Neutron polarizabilities and new physics searches with $\gamma d \to e^+e^-pn$

Cornelis Mommers, JGU Mainz, 2026-03-26

Phys. Rev. D 109, 095010

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  - Values electric and magnetic neutron polarizabilities
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- For both need to measure processes on the neutron

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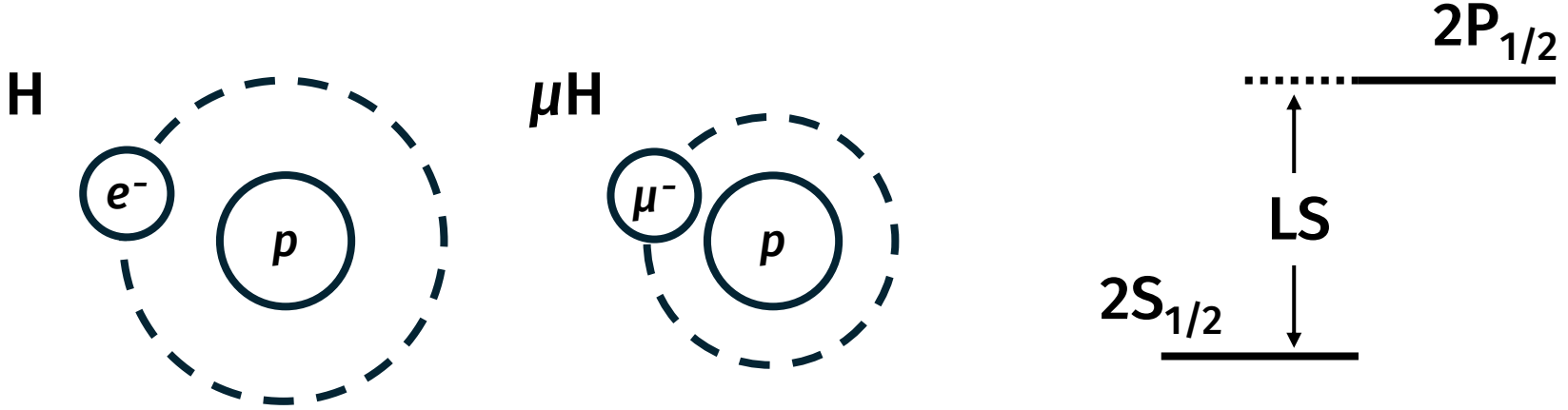
- Example: Lamb shift muonic atoms



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- LS_{theo} = 1668.489(14) meV — Bound-state QED
  − 106.220(8) meV $fm^{-2} \times r_\alpha^2$ + 0.0112 meV — Finite-size effects
  + 9.340(250) meV — 2PE
  − 0.150(150) meV — 3PE

r_α^2: α r.m.s charge radius

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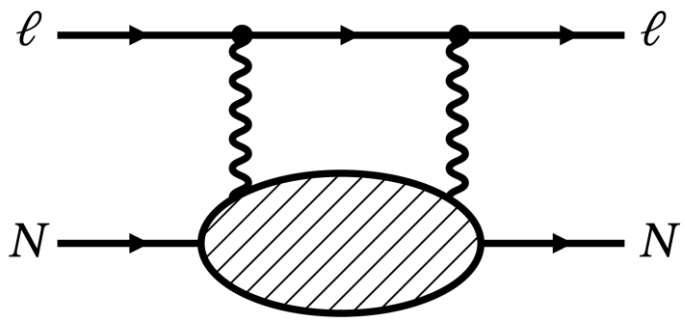

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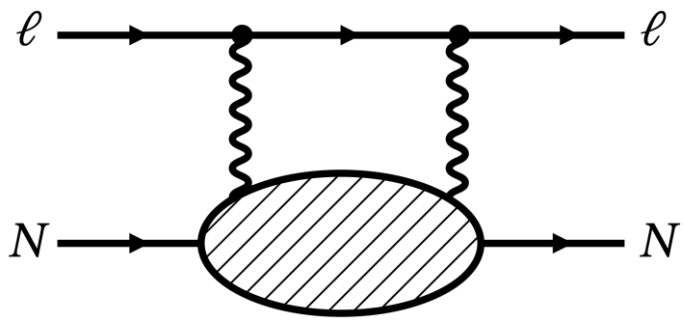

- δ_{exp} = 0.048 meV
- δ_{th}(2PE) = 0.250 meV = 520% of δ_{exp} → Theory improvements needed!
  - δ_{th}(2PE, polarizabilities) = 41% of δ_{th}(2PE) → Better extraction needed!
    Diepold et al. *Annals Phys.* 396 (2018) 220-244 → Similar for other μ atoms

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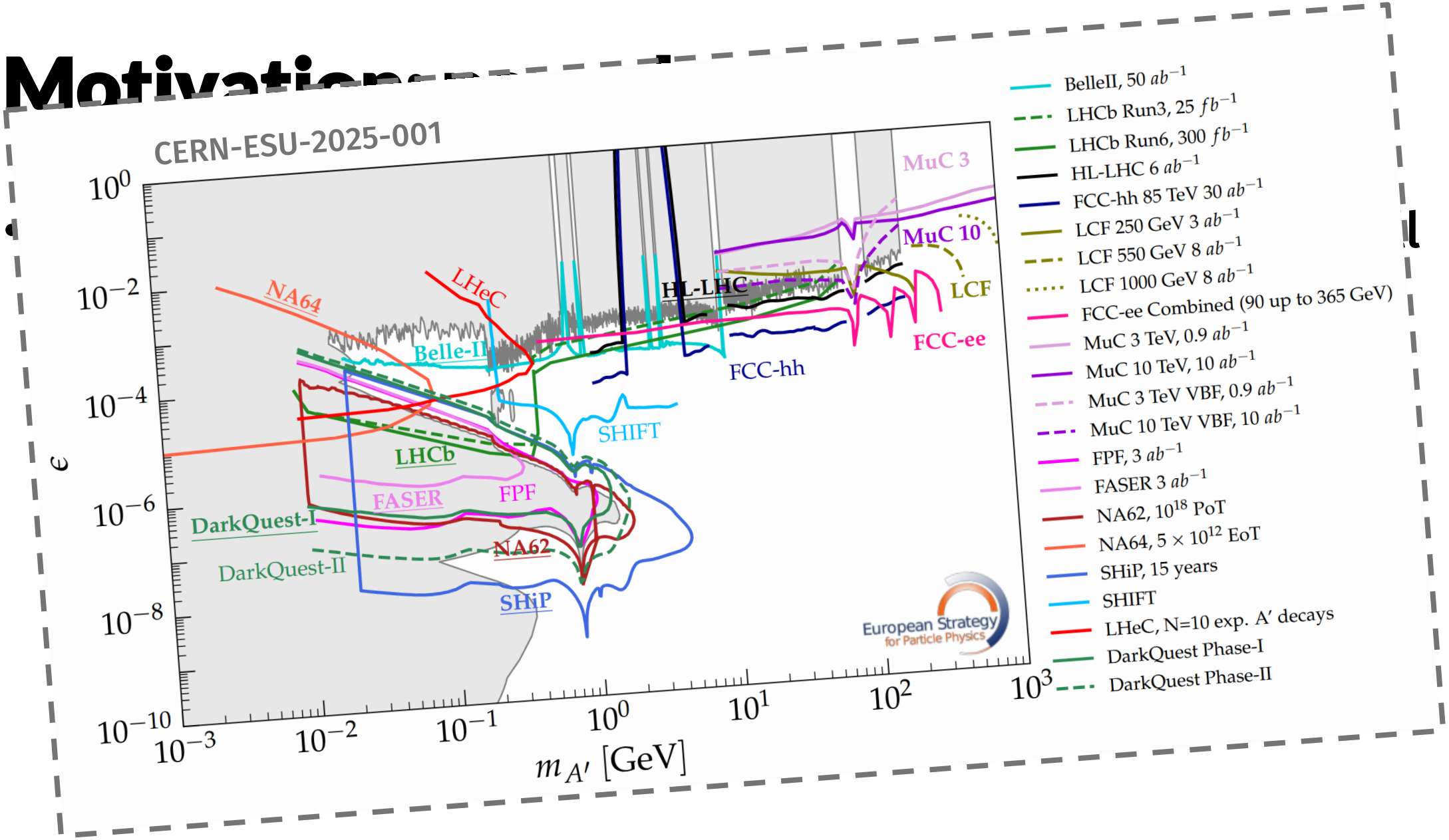
CERN-ESU-2025-001
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
ϵ
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
$m_{A'}$ [GeV]
NA64
LHeC
Belle-II
HL-LHC
MuC 3
MuC 10
LCF
FCC-ee
FCC-hh
SHIFT
LHCb
FASER
FPF
DarkQuest-I
DarkQuest-II
NA62
SHiP
European Strategy for Particle Physics
BelleII, 50 ab^{-1}
LHCb Run3, 25 fb^{-1}
LHCb Run6, 300 fb^{-1}
HL-LHC 6 ab^{-1}
FCC-hh 85 TeV 30 ab^{-1}
LCF 250 GeV 3 ab^{-1}
LCF 550 GeV 8 ab^{-1}
LCF 1000 GeV 8 ab^{-1}
FCC-ee Combined (90 up to 365 GeV)
MuC 3 TeV, 0.9 ab^{-1}
MuC 10 TeV, 10 ab^{-1}
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FPF, 3 ab^{-1}
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NA62, 10^{18} PoT
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SHiP, 15 years
SHIFT
LHeC, N=10 exp. A' decays
DarkQuest Phase-I
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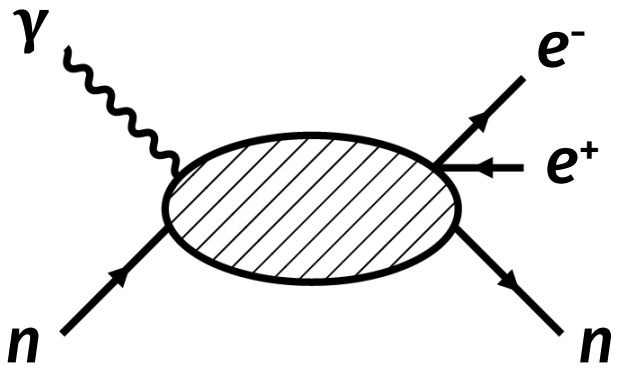
- Separate nucleon constraints can be translated to constraints on couplings of *u* and *d* quarks
- Together with lepton constraints severely restrict permissible new-physics models
- Improved constraints for neutron-*X* coupling with m_X ~ 10-100 MeV possible?

Consider $\gamma n \longrightarrow e^+e^-n$

- Consider $\gamma n \rightarrow e^+e^-n$ at low virtualities



Consider $\gamma n \to e^+e^-n$

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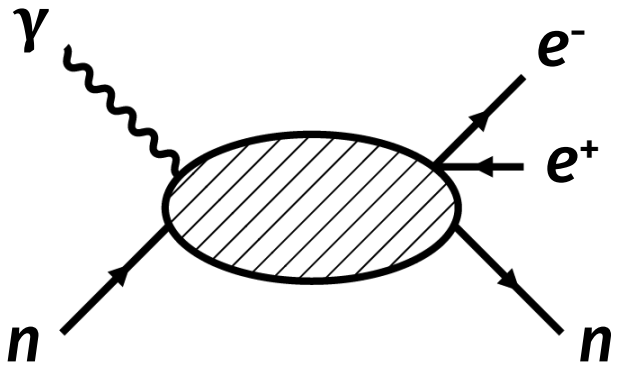
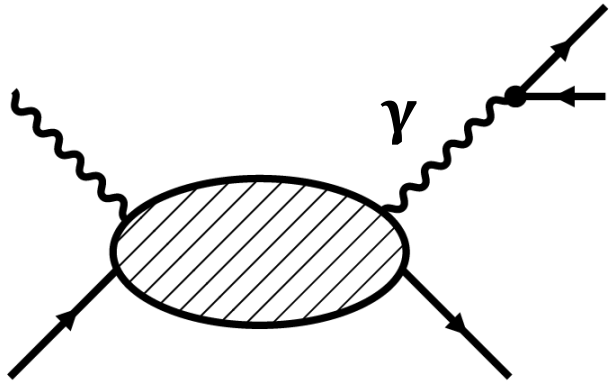
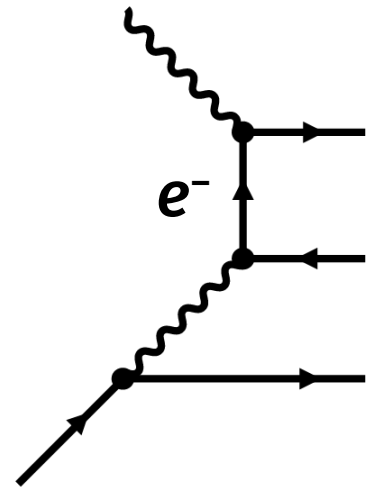




Born + non-Born terms
(Nucleon Compton)



Bethe-Heitler
(crossed not shown)

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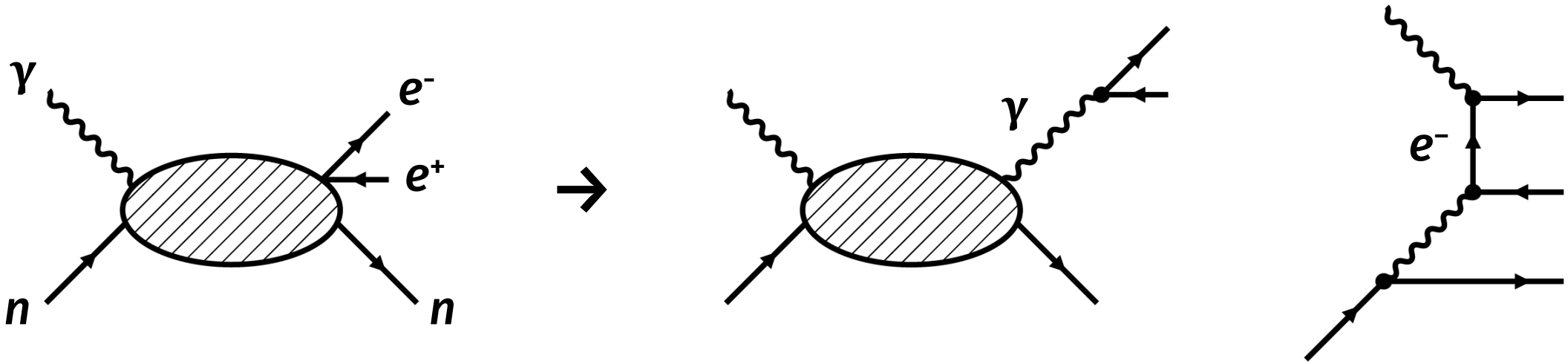
- Nucleon Compton scattering + Bethe-Heitler
- Enhanced sensitivity polarizabilities via Bethe-Heitler interference! (c.f. $\gamma n \rightarrow \gamma n$)



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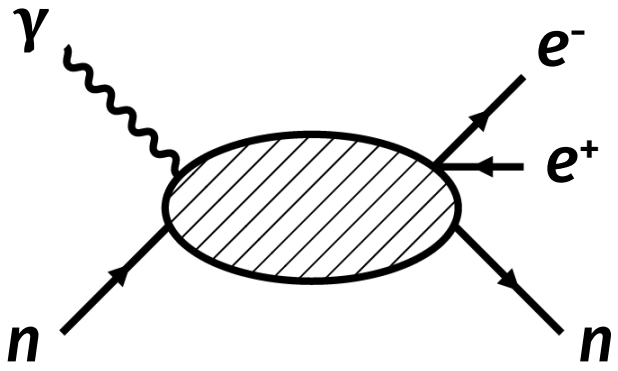

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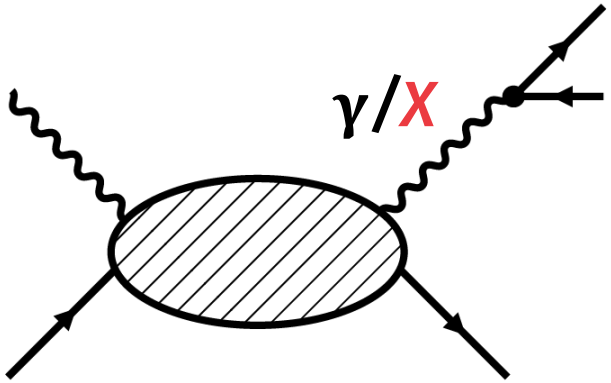

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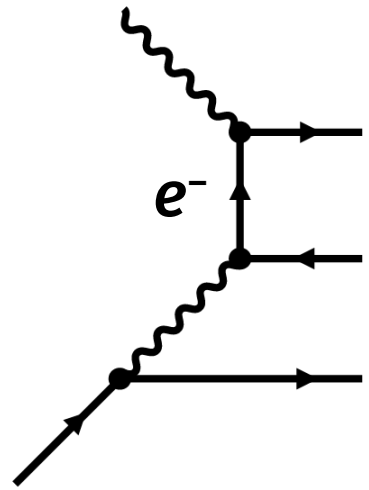

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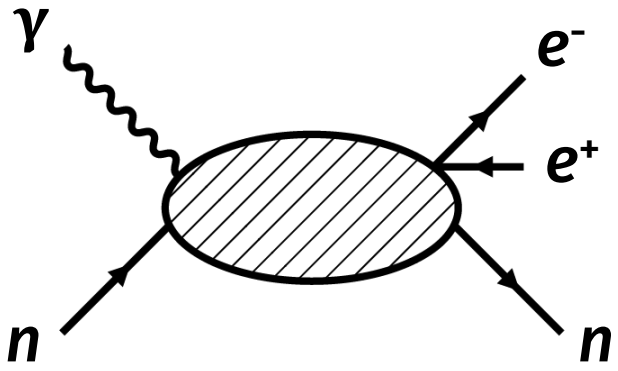

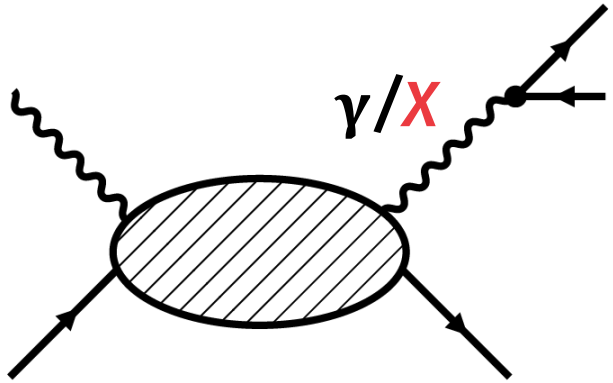

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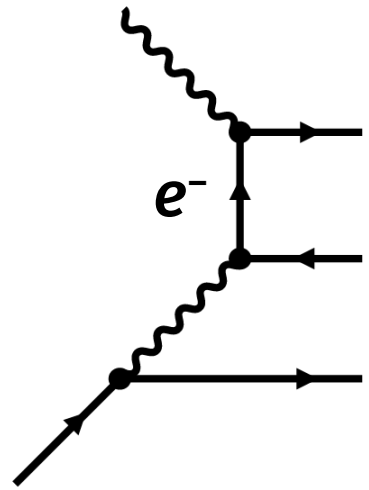

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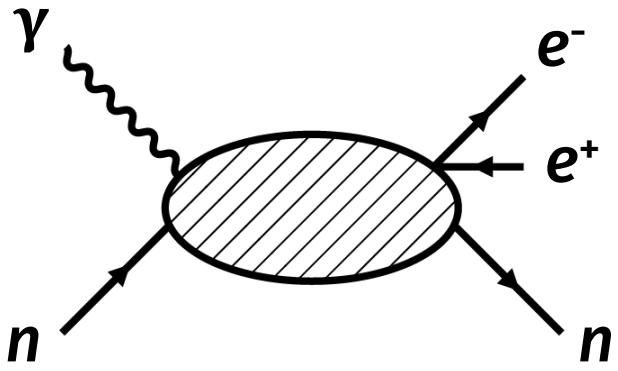

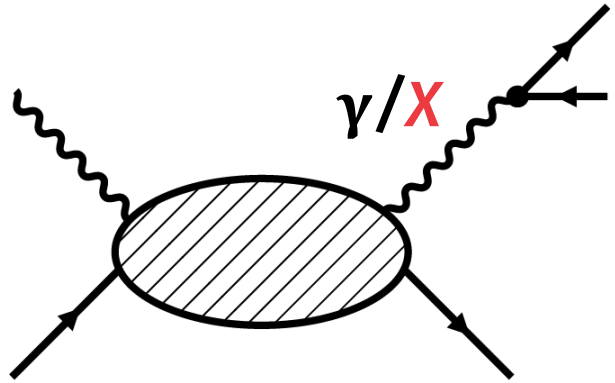

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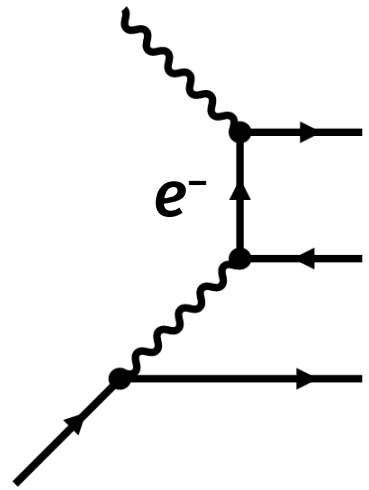

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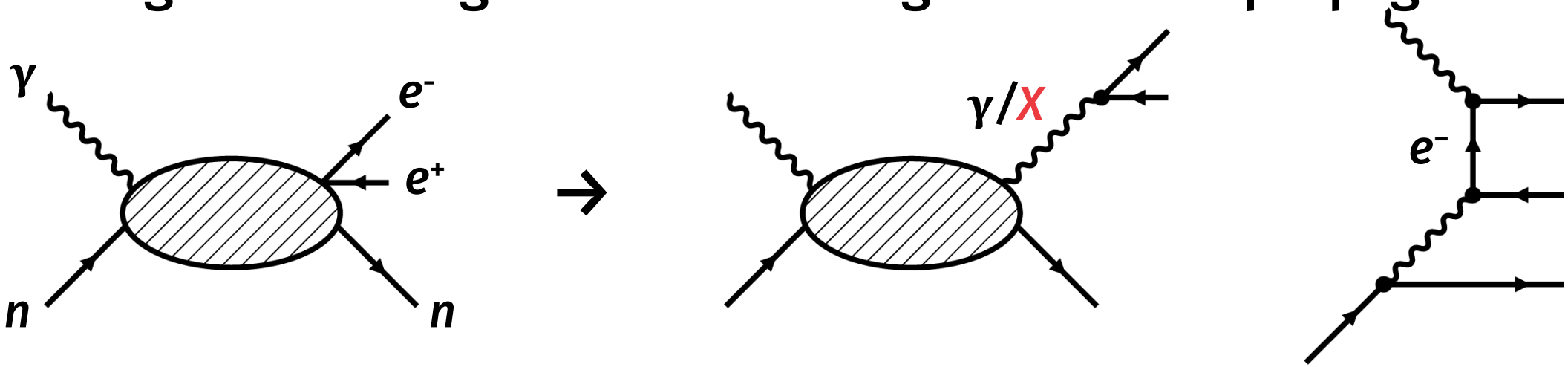
- In single bin strong enhancement signal due to X propagator



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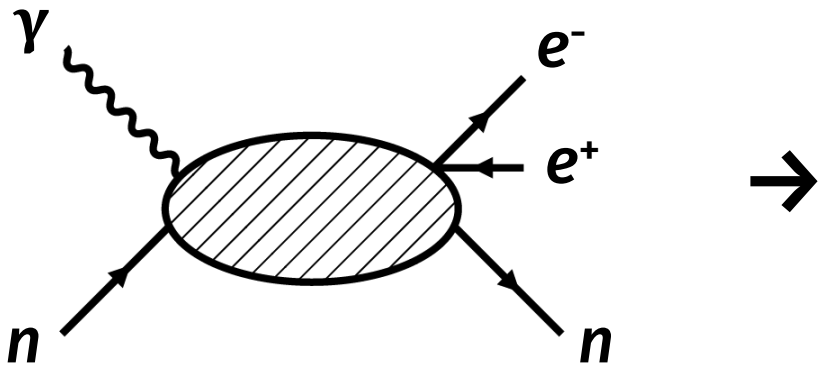

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- Consider $\gamma n \rightarrow e^+e^-n$ at low virtualities
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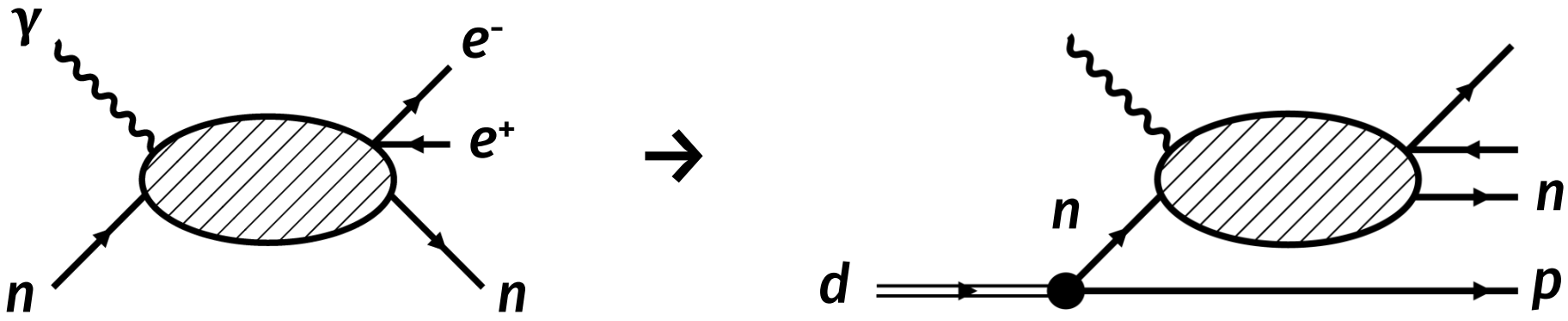
  - Need theoretical approach matching what can be measured
  - A solution: use $\gamma d \rightarrow e^+e^-pn$ (similar approaches previously successful)



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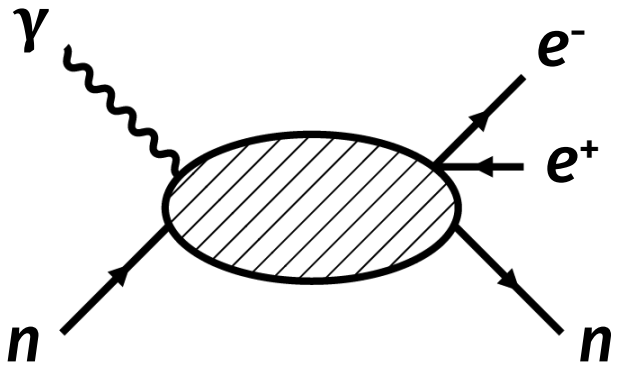
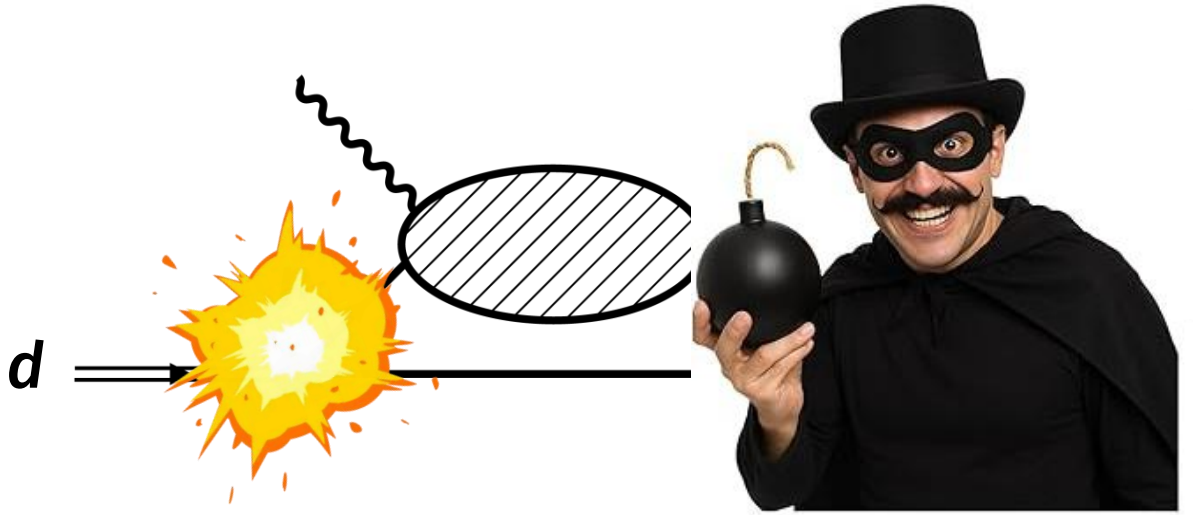
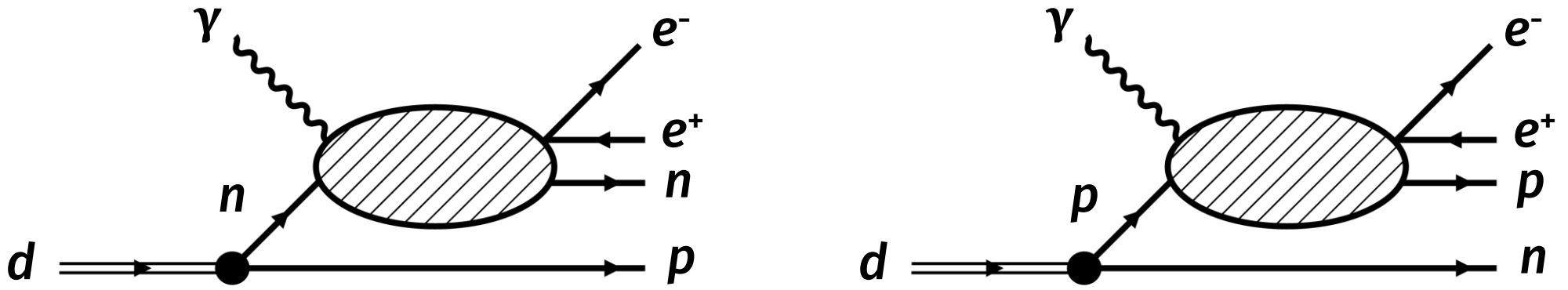




Some complications

- Can also strike proton



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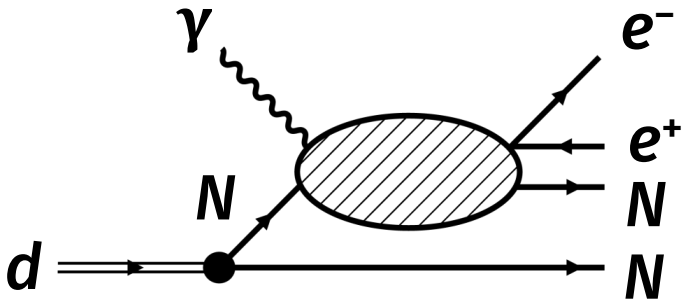
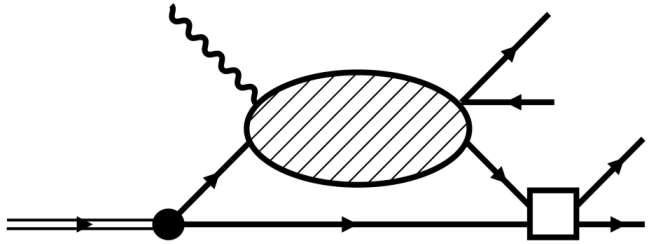
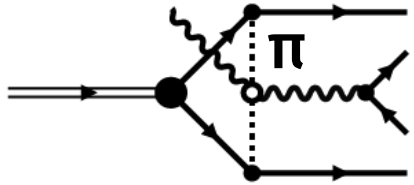


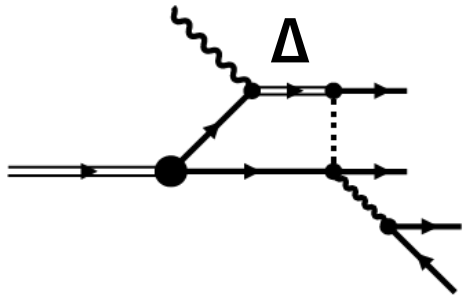
Impulse approximation



Final state interaction

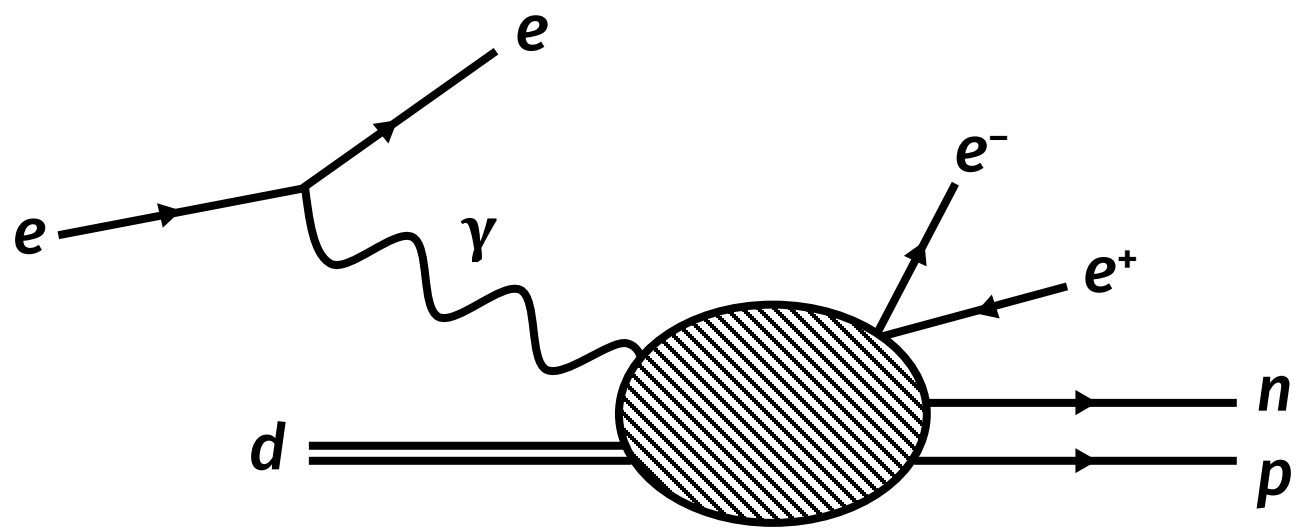


Meson exchange currents



Δ-isobar

Some complications

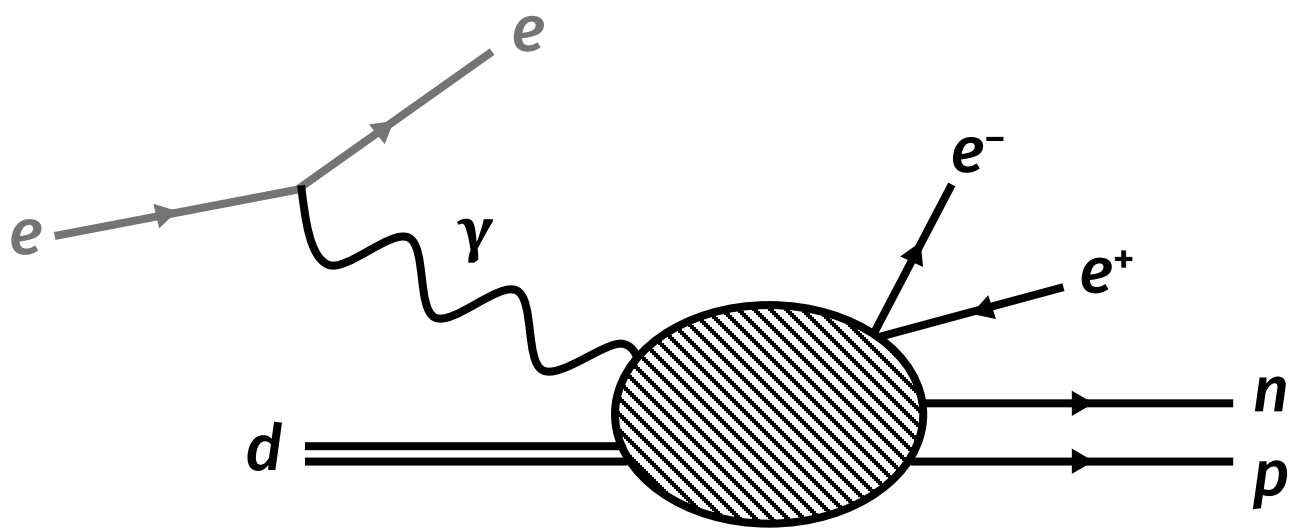


Scope of talk

- How to manage these ‘complications’
- Results

Deuteron disintegration

- For pilot calculation start with photodisintegration



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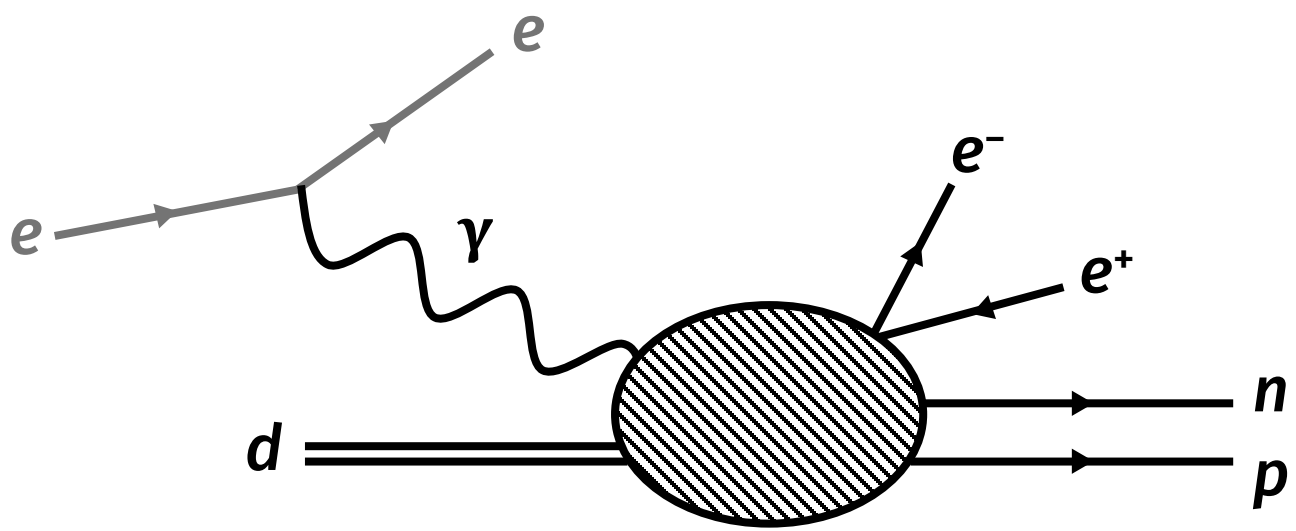
- Consider possible experiment at MAGIX@MESA (see prev. talk)



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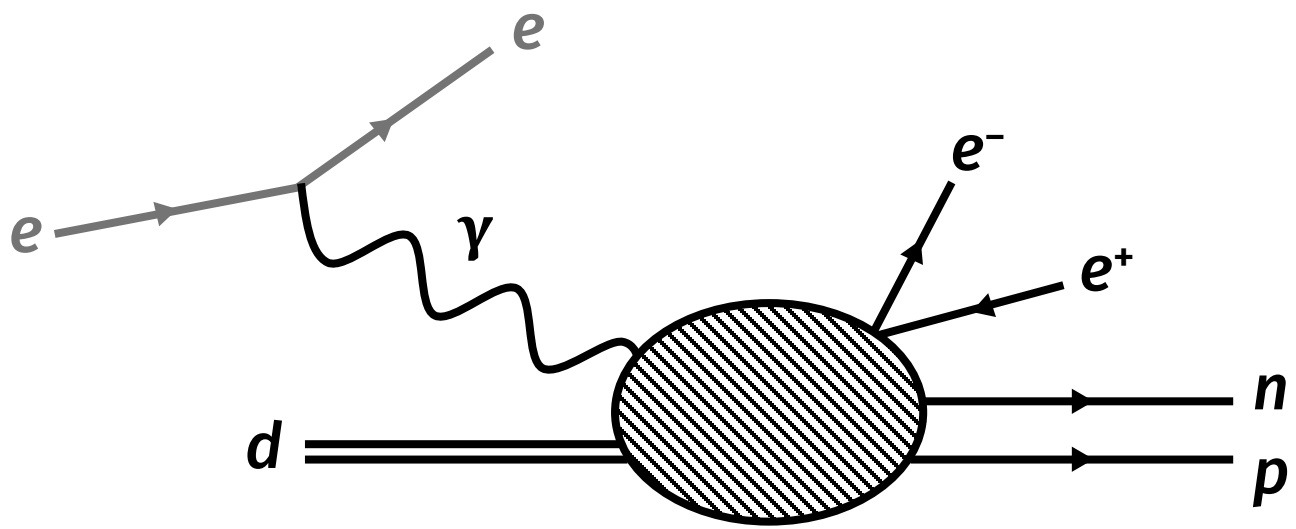
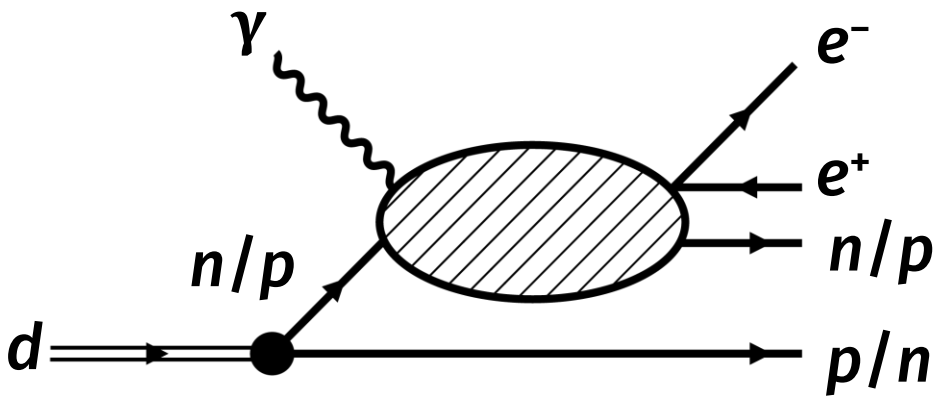


- Restrict kinematics:
  - Beam energies: 105 MeV
  - O(10 MeV) m_{ee}

Dominant topologies



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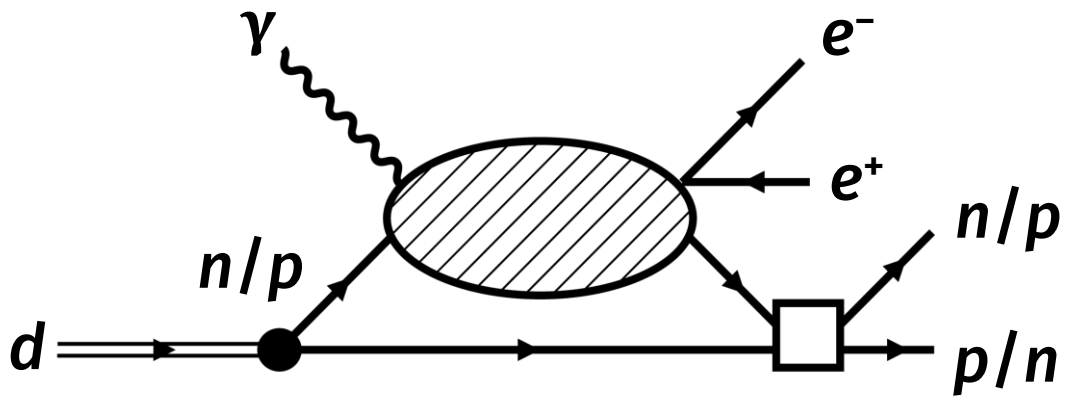
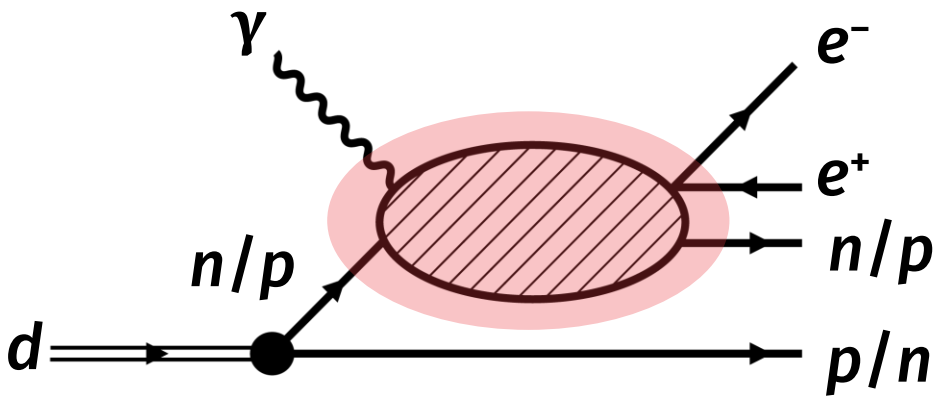


Final state interaction

- **IA dominant contribution, FSI ~ 20-30% correction**
  see e.g., Few Body Syst. 16 (1994) 101-125
- **Higher energies require different models,**
  see e.g., Phys. Rev. C 78, 014007 (2008)

Components of the model



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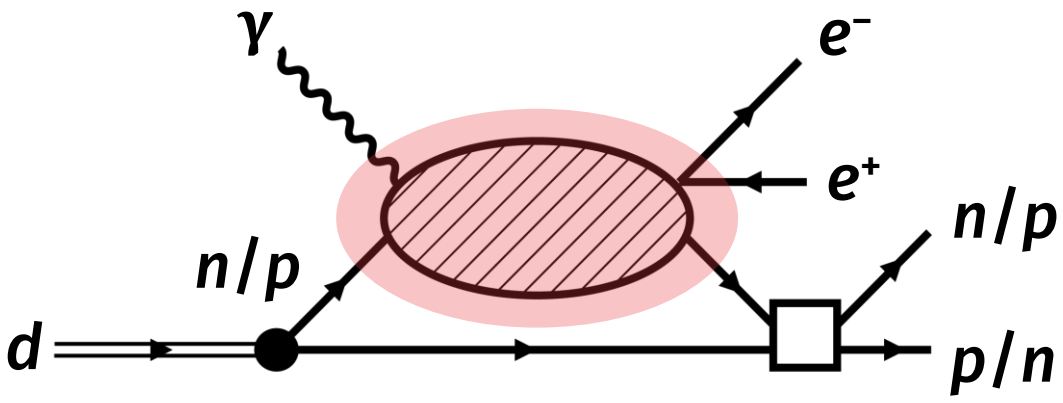
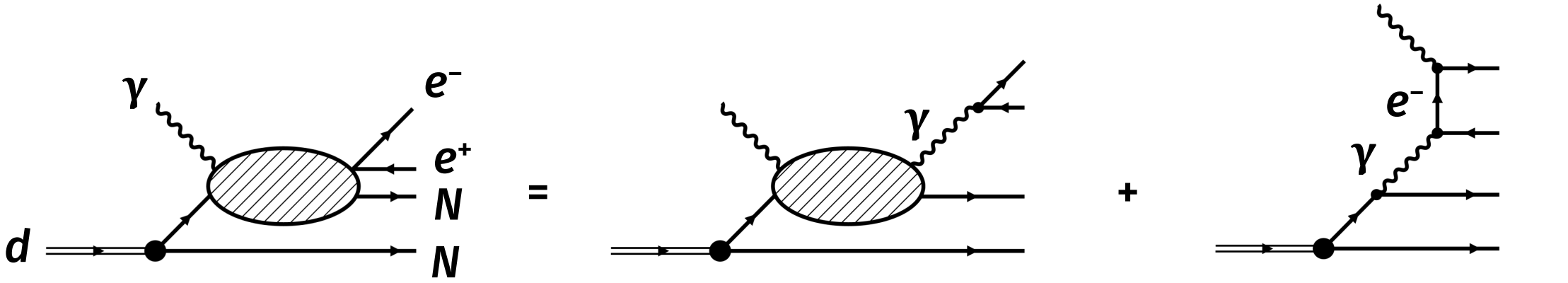


Final state interaction

- $\gamma N \rightarrow e^+e^-N$ interaction

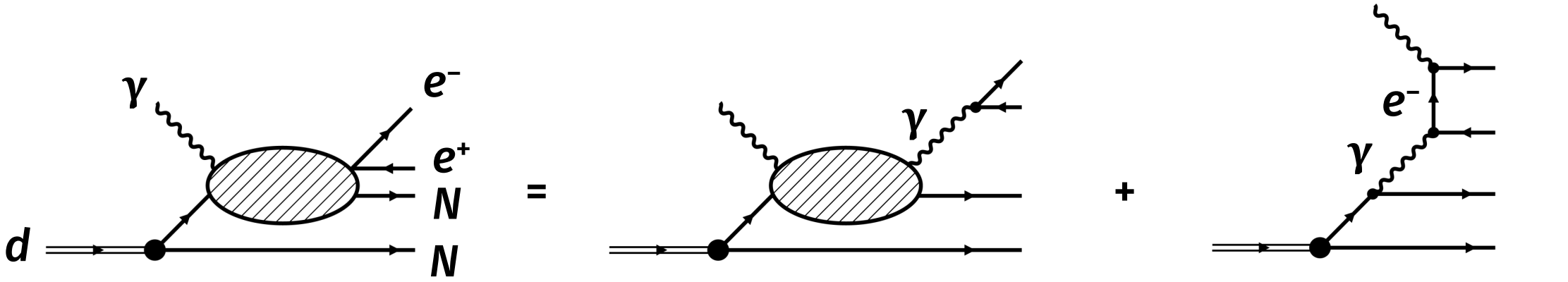
$\gamma N \to e^+e^-N$



Born + non-Born terms
(Nucleon Compton)

Bethe-Heitler
(crossed not shown)

$\gamma N \to e^+e^-N$

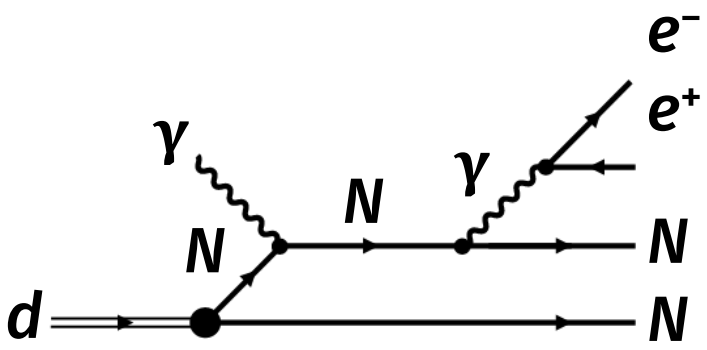


Born + non-Born terms
(Nucleon Compton)

Bethe-Heitler
(crossed not shown)

Bethe-Heitler not nuisance
but amplifier!

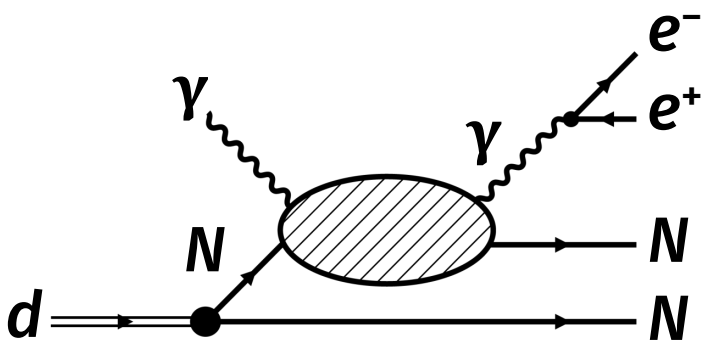
$\gamma N \to e^+e^-N$ (nucleon Compton)



Born term
(crossed not shown)

- Born term *defined* as nucleon pole,
  see e.g., Guichon, Liu & Thomas, *Nucl. Phys. A* 591 (1995) 606-638

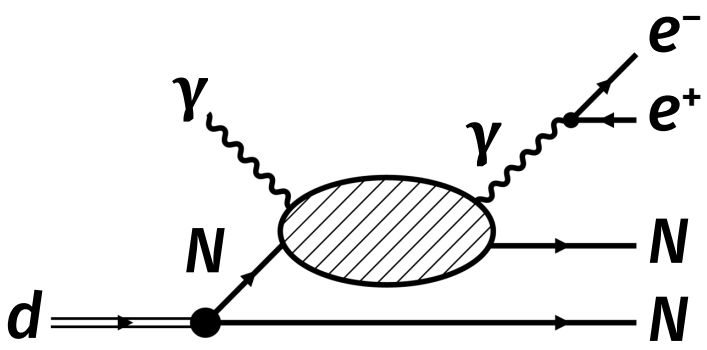
$\gamma N \to e^+e^-N$ (non-Born nucleon Compton)



Non-Born terms

- Non-Born terms:

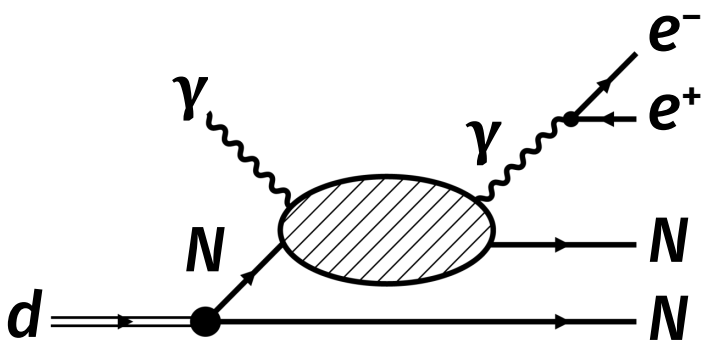
$\gamma N \to e^+e^-N$ (non-Born nucleon Compton)



Non-Born terms

- Non-Born terms:
  - Expand in 18 independent amplitudes

$\gamma N \to e^+e^-N$ (non-Born nucleon Compton)



Non-Born terms

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  - Reduces to 12 for virtual Compton scattering ($q^2 = 0$, $q'^2 < 0$)

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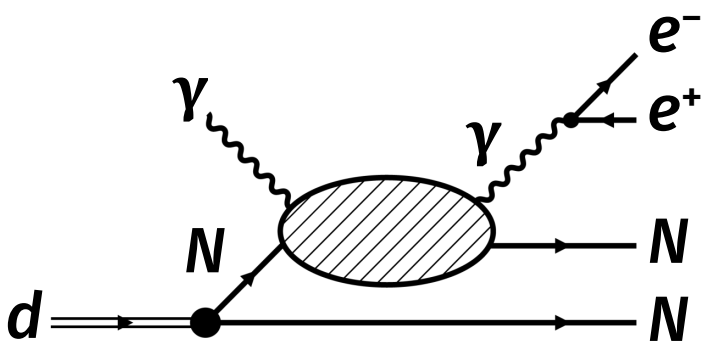

Non-Born terms

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  - Reduces to 12 for virtual Compton scattering ($q^2 = 0$, $q'^2 < 0$)
  - Reduces to 4 in forward limit, $(q'-q)^2 \longrightarrow 0$
    - 2 spin flip
    - 2 spin independent

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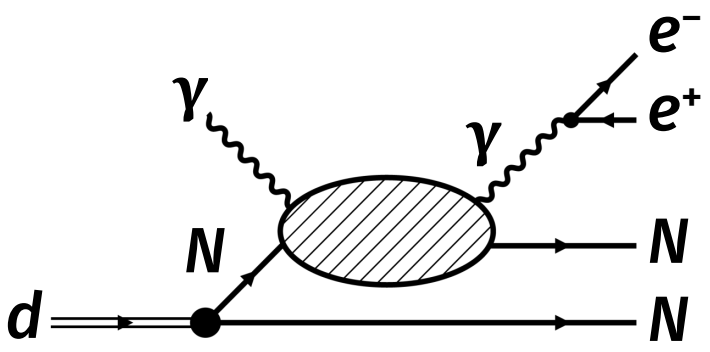

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  - Leading term spin-independent terms proportional to generalized polarizabilities

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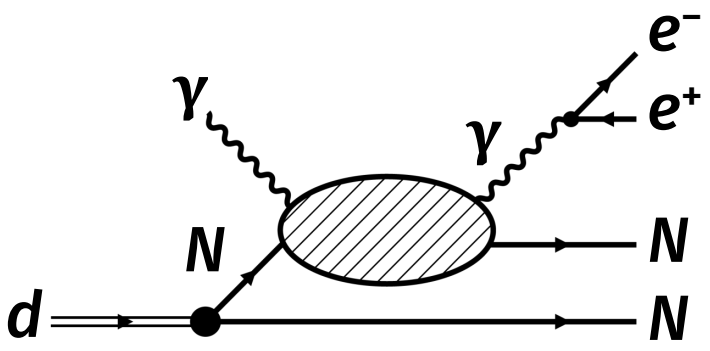

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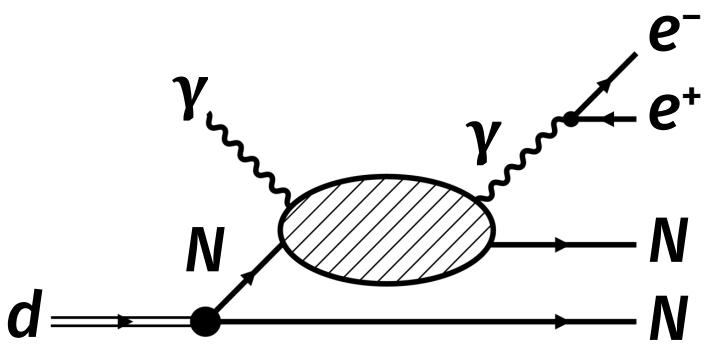

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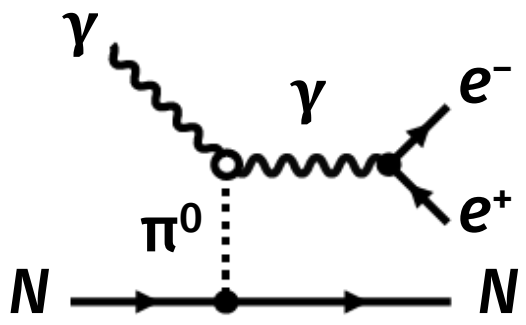

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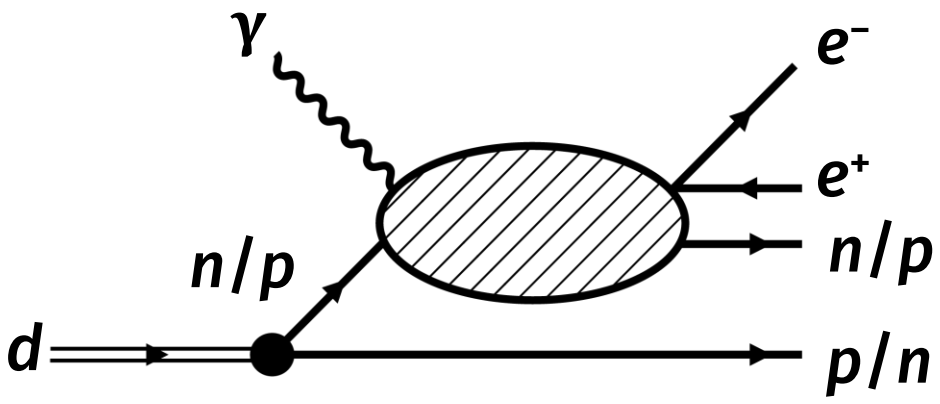
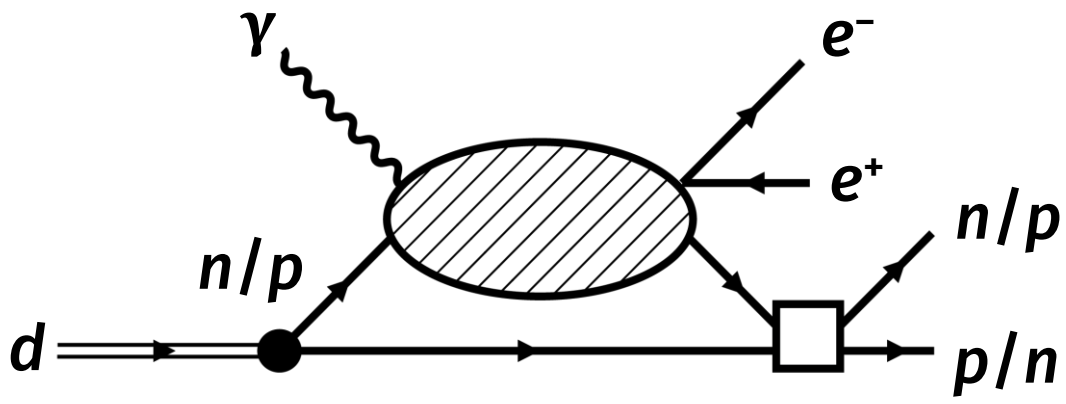
    - 2 spin flip
    - 2 spin independent
  - Leading term spin-independent terms proportional to generalized polarizabilities
  - Since close to real Compton scattering ($q'^2 \approx 0$) use static polarizabilities
  - Estimate spin-flip terms with pion pole

Components of the model

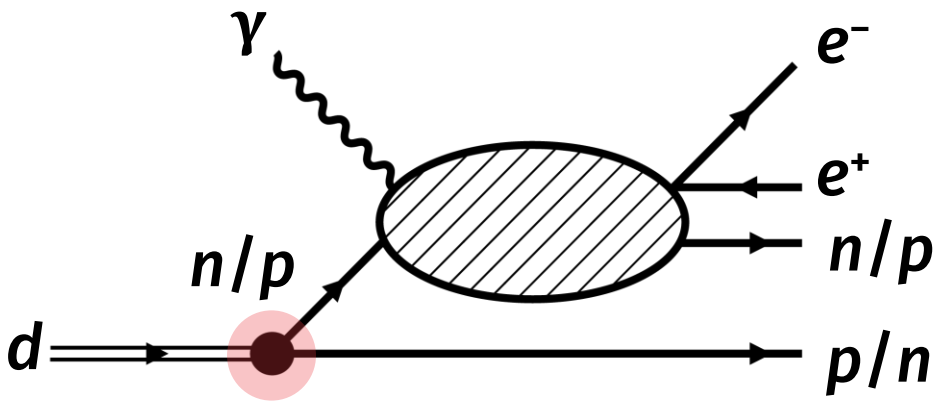


Impulse approximation



Final state interaction

Components of the model



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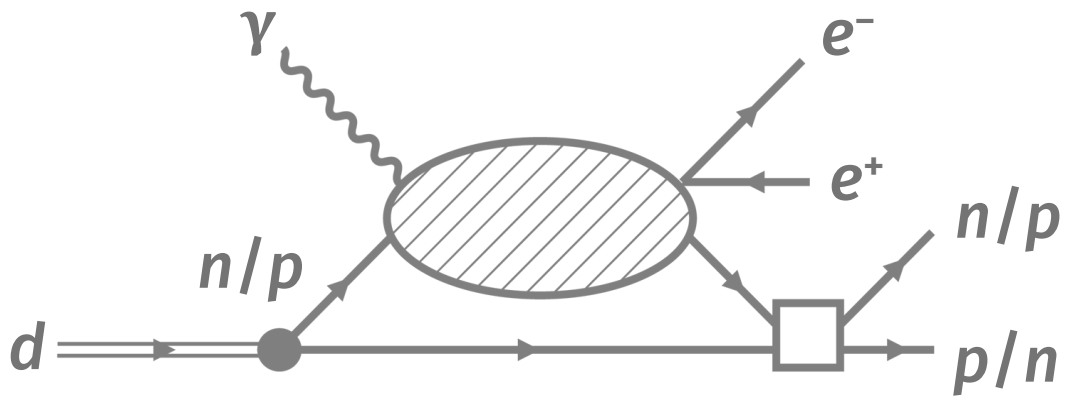
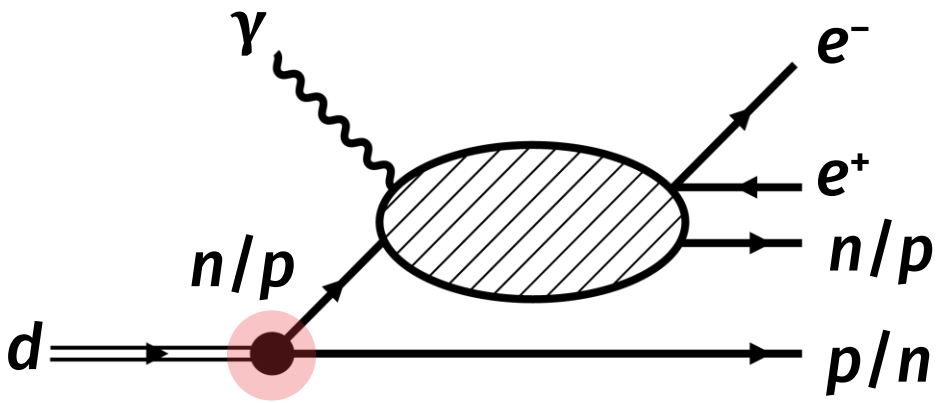
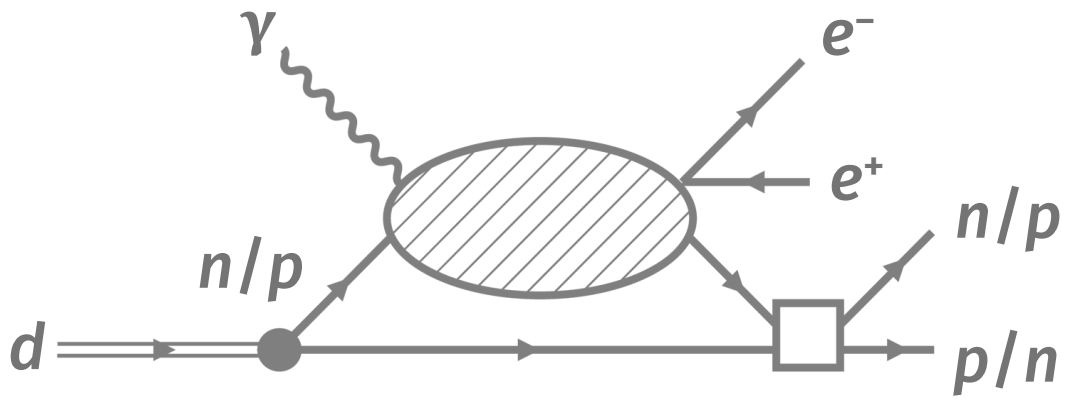


- *dNN* vertex with one nucleon on shell

Components of the model



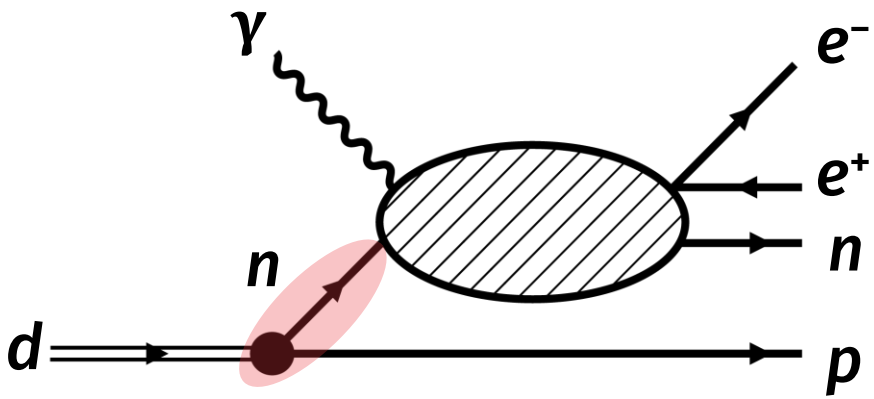


Impulse approximation

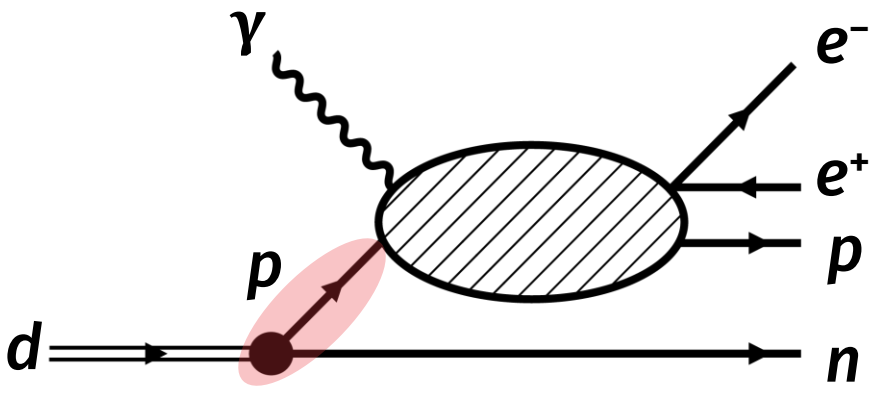
- *dNN* vertex with one nucleon on shell
- Calculated and parametrized by Gross et al.

  see e.g., *Phys. Rev. C* 82 (2010) 034004

Neutron quasi-free peak



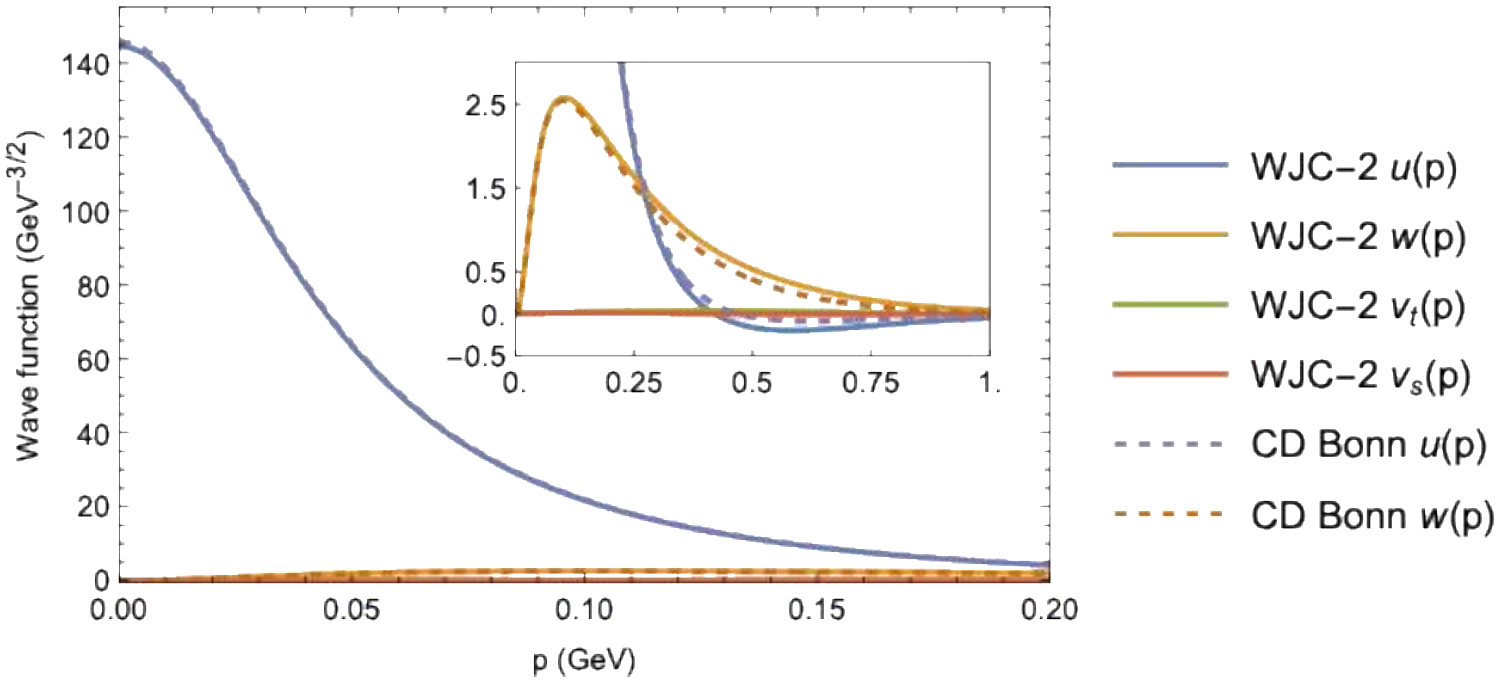
Spectator proton



Spectator neutron

- *dNN* vertex with one nucleon on shell + nucleon propagator
  = deuteron wave function (*S*-, *D*-, 2x *P*-waves)

Neutron quasi-free peak



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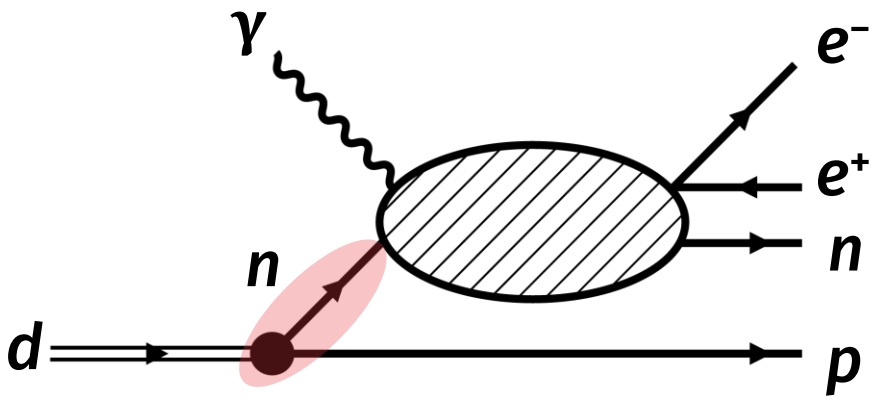

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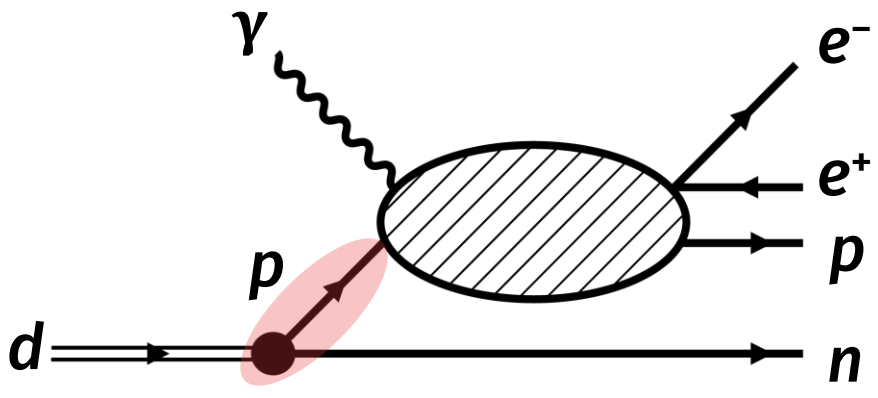
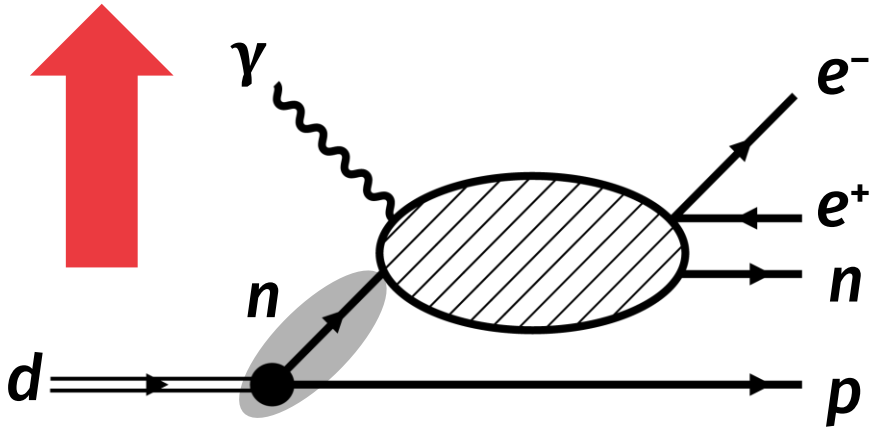


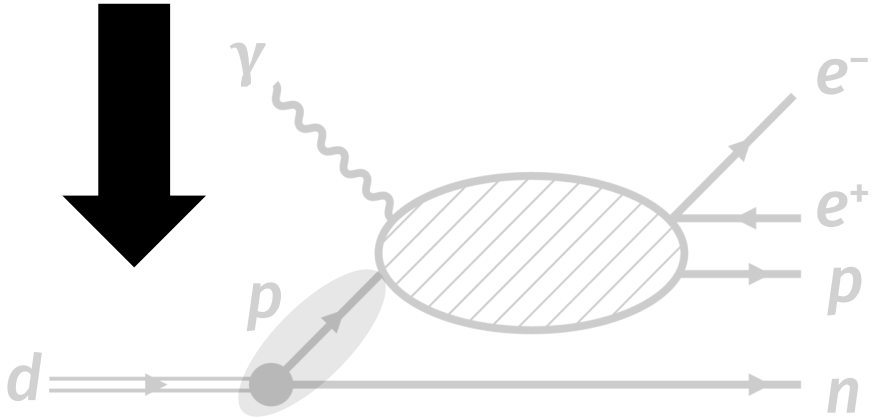
Spectator neutron

- Spectator proton and spectator neutron diagrams probe deuteron wave function differently
- Use to suppress processes where proton *not* spectator!

Neutron quasi-free peak



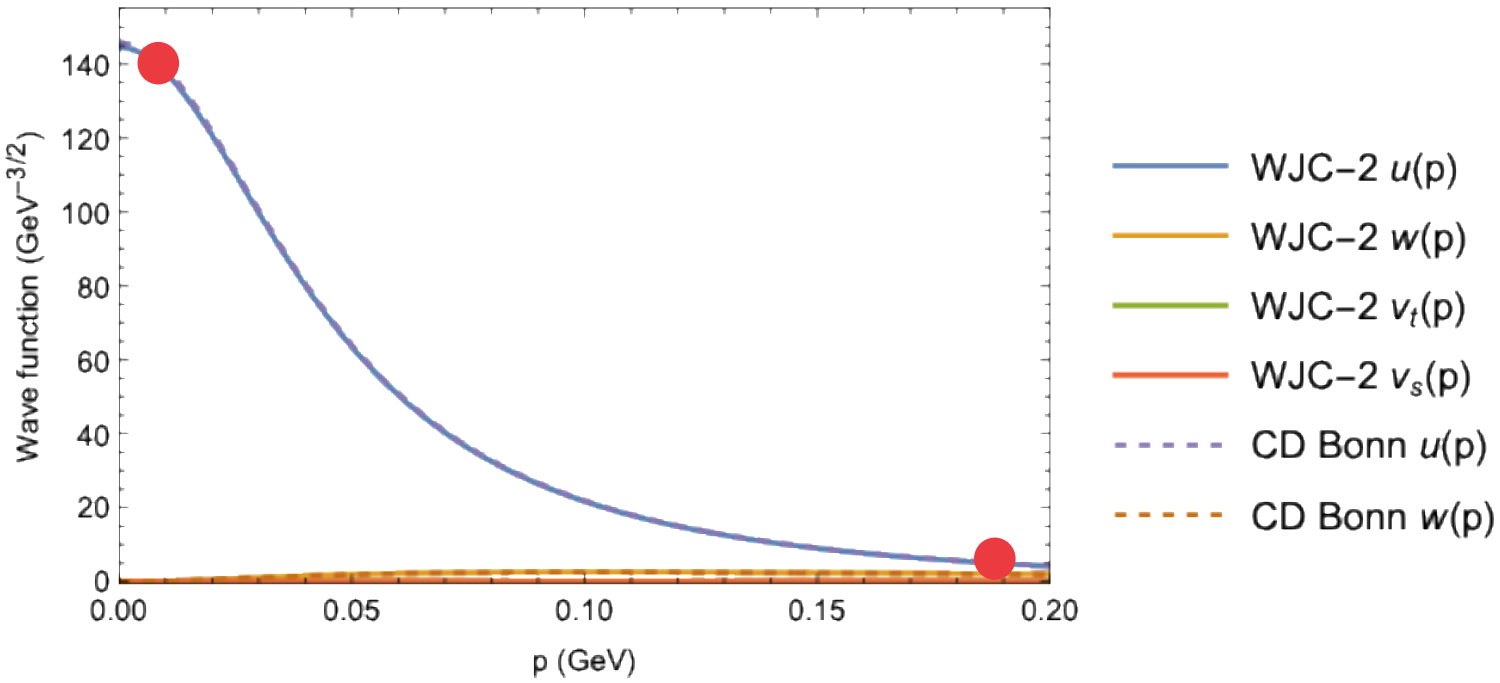
Spectator proton



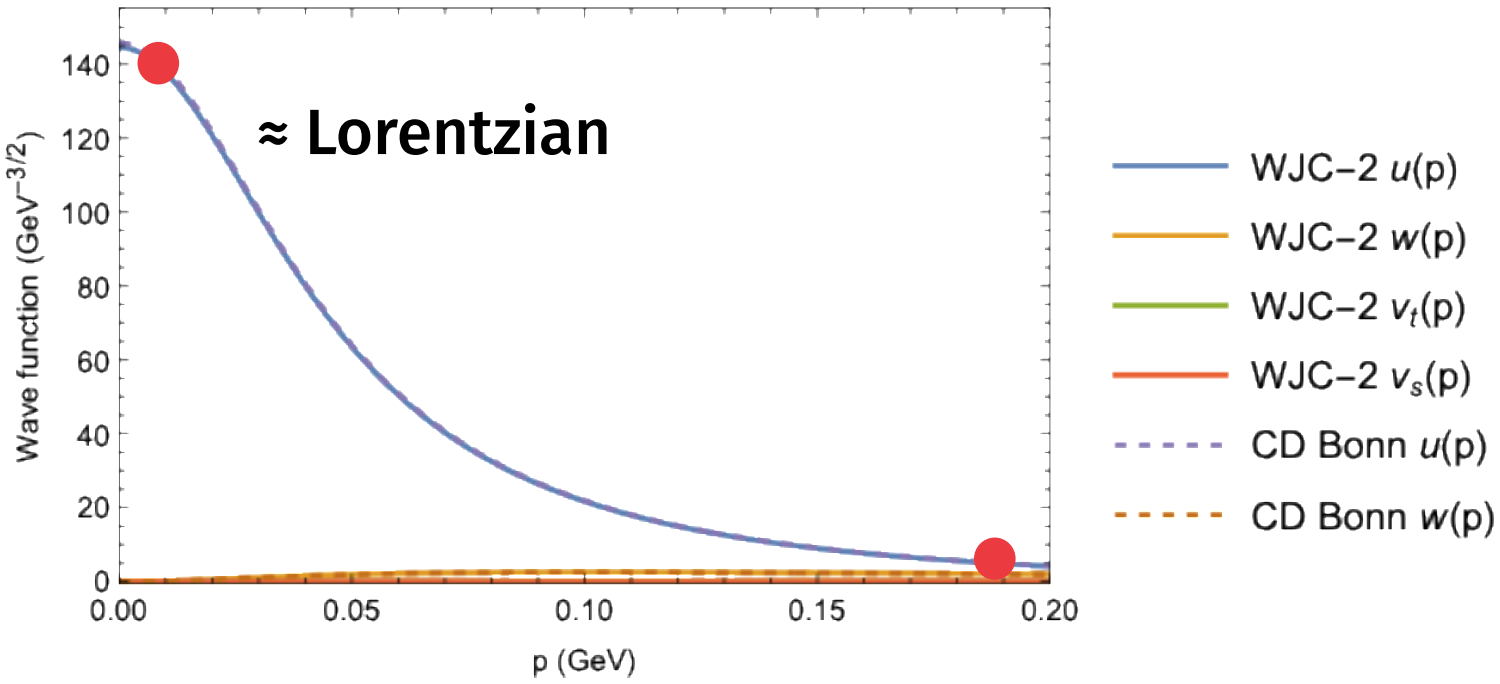
Spectator neutron

- Cut on outgoing proton momentum ($p_p \lesssim 45.7$ MeV) ensures that in remaining processes proton is spectator (NQFP)
- Still compute spectator neutron processes, but magnitude < 1%

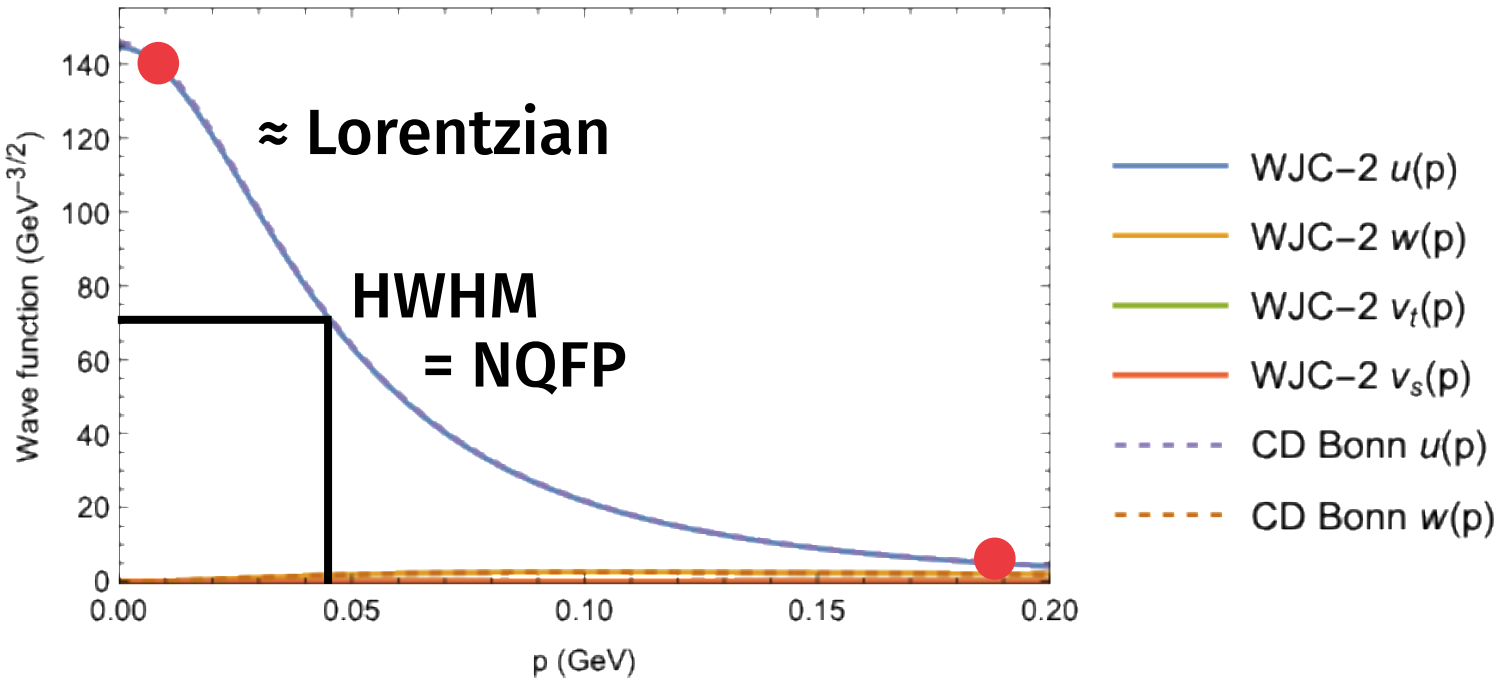
Neutron quasi-free peak



Neutron quasi-free peak

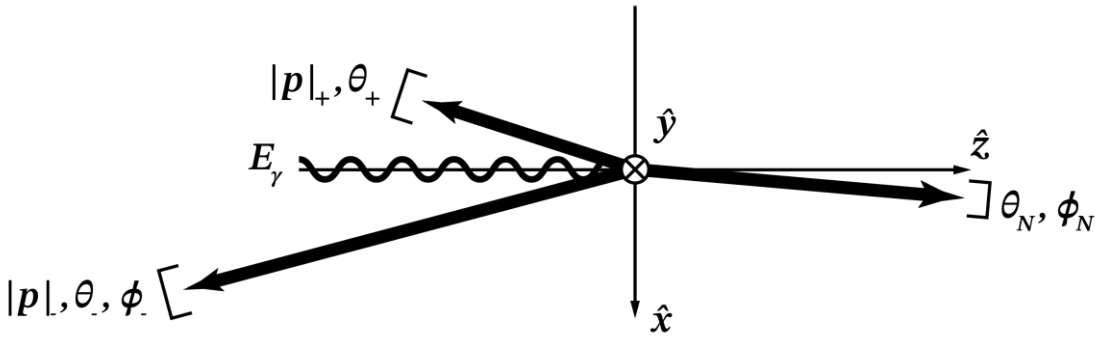


Neutron quasi-free peak



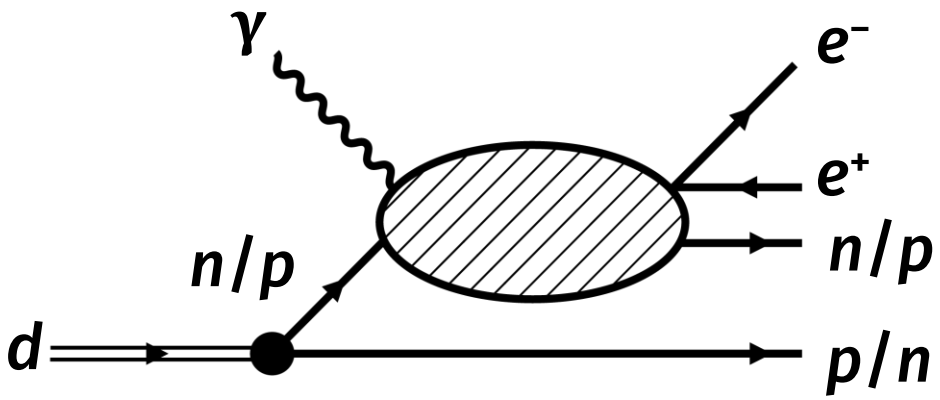
Neutron quasi-free peak

Typical NQFP kinematics:
asymmetric backward leptons

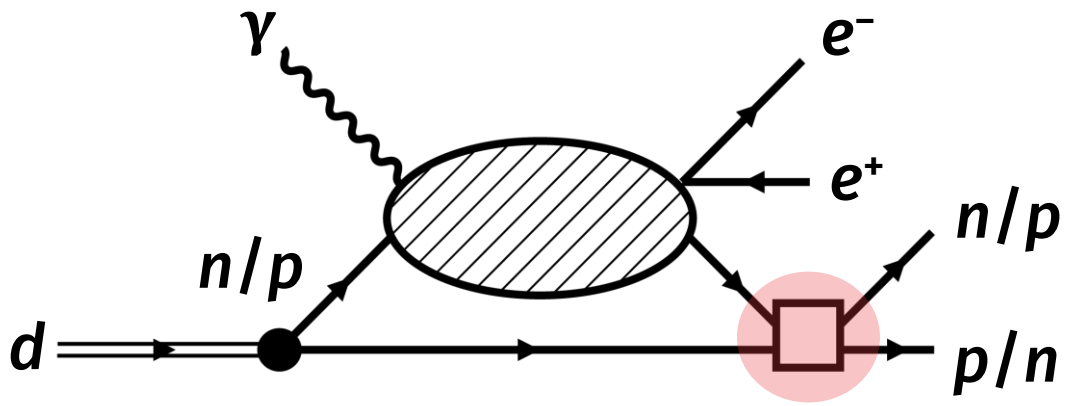


- So, at neutron quasi-free peak
  - $\gamma d \rightarrow e^+e^-pn$ ‘proportional to’ $\gamma n \rightarrow e^+e^-n$ (proton spectator)
- Restrictions kinematics
  - 105 MeV beam energies
  - O(10 MeV) m_{ee}
  - $p_p \lesssim 45.7$ MeV

Final state interactions



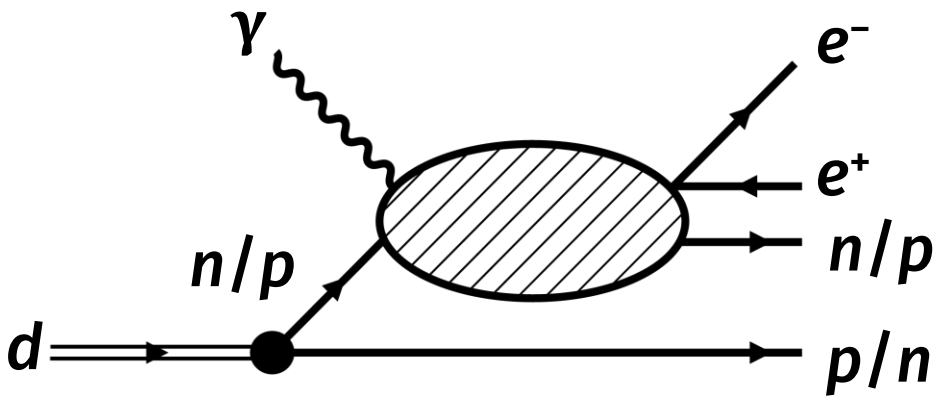
Impulse approximation



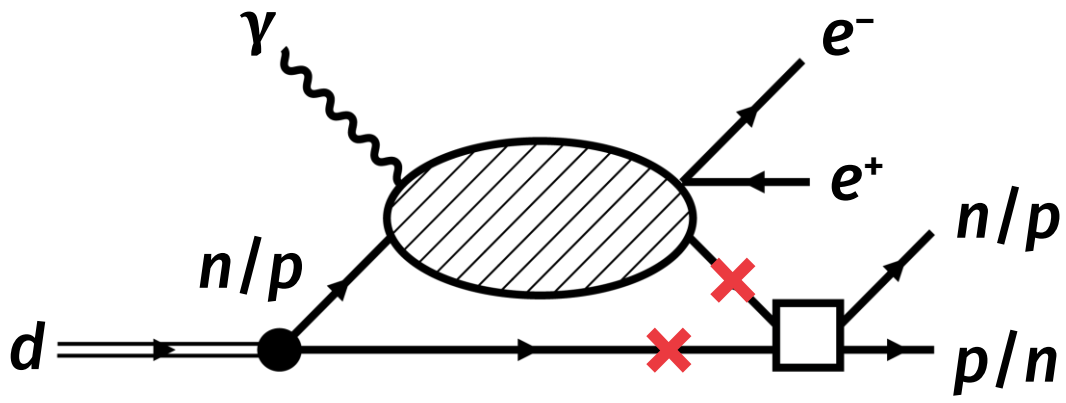
Final state interaction

- NQFP kinematics beneficial for FSI as well

Final state interactions



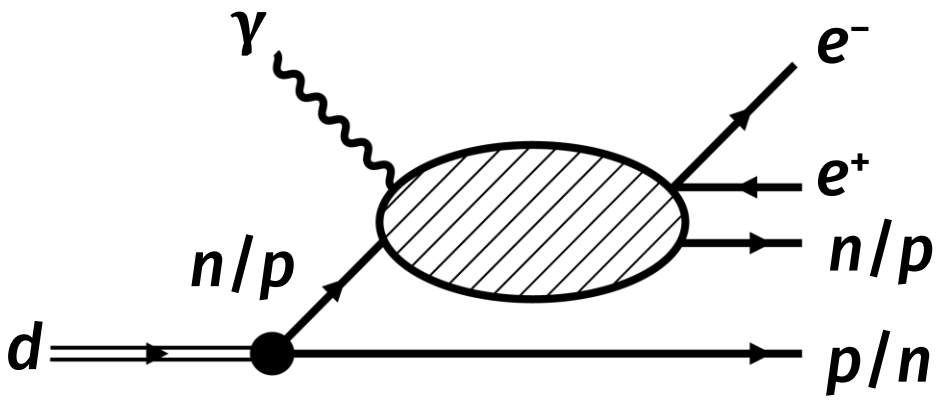
Impulse approximation



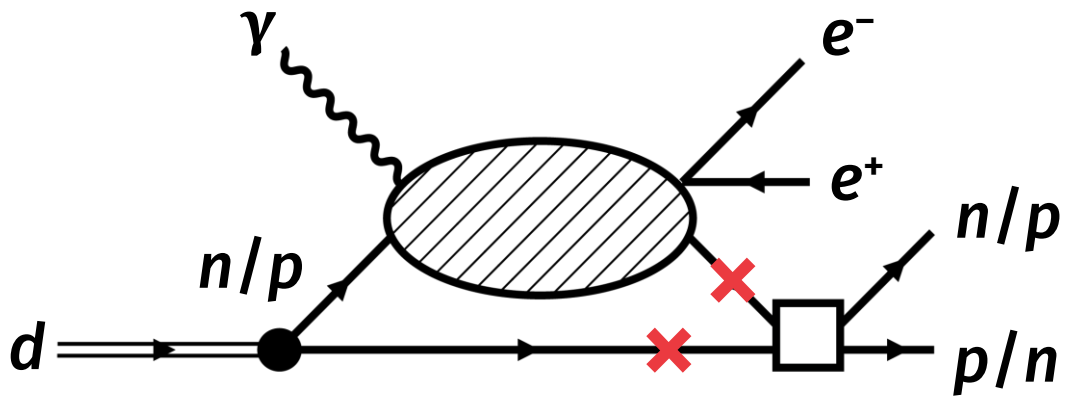
Final state interaction

- NQFP kinematics beneficial for FSI as well
- For off-shell momenta × need half-off shell *NN* T-matrix
- Model dependent!

Final state interactions



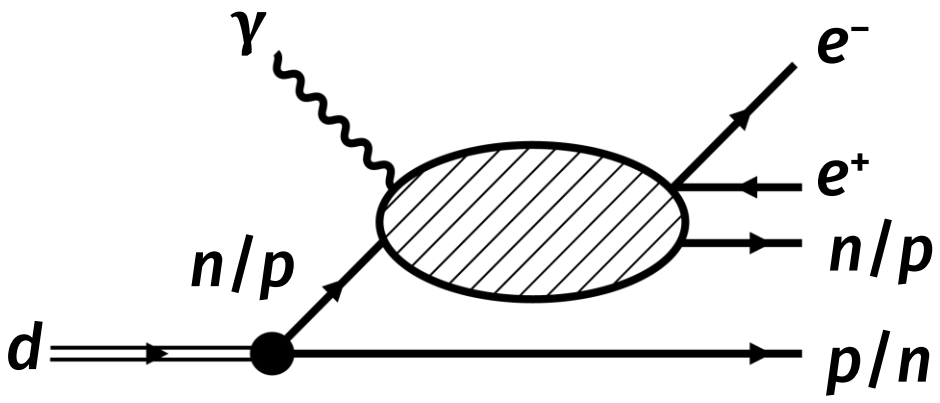
Impulse approximation



Final state interaction

- NQFP kinematics beneficial for FSI as well
- For off-shell momenta × need half-off shell *NN* T-matrix
- For NQFP kinematics × off shell by at most 1-2%

Final state interactions



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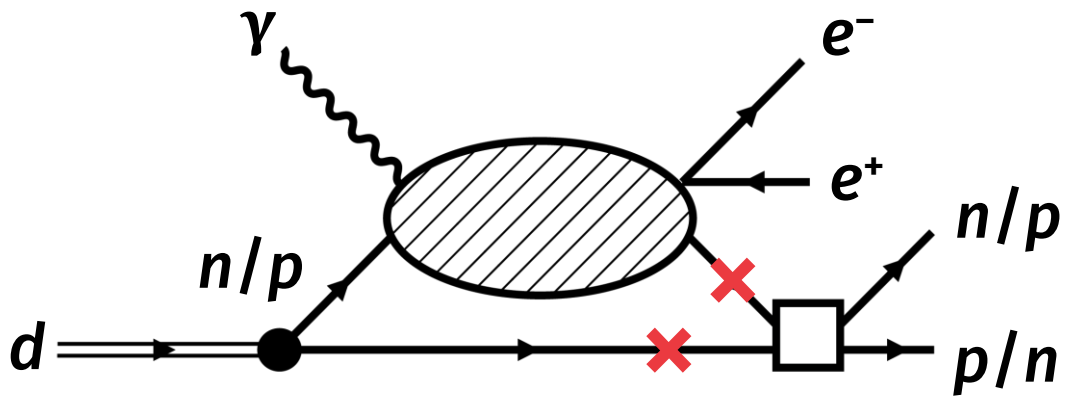
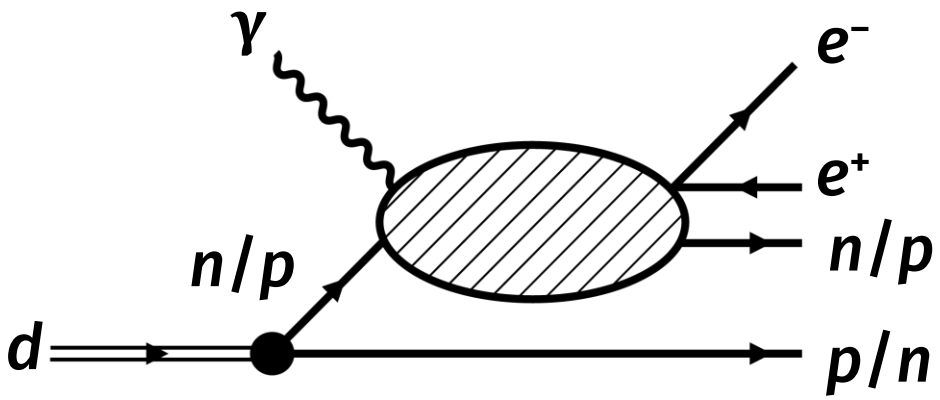


Final state interaction

- Dominant contribution FSI from on-shell *NN* T-matrix
- Fixed by data (*NN* phase shifts)
- Model *in*dependent

Final state interactions



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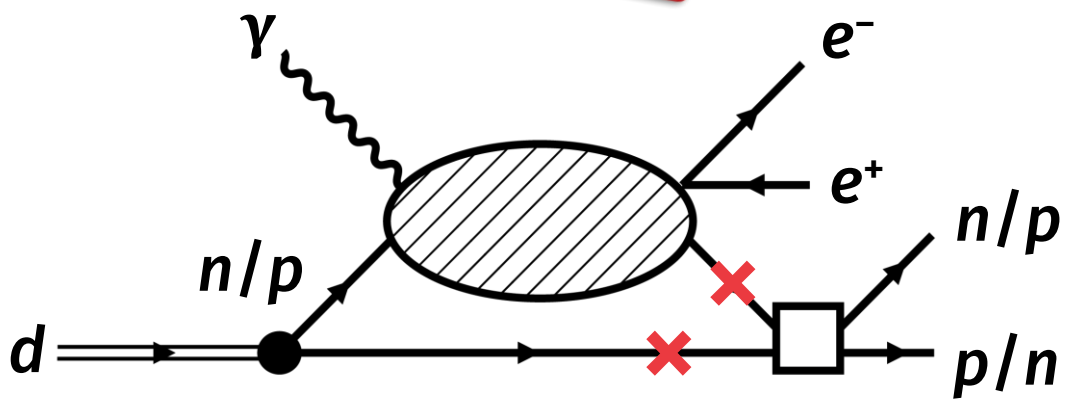
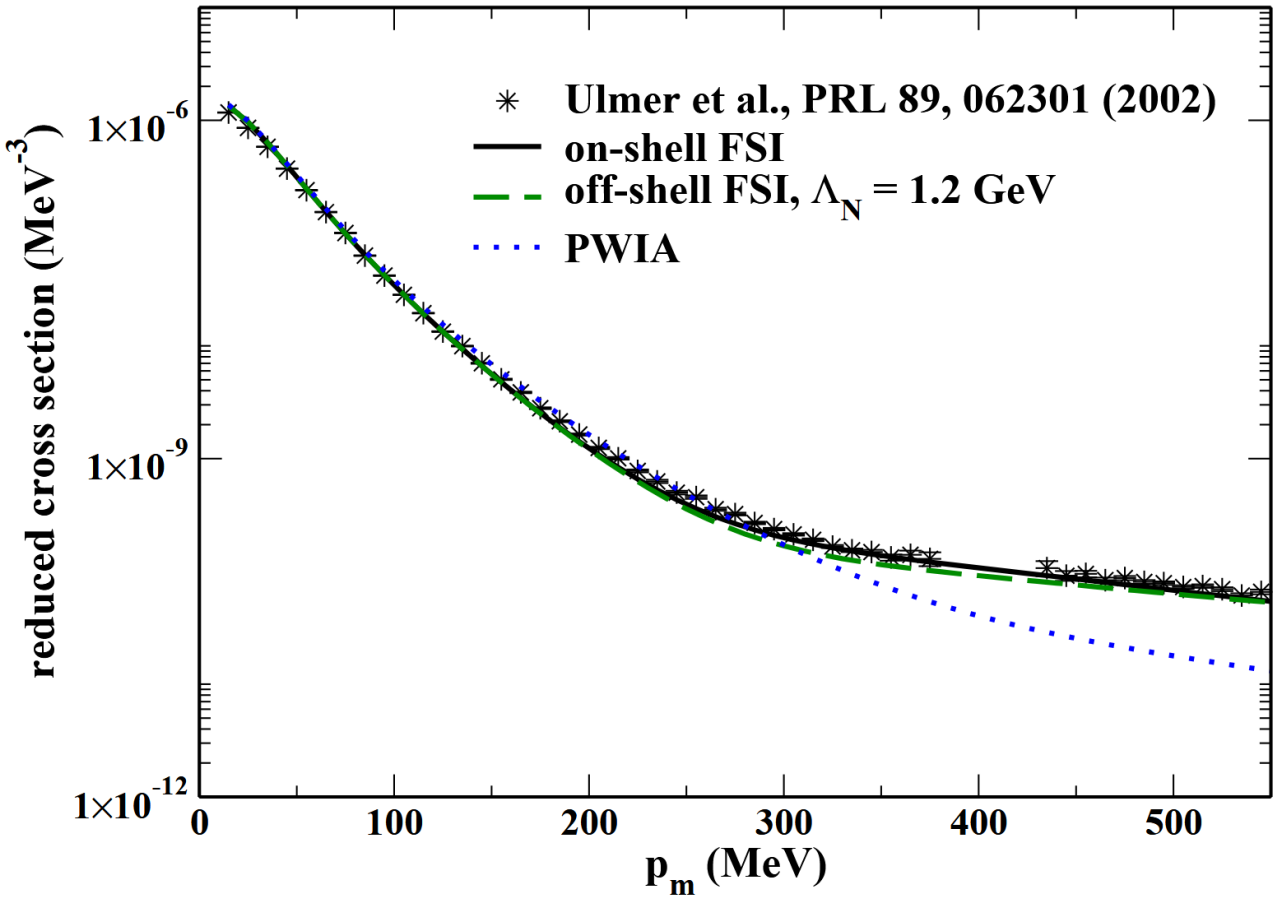


Final state interaction

- Given model for *NN* T-matrix, off-shell effects can be estimated
- Currently WIP, also error from *NN* phase shifts
- Result: theory error (“bands”), expected to be small for NQFP kin.

Example: $\gamma d \rightarrow \gamma pn$ at GeV energies

Phys.Rev.C 78 (2008) 014007



- Similar process
- Much higher energies (3.1 GeV beam)

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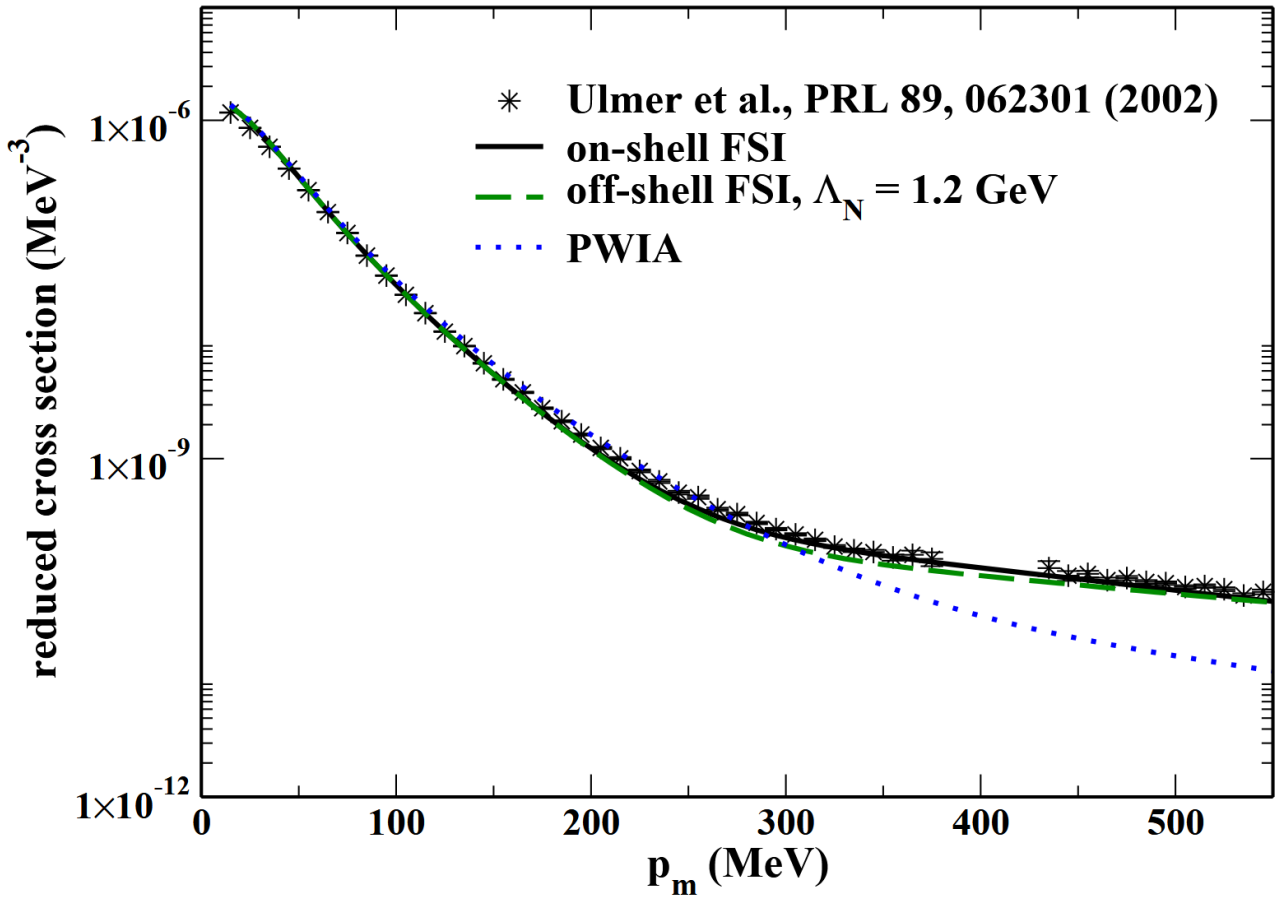

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- Much higher energies (3.1 GeV beam)
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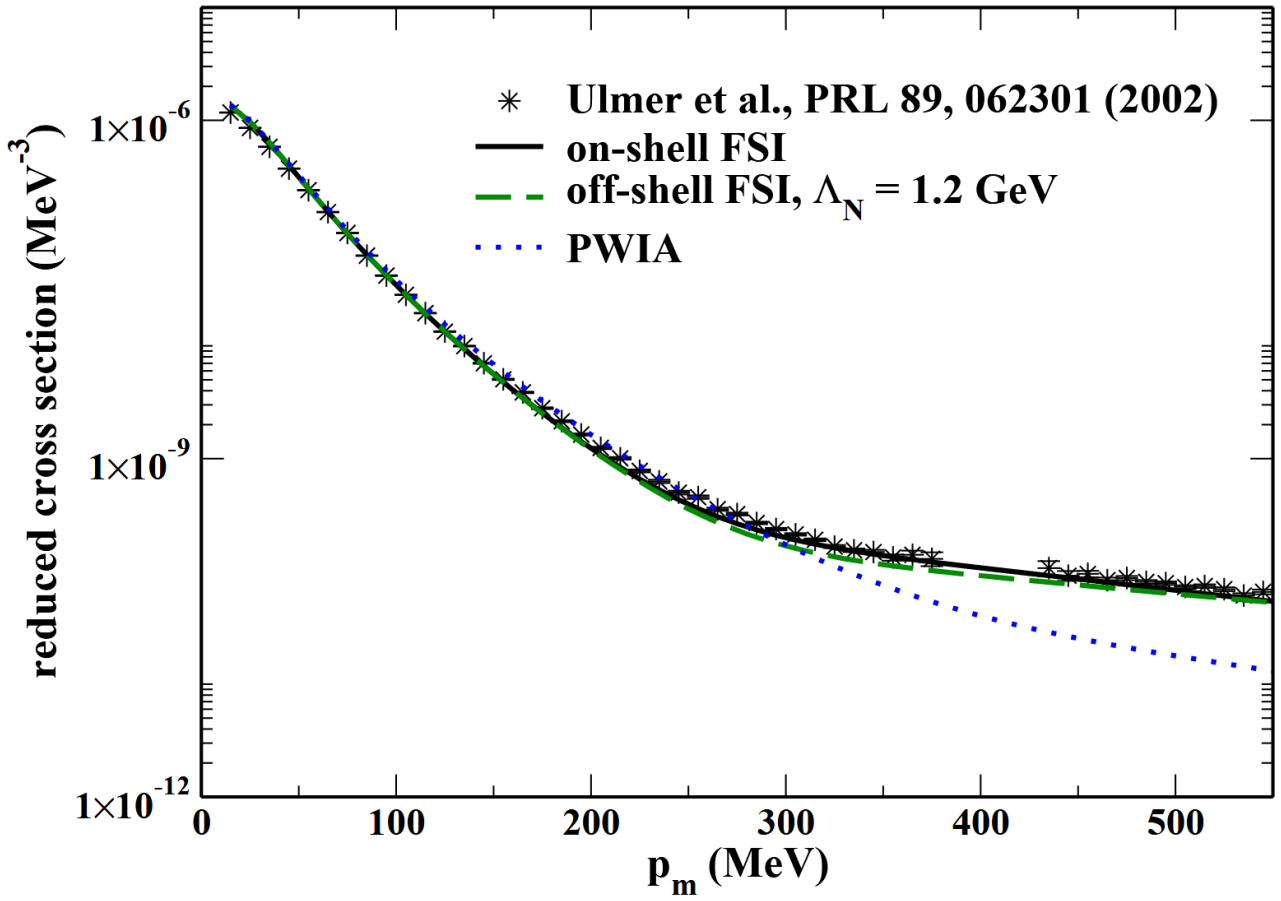
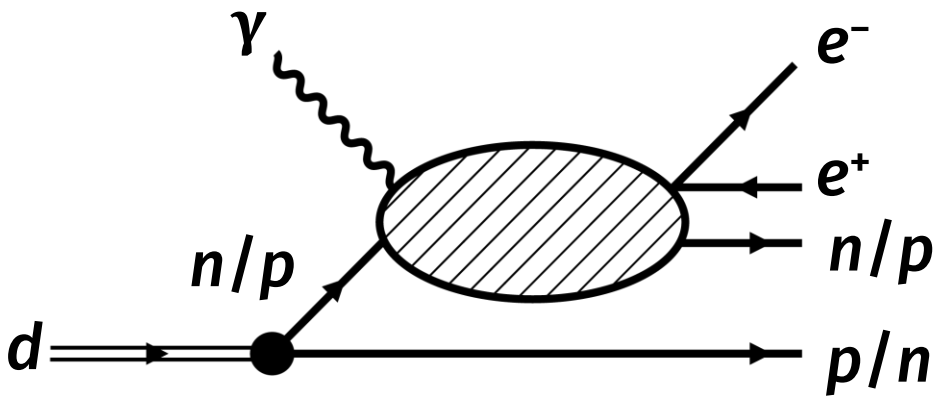


- Similar process
- Much higher energies (3.1 GeV beam)
- Off-shell effects more important at higher beam energies
- Off-shell contributions for our kinematics expected to be even smaller!

Summary



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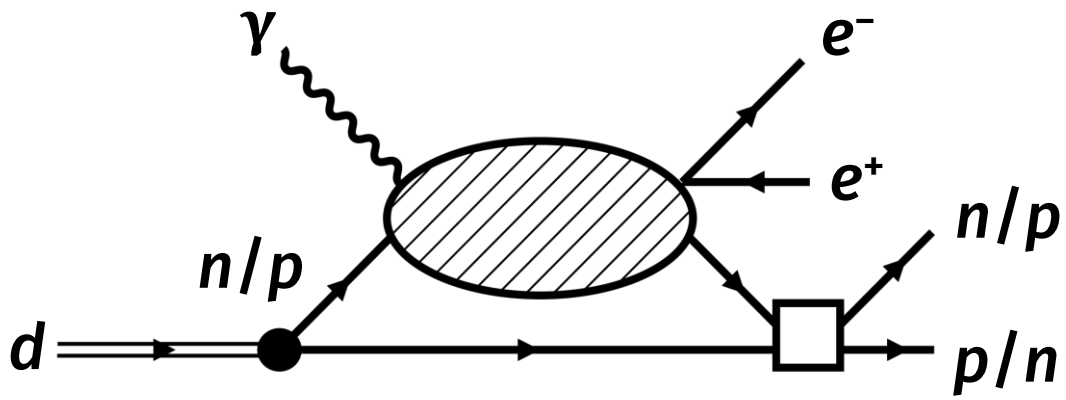
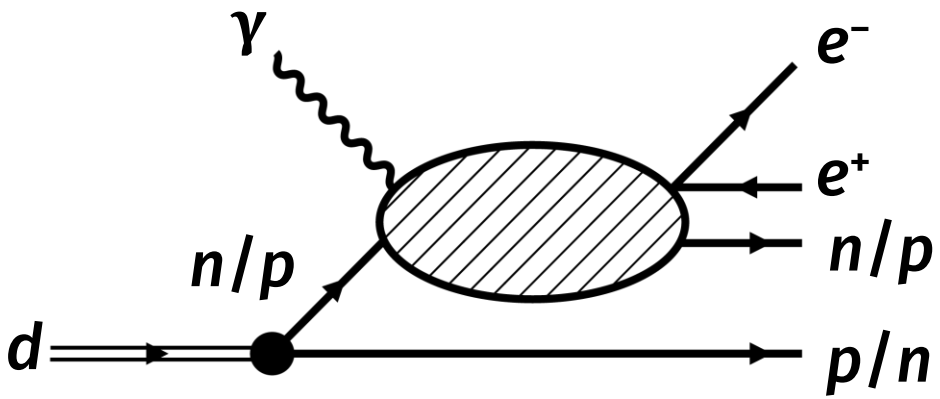


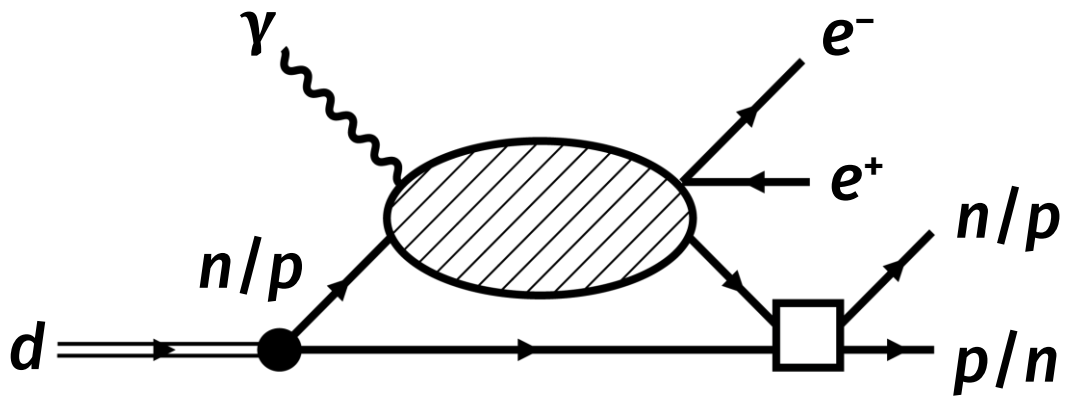
Final state interaction

- Model for $\gamma d \rightarrow e^+e^-pn$ valid for
  - Beam energies ~ 105 MeV
  - O(10 MeV) m_{ee}
  - $p_p \lesssim 45.7$ MeV

Summary



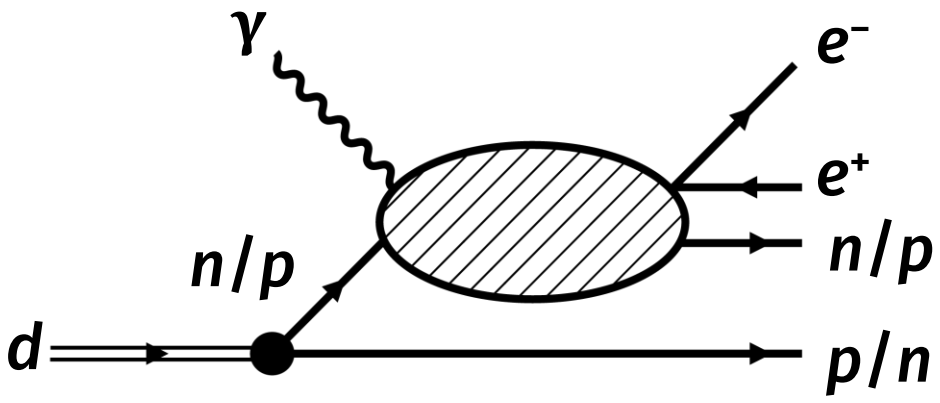
Impulse approximation



Final state interaction

- Small theory error from FSI
  - *NN* phase shifts
  - Off-shell contributions

Summary



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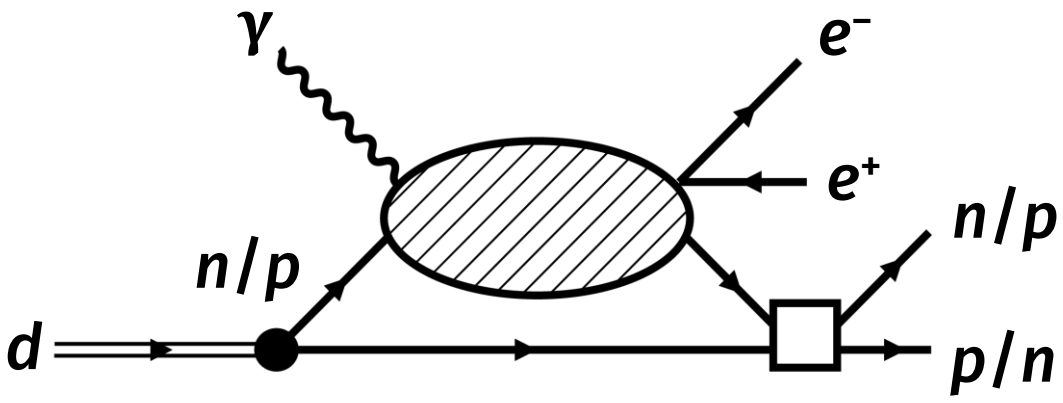

Final state interaction

- How to…
  - Extract neutron polarizabilities?
  - Detect new physics?

Light new physics searches

- Assume for new boson
  - Mass 10-100 MeV
  - Scalar, pseudoscalar, vector, or axial vector
  - Coupling to at least $e^{\pm}$, p, n
  - Narrow width (<< 0.1 MeV)

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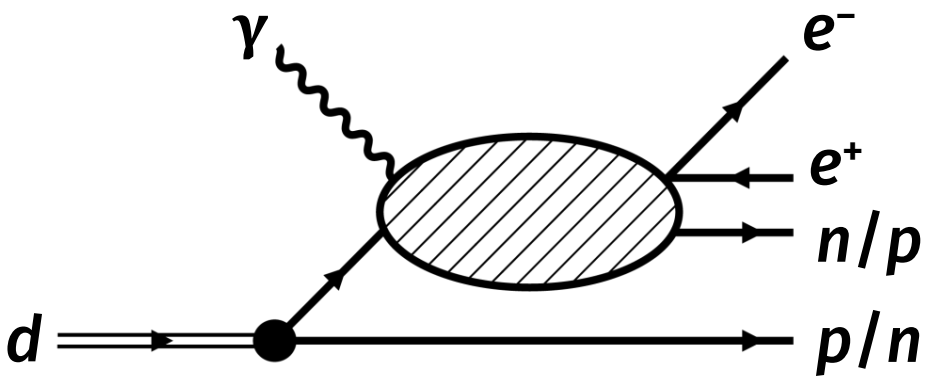
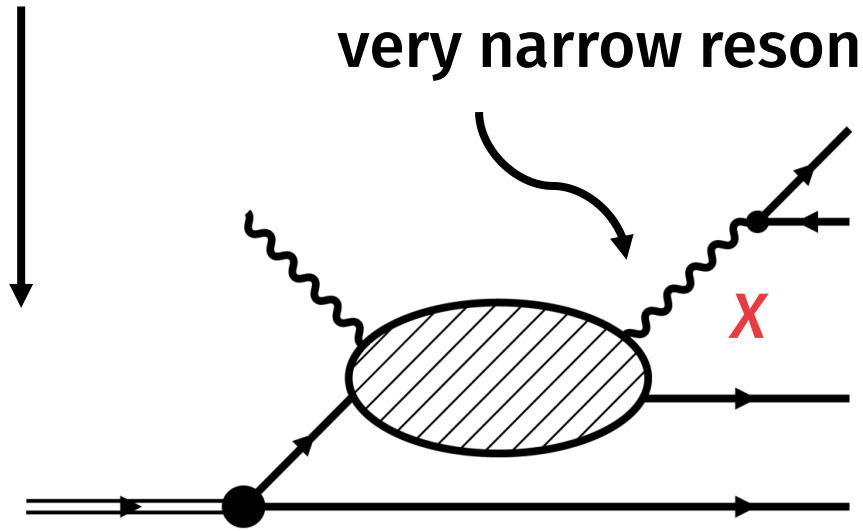


+ FSI

New boson detectable as very narrow resonance



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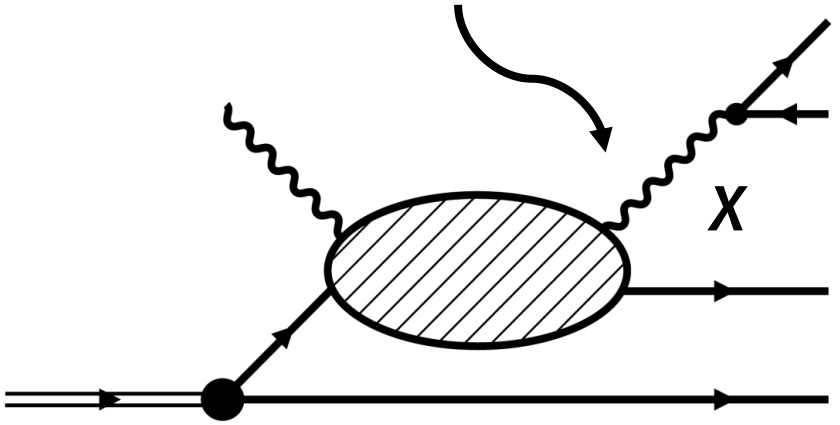

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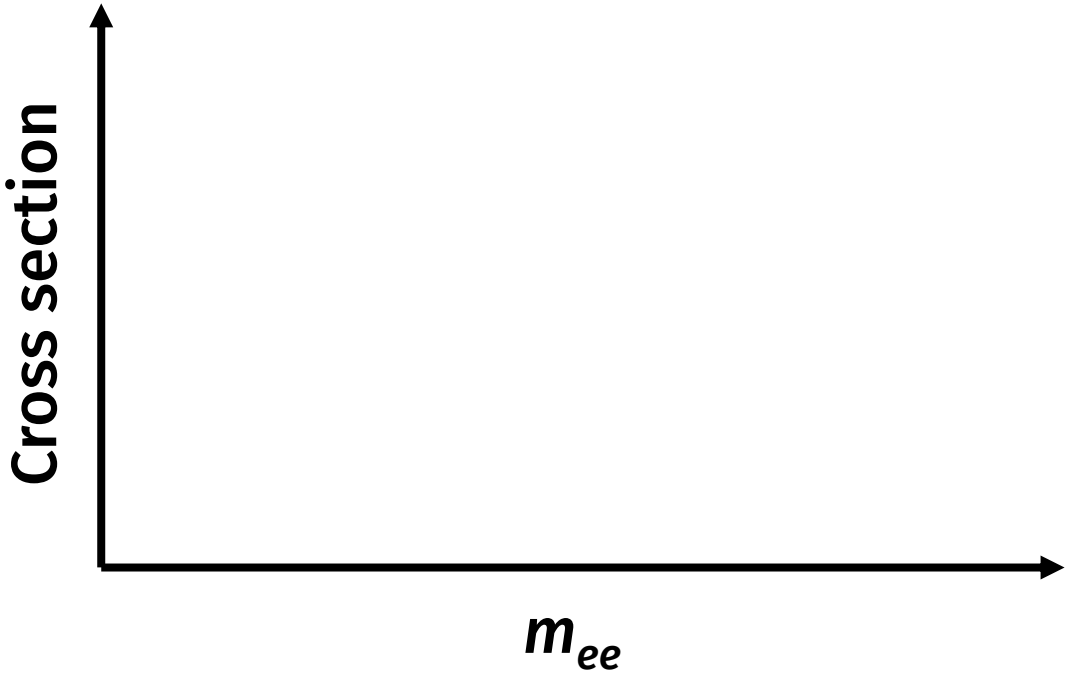

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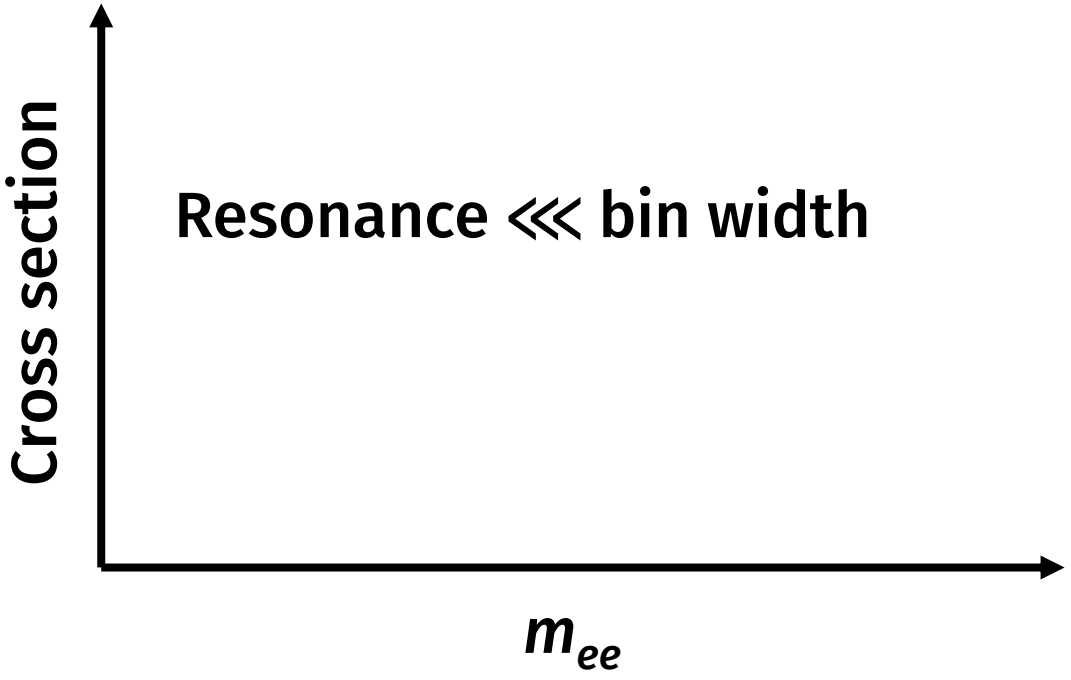

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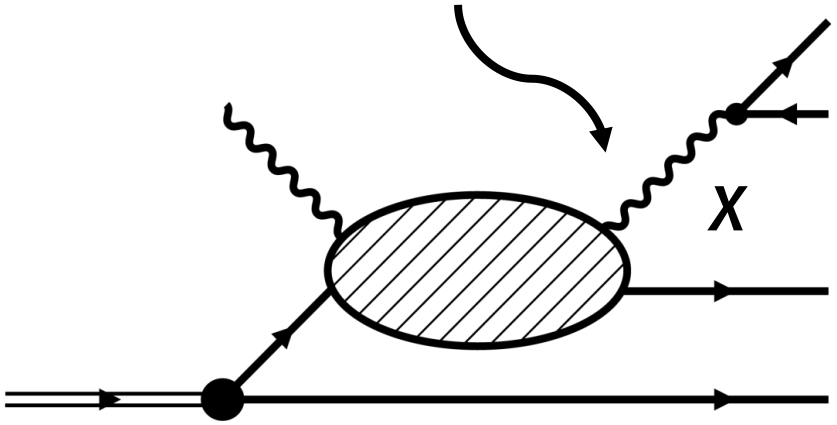

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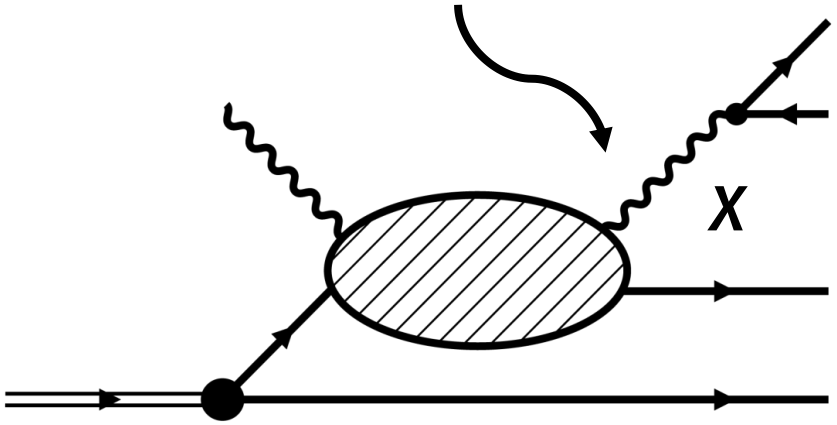

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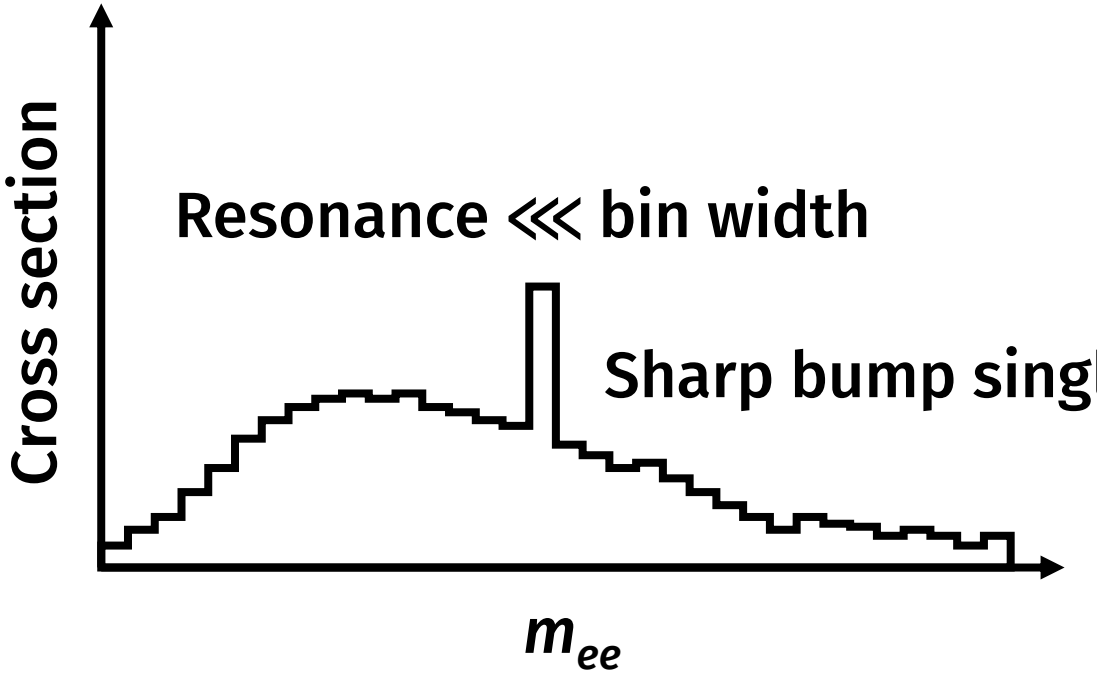

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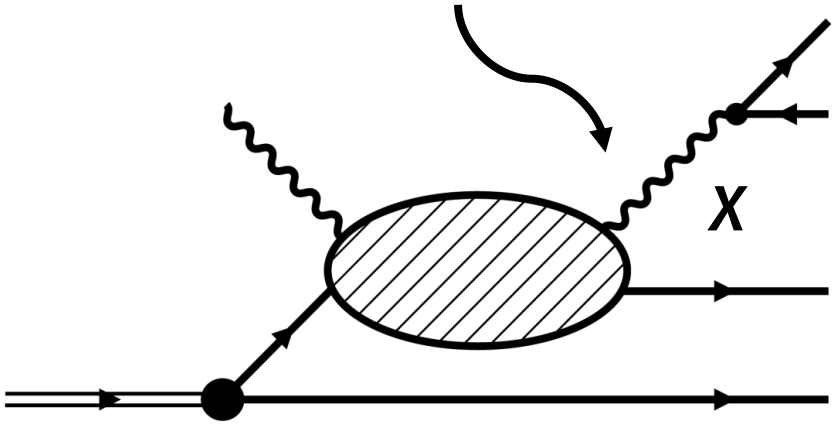

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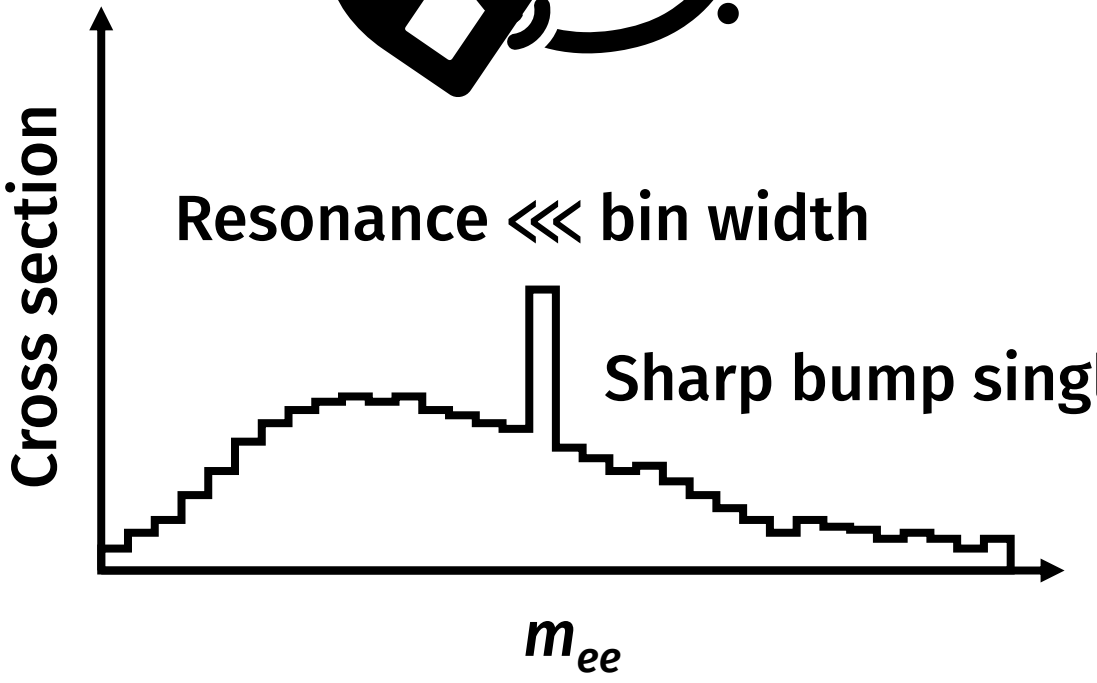

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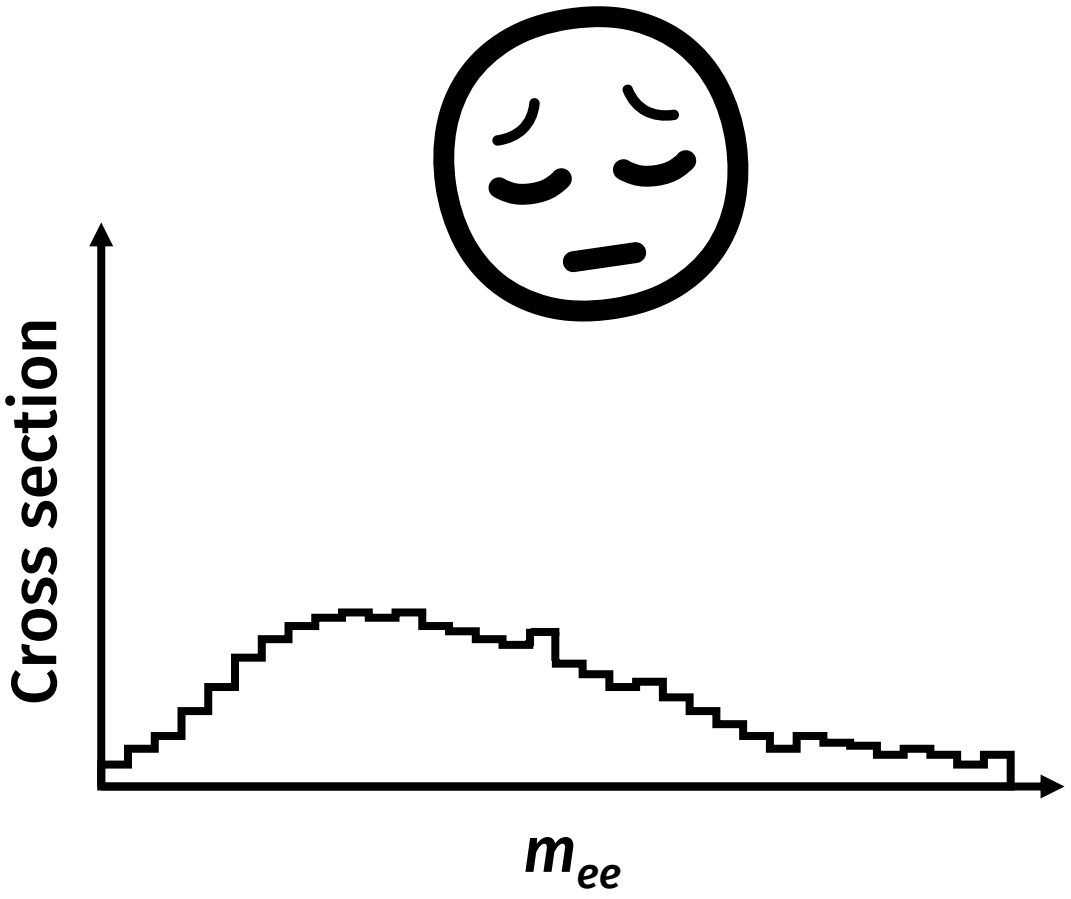


- Likely no signal

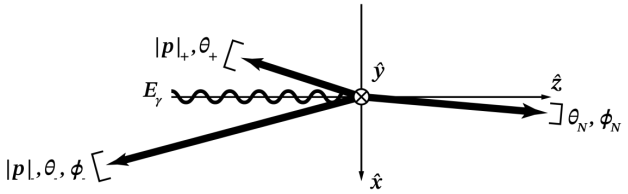
Light new physics searches

- Likely no signal
- Use absence of signal to constrain neutron coupling
  - $\mathcal{L}_S = g_S \bar{N} N X$
  - $\mathcal{L}_P = g_P \bar{N} i\gamma_5 N X$
  - $\mathcal{L}_V = g_V \bar{N} \gamma_\mu N X^\mu$
  - $\mathcal{L}_A = g_A \bar{N} \gamma_\mu \gamma_5 N X^\mu$

Results

Phys. Rev. D 109, 095010

- Projected exclusion limits from IA diagrams
- $L = 7.2 \times 10^8$ nb^{-1}
- $\delta m_{ee} = 0.1$ MeV
- Reminder: typical NQFP kinematics



^{208}Pb-n constraints from Phys. Lett. B 57, 270 (1975)

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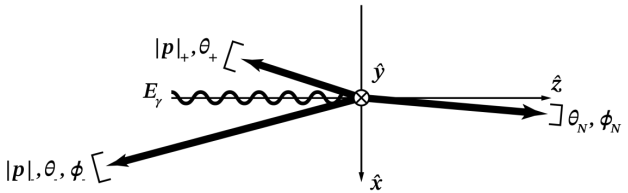

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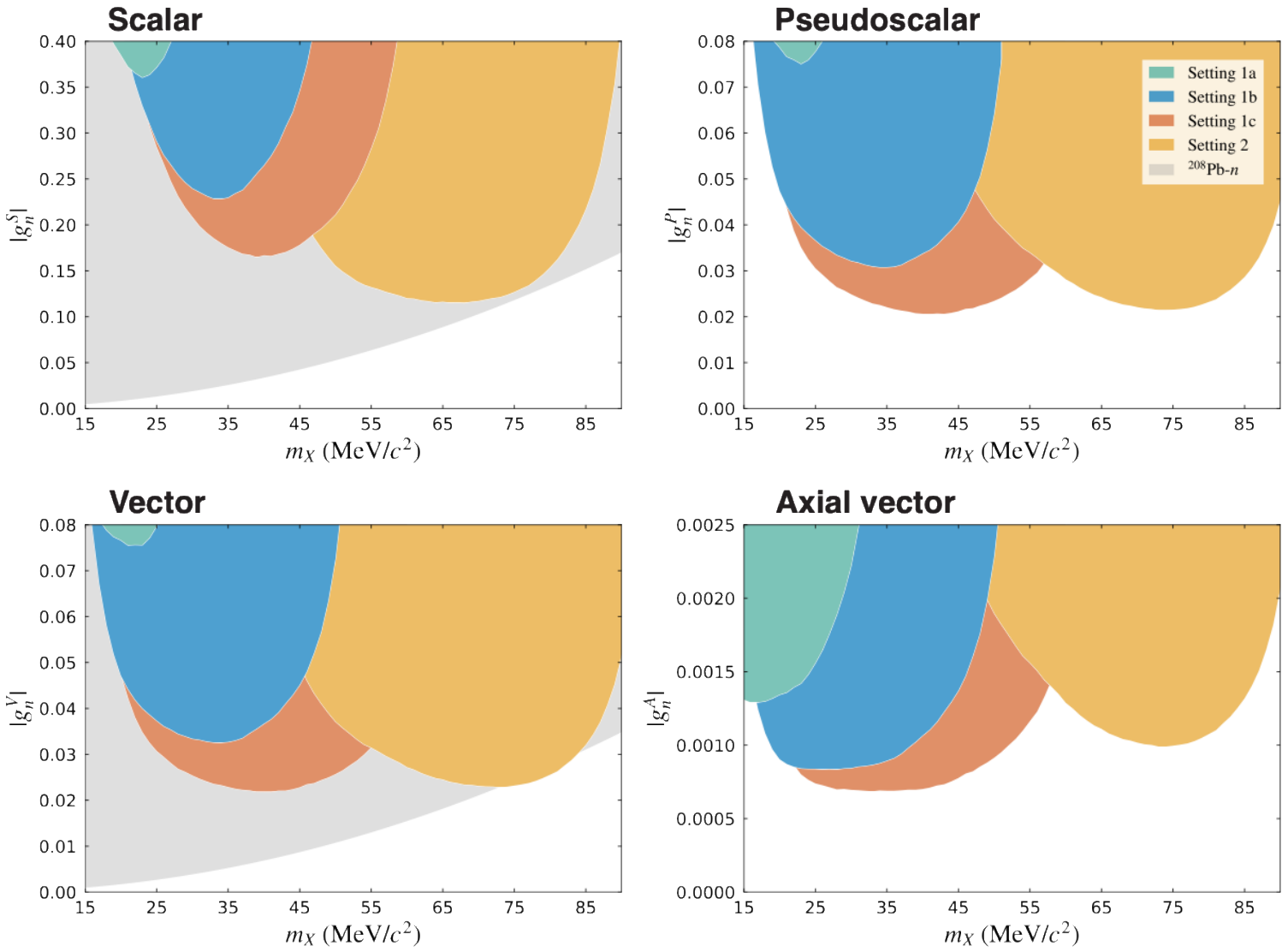

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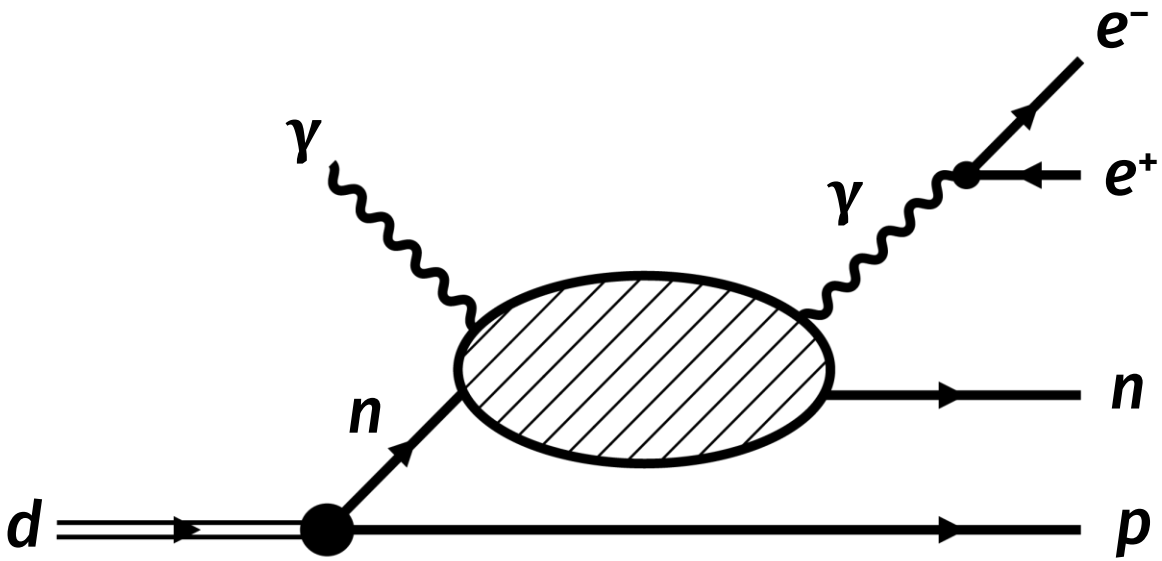
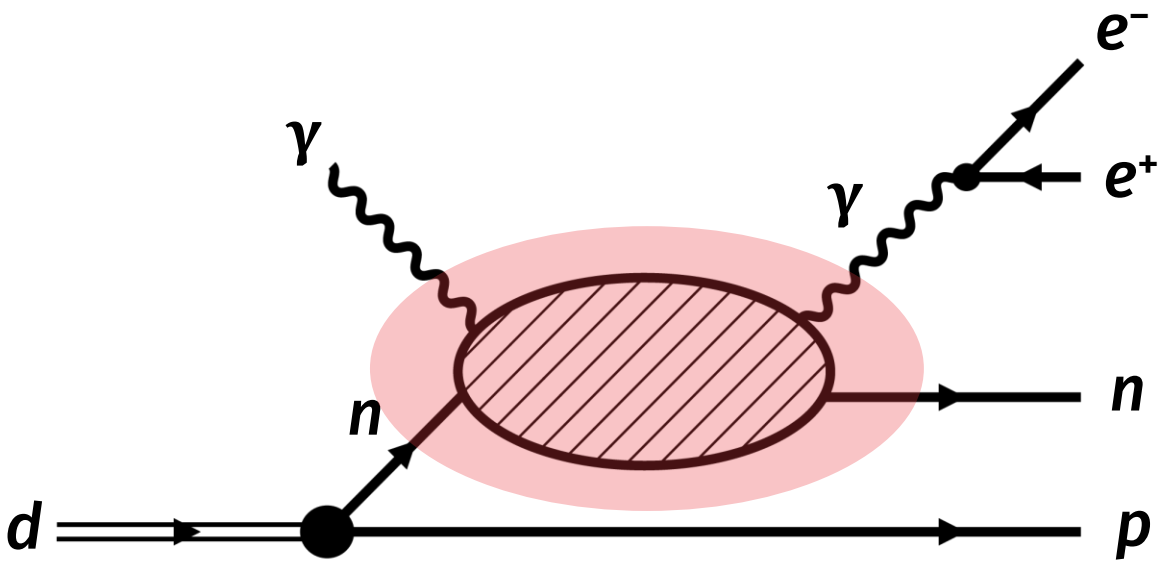
Neutron polarizability extraction



+ FSI

Neutron polarizability extraction

- Neutron polarizabilities appear in $\gamma n \to \gamma n$ blob



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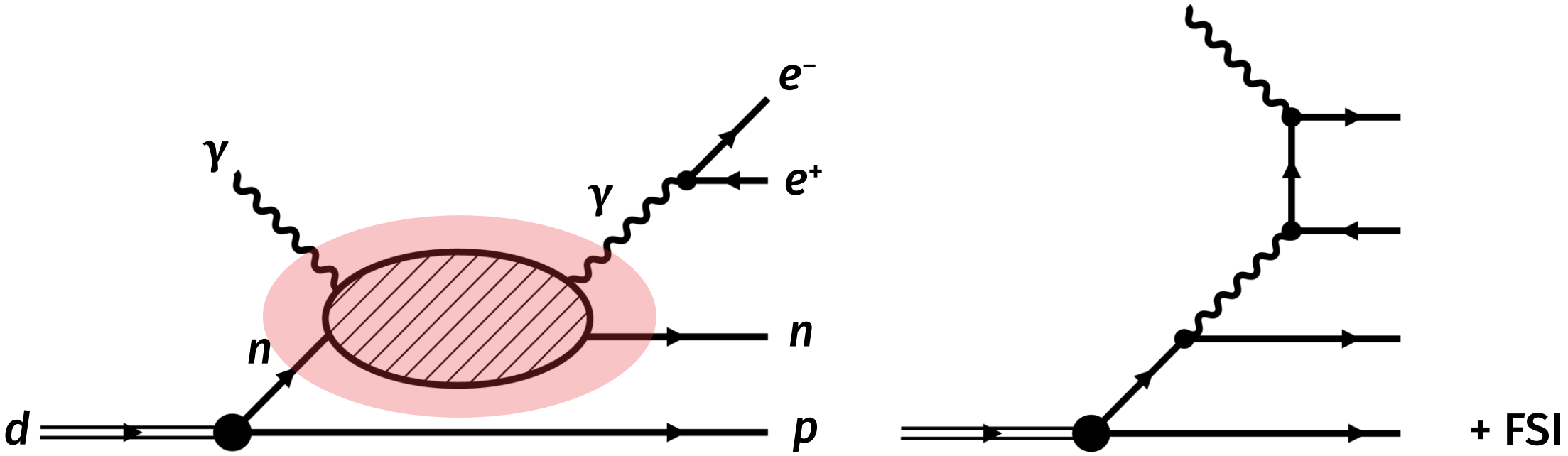
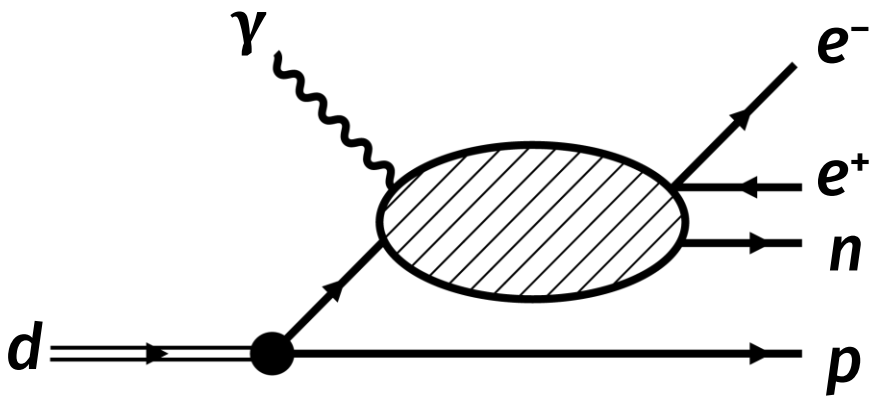
- Bethe-Heitler amplifier sensitivity due to interference



Neutron polarizability extraction

- IA calculation indicates sensitivity to neutron polarizabilities in same kinematic region where sensitive to new physics



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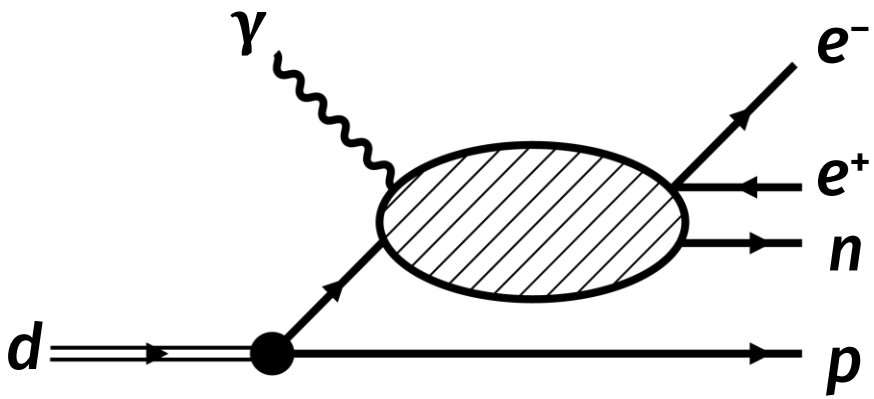

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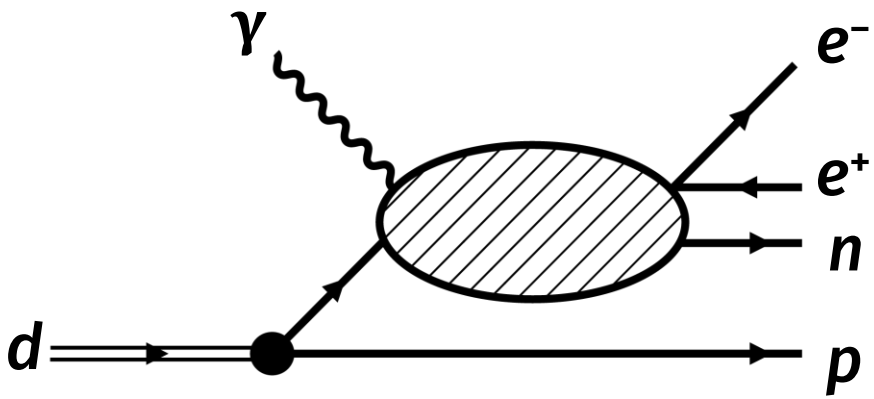

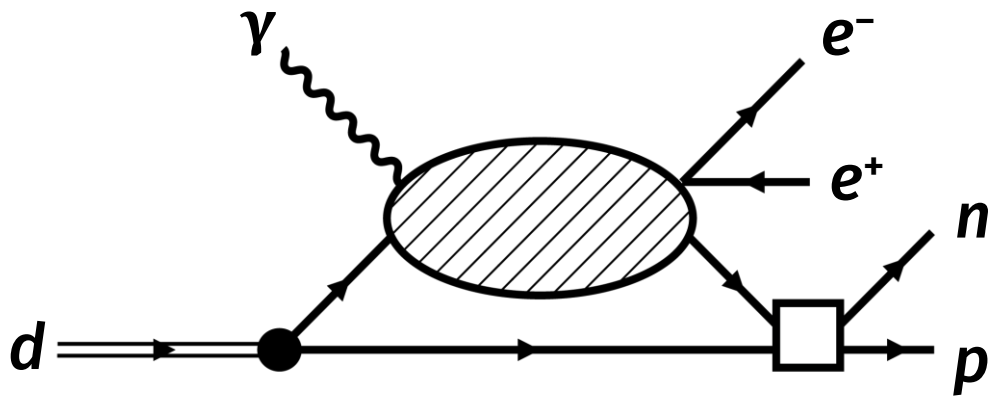

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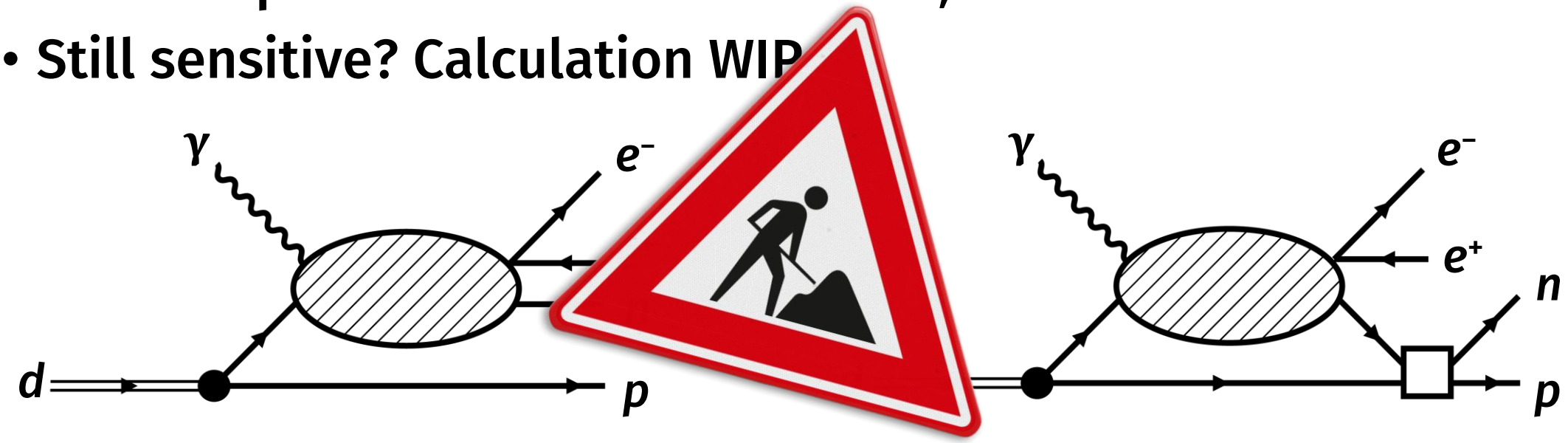
- Still sensitive? Calculation WIP



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- If results promising,
  - Various model improvements
  - Electrodisintegration
- Extensions for JLab energies possible (similar works already exist)

Questions?

Neutron polarizabilities and new physics searches with $\gamma d \to e^+e^-pn$

Cornelis Mommers, JGU Mainz, 2026-03-26

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