Cold QCD update: physics analysis and forward upgrade

Mini-PAC meeting, May 27, 2020

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- Run-15 results
- Run-17 analysis progress
- STAR forward upgrade status
- Summary

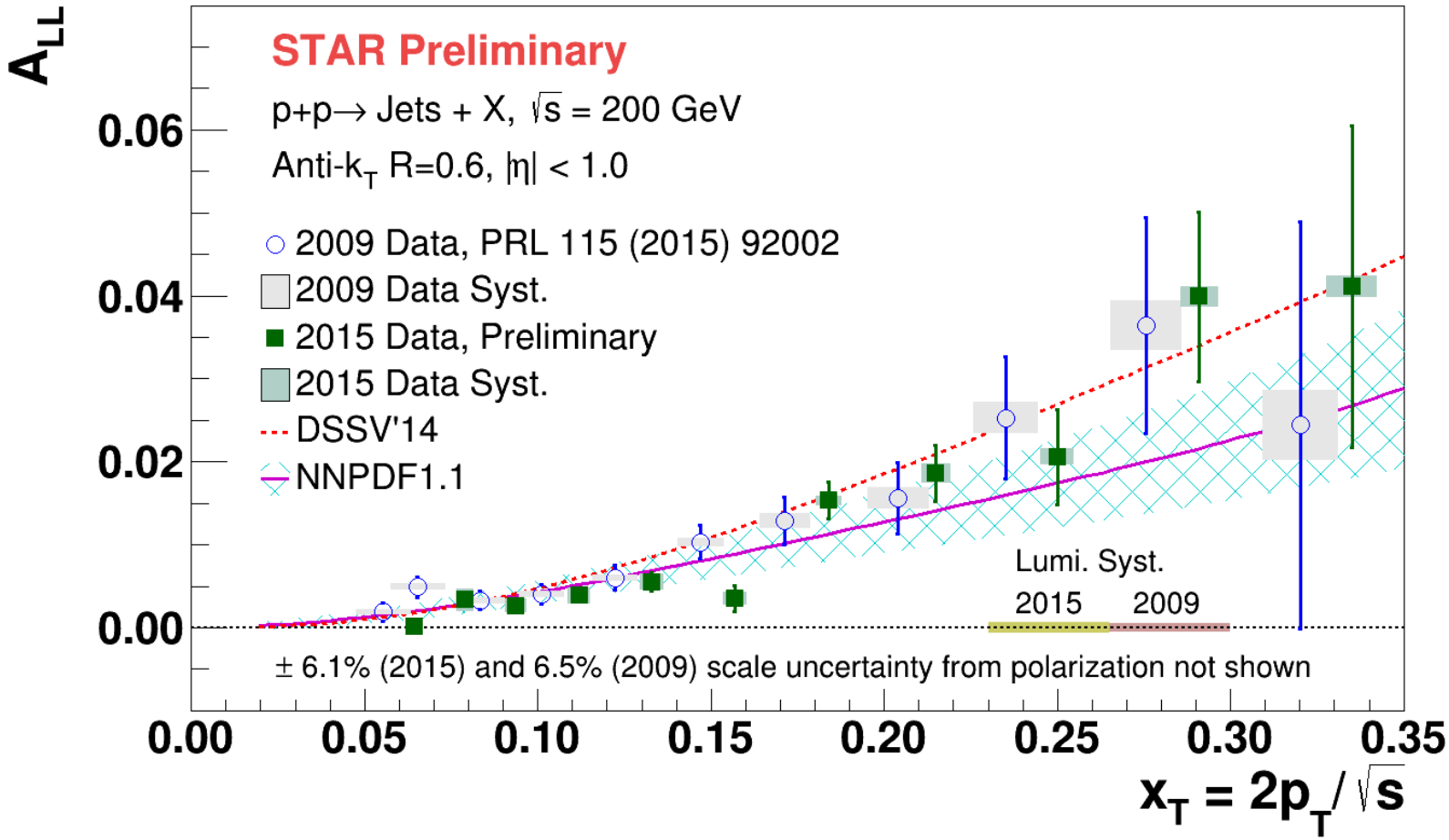
Run 15 BUR cold QCD goals in p+p and p+A

Run 15 BUR goals	Analysis and paper status
Longitudinally polarized pp: • A_{LL} inclusive jets and di-jets for gluon polarization	inclusive jets ready, paper draft in preparation for PRD-Rapid Communication; di-jet analysis in an advanced state
Transversely polarized pp: • Determining the underlying physics process responsible for the large transverse single spin asymmetries at forward rapidities • Mid-rapidity IFF for transversity • Mid-rapidity Collins effect for transversity and Collins FF • A_N for forward direct photons to identify the Sivers contribution • Not foreseen in the BUR: Mid- and intermediate rapidity di-jet Sivers effect	• significant progress via comparison of multiple observables in pp at 200 and 500 GeV, paper draft and analysis note for PRD under review by the PWG • spin asymmetries have been extracted, systematics under evaluation • analysis complete including 80-page Analysis Note, paper draft for PRD in preparation • With better understanding of timing issues in FMS trigger and readout, this analysis now becomes possible • paper draft in preparation for PRL
Physics with Tagged Forward Protons in Roman Pots: • Central Exclusive Production • Elastic and total cross sections	• paper under review at JHEP • paper under review at PLB
Unpolarized p+A: • Di-pion correlations for signatures of non-linear effects • R_{pA} for forward direct photons to constrain the nuclear gluon distribution • UPC J/psi to constrain the nuclear gluon distribution	• pp and pAu ready to go, pAl underway • With better understanding of timing issues in FMS trigger and readout, this analysis now becomes possible • preliminary result released last year
Polarized p+A: • $A_N(pA)/A_N(pp)$ to search for onset of saturation behavior • A_N for UPC J/psi to constrain the GPD E_g	• results final, paper in GPC • proof-of-principle preliminary result released last year

Red: no preliminary yet
Magenta: preliminary or ready to be shown
Light green: paper draft in PWG or GPC
Dark green: submitted

Probe gluon helicity ΔG with jets

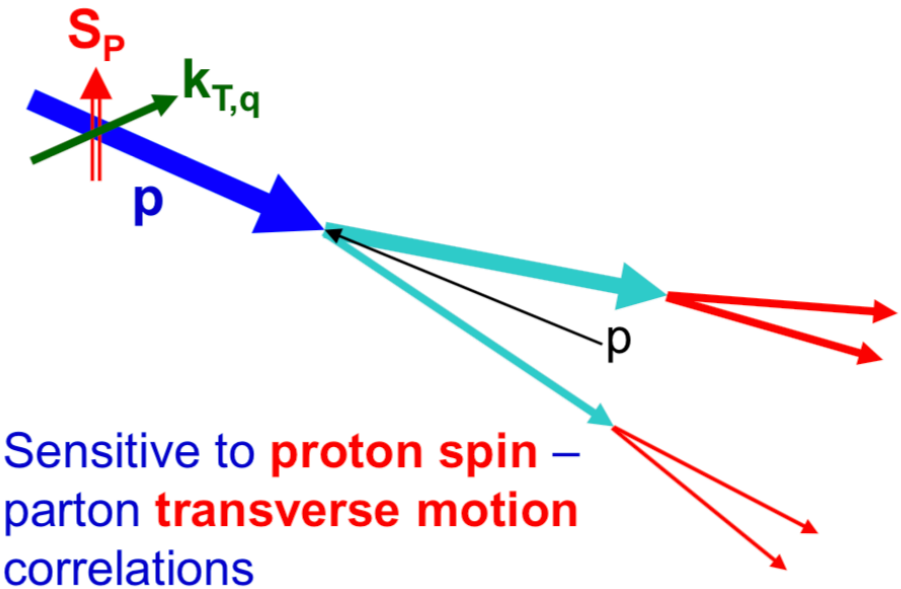
Impactful new preliminary result on A_{LL} of inclusive jet production from 2015 data



- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
- Twice larger figure-of-merit (LP^4) with improved systematics
- Di-jet A_{LL} analysis of 2015 data underway

Silvers vs. Collins effect

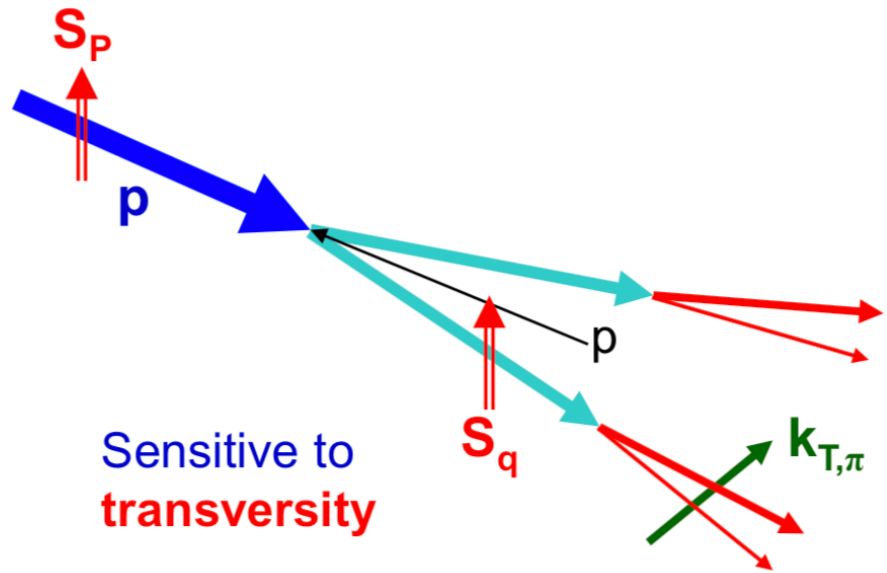
Sivers or twist-3 mechanisms:



Sensitive to **proton spin** – parton **transverse motion** correlations

- Signatures:
  - A_N for jets or direct photons
  - A_N for $W^{+/-}$, Z^0, Drell-Yan
  - A_N for heavy flavor (gluon)
- Sivers NOT universal
  - Sign change from SIDIS to W, Z, and Drell-Yan

Collins or novel FF mechanisms:



Sensitive to **transversity**

- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - A_N for pions → novel FF
- Collins predicted to be universal

Courtesy of Carl Gagliardi, Krakow Juniors Session

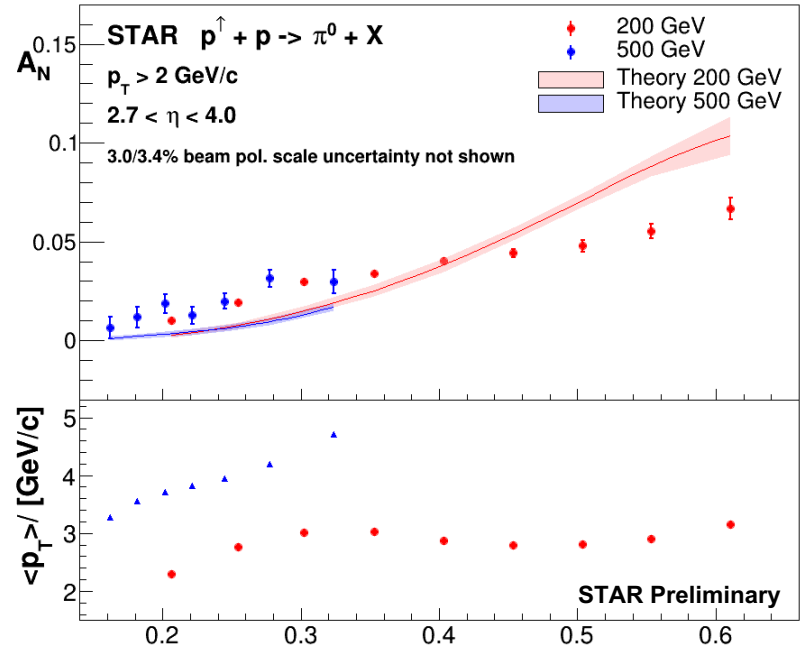
Probe Collins effect with π^0 A_N

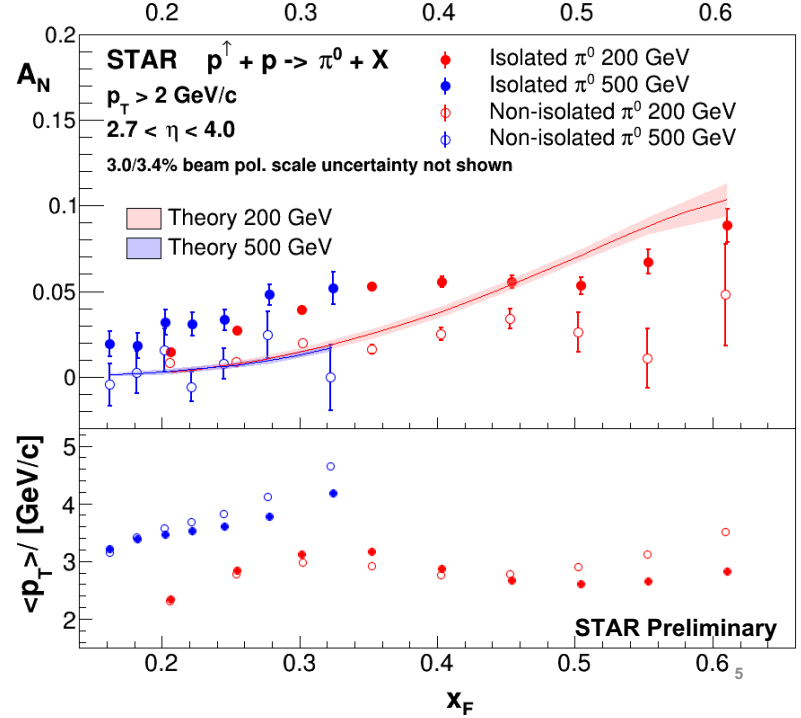
Physics motivation:
to understand the underlying mechanism (initial/final state effect);

Transverse momentum dependent effects in the initial (PDF) and final state (FF), thought to drive the large asymmetries

Major conclusions:

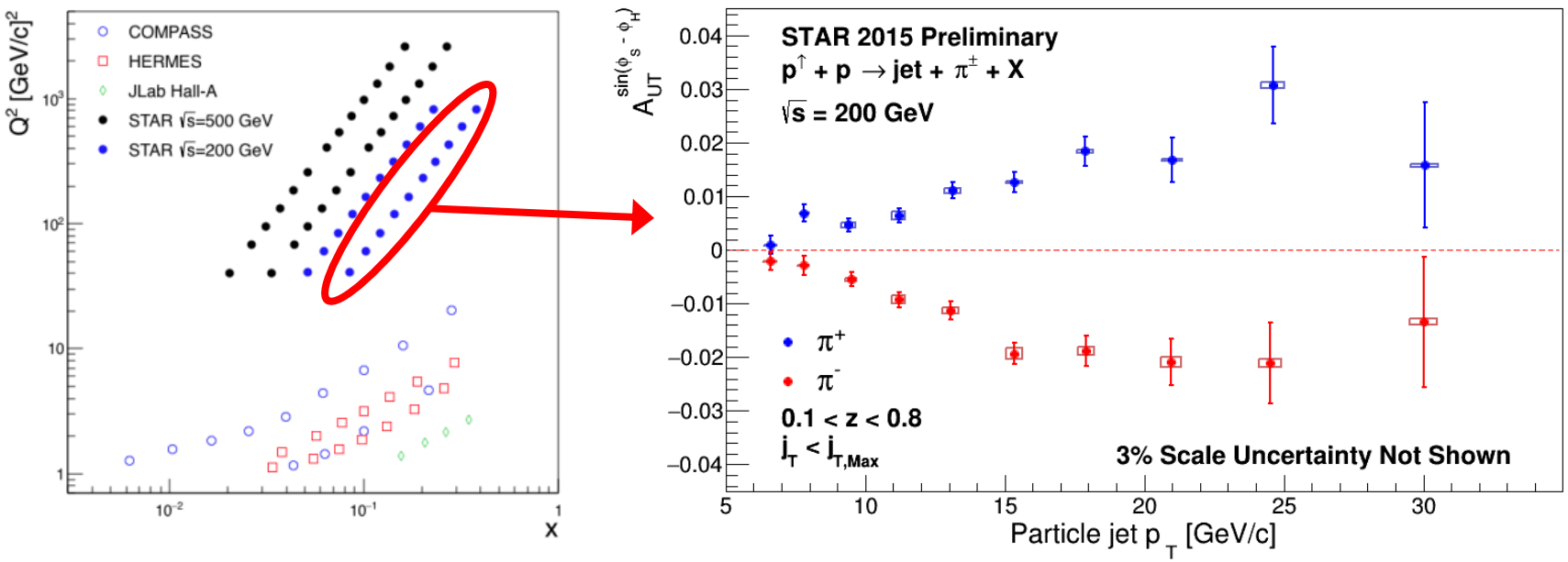
- significant asymmetries for π^0
  - asymmetry larger if π^0s isolated by a cone around them
- small asymmetries for electromagnetic jets and the Collins asymmetries studied through π^0 in an electromagnetic jets (shown in backup)
- suggests a different mechanism other than the initial/final states effects to explain the π^0 A_N.
- Theory calculations (arXiv 2002.08384) based on a global fit to SIDIS and earlier RHIC pp data → Collins effect





Collins effect in 200 GeV 2015 pp data

Probing transversity in the proton and factorization, universality and evolution of the Collins fragmentation function



- 200 GeV pp explores similar *x* range as SIDIS, but at order-of-magnitude higher Q^2
- Asymmetries are comparable in magnitude to those in SIDIS, favoring weak evolution effects
- Multi-dimensional binning in p_T, z and j_T also available to separate initial- vs. final-state effects
- Complementary transversity analysis involving di-pion interference fragmentation functions also underway

Single-spin asymmetry in dijet production

- A direct measurement of the Sivers Effect, spin-dependent transverse partonic motion
- Asymmetry measured for transverse opening angle, then converted to $\langle \vec{k}_T \rangle$ based on a simple kinematic model
- Flavor tagging (charge sorting) applied to jets to enhance the fraction of u quarks (+tagging) and d quarks (-tagging) separately

➢ First clear observation of non-zero Sivers signals from dijet production in pp collisions!

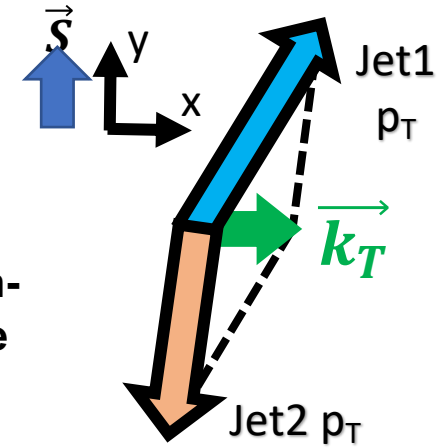
➢ High statistics asymmetries appear to be consistent with SIDIS measurements, though measured at much higher Q^2 ~ 160 GeV^2.

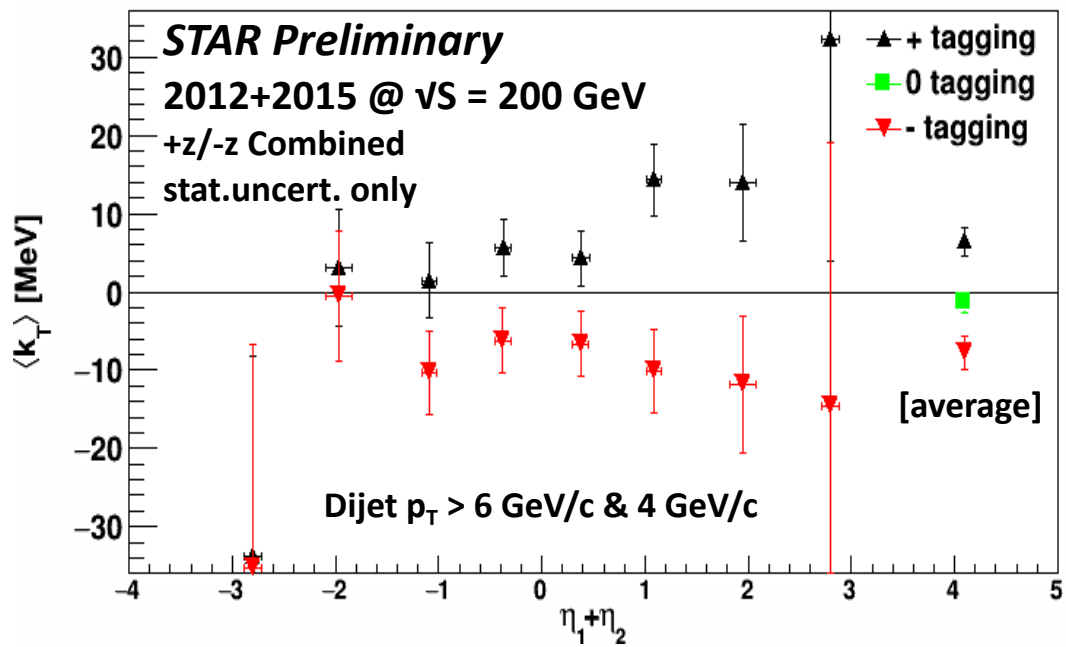
- Possibility of extracting $\langle \vec{k}_T \rangle$ for individual partons (*u, d, g*) is being worked on.

Sivers Effect

$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle \neq 0$$

Parton $\vec{k}_T$ preference leads to a spin-dependent tilt in dijet opening angle

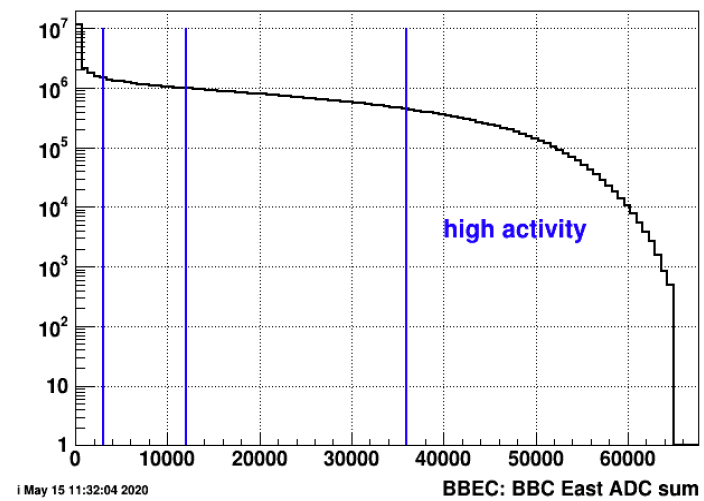




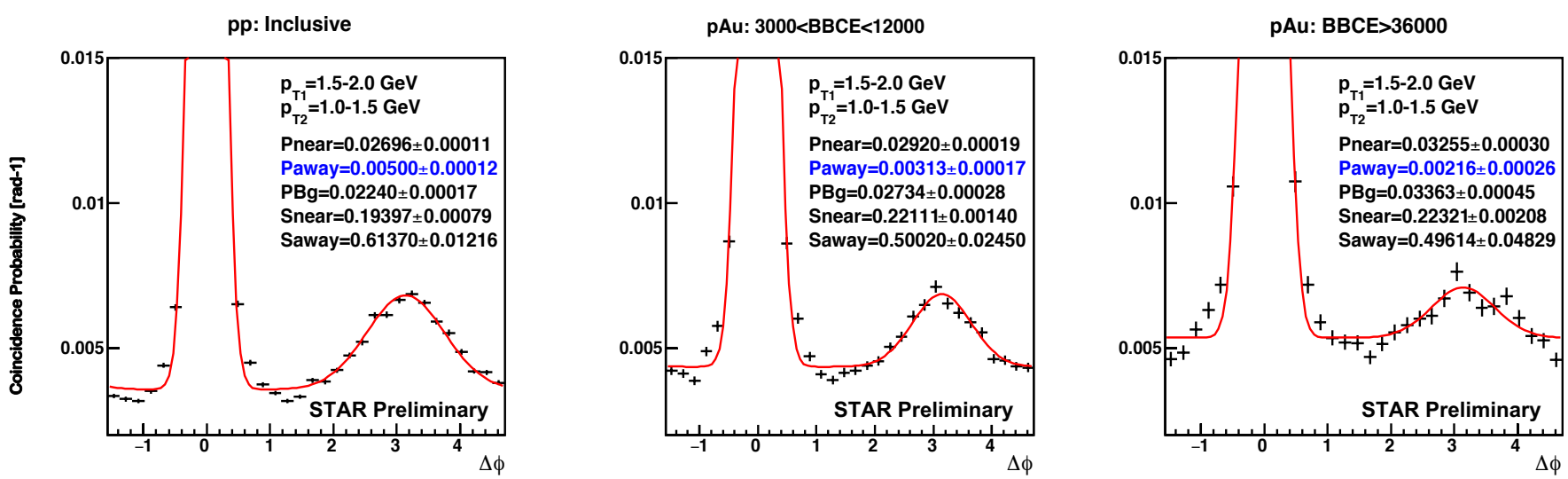
Result is dominated by statistical uncertainty. Systematic uncertainty is not shown.

Di-π^0 correlation in Run15 pAu pp collisions

- Physics goal: access the underlying gluon dynamics in nonlinear evolution region
- Advantage: Run15 pAu results show smaller background than Run8 dAu results in comparison with pp.
- First stage results indicate:
  - Away-side peak suppressed in "high activity" (BBCE>36000) pAu collisions compared with pp collisions.
- Current status: Finalize Run15 pAu and pAl calibration. Di-π^0 correlation in Run15 pAl is in progress.

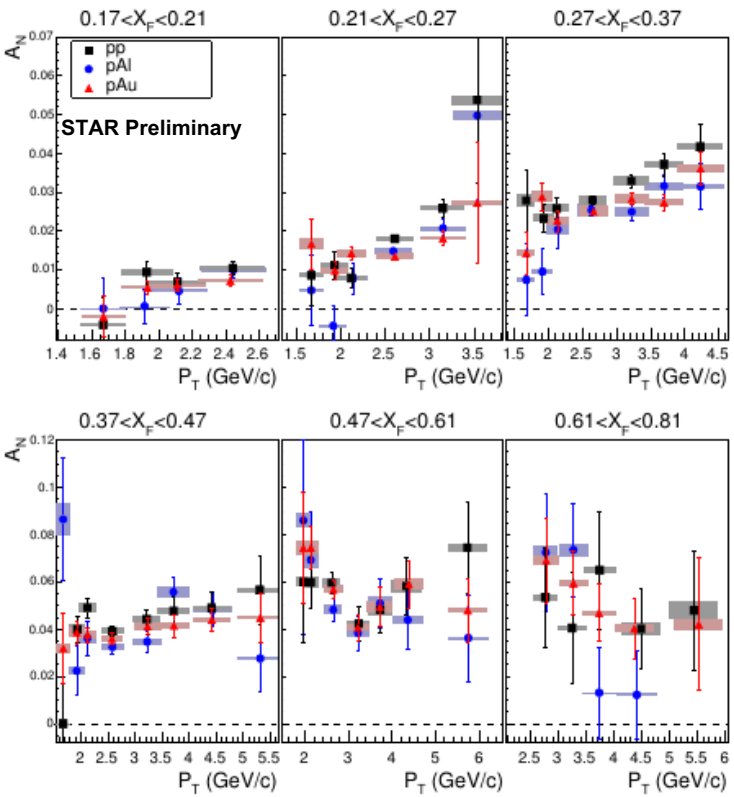


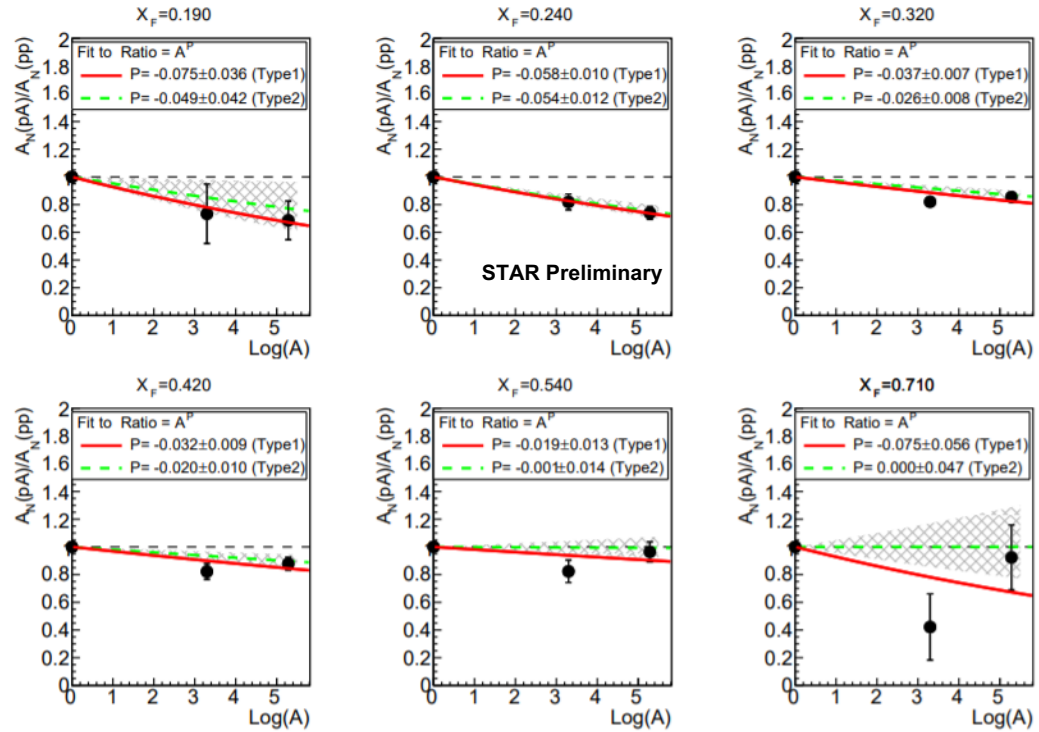
200 GeV in pp and pAu collisions.



π° A_N in pp, pAl and pAu at 200 GeV

pp pAl pAu





Transverse single spin asymmetry for forward ($2.7 < \eta < 3.8$) π° production

1) A_N Increases with X_F
2) A_N Increases with P_T for $X_F<.6$
3) Small nuclear modification of A_N (little A dependence).
4) A_N largest for isolated π° events (similarly for pp, pAl and pAu collisions, in backup)

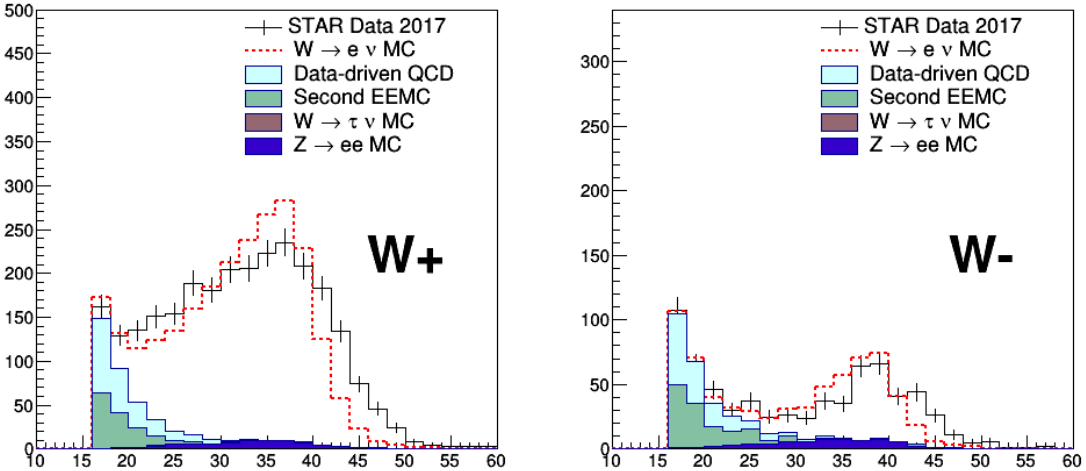
Run17 motivation

STAR BUR for Run 17:

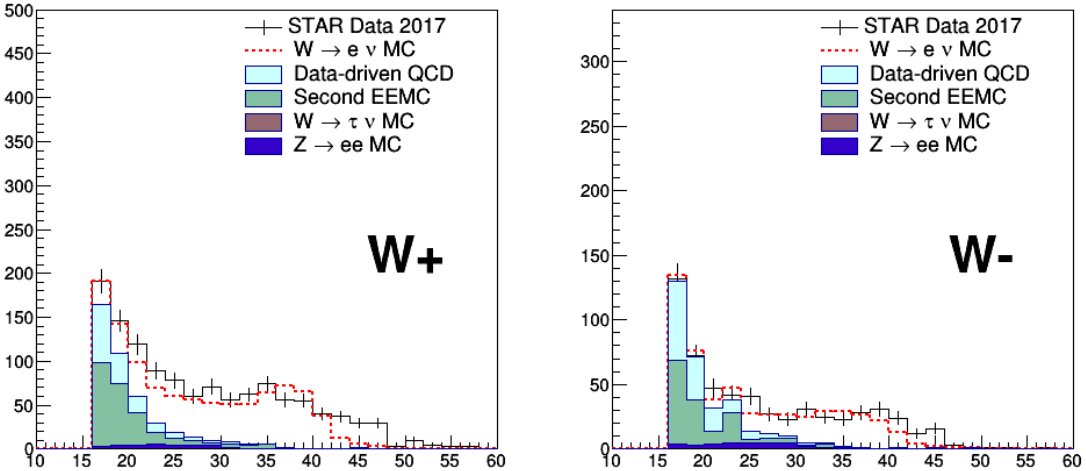
"STAR's highest scientific priority is the first significant measurement of the sign change of the Sivers function, as compared to the value measured in semi-inclusive deep inelastic scattering experiments, through measurements of single spin asymmetries in W+/-, Z, direct photon and Drell-Yan production in transversely polarized $\sqrt{s}$ = 500 GeV p+p collisions. This measurement will also shed light on the size and nature of the evolution of these transverse momentum dependent distributions. The sign change measurement is a fundamental test of QCD and is being pursued by other experiments, making a timely measurement imperative. We therefore request 13 weeks of 500 GeV p+p running in Run17."

$W^{\pm}$ candidates

E_T distribution of final $W^{\pm}$ candid. ($\eta \sim 0$)



E_T distribution of final $W^{\pm}$ candid. ($\eta \sim 1$)

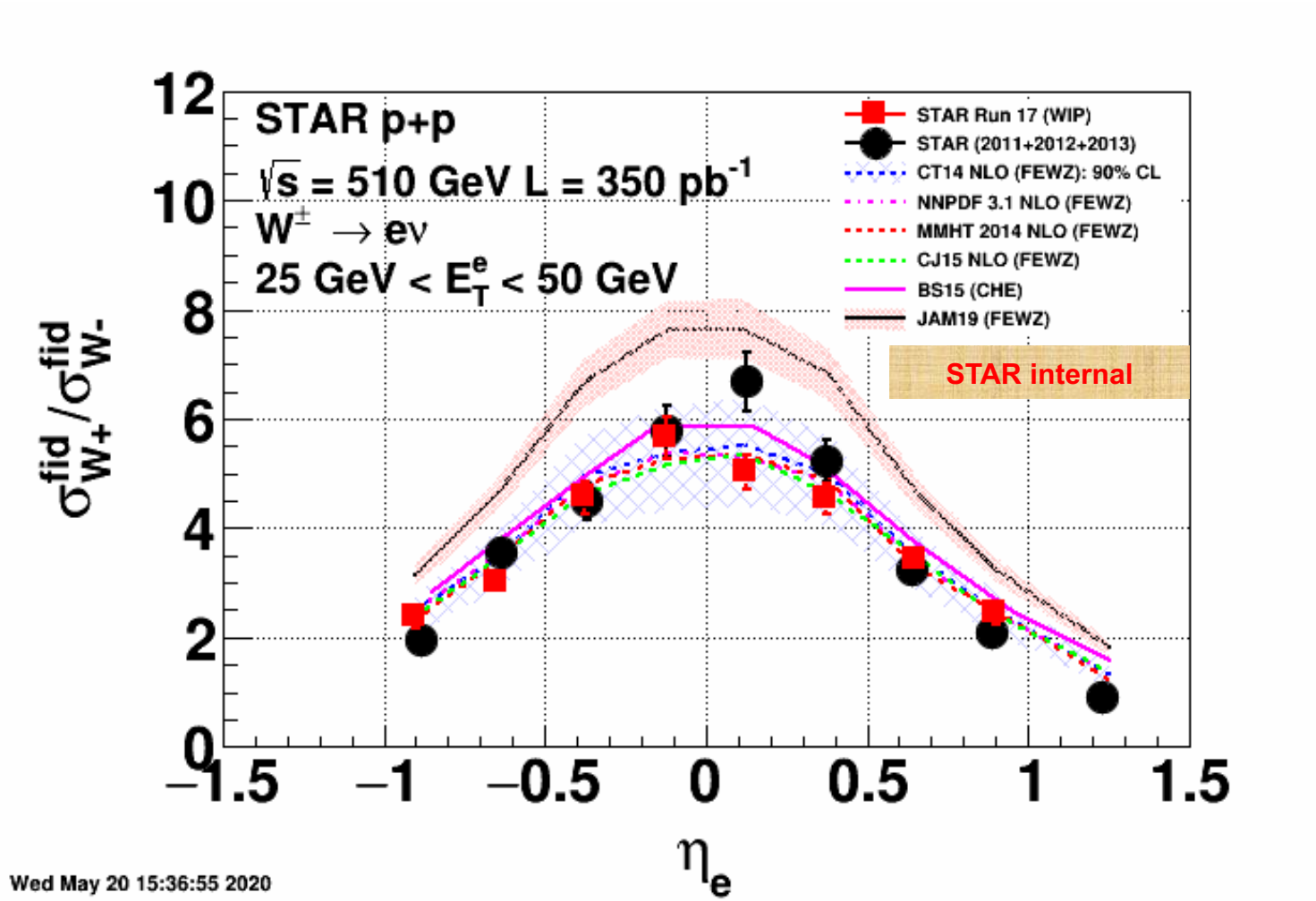


- Good matching in yield.
- Wider Jacobian peak in data.
  - Potentially due to a smearing effect from the non-optimal calibration of EMC.

→ Optimal calibration will be completed once the reproduction of Run 17 is done.

STAR is currently producing isobar phase II data.

W^+/W^- cross section ratio Run 17



- Efficiency correction has not been applied ($R_\epsilon = 1.0$ for all η)
- Systematic uncertainty not included.
- Endcap ratio needs to be calculated.

Paper describing 2011-13 weak boson cross sections and cross-section ratios, including the W+/W- results shown in the plot, is currently in GPC

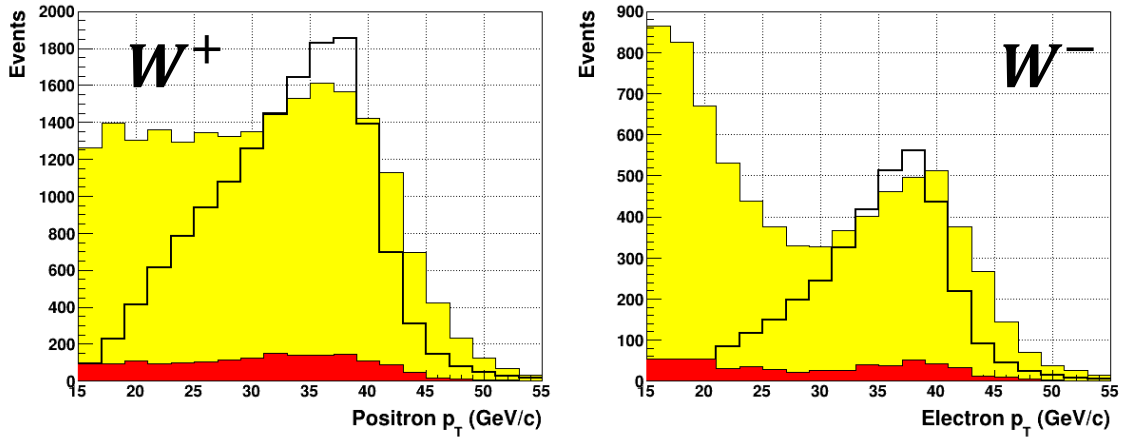
W A_N analysis status

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

Run 17 data (350 pb^{-1})

Embedding

Run 11 data (25 pb^{-1})



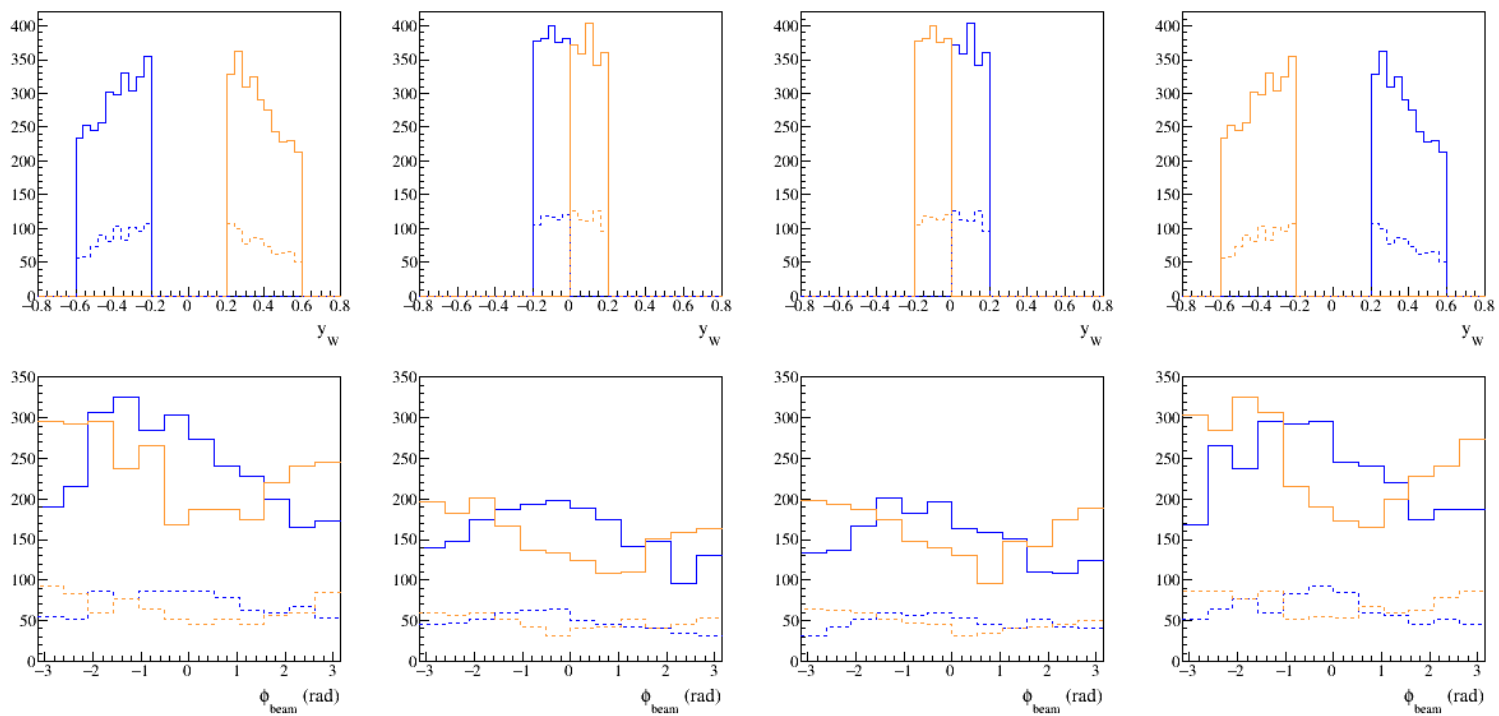
Fully reconstructed $W^{\pm}$ kinematics: $p_{T,e} > 25\ \mathrm{GeV}/c, p_{T,W} < 10.0\ \mathrm{GeV}/c$

W^+

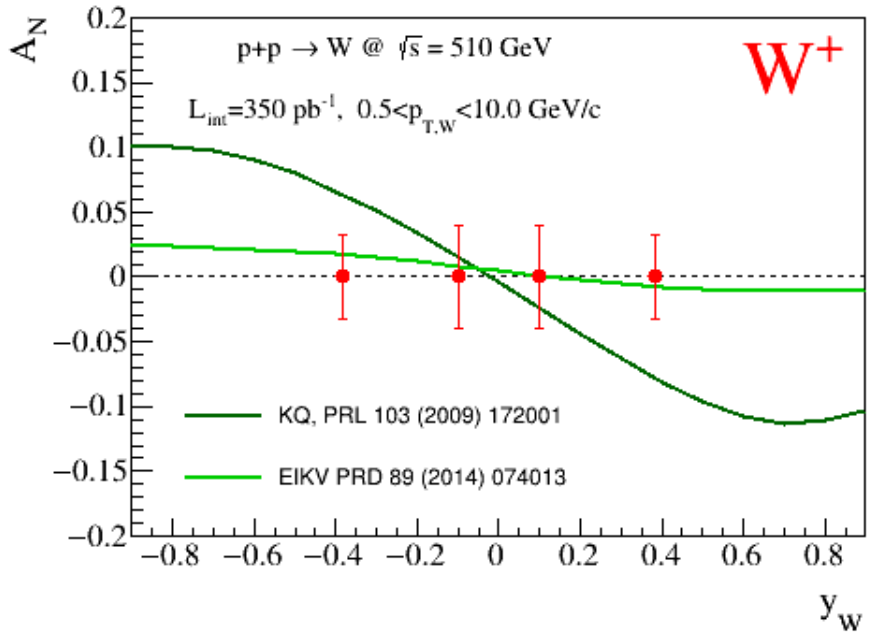
W^-

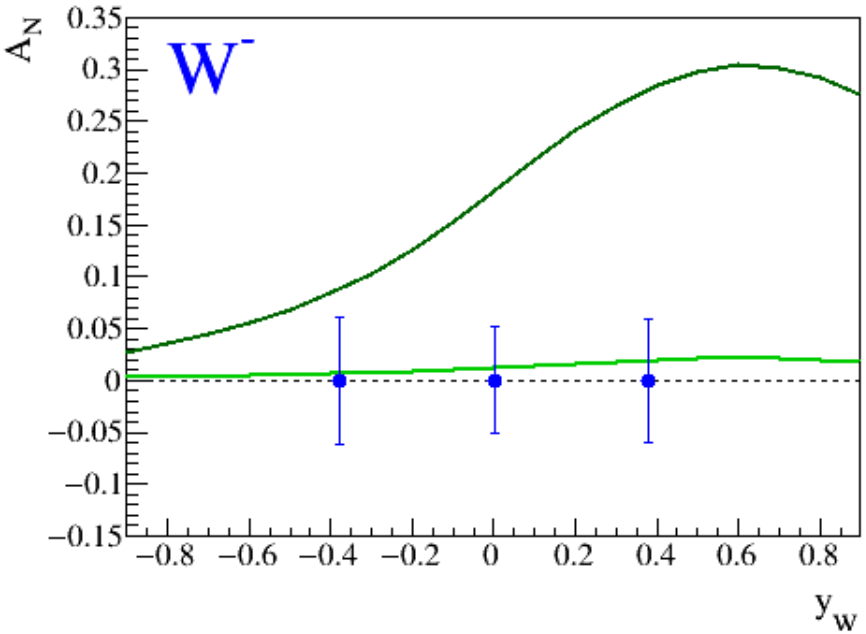
rapidity

azimuthal angle w.r.t beam



W A_N projected uncertainties



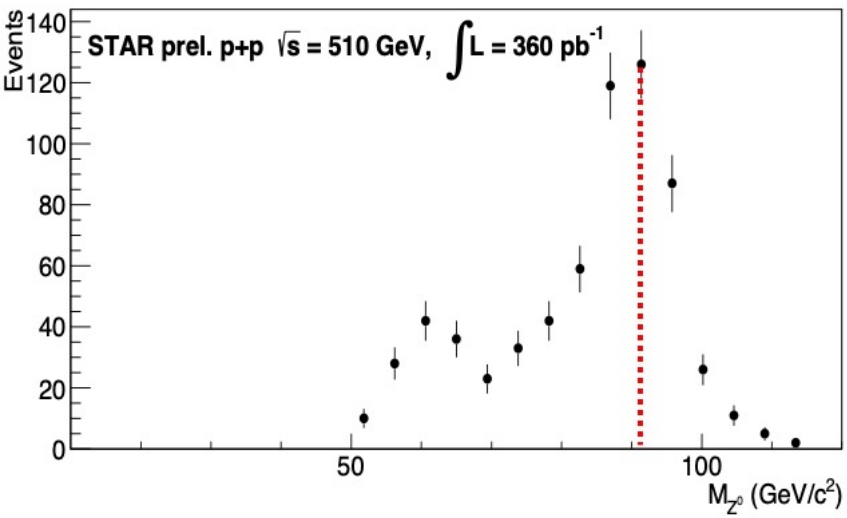


Run 17 statistics will provide important input for

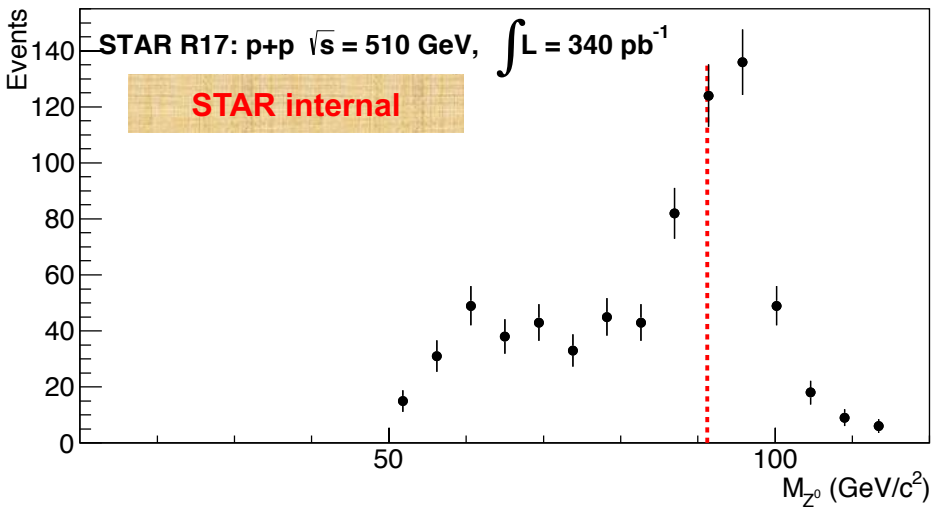
- confirmation of Sivers effect sign change and
- magnitude of TMD evolution

Run 17 Z^0 candidates: invariant mass

Prelim. RUN 11->13



RUN 17



Collected Luminosity

- Run 11t -> 25.9 pb^{-1}
- Run 12 -> 77.44 pb^{-1}
- Run 13 -> 254.2 pb^{-1}

Total (Run 11tr.->13) = 358 pb^{-1}

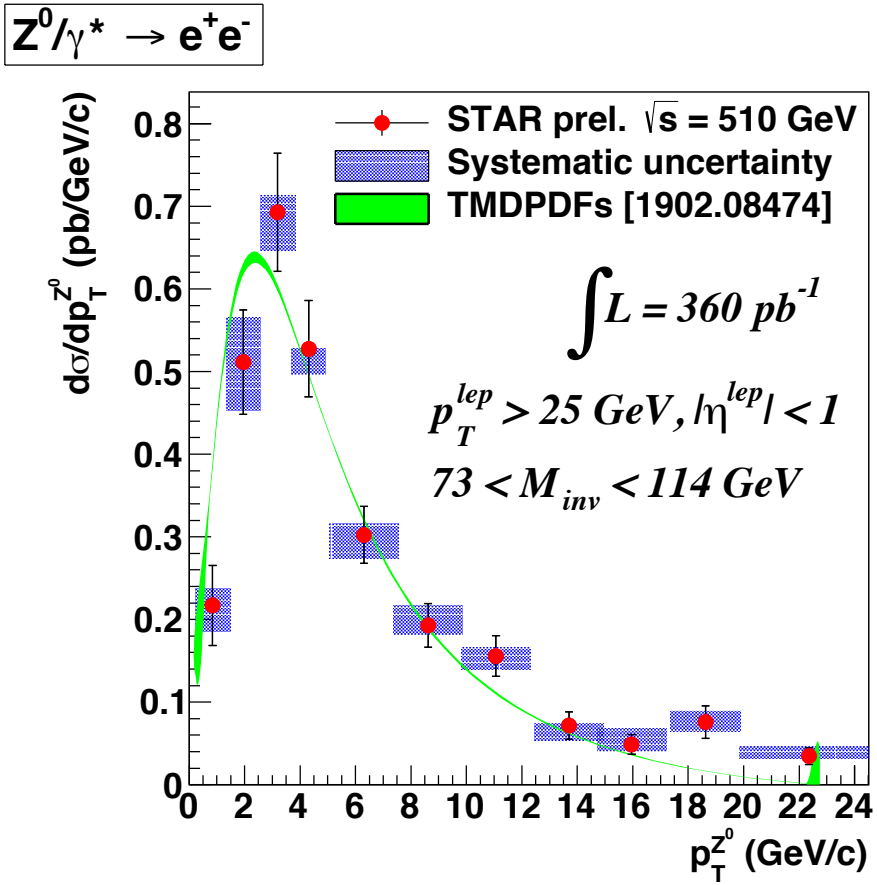
Run 11->13 selection: 501 Z^0

Collected Luminosity ~ 340 pb^{-1}

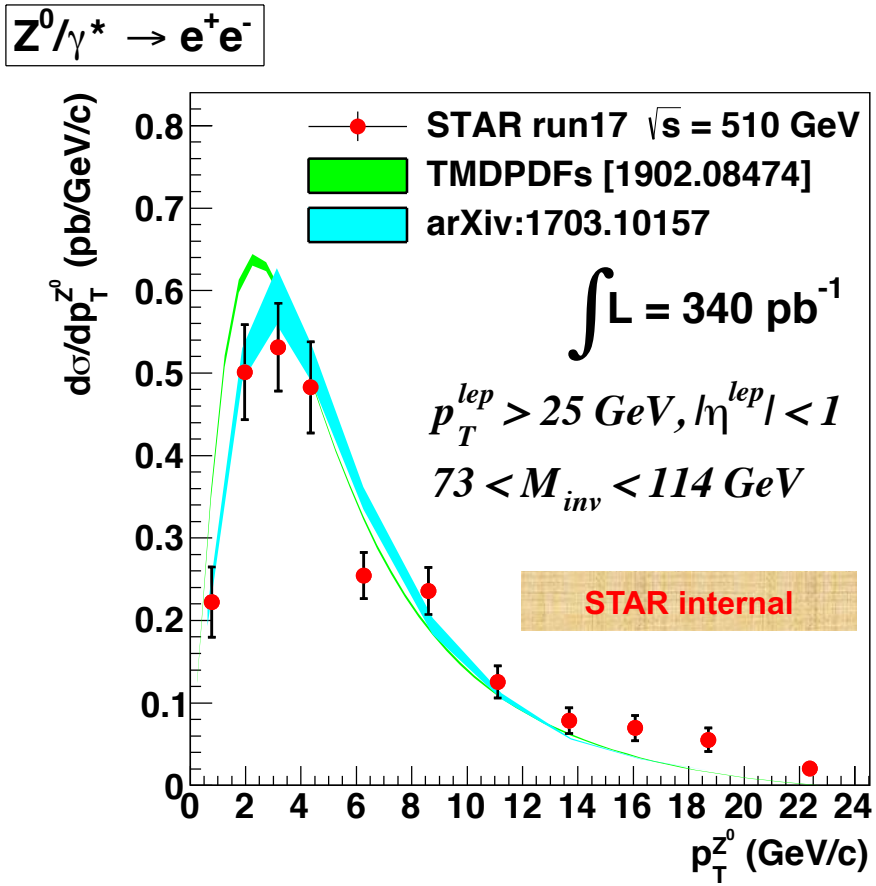
Run17 selection: 533 events

Run17 Z^0 differential cross section

Prelim. RUN 11->13



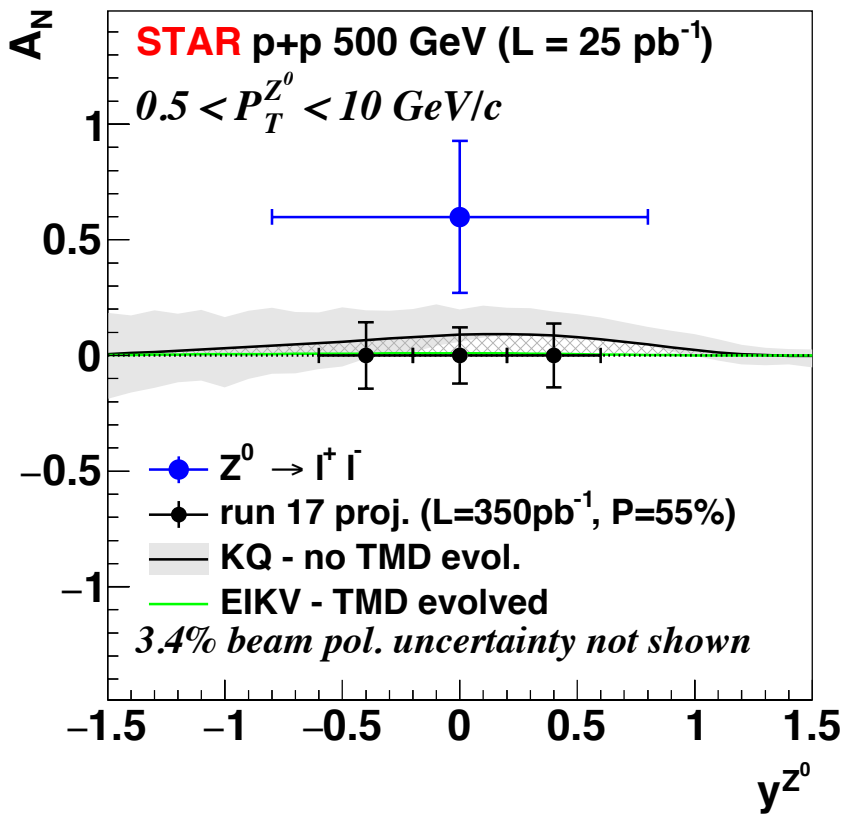
RUN 17



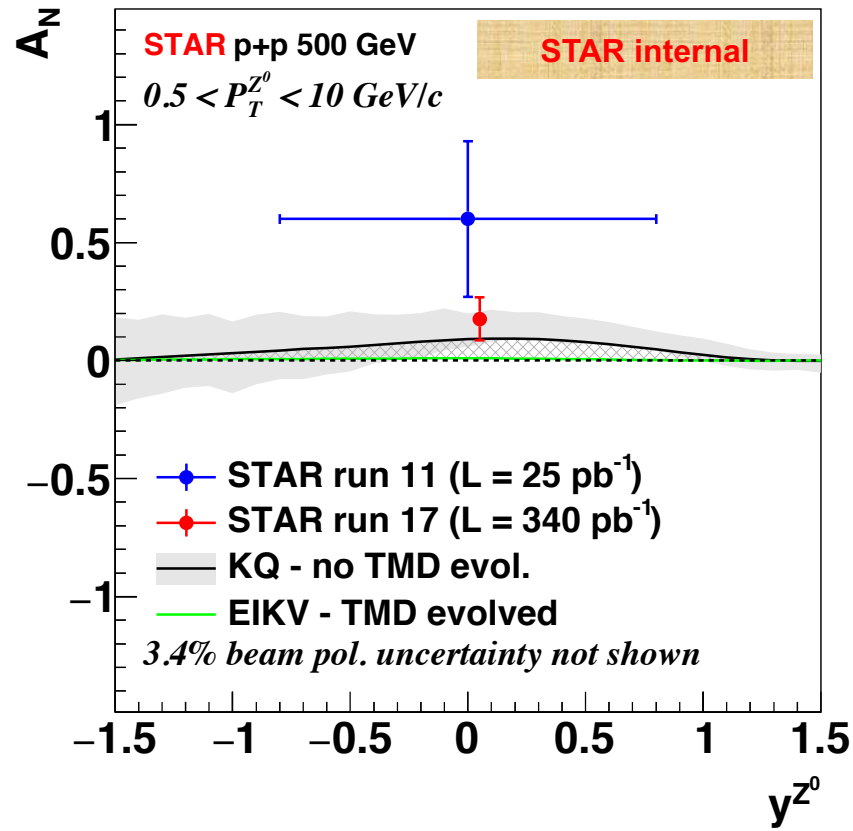
- Overall uncertainty on luminosity (8.5%) non shown on the plots
- Dominant sys. from EMC calib. gains

Run17 Z^0 transverse spin asymmetry

Run 11 Published & projections



Run 17 vs run 11



Our projections:

- ~15% uncertainty in three bins

- ~10% uncertainty in one bin
- Run17 point staggered for visibility

STAR physics program after BES-II

Forward-rapidity 2.8< η <4.2

A+A

Beam:
Full Energy AuAu

Physics Topics:

- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization
  → strong rapidity dependence

p+p & p+A

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:

- TMD measurements at high x
  transversity → tensor charge
- Improve statistical precision for Sivers through DY
- Δg(x,Q2) at low x through Di-jets
- Gluon PDFs for nuclei
  - R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

Observables:

- Inclusive jets and di-jets
- Hadrons in jets
- Photons
- Drell-Yan e^+e^-
- Lambda's
- Mid-forward & forward-forward
- rapidity correlations

Requirements:

- Good *e*/*h* separation
- Hadrons, photons, π^0 identification

2021/22: 500 GeV polarized pp run

Additional pp, pA, and AA data taking in parallel to the sPHENIX campaign

STAR forward upgrade proposal: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

STAR forward upgrade institutions

sTGC

- Brookhaven National Laboratory
- Shandong University
- University of Science and Technology of China

Silicon

- UIC University of Illinois at Chicago
- Brookhaven National Laboratory
- National Cheng Kung University
- Shandong University
- Indiana University

ECal

- Kentucky
- Valparaiso University
- Abilene Christian University

HCal

- UCLA
- Texas A&M University
- Indiana University
- Rutgers
- Abilene Christian University
- Ohio State

DAQ/Readout

- Brookhaven National Laboratory
- Indiana University
- Kentucky
- UCLA
- Texas A&M University

Software

- Brookhaven National Laboratory
- UIC University of Illinois at Chicago
- Indiana University
- Texas A&M University
- National Cheng Kung University

Integration

- Brookhaven National Laboratory

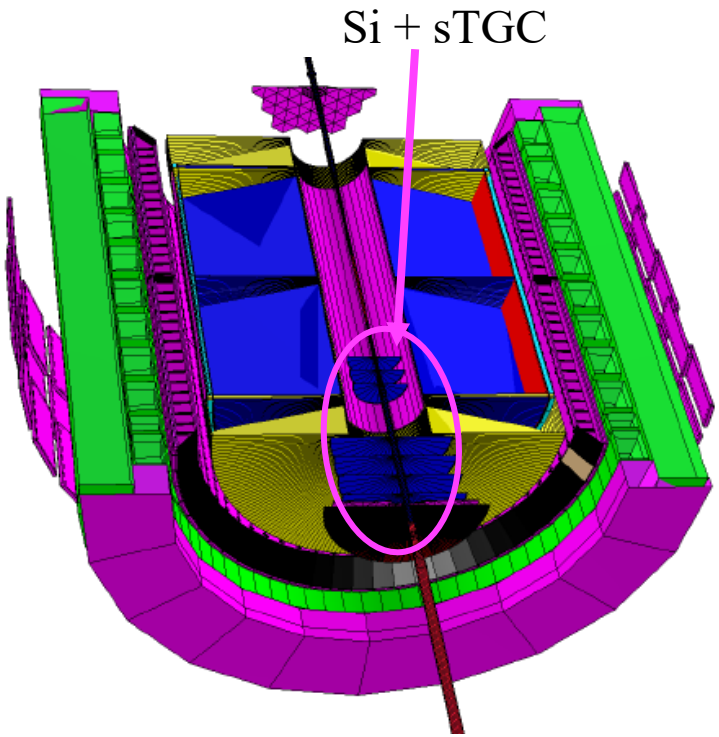
Calibration

- UC Riverside
- Temple University

Slow Controls

- Valparaiso University
- Abilene Christian University
- Creighton University

Silicon and sTGC



3 Silicon disks: at 139.9, 163.2, and 186.5 cm from IP

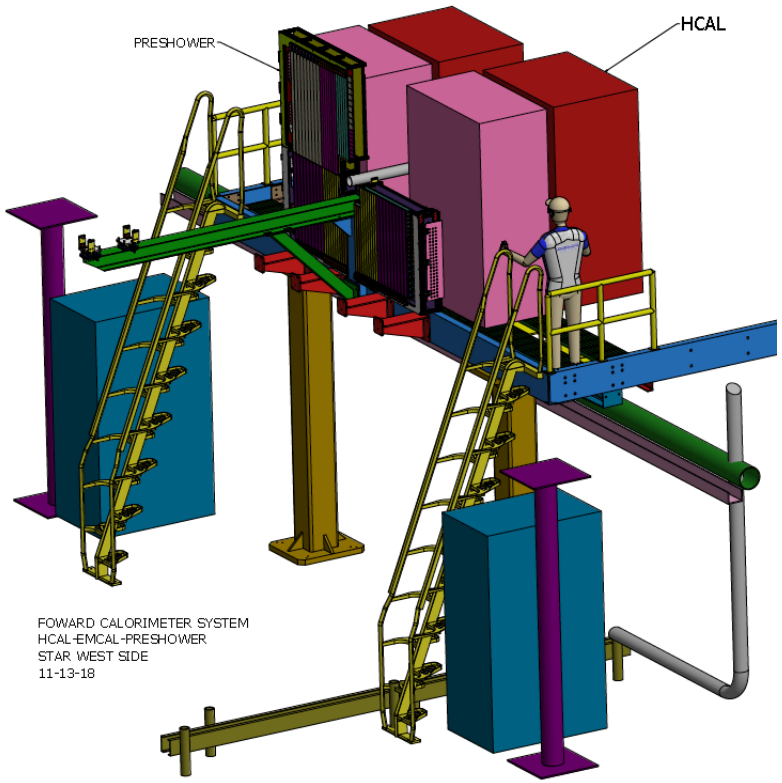
Built on successful experience with STAR IST

- Single-sided double-metal mini-strip sensors
  - Granularity: fine in ϕ and coarse in R
  - Si from Hamamatsu
- Frontend chips: APV25-S1 → IST all in hand
- Material budget: <1% per disk
- Reuse
  - IST DAQ system for FTS
  - IST cooling system

4 sTGC disks: at 273, 303, 333 and 363 cm from IP

- location inside Magnet pole tip opening
  - inhomogeneous magnetic field
- 4 quadrants double sided sTGC → 1 layer
- Position resolution: ~100 μm
- Material budget: ~0.5% per layer,
- Readout: based on VMM chips
  - 24000 channels

ECal & HCal



Location: 7 m from the IP on the "FMS platform"
Readout: SiPMs

- Used in Trigger
- Split in 2 movable halves inside and outside of ring
- Slightly projective

ECal:

reuse PHENIX PbSC calorimeter with new readout on front phase → 1496 channels

- Secured one Sector (2592 towers) PbSc towers: 5.52 x 5.52 x 33 cm3 (18 $X0$)
  66 sampling cells with 1.5 mm Pb,
  4 mm SC & Wavelength shifting fibers

HCal:

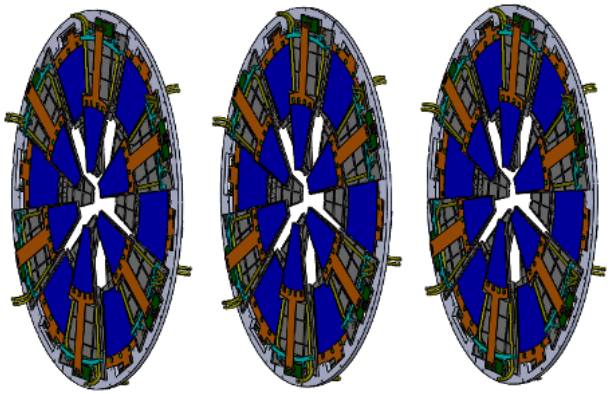
- Fe/Sc (20mm/3 mm) sandwich.
- 520 readout channels
- Lateral tower size 10 x 10 cm2, ~ 4.5 l
  - in close collaboration with EIC R&D

Preshower

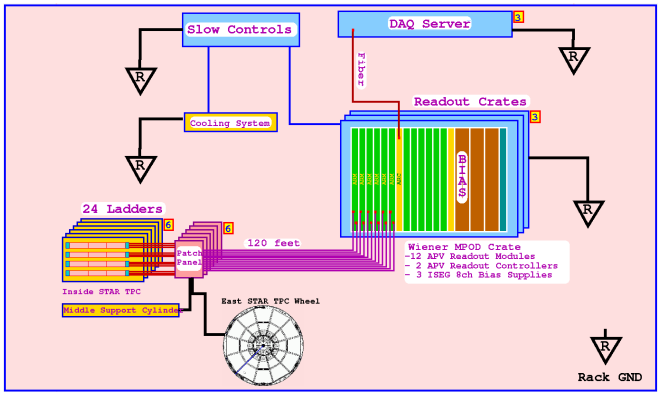
- Use STAR event plane detector

STAR Forward Silicon Tracker

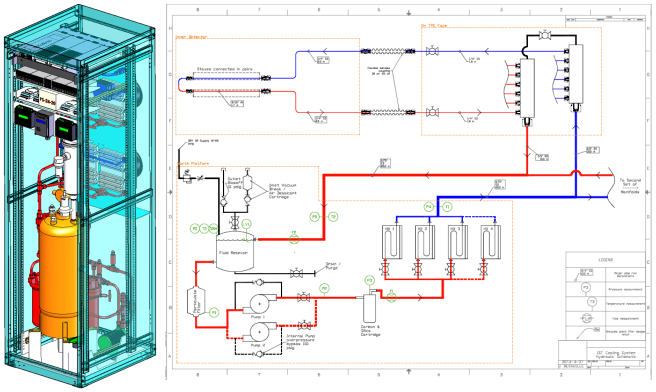
- Three disks, thirty-six wedge modules
  - Silicon microstrip sensors
  - APV25 frontend readout chips
  - Flexible hybrid
  - Mechanical structure



- DAQ system
  - Inner signal cables
  - Outer signal cables, patch panel boards, readout modules, readout controllers, crates



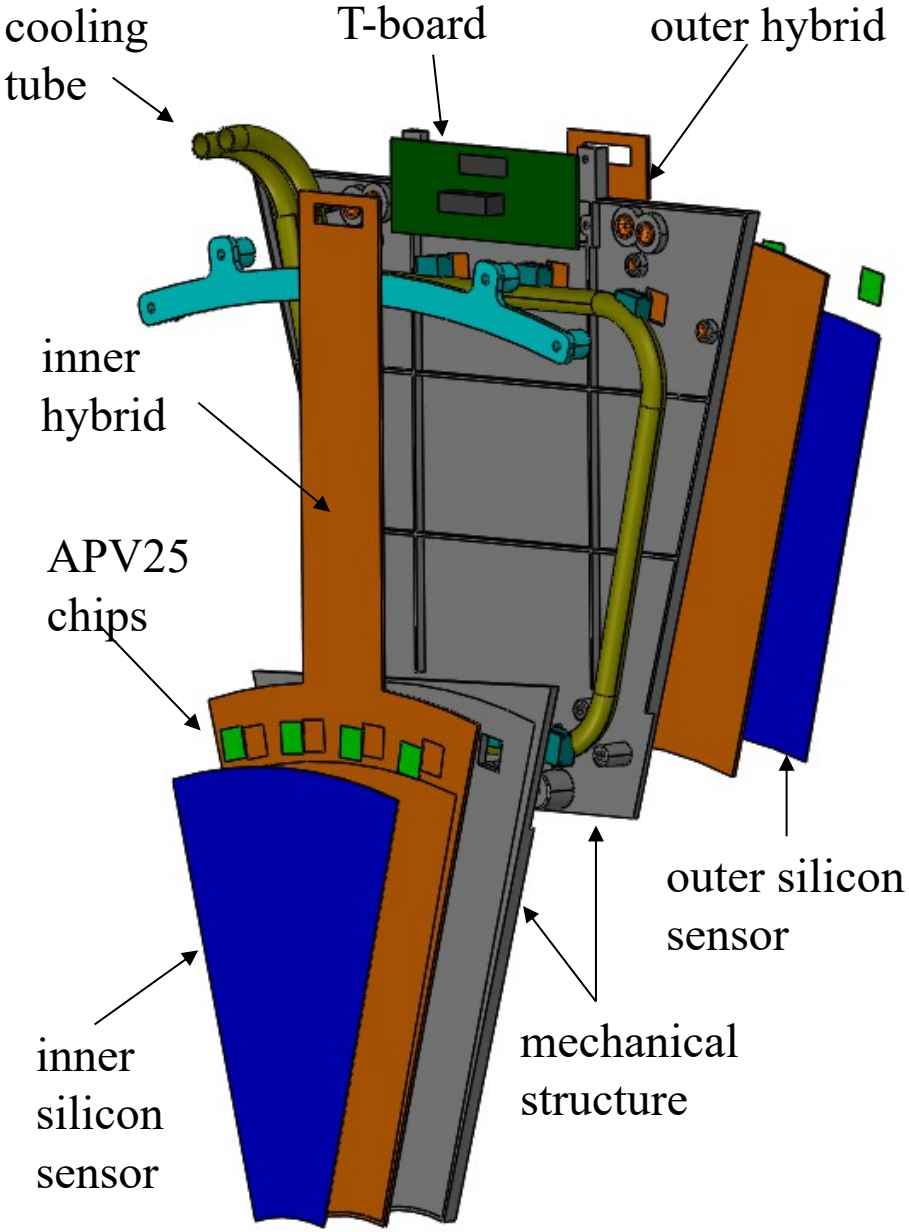
- Cooling system
  - cooling manifold, cooling lines
  - rack (cooler, pumps)

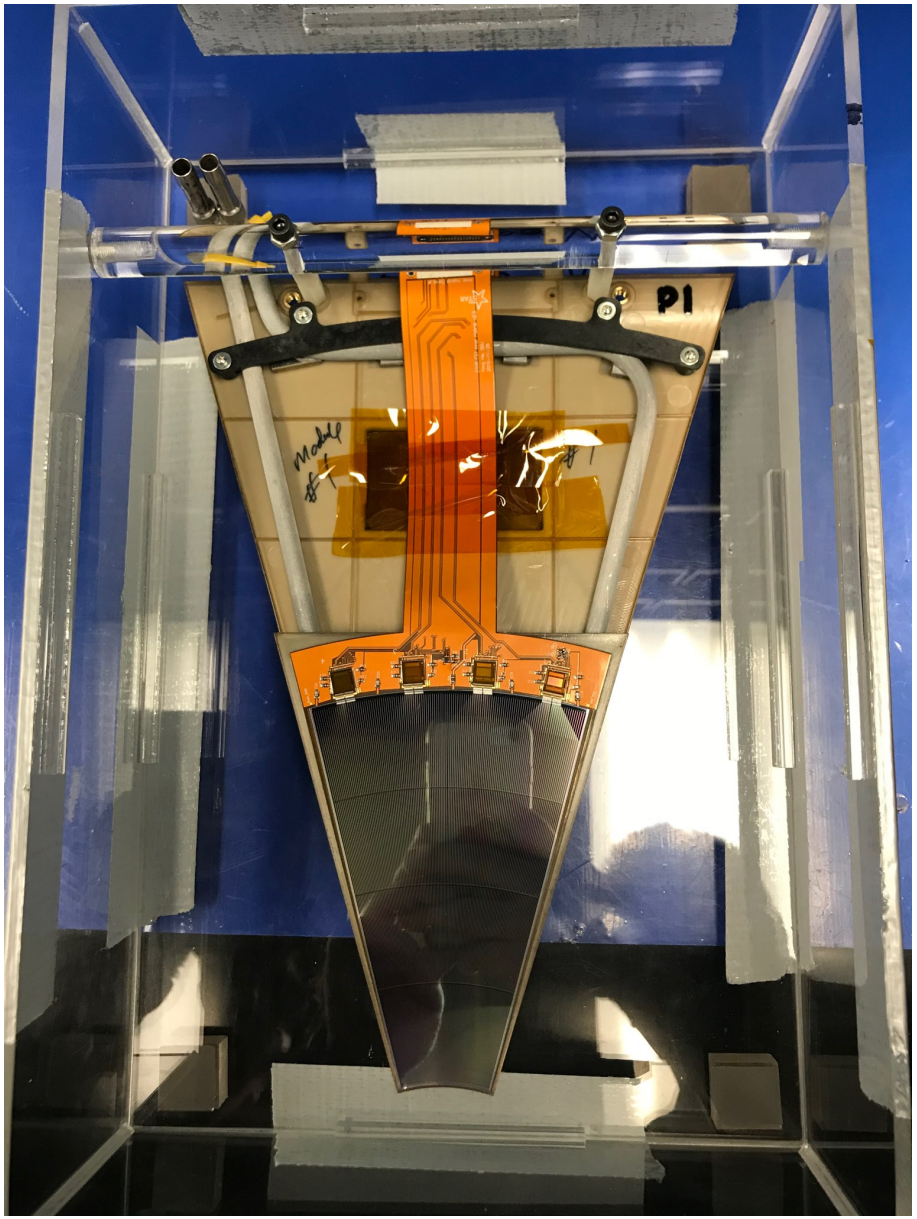


- Integration
  - supporting structure and installation

Blue: existing Red: new

STAR Forward Silicon Tracker – prototype module





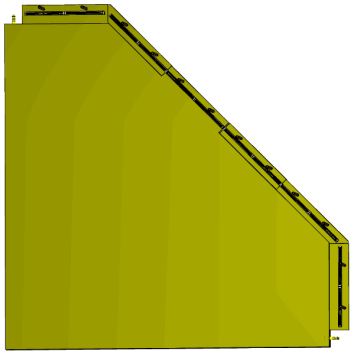
STAR Forward Silicon Tracker – milestones

- **Detector Module Prototype**
  - Silicon sensor: **08/23/2019**
  - Flexible hybrid: **12/26/2019**
  - Mechanical structure: **12/20/2019**
  - Inner signal cable and T-board: **02/05/2020**
  - Detector module assembly: 02/28/2020 -> **06/30/2020**
  - Detector module testing: 04/30/2020 -> **07/31/2020**
- **Detector Module Production**
  - Ordering: 05/31/2020 -> **08/31/2020**
  - 1st batch of flexible hybrid: 07/31/2020 -> **10/31/2020**
  - 1st batch of mechanical structure: 09/31/2020 -> **12/31/2020**
  - 1st batch of Silicon sensors: 12/31/2020 -> **02/28/2021**
  - Detector module assembly complete: 04/30/2021 -> **06/30/2021**
- **Supporting structure and cooling system**
  - Design 04/30/2020 -> **08/31/2020**
  - Fabrication 09/31/2020 -> **12/31/2020**
- **Installation**
  - Installed onto supporting structure: 06/15/2021 -> **07/31/2021**
  - Installed into STAR: 07/15/2021 -> **08/15/2021**
  - Ready for data taking: 08/31/2021 -> **08/31/2021**

STAR Forward sTGC Tracker

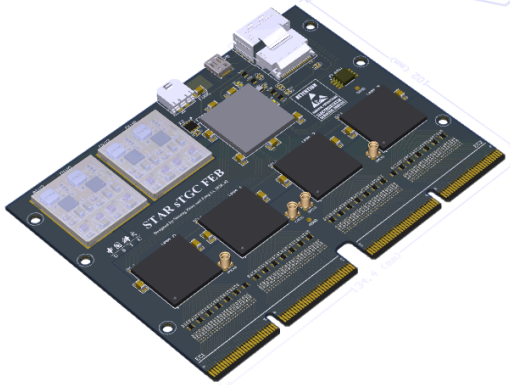
Detector:

- sTGC R&D and produce at SDU
- 4 layers, 4 modules/layer, 2 chambers/module
- Pentagon shape for integration



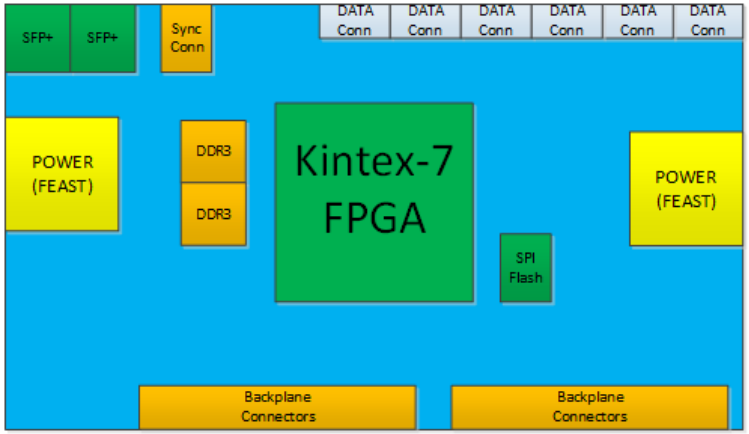
Electronics:

- Based on VMM chips, to be purchased.
- FEB and ROB R&D and produce at USTC
- Will be tested together with sTGC at SDU
- Will be tested and commissioned at BNL



Integration:

- Supporting structure on detector will be done by SDU together with the chamber
- Integration will be designed and done by BNL integration group

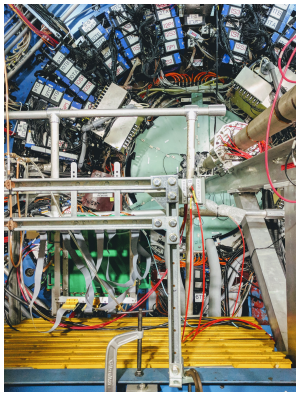


Software:

- Will be done by BNL and SDU

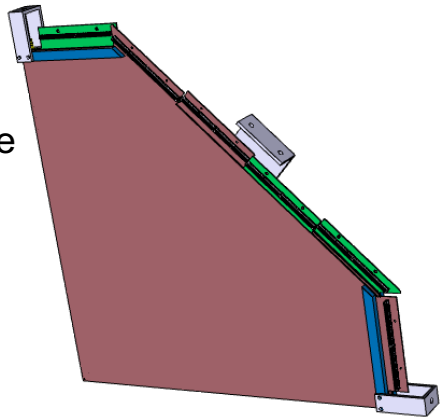
sTGC R&D and production status

✓30 cm x 30 cm prototype finished in Oct. 2018, delivered to BNL in Jan. 2019, installed in STAR on Jun. 2019

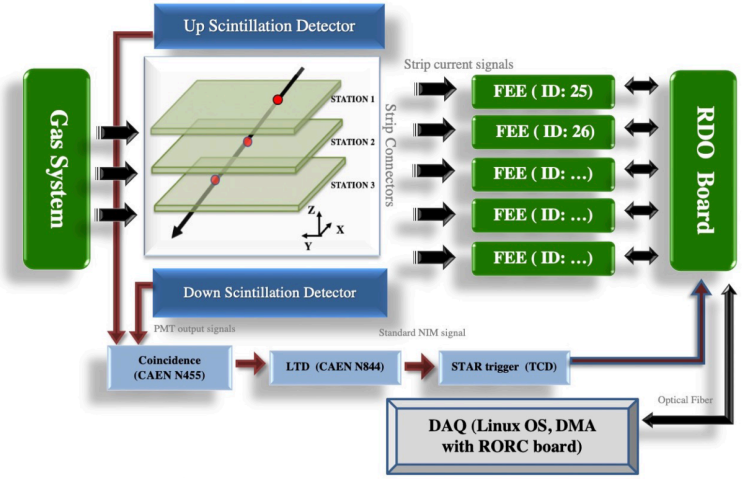


✓60cm x 60cm prototype finished in Jan.2020, will be delivered to BNL once the lab is reopened.

✓Pentagon prototype designation finished, materials in vendor production



Performance test system at SDU



The cosmic-ray tests at both BNL and SDU show consistent efficiencies at the level of 98%

Performance test show that the position resolution, detection efficiency, stability and geometry uniformity met the requirements.

sTGC schedule

Items	Last f2f meeting schedule	Current finished date or expected schedule
Module production		
Pentagon prototype design	Dec.2019 to Jan. 2020	Finished in Feb. 2020
Vender production	Jan. to Mar. 2020	Expecting in May.2020
Prototype production	Mar. to Jun. 2020	Expecting from Jun.2020 to Aug.2020
Final Design	Apr. to Jul. 2020	Expecting from Jul.2020 to Sep.2020
Vender production	Jul.2020 to Sep.2020	Expecting from Aug.2020 to Oct.2020
Mass production	Aug. 2020 to Jun.2021	Expecting from Sep.2020 to Jun.2021
Electronics production		
FEB prototype production	Apr. 2020	Expected to be finished in May. 2020.
ROD prototype production	Apr. 2020	Still in designation.
FEB and ROD test with sTGC	May. To Jul. 2020	Expected to be done from Jul.2020 to Sep. 2020
ROD firmware design, FEB site test, ROD interface protocol	Jul. 2020	Pending
Final Design	Oct. 2020	Pending
Mass production	Dec. 2020	Pending on VMM purchasing
VMM order placing	Pending	Pending
Integration		
Gas system	Apr.2020	Expecting two months after lab reopens
HV & HV distribution box	Apr.2020	May.2020
Interlock system	Apr.2020	Expecting two months after lab reopens
Cooling		Expecting two months after lab reopens
Supporting frame - STSG Prototype	Apr.2020	Constructed
Installation Structure - STSG Final Design	Sep.2020	Sep.2020
Fabrication of Parts-STSG	Dec.2020	Dec.2020
Installation Structure - FST Final design	Aug.2020	Aug.2020
Fabrication of Parts -FST	Dec. 2020	Dec. 2020
LV power supply		Dec. 2020
Software		
Develop cluster finding algorithm		Jun.2020
Algorithm for constructing space points & rejecting ghost hits using diagonal strip information		Jul.2020
Develop an sTGC slow simulator		Summer 2020

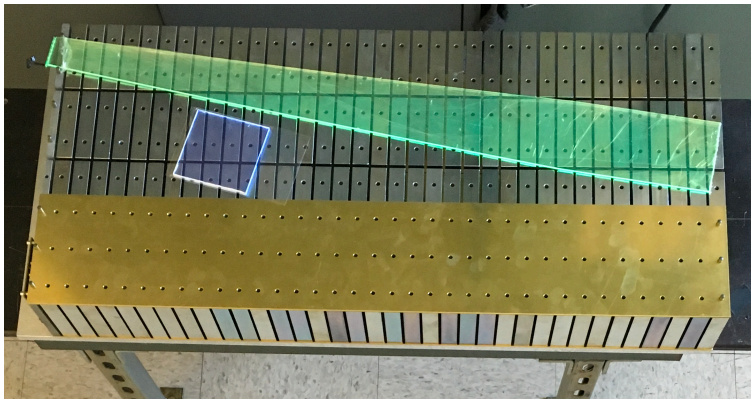
FCS status

- Small 16 ch. FCS prototype was tested at FNAL in April 2019.
- Small 64 ch. ECal and 16 ch. HCal prototypes were operational in Run 19 at STAR.
- ECal installed at STAR IP in the fall 2019.

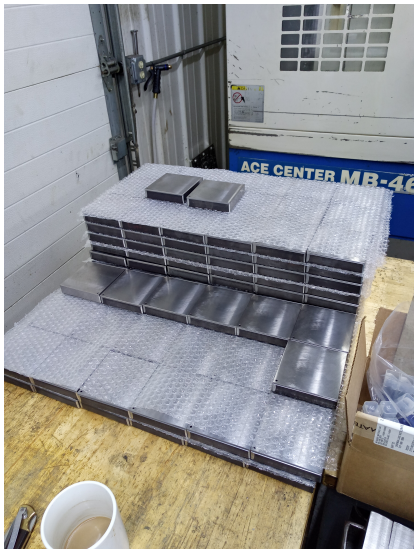
HCal status

Major Components for HCal, Status.

- Scintillation tiles: EJ produced all scintillation sheets. Approximately 30% of al Sc. Tiles were machined (OSU/UCLA). And 10% tiles are completed with polishing and painting for installation.
- Absorber Blocks: first batch (~ 17% of total) expected to be delivered to BNL second week of June. With consequent shipments bi-weekly.
- WLS plates: 80% produced and delivered, last shipment by the end of May.
- SiPMs: 9k SiPMs delivered. All components for SiPM board assemblies are in hand.
- FEE: production start by the end of May. Testing and calibration ends in Aug.



Sc tiles preparations at BNL. Summer 2019



Absorber Production at Chapman Lakes (Indiana) Feb. 2020

Covid-19 impact

- Prior COVID 19 shutdown, FCS project was moving well with targeted date to start installation at BNL in Aug. 2020
- Since about mid March, all Universities carrying different tasks halted production. In a few cases production has not started (not time-critical items), although almost all raw materials for production were acquired by that time.
- Prior COVID19 universities committed about 15 students x 3 months to carry different tasks, many of which were planned at BNL.
- The most impacted areas will be the one which depends on assumed students labor.
- At the moment in most cases we don't have estimates when Universities will be allowed to be back to labs. We also don't know new safety polices and protocols and how they may affect production once it will re-start or how they will affect installation at BNL.
- Outside vendors were producing major components during COVID19 and either completed orders (Scintillation Sheets, WLS Plates, SiPMs), or on path to deliver parts according to original schedule such as Absorber Blocks.
- Revised milestones for 2020 are to instrument ECal and to install and instrument 50% of HCal. If time and available parts allow we also want to install as much as possible rest of HCal, and then finish HCal installation and instrumentation in 2021.

- **DAQ, integration, and software are well on track.**

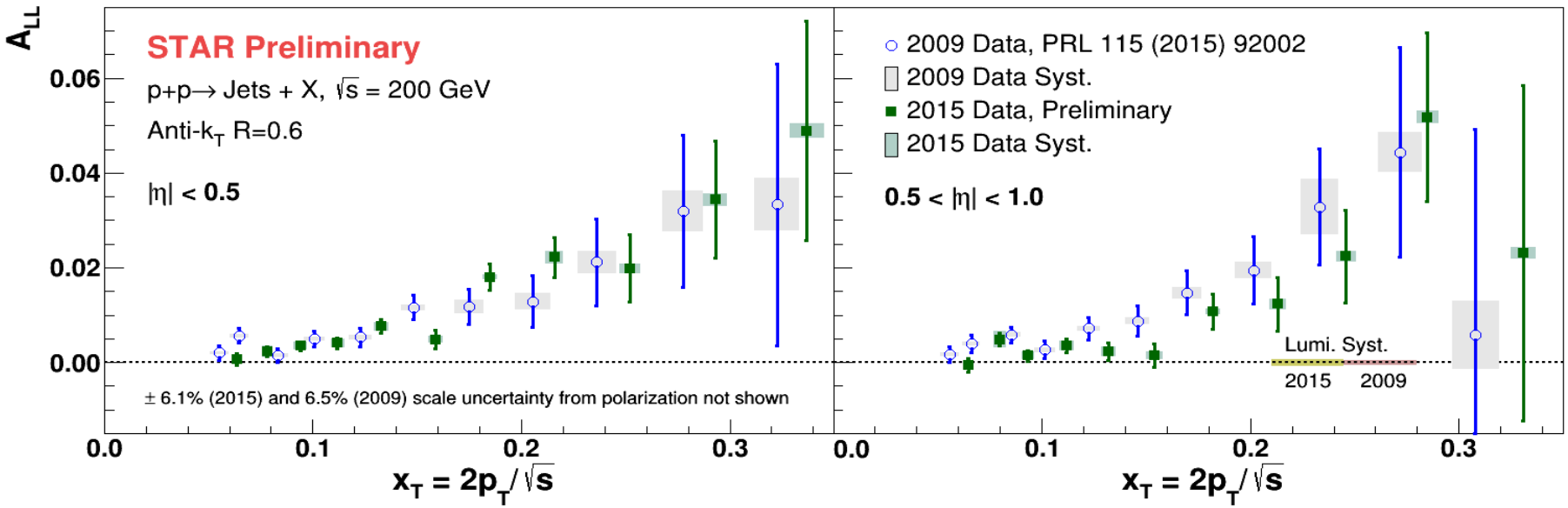
Summary

- We made great progress on analyzing our Run15 data.
- Pre-preliminary results from Run17 show data quality is good and results are very promising.
- STAR forward upgrade is on track. We have been carefully following the impact of Covid-19. We need plan our shut down schedule very carefully for integration and installation.

Backup slides

Probe gluon helicity ΔG with jets

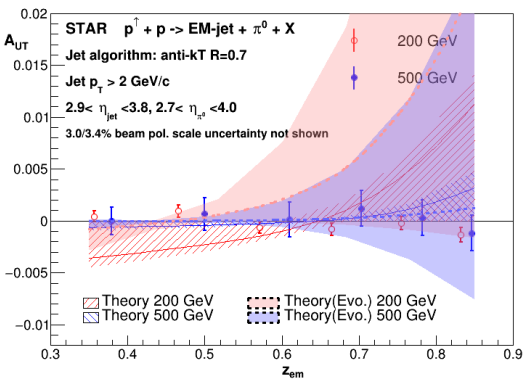
Impactful new preliminary result on A_{LL} of inclusive jet production from 2015 data

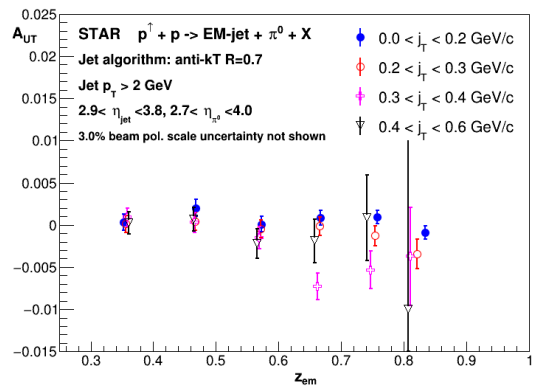


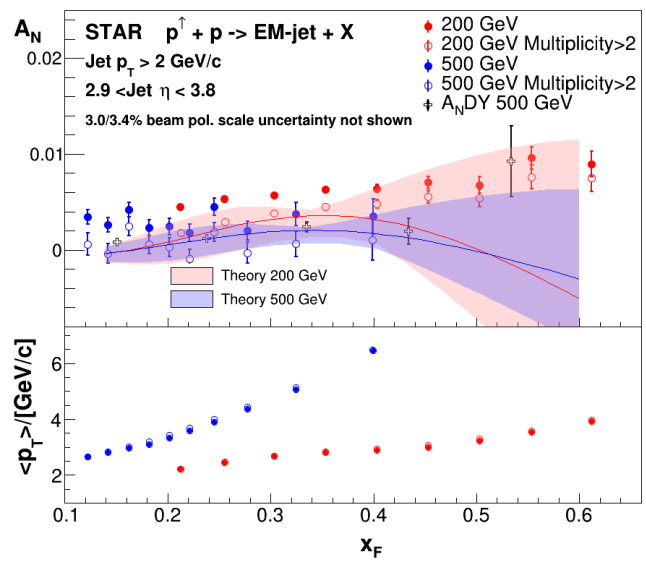
- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
- Twice larger figure-of-merit (LP_4) with improved systematics
- Di-jet A_{LL} analysis of 2015 data underway

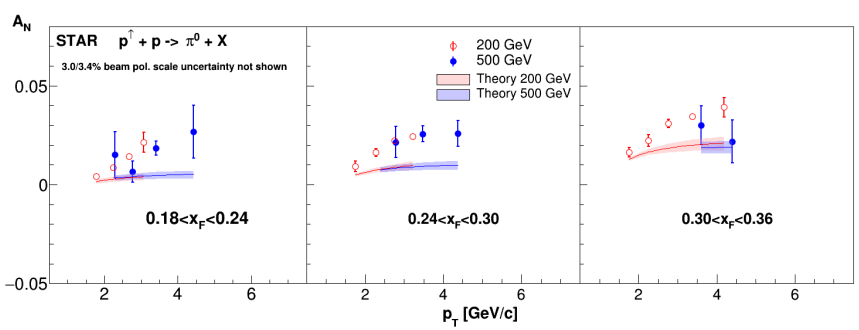
Collins asymmetries for π^0 within an EM jet and A_N for EM jet

- The Collins asymmetries for π^0 within an electromagnetic jet are small for both energies and exhibit a sign of j_T dependence at 200 GeV. (Left/middle)
- The asymmetries for electromagnetic jets which relate to the initial state effect are consistent with zero in 500 GeV but slightly above zero in 200 GeV.









- π^0 transverse single-spin asymmetry as function of p_T .(Bottom)

Probe gluon helicity ΔG with jets

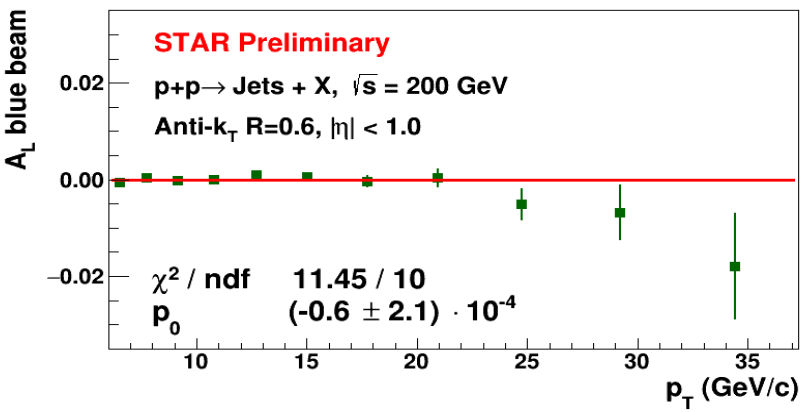
Analysis aspects

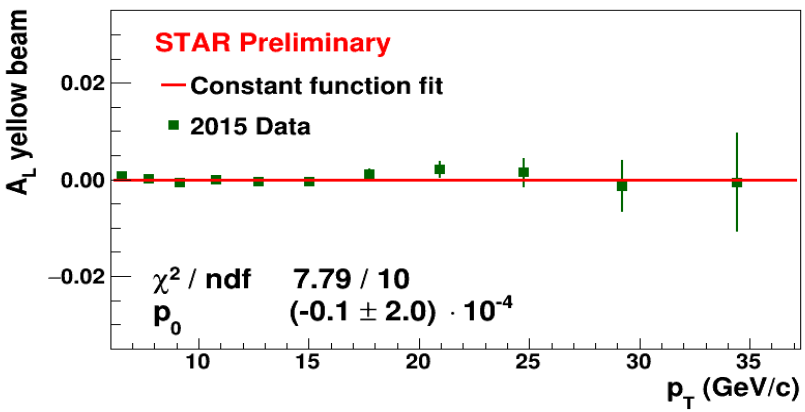
- Jets reconstructed with anti-kT algorithm with R = 0.6
- Jet-by-jet underlying event correction using off-axis cone method ALICE, PRD 91, 112012

- **Simulations:** Perugia 2012 with a tuned $p_{T,0}$ scale param to reduce multiple parton interaction contribution
  - Detector jet p_T – parton jet p_T correction based on the simulation applied
  - Trigger bias and reconstruction efficiency estimated using replicas from polarized NNPDF1.1 PDF set

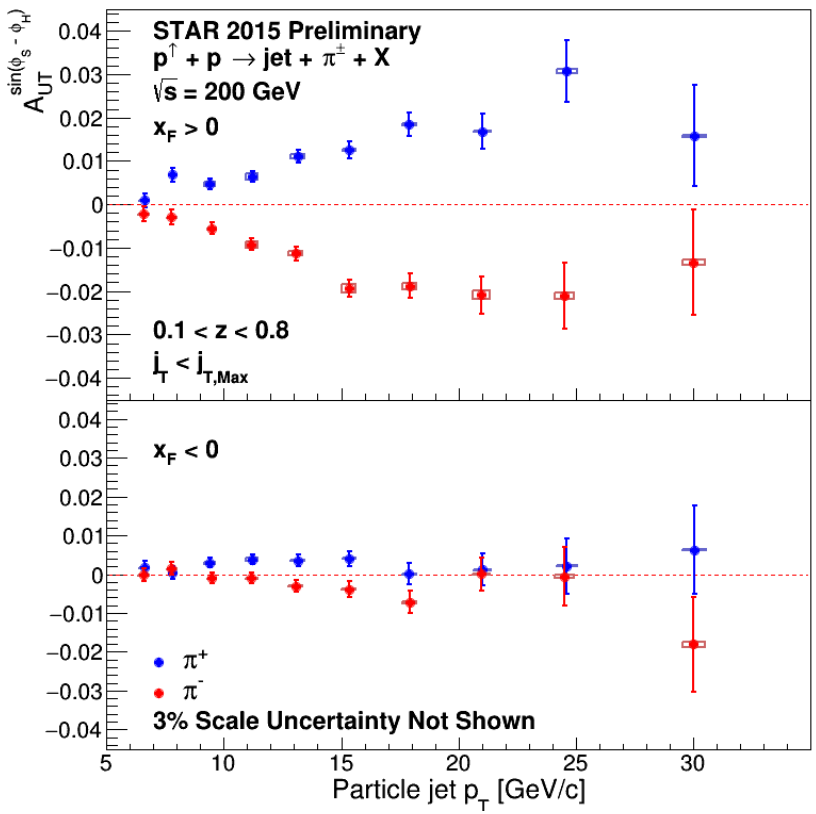
- Main improvements in systematics in respect to the 2009 result came from:
- application of the UE correction, smaller residual transverse polarization

- **Relative luminosity** calculated using VPD scalers with uncertainty similar to 2009 data
- Single spin asymmetries as well as like-sign and unlike-sign double spin asymmetries determined to **cross-check of the relative luminosity** calculations
  - All well consistent with zero within uncertainties



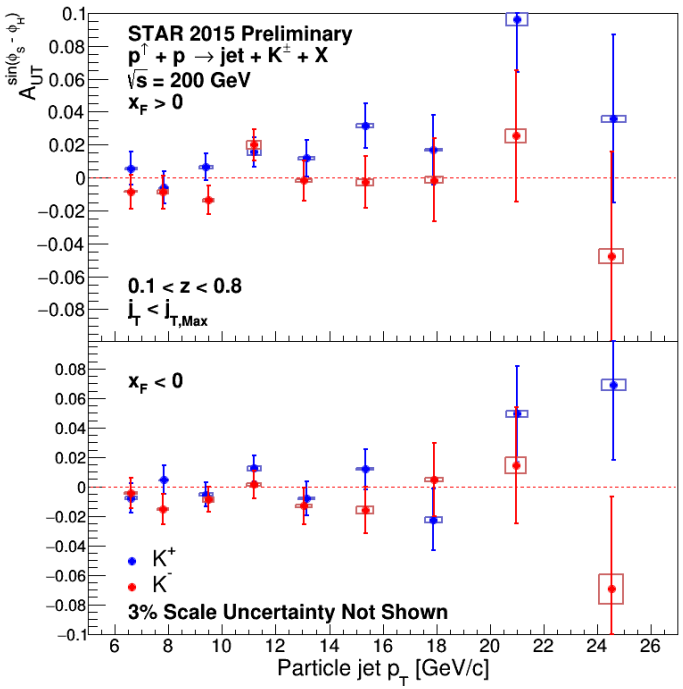


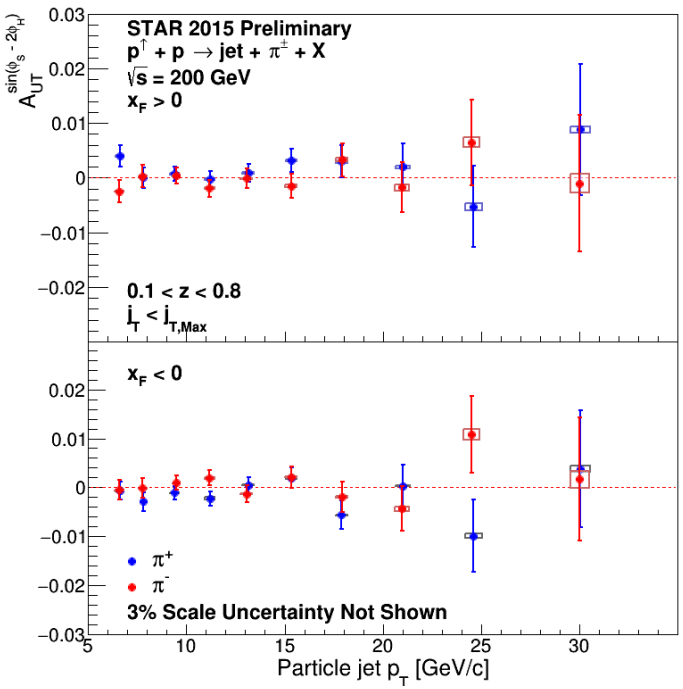
Collins effect in 200 GeV 2015 pp data



- Collins effect involves convolution of the quark transversity in the proton with the spin-dependent Collins fragmentation function, leading to azimuthal modulations of identified charged hadron yields about the jet axis;
  - Integral of transversity gives the nucleon tensor charge;
  - Difference of helicity and transversity has direct x-dependent connection to quark orbital angular momentum;
  - Collins fragmentation function in pp probes fundamental questions regarding factorization, universality, and evolution of TMDs.
- 200 GeV pp provides sensitivity up to $x \sim 0.4$, where SIDIS statistics are very limited.
- Several new analysis techniques developed to minimize systematic uncertainties.
- 2015 asymmetries agree with previous 2012 results and have uncertainties smaller by approximately $1/\sqrt{2}$.
- Multi-dimensional binning and other physics asymmetries have also been measured (examples in the backup).
- Paper draft in preparation and Analysis Note written.
- Complementary 200 GeV transversity analysis involving di-pion interference fragmentation functions is also underway.

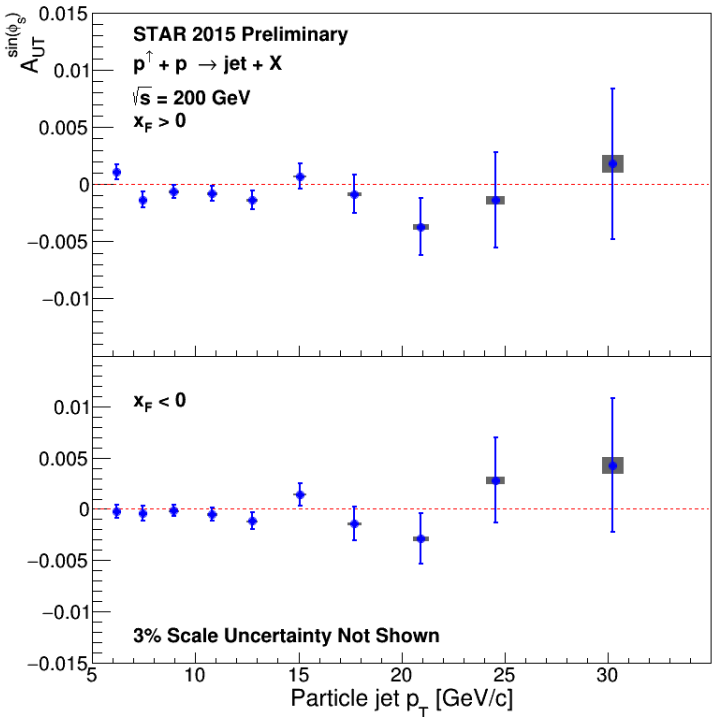
Some additional hadron+jet transverse single-spin asymmetries in 2015 200 GeV pp data

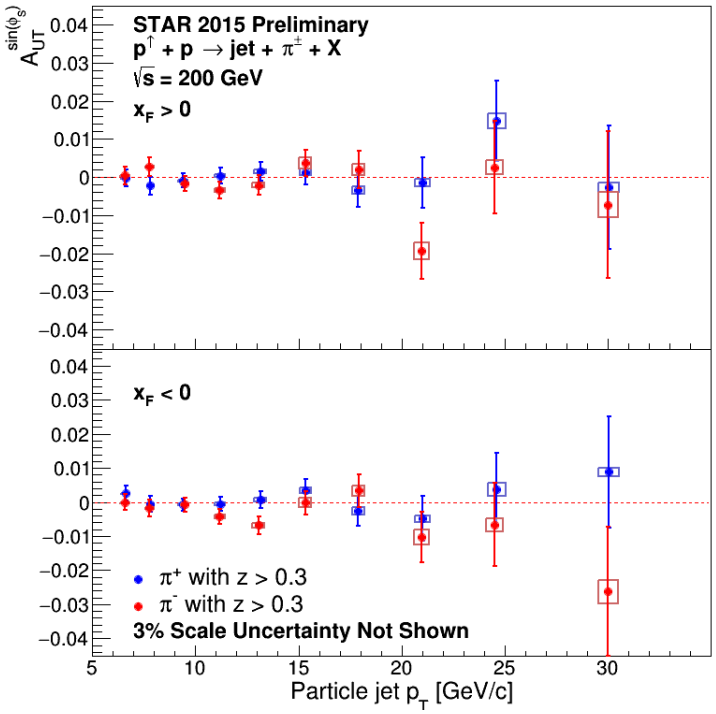




- K^+ Collins effect shows positive asymmetries for forward jets, consistent within the currently large statistical uncertainties with the π^+ asymmetries.
- Collins-like effect is sensitive to the linearly polarized gluons in a polarized proton.

Inclusive jet transverse single-spin asymmetries in 2015 200 GeV pp data



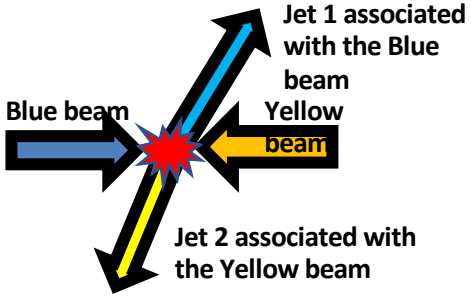


- Inclusive jet A_N is sensitive to the Sivers function via the twist-3 correlators;
  - Left panel shows all jets, primarily sensitive to the gluon Sivers effect;
  - Right panel only considers jets with high-*z* $\pi^{\pm}$ to enhance sensitivity to *u*- and *d*-quark Sivers effects.

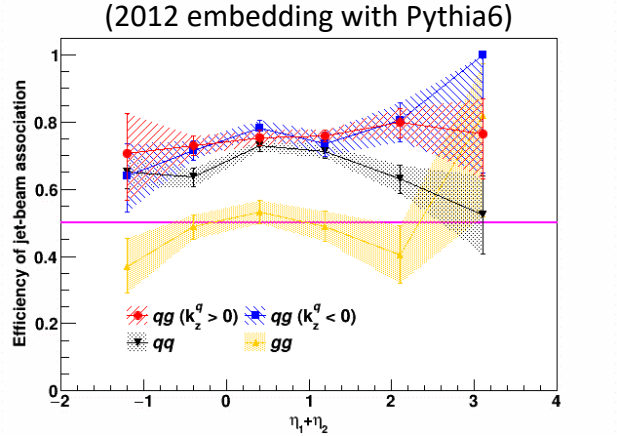
Jet-beam association

To figure out the "parton flow" from beam to jets, a jet-beam association is performed.

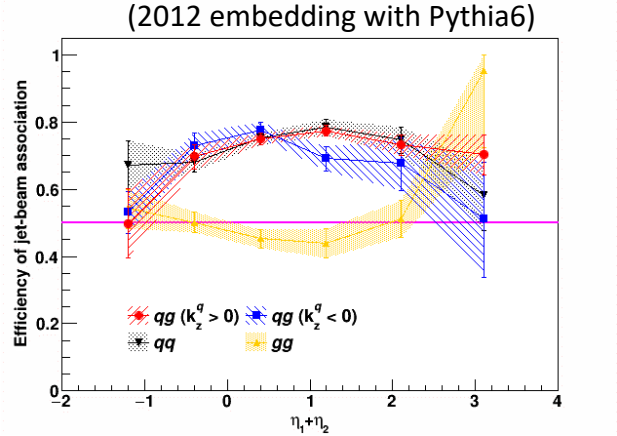
We assume the forward (backward) jet is more likely fragmented from the parton that comes out of Blue(Yellow) beam.



Association efficiency for Events taken by JetPatch2 Trigger (2012 embedding with Pythia6)



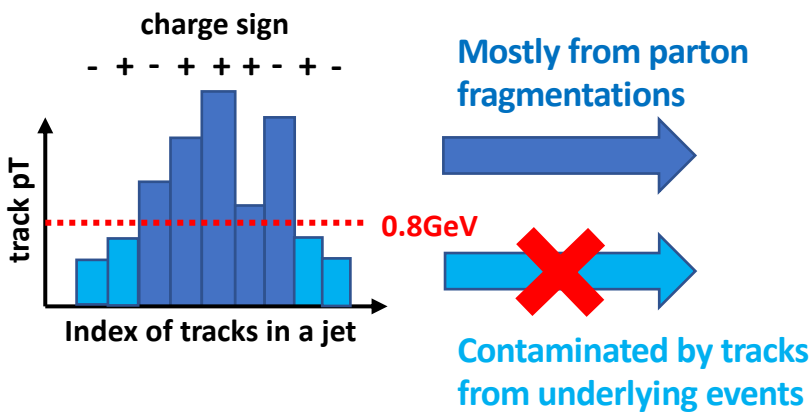
Association efficiency for Events taken by JetPatch1 Trigger (2012 embedding with Pythia6)



* The efficiency represents how often we get the association right.
* The error bar/band represents the statistical error.

Flavor tagging

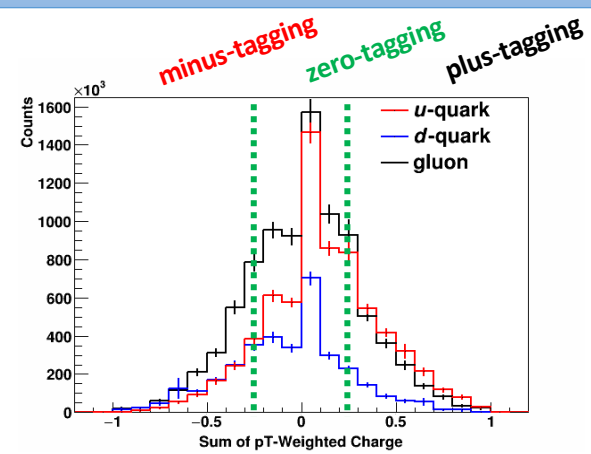
We employ **a method of tagging on the associated jets** to enhance the purities of ***u*-quarks and *d*-quarks** separately.



$$Q = \sum_{\substack{all\ the\ tracks \\ with\ pT>0.8GeV}} \frac{track\ pT}{jet\ pT} \cdot track\ charge$$

Data is divided into three groups:

1. **Plus-tagging** ($Q > 0.25$) : enhances the *u*-quark purity.
2. **Minus-tagging** ($Q < -0.25$) : enhances the *d*-quark purity.
3. **Zero-tagging** ($-0.25 < Q < 0.25$) : *u* /*d* fractions are more balanced than the other two taggings.

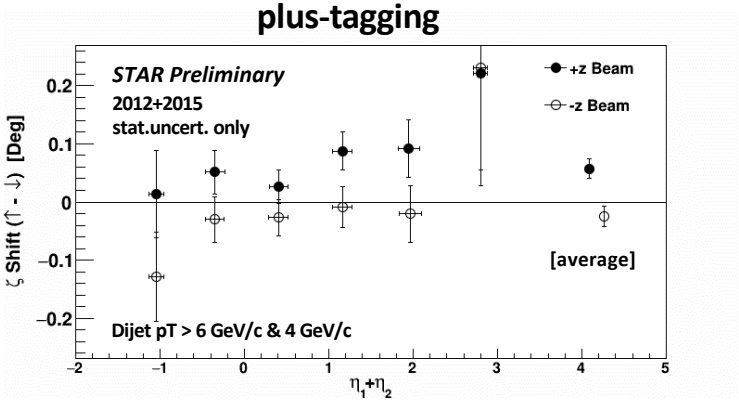


Distribution of *Q* for Events taken by JetPatch2 Trigger (2012 embedding with Pythia6)

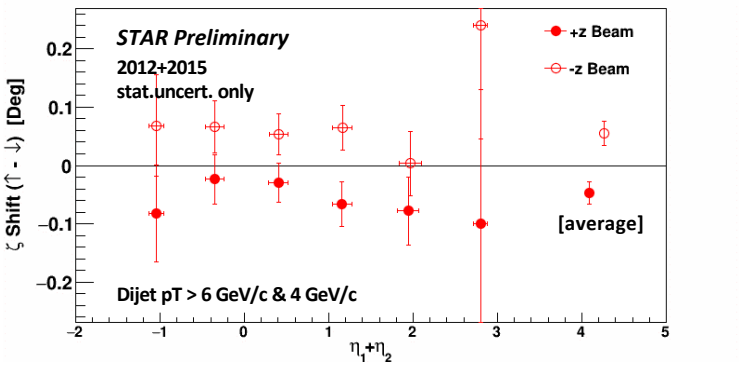
2012+2015 data — dijet Sivers asymmetry

- **Asymmetries** with **associated statistical uncertainties** measured **in STAR coordinate system**.
- The points in the far right ([4,5] bin) represent the average.

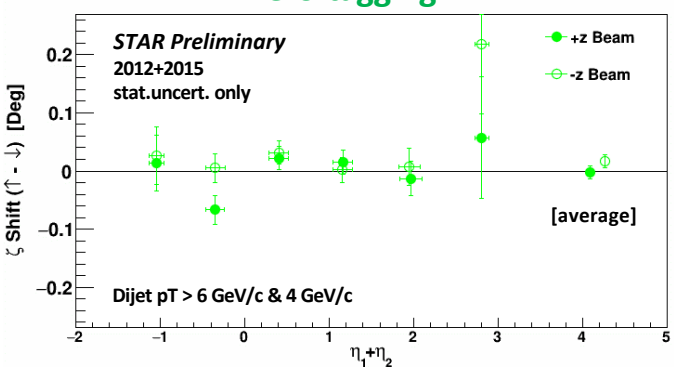
plus-tagging



minus-tagging



zero-tagging



- **Some expected features of the signals are reflected in the Data !**
  - ✓ Separation between Blue Beam and Yellow Beam
  - ✓ Blue Beam and Yellow Beam measurements are symmetric about (0, 0), e.g., for **plus** vs. **minus** tagging.
- **Data points are mostly one-sided from the x-axis for plus-tagging and minus-tagging.**
- **Zero-tagging is consistent with zero.**

Converting the $\Delta\zeta$ result to a $<k_T>$ result

The $<k_T>$ is the key information of the Sivers asymmetry.

To get an estimate of the $<k_T>$, we need to convert the $\Delta\zeta$ result to a $<k_T>$ result. Since $<k_T>$ is a parton level quantity, we will need to correct the pT of detector jets to parton level.

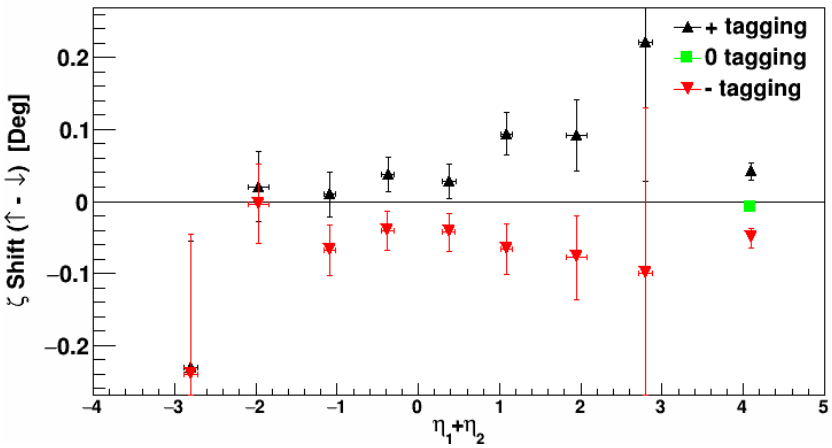
Steps for estimating the corresponding $<k_T>$ for $\Delta\zeta$:

1. **Correct detector jet pT to parton pT.**
2. **Use simple modeling of $<k_T>$, calculate $\Delta\zeta$ with corrected pT, and get $\Delta\zeta$-$<k_T>$ correlation.**
3. **Convert the $\Delta\zeta$_vs_η_1+η_2 results to $<k_T>$_vs_η_1+η_2 results.**

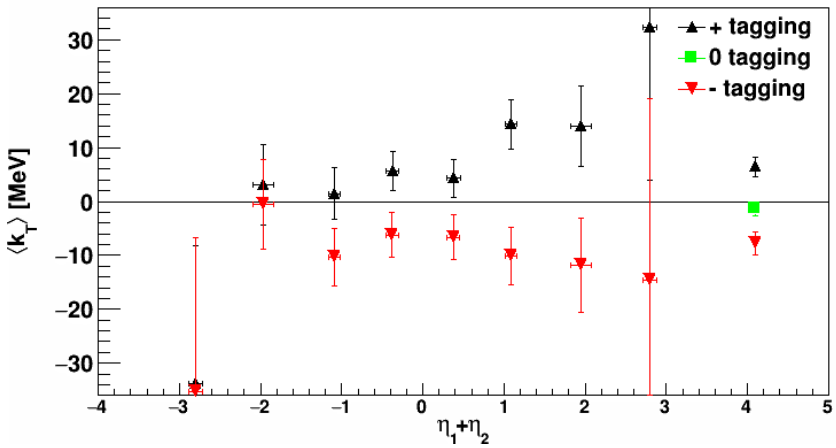
Converting $\Delta\zeta$ to $<k_T>$

$$<k_T> = \Delta\zeta \ / \ \text{slope}$$

$\Delta\zeta$ result



$<k_T>$ result

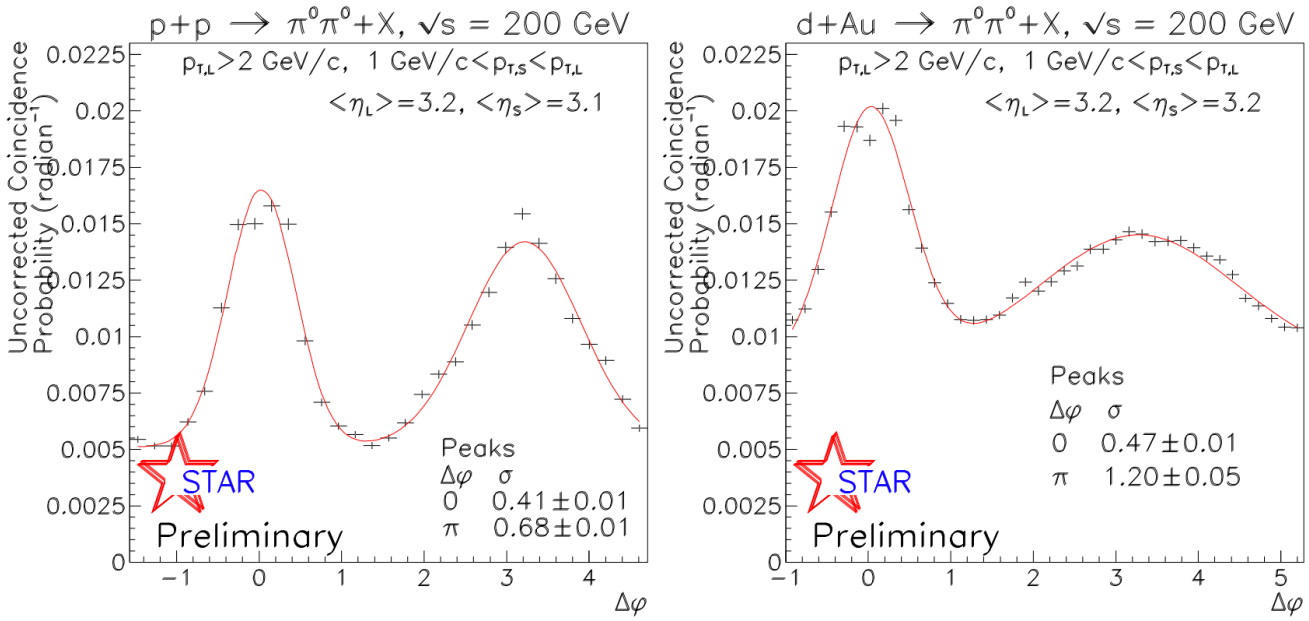


With the simple kinematic model, $<k_T>$ is estimated to be around +6 MeV for the plus-tagging, and -8 MeV for the minus-tagging on average.

Really tiny signal accessed through the STAR detector!

p+p, dAu Run8 di-π^0 correlations

ref:
arXiv:1109.0649



dAu results show a factor of two larger background than pp results in Run8.

π° A_N in pp, pAl and pAu at 200 GeV

$$\frac{A_N(pA)}{A_N(pp)} = A^P$$

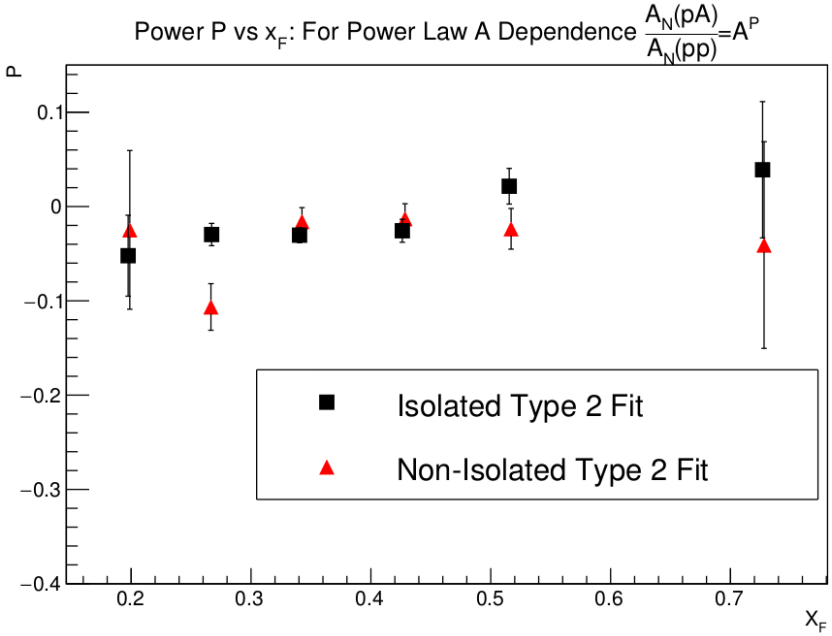
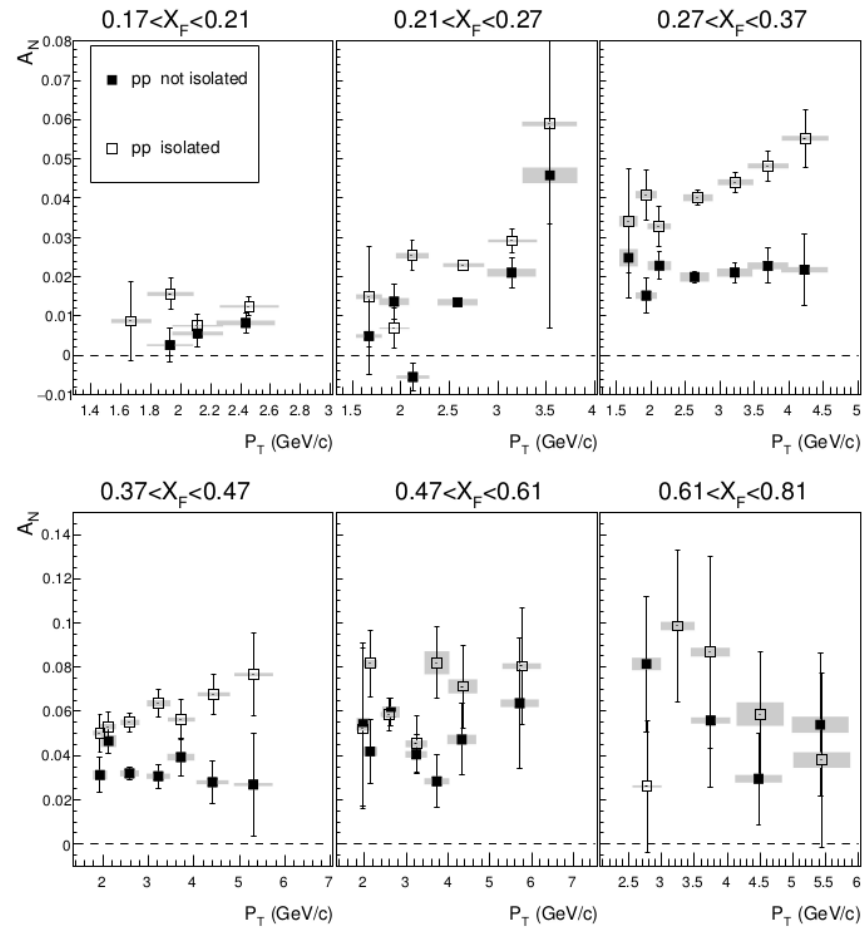


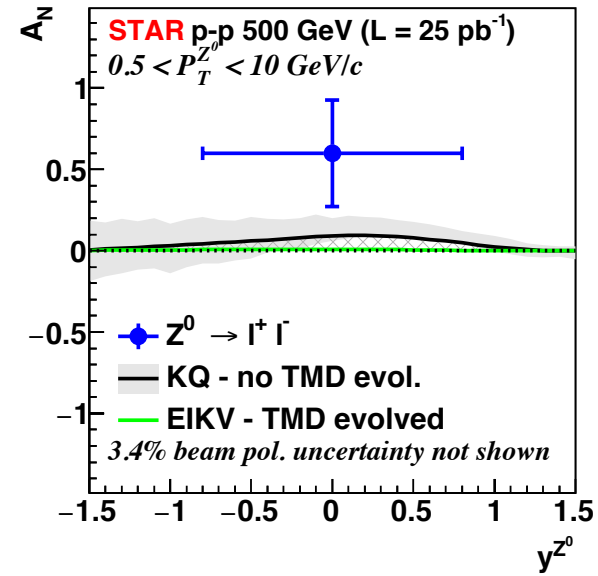
FIG. 13. This plot compares the Nuclear A dependence of A_N for events with isolated π^0s and events with non-isolated π^0s. The exponent P of the nuclear A dependence is shown as a function of X_F. The power is defined in Eq. 9. The points shown are averaged over the full p_T range with a Type 2 fit at each p_T and X_F similar to the points of Fig. 9.



- P is near zero and nearly independent of X_F.
- Isolated pion production has significantly larger transverse asymmetry that non-isolated
- production.
- P is similar for isolated pions and non-isolated pions.

Z^0 bosons - motivations

PRL 116, 132301 (2016)

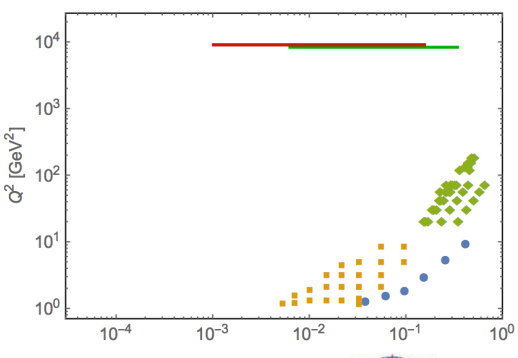


- Differential Z^0 cross section is used in global fits to constrain TMDs
  - RHIC data can constrain large x!
- TSSA of weak bosons sensitive to Sivers sign-change and TMD evolution effects
  - Z^0 kinematics easy to reconstruct compared to Ws

Quark unpol. TMD: measurements

Z production@ LHC

Z production@ Tevatron



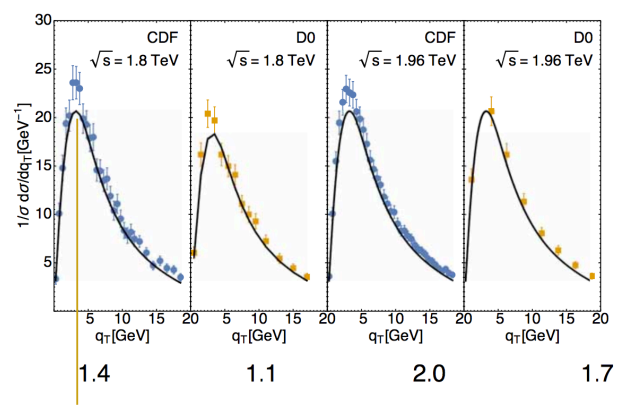
Drell-Yan@ Fermilab

SIDIS@ hermes

SIDIS@ COMPASS

Alessandro Bacchetta
INT Program INT-17-3

Z-boson data



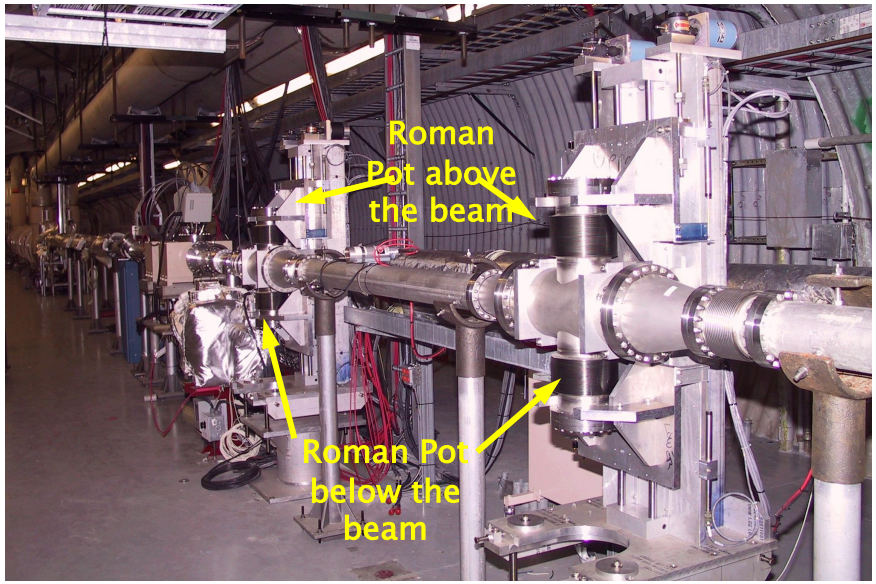
the peak now is at 4 GeV

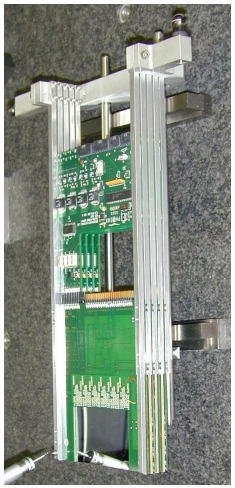
Most of the χ^2 due to normalization, not to shape

Total cross sections and diffraction in pp at RHIC (with detection of forward protons in Roman Pots)

Experimental setup at STAR uses pp2pp experiment's Roman Pots, which were integrated with STAR in 2009

1. The Physics Program includes:
   - Elastic and total cross section in proton – proton scattering
   - Central Exclusive Production (CEP), exotic searches
   - Central Production (CP)
   - Single Diffractive Dissociation (SDD)
2. The experience gained is very important for EIC, where the crucial measurements include the detection and measurement of forward protons:
   - Producing physics result with forward proton measurements
   - Integration with the major detector (STAR)
   - Very important operational experience in the collider environment:
     - Optics optimization for the forward proton measurement
     - Integration with the accelerator (Roman Pots are part of the beam line)
     - Accelerator controls
     - Accelerator vacuum
     - Accelerator and radiation safety

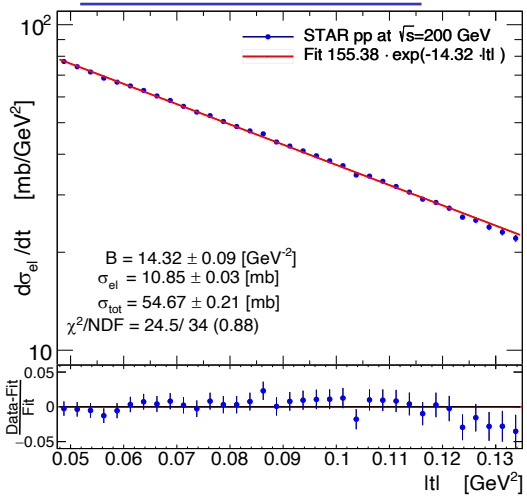




Roman Pot and Si detector package

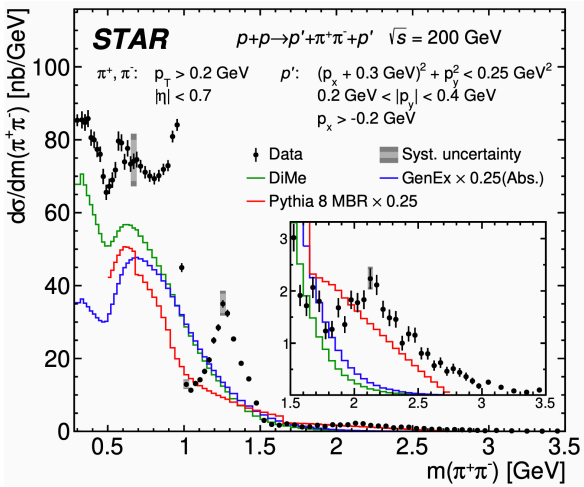
Results from Roman Pots

arXiv:2003.12136



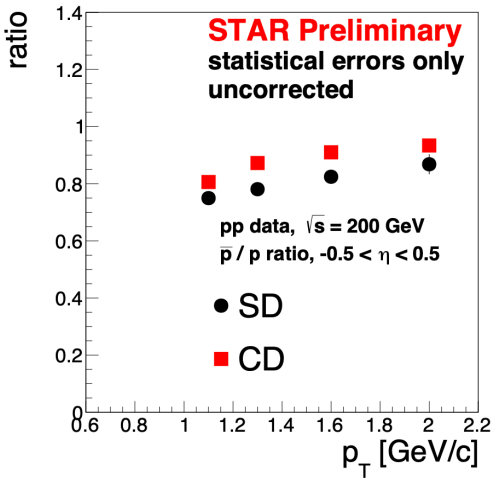
Elastic scattering σ_{tot}, σ_{el}, σ_{inel}, B.
(submitted to PLB)

arXiv:2004.11078



Central Exclusive Production
(submitted to JHEP)

arXiv:1906.04963

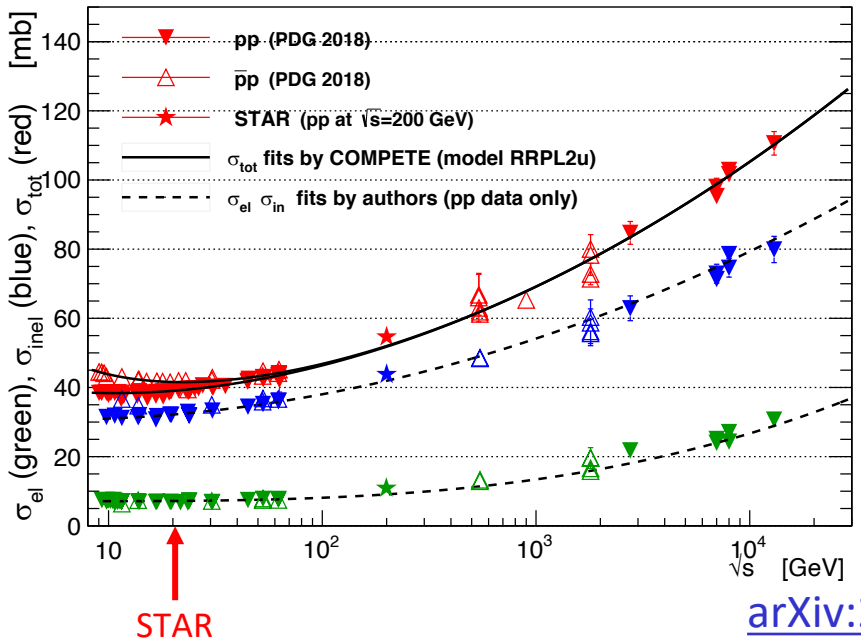


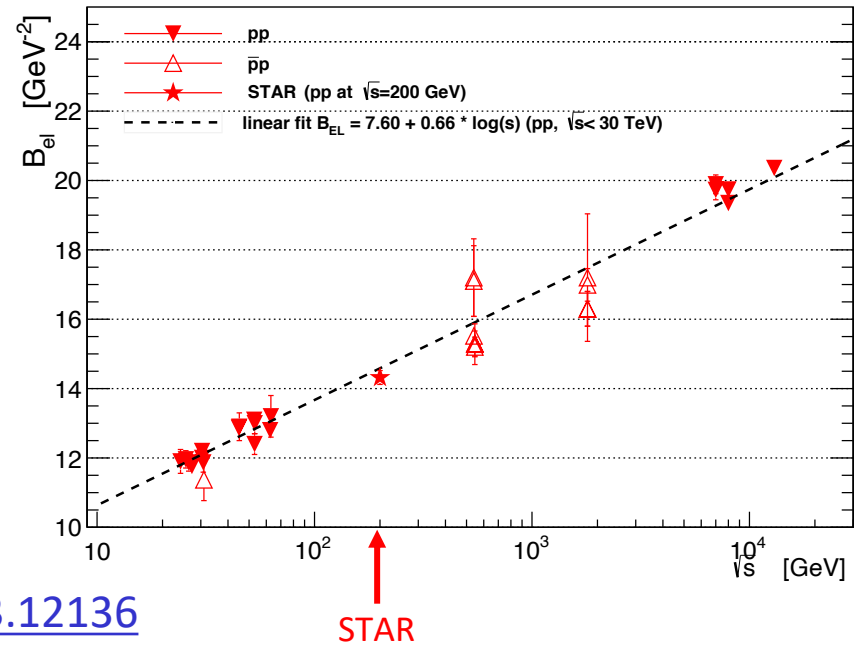
Particle ratios in CD and SDD
In preparation for publication

Other papers published and in preparation

1. Single spin asymmetry A_N measurement in pp at √s = 200 GeV (PLB 719 2013, (62-69)
2. Measurement of pp elastic cross section at √s =510 GeV
3. Measurement od double spin asymmetry A_{NN} in pp at √s = 200 GeV
4. Particle production in CP and SDD at √s = 200 GeV

Elastic and total cross sections comparison of STAR Data with world data





arXiv:2003.12136

Total, elastic and inelastic cross sections

B-slope of the elastic cross section

Key performance requirements

Charged sign separation for cold QCD physics

Momentum resolution 20-30% for peripheral heavy ion physics

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

STAR Forward Silicon Tracker – status and plan

- Detector Module
  - Ongoing cosmic ray test of the 1st half prototype. Working on improving the quality of mechanical structure and hybrid mounting. Plan to assemble two good prototype modules, test with cosmic rays and laser, before production

- DAQ
  - Crates and boards status examined in September 2019. No issue found.

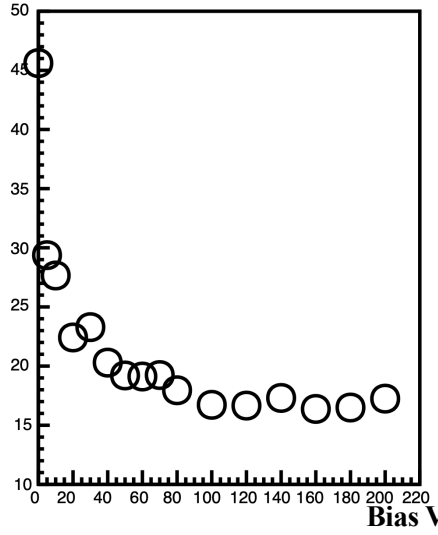
- Cooling System
  - cooling rack: coolant, parts and leakage seals ordered. Plan to turn the system back on after BNL reopens to assess the status.
  - cooling tubes: on-going test of plastic tubes following vendor's recommendation. Plan to look into radiation hardness and flexible metal tubes.

- Integration
  - Conceptual design exists, new designer hired by BNL started first week in May. Plan to finish the design by Aug. 2020, and produce all the parts by Dec. 2020.

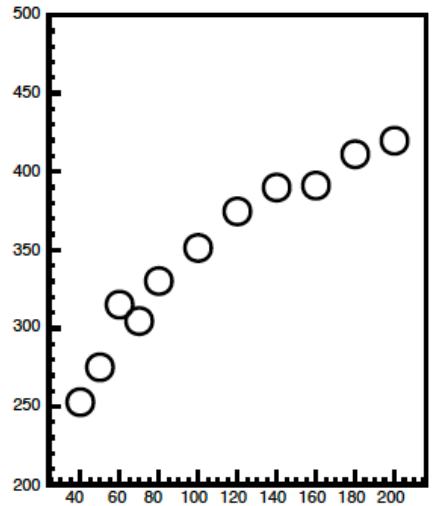
- Online and Offline Software
  - Plan to adapt existing IST software structures.

STAR Forward Silicon Tracker – prototype module

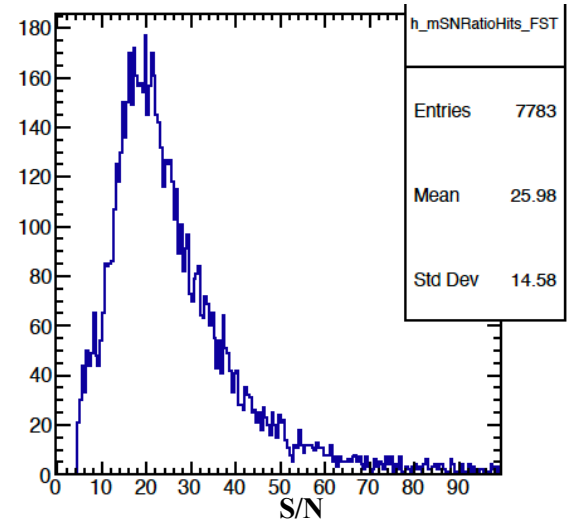
Noise



Signal

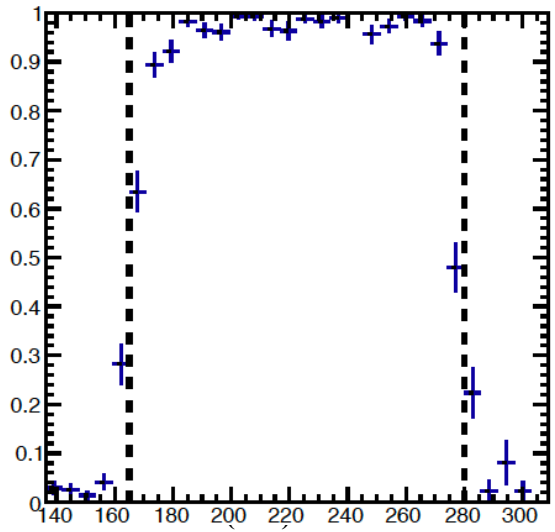


Signal/Noise at 200V

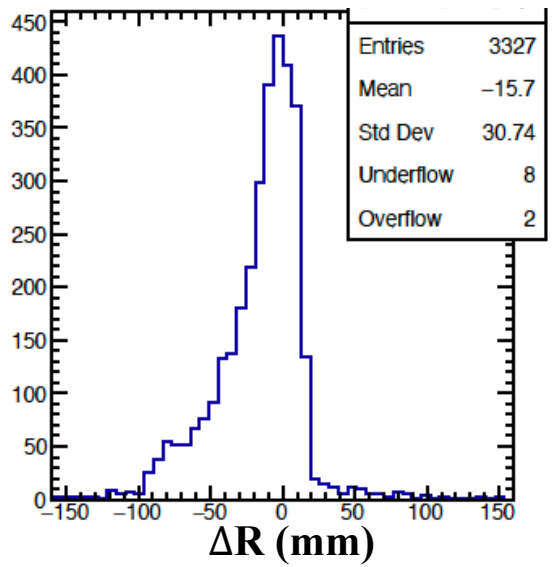


- On-going cosmic ray test of the 1st FST prototype with outer sensors
- Testing of inner sensors planned in June-July

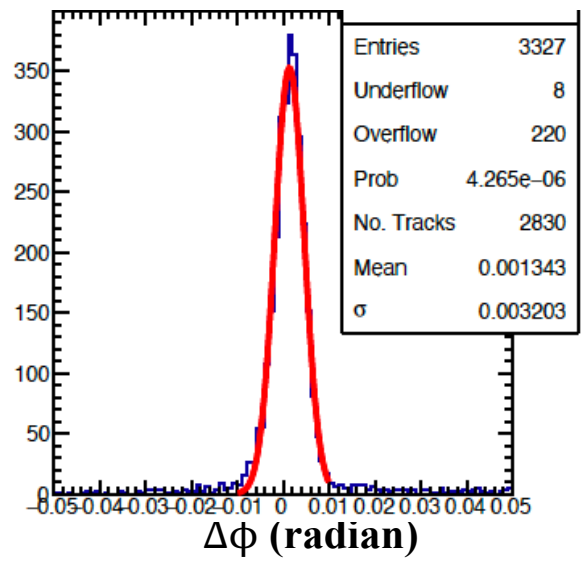
Hit Efficiency



Residual in R



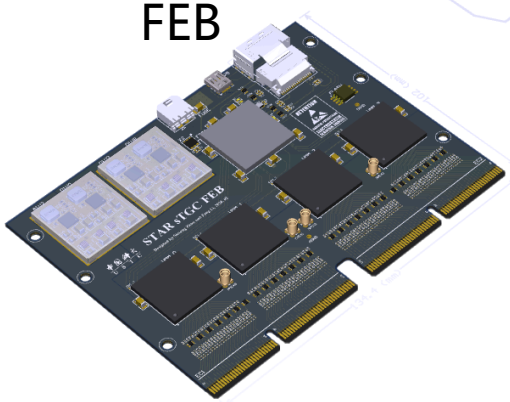
Residual in ϕ



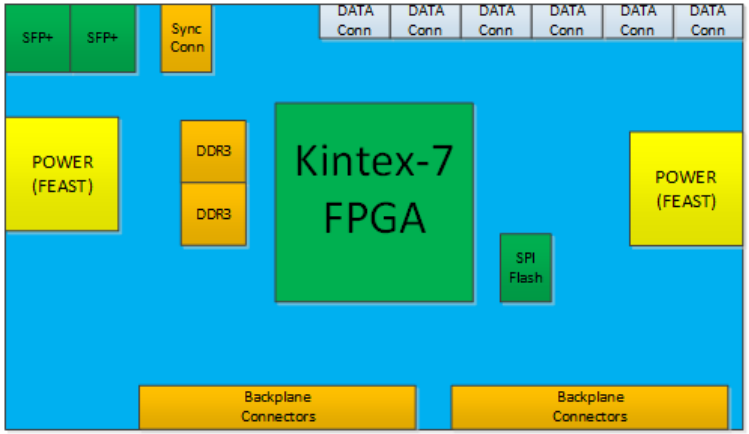
sTGC electronics

- Based on VMM chips. The chips will be purchased by BNL through CERN. After the order is placed, 20 weeks are needed for wafer production.
- 4 chips per FEB, 96 FEB in total, 16 ROD in total.
- USTC group is designing the board. FEB prototype designation finished, in soldering. ROD in designation.
- BNL will work on the commissioning and integration.
- Efficient communication between BNL and USTC. Before ROD was sent to BNL for commissioning, Vivado project will be shared for exercise.
- Plan to use video to record the STAR environment for USTC group's reference.

FEB



ROD



The rest of HCal parts:

Rutgers – master plates , raw materials in hand but production has not started.

UCLA – electronics shop is ready for assembly of SiPM boards. Test/calibration setup prepared, used for 10% pre-production. Polishing setup exist to move Sc tiles polishing/painting from planned at BNL.

VALPO – preparing scintillation tile production setup at home, instead of planned work at BNL.

UKY – completed purchases of WLS and SiPMs. Preparing for FEE testing/calibration with IUCF.

UCR – will be sending students to UCLA to calibrate SiPM boards when ready. (most likely will not happen)

BNL (STSG) – shell for Hcal, not started

TEMPL - parts for shells and HCAL FEE interface plates. Indications there are no problems to produce these parts by requested dates., not started

ACU - continuing producing scintillation tiles at reduced speed.

DAQ for the STAR Forward Upgrade

- 3 different detectors require readout: **FST, STGC, FCS**
- FST
  - digitizer electronics boards (“ARM”) and readout multiplexers (“ARC”) re-used from the IST detector
  - crates, trigger cables & fibers also exist from IST
  - DAQ Receiver Boards and DAQ PCs also taken over from IST
  - Slow Controls and DAQ readout software need to be adapted from IST (simple task)
  - **pre-check of DAQ already complete** ⇒ system test once we have a prototype stave
- STGC
  - new frontend electronics designed in China
  - 5x custom DAQ Receiver Boards ordered (**Jul 1**); 5x DAQ PCs will be ordered and installed by **Aug 1**
  - expect electronics⇔DAQ integration, readout firmware, development, commissioning & software support once the first prototypes of the new electronics available (**Aug-Dec 2020**)
  - LV power supplies in design
    - prototypes - **Jun 1**
    - final version after tests - **Aug 1**
    - finished **Dec 1**

FCS

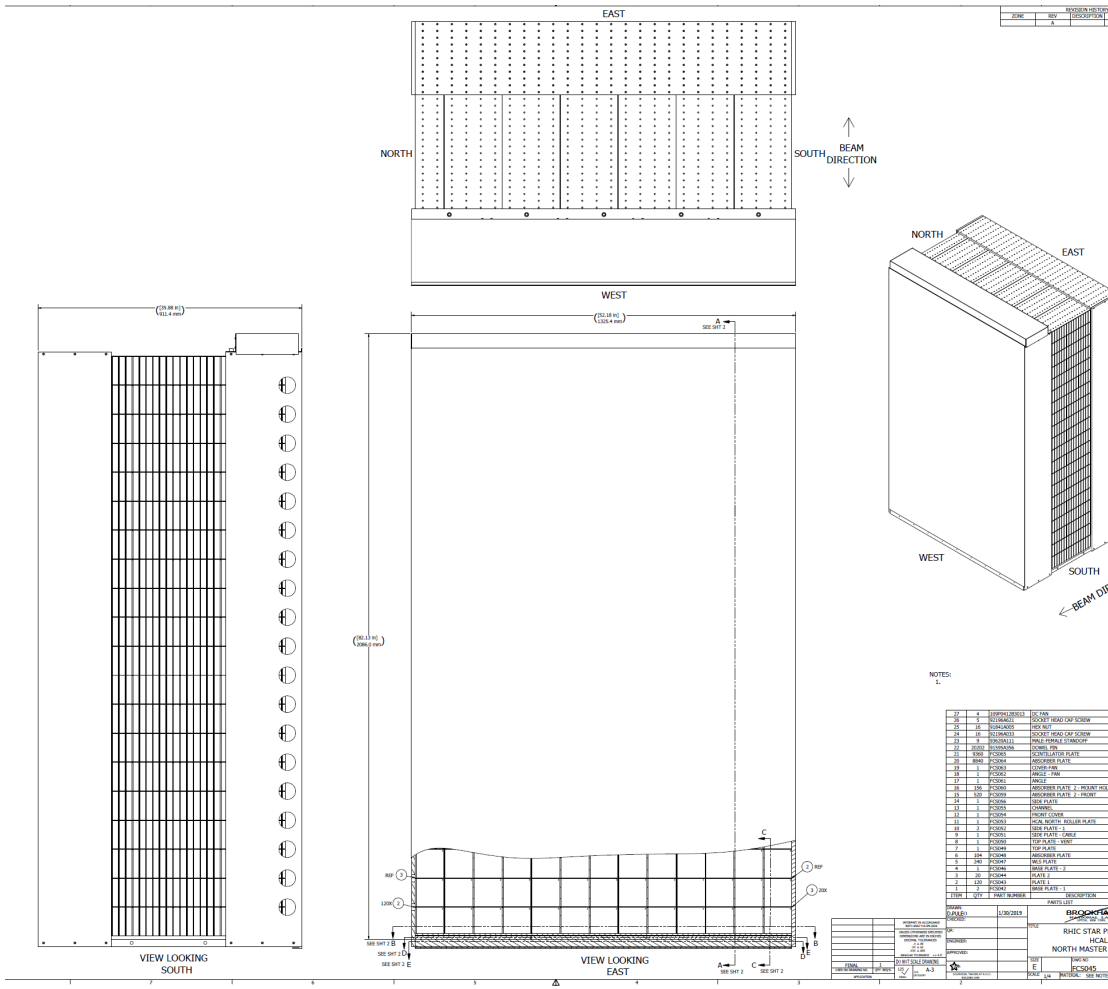
- Digitizer Electronics Boards (“DEP/ADC”)
  - all PCBs completed
  - boards currently in assembly ⇒ vendor expects **Jun 15**
  - Q&A & FPGA programming in the lab (after start-work); assembly into crates (6 weeks, completed by **Aug 1**)
- Trigger Electronics Boards (“DEP/IO” and “DEP/patch”)
  - all 5 required boards complete and at BNL
  - 1 board fully commissioned, 4 boards waiting for Q&A ⇒ **Aug 1**
- DAQ Receiver Boards
  - all required boards at BNL
  - firmware installation and commissioning is waiting for start-work (2 weeks, e.g. by **Jun 15**)
- DAQ PCs
  - all PCs installed, waiting for commissioning at start-work time (1 week, e.g. by **Jun 15**)
- Crates, Power Supplies, Fibers
  - all parts at BNL but still need some assembly & commissioning (2 weeks) ⇒ **Jul 1**

Installation into STAR

- we need access to the experiment to start installation tasks (2 weeks e.g. **Aug 1-15**)
  - fiber installation (FCS & STGC)
  - DEP electronics crates w associated power connections (FCS)
  - FEE board cabling
  - trigger system cabling
- system commissioning (2 weeks e.g. **Aug 15-31**)
  - potentially needs sporadic physical access to fix/improve hardware
- DAQ software debugging, FPGA firmware debugging, Trigger algorithm development will be ongoing and requires no physical access (**Sep+ 2020**)

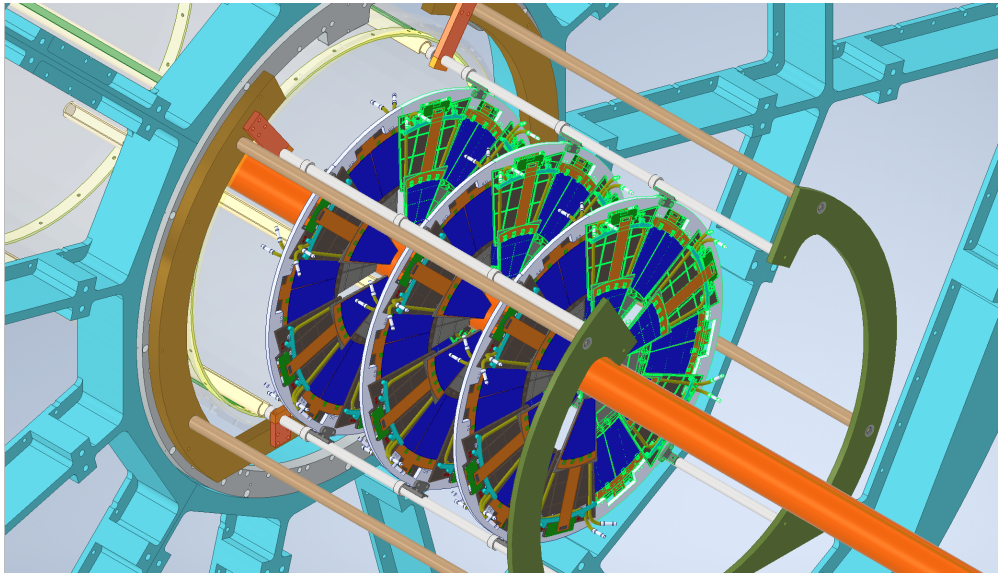
Integration – HCAL/EMCAL

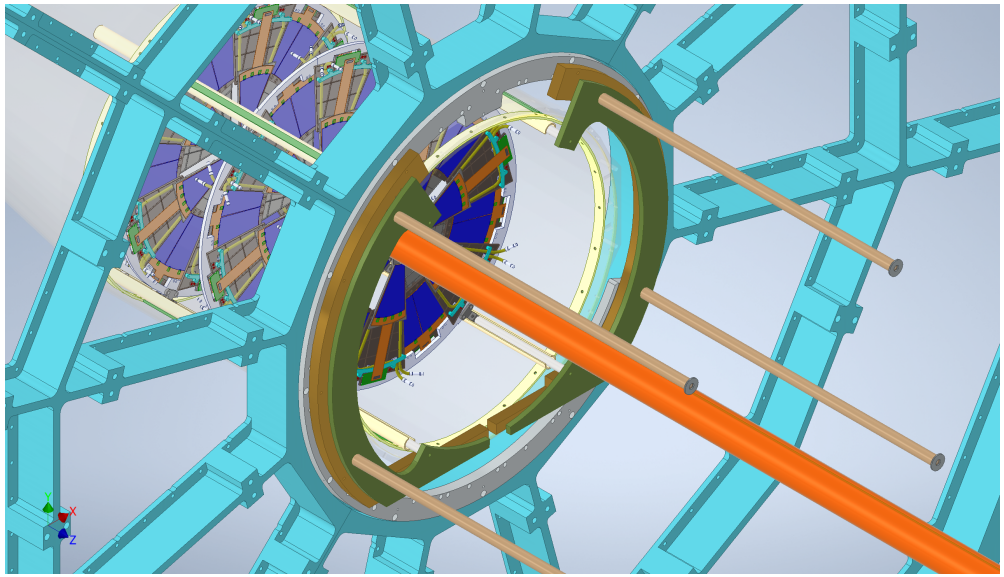
- EMCAL Mechanical Installation Complete
- HCAL Detail design - Complete
- HCAL Roller Plates installation - Complete
- HCAL Parts – in Production
- HCAL Installation – Oct 2020 to Feb 2021
- EMCAL Electronics installation and commissioning: October to November 2020



Integration FST

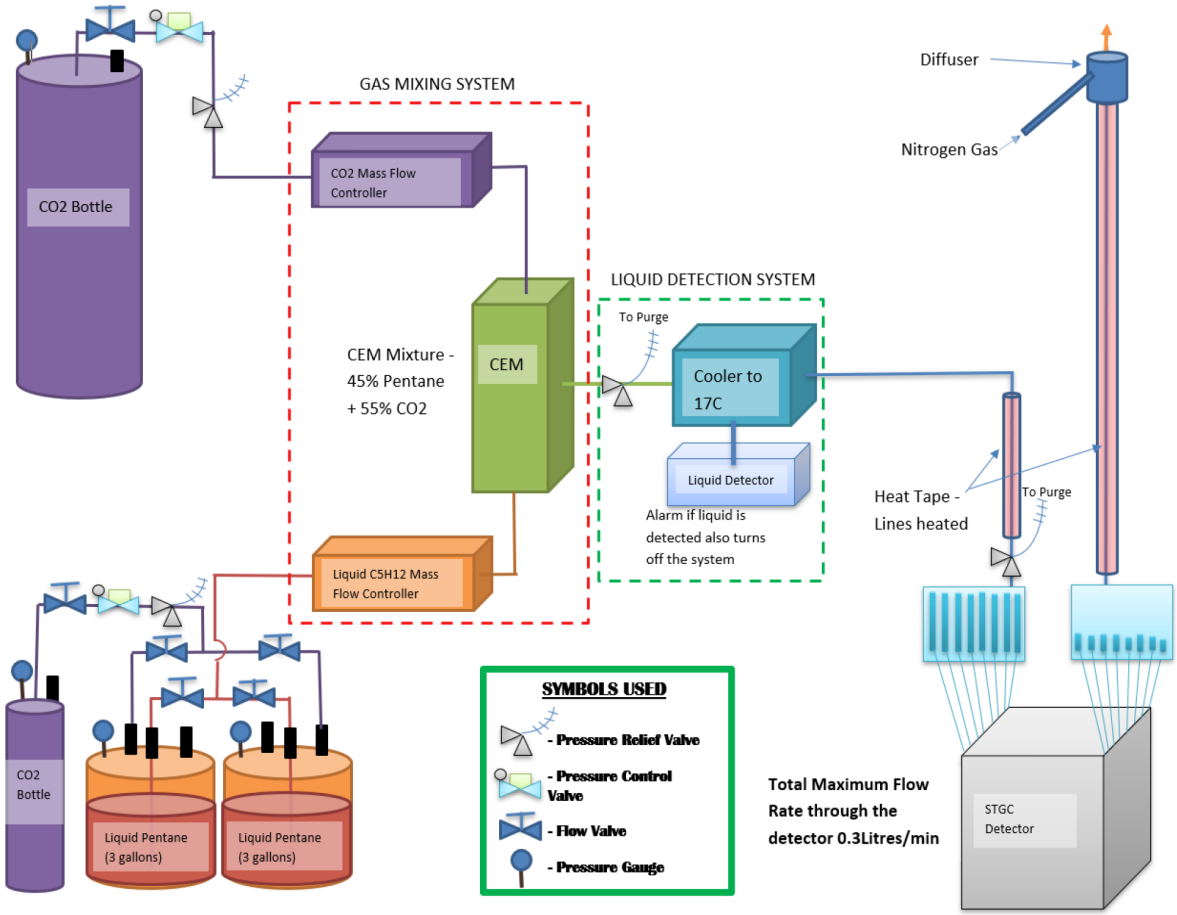
- Conceptual Design – Complete
- Detail Design – August 31, 2020
- Parts Fabrication: October 31st, 2020
- Mockup testing inside cone: Dec, 2020
- Novec Cooling System – August 2020
- Detector installation: 2021 Shutdown





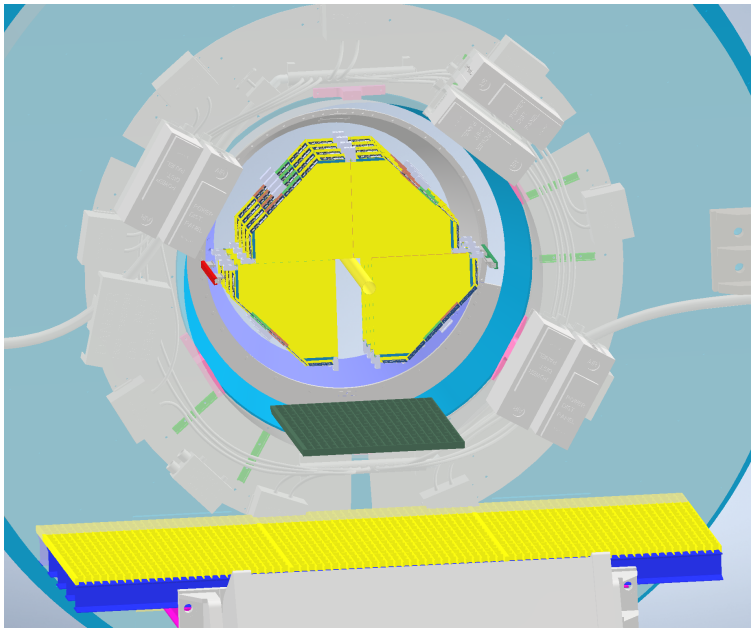
Integration sTGC gas system

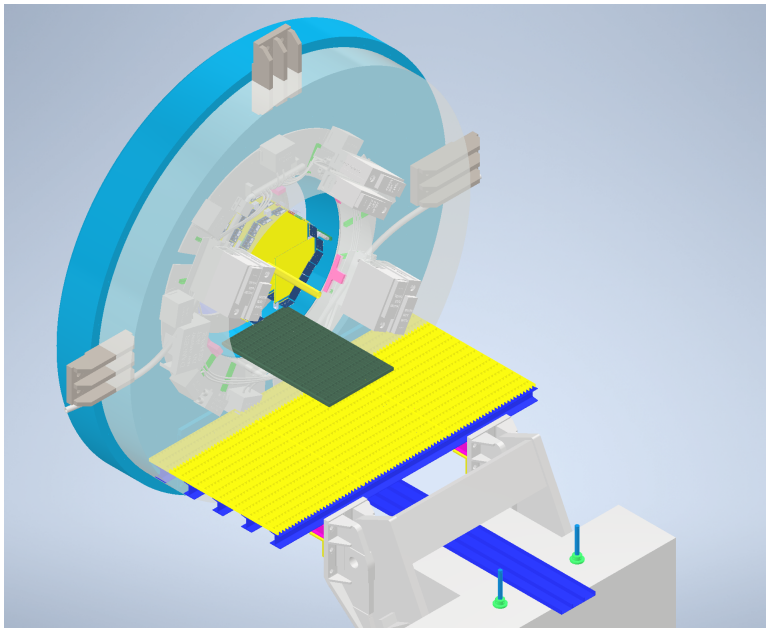
- Gas System Design: Complete
- Gas System Design Review: Complete
- Gas System Interlocks Design Review: Complete
- Parts: Most parts in hand. Others on Order. Delays due to COVID-19.
- Expected Completion Date: Depends upon when we can start working on it. Under current circumstances it seems to be August, 2020.



Integration sTGC

- Conceptual Design – Complete
- Detail Design : September 30, 2020
- Parts Fabrication: December 30, 2020
- Mockup /testing: January, 2021
- Detector installation: 2021 shut down





Forward software milestones & timeline

- Tasks related to small-strip Thin Gap Chambers (sTGC):
  - Develop cluster finding algorithm which includes information from x, y and diagonal strips (~June 2020)
  - Algorithm for efficiently constructing space points & rejecting ghost hits using diagonal strip information (~July 2020)
  - Develop an sTGC slow simulator (~summer 2020)

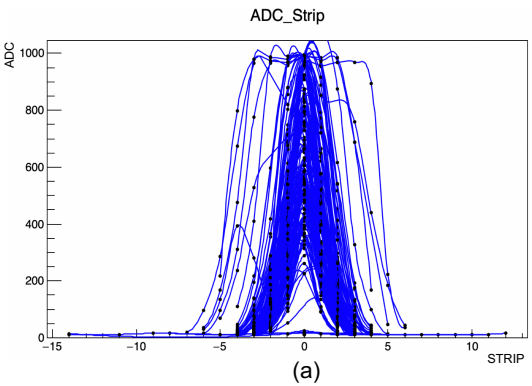
- Tasks related to Forward Silicon Tracker (FST):
  - Optimize and finalize z-location of detector planes (~May)
  - Develop an FST slow simulator (~ summer + fall 2020)

- Forward Tracking, reaching v1.0:
  - Full integration into STAR software framework (~June 2020)
  - Integration with the individual fast/slow simulators, currently GEANT input (fast simulator ~June 2020, slow simulators ~summer/fall 2020)
  - Demonstration of performance in p+p and Au+Au events using Pythia & HIJING simulation (partially complete, ~June/July 2020)
  - Ongoing optimization work (improving speed and tracking performance)

- Integration Tasks (~fall 2020 – 2021):
  - Data acquisition “plumbing” software – connecting raw detector readout to STAR event reconstruction framework
  - Matching forward tracks to calorimeter hits. Explore possibility of re-fitting track momentum with energy as measured by calorimeter
  - Primary vertex finding with only the forward detectors (to allow running at high rate without mid-rapidity detectors)

Small-strip Thin Gap (sTGC) related items

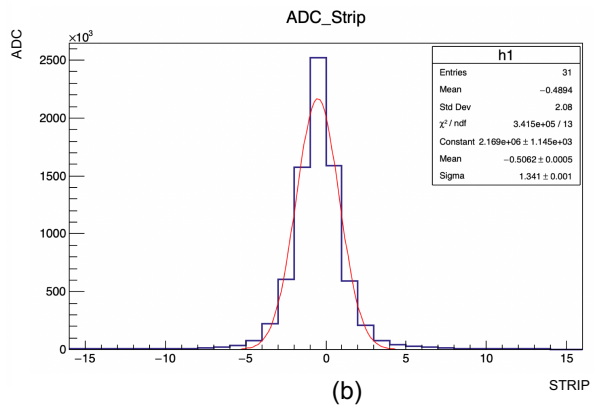
- Tasks related to small-strip Thin Gap Chambers (sTGC):
  - Update fast simulator with final pentagon design including diagonal strips (~May-June 2020)
  - Develop cluster finding algorithm which includes information from x, y and diagonal strips (~June 2020)
  - Algorithm for efficiently constructing space points & rejecting ghost hits using diagonal strip information (~July 2020)
  - Develop an sTGC slow simulator (~summer 2020)



(a)

1. For each event, get the TB of MaxADC.
2. At same TB, the ADC distribution varies with the strip.

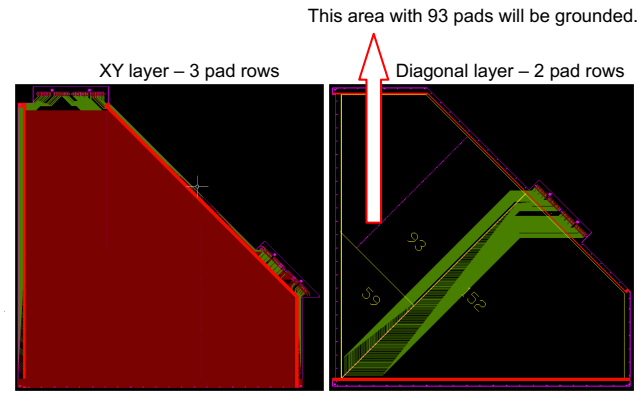
Use data from prototype testing to guide the development of the full (slow) simulator and cluster finder.



(b)

The sumADC distribution of each event at the same the strip.

STRIP number >3sigma ➔ STRIP>=4

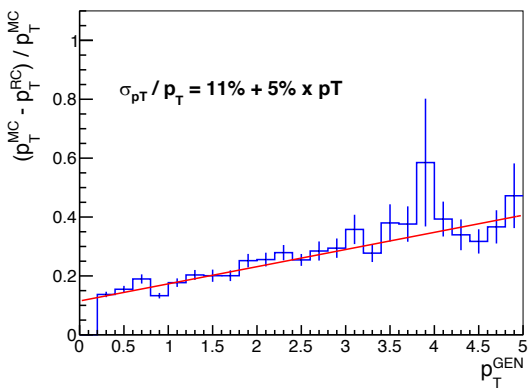


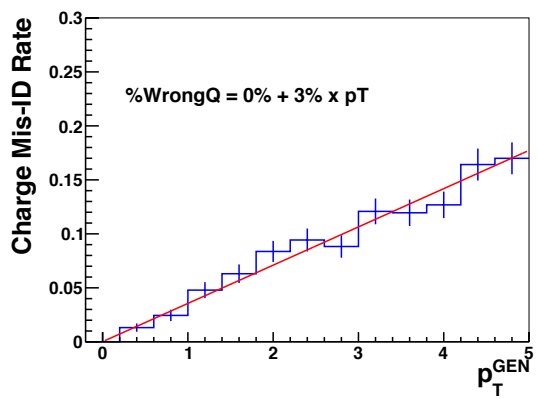
Fast simulator (digitizes GEANT hits) needs to implement the pentagonal design including the subdivisions in the XY + diagonal layers

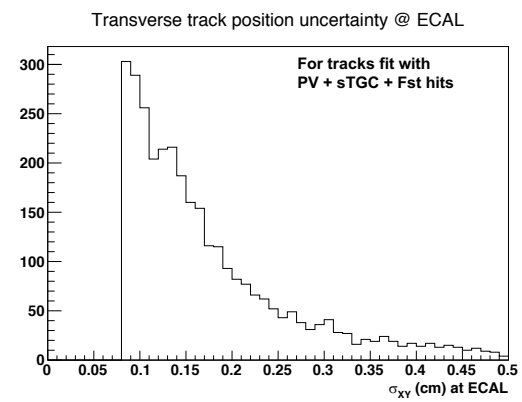
Forward software milestones & timeline

- Forward Tracking, reaching v1.0:
  - Full integration into STAR software framework (~June 2020)
  - Integration with the individual fast/slow simulators, currently GEANT input (fast simulator ~June 2020, slow simulators ~summer/fall 2020)
  - Demonstration of performance in p+p and Au+Au events using Pythia & HIJING simulation (partially complete, ~June/July 2020)
  - Ongoing optimization work (improving speed and tracking performance)

Tracking performance in low multiplicity (p+p like events) already well establish.
Future studies - optimize iterative tracking for maximum performance in higher multiplicity events (Au+Au)

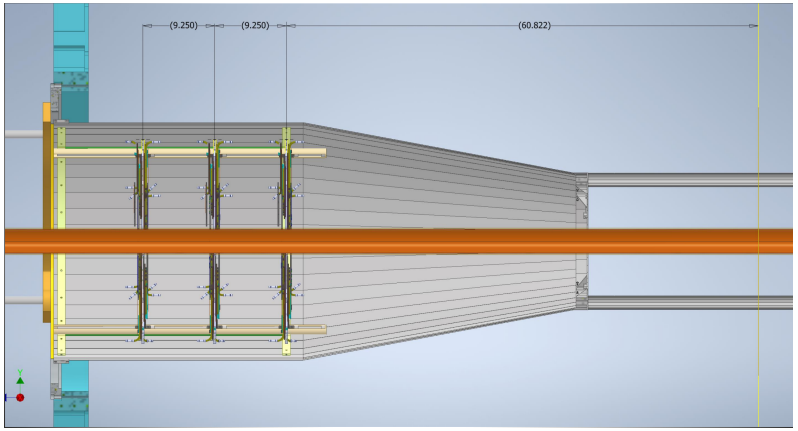






Forward Silicon Tracker

- Tasks related to Forward Silicon Tracker (FST):
  - Optimize and finalize z-location of detector planes (~May)
  - Develop the FST slow simulator (~ summer + fall 2020)
  - Prepare framework for mis-alignment of ideal silicon geometry to provide precise mirroring of “real” geometry as installed in STAR.

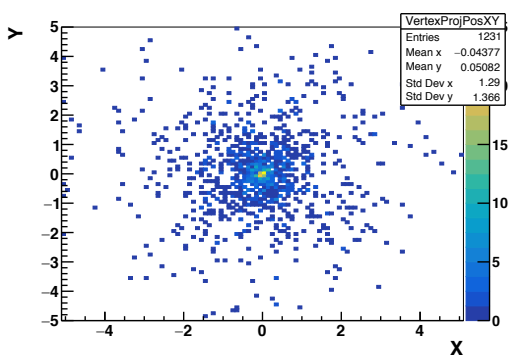


Optimize Z-location of silicon disks to maximize performance of full tracking system (FST + sTGC)

Forward software milestones & timeline

- Integration Tasks (~fall 2020 – 2021):
  - Data acquisition “plumbing” software – connecting raw detector readout to STAR event reconstruction framework
  - Matching forward tracks to calorimeter hits. Explore possibility of re-fitting track momentum with energy as measured by calorimeter
  - Primary vertex finding with only the forward detectors (to allow running at high rate without mid-rapidity detectors)

Estimate of Primary Vertex location (XY) with forward tracks only. Does not include beam-line constraint and does not use full simultaneous fit. Room for significant improvement



Data structures for the raw data formats read from detectors

```
class StFtsStgcHit : public StObject {
   ...

 protected:
        UShort_t mRdo=0;
        UShort_t mSec=0;
        UShort_t mAltro=0;
        UShort_t mFEE=0;
        UShort_t mCH=0;
        UShort_t mNTimebins=0;
        TArrayS* mAdcs=0;
        TArrayS* mTimebins=0;

        ClassDef(StFtsStgcHit,0)
};
```