Proton polarimetry: RHIC→EIC

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for the RHIC polarimetry group

Polarization/polarimetry @ EIC workshop
June 29, 2020

- Polarimetry requirements
  absolute, beam details
- Implementation @ RHIC
  Hjet absolute, pC relative
- Results @ RHIC
  for experiments, beam properties
- Limitations @ RHIC
- Challenges RHIC→EIC

Polarimetry requirements

- Absolute polarization:

  absolute scale

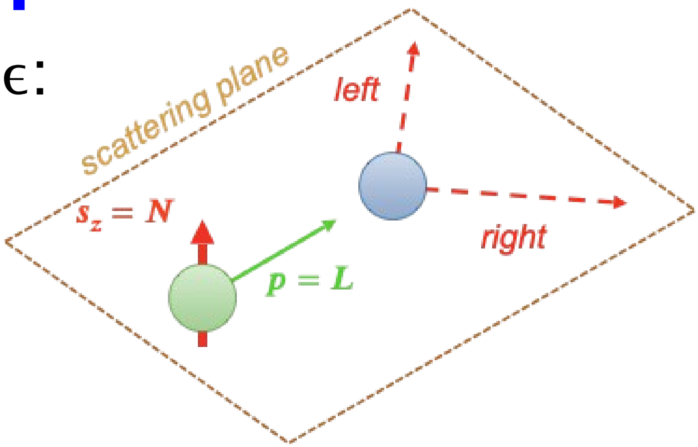
- Beam details:

  time dependence, bunch structure

Requirements: absolute polarization

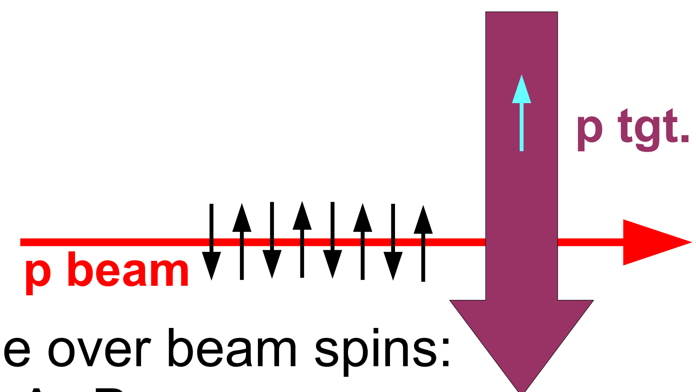
- Transverse L/R Single Spin Asymmetry (SSA) ϵ:

$$\epsilon = \frac{N_R - N_L}{N_R + N_L} = P \cdot A_N$$

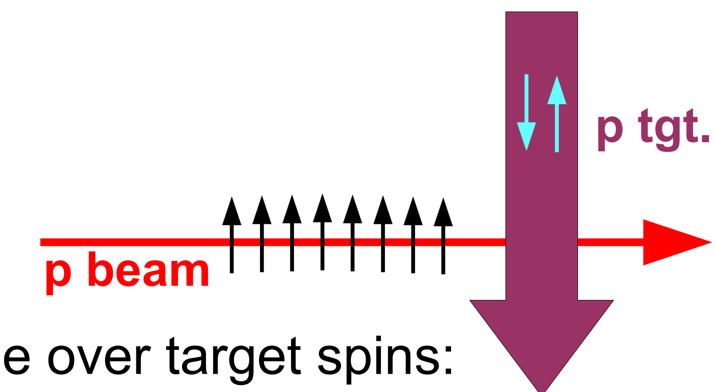


- Proportionality constant 'analyzing power' A_N:
  - lepton polarimetry: known from QED
  - hadron polarimetry? It's actually what spin physics studies

- Absolute polarimeter: polarized beam & target, both spin states ↑↓:



average over beam spins:
$\epsilon_{target} = A_N P_{target}$



average over target spins:
$\epsilon_{beam} = A_N P_{beam}$

- Measure ϵ_{beam}, ϵ_{target}, P_{target}: $$P_{\mathrm{beam}} = \frac{\epsilon_{\mathrm{beam}}}{\epsilon_{\mathrm{target}}} P_{\mathrm{target}}$$

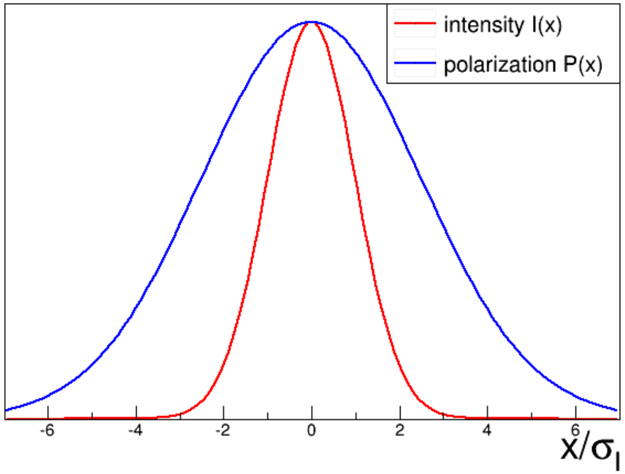
$\Rightarrow$ independent of details of A_N

Requirements: beam details

- RHIC stores last ~6-8 hours:

  polarization will inevitably decay: $P(t) = P_{t=0}\, e^{-t/\tau}$

  ⇒ need to measure polarization lifetime τ



- P not uniform transversely (x) across beam:
  - beam intensity: $I(x) \propto \mathrm{Gaus}(x,\sigma_I)$
  - polarization: $P(x) = P_0\, \mathrm{Gaus}(x,\sigma_P)$
- Transverse profile parameter: $R = (\sigma_I/\sigma_P)^2$
- Convolutions in 2d (x,y):
  - average P across beam: $P_{avg} = \langle P(x) \otimes I(x) \rangle_I = P_0/(1+R)$

  2 beams 1,2 polarizations P_1, P_2
  - single spin asym. w.r.t. 1: $P_{SSA1} = \langle P_1(x) \otimes I_1(x) \otimes I_1(x) \rangle_{I1,I2} = P_{01}/(1+½R)$
  - double spin asym.: $P^2_{DSA} = \langle P_1(x) \otimes P_2(x) \otimes I_1(x) \otimes I_2(x) \rangle_{I2,I2} = P_{01} P_{02}/(1+R)$
- Profile corrections needed for collider experiments

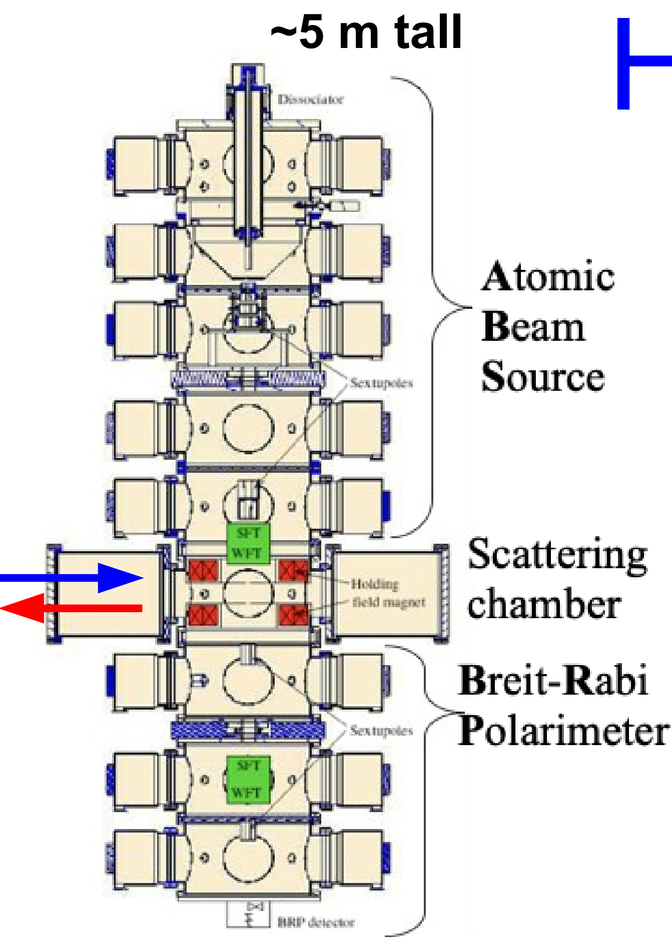
  ⇒ need to measure polarization profile R

W. Fischer and A. Bazilevsky, Phys. Rev. ST Accel. Beams 15, 041001 (2012)

Implementation @ RHIC

- Polarized hydrogen (Hjet) polarimeter:
  absolute P scale
  slow, coarse grained
- p-carbon (pC) polarimeter:
  relative P scale
  fast, fine grained
- pC/Hjet normalization:
  fill time dependence
  data groups for normalization

Hjet polarimeter



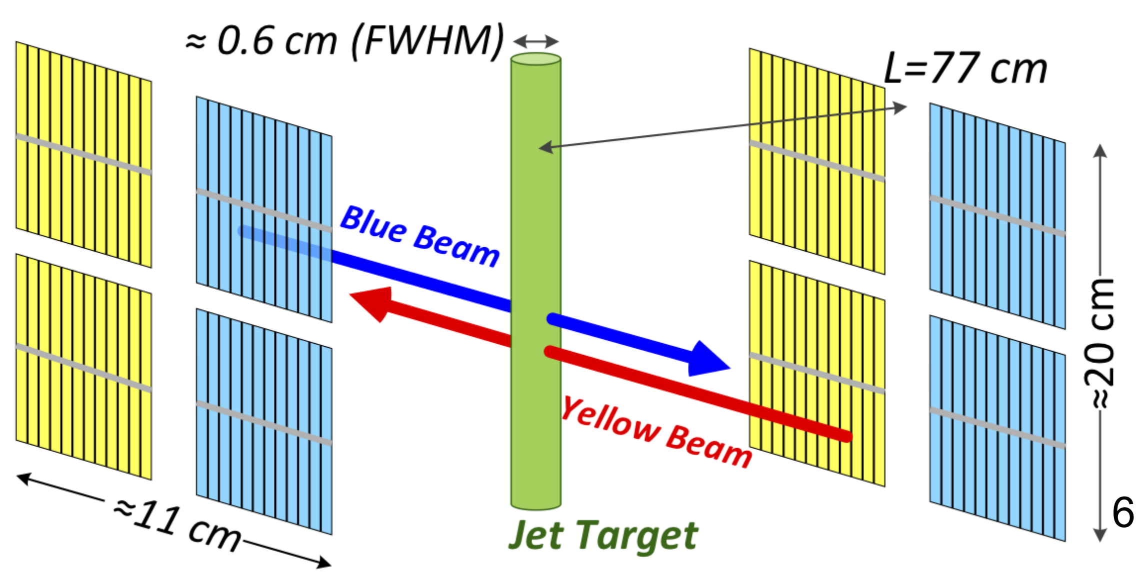
Substantial installation @ RHIC IP12

- Polarized atomic H source
  1.2×10^{12} atoms/cm^2
- Beams cross but don't collide
  inside target / scattering chamber
- P_{target} measured w/ Breit-Rabi polarim.
  $P_{target} \approx 96\%$

Inside scat. chamber:

- Si strip detectors
- Blu, Yel beams cross in target (but don't collide)
- Separate Blu, Yel downstream sides

12 strips, 3.75 mm pitch



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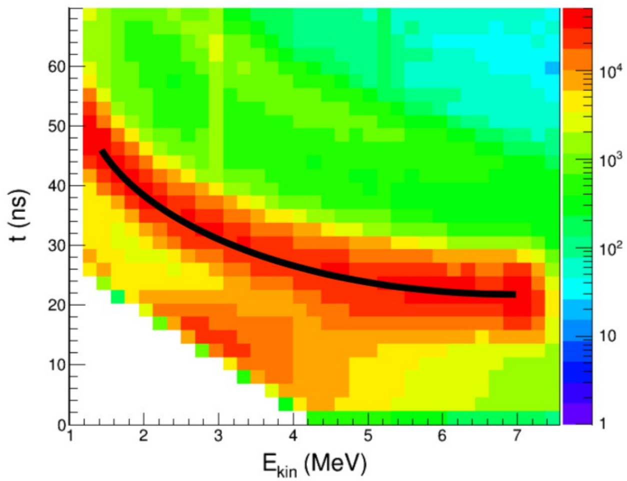
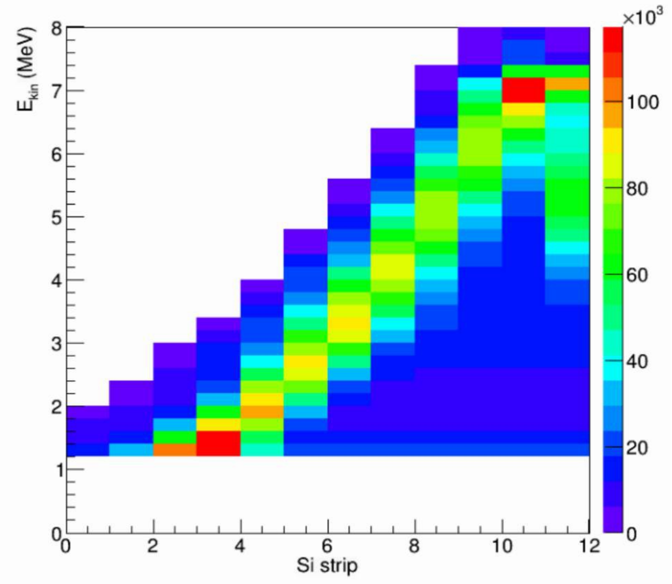
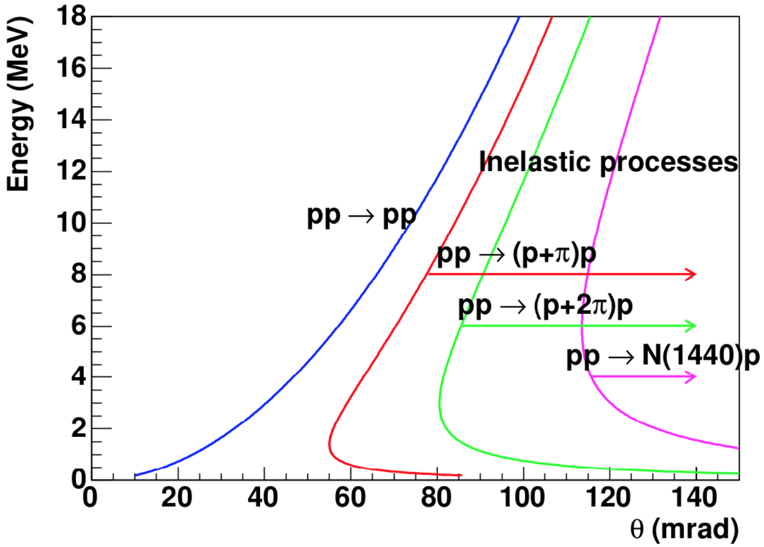
Hjet polarimeter



- Si strips E scale calibrated w/ Am,Gd α sources
- Si strips → WFDs: pulse amplitude & time
- Proton PID via TOF: TOF $\propto 1/\sqrt{E_{kin}}$ (banana curve)

  - Strip # $\propto$ scattering angle
  - Select E range / strip: reject inelastic pp → ppX:



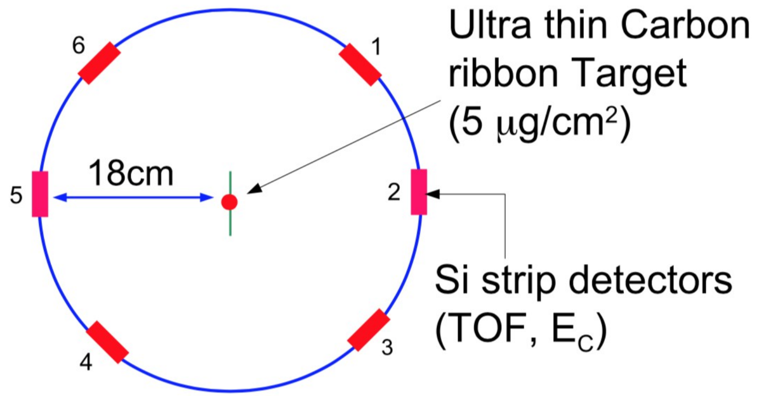


- Asymmetry from 'cross ratio' (extra slide)
  - count hits separately: L/R side detectors +/- beam spin states
  - cancelled: L/R detector acceptances +/- beam # protons

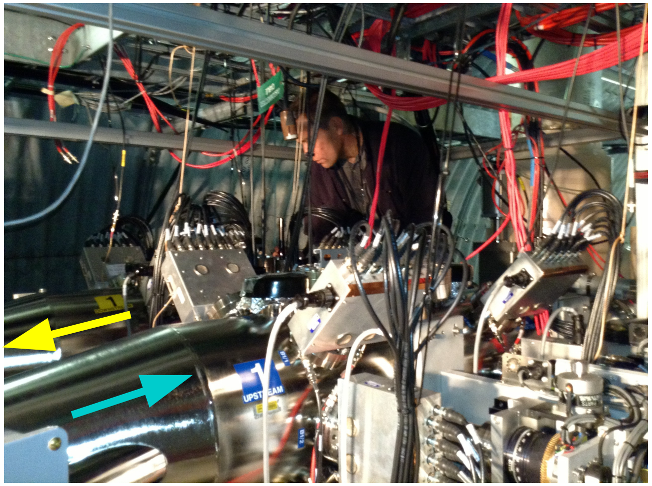
$$\epsilon = \frac{\sqrt{N_{R+}N_{L-}} - \sqrt{N_{L+}N_{R-}}}{\sqrt{N_{R+}N_{L-}} + \sqrt{N_{L+}N_{R-}}}$$

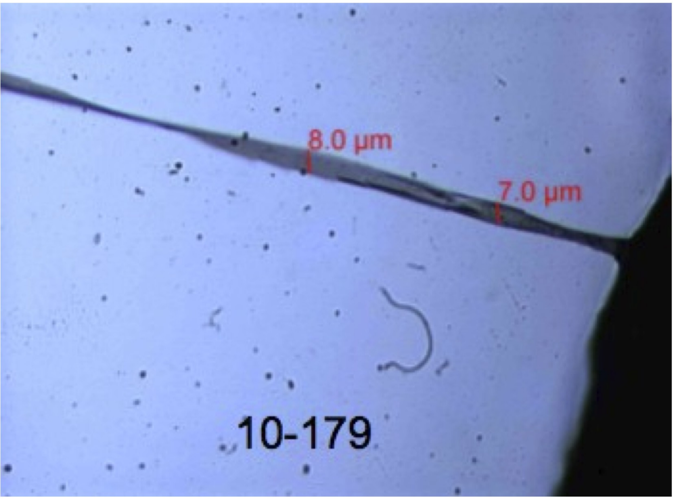
pC polarimeters

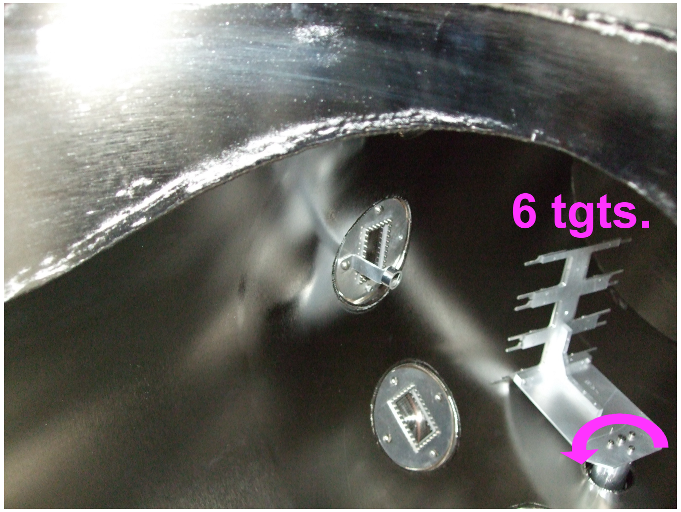
- 6 Si strip detectors around beam
- C target passed across beam:
  P(x) ⇒ polar. profile



- 2 pC polarims. / beam
  horiz., vert. tgt. each: 2d profiles



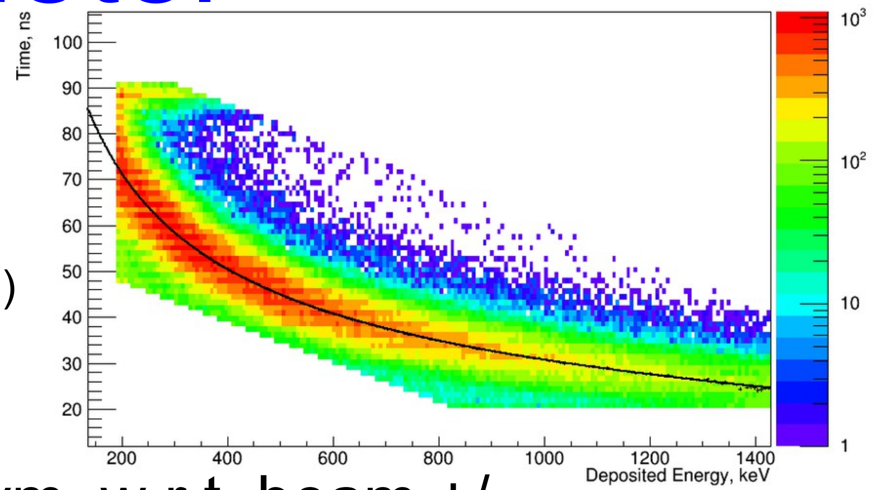


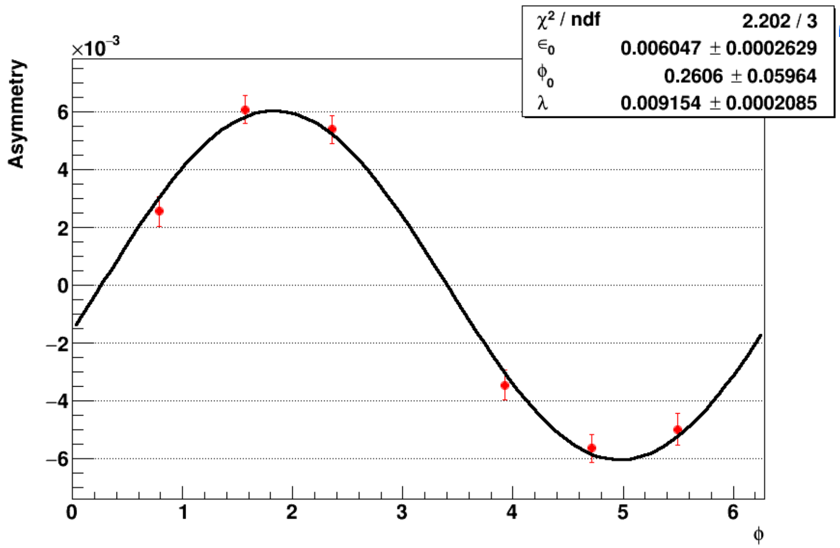


- Nominal target size:
  2.5 cm × 10 μ × 50 nm
  that's ~230 C atoms thick!
- Passed across beam & back
  ~2-5 sec. in beam each pass
  lifetime: few - few hundred passes

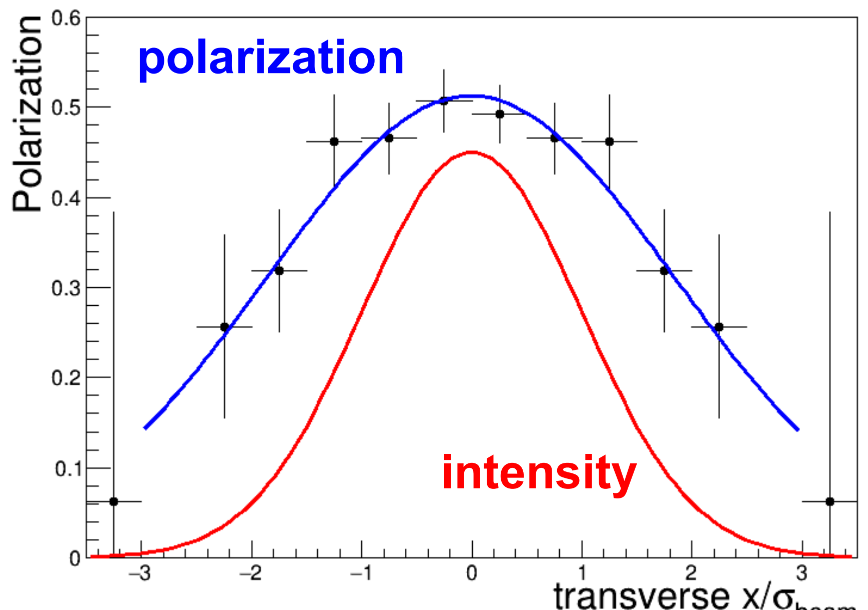
pC polarimeter

- E scale calibrated w/ Am,Gd α sources
- Si strips $\rightarrow$ WFDs: amplitude & time
- Carbon PID via TOF: TOF $\propto 1/\sqrt{E_{kin}}$ (curve)
- Fit to curve $\Rightarrow$ t0, Si dead layer





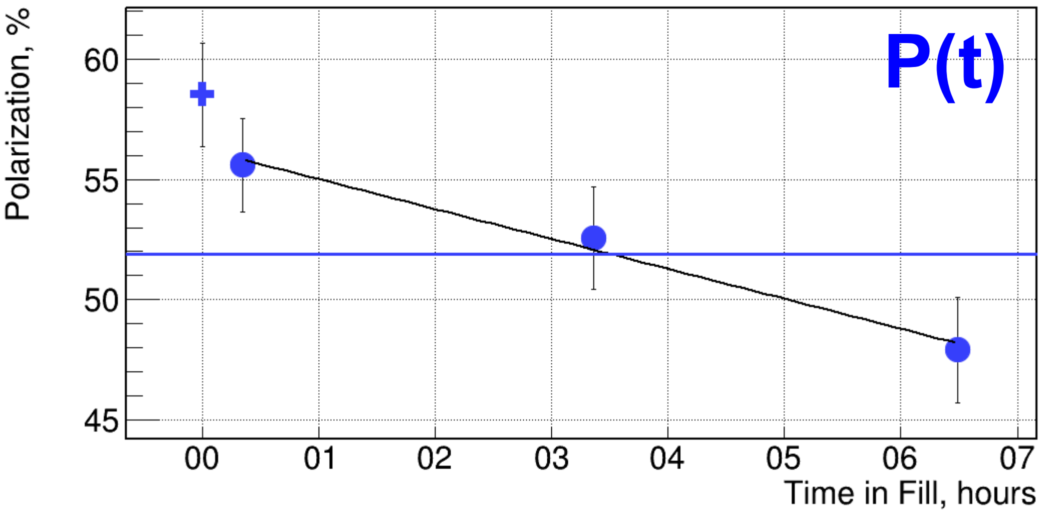
- Fit 6 det. asym. w.r.t. beam +/-, generalization of cross ratio:
  - max. asymmetry ϵ_0
  - beam spin tilt from vert. ϕ_0
  - asymmetry +/- beam λ

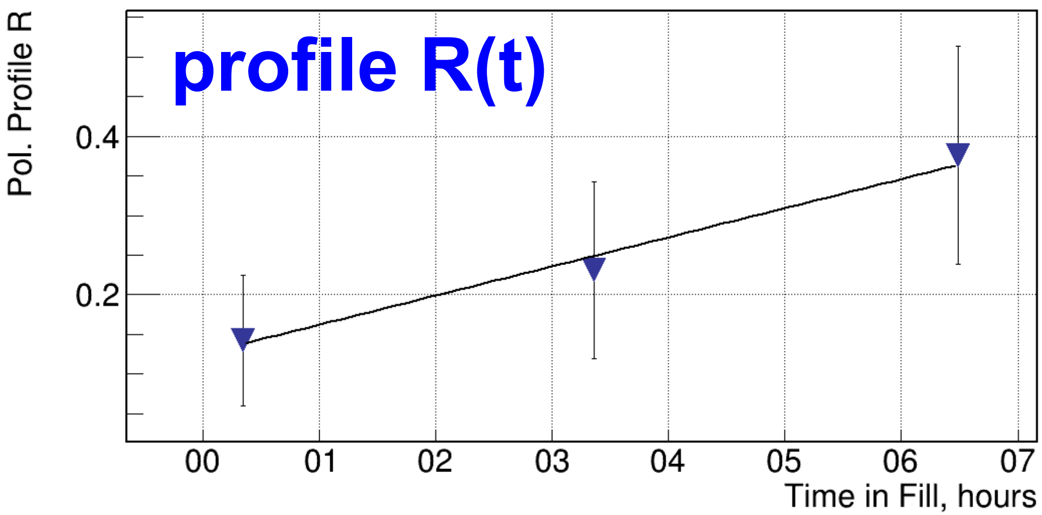


- Transverse x no direct measure rate$\rightarrow$x: $x/\sigma_{beam} \propto$ Gaus^{-1}(rate)
- Measure P in bins of x/σ_{beam}:
- $R = (\sigma_{beam}/\sigma_P)^2$

pC polarimeters

- pC measurements: before 24→255 GeV ramp (✚)
  start of physics store
  middle of physics store (or every 3 hours)
  end of physics store
- pC results, one polarim., one fill:





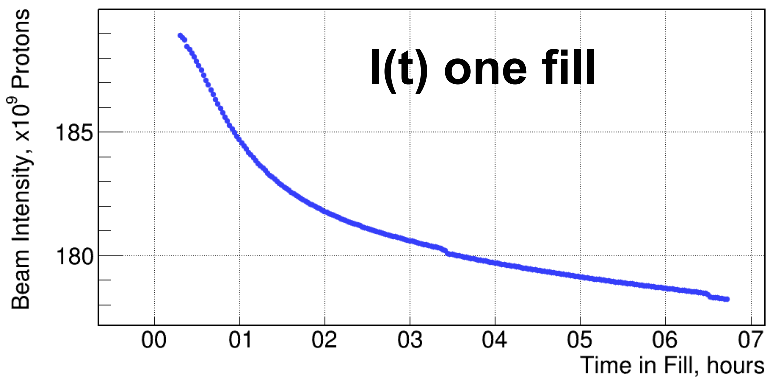
- Measured: $P \propto e^{-t/\tau} \approx 1 - t/\tau$; $\tau \approx$ 200-400 hours
  lifetime τ used in pC/Hjet normalization ↘

aside:

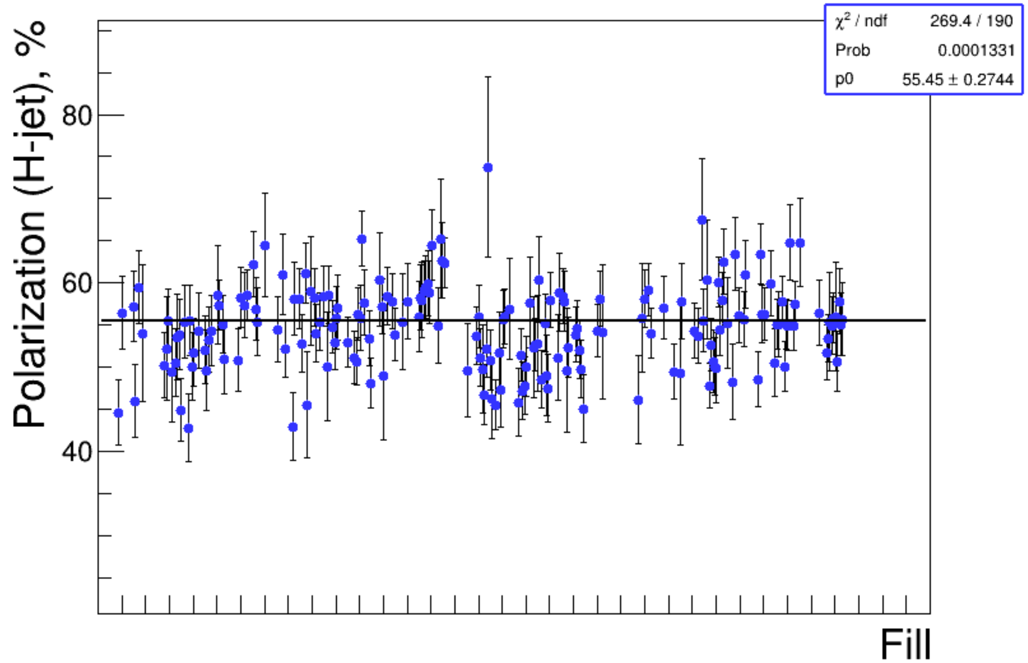
- P drops with time, R grows with time
- Beam spin physics: P↔R inversely related ✓

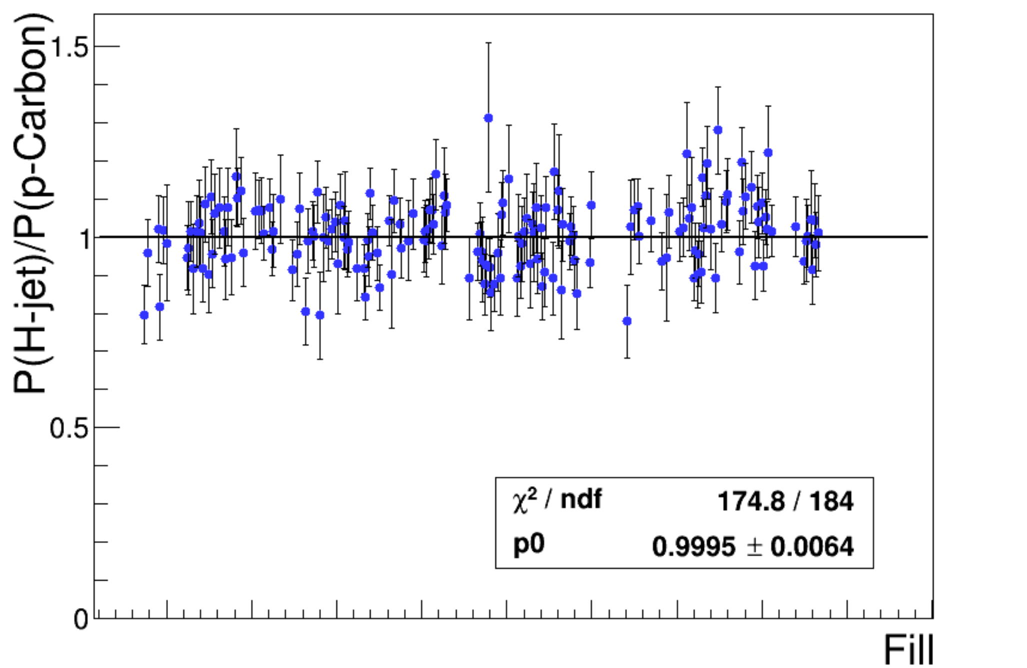
pC/Hjet normalization

- All Run17 Hjet Blu beam, each fill:
- Jet measures beam current I(t) weighted average P thru fill:
  $P_{Hjet} = \int P(t)I(t)dt \,/\, \int I(t)dt$



- pC fill result: correct to I(t) avg., normalize to P_{Hjet}:
- Normalization each year for:
  - each of 4 pC polarimeters
  - if statistics allow, individual targets of pC polarimeter
- Scale uncertainty: ~1-1.5%





Polarimetry results

- Results for collider experiments:

  profile corrected P

- Info for beam-spin physics:

  longitudinal polarization profile
  spin tilt from vertical
  spin tune measurements

Results for experiments

Fill	Energy	Start	Stop	BLUE P0	+- d(P0)	BLUE dP/dt	+- d(dP/dt)	YELLOW P0	+- d(P0)	YELLOW dP/dt	+- d(dP/dt)
20512	255	1487656902	1487658226	61.97	2.95	-0.18	0.40	64.06	3.30	-0.30	0.38
20519	255	1487734097	1487776187	53.80	2.28	-0.68	0.28	54.13	3.62	-0.30	0.38
20522	255	1487807184	1487862390	62.81	1.68	-0.29	0.14	54.75	1.76	-0.41	0.14
20532	255	1487906101	1487951885	63.73	2.04	-0.23	0.19	55.63	1.69	-0.42	0.16

etc.

- Polarization corrected with profile R for colliding Single Spin Asym. measurements: P_{SSA}
- Table provides P_{SSA} each beam, fill:
  - P_0, dP/dt: $P(t) = P_0 + dP/dt \cdot (t-t_0)$
  - Unix time stamp for t_0

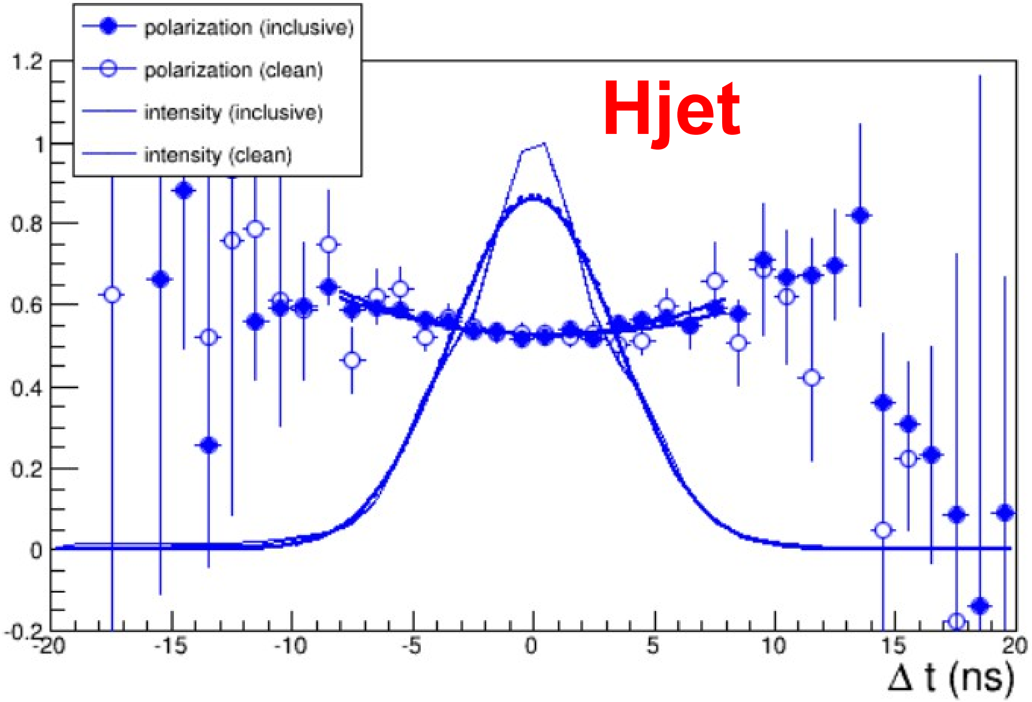
    specifies P for period in fill when data sets collected

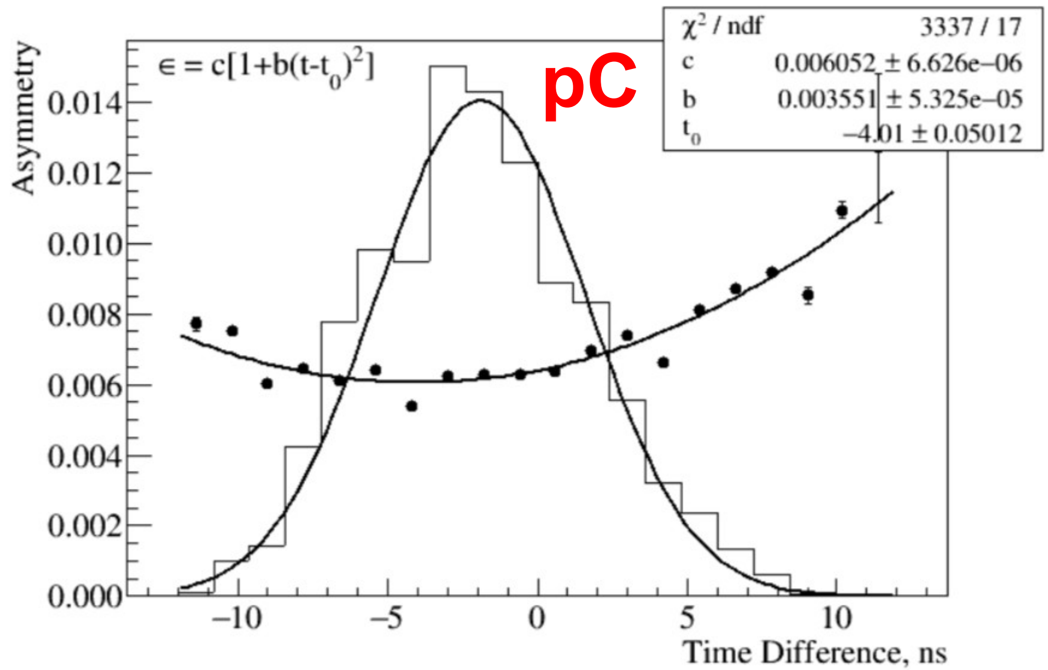
- For Double Spin Asymmetry, lowest order in R:

$$P^2_{DSA} \approx P_{SSABlu} \cdot P_{SSAYel}$$

Longitudinal polarization profile

- Well known transverse polar. profile:
  polarization drops at edges of beam
- Longitudinal profile?
- Asymmetry in t bins along proton bunch:

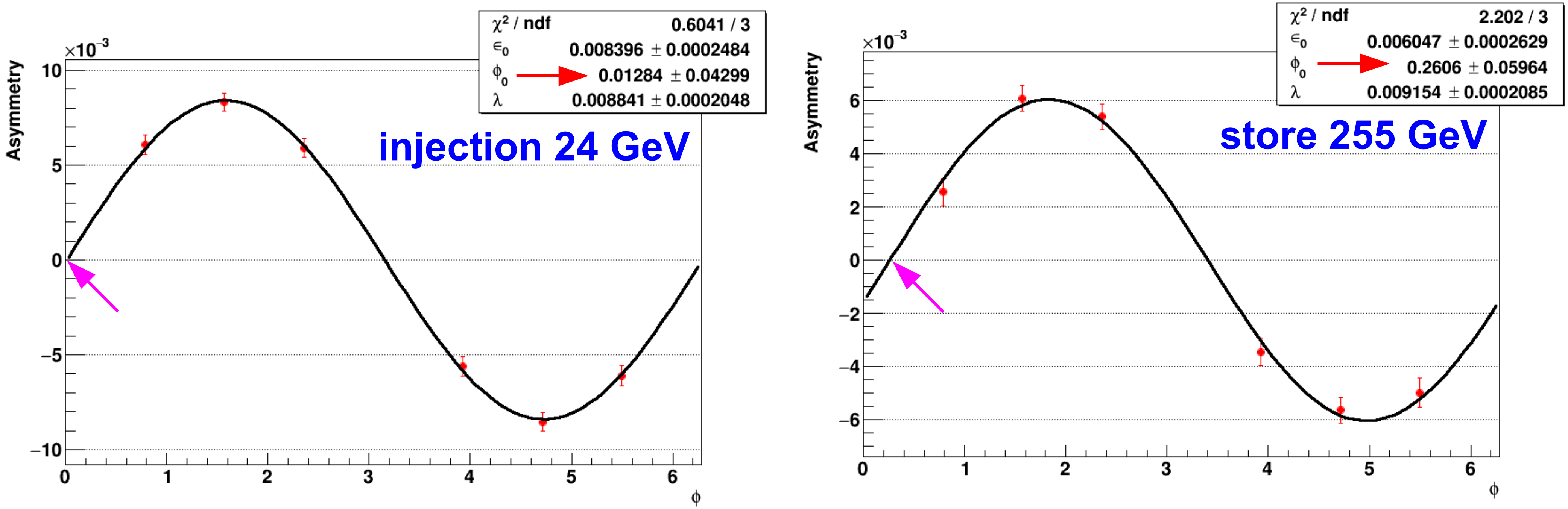




- Polarization lower center of bunch; beam-beam effect?
- Not anticipated, beam physicists considering...

Spin tilt

- pC asymmetry fit: ϕ_0, spin tilt from vertical
- Same fill, injection & store energies:



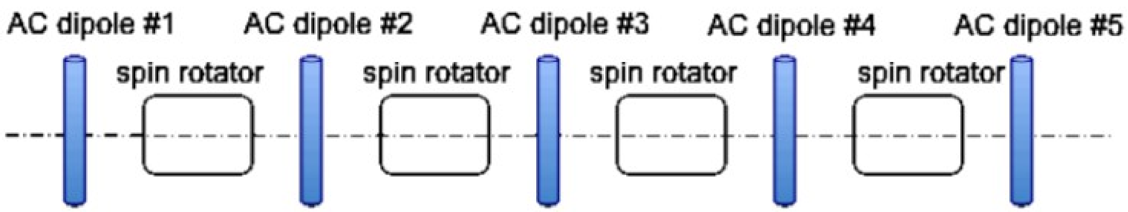
- No tilt @ 24 GeV, significant tilt @ 255 GeV:
  10-15° (Blu), 7-9° (Yel)
- No tilt other store energies 100, 250 GeV
- Not anticipated, beam physicists considering...

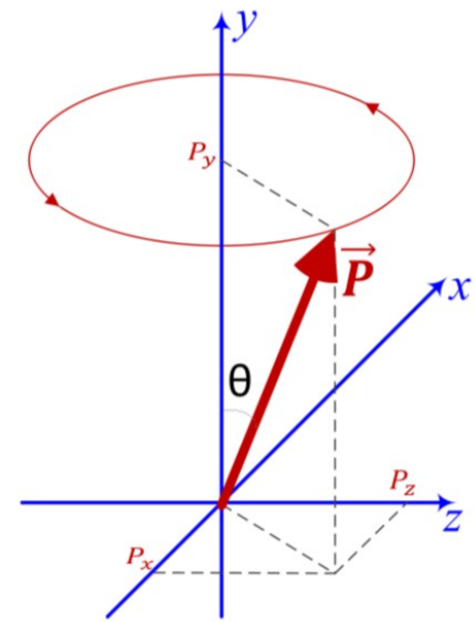
Also:

- Hjet only measures vertical spin component,
  correction applied in pC/Hjet normalization

Spin tune ν_s measurement

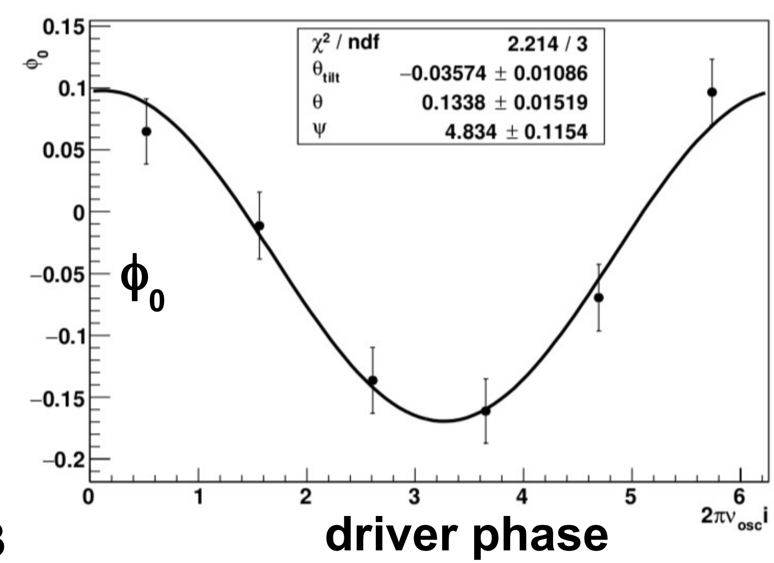
- 'Spin flipper' in RHIC: AC&DC dipoles, manipulate proton spin:





- Pulsed mode: flip spin orientation
- Continuous mode: precess spin about stable axis:
  driver ν_{osc}; opening angle $\tan\theta \propto 1/(\nu_s-\nu_{osc})$
- Measure $\theta \Rightarrow$ measure ν_s

- pC can measure spin tilt ϕ_0 in *xy* plane
- driver phase $\rightarrow$ pC DAQ:
  measure ϕ_0 bins of driver phase:
- Amplitude of ϕ_0 oscillation ~ θ
- 1st nondestructive measurement of ν_s
  @ high energy collider*



*H. Huang et al., Phys.Rev.Lett. 122 (2019) 20, 204803

Limitations @ RHIC

- Polarized atomic target H_2 contamination:

  Hjet P scale
- Backgrounds:

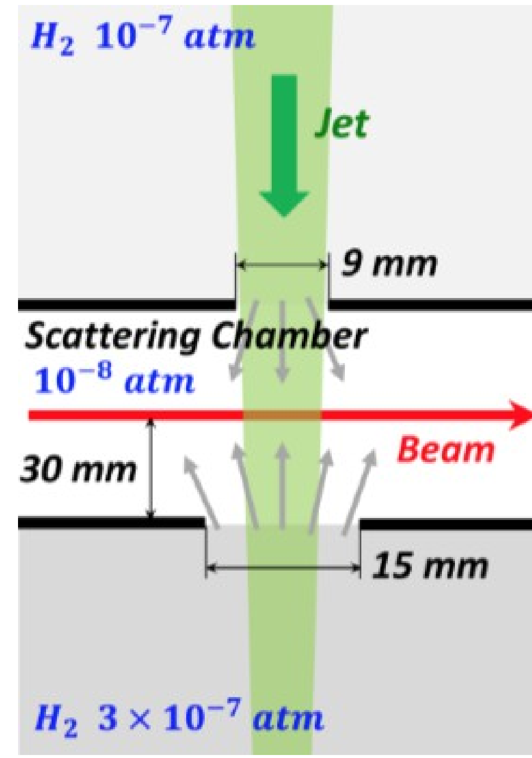
  Hjet pp→pp elastic selection
- E-scale calibration:

  $E_{measured} \leftrightarrow A_N$ analyzing power
- Carbon targets:

  lifetime
  non-rigidity
  E loss in target

Hjet molecular H_2 contamination

- Hjet target: polarized atomic $H_1\uparrow$
- Molecular H_2 contamination:
  likely unpolarized, dilution of target P
- Sources: H_2 not dissociated in beam
  recombined H_2 from exit chambers

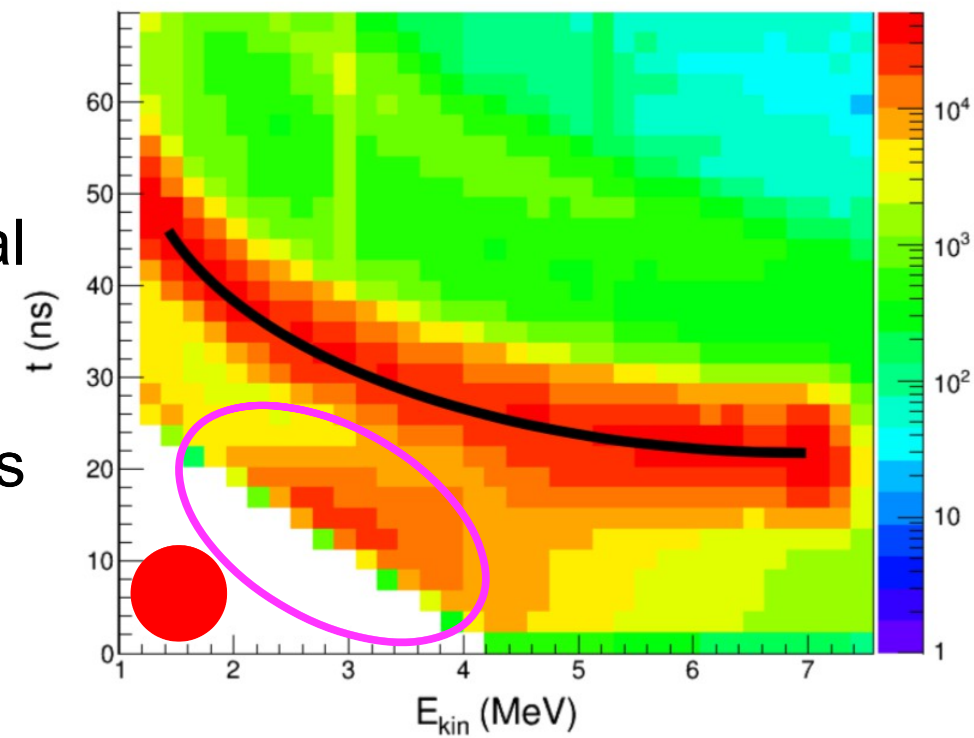


- Long time largest systematic uncert.:
  - test bench measurement 2000's, not *in situ*, large uncertainty
- 2017 *in situ* measurements:
  - special runs dissociator off, pure H_2 jet
  - collimators removed, measure broad distribution H_2 back-scattered from exit chambers

- Collimator removal handicapped elastic background measurement
- Needed: continuous monitor of H_2 contamination
- Limitation on Hjet P scale

Backgrounds

- Hjet select protons via TOF $\propto 1/\sqrt{E_{kin}}$ relation (curve):
- Absolute P measurement requires pure protons from pp→pp
- Clear background leaking under signal (from mountain ● outside cut)
- Background was estimated & subtracted from kinematic distributions
- No longer feasible when collimators removed for H_2 measurement

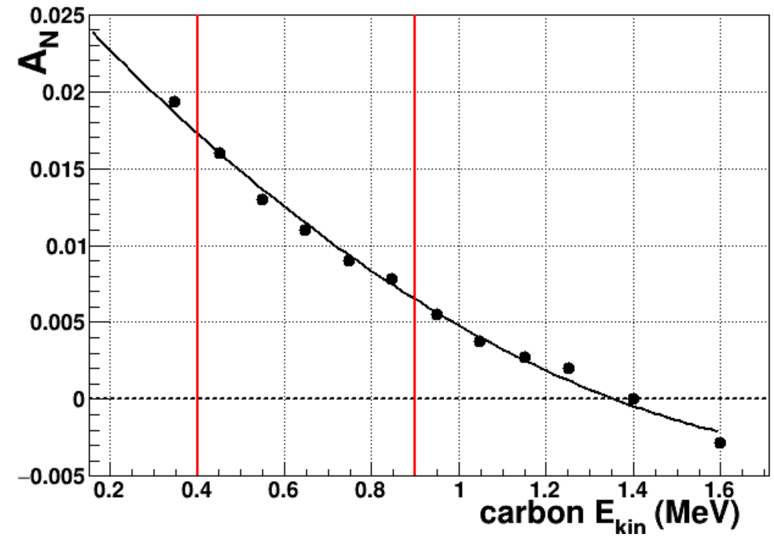


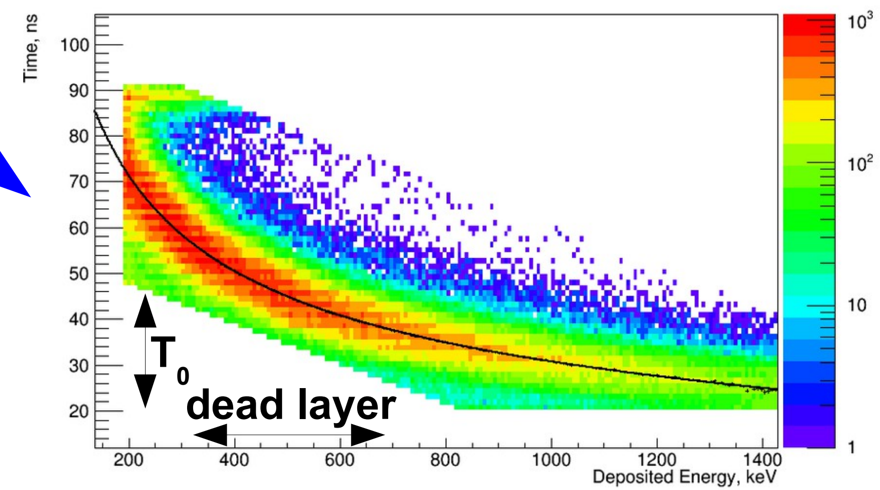
- Source not clear: beam bkg., pp→X prompts, other?
- Under study
- Limitation on Hjet P systematic uncert.

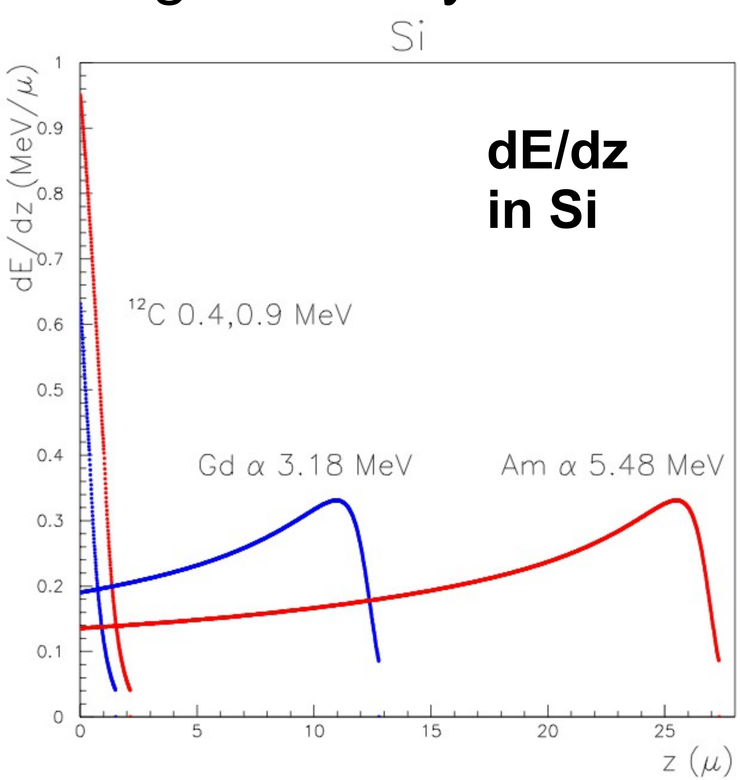
- Note: pC has similar bkg. under carbon signal
- Not serious, calibrated out in pC/Hjet calibration
- But will be problem at EIC, more later...

E-scale calibration

- Measure carbon $0.4<E_{kin}<0.9$ MeV
- A_N steep dependence on E_{kin}: sensitive to E-scale calib.
- Fit to TOF vs. $E_{deposited}$ params.:
  - T_0
  - Si dead layer E_{kin}-$E_{deposited}$
- Significant systematics





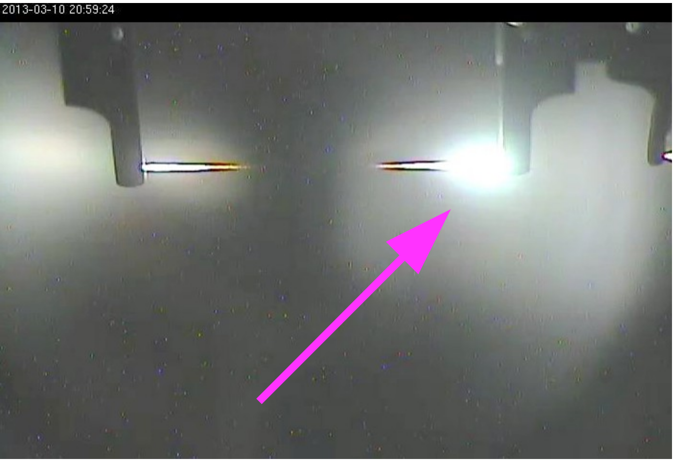


- dead layer ~ 0.2 μ
- α calibration: negligible effect from dead layer
- $0.4<E_{kin}<0.9$ MeV carbon range 1-2 μ: dead layer 10-20% effect on C energy
- Large syst. uncert.: dead layer, E calib.

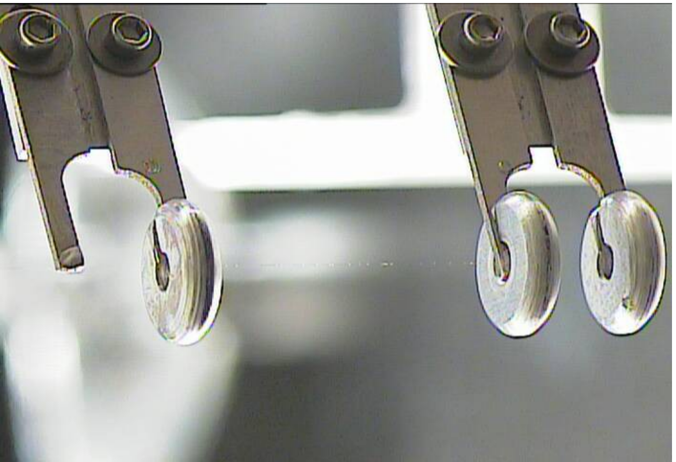
C target lifetime

- Targets often happily passing through beam:

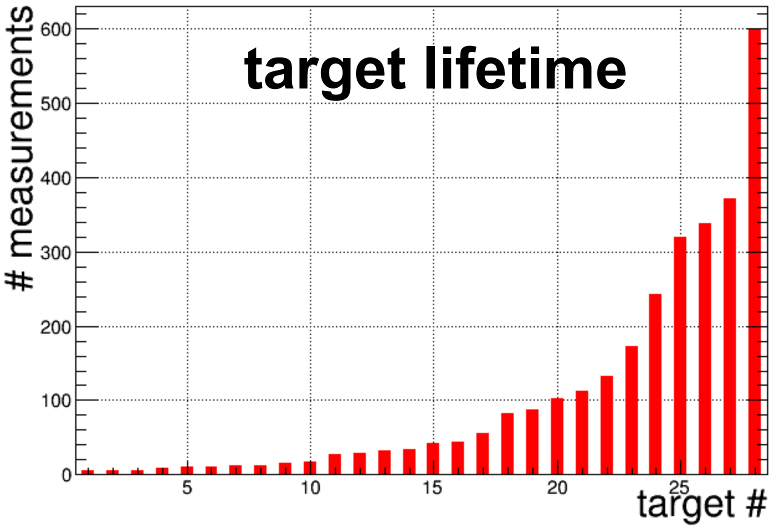
- But eventually:



- Heating at edge
- Discs added, reduce |E| field, > lifetime:

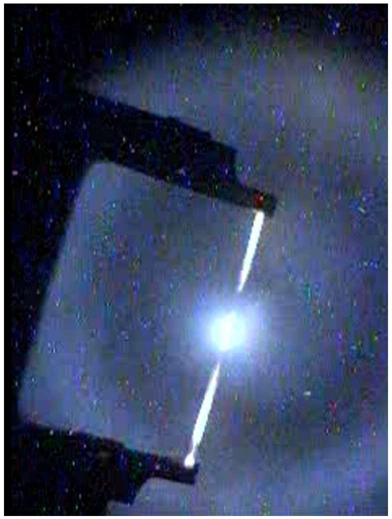


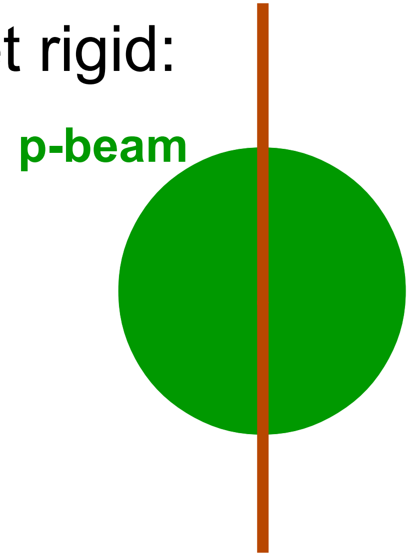
- Still, targets survive few - few 100's passes thru beam:
- Break:
  → new target
- Systematics (A_N) different targets
- Lose all 6 targets on ladder: break in RHIC ops to replace



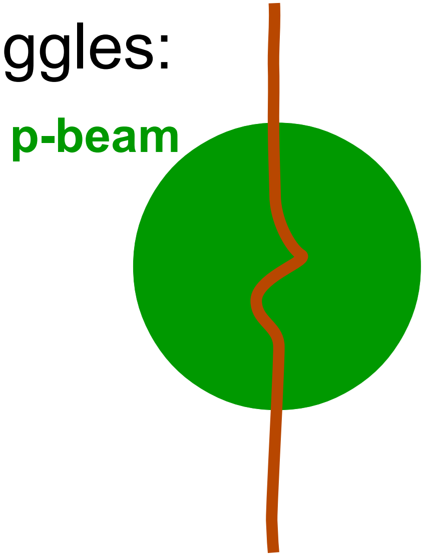
C target non-rigidity

- Sometimes target rigid:





- Sometimes target wiggles:



- Measure of profile R (slide 9) requires rate ↔ transverse position related:

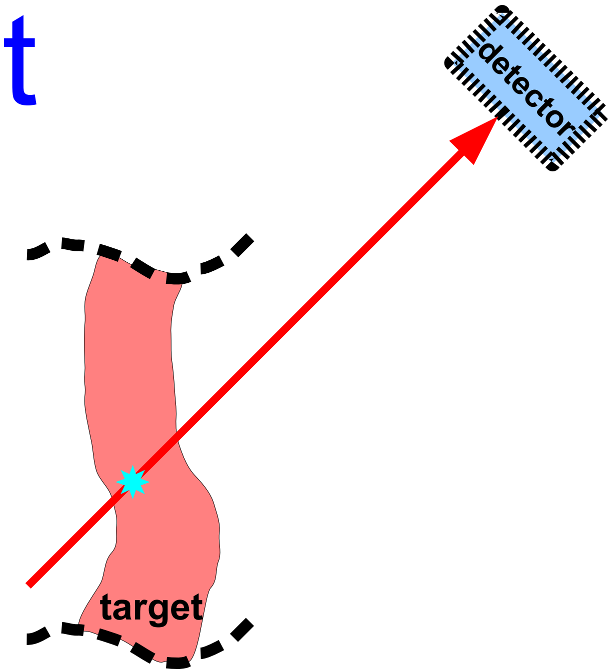
$$I(x) \propto \mathrm{Gaus}(x,\sigma_I)$$

- Only true for rigid target; not true:
  - target covers varying values of x
  - target material in beam varies with x
- Limiting systematic effect on profile R

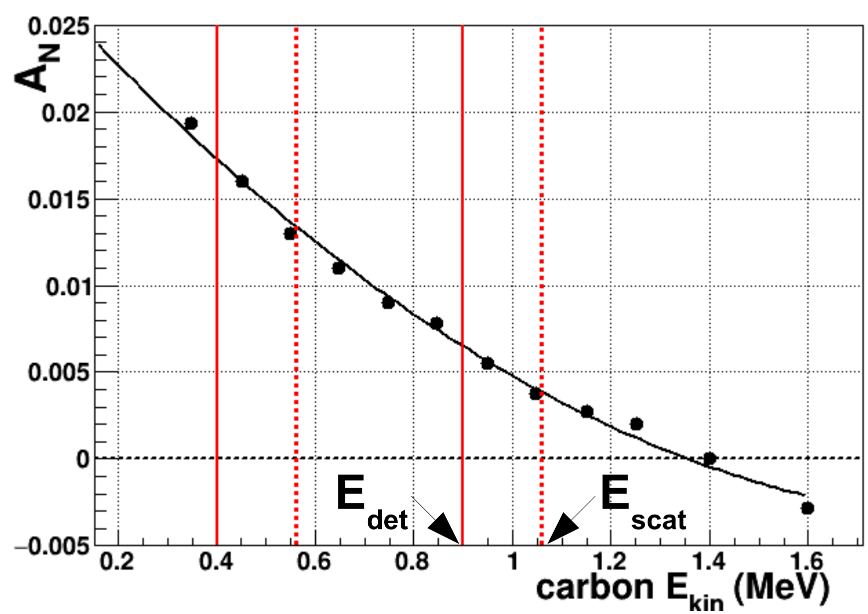
E loss in target

- pC→pC scattering inside target
- Recoil C passes through target material en route to detector
- Loses energy via dE/dx: $E_{scat} \rightarrow E_{det}$
- Nominal target thickness 50 nm but target orientation varies: Δx few 100 nm

  $E_{scat} - E_{det} \sim 100$ keV



- Asymmetry $A_N(E_{scat})$, measure in $0.4 < E_{det} < 0.9$ MeV
- Lower A_N from higher E_{scat}:



- Varying: target orientation

  → E loss

  → measurement A_N
- Limitation on stability pC measurement

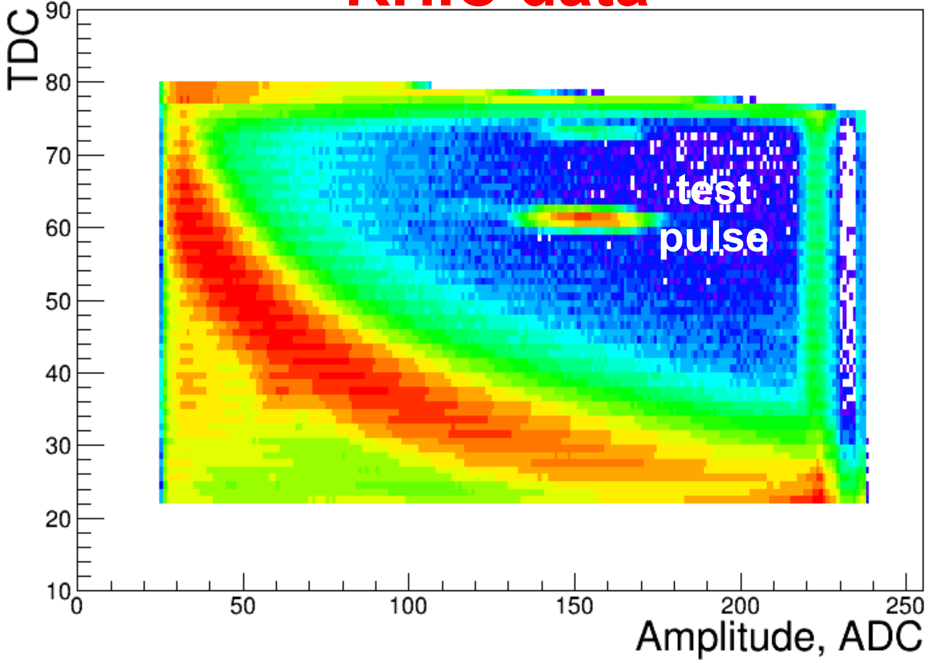
Challenges RHIC→EIC

- High bunch ×ing frequency:
  TOF > bunch spacing
  overlap signal/bkg. different bunches
- Target viability:
  heating from RF, dE/dx

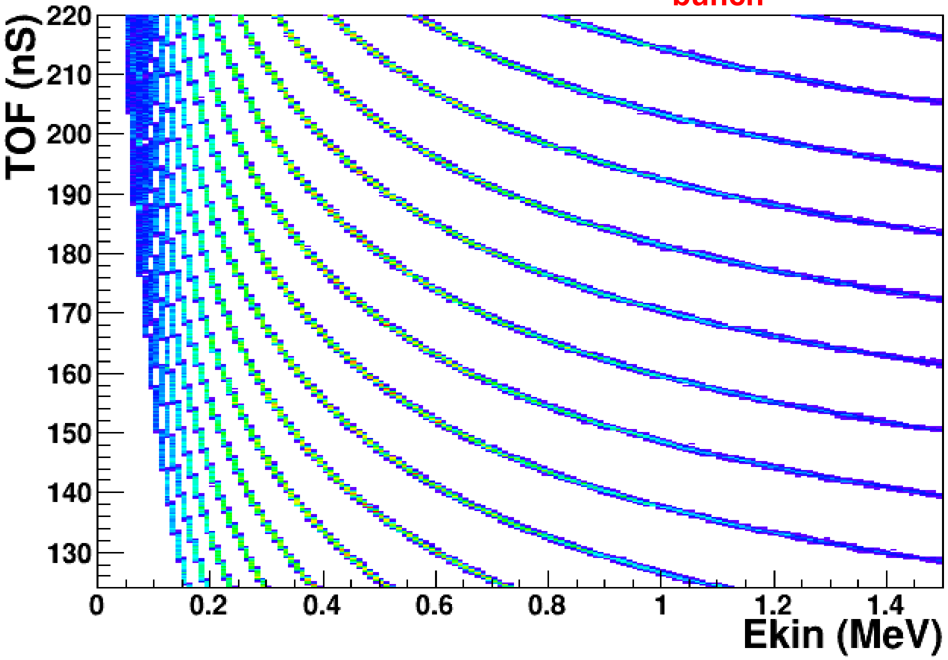
120→1160 bunches

- Carbon TOF ~20-90 nS; bunch spacing 11 nS
  carbons from several bunch ×ings in system simultaneously:

RHIC data



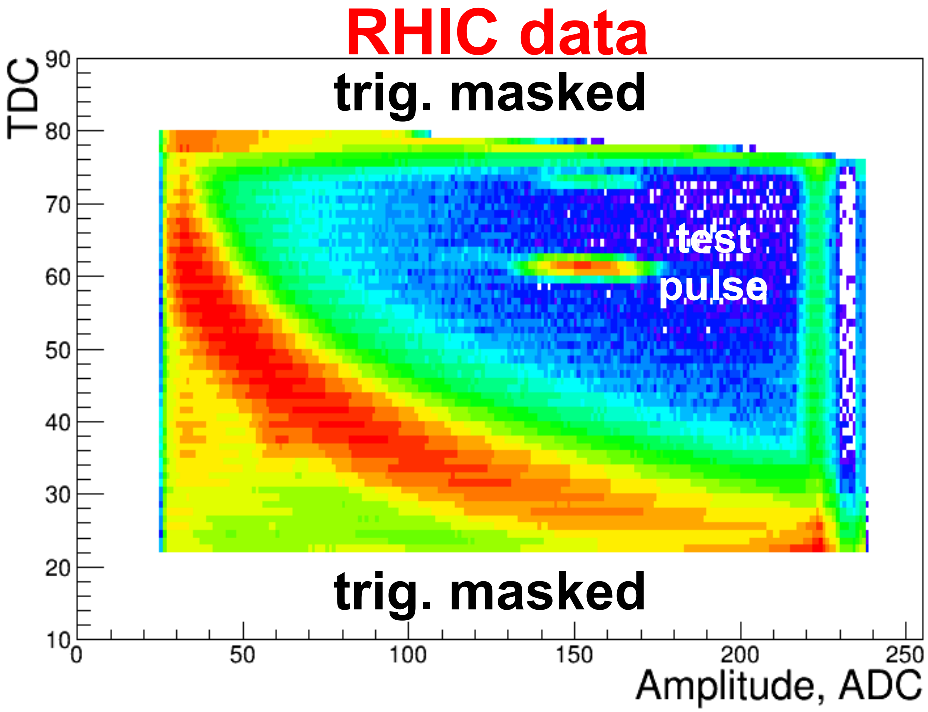
EIC toy MC: smear L_{bunch} 0.2 nS

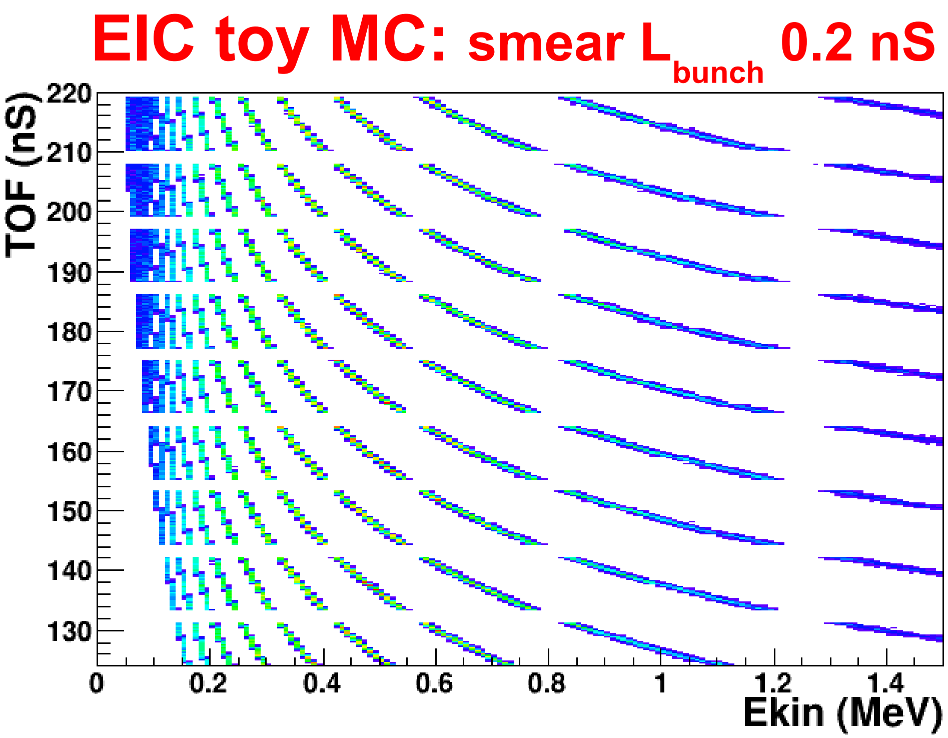


- Need to sort (Ekin,TOF) bands → bunch ×ings
- Hjet: similar difficulties

120→1160 bunches

- EM pulse during beam crossing:
  WFD triggering masked ~ beam ×ing time

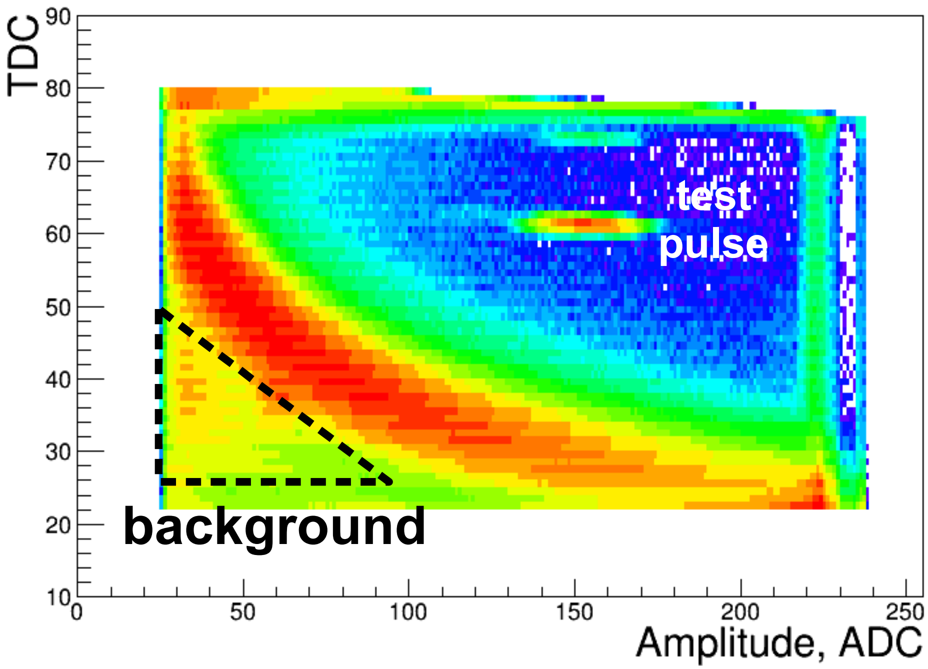


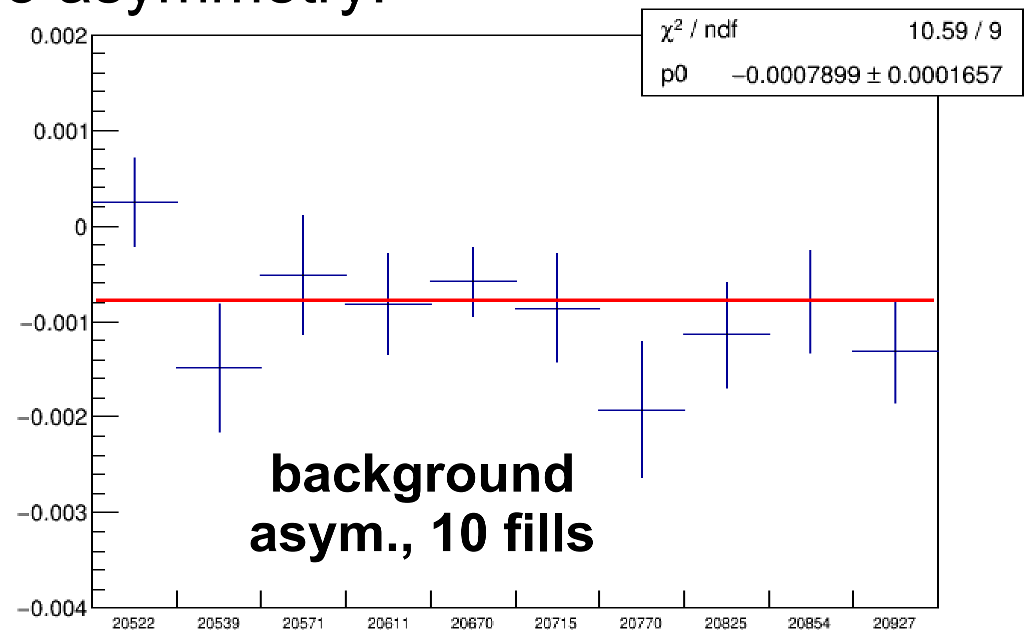


- Need to sort (Ekin,TOF) segments → bunch ×ings
- Hjet: similar difficulties

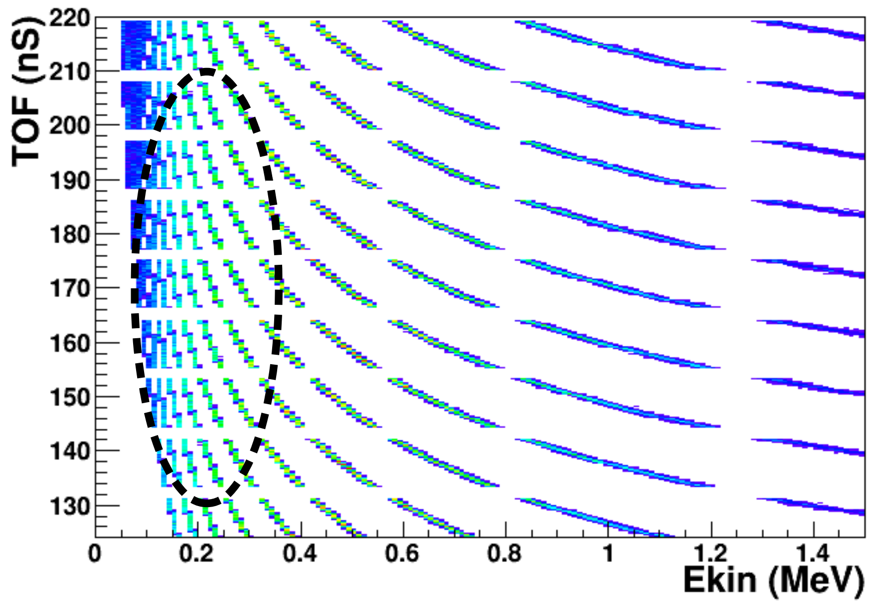
Signal/background overlap

- Non-carbon background under signal, nature unclear
- Events this region small non-zero asymmetry:





- @ RHIC: asym. calibrated out pC/Hjet
- @ EIC:
  - overlaps w/ adjacent bunches
  - may be same/opposite +/- beam spin
  - dilute/enhance asymmetry
  - a real mess...
- Hjet: similar difficulties



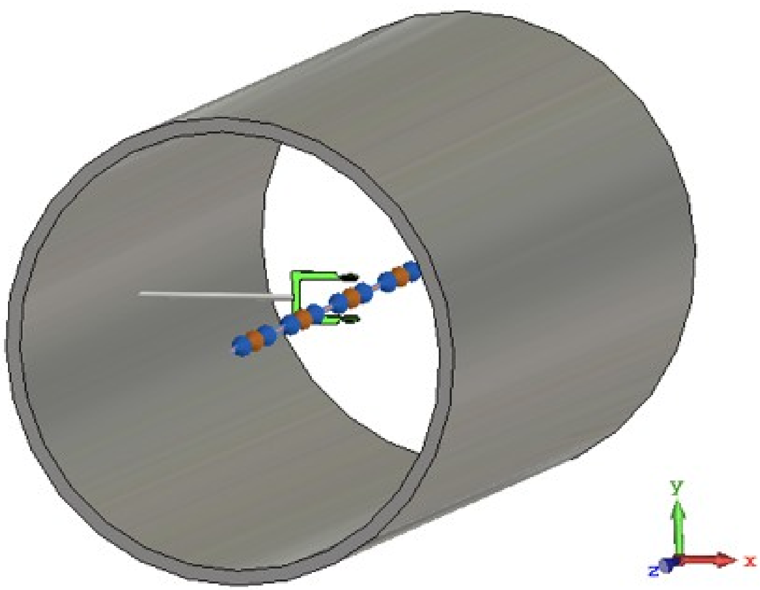
Target viability

Results from
P. Thieberger

RHIC→EIC

- same # protons / bunch, shorter bunch length ⇒ higher E fields
- higher bunch ×ing frequency ⇒ RF effects

- Model using Particle Studio®:



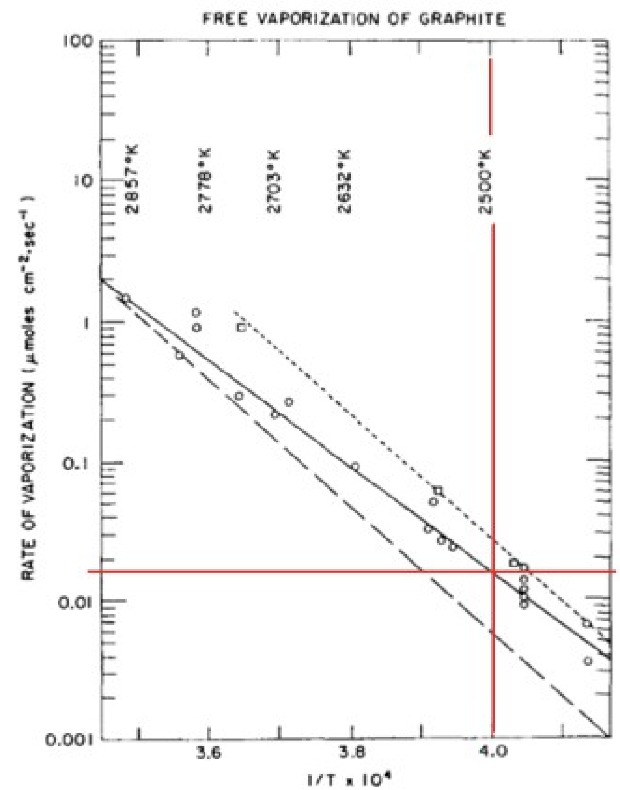


FIG. 2. Rate of vaporization of graphite, 2400–2800°K.

- Consider carbon sublimation:
  - benchmark T = 2500 K = 2227 °C
  - sublimation rate (plot), target area density

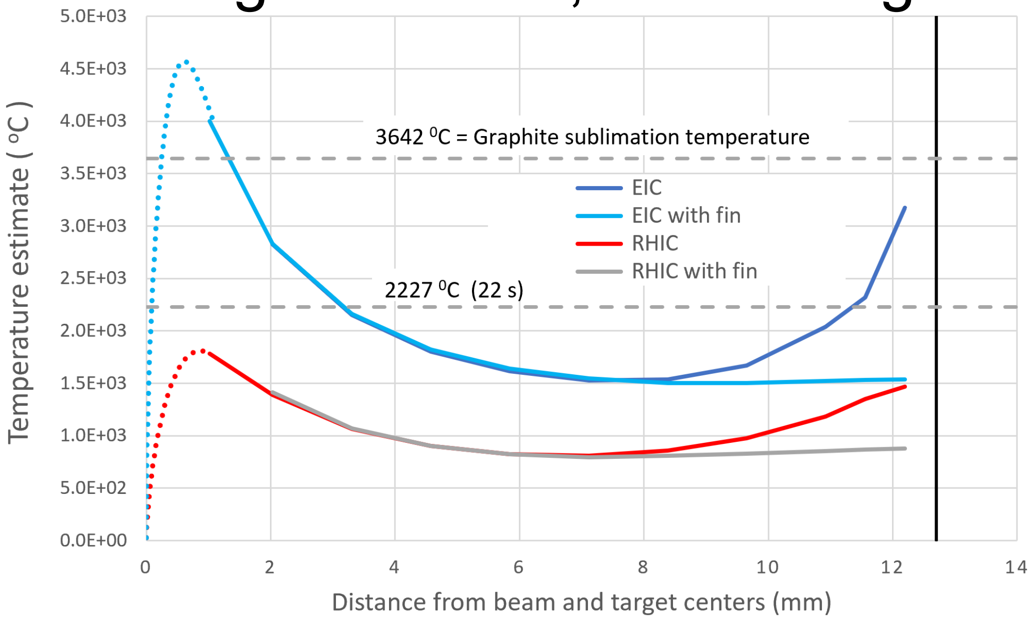
⇒ target @2500 K sublimates away ~ 20 sec
(a few pC measurements)

Target viability

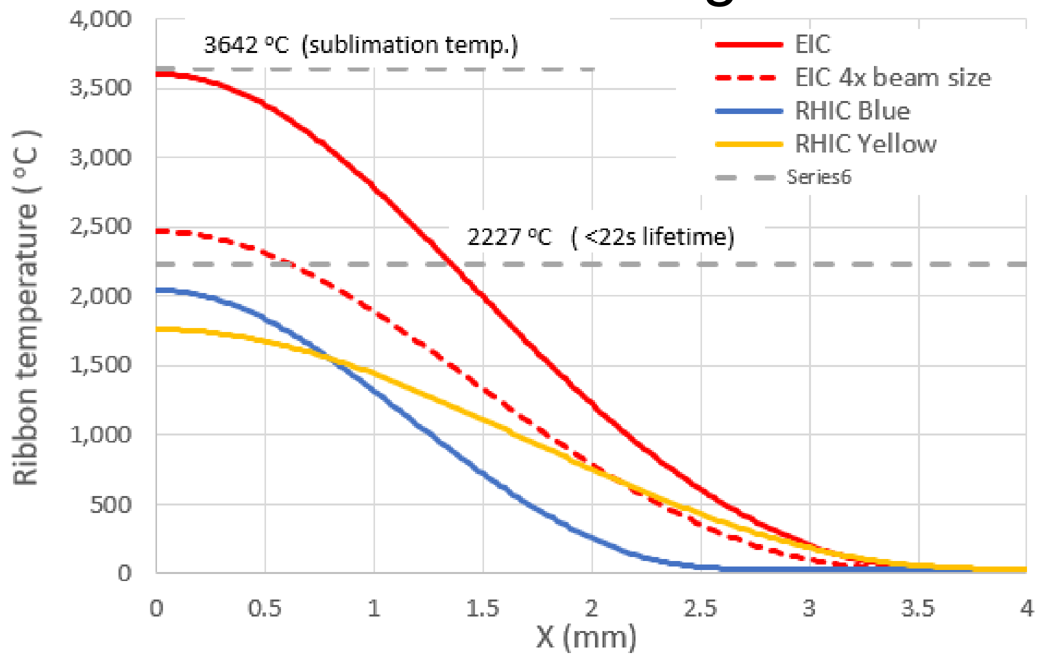
Results from
P. Thieberger

- Simulated temp. along target center → edge

- Target in beam, RF heating:



- Beam dE/dx heating:



- @ RHIC: targets close to rapid sublimation
  estimated lifetime ~440 sec, few 100 measurements
  consistent with observed target lifetime
- @ EIC: targets well into rapid sublimation (few seconds)

SERIOUS DOUBTS: TARGET VIABILY @ EIC

Light ion polarimetry

- Discussed here direct application:

  RHIC proton polarimetry → EIC

- EIC will also have polarized light ions (d, ^{3}He)

- Existing RHIC polarimeters may be applied

  See talks by: Andrei Poblaguev
  Ana Nunes

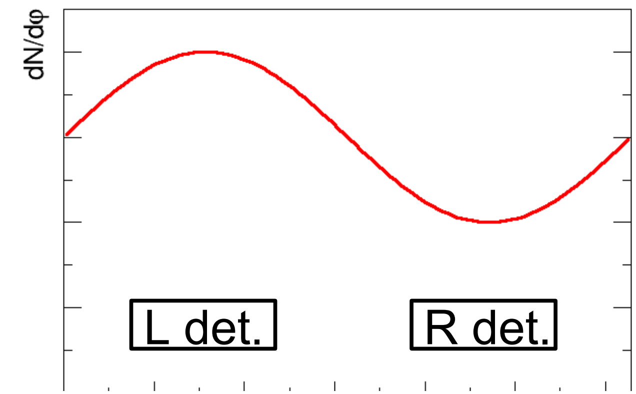
Summary

- Over last decade+ polarimetry evolved with RHIC, now providing:
  - physics quality beam P for experiments
  - beam spin properties for beam spin physics
- Polarimeters ~reached technical limits, mainly:
  - backgrounds
  - detector calibrations
  - carbon targets
- Limitations remain at EIC, and worse, including:
  - signal/background overlaps
  - carbon target viability
- Clear need: new ideas, R&D, ...

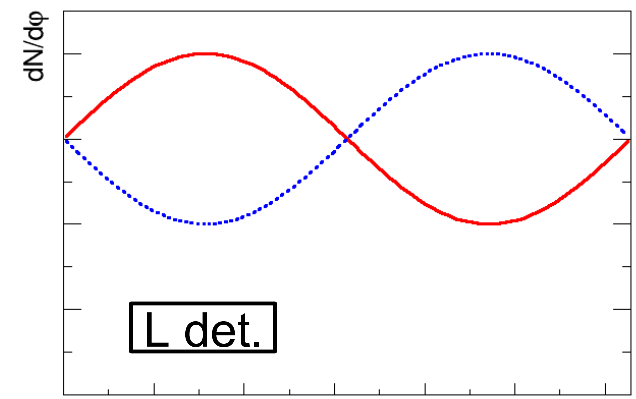
Extras

Cross-ratio (for non-spin experts)

- If have one beam w/ spin up, and detectors left (L) and right (R) of beam, can measure asym. but would need to know relative acceptances of L/R detectors

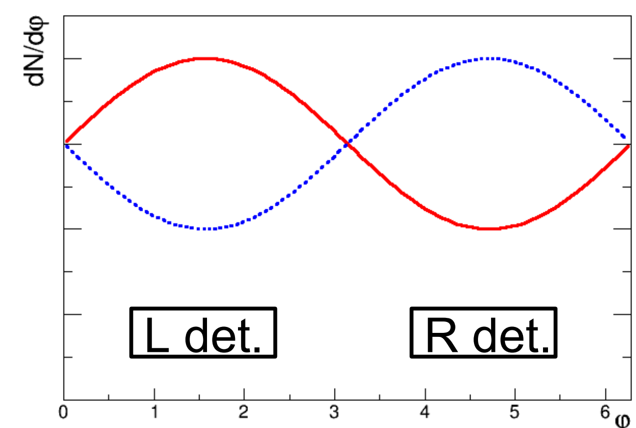


- If have one detector left of beam, and beam bunches w/ spin up (+) and down (-), can measure asym., but would need to know relative luminosities of +/- beams



- If have both L/R detectors and +/- bunches, acceptances and luminosities cancel out in the "cross-ratio"*:

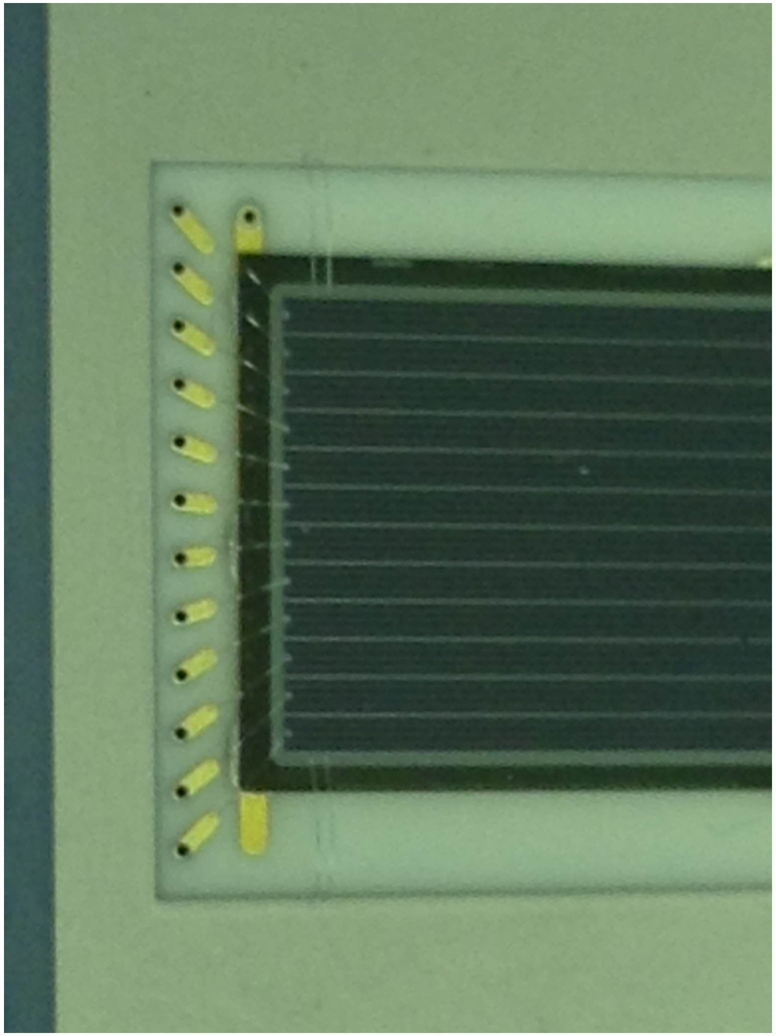
$$\epsilon = \frac{\sqrt{N_{R+}N_{L-}} - \sqrt{N_{L+}N_{R-}}}{\sqrt{N_{R+}N_{L-}} + \sqrt{N_{L+}N_{R-}}}$$



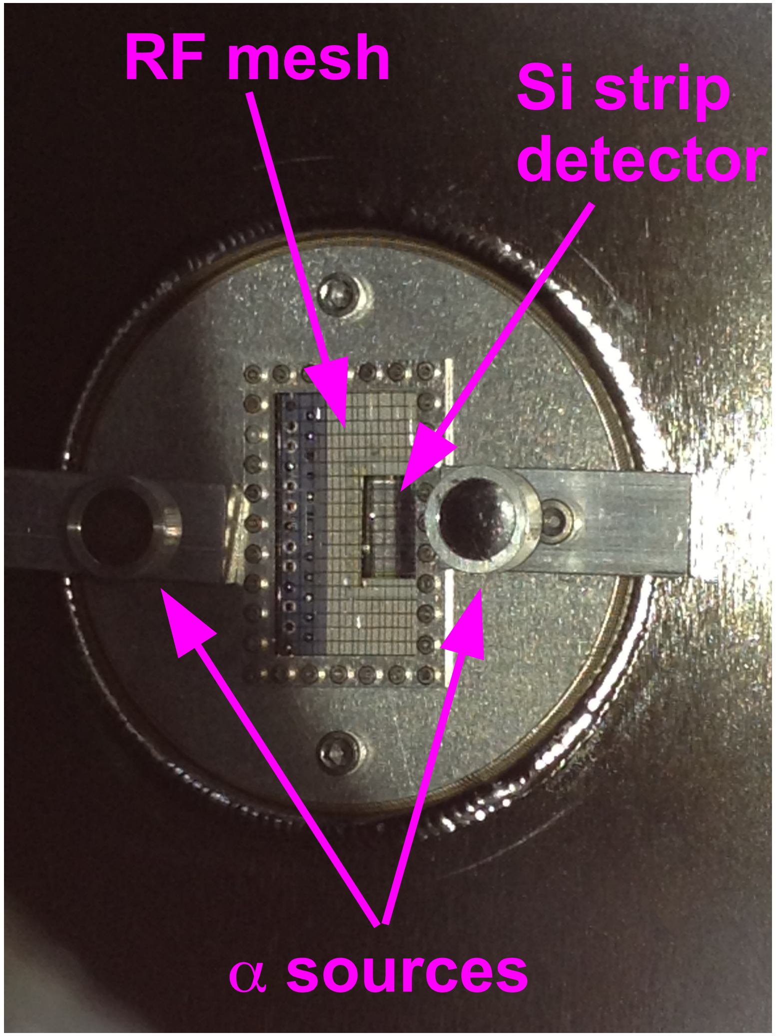
*G. Ohlsen and P.W. Keaton, NIM 109 (1973) 41

*http://www4.rcf.bnl.gov/~cnipol/Documentations/Papers/TechniquesForMeasurementOfSpinHalfAndSpin1PolarizationAnalyzingTensors.pdf

pC detectors

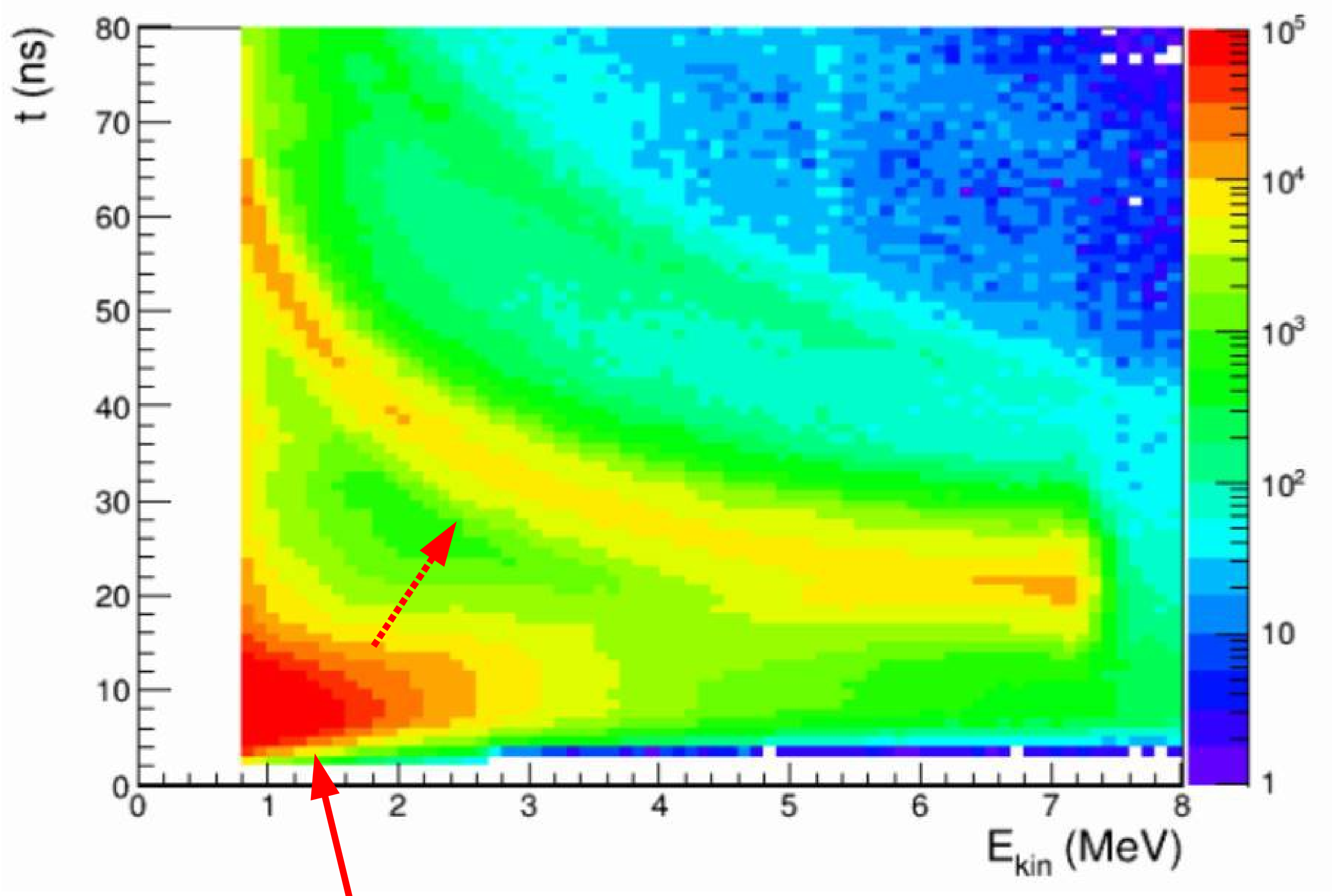


Si strip detector & bonds on ceramic board



detector viewed from inside scattering chamber

Hjet background



Mountain of noise
leaks under signal