Spin Physics Highlights from STAR

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For the STAR Collaboration

ICNFP 2014
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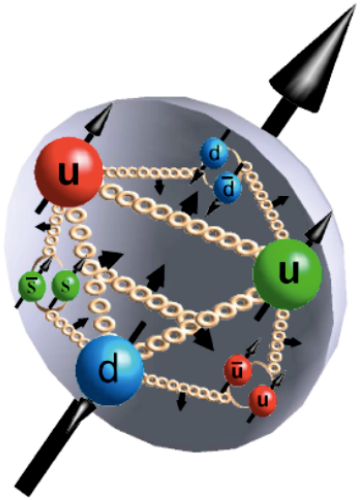
U.S. DEPARTMENT OF ENERGY
Office of Science

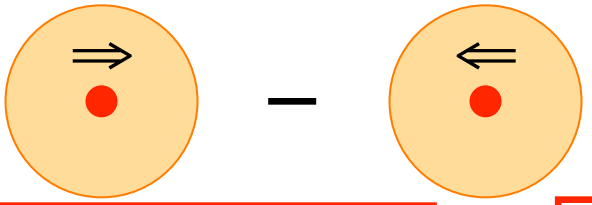
Contributions to the Proton's Spin



Consider proton moving right

Proton spin ⇒

$\Delta q(x)$
$\Delta g(x)$



Longitudinal Polarization

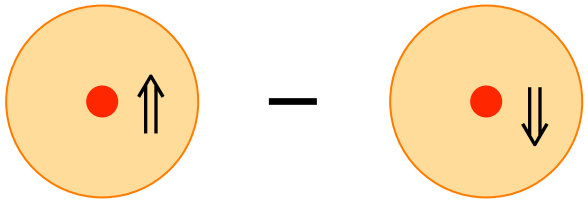
Polarized DIS: ~0.3
Puzzling for ~25 years

Relatively poorly constrained
But S_g coming into focus!

Proton spin sum rule: $\frac{1}{2}\hbar = \frac{1}{2}\sum_q S_q^z + S_g^z + \sum_q L_q^z + L_g^z$

Proton spin ⇑

$\delta q(x)$



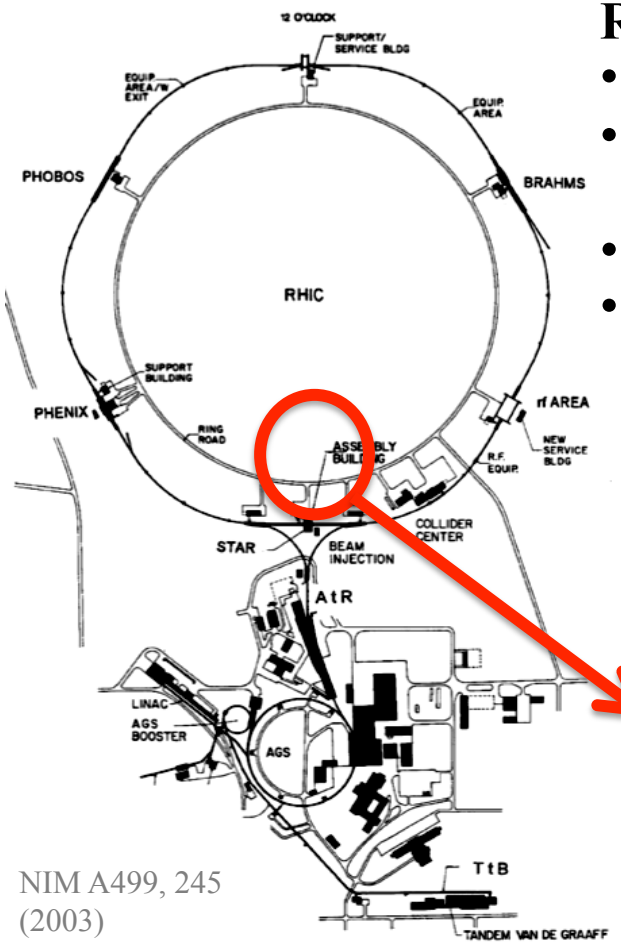
Transverse Polarization

Transversity

Understanding Spin in Proton Collisions at STAR

- Probing Gluon Polarization with Jets and π^0's
- Probing Sea Quark Polarization with W's
- Probing Transverse Structure with Jets and π^0's
  - And with W's, Z's, and other probes
- Looking to the Future

Solenoidal Tracker at RHIC

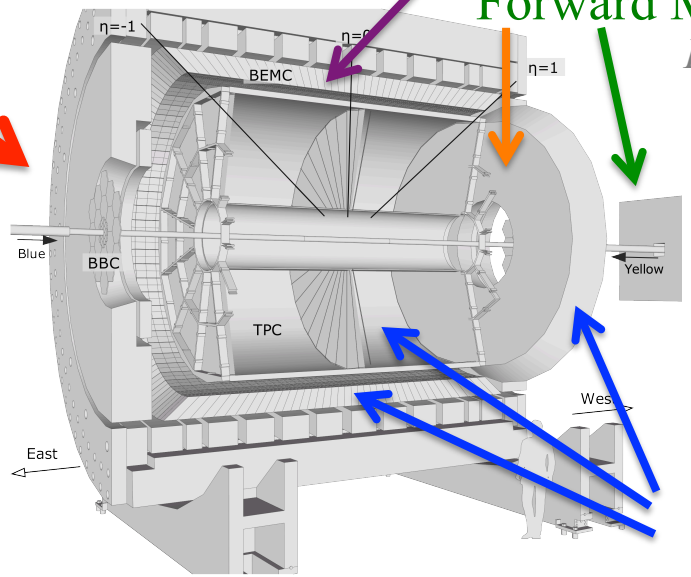


NIM A499, 245 (2003)

RHIC as Spin Collider

- "Siberian Snakes" → mitigate depolarization resonances
- Spin rotators provide choice of spin orientation *independent of experiment*
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Inclusive hadron measurements:
Barrel E/M Calorimeter (BEMC),
Endcap E/M Calorimeter (EEMC),
Forward Meson Spectrometer (FMS)
FPD (east) not shown



Jet and W/Z measurements:
TPC + Barrel + Endcap EMC

Solenoidal Tracker at RHIC

Inclusive hadron measurements:

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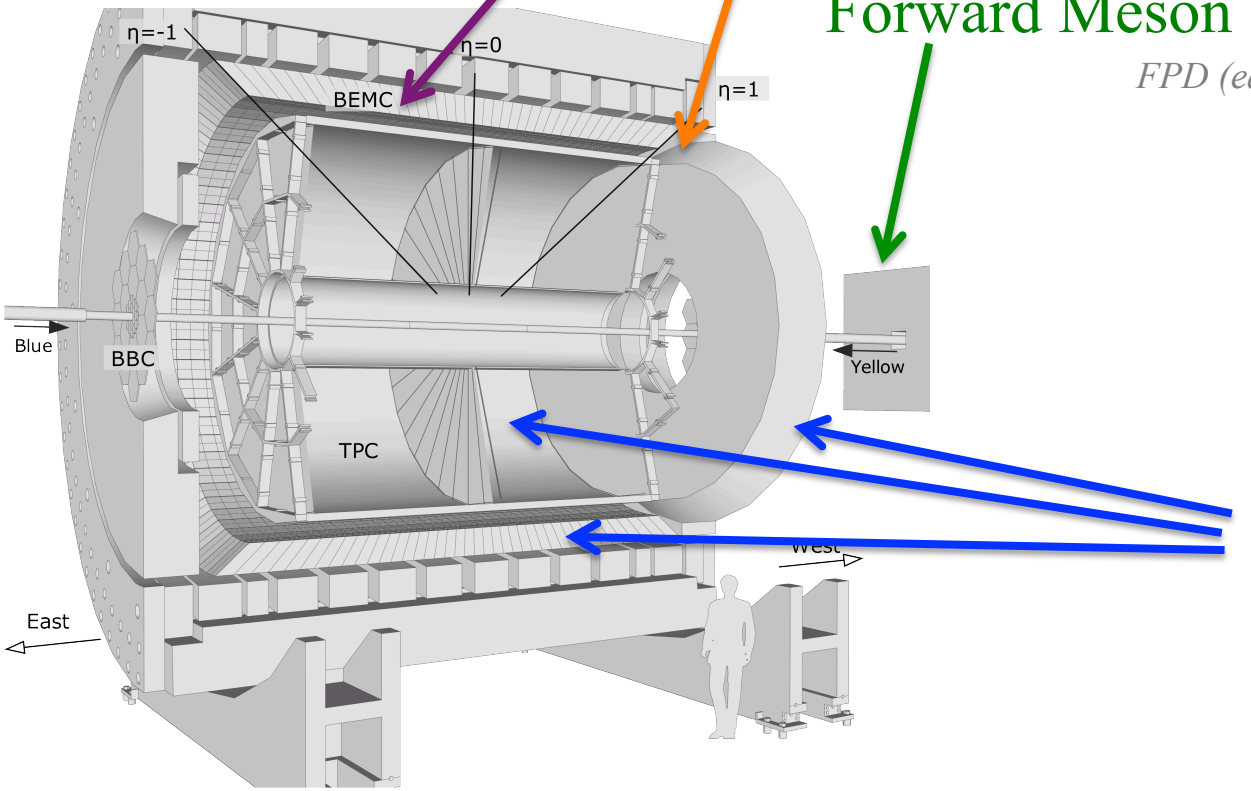


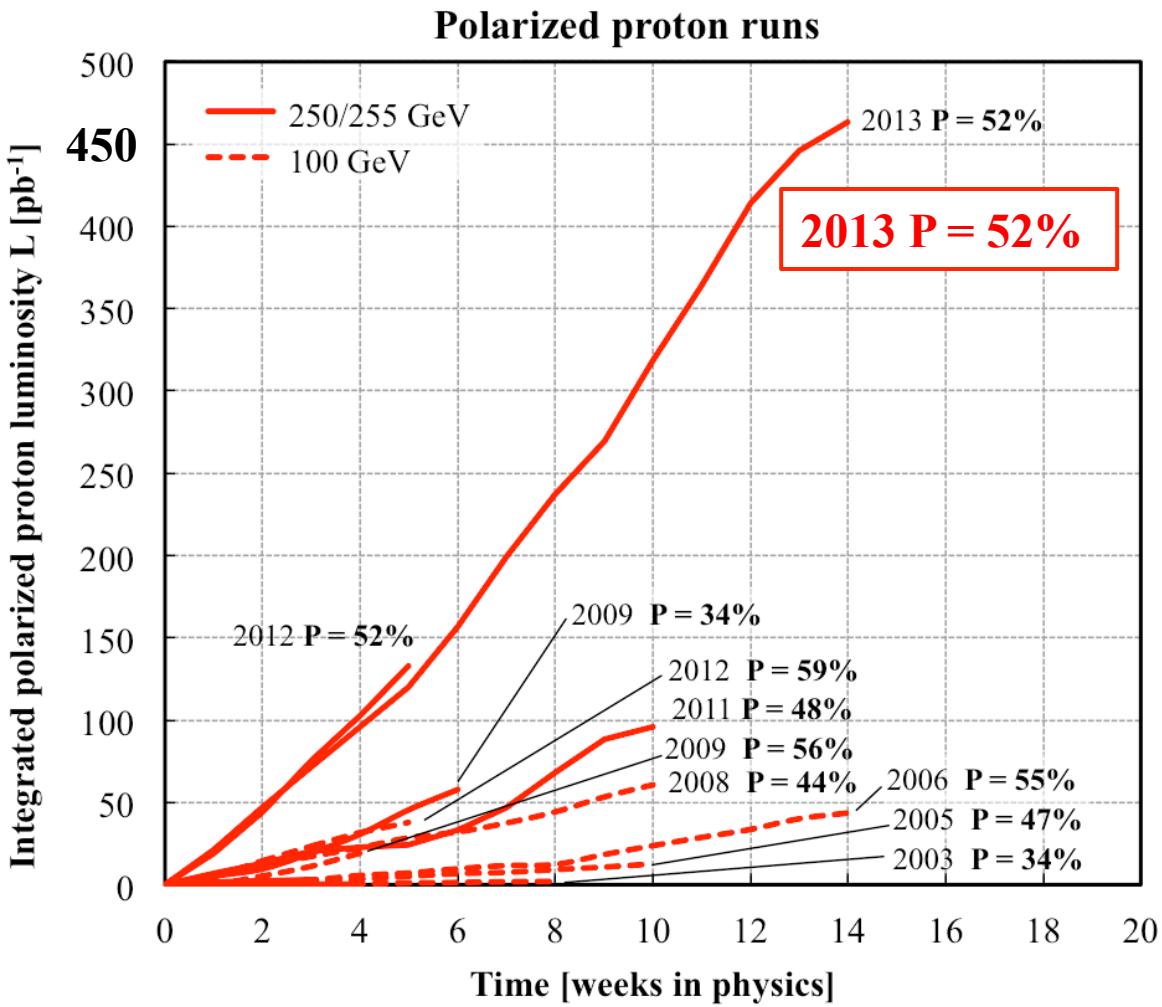
Jet and W/Z measurements:

TPC +

Barrel + Endcap EMC

Datasets from RHIC at STAR

- Many published results from 2006, 2009 datasets
  - And W's more recently
- Preliminary results and work in progress from, especially
  - 2011 500 GeV trans.
  - 2012 200 GeV trans.
  - ***Large*** 510 GeV long. datasets in 2012 and 2013



Understanding Spin in Proton Collisions at STAR

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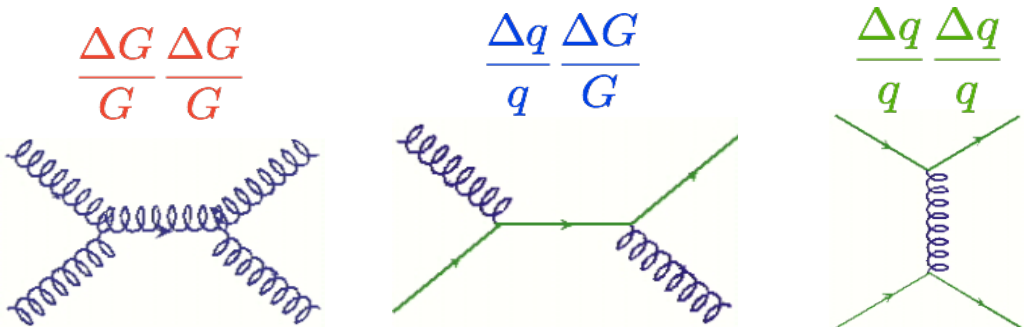
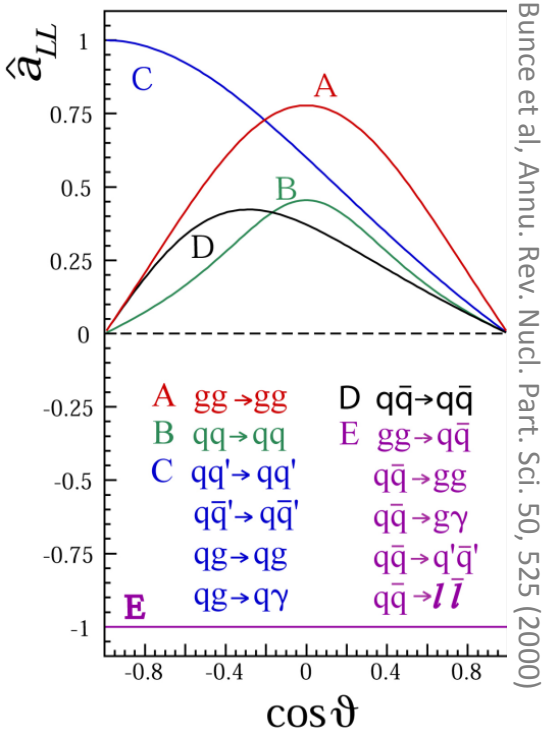
Probing (Gluon) Polarized PDF's With Jets

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

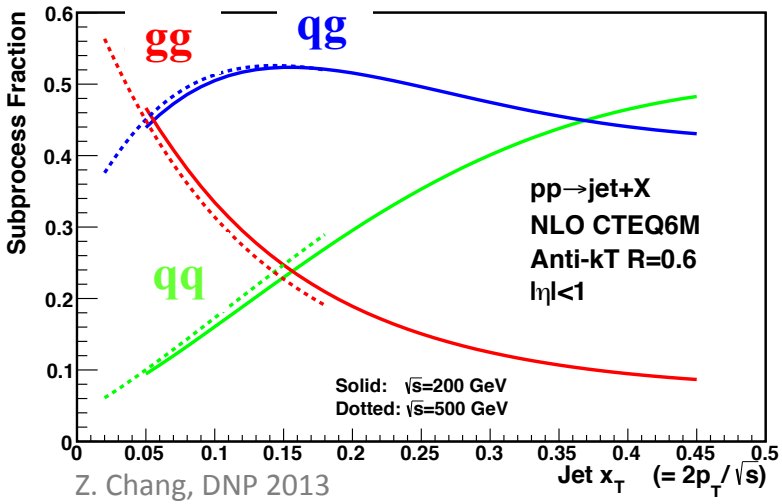
A_{LL} for, e.g. jets, sensitive to ***polarized PDF's*** (Δf) and ***partonic asymmetry***, $\hat{a}_{LL}$





Asymmetries at different values of p_T or $\sqrt{s}$

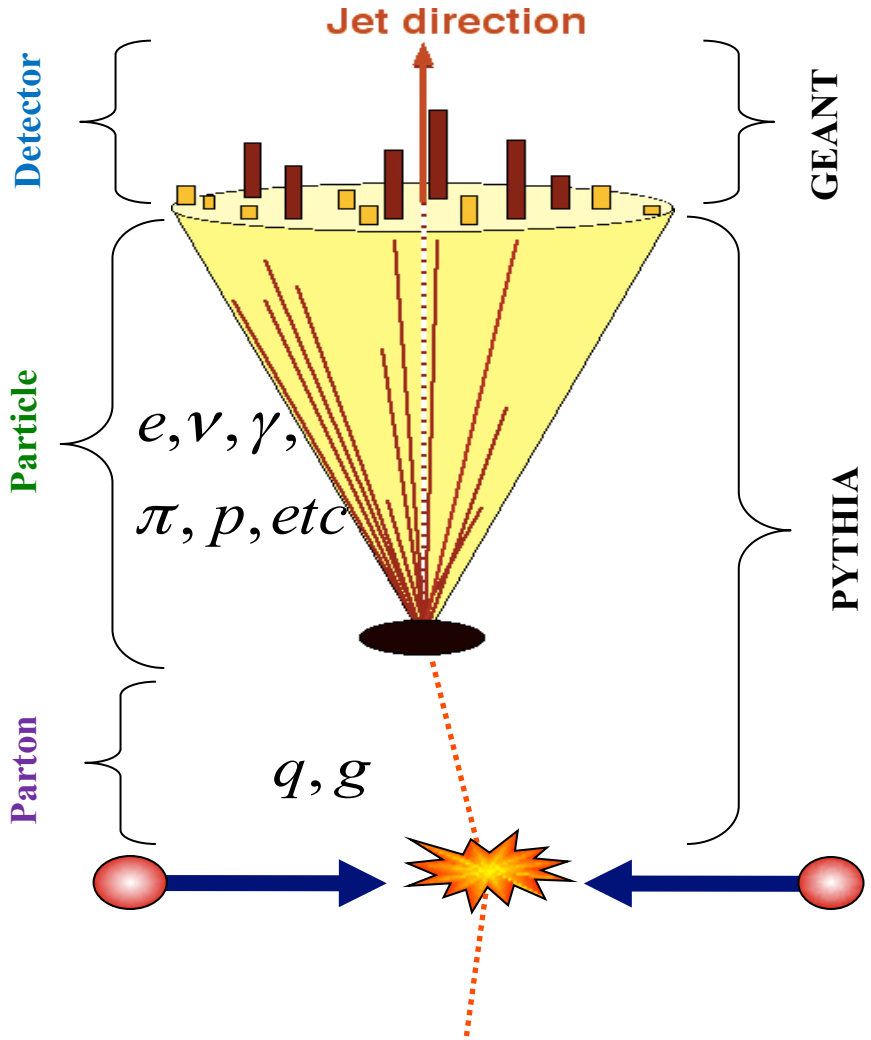
→ ***sample different mix of partonic subprocesses***



Jet Reconstruction

Jet Levels

MC Jets



STAR Detector has:

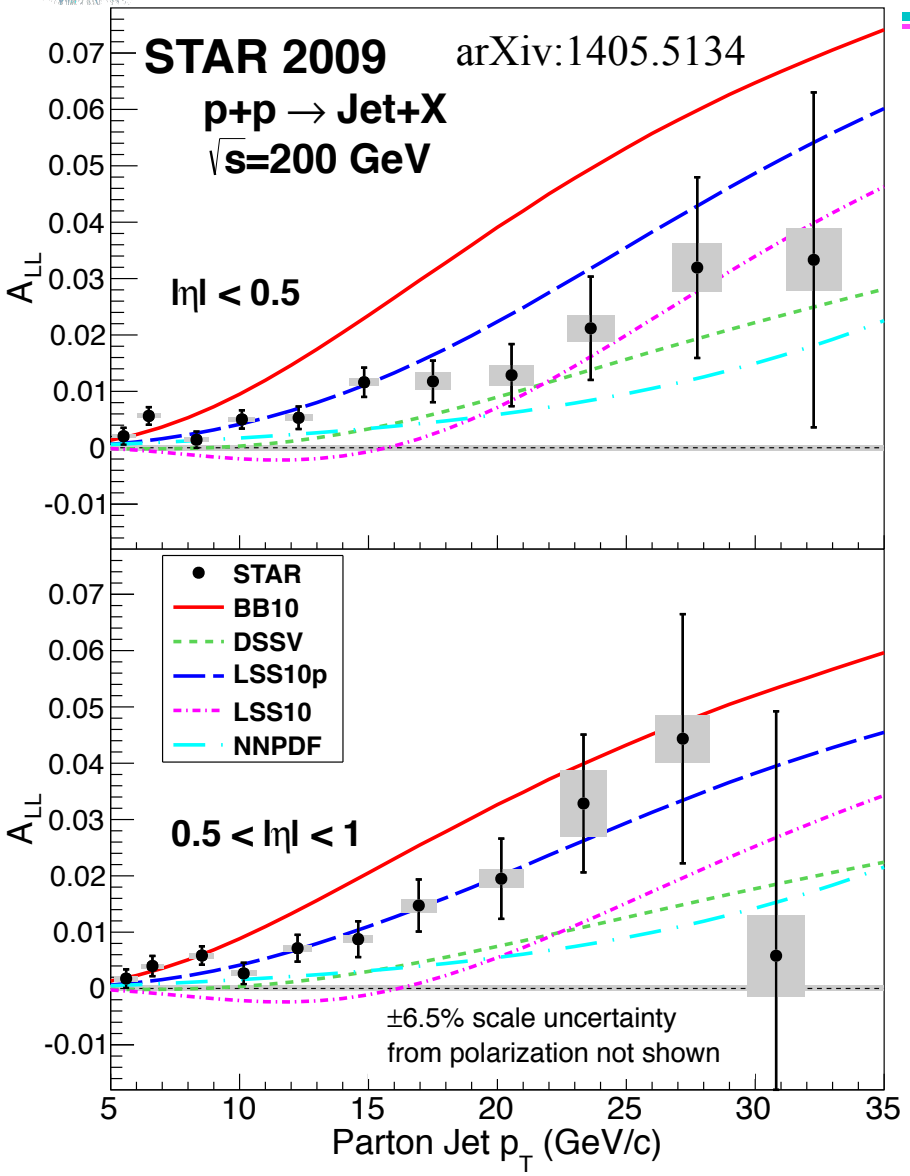
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-K_T Jet Algorithm:

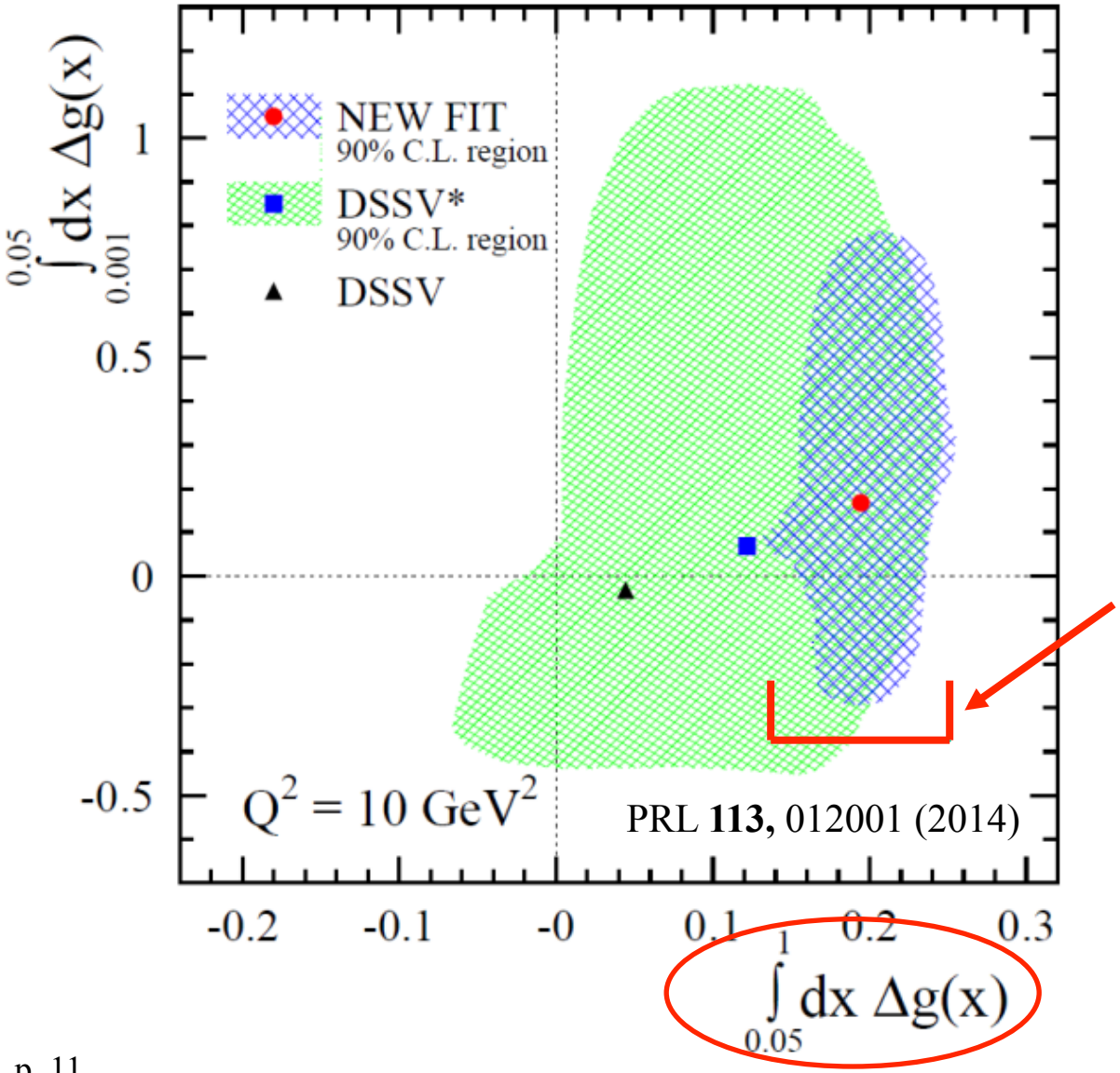
- Radius = 0.6
- Used in both data and simulation

2009 Inclusive Jet A_{LL}



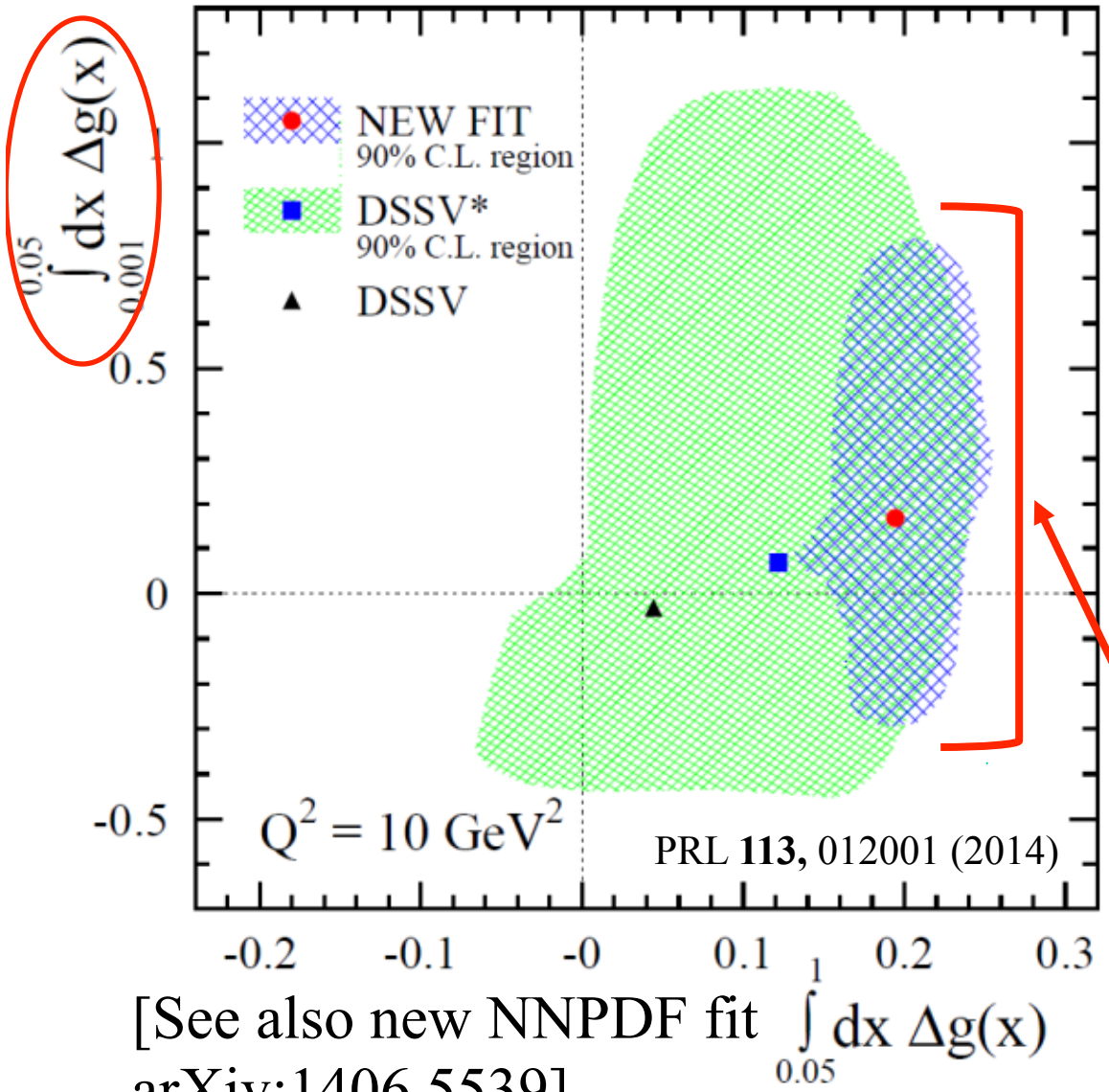
- 2009 results have factor of 3 to 4 better statistical precision than 2006 results
- Result divided into two pseudorapidity ranges which emphasize different partonic kinematics
- Result lies consistently above the 2008 DSSV fit

New DSSV Fit and Results



- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- **First firm evidence of non-zero gluon polarization!**

New DSSV Fit Results

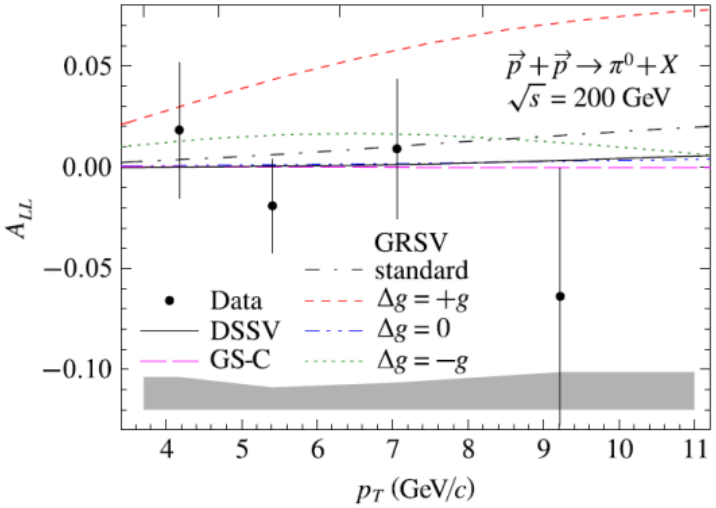


- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable

[See also new NNPDF fit arXiv:1406.5539]

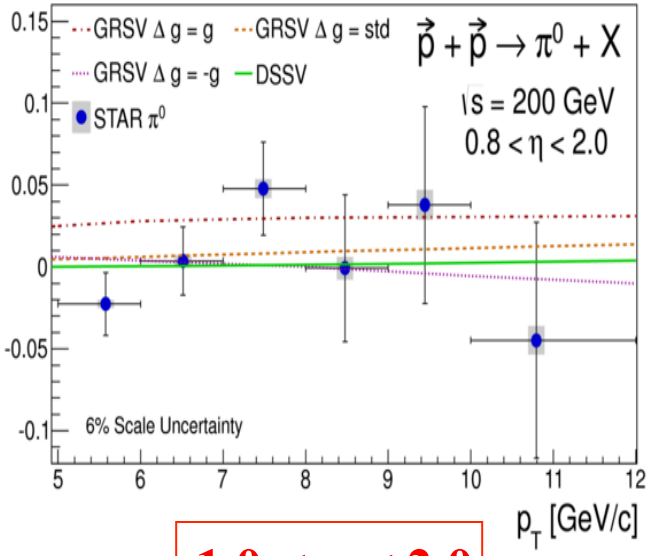
Probing Low *x* Gluons With π^0 A_{LL}

PRD 80, 111108(R) (2009)



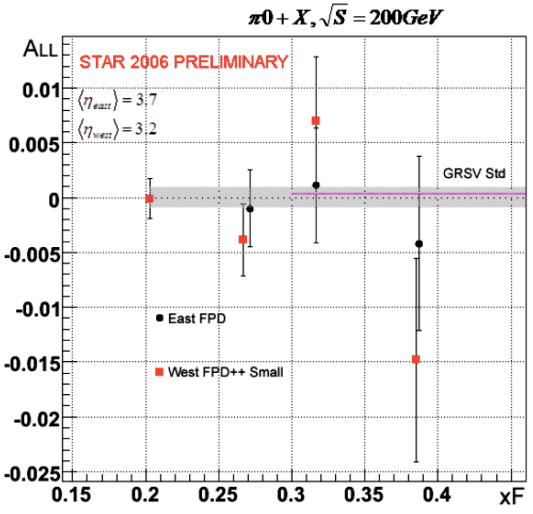
$|\eta| < 0.95$

PRD 89, 012001 (2014)



$1.0 < \eta < 2.0$

Wissink SPIN2008

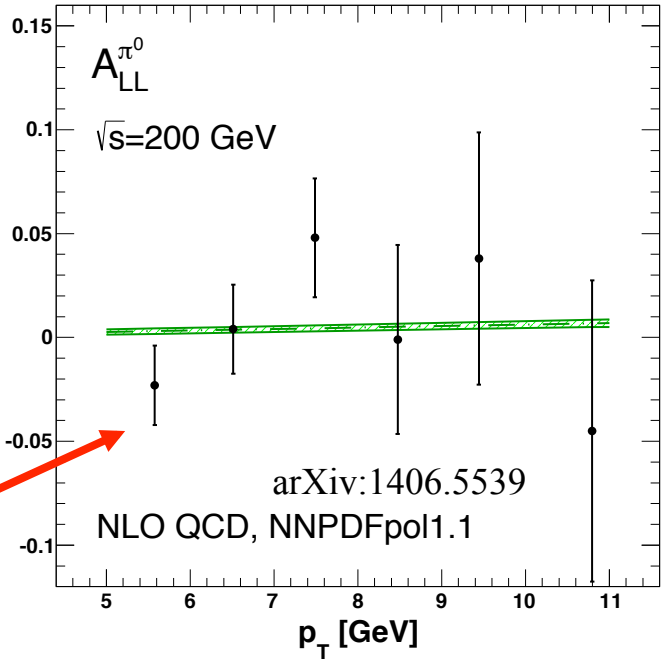


$\eta = 3.2, 3.7$

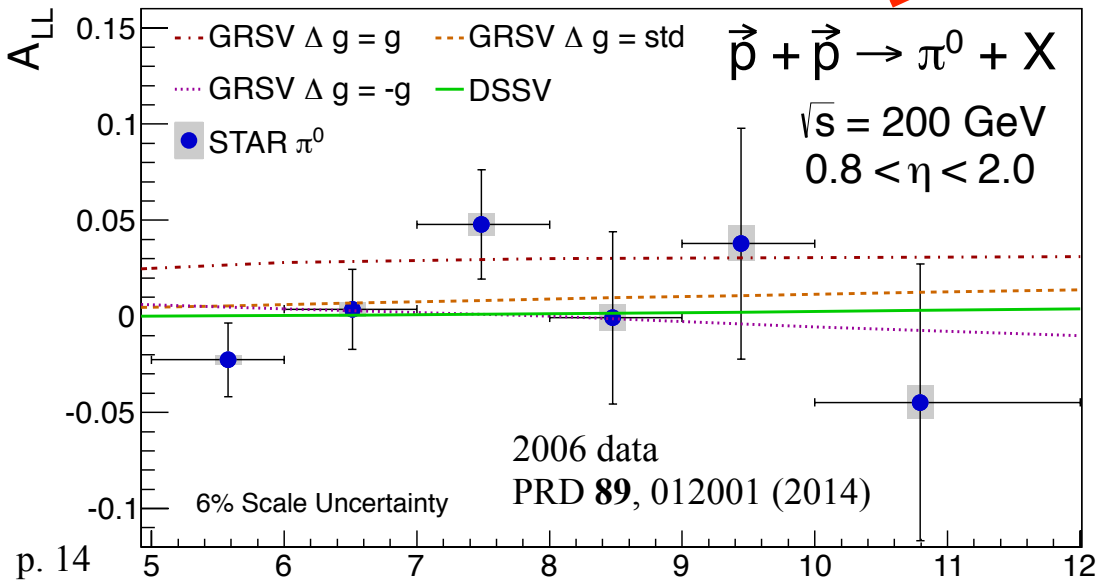
- STAR has measured π^0 A_{LL} in three different pseudorapidity ranges
  - Different kinematics, different fragmentation, different systematics
  - Here with data from 2006
- qg scattering dominates at high η with high *x* quarks and low *x* gluons
- **No large asymmetries seen**

Updated Prediction for π^0 A_{LL}

- NNPDFpol1.1 includes jet results from STAR and PHENIX, including the recently submitted 2009 STAR inclusive jets
- Greater precision needed to constrain the fit

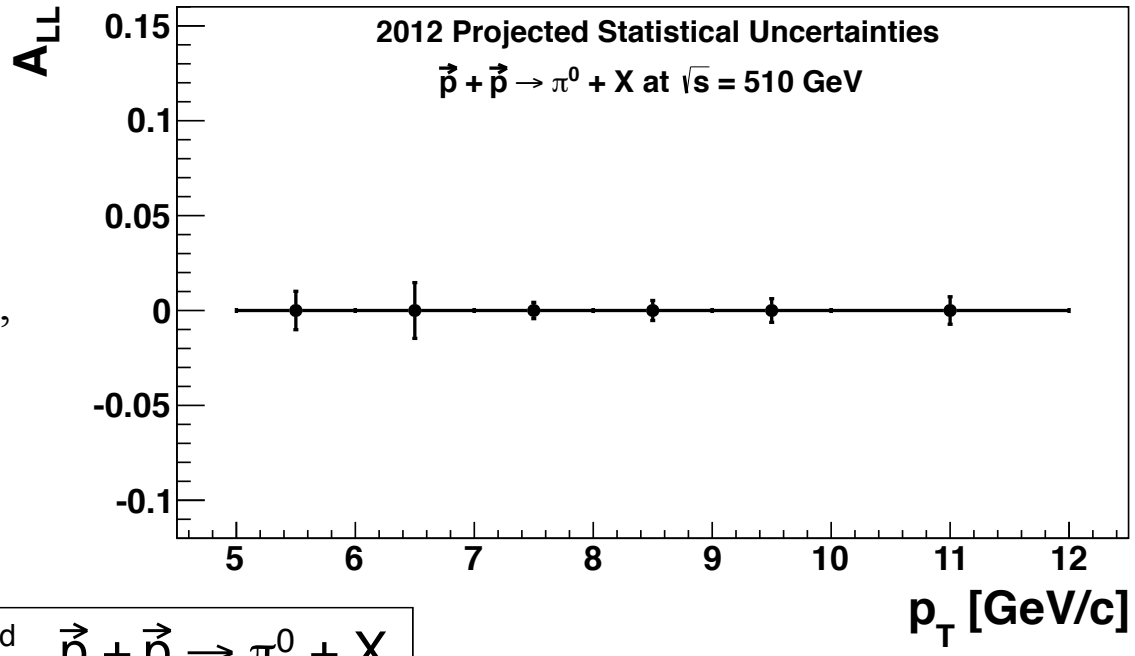


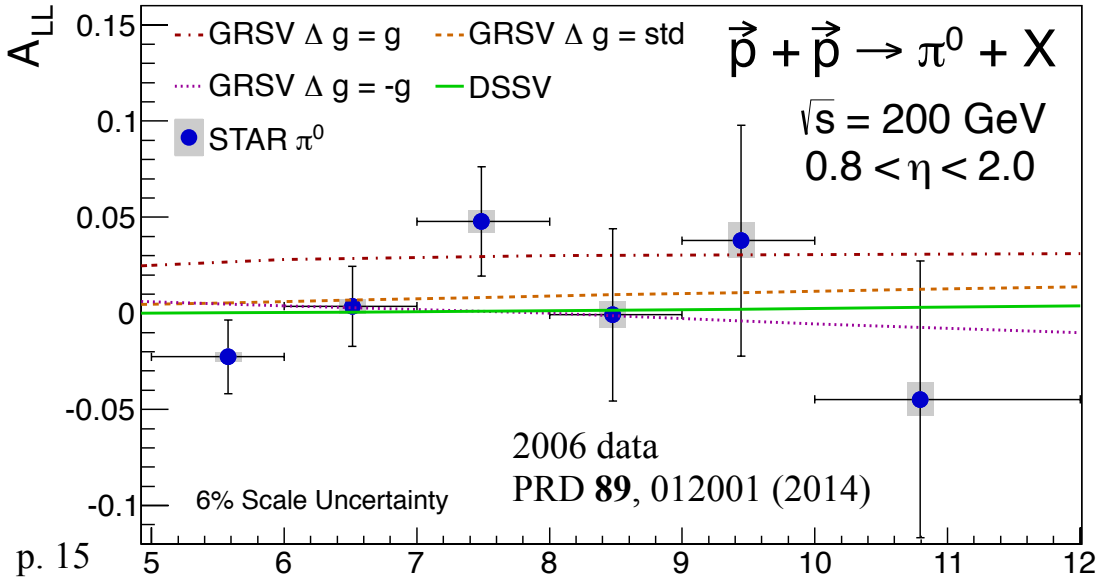
STAR data with NNPDF predictions



π^0 A_{LL} Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 luminosity) at intermediate pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown
- And with 2012 and 2013 datasets at forward pseudorapidity





- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower *x* gluon

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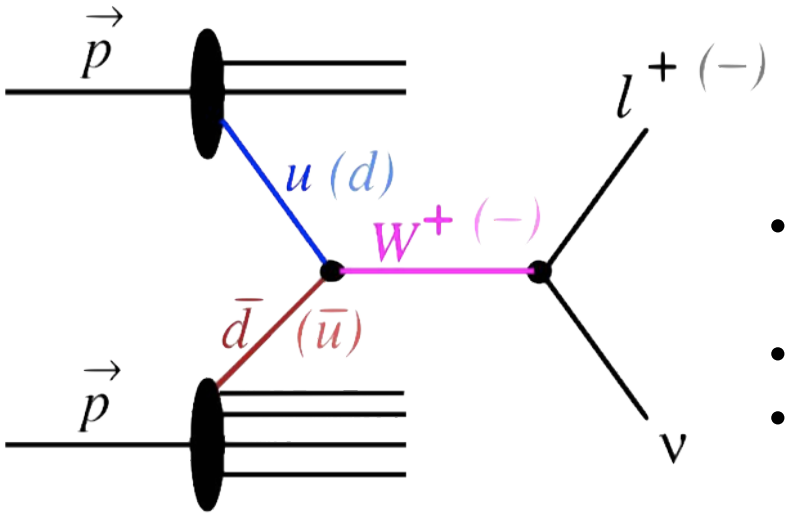
Probing Sea Quark Polarizations With W's



$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$

$$d + \bar{u} \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

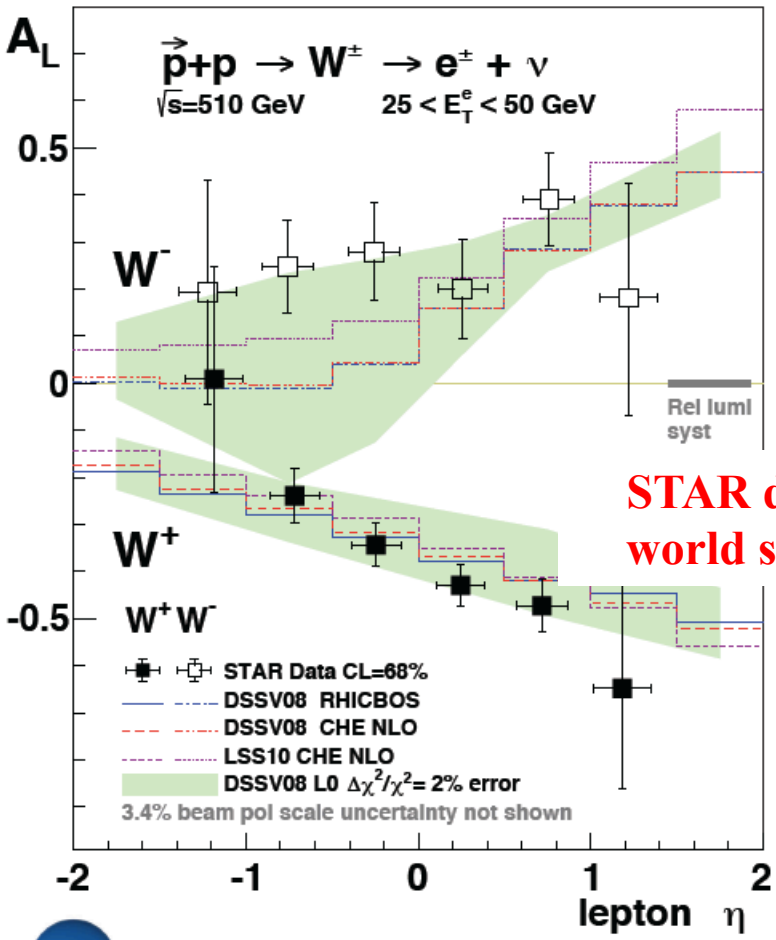
- W's couple directly to the quarks and antiquarks of interest
- Detect W's through e^+/e^- decay channels
- Longitudinally, excellent probes of sea quark polarizations
- Also an important probe of transverse physics

Measure parity-violating single-spin asymmetry:

(Helicity flip in one beam while averaging over the other)

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Results from 2012 W's



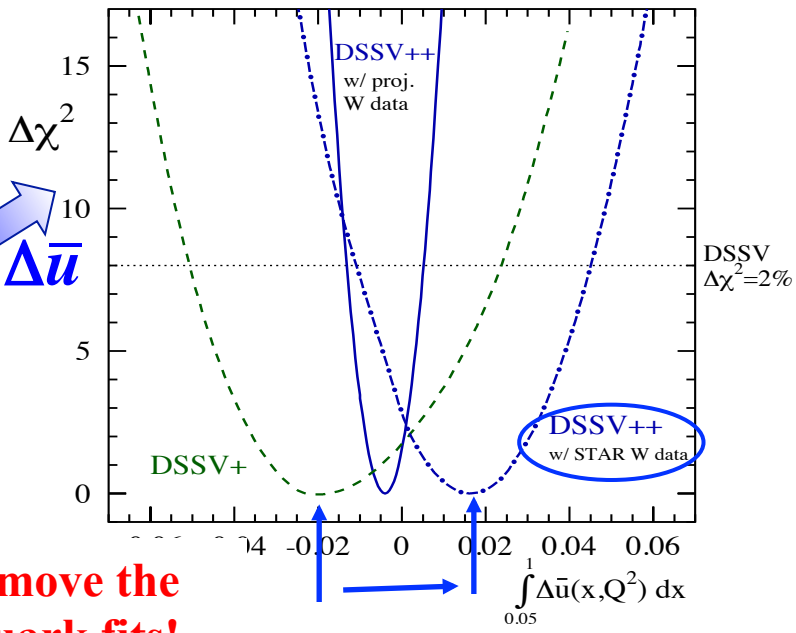
NEW arXiv:1404.6880 [Accepted by PRL]

[See also new NNPDF fit arXiv:1406.5539]

DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj. (2009-2013)

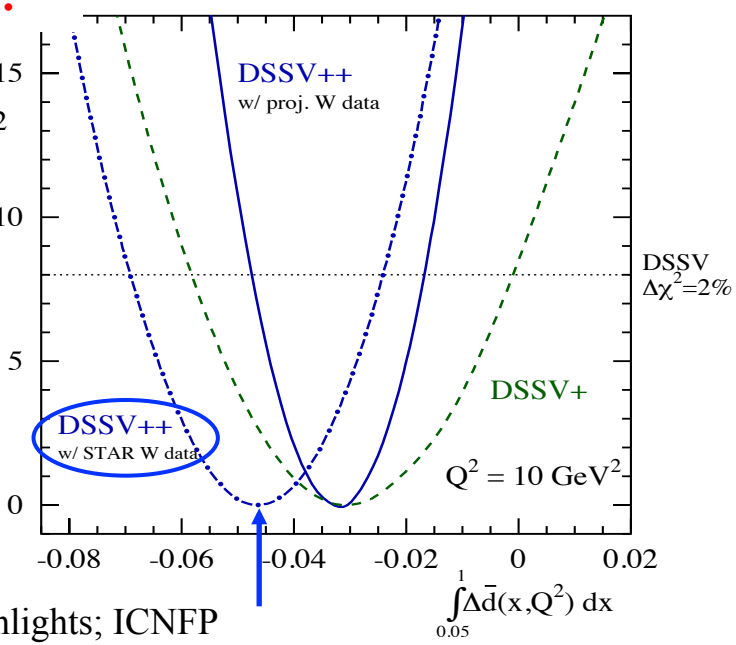
arXiv:nucl-ex/1304.0079

$\Delta\bar{u}$



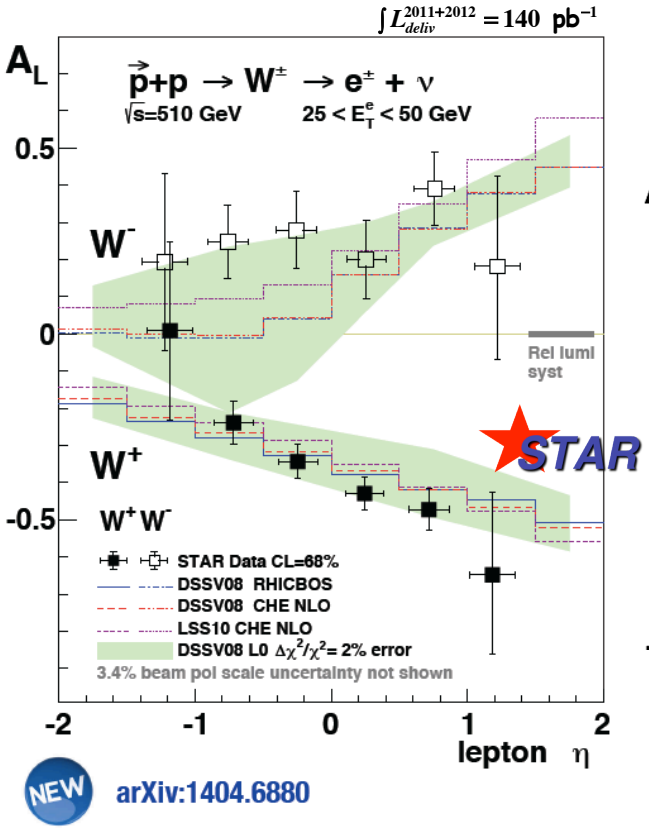
STAR data move the world sea quark fits!

$\Delta\bar{d}$



W Projections

2011-2012 Results



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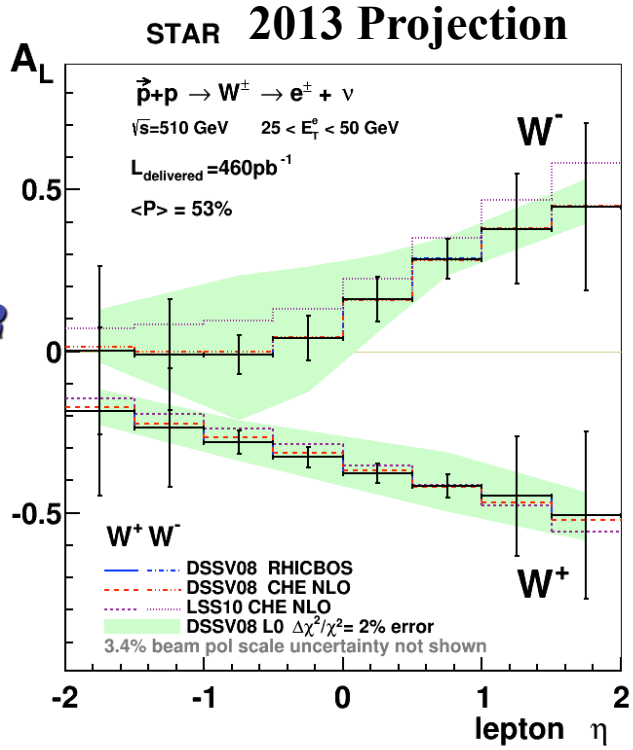

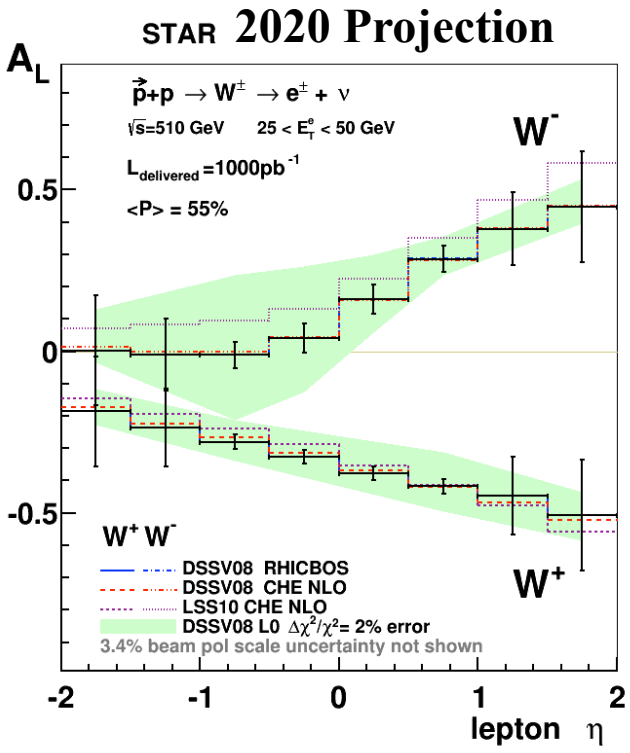

Includes **F**orward **G**EM **T**racker at STAR, fully installed in 2013

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Puzzle of Large Transverse Spin Asymmetries, A_N

- Anomalously large A_N observed for nearly 40 years
  - In naïve, co-linear, leading-order/leading-twist QCD expect very small A_N, especially at high sqrt(s)

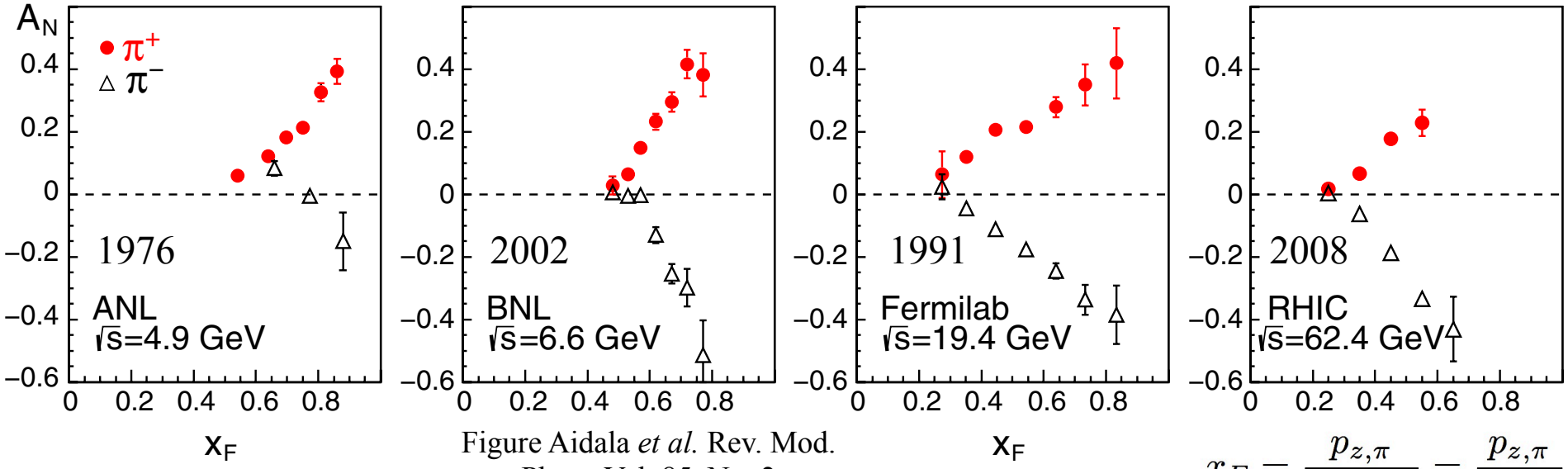
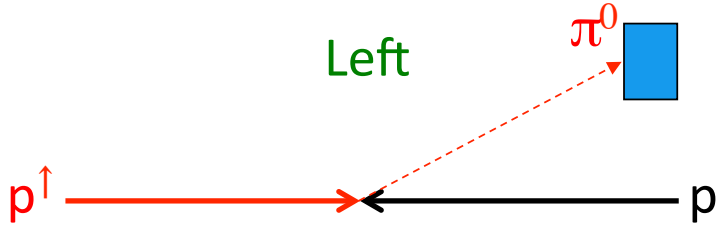


Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

$$x_F = \frac{p_{z,\pi}}{p_{z,\max}} = \frac{p_{z,\pi}}{\sqrt{s}/2}$$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$d\sigma^{\uparrow(\downarrow)}$ – cross section for leftward scattering when beam polarization is spin-up(down)

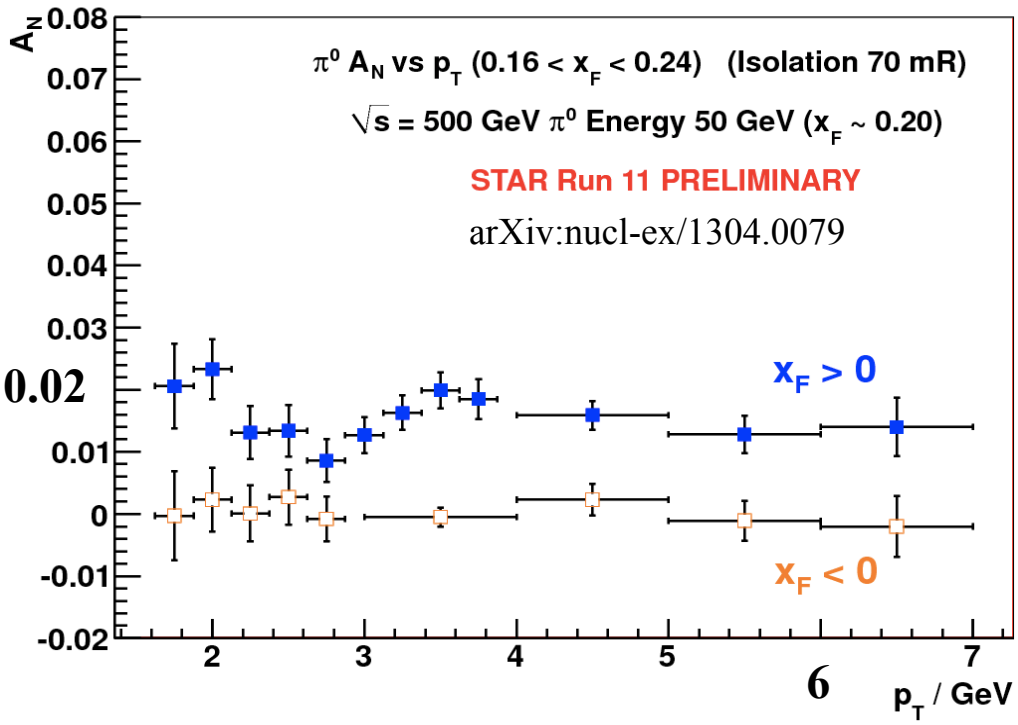


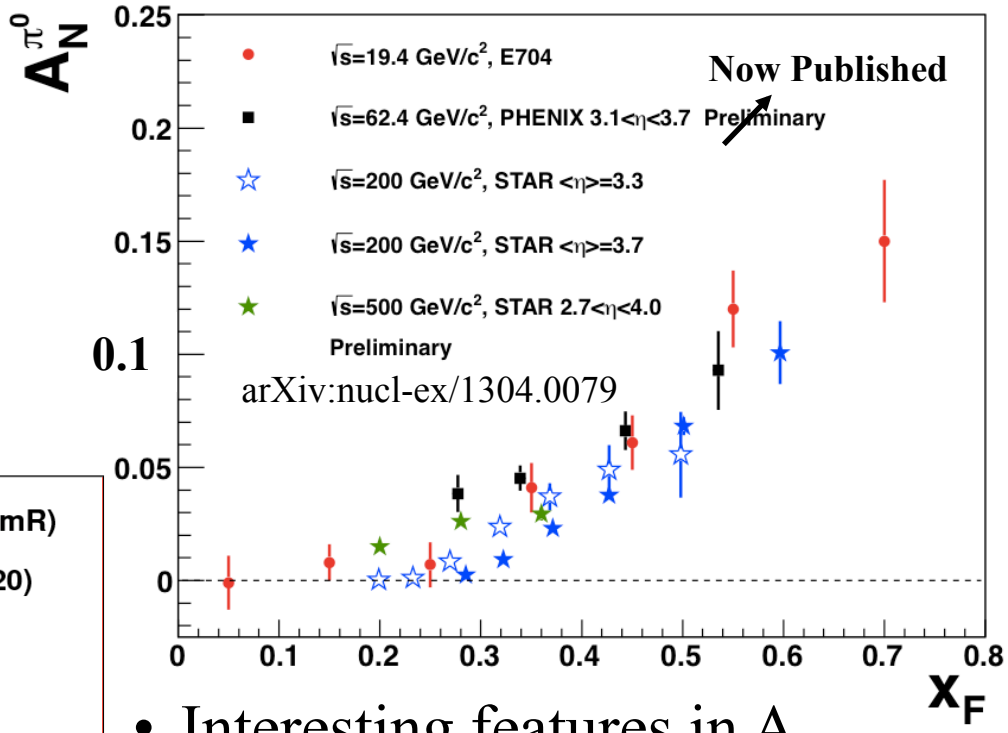
Positive A_N – more π^0 to ***left*** of (up) polarized beam

For a 2π detector, A_N manifests as an azimuthal (ϕ) asymmetry

Puzzle of Large Transverse Spin Asymmetries, A_N

- Persists at STAR/RHIC
  - At forward pseudorapidity
  - At high x_F



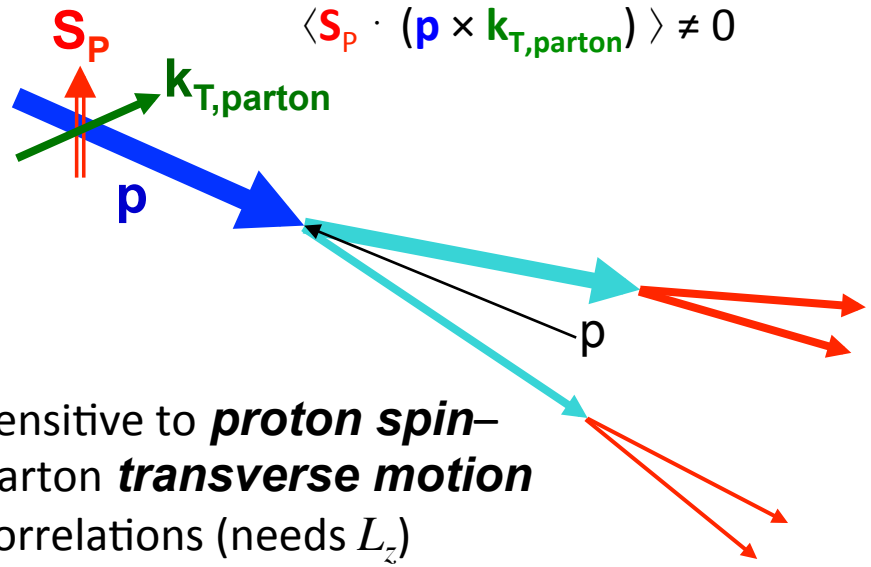


- Interesting features in A_N
  - –Persists to surprisingly large p_T
  - –Larger in η's than π^0's?
  - –In relatively isolated π^0's, not in jets
  - –Smaller when there's central activity

Mechanisms for Transverse Single-spin Asymmetries

Sivers mechanism: asymmetry in the forward jet or γ *production*

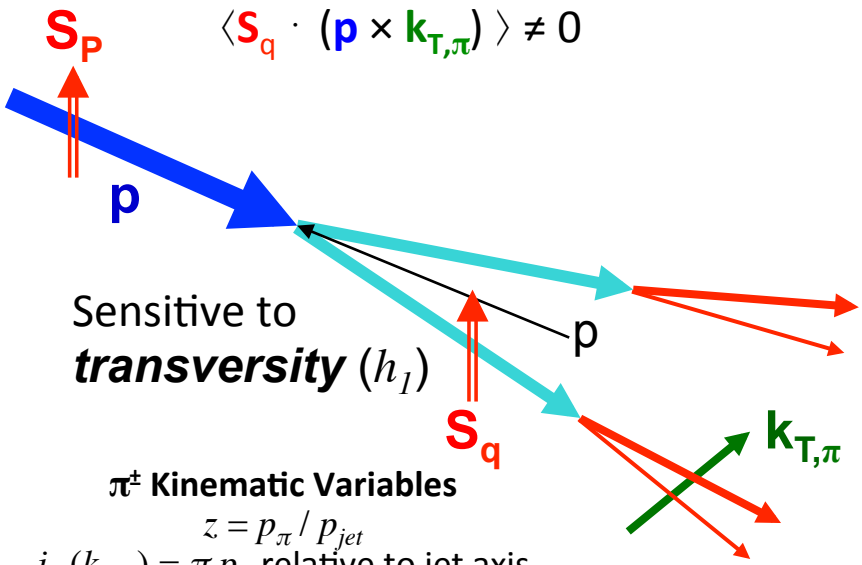
D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)



Sensitive to ***proton spin–*** parton ***transverse motion*** correlations (needs L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

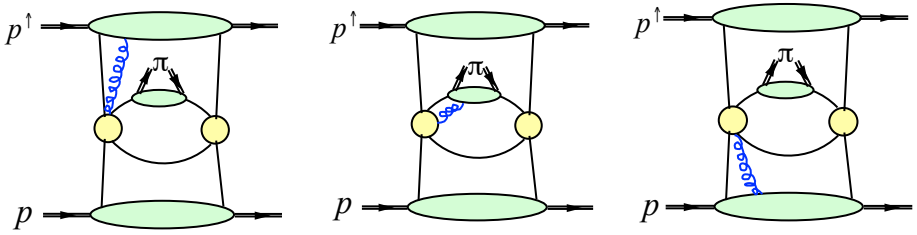
J. Collins, NP B396, 161 (1993)



$\pi^{\pm}$ Kinematic Variables

$z = p_\pi / p_{jet}$

$j_T\,(k_{T,\pi}) = \pi\, p_T$ relative to jet axis



Y. Koike, RSC Discussion (2004)

Twist-3 mechanism: Asymmetry from multi-parton correlation functions

e.g. Qiu and Sterman, PRL 67, 2264 (1991); PRD 59, 014004 (1998)

Correlators closely related to k_T moments of TMD's

Boer, Mulders, Pijlman, NPB 667, 201 (2003)

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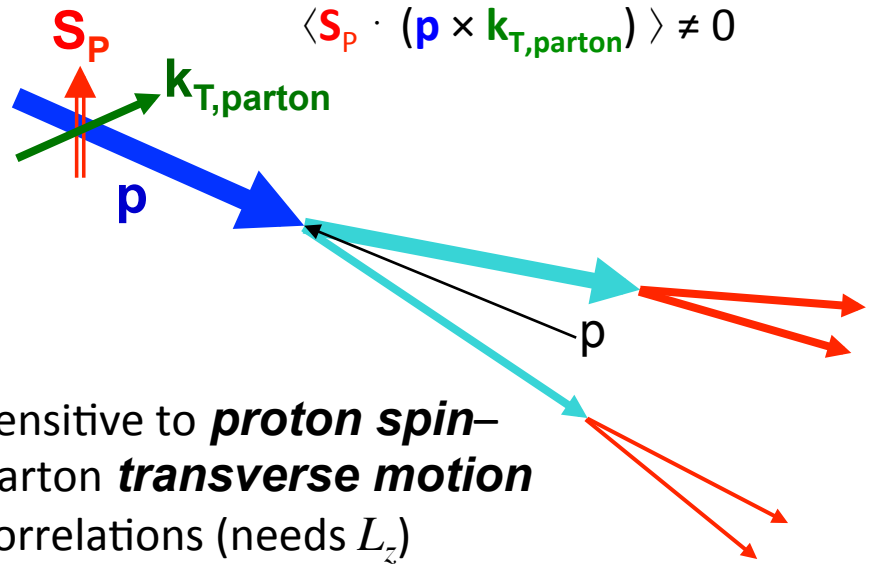

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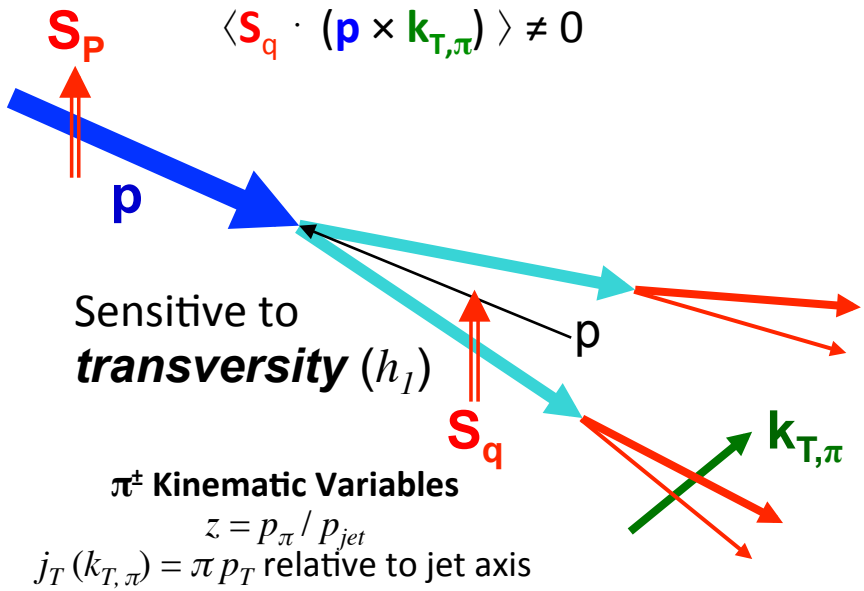

$\pi^{\pm}$ Kinematic Variables

$z = p_\pi / p_{jet}$

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Inclusive hadron asymmetries:

Unable to islolate contributions

Sivers, Collins, twist-3 ~ $\sin(\phi_S)$

ϕ_S—angle between spin and event plane

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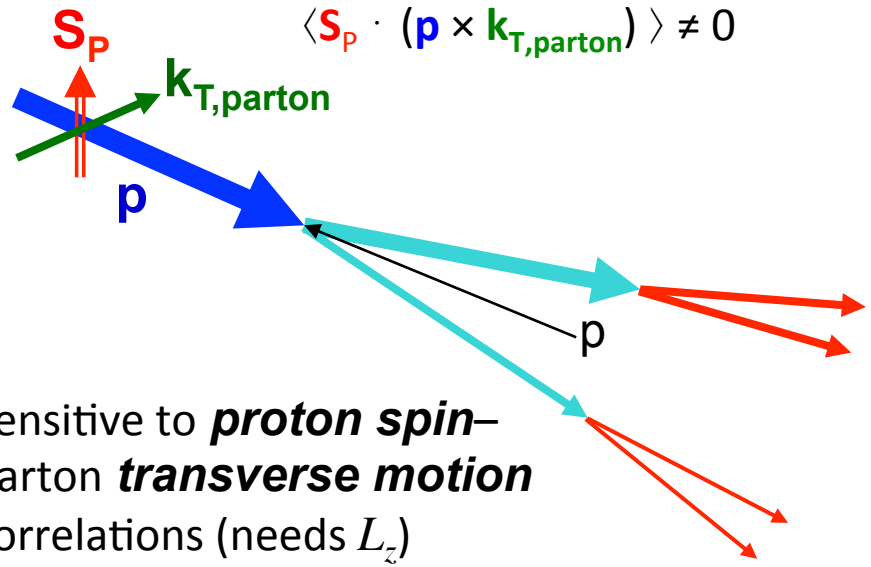
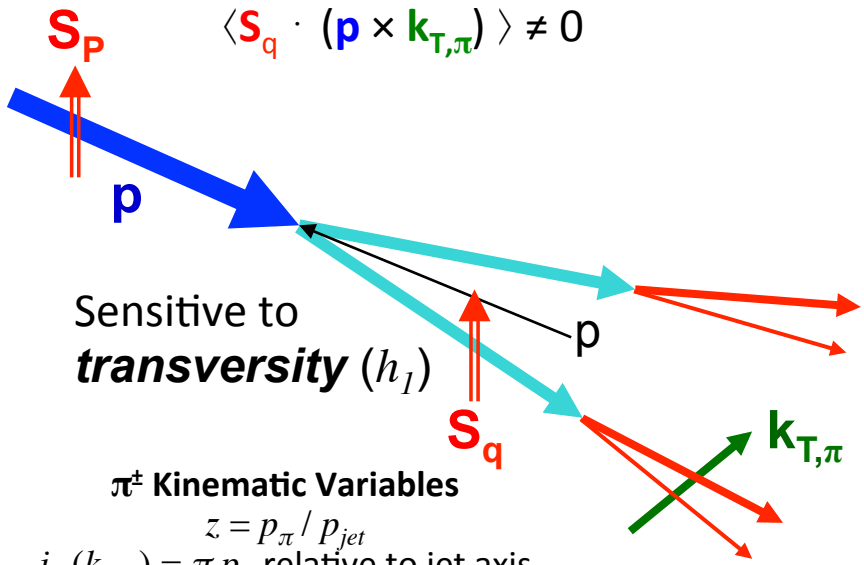
D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)



Sensitive to ***proton spin***–parton ***transverse motion*** correlations (needs L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

J. Collins, NP B396, 161 (1993)



$\pi^{\pm}$ Kinematic Variables

$z = p_\pi / p_{jet}$

$j_T\,(k_{T,\pi}) = \pi\, p_T$ relative to jet axis

Separate Sivers and Collins:

Go beyond inclusive production - *e.g. Jets, correlations, direct photons*

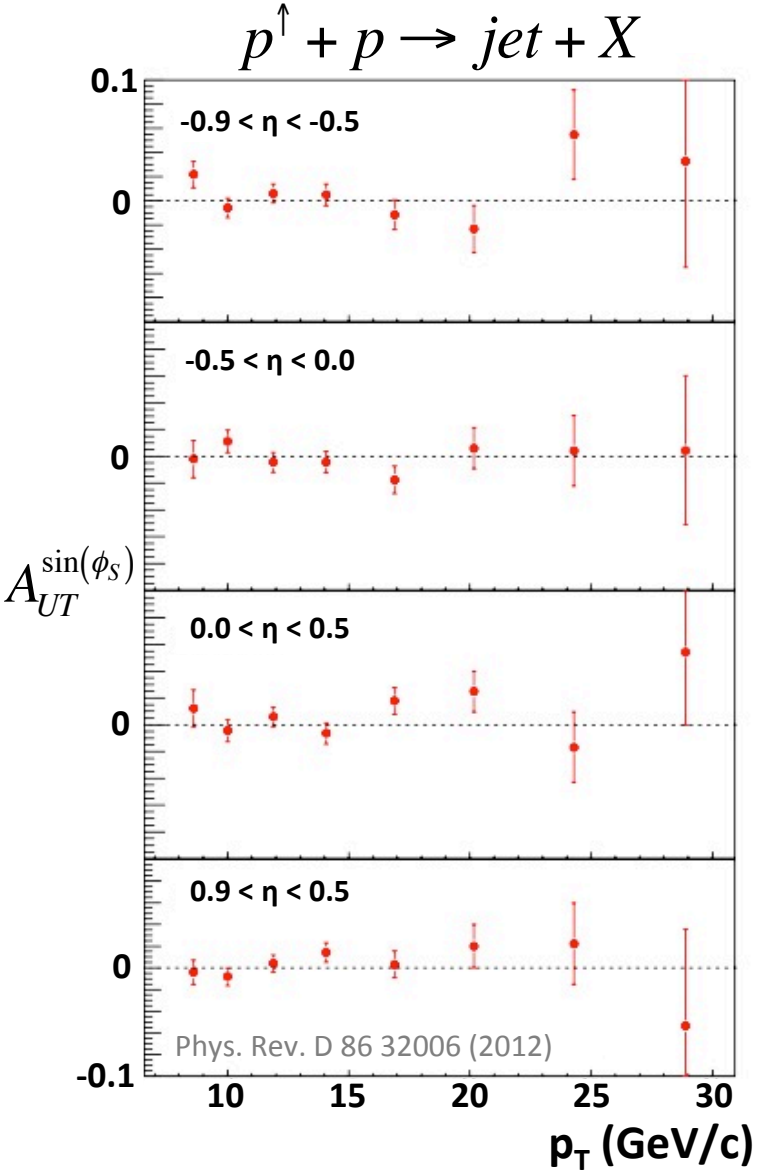
Sivers $\sim \sin(\phi_S)$

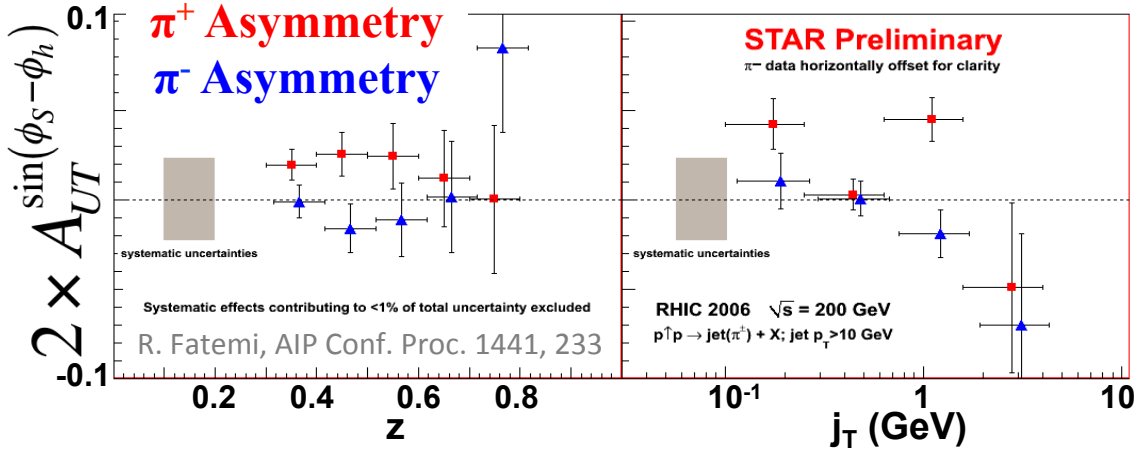
ϕ_S—*angle between spin and event plane*

Collins $\sim \sin(\phi_S - \phi_h)$

ϕ_h—*angle of hadron around jet axis*

Sivers and Collins Analyses for Jets at 200 GeV





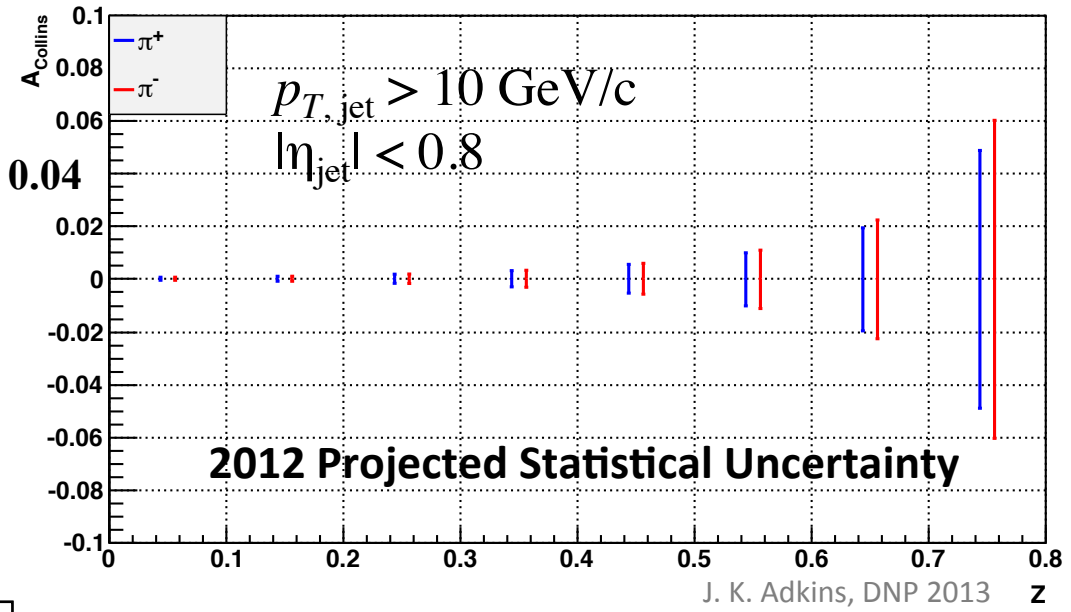
STAR measured transverse single-spin asymmetries for inclusive jet production at central pseudorapidity and $\sqrt{s} = 200$ GeV (2006)

$A_{UT}^{\sin(\phi_S)}$: consistent with zero

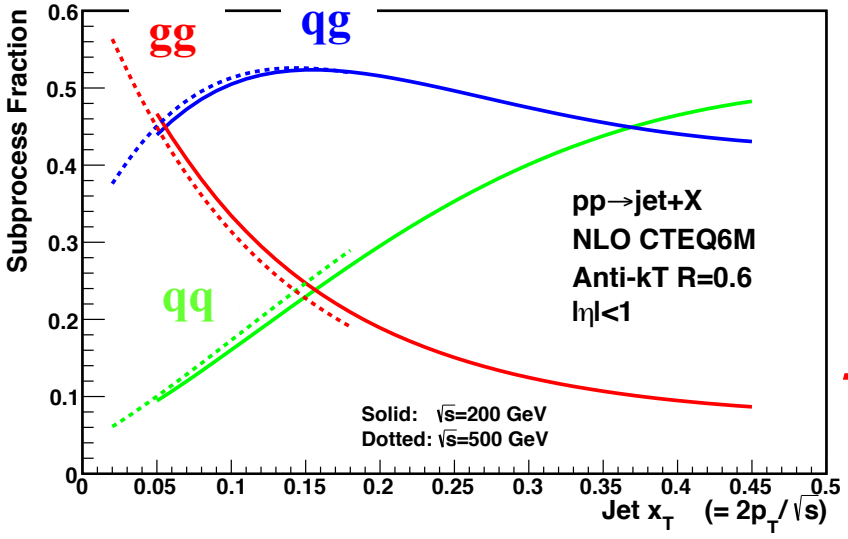
$A_{UT}^{\sin(\phi_S - \phi_h)}$: hints of non-zero asymmetry with charge-sign dependence

Prospects for Sivers and Collins Jet Analyses

2012 STAR data provide opportunity for ***higher precision*** *and* ***greatly reduced systematic uncertainties*** *at* $\sqrt{s} = 200$ *GeV* ***analysis well underway***



J. K. Adkins, DNP 2013



2011 STAR data provide opportunity for first measurements of **central pseudorapidity inclusive jet asymmetries at** $\sqrt{s} = 500$ **GeV**

→ ***Increased sensitivity to gluonic subprocesses***

No sign of large asymmetry in preliminary results – consistent with 200 GeV and also with theoretical expectations.

Understanding Spin in Proton Collisions at STAR

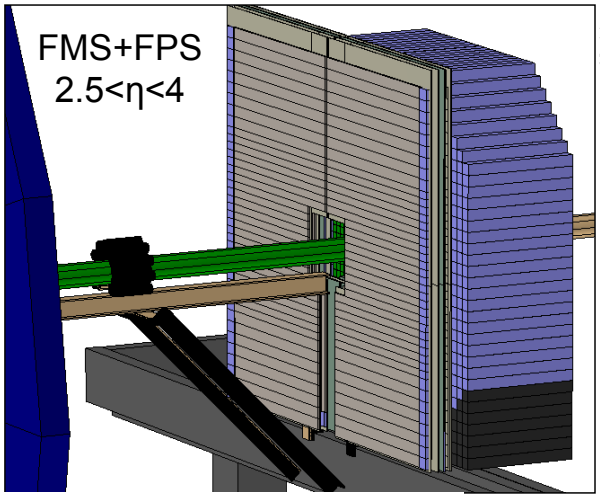
- Probing Gluon Polarizations with Jets and π^0's
- Probing Sea Quark Polarization with W's
- Probing Transverse Structure with Jets and π^0's
  - And with W's, Z's, and other probes
- Looking to the Future

Sivers Function and Sign Change Prospects at STAR with W, Z, Drell-Yan

- A_N in Drell-Yan, W/Z production at RHIC provide excellent complement to SIDIS
  - Attractive from a theoretical perspective (no frag. func. needed as for π^0's, etc.)
  - Sivers function "famously" changes sign when comparing with transverse asymmetries from SIDIS
    - Collins, J. C., 2002, Phys. Lett. B 536, 43
  - Direct photon sign change as well
  - Probe wide range of Q^2
  - Test the universality and factorization of TMD's, constrain their evolution – important tests of QCD
  - **Major targets for 2015-2016**

- FMS (forward EM calorimetry) Preshower Upgrade in 2015
  - Allows separation among photons, π^0's, charged hadrons, and electrons
  - Supports direct photon and DY measurements

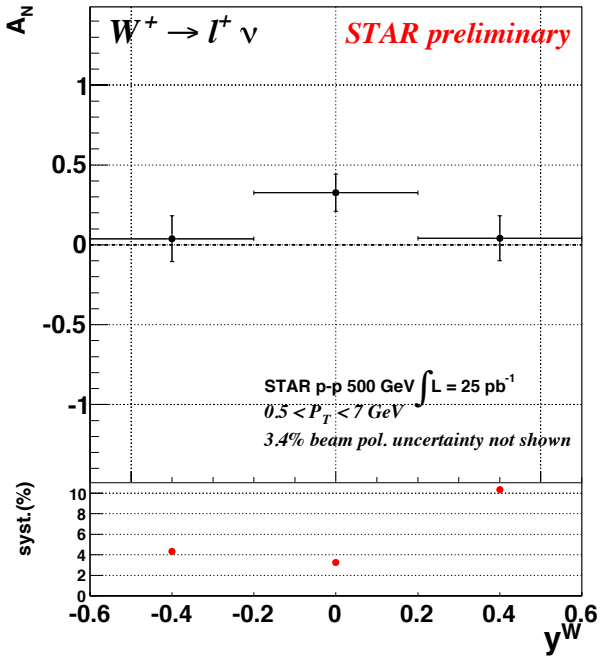
STAR FMS-PreShower:

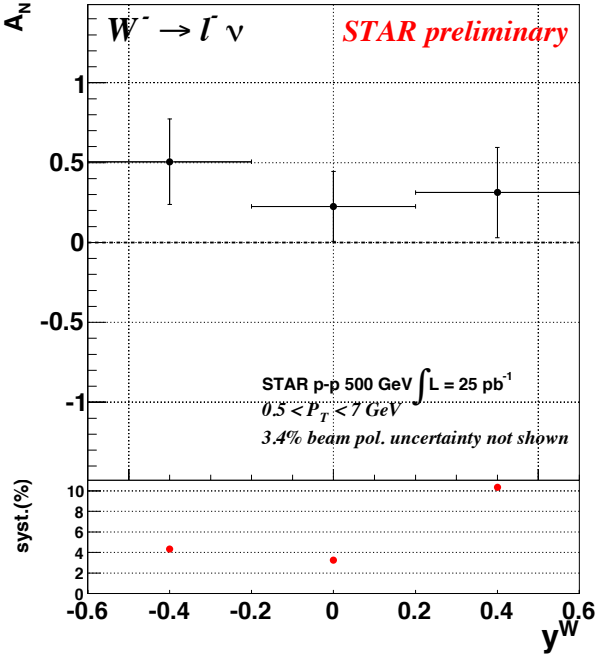


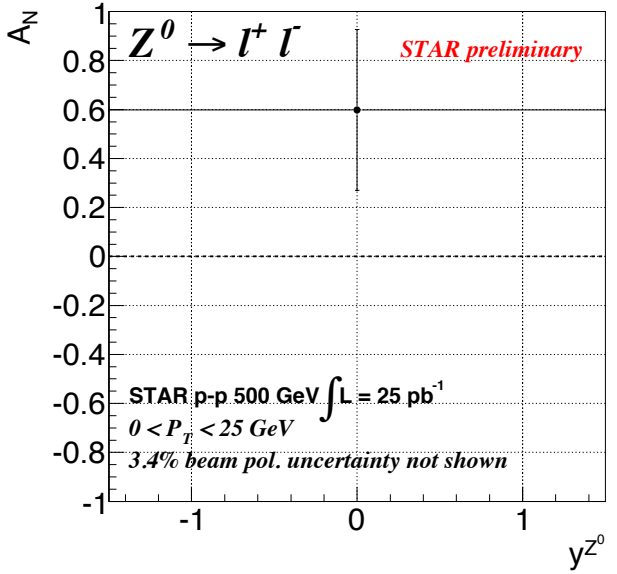
$A_N(W^{+/-}, Z^0)$ Results from 2011

- Preliminary results with 25 pb^{-1} of data
- Projections for 2016 show $A_N(W^{+/-},Z^0)$ will constrain sea quark Sivers distribution ***and*** make a statement on the Sivers sign change

S. Fazio and D. Smirnov PoS(DIS2014)237





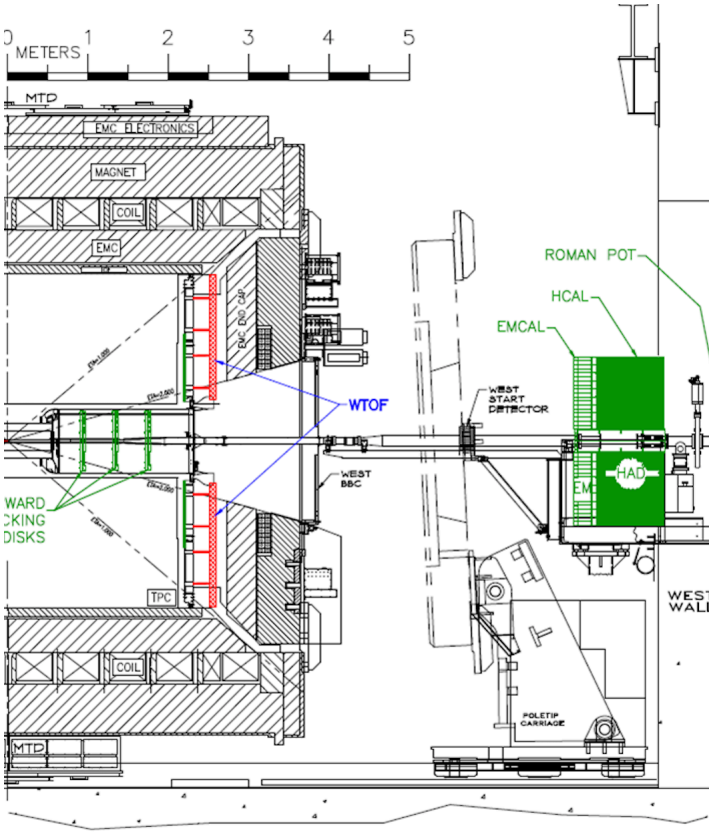


- An excellent complement to SIDIS
  - No fragmentation (and so no fragmentation function uncertainty)
  - High Q^2
  - Sign flip

Understanding Spin in Proton Collisions at STAR

- Probing Gluon Polarizations with Jets and π^0's
- Probing Sea Quark Polarization with W's
- Probing Transverse Structure with Jets and π^0's
  - And with W's, Z's, and other probes
- Looking to the Future

Probing *very* low x gluons with Forward Calorimeter Upgrade: 2020



ECal:

Tungsten-Powder-Scintillating-fiber

2.3 cm Moliere Radius, Tower-size: 2.5x2.5x17 cm^3

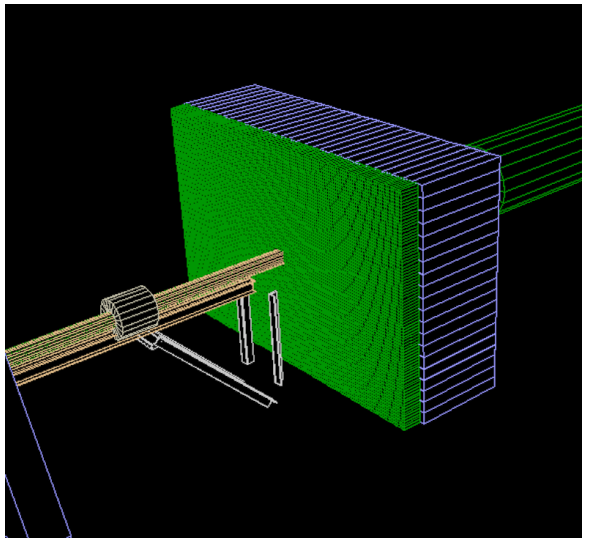
23 X_o

HCal:

Lead and Scintillator tiles, Tower size of 10x10x81 cm^3

4 interaction length

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605



$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

Dijet measurements provide direct access, at leading order, to parton x's (contrast inclusive jets)

Dijet Projections with the Forward Calorimeter Upgrade

$\sqrt{s}=500\ GeV$

$-1<\eta<2$

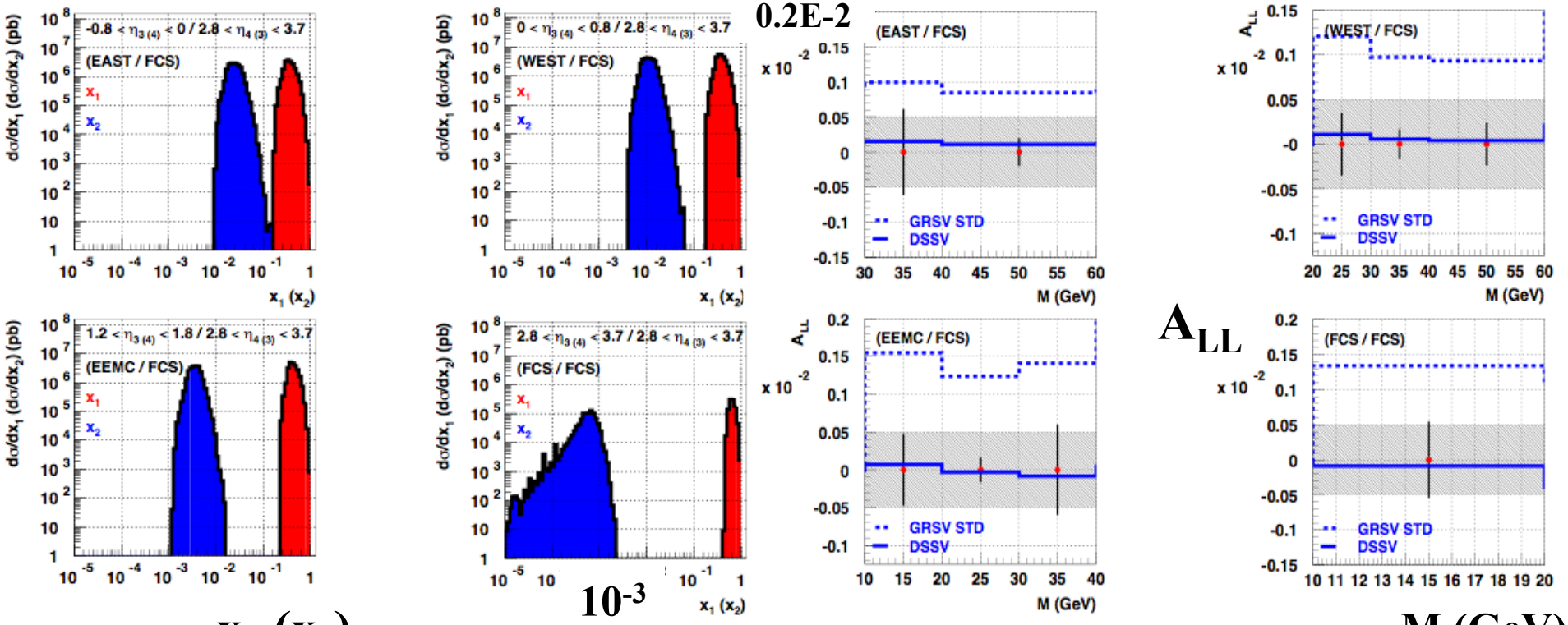
$2.8<\eta<3.7$

$R_{cone}=0.7$
$E_{T1}>8$ GeV
$E_{T2}>5$ GeV

$L=1fb^{-1}$
$P=60\%$

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605

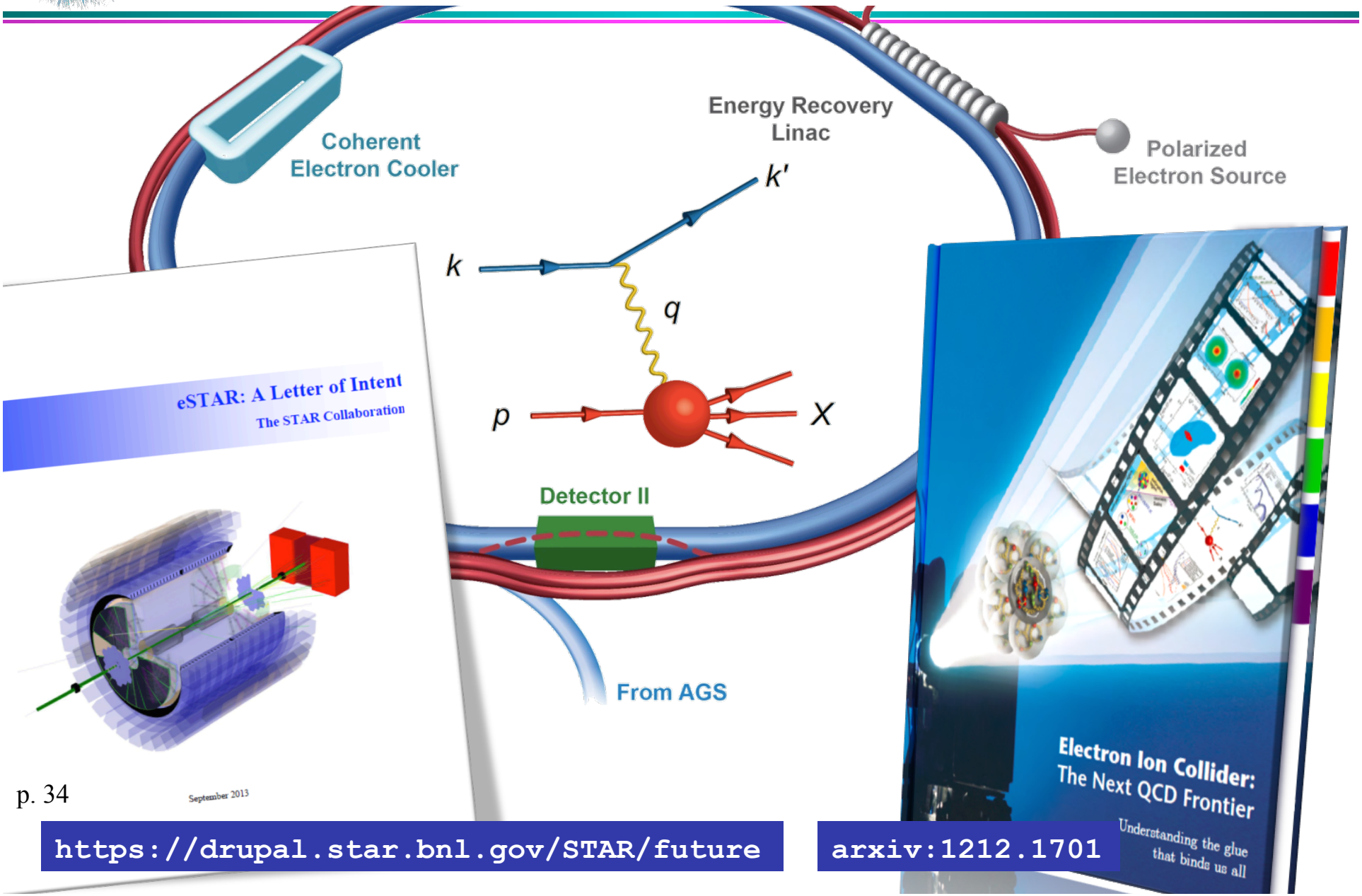
B. Surrow PoS(DIS2014) 241



Probe gluons to $x \sim 10^{-3}$

An attractive probe at rather low x before the EIC era

eRHIC and eSTAR (>2025) will offer unprecedented reach in Q^2 and x



p. 34

https://drupal.star.bnl.gov/STAR/future

arxiv:1212.1701

Intrigued?

- By Spin Physics?
  - Studies on nucleon **spin at PHENIX**, K. Tanida in this session
  - The New **Spin Physics Program of the COMPASS Experiment**, L. Silva, Saturday 16:30
- By detector upgrades?
  - The **Heavy Flavor Tracker and its performance in STAR** at RHIC, S. Margetis, Tuesday 17:50
  - **PHENIX Upgrade**, E. Mannel, Tuesday 17:30
- By STAR?
  - **STAR** highlight talk on **Heavy Ion Physics**, S. Shi in this session
  - **Quarkonia at STAR**, B. Trzeciak, Saturday 15:50
  - **Pion-kaon femtoscopy in Au+Au collisions at STAR**, K. Poniatowska, Sat. 17:15
  - **Open Heavy Flavor Measurements at STAR**, D. Tlusty, Wed. 11:20
  - Overview of results from phase I of the **Beam Energy Scan Program at RHIC**, D. McDonald, last Tues.

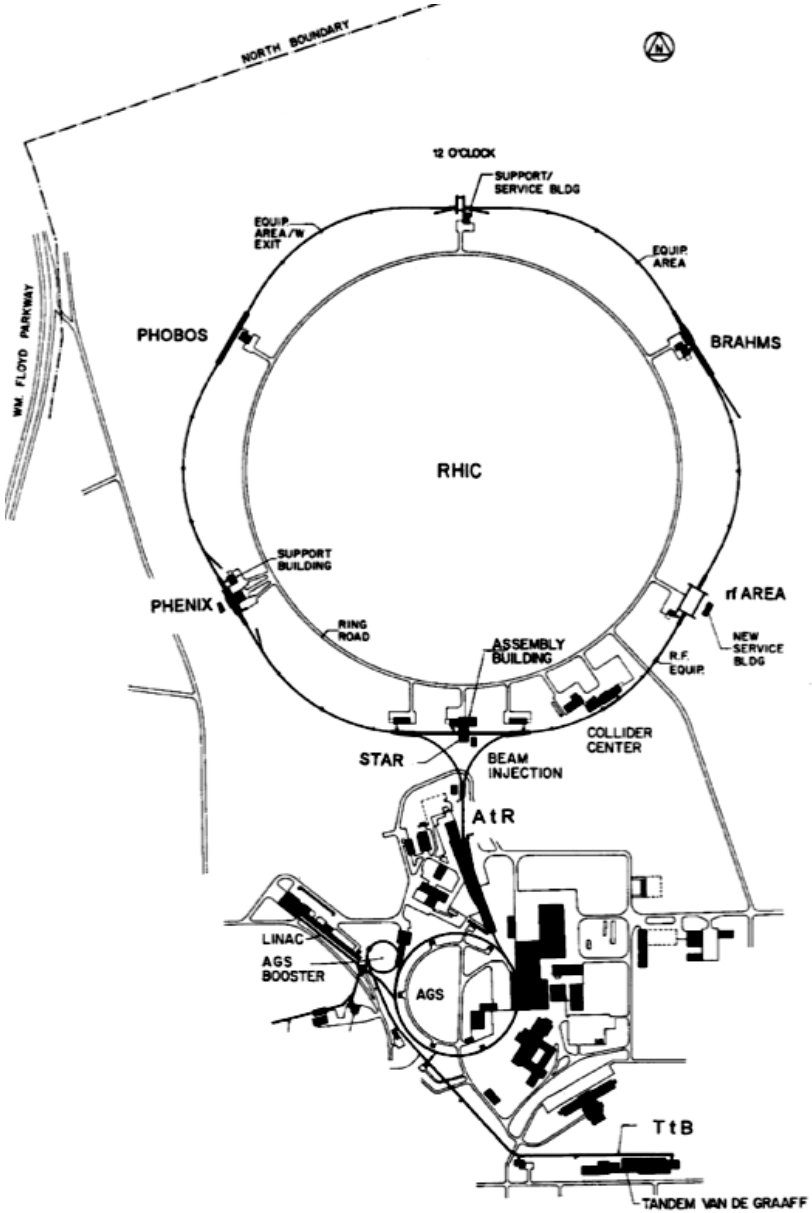
Spin Physics at STAR

- Inclusive Jets
  - After 25 years, **evidence of non-zero gluon polarization** in the proton
- Pushing to **lower *x* gluons**
  - With forward detectors, sqrt(s) = 510 GeV, large datasets, detector upgrades
- **W's and Z's** improving our understanding of **sea quark polarizations**
- Exploration of large transverse asymmetries, A_N, continues
  - **TMD (e.g Sivers, Collins) and Twist-3 phenomenology**
  - Efforts to **disentangle initial-state (e.g. Sivers) and final-state (e.g. Collins) effects;** and **confirming both in a pp environment**
  - **Tests of universality, factorization, and evolution of TMD's**
- **Large datasets on hand, analyses underway**
  - 2011, 2012, 2013
- **Detector upgrades continue**
  - FGT forward tracking 2013, forward calorimetry: FPS+FMS 2015, FCS 2020
- **Continuing data taking planned**
  - 2015, 2016, and beyond
- **Stay tuned!**

Backup

Year	#	NSAC LRP **Milestone**
2013	HP8	Measure flavor-identified q and $\overline{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2013	HP12 (update of HP1, met in 2008)	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering.

Relativistic Heavy Ion Collider as a Spin Collider



Concert of Facilities

- OPPIS → LINAC → AGS → RHIC

Polarized-proton Collider

- Mitigate effects of depolarization resonances with "Siberian Snakes"
- Polarization measured with CNI polarimeter
- Spin rotators provide choice of spin orientation *independent of experiment*

RHIC Beam Characteristics

- Clockwise beam: "**blue**"; counter-clockwise beam: "**yellow**"
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Solenoidal Tracker at RHIC

Inclusive hadron measurements:

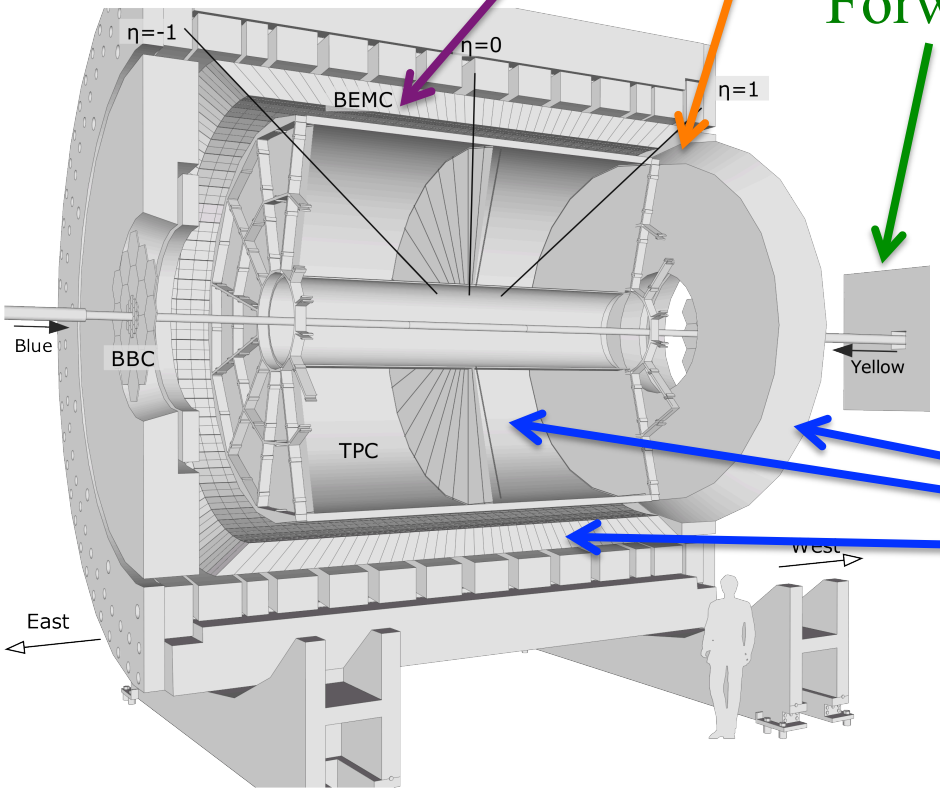
Barrel ElectroMagnetic Calorimeter (BEMC),

Endcap ElectroMagnetic Calorimeter (EEMC),

and

Forward Meson Spectrometer (FMS)

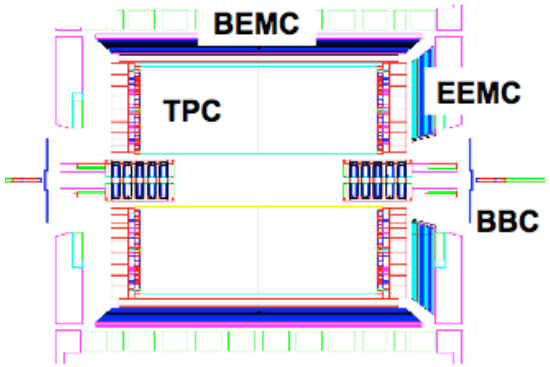
FPD (east) not shown

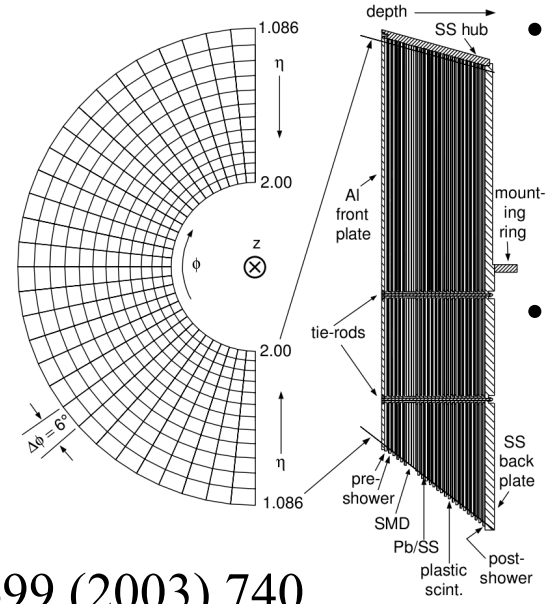


Jet and W/Z measurements:

TPC + Barrel + Endcap EMC

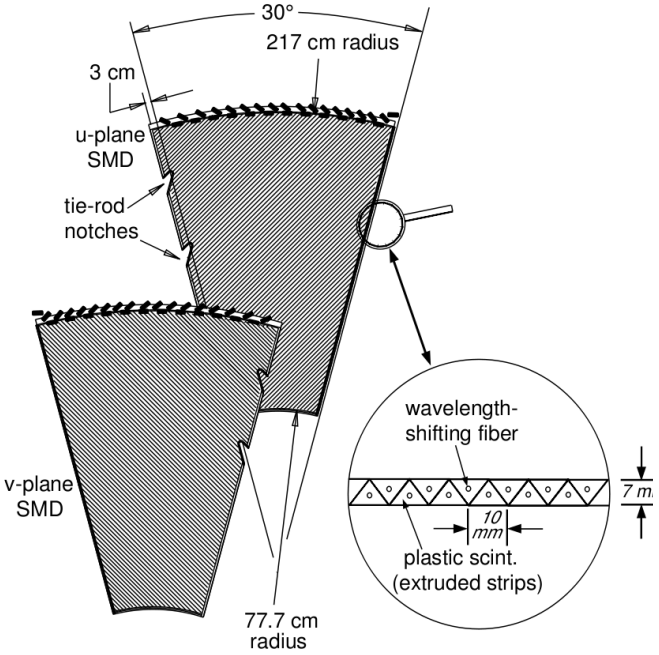
STAR's Endcap Electromagnetic Calorimeter





- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm

- Nucl. Instrum. Meth. **A** 499 (2003) 740.
- Lead/scintillator sampling EM calorimeter
  - Covers $1.09 < \eta < 2.00$ over full 2π azimuth
  - 720 optically isolated projective towers (~22 X_0)
  - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- Photon trigger places thresholds on maximum tower energy and the 3x3 patch of surrounding towers

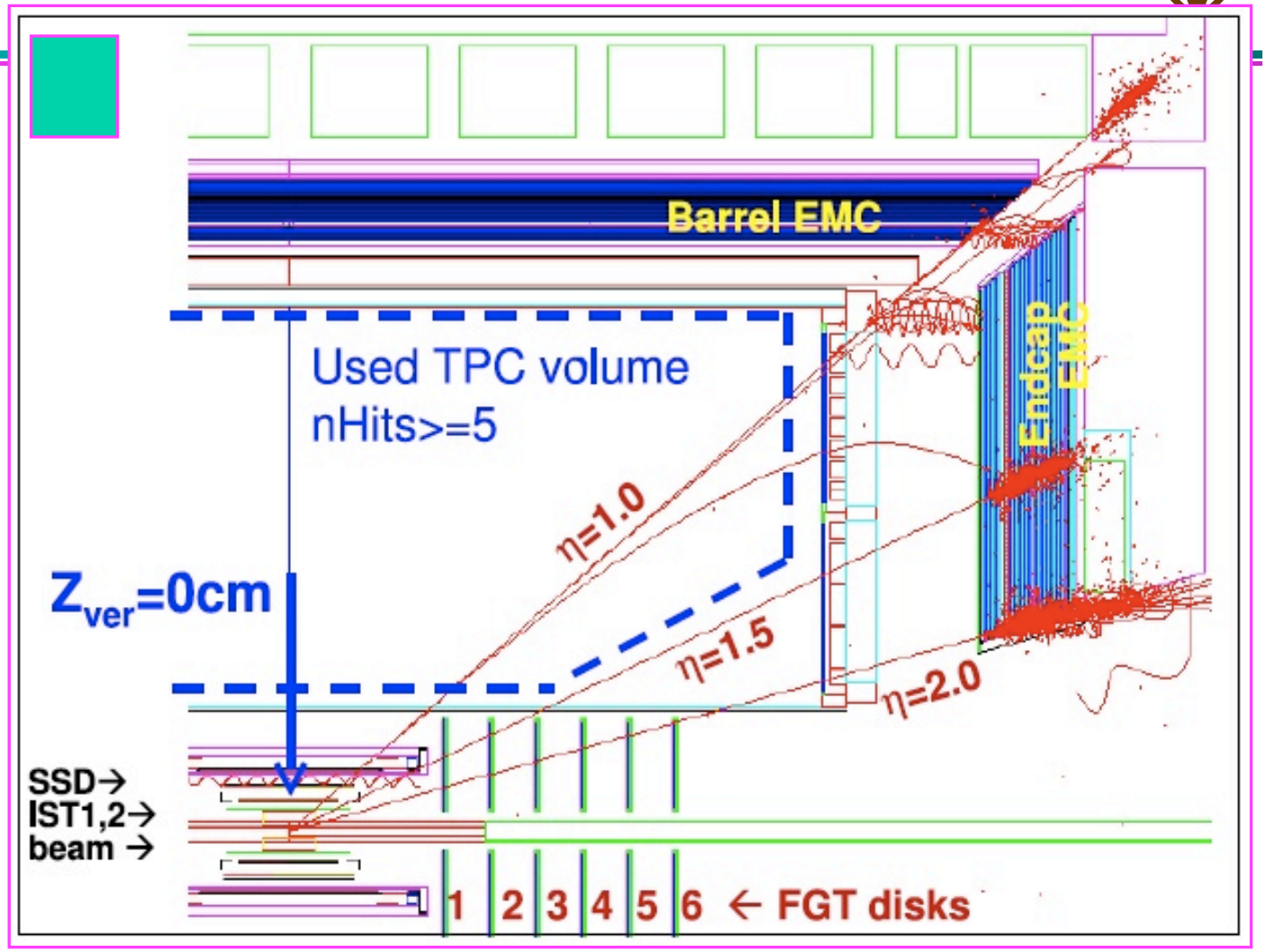


STAR FGT Detector

Improve charged particle tracking at very forward angles

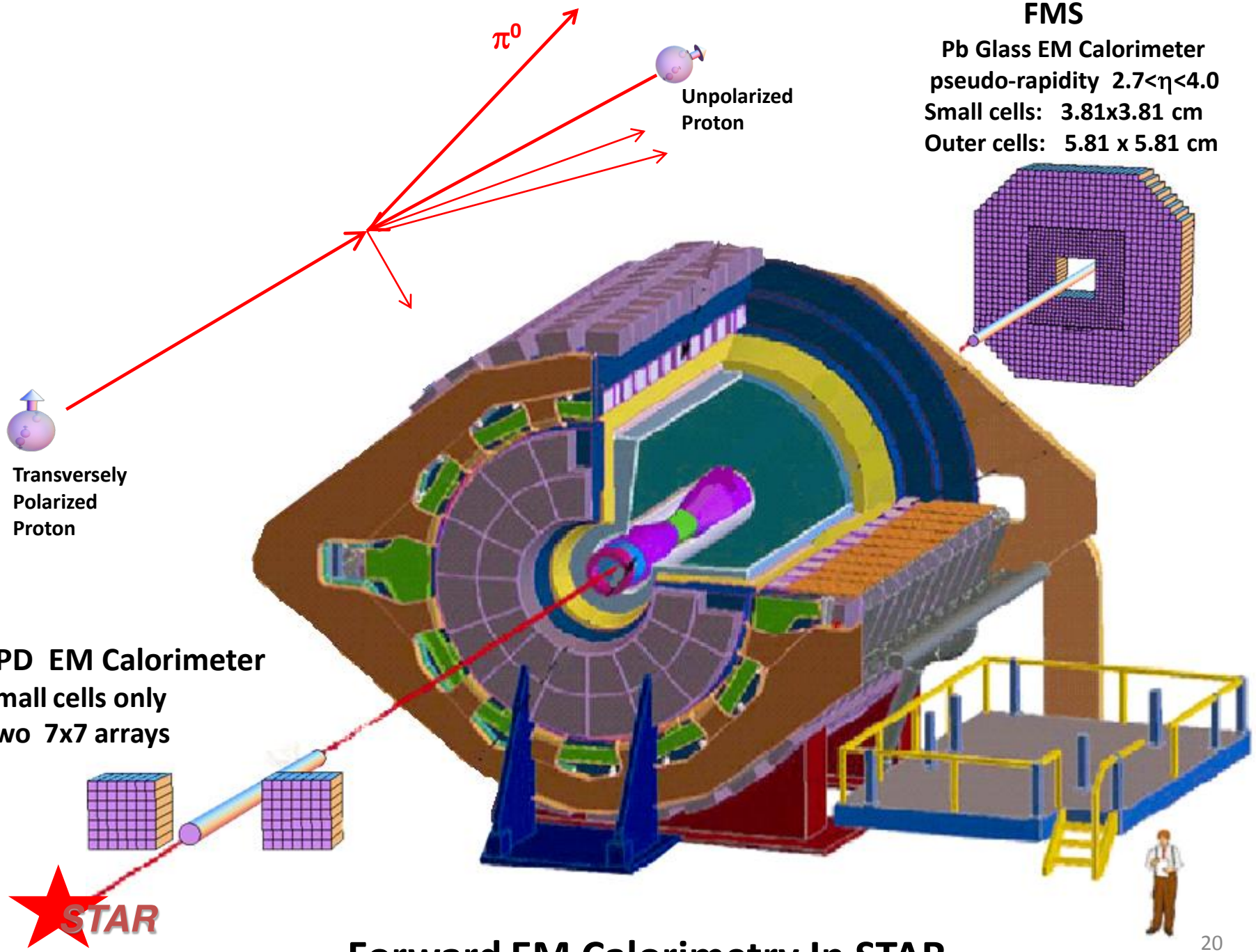
Obtain better measurement of W decay particles

Install 6 planes of GEM detectors



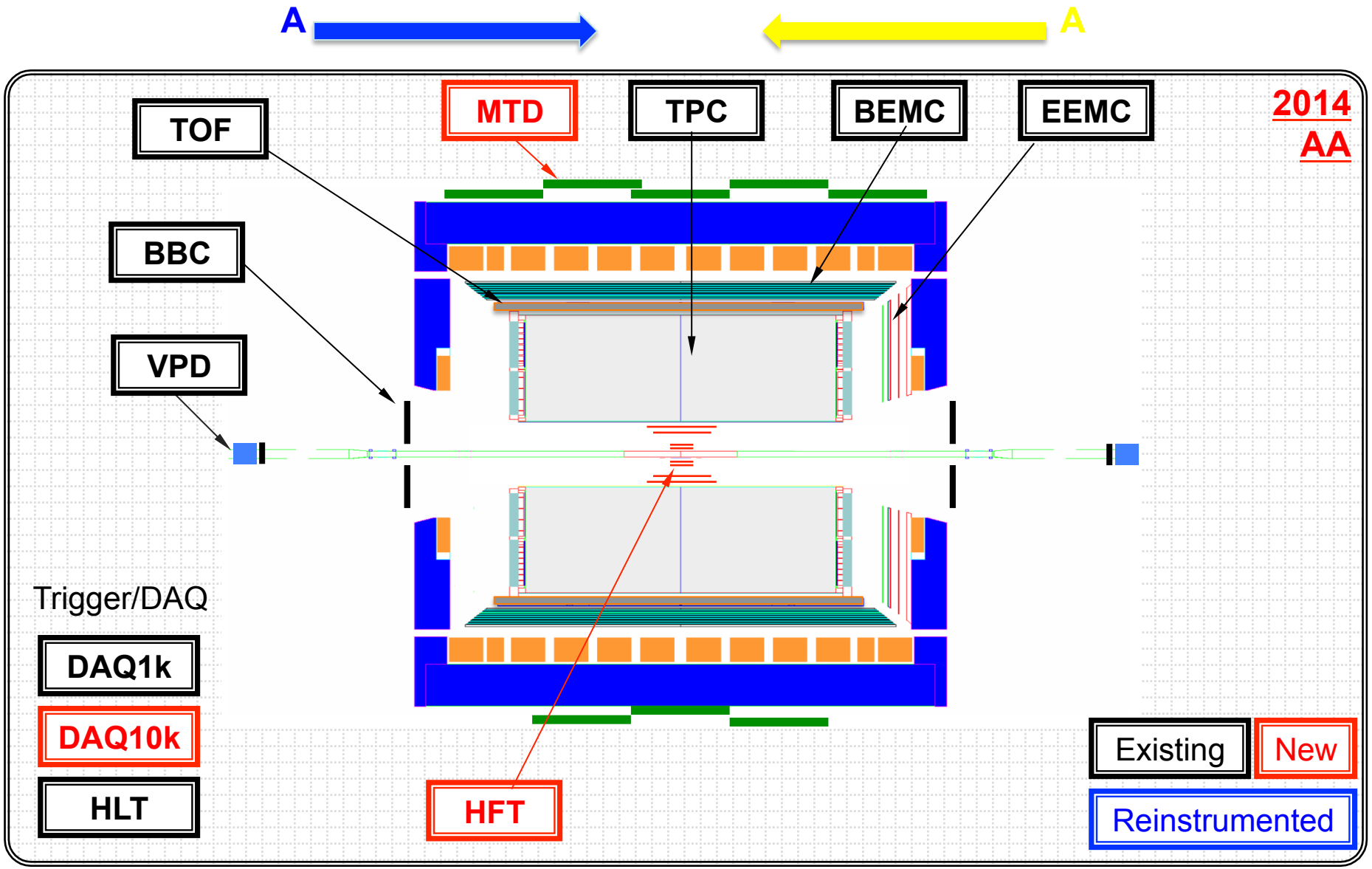
FGT = Forward GEM Tracker

GEM = gaseous electron multiplier



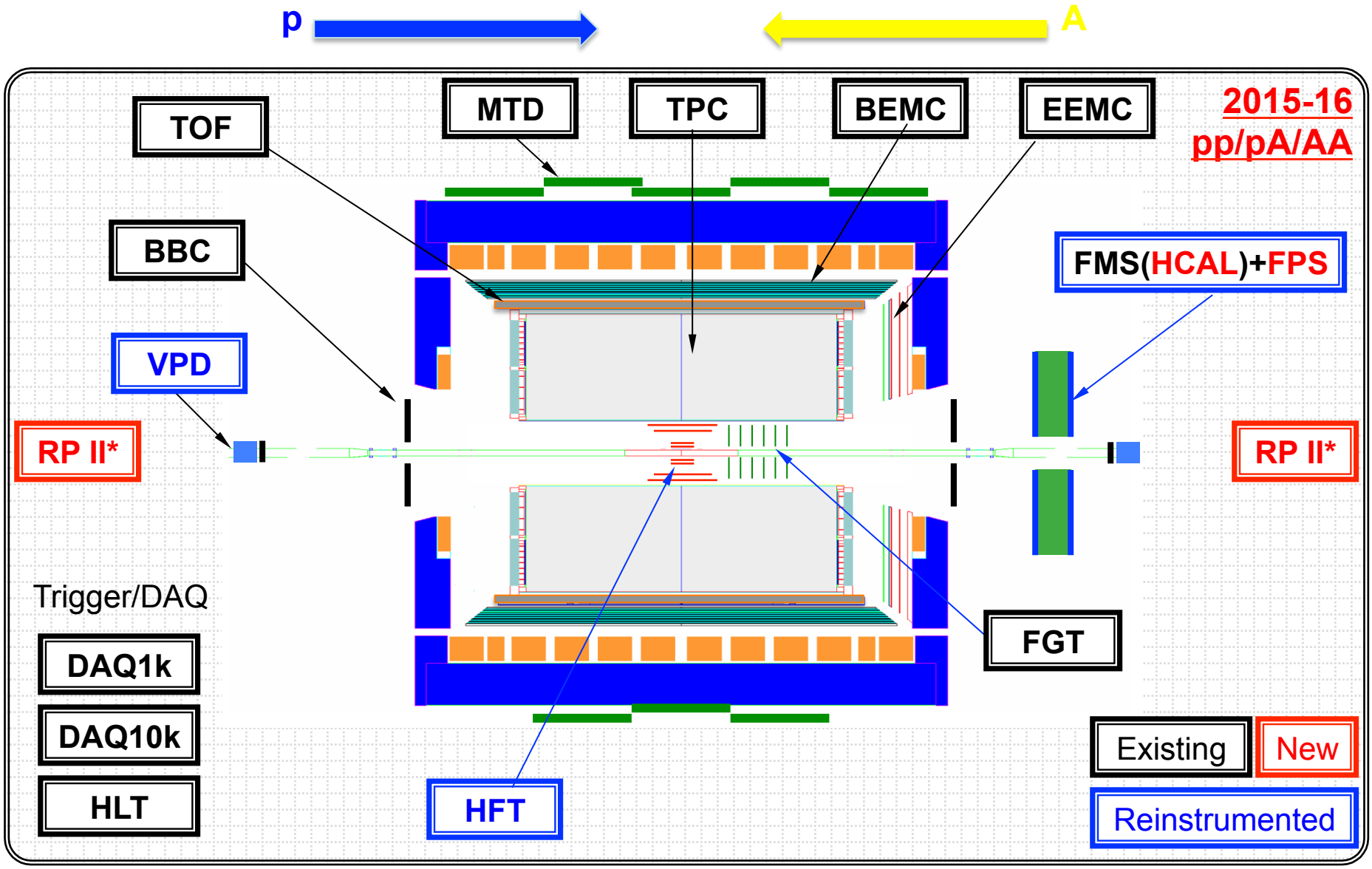
Forward EM Calorimetry In STAR.

STAR Detector in 2014



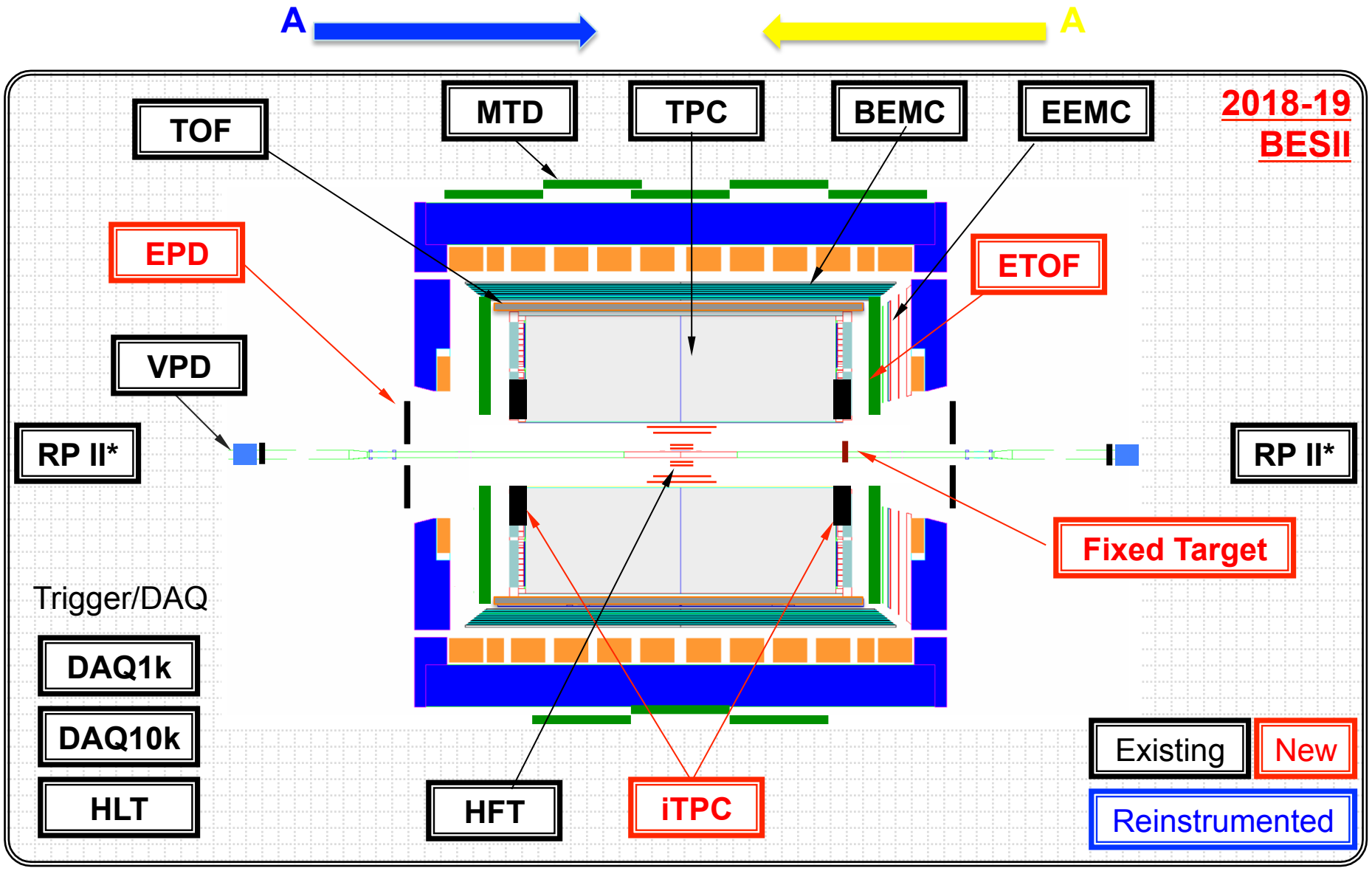
HFT: Heavy Flavor Tracker, **MTD**: Muon Telescope Detector

STAR Detector in 2015-2016



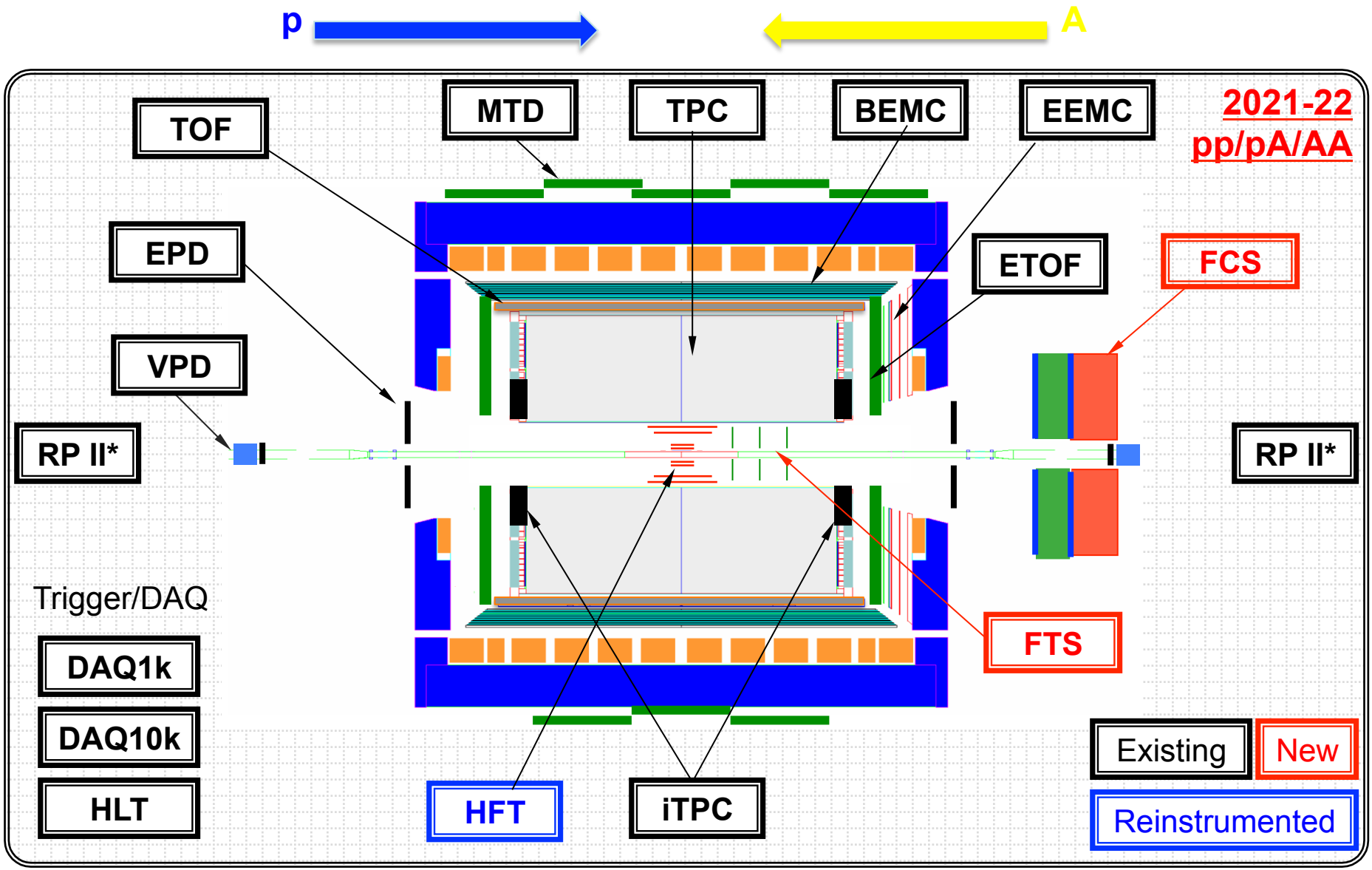
FMS: Forward Meson Spectrometer, **FPS**: Forward Preshower, **RP II***: Roman Pot Phase II*

STAR Detector in 2018-2019



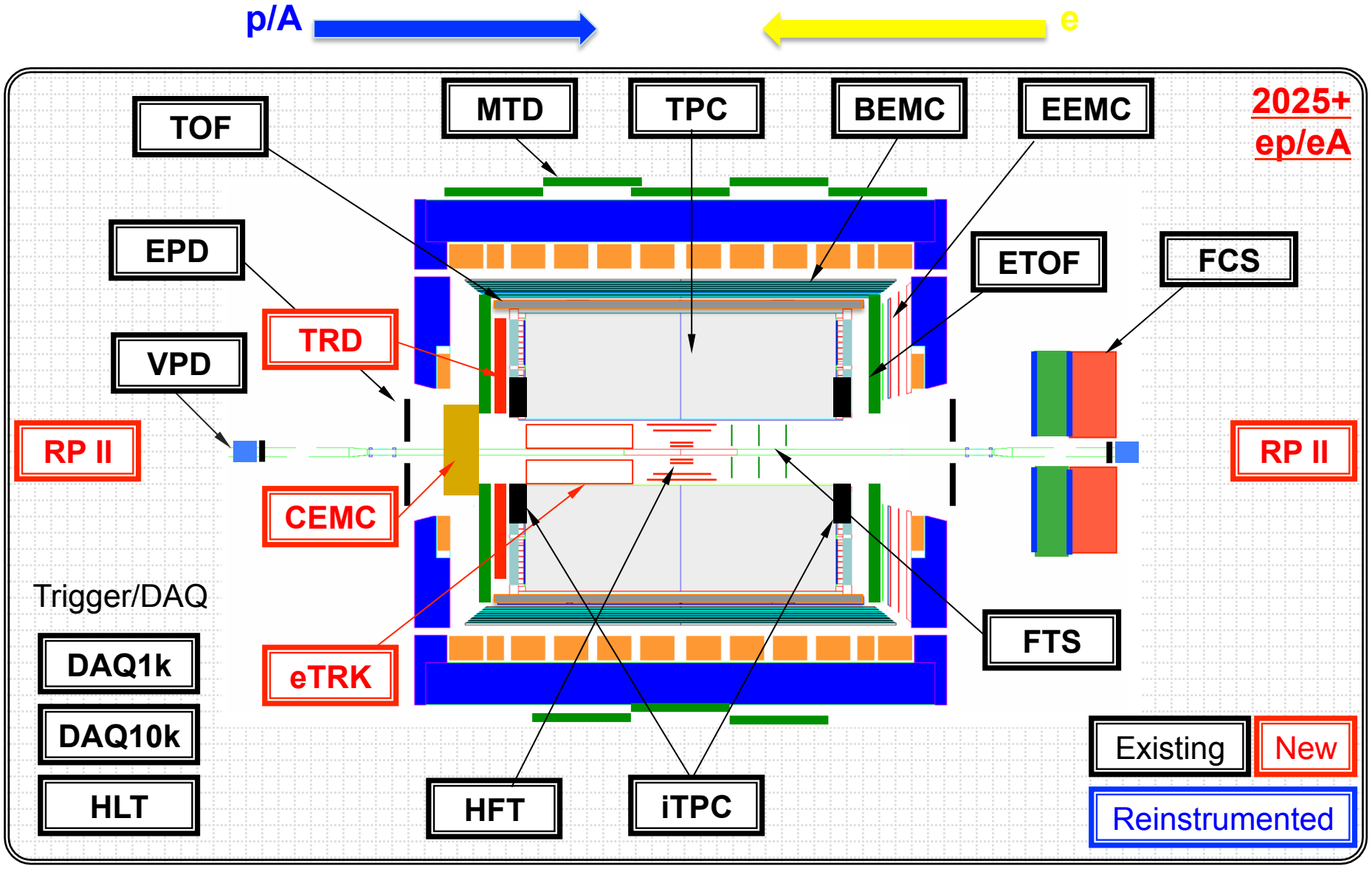
iTPC: inner TPC, **EPD:** Event Plane and Centrality Detector, **ETOF:** End-cap TOF, **Fixed Target**

STAR Detector in 2021-2022



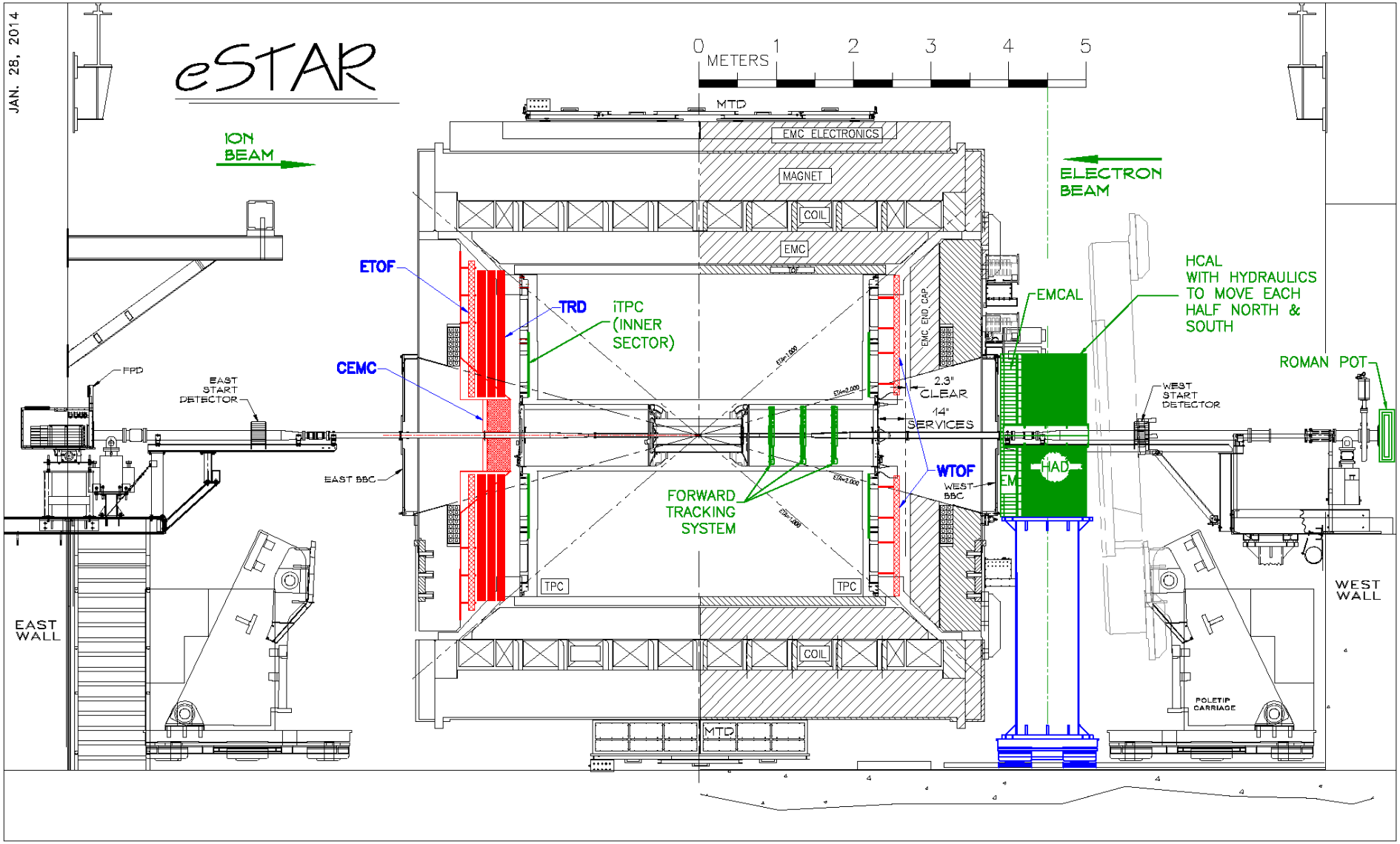
FCS/FTS: Forward Calrimeter/Tracking System, **RP II:** Full Roman Pot Phase II

STAR Detector in 2025+



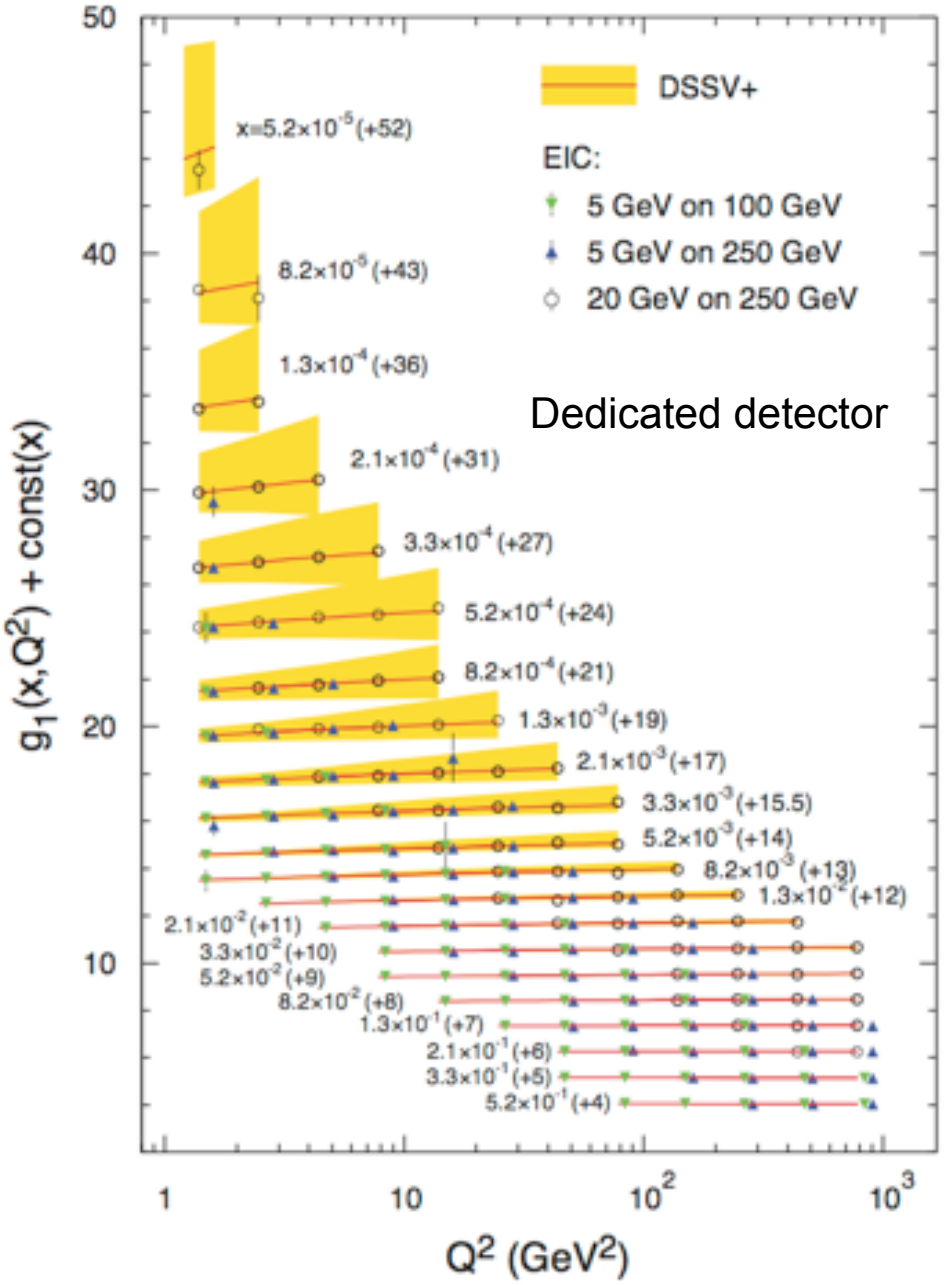
CEMC: Central EM Calorimeter, **eTRK:** electron Tracker, **TRD:** Transition Radiation Detector

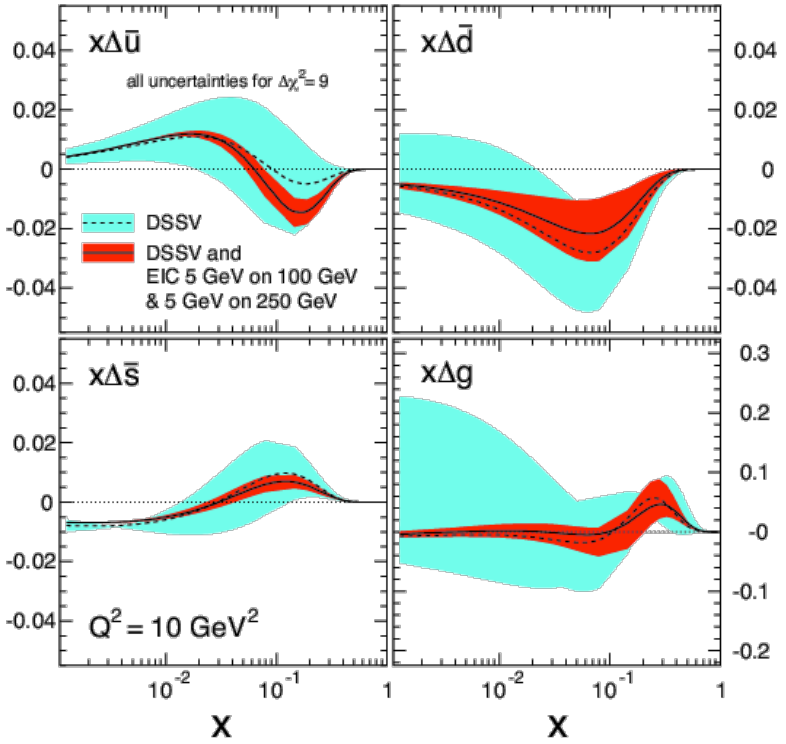
eSTAR Detector in 2025+

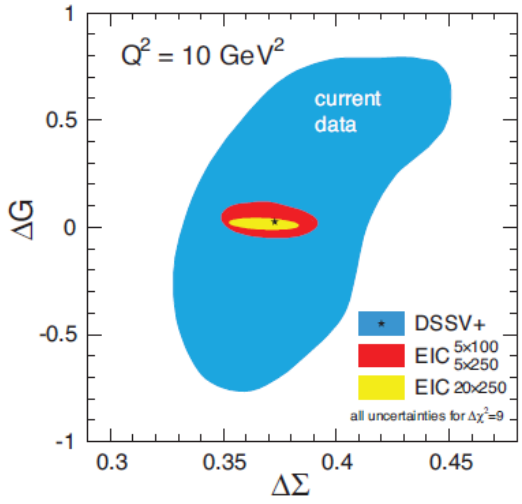


The very successful STAR detector will **evolve into an EIC detector**

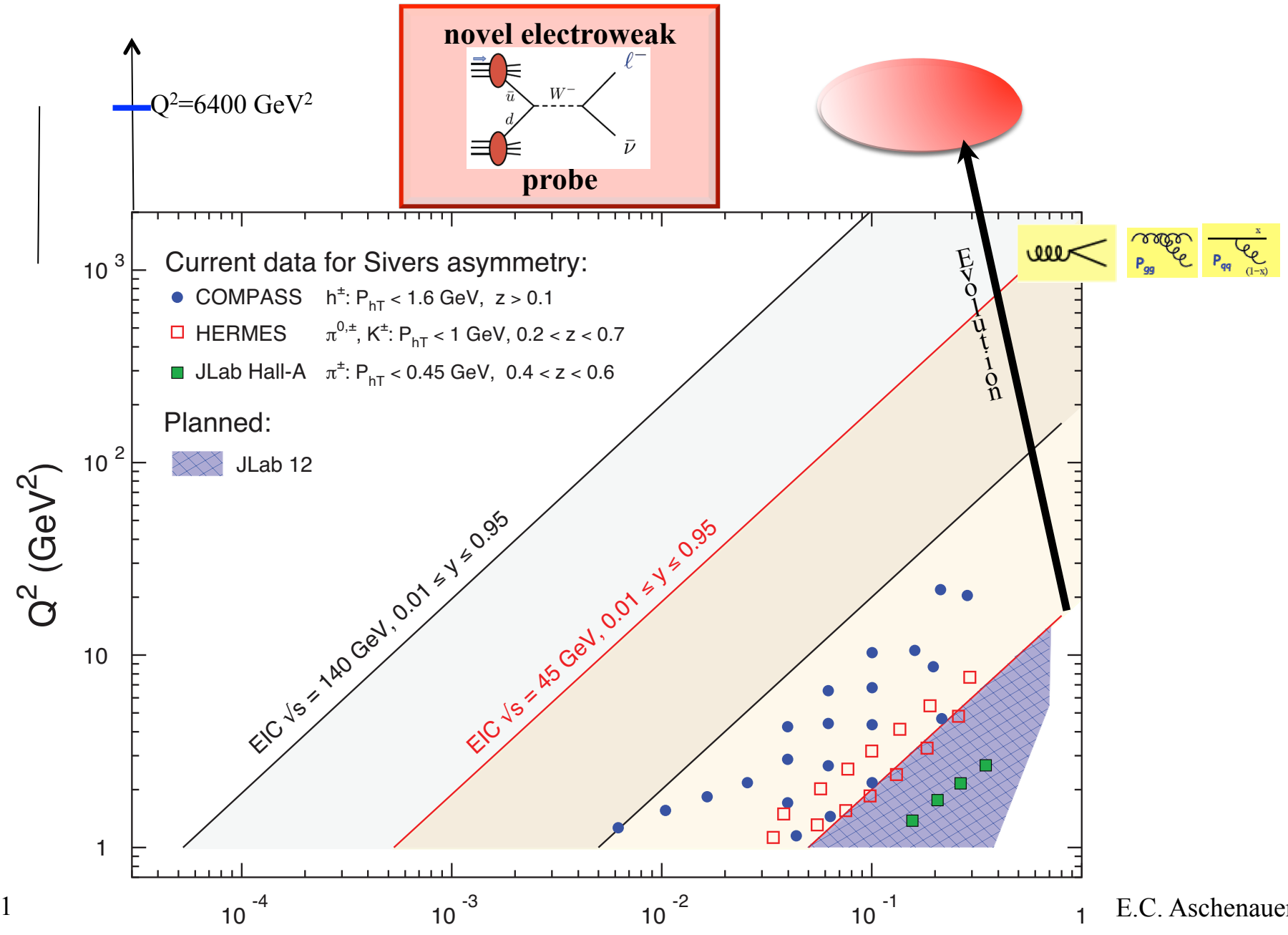
Proton Helicity Structure





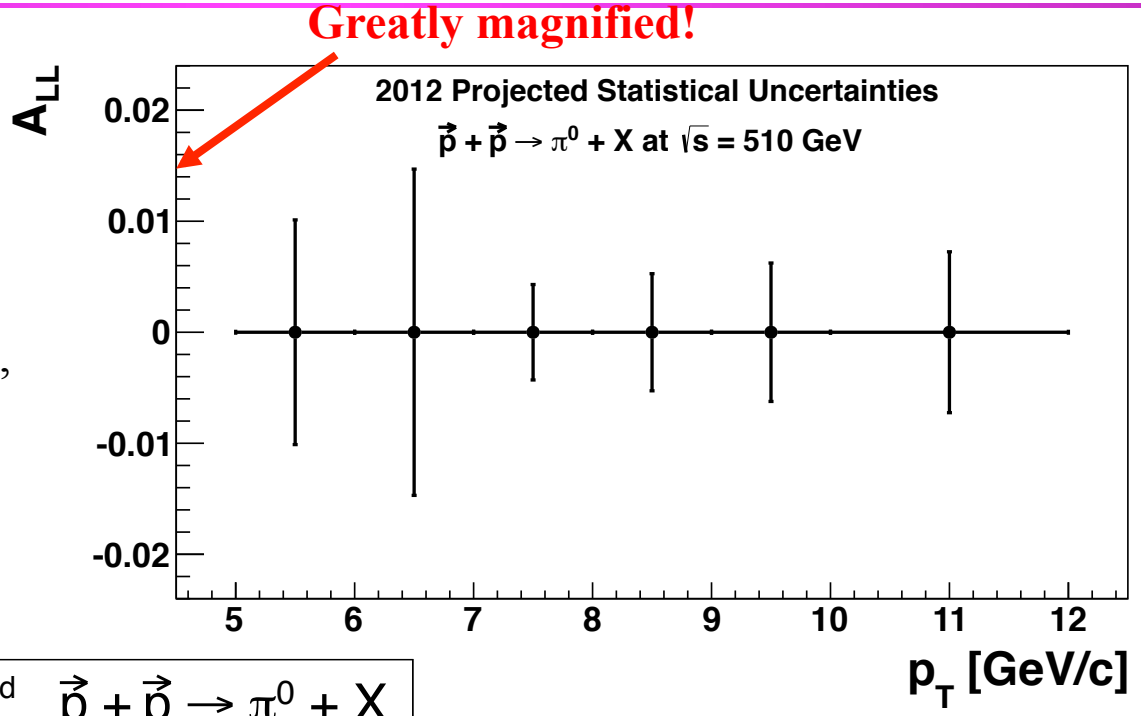


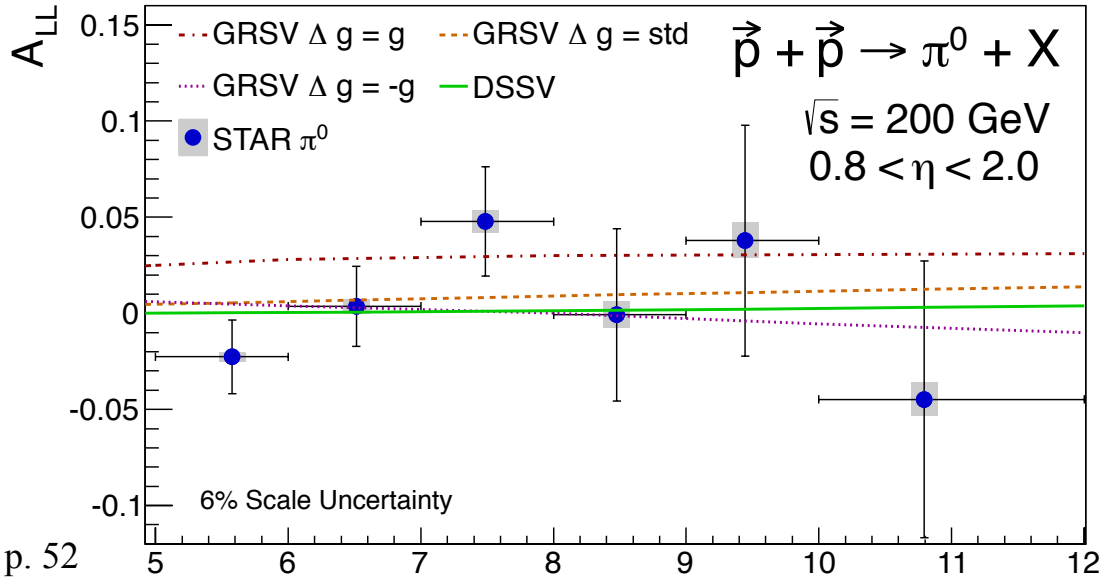
THE Beauty of Colliders: Kinematic Coverage



π^0 A_{LL} Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 luminosity) at intermediate pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown
- And with 2012 and 2013 datasets at forward pseudorapidity

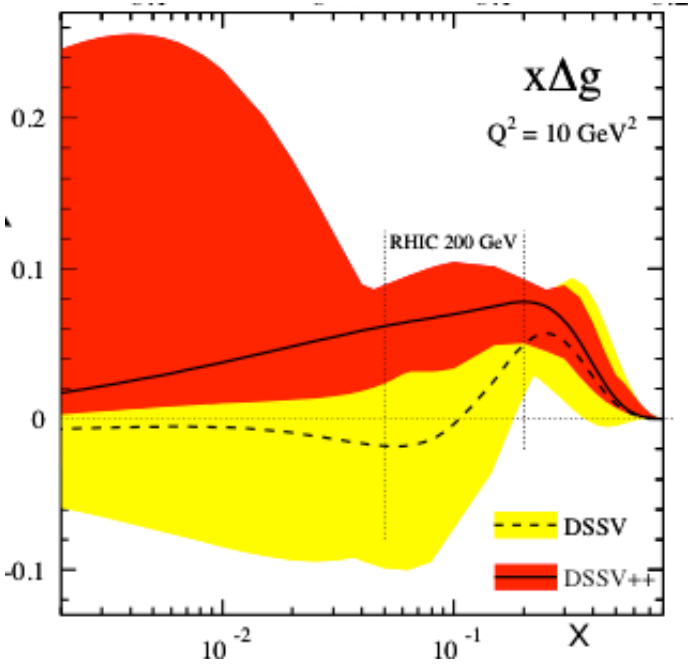




- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower *x* g

2006 data
PRD **89**, 012001 (2014)

- DSSV++



- DSSV 14

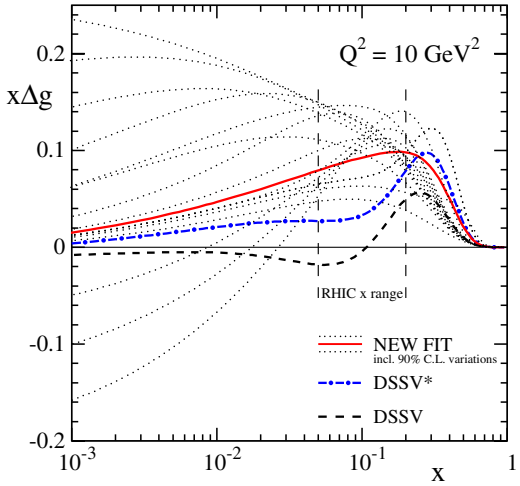
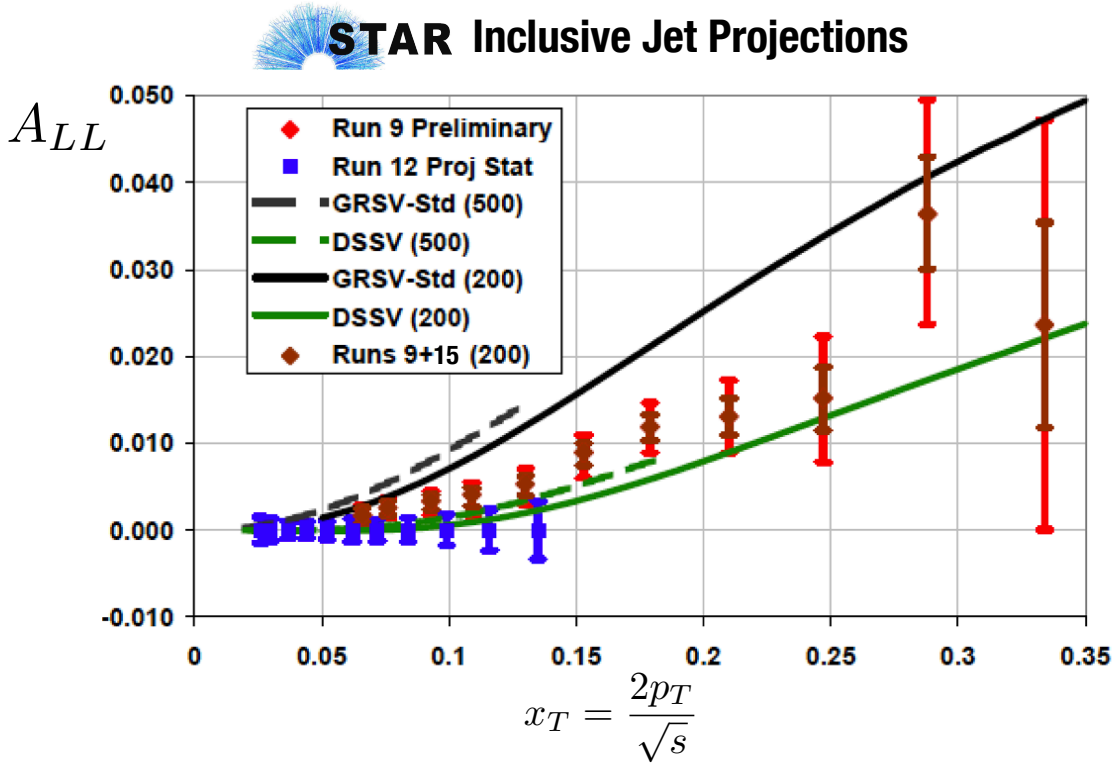


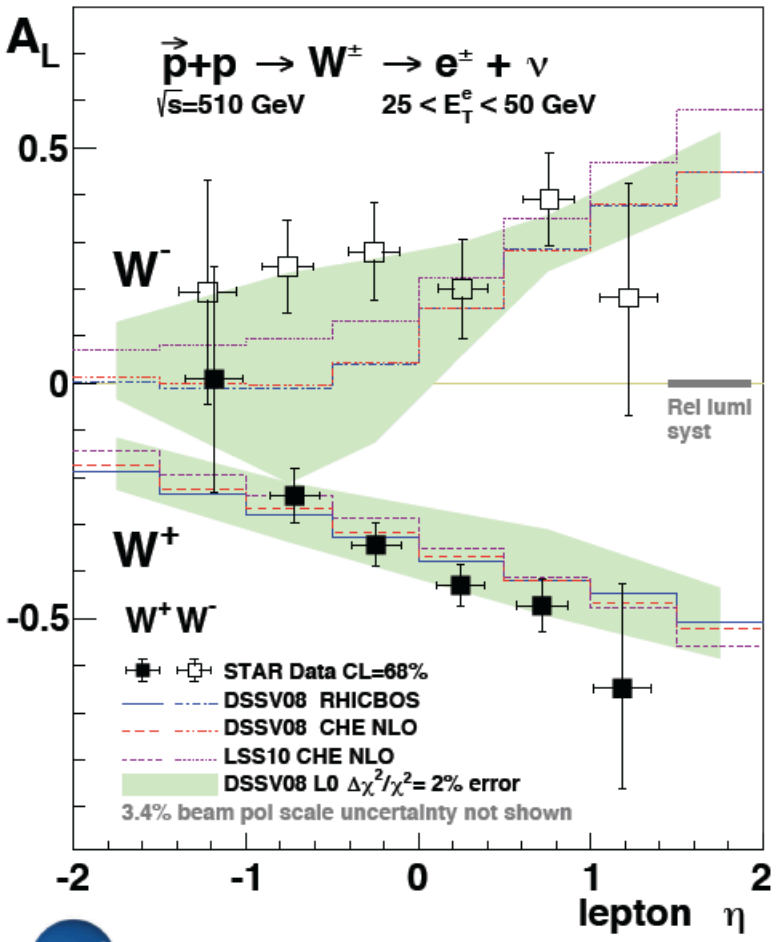
FIG. 1 (color online). Gluon helicity distribution at $Q^2 = 10$ GeV^2 for the new fit, the original DSSV analysis of [3], and for an updated analysis without using the new 2009 RHIC data sets (DSSV*, see text). The dotted lines present the gluon densities for alternative fits that are within the 90% C.L. limit. The x range primarily probed by the RHIC data is indicated by the two vertical dashed lines.

Inclusive jet projections

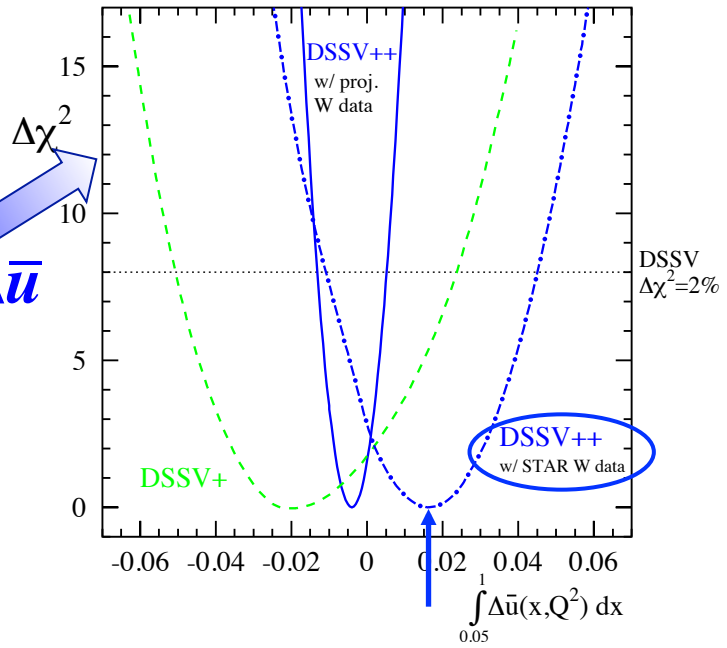


- Significant improvement in statistical precision with data collected in 2011-2013 and expected in 2015
- Expect to reduce uncertainties on Δg by a factor of ~2

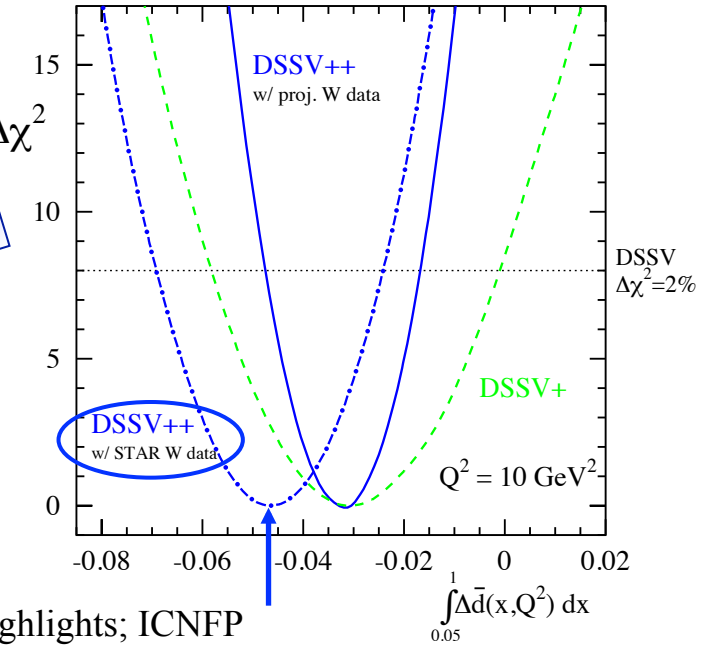
Results from 2012 W's



$\Delta\bar{u}$



$\Delta\bar{d}$



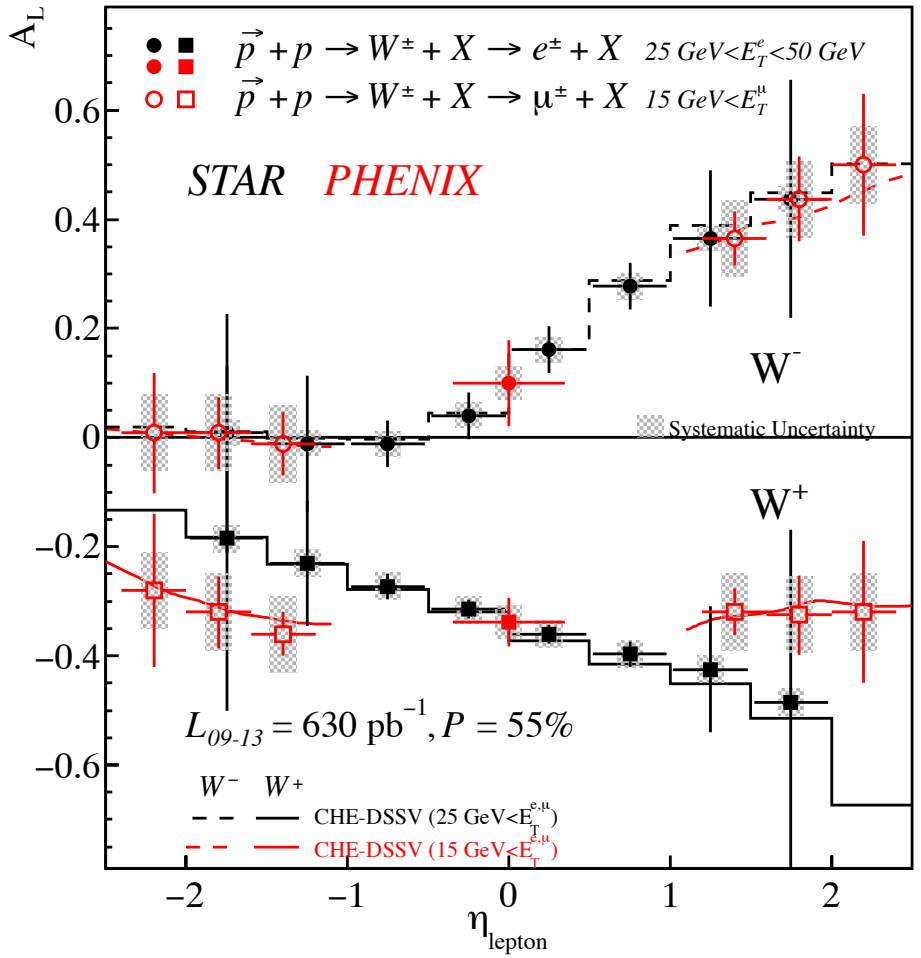
NEW arXiv:1404.6880 [Accepted by PRL]

[See also new NNPDF fit arXiv:1406.5539]

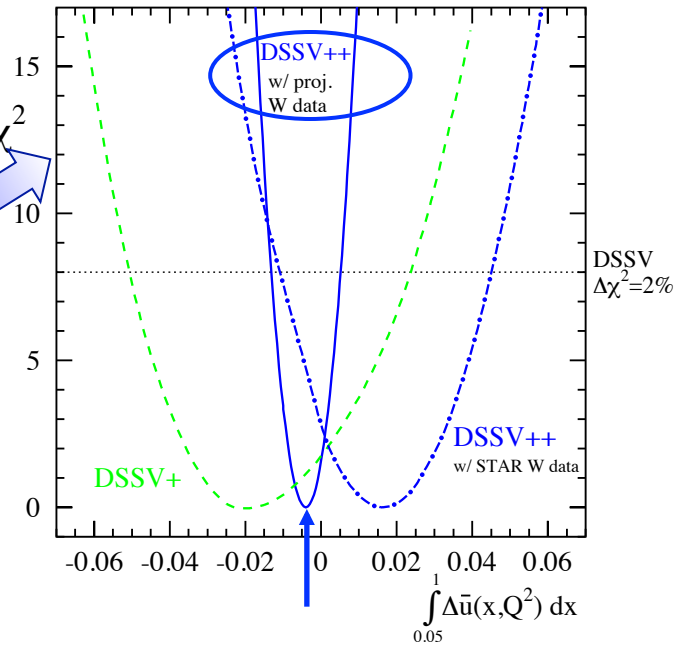
DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj. (2009-2013)

W Projections

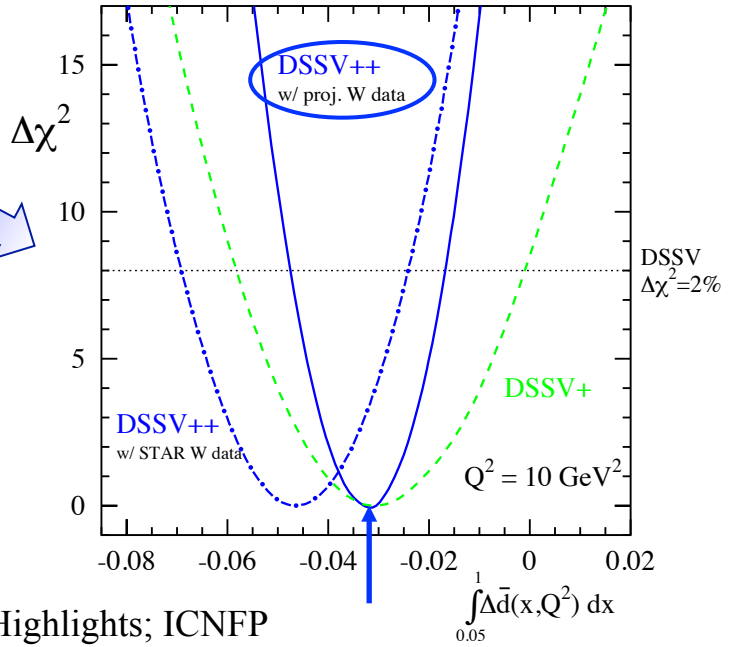
pseudo-data randomized around DSSV



$\Delta\bar{u}$



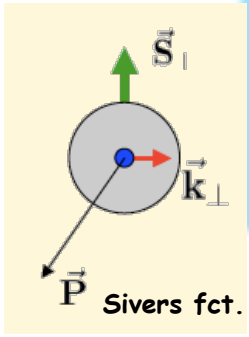
$\Delta\bar{d}$



DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj. (2009-2013)

Includes **F**orward **G**EM **T**racker at STAR, fully installed in 2013

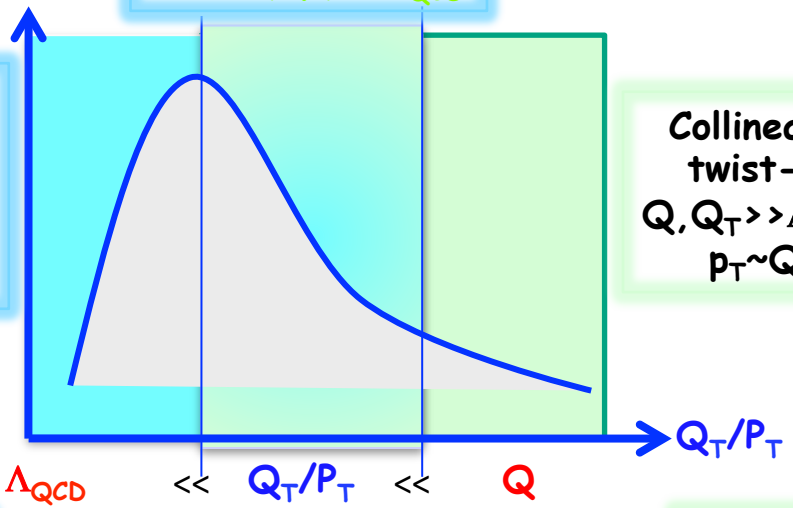
Theory: TMDs vs. Twist-3



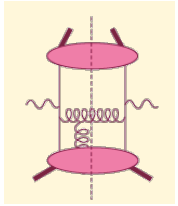
Sivers fct.

Transverse momentum dependent
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$

Intermediate Q_T
$Q >> Q_T/p_T >> \Lambda_{QCD}$



Collinear/ twist-3
$Q, Q_T >> \Lambda_{QCD}$
$p_T \sim Q$



Efremov, Teryaev;
Qiu, Sterman

Need 2 scales
Q^2 and p_t
Remember pp:
most observables one scale
Exception:
DY, W/Z-production

Need only 1 scale
Q^2 or p_t
But
should be of reasonable size

should be applicable to most pp observables
$A_N(\pi^0/\gamma/\text{jet})$

A_N: How to get to THE underlying Physics

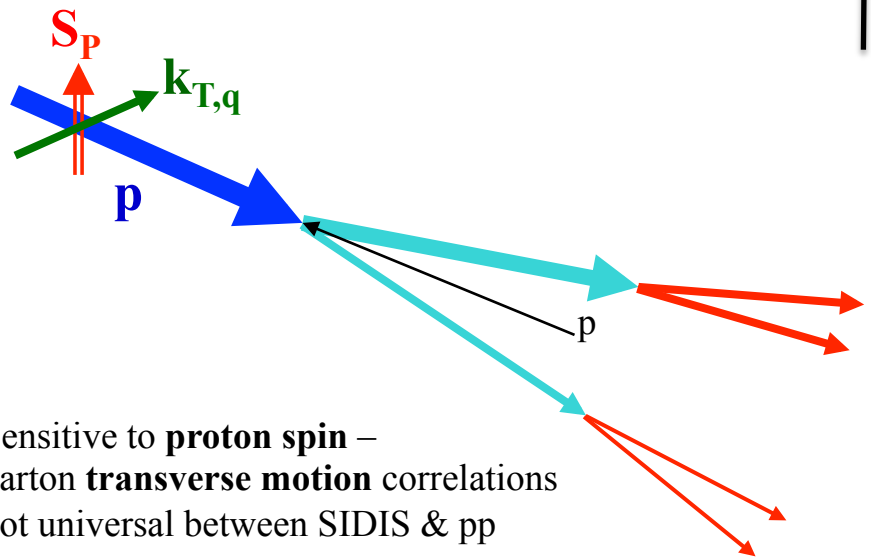
Goal: measure less inclusive

SIVERS/Twist-3

Rapidity dependence of

- **A_N for π^0 and eta with increased p_t coverage**

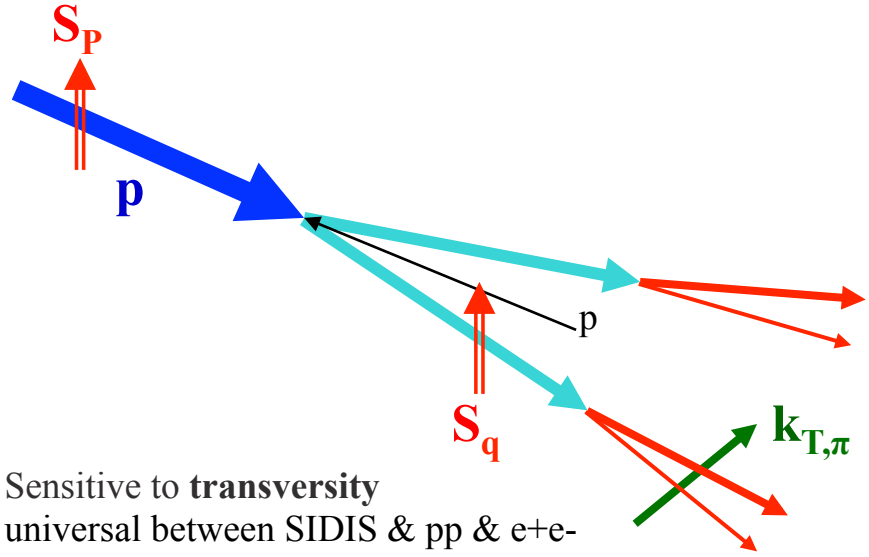
- **A_N for jets, direct photons**
- **A_N for heavy flavour → gluon**
- A_N for $W^{+/-}$, Z^0



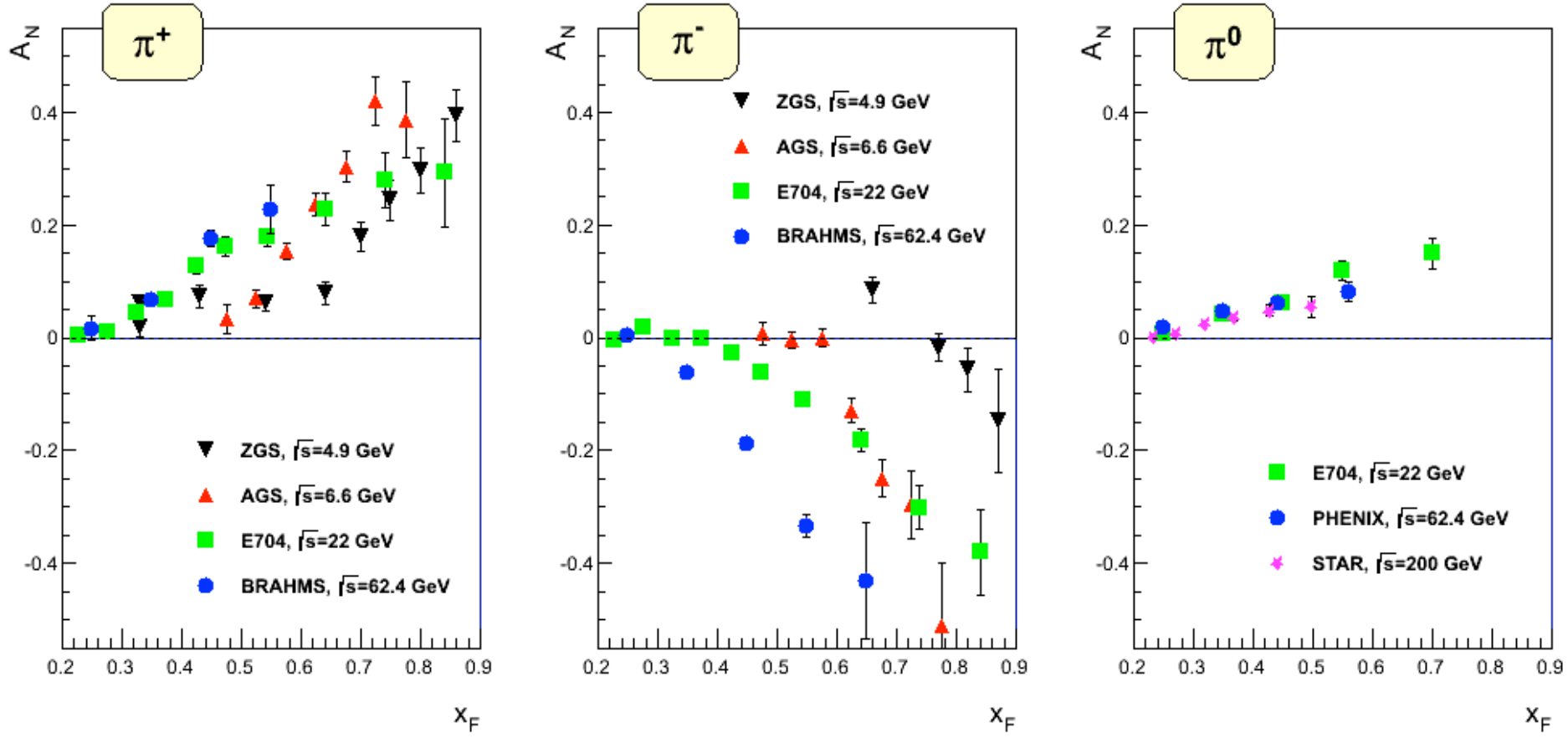
Sensitive to **proton spin** –
parton **transverse motion** correlations
not universal between SIDIS & pp

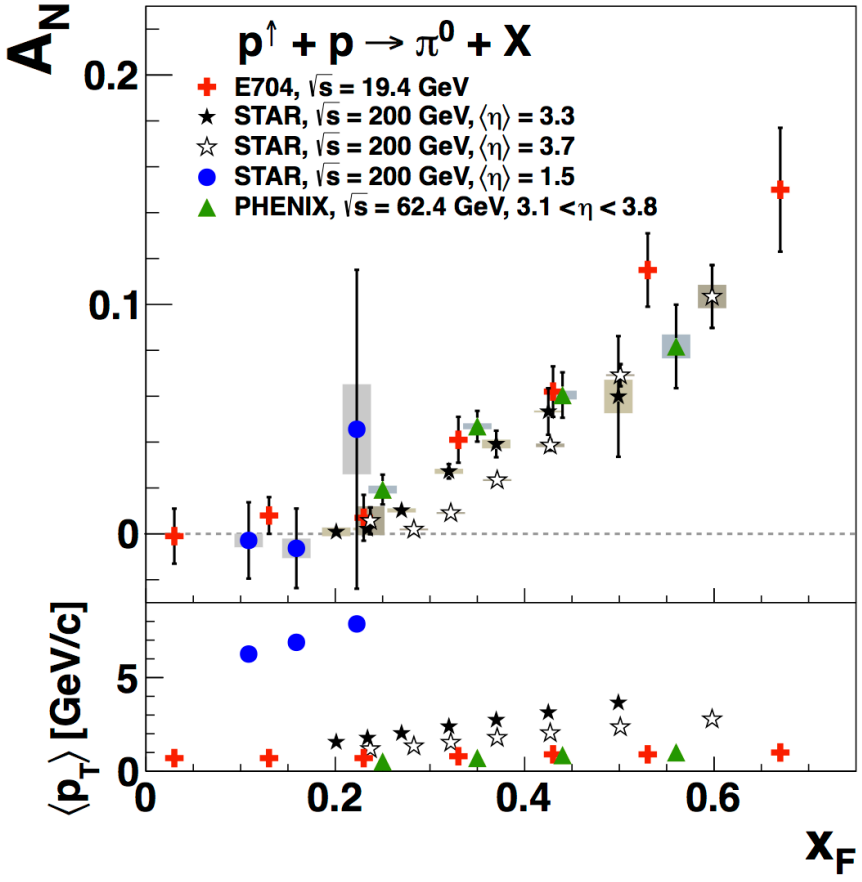
Collins Mechanism

- asymmetry in jet fragmentation
  - **$\pi^{+/-}\pi^0$ azimuthal distribution in jets**
  - **Interference fragmentation function**



Sensitive to **transversity**
universal between SIDIS & pp & e+e-


π^+
A_N
x_F
ZGS, $\sqrt{s}$=4.9 GeV
AGS, $\sqrt{s}$=6.6 GeV
E704, $\sqrt{s}$=22 GeV
BRAHMS, $\sqrt{s}$=62.4 GeV
π^-
A_N
x_F
ZGS, $\sqrt{s}$=4.9 GeV
AGS, $\sqrt{s}$=6.6 GeV
E704, $\sqrt{s}$=22 GeV
BRAHMS, $\sqrt{s}$=62.4 GeV
π^0
A_N
x_F
E704, $\sqrt{s}$=22 GeV
PHENIX, $\sqrt{s}$=62.4 GeV
STAR, $\sqrt{s}$=200 GeV

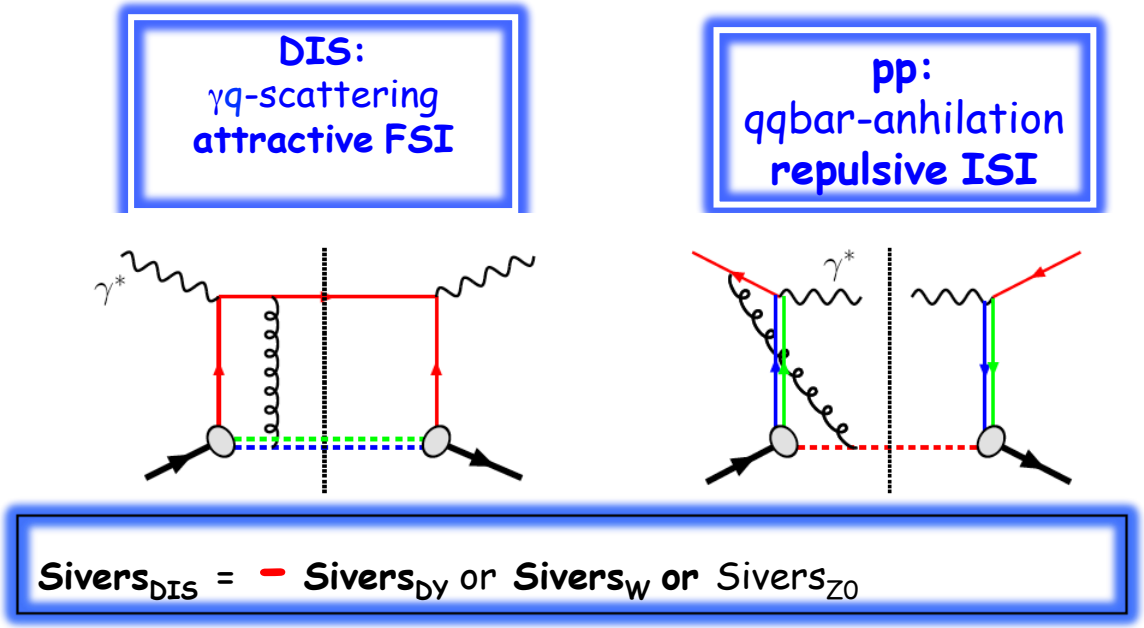

A_N
$p^\uparrow + p \rightarrow \pi^0 + X$
E704, $\sqrt{s}$ = 19.4 GeV
STAR, $\sqrt{s}$ = 200 GeV, $\langle\eta\rangle$ = 3.3
STAR, $\sqrt{s}$ = 200 GeV, $\langle\eta\rangle$ = 3.7
STAR, $\sqrt{s}$ = 200 GeV, $\langle\eta\rangle$ = 1.5
PHENIX, $\sqrt{s}$ = 62.4 GeV, 3.1 < η < 3.8
0.2
0.1
0
$\langle p_T \rangle$ [GeV/c]
5
0
0
0.2
0.4
0.6
x_F

The famous sign change of the Sivers fct.

critical test for our understanding of TMD's and TMD factorization

Twist-3 formalism predicts the same

QCD:



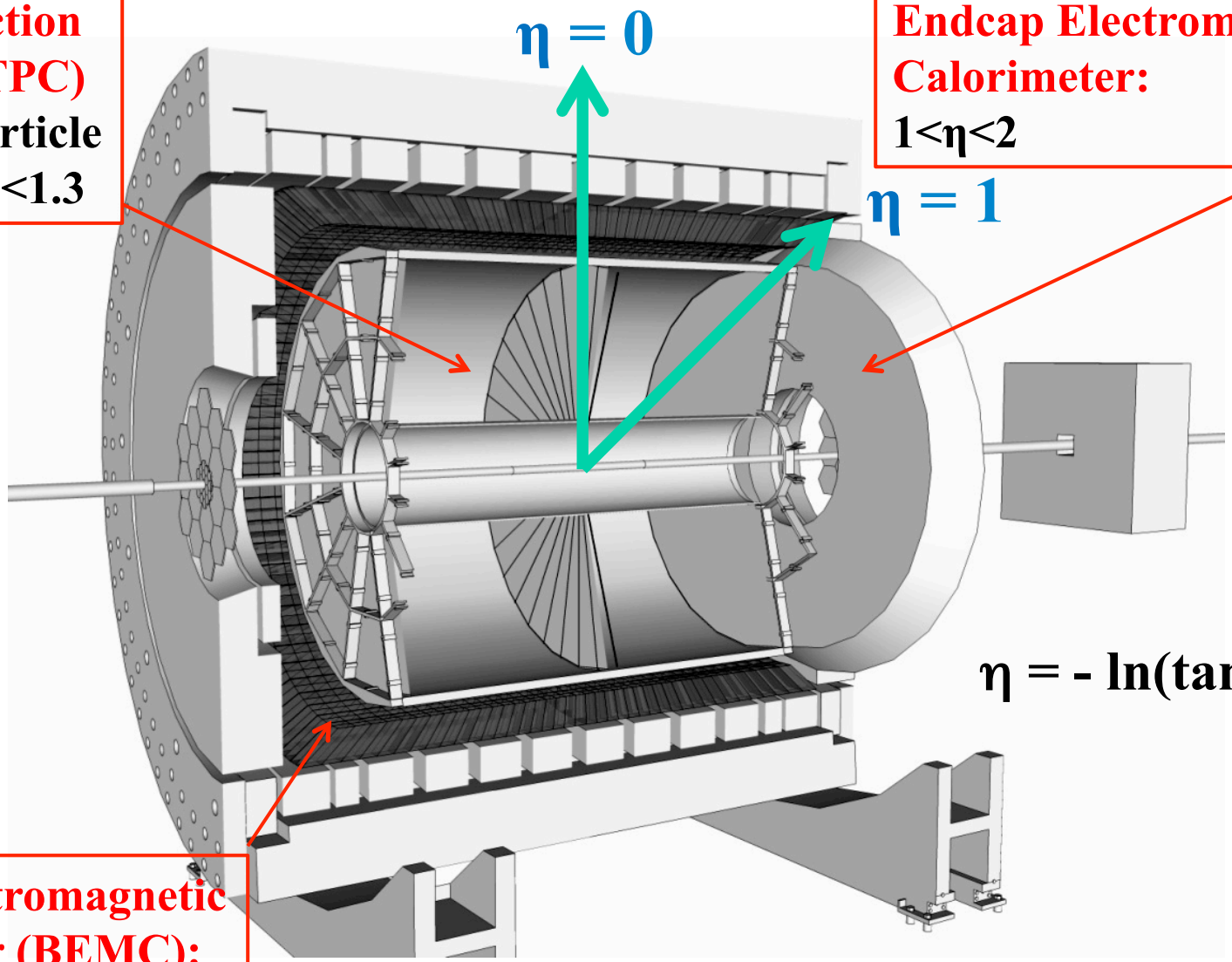
A_N(direct photon) measures the sign change through Twist-3

will also be A_N(DY) and $A_N(W^{+/-},Z^0)$ test of TMD evolution

All three observables can be attacked in one 500 GeV Run by STAR

STAR Detector

Time Projection Chamber (TPC)
Charged Particle Tracking $|\eta|<1.3$



Endcap Electromagnetic Calorimeter:
$1<\eta<2$

$$\eta = -\ln(\tan(\theta/2))$$

Barrel Electromagnetic Calorimeter (BEMC):
$|\eta|<1$

STAR