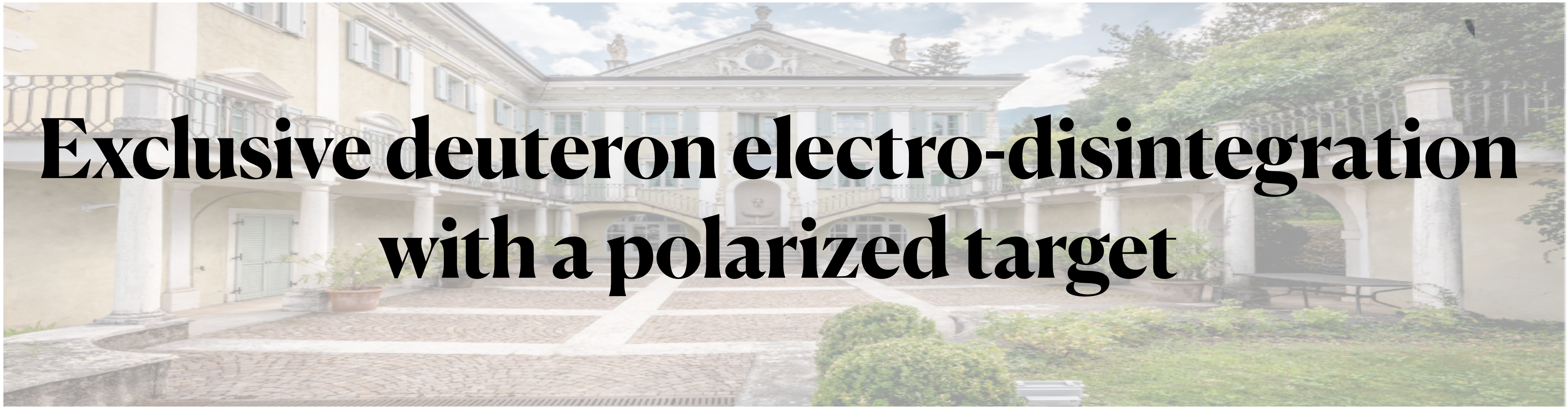


Exclusive deuteron electro-disintegration with a polarized target

N. Santiesteban and C. Yero

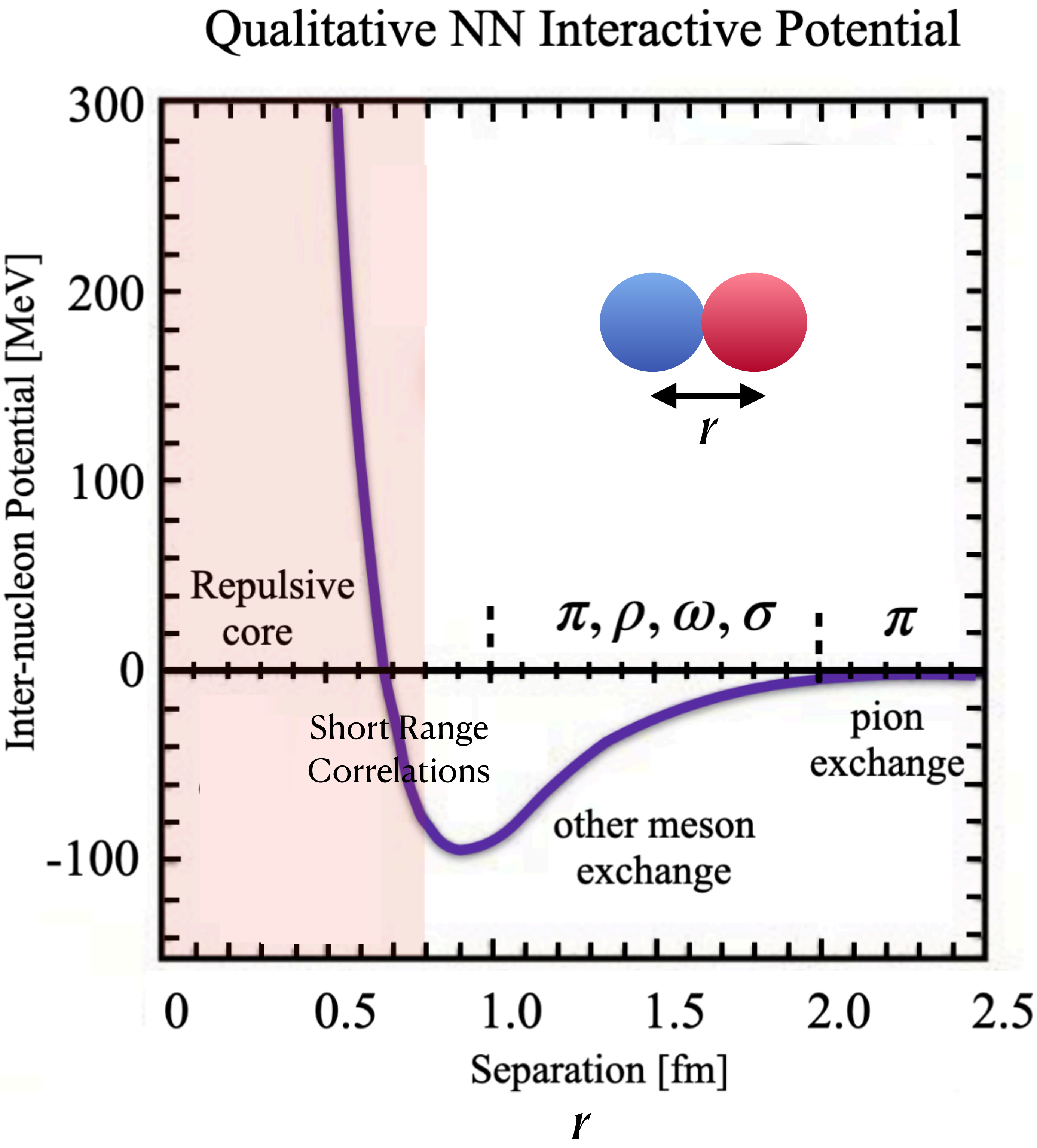
with acknowledgments to
M. Sargsian and W. Boeglin

This project is a work in progress...

Note: Many slides are courtesy of C. Yero

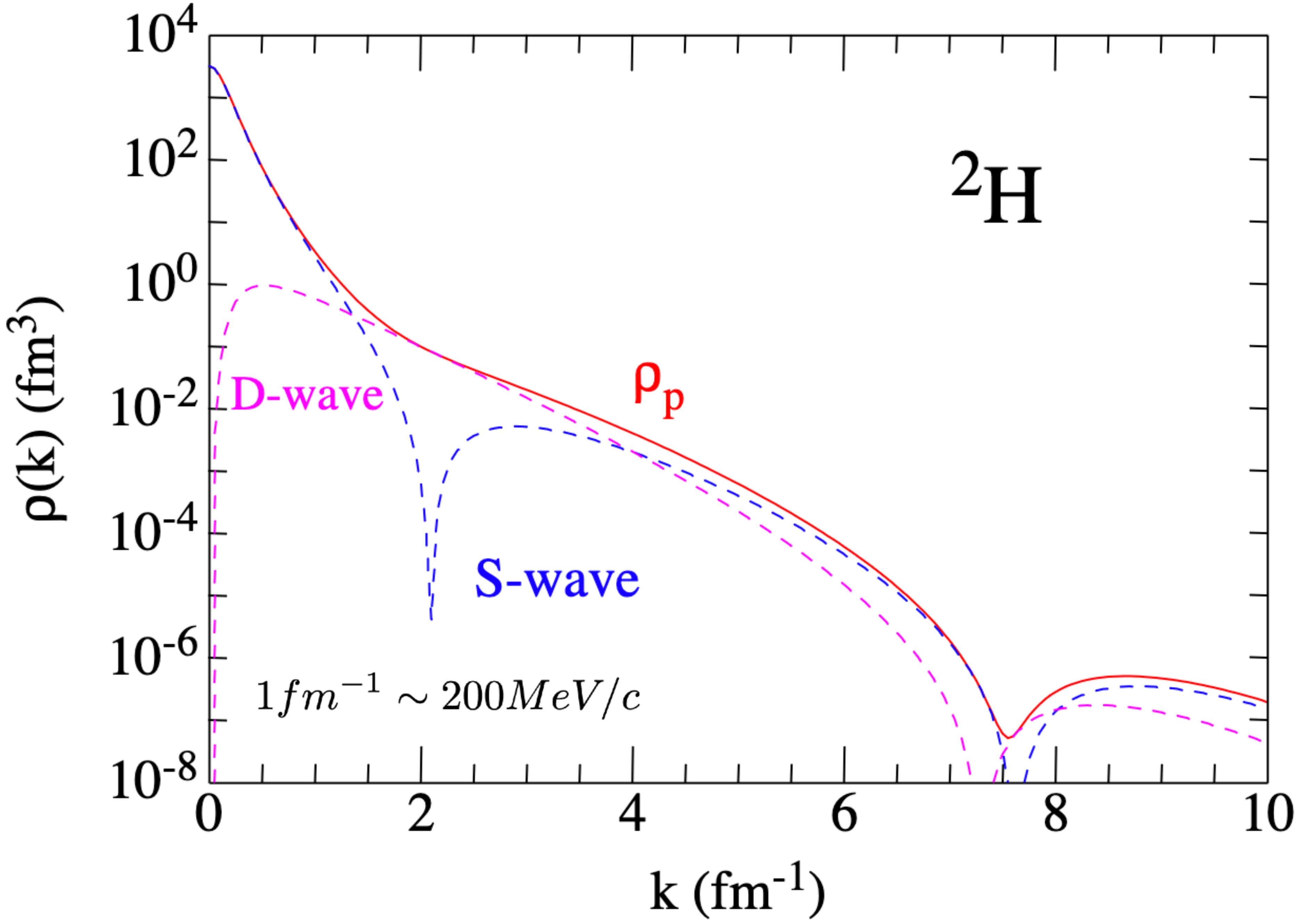
Why Deuterium?

- Simplest nuclei to study nucleon-nucleon interaction.
- We are still working in its understanding at all length scales.
- Fundamental to understand SRCs.



Proton Momentum Distribution

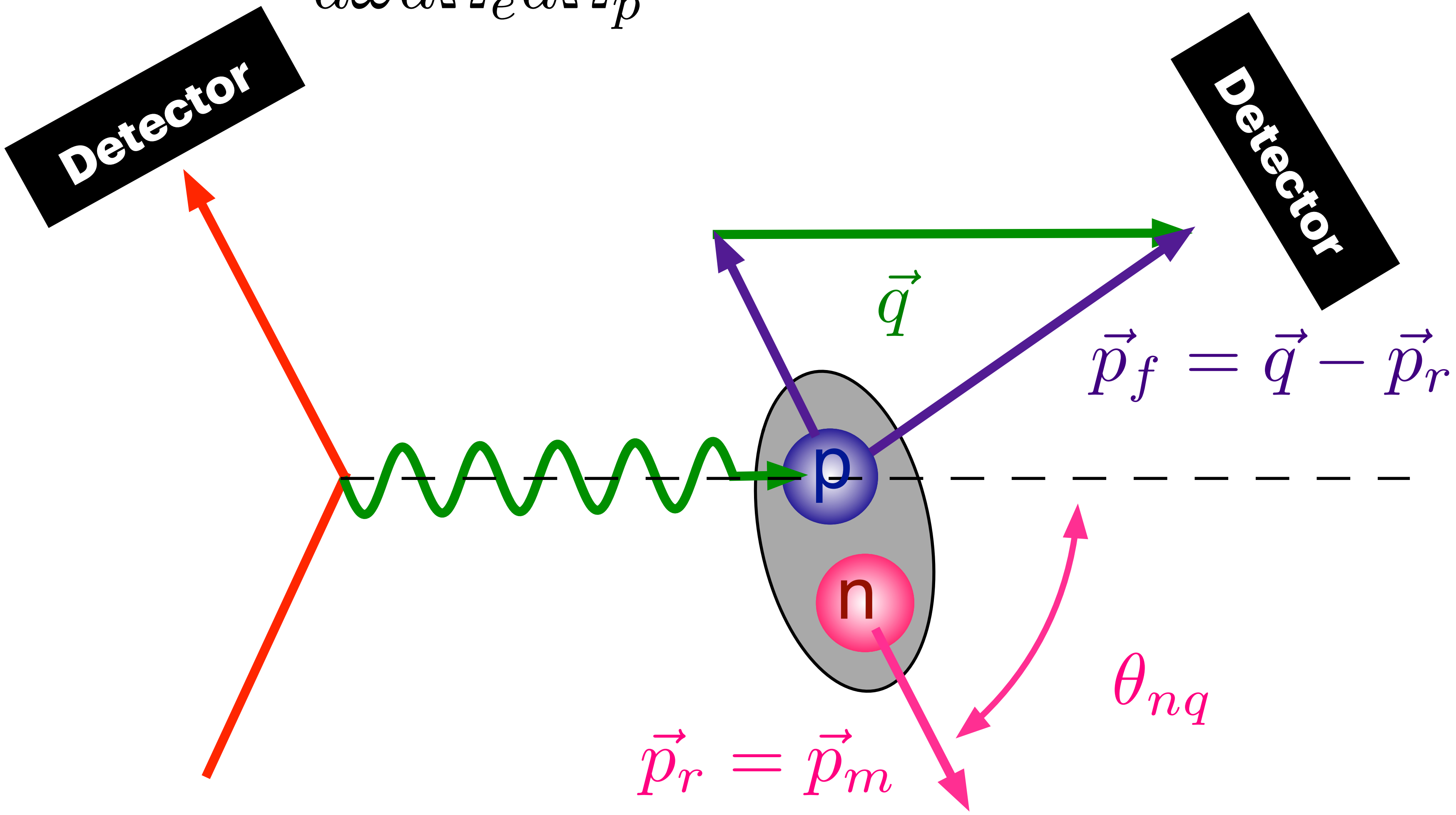
How can we really probe the D- and S- wave contributions?



Wiringa, Schiavilla, Pieper, Carlson, PRC 89 (2014) 024305

Probing the deuteron with electron-scattering

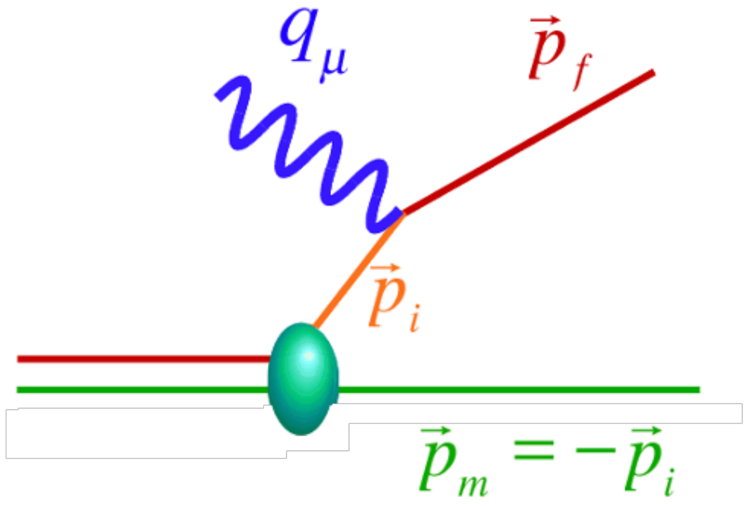
$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = k\sigma_{ep}\rho(p_r)$$



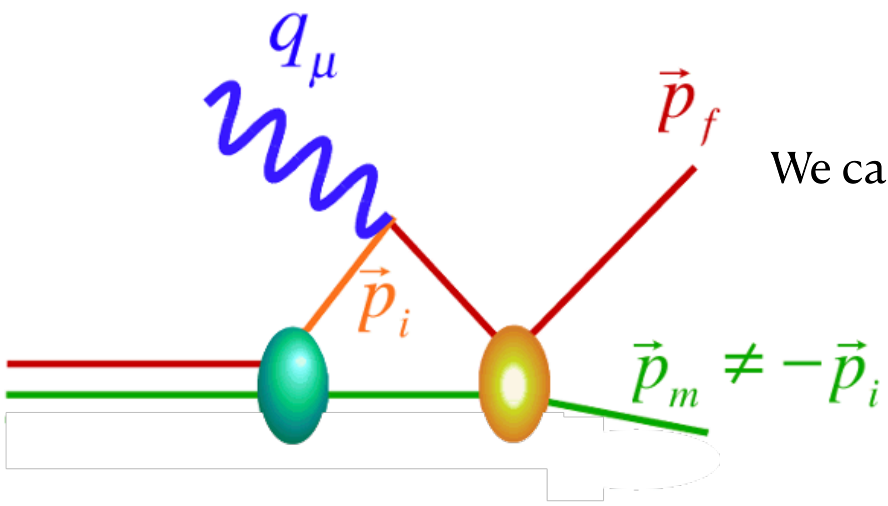
In the plane wave impulse approximation (PWIA)

$$\rho(p_r) = \frac{\sigma_{exp}}{k\sigma_{ep}}$$

PWIA



FSI



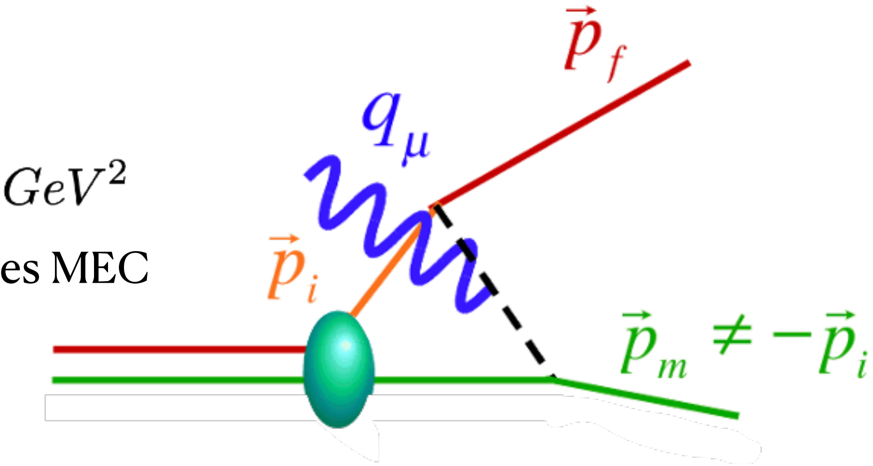
We can reduce at the right kinematics

In reality ...

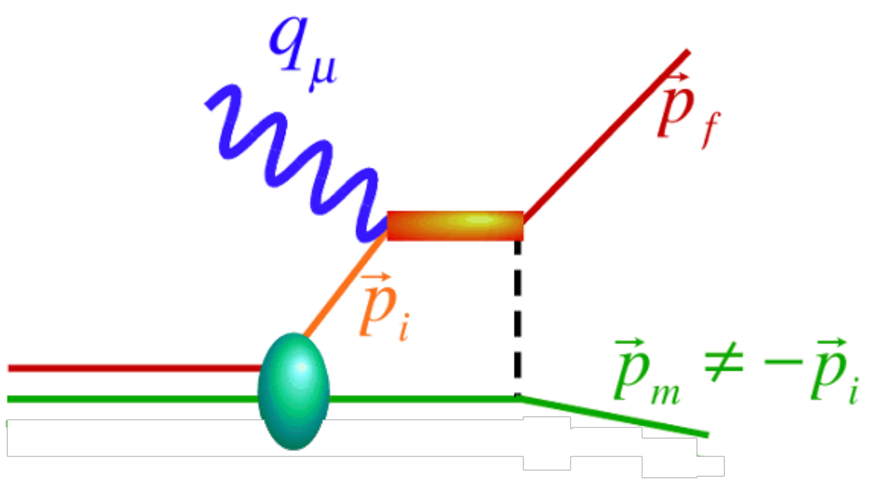
MEC

$Q^2 > 2GeV^2$

Suppresses MEC



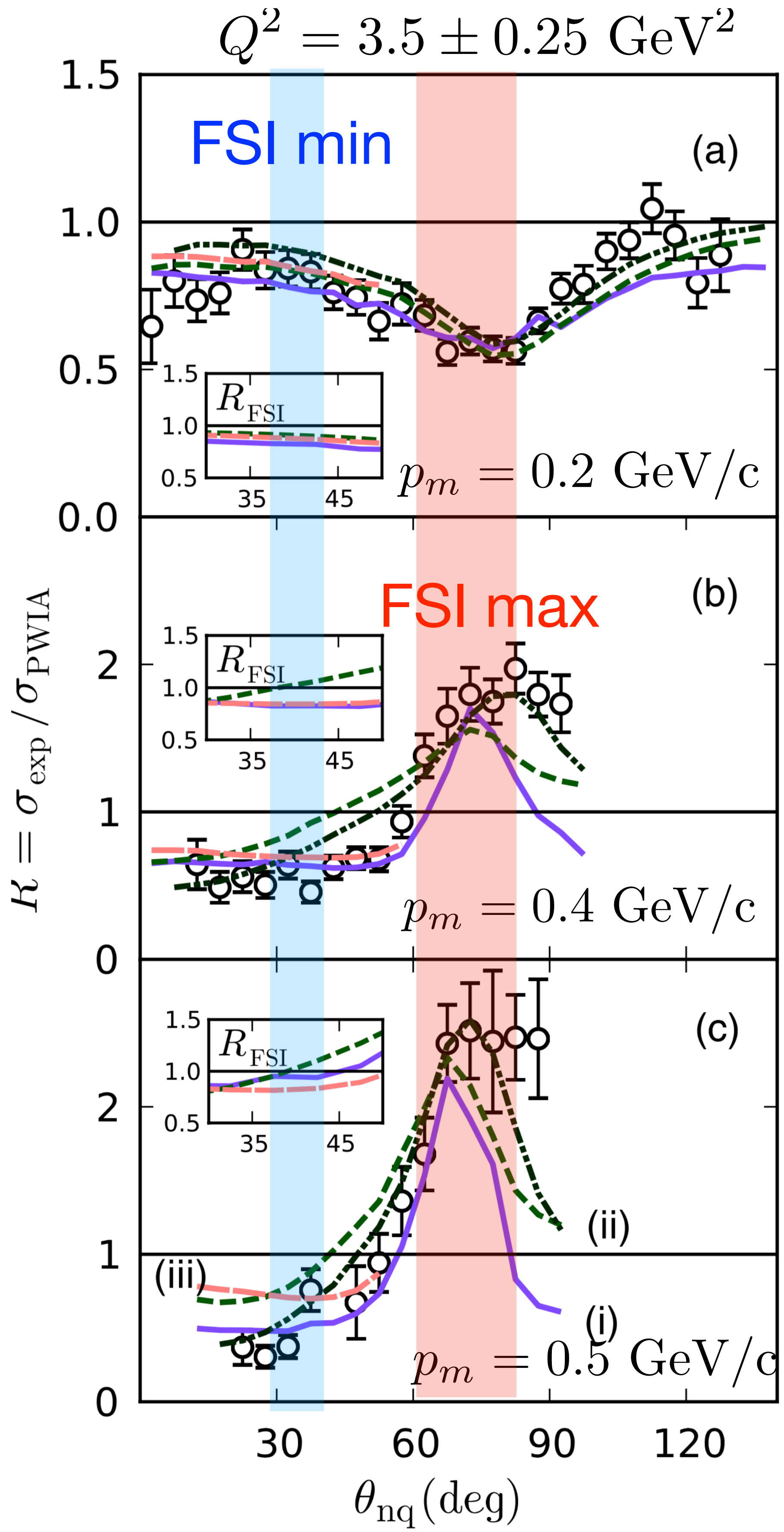
IC



$x > 1$

Suppresses IC

How do we control FSI?



minimal FSI at $\theta_{nq} \sim 35 - 45^{\circ}$

CD-Bonn FSI (Calculations: Misak Sargsian)
Misak M. Sargsian Phys.Rev.C82014612 (2010)

JVO Model (Calculations: J.W. Van Orden & S. Jeschonnek)
S.Jeschonnek and J. W. VanOrden Phys.Rev.C80054001 (2009)

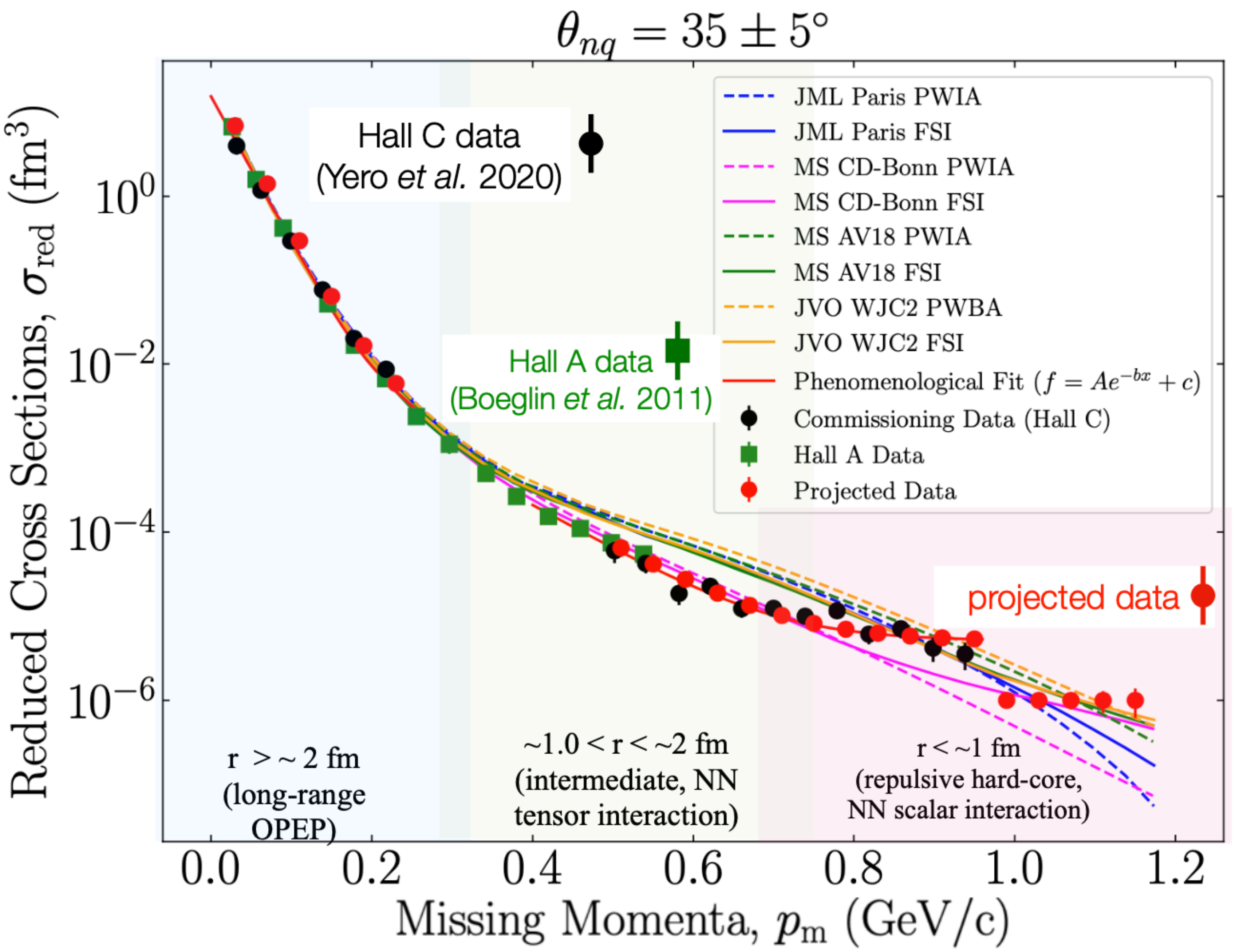
Paris FSI (Calculations: J.M. Laget)
J. Laget Phys.Lett.B60949 (2005)

Paris FSI+MEC+IC (Calculations: J.M. Laget)
J. Laget Phys.Lett.B60949 (2005)

Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)
K. S. Egiyan et al. (CLAS) Phys. Rev. Lett. 98, 262502 (2007)

FSI peak at $\theta_{nq} \sim 70^{\circ}$

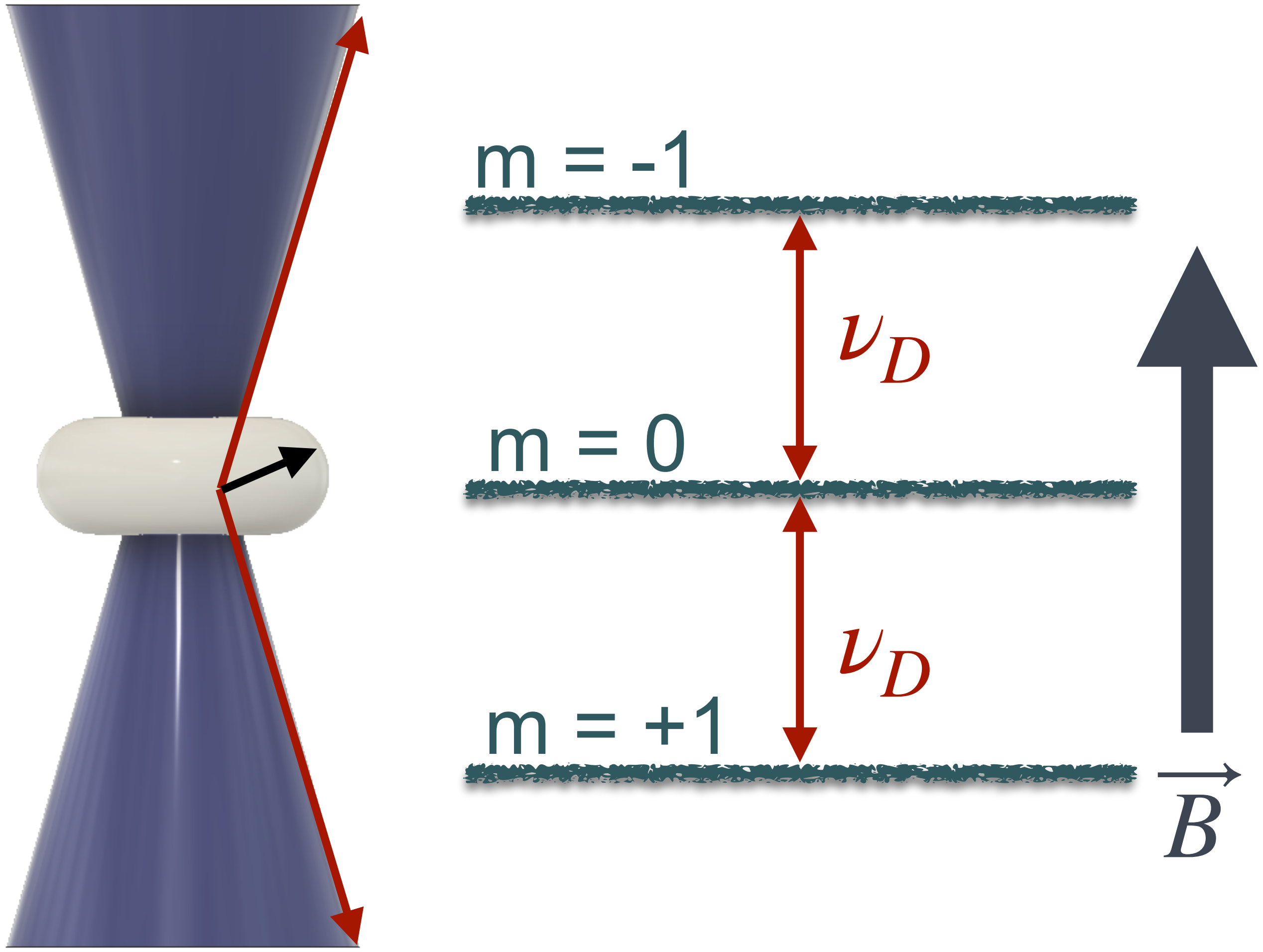
Some other results



- non-relativistic theory calc. using CD-Bonn (M. Sargsian) reproduce data up to $p_{\rm m} \sim 0.7$ GeV/c
- no model reproduces data $p_{\rm m} > 0.7$ GeV/c (non-nucleonic degrees of freedom?, quarks?)

C. Yero et al. Phys.Rev.Lett. 125, 262501 (2020)

Deuteron Polarization



$$\nu_D = \frac{\mu_D B}{h}$$

$$\nu_D = 6.54 MHz/T$$

Spin 1 System

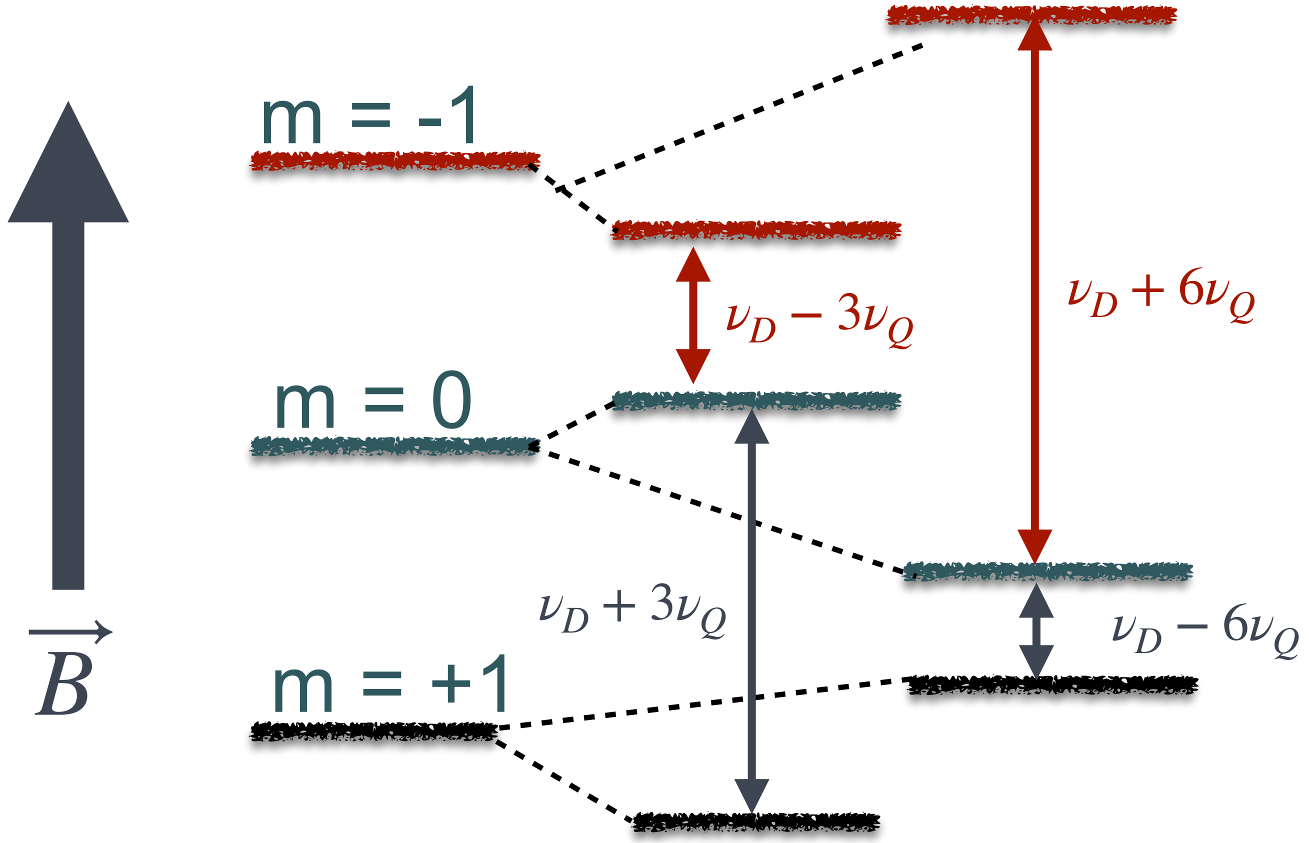
- In a magnetic field: 3 sublevels (+1, 0, 1) due to Zeeman interaction.
- Two energy transitions with intensities I_+(+1 to 0) and I_(0 to -1).

Deuteron Polarization

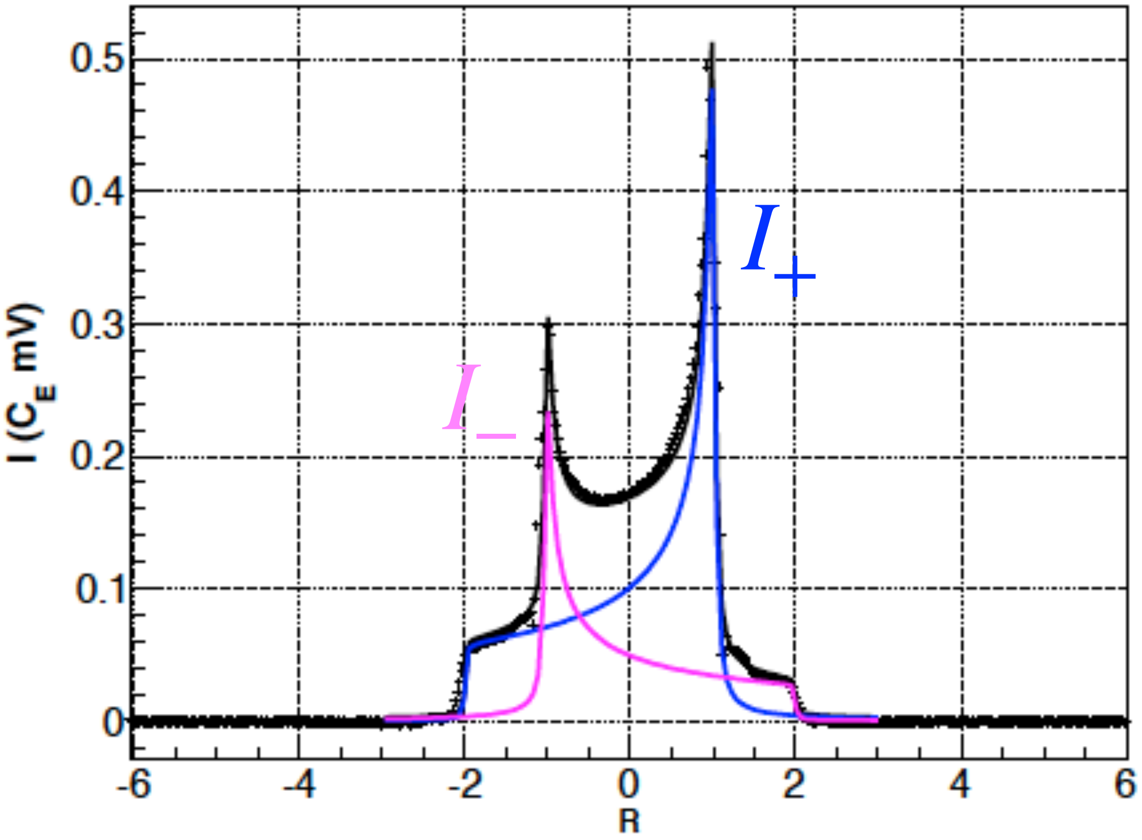
$$E_m = -h\nu_D m + h\nu_Q(cos^2\theta - 1)(3m^2 - 2)$$

eQ : Electric Quadrupole interaction shifts energy levels
eq : Electric field gradient
θ : angle between *eq* and *B*

$\nu_Q = \frac{e^2 qQ}{8h}$: Quadrupole Frequency



Keller, D. Eur. Phys. J. A53 (2017) .



$$R = \frac{\nu - \nu_D}{3\nu_Q}$$

Deuteron NMR Line-shape.

Vector Polarization

$$P_z = N_{+1} - N_{-1}$$

$$-1 < P_z < +1$$

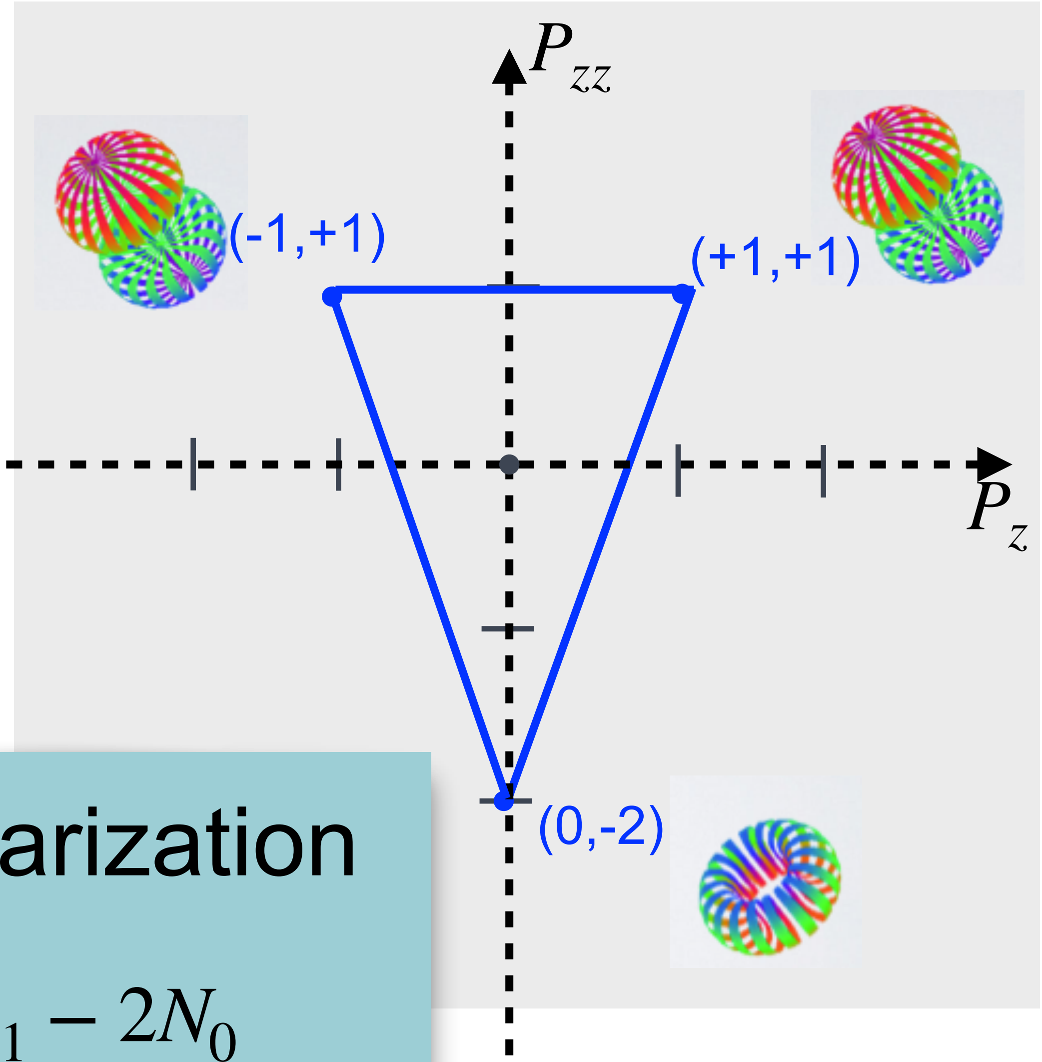
Tensor Polarization

$$P_{zz} = N_{+1} + N_{-1} - 2N_0$$

$$-2 < P_{zz} < +1$$

Normalization:

$$N_{+1} + N_{-1} + N_0 = 1$$



Vector Polarization

$$P_z = N_{+1} - N_{-1}$$

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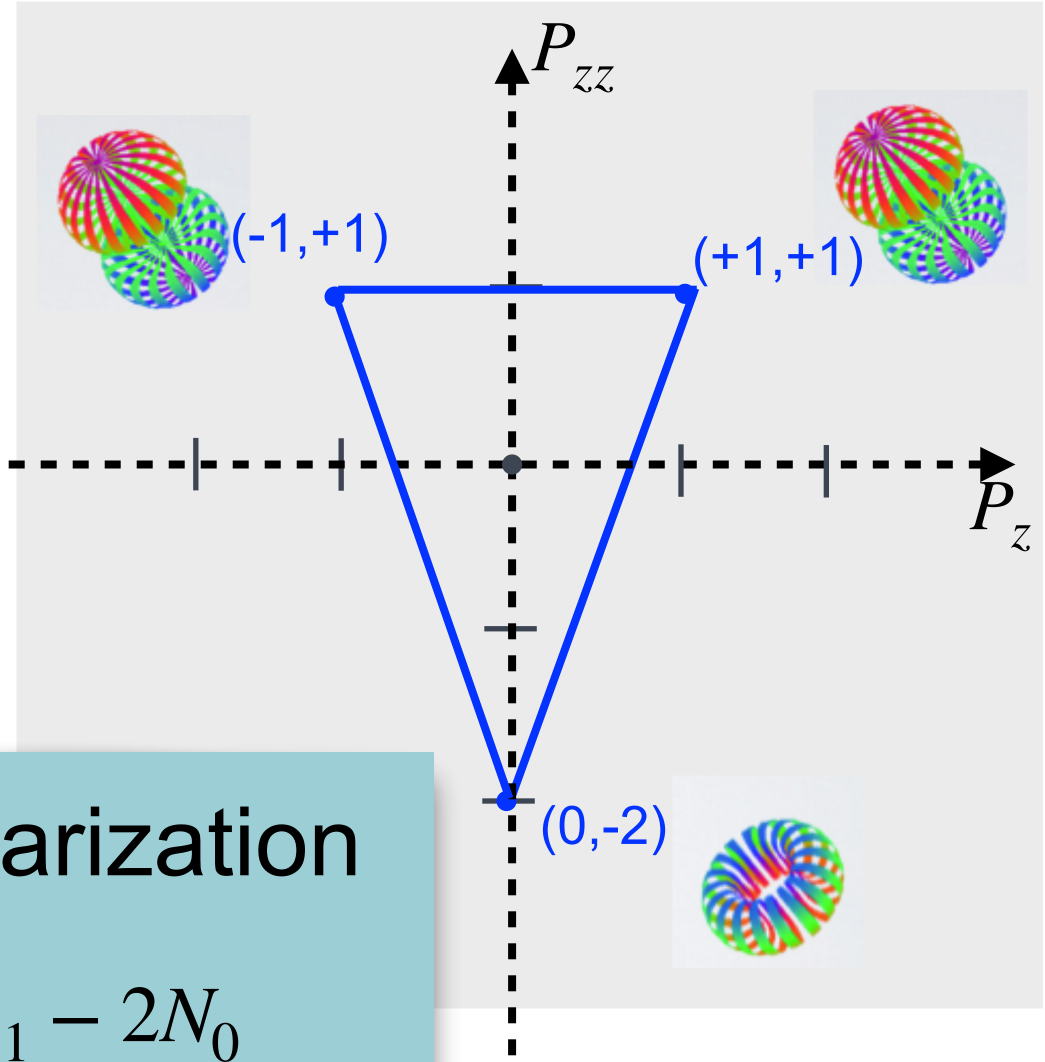
Normalization:

$$N_{+1} + N_{-1} + N_0 = 1$$

Vector Polarization

$$P_z = N_{+1} - N_{-1}$$

$$-1 < P_z < +1$$



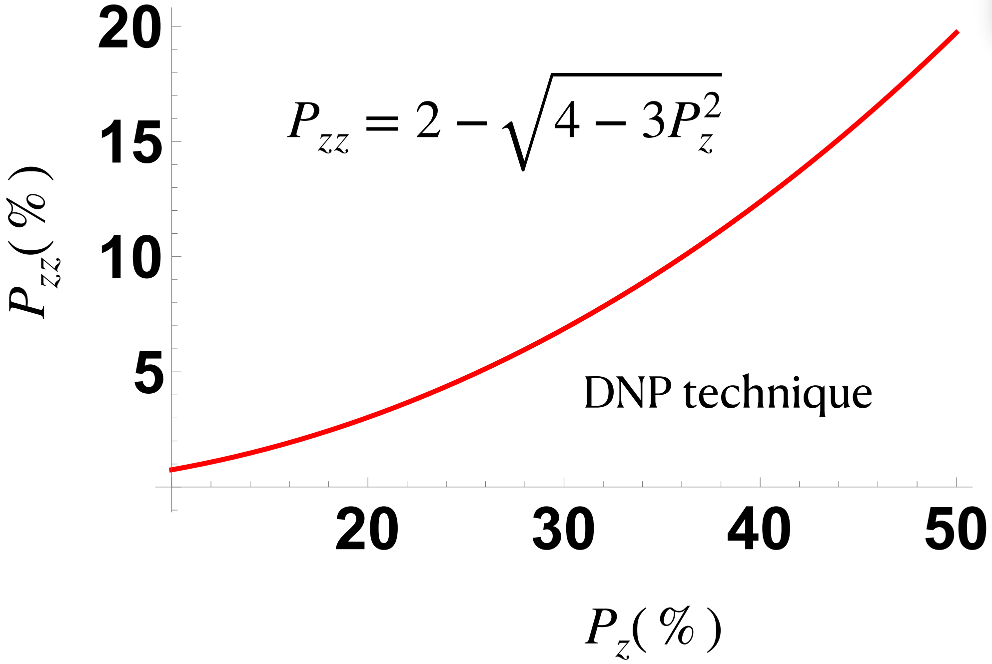
Tensor Polarization

$$P_{zz} = N_{+1} + N_{-1} - 2N_0$$

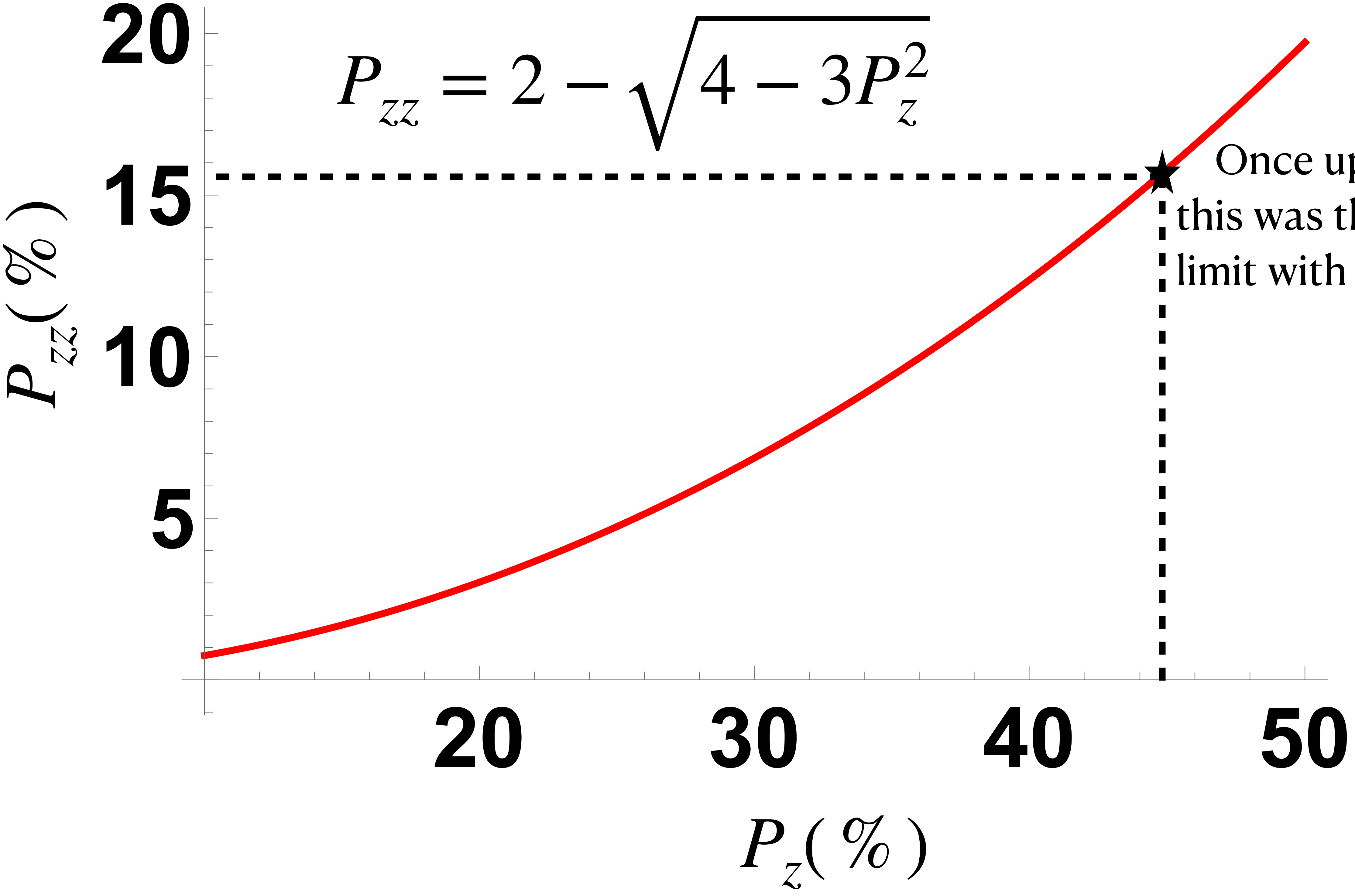
$$-2 < P_{zz} < +1$$

Normalization:

$$N_{+1} + N_{-1} + N_0 = 1$$



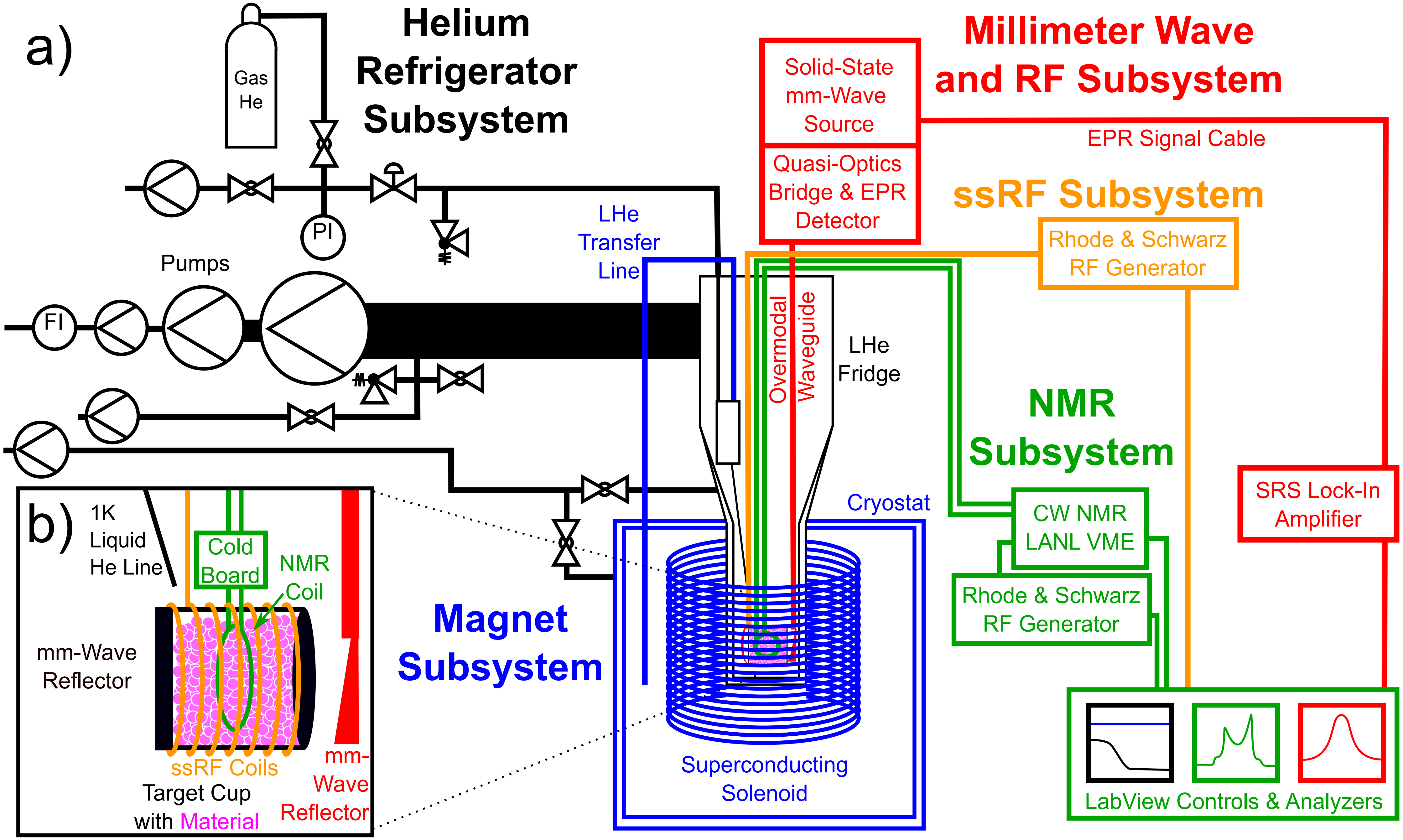
DNP technique



$$P_{zz} = 2 - \sqrt{4 - 3P_z^2}$$

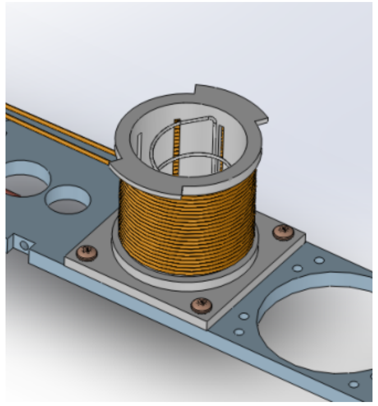
Once upon a time
this was the maximum
limit with solid targets

DNP System

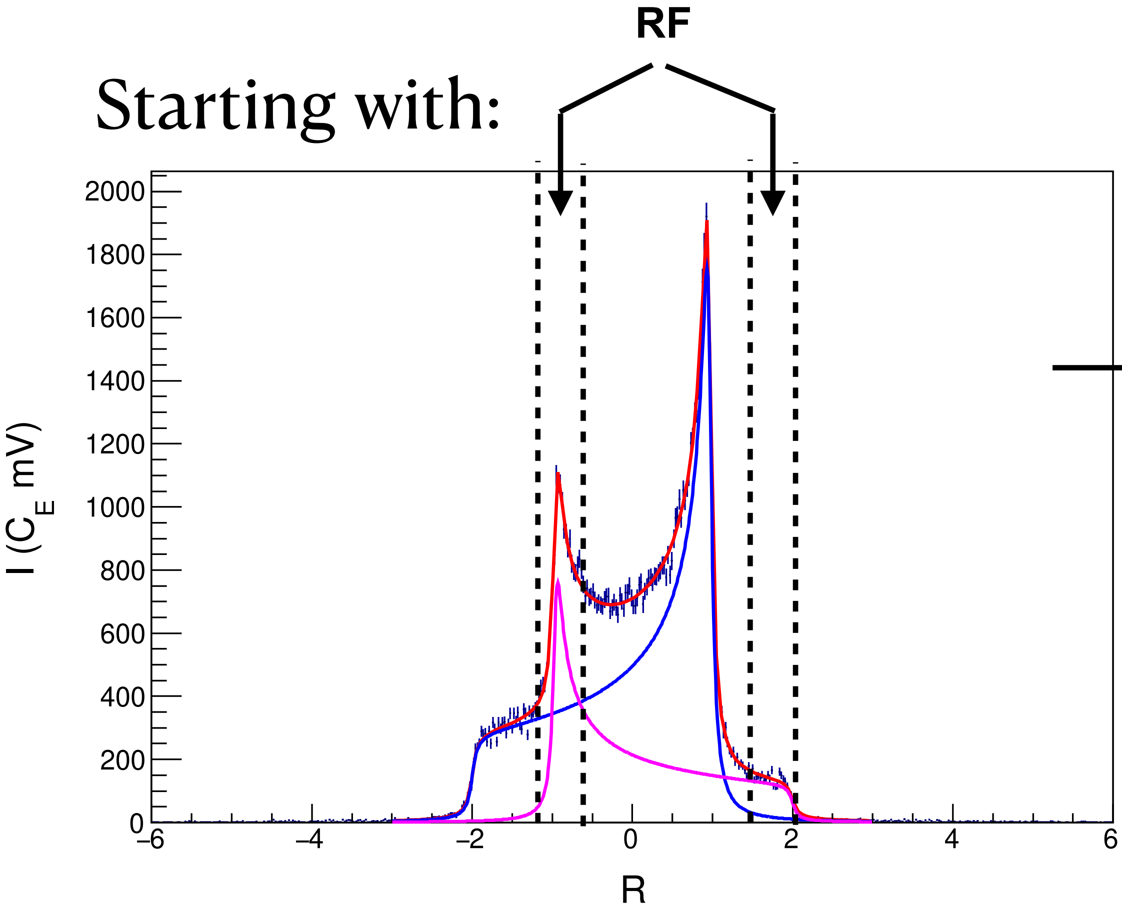


UNH System

Semi-Saturating RF (ss-RF)



Starting with:

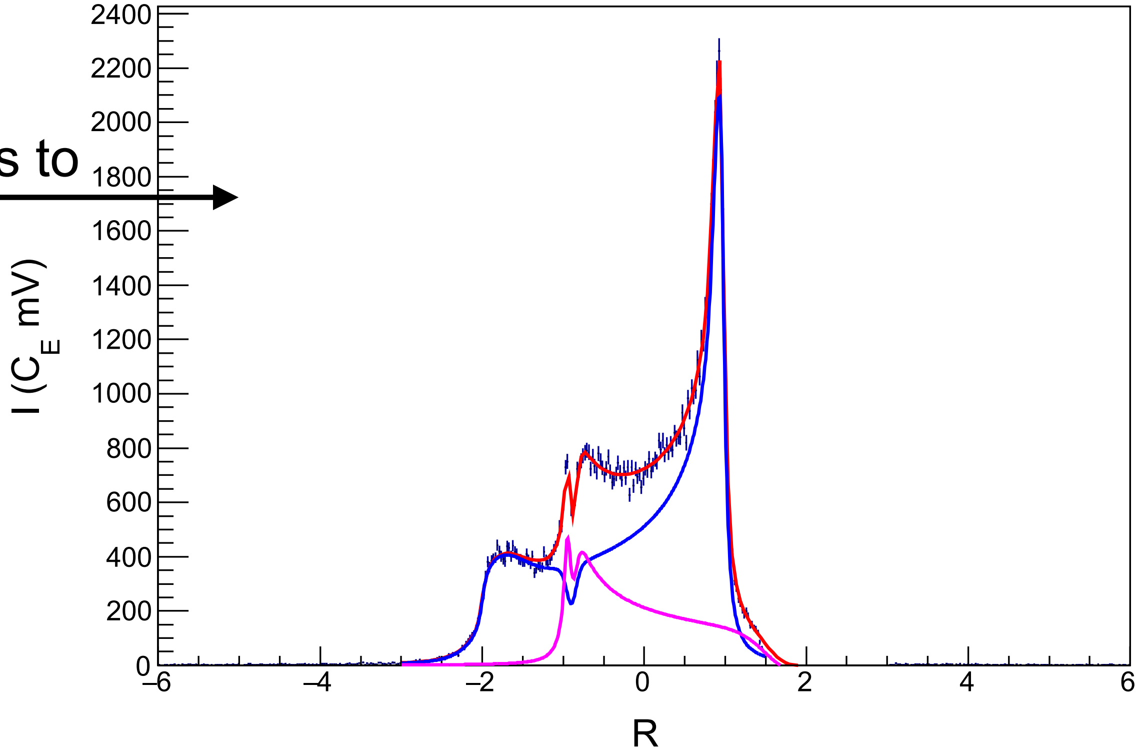


DNP polarized enhanced signal

$P_{zz} = 19.7\ \%$

Tensor enhanced signal:

goes to

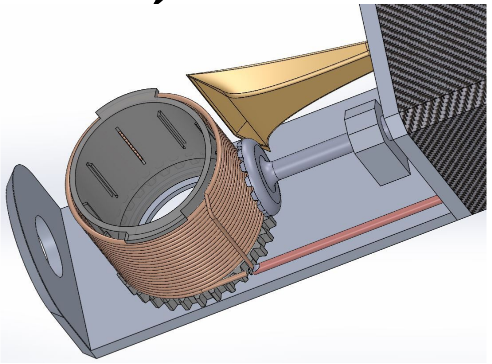


ss-RF enhanced signal

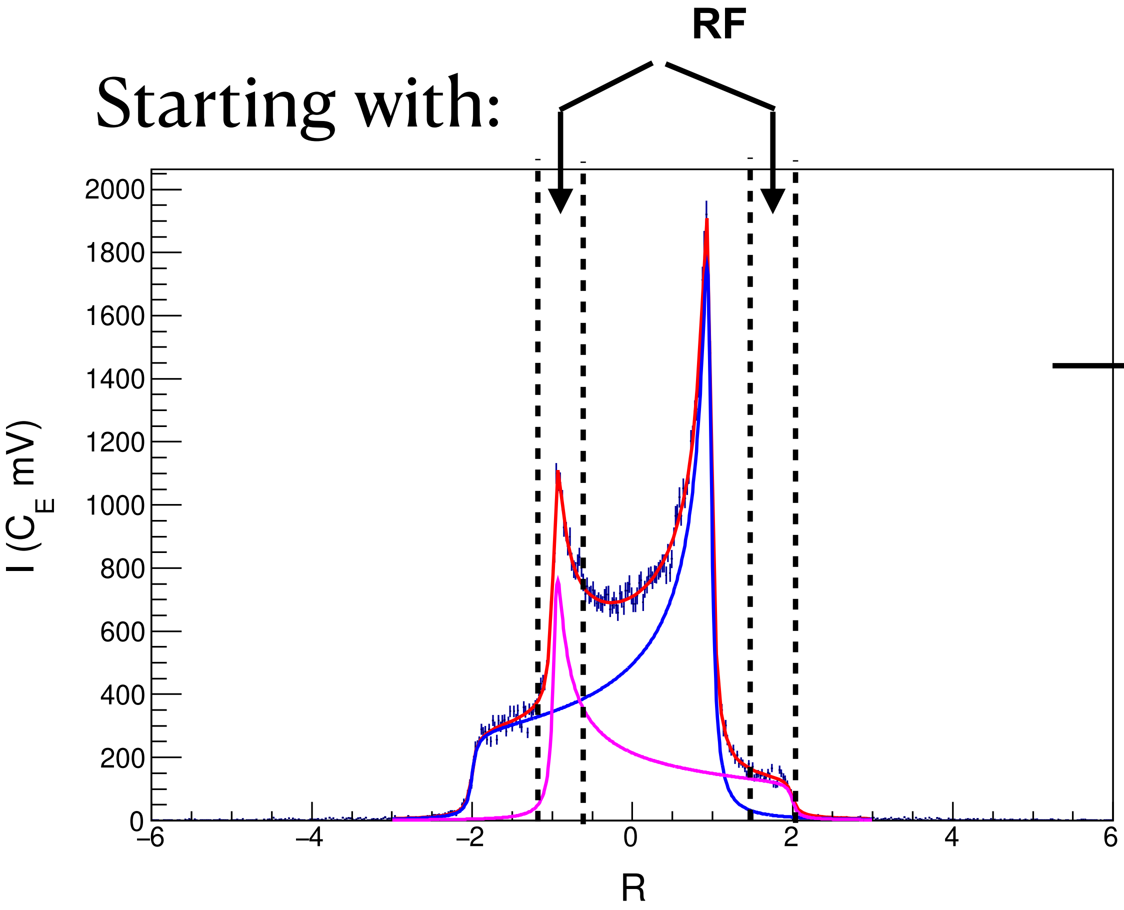
$P_{zz} = 28.8\ \%$

D. Keller. Nucl. Instrum. Meth. A 981 (2020).

Rotating Semi-Saturating RF (ss-RF)

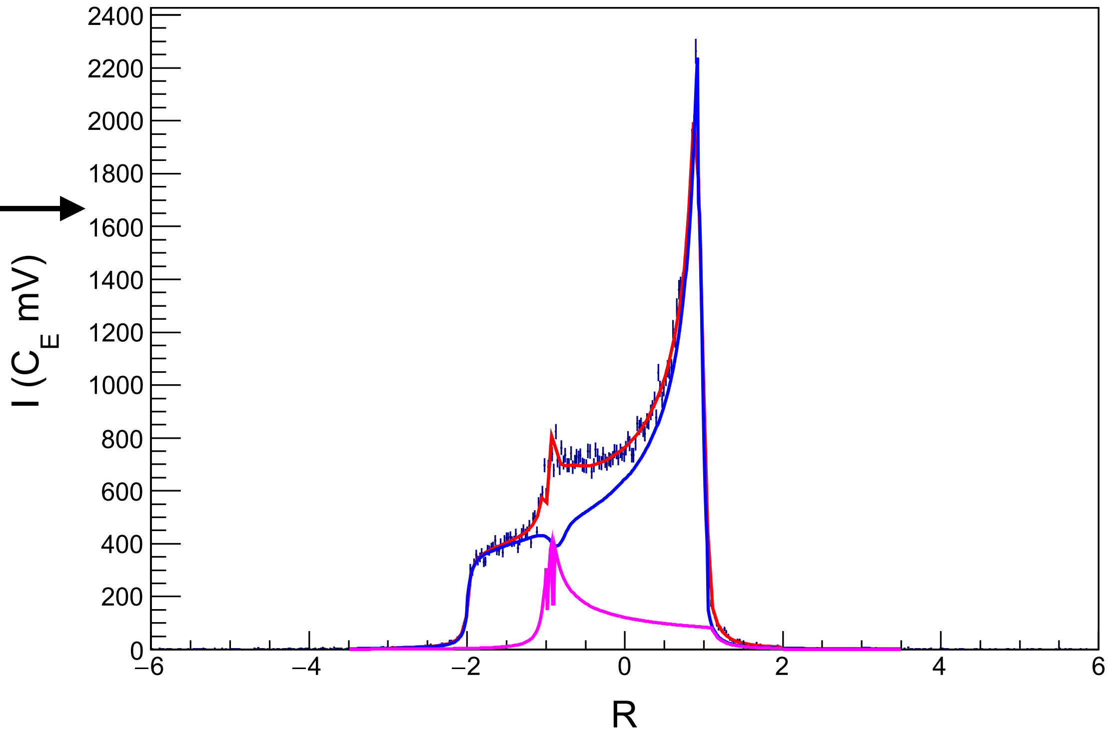


Starting with:



goes to

Tensor enhanced signal:



DNP polarized enhanced signal

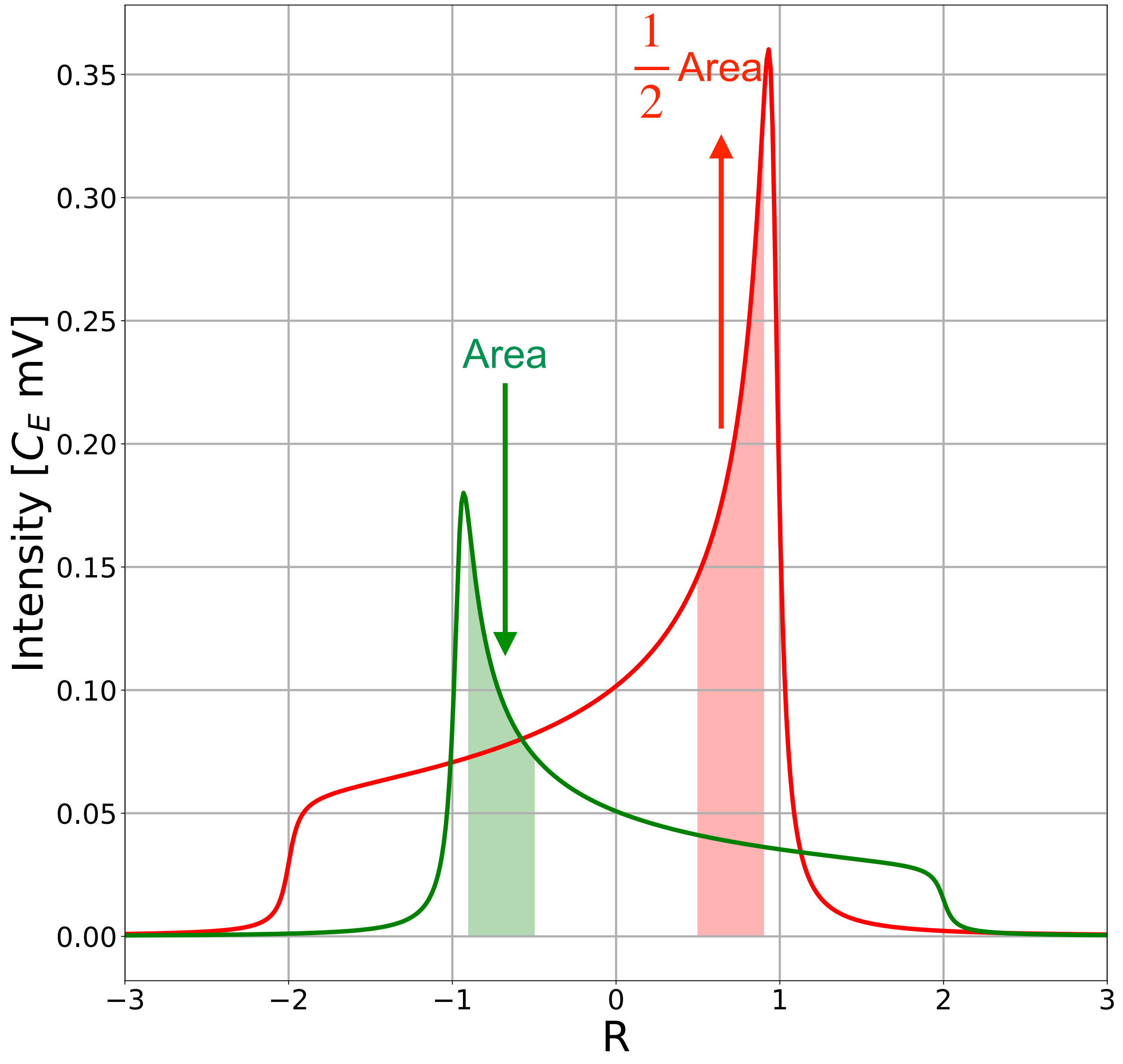
$P_{zz} = 19.7\,\%$

rss-RF enhanced signal

$P_{zz} \sim 36\,\%$

D. Keller. Nucl. Instrum. Meth. A 981 (2020).

Manipulation of spin-1 solid-state targets



Measurement:

1. **Differential binning**
2. **Spin temperature consistency**

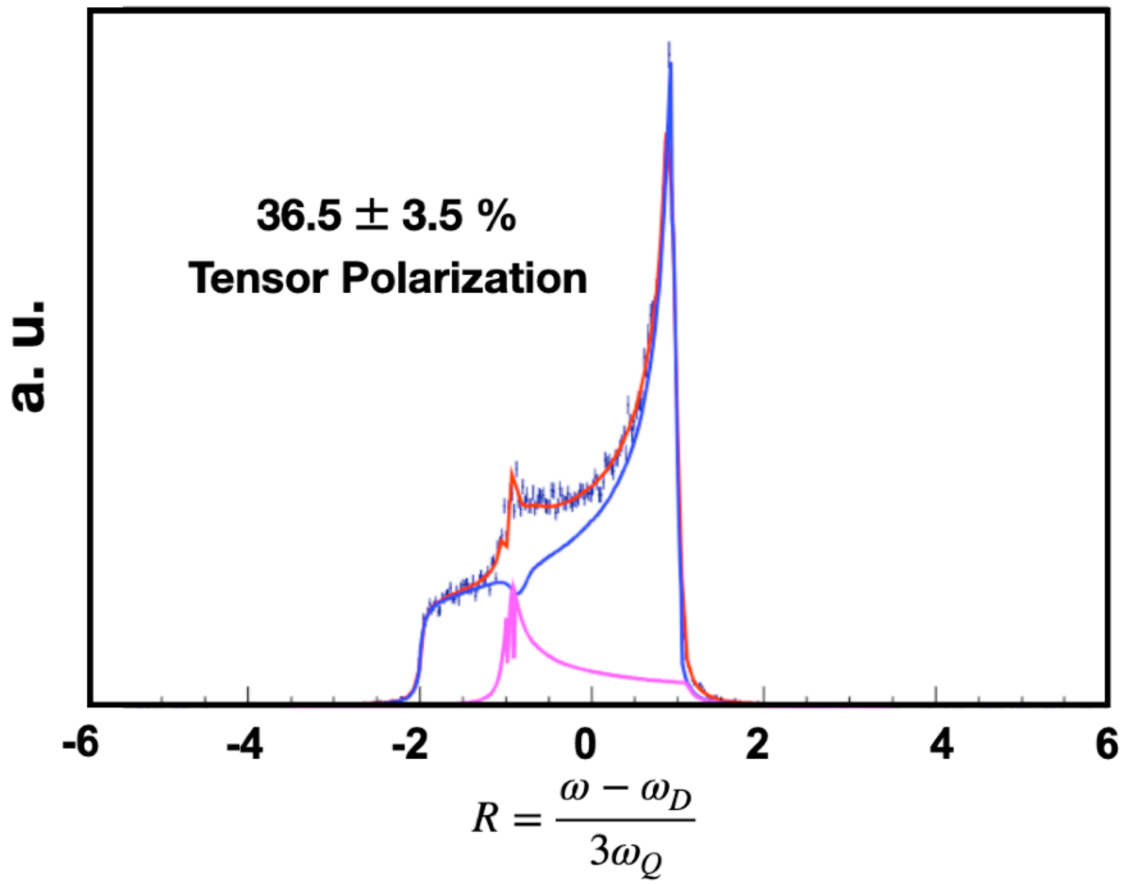
$$P_z = C(I_+ + I_-)$$
$$P_{zz} = C(I_+ - I_-)$$

3. **Rate response**

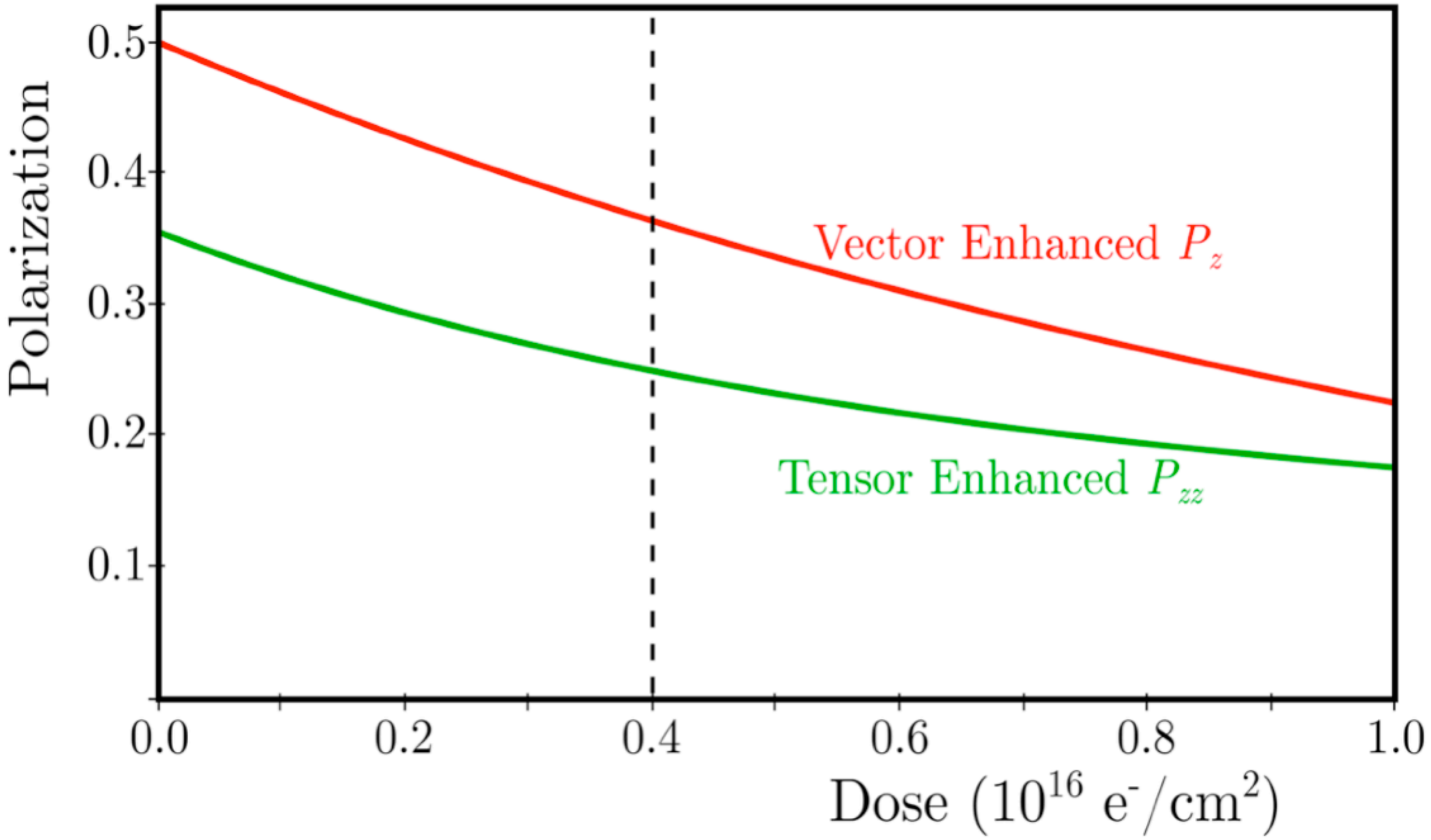
$$A_{lost} = \frac{1}{2}A_{gained}$$

D. Keller. Nucl. Instrum. Meth. A 1050 (2023).

In reality…



Starting with a **vector polarization** of **50%**



With a beam current of **80 nA**
Annealing once per day (100% efficiency - for one cup)

Current Experimental Setup

DNP

5 T magnet

1 K with an evaporation refrigerator

(1 W cooling power)

0.3 W microwave on material

Material

Irradiated Butanol (C_4D_9OH)

Note: Tensor enhancement can be treated similarly for materials with the same lineshape (ND_3).

ssRF: ~30 ± 7 % (rel)

rssRF: ~ 36 ± 9.5 % (rel)

SOLID POLARIZED TARGET GROUP *at the*
UNIVERSITY *of* VIRGINIA

What do we measure?

$$\sigma_{\text{pol}} = \sigma_{\text{unpol}}\left[1 + P_z A_z + \frac{1}{2} P_{zz} A_{zz} + h_e (A_e + P_z A_{e,z} + P_{zz} A_{e,zz})\right]$$

$$\sigma_i \equiv \frac{d^5 \sigma_i}{dE' d\Omega_e d\Omega_p}$$

P_z : target vector polarization

P_{zz} : target tensor polarization

h_e : electron beam helicity

A_e : electron beam analyzing power

$A_{z,(zz)}$: target vector (tensor) analyzing power

$A_{e,z(zz)}$: beam – target vector (tensor) analyzing power

Can we manipulate it?

$$\sigma_{\mathrm{pol}} = \sigma_{\mathrm{unpol}}\left[1 + P_z A_z + \frac{1}{2} P_{zz} A_{zz} + \cancel{h_e\left(A_e + P_z A_{e,z} + P_{zz} A_{e,zz}\right)}\right]$$

integrate over
electron beam-helicity

$$\sigma_i \equiv \frac{d^5\sigma_i}{dE' d\Omega_e d\Omega_p}$$

P_z : target vector polarization

P_{zz} : target tensor polarization

h_e : electron beam helicity

A_e : electron beam analyzing power

$A_{z,(zz)}$: target vector (tensor) analyzing power

$A_{e,z(zz)}$: beam – target vector (tensor) analyzing power

Can we manipulate it? More....

$$\sigma_{\text{pol}} = \sigma_{\text{unpol}}\left[1 + \cancel{P_z A_z} + \frac{1}{2} P_{zz} A_{zz} + \cancel{h_e(A_e + P_z A_{e,z} + P_{zz} A_{e,zz})}\right]$$

$$\sigma_i \equiv \frac{d^5\sigma_i}{dE' d\Omega_e d\Omega_p}$$

integrate over
vector polarization

integrate over
electron beam-helicity

P_z : target vector polarization

P_{zz} : target tensor polarization

h_e : electron beam helicity

A_e : electron beam analyzing power

$A_{z,(zz)}$: target vector (tensor) analyzing power

$A_{e,z(zz)}$: beam – target vector (tensor) analyzing power

We will measure...

$$\sigma_{\text{pol}} = \sigma_{\text{unpol}}\left[1 + \frac{1}{2}P_{zz}A_{zz}\right]$$

Simplified tensor-polarized cross sections from which tensor-asymmetry is extracted

$$\Longrightarrow A_{zz} = \frac{2}{P_{zz}}\left(\frac{\sigma_{\text{pol}}}{\sigma_{\text{unpol}}} - 1\right)$$

P_{zz} : target tensor polarization

$\sigma_{\text{pol, unpol}}$: polarized, unpolarized cross sections

A_{zz} : target tensor analyzing power

Azz can also be expressed in terms of the spin-dependent cross sections and can be substituted above and solve for spin-dependent absolute cross sections →

$$A_{zz} = \frac{(\sigma_{+1} - \sigma_0) + (\sigma_{-1} - \sigma_0)}{\sigma_{-1} + \sigma_0 + \sigma_{+1}}$$

$$= \frac{2}{3}\frac{(\sigma_{\pm 1} - \sigma_0)}{\sigma_{unpol}}$$

See W U Boeglin 2014 J. Phys.: Conf. Ser. 543 012011
for detailed step-by-step calculations of the above Azz expressions

Spin-Dependent d(e, e'p) polarized cross section

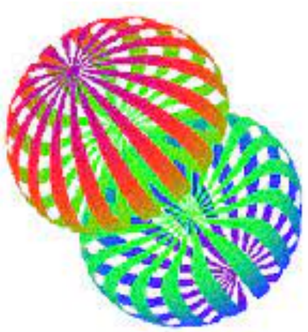
spin-dependent cross sections may be expressed as: $\sigma_m = \sigma_m(P_{zz}, \sigma_{\text{pol}}, \sigma_{\text{unpol}})$

$$\sigma_0 = \sigma_{\text{unpol}}\left(1 - \frac{2}{P_{zz}}\left(\frac{\sigma_{\text{pol}}}{\sigma_{\text{unpol}}} - 1\right)\right)$$

"torus" component

$$\sigma_{\pm1} = \sigma_{\text{unpol}}\left(1 + \frac{1}{P_{zz}}\left(\frac{\sigma_{\text{pol}}}{\sigma_{\text{unpol}}} - 1\right)\right)$$

"dumbbell" component



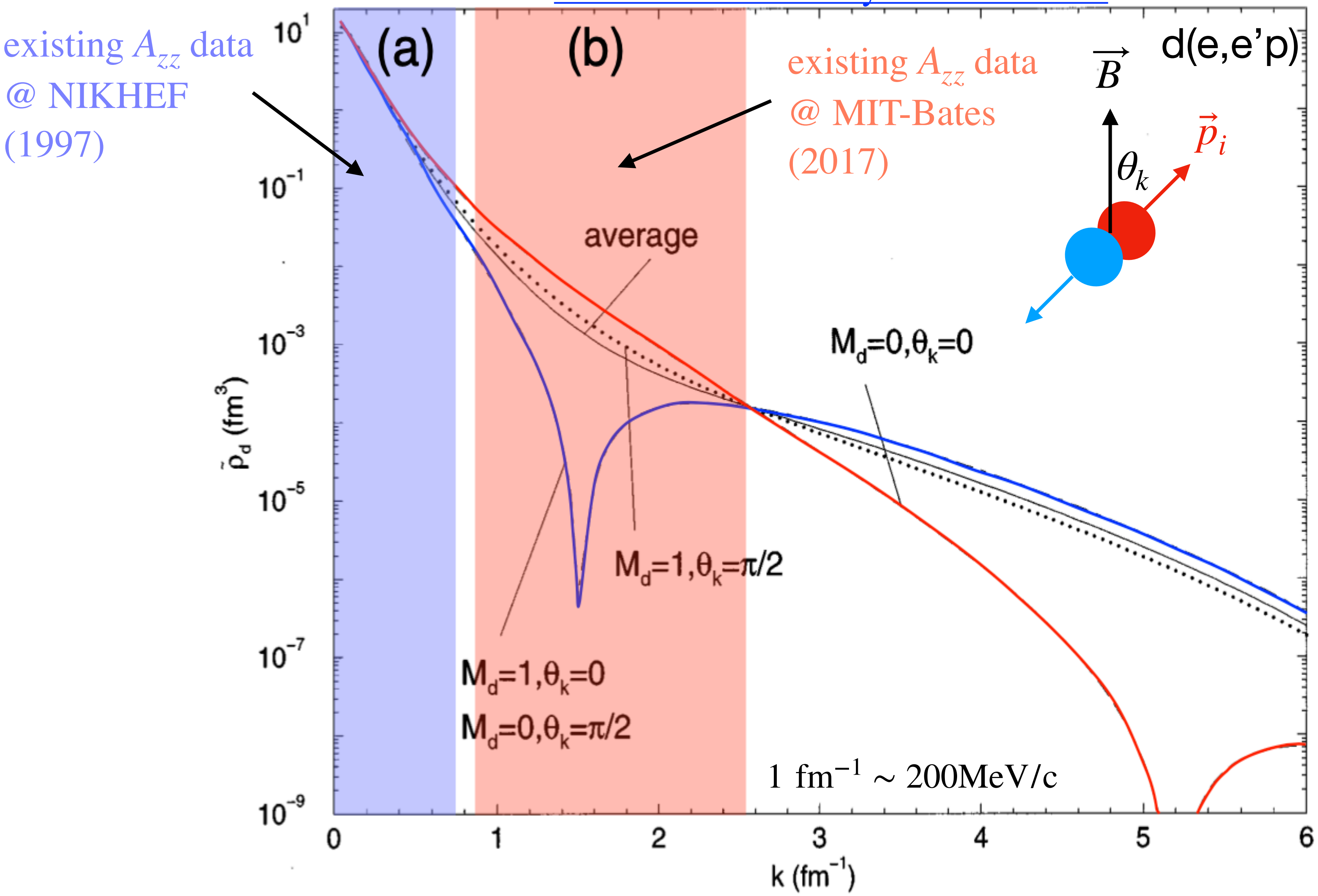
Under PWIA assumption: spin-dependent ~momentum distributions ($\rho(p_m)_{0,\pm1}$) can be extracted from the spin-dependent cross sections $\sigma_{0,\pm1}$

$$\sigma_{red} \equiv \frac{\sigma_{0,\pm1}}{k \cdot \sigma_{eN}} \sim \rho_{0,\pm1}(p_i)$$

spin-dependent reduced cross sections
(are ~spin-dependent momentum distributions under PWIA)

Previous measurements

Forest J et al. 1996 Phys. Rev. C 54 646



existing A_{zz} data @ NIKHEF (1997)

existing A_{zz} data @ MIT-Bates (2017)

$1\ \mathrm{fm}^{-1} \sim 200\mathrm{MeV/c}$

(a) $k < 150$ MeV/c missing momenta covered by NIKHEF: Zhou Z L et al. 1999 Phys. Rev. Lett. 82 687

(a), (b) $k < 500$ MeV/c missing momenta covered by MIT-Bates: A. DeGrush *et al*. (BLAST Collaboration) Phys. Rev. Lett. **119**, 182501 (2017)

Previous measurements

Z.-L. Zhou *et al.* Phys. Rev. Lett. **82**, 687 (1999)

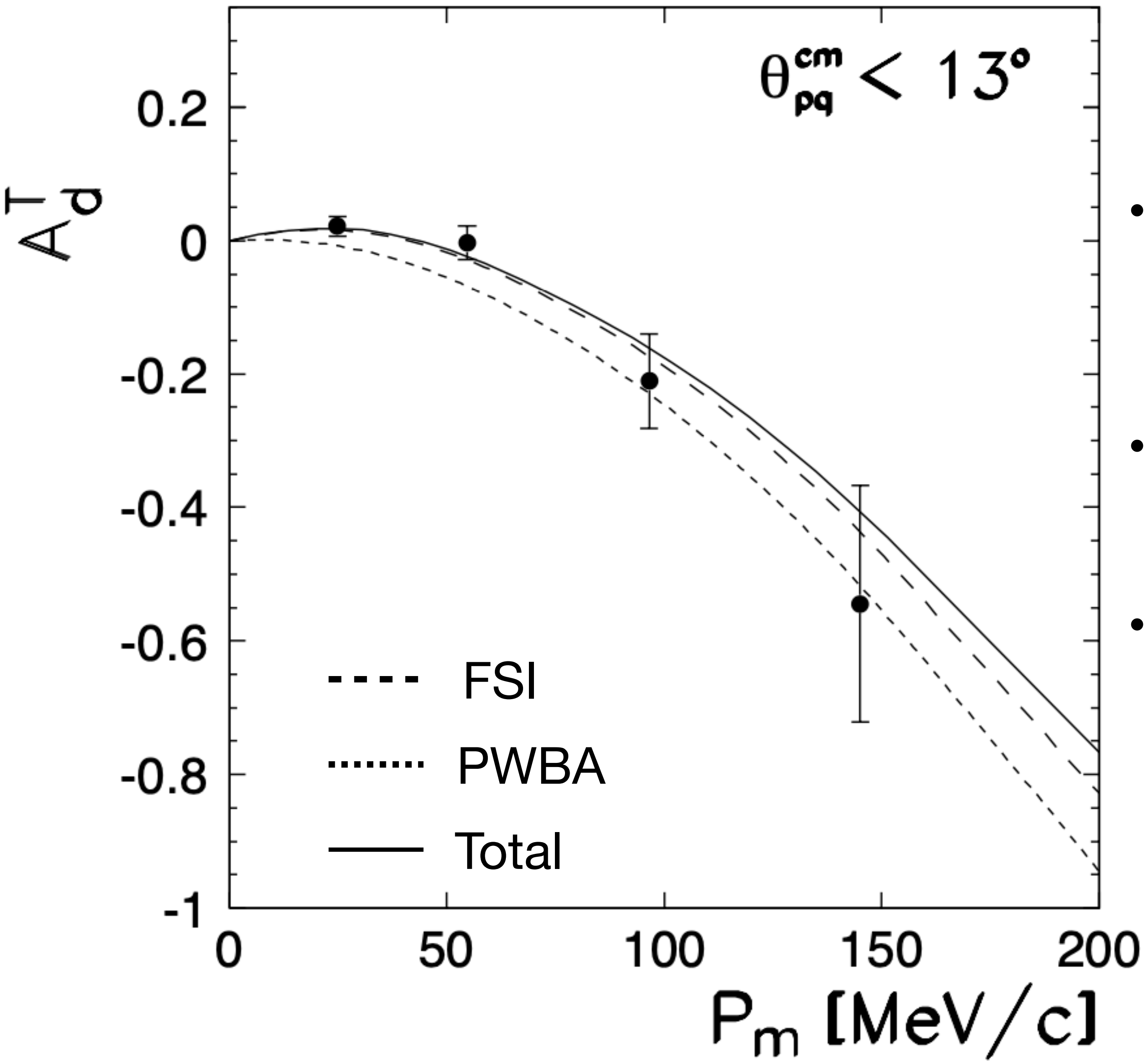


FIG. 3. A_d^T as a function of p_m for parallel kinematics (i.e., $\theta_{pq}^{\rm cm} < 13°$). The short-dashed curve represents the result for PWBA; in the long-dashed curve FSI effects are also included, and the solid curve represents the full calculation.

- **@ NIKHEF:** first-ever exclusive d(e, e’p) tensor-polarized data ($Q^2 < 1$ GeV^2 , Pm < 150 MeV/c)
- extracted deuteron tensor-asymmetry A_d^T(or, A_{zz}) at 3-momentum transfers $|\vec{q}| = 1.7\text{fm}^{-1}$ (~340 MeV)
- dominated by FSI, MEC, IC, but effects well described by theoretical model

Theory calculations:
H. Arenhövel, W. Leidemann,
and E.L. Tomusiak, Phys.
Rev. C **52**, 1232 (1995).

Previous measurements

A. DeGrush *et al.* (BLAST Collaboration) Phys. Rev. Lett. **119**, 182501 (2017)

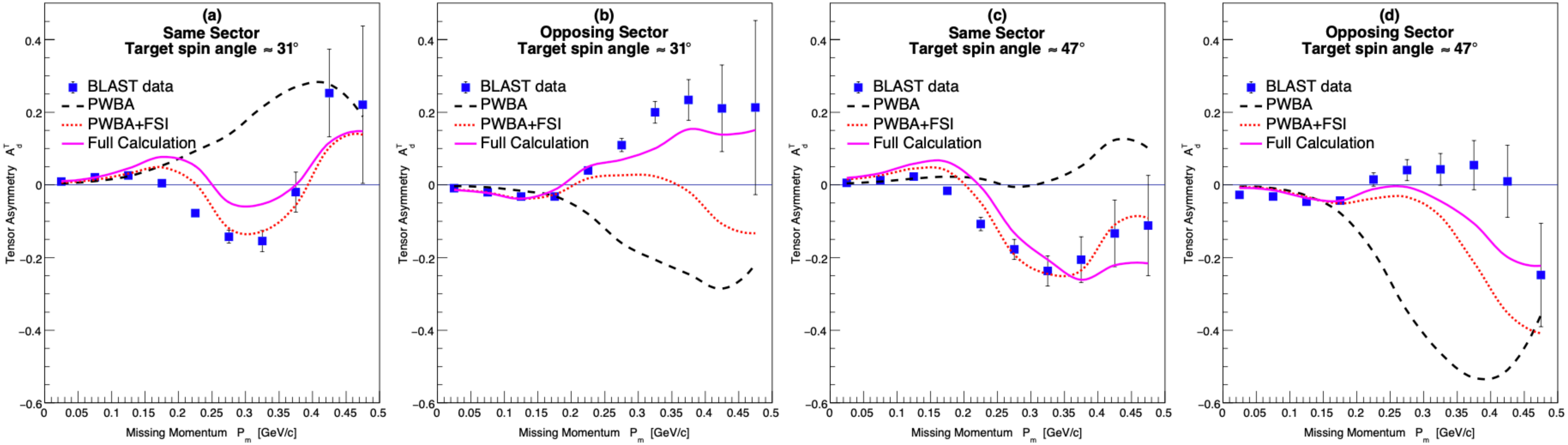


FIG. 3. Tensor asymmetries A_d^T for $0.1 < Q^2 < 0.5$ (GeV/c)^2 vs. p_m. Panels (a) and (c) refer to *same sector* kinematics for target spin angles ≈ 32° and ≈ 47°. Panels (b) and (d) refer to *opposing sector* kinematics for the same target spin angles.

- **@ MIT-Bates:** exclusive d(e, e'p) tensor-polarized data ($Q^2 \sim 0.1 - 0.5$ GeV^2 , up to Pm ~ 500 MeV/c, the highest-to-date)

- extracted A_{zz} analyzing power dominated by FSI, MEC, IC, but effects mostly well-described by theoretical calculations

Theory calculations: H. Arenhovel, W. Leidemann, and E.L. Tomusiak, Eur. Phys. J. **A23**, 147–190 (2005)

tensor-polarized d(e, e’p) measurements @ Hall C at large Q^2 and $x_{bj} > 1$

NO exclusive d(e, e’p) A_{zz} measurements
at $Q^2 > 1\ \mathrm{GeV}^2$ exist to-date

NO $\rho_{0,\pm}$ spin-dependent d(e, e’p)
momentum distributions exist to-date

We propose to:

(1) measure tensor-analyzing power A_{zz},

(2) measure absolute unpolarized/polarized cross sections, $\sigma_{\mathrm{pol,unpol}}$

(3) extract the spin-dependent momentum distributions $\rho_{0,\pm}$

Selecting Optimal Central Kinematics

$E_b = 10.549 [\mathrm{GeV}]$
LD2 10 cm
$I_b = 100$ [nA]

$\rho_t = 0.167 [\mathrm{g/cm^3}]$
$\sigma_t = 1670 [\mathrm{mg/cm^2}]$
168 [hrs]

radiative_effects: ON

limiting_factor: 5T magnet opening angle +/- 35 deg
limits HMS (proton) angles we can explore to < 35 deg
(will need to re-calculated !)

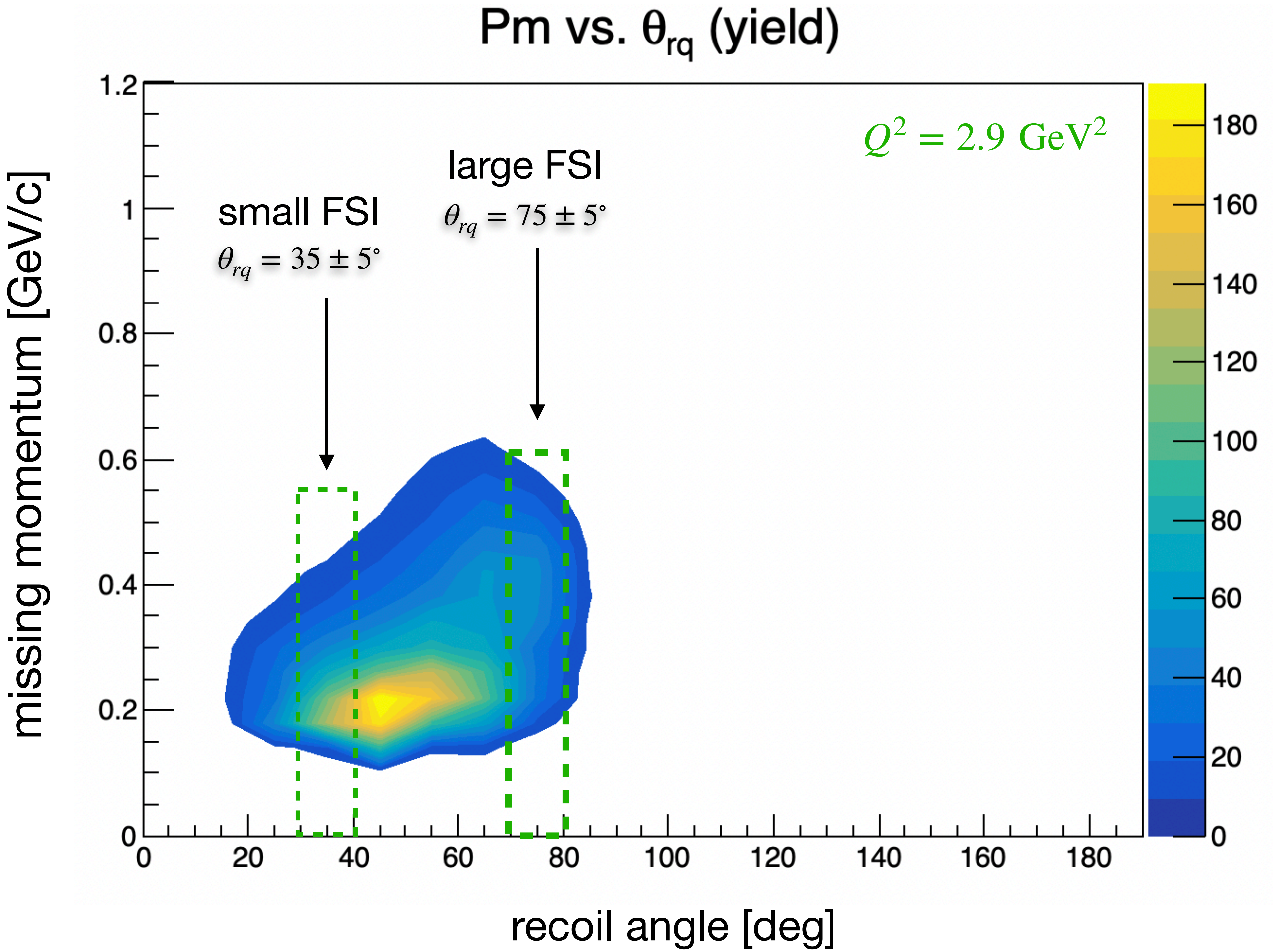
P_{miss}[MeV]	k_f[GeV]	θ_e[deg]	p_f[GeV]	θ_p[deg]	$\lvert\vec{q}\rvert$[GeV]	θ_q[deg]	θ_{rq}[deg]	θ_{pq}[deg]	$Q^2[\mathrm{GeV}^2]$
300	9.7261	8.204	1.4322	63.346	1.6665	56.3924	35.311	6.9542	2.1
300	9.3870	9.817	1.8241	56.346	2.0616	50.9282	35.0368	5.4179	2.9
300	9.1252	10.941	2.1142	52.191	2.3510	47.4551	35.5878	4.7366	3.5

Courtesy of C. Yero

```
 ------------------------------
   d(e,e'p) Rate Estimates
 ------------------------------


Q2 = 2.1 GeV^2
Pm Setting: 300
Model: Laget FSI
Ib [uA]      = 0.100
time [hr]    = 168.000
charge [mC] = 60.480
Pm counts   = 1535.644
d(e,e'p) Rates [Hz] = 2.539E-03
DAQ Rates [Hz] = 0.032
 ------------------------------
```

```
 ------------------------------
   d(e,e'p) Rate Estimates
 ------------------------------


Q2 = 2.9 GeV^2
Pm Setting: 300
Model: Laget FSI
Ib [uA]      = 0.100
time [hr]    = 168.000
charge [mC] = 60.480
Pm counts   = 3275.409
d(e,e'p) Rates [Hz] = 5.416E-03
DAQ Rates [Hz] = 0.010
 ------------------------------
```

```
 ------------------------------
   d(e,e'p) Rate Estimates
 ------------------------------


Q2 = 3.5 GeV^2
Pm Setting: 300
Model: Laget FSI
Ib [uA]      = 0.100
time [hr]    = 168.000
charge [mC] = 60.480
Pm counts   = 1503.470
d(e,e'p) Rates [Hz] = 2.486E-03
DAQ Rates [Hz] = 0.005
 ------------------------------
```



Pm vs. θ_{rq} (yield)

small FSI

$\theta_{rq} = 35 \pm 5^{\circ}$

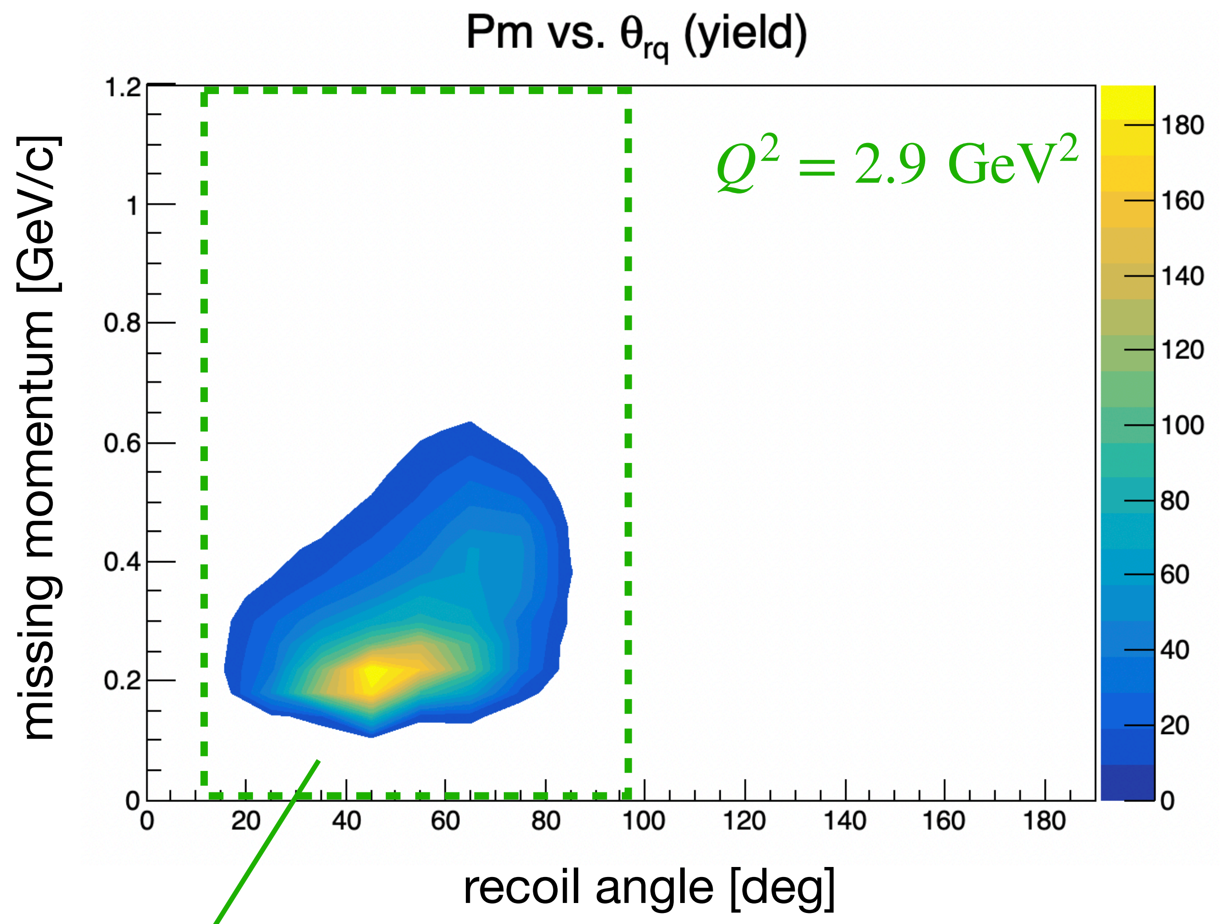
large FSI

$\theta_{rq} = 75 \pm 5^{\circ}$

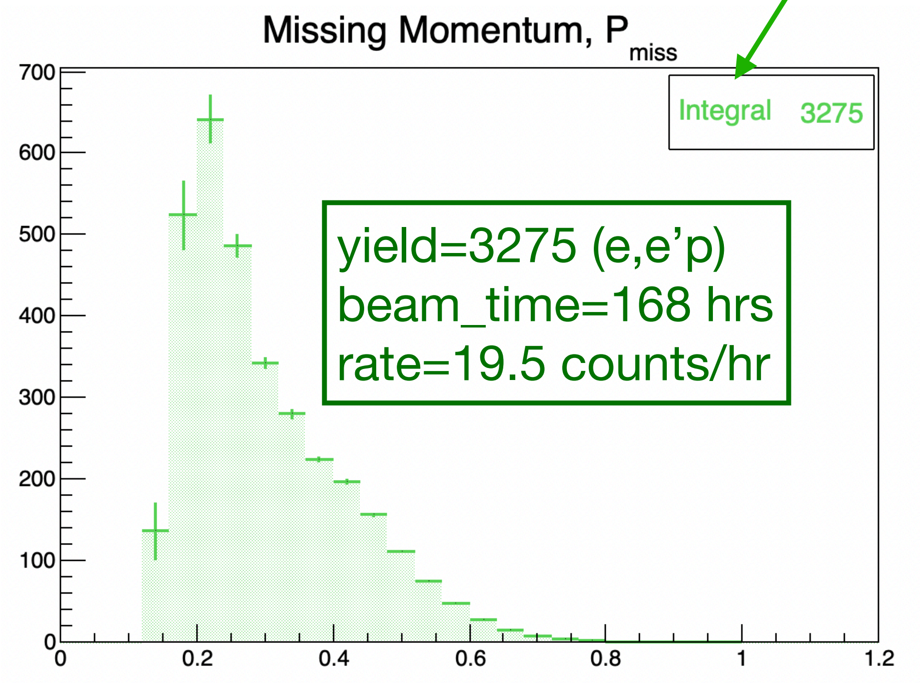
$Q^2 = 2.9\ \mathrm{GeV}^2$

Courtesy of C. Yero

Selecting minimal FSI d(e, e’p) kinematical bins



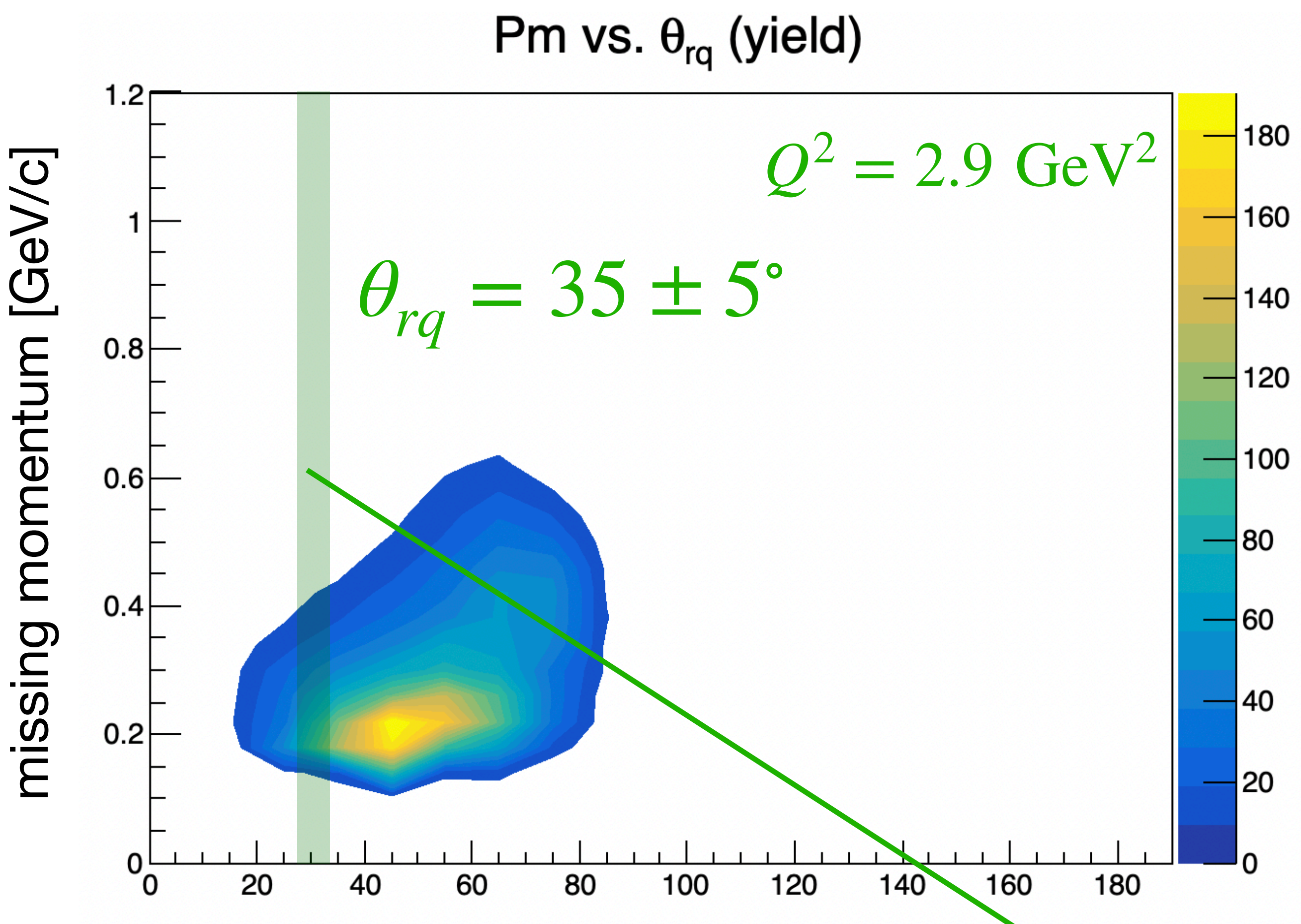
$Q^2 = 2.9\ \mathrm{GeV}^2$



yield=3275 (e,e’p)
beam_time=168 hrs
rate=19.5 counts/hr

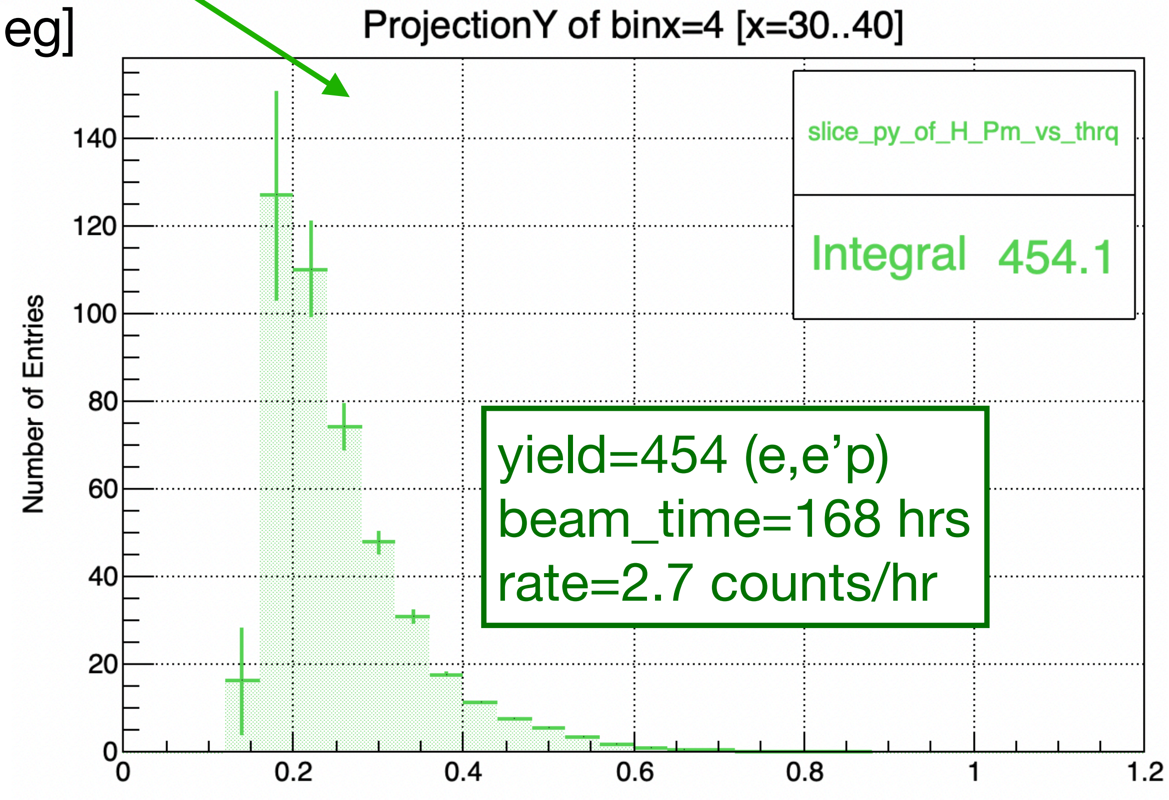
- integrated over all recoil θ_{rq} angles (1D projection)
- includes bins where FSI are large (>45 deg), therefore NOT ideal for extracting momentum distributions $\rho(p_m)_{o,\pm}$, as PWIA condition NOT met

Courtesy of C. Yero



$Q^2 = 2.9$ GeV^2

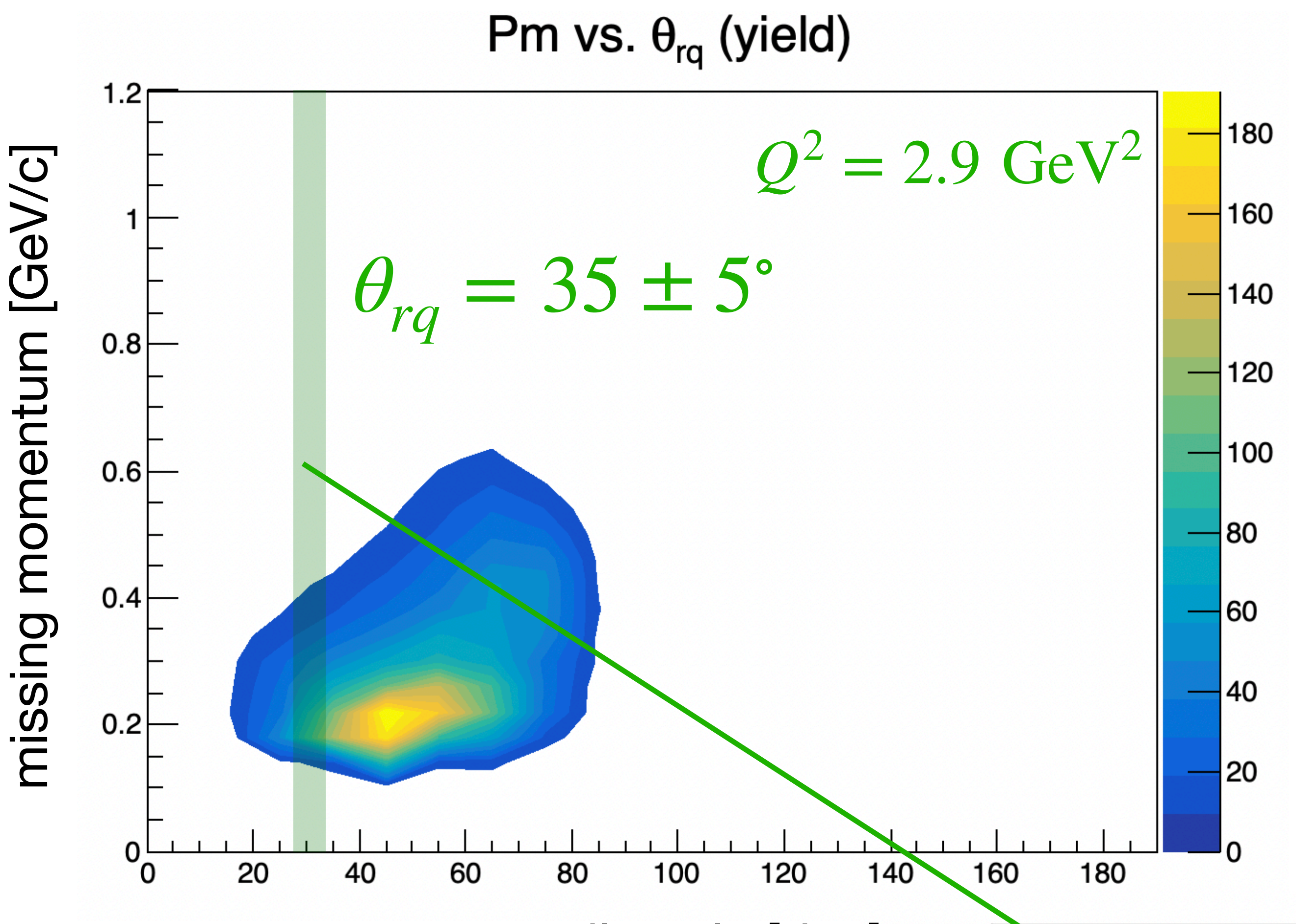
$\theta_{rq} = 35 \pm 5°$



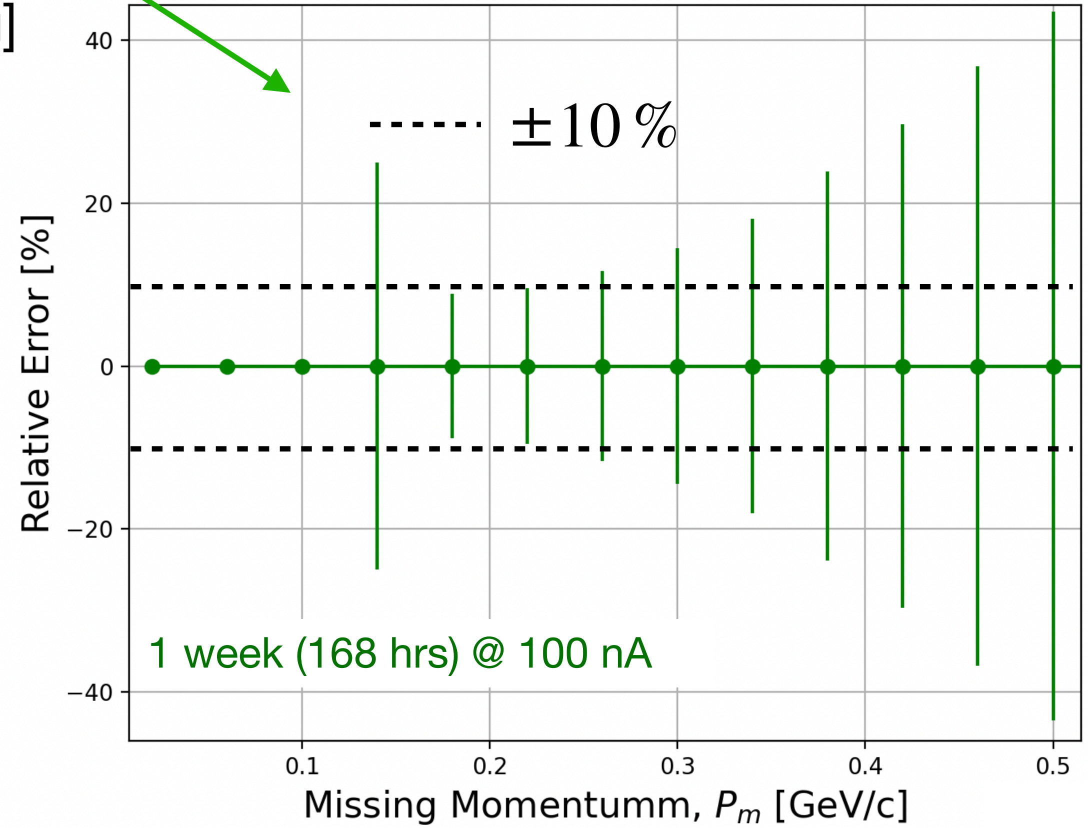
yield=454 (e,e'p)
beam_time=168 hrs
rate=2.7 counts/hr

- selected bin $\theta_{rq} \sim 35°$ (1D projection) where FSI reduced
- rates drop dramatically (maybe widen bin?)

Courtesy of C. Yero

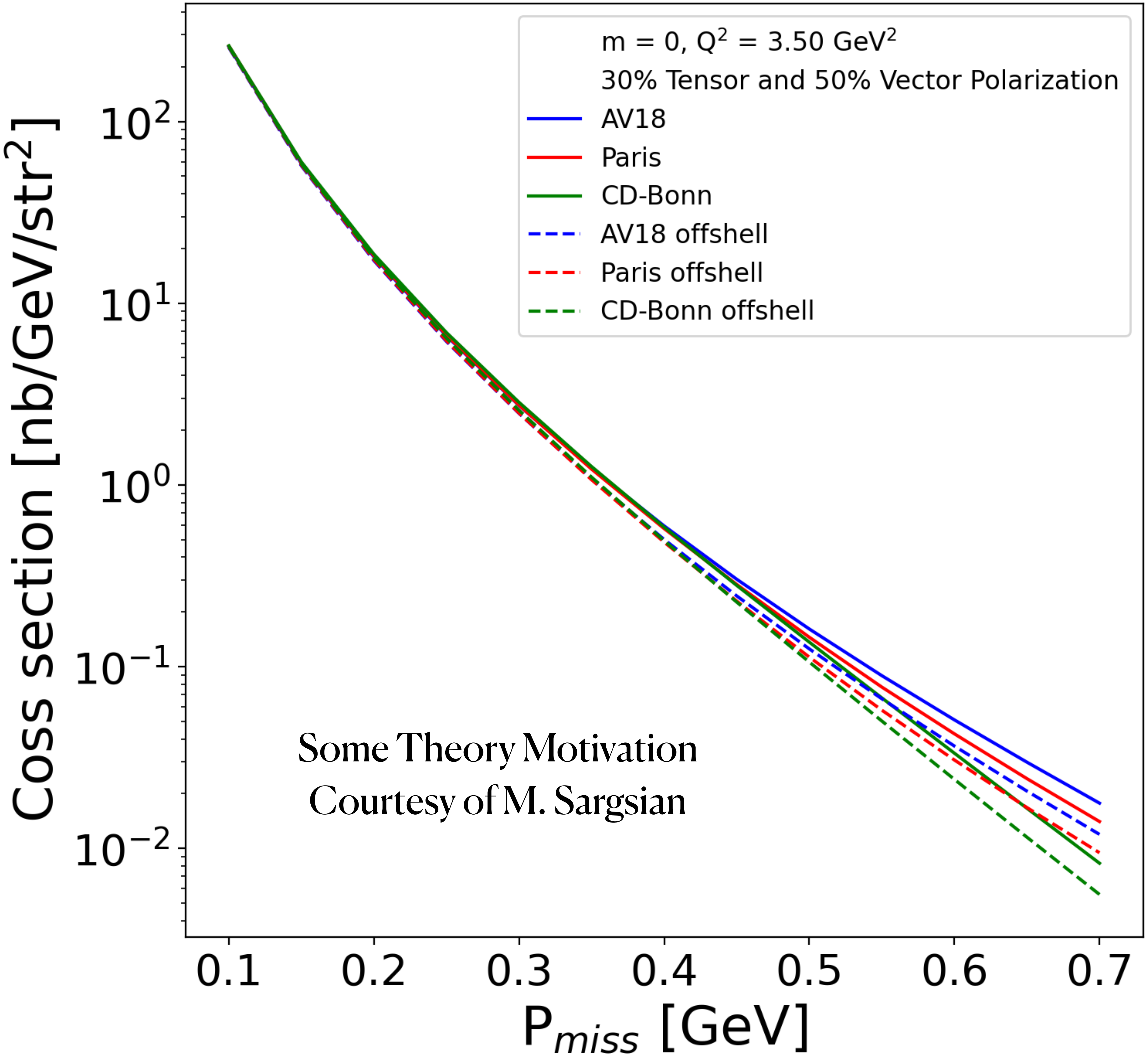


Courtesy of C. Yero

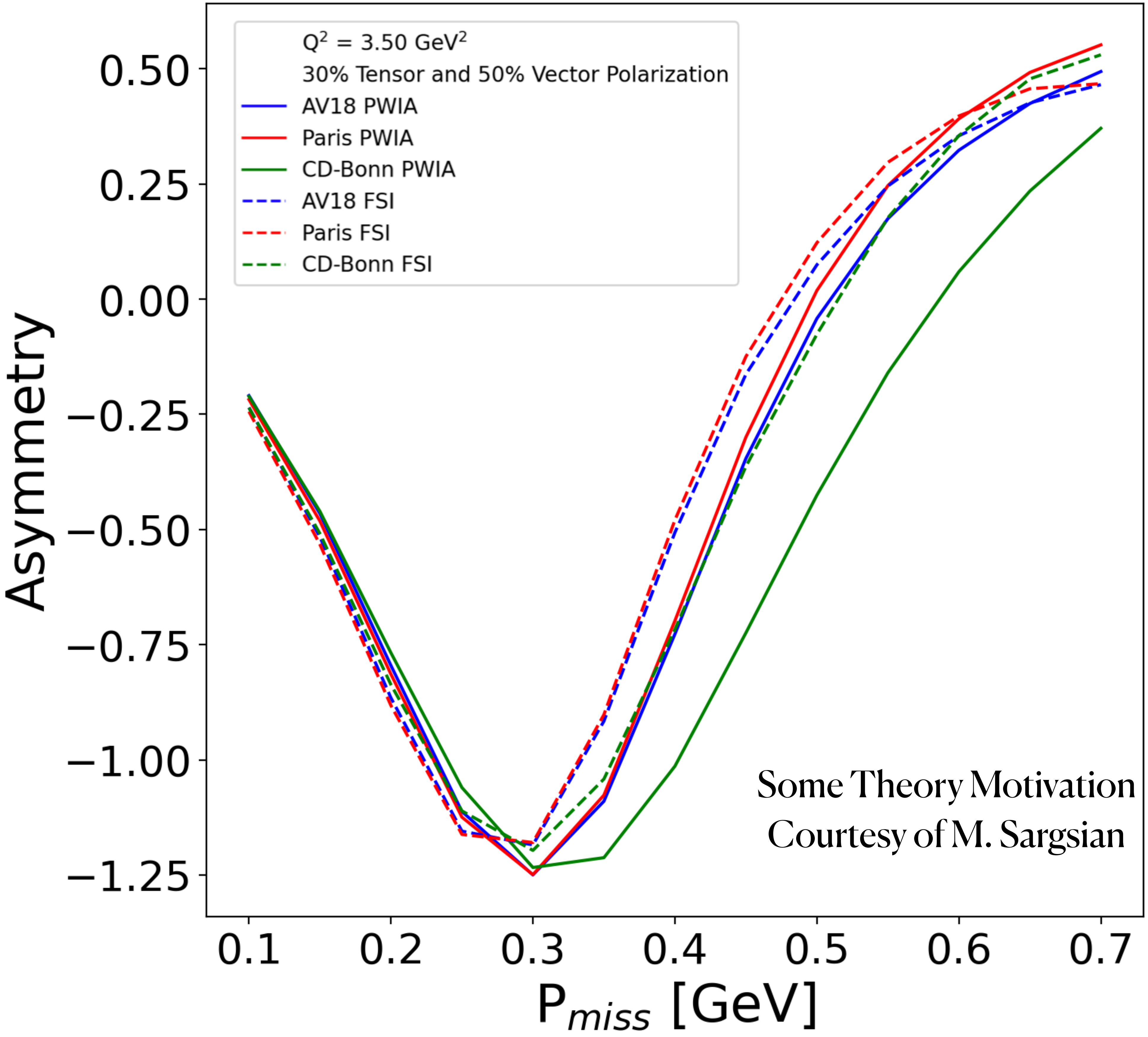


- selected bin $\theta_{rq} \sim 35°$ (1D projection) where FSI reduced
- rates drop dramatically (maybe widen bin?)
- 1 week (168 hrs) @ 100 nA (unpolarized)
  < 20 % stats error for missing momenta
  Pm ~ 180 - 340 MeV/c

Courtesy of C. Yero



Some Theory Motivation
Courtesy of M. Sargsian



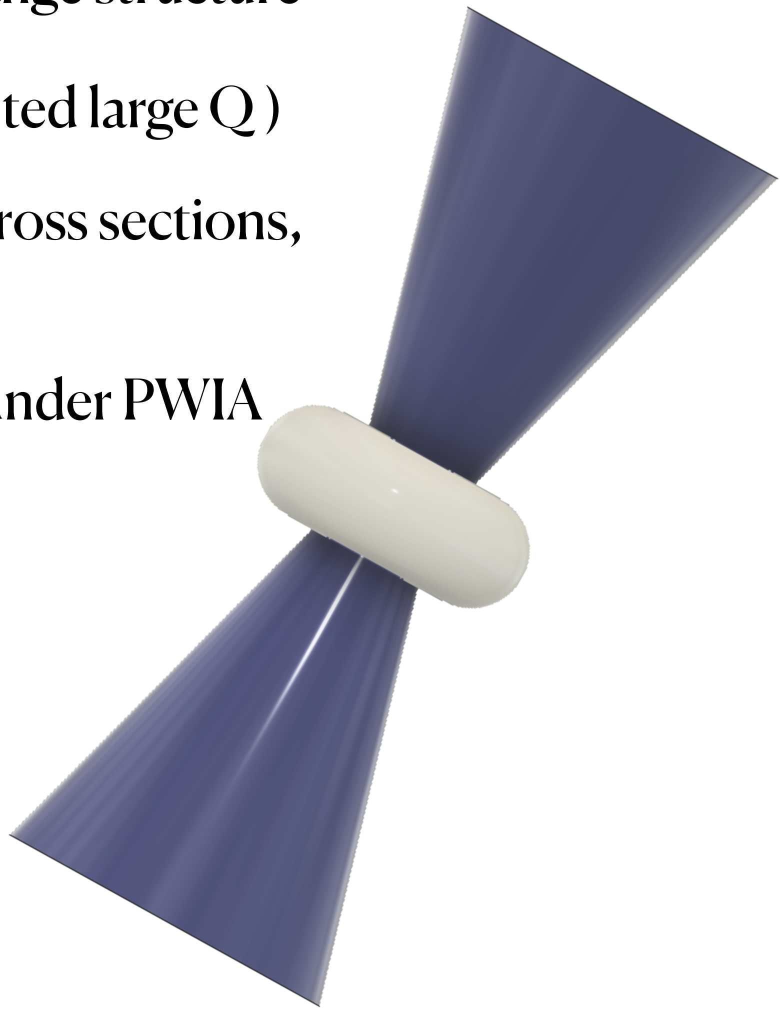
Some Theory Motivation
Courtesy of M. Sargsian

Summary

- Tensor-polarized d(e, e’p) provides unique opportunity

- We are working in optimizing the kinematics.

- We propose: to carry out detailed study of deuteron short-range structure
  - ✦ measure exclusive tensor asymmetry A_{zz} (at unprecedented large Q)
  - ✦ measure absolute spin projection dependent absolute cross sections, $\sigma_{0,\pm1}$
  - ✦ extract spin-dependent reduced cross sections, which under PWIA ~ momentum distributions $\rho(p_m)_{0,\pm1}$



Thank You