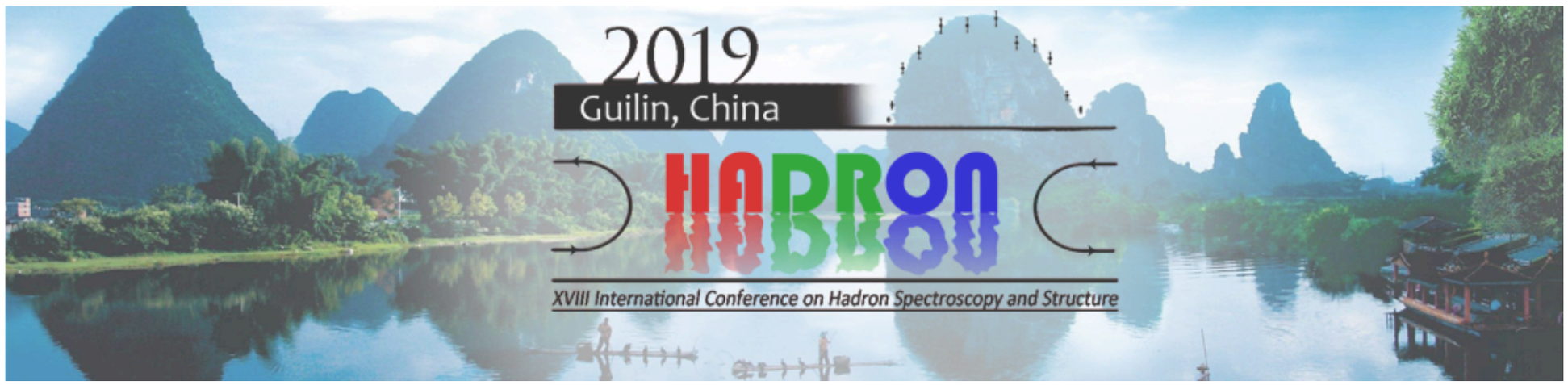
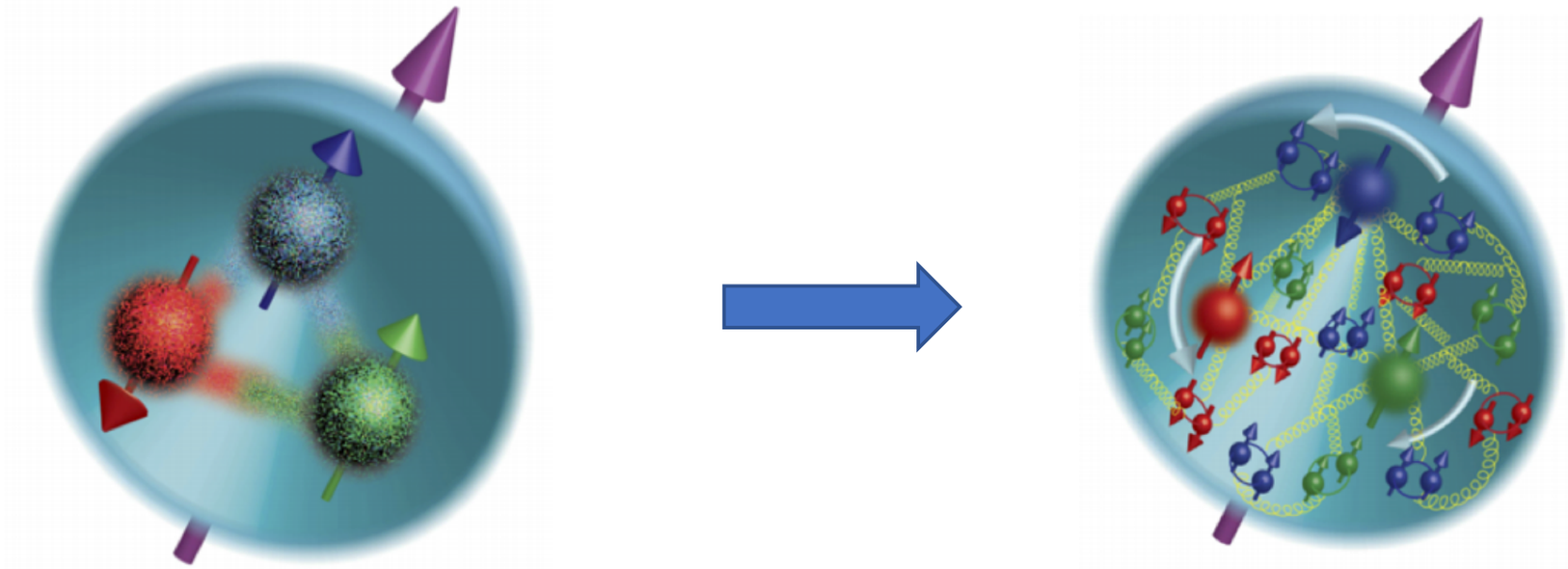
Measurement of Longitudinal Spin Asymmetries for Weak Boson Production at STAR

Jinlong Zhang (Stony Brook University)
for the STAR Collaboration



Proton Spin Structure



- Proton spin puzzle: integral of quark polarization measured in DIS to be only ~30% of the proton spin

- Contributions from quark/antiquarks spin ($\Delta\Sigma$), gluon spin (ΔG) and possibly from the orbital angular momentum (L)

$$< S_p > = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

Jaffe-Manohar 1990

Proton Spin Structure

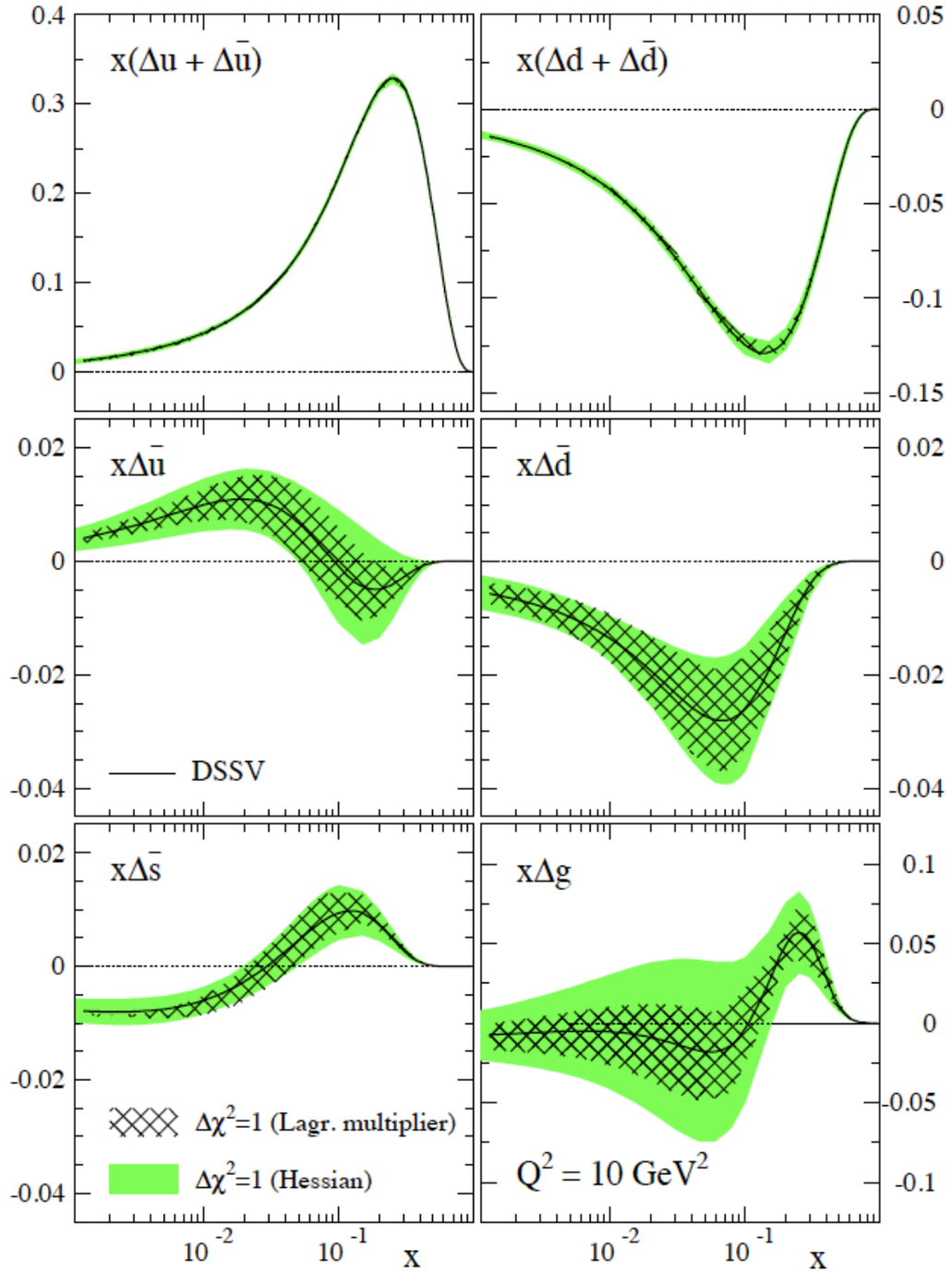
Before RHIC, mostly polarized DIS

- Total quark spin contributions pinned down pretty well
- Flavor separation was accessible via semi-inclusive DIS but has to rely on Fragmentation Functions; additional uncertainty introduced
- No direct access to gluon spin

RHIC spin program

- Direct access to gluon spin
- Direct access to sea quarks
- Transverse spin

DSSV2008
(Mostly pDIS + earlier RHIC results)



PRD 80, 034030 (2009)

Proton Spin Structure

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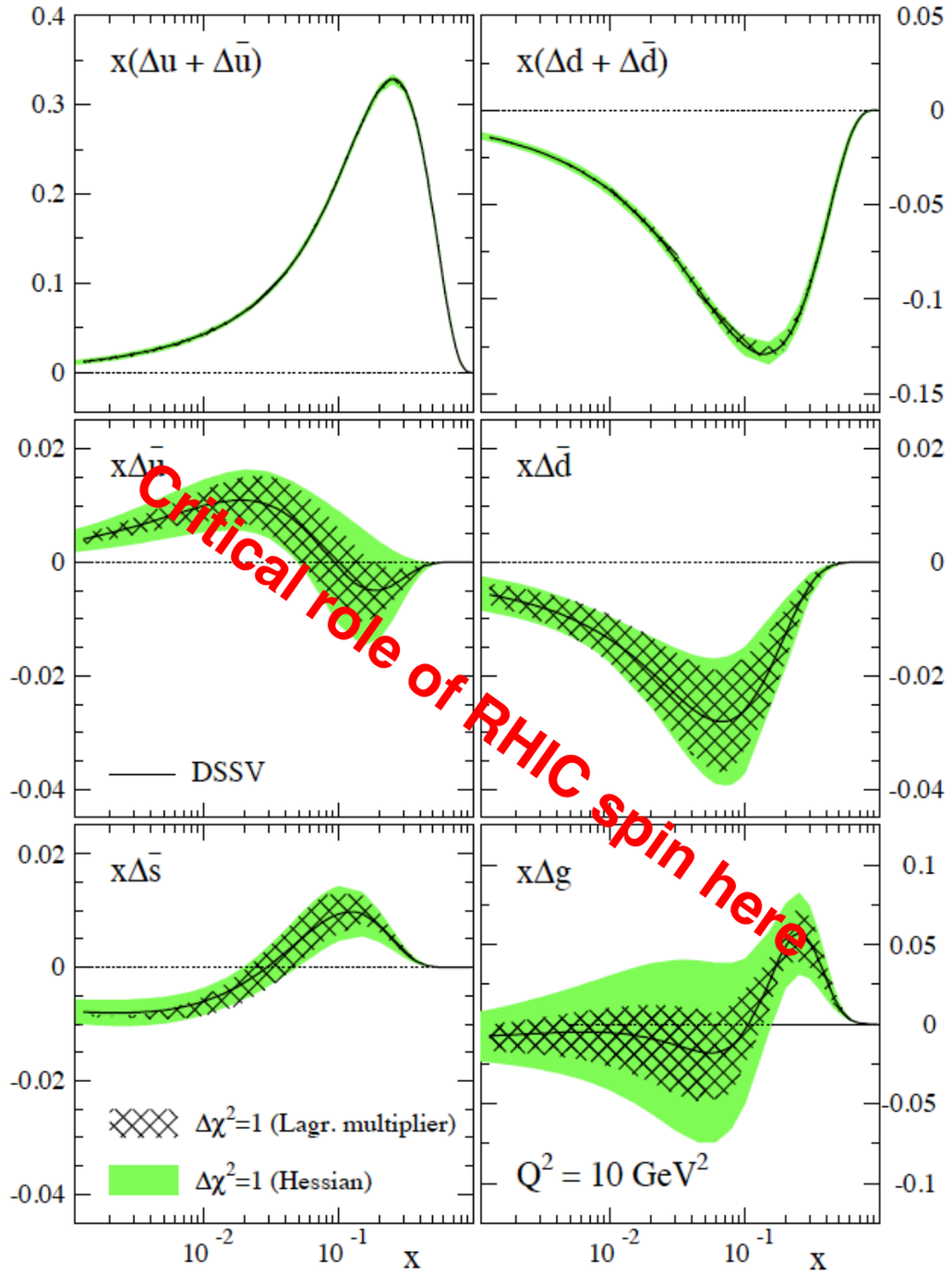
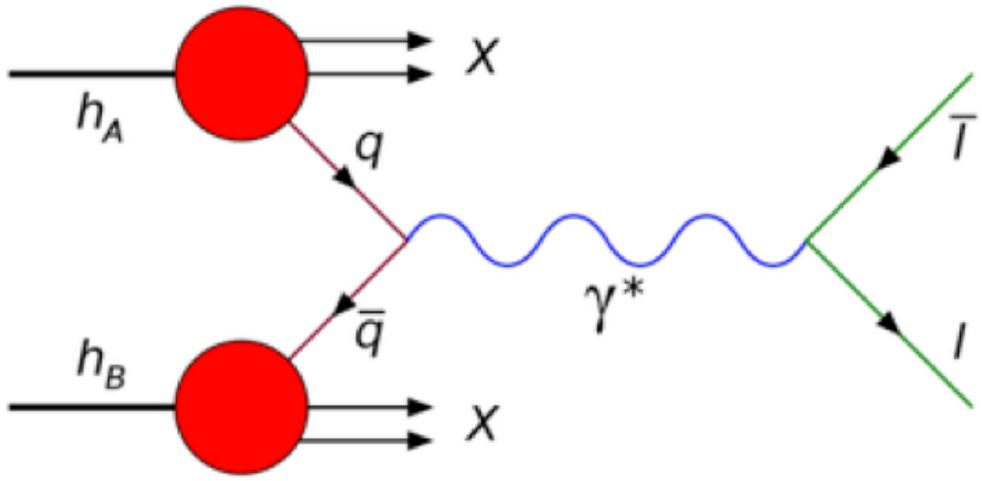
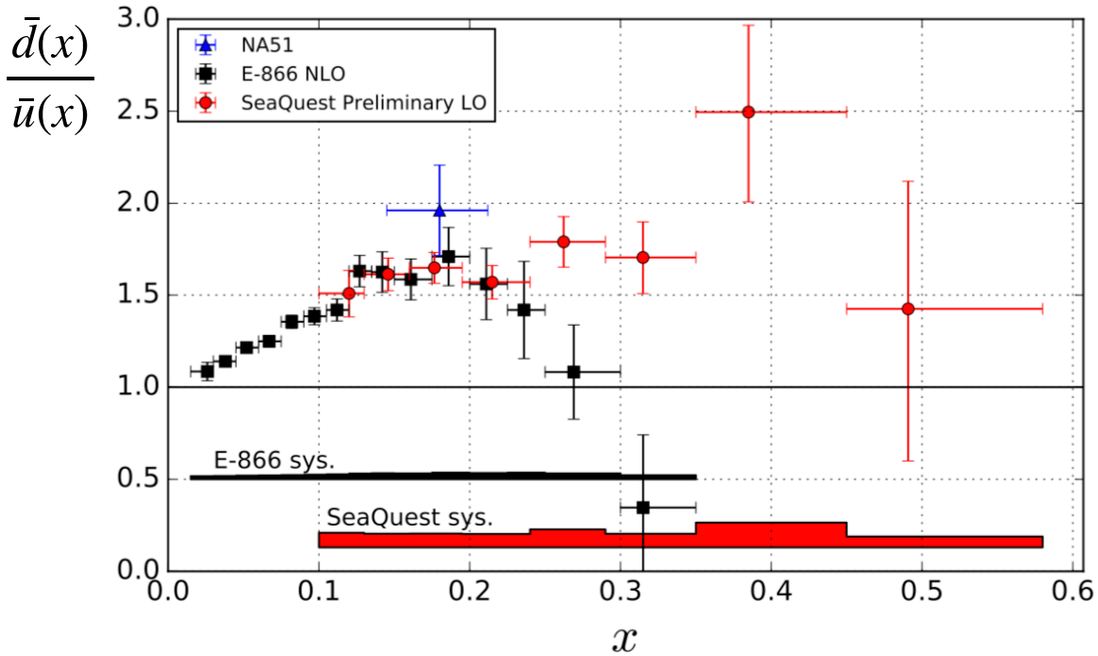


PRD 80, 034030 (2009)

Sea Quark Flavor Asymmetry



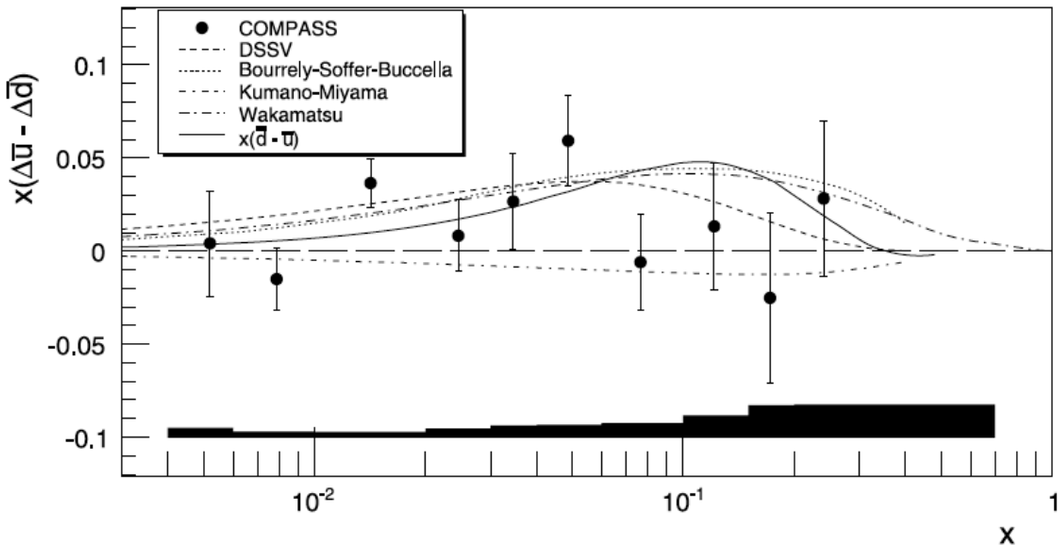
Kerns et al. (SeaQuest Collaboration), APS April Meeting 2016



- Surprisingly, flavor asymmetry was observed in unpolarized sea with $\bar{d}(x) > \bar{u}x$

- Different models explaining the flavor asymmetry give different predictions for polarized asymmetry

- Critical role of *RHIC Cold QCD* program is also here.

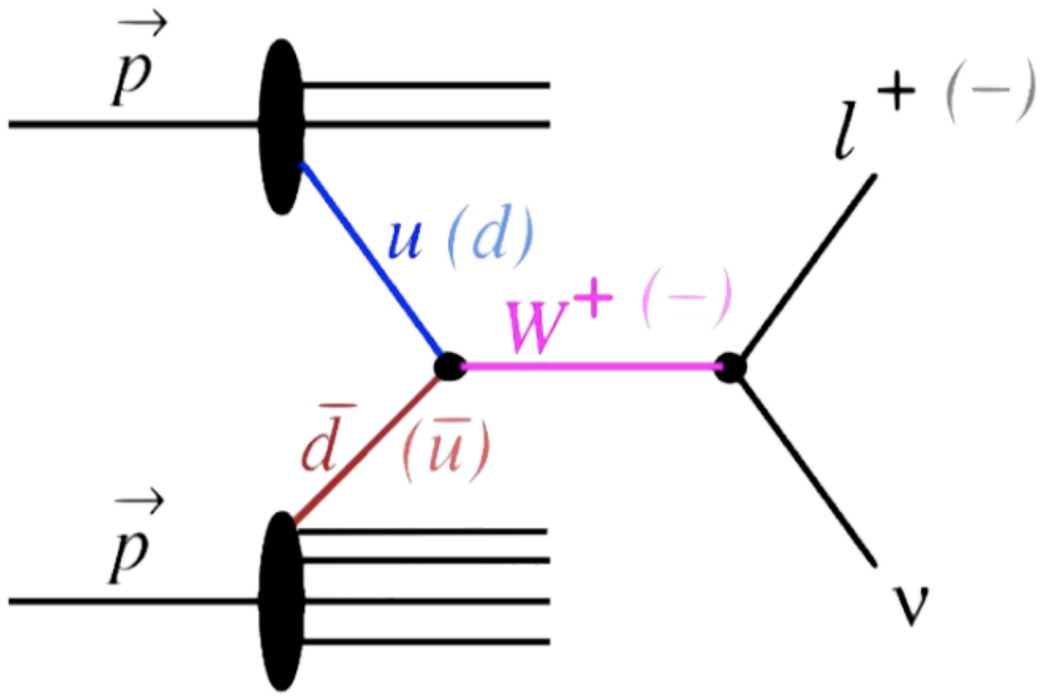


COMPASS, PLB 693, 227 (2010)

Probing Sea Quarks via W Production

Unique way to study proton spin flavor structure:

- RHIC provides polarized proton beams
- W boson selects quarks/antiquarks with specific helicity
- STAR measures W boson via the leptonic decays

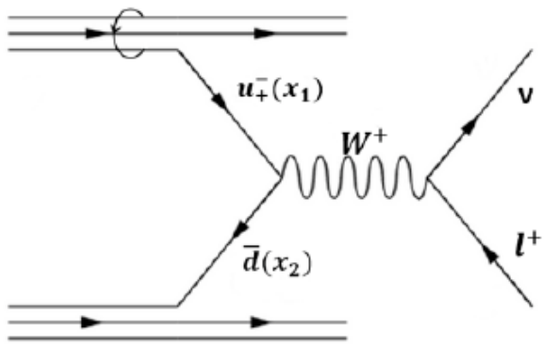


Parity-violating longitudinal single-spin asymmetry:

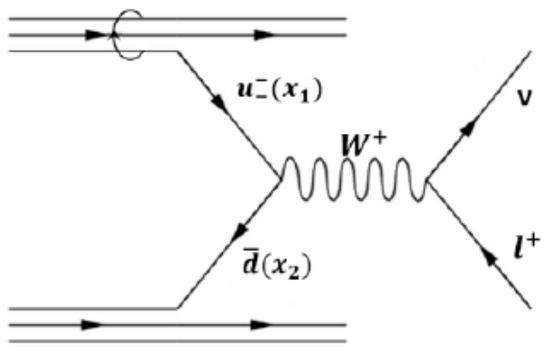
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

From W A_L to Quark/anti-Quark Spin

A. Polarized (subscript) proton provides u

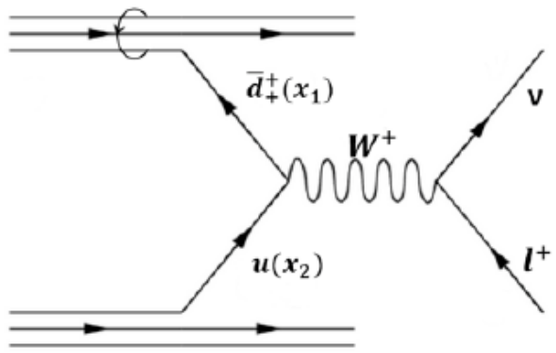


A.1 Proton helicity = "+"

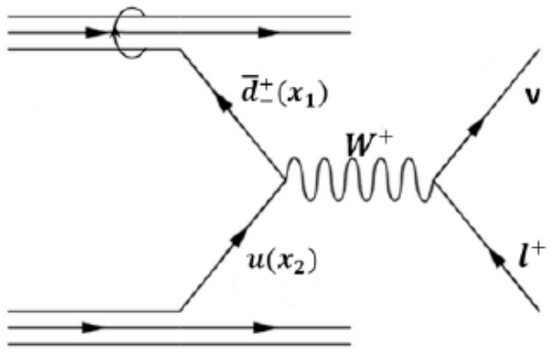


A.2 Proton helicity = "-"

B. Polarized (subscript) proton provides $\bar{d}$



B.1 Proton helicity = "+"



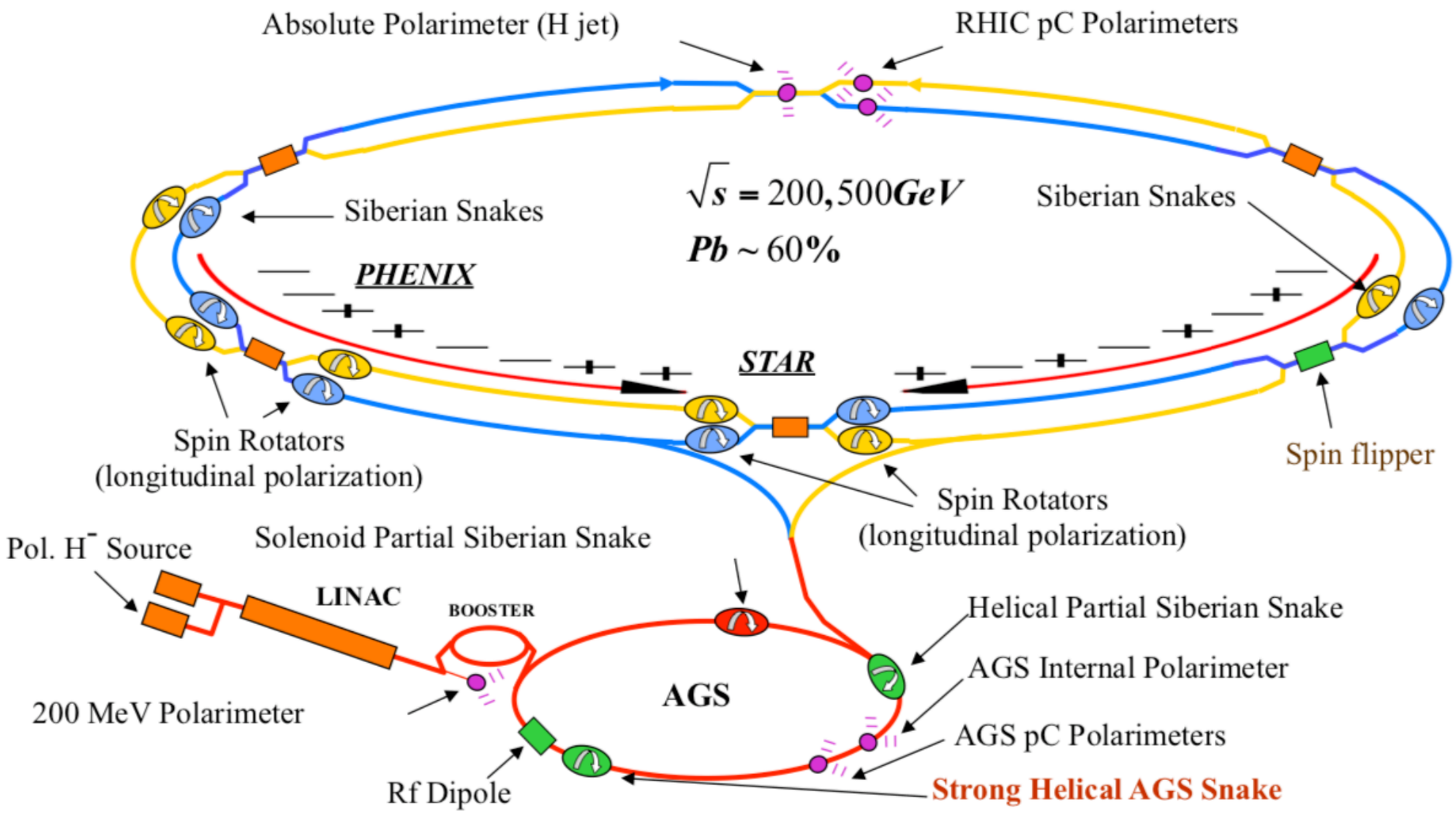
B.2 Proton helicity = "-"

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \simeq \begin{cases} -\frac{\Delta u(x_1)}{u(x_1)}, & y_W \gg 0 \ (x_1 \gg x_2) \\ \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \simeq \begin{cases} -\frac{\Delta d(x_1)}{d(x_1)}, & y_W \gg 0 \ (x_1 \gg x_2) \\ \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

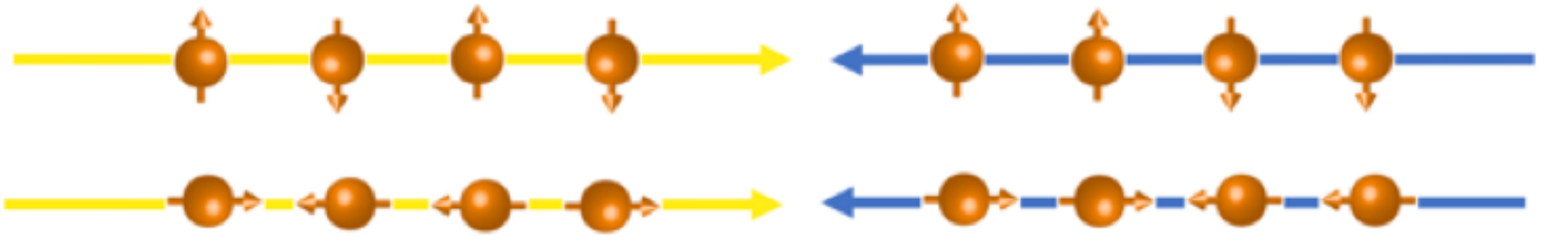
- Flavor separation as forward/backward rapidity

RHIC—as Polarized Proton collider

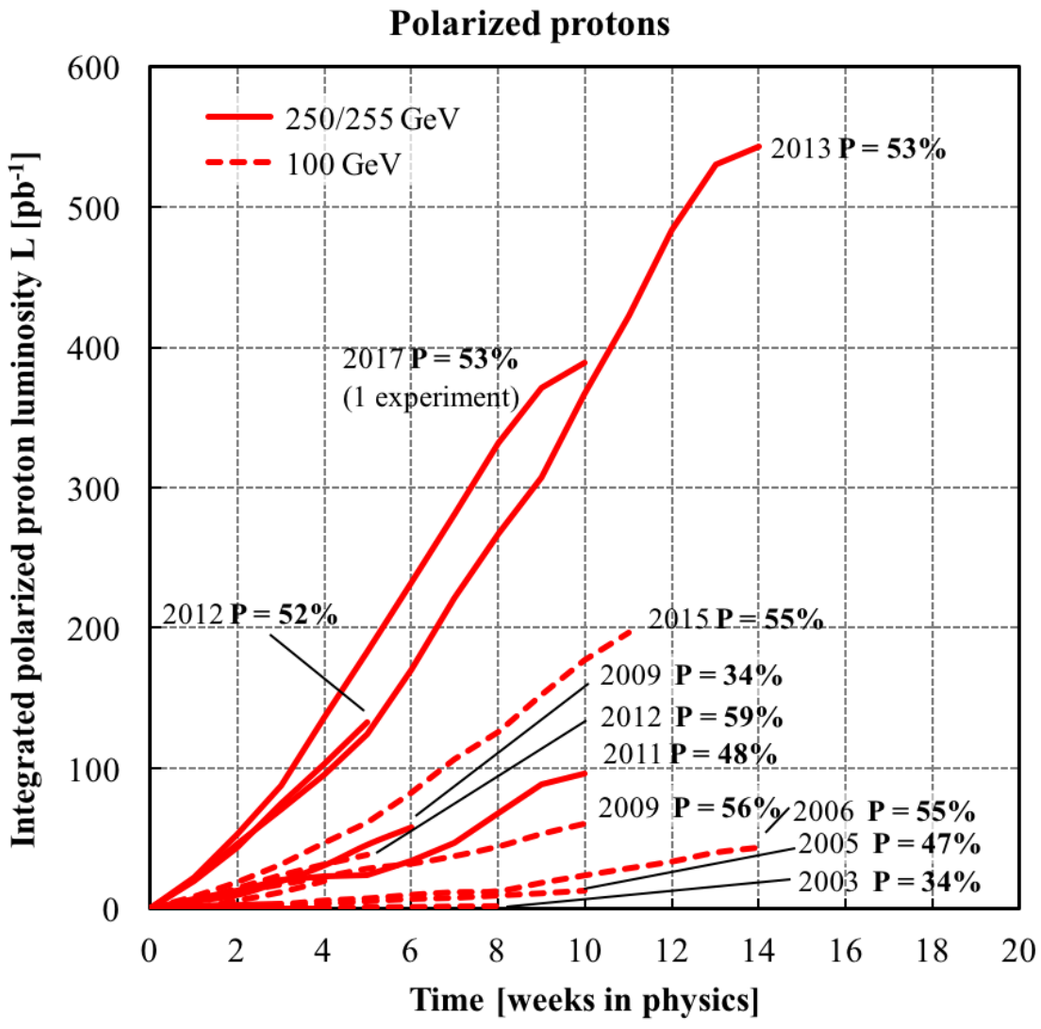


Transverse

Longitudinal



RHIC/STAR Data Sets

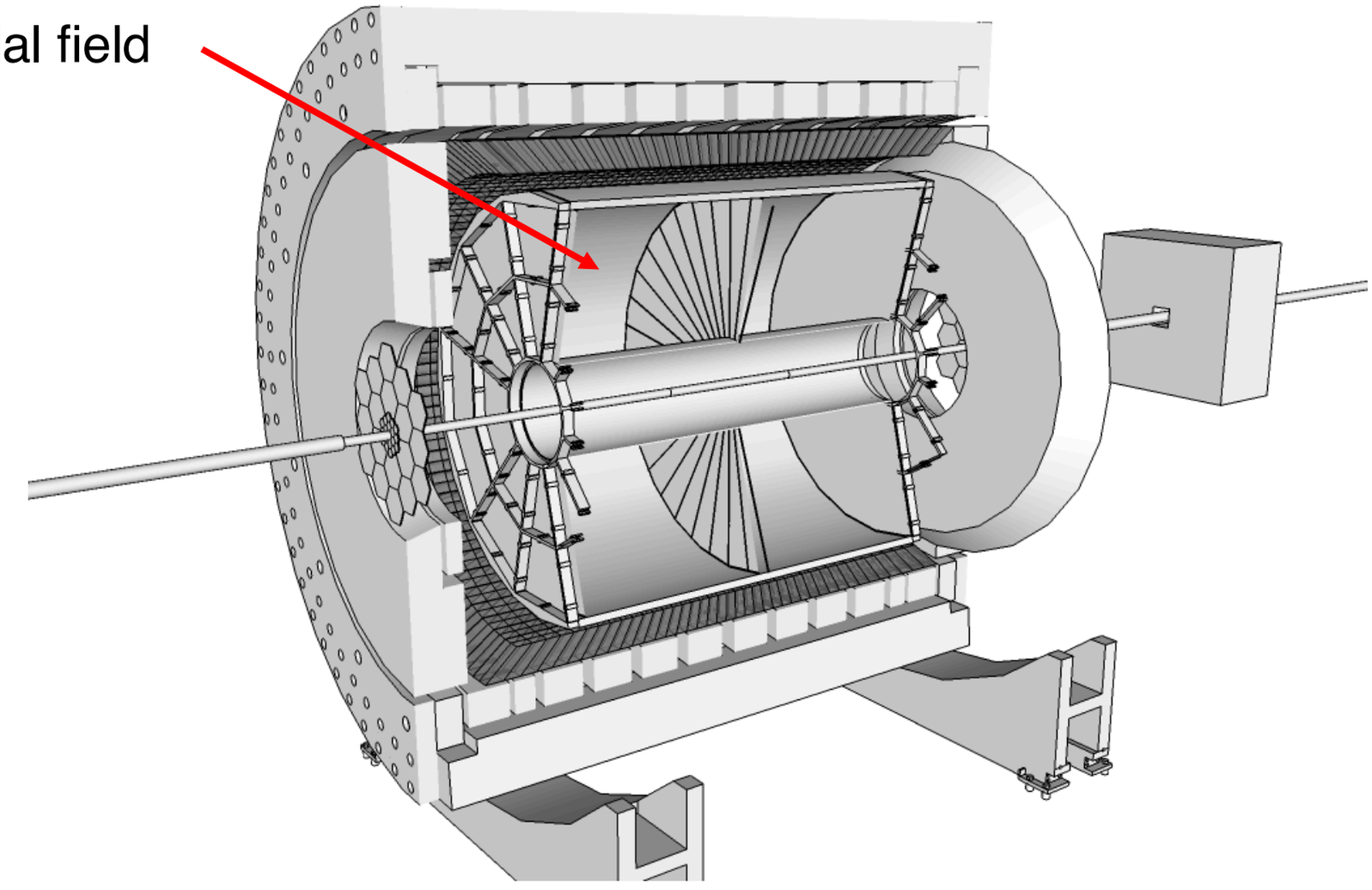


	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	**500**	**12**	**48**
	2012	**510**	**82**	**56**
	2013	**510**	**256**	**56**
	2015	200	50	60
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	50	60
	2017	510	356	55

STAR Detector

Nucl. Instrum. Meth. A499, 624, 2003

0.5 T solenoidal field



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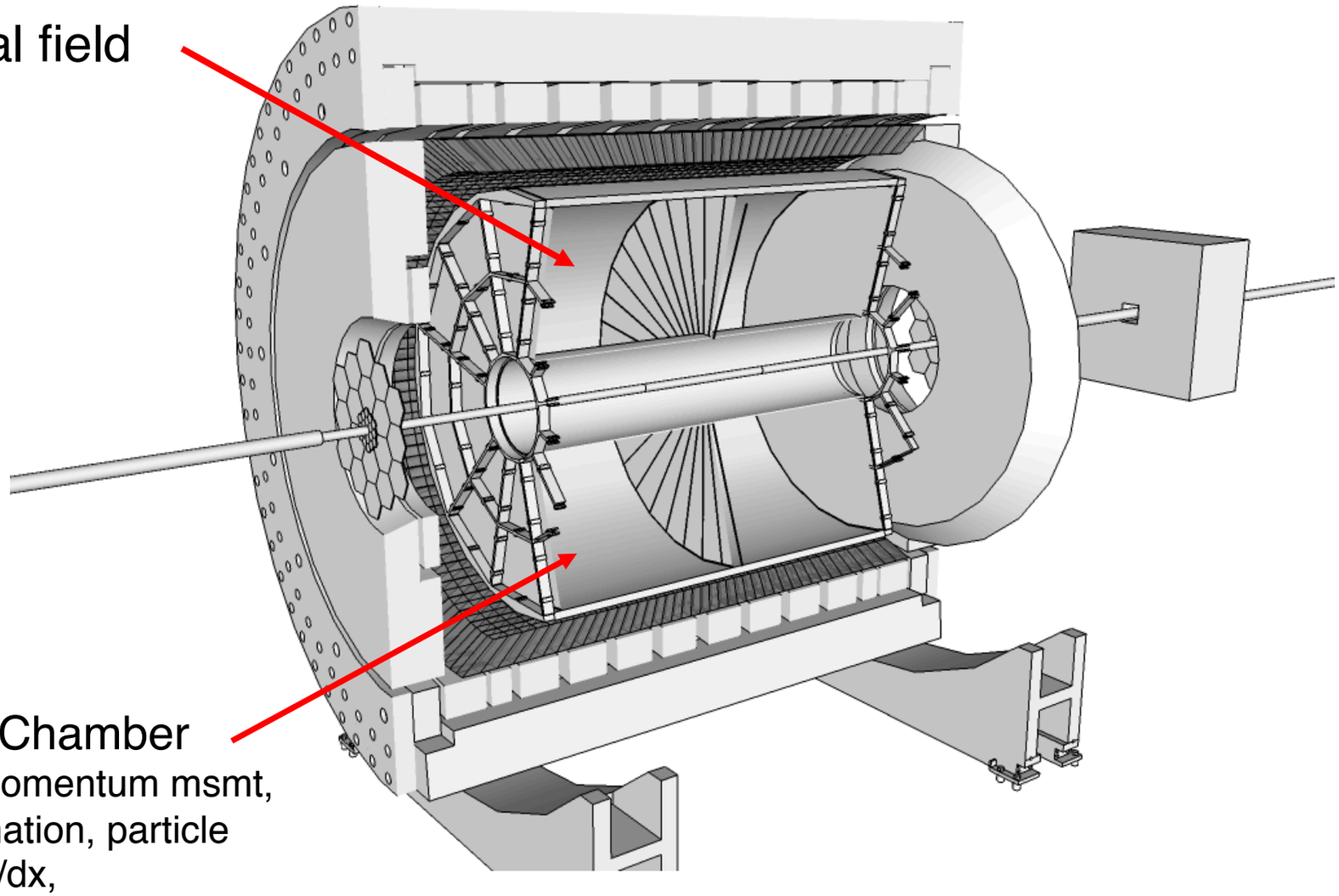


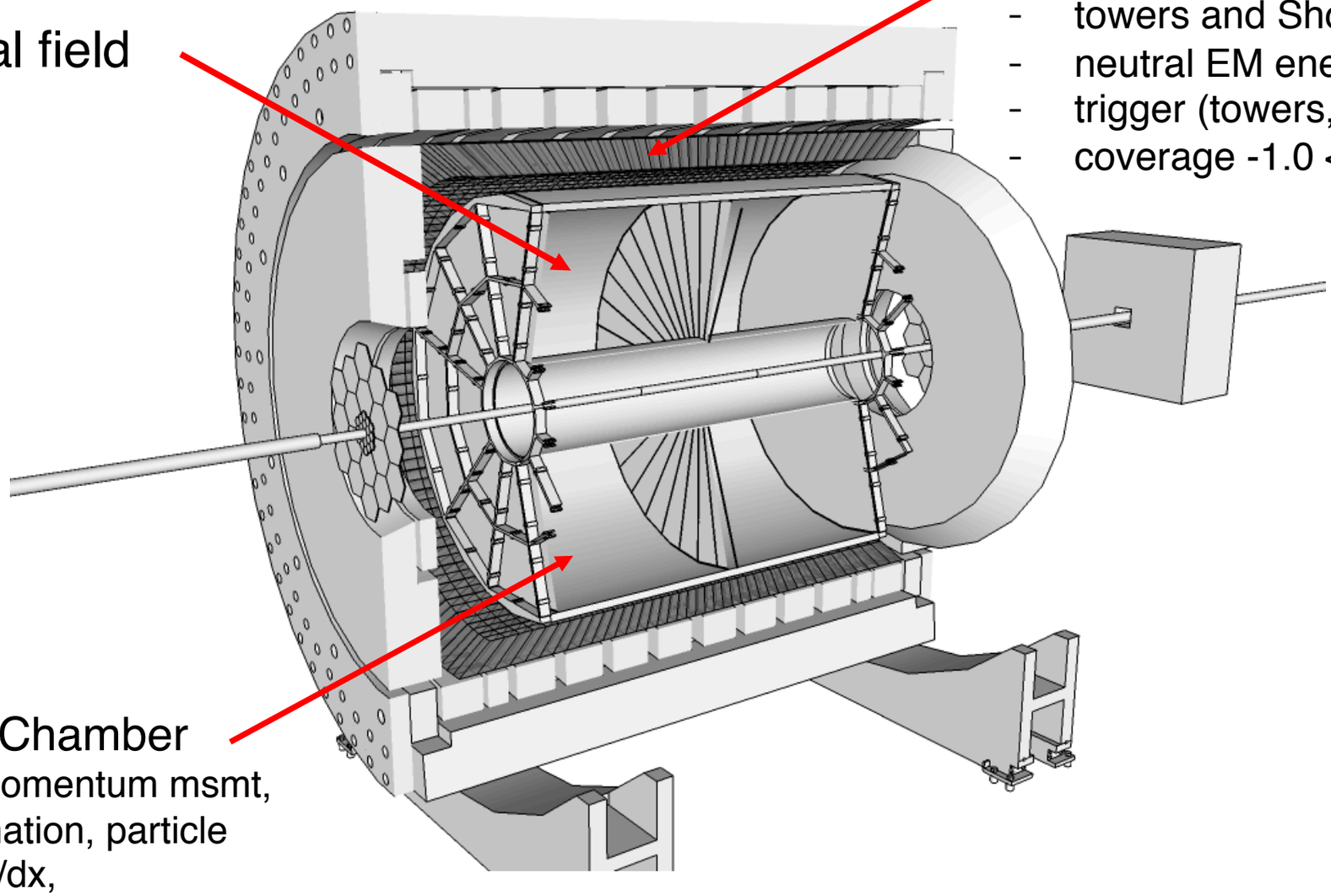
Time Projection Chamber

- charged track momentum msmt,
- charge determination, particle identification dE/dx,
- collision vertex reconstruction
- coverage $-1.3 < \eta < 1.3$

STAR Detector

0.5 T solenoidal field

Nucl. Instrum. Meth. A499, 624, 2003



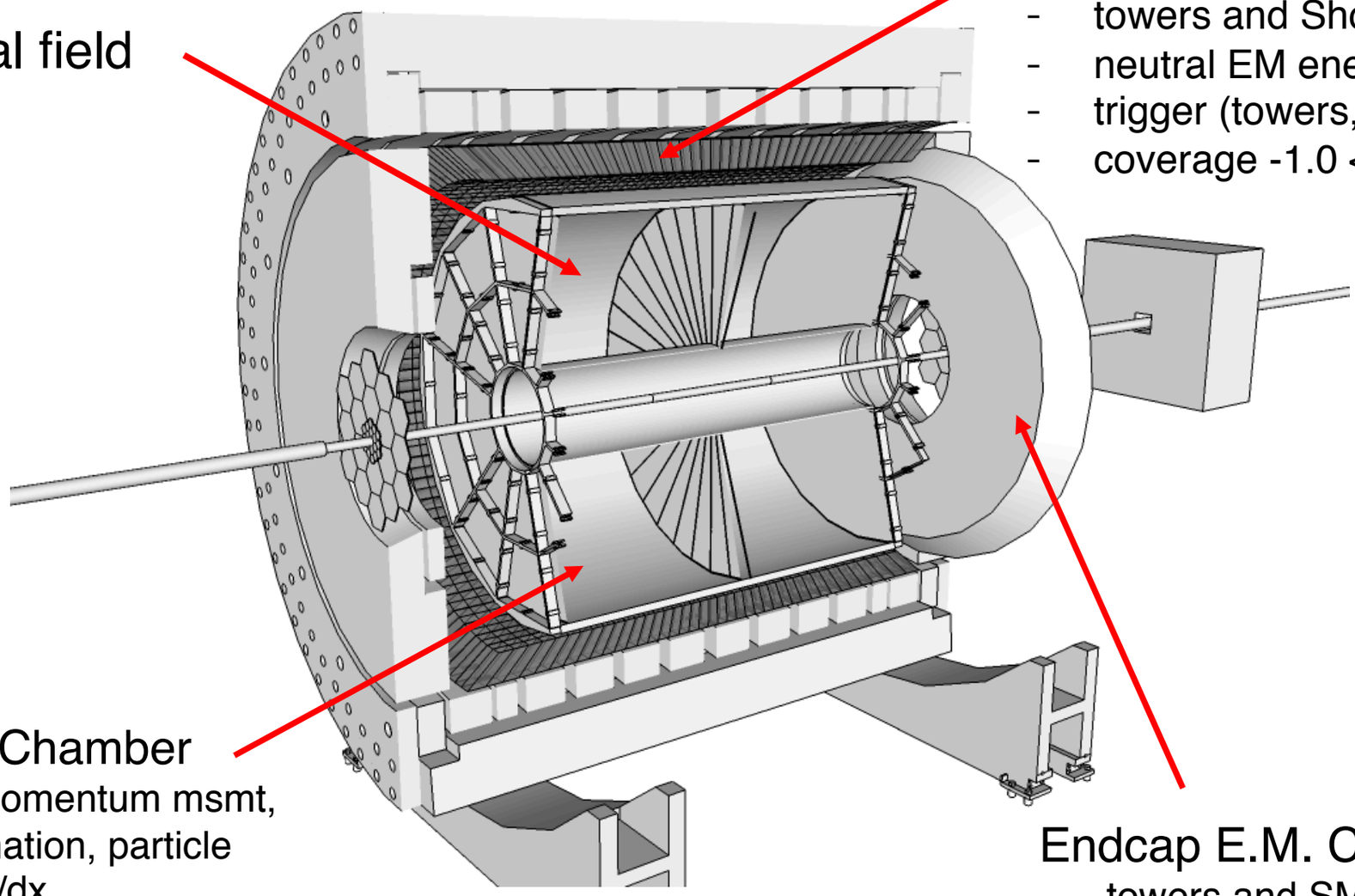
Barrel E.M. Calorimeter
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $-1.0 < \eta < 1.0$

Time Projection Chamber
- charged track momentum msmt,
- charge determination, particle identification dE/dx,
- collision vertex reconstruction
- coverage $-1.3 < \eta < 1.3$

STAR Detector

0.5 T solenoidal field

Nucl. Instrum. Meth. A499, 624, 2003

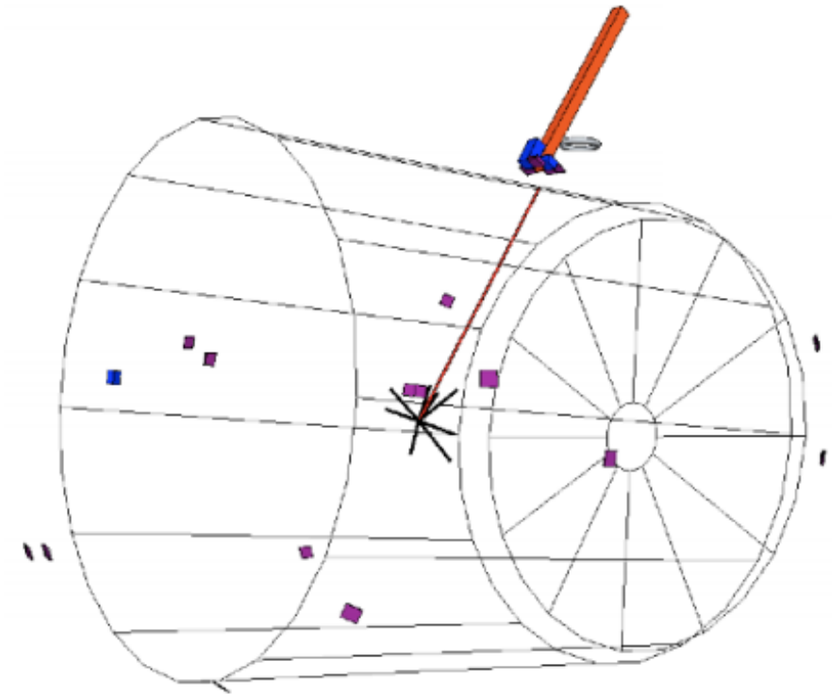


Barrel E.M. Calorimeter
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage -1.0 < η < 1.0

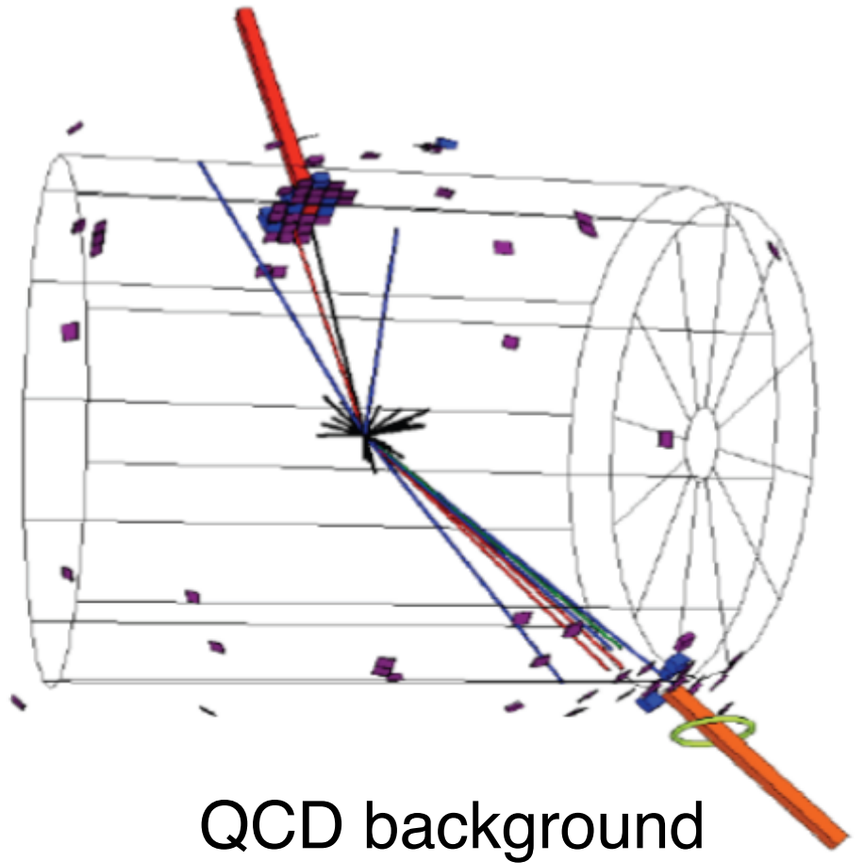
Time Projection Chamber
- charged track momentum msmt,
- charge determination, particle identification dE/dx,
- collision vertex reconstruction
- coverage -1.3 < η < 1.3

Endcap E.M. Calorimeter
- towers and SMD.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage 1.1 < η < 2.0

Measuring W at STAR



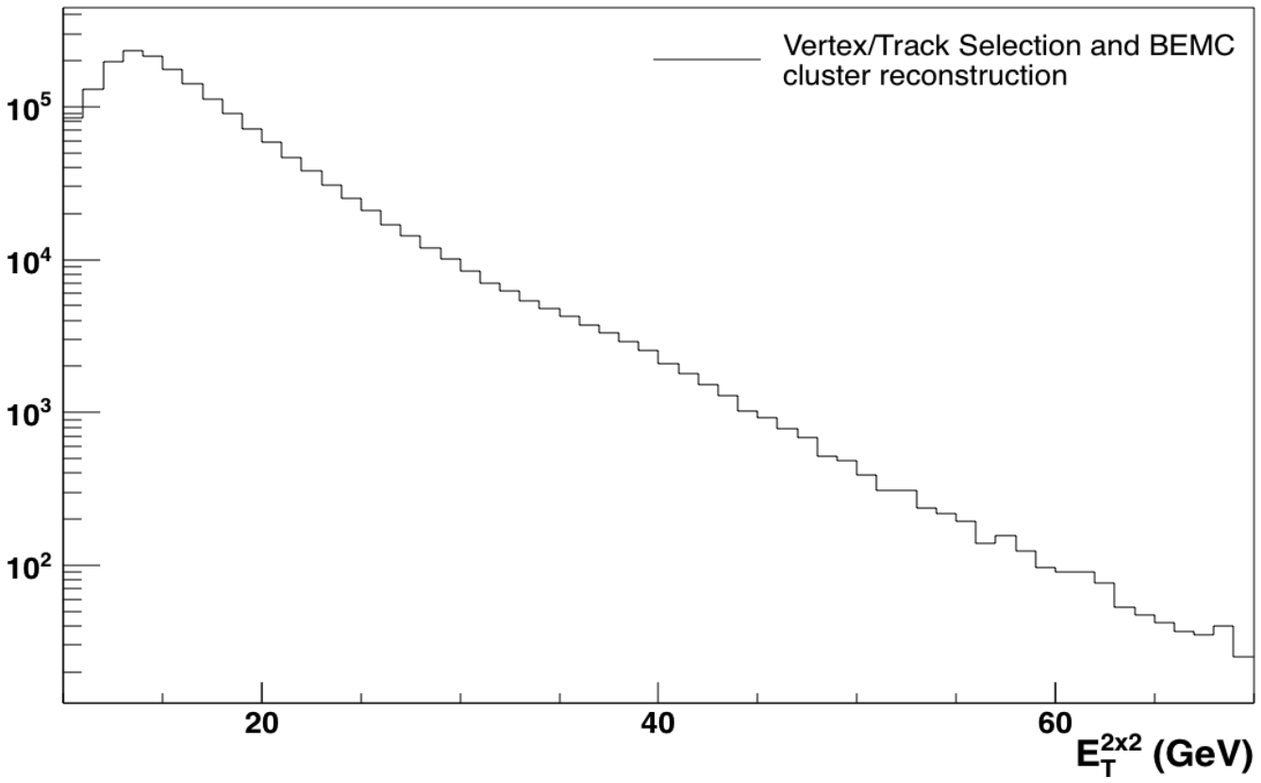
$W \rightarrow e + \nu_e$

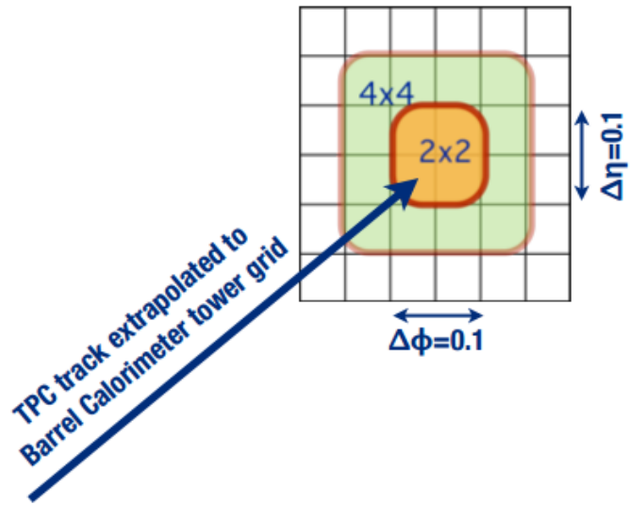


QCD background

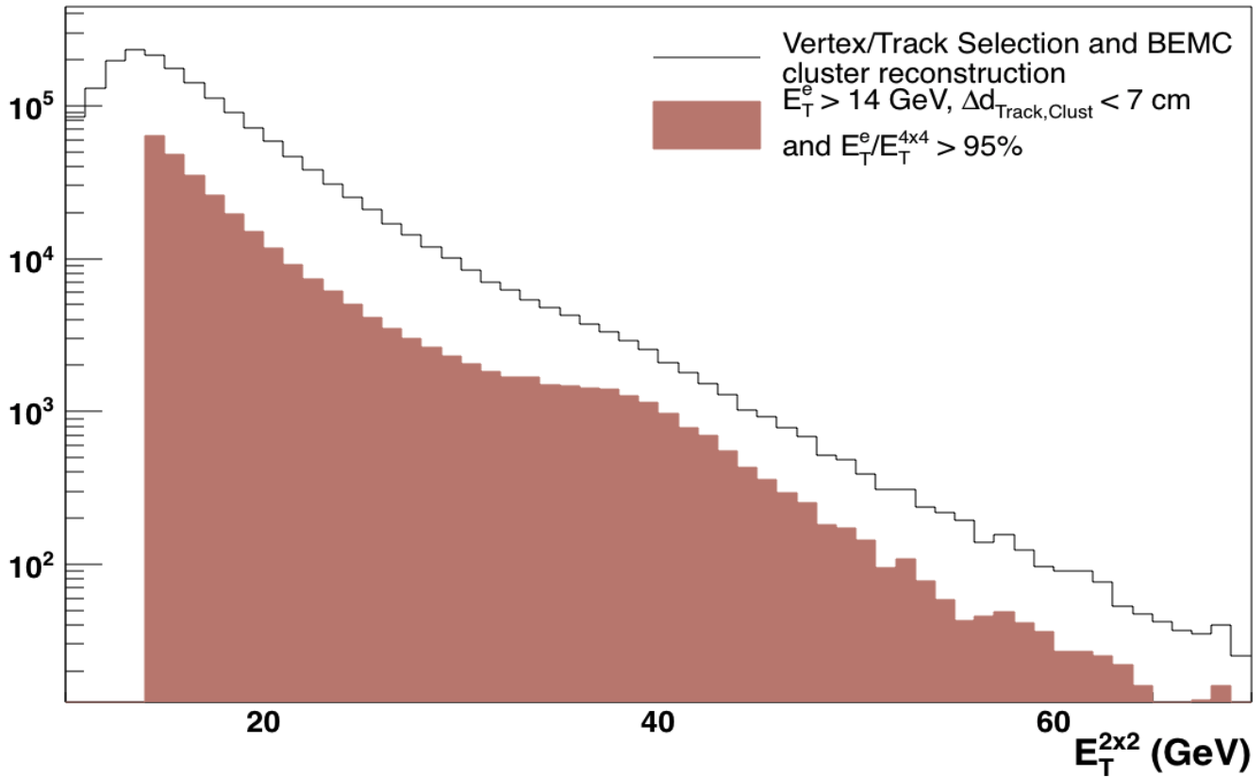
- Isolated $e^+(e^-)$: isolated high momentum track + isolated EM cluster
- Undetected $\nu_e(\bar{\nu}_e)$: large missing energy opposite to $e^+(e^-)$
- Jacobian peak: $e^+(e^-)\ p_T$ peak around $M_W/2$ (~40 GeV)

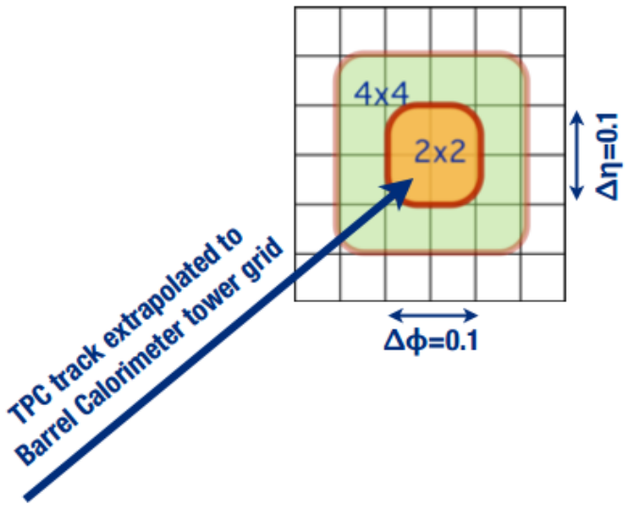
W Selection

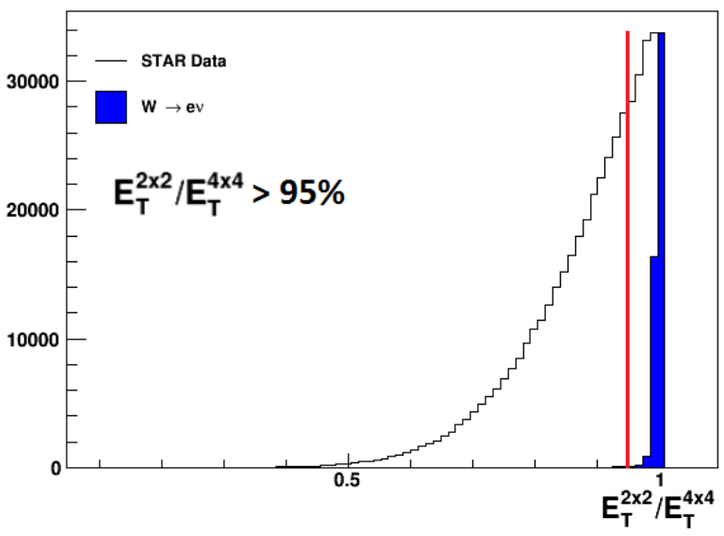

Vertex/Track Selection and BEMC cluster reconstruction
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)


4x4
2x2
Δη=0.1
Δϕ=0.1
TPC track extrapolated to Barrel Calorimeter tower grid

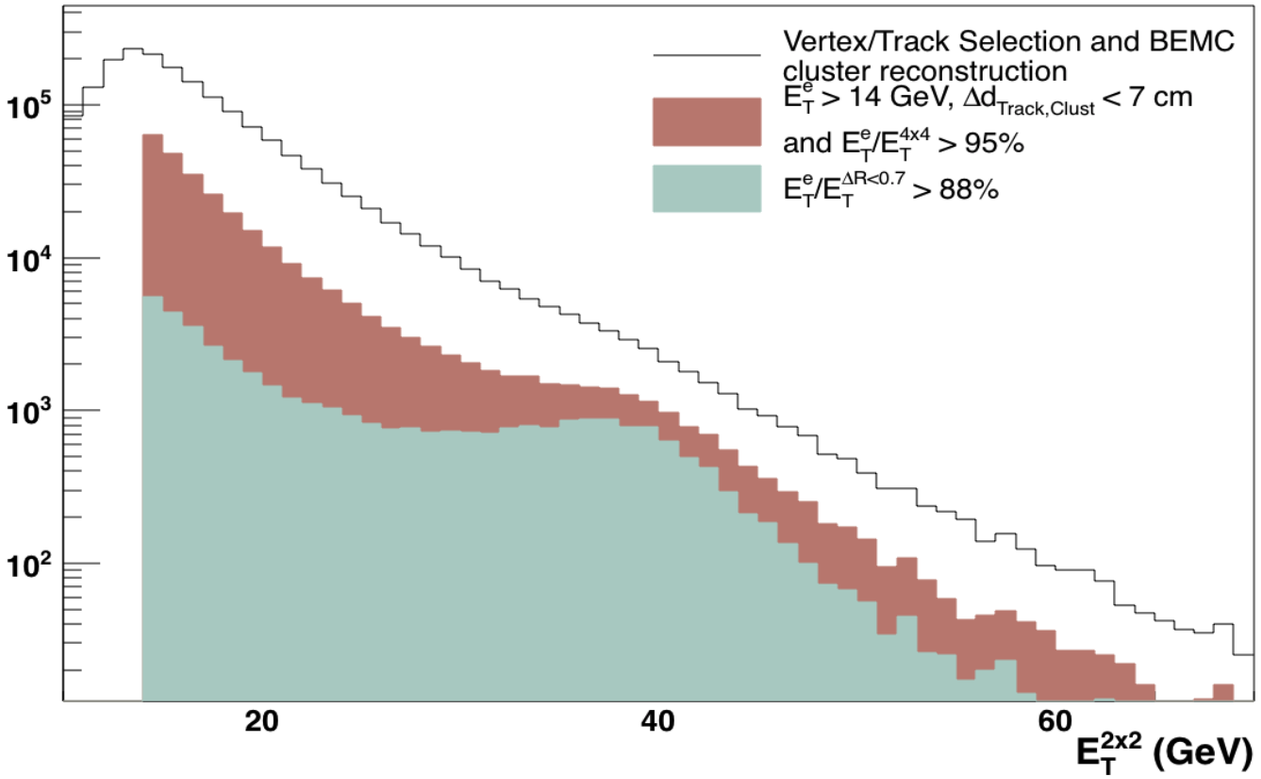
W Selection

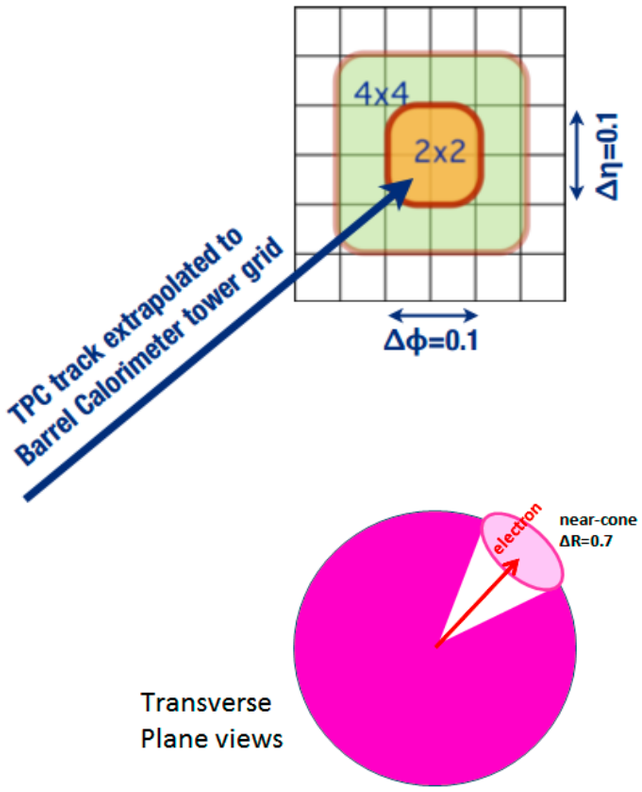

Vertex/Track Selection and BEMC cluster reconstruction
$E_T^e > 14$ GeV, $\Delta d_{Track,Clust} < 7$ cm
and $E_T^e/E_T^{4x4} > 95\%$
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)

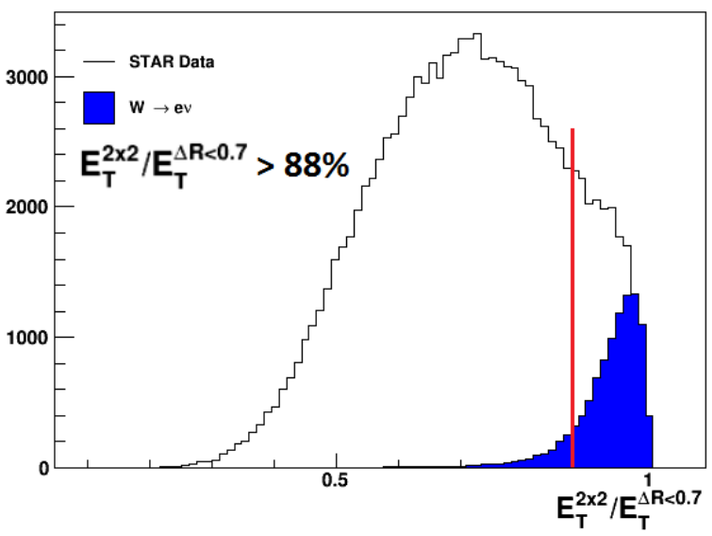

4x4
2x2
$\Delta\eta$=0.1
$\Delta\phi$=0.1
TPC track extrapolated to
Barrel Calorimeter tower grid


STAR Data
W → ev
$E_T^{2x2}/E_T^{4x4} > 95\%$
30000
20000
10000
0
0.5
1
E_T^{2x2}/E_T^{4x4}

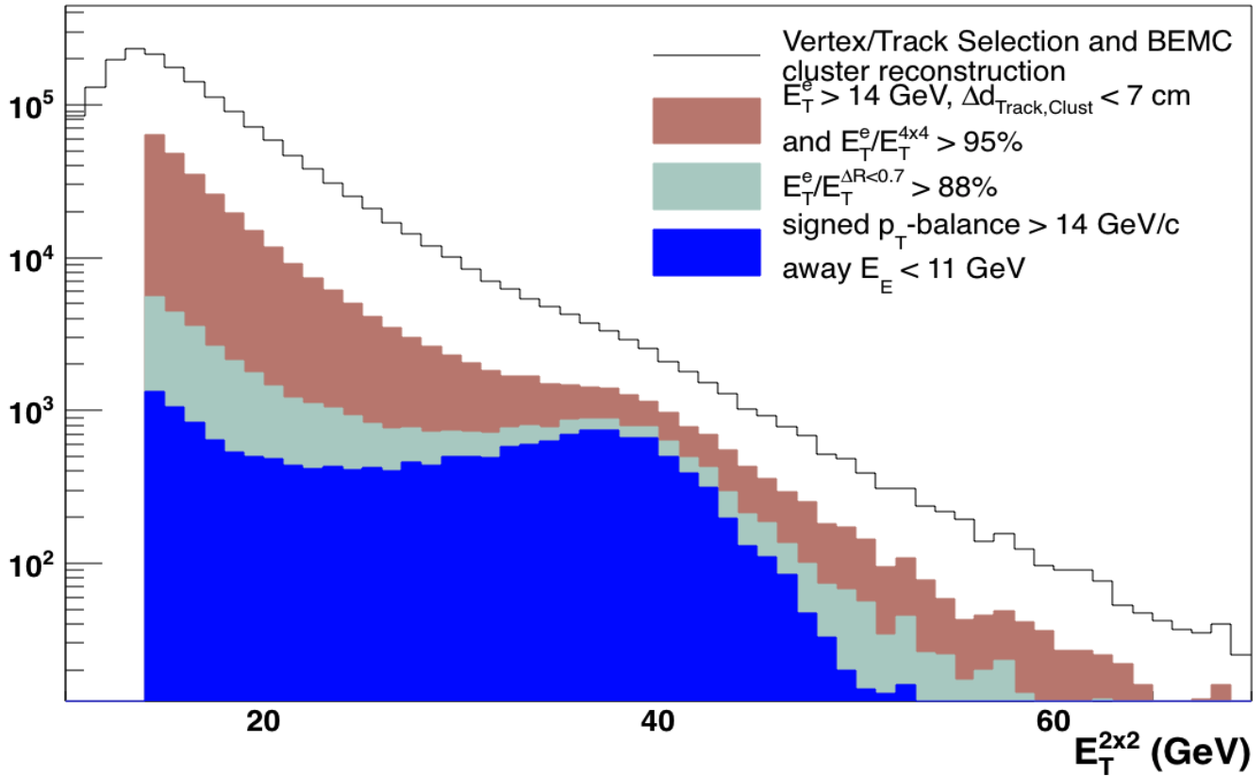
W Selection

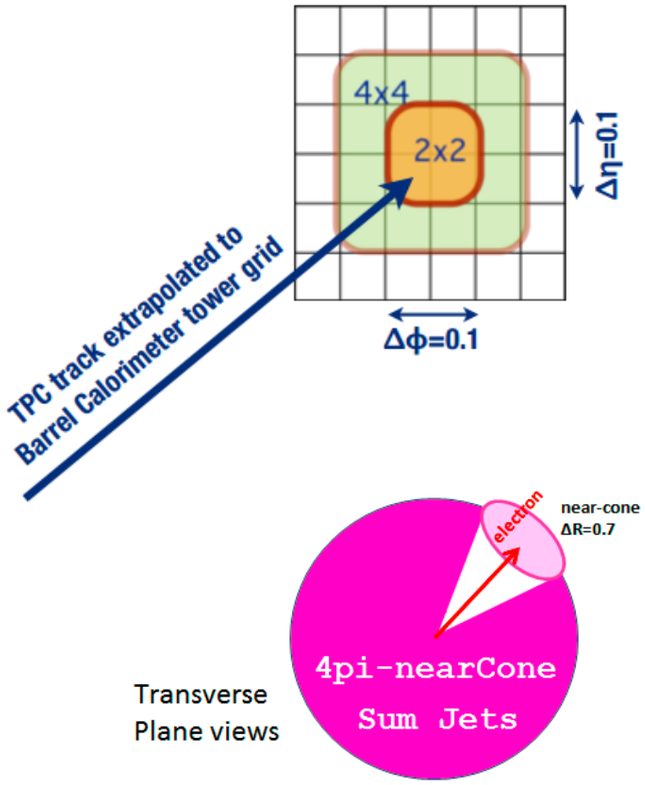

Vertex/Track Selection and BEMC cluster reconstruction
E_T^e > 14 GeV, $\Delta d_{Track,Clust}$ < 7 cm
and E_T^e/E_T^{4x4} > 95%
$E_T^e/E_T^{\Delta R<0.7}$ > 88%
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)

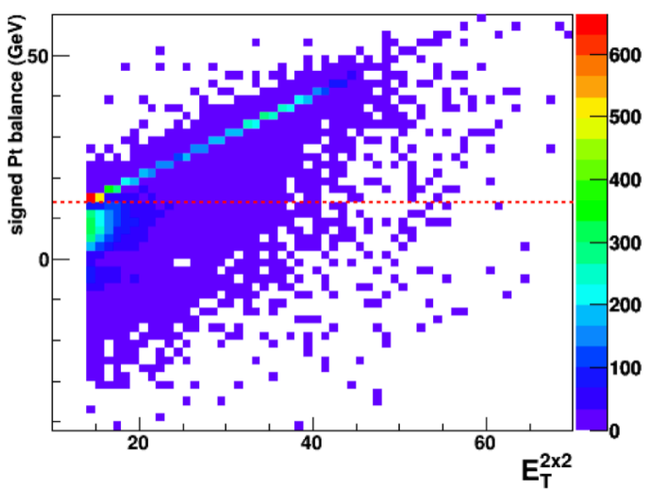

4x4
2x2
Δη=0.1
Δϕ=0.1
TPC track extrapolated to Barrel Calorimeter tower grid
near-cone ΔR=0.7
election
Transverse Plane views

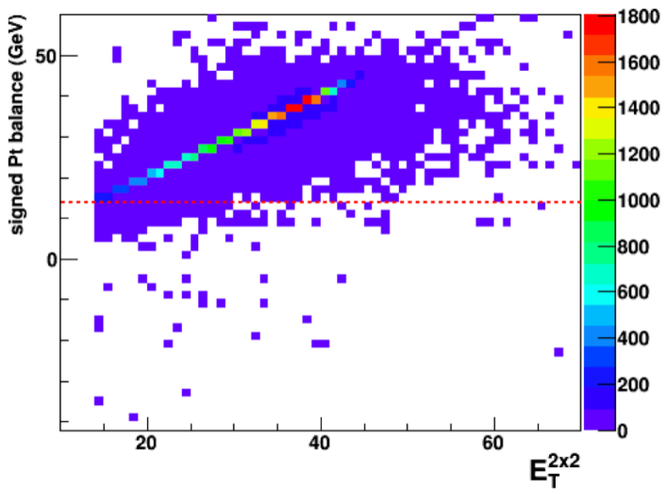

STAR Data
W → eν
$E_T^{2x2}/E_T^{\Delta R<0.7}$ > 88%
3000
2000
1000
0
0.5
1
$E_T^{2x2}/E_T^{\Delta R<0.7}$

W Selection





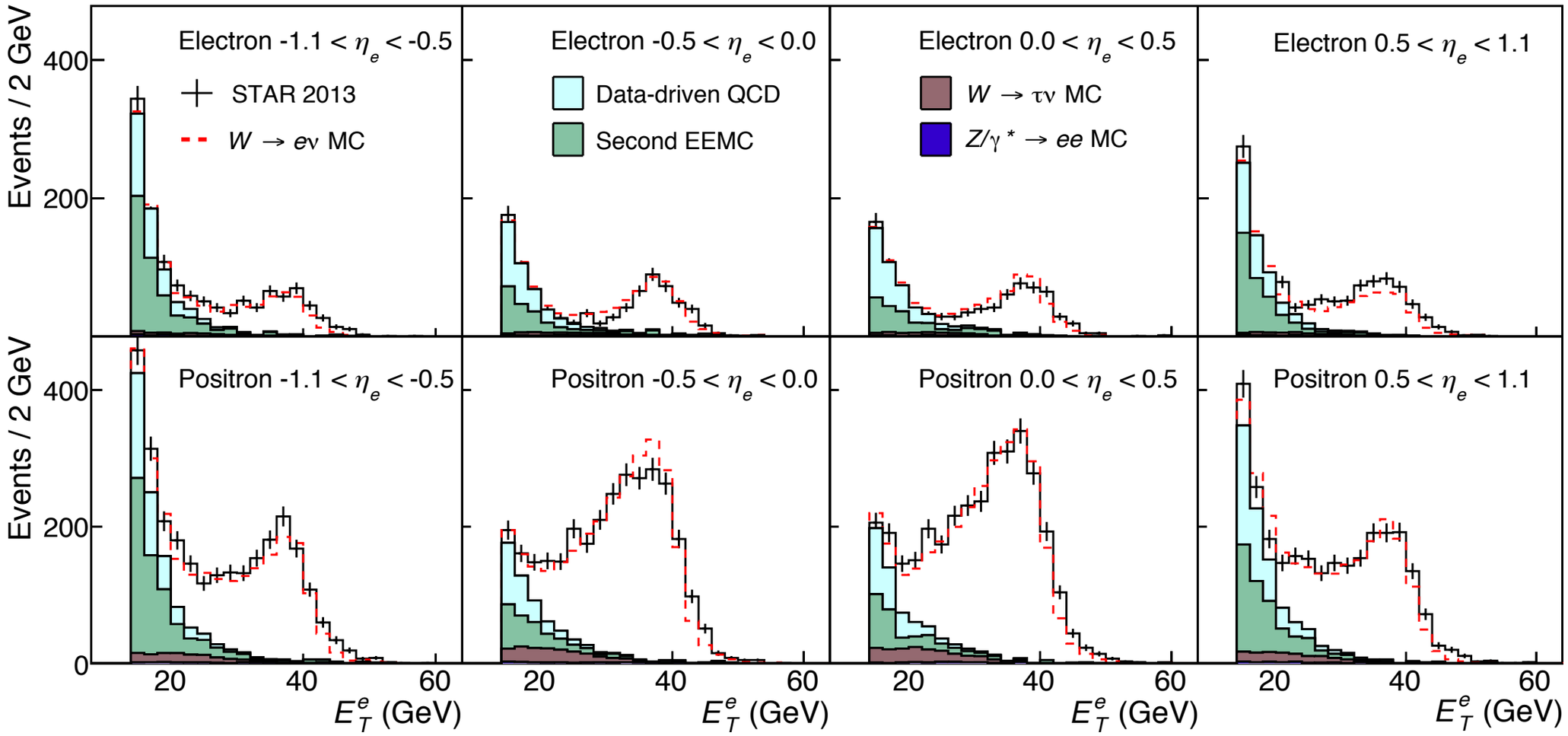




$$\vec{p}_T^{\,bal} = \bar{p}_T^{\,e} + \Sigma_{\Delta R>0.7}\vec{p}_T^{\,jets}$$

$$\text{Signed-}p_T\text{ balance} = \frac{\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,bal}}{|\vec{p}_T^{\,e}|}$$

Background Analysis

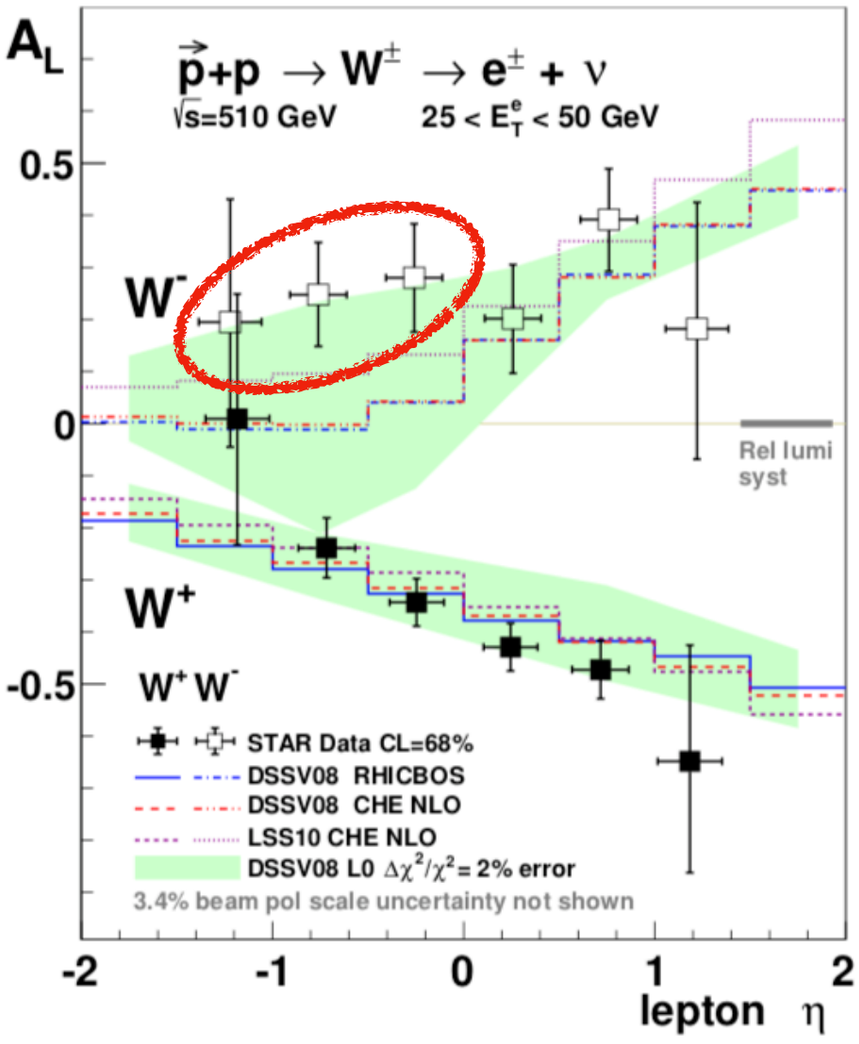


Residual background:

- W decays to tau and then to electron/positron
- Z to electron-positron pair but one of them undetected
- QCD background

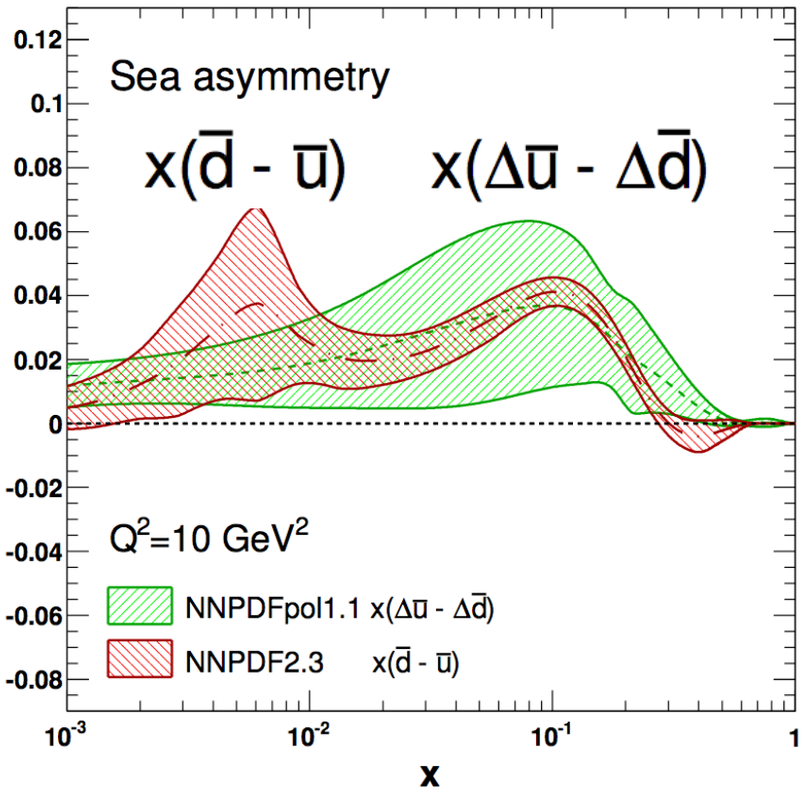
Earlier STAR W A_L results

- First W A_L from the initial 500 GeV run in 2009
- First eta-dependent results from 2011+2012 data



STAR, PRL 113, 072301 (2014)

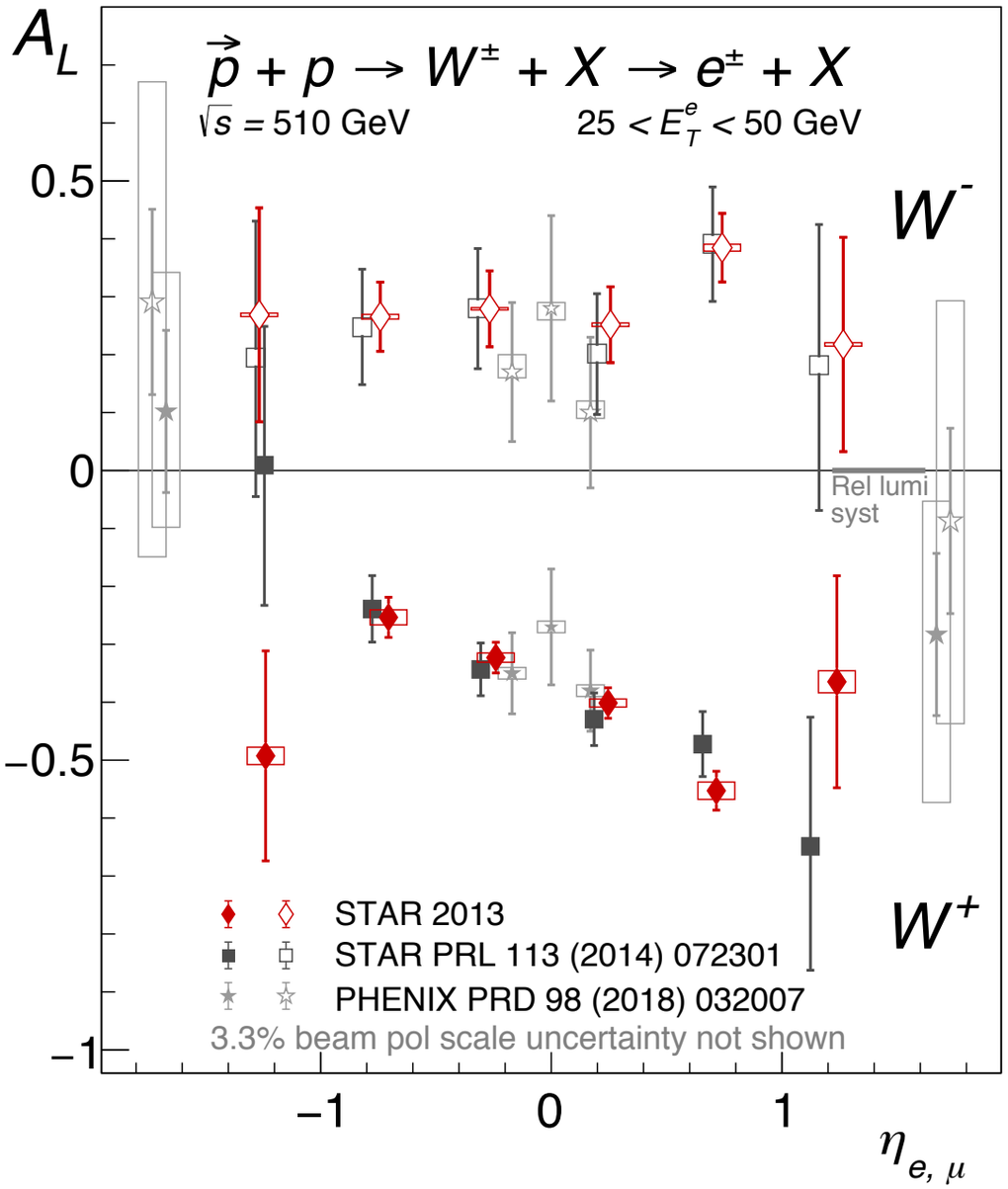
E. Nocera, PoS(DIS2014)204



$\Delta\bar{u} > \Delta\bar{d}$? Opposite to unpolarized sea.

Motivation for more precise data.

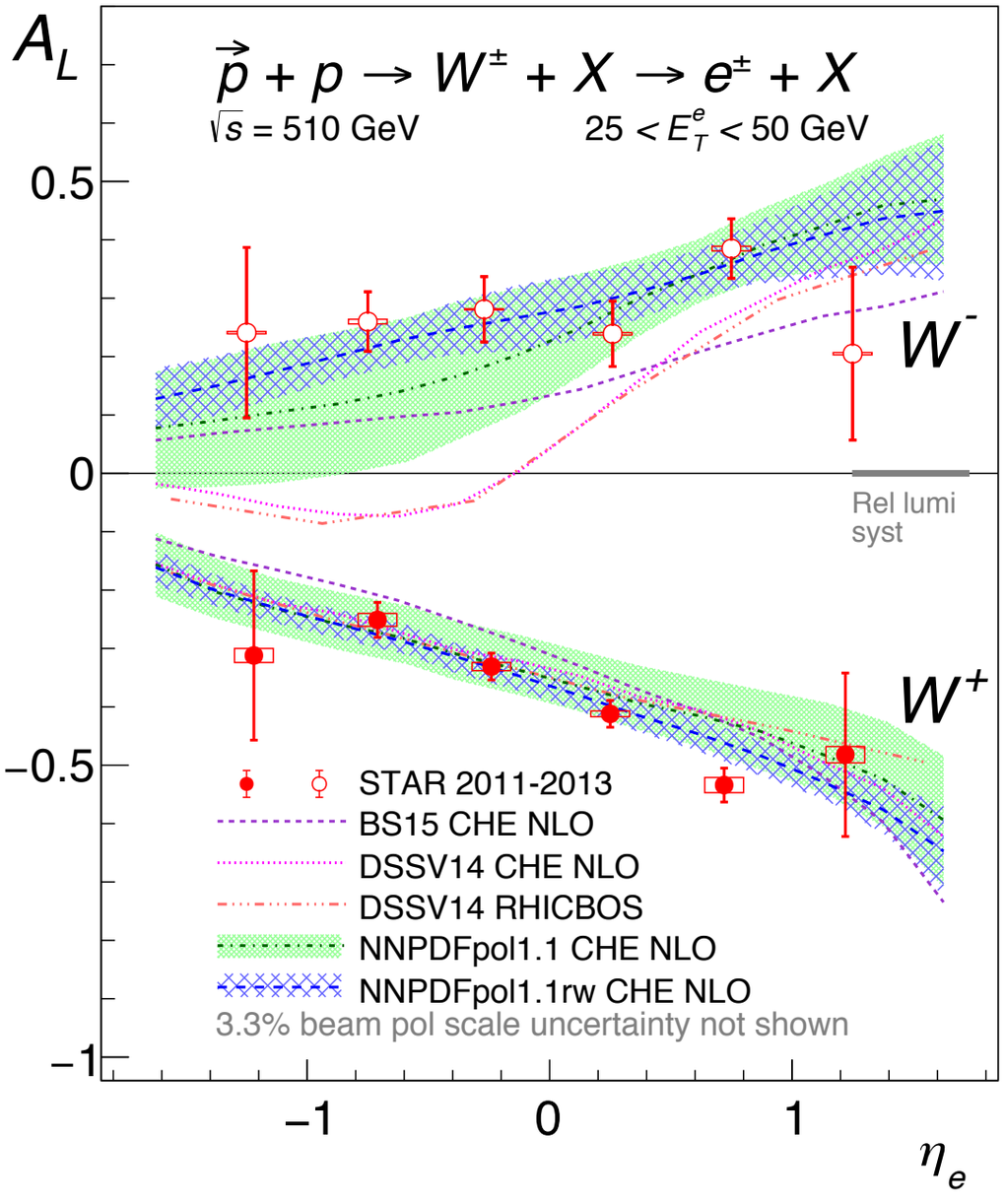
STAR 2013 Results



PRD 99, 051102(R) (2019)

- Most precise W A_L results from 2013 dataset
- Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012
- Confirmed the preference of the larger than initially expected anti-up quark polarization first seen in the 2011+2012 data.

STAR 2013 Results



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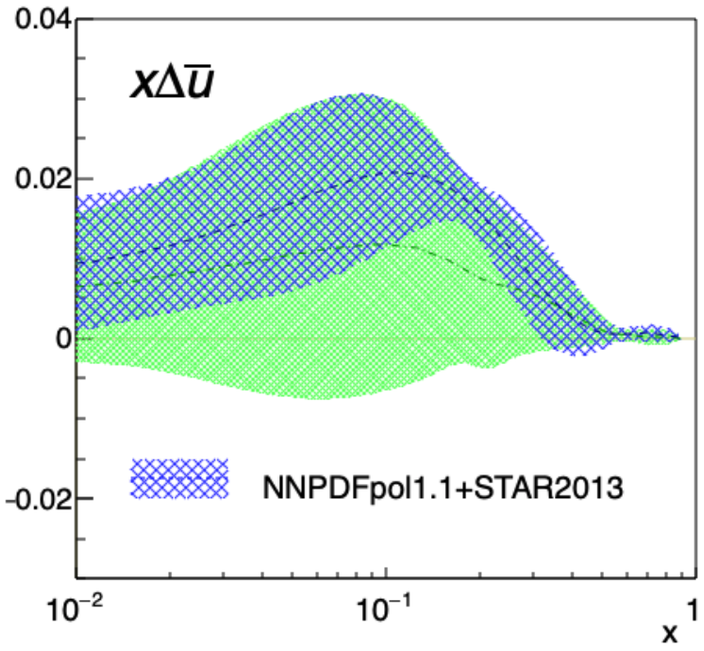
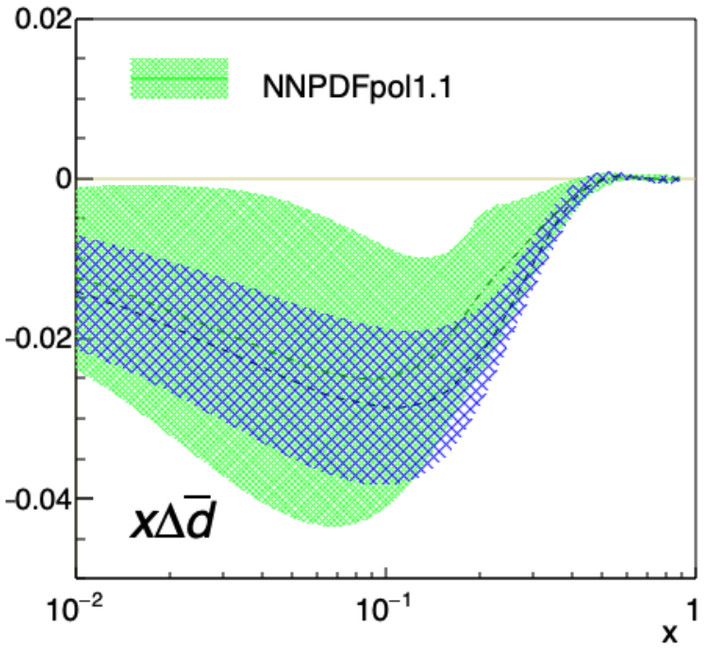
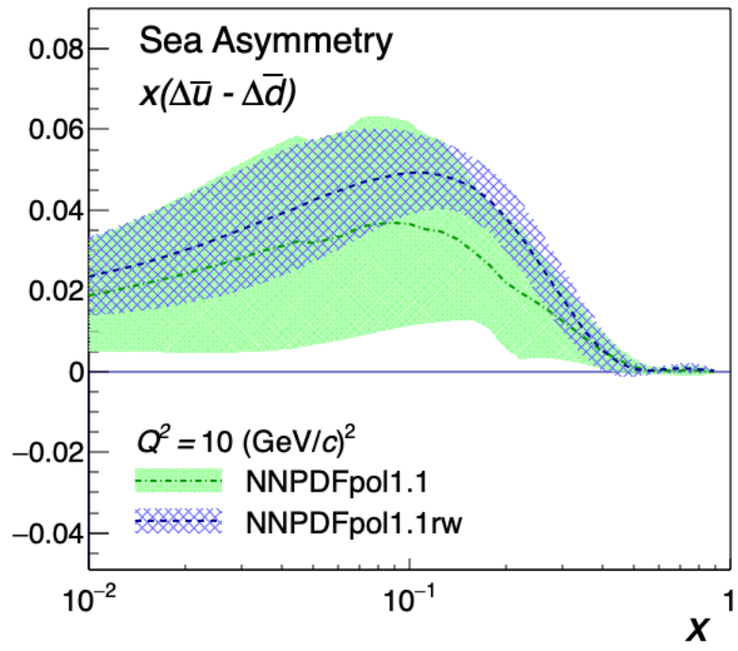
- Combined results in comparison with theoretical predictions

Impact of STAR 2013 Results

PRD 99, 051102(R) (2019)

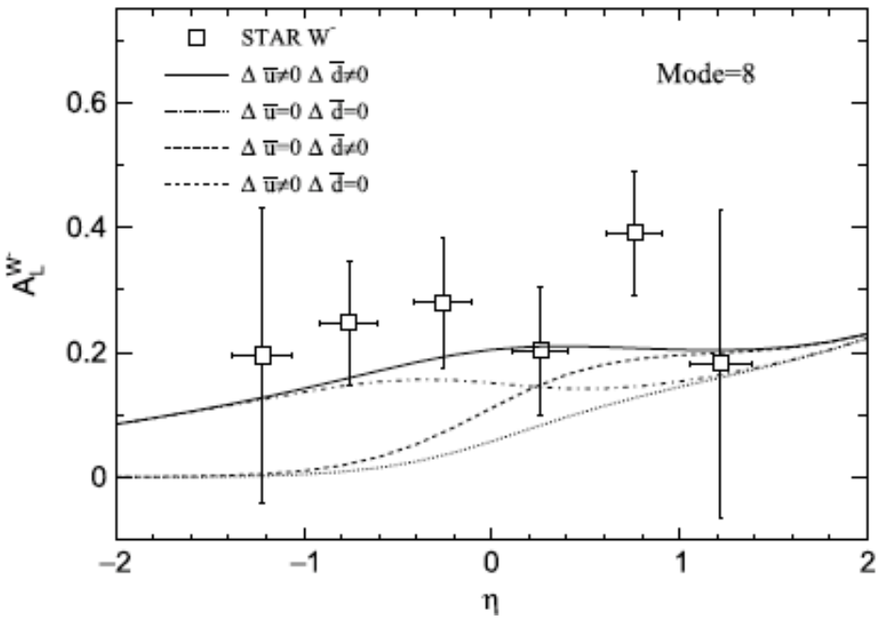


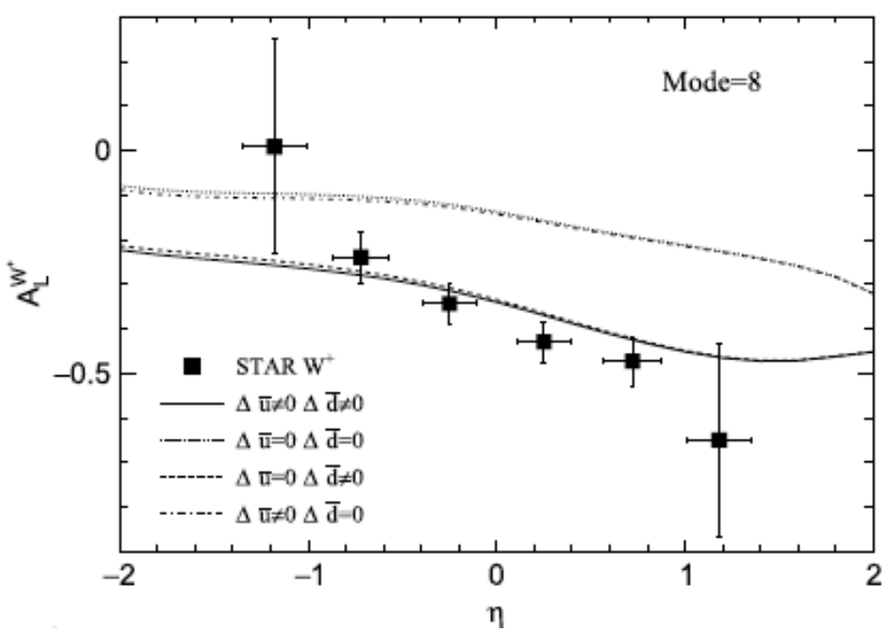




- $\Delta\bar{u}$ is now known to be positive while $\Delta\bar{d}$ is negative, at intermediate Bjorken-x
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized flavor asymmetry $\bar{u} - \bar{d}$

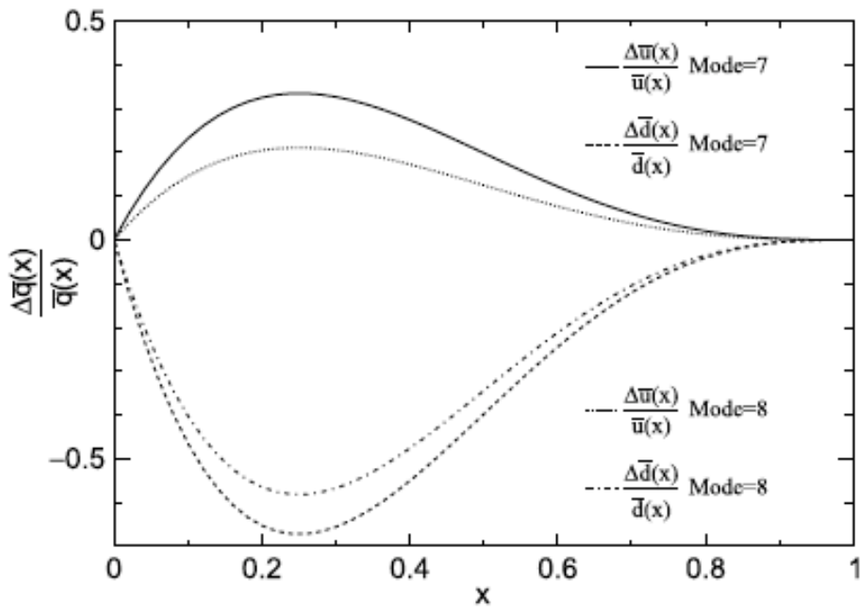
From quark-spectator-diquark model perspective





- Intuitive picture given by numerical calculation based on quark-spectator-diquark model
- Consistently, positive $\Delta\bar{u}$ and negative $\Delta\bar{d}$

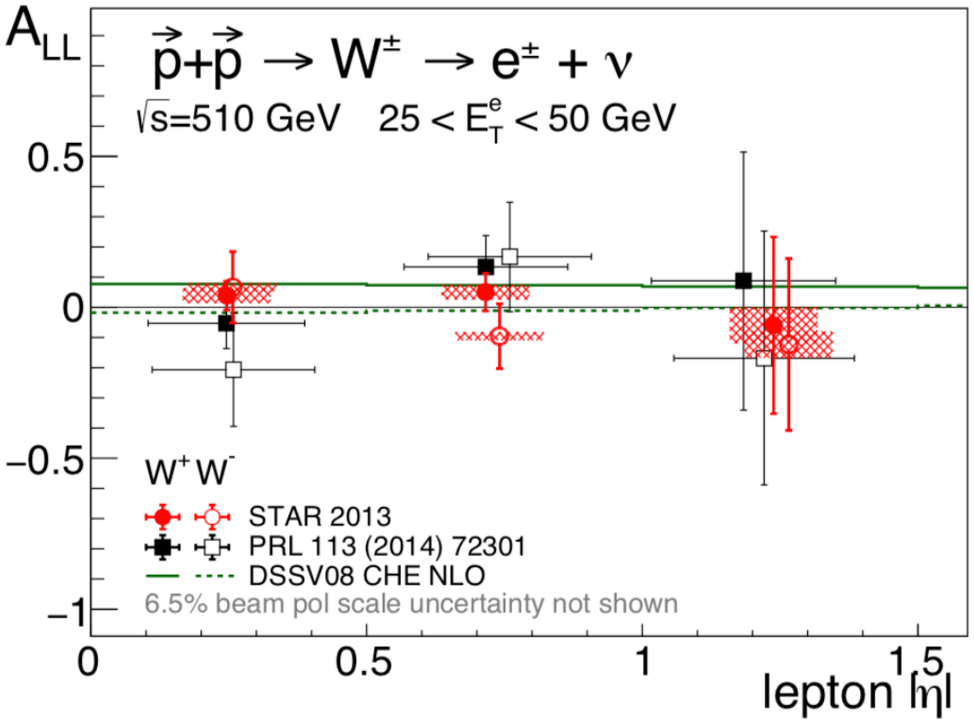
F. Tian *et al.* Nucl.Phys. A961 (2017) 154-168
M. Liu and B-Q Ma, Phys. Rev. D **98**, 036024



Double-Spin Asymmetry

- Besides the single-spin asymmetry, A_L, we have also measured the double-spin asymmetry A_{LL}

$$A_{LL} \equiv \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})}$$



PRD 99, 051102(R) (2019)

- Can also provide access to $\Delta\bar{u}$, $\Delta\bar{d}$

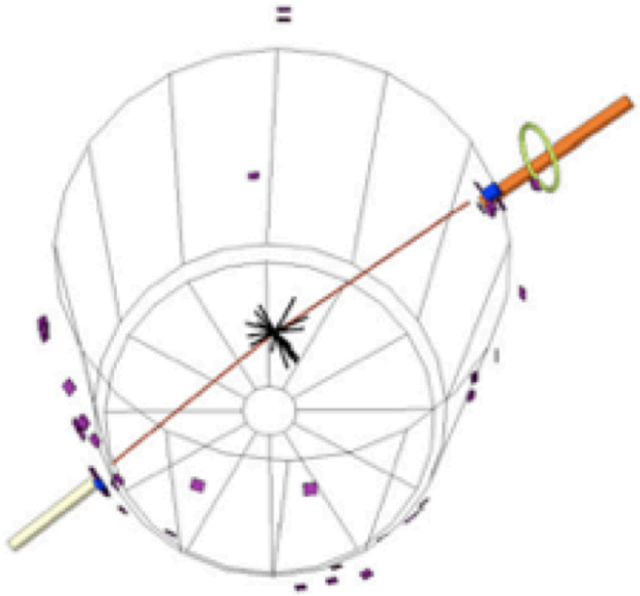
$$A_{LL}^{W^+} \propto \frac{\Delta u}{u}\frac{\Delta \bar{d}}{\bar{d}} \qquad A_{LL}^{W^-} \propto \frac{\Delta d}{d}\frac{\Delta \bar{u}}{\bar{u}}$$

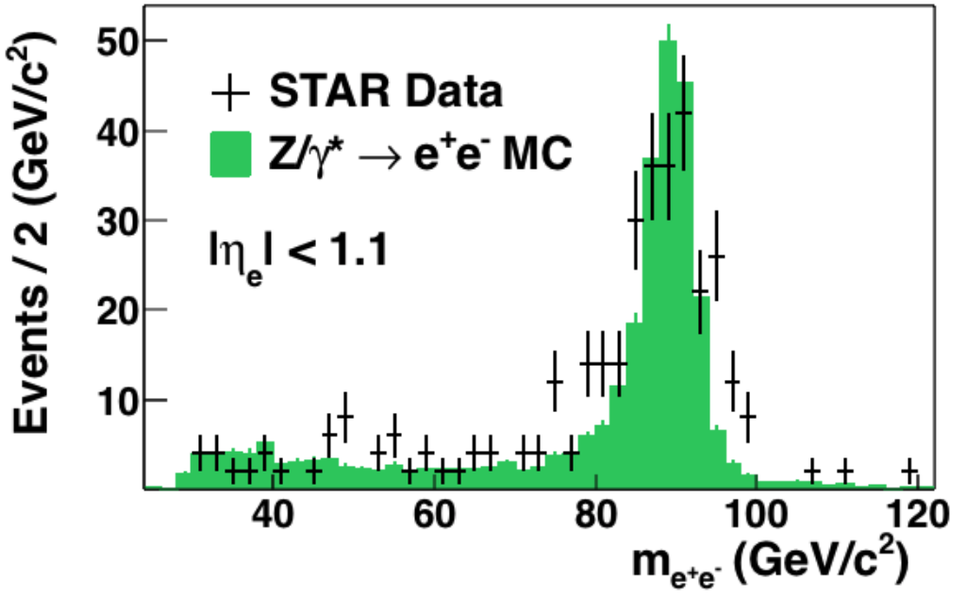
- Positivity constraints using combination of A_L and A_{LL}

$$1 \pm A_{LL}^{\pm}(y_W) > |A_L^{W^\pm}(y_W) \pm A_L^{W^\pm}(-y_W)|$$

Z.Kang, J.Soffer, Phys.Rev.D83, 114020 (2011)

Single-Spin Asymmetry for Z/γ^*

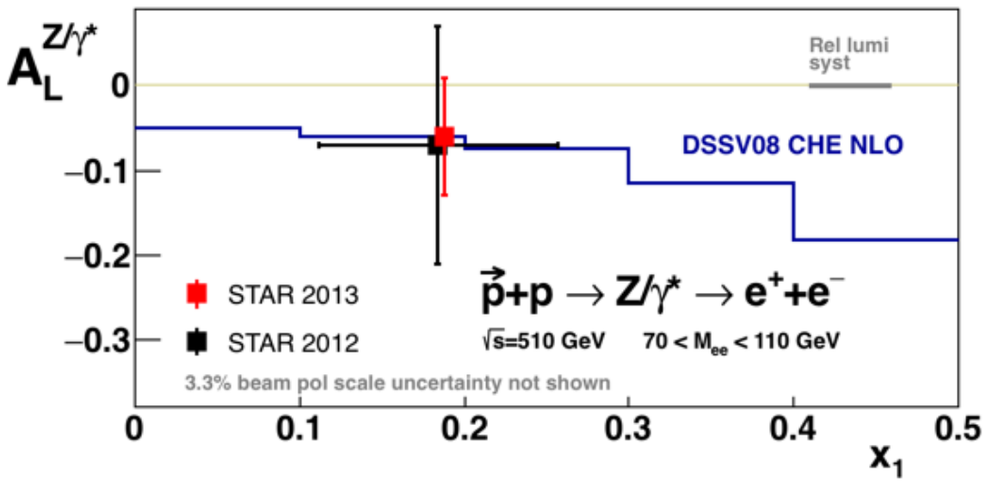




- Z/γ^* can be fully reconstructed

$$Z/\gamma^* \rightarrow e^+e^-$$

- Z/γ^* A_L is sensitive to the combination of u, $\bar{u}$, d, and $\bar{d}$ polarizations.



PRD 99, 051102(R) (2019)

Summary

- Unique probe to the sea quark helicity distribution via weak boson production in proton-proton collisions.

- Most precise results from STAR 2013:

  - STAR, PRD 99, 051102 (R) (2019)

- First experimental observation of a flavor-asymmetry between anti-up and anti-down polarizations, opposite to the unpolarized distributions.

- Many other results from STAR spin program, e.g. :

  - Strange quark polarization via $\Lambda/\bar{\Lambda}$ spin transfer measurements

  - Gluon polarization via (inclusive-/di-) jet production