National Science Foundation

Deuteron Disintegration at Large Missing Momenta

C. Yero

Science at the Luminosity Frontier: Jefferson Lab 22 GeV Workshop

January 23 - 25, 2023

FIU

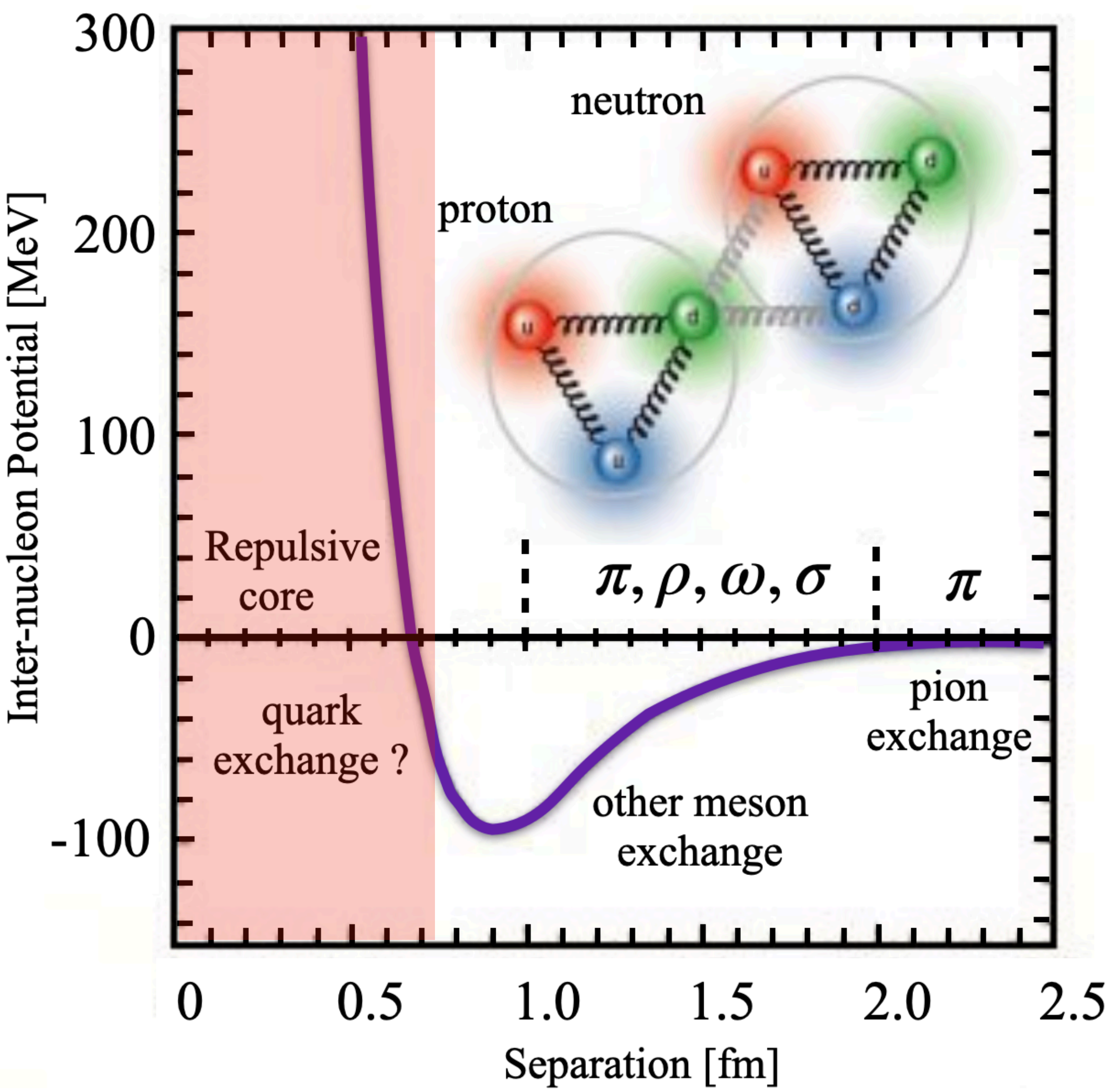
Jefferson Lab
Exploring the Nature of Matter

Old Dominion University

Motivation

- How does the nuclear force work?
- What is the structure of nuclear matter?

- Short-range part of NN interaction is NOT well understood ! ! !
  - difficult to generate NN potentials at high nucleon momentum / short distance
  - difficult to calculate heavy nuclei from NN potentials
  - lack of experimental data on nuclei at high momentum or short distances



d(e, e'p)n break-up at ~ PWIA

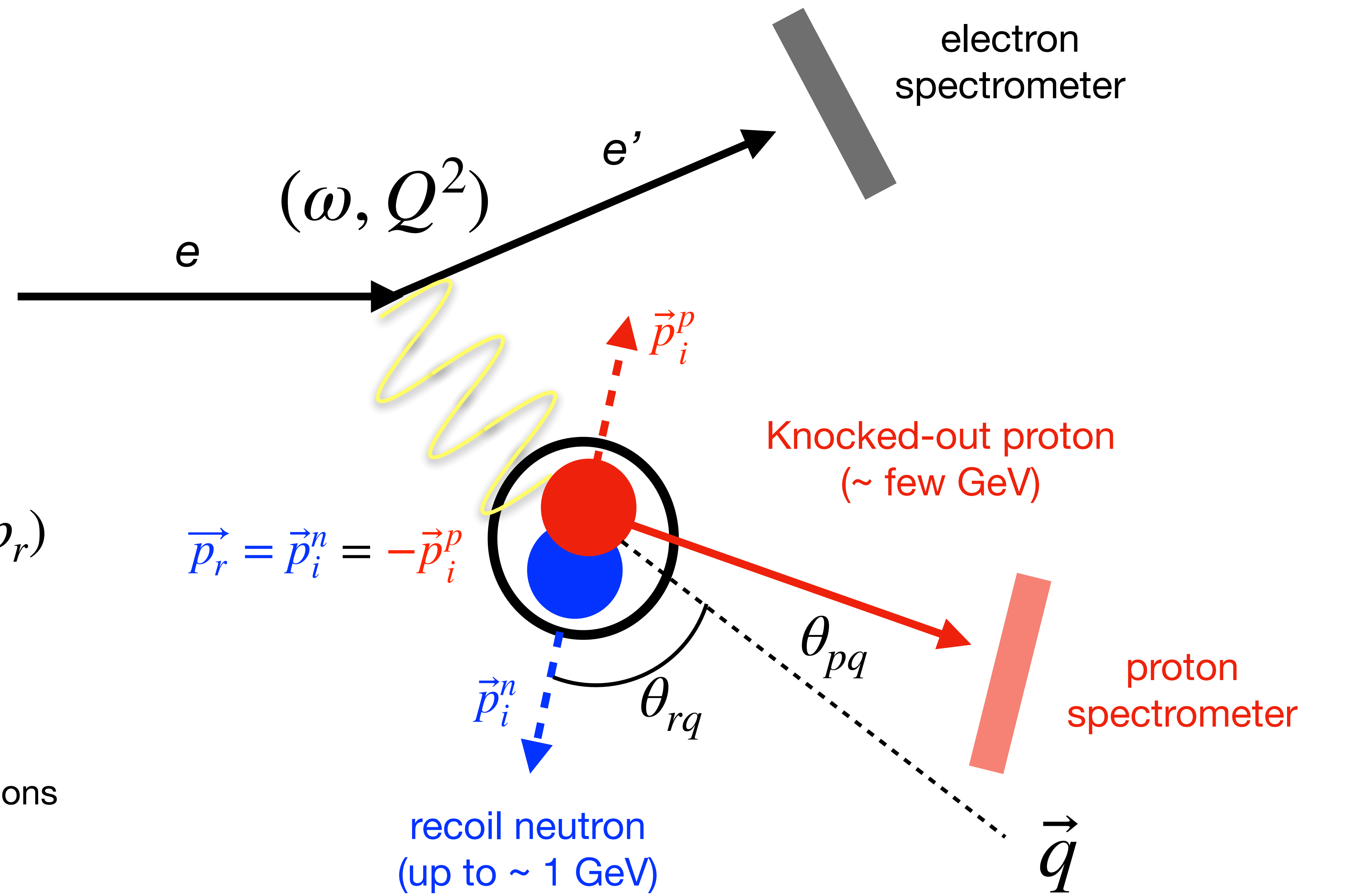
PWIA:

- no re-interaction between ejected nucleons

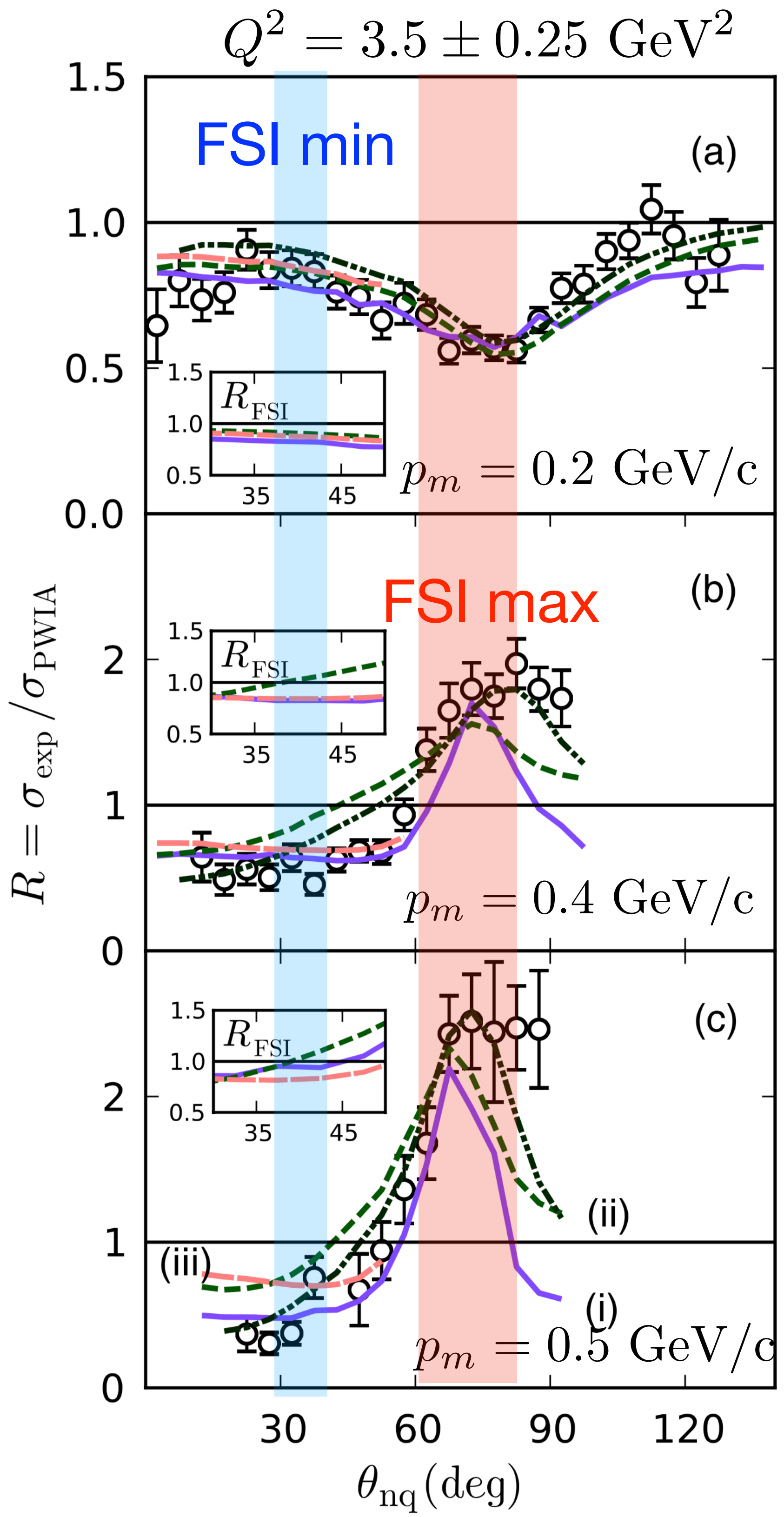
$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = k\sigma_{ep}\rho_m(p_r)$$

Experimental momentum distributions

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{k\sigma_{ep}} \approx \rho_m(p_r)$$



first d(e, e'p)n at high Q^2 (> 1 GeV^2)



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)

DATA

FSI strongly anisotropic (angular-dependent):

- Sargsian uses GEA, Laget uses fully relativistic
- FSI peak at $\theta_{nq} \sim 70°$
- minimal FSI at $\theta_{nq} \sim 35 - 45°$

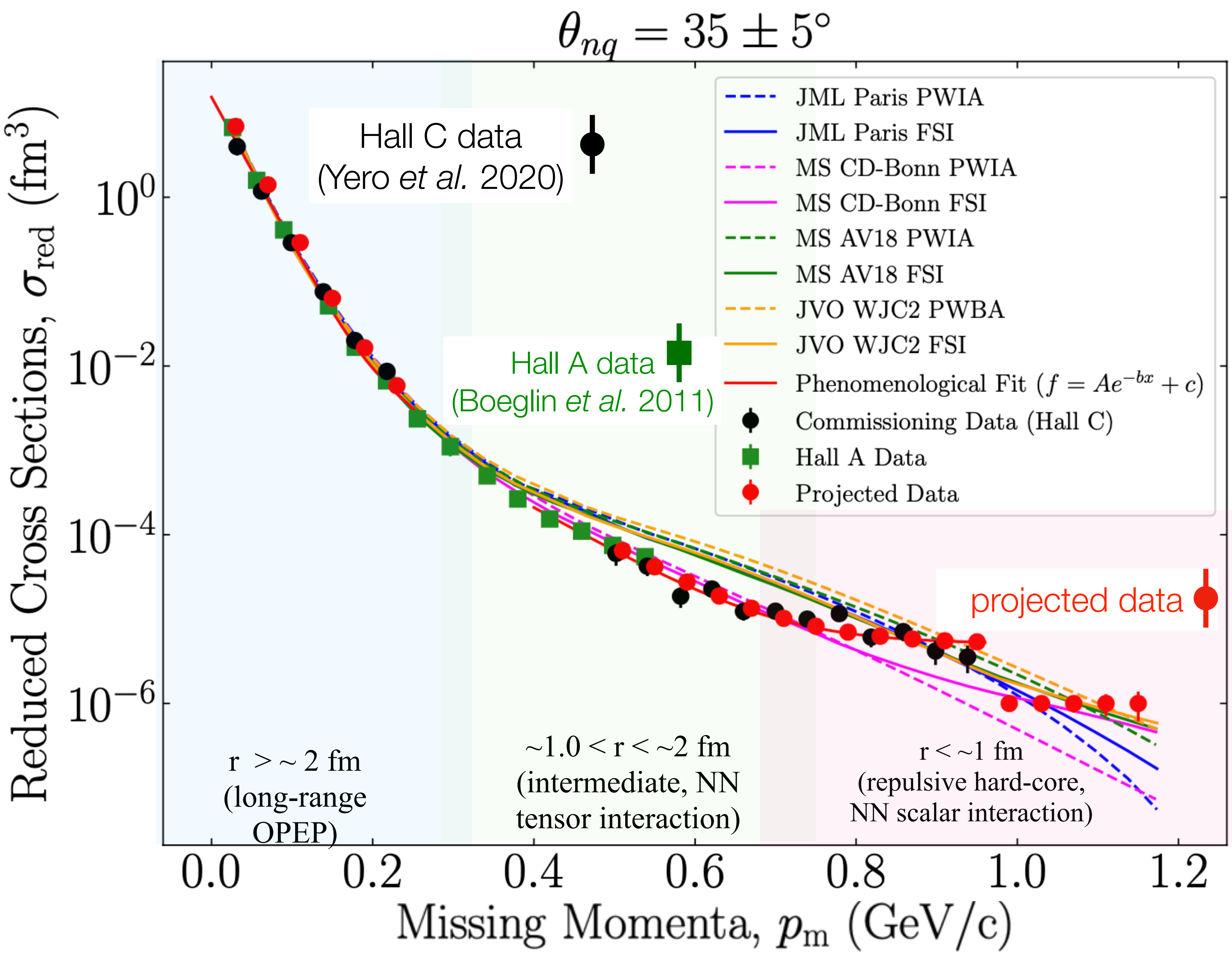
Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)

K. S. Egiyan et al. (CLAS) Phys. Rev. Lett. 98, 262502 (2007)

GEA theory:

L. L. Frankfurt, M. M. Sargsian, and M. I. Strikman Phys.Rev.C561124 (1997)

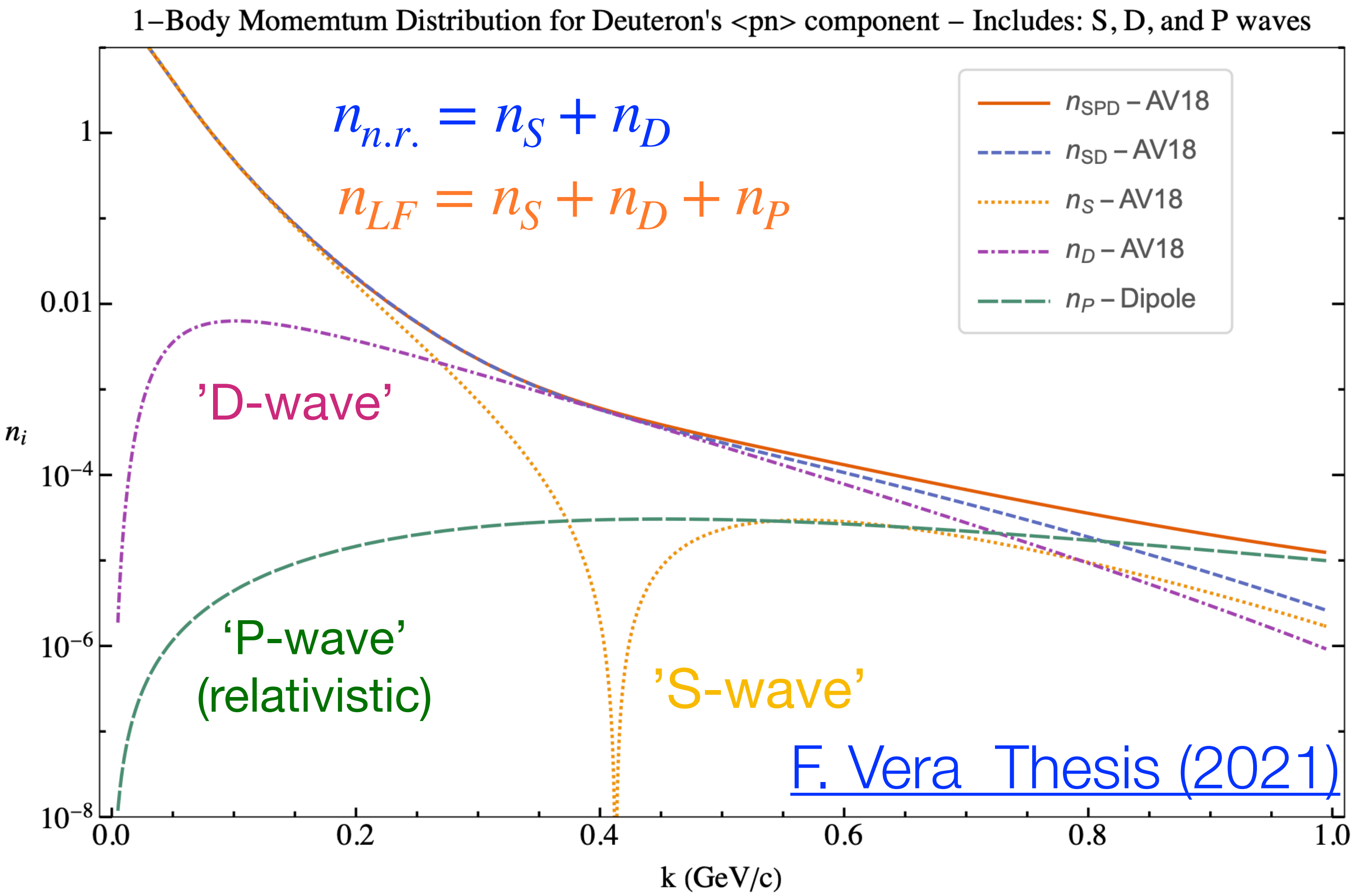
experiment: probing the deuteron *NN* core



- 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)

theory: probing the deuteron *NN* core



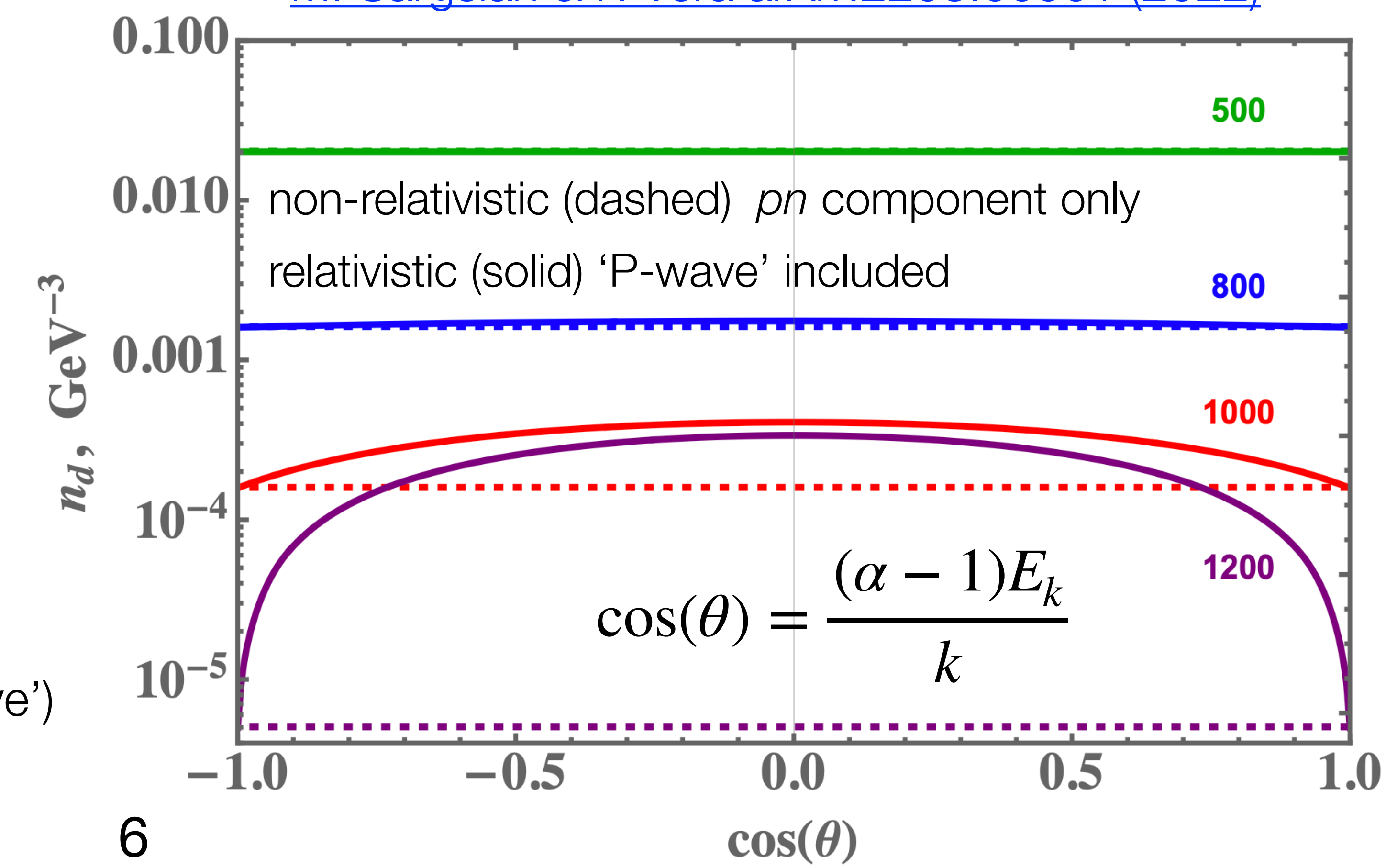
- non-relativistic deuteron w.f. (only S + D wave)
- fully relativistic calculation of deuteron w.f. in the LF give rise to a 'P-wave' -like component
- P-wave starts to dominate at ~ $k \sim 800$ MeV/c
  - angular dependence of momentum distributions (n_d)
  - n_d modified by non-nucleonic components

non-relativistic relativistic (non-nucleonic)

$$\Psi_d = \boxed{\Psi_{pn}} + \boxed{\Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} + \Psi_{NN\pi} \cdots}$$

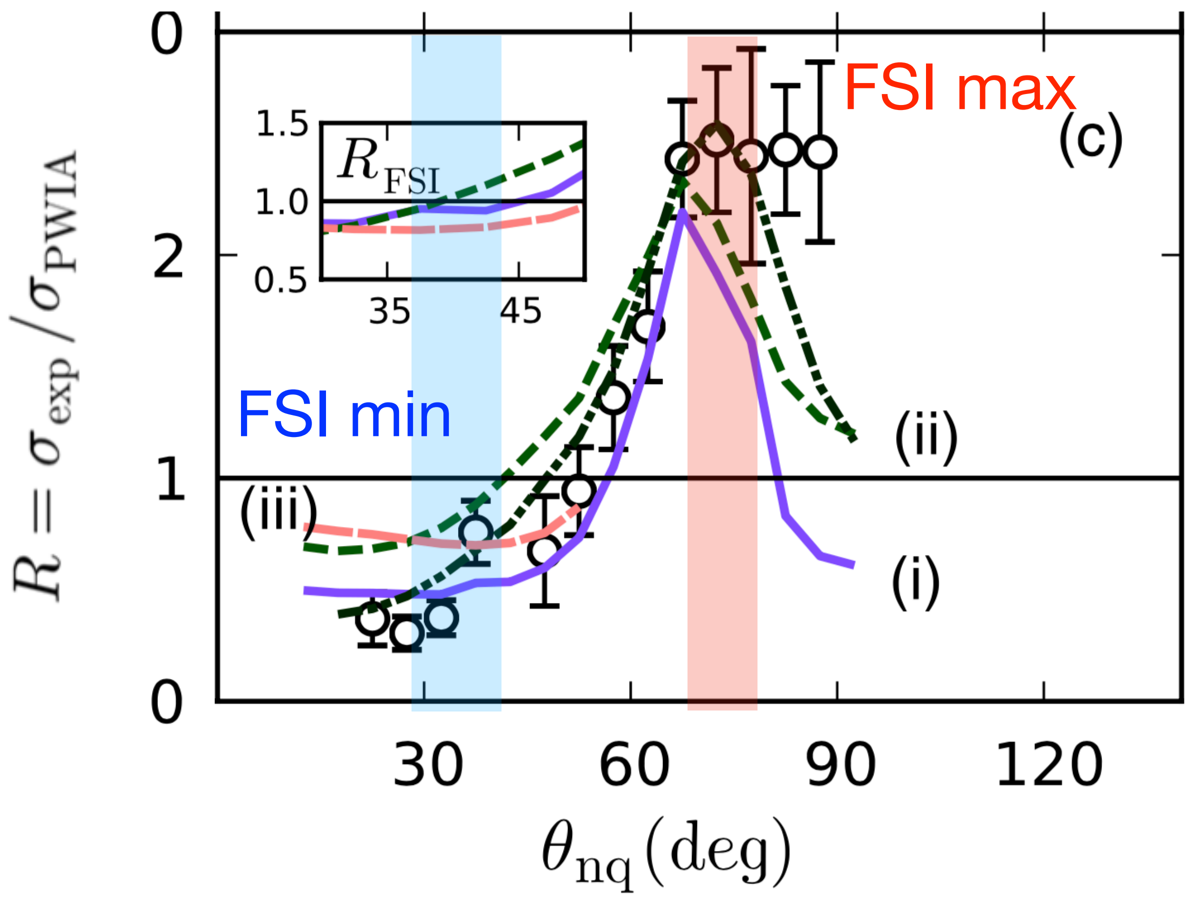
- relativistic deuteron more complex than simple *pn* -> *pn* transition
- possible non-nucleonic transitions (relativistic 'P-wave') $\Delta\Delta \to np,\ NN^* \to np,\ hc \to np, NN\pi \to np$

M. Sargsian & F. Vera arXiv:2208.00501 (2022)



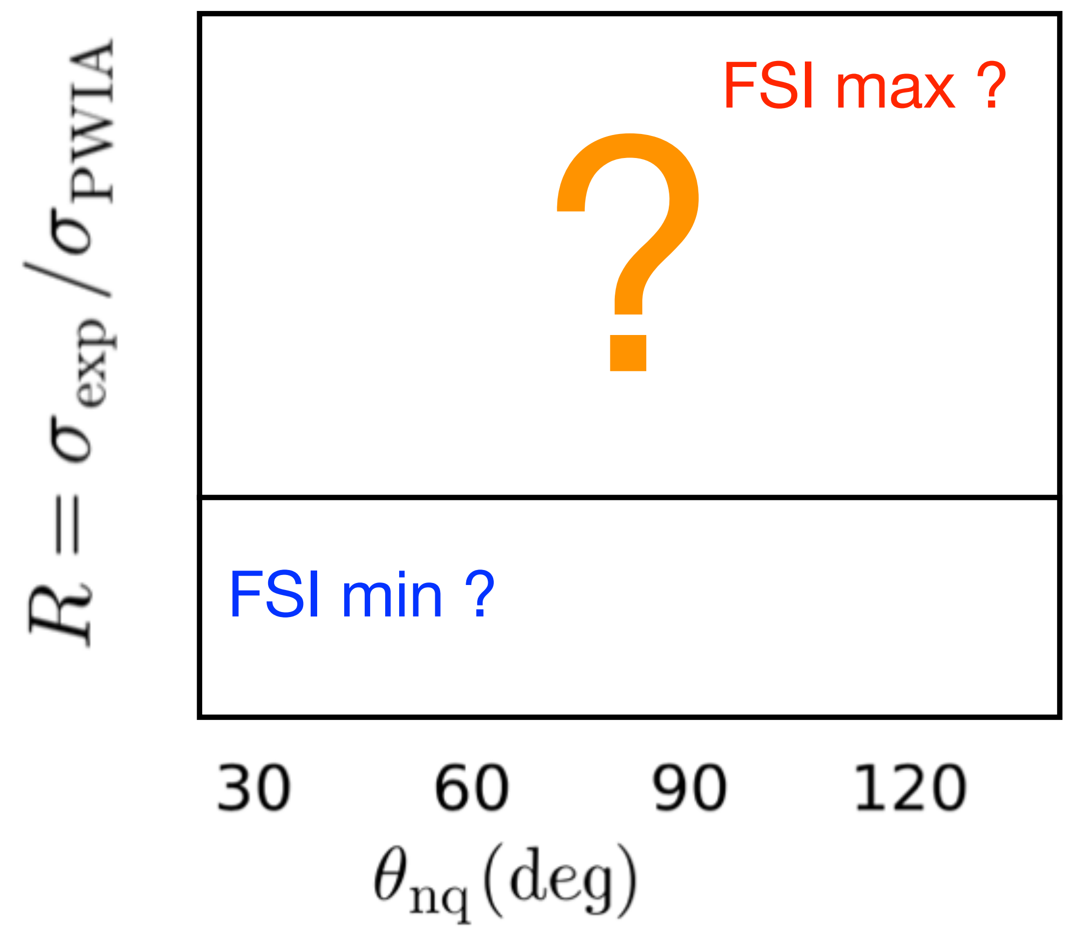
need angular distributions at high Q^2 and $P_m > 500$ MeV/c

$P_m = 500$ MeV/c, $Q^2 = 3.5$ GeV^2



Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)

$P_m > 500$ MeV/c, $Q^2 = 4.5$ GeV^2



- d(e, e'p) measurements are approaching NN core (~ 1 GeV/c) —> Yero *et. al* 2020
  - need for extending angular distribution > 500 MeV/c to demonstrate FSI are still small at $\theta_{rq} \sim 35 - 45$ deg,

- we explore the possibilities of taking advantage of a beam energy upgrade (22 GeV) for these measurements (2nd part of this talk, remaining slides)

Optimizing d(e, e'p) Kinematics (in a future 22 GeV upgrade)

1) How high in beam energy can we go while keeping Q^2 fixed?
   —> Does it really work out ?

2) Consider e- arm spectrometer upgrade (up to ~ 20.5 GeV/c)
   —> with upgrade, kinematics can reach $E_b = 22$ GeV while keeping $Q^2 = 4.5$ GeV^2

3) Consider luminosity upgrade (double the beam current 80 -> 160 uA)
   —> used baseline kinematics ($E_b = 11$ GeV, $Q^2 = 4.5$ GeV^2) to estimate increase in rates

Simulation Reaction: d(e,e'p), electrons: SHMS, protons: HMS

Fixed Parameters: 80 uA, 1 hour, 20 cm-long deuterium target,
Model: AV18 FSI (SIMC)

Angular Settings: (θ_{rq} ~27, ~49, ~65) deg at fixed $Q^2 = 4.5,\ P_m = 1 \pm 0.02$ GeV/c
(3 settings provide wide angular coverage for FSI studies)

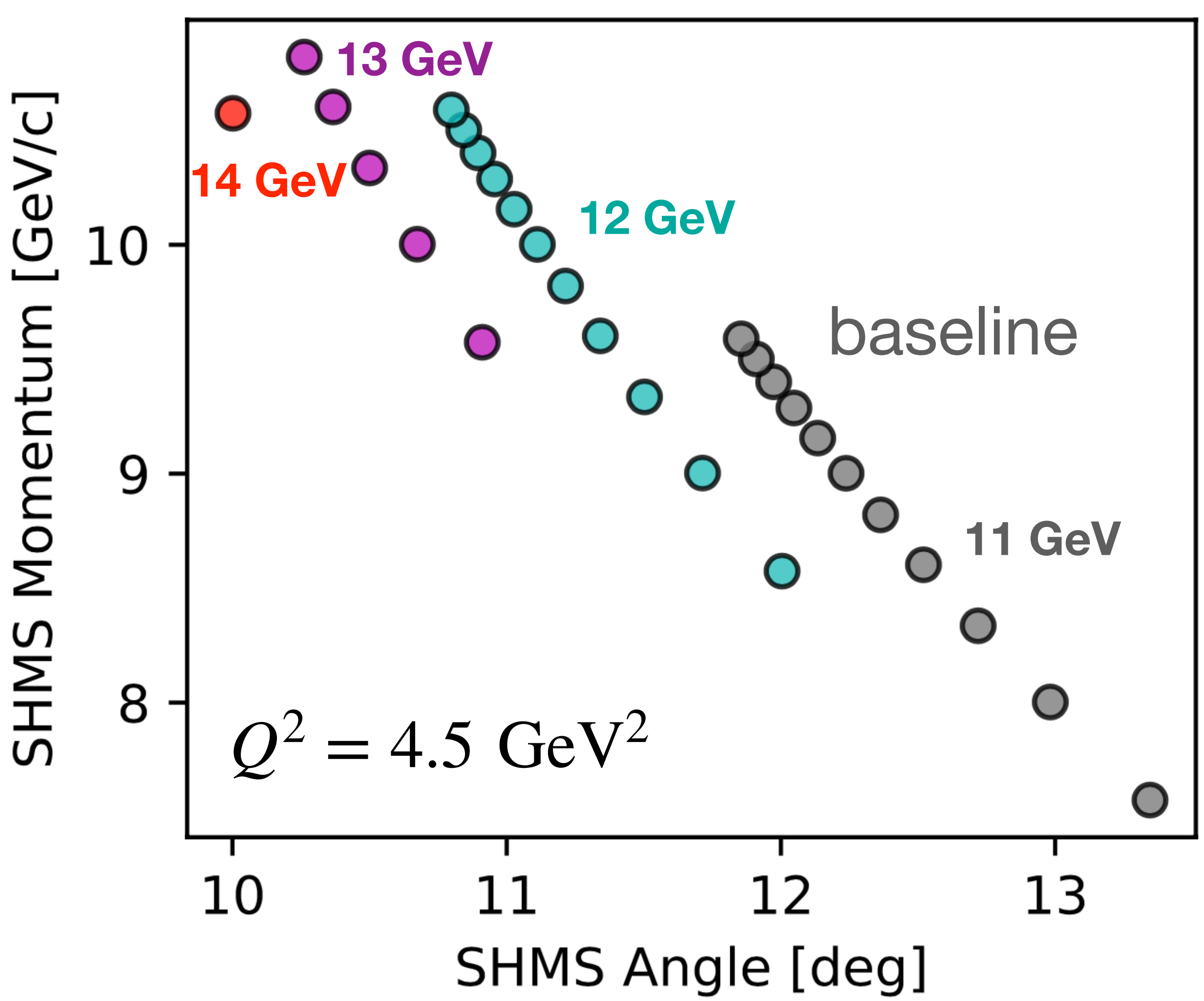
Baseline Kinematics

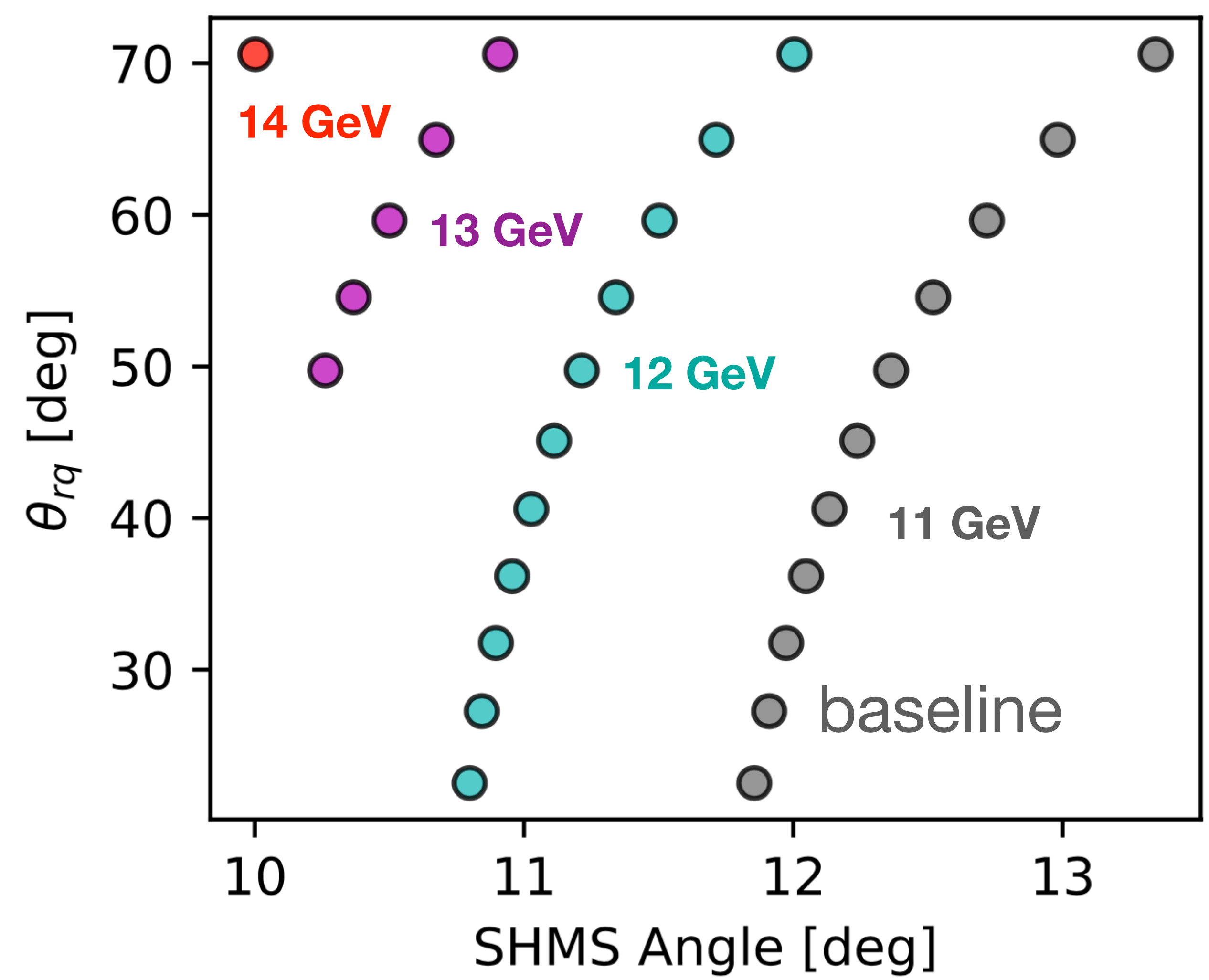
Baseline

- use existing spectrometer + no beam energy upgrade

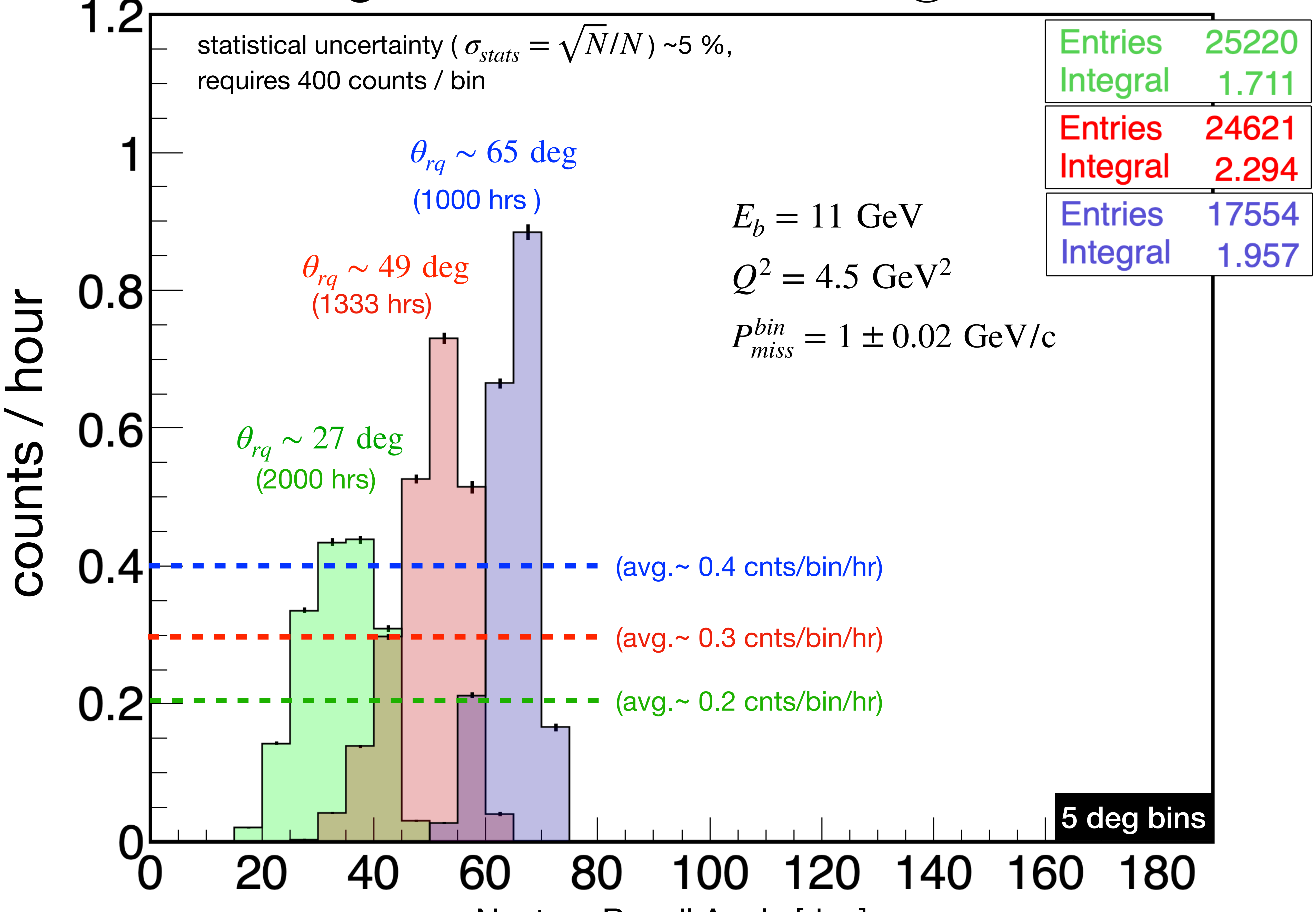
Energy Upgrade

- full angular coverage up to 12 GeV
  (limited by spectrometer momentum)

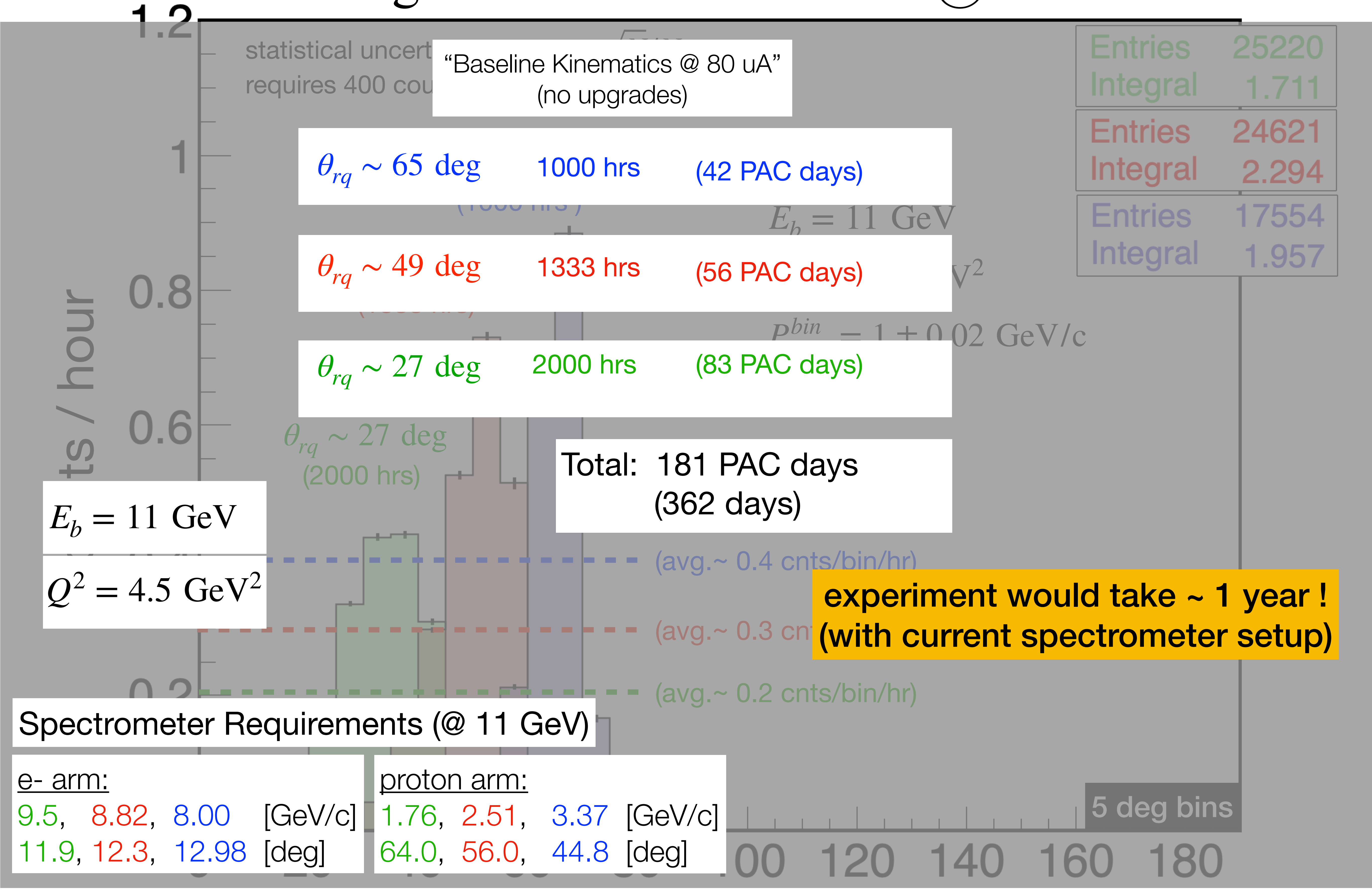




Angular Distribution Rates @ 80 uA



Angular Distribution Rates @ 80 uA



"Baseline Kinematics @ 80 uA"
(no upgrades)

$\theta_{rq} \sim 65$ deg	1000 hrs	(42 PAC days)
$\theta_{rq} \sim 49$ deg	1333 hrs	(56 PAC days)
$\theta_{rq} \sim 27$ deg	2000 hrs	(83 PAC days)

Total: 181 PAC days
(362 days)

$E_b = 11$ GeV

$Q^2 = 4.5$ GeV^2

experiment would take ~ 1 year !
(with current spectrometer setup)

Spectrometer Requirements (@ 11 GeV)

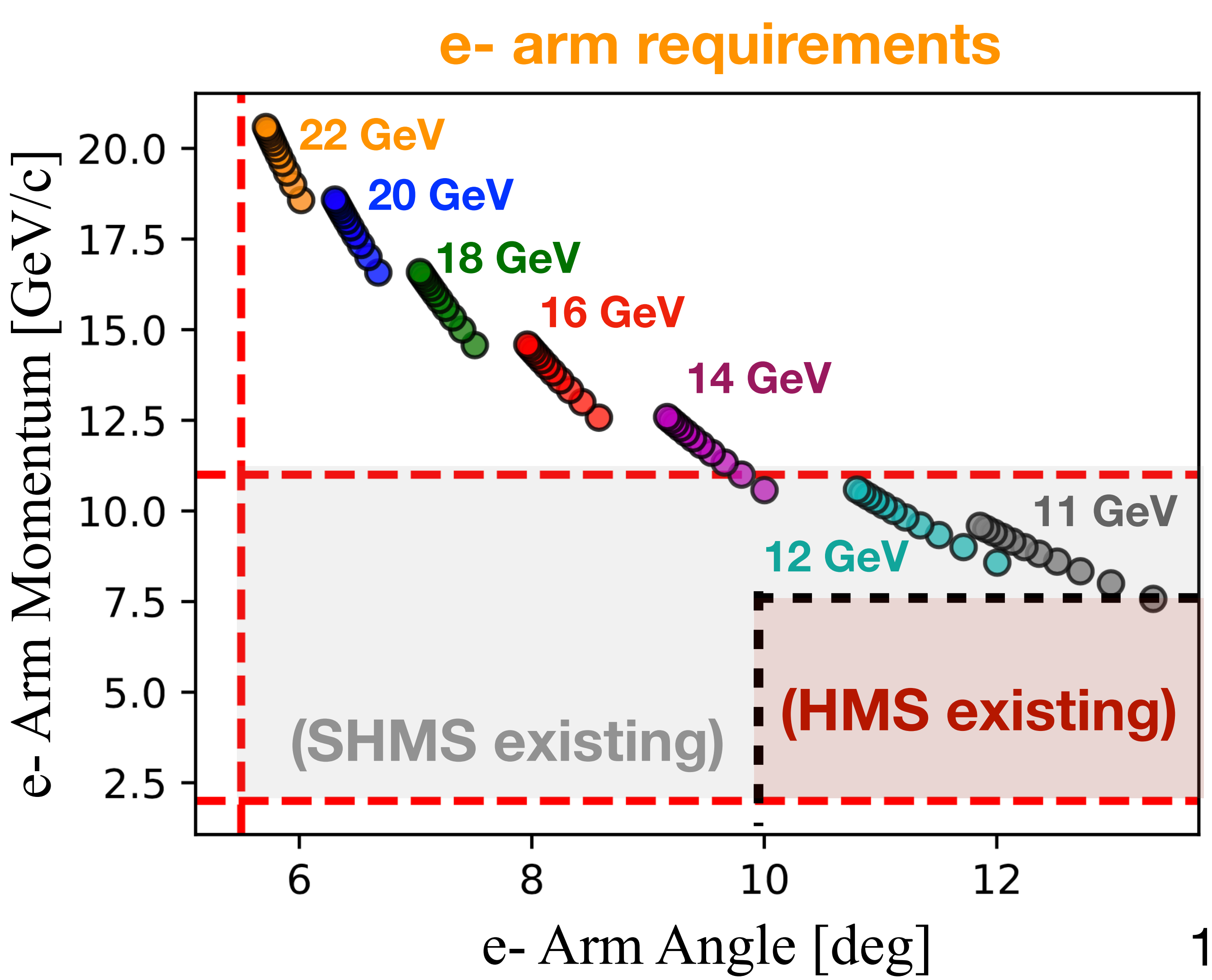
e- arm:
9.5, 8.82, 8.00 [GeV/c]
11.9, 12.3, 12.98 [deg]

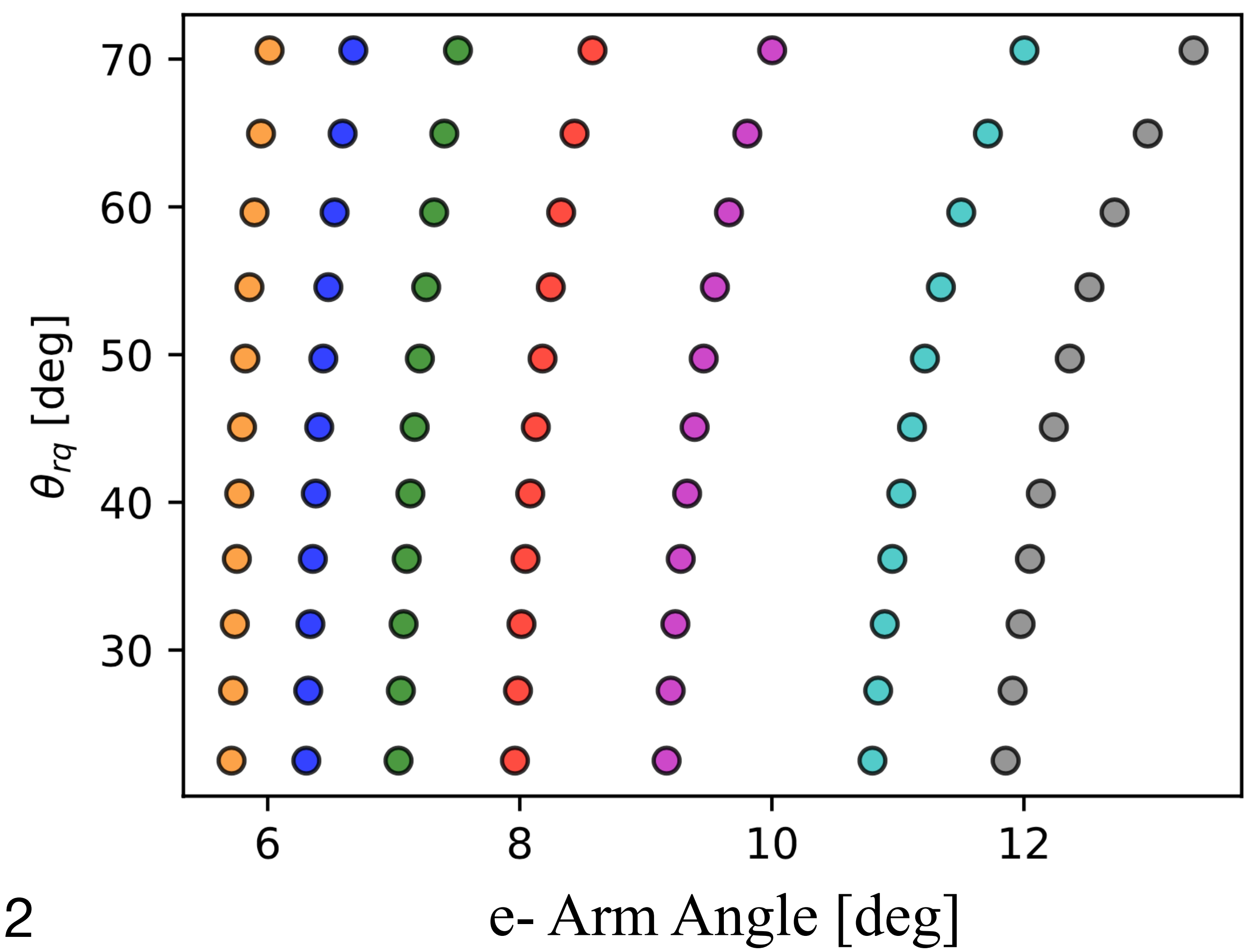
proton arm:
1.76, 2.51, 3.37 [GeV/c]
64.0, 56.0, 44.8 [deg]

Neutron Recoil Angle [deg]

consider electron arm spectrometer upgrade

- If electron arm (HMS?) momentum upgraded up to ~20 GeV/c (*wishful thinking* . . .)
  - full angular coverage becomes available at all energies (11-22 GeV) while keeping fixed at $Q^2 = 4.5\ \mathrm{GeV}^2$
  - **problem:** small e- angles (< 10 deg) required for Eb >= 14 GeV (need to modify HMS/beamline for lower angles)
  - **problem:** SHMS cannot be further upgraded !

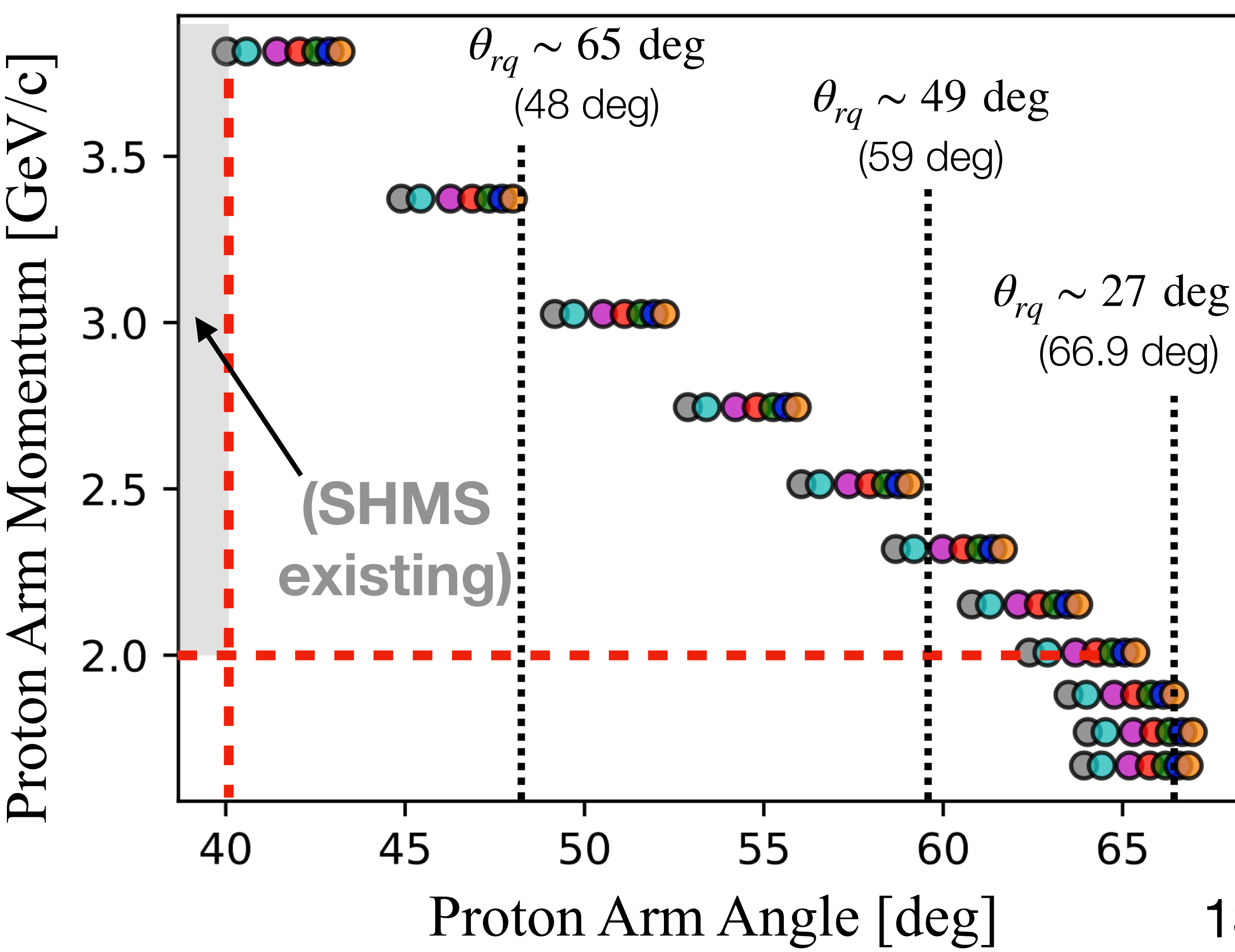


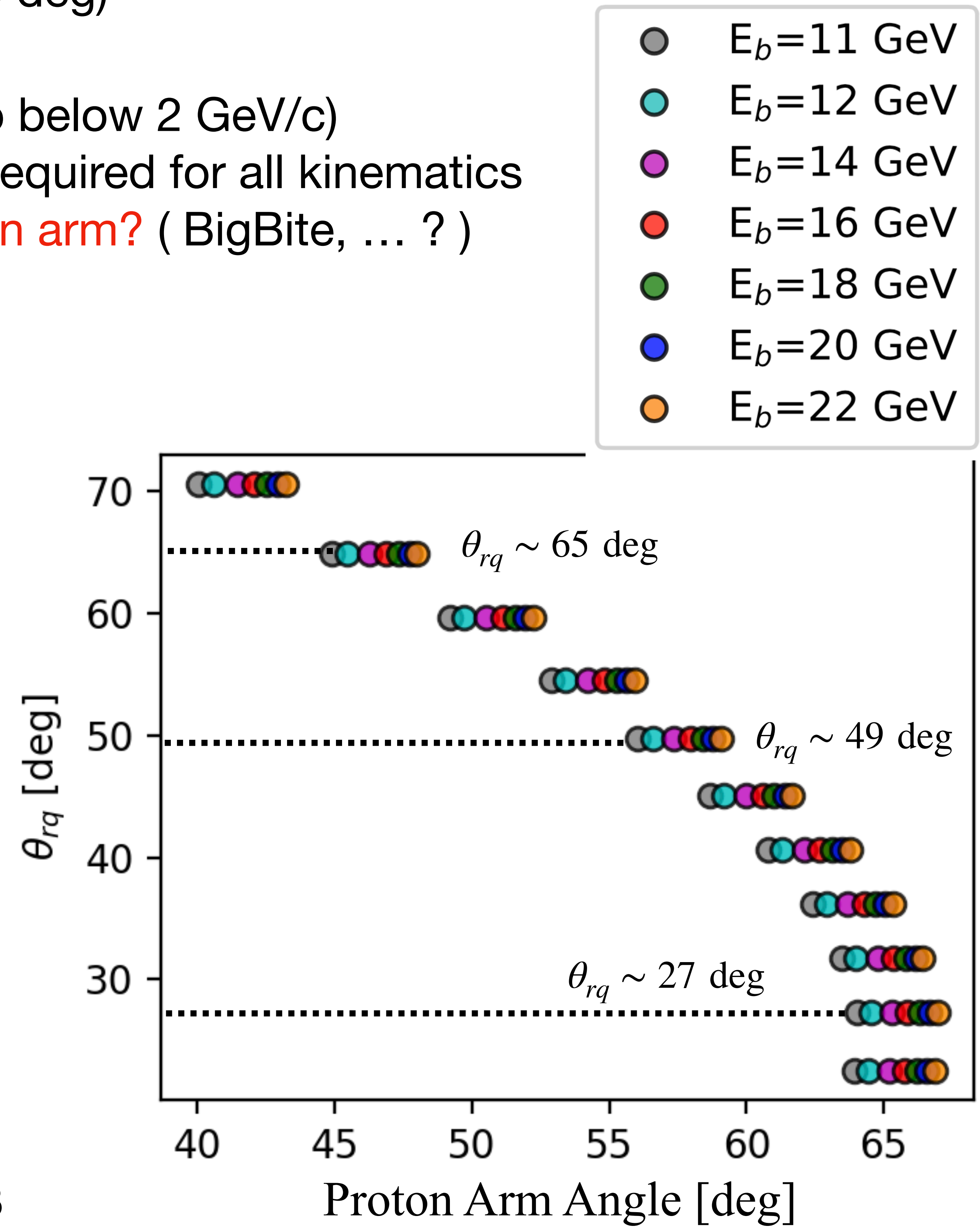


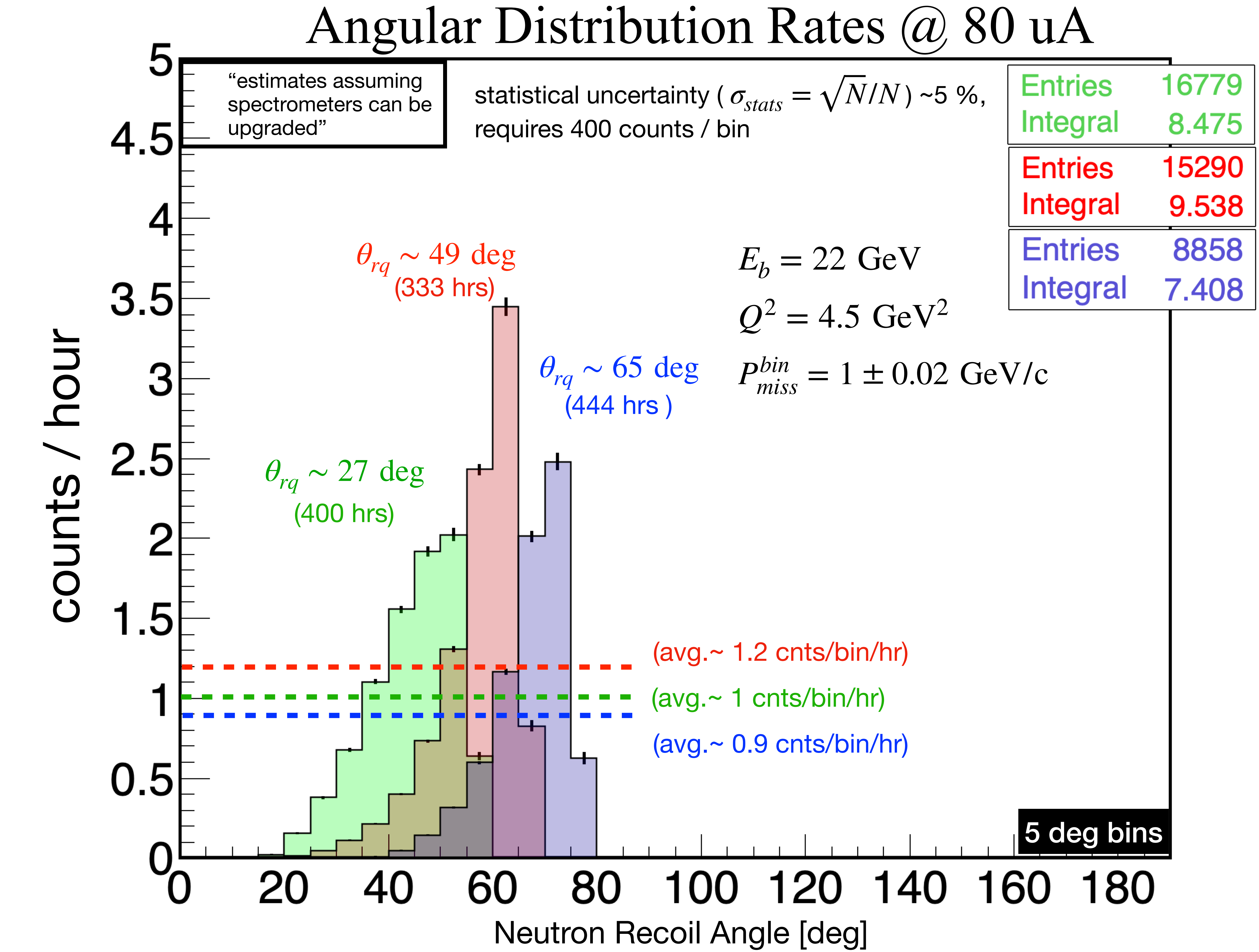
consider proton arm spectrometer upgrade

- SHMS **CANNOT** be used as proton arm
  - limited mainly by the maximum angle (~40 deg) while keeping fixed at $Q^2 = 4.5\ \mathrm{GeV}^2$
  - Limited partially by momentum (cannot go below 2 GeV/c)
  - **problem:** large proton angles (>40 deg) required for all kinematics
  - **key question:** What can be used as proton arm? (BigBite, … ?)

proton arm requirements

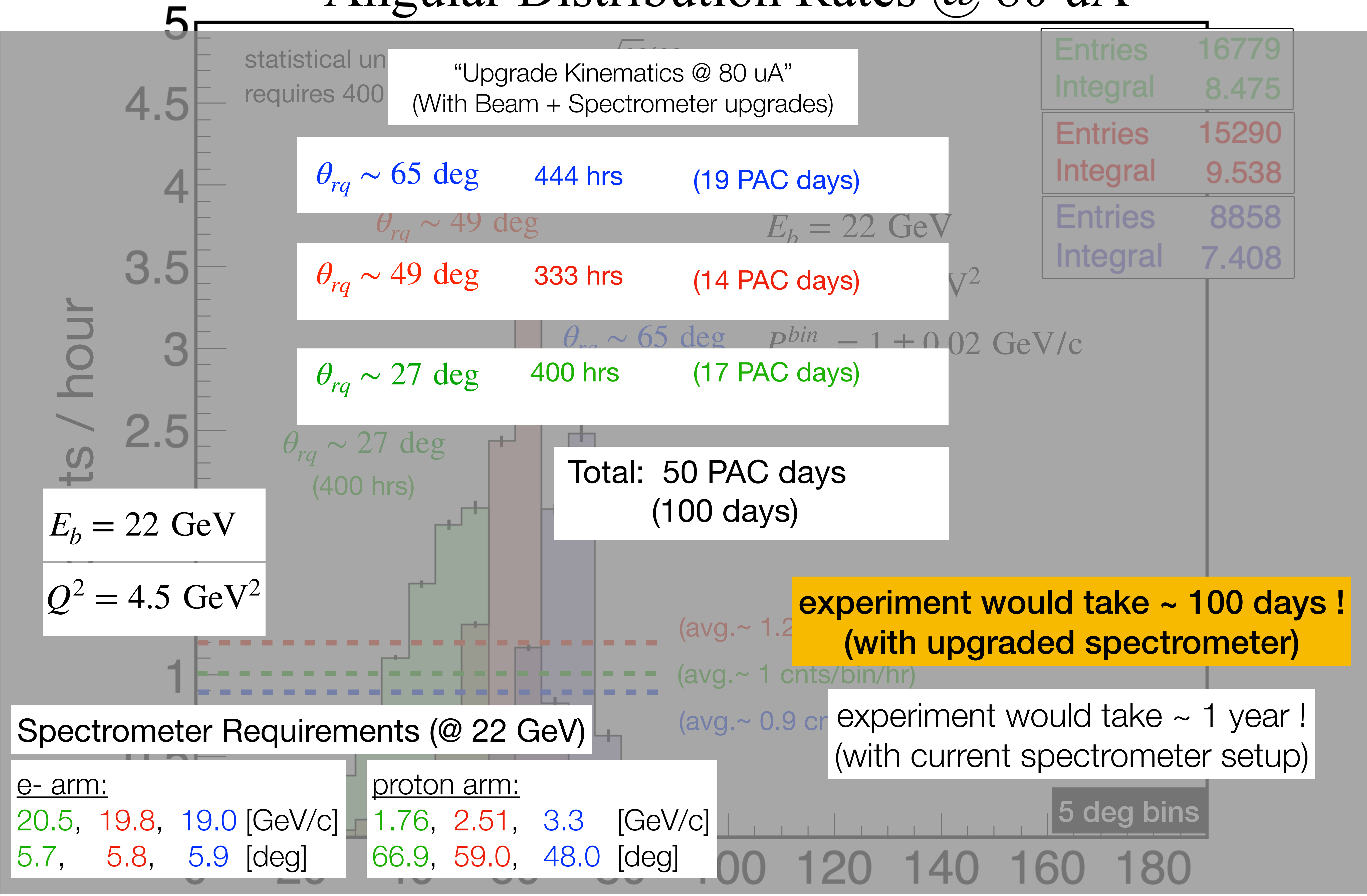






Angular Distribution Rates @ 80 uA
"estimates assuming spectrometers can be upgraded"
statistical uncertainty ($\sigma_{stats} = \sqrt{N}/N$) ~5 %, requires 400 counts / bin
Entries 16779
Integral 8.475
Entries 15290
Integral 9.538
Entries 8858
Integral 7.408
$E_b = 22$ GeV
$Q^2 = 4.5$ GeV^2
$P_{miss}^{bin} = 1 \pm 0.02$ GeV/c
$\theta_{rq} \sim 49$ deg
(333 hrs)
$\theta_{rq} \sim 65$ deg
(444 hrs)
$\theta_{rq} \sim 27$ deg
(400 hrs)
(avg.~ 1.2 cnts/bin/hr)
(avg.~ 1 cnts/bin/hr)
(avg.~ 0.9 cnts/bin/hr)
5 deg bins
counts / hour
Neutron Recoil Angle [deg]

Angular Distribution Rates @ 80 uA



"Upgrade Kinematics @ 80 uA"
(With Beam + Spectrometer upgrades)

$\theta_{rq} \sim 65$ deg	444 hrs	(19 PAC days)
$\theta_{rq} \sim 49$ deg	333 hrs	(14 PAC days)
$\theta_{rq} \sim 27$ deg	400 hrs	(17 PAC days)

Total: 50 PAC days
(100 days)

$E_b = 22$ GeV

$Q^2 = 4.5$ GeV^2

experiment would take ~ 100 days !
(with upgraded spectrometer)

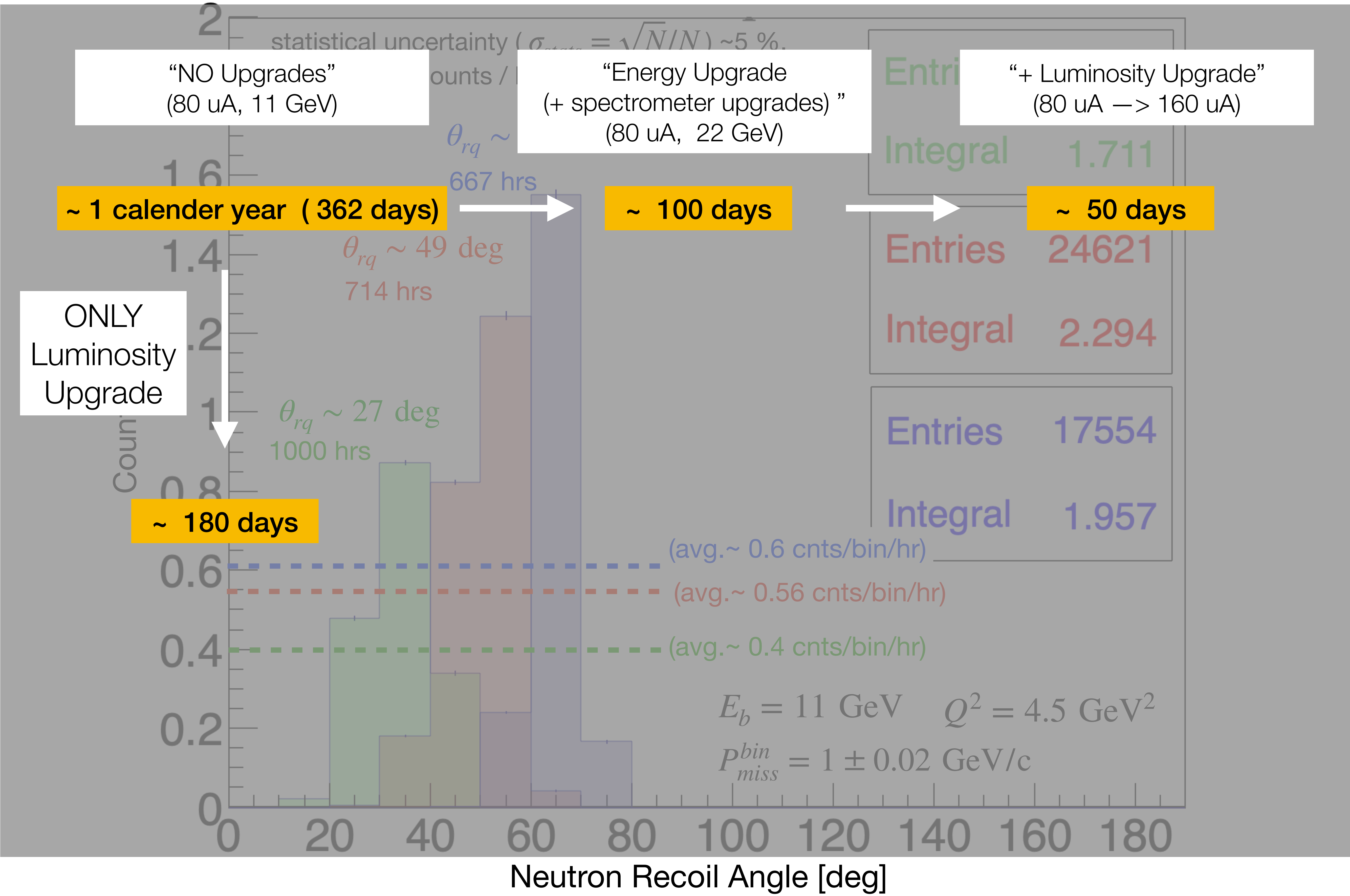
experiment would take ~ 1 year !
(with current spectrometer setup)

Spectrometer Requirements (@ 22 GeV)

e- arm:				proton arm:			
20.5,	19.8,	19.0	[GeV/c]	1.76,	2.51,	3.3	[GeV/c]
5.7,	5.8,	5.9	[deg]	66.9,	59.0,	48.0	[deg]

Neutron Recoil Angle [deg]

Consider Luminosity Upgrade (80 uA -> 160 uA)



Summary

- need to measure angular distributions (θ_{rq}) beyond $P_r \sim 500$ MeV/c
- with existing spectrometer, can only take advantage up to 12 GeV (while fixing $Q^2 \sim 4.5$ GeV^2)
  - can take ~ 1 calender year for a ~5 % measurement per angular bin $\theta_{rq} \pm 5$ deg (unrealistic beam time requirement)
- to take advantage of full 22 GeV upgrade requires spectrometer upgrades
  - Our measurements require:
    - electron: 18.5 - 20.5 GeV/c @ 5.7 -6 deg
    - proton: 1.6 - 3.8 GeV/c @ 43 - 66.8 deg
  - Possible / impossible spectrometer upgrades:
    - HMS can be used as e- arm, if momentum can be upgraded (by how much? 15, 21 GeV/c ?) (HMS is limited to 10 deg, can it be modified for lower angles?)
    - SHMS cannot be further upgraded (can't be used as e- arm), and can't be used as proton arm (due to its limitation in angle and momentum)
    - Can Big Bite spectrometer be used as proton arm? Any other ideas ?
- Could it be more cost-effective to propose a luminosity upgrade (80 uA —> 160 uA ?)

Acknowledgements

I would like to thank Drs. Werner Boeglin, Mark Jones and Misak Sargsian for their insight and useful discussions on this topic

"This material is based upon work supported by the National Science Foundation under Grant No. 2137604"

Back-Up Slides

“Baseline” Kinematics
(Without spectrometer upgrade)

Eb	Pr	xbj	kf	th_e	Pf	th_p	q	th_q	th_rq	th_pq	Q2
11.00	1.0000	0.7000	7.5742	13.3458	3.8155	40.0272	4.0294	25.7154	70.5957	14.3118	4.5000
11.00	1.0000	0.8000	8.0025	12.9823	3.3729	44.8930	3.6722	29.3112	64.9598	15.5817	4.5000
11.00	1.0000	0.9000	8.3355	12.7192	3.0258	49.1733	3.4058	32.6062	59.6289	16.5670	4.5000
11.00	1.0000	1.0000	8.6020	12.5198	2.7456	52.8847	3.2016	35.6212	54.5680	17.2635	4.5000
11.00	1.0000	1.1000	8.8200	12.3635	2.5141	56.0471	3.0418	38.3777	49.7378	17.6694	4.5000
11.00	1.0000	1.2000	9.0016	12.2376	2.3192	58.6796	2.9143	40.8976	45.0951	17.7820	4.5000
11.00	1.0000	1.3000	9.1554	12.1341	2.1525	60.7968	2.8112	43.2022	40.5911	17.5946	4.5000
11.00	1.0000	1.4000	9.2871	12.0474	2.0079	62.4047	2.7265	45.3119	36.1692	17.0928	4.5000
11.00	1.0000	1.5000	9.4013	11.9737	1.8811	63.4940	2.6563	47.2456	31.7588	16.2483	4.5000
11.00	1.0000	1.6000	9.5012	11.9104	1.7688	64.0296	2.5974	49.0208	27.2617	15.0088	4.5000
11.00	1.0000	1.7000	9.5894	11.8553	1.6683	63.9256	2.5475	50.6533	22.5203	13.2722	4.5000

Not so "Optimum" Kinematics (Without spectrometer upgrade)

Eb	Pr	xbj	kf	th_e	Pf	th_p	q	th_q	th_rq	th_pq	Q2
14.00	1.0000	0.8000	7.6719	17.1034	6.7668	26.6915	7.0388	18.6960	70.2595	7.9955	9.5000
14.00	1.0000	0.9000	8.3750	16.3646	6.0562	30.1773	6.4141	21.5852	64.7956	8.5921	9.5000
14.00	1.0000	1.0000	8.9375	15.8378	5.4863	33.3306	5.9270	24.3016	59.4273	9.0289	9.5000
14.00	1.0000	1.1000	9.3977	15.4427	5.0188	36.1481	5.5390	26.8574	54.1203	9.2907	9.5000
14.00	1.0000	1.2000	9.7813	15.1351	4.6281	38.6225	5.2247	29.2618	48.8297	9.3608	9.5000
14.00	1.0000	1.3000	10.1058	14.8888	4.2964	40.7411	4.9664	31.5227	43.4944	9.2184	9.5000
14.00	1.0000	1.4000	10.3839	14.6869	4.0113	42.4818	4.7514	33.6479	38.0255	8.8339	9.5000
14.00	1.0000	1.5000	10.6250	14.5184	3.7633	43.8036	4.5706	35.6451	32.2798	8.1585	9.5000
14.00	1.0000	1.6000	10.8359	14.3756	3.5455	44.6216	4.4172	37.5217	25.9904	7.0999	9.5000

*NOTE: baseline kinematics (Eb=11 GeV) are actually better than optimal (Eb=14 GeV) since, optimal requires Q2 —> 9.5 GeV^2, which significantly reduces count rates

Kinematics
(With spectrometer upgrade)

electron proton

Eb	Pr	xbj	kf	th_e	Pf	th_p	q	th_q	th_rq	th_pq	Q2
22.00	1.0000	0.7000	18.5742	6.0154	3.8155	43.1983	4.0294	28.8865	70.5957	14.3118	4.5000
22.00	1.0000	0.8000	19.0025	5.9471	3.3729	48.0037	3.6722	32.4219	64.9598	15.5817	4.5000
22.00	1.0000	0.9000	19.3355	5.8956	3.0258	52.2394	3.4058	35.6724	59.6289	16.5670	4.5000
22.00	1.0000	1.0000	19.6020	5.8554	2.7456	55.9167	3.2016	38.6531	54.5680	17.2635	4.5000
22.00	1.0000	1.1000	19.8200	5.8231	2.5141	59.0519	3.0418	41.3825	49.7378	17.6694	4.5000
22.00	1.0000	1.2000	20.0016	5.7966	2.3192	61.6624	2.9143	43.8804	45.0951	17.7820	4.5000
22.00	1.0000	1.3000	20.1554	5.7744	2.1525	63.7614	2.8112	46.1668	40.5911	17.5946	4.5000
22.00	1.0000	1.4000	20.2871	5.7556	2.0079	65.3539	2.7265	48.2611	36.1692	17.0928	4.5000
22.00	1.0000	1.5000	20.4013	5.7394	1.8811	66.4301	2.6563	50.1818	31.7588	16.2483	4.5000
22.00	1.0000	1.6000	20.5012	5.7254	1.7688	66.9544	2.5974	51.9456	27.2617	15.0088	4.5000
22.00	1.0000	1.7000	20.5894	5.7132	1.6683	66.8405	2.5475	53.5683	22.5203	13.2722	4.5000

electron arm requirements

P: 18.5-20.5 GeV/c

angle: 5.7 - 6 deg

proton arm requirements

P: 1.6-3.8 GeV/c

angle: 43 - 66.8 deg

Integrated Count Rates Estimates @ 80 uA

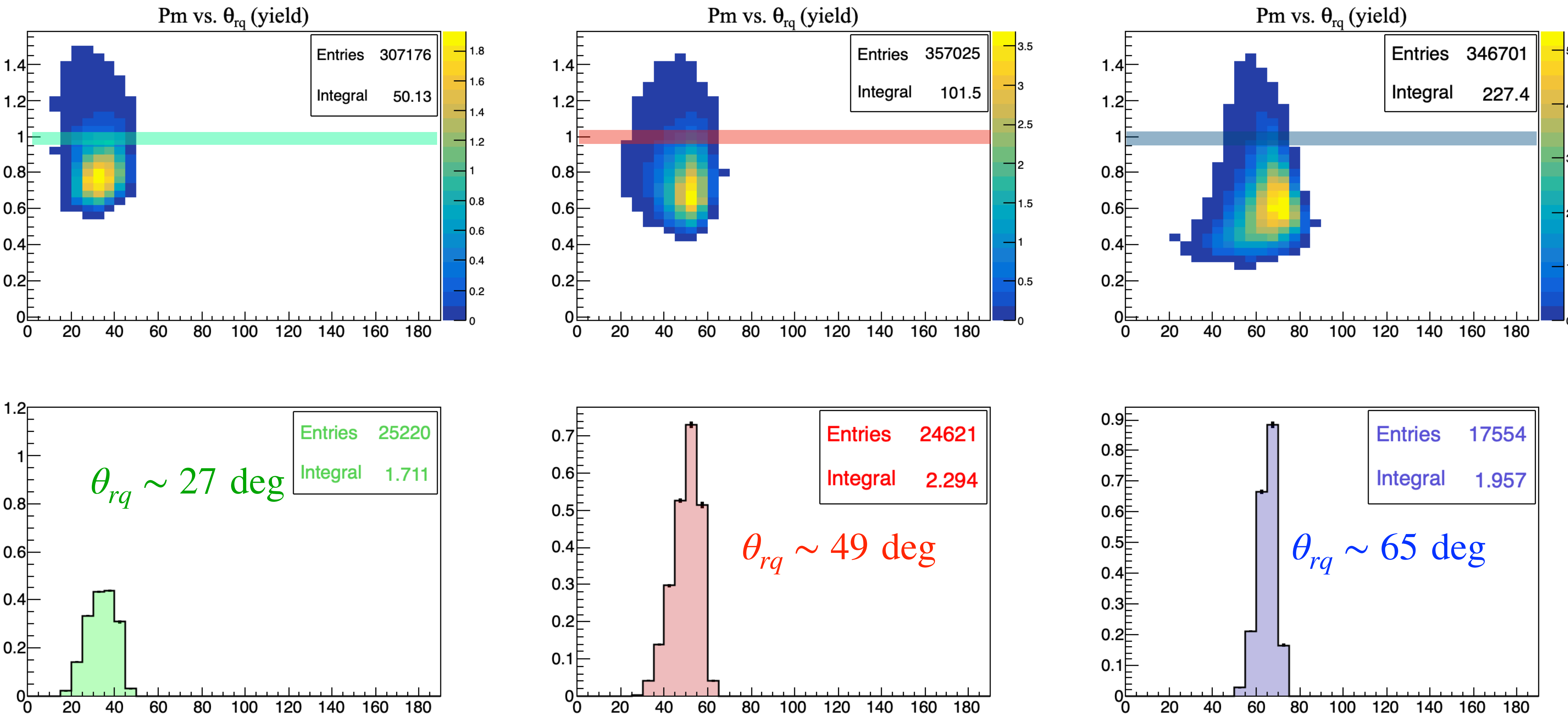
5 deg bins

$E_b = 11$ GeV

$Q^2 = 4.5$ GeV^2

$P_{miss}^{bin} = 1 \pm 0.02$ GeV/c

2D Projections



Integrated Count Rates Estimates @ 80 uA

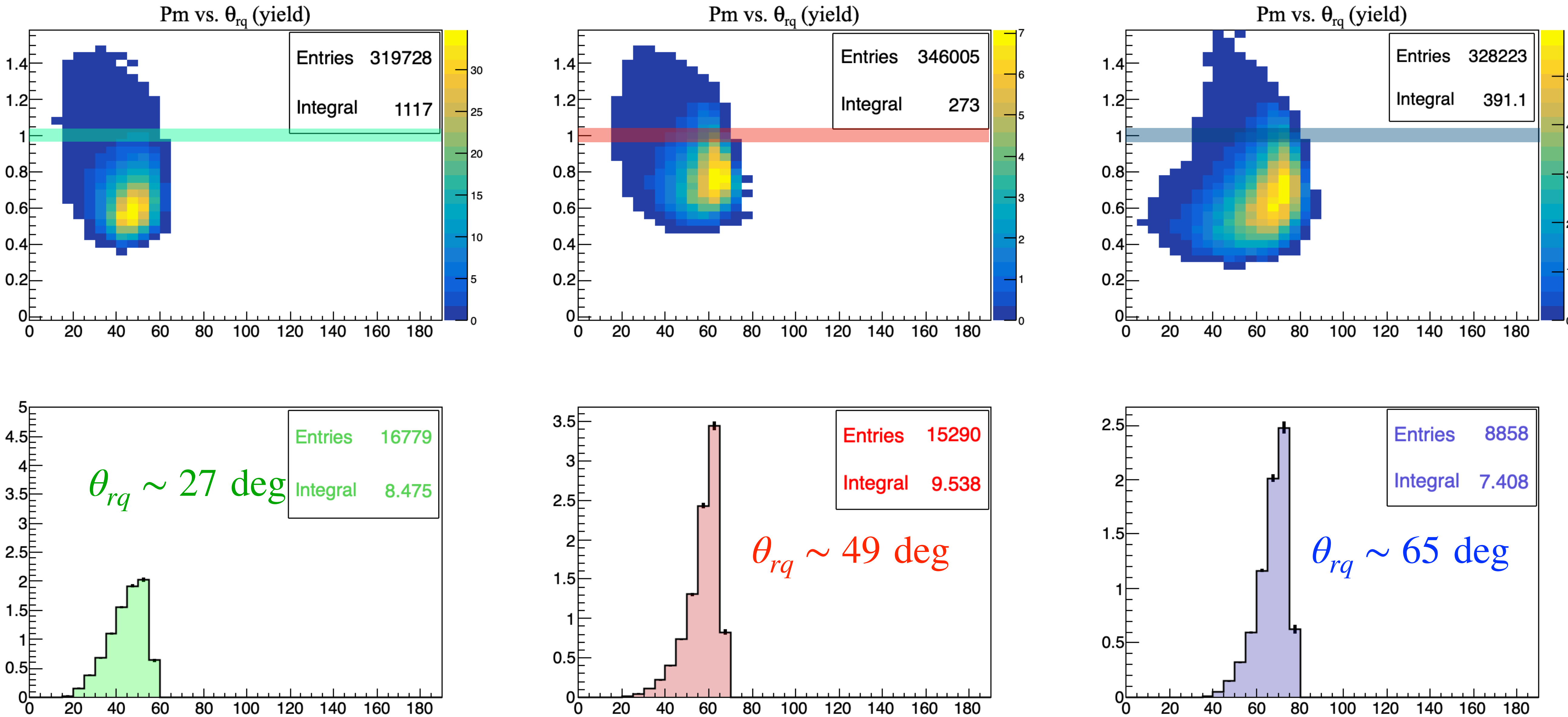
5 deg bins

$E_b = 22$ GeV

$Q^2 = 4.5$ GeV^2

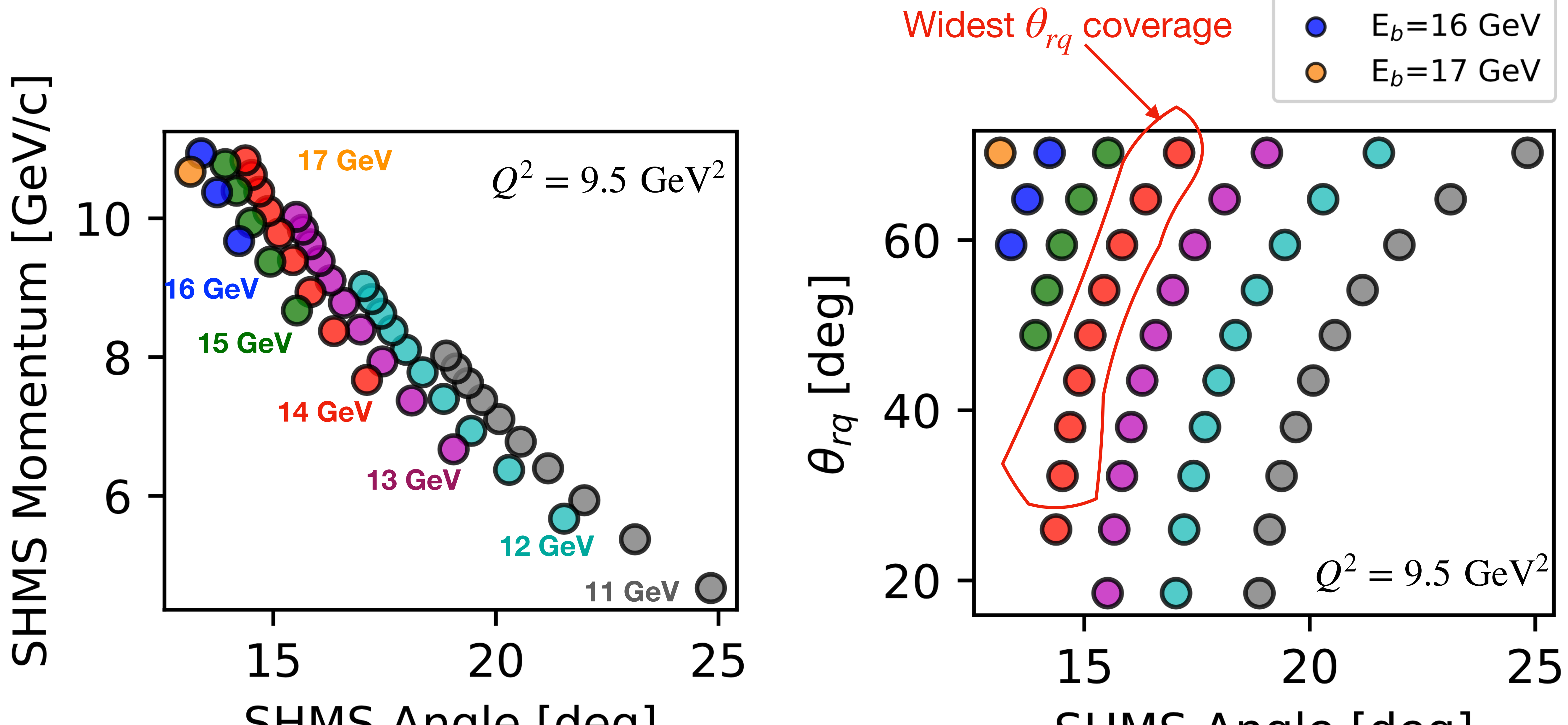
$P_{miss}^{bin} = 1 \pm 0.02$ GeV/c

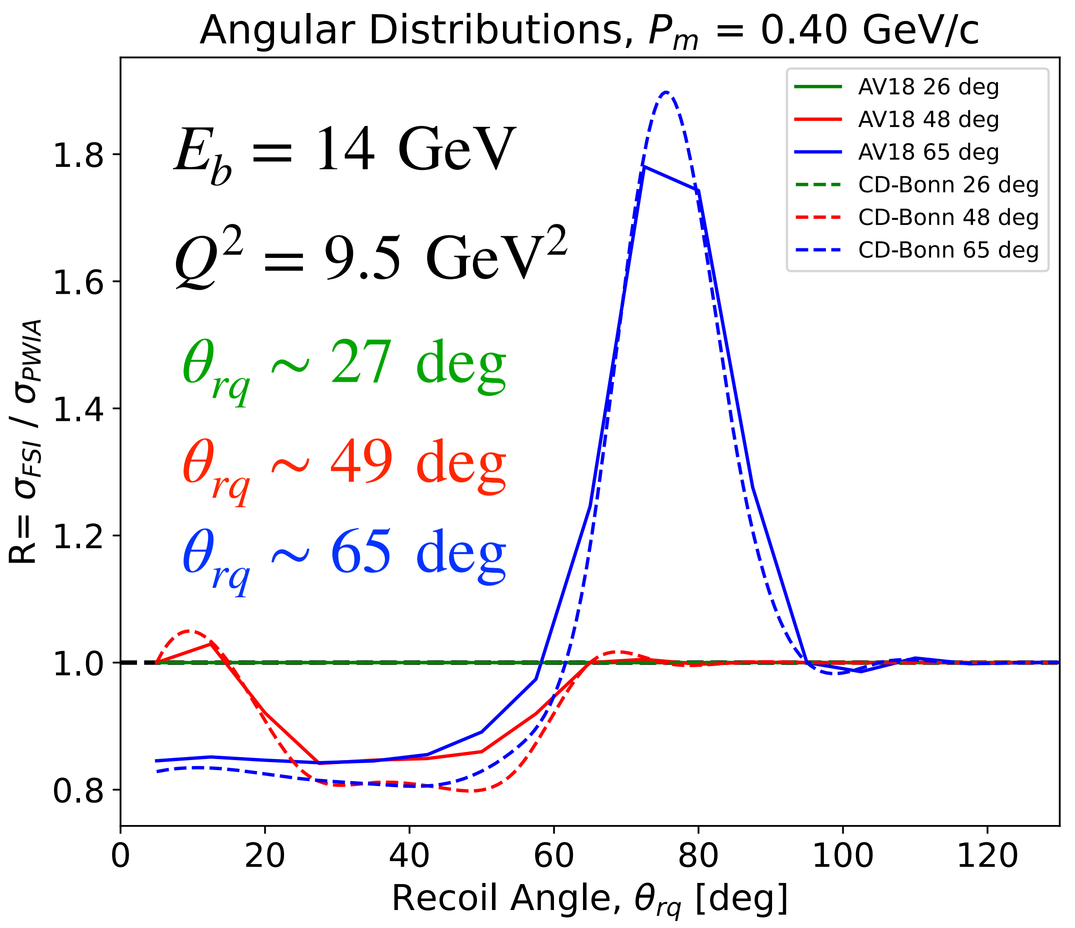
2D Projections

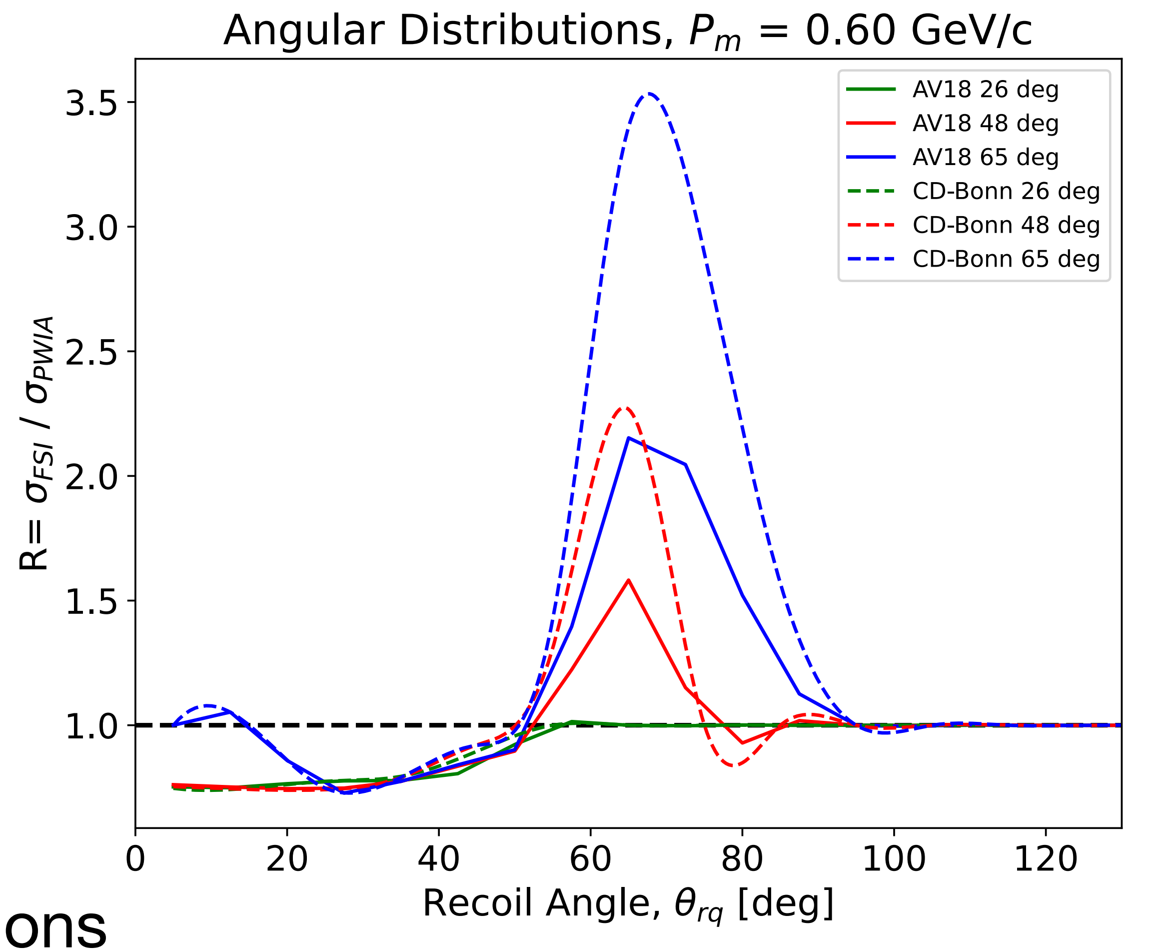


Find Optimum Kinematics (at higher Q2)

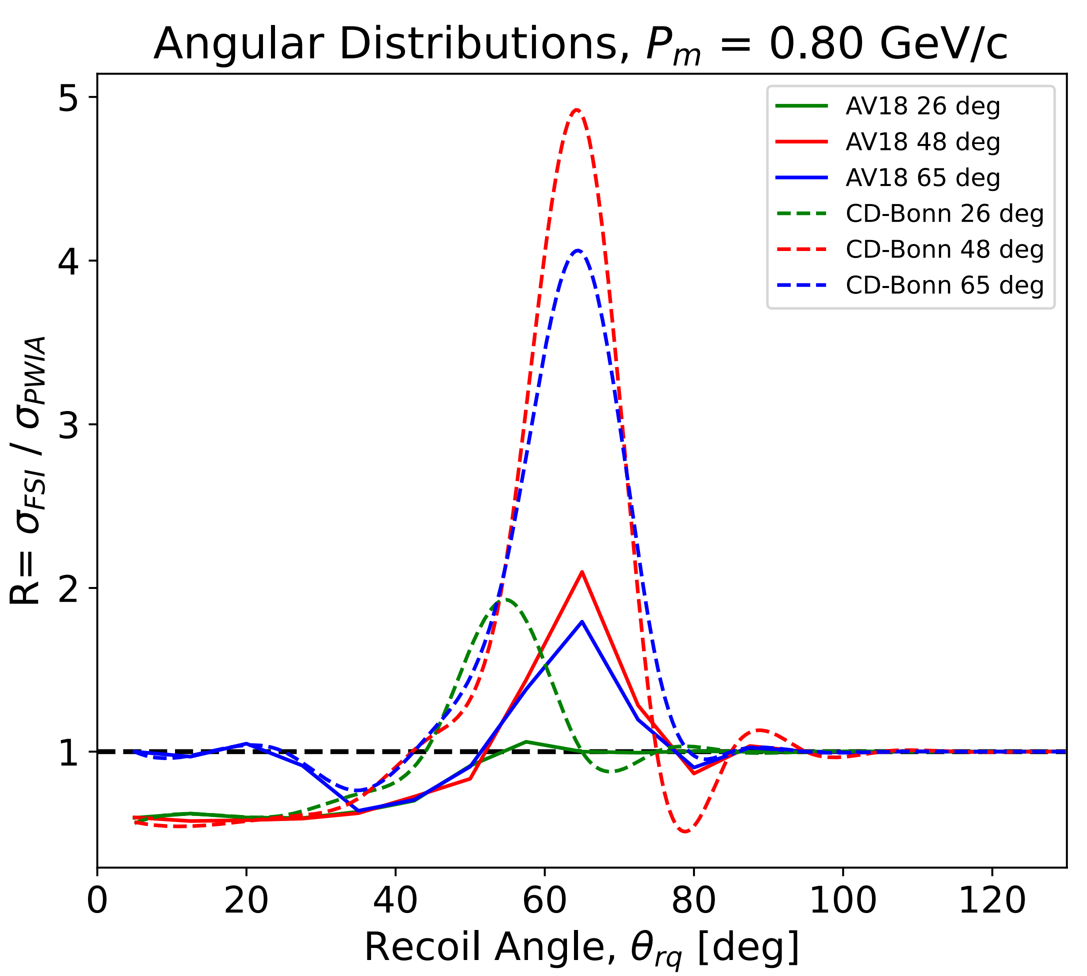
- optimum kinematics @ Eb = 14 GeV, Q2 = 9.5 GeV^2
  (optimum -> widest angular coverage at highest possible beam energy)
  - increase in beam energy requires increase in Q^2 in order to keep electron spectrometer within limits
  - **problem**: higher Q^2 —> reduced count rates

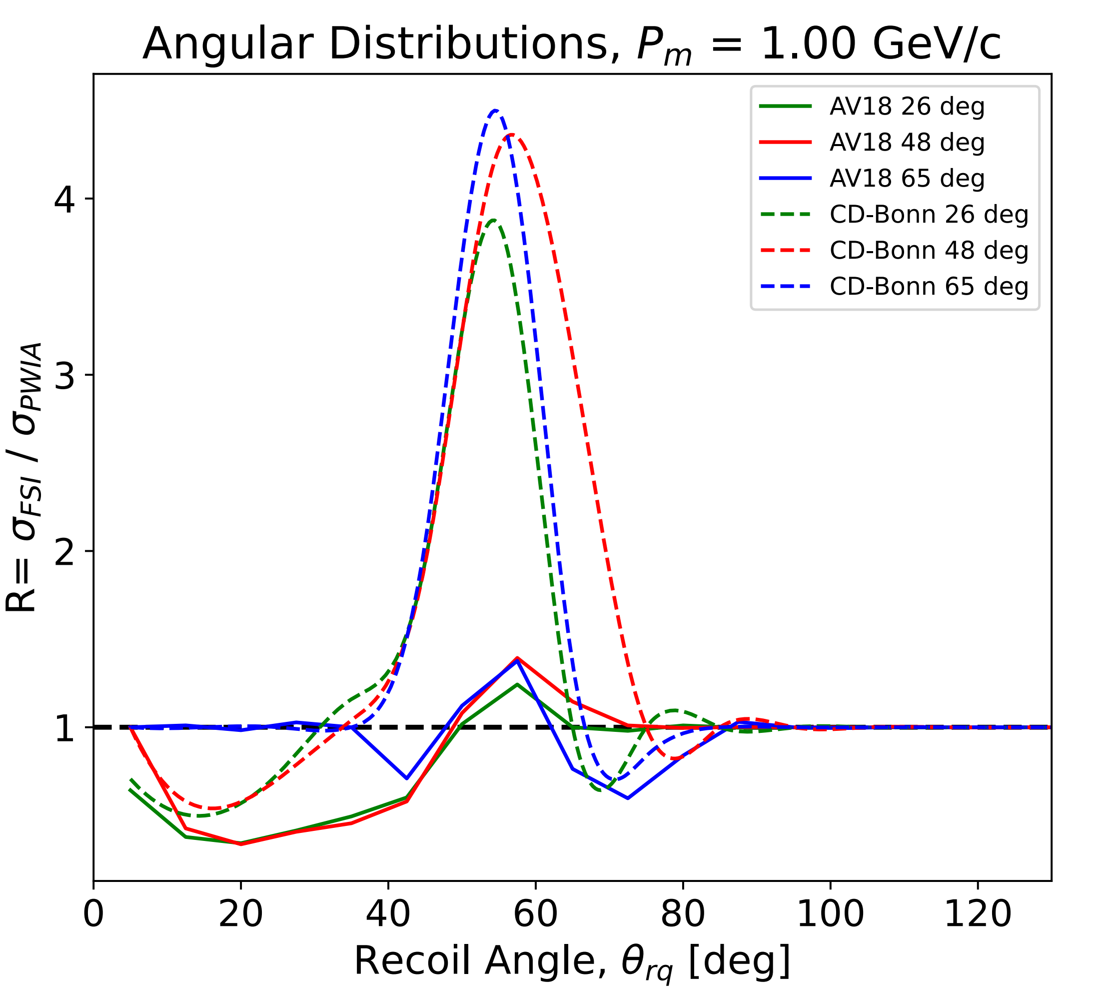


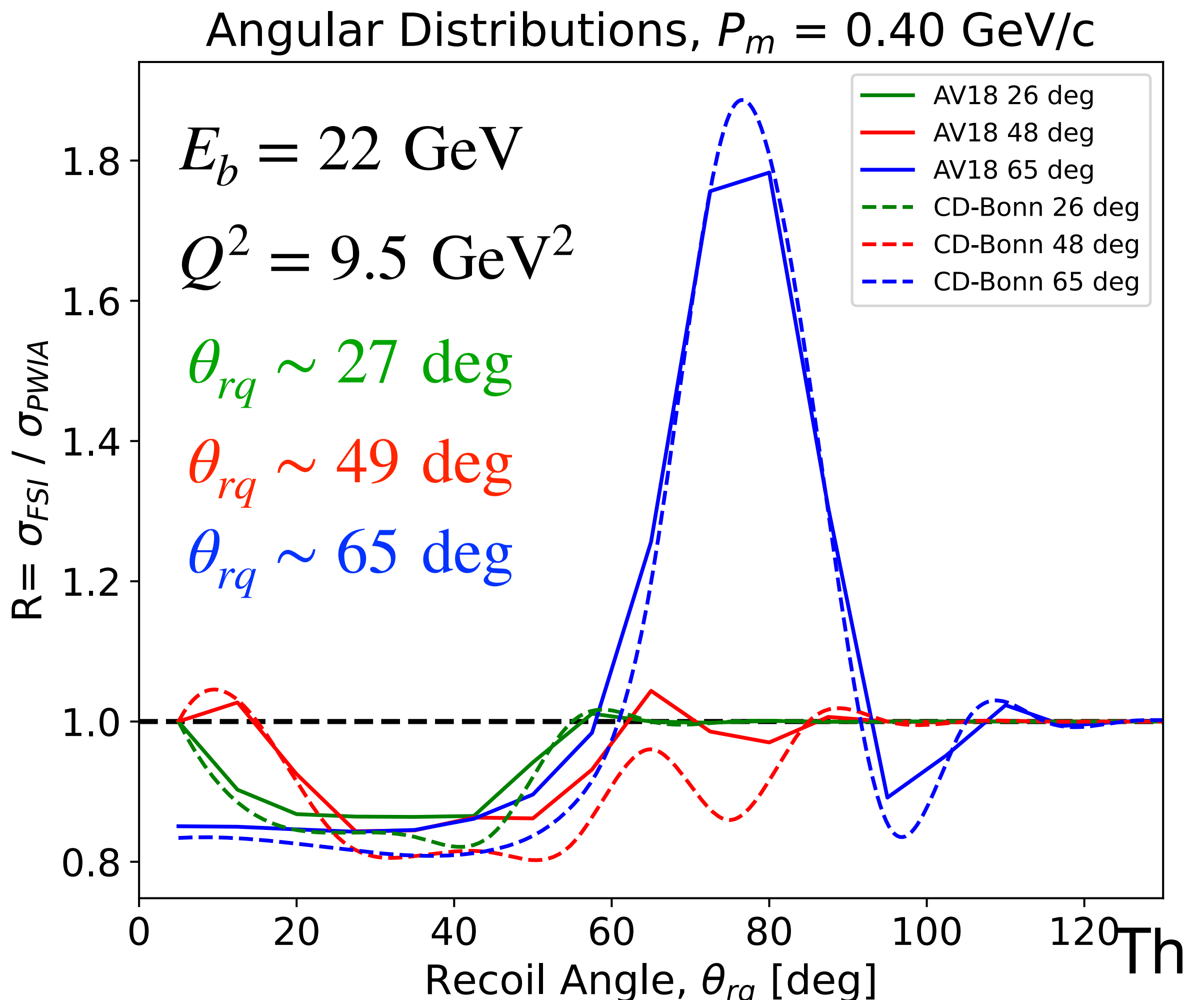


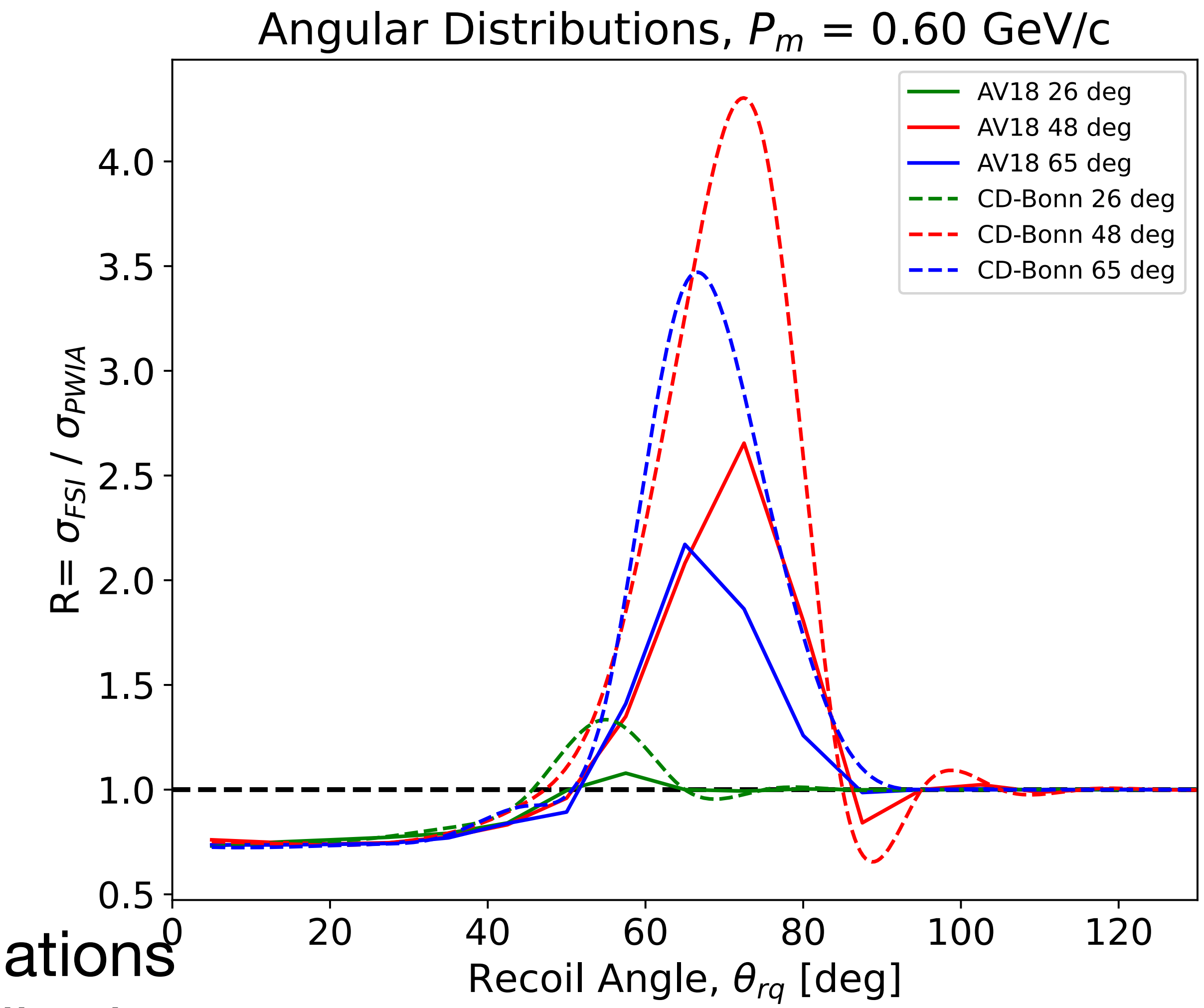


Theory calculations of angular distributions (by. M. Sargsian)

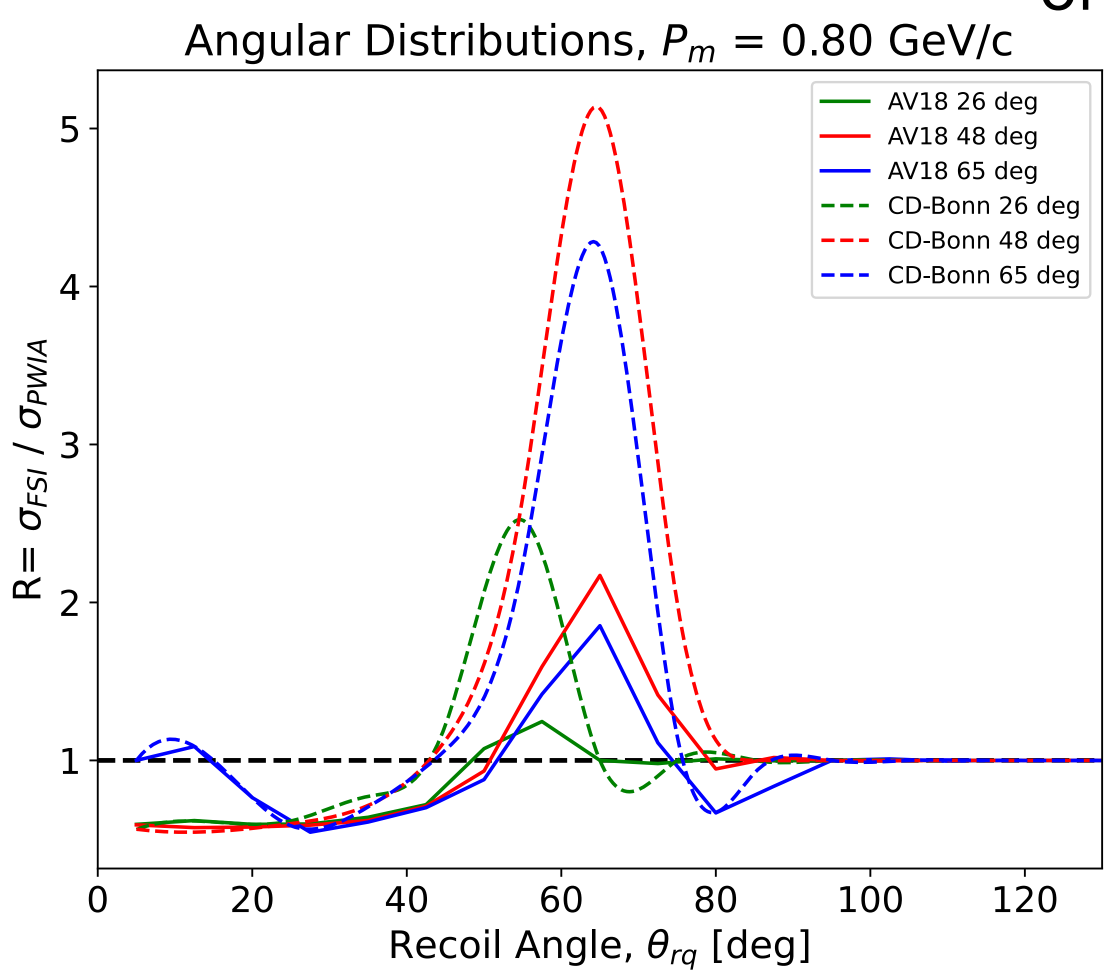


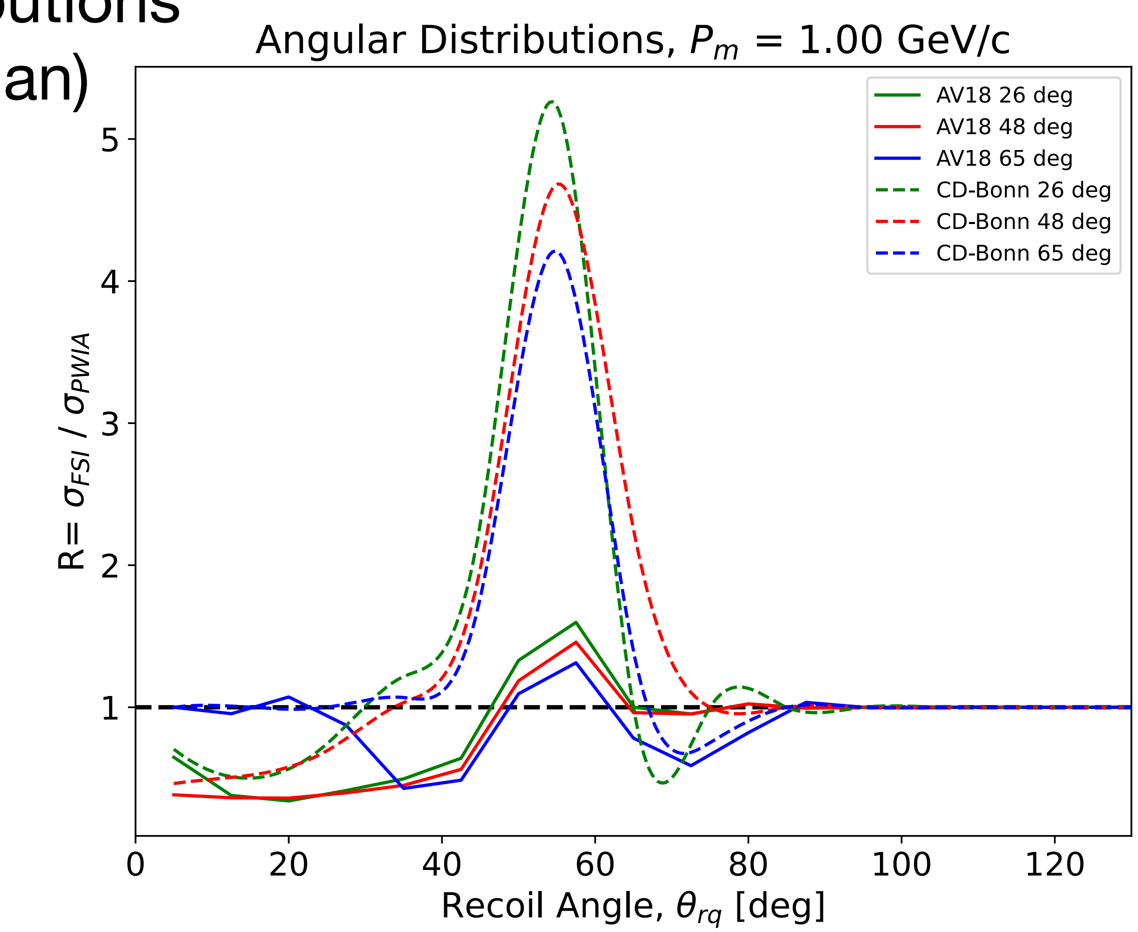




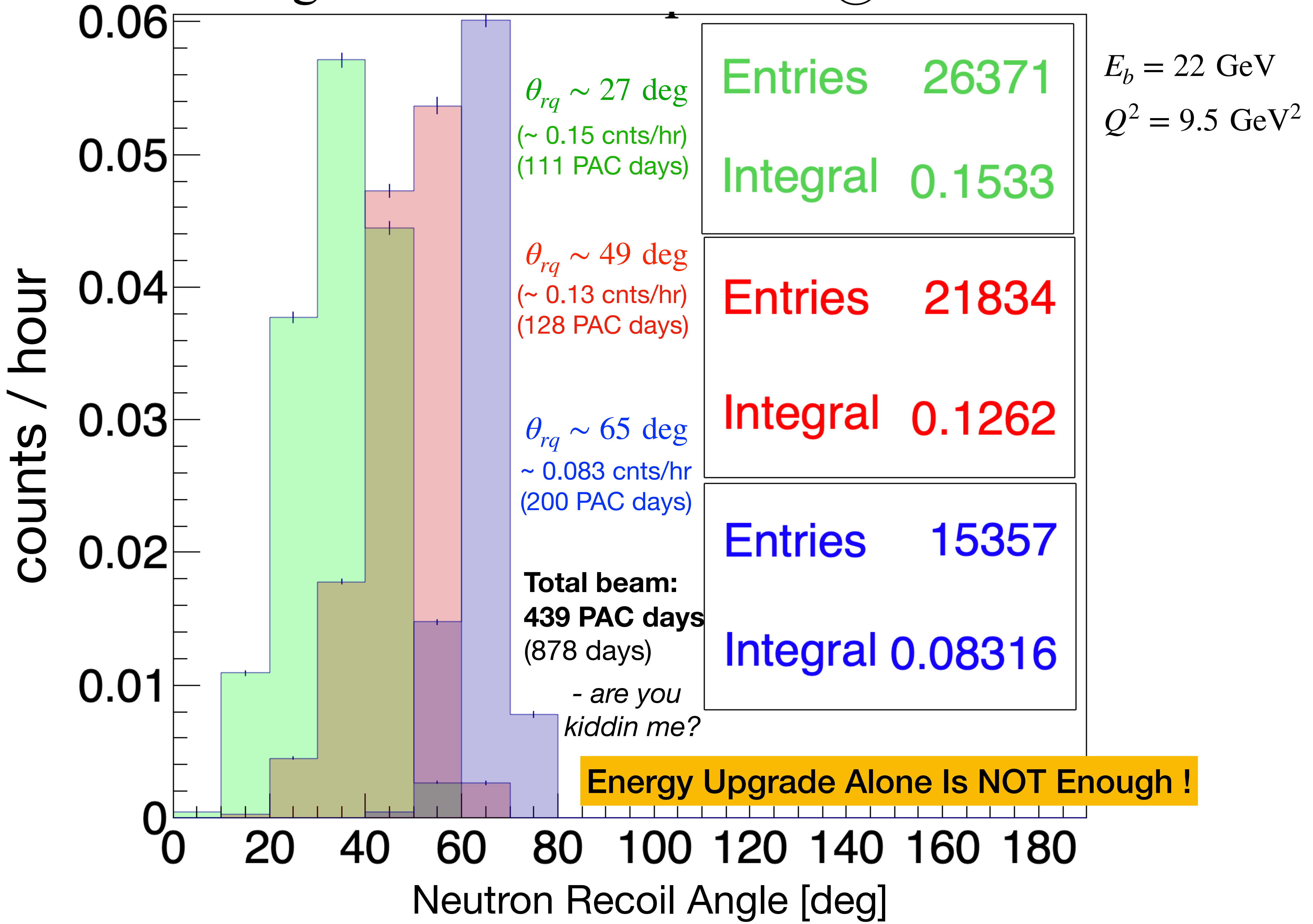


Theory calculations of angular distributions (by. M. Sargsian)





Angular Distribution Rates @ 80 uA

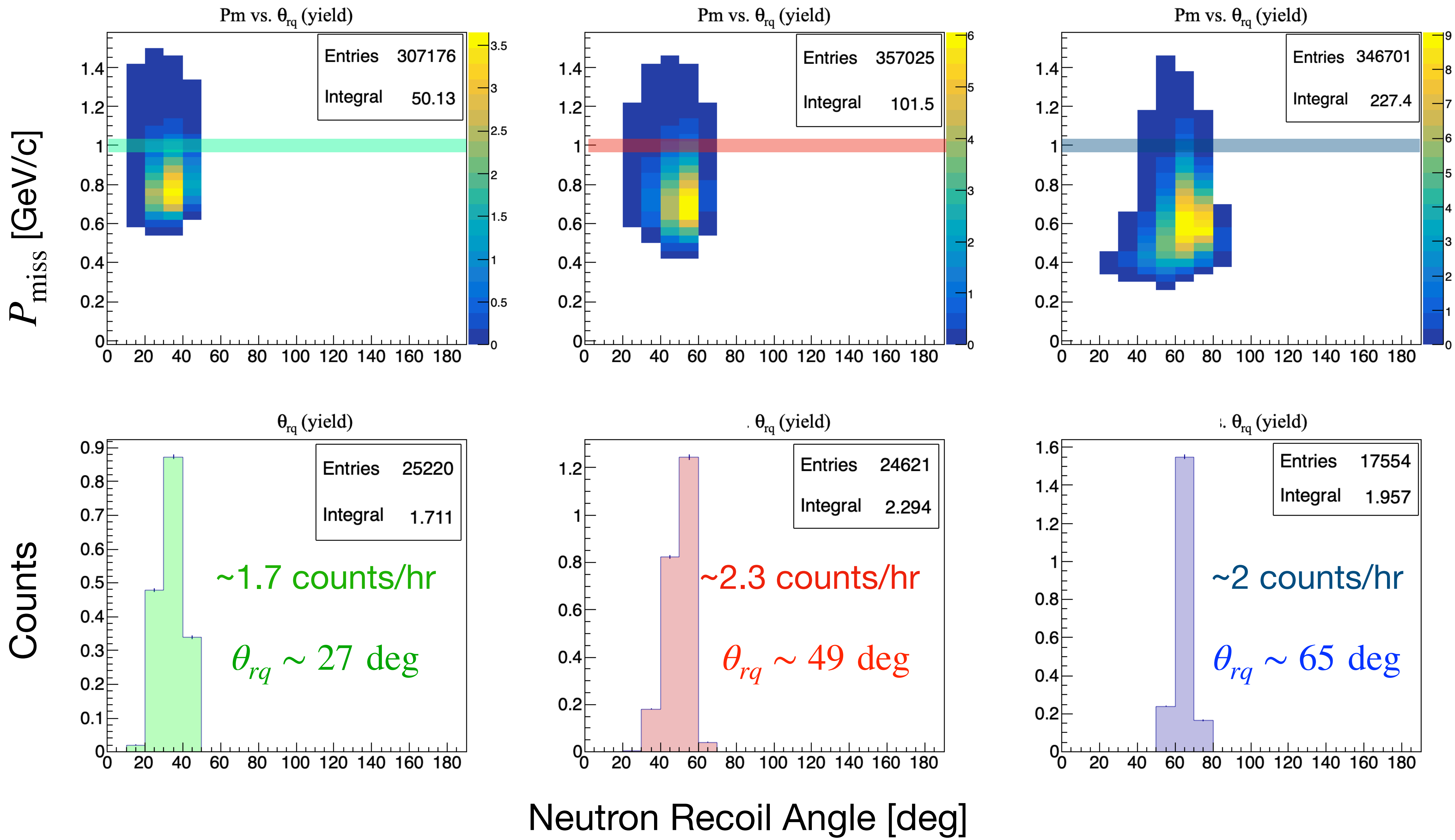


Baseline Integrated Count Rates Estimates @ 80 uA

10 deg bins

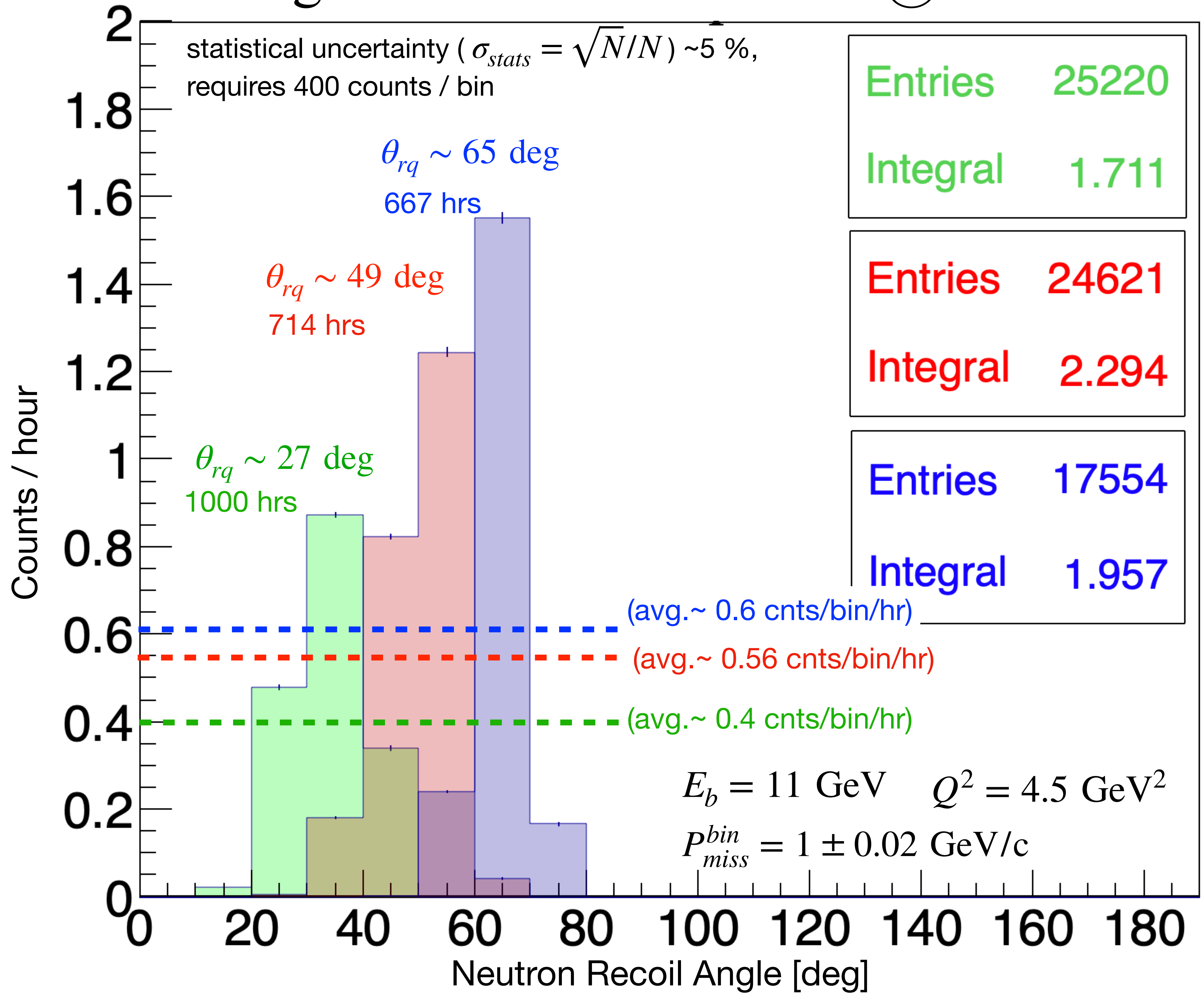
Baseline

- no spectrometer upgrade or energy upgrade required
- Plotted 2D Missing Momentum vs. Recoil Angle
- Projected Angular Distribution for Missing Momentum bin $P_{miss}^{bin} = 1 \pm 0.02$ GeV/c



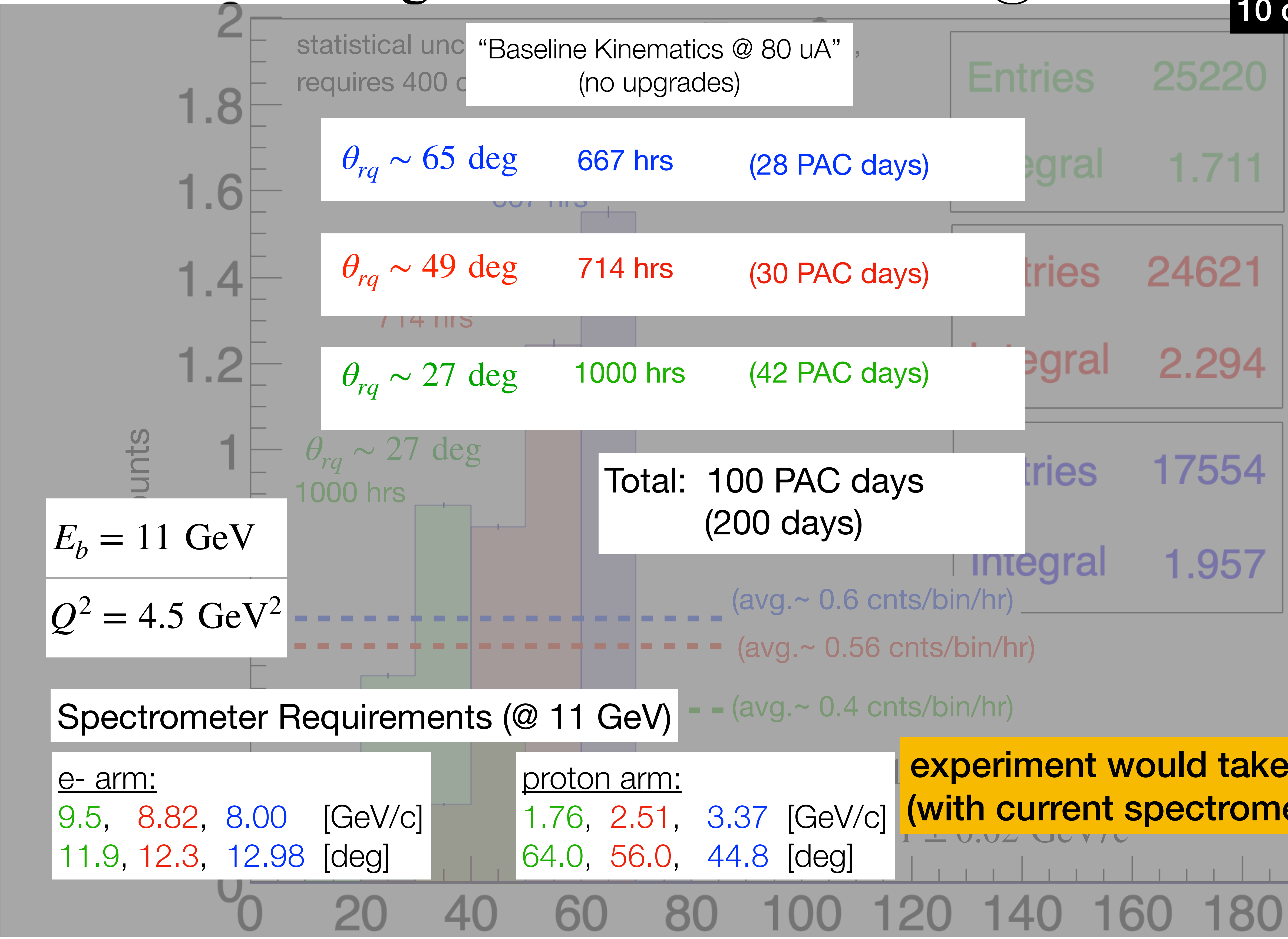
Angular Distribution Rates @ 80 uA

10 deg bins



Angular Distribution Rates @ 80 uA

10 deg bins



"Baseline Kinematics @ 80 uA"
(no upgrades)

$\theta_{rq} \sim 65$ deg	667 hrs	(28 PAC days)
$\theta_{rq} \sim 49$ deg	714 hrs	(30 PAC days)
$\theta_{rq} \sim 27$ deg	1000 hrs	(42 PAC days)

Total: 100 PAC days
(200 days)

$E_b = 11$ GeV

$Q^2 = 4.5$ GeV^2

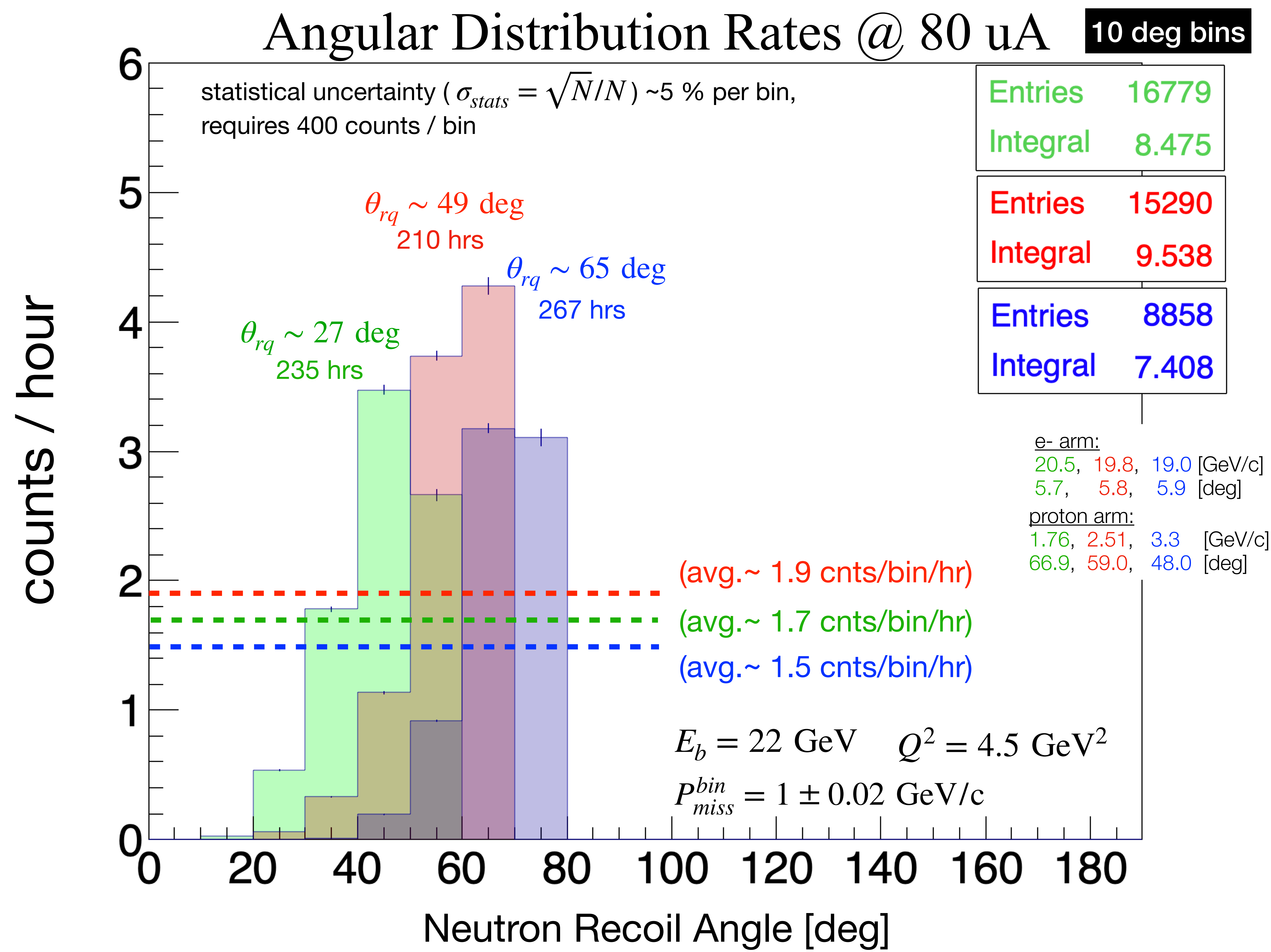
Spectrometer Requirements (@ 11 GeV)

e- arm:			
9.5,	8.82,	8.00	[GeV/c]
11.9,	12.3,	12.98	[deg]

proton arm:			
1.76,	2.51,	3.37	[GeV/c]
64.0,	56.0,	44.8	[deg]

experiment would take too long !
(with current spectrometer setup)

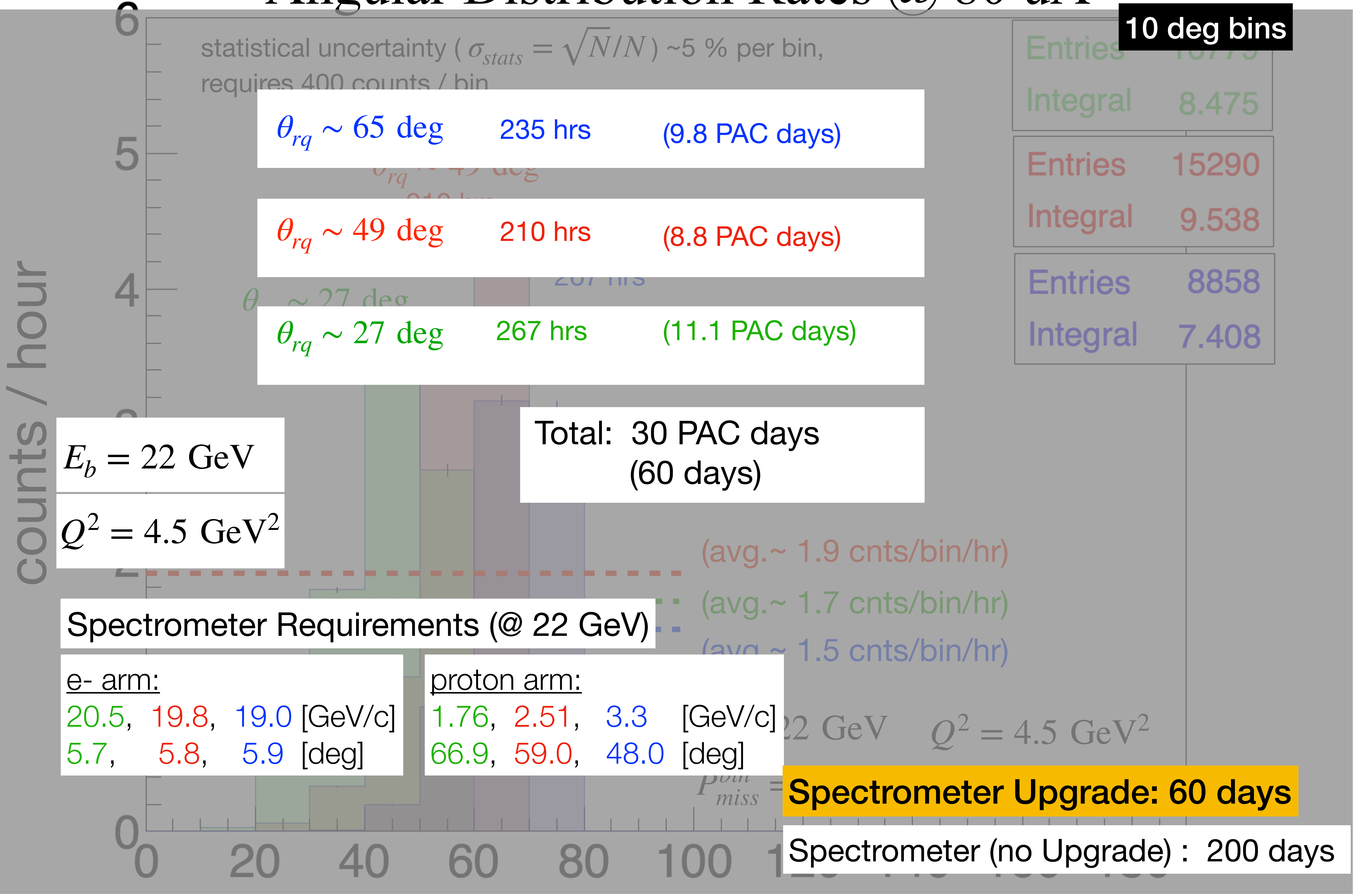
Neutron Recoil Angle [deg]



Angular Distribution Rates @ 80 uA
10 deg bins
statistical uncertainty ($\sigma_{stats} = \sqrt{N}/N$) ~5 % per bin,
requires 400 counts / bin
$\theta_{rq} \sim 49$ deg
210 hrs
$\theta_{rq} \sim 65$ deg
267 hrs
$\theta_{rq} \sim 27$ deg
235 hrs
Entries 16779
Integral 8.475
Entries 15290
Integral 9.538
Entries 8858
Integral 7.408
e- arm:
20.5, 19.8, 19.0 [GeV/c]
5.7, 5.8, 5.9 [deg]
proton arm:
1.76, 2.51, 3.3 [GeV/c]
66.9, 59.0, 48.0 [deg]
(avg.~ 1.9 cnts/bin/hr)
(avg.~ 1.7 cnts/bin/hr)
(avg.~ 1.5 cnts/bin/hr)
$E_b = 22$ GeV $Q^2 = 4.5$ GeV^2
$P_{miss}^{bin} = 1 \pm 0.02$ GeV/c
counts / hour
Neutron Recoil Angle [deg]
0 1 2 3 4 5 6
0 20 40 60 80 100 120 140 160 180

Angular Distribution Rates @ 80 uA

10 deg bins



$\theta_{rq} \sim 65$ deg   235 hrs   (9.8 PAC days)

$\theta_{rq} \sim 49$ deg   210 hrs   (8.8 PAC days)

$\theta_{rq} \sim 27$ deg   267 hrs   (11.1 PAC days)

Total: 30 PAC days
(60 days)

$E_b = 22$ GeV

$Q^2 = 4.5$ GeV^2

Spectrometer Requirements (@ 22 GeV)

e- arm:			
20.5,	19.8,	19.0	[GeV/c]
5.7,	5.8,	5.9	[deg]

proton arm:			
1.76,	2.51,	3.3	[GeV/c]
66.9,	59.0,	48.0	[deg]

Spectrometer Upgrade: 60 days

Spectrometer (no Upgrade) : 200 days