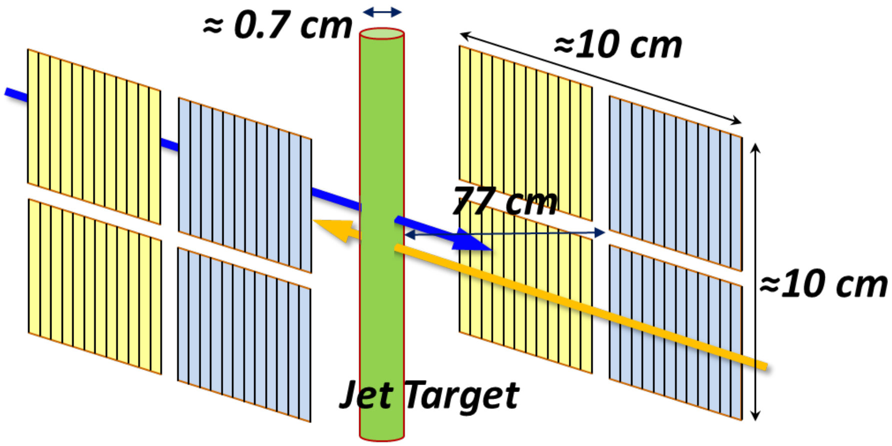
A. Poblaguev

- ***Systematic errors in the HJET (Run15)***
  - ✓ ***Background subtraction***
  - ✓ ***Evaluation of molecular hydrogen contribution and systematic errors***
  - ✓ ***Comments about "Blue beam asymmetry problem"***

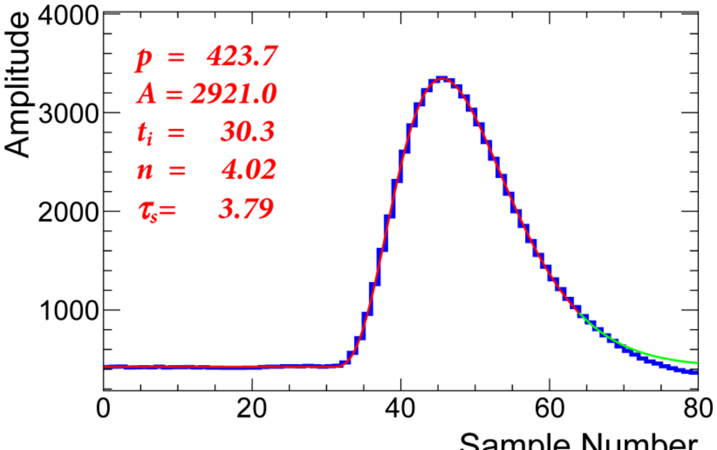
The HJET (a schematic view)



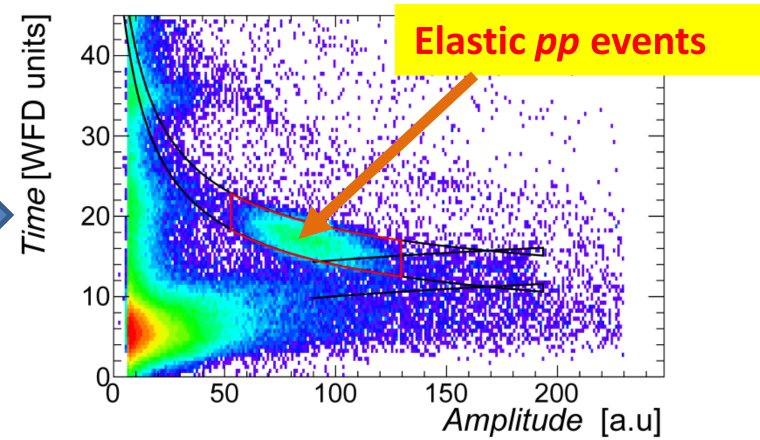
The Hjet in Run 2015

- New Si detectors
  (larger acceptance, better performance)
- New FADC250 (VME) based DAQ
  (part of the Run, better performance)
- 8 detectors (12 Si strips each) are operationally divided on Blue and Yellow depending on which beam polarization they measure

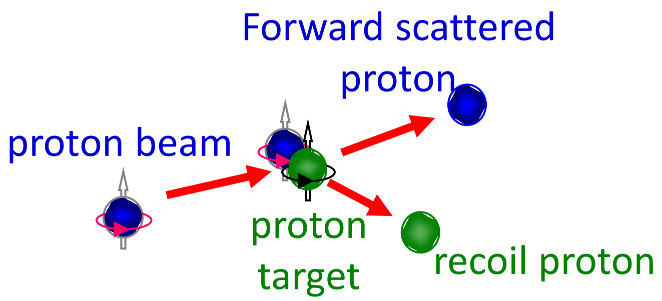
Full waveform is recorded for every signal above threshold



time, amplitude



Polarization measurement



$$t = (p_{out} - p_{in})^2 = -2m_p T_R$$

Left/right asymmetry of the recoil proton production is proportional to the beam polarization

$$a = \frac{N_L - N_R}{N_L + N_R} = \langle A_N(t) \rangle \cdot P$$

If polarization is flipped then the asymmetry measurement is systematic error free

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

IF

- $\langle A_N(t) \rangle$ ***is the same for left and right detectors***
- ***Polarization is the same for up (↑) and down (↓) beams***
- ***Event detection efficiency (acceptance) does not depend on the beam polarity ↑↓***

In the HJET measurements both, the beam and the target (jet) are polarized, and the jet polarization is well known (measured) $P_{jet} \approx 96\%$.

Thus, for pure elastic pp scattering:

$$\langle A_N(t) \rangle = \frac{a_{jet}}{P_{jet}}$$

$$P_{beam} = \frac{a_{beam}}{\langle A_N(t) \rangle} = \frac{a_{beam}}{a_{jet}} P_{jet}$$

Systematic errors due to background

The beam polarization measurement is based on the equality of the analyzing powers $A_N(t)$ for beam a_{beam} and jet a_{jet} asymmetries.
Background generally violates this equality

$$A_N^{(meas)} = \frac{A_N + rA_N^{(jet)}}{1+r}$$

$$P_{beam}^{(meas)} = P_{beam} \times \frac{A_N + rA_N^{(beam)}}{A_N + rA_N^{(jet)}}$$

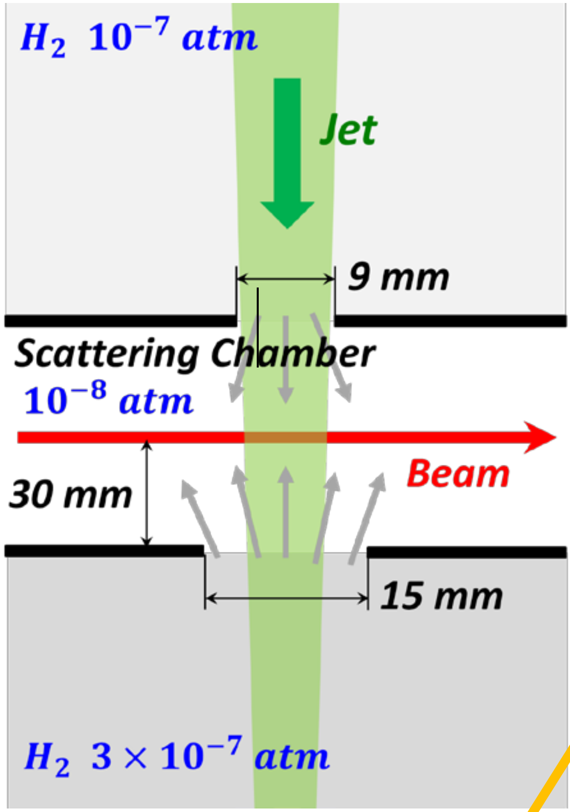
Where r is fraction of background events and $A_N^{(beam)}$ and $A_N^{(jet)}$ are background analyzing powers for beam and jet asymmetries, respectively.

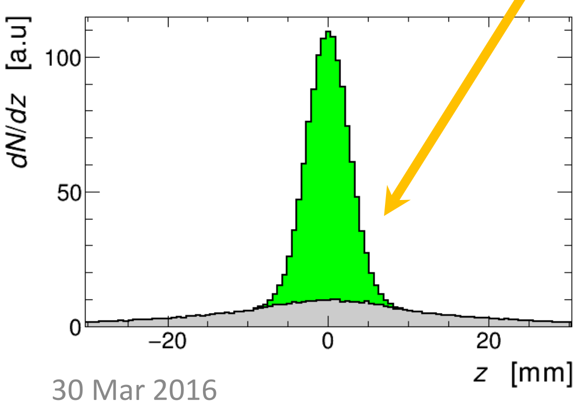
For most (if not all) backgrounds we may expect $A_N^{(jet)} = 0$.

For the "molecular hydrogen" component in the jet / beam gas $A_N^{(beam)} = A_N$, which results in a factor $1 + r_{mol}$ overestimation of the measured beam polarization.

Based on experimental evaluation of the r_{mol} (10 years ago) the RHIC Spin Group decided to use the jet polarization $92.4 \pm 1.8\%$ instead of $\approx 0.96\%$ measured by Breit-Rabi Polarimeter for atomic component to account the molecular hydrogen admixture of $r_{mol} \approx 3.7\%$.

Molecular Hydrogen





The hydrogen density in the HJET scattering chamber may be approximated as

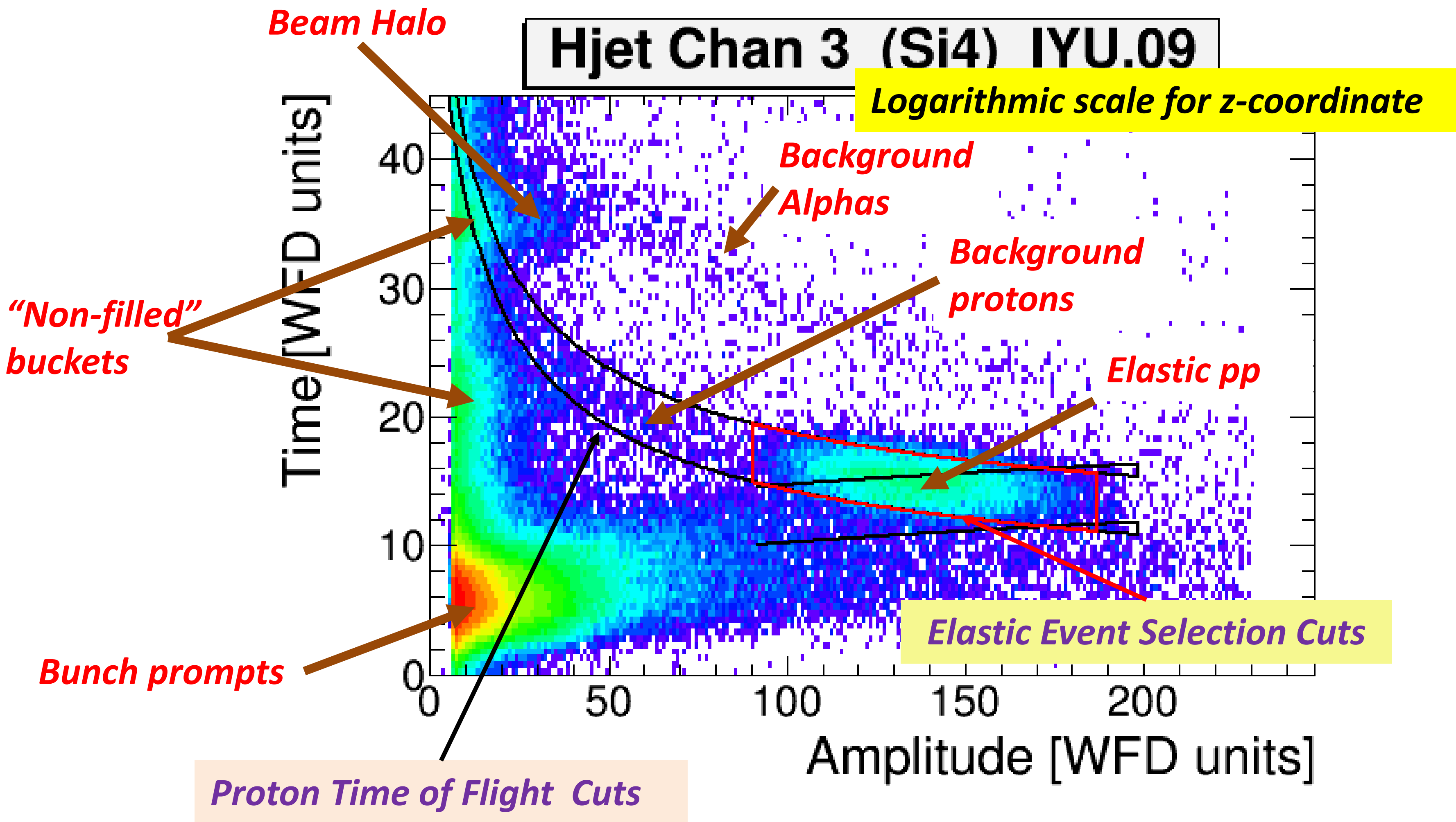
$$\frac{dN}{dxdz} \propto e^{-\frac{x^2+z^2}{2\sigma^2}} + r_{mol} e^{-\frac{x^2+z^2}{2\sigma_{mol}^2}}$$

Where first term corresponds to the atomic polarized hydrogen (jet) and the second term describes molecular hydrogen (unpolarized) background.

A simple simulation of the H2 flow gives an estimate $\sigma_{mol} \approx 5\sigma$. Since the H2 scattering on the chamber walls was not accounted, a realistic σ_{mol} is expected to be much larger. We will assume flat molecular hydrogen distribution.

Possible methods of experimental estimate of the σ_{mol} are being discussed

- shift the beam position horizontally to enhance the molecular hydrogen component (Yousef)
- **Inject hydrogen to the chamber and make measurements with no atomic jet hydrogen (Anatoli).**



Kinematically, detected prompts and α-particles cannot be generated in pp scattering. The inelastic processes $pA \to X$, where A stands for oxygen (?), nitrogen (?) … components in the beam gas / jet has to be included into consideration.

Isolation of elastic pp scattering

Since the HJET polarimeter does not have neither particle identification detectors nor veto system, the DAQ acquire

$$p_{beam}^{\uparrow\downarrow} + p_{jet}^{\uparrow\downarrow} \to x + X$$

All non-detected particles (X)

A particle which hit Si detector (x)

events contaminated by

$$p_{beam}^{\uparrow\downarrow} + A \to x + X$$

<u>For polarization measurement we should</u>

- prove that $m_x = M_p$ (recoil mass cut)
- prove that $M_X = \left(p_{beam}^2 + p_{jet}^2 - p_{rec}^2\right)^{1/2} = M_p$ (missing mass cut)
- Subtract background events

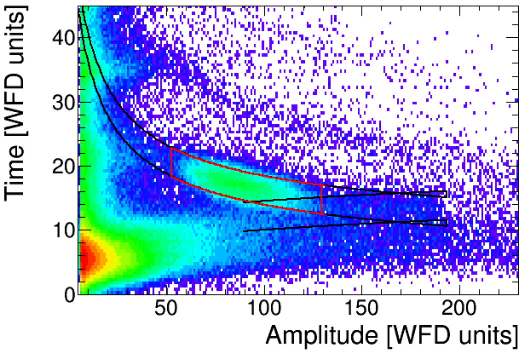
The Recoil Mass cut

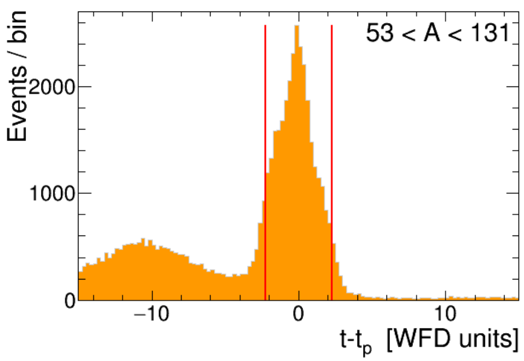
To isolate recoil proton the time of flight energy is compared with energy deposited in detector:

Waveform $\rightarrow$ Signal amplitude (***A***) and time (***t***)

$$E_{\rm kin} = \frac{M_p L^2}{2(t-t_0)^2} = \alpha A + E_{\rm loss}(A, x_{\rm DL})$$

Parameters α, t_0, and x_{DL} are determined in the calibration





t_0, which is actually a scattering time, is the main source of the uncertainty in the above equation due to beam bunch length.

It is convenient to implement the recoil proton cut as cut for

$$t_{RM} = t - t_p(A) = t - t_0 - L\sqrt{M_p / 2E_{kin}(A)}$$

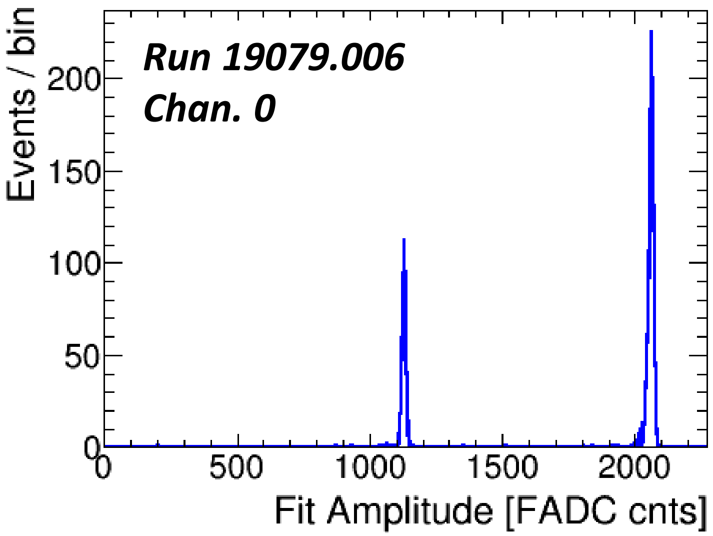
For recoil protons, the t_{RM} distribution is defined by the bunch length

$$dN/t_{RM} \propto f(ct_R)$$

where $f(z_0 - z)$ is longitudinal profile of the bunch.

This cut is the same for all Si strips and is independent on proton energy.

Calibration Using Alpha-sources



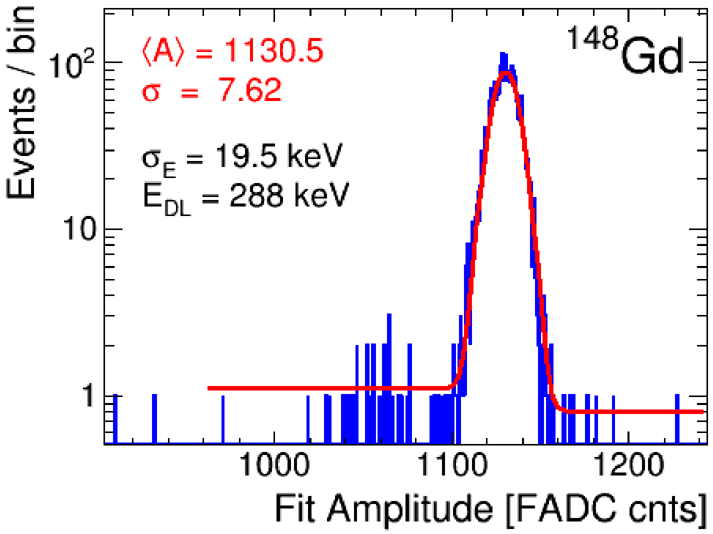
All Si detectors are exposed by 2 α-sources:

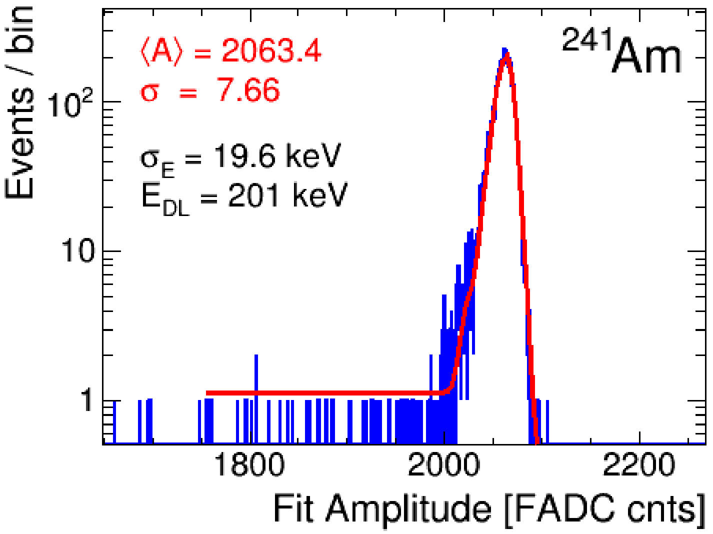
$^{148}Gd\ \ (3.183\ MeV)$

$^{241}Am\ \ (5.486\ MeV)$

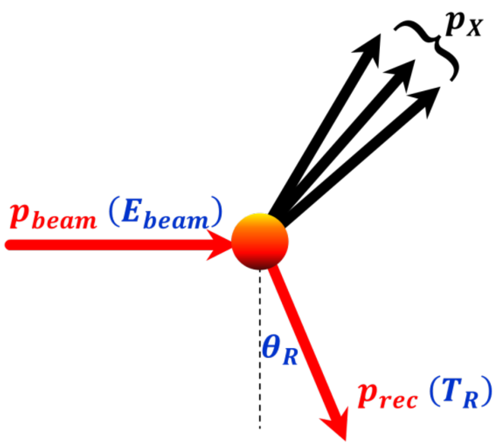
Gain ($\alpha \sim 2.5\ \ keV/cnt$) and dead-layer thickness ($x_{DL} \sim 0.37\ mg/cm^2$) were measured for every Si strip.

Energy resolution $\sigma_E\ \approx\ 20\ keV$ is dominated by electronic noise.
(For CAMAC DAQ $\sigma_E \sim 30\ keV$)





The Missing Mass cut



$$M_X^2 = M_p^2 - 2(E_{beam} + M_p)T_R + 2\sqrt{E_{beam}^2 - M_p^2}\sqrt{2M_pT_R + T_R^2}\sin\theta_R$$

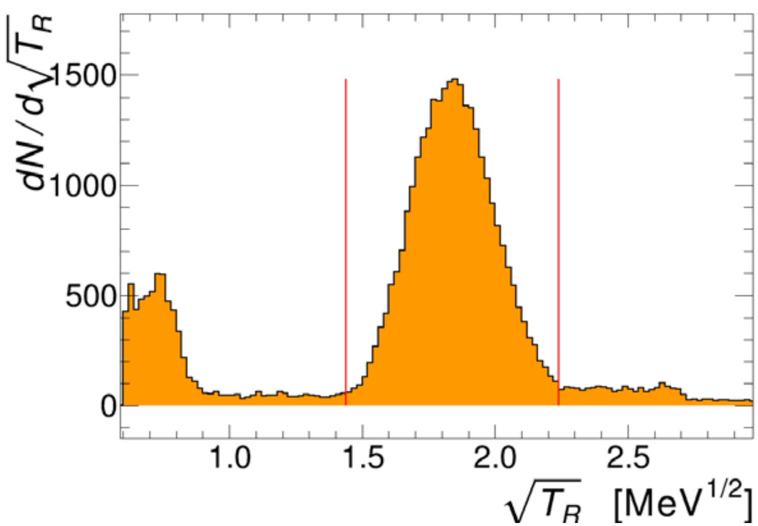
$$\tan\theta_R = \sqrt{\frac{T_R}{2M_p}\,\frac{E_{beam}+M_p}{E_{beam}-M_p-\cancel{T_R}}} = \frac{z_{str}-z_{jet}}{L}$$

Since the mean value of the $\sqrt{T_R}$ distribution linearly depends on z-coordinate of the strip, and RMS of this distribution is strip and kinetic energy independent

$$\kappa = \frac{\sqrt{2M_p}}{L}\sqrt{\frac{E_{beam}-M_p}{E_{beam}+M_p}} = 0.557\ \mathrm{MeV}^{1/2}/\mathrm{cm}$$

$$\langle\sqrt{T_R}\rangle \approx T_{str} = \kappa\cdot(\langle z_{str}\rangle - \langle z_{jet}\rangle)$$

$$\left\langle\left(\sqrt{T_R}-\sqrt{T_{str}}\right)^2\right\rangle^{1/2} \approx \kappa\cdot\sqrt{\sigma_{jet}^2 + d_{str}^2/12} \approx 0.15\ MeV^{1/2}$$



the $\sqrt{T_R}$ base is an optimal implementation of the Missing Mass Cut

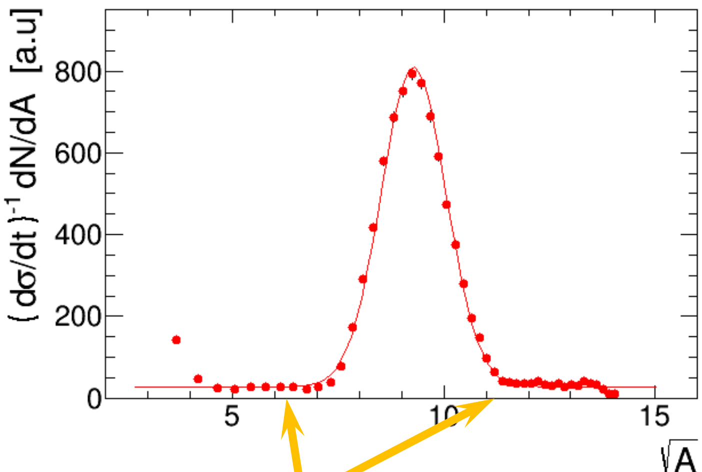
The jet intensity profile

For elastic pp scattering (and very narrow silicon strips) the cross-section corrected distribution

$$\eta\left(\sqrt{T_R}\right) = \left(\frac{d\sigma}{dt}\right)^{-1} \frac{dN}{dT_R} = \left(2\sqrt{T_R}\,\frac{d\sigma}{dt}\right)^{-1} \frac{dN}{d\sqrt{T_R}}$$

describes z-coordinate profile of target proton density

$$\frac{dn}{dz} \propto \eta(\kappa z).$$



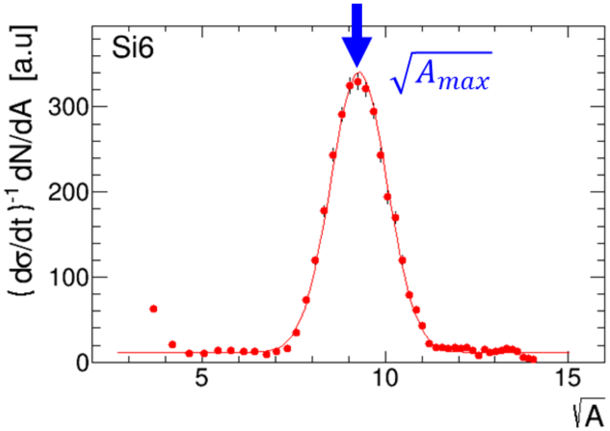
No evidence of "non-flat" molecular hydrogen component

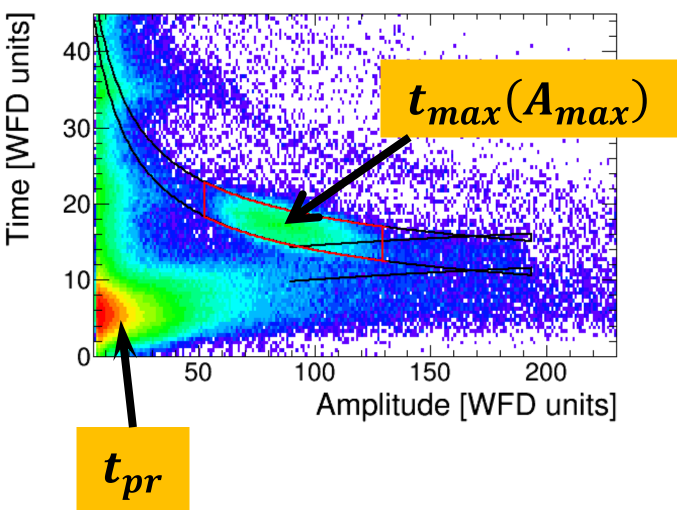
A finite Si strip width of 3.7 mm results only in increasing of the measured jet width (σ) 2.4 $mm \rightarrow$ 2.7 mm

In fact, the measured amplitude $\sqrt{A}$ can be used instead.

Analysis of the measured $\eta\left(\sqrt{A}\right)$ distributions appeared to be a powerful tool for calibration and monitoring the HJET Si detectors as well as for backgrounds subtraction

Employing the $\eta(\sqrt{A})$ for *in situ* calibration





$$\sqrt{A_{max}} \Leftrightarrow \sqrt{T_{str}} = \kappa \cdot (z_{str} - z_{jet})$$

To achieve a $\sim 1\%$ of the calibration, z-coordinates of Si strips as well as corrections due to magnetic field and beam angle have to be known with accuracy $\sim 100\ \mu m$.

A combined (for all Si strips) comparison in of the elastic pp time $t_{max}(A_{max})$ with the prompt time t_{pr}

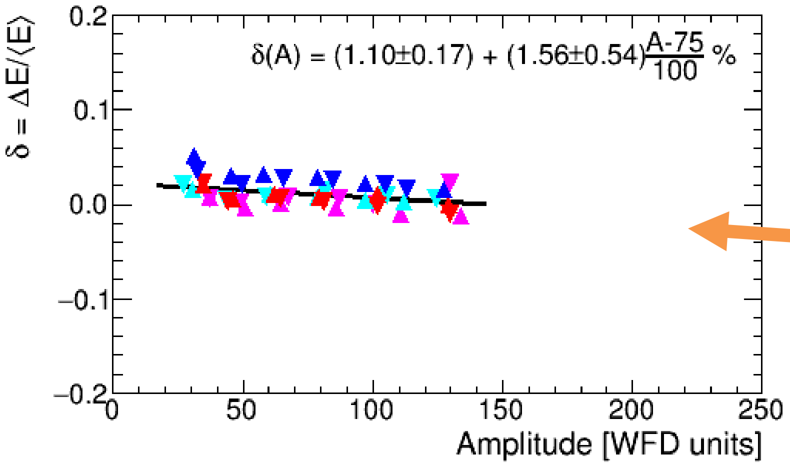
$$\Delta t = t_{pr} - t_0 = t_{pr} - t_{max}(A_{max}) + \text{tof}(T_{str})$$

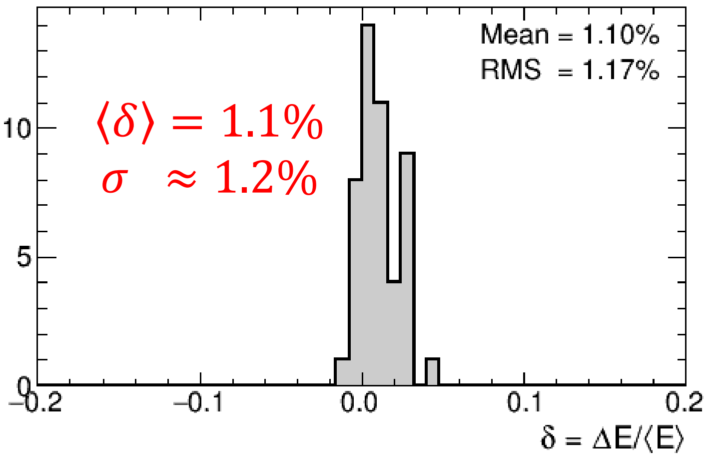
allows us to determine all alignment corrections with a required precision

The geometry based calibration is very helpful for monitoring the HJET performance.

The described method can be also used for measurement of the elastic cross-section $d\sigma/dt$ parameterization.

Comparison of geometry based and alpha-calibrations.





The geometry based and alpha calibrations are absolutely independent, but they may be directly compared.

$$\Delta E = T_{\mathrm{str}}(z_{str}) - E_{cal}(A_{max}, \alpha, x_{\mathrm{DL}})$$

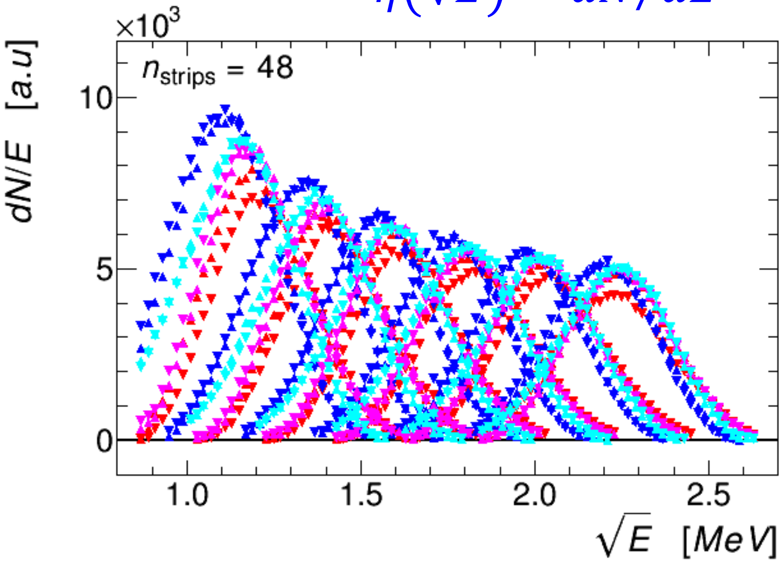
For proton energy range 1-6 MeV the calibrations were found to be consistent within 1-2% precision

A small discrepancy ~1% may be caused, for-example, by

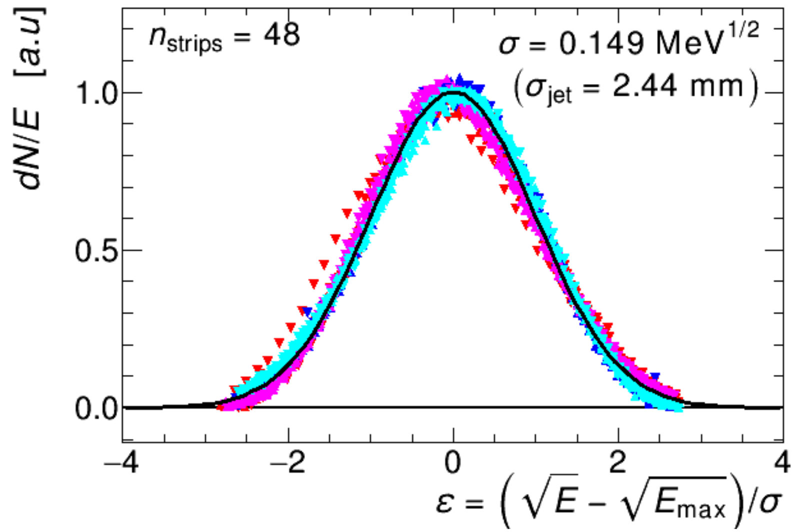
- systematic errors in alpha-calibration
- dependence of measured time on amplitude
- …

Another method for geometrical alignment

$$\eta(\sqrt{E}) = dN/dE$$



$$\tilde{\eta}(\varepsilon) = \frac{n_d}{d\sigma/dt}\,\eta\left(\sqrt{E_{str}} + \varepsilon\sigma\right) = e^{-\varepsilon^2/2}$$



n_d ***is a normalization factor (detector dependent)***

E_s ***is a geometry dependent Si strip energy***

<u>Advantage</u>:

More simple in implementation.

Cross section $d\sigma/dt$ could be measured.

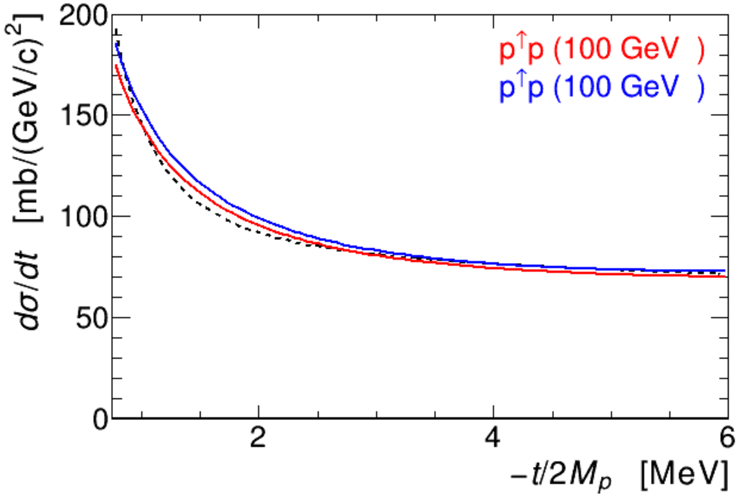
"Missing mass cut" can easily be parameterized

<u>Disadvantage:</u>

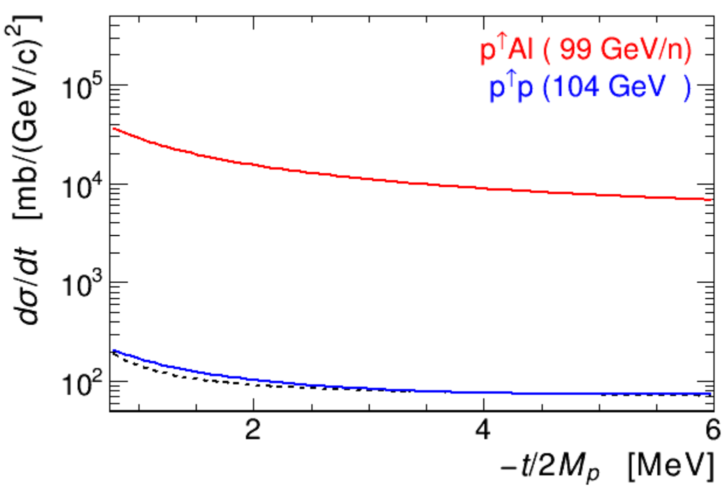
Does not allow to make independent energy calibration.

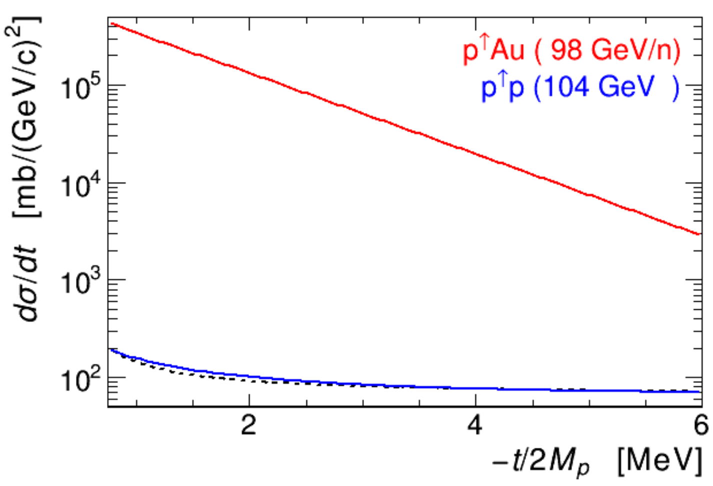
The method is under development yet

Experimental evaluation of elastic cross-section (proper background subtraction is required)

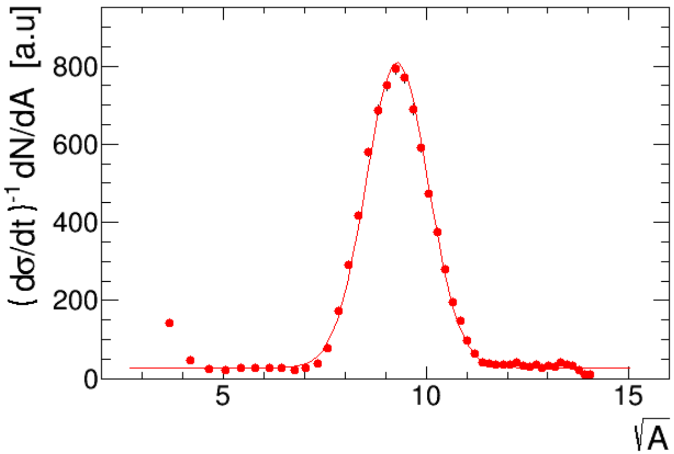


- ✓ Black dashed lines is a theoretical expectation assuming $\sigma_{tot} = 39.46\ mb$ and $\rho = 0.009$ (real-to-imaginary ratio for hadronic amplitude)
- ✓ Cross-section dependence on t for blue and yellow beams was evaluated concurrently
- ✓ Blue beam (pp) cross-sections were normalized to the theoretical dependence at arbitrarily chosen recoil proton energy $E_{norm} = 4\ MeV$.
- ✓ Yellow beam cross-sections were normalized to the blue beam by comparison beam intensities and rate in detectors. Detector acceptance was assumed the same for both beams



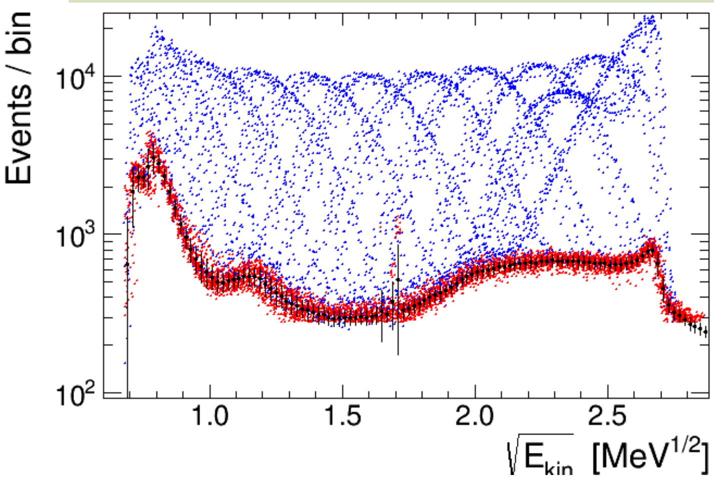


Background

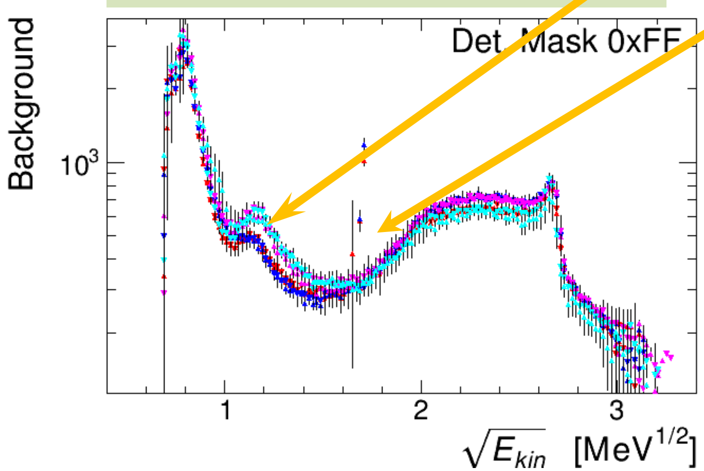


- For all Si strips, the (Gaussian) elastic pp signal is expected to have the same height and width but different position depending on z-coordinate of the strip
- The molecular hydrogen contribution is expected to be flat and, thus, the same for all strips.
- The distributions for inelastic background is expected to be the same for all strips, because the acceptance angle is small and there is no strong correlation between energy and angle.
- **Selecting events $\pm 4\sigma$ $(0.6\ MeV^{1/2})$ outside the elastic peak we can determine the background contribution as a function of energy (amplitude)**

Superposition of $\sqrt{E}$ distributions for all Si strips. Points selected for background evaluation are marked red



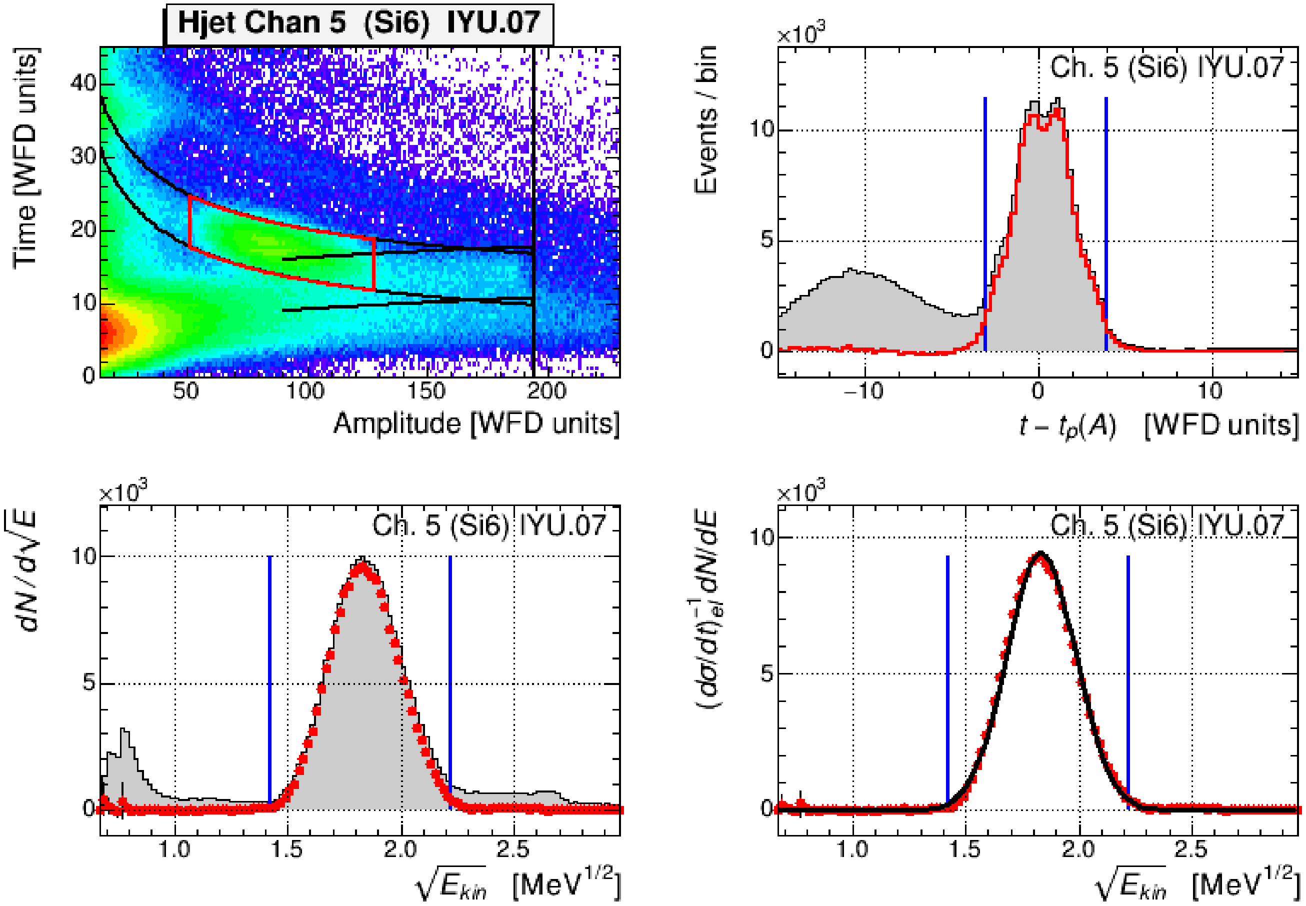
Background distributions determined for each detector separately.



- Beam halo is not the same for inner and outer detectors.
- Some alpha source particles in the data
- Background is slightly detector dependent.

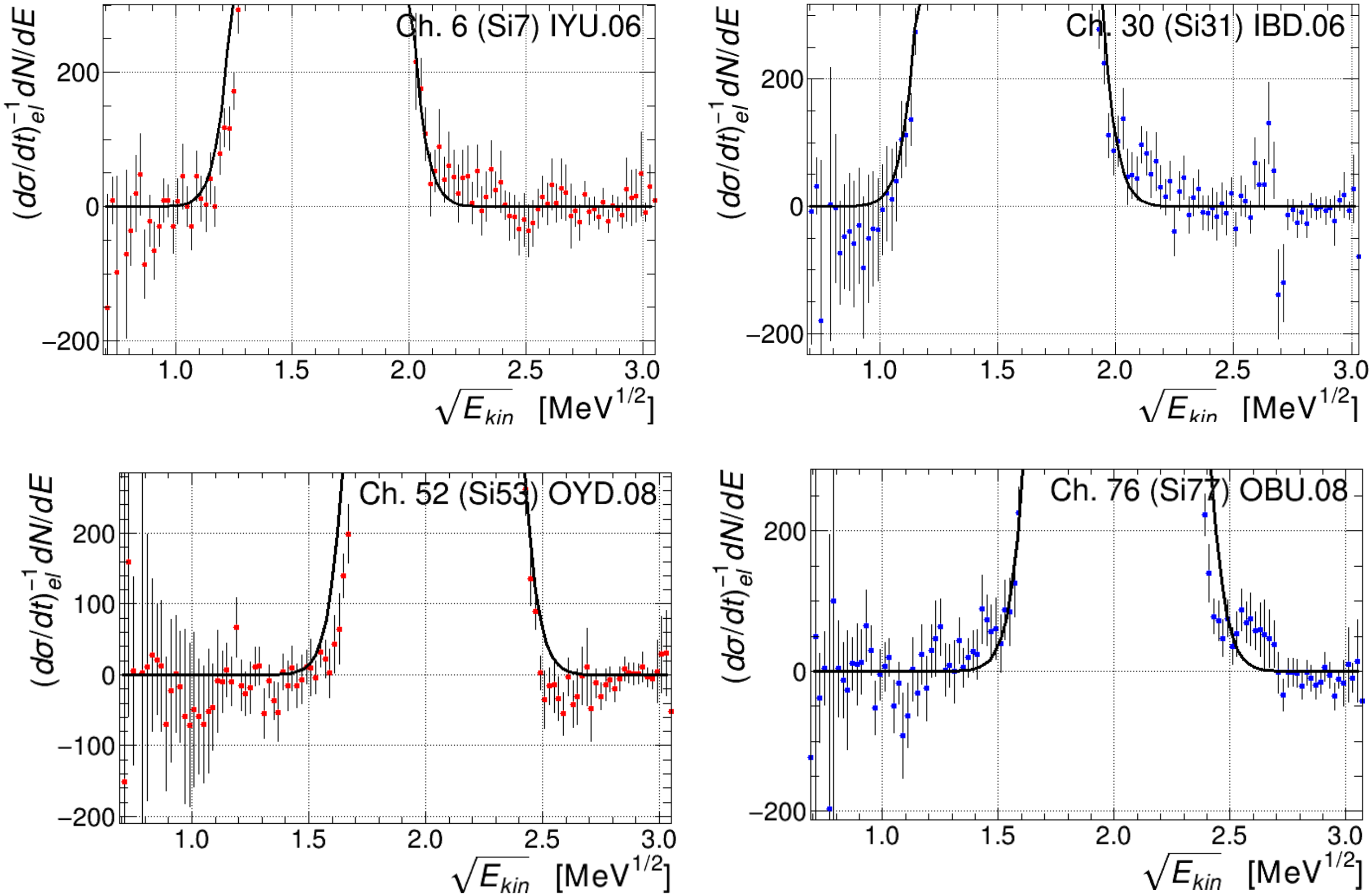
Background should be measured separately for every detector and every beam / jet polarization

How background subtraction works



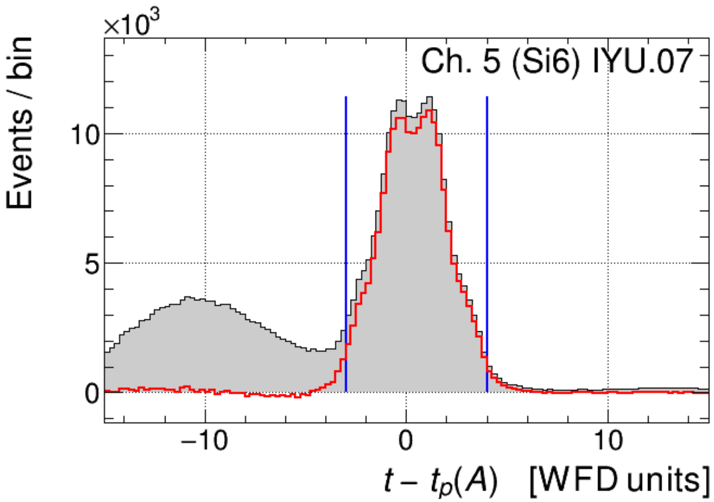
No visible background remained in the event selection cut distributions.

A high resolution comparison



- ***The background rate should be compared with the distribution maximum of about 10000.***
- ***The residual background is below 1% level***

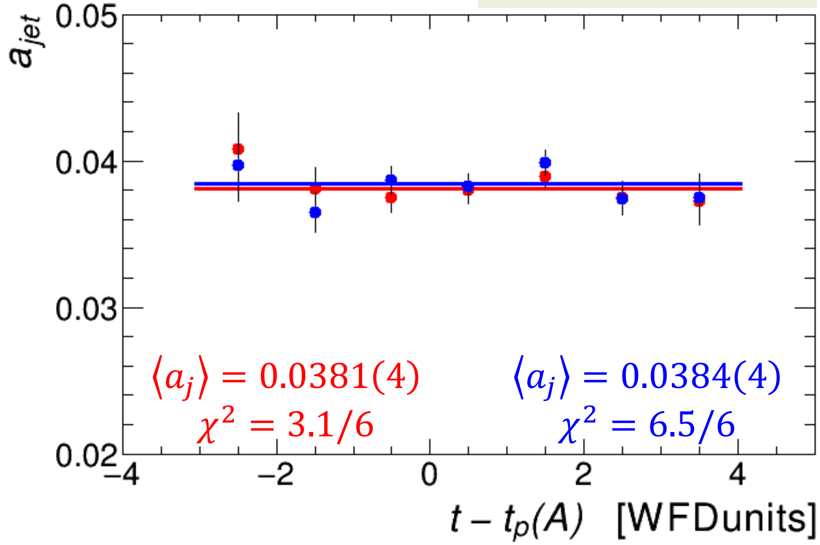
The $t - t_p(A)$ test



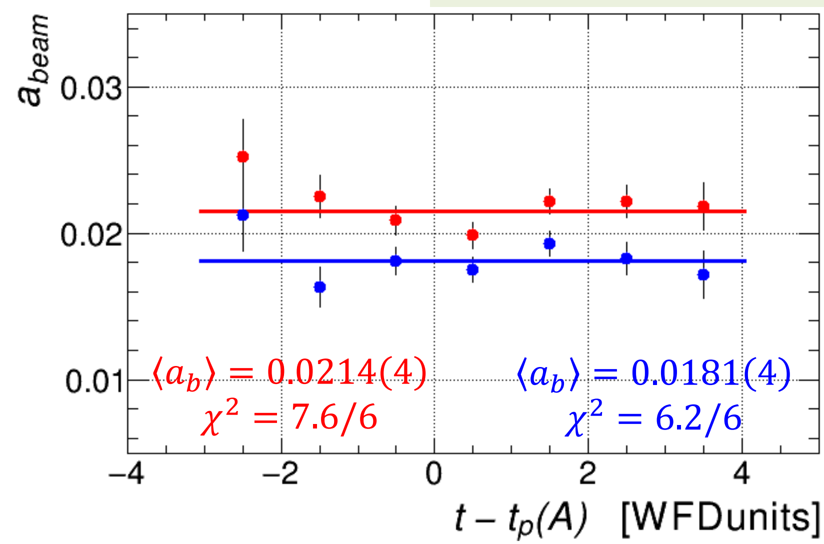
Non-subtracted background will make asymmetry measurement dependent on time cut (Recoil Mass Cut)

For beam asymmetry the dependence on time cut may also be caused by longitudinal polarization profile.

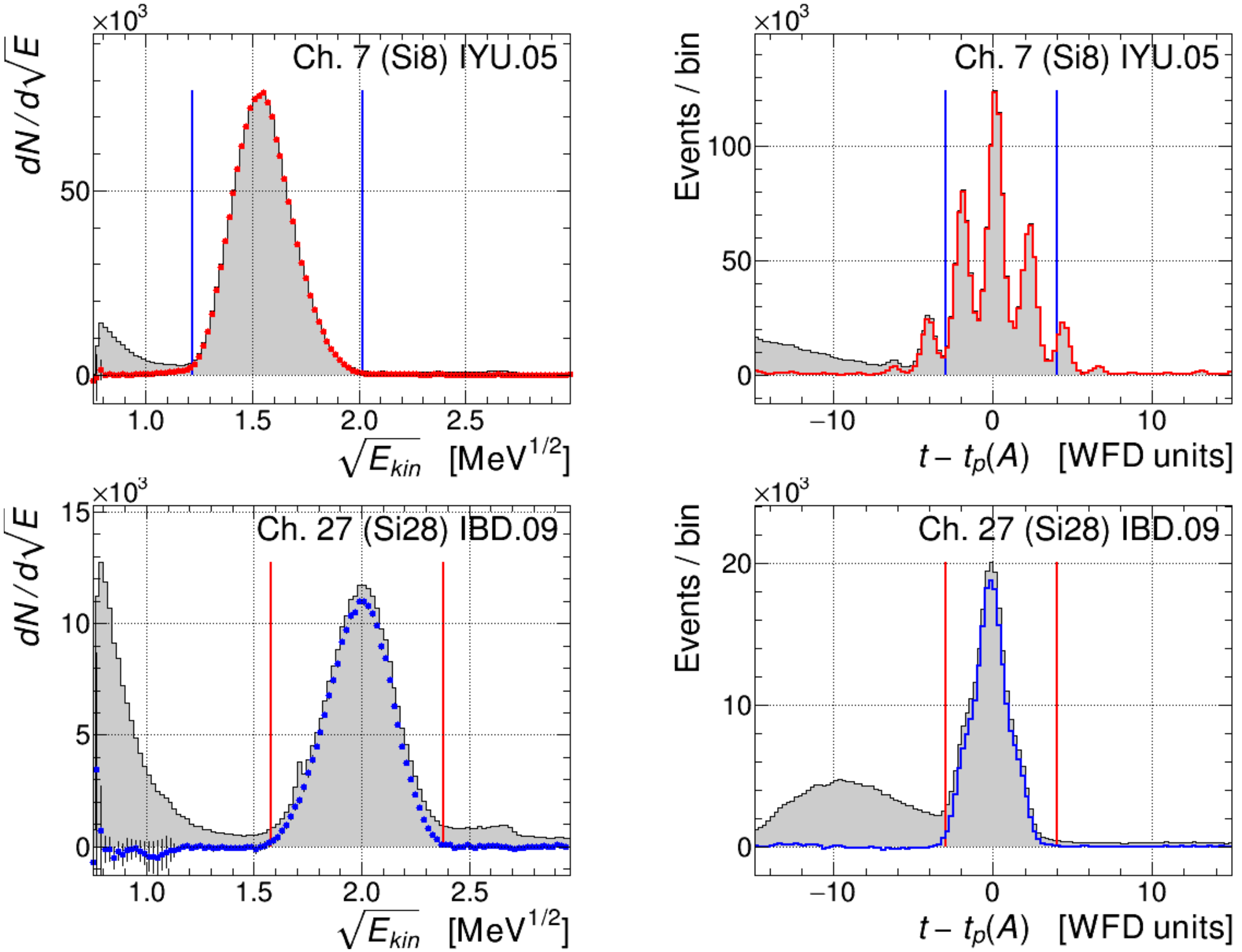
Jet Asymmetry



Beam Asymmetry



Proton-Gold Run



Yellow (Gold) beam

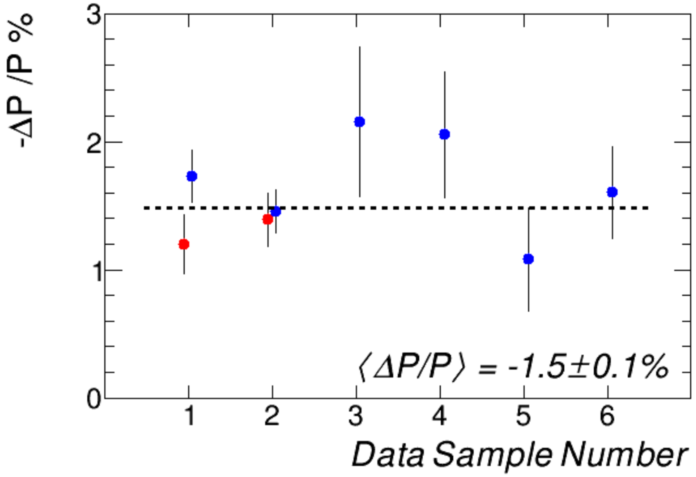
Elastic pAu scattering can be studied !

Blue (proton) beam

Low energy background is much larger (compared to pp)
but background subtraction still works

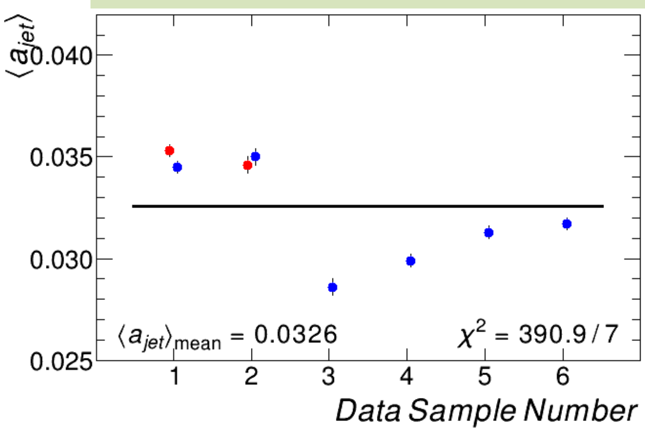
First results in a glance

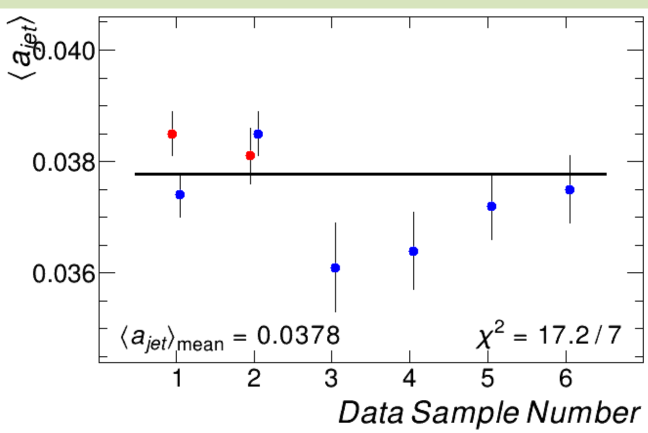
Energy range 0.75 - 7.0 MeV



- ***Background subtraction reduces the measured polarization by 1.5% (should be compared with 3% used in the regular analysis)***
- ***The correction accounts molecular hydrogen as well as inelastic backgrounds, if any, sensitive to the beam polarization.***
- ***The consistency of the measured analyzing power was improved significantly, but still is not perfect. The problem may be attributed to Gold and Aluminum runs***

Analyzing power, $\langle a_{jet} \rangle$, before and after background subtraction

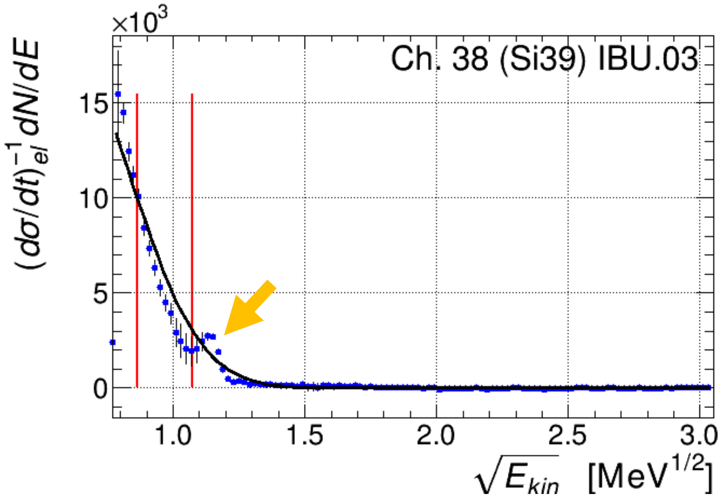


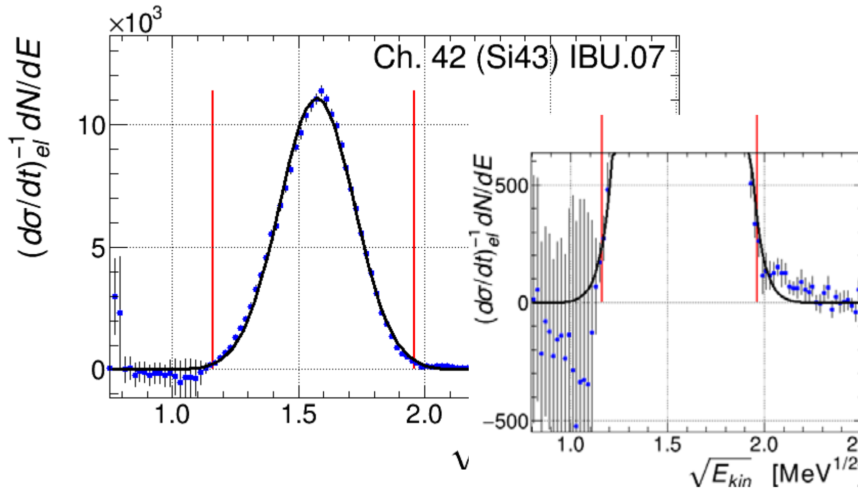


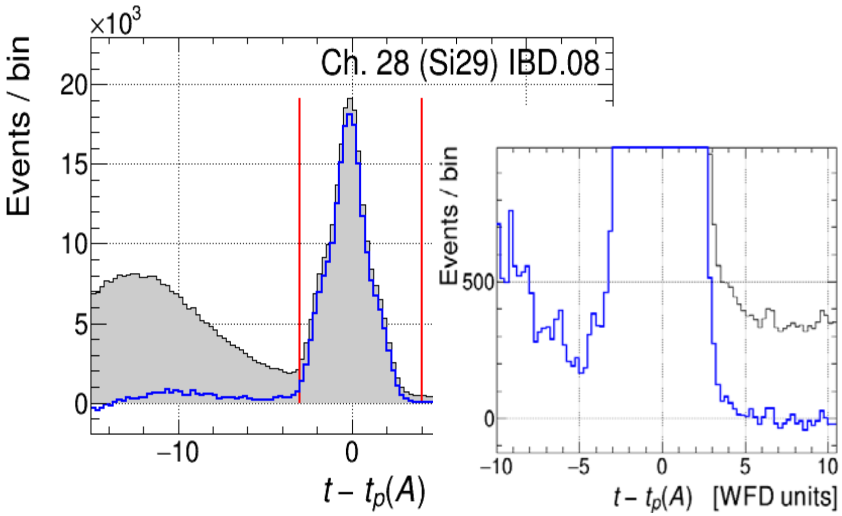
Data samples:

1. 18920-18926 pp, CAMAC
2. 18950-18953 pp, VME
3. 19060-19069 pAu, CAMAC
4. 19094-19099 pAu, VME
5. 19125-19134 pAu, VME
6. 19237-19248 pAl, VME

A detailed look on the pAu data

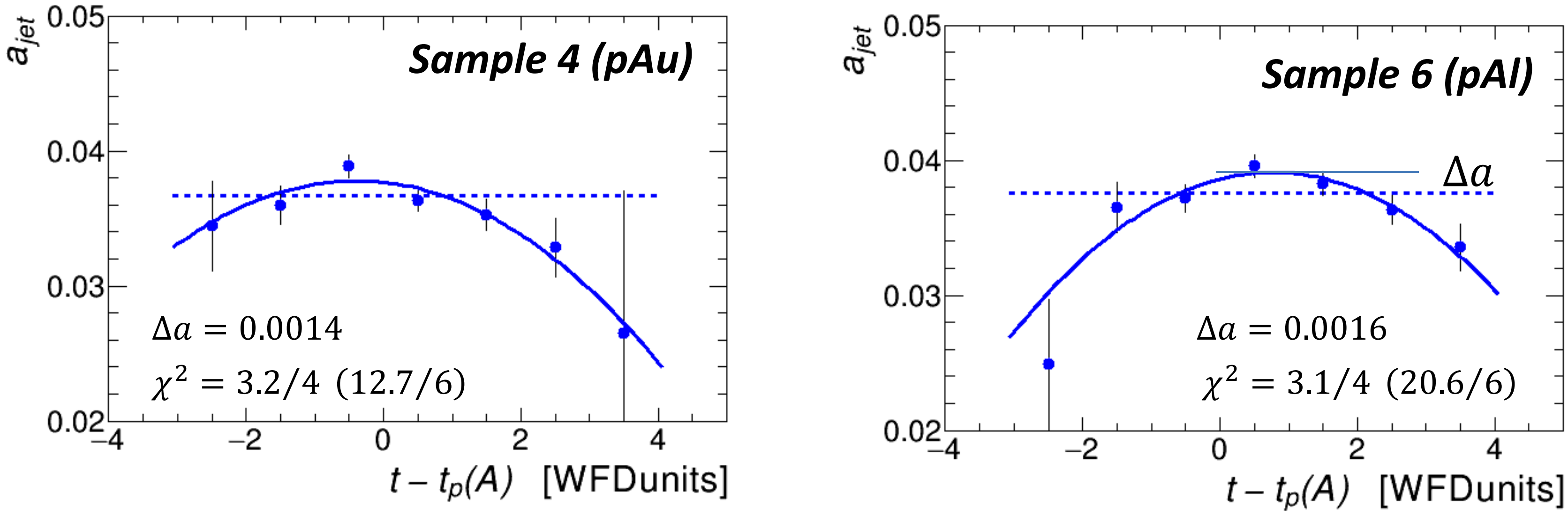






- ***The residual background is up to several percent.***
- ***The issue has to be studied.***
- ***A likely reason is some problems with calibration / alignment of the detectors.***
- ***It has to be noted that in this study detectors were well calibrated and monitored only for Data Sample 2 (pp, VME)***

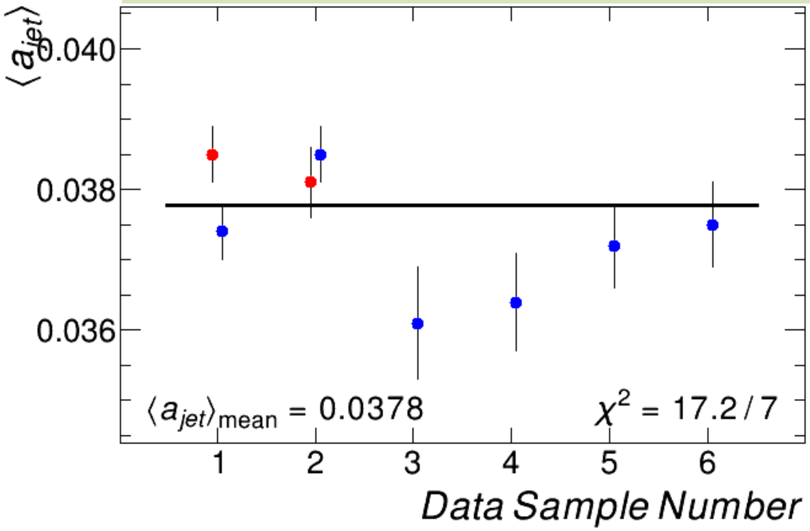
The $t - t_p(A)$ test for the pA data

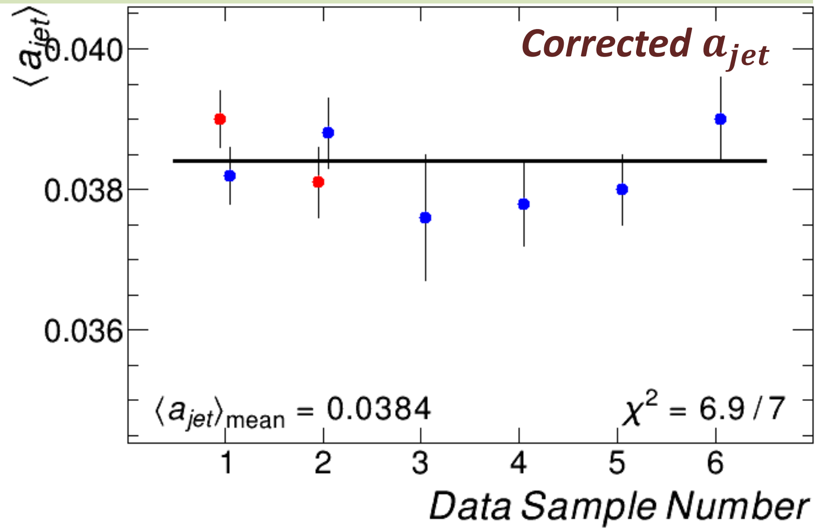


- The dependence the a_{jet} on the time cut is clearly seen
- The fit maximum corresponds to the minimally corrupted measurement
- The correction Δa could be calculated

Corrected results for analyzing power $\langle a_{jet} \rangle$

Recoil Proton kinetic energy range 0.75 – 7.0 MeV
Background was subtracted





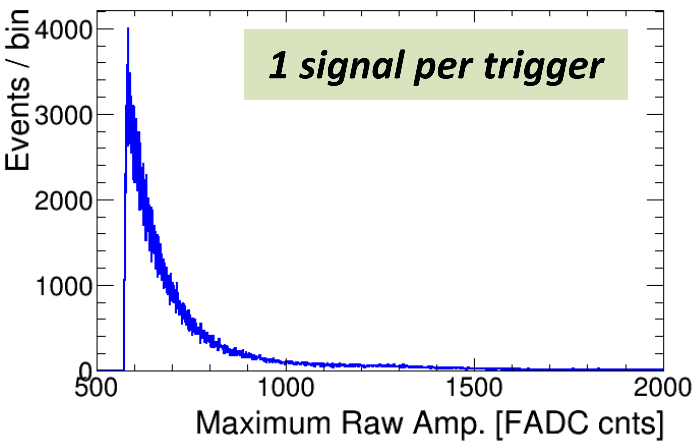
- **The corrected $\langle a_{jet} \rangle$ is consistent for all 8 measurements**
- **The average correction is 1.6%**
- **The average correction in the pA data is 3.2%**
- **The sample 2 (*pp*, VME) measurement was corrected by less than 0.5%**

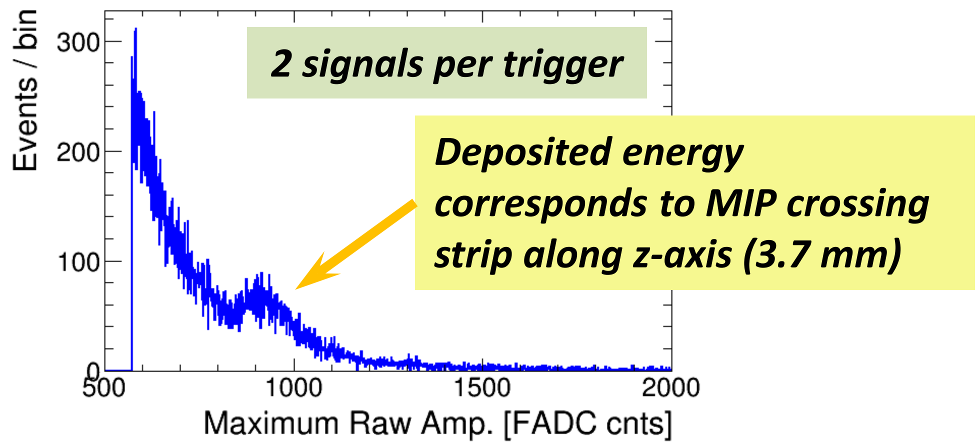
Alternative methods to suppress background

Optimization of the recoil protons energy cuts

- The background may be substantially suppressed by increasing lower threshold for recoil proton energy.
- In this study this threshold of 0.75 MeV was kept as lower as possible
- The optimization of the energy cuts has to be done

Suppression of multi-hit events (Beam halo)





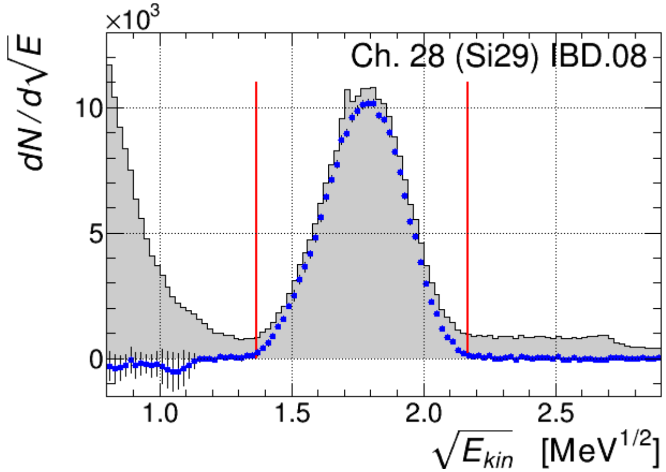
- Beam Halo signals may be isolated by searching simultaneous hits in different strips of a detector.
- A partial suppression of the Halo was tested.
- No improvement for described above results was found.

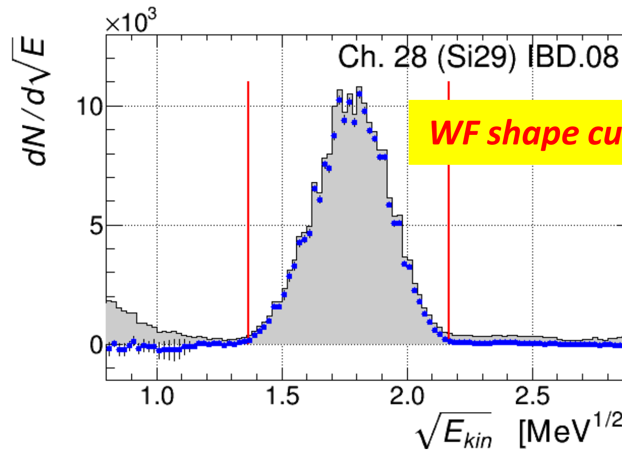
Reconstruction of punched through protons

A waveform shape analysis for event selection was developed to separate punched through and stopped recoil protons (not used in this report)

By a product this method strongly suppress background events in the stopped proton area.

pAu data



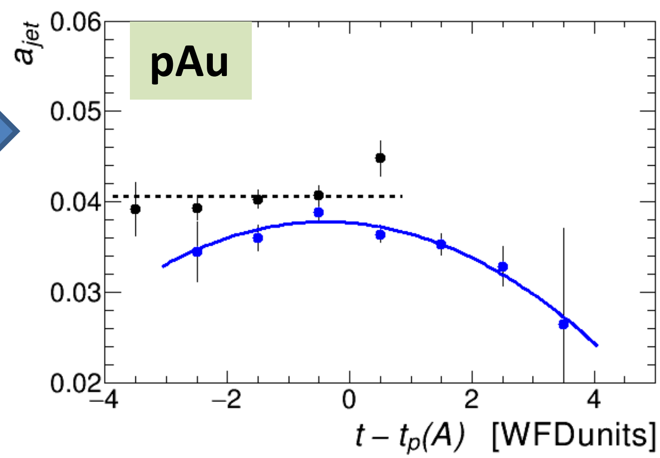


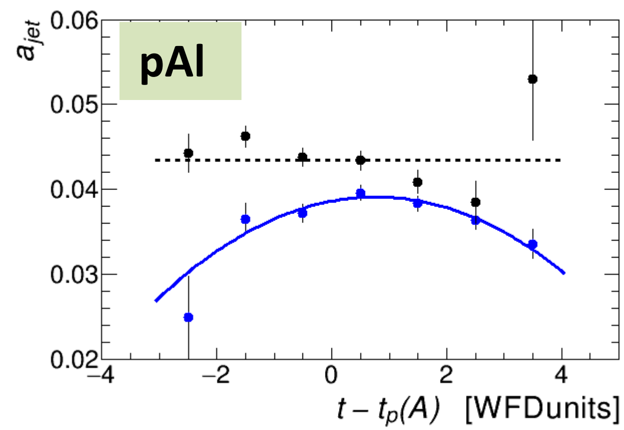
WF shape cuts

The $t - t_p(A)$ test

The WF cut results are shown by black points.

Mean values of a_{jet} are not expected to be the same





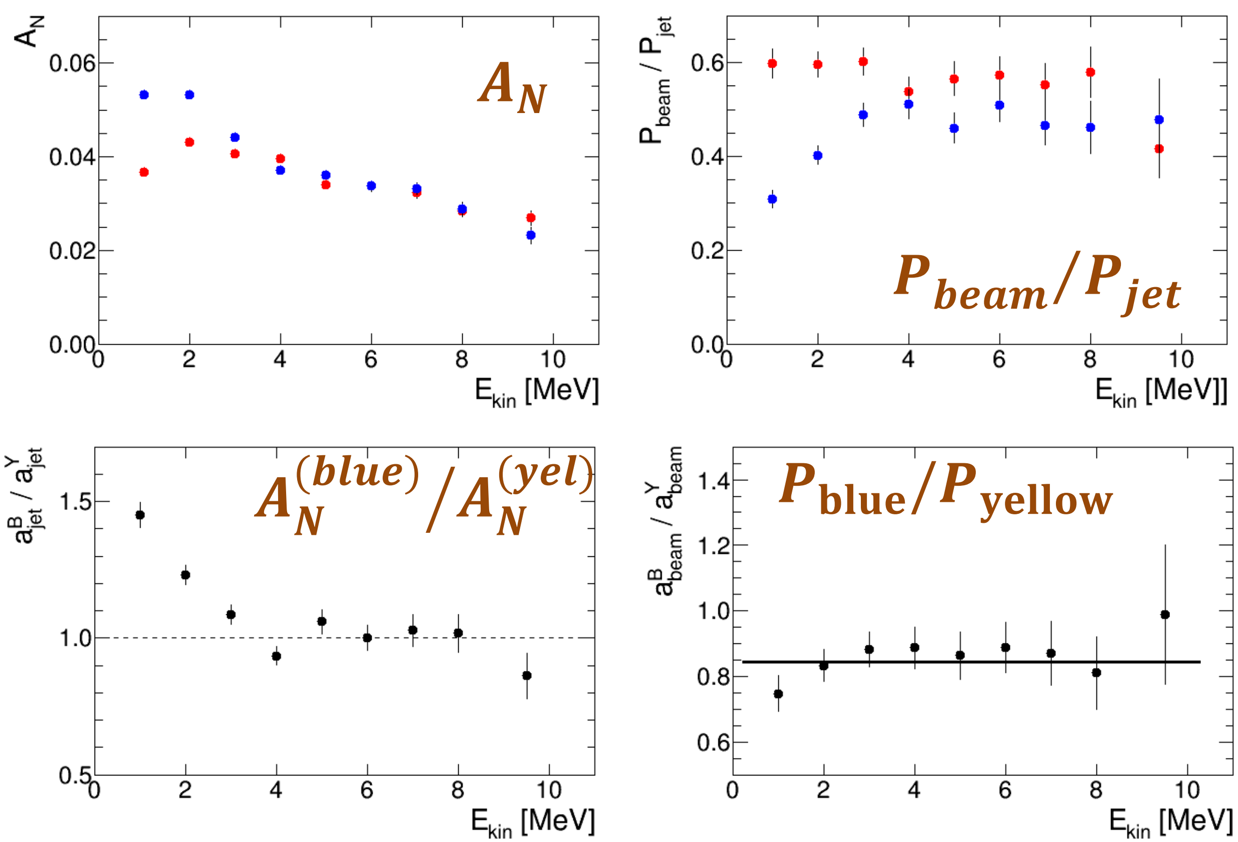
There is an indication that WF shape cuts strongly improve the $t - t_p(A)$ test, but statistics is too low for a final conclusion.

Controls for the systematic errors

- $A_N^{blue}(t) = A_N^{yellow}(t) = A_N(t)$
- $P_{beam}(t) \propto a_{beam}(t)/a_{jet}(t)$ is t independent
- $\frac{P_{beam}^{blue}(t)}{P_{beam}^{yellow}(t)} = const$
- a_{jet} is independent on the $t - t_p(A)$ cut

All these controls are insensitive to the molecular hydrogen background

Asymmetry dependencies on recoil proton energy

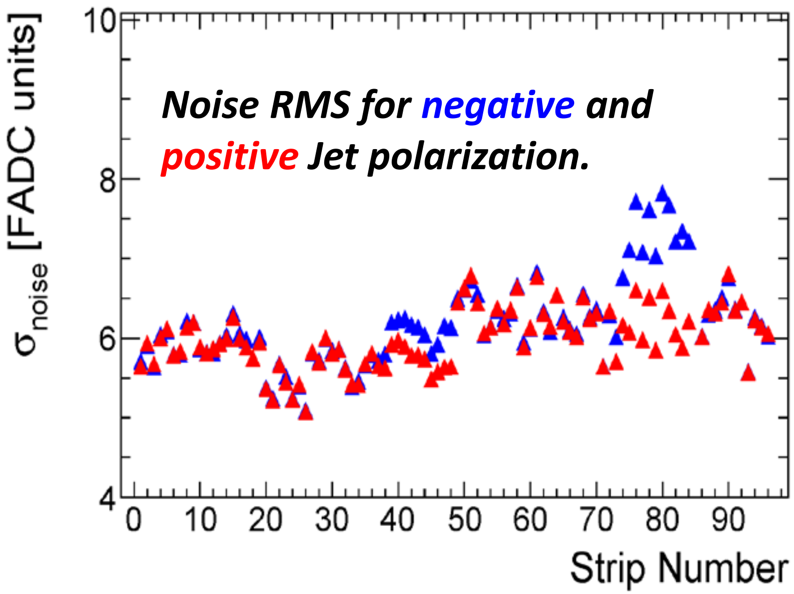


RHIC Fills 18950-18953
(2 days of measurements)
VME data

For demonstration purposes, the data with strongly enhanced systematic errors due to noise in the Jet Negative Polarization is presented

- ***For low energy recoil protons, there is a discrepancy for analyzing power measured by blue and yellow detectors.***
- ***The discrepancy was caused by wrong measurement in blue detectors.***
- ***The similar problem was observed in CAMAC data.***
- ***No evidence of issue with other measured asymmetries.***

Noise correlated with the Jet Polarization State

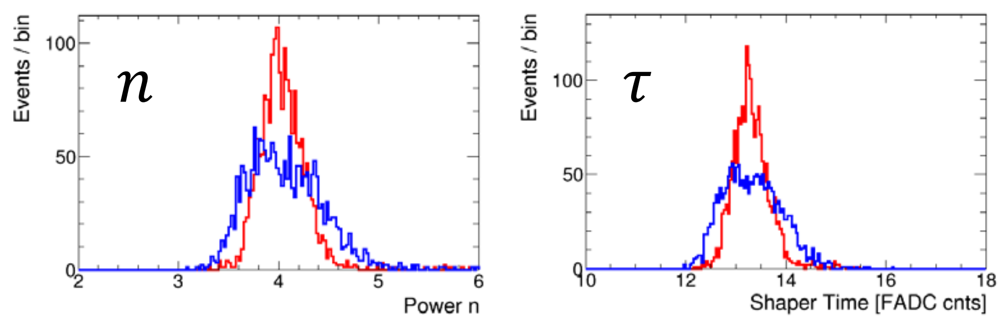


$$a = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}$$

The event selection efficiency dependence on polarization state violates the "Square Root Formula" conditions and, thus, results in systematic errors of the measurements.

On previous page, the distributions were obtained with a tight cuts on waveform shape. This is why, the jet asymmetries in Blue detectors were strongly affected.

Run 19122.002. Ch #79 **Gd (3.183 MeV)**



- ***In Run 15 the problem was found in 2 detectors.***
- ***The problem was enhanced when Waveform shape cuts were applied.***
- ***It has to be fixed at hardware level.***
- ***A software solution is still under investigation.***
- ***A minimal solution is to exclude detectors 4 and 7 from the jet asymmetry measurements.***

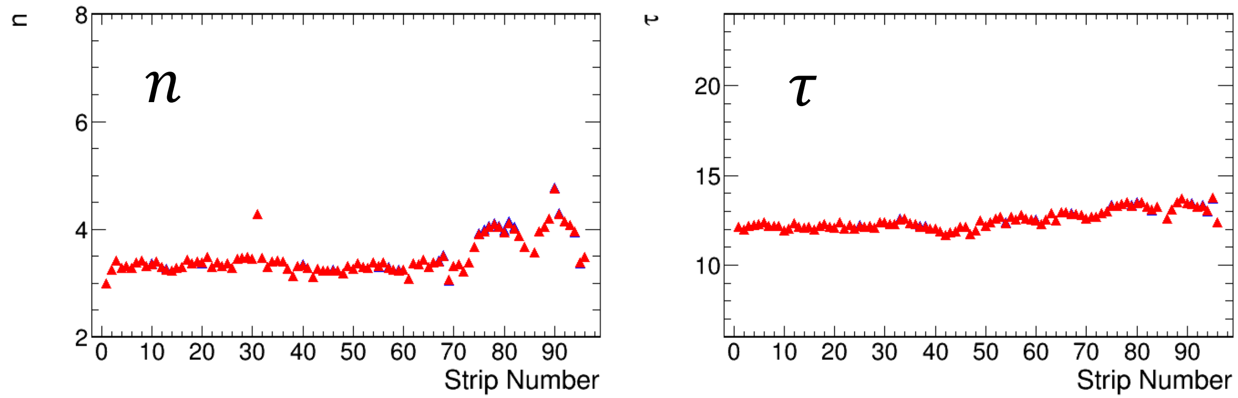
Calib. run 19122.002 (Run15)

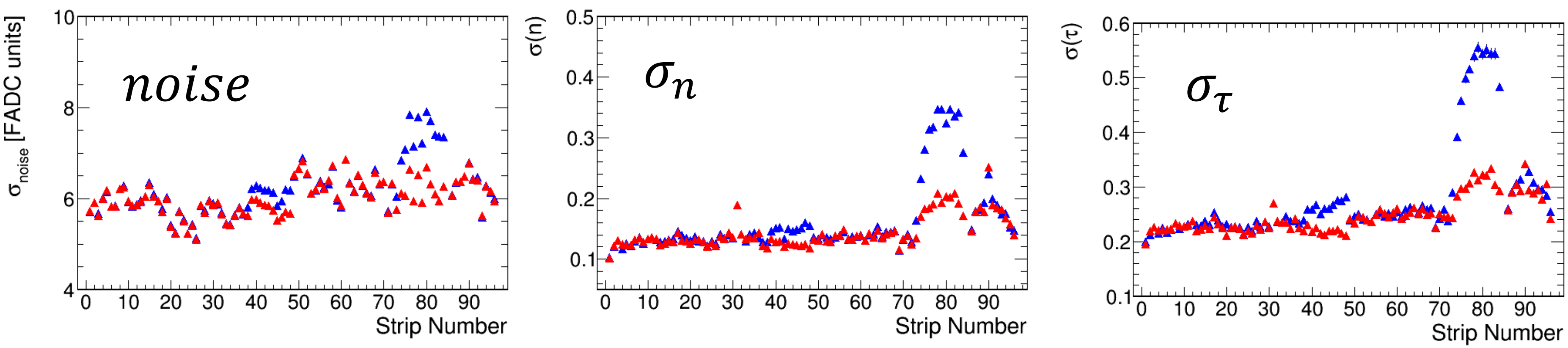
Waveform parametrization: $$A(t) = p + A_{max}\left(\frac{t-t_0}{\tau}\right)^n e^{-n(t-t_0-\tau)/\tau}$$

Waveform parameters n and τ were measured for Gd, σ_n and σ_τ are measured RMS for these parameters

▲ - **Jet + 1**

▲ - Jet - 1





Calib. run 19707.001 (Run16)

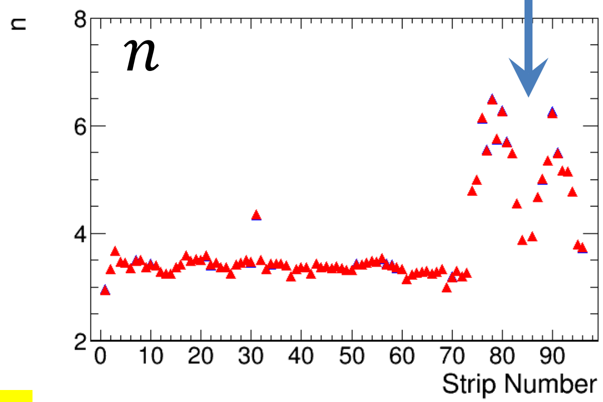
Waveform parametrization: $$A(t) = p + A_{max}\left(\frac{t-t_0}{\tau}\right)^n e^{-n(t-t_0-\tau)/\tau}$$

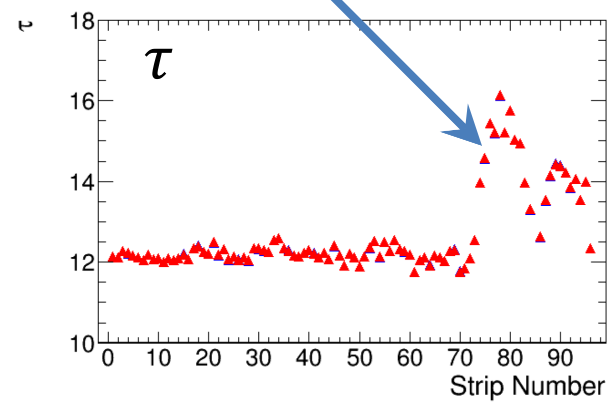
Waveform parameters n and τ were measured for Gd, σ_n and σ_τ are measured RMS for these parameters

▲ - Jet + 1

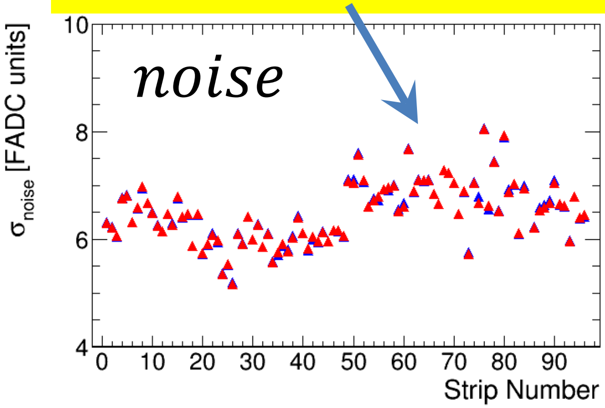
▲ - Jet - 1

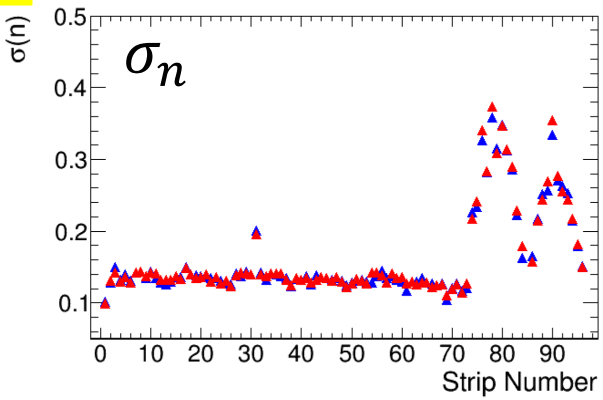
Waveform shape in detectors 7 and 8 (Blue, Outer) is essentially different from other detectors

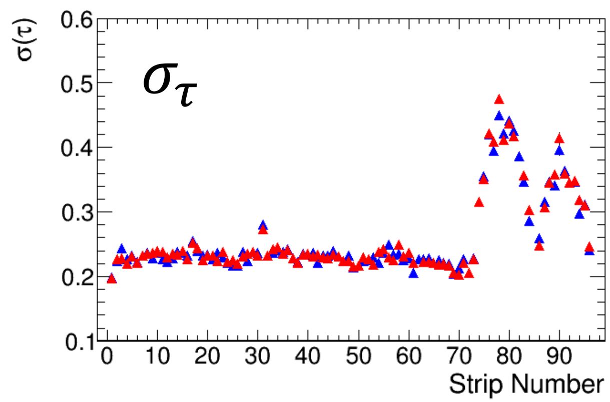




Non-working fan was switched on !







Calib. run 19717.001 (Run16)

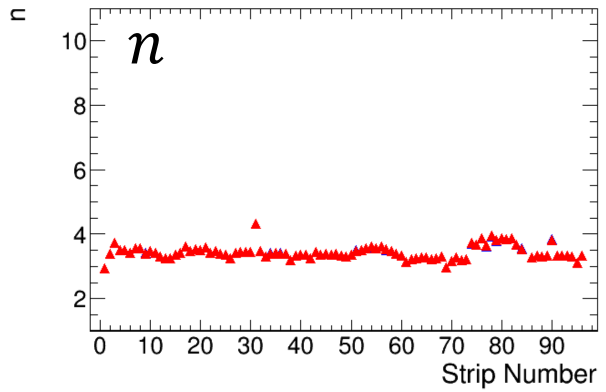
Waveform parametrization: $$A(t) = p + A_{max}\left(\frac{t-t_0}{\tau}\right)^n e^{-n(t-t_0-\tau)/\tau}$$

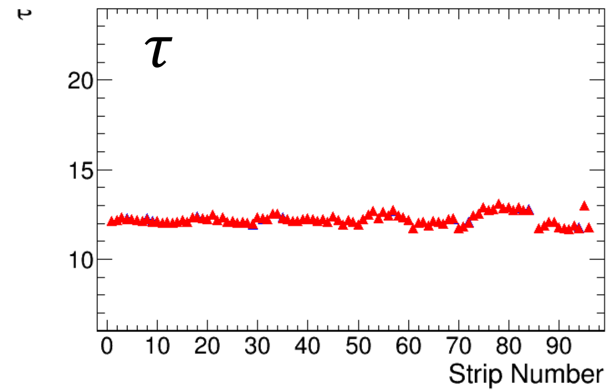
The problem with waveform shape in detectors 7 and 8 mostly gone after inspecting preamplifier boxes (!?).

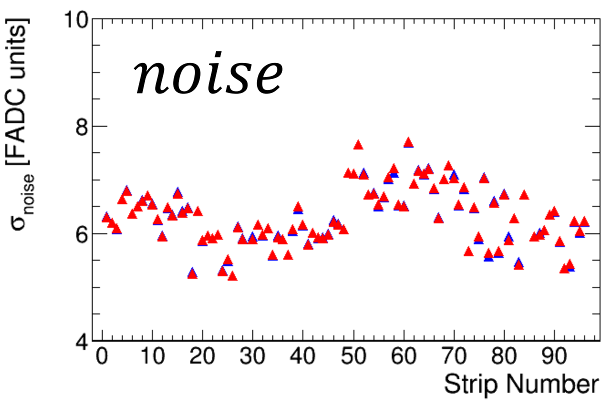
Waveform parameters n and τ were measured for Gd, σ_n and σ_τ are measured RMS for these parameters

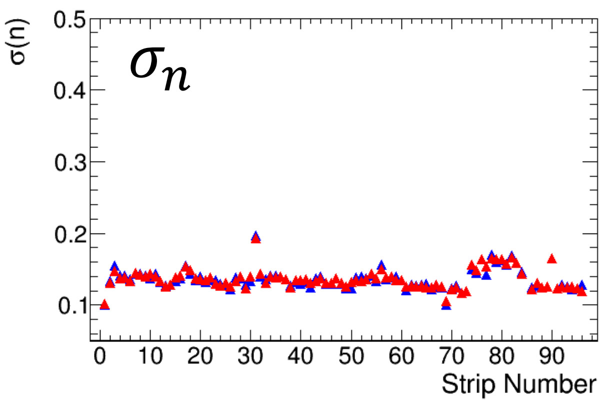
▲ - **Jet + 1** (red)

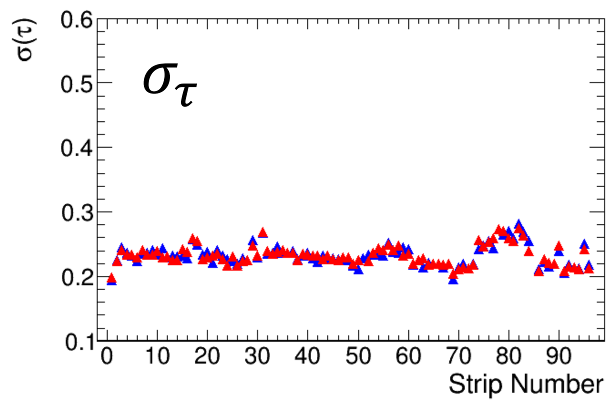
▲ - Jet - 1 (blue)











Summary

- A fast method of background subtraction was implemented in the HJET data analysis.
- Elastic pp peaks may be well isolated with only a small remaining background.
- Background related corrections to the measured beam polarization were found to be $\approx -1.5\%$.
- For thoroughly calibrated Fills 18950-18953, background related systematic errors in Analyzing Power measurements were estimated as $\lesssim 1\%$.
- In $p\mathrm{Au}$ and $p\mathrm{Al}$ runs with significantly larger backgrounds, the residual background of about 3% was detected. However, the corrections to measured Analyzing Power may be evaluated in a simple way.
- Method of control for background related systematic errors was discussed.
- Systematic errors due to noise in the Jet Polarization Cavity was discussed.

The suppression of the molecular hydrogen contribution is based on the assumption of the flat molecular hydrogen distribution.
Even though this is in a visual agreement with the data, an experimental verification of the assumption is still needed.