Clean measurement of the nucleon axial-vector form factor

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Work done in collaboration with Carlos Munoz-Camacho and Simon Širca

Goal

Measure the Q^2 dependence of $g_A(Q^2)$, the isovector axial form factor of the nucleon.

Axial form factor: maps the spatial distribution of the nucleon spin i.e., how the net parton polarization evolves from the center of the nucleon to its outskirts.

The experiment, as described here, does not use a positron beam (just electrons). However, it requires a very high current, low energy, polarized beam.

Motivations

Form Factors:

- Basic quantities describing the coherent structures of hadrons;
- Benchmark measurements to test approaches to strong QCD (e.g. Lattice QCD, χpT);
- Constraints for Generalized Parton Distributions.

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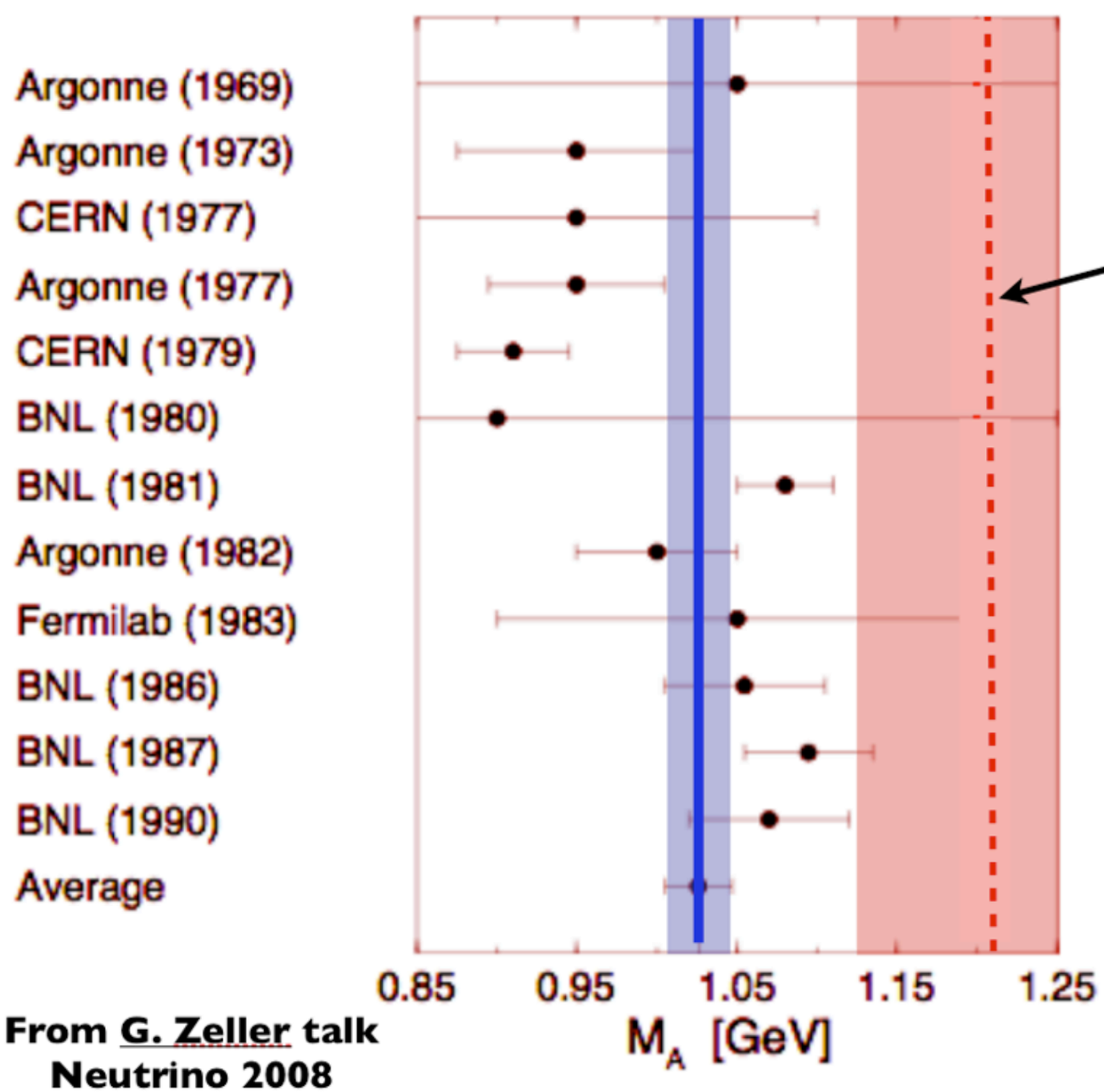
$g_A(Q^2)$:

- Much less known than nucleon's electromagnetic form factors $G_M^{p,n}(Q^2)$ and $G_E^{p,n}(Q^2)$;
- Interesting interpretation: parton polarization's spacial distribution;
- Calculations available from lattice QCD and χpT;
- No clean measurement available:
  - Neutrino elastic scattering: nuclear targets, neutrino beam flux and energy not well known (contamination: not sure if reaction is elastic), MC+models needed to interpret data;
  - Pion electroproduction: Model needed to link measurement to g_A.
- Until 1992, disagreement between pion and neutrino data, until a new correction from χpT seems to resolve discrepancy. This needs to be verified experimentally;
- New disagreement between newer data (including MiniBooNE neutrino data on light nuclear target, ^{12}C) and older data.

Motivations

Parameterizing g_A with a dipole form: $g_A(Q^2) = \frac{g_a}{(1+Q^2/M_A^2)^2}$

$\Rightarrow$ Axial mass M_A.



From G. Zeller talk
Neutrino 2008

- **K2K SciFi** (^{16}O, Q^2>0.2)
  Phys. Rev. **D74**, 052002 (2006)
  M_A=1.20 ± 0.12 GeV
- **K2K SciBar** (^{12}C, Q^2>0.2)
  M_A=1.14 ± 0.11 GeV
- **MiniBooNE** (^{12}C, Q^2>0.25)
  Phys. Rev. Lett. **100**, 032301 (2008)
  M_A=1.25 ± 0.12 GeV
- **MiniBooNE** (2010):
  Phys. Rev. D81:092005 (2010)
  M_A=1.35 ±0.17GeV

Discrepancy persists, as of 2023, see e.g., arXiv:2210.02455

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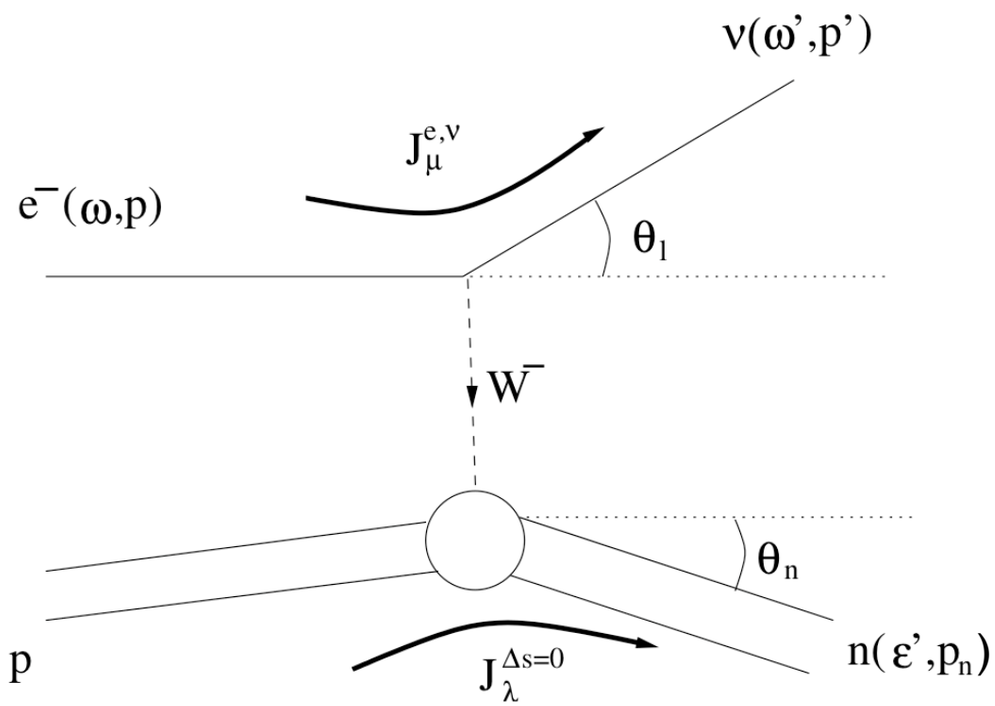
$\Rightarrow$ Important to measure $g_A(Q^2)$ with independent and clean technique.

Possible experiment: measurement of charged weak current with electron beam



5 nucleon form factors involved in the reaction: $G_E^p - G_E^n = G_E$, $G_M^p - G_M^n = G_M$, g_A

Elastic reaction: only the neutron is detected.
Would provide g_A with the typical electron scattering quality data.

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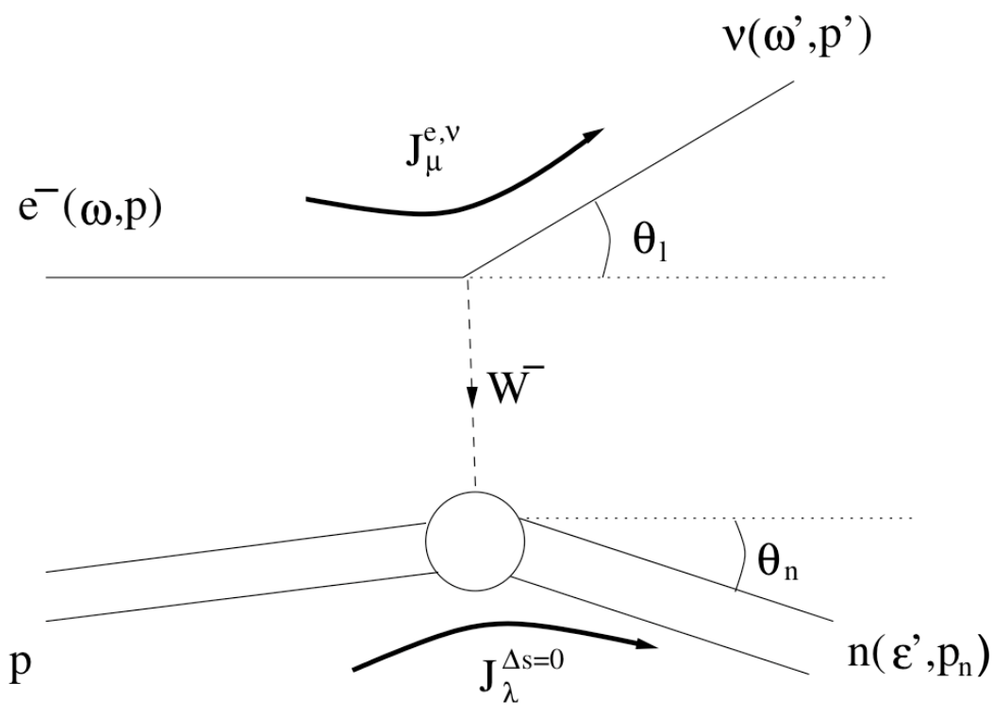

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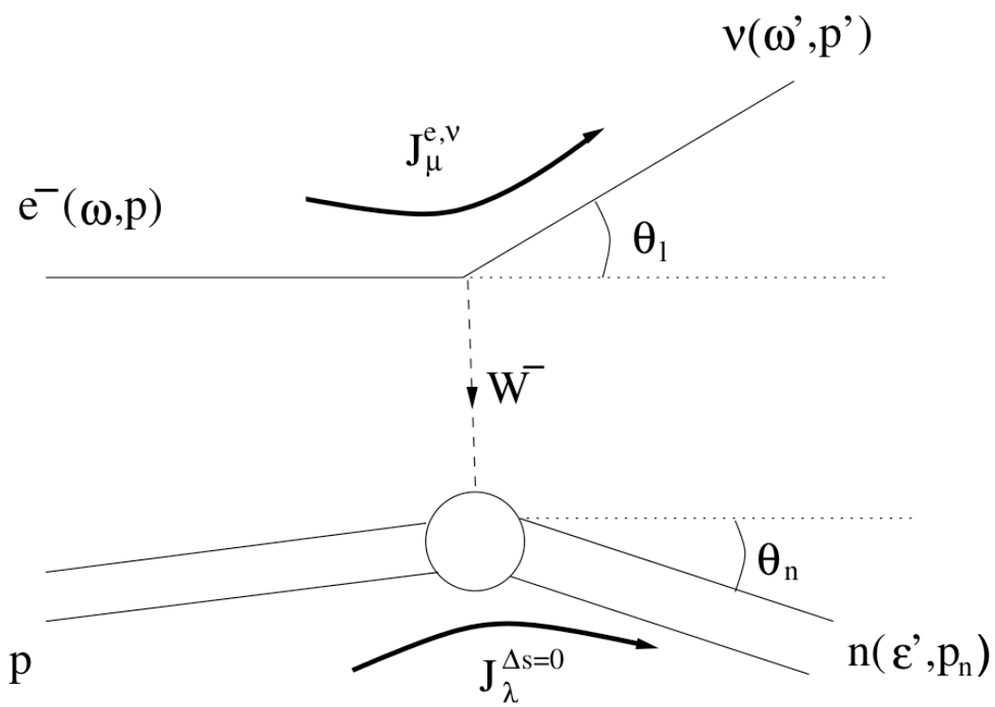

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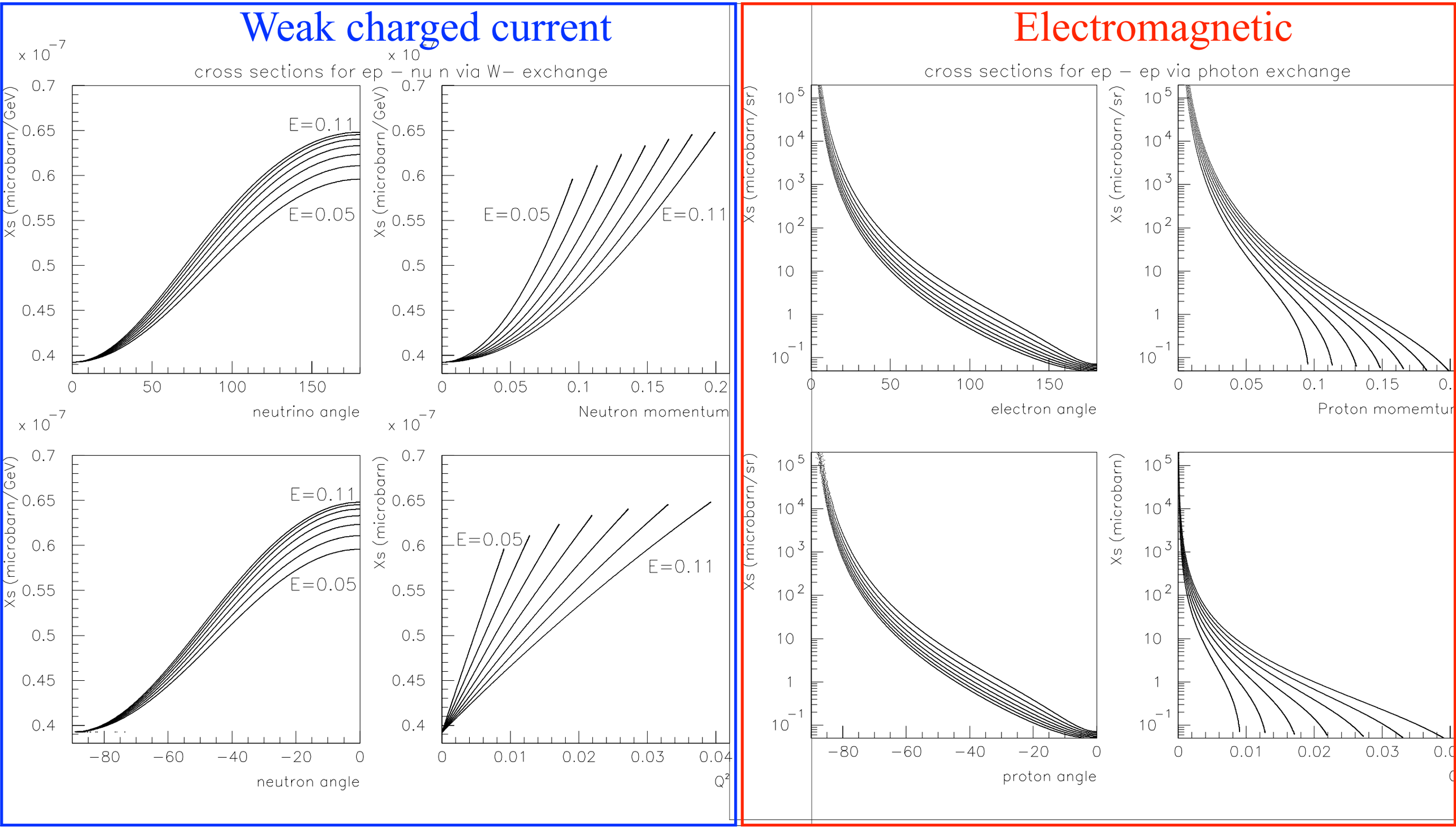
Difficulties:

- Detect neutron with precise kinematics determination (select elastic: no electromagnetic (EM) reaction below pion production threshold);
- Small cross-sections: $\sim 10^{-40}$ cm²/Sr;
- Weak reaction buried deep under electromagnetic backgrounds.

Weak charged current and EM cross sections at low energy



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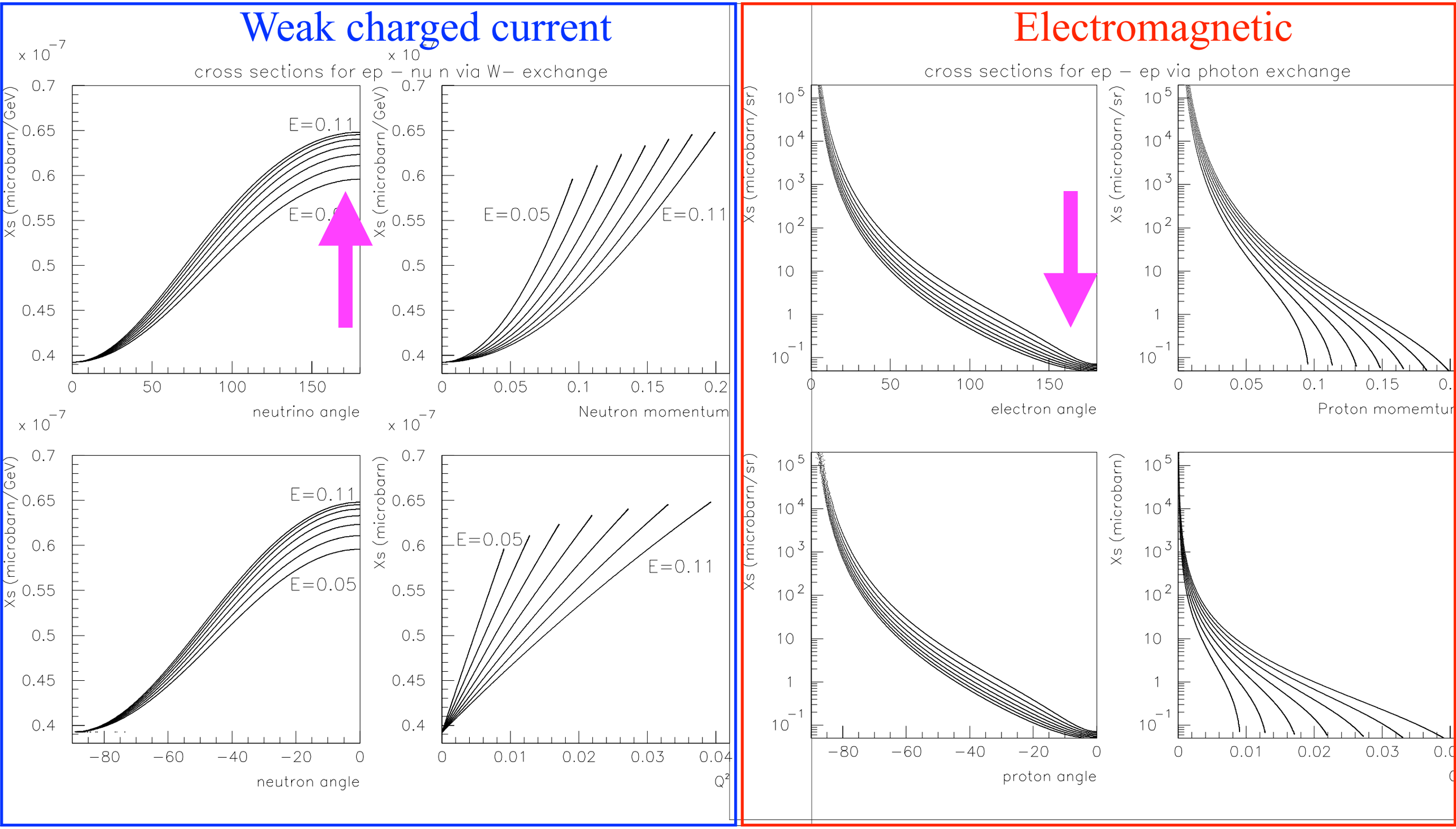

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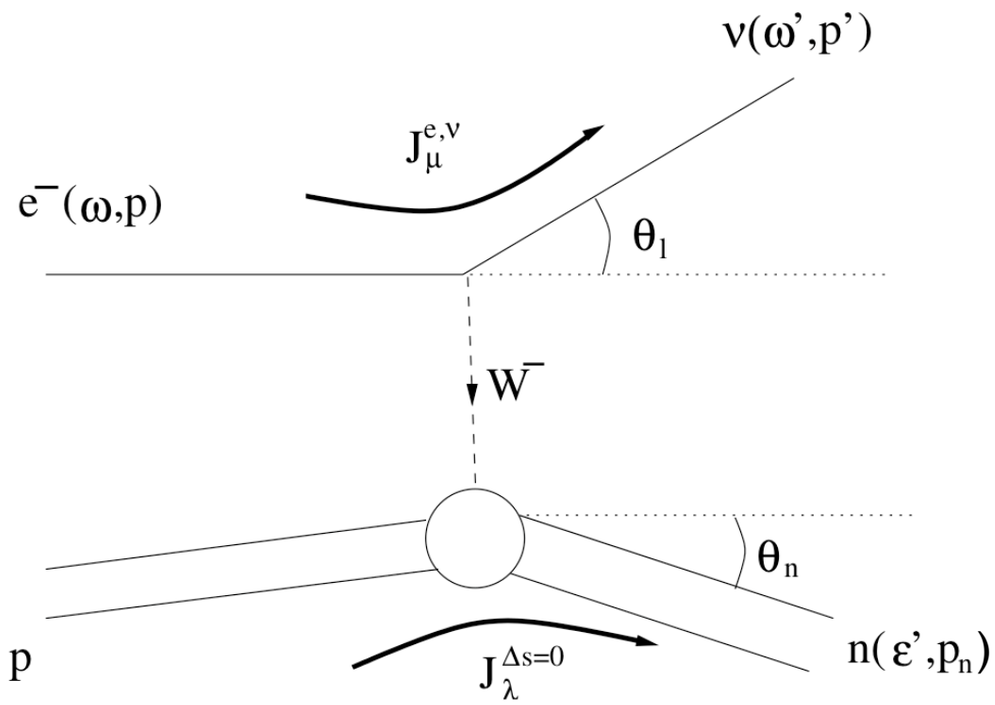

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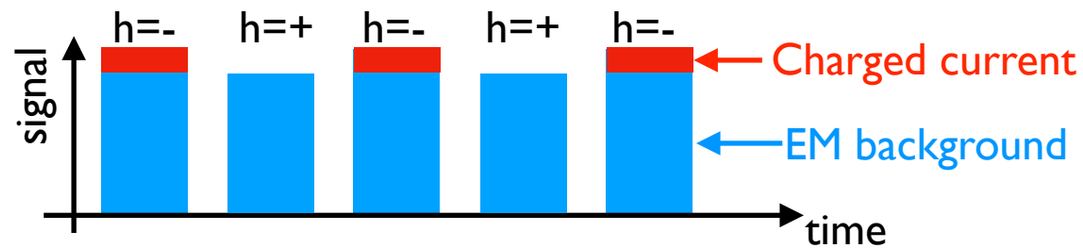
Strategy:

- Low energy (<120 MeV) beam to stay below pion production threshold;
- Backward reaction to enhance Weak/EM cross-sections: detect only neutrons at forward angles;
- High luminosity JLab-type beam + long hydrogen cryotarget: $\mathscr{L} \simeq 5 \times 10^{38}$ cm^{-2} s^{-1};
- Polarized beam for EM background cleanup;
- Pulsed beam to remove prompt EM backgrounds and TOF technique for neutrons.
- kinematic identification of the elastic reaction

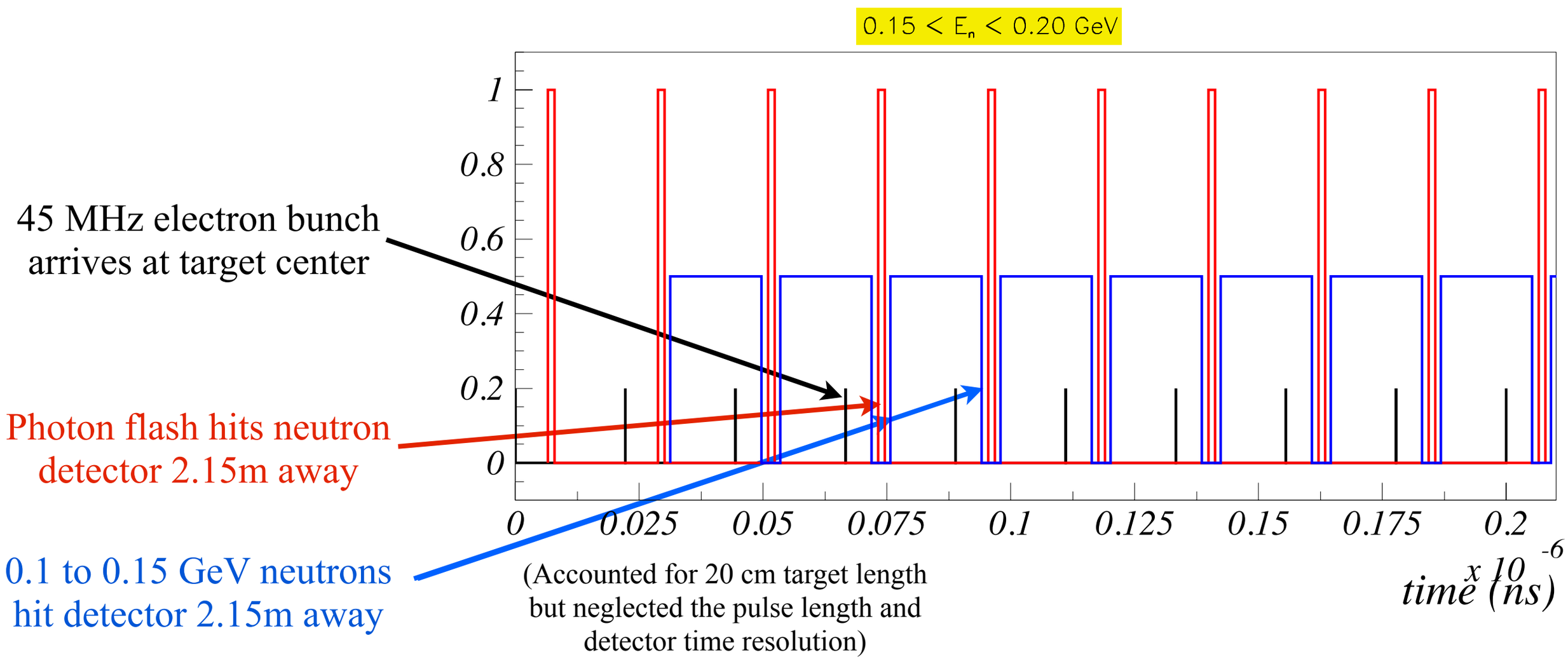
Necessary/desirable beam characteristics

- High current: ~100 μA (averaged, not peak-to-peak);
- Highly polarized: weak reaction asymmetry:100%. EM background asymmetry is 0;

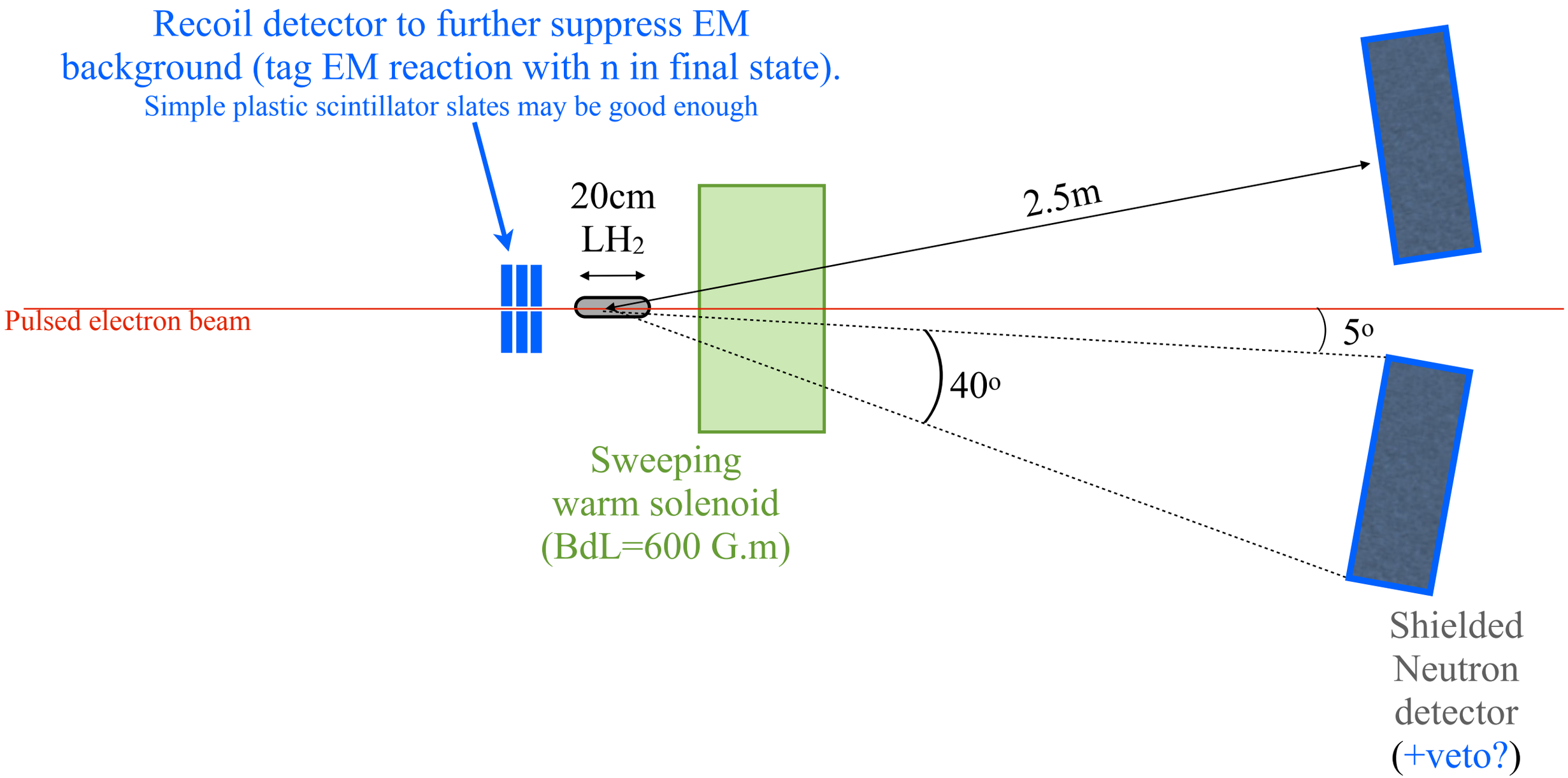


⇒pulse(+) to pulse(-) subtraction: clean cancellation of background;

- Pulsed (~50MHz): cuts prompt EM background. Leaves time for neutrons to reach detector.



Experimental components



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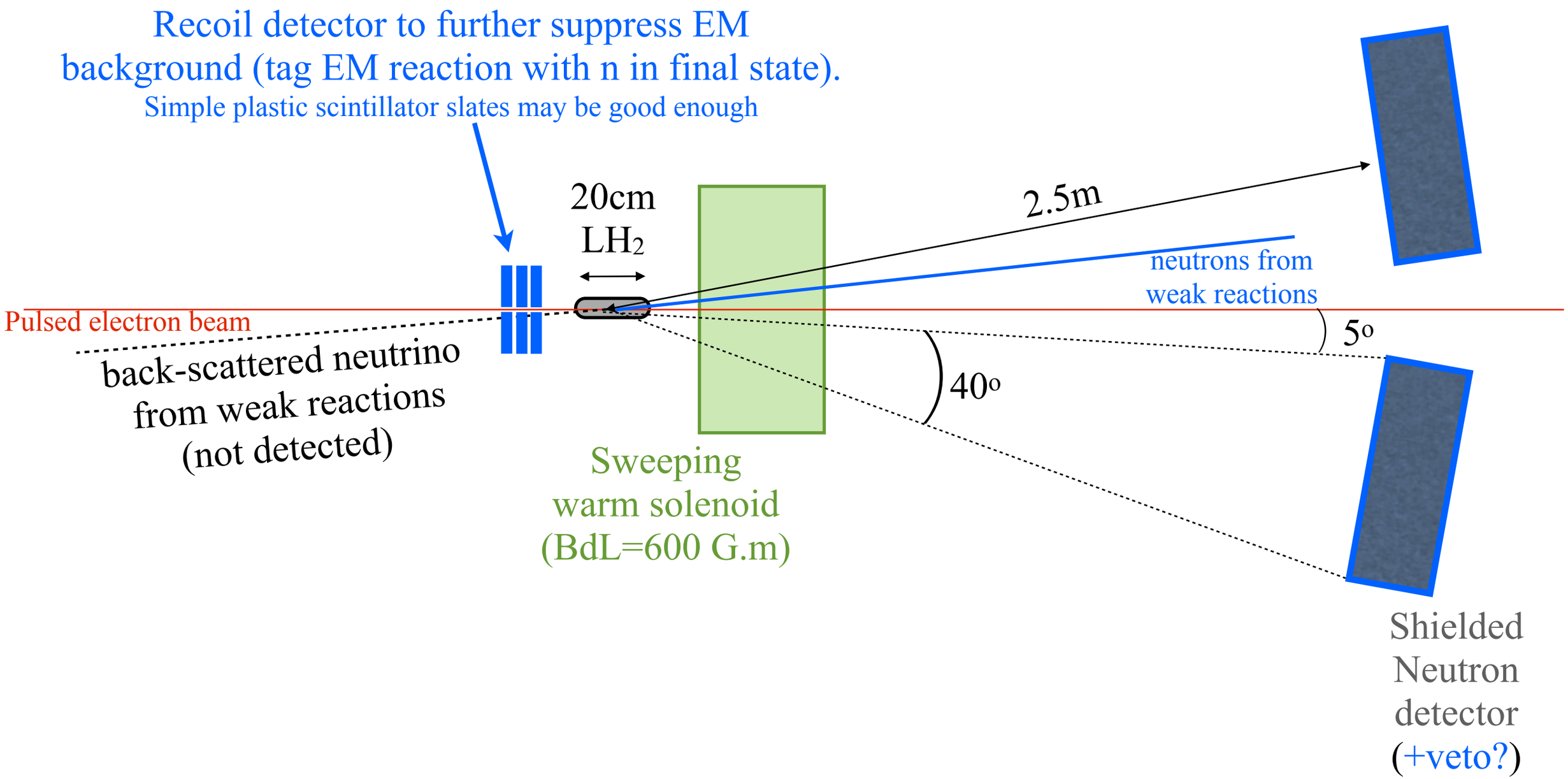

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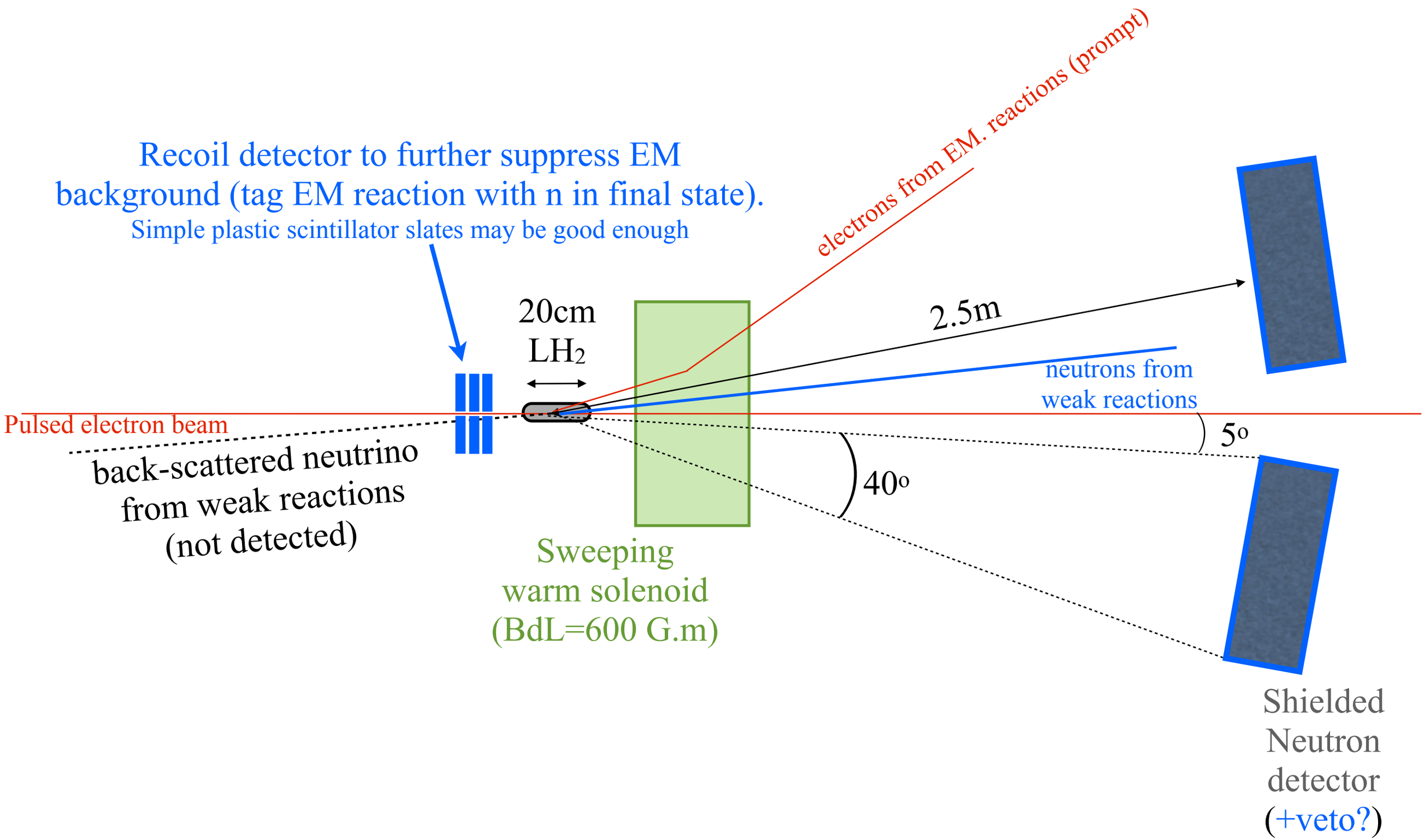

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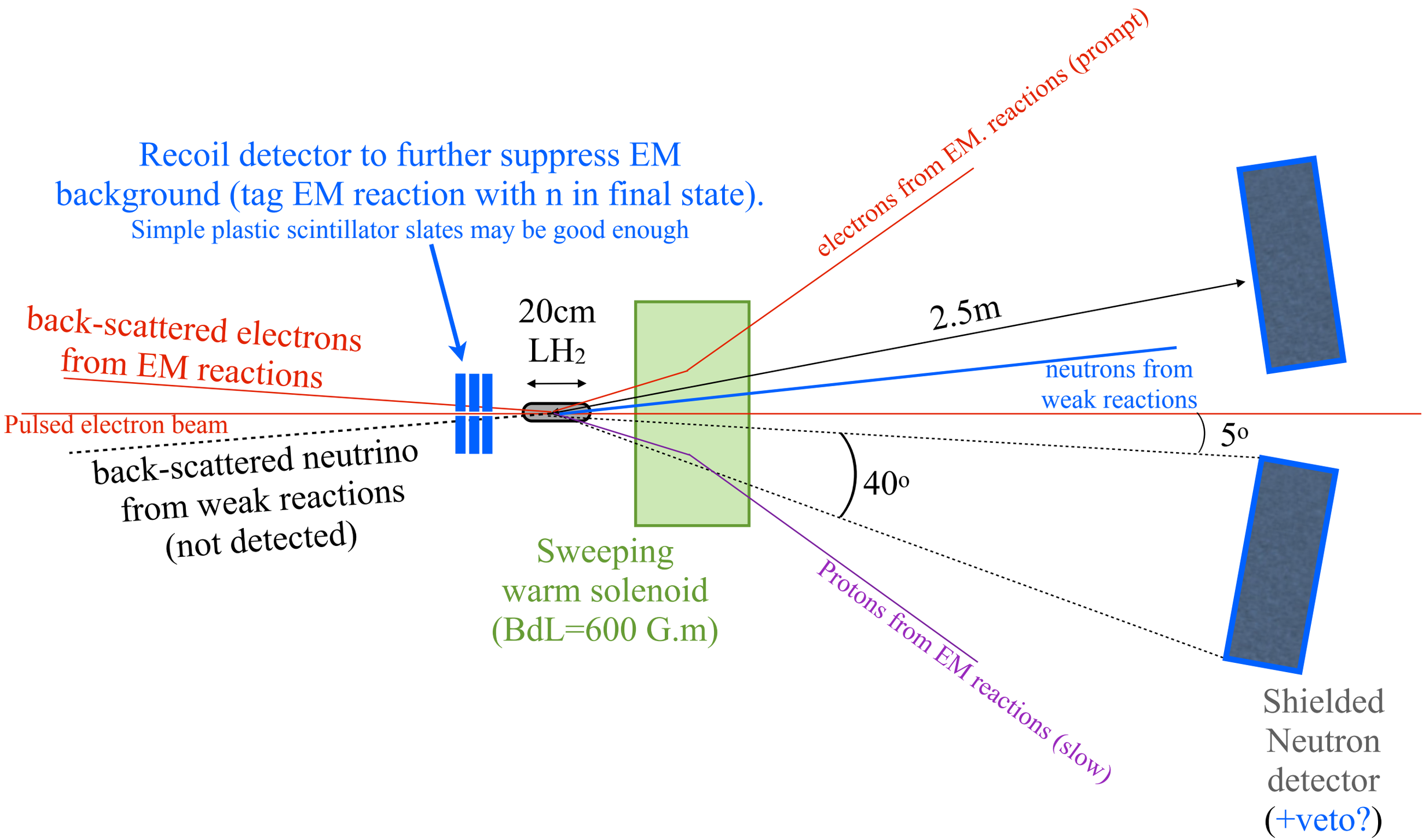

Experimental components (examples)

Neutron detector:

- A few meters away from vertex for good TOF measurements;
- Large acceptance: 2π polar angle coverage, 5° to 45° azimuthal coverage;
- High neutron detection efficiency: absolute cross-section measurement (e.g. LAND detector at GSI: $\varepsilon \sim 1$);
- Segmentation for angular resolution. With TOF, selects elastic (limited by short distance from vertex and by target length);
- Shielded to cut low energy background;
- VETO to cut down (remaining) charged particle background and cosmic rays.

Sweeping magnet:

- Sweeps all charged particles from EM reactions (electrons from forward scattering and protons from backward scattering);
- Low beam energy ⇒ warm magnet is sufficient.

Electron recoil detector:

- High detection efficiency. To reduce EM background.

Cryotarget:

- 20cm long;
- High purity;
- 10 mil Be windows;
- H_2 chamber for data taking, D_2 chamber or C foil for neutron detector calibration.

Backgrounds

•Windows: $Be+e^- \rightarrow n+e^- +X$: noise/signal 8×10^3 at worst (E=0.11GeV, 45°). Can be reduced to < unity by selecting nucleon elastic reaction and with recoil electron detector rejecting (e^-,n) coincidences;

•Prompt EM (photon flash, electrons): negligible after timing cuts; However, photon re-emissions is significant. ⇒ May need more delay between pulses or better shielding/vetoing.

•D contamination in cryotarget: Negligible with 99.9995% pure H and recoil detector;

•Protons undergoing charge exchange ($p \rightarrow n$) when crossing the cell window: vetoed by recoil detector;

•Scattered electrons (Moller, nuclear scattering) and beam halo knocking neutrons off the cell wall: vetoed by recoil detector;

•Bath of neutrons from accelerating cavity and secondary reactions. Negligible.

Kinematic and rates (100 μA-average, 20cm long LH_2 target)

E	θ_n	P'	$\langle Q^2 \rangle$	Xs ($10^{-7}\mu b$)	R (Hz)
0.11	5°-10°	0.0892-0.0897	0.0385	0.644	0.019
0.11	10°-15°	0.0897-0.0905	0.0372	0.637	0.031
0.11	15°-20°	0.0905-0.0916	0.0356	0.628	0.041
0.11	20°-25°	0.0916-0.0929	0.0335	0.616	0.048
0.11	25°-30°	0.0929-0.0944	0.0307	0.600	0.054
0.11	30°-35°	0.0944-0.0960	0.0278	0.582	0.056
0.11	35°-40°	0.0960-0.0978	0.0245	0.562	0.061
0.11	40°-45°	0.0978-0.0996	0.0213	0.540	0.058
0.09	5°-10°	0.0756-0.0760	0.0267	0.636	0.015
0.09	10°-15°	0.0760-0.0765	0.0259	0.629	0.019
0.09	15°-20°	0.0765-0.0772	0.0247	0.617	0.026
0.09	20°-25°	0.0772-0.0781	0.0231	0.606	0.033
0.09	25°-30°	0.0781-0.0792	0.0213	0.591	0.039
0.09	30°-35°	0.0792-0.0803	0.0193	0.574	0.038
0.09	35°-40°	0.0803-0.0815	0.0171	0.553	0.040
0.09	40°-45°	0.0815-0.0828	0.0147	0.532	0.041
0.07	5°-10°	0.06098-0.06118	0.0168	0.620	0.007
0.07	10°-15°	0.06118-0.06152	0.0162	0.613	0.013
0.07	15°-20°	0.06152-0.06198	0.0150	0.597	0.016
0.07	20°-25°	0.06198-0.06254	0.0145	0.591	0.020
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0.07	30°-35°	0.06319-0.06391	0.0121	0.559	0.024
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0.05	5°-10°	0.0452-0.0453	0.0089	0.592	0.0036
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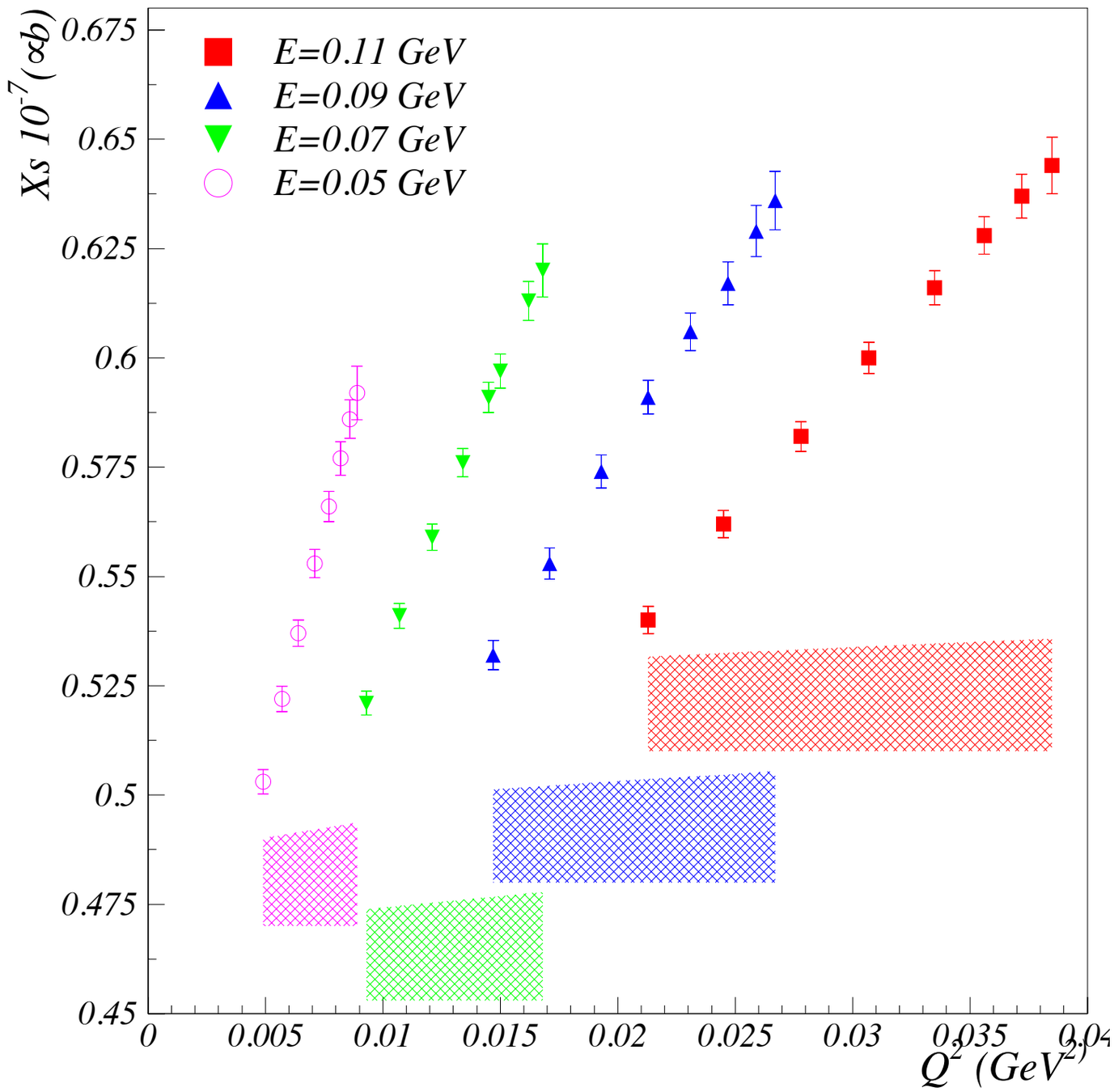
0.05	40°-45°	0.04718-0.04759	0.0049	0.503	0.0124

Expected cross-sections with 6 days at 110MeV, 7 days at 90MeV, 17 days at 70MeV and 30 days at 50MeV. Error bars: statistics. Bands: 4% systematics. Numbers are for 100% efficiency and no backgrounds.



$\Rightarrow$24 Q^2 points. Each: Δg_A~0.9%(stat)+4%(syst)

(most recent experiment: ΔM_A=12.6%)

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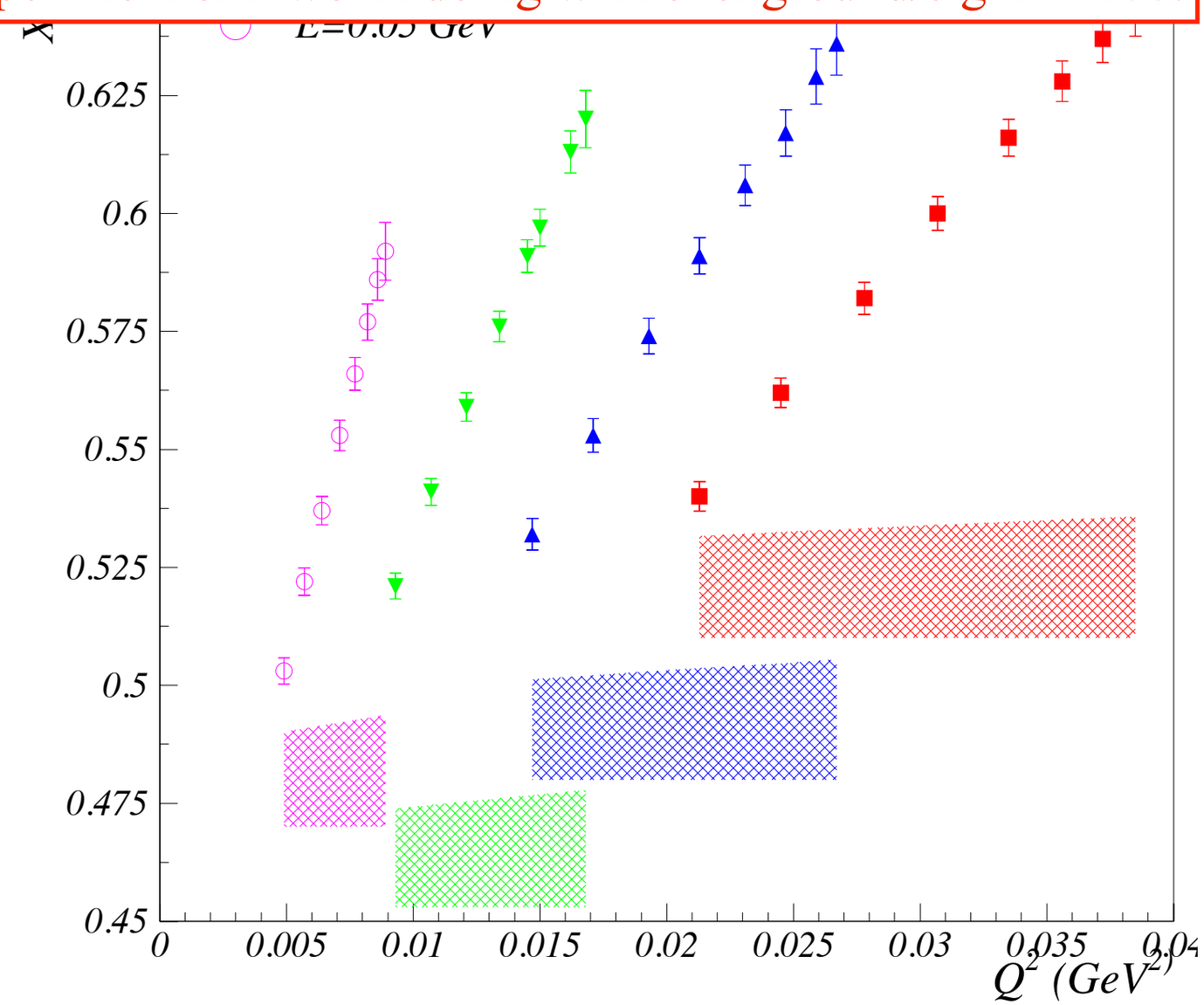
If we have a background/signal ~ 25, then stats≃syst, which is optimal.
Experiment still worth doing with background/signal ~100.



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Conclusion

- Pioneering experiment. Measurement of axial form factor with electron scattering technique quality. Numerous physics interests in such measurement;

- No new technology needed but large backgrounds demand well-designed detectors and background suppression techniques;

- Relatively quick: ~a few months if backgrounds are under control (background/signal≲10), and good neutron efficiency (50%), assuming 100 μA (and without accounting for commissioning time);

- Cleaner, cheaper than a (dedicated) neutrino experiment. Maybe easier too;

- Limited to very low Q^2 ($0.005 \leq Q^2 \leq 0.04$ GeV^2) but:
  - Possibility to reach larger Q^2 using positrons: See talk by D. Dutta tomorrow morning;
  - Experience with low Q^2 would tell us the feasibility of the same experiment above pion threshold (additional EM backgrounds).