Recent results from STAR for parton distribution functions at low and high x in proton-proton collisions

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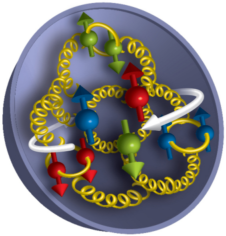
Supported in part by:

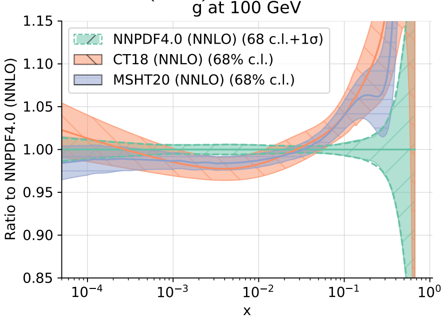
The internal structure of the proton

- The naive three valence quark picture evolves into a highly complex system of quarks, anti-quarks and gluons
- Particle productions from high energy *pp* collisions can be factorized in terms of partonic cross-sections and parton distribution functions (PDFs)

$$\sigma = \sum_{a,b} f_a(x,Q) \bigotimes \hat{\sigma}_{a,b} \bigotimes f_b(x,Q)$$



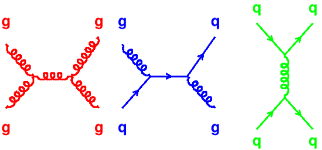
NNPDF, EPJC 82 (2022), 428



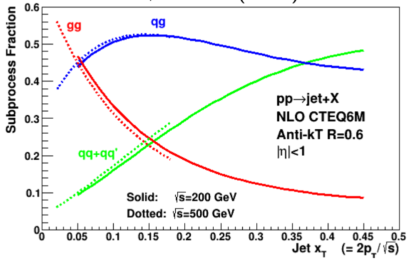
- $\hat{\sigma}_{a,b}$ can be calculated perturbatively
- PDFs are non-perturbative but can be determined from experimental data
- PDFs depend on the momentum fraction of the parton, x, and the probe scale, Q
- Recent global analyses, NNPDF4.0, CT18, and MSHT20 showed at the NNLO the PDF uncertainties of gluons at $x > 0.2$ were large

Jet production in *pp* collisions at $\sqrt{s} = 200$ and 510 GeV

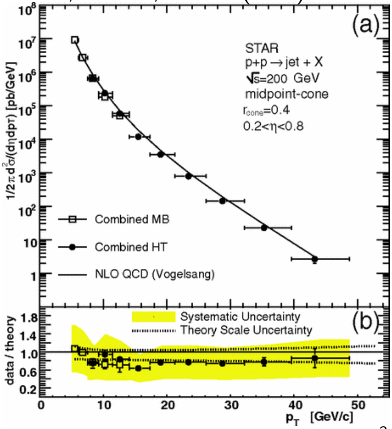
- Jets, clusters of collimated particles, are produced through *qg*, *gg* and *qq* parton scatterings
- Reconstruction algorithms: for example anti-k_T algorithm with a jet parameter R characterizing the size of the jet



STAR PRD 100, 052005 (2019)

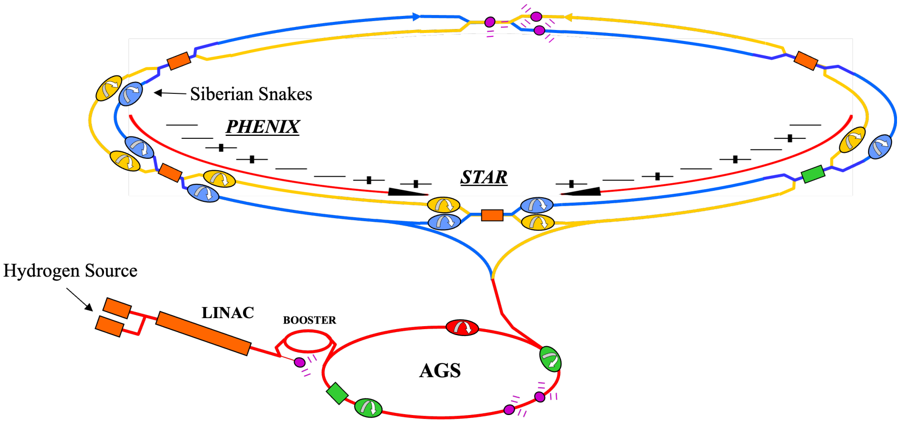


STAR, PRL 97, 252001 (2006)



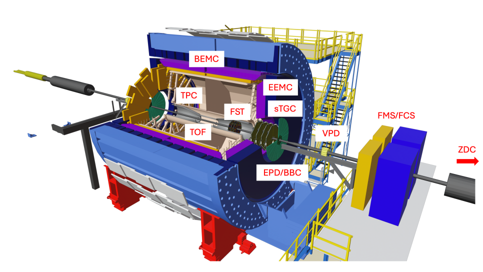
- *qg* and *gg* processes dominate the jet production at RHIC energies
- Previous STAR publication of inclusive jet cross section at $\sqrt{s} = 200$ GeV in 2006 had large systematic uncertainties

RHIC, the world's only polarized hadron collider



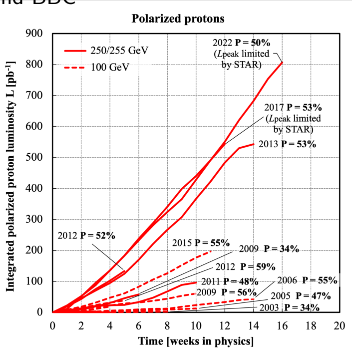
- 2.4 mile in circumference, two lane "racetrack"
- Proton beams are carried by RF buckets, equally distributed along each ring
- Protons in each bucket can be polarized in the transverse plane relative to their momentum direction

STAR experiment



- Full 2π coverage in azimuthal for charged particle tracking and EM calorimetry
- Tracking with TPC: $|\eta| < 1.3$
- EM energy and triggering with:

  BEMC: $-1.0 < \eta < 1.0$
  EEMC: $1.0 < \eta < 2.0$
  FMS: $2.6 < \eta < 4.0$
- Luminosity monitoring detectors: ZDC, VPD and BBC

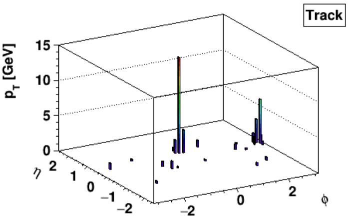


- Recent *pp* collision datasets

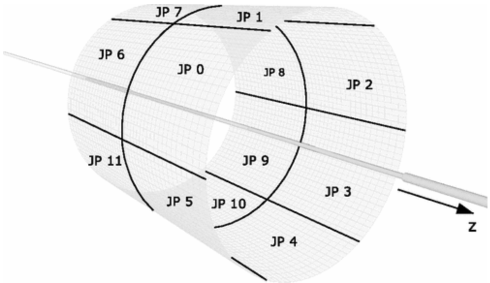
Year	$\sqrt{s}$ (GeV)	Sampled L (pb^{-1})
2011	500	39
2012	510	82
2013	510	300
2015	200	106
2017	510	350
2022	508	452
2024	200	170 (goal, ongoing)

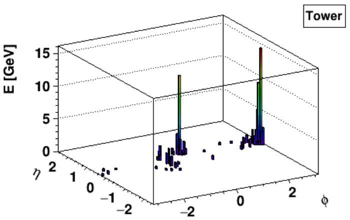
Jet reconstruction

- High p_T jet events triggered by the summed ADCs above thresholds over a jet patch spanning 1×1 in η-ϕ space (20×20 towers) in the BEMC and EEMC
- Input: charged tracks from the TPC and towers in the BEMC and EEMC (0.05×0.05 in η-ϕ space)
- Algorithm: anti-k_T, with jet parameter $R = 0.6$ at $\sqrt{s} = 200$ GeV, and $R = 0.5$ at $\sqrt{s} = 510$



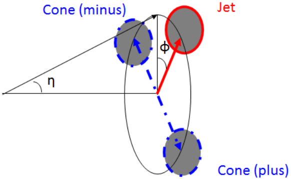
STAR, PRD 86, 032006 (2012)



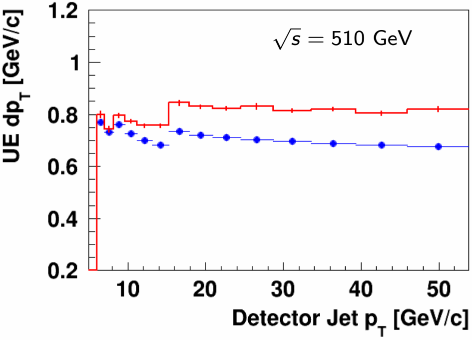


Underlying event corrections

- Two off-axis cones centered at $\pm\frac{\pi}{2}$ away in ϕ and the same η relative to the jet are used to estimate the underlying event contribution to the measured jet momentum
- $\Delta p_T = \rho A$, where ρ is the average energy density from the two cones and A is the jet area



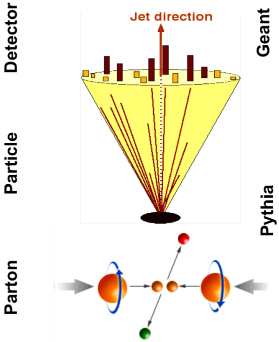
STAR, PRD 100, 052005 (2019)



- Underlying event correction $\Delta p_T < 1$ GeV$/c$
- Difference between data (blue) and simulation (red) is about 0.1 GeV$/c$, negligible systematic uncertainties on the jet cross section measurements

Simulations

- PYTHIA 6 using the default Perugia 2012 tune was adjusted to reproduce RHIC data by reducing the parameter P_{90} from 0.24 to 0.213
- Jet reconstructions from partons, particles, and simulated detector response
- Simulated jet quantities match data very well at the detector level



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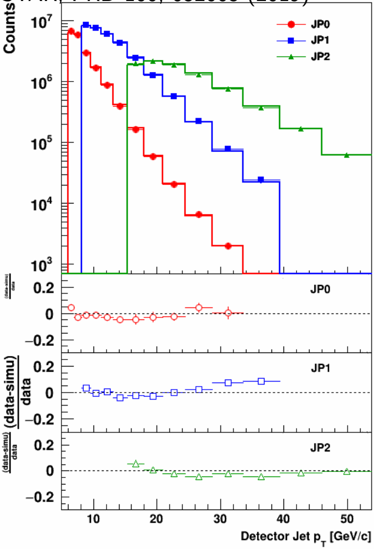
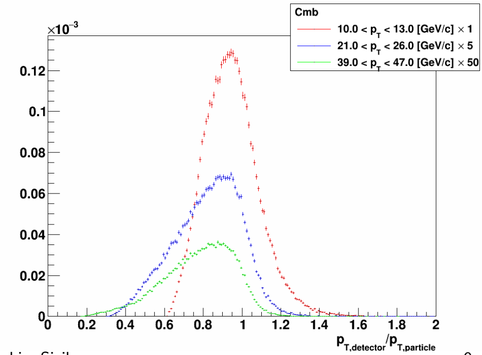


Unfolding

- To obtain the particle jets spectrum, x, we need to correct the measured detector spectrum, b, with the bin migrations due to detector effects, in this case 2D jet kinematic bins with respect to p_T and η
- Three elements:
  1. Fake ratios: fractions of detector jets that are not matched to particle jets
  2. Unfolding matrix A: a probability matrix quantifying bin migrations from particle jets to detector jets
  3. Efficiency: fractions of particle jets associated with detector jets to obtain the "unbiased truth"

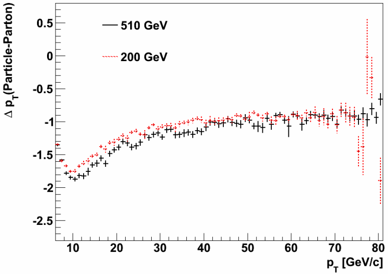
- Solving $Ax = b$: $\min\{(Ax - b)^T V^{-1}(Ax - b)\}$, where V is the statistical variance matrix for detector jets
- Minimizing bias in the unfolding process, and the variance is controlled by the jet p_T bin width



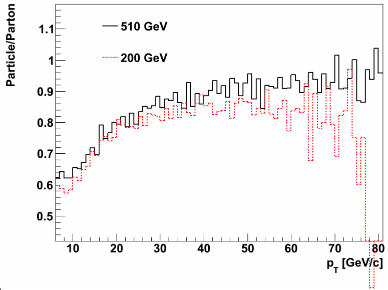
Hadronizaiton correction

- Fixed-order pQCD calculations are calculated at the level of parton jets
- In order to compare our results with the theoretical calculations, a hadronizaiton correction factor is needed to make the connection between the unfolded particle jets and the parton jets

$\Delta p_T \sim 1$ GeV/c at 200 and 510 GeV

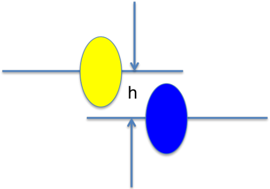


- The connection can be interpreted as a p_T shift, Δp_T, from parton jets to particle jets. This will lead to a change in the jet cross section in a given jet p_T bin, characterized by the ratio $C_{had} = \frac{\sigma_{particle}}{\sigma_{parton}}$
- At $\sqrt{s} = 200$ GeV the jet cross section falls more rapidly than at 510 GeV, a similar p_T shift would lead to a larger correction factor



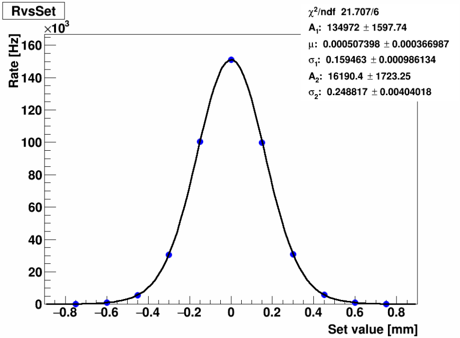
Luminosity determination

- The luminosity at the head-on collisions: $L_0 = \frac{N_1 N_2 f N_b}{2\pi\Sigma_x\Sigma_y}$, where $\Sigma_{x,y}$ is the effective beam overlapping size, $f = 9.8$ MHz is the RHIC bunch crossing frequency, N_b is the number of bunch crossings, and $N_{1,2}$ is the bunch intensity
- Given the collision rate, R_0, at the head-on collisions, an effective cross-section $\sigma_{\rm eff} = \frac{R_0}{L_0}$ can be calculated
- To monitor the collision luminosity during normal data taking, $L = \frac{\sum_i R_{\rm i,mon}}{\sigma_{\rm eff}}$

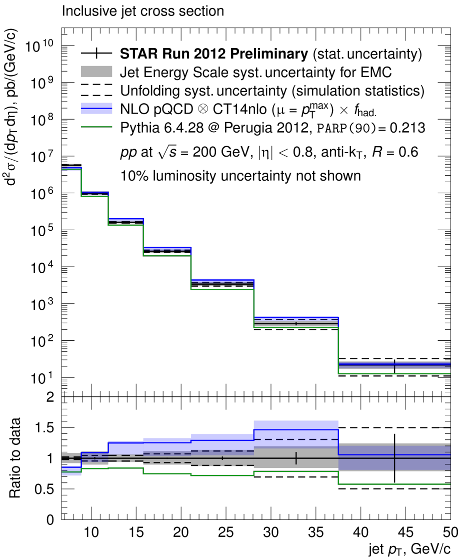


- Technique: Van Der Meer scan (vernier scan)
- Monitoring detector: ZDC, 18m upstream and downstream of the interaction point, and detecting forward neutral particles
- $\Sigma_{x,y} = \frac{A_1\sigma_1 + A_2\sigma_2}{A_1 + A_2}$ by fitting the ZDC rates vs. beam displacements with

$$R_{ZDC} = A_1 e^{-\frac{1}{2}(\frac{x_d - \mu}{\sigma_1})^2} + A_2 e^{-\frac{1}{2}(\frac{x_d - \mu}{\sigma_2})^2}$$

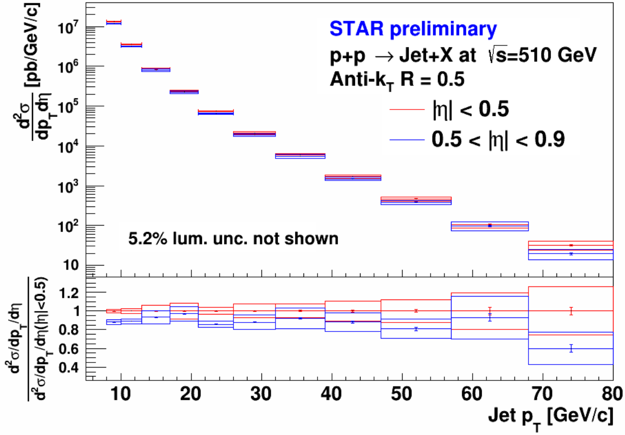


Preliminary results: inclusive jet cross-sections at $\sqrt{s} = 200$ GeV



- $\frac{d^2\sigma}{dp_T d\eta}$ vs. p_T in $|\eta| < 0.8$
- Systematic uncertainties come from jet energy scale and unfolding
- Included the underlying event correction
- Our data sit below the recent NLO calculation by about 20% at high p_T after the hadronization correction
- STAR tuned Pythia 6 reproduces well the shape of the inclusive jet cross section, however the absolute scale is about 20% lower
- Sensitive to gluon PDFs at $x > 0.2$
- Provide the reference line to study inclusive jet $R_{\rm AA}$ in heavy ion collisions

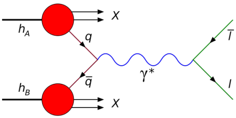
Preliminary results: inclusive jet cross-sections at $\sqrt{s} = 510$ GeV

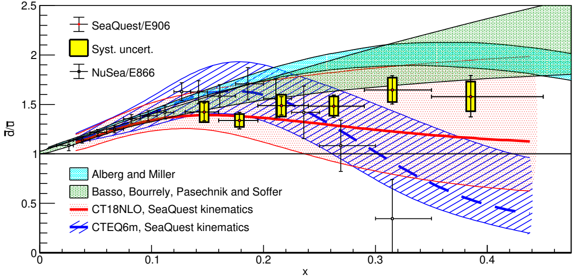


- $\frac{d^2\sigma}{dp_T d\eta}$ vs. p_T in $0 < |\eta| < 0.5$ and $0.5 < |\eta| < 0.9$
- Similar features as the 200 GeV results when compared to NLO and Pythia predictions
- Final results expected soon, comparisons to tunes in Pythia and the NLO and NNLO pQCD calculations, and invariant jet cross-sections vs. $x_T = \frac{2p_T}{\sqrt{s}}$ at both $\sqrt{s}$s

Sea quark PDFs

- Sea quarks PDFs can be studied through Drell-Yan (DY) process, with proton beams impinging on fixed hydrogen and deuterium targets
- From the early New Muon Collaboration (NMC), a flavor asymmetry, $\bar{d} > \bar{u}$ was discovered
- Recent SeaQuest results showed $\frac{\bar{d}}{\bar{u}}$ vs. x, Nature, 590, 561-565 (2021)

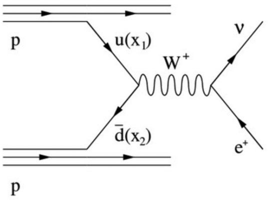


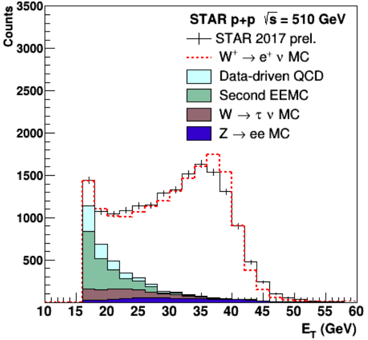


- Different trends at high x comparing to the NuSea results
- Several theoretical predictions to explain the behavior at high x measured by both experiments

W production at RHIC

- At $\sqrt{s} = 510$ GeV, $W^\pm$ can be produced and measured by the high energy decay $e^\pm$ at STAR
- $R_W = \frac{\sigma(W^+)}{\sigma(W^-)} \approx \frac{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)} \propto \frac{\bar{d}}{\bar{u}}$ at the leading order
- Can probe anti-quark PDFs at large momentum scale compared to DY, $Q^2 = M_W^2$
- Explore the region, $0.06 < x < 0.4$ with $-1.0 < \eta_W < 1.5$

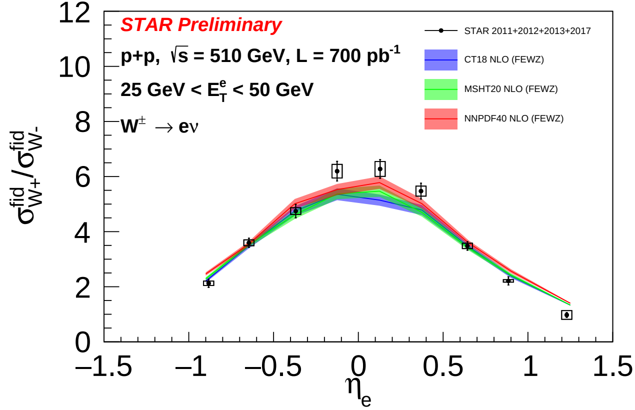




- Isolated electron candidates from a 2×2 tower cluster spanning 0.1×0.1 in η-ϕ
- Large p_T imbalance to account for missing final state ν
- Backgrounds include electroweak residuals, and the QCD dijet contributions

Preliminary results: $W^\pm$ cross-section ratio

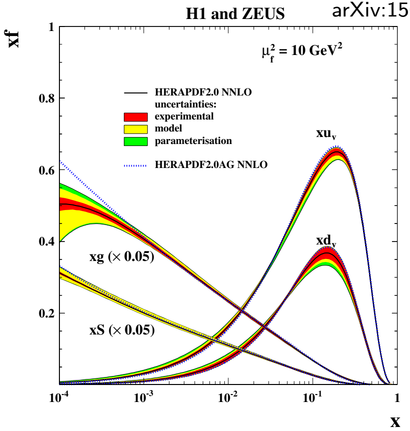
- $R = \frac{\sigma^{\rm fid}_{W+}}{\sigma^{\rm fid}_{W-}}$ vs. η_e

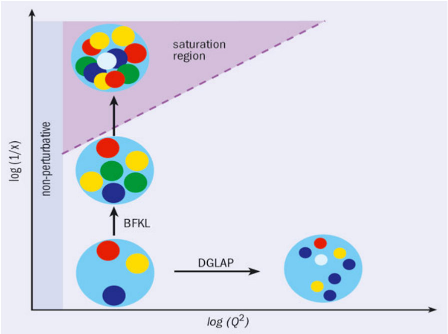


- Combined data from years 2011, 2012, 2013, and 2017 with integrated luminosity $L = 700\ \mathrm{pb}^{-1}$
- Our results agree well with the recent NLO calculations, for example, CT18, MSHT20, and NNPDF4.0, where NNPDF4.0 includes SeaQuest data

Low x gluons

arXiv:1506.06042 [hep-ex]

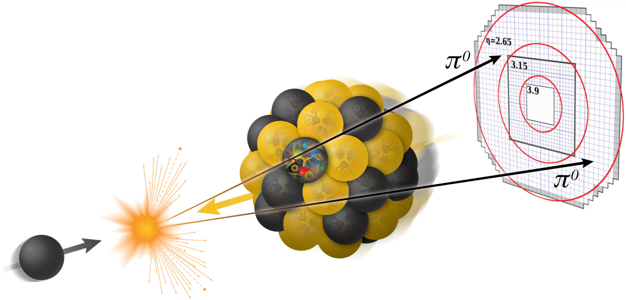




- Inside the proton at low x most of partons are gluons
- As x becomes smaller, the number of gluons increases. At some point, gluons begin to saturate where the splitting process balances out the recombination process
- The saturation scale, Q_S, depends on x
- In heavier nuclei than the proton, for example Al and Au, $Q_S^2 \propto A^{\frac{1}{3}}$

Di-π^0 in the forward region

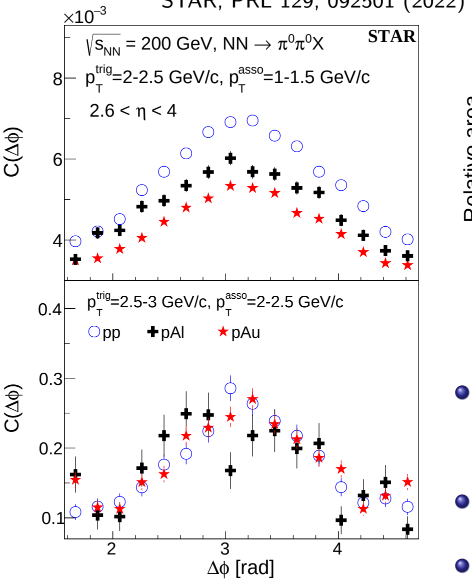
- Color glass condensate (CGC) framework predicts a suppression and an azimuthal broadening of the back-to-back di-hadrons in $p\mathrm{A}$ collisions compared to pp when gluon saturation appears
- The di-π^0 azimuthal correlation in $2.6 < \eta < 4.0$ allows one to study low x gluons, x as low as 10^{-4} in pp, $p\mathrm{Al}$ and $p\mathrm{Au}$ at $\sqrt{s} = 200$ GeV

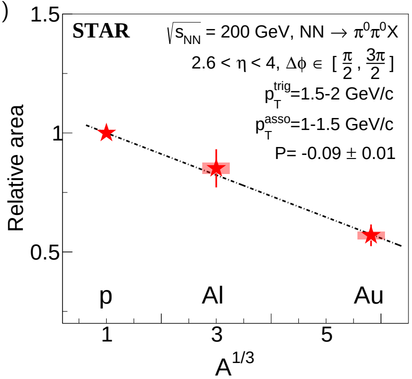


- π^0 is reconstructed from decay photons detected in the FMS
- Correlation function $C(\Delta\phi) = \frac{N_{\mathrm{pair}}(\Delta\phi)}{N_{\mathrm{trig}} \times \Delta\phi_{\mathrm{bin}}}$, where the trigger π^0 is the higher p_T one of the di-π^0 pair and the associate π^0 is the lower p_T one

Di-π^0 correlation in pAl and pAu compared to pp

STAR, PRL 129, 092501 (2022)

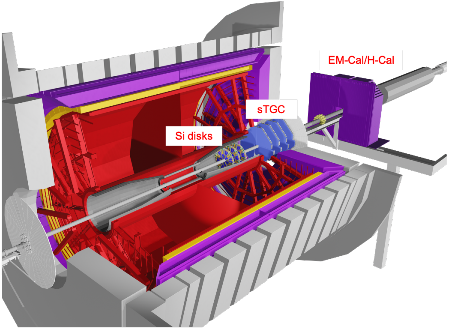


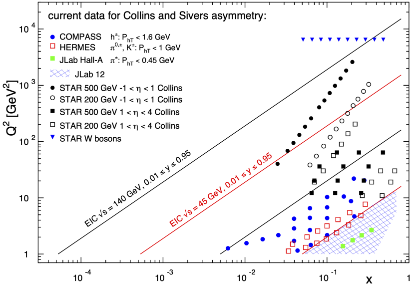


- Suppression observed (relative area under $C(\Delta\phi)$ from $\Delta\phi = \frac{\pi}{2}$ to $\frac{3\pi}{2}$), especially at $p_T^{\text{asso}} = 1\text{-}1.5\ \text{GeV}/c$ where gluon density is large and expected to saturate
- The relative area follows linearly as a function of $A^{\frac{1}{3}}$
- No angular broadening was observed

STAR forward upgrade

- $2.6 < \eta < 4.0$
- Forward Calorimeter System (FCS), EMCal and HCal
- Forwarding Tracking System (FTS), silicon detectors (Si) and a small thin gap gas chamber (sTGC)
- Successfully commissioned and included in the data taking operation beyond 2022





- Forward upgrade enables to study asymmetric partonic collisions $x_1 \gg x_2$, therefore can explore both high-x and low-x regimes
- Extend coverage of valence quark up to $x > 0.5$, where no current experiment has probed
- Lay the groundwork for the realization of the future Elector Ion Collider (EIC)

Conclusion

- The inclusive jet cross section measurement at $\sqrt{s} = 200$ and 510 GeV is a great channel to study the gluon PDF, final results expected to be published soon
  1. Constrain the gluon PDF in the region of $x > 0.2$, where the current uncertainties are large
  2. Will provide crucial input to the recent NLO and NNLO pQCD global analyses
  3. Further tune the event generator such as Pythia
  4. Serve as reference data to study the Quark-gluon Plasma in AuAu collisions
- W cross section ratio measurement at $\sqrt{s} = 510$ GeV is sensitive to the sea quark PDFs
  1. Study flavor asymmetry, $\frac{\bar{d}}{\bar{u}}$ at $0.06 < x < 0.4$ and $Q^2 = M_W^2$
  2. Complimentary to the fix target experiments
  3. Compared with recent pQCD calculations
- Back-to-back di-π^0 correlation measurement in the forward region $2.6 < \eta < 4.0$ is ideal to study the gluon saturation effect
  1. x as low as 10^{-4} and $Q^2 \sim O(1)\ \mathrm{GeV}^2$
  2. A suppression of di-π^0 proportional to $A^{\frac{1}{3}}$ was shown in $p\mathrm{Al}$ and $p\mathrm{Au}$ compared to pp, however no azimuthal broadening was found
- More exciting future results with the STAR forward upgrade in the region of $2.6 < \eta < 4.0$