Far-forward particle detection and second focus

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Forward detection at the EIC is unique

- In most colliders, the only way to detect very forward particles is to let them drift far downstream until a small angular difference separates them from the beam.
  - Acceptance is limited by the beam angular divergence at the IP (β^*).

- At the EIC, the longitudinal momentum loss of the scattered beam particles is not negligible, and is comparable to the intrinsic beam momentum spread.
  - In DIS, $dp/p \sim x$ (the momentum of the struck parton).
  - The beam momentum spread (1σ) is typically a few times 10^{-4}.

- Thus, for x sufficiently greater than the beam momentum spread (typically a 10σ margin is assumed), we should be able to detect *all* particles – even ones with $p_T = 0$.

- Heavy ions that change their rigidity (A/Z) behave like a that proton experienced a longitudinal momentum loss.
  - Losing one nucleon changes the rigidity by $\sim 10^{-2}$, which is also comparable to the beam momentum spread and a typical value of x in EIC kinematics (A-1 tagging possible)

A forward spectrometer for the EIC

- To separate $p_T = 0$ particles from the beam we introduce dispersion (D), which translates a longitudinal momentum loss into a transverse displacement.
  - dx = D dp/p, where dx is the displacement
  - With D = 0.5 m and dp/p = 0.01, the transverse displacement would be 5 mm.

- The beam size puts a limit on how close we can move our detector
  - The beam size depends on the emittance and β (focusing), but is
  - The emittance is global, but β can be adjusted as needed at the location of the detectors (Roman pots). The optimal configuration is to have a 2nd focus.
  - For comparison, the 1σ beam size at the focus in IR8 is about 0.2 mm.

$$\sigma = \sqrt{\beta\epsilon + \left(D\frac{\Delta p}{p}\right)^2}$$

- The dispersion (D) and beam momentum spread (dp/p) in the 2nd term limit how much one can benefit from a focus (β_2). However, since dp/p depends on ion and running conditions, one needs to choose a global optimum for β_2 – or make it possible to adjust it independently of β^*.

Beam momentum spread for protons

Table 4: Parameters used in the PYTHIA-8 implementation taken from Table 3.3 in the CDR. The designations h and v stand for horizontal (x direction) and vertical (y direction).

Species Energy [GeV]	Proton 275	Electron 18	Proton 41	Electron 5
RMS Emittance h/v [nm]	18/1.6	24/20	44/10	20/3.5
β^* h/v [cm]	80/7.1	59/5.7	90/7.1	196/21
RMS $\Delta\theta$ h/v [μrad]	150/150	202/187	220/380	101/129
RMS Bunch Length [cm]	6	0.9	7.5	0.7
RMS $\frac{\Delta p}{p}$ [10^{-4}]	6.8	10.9	10.3	6.8

From "Accelerator and beam conditions critical for physics detector simulations for the EIC"

At low energy, beam quality deteriorates making exclusive measurements a little more challenging than one might think

Beam momentum spread

- In general, momentum spread can be reduced at the expense of luminosity, but baseline beam parameters from the CDR were not optimized for momentum spread.

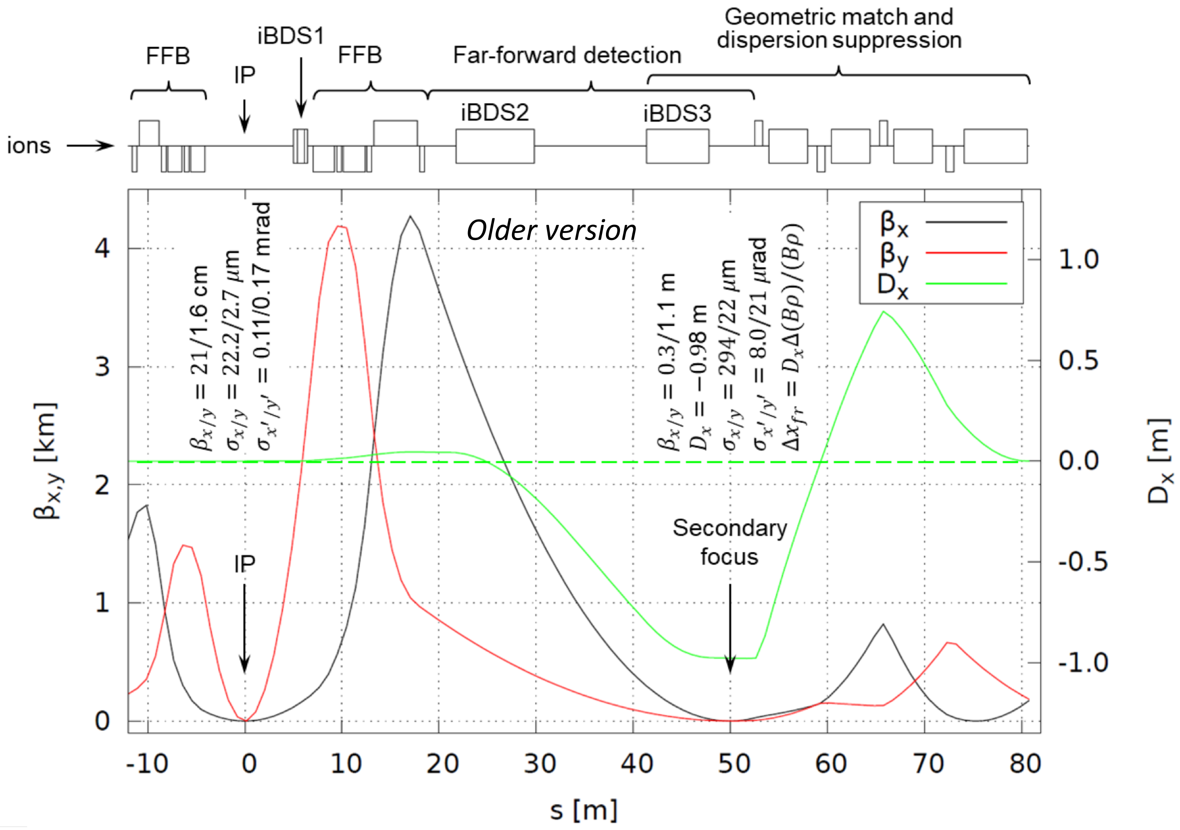
- A recent study made by the BNL accelerator group suggests that for protons there is significant headroom and that for 275 GeV protons and 10 GeV electrons a luminosity of 1.2 x 10^{34} can be reached with a momentum spread of 4.1 x 10^{-4}.
  - See details on next slide

Low-momentum-spread configuration for protons

	strong Longitudinal	
	p	**e**
	3833.845	3833.845
Energy, GeV/u	275	10
Center mass energy, GeV	104.880885	
Ion charge	1	1
Atomic number	1	1
Rest mass, GeV/u	9.38E-01	5.11E-04
gamma	293.09	19569.47
beta factor (v/c)	0.99999418	1.00000000
Number of bunches	1160	
Bunch spacing, m	3.30503879	3.30503879
Bunch spacing, ns	11.02	11.02
Bunch freq., MHz	90.707169	90.707169
Bunch population,e9	69	1.72E+02
Nucleon per bunch,e9	69	
Bunch charge, nC	1.10E+01	2.76E+01
Revolution freq.,kHz	78.195836	
Beam current,A	1.001	2.500
Peak Current, A	22.765	590.189
RMS Normal. emmit. X, e-6	2.94	391.000
Emmittance, X e-9	10.031	19.980
RMS Normal. emmit. y, e-6	0.300	26.000
Emmittance, y e-9	1.024	1.329
Beta*_x, m	0.72	0.361
Beta*_y, m	0.059	0.045
Beam size x, mm	8.50E-02	8.50E-02
Beam size y, mm	7.77E-03	7.77E-03
K, size ratio	9.14E-02	9.14E-02
kp, emittance ratio	1.02E-01	6.65E-02
Angle spread x, mrad	1.18E-01	2.35E-01
Angle spread y, mrad	1.32E-01	1.71E-01
Beam-beam param. X	1.31E-02	7.25E-02
Beam-beam param. Y	1.17E-02	9.97E-02
rms bunch length, ps	1.93E+02	2.33E+01
rms bunch length, cm	5.80E+00	7.00E-01
Momentum spread,1e-3	**4.10E-01**	5.80E-01
Long.emittance,ps.kev		2.65E+05
Beam disruption x	1.60E-03	1.46E-01
Beam disruption y	1.75E-02	1.60E+00
Space charge tune shift x	1.33E-03	8.96E-05
Space charge tune shift y	4.17E-03	
bunch length /beta*	8.06E-02	1.94E-02
Hourglass factor		9.40E-01
Pinch effect lumi enhancement		1.00E+00
Luminosity, e33		**12.211**

Calculation by E. Wang *et al.* from 6/25/2021 based on an optimized cooling scheme

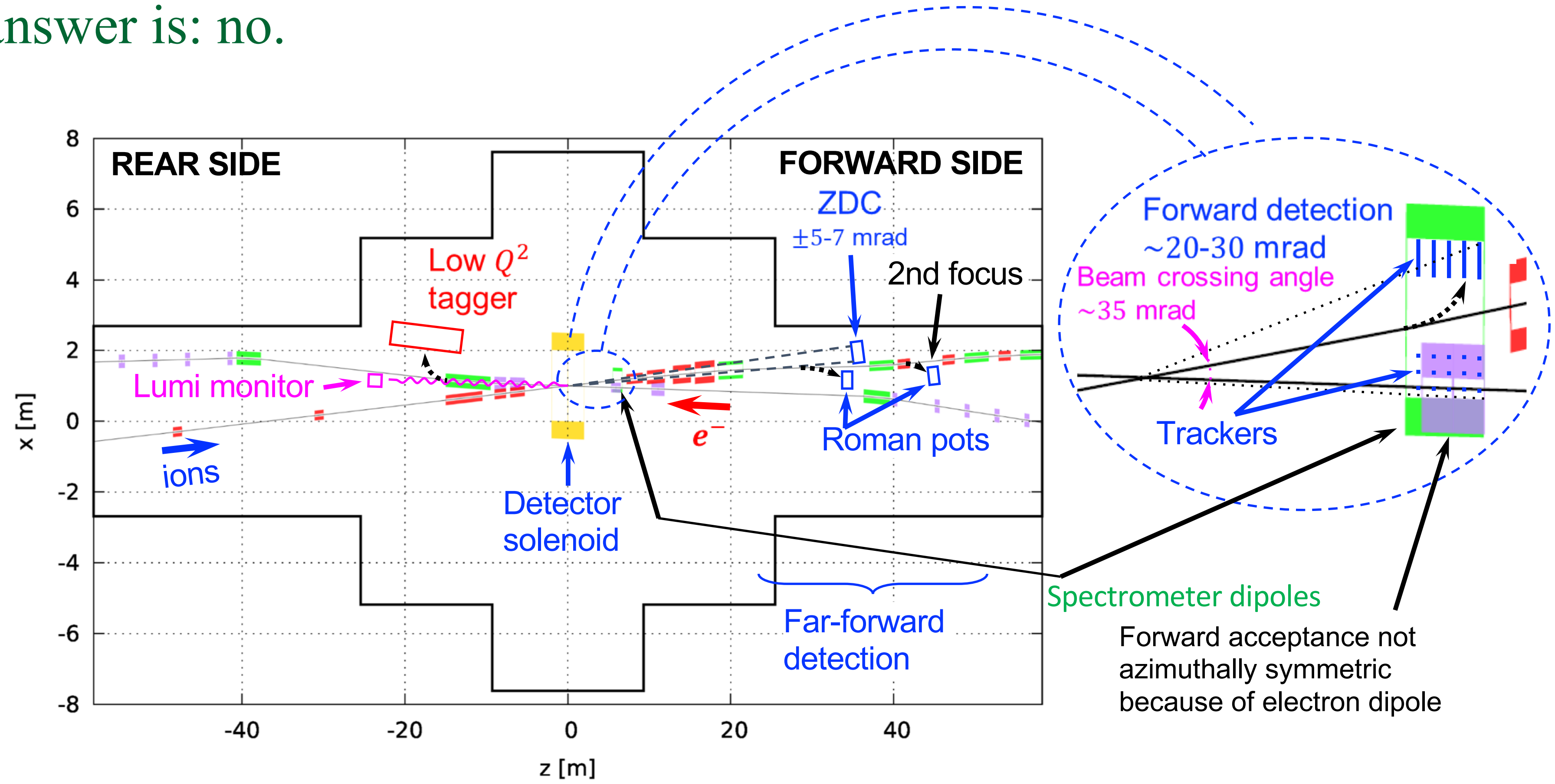
Beam optics



- IR magnets change the values of D and β.
  - Dipoles change D
  - Quadrupoles change β.
- An optics with a 2nd focus provides the best low-p_T acceptance at maximum luminosity (small β^*).
- A flat dispersion around the 2nd focus put $p_T = 0$ trajectories parallel to the beam, making angular measurements easier.
  - Disambiguates whether position in Roman pot is due to initial angle or longitudinal momentum

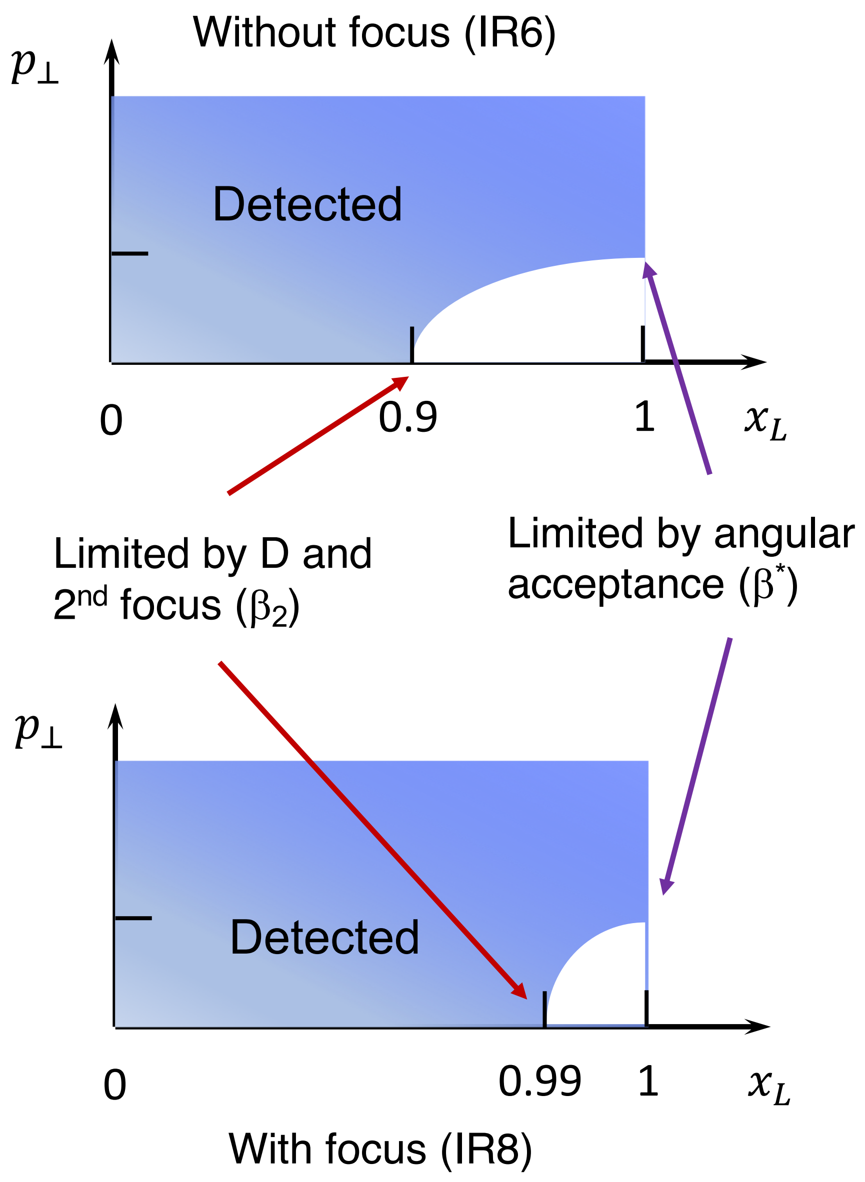
Does the crossing angle matter for low-p_T?

- the short answer is: no.



- However, the slightly longer answer is yes, because the dispersion depends on the bending angle of the dipoles and the drift space. And with a larger crossing angle the bending can be made larger, making it possible to reach a higher dispersion in a shorter distance.

p_T-acceptance



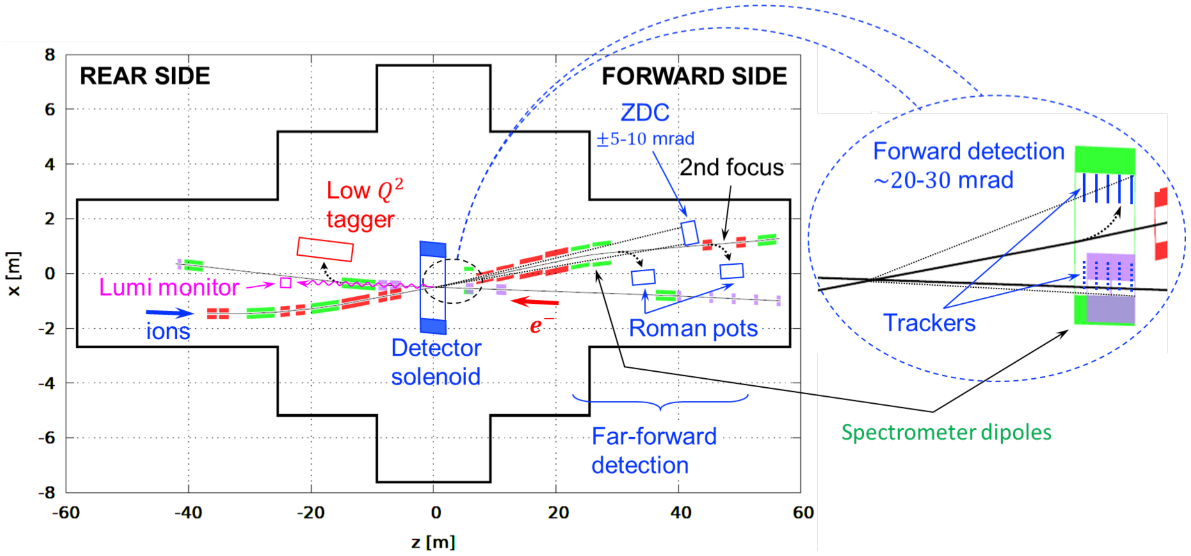
- A spectrometer is sensitive to changes in rigidity, which corresponds to x or a change in A/Z for ions

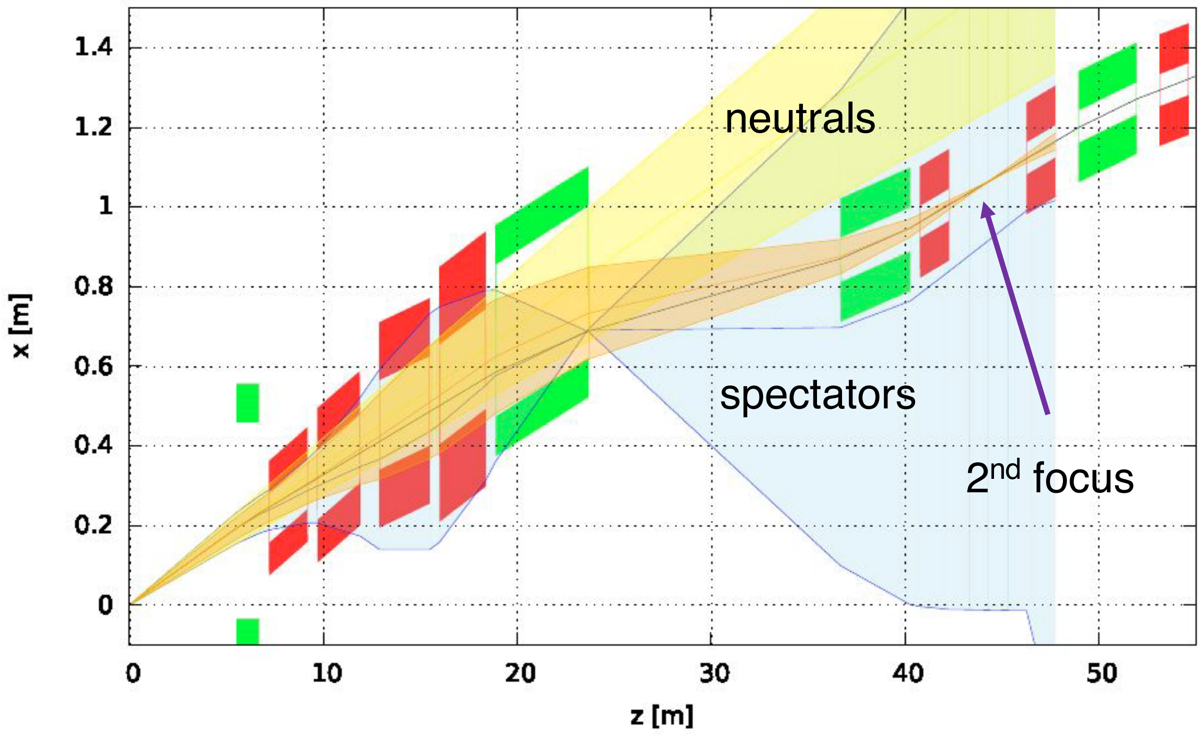
- It is, however, popular to use $x_L \sim 1 - x$ instead of x for acceptance studies for protons, which can make the connection to ions a little less intuitive

- The p_T acceptance depends on the acceptance in rigidity and angle
  - Rigidity acceptance depends on D and β_2 (2nd focus)
  - Angular acceptance depends on β^*

- Note that a 2nd focus greatly improves the p_T acceptance at low x (high x_L), where $p_T = 0$ is no longer accessible
  - Furthermore, the region that is "filled in" by the 2nd focus cannot be accessed in IR6 by changing β^*.

Large-p_T acceptance

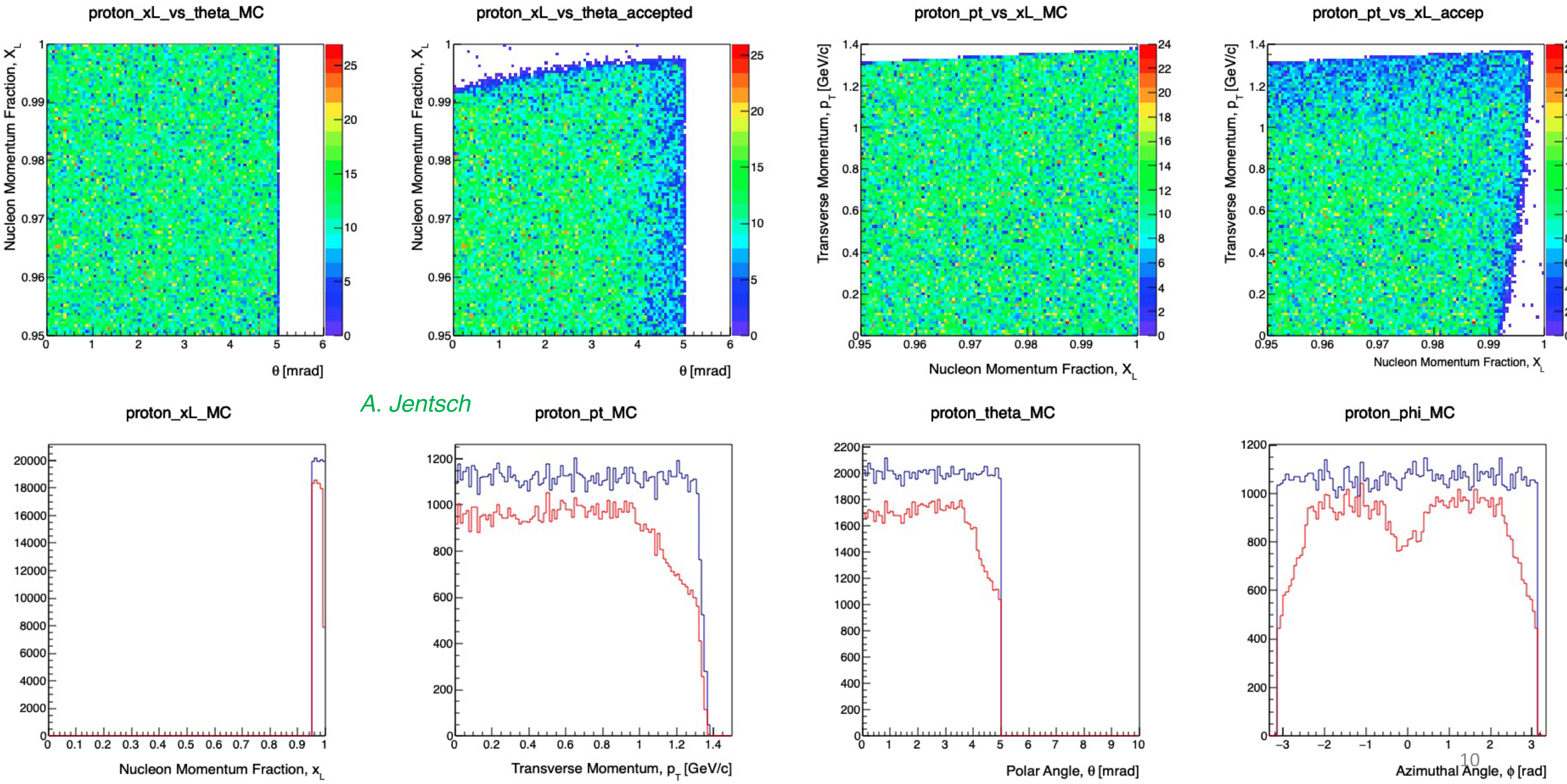




- In contrast to low-p_T, where acceptance is limited by the beam, there is no upper limit in p_T.
  - Particles that are not detected at the 2nd focus will be detected in the drift section before it, or in the B0 magnet in front of the quads (red), or in the hadron endcap of the central detector

- Losses will, however, occur in the transition between each region.
  - A global optimization of the transitions is important

MC study of 275 GeV protons with the default IR8 layout and CDR Δp/p



2^{nd} focus – examples of physics opportunities with nuclei

- Coherent scattering on light ions
  - Light ion detected
  - Transverse spatial imaging, diffraction, shadowing

Talk by W. Cosyn

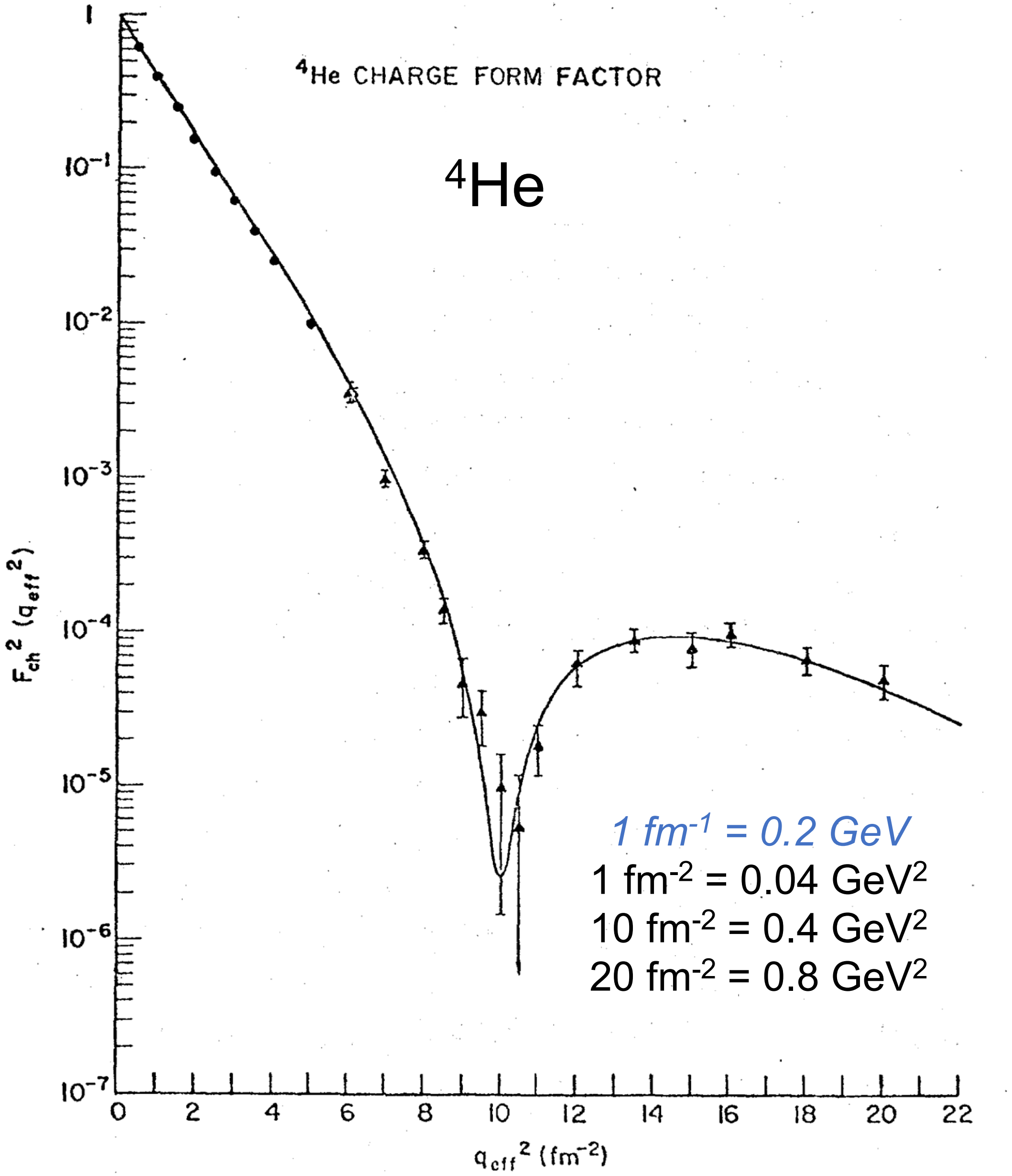
- DVCS on nuclei
  - Tagging of scattered light ion *or* veto of breakup of heavy ion
  - In combination with high-resolution photon detection

Talk by C. Hyde

- Coherent diffraction on heavy nuclei
  - Veto of breakup
  - Sensitive to gluon saturation
- Rare isotopes
  - Detection of heavy fragments
  - Excited states of exotic, short-lived nuclei

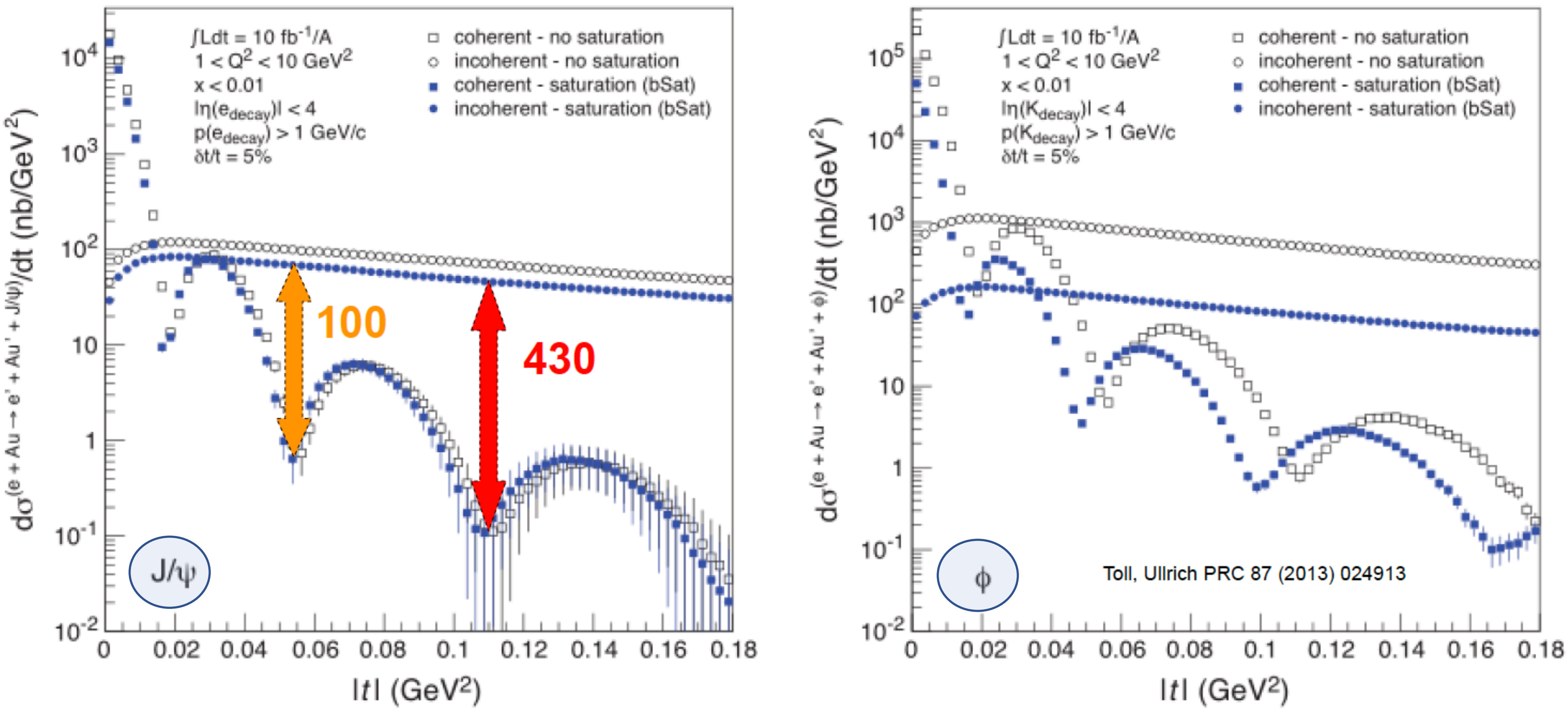
Exclusive coherent scattering on nuclei

Talk by W. Cosyn



- Detection of the reoiling ion cleanly removes incoherent backgrounds, but two effects conspire to make this more challenging than for protons
  - For any given momentum transfer (longitudinal and transverse), the response of the ion scales unfavorably with A, making it harder to detect.
  - For nuclei, which have a larger radius than a proton, the cross section peaks at lower t.
- For transverse imaging one thus needs to have much better low-p_T coverage than for protons
  - A 2nd focus is very important for achieving this
- High-p_T coverage is, on the other hand, easier than for protons, so light ions do not add any requirement for high p_T..

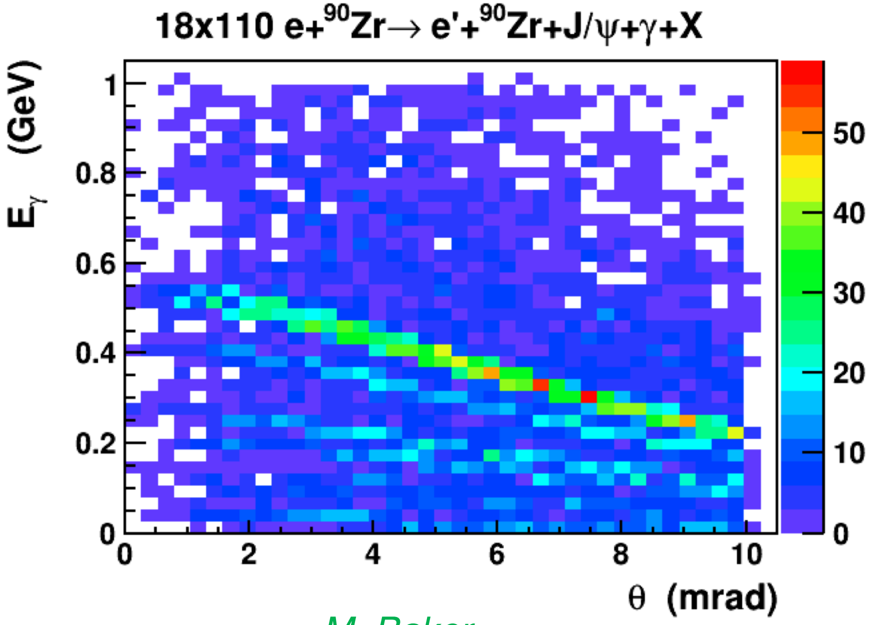
Coherent diffraction on heavy nuclei



- Coherent diffraction gives access to 2D imaging of nuclei and is sensitive to saturation
- Is there a way of cleanly suppressing the large incoherent background (as for light nuclei)?

A-1 veto for ^{90}Zr

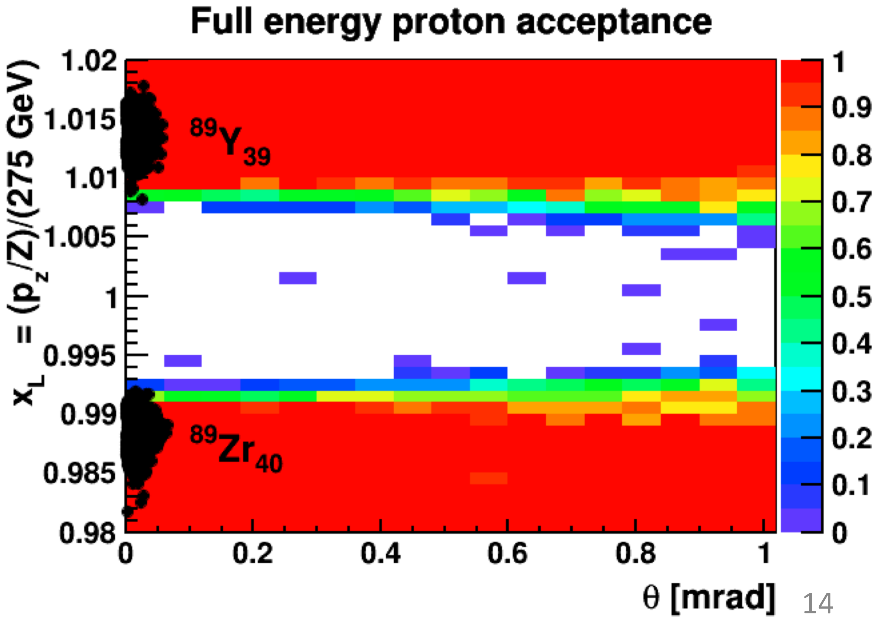
- The radius (~ $A^{1/3}$) of ^{90}Zr is 76% of ^{208}Pb, the maximum beam energy is 13% greater, and the incoherent background is much easier to veto.
  - This makes ^{90}Zr is a good option for studying saturation



M. Baker

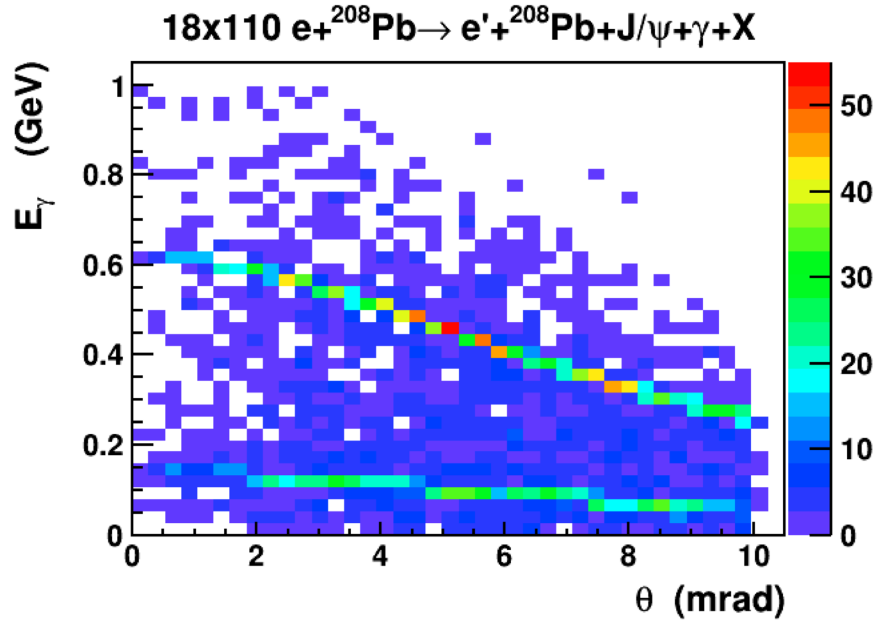
- The most difficult part of the incoherent background are events where only one neutron is lost.
  - The efficiency of the ZDC is too low to reliably veto a single neutron, and the photon acceptance is too low

- By tagging the A-1 nuclei, we can efficiently suppress the incoherent background.
  - The rigidity change after losing one neutron is 1%, which is well within the acceptance of the spectrometer



A-1 veto for ^{208}Pb?

- Can we do the same with ^{208}Pb?
- Maybe, but it is more difficult
  - Rigidity change after losing one neutron is 0.48%
  - The nominal beam momentum spread is 0.062%
  - This is a separation of only 7.7 σ.
- However. calculations by the BNL accelerator group show that a momentum spread of 0.032 can be reached with a slightly lower luminosity.
  - 1.7 x 10^{32} vs 5.9 x 10^{32} for 18 GeV e on 110 GeV/A ions.
  - This is a 15 σ. separation in momentum.
- This shoes that at least in principle it is possible to make a clean measurement of ^{208}Pb and intermediate nuclei



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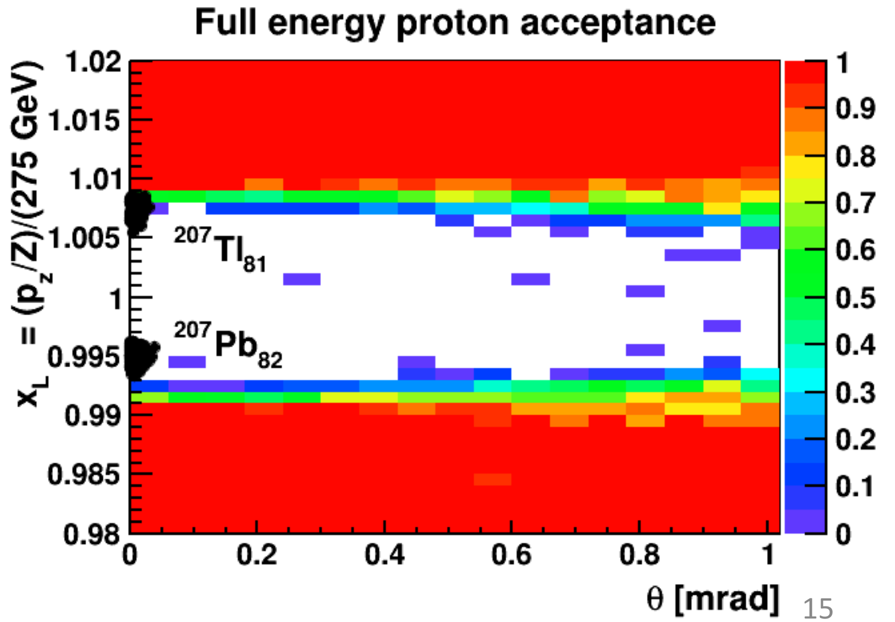


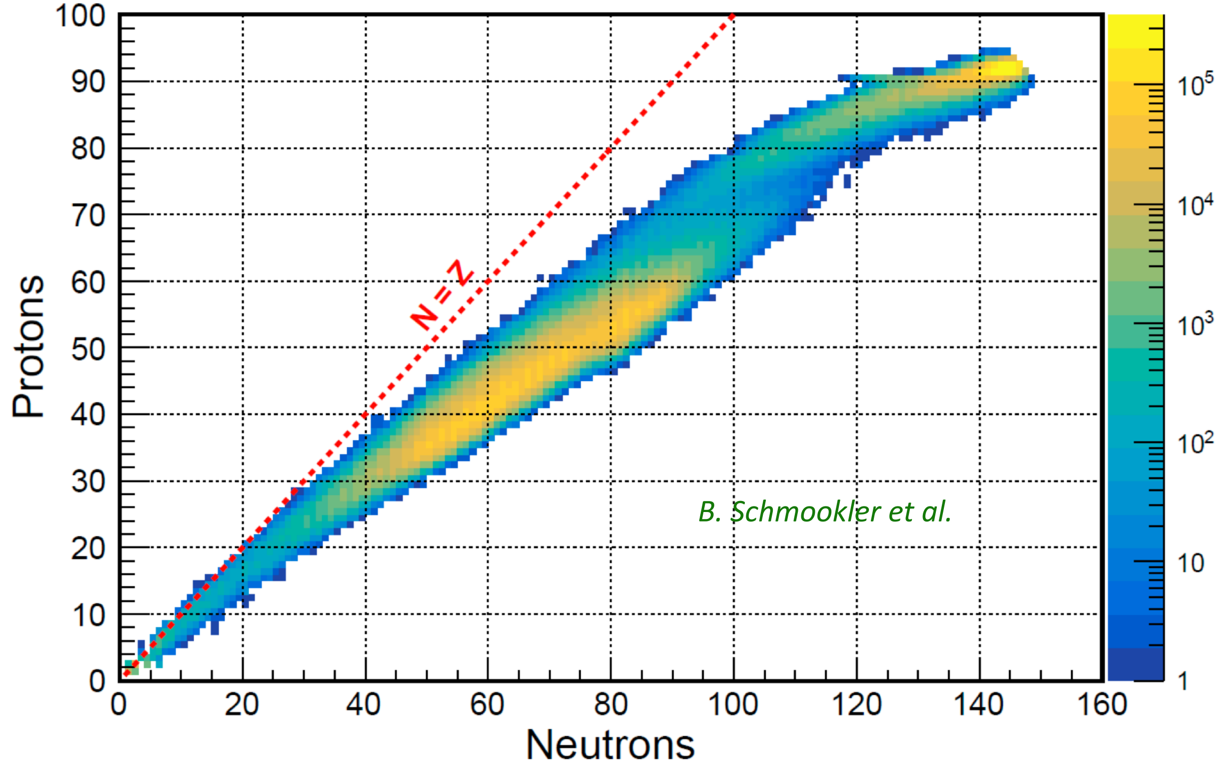
Beam momentum spread for heavy ions

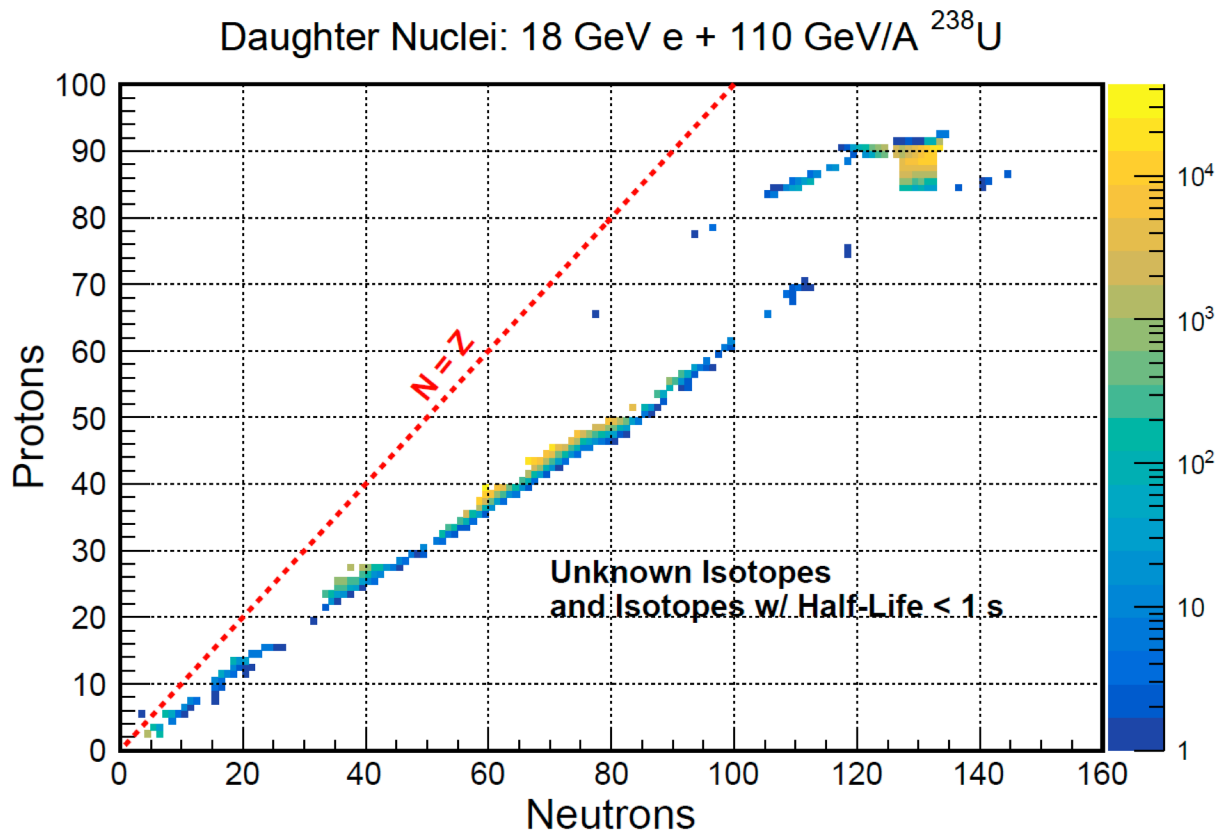
Table 3.5: EIC beam parameters for e-Au operation for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling.

Species	Au ion	electron	Au ion	electron	Au ion	electron	Au ion	electron
Energy [GeV]	110	18	110	10	110	5	41	5
CM energy [GeV]	89.0		66.3		46.9		28.6	
Bunch intensity [10^{10}]	0.08	7.29	0.05	17.2	0.05	17.2	0.036	17.2
No. of bunches	290		1160		1160		1160	
Beam current [A]	0.23	0.26	0.57	2.50	0.57	2.50	0.41	2.50
RMS norm. emit., h/v [μm]	5.1/0.7	705/20	5.0/0.4	391/20	5.0/0.4	196/20	3.0/0.3	196/20
RMS emittance, h/v [nm]	43.2/5.8	20.0/0.6	42.3/3.0	20.0/1.0	42.3/3.0	20.0/2.0	68.1/5.7	20.0/2.0
β^*, h/v [cm]]	91/4	196/41	91/4	193/12	91/4	193/6	90/4	307/11
IP RMS beam size, h/v [μm]	198/15		196/11		197/11		248/15	
K_x	0.077		0.057		0.056		0.061	
RMS $\Delta\theta$, h/v [μrad]	218/379	101/37	216/274	102/92	215/275	102/185	275/377	81/136
BB parameter, h/v [10^{-3}]	1/1	37/100	3/3	43/47	3/2	86/47	5/4	61/37
RMS long. emittance [10^{-3}, eV·s]	16		16		16		16	
RMS bunch length [cm]	7	0.9	7	0.7	7	0.7	11.6	0.7
RMS $\Delta p/p$ [10^{-4}]	6.2	10.9	6.2	5.8	6.2	6.8	10	6.8
Max. space charge	0.007	neglig.	0.008	neglig.	0.008	neglig.	0.038	neglig.
Piwinski angle [rad]	4.4	1.1	4.5	1.2	4.5	1.5	5.8	1.2
Long. IBS time [h]	0.33		0.36		0.36		0.85	
Transv. IBS time [h]	0.81		0.89		0.89		0.16	
Hourglass factor H	0.85		0.85		0.85		0.71	
Luminosity [10^{33}cm^{-2}s^{-1}]	0.59		4.76		4.77		1.67	

Calculation by E. Wang *et al.* from 6/25/2021 shows that a momentum spread of 3.2 x 10^{-4} can be reached at a luminosity of 0.12 x 10^{33} in collisions between 18 GeV electrons and 110 GeV/A Au ions (Pb similar).

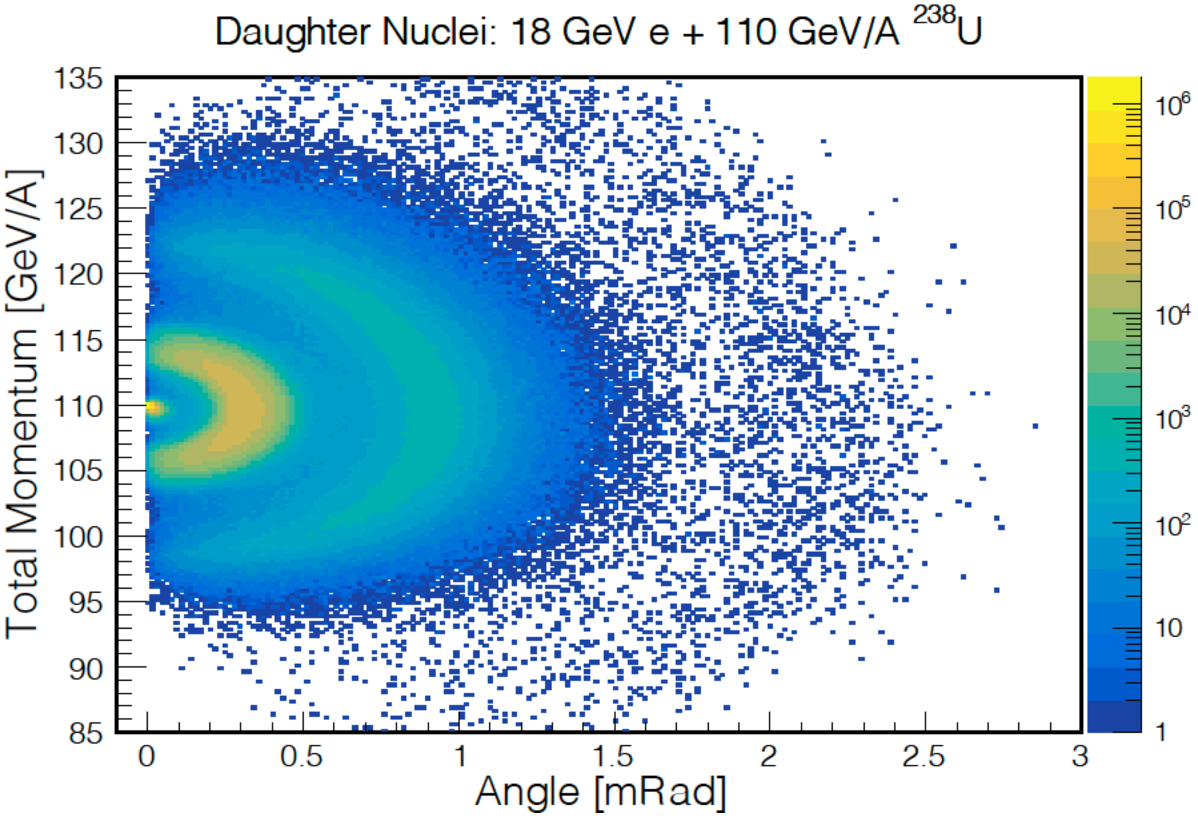
Isotopes produced in a minute of beam time

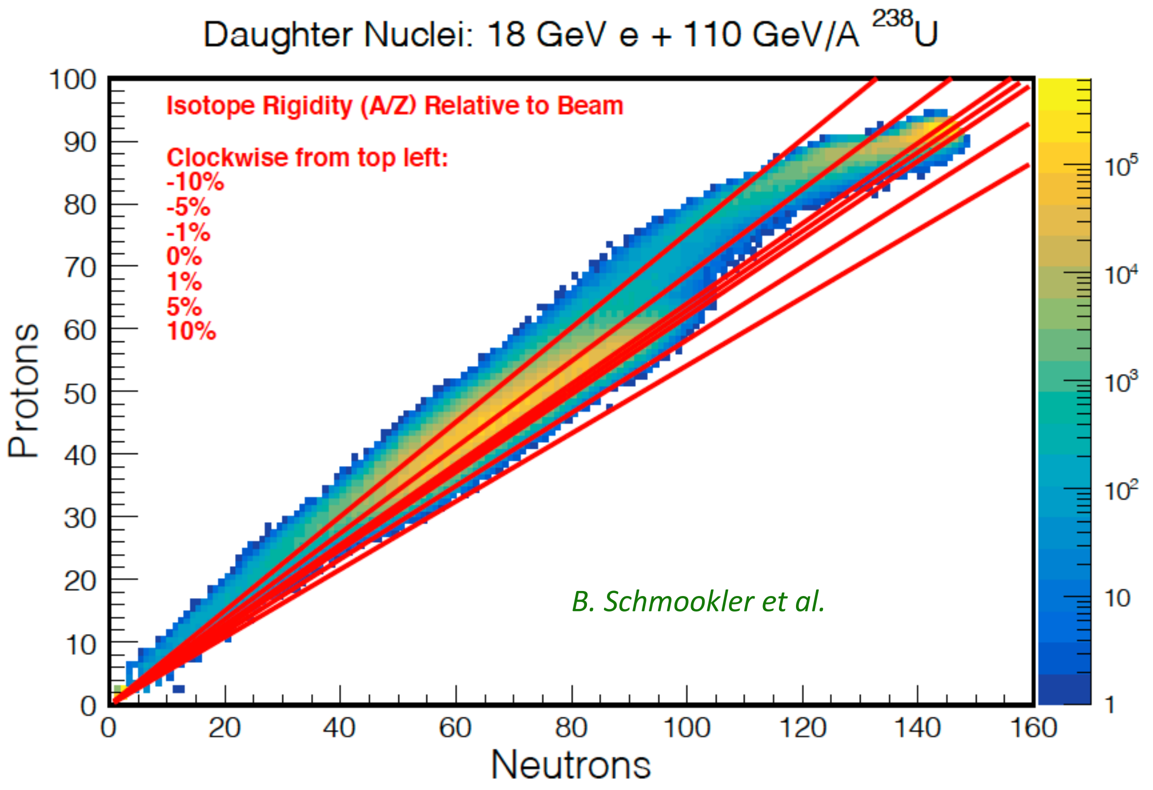




- Relativistic kinematics may give the EIC a unique ability to study the properties of short-lived rare isotopes in way that is complementary to FRIB.
  - No in-flight decays due to long lifetime in the lab frame
  - Decay photons are boosted forward and to energies above natural backgrounds, making it possible to study excited states of rare isotopes (a key goal for low-energy nuclear physics).

Impact of rigidity (x_L) acceptance





- In incoherent processes, heavy ions change their rigidity (A/Z) as they lose nucleons, but the change in angle is small.
- The rigidity acceptance of the forward spectrometer will determine how many of the produced isotopes can be detected

Thank you!