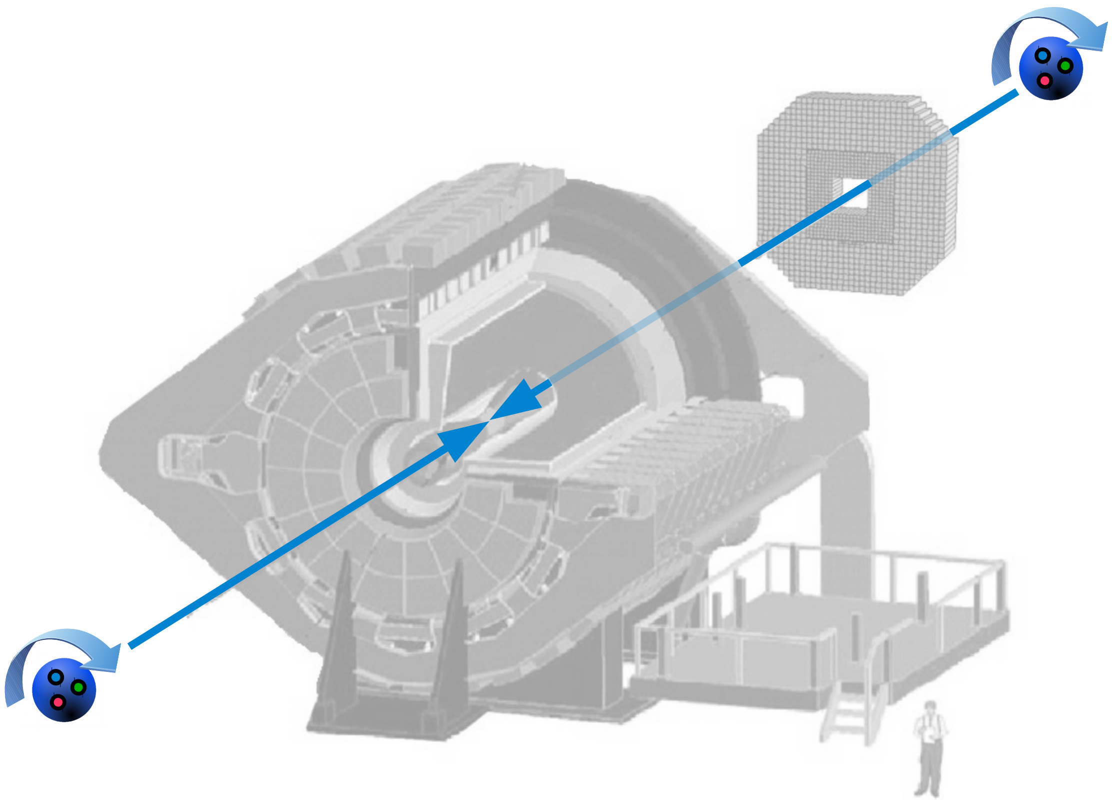
Overview of Gluon Helicity Measurements at STAR



Christopher Dilks
for the STAR Collaboration

SPIN 2018 – Ferrara, Italy

12 September 2018

PennState

STAR

Proton Spin Composition

Jaffe-Manohar Spin Sum Rule:

$$S_p = \frac{1}{2} = \Delta\Sigma/2 + \Delta G + L$$

Quark spin contribution: $\Delta\Sigma \approx 0.2\text{–}0.3$

Gluon helicity contribution: ΔG

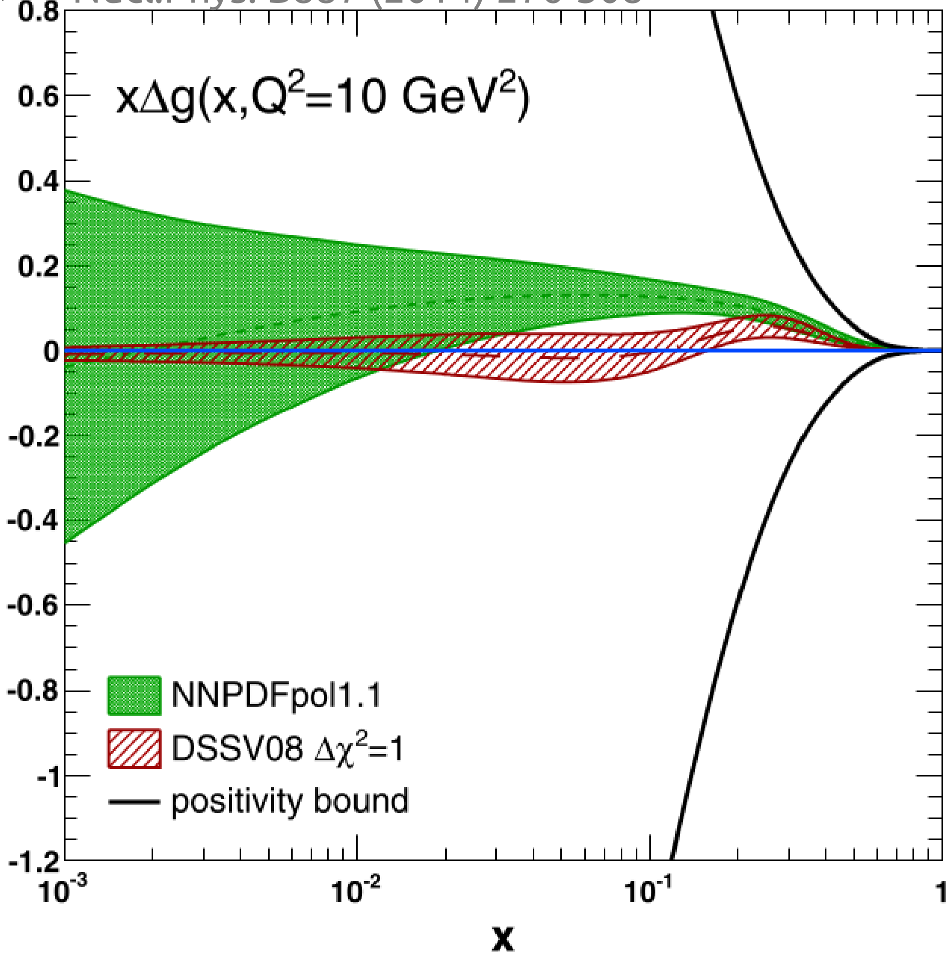
~0.2 for x > 0.05

Unconstrained for lower *x*

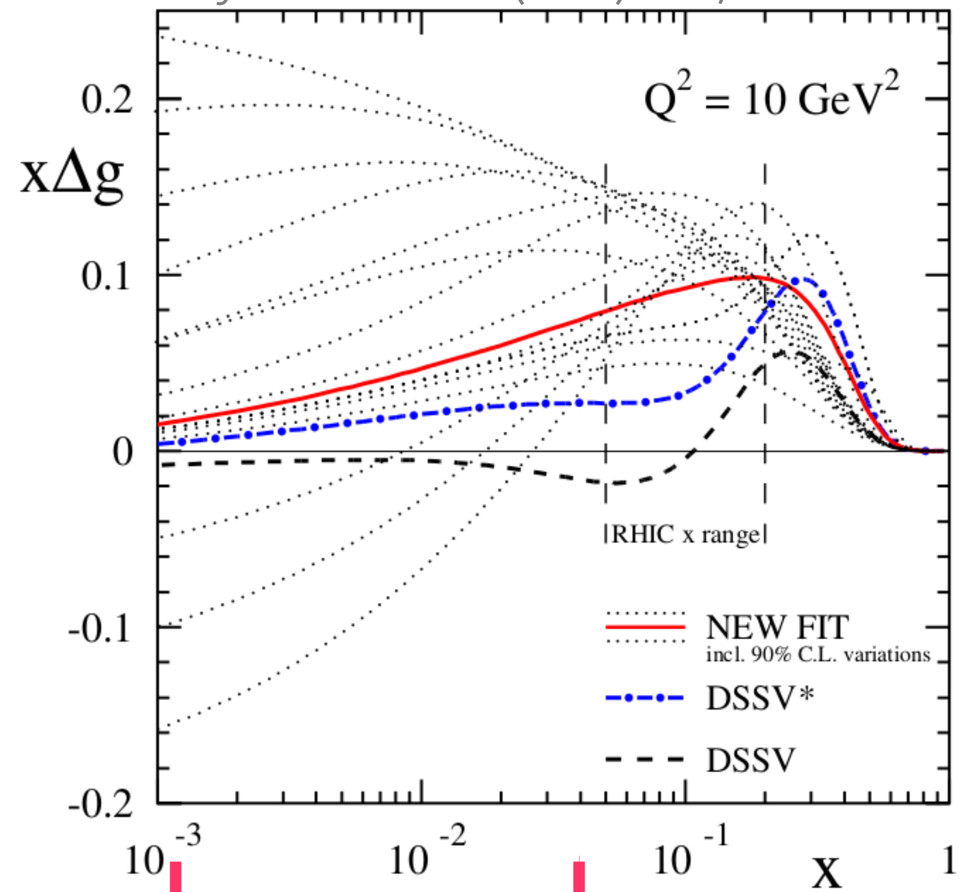
Partonic Orbital Angular Momentum: L – unknown

Polarized Gluon Distributions

Nucl.Phys. B887 (2014) 276-308



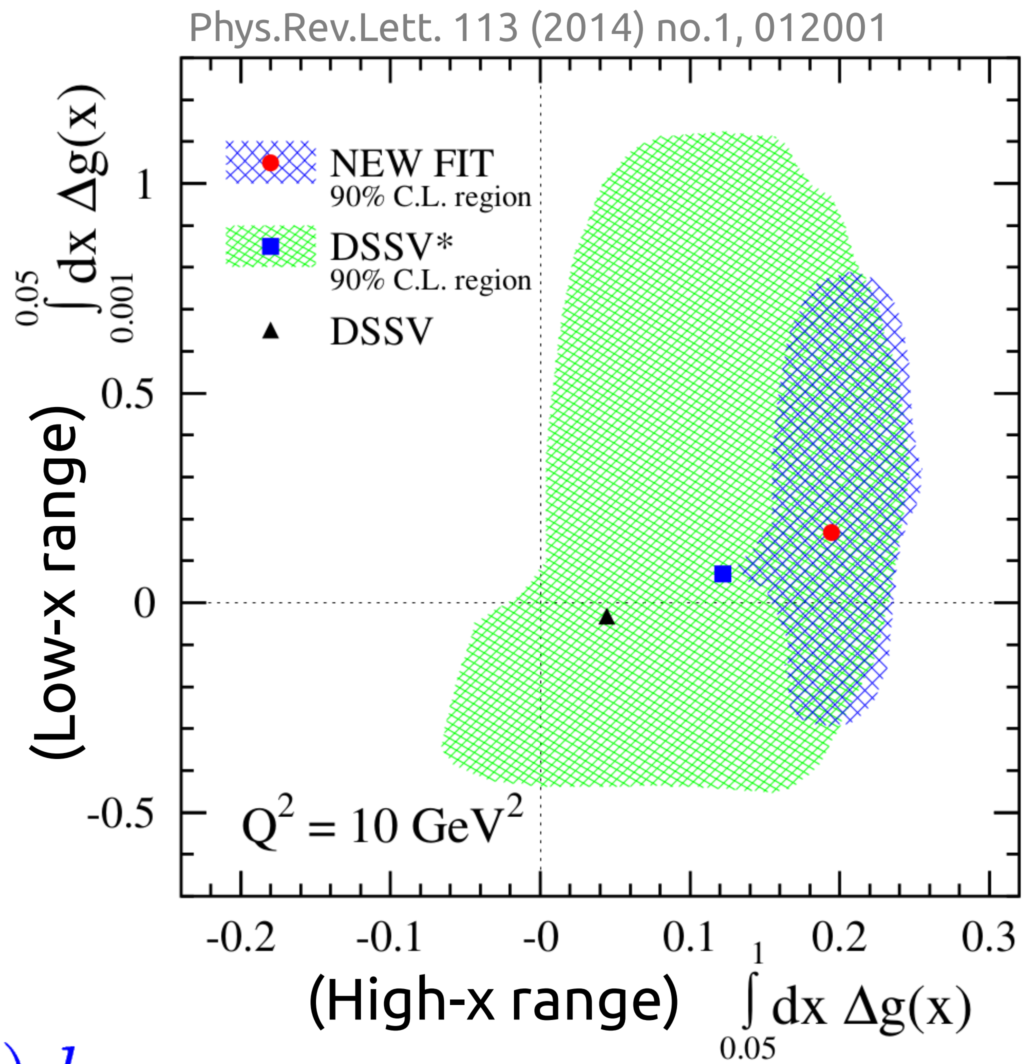
Phys.Rev.Lett. 113 (2014) no.1, 012001



$$\Delta g(x) = g^{\rightarrow}_{\Rightarrow}(x) - g^{\leftarrow}_{\Rightarrow}(x)$$

The uncertainty of Δg at low *x* remains large

Gluon Polarization



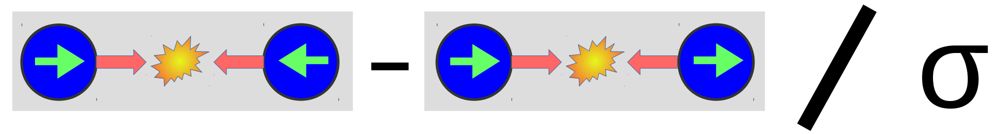
unconstrained for x < 0.05

$$\Delta G = \int_0^1 \Delta g(x) dx$$

ΔG ~ 0.20 +0.06 / –0.07 for x > 0.05

Longitudinal Double-Spin Asymmetry

The Observable: A_{LL}



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum \Delta f_a \otimes \Delta f_b \otimes (\hat{\sigma}\hat{a}_{LL}) \otimes D}{\sum f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

- **Unpolarized PDFs:** f — Well-understood
- **Polarized PDFs:** Δf
  - Dominant quarks well-understood
  - **Gluons unconstrained at low *x***
- **Hard Scattering Cross Section & Asymmetry:** $\hat{\sigma},\ \hat{a}_{LL}$ — Well-understood
- **Fragmentation Functions:** D
  - **Only needed if measuring final-state hadrons**
  - Well-understood for quarks
  - Larger uncertainties for gluons

How to Measure A_{LL}

The Observable: $$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

Requires 3 coincident measurements:

Yields (jets, dijets, pions, *et al.*)
for each proton spin combination

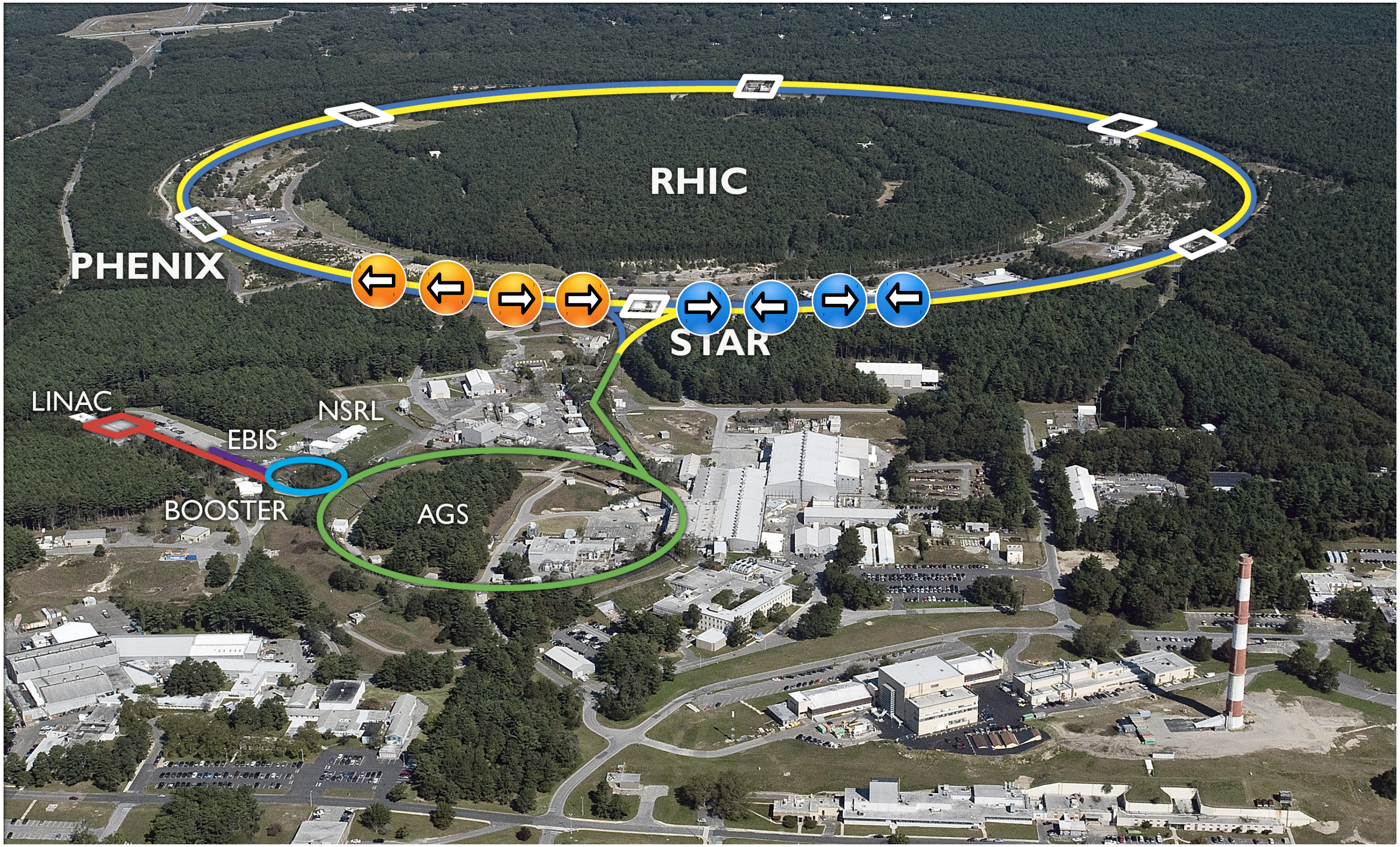
$$A_{LL} = \frac{1}{P_1 P_2} \cdot \frac{N_{++} - \left(\frac{L_{++}}{L_{+-}}\right) N_{+-}}{N_{++} + \left(\frac{L_{++}}{L_{+-}}\right) N_{+-}}$$

Beam Polarizations

Relative Luminosity

See Ting Lin's presentation (up next!) for further detail

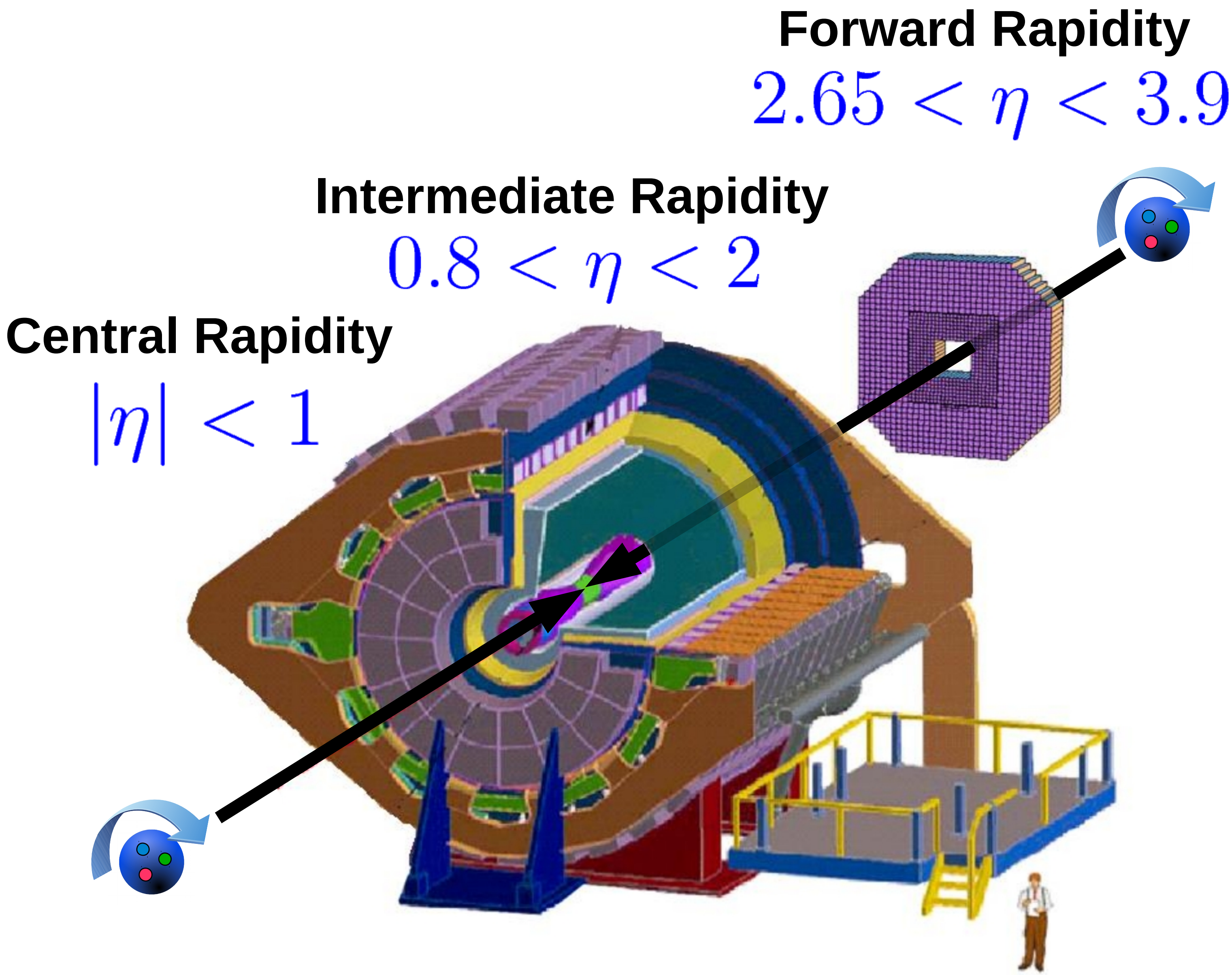
Relativistic Heavy Ion Collider (RHIC)



Brookhaven National Laboratory
Long Island, NY

- World's **only** polarized synchrotron collider
- Spin state known for **every** proton bunch
- Longitudinally polarized collisions achieved with **Spin Rotators**

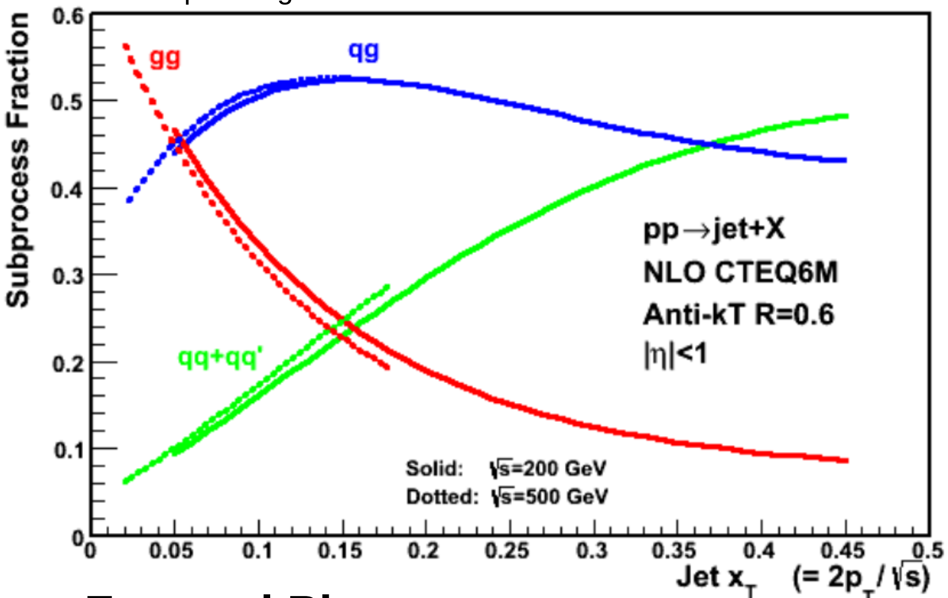
STAR Experiment



Subprocess Sensitivity

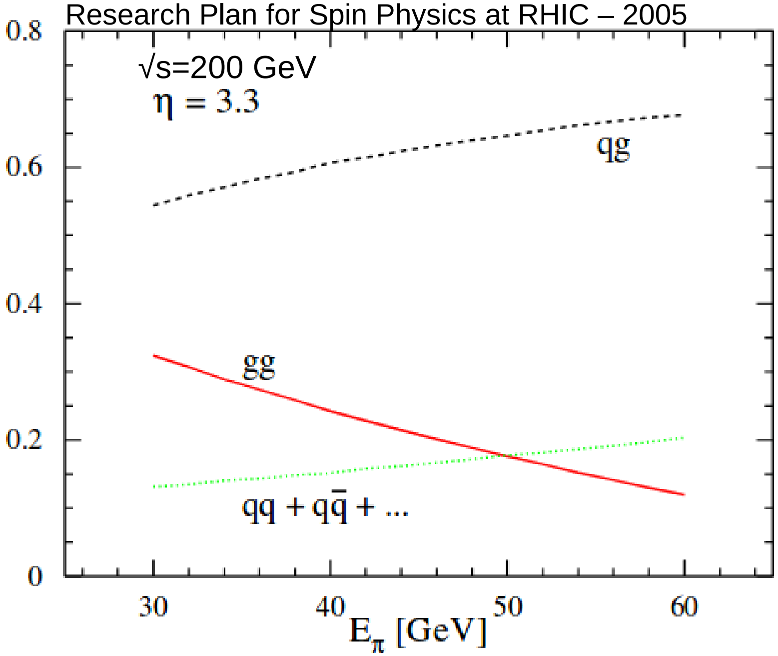
Central Jets

RHIC Spin Program – arXiv:1501.01220

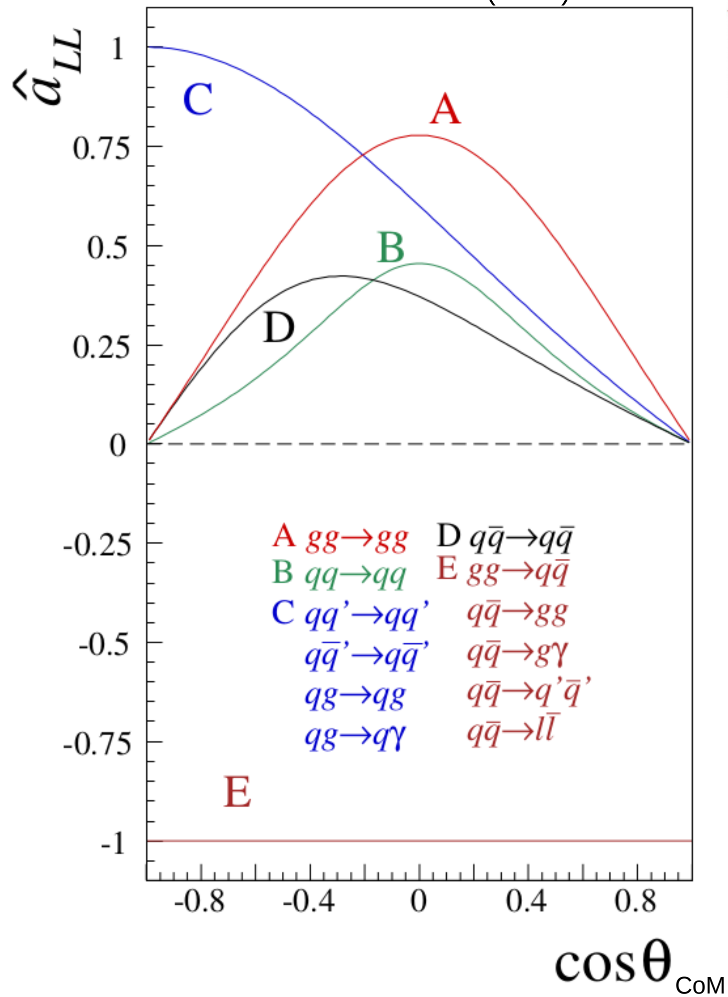


Forward Pions

Research Plan for Spin Physics at RHIC – 2005



Ann.Rev.Nucl.Part.Sci. 50 (2000) 525-575



- STAR observables are dominantly sensitive to **qg** scattering, as well as **gg** at low p_T
- Refer to processes "**C**" and "**A**" in the parton-level asymmetry $\hat{a}_{LL}$ figure above

$$A_{LL} \rightarrow \Delta g(x)$$

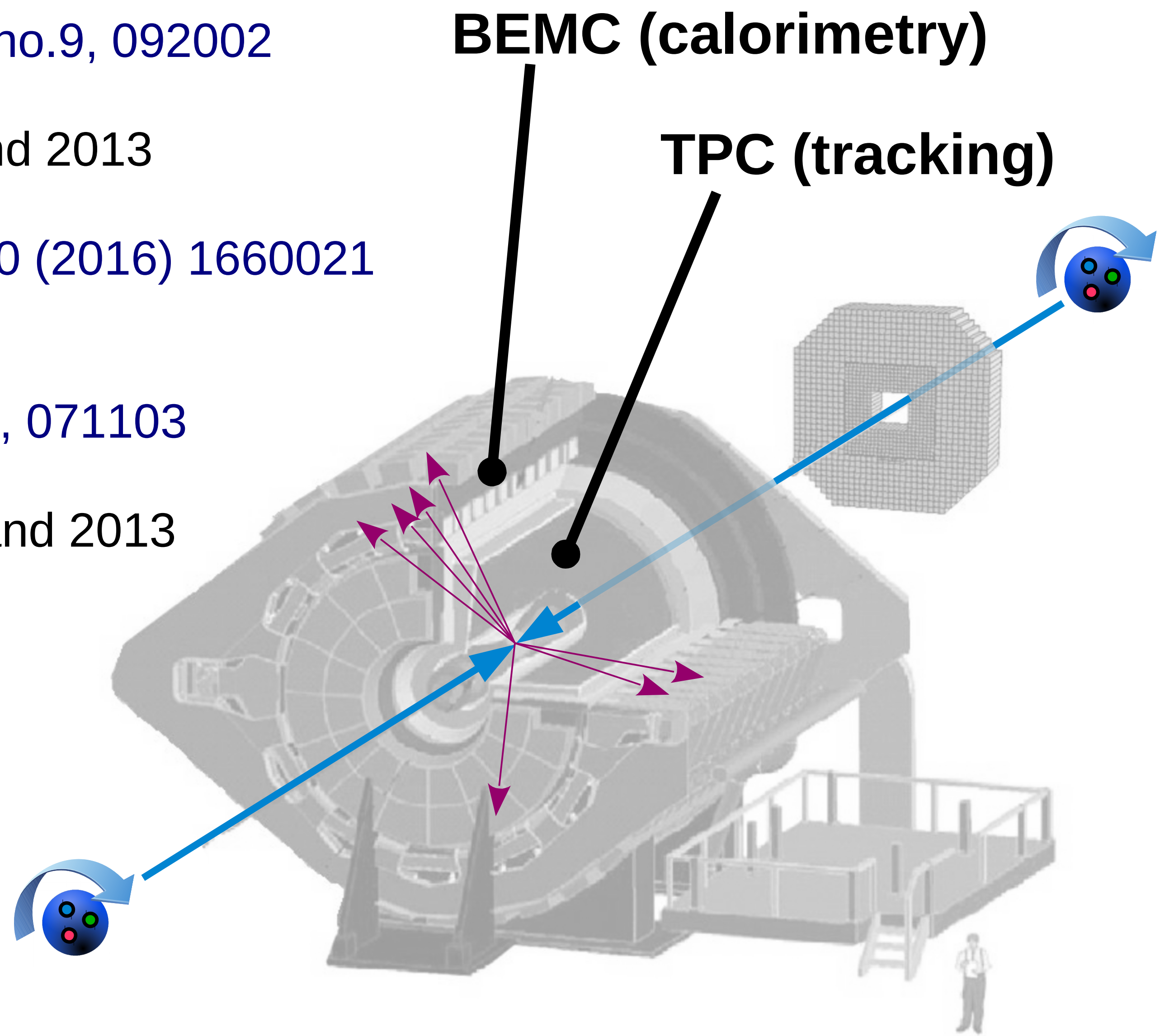
Central Rapidity $|\eta| < 1$

- Jets at 200 GeV in 2009
  Phys.Rev.Lett. 115 (2015) no.9, 092002

- Jets at 510 GeV in 2012 and 2013
  (STAR Preliminary)
  Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660021

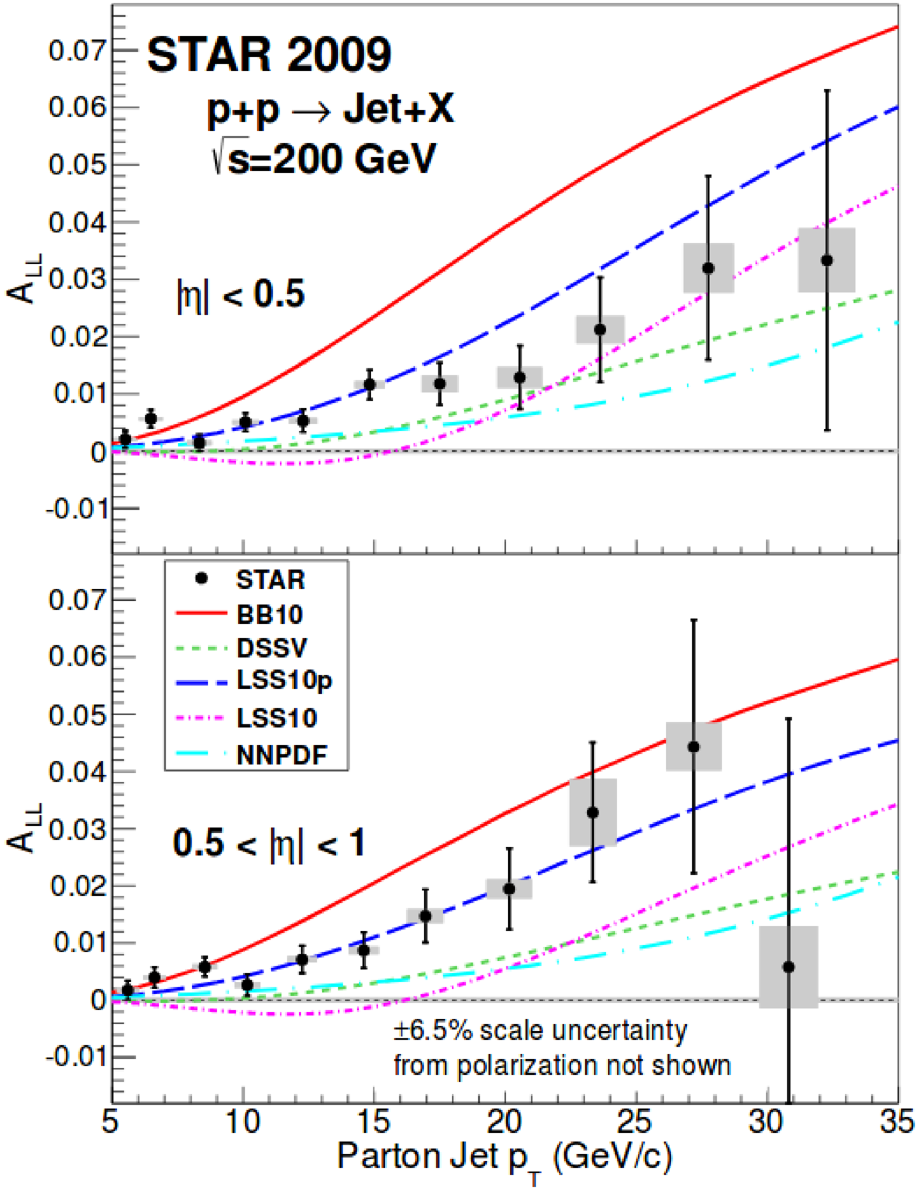
- Dijets at 200 GeV in 2009
  Phys.Rev. D95 (2017) no.7, 071103

- Dijets at 510 GeV in 2012 and 2013
  (STAR Preliminary)



Central Jets at 200 GeV in 2009

Phys.Rev.Lett. 115 (2015) no.9, 092002



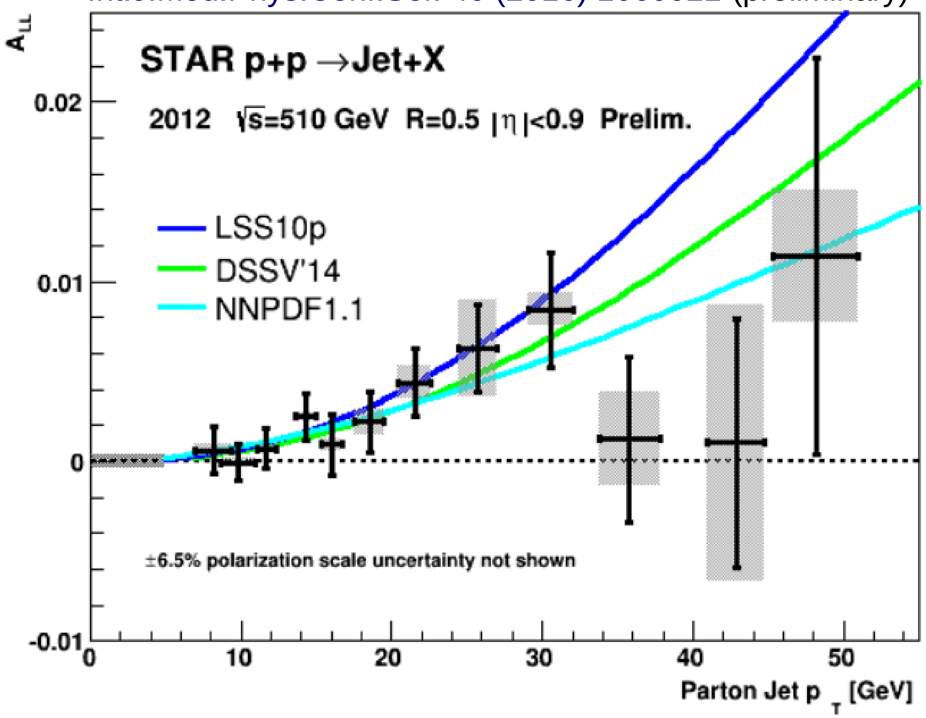
- Jets reconstructed from anti-k_T algorithm with R=0.6
- Jet p_T corrected to parton-level, which excludes underlying event / beam remnants
- Positive A_{LL} above DSSV08 fit is evidence of positive *Δg(x)* at high *x*

x > 0.05

Central Jets at 510 GeV in 2012 & 2013

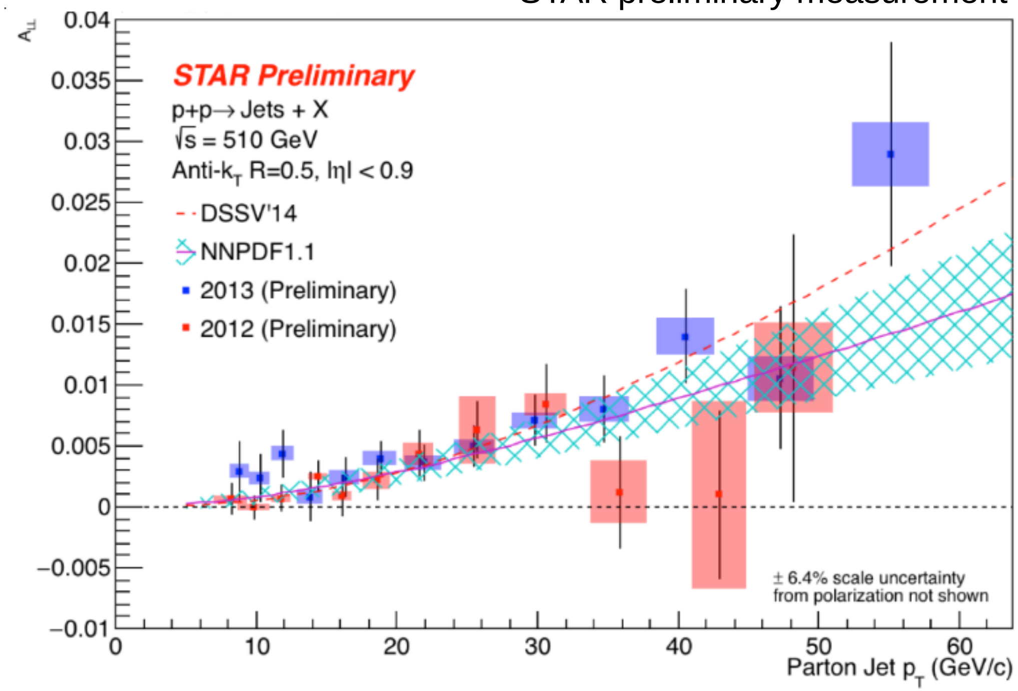
2012 Data

Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660021 (preliminary)



2013 Data (compared to 2012)

STAR preliminary measurement

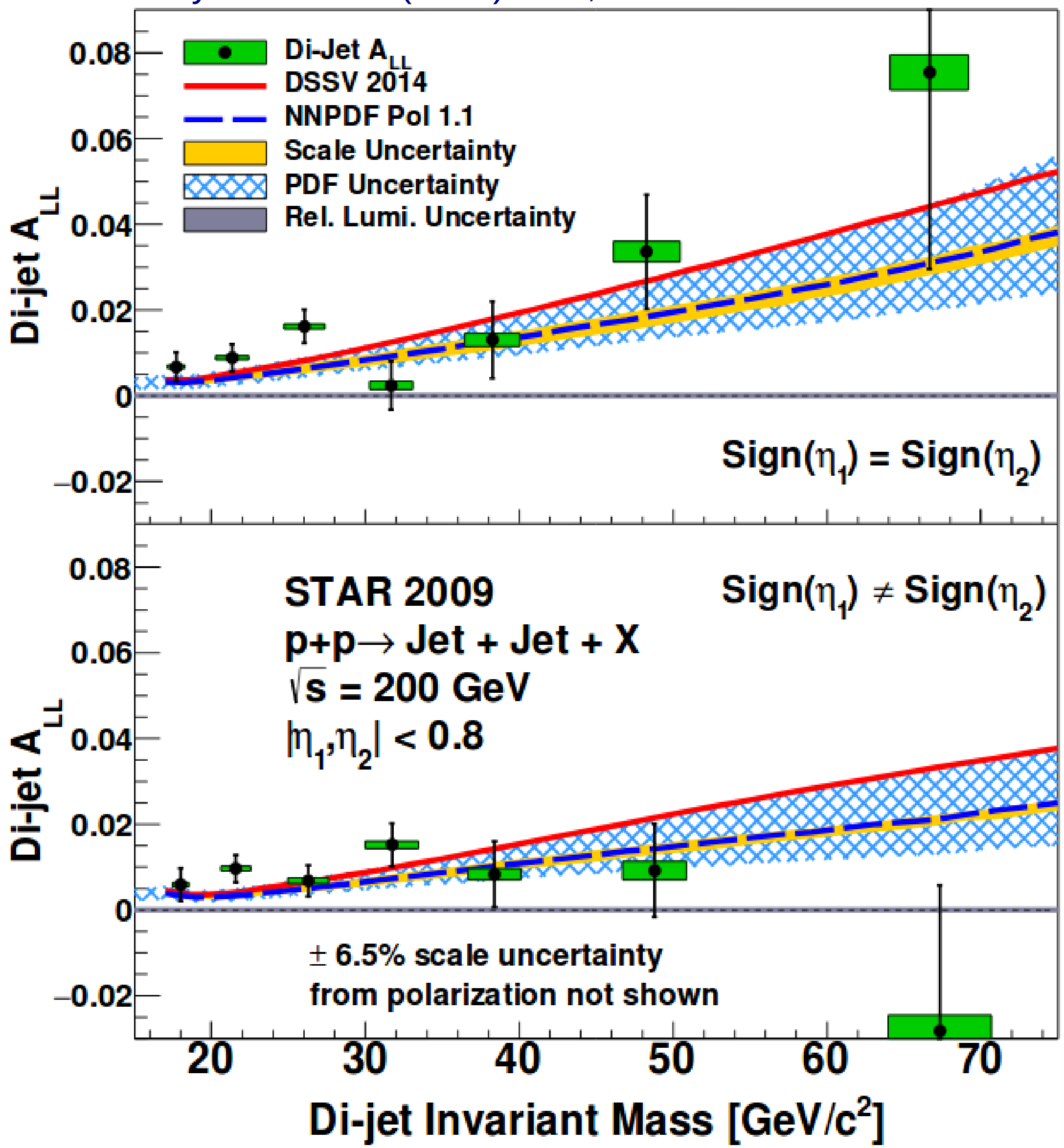


- 510 GeV measurement agrees with 200 GeV measurement from 2009
- Reconstruction using anti-k_T algorithm with R=0.5
- Higher √s pushes sensitivity to lower *x*: $x_{510} = \frac{200}{510} \cdot x_{200}$

x > 0.02

Central Dijets at 200 GeV in 2009

Phys.Rev. D95 (2017) no.7, 071103



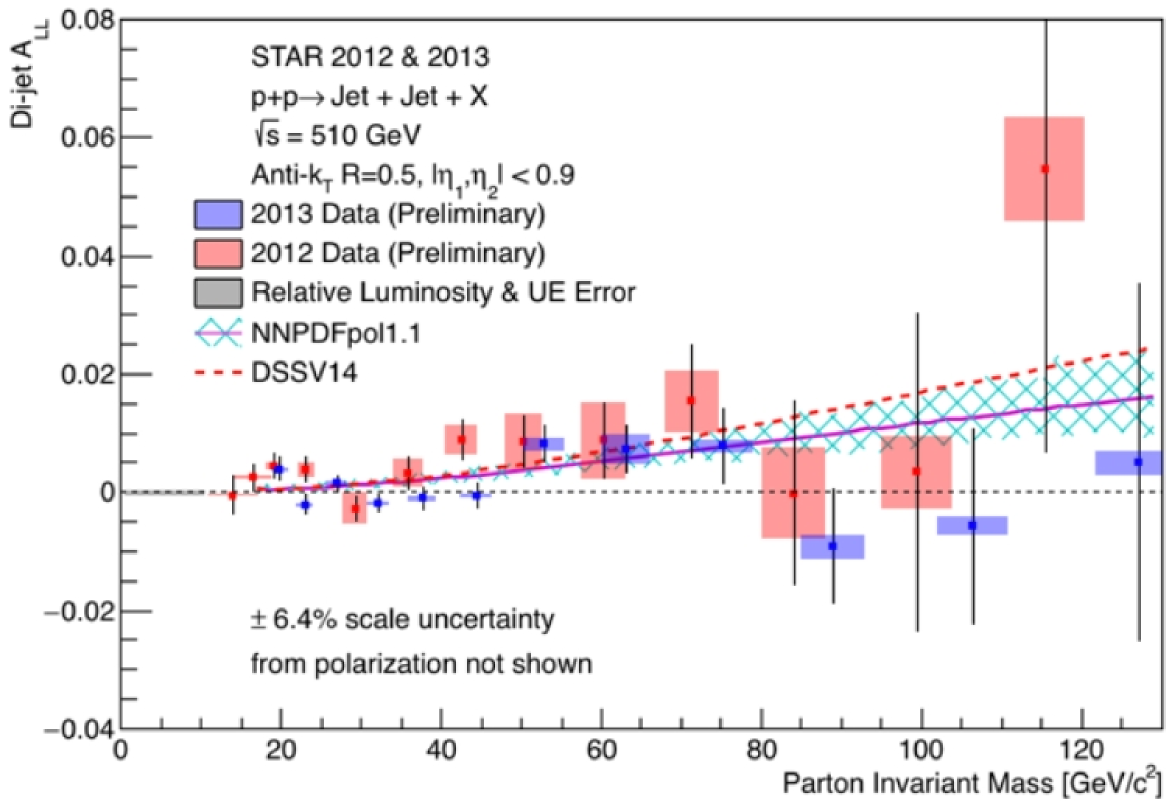
- Dijets probe a narrower *x* region
- Anti-k_T with R=0.6
- Plotted vs. dijet invariant mass

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

- Two topologies shown
  - same side jets
  - opposite side jets
- Asymmetries agree with models that predict *ΔG~0.2* for *x>0.05*

x > 0.05

Central Dijets at 510 GeV in 2012 & 2013

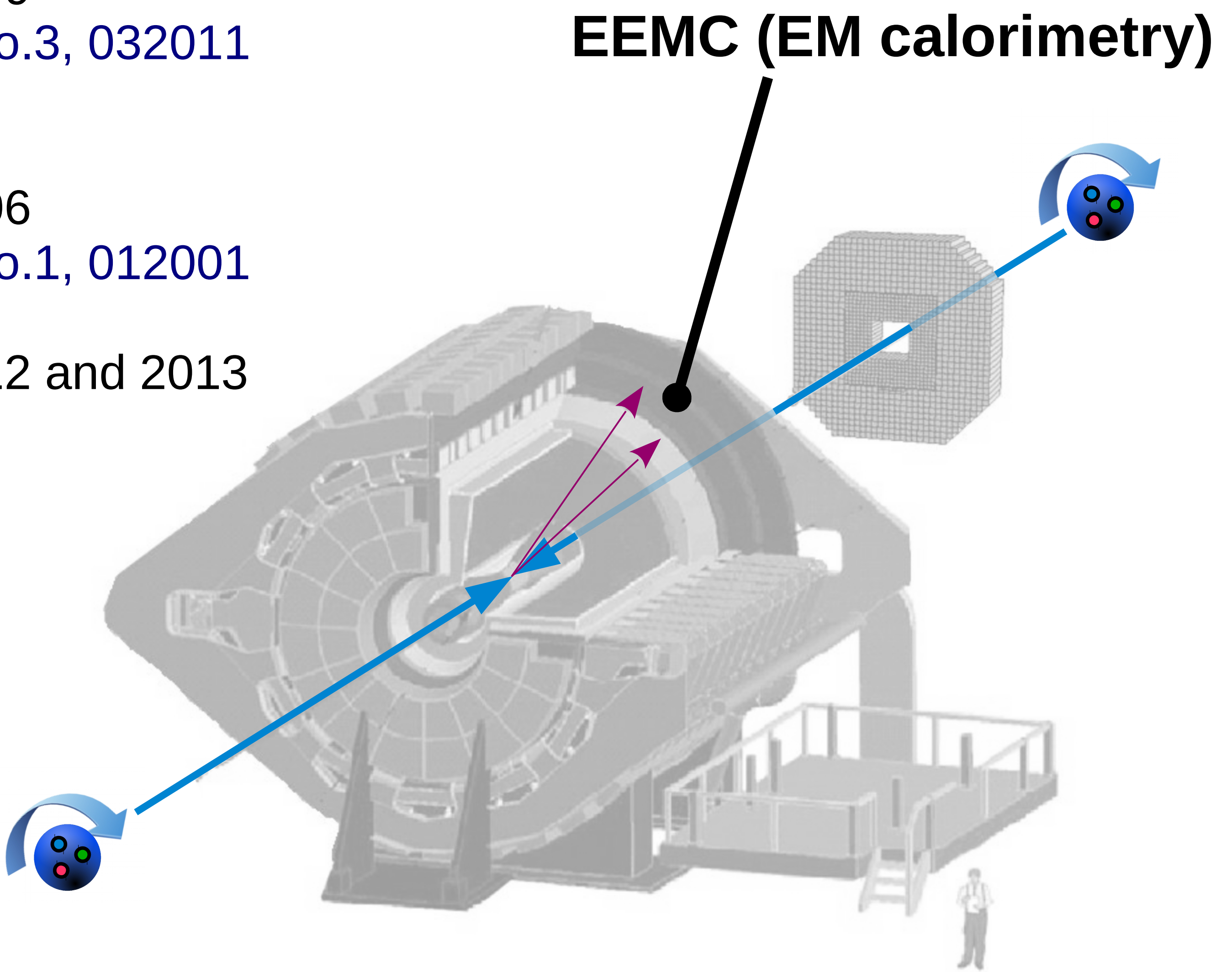


- Higher $\sqrt{s}$ pushes to lower *x*
- Anti-k_T with R=0.5
- Plotted vs. parton invariant mass
- Full central region shown
- Asymmetries also agree with models

***x* > 0.02**

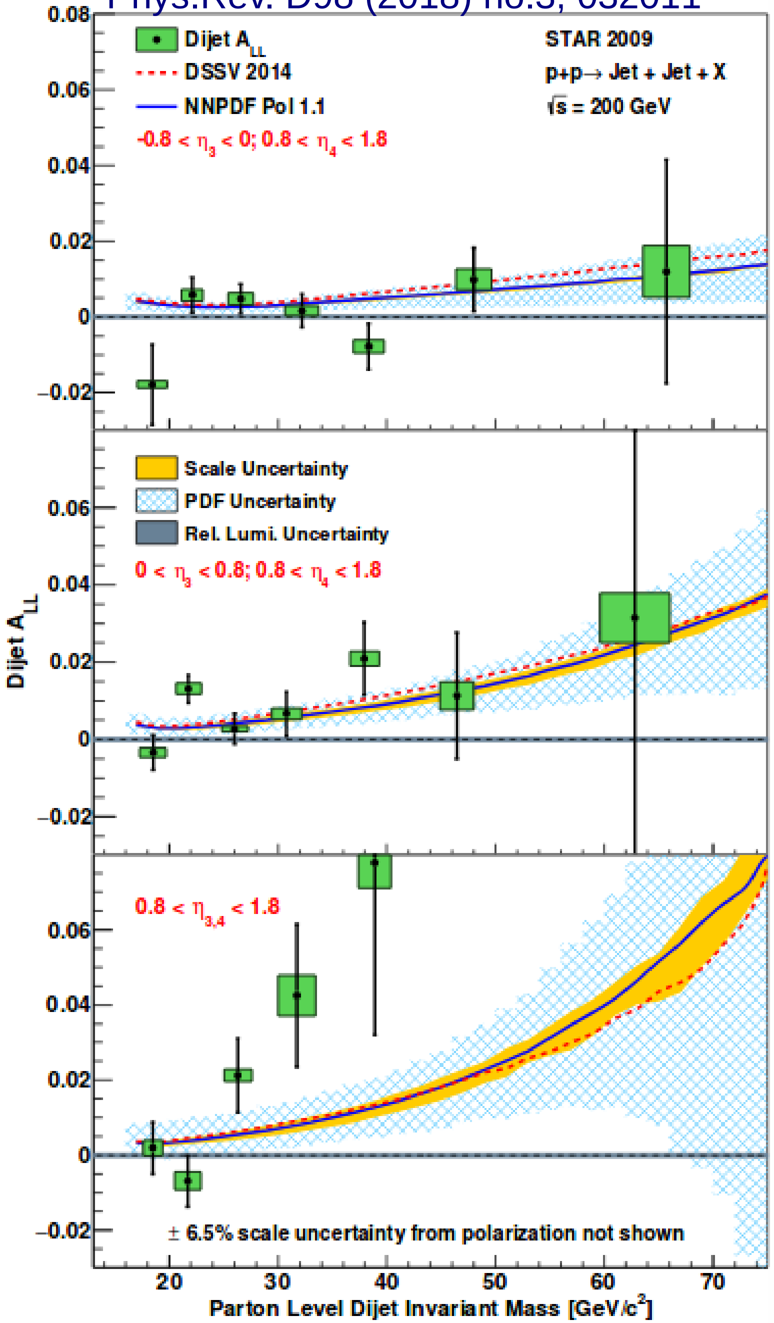
Intermediate Rapidity $0.8 < \eta < 2$

- Dijets at 200 GeV in 2009
  Phys.Rev. D98 (2018) no.3, 032011
  *** new result!**
- Pions at 200 GeV in 2006
  Phys.Rev. D89 (2014) no.1, 012001
- Pions at 510 GeV in 2012 and 2013
  Analysis Underway



Intermediate Dijets at 200 GeV in 2009

Phys.Rev. D98 (2018) no.3, 032011

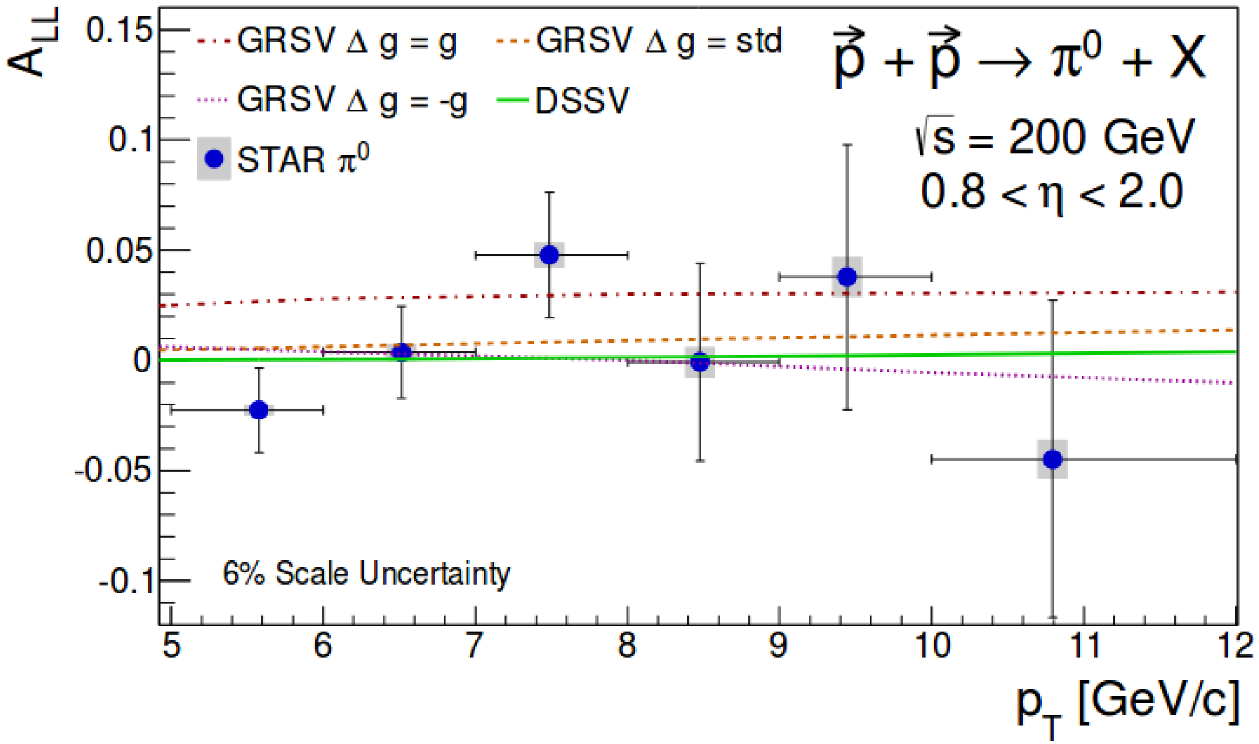


- More-forward production probes lower x, down to 0.01
- Provides tighter constraints to size and especially shape of Δg(x) for x>0.05
- Three topologies shown:
  - – one jet forward, other jet central (opposite side)
  - – one jet forward, other jet central (same side)
  - – both jets forward
  - forward-forward case probes lowest x
- Anti-k_T with R=0.6
- **See Ting Lin's (up next) presentation for further detail**
- Analysis of 510 GeV data underway

x > 0.01

Intermediate Pions at 200 GeV in 2006

Phys.Rev. D89 (2014) no.1, 012001

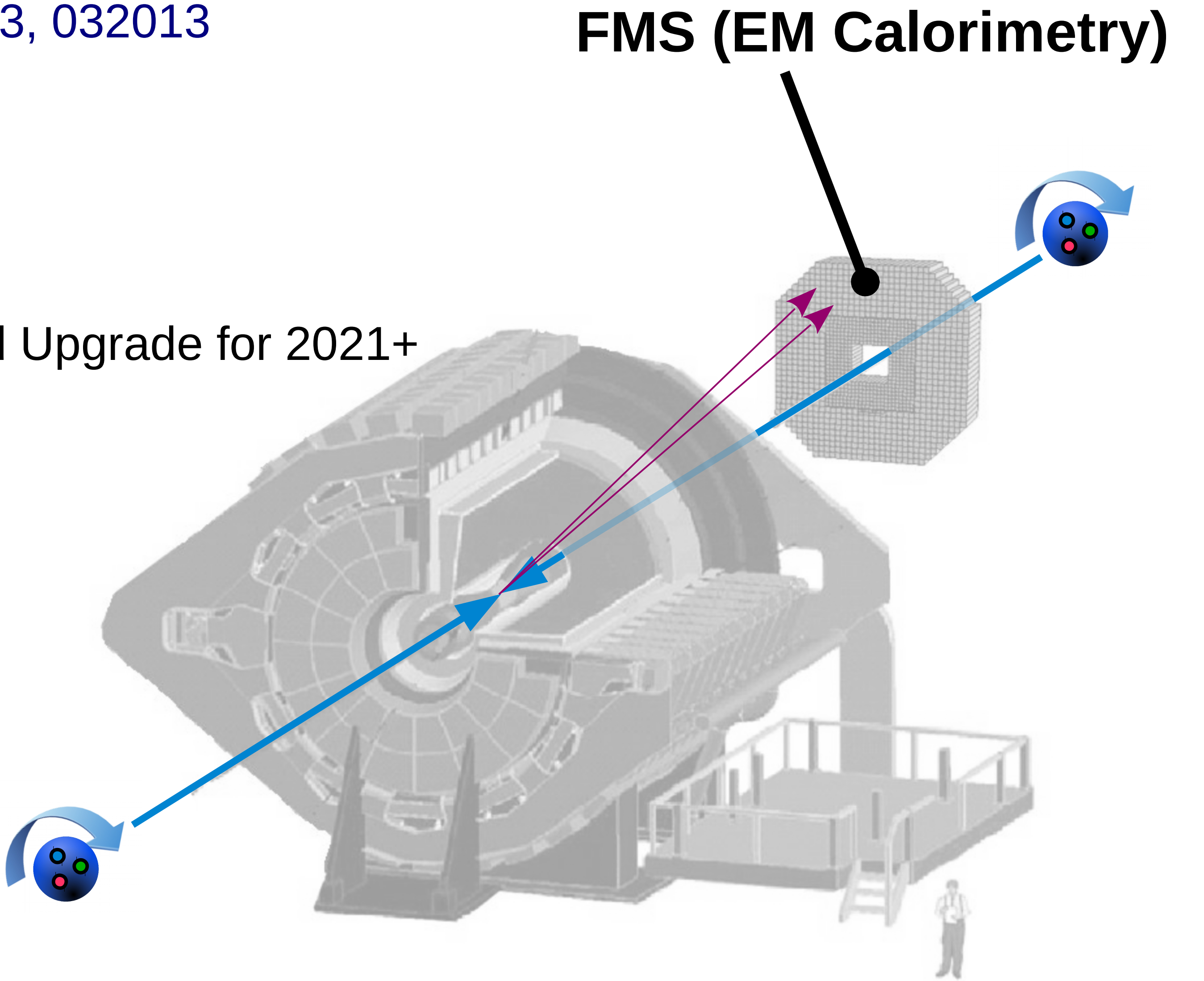


- Plotted for pion p_T
- Agrees with models for varying degrees of gluon polarization
- This is an older result (pre-DSSV14), and data were not yet sensitive to distinguish between available models
- Analysis 510 GeV data from 2012 and 2013 is underway; it is sensitive down to x~0.004

x > 0.01

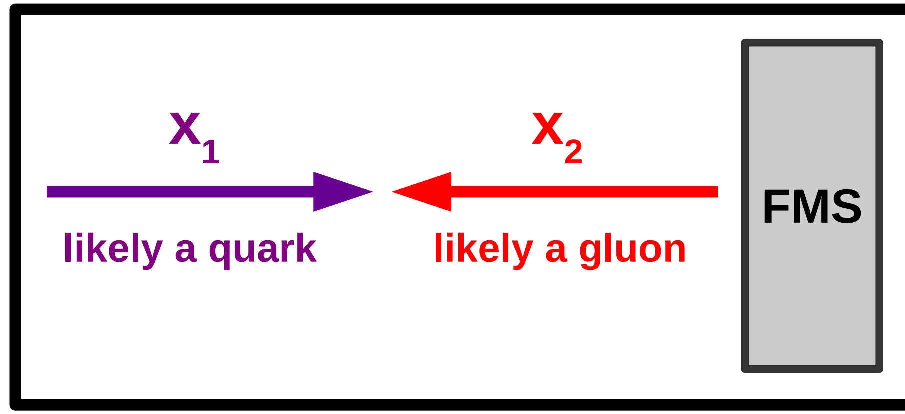
Forward Rapidity $2.65 < \eta < 3.9$

- Pions at 510 GeV in 2012 and 2013
  Phys.Rev.D 98 (2018) no.3, 032013
  *** new result!**
- Pions at 200 GeV in 2015
  Analysis Underway
- Dijets et al. in the Forward Upgrade for 2021+
  Analysis for the Future

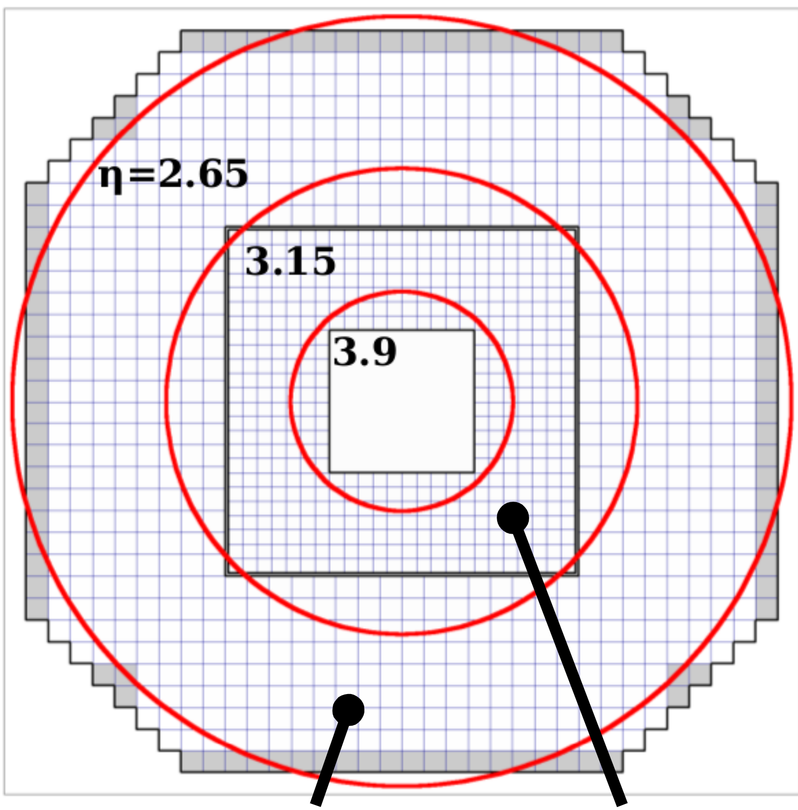


Forward Meson Spectrometer

- Pb-Glass EM Calorimeter
- Primarily sensitive to π^0s
- Analyzed 4 p_T bins in two η regions
- p_T bins chosen to equalize yields in each

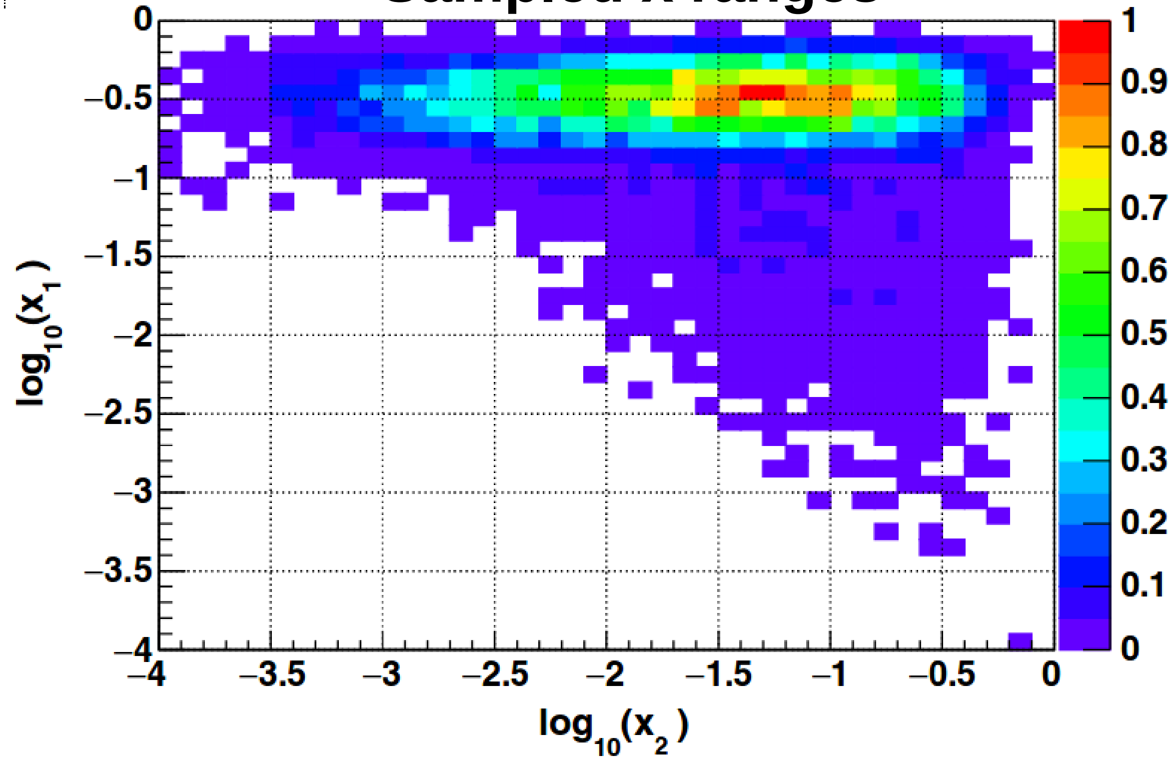


FMS Schematic



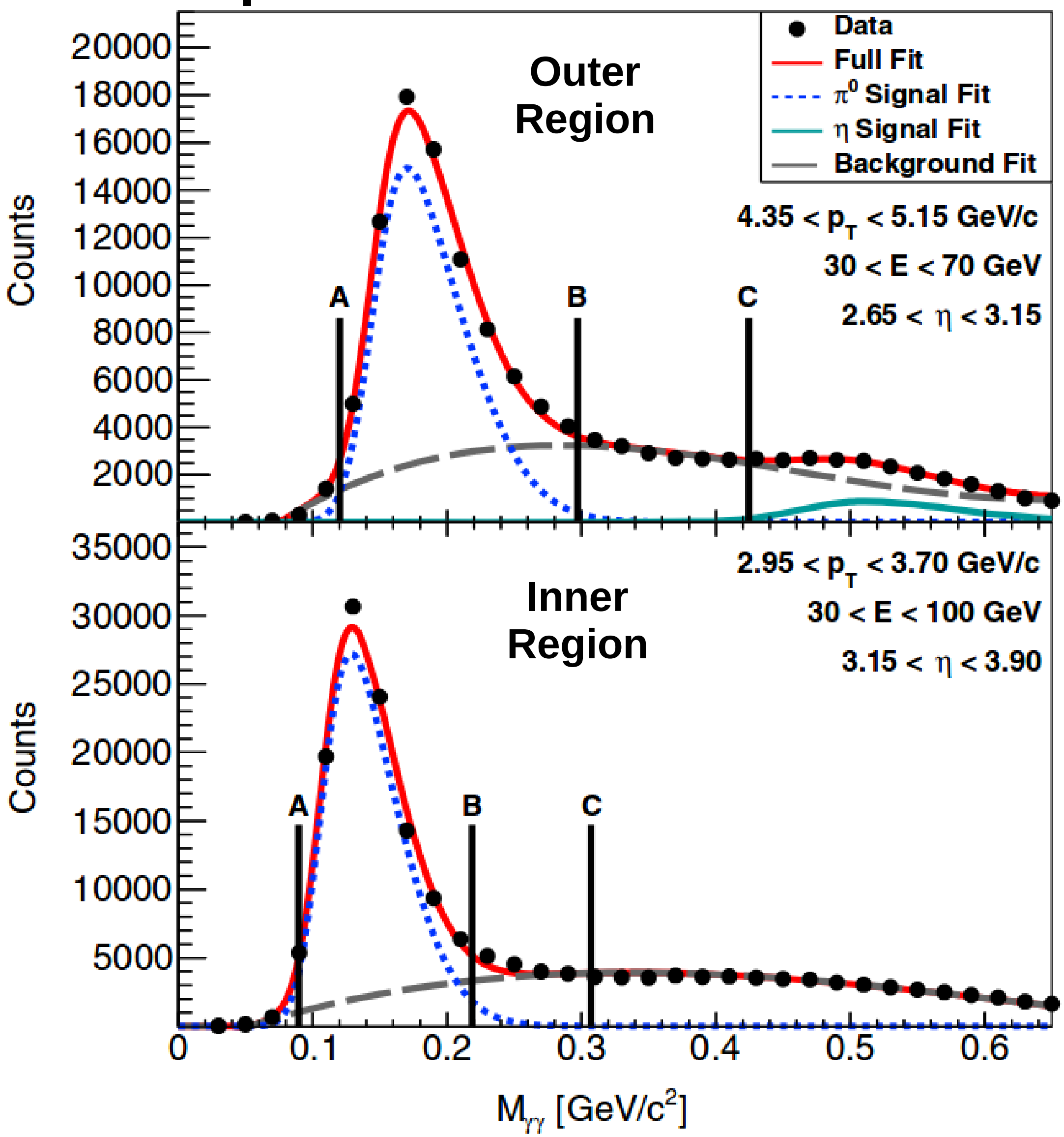
Outer Region **Inner Region**

Sampled x ranges



Pion Event Sample

2-photon Invariant Mass



- Mass Region [AB] – Pions
- Region [BC] – Sideband, for BG
- BG corrections applied to A_{LL}

Full A_{LL} from π^0 mass window

Extracted π^0 Signal A_{LL}

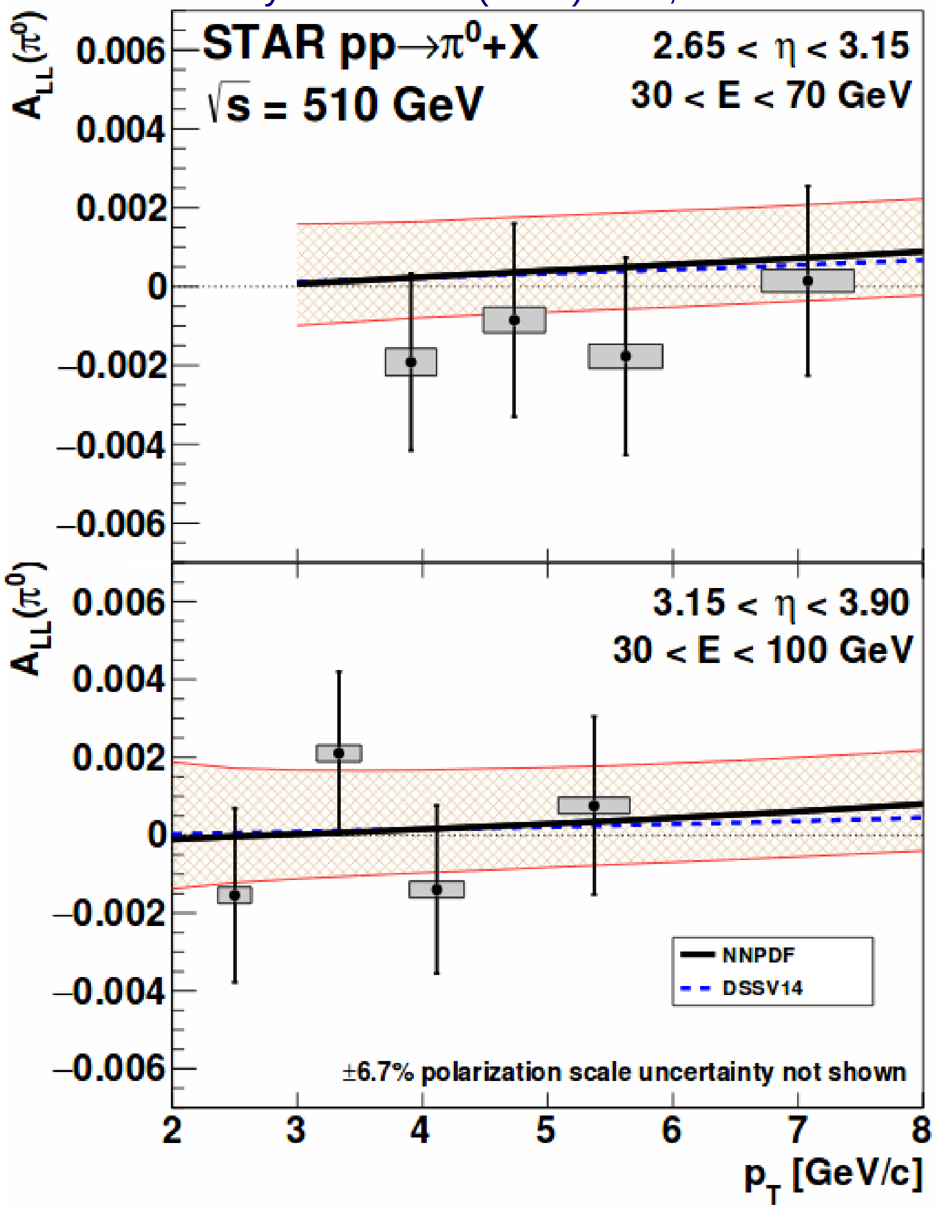
BG A_{LL} from sideband mass window

$$A_{LL}^{\pi^0} = \frac{1}{F} \cdot A_{LL}^{\mathrm{Tot}} - \frac{1-F}{F} \cdot A_{LL}^{\mathrm{BG}}$$

F = π^0 Purity: fraction of events in π^0 mass window which are likely π^0s

Forward Pions at 510 GeV in 2012 & 2013

Phys.Rev.D 98 (2018) no.3, 032013

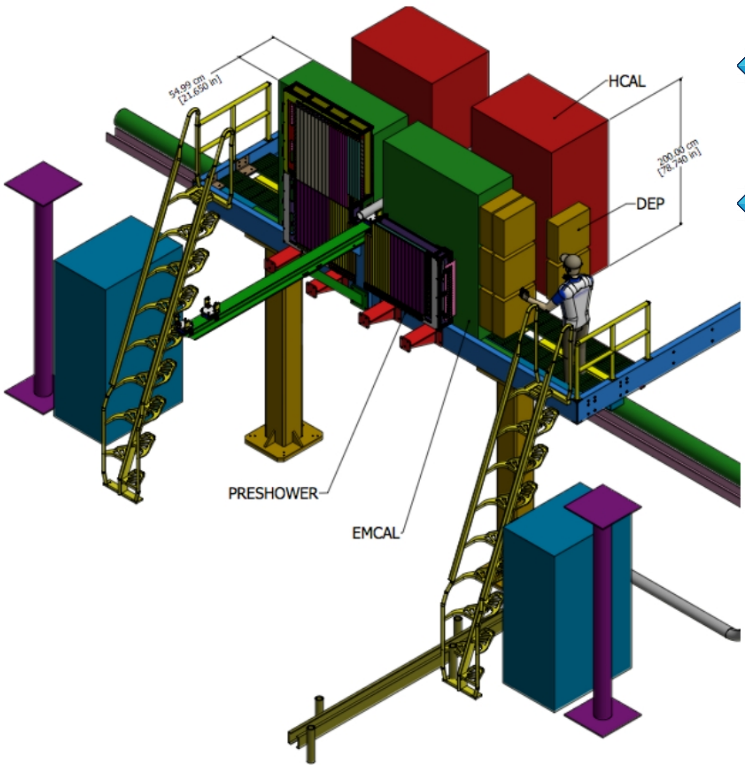


- Pushing even farther forward probes x down to 0.001
- Provides constraints to the unexplored low-*x* region, which is *abundant* with soft gluons
- Shown for two pseudorapidity regions
- Analysis for 200 GeV is underway, and although it will not probe to as low of *x*, it will help improve constraints on Δg(x)

x > 0.001

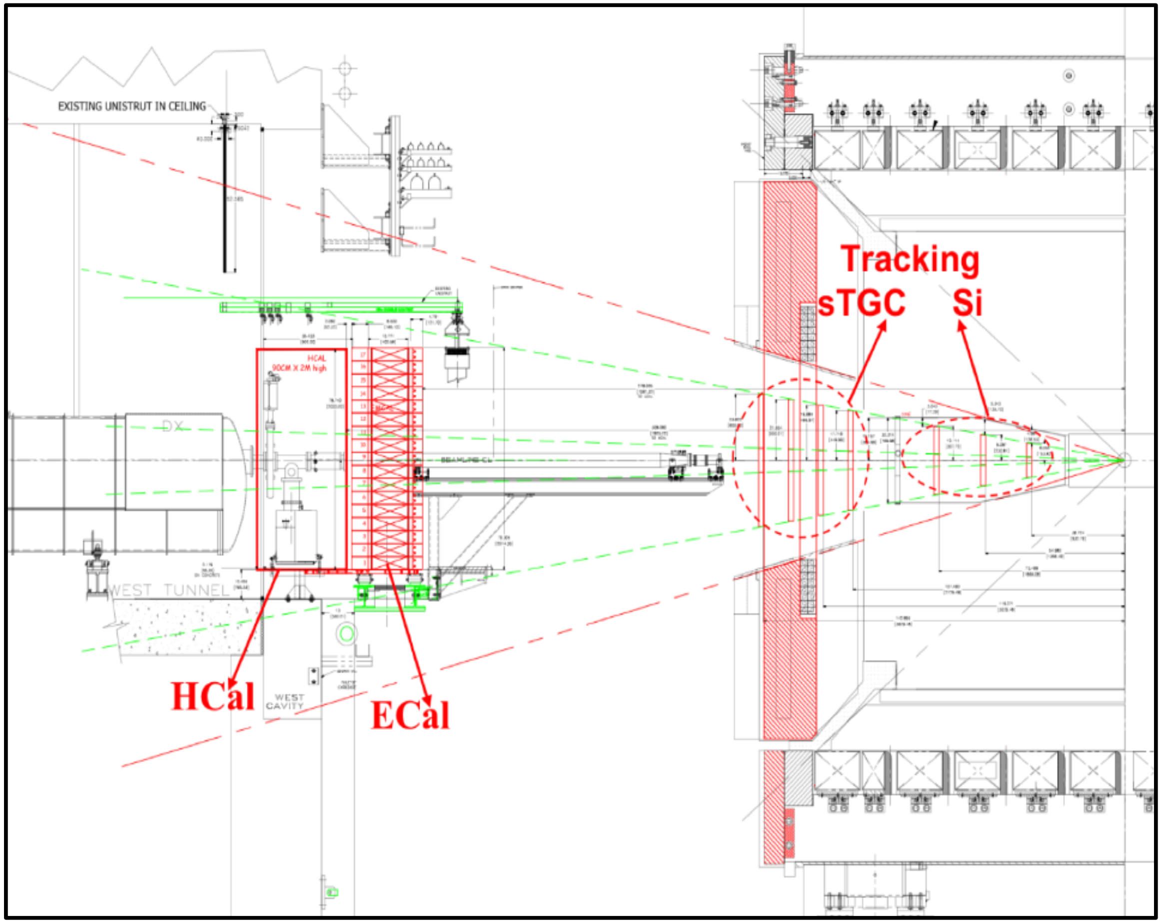
Forward Upgrade for 2021+

STAR Note SN0648 – The STAR Forward Calorimeter System and Forward Tracking System



x > 0.001

- Plans for a forward tracking system for charged hadrons
- Plans for upgraded forward calorimeters: EM and Hadronic
- Forward (di)jets will help more precisely probe Δg(x) down to x~0.001
- **See Kenneth Barish's talk for more info**



Summary: Recent A_{LL} Measurements

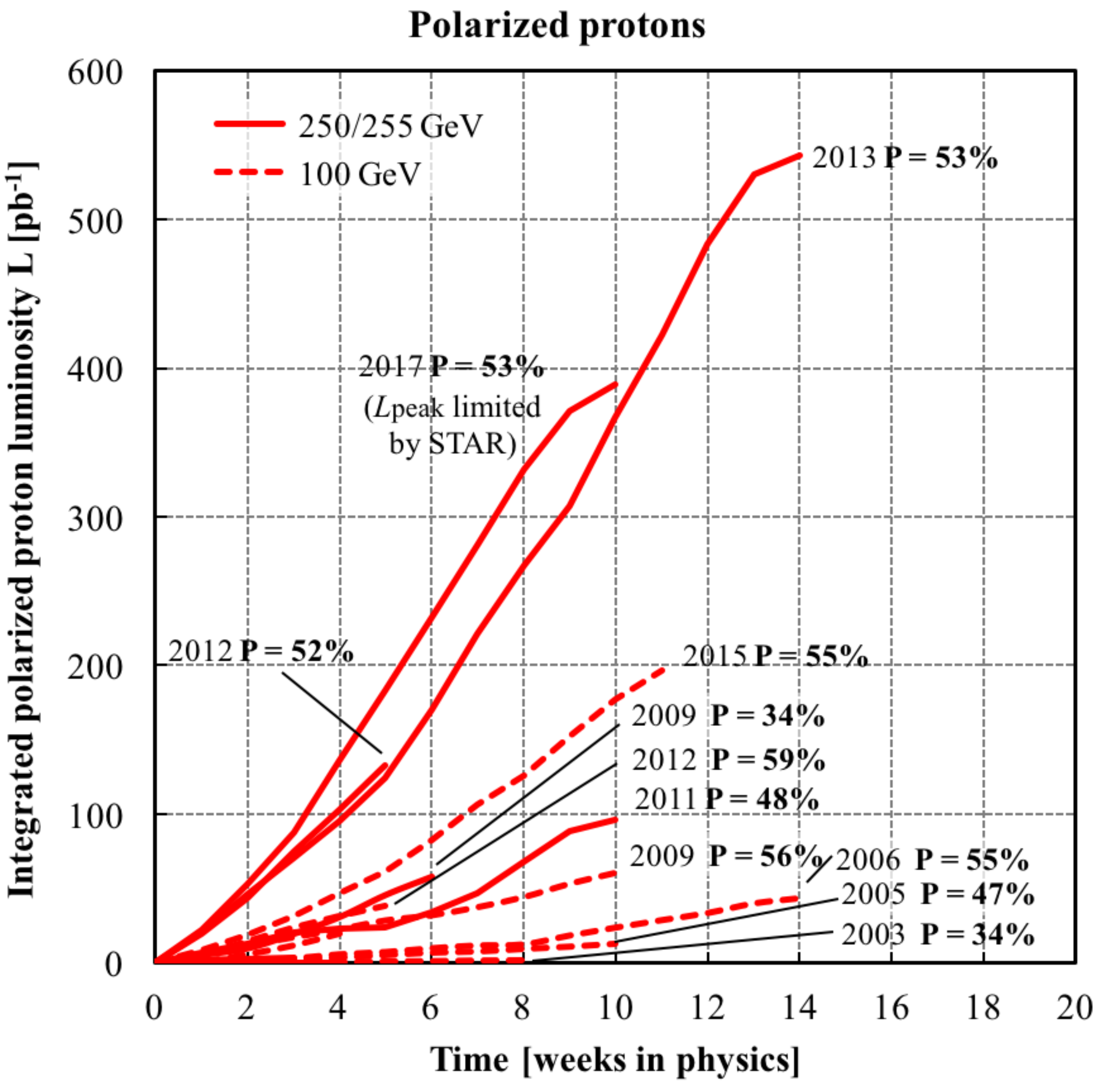
√s (GeV)	RHIC Run	Central Jets	Central Dijets	Interm. Dijets	Interm. Pions	Forward Pions	Forward Dijets
200	2006	Published* x>0.05			Published x>0.01		n/a
200	2009	Published x>0.05	Published x>0.05	Published x>0.01			n/a
200	2015	Underway x>0.05	Underway x>0.05			Underway x>0.0025	n/a
510	2012	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
510	2013	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
200 & 510	2021+						Future x>0.001

* not presented

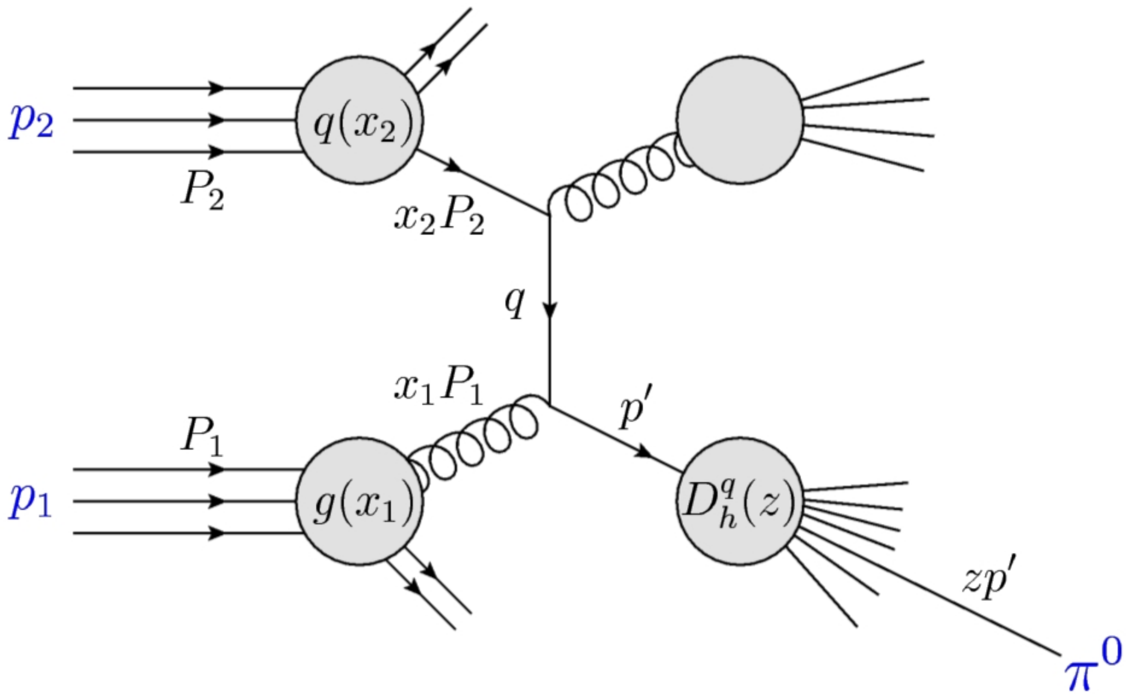
backup

Recent RHIC Longitudinal pp Runs

- Run 6 – 2006 – 200 GeV
- Run 9 – 2009 – 200 GeV
- Run 12 – 2012 – 510 Gev
- Run 13 – 2013 – 510 GeV
- Run 15 – 2015 – 200 GeV



Factorized A_{LL}



$$A_{LL}^{\pi^0} = \frac{d\Delta\sigma^{pp\to\pi^0 X}/dK}{d\sigma^{pp\to\pi^0 X}/dK} = \frac{\sum_{f_1,f_2,f_3} \Delta f_1 \otimes \Delta f_2 \otimes \left[d\hat{\sigma}^{f_1 f_2 \to f_3 X'} \hat{a}_{LL}^{f_1 f_2 \to f_3 X'} \right] \otimes D_{f_3}^{\pi^0}}{\sum_{f_1,f_2,f_3} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f_3 X'} \otimes D_{f_3}^{\pi^0}}$$

Measuring A_{LL} in pp Scattering

$$A_{LL} = \frac{1}{P_a P_b} \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$

proton beam polarizations

$$P = \frac{I_+ - I_-}{I_+ + I_-}$$

measured by RHIC polarimetry

Luminosity: $L = \frac{dN/dt}{\sigma} \Rightarrow \sigma = \frac{N}{L_{int}}$

Relative Luminosity: $R_3 = \frac{L_{++} + L_{--}}{L_{+-} + L_{-+}}$

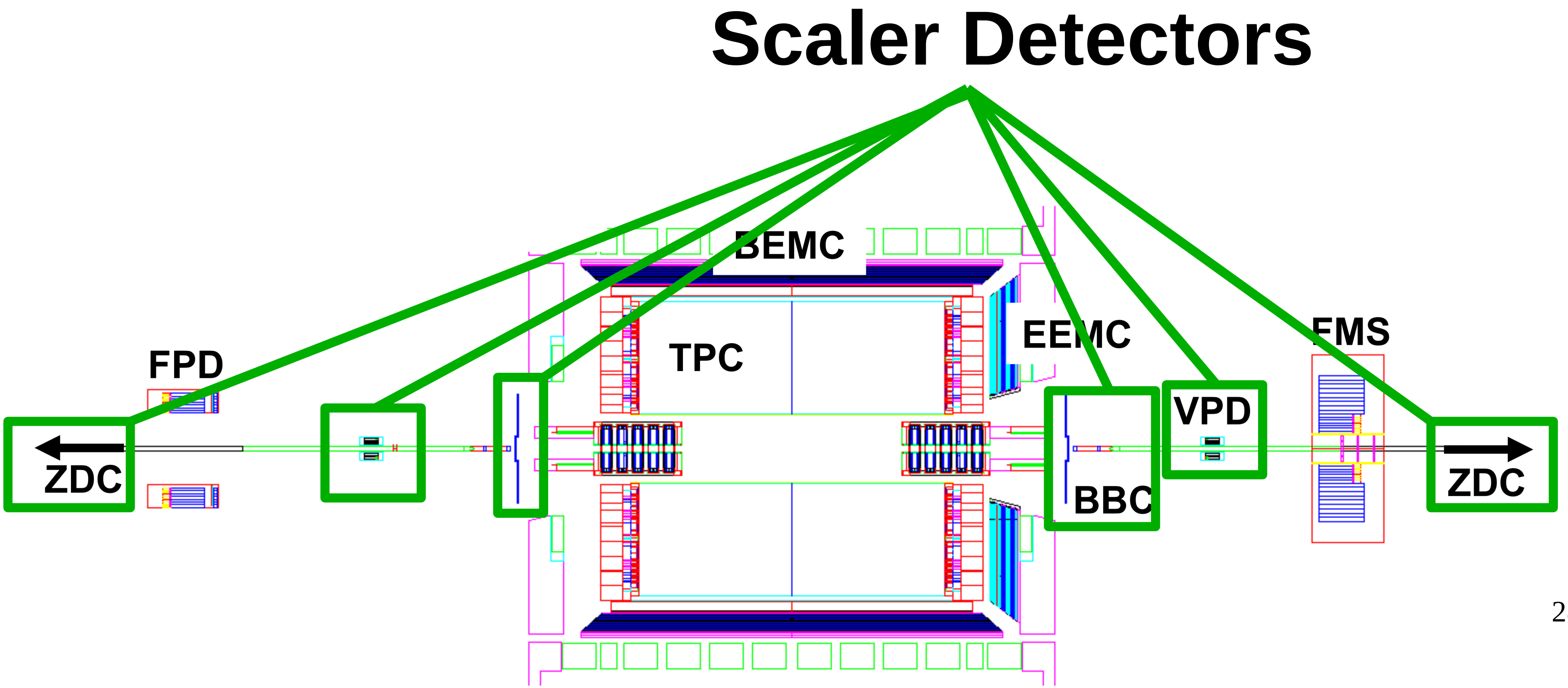
$$A_{LL} = \frac{1}{P_a P_b} \frac{N_{++} + N_{--} - R_3 \left(N_{+-} + N_{-+}\right)}{N_{++} + N_{--} + R_3 \left(N_{+-} + N_{-+}\right)}$$

Measuring Relative Luminosity

3 scaler subsystems for relative luminosity and local polarimetry

We primarily use VPD and ZDC

$$R_3 = \frac{L_{++} + L_{--}}{L_{+-} + L_{-+}}$$



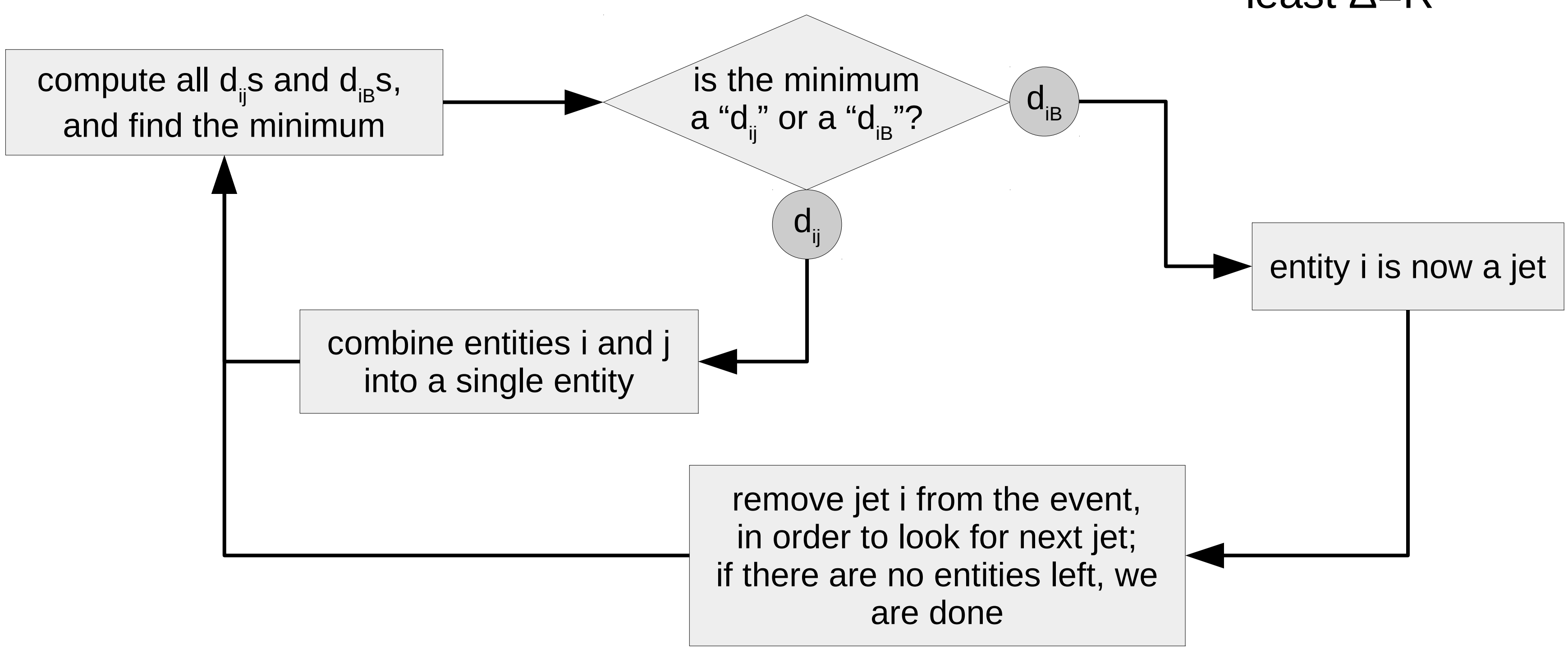
Anti-k_T algorithm for jet reconstruction

$$d_{ij} = \min\left(\frac{1}{k_{Ti}^2}, \frac{1}{k_{Tj}^2}\right) \cdot \frac{\Delta_{ij}^2}{R^2} \qquad \Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = \frac{1}{k_{Ti}^2}$$

- i and j represent entity (particle, jet, et al) i and j
- k_{Ti} is transverse momentum of entity i
- B represents "beam"
- R is the "resolution parameter"

R scales d_{ij} with respect to d_{iB}: any 2 jets are separated by at least Δ=R



Anti-kT Algorithm Example

Source: JHEP 0804 (2008) 063

- Example: few hard particles and many soft particles
- d_{1j} between hard particle "1" and soft particle "j" ($k_{T1} >> k_{Tj}$):
- If entity "1" was instead a soft particle ($k_{T1} \approx k_{Tj}$), d_{1j} would be much larger
- Result: soft particles tend to cluster with hard particles before they cluster with each other
- If a hard particle has no other hard particles within a distance of 2R, then it accumulates all soft particles within a circle of radius R, forming a (conical) jet

If another hard particle 2 is present such that $R < \Delta_{12} < 2R$ then there will be two hard jets. It is not possible for both to be perfectly conical. If $k_{t1} \gg k_{t2}$ then jet 1 will be conical and jet 2 will be partly conical, since it will miss the part overlapping with jet 1. Instead if $k_{t1} = k_{t2}$ neither jet will be conical and the overlapping part will simply be divided by a straight line equally between the two. For a general situation, $k_{t1} \sim k_{t2}$, both cones will be clipped, with the boundary b between them defined by $\Delta R_{1b}/k_{t1} = \Delta_{2b}/k_{t2}$.

Similarly one can work out what happens with $\Delta_{12} < R$. Here particles 1 and 2 cluster to form a single jet. If $k_{t1} \gg k_{t2}$ then it will be a conical jet centred on k_1.