Probing the Gluons with Jets from RHIC to EIC

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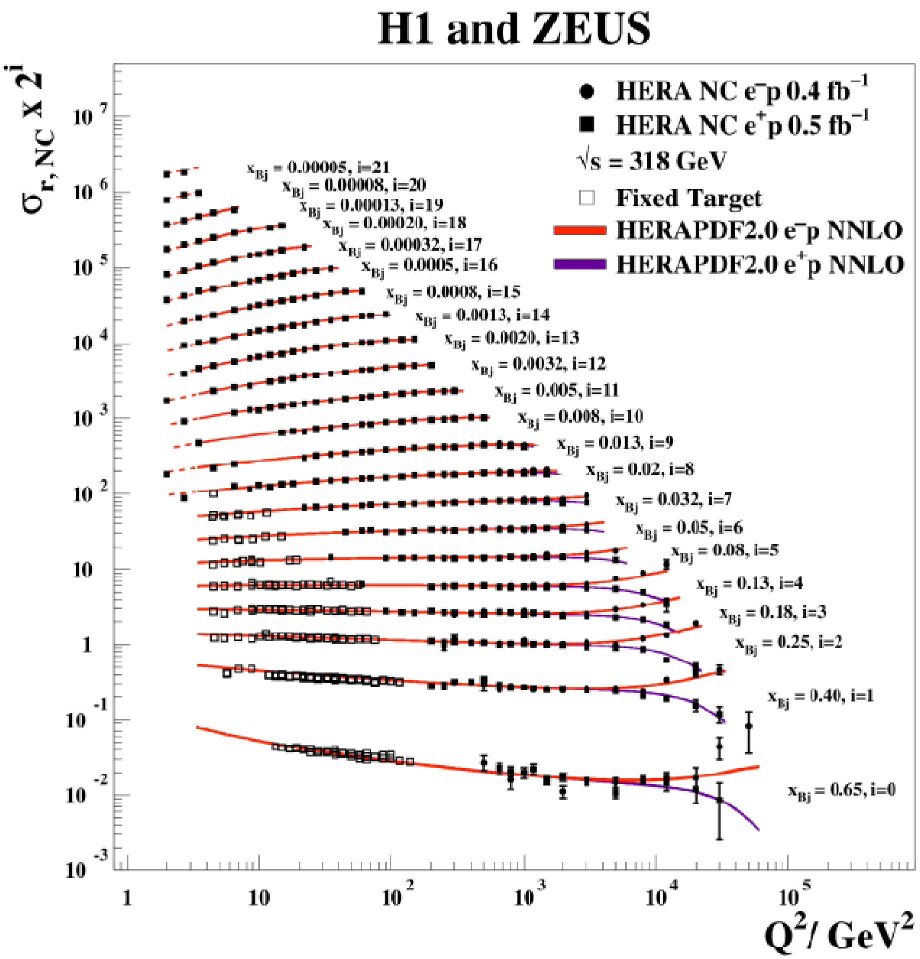
Outline and Some Caveats …

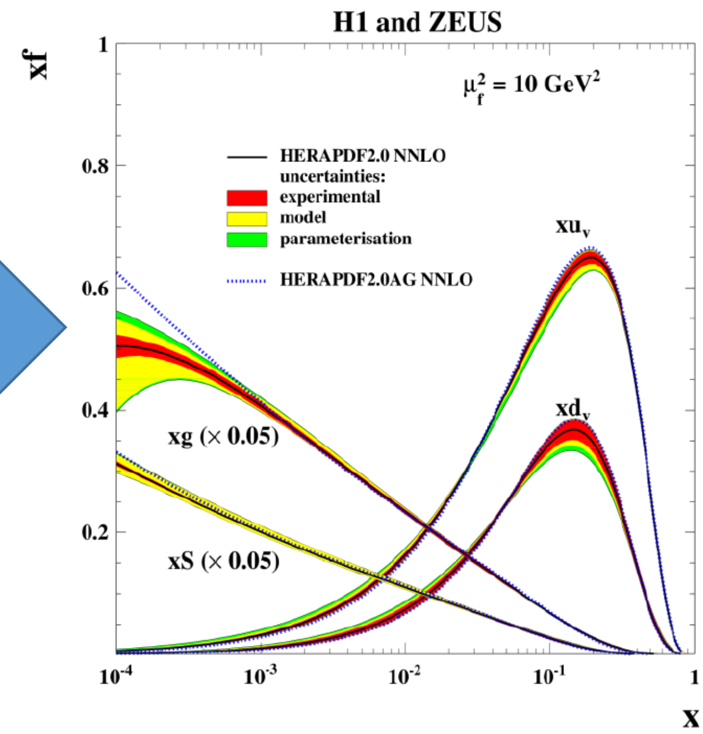
- Reminder from HERA
- RHIC Jet Results
- Jets at an EIC

- Focus on helicity
- "Probing the Gluons with Jets" -> Focus on STAR
- Many applications I don't have time to cover

Unpolarized Gluons from DIS

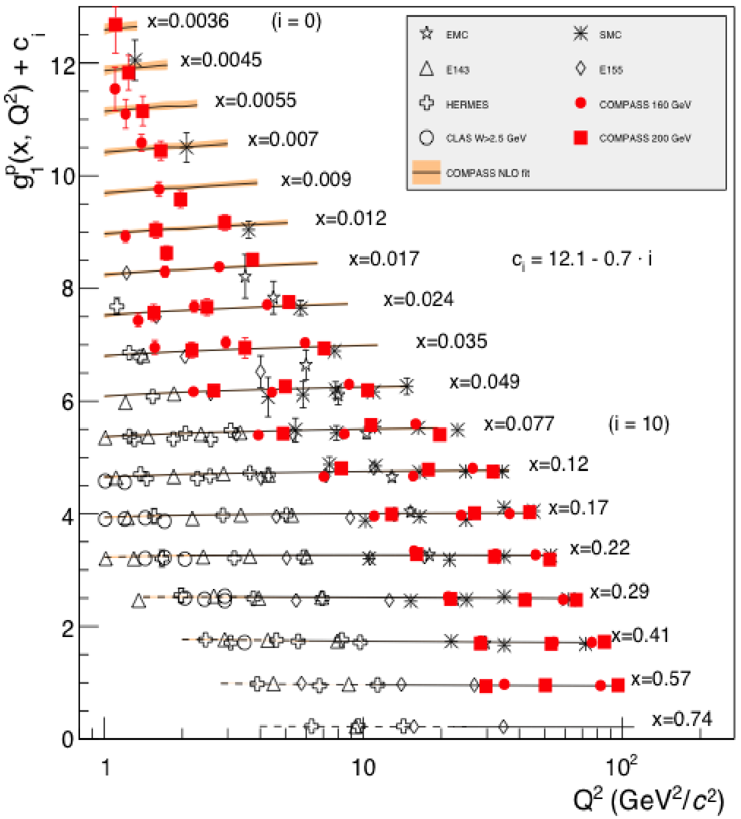


arxiv:1506.06042



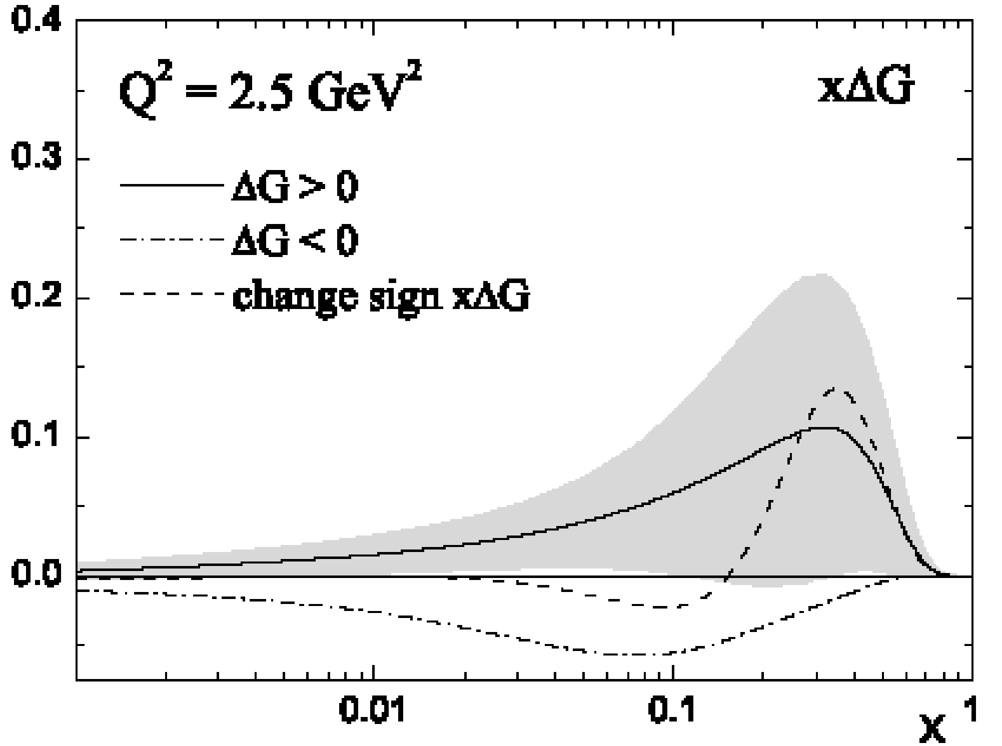
- Measurements of inclusive reduced cross section covers large x-Q^2 region
- Results in tight constraints on quark and gluon PDFs

Polarized Gluons from DIS



$$\frac{dg_1(x,Q^2)}{dln(Q^2)} \approx -\Delta g(x,Q^2)$$

- Early polarized fixed target DIS Data did not have the Q^2 reach to provide meaningful constrains



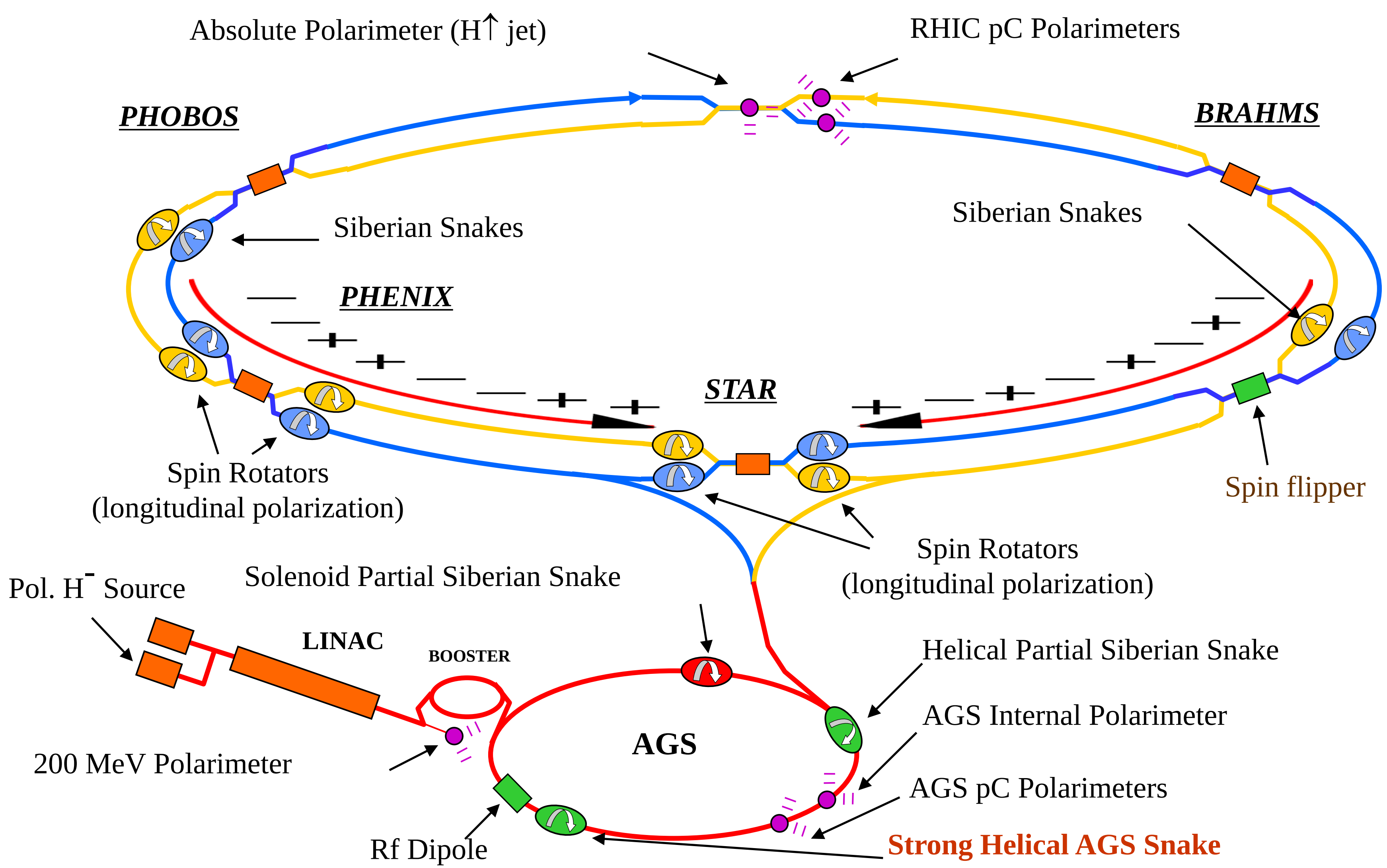
Three recent fits of equal quality:

- ΔG = 0.13 ± 0.16
- ΔG ~ 0.006
- ΔG = -0.20 ± 0.41

all at Q^2 = 1 GeV^2

Leader et al, PRD 75, 074027

RHIC

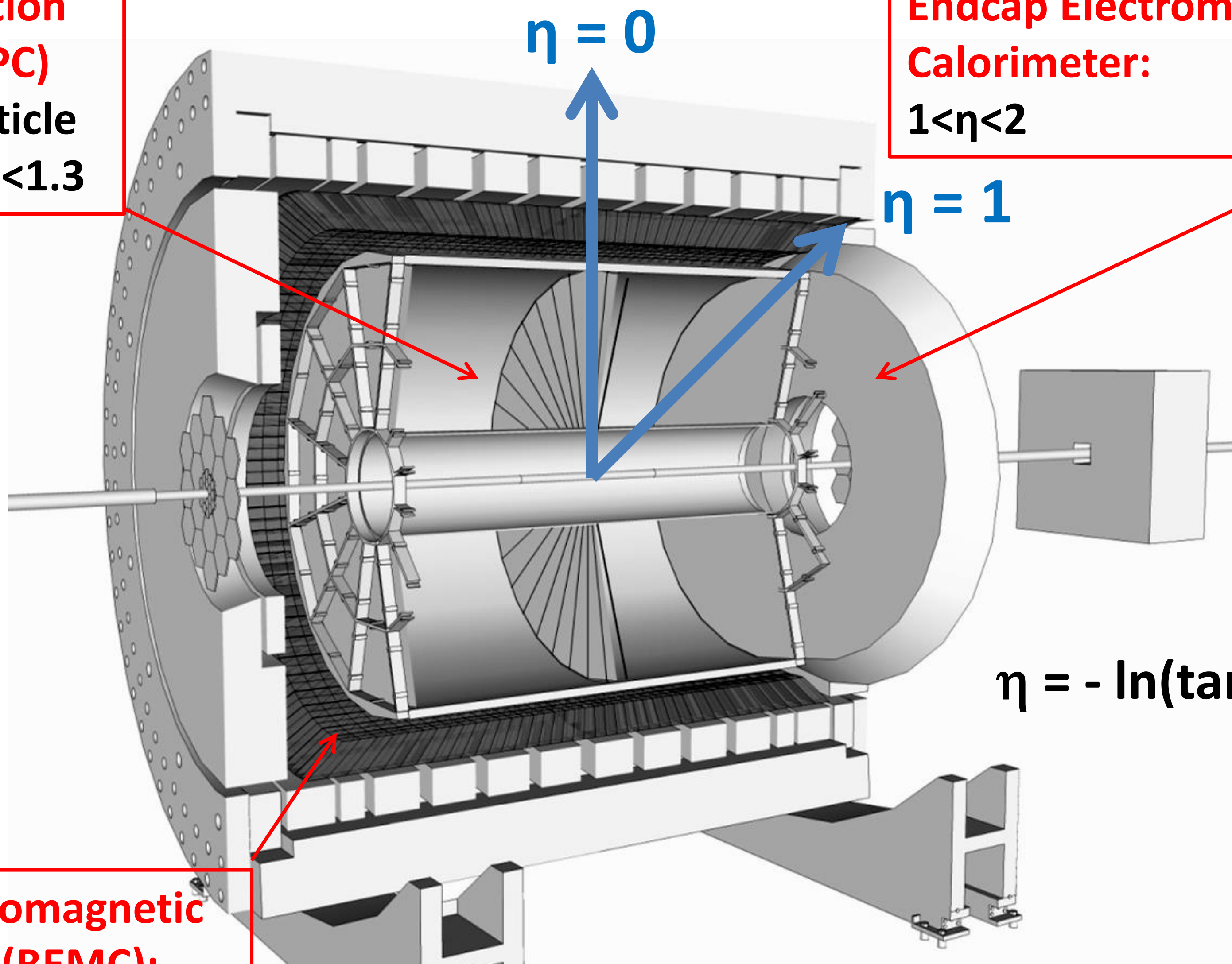


Absolute Polarimeter (H↑ jet)
RHIC pC Polarimeters
PHOBOS
BRAHMS
Siberian Snakes
Siberian Snakes
PHENIX
STAR
Spin Rotators
(longitudinal polarization)
Spin flipper
Spin Rotators
(longitudinal polarization)
Pol. H⁻ Source
Solenoid Partial Siberian Snake
LINAC
BOOSTER
Helical Partial Siberian Snake
AGS
AGS Internal Polarimeter
200 MeV Polarimeter
AGS pC Polarimeters
Rf Dipole
Strong Helical AGS Snake

STAR Detector

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

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



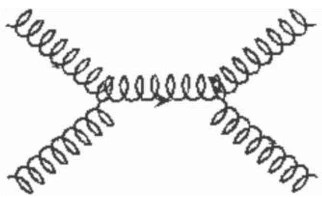
$$\eta = -\ln(\tan(\theta/2))$$

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

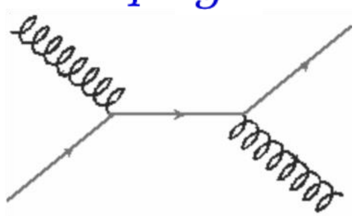
Accessing (Polarized) Gluons at RHIC

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}$$

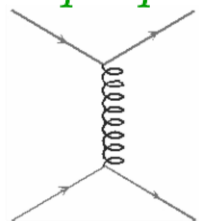
$\frac{\Delta g}{g} \frac{\Delta g}{g}$



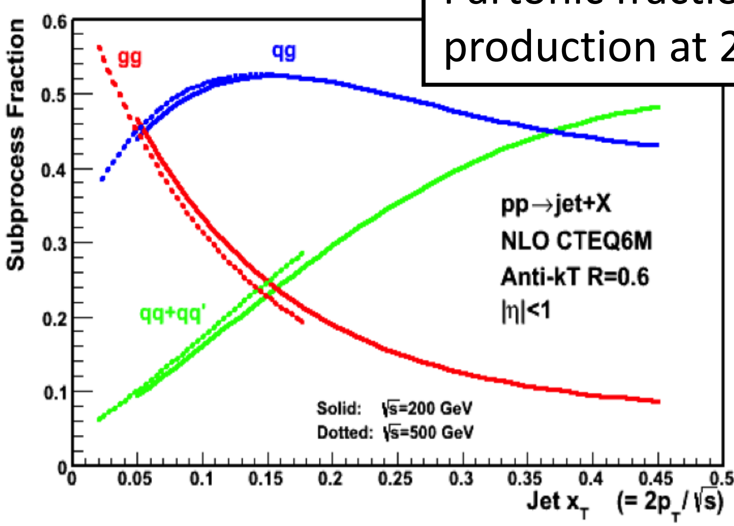
$\frac{\Delta q}{q} \frac{\Delta g}{g}$



$\frac{\Delta q}{q} \frac{\Delta q}{q}$

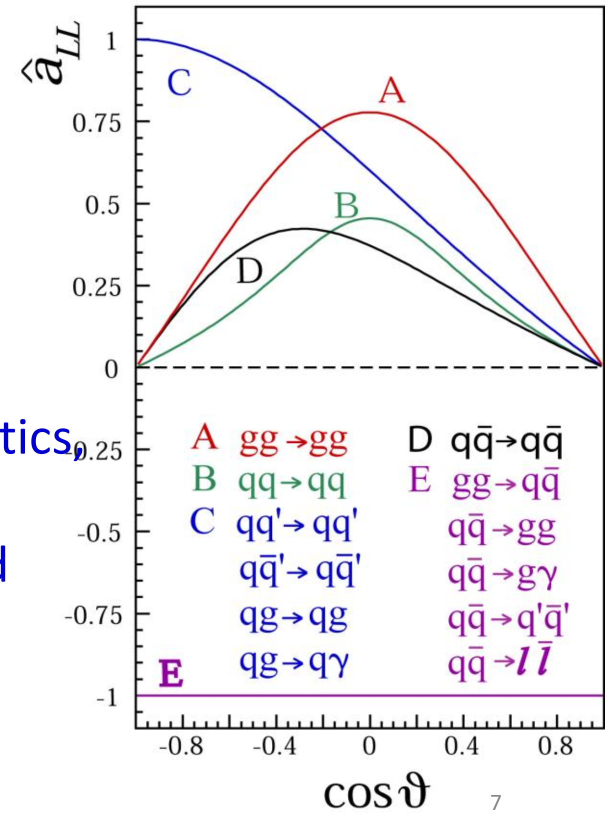


Partonic fractions in jet production at 200/500 GeV

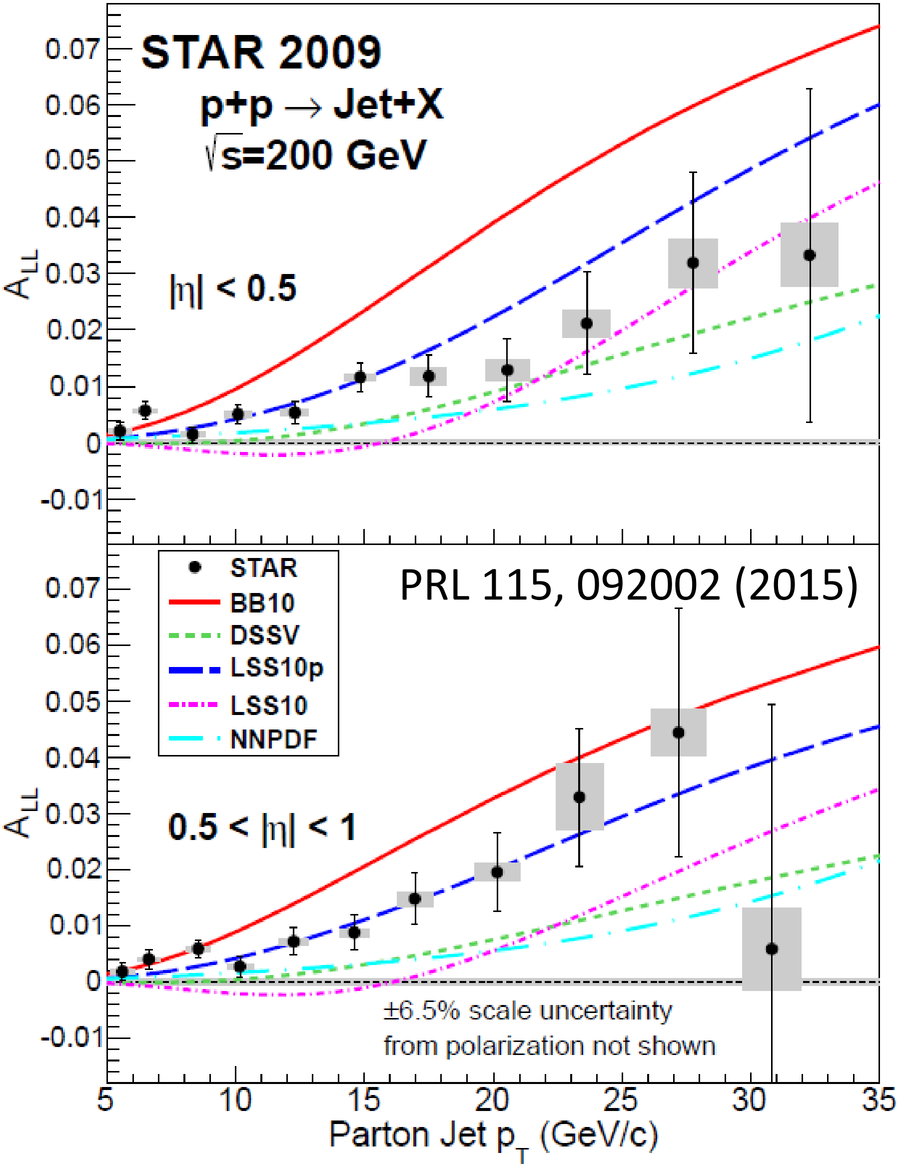


For most RHIC kinematics, **gg** and **qg** dominate, making A_{LL} for jets and hadrons sensitive to **gluon polarization.**

Parton Level Asymmetry

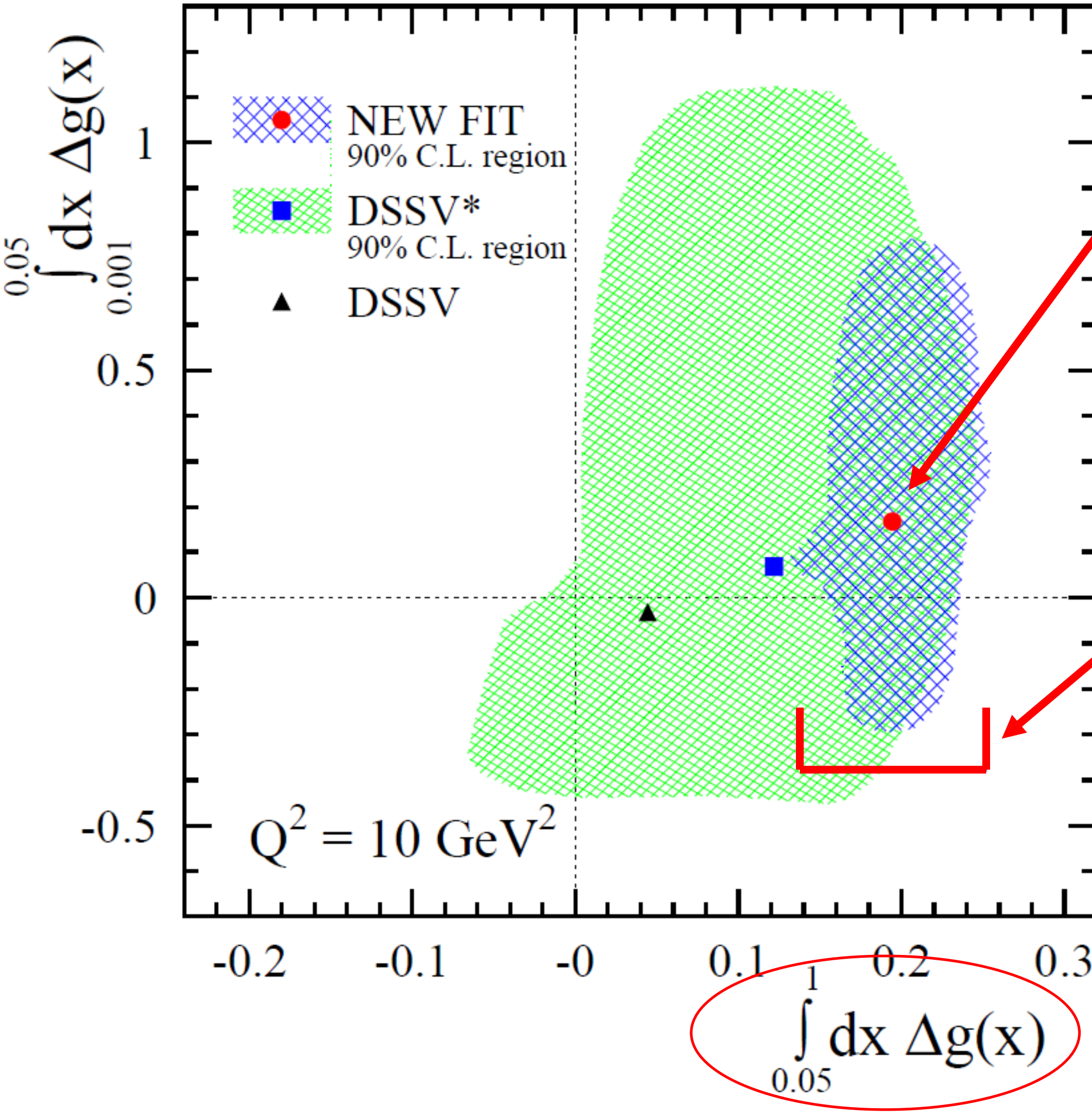


2009 Inclusive Jet Results



- 2009 STAR 200 GeV inclusive jet results have factor of 3 to 4 better statistical precision than previous results
- Results divided into two pseudorapidity ranges which emphasize different partonic kinematics
- Results sit consistently above the 2008 DSSV curve (but within uncertainties) which was consistent with zero gluon polarization
- These data and π^0 data from PHENIX included in next round of fits from DSSV and NNPDF

DSSV 2014 Global Analysis



Phys. Rev. Lett. 113, 012001 (2014)

- Integral of Δg(x) in range 0.05 < x < 1.0 increases from roughly 0.05 to $0.20^{+0.06}_{-0.07}$. First indication of non-zero gluon polarization!
- Uncertainty shrinks substantially from DSSV* to new DSSV fit

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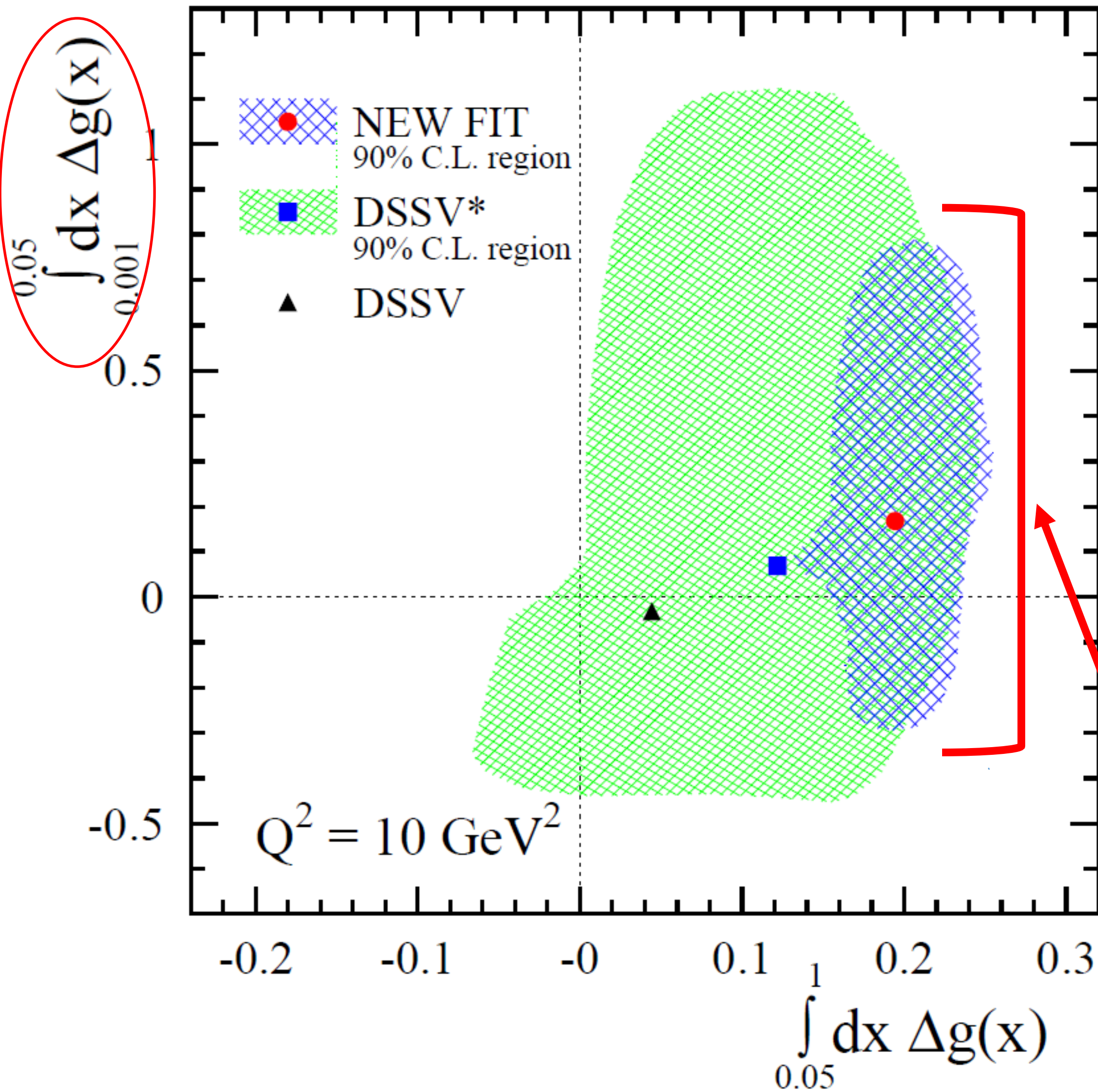


Phys. Rev. Lett. 113, 012001 (2014)

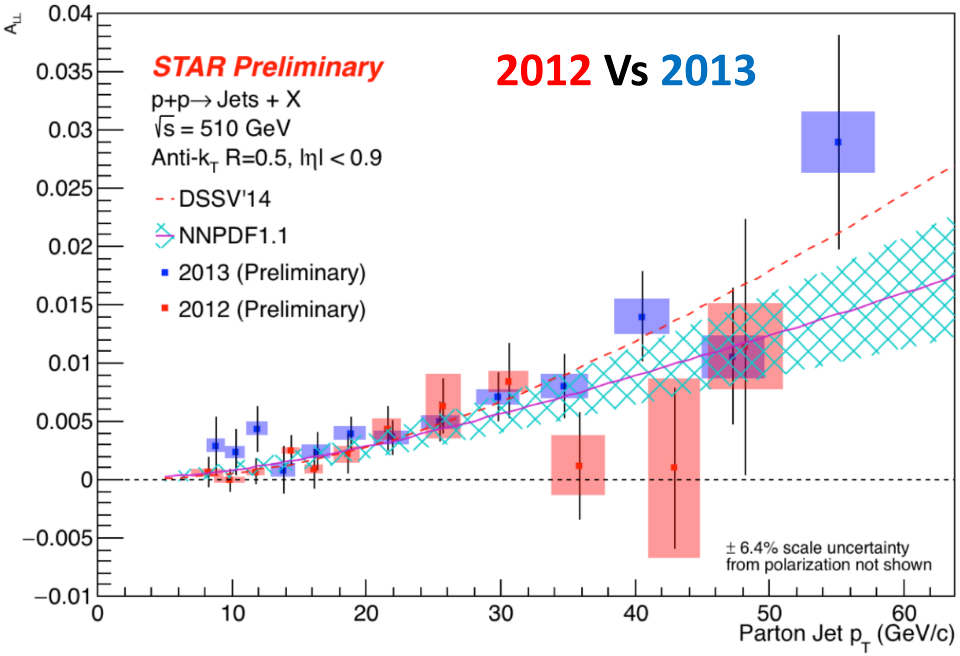
- Integral of Δg(x) in range 0.05 < x < 1.0 increases from roughly 0.05 to $0.20^{+0.06}_{-0.07}$. First indication of non-zero gluon polarization!
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable (only √s = 200 GeV RHIC data)

Present RHIC Analyses

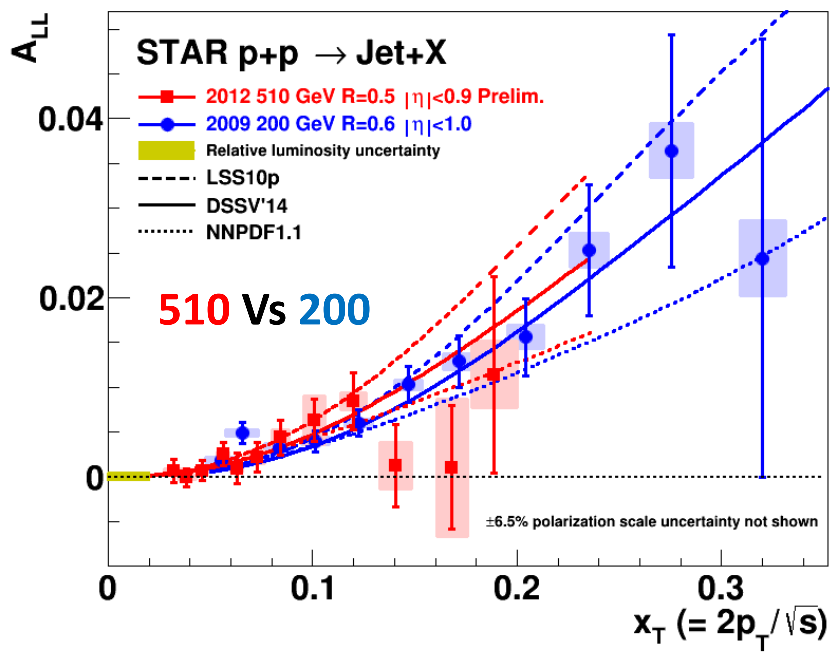
- The push to lower x
  - Higher collision energies
  - Forward Rapidities

- Moving beyond inclusive observables: Di-jets

Inclusive Jets at 500 GeV

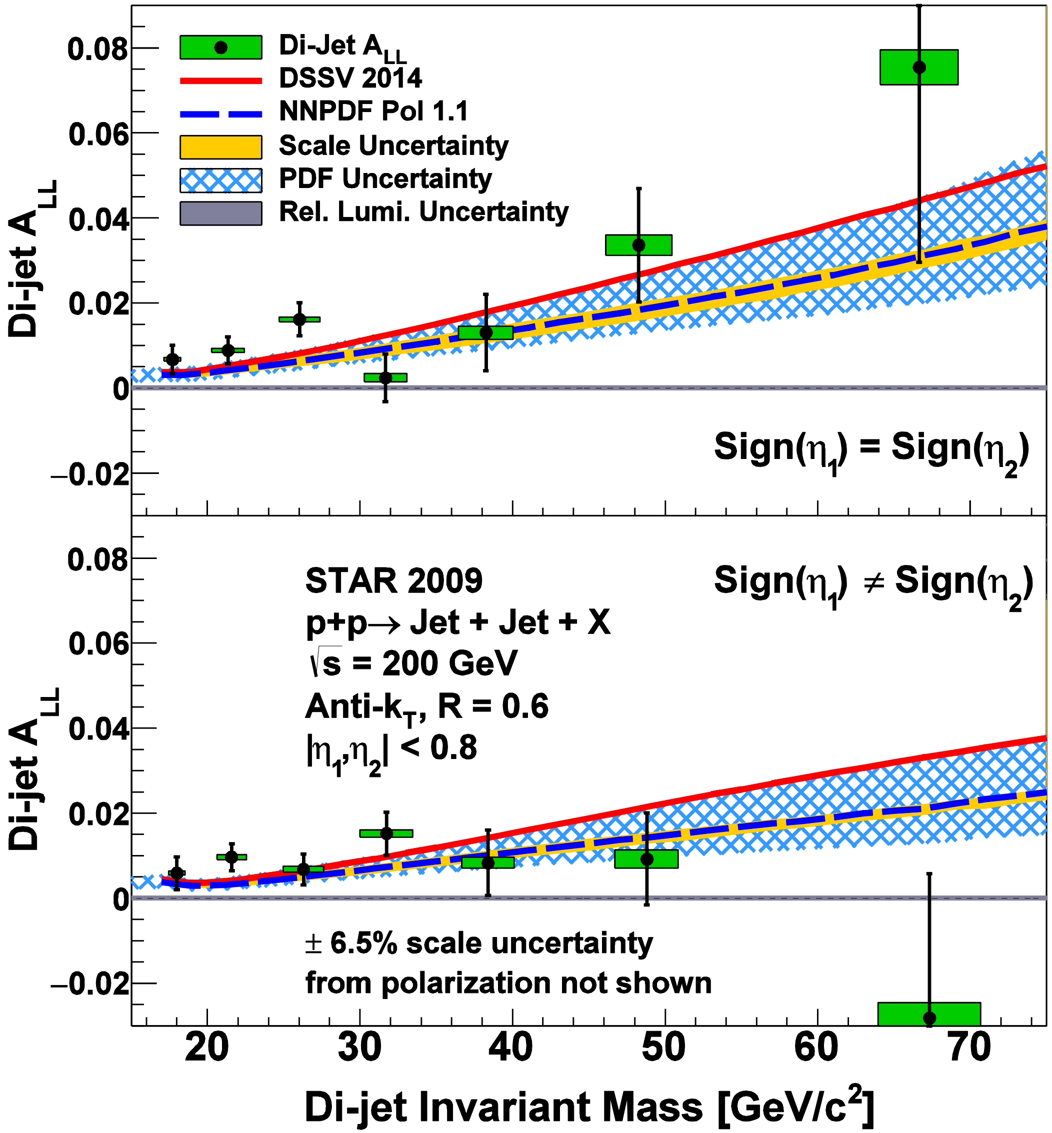


- 2013 results just made preliminary and 2012 ready for final release
- Final systematic uncertainties on 2012 result shrink substantially
- 2013 result based on roughly half of total dataset – full dataset for final result



- 2012 500 GeV result compared to 2009 200 GeV on same scale
- 500 GeV pushes to lower x while 200 GeV results give better precision at high x
- Good agreement in overlap region seen

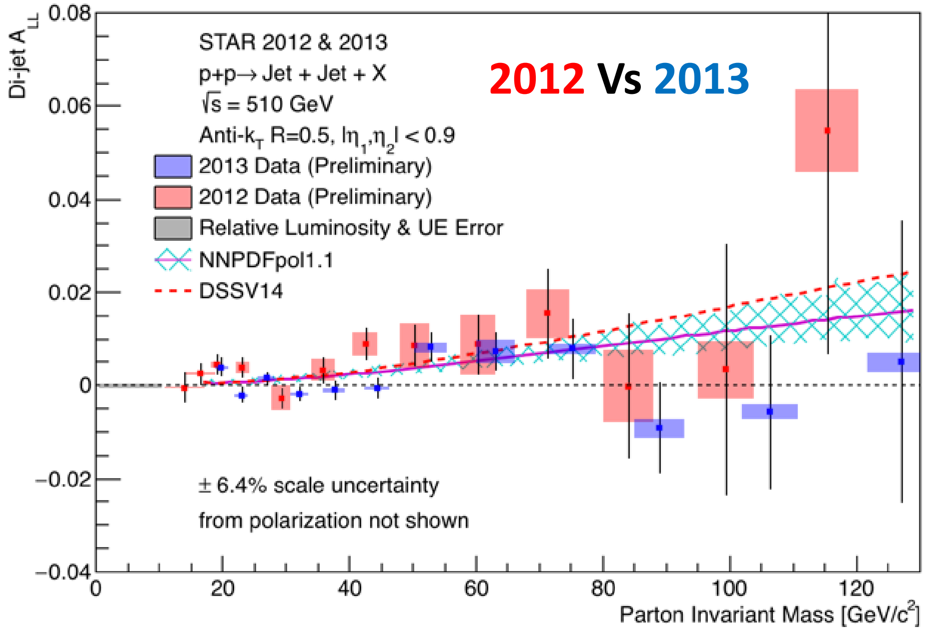
Di-jets at 200 GeV



PRD 95, 071103(R) (2017)

- Mid-rapidity di-jet A_{LL} presented for two topologies as a function of di-jet invariant mass corrected to parton level
- Data compared to expectations from DSSV14 and NNPDFpol1.1 polarized PDFs, both of which contain 2009 inclusive jet results
- Systematic bands from PDF and scale uncertainties shown for NNPDFpol1.1 curve

Di-jets at 510 GeV



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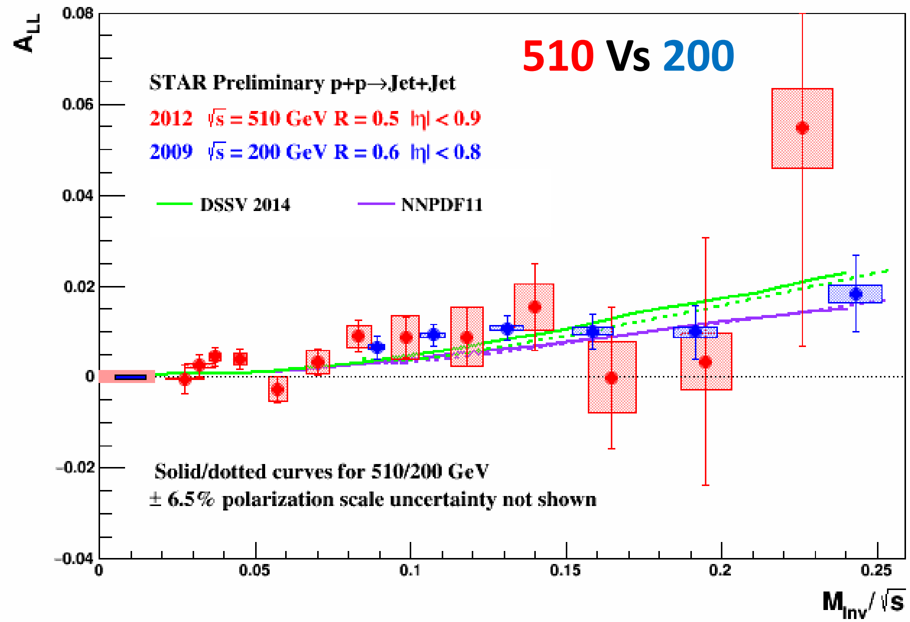
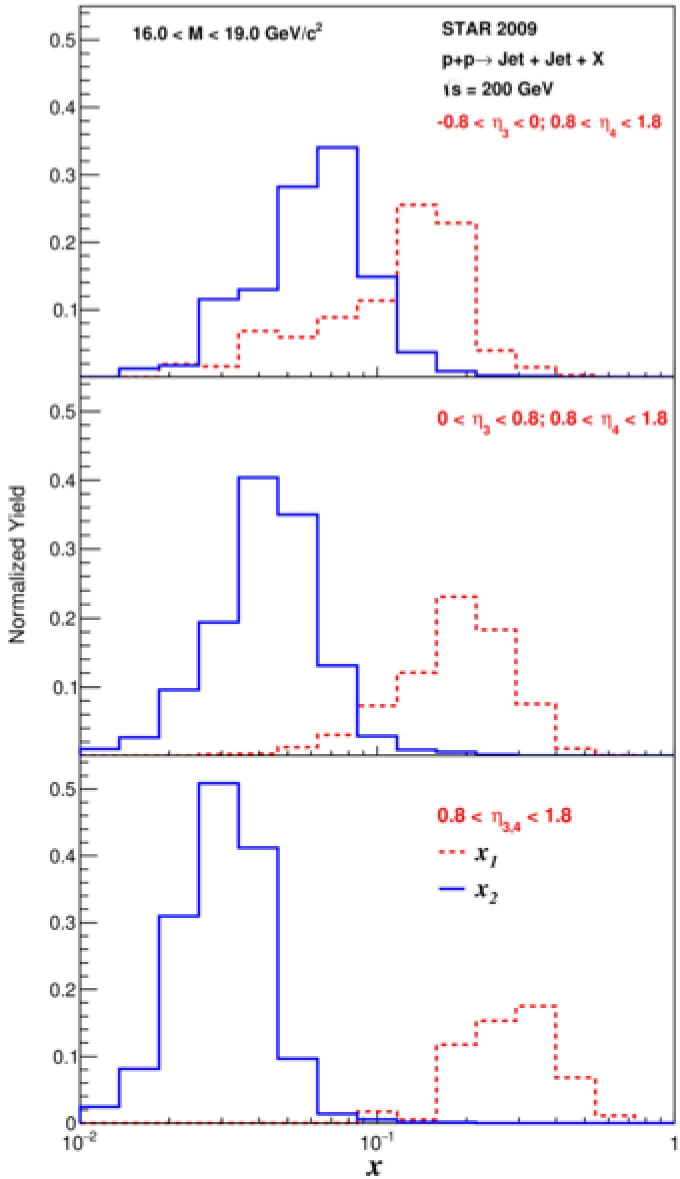
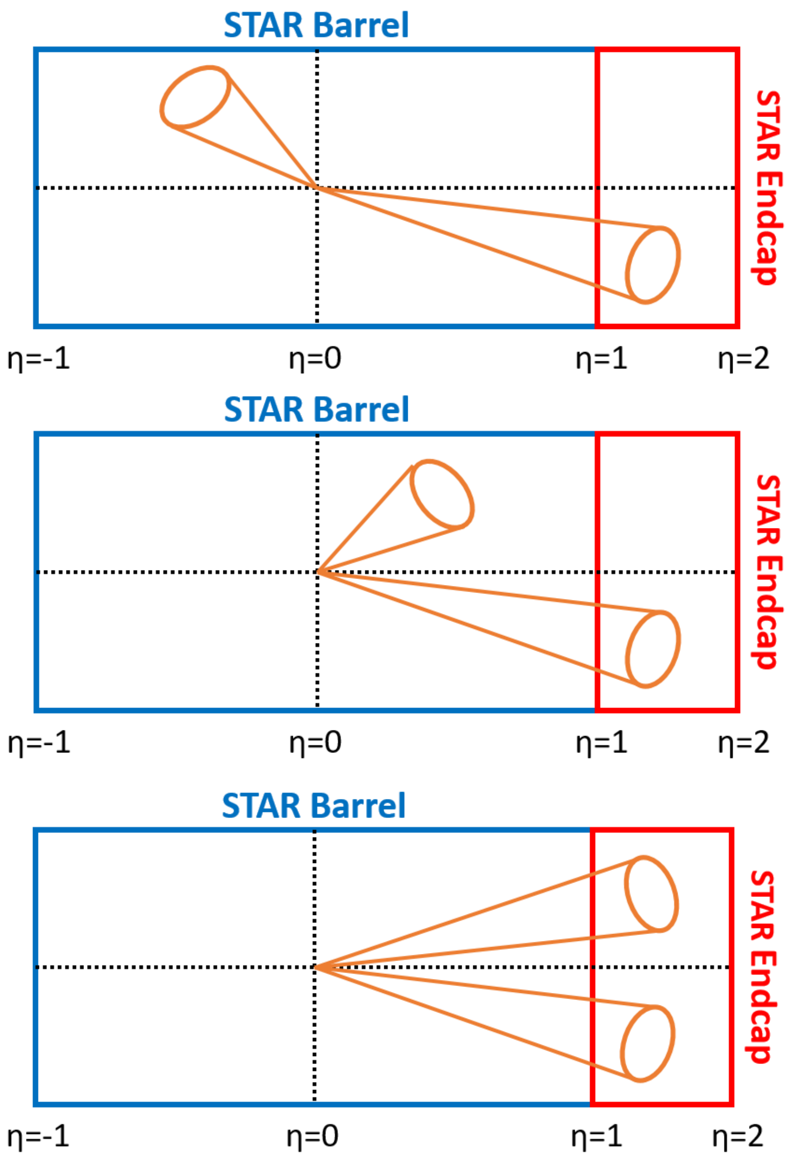


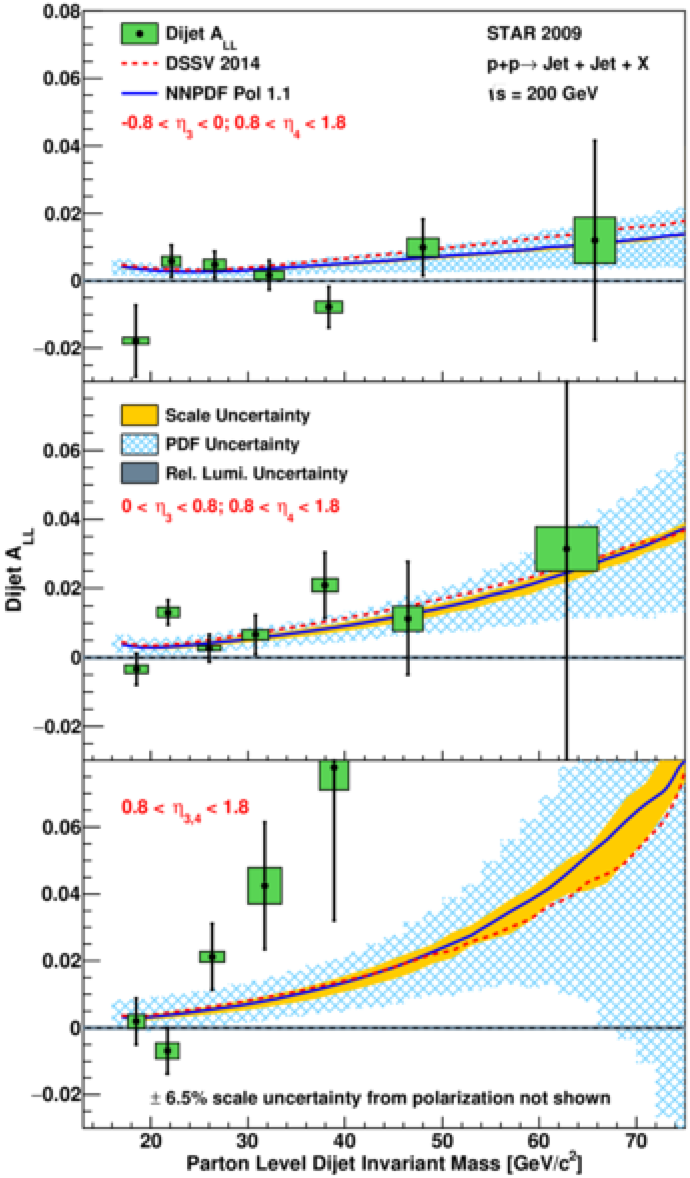
- For final release, these results will be split into four topologies based on jet pseudorapidity
- See excellent agreement between 2012 and 2013 as well as between 200 and 510 GeV

Forward Di-jets at 200 GeV



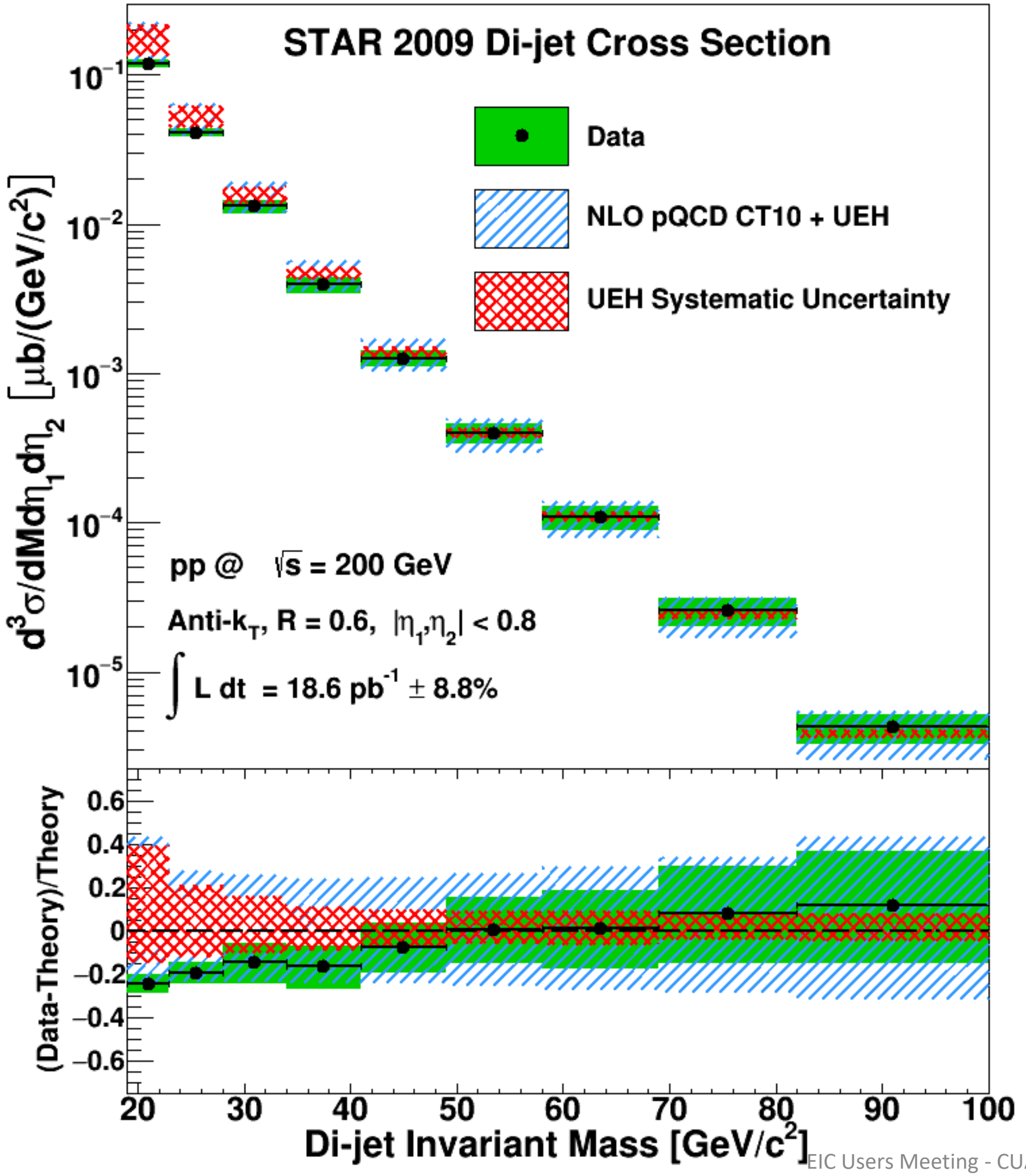


Forward Di-jets at 200 GeV



- Di-jet A_{LL} shown for three Barrel-Endcap topologies
- These forward di-jets will access gluons with lower momentum fraction than mid-rapidity results
- Results compared to DSSV14 and NNPDFpol1.1 expectations

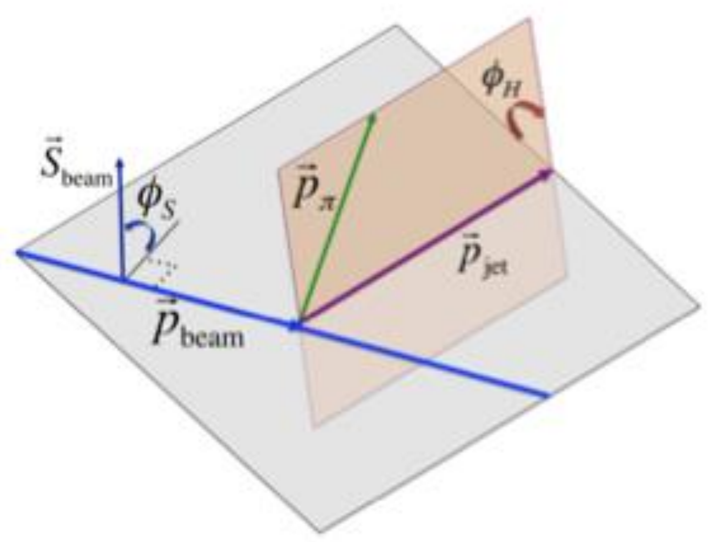
Di-jet Cross Section

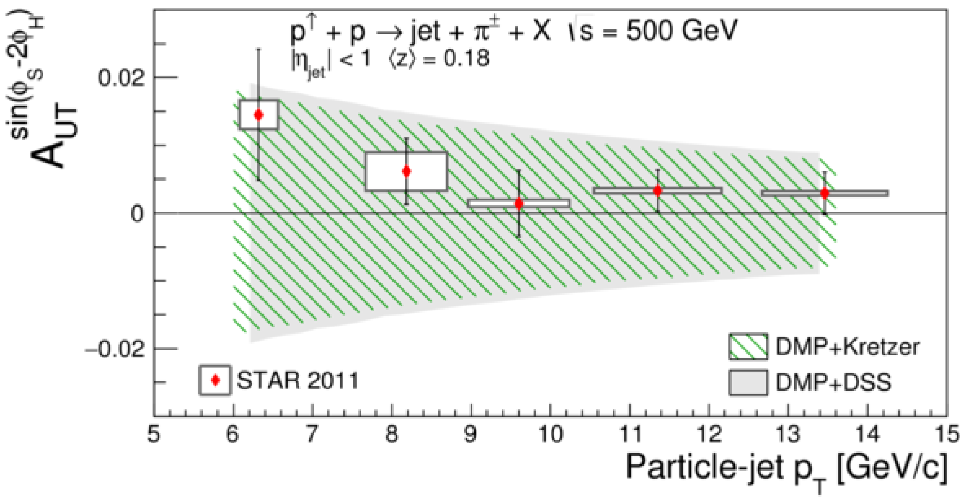


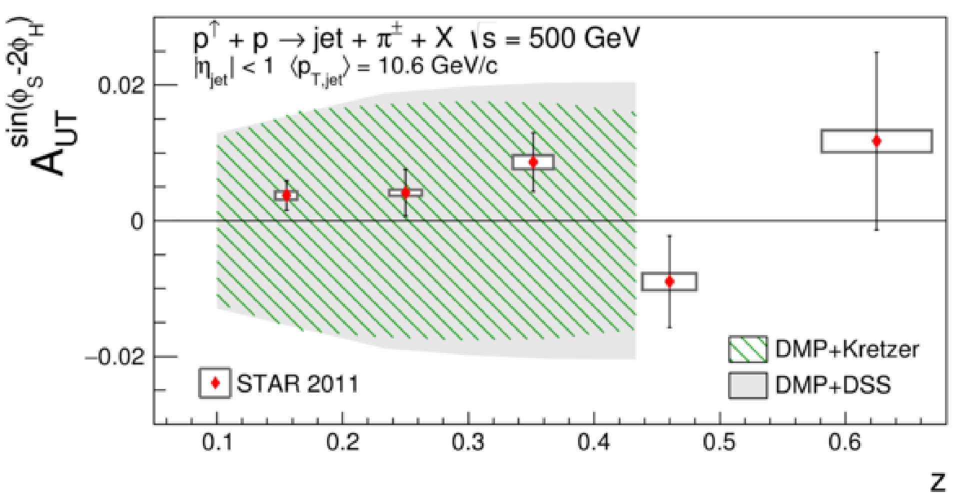
PRD 95, 071103(R) (2017)

- Unpolarized di-jet cross section was extracted and compared to NLO pQCD theoretical prediction
- Theoretical prediction was corrected for underlying event and hadronization (UEH) effects; the systematic on this correction is shown as the red band
- Blue band is the quadrature sum of the UEH systematic and uncertainty on the theoretical prediction due to PDF uncertainty and scale variation
- Inclusive cross sections at 200 and 500 GeV currently being analyzed

Hadrons in Jets





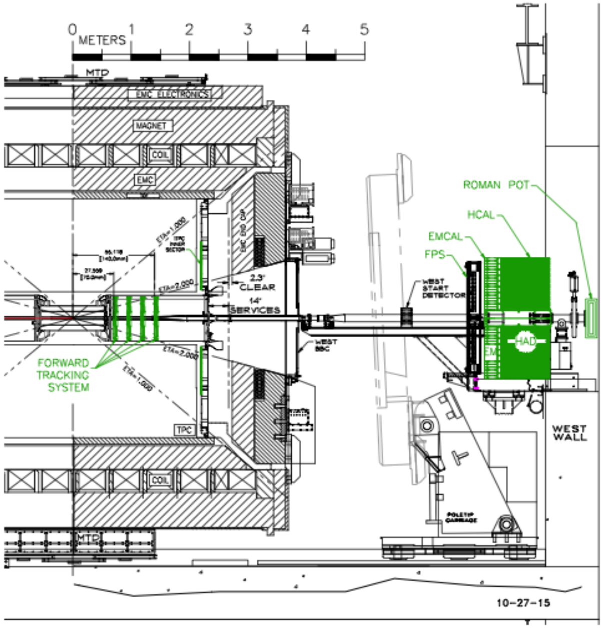


- STAR also has a rich transverse spin program
- One interesting observable is the transverse single spin asymmetry for identified hadrons within a jet
- Sin($\phi_S - 2\phi_H$) modulation sensitive to linearly polarized gluons

STAR Forward Upgrade

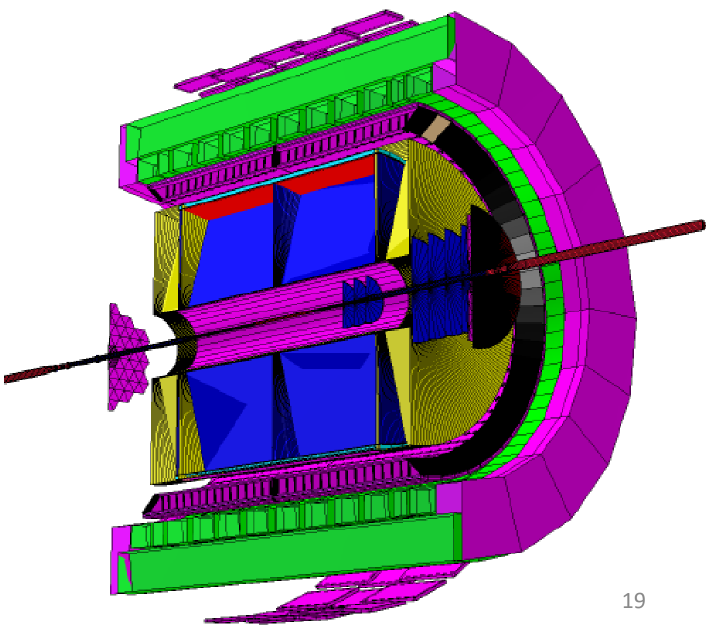
Calorimetry: EM & Hadronic

RHIC Cold QCD Plan arXiv:1602.03922



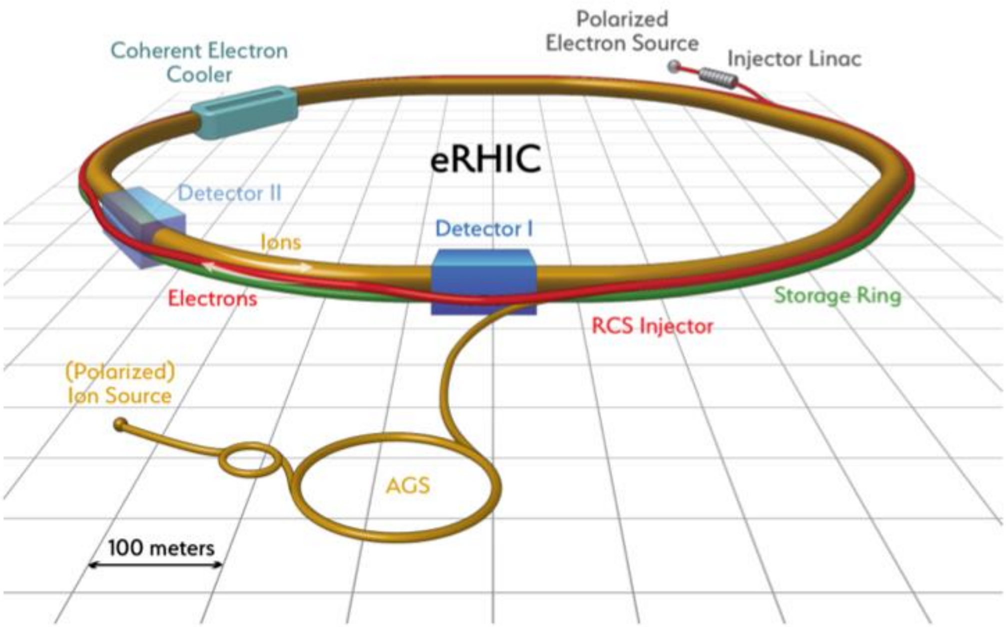
Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

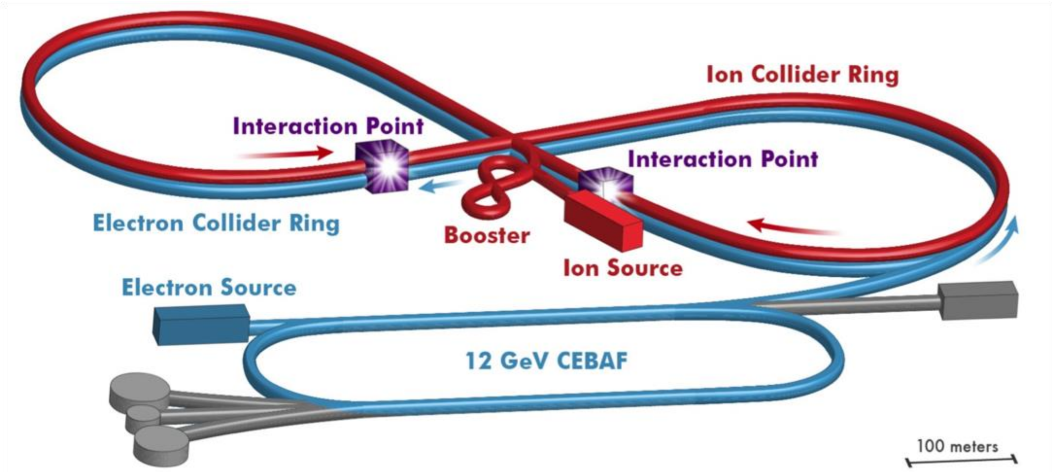
Tracking



- ECal reuses PHENIX PbSC calorimeter with new readout for cost savings
- HCal is sandwich iron-scintillator plate sampling Calo
- Tracker consists of 3 Si disks in the detector and 4 Small-strip Thin Gap Chambers outside

Potential EIC Realizations

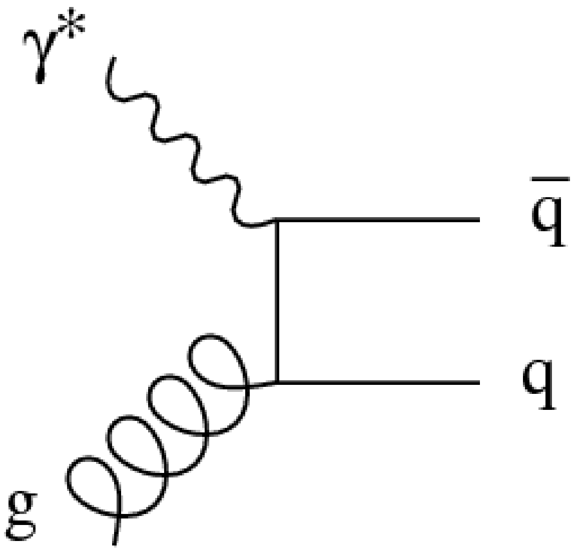




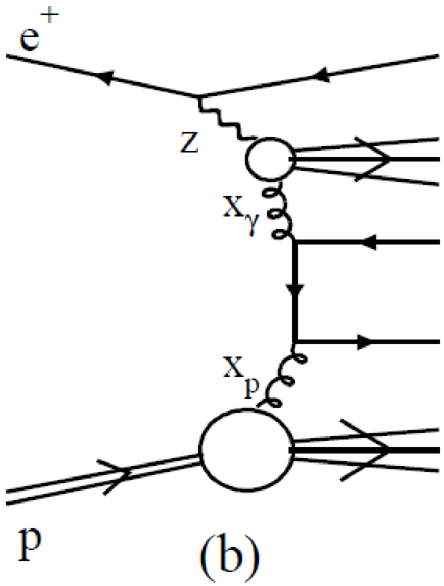
- Two designs are in active development:
  - eRHIC (BNL)
  - JLEIC (JLab)
- eRHIC utilizes the existing RHIC hadron facility and adds an electron ring and injector
- JLEIC utilizes CEBAF as an electron accelerator and adds a hadron source / booster and collider rings
- Broad tradeoff: eRHIC will start with lower luminosities but have larger center of mass energies while JLEIC will prioritize luminosity but with smaller collision energies

Accessing Gluons with Jets in DIS

Photon-Gluon Fusion



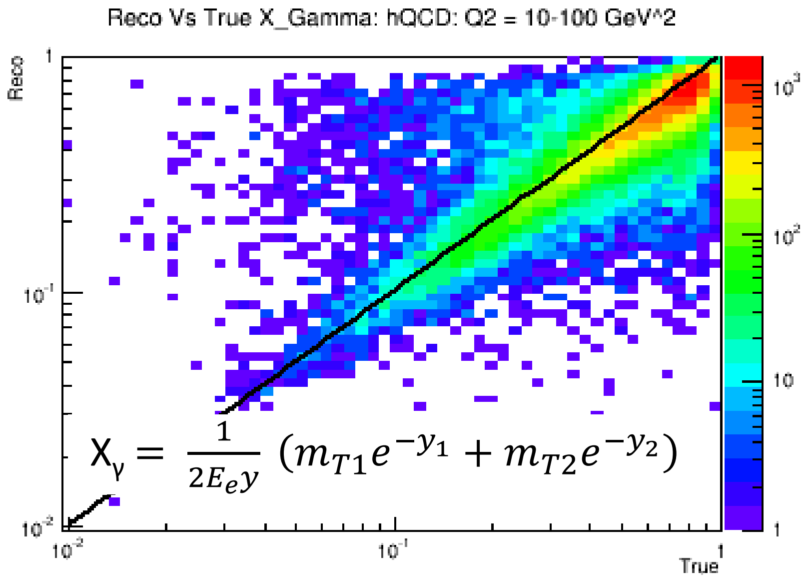
Resolved

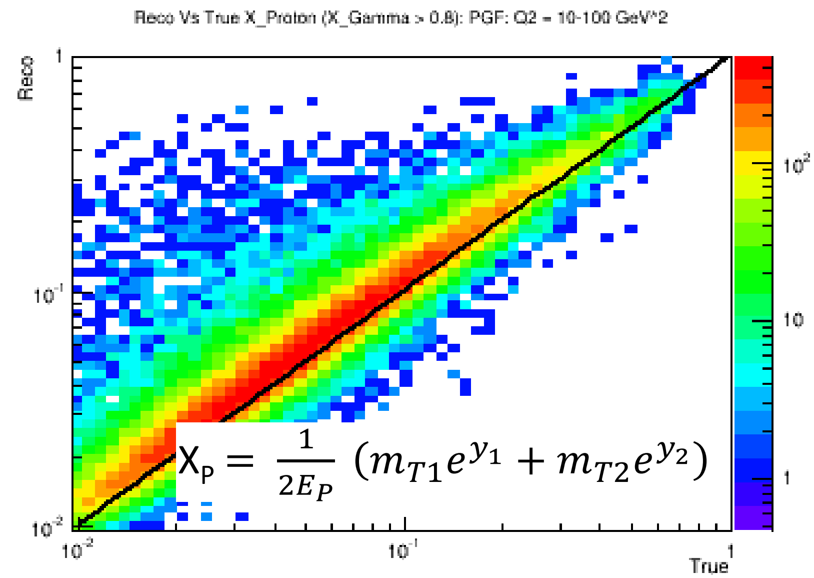


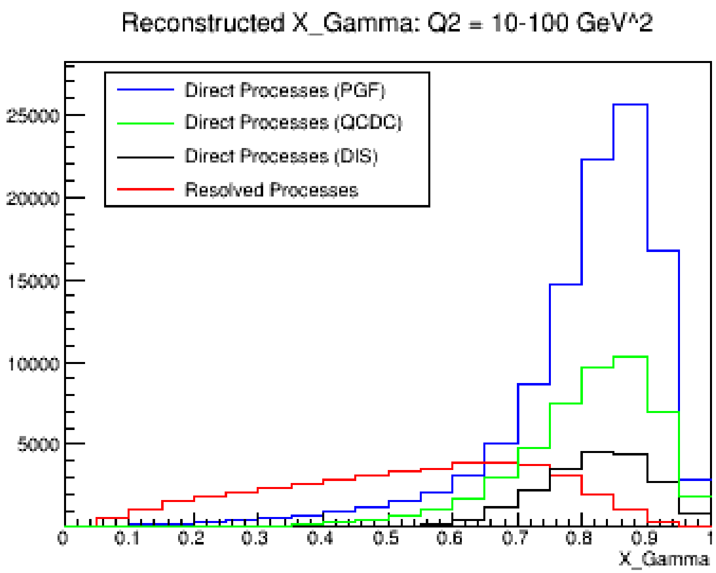
- In addition to scaling violations, gluon information can be accessed via the higher-order photon gluon fusion process
- Outgoing partons have high transverse momentum relative to the photon-parton axis -> jets

- At low Q^2, resolved processes in which the photon assumes a hadronic structure begin to dominate
- Production cross section convolutes proton and photon PDFs, the later of which is not well known
- Will measure photon structure at the EIC

Subprocess Tagging with Di-jets

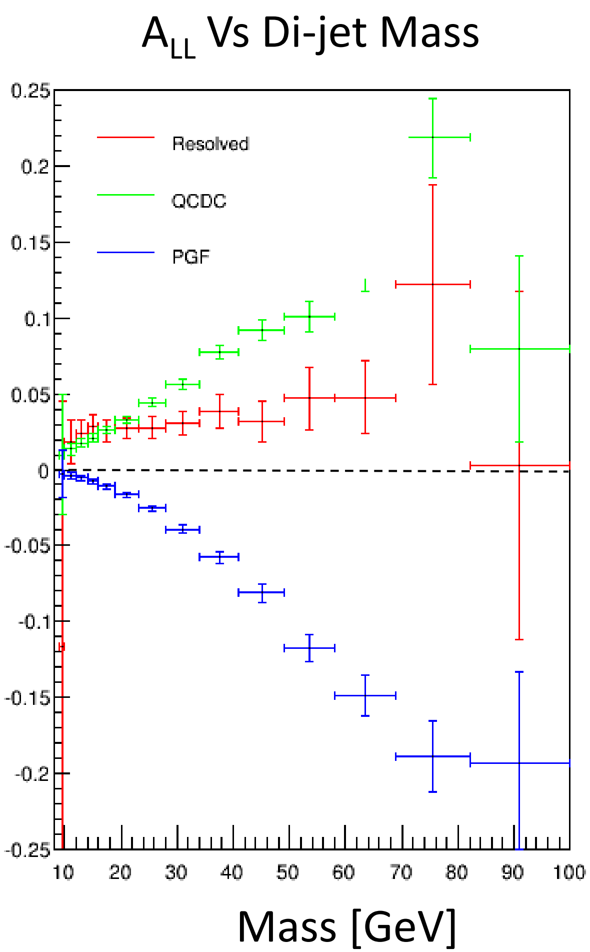


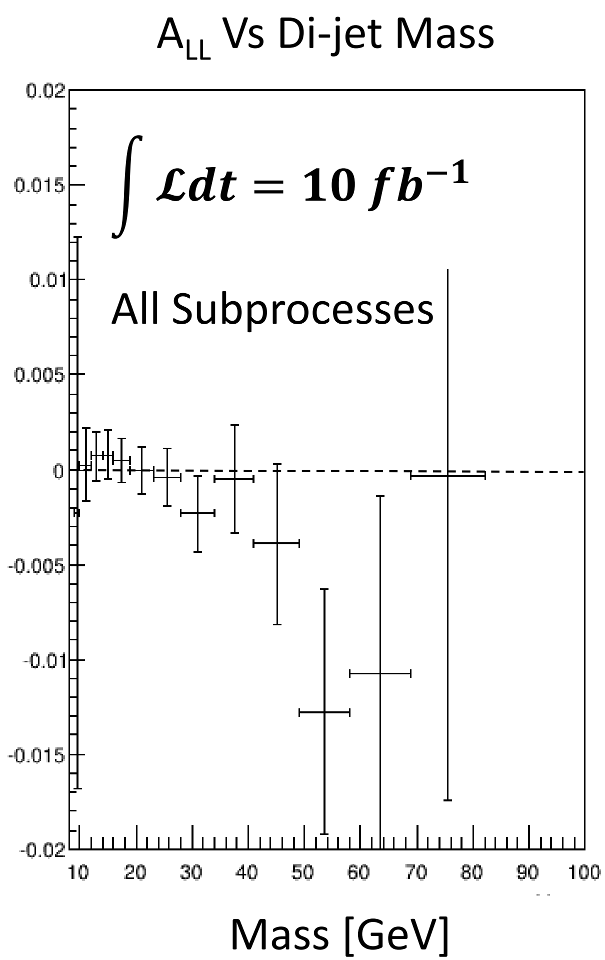




- Use di-jet energy and momentum to reconstruct x_γ and x_P
- Cutting on x_γ can enhance or reduce resolved contribution (which becomes more prominent at low Q^2) depending on the analysis needs
- Both x_γ and x_P accurately reconstructed

A_{LL} Vs Di-jet Mass



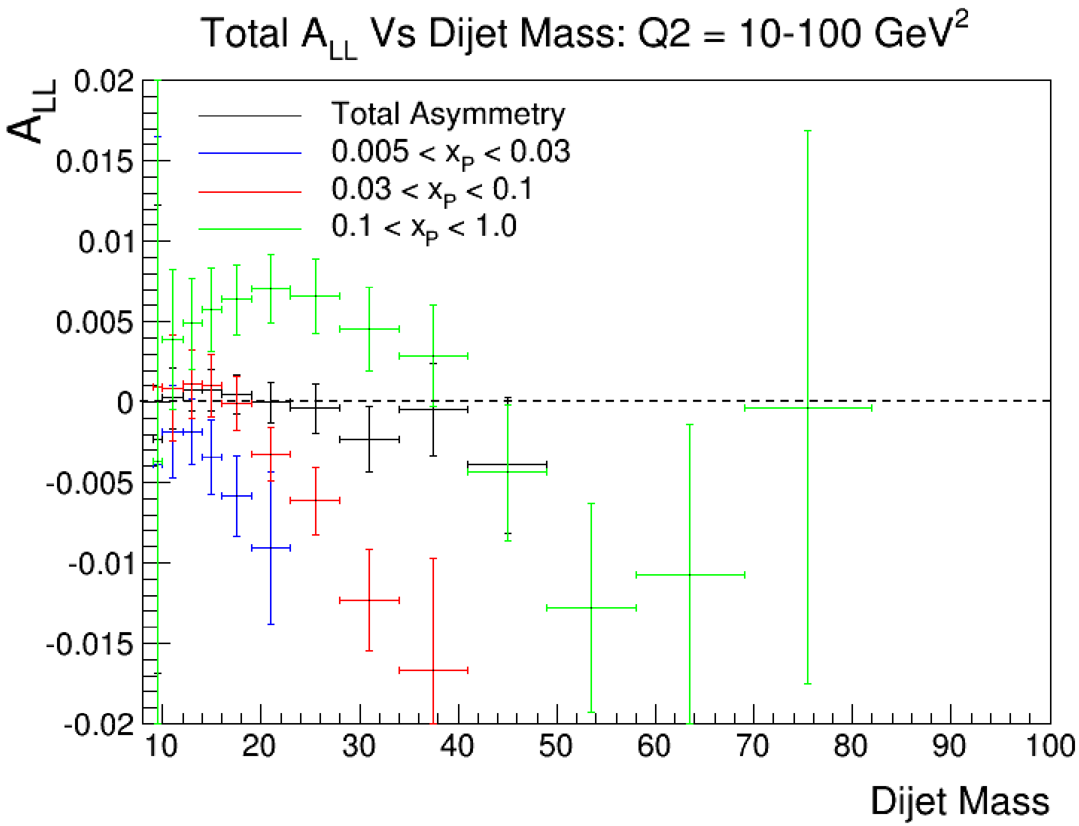


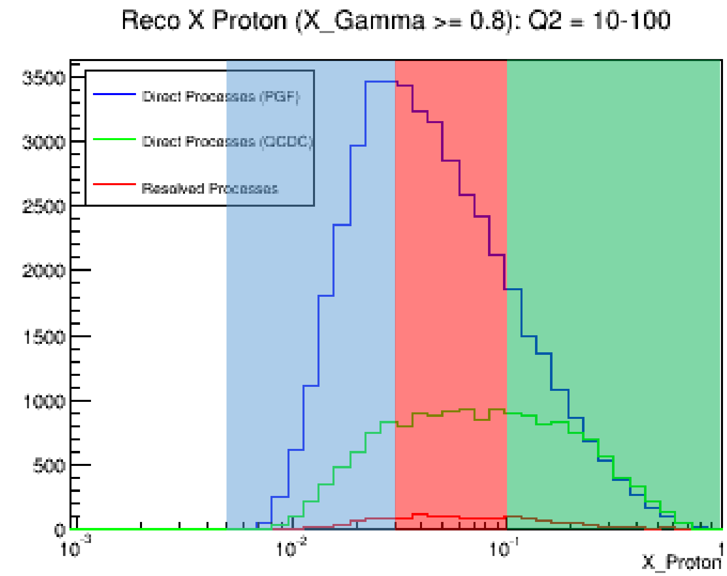
$Q^2 = 10 - 100\ GeV^2$

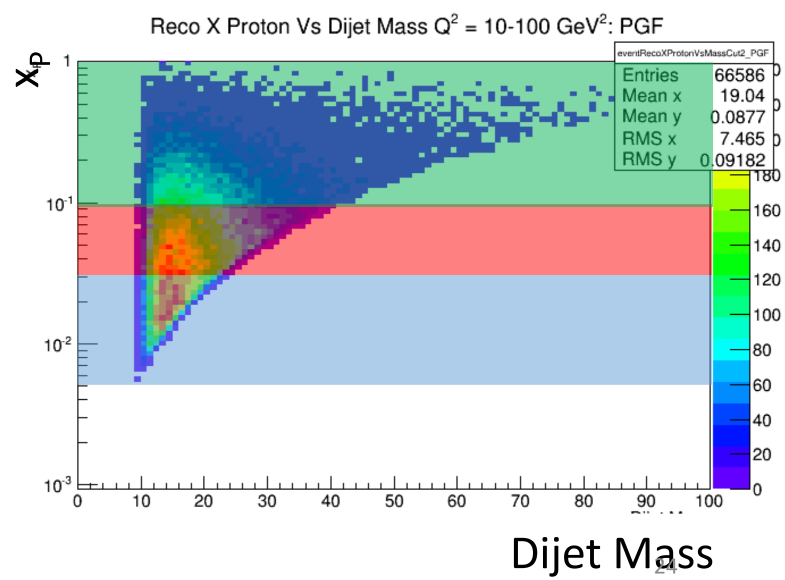
$$\sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}}$$

- Plot the expected A_{LL} as a function of di-jet invariant mass for each sub-process separately as well as the combined sample
- PGF asymmetry is nearly canceled out by QCDC asymmetry with opposite sign – would like to reduce QCDC contribution
- Need high integrated luminosity and high energy to probe the high-mass region where asymmetries can be sizable
- Control of systematics will be essential

A_{LL} Vs Di-jet Mass: x_P Cuts

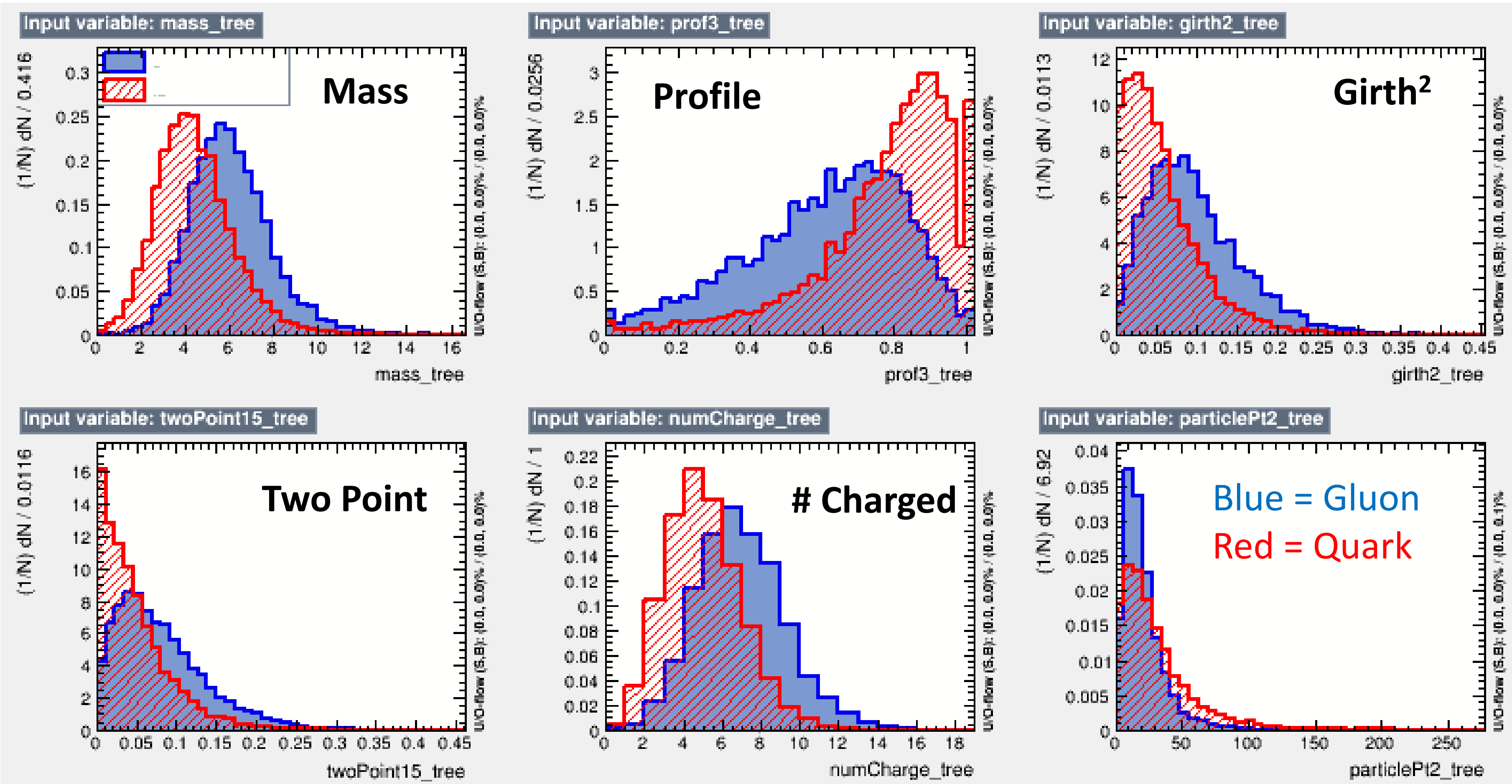






- Selecting events with $0.005 < x_P < 0.03$ enhances PGF asymmetry but restricts mass range
- Intermediate x_P values get more QCDC contribution
- Largest x_P values have roughly equal amounts of PGF and QCDC

Quark – Gluon Discrimination

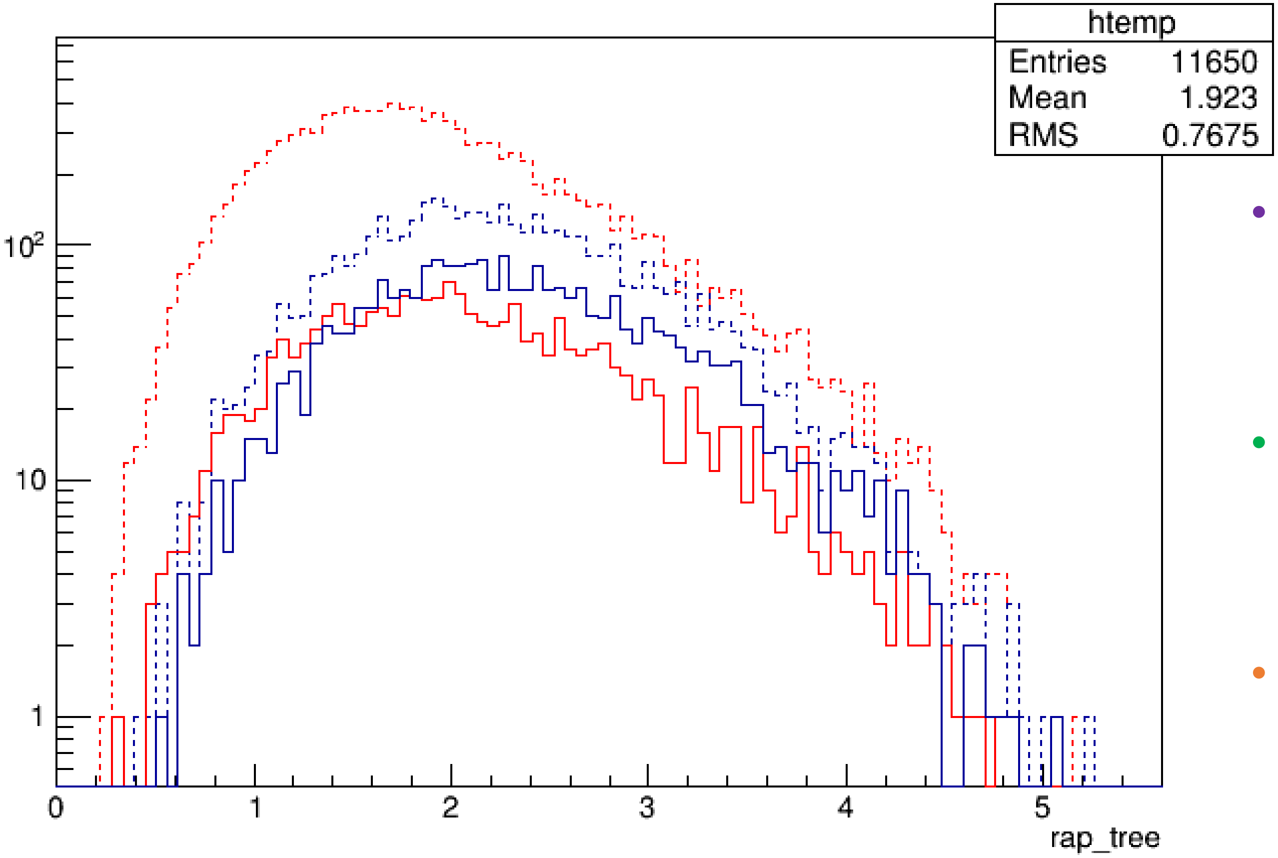


Jet p_T > 10 GeV/c

$$\text{Girth}^2 = \sum_i \frac{p_{Ti}}{p_{Tjet}} |r_i|^2$$

$$\text{2 Point} = \frac{1}{p_{Tjet}^{\;2}} \sum_{i \neq j} p_{Ti} * p_{Tj} * |r_{ij}|^{\beta}$$

Jet Rapidity Spectra



- After cut is applied, can plot quark and gluon jets vs any relevant variable
- Here we see that gluons dominate at higher rapidity
- Look at jets with rapidity > 1.8 to further enhance gluon fraction

Dotted Red = All Quarks (11650)
Dotted Blue = All Gluons (4511)
Solid Red = Quarks After Cut (1964)
Solid Blue = Gluons After Cut (2568)

G/Q Before Cut = 0.39
G/Q After Cut = 1.31
G/(G+Q) Before = 28%
G/(G+Q) After = 57%

Summary

- RHIC jet (and π^0) data have made considerable contributions to our knowledge of the polarized gluon distributions

- Recent and future jet and di-jet measurements from STAR will further constrain the functional form and low-x behavior of $\Delta g(x)$

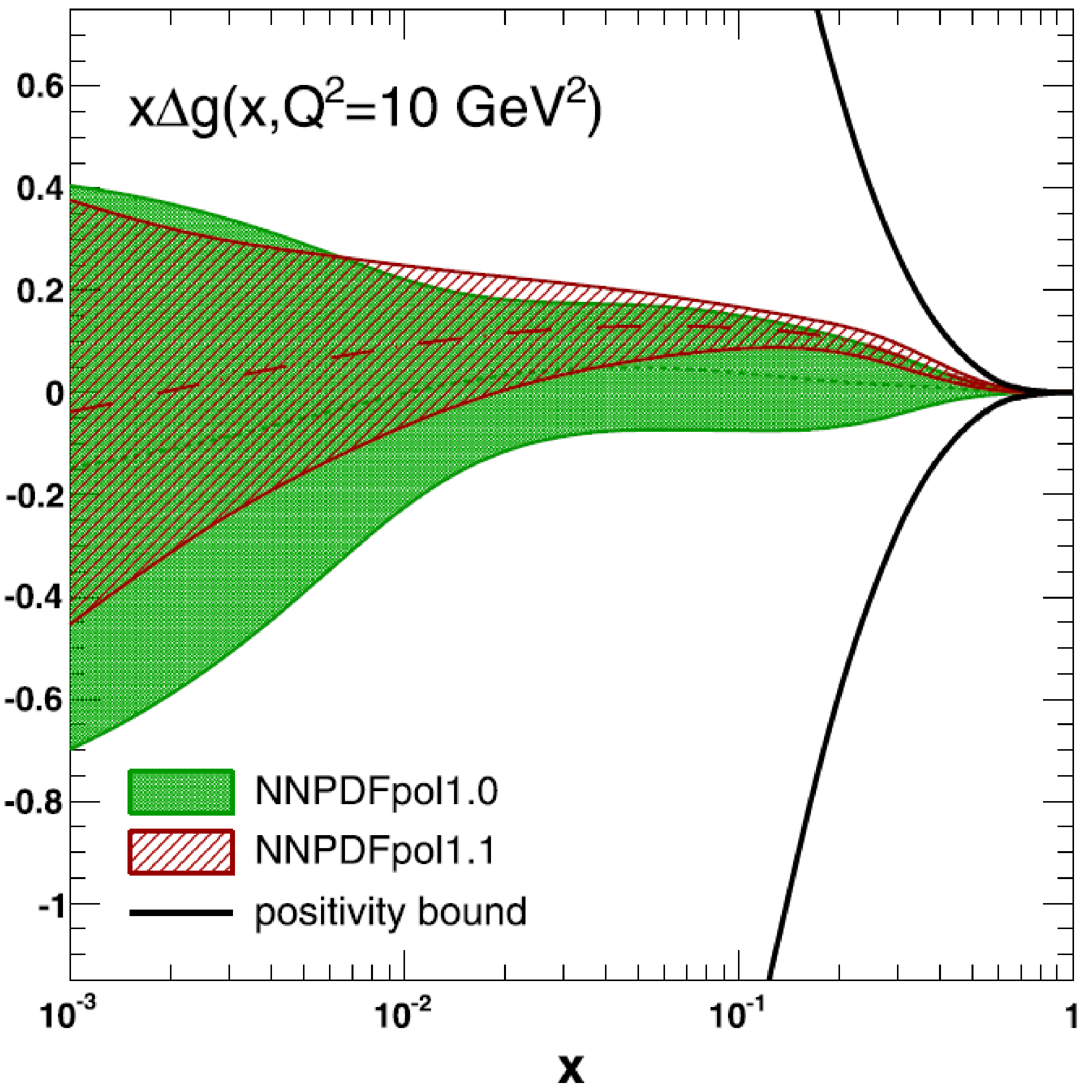
- Many applications for jets beyond gluon helicity measurements, including unpolarized cross sections, constraining linear polarization of gluons, and possible access to gluon Wigner function via UPC di-jet production (see arxiv:1706.01765)

- Can also access gluon information in DIS by measuring jets from the photon gluon fusion process

- Possibility for selecting enhanced samples of gluon dominated jet

Backup

NNPDFpol1.1 Global Analysis



Nucl. Phys. B 887, 276 (2014)

- Original NNPDF $\Delta g(x,Q^2)$ extraction (DIS data only) in green and new extraction including RHIC jet data in red (π^0 data waiting for fragmentation functions)

- Integral of $\Delta g(x,Q^2)$ for $0.05 < x < 0.2$ increases from 0.05 ± 0.15 to 0.17 ± 0.06

- Integral of $\Delta g(x,Q^2)$ for $x > 0.05$ is 0.23 ± 0.06 and is in agreement with new DSSV result of $0.20^{+0.06}_{-0.07}$ over the same x range

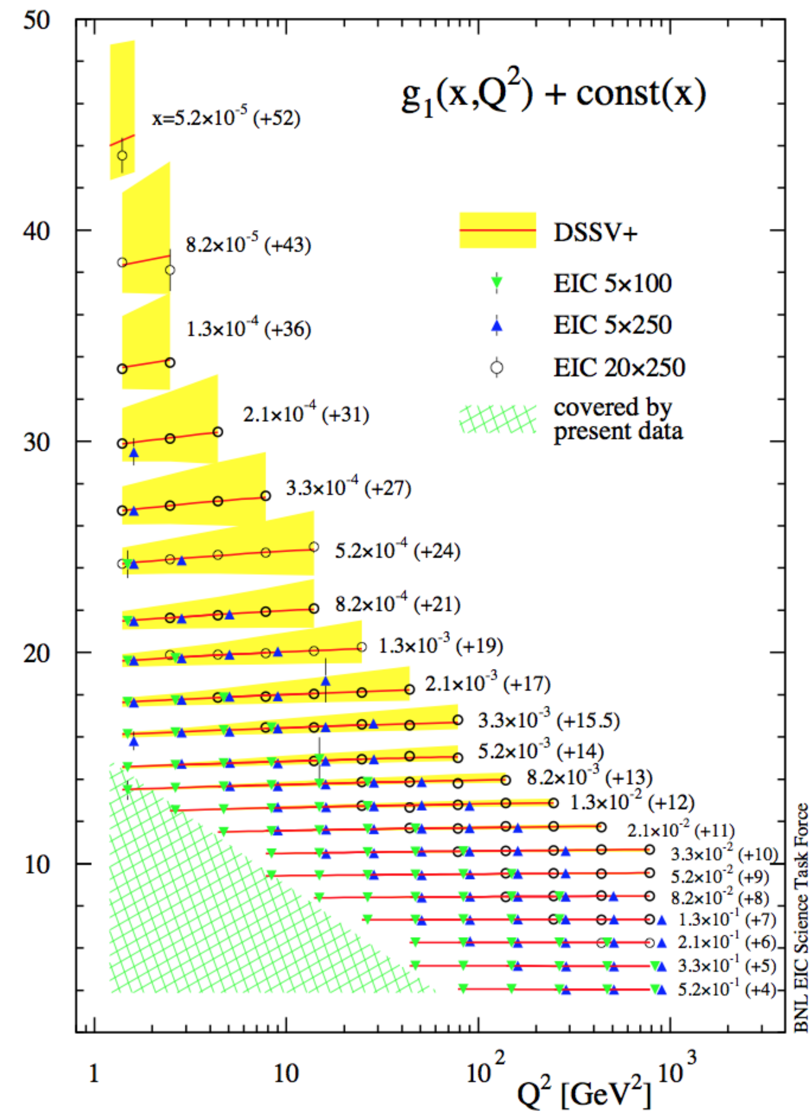
Accessing ΔG in DIS

- Several observables are sensitive to ΔG in DIS but golden measurement at an EIC would be scaling violation of $g_1(x,Q^2)$

$$\frac{dg_1(x,Q^2)}{dln(Q^2)} \approx -\Delta g(x,Q^2)$$

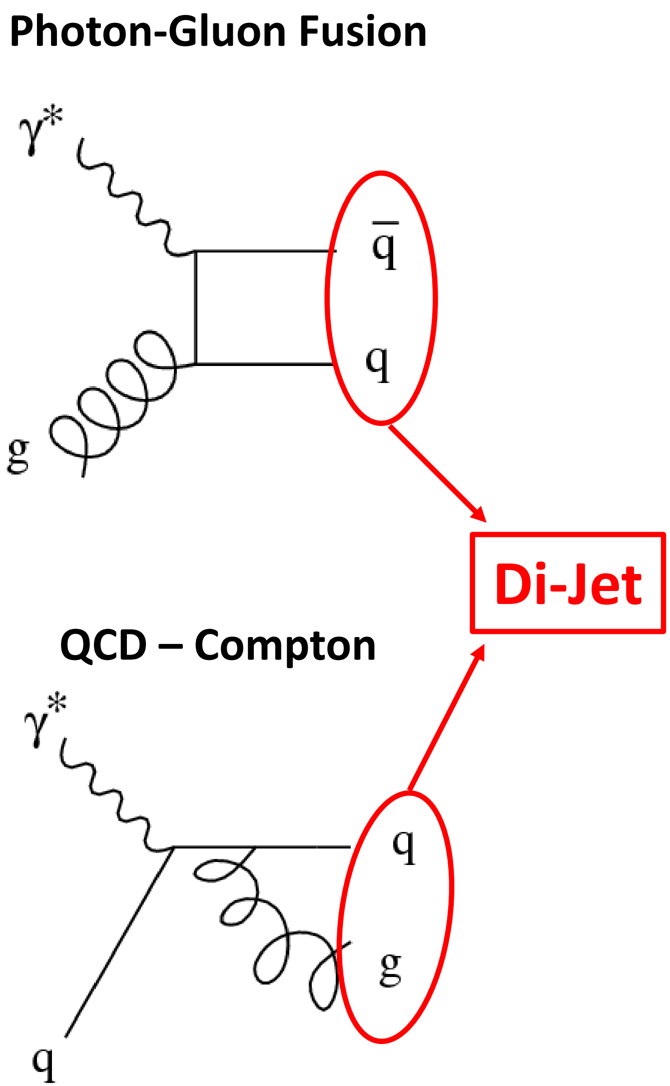
- Current DIS constraints on ΔG hampered by limited x & Q^2 coverage

- EIC would greatly expand kinematic reach and precision of $g_1(x,Q^2)$ measurements!



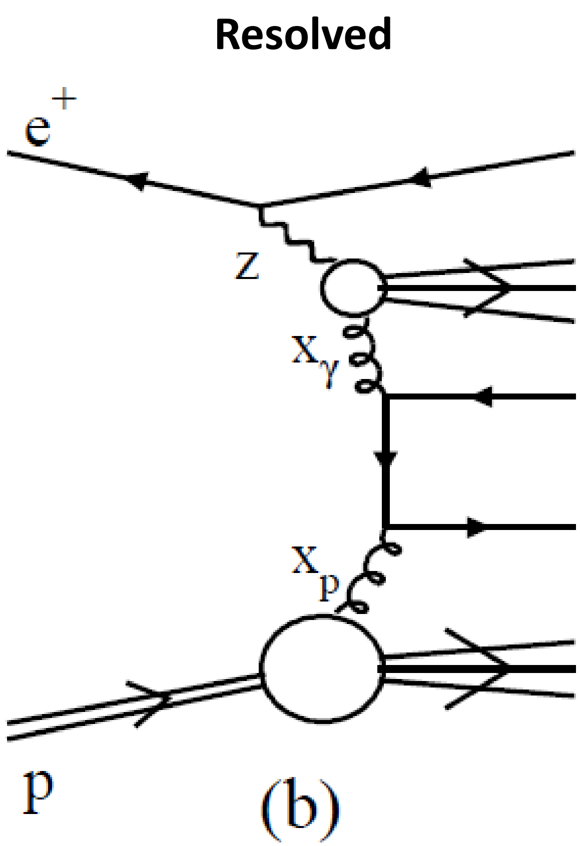
arXiv:1206.6014

Gluon Polarization with Di-jets



- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet

Gluon Polarization with Di-jets



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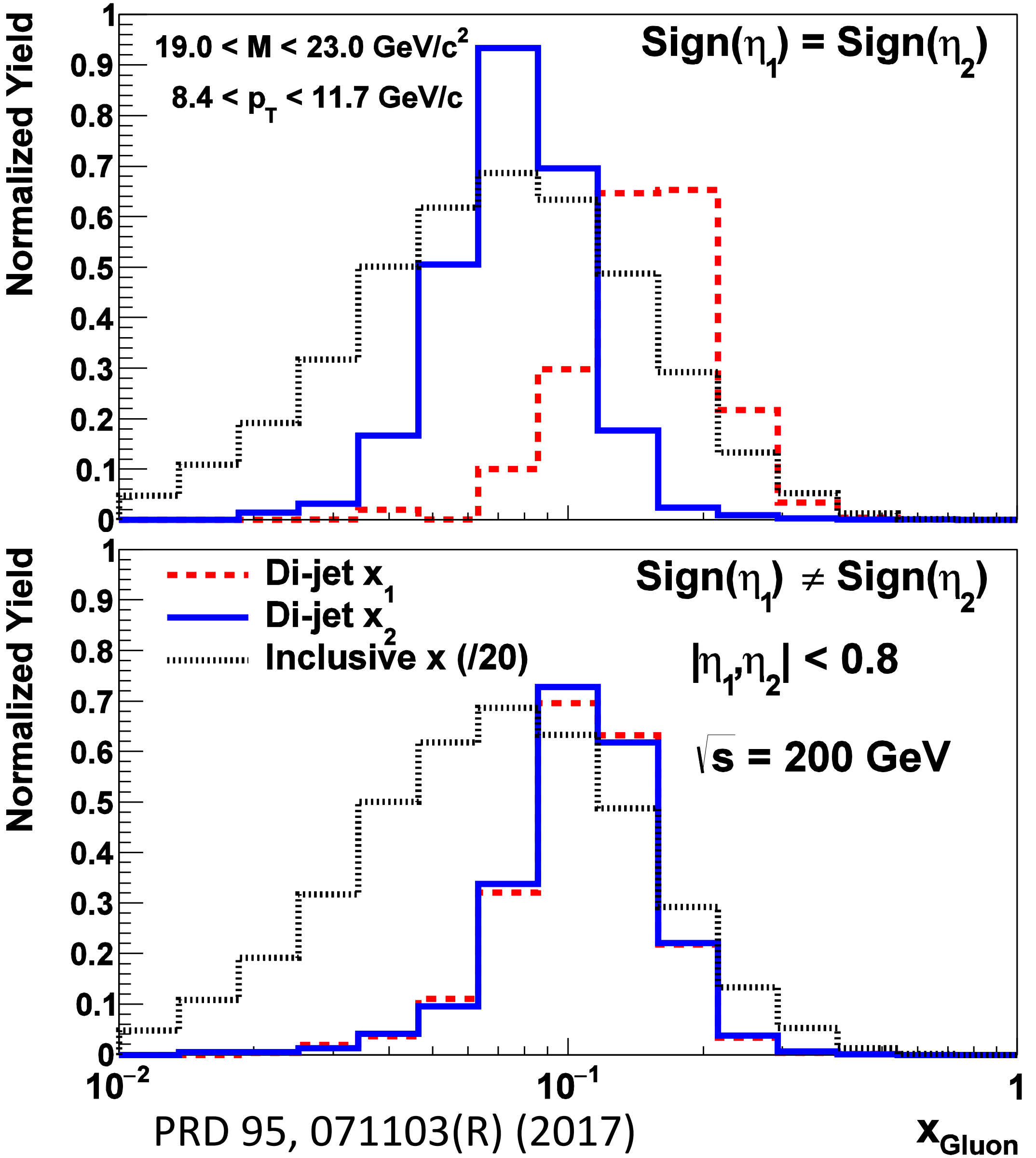
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet
- At lower Q2, resolved processes in which the photon assumes a hadronic structure begin to dominate
- Asymmetry is a convolution of polarized PDF from the proton and polarized photon structure – which is completely unconstrained
- Would like to suppress the resolved component

Correlation Measurements



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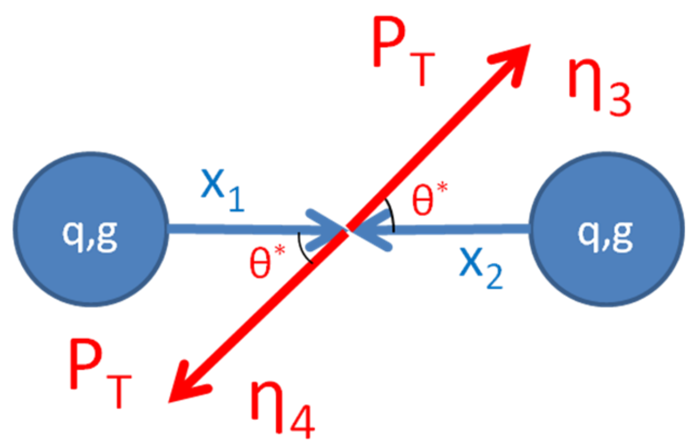
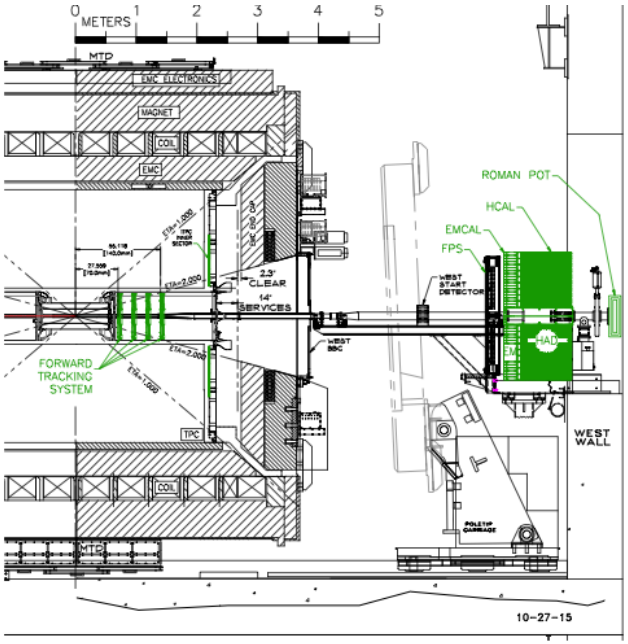
- Correlation measurements capture more information about the hard scattering
- Di-jet measurements provide better resolution on the gluon momentum fraction



Requirements from Physics:

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	0.2<p_T<2 GeV/c with 20-30% $1/p_T$



Calorimeter System:

Intensive R&D work on both ECal and Hcal as part of STAR and EIC Detector R&D

→ several beam test and STAR in situ tests

→ system optimized for cost and performance

ECal:

- ❑ reuse PHENIX PbSC calorimeter
  with new readout on front instead of W/ScFi SPACAL
  significant cost reduction ☺
  uncompensated calorimeter system ☹

HCal:

- ❑ sandwich iron-scintillator plate sampling Calo

Same readout for both calorimeters → cost

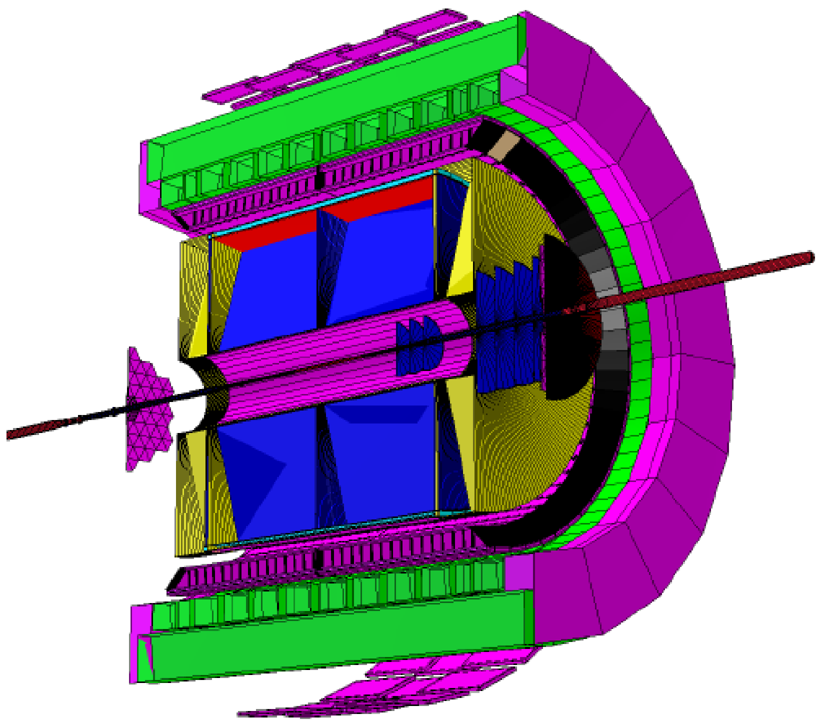
Cost:

ECal: 0.57 M$
Hcal: 1.53 M$
Preshower: 0.06 M$

Total: 2.2 M$

based on extensive experience from prototypes
contingency and manpower included

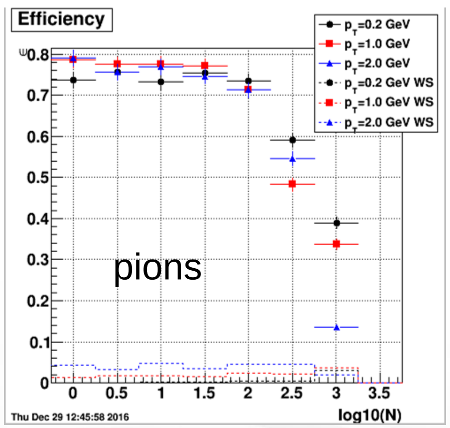
Si + Small-strip Thin Gap Chambers

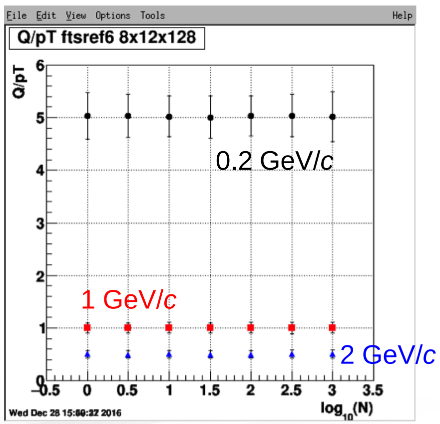


3 Si disks + 4 sTGC
Si- disks:
90, 140, 187 cm from IP

sTGC:
270, 300, 330, 360 cm
from IP (outside Magnet)

Momentum resolution: 20-30%
for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 80%@100 tr/ev

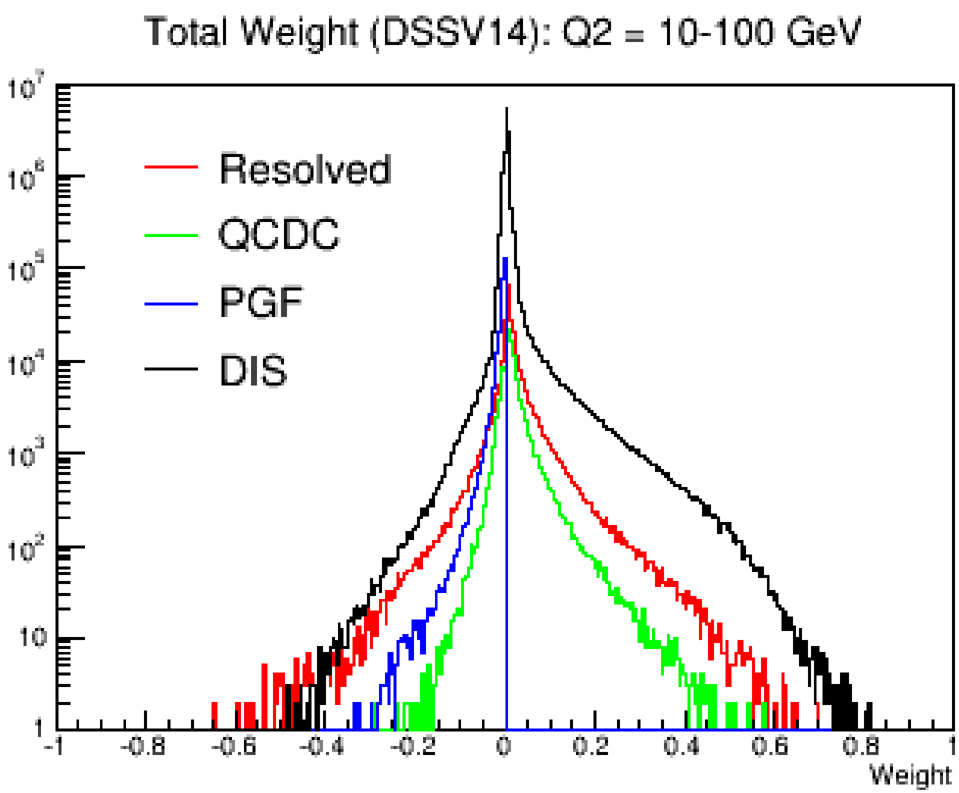




Cost: 3.3 M$

Weighting PYTHIA

$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^{N}(x_b,\mu^2)}{f_b^{N}(x_b,\mu^2)}$$



- PYTHIA does not include parton polarization effects, but an asymmetry can be formed by assigning each event a weight depending on the hard-scattering asymmetry and (un)polarized photon and proton PDFs

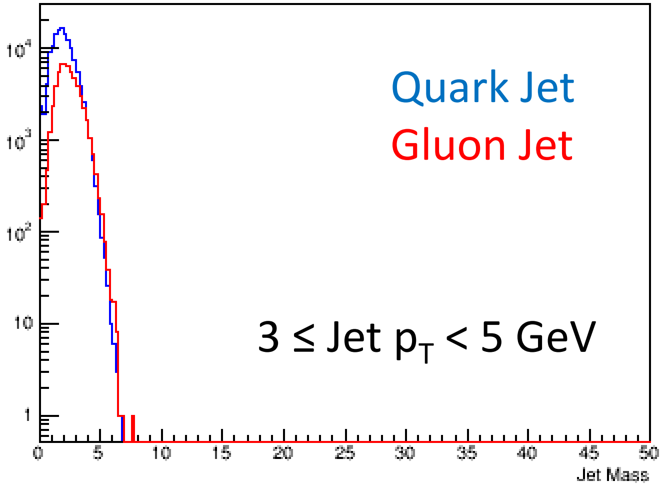
- Expected asymmetry is then the average over weights

- Weights are sharply spiked near zero -> expect small asymmetries

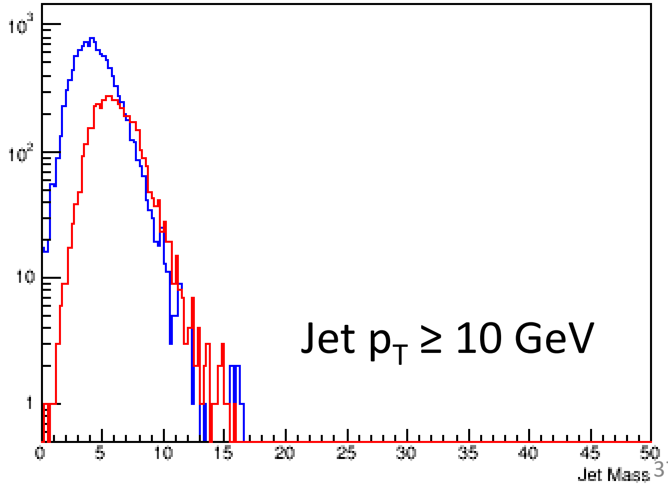
Quark – Gluon Discrimination

- Can we discriminate between jets arising from quarks and those arising from gluons?
- For this study, only consider light quarks: u, d, and s. Assume that heavy quark tagging will employ different methods
- Jets (part of a di-jet) are found in the Breit frame from events with Q^2 = 10 – 100 GeV^2 and resolved, QCDC, and PGF subprocess
- Look only at jets with $p_T \geq 10$ GeV as the separation between quark and gluon jets is more pronounced

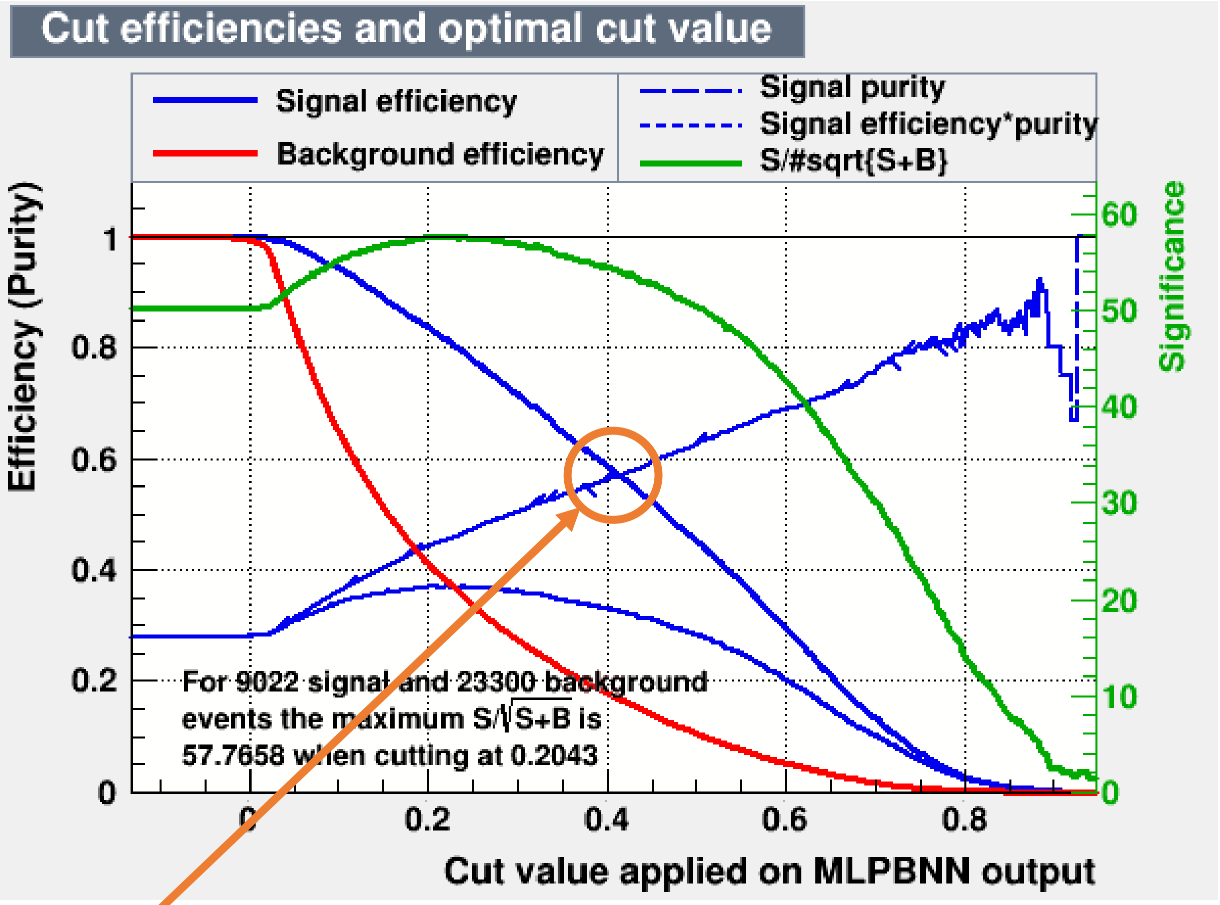
Jet Mass: Low Jet p_T



Jet Mass: High Jet p_T



Cut Optimization



- TMVA evaluates all input and maps them to a single variable with more signal-like events having a higher value
- Plot signal & background efficiency, signal purity, significance, etc as a function of this cut value
- This plot shows where to place cut in order to maximize purity, efficiency, or whatever an analysis requires

- For current study, place cut where signal purity = signal efficiency

MLPBNN Response