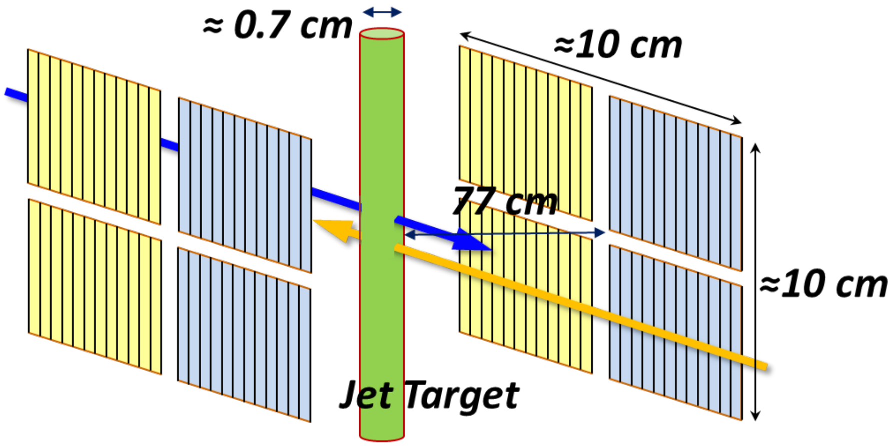
A. Poblaguev

1. ***Systematic errors in the HJET (Run15)***
   - ✓ ***Background subtraction***
   - ✓ ***Evaluation of molecular hydrogen contribution and systematic errors***

2. ***Experimental evaluation of molecular hydrogen distribution in the HJET (Run16, APEX)***

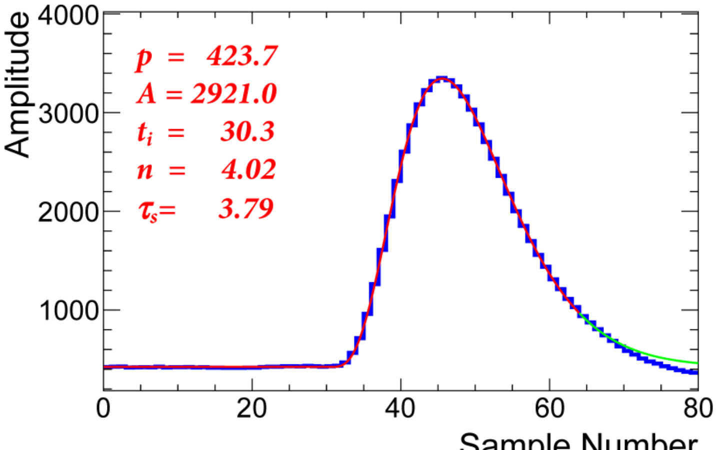
The HJET (a schematic view)



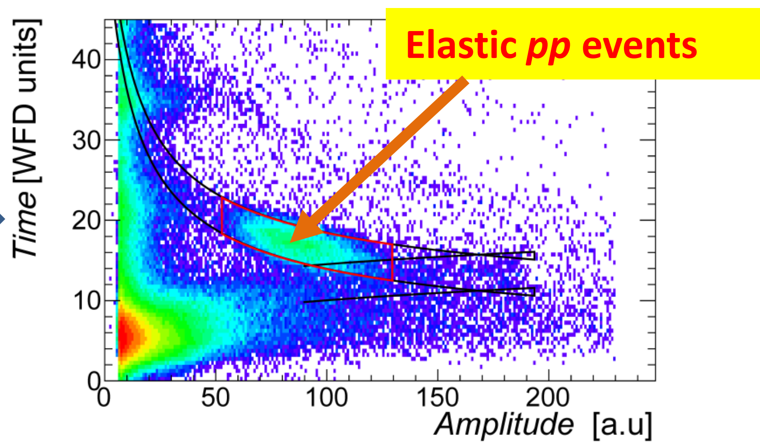
The Hjet in Run 2015

- 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

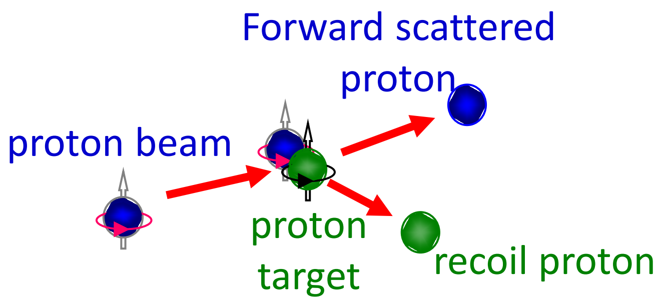
Full waveform is recorded for every signal above threshold



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

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

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

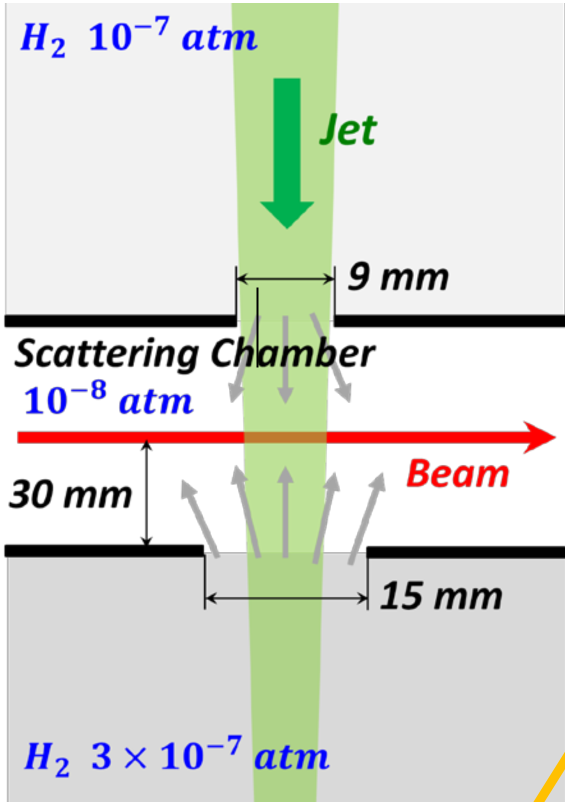
Where r is fraction of background events and $A_N^{(beam)}$ and $A_N^{(jet)}$ are background analyzing powers for beam and jet asymmetries, respectively.

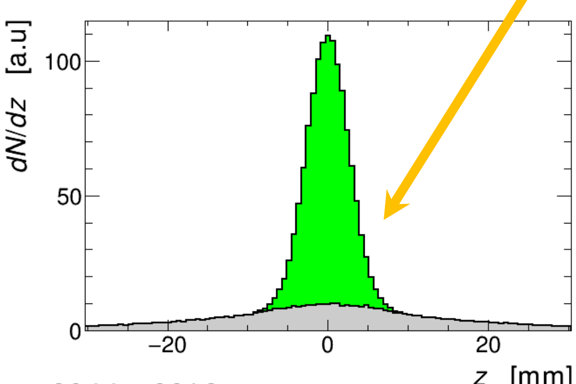
For most (if not all) backgrounds we may expect $A_N^{(jet)} = 0$.

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

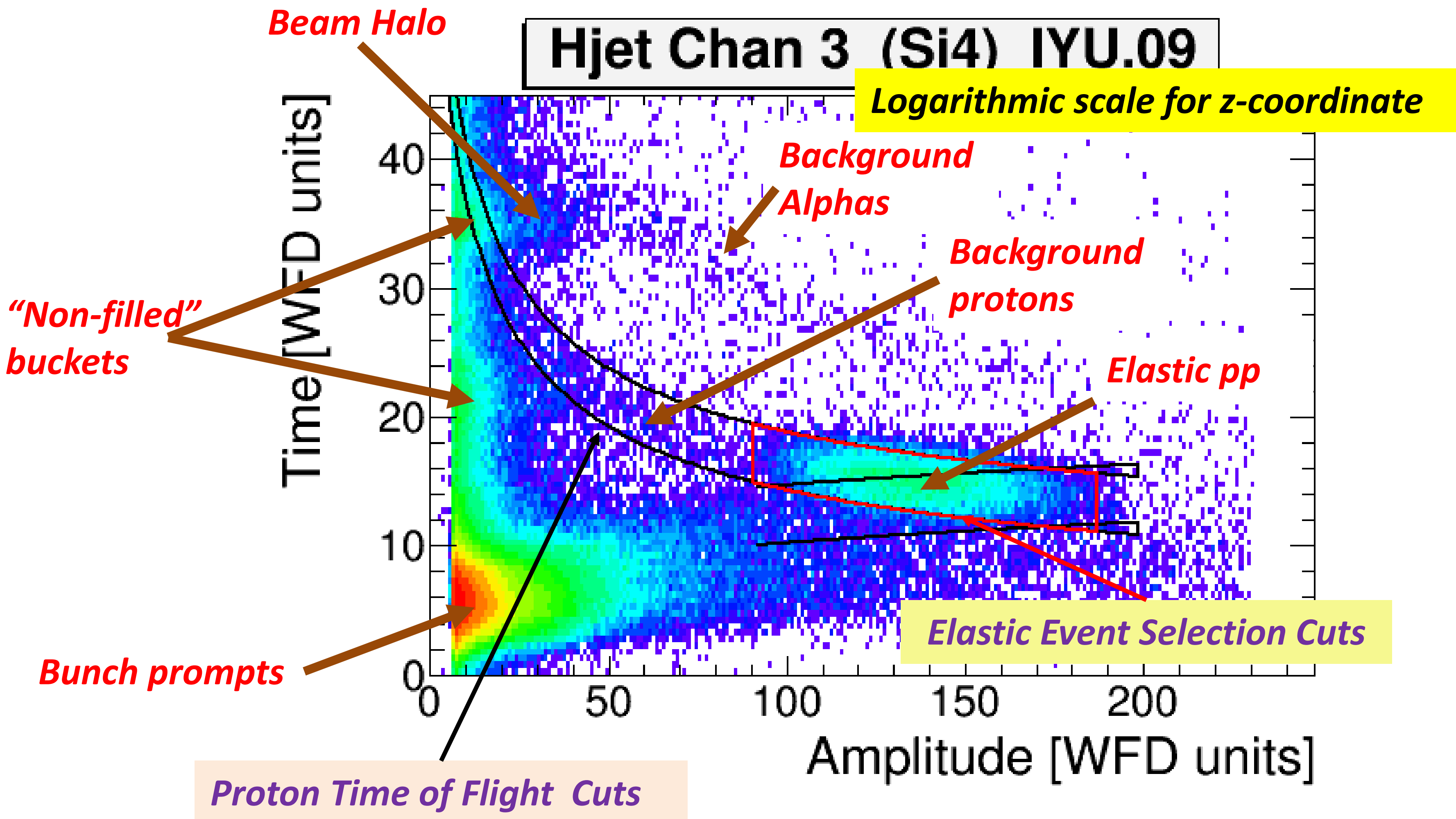
$$\frac{dN}{dxdz} \propto e^{-\frac{x^2+z^2}{2\sigma^2}} + r_{mol} e^{-\frac{x^2+z^2}{2\sigma_{mol}^2}}$$

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

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

All non-detected particles

events contaminated by

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

A particle which hit Si detector

For polarization measurement we should

- 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

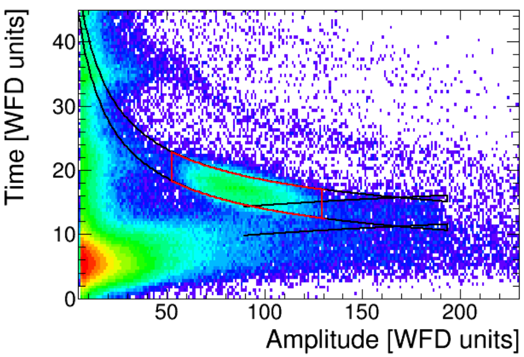
The Recoil Mass cut

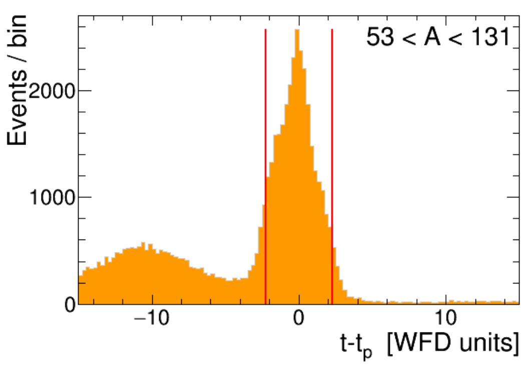
To isolate recoil proton the time of flight energy is compared with energy deposited in detector:

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

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

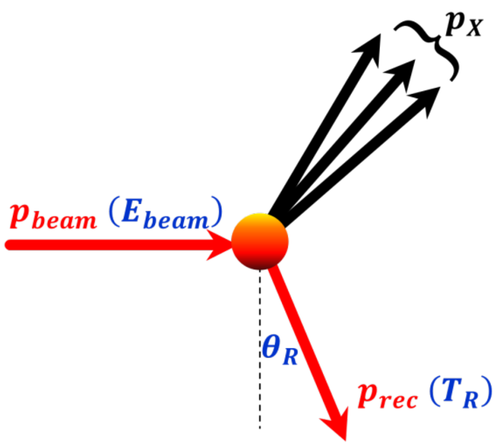
For recoil protons, the t_{RM} distribution is defined by the bunch length

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

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.

The Missing Mass cut



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

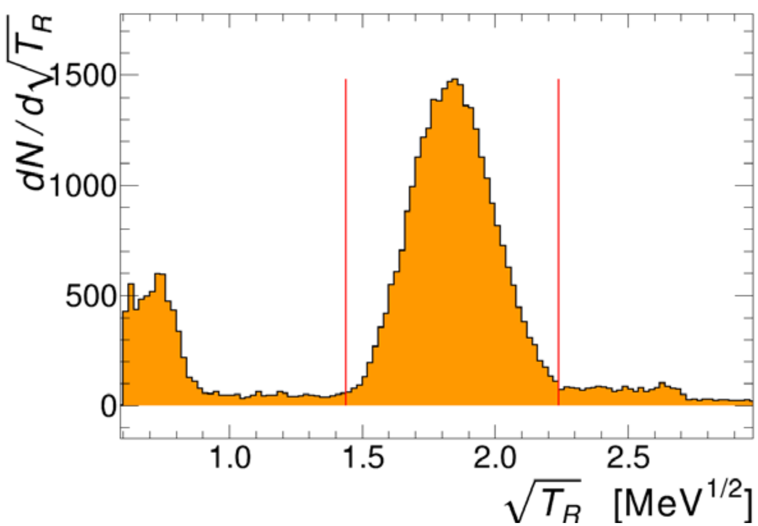
$$\tan\theta_R = \sqrt{\frac{T_R}{2M_p}\,\frac{E_{beam} + M_p}{E_{beam} - M_p - T_R}} = \frac{z_{str} - z_{jet}}{L}$$

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

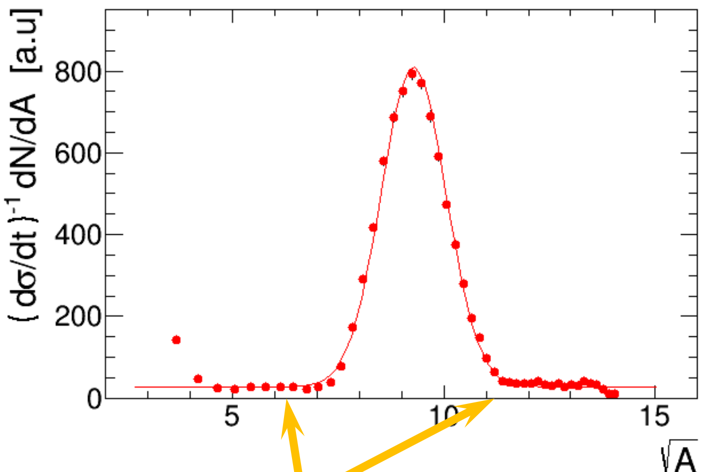
The jet intensity profile

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

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



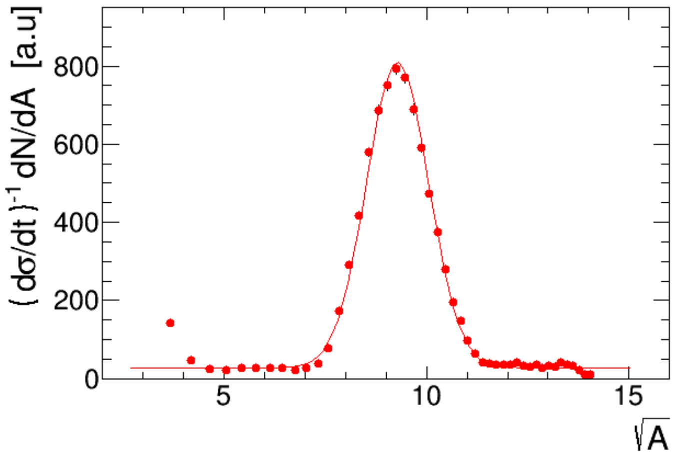
No evidence of "non-flat" molecular hydrogen component

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

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

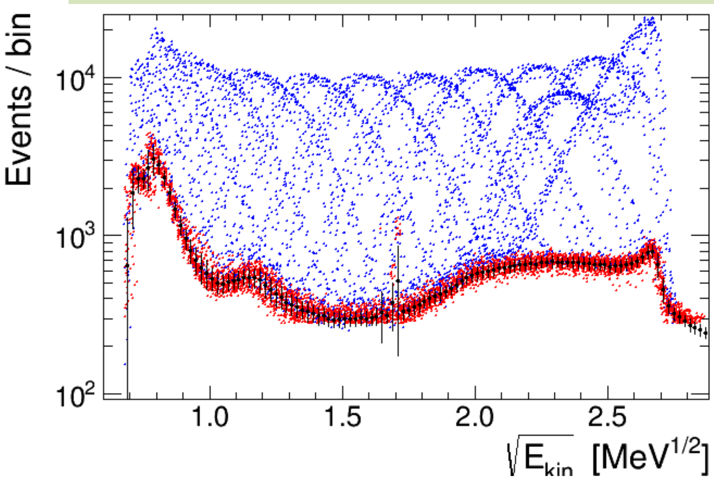
Analysis of the measured $\eta\left(\sqrt{A}\right)$ distributions appeared to be a powerful tool for calibration and monitoring the HJET Si detectors as well as for backgrounds subtraction

Background

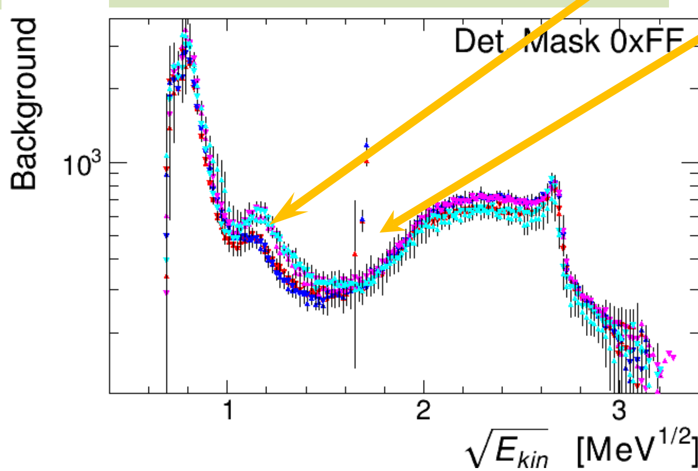


- For all Si strips, the (Gaussian) elastic pp signal is expected to have the same height and width but different position depending on z-coordinate of the strip
- The molecular hydrogen contribution is expected to be flat and, thus, the same for all strips.
- The distributions for inelastic background 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



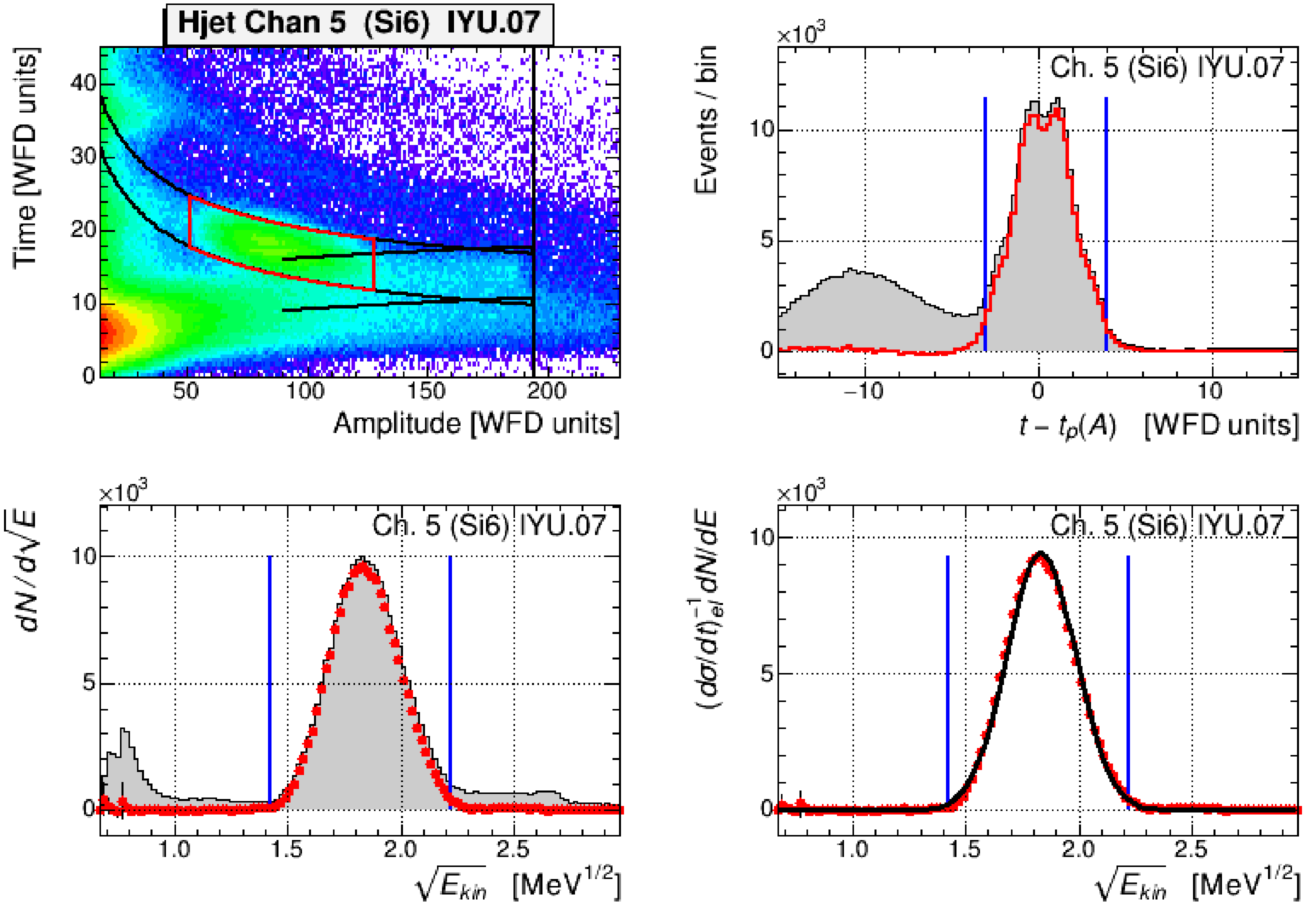
Background distributions determined for each detector separately.



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

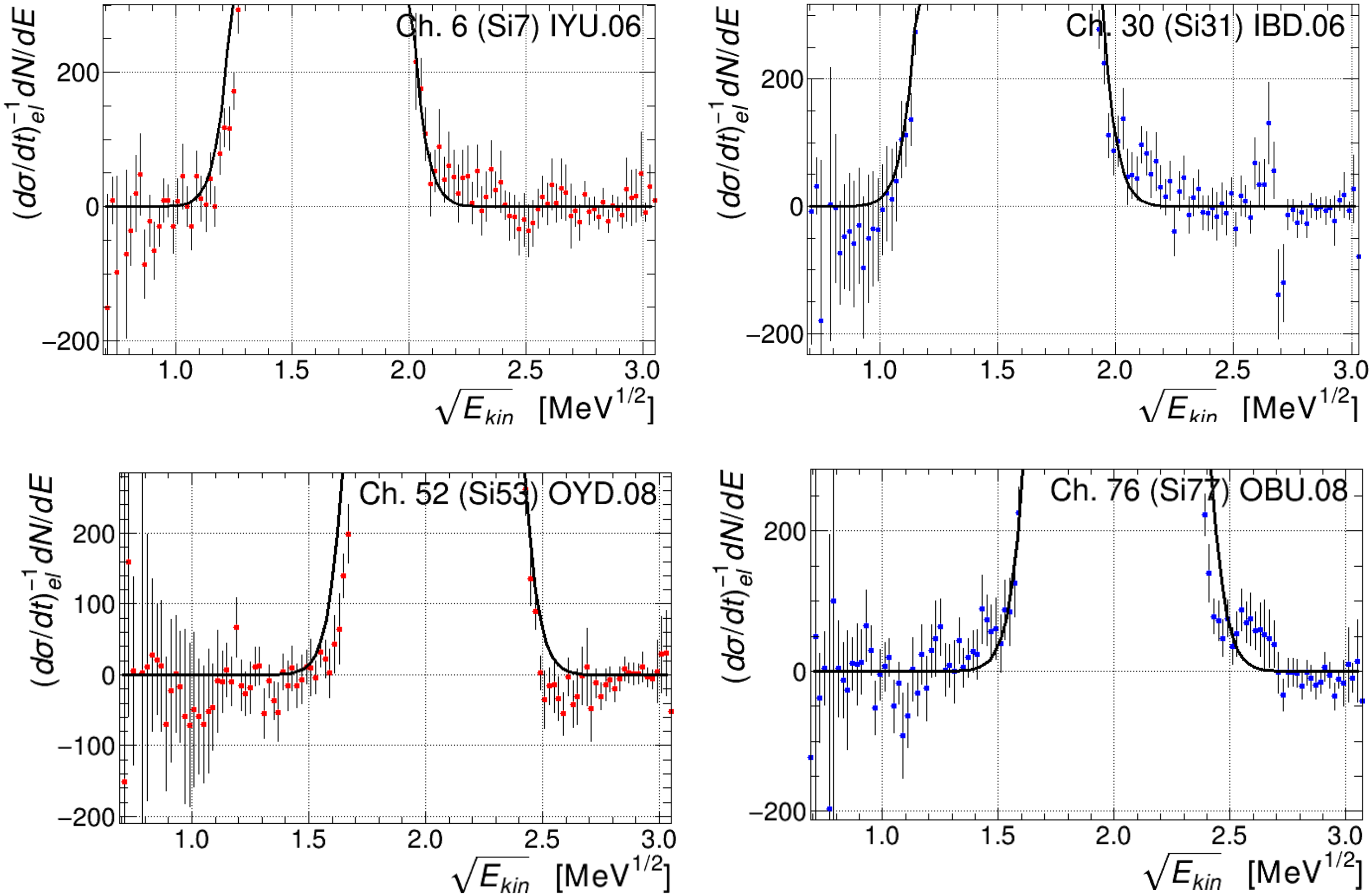
Background should be measured separately for every detector and every beam / jet polarization

How background subtraction works



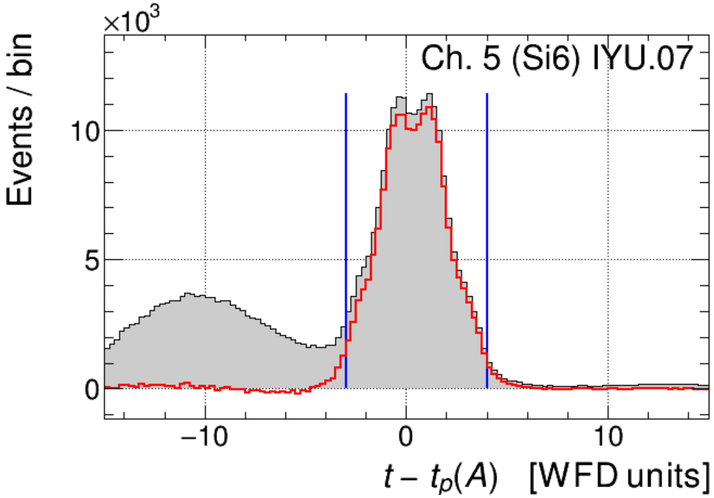
No visible background remained in the event selection cut distributions.

A high resolution comparison



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

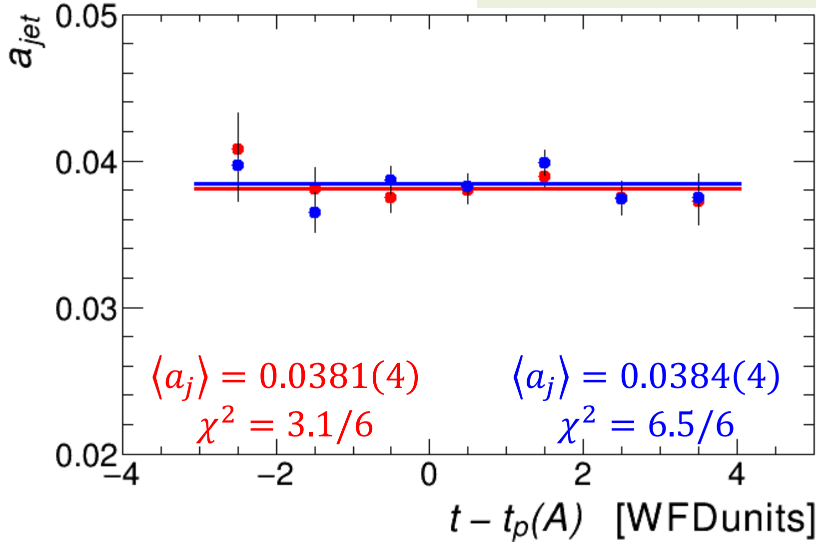
The $t - t_p(A)$ test



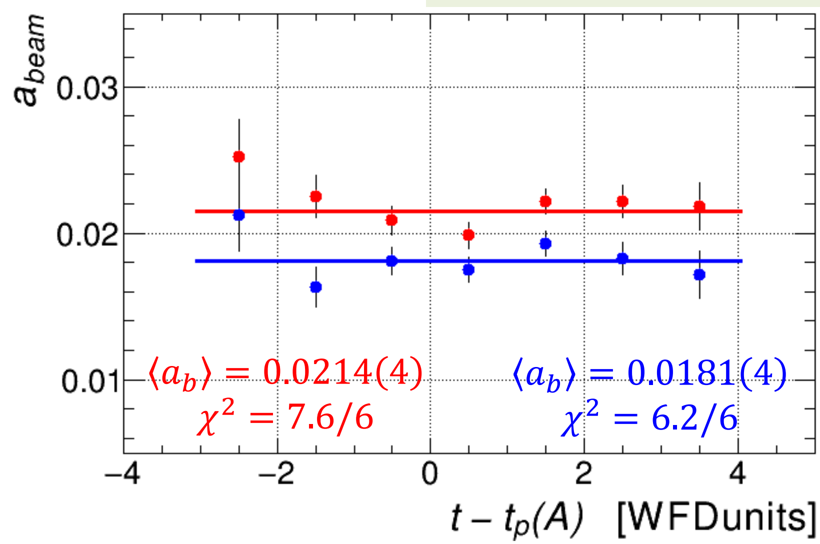
Non-subtracted background will make asymmetry measurement dependent on time cut (Recoil Mass Cut)

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

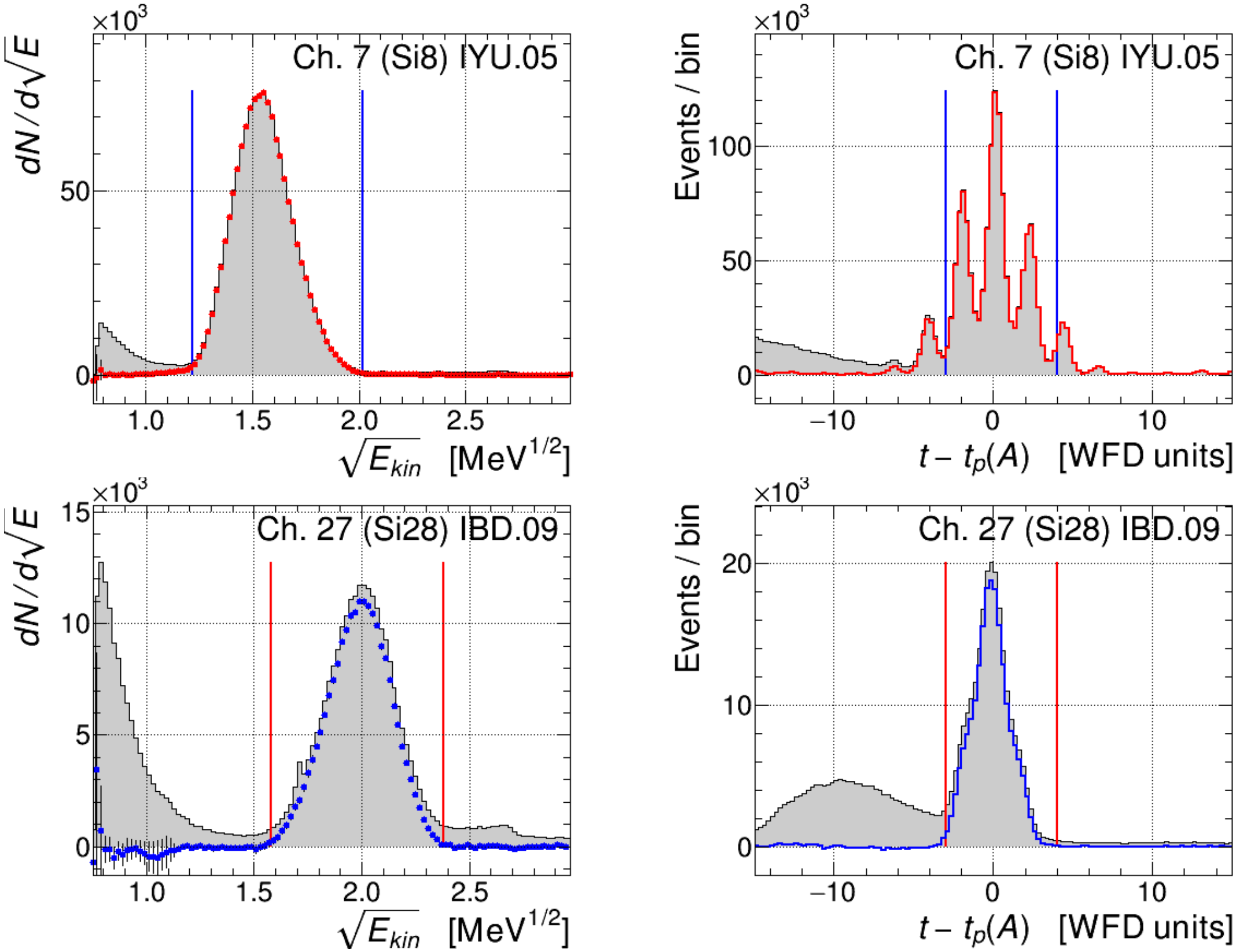
Jet Asymmetry



Beam Asymmetry



Proton-Gold Run



Yellow (Gold) beam

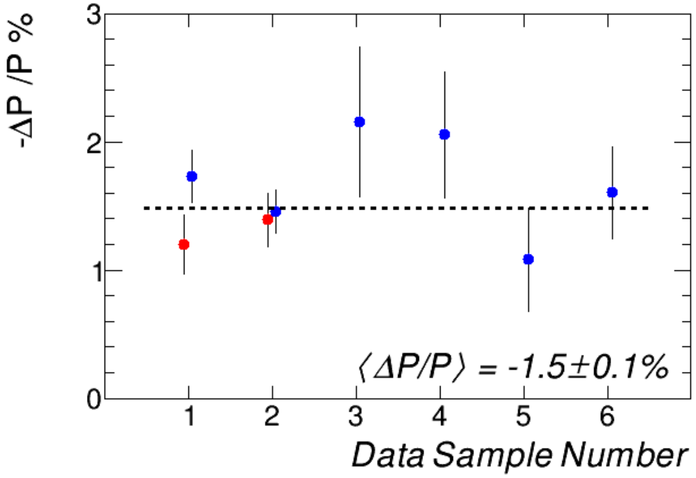
Elastic pAu scattering can be studied !

Blue (proton) beam

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

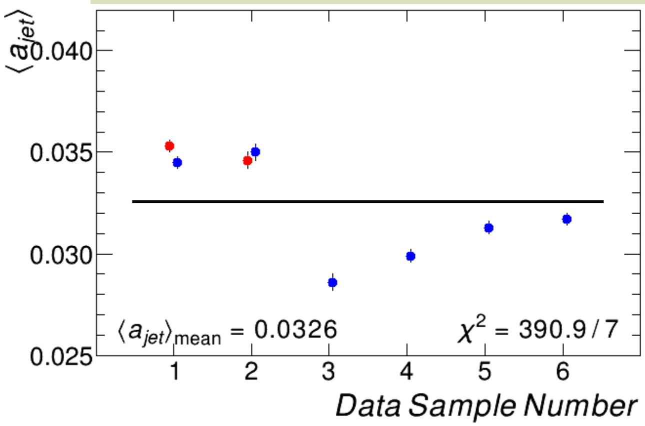
First results in a glance

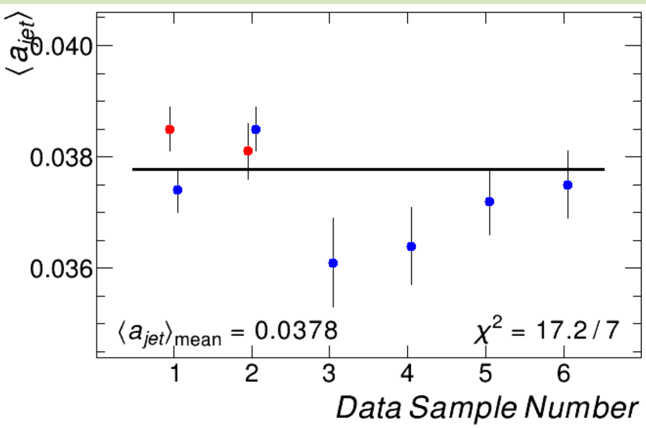
Energy range 0.75 - 7.0 MeV



- ***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

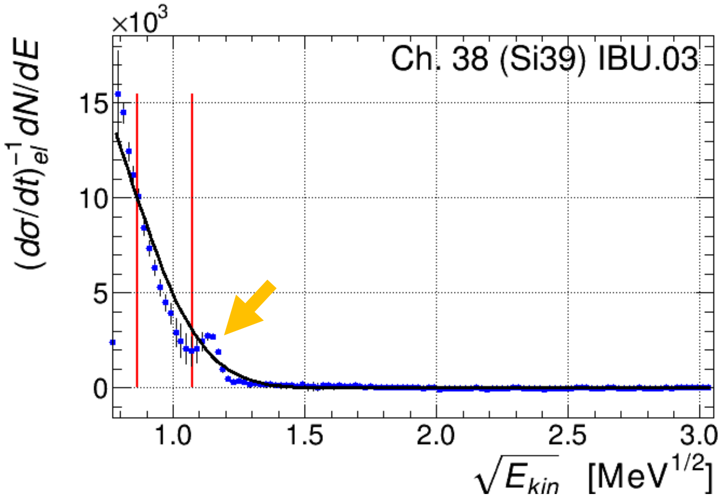


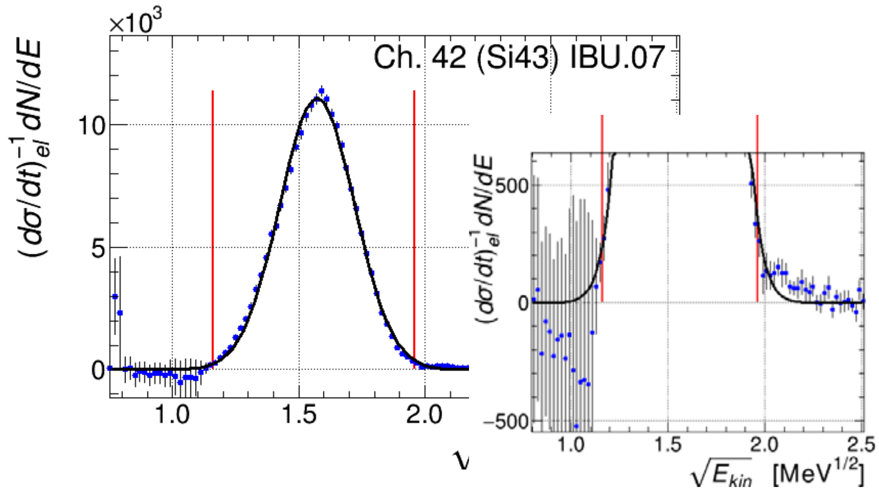


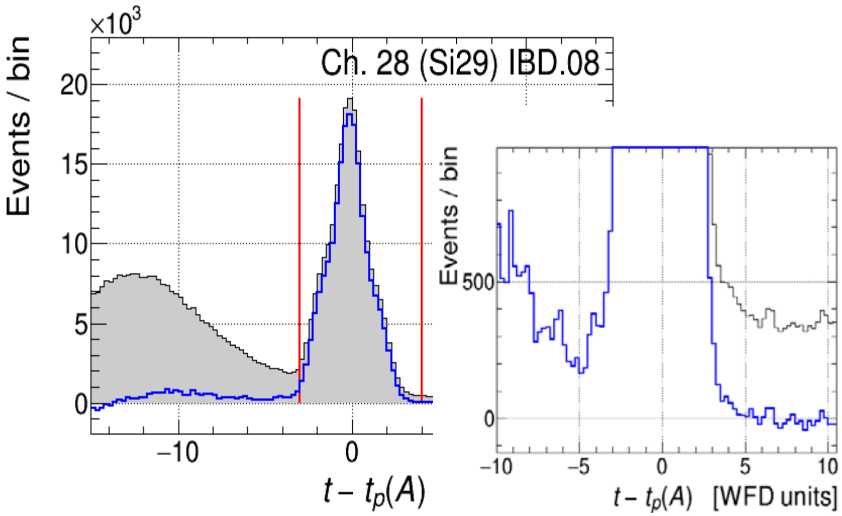
Data samples:

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



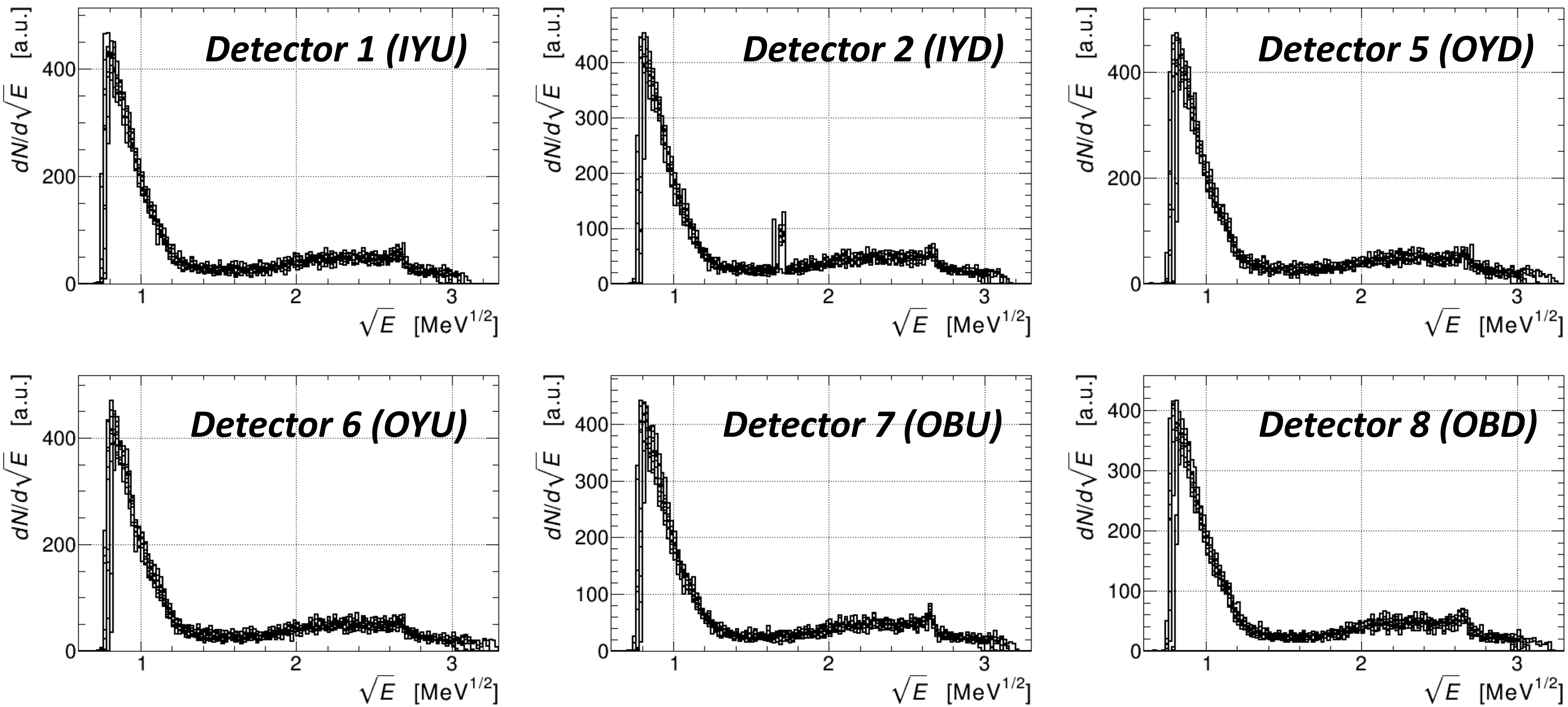




- ***The residual background is up to several percent.***
- ***The issue has to be studied.***
- ***It has to be noted that in this study detectors were well calibrated and monitored only for Data Sample 2 (pp, VME)***
- ***An empty target run (p-Al) gives some explanation of the problem.***

Fill 19205 (pAl) Empty Target

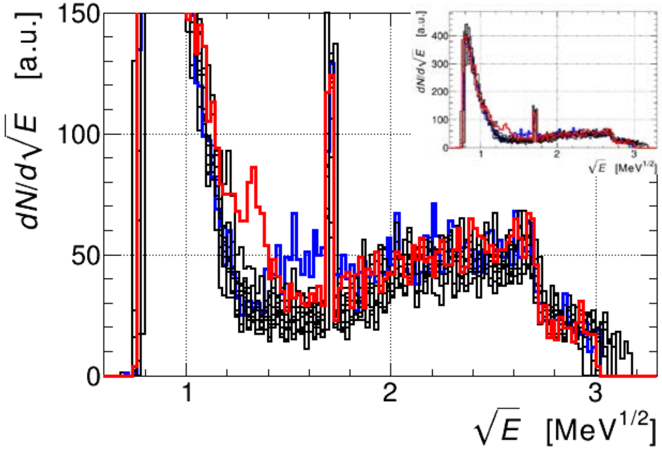
In the empty target run (Jet OFF) we can easily check if non-Jet background is the same for all datectors.

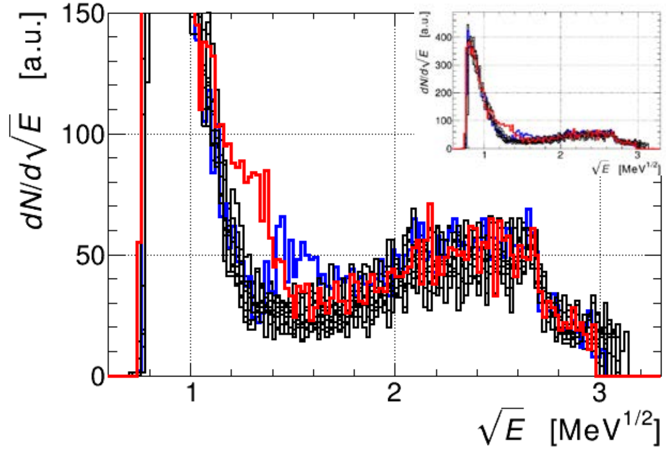


No issue in any detectors except for Inner Blue.

Inelastic background issue in Inner Blue Detectors

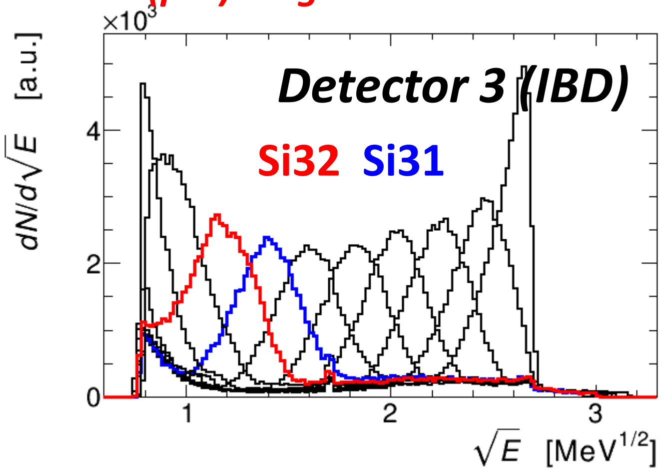
Fill 19205 (pAl) Empty Target

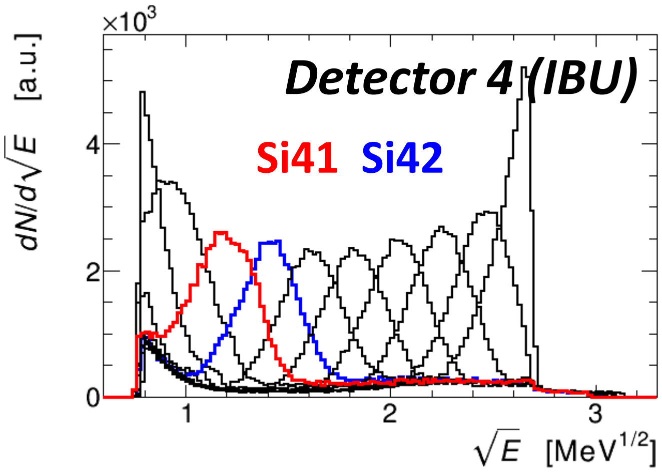




Some background is observed only in strips #5 and #6 of Inner Blue detectors and, thus, can not be eliminated by comparison with other strips.

Fill 19237 (pAl) Regular Jet Run



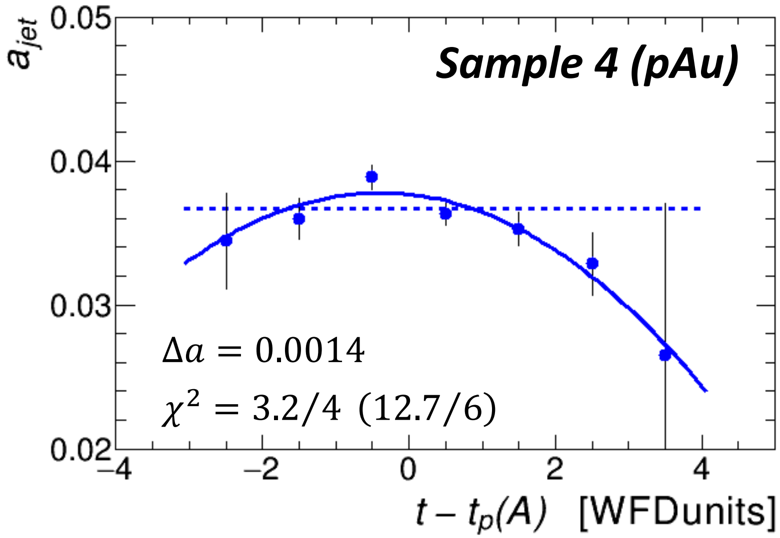


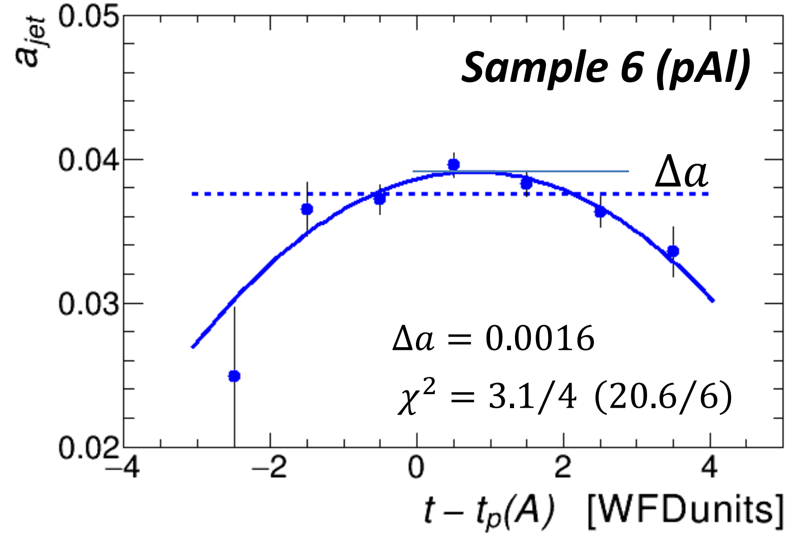
The discrepancy should be compared with expected Jet elastic peak height of about 600-700 counts

The unsubtracted background is "hidden" under the elastic peak.

The assumption that inelastic background is the same for all strips is definitely violated for several strips in Inner Blue Detectors.

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

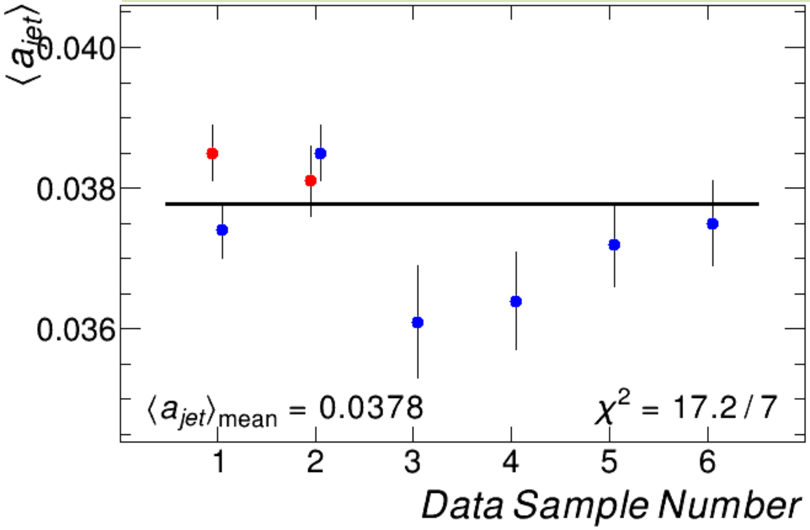


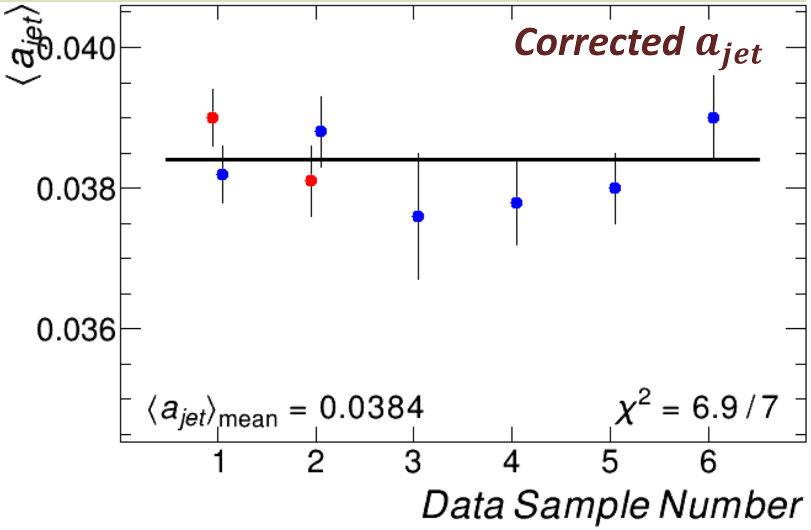


- The dependence the a_{jet} on the time cut is clearly seen
- The fit maximum corresponds to the minimally corrupted measurement
- The correction Δa could be calculated

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

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





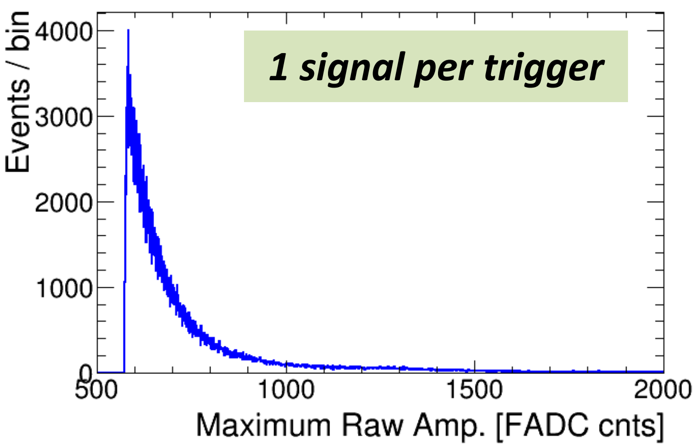
- **The corrected $\langle a_{jet} \rangle$ is consistent for all 8 measurements**
- **The average correction is 1.6%**
- **The average correction in the pA data is 3.2%**
- **The sample 2 (*pp*, VME) measurement was corrected by less than 0.5%**

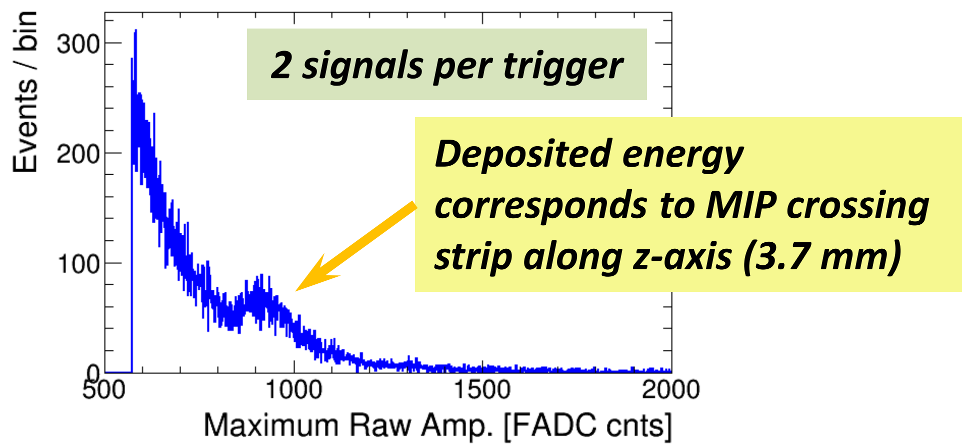
Alternative methods to suppress background

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)





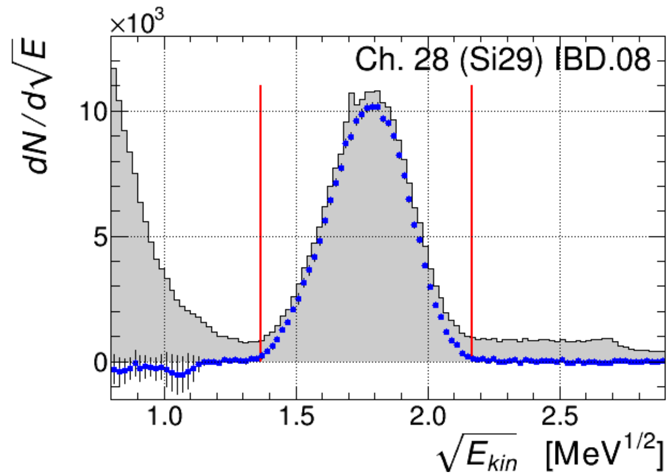
- Beam Halo signals may be isolated by searching simultaneous hits in different strips of a detector.
- A partial suppression of the Halo was tested.
- No improvement for described above results was found.

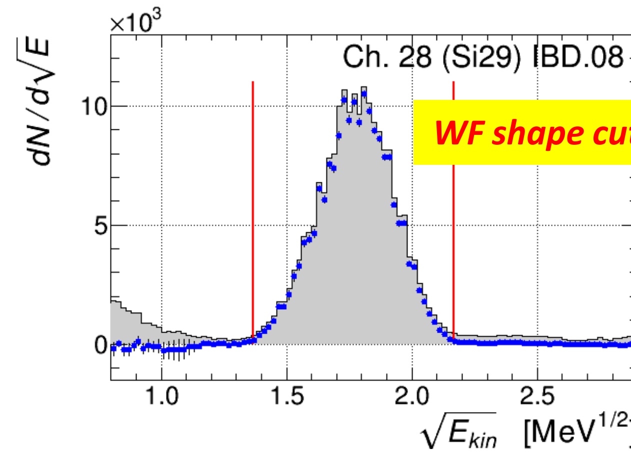
Reconstruction of punched through protons

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



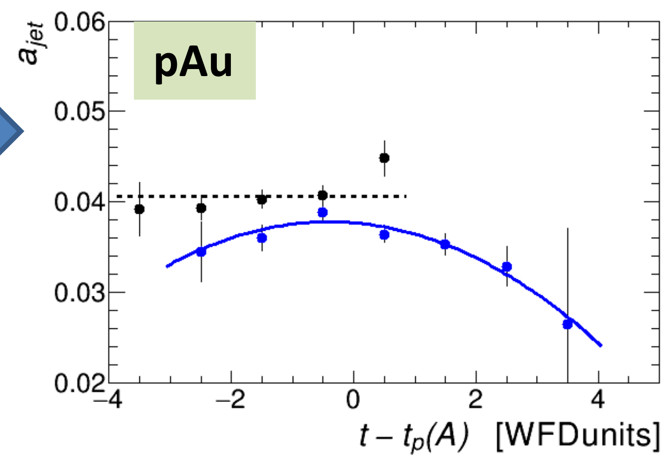


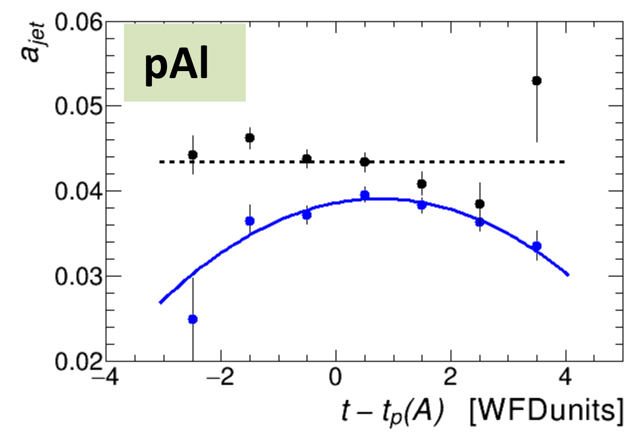
WF shape cuts

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





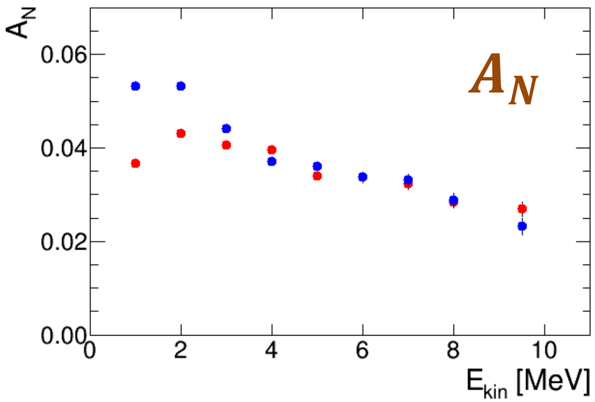
There is an indication that WF shape cuts strongly improve the $t - t_p(A)$ test, but statistics is too low for a final conclusion.

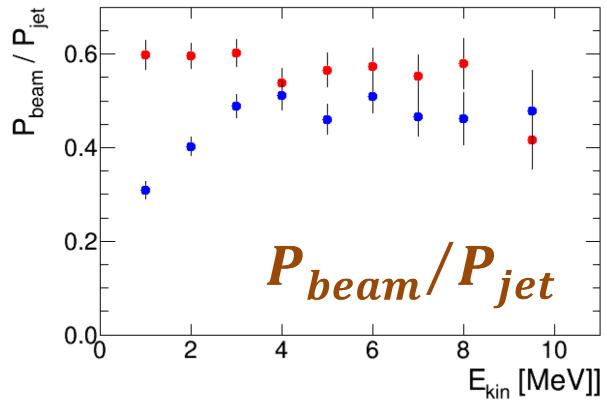
Controls for the systematic errors

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

- ***These controls (except for last one) were not applied yet for the discussed method of background subtraction.***
- ***All these controls are insensitive to the molecular hydrogen background.***

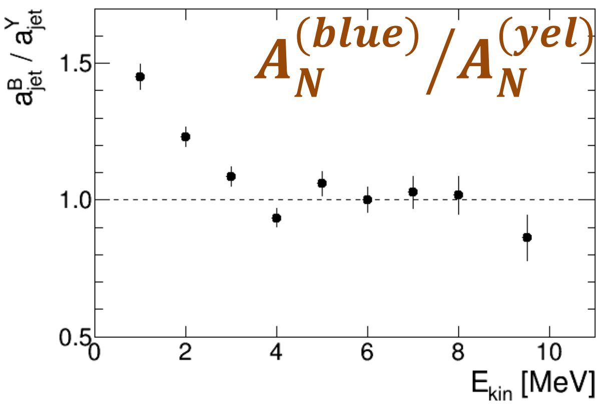
Asymmetry dependencies on recoil proton energy

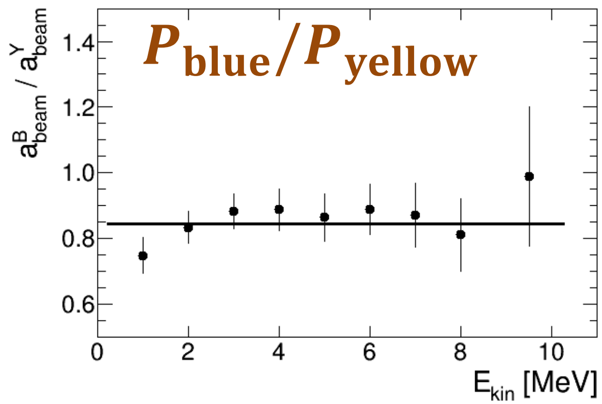




RHIC Fills 18950-18953
(2 days of measurements)
VME data

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.***

Summary (Part 1)

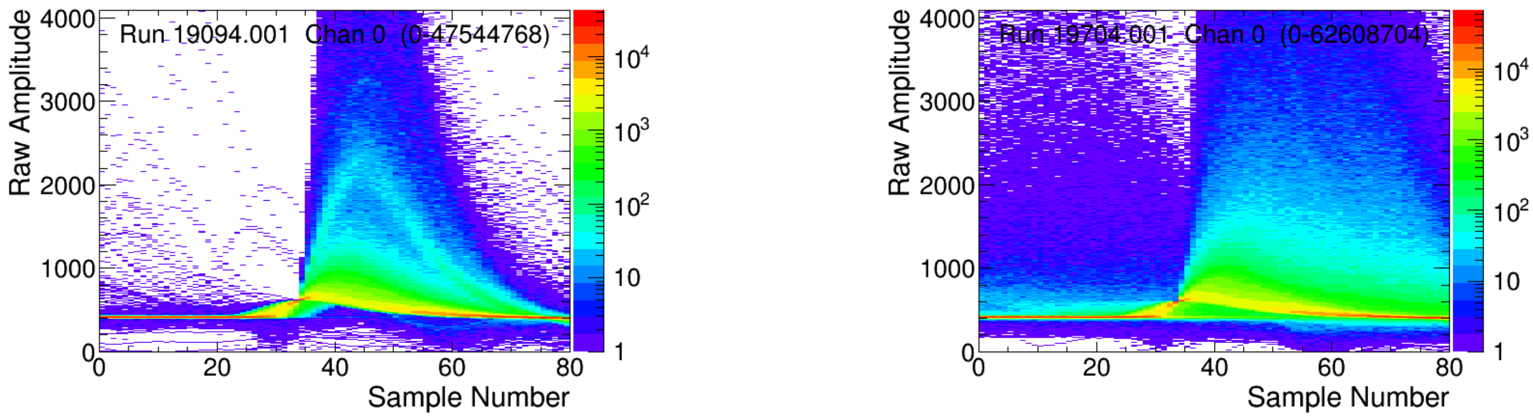
- A fast method of background subtraction was implemented in the HJET data analysis.
- Elastic pp peaks may be well isolated with only a small remaining background.
- Background related corrections to the measured beam polarization were found to be $\approx -1.5\%$*.
- For thoroughly calibrated Fills 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.

****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.

Rate in Hjet detectors

Superposition of waveforms in a single Si strip (Ch.0, Gold beam):

Run 19094.001 (2015) 120 min ***Run 19704.001 (2016) 10 min***



Currently the rate is about factor 20 higher then in p-Au Run15. Perhaps, this is caused by shifted beam position (beam halo scattering on Hjet frame).

		Beam Intensity		***Beam Position (mm)***				Rate (Hz)
Fill		Blue	Yellow	xB	yB	xY	yY	Ch. 0
18950	p p	229	225	-0.08	-0.31	-0.11	-3.25	77
19094	p Au	235	1.75	-3.12	-0.25	-2.67	-3.32	78
19237	p Al	206	9.17	-2.51	-0.64	-2.61	-3.80	64
19704	**Au Au**	**2.20**	**2.31**	**1.00**	**5.71**	**0.96**	**-4.98**	**1300**

Study of the rate in HJET

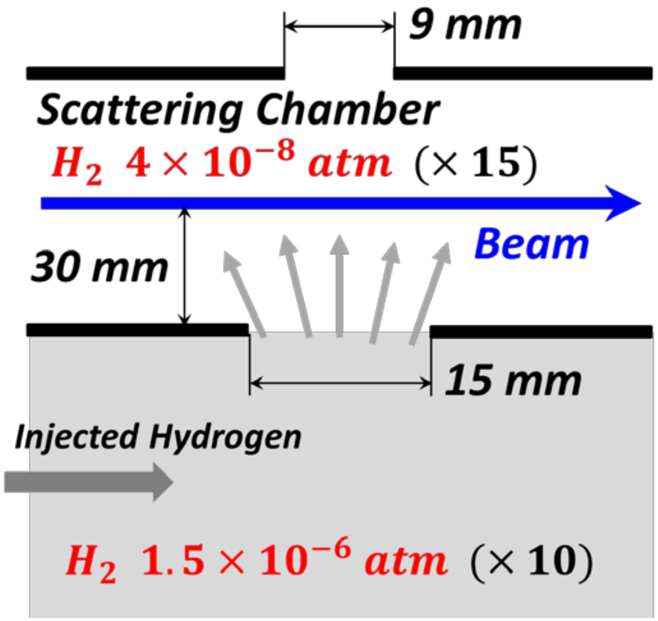
Rate in the HJET was studied in several short (few minutes) empty target runs at the end of a store:

- The rate was almost independent on the beam position
- The main source of the rate was beam-beam interaction. Beam dump significantly improve the rate

Yellow beam only: Au + Au (890 Hz) => Au (35 Hz)
Blue beam only: Au + Au (890 Hz) => Au (3 Hz)

To minimize inelastic background contribution, the study of the molecular hydrogen distribution had been done with single blue.

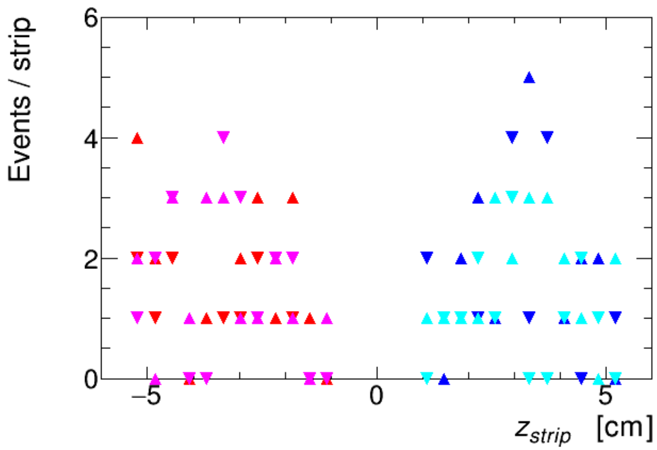
Molecular Hydrogen Profile



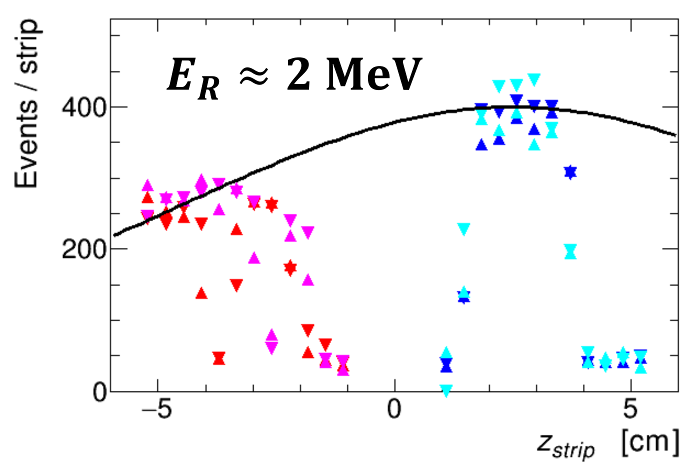
- 1 hour run (APEX) was taken. Single blue beam at injection ($E_{\mathrm{Au}} = 9.8\ \mathrm{GeV/n}$)
- To emulate molecular hydrogen distribution in the HJET, hydrogen was injected to the Chamber 7 (while Jet OFF).
- Relative fixed energy (consequently fixed scattering angle) rate in Si strips describes the distribution of hydrogen in the HJET

$$z_{str} - z_{jet} = k\sqrt{E_R}\,, \quad k = 2\ \mathrm{cm/MeV^{1/2}}$$

No injected hydrogen (10 min)

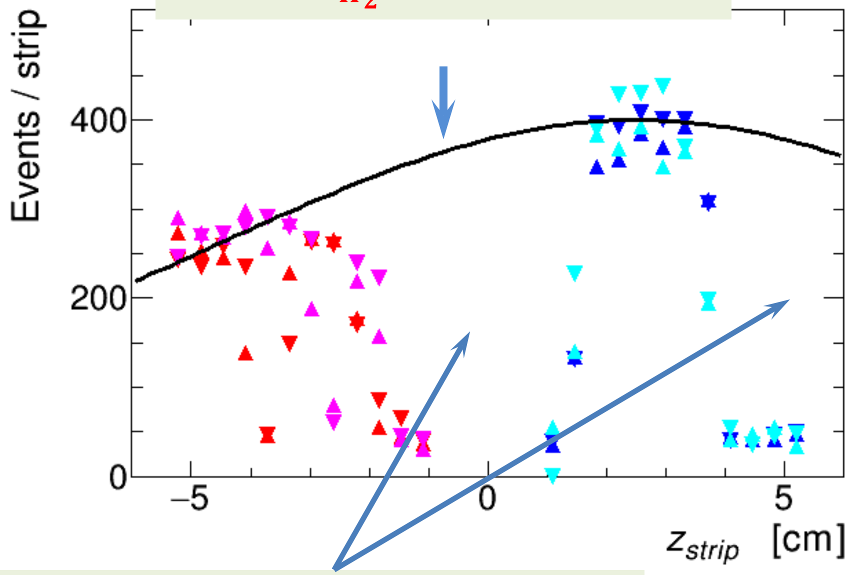


Hydrogen was injected (20 min)



Interpretation of the measurement

Molecular hydrogen profile:
$\sigma_{H_2} \approx 7.5\ cm$

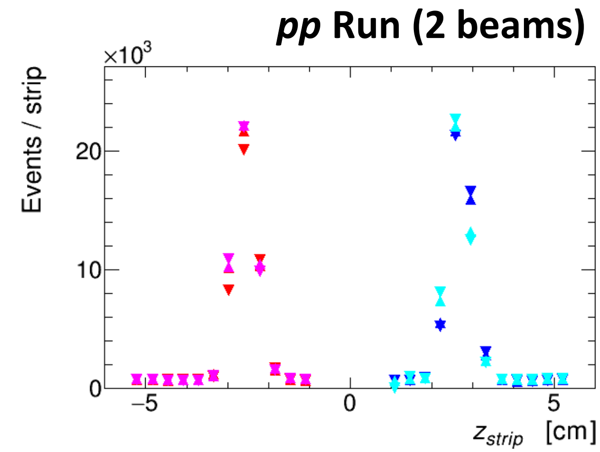


Si strips are partially screened by the RF shield and collimators

Recoil proton energy:

$$\sqrt{E_R} = 1.4 \pm 0.1\ \ MeV^{1/2}$$

Strips are partially screened by the RF shielding and collimators



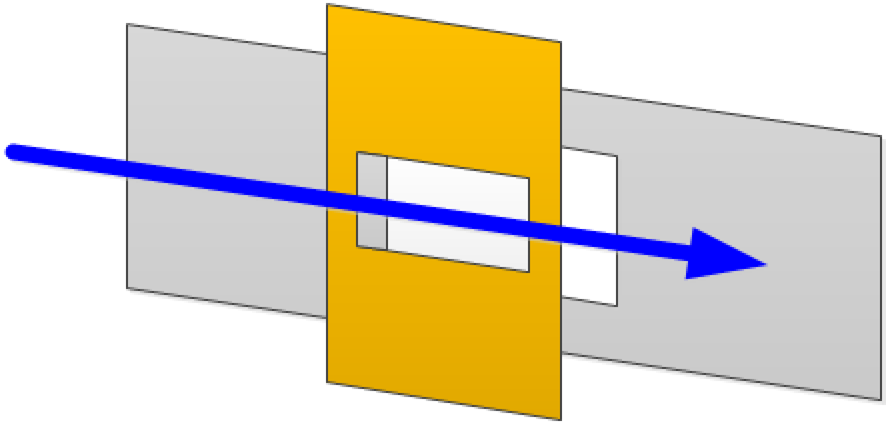
Good News: *molecular hydrogen distribution is flat*.

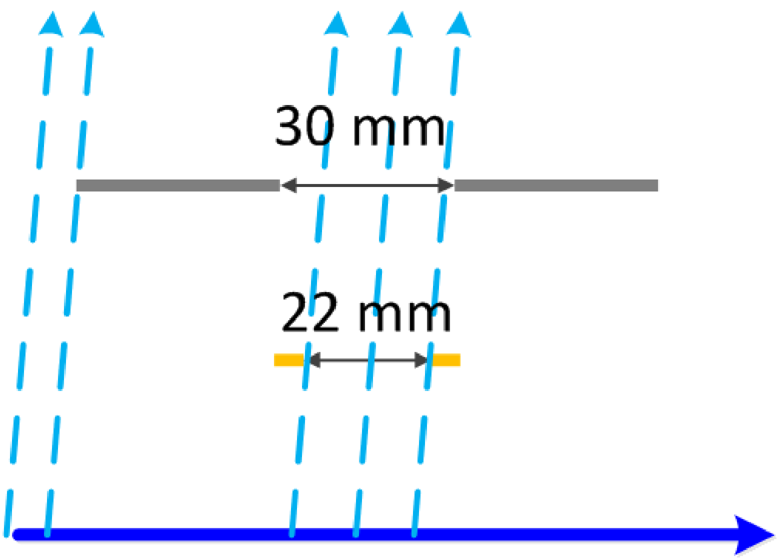
Bad News: *The flatness is corrupted by collimators.*

It is likely that molecular hydrogen was underestimated in the previous Run15 analysis. More study is needed.

Do we really need collimators ?

Do we need collimators in HJET ?



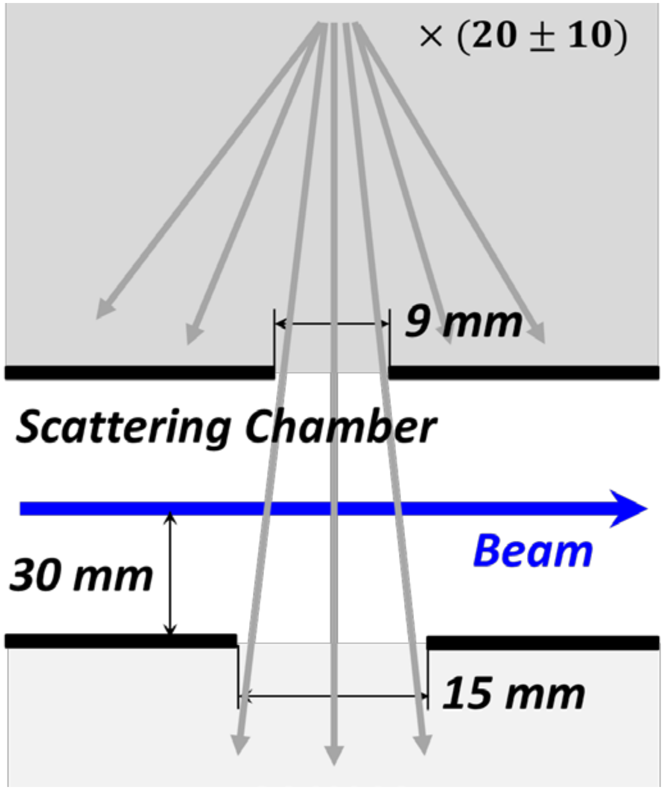


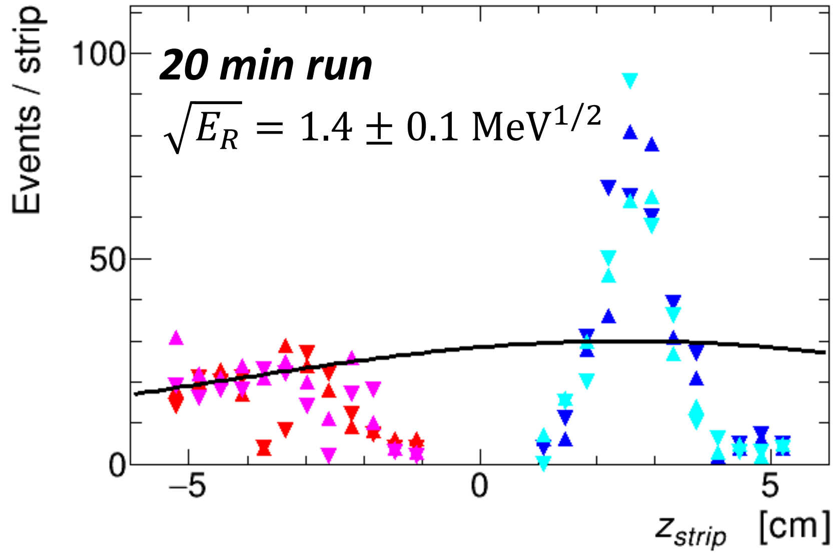
Collimators allows us to suppress recoil protons form opposite beam scattering on molecular hydrogen cloud

- **These events do not affect the polarization measurements (if there is no polarization correlation in simulatneous ("colliding") yellow and blue bunches.**
- **These events does not change background statistics significantly.**

Collimators makes background subtraction more difficult.

Molecular Hydrogen from dissociator





- The “molecular hydrogen Jet” is visible.
- Corrections to measured beam polarization can not be eliminated by the background subtraction.
- However, the expected corrections are estimated to be 0.3-0.5%

Summary (Part 2)

- Molecular hydrogen distributions in HJET were experimentally emulated.
- In the single blue beam measurements (APEX) it was evaluated that
  - ✓ The molecular hydrogen cloud in the HJET collision chamber has flat z-coordinate distribution and, thus, may be properly accounted in the data analysis.
  - ✓ The admixture of molecular hydrogen atoms in the atomic Jet does not exceed 0.5%
  - ✓ Partial screening of the Si strips by the RF shield and collimators may seriously affect the efficiency of molecular hydrogen suppression in data analysis.
- Taking into account non-uniform screening, the estimates of the Run15 systematics errors due to molecular hydrogen must be revisited.