Uncertainties in the Transverse Double Spin Asymmetries due to the Luminosity Normalization

D. Svirida for the STAR Collaboration

Institute for Theoretical and Experimental Physics
25 B.Cheremushkinskaya Moscow 117218 Russia
E-Mail: Dmitry.Svirida@itep.ru

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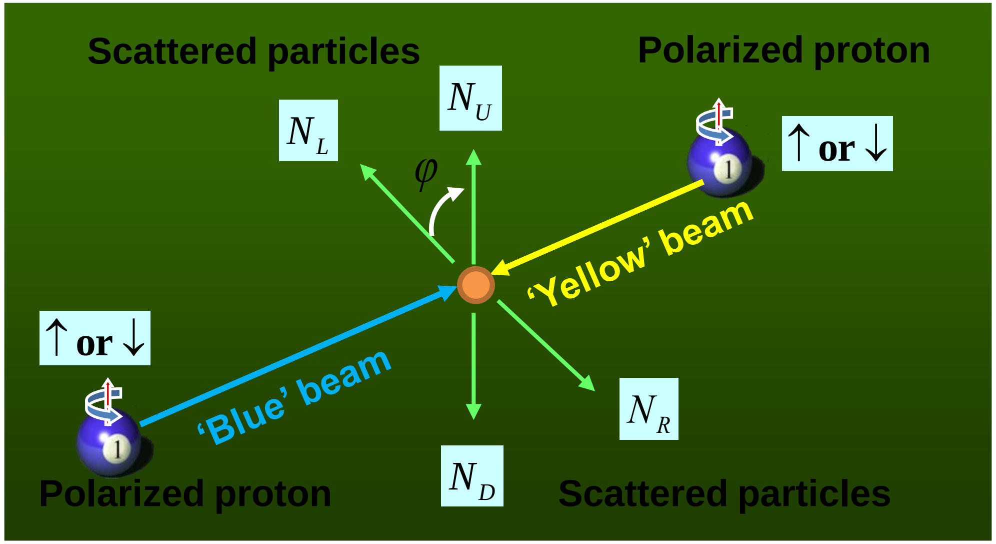
Experimental conditions – pp collider



- Colliding beams of identical spin ½ polarized particles – protons
- Vertical spin direction
- All possible spin combinations: ↑↑, ↑↓, ↓↑, ↓↓
- Looking at azimuthal distributions of reaction products
- Typically small or very small single and double spin asymmetries
- Must use luminosity normalization for double spin experiment

Polarized cross sections and asymmetries

Cross-section angular dependence for transversely polarized collider beams

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

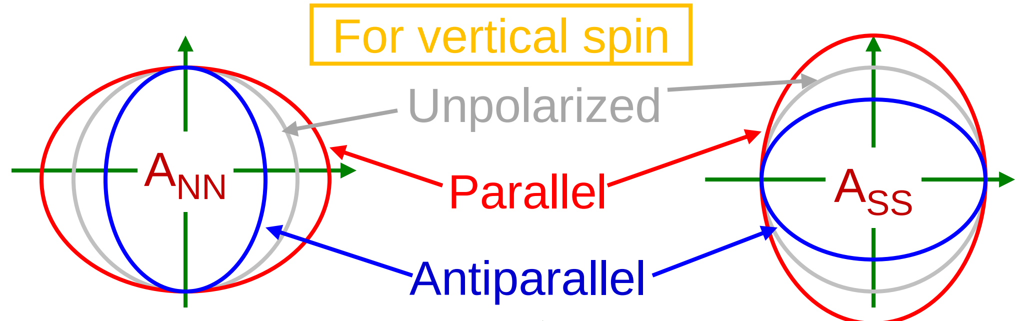
$\vec{n}$ - vector normal to the scattering plane $\vec{P}_B ; \vec{P}_Y$ - polarization vectors of the beams

$\vec{s} = \dfrac{\vec{n} \times \vec{p}}{|\vec{n} \times \vec{p}|}$ - 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:

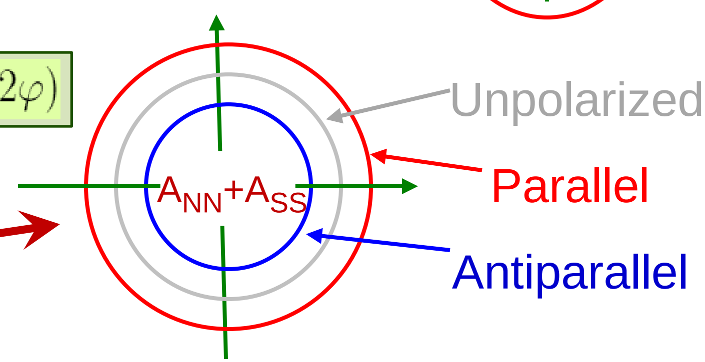
$$A_{NN} ; A_{SS} : \quad \frac{\sigma^{\uparrow\uparrow + \downarrow\downarrow} - \sigma^{\uparrow\downarrow + \downarrow\uparrow}}{\sigma^{\uparrow\uparrow + \downarrow\downarrow} + \sigma^{\uparrow\downarrow + \downarrow\uparrow}}$$



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 2φ dependence for $A_{NN} - A_{SS}$
- ✓ NO angular dependence for $A_{NN} + A_{SS}$
  Effectively cross section difference



Normalized counts and normalization ratios

Cannot use 'square root formula', have to rely on normalized counts K^{by} :

$$A_2(\varphi) = A_{2+} + A_{2-}\cos 2\varphi = \frac{(K^{++}(\varphi) + K^{--}(\varphi)) - (K^{+-}(\varphi) + K^{-+}(\varphi))}{(K^{++}(\varphi) + K^{--}(\varphi)) + (K^{+-}(\varphi) + K^{-+}(\varphi))}$$

$$K^{by}(\varphi) = N^{by}(\varphi)/L^{by}$$

$N^{by}(\varphi)$ - event counts for spin combination b,y= + or – of 'Blue' and 'Yellow' colliding beams

L^{by} - luminosity monitor counts for these b,y

Natural normalization ratios $r^{BY} = 2L^{BY}/L$ -- not independent:

$L = L^{++} + L^{--} + L^{+-} + L^{-+}$ - total monitor counts => $(r^{++} + r^{--} + r^{+-} + r^{-+})/2 = 1$

Independent normalization ratios:

$\boxed{R_2 = (L^{++} + L^{--})/L - \text{is the relative part of the parallel spin interactions}}$ - most important

$R_B = (L^{++} + L^{+-})/L$ – is the relative part of the interactions with spin UP in the BLUE beam

$R_Y = (L^{++} + L^{-+})/L$ – is the relative part of the interactions with spin UP in the YELLOW

$$r^{++} = R_2 + R_B + R_Y - 1 \qquad r^{+-} = R_B + 1 - R_2 - R_Y$$

$$r^{--} = R_2 + 1 - R_B - R_Y \qquad r^{-+} = R_Y + 1 - R_2 - R_B$$

and $\partial r^{BY}/\partial R_j = +1 \text{ or } -1$

Raw asymmetry and its uncertainty

$$A_2 = \frac{\left(\frac{N^{++}}{L^{++}} + \frac{N^{--}}{L^{--}}\right) - \left(\frac{N^{+-}}{L^{+-}} + \frac{N^{-+}}{L^{-+}}\right)}{\left(\frac{N^{++}}{L^{++}} + \frac{N^{--}}{L^{--}}\right) + \left(\frac{N^{+-}}{L^{+-}} + \frac{N^{-+}}{L^{-+}}\right)} = \frac{\frac{N^{++}}{r^{++}} + \frac{N^{--}}{r^{--}} - \frac{N^{+-}}{r^{+-}} - \frac{N^{-+}}{r^{-+}}}{\frac{N^{++}}{r^{++}} + \frac{N^{--}}{r^{--}} + \frac{N^{+-}}{r^{+-}} + \frac{N^{-+}}{r^{-+}}} = \frac{D}{S}$$

$$\delta A_2 = \sqrt{\left(\delta R_2 \cdot \frac{\partial A_2}{\partial R_2}\right)^2 + \left(\delta R_B \cdot \frac{\partial A_2}{\partial R_B}\right)^2 + \left(\delta R_Y \cdot \frac{\partial A_2}{\partial R_Y}\right)^2}$$

and we are interested in the partial derivatives

$$\frac{\partial A_2}{\partial R_j} = \frac{S \cdot \frac{\partial D}{\partial R_j} - D \cdot \frac{\partial S}{\partial R_j}}{S^2} = \frac{\frac{\partial D}{\partial R_j} - \cancel{A_2 \cdot \frac{\partial S}{\partial R_j}}}{S}$$

$$\frac{\partial D}{\partial R_j} = \sum_{B,Y=+,-}^{(4)} \frac{\partial D}{\partial r^{BY}} \frac{\partial r^{BY}}{\partial R_j}$$

$\pm\frac{N^{BY}(\varphi)}{(r^{BY})^2}$ $\qquad \pm 1$

$$\boxed{-\frac{\partial D}{\partial R_2} = \frac{N^{++}}{(r^{++})^2} + \frac{N^{--}}{(r^{--})^2} + \frac{N^{+-}}{(r^{+-})^2} + \frac{N^{-+}}{(r^{-+})^2}}$$

All +

$$-\frac{\partial D}{\partial R_B} = \frac{N^{++}}{(r^{++})^2} - \frac{N^{--}}{(r^{--})^2} - \frac{N^{+-}}{(r^{+-})^2} + \frac{N^{-+}}{(r^{-+})^2}$$

$$-\frac{\partial D}{\partial R_Y} = \frac{N^{++}}{(r^{++})^2} - \frac{N^{--}}{(r^{--})^2} + \frac{N^{+-}}{(r^{+-})^2} - \frac{N^{-+}}{(r^{-+})^2}$$

Alternating sign

$$-\frac{\partial S}{\partial R_2} = \frac{N^{++}}{(r^{++})^2} + \frac{N^{--}}{(r^{--})^2} - \frac{N^{+-}}{(r^{+-})^2} - \frac{N^{-+}}{(r^{-+})^2}$$

$$-\frac{\partial S}{\partial R_B} = \frac{N^{++}}{(r^{++})^2} - \frac{N^{--}}{(r^{--})^2} + \frac{N^{+-}}{(r^{+-})^2} - \frac{N^{-+}}{(r^{-+})^2}$$

$$-\frac{\partial S}{\partial R_Y} = \frac{N^{++}}{(r^{++})^2} - \frac{N^{--}}{(r^{--})^2} - \frac{N^{+-}}{(r^{+-})^2} + \frac{N^{-+}}{(r^{-+})^2}$$

LO: Typical collider conditions -- all spin combinations equally filled, asymmetries small

$$r^{++} \approx r^{--} \approx r^{+-} \approx r^{-+} \approx r = 1/2$$
$$N^{++} \approx N^{--} \approx N^{+-} \approx N^{-+} \approx N$$

$$\boxed{\frac{\partial A_2}{\partial R_2} \approx -1/r = -2\,;} \qquad \boxed{\frac{\partial A_2}{\partial R_B} \approx \frac{\partial A_2}{\partial R_Y} \approx 0}$$

Probing NLO

Spin combinations equally filled, but A_N is not negligible

$$r^{++} \approx r^{--} \approx r^{+-} \approx r^{-+} \approx r = 1/2$$

$$\cancel{N^{++} \approx N^{--} \approx N^{+-} \approx N^{-+} \approx N}$$

$$-\frac{\partial D}{\partial R_B} = \frac{A_Y}{r} \cdot S$$

$$\boxed{\frac{\partial A_2}{\partial R_B} = -\frac{A_Y}{r} = -2 \cdot A_Y \ll \frac{\partial A_2}{\partial R_2}}$$

A_Y is the raw single spin asymmetry with the opposite beam

Asymmetries are small, but spin combinations are missing (e.g. 1 of 100)

$$\cancel{r^{++} \approx r^{--} \approx r^{+-} \approx r^{-+} \approx r = 1/2}$$

$$N^{BY} = C \cdot r^{BY}$$

$$\boxed{\frac{\partial A_2}{\partial R_B} = -\frac{1}{4} \cdot \left(\frac{1}{r^{++}} - \frac{1}{r^{--}} - \frac{1}{r^{+-}} + \frac{1}{r^{-+}} \right) = \pm \frac{2}{3} \cdot \frac{\Delta r}{r} \approx 0.01}$$

NLO effects are very small, can be neglected:

$$\delta A_2 = \sqrt{\left(\delta R_2 \cdot \frac{\partial A_2}{\partial R_2}\right)^2 + \left(\delta R_B \cdot \frac{\partial A_2}{\partial R_B}\right)^2 + \left(\delta R_Y \cdot \frac{\partial A_2}{\partial R_Y}\right)^2}$$

$$\boxed{\delta A_2 = 2 \cdot \delta R_2}$$

- **Only double spin ratio R_2 matters**
- **Manifests as a shift of the raw asymmetry, not as a scaling factor**
- **Does not depend on the azimuthal angle**

Physics asymmetries

$$A_2(\varphi) = A_{2+} + A_{2-}\cos 2\varphi$$

$$A_{2+} = P_B P_Y (A_{NN} + A_{SS})/2$$

$$A_{2-} = P_B P_Y (A_{NN} - A_{SS})/2$$

- A_{2+} is effectively the average of $A_2(\varphi)$ over $[0; 2\pi]$ => all conclusions hold:

$$\boxed{\delta A_{2+} = 2 \cdot \delta R_2}$$

- The uncertainty of the above type is a shift in $A_2(\varphi)$ and does not change A_{2-}:

LO: $\boxed{\delta A_{2-} \approx 0}$

- for NLO estimates, using symmetric form:

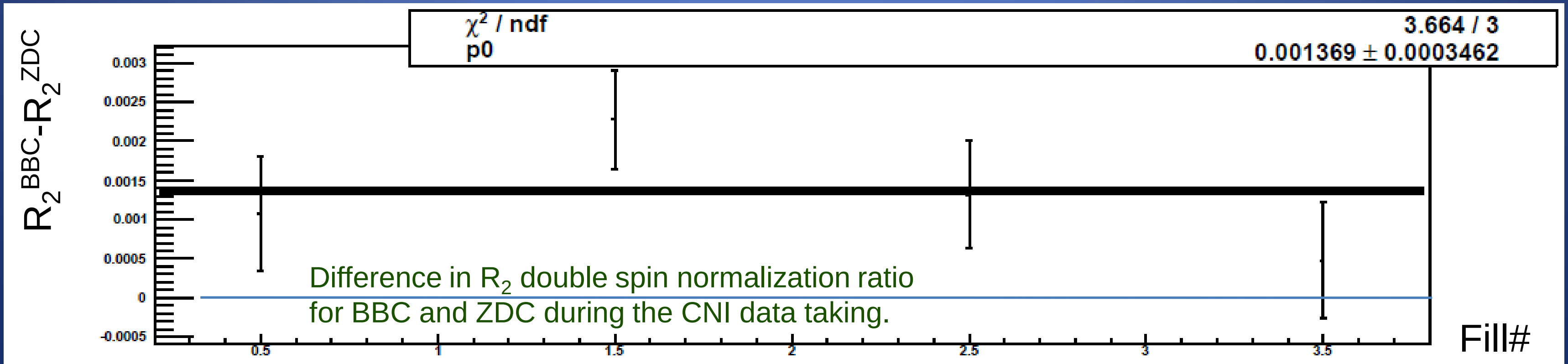
$$A_{2-} = \frac{1}{2}\left(\frac{(A_2(0) - A_2(\pi/2)) + (A_2(\pi) - A_2(3\pi/2))}{2}\right)$$

one can obtain:

$\frac{\partial A_{2-}}{\partial R_2} = -4A_{2-}(R_2 - \frac{1}{2})$ -- very small; $\frac{\partial A_{2-}}{\partial R_B} = 0.$

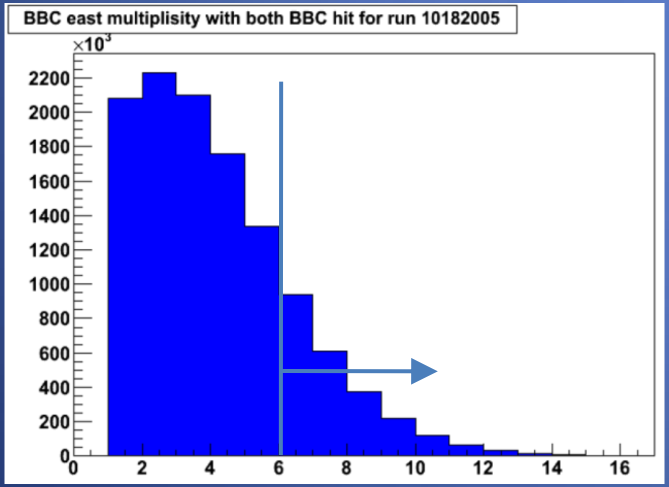
STAR example: BBC and ZDC

- Luminosity monitors must not have double spin effects
- Main assumption: two (or more) different processes can have the same spin sensitivity only in the case if it is zero in both (or all) 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
- Most careful choice of STAR subsystem as luminosity monitor: ZDC or BBC
- Many consistency checks including electronics, intensity and bunch # dependence
- Proper E-W coincidence combination and account for accidentals and multiples
- Difference in R_2 normalization ratio for BBC and ZDC is systematically shifted from zero at the level of $1.5\cdot10^{-3}$, averages out with fake polarization pattern
- Have to conclude: one of the two monitors feels double spin effects at this level

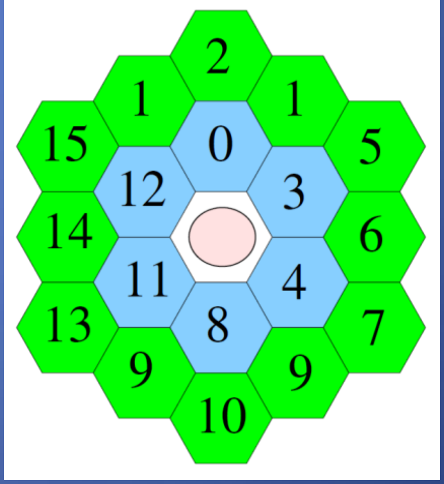


Inside BBC

- Three different subprocesses are compared to each other and to BBC as a whole:
  - 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

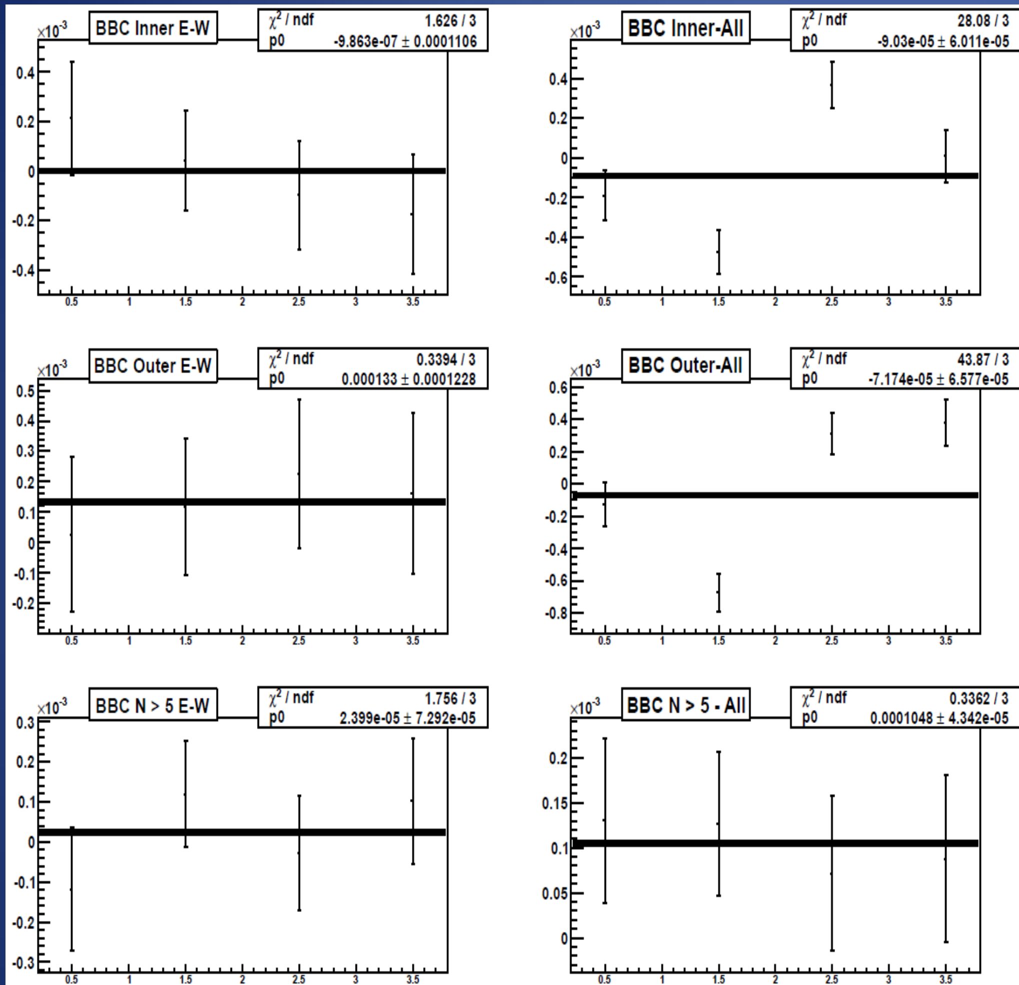


BBC multiplicity



BBC Inner (blue) and Outer (green) tiles

Inside BBC - continued



Difference in R_2 ratio for various BBC parts:
left – East and West arms for the 3 processes,
right – comparison to the BBC as a whole

- East and West arms show extremely good consistency – average them
- Compare subprocesses to BBC as a whole
- Though 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:

$$\delta R_2 = 1.56 \cdot 10^{-4}$$

- δR_B and δR_Y are 5 times larger, but can be safely neglected:

$$\boxed{\delta \frac{A_{NN} + A_{SS}}{2} = \frac{2}{P_B P_Y} \delta R_2 = 8.4 \cdot 10^{-4}}$$

Summary

- Double spin asymmetries are typically small in collider experiments and require external luminosity normalization – uncertainty important
- Comprehensive study of the luminosity uncertainty and its influence on the transverse asymmetries was made within the framework of CNI region measurements at STAR
- Both LO and NLO estimates performed (see table below)
- Conclusions on A_{2+} also applicable to longitudinal asymmetry A_{LL}
- Formulas checked by numeric derivatives calculations from data
- The only significant uncertainty is that of the double spin normalization ratio R_2

	$\frac{\partial}{\partial R_2}$		$\frac{\partial}{\partial R_B}$	
Observable	LO	NLO	LO	NLO
$A_{2+} = P_B P_Y (A_{NN} + A_{SS})/2$	-2	–	0	$\pm\frac{2}{3} \cdot \frac{\Delta r}{r}$
$A_{2-} = P_B P_Y (A_{NN} - A_{SS})/2$	0	$-4A_{2-}(R_2 - \frac{1}{2})$	0	0

$$\boxed{\delta[P_B P_Y (A_{NN} + A_{SS})/2] \approx 2 \cdot \delta R_2}$$

$$\boxed{\delta[P_B P_Y (A_{NN} - A_{SS})/2] \approx 0}$$