Exploring universality of **Transversity** in *p-p* collisions

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INFN - Pavia

in collaboration with:
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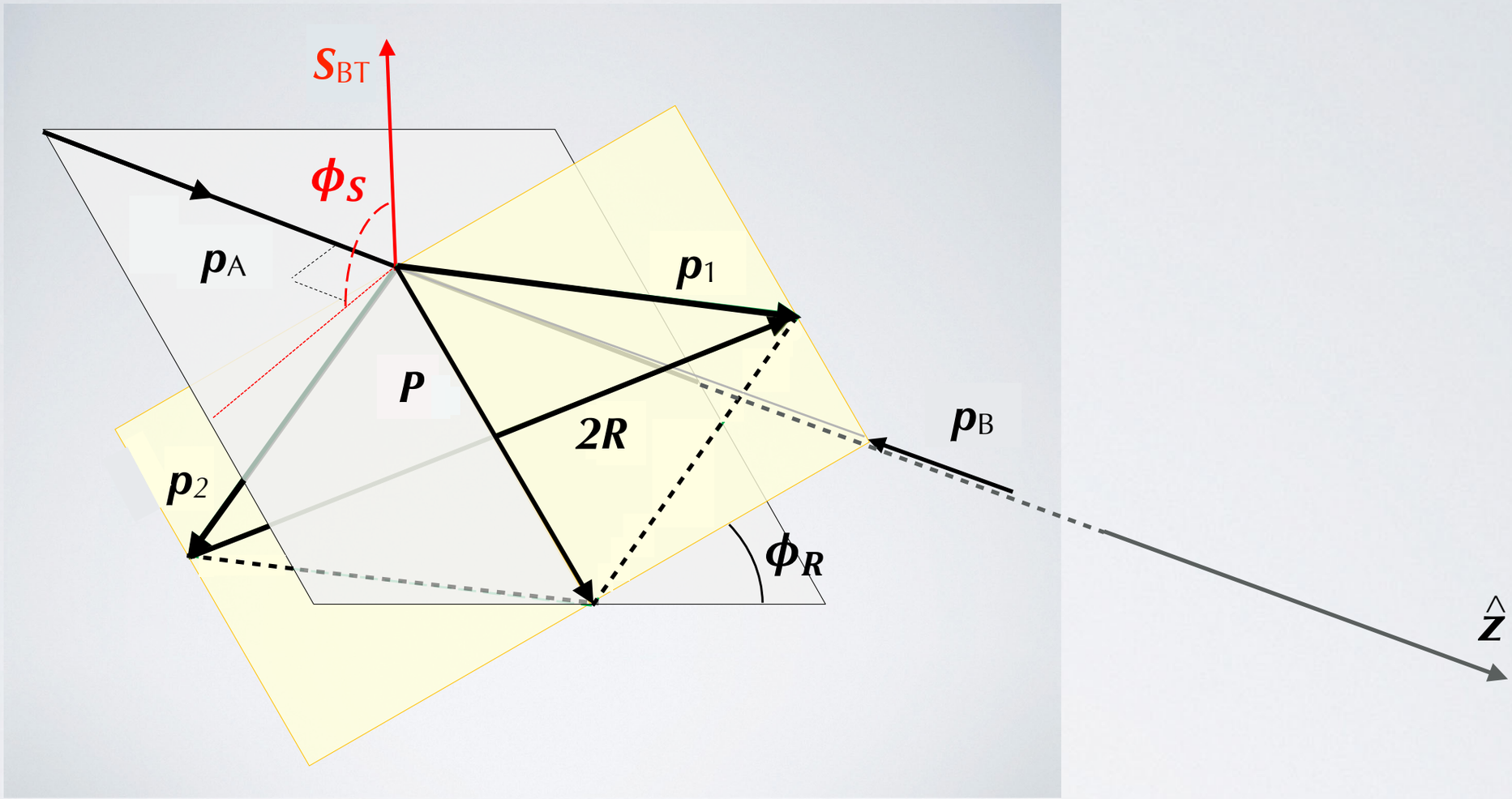
A.M. Ricci (Univ. Pavia)
[A. Mukherjee (IIT, Bombay)]

European Research Council

3DSPIN MAPPING THE PROTON IN 3D

INFN Istituto Nazionale di Fisica Nucleare

the process $p + p^{\uparrow} \rightarrow (\pi\,\pi) + X$



$$\cos\phi_{S_B} = \frac{(\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{P}})}{|\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{P}}|} \cdot \frac{(\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{S}}_B)}{|\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{S}}_B|}$$

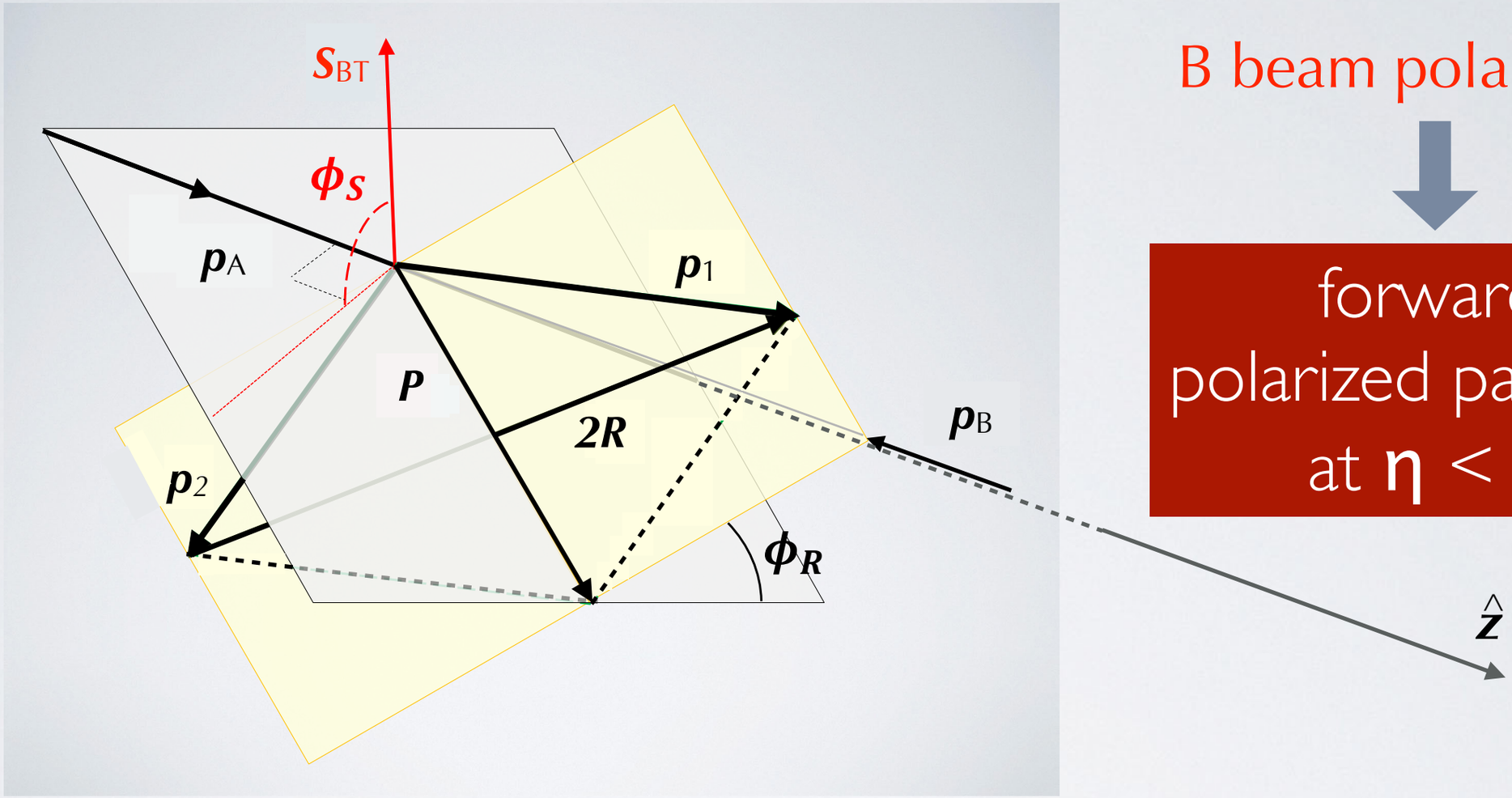
$$\cos\phi_R = \frac{(\hat{\boldsymbol{P}} \times \hat{\boldsymbol{P}}_A)}{|\hat{\boldsymbol{P}} \times \hat{\boldsymbol{P}}_A|} \cdot \frac{(\hat{\boldsymbol{P}} \times \hat{\boldsymbol{R}})}{|\hat{\boldsymbol{P}} \times \hat{\boldsymbol{R}}|}$$

unpolarized cross section

search for $d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$

*Bacchetta & Radici, P.R. D**70** (04) 094032*

the process $p + p^{\uparrow} \rightarrow (\pi\,\pi) + X$



B beam polarized

forward polarized particles at $\eta < 0$

$$\cos\phi_{S_B} = \frac{(\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{P}})}{|\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{P}}|} \cdot \frac{(\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{S}}_B)}{|\hat{\boldsymbol{P}}_B \times \hat{\boldsymbol{S}}_B|}$$

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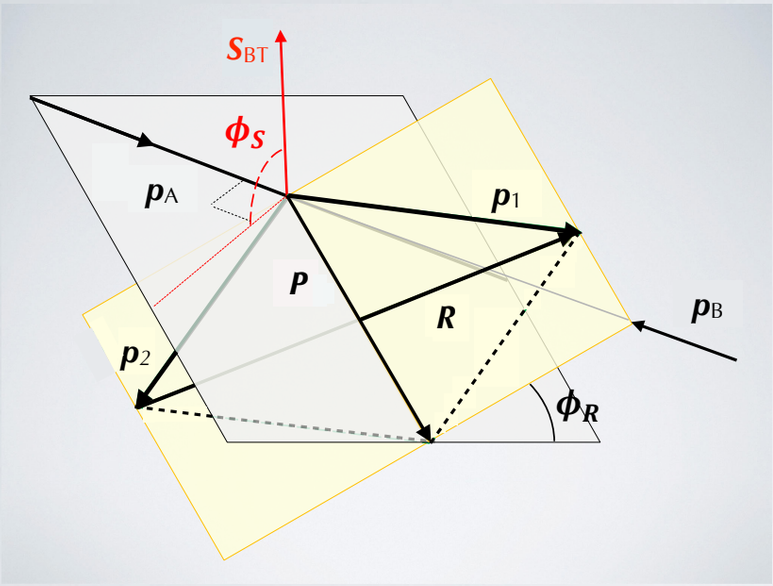


$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$

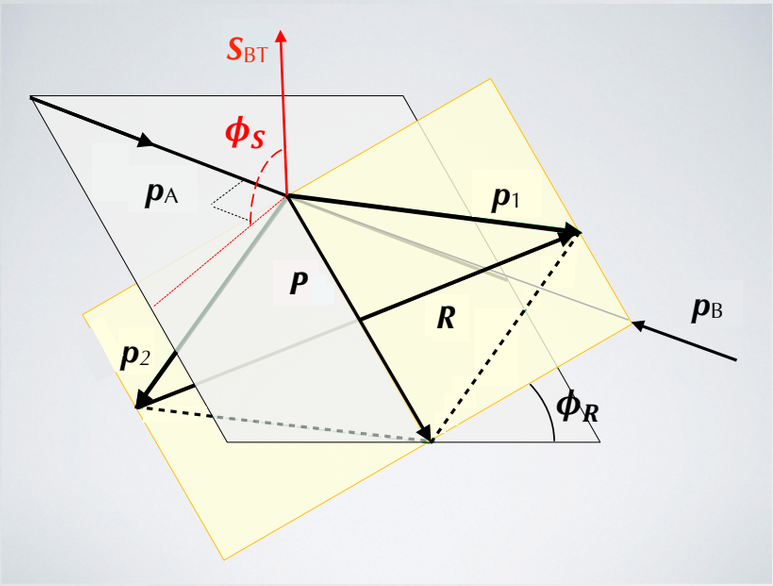
$$d\sigma^0 \sim f_1^a \otimes f_1^b \otimes d\hat{\sigma}_{ab\rightarrow cd} \otimes (\, D_1^c + \ldots \,)$$

$$d\sigma_{UT} \sim f_1^a \otimes \mathbf{h_1^b} \otimes d\Delta\hat{\sigma}_{a\mathbf{b}^{\uparrow}\rightarrow \mathbf{c}^{\uparrow}d} \otimes (\, \sin\theta \;\; H_{1,sp}^{\sphericalangle\, \mathbf{c}} + \ldots \,)$$

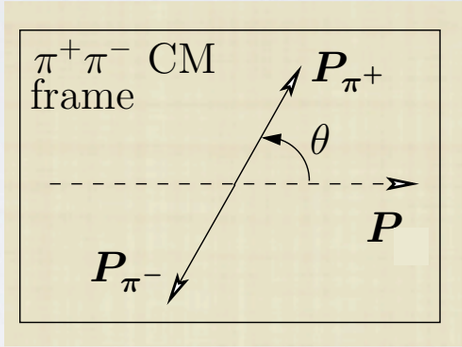
ab → cd
all possible combinations
of quarks & gluons

Bacchetta & Radici,
*P.R. D**70** (04) 094032*

the process $p + p^{\uparrow} \rightarrow (\pi\,\pi) + X$



$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$



$$d\sigma^0 \sim f_1^a \otimes f_1^b \otimes d\hat{\sigma}_{ab\rightarrow cd} \otimes (\, D_1^c + \ldots\,)$$

$$\sim Im[\ |(\pi^+,\pi^-)_s\rangle\langle(\pi^+,\pi^-)_p|\ ]$$

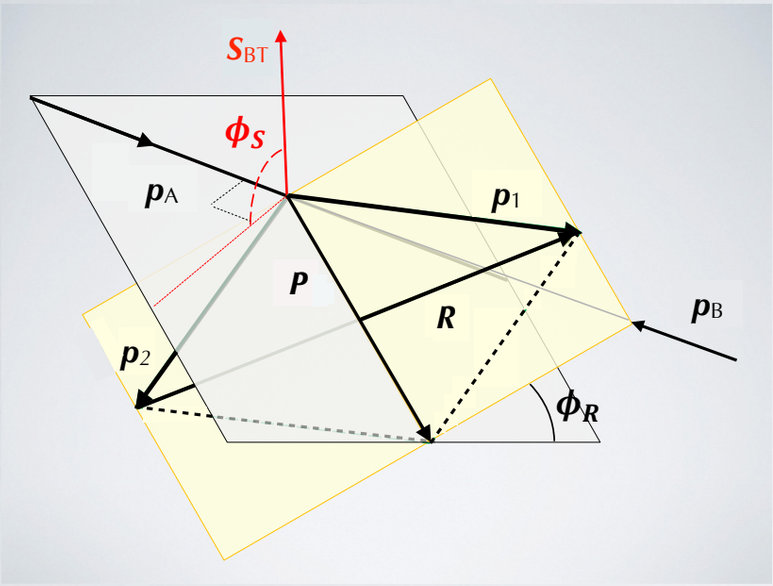
$$d\sigma_{UT} \sim f_1^a \otimes \mathbf{h_1^b} \otimes d\Delta\hat{\sigma}_{a\mathbf{b}^{\uparrow}\rightarrow \mathbf{c}^{\uparrow}d} \otimes (\, \sin\theta\ \ H_{1,sp}^{\sphericalangle\, \mathbf{c}} + \ldots\,)$$

Interference
Fragm. **F**unct.

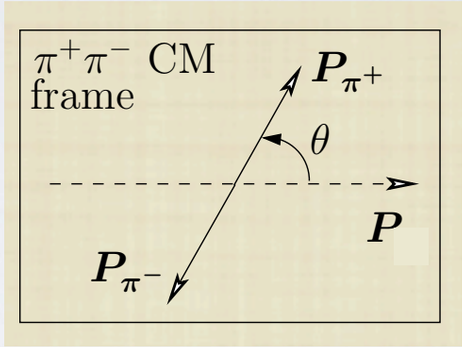
ab → cd
all possible combinations
of quarks & gluons

Bacchetta & Radici,
*P.R. D**70** (04) 094032*

the process $p + p^{\uparrow} \rightarrow (\pi\,\pi) + X$



$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$



$$d\sigma^0 \sim f_1^a \otimes f_1^b \otimes d\hat{\sigma}_{ab\to cd} \otimes (\, D_1^c + \ldots\,)$$

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Interference Fragm. Funct.

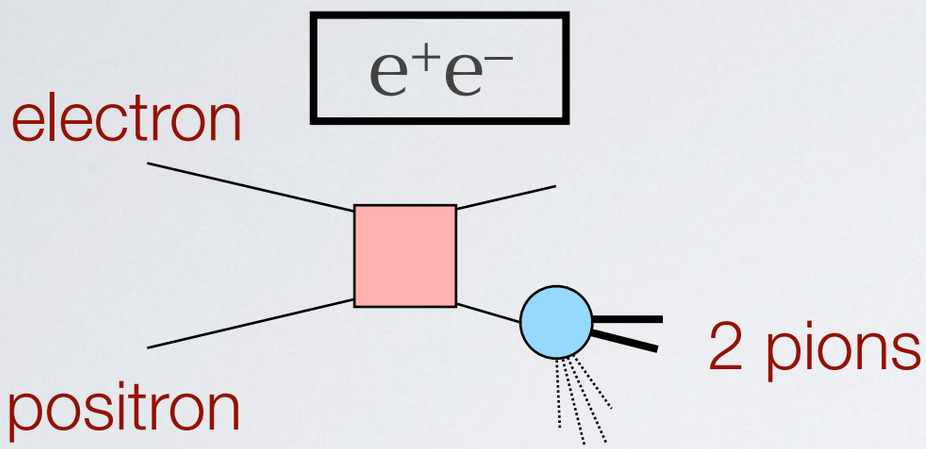
ab → cd
all possible combinations
of quarks & gluons

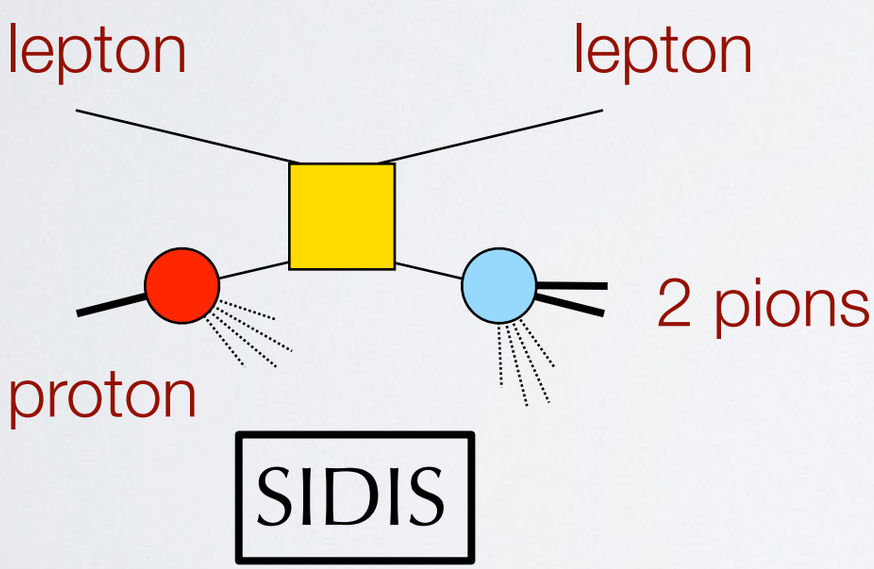
same Transversity and IFF
extracted from SIDIS & e+e−

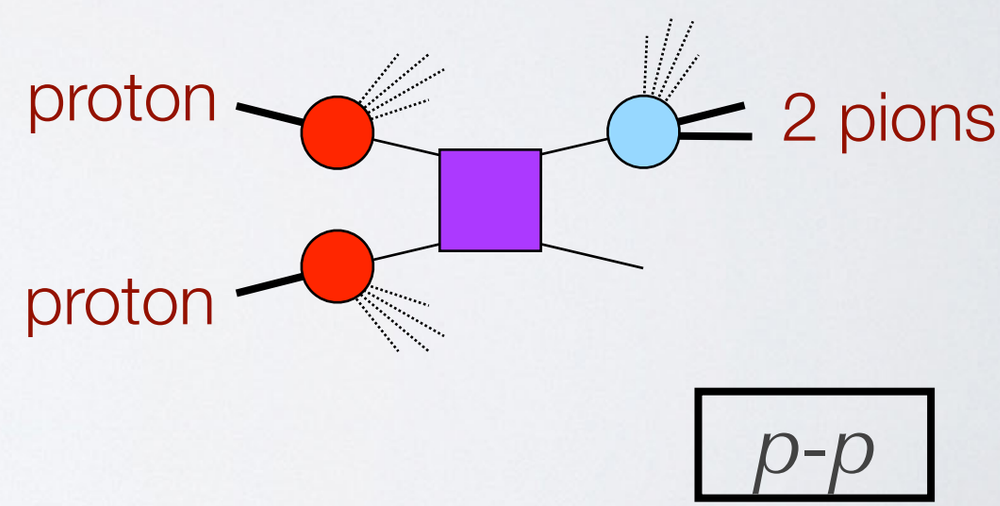
Bacchetta & Radici,
*P.R. D**70** (04) 094032*

collinear factorization in hard processes

(at one loop)







collinear factorization in hard processes

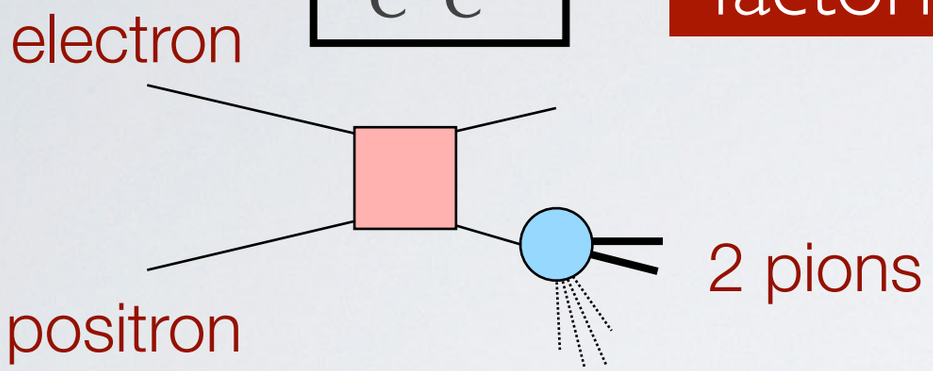
(at one loop)

Artru & Collins, Z.Phys. ***C69*** *(96) 277*
*Boer, Jakob, Radici, P.R.D****67*** *(03) 094003*

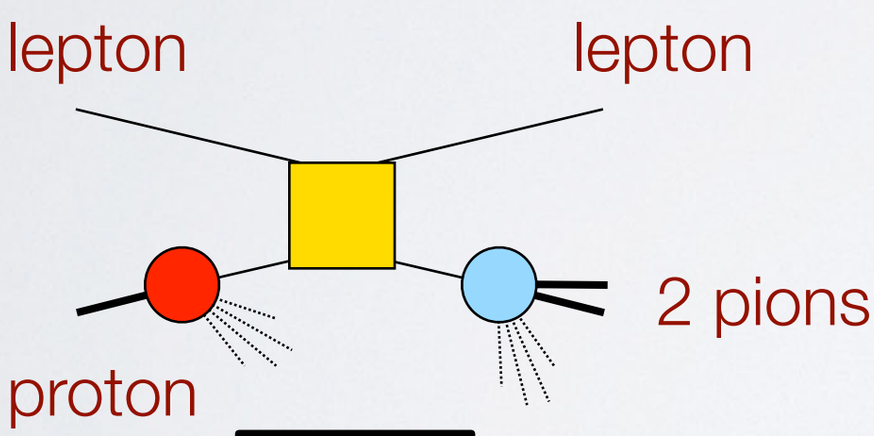
*DeFlorian & Vanni, P.L.****B578*** *(04) 139*
*Ceccopieri, Radici, Bacchetta, P.L.****B650*** *(07) 81*
(see also
Zhou and Metz, P.R.L. ***106*** *(11) 172001*
for M_h—evolution of DiFFs)

e^+e^-

factorization

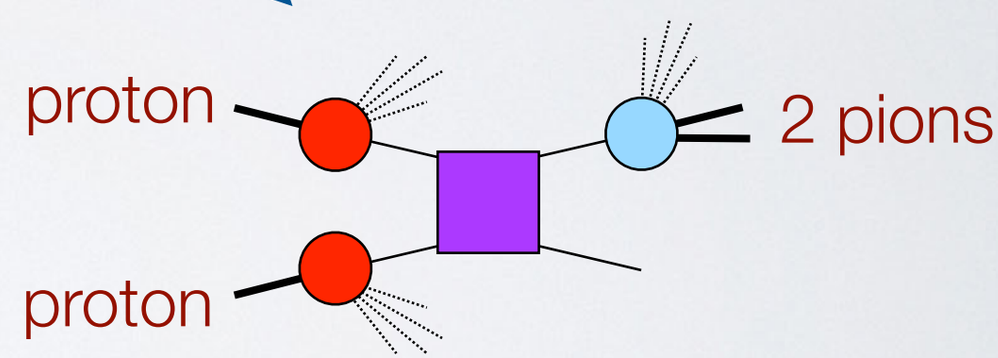


standard DGLAP evolution eq.'s



SIDIS

factorization



factorization

p-p

*Jaffe, Jin, Tang, P.R.L.****80*** *(98) 1166*
*Radici, Jakob, Bianconi, P.R.D****65*** *(02) 074031*
*Bacchetta & Radici, P.R. D****67*** *(03) 094002*

*Bacchetta & Radici, P.R. D****70*** *(04) 094032*

$p + p^{\uparrow} \to (\pi\,\pi) + X$: A_{UT} (....)

$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$

$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma^0}$$

$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_1^c(\bar{z}, M)$$

$$\hat{t} = t\, x_a/\bar{z}$$

$$\frac{d\sigma_{UT}}{d\eta\, d|\boldsymbol{P}_T|\, dM} = |\boldsymbol{S}_{BT}|\, 2\,|\boldsymbol{P}_T|\, \frac{|\boldsymbol{R}|}{M}\, \sin\theta \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}}\, H_1^{\sphericalangle c}(\bar{z}, M)$$

what does A_{UT} depend on ?

$p + p^{\uparrow} \to (\pi\,\pi) + X$: A_{UT} (M, ...)

$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$

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what does A_{UT} depend on ?

$$\frac{|\boldsymbol{R}|}{M} = \frac{1}{2}\sqrt{1 - 4\frac{m_\pi^2}{M^2}}$$

M = invariant mass of ($\pi\ \pi$)

$p + p^{\uparrow} \to (\pi\,\pi) + X$: A_{UT} (M, η, ...)

$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$

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$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_1^{\pi}(\bar{z}, M)$$

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what does A_{UT} depend on ?

η = pseudorapidity

conservation of momenta in $ab \to cd$

⇒ (ππ) fract. energy fixed to

$$\bar{z} = \frac{|\boldsymbol{P}_T|}{\sqrt{s}}\, \frac{x_a e^{-\eta} + x_b e^{\eta}}{x_a x_b}$$

$p + p^{\uparrow} \to (\pi\,\pi) + X$: $A_{UT}\,(M, \eta, |P_T|)$

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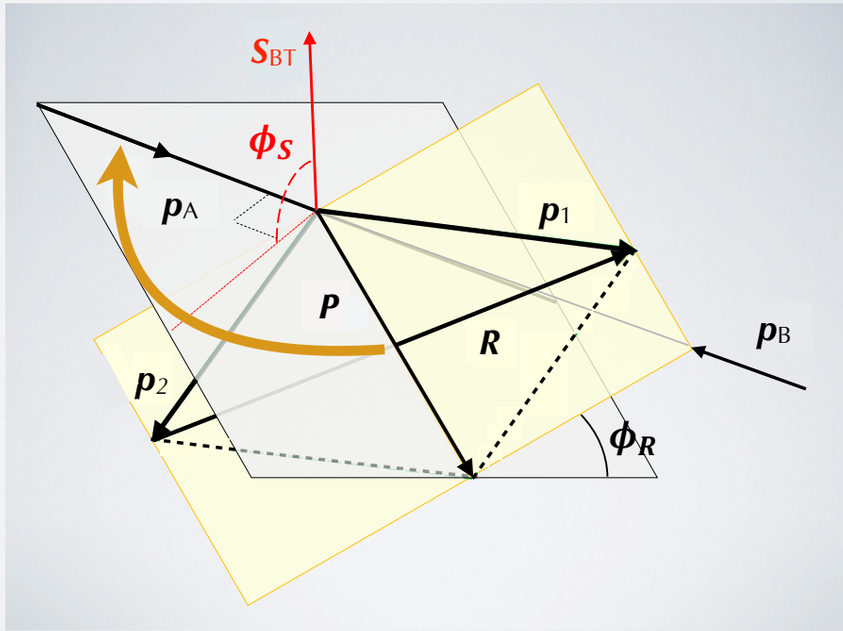
what does A_{UT} depend on ?

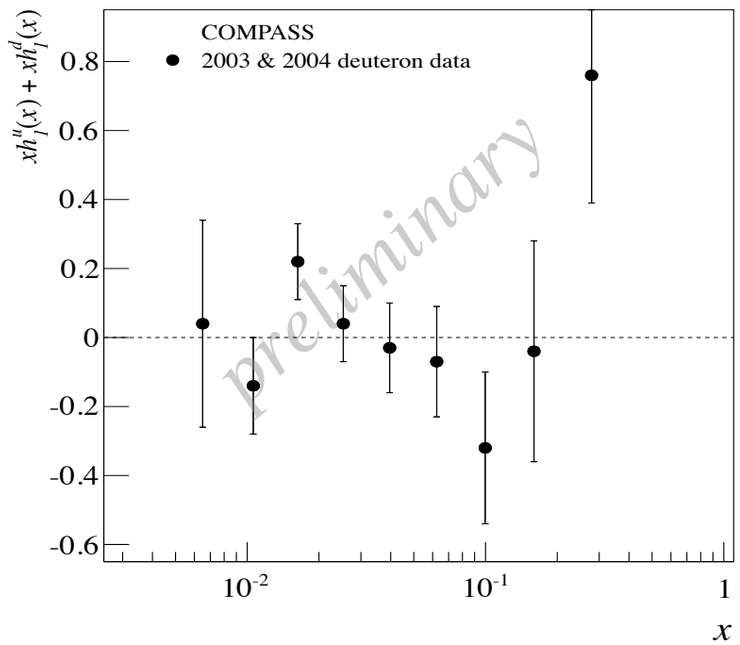
$|\boldsymbol{P}_T|$ = transverse component of pair total momentum with respect to A beam

hard scale $|\boldsymbol{P}_T| \gg M, M_A, M_B$

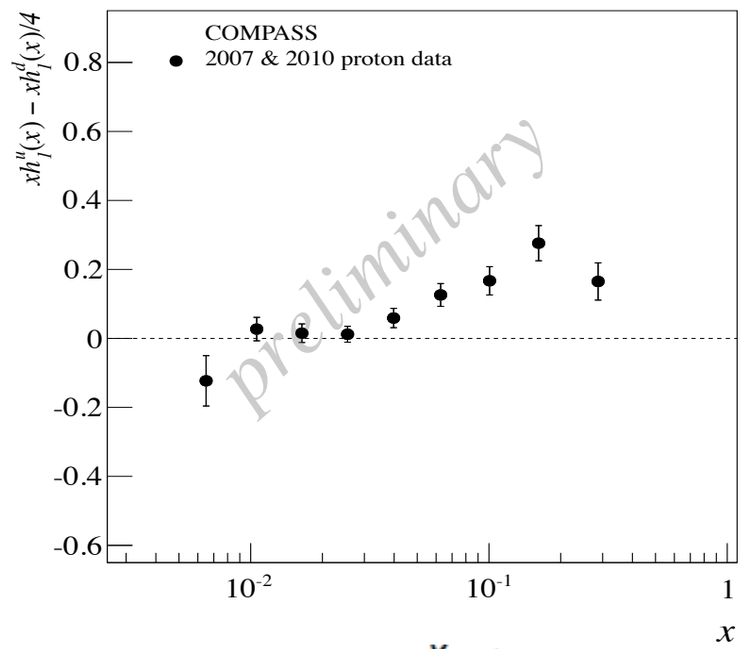


STAR kinematics complementary to SIDIS

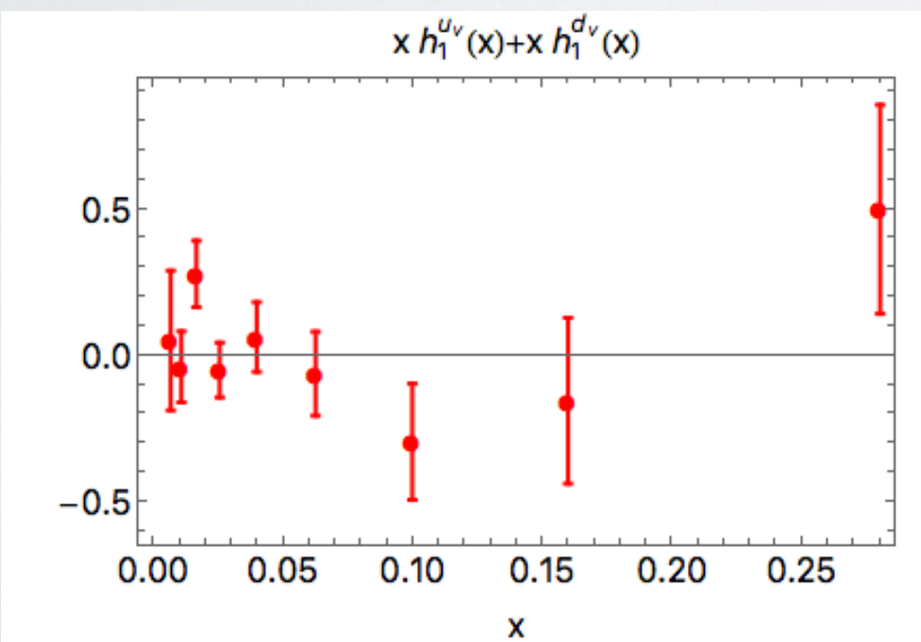
$xh_{1,d} = xh_1^u(x;Q^2) + xh_1^d(x;Q^2)$
from deuteron data:

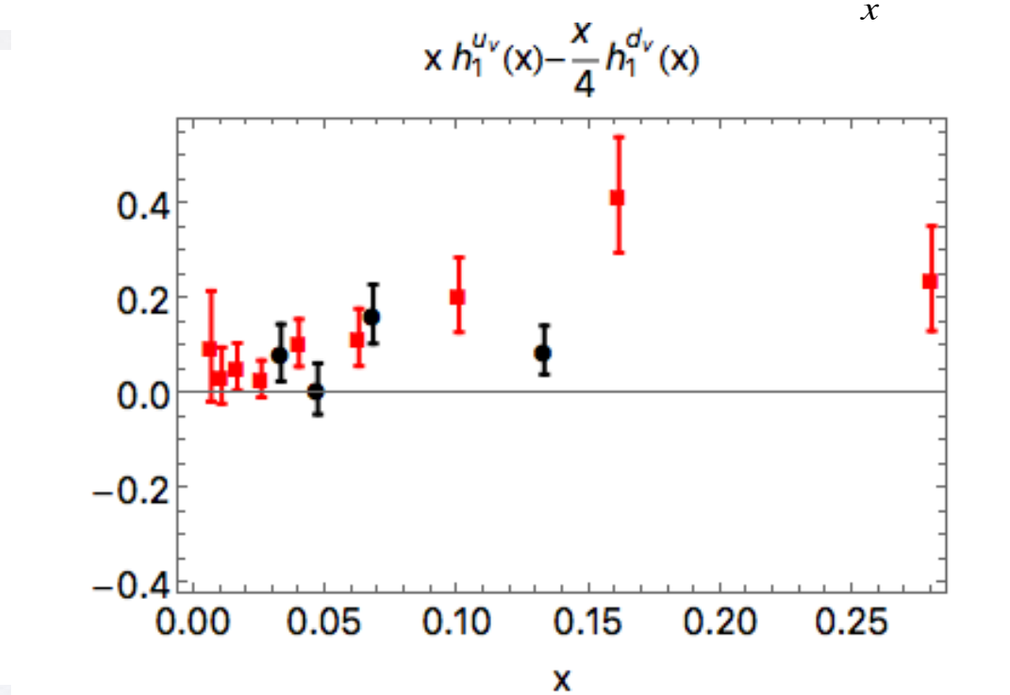


$xh_{1,p} = xh_1^u(x;Q^2) - \frac{1}{4}xh_1^d(x;Q^2)$
from proton data:



Braun et al.,
E.P.J. Web Conf. **85** (15) 02018





Airapetian et al.,
JHEP **0806** (08) 017

Adolph et al.,
P.L. **B713** (12)

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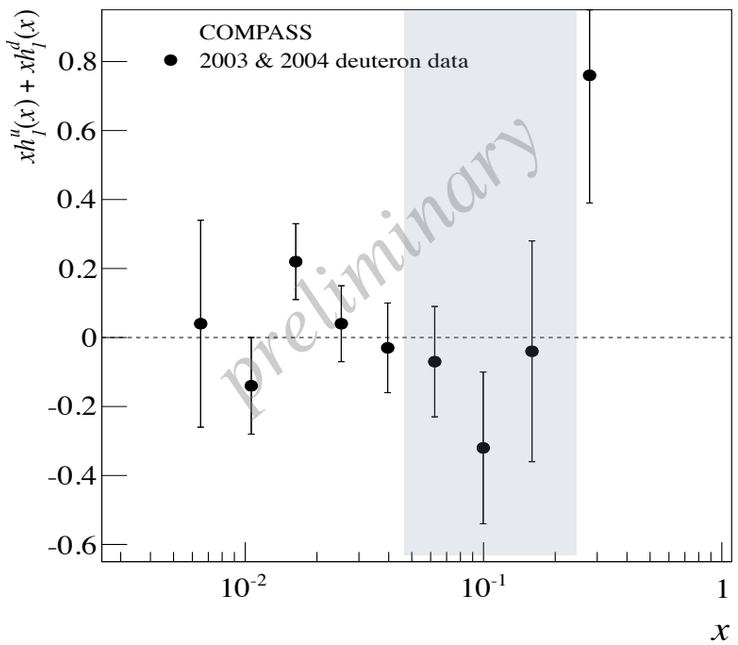

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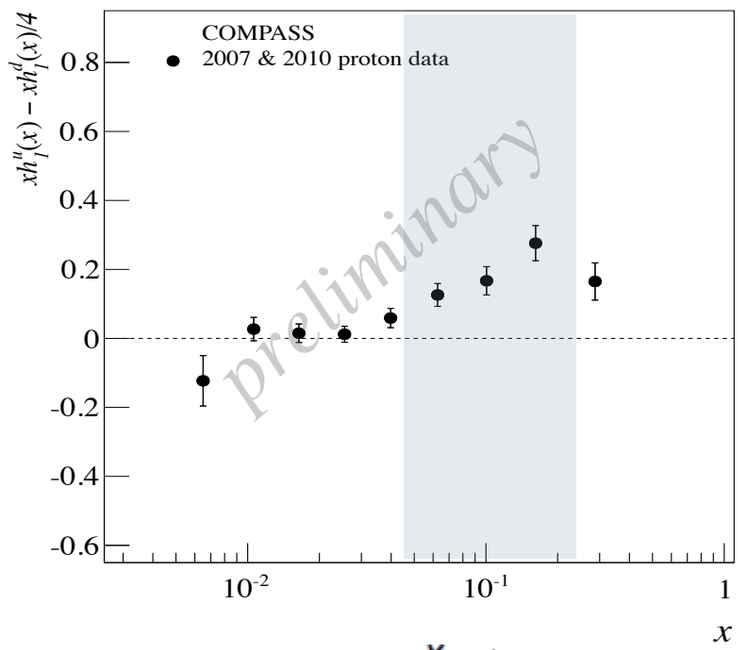

Braun et al.,
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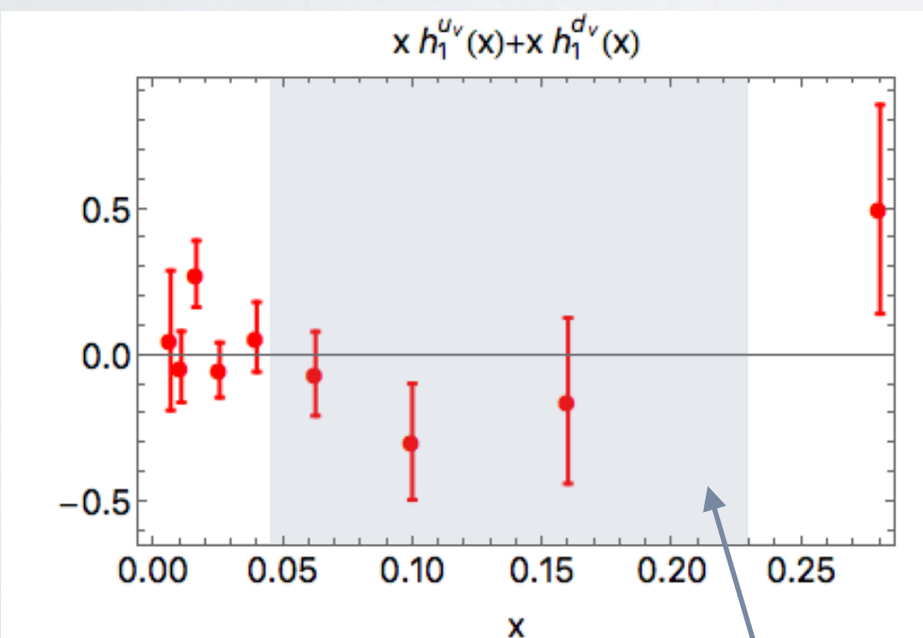
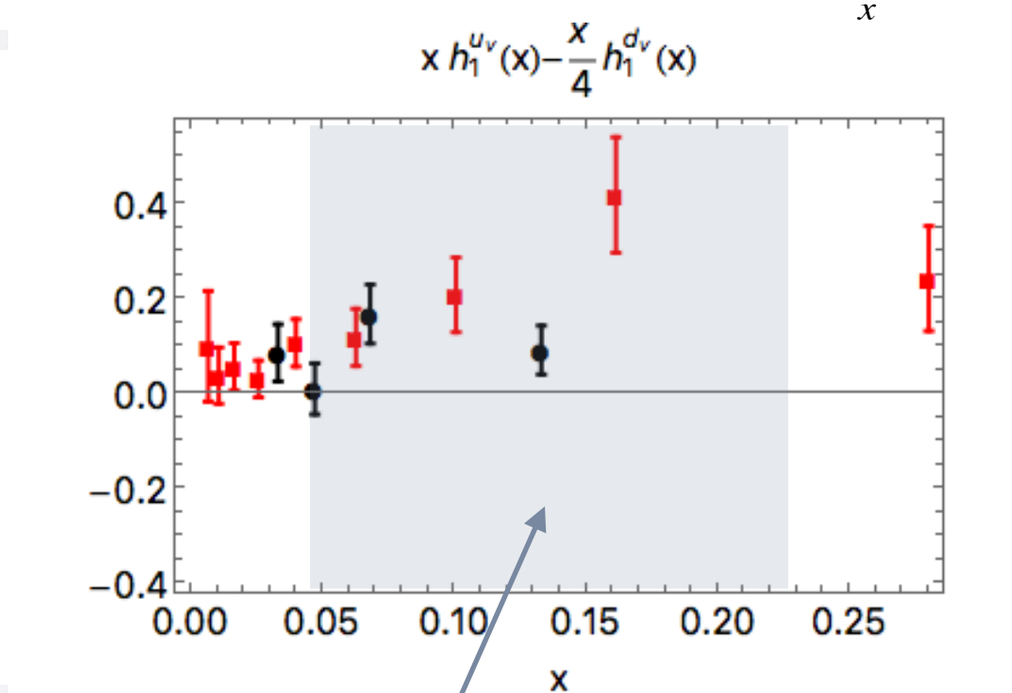


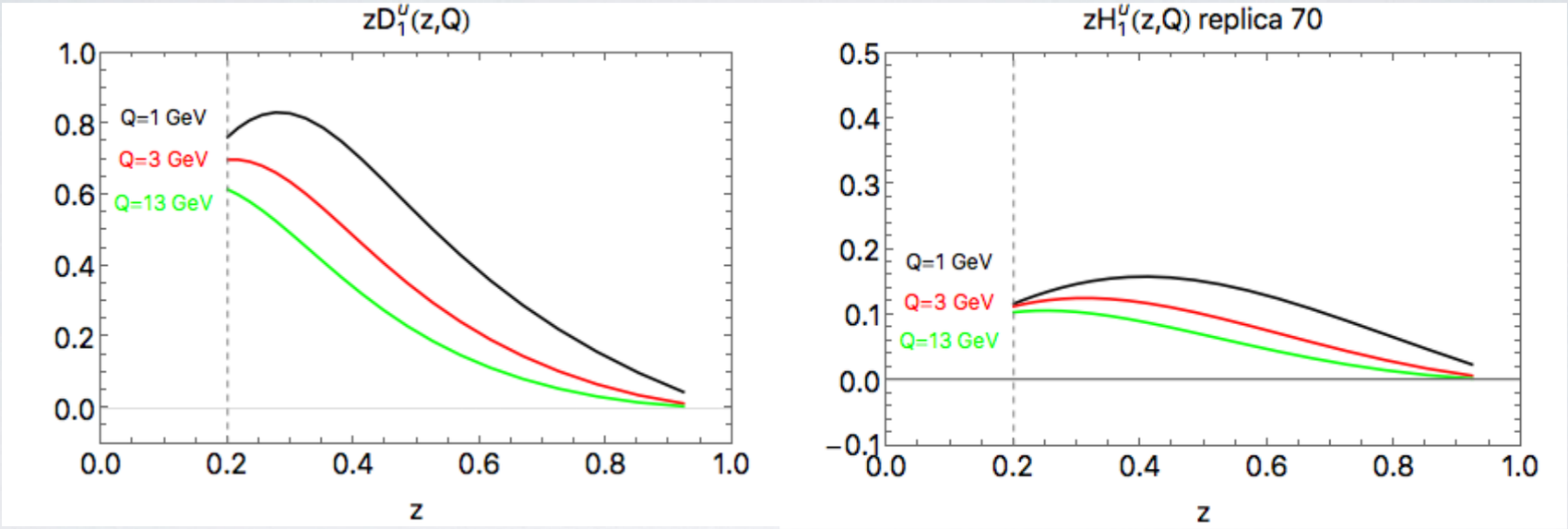


Airapetian et al.,
JHEP **0806** (08) 017

Adolph et al.,
P.L. **B713** (12)

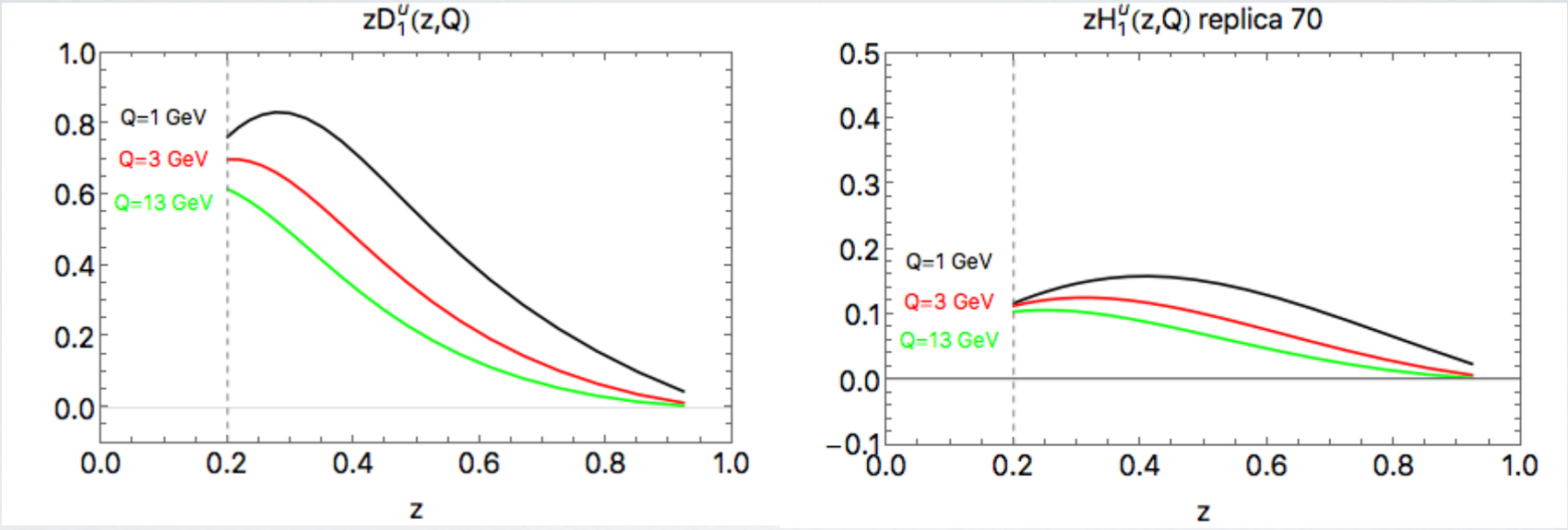
coverage at effective high Q^2

… and complementary to e+e−



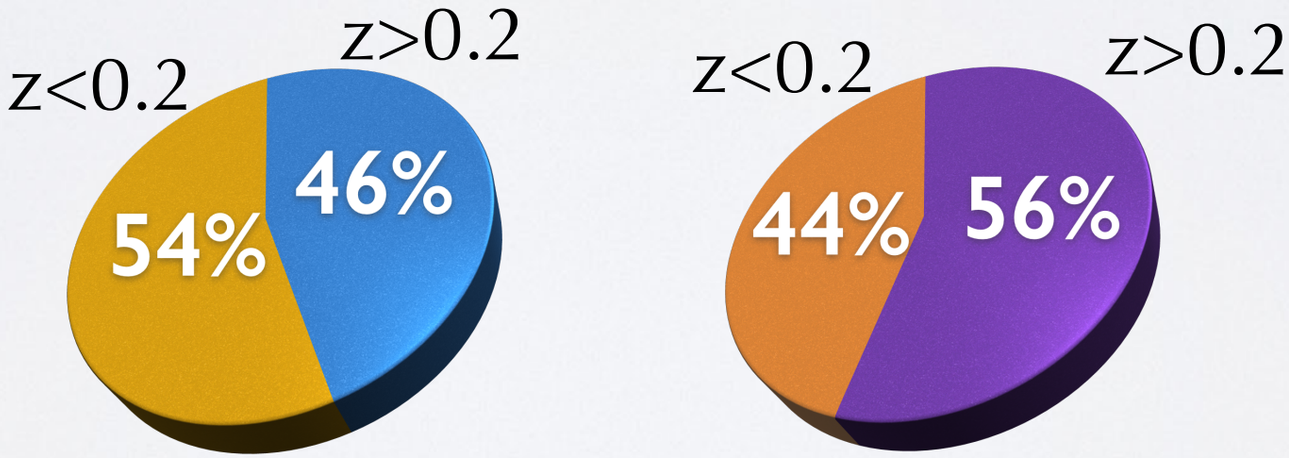
e+e− data do not constrain DiFFs at $z < 0.2$

… and complementary to e+e−



e+e− data do not constrain DiFFs at $z < 0.2$

MC sample of $d\sigma^0$ ~ 47k pts



MC sample of $d\sigma_{UT}$ ~ 65k pts

but STAR kin. at $z < 0.2$ for ~ 50%

although contribution to integral is small

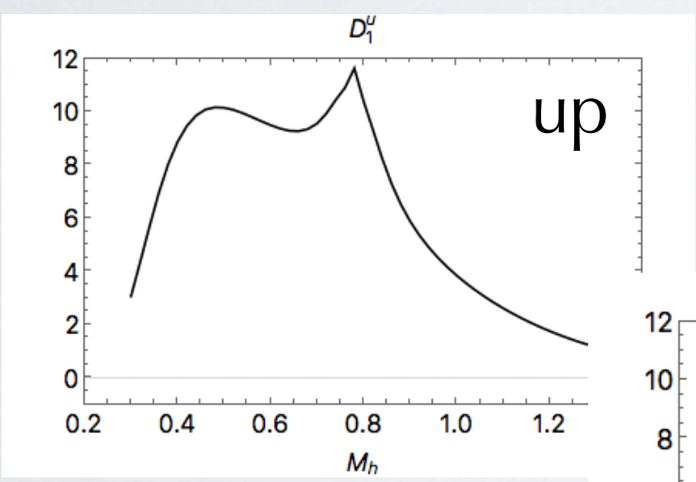
$D_1^q(z, M; Q)$ for $q = u, d, s, c$ at all z

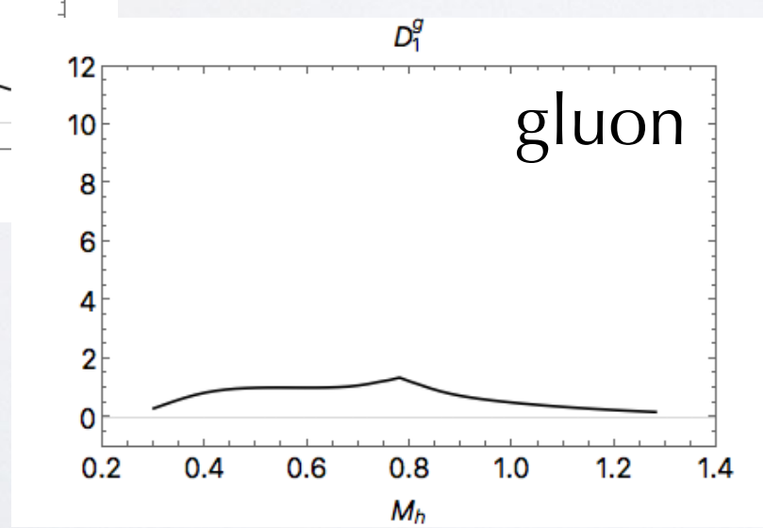
need $d\sigma^0$ for $p + p^{\uparrow} \rightarrow (\pi\pi) + X$

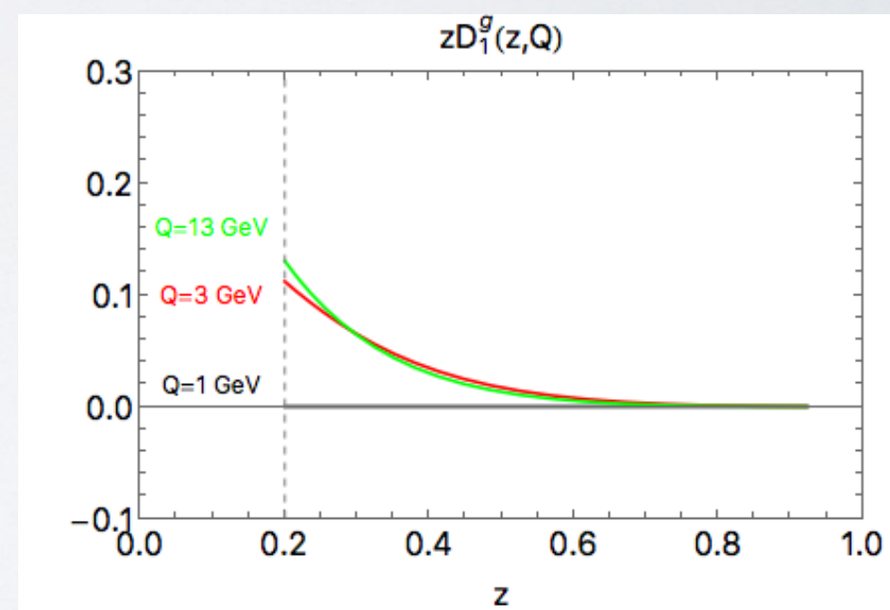
$D_1^q(z, M; Q)$ for $q = u, d, s, c$ at all z

need $d\sigma^0$ for $p + p^\uparrow \rightarrow (\pi\pi) + X$

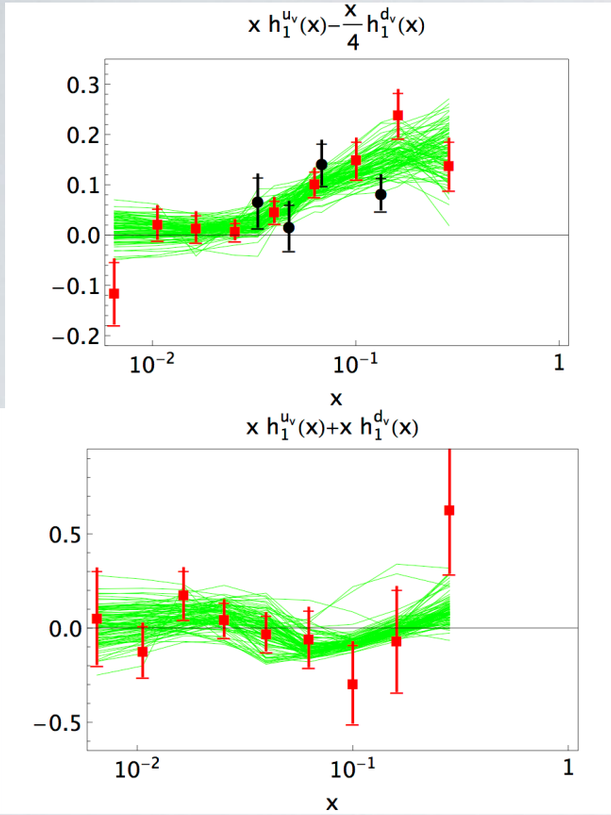
$D_1^g(z, M; Q)$ [now, $D_1^g(z, M; Q_0) = 0$]





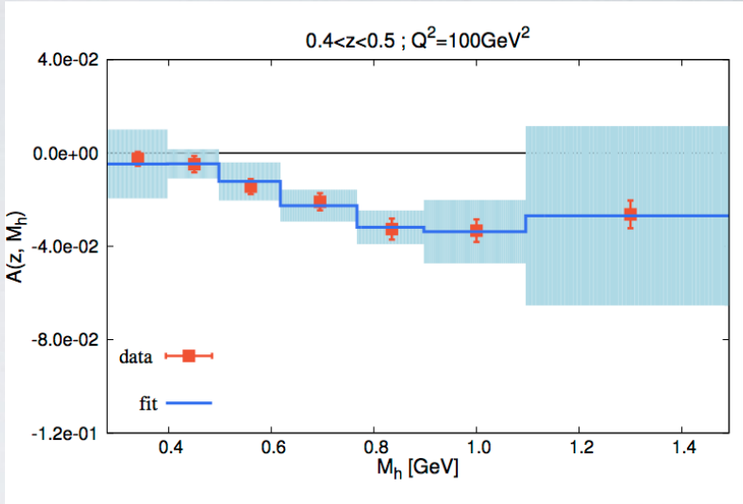


forward $A_{UT}(M)$



*Radici et al., JHEP **1505** (15) 123*

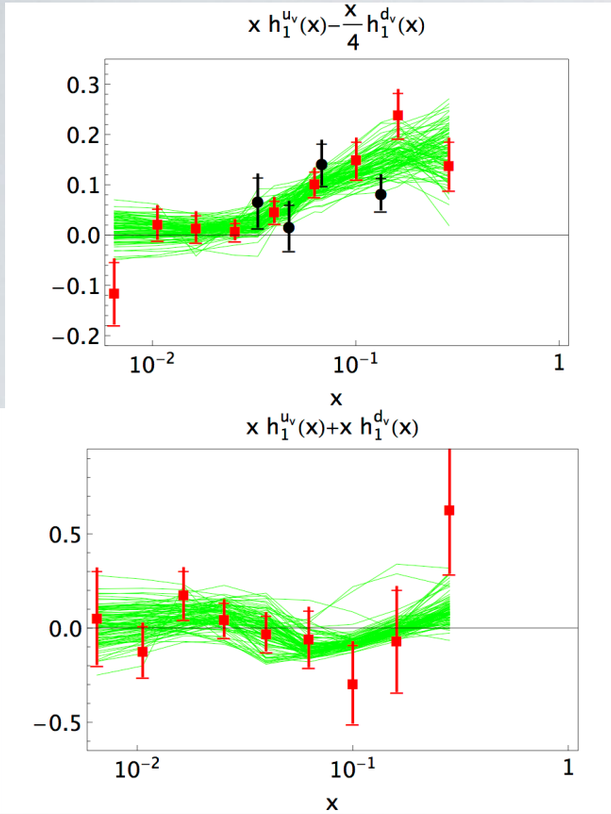
100 replicas
fitting SIDIS
$e+(p^{\uparrow}/D^{\uparrow}) \rightarrow e'+(\pi^+\pi^-)+X$



100 replicas
fitting
$e^+e^- \rightarrow (\pi^+\pi^-)+(\pi^+\pi^-)+X$

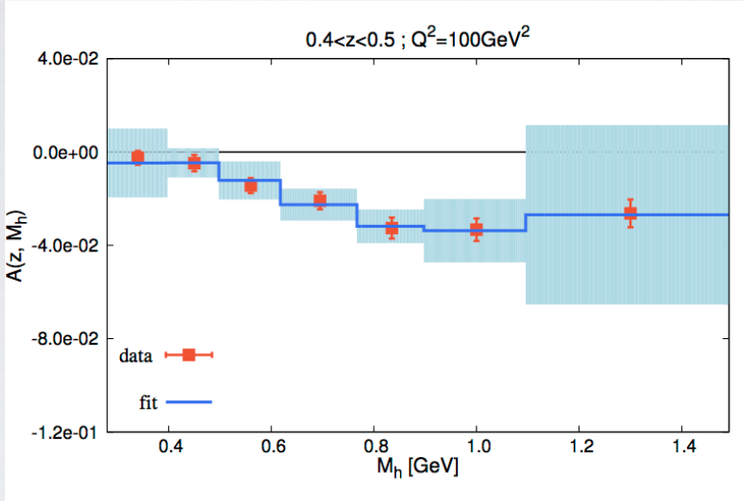
Courtoy et al.,
*P.R. D**85** (12) 114023*

forward $A_{UT}(M)$



*Radici et al., JHEP **1505** (15) 123*

100 replicas
fitting SIDIS
$e+(p^{\uparrow}/D^{\uparrow}) \rightarrow e'+(\pi^+\pi^-)+X$



100 replicas
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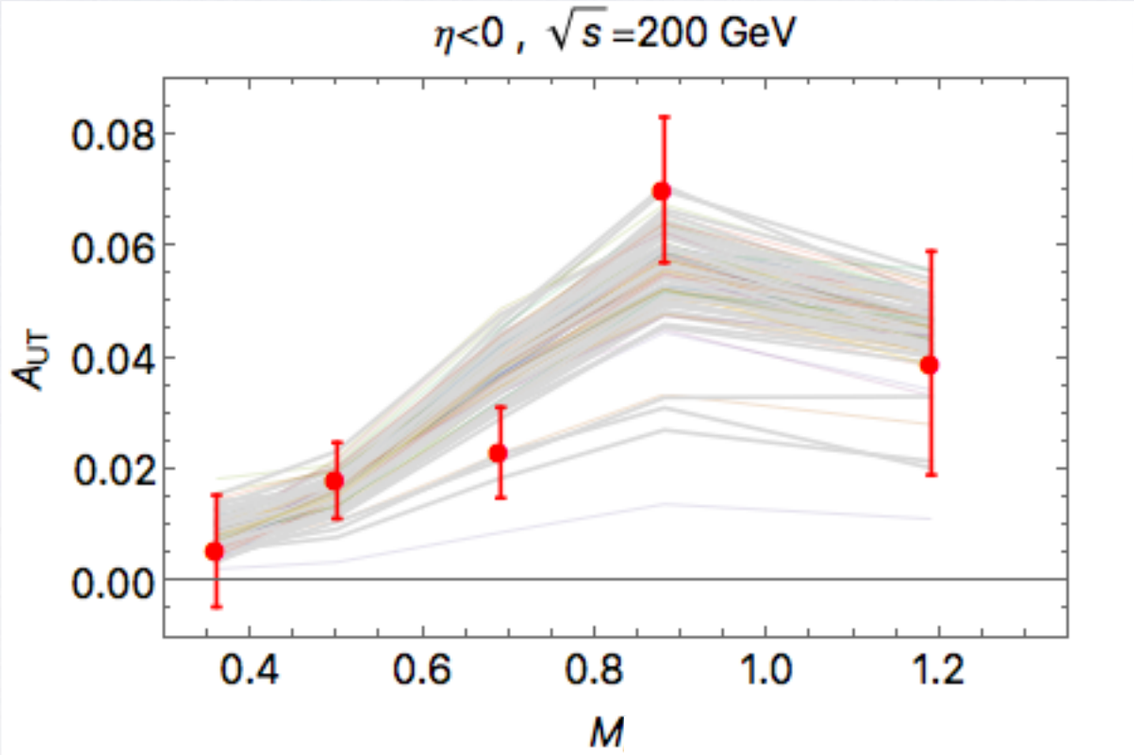
$e^+e^- \rightarrow (\pi^+\pi^-)+(\pi^+\pi^-)+X$

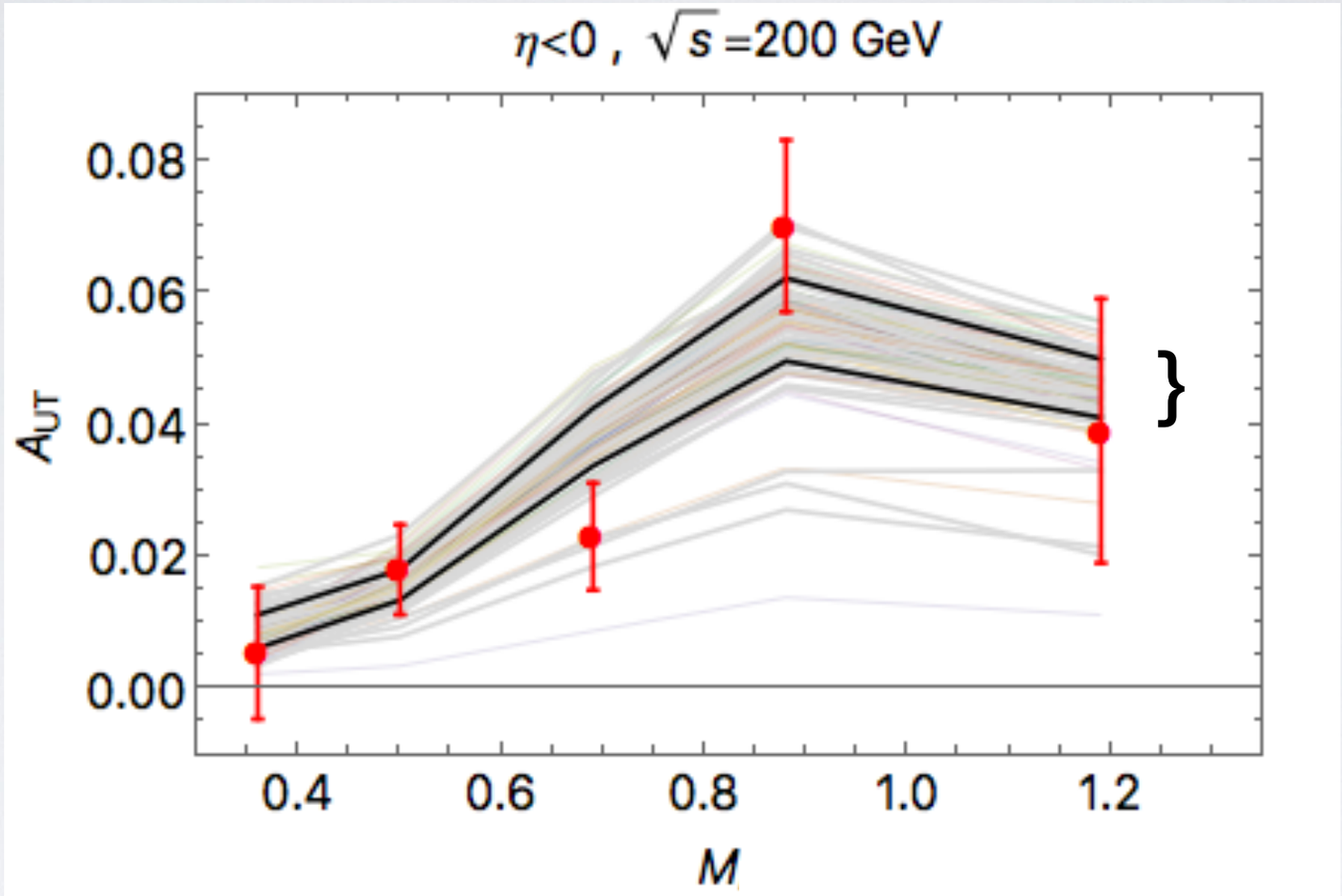
Courtoy et al.,
*P.R. D**85** (12) 114023*



prediction of STAR data for forward $A_{UT}(M)$

data from *Adamczyk et al. (STAR), P.R.L. **115** (15) 242501*

forward $A_{UT}(M)$



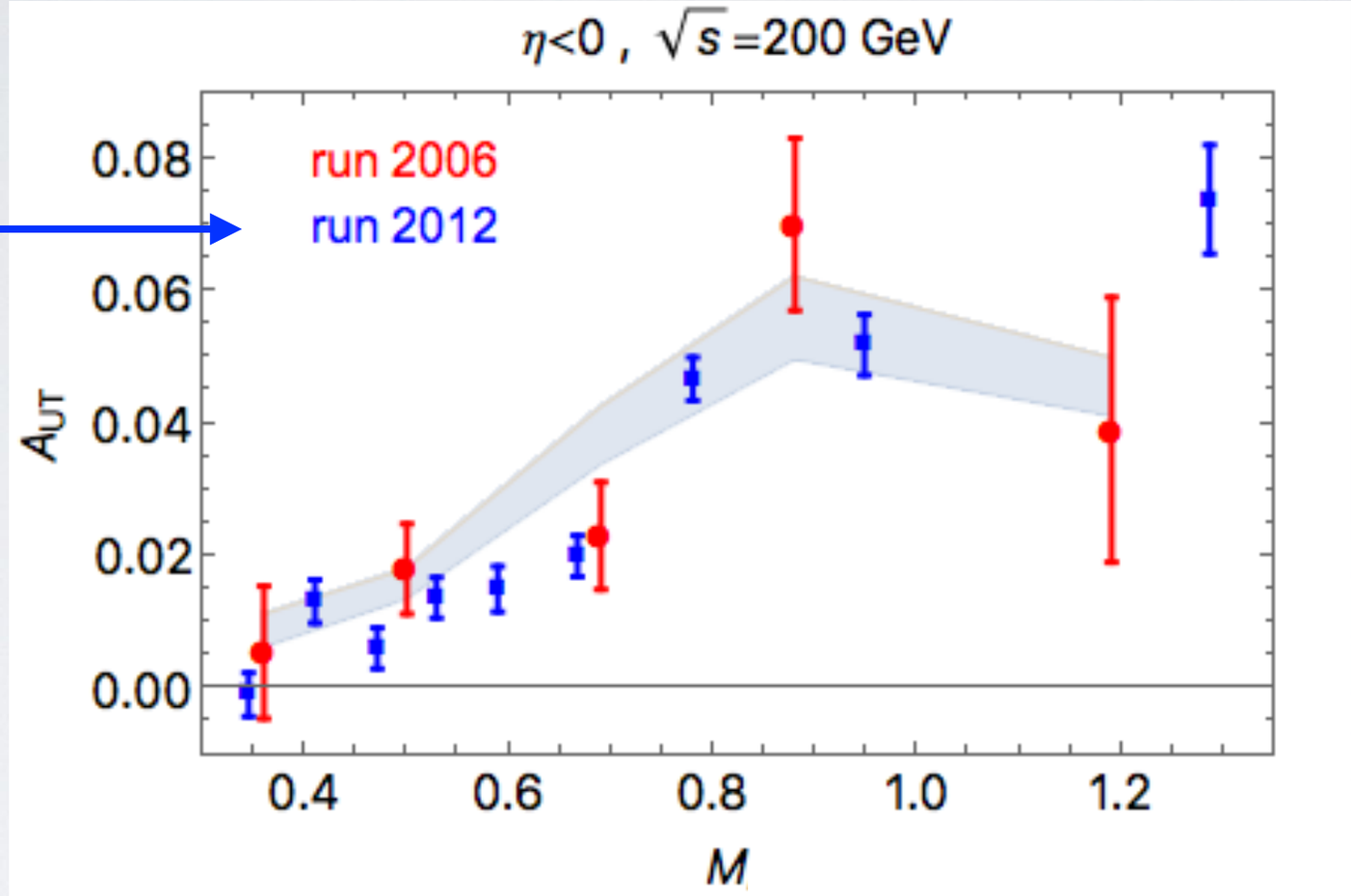
68%

prediction of STAR data using 68% of replicas forward $A_{UT}(M)$

data from *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

forward $A_{UT}(M)$

PRELIMINARY

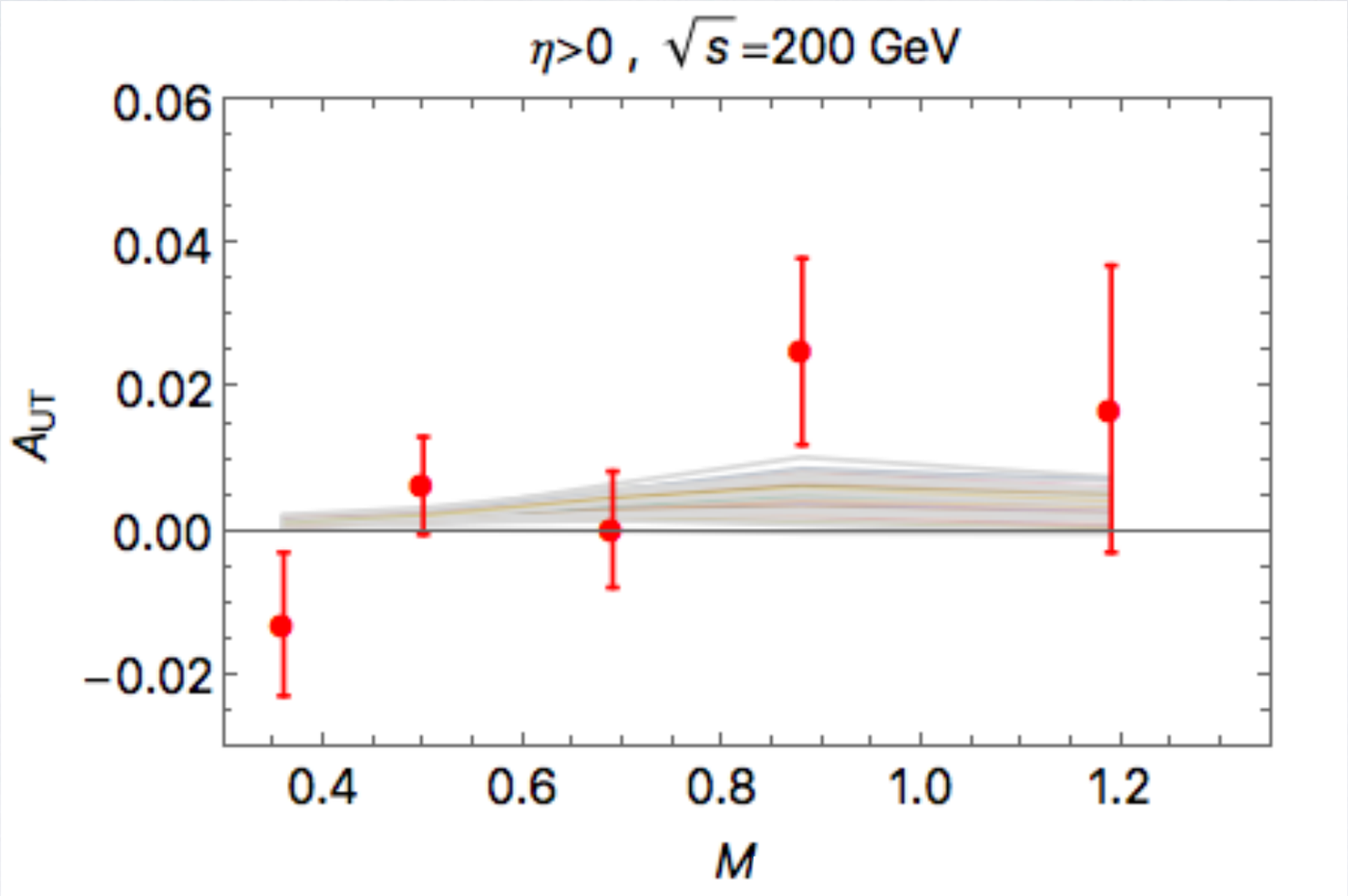


prediction of new STAR data using 68% of replicas
forward $A_{UT}(M)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

run 2012 *K. Landry, talk at APS 2015*

backward $A_{UT}(M)$

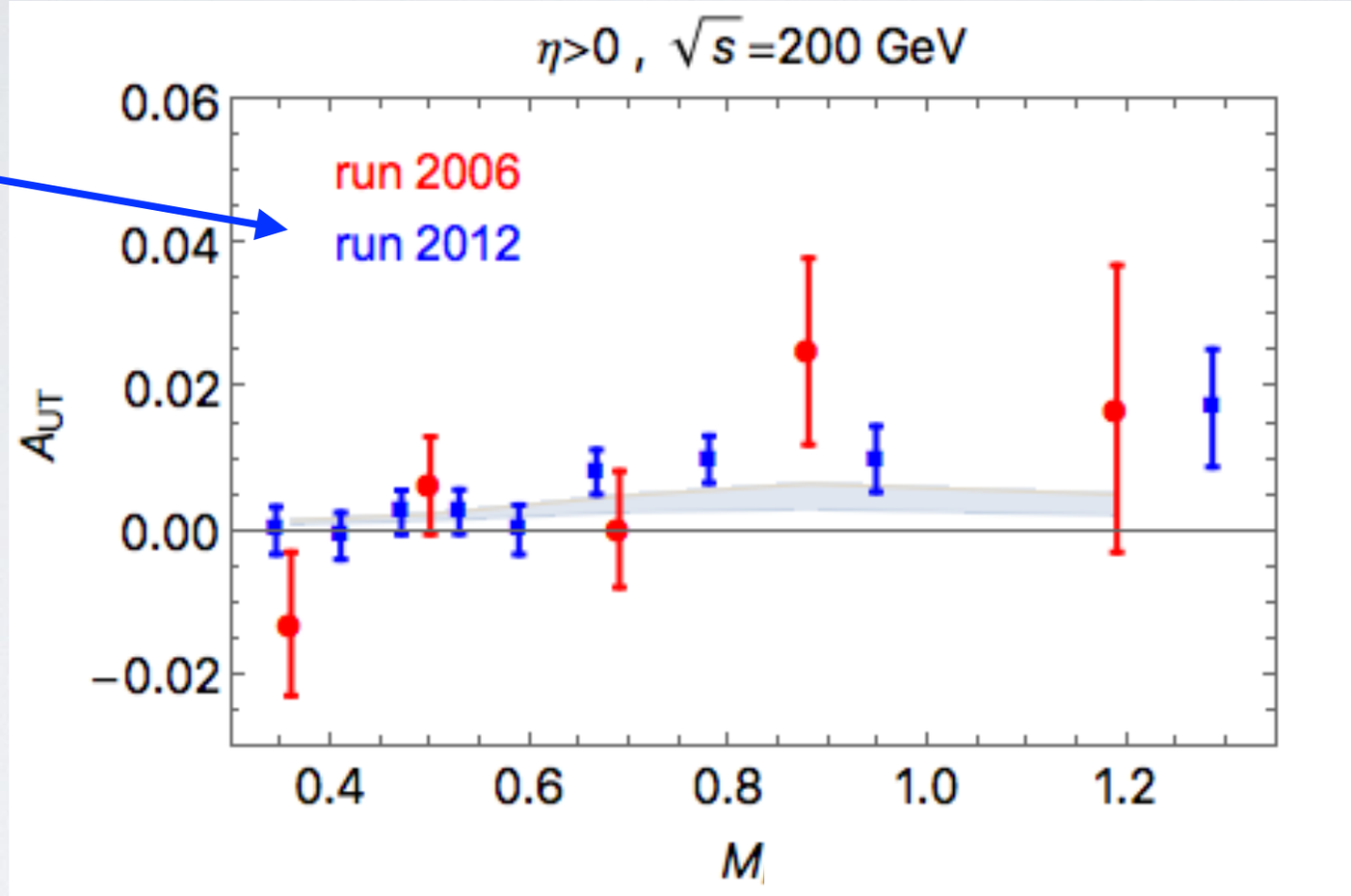


prediction of STAR data for backward $A_{UT}(M)$

data from *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

backward $A_{UT}(M)$

PRELIMINARY

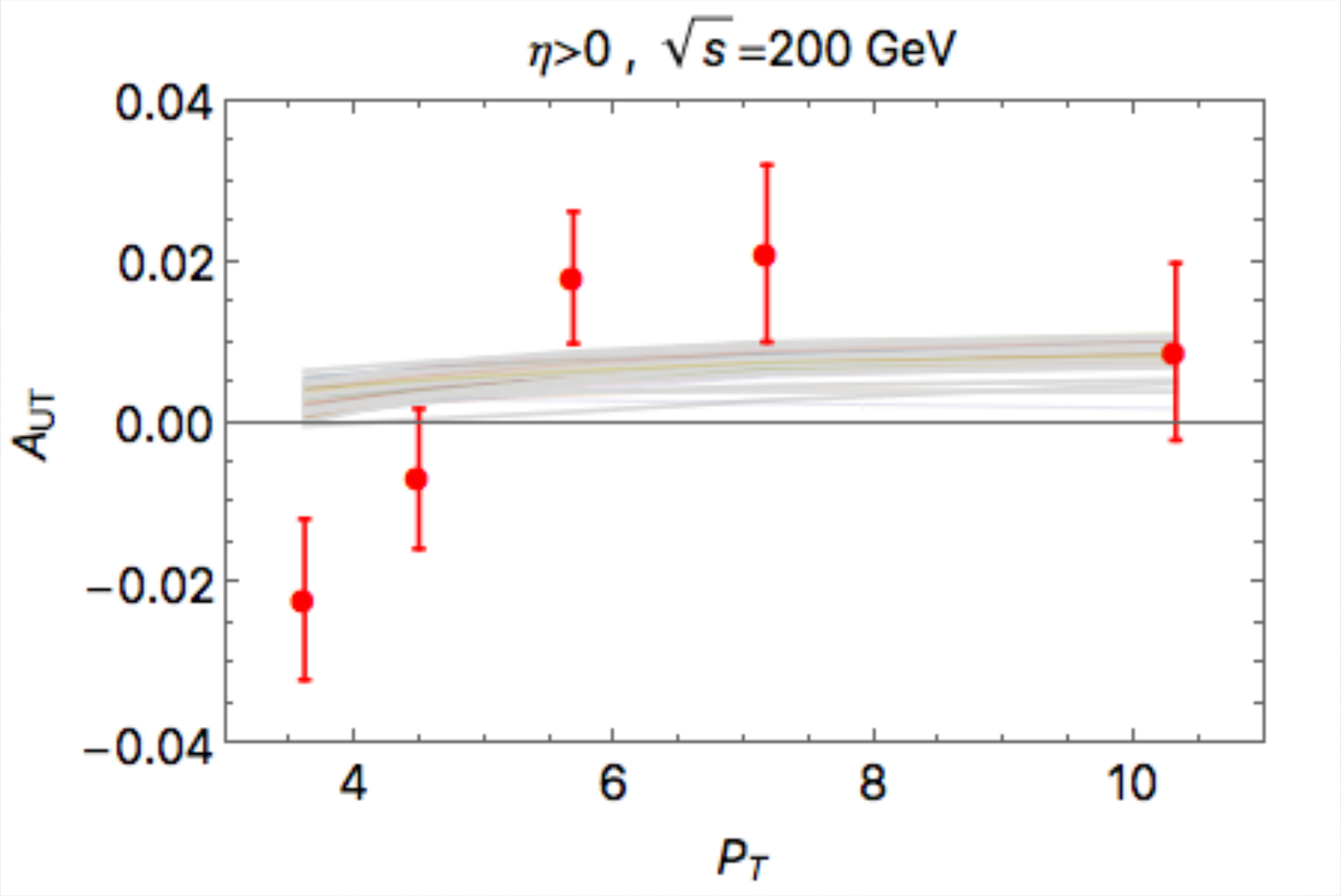


prediction of new STAR data using 68% of replicas
backward $A_{UT}(M)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

run 2012 *K. Landry, talk at APS 2015*

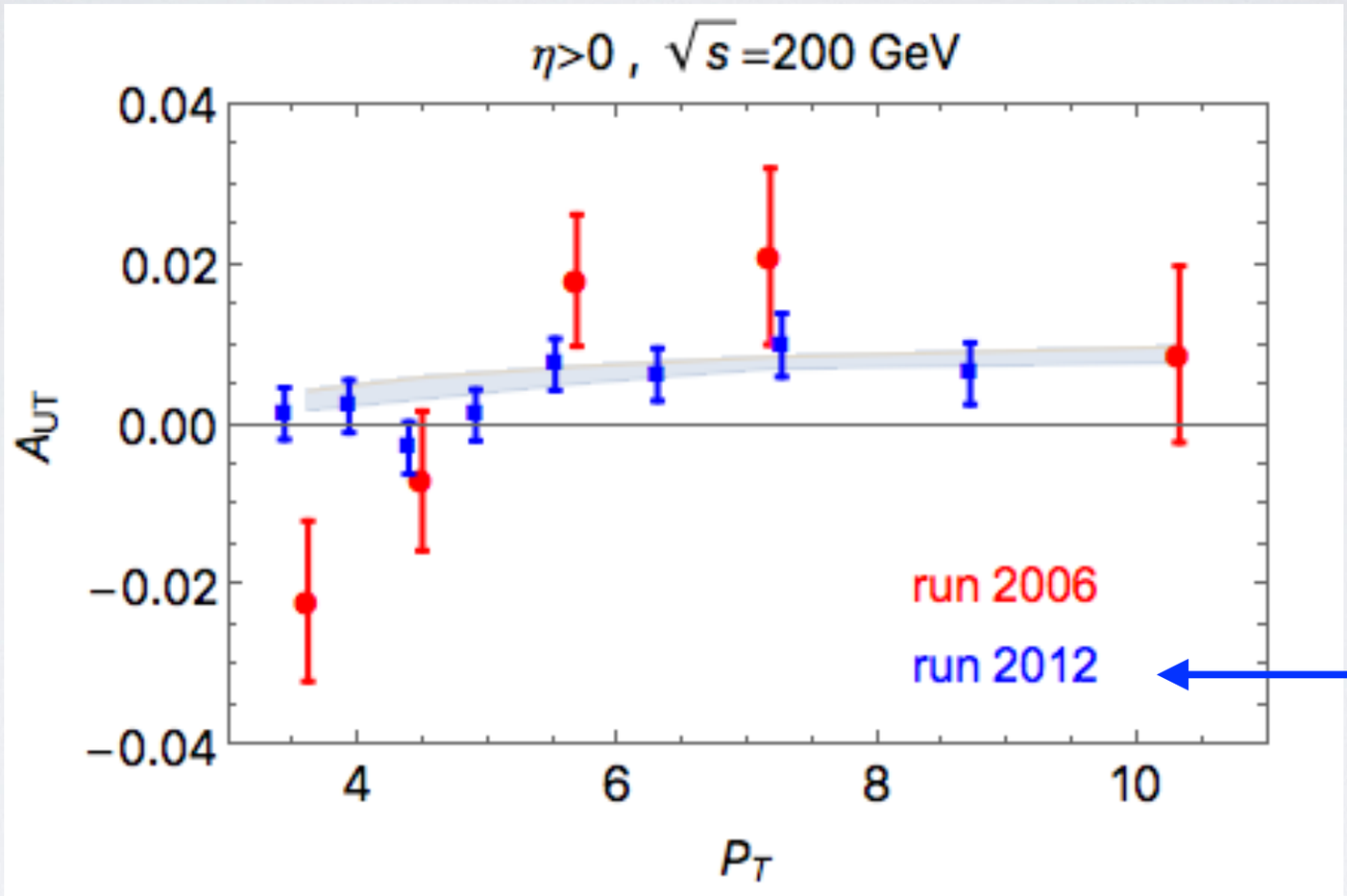
backward $A_{UT}(P_T)$



prediction of STAR data for backward $A_{UT}(P_T)$

data from *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

backward $A_{UT}(P_T)$



PRELIMINARY

prediction of new STAR data using 68% of replicas
backward $A_{UT}(P_T)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

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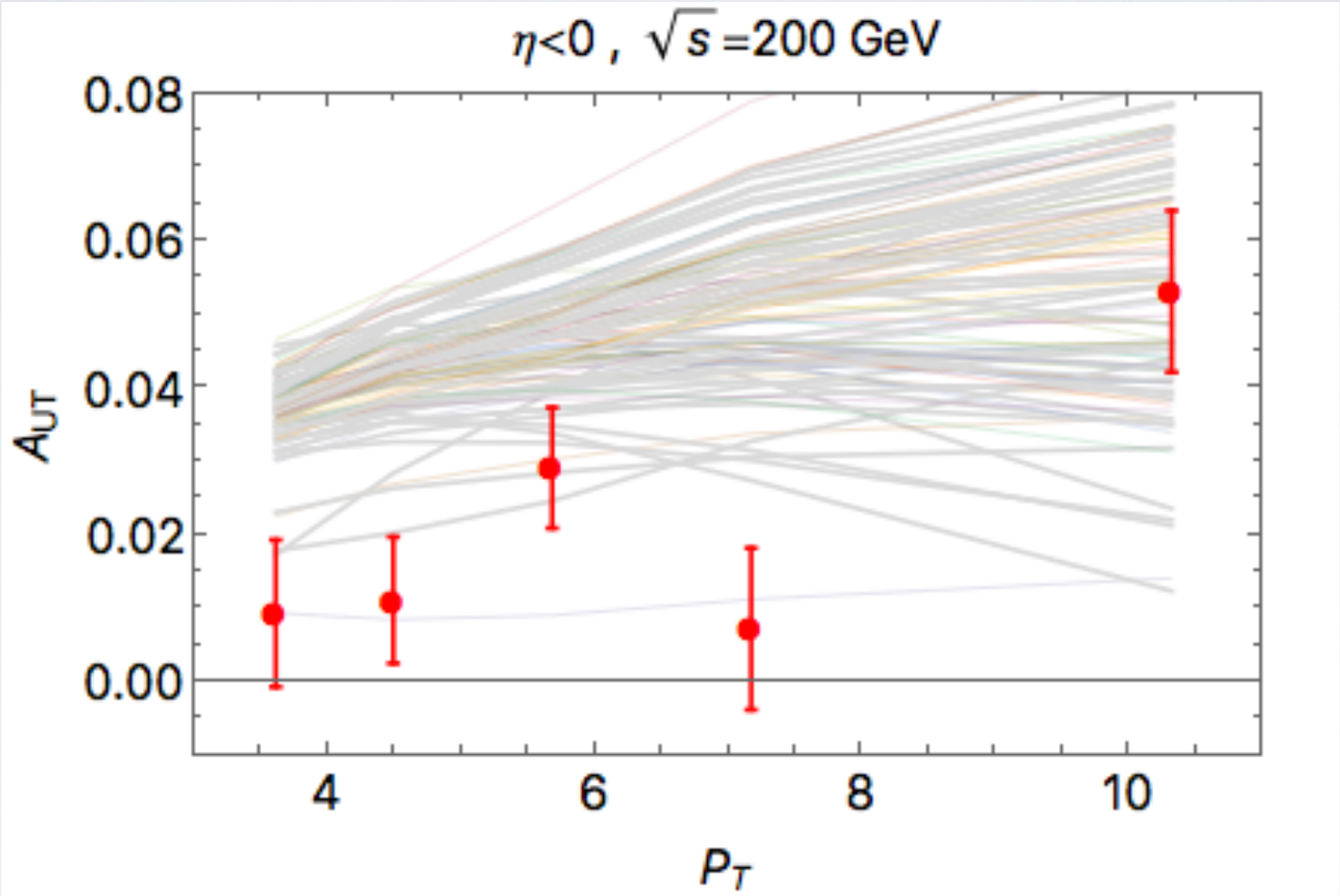
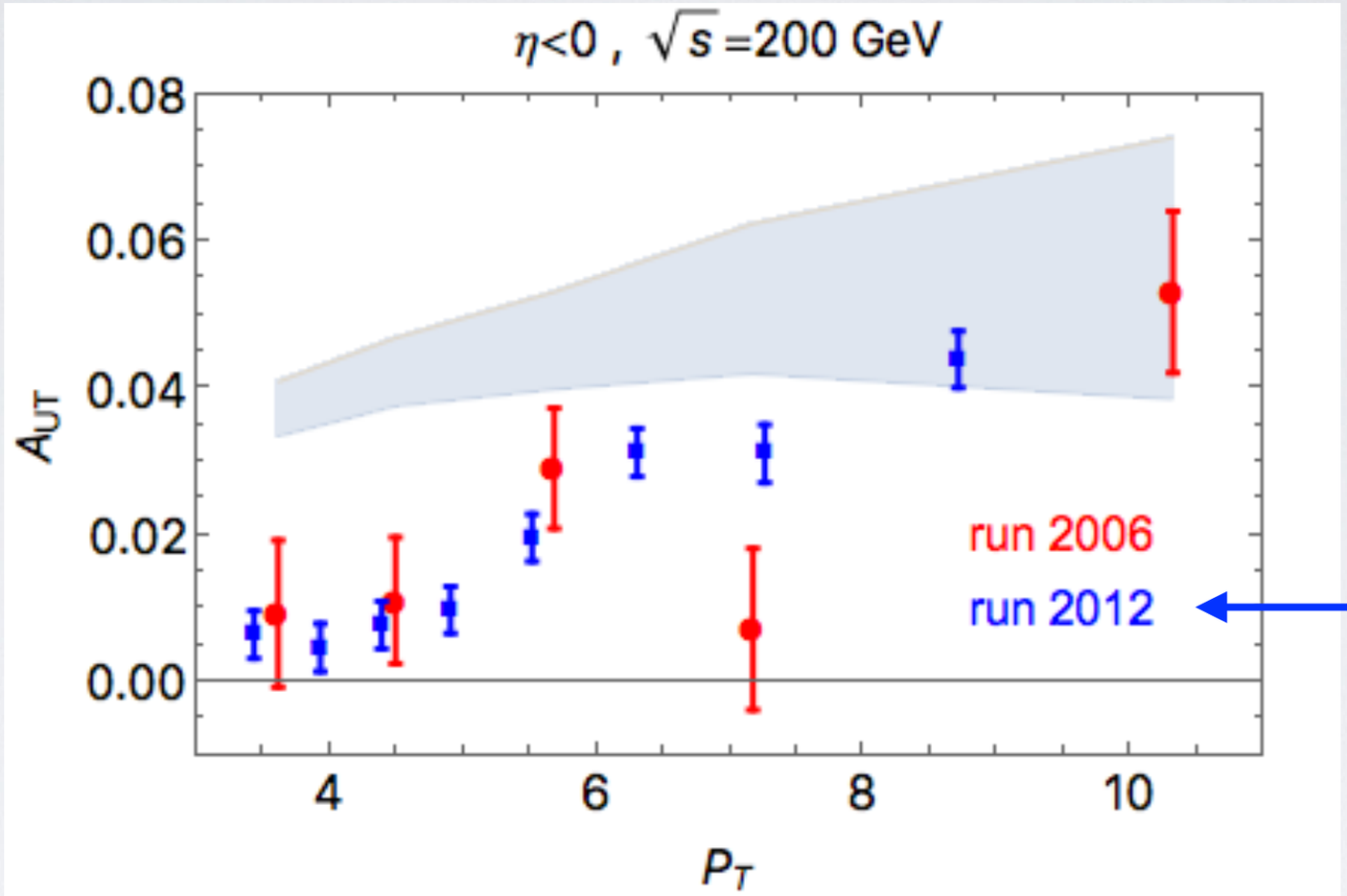


prediction of STAR data for forward $A_{UT}(P_T)$

data from *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

forward $A_{UT}(P_T)$



PRELIMINARY

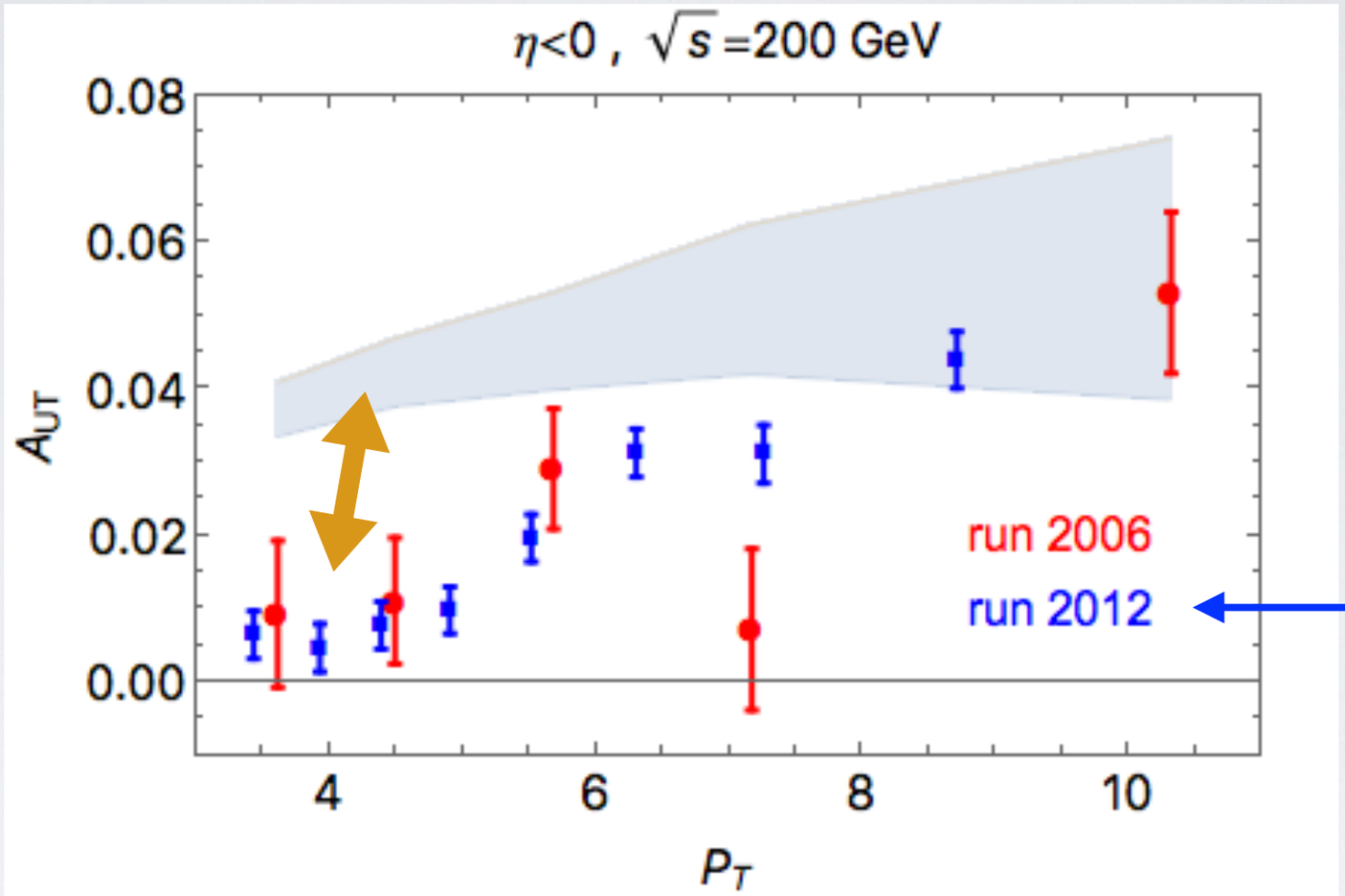
prediction of new STAR data using 68% of replicas forward $A_{UT}(P_T)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

run 2012 *K. Landry, talk at APS 2015*

forward $A_{UT}(P_T)$

higher twists ?



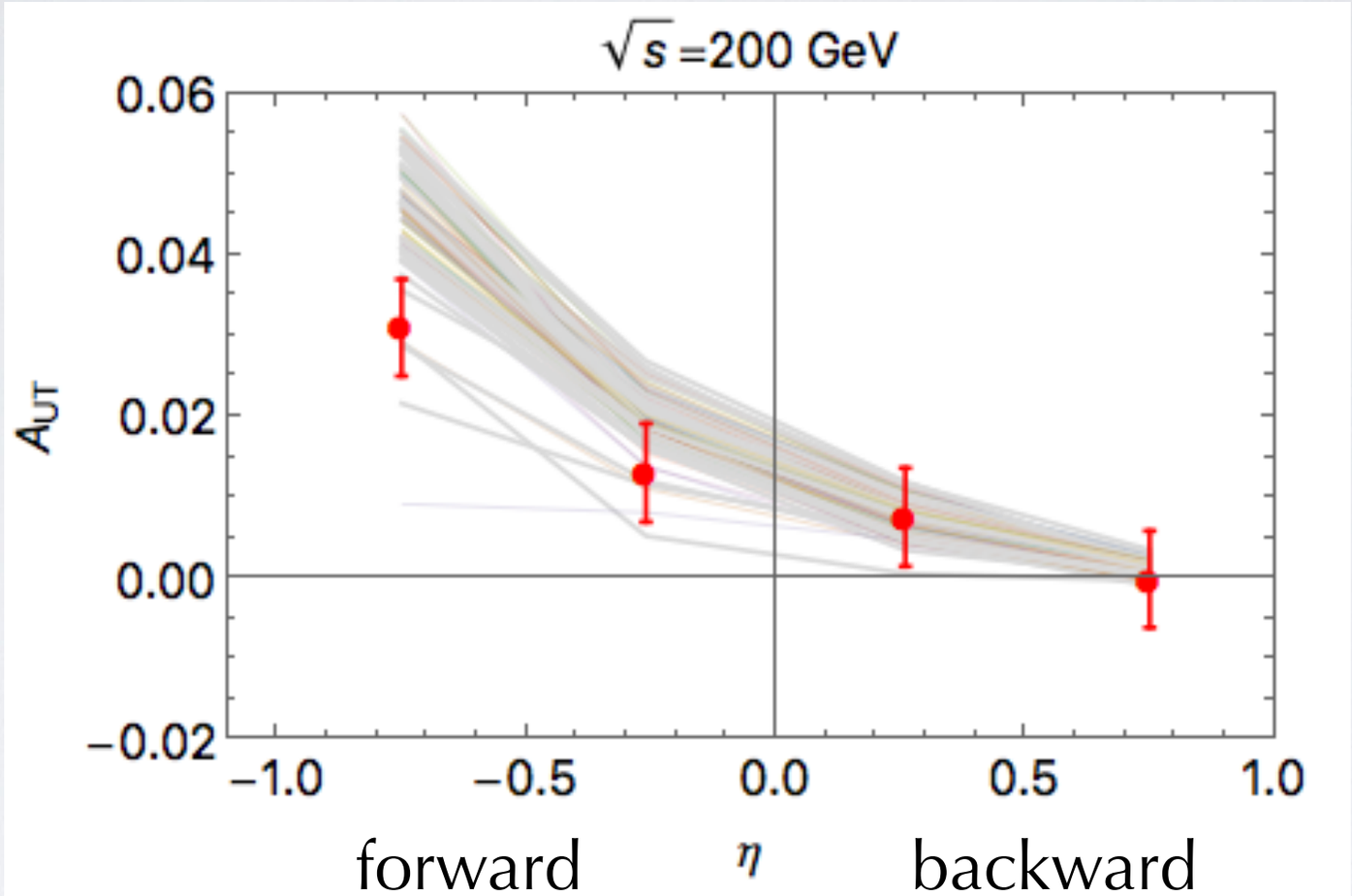
PRELIMINARY

prediction of new STAR data using 68% of replicas forward $A_{UT}(P_T)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

run 2012 *K. Landry, talk at APS 2015*

$A_{UT}(\eta)$

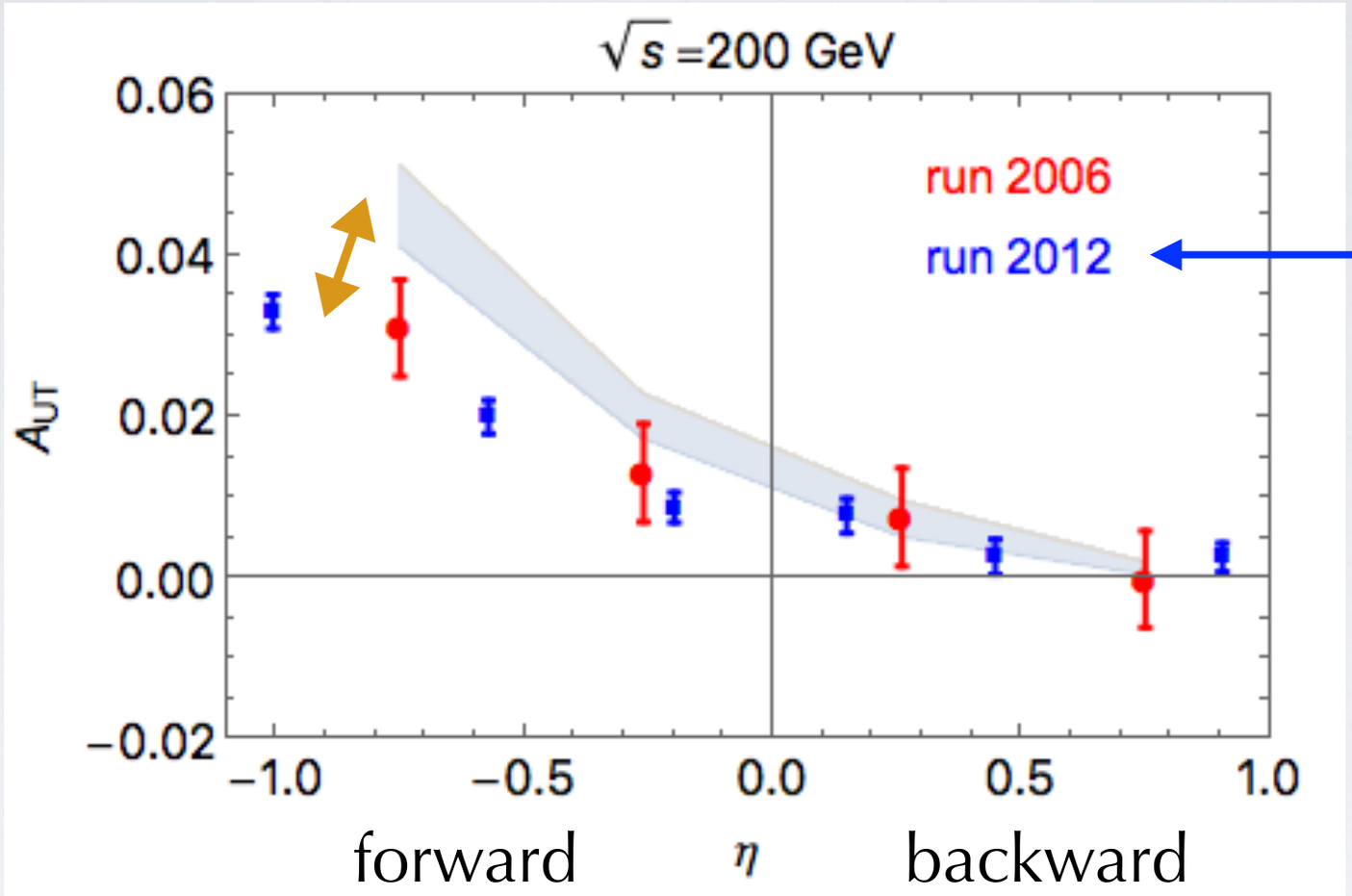


prediction of STAR data for $A_{UT}(\eta)$

data from *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

$A_{UT}(\eta)$

similar problem ?



PRELIMINARY

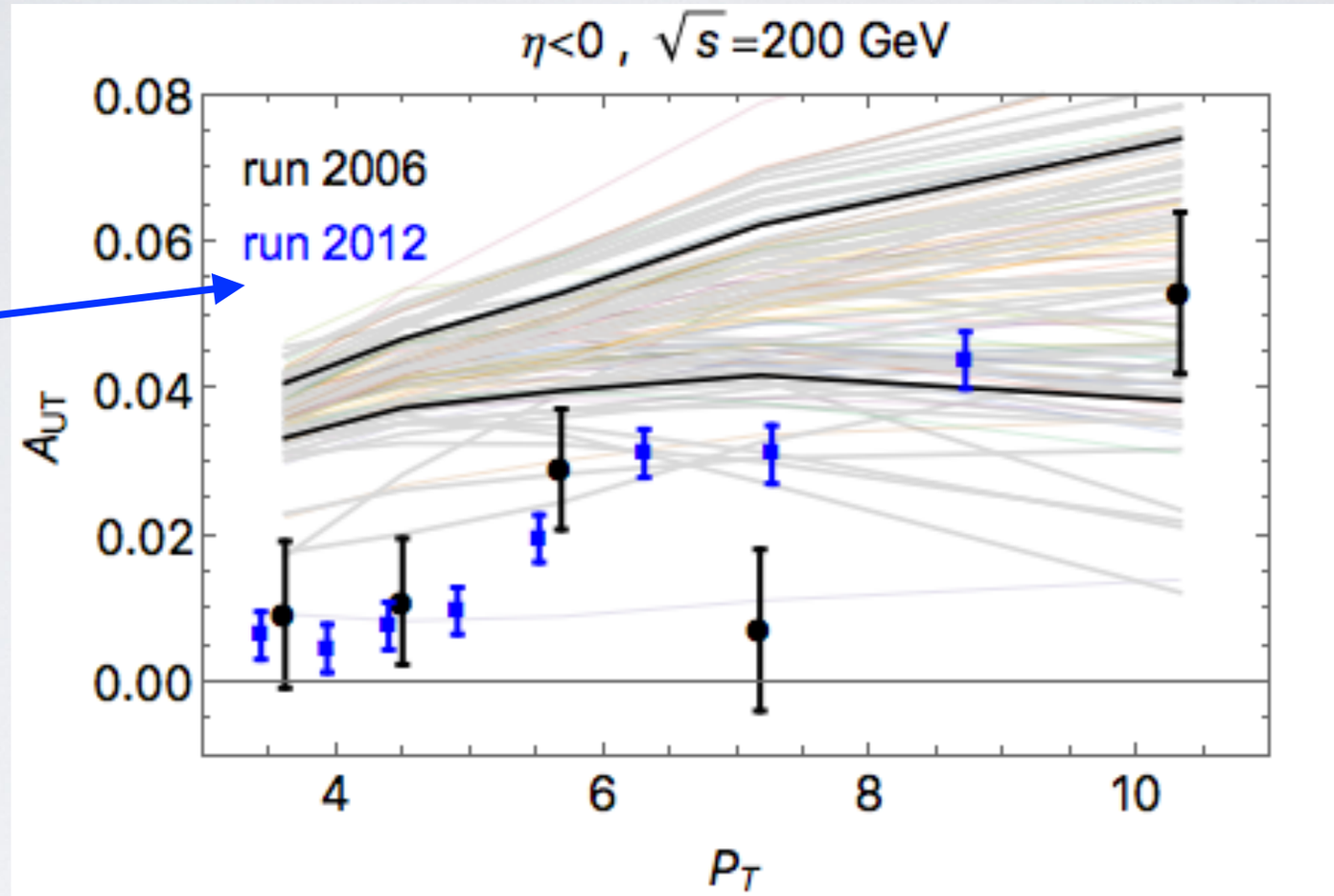
prediction of new STAR data using 68% of replicas $A_{UT}(\eta)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

run 2012 *K. Landry, talk at APS 2015*

reconsider forward $A_{UT}(P_T)$

PRELIMINARY



replicas extra 68% for forward $A_{UT}(P_T)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

run 2012 *K. Landry, talk at APS 2015*

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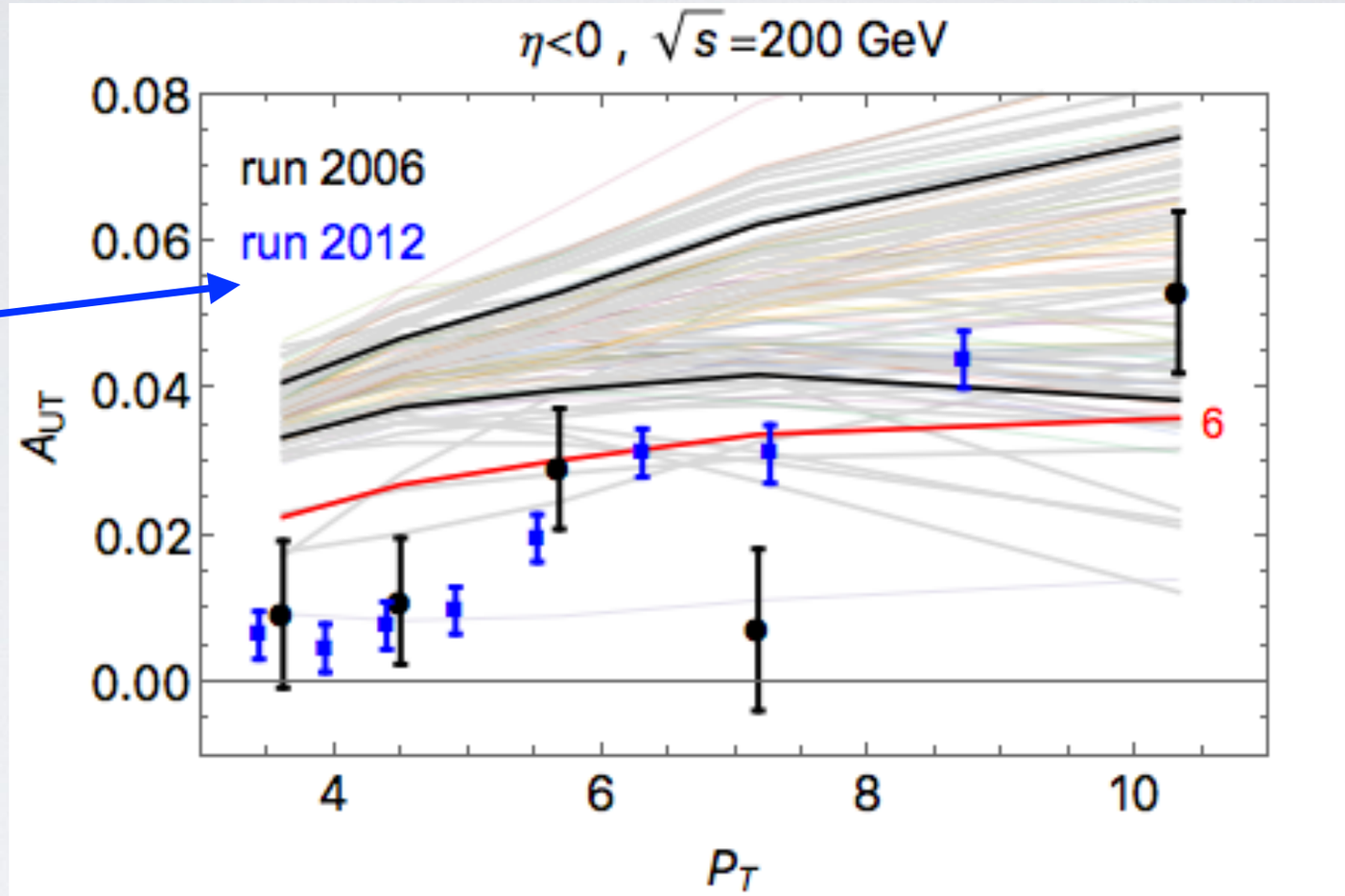
PRELIMINARY



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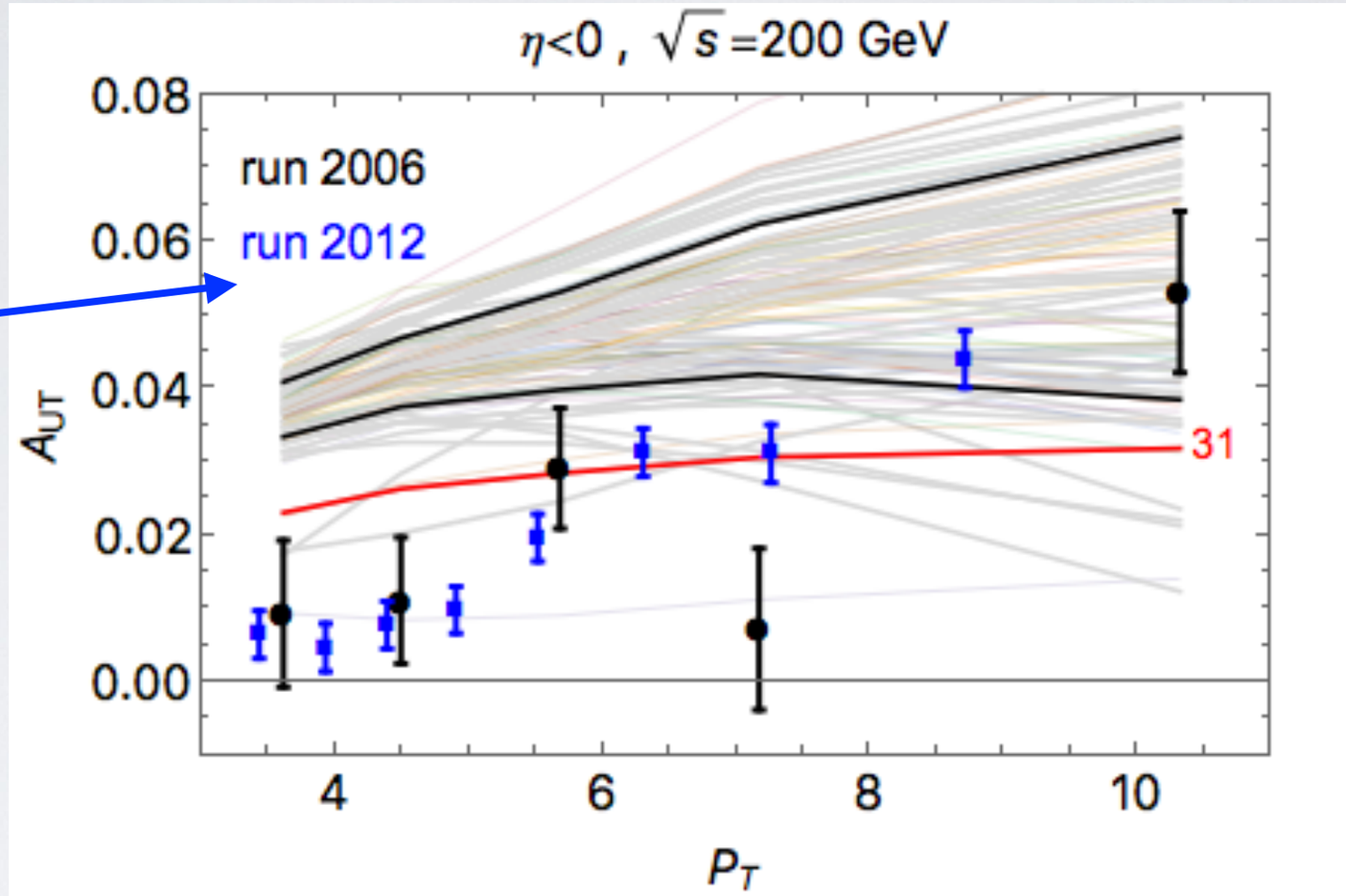

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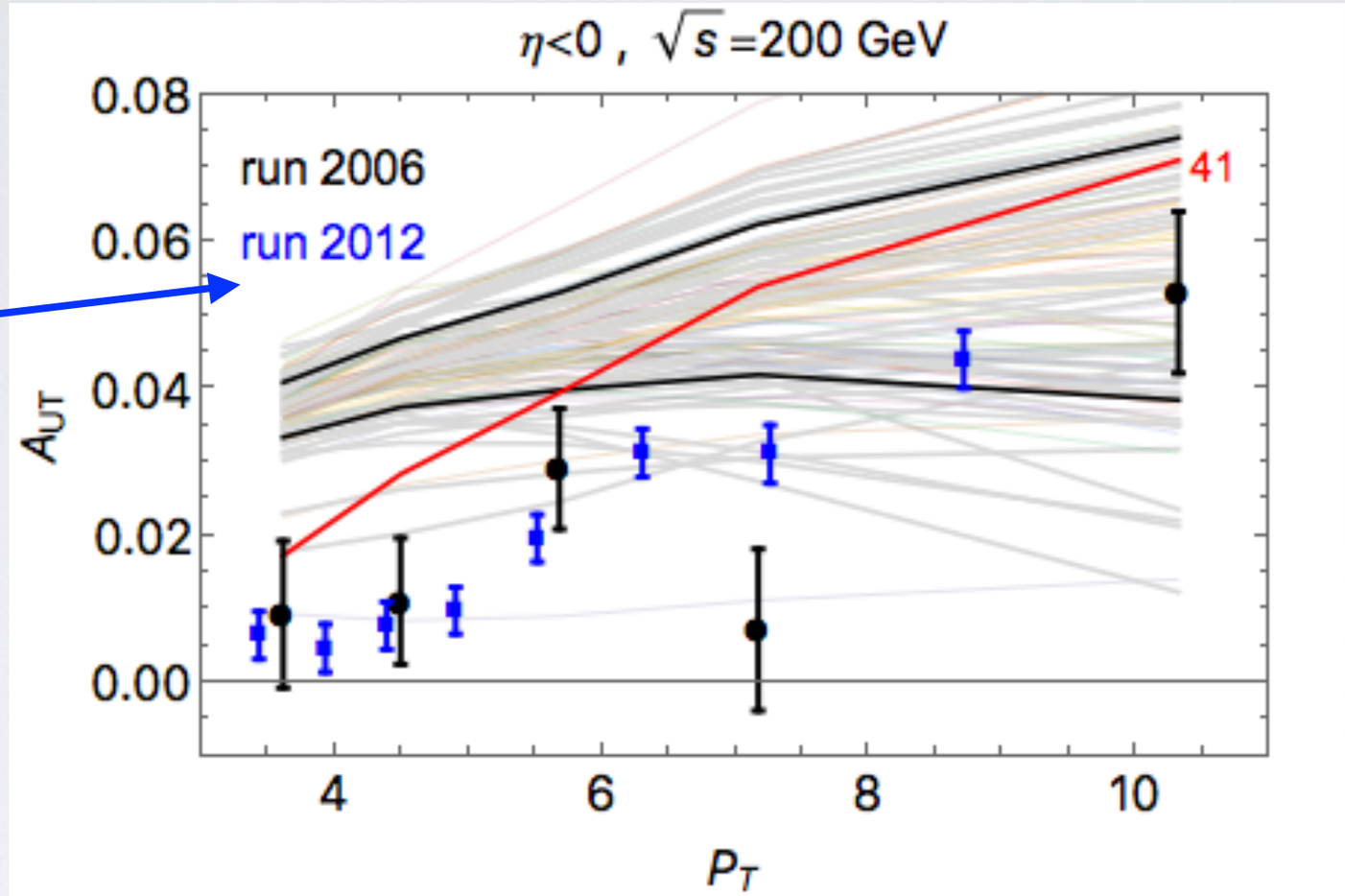

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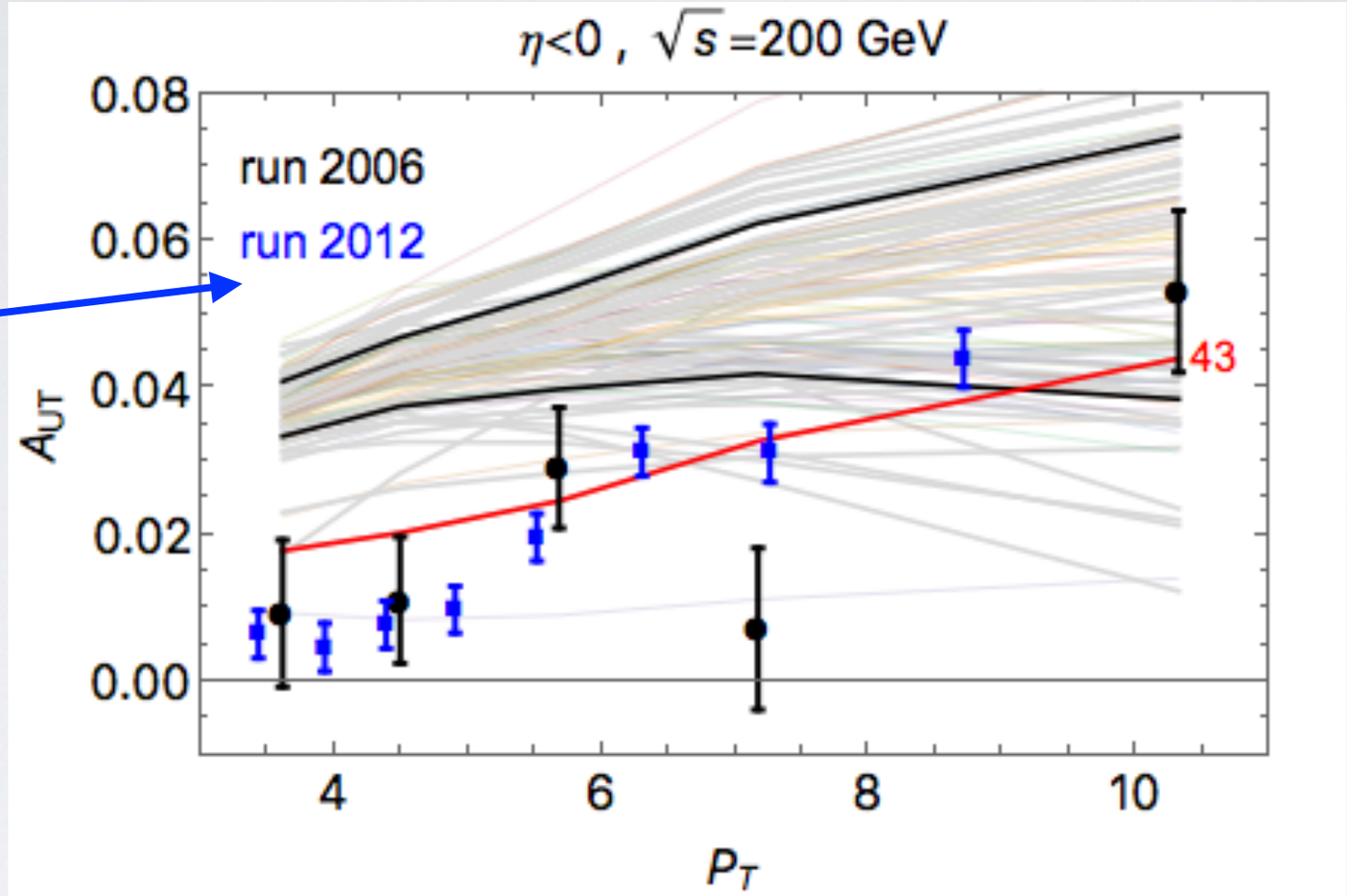

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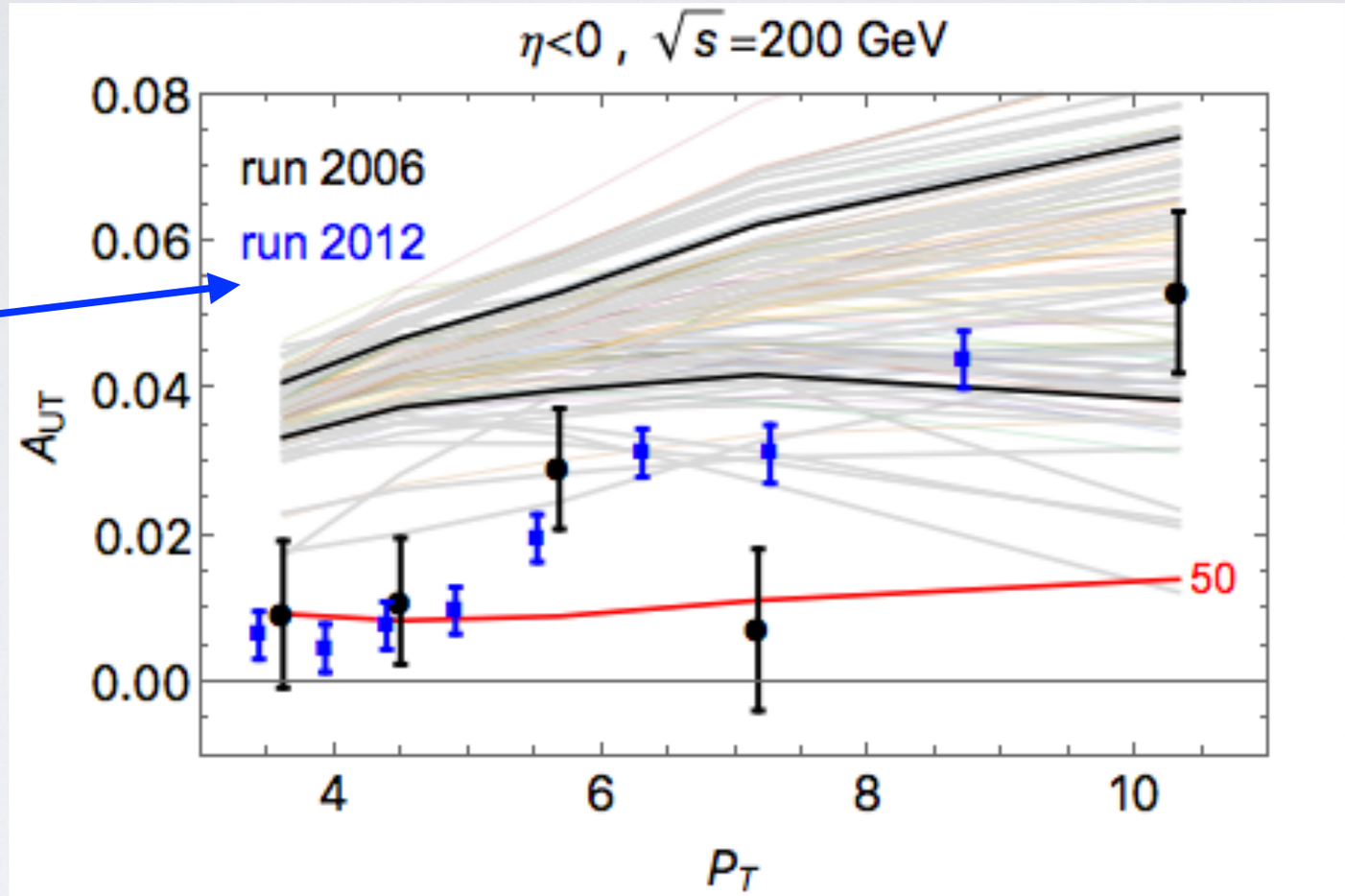

replicas extra 68% for forward $A_{UT}(P_T)$

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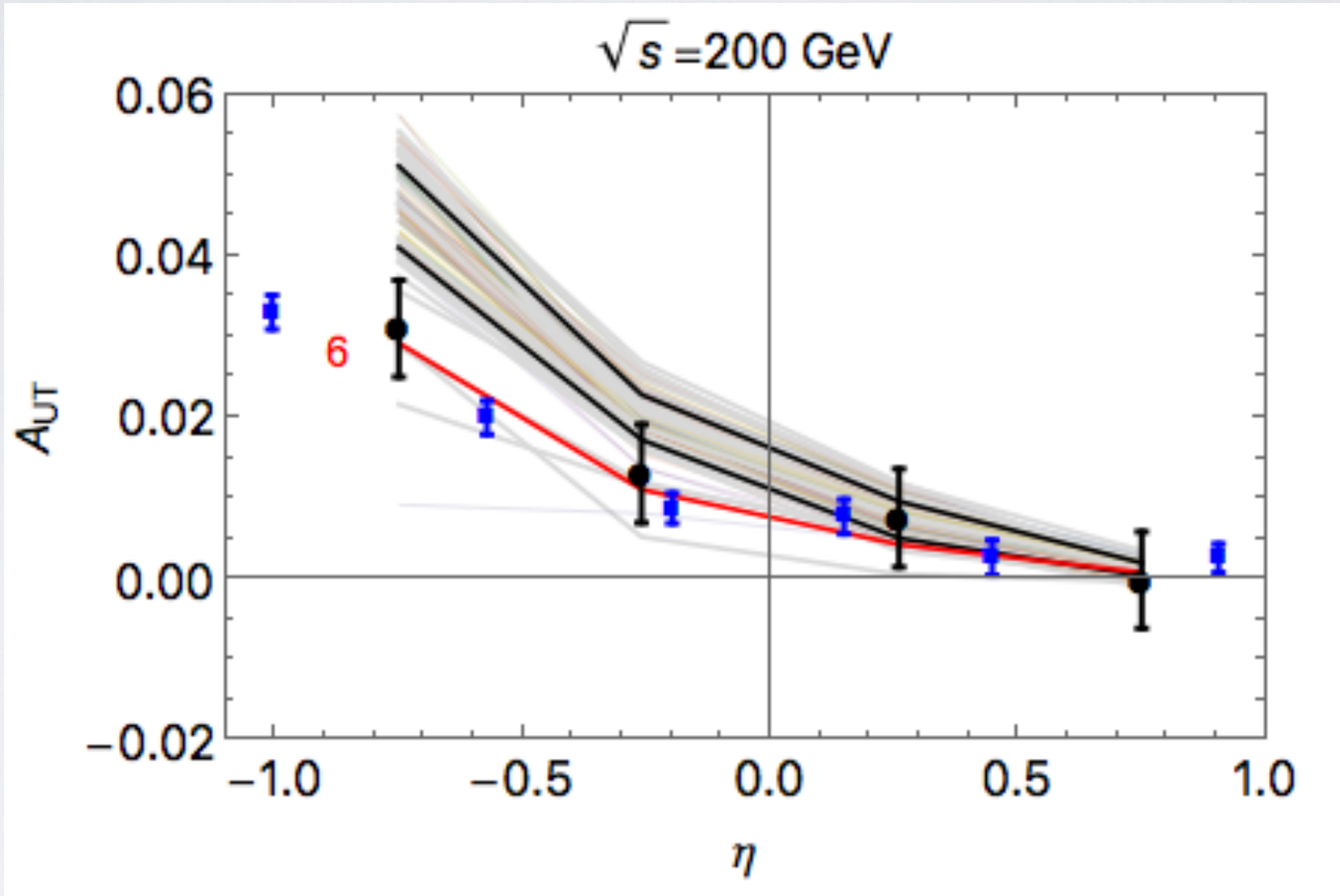
run 2012 *K. Landry, talk at APS 2015*

reconsider forward $A_{UT}(\eta)$

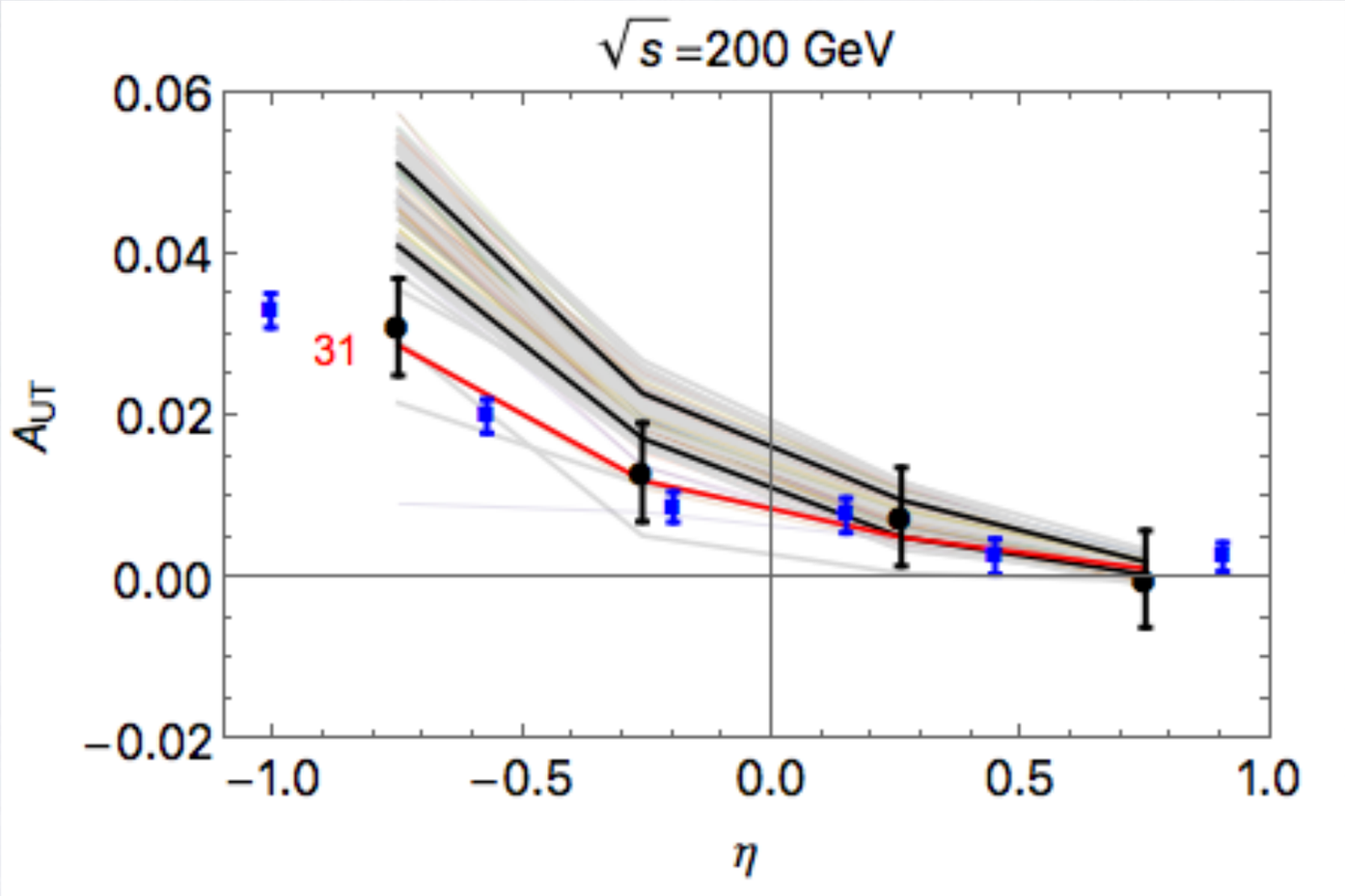


replicas extra 68% for $A_{UT}(\eta)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

PRELIMINARY → **run 2012** *K. Landry, talk at APS 2015*

reconsider forward $A_{UT}(\eta)$



replicas extra 68% for $A_{UT}(\eta)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

PRELIMINARY → **run 2012** *K. Landry, talk at APS 2015*

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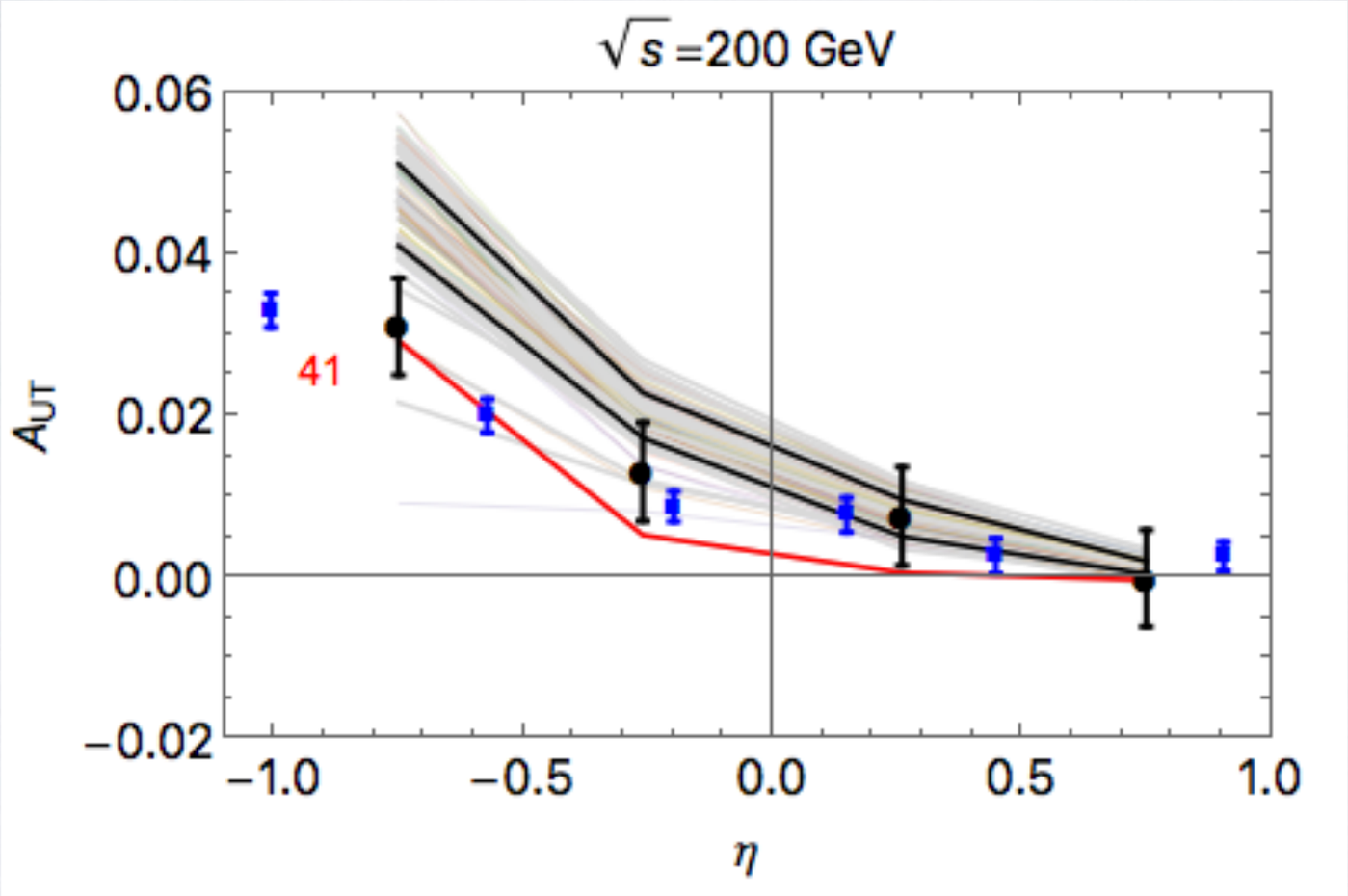

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run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

PRELIMINARY → **run 2012** *K. Landry, talk at APS 2015*

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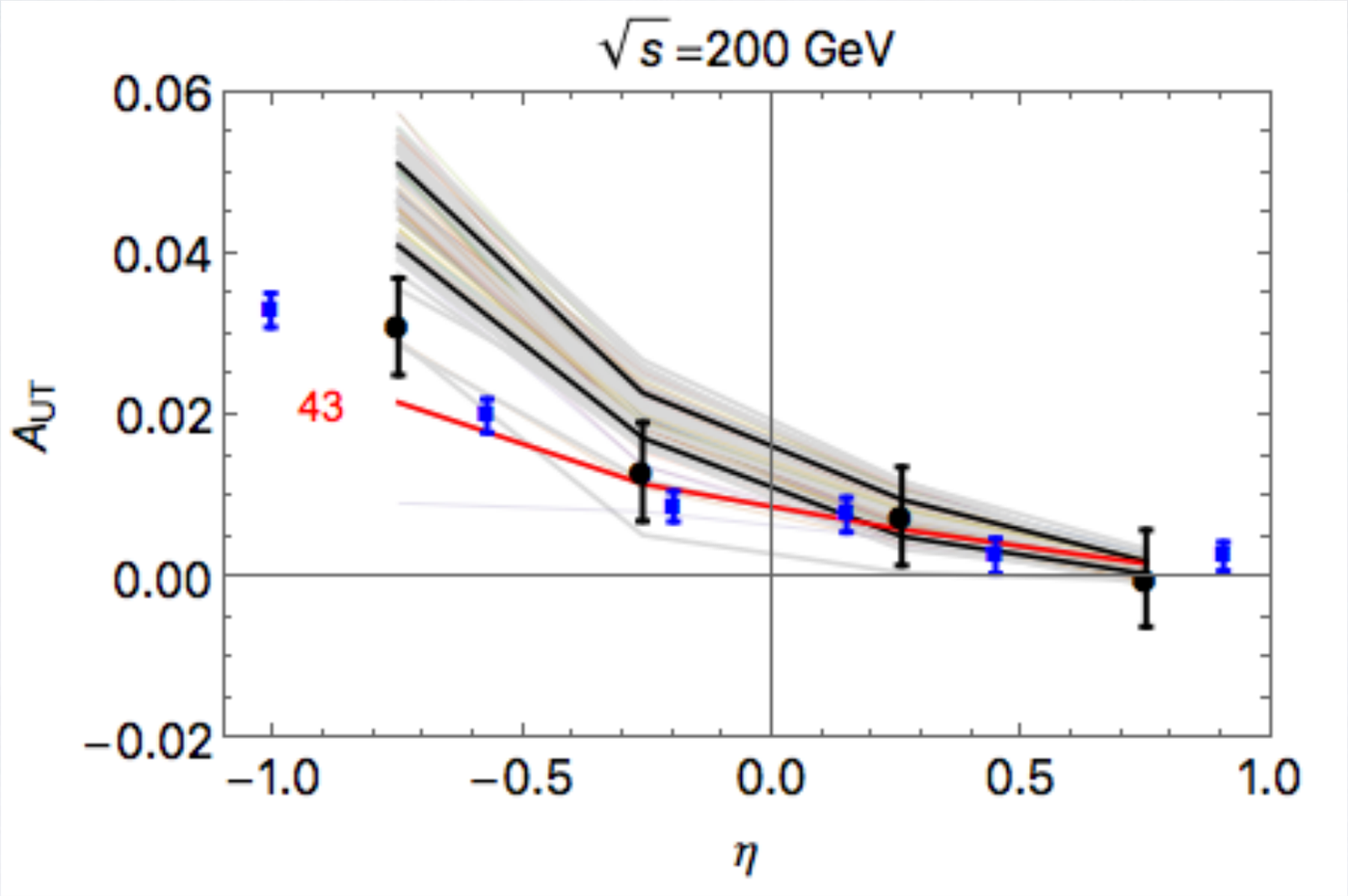
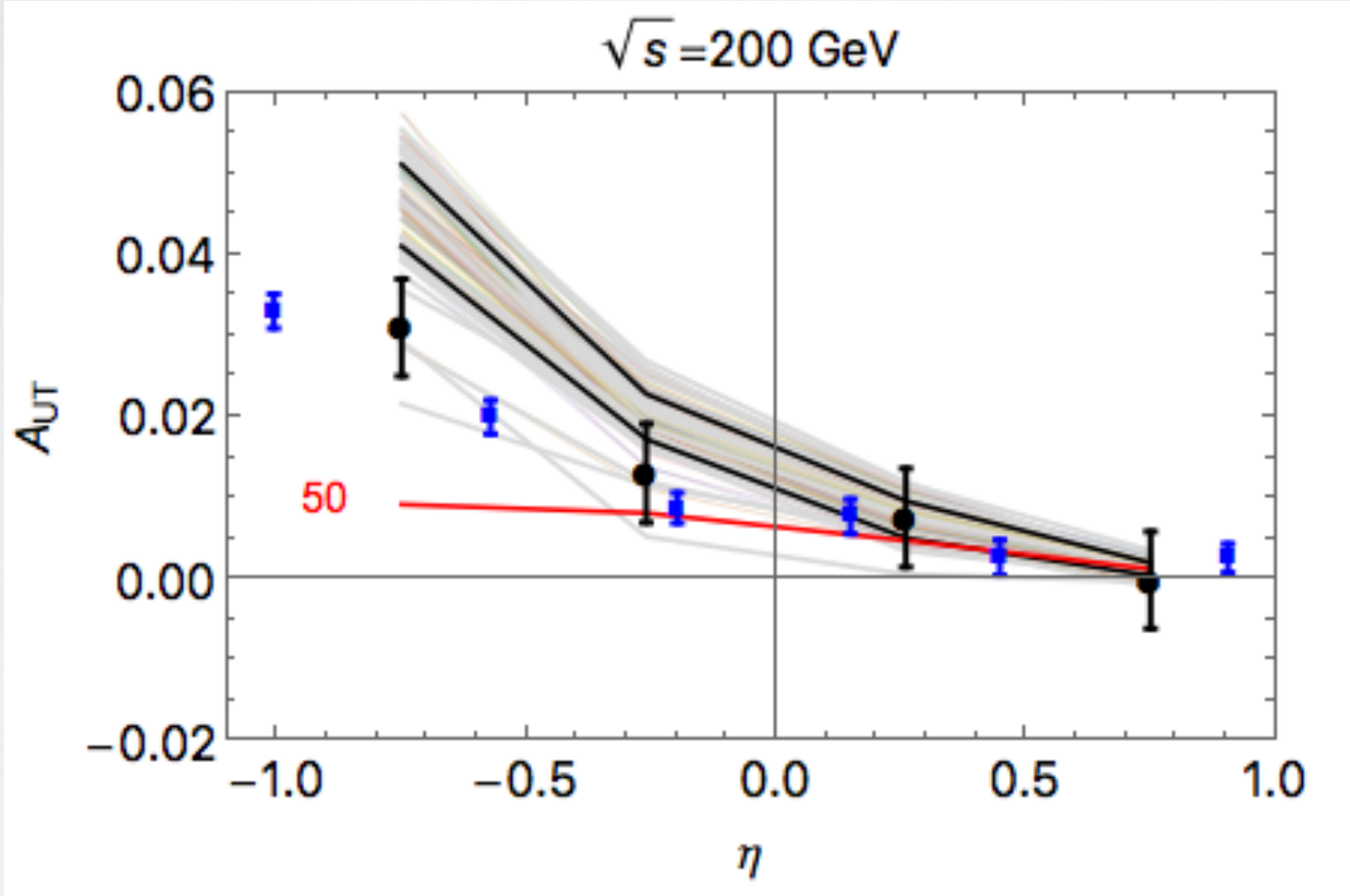


replicas extra 68% for $A_{UT}(\eta)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

PRELIMINARY → **run 2012** *K. Landry, talk at APS 2015*

reconsider forward $A_{UT}(\eta)$



replicas extra 68% for $A_{UT}(\eta)$

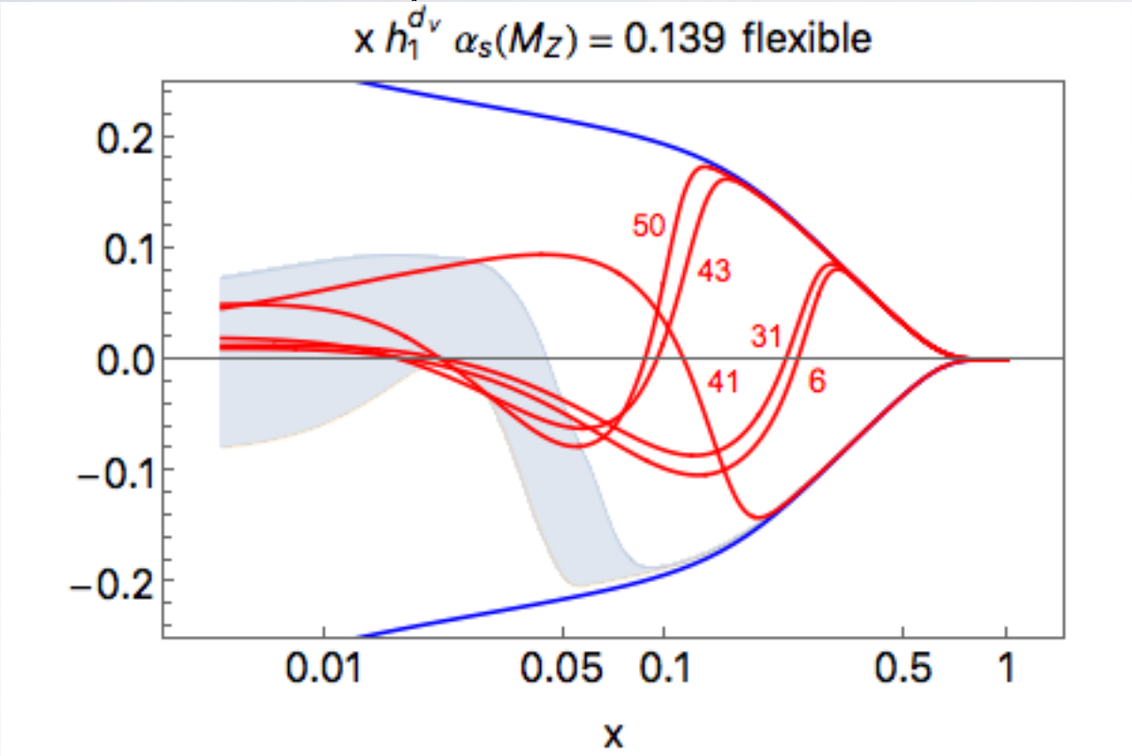
run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(15) 242501*

PRELIMINARY → **run 2012** *K. Landry, talk at APS 2015*

where are these replicas in the SIDIS fit ?

*Radici et al., JHEP **1505** (15) 123*

transversity for valence down



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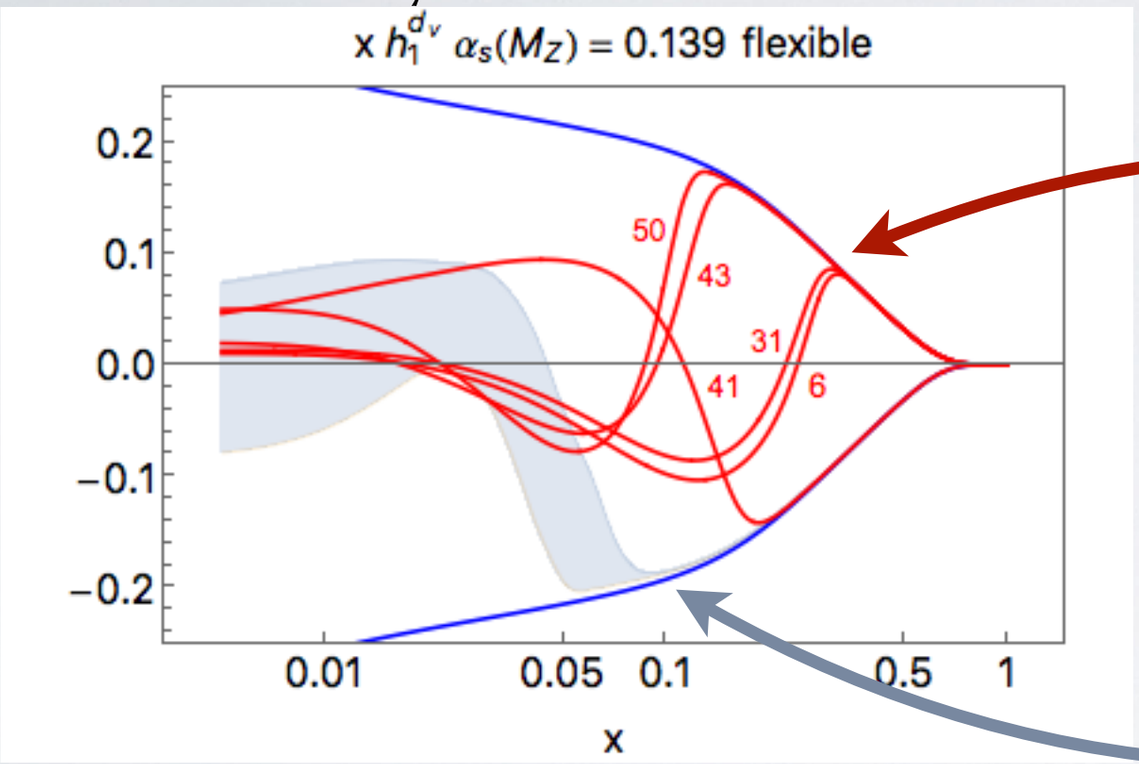
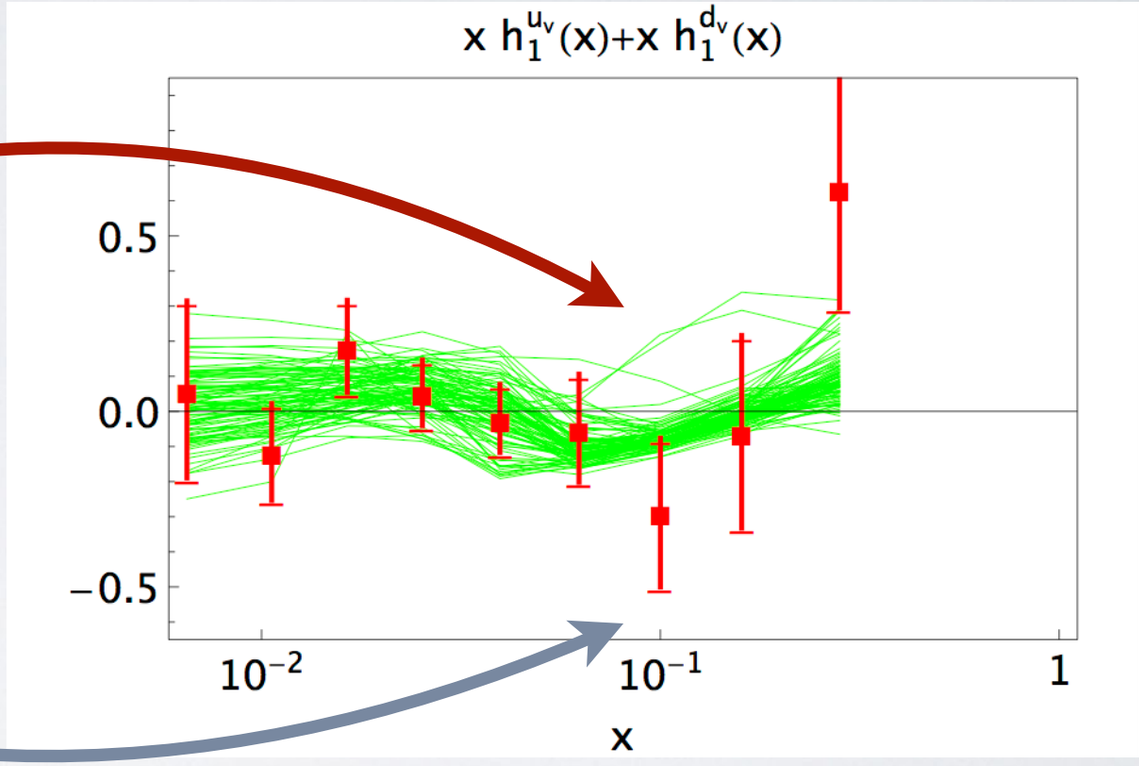
*Radici et al., JHEP **1505** (15) 123*

transversity for valence down



fit SIDIS data on deuteron

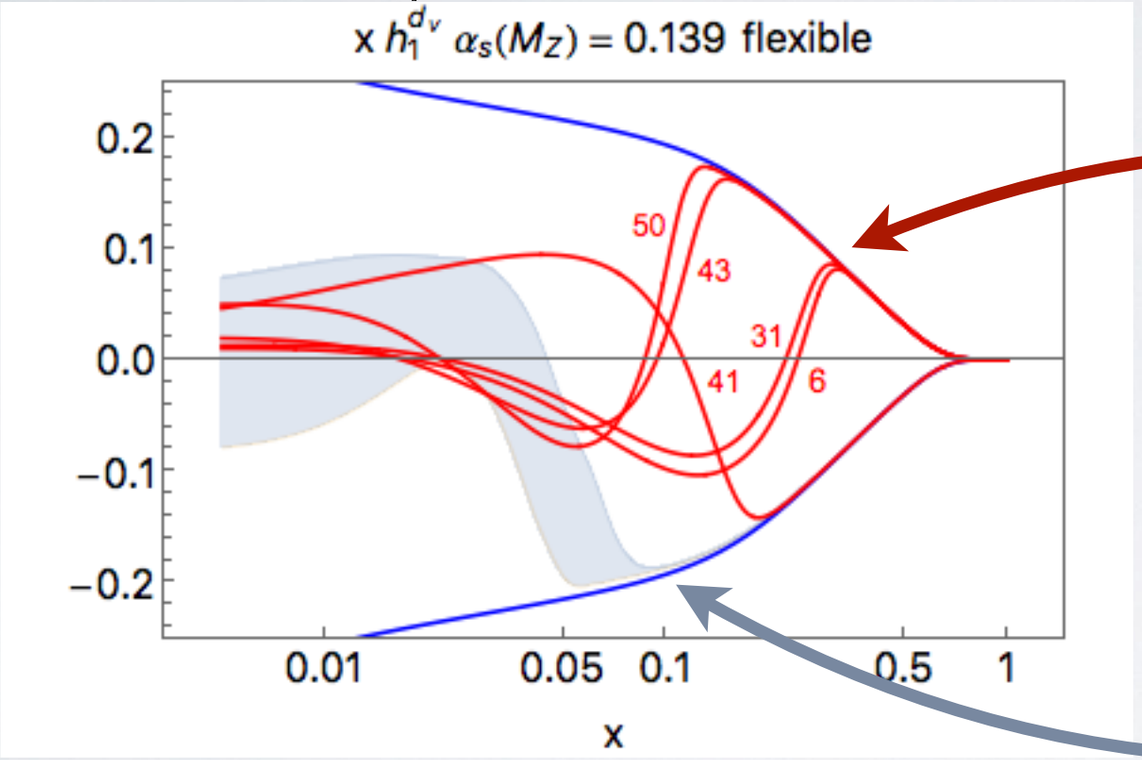


we know that saturation of 68% of replicas
on the Soffer bound is due to this bin

where are these replicas in the SIDIS fit ?

*Radici et al., JHEP **1505** (15) 123*

transversity for valence down



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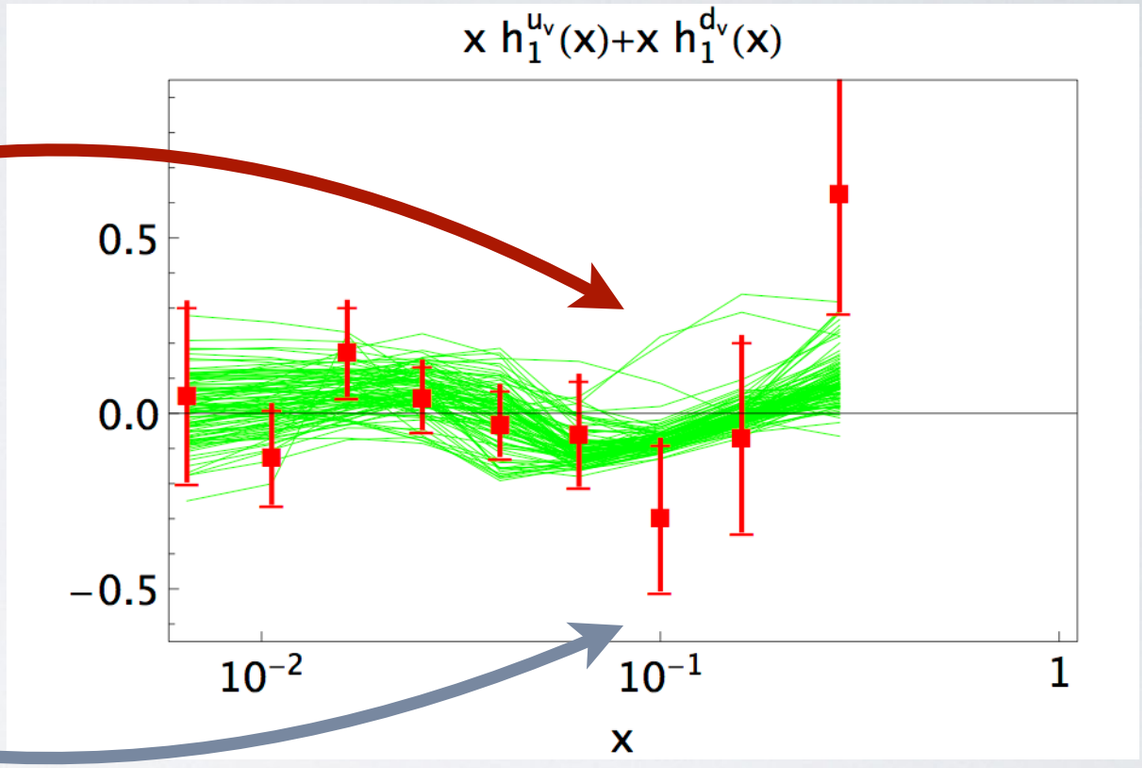

we know that saturation of 68% of replicas
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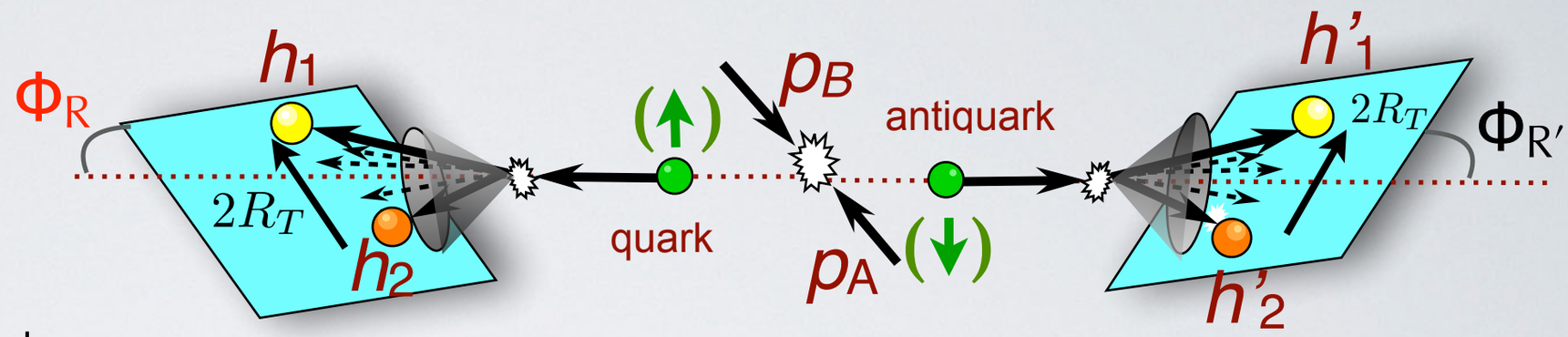
replicas following the forward $A_{UT}(P_T)$ & $A_{UT}(\eta)$
do not saturate on Soffer bound at valence x, but later.
They are incompatible with bin #7 in SIDIS deuteron data

the process $p + p \to (\pi\,\pi) + (\pi\,\pi) + X$



$$d\sigma \sim d\sigma^0 + \cos(\Phi_R - \Phi_{R'})\, d\sigma_{TT} + \cos(2\Phi_R - 2\Phi_{R'})\, d\sigma_{gg}$$

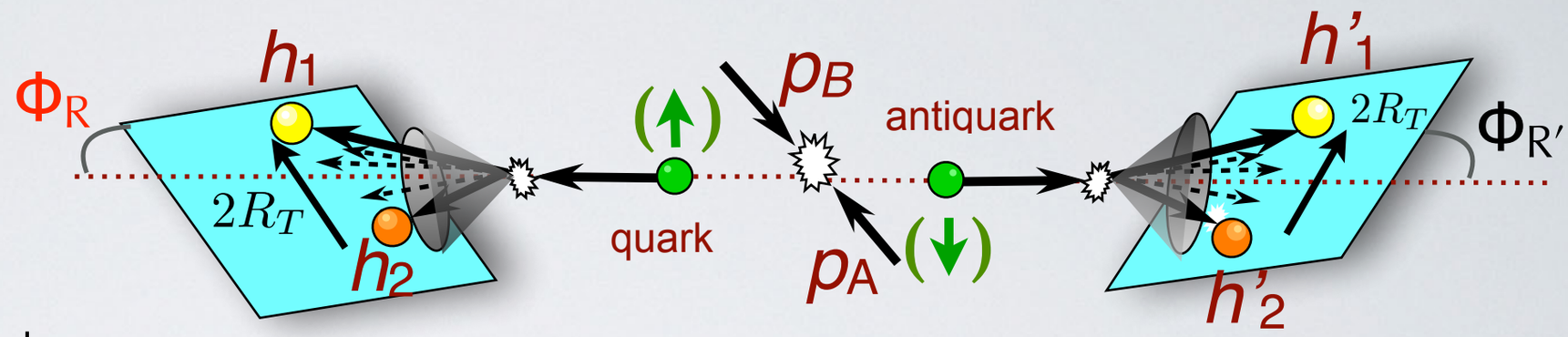
$$d\sigma^0 \sim f_1^a \otimes f_1^b \otimes d\hat{\sigma}_{ab\to cd} \otimes D_1^c \otimes D_1^d$$

$$d\sigma_{TT} \sim f_1^a \otimes f_1^b \otimes d\Delta\hat{\sigma}_{ab\to c^\uparrow d^\uparrow} \otimes \sin\theta\, H_{1,sp}^{\sphericalangle\, c} \otimes \sin\theta'\, H_{1,sp}^{\sphericalangle\, d}$$

$$d\sigma_{gg} \sim f_1^a \otimes f_1^b \otimes d\Delta\hat{\sigma}_{ab\to g^\uparrow g^\uparrow} \otimes \sin^2\theta\, \delta\hat{G}^{\sphericalangle c} \otimes \sin^2\theta'\, \delta\hat{G}^{\sphericalangle d}$$

Bacchetta & Radici,
*P.R. D**70** (04) 094032*

the process $p + p \rightarrow (\pi\,\pi) + (\pi\,\pi) + X$



$$d\sigma \sim d\sigma^0 + \cos(\Phi_R - \Phi_{R'})\, d\sigma_{TT} + \cos(2\Phi_R - 2\Phi_{R'})\, d\sigma_{gg}$$

only unpolarized measurement

$$d\sigma^0 \sim f_1^a \otimes f_1^b \otimes d\hat{\sigma}_{ab\rightarrow cd} \otimes D_1^c \otimes D_1^d$$

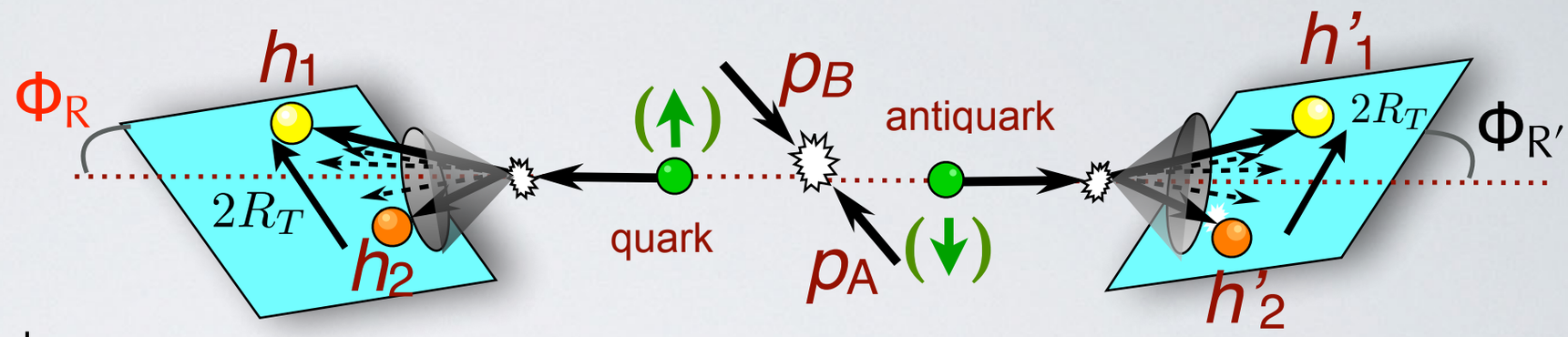
independent extraction of IFF

$$d\sigma_{TT} \sim f_1^a \otimes f_1^b \otimes d\Delta\hat{\sigma}_{ab\rightarrow c^\uparrow d^\uparrow} \otimes \sin\theta\, H_{1,sp}^{\sphericalangle\, c} \otimes \sin\theta'\, H_{1,sp}^{\sphericalangle\, d}$$

$$d\sigma_{gg} \sim f_1^a \otimes f_1^b \otimes d\Delta\hat{\sigma}_{ab\rightarrow g^\uparrow g^\uparrow} \otimes \sin^2\theta\, \delta\hat{G}^{\sphericalangle\, c} \otimes \sin^2\theta'\, \delta\hat{G}^{\sphericalangle\, d}$$

Bacchetta & Radici,
*P.R. D**70** (04) 094032*

the process $p + p \rightarrow (\pi\,\pi) + (\pi\,\pi) + X$



$$d\sigma \sim d\sigma^0 + \cos(\Phi_R - \Phi_{R'})\, d\sigma_{TT} + \cos(2\Phi_R - 2\Phi_{R'})\, d\sigma_{gg}$$

only unpolarized measurement

$$d\sigma^0 \sim f_1^a \otimes f_1^b \otimes d\hat{\sigma}_{ab\rightarrow cd} \otimes D_1^c \otimes D_1^d$$

independent extraction of IFF

$$d\sigma_{TT} \sim f_1^a \otimes f_1^b \otimes d\Delta\hat{\sigma}_{ab\rightarrow c^\uparrow d^\uparrow} \otimes \sin\theta\, H_{1,sp}^{\sphericalangle\, c} \otimes \sin\theta'\, H_{1,sp}^{\sphericalangle\, d}$$

$$d\sigma_{gg} \sim f_1^a \otimes f_1^b \otimes d\Delta\hat{\sigma}_{ab\rightarrow g^\uparrow g^\uparrow} \otimes \sin^2\theta\, \delta\hat{G}^{\sphericalangle\, c} \otimes \sin^2\theta'\, \delta\hat{G}^{\sphericalangle\, d}$$

access fragmentation from linearly transverse polarization of gluons

*Bacchetta & Radici, P.R. D**70** (04) 094032*

Conclusions

- Semi-inclusive di-hadron production allows to **address transversity** in all hard processes **using collinear factorization**. Theoretical framework well under control.
- The best 68% replicas of h_1^{qv} and $H_1^{\sphericalangle}$ that **fit** ($\pi^+\pi^-$) **SIDIS data** give very **good predictions** for all backward A_{UT} in polarized ***p-p* collisions** and for forward $A_{UT}(M)$.

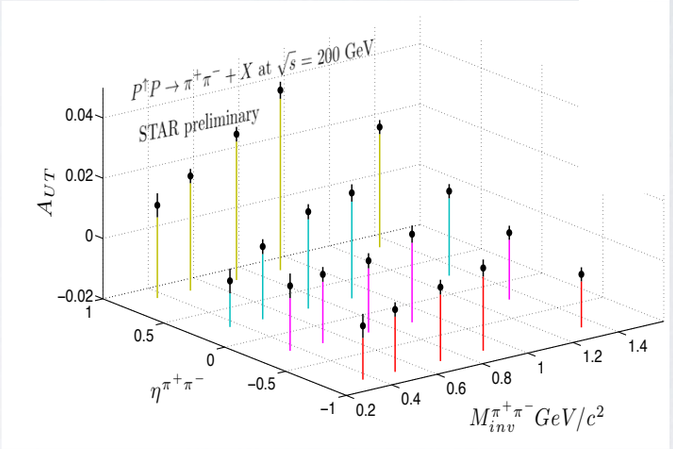
  Deviations from forward $A_{UT}(P_T)$ [large] and $A_{UT}(\eta)$ [small].
- Some extra-68% replicas follow forward $A_{UT}(P_T)$ and $A_{UT}(\eta)$ but are incompatible with SIDIS deuteron data

Universality of transversity seems in good shape…

- Next: a combined fit of e^+e^- / SIDIS / *p-p* data

Backup

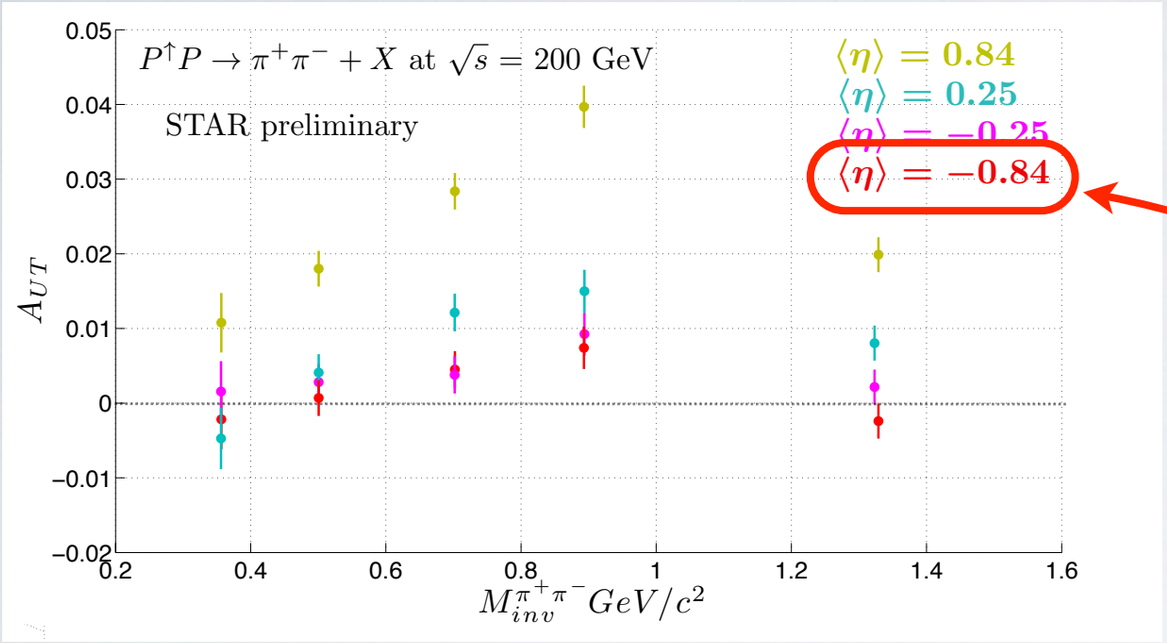
- Bidimensional mapping of A_{UT} with STAR data from run 2012 at $\sqrt{s}$ = 200 GeV



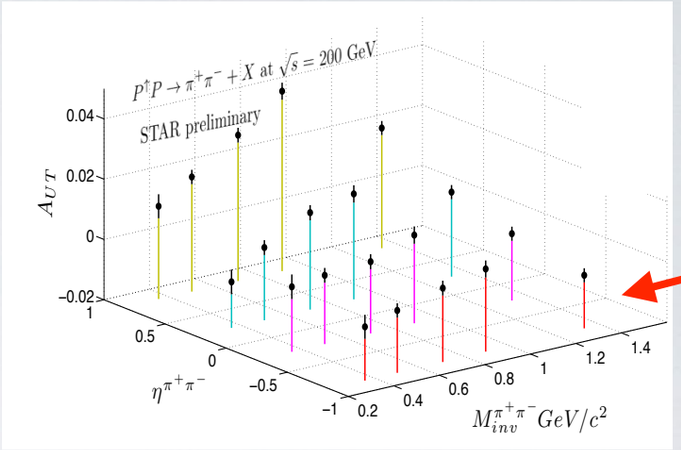
PRELIMINARY

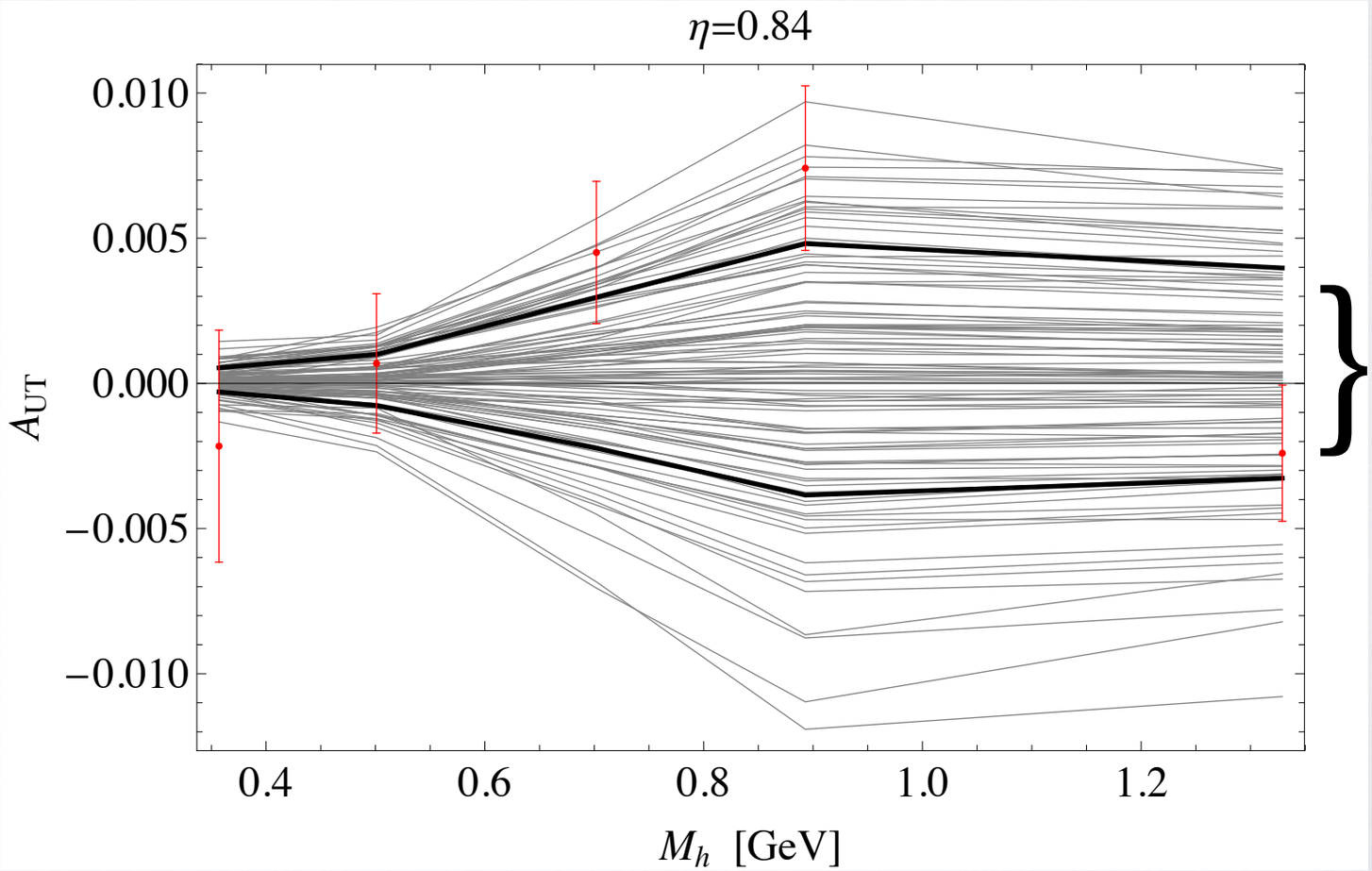
- Bidimensional mapping of A_{UT} with STAR data from run 2011 at $\sqrt{s}$ = 500 GeV

Backup: *M* vs. η at √s = 200 GeV

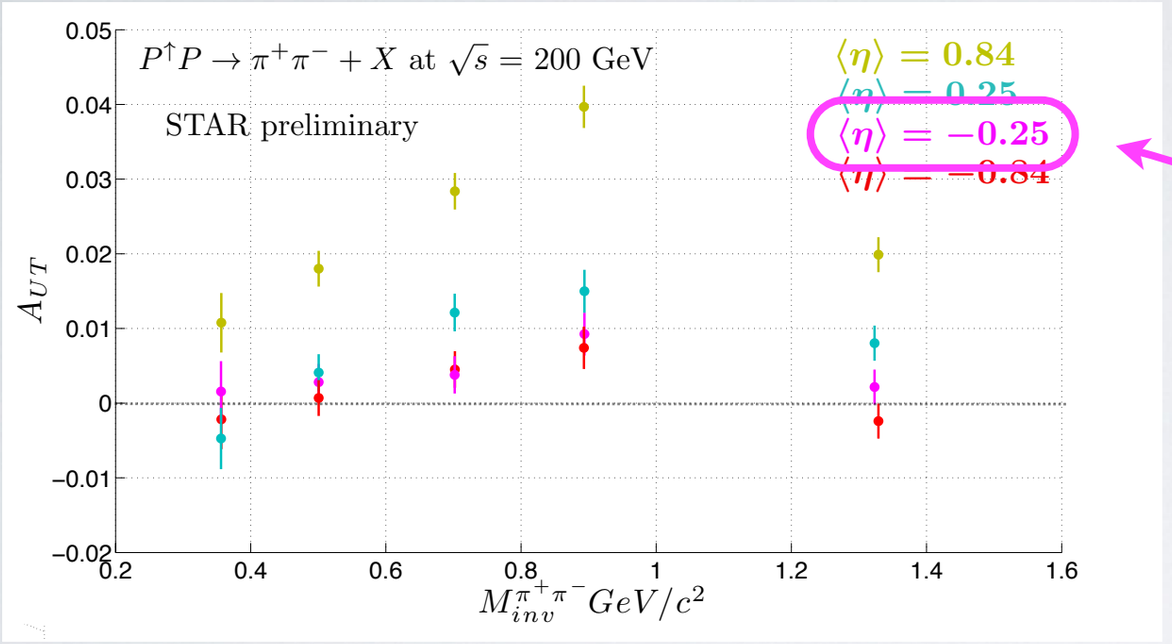


K. Landry, talk at APS 2015





Backup: *M* vs. η at √s = 200 GeV



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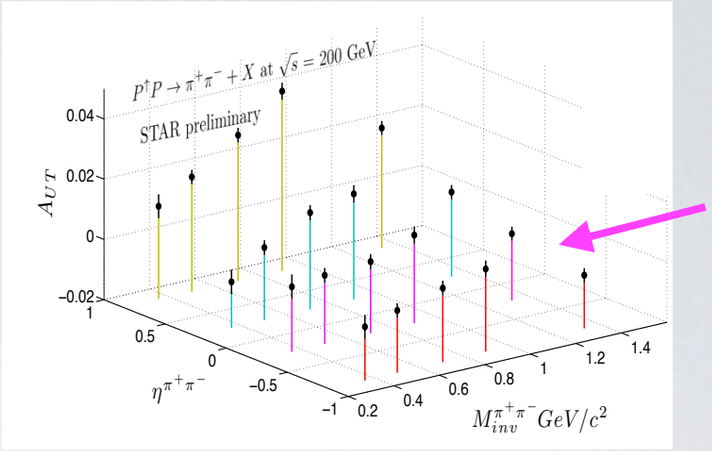
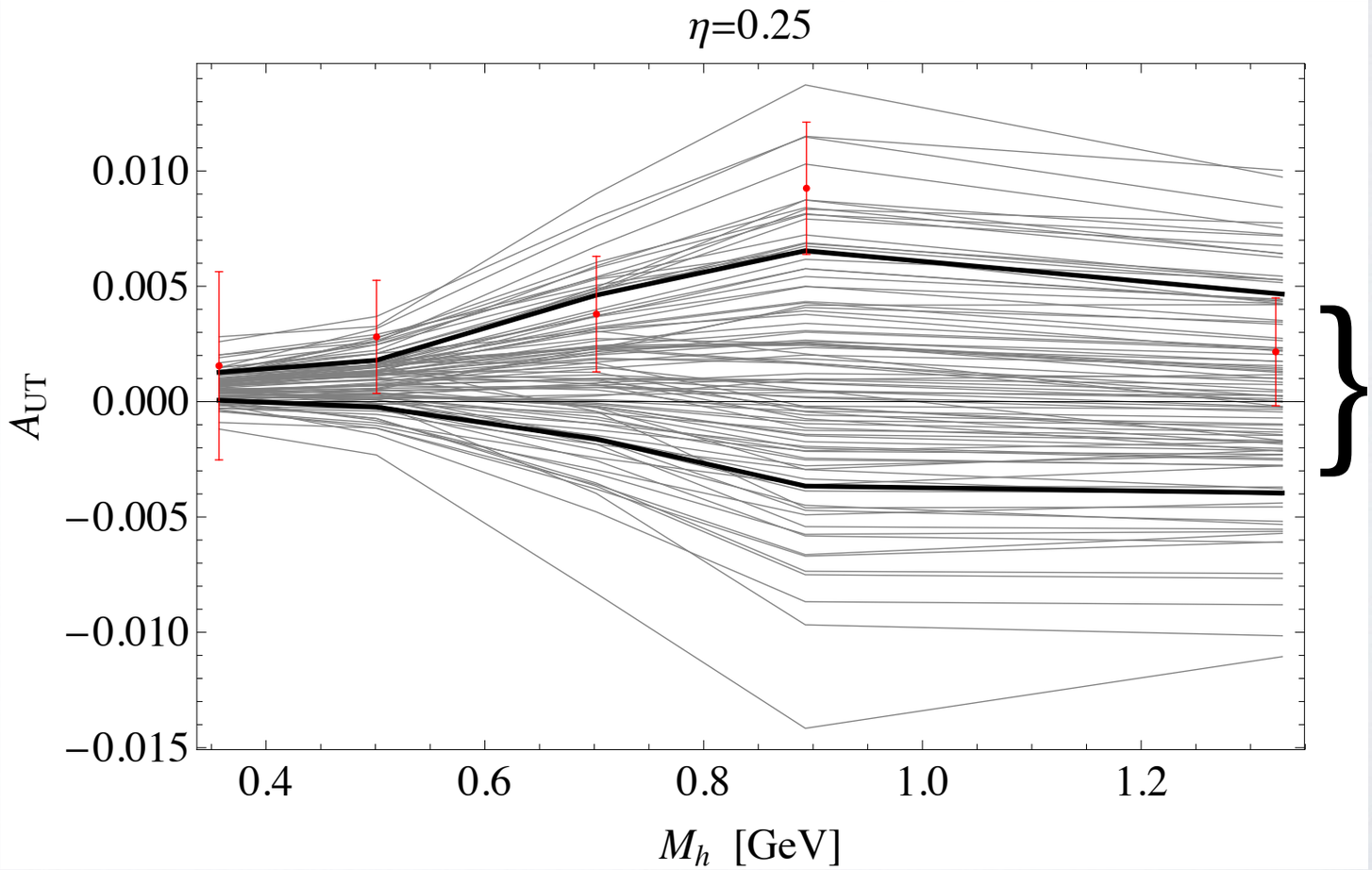
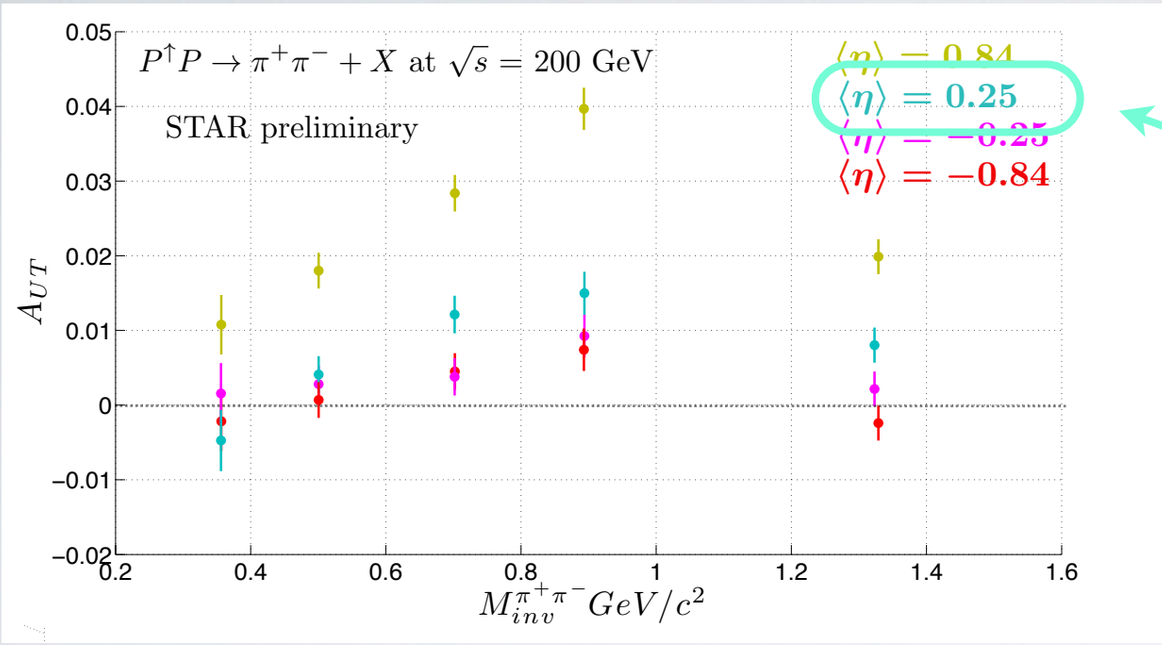




Backup: *M* vs. η at √s = 200 GeV



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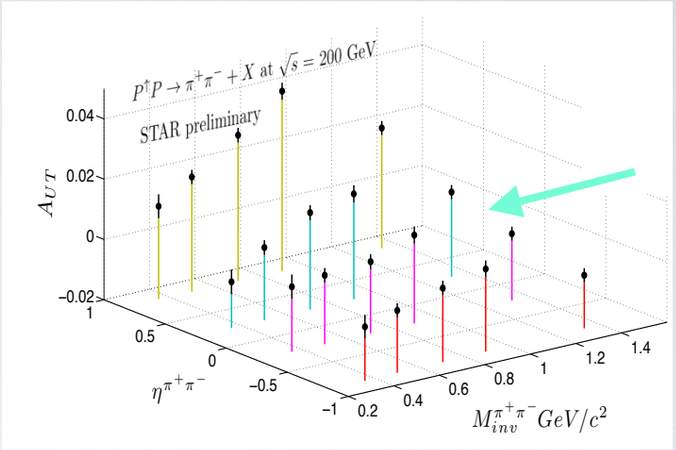
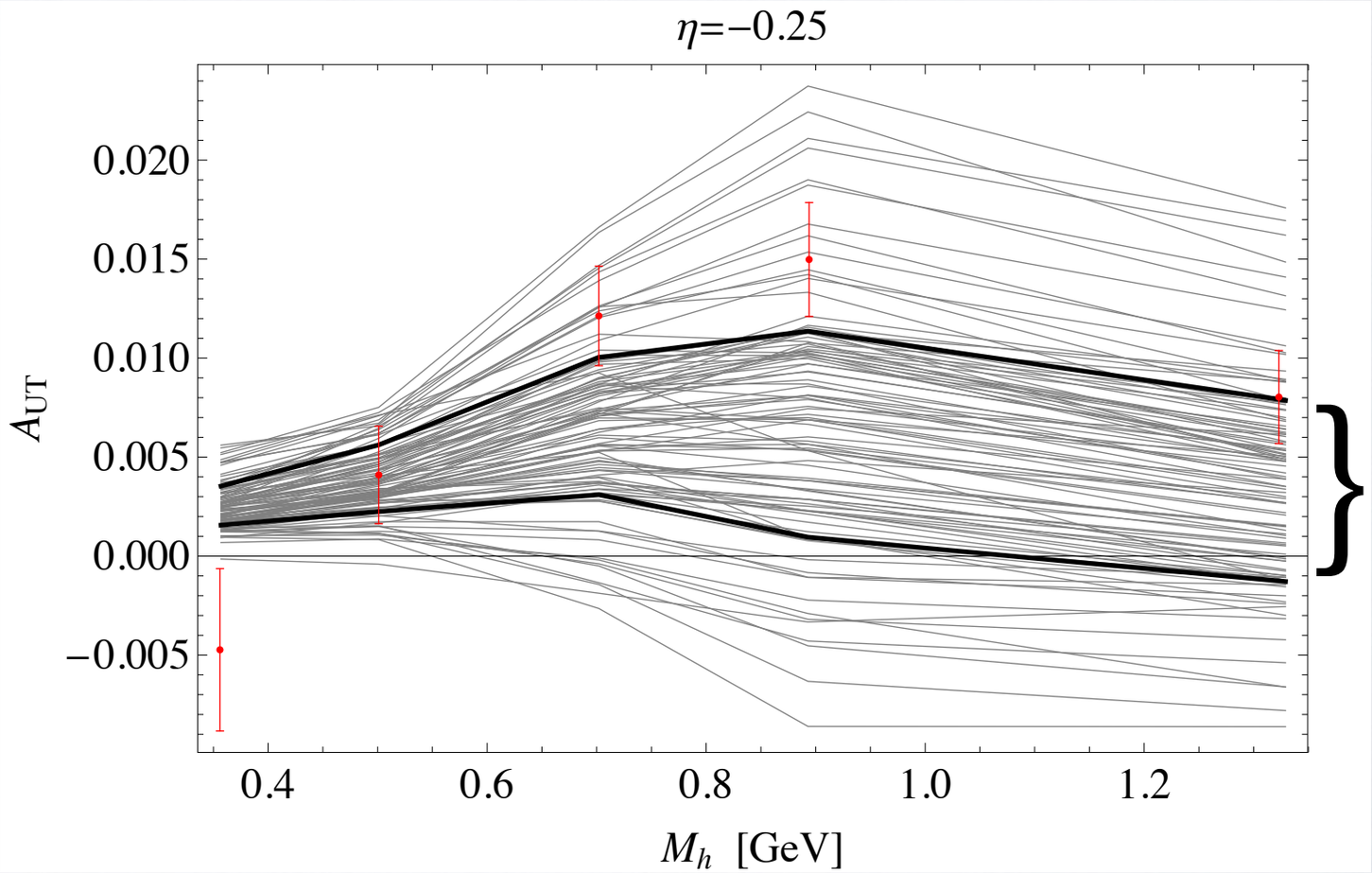
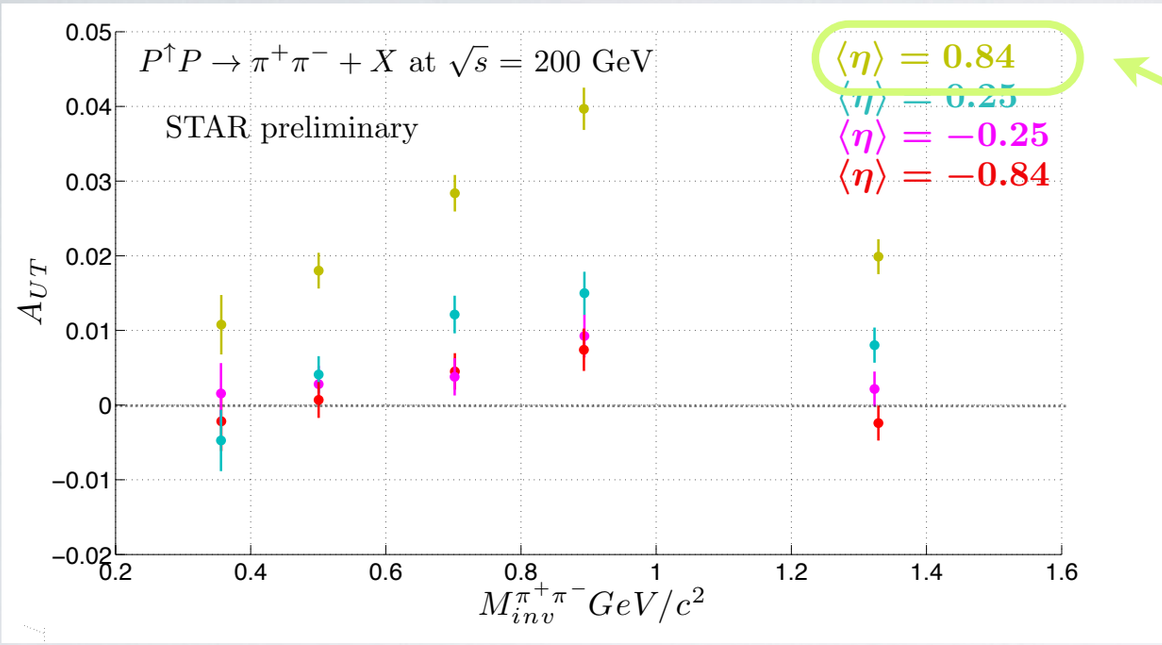




Backup: *M* vs. η at √s = 200 GeV



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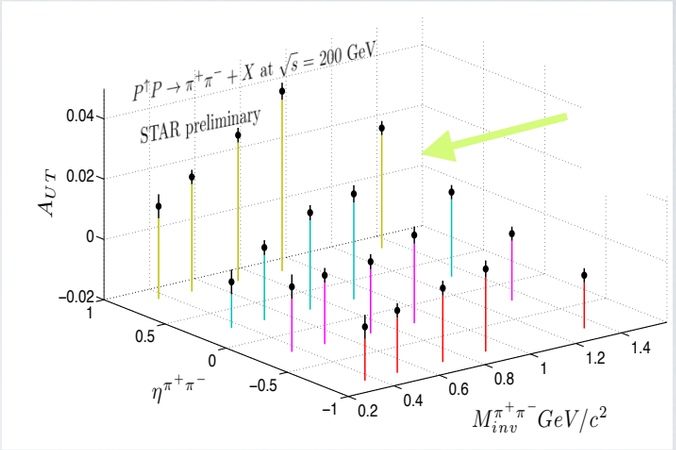
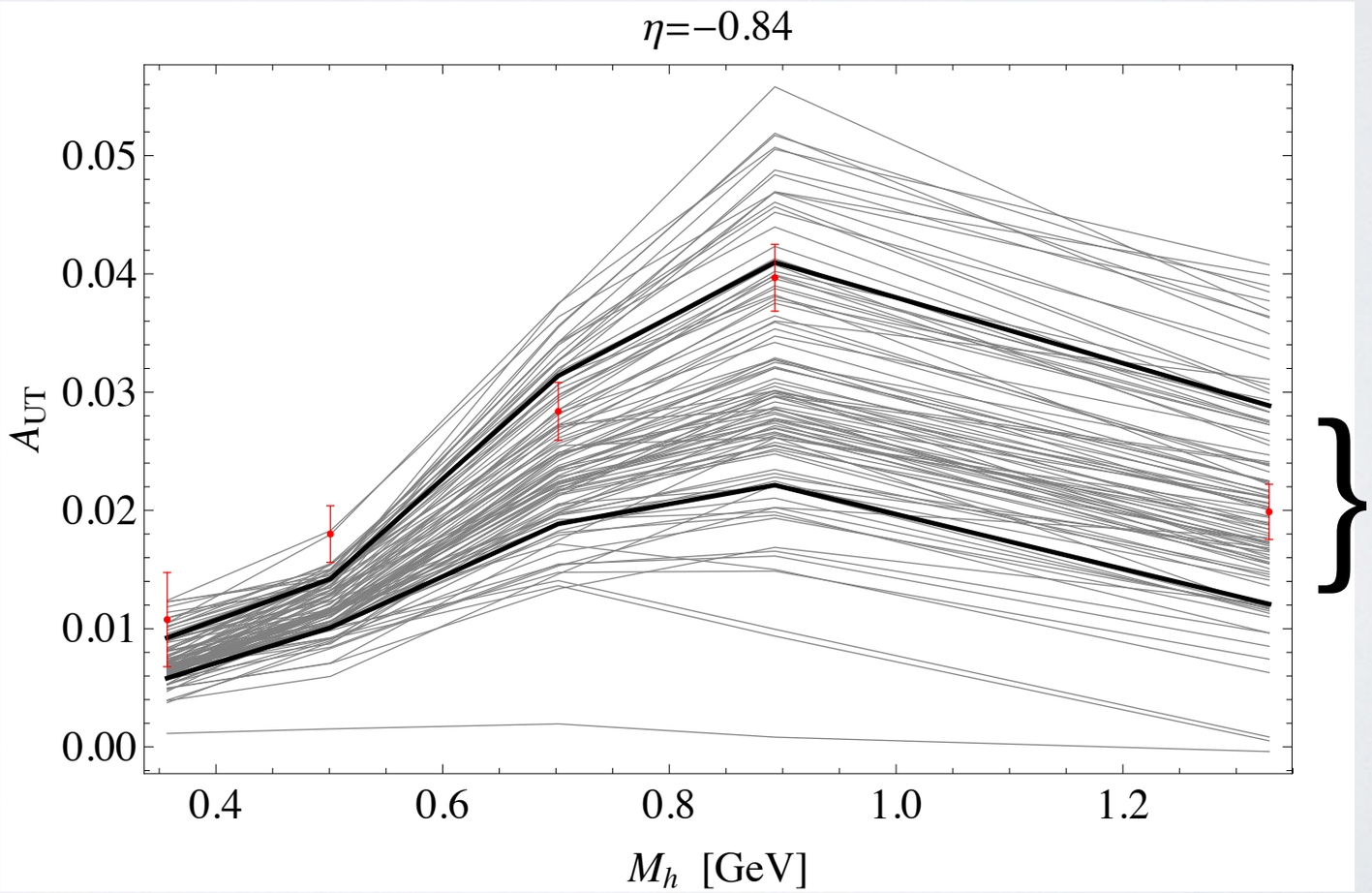
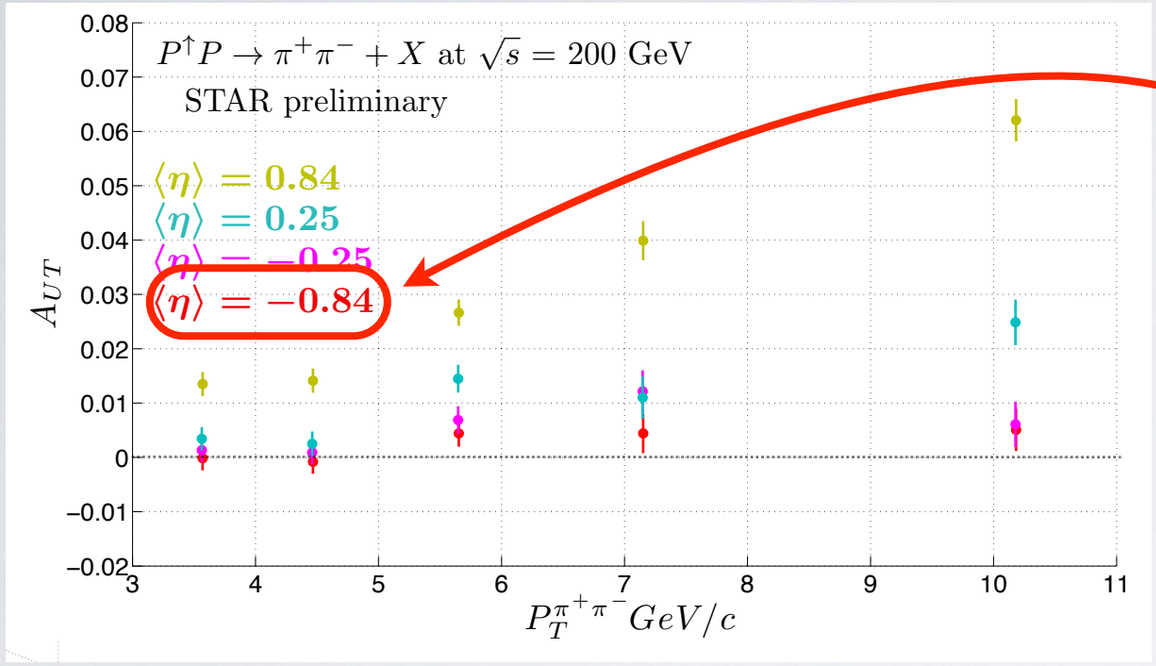




} 68%

Backup: P_T vs. η at $\sqrt{s}$ = 200 GeV



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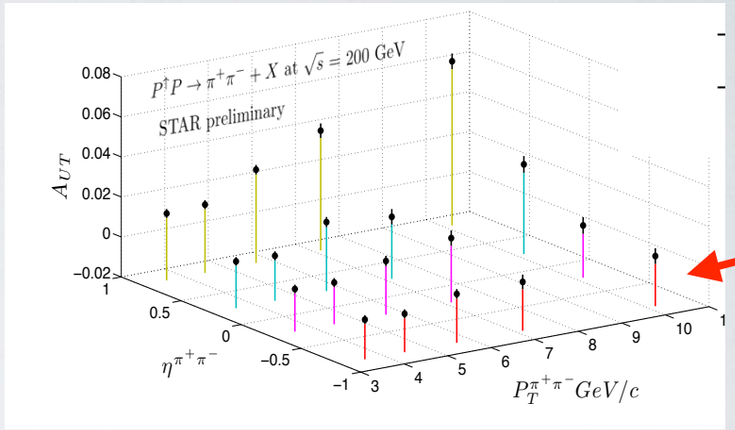

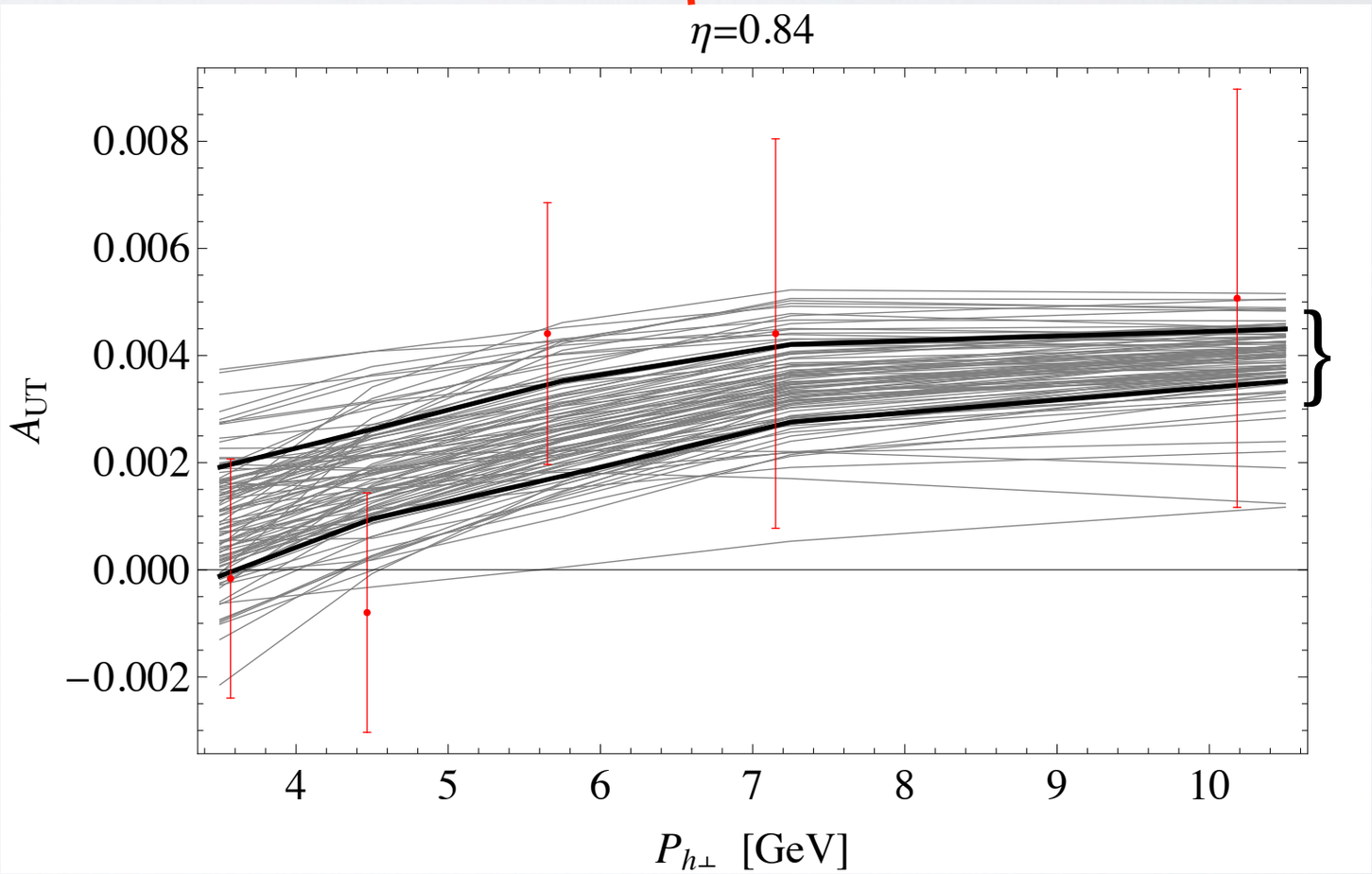

68%

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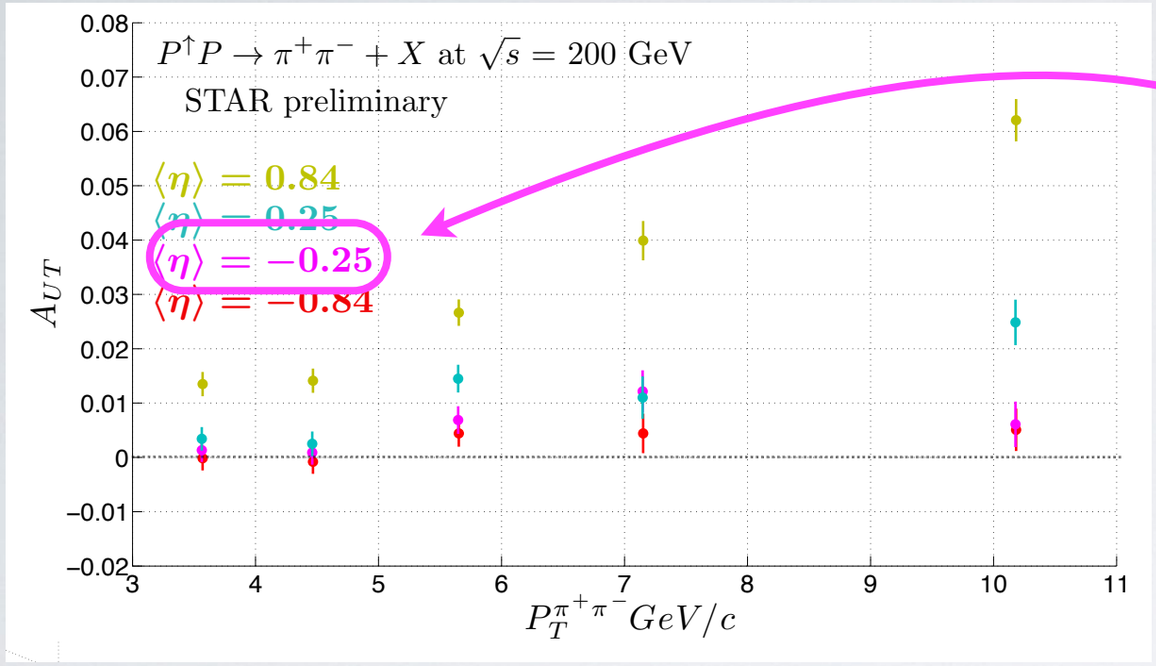

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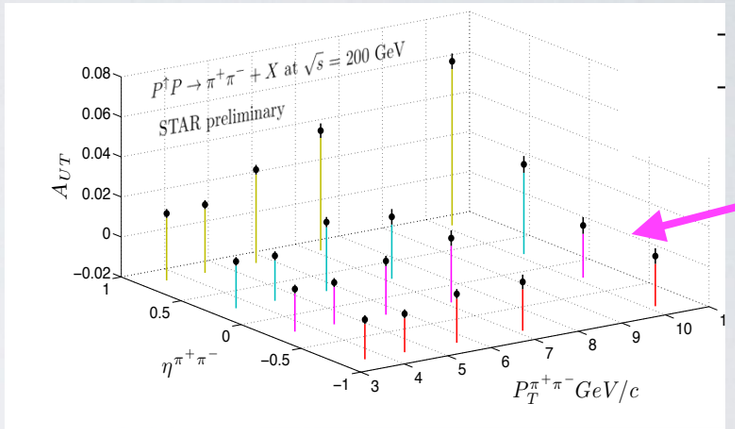

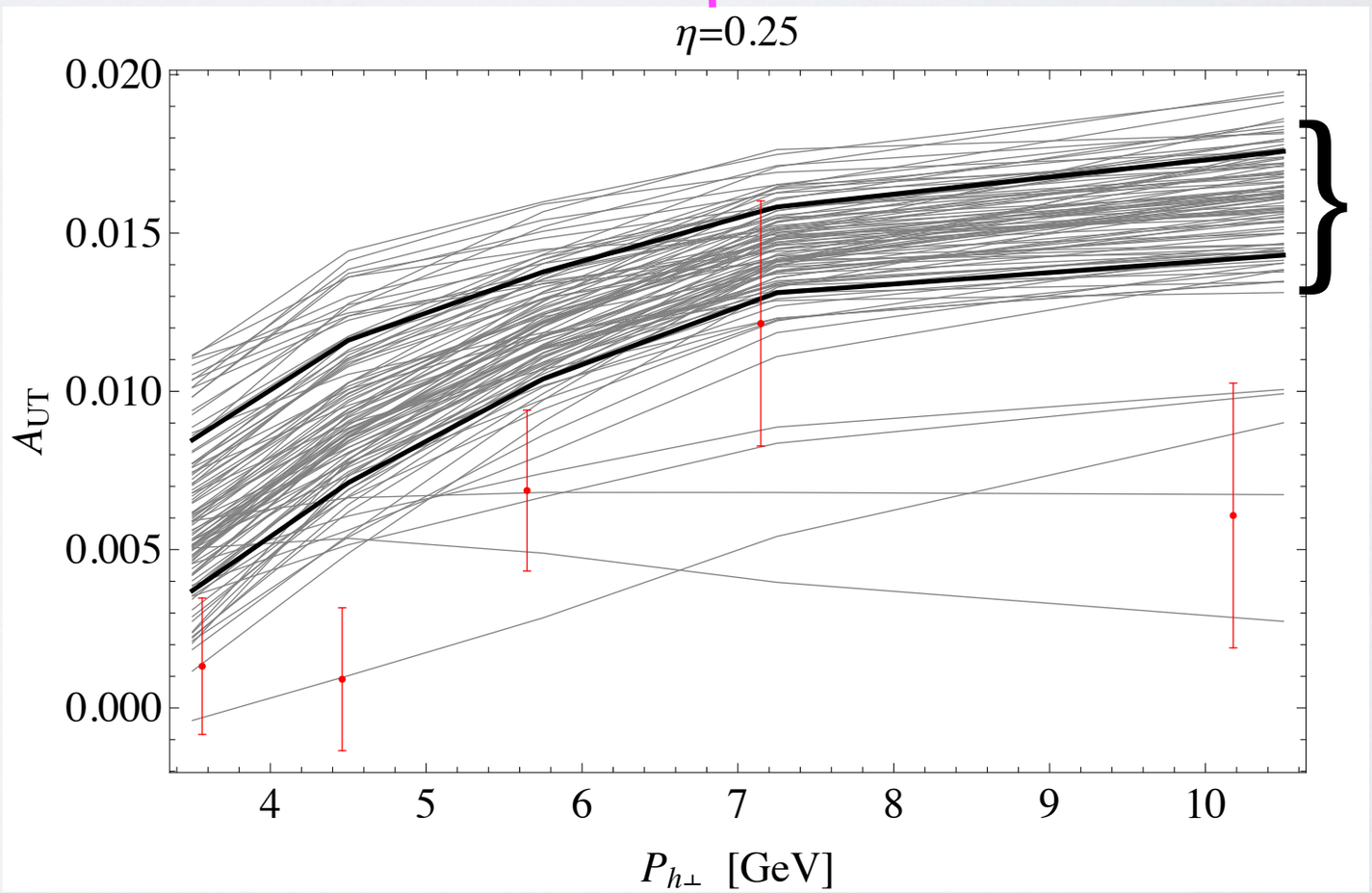

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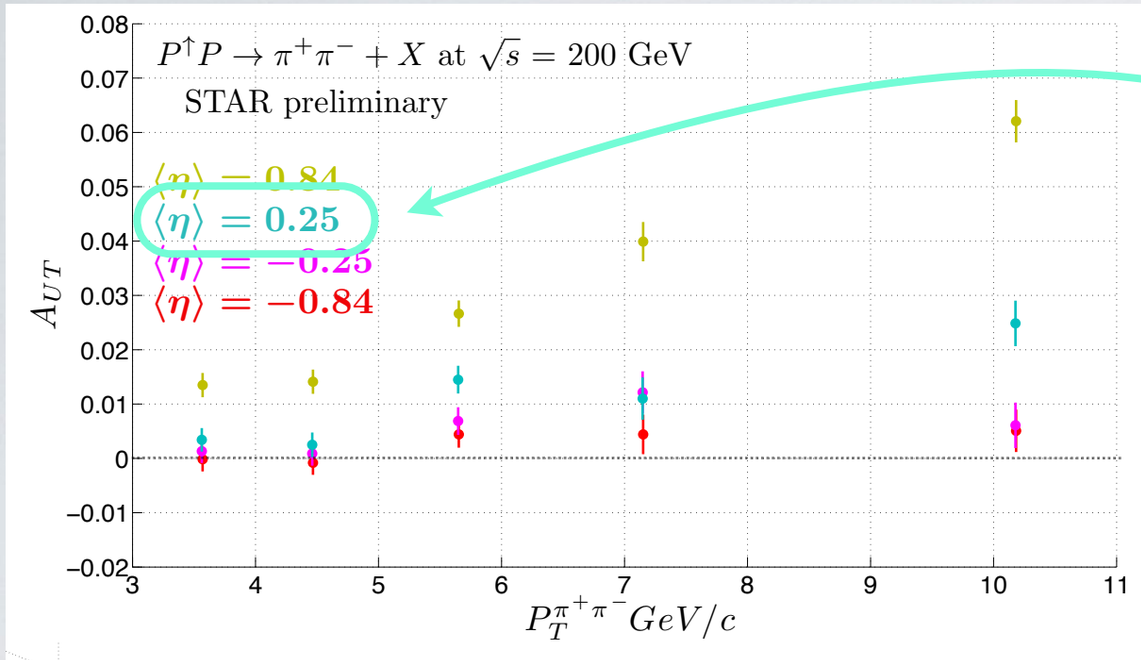

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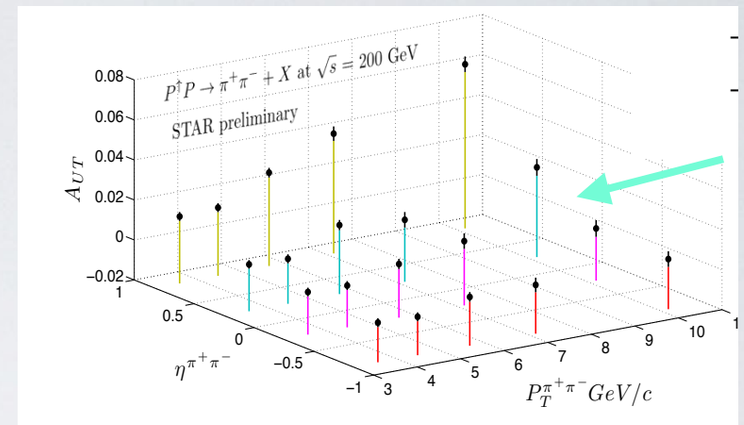

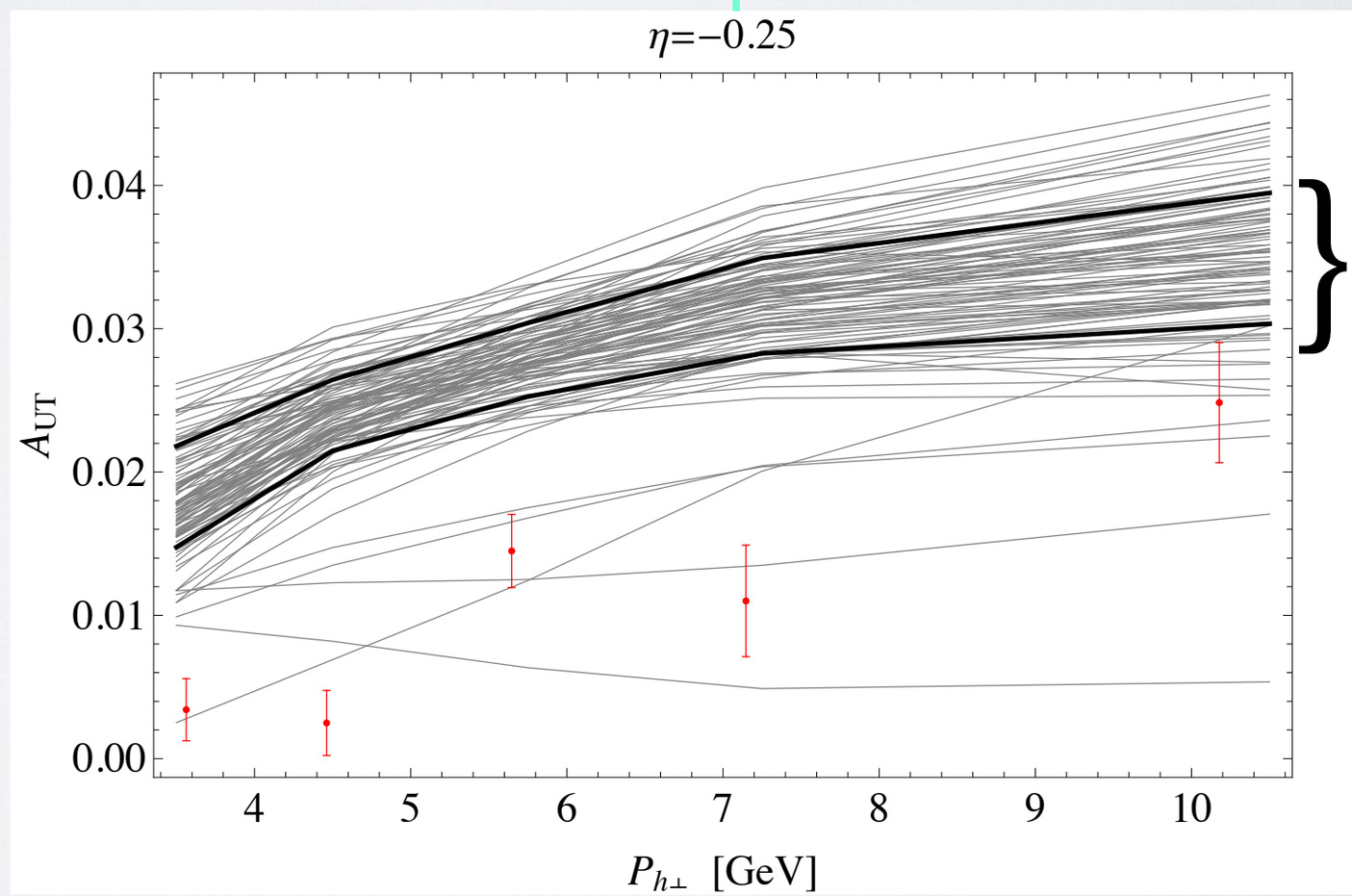

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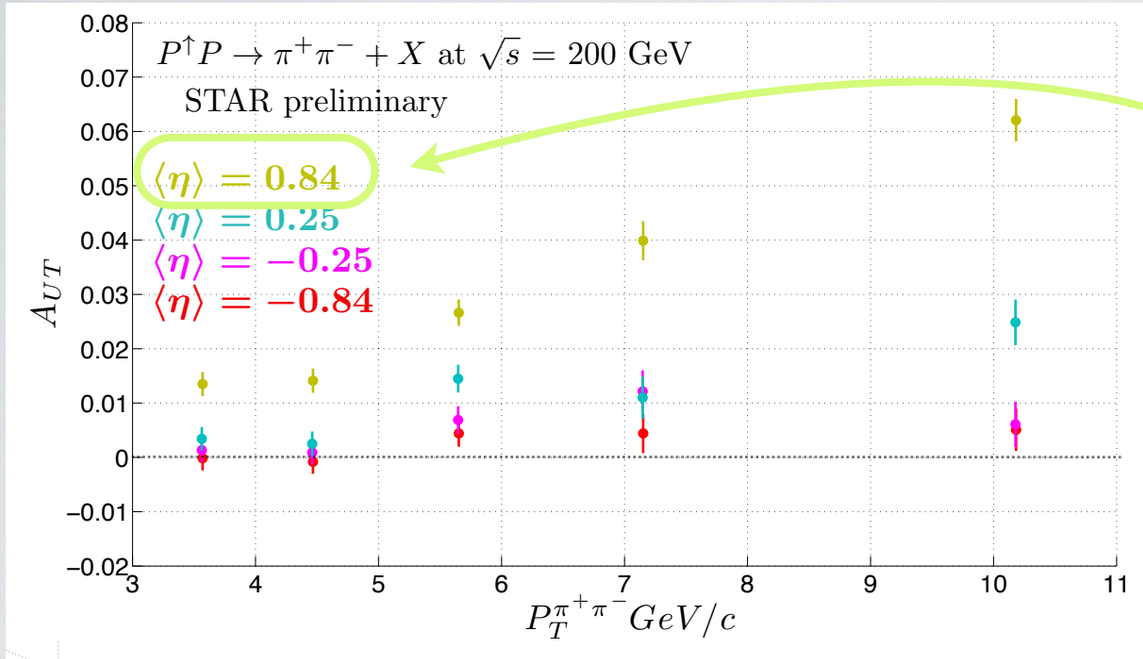

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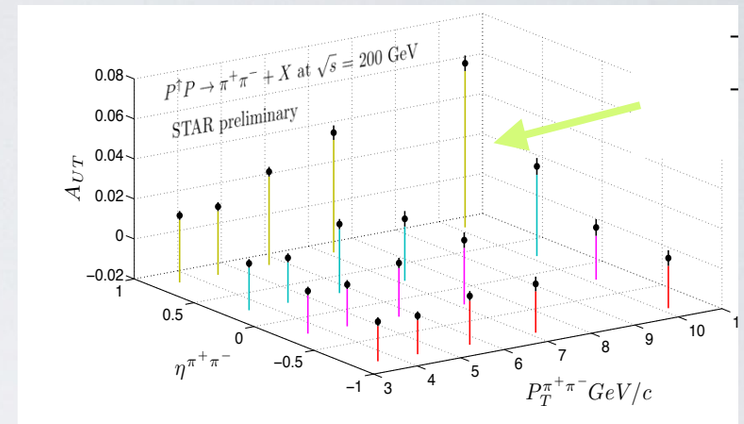
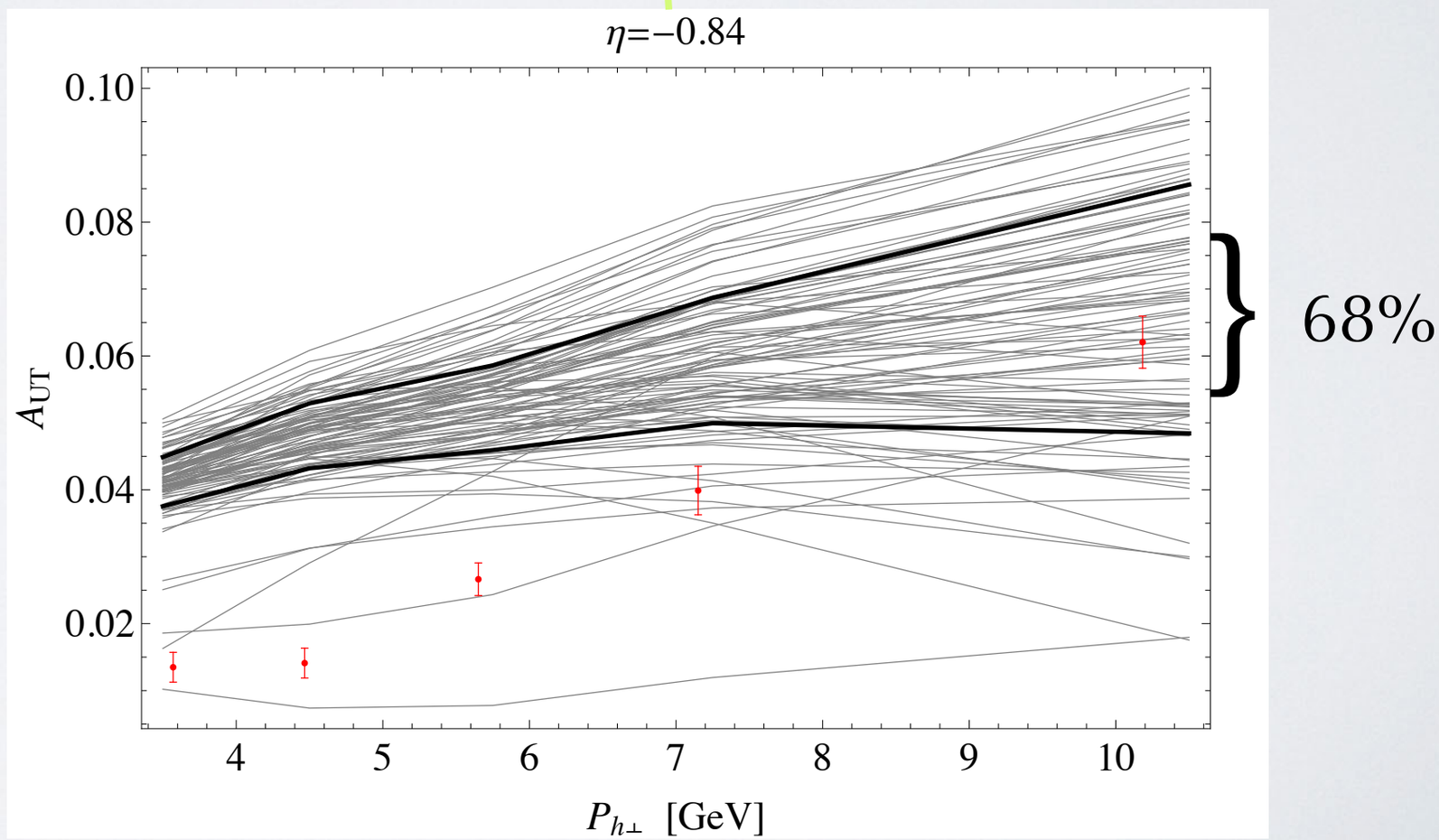
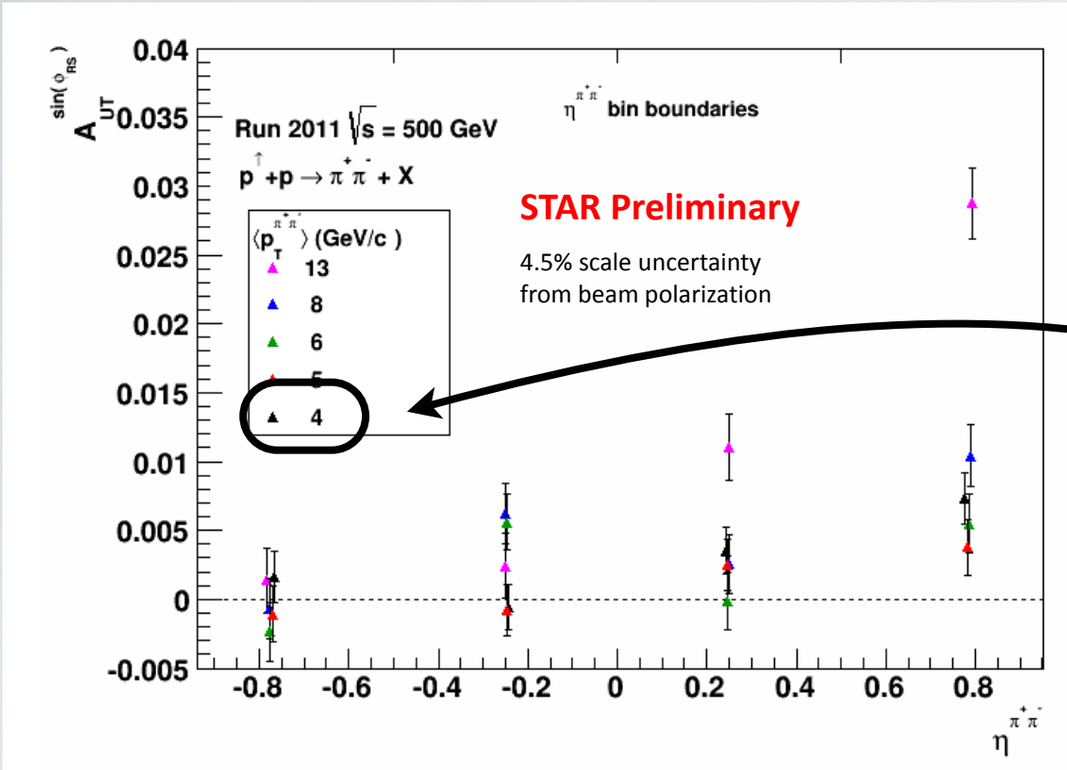




Backup: η vs. P_T at $\sqrt{s}$ = 500 GeV



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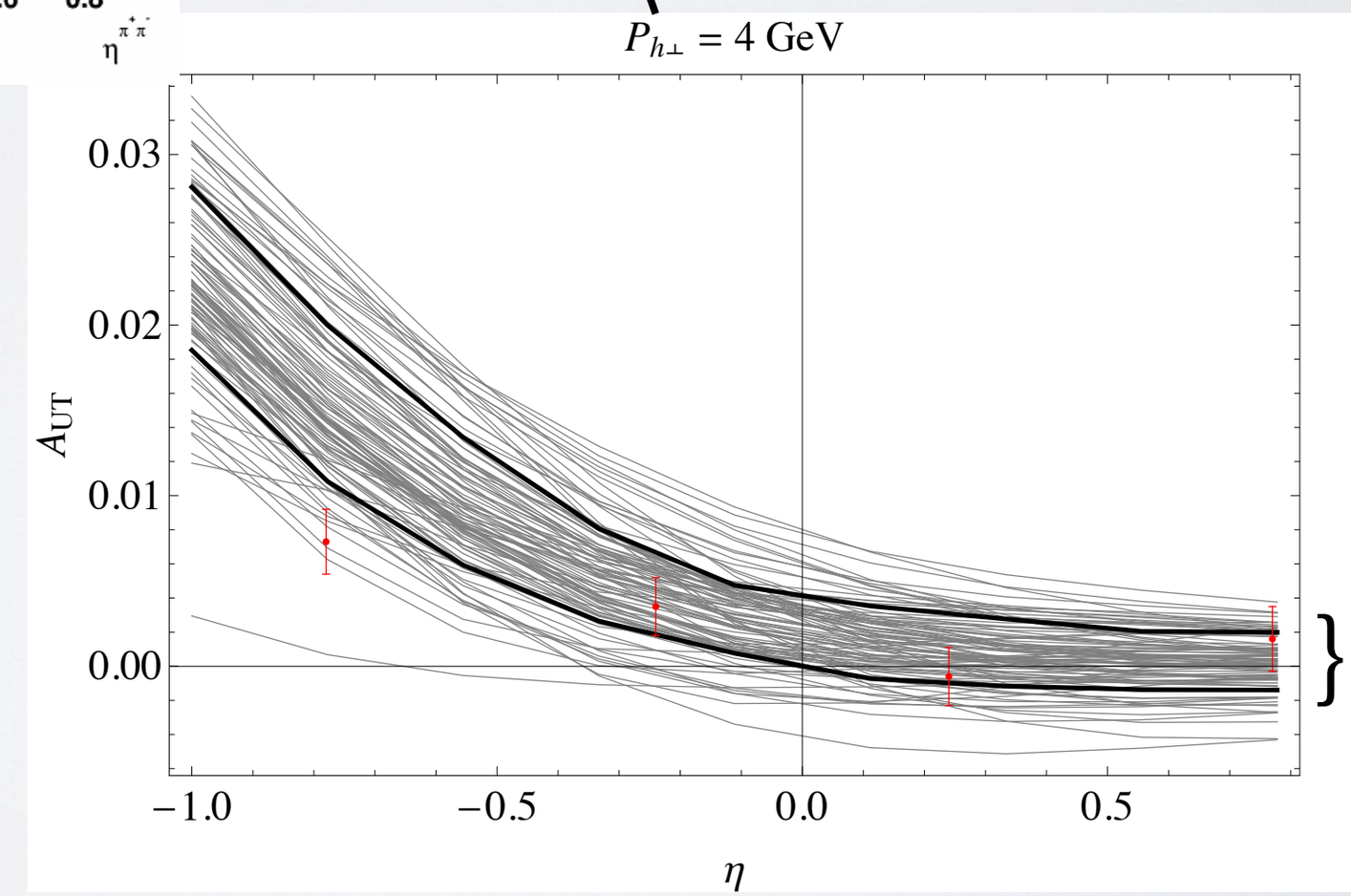

} 68%

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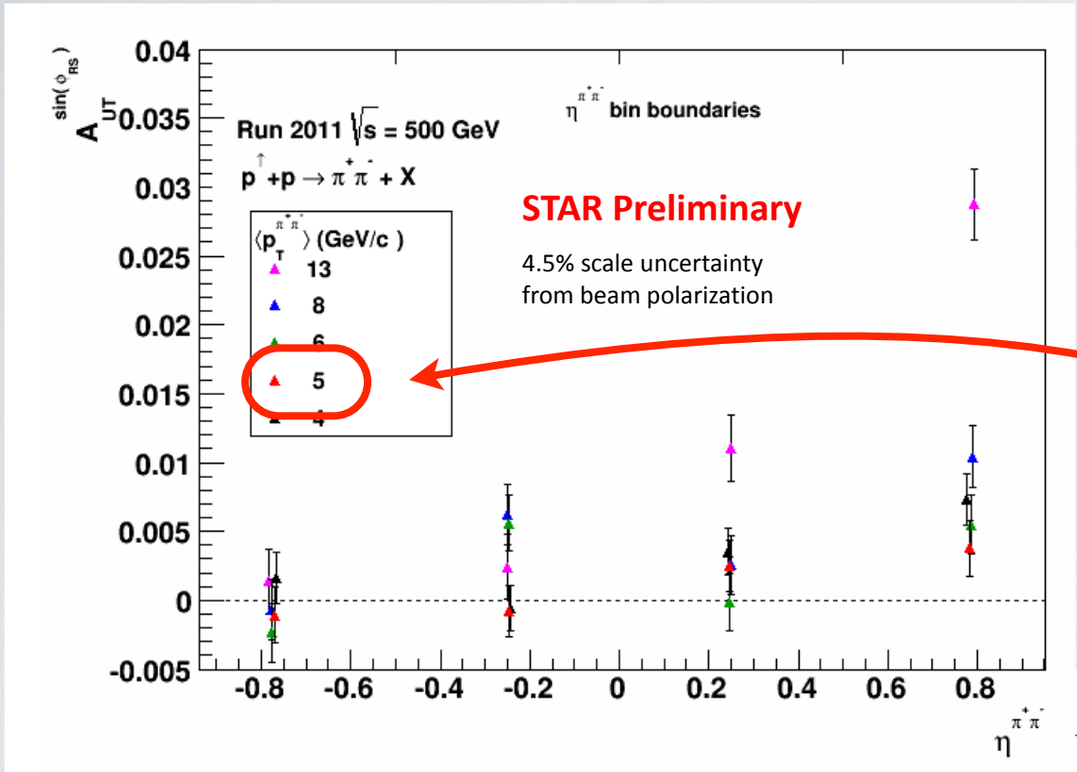

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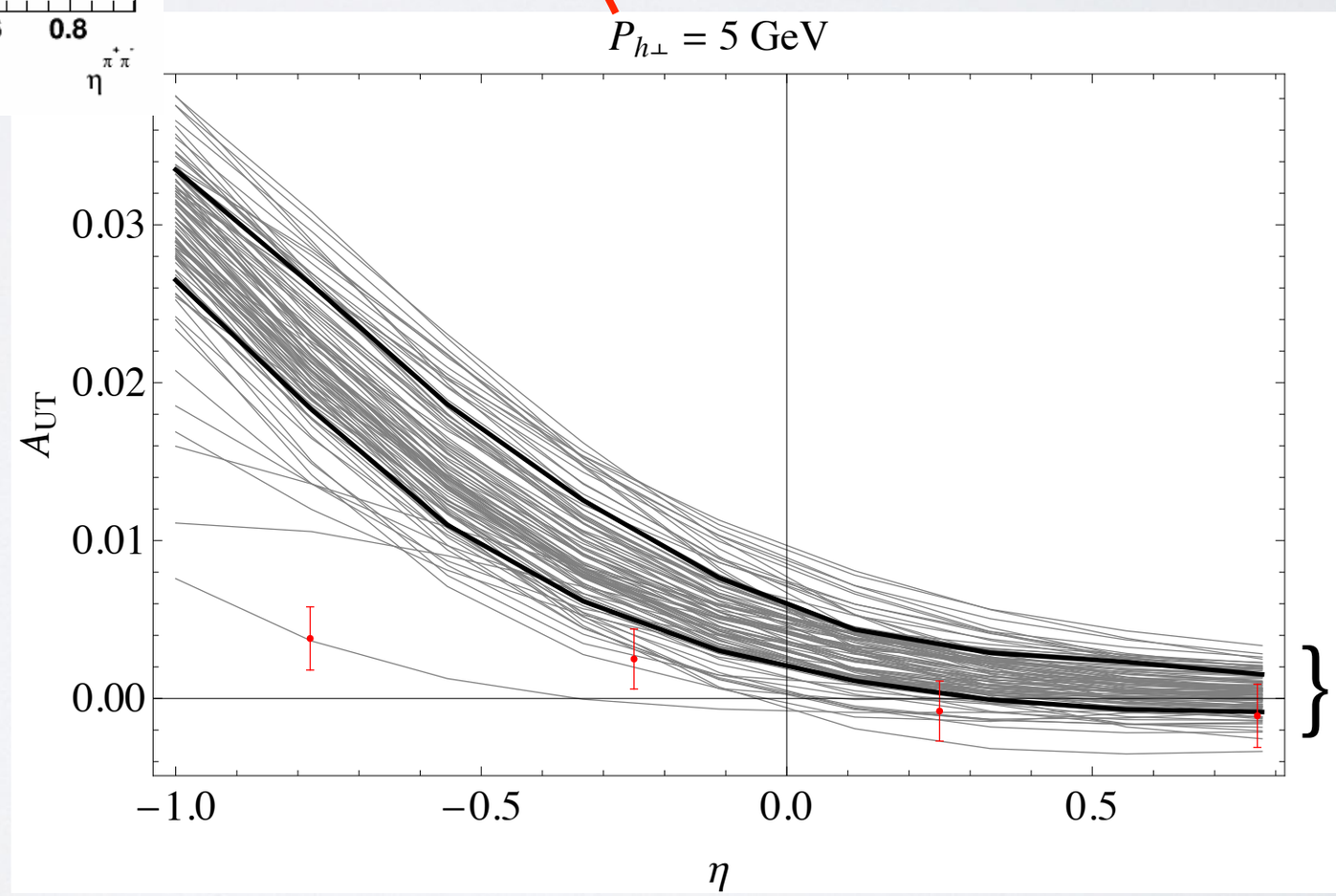

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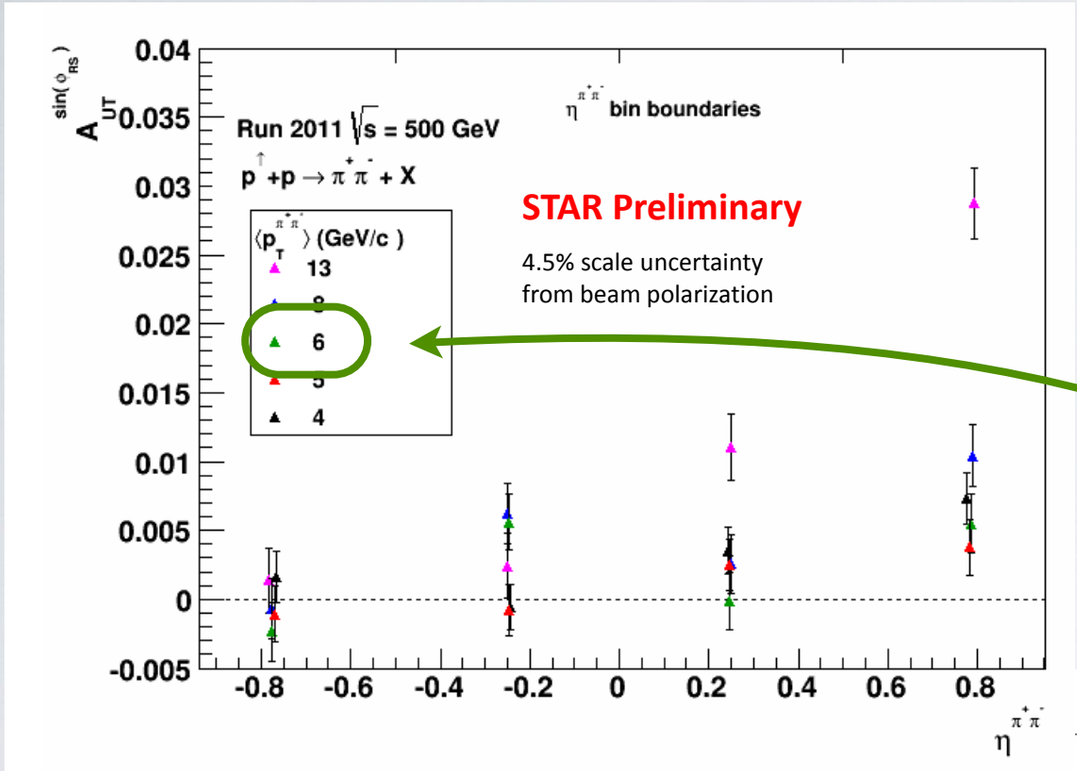

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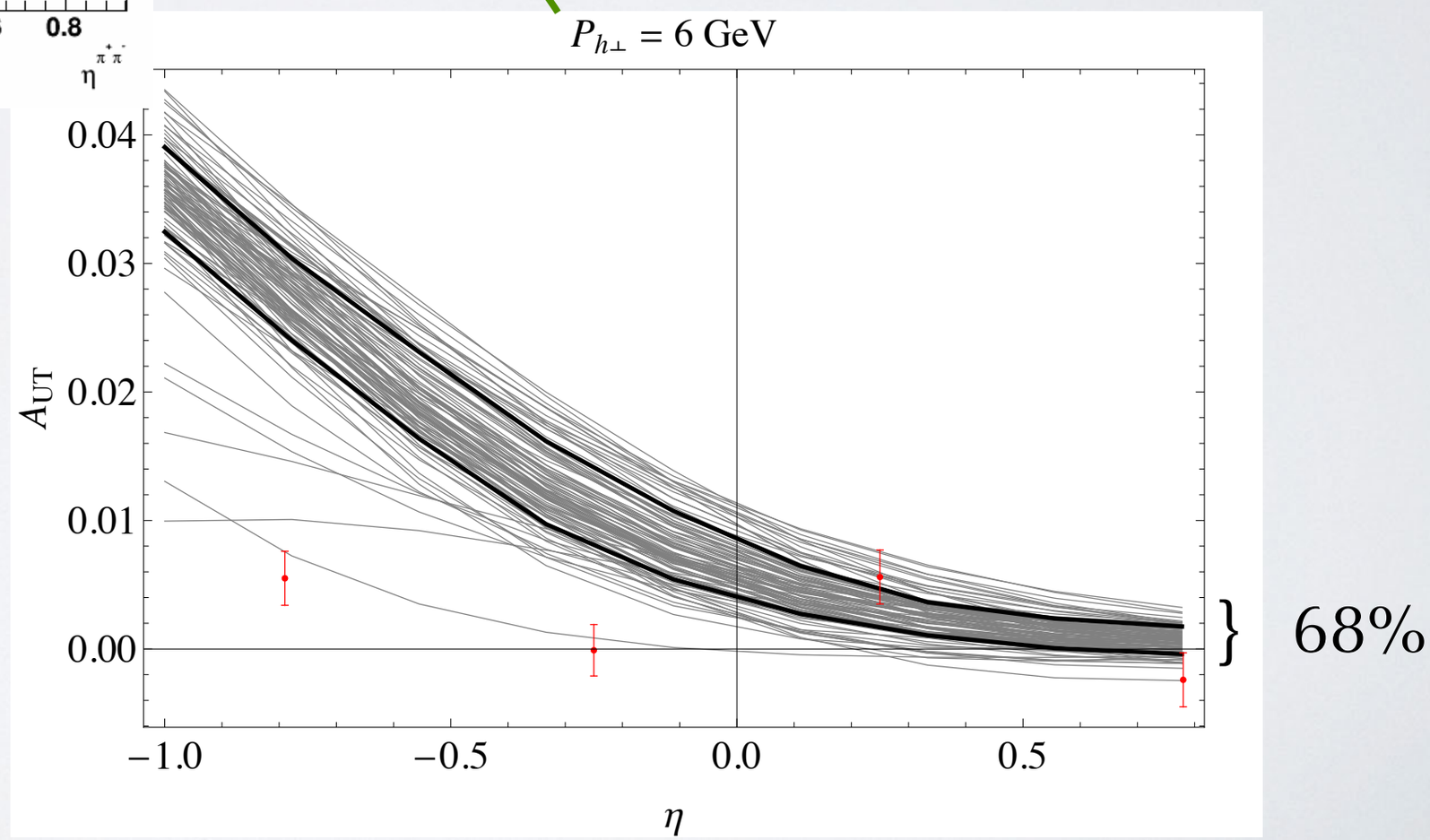

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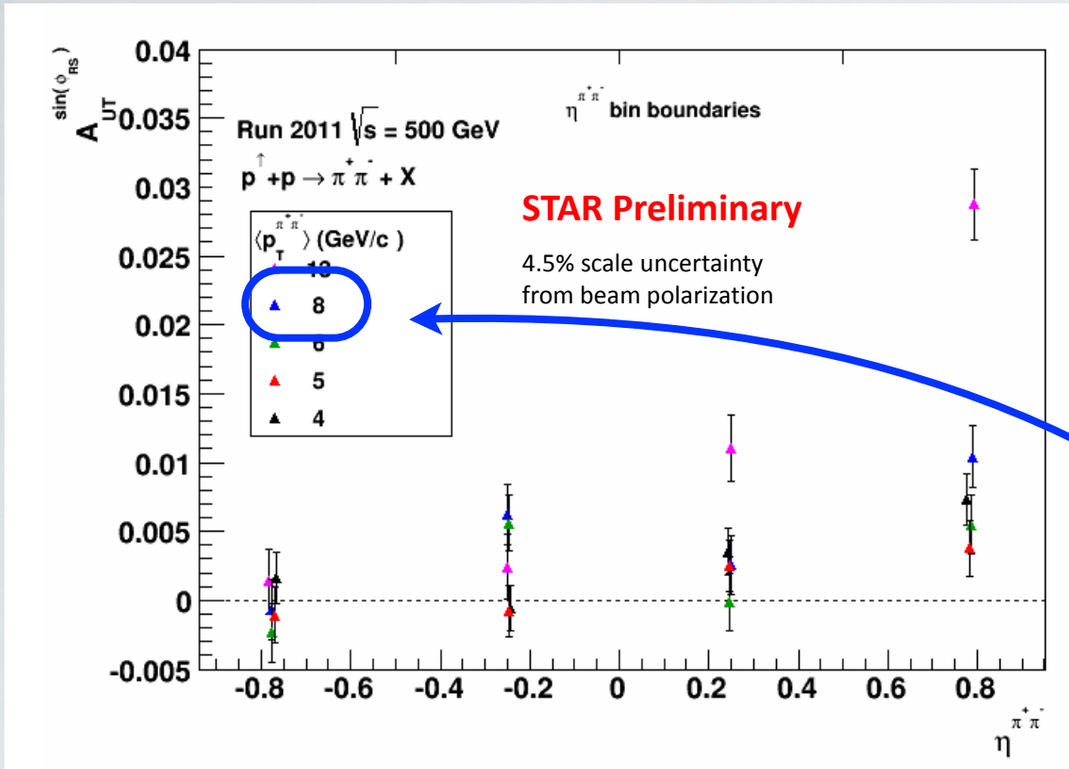

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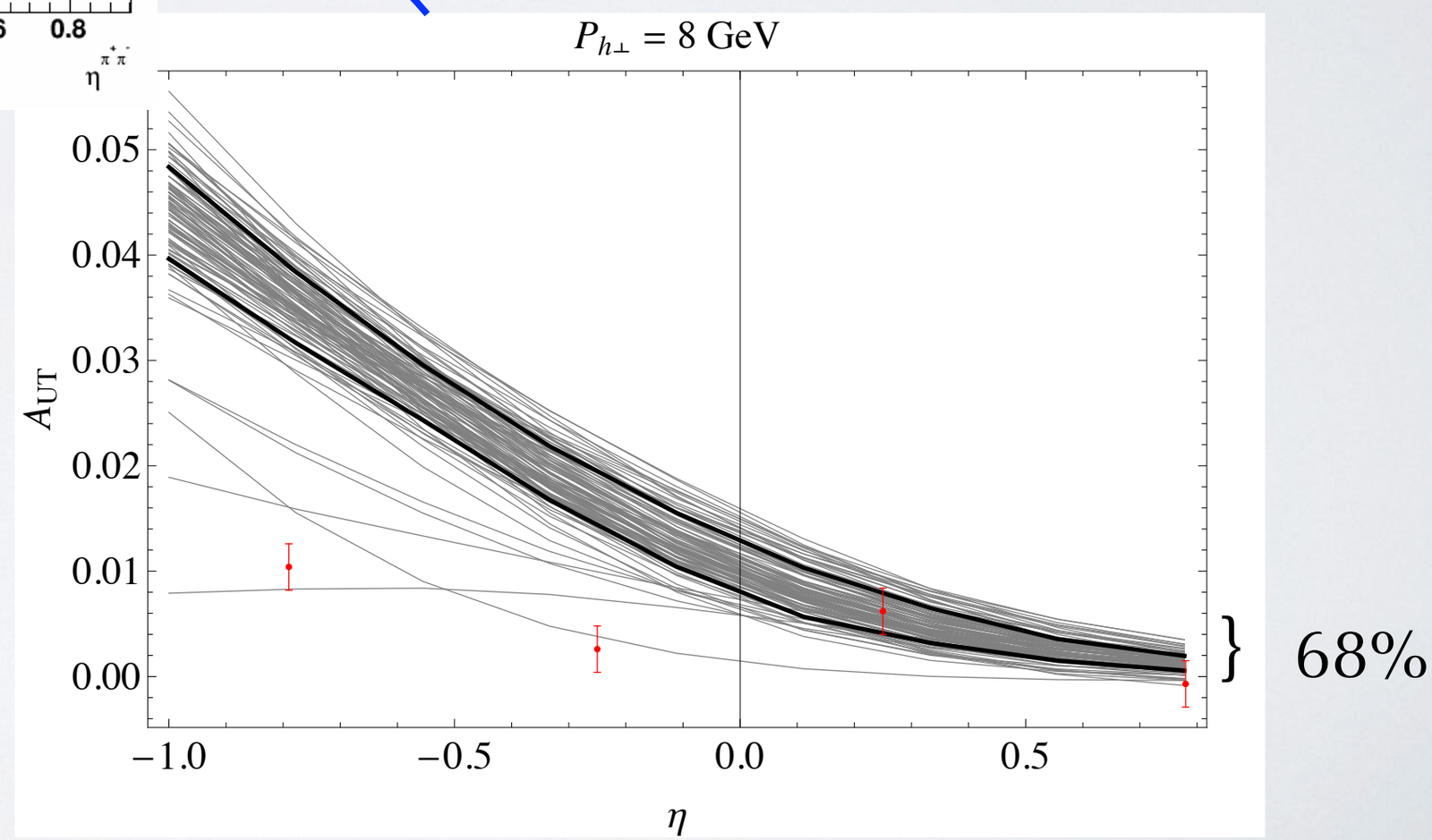

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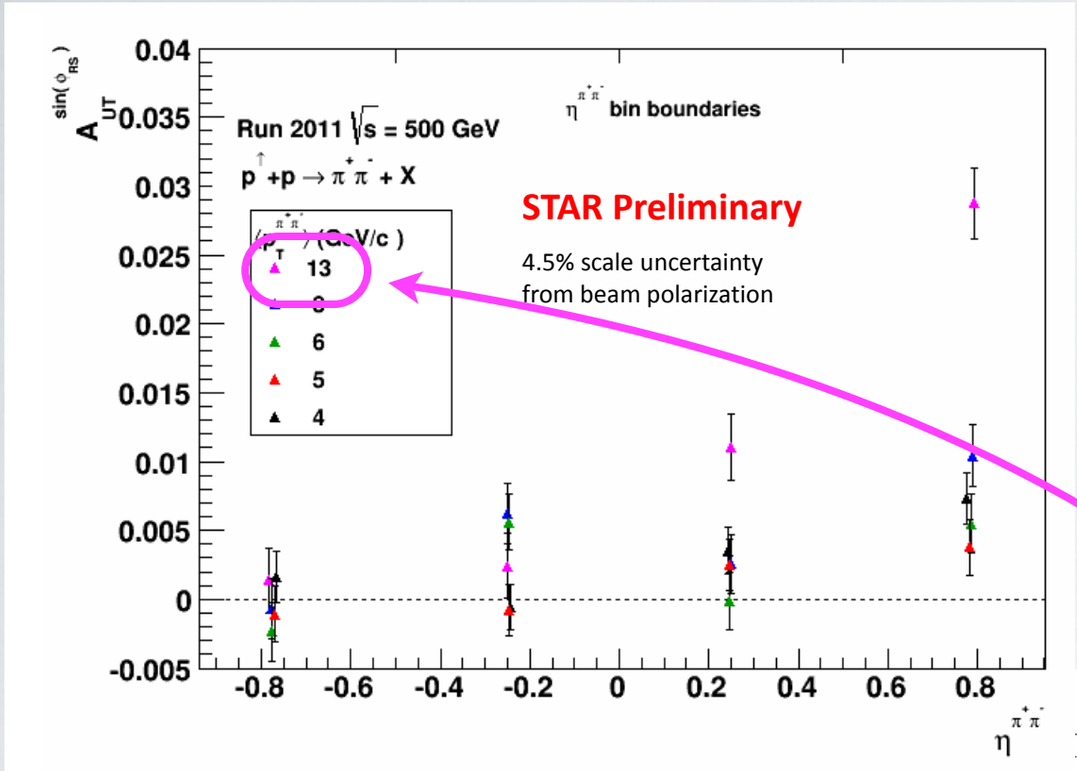

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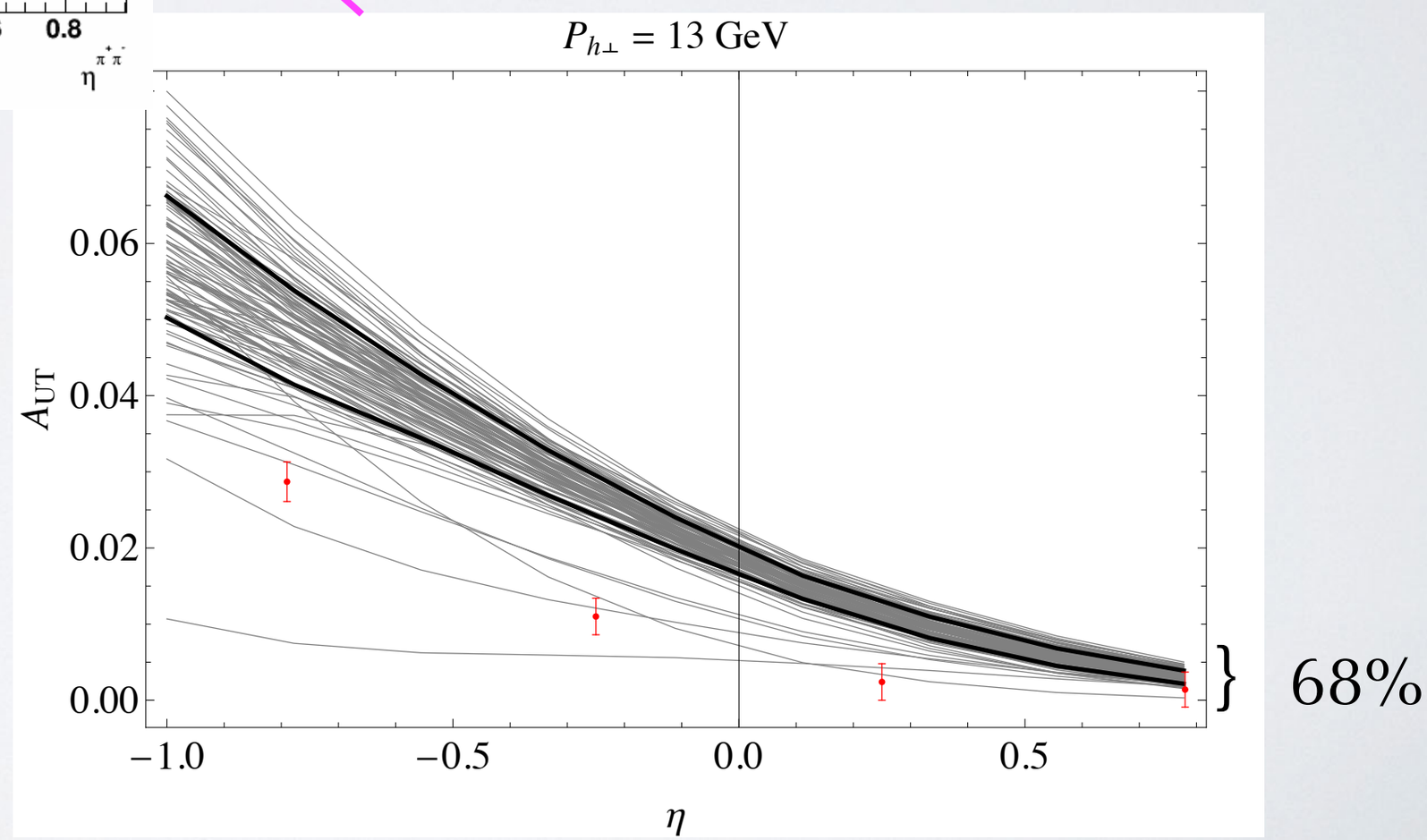
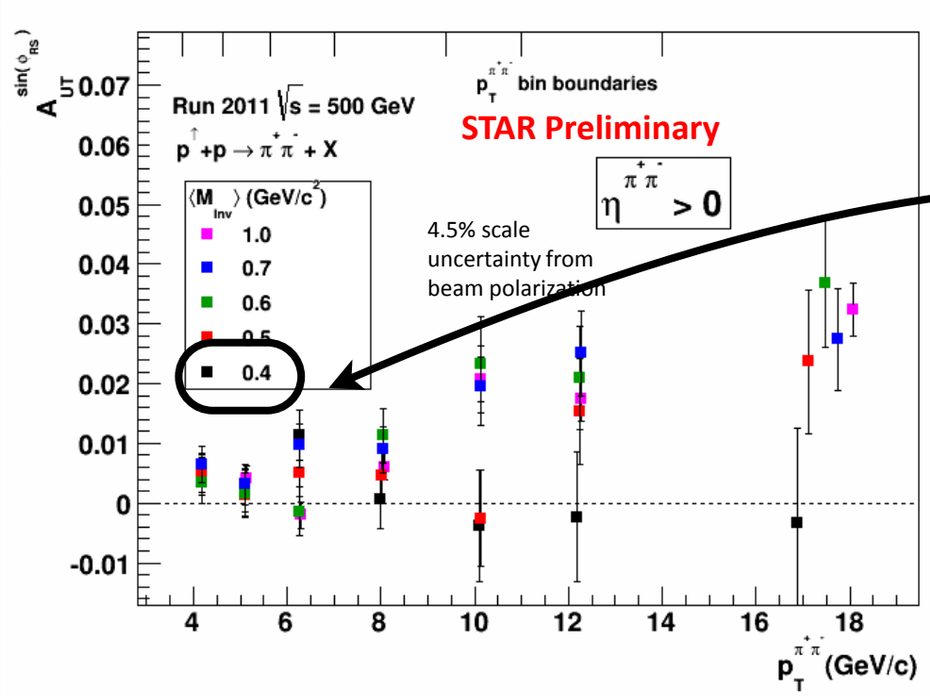


Backup: P_T vs. M at $\sqrt{s}$ = 500 GeV



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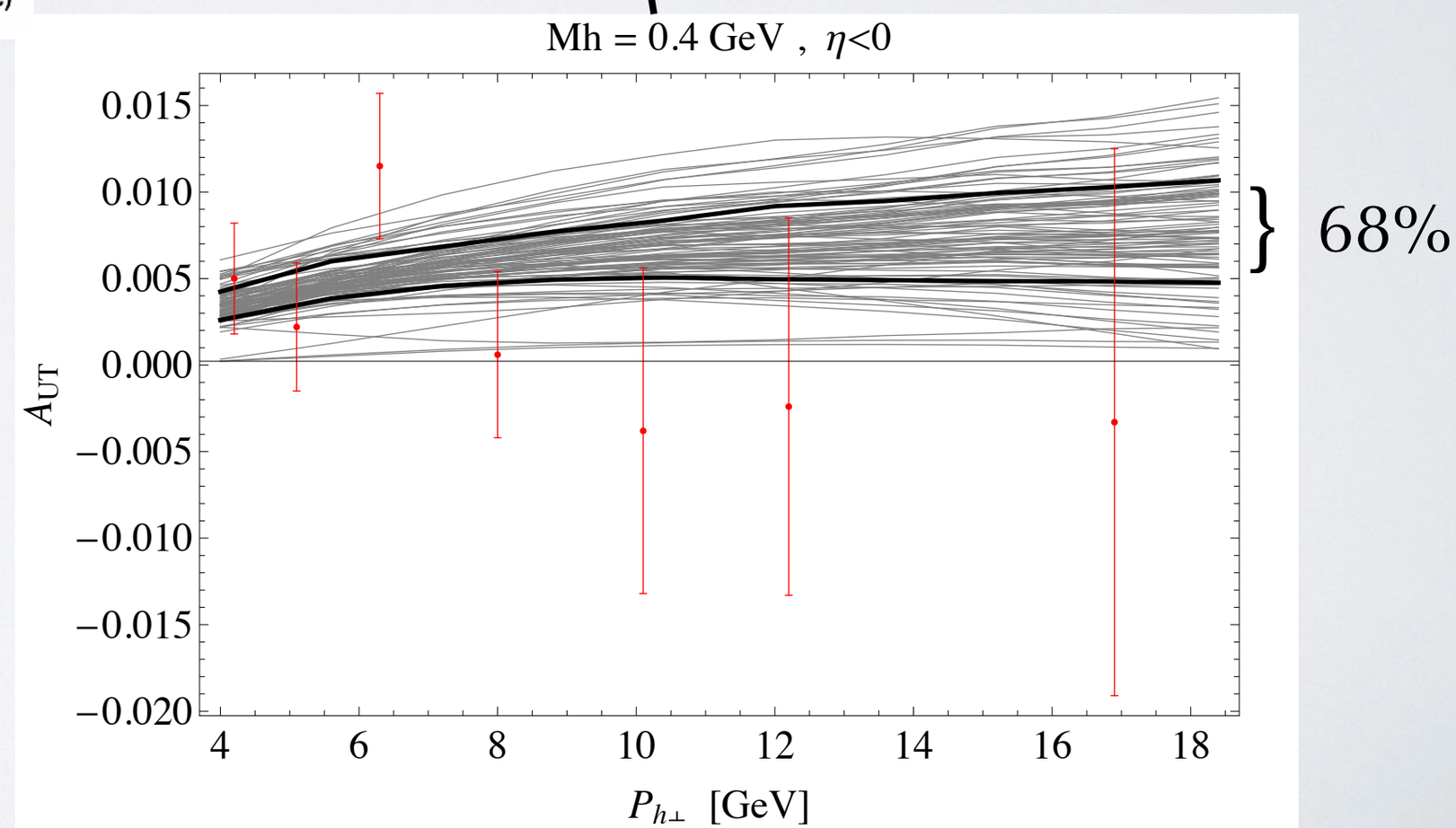

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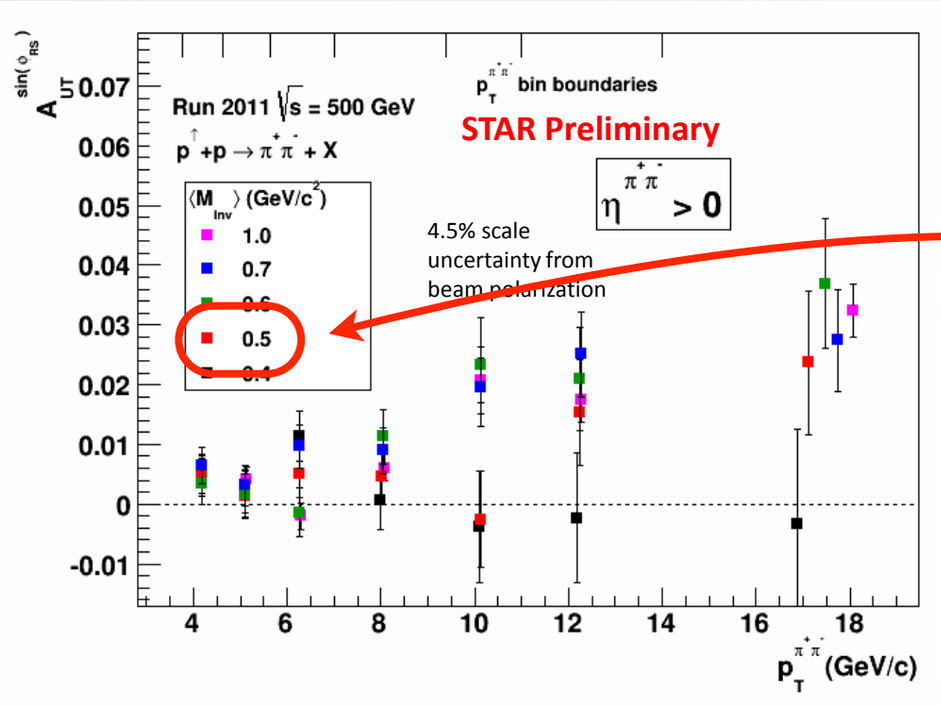

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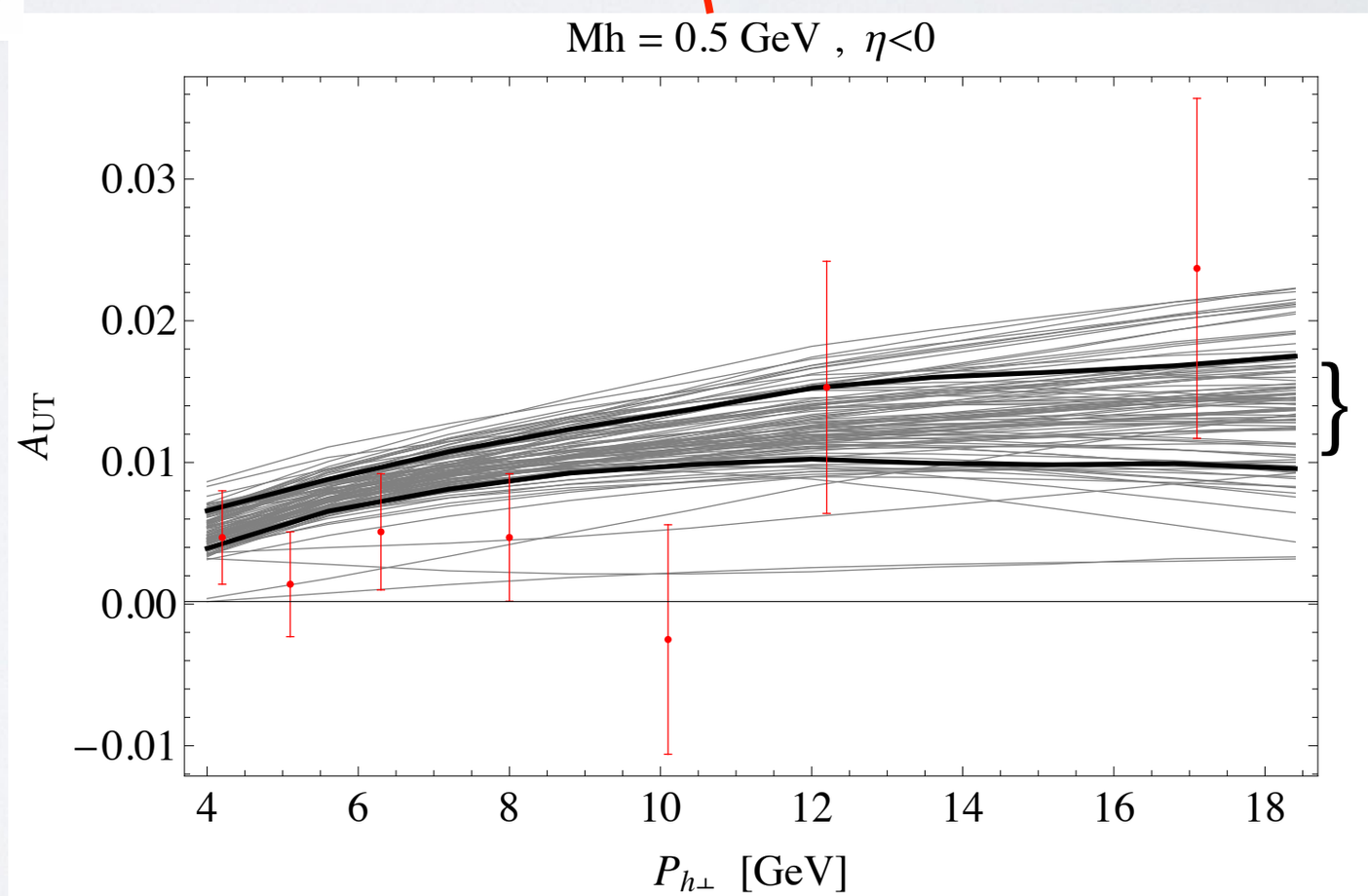

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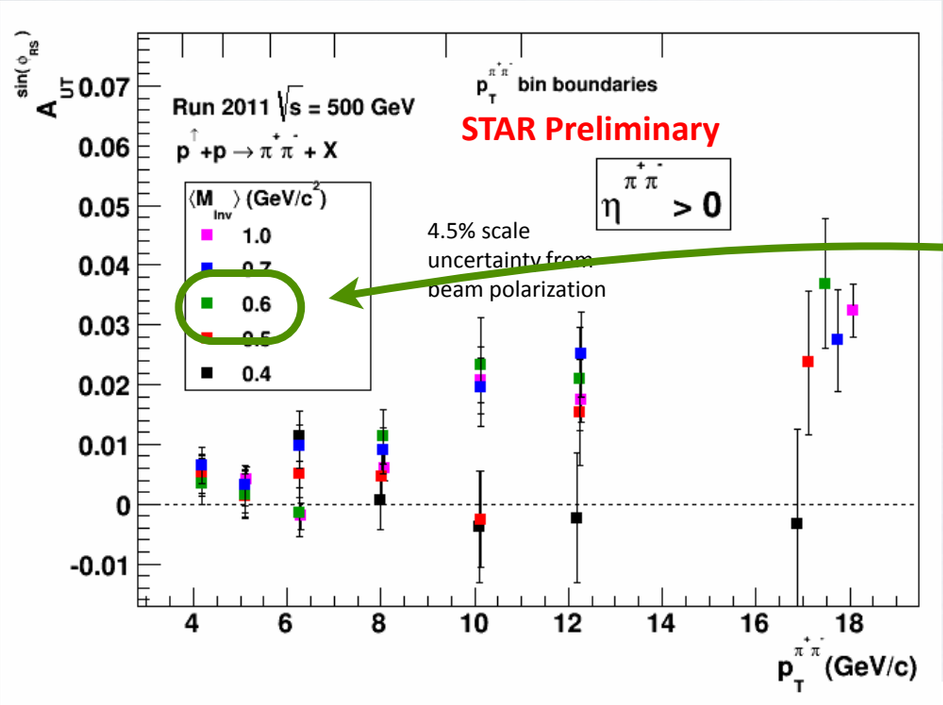
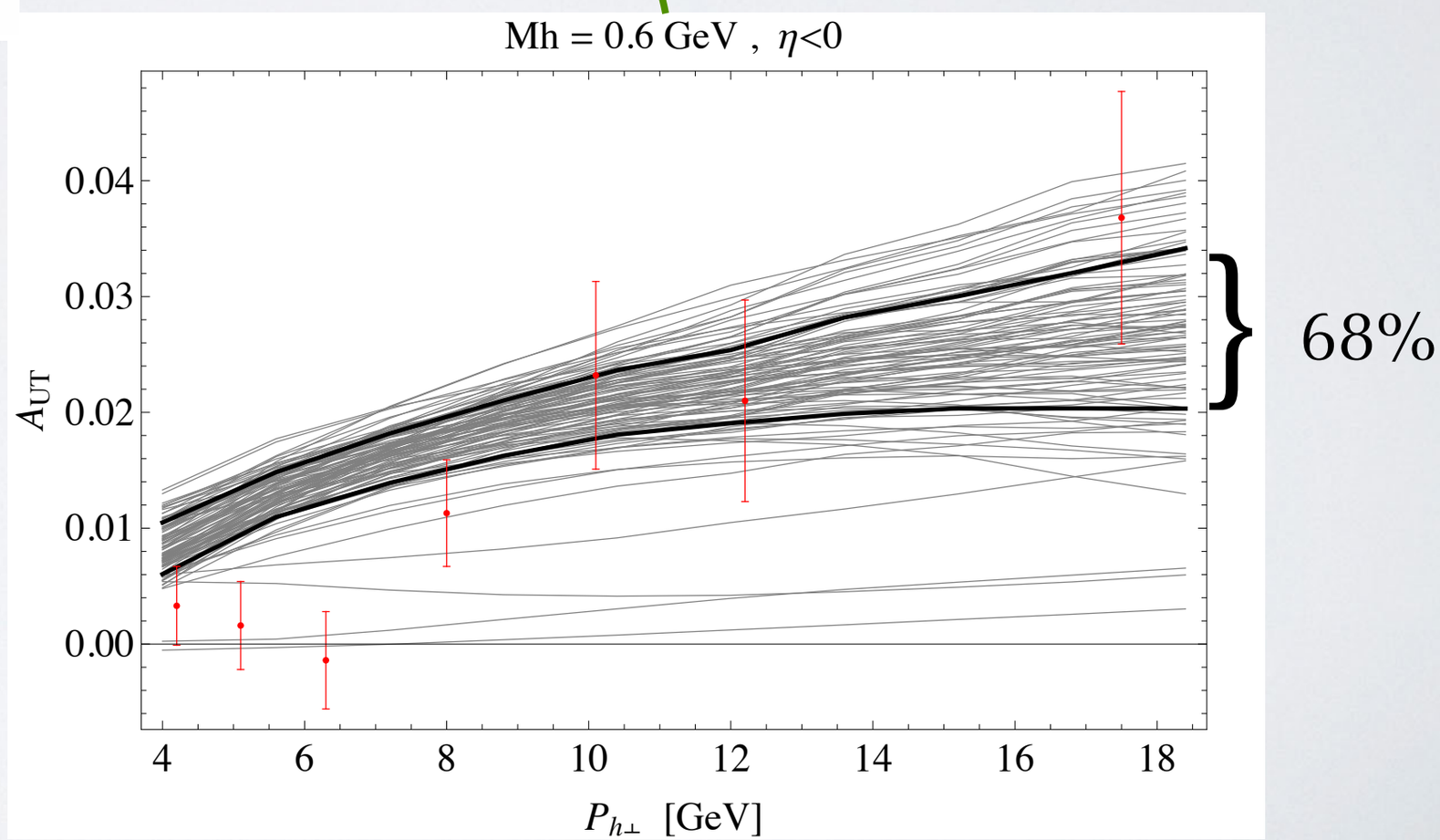


M. Skoby, talk at SPIN 2014



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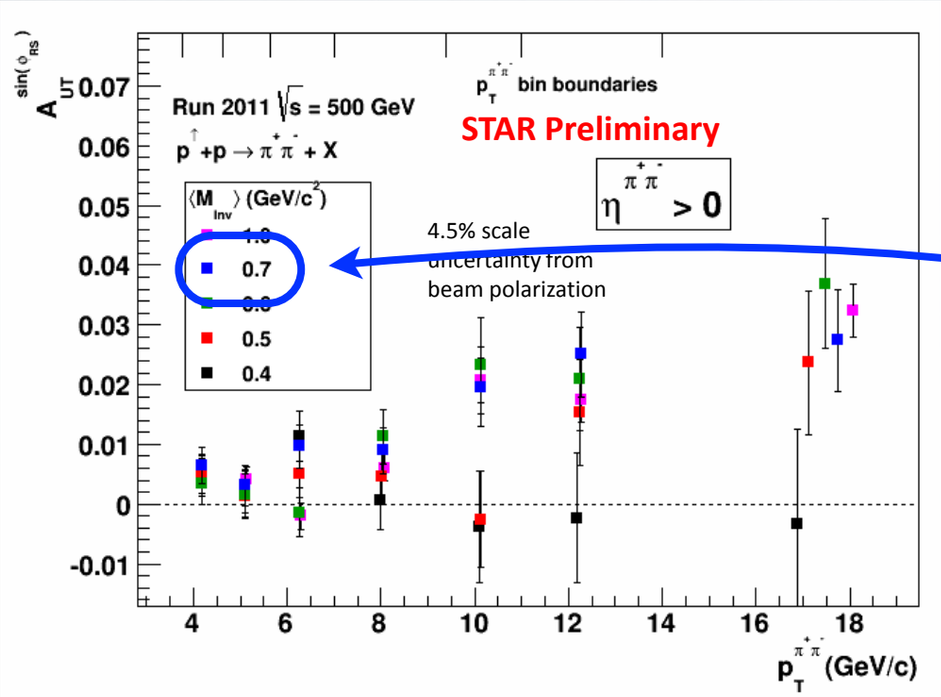
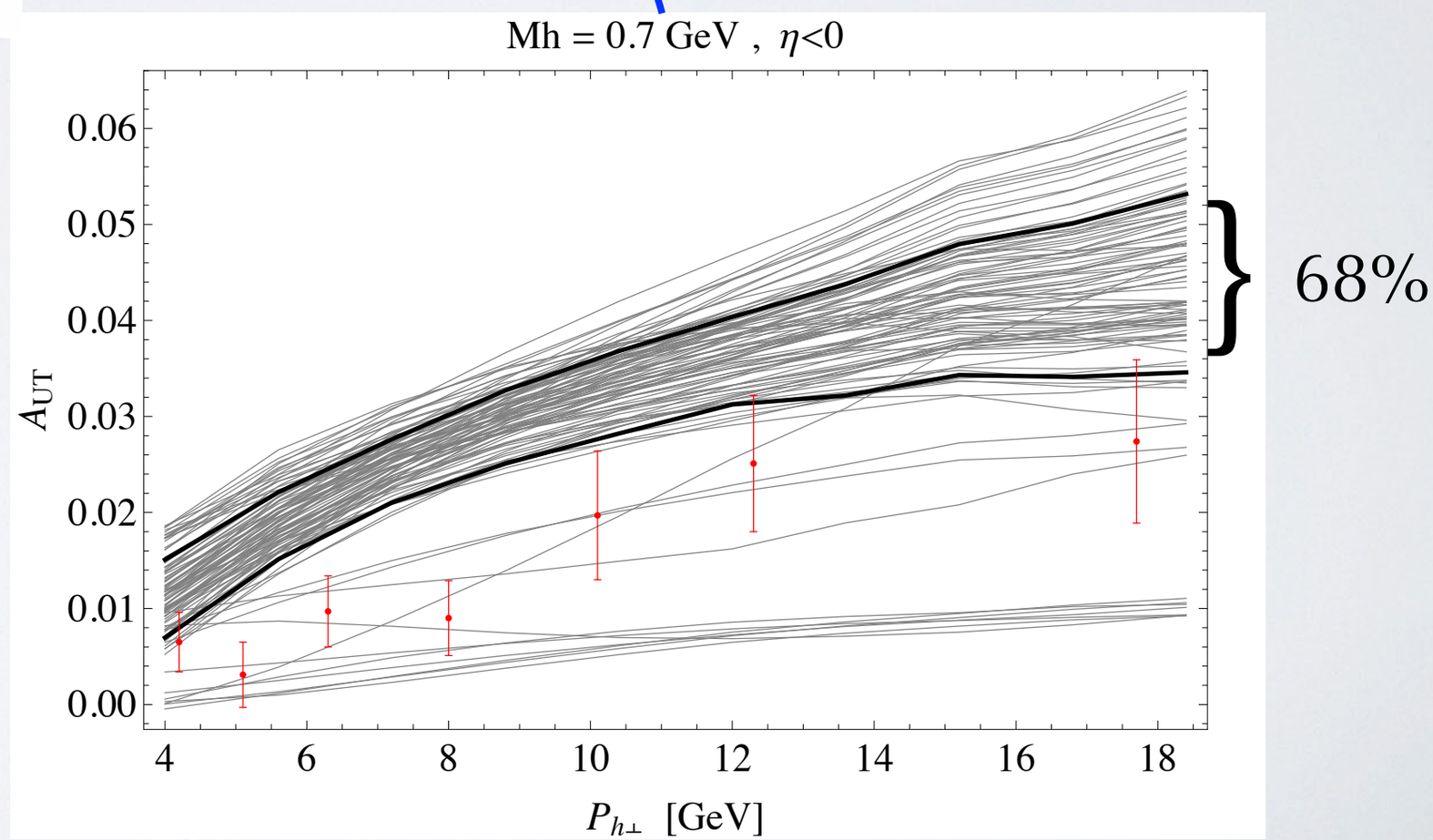
M. Skoby, talk at SPIN 2014