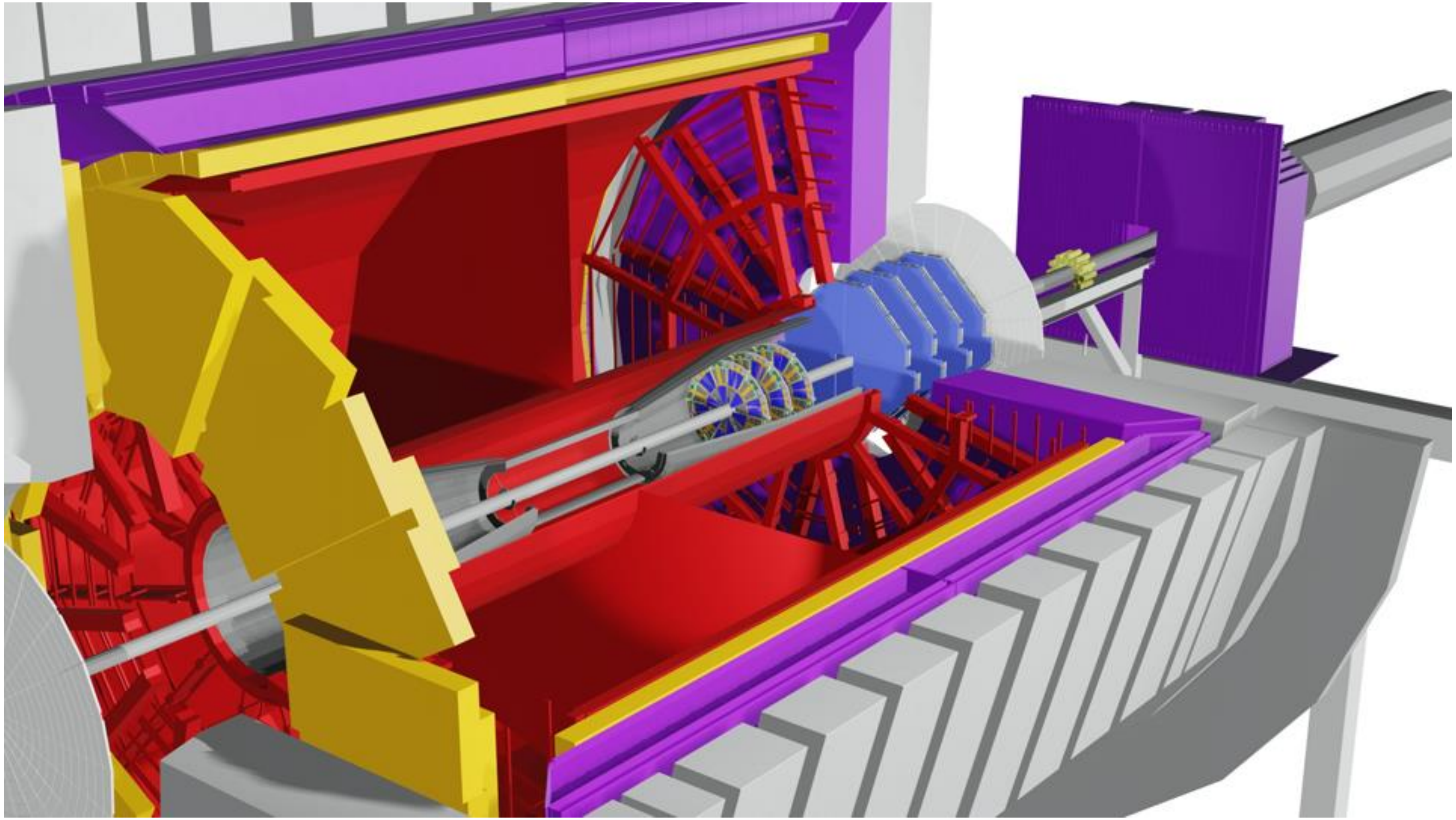
STAR forward upgrades – small-Strip Thin Gap Chamber (sTGC)



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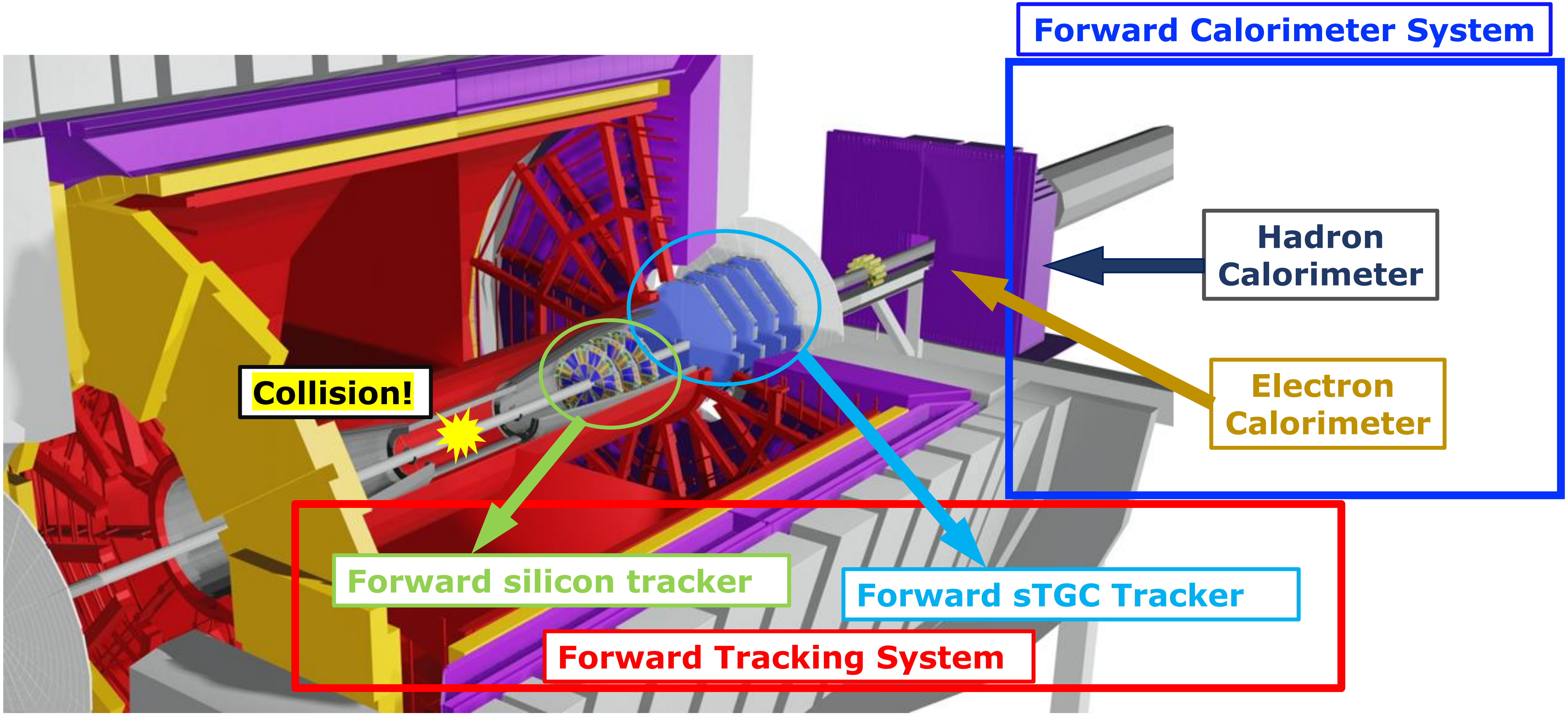
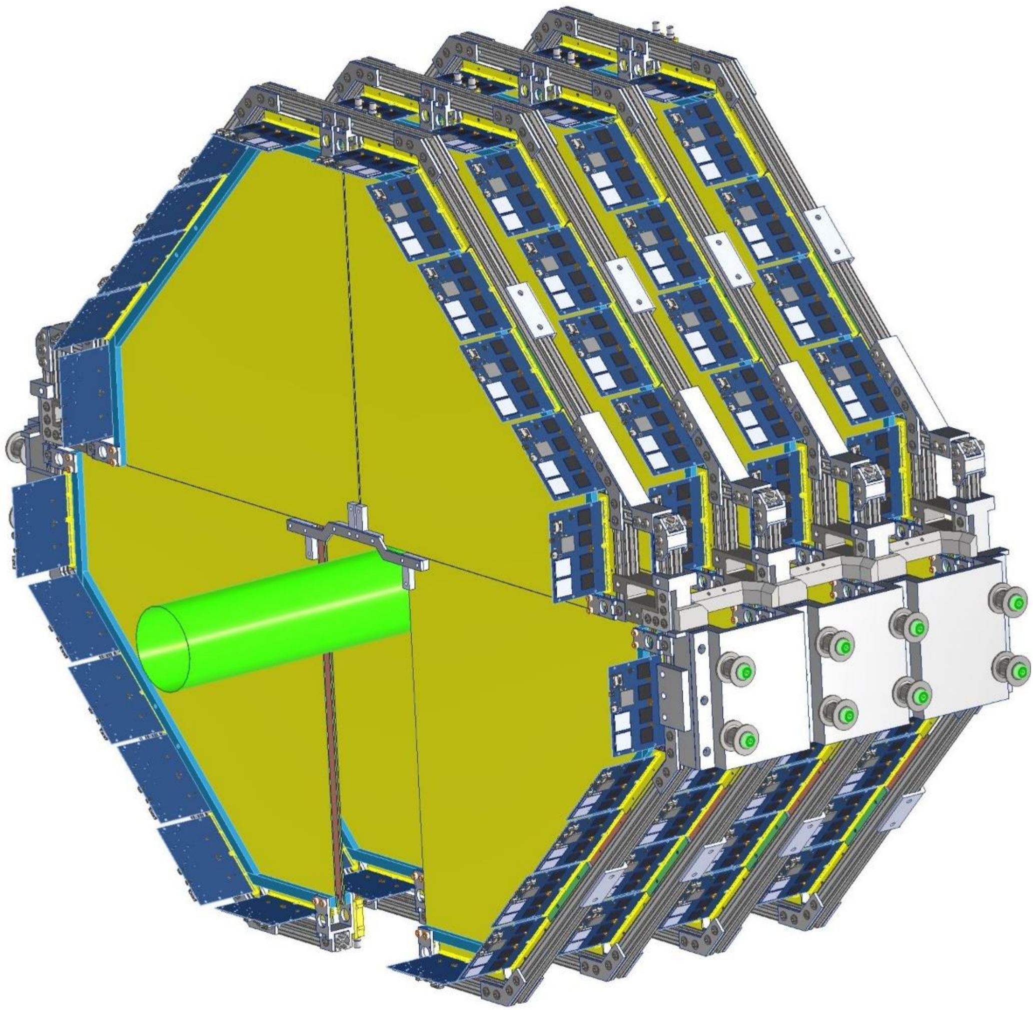
August 8, 2020

Forward upgrade @ STAR



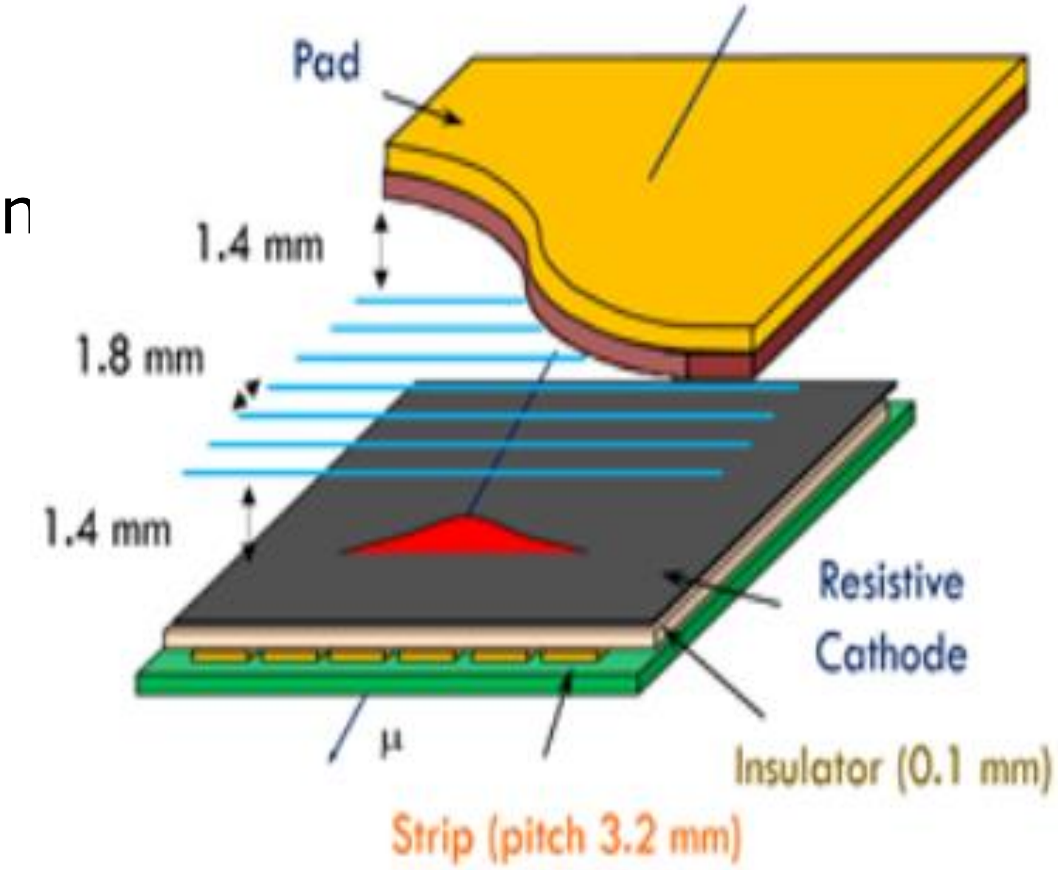
sTGC basics

- The sTGC is a detector system currently being tested and assembled as an upgrade to STAR
- The technology has been around for decades, but has recently been used at ATLAS
- Potential use in the Electron ion Collider
- Pros: low cost and low material budget
- cons: good, but not incredible position resolution and only useful in low particle flux



sTGC construction

- Sealed volume filled with gas
- Anode (-HV): 50 μm Gold plated tungsten wires held at a potential of ~ -2900 V
- Cathode(Ground): graphite epoxy mixture with high resistivity
- Sprayed on G-10 (fiberglass) insulator
- Readout: Small copper strips, perpendicular to anode wires, outside of cathode, printed on single large PCB
  - Wires and pads may also be read out, but are not used here



sTGC process

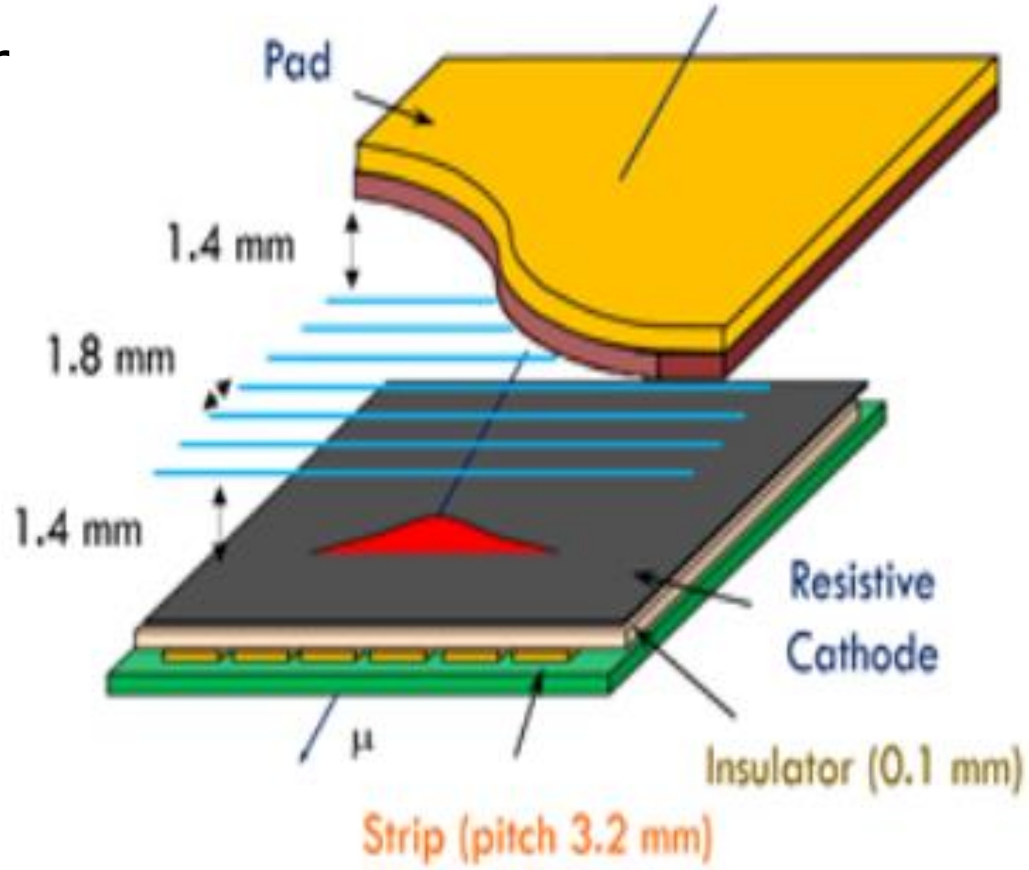
- Essentially a Multi-Wire Proportional Chamber (MWPC)

- MWPC: Invented in the 60s to replace bubble chambers
  - At least three orders of magnitude faster
  - The STAR TPC is an example of a MWPC
  - 1992 Nobel prize

- Charged particles pass through ionizing gas

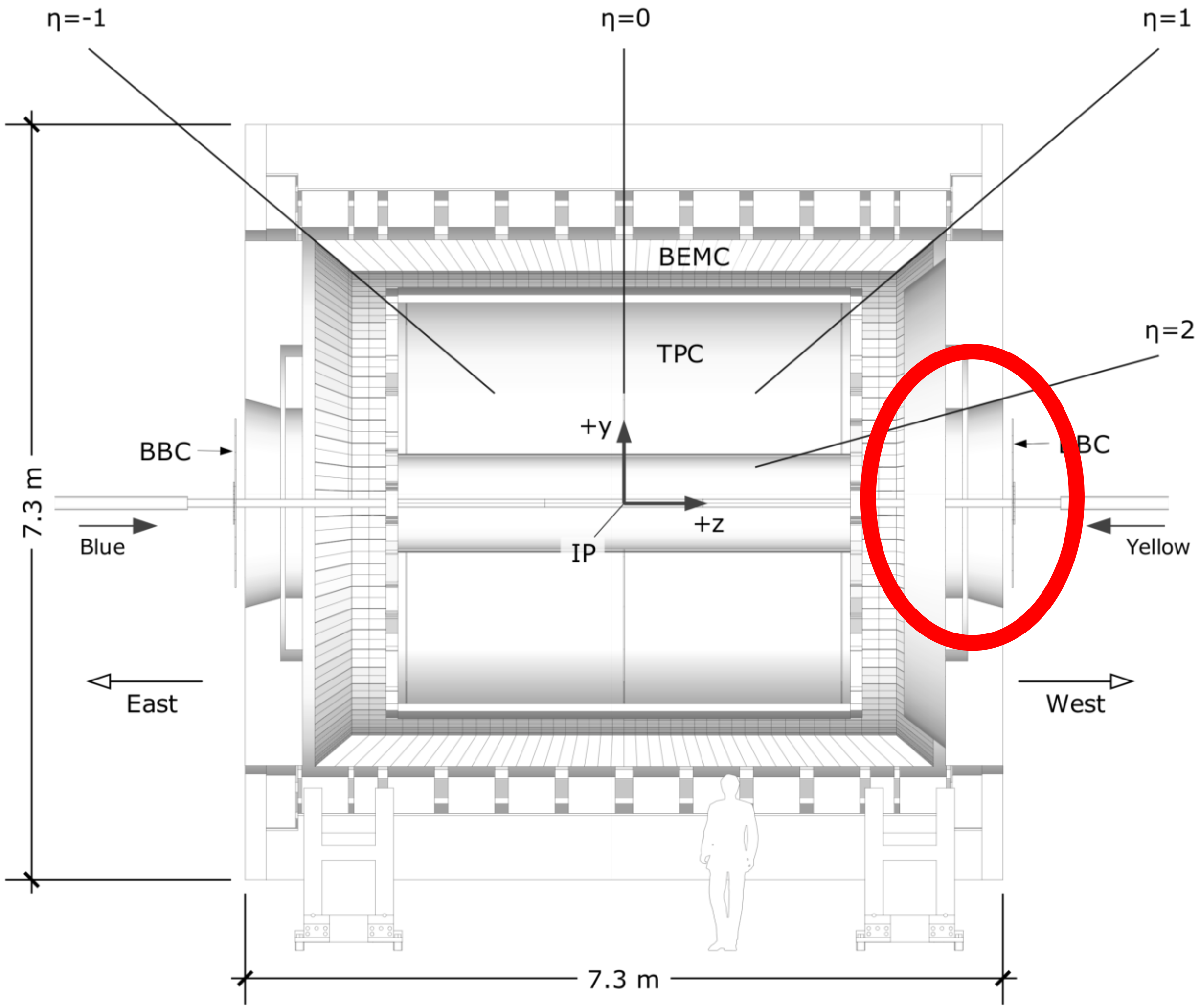
- Electron from ionization makes cascade in electric field

- Cascade is measured in the strips as a hit



STAR performance parameters

- In STAR the sTGC is part of the forward upgrade system
- sTGC expected to properly separate charge (identify + vs – particles) and facilitate tracking (along with the FST)
- Coverage: $2.4 < \eta < 4$ @ 270, 300, 330, 360 cm from the Interaction Point (IP)
- Position resolution: <200um
- Dead channels: <1% (detector + electronics)
- Detection efficiency: > 95%



STAR sTGC team

This list is not exhaustive, I just want to give a rough idea on what goes into a project like this

- Much of the software and simulation – BNL

- Detector construction and design – Shandong University (SDU)
  - SDU ATLAS group also made the sTGCs for them, so this was a significant advantage

- Electronics for readout – University of Science and Technology of China (USTC) + BNL

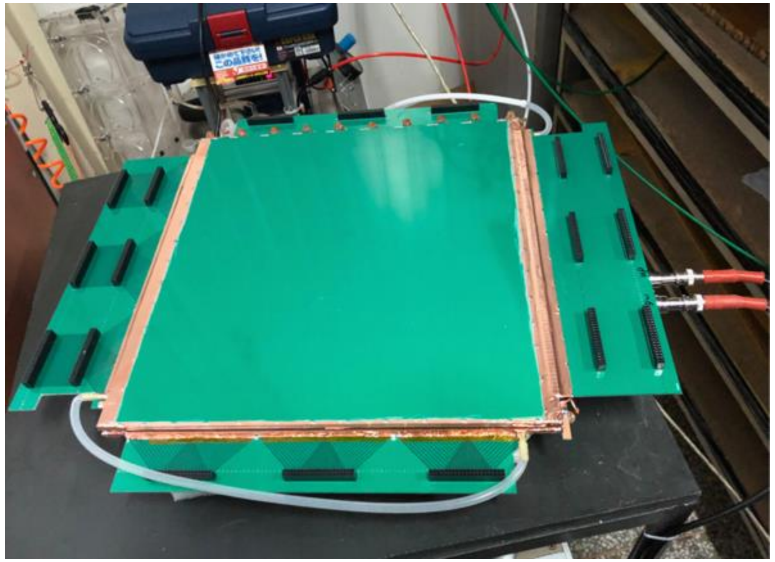
- Testing and characterizing modules shipped from SDU – BNL

- Integration into STAR – BNL

- Triggering and remote control of detector in STAR – STAR groups

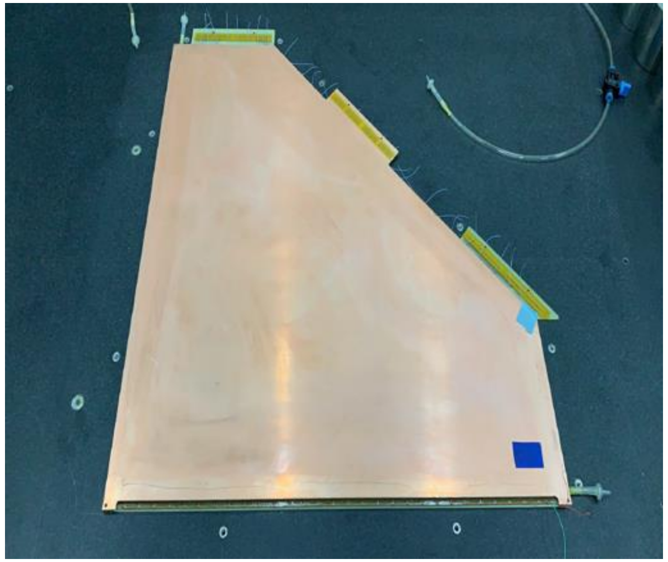
“Stations” from SDU

30cm*30cm square



60cm*60cm square

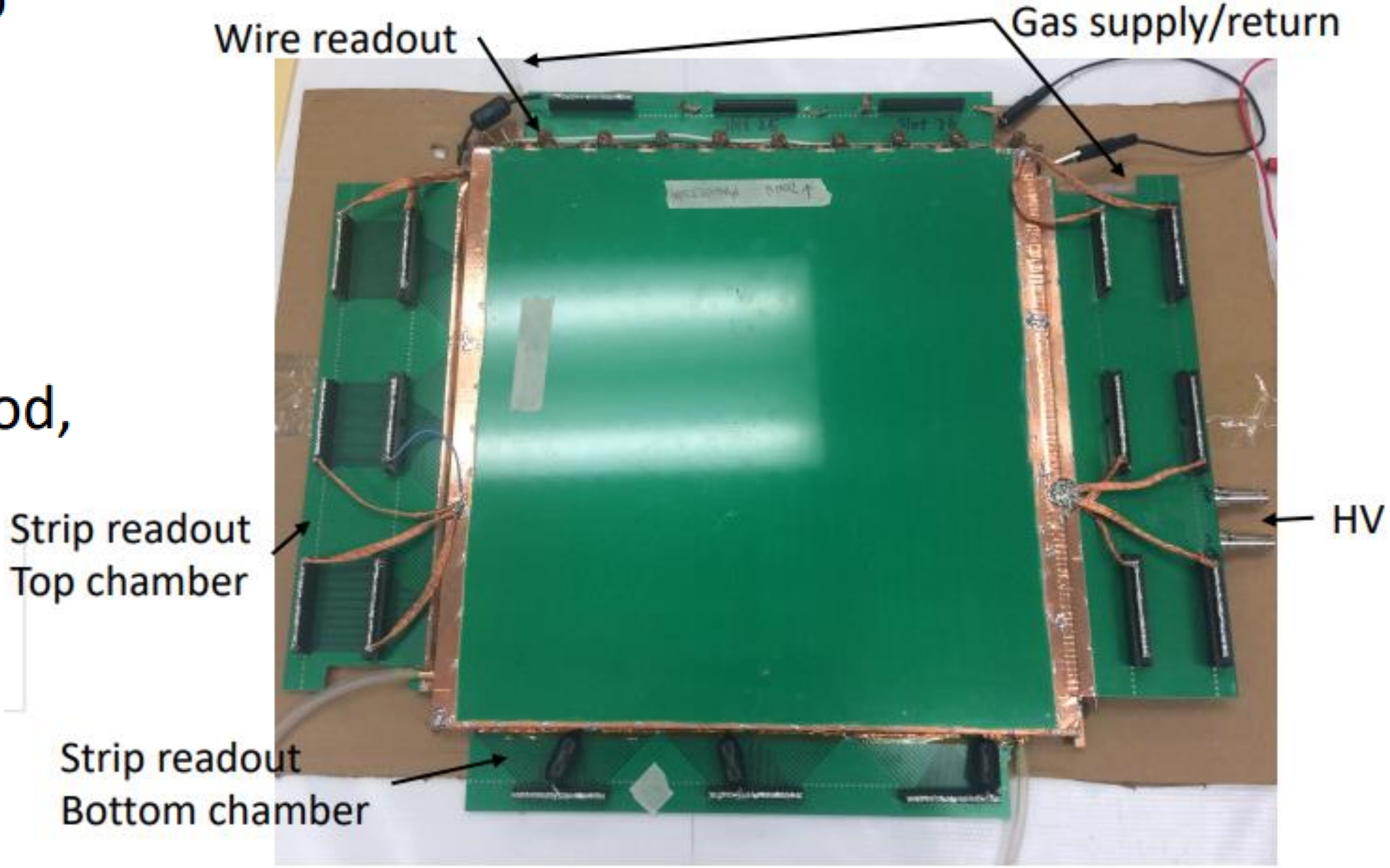
~55cm*55cm pentagon



- A “station” is an x and a y plane sandwiched together to make a grid for hits
- 30cm*30cm square prototype finished in Oct. 2018, 1 station is produced, delivered to BNL in Jan. 2019, installed in STAR on Jun. 2019
- 60cm*60cm square prototype finished in Jan. 2019, 4 stations are produced, delivered to BNL in Jul. 2020, installed in STAR
- 55cm*55cm pentagon 19 stations completed and sent to BNL (as of last week!)

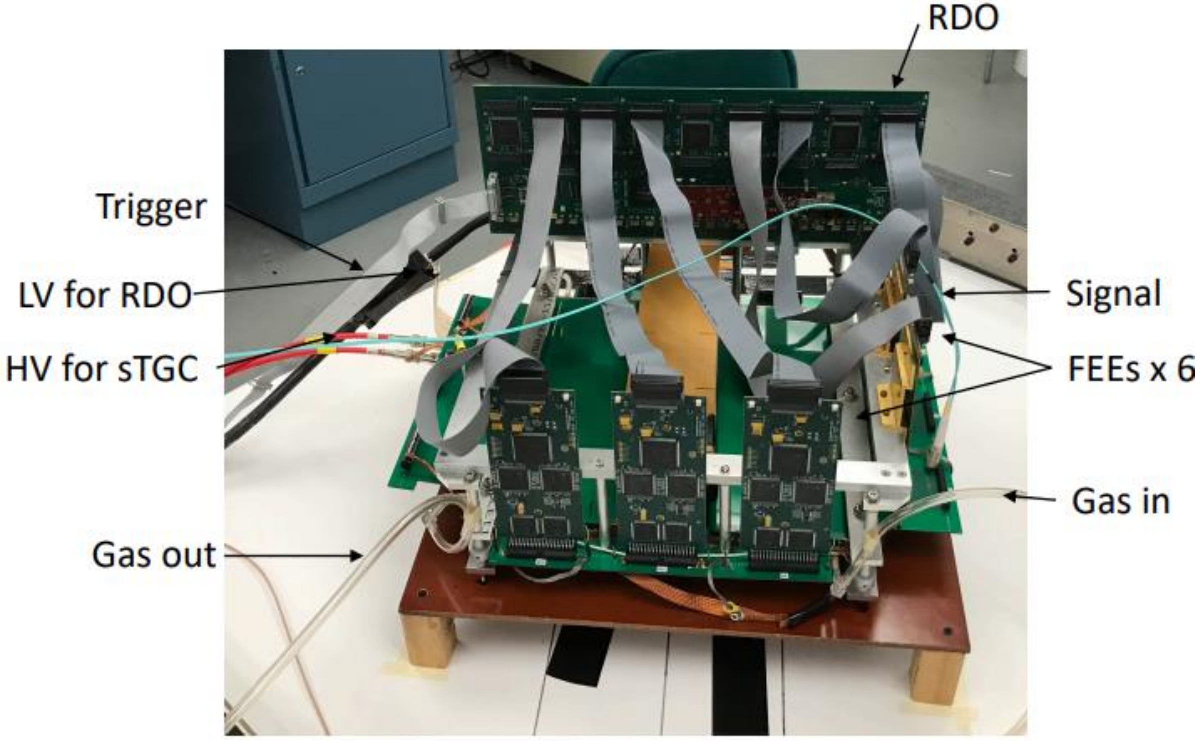
First “30x30”prototype – 2019

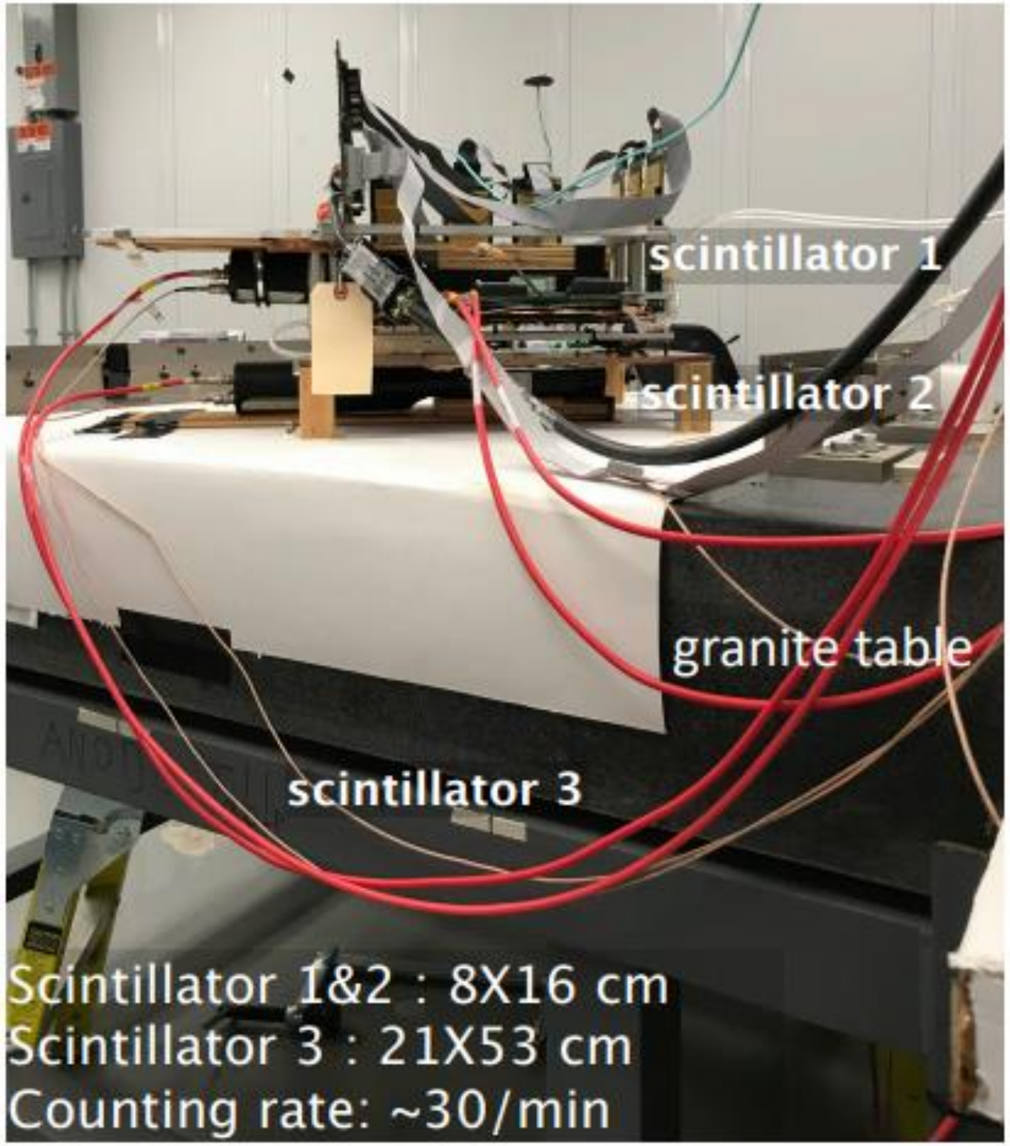
- Two chambers, perpendicular to each other
  - 2D readout, strips and wires
  - each 30 × 30 × 0.28 cm
  - 94 channels per chamber
- Leaks from the chambers are tested with pressure drop method, and found less than 10 cc/hr



30x30 cosmic rays

- Start BNL tests with cosmic rays – trigger on scintillator triple coincidence
- No custom electronics yet, so we use old TPC electronics





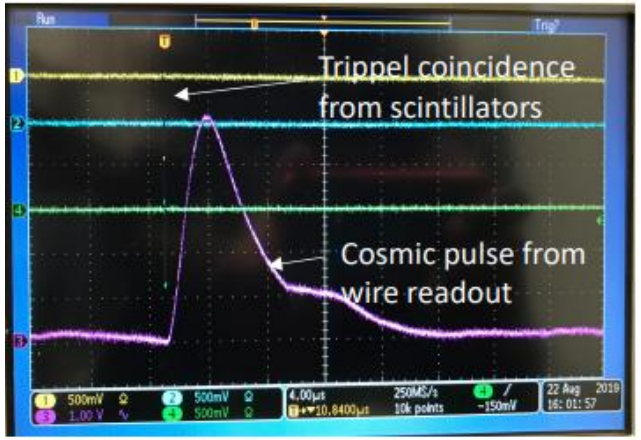
30x30 cosmic ray trigger

- We can't see the strip response on a scope and the wire response is much too wide to use
  - Wire still indicates it's working

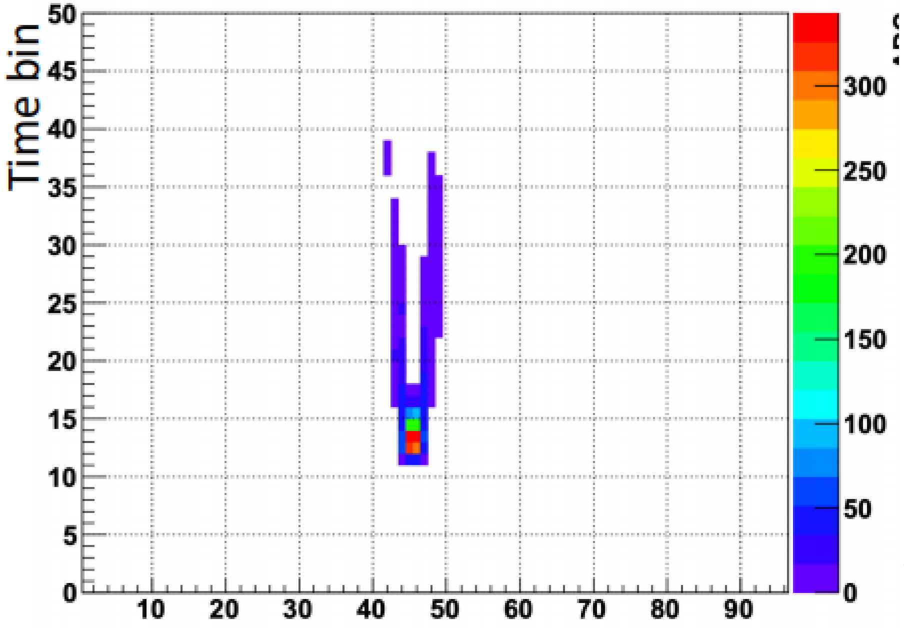
- Use data acquisition (DAQ) → if there are three scintillator hits at the "same time" read out electronics

- Good single-muon signal

Scope trace of trigged cosmic muon from wires



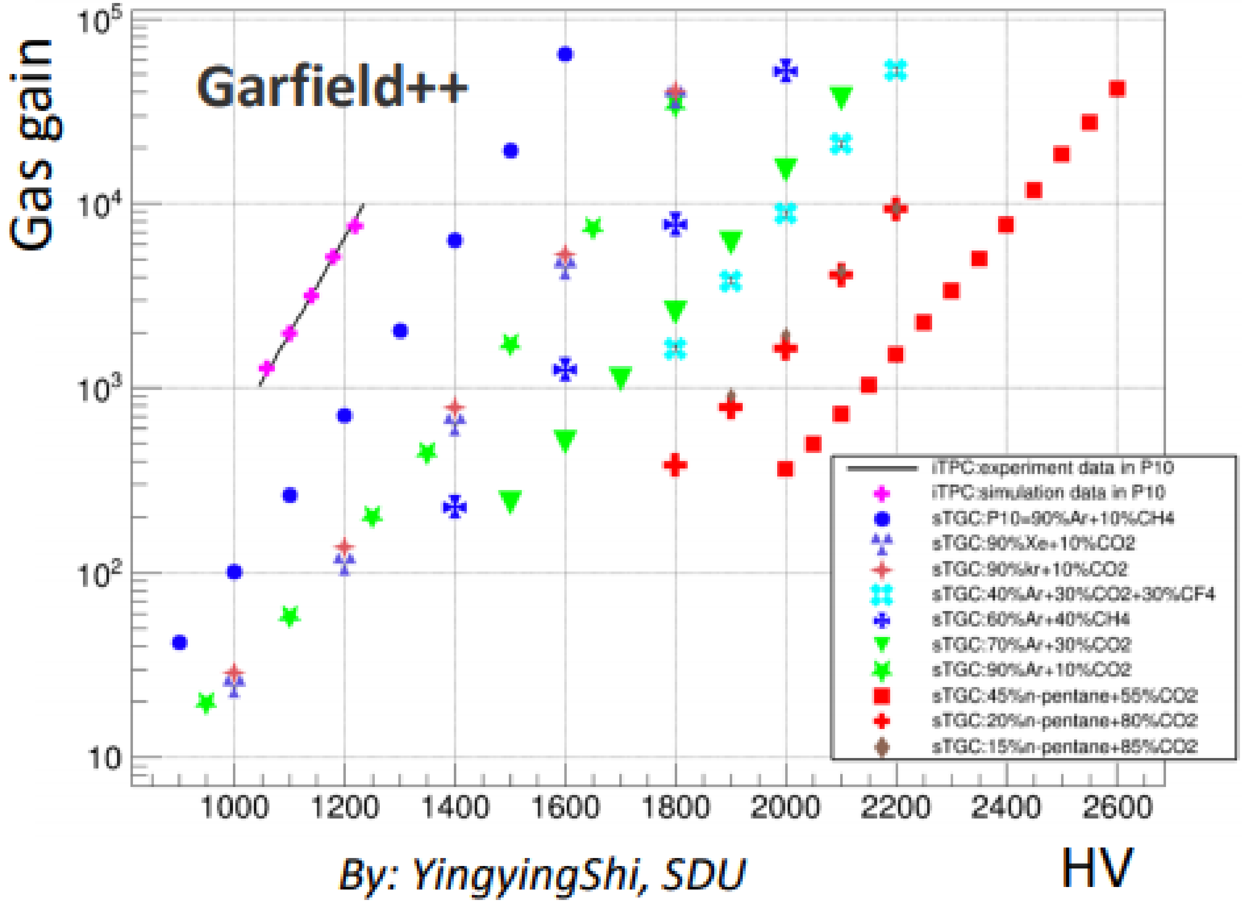
Signal from a single cosmic ray



- ADC threshold >= 10
- Number of strip>= 4
- Number of time bins >= 4

30x30 gas tests

- sTGC uses n-pentane + CO2 (55+45)% in ATLAS
- n-pentane is flammable and liquid below 960 F (360 C) (like gasoline)
- This gives us RHIC safety issues
- Trying different gases:
  - C10 -> Ar 90% + CO2 10%
  - P8.5 -> Ar 91.5% + CH4 8.5%
  - i-Butane(C4H10) + Ar (30+70)%
  - n-pentane(C5H12) + CO2 (45+55)%



30x30 gas results

- n-pentane allows for higher voltages and, consequently much better efficiencies

- → it cannot be replaced

Gas	Signal at wire readout		Operation
	Low HV (V)	High HV (V)/ Trip limit	
C10 -> $Ar+CO_2$ (90%+10%)	1250	1600	Stable
P8.5 -> $Ar+CH_4$ (91.5%+8.5%)	1400	1600	Not stable
i-Butane(C_4H_{10}) + Ar (30+70)%	1500	1800	Not stable
n-pentane(C_5H_{12}) + CO_2 (45+55)%	2200	2800+	Stable

C10 gas efficiency

Total triggered events:

$$\frac{top\ \ layer\ respond}{Total\ Events} = 1\%$$

$$\frac{bottom\ layer\ respond}{Total\ Events} = 1.8\%$$

$$\frac{at\ least\ one\ layer\ respond}{Total\ Events} = 2.7\%$$

Self trigger:

$$\frac{two\ layer\ respond}{bottom\ layer\ respond} = 7.3\%$$

$$\frac{two\ layer\ respond}{top\ layer\ respond} = 13.0\%$$

n-pentane + CO_2 efficiency

Total triggered events:

$$\frac{top\ \ layer\ respond}{Total\ Events} = 98.3\%$$

$$\frac{bottom\ layer\ respond}{Total\ Events} = 98.8\%$$

$$\frac{at\ least\ one\ layer\ respond}{Total\ Events} = 99.8\%$$

Self trigger:

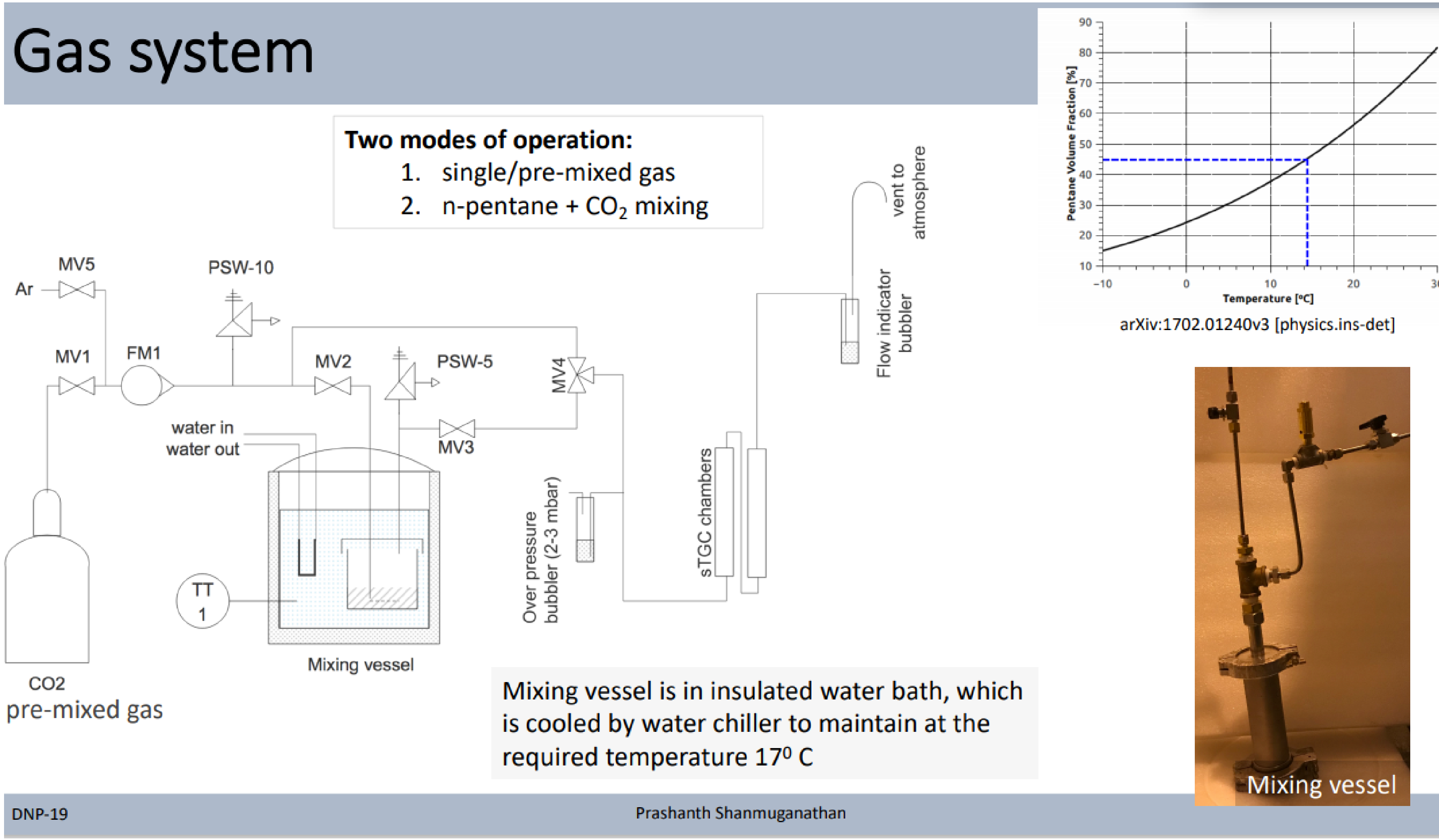
$$\frac{two\ layer\ respond}{bottom\ layer\ respond} = 98.5\%$$

$$\frac{two\ layer\ respond}{top\ layer\ respond} = 99.0\%$$

Efficiency is found to be independent of temperature change (17 ± 2^0 C) (and flow rate)

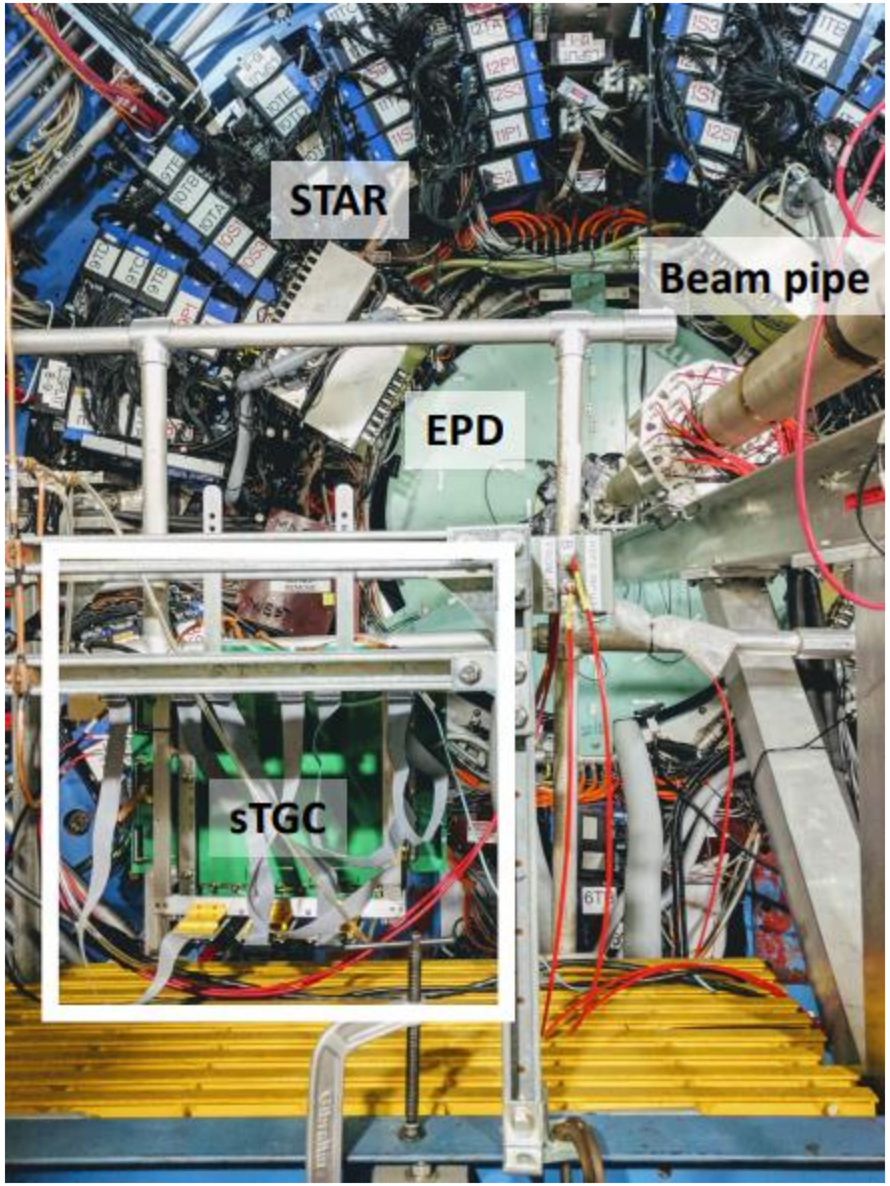
Pentane gas system

- Pentane is liquid, CO_2 is bubbled through it
- How much pentane is carried away and is very dependent on temperature
- Temp. cannot change too much, or you get flammable gas in the tubes!
- This becomes a huge effort for the final detector

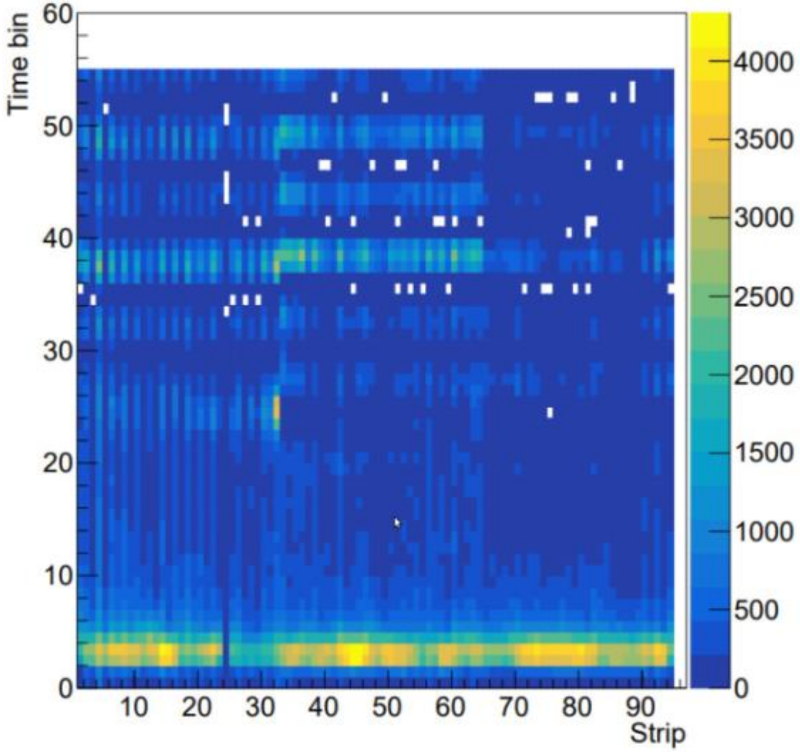


Prototype in STAR

- Prototype mounted on the west platform on 06/05/19
- Electronics and DAQ were integrated to STAR + remote control
- Used pre-mixed C10 gas – pentane not approved
- Collected data with Au+Au 7.7, 9.2, and 200 GeV collisions

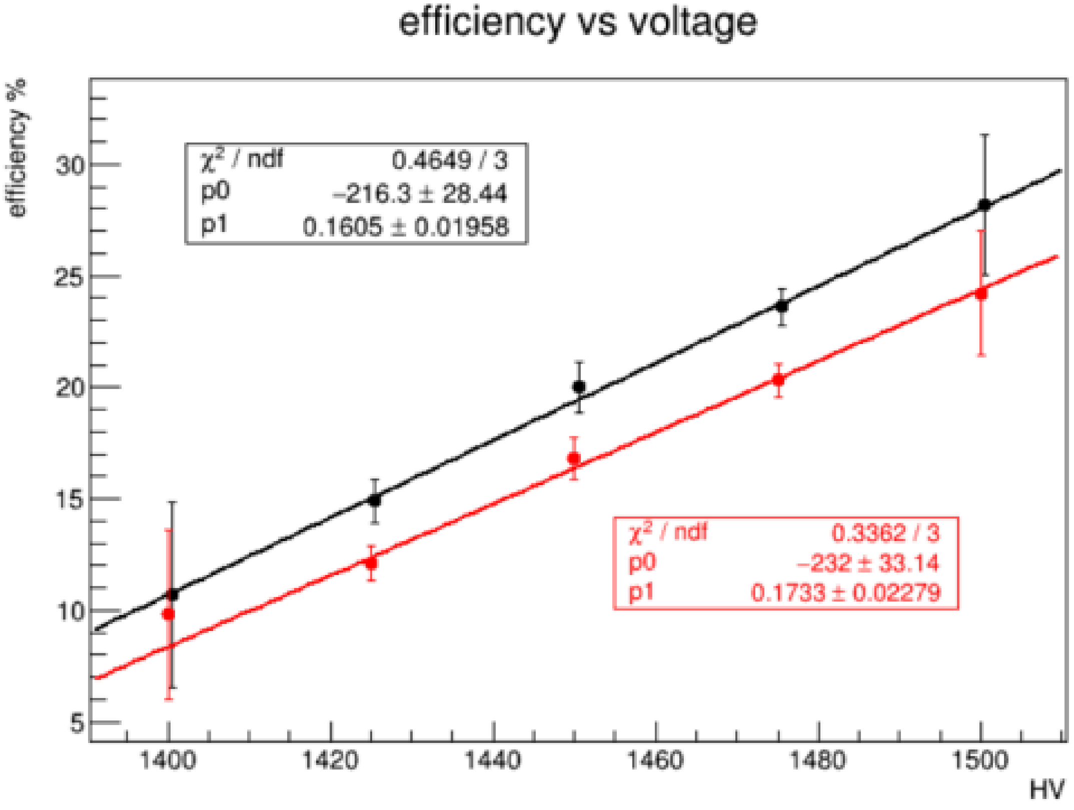


- Collected data was analyzable
- Detector exhibited good uniformity

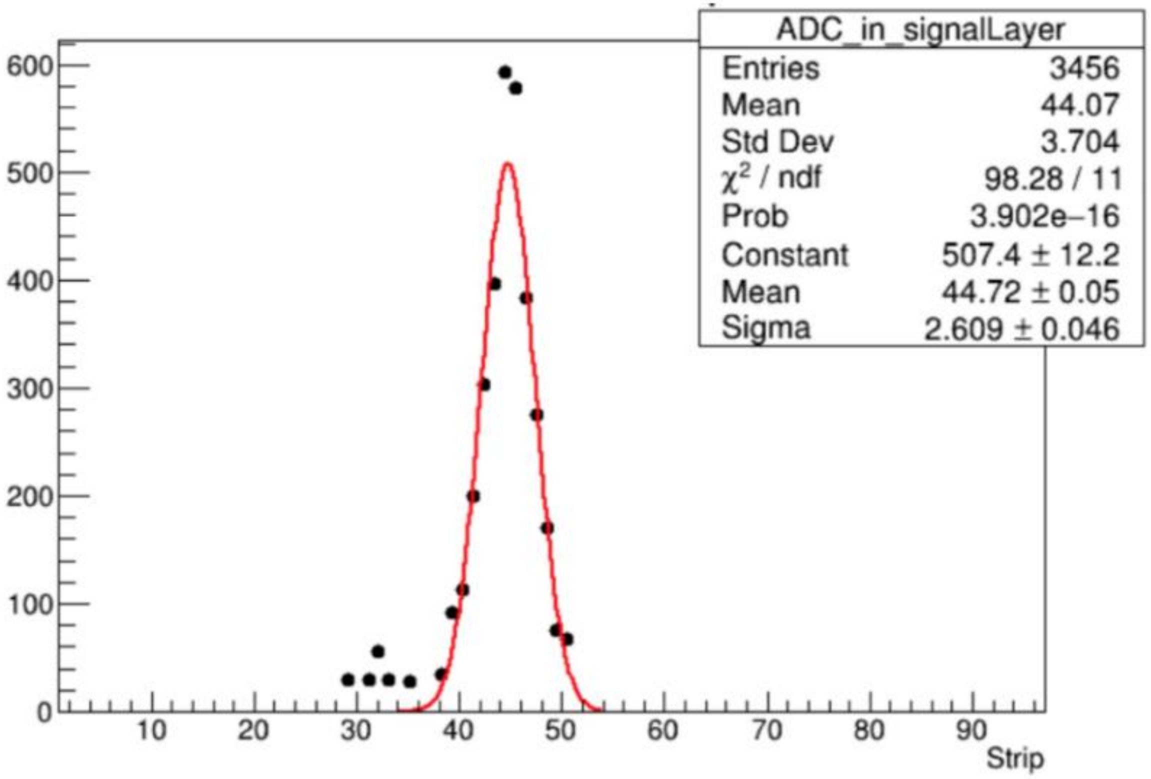


Prototype data analysis

- Efficiency low, but measurable, and rising with voltage

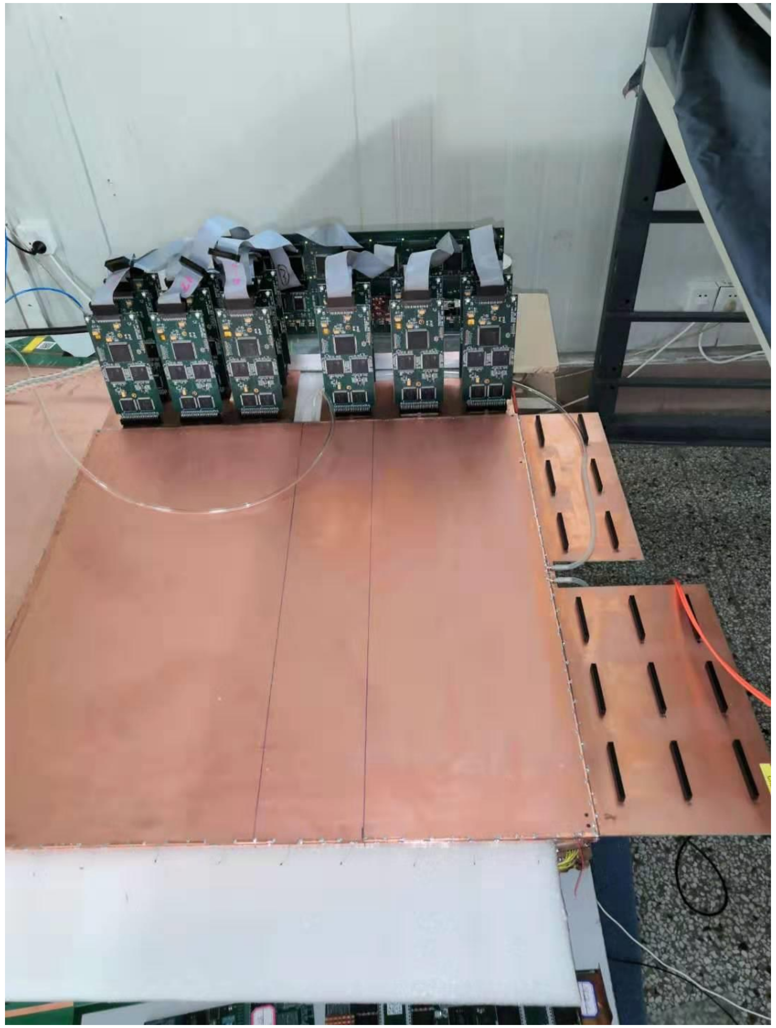


- Shower size analysis possible



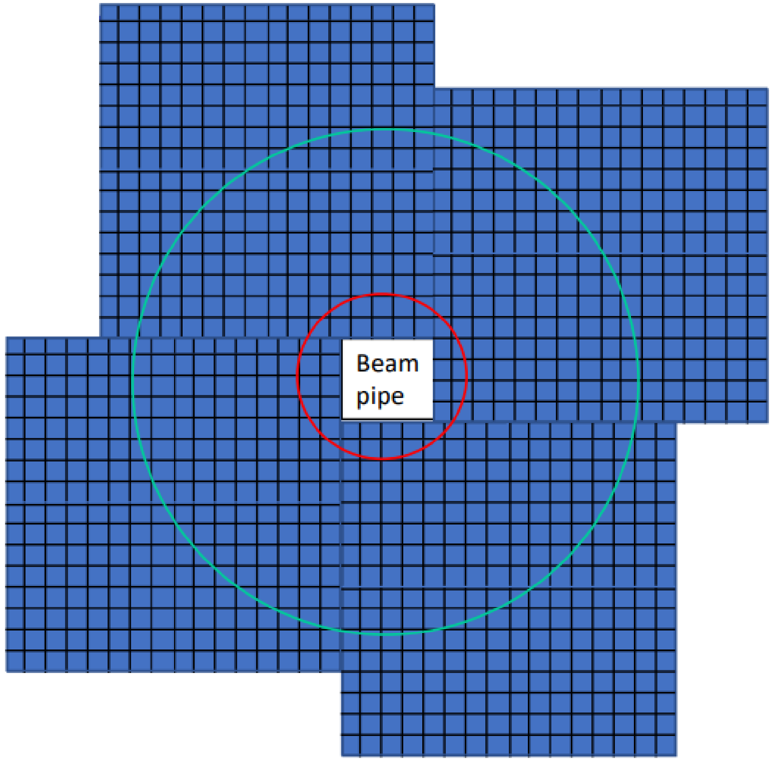
60x60 prototype (2020)

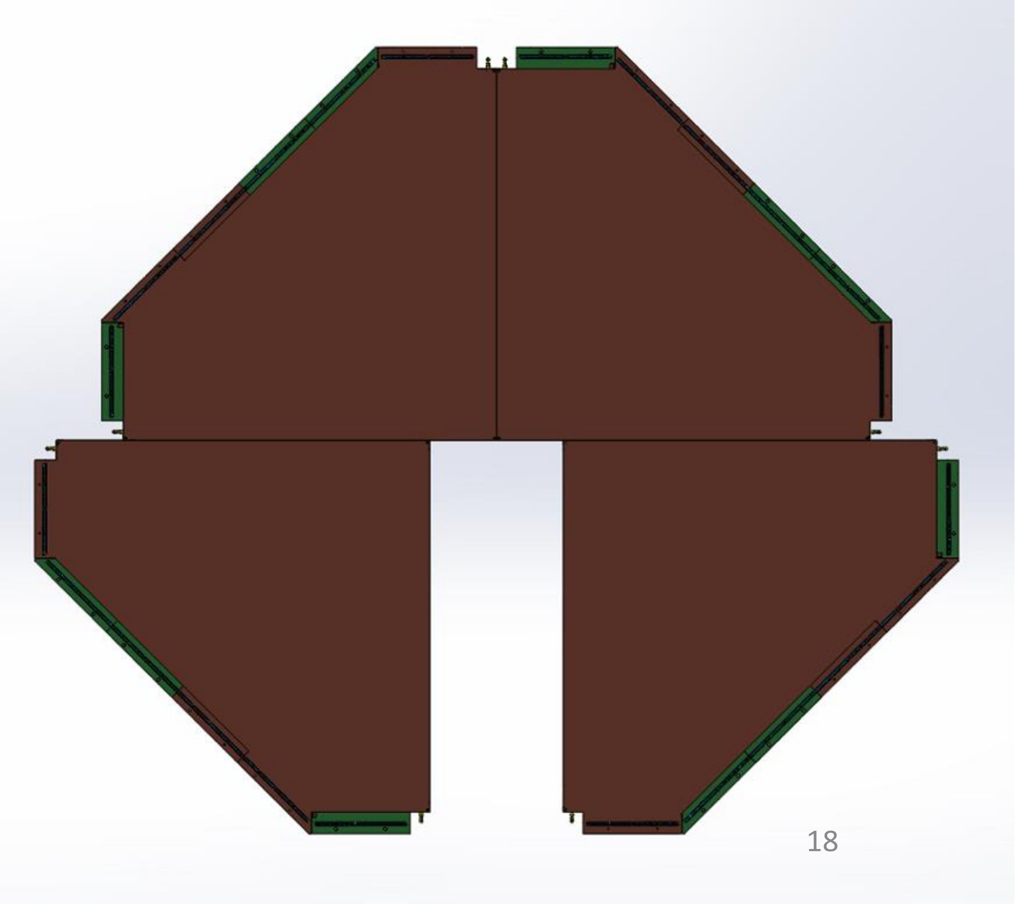
- Detector arrived with no leaks
- Efficiency studies prevented by lack of available resources
- Used bespoke sTGC electronics for the first time
- n-pentane brought into STAR hall for the first time, gas system approved and working



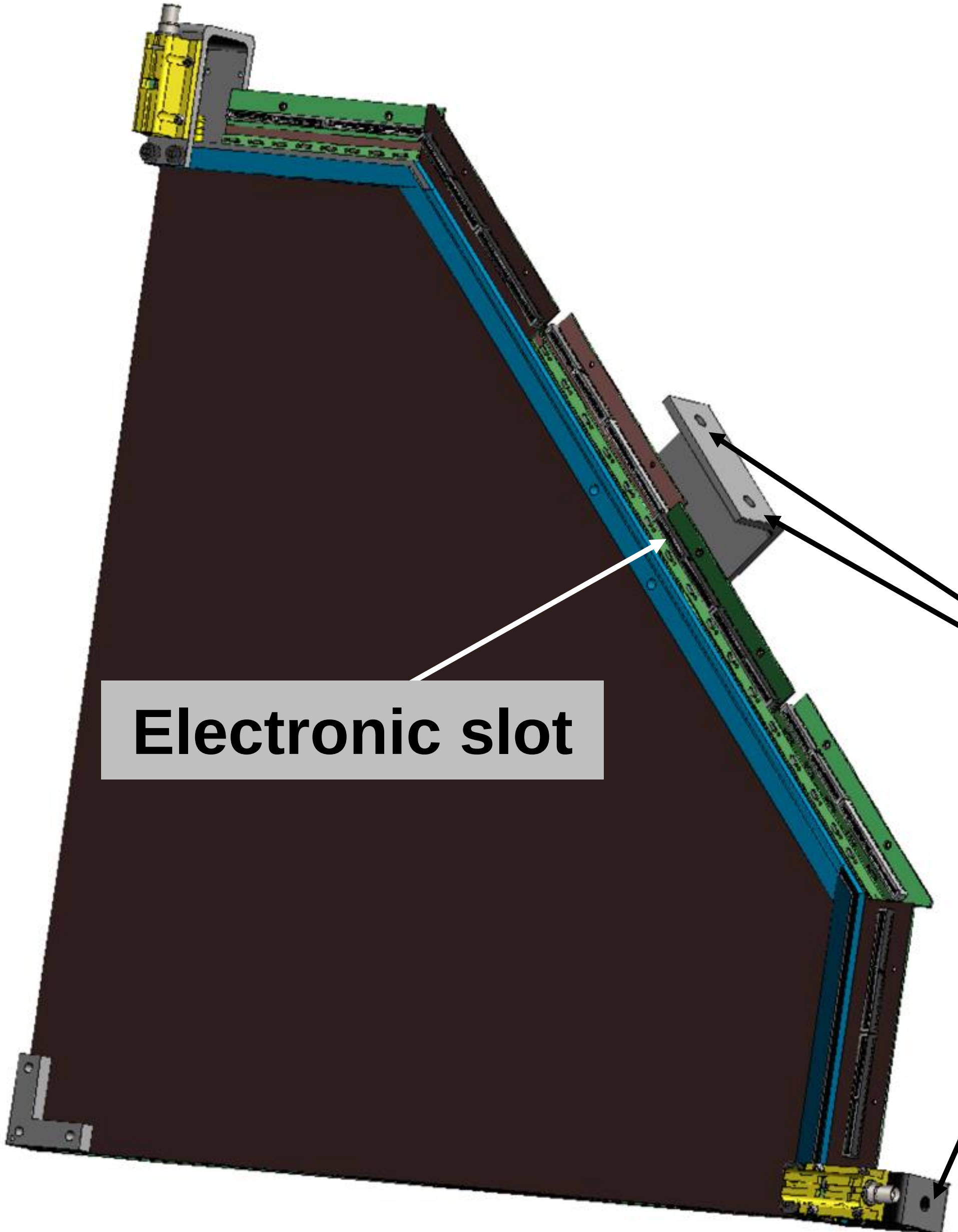
Final production

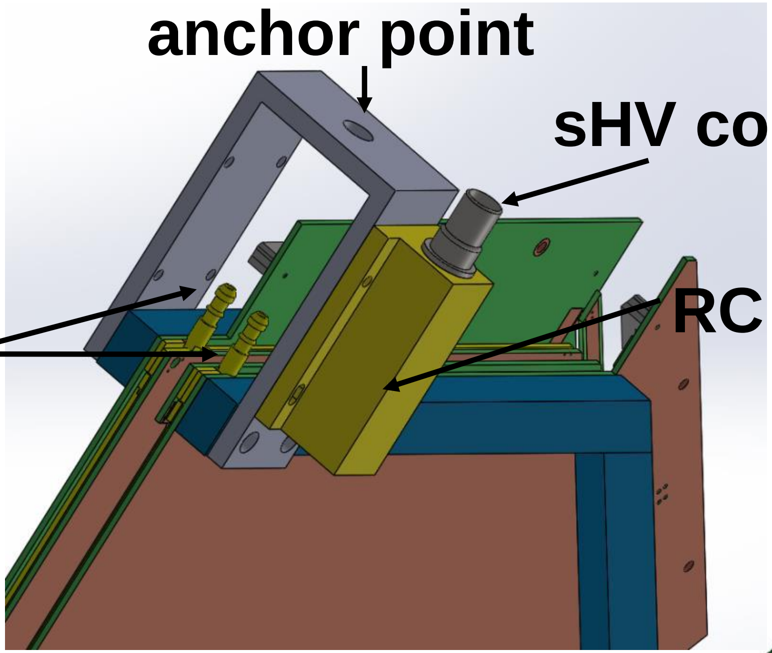
- With lessons learned from constructing the prototype SDU was ready to start with the final design
- Square sTGC stations had to become irregular pentagons to make space for the pole tip bar

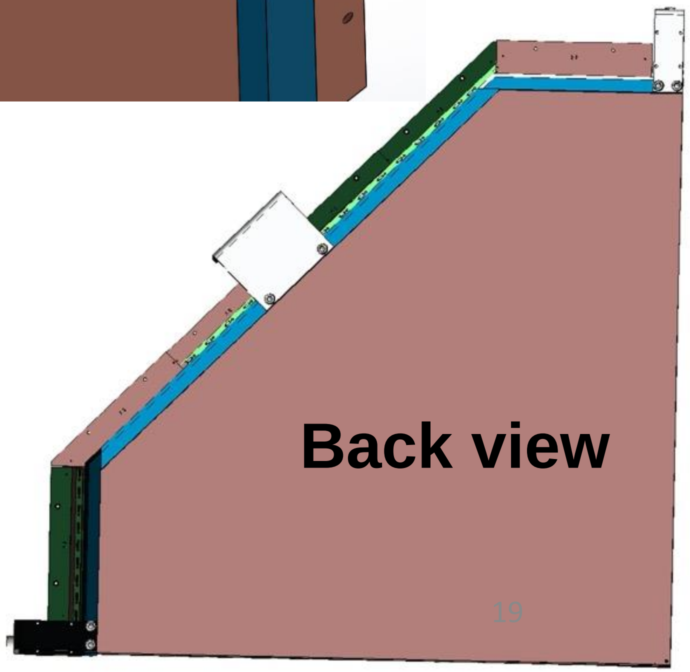




Final design



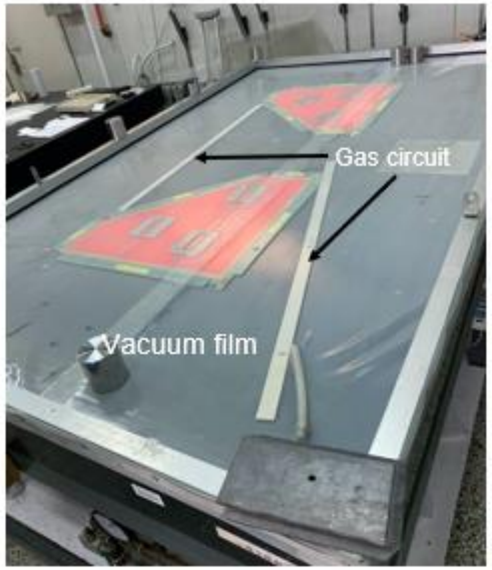




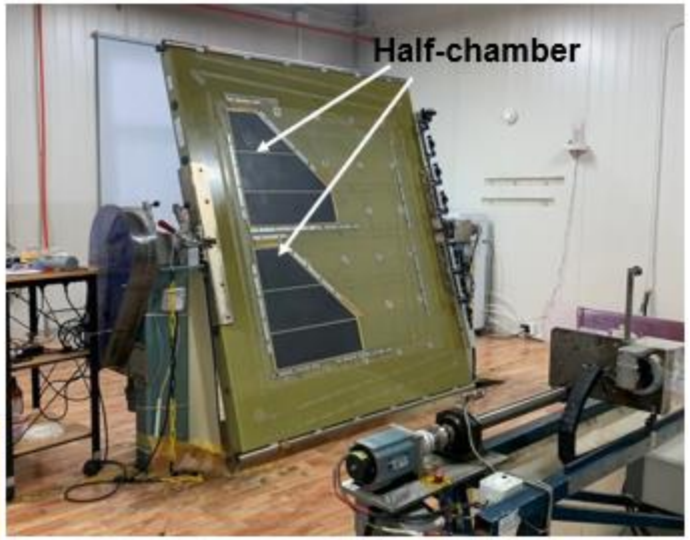
Production steps 1

production precdure
- pre-production
  - PCB inspection
- PCB board
  - Graphite coating
- Half-chamber
  - Supporting frame installtion
  - Leakage current test
- Wire-winding

Supporting frame installation



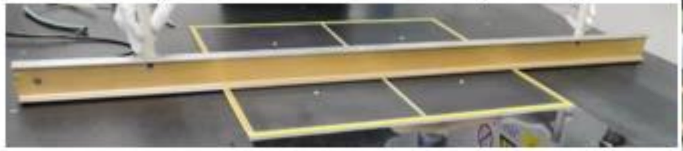
Half-chamber in vacuum system



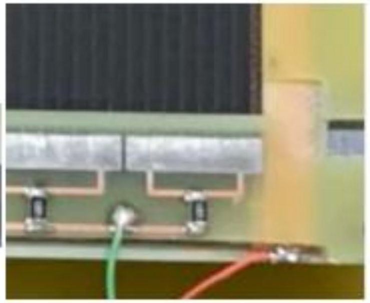
Wire-winding system

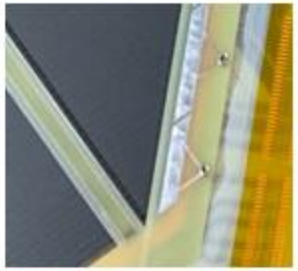
- Soldering temperature: 350°
- Soldering process should less than 3 s for each wire

A picture from full size sTGC (60 * 60)

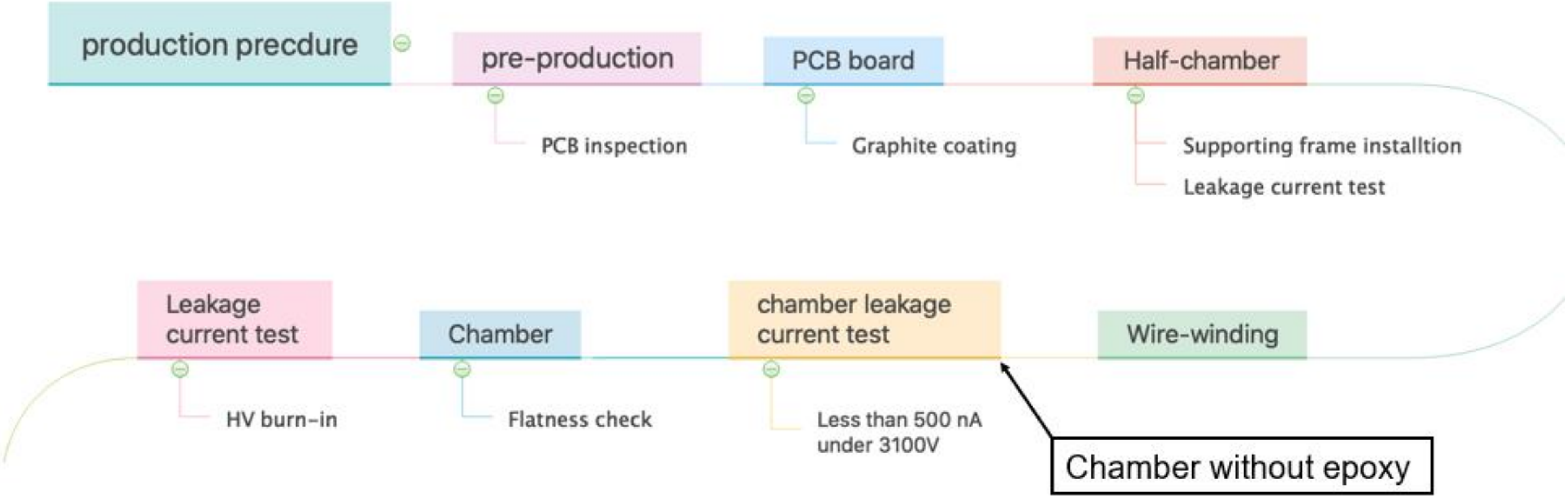


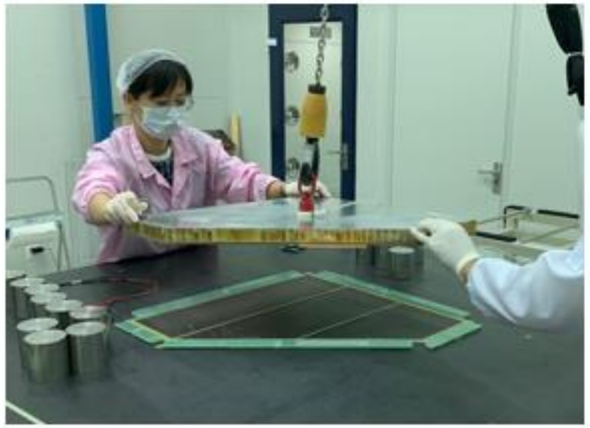
3100V
Leakage current < 50 nA





Production steps 2



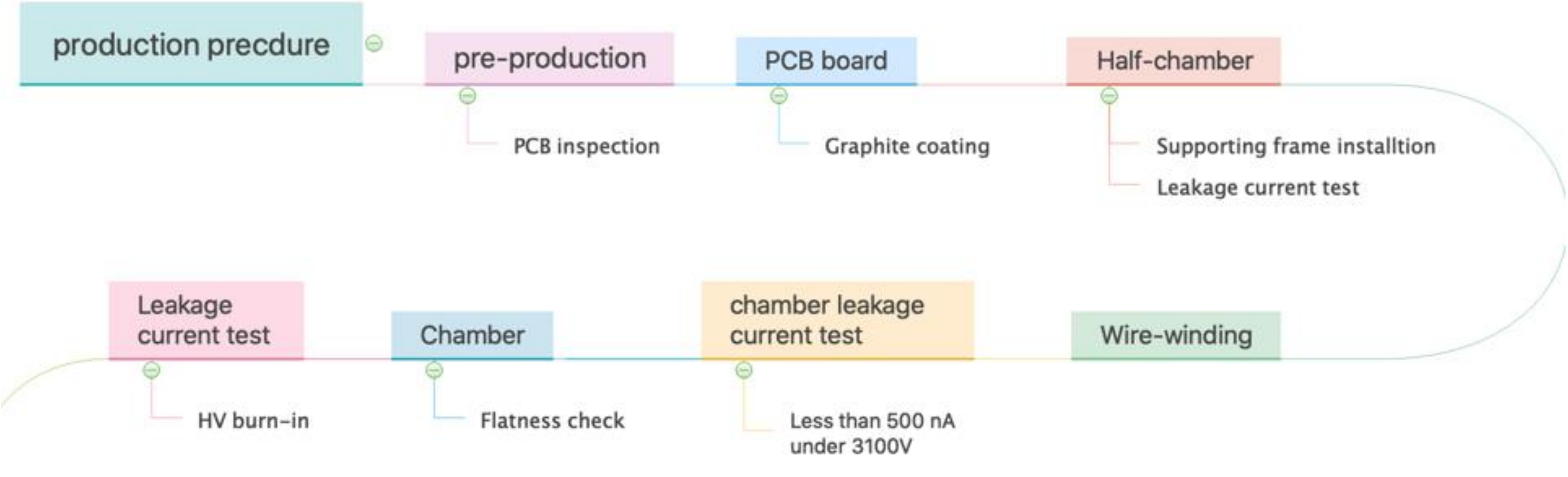


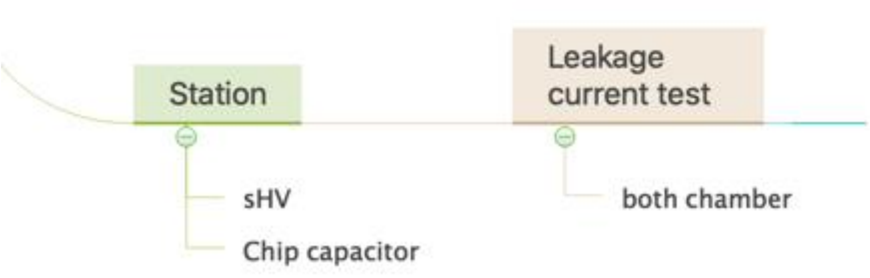
Chamber assembly in clear room

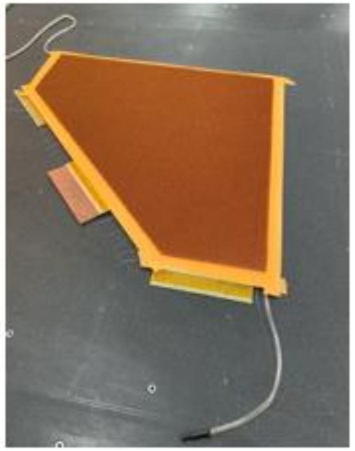
Leakage current test system in clear room

Leakage current test system in hall

Production steps 3







Chamber with honeycomb

Station under massive stainless

Production steps 4

- production precdure
  - pre-production
    - PCB inspection
  - PCB board
    - Graphite coating
  - Half-chamber
    - Supporting frame installtion
    - Leakage current test
  - Wire-winding
  - chamber leakage current test
    - Less than 500 nA under 3100V
  - Chamber
    - Flatness check
  - Leakage current test
    - HV burn-in
  - Station
    - sHV
    - Chip capacitor
  - Leakage current test
    - both chamber
  - Testing at Qingdao
    - performance test
  - Station

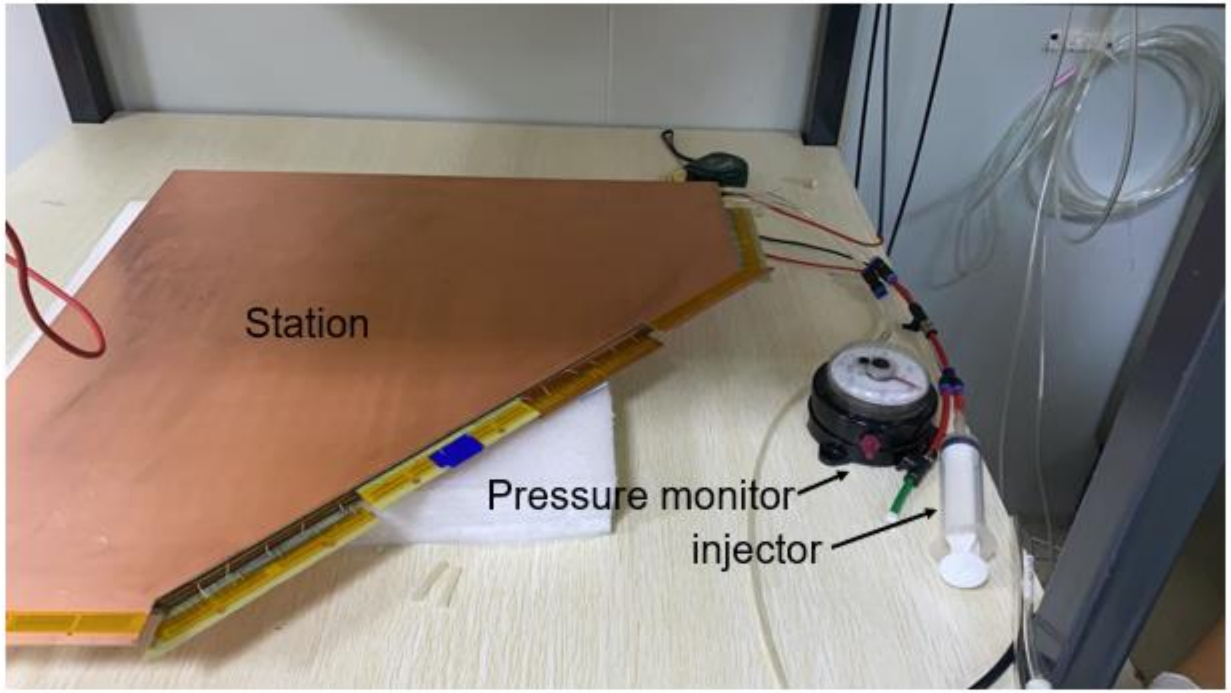
Gas leakage test
Leakage current test

Detector efficiency
Position resolution

Performance test system

Production QA 1

- **Gas leakage test**

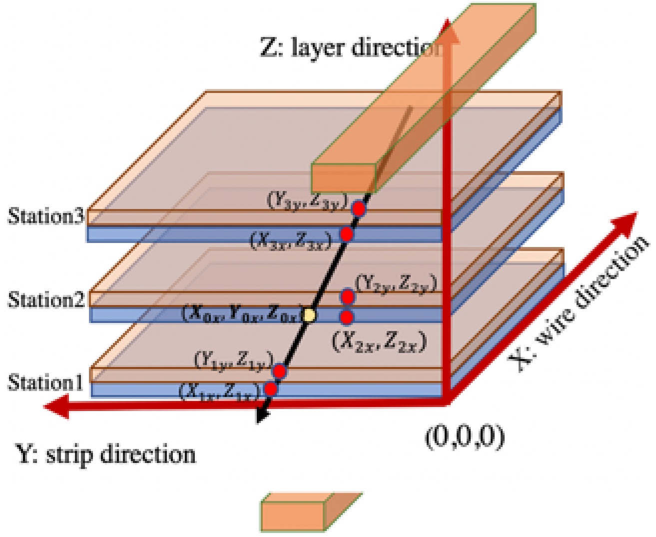


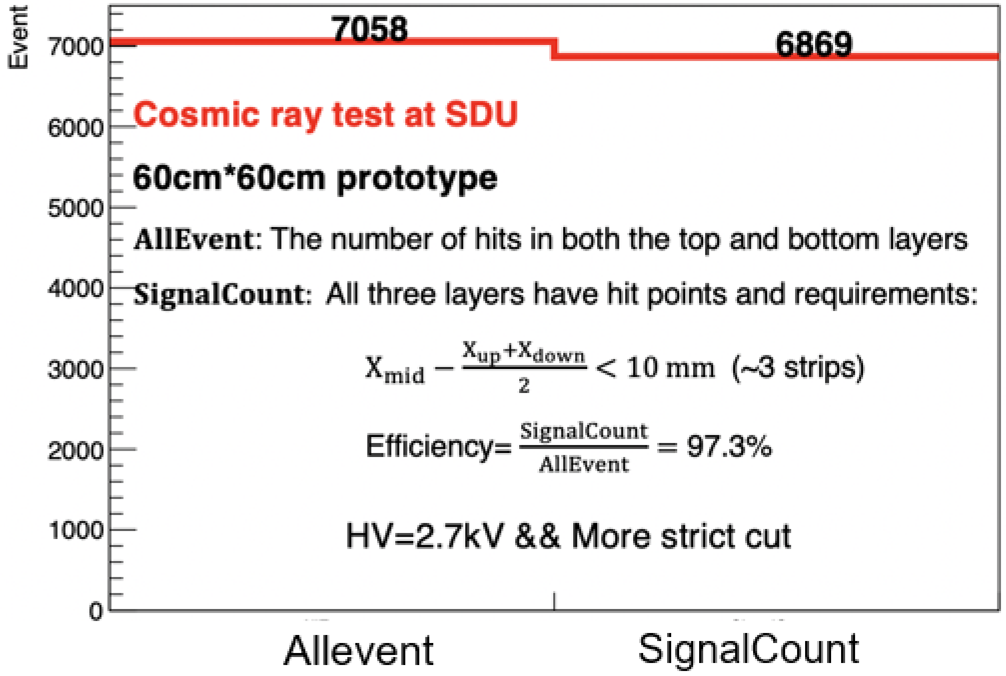
- Initiating -6mb pressure difference between chamber and atmospheric pressure
- The pressure difference should not < -5.8mb after at least 5 minutes later

(the same test is repeated at BNL after shipping)

Production QA 2

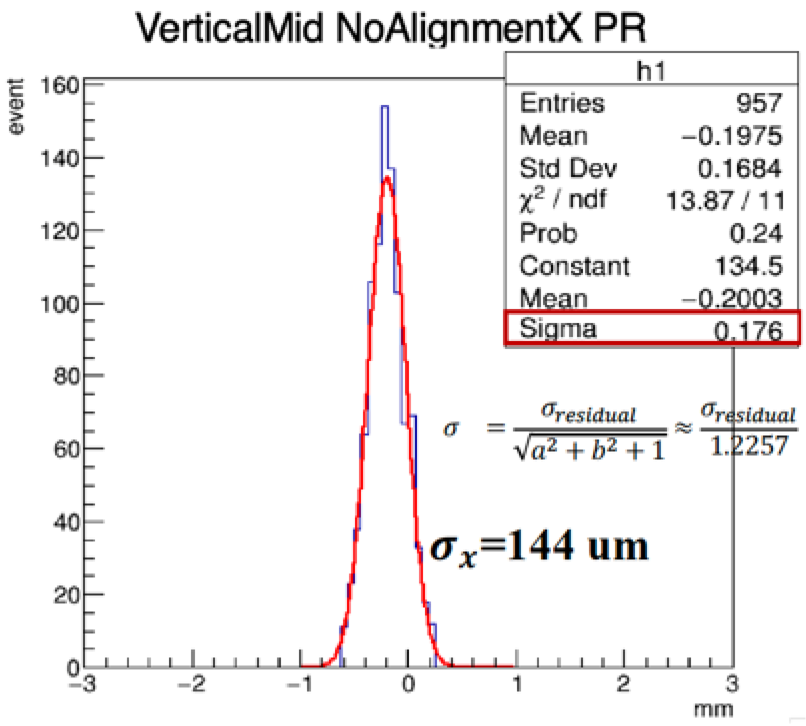
The detection efficiency is required to larger than 95%

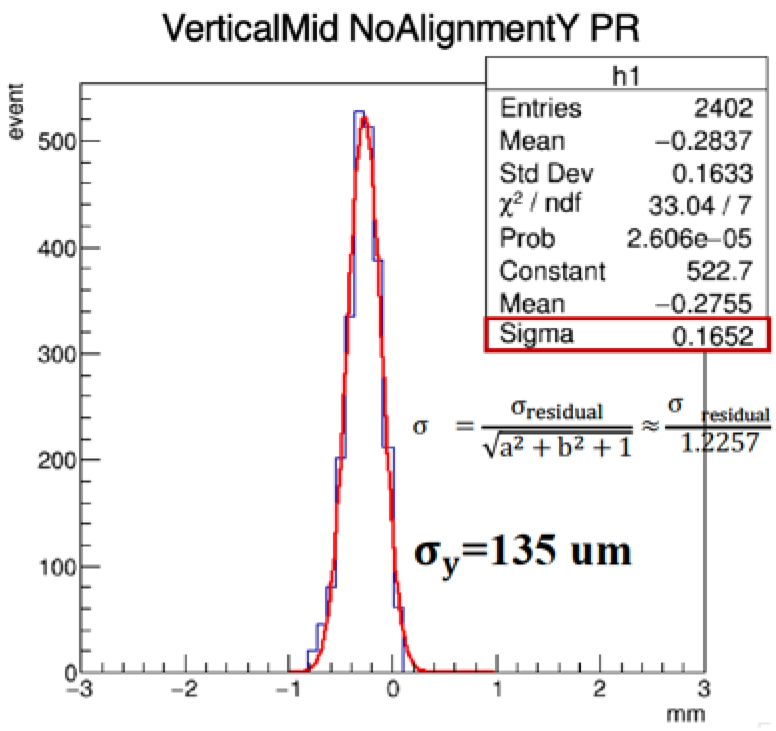




Production QA 3

Position resolution requirement < 200 um

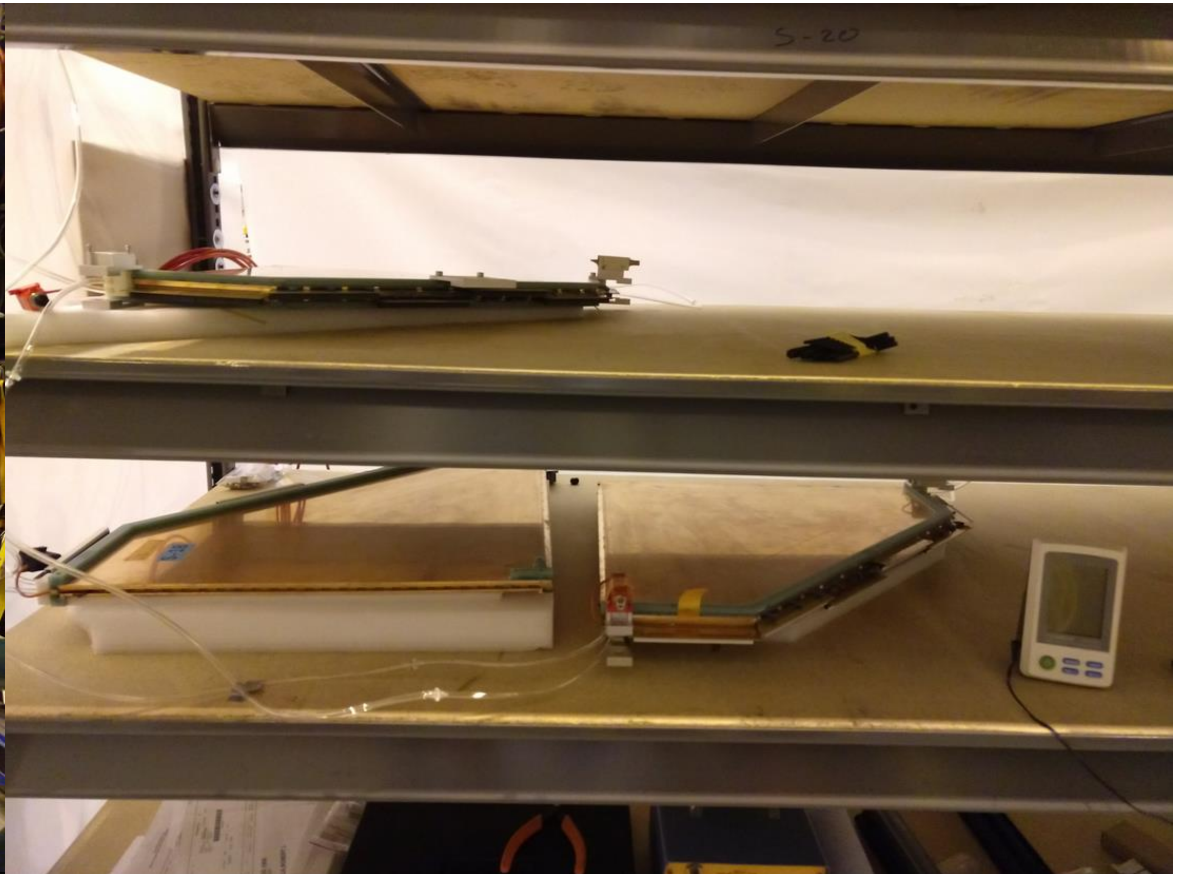




- Position resolution of 60 cm*60 cm prototype is about 140 um at 2.7kV

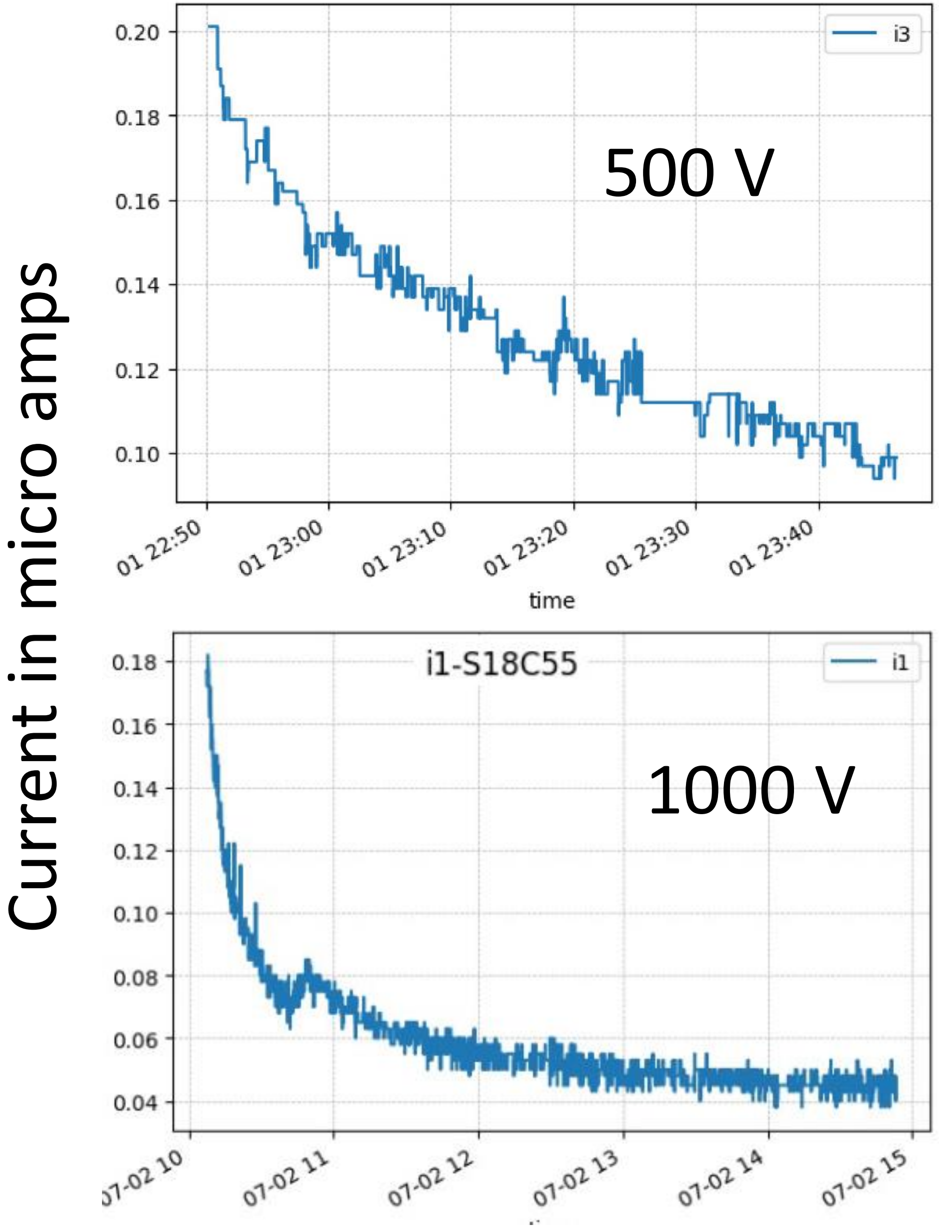
BNL QA

- After arriving in BNL stations are unpacked, gas leak tested, and gas is flowed
- We flow N_2 for a few days to dry them out and then flow CO_2 to “burn” the chambers



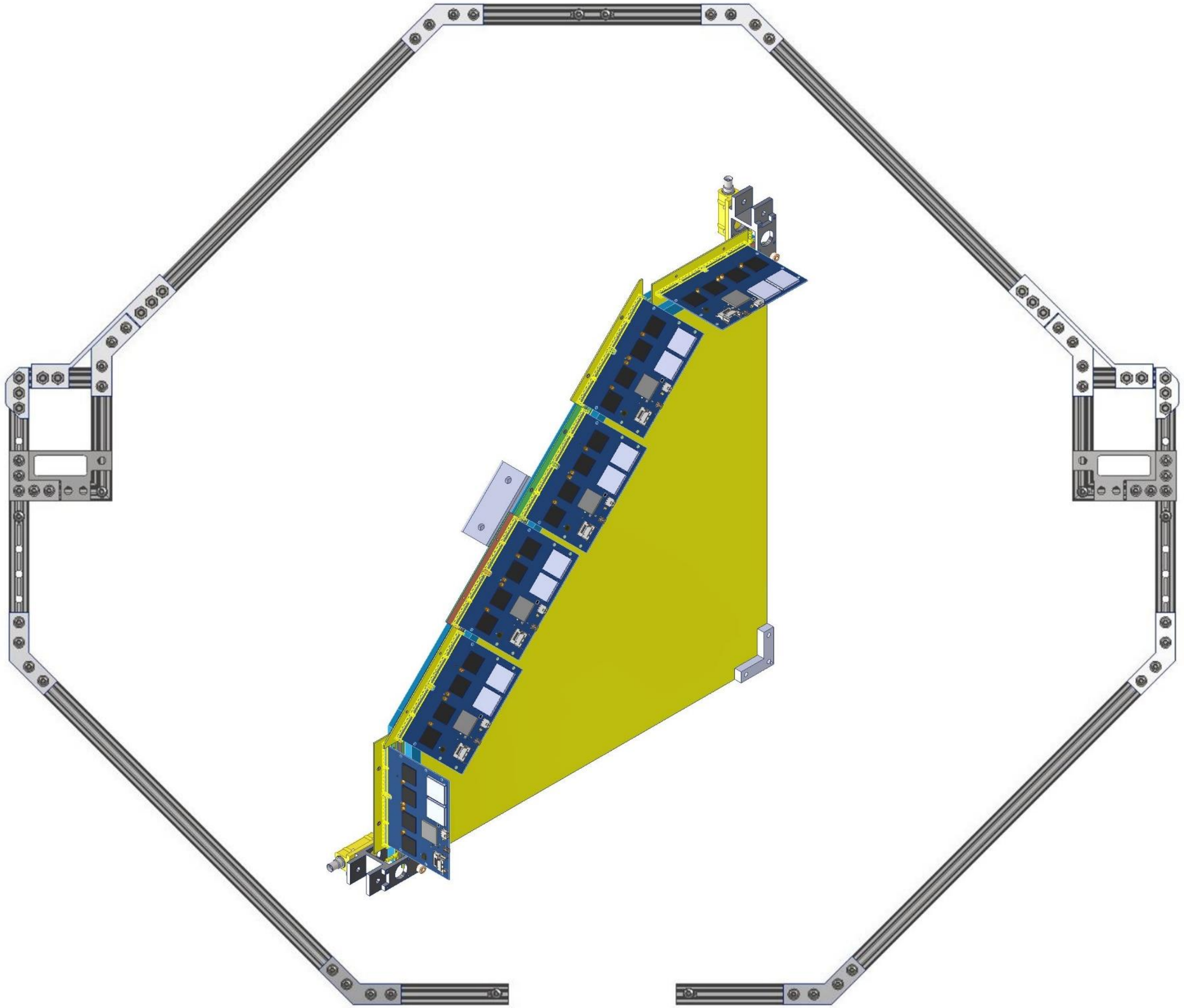
BNL burning

- Burning means we slowly ramp up the voltage to operating voltage (2900 V)
- We watch the current the chamber draws until it evens out over the course of a few days
- We are nearly done with four stations and can do the rest simultaneously



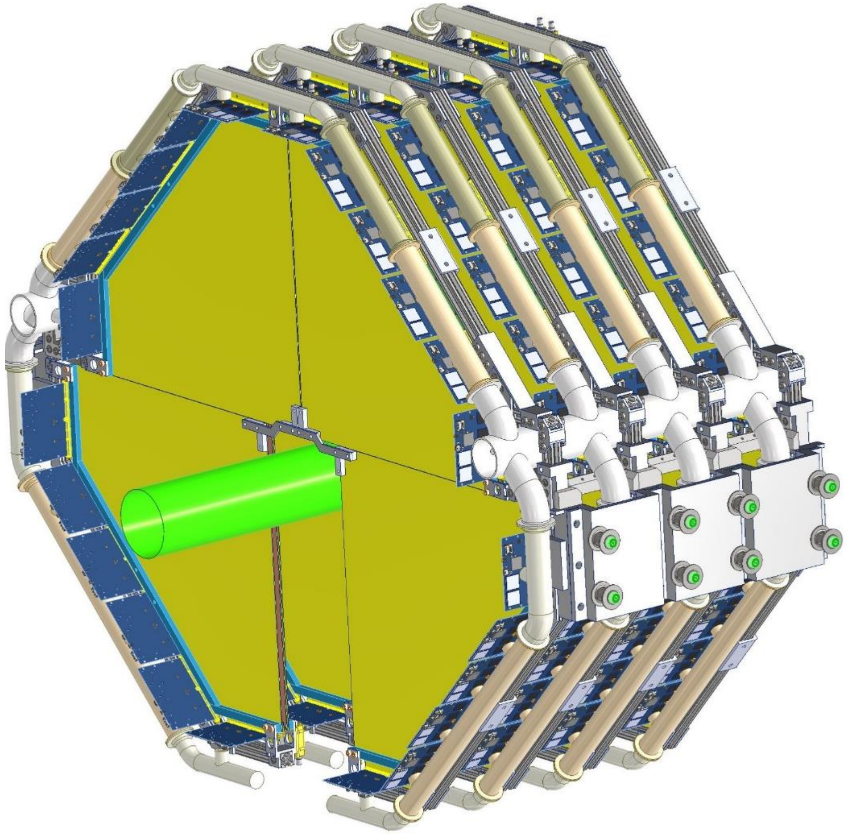
Future: installation 1

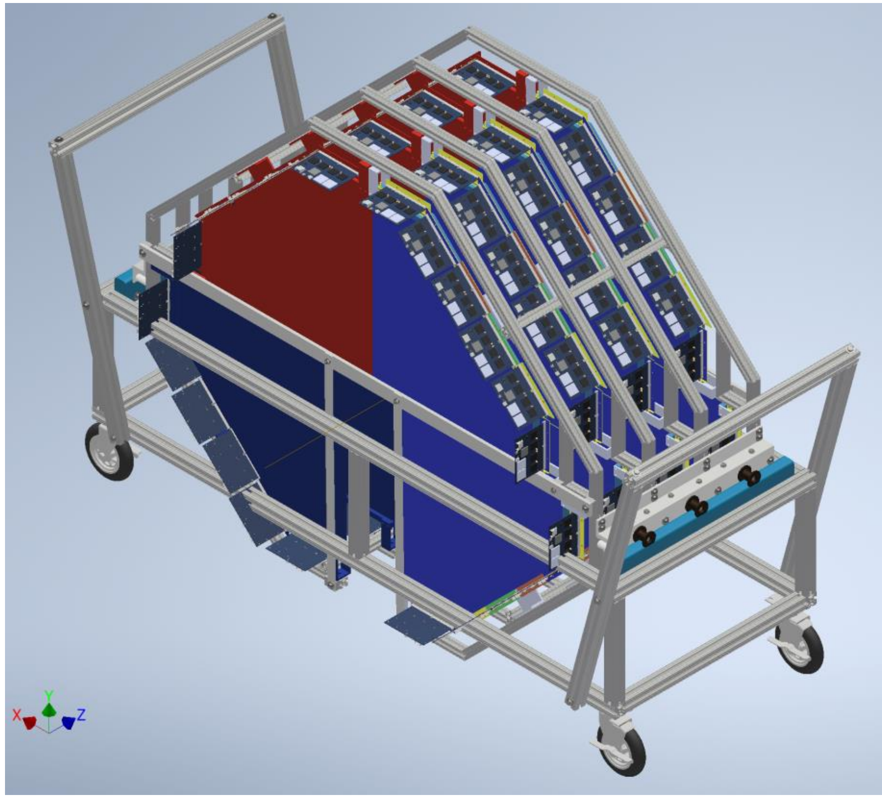
- FEE cards connected to quarters
- Quarters put inside of support structure
- We plan on filling one such structure this week



Future: installation 2

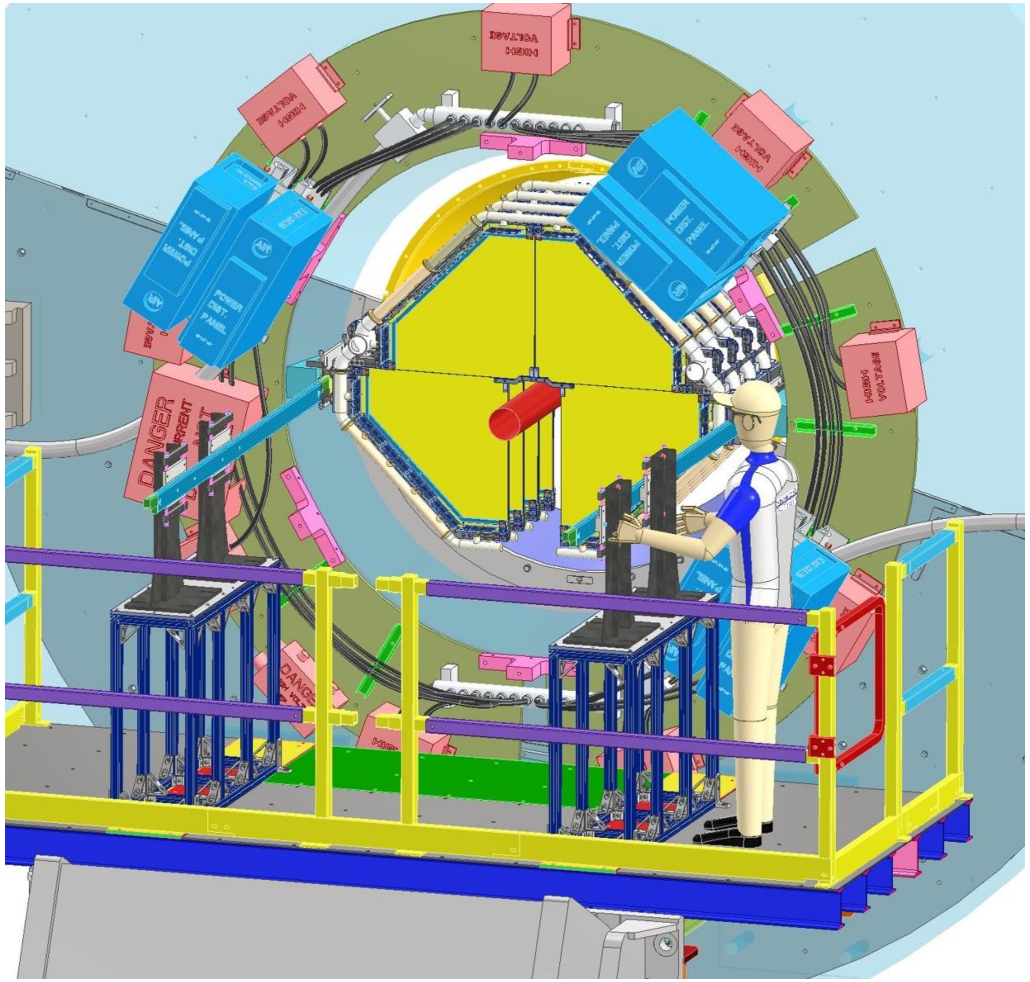
- Once assembled they're ready to be moved into the STAR hall

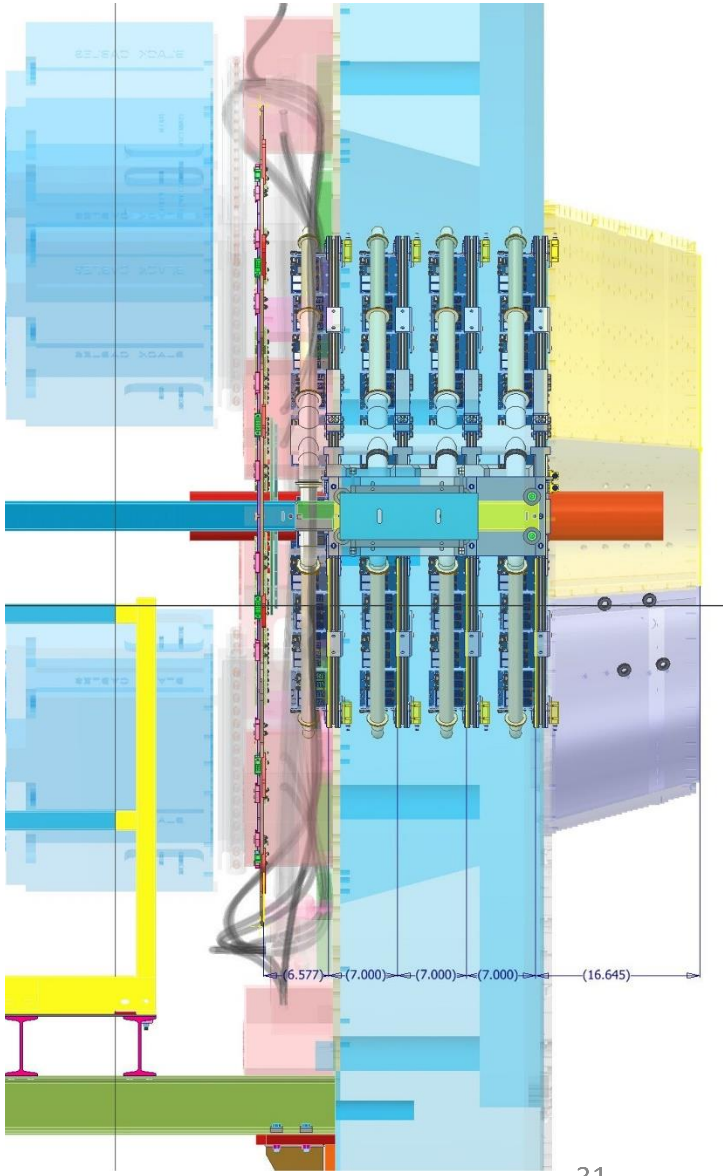




Future: installation 3

- From there they're brought on a lift and secured behind the STAR poletip

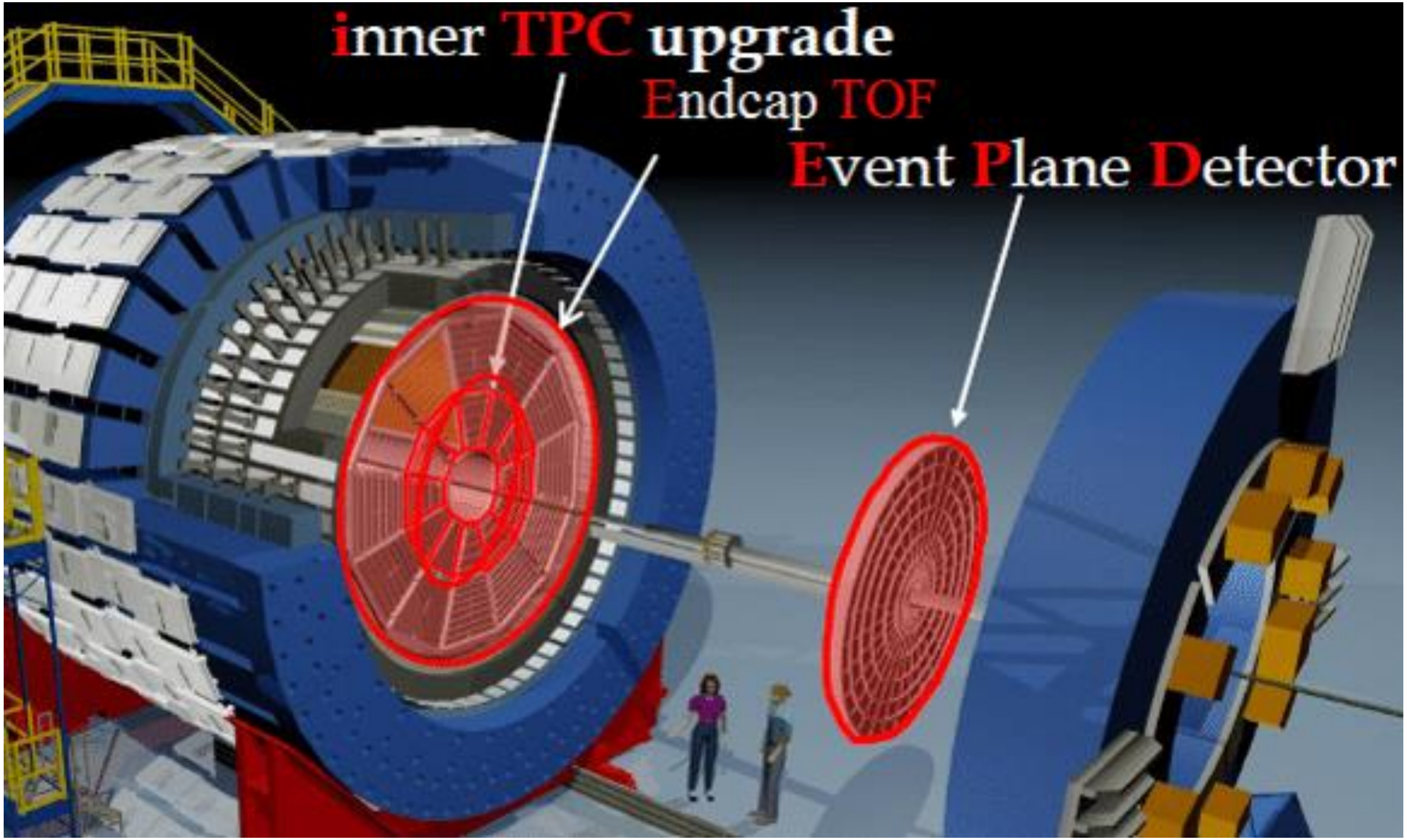




Extra STAR view

- The pole tip is the large piece of blue iron on the right

- It gets closed before we take data



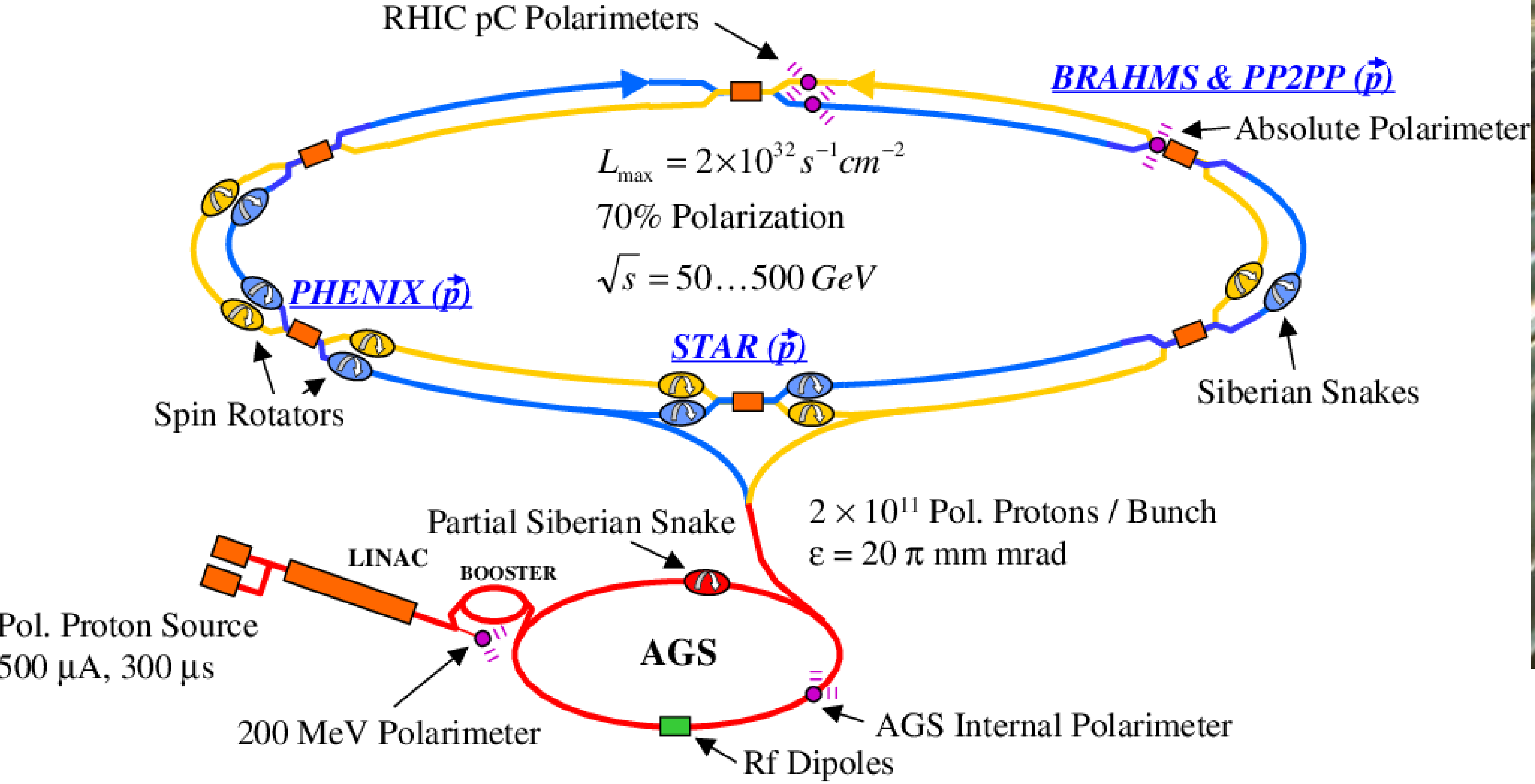
Why a forward upgrade?

RHIC

- RHIC is an incredibly versatile collider
- Systems: p, d, t, O, Al Cu, Zr, Ru, Au, and U (+ combinations thereof)
- Collider energies: 7.7 – 200 GeV (ion), 500 GeV (pp), and 3 – 7.7 GeV (fixed-target)
- In addition to this, RHIC can collide transversely and longitudinally polarized protons

RHIC polarization schematic

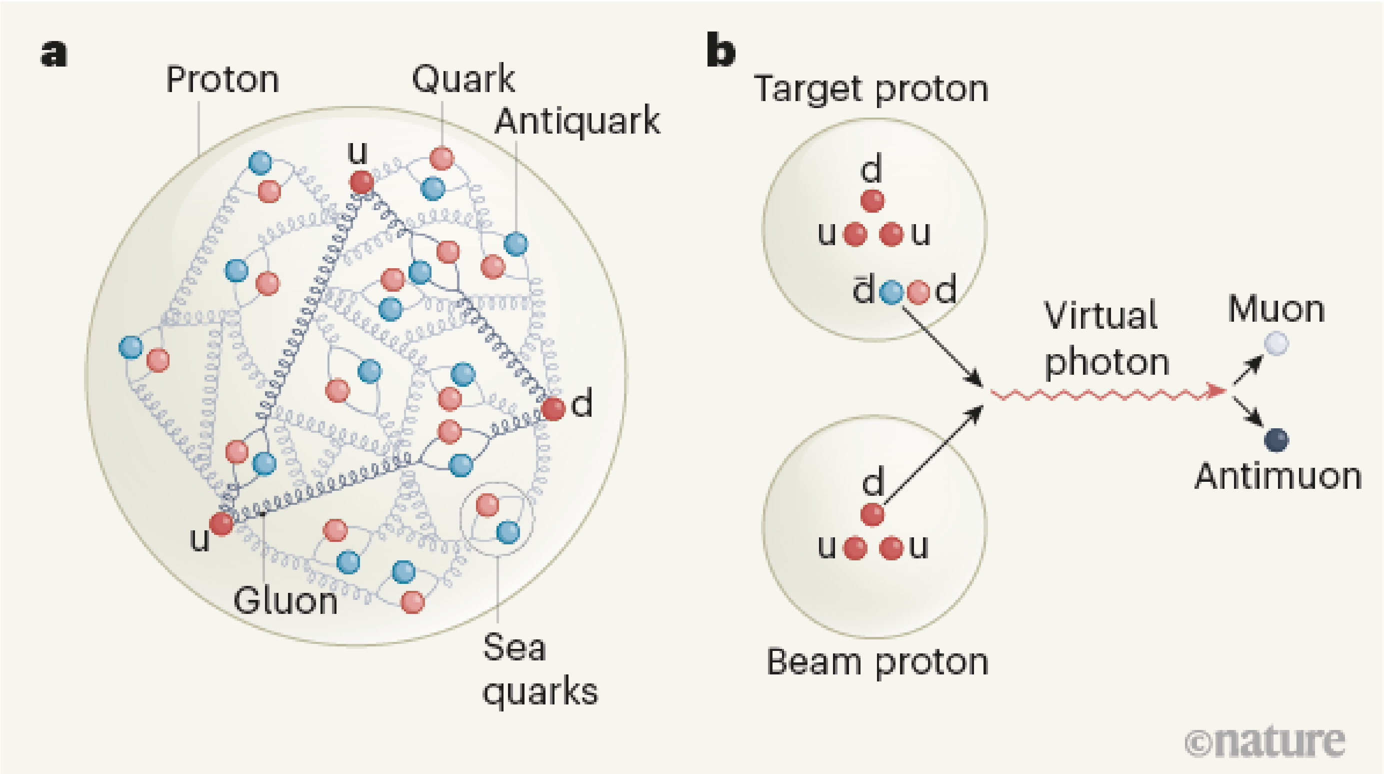
- Forward upgrade largely driven by spin physics (a truly unique capability at RHIC)
- Heavy-ion physics also hopes to learn something along the way

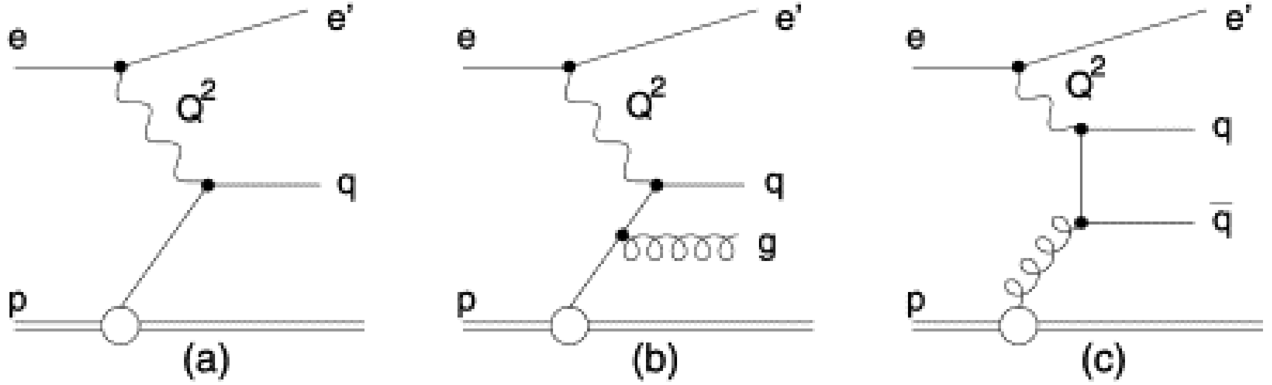


Siberian snake polarizing magnets

Picture of a proton

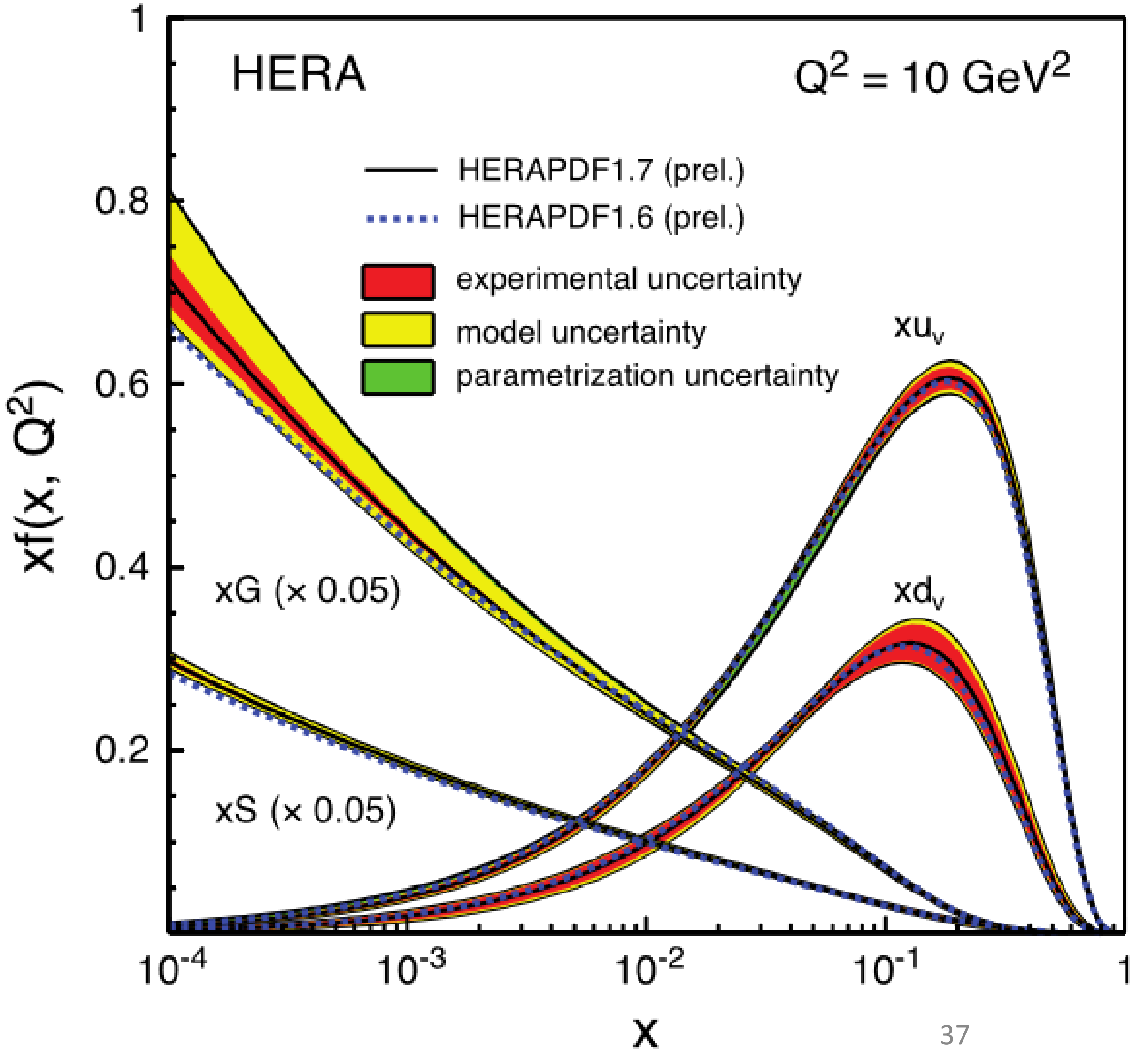
- It is natural to think of the proton as being composed of only its valence quarks (uud), however this is simplistic
- Protons are also composed of off-shell sea quarks and gluons
- The momentum fraction of the constituents can be determined via deep inelastic scattering (scattering a lepton onto a hadron)





DIS -> PDF

- This momentum fraction (x) is generally plotted against xf, the fraction of the proton's momentum coming from each constituent.
- At low x this is dominated by gluons
- The particular shape will also depend on the momentum transfer of the lepton (Q^2)
- This distribution is the Parton Distribution Function (PDF)



Nuclear PDF

- At RHIC we're interested in many emergent properties of large systems.
- Effects from the distributions of partons are often seen in our observables
- Though free-nucleon PDFs are well constrained, the PDF of a nucleon bound inside of a large nucleus is not
- In order to better understand and constrain our measurements we need to such distributions, called nuclear PDFs (nPDFs)
- Such distributions are not measured directly, but calculated via models from spin measurements of pA data

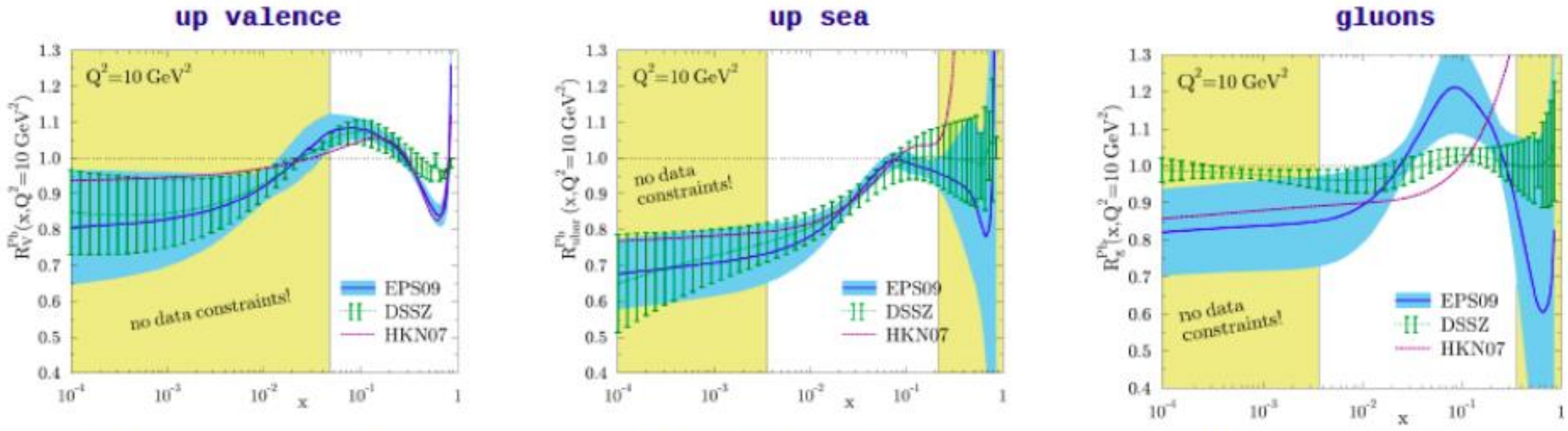


Figure 2-15: Summary of the most recent sets of nPDFs. The central values and their uncertainty estimates are given for the up valence quark, up sea quark, and the gluon. The yellow bands indicate regions in x where the fits are not constrained by any data (taken from Ref. [67]).

Nuclear PDF – Forward Upgrade

- STAR can compete with the EIC in a way the LHC cannot
- This provides not only useful unique data, but also a measurement for the EIC analysis to compare to
- It has also been suggested that we take p-Al data to further map out the p-A dependence of the nPDF
- Forward instrumentation increases the x range of the measurement

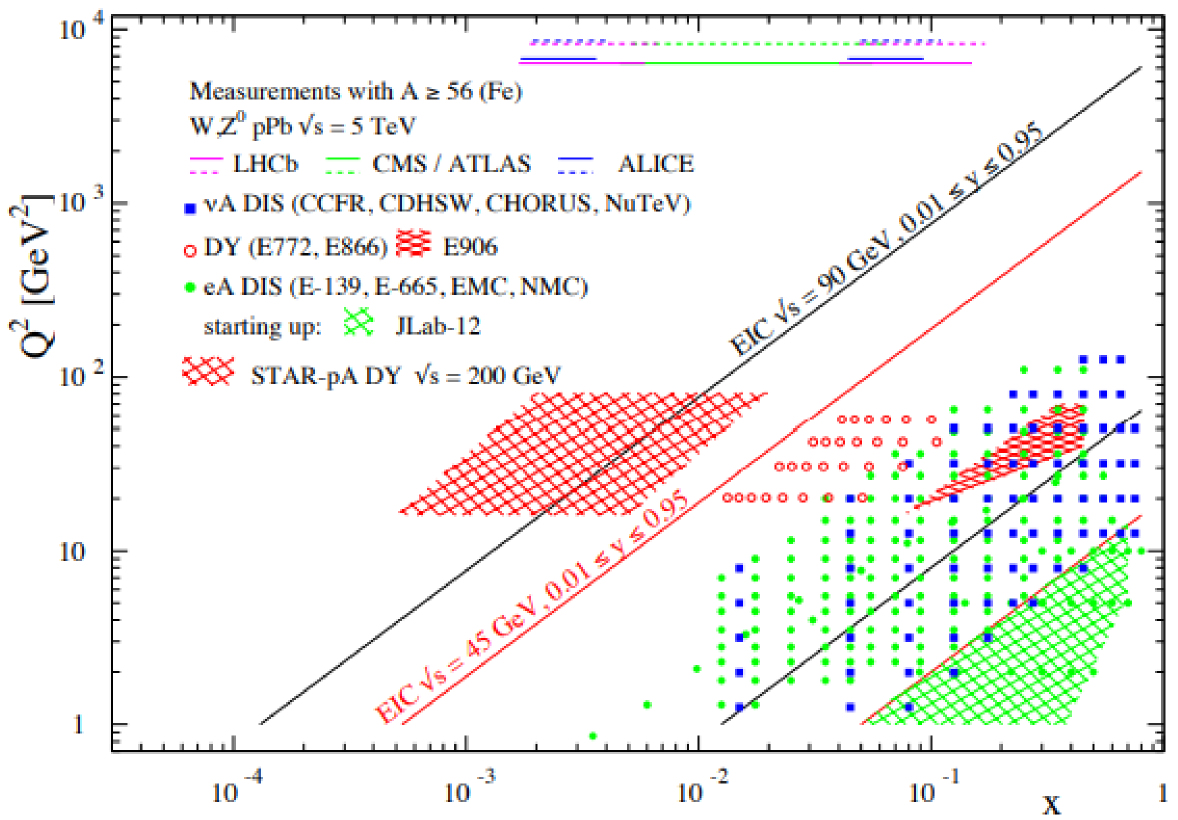


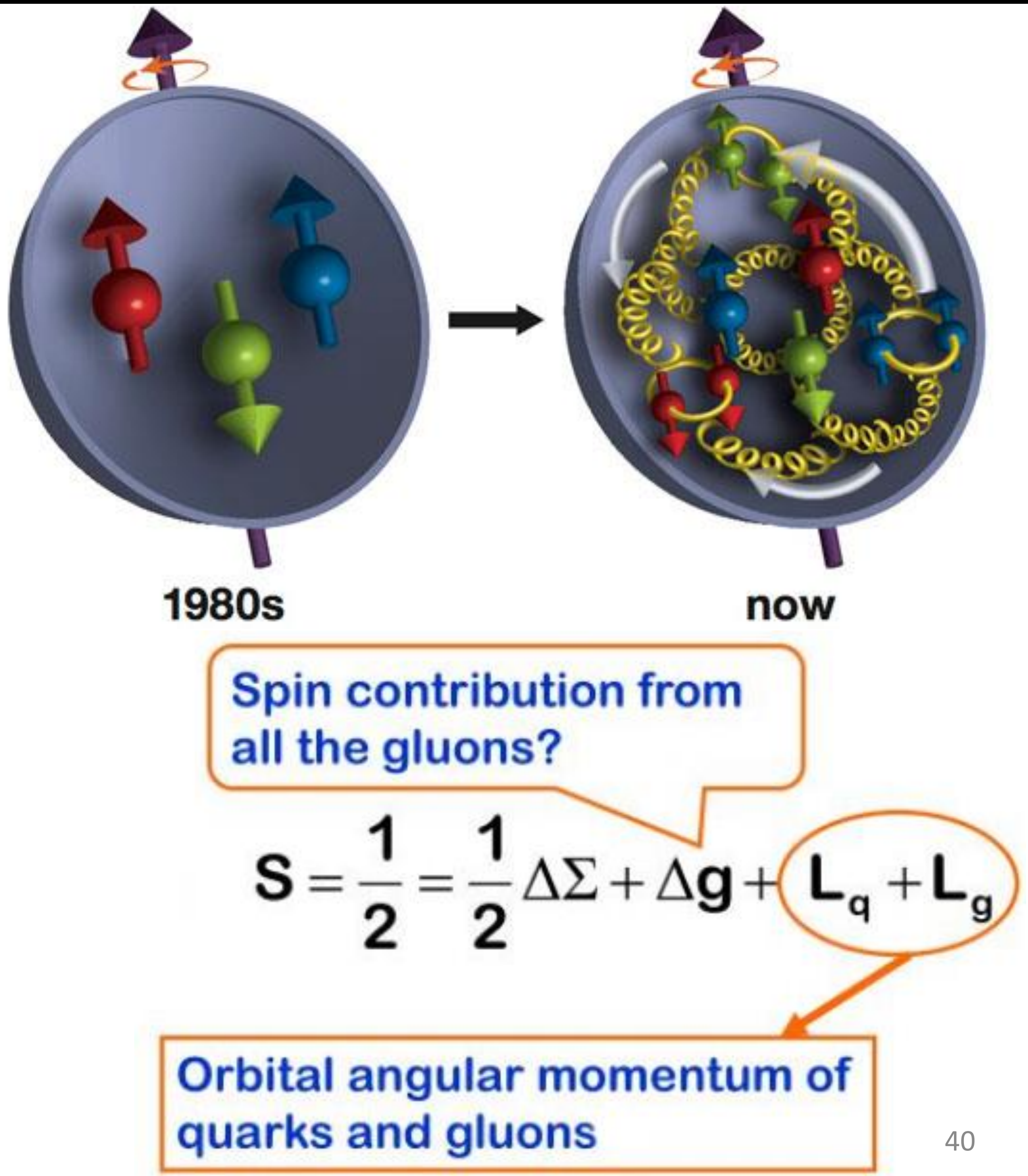
Figure 2-20: The kinematic coverage in x–Q^2 of past, present and future experiments constraining nPDFs with access to the exact parton kinematics event-by-event and no fragmentation in the final state.

Proton spin

- In the 1980s physicists assumed the spin of the proton came from the simple addition of the spin of the valence quarks

- The EMC experiment proved that quark spin was a small fraction of the proton spin (called proton spin crisis!)

- Where is the missing angular momentum?
  - In the gluons and the orbital angular momentum of the partons

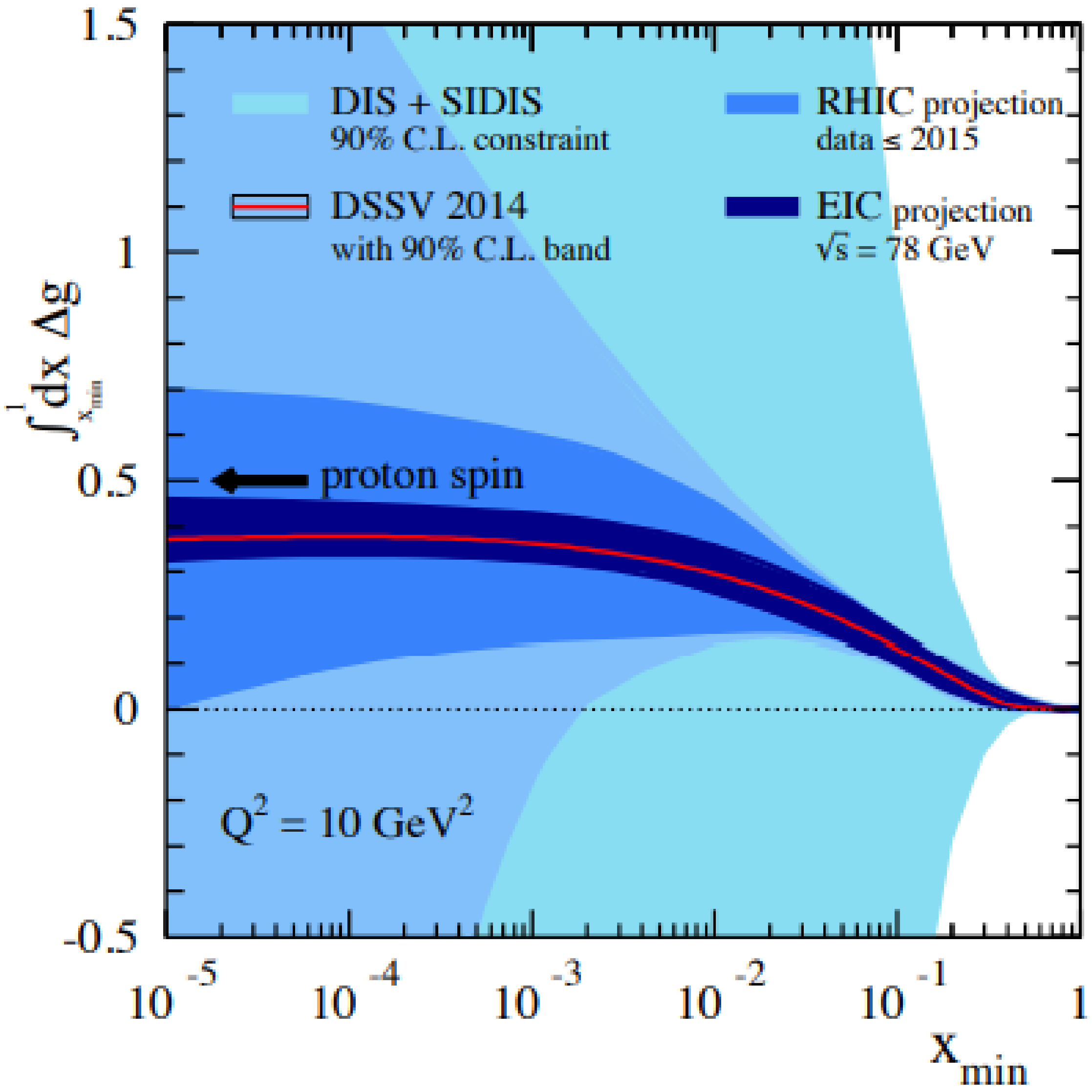


Gluon spin component

- Measurements at pp 500 GeV can constrain the gluon polarization component of the proton spin

- This again is the product of a fit of measurements, in this case dijet measurements, which can be done at STAR

- Forward instrumentation allows measurements at wider ranges of x to better constrain the fits.



Transversity

- Spin degrees of freedom are different for transversely polarize protons.
- Knowing both distributions give insight into physics which is beyond the scope of this talk
- The coverage of STAR's measurements of the Collins and Sivers asymmetries are greatly enhanced in the forward region

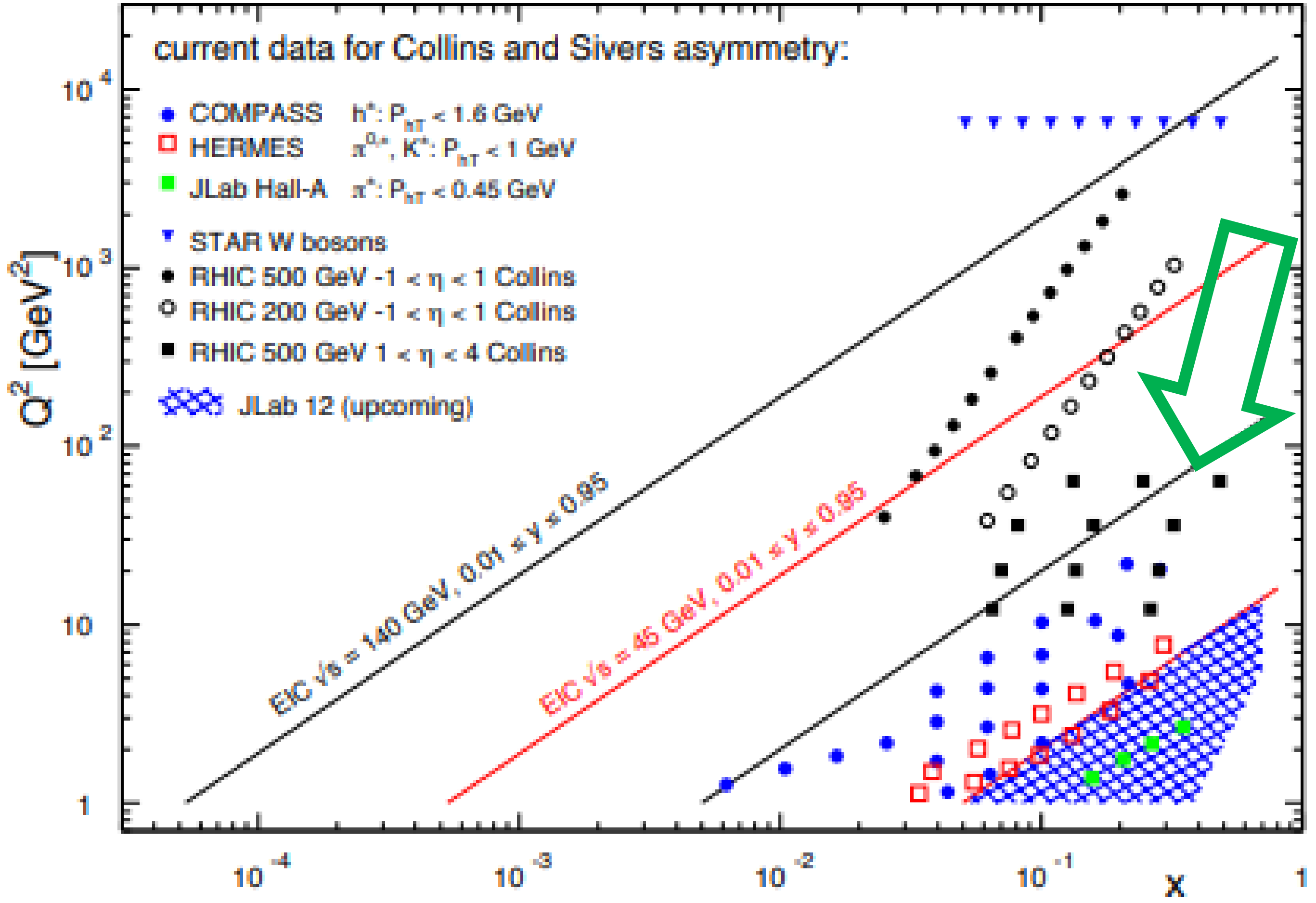


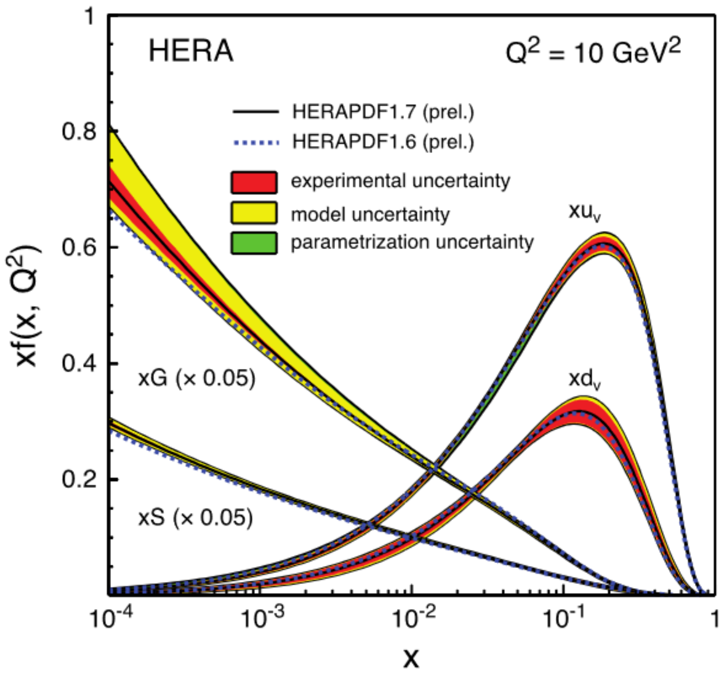
Figure 2-6: The x-Q^2 plane for data from the future EIC and Jlab-12 GeV as well as the current SIDIS data and the W-boson data from RHIC. All data are sensitive to the Sivers function and transversity times the Collins FF in the TMD formalism.

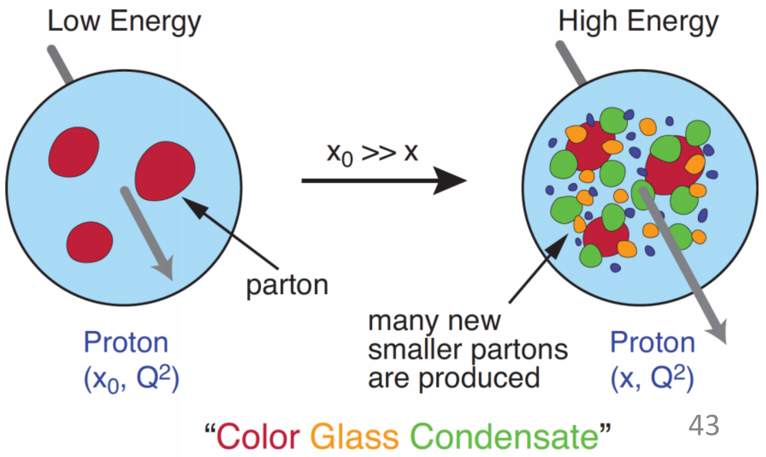
Saturation

- At arbitrarily low x the gluon component of the PDF dominates, but it is expected that there is a regime at which the production of partons is balanced by their recombination. This is called gluon saturation

- Saturation provides an infrared cutoff of the strong coupling constant, allowing tree-level perturbative QCD calculations
  - Essentially we have deconfinement

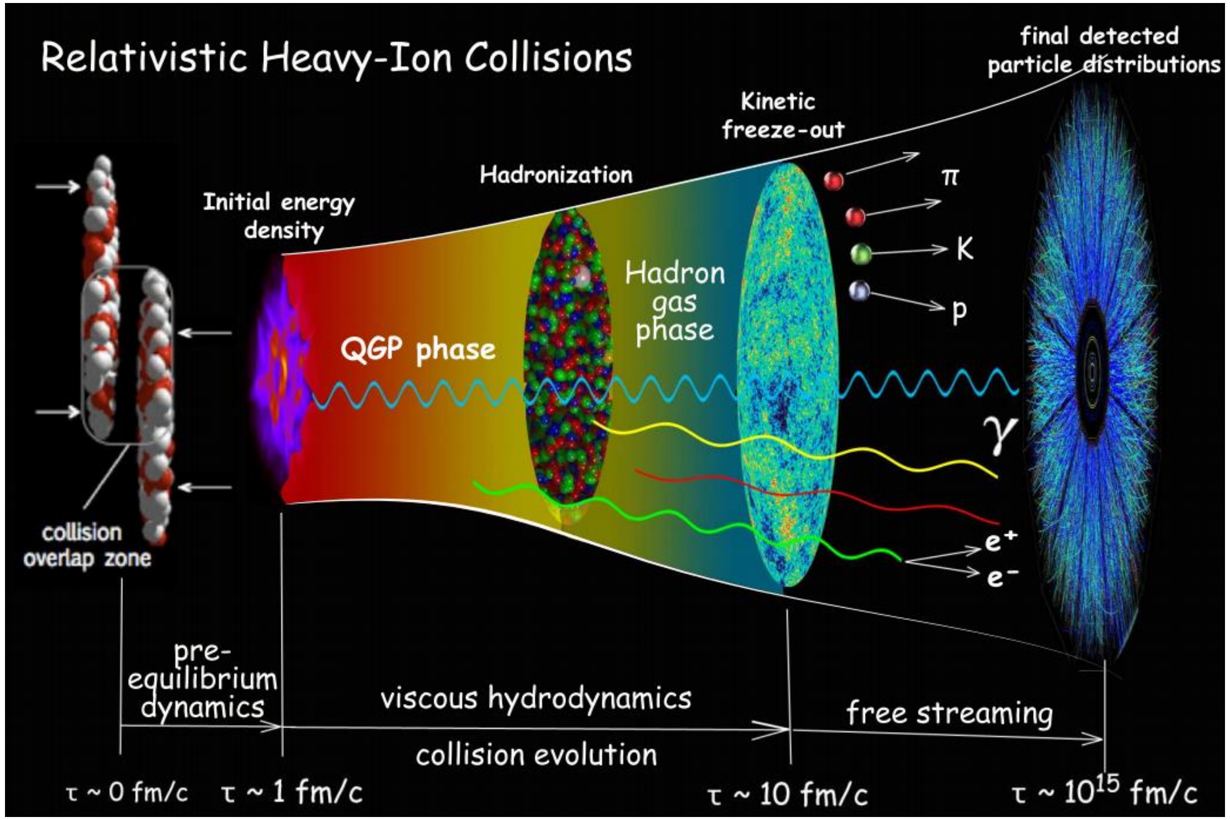
- The saturation scale grows with system size (A), so study pA collisions





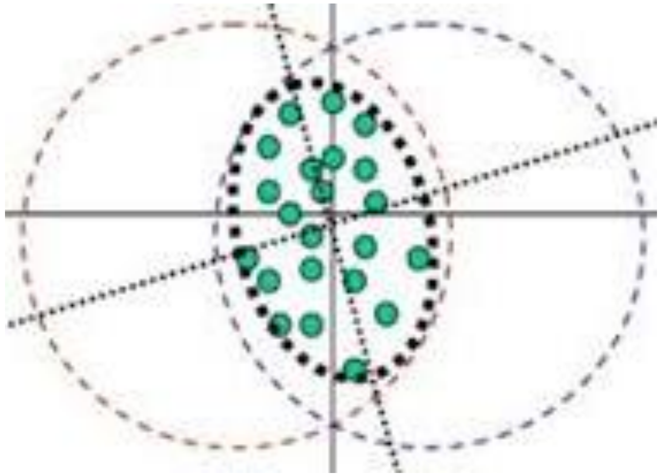
Why care about saturation?

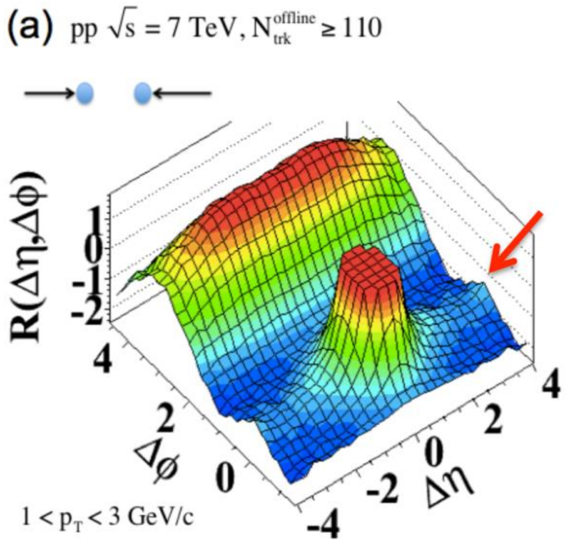
- The standard model of heavy-ion collisions looks like this →
- The data we get is at the extreme right of this evolution
- In order to learn something about the medium phase – the Quark Gluon Plasma (QGP) we have to project backwards in time via models
- Such models, e.g. hydrodynamics start after the pre-equilibrium dynamics, which are poorly constrained
- Typically models use a parameterization, but real calculations may be possible with saturation physics

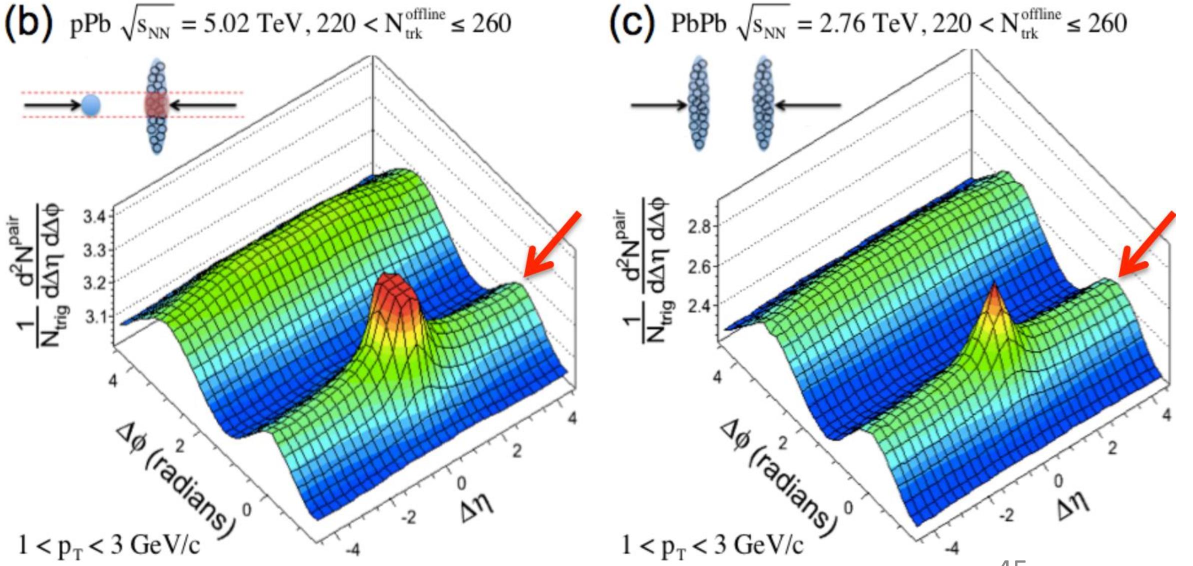


Flow – "the ridge"

- Off-center AA collisions have a spatial anisotropy along the direction of the impact parameter.
- If there is a medium this is translated into a momentum anisotropy, called elliptic flow
- In two-particle collisions this causes a long-range (large η) correlation at Δφ=0
- ATLAS has seen a ridge in *high multiplicity* pp collisions adding to a heated debate on if QGP is possible in such small systems
- With a forward upgrade STAR can make plots with comparable η ranges







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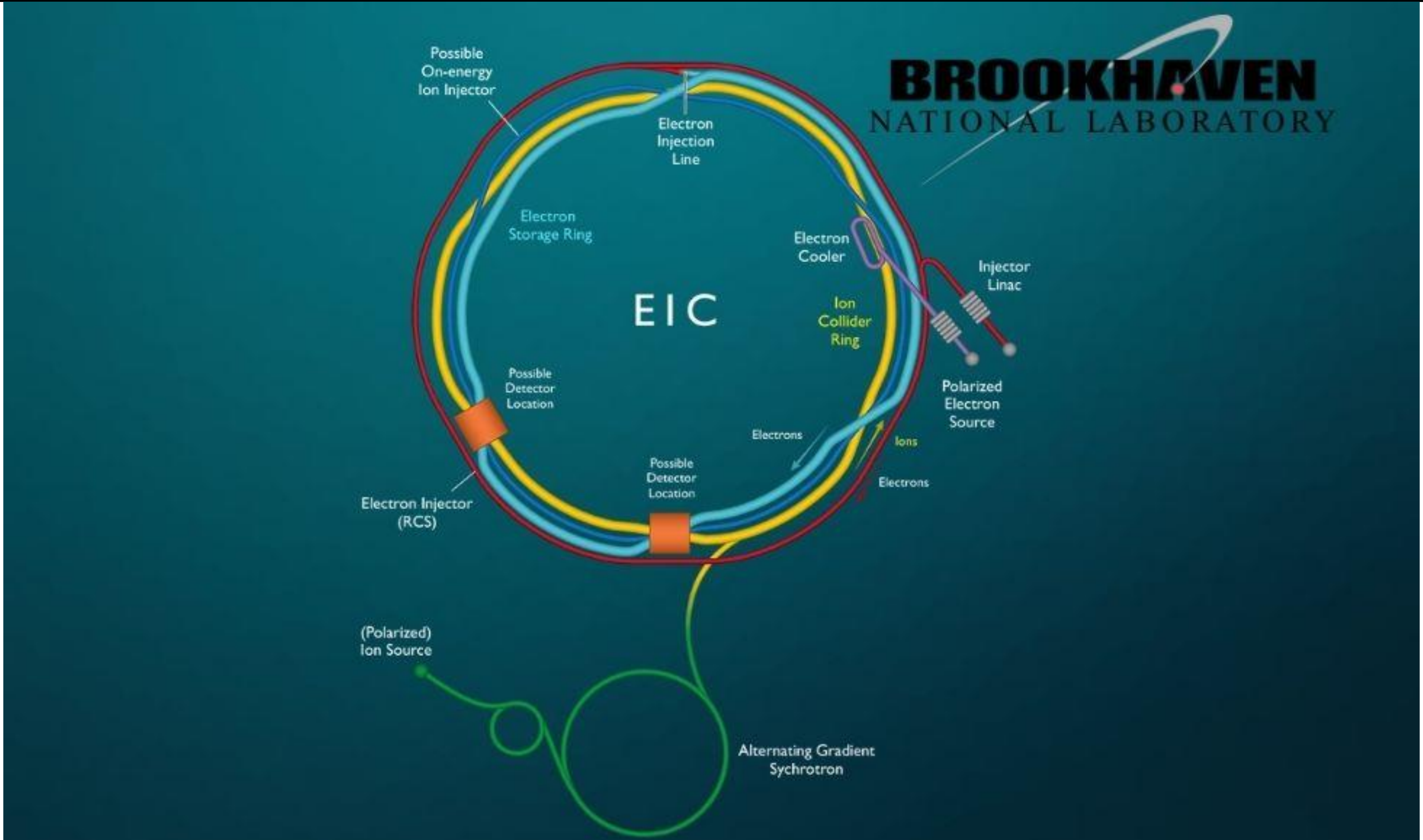
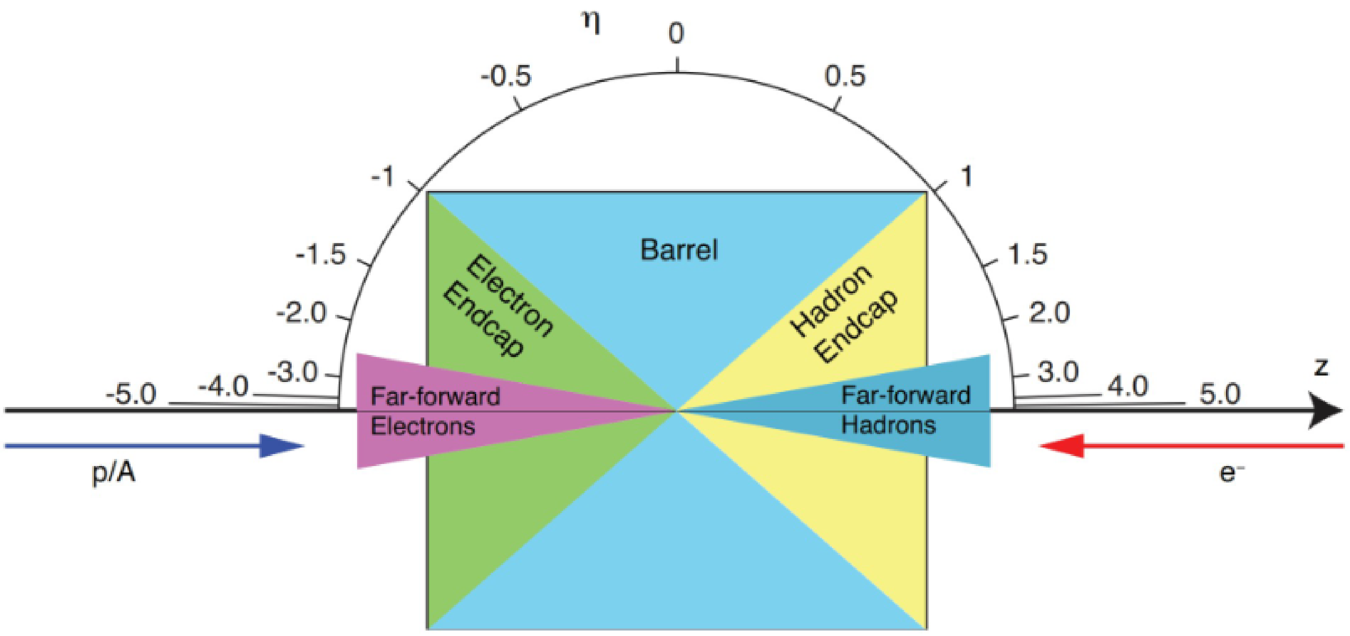
Electron-ion collider @ BNL



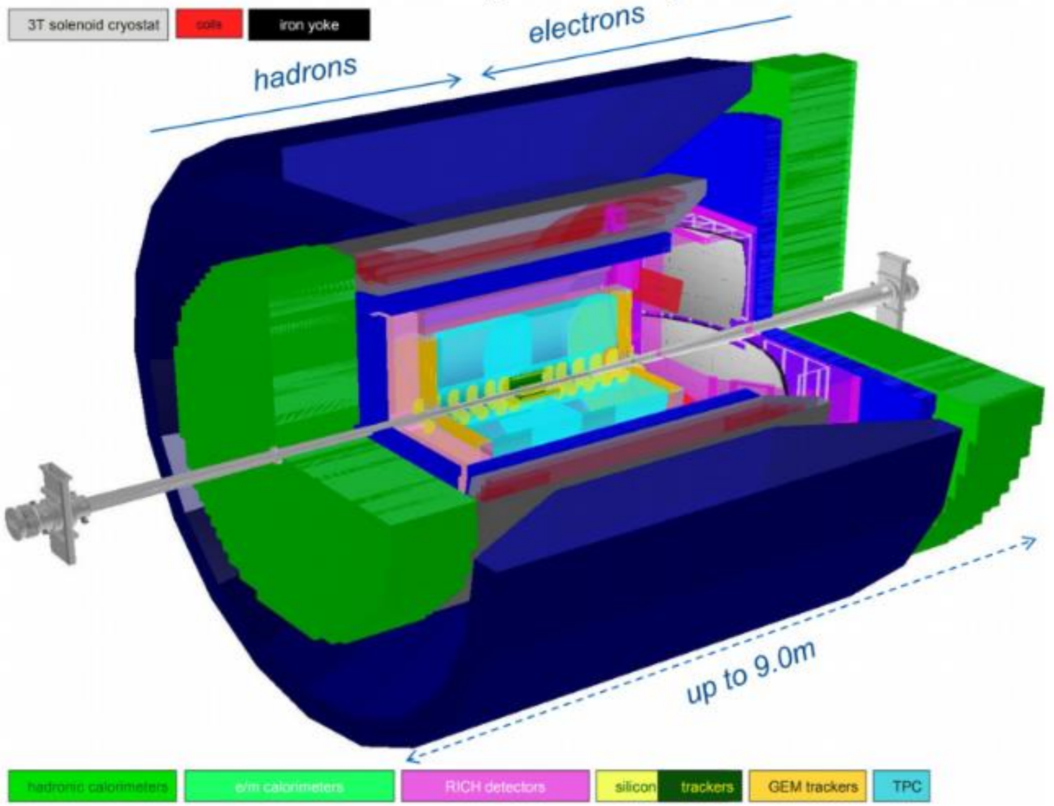
EIC detector requirements

- Far-forward tracking and PID essential for an EIC detector
- Good to have trackers before PID (RICH) and between PID and calorimeters
- For reasonable momentum resolution at p = 30-50 GeV/c, 50 μm spatial resolution is desirable (EIC handbook)
- Because the magnetic field drops at large |z|, detector should be thin to precisely constrain hit in z
- Detector should be low mass
- sTGC may be more cost effective alternative to MAPS and GEMs

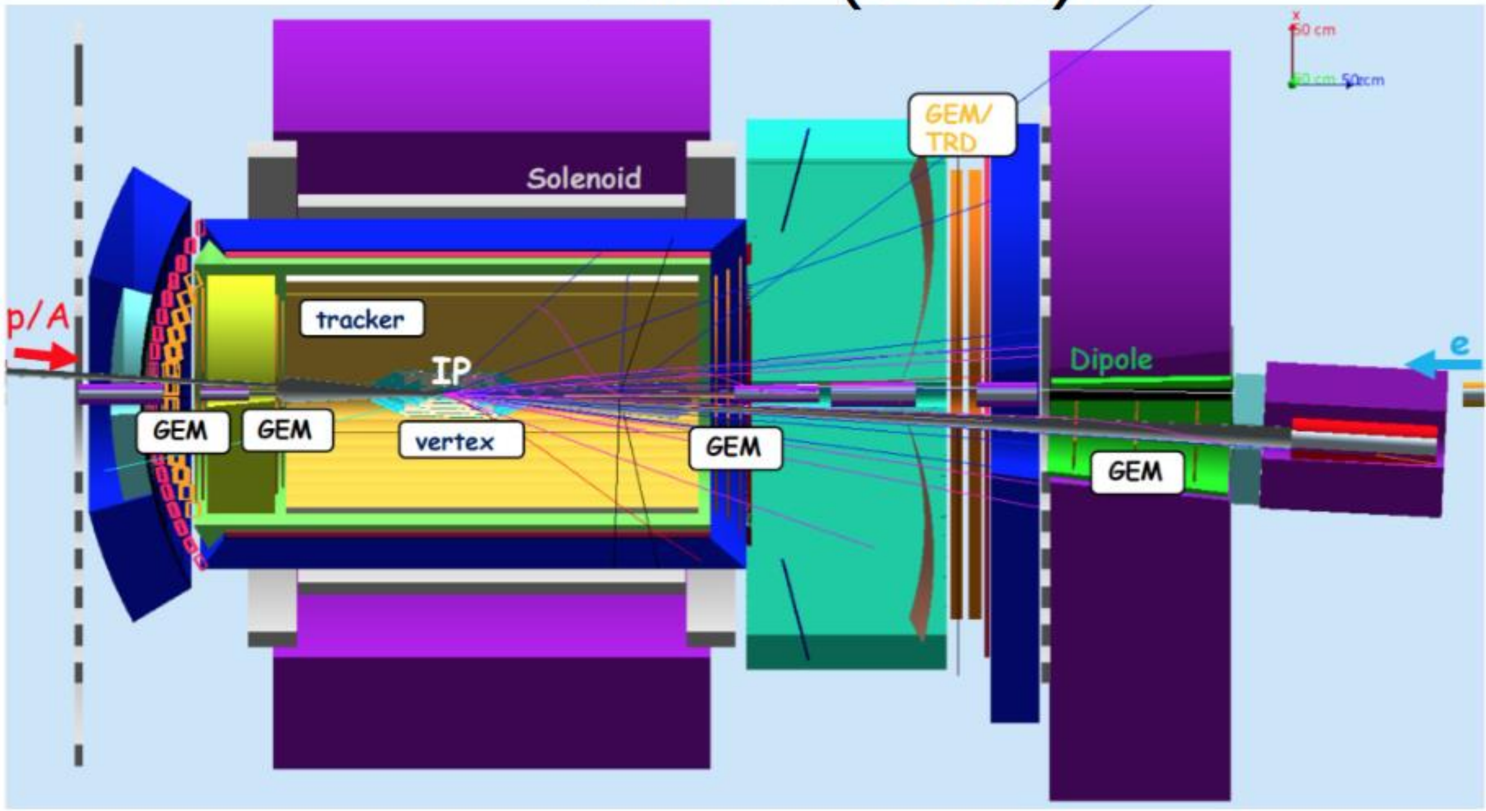


EIC concept detectors 1

BeAST (BNL)

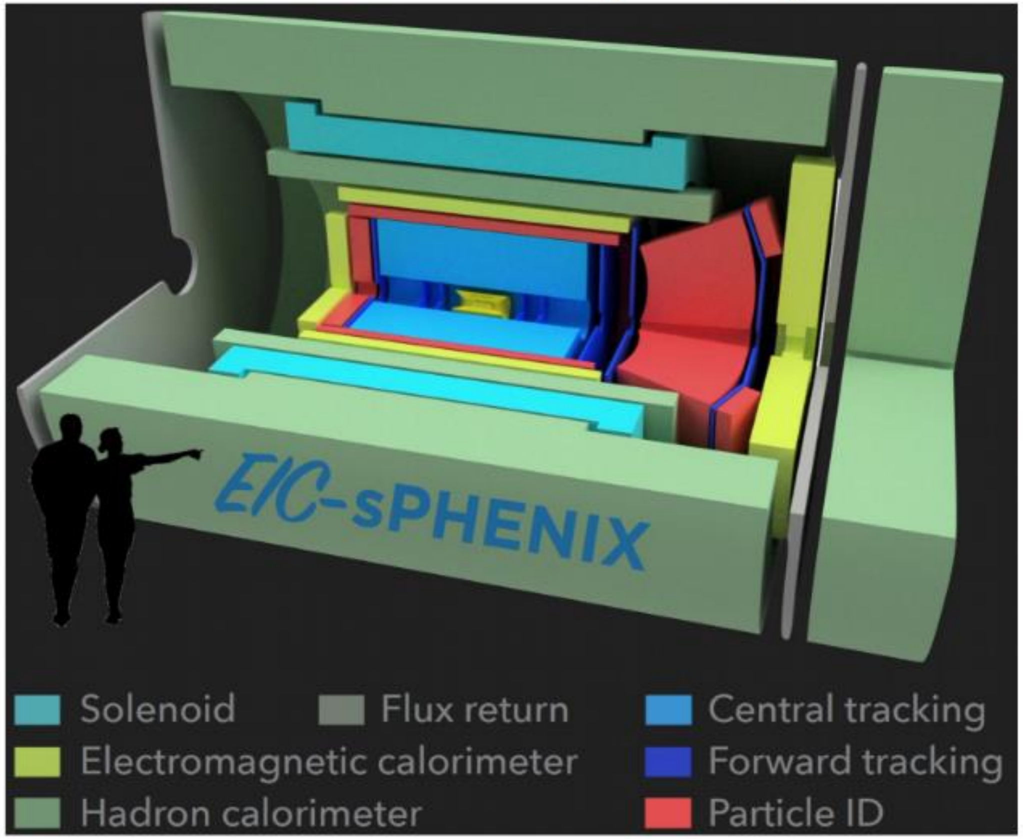


JLEIC (JLab)

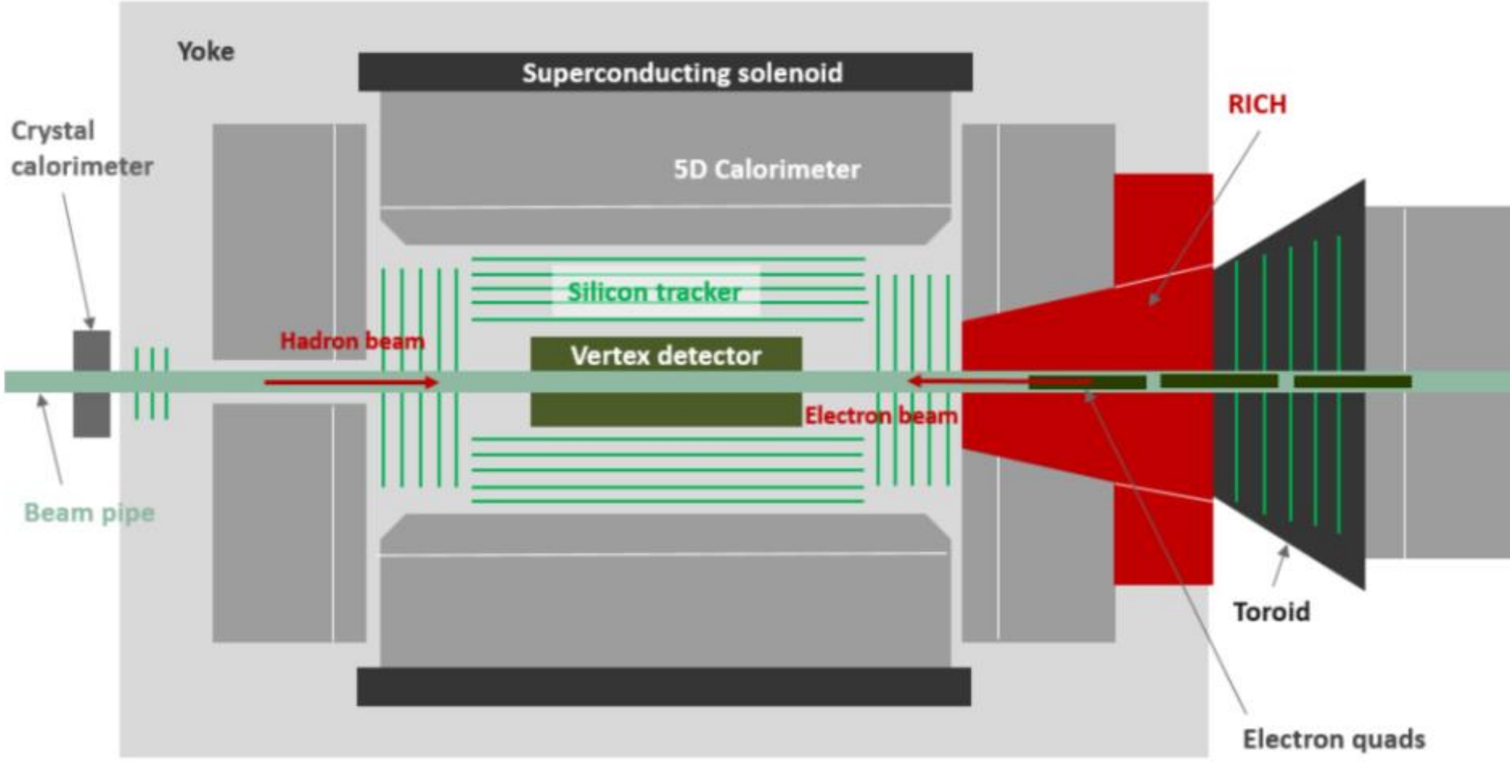


EIC concept detectors 2

ePHENIX (BNL)

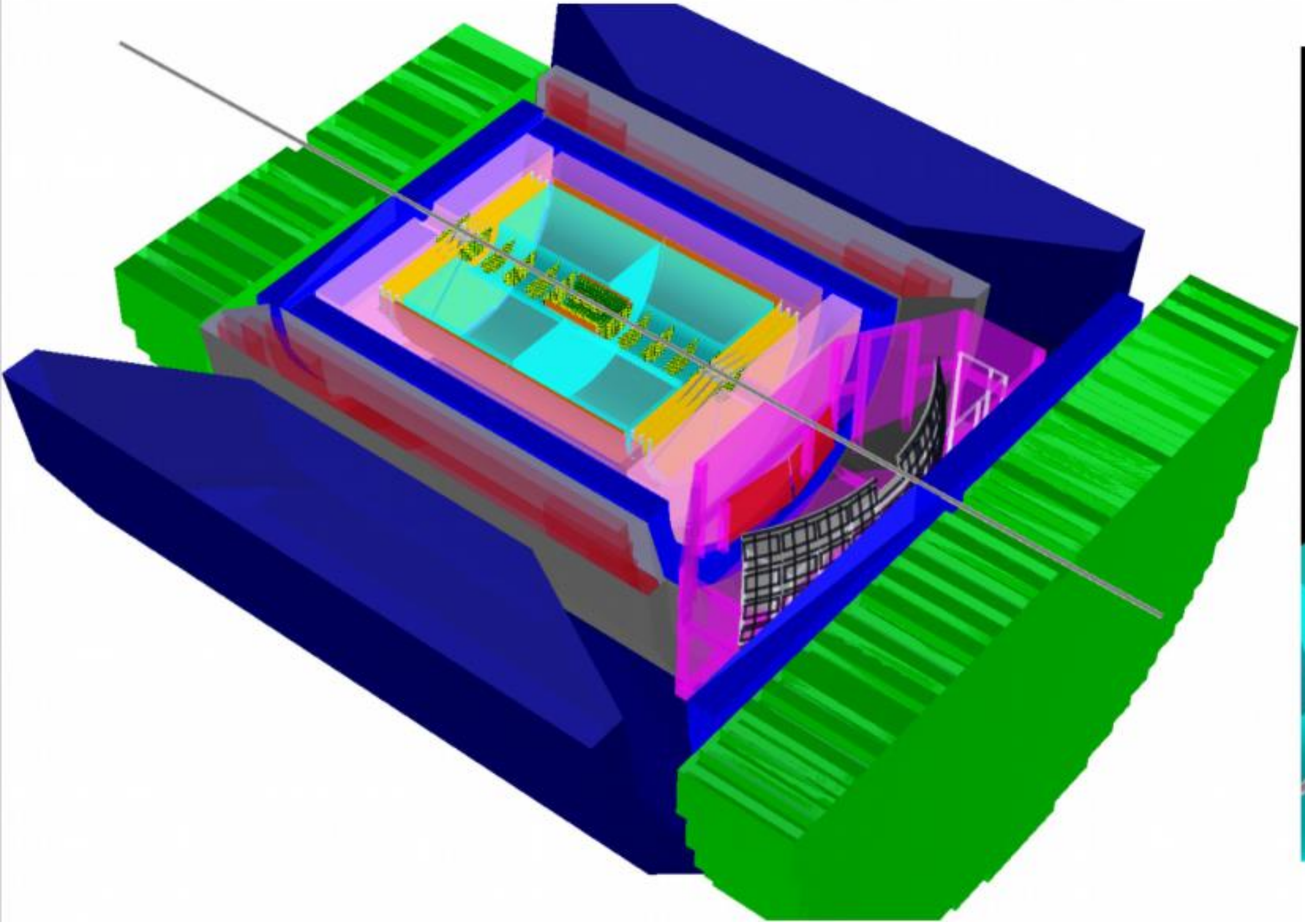


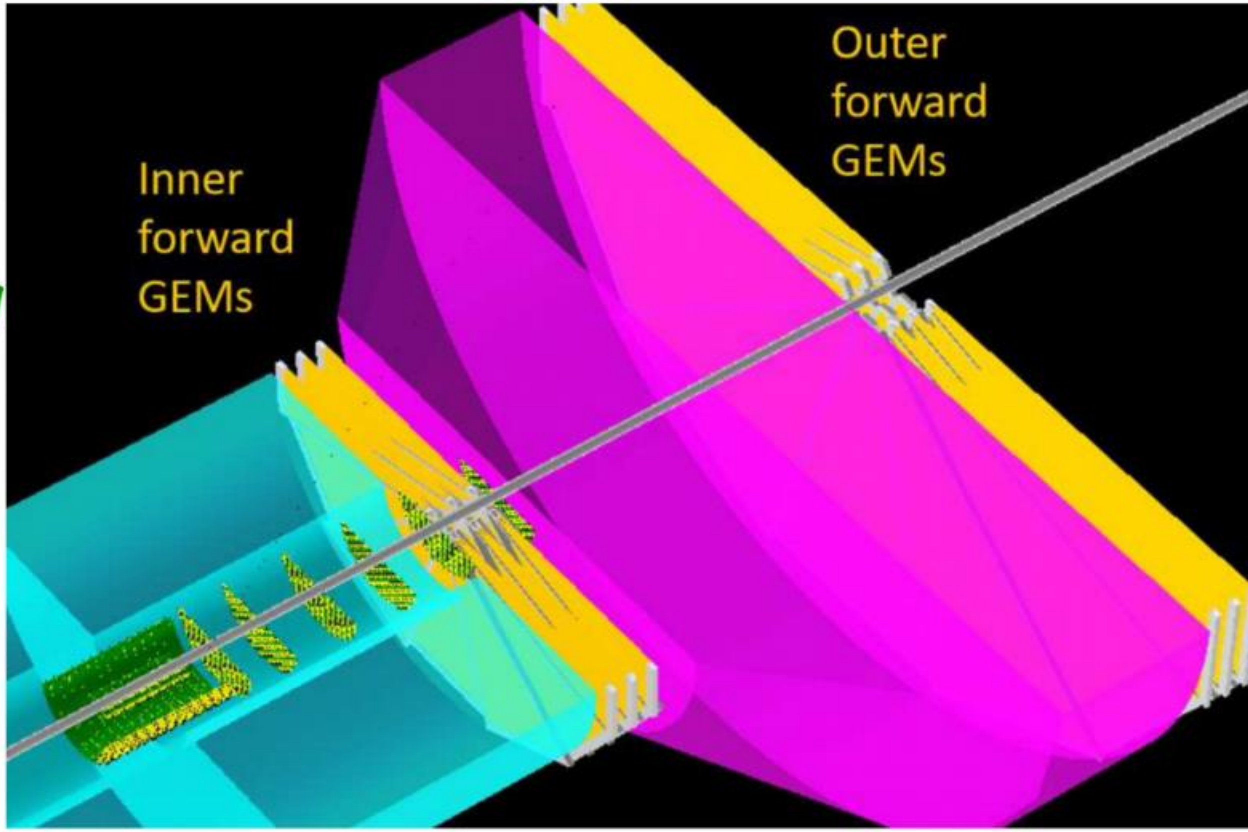
TOPSiDE (ANL)



sTGC @ EIC

- STGCs could replace GEMs, especially the larger outer forward GEMs, which have looser resolution requirements





Conclusions

- sTGC has managed to stay within time and hit all major QA guidelines so far
  - Important consideration for EIC detectors
- Burning still in progress
- Installation work yet to be done, as well as some remote control software work
- After this it should be ready to take data and we can see how well it can track!