Precise measurements of the single $A_N(t)$ and double $A_{NN}(t)$ spin-flip asymmetries in CNI region in elastic $p^{\uparrow}p^{\uparrow}$ scattering at $\sqrt{s} = 13.76\ \mathrm{GeV}$ and $\sqrt{s} = 21.92\ \mathrm{GeV}$ at RHIC HJET polarimeter

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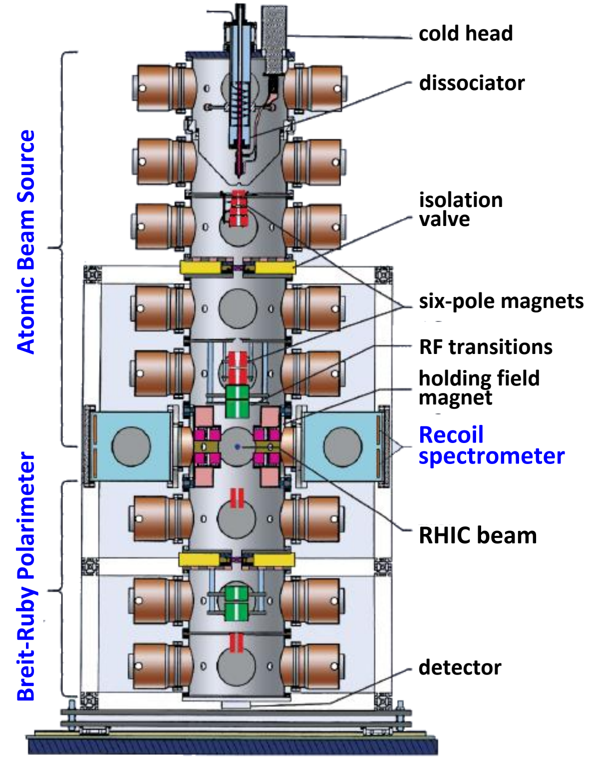
Polarized Atomic Hydrogen Gas Jet Target (HJET)

HJET designed to measure absolute polarization of RHIC proton beams is, in fact, a fixed target experiment performed concurrently with RHIC colliding experiments.

The Jet proton target polarization, $\boldsymbol{P_{jet} = 0.96}$, is flipped every 5-10 minutes.

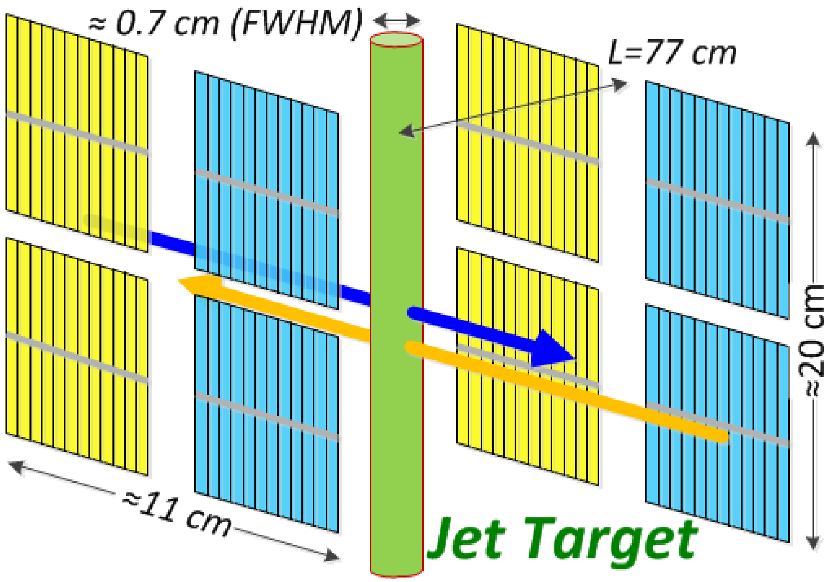
This report includes analysis of single- and double spin-flip analyzing power in elastic pp scattering in two RHIC runs:

- **Run15:** $\boldsymbol{E_{beam} = 100\ \mathrm{GeV}\ \left(\sqrt{s} = 13.76\ \mathrm{GeV}\right)}$
- **Run17:** $\boldsymbol{E_{beam} = 255\ \mathrm{GeV}\ \left(\sqrt{s} = 21.92\ \mathrm{GeV}\right)}$



- ➢ A technical description of HJET was given by Anatoli Zelenski
- ➢ Theoretical basis for elastic polarized $p^{\uparrow}p^{\uparrow}$ measurements was discussed by Nigel Buttimore.
- ➢ A detailed description of the HJET data analysis method can be found in PSTP 2017 Proceedings, *A. Poblaguev et al., PoS(PSTP2017)022*.

HJET detector configuration



- HJET consist of 8 Silicon detecors, 12 strips. each. 4 detectors per RHIC beam.
- Full waveform is recorded for every event.
- For elastic scattering, the detected recoil proton kinetic energy T_R range is defined by HJET geometry

$$0.5 < T_R < 11\ \mathrm{MeV}$$

- The momentum transfer is proportional to T_R

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

- Both RHIC beams (**Blue** and **Yellow**) are measured simultaneously.
- The waveform shape analysis was employed to separate stopped and punched-trough ($T_R > 7.8$ MeV)recoil protons.
- The detectors granulation (vertical strips) allowed us to accurately identify backgrounds and subtract them separately for
  - *every detector*
  - *every* $\sqrt{T_R}$ *bin*
  - *every combination of beam/jet spins*

Systematic correction and uncertainties

Detailed study of systematic errors for the polarization measurements at **255 GeV** is given in PSTP 2017 Proceedings.

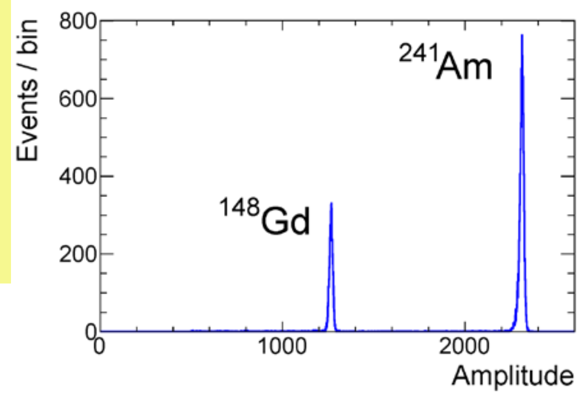
The inelastic scattering $pp \to Xp$ uncertainty is irrelevant for **100 GeV**

For analyzing power measurements we should also consider systematic corrections/uncertainties which are effectively canceled in the beam polarization measurements.

Source	$\delta P/P$ (%)	σ_P/P (%)
Long term stability		$\mathbf{0.1}$
Jet Polarization		$\mathbf{0.1}$
Jet $\mathrm{H_2}$		$\mathbf{0.06}$
Flat $\mathrm{H_2}$	$\mathbf{+0.06}$	$\lesssim \mathbf{0.1}$
pA scattering		$\lesssim \mathbf{0.2}$
p+p→X+p	$\mathbf{+0.15}$	$\mathbf{0.1}$
Jet spin correlated noise		$\lesssim \mathbf{0.2}$
Total	$\mathbf{+0.21}$	$\lesssim \mathbf{0.37}$

- Corrections to the background subtraction due to the recoil proton tracking in the Holding Field Magnet were simulated
- Corrections due to vertical size of the detectors $\boldsymbol{P_{jet}^{\mathrm{eff}} = P_{jet}\langle \sin\varphi\rangle = 0.997\, P_{jet}}$
- The energy calibration (gains and dead-layers) was done using α-sources. It was not verified for recoil protons. Using indirect methods we established an upper limit for the calibration uncertainty as

$$\boldsymbol{\delta T = (\pm 15\ \mathrm{keV}) \oplus (\pm 0.01\, T)}\ .$$



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

For transversely polarized beam and target (Jet) the azimuthal dependence of cross-section is given by:

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

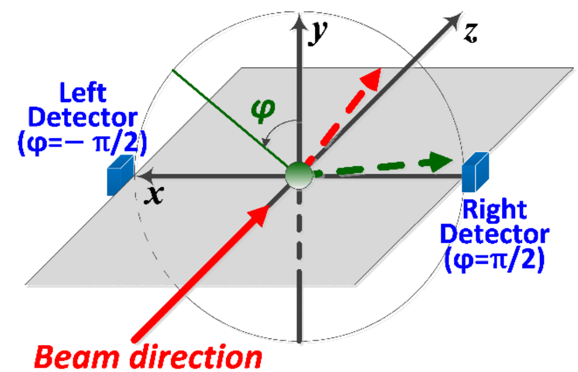
For HJET $\sin\varphi = \pm 1$
and $\cos\varphi = 0$.

Three measured spin-correlated asymmetries:

$$a_N^{jet} = |P_{jet}|A_N, \quad a_N^{beam} = |P_{beam}|A_N, \quad a_{NN} = |P_{jet}P_{beam}|A_{NN}$$

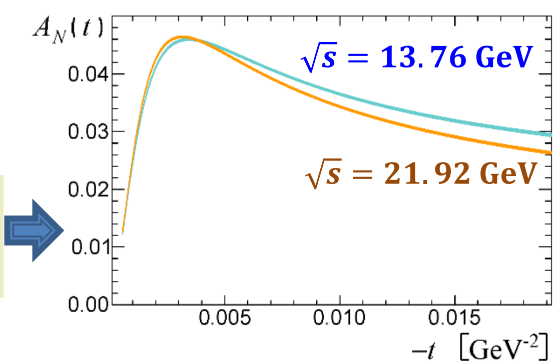
allows us to determine:

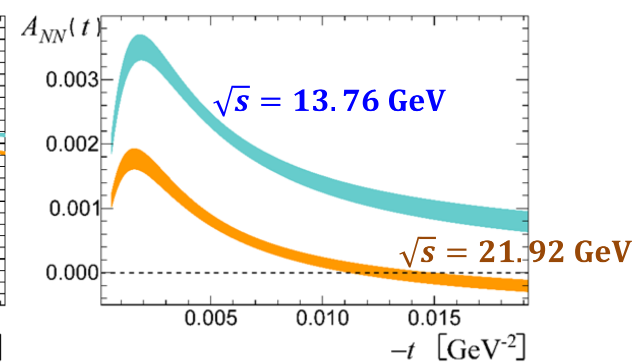
- **Beam polarization** $\quad P_{beam} = P_{jet}\,\langle a_N^{beam}\rangle / \langle a_N^{jet}\rangle$
- **Single-spin analyzing power** $\quad A_N(t) = a_N^{jet}/P_{jet}$
- **Double spin analyzing power** $\quad A_{NN}(t) = a_N^{jet}a_{NN}/a_N^{beam}P_{jet}^2$



$$P_{jet} = 0.96\,, \qquad P_{beam} \sim 0.55$$

Analyzing powers $A_N(t)$ and $A_{NN}(t)$ as measured in this work.





Measurement of the Spin Correlated Asymmetries

Spin correlated asymmetries a_N^{beam}, a_N^{jet}, and a_{NN} are derived from 8 numbers of the detected events corresponding to 8 combinations of the jet spin **(+−)** , beam spin (↑↓), and detector side (**LR**)

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

The event numbers also depend on the spin correlated integral statistics asymmetry for jet $\boldsymbol{\lambda_{jet}}$ and beam $\boldsymbol{\lambda_{beam}}$ as well as on left/right acceptance asymmetry $\boldsymbol{\epsilon}$.

The equations have **the exact** solution which eliminates uncertainties associated with $\boldsymbol{\lambda_{jet}}$, $\boldsymbol{\lambda_{beam}}$, $\boldsymbol{\epsilon}$.

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

$$\boldsymbol{\lambda_{jet}} = \frac{\sqrt[4]{N_R^{\uparrow+}N_R^{\downarrow+}N_L^{\uparrow+}N_L^{\downarrow+}} - \sqrt[4]{N_R^{\uparrow-}N_R^{\downarrow-}N_L^{\uparrow-}N_L^{\downarrow-}}}{\sqrt[4]{N_R^{\uparrow+}N_R^{\downarrow+}N_L^{\uparrow+}N_L^{\downarrow+}} + \sqrt[4]{N_R^{\uparrow-}N_R^{\downarrow-}N_L^{\uparrow-}N_L^{\downarrow-}}}$$

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

$$\boldsymbol{\lambda_{beam}} = \frac{\sqrt[4]{N_R^{\uparrow+}N_R^{\uparrow-}N_L^{\uparrow+}N_L^{\uparrow-}} - \sqrt[4]{N_R^{\downarrow+}N_R^{\downarrow-}N_L^{\downarrow+}N_L^{\downarrow-}}}{\sqrt[4]{N_R^{\uparrow+}N_R^{\uparrow-}N_L^{\uparrow+}N_L^{\uparrow-}} + \sqrt[4]{N_R^{\downarrow+}N_R^{\downarrow-}N_L^{\downarrow+}N_L^{\downarrow-}}}$$

$$\boldsymbol{a_{NN}} = \frac{\sqrt{N_R^{\uparrow+}N_L^{\downarrow-}} - \sqrt{N_R^{\downarrow+}N_L^{\uparrow-}} - \sqrt{N_R^{\uparrow-}N_L^{\downarrow+}} + \sqrt{N_R^{\downarrow-}N_L^{\uparrow+}}}{\sqrt{N_R^{\uparrow+}N_L^{\downarrow-}} + \sqrt{N_R^{\downarrow+}N_L^{\uparrow-}} + \sqrt{N_R^{\uparrow-}N_L^{\downarrow+}} + \sqrt{N_R^{\downarrow-}N_L^{\uparrow+}}}$$

$$\boldsymbol{\epsilon} = \frac{\sqrt[4]{N_R^{\uparrow+}N_R^{\uparrow-}N_R^{\downarrow+}N_R^{\downarrow-}} - \sqrt[4]{N_L^{\uparrow+}N_L^{\uparrow-}N_L^{\downarrow+}N_L^{\downarrow-}}}{\sqrt[4]{N_R^{\uparrow+}N_R^{\uparrow-}N_R^{\downarrow+}N_R^{\downarrow-}} + \sqrt[4]{N_L^{\uparrow+}N_L^{\uparrow-}N_L^{\downarrow+}N_L^{\downarrow-}}}$$

This is a systematic error free solution if
the effective analyzing powers are the same for left/right detectors and
the detector acceptance is beam/jet spin independent.

Overview of possible systematic errors

Systematics corrections in the spin asymmetry measurements may be approximated as:

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

$\boldsymbol{\delta A_N}$ is a discrepancy between actual and assumed analyzing powers due to background and/or wrong energy calibration.

$\boldsymbol{\delta\epsilon = \frac{\epsilon^{\uparrow}-\epsilon^{\downarrow}}{\epsilon^{\uparrow}+\epsilon^{\downarrow}}}$ is a spin correlated asymmetry of the detector acceptance.

Generally, $\boldsymbol{\delta A_N}$ and $\boldsymbol{\delta\epsilon}$ are left/right and jet/beam dependent.

In HJET, $\boldsymbol{\delta\epsilon} = 0$ for the beam spin. However, in Run 15 significant Jet spin correlated $\boldsymbol{\delta\epsilon}$ corrections were observed in two *blue* detectors. These detectors were removed from the data analysis.

Monitoring of the measured beam/jet intensity asymmetries $\lambda(T_R)$ dependence on the recoil proton energy is an important part of the systematic error control.

$p^{\uparrow}p$ *Single Spin-Flip Analyzing Power* $A_N(t)$

Helicity amplitudes describing elastic $p^{\uparrow}p^{\uparrow}$ ***scattering:***

spin non-flip $\phi_1(s,t) = \langle + + | + + \rangle$, $\phi_3(s,t) = \langle + - | + - \rangle$

double spin flip $\phi_2(s,t) = \langle + + | - - \rangle$, $\phi_4(s,t) = \langle + - | - + \rangle$

single spin flip $\phi_5(s,t) = \langle + + | + - \rangle$

$$\phi_i(s,t) = \phi_i^{had}(s,t) + \phi_i^{em}(s,t) e^{\delta_C(s,t)}$$

$$\phi_{\pm}(s,t) = \frac{\phi_1(s,t) \pm \phi_3(s,t)}{2}$$

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

Hadronic spin-flip amplitude: $r_5 = \dfrac{m_p\, \phi_5^{had}}{\sqrt{-t}\, \mathrm{Im}\, \phi_+^{had}}$

Elastic pp parameters $\boldsymbol{\sigma_{tot}}$, $\boldsymbol{\rho}$, $\boldsymbol{B}$ are well known from unpolarized experimental data.

$\kappa = \mu_p - 1 = 1.79$

$\delta_C(B) \sim 0.02$

$-t_c = 8\pi\alpha/\sigma_{tot} \sim 0.002\ \mathrm{GeV}^2$

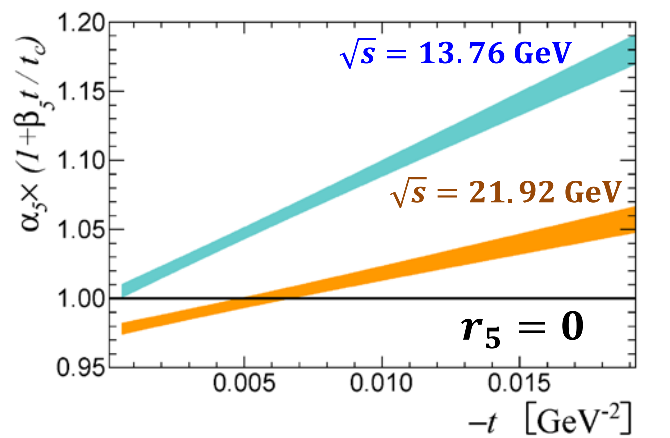
$\rho = -(0.01 \div 0.08)$

For visual control it is convenient to use normalized asymmetry

$$a_n(t) = a_N(t)/A_N^{(0)}(t) = P\alpha_5\left(1 + \beta_5 \frac{t}{t_c}\right)$$

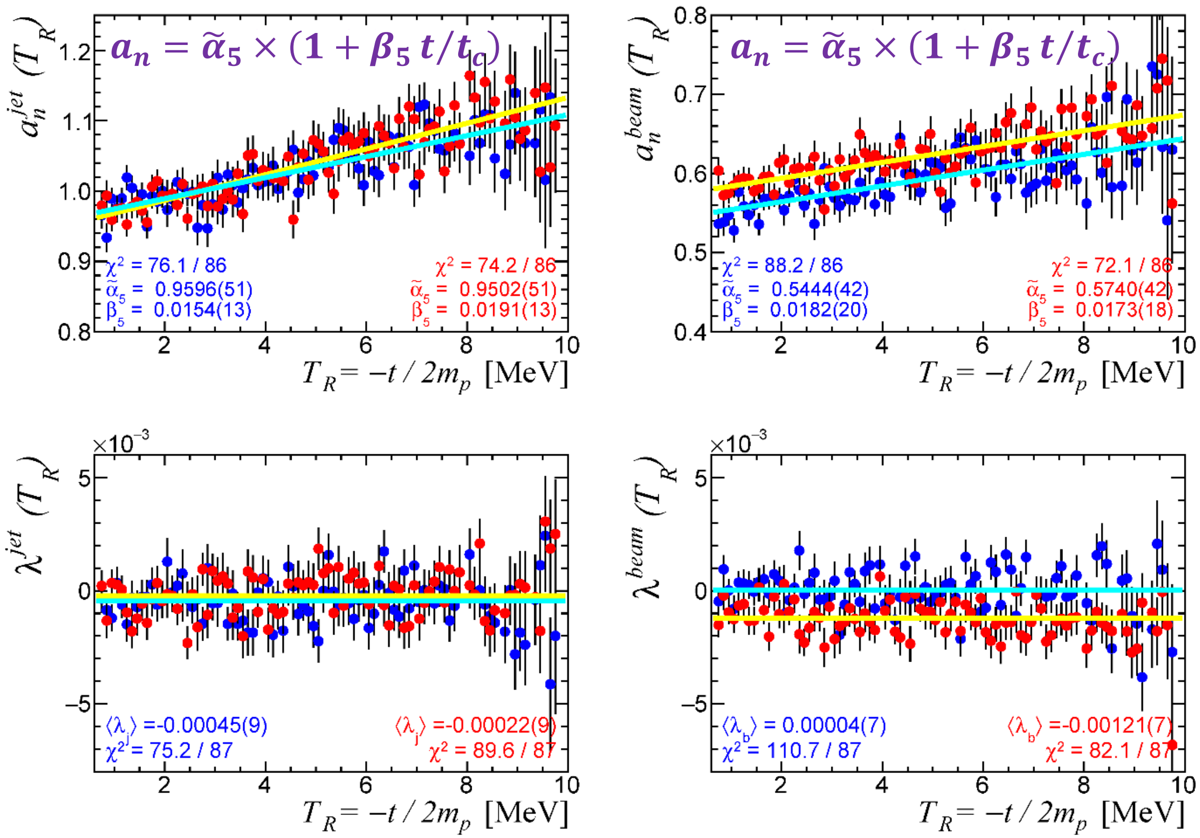
$A_N^{(0)}(t) = A_N(t, r_5 = 0)$

$\alpha_5 \approx 1 - \frac{2}{\kappa}\mathrm{Im} r_5 \quad \beta_5 \approx -\frac{2}{\kappa}\mathrm{Re} r_5$



Single Spin asymmetry 100 GeV (Run 2015)

$\tilde{\alpha}_5 = P\alpha_5$



The results are shown separately for Blue and Yellow RHIC beams

Jet spin asymmetry *fit range* :
$0.7 < T_R < 9.9\ \mathrm{MeV}$

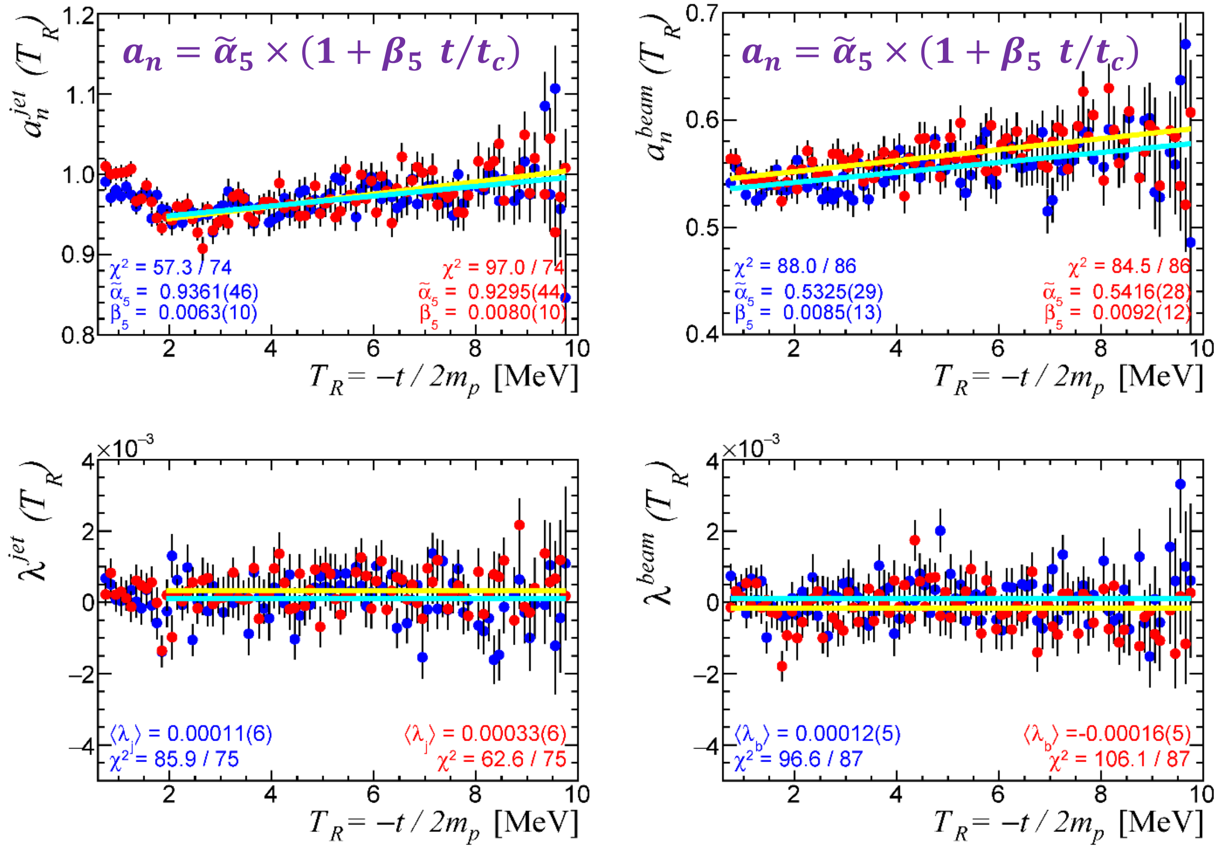
Beam spin asymmetry *fit range* :
$0.7 < T_R < 9.9\ \mathrm{MeV}$

No evidence of uncontrolled systematic errors for the used event selection cuts

- ***Measured normalized spin asymmetries a_N linearly depend on T_R***
- $\langle\beta_5\rangle = 0.0174 \pm 0.0008, \quad \chi^2/\mathrm{ndf} = 4.24/3$
- ***Measured intensity asymmetries λ do not depend on T_R***

Single Spin asymmetry 255 GeV (Run 2017)

$\widetilde{\alpha}_5 = P\alpha_5$



The results are shown separately for Blue and Yellow RHIC beams

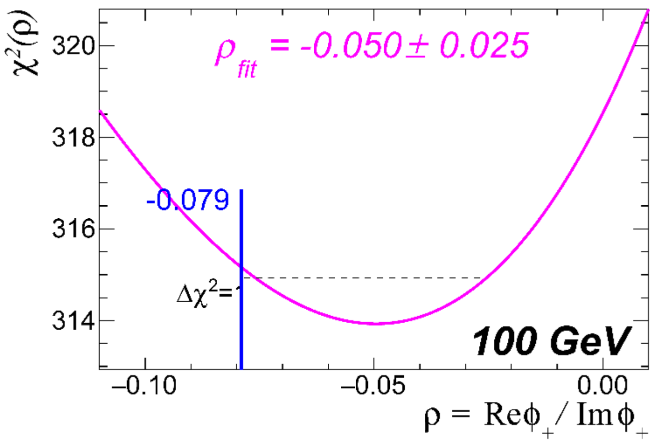
Jet spin asymmetry *fit range* :
$$1.9 < T_R < 9.9\ \text{MeV}$$

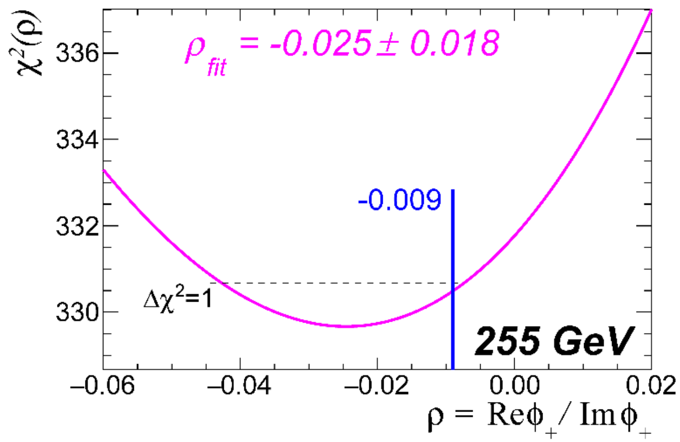
Beam spin asymmetry *fit range* :
$$0.7 < T_R < 9.9\ \text{MeV}$$

For Jet spin asymmetry $a_n^{jet}(T_R)$, there is uncontrolled systematics for $T_R < 1.9$ MeV. This data is not used in the fit.

- ***Measured normalized spin asymmetries a_N linearly depend on T_R***
- $\langle\beta_5\rangle = 0.0078 \pm 0.0006, \quad \chi^2/\text{ndf} = 3.94/3$
- ***Measured intensity asymmetries λ do not depend on T_R***

Forward elastic Re / Im ratio ρ *from the spin asymmetries*

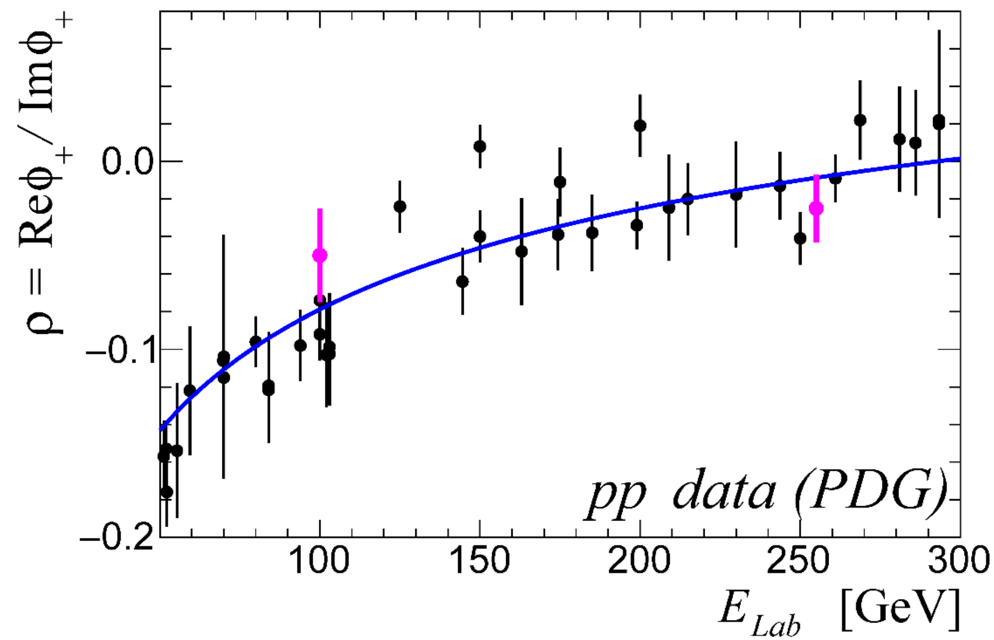




To test HJET data for possible "hidden" systematic uncertainties we fit HJET data with ρ being a free parameter.

$$A_N = A_N(t, r_5, \rho)$$

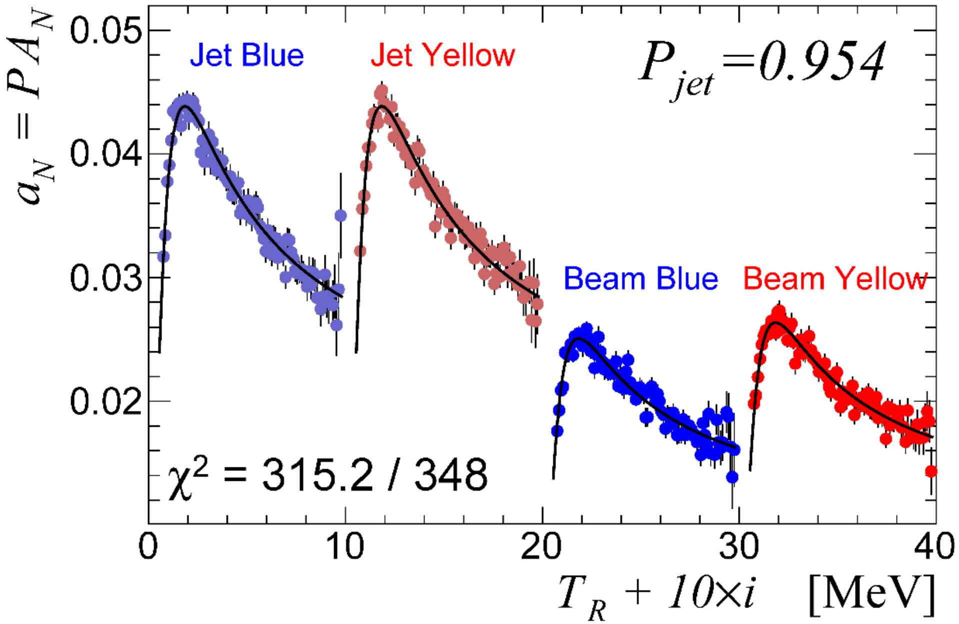
- **This unusual method of experimental determination of the Re/Im ratio ρ from the measured spin correlated asymmetries gave the results comparable and consistent with other entries to the PDG data.**
- **However, the global fit of the PDG data provides much better accuracy for $\rho(s)$.**

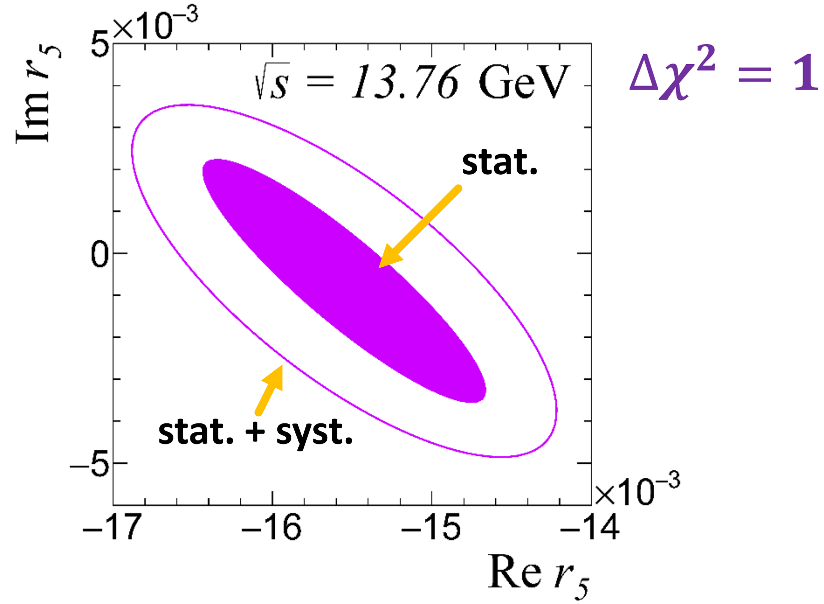


Single spin-flip $A_N(t)$ at 100 GeV $\left(\sqrt{s} = 13.76\ \mathrm{GeV}\right)$

Measured asymmetry $a_N = PA_N(t, r_5)$

$\rho = -0.079,\ \sigma_{tot} = 38.39\ \mathrm{mb},\ \mathrm{B} = 11.4\ \mathrm{GeV}^{-1}$
Beam polarizations are free parameters in the fit





$$\mathrm{Re}\, r_5 = \left(-15.5 \pm 0.9_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}} + 0.5_{\rho}\right) \times 10^{-3}$$
$$\mathrm{Im}\, r_5 = \left(-0.7 \pm 2.9_{\mathrm{stat}} \pm 3.5_{\mathrm{syst}} - 4.5_{\rho}\right) \times 10^{-3}$$

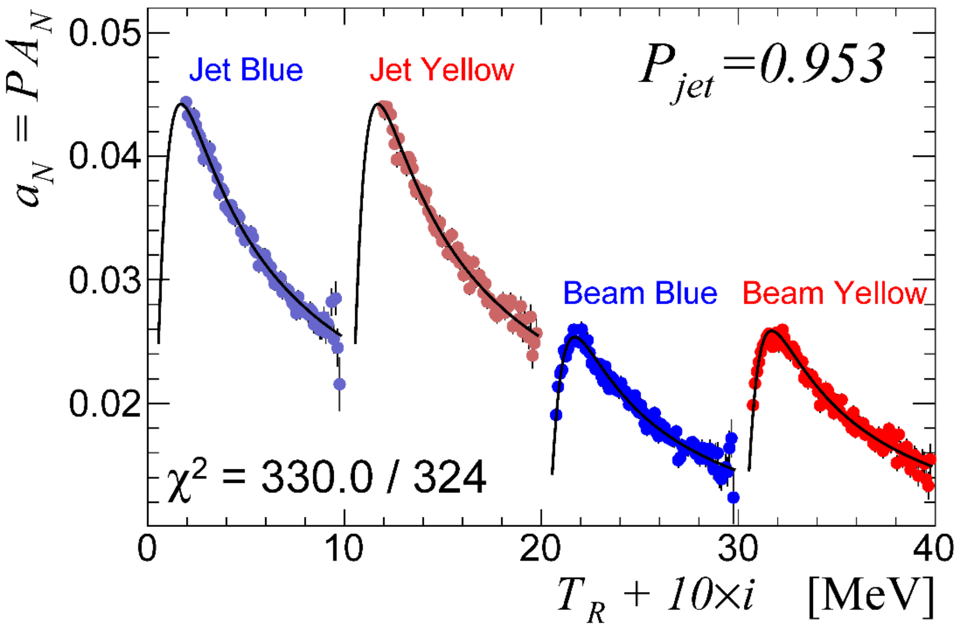
Hadronic single spin-flip amplitude is well isolated at $\sqrt{s} = 13.76$ GeV

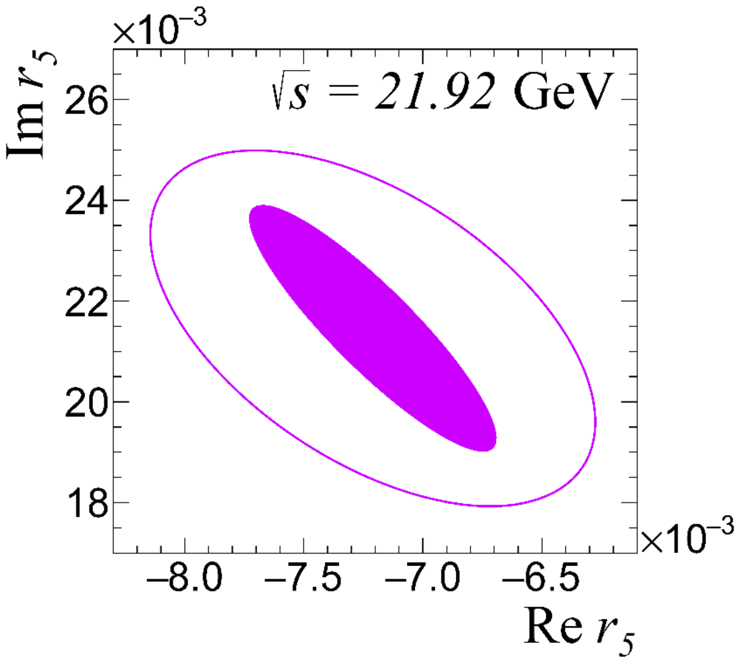
δ_ρ **is a correction if** $\rho = -0.079$ (pp and $p\bar{p}$) $\Rightarrow$ $\rho = -0.083$ (PDG)

Single spin-flip $A_N(t)$ at 255 GeV $\left(\sqrt{s} = 21.92\ \mathrm{GeV}\right)$

Measured asymmetry $a_N = PA_N(t, r_5)$

$\rho = -0.009$, $\sigma_{tot} = 39.19\ \mathrm{mb}$, $\mathrm{B} = 12\ \mathrm{GeV}^{-1}$
Beam polarizations are free parameters in the fit





$$\mathrm{Re}\,r_5 = \left(-7.3 \pm 0.5_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}} + 0.1_{\rho}\right) \times 10^{-3}$$
$$\mathrm{Im}\,r_5 = \left(21.5 \pm 2.5_{\mathrm{stat}} \pm 2.5_{\mathrm{syst}} - 3.3_{\rho}\right) \times 10^{-3}$$

Hadronic single spin-flip amplitude is well isolated at $\sqrt{s} = 21.92$ GeV

δ_ρ **is a correction if** $\rho = -0.009$ (pp and $p\bar{p}$) $\Rightarrow$ $\rho = -0.012$ (PDG)

Double Spin-Flip Analyzing Power $A_{NN}(t)$

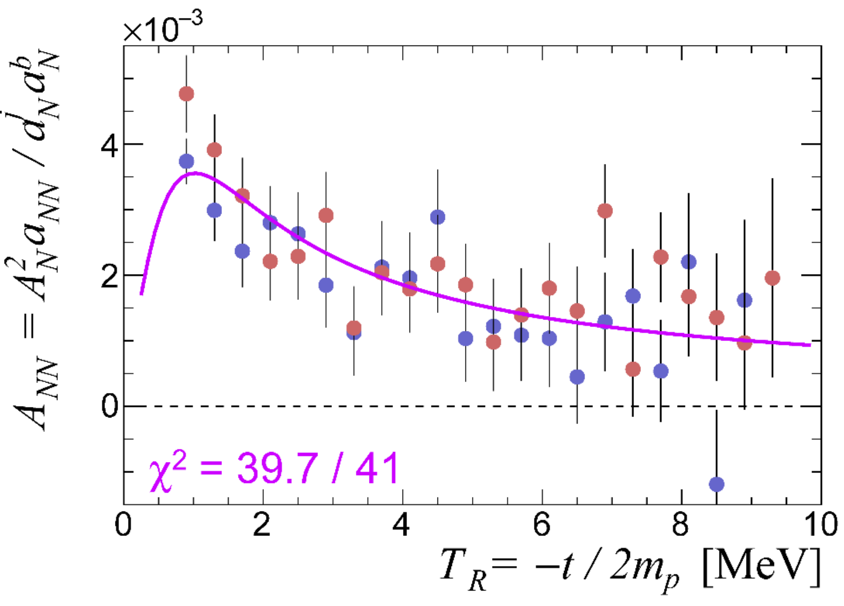
$$A_{NN}(t) = \frac{-2(\mathrm{Re}\, r_2 + \delta_C \mathrm{Im}\, r_2)\frac{t_c}{t} + 2\mathrm{Im}\, r_2 + 2\rho \mathrm{Re}\, r_2 - \rho \frac{t_c \kappa^2}{2m_p^2} + \frac{2t_c\kappa}{m_p^2}\mathrm{Re}\, r_5}{\left(\frac{t_c}{t}\right)^2 - 2(\rho + \delta_C)\frac{t_c}{t} + 1 + \rho^2}$$

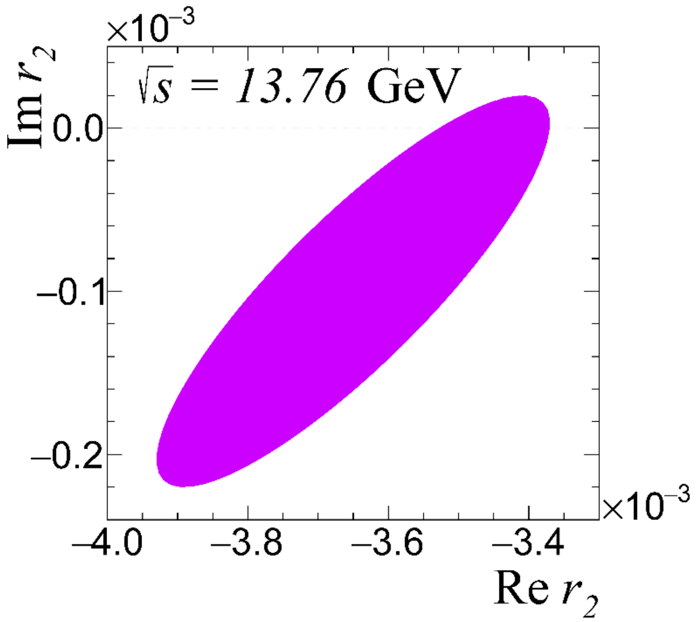
Hadronic double spin flip amplitude: $r_2 = \frac{\phi_2^{had}}{2\,\mathrm{Im}\,\phi_+^{had}}$

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

- Jet spin correlated systematic uncertainties are canceled in the measured asymmetries $a_{NN}(t)/a_N^{jet}(t)$ ratio.
- r_5 as well as $A_N(t, r_5)$ are well known from the single spin-flip asymmetry study.
- **Uncertainties in the $A_{NN}(t)$ measurement are strongly dominated by statistical errors.**

Double spin-flip $A_{NN}(t)$ at 100 GeV $\left(\sqrt{s} = 13.76\ \text{GeV}\right)$

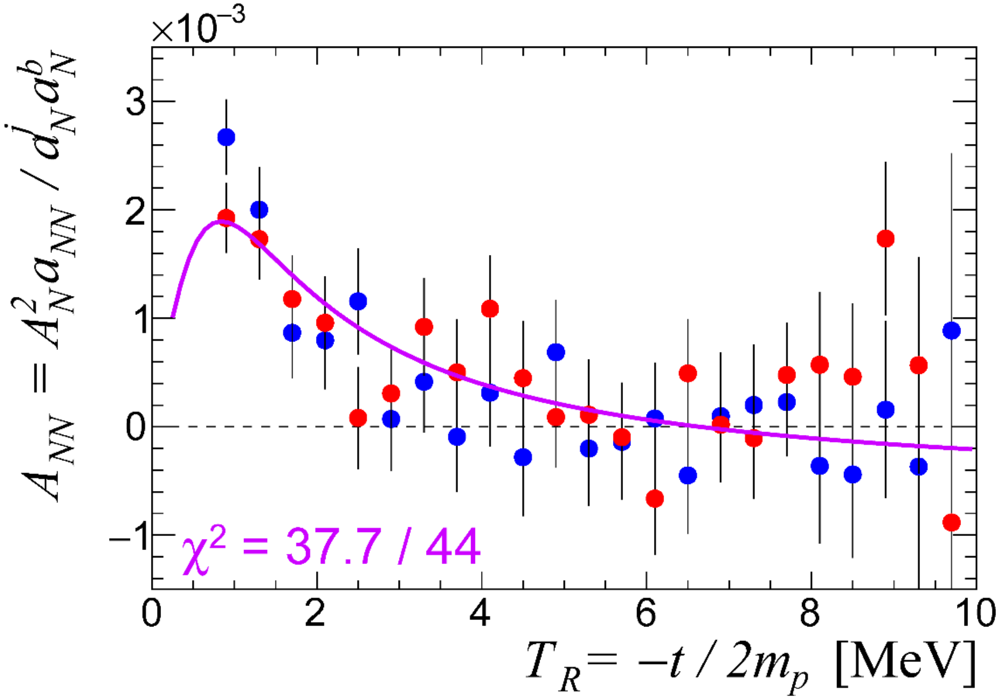


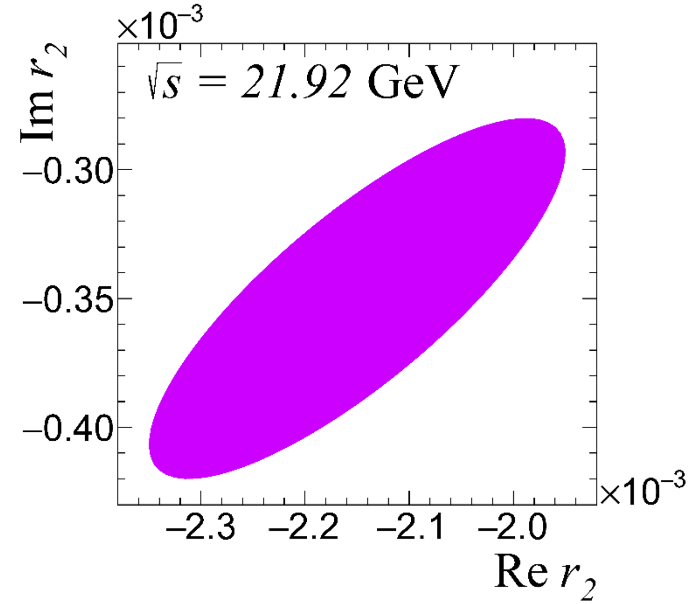


$$\mathbf{Re}\ r_2 = (-3.65 \pm 0.28_{\text{stat}}) \times 10^{-3}$$
$$\mathbf{Im}\ r_2 = (-0.10 \pm 0.12_{\text{stat}}) \times 10^{-3}$$

Hadronic double spin-flip amplitude is well isolated at $\sqrt{s} = 13.76$ GeV

Double spin-flip $A_{NN}(t)$ at 255 GeV $\left(\sqrt{s} = 21.92\ \text{GeV}\right)$

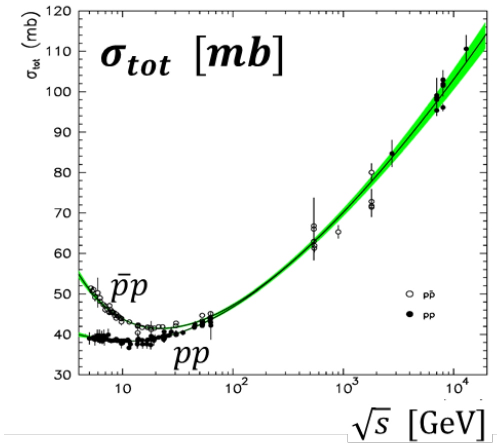


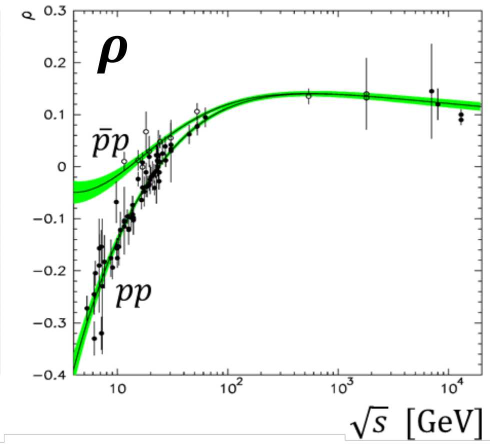


$$\mathrm{Re}\, r_2 = (-2.15 \pm 0.20_{\mathrm{stat}}) \times 10^{-3}$$
$$\mathrm{Im}\, r_2 = (-0.35 \pm 0.07_{\mathrm{stat}}) \times 10^{-3}$$

Hadronic double spin-flip amplitude is well isolated at $\sqrt{s} = 21.92$ GeV

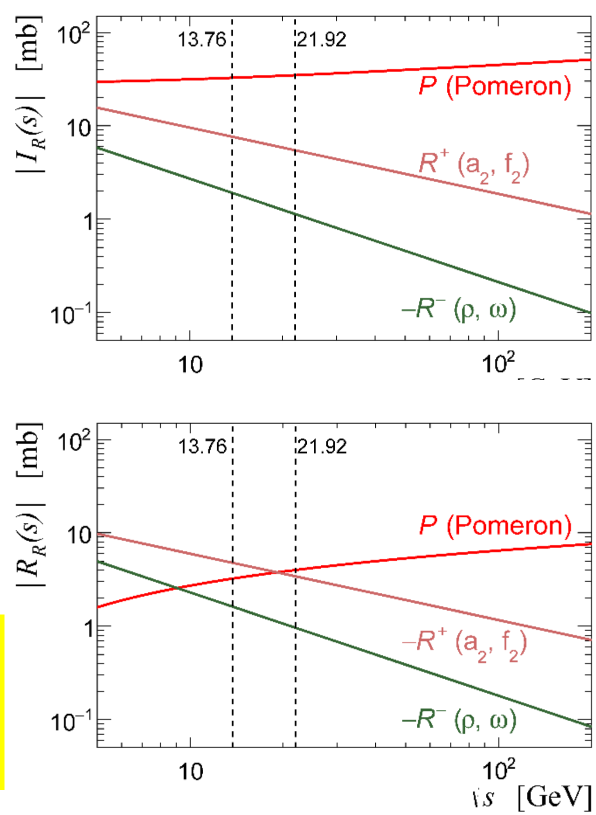
Energy dependence of elastic pp scattering





For unpolarized protons, elastic pp ($\bar{p}p$) scattering can be described accurately with five Regge poles, Pomeron $\boldsymbol{P}$ and the dominant $C = \pm 1$ poles for $I = 0{,}1$ $\boldsymbol{R^+}$ $(\boldsymbol{f_2, a_2})$ and $\boldsymbol{R^-}$ $(\boldsymbol{\omega, \rho})$.

$R^{\pm}$ P



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unpolarized amplitude $\propto$ $(\boldsymbol{\rho} + \boldsymbol{i})$

$$\boldsymbol{\sigma_{tot}(s) = I_P(s) + I_{R+}(s) + I_{R-}(s)}$$
$$\boldsymbol{\sigma_{tot}(s)\rho(s) = R_P(s) + R_{R+}(s) + R_{R-}(s)}$$

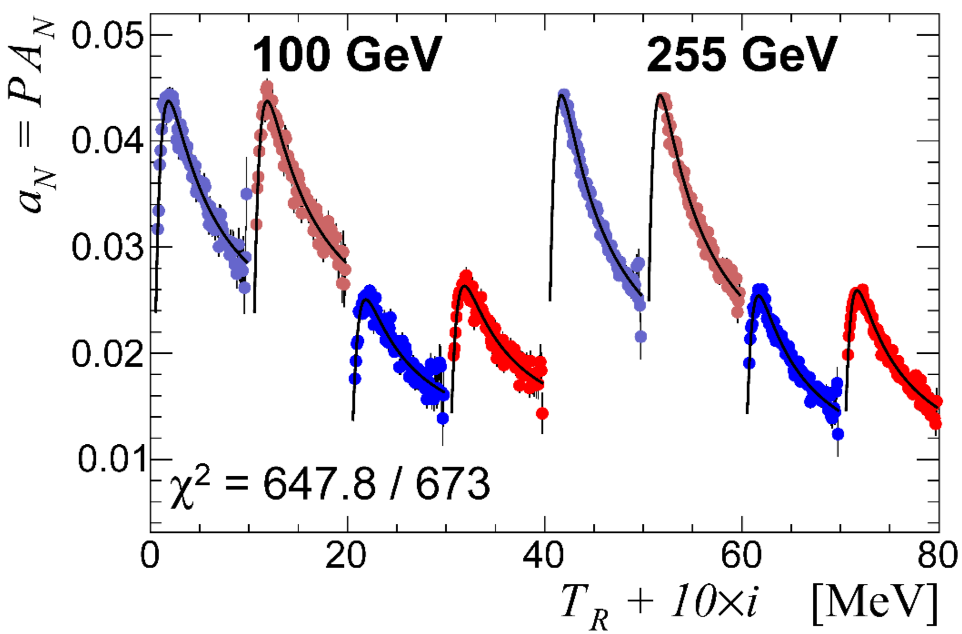
Single spin-flip amplitude
$\propto$ $(\mathrm{Re}\, r_5 + \boldsymbol{i}\, \mathrm{Im}\, r_5)$

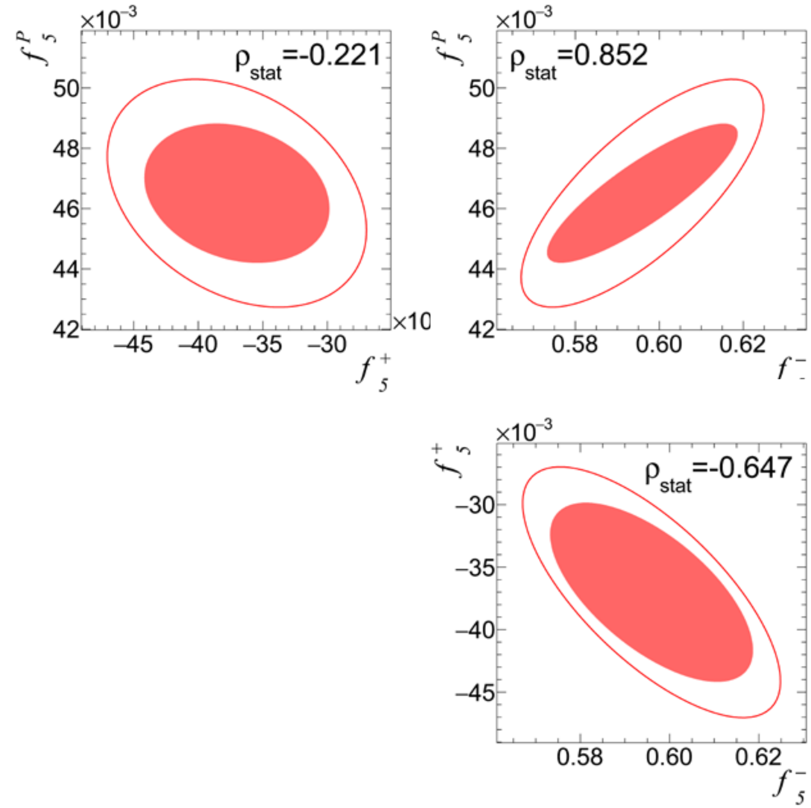
$$\boldsymbol{\sigma_{tot}(s)\, \mathrm{Im}\, r_5 = f_5^P\, I_P(s) + f_5^+\, I_{R^+}(s) + f_5^-\, I_{R^-}(s)}$$
$$\boldsymbol{\sigma_{tot}(s)\, \mathrm{Re}\, r_5 = f_5^P\, R_P(s) + f_5^+\, R_{R^+}(s) + f_5^-\, R_{R^-}(s)}$$

Spin-flip factors f_5^P, $f_5^{\pm}$ can be determined from the HJET data.

Single spin-flip factors in the $R^{\pm}P$ approximation

Measured asymmetry $a_N = PA_N(t, s, f_5^{\pm}, f_5^P)$





$$f_5^+ = -0.037 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}} - 0.007_{\rho}$$
$$f_5^- = 0.596 \pm 0.023_{\text{stat}} \pm 0.019_{\text{syst}} + 0.006_{\rho}$$
$$f_5^P = 0.0465 \pm 0.0023_{\text{stat}} \pm 0.0034_{\text{syst}} - 0.0028_{\rho}$$

Pomeron spin-flip amplitude is well isolated!

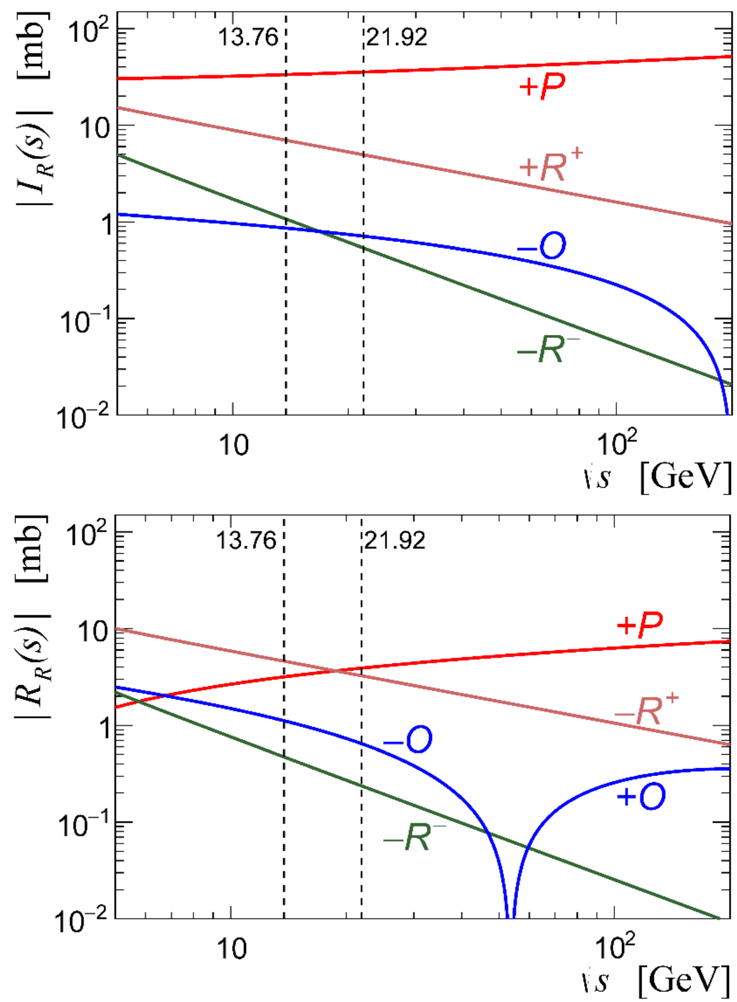
Search for Odderon

Recent measurement of surprisingly low $\rho^{pp} = 0.10 \pm 0.01$ at $\sqrt{s} = 13$ TeV (TOTEM) may indicate a presence of Odderon (C-odd gluon exchange) amplitude in elastic pp scattering.

The HJET data was used to search for spin-flip Odderon amplitude in a Froissaron-Maximal Odderon model. However, due to very strong correlation between $\boldsymbol{O}$ and $\boldsymbol{R^-}$ contributions, the uncertainties are large.

$$f_5^+ = 0.12 \pm 0.06_{\text{stat}}$$
$$f_5^- = 2.24 \pm 0.73_{\text{stat}}$$
$$f_5^P = 0.024 \pm 0.009_{\text{stat}}$$
$$f_5^O = -0.84 \pm 0.61_{\text{stat}}$$

$R^{\pm}$ P O

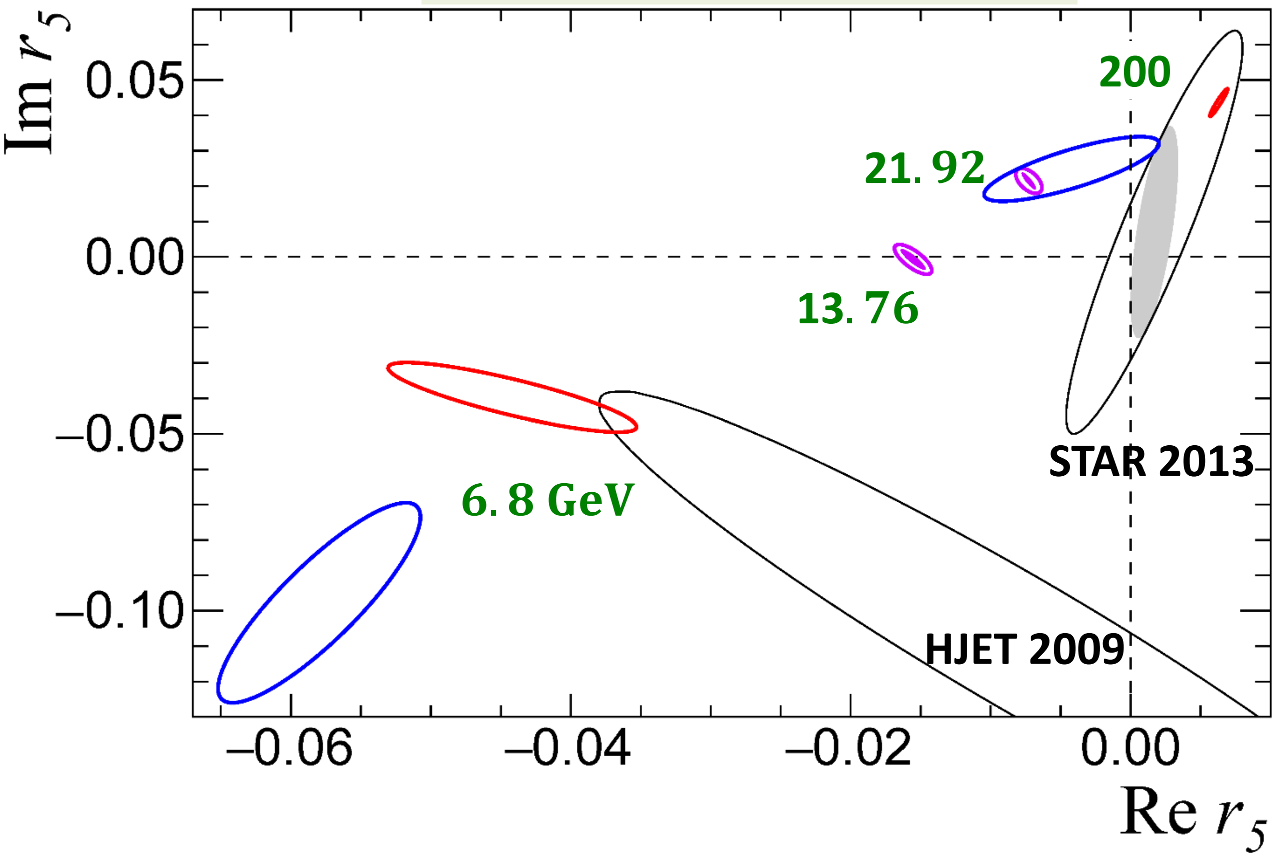


E. Martynov, B. Nicolescu Phys. Lett. **B 778** (2018) 414.

Hadronic Single Spin-Flip Amplitude $r_5(\sqrt{s})$

Color Legend:

This work (13.76 and 21.92 GeV)
R±P extrapolation to 6.8 and 200 GeV
R±PO extrapolation to 6.8 and 200 GeV
Other measurements (6.8 and 200 GeV)



Combined Fit

$R^{\pm}\ P$

$f_5^+ = -0.037 \pm 0.010$
$f_5^- = \quad 0.588 \pm 0.028$
$f_5^P = \quad 0.046 \pm 0.004$
$f_5^O = \quad 0$ (fixed)
$\chi^2 = 2.2/5$

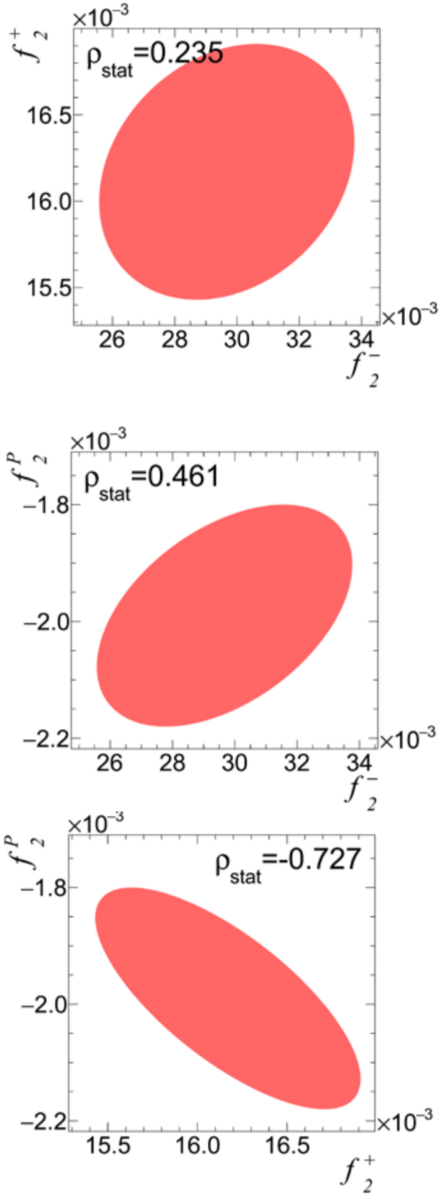
$R^{\pm}\ P\ O$

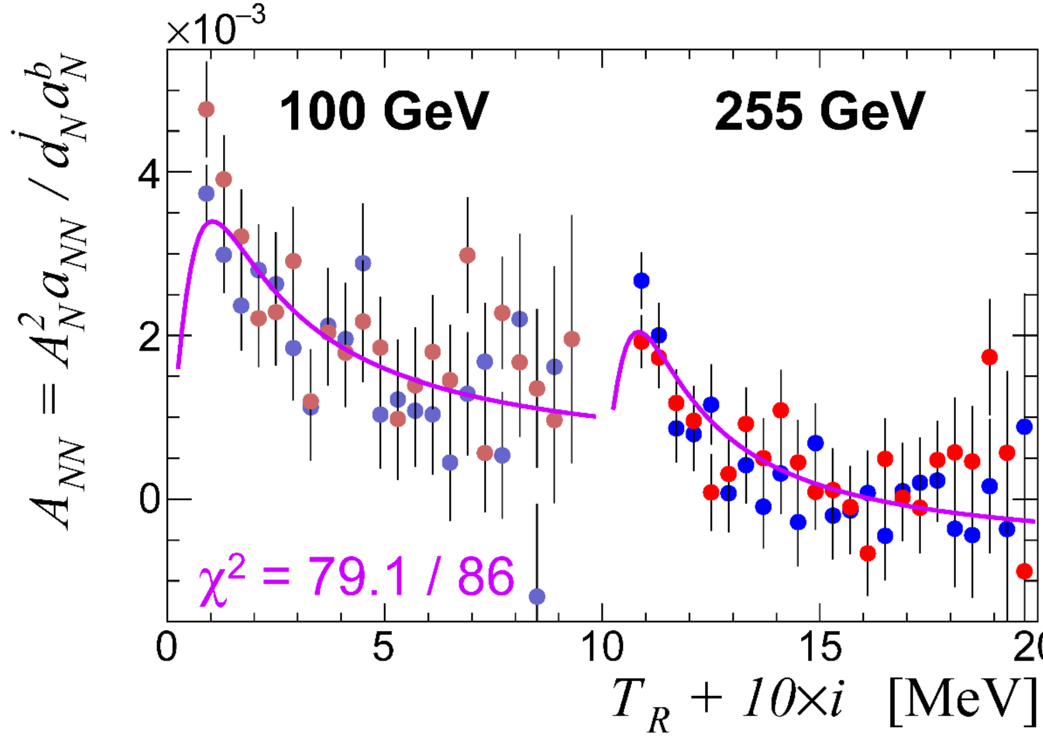
$f_5^+ = \quad 0.057 \pm 0.034$
$f_5^- = \quad 1.141 \pm 0.239$
$f_5^P = \quad 0.032 \pm 0.009$
$f_5^O = -0.107 \pm 0.252$
$\chi^2 = 7.7/4$

STAR 2013: ($\sqrt{s} = \mathbf{200\ GeV}$), L. Adamczyk et al, Phys. Lett. B **719** (2013) 62.
HJET 2009: ($\sqrt{s} = \mathbf{6.8\ GeV}$), I.G. Alekseev et. al., Phys. Rev. D **79**, 094014 (2009)

Double Spin-Flip Factors

$\Delta\chi^2 = 1$ correlation plots for R± P extrapolation



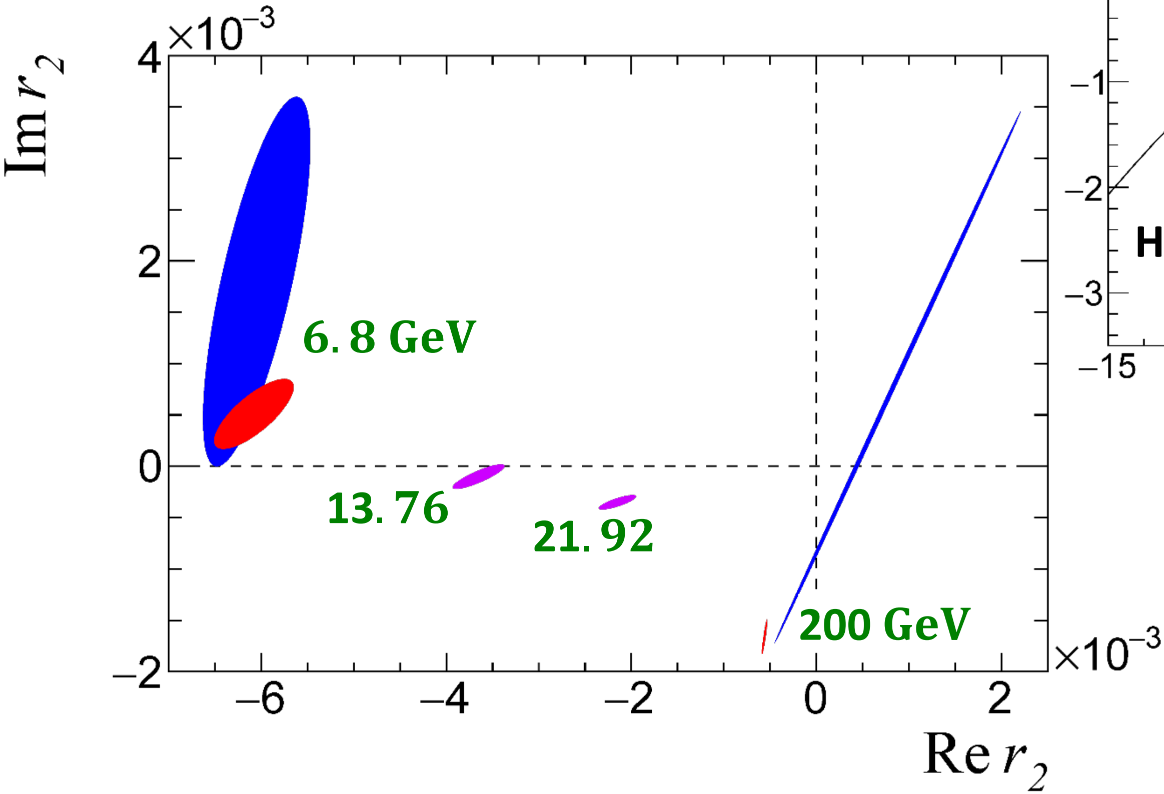


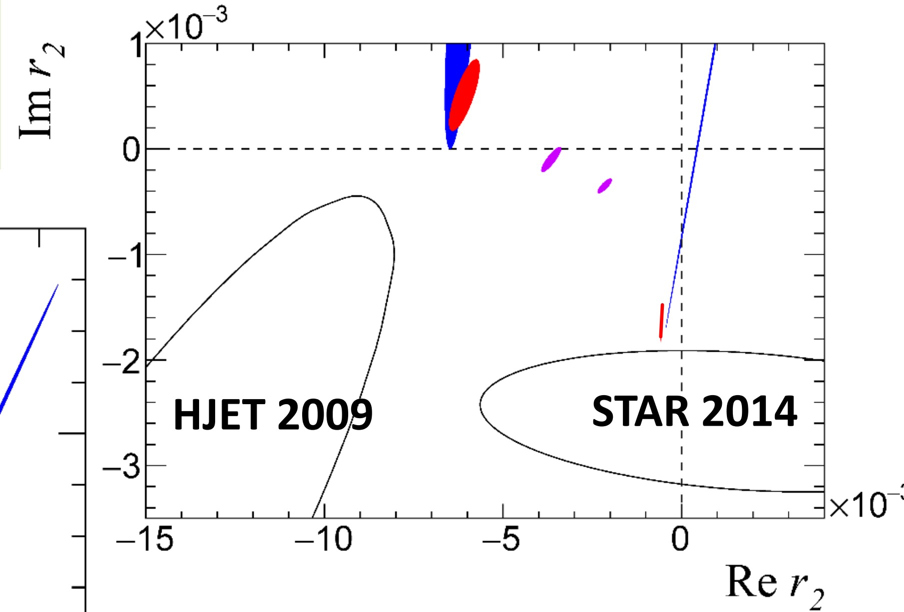
	R± P	R± P O
$10^3\ f_2^+$	16.2 ± 0.7	5 ± 13
$10^3\ f_2^-$	29.7 ± 4.1	-38 ± 82
$10^3\ f_2^P$	-1.99 ± 0.19	0.8 ± 2.7
$10^3\ f_2^O$	$-$	122 ± 102

Double Spin-Flip Hadronic Amplitude $r_2(\sqrt{s})$

Color Legend:

This work (13.76 and 21.92 GeV)
R±P extrapolation to 6.8 and 200 GeV
R±PO extrapolation to 6.8 and 200 GeV
Other measurements (6.8 and 200 GeV)

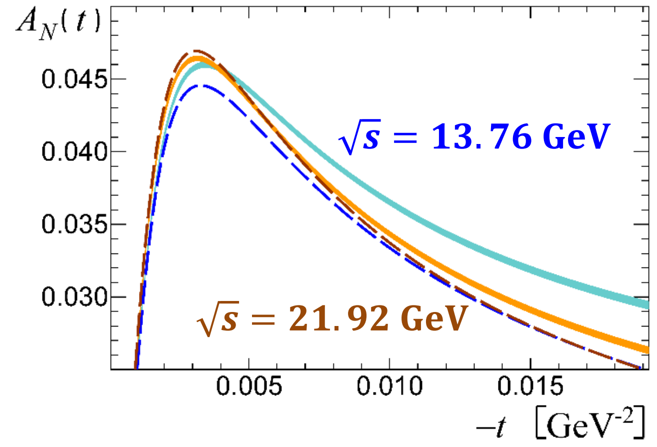




STAR 2014: $(\sqrt{s} = 200\ \mathrm{GeV})$,
D. Svirida, SPIN 2014 Proceedings.
HJET 2009: $(\sqrt{s} = 6.8\ \mathrm{GeV})$,
I.G. Alekseev et. al., Phys. Rev. D **79**, 094014 (2009)

In HJET 2009, A_{NN} was given with wrong sign. The displayed above result was calculated by us.

Summary: Analyzing Power



- **Elastic $p^{\uparrow}p$ single spin-flip analyzing power $A_N(t)$:**
  - $A_N(t)$ was measured with a high precision
    $$\sigma_{A_N}/A_N \lesssim 1\%$$
    in CNI region at two beam energies 100 and 255 GeV.
  - Hadronic single spin-flip amplitudes were well isolated:

100 GeV: $\mathrm{Re}\, r_5 = (-15.5 \pm 0.9_{stat} \pm 1.0_{syst} + 0.5_{\rho}) \times 10^{-3}$
$\mathrm{Im}\, r_5 = (\;-0.7 \pm 2.9_{stat} \pm 3.5_{syst} - 4.5_{\rho}) \times 10^{-3}$

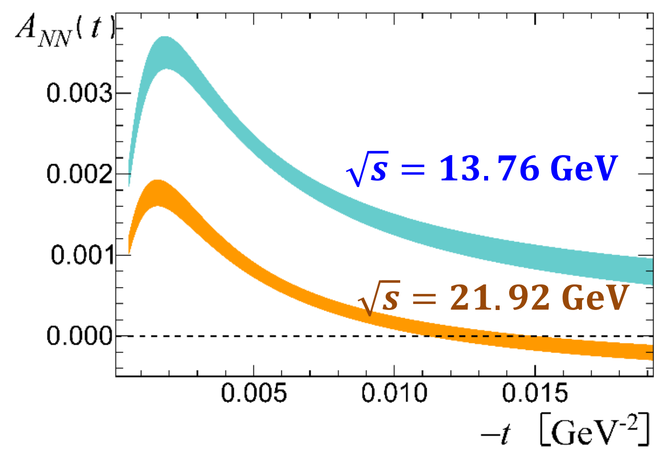
255 GeV: $\mathrm{Re}\, r_5 = (\;-7.3 \pm 0.5_{stat} \pm 0.8_{syst} + 0.1_{\rho}) \times 10^{-3}$
$\mathrm{Im}\, r_5 = (\;21.5 \pm 2.5_{stat} \pm 2.5_{syst} - 3.3_{\rho}) \times 10^{-3}$

Dashed lines: $A_N^{(0)}(t)$
Filled areas: $\pm\sigma$ (stat.+syst.) for measured $A_N(t)$ and $A_{NN}(t)$

- **Elastic $p^{\uparrow}p^{\uparrow}$ double spin-flip analyzing power $A_{NN}(t)$:**
  - $A_{NN}(t)$ was measured with a high precision
    $$\delta A_{NN} \lesssim 0.0002$$
    in CNI region at two beam energies 100 and 255 GeV.
  - Hadronic double spin-flip amplitudes were well isolated:

100 GeV: $\mathrm{Re}\, r_2 = (-3.65 \pm 0.28_{stat}) \times 10^{-3}$
$\mathrm{Im}\, r_2 = (-0.10 \pm 0.12_{stat}) \times 10^{-3}$

255 GeV: $\mathrm{Re}\, r_2 = (-2.15 \pm 0.20_{stat}) \times 10^{-3}$
$\mathrm{Im}\, r_2 = (-0.35 \pm 0.07_{stat}) \times 10^{-3}$



Summary: Regge poles spin-flip couplings

- $R^+(f_2, a_2)$, $R^-(\omega, \rho)$, Pomeron approximation (R±P).
  - Single and double spin-flip factors were measured with notable accuracy

$$f_5^+ = -0.037 \pm 0.007_{stat} \pm 0.007_{syst} - 0.007_\rho \qquad f_2^+ = 0.0162 \pm 0.0007$$
$$f_5^- = 0.596 \pm 0.023_{stat} \pm 0.019_{syst} + 0.006_\rho \qquad f_2^- = 0.0297 \pm 0.0041$$
$$f_5^P = 0.0465 \pm 0.0023_{stat} \pm 0.0034_{syst} - 0.0028_\rho \qquad f_2^P = -0.0020 \pm 0.0002$$

  - Extrapolation of r_5 to $\sqrt{s} = 6.8$ and 200 GeV remarkably consistent with available experimental data.
- $R^+(f_2, a_2)$, $R^-(\omega, \rho)$, Pomeron, Odderon approximation (R±PO).
  - Due to the strong correlation between R^- and O contributions at HJET energies, the spin-flip couplings can be evaluated only with large uncertainties.
  - Using other experimental data the single spin-flip couplings can be evaluated as

$$f_5^+ = 0.057 \pm 0.034$$
$$f_5^- = 1.141 \pm 0.239$$
$$f_5^P = 0.032 \pm 0.009$$
$$f_5^O = -0.107 \pm 0.252$$

- Precision measurements of r_5 and/or r_2 may crucially improve confidence in the evaluation of the Odderon term.
- Technically, it is possible to study $p^\uparrow p^\uparrow$ ($E_{Lab} = 24$ GeV), and $p^\uparrow$C ($E_{Lab} = 24, 100$ GeV) at HJET.
- During 2015-18 we accumulated the following proton nucleus data:
  - $p^\uparrow d$, $p^\uparrow$Al, $p^\uparrow$Zr, $p^\uparrow$Ru, and $p^\uparrow$Au ($E_{Lab} = 100$ GeV).
  - $p^\uparrow$Au, ($E_{Lab} = 3.9, 10, 13.6, 19.5, 27, 31, 100$ GeV).
  - $p^\uparrow d$, ($E_{Lab} = 10, 19.5, 31, 100$ GeV).

Important Comment

Boris Kopeliovich:

20 years ago we had no data and didn't expect precise data so soon. Therefore we have done some rough simplifying approximations, which now must be replaced by accurate expressions. Such a change significantly alters results of the fits for r5 and r2.

Boris Kopeliovich and Michal Krelina are working on the corrections which include:

- Absorptive corrections (reported yesterday by M. Krelina)
- Differences in the electromagnetic and hadronic form-factors.

My interpretation of the comment:

We can continue to use formulas for $A_N(t)$ and $A_{NN}(t)$ for data analysis but it should be understood that

$$\boldsymbol{r_{5,2}^{meas} = r_{5,2} + R_{5,2} + iI_{5,2}}$$

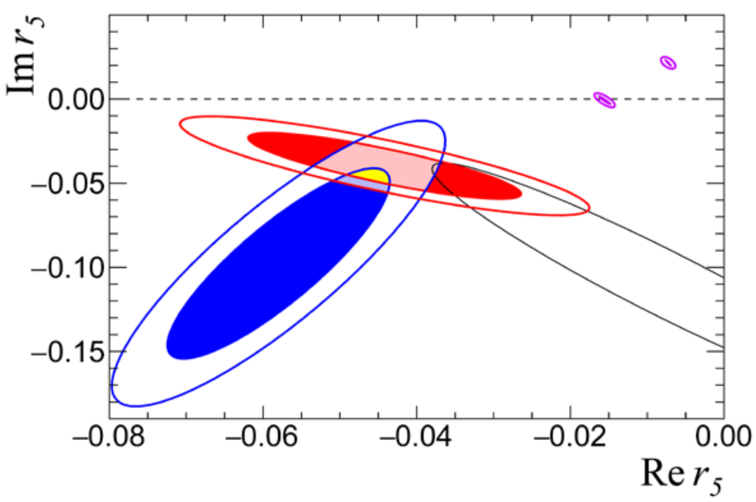
and the correction R+iI may be as large as r_5.

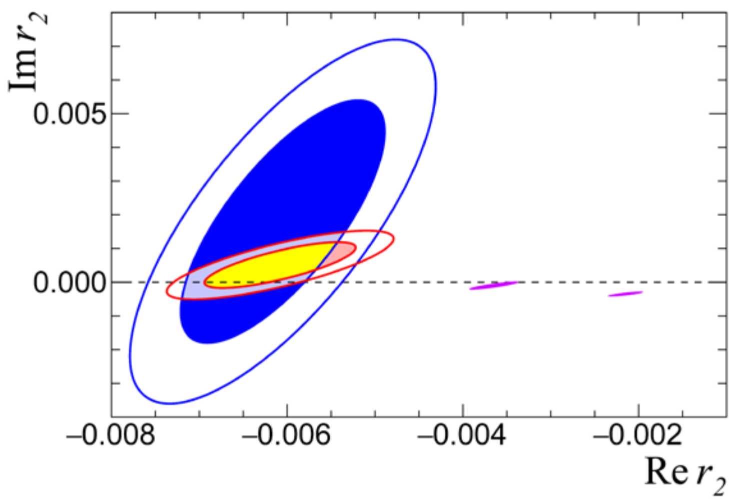
- The corrections do not affect the single and double spin analyzing power measurements. Actually this was tested and verified in our data analysis within the accuracy of the measurements.
- The evaluation of Reggeon and Pomeron spin-flip factors have to be interpreted with caution. This part of the work should be considered as a test of how the method will work after corrections $R + iI$ will have been well determined.

Backup

Could measurement at $\sqrt{s} = 6.8$ GeV distinguish between R±P and R±PO models

For both, **R±P** and **R±PO**, extrapolations of HJET results to $\sqrt{s} = 6.8$ GeV error correlation ellipses corresponding to $\boldsymbol{\Delta\chi^2 = 4\ (86.4\%)}$ and $\boldsymbol{\Delta\chi^2 = 9\ (98.9\%)}$ are displayed.





Precise measurements of r_5 and/or r_2 at $\sqrt{s} = 6.8$ GeV can potentially distinguish between **R±P** and **R±PO** models:

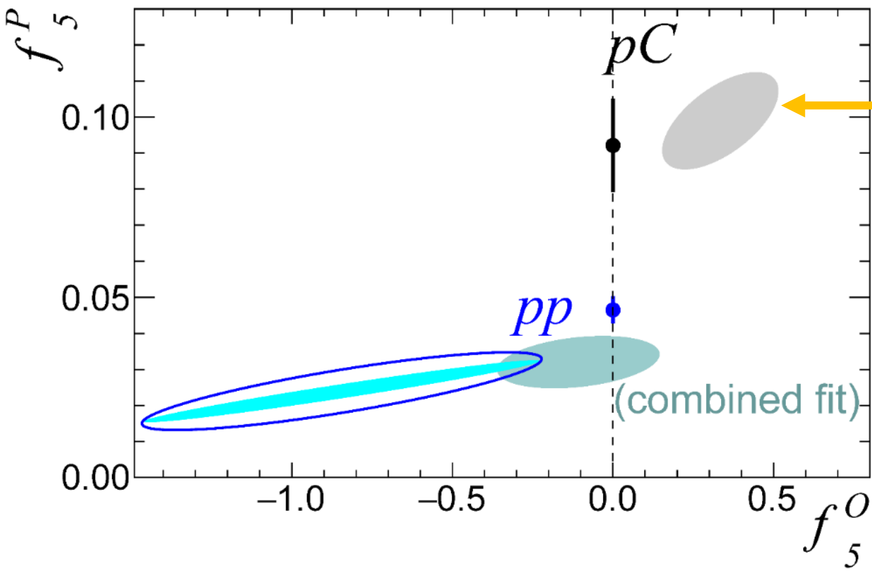
Comparison with p-Carbon data

p-Carbon analyzing power measurements:

- **BNL E950** ($E_{lab} = 21.5$ GeV), Tojo *et al.*, Phys. Rev. Lett. **89**, 052302 (2002)
- **RHIC pCarbon** ($E_{lab} = 100$ GeV), O. Jinnouchi *et al.*, SPIN 2004 Proceedings, p. 515.

were analyzed by T. L. Trueman, Phys. Rev. D **77**, 054005 (2008).

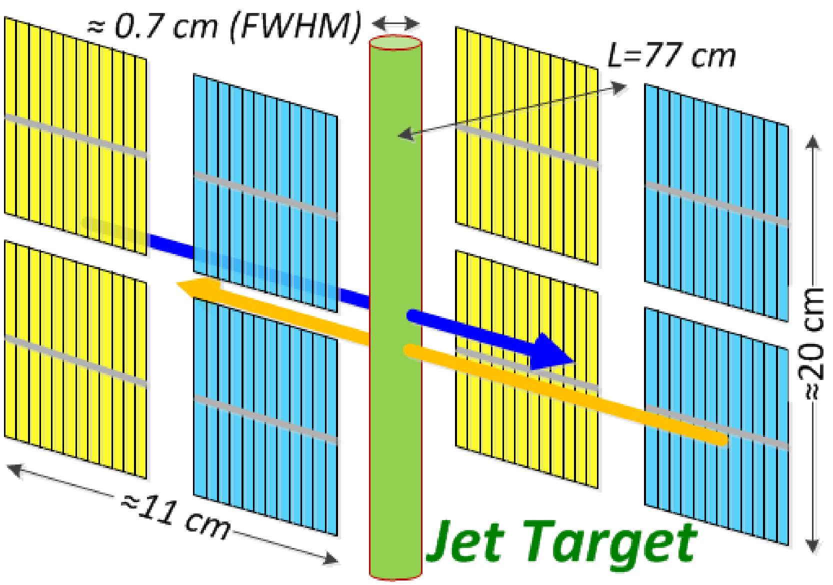
The values of r_5 were extracted from the data and Pomeron Spin coupling was evaluated:



Evaluation of the Odderon coupling from the p-Carbon measurements was done by us using the data from Trueman's paper.

- p-Carbon results are not well consistent with our measurements. However, RHIC pCarbon measurements were not published and systematic errors were not included to the analysis.
- r_5 values for 21 and 100 GeV provides much better evaluation of Odderon coupling that measurements at 100 and 255 GeV.

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:

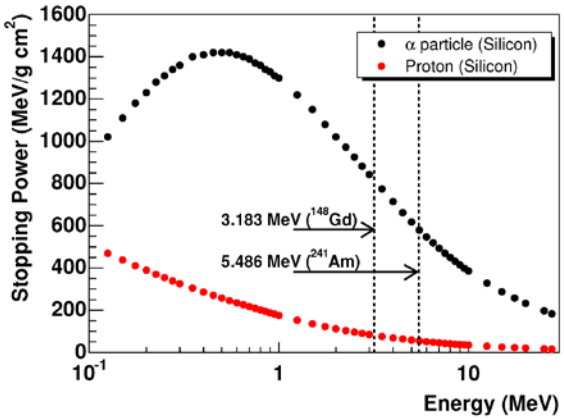
$$\tan\theta_R = \frac{z_{det} - z_{jet}}{L} = \frac{\kappa\sqrt{T_R}}{L} \qquad \kappa = \sqrt{\frac{T_R}{2m_p}\frac{E_{beam} + m_p^2/M_{beam}}{E_{beam} - m_p + \cancel{T_R}}} \approx 18\frac{\text{mm}}{\text{MeV}^{1/2}}$$

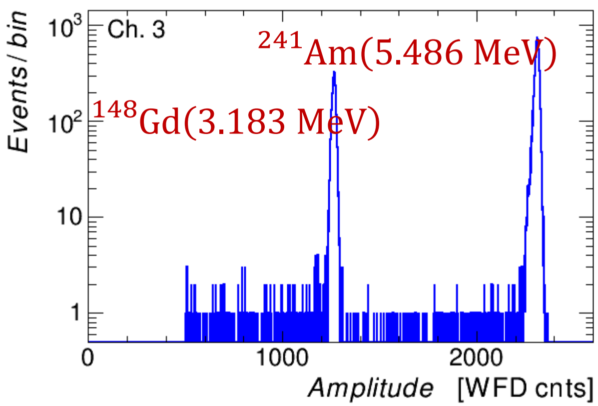
In a Si strip

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

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

Energy calibration using alpha-sources





$$E_{kin} = gA + E_{loss}(gA, x_{DL})$$

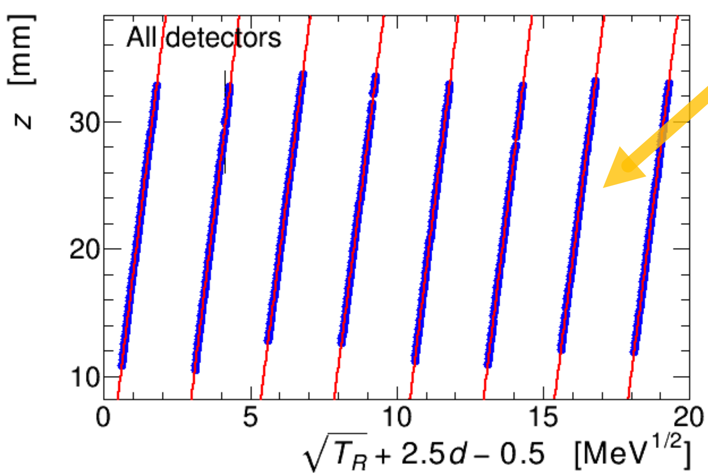
$g \sim 2.5\ keV/cnt$

$x_{DL} \sim 0.37\ mg/cm^2$

$\sigma_E \sim 20\ keV$

- **Energy losses in dead-layer has to be accounted**
- **Two alpha-sources allows us to determine both gain g and dead-layer thickness x_{DL}.**

<u>Verification of the calibration using recoil protons from elastic scattering:</u>



$$\langle z_{det} - z_{jet} \rangle = \kappa\sqrt{T_R}, \qquad \kappa = 18\ \mathrm{mm}/MeV^{1/2}$$

A discrepancy is being observed:

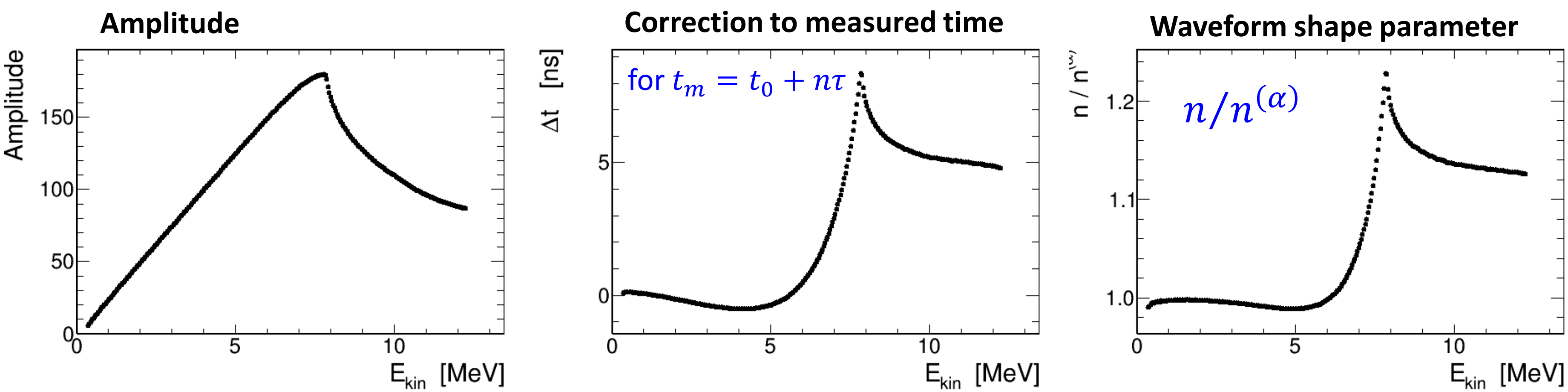
$$\delta\sqrt{T_R} \approx 0.035 + 0.009\sqrt{T_R}$$

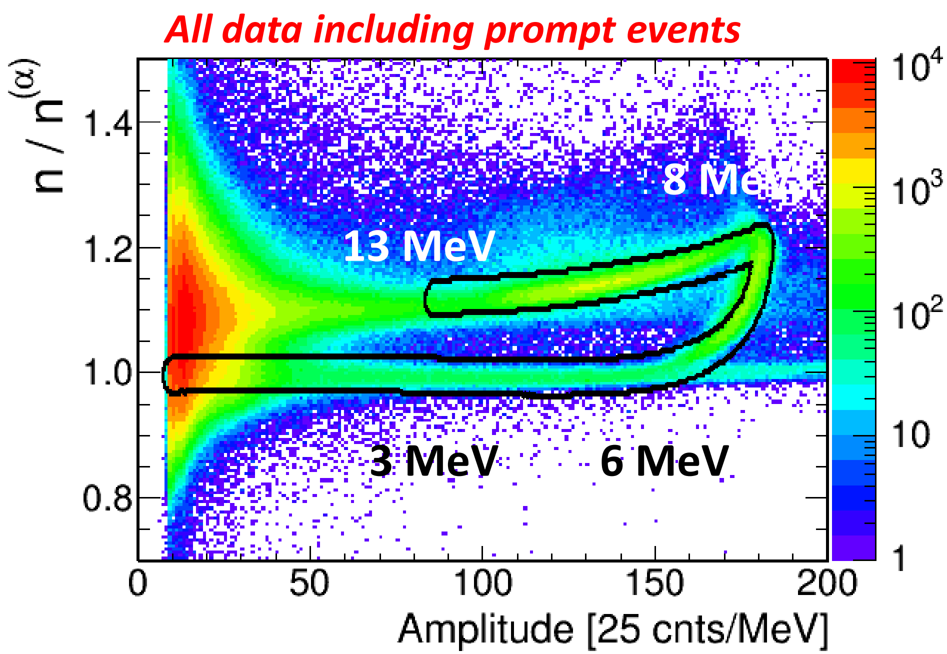
$\Rightarrow$ $\langle \Delta T/T \rangle \approx 3\%$ **and** $\langle \Delta T \rangle = 180\ \mathrm{keV}$

After corrections: $\langle \sigma_T^{syst}/T \rangle \approx 0.9\%$ **and** $\langle \sigma_T^{syst} \rangle \approx 20\ \mathrm{keV}$

Since the source of discrepancy (calibration?, geometry?, magnetic field corrections?, …?) is not proved yet, the corrections are not validated. The study is being continued.

Separation of the stopped and punched through protons





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

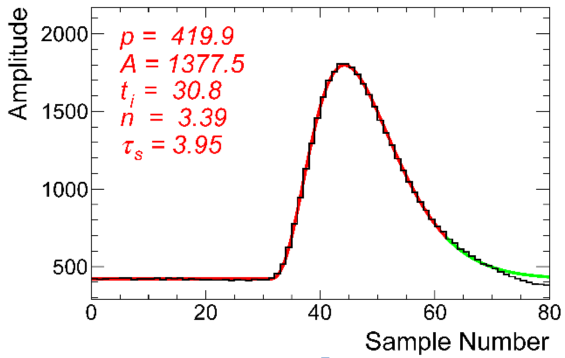
$$\left(\boldsymbol{A}, \boldsymbol{n}/\boldsymbol{n}^{(\alpha)}\right) \rightarrow \boldsymbol{T_R}$$

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

DAQ

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

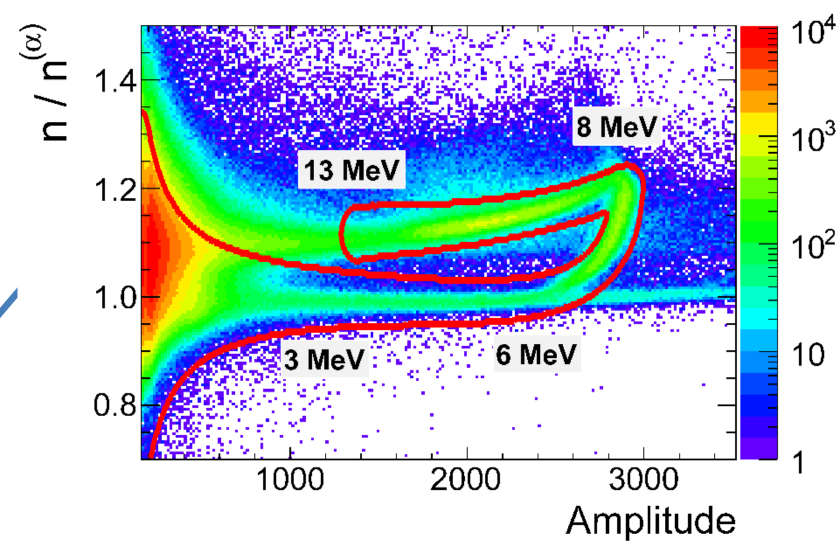
Full waveform (80 samples) was recorded for every signal above threshold (~0.5 MeV).



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

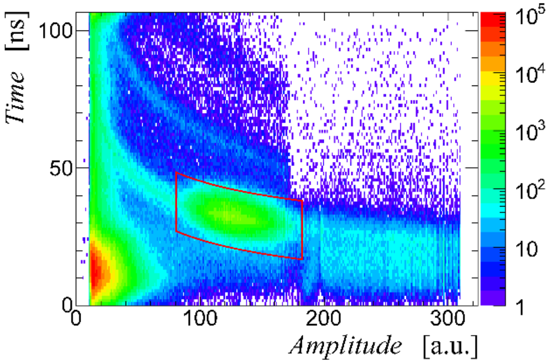
- *measured waveform*
- *fit function W(t)*
- *continuation of the fit function*

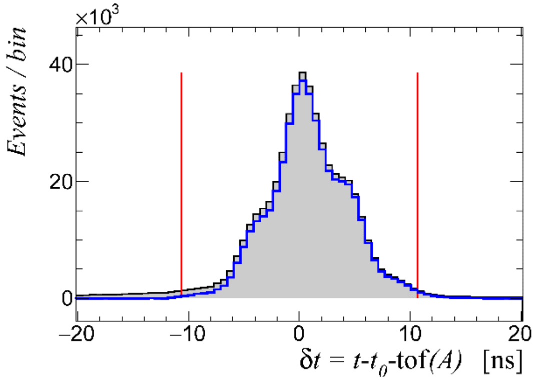
- For every event , recoil proton kinetic energy $T_R(A)$, time t_m , and waveform shape parameters n and τ_s are determined.
- The fit of waveform shape is important
  - ✓ for better amplitude measurement
  - ✓ to separate stopped and punch through recoil protons and, thus, to reconstruct kinetic energy of the punch through proton.
- For polarization measurement, elastic *pp* events have to be isolated.

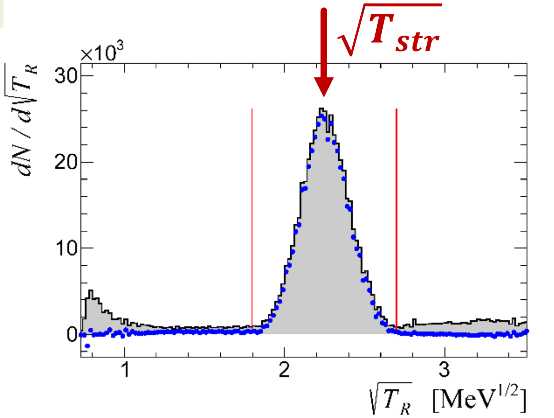


Event Selection Cuts.

1. **Recoil proton kinetic energy** T_R.
   The measured kinetic energy range (0.7 ÷ 10 MeV) is limited by the detector geometry and the trigger threshold)
2. **"Recoil mass cut":** $\delta t = t_m - t_p(A)$
   $t_p(A)$ is the expected proton signal time for the measured amplitude A. It depends on gain, dead-layer and time offset which are found in calibrations.
   The δt distribution is defined by the beam bunch longitudinal profile.
3. **"Missing mass cut"** $M_X^2 = m_p^2 + 2(E_{beam} + m_p)\sqrt{T_R}\,\delta\sqrt{T_R}$
   $$\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{strip}}$$
   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.







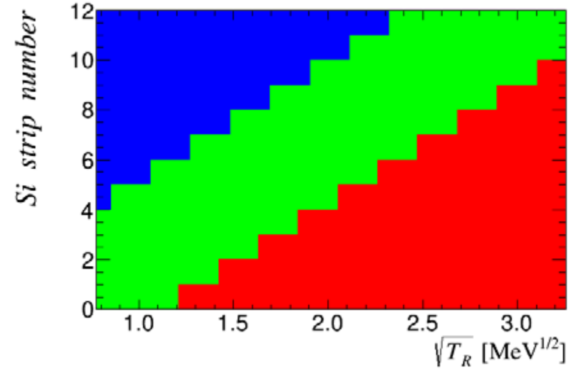
For elastic scattering, the $\left(\frac{d\sigma}{dt}\sqrt{T_R}\right)^{-1}\frac{d^2N}{d\delta t\, d\delta\sqrt{T_R}}$ distribution is the same for all Si strips.

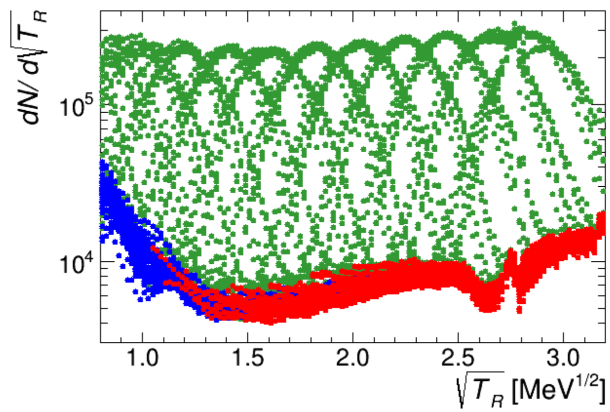
Background subtraction

In HJET, the dominant backgrounds are:

- The beam scattering on Oxygen in Jet and beam line gas
- Molecular hydrogen which has a flat z-coordinate distribution

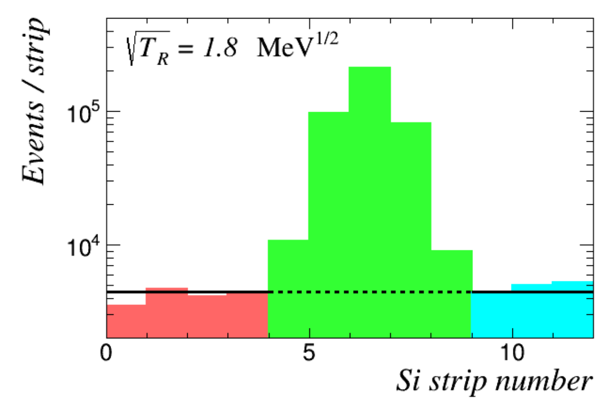
The background $dN/d\sqrt{T_R}$ distribution is the same for all Si strips.





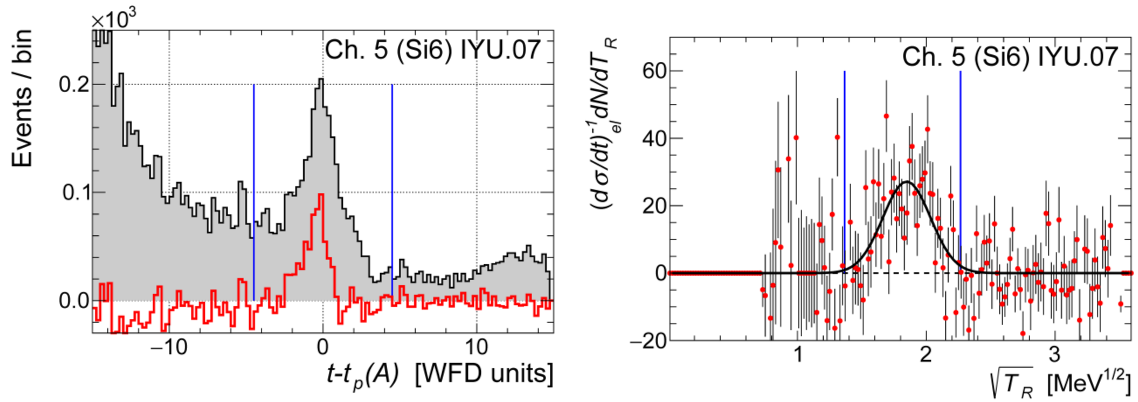
In the data analysis, the background is determined/subtracted independently for

- every detector
- every $\sqrt{T_R}$ bin
- every combination of beam/jet spins (to properly account background analyzing power if any)

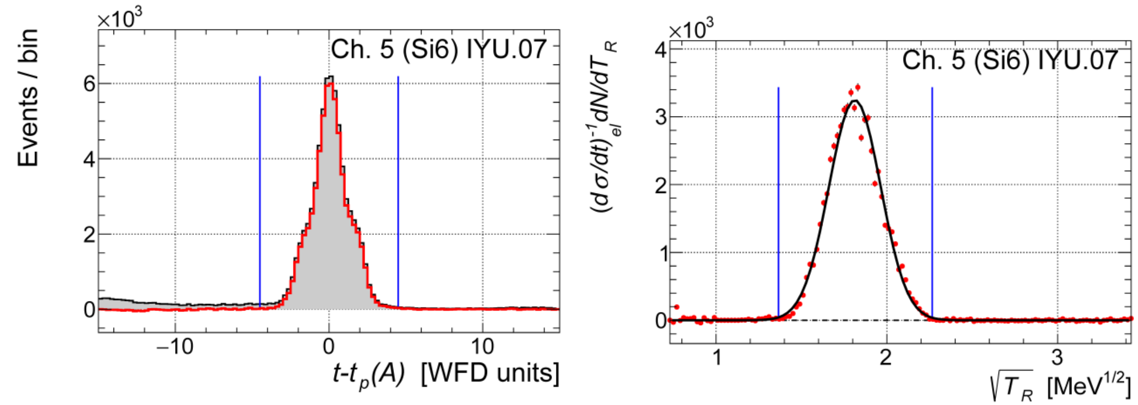


Molecular Hydrogen from the dissociator

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.



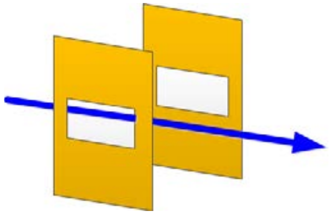
Fills	Time (h)	⟨WCM⟩	Events (k)	
20692-20695	8.63	21.12	927.6	Blue
		20.94	994.8	Yellow
20697-20698	11.47	20.60	7.1	Blue
		21.42	8.4	Yellow

Normalized good event rate ratio

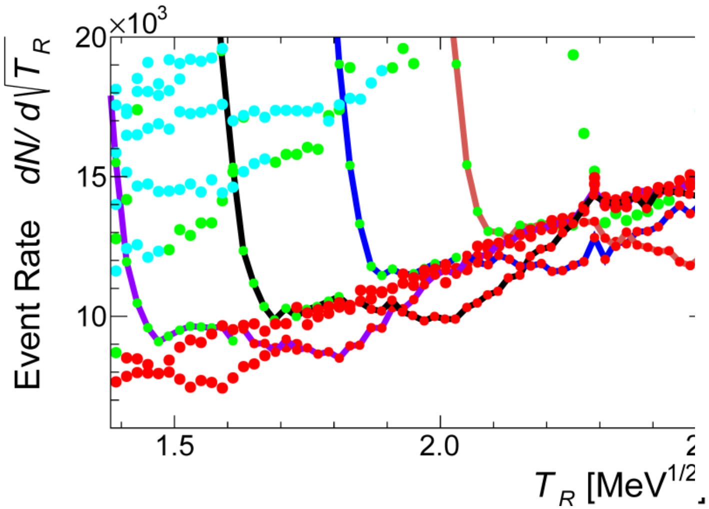
$$\frac{\mathbf{MH}}{\mathbf{Jet}} = \mathbf{0.6\%} \xrightarrow{1/f} \lesssim \mathbf{0.03\%}$$

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

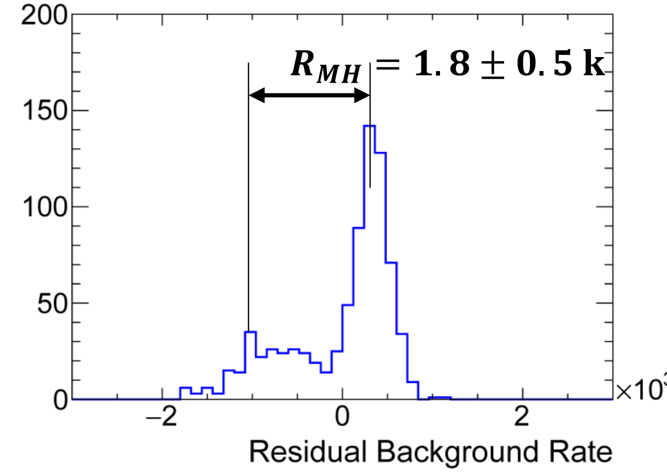
Molecular Hydrogen (2) background



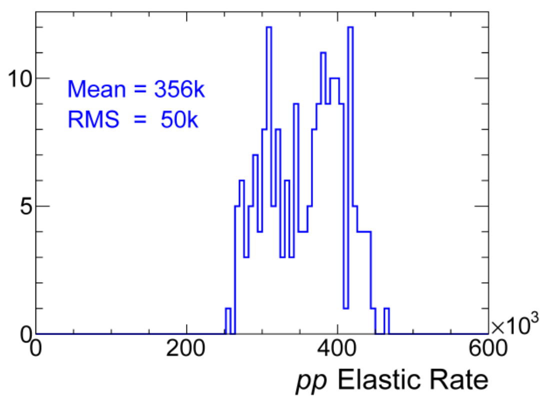
Forward beam elastic events from forward are shadowed by the collimators. This may be employed for normalization of the molecular Hydrogen density.

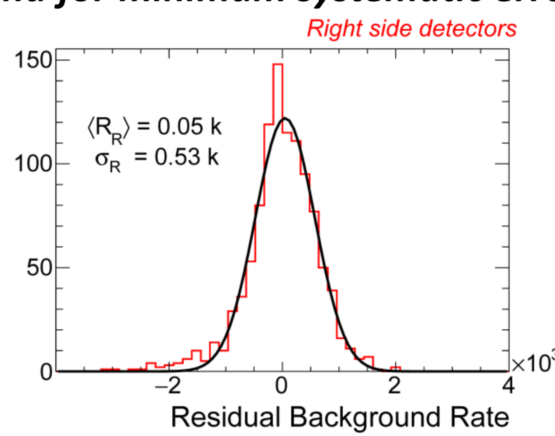


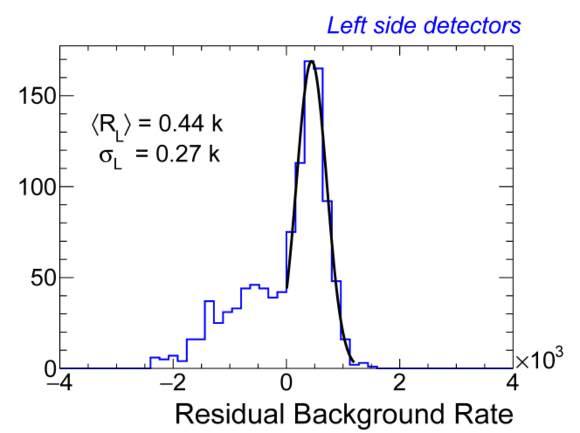
Y-projection after background subtraction.



Background for minimum systematic error cuts







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

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

The bias due to shadowing
$\boldsymbol{b_L / b_{MH} = 0.25}$