Small Angle GDH
&
polarized ^{3}He target

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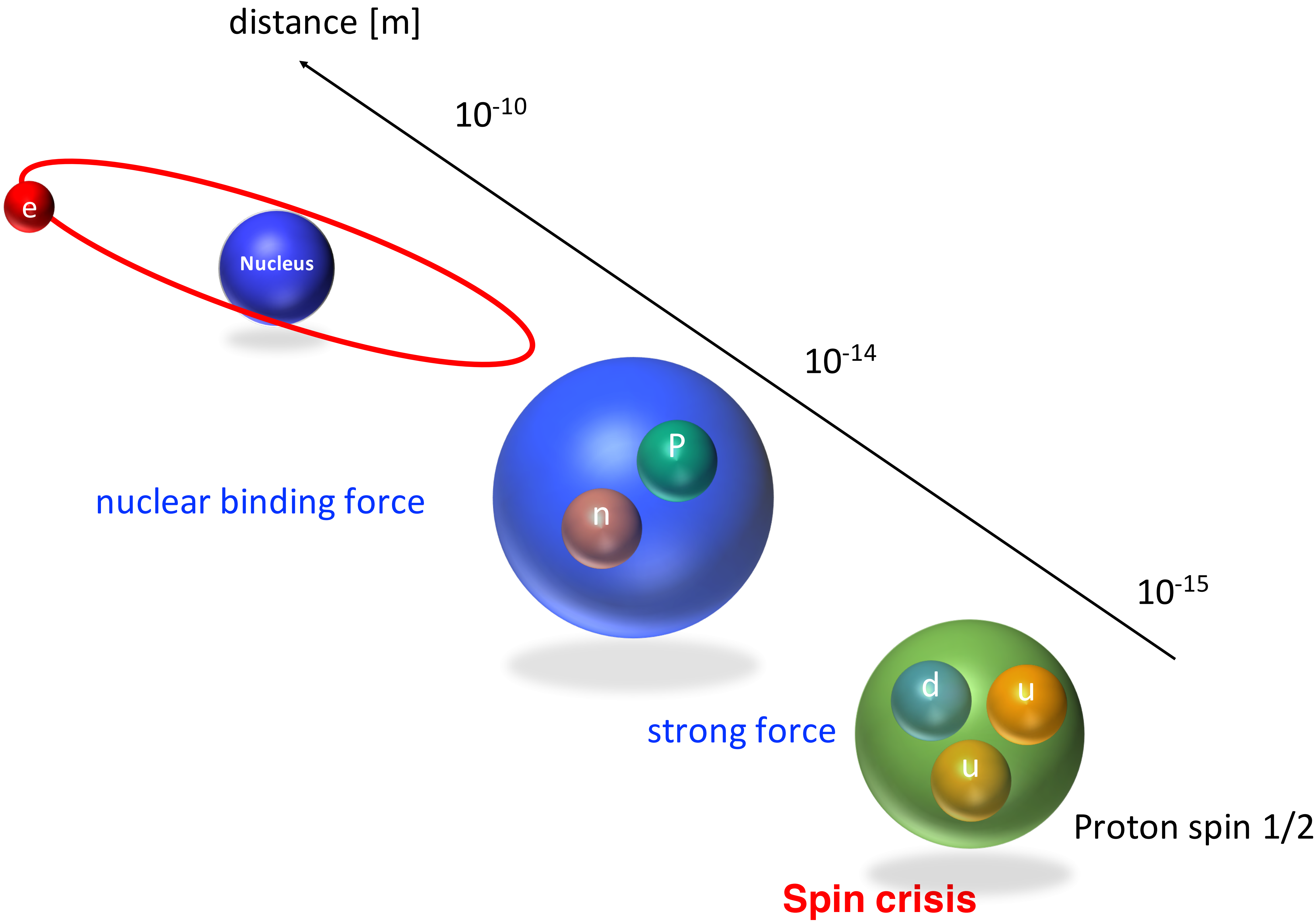
Outline

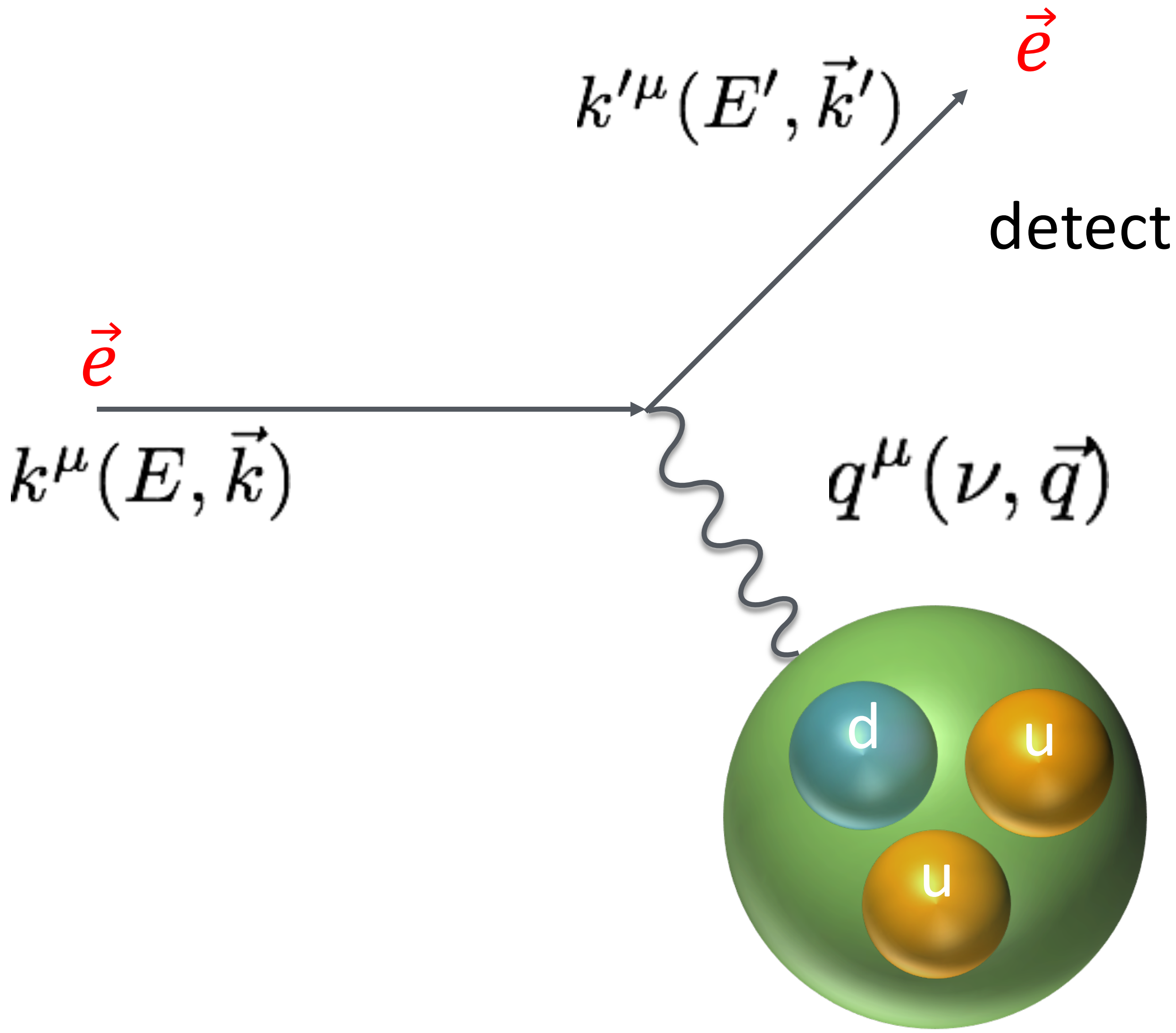
- Physics:
  - Electron scattering
  - GDH theory: sum rules.
- Experiment E97110 at Jefferson Lab:
  - Setup
  - Analysis status: asymmetries, elastic carbon cross sections
  - Future plan
- Polarized ^{3}He target:
  - Spin exchange optical pumping
  - Polarimetries: NMR, EPR and Pulse-NMR

Small angle GDH (Gerasimov-Drell-Hearn)

- **Theory:**
- Electron scattering
- Sum rules:
  - GDH for real photon.
  - GDH for virtual photon.


distance [m]
10-10
10-14
10-15
e
Nucleus
nuclear binding force
P
n
strong force
d
u
u
Proton spin 1/2
Spin crisis

Probing a nucleon

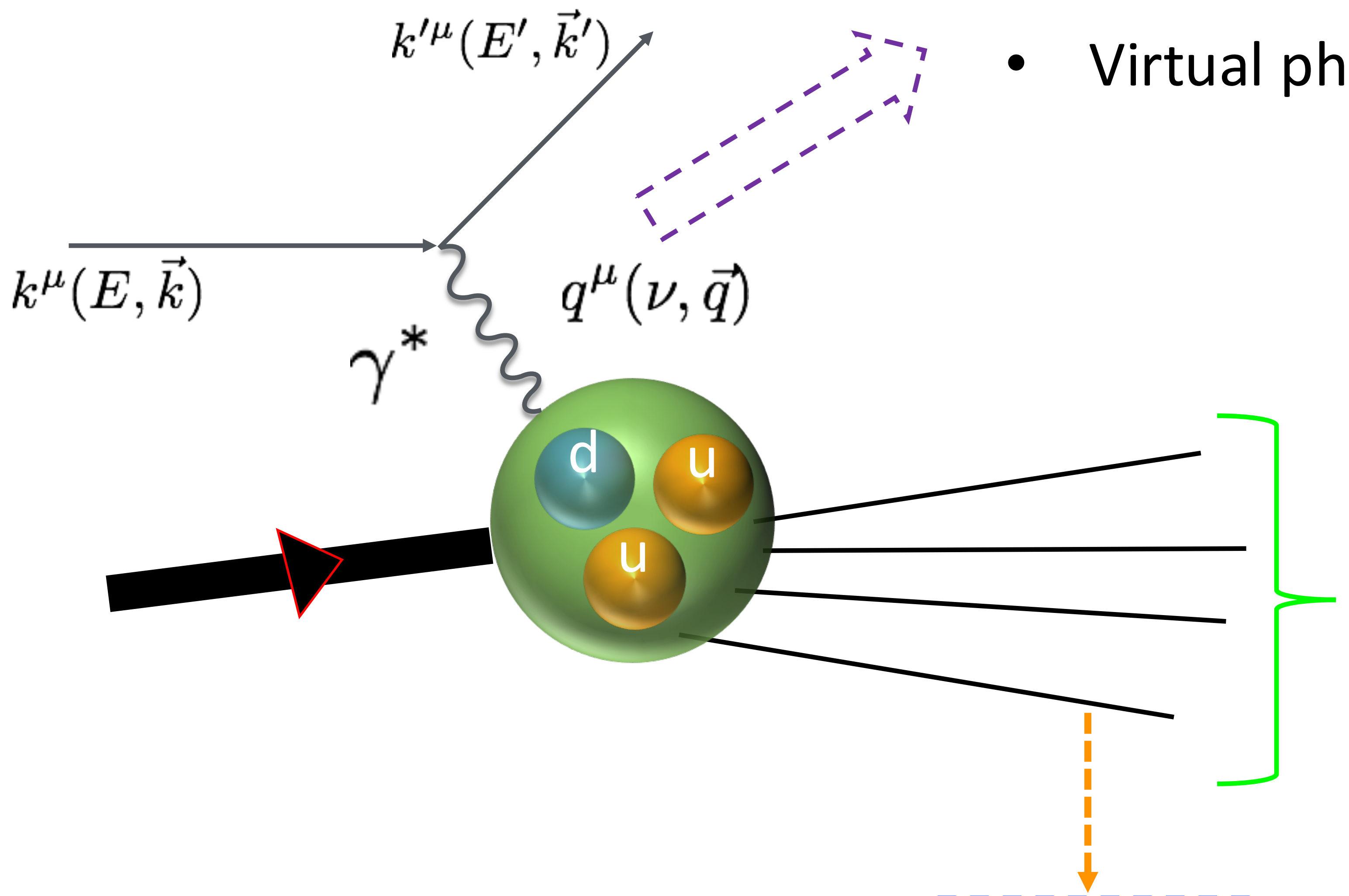


Advantages of electron scattering?

- QED is well-known and perturbative calculable.
- Clean probe.

Kinematic variables

- 4-momentum: $q^2=-Q^2$.
- Virtual photon energy: $\nu = E - E'$

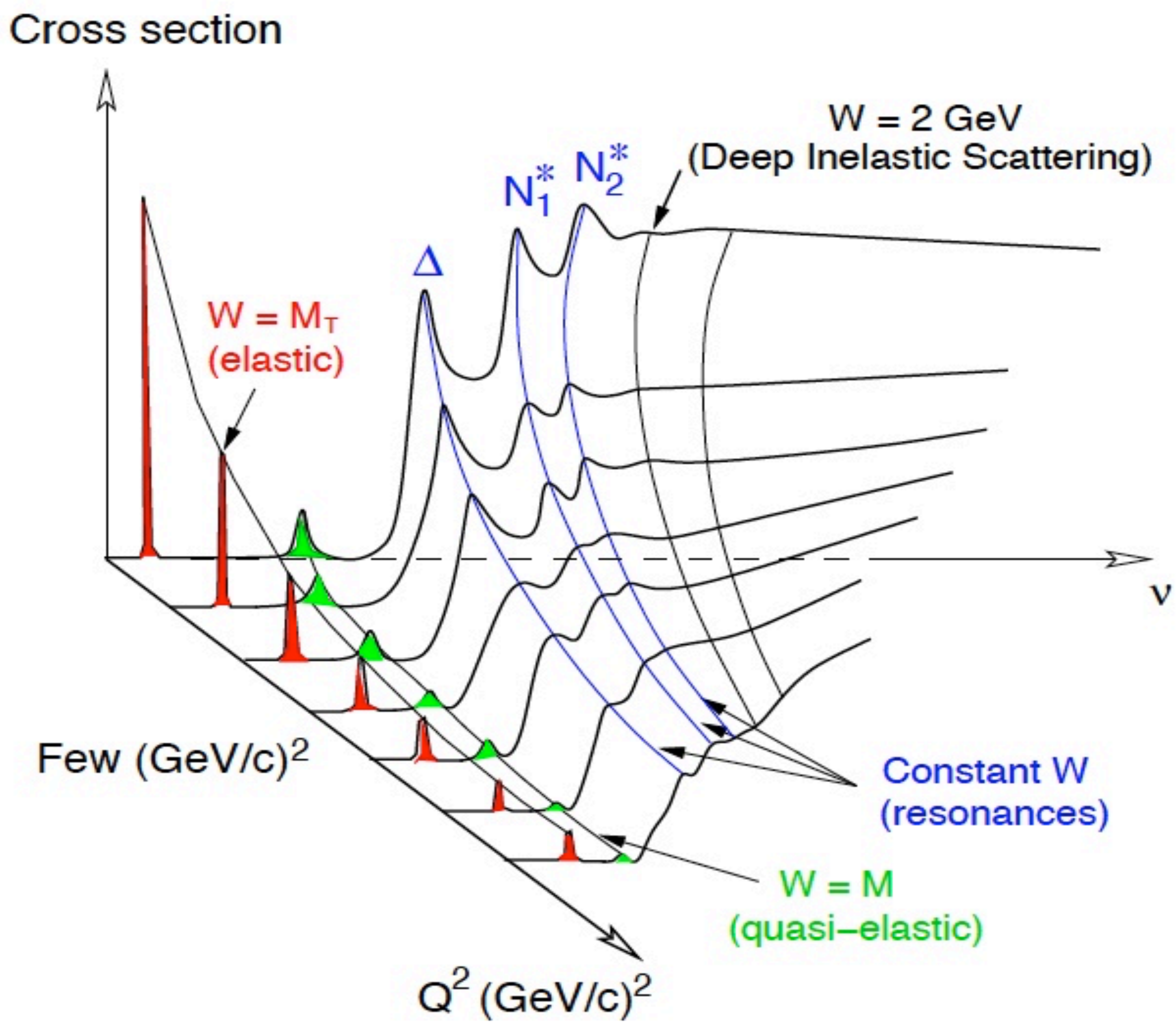


Final state invariant mass

$$W^2 = M^2 + 2M\nu - Q^2$$

In Bjorken limit $Q^2, \nu \to \infty$ $\quad x = \dfrac{Q^2}{2M\nu}$ $\quad$ in deep inelastic region

Electron scattering



Cross section

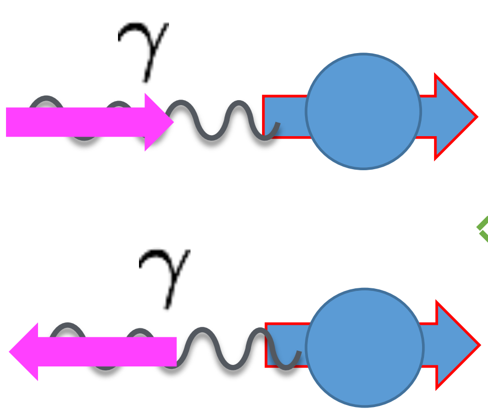
Cross section = (point-like) x (spin-independent + spin-dependent)

- F_1,F_2: unpolarized structure function.
- $F_1=\frac{1}{2}\sum_i e_i^2 q_i(x)$ Quark's momentum distribution.

- g_1,g_2: polarized structure function.
- $g_1=\frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$ Quark's polarization distribution.

❖ Electron scattering cross section with exchange of virtual photon:

Cross section $= f(\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT})$



$$\sigma_T = \frac{\sigma_{3/2}+\sigma_{1/2}}{2}$$

$$\sigma_{TT} = \frac{\sigma_{3/2}-\sigma_{1/2}}{2}$$

F_1

g_1, g_2

Sum rule

$\sum$ All energies

Internal properties:

Form factors,

Structure functions

$\equiv$

Global properties:

Mass,

anomalous magnetic moment,

Coupling constant

(Compton scattering amplitude)

Gerasimov-Drell-Hearn (GDH) sum rule (Q^2= 0, real photon)

$$I_{GDH} = \int_{\nu_{thr}}^{\infty} (\sigma^{1/2} - \sigma^{3/2}) \frac{d\nu}{\nu} = \frac{-2\alpha\pi^2\kappa^2}{M^2}$$

Experimentally measured

Static property of target

Theory prediction

$\sigma^{1/2}$, $\sigma^{3/2}$: photon absorption cross section, with photon helicity is anti-parallel or parallel to target spin.
κ: anomalous magnetic moment
M: target's mass

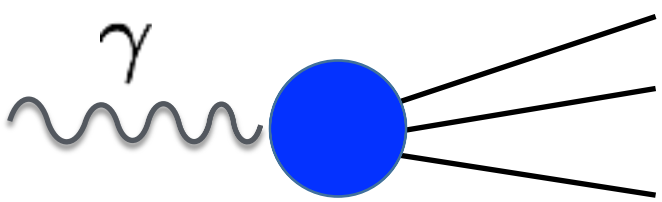
GDH at Q^2=0

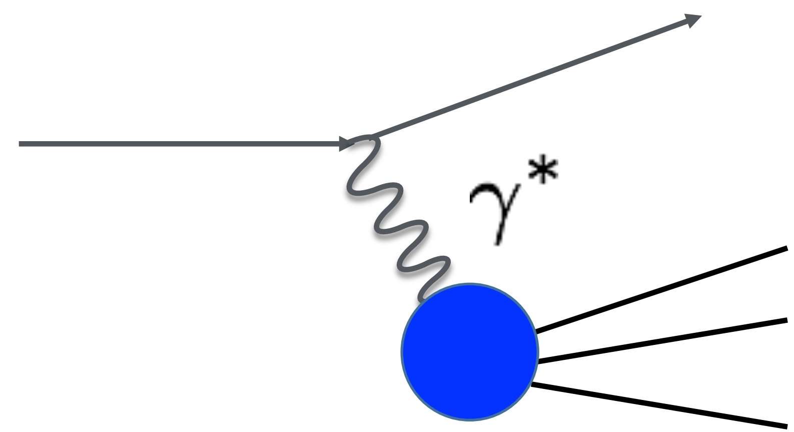
Q^2

Generalized GDH sum rule (virtual photon, $Q^2>0$)

- From real to virtual photon: change photon production cross section with electro-production cross section

$$\sigma^{1/2}(\nu), \sigma^{3/2}(\nu) \rightarrow \sigma^{1/2}(\nu, Q^2), \sigma^{3/2}(\nu, Q^2)$$





Or rewrite it in term of Compton scattering amplitudes (By Ji and Osborne): $S_1(Q^2)$, $S_2(Q^2)$ which are calculable at all Q^2.

$$\frac{16\alpha\pi^2}{Q^2}\int_0^1 g_1 dx = 2\alpha\pi^2 S_1$$

Hadronic d.o.f

Generalized GDH

GDH at $Q^2=0$

Q^2

Bjorken sum rule

$$\int_0^1 (g_1^p(x) - g_1^n(x))dx = \frac{1}{6} g_a$$

Experimentally measured
Difference in spin structure functions

Theory

Well-measured
Axial charge
from neutron decay

Compare

GDH at Q^2=0

Q^2

$Q^2 \to \infty$

Bjorken sum rule

$$\int_0^1 (g_1^p(x) - g_1^n(x))dx = \frac{1}{6} g_a$$

Experimental measured
Difference in spin structure functions

Theory

Well-known
Axial coupling constant
from neutron decay

- For finite Q^2, Bjorken sum rule is:

$$\int_0^1 (g_1^p(x,Q^2) - g_1^n(x,Q^2))dx = \frac{1}{6} g_a \left(1 + \frac{\alpha_s(ln(Q^2))}{\pi} + \ldots\right) + \ldots$$

Low Q^2

- Chiral perturbation theory: effective theory at low energy
- Virtual forward Compton spin-dependent scattering amplitudes $S_{1,2}(Q^2)$

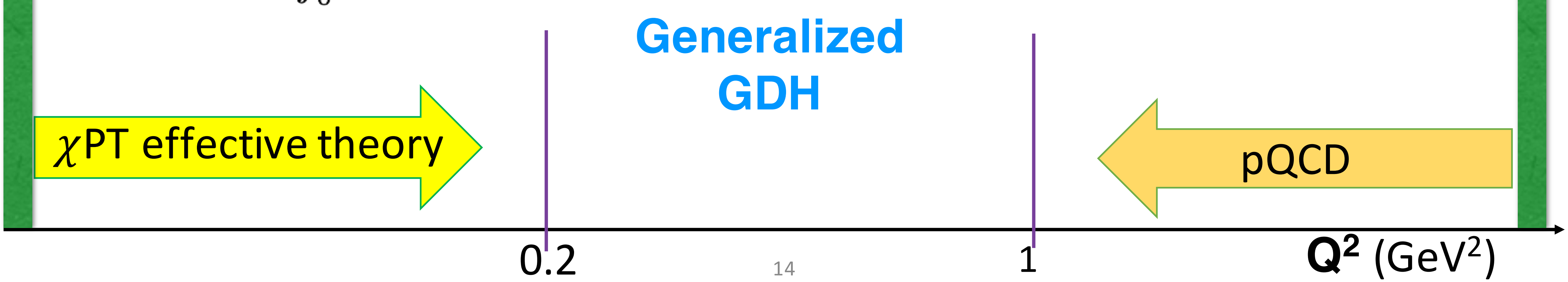
High Q^2

- Use Operator Product Expansion: (perturbative)*(non-perturbative).
- $g_a \sim g_a$ * (1+QCD radiative corrections)

$$\Gamma_p(Q^2) - \Gamma_n(Q^2) = \int_0^{x_0} (g_1^p - g_1^n)dx$$

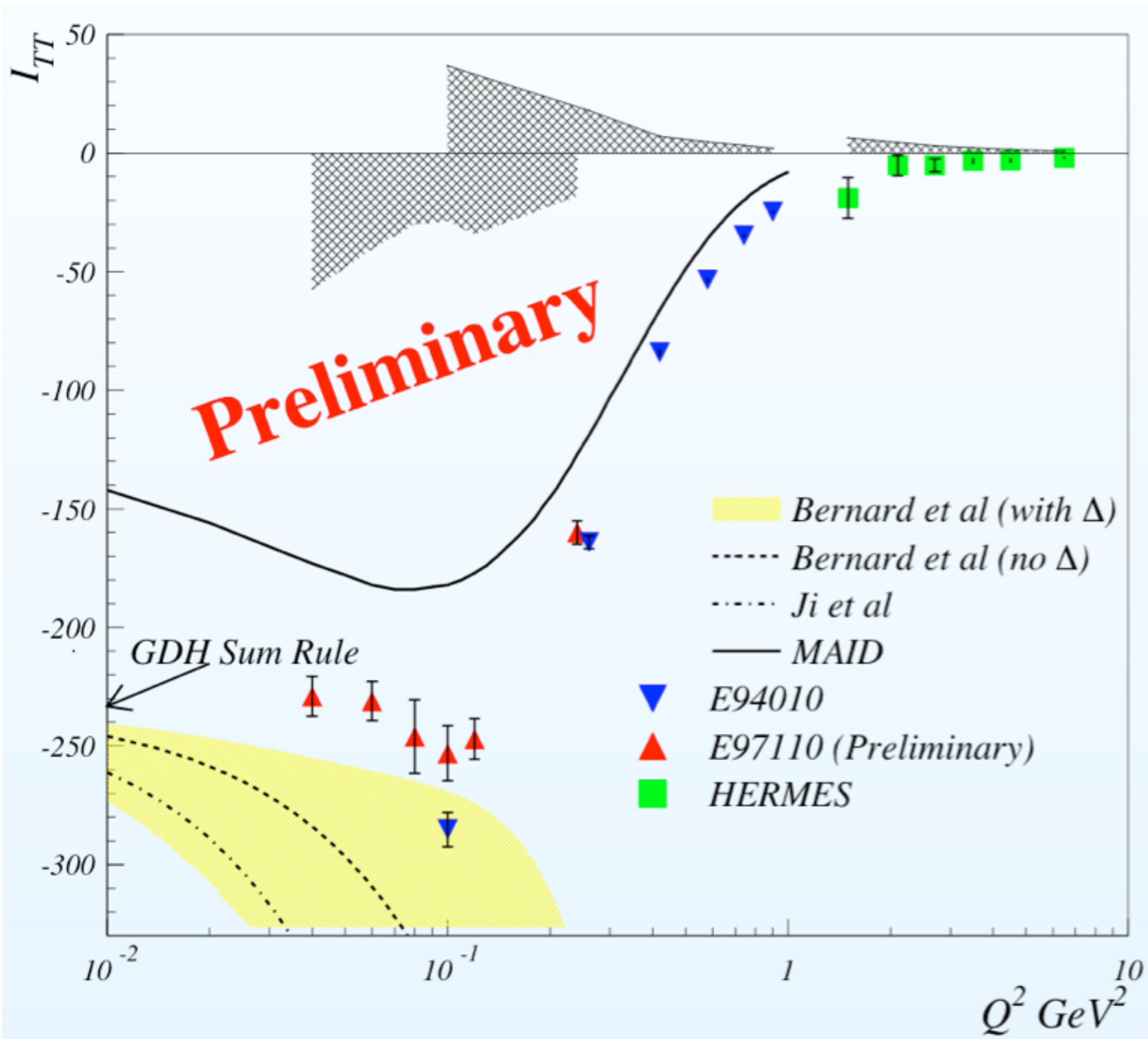
$$\int_0^1 (g_1^p - g_1^n)dx = \frac{g_a}{6}(pQCD)$$

$$\Gamma_N(Q^2) \equiv \int_0^{x_0} g_1^N(x, Q^2)dx$$



Current data for GDH at low Q^2 region

Sum rule on neutron



Experiment:

- E94010 (1998) Hall A.
- E97110 (2003) Hall A.

Figure from V. Sulkosky

Show a smooth transition from partonic to hadronic, we expect a sharp change in slope at Q^2<0.1 GeV^2 → important to do experiment at lower Q^2

Gerasimov-Drell-Hearn (GDH) sum rule (Q^2= 0, real photon)

$$I_{GDH} = \int_{\nu_{thr}}^{\infty} \left(\sigma^{1/2} - \sigma^{3/2}\right) \frac{d\nu}{\nu} = \frac{-2\alpha\pi^2\kappa^2}{M^2}$$

Experimental measured

Theory prediction

Static property of target

$\sigma^{1/2}$, $\sigma^{3/2}$: photon absorption cross section, with photon helicity is anti-parallel or parallel to target spin.

κ: anomalous magnetic moment

M: target's mass

GDH at Q^2=0

Q^2

Current data for GDH at low Q^2 region

Sum rule on neutron

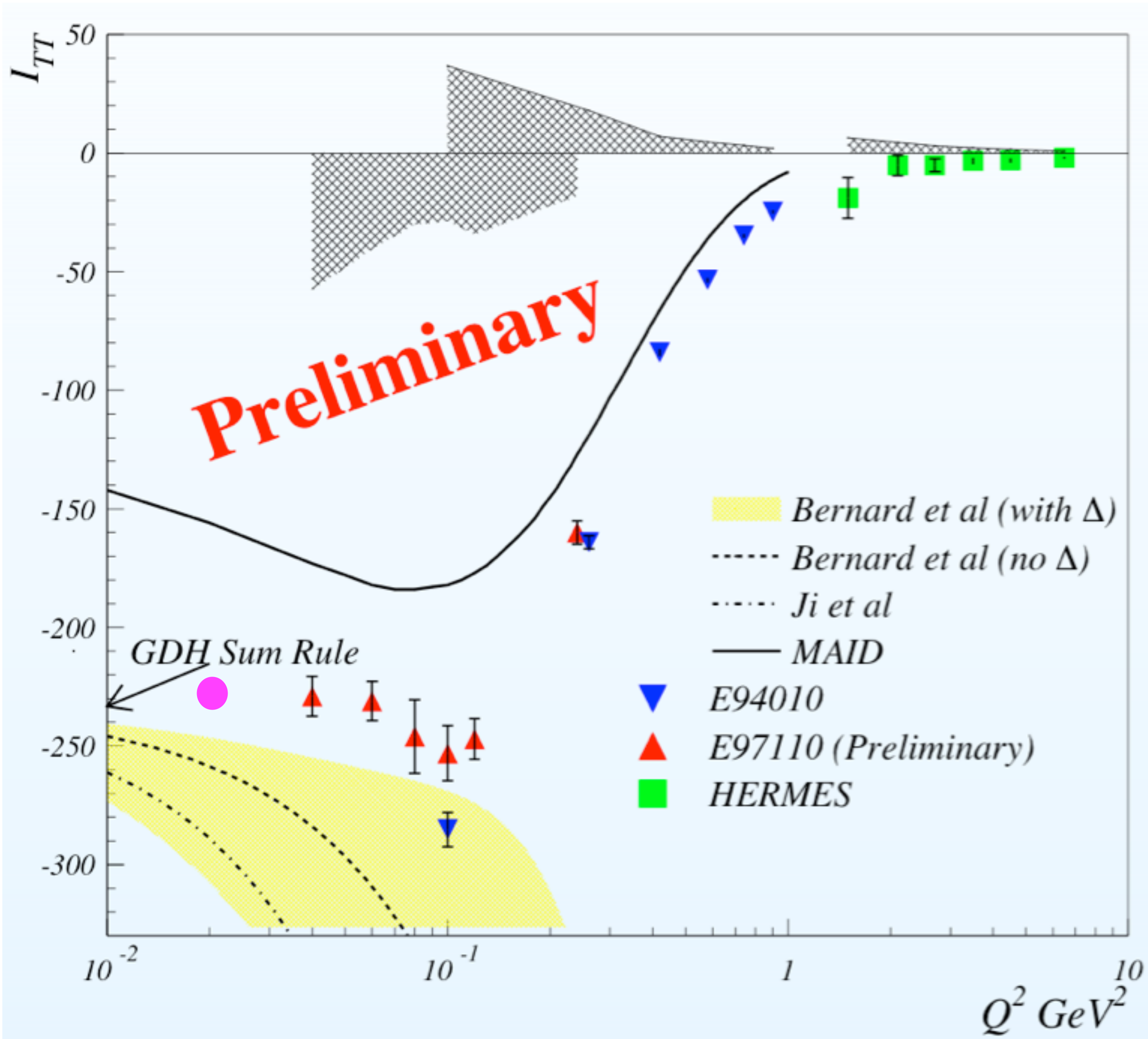


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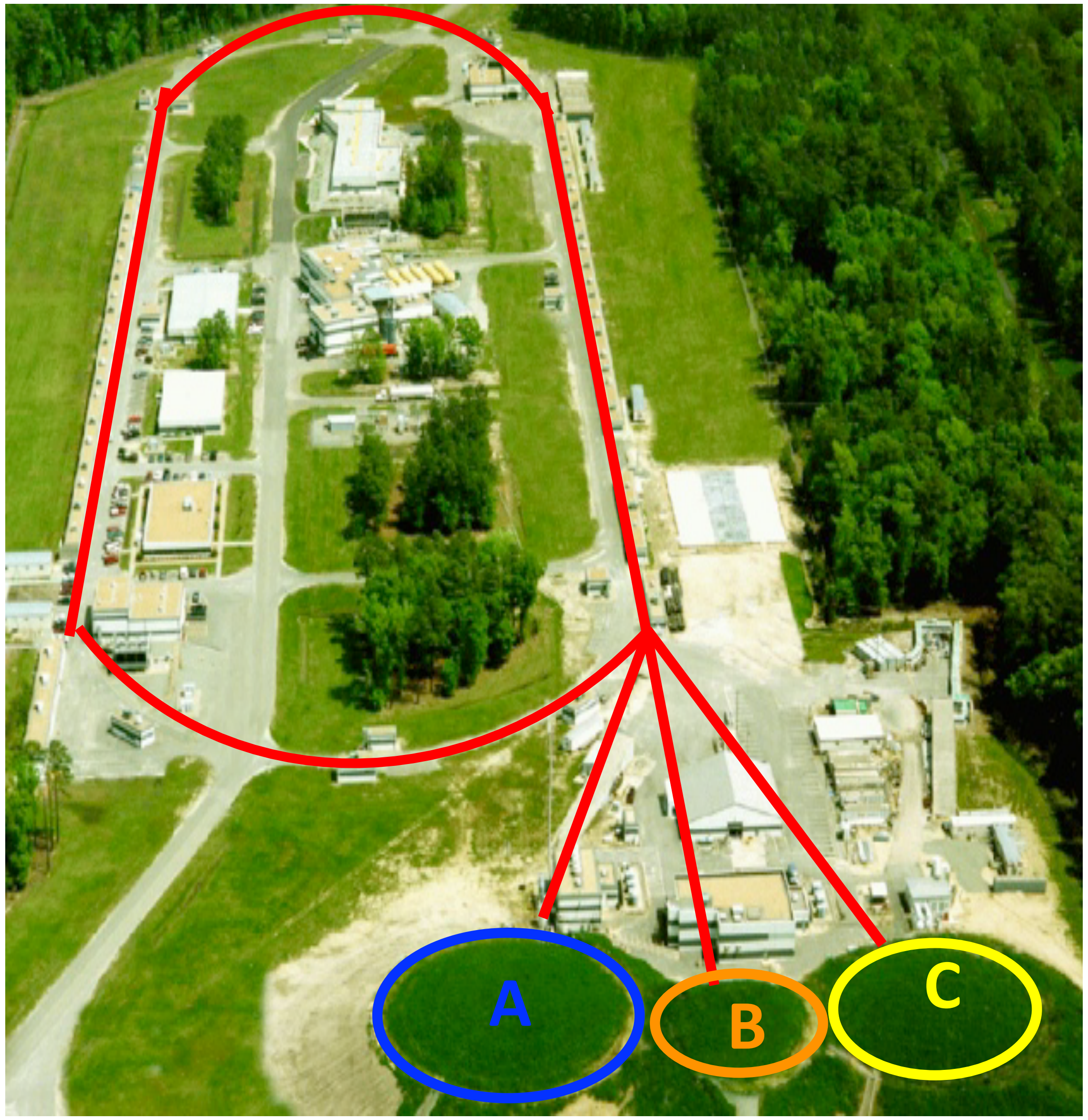
Figure from V. Sulkosky

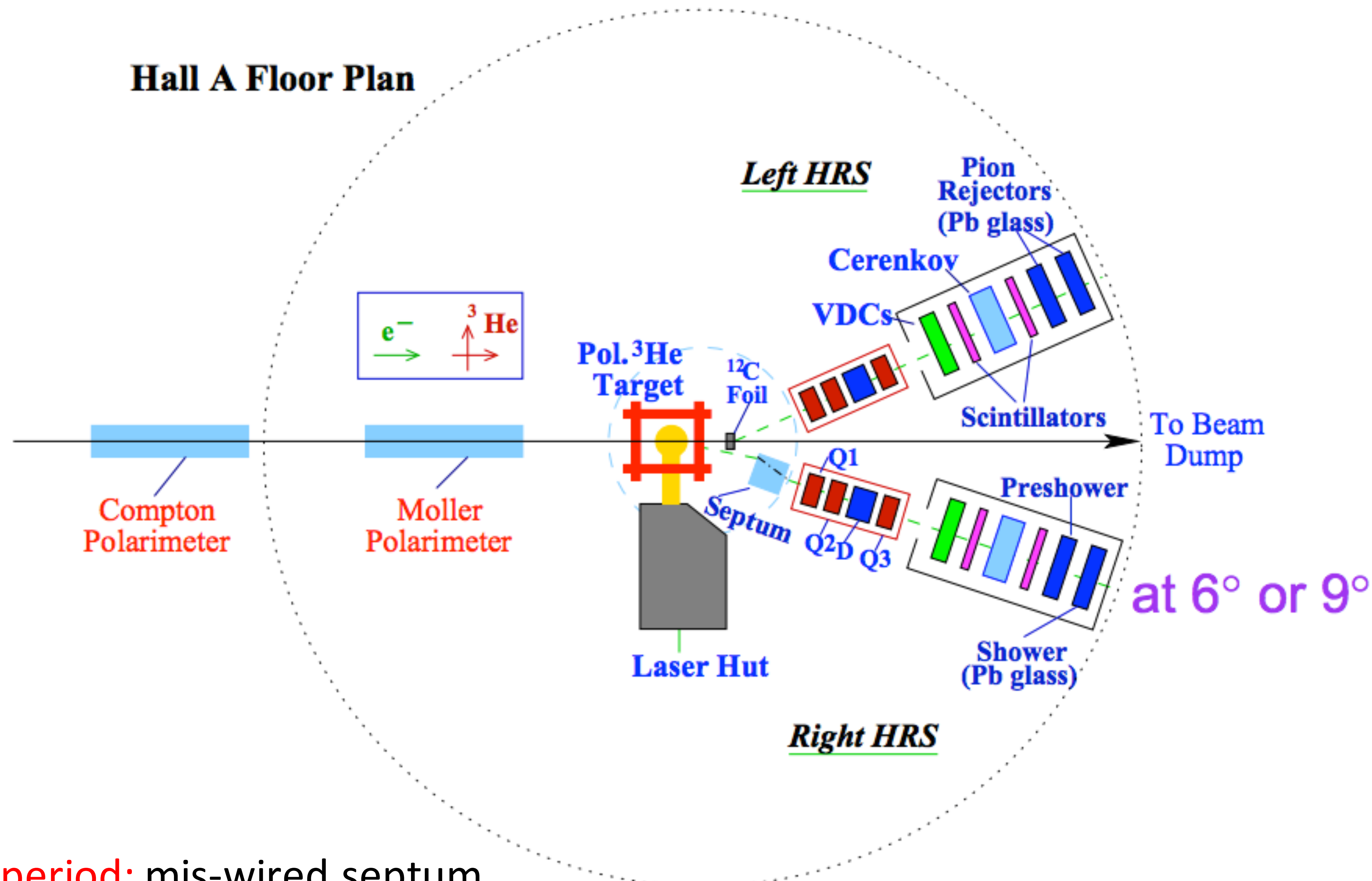
Show a smooth transition from partonic to hadronic, we expect a sharp change in slope at Q^2<0.1 GeV^2 → important to do experiment at lower Q^2

Experiment E97110

- Precise measurement of generalized GDH integral at $0.02<Q^2<0.3$ GeV^2.
- Inclusive experiment: $\overrightarrow{{}^3He}(\vec{e}, e')X$
- Measured polarized cross section differences.
- Continuous beam with P_e~85%. Seven different beam energies from 1.1 GeV to 4.4 GeV and two angles (6^o and 9^o).
- Polarized ^{3}He: P_t~40%.
- Spokespersons: J.P Chen, A. Deur, F. Garibaldi.



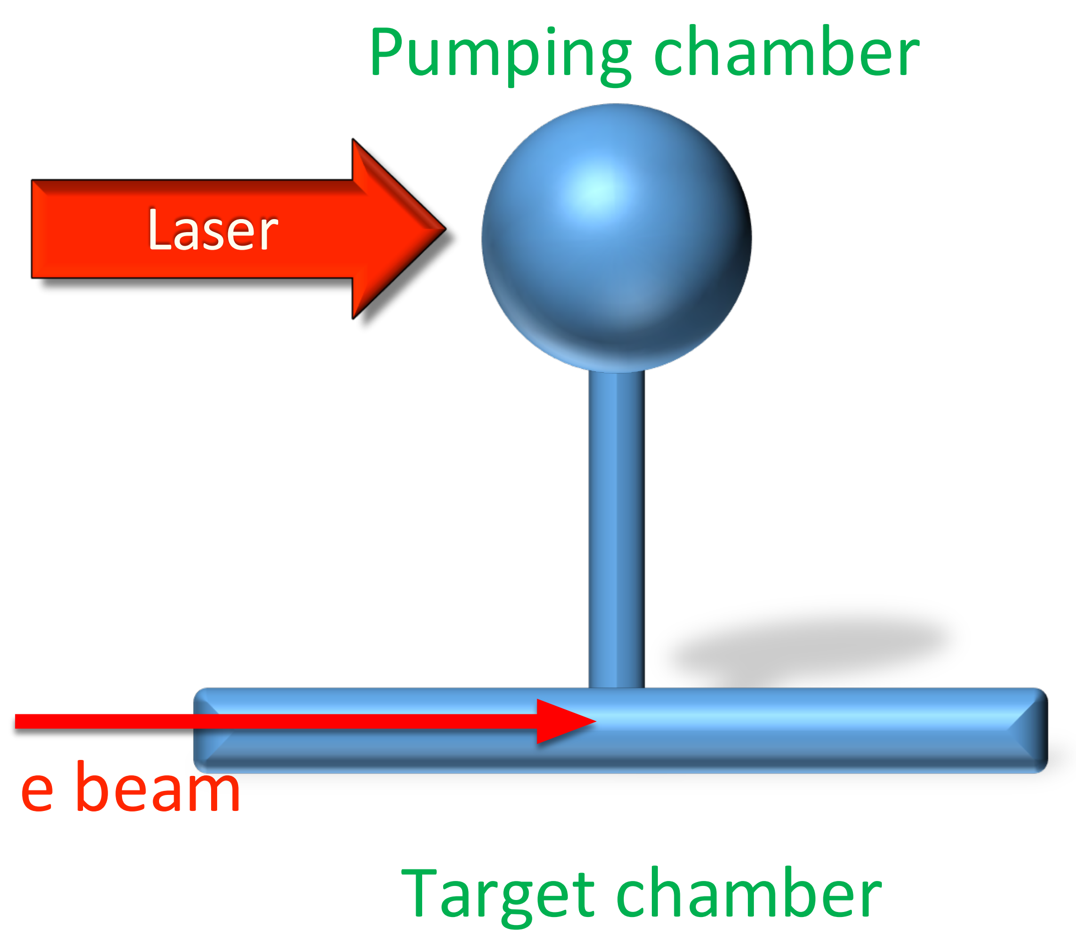
Experiment setup



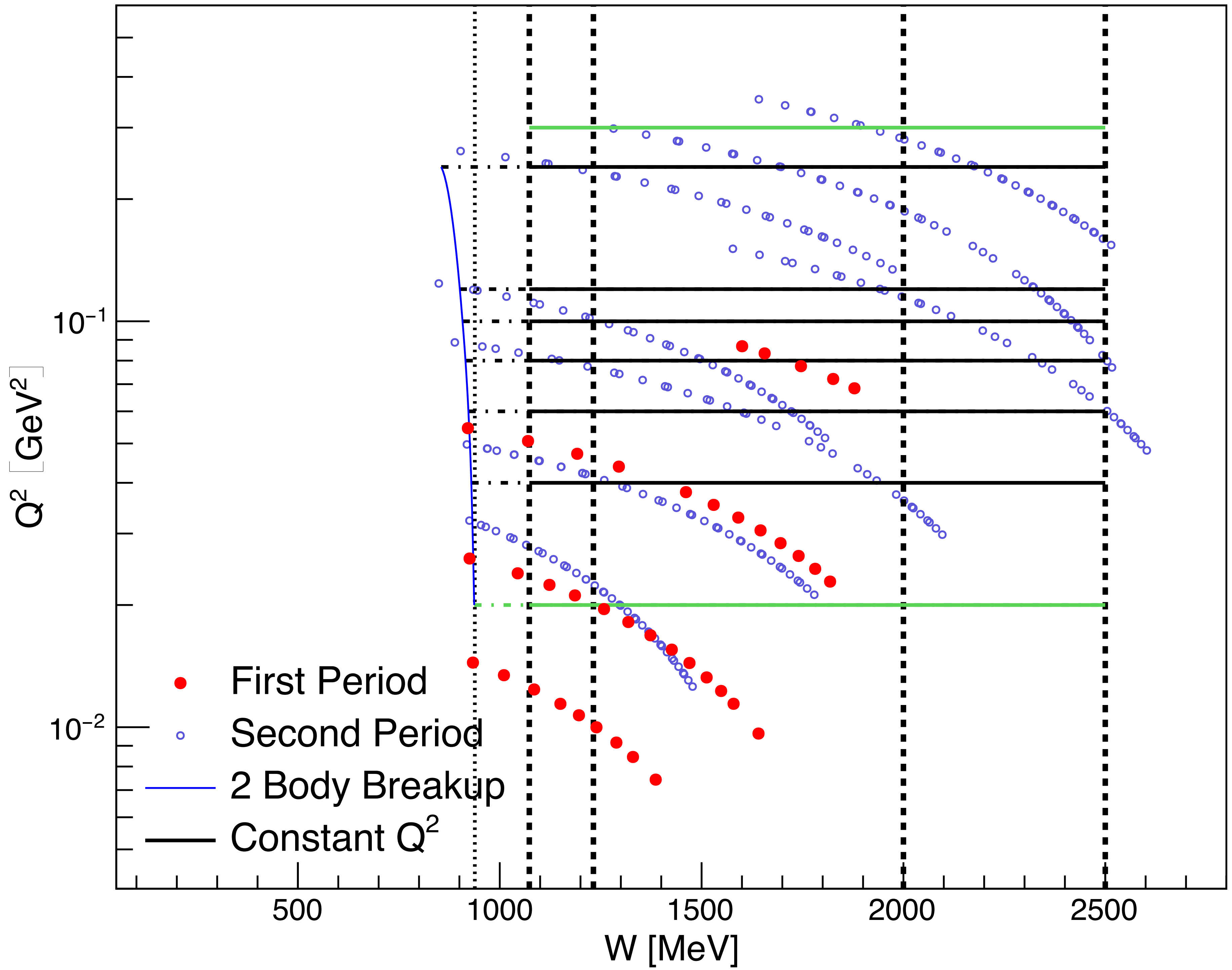
- 1st period: mis-wired septum
- 2nd period: good septum

$0.02<Q^2<0.3$ GeV^2

6 GeV target cell



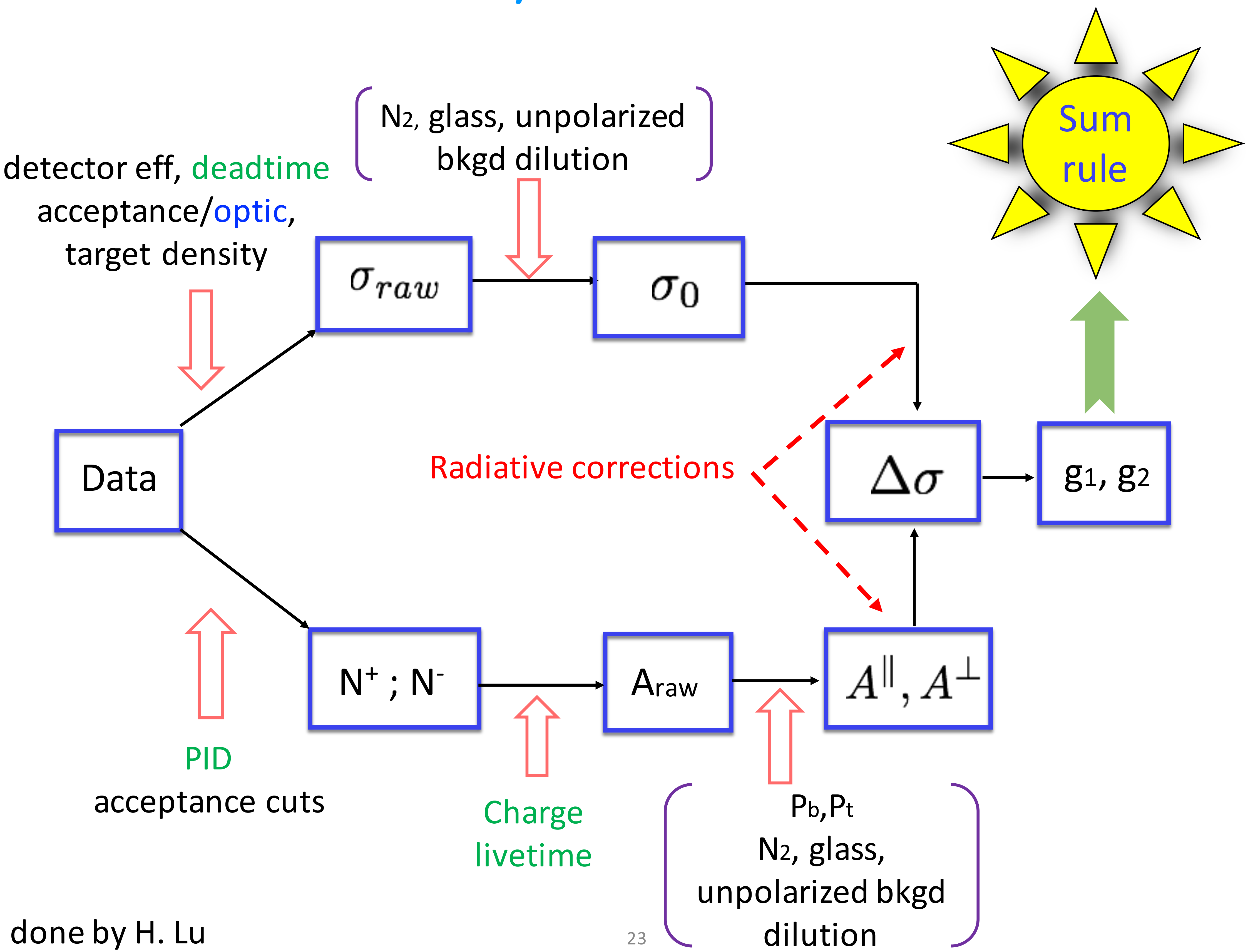
Kinematic plot for experiment



Analysis working people

- Supervisors: Jian-ping Chen, Alexandre Deur.
- Ph. D thesis: Vincent Sulkosky, Jaideep Singh, Jing Yuan (2^{nd} period).
- Others: Nilanga Liyanage, Timothy Holmstrom, Hai-jiang Lu.
- Present students: Chao Peng (work on 2^{nd} period), Nguyen Ton (work on 1^{st} period)

Analysis flow chart



PID done by H. Lu

Scaler asymmetry

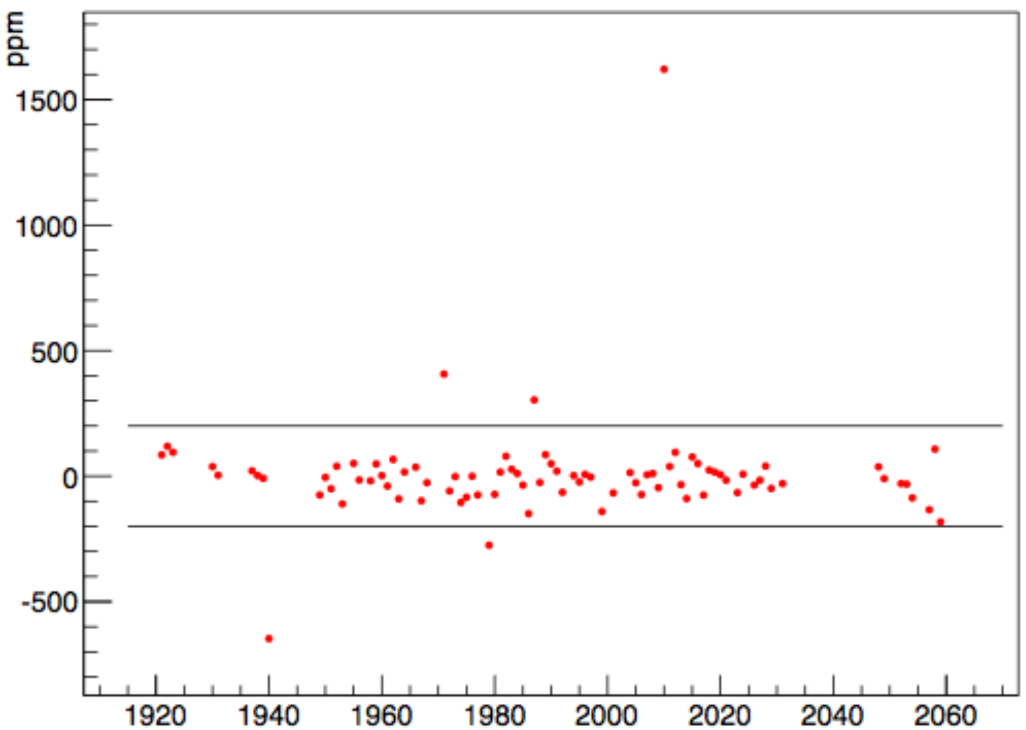
- Charge asymmetry: $A_Q = \frac{Q^+ - Q^-}{Q^+ + Q^-}$
- Livetime asymmetry: $A_{LT} = \frac{\frac{N_{acc}^+}{N^+} - \frac{N_{acc}^-}{N^-}}{\frac{N_{acc}^+}{N^+} + \frac{N_{acc}^-}{N^-}}$
- Raw/scaler asymmetry: $A_{raw} = \frac{N^+ - N^-}{N^- + N^-}$

Where Q^+, Q^- are accumulated beam charge for helicity plus and helicity minus.
N^+, N^- are number of total trigger for each helicity.
N_{acc}^+, N_{acc}^- are number of accepted trigger for each helicity.

$$I = \frac{\frac{N_a}{t} - offset_a}{Calibration\ constant}$$

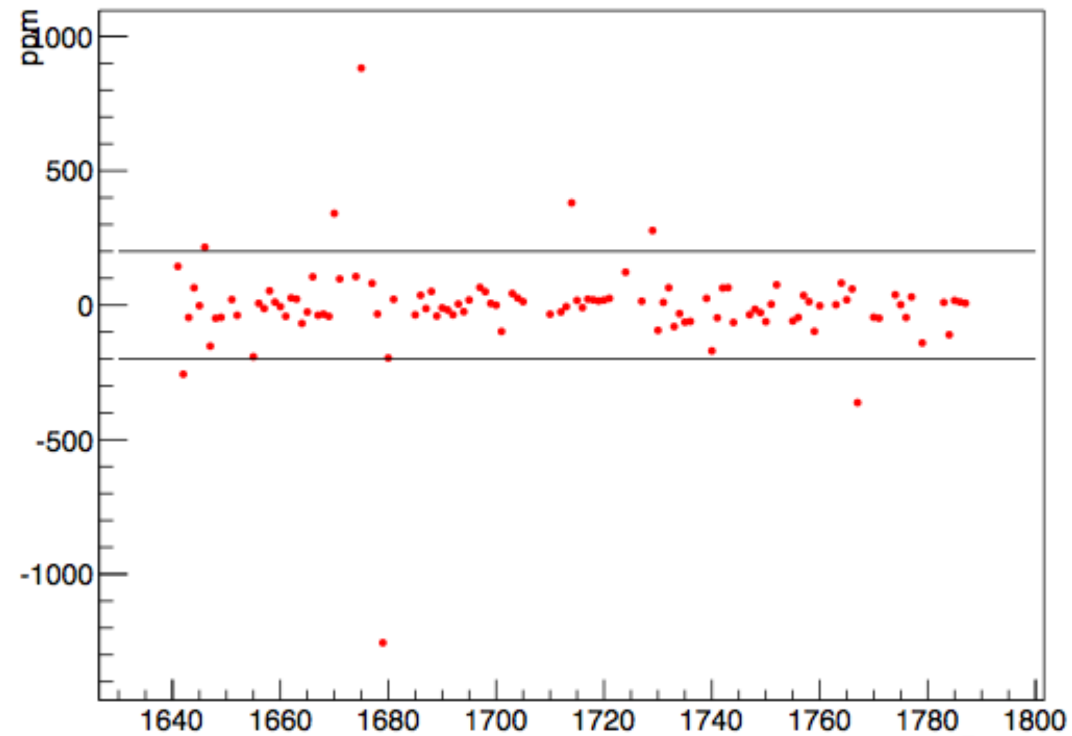
Charge asymmetry for 1st period

Charge Asymmetry for 1.1GeV beam, x3

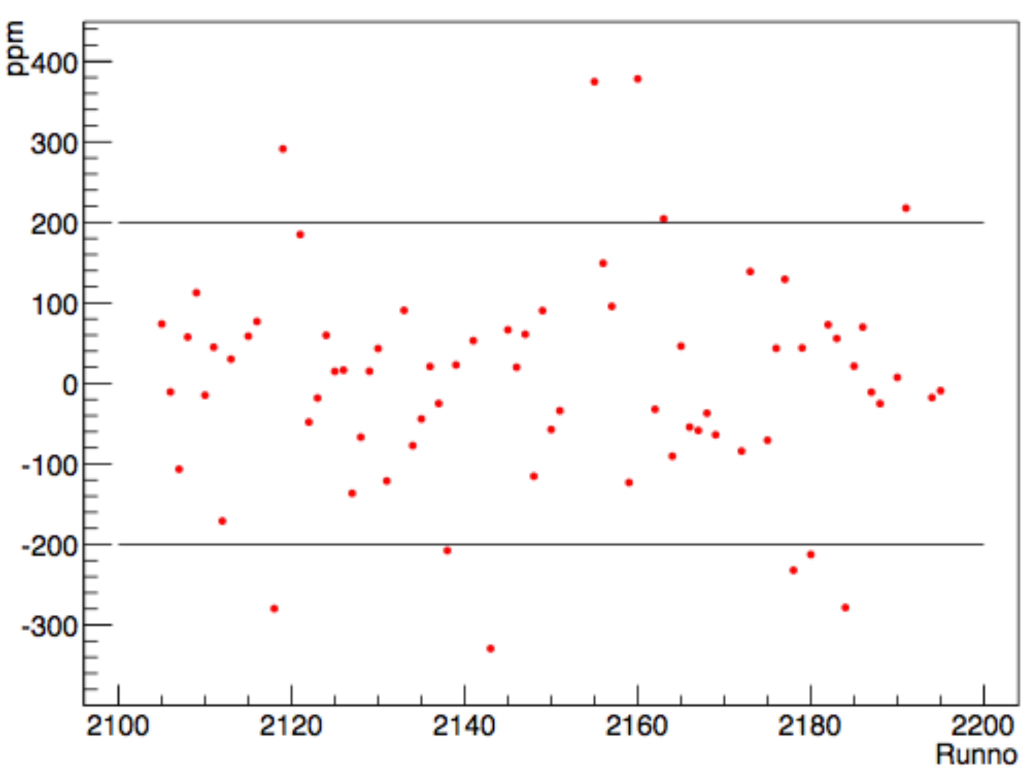


Run#

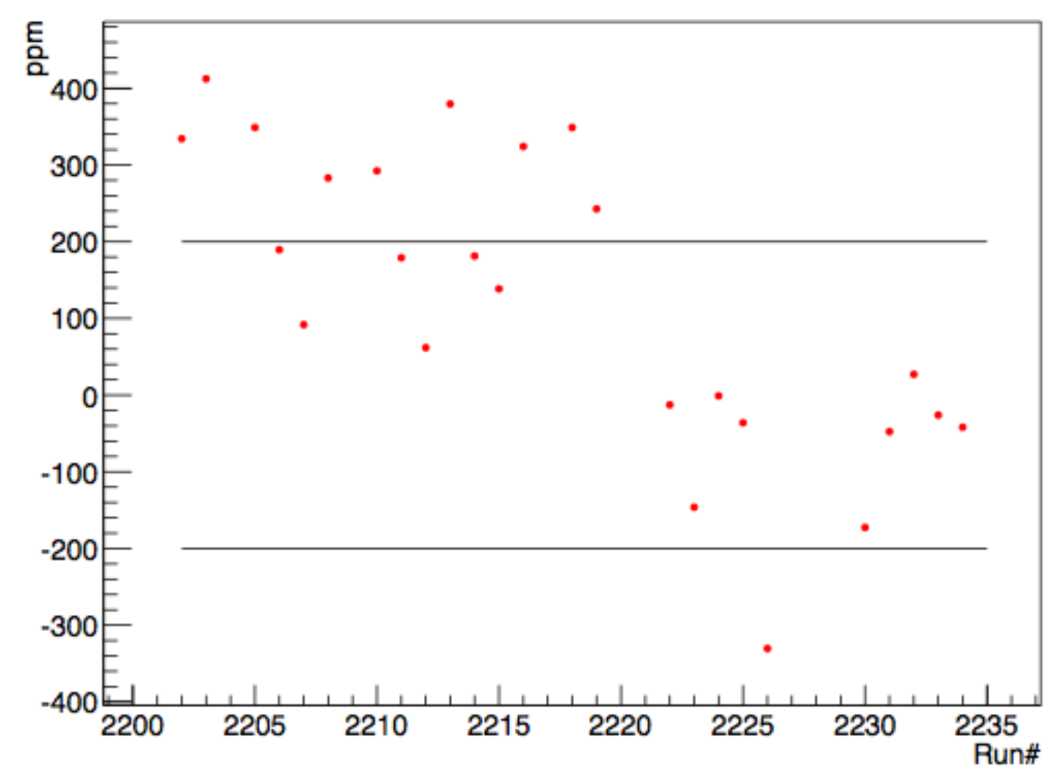
Charge Asymmetry for 1.5GeV beam, x3



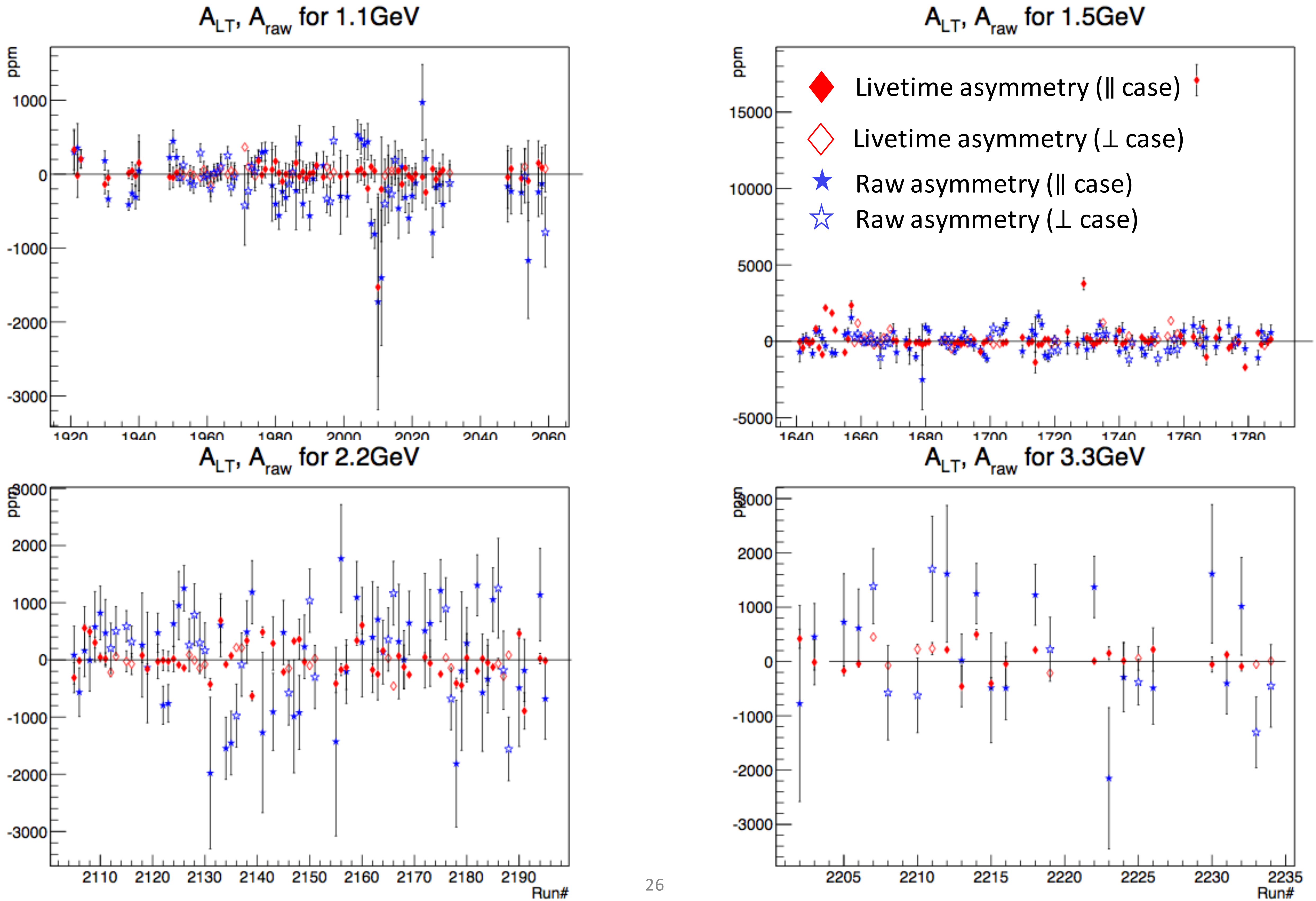
Charge Asymmetry for 2.2GeV beam, x3



Charge asymmetry for 3.3GeV, x3



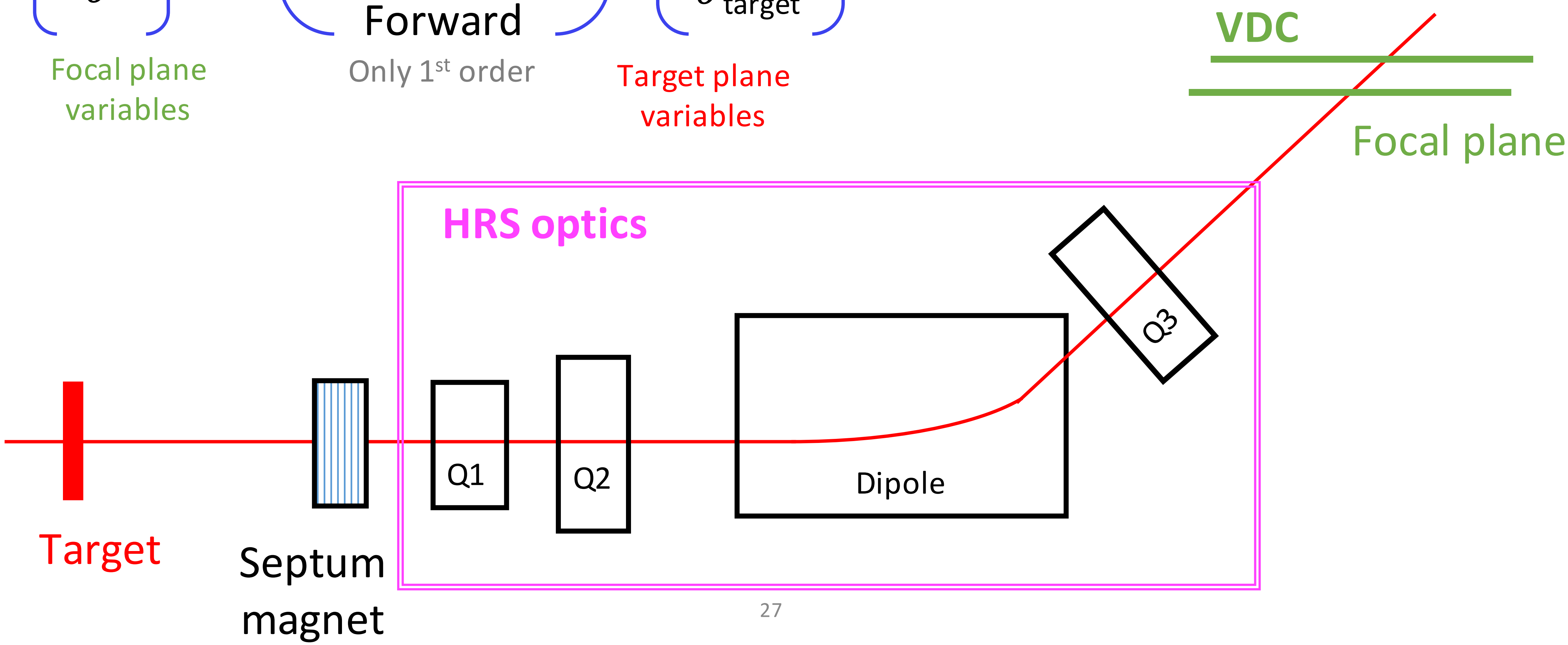
Livetime and raw asymmetry



Septum+ HRS (high resolution spectrometer) optics

$$\begin{pmatrix} x \\ y \\ \phi \\ \theta \end{pmatrix} = \Big(M \Big) \begin{pmatrix} \delta \\ Y_{target} \\ \phi_{target} \\ \theta_{target} \end{pmatrix}$$

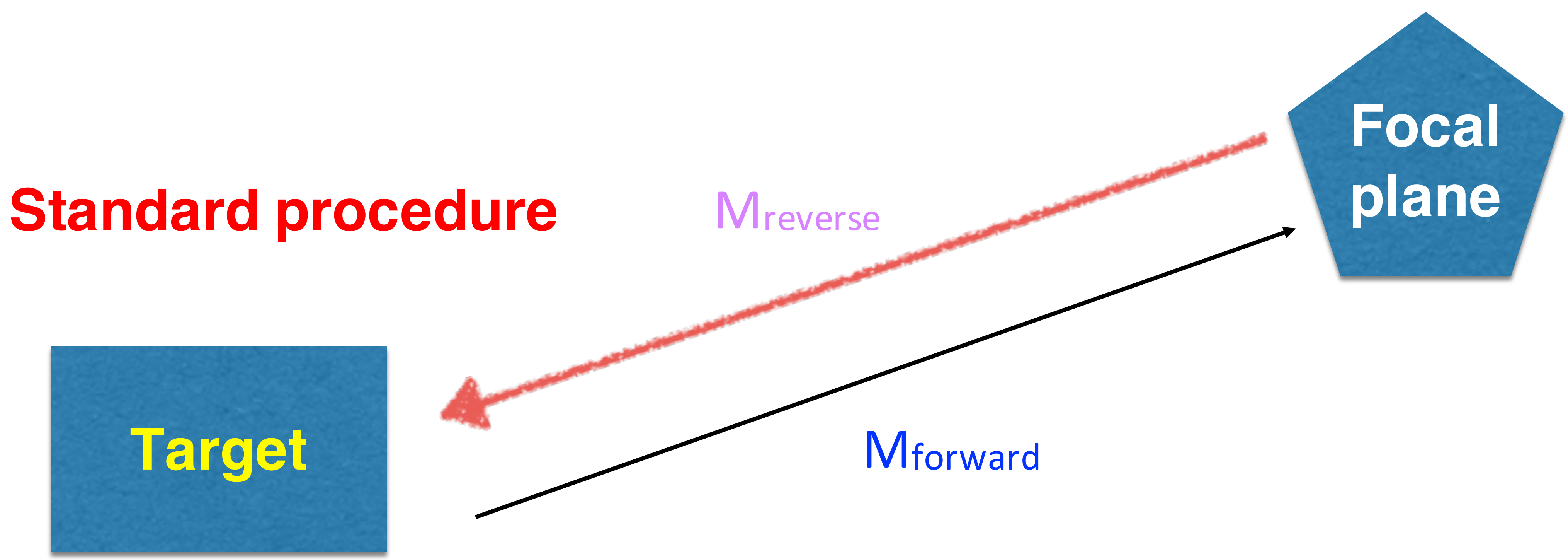
Focal plane variables — Forward, Only 1st order — Target plane variables



Optics study

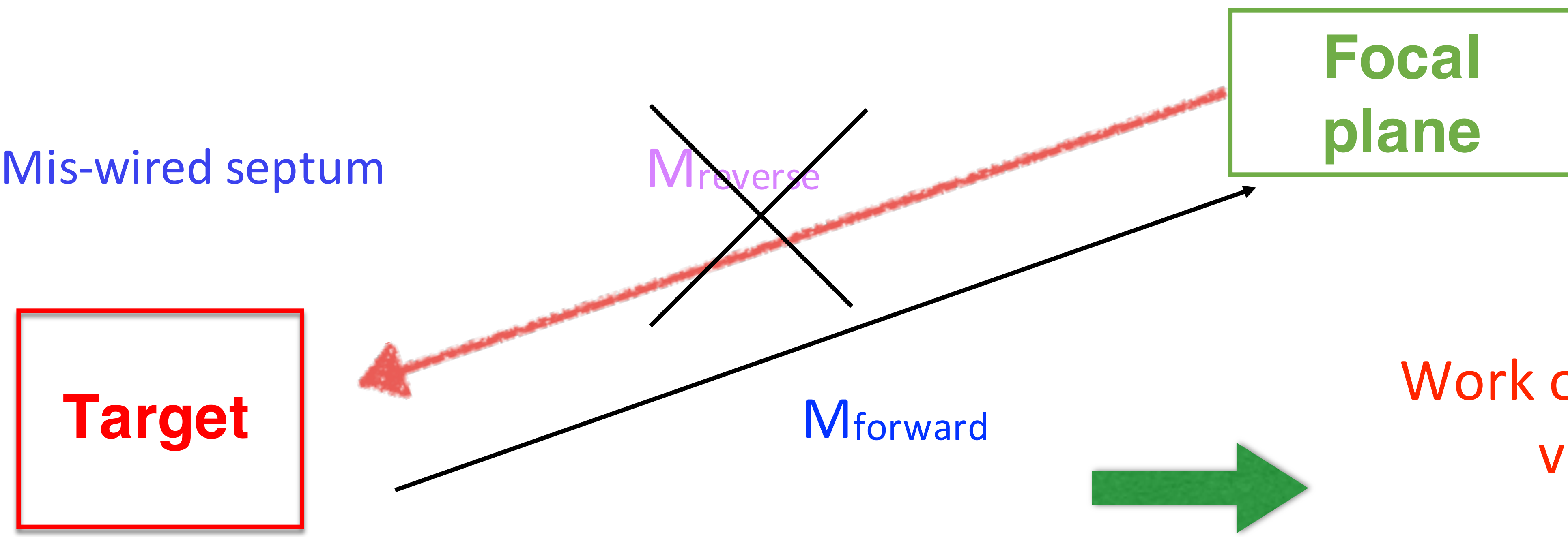
- Normal analysis procedure (2nd period), we have **both** forward and reverse matrices. Optimize transport matrix to get best match between target reconstructed variables and target quantities from survey.

- Our case (1st period), **only** have focal plane quantities (which come from detector). There is no standard way to deal with this.



Optics study

Mis-wired septum



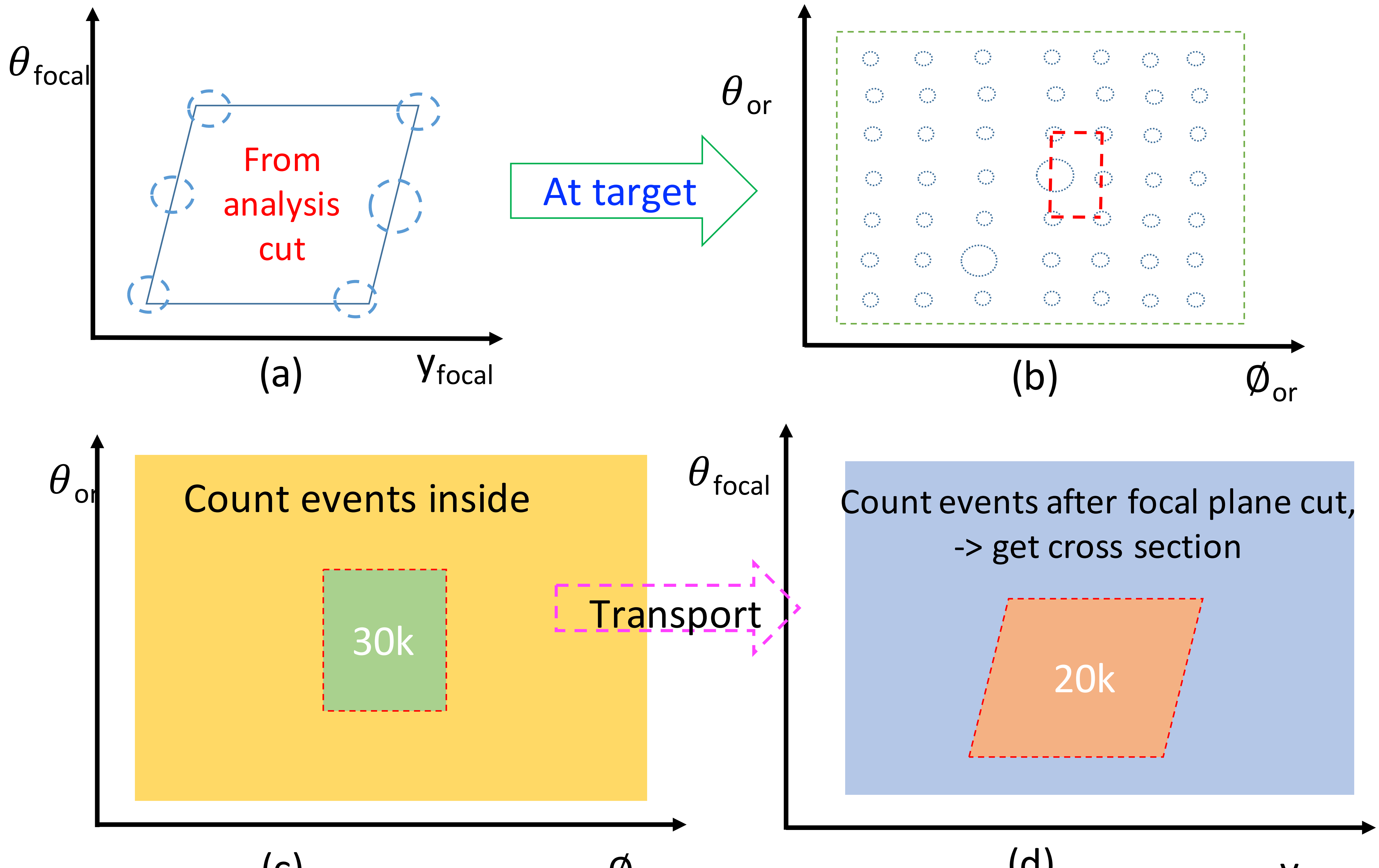
Work on focal plane variables
&
rely on simulation

- Use forward matrix to transport from target to focal plane (simulation).
- Use target variables (phi and theta) to get geometry solid angle and then get experimental cross section.

How good is our optics? How to test it?

Single carbon foil
+ elastic

Procedure to get cross section for focal plane method



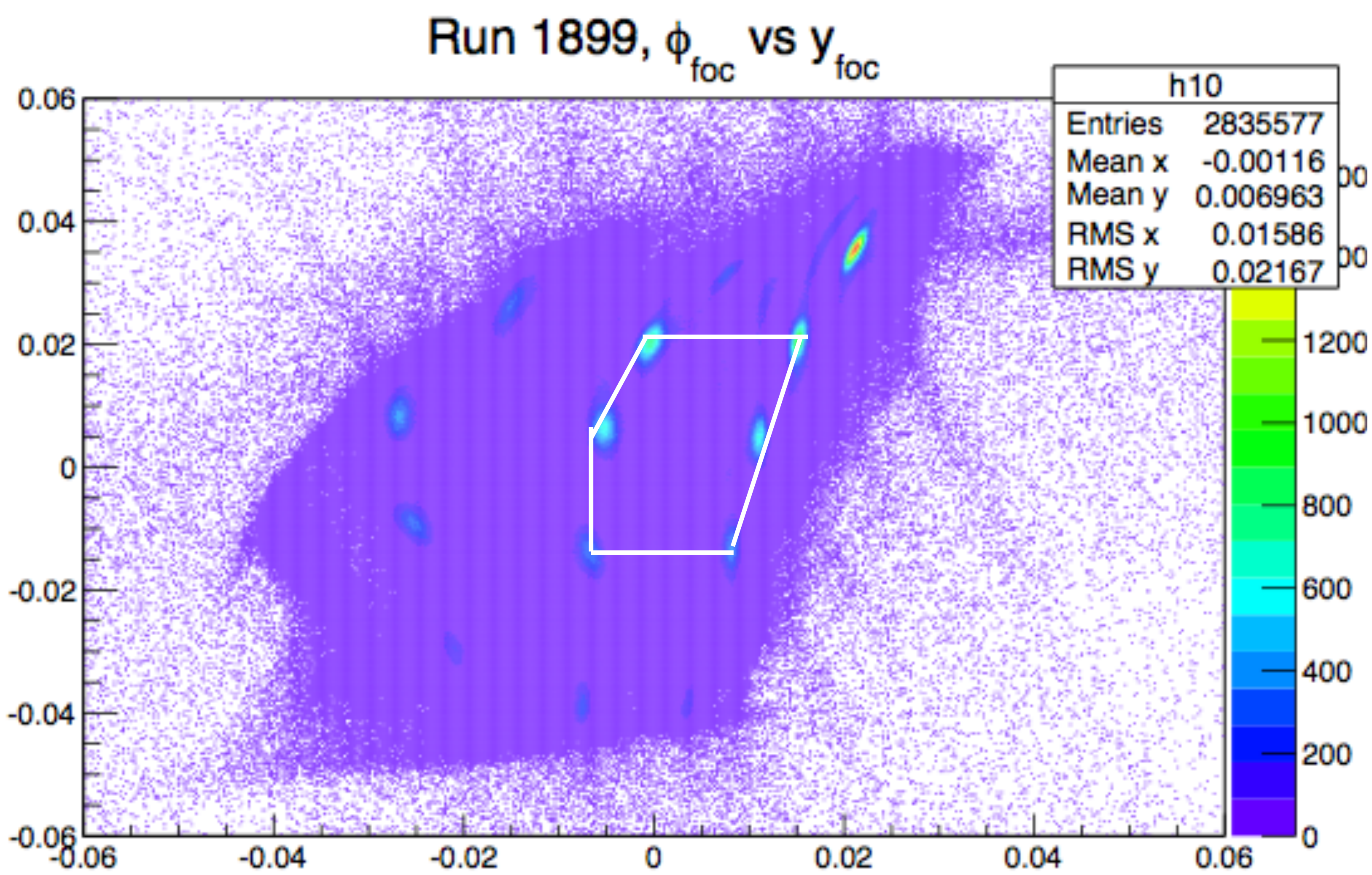
Elastic carbon cross section result with focal plane method for 2nd period (with good septum)

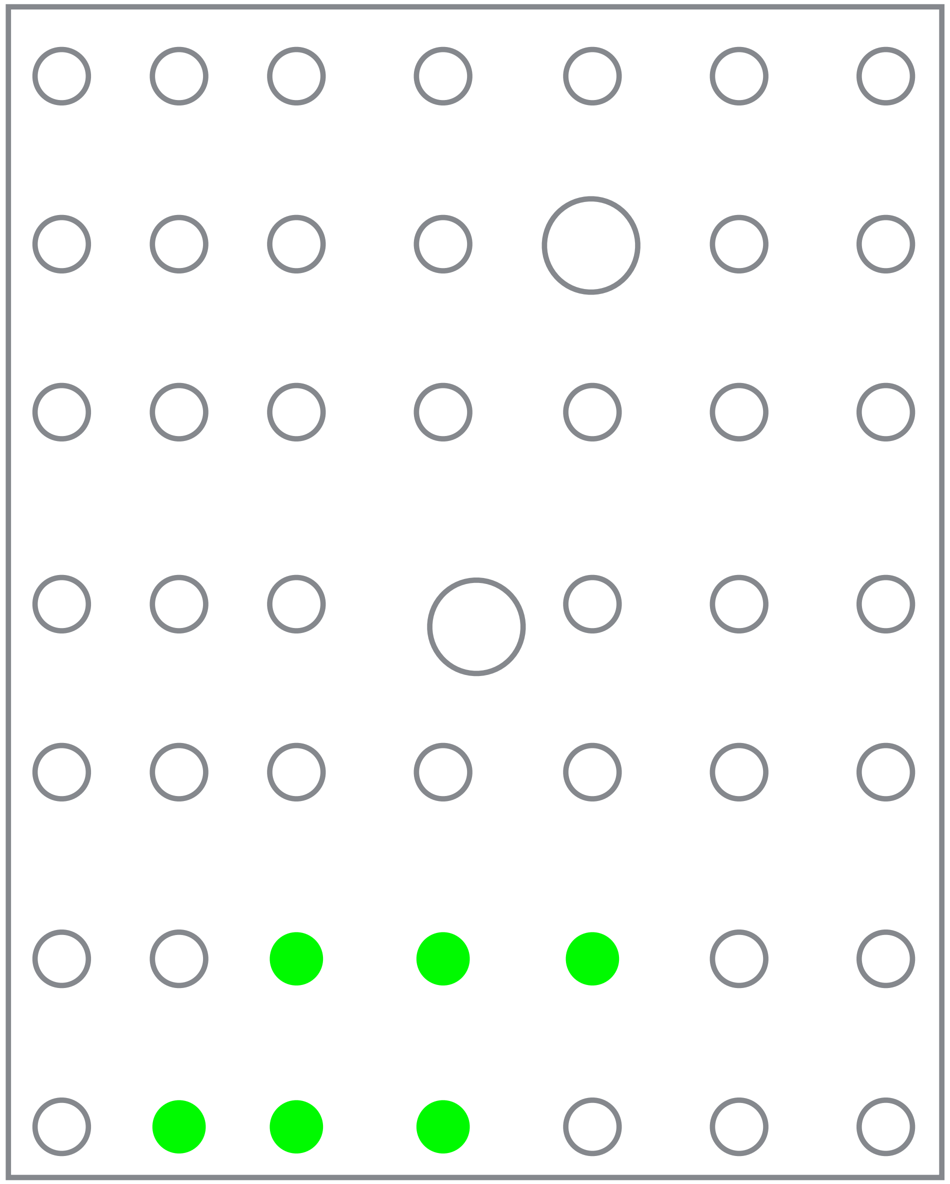
Center foil	δp=0%	δp=-2%
σ_{sim} (ub)	250	262
σ_{data} (ub)	270	246
% data & sim	7%	6%

Conclusion: Focal plane method works well

δp: position of elastic peak at focal plane

Apply focal plane method to 1st period





Elastic carbon cross section result for 1st period (with defective septum)

Center foil	δp= 0 %	δp= -2 %
σ_{sim} (ub)	4466	4540
σ_{data} (ub)	4337	4853
% difference	3	6

Focal plane method works well for 1st period (with defective septum) with single foil at center position.

Future plan

- Finish single carbon foil for other beam energies, and foil positions.
- Move to extended target: N_2, ^{3}He.
- Inelastic cross sections and asymmetries.

Polarized ^3He target for 6 GeV experiments

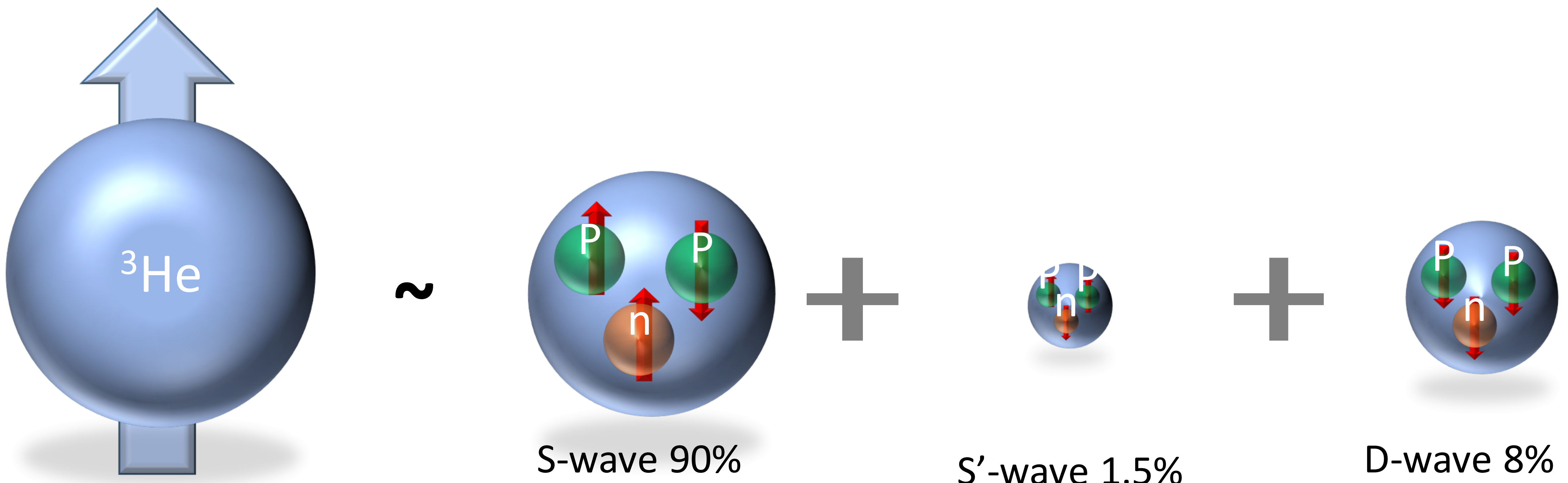
Polarized ^{3}He Target

✓ $^3\overrightarrow{He}$ as an effective polarized neutron target.

❑ Neutron decay time ~ 15 mins (no free neutron target).

❑ Deuteron (1p+1n -> uncertainty comes from extracting n and there is >50% contribution from p).

^{3}He wavefunction =

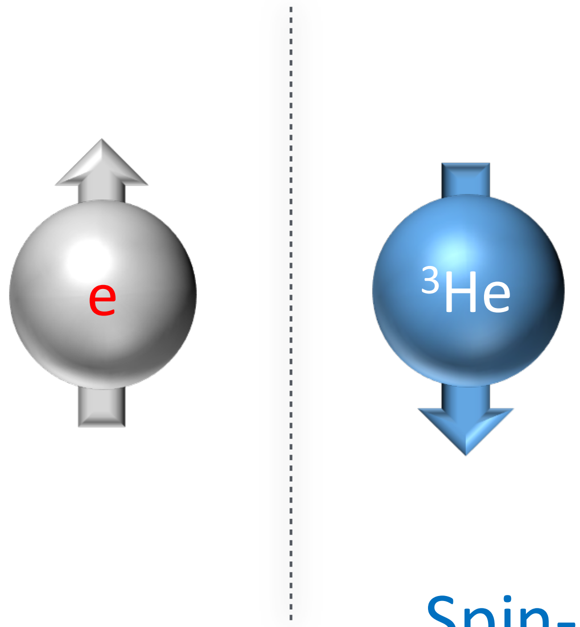


How to polarized ^{3}He

- We can polarized ^{3}He directly by metastability exchange optical pumping. Usually for low density gas.

- For our case, high density (use for electron scattering), we use spin exchange optical pumping. An indirect method: use electron from alkali atom.

Alkali electron



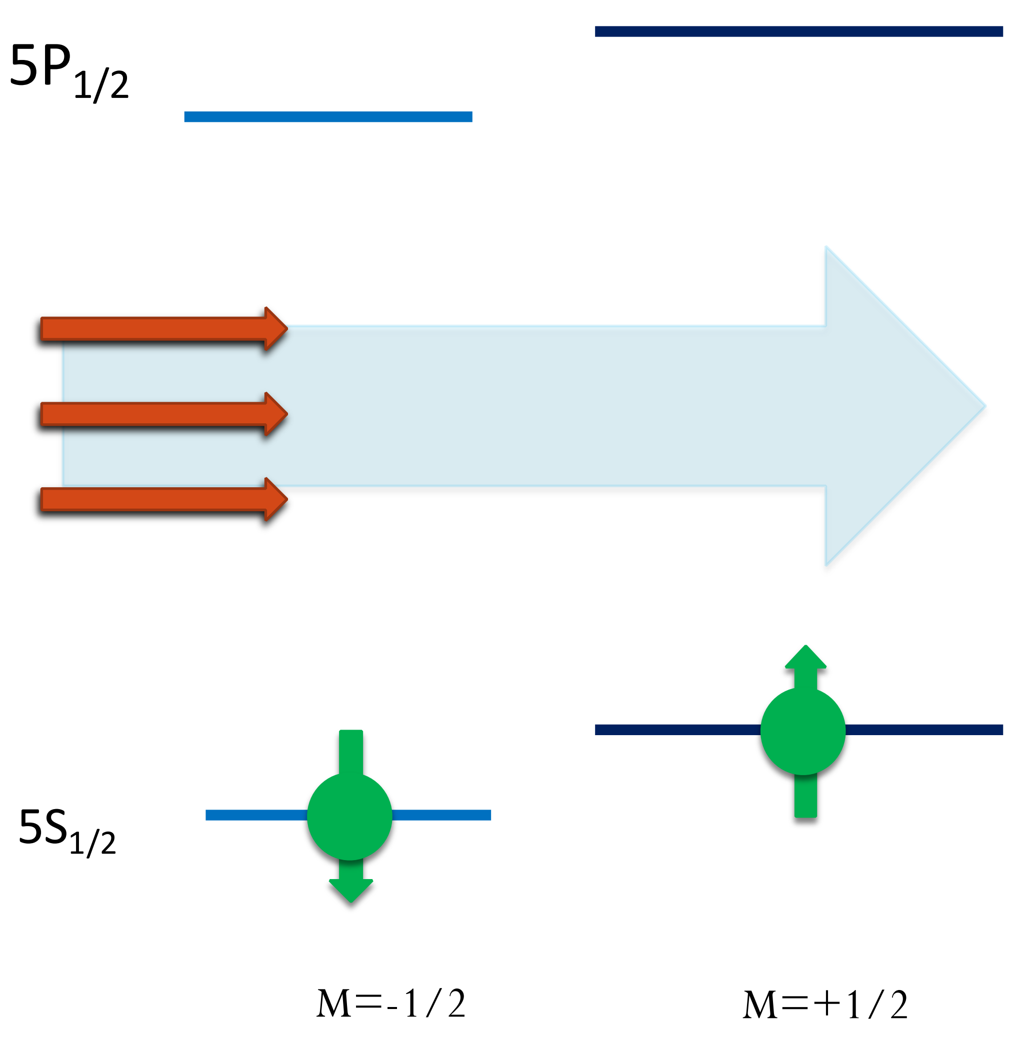
nucleus

Optical pumping

Spin-exchange alkali-^{3}He

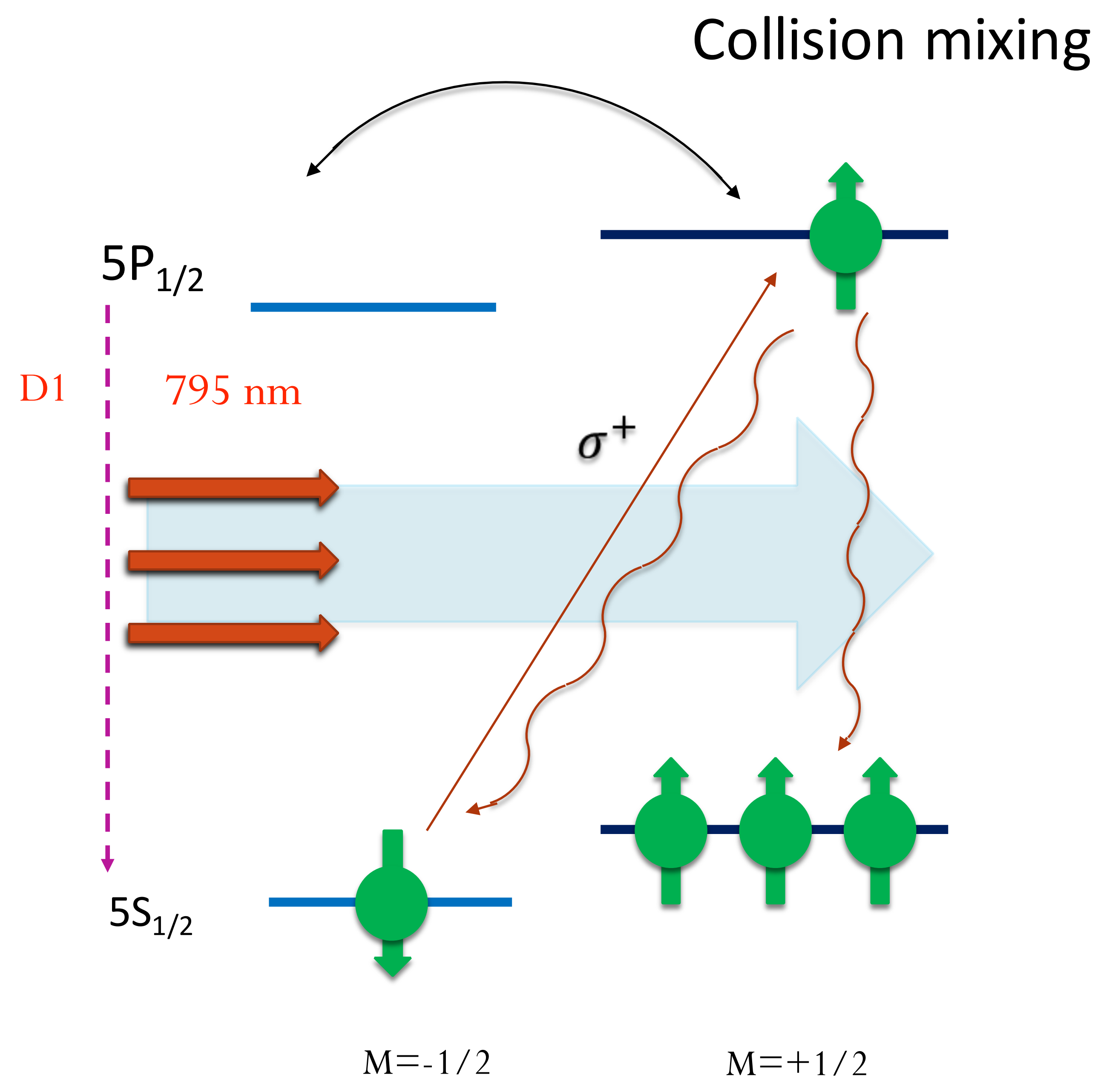
Optical pumping

- Apply magnetic field, energy split between $5S_{1/2}$ & $5P_{1/2}$.
- Use circularly polarized laser with 795nm.



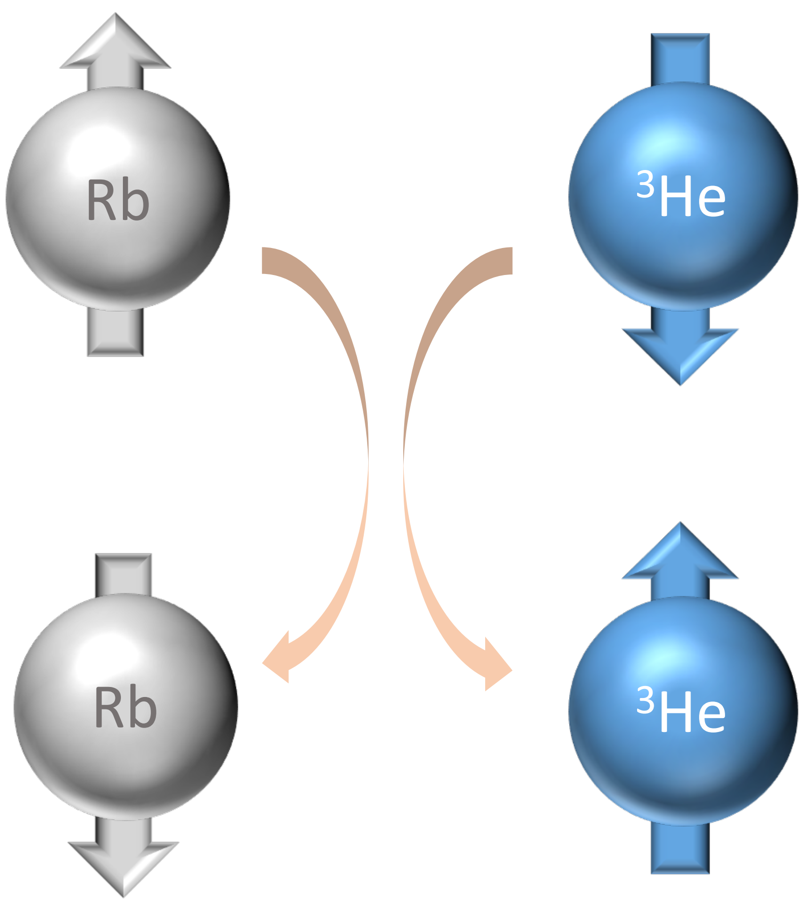
Optical pumping

- Apply magnetic field, energy split between $5S_{1/2}$ & $5P_{1/2}$.
- Use circularly polarized laser with 795nm.
- $5S_{1/2}$ absorbs σ^+ -> excited state.
- Decay back to m_s =+1/2 or m_s=-1/2 equally.
- Finally, electrons end up in m_s=1/2 state



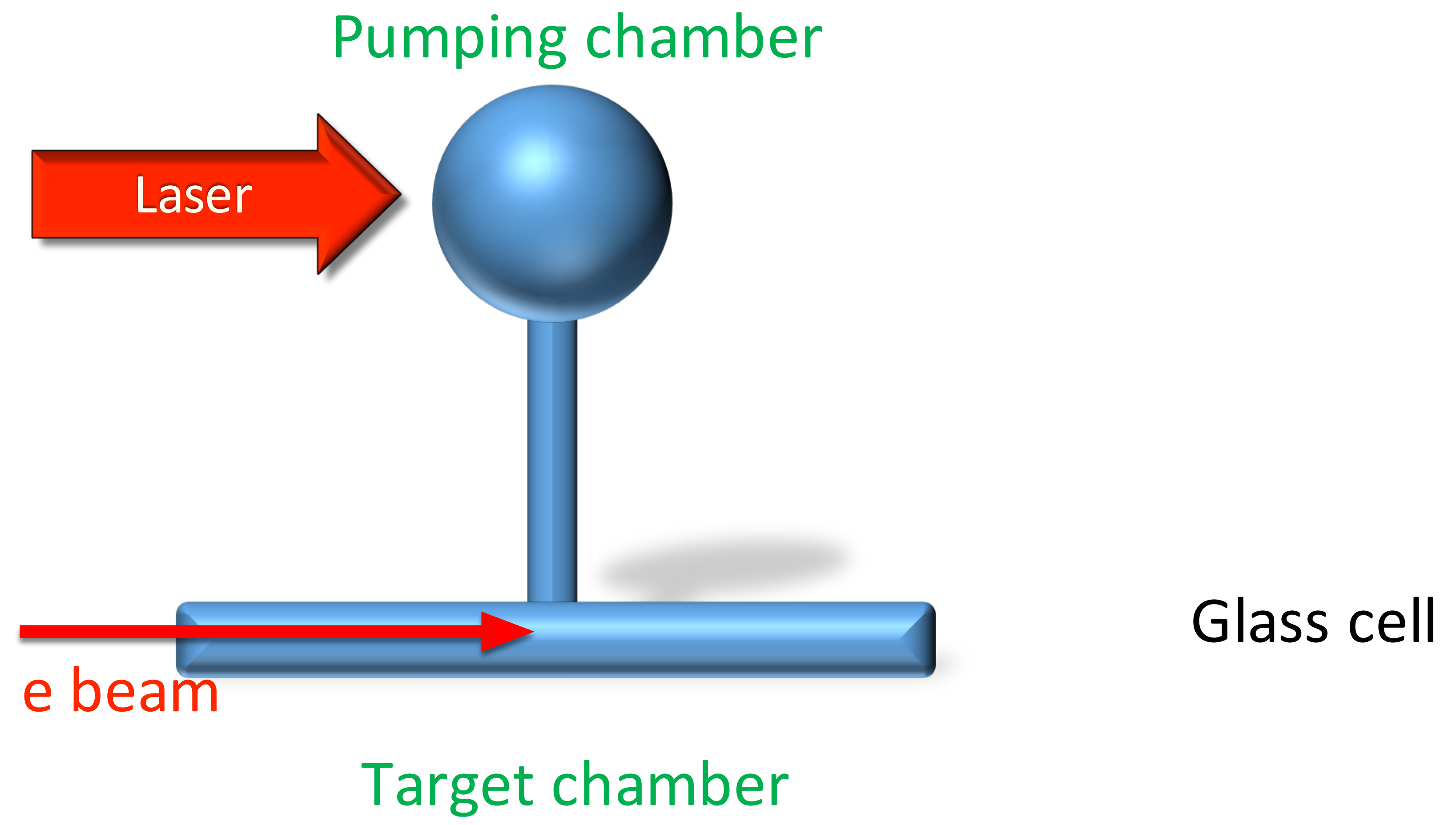
Spin-exchange

- Alkali-^{3}He interact through: hyperfine interaction.



^{3}He is polarized

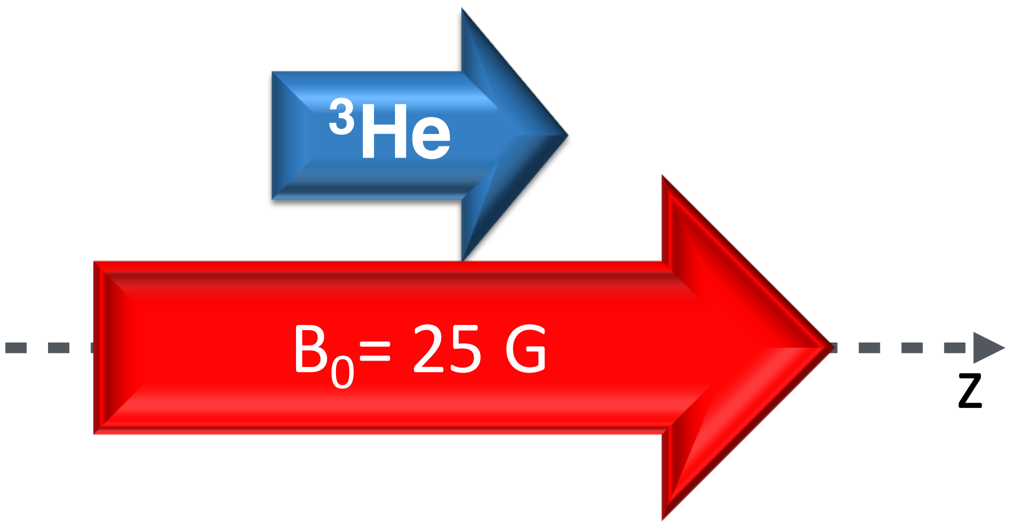
6 GeV target cell



Polarimetry (polarization measurement)

- NMR: nuclear magnetic resonance (relative/absolute).
- EPR: electron paramagnetic resonance (absolute).

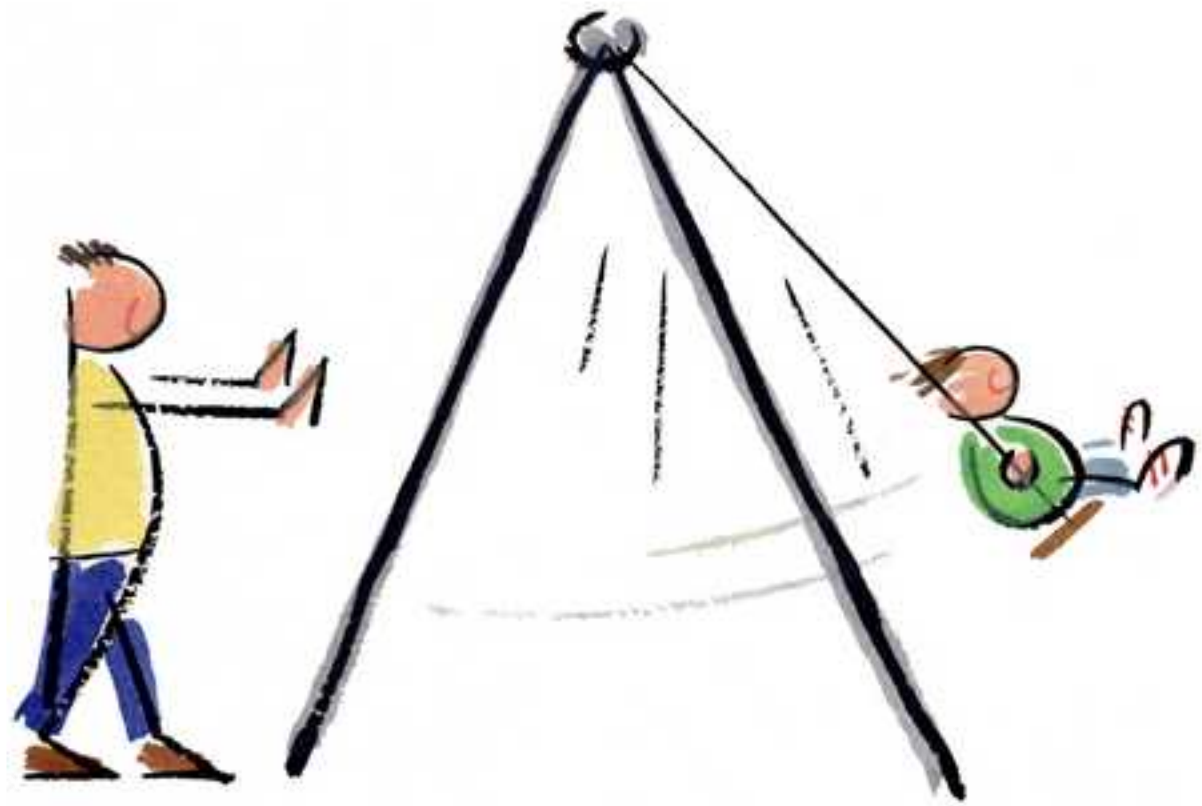
General principle

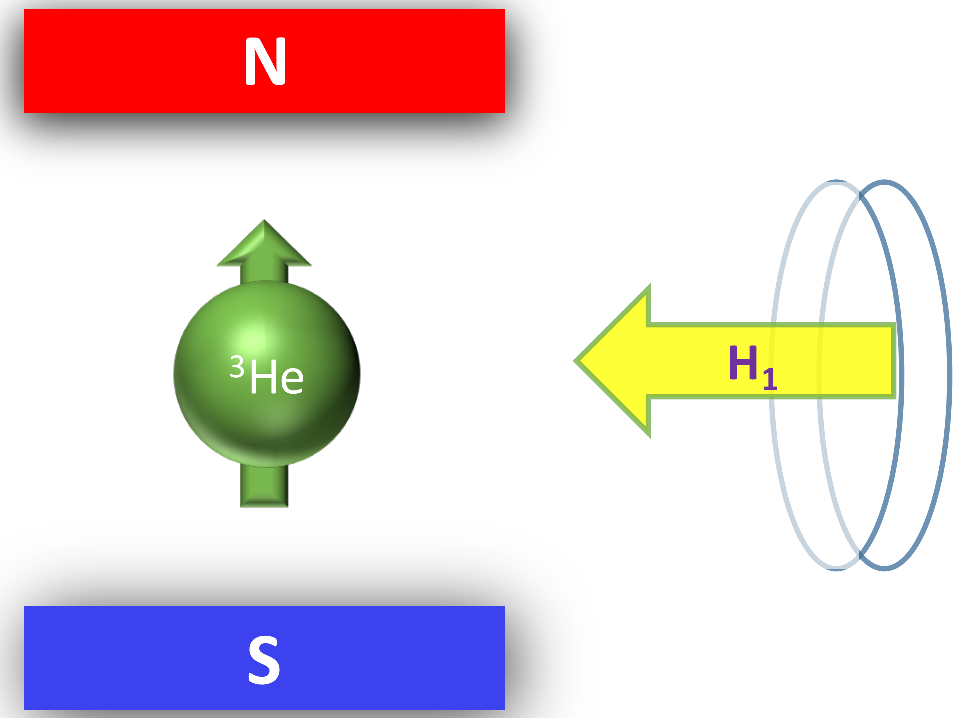


Change to transverse plane (NMR).

Keep along Z-axis but flip (EPR)

NMR (nuclear magnetic resonance)

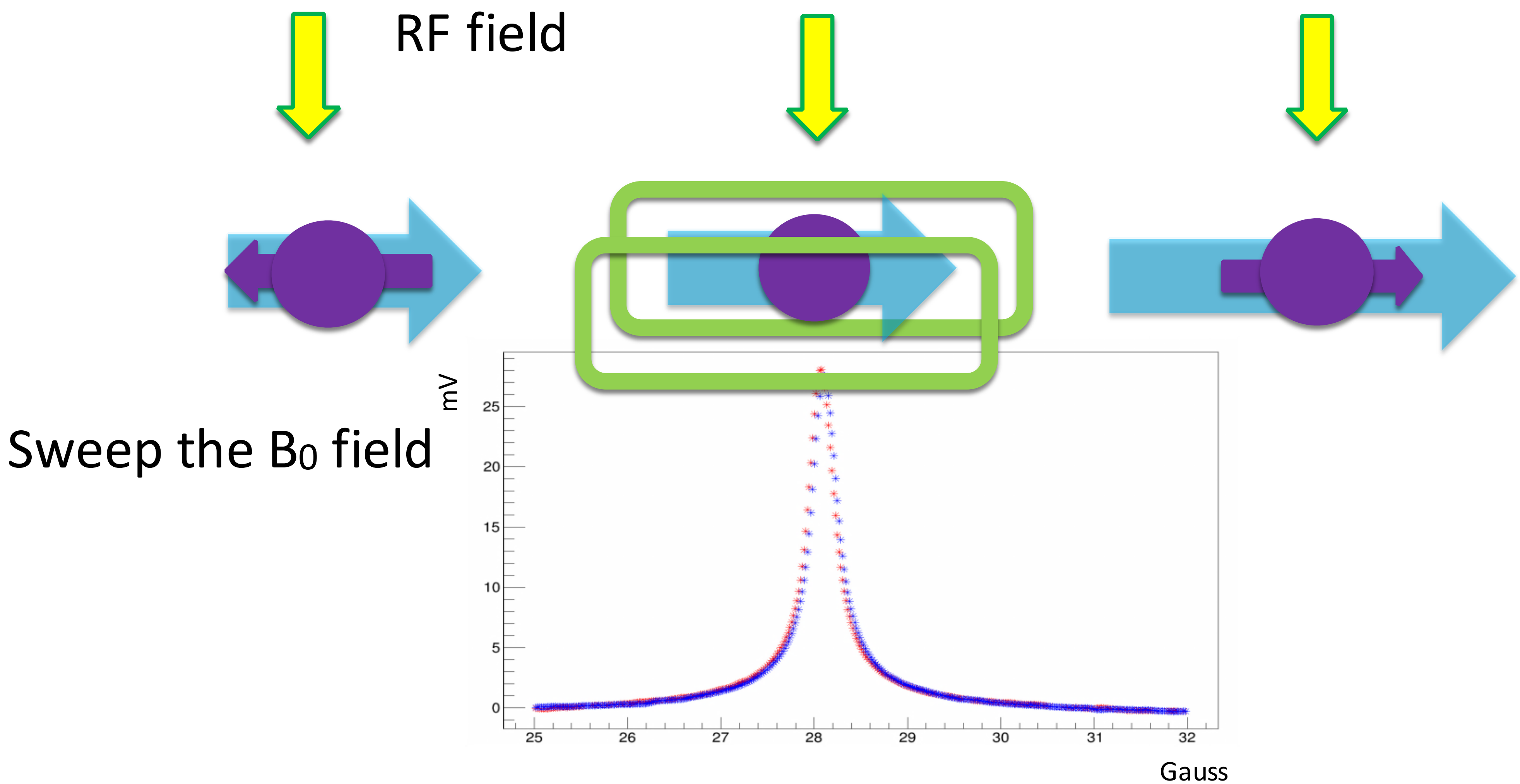




At the right frequency, resonance will happen.
Natural frequency of spin is the Larmor frequency: $\omega = \gamma \cdot B_0$
Where γ is the gyromagnetic magnetic ratio of ^{3}He

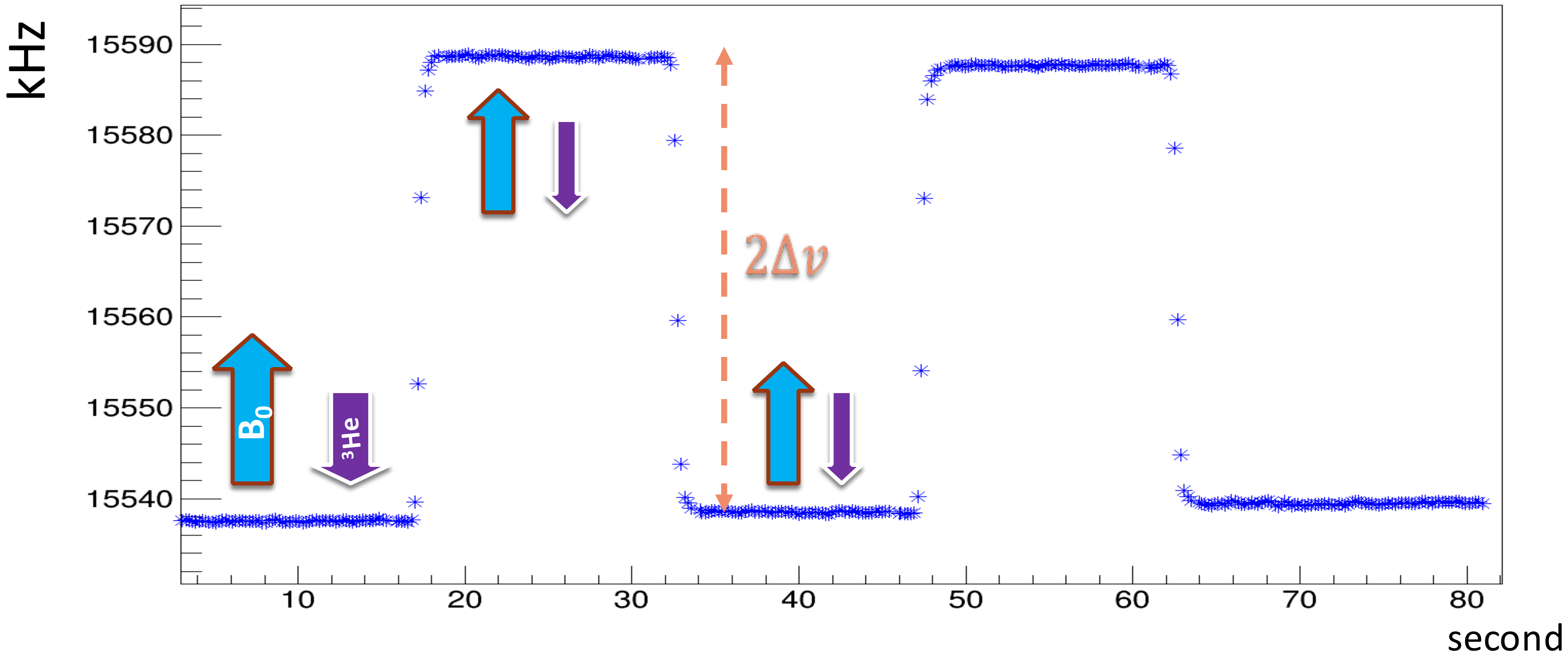
NMR cont.

- AFP(adiabatic fast passage): slow & fast.
- Measure the transverse component of magnetization which induces signal in pair of pick-up coils.
- Relative measurement, need to calibrate with EPR or with known thermal equilibrium polarization of water.



EPR (electron paramagnetic resonance)

- **Principle**: Use Alkali EPR resonance frequency and the shift in frequency due to small contribution from ^{3}He field.

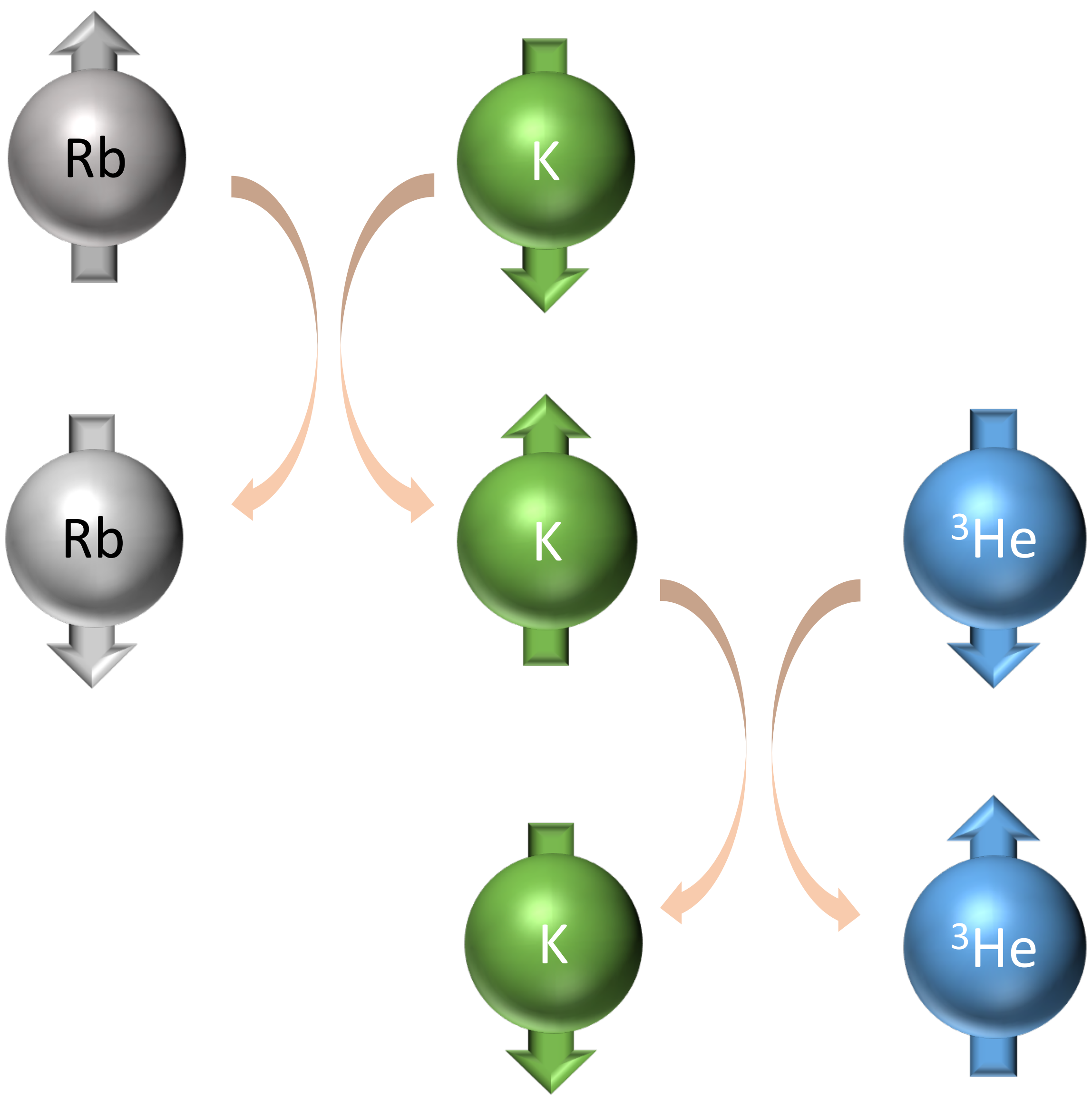


- From frequency difference, ^{3}He polarization is extracted.

6 GeV improvements from target

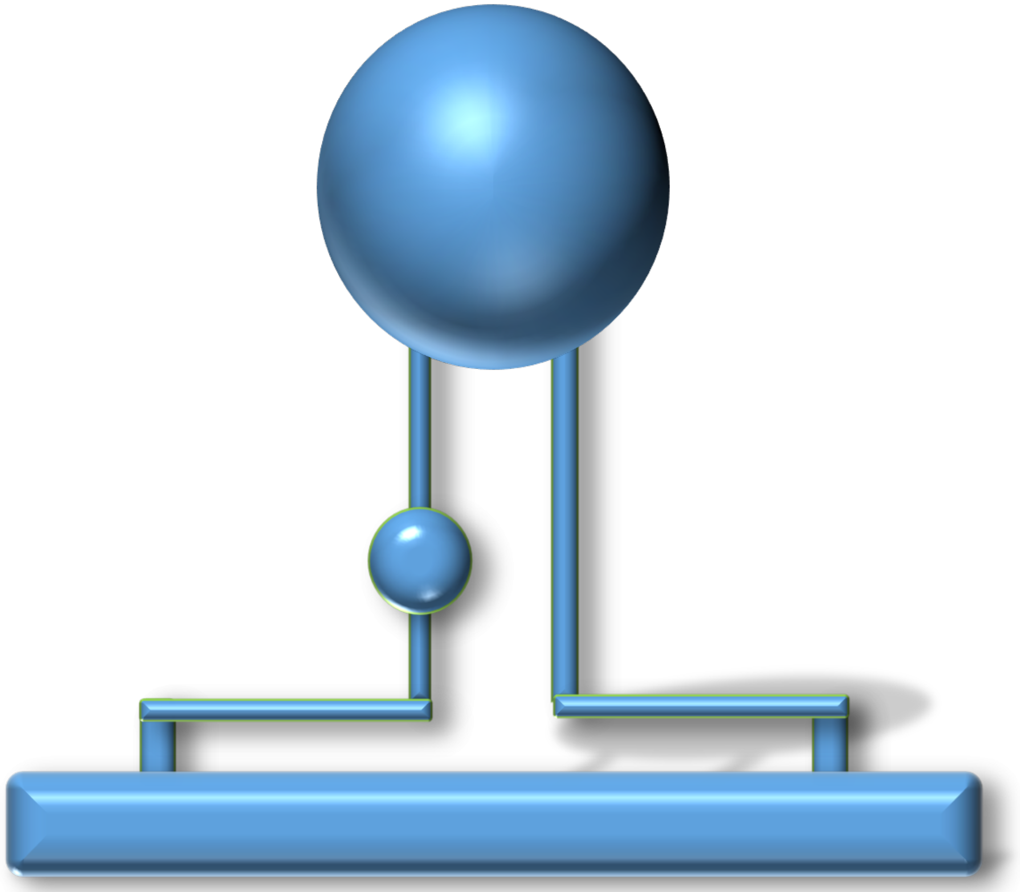
- ❑ Spectrally-narrowed diode laser (FWHM = 0.2 nm), improves absorption efficiency.
- ❑ Hybrid mixture (K-Rb) increases spin-exchange efficiency.

Polarization 42% -> **60%** (in-beam)
70% without beam



Overview of ^{3}He target upgrade plan

- Target will take 30 uA beam current with convection cell.
- 3% systematic uncertainty for polarimetry.
- Using convection cell: decrease polarization gradient.
- Pulse NMR calibrated with EPR/NMR.



Convection cell

Pulse NMR

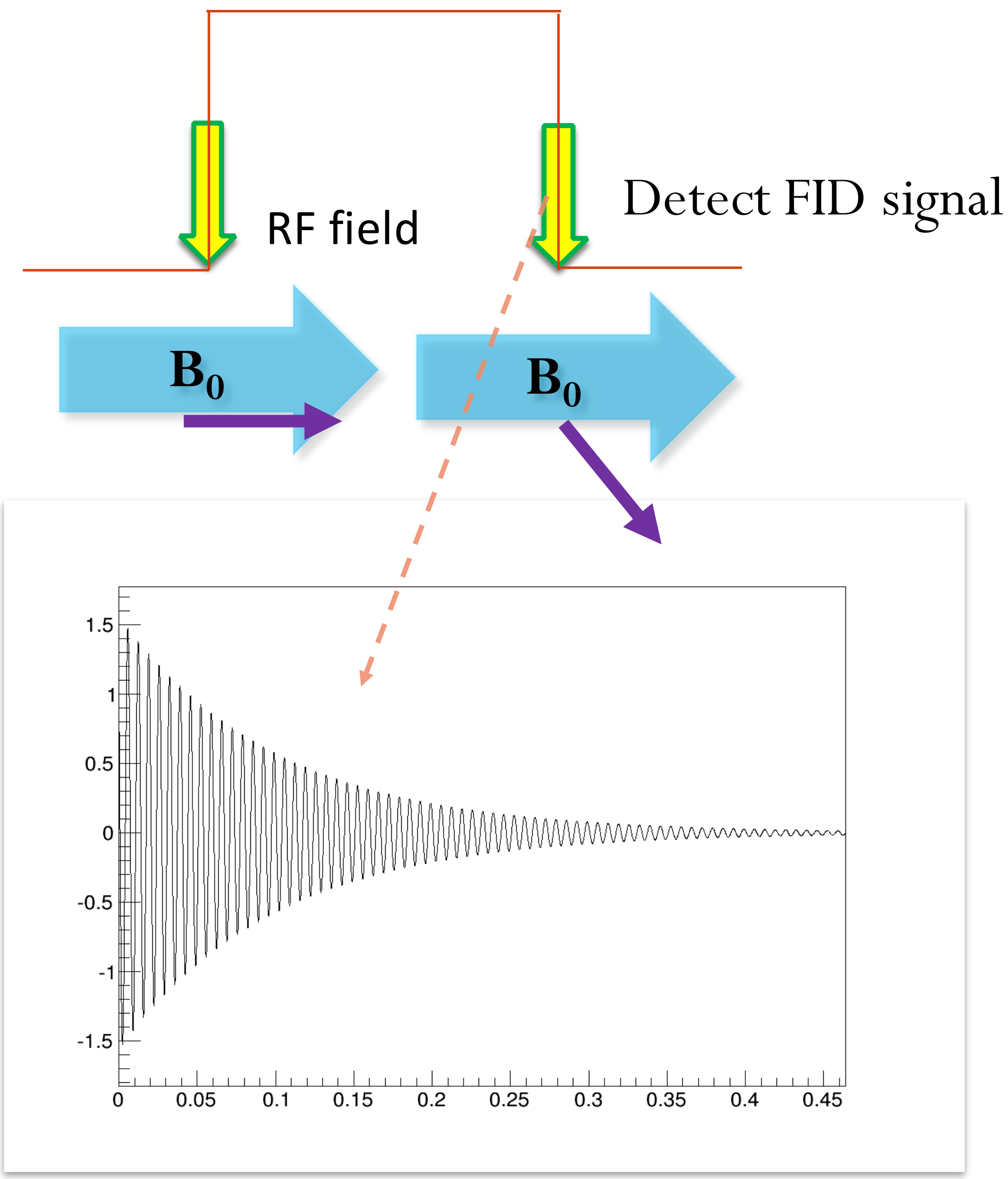
- ❑ **PNMR**: metal windows target chamber, can't send RF field through metal. (end of target chamber).

- ❑ **Principle:**

- ❑ Send a pulse at Larmor frequency (81kHz).

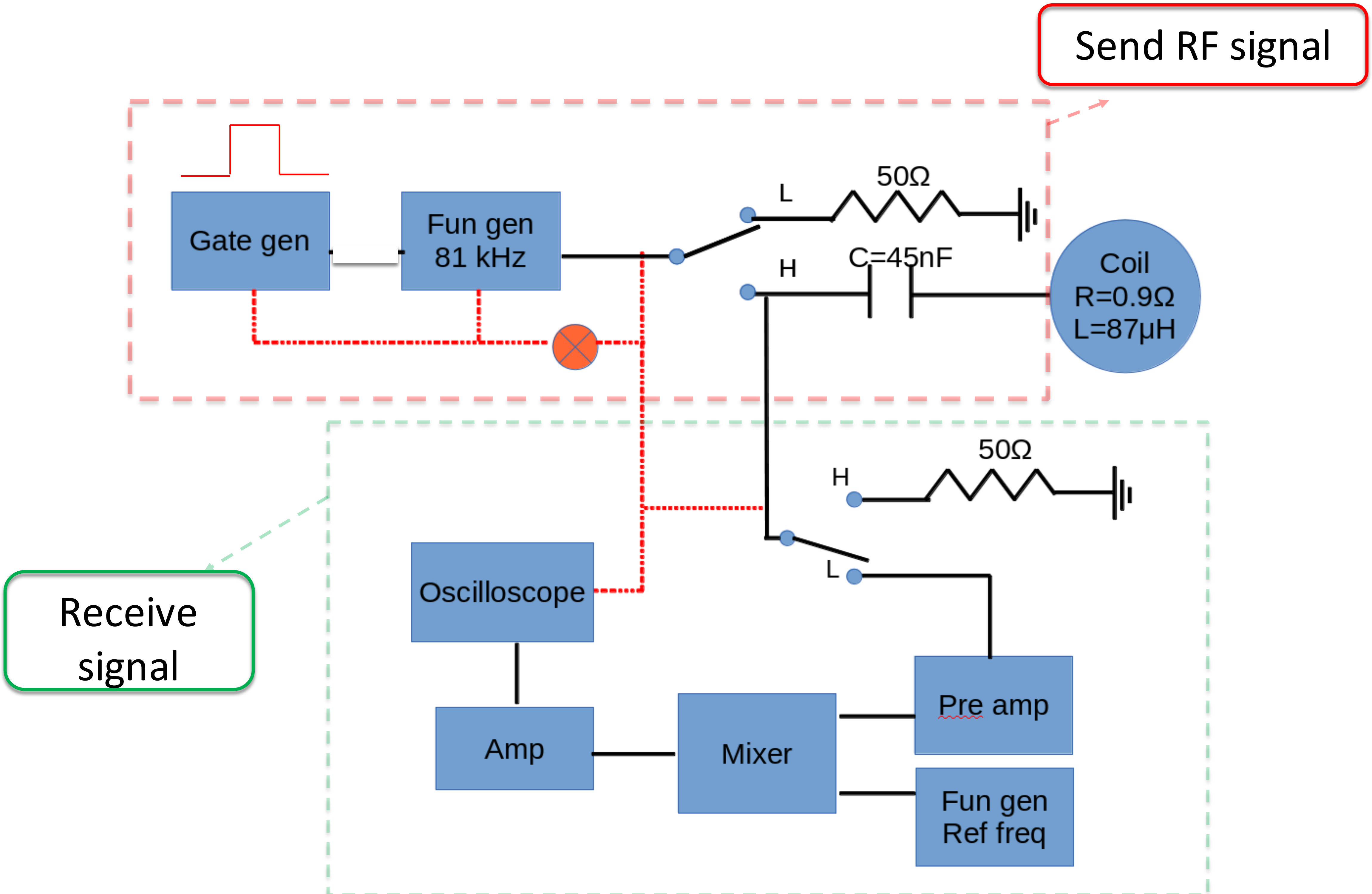
- ❑ ^{3}He spin precesses and tips away from main field.

- ❑ Detect free-induction-decay signal (FID). Measure the transverse component of magnetic moment.



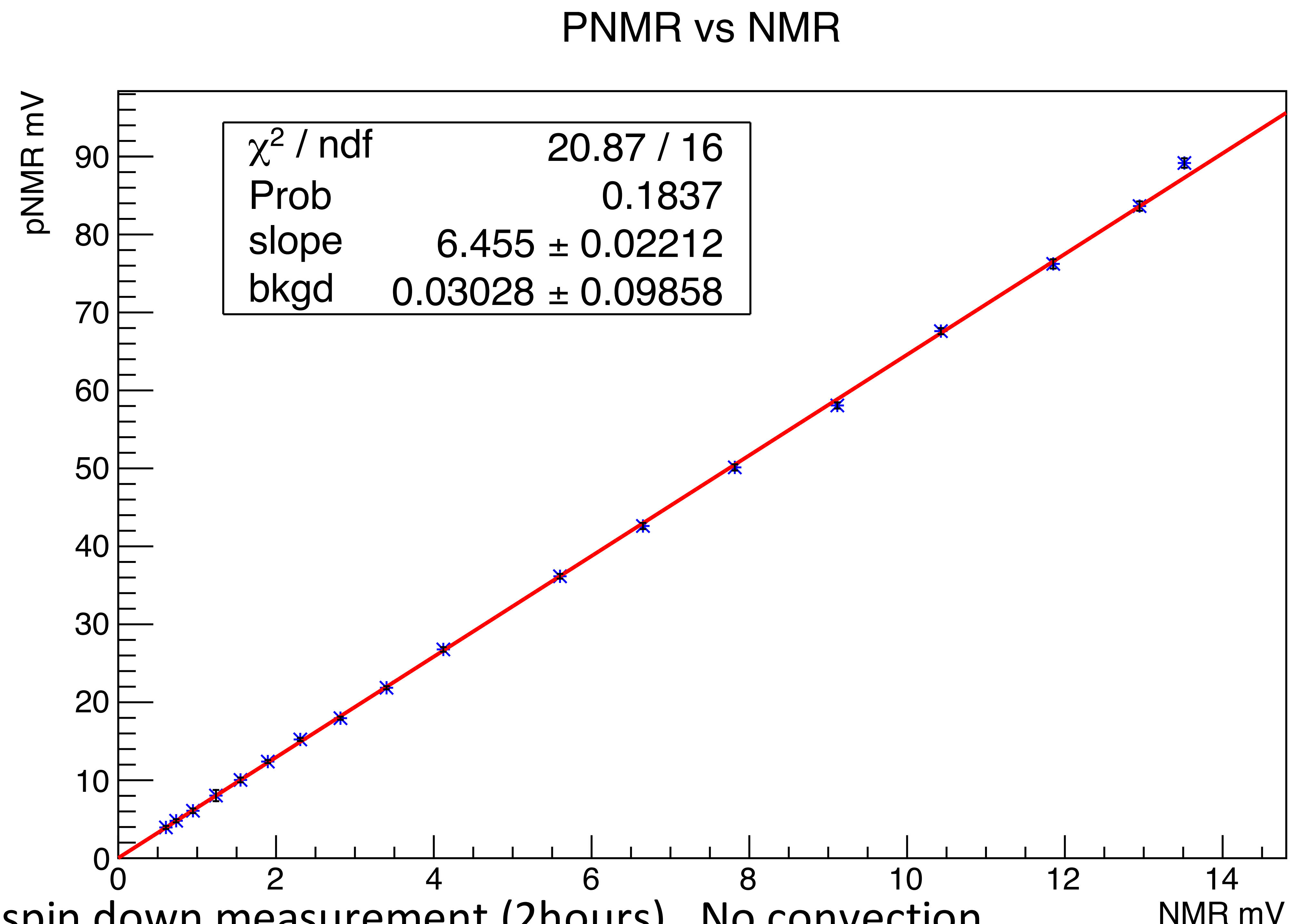
$$S \sim M_z \sin(\theta_{tip})\, e^{-t/T2} \sin(\omega t)$$

PNMR setup



Send RF signal
Gate gen
Fun gen
81 kHz
L
50Ω
H
C=45nF
Coil
R=0.9Ω
L=87μH
50Ω
H
L
Receive
signal
Oscilloscope
Amp
Mixer
Pre amp
Fun gen
Ref freq

PNMR vs NMR in target chamber



Hot spin down measurement (2hours). No convection.

Pulse NMR measure at target chamber.

Pulse NMR works for spin up, hot spin down with and without convection.

People at working on ^{3}He target (at JLab)

- ❑ Supervisor: Jian-ping Chen
- ❑ Student:
- Kai Jin
- Jie Liu
- Nguyen Ton

Next steps

- Get uncertainty at low polarization region and high polarization region.
- Get uncertainty of calibration constant from pNMR vs NMR measurement.
- Aim to reach 1%.
- Then move to do measurement at transfer tube instead of target chamber.
- Characterize new cell, optimize conditions to get high polarization.

Conclusion

❖ Small angle GDH (1st period):

- Done scaler.
- Optics is on going.
- Plans: Finish optics, elastic ^3He, inelastic N_2, ^3He.

❖ Polarized target:

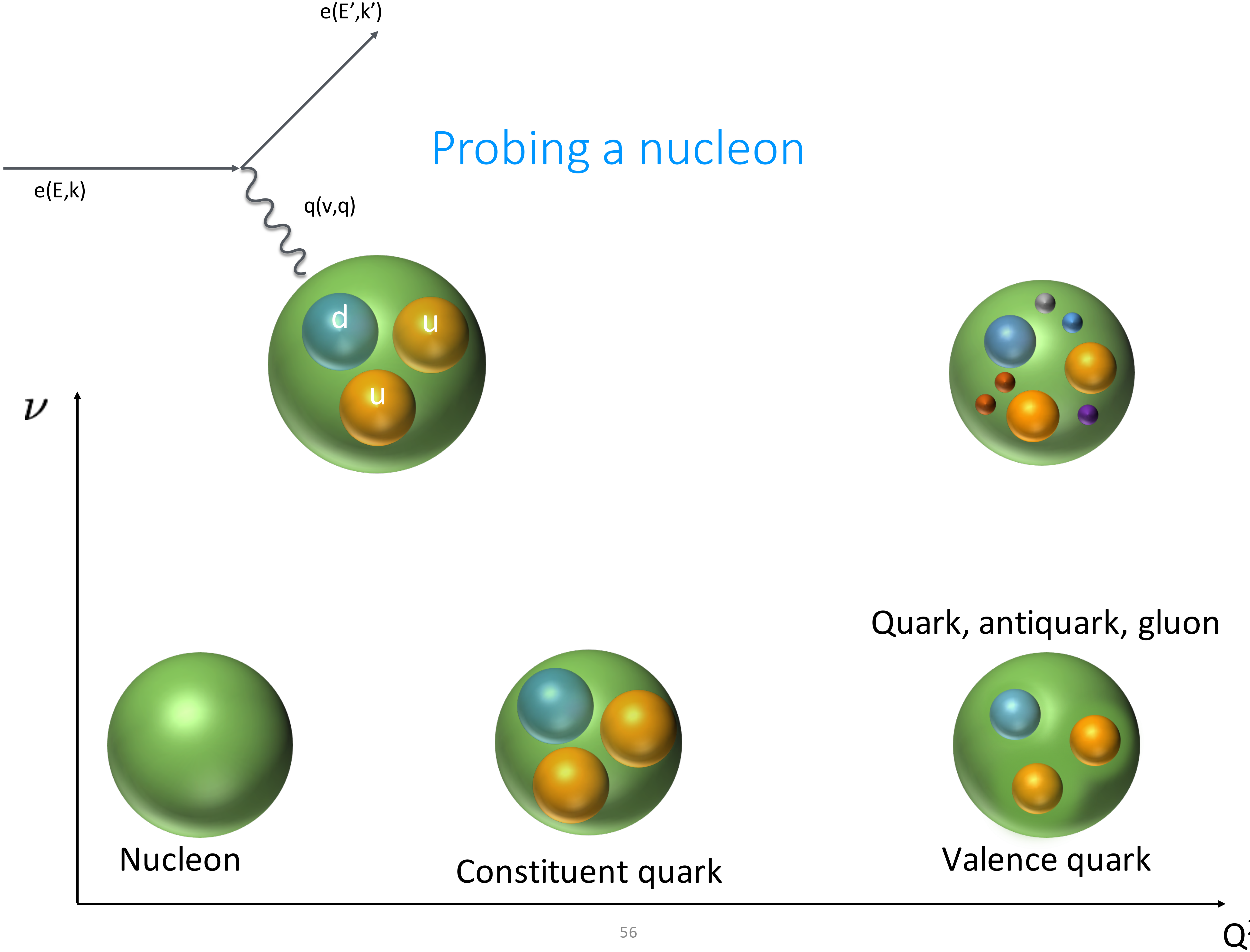
- Finish pulse NMR test and get uncertainty.
- Characterize new cell, optimize conditions to get high polarization.

Thanks to:

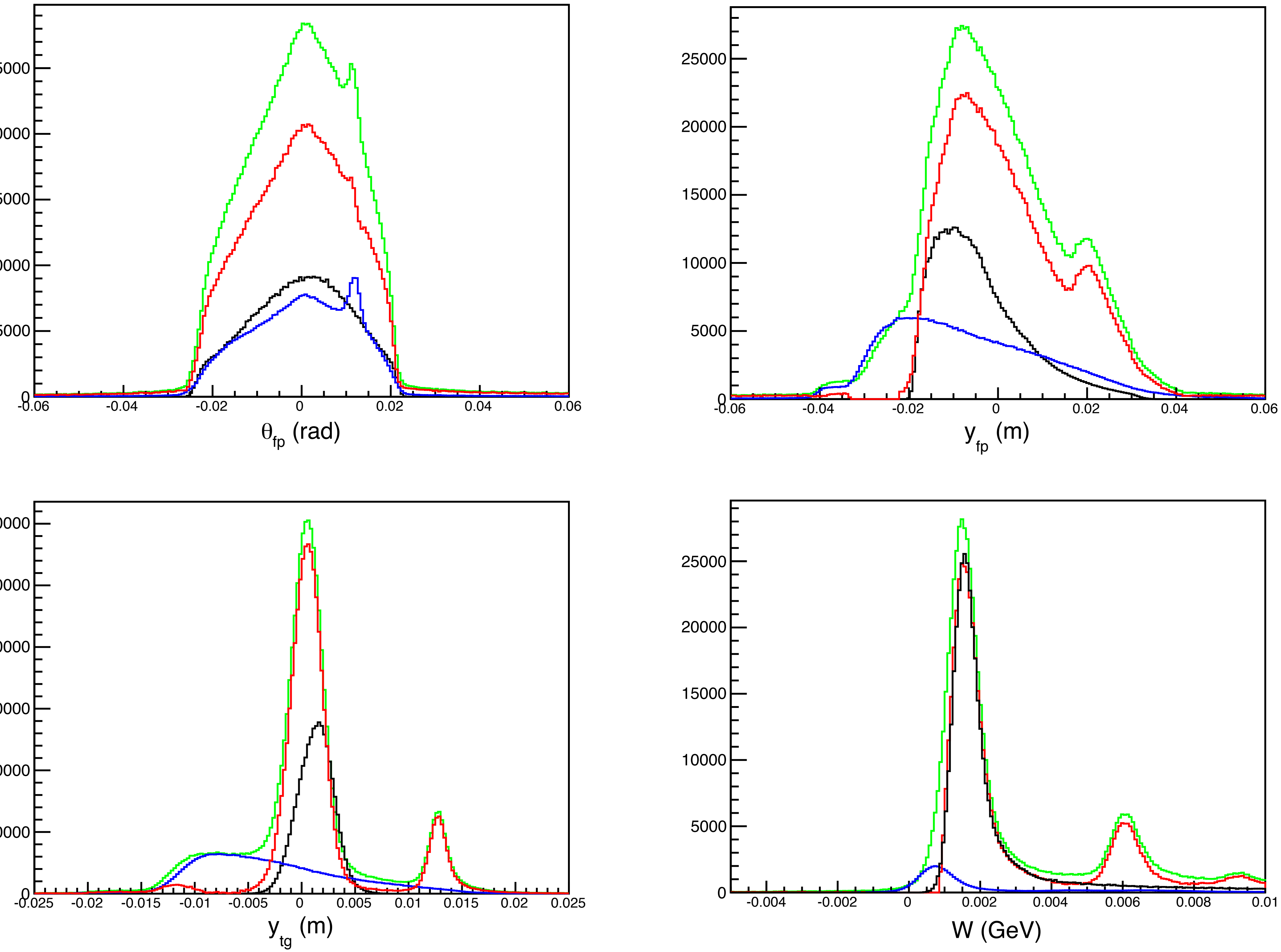
- People at Jlab: Jian-ping Chen, Alexandre Deur.
- People at Uva: Xiaochao Zheng, Vincent Sulkosky, Jie Liu

Thank you all for coming and listening

Probing a nucleon



1D plot for target and focal plane quantities for 2nd period



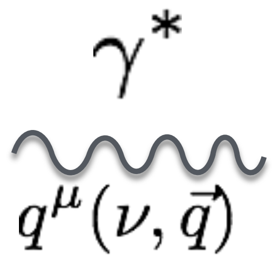
Result for downstream foil

Downstream foil, δp=0%	Standard method	Focal plane method
σ_{sim} (ub)	28.70	18.88
σ_{data} (ub)	24.38	15.63
% data & sim	15	17

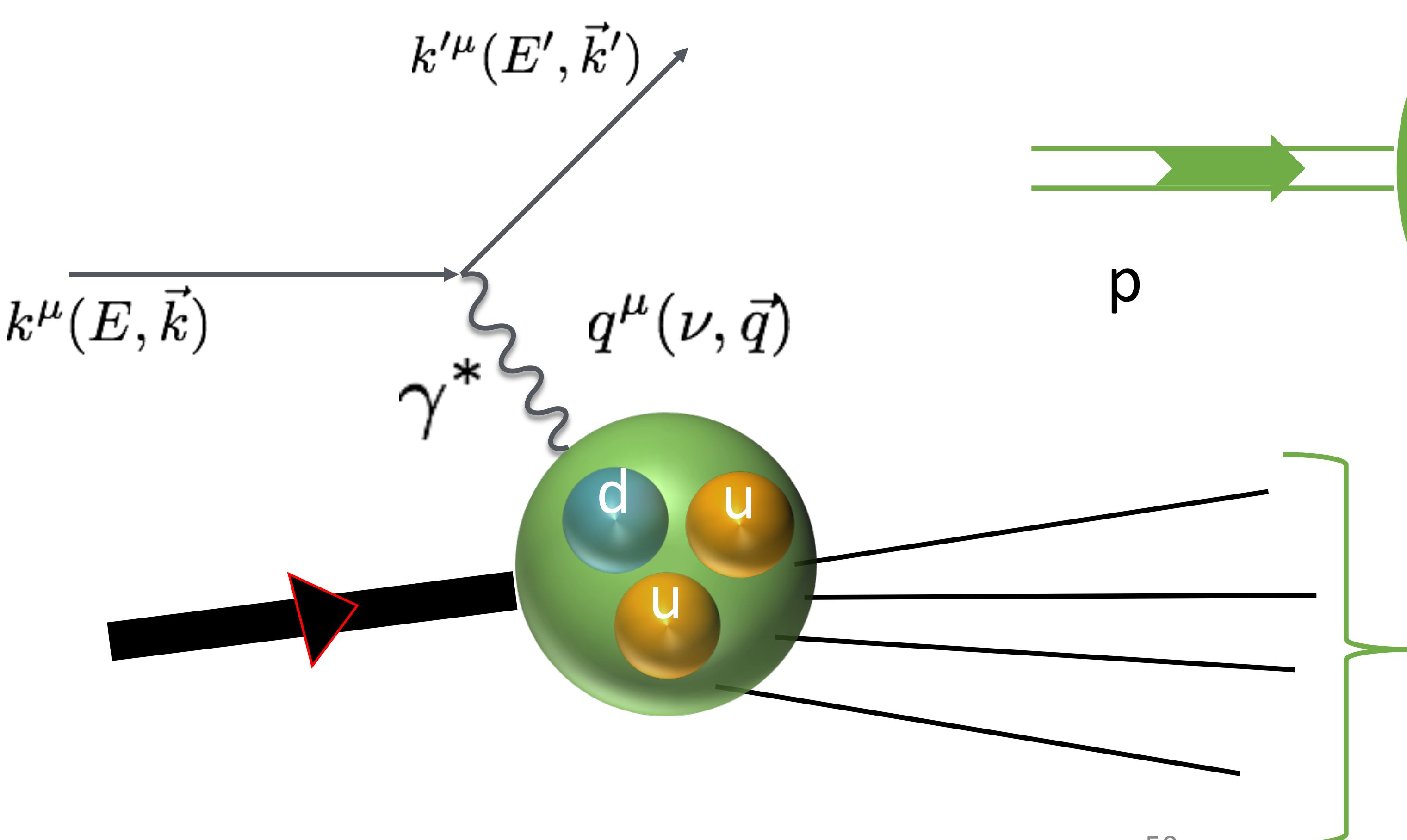
Reason:

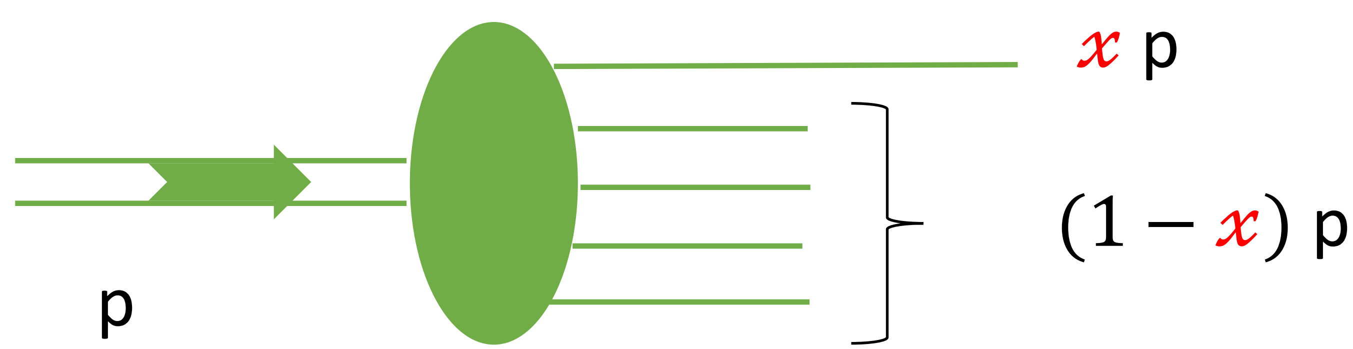
- Falling edge of acceptance.
- Focal plane method works well in this area too. But due to cut was not the same between 2 methods, it created the difference between 2 methods.

Kinematic variables



- 4-momentum: $q^2=-Q^2$ → how hard
- Virtual photon energy: $\nu = E - E'$
- In Bjorken limit $Q^2, \nu \to \infty$: $x = \frac{Q^2}{2M\nu}$ finite





Final state invariant mass

$$W^2 = M_T^2 + 2M_T\nu - Q^2$$

Relation between electro-production cross section and structure functions

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma[\sigma_T + \epsilon\sigma_L - hP_x\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT} - hP_z\sqrt{1-\epsilon^2}\sigma_{TT}]$$

$$\sigma_T = \frac{4\pi^2\alpha}{MK}F_1$$

$$\sigma_L = \frac{4\pi^2\alpha}{K}[\frac{F_2}{\nu}(1+\gamma^2) - \frac{F_1}{M}]$$

$$\sigma_{LT} = \frac{4\pi^2\alpha}{MK}\gamma(g_1 + g_2)$$

$$\sigma_{TT} = \frac{4\pi^2\alpha}{MK}(g_1 - \gamma^2 g_2)$$

AFP loss and lifetime for protovec-1

AFP loss	Pumping chamber(%)	Target chamber(%)
Cool without convection	1.18	0.21
Hot without convection	0.95	0.37
Hot with convection	1.43	1.44

Lifetime	Pumping chamber(hr)	Target chamber(hr)
Cool without convection	26.57	23.11
Hot without convection	13.49	15.97
Hot with convection	14.56	14.54