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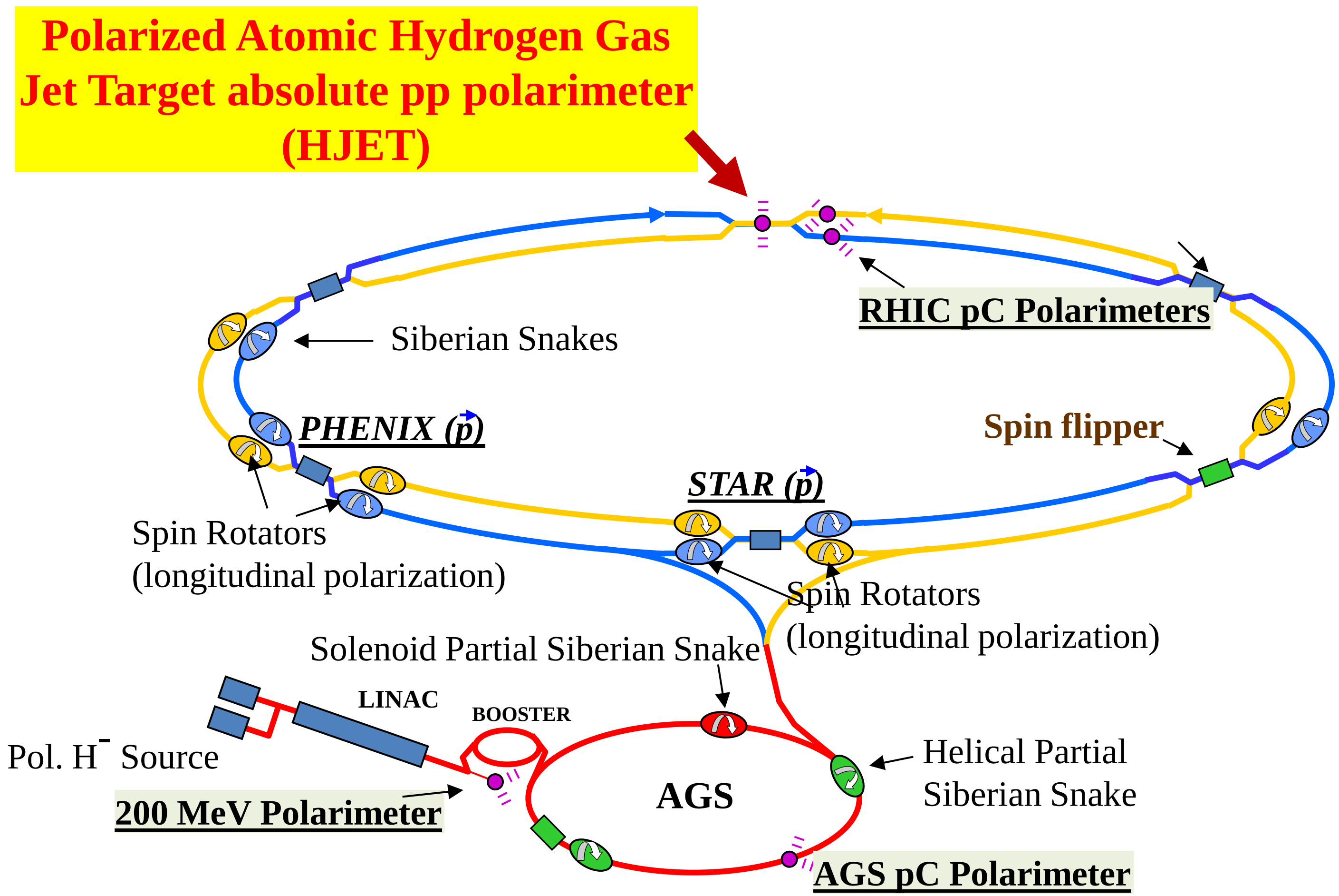
Hydrogen Jet Polarimeter (HJET) in RHIC Run 17

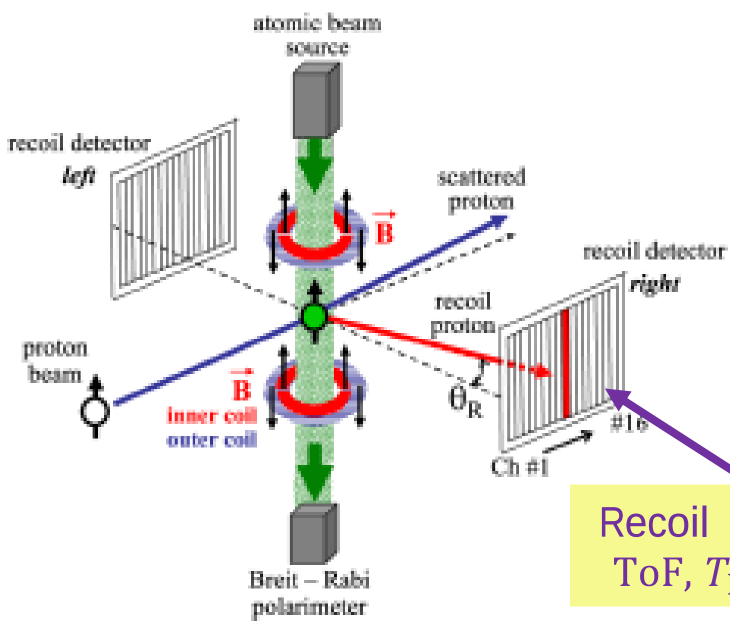
1. Systematic errors in the beam absolute polarization measurements.
2. Longitudinal Polarization Profile ?
3. Physics at HJET
   - Precise measurement of single spin $A_N(t)$ and double spin $A_{NN}(t)$ analyzing powers in elastic pp scattering at $\sqrt{s} = 21.2\ \mathrm{GeV}$.
   - Experimental evaluation of analyzing power in inelastic scattering $p^{\uparrow}p^{\uparrow} \rightarrow X + p$
   - Measurement of analyzing power of polarized proton scattering on Gold ($p_{lab} = 27.2\ \mathrm{GeV}$)

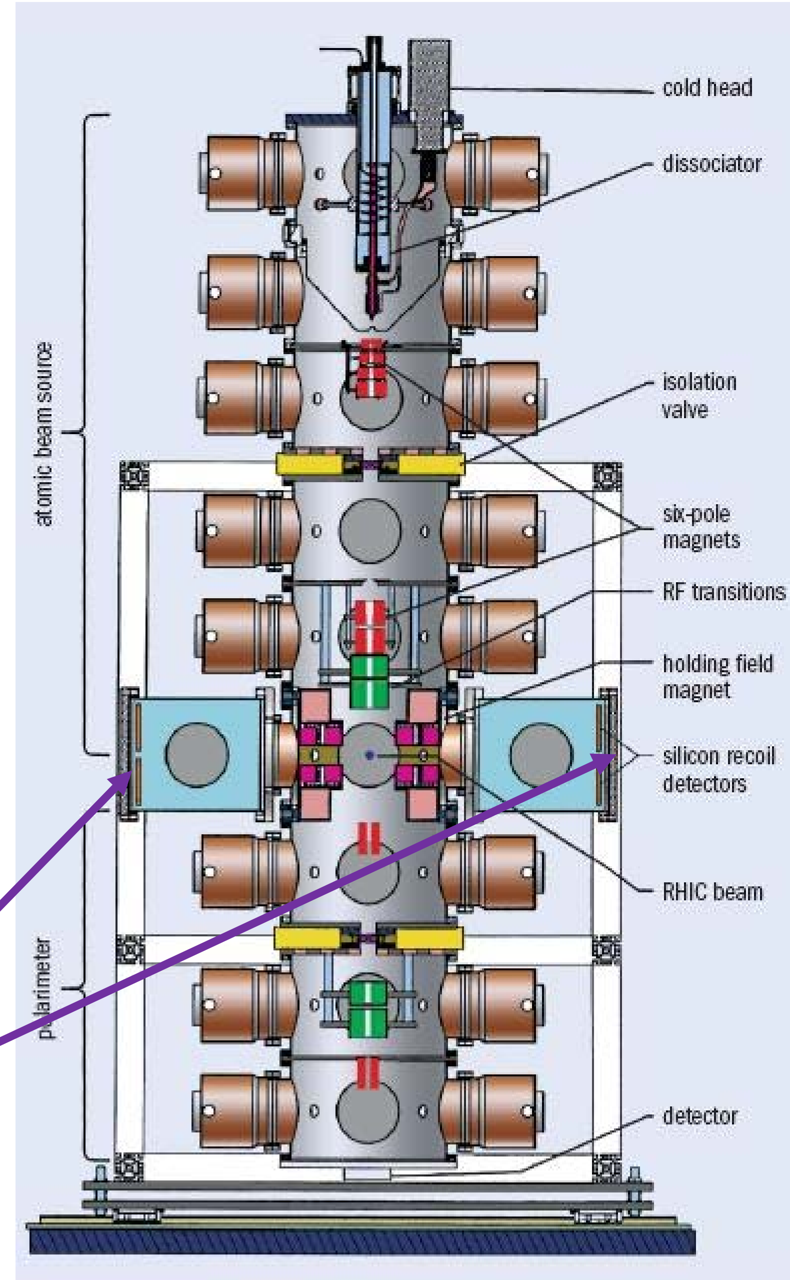
Polarized Proton Beams at RHIC



Polarized Atomic Hydrogen Gas Jet Target (HJET)

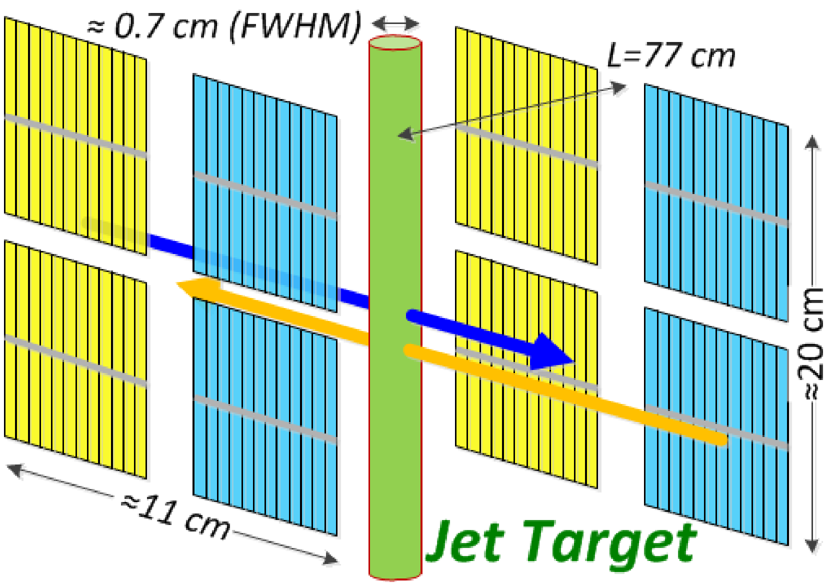
- **The HJET polarimeter was commissioned in 2004.**
- **It was designed to measure absolute polarization of 24-250 GeV/c proton beams with systematic errors better than $\Delta P/P \leq 0.05$**
- **The atomic hydrogen polarization in the Jet is 95.7%**
- **Jet intensity 12.6×10^{16} atoms/sec**
- **Jet density 1.2×10^{12} atoms/cm^2**
- **The Jet polarization is flipped every 10 min.**





Recoil detectors
ToF, T_{REC}, θ_{REC}

HJET detector configuration



Both RHIC beams (Blue and Yellow) are measured simultaneously

Lorentz invariant momentum transfer :

$$t = (p_R - p_t)^2 = -2m_p T_R$$

For elastic scattering:

$$\tan\theta_R = \frac{z_{det} - z_{jet}}{L} = \frac{\kappa\sqrt{T_R}}{L} \qquad \kappa = \sqrt{\frac{T_R}{2m_p}\frac{E_{beam} + m_p^2/M_{beam}}{E_{beam} - m_p + T_R}} \approx 18\frac{\text{mm}}{\text{MeV}^{\frac{1}{2}}}$$

In a Si strip

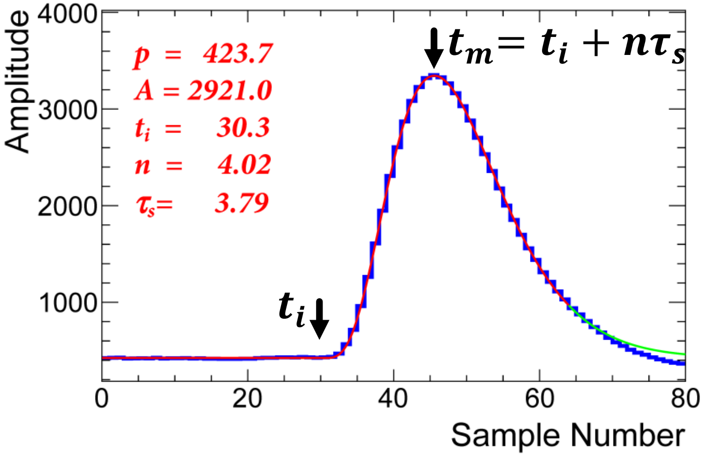
$$\left(\frac{d\sigma}{dt}\sqrt{T_R}\right)^{-1}\frac{dN}{d\sqrt{T_R}} = f\left(\kappa\sqrt{T_R} - \kappa\sqrt{T_{\text{strip}}}\right),$$

where $f(z)$ is jet density profile and T_{strip} is kinetic corresponding to the strip position.

DAQ

The HDAQ DAQ is based on VME 12 bit 250 MHz FADC250 (Jlab)

Full waveform (80 samples) was recorded for every signal above threshold (~0.5 MeV).

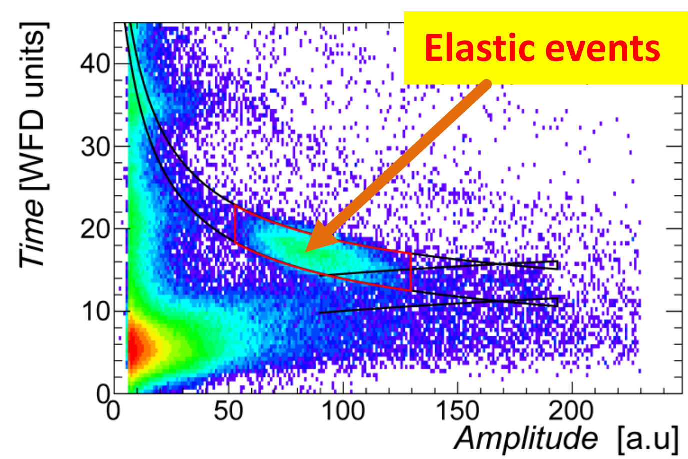


Signal parametrization:

$$W(t) = p + A\,(t - t_i)^n \exp\left(-\frac{t - t_i}{\tau_s}\right)$$

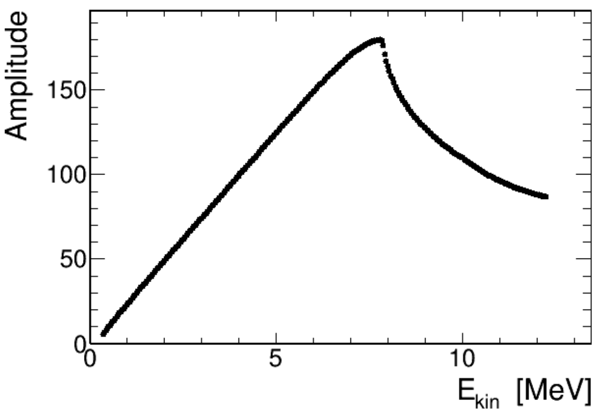
- measured waveform (blue)
- fit function *W(t)* (red)
- continuation of the fit function (green)

- For every event, recoil proton kinetic energy $T_R(A)$, time t_m, and waveform shape parameters n and τ_s are measured.
- For polarization measurement elastic events have to be isolated.

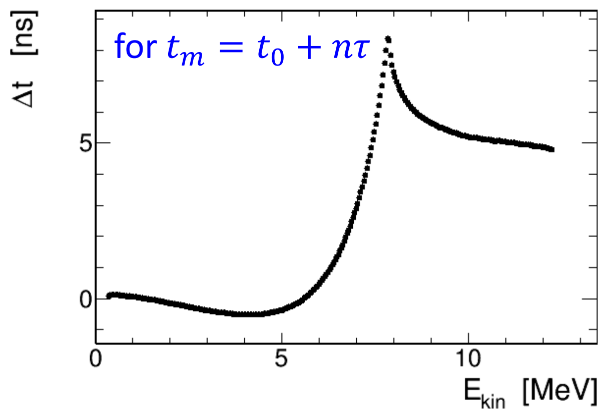


Separation of the stopped and punched through protons

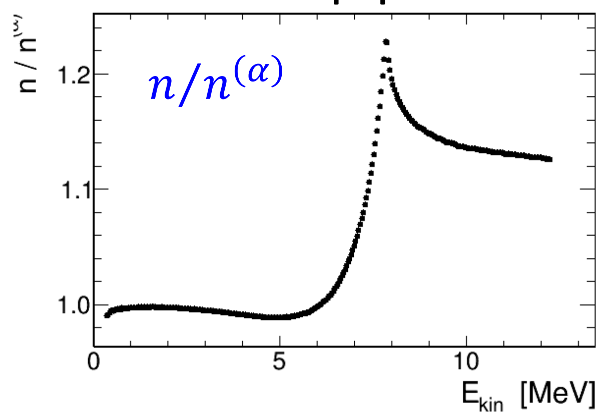
Amplitude

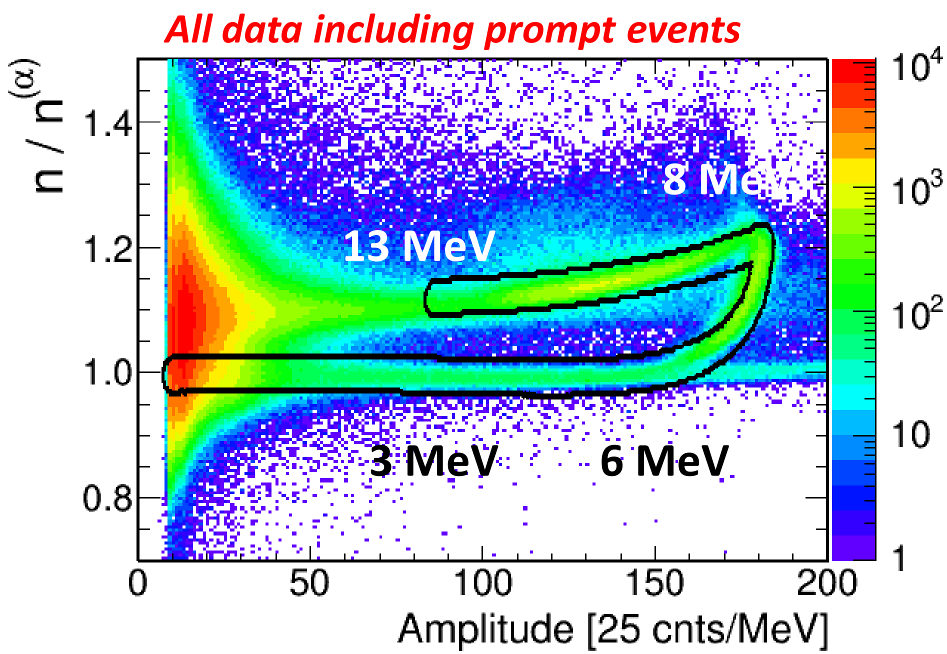


Correction to measured time



Waveform shape parameter





Protons with energy above 7.8 MeV punch through the Si detector. Only part of protons kinetic energy is deposited.

To separate stopped and punched through protons, a conversion function

$$\left(A, n/n^{(\alpha)}\right) \to T_R$$

was simulated and adjusted using alpha-calibration data. $n^{(\alpha)}$ is parameter n measured in alpha-calibration.
Time corrections were also applied.

Event Selection Cuts.

1. **Recoil proton kinetic energy** $\boldsymbol{T_R}$.
   The possible range ($0.5 \div 11$ MeV) is limited by the detector geometry and the trigger threshold)
2. **"Recoil mass cut":** $\boldsymbol{\delta t = t_m - t_p(A)}$
   $t_p(A)$ is expected proton time for measured amplitude A. It depends gain, dead-layer and time offset which are determined in calibrations. The δt distribution is defined by the beam bunch longitudinal profile.
3. **"Missing mass cut":** $\boldsymbol{\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{strip}}}$
   T_{strip} is the energy corresponding to the strip center. It is determined in the geometry alignment. The $\delta\sqrt{T_R}$ distribution is defined by the jet density profile.

For elastic scattering, the $\left(\frac{d\sigma}{dt}\sqrt{T_R}\right)^{-1} \frac{d^2N}{d\delta t\, d\delta\sqrt{T_R}}$ distribution is the same for all Si strips.

Two sets of cuts used in Run 2017 analysis

Minimum statistical error cuts

$0.6 < T_R < 10$ MeV

$-7 < \delta t < 7$ ns

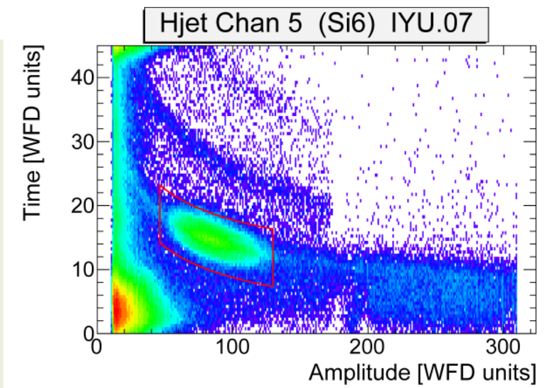
$-0.4 < \delta\sqrt{T_R} < 0.4$ MeV$^{1/2}$

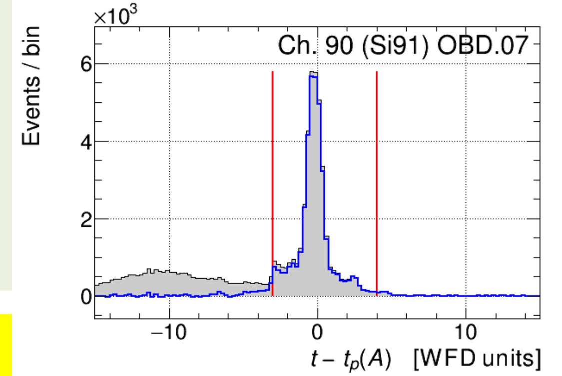
Minimum systematic error cuts

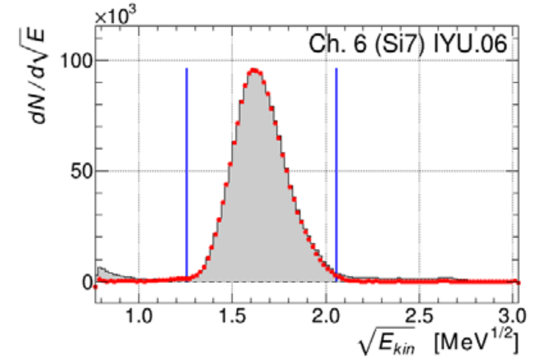
$3.2 < T_R < 7.6$ MeV

$-7 < \delta t < 7$ ns

$-0.18 < \delta\sqrt{T_R} < 0.3$ MeV$^{1/2}$



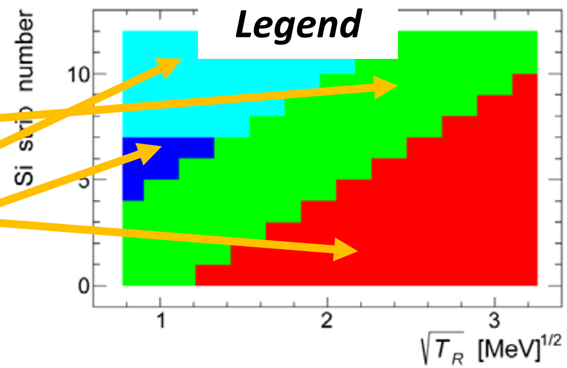


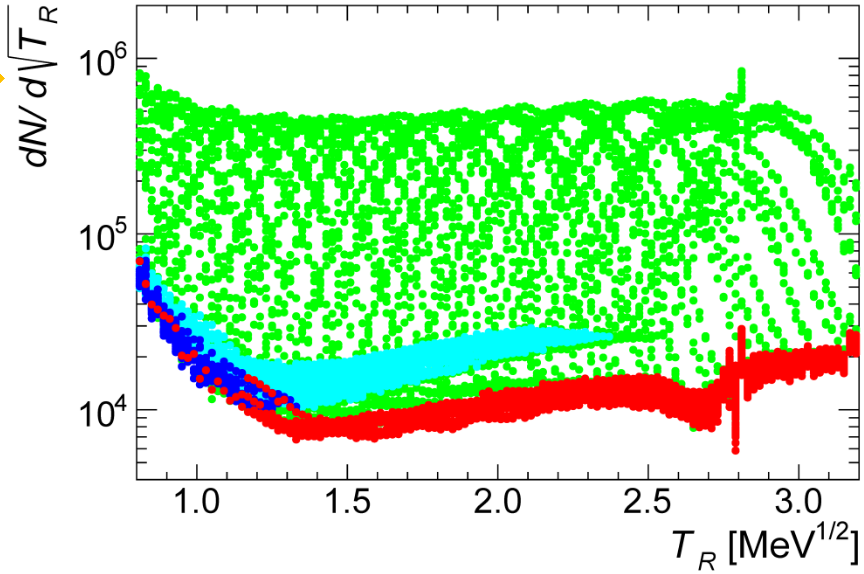


Background subtraction

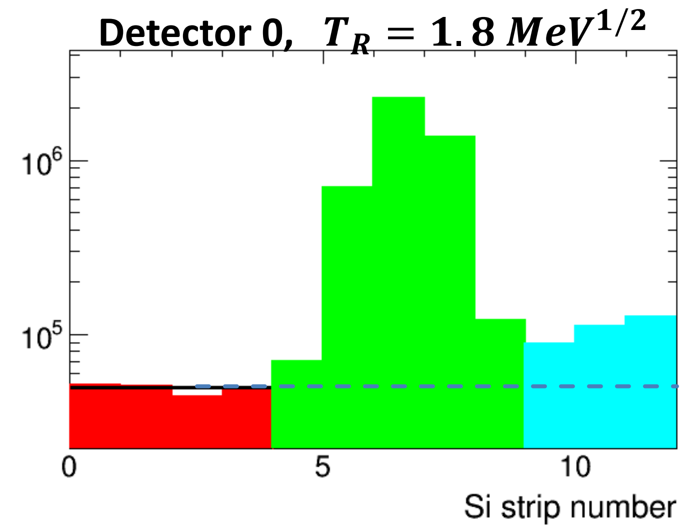
Superposition of the $dN/d\sqrt{T_R}$ for all Si strips.

- **Elastic *pp***
- **Inelastic pp**
- **Background**





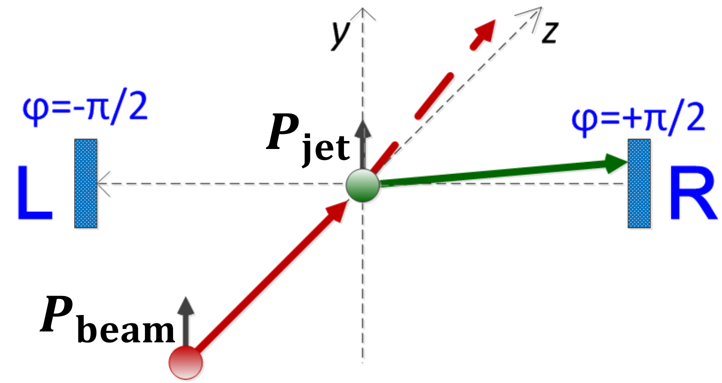
- **The background subtraction is based on assumption that for background the $dN/d\sqrt{T_R}$ is the same for all Si strips.**
- **In the data analysis, the background is determined/subtracted independently for every detector and every combination of beam/jet spins.**



Spin Correlated Asymmetries in elastic $p^{\uparrow}p^{\uparrow}$ scattering

$$\frac{d^2\sigma}{dt\,d\varphi} = \frac{1}{2\pi}\frac{d\sigma}{dt}\left[1 + \left(P_{jet} + P_{\rm beam}\right)A_N \sin\varphi + P_{\rm jet}P_{\rm beam}\left(A_{NN}\sin^2\varphi + A_{SS}\cos^2\varphi\right)\right]$$

In HJET $\sin\varphi = \pm 1$ and $\cos\varphi = 0$.



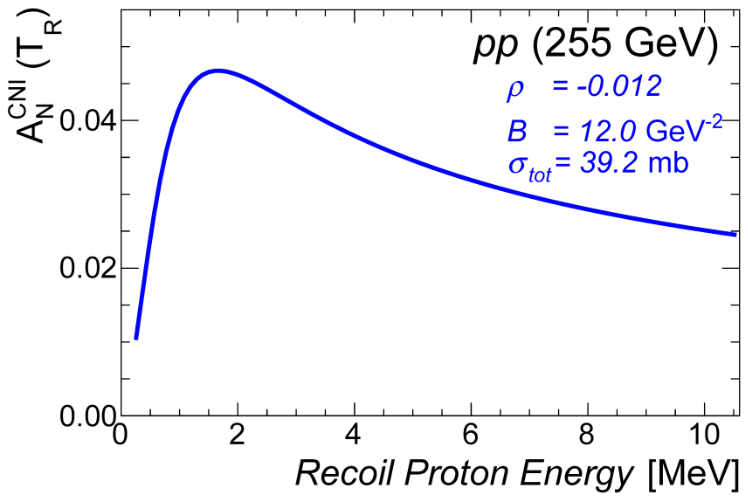
The measured single spin correlated asymmetry is used to determine beam polarization:

$$a = \frac{N_R^{\uparrow} - N_R^{\downarrow}}{N_R^{\uparrow} + N_R^{\downarrow}} = \frac{N_R^{\uparrow} - N_L^{\uparrow}}{N_R^{\uparrow} + N_L^{\uparrow}} = A_N P$$

Single spin analyzing power A_N is well approximated by theoretically known interference of spin-flip electromagnetic and spin-non-flip nuclear amplitudes (Coulomb-Nuclear Interference):

$$A_N(t) = A_N^{\rm CNI}(t) \times \alpha_5\left(1 + \beta_5\frac{t}{t_c}\right)$$

$\alpha_5 - 1 \approx 0$ and $\beta_5 \approx 0$ are corrections due to hadronic spin-flip amplitude and $t_c = -8\pi\alpha/\sigma_{tot}$



A normalized asymmetry: $a_n(t) = a(t)/A_N^{CNI}(t) = P\alpha_5(1 + \beta_5\ t/t_c)$
is a very convenient parameterization because it linearly depends on t with the same slope β_5 fo beam and jet spins.

Measurement of the Spin Correlated Asymmetries

Numbers of events for 8 different combination of beam spin (↑↓), jet spin (+-) , and detector side (LR)

$$N_{(LR)}^{(\uparrow\downarrow)(+-)} = N_0\left(1 \pm a_N^j \pm a_N^b \pm a_{NN}\right)\left(1 \pm \lambda_j\right)(1 \pm \lambda_b)(1 \pm \epsilon)$$

are, generally , functions of spin correlated asymmetries

$\boldsymbol{a_N^j = P_{jet}\langle A_N\rangle}$, $\boldsymbol{a_N^b = P_{beam}\langle A_N\rangle}$, $\boldsymbol{a_{NN} = P_{jet}P_{beam}\langle A_{NN}\rangle}$,

beam and jet intensity asymmetries $\boldsymbol{\lambda_j}$ and $\boldsymbol{\lambda_b}$, and left/right acceptance asymmetry $\boldsymbol{\epsilon}$

This equations have exact solution

$$a_N^j = \frac{\sqrt{N_L^{\uparrow+}N_R^{\downarrow+}} + \sqrt{N_L^{\uparrow-}N_R^{\downarrow+}} - \sqrt{N_L^{\downarrow+}N_R^{\uparrow-}} - \sqrt{N_L^{\downarrow-}N_R^{\uparrow+}}}{\sqrt{N_L^{\uparrow+}N_R^{\downarrow+}} + \sqrt{N_L^{\uparrow-}N_R^{\downarrow+}} + \sqrt{N_L^{\downarrow+}N_R^{\uparrow-}} + \sqrt{N_L^{\downarrow-}N_R^{\uparrow+}}}$$

and ***similar for other asymmetries***.

This is systematic error free solution if asymmetries $\boldsymbol{\lambda_j}$ and $\boldsymbol{\lambda_b}$, and $\boldsymbol{\epsilon}$ are uncorrelated

The beam polarization P_{beam} could be related to the know jet polarization $P_{jet} = 96\%$:

$$P_{beam} = \frac{a_N^b}{a_N^j} P_{jet}$$

Overview of possible systematic errors

The first order systematic corrections may be caused by

- the discrepancy between actual and assumed (true) analyzing powers $\boldsymbol{\delta A_N = \frac{b}{1+b}\left(A_N^{\text{bgr}} - A_N\right)}$, b is the background to signal ratio and A_N^{bgr} is effective analyzing power for background.
- a possible dependence $\boldsymbol{\delta\epsilon = \frac{\epsilon^{\uparrow}-\epsilon^{\downarrow}}{\epsilon^{\uparrow}+\epsilon^{\downarrow}}}$ of the detector acceptance on the spin.

Generally, δA_N and $\delta\epsilon$ are not the same for left and right detectors.

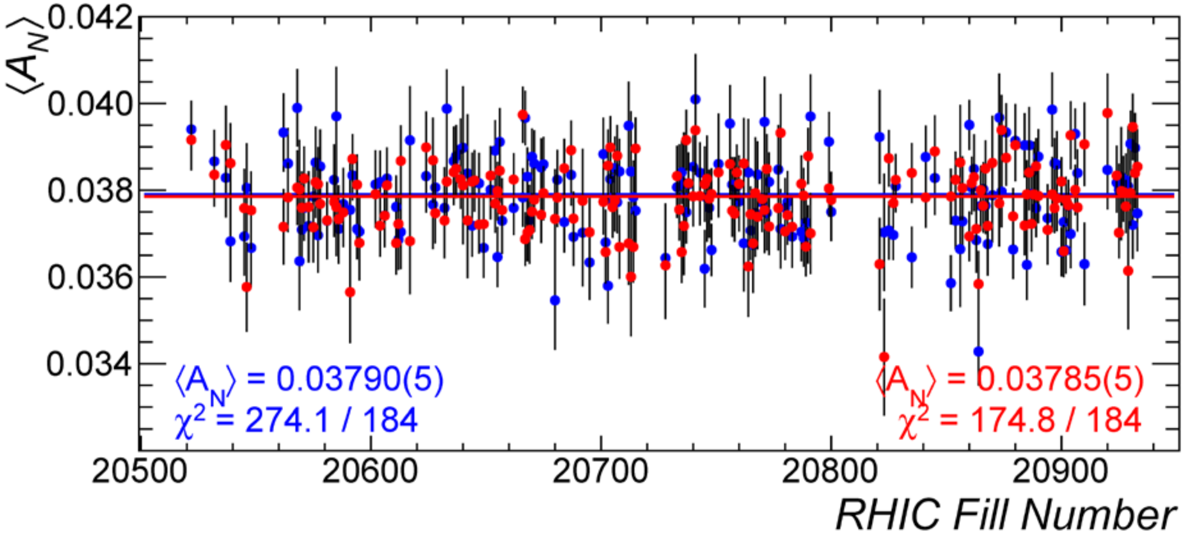
Systematic errors:

$$\boldsymbol{\delta a_N = P\,\frac{\delta A_N^{(R)} + \delta A_N^{(L)}}{2} + \frac{\delta\epsilon_R - \delta\epsilon_L}{2}}$$

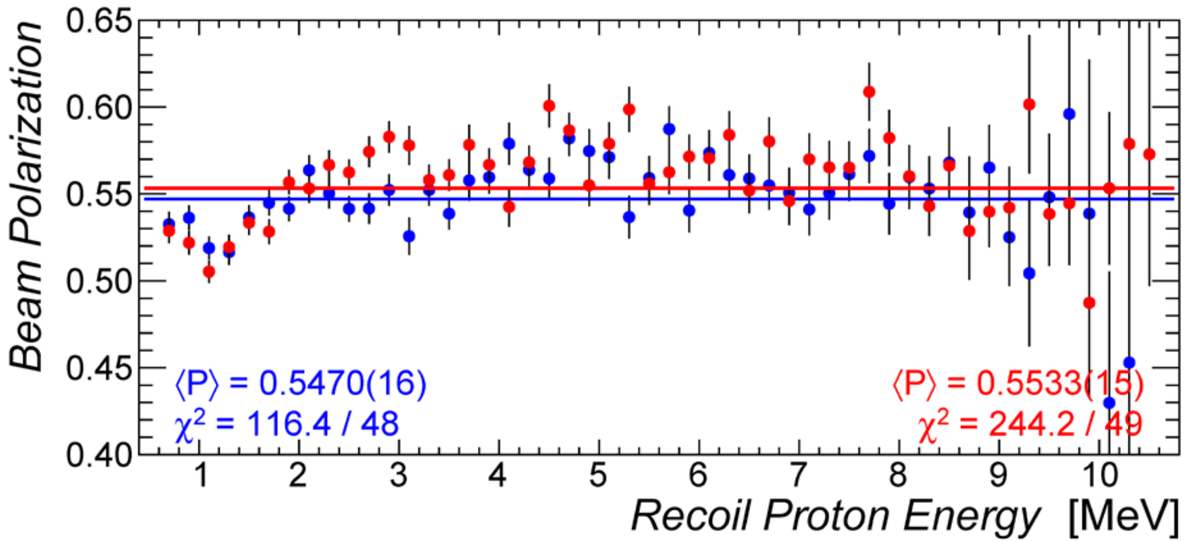
$$\boldsymbol{\delta\lambda \;\; = P\,\frac{\delta A_N^{(R)} - \delta A_N^{(R)}}{2} + \frac{\delta\epsilon_R + \delta\epsilon_L}{2}}$$

- Since measured intensity asymmetry λ has to be independent of the recoil proton energy T_R, the $\lambda(T_R)$ dependence is a good test for systematic errors.
- There is no systematic correction to the beam polarization measurement if A_N^{bgr} is the same for the beam and jet spins.

Results for minimum statistical error cuts



- **Analyzing powers for blue and yellow beams are consistent within statistical error of about $\sigma_A/A_N \sim 0.1\%$.**
- **Long term (1-100 days) stability of measurements is $\sigma_A/A_N \lesssim 0.1\%$.**



Measured polarization is the recoil proton energy dependent. This is an indication of the systematic errors in measurements

Optimization of the polarization measurement

Due to high stability of the jet spin asymmetry measurements, we can use the Run average jet asymmetry in the beam polarization measurements.

$$P_{\text{beam}} = \frac{a_{\text{beam}}}{\langle a_{\text{jet}} \rangle} P_{\text{jet}} (1 + \delta_{\text{syst}}) = \frac{a_{\text{beam}}}{A_N^{\text{eff}}}$$

To find systematic correction δ_{syst} and, thus, the effective analyzing power A_N^{eff} we can make measurements with more tight cuts which allows us to control the systematic errors

$$P_{\text{beam}} = \frac{\widetilde{a_{\text{beam}}}}{\langle \widetilde{a_{\text{jet}}} \rangle} P_{\text{jet}} (1 + \widetilde{\delta_{\text{syst}}})$$

⇓

$$\boldsymbol{A_N^{\text{eff}} = \frac{\langle \widetilde{a_{jet}} \rangle}{P_{jet} (1 + \widetilde{\delta_{syst}})} \frac{\langle a_{beam} \rangle}{\langle \widetilde{a_{beam}} \rangle}}$$

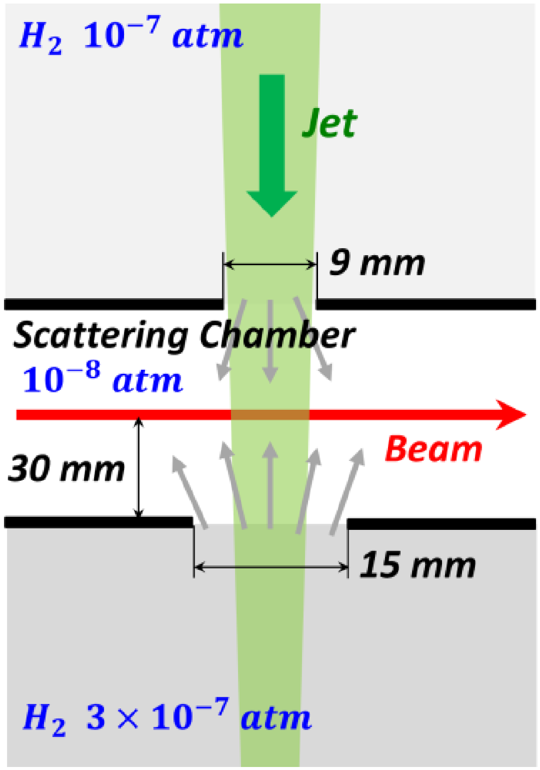
Minimum statistical error cuts

$$0.6 < T_R < 10 \text{ MeV}$$
$$-7 < \delta t < 7 \text{ ns}$$
$$-0.4 < \delta \sqrt{T_R} < 0.4 \text{ MeV}^{1/2}$$

Minimum systematic error cuts

$$3.2 < T_R < 7.6 \text{ MeV}$$
$$-7 < \delta t < 7 \text{ ns}$$
$$-0.18 < \delta \sqrt{T_R} < 0.3 \text{ MeV}^{1/2}$$

Sources of systematic errors in HJET : Molecular Hydrogen



- **In HJET the atomic hydrogen polarization of about 96% is controlled with high accuracy $\sim0.1\%$ by means of holding magnetic field and Breit-Ruby polarimeter).**
- **The molecular hydrogen effectively dilute the Jet polarization by a factor $b_{MH}/(1+b_{MH})$**
- **About 10 years ago, the molecular hydrogen background was evaluated $b_{MH}\sim3\%$ (*with a large experimental uncertainty)* using quadrupole mass spectrometer.**

1. **Molecular hydrogen in the Jet**
   Could be experimentally evaluated by turning off RF transition : $b_{MH}^{(1)} = 0.03 \pm 0.03\%$
2. **Molecular hydrogen diffused from chambers 5 and 7.**
   Since this background has a wide (flat) z-coordinate density profile, it is expected to have the same

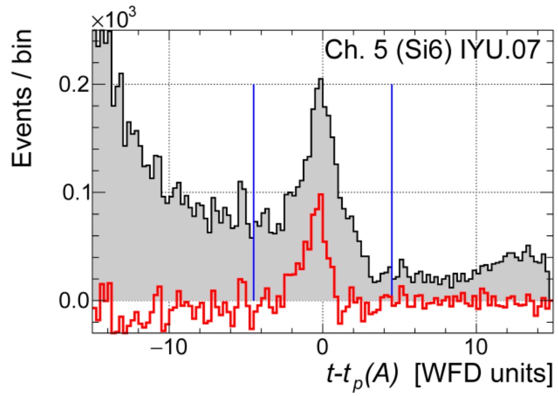
$dN/d\sqrt{T_R}$ distribution for all Si strips and, thus, it may be efficiently eliminated by the background subtraction. In-situ evaluation of the background level is $\sim0.55 \pm 0.15\%$

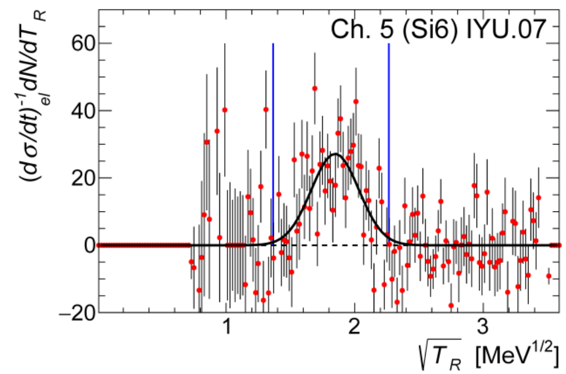
The residual level after background subtraction $b_{MH}^{(2)} = 0.08 \pm 0.11\%$

for the minimum systematic error cuts.

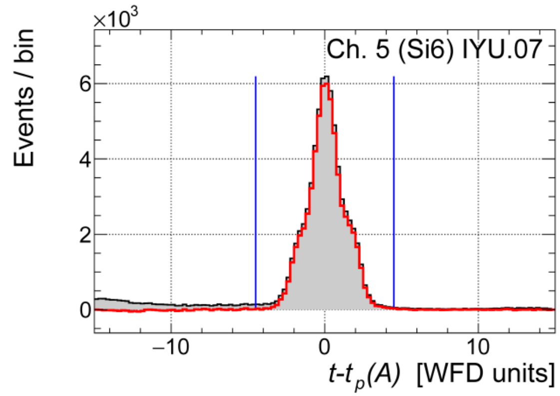
Molecular Hydrogen from the dissociator

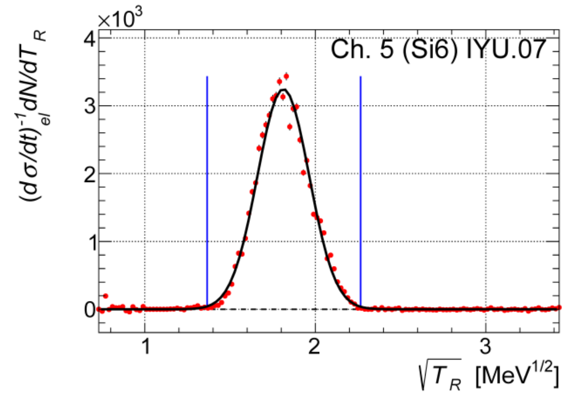
Fills 20697-20698 (11.5 hours)
RF transition off. Only molecular hydrogen from dissociator.
MH intensity is enhanced by a factor $\boldsymbol{f \gtrsim 20}$.





Fills 20692-20695 (8.6 hours)
Regular HJET run.





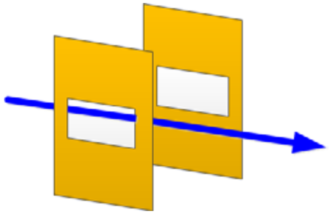
Fills	Time (h)	⟨WCM⟩	Events (k)	
20692-20695	8.63	21.12	927.6	Blue
		20.94	994.8	Yellow
20697-20698	11.47	20.60	7.1	Blue
		21.42	8.4	Yellow

Normalized good event rate ratio

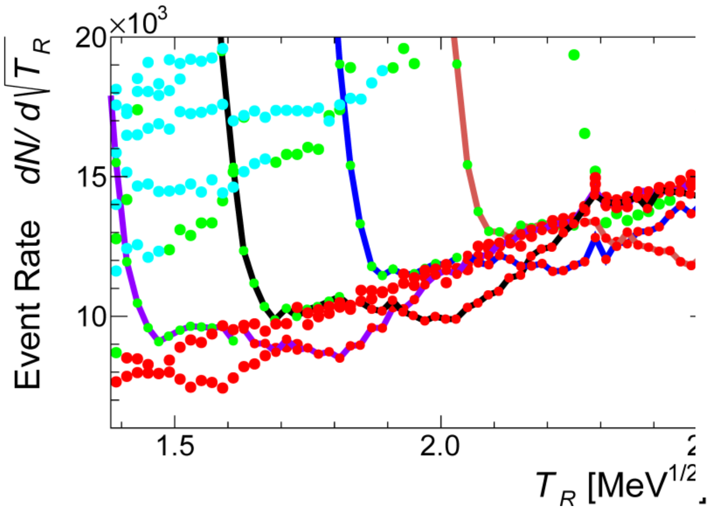
$$\frac{\mathbf{MH}}{\mathbf{Jet}} = \mathbf{0.6\%} \xrightarrow{1/f} \lesssim \mathbf{0.03\%}$$

Effective background: $\mathbf{0.03 \pm 0.03\%}$

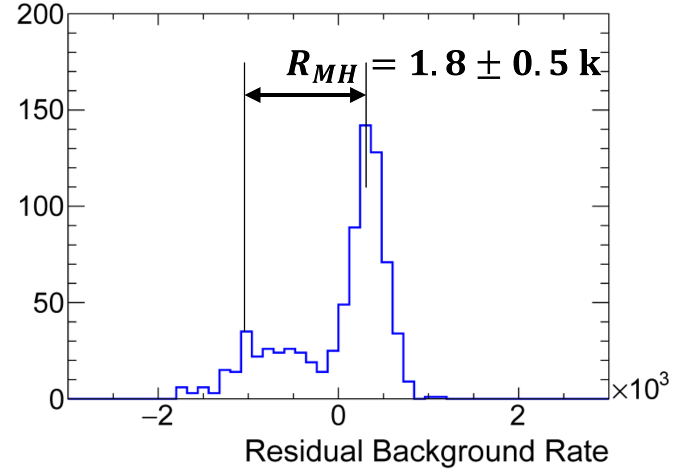
Molecular Hydrogen (2) background



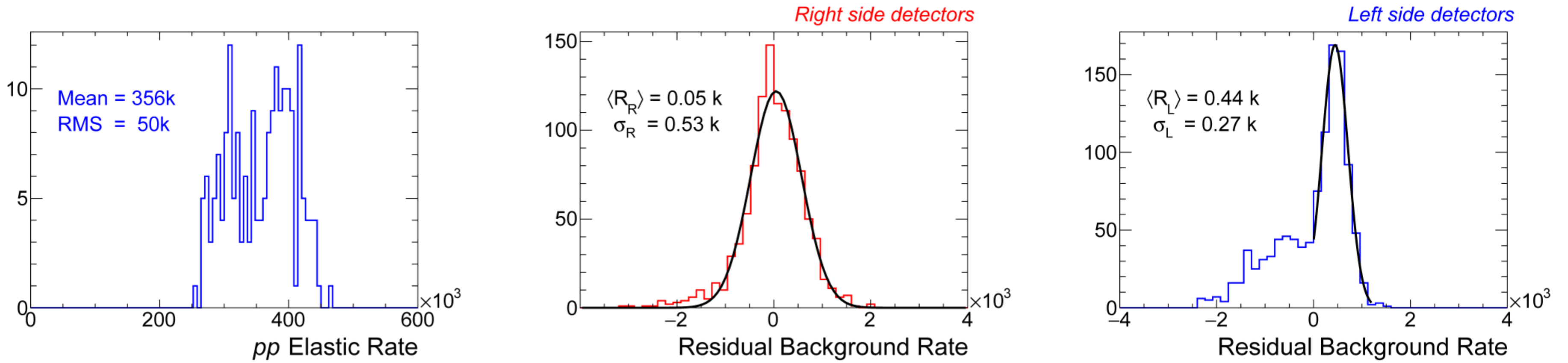
Forward beam elastic events from forward are shadowed by the collimators. This may be employed for normalization of the molecular Hydrogen density.



Y-projection after background subtraction.



Background for minimum systematic error cuts



$$b_{MH} = 0.54 \pm 0.17\%$$

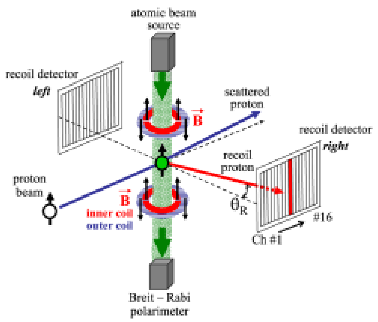
A 1.07 correction due to tracking in the magnetic field is accounted.

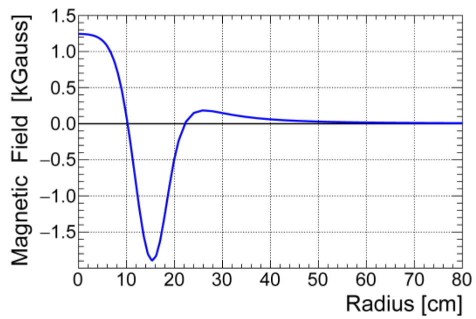
The bias due to shadowing

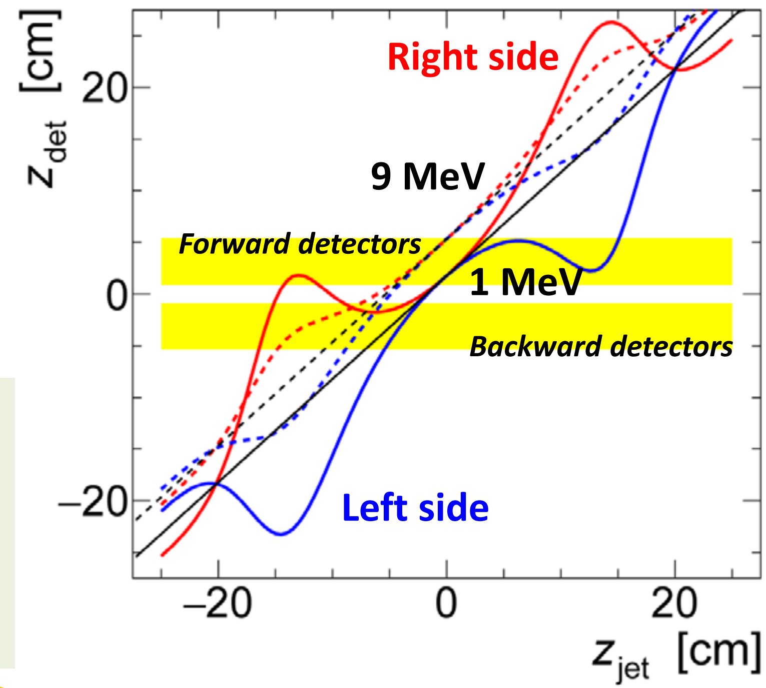
$$b_L / b_{MH} = 0.25$$

Sources of systematic errors in HJET:

Recoil proton tracks in the magnetic field

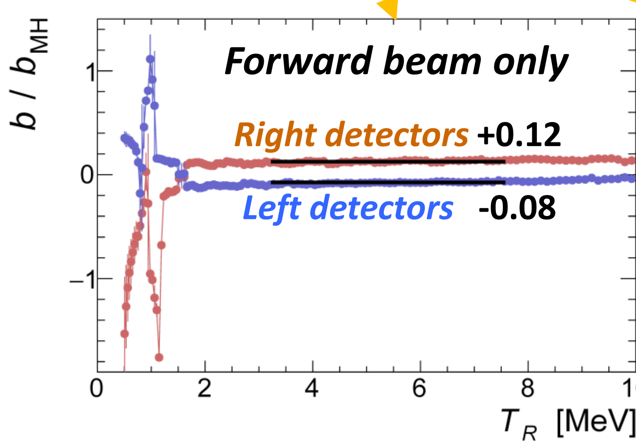


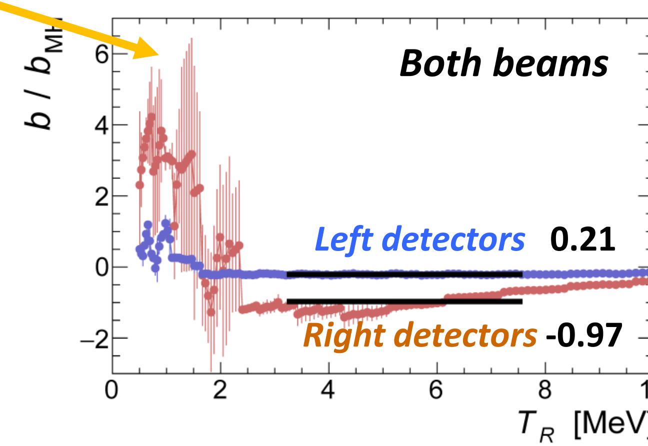




- The recoil proton track bending in the holding magnetic field affects the background subtraction.
- In the worse case ($T_R < 2$ MeV) systematic error may be $1 \div 3\%$ (if $b_{MH} = 0.5\%$)
- The residual background may be simulated with accuracy $\delta b / b_{MH} \sim 0.2$ for left detectors and $T_R > 2$ MeV

- For the beam polarization measurements only forward beam backgrounds are essential.
- For analyzing power both beams are essential.

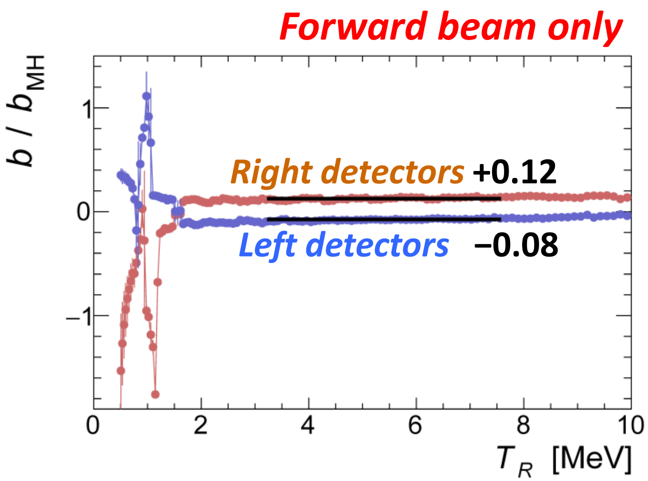


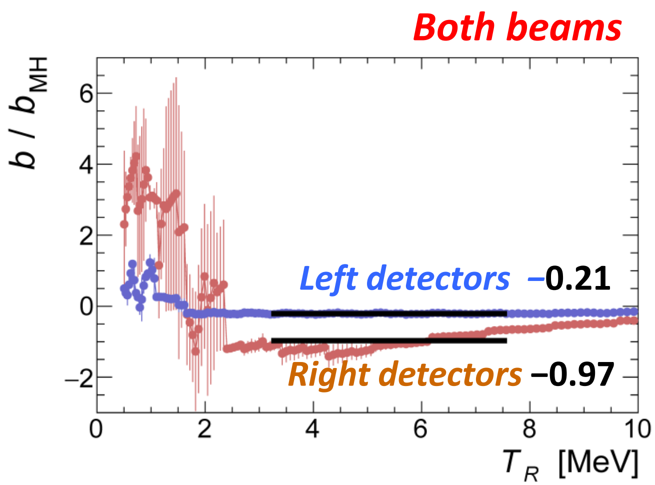


Molecular hydrogen background corrections

Simulation:

- For the ***"forward beam only"*** the simulation accuracy is about ~0.2 (correlated for left and right detectors)
- For the ***"both beams"*** the accuracy is about ~0.2 (left detectors) and ~0.5 (right detectors)
- The $b_L/b_{\mathrm{MH}} = 0.25$ bias in the background subtraction has to be added to the consideration.
- $\boldsymbol{b_{MH} = 0.54 \pm 0.17\%}$





Correction to the beam polarization measurement:

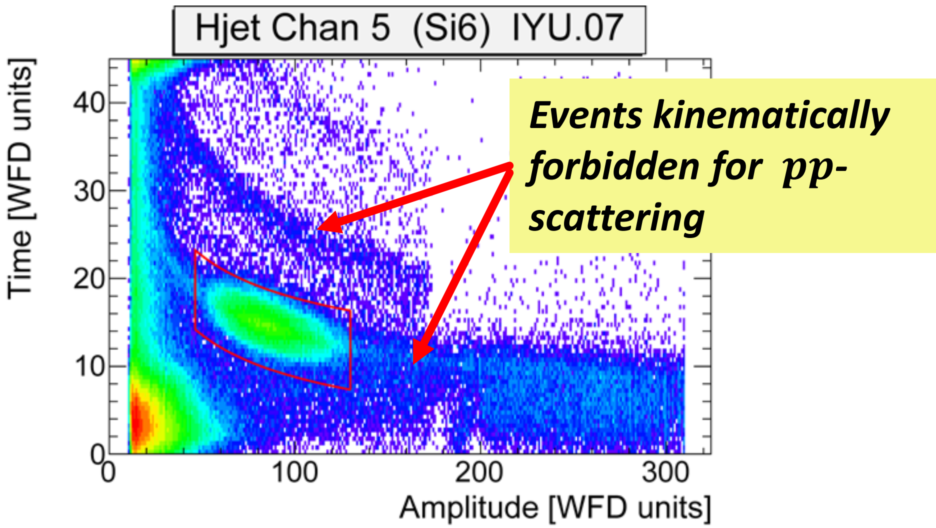
$$\frac{\delta P}{P} = -\frac{(0.12)_R + (-0.08+0.25)_L}{2} \times b_{MH} = (-0.08 \pm 0.11)\%$$

Corrections to the intensity asymmetry measurement (min. systematic error cuts)

$$\delta\lambda^{\text{jet}} = -\frac{(-0.21+0.25)_L - (-0.97)_R}{2} \times b_{MH} \left\langle a_N^{\text{jet}} \right\rangle = (-10 \pm 5) \times 10^{-5}$$

$$\delta\lambda^{\text{beam}} = 0$$

Sources of systematic errors: $p + A \to X + p_R$ *scattering*



The Jet is contaminated by a small amount of O, N, … nuclei . The proton beam scattering pA on the Jet and beam gas nuclei manifests itself by detection of protons and alpha-particles from nuclei dissociation.

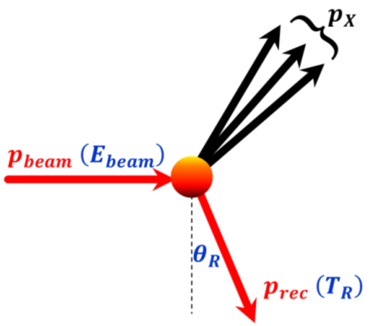
For the pA background we expect $\delta A_N^{jet} = 0$ and $\delta A_N^{beam} \sim 0.02$ (?)
(the latter was experimentally evaluated using "abort gap bunches")

Since the correlation between recoil proton energy T_R and recoil angle θ_R is strongly smeared within HJET acceptance, the $dN/d\sqrt{T_R}$ dependence for the pA protons is expected to be the same in all Si strips. Such a background could be strongly suppressed by the *background subtraction.*

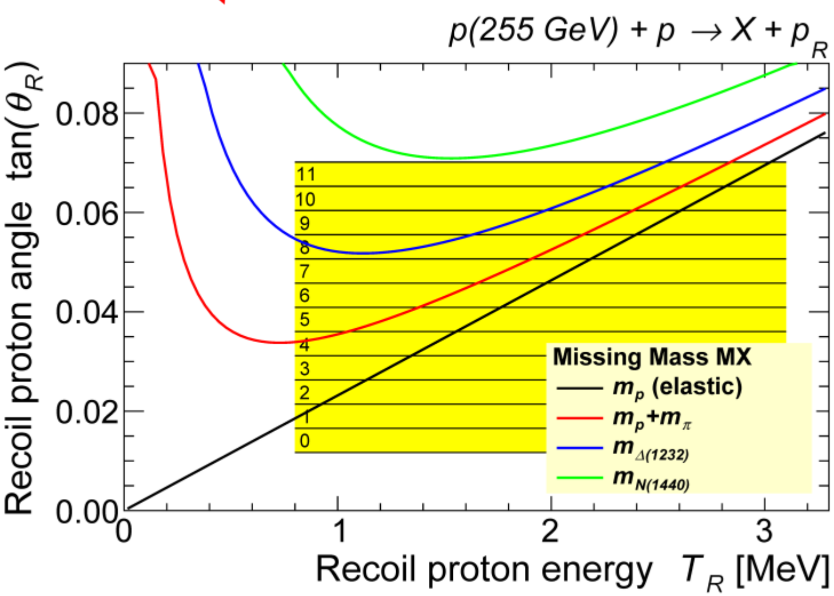
$$\delta^{syst} P/P \approx 0 \pm 0.2\%$$

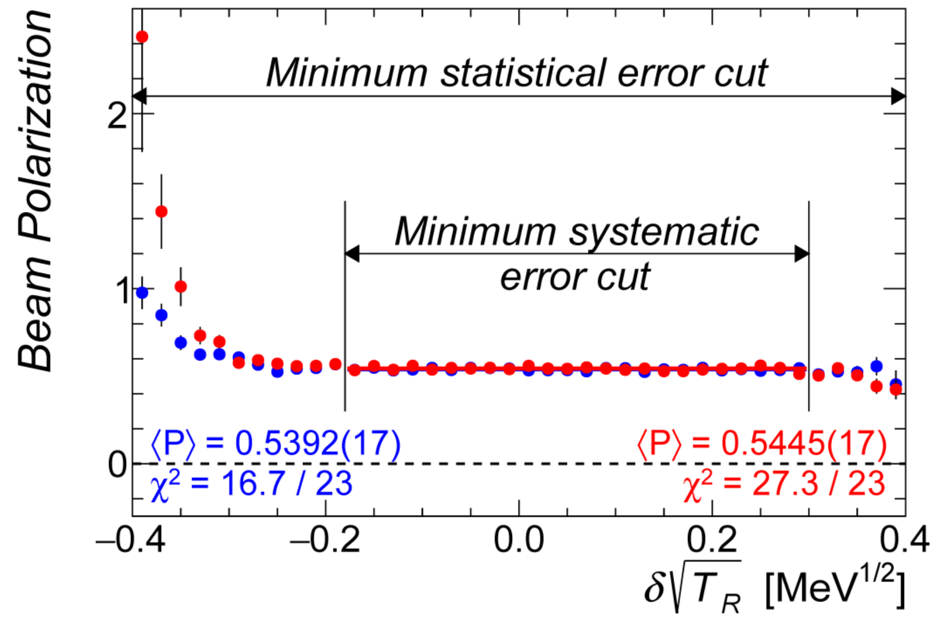
Sources of systematic errors in HJET:

Inelastic scattering $p + p \to X + p$



$$\tan\theta_R \approx \frac{\kappa\sqrt{T_R}}{L}\left(1 + \frac{m_p\Delta}{T_R E_{\text{beam}}}\right), \qquad \Delta = M_X - m_p$$



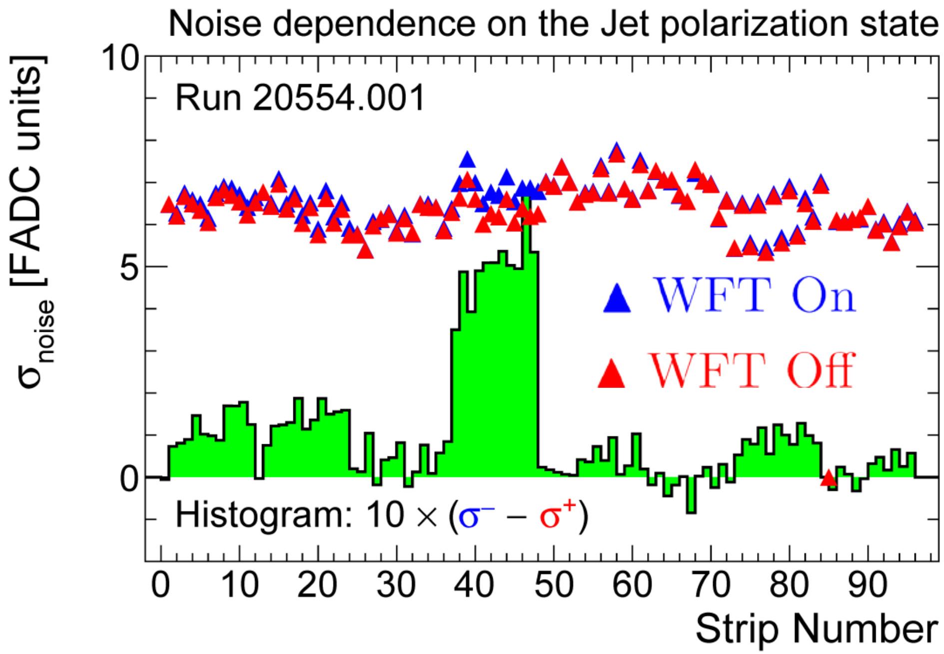


- For 255 GeV proton beam, a few percent of inelastic events is detected.
- To separate signal from this background the $\delta\sqrt{T_R}$ cut can be used.
- After applying the *minimum systematic error cuts*, the residual systematic correction is

$$\delta^{\text{syst}}P/P \approx 0.15 \pm 0.15\%$$

Sources of systematic errors in HJET:

Noise dependence on the Jet Spin



HJET detectors/preamplifiers appeared to be sensitive to the Weak Field Transition (WFT) 14 MHz frequency.

In the Inner Blue Up detector (Si strips 36-47) the WFT induced noise was about 8 keV.

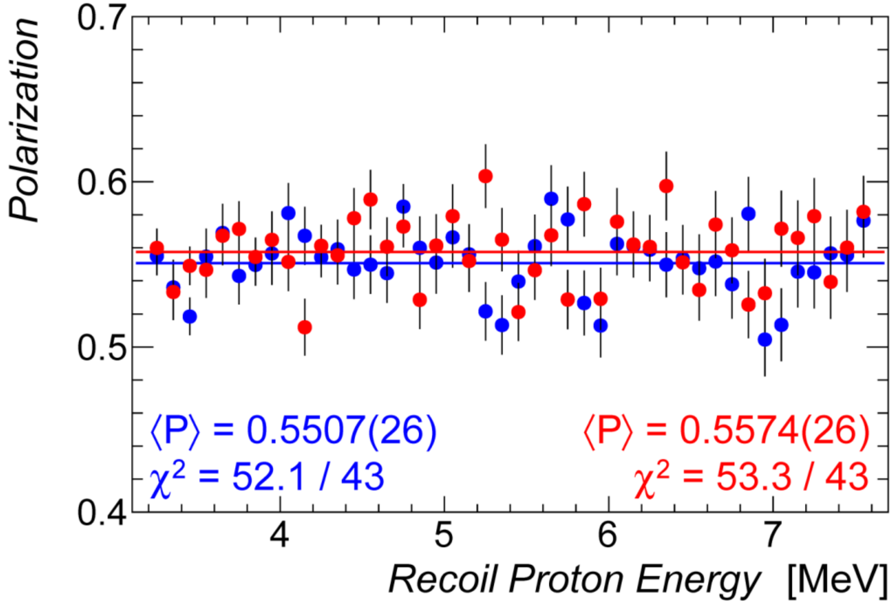
Potentially it may results in acceptance dependence on the Jet spin.

Noise dependence on the Jet spin was a problem in the Run 2015.

No evidence of such a systematic corrections was found in the Run 2017 data

$$\delta^{\rm syst}P/P \approx 0 \pm 0.2\%$$

Results for minimum systematic error cuts



Systematic correction summary $\widetilde{\delta_{corr}}$

Source	Correction (%)	Error (%)
Long term stability		0.1
Jet Polarization		0.1
Molecular Hydrogen (1)	−0.03	0.03
Molecular Hydrogen (2)	−0.08	0.11
pA scattering		< 0.2
p+p→X+p	−0.15	0.15
Jet spin correlated noise		< 0.2
Total Systematic	**−0.26**	**< 0.37**

Strong elimination of the systematic error sources resulted in a $\sim 0.7\%$ correction to the $\delta P/P$. The residual systematic error of 0.4% does not look underestimated.

$$\langle P_{\text{jet}} \rangle = 0.957 \pm 0.001 \qquad \widetilde{\delta_{\text{corr}}} = (-0.3 \pm 0.4_{syst})\%$$

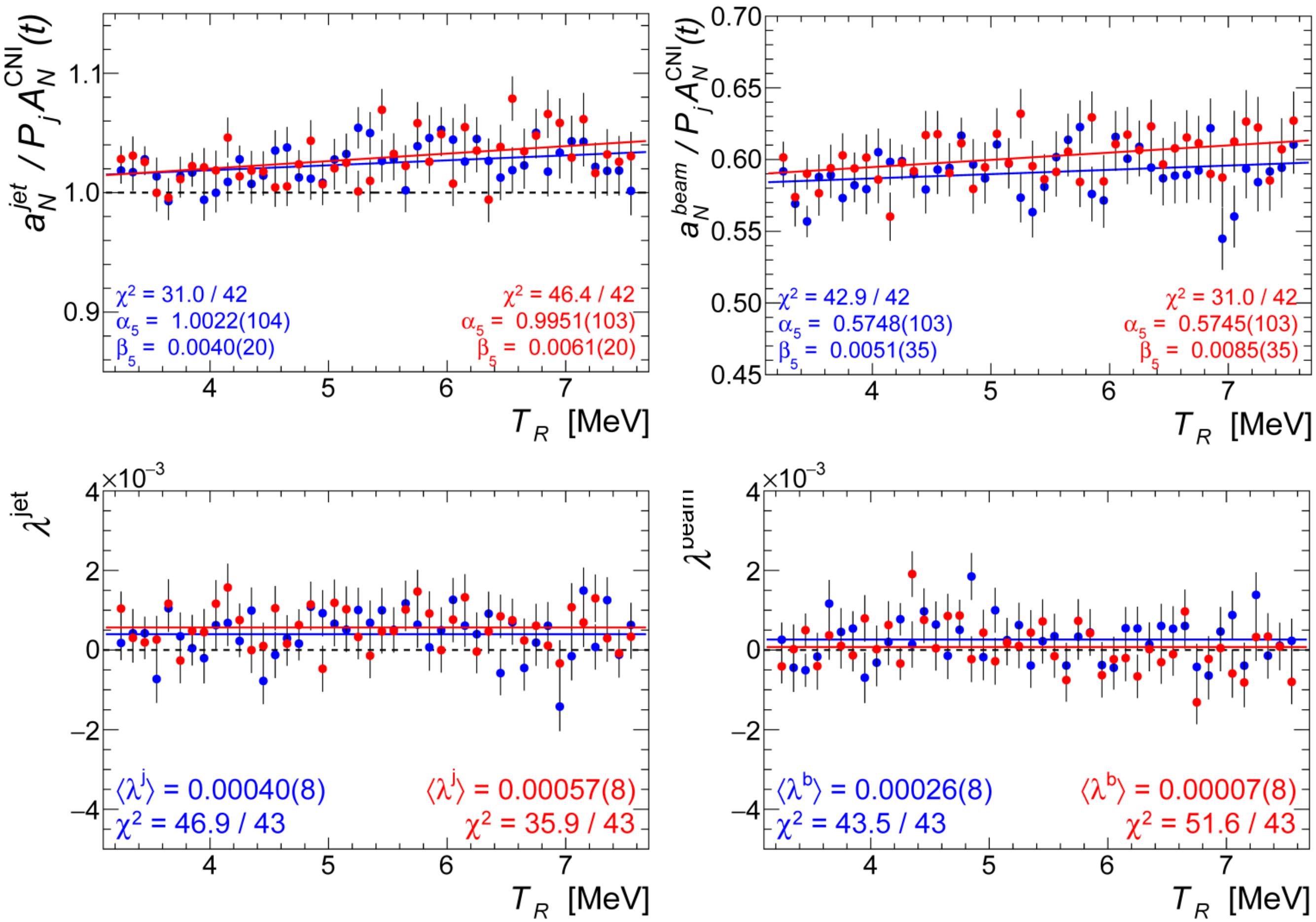
$$\boldsymbol{P_{jet}^{\text{eff}} = 0.955 \pm 0.004_{\text{syst}}}$$

$$\boldsymbol{A_N^{\text{eff}} = 0.03752 \times (1 \pm 0.004_{\text{syst}} \pm 0.004_{\text{stat}})}$$

$$\boldsymbol{A_N^{\text{eff}} = 0.03745 \times (1 \pm 0.004_{\text{syst}} \pm 0.004_{\text{stat}})}$$

Effective systematic error $\boldsymbol{0.6\%}$

Results for minimum systematic error cuts II



$$a_N = a_N^{\mathrm{meas}} + P\Delta_{\mathrm{bgr}}$$

$$\lambda_N = \lambda_N^{\mathrm{meas}} + P\Delta_{\mathrm{bgr}}$$

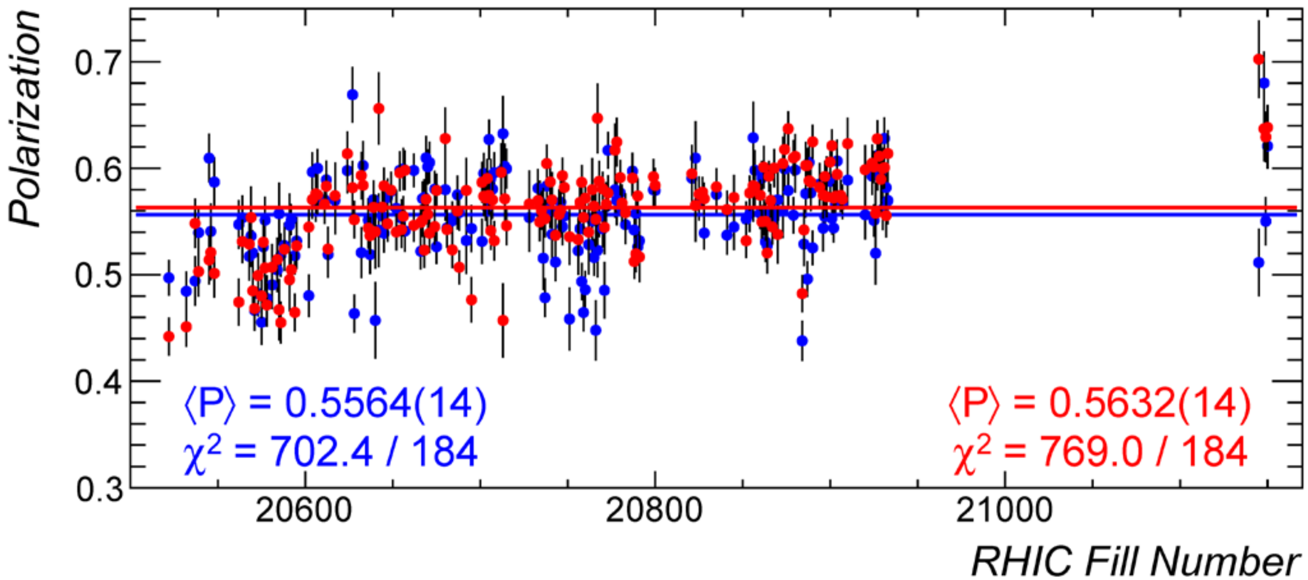
$$\langle\Delta_{\mathrm{bgr}}\rangle \sim (-1 \pm 0.5) \times 10^{-4}$$

(from the recoil proton track simulation)

- The slopes β_5 are consistent for all 4 measurements.
- The χ^2 test does not indicate any significant dependence of the Δ_{bgr} on T_R.

Absolute Beam Polarization measurement in Run 2017

A typical result for a 8-hour store: $\langle P_{\mathbf{beam}} \rangle = (\sim 56 \pm 2.0_{stat} \pm 0.3_{syst})\%$



Statistical error summary:

RHIC Fill	Blue Beam	Yellow Beam
20522 - 20592	52.08 ± 0.41	49.57 ± 0.40
20598 - 20712	56.84 ± 0.26	55.93 ± 0.25
20728 - 20845	54.77 ± 0.27	56.97 ± 0.26
20852 - 20933	56.50 ± 0.25	58.47 ± 0.25
21145 - 21150	59.30 ± 1.20	64.40 ± 1.30
Run Average	$\mathbf{55.64 \pm 0.14}$	$\mathbf{56.32 \pm 0.14}$

Known Issues

1. Two ways to calculate the Run average asymmetry:

- Combine raw data (just like it was continuous measurement)
- Measure asymmetry for each RHIC store and then calculate weighted average.

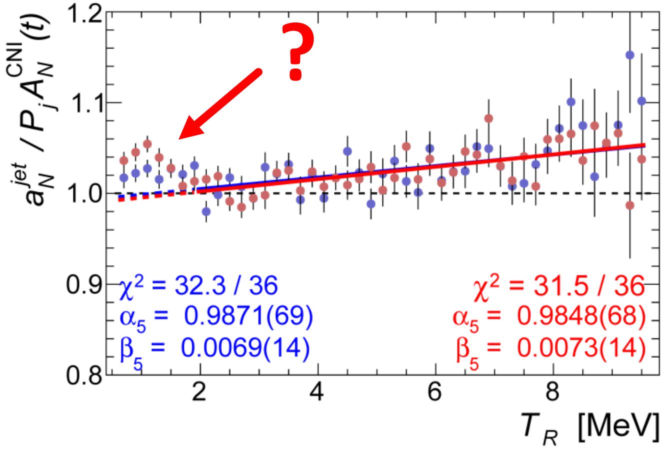
	Beam	Min. stat. Error		Min. syst. error		A_N^{eff}	$\langle P_{\mathrm{beam}} \rangle$
		$\langle a_N^j \rangle$ %	$\langle a_N^b \rangle$ %	$\langle a_N^j \rangle$ %	$\langle a_N^b \rangle$ %		
Total stat. average	Blue	3.606(5)	2.068(5)	3.351(8)	1.933(8)	3.750	55.13
	Yellow	3.601(5)	2.092(5)	3.367(8)	1.966(8)	3.747	55.83
RHIC Fill average	Blue	3.623(5)	2.084(5)	3.349(8)	1.937(8)	3.769	55.28
	Yellow	3.619(5)	2.109(5)	3.367(8)	1.978(8)	3.757	56.15

There are essential (compared to the declared systematic error) discrepancies. Actually this is a mathematical problem and it has to be resolved by mathematical analysis. In a worse case, we should add another systematic error $\sim 0.5\%$ (relative).

Known Issues

2. Measured Jet spin asymmetry for the low recoil proton energies

- It looks like the subtracted background was overestimated.
- At the moment, no good understanding of the source of the problem.
- This problem must not affect the beam polarization measurement (it was implicitly included to the effective analyzing power)

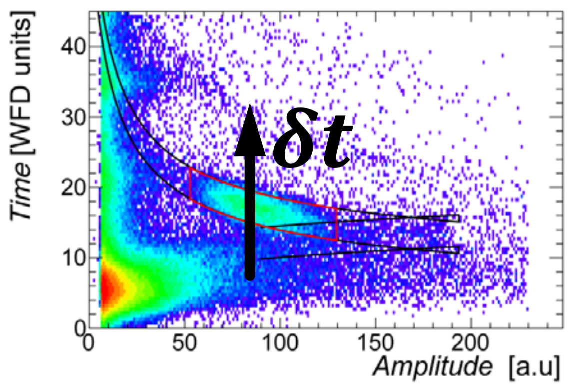


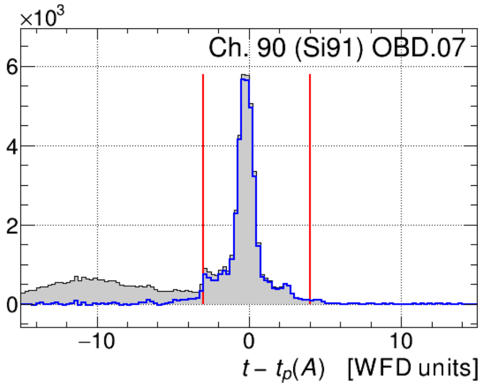
3. *p*A background.

- It was implicitly assumed that A is concentrated in the jet.
- Possible contribution of the beam gas A was not thoroughly studied.
- However, I expect that possible contribution from the beam gas A is accounted in the upper limit to the pA background of 0.2%.

Known issues

4. Longitudinal polarization profile

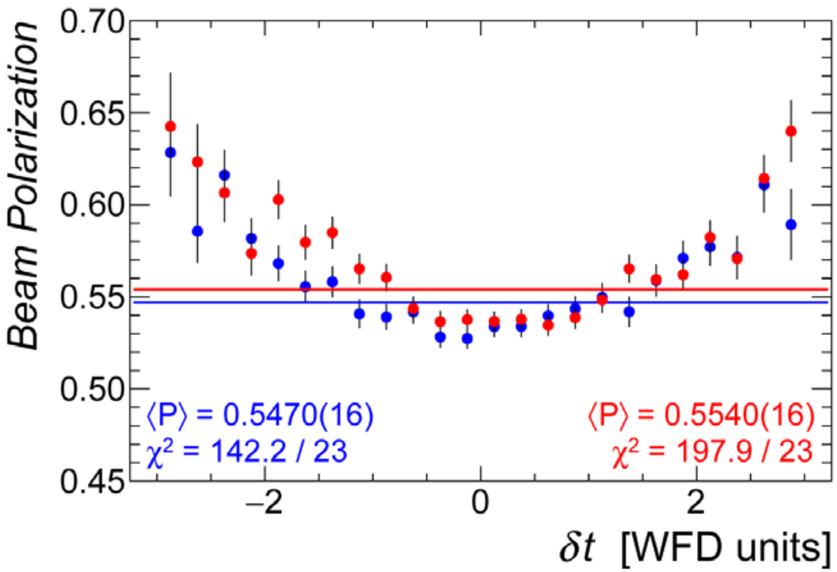




For the elastic pp events the $\delta t = t_{\text{meas}} - t_p(A)$ distribution is defined by the beam intensity profile.

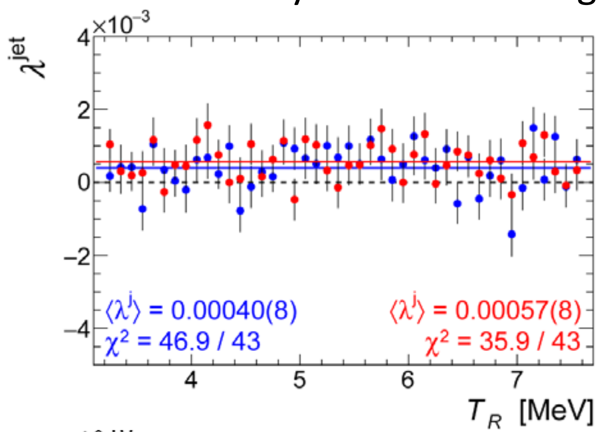
- The jet spin asymmetry must not depend on δt.
- Such a dependence of the beam spin asymmetry should be associated with tee beam polarization profile.

- The jet spin asymmetry does not depend on the δt.
- At the moment, no good understanding of such a dependence for the beam spin asymmetry.
- The RHIC pCarbon measurements may shed light on the issue,



Single Spin asymmetry 255 GeV (Run 2017)

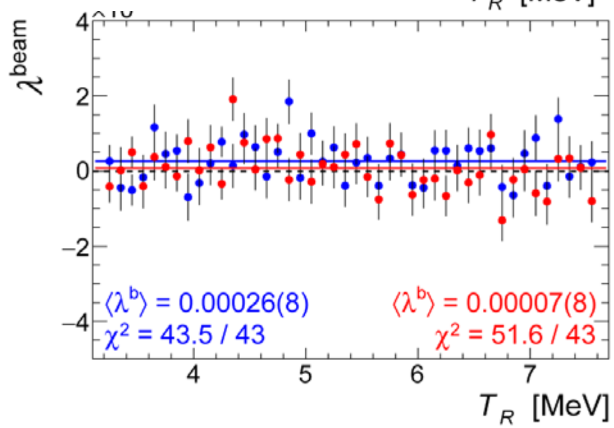
- To measure single spin analyzing power it is strongly preferable to use only left side detectors because background in the right side detectors is not well controlled.
- Since for left side detectors only analysis the "square root formula" does not work, we need to know the luminosity asymmetries λ with very high precision.
- Luminosity asymmetries λ could be found from the combined left/right measurement corrected by evaluated background contribution Δ.



$$\lambda = \lambda^{meas} - P\Delta$$

Minimum systematic error cuts

$$\langle \Delta_{bgr} \rangle \sim (-10 \pm 5) \times 10^{-5}$$



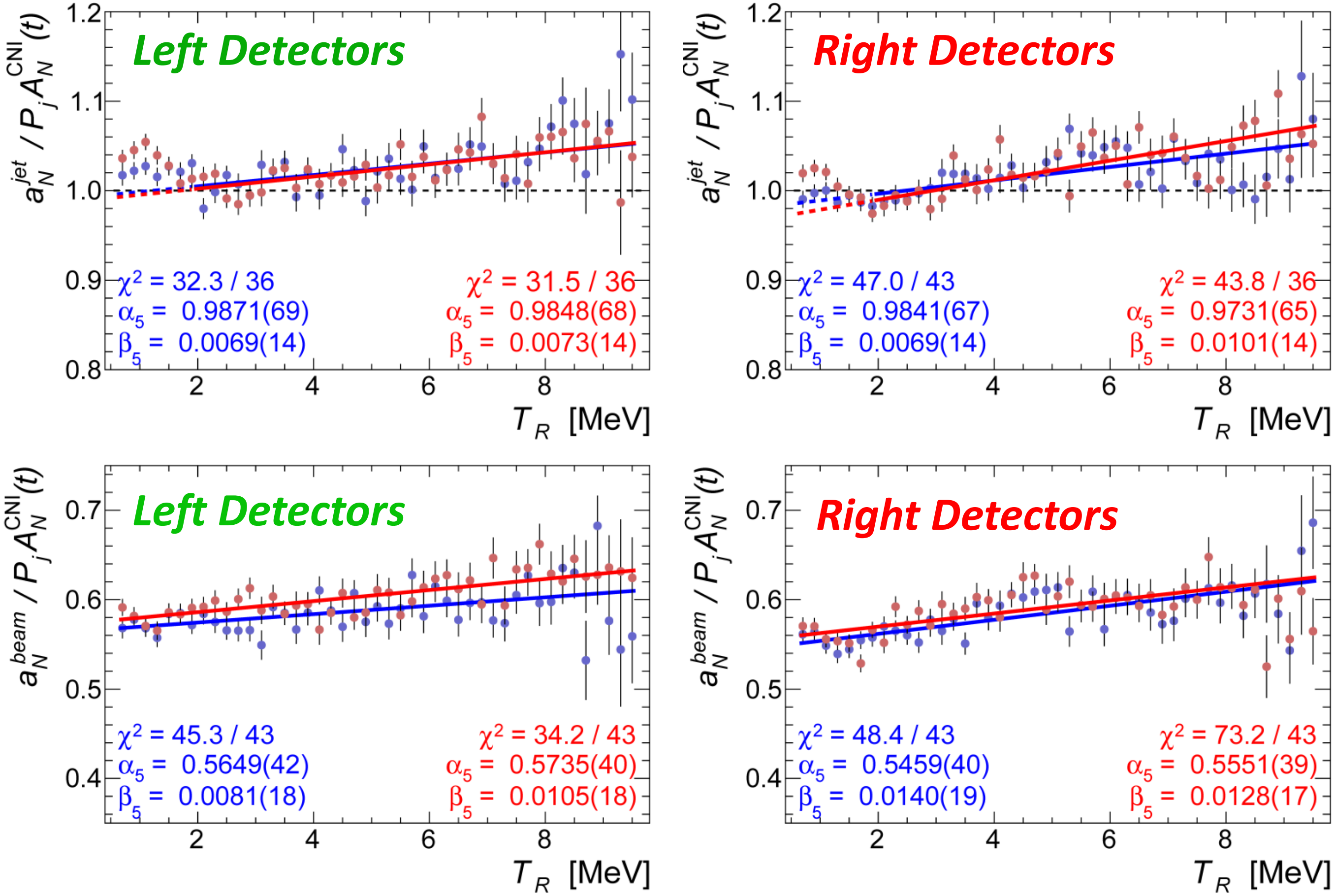
$$\lambda_{jet}^{blue} = (30 \pm 8_{stat} \pm 5_{syst}) \times 10^{-5}$$

$$\lambda_{jet}^{yellow} = (47 \pm 8_{stat} \pm 5_{syst}) \times 10^{-5}$$

$$\lambda_{beam}^{blue} = (20 \pm 8_{stat} \pm 3_{syst}) \times 10^{-5}$$

$$\lambda_{beam}^{yellow} = (\ 1 \pm 8_{stat} \pm 3_{syst}) \times 10^{-5}$$

Single Spin asymmetry 255 GeV (Run 2017)



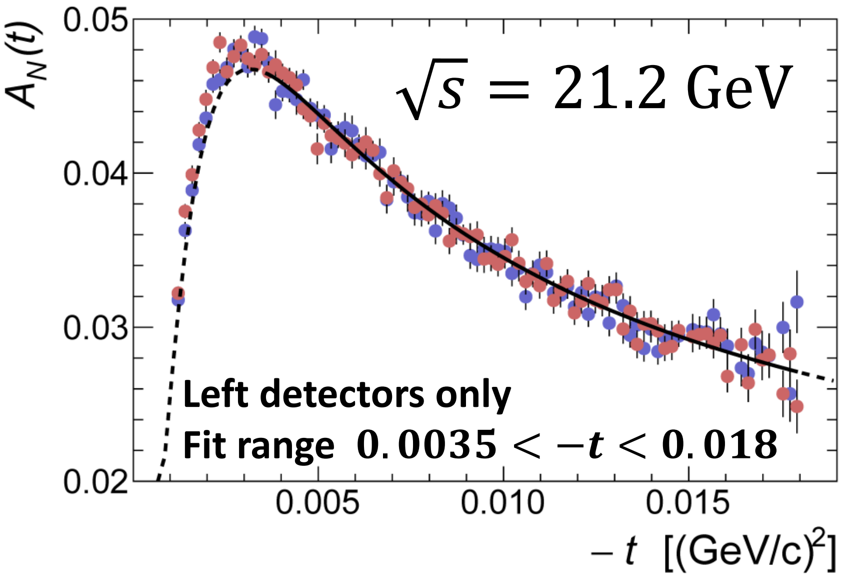
Jet spin asymmetry
***fit range* :**
$1.9 < T_R < 9.6$ MeV

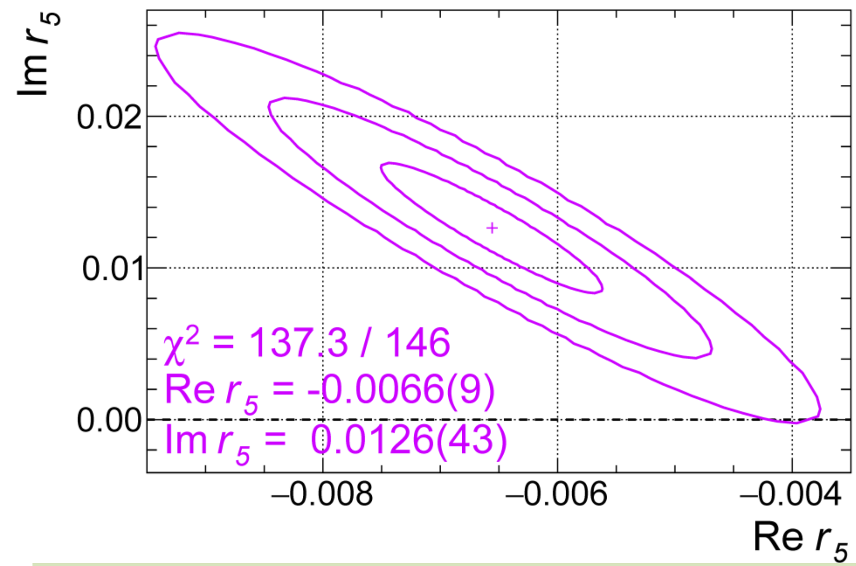
Beam spin asymmetry
***fit range* :**
$0.6 < T_R < 9.6$ MeV

- ***For the jet asymmetry there is uncontrollable background for*** $T_R < 1.9$ **MeV.**
- ***For the right detectors measurement there is a visible deviation from linearity.***
- ***We will use only left detectors to measure single spin analyzing power*** $A_N(t)$.

Single Spin Analyzing Power $A_N(t)$

$$A_N(t) = \frac{\sqrt{-t}}{m_p} \frac{[\kappa(1-\rho\delta_C) - 2(\mathrm{Im}\, r_5 - \delta_C \mathrm{Re}\, r_5)]\frac{t_c}{t} - 2\mathrm{Re}\, r_5 + 2\rho \mathrm{Im}\, r_5}{\left(\frac{t_c}{t}\right)^2 - 2(\rho + \delta_C)\frac{t_c}{t} + 1}$$





Analyzing power parameterization:

$\rho = -0.001,$

$B = 12.0\ (GeV/c)^{-2},$

$\sigma_{tot} = 39.24\ mb$

Systematic corrections:

$$10^3 \Delta \mathrm{Re}\, r_5 = -0.1 \frac{\Delta P_{jet}}{0.01} + 0.2 \frac{\Delta \lambda_{jet}^{\mathrm{corr}}}{0.0001} - 0.7 \frac{\Delta \rho}{0.01}$$

$$10^3 \Delta \mathrm{Im}\, r_5 = +9.2 \frac{\Delta P_{jet}}{0.01} - 1.4 \frac{\Delta \lambda_{jet}^{\mathrm{corr}}}{0.0001} + 7.6 \frac{\Delta \rho}{0.01}$$

For $P_{jet} = 0.955 \pm 0.004$

$\lambda_{jet}^{\mathrm{corr}} = (-1.0 \pm 0.5) \times 10^{-4}$

$\rho = (-1.0 \pm 0.6) \times 10^{-2}$

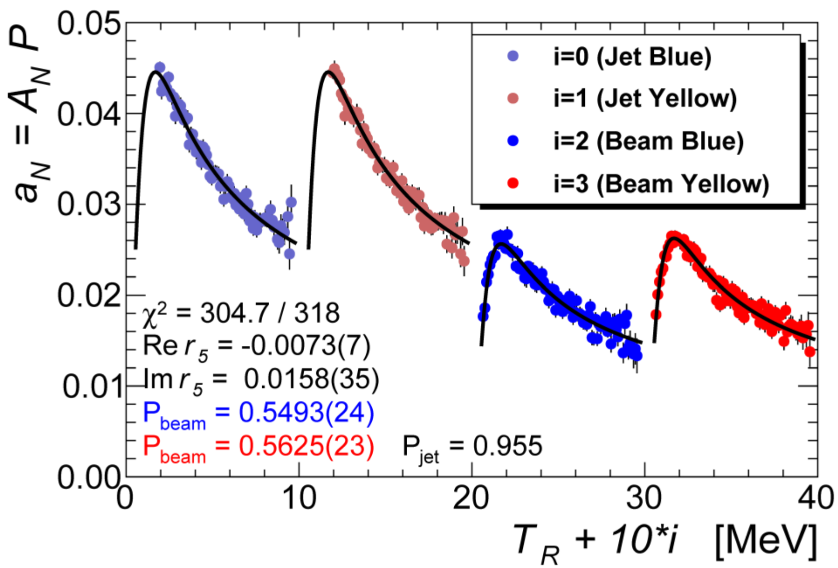
$$\mathrm{Re}\, r_5 = (-6.0 \pm 0.9_{\mathrm{stat}} \pm 0.4_{syst} \pm 0.4_{\rho}) \times 10^{-3}$$

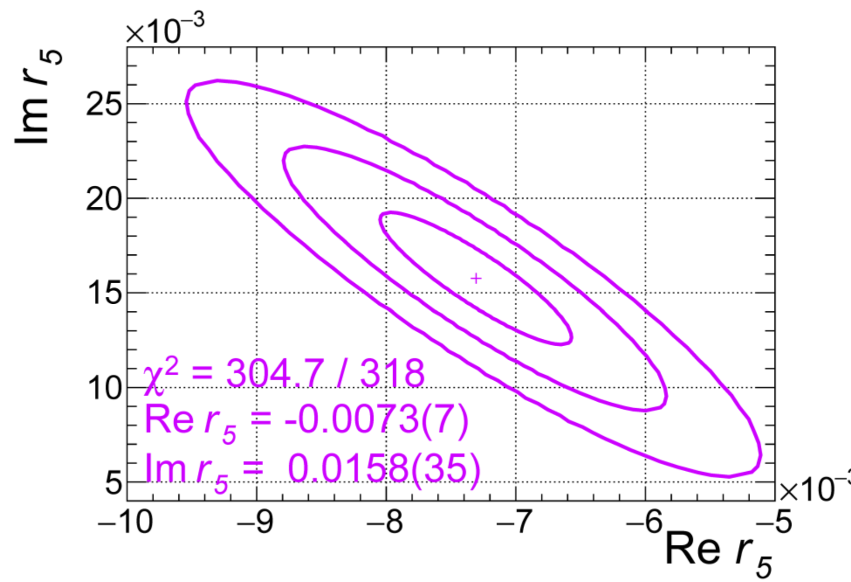
$$\mathrm{Im}\, r_5 = (10.2 \pm 4.3_{\mathrm{stat}} \pm 4.2_{syst} \pm 4.6_{\rho}) \times 10^{-3}$$

(Fit result dependence on the fit range is accounted)

Combined beam / jet analyzing power

Fit Range: $1.9 < T_R < 9.6$ MeV (jet)
$0.6 < T_R < 9.6$ MeV (beam)





Systematic corrections:

$$10^3 \Delta \mathrm{Re}\, r_5 = -0.1 \frac{\Delta P_{jet}}{0.01} + 0.1 \frac{\Delta \lambda_{jet}^{corr}}{0.0001} - 0.7 \frac{\Delta \rho}{0.01}$$

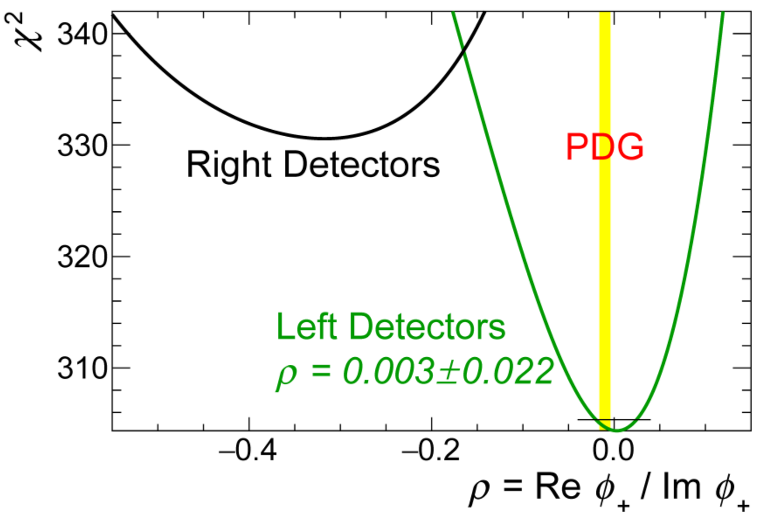
$$10^3 \Delta \mathrm{Im}\, r_5 = +9.1 \frac{\Delta P_{jet}}{0.01} - 1.9 \frac{\Delta \lambda_{jet}^{corr}}{0.0001} + 8.0 \frac{\Delta \rho}{0.01}$$

$$\mathrm{Re}\, r_5 = \left(-6.7 \pm 0.7_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}} \pm 0.4_{\rho}\right) \times 10^{-3}$$

$$\mathrm{Im}\, r_5 = \left(13.7 \pm 3.5_{\mathrm{stat}} \pm 4.3_{\mathrm{syst}} \pm 4.8_{\rho}\right) \times 10^{-3}$$

(Fit result dependence on the T_R is accounted)

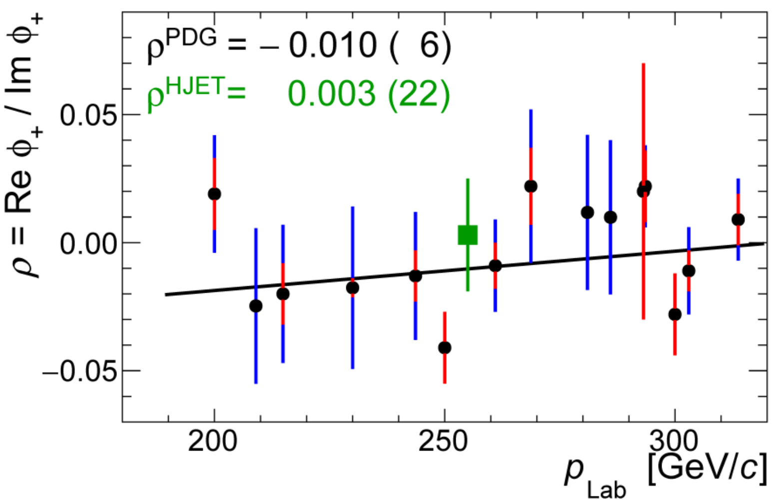
Forward Elastic Re/Im *ratio ρ*



$$A_N(t) = A_N(t, \boldsymbol{\rho}, \mathrm{Im}\, r_5, \mathrm{Re}\, r_5)$$

Considering ρ as a free parameter in the fit, we can experimentally evaluate it value.

- **For the left detectors**, the fit is in a good agreement with PDG data, which mean a good consistency between experimental data and the theoretical model.
- **For the right detectors**, there is a significant discrepancy between HJET data and theoretical expectations. This may be explained by incorrectly subtracted backrounds .



Interpretation of the PDG data for elastic pp scattering:

- For every measurement, the error of the measurement is a simple (linear) sum of the statistical (red) and systematic (blue) errors.
- The value of ρ at 255 GeV was found in the linear fit assuming that errors in all measurements are uncorrelated.

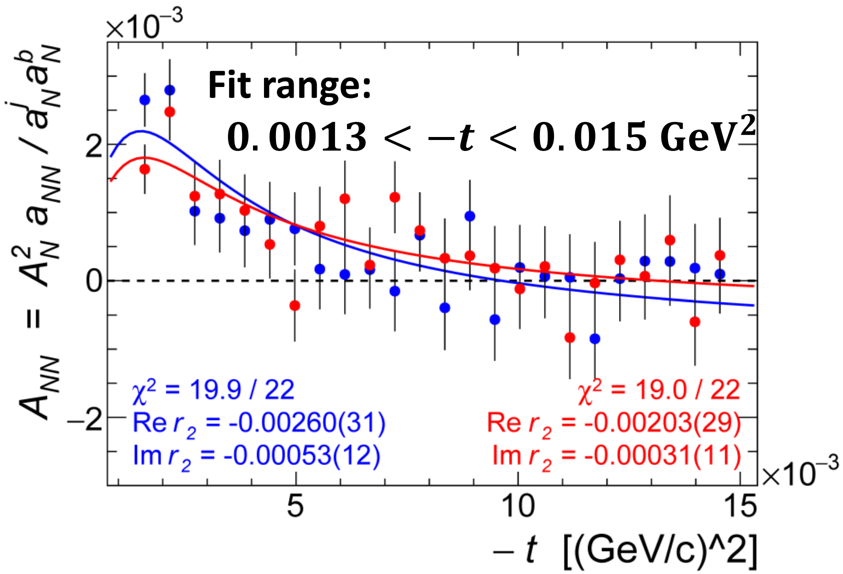
Double Spin Asymmetry $A_{NN}(t)$

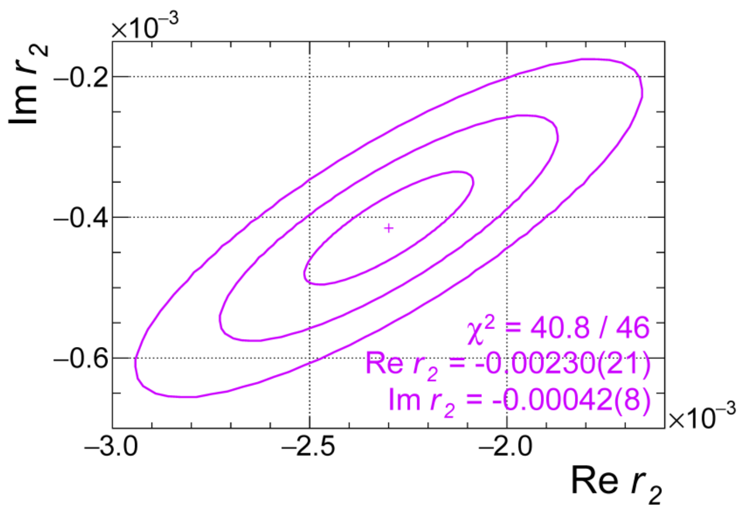
Parameterization:

$$A_{NN}(t) = \frac{-2(\text{Re}\, r_2 + \delta_C \text{Im}\, r_2)\frac{t_c}{t} + 2\text{Im} r_2 + 2\rho \text{Re}\, r_2 - \rho\frac{t_c \kappa^2}{2m_p^2} + \frac{2t_c\kappa}{m_p^2}\text{Re}\, r_5}{\left(\frac{t_c}{t}\right)^2 - 2(\rho + \delta_C)\frac{t_c}{t} + 1}$$

$$A_{NN}(t) = \frac{a_{NN}(t)}{P_{\text{beam}} P_{jet}} = \frac{A_N^2(t, r_5)}{a_N^{\text{beam}}(t)} \frac{a_{NN}(t)}{a_N^{\text{jet}}(t)}$$

- Molecular Hydrogen and *pA* background contributions are canceled in the a_{NN}/a_N^{jet} ratio.
- $A_N(t, r_5)$ is known sufficiently well.
- $\text{Re}\, r_5 = -0.0073, \quad \text{Im}\, r_5 = 0.0158$



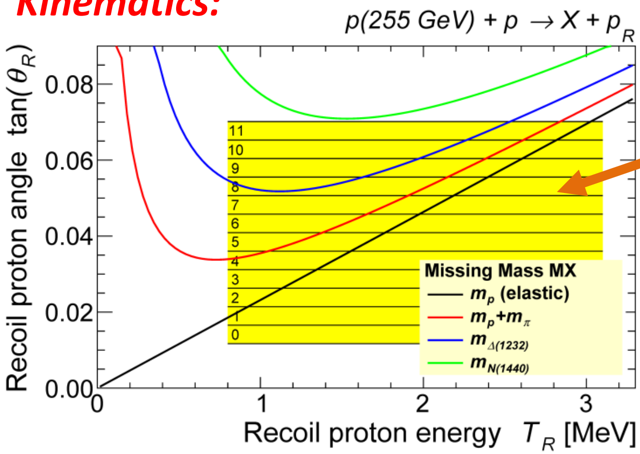


Systematic errors are expected to be smaller than statistical errors.

$$\text{Re}\, r_2 = (-2.30 \pm 0.21_{\text{stat}}) \times 10^{-3}$$
$$\text{Im}\, r_2 = (-0.42 \pm 0.08_{\text{stat}}) \times 10^{-3}$$

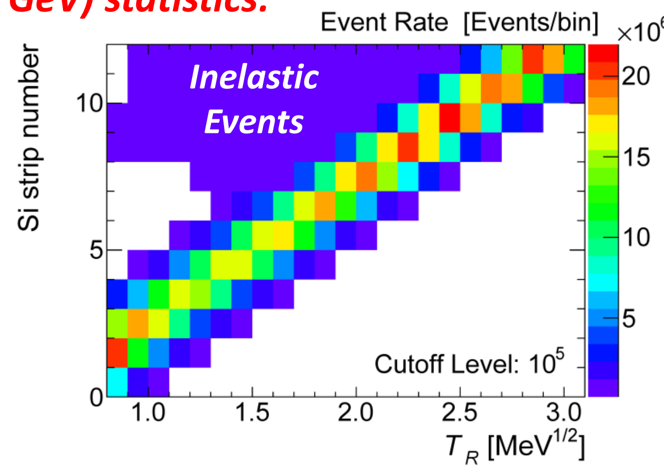
Inelastic scattering $p^{\uparrow}_{beam} + p^{\uparrow}_{jet} \rightarrow X + p_{recoil}$ at 255 GeV

Kinematics:

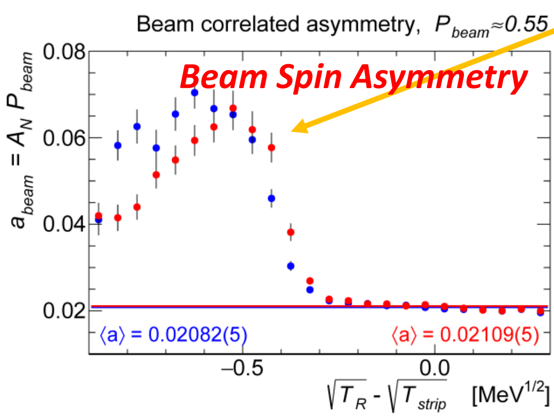


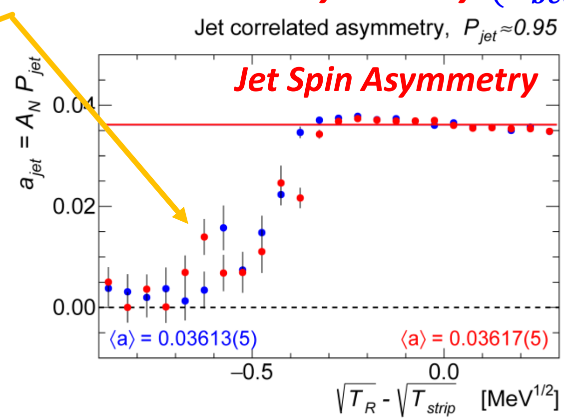
Detector (12 Si strips) acceptance

Run2017 (255 GeV) statistics:



Inelastic contribution to the measured asymmetry $(P_{beam} \approx 0.95, \quad P_{jet} \approx 0.55)$





T_{strip} is recoil proton energy corresponding to the strip (for elastic scattering)

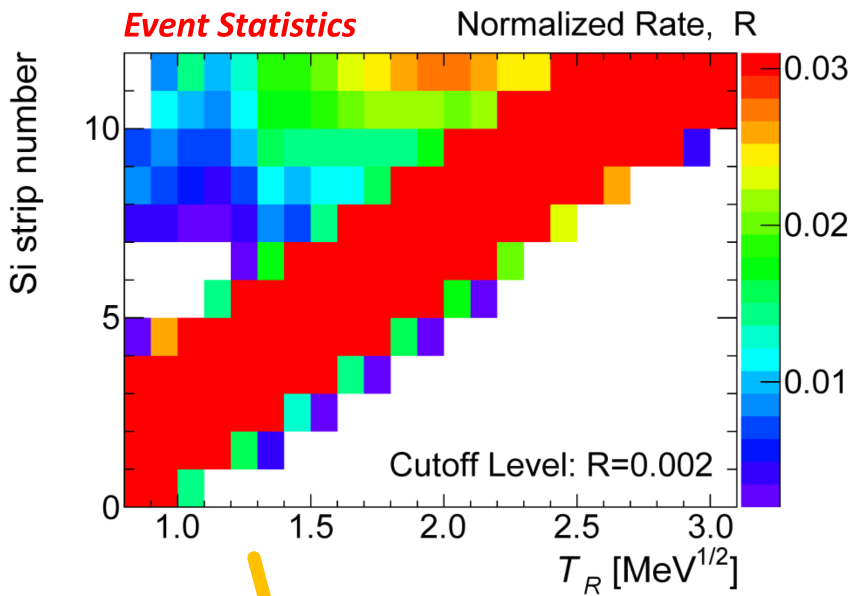
$\langle A_N \rangle \sim 10\%$

for $p^{\uparrow}_b + p_j \rightarrow X + p_j$

$\langle A_N \rangle \sim 1\%$

for $p_b + p^{\uparrow}_j \rightarrow X + p_j$

Inelastic scattering. A detailed analysis.



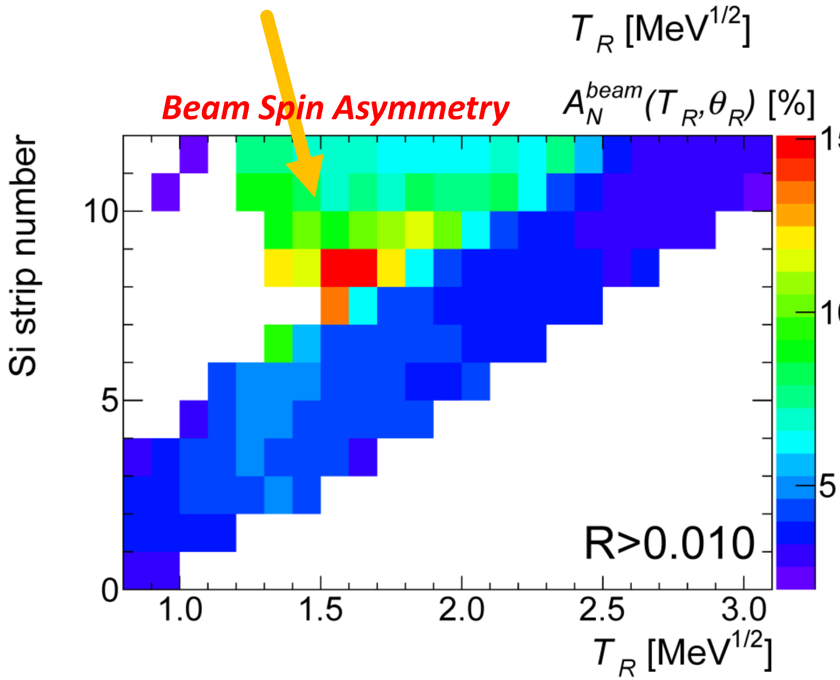
$R = N/N_{\max}$, where N is statistics in the histogram bin.

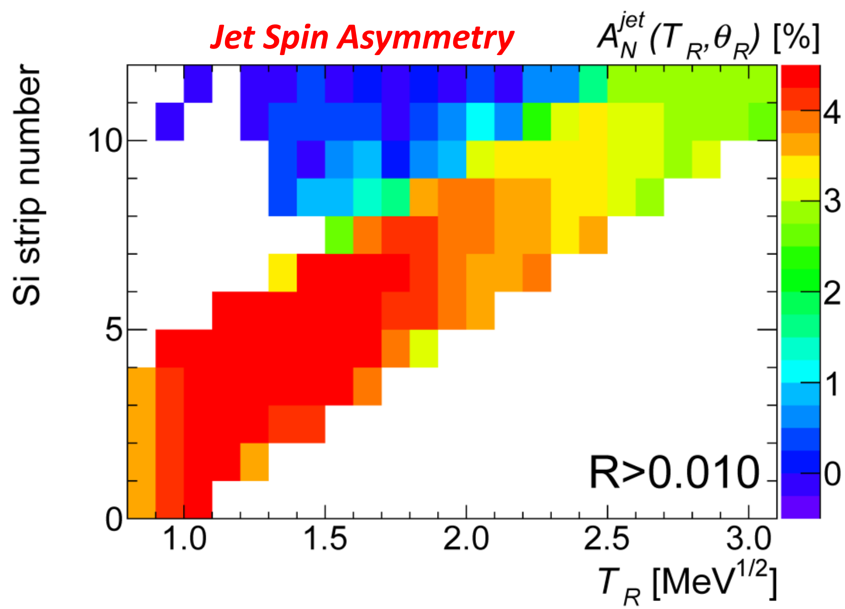
No visual evidence of $\Delta^+(1232)$ resonance in the event rate distribution, but, possibly, a strong signal in the A_N distributions.

?!

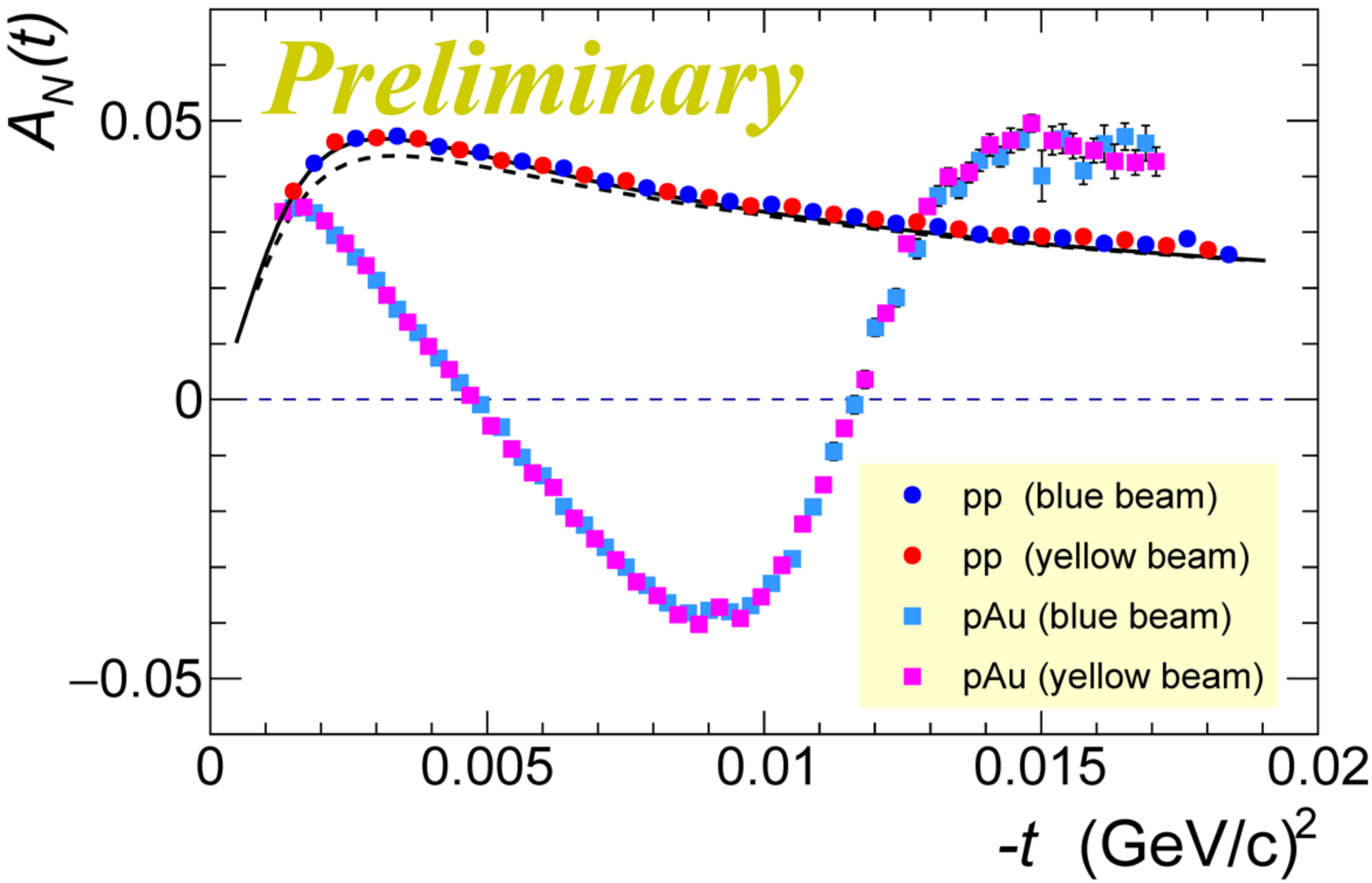
$A_N^{beam}(t \sim -0.003) > 15\%$

for $p_b^{\uparrow} + p_j \rightarrow \Delta^+ + p_j$





RHIC Run 2017: $p^{\uparrow}p^{\uparrow}$ (255 GeV), AuAu (27 GeV/n)



- Solid black line is proton-proton $A_N^{\mathrm{CNI}}(t)$ for 255 GeV beam.
- Dashed black line is proton-proton $A_N^{\mathrm{CNI}}(t)$ for 100 GeV beam

Summary

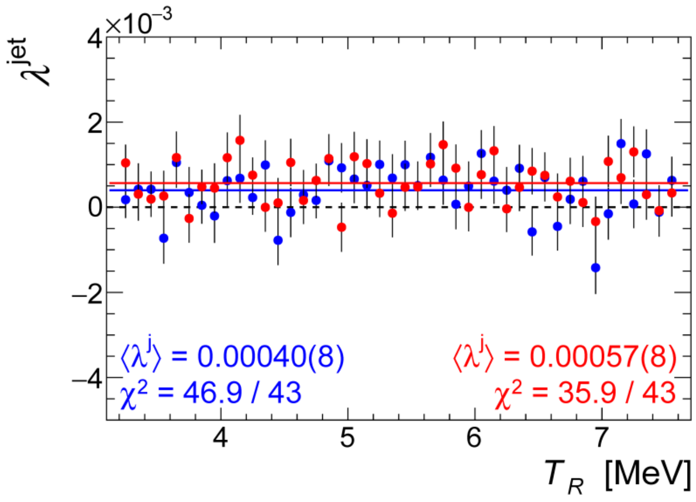
- Long term (1-100 days) stability $\sigma_A/A_N \lesssim 0.1\%$ of the spin correlated asymmetry measurement was observed.
- The effective systematic error in absolute polarization measurement was found to be $0.6\% = 0.4_{\text{syst}}\% \oplus 0.4_{\text{stat}}\%$.
- The measured dependence of beam polarization on the time parameter δt may be interpreted as observation of the longitudinal polarization profile.
- Single and double spin analyzing powers for elastic $p^{\uparrow}p^{\uparrow}$ scattering was measured. Hadronic spin-flip r_5 and double-spin-flip r_2 amplitudes were experimentally evaluated.
- Analyzing power of the inelastic scattering $p^{\uparrow}p^{\uparrow} \to X + p$ have been experimentally evaluate.
- Analyzing power of the $p^{\uparrow}\mathrm{Au}$ scattering was measured.

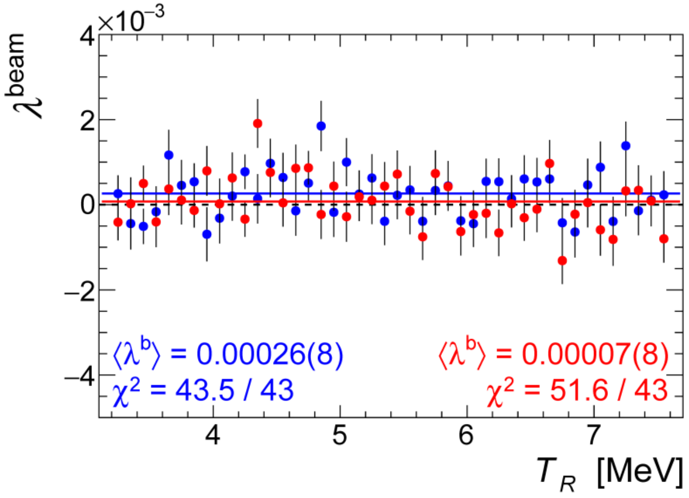
Some issues:

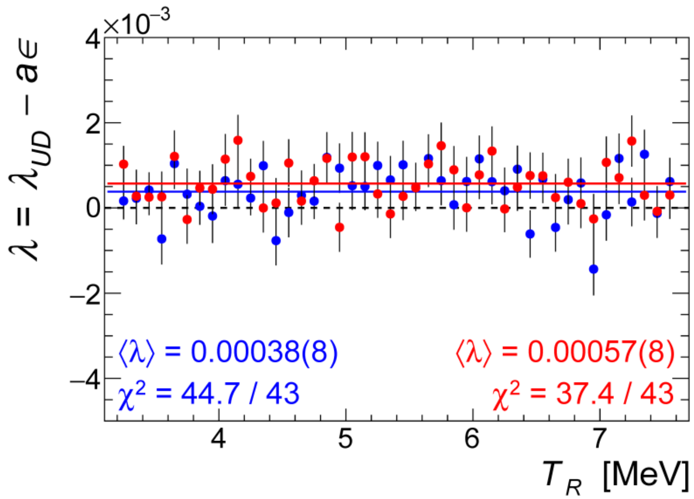
- The average Jet polarization used in the analysis has to be verified.
- No satisfactory explanation of the observed beam "longitudinal polarization profile"
- No explanation of the discrepancy in the Jet spin correlated asymmetry at low recoil proton energies.

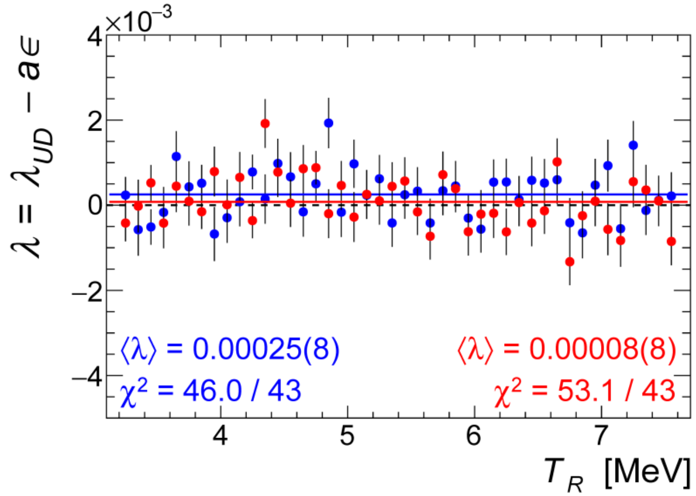
Backup

Intensity asymmetries λ in Run2017









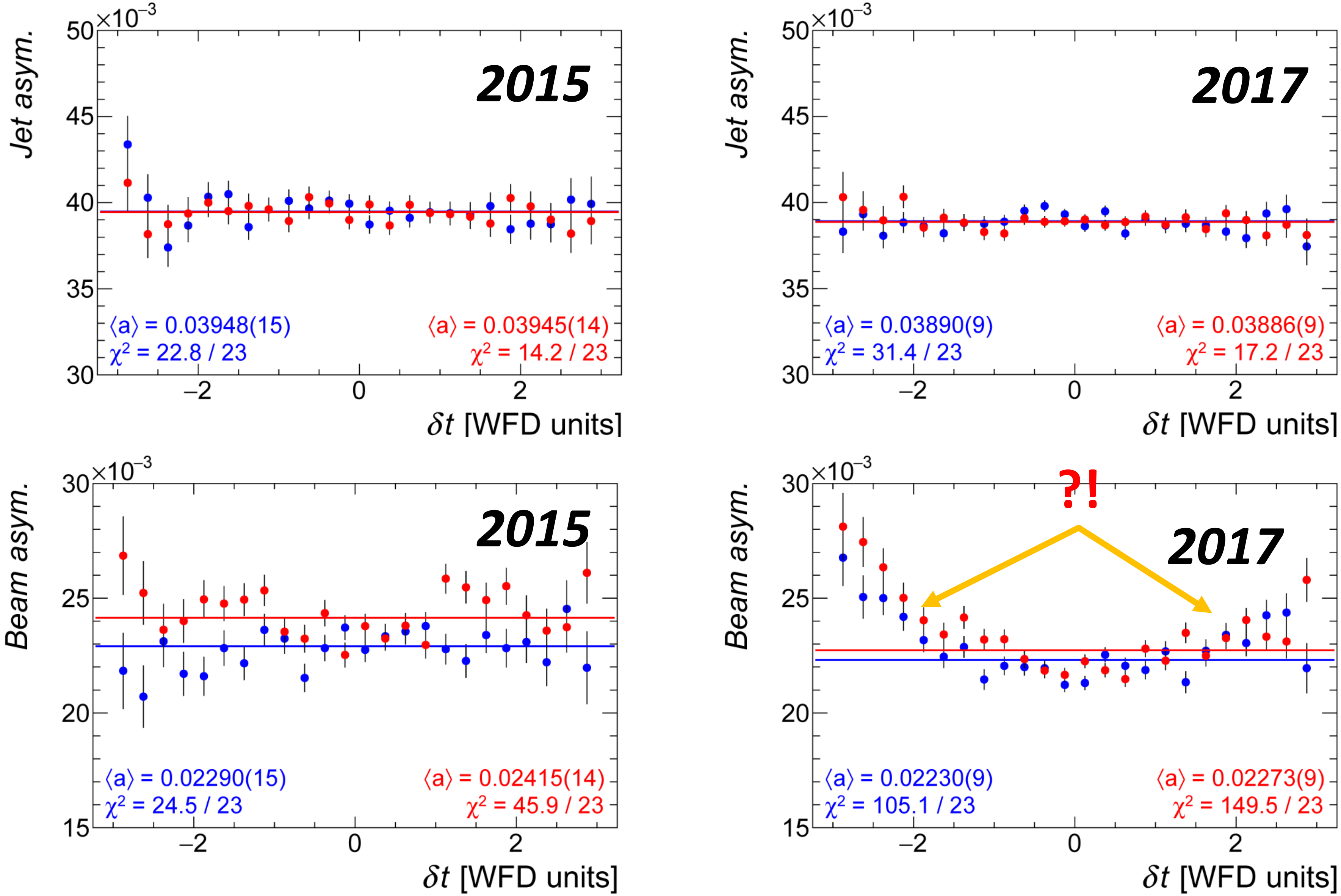
Systematic error summary
(for minimum syst. error cuts)

Source	Correction (%)	Error (%)
Long term stability		0.1
Jet Polarization		0.1
Molecular Hydrogen (1)	−0.03	0.03
Molecular Hydrogen (2)	−0.08	0.11
pA scattering		< 0.2
p+p→X+p	−0.15	0.15
Jet spin correlated noise		< 0.2
Total Systematic	**−0.26**	**< 0.37**

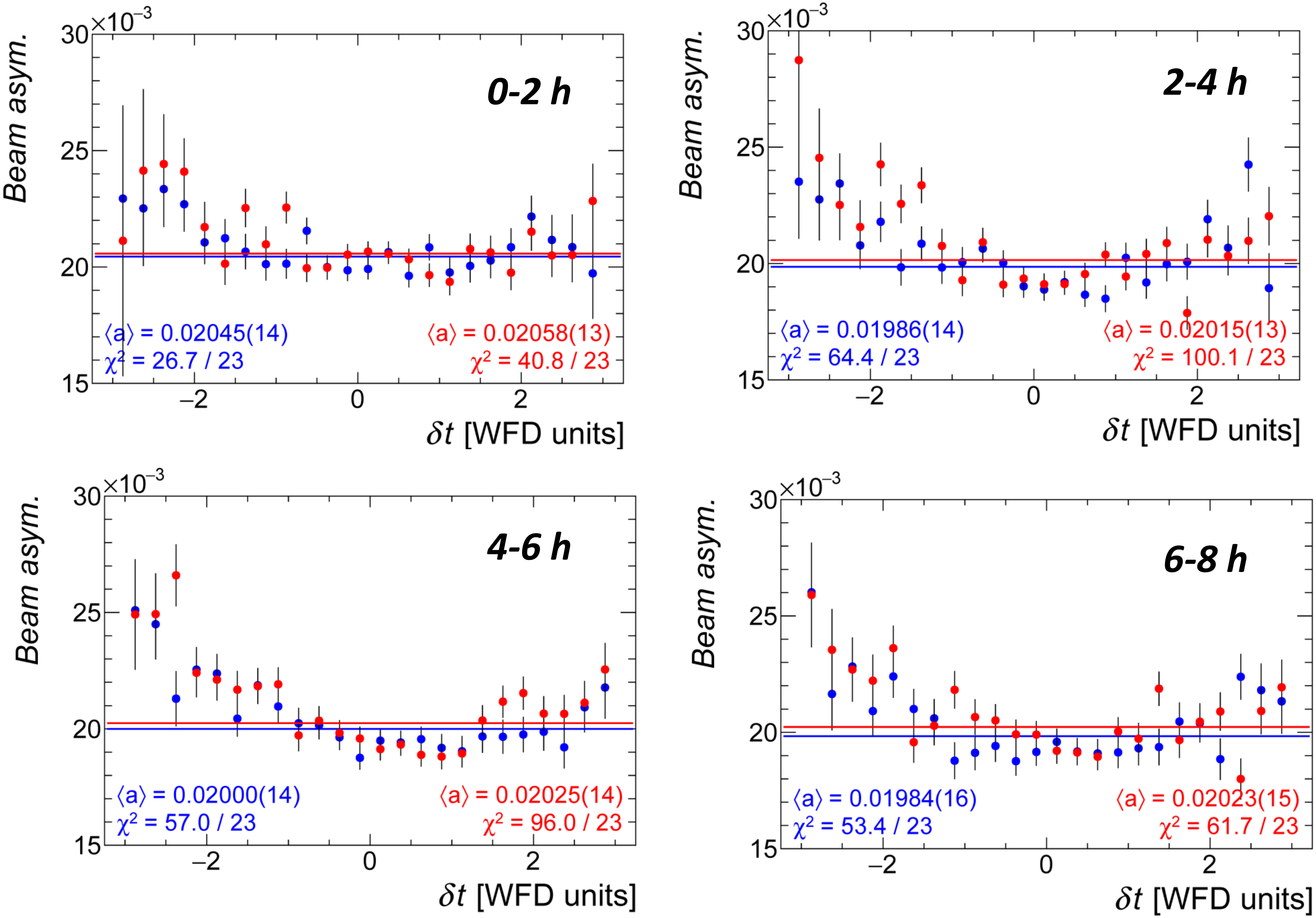
The atomic hydrogen polarization:

$$\mathbf{P_{jet} = 0.957 \pm 0.001 \quad \Longrightarrow \quad P_{jet}^{eff} = 0.955 \pm 0.004}$$

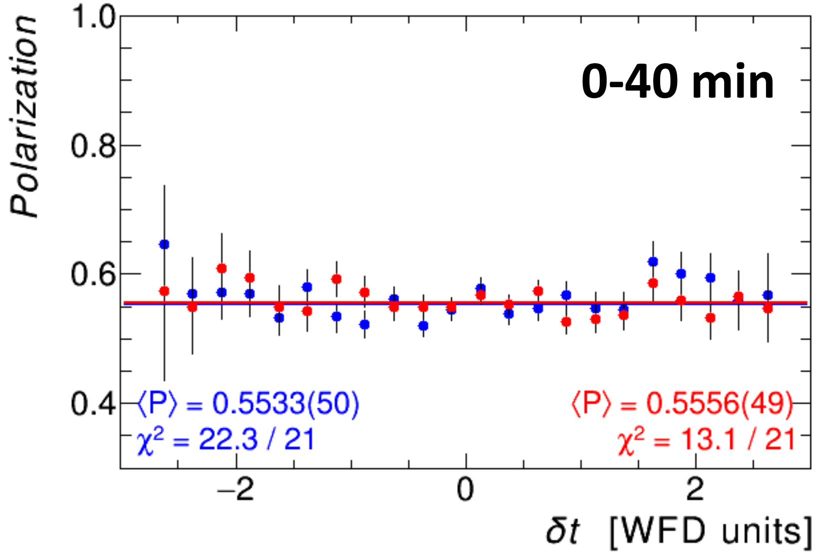
Longitudinal Polarization Profile II

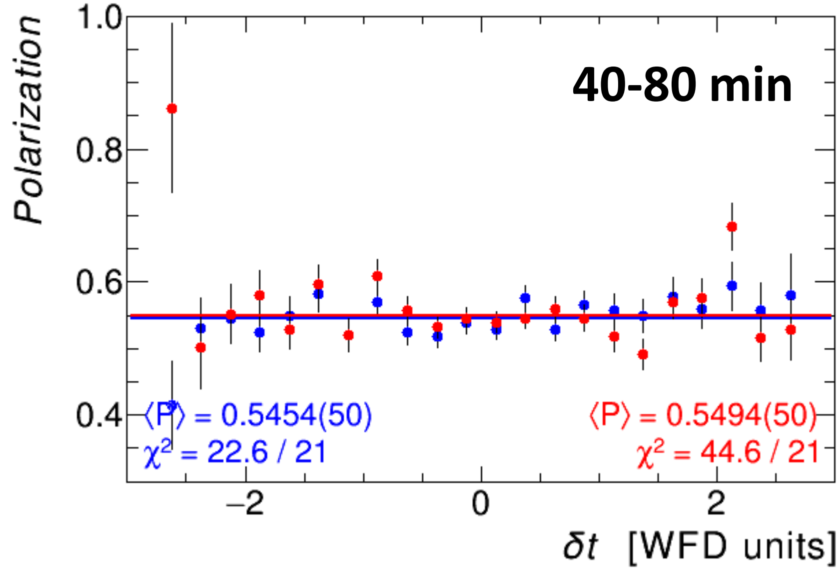


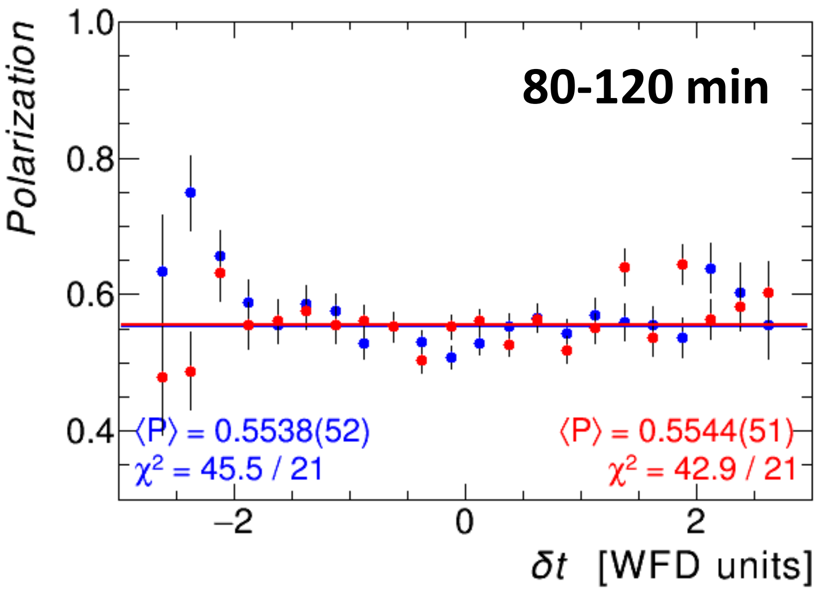
"Longitudinal Profile" evolution during the store



“Longitudinal Profile” evolution during first 2 hours







- **The distribution is almost flat in the beginning of the store.**
- **The flatness degrades fast.**
- **The average polarization does not change drastically.**

I have no satisfactory explanation of the issue.

Summary

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