STAR

SPIN 2014

The 21st International Spin Physics Symposium

Transverse Spin Asymmetries in the CNI region of elastic proton-proton scattering at $\sqrt{s}$=200 GeV

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Helicity amplitudes for spin ½ ½ → ½ ½

Matrix elements

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

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

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

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

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

$\phi_i(s,t) = \phi_i^{EM}(s,t) + \phi_i^{HAD}(s,t)$ **CNI**

Single spin asymmetry

$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\,\mathrm{Im}\left\{ \phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4)\right\}$$

$$A_N \frac{d\sigma}{dt} \approx -\frac{4\pi}{s^2}\,\mathrm{Im}\,\phi_5^*\phi_+$$

Probe for ϕ_5^{had}

$$r_5 = \frac{2m_p}{\sqrt{-t}}\,\frac{\phi_5^{had}}{\mathrm{Im}\,\phi_+^{had}}$$

Cross section

$$\sigma_{tot} = \frac{4\pi}{s}\,\mathrm{Im}\{\phi_1 + \phi_3\}_{t=0} = \frac{4\pi}{s}\,\mathrm{Im}\,\phi_+\big|_{t=0}$$

Double spin asymmetries

$$A_{NN}(s,t)\frac{d\sigma}{dt} = \frac{4\pi}{s^2}\left\{2|\phi_5|^2 + \mathrm{Re}\left(\phi_1^*\phi_2 - \phi_3^*\phi_4\right)\right\}$$

$$A_{SS}(s,t)\frac{d\sigma}{dt} = \frac{4\pi}{s^2}\,\mathrm{Re}\left\{\phi_1\phi_2^* + \phi_3\phi_4^*\right\}$$

$$\frac{A_{NN} + A_{SS}}{2}\frac{d\sigma}{dt} \approx \frac{4\pi}{s^2}\,\mathrm{Re}\,\phi_1\phi_2^*$$

Probe for ϕ_2^{had}

$$r_2 = \frac{\phi_2^{had}}{2\,\mathrm{Im}\,\phi_+^{had}}$$

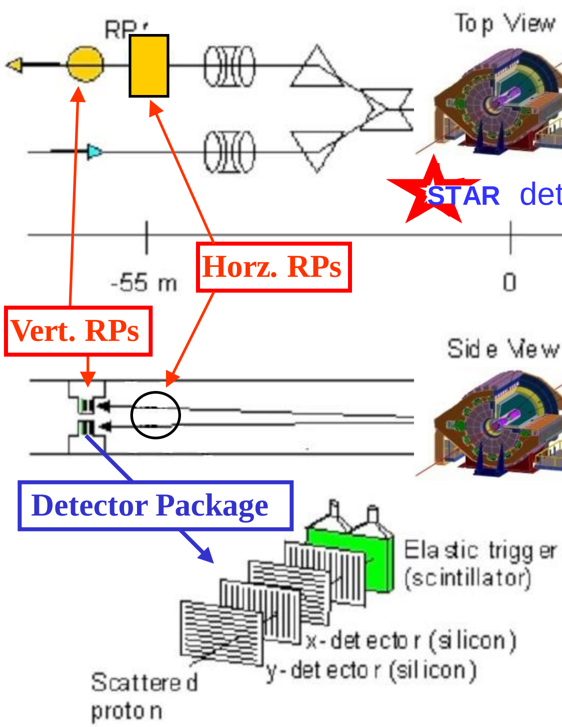
$$\frac{A_{NN} - A_{SS}}{2}\frac{d\sigma}{dt} \approx -\frac{4\pi}{s^2}\,\mathrm{Re}\,\phi_1\phi_4^* \approx 0$$

$$r_4 = \frac{m_p^2}{-t}\,\frac{\phi_4^{had}}{\mathrm{Im}\,\phi_+^{had}}$$

$\phi_4^{had} \sim t \to 0$

small in CNI

Detector and experimental conditions



- ✓ Roman Pots integrated with STAR detector – closest proximity to the beam.
- ✓ CNI region : $0.003 < -t < 0.03$.
- ✓ Ideal beam optics: $\beta^* = 21$m and parallel to point focusing – terms other than L_{EFF} in the transport matrix very small.

$$x_D \approx L^x_{eff}\, \Theta_x^*$$
$$y_D \approx L^y_{eff}\, \Theta_y^*$$

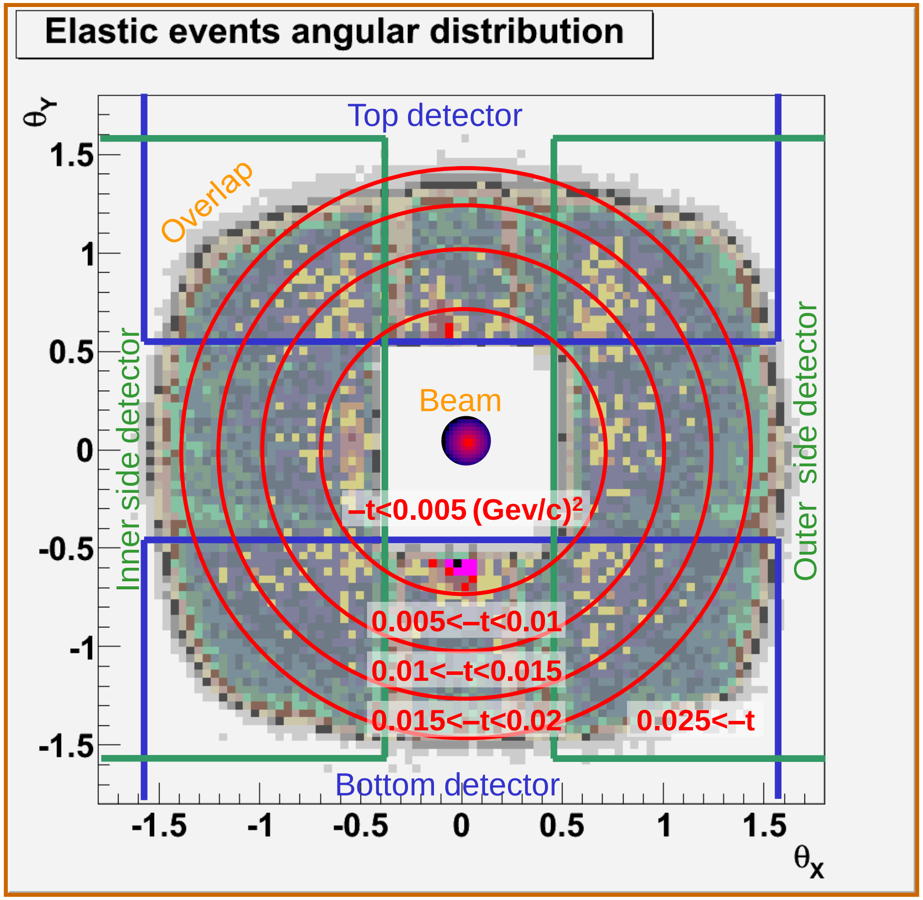
- ✓ High transverse polarization of both beams ~60%.
- ✓ Excellent detector performance – nearly 100% efficiency and only 5 dead/noisy strips per ~14000 active strips.

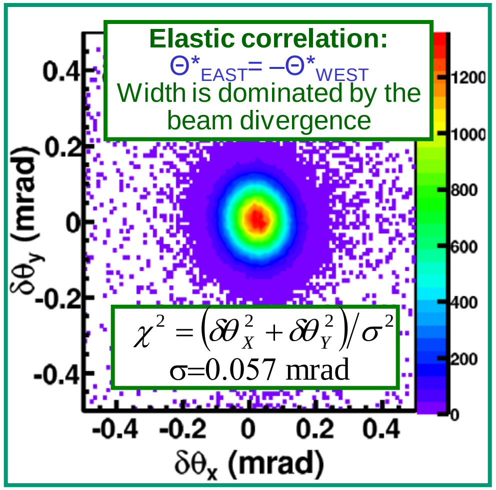
$P_B P_Y = 0.372 \pm 0.056$

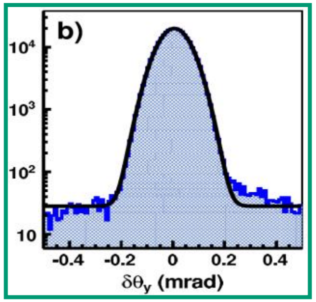
*Averaged for 4 fills from the official Run'09 RHIC polarimeter data: https://wiki.bnl.gov/rhicspin/Results

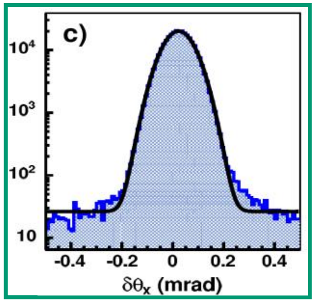
Unique possibility to measure A_N, A_{NN}, A_{SS} and, in general, A_{LL} at collider energies

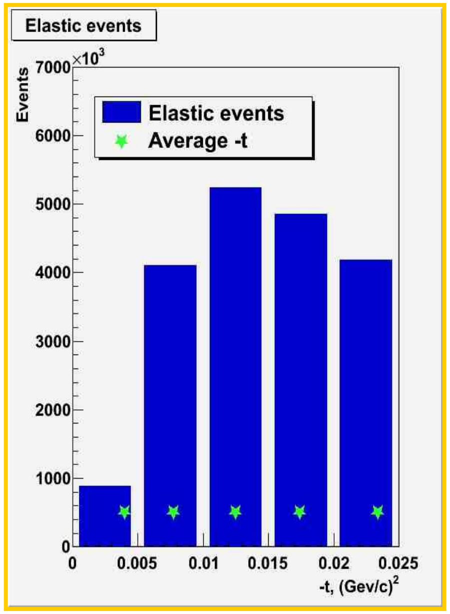
Elastic events, acceptance and t-ranges











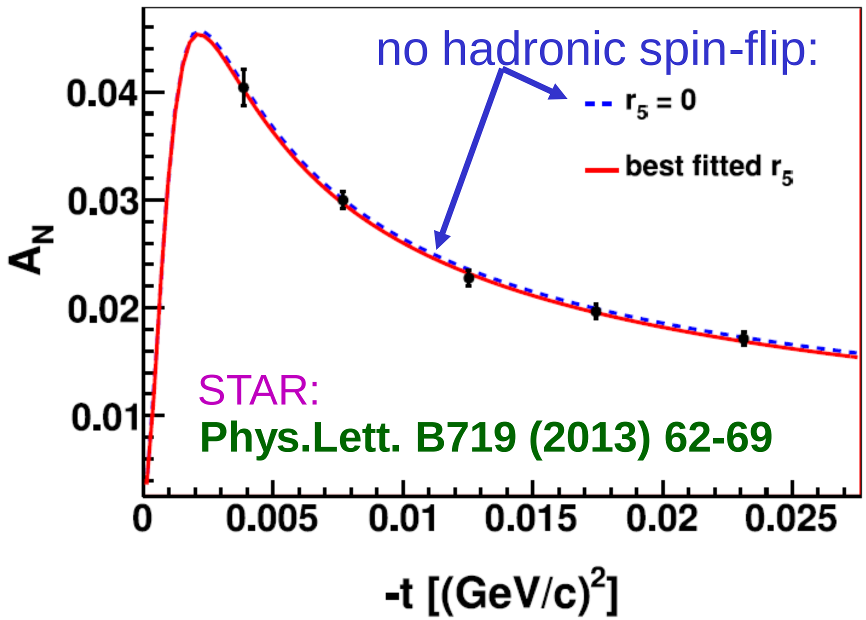
- ✓ 2π acceptance in azimuthal angle.
- ✓ Exactly the same sample of elastic events for A_N and A_{NN}&A_{SS} studies

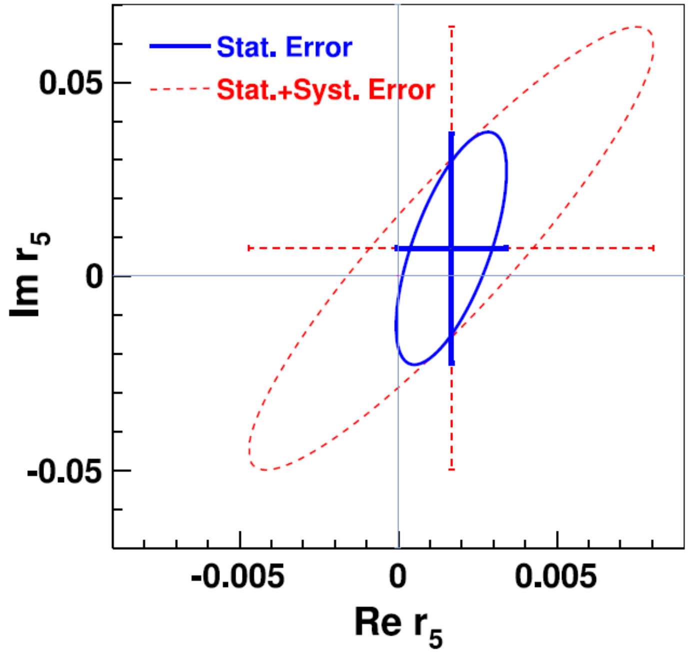
- ✓ $2 \cdot 10^7$ elastic events, <1% background.
- ✓ 5 *t*-ranges <0.03 $(GeV/c)^2$

Single spin asymmetry A_N

- "Square root formula" – no need for external luminosity normalization

$$\varepsilon_N(\varphi) = \frac{(P_B + P_Y)A_N\cos\varphi}{1+\delta(\varphi)} = \frac{\sqrt{N^{++}(\varphi)N^{--}(\pi+\varphi)} - \sqrt{N^{--}(\varphi)N^{++}(\pi+\varphi)}}{\sqrt{N^{++}(\varphi)N^{--}(\pi+\varphi)} + \sqrt{N^{--}(\varphi)N^{++}(\pi+\varphi)}}$$





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

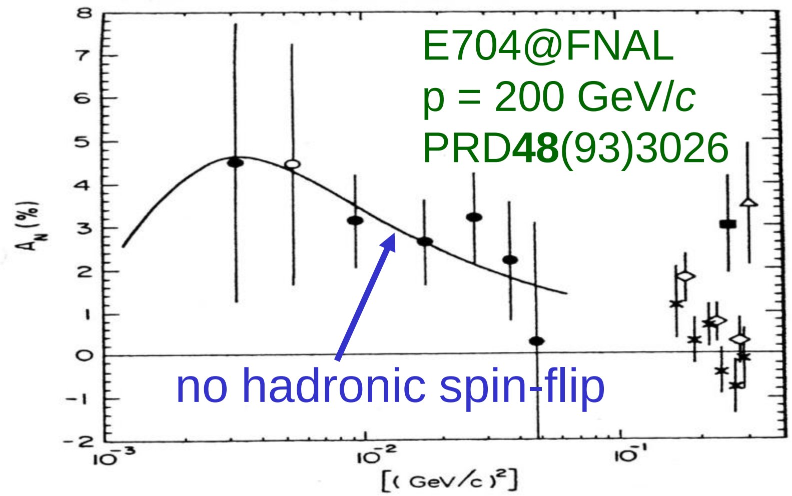
- Statistical error of <3% in each of 5 points
- Many systematics checks
- Highest accuracy in extraction of r_5

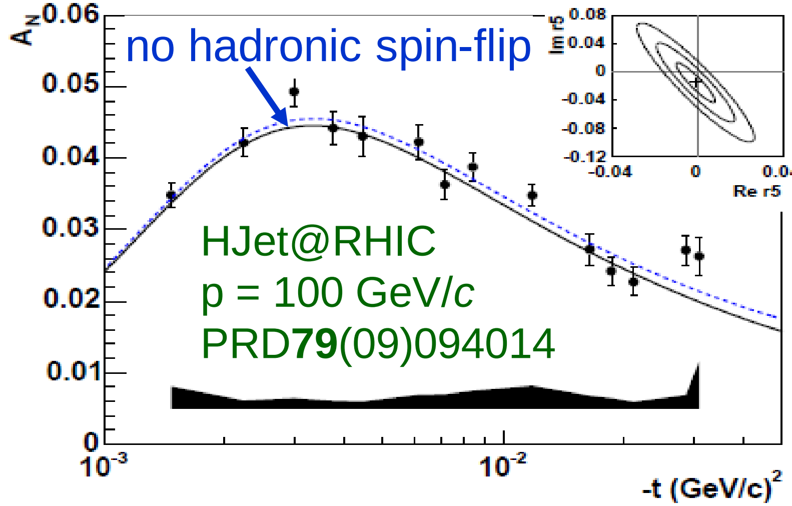
$\mathrm{Re}\,r_5 = 0.0017 \pm 0.0063$

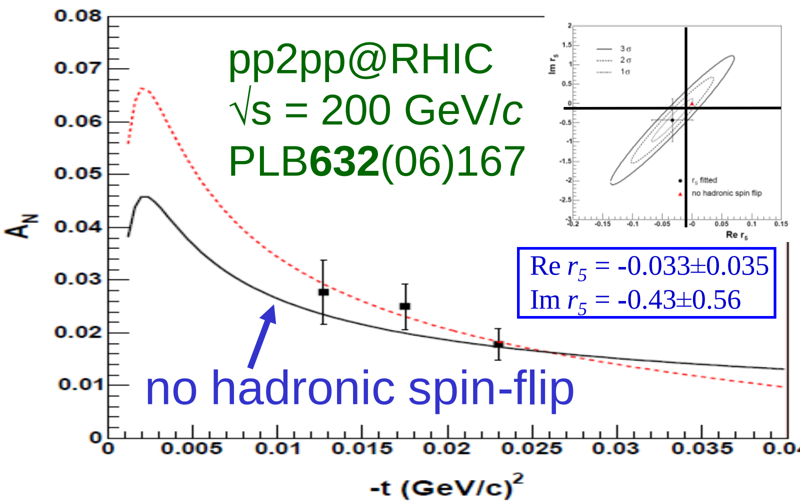
$\mathrm{Im}\,r_5 = 0.007 \pm 0.057$

Other A_N measurements in CNI region

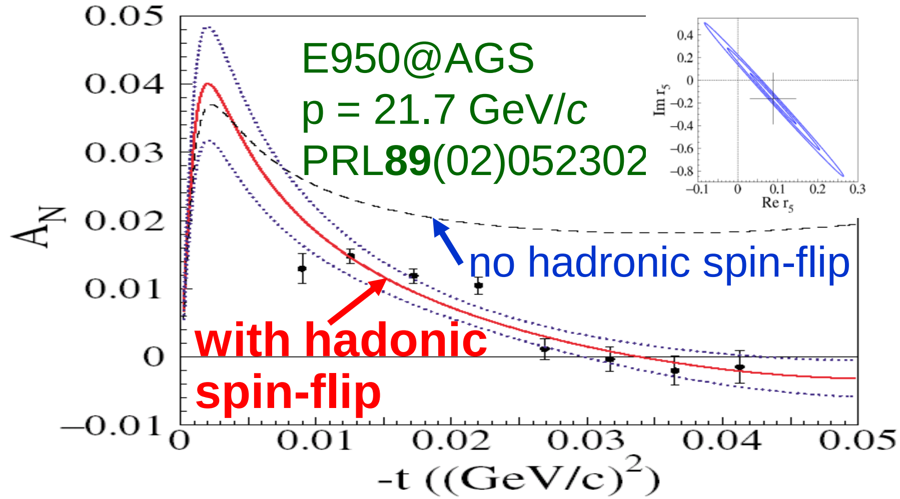
Proton-proton A_N







Proton-carbon A_N



Double spin asymmetries

Cross section azimutual angular dependence for transversely polarized beams:

$$\sigma = \sigma_0 \left[1 + A_N (\vec{P}_B + \vec{P}_Y)\cdot\vec{n} + A_{NN}(\vec{P}_B\cdot\vec{n})(\vec{P}_Y\cdot\vec{n}) + A_{SS}(\vec{P}_B\cdot\vec{s})(\vec{P}_Y\cdot\vec{s}) \right]$$

$\vec{n}$ - vector normal to the scattering plane $\vec{P}_B;\vec{P}_Y$ - polarization vectors of the two beams

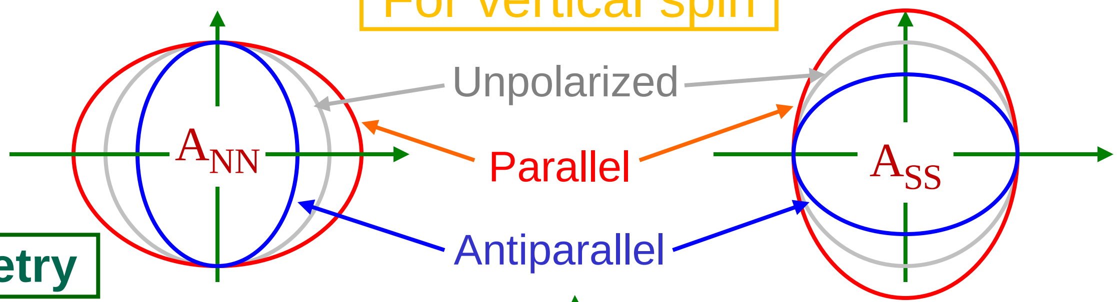
$\vec{s} = \frac{\vec{n}\times\vec{p}}{|\vec{n}\times\vec{p}|}$ - is the vector in the scattering plane, normal to the initial momentum

$$2\pi \frac{d^2\sigma}{dt\,d\varphi} = \frac{d\sigma}{dt}\cdot\left(1 + (P_B + P_Y)A_N \cos\varphi + P_B P_Y (A_{NN}\cos^2\varphi + A_{SS}\sin^2\varphi)\right)$$

Double-spin effects

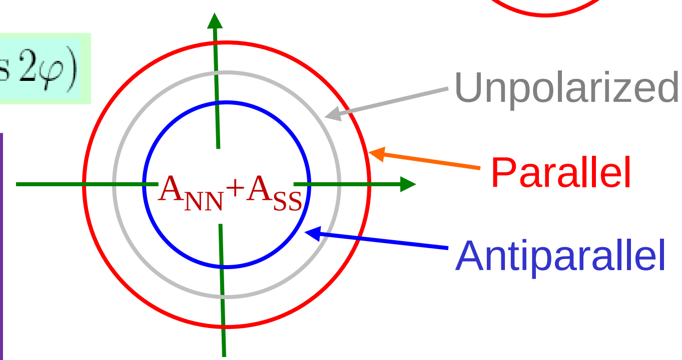
$$A_{NN};A_{SS} = \frac{\sigma^{\uparrow\uparrow+\downarrow\downarrow} - \sigma^{\uparrow\downarrow+\downarrow\uparrow}}{\sigma^{\uparrow\uparrow+\downarrow\downarrow} + \sigma^{\uparrow\downarrow+\downarrow\uparrow}}$$

For vertical spin



Raw double-spin asymmetry

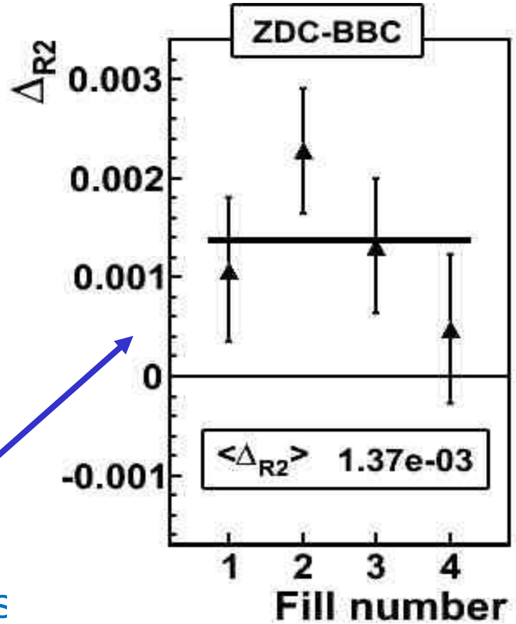
$$A_2(\varphi) = P_B P_Y((A_{NN} + A_{SS})/2 + (A_{NN} - A_{SS})/2 \cdot \cos 2\varphi)$$



- ✓ $\cos 2\varphi$ dependence for $A_{NN}-A_{SS}$
- ✓ NO angular dependence for $A_{NN}+A_{SS}$
- ✓ **Cannot use square root formula**
- ✓ Must use **external normalization**

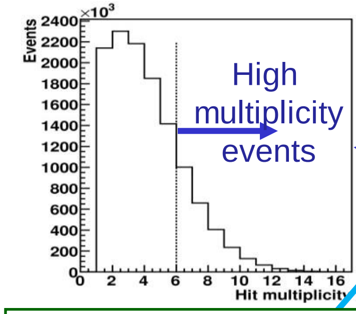
Luminosity monitors: BBC and ZDC

- **Luminosity monitors must not have double spin effects**
- For normalization studies use 3 independent luminosity ratios (*N – total monitor count*) :
  - $R_2 = (N^{++} + N^{--})/N$ – fraction of parallel spin interactions (double spin)
  - $R_B = (N^{++} + N^{+-})/N$ – fraction of interactions with spin UP in Blue beam
  - $R_Y = (N^{++} + N^{-+})/N$ – fraction of interactions with spin UP in Yellow beam
- **Uncertainties:** $\delta[P_B P_Y (A_{NN} + A_{SS})/2] \approx 2 \cdot \delta R_2$ $\delta[P_B P_Y (A_{NN} - A_{SS})/2] \approx 0$
- Manifests as a shift in raw asymmetry, not a scaling factor !
- Main assumption: two *different* processes can have the same spin sensitivity **only** in the case if it is zero in both of them
- Numerically, two (or more) processes can be considered free of spin effects if they give zero difference in corresponding independent normalization ratios R_2, R_B, R_Y
- Careful choice of STAR subsystems as luminosity monitors – best consistency checks, high statistics, two arms each:
  - ZDC – zero degree calorimeters
  - BBC – beam-beam counters
- Difference in R_2 normalization ratio for BBC and ZDC is systematically shifted from zero at the level of $1.4 \cdot 10^{-3}$, averages out with fake polarization pattern
- Have to conclude: one of the two monitors feels double spin effects at this level => further investigation

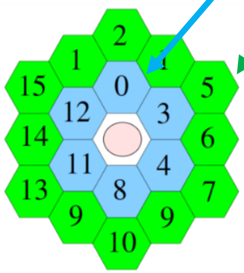


Difference in R_2 double spin normalization ratio for BBC and ZDC

Luminosity monitors: inside BBC

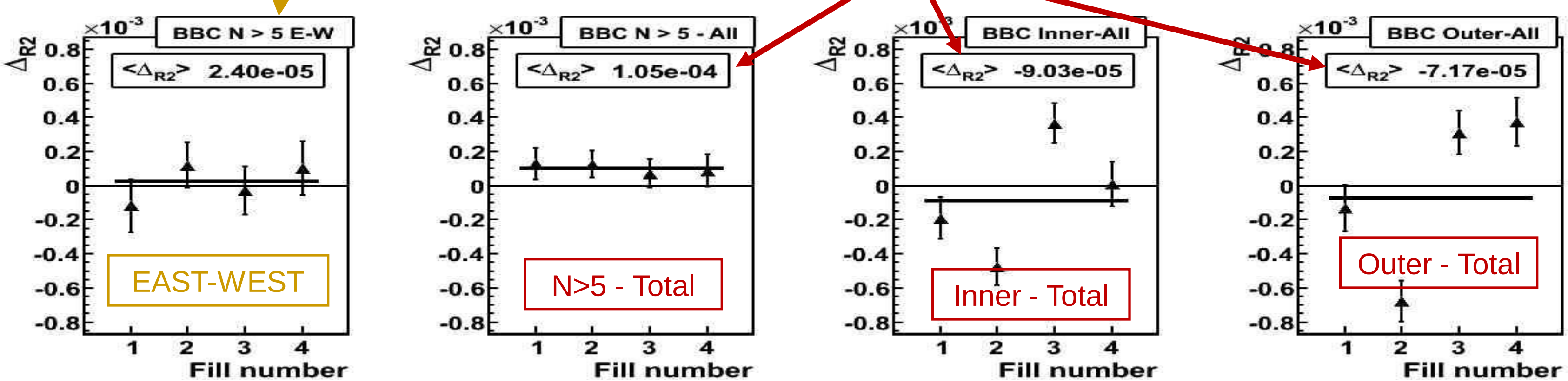


Hit multiplicity in STAR BBC

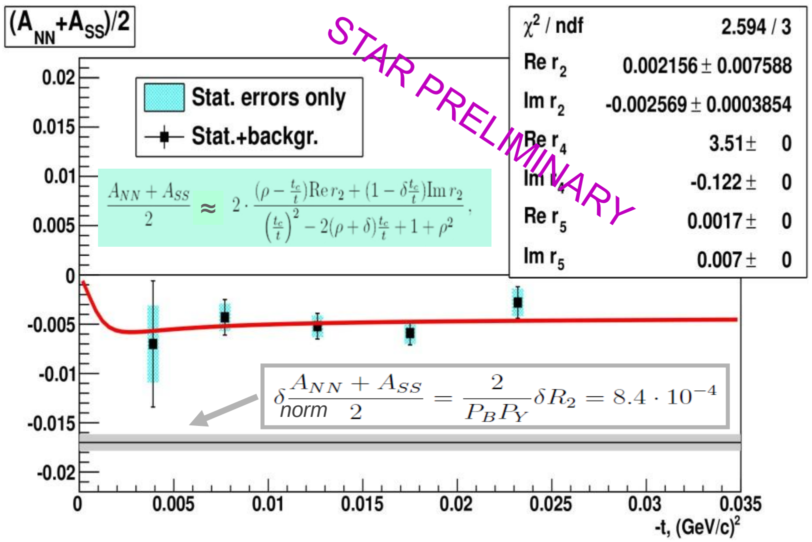


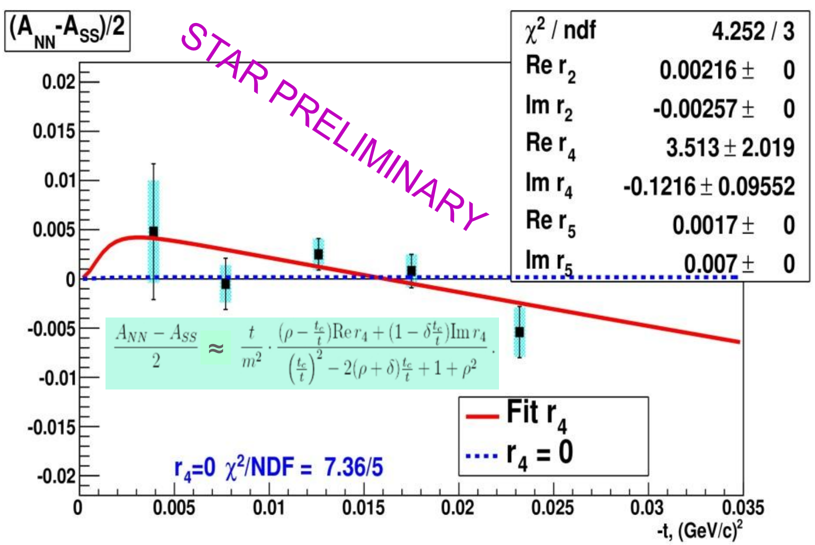
BBC Inner and Outer tiles

- Three different subprocesses were compared to each other and to BBC as a whole in terms of R_2 normalization ratio:
  - High multiplicity: N>5 tiles in one arm and a hit in the opposite arm
  - Inner: single hit in one of the Inner tiles and a hit in the opposite arm
  - Outer: single hit in one of the Outer tiles and a hit in the opposite arm
- Confirmed that the subprocesses have significantly different physics -- angular dependence of single spin ratios R_B, R_Y is of opposite sign
- East and West arms show extremely good consistency – average them
- Though R_2 spread is relatively large fill by fill, the averages for our 4 fills are very close to zero at 10^{-4} level
- Averaged ΔR_2 of each subprocess and the whole BBC are added in quadratures to form the total uncertainty δR_2: $\delta R_2 = 1.56 \cdot 10^{-4}$

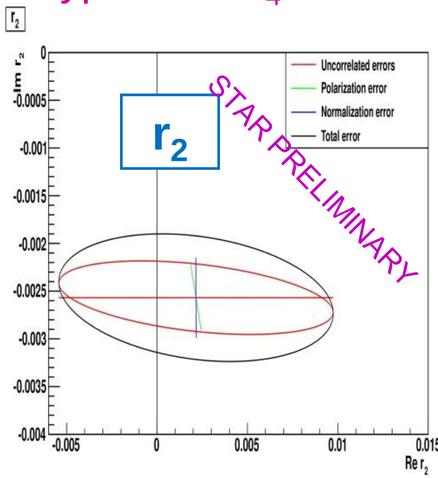


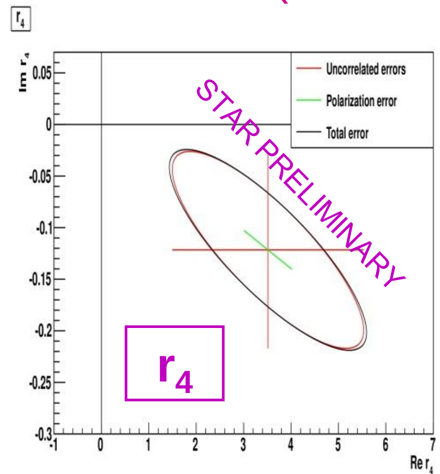
Asymmetries and relative amplitudes





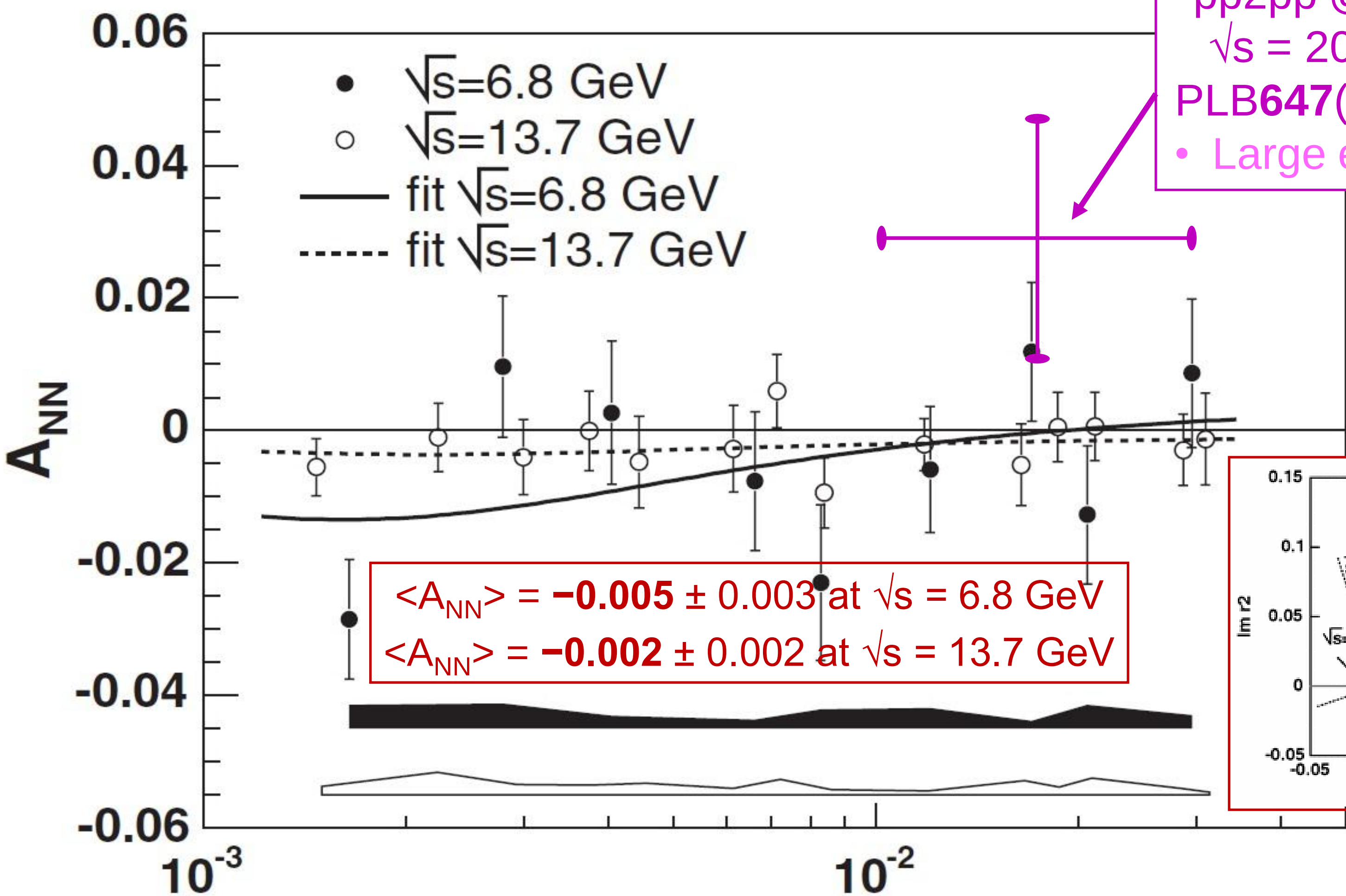
- Accurate formulae for amplitudes from N. H. Buttimore et al, Phys.Rev. D59 114010 (1999)
- Approximate expressions decouple r_2 and r_4 -- successive iterative fits
- $(A_{NN}-A_{SS})/2$ close to zero => $A_{NN} \approx A_{SS}$
- $(A_{NN}+A_{SS})/2$ significantly below zero, >6σ on average, t-dependence is flat
- Relative amplitudes include common errors
- Im r_2 is well constrained – small negative value
- Re r_2 is compatible with 0
- Hypothesis r_4=0 is noncontroversial (85% c.l.)





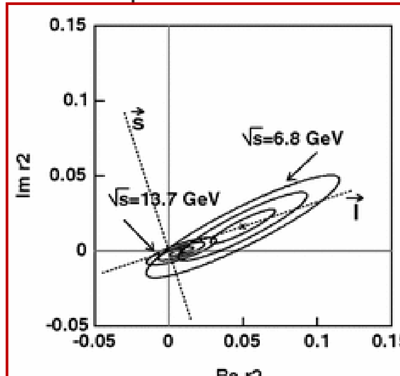
Previous measurements of A_{NN}

HJET @ RHIC Phys. Rev. **D79** (2009) 094014
- Small negative values, compatible with our data



pp2pp @ RHIC
√s = 200 GeV
PLB**647**(2007)98
- Large error

$\langle A_{NN} \rangle$ = **−0.005** ± 0.003 at √s = 6.8 GeV
$\langle A_{NN} \rangle$ = **−0.002** ± 0.002 at √s = 13.7 GeV

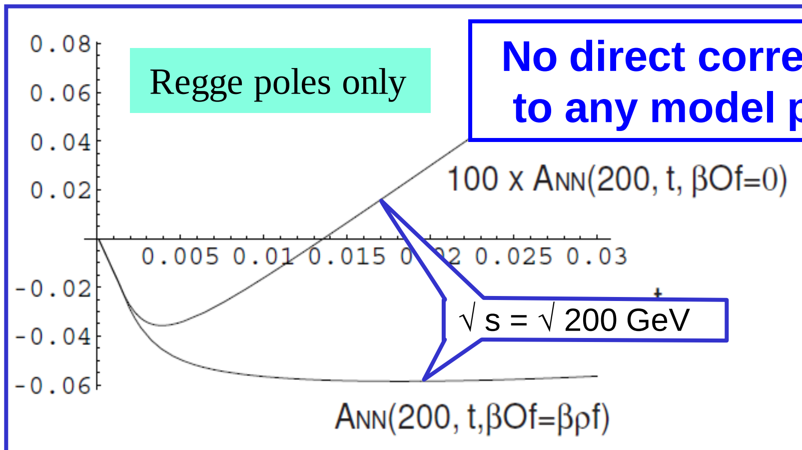


Theoretical models, Odderon

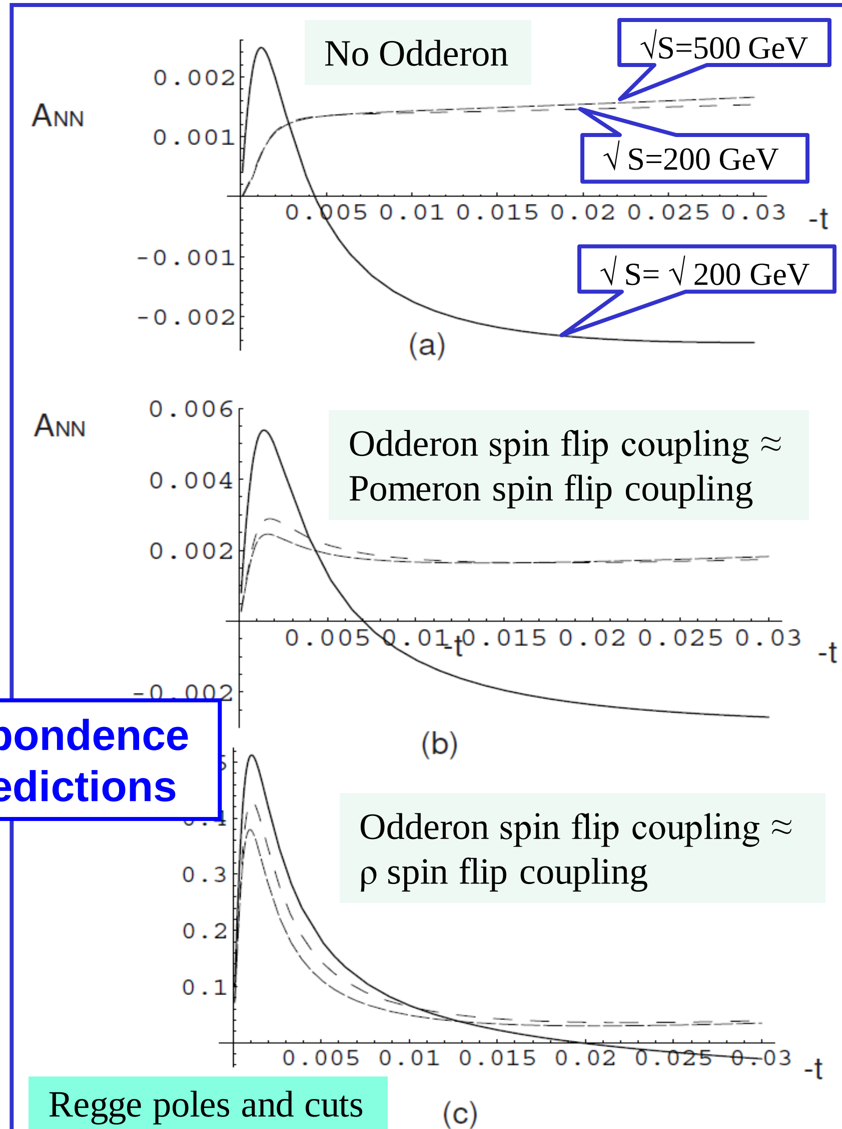
E.Leader, T.L.Trueman
"The Odderon and spin dependence of high-energy proton-proton scattering",
***PR* D61, 077504 (2000)**

- Pomeron and Odderon are 90deg out of phase
- 5% Odderon contribution → 5% A_{NN}

T.L.Trueman
"Double-spin asymmetry in elastic proton-proton scattering as a probe for the Odderon",
arXiv:hep-ph/0604153 (2006)



No direct correspondence to any model predictions

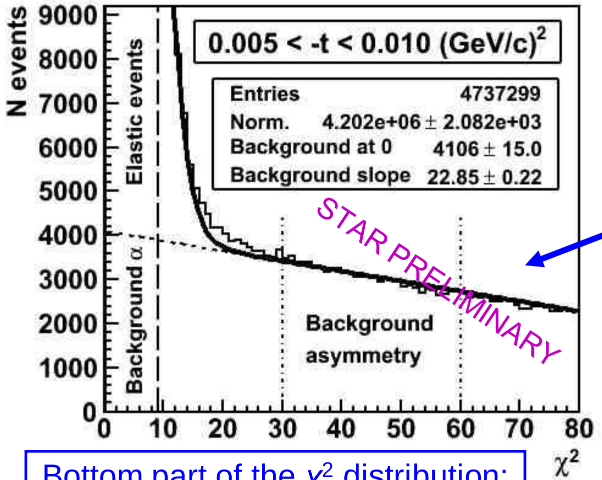


Conclusions

- Very clean data set of ~20 million *pp*-elastic events is taken with Roman Pots integrated into the STAR detector for low *t* studies
- Both single and double spin asymmetries are extracted with unprecedented accuracy in 5 *t*-ranges at $\sqrt{s}$=200 GeV.
- A_N result confirms conclusions at lower energies: $r_5=0$, no hadronic single spin flip is seen
- $(A_{NN} - A_{SS})/2$ found to be close to 0, i.e. $A_{NN} \approx A_{SS}$ and $\phi_4 \approx 0$ as required by angular momentum conservation
- $(A_{NN} + A_{SS})/2$ is significantly different from zero and have small negative values about $5 \cdot 10^{-3}$
- r_2 is well constrained in its imaginary part and compatible with zero in real part
- r_4 has large errors as expected and hypothesis $r_4=0$ is not controversial
- Hadronic double spin-flip amplitudes ϕ_2 and ϕ_4 behave differently at our kinematic range. This indicates that the exchange mechanism is more complex than an exchange of Regge poles only (factorization of amplitudes does not hold).
- Results are at variance with the latest models and may attract the attention of theorists

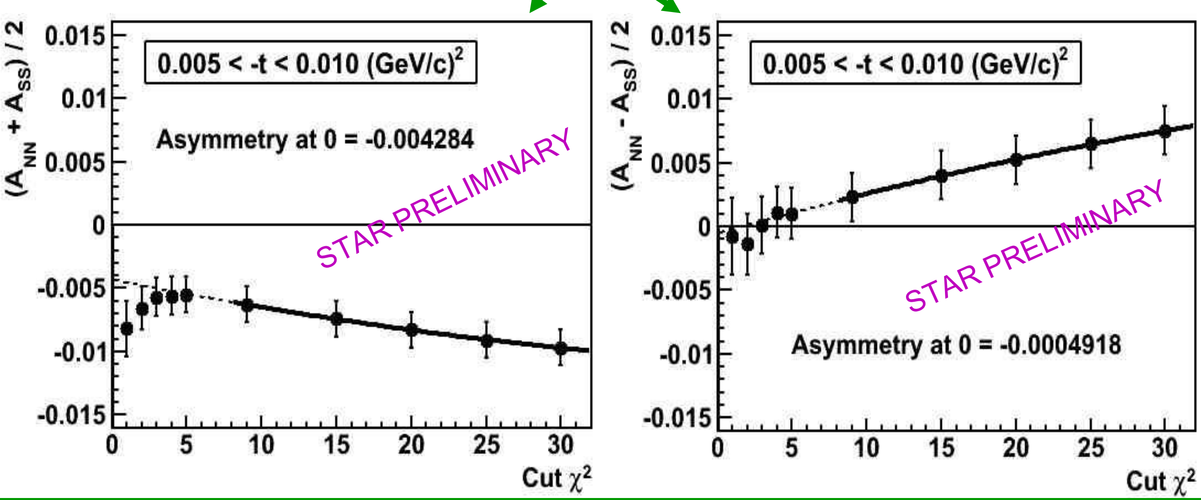
Backups

Background subtraction



Bottom part of the χ^2 distribution: event selection for the traditional approach

- Small background fraction 0.2—3%
- Yet high **fake** background asymmetry, x10 the effect, due to invalid luminosity normalization
- Traditional approach: extrapolate background, define background fraction and asymmetry for 'pure' background
- Advantage -- accurate statistical error estimates
- Drawback -- asymmetry from high χ^2 is applied to low χ^2
- Alternative: study asymmetry evolution when changing the cut on χ^2 , extrapolate to zero background
- Disadvantages – no error estimates, cuts at low χ^2 affect spatial elastic event selection and invalidate luminosity normalization
- Systematic error estimate by difference of the two methods
- Total error for each point by adding statistical and systematic errors in quadratures



Evolution of the asymmetries with cut χ^2 value and extrapolation to zero background