Probing Low x Gluons at STAR with Forward Asymmetry Measurements

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For the STAR Collaboration

PANIC 2014
August 25, 2014

U.S. DEPARTMENT OF ENERGY
Office of Science

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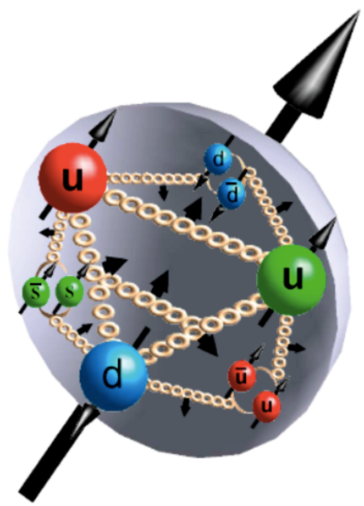
- Current Understanding of $\Delta g(x)$
- STAR Detector and Datasets
- Pushing to Low x with Forward π^0's
  - In the Endcap
  - In the Forward Calorimeter
- Prospects for Very Low x with Dijets and a Calorimeter Upgrade

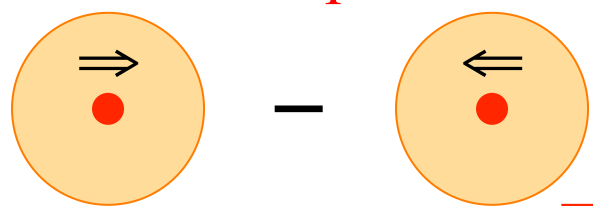
Contributions to the Proton's Spin



Consider proton moving right

Proton spin ⇒

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



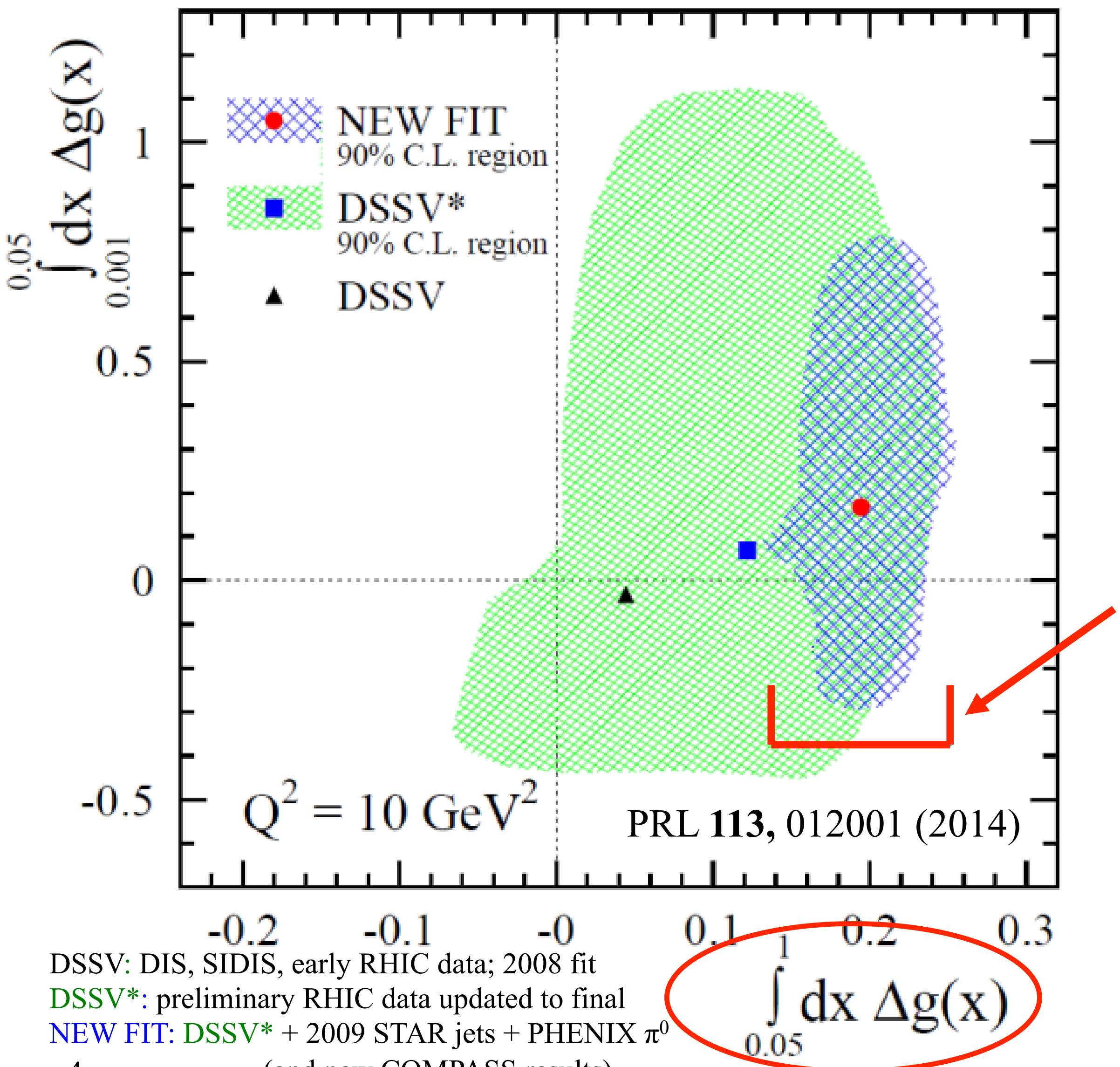
Longitudinal Polarization

Polarized DIS: ~0.3
Puzzling for ~25 years

Relatively poorly constrained
But ΔG coming into focus!

Proton spin sum rule: $$\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\overbrace{\Delta G+L_q+L_g}$$

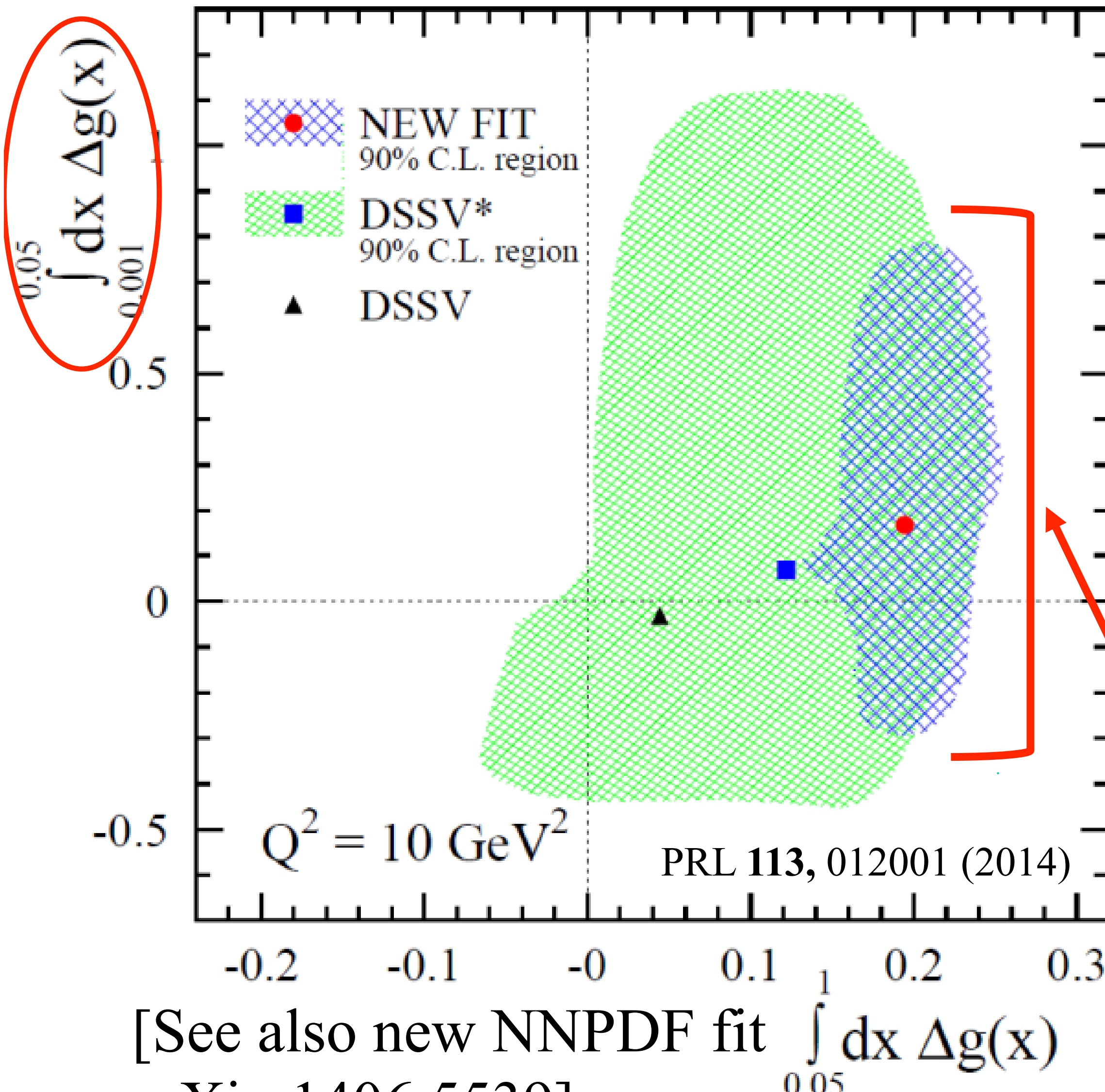
New DSSV Fit – G Comes into Focus



DSSV: DIS, SIDIS, early RHIC data; 2008 fit
DSSV*: preliminary RHIC data updated to final
NEW FIT: DSSV* + 2009 STAR jets + PHENIX π^0
(and new COMPASS 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 – Low x Remains Blurry



- 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]

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Solenoidal Tracker at RHIC

π^0 **Measurements**:

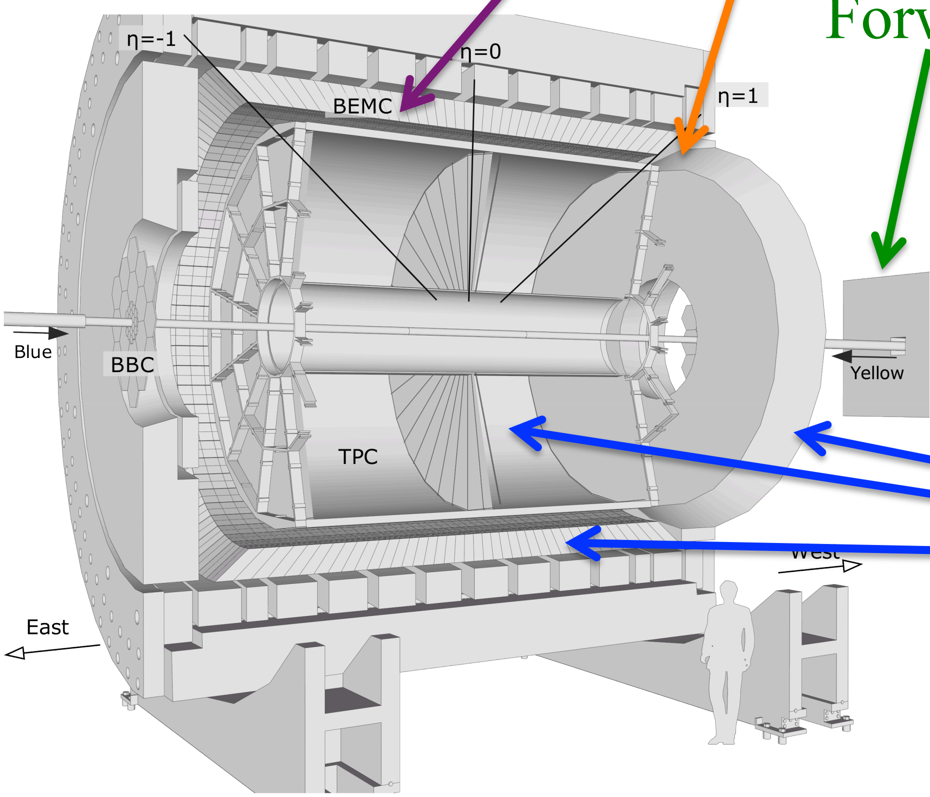
Barrel ElectroMagnetic Calorimeter (BEMC),

Endcap ElectroMagnetic Calorimeter (EEMC),

and

Forward Meson Spectrometer (FMS)

FPD (east) not shown



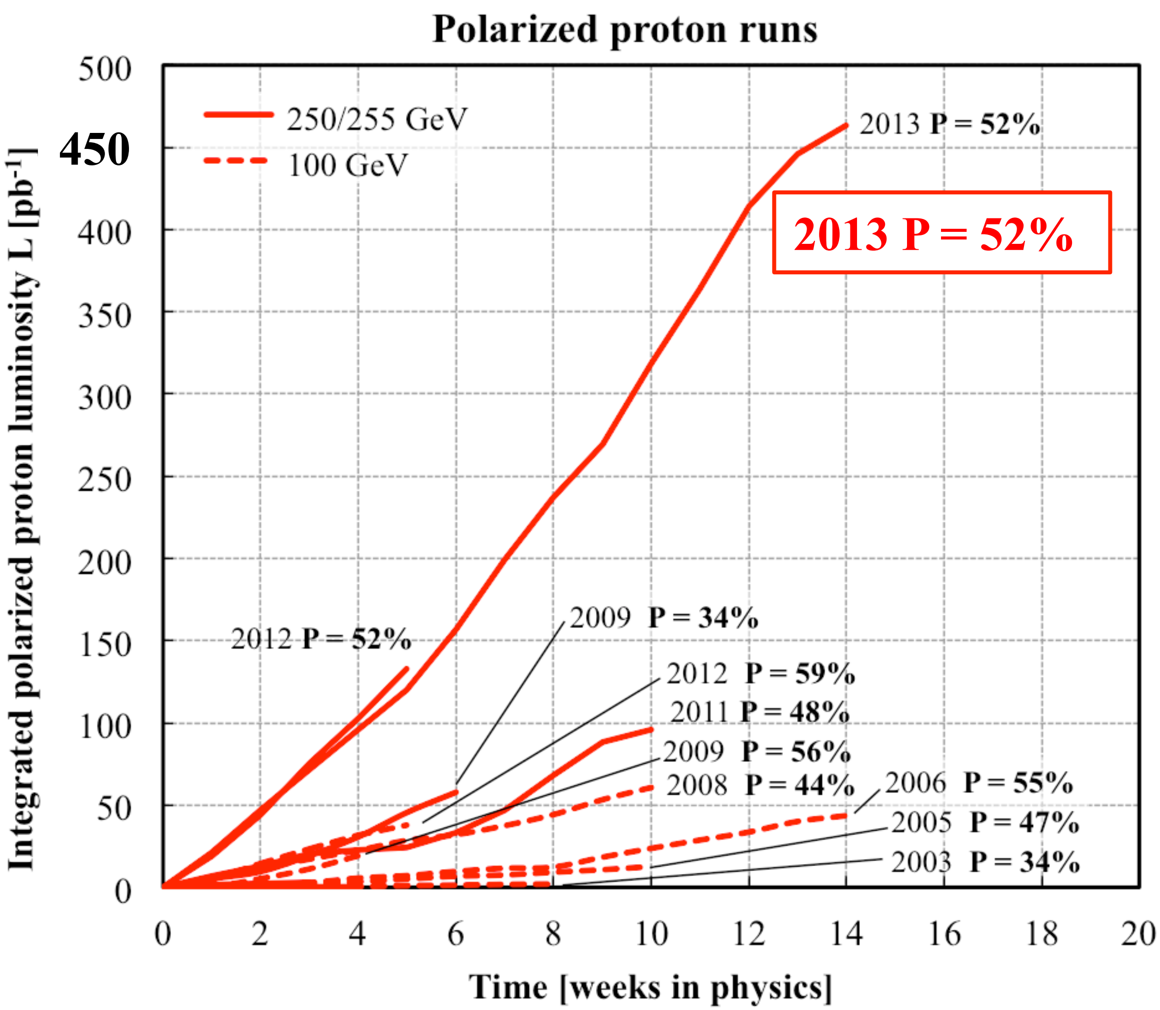
Current Jet Measurements:

TPC +

Barrel + Endcap EMC

Datasets from RHIC at STAR

- Published results from 2006 longitudinal dataset at 200 GeV
  - ~7 pb^{-1} recorded
- Work in progress from
  - 2009 200 GeV long. ~25 pb^{-1}
  - 2012 510 GeV long. ~80 pb^{-1}
  - 2013 510 GeV long. ~300 pb^{-1} *recorded*
- Caveats
  - Other datasets, publications, for other measurements
  - 2013 >450 pb^{-1} *delivered*
  - Prescales can affect individual measurements



Probing Low x Gluons at STAR with Forward Asymmetry Measurements

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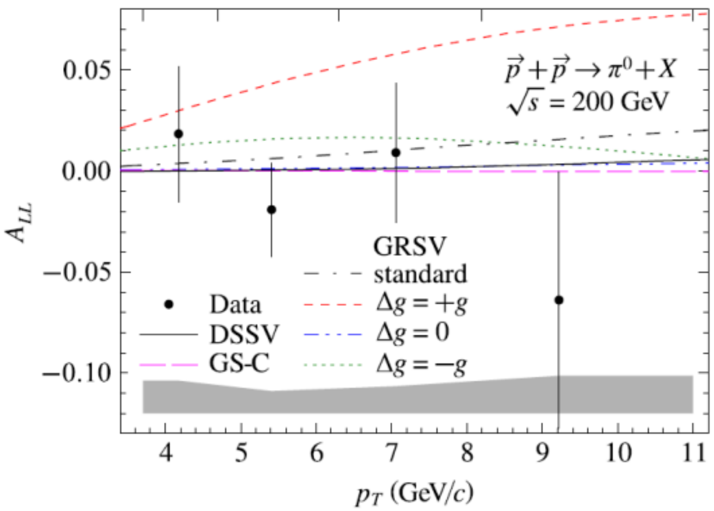
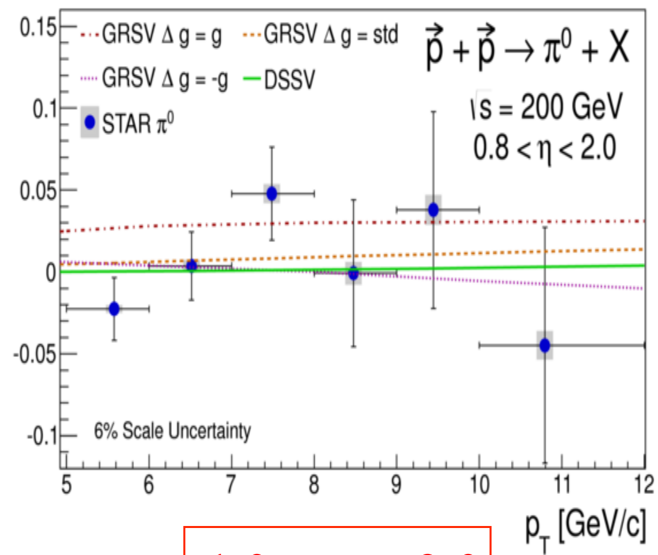
Probing Low x Gluons With π^0 A_{LL}

PRD 80, 111108(R) (2009)



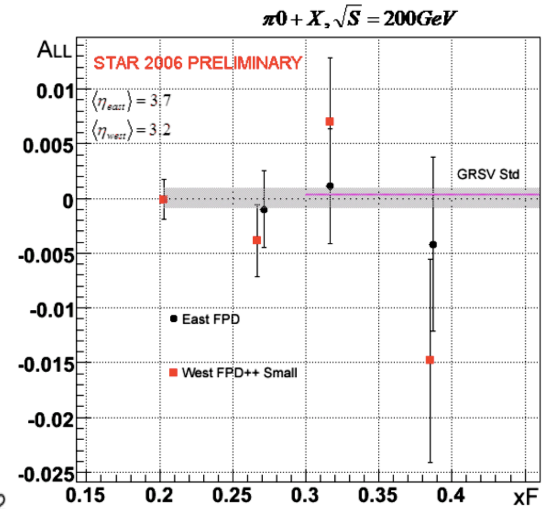
$|\eta| < 0.95$

PRD 89, 012001 (2014)



$1.0 < \eta < 2.0$

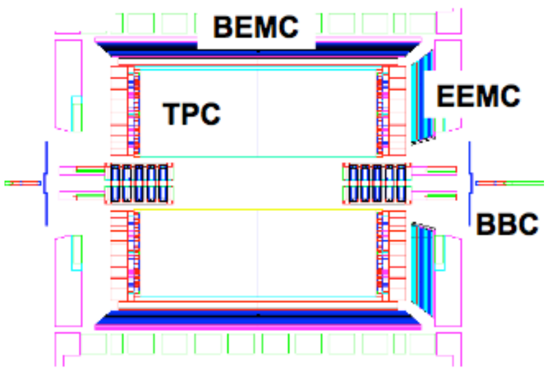
Wissink SPIN2008

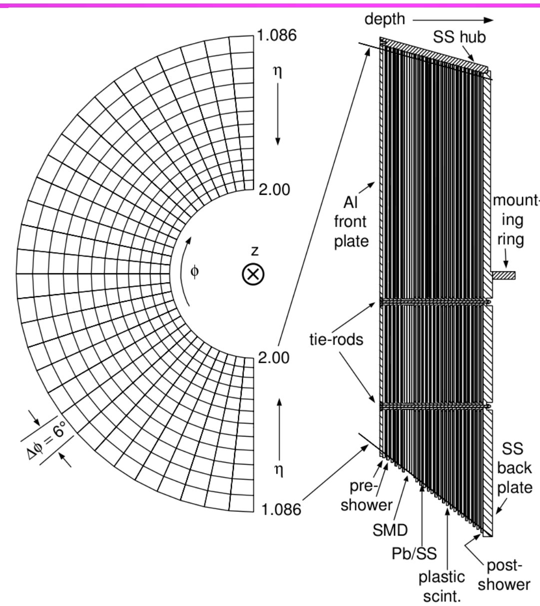


$\eta = 3.2, 3.7$

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

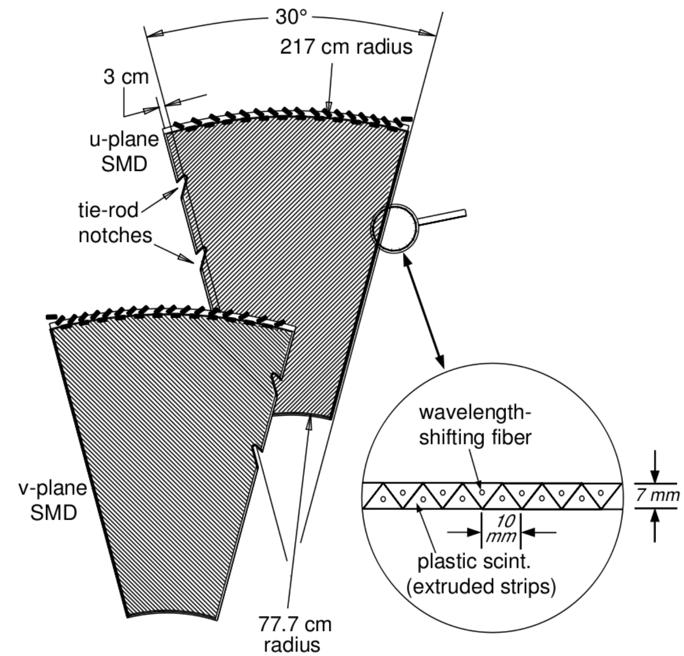
STAR's Endcap Electromagnetic Calorimeter





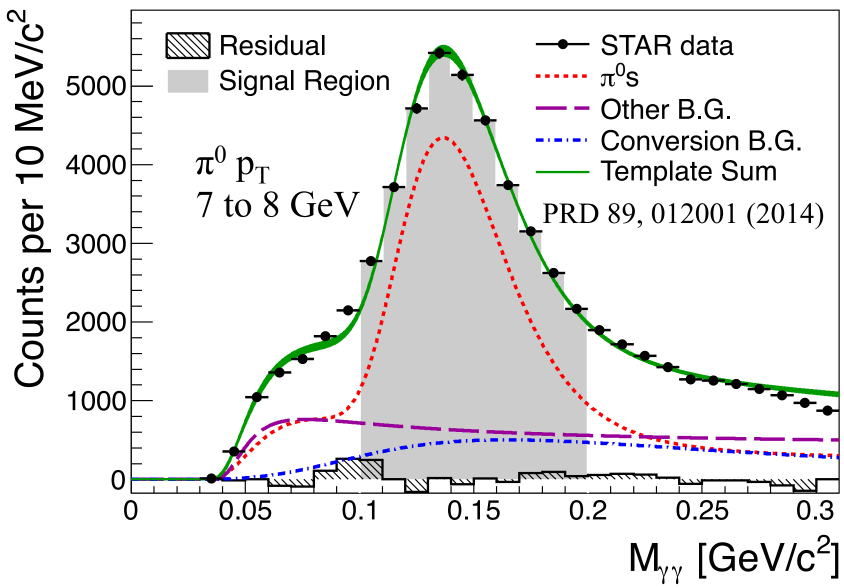
- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm

- 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

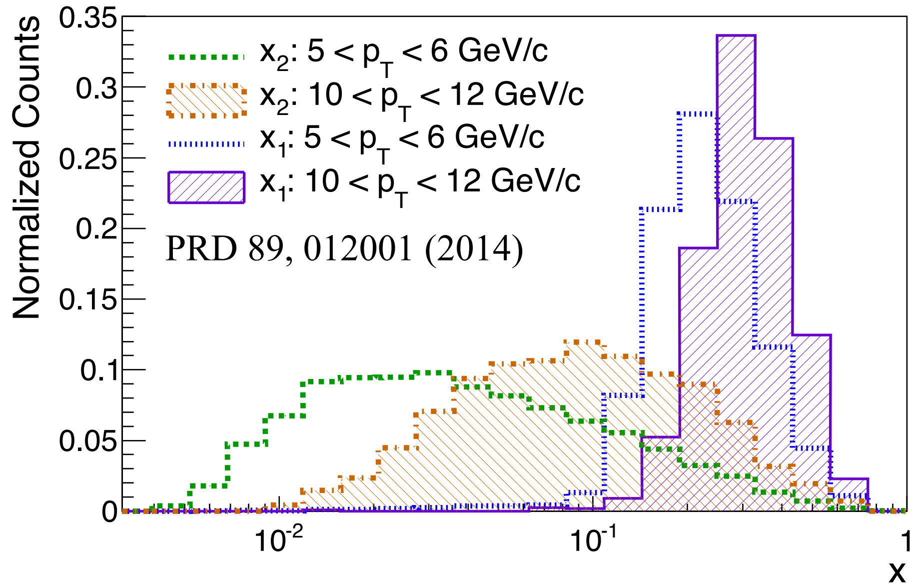


π^0 Background and Cross-Section Computation $0.8 < \eta < 2.0$ with 2006 Dataset

- Inclusive π^0 mass distribution fit to MC templates, in bins of π^0 p_T
  - Signal
  - Conversion BG (π^0 candidate is from gamma → e+ e-)
  - All other BG (extra or missing photons, π^0 candidate is gamma and e-, etc.)
  - Shapes from MC, relative fraction (and thus signal fraction) extracted from fit to data



STAR π^0's at low and high p_T,
for sqrt(s) 200 GeV
(PYTHIA, unpolarized CTEQ 5L)



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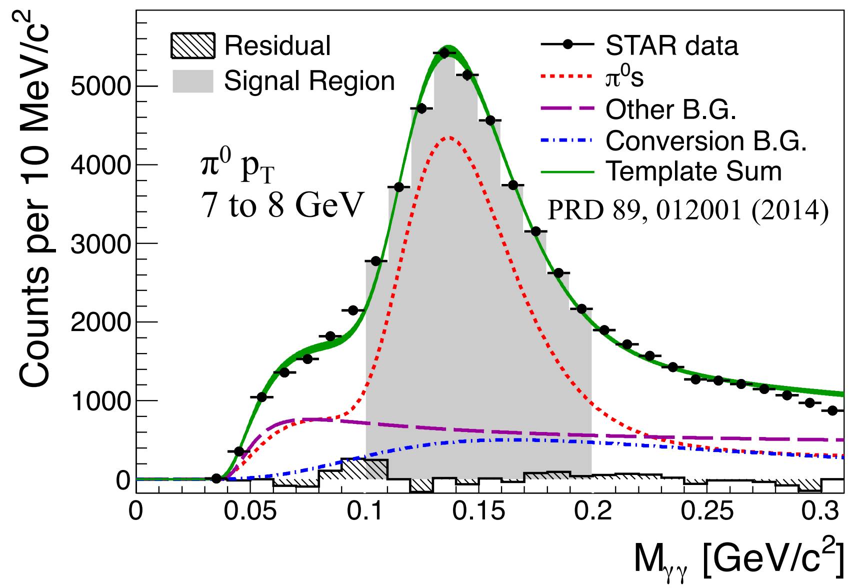
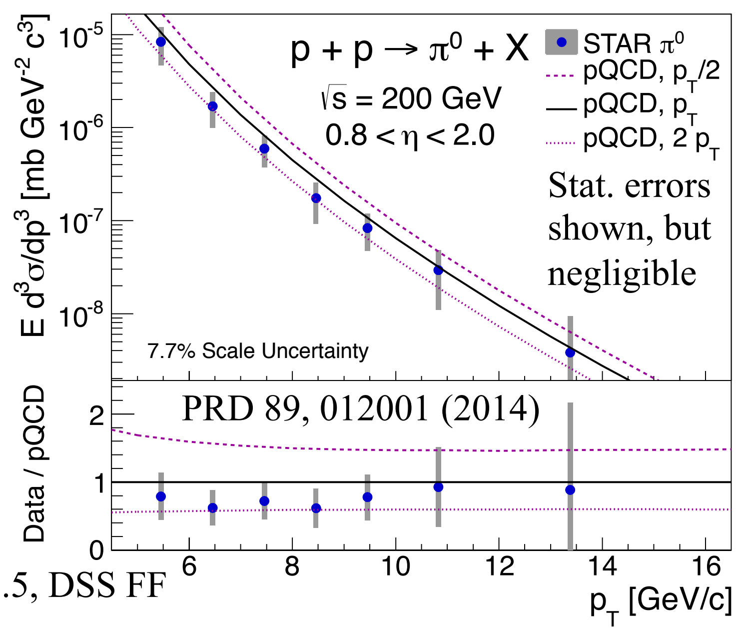
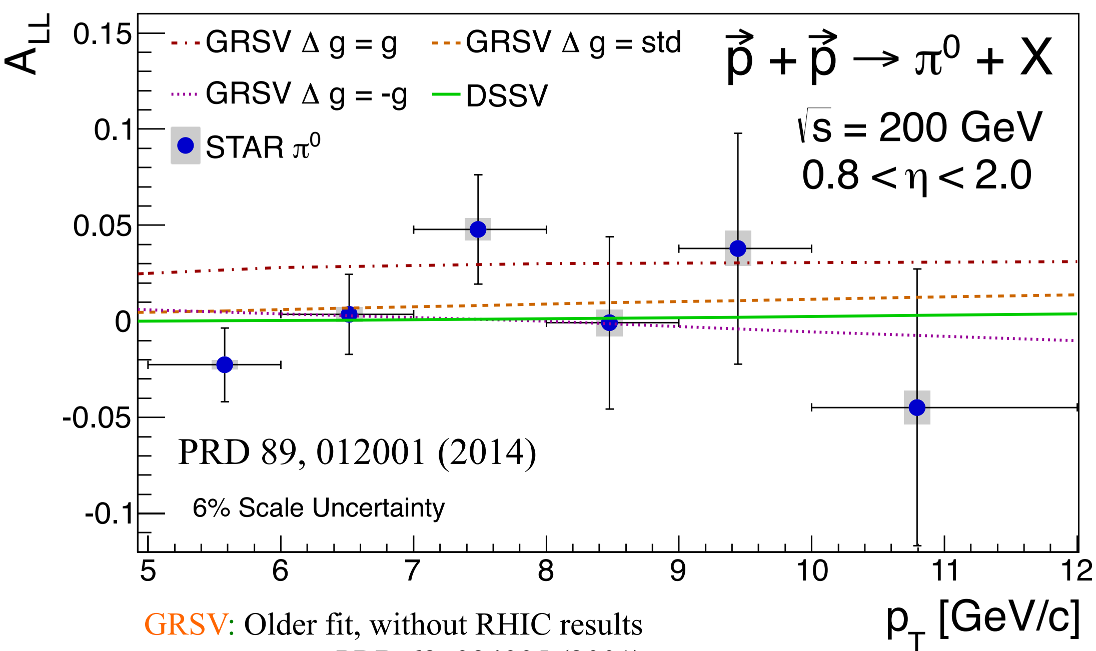
  - All other BG (extra or missing photons, π^0 candidate is gamma and e-, etc.)
  - Shapes from MC, relative fraction (and thus signal fraction) extracted from fit to data
- Lowest analyzed bin is 5-6 GeV π^0 p_T
  - Data-MC agreement unsatisfactory below this
  - Large amount of passive material, not well modeled
- Unfolded cross section calculated with a "smearing matrix"
  - Dominant systematic is EEMC energy scale
  - Consistent with NLO pQCD (thanks M. Stratmann)
    - B. Jaeger et al., Phys. Rev. D 67, 054005 (2003) CTEQ 6.5, DSS FF





A_{LL} in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

- Raw longitudinal asymmetry corrected for
  - Luminosity asymmetries (small)
  - Beam polarizations
  - Background asymmetries
    - Estimated from mass sidebands, and consistent with zero (with uncertainty ~0.01)
- Statistical error (bars) dominate
- Systematic error (boxes)
  - Signal fraction uncertainties from template fits
  - Uncertainty on background asymmetry
- Integrated across p_T probably constrains GRSV Δg-max?
- PRD 89, 012001 (2014)

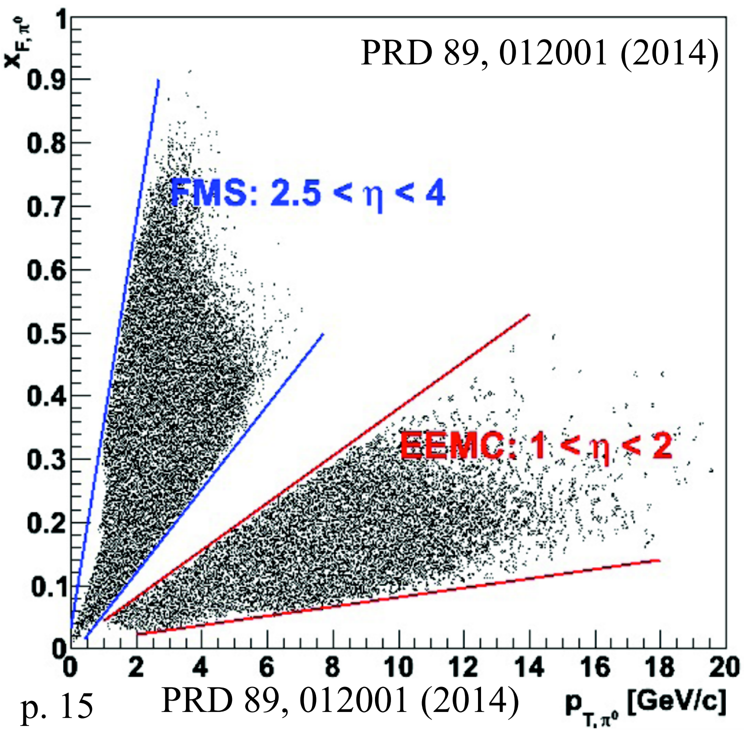


GRSV: Older fit, without RHIC results
PRD 63, 094005 (2001)
DSSV: First fit to include RHIC results
PRL 101, 072001 (2008)

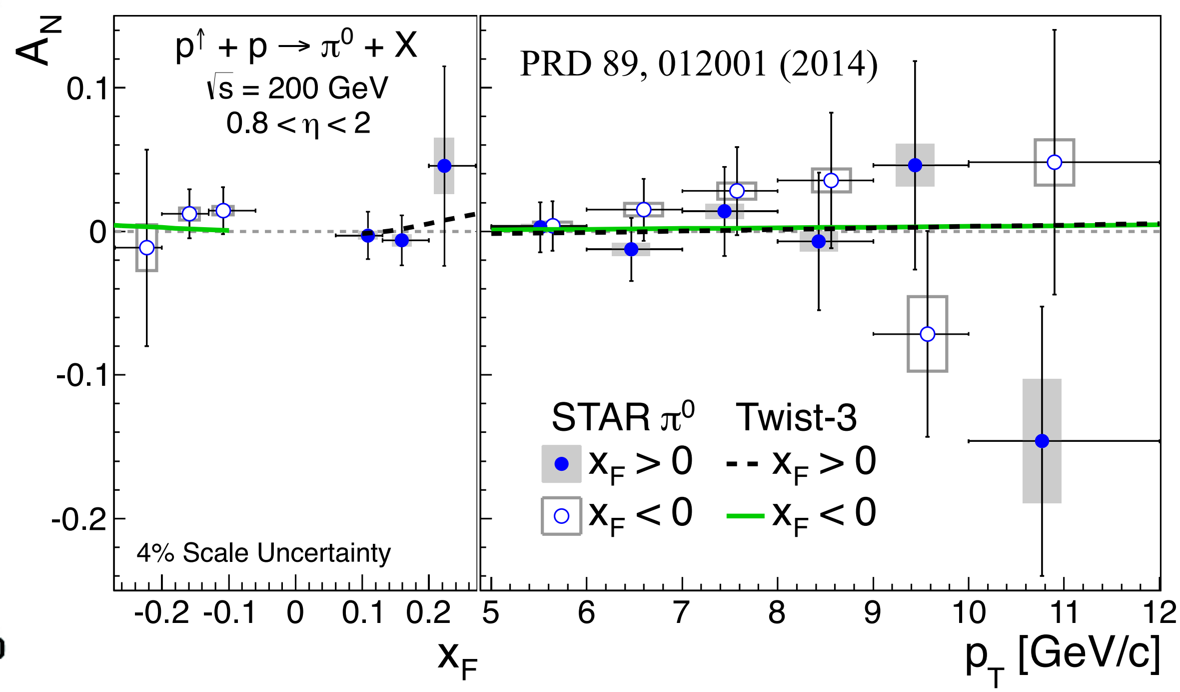
A_N in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

- Transverse asymmetries as well!
- Plotted in bins of π^0 p_T (integrated over $0.06 < x_F < 0.27$), and in bins of x_F
- Statistical error (bars) dominates over systematic error (boxes)
- Twist-3 prediction
  - K. Kanazawa and Y. Koike,
  - Phys. Rev. D 83, 114024 (2011)

STAR at sqrt(s) 200 GeV

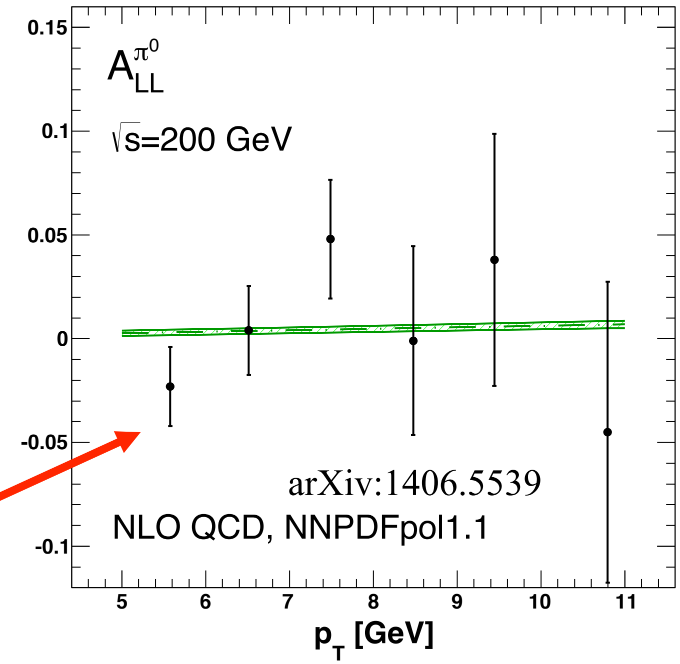


PRD 89, 012001 (2014)

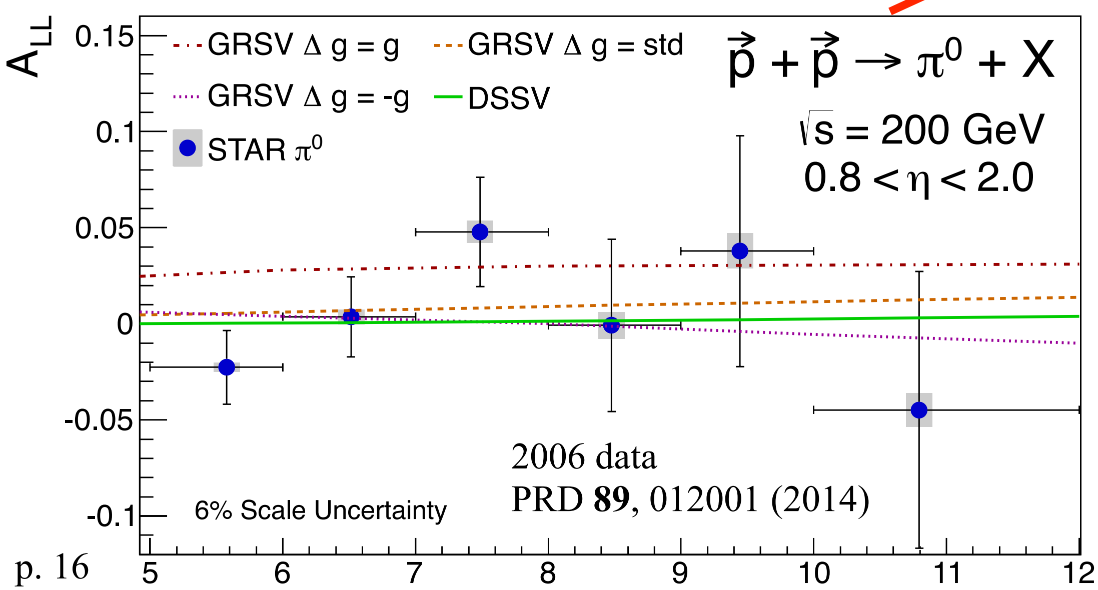


Updated Prediction for π^0 A_{LL} , $0.8 < \eta < 2.0$

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

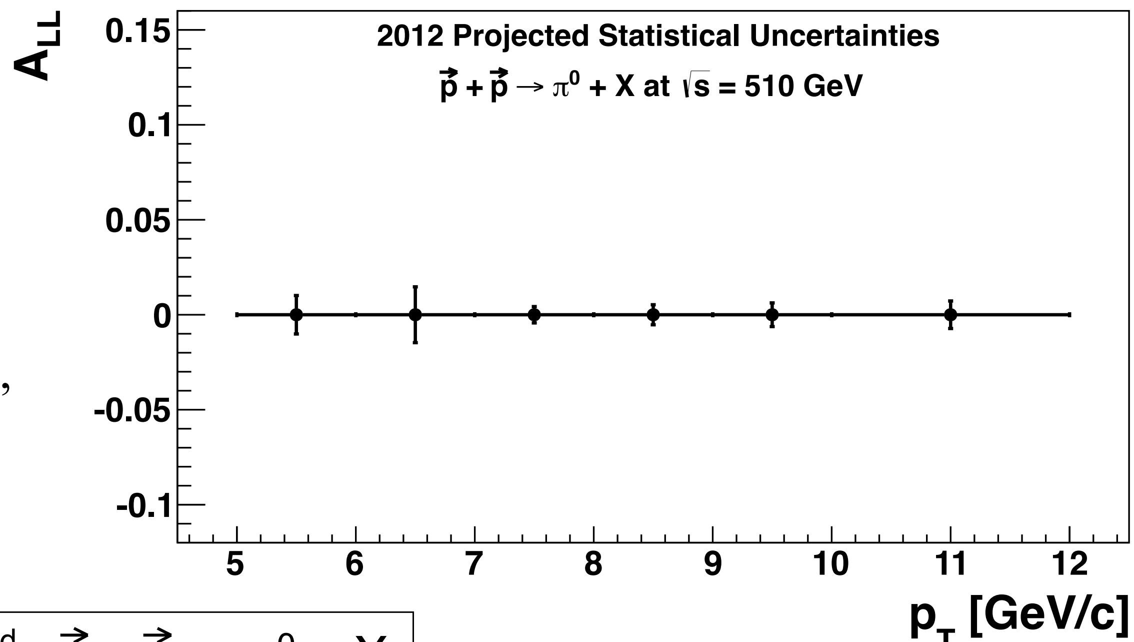


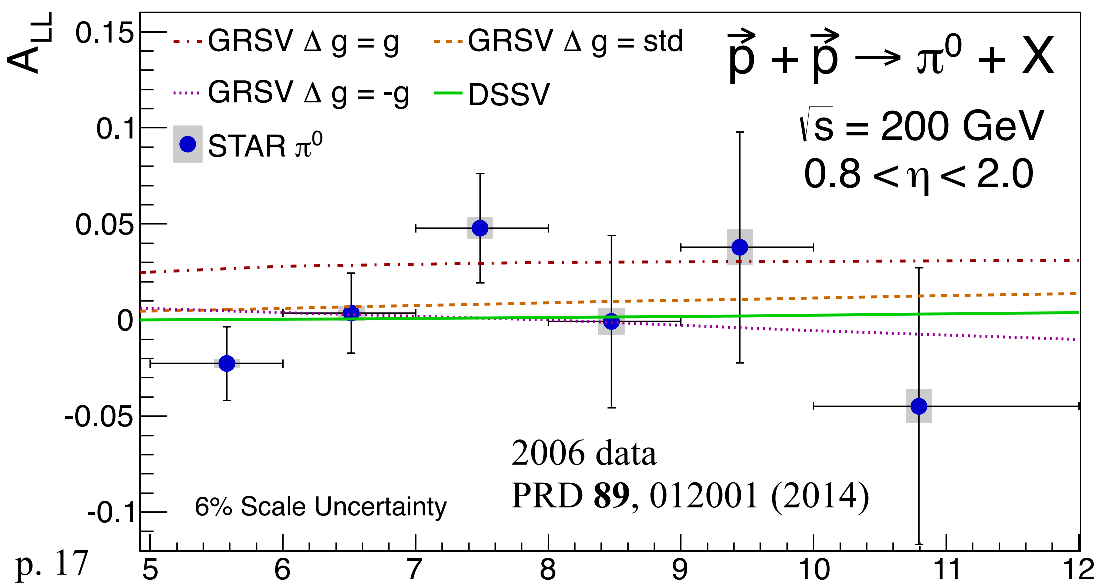
STAR data with NNPDF predictions



π^0 A_{LL} Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 the 2006 luminosity) at intermediate (endcap) pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown





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

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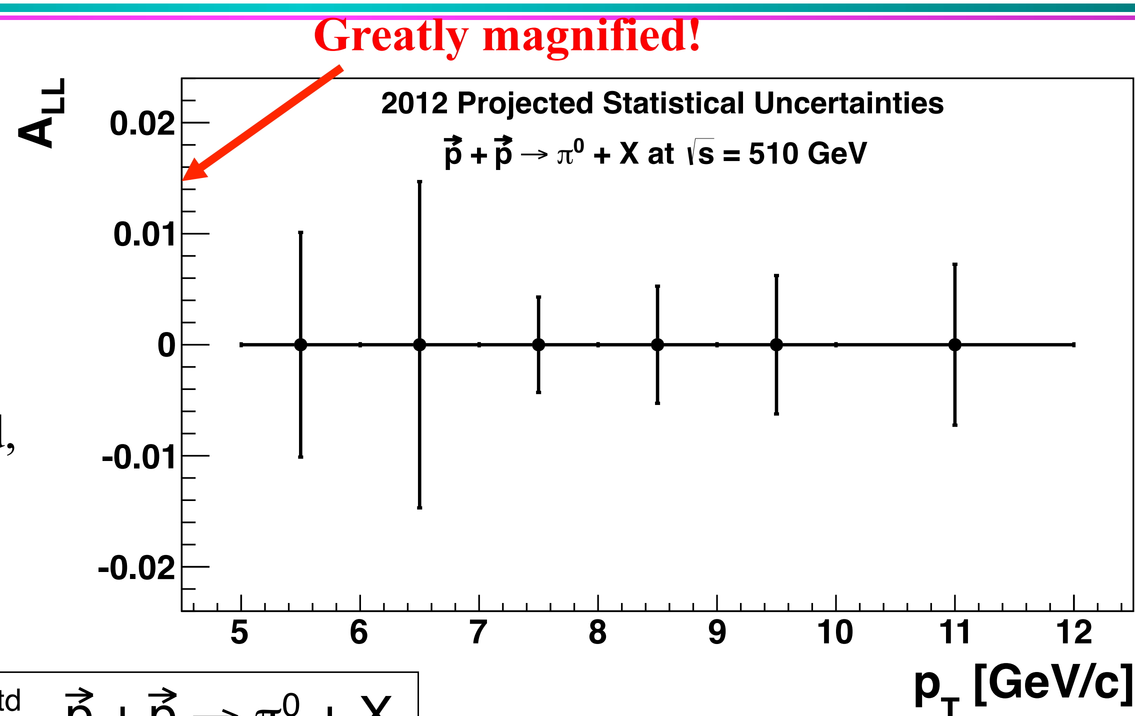
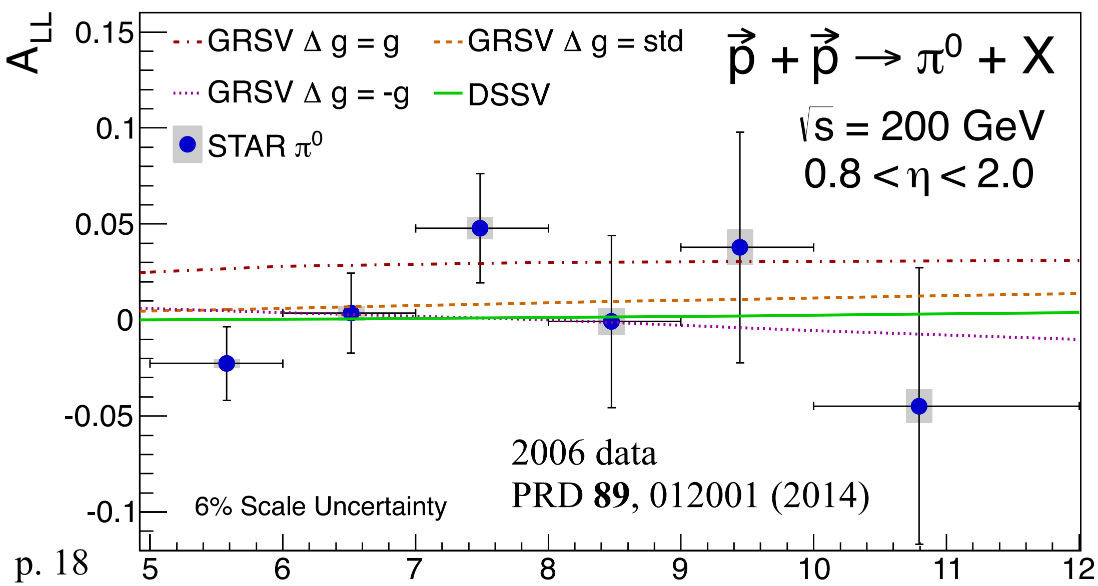




- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower *x* gluon

FMS
Pb Glass EM Calorimeter
pseudo-rapidity $2.7<\eta<4.0$
Small cells: 3.81x3.81 cm
Outer cells: 5.81 x 5.81 cm

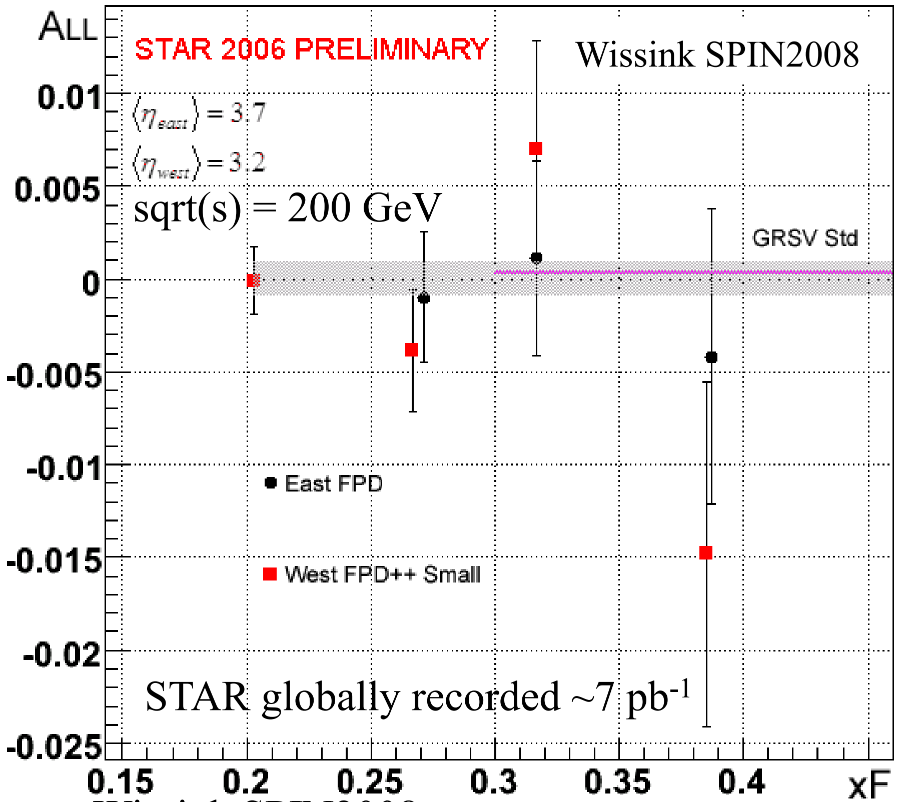
FPD EM Calorimeter
Small cells only
Two 7x7 arrays

STAR

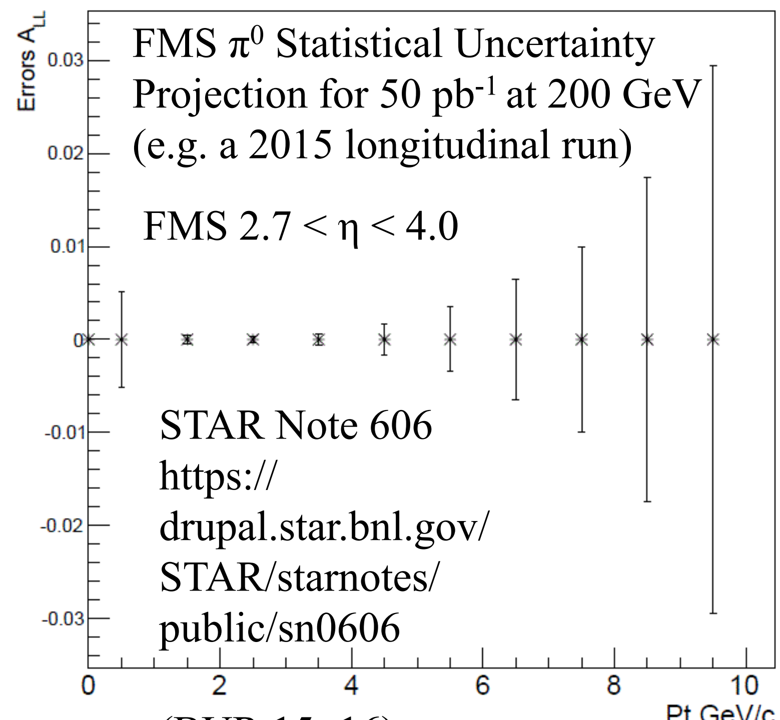
Forward EM Calorimetry In STAR.

π^0 A_{LL} Prospects in Forward Calorimeters

- Pushing even further forward, with the FPD and FMS
- Work underway with large 2012 and 2013 datasets at 510 GeV
  - Prescales lead to effectively ~50 pb^{-1} in 2012, focused at high p_T
    - And ~10 pb^{-1} in 2013, focused at lower p_T
  - An older preliminary result also exists



Wissink SPIN2008



(BUR 15+16)

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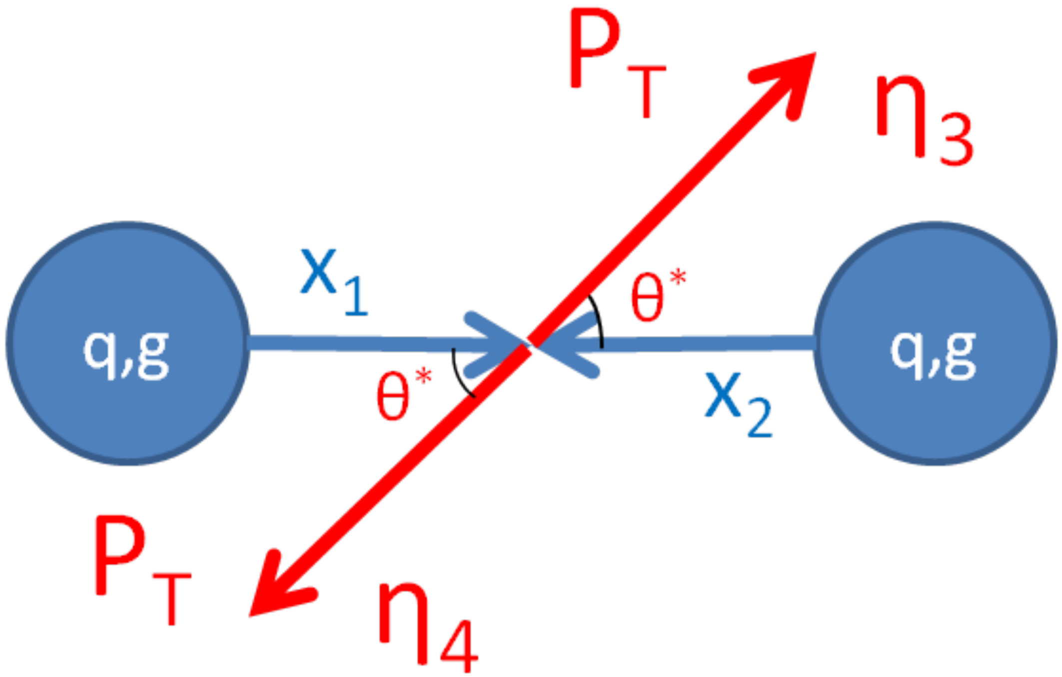
- **Prospects for Very Low *x* with Dijets and a Calorimeter Upgrade**

Dijet Measurements



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

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

$$M = \sqrt{x_1 x_2 s}$$

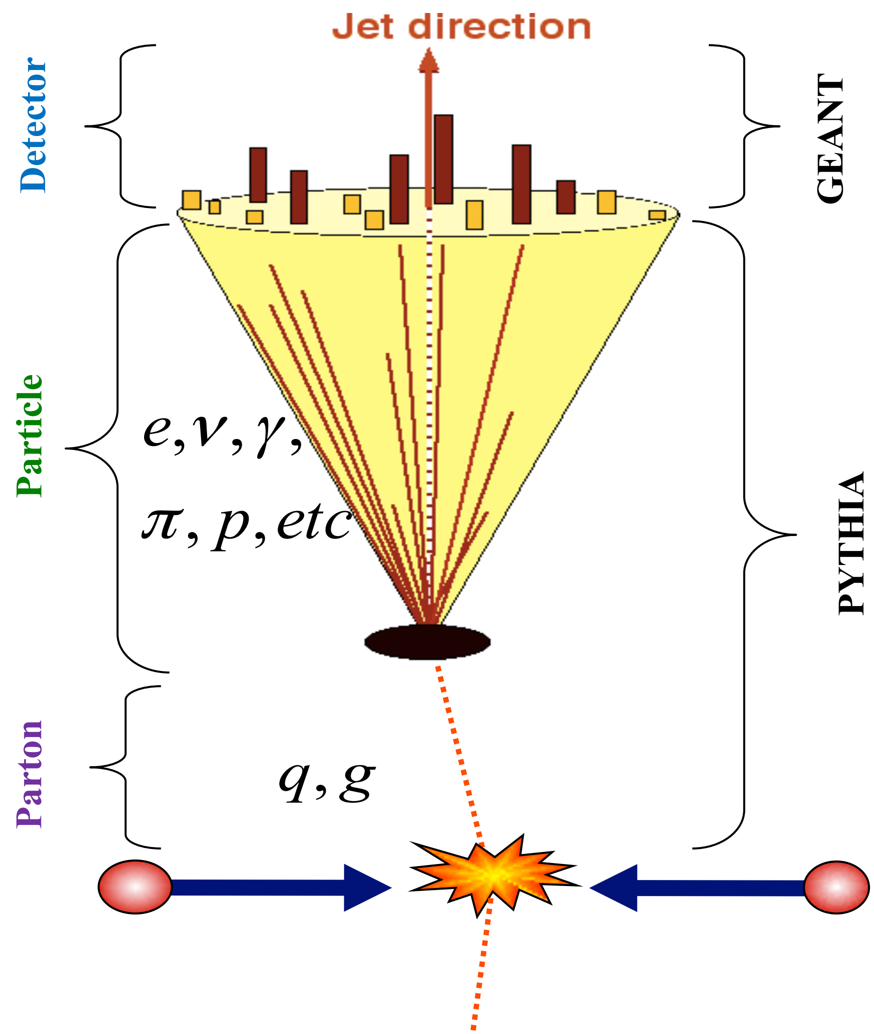
$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

$$|\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

- Inclusive measurements have been the workhorse of STAR ΔG program to date
- Broad *x* range sampled in each p_T bin
- Dijet or other correlation measurements which reconstruct the full final state are sensitive to initial kinematics at leading order
    - Prospect of mapping out the shape of $\Delta g(x)$

Jet Reconstruction

Jet Levels MC Jets



STAR Detector has:

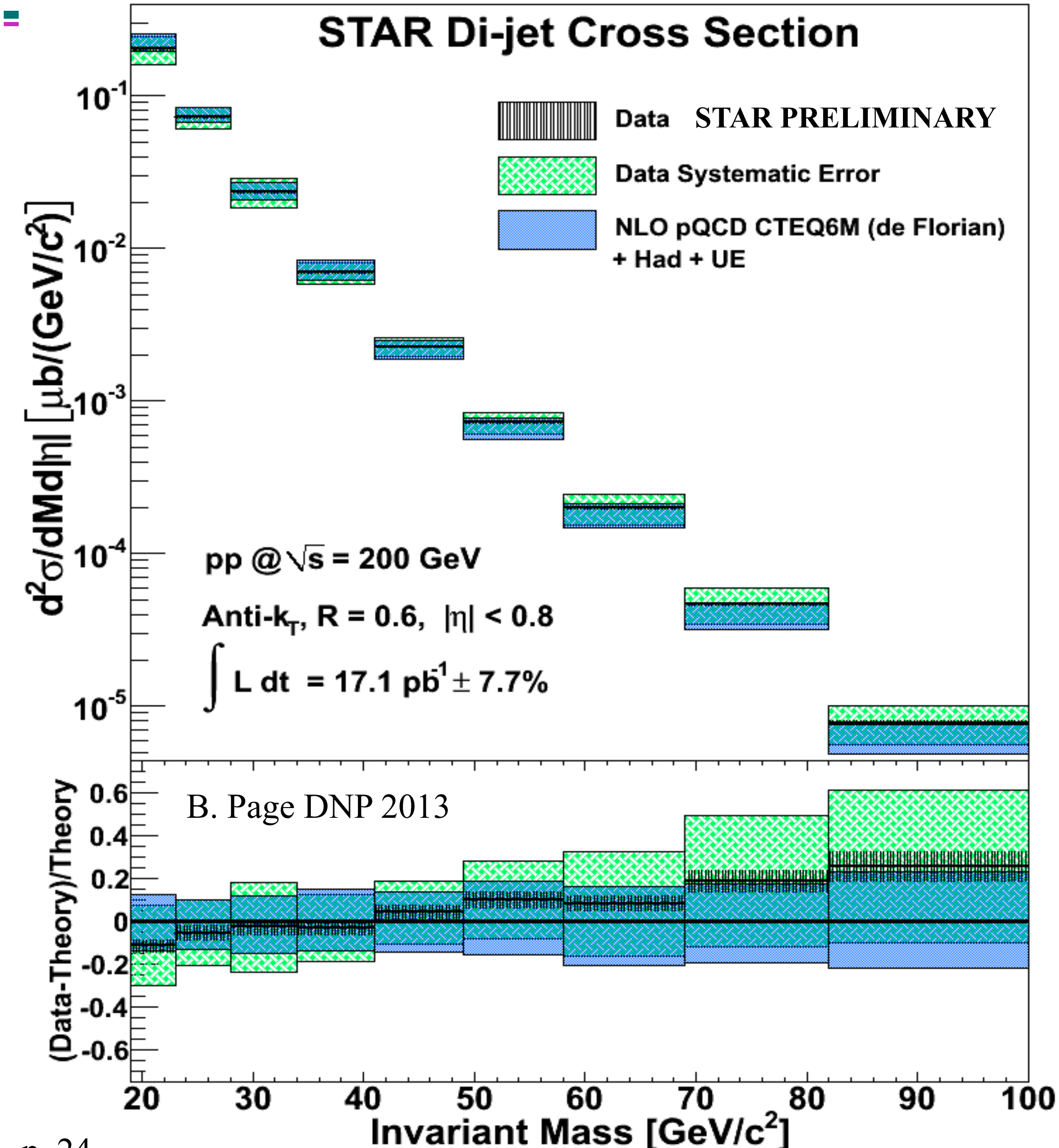
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-K_T Jet Algorithm:

- Radius = 0.6
- Used in both data and simulation

2009 Dijet Cross Section Results

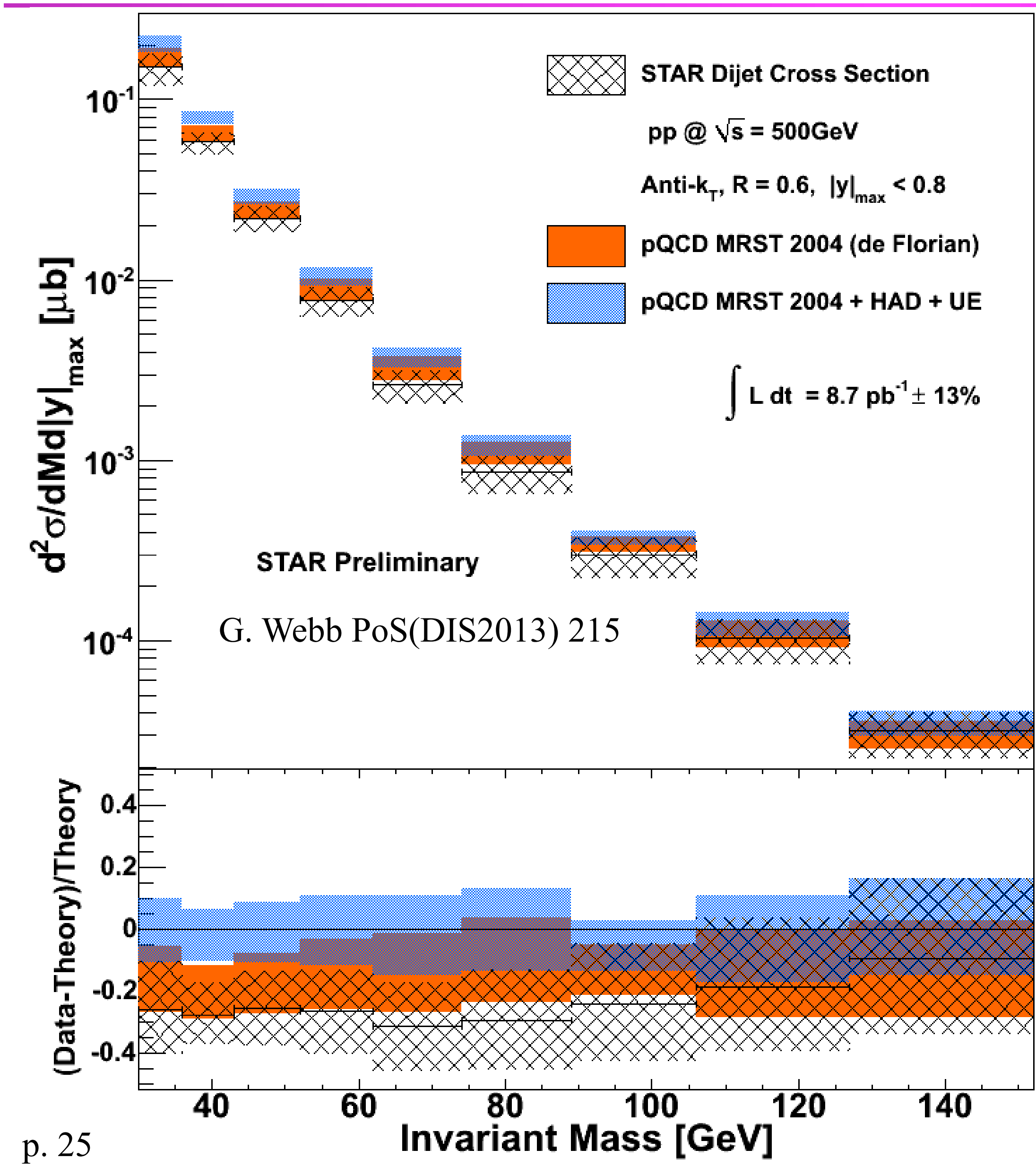


Thickness of vertical black hashing represents size of statistical error on the measurement

Green hatched box is symmetric about data point and is the quadrature sum of all systematic errors

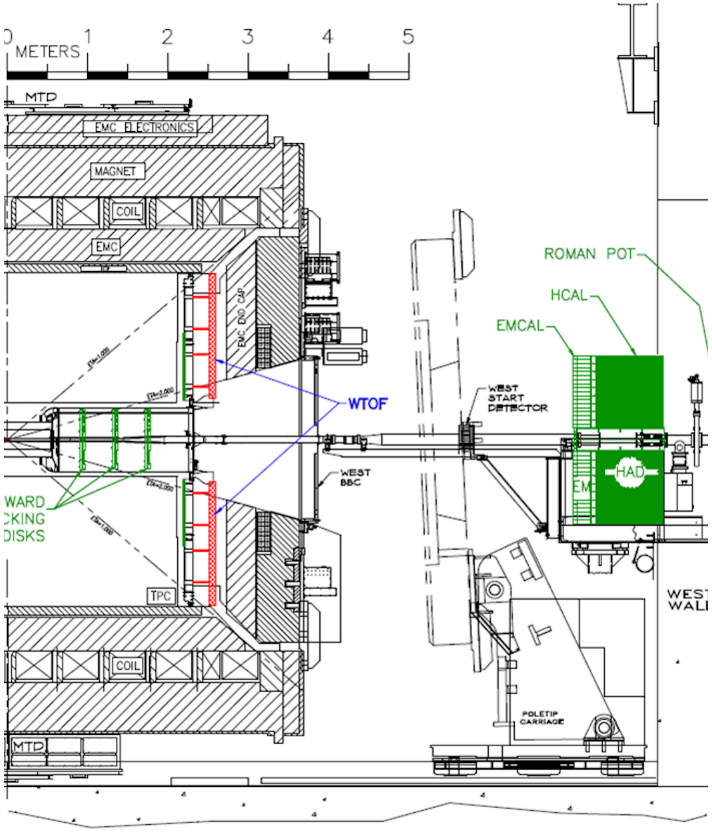
Thickness of blue box represents error on theory determined by changing factorization and renormalization scales by factor of 0.5 and 2

2009 Dijet Cross Section at 500 GeV



- Also a preliminary 2006 dijet cross section at 200 GeV
  - T. Sakuma, M. Walker, Journal of Physics: Conference Series 295, 012068 (2011).

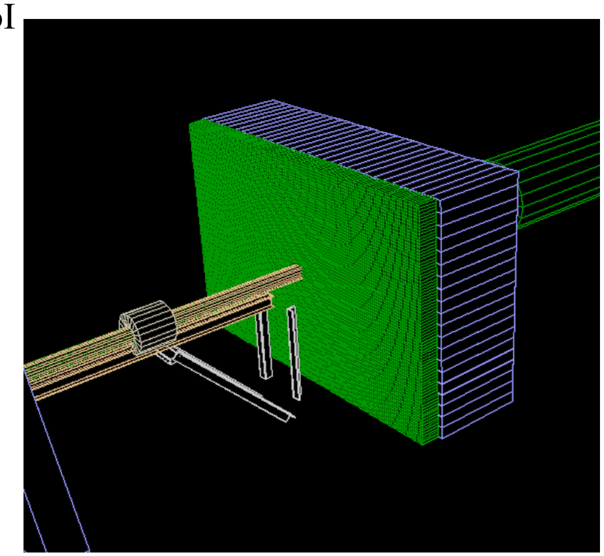
Probing *very* low *x* gluons with Forward Calorimeter Upgrade: 2020



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
STAR polarized p+p and p+A LoI



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

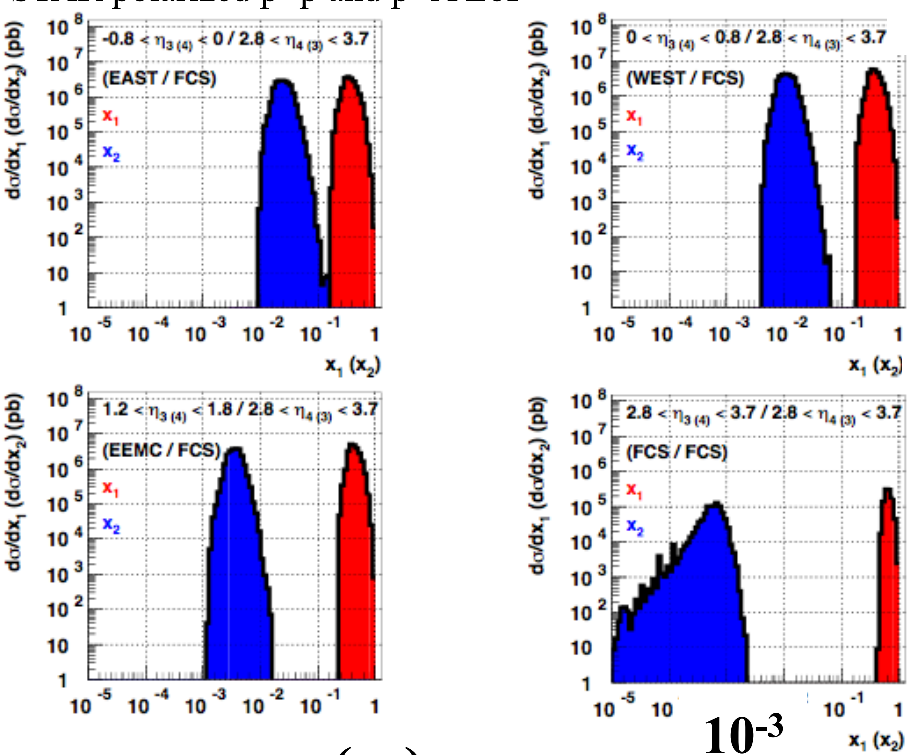
$L=1fb^{-1}$

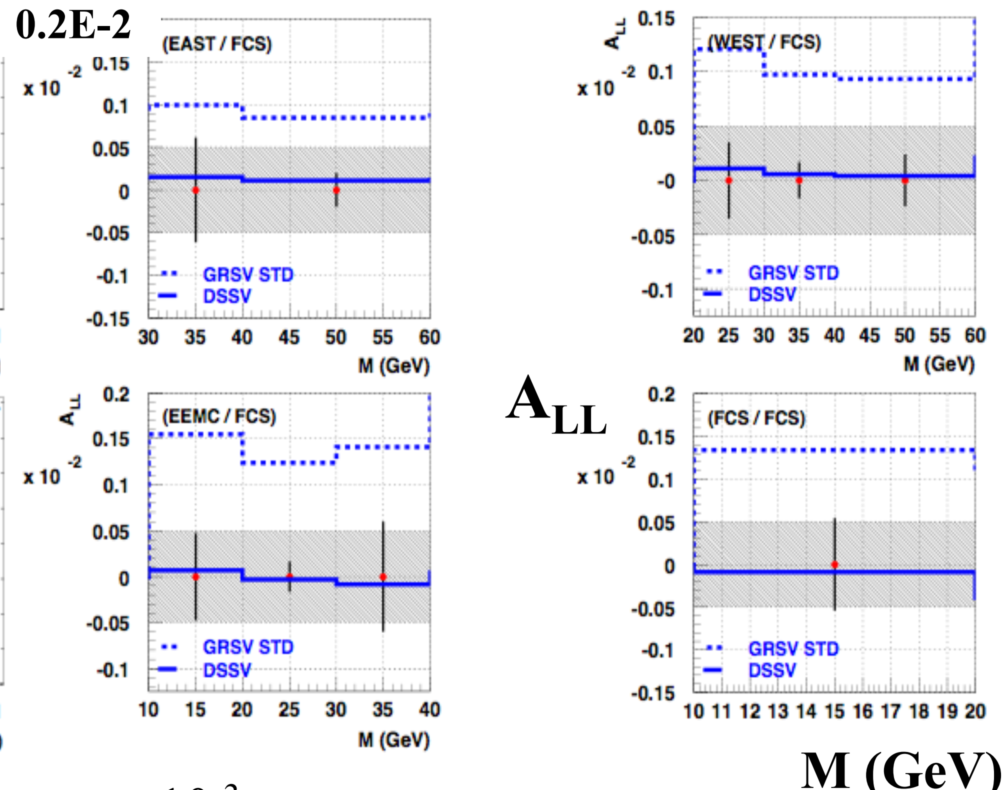
P=60%

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

STAR polarized p+p and p+A LoI

B. Surrow PoS(DIS2014) 241

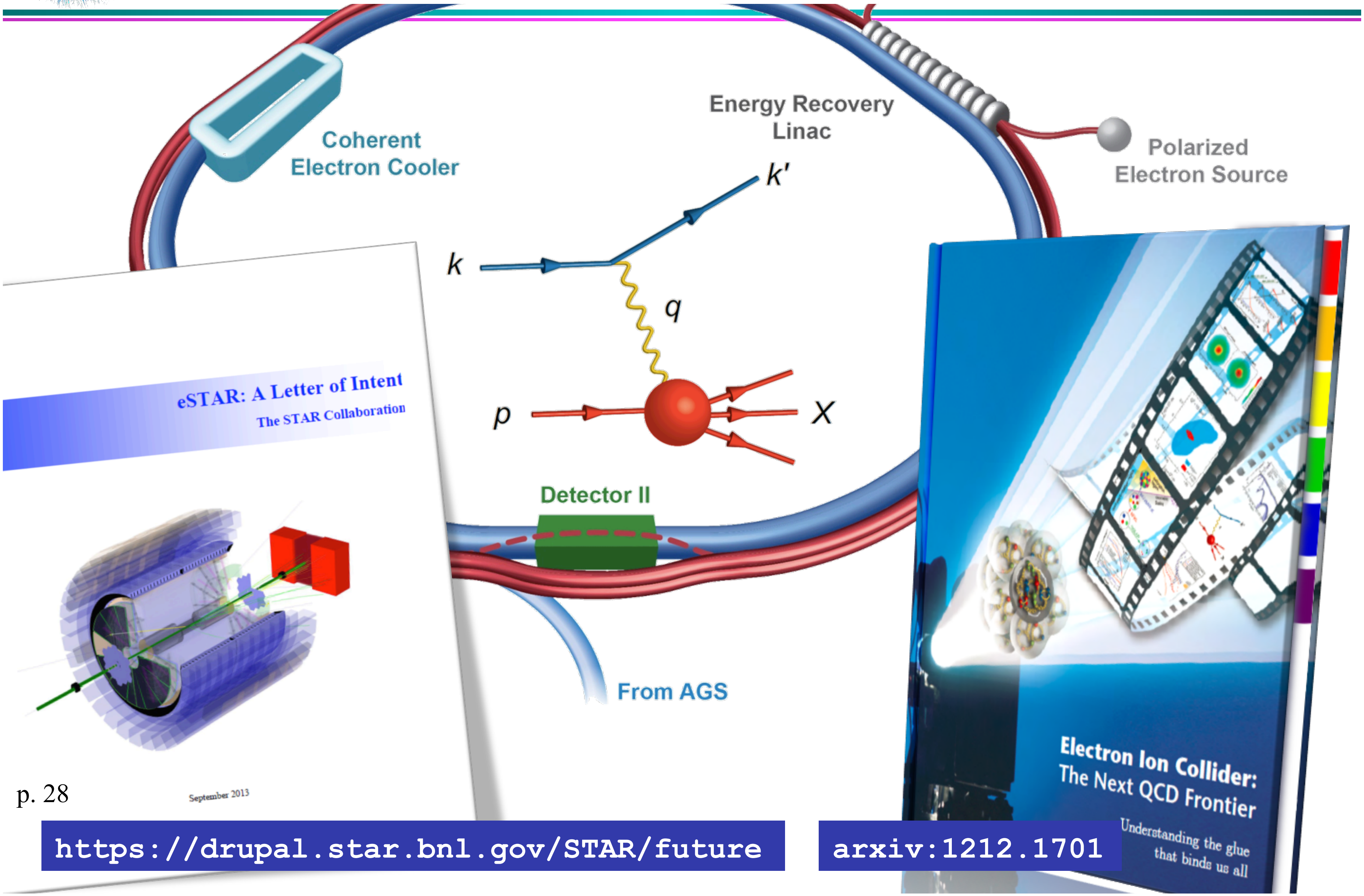




Probe gluons to $x \sim 10^{-3}$

An attractive probe at rather low x before the EIC era

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



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

arxiv:1212.1701

Conclusions

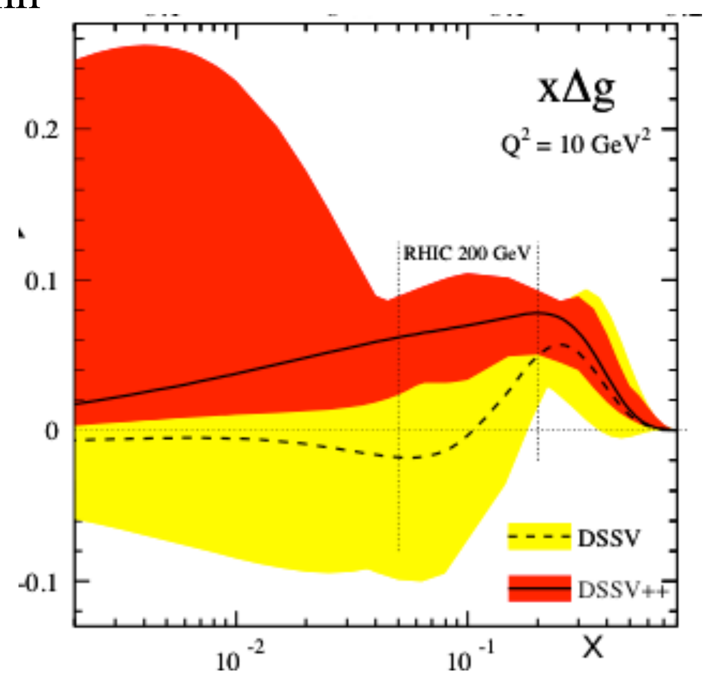
- **Δg coming into focus**, but still **poorly constrained at low *x***
- Can **push to lower *x* with forward measurements**, and higher sqrt(s)
- Proof of **principle result exists with π^0 A_{LL} in endcap** ($0.8 < \eta < 2.0$)
  - PRD 89, 012001 (2014)
  - Work underway with **large 2012 dataset at 510 GeV**
- Preliminary **π^0 A_{LL} with forward calorimeters** ($\sim 3 < \eta < \sim 4$)
  - Work underway with **large 2012 and 2013 datasets at 510 GeV**
- Preliminary **dijet cross sections**
  - **Exciting prospects for very low *x* gluons with upgraded calorimeter at forward η**
- **Large datasets on hand, analyses underway**
  - 2012, 2013
- **Detector upgrades continue**
  - Forward calorimetry: FPS+FMS 2015, FCS 2020
- **Continuing data taking planned**
  - 2015, 2016, and beyond
- **Stay tuned!**

Backup

- DSSV++

arXiv:nucl-ex/1304.0079

and this plot courtesy M. Stratmann



- DSSV 14

PRL **113,** 012001 (2014)

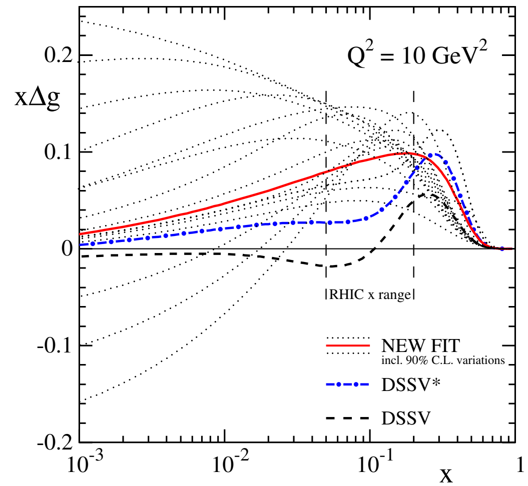
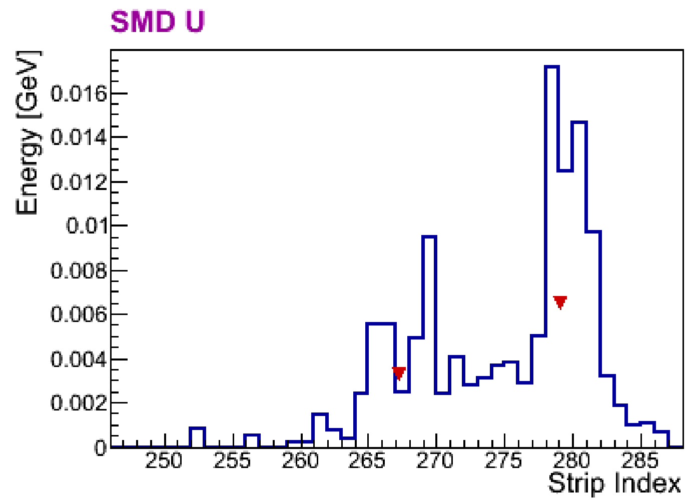
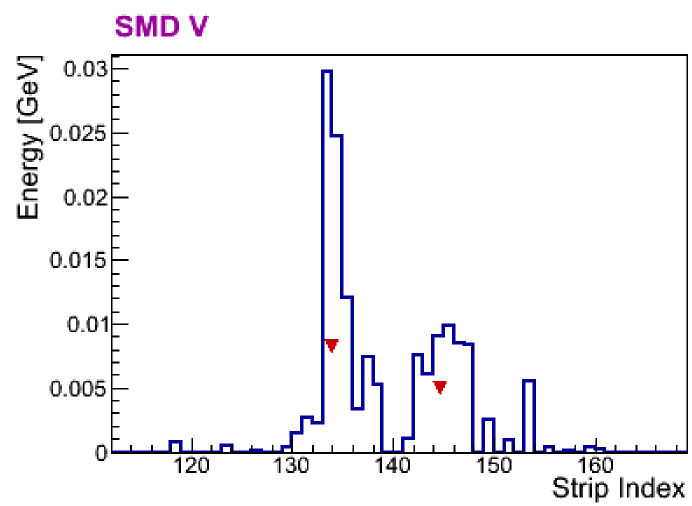


FIG. 1 (color online). Gluon helicity distribution at $Q^2 = 10\ \mathrm{GeV}^2$ for the new fit, the original DSSV analysis of [3], and for an updated analysis without using the new 2009 RHIC data sets (DSSV*, see text). The dotted lines present the gluon densities for alternative fits that are within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

Particle Reconstruction in the EEMC

- EM Particle Reconstruction Procedure
  - Identify clusters in the u and v strips
  - Determine which u and v clusters to associate with incident particles
  - Compute energy of incident particles (e.g. photons) from the towers
  - Compute momentum from the vertex and SMD cluster positions
- SMD response (right) in π^0 candidate event from data
  - Blue histograms show energy response per strip
  - Red triangles represent clusters drawn at mean strip position, and 10% of the cluster energy
- SMD clusters are found by
  - Smoothing the histogram using the method of J. Tukey
  - Identifying clusters as a strip above an energy threshold, with +-3 adjacent strips with monotonically decreasing energy
  - Setting cluster position to energy-weighted mean position of strips
- EM particle candidates built from pairs of u-v clusters
  - Clusters matched by energy of u and v strips
  - Required to have associated tower energy above threshold
  - Often have e.g. two photons from one π^0 deposited in one tower
- Reconstruction difficulties include
  - Upstream passive material: π^0 opening angle on the same order as photon conversions
  - Single particles sometimes look like two particles, and vice versa

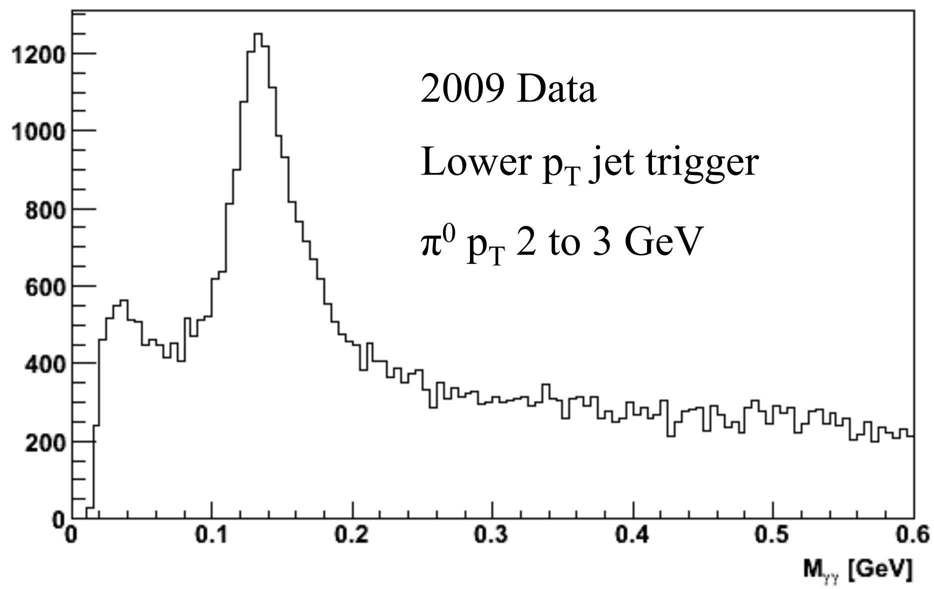




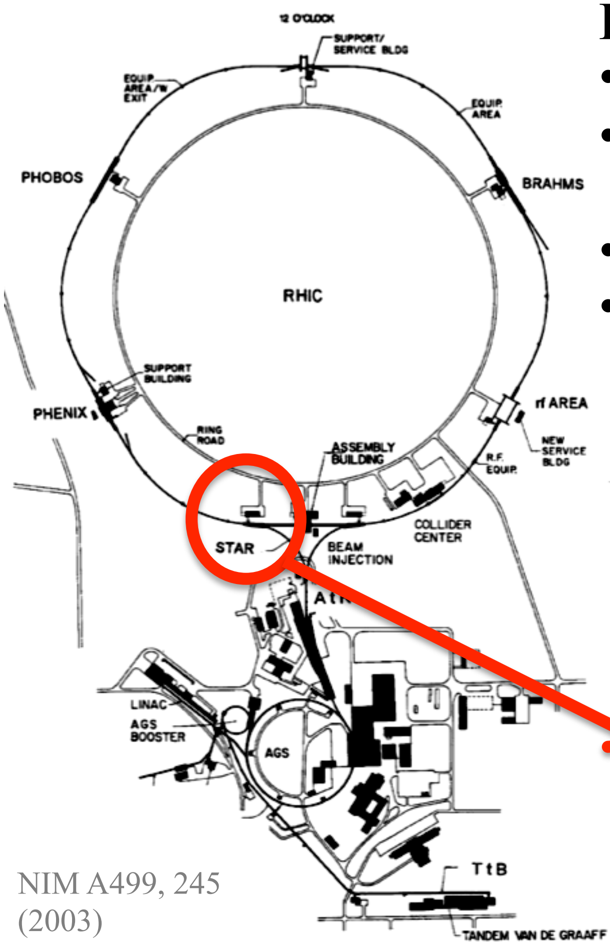
Prospects with 2009 Data, cont.

From DNP 2014

- Today showing a glimpse at only a tiny fraction of the 2009 datasets
- Larger jet trigger patch allows events with more jet background, softer π^0
- Background somewhat higher than for photon triggers
  - But can probe to considerably lower π^0 pT
  - Very reasonable π^0 peak
  - Possibility to extend reach to lower x?
- Work remains on MC validation, understanding of π^0's in "jettier" environment, etc.



Solenoidal Tracker at RHIC

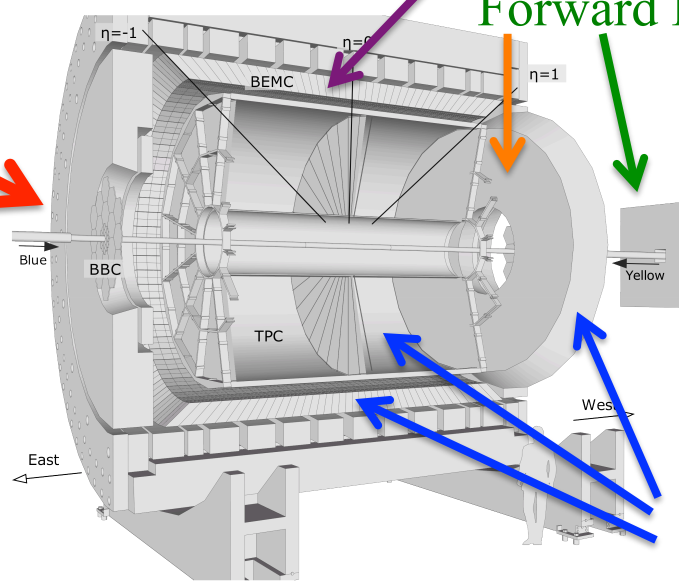


NIM A499, 245 (2003)

RHIC as Spin Collider

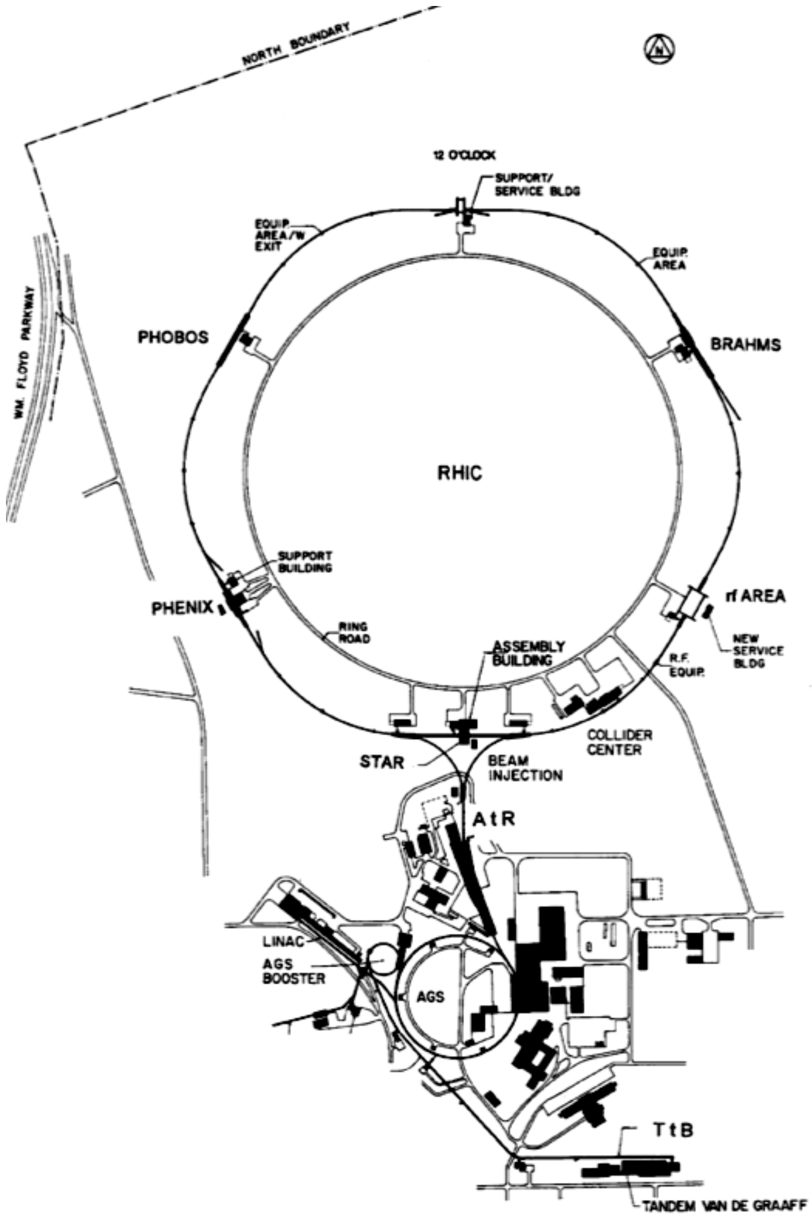
- "Siberian Snakes" → mitigate depolarization resonances
- Spin rotators provide choice of spin orientation *independent of experiment*
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

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

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*

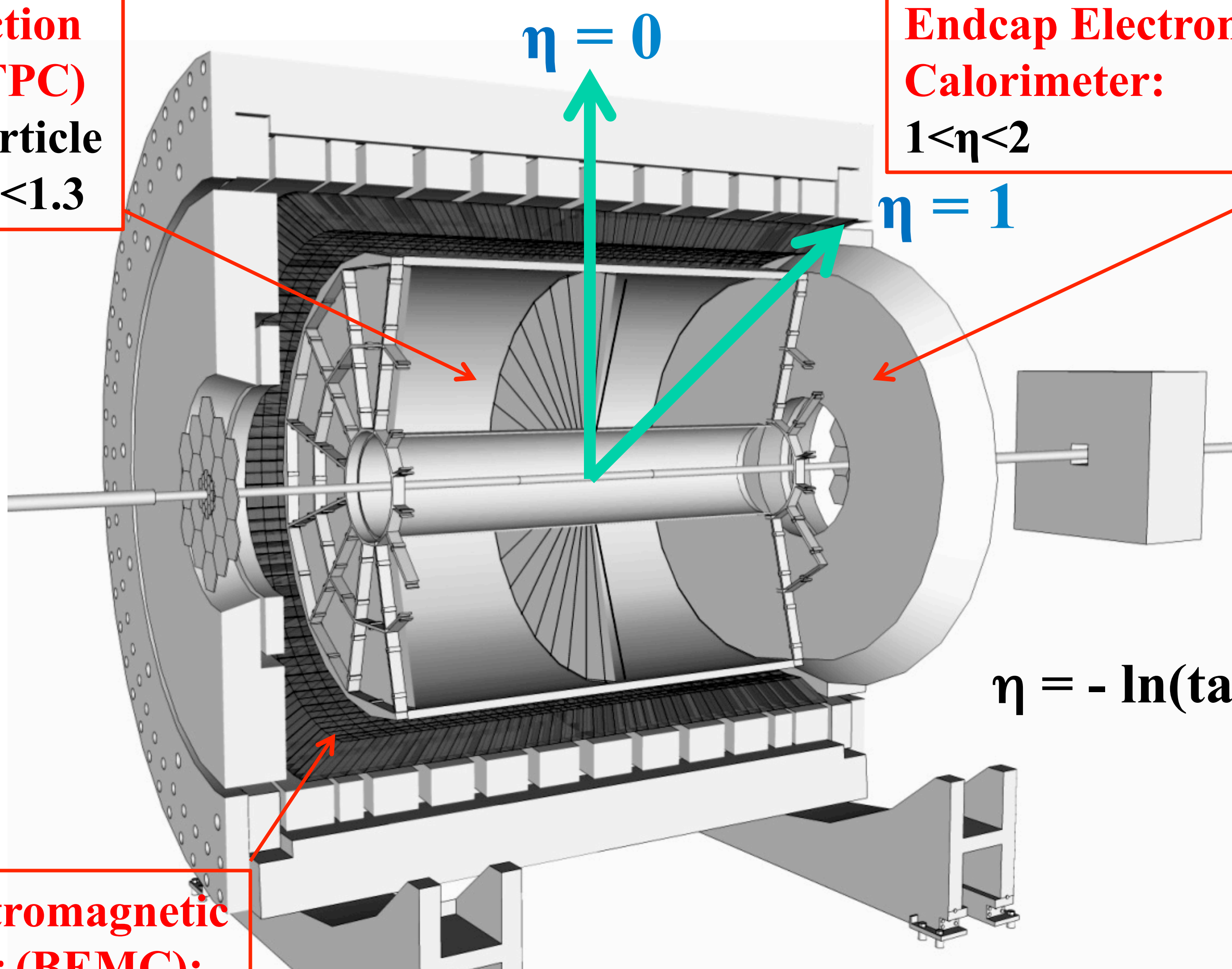
RHIC Beam Characteristics

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

STAR Detector

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

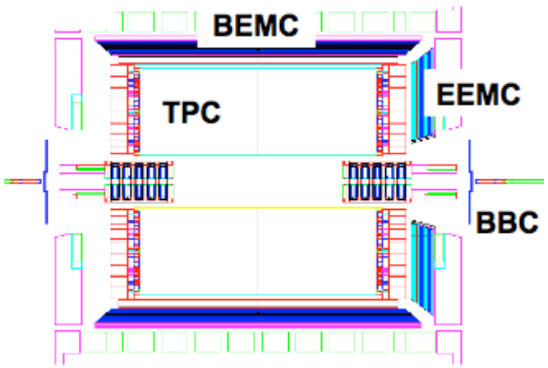
Endcap Electromagnetic Calorimeter:
$1<\eta<2$

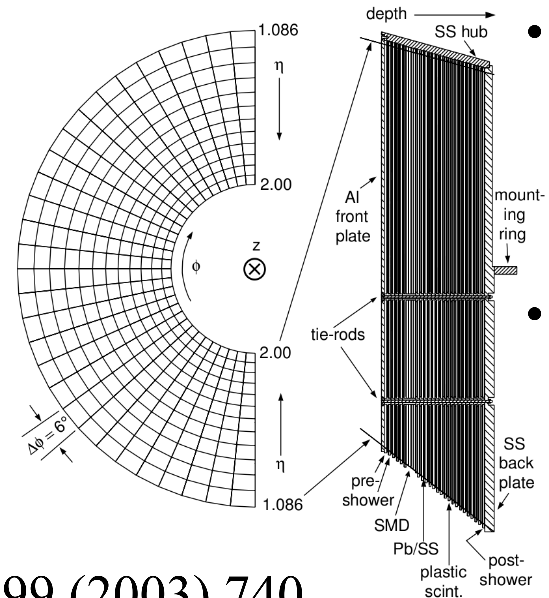


$$\eta = -\ln(\tan(\theta/2))$$

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

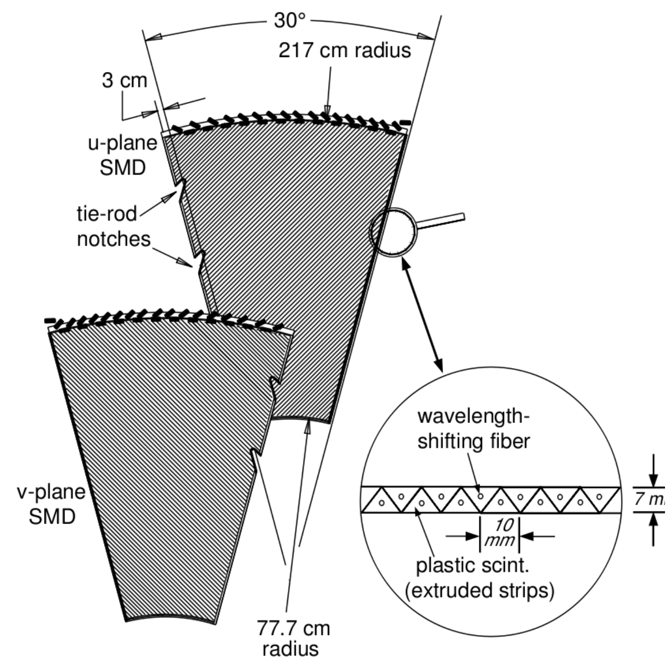
STAR's Endcap Electromagnetic Calorimeter



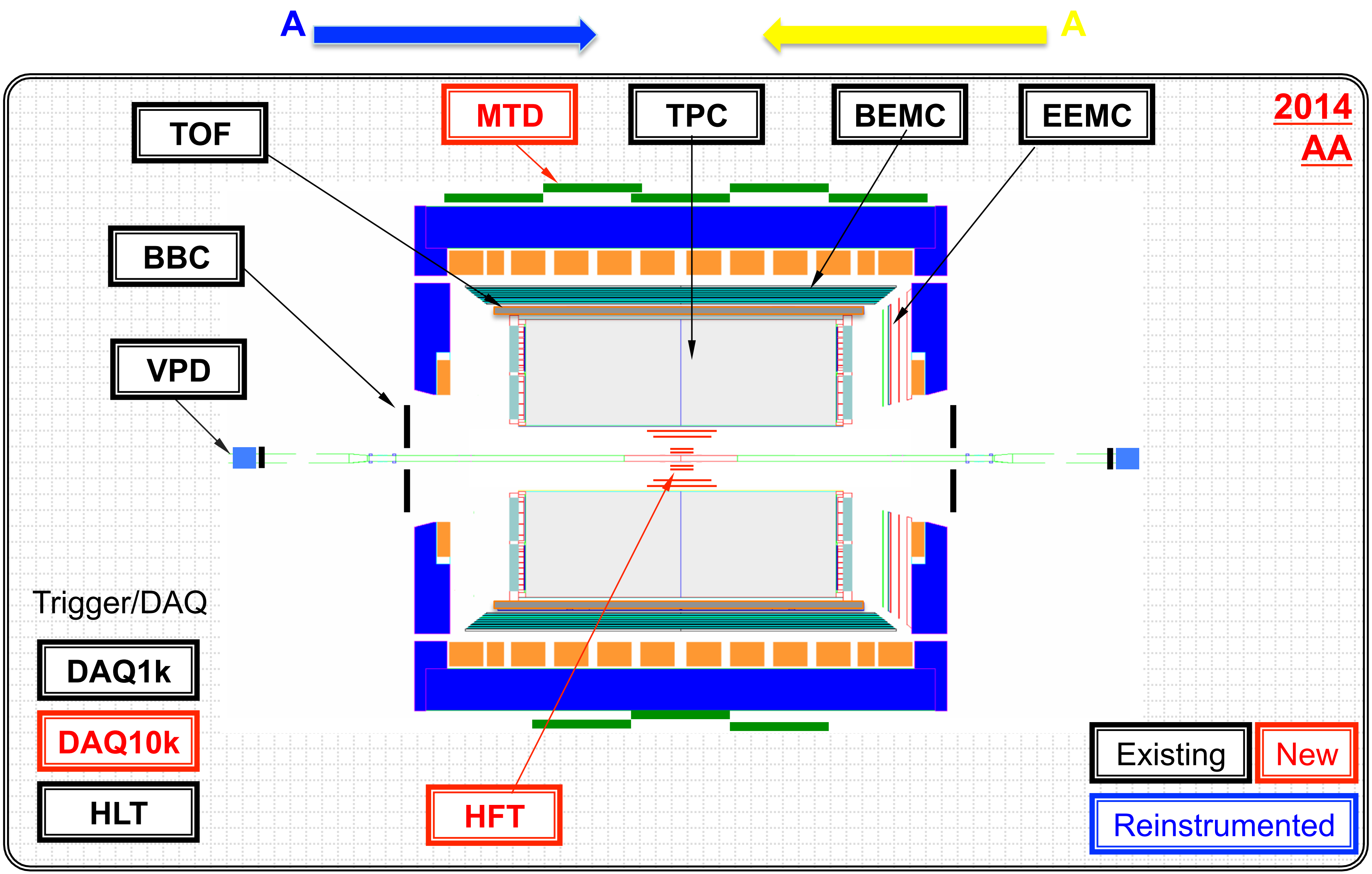


- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm

- 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 ($\sim 22\ X_0$)
  - 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

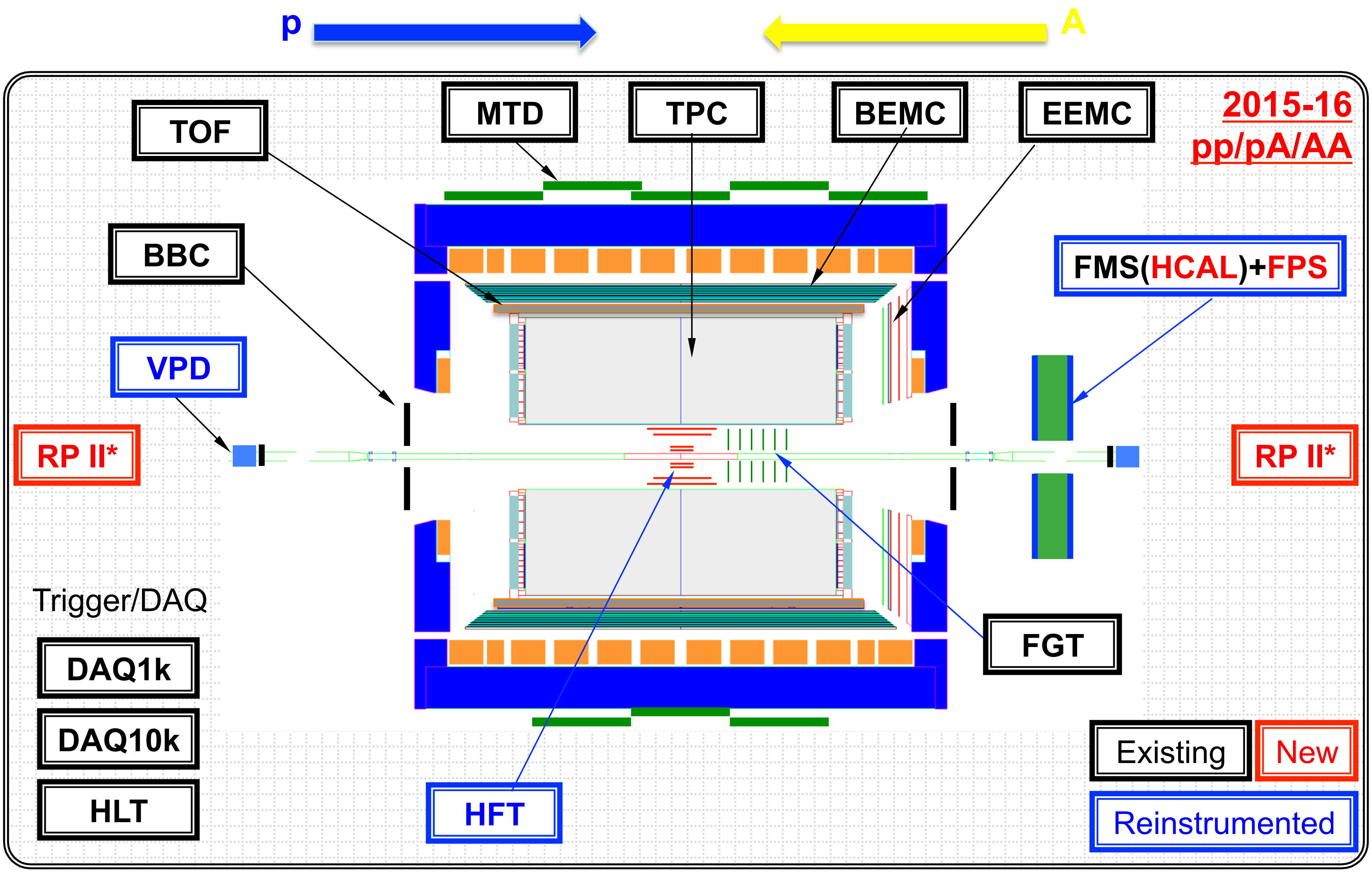


STAR Detector in 2014



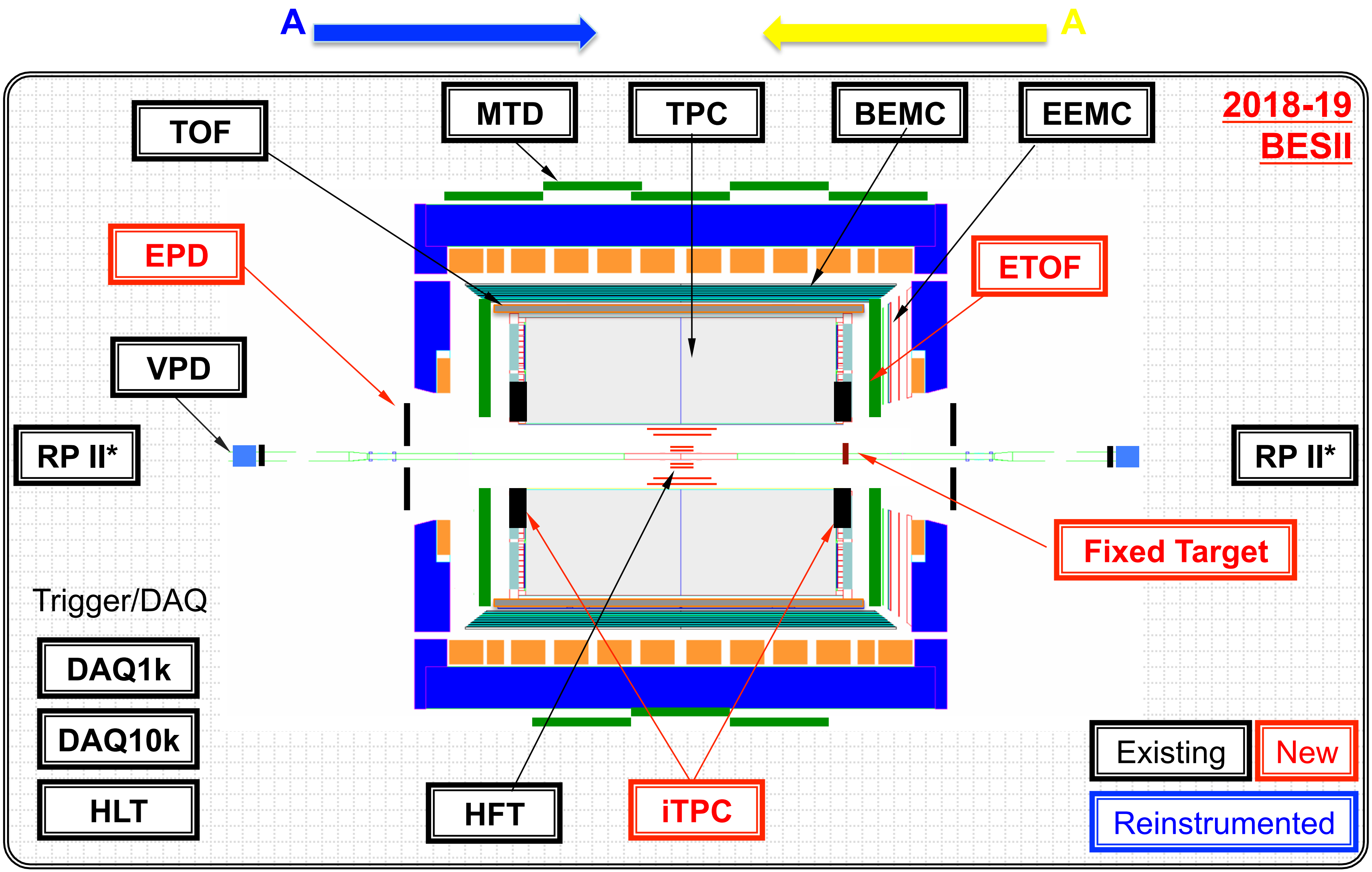
HFT: Heavy Flavor Tracker, **MTD**: Muon Telescope Detector

STAR Detector in 2015-2016



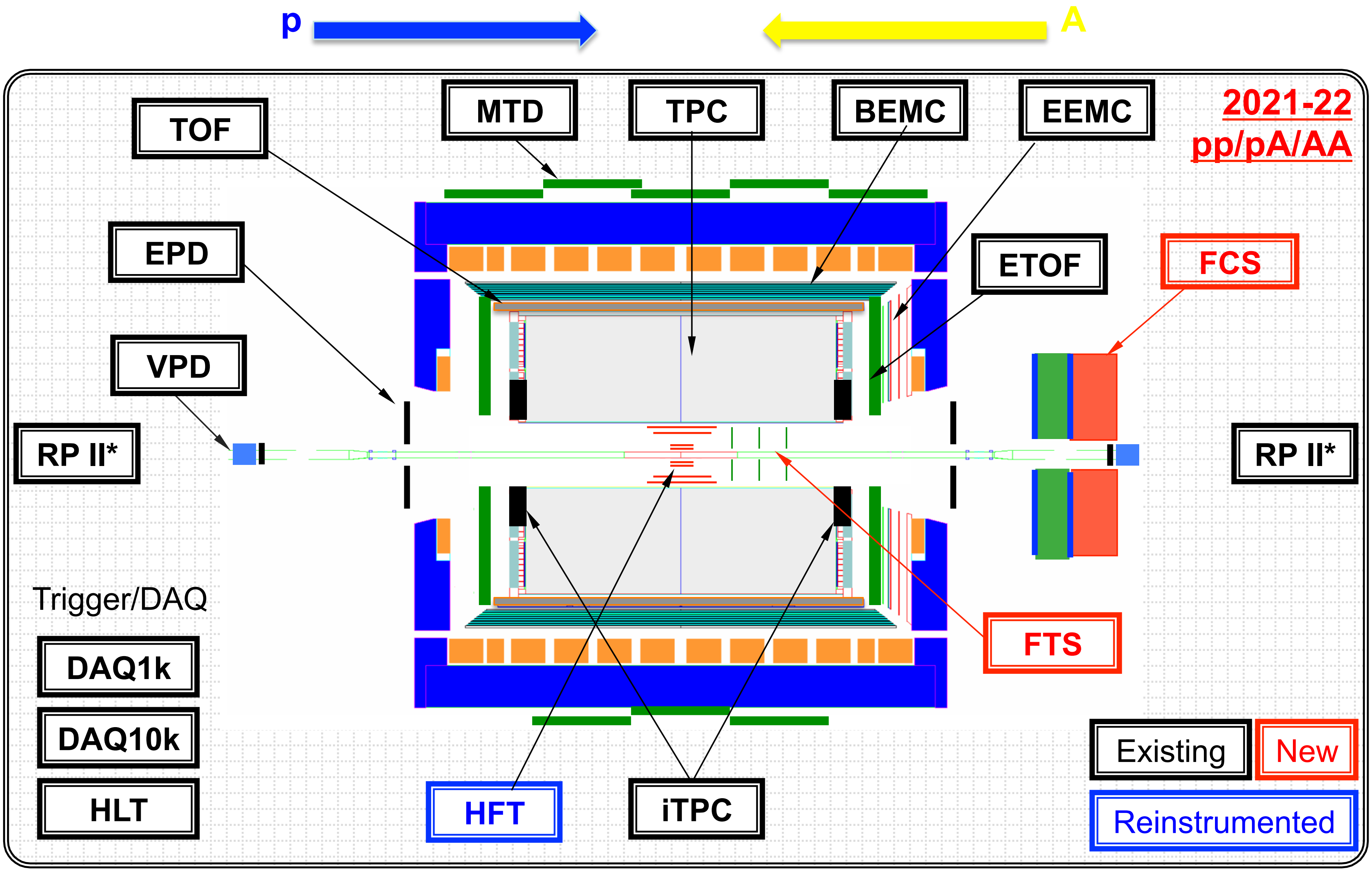
FMS: Forward Meson Spectrometer, **FPS**: Forward Preshower, **RP II***: Roman Pot Phase II*

STAR Detector in 2018-2019



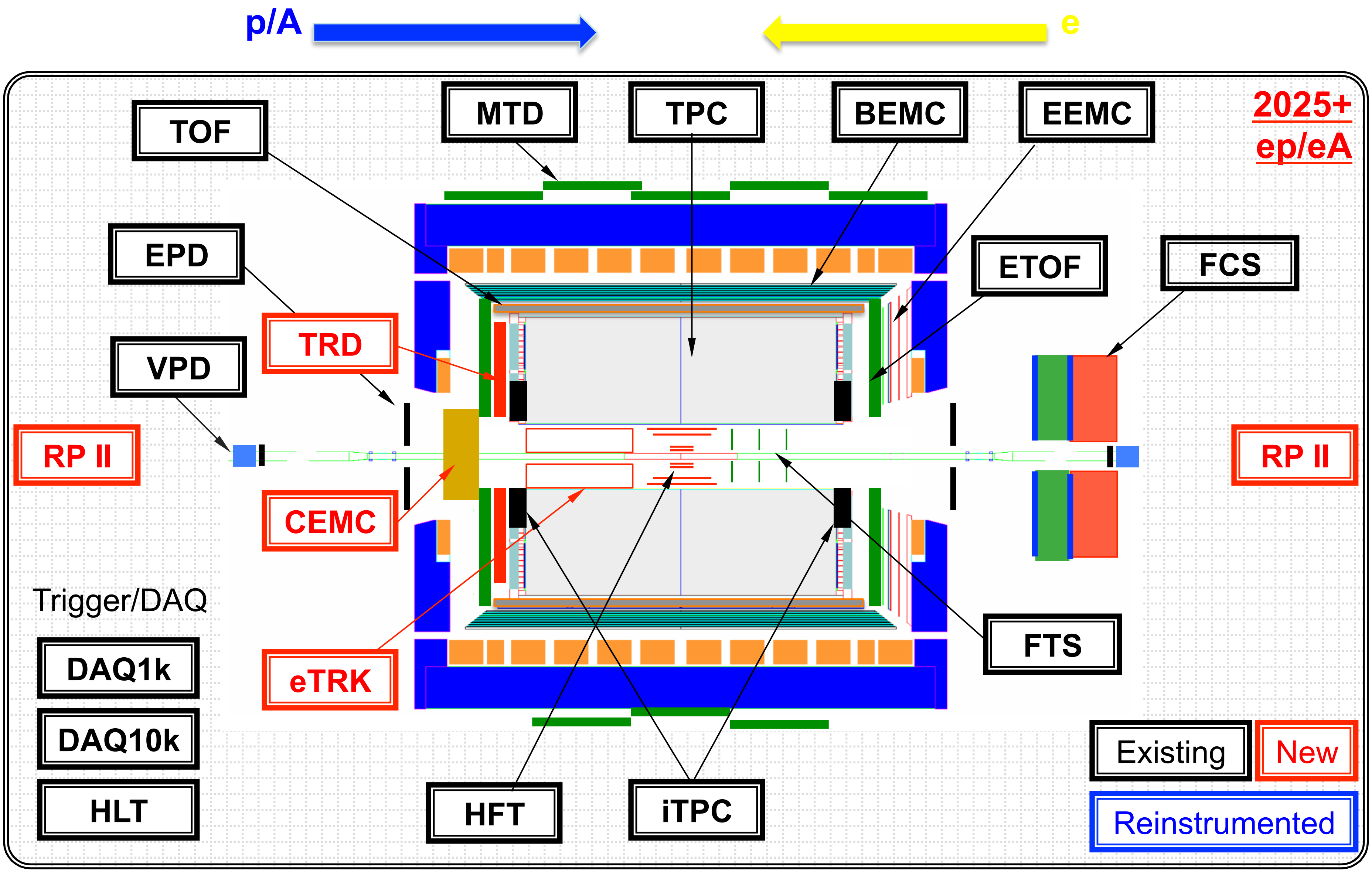
iTPC: inner TPC, **EPD**: Event Plane and Centrality Detector, **ETOF**: End-cap TOF, **Fixed Target**

STAR Detector in 2021-2022



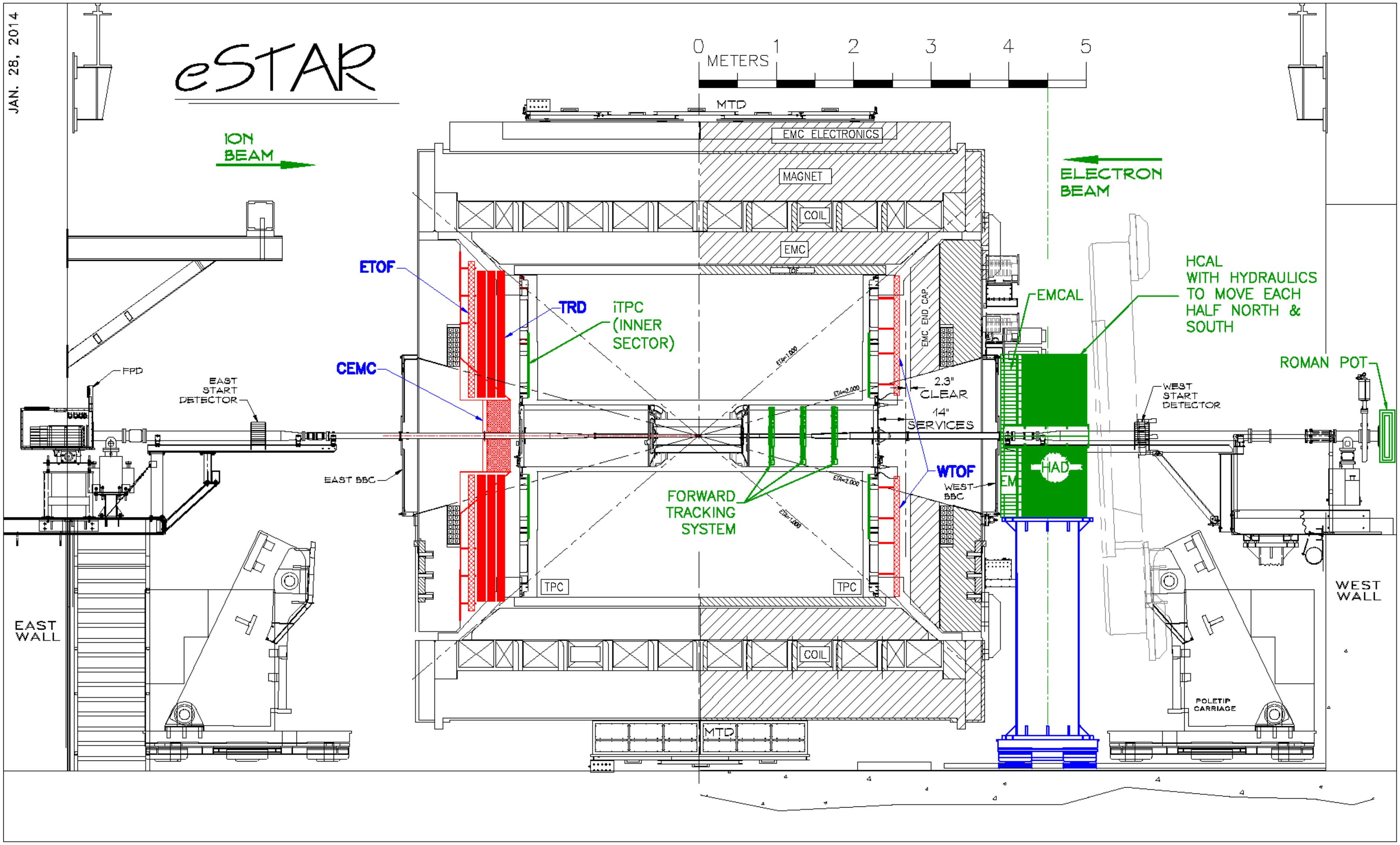
FCS/FTS: Forward Calrimeter/Tracking System, **RP II**: Full Roman Pot Phase II

STAR Detector in 2025+



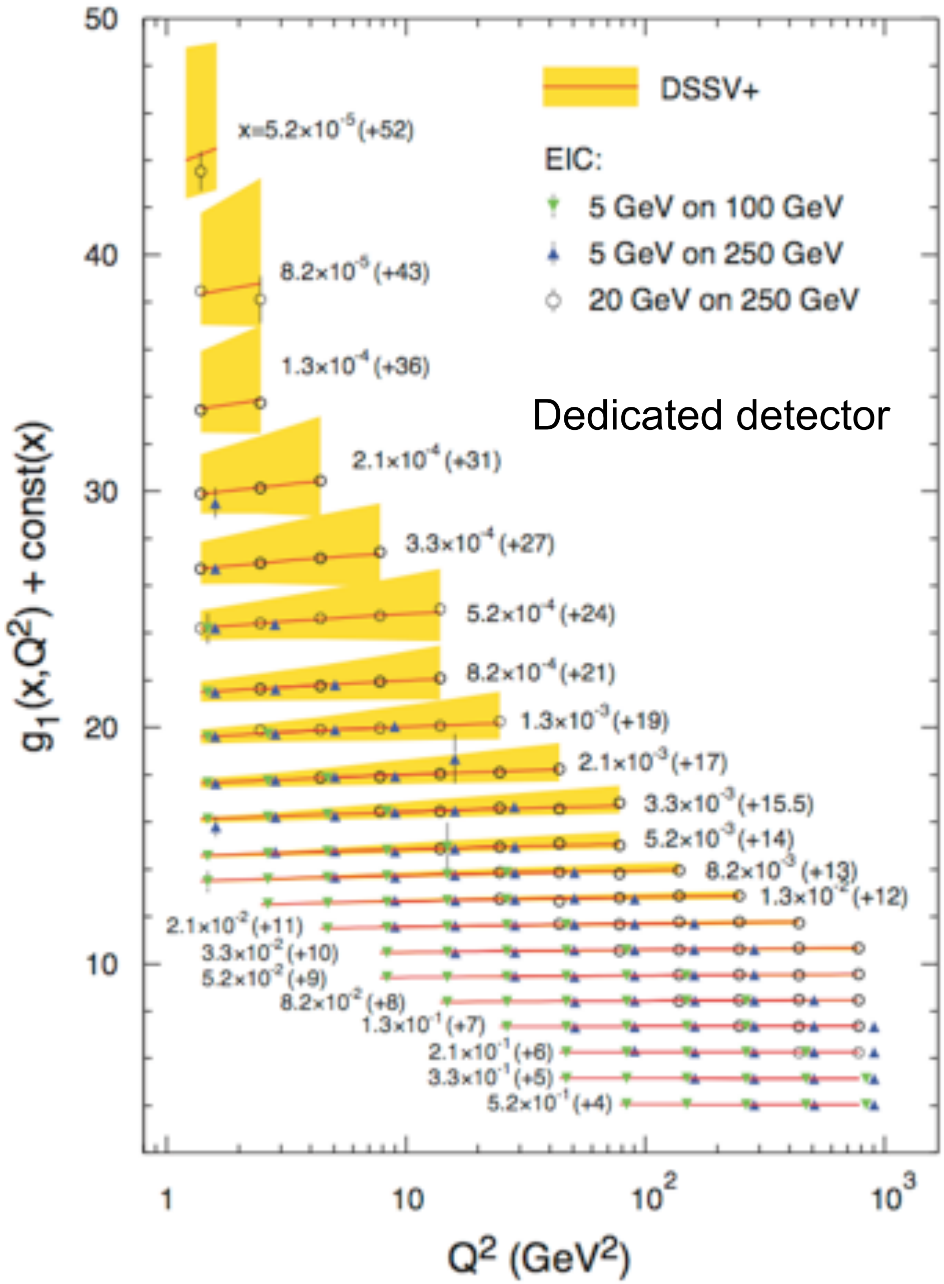
CEMC: Central EM Calorimeter, **eTRK:** electron Tracker, **TRD:** Transition Radiation Detector

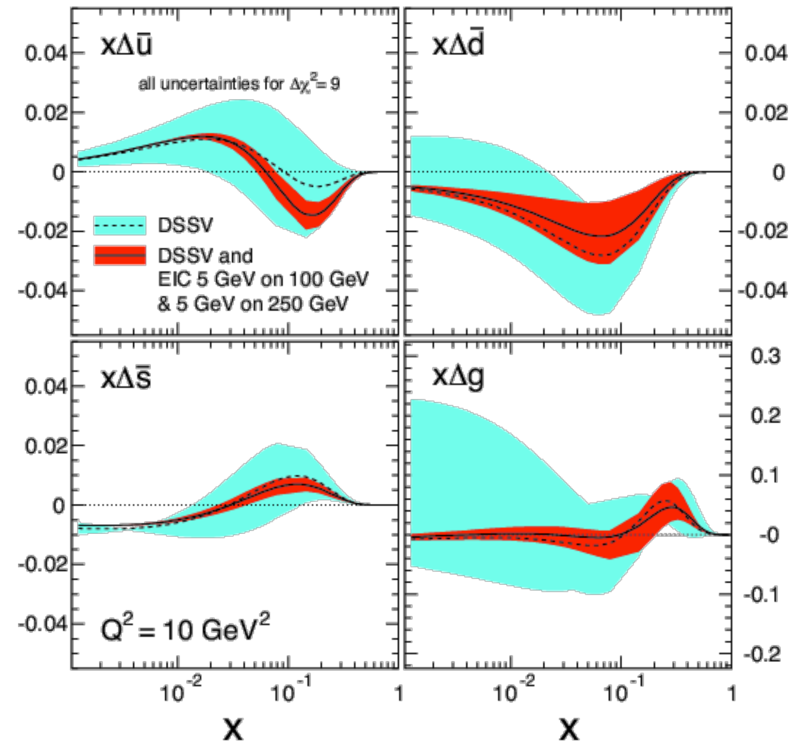
eSTAR Detector in 2025+

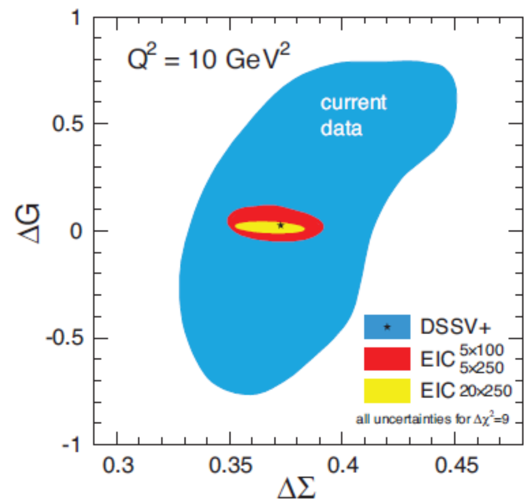


The very successful STAR detector will **evolve into an EIC detector**

Proton Helicity Structure







THE Beauty of Colliders: Kinematic Coverage