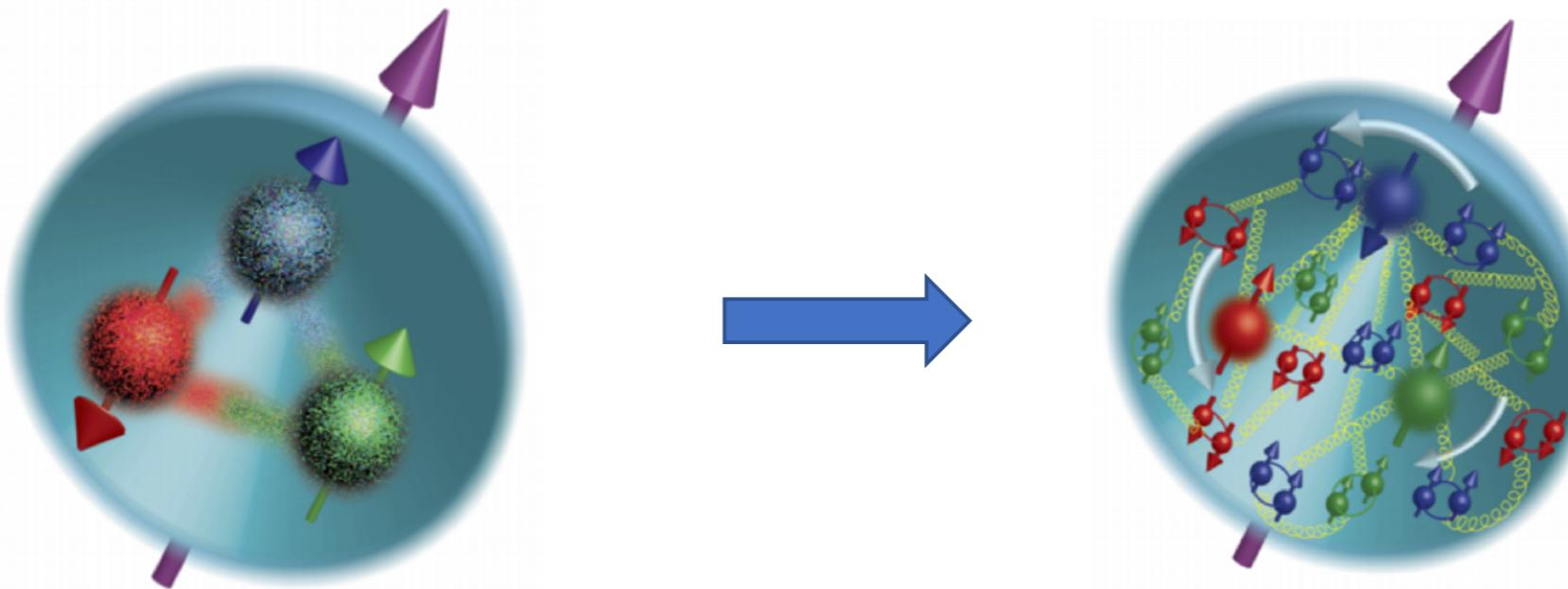


Measurement of Longitudinal Spin Asymmetries for Weak Boson Production at STAR

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)

$$\langle S_p \rangle = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

Jaffe-Manohar 1990

Proton Spin Structure

Before RHIC, mostly polarized DIS

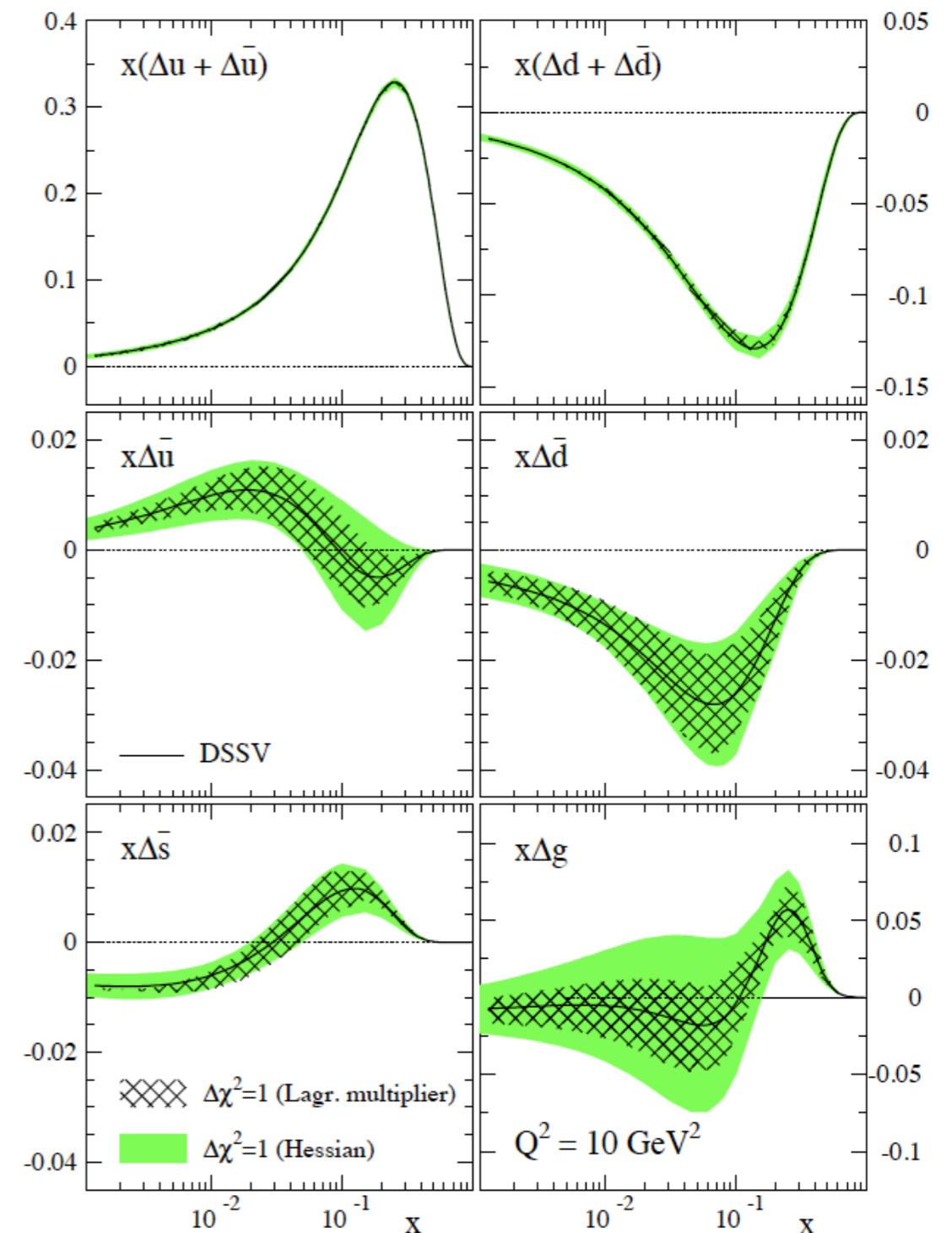
- Total quark spin contributions pinned down pretty well
- Flavor separation was accessible via semi-inclusive DIS but has to rely on Fragmentation Functions; additional uncertainty introduced
- No direct access to gluon spin

RHIC spin program

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

DSSV2008

(Mostly pDIS + earlier RHIC results)



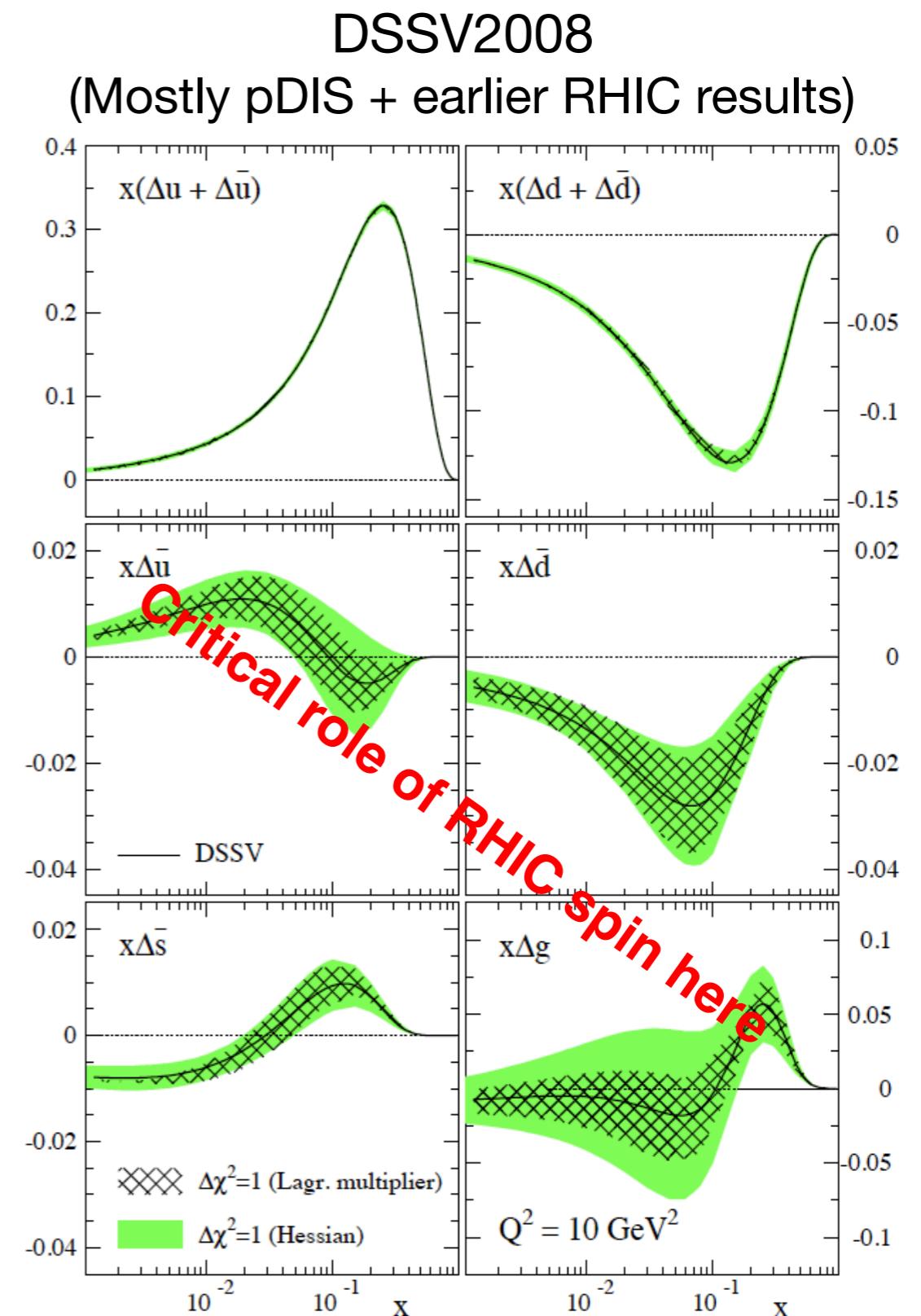
Proton Spin Structure

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

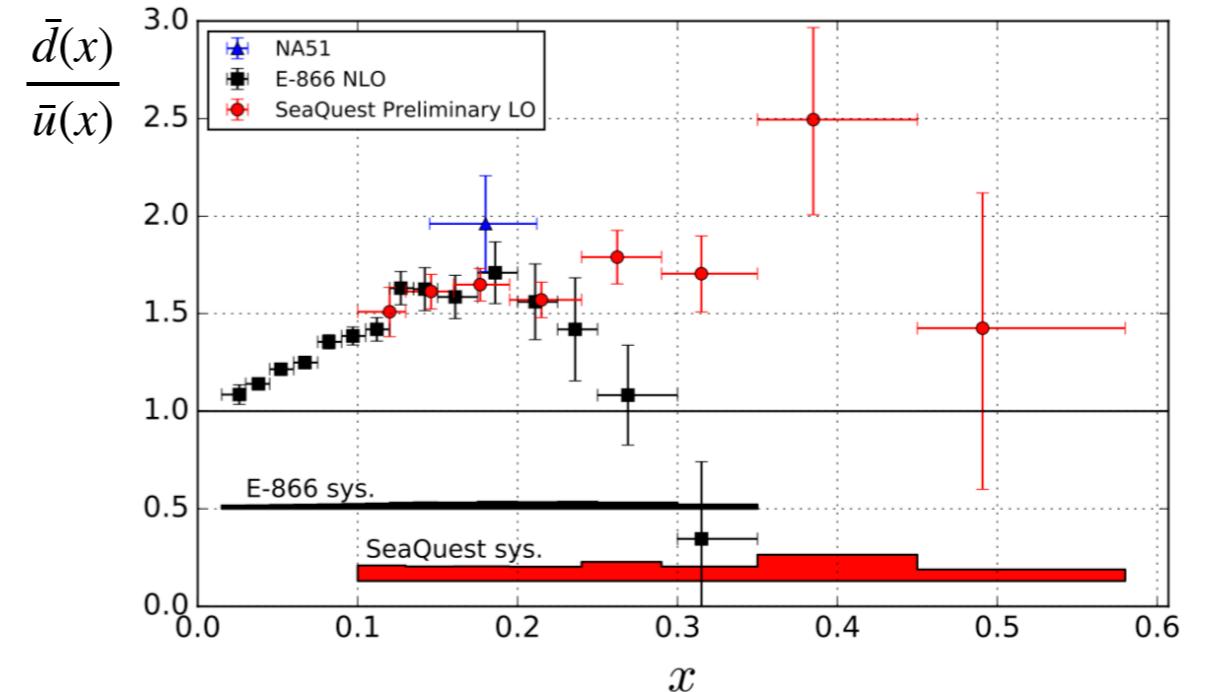
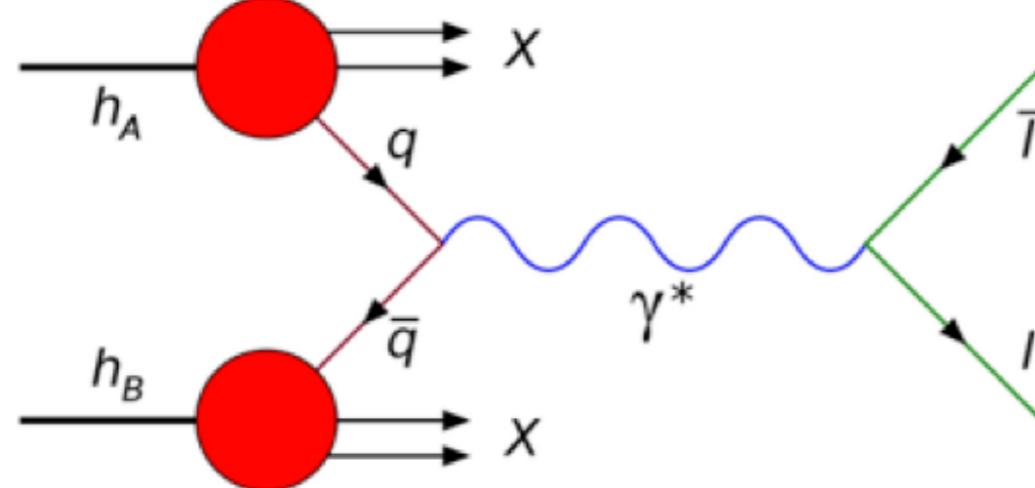
RHIC spin program

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

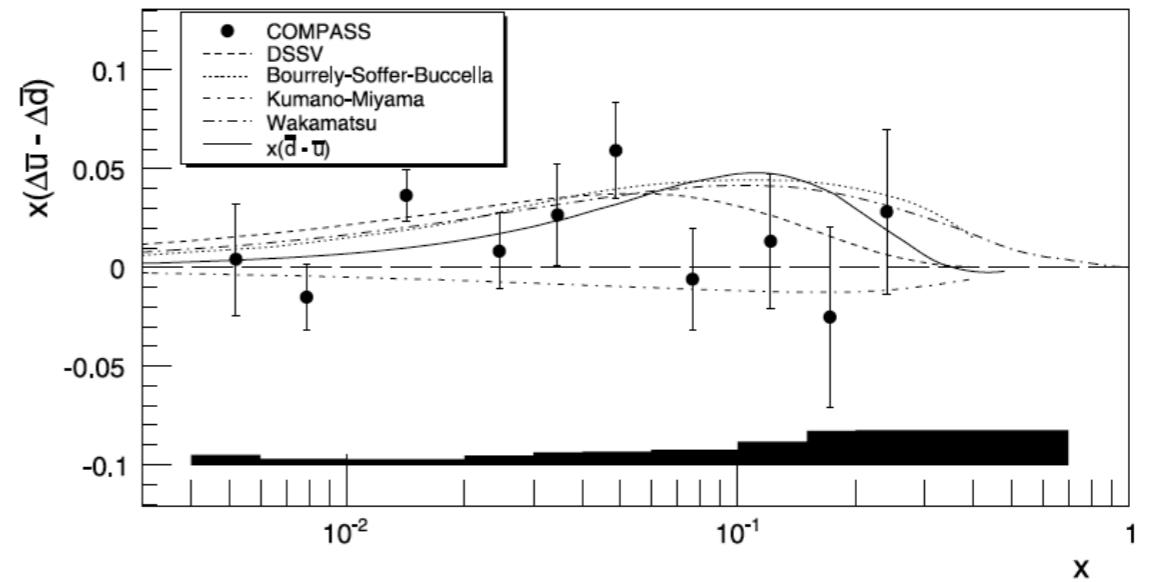


Sea Quark Flavor Asymmetry

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.

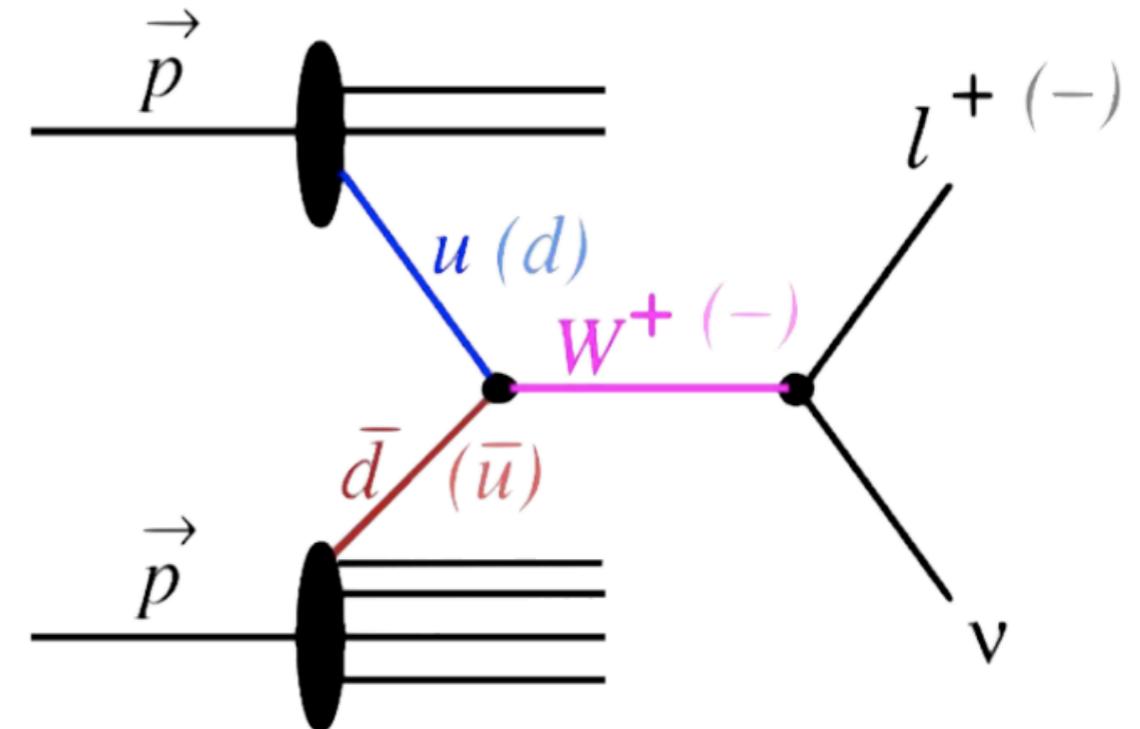


COMPASS, PLB 693, 227 (2010)

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

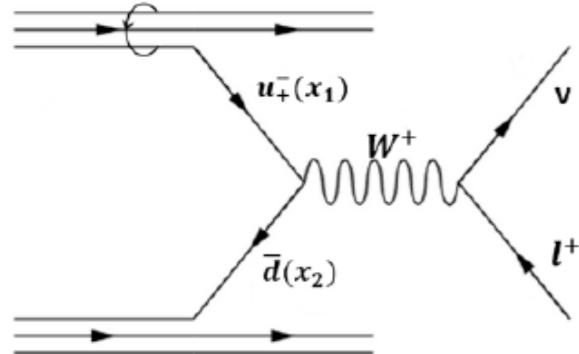


Parity-violating longitudinal single-spin asymmetry:

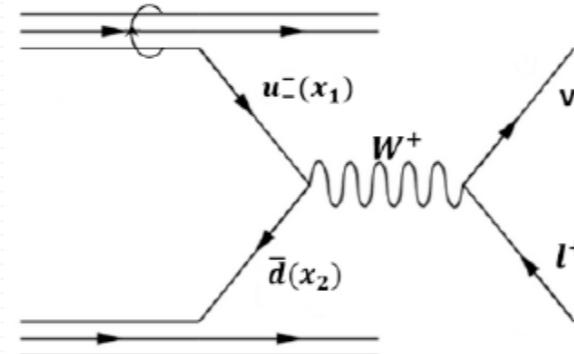
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

From $W A_L$ to Quark/anti-Quark Spin

A. Polarized (subscript) proton provides u

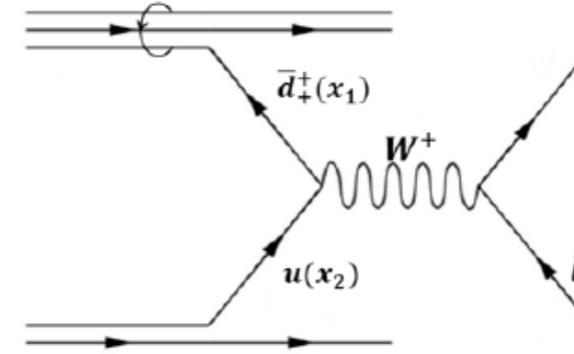


A.1 Proton helicity = “+”

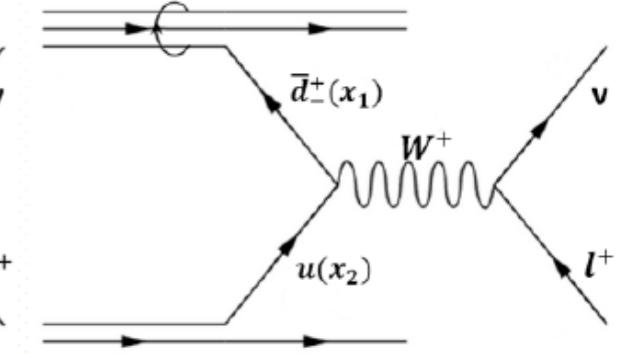


A.2 Proton helicity = “-”

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



B.1 Proton helicity = “+”



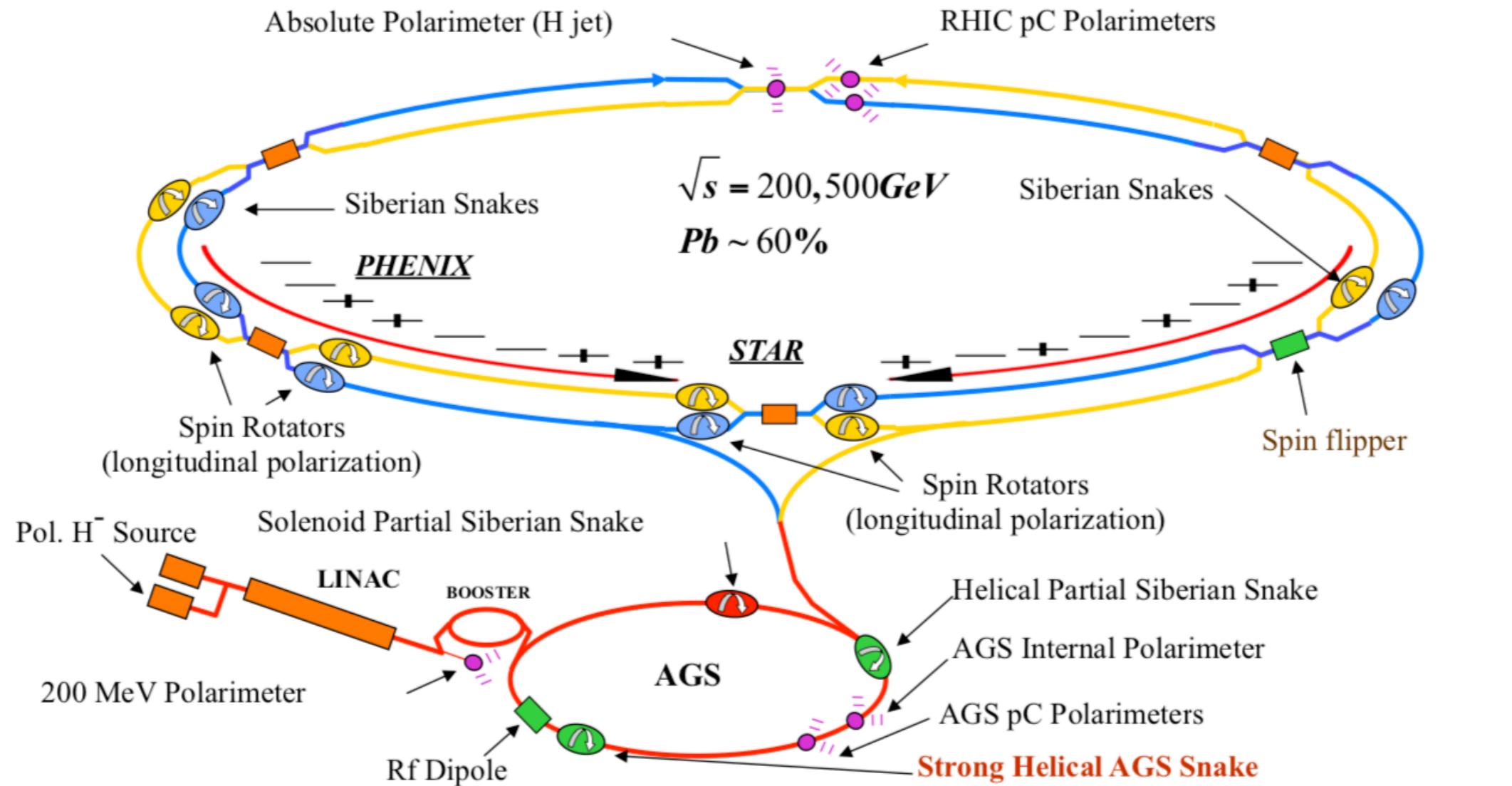
B.2 Proton helicity = “-”

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

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

- Flavor separation as forward/backward rapidity

RHIC – as Polarized Proton collider



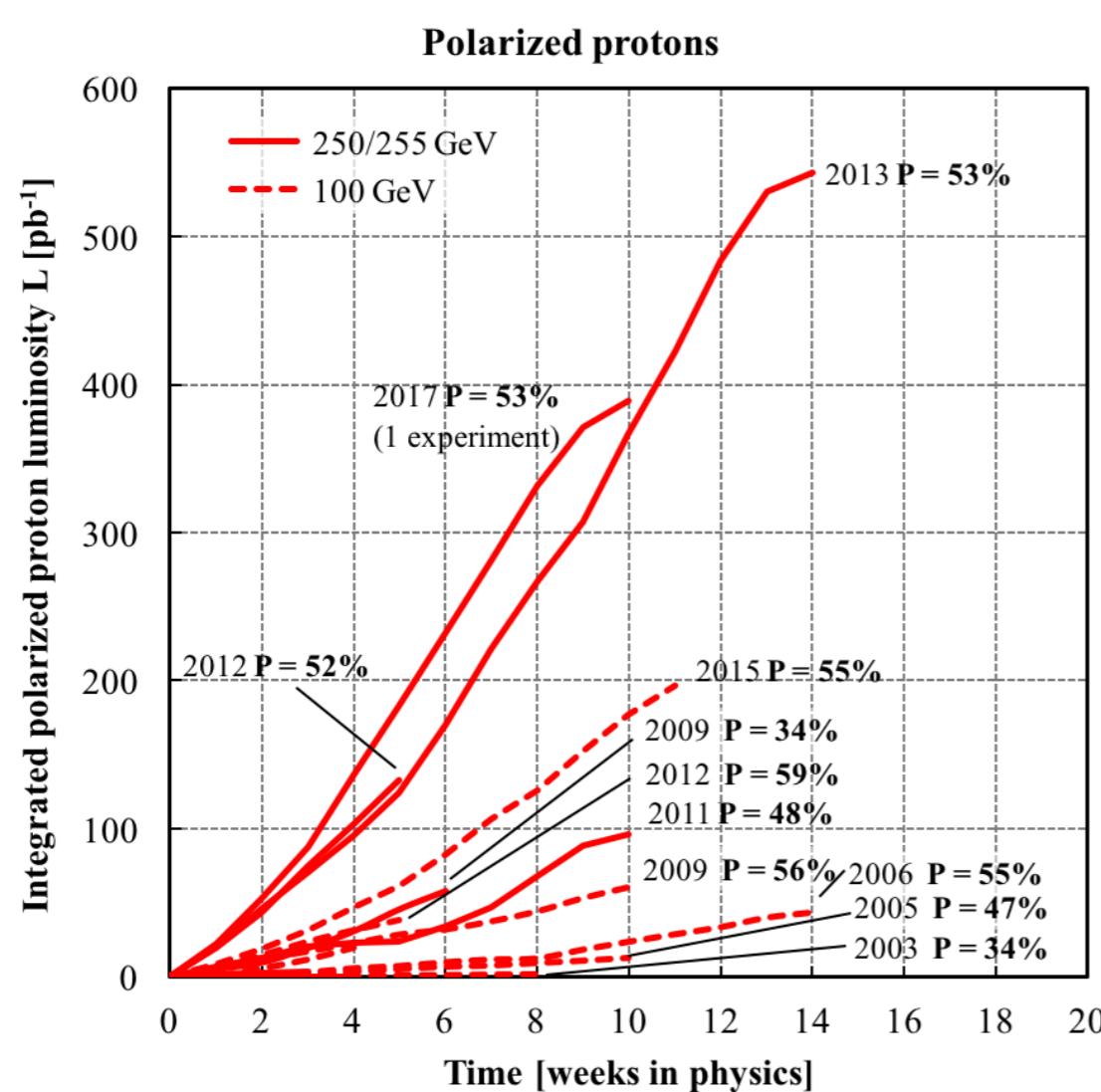
Transverse



Longitudinal



RHIC/STAR Data Sets

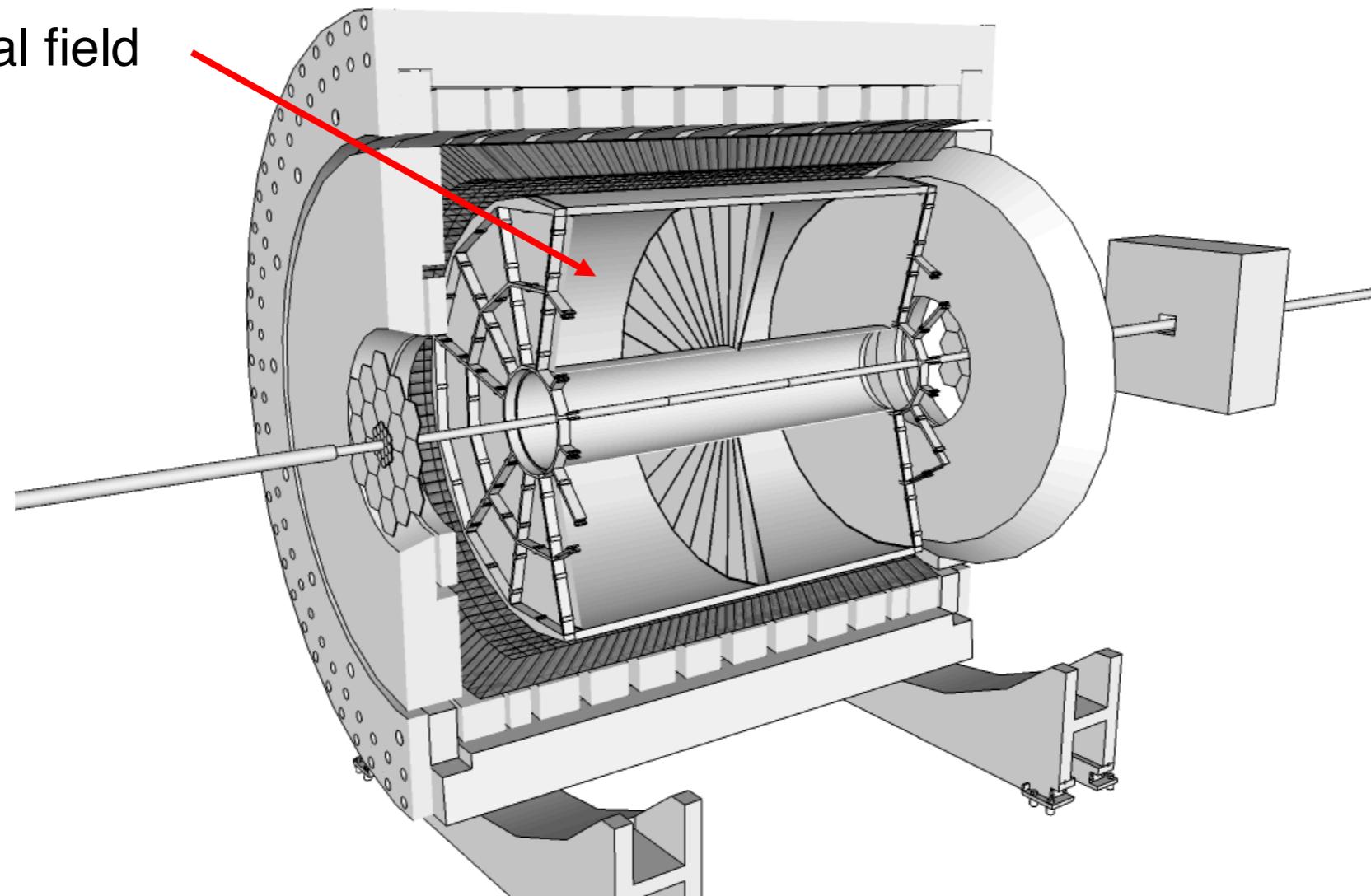


	Year	\sqrt{s} (GeV)	L (pb^{-1})	$\langle P \rangle$ (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
Trans	2013	510	256	56
	2015	200	50	60
	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	50	60
	2017	510	356	55

STAR Detector

Nucl. Instrum. Meth. A499, 624, 2003

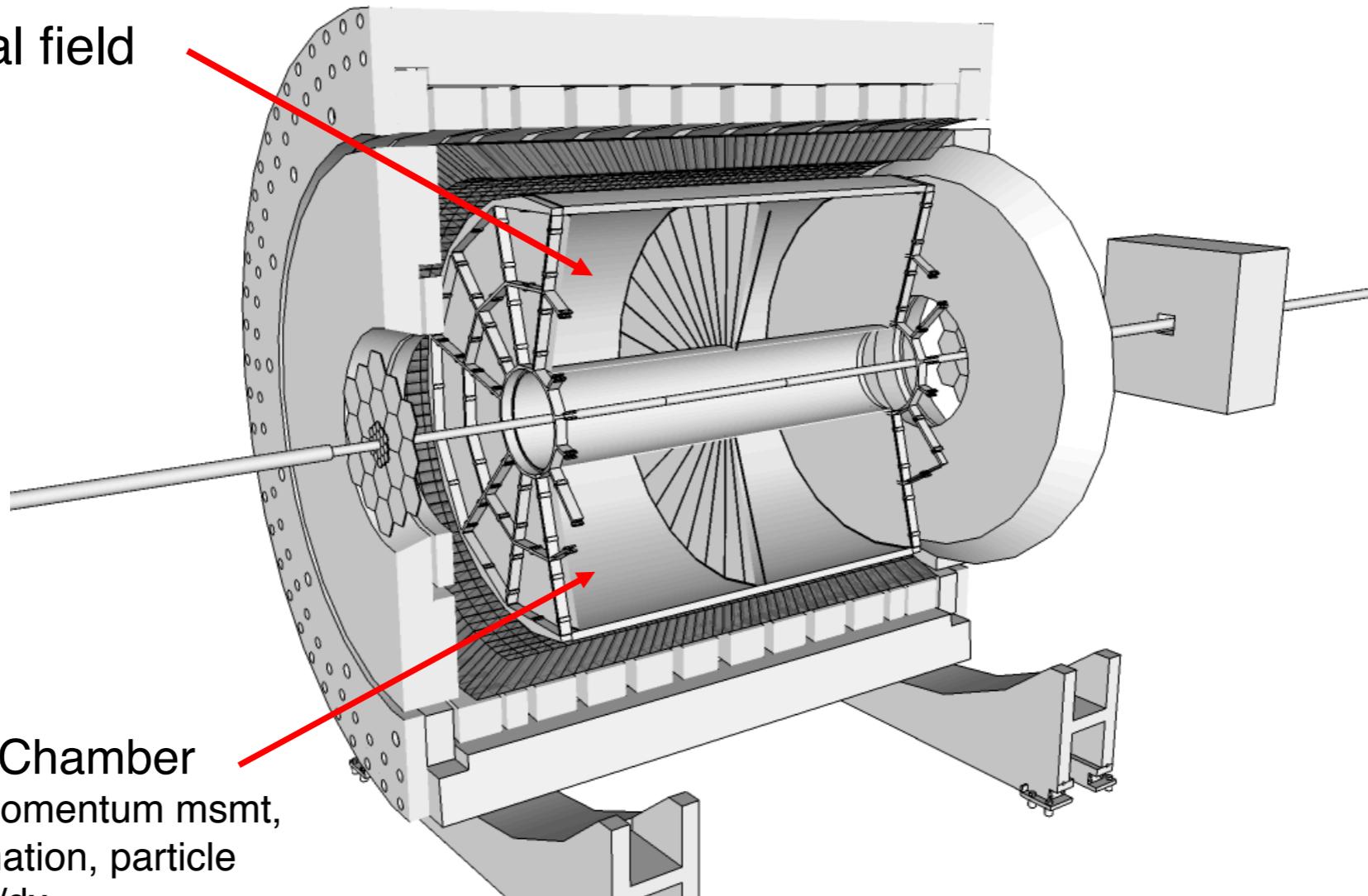
0.5 T solenoidal field



STAR Detector

Nucl. Instrum. Meth. A499, 624, 2003

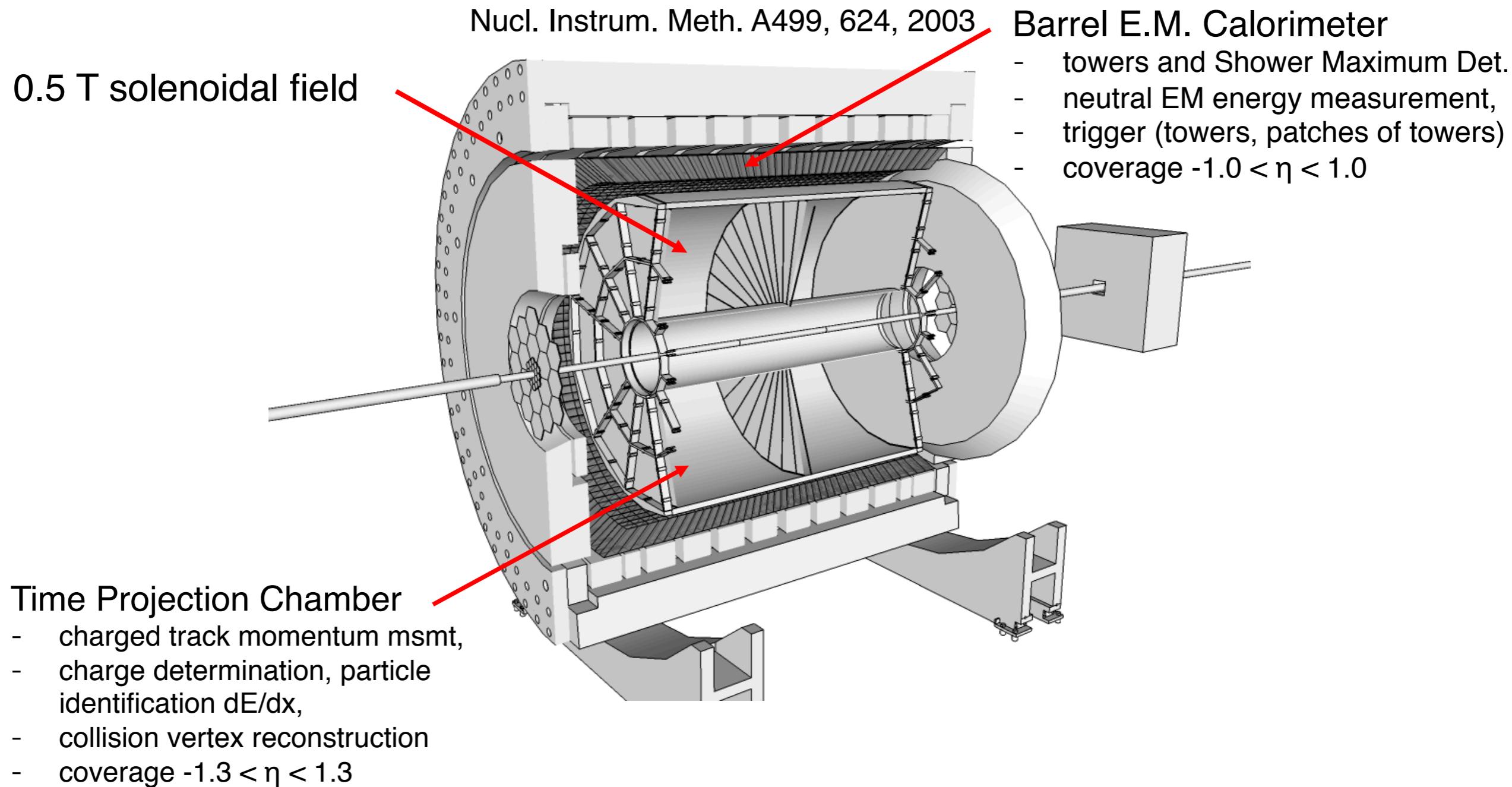
0.5 T solenoidal field



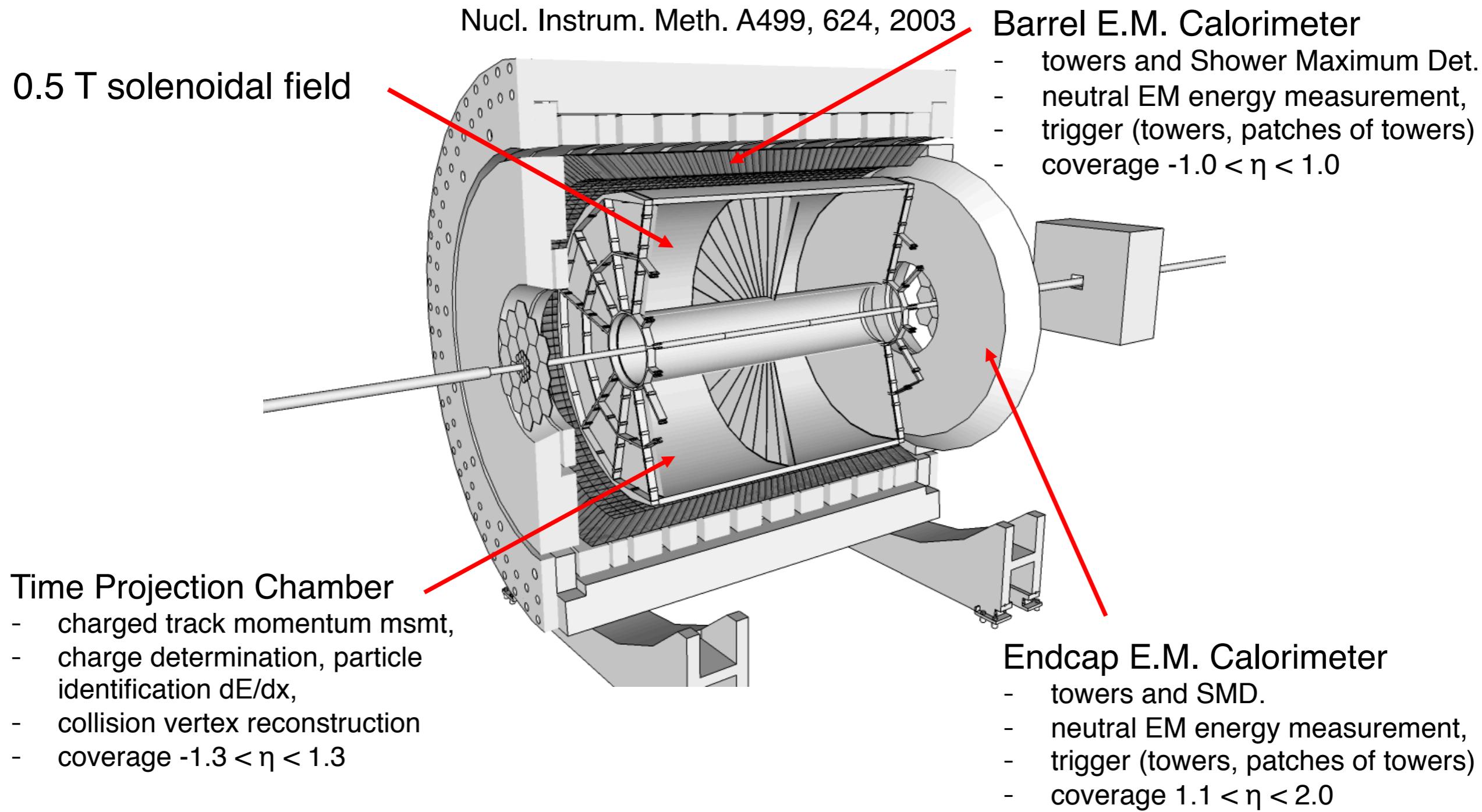
Time Projection Chamber

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

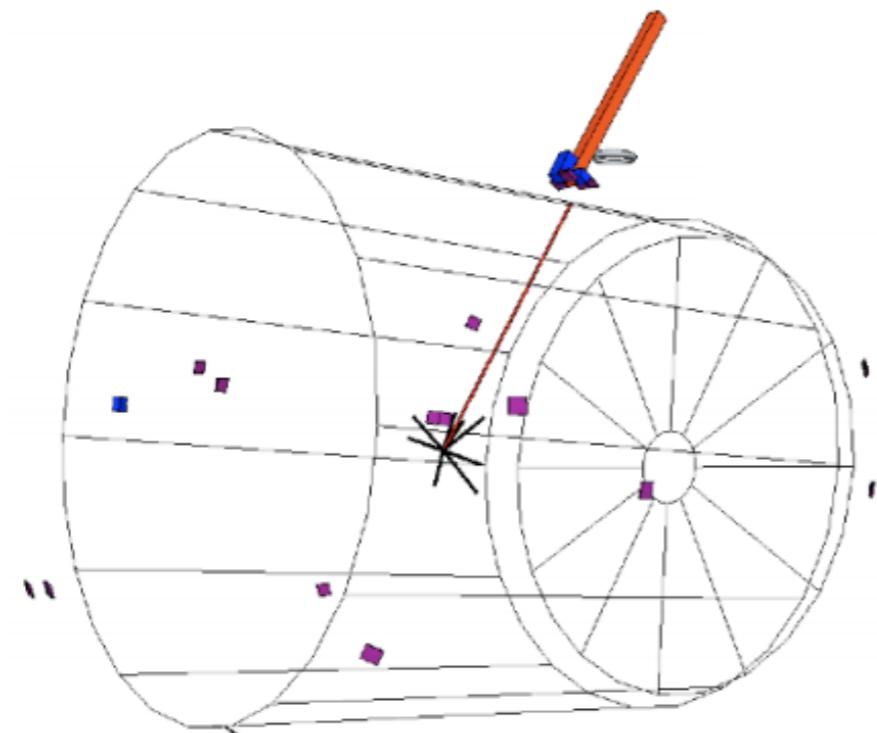
STAR Detector



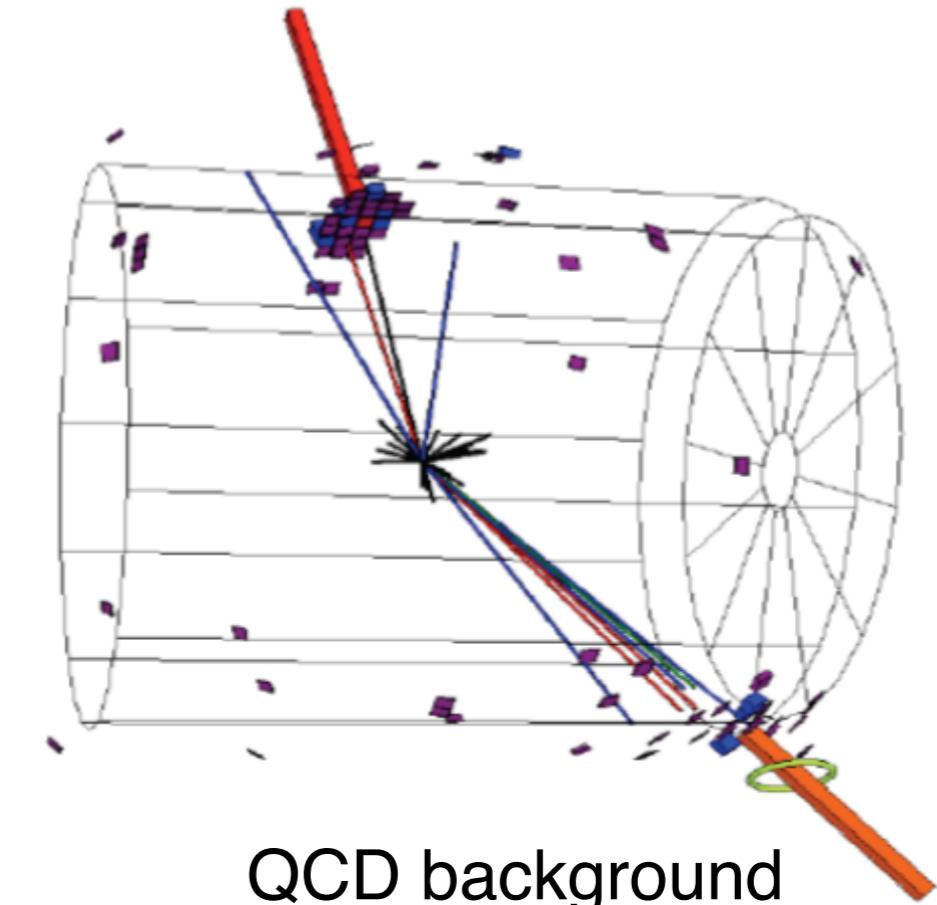
STAR Detector



Measuring W at STAR



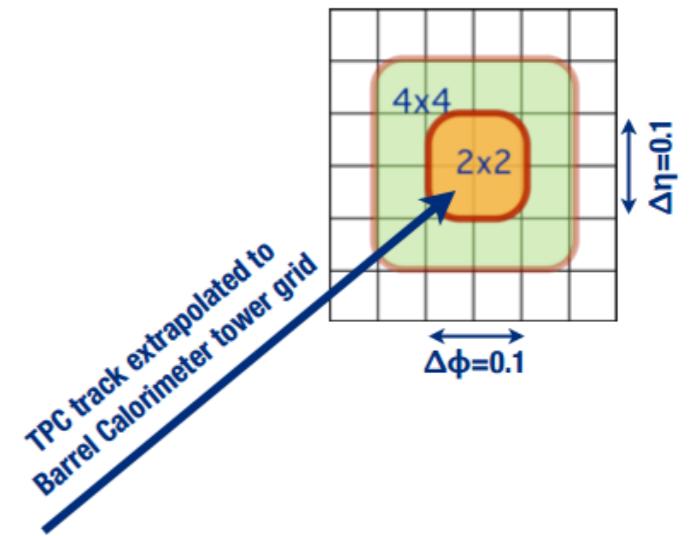
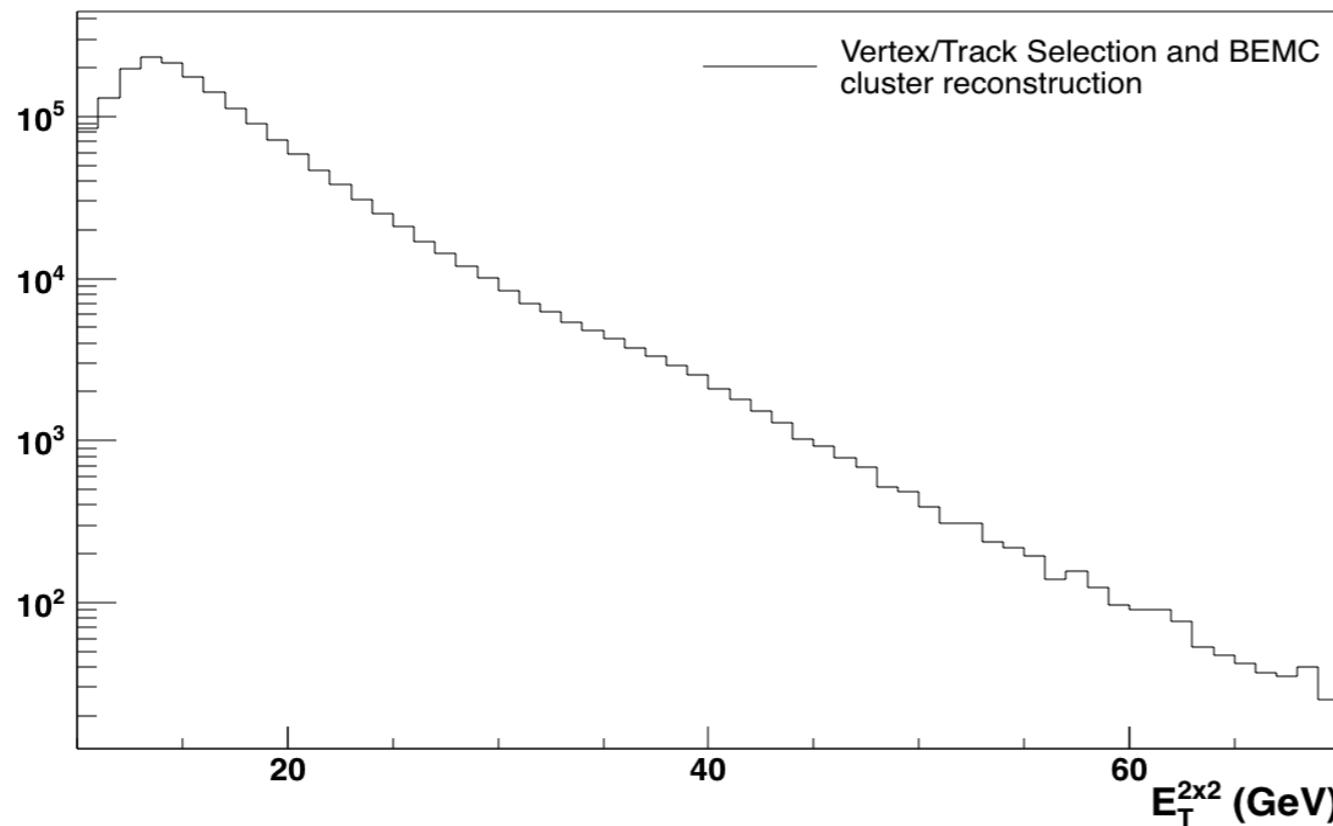
$$W \rightarrow e + \nu_e$$



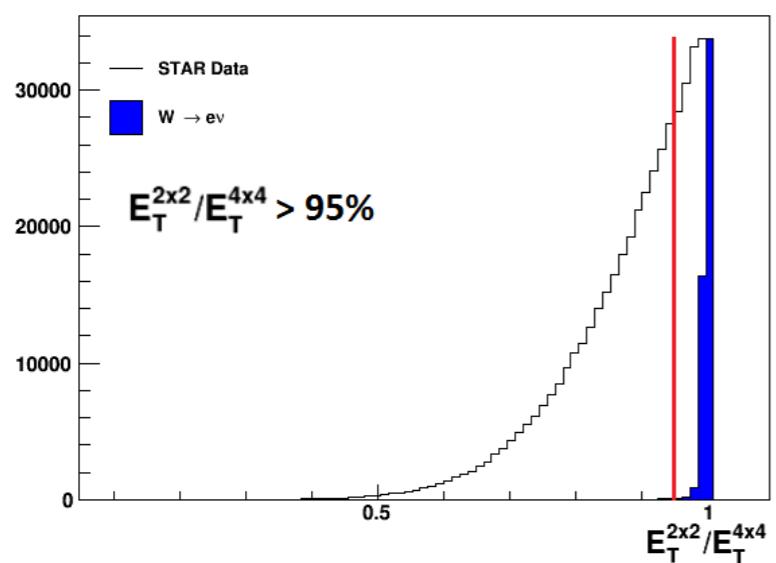
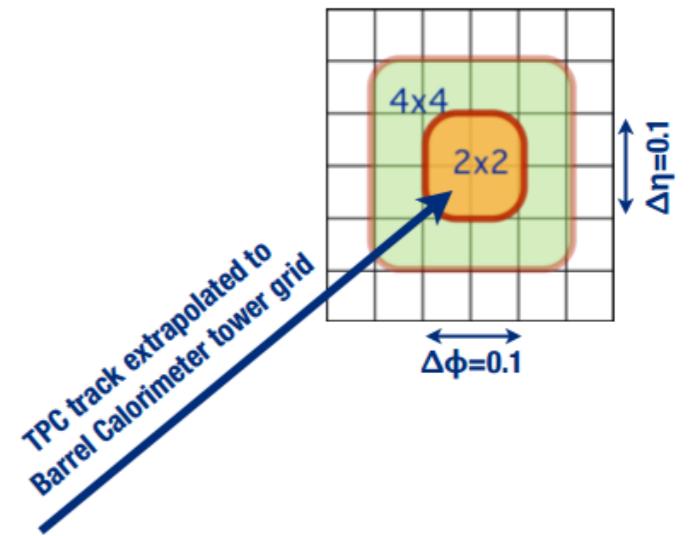
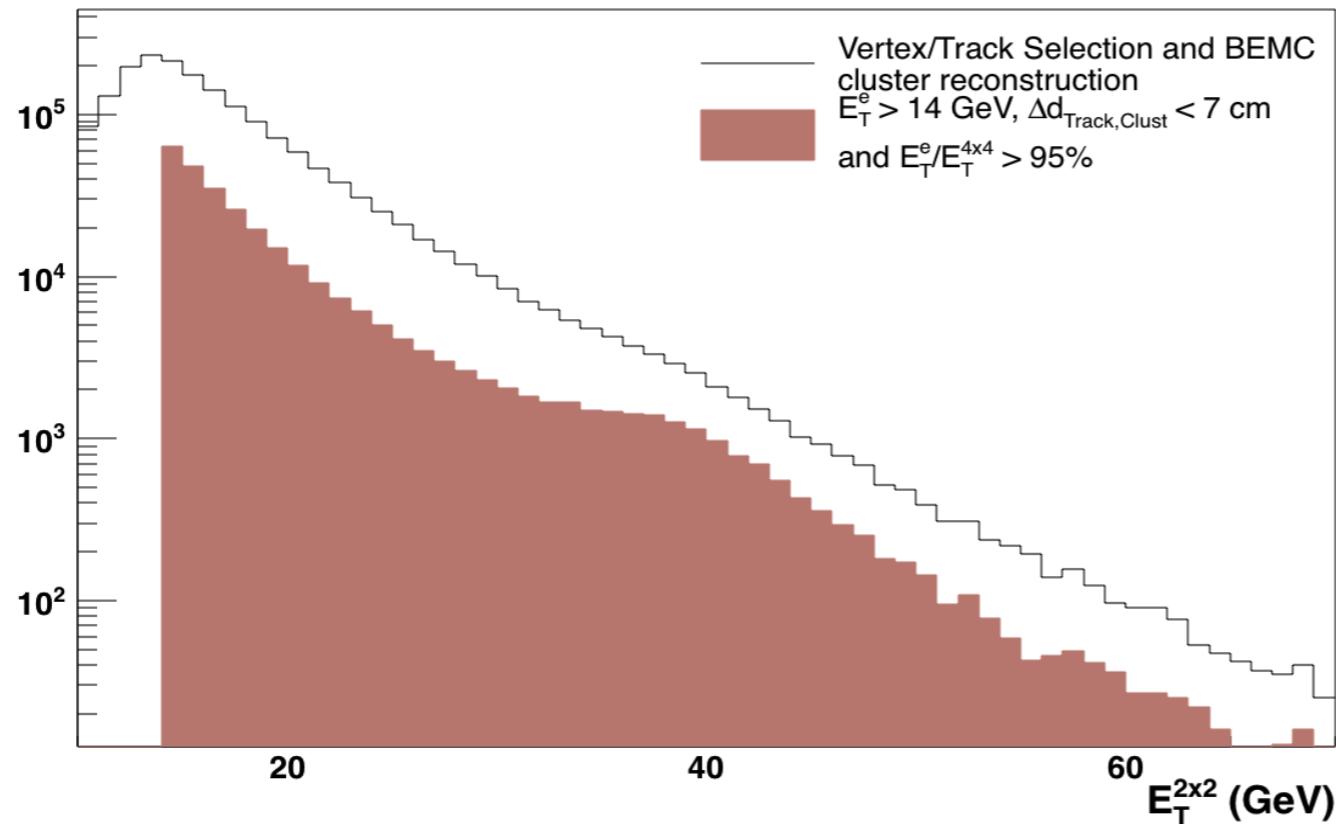
QCD background

- 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)

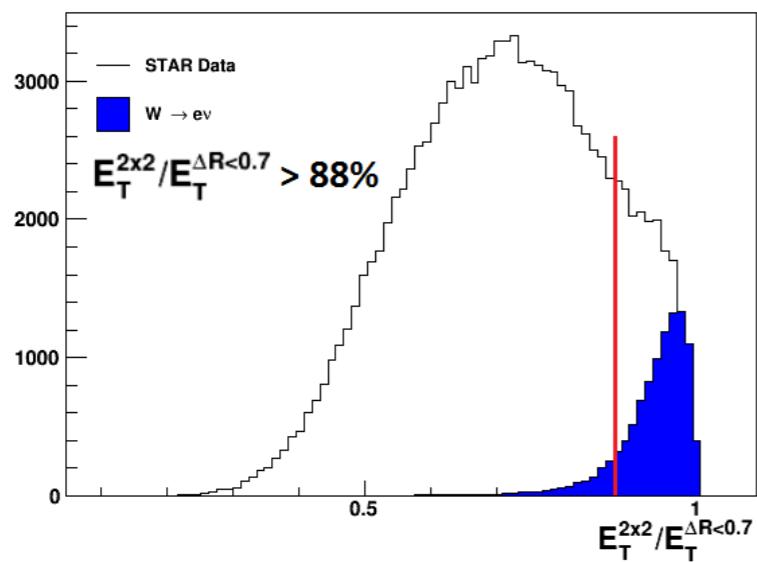
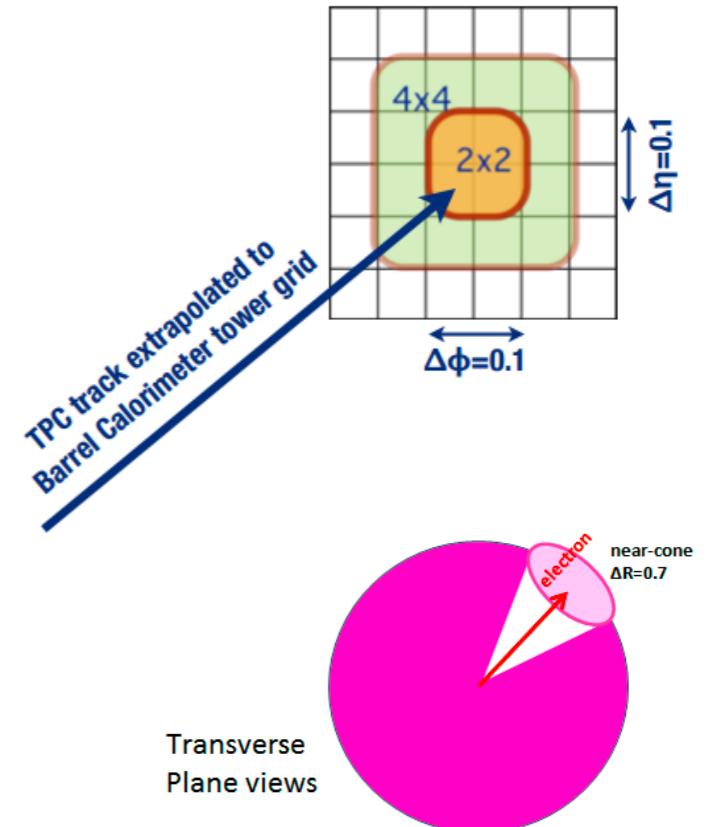
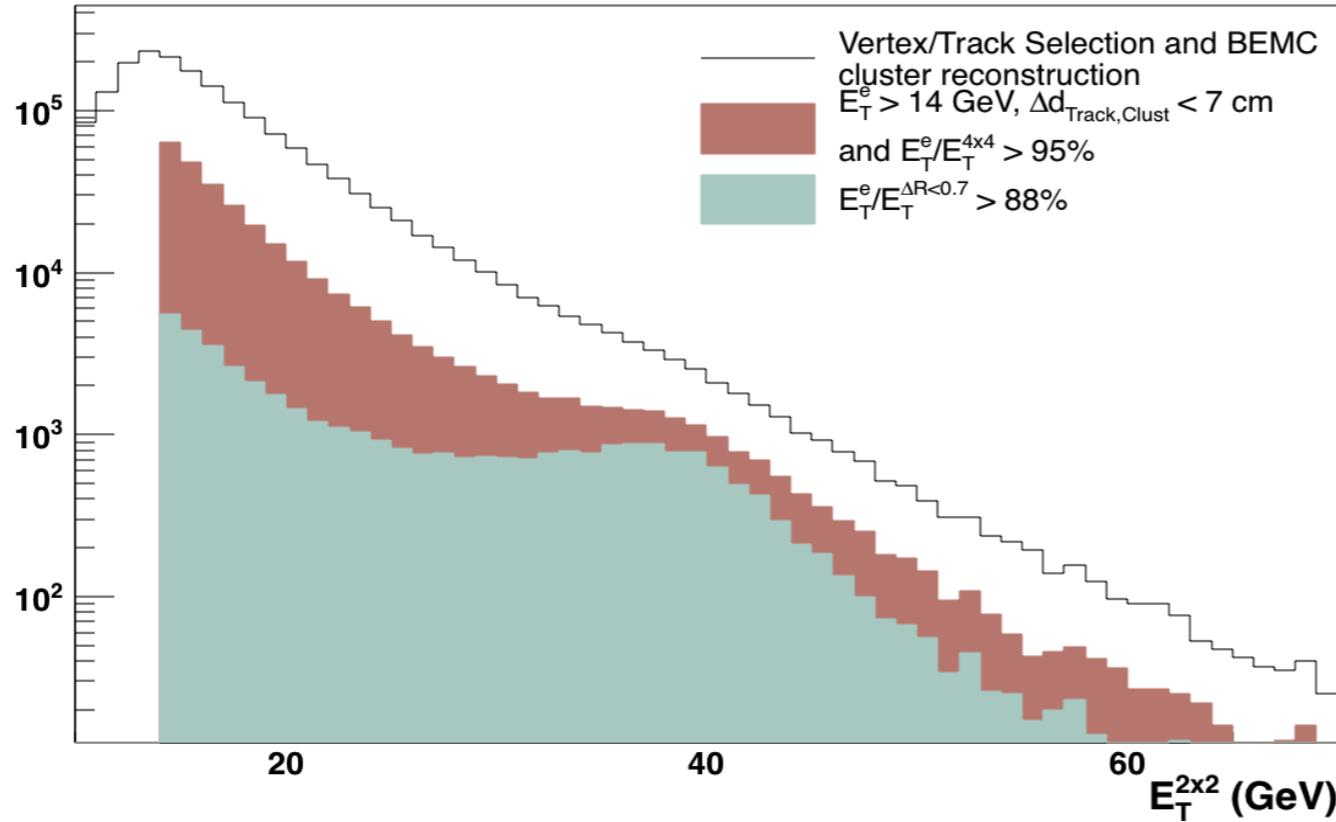
W Selection



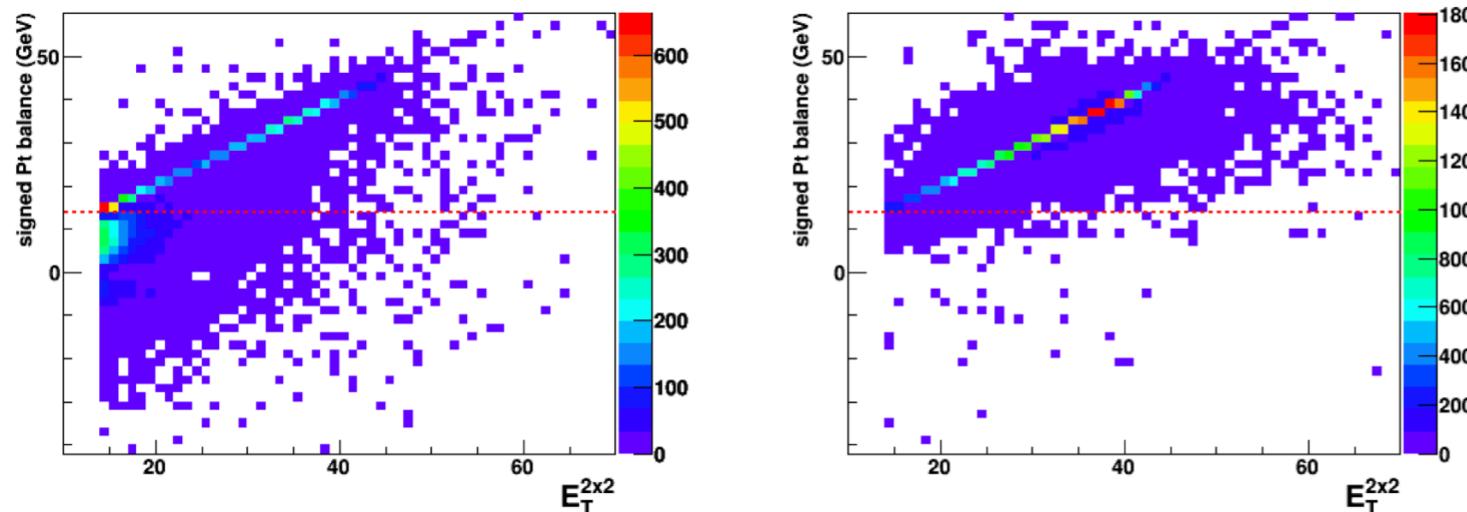
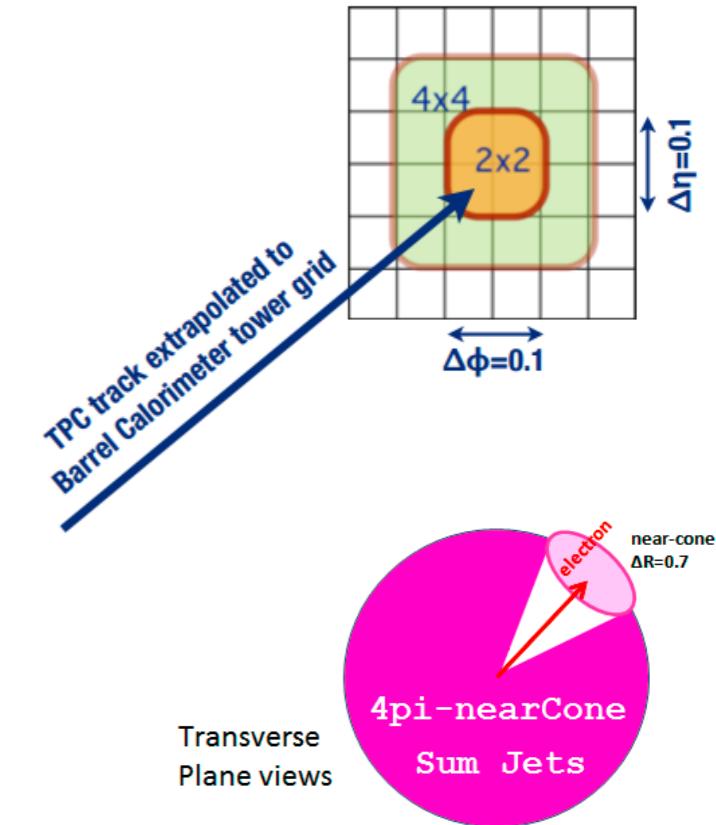
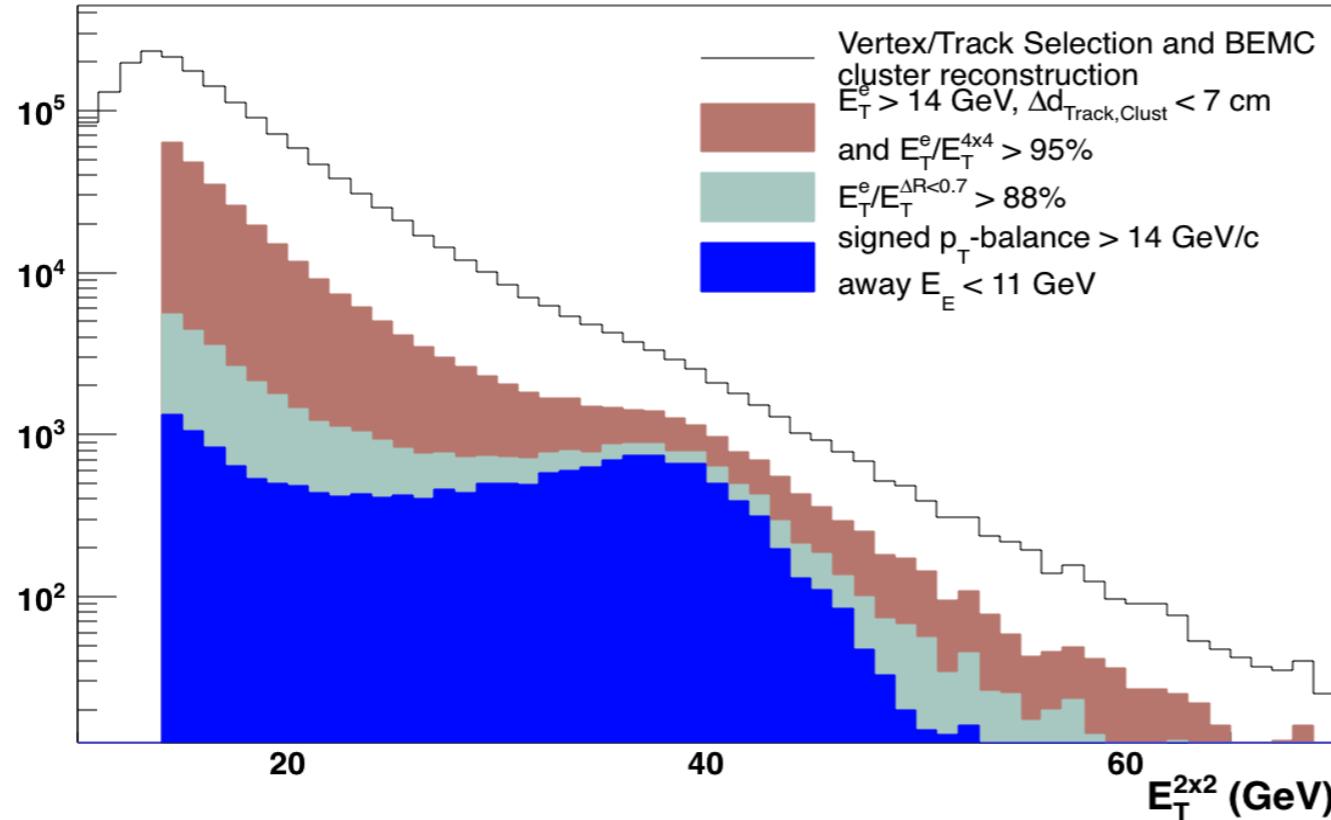
W Selection



W Selection



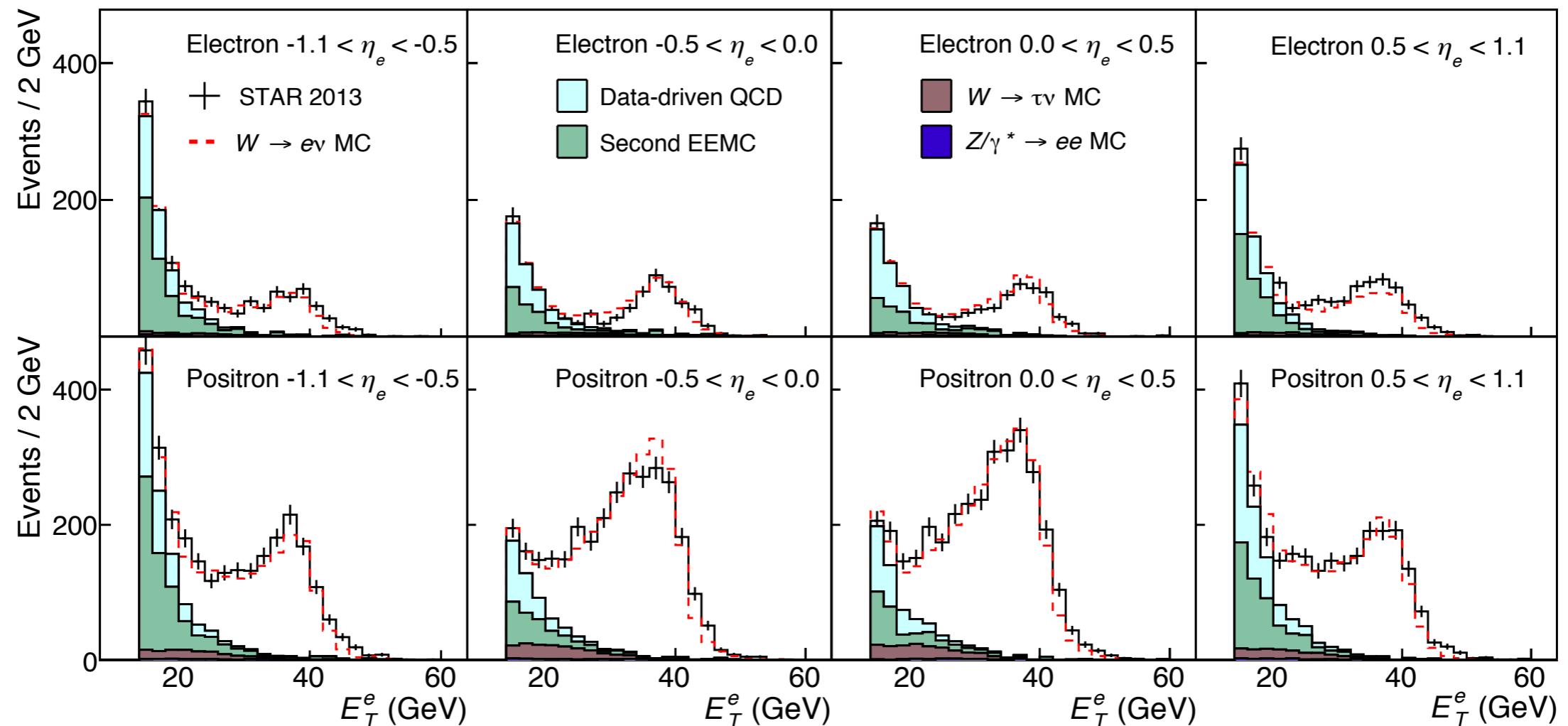
W Selection



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

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

Background Analysis

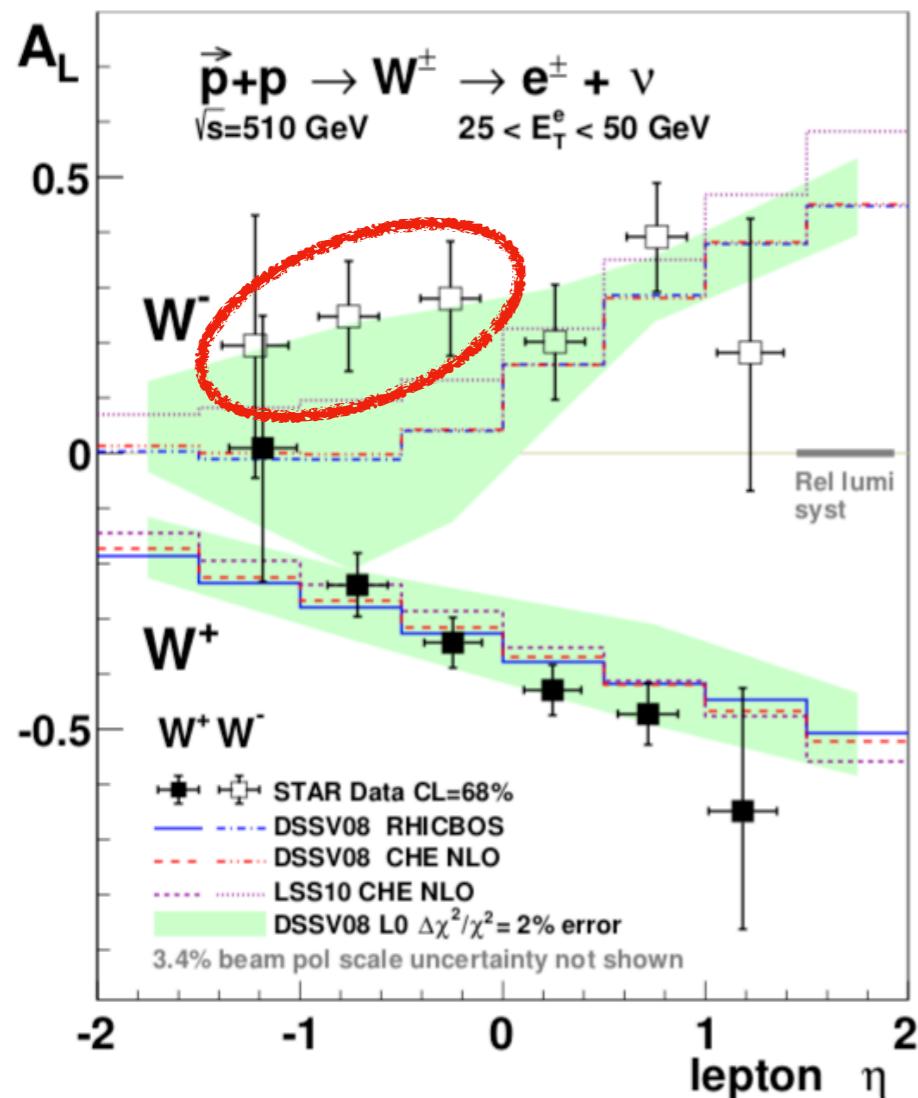


Residual background:

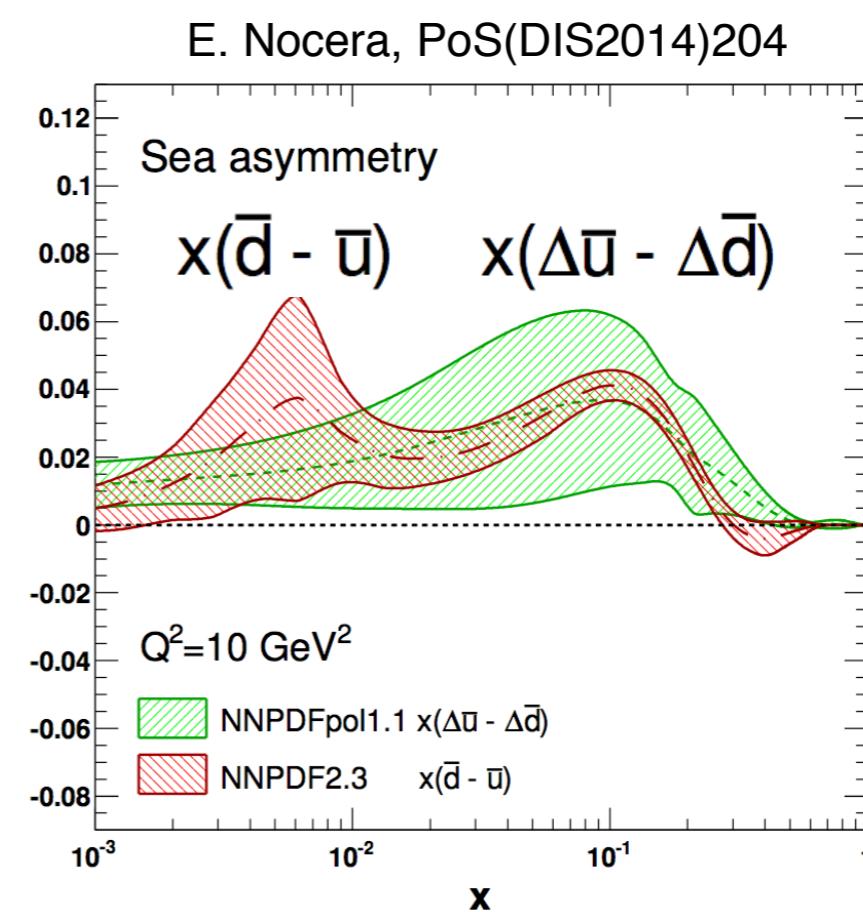
- W decays to tau and then to electron/positron
- Z to electron-positron pair but one of them undetected
- QCD background

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



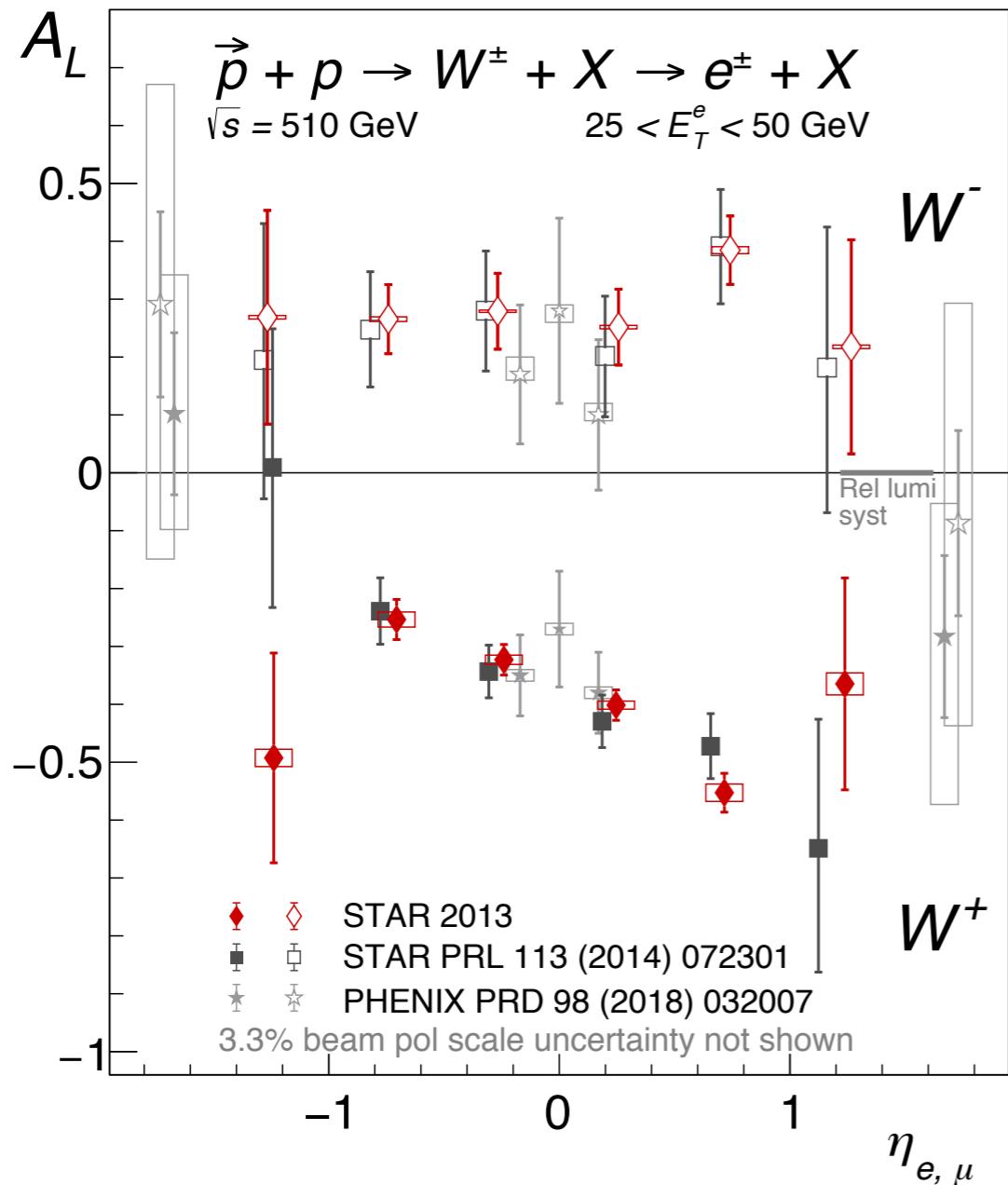
STAR, PRL 113, 072301 (2014)



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

Motivation for more precise data.

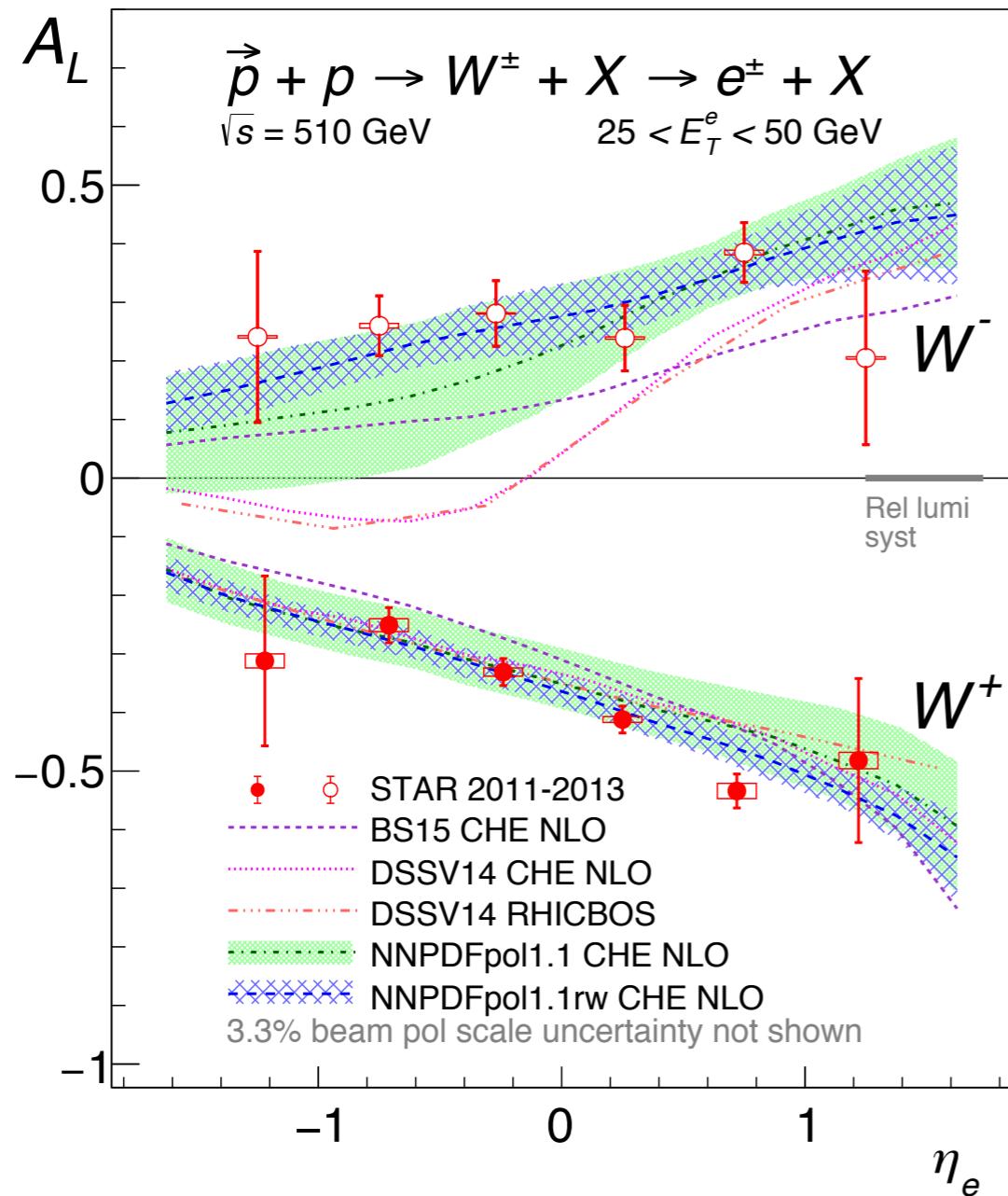
STAR 2013 Results



- 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.

PRD 99, 051102(R) (2019)

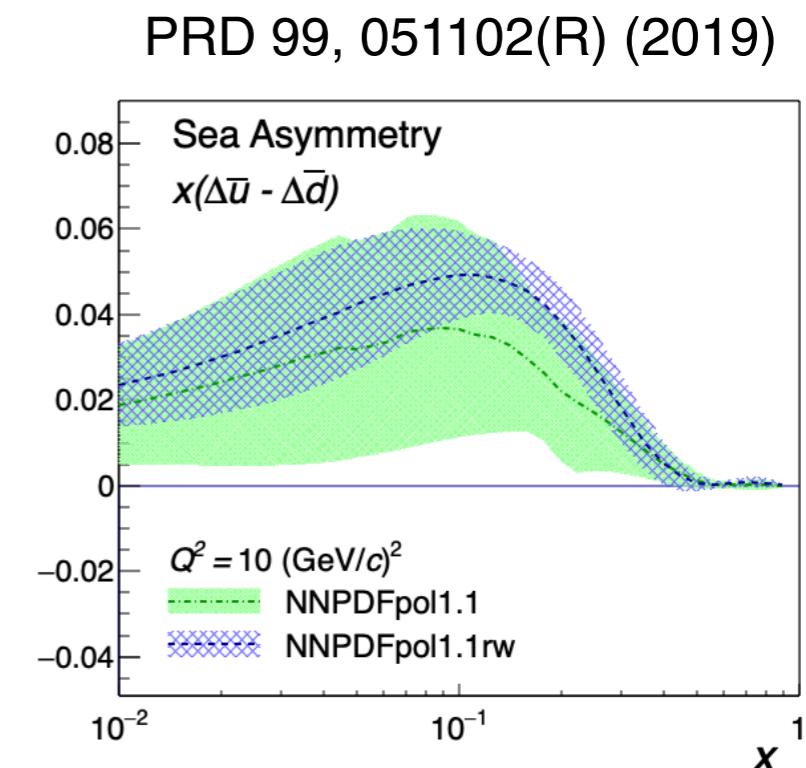
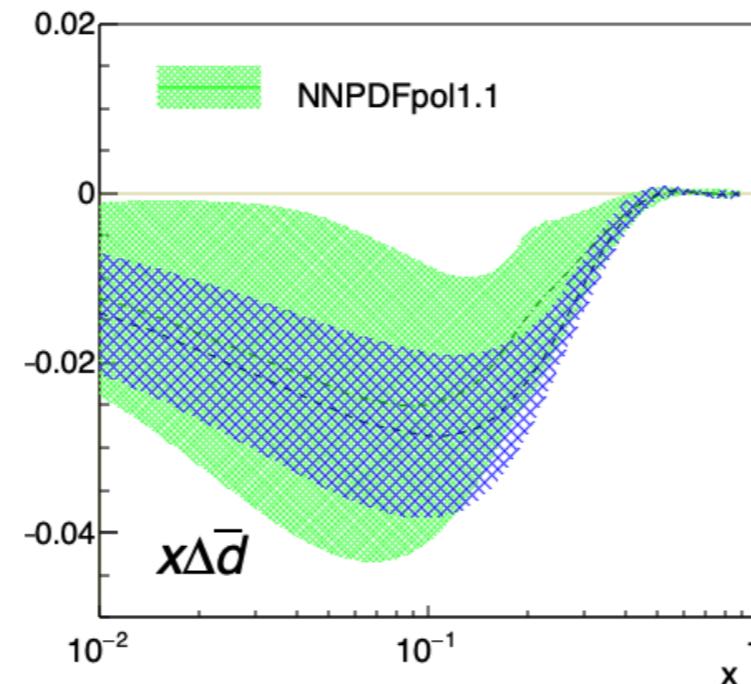
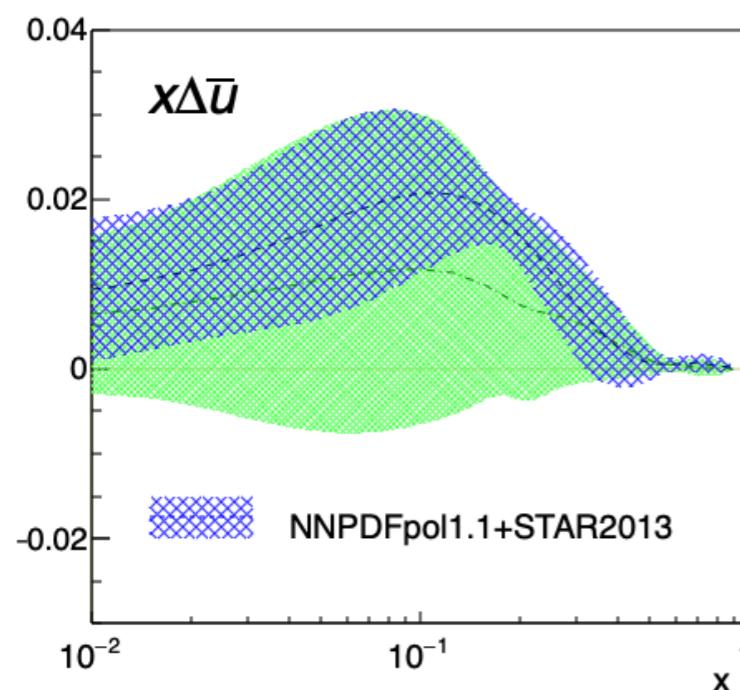
STAR 2013 Results



- 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.
- Combined results in comparison with theoretical predictions

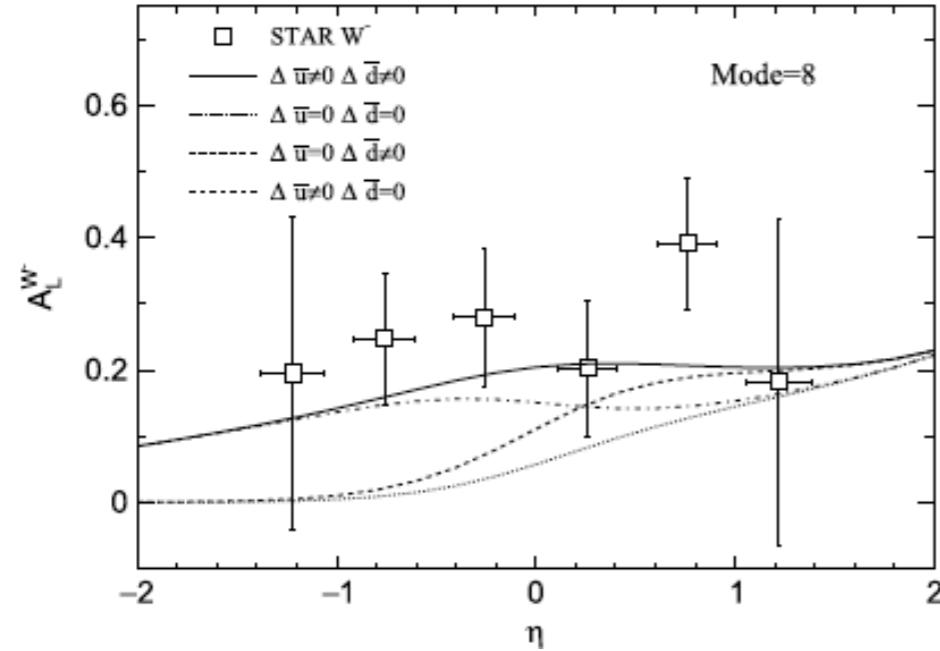
PRD 99, 051102(R) (2019)

Impact of STAR 2013 Results



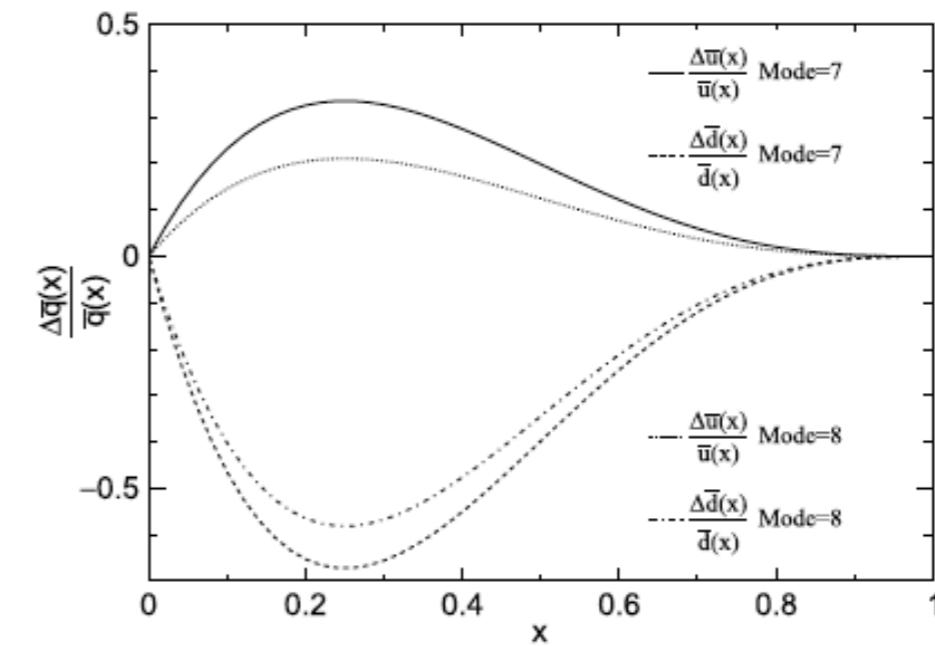
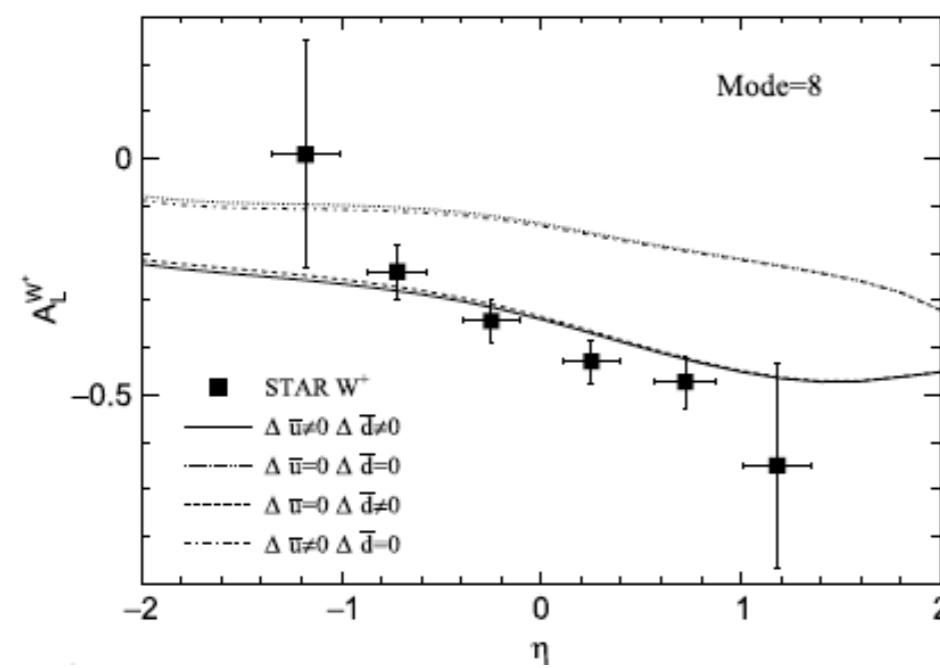
- $\Delta\bar{u}$ is now known to be positive while $\Delta\bar{d}$ is negative, at intermediate Bjorken- x
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized flavor asymmetry $\bar{u} - \bar{d}$

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 $\Delta\bar{d}$

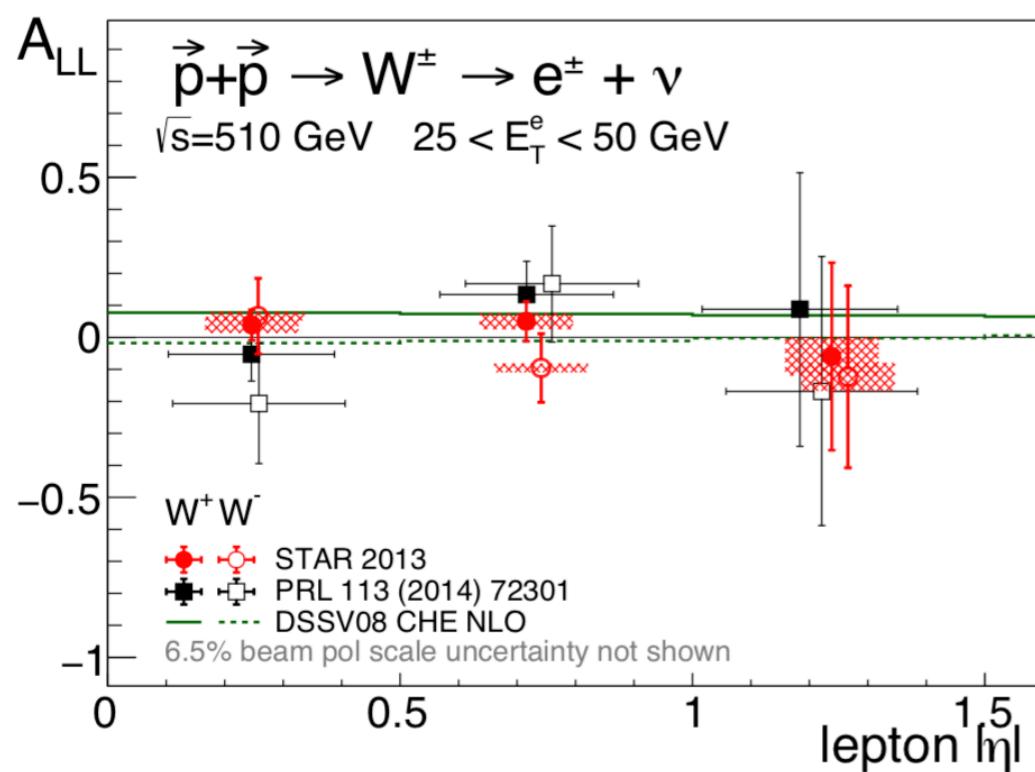
F. Tian *et al.* Nucl.Phys. A961 (2017) 154-168
 M. Liu and B-Q Ma, Phys. Rev. D **98**, 036024



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 $\Delta\bar{u}$, $\Delta\bar{d}$

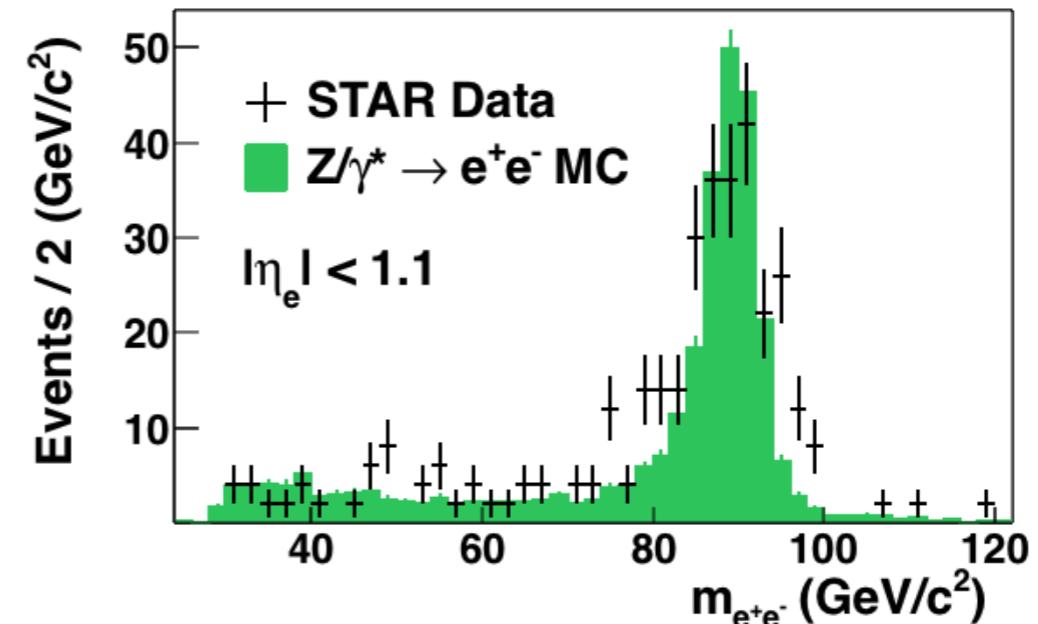
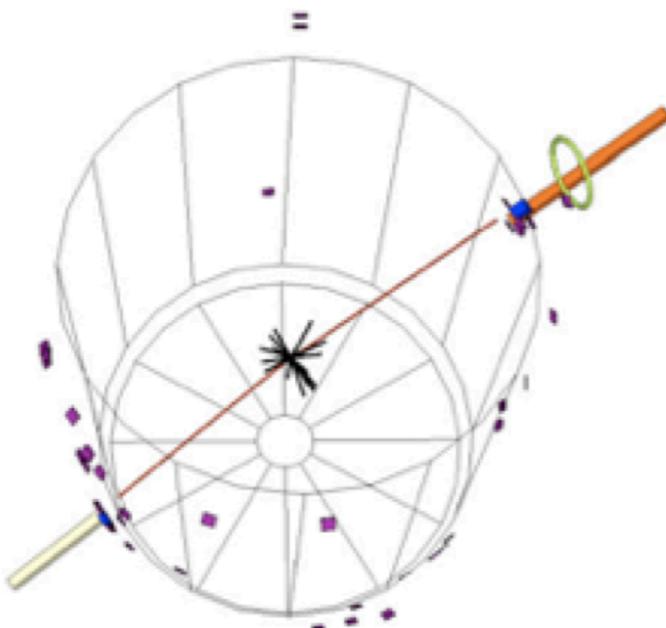
$$A_{LL}^{W^+} \propto \frac{\Delta u}{u} \frac{\Delta \bar{d}}{\bar{d}} \quad A_{LL}^{W^-} \propto \frac{\Delta d}{d} \frac{\Delta \bar{u}}{\bar{u}}$$

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

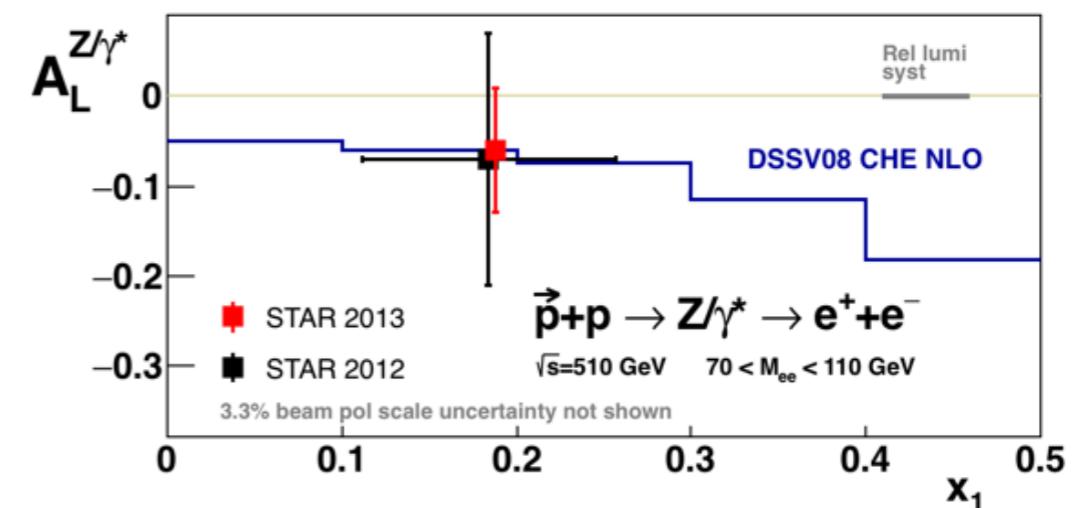
$$1 \pm A_{LL}^\pm(y_W) > |A_L^{W^\pm}(y_W) \pm A_L^{W^\pm}(-y_W)|$$

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

Single-Spin Asymmetry for Z/γ^*



- Z/γ^* can be fully reconstructed
 $Z/\gamma^* \rightarrow e^+e^-$
- $Z/\gamma^* A_L$ 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

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

Thank you for your attention!