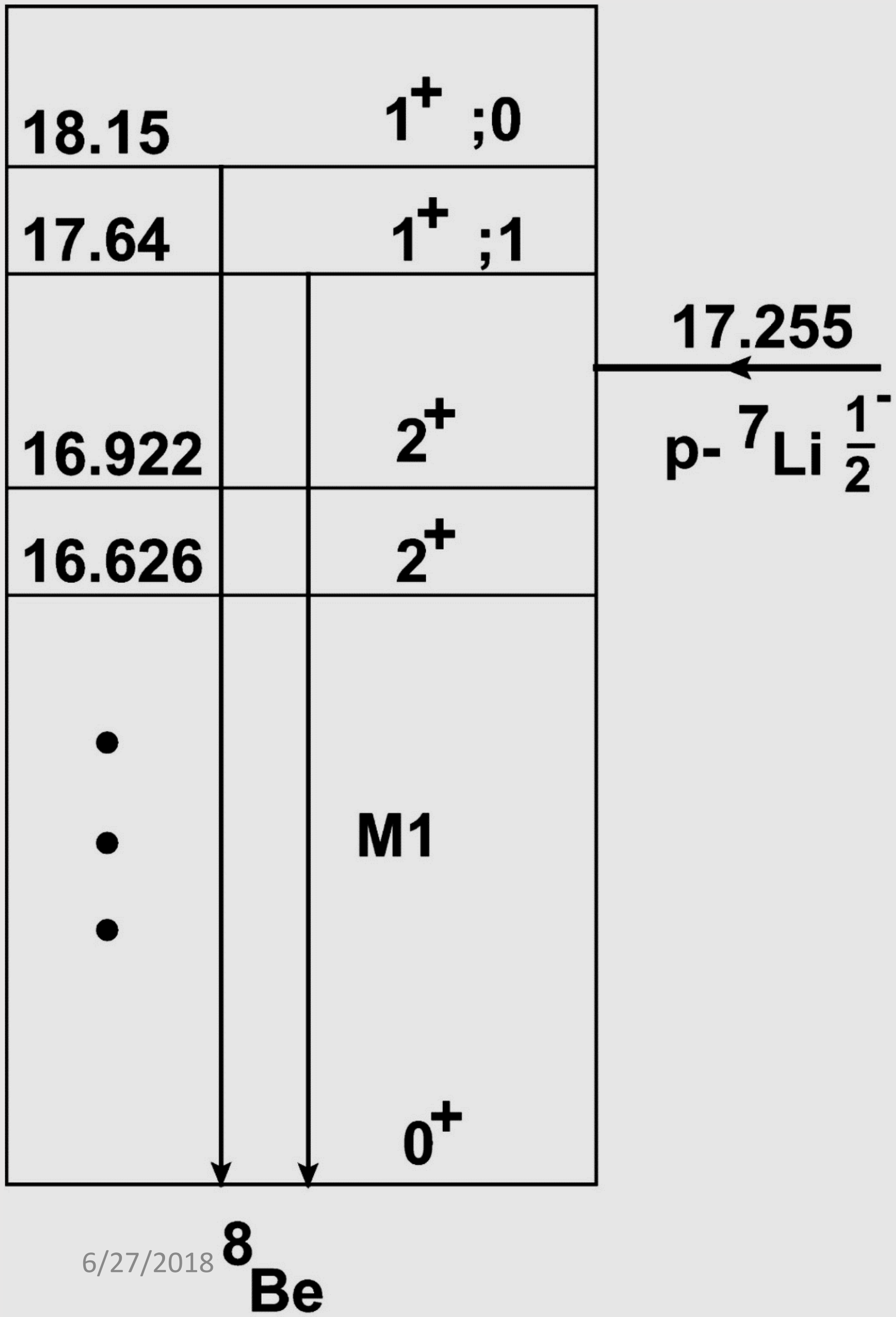
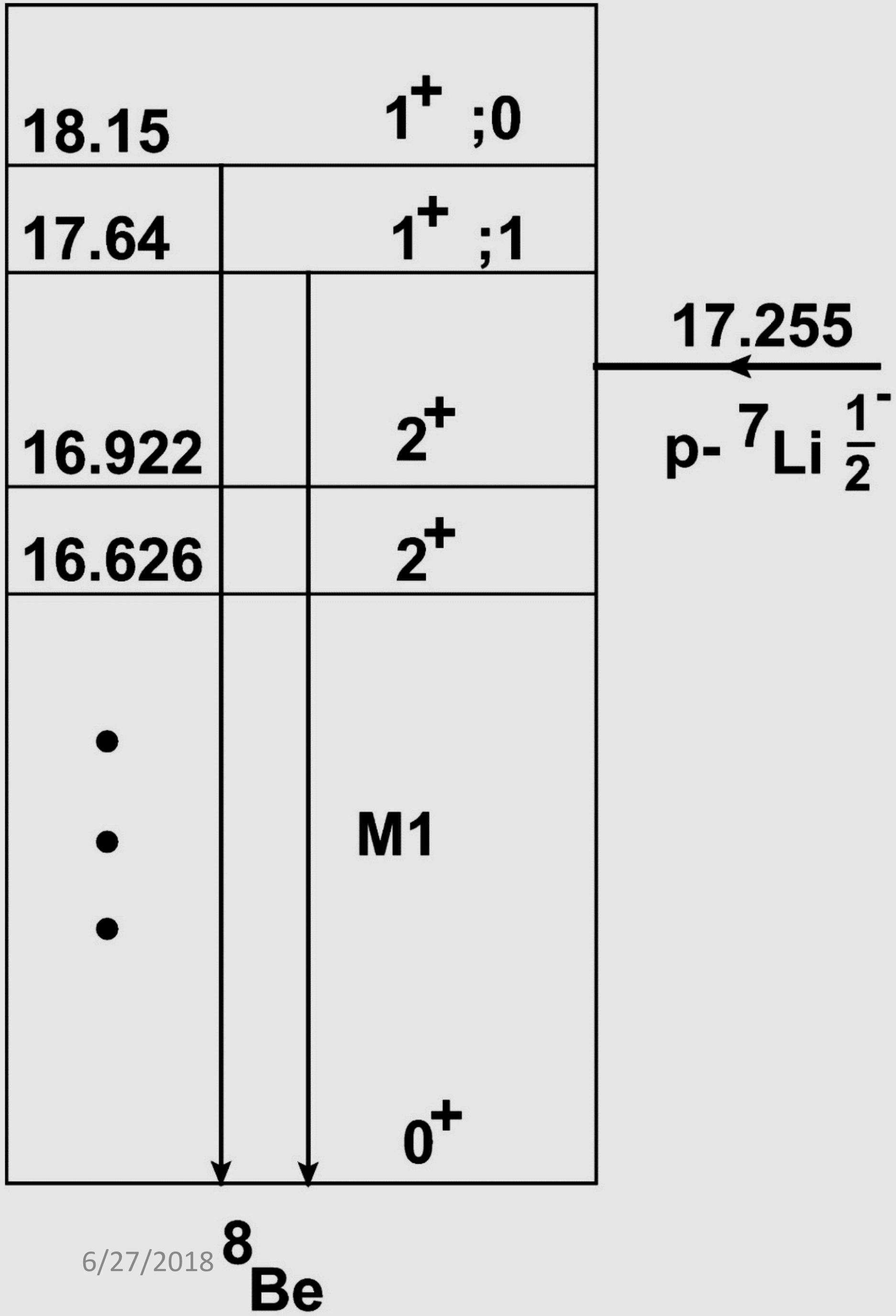
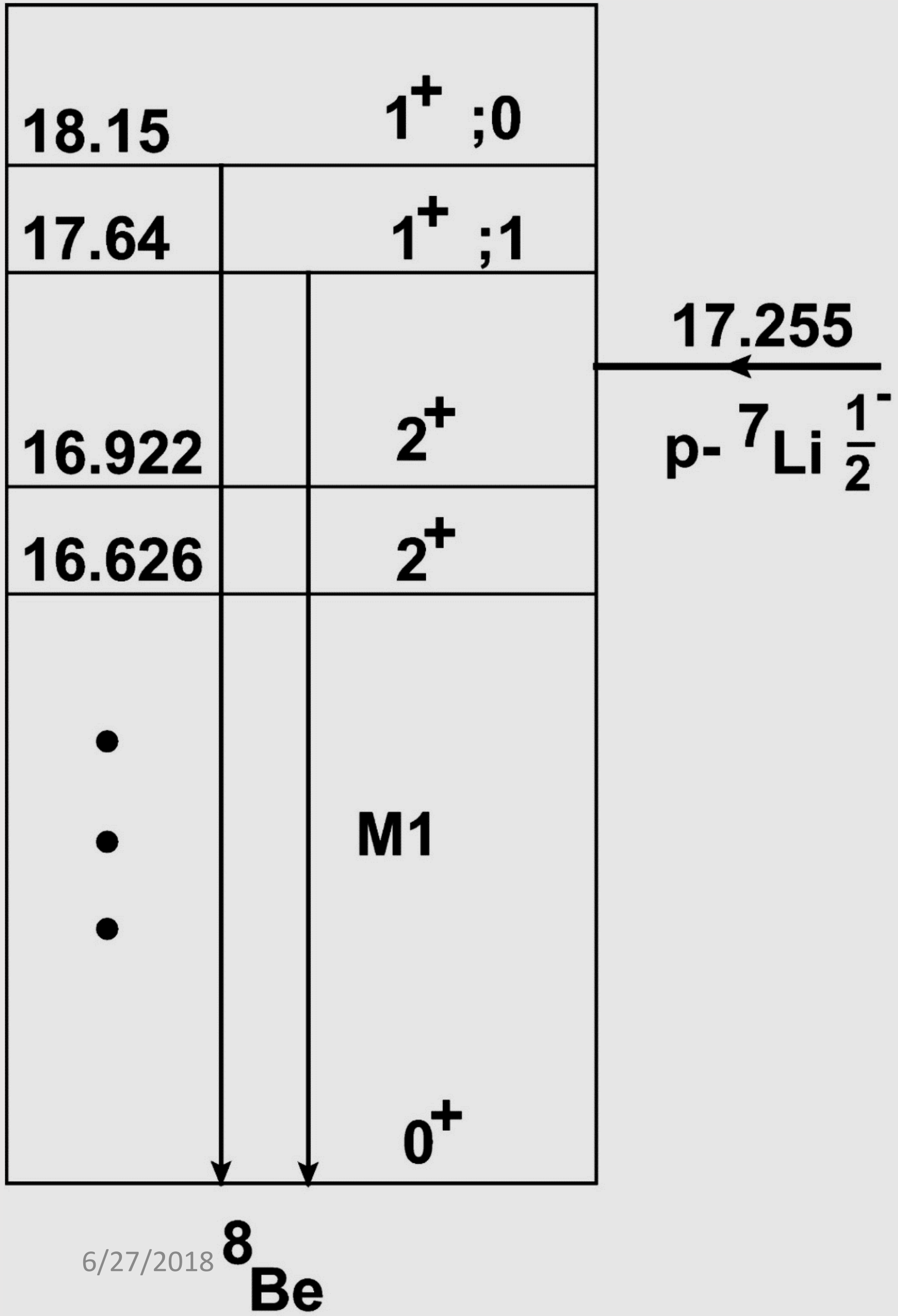




EM transitions

$U_{\lambda SL}$	λ	S	L
E1	1	1	0
M1	1	1, 2	1
E2	2	1, 2	1



EM transitions

Operator rank

$U_{\lambda SL}$	λ	S	L
E1	1	1	0
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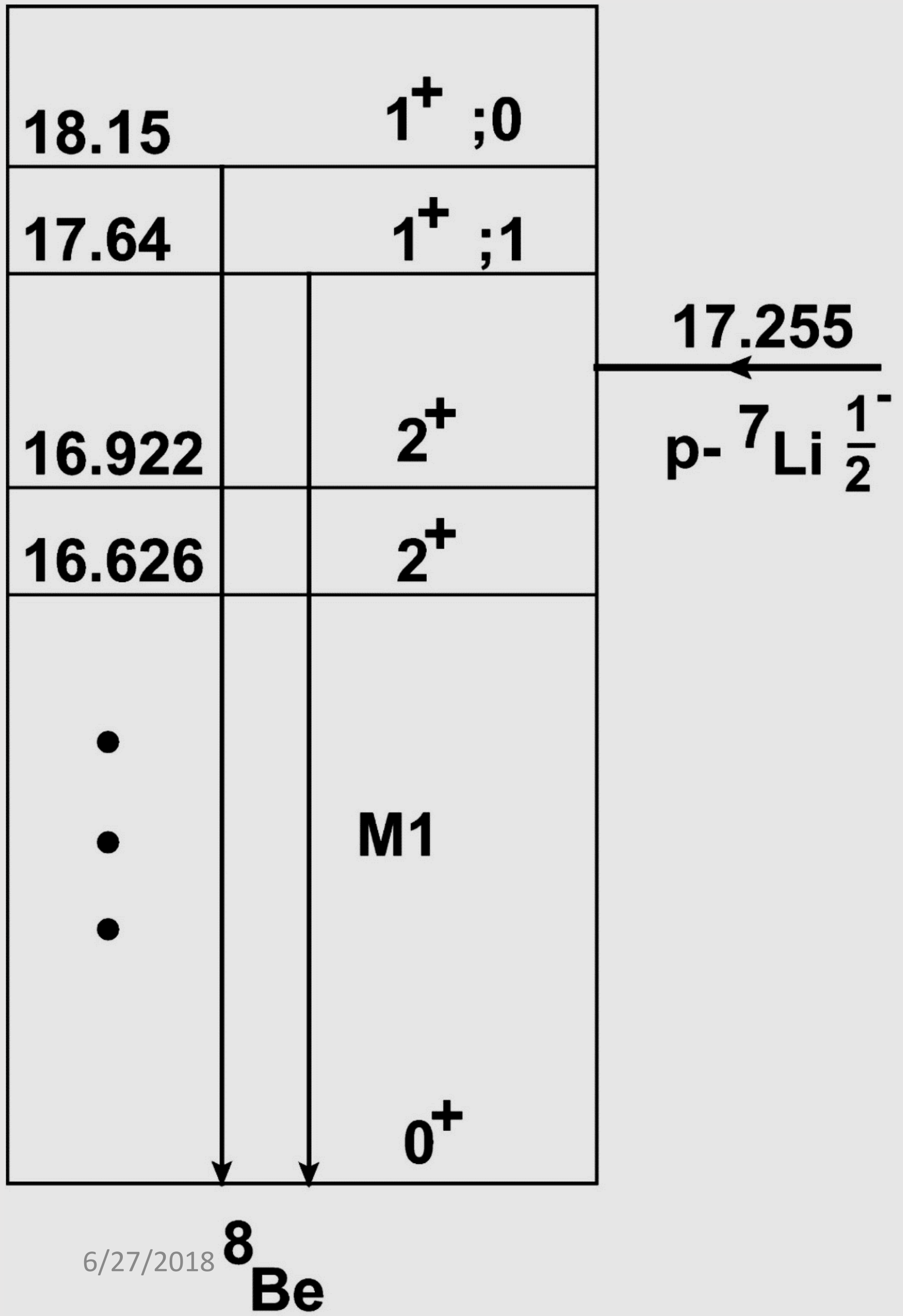
E2	2	1, 2	1



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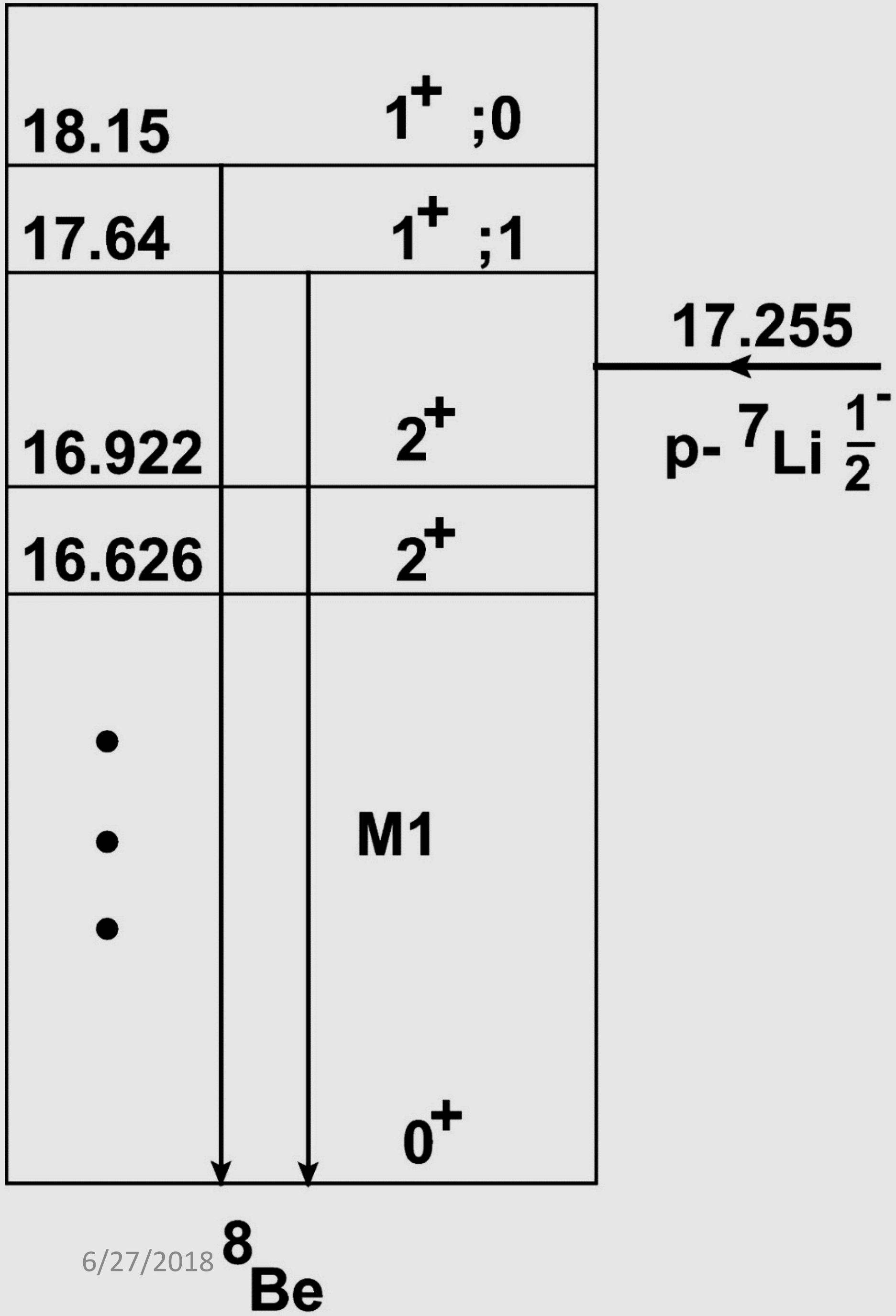
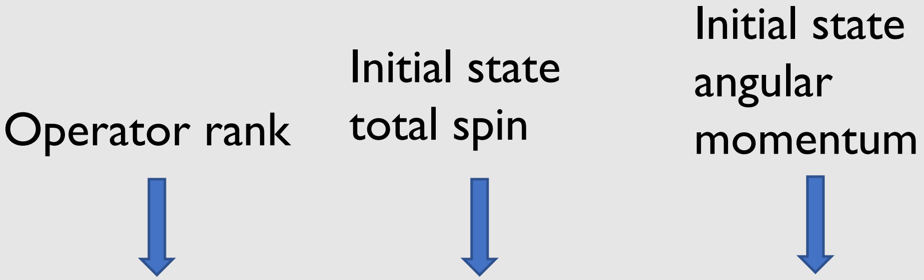


EM transitions



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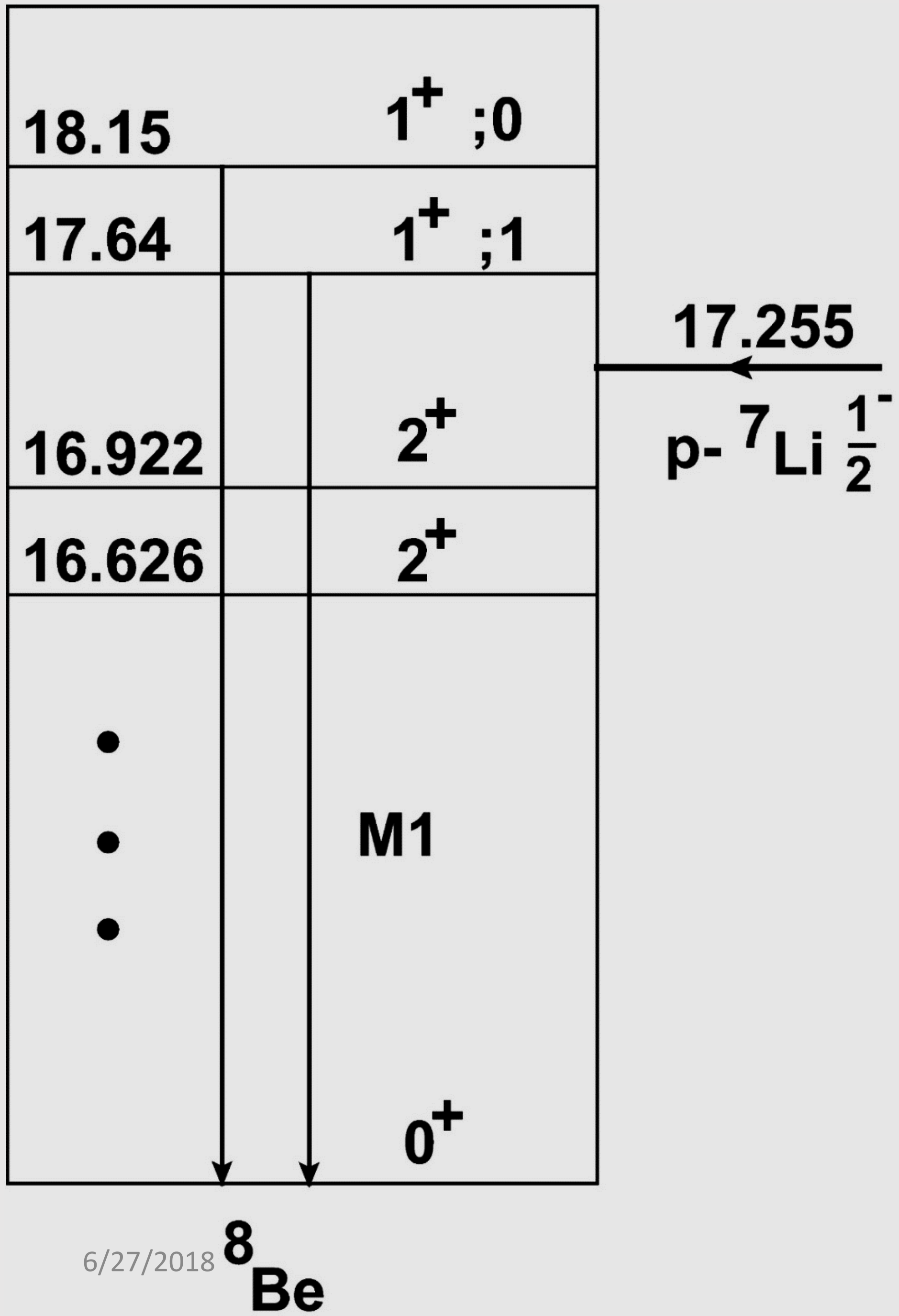

EM transitions

Operator rank ↓ (λ)
Initial state total spin ↓ (S)
Initial state angular momentum ↓ (L)

$U_{\lambda SL}$	λ	S	L
E1	1	1	0
M1	1	1, 2	1
E2	2	1, 2	1

X.Z. and G. Miller, 2017: they interfere!

Photon production data

D. Zahnow et.al., *Z. Phys. A* **351**, 229 (1995); B. MainsBridge, *Nucl.Phys.* **21**, 1(1960); D.J. Schlueter, et.al., *Nucl.Phys.* **58**, 254 (1964)

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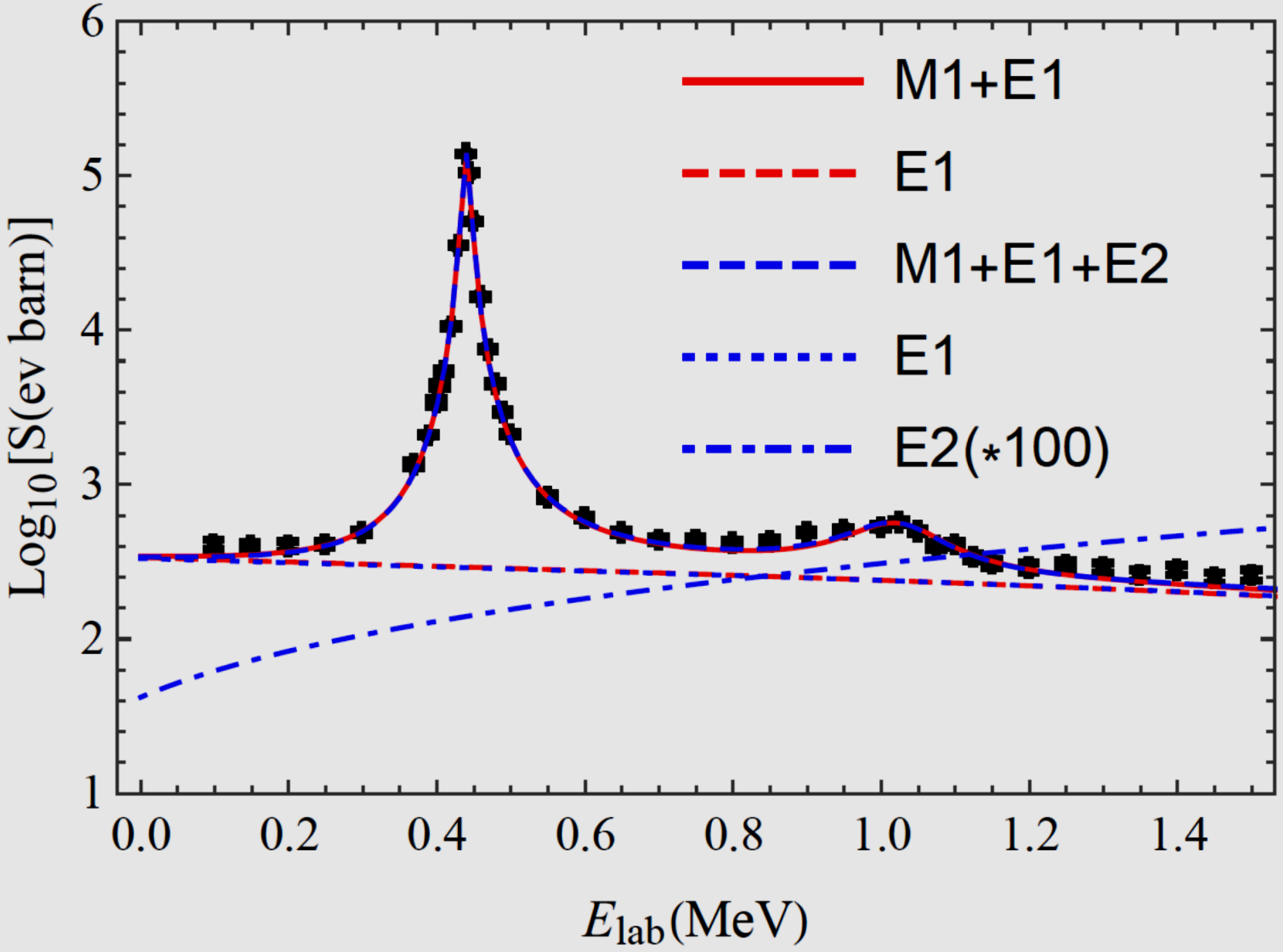

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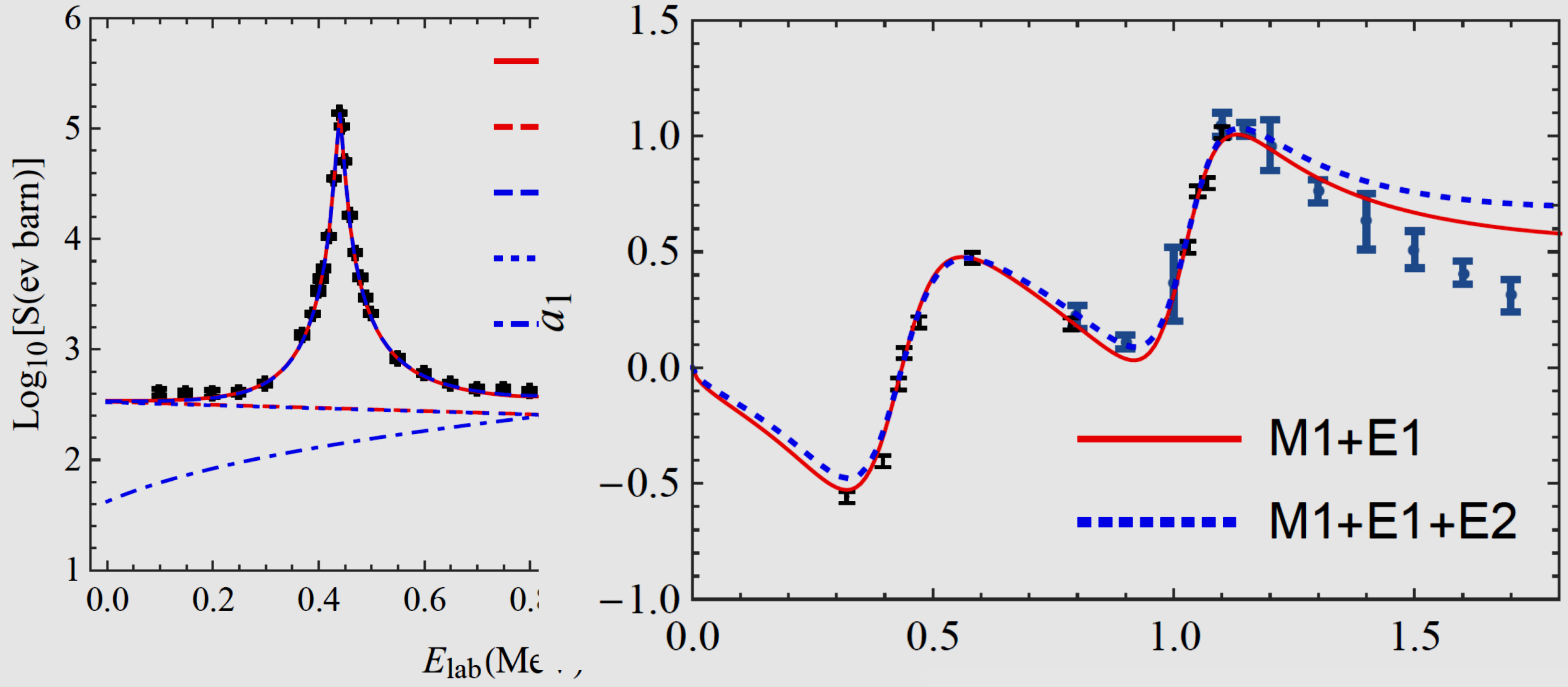
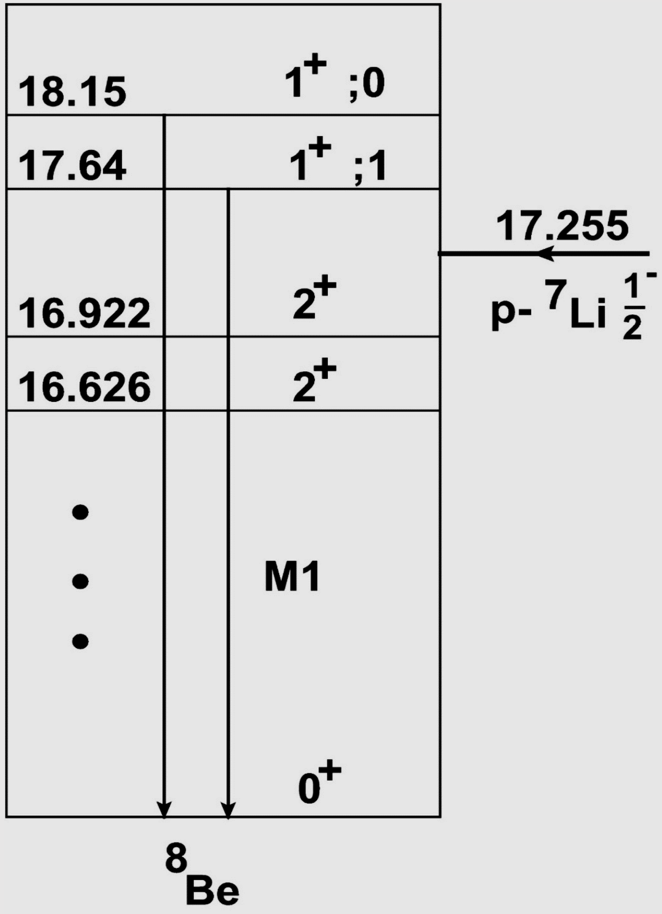
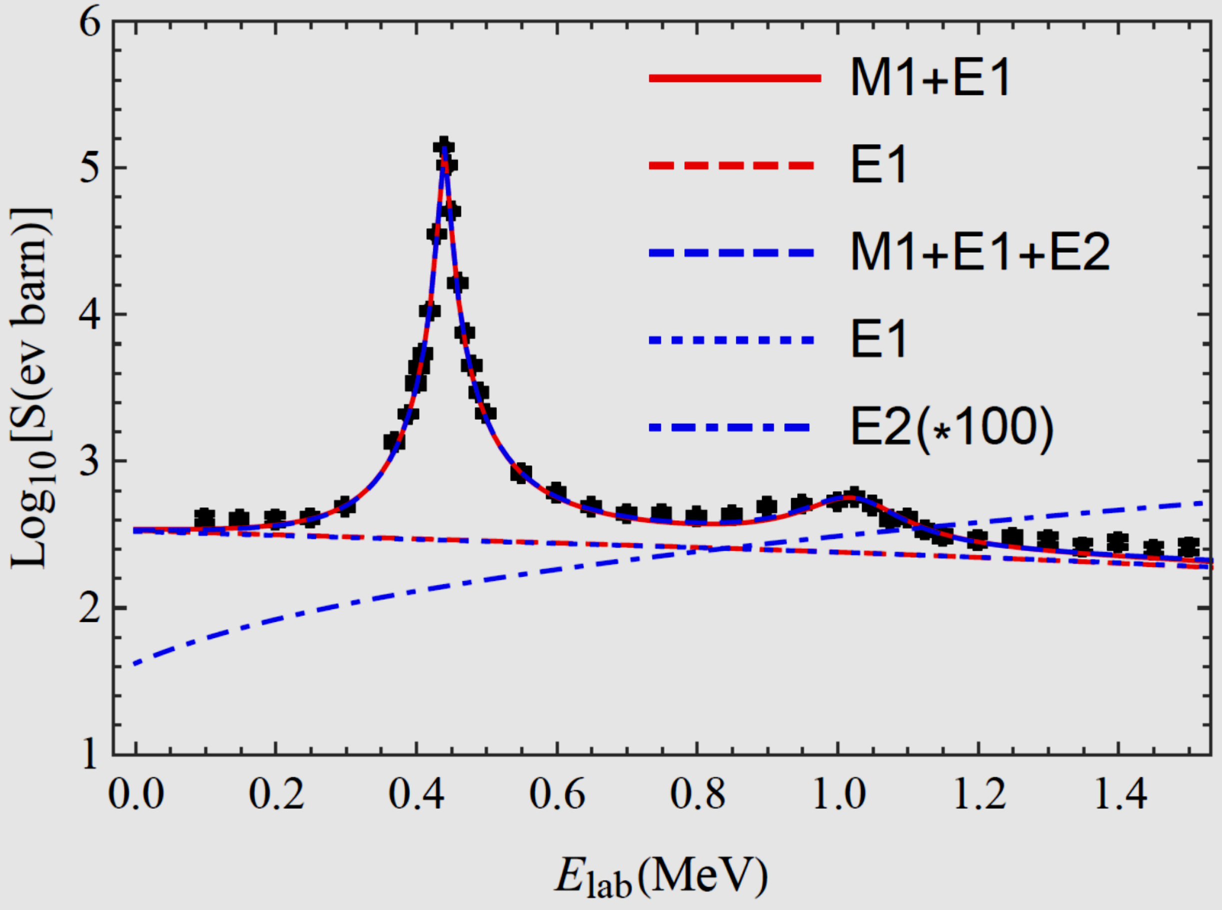
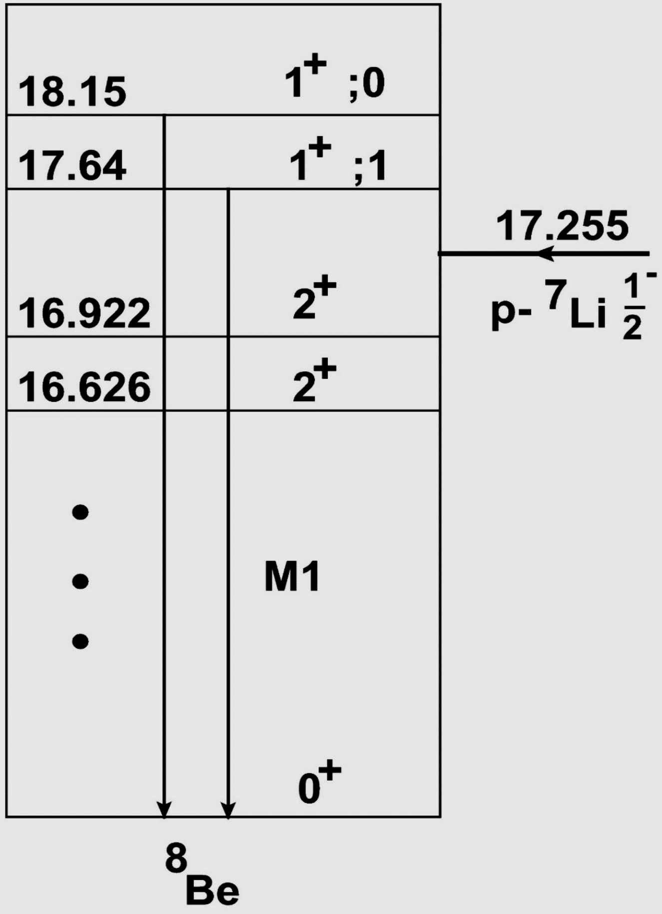


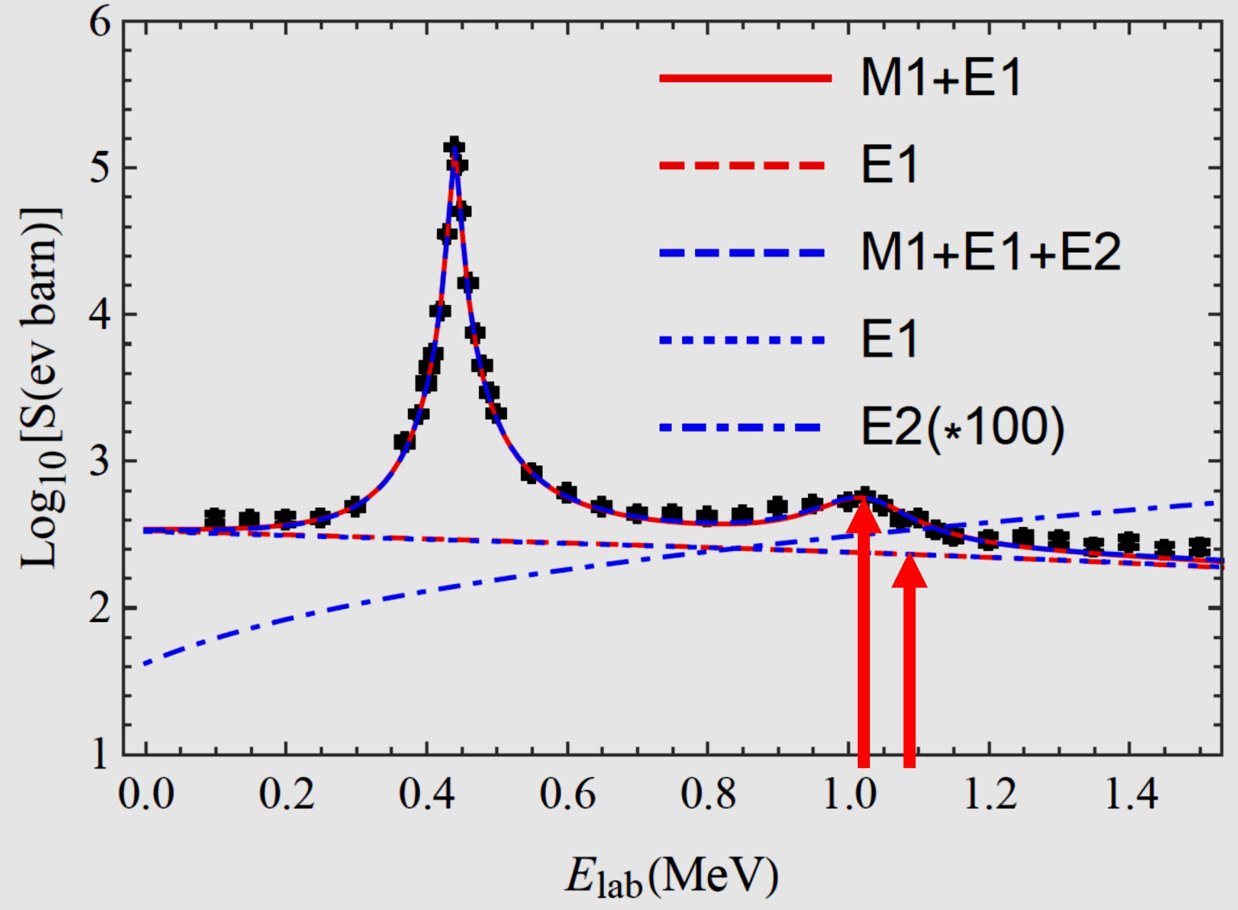
On dark-photon explanation





On dark-photon explanation





- *A dark-photon with 17-MeV mass might be the cause (e.g. J. L. Feng et.al., 2017)*
- → $J_{dark\,\gamma} = J_{EM,vec}$ → E1 and M1 have similar size for photon → smooth background production of dark photon (not seen experimentally)

Summary

- A theoretical calculation with well-understood systematical uncertainty is really useful for predictions and guiding experiments (lesson from the EFT application in radiative capture reactions)
- The NC photon production couldn't fully explain the MiniBooNE low energy event excess (not then and not now)
- Weak-Compton scattering amplitude is relevant for the NC photon production, and radiative correction to weak processes (parity-violating electron-nucleon scattering, neutrino-nucleon scattering, and neutron beta decay)
- Nucleon axial current form factors are being studied in a light-front quark model as well as other approaches. Stay tuned
- Be-8 anomaly: the dark-photon explanation seems inconsistent with the experiment

EFT-based model for $J \equiv \langle \mathrm{Be} | \hat{J} | \mathrm{Li} + \mathrm{p} \rangle$

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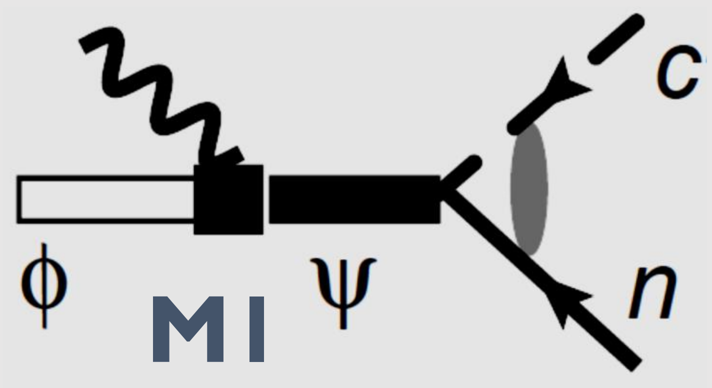
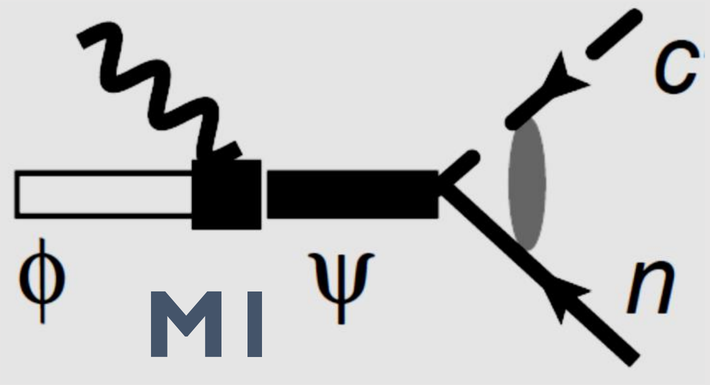
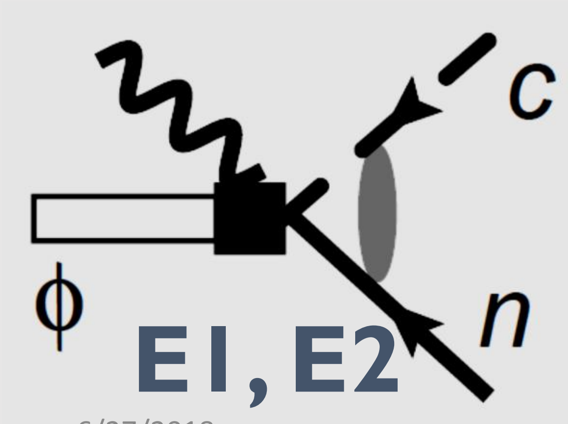


EFT-based model for

$$J \equiv \langle \mathrm{Be} | \hat{J} | \mathrm{Li} + \mathrm{p} \rangle$$



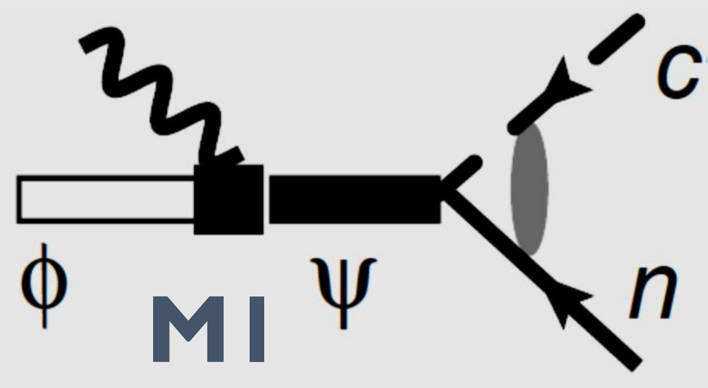


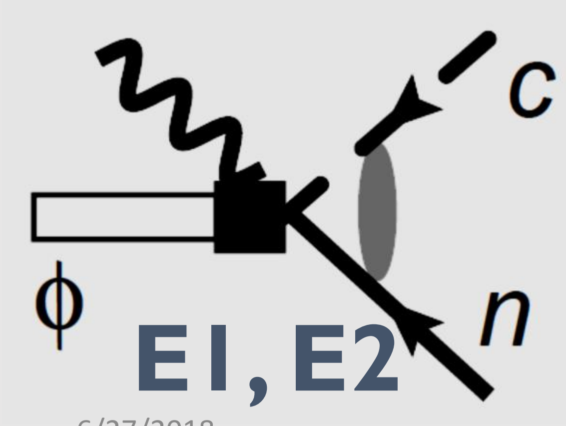
EFT-based model for

$$J \equiv \langle \text{Be} | \hat{J} | \text{Li} + \text{p} \rangle$$

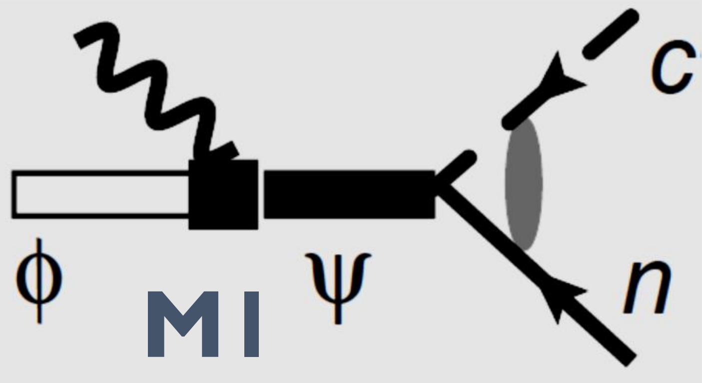
$$J^t = (CG)\, q\, U_{E1} + q^2 \frac{p}{M} \left[(CG)\, U_{E2,1} + (CG)\, U_{E2,2} \right]$$

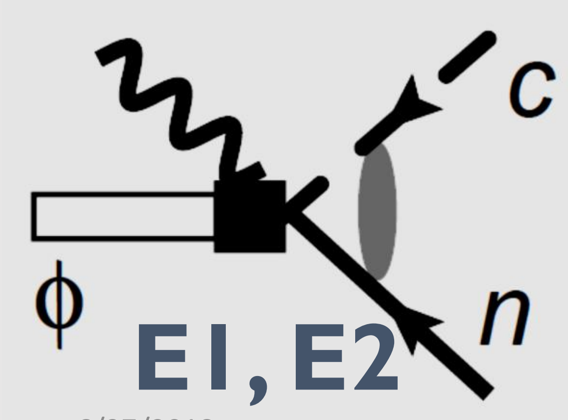
$$J^i = (CG)\, \omega\, U_{E1} + q \frac{p}{M} \begin{bmatrix} (CG)\, U_{M1,1} + (CG)\, U_{M1,2} \\ +(CG)\, \omega\, U_{E2,1} + (CG)\, \omega\, U_{E2,2} \end{bmatrix}$$





EFT-based model for $J \equiv \langle \mathrm{Be} | \hat{J} | \mathrm{Li} + \mathrm{p} \rangle$





$$J^t = (CG)\, q\, U_{E1} + q^2 \frac{p}{M}\left[(CG)\, U_{E2,1} + (CG)\, U_{E2,2}\right]$$

$$J^i = (CG)\, \omega\, U_{E1} + q \frac{p}{M}\begin{bmatrix}(CG)\, U_{M1,1} + (CG)\, U_{M1,2} \\ +(CG)\, \omega\, U_{E2,1} + (CG)\, \omega\, U_{E2,2}\end{bmatrix}$$

$$U_{M1,1} \sim -\frac{\sqrt{\Gamma_{\gamma(0)}\Gamma_{(0)}X_{(0)}}}{E - E_{(0)} + i\frac{\Gamma_{(0)}}{2}} + \frac{\sqrt{\Gamma_{\gamma(1)}\Gamma_{(1)}X_{(1)}}}{E - E_{(1)} + i\frac{\Gamma_{(1)}}{2}}$$

$$U_{M1,2} \sim \frac{\sqrt{\Gamma_{\gamma(0)}\Gamma_{(0)}(1 - X_{(0)})}}{E - E_{(0)} + i\frac{\Gamma_{(0)}}{2}} + \frac{\sqrt{\Gamma_{\gamma(1)}\Gamma_{(1)}(1 - X_{(1)})}}{E - E_{(1)} + i\frac{\Gamma_{(1)}}{2}}$$

$$U_{E1} \sim d_{E1}(1 - d'_{E1}\frac{p^2}{\Lambda^2}); \quad U_{E2,1} \sim d_{E2,1}; \quad U_{E2,2} \sim d_{E2,2}$$