The Compact TPC of the sPHENIX Experiment

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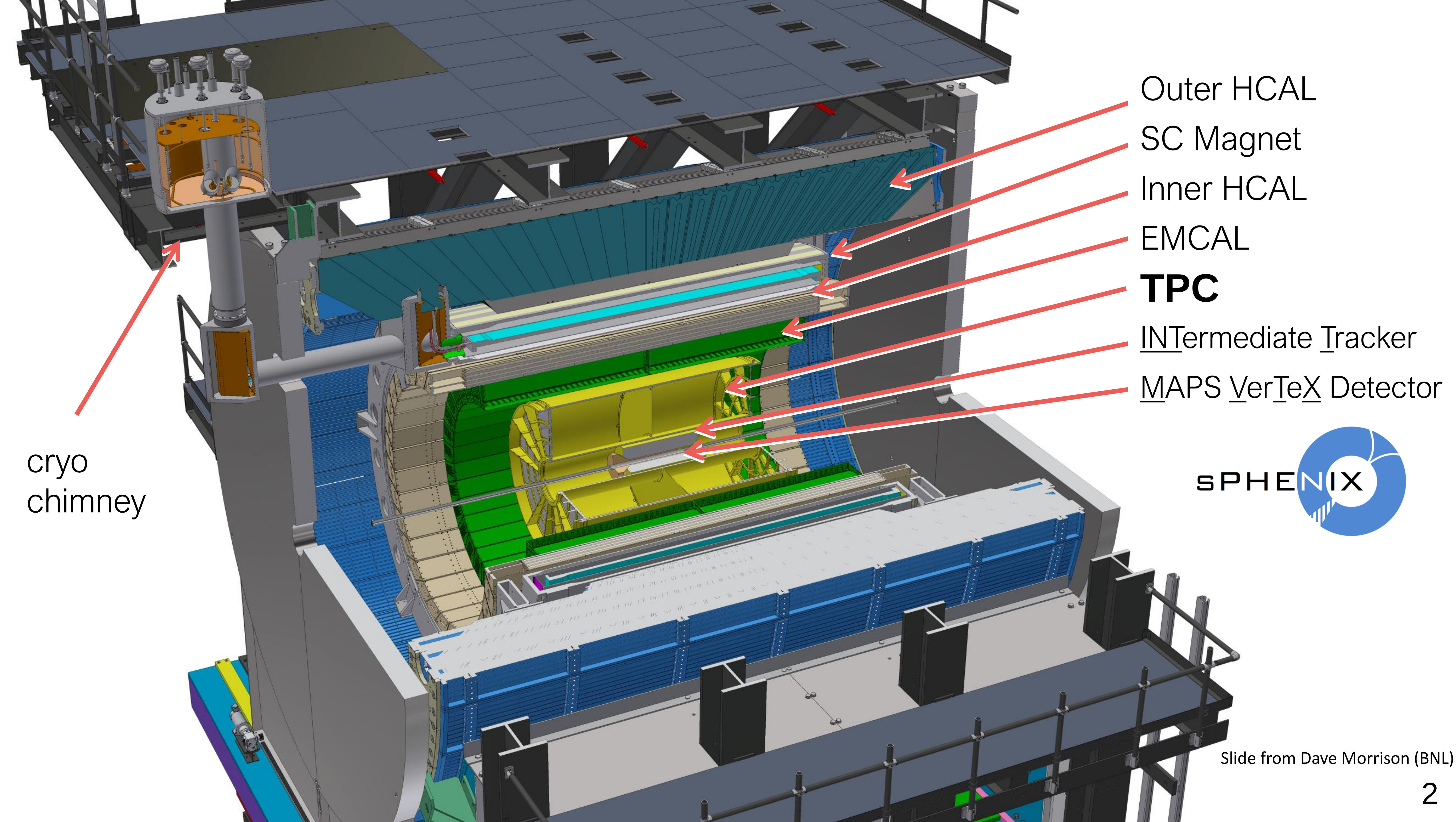
TIPP 2021 International Conference on Technology and Instrumentation in Particle Physics

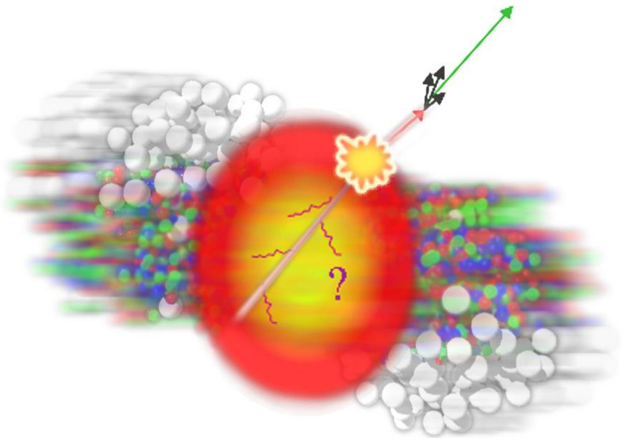


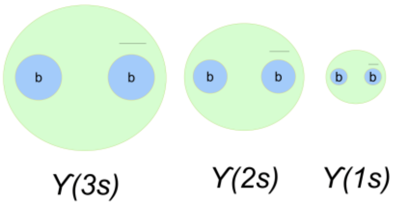
sPHENIX

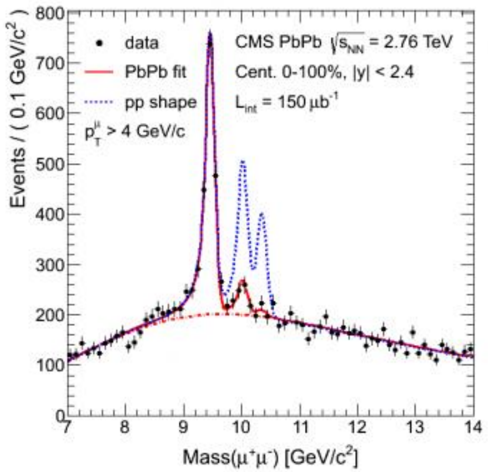
Slide from Dave Morrison (BNL)

sPHENIX Physics Goals

- Studying QGP in Heavy Ion Collisions at RHIC
  - High multiplicity, hundreds of particles per event
  - Up to 100 kHz Au+Au event rate available
- Jet Quenching, Parton Energy Loss
  - Jet azimuthal deflection, momentum imbalance, Heavy flavor jet tagging
- Quarkonium Spectroscopy
  - $\Upsilon(1S, 2S, 3S)$, J/ψ daughter electrons measured with invariant mass resolution ~125 MeV
- TPC as Central Tracker
  - Requires high rate capability, large acceptance, excellent momentum resolution

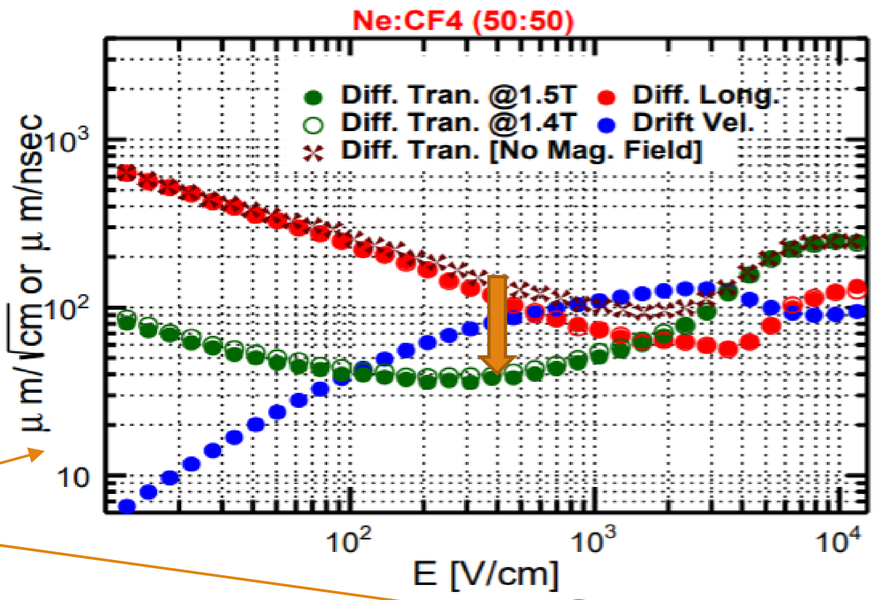




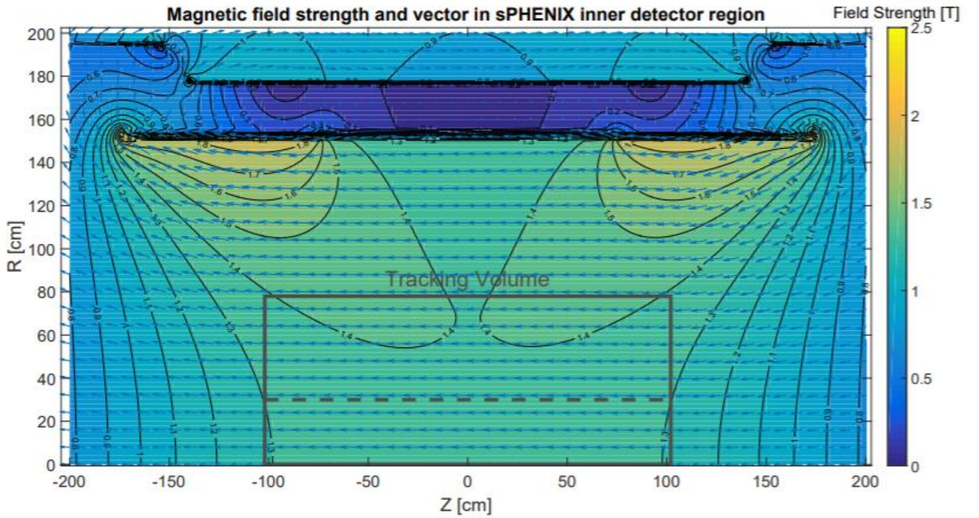


TPC Design Considerations

- **High Position Resolution**
  - 1.4T B-field improves high-p_T momentum resolution
    - Significantly decreases transverse diffusion in gas, σ_x strong function of B
  - Must combat space charge distortion of tracks ⟶ gas selection, laser calibration, ion backflow suppression
- **High Statistics**
  - Maximize statistics for rare probes
  - Streaming readout and ungated gain stage ⟶ **no dead time!**
  - Rate capability increased by a factor of ~10 over gated TPCs
- **Low Material Budget**
  - Minimize multiple scatterings/photon conversions
- **Size**
  - Allow room for calorimetry inside magnet
  - Takes advantage of most uniform section of magnetic field inside solenoid

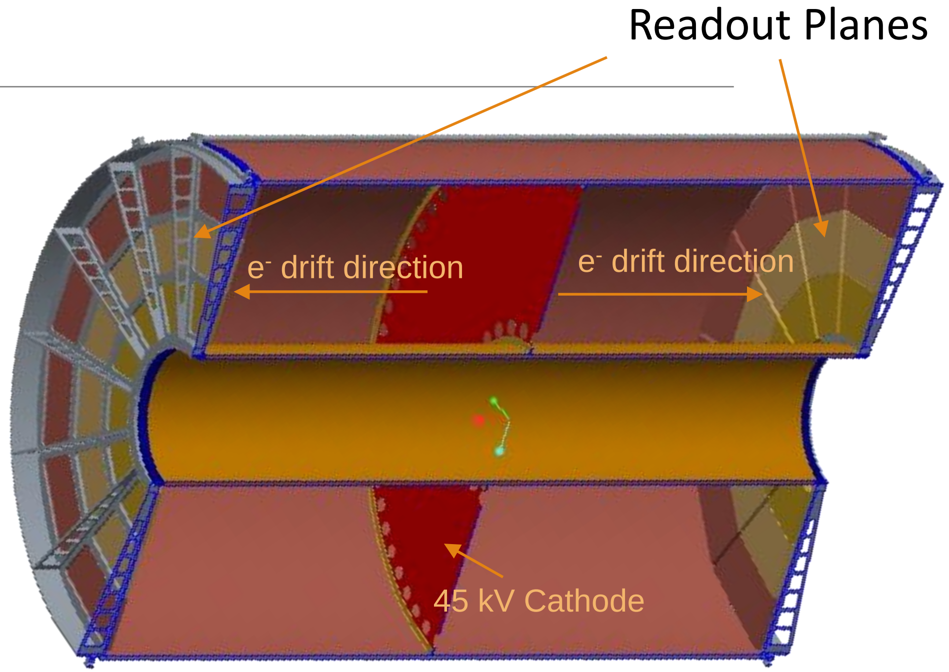


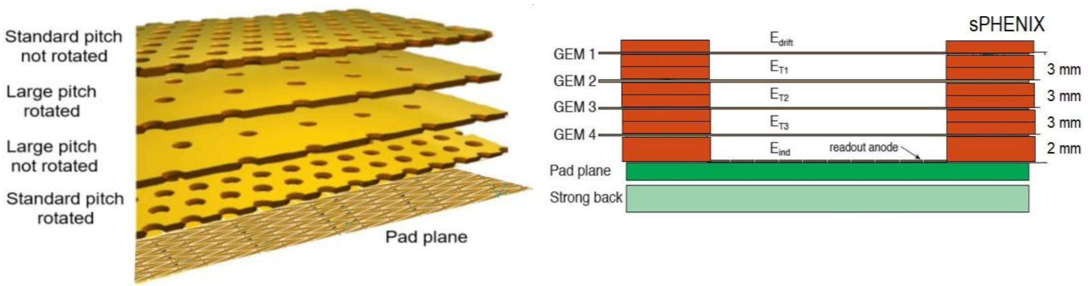
$$\sigma_x^2 = \sigma_{pad}^2 + \frac{D_T^2 L}{N_{eff}} + \sigma_{sc}^2$$



sPHENIX TPC Design

- 20 cm<R<78 cm, |η|<1.1 (2.11 meters long)
  - Outer radius smaller than ALICE TPC inner radius!
- 1-meter drift length in Ne:CF4 50-50 mixture, drift field of 400 V/cm
  - Electron drift needs to be fast to avoid over-occupancy
- Readout segmented 3x in R
- Utilizes Quad-GEM gain stage, a la ALICE upgrade
- Metallized central cathode





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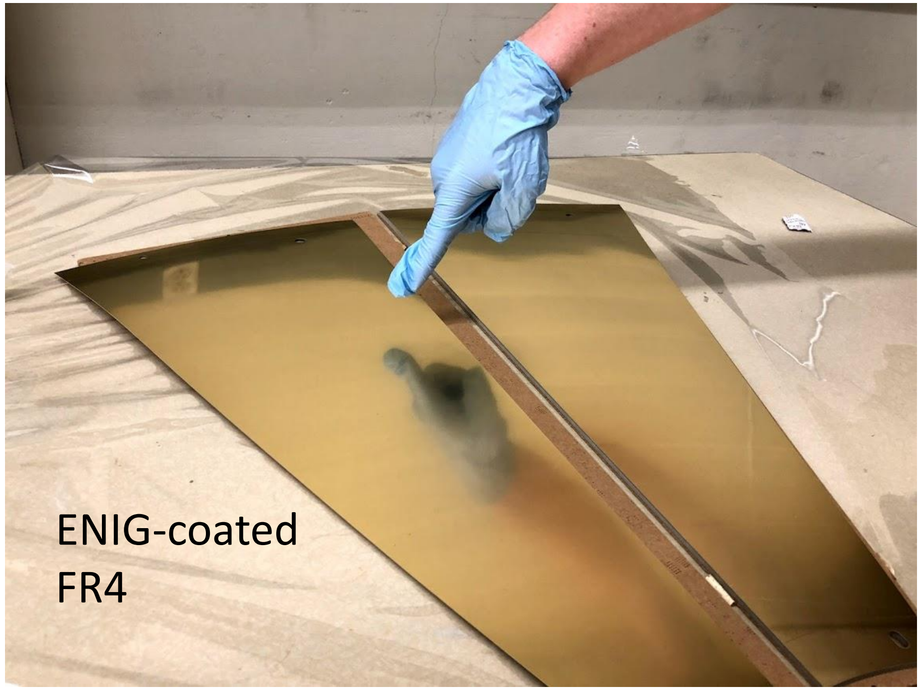
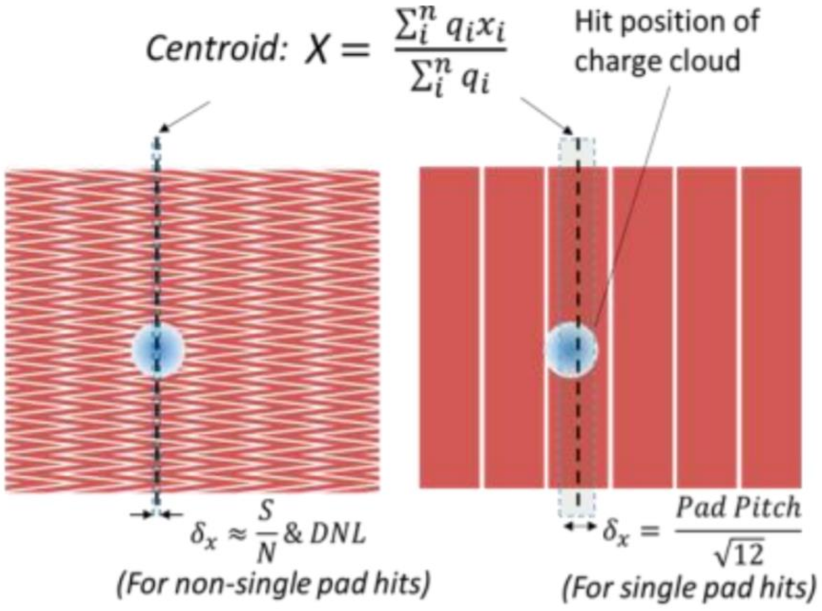


Resolution Optimization

- $\sigma_x \propto \sigma_p$
- Gas choice controls D_T, N_{eff}, and σ_{sc}
- Ne-CF4 50-50 preferable
  - Explored in Garfield++, test beam, and bench experiments
- Zig-zag patterned pads improve σ_{pad} significantly
  - Introduces a small differential non-linearity (correctable!)
    - For more info on readout planes see talk at 8:06 “2D charge-sharing readout planes for GEM, uRWELL and other detector applications” – A. Kiselev
- Space charge predominantly from ion backflow, Quad-GEMs can reduce IBF fraction to 1% or less!

Transverse diffusion coefficient

$$\sigma_x^2 = \sigma_{pad}^2 + \frac{D_T^2 L}{N_{eff}} + \sigma_{sc}^2$$



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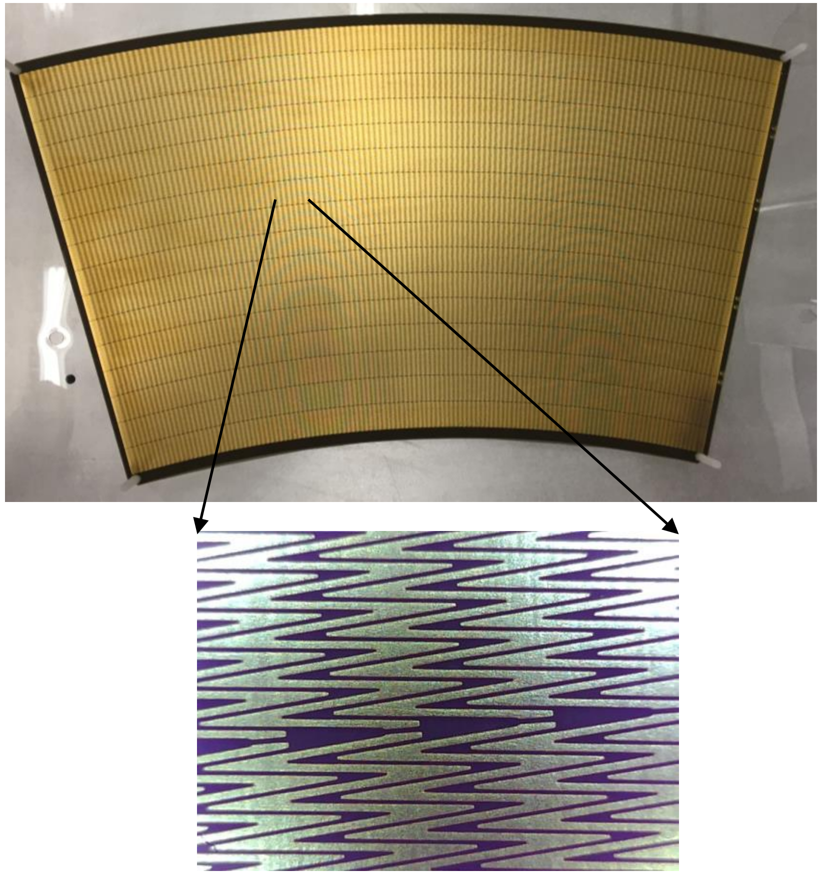
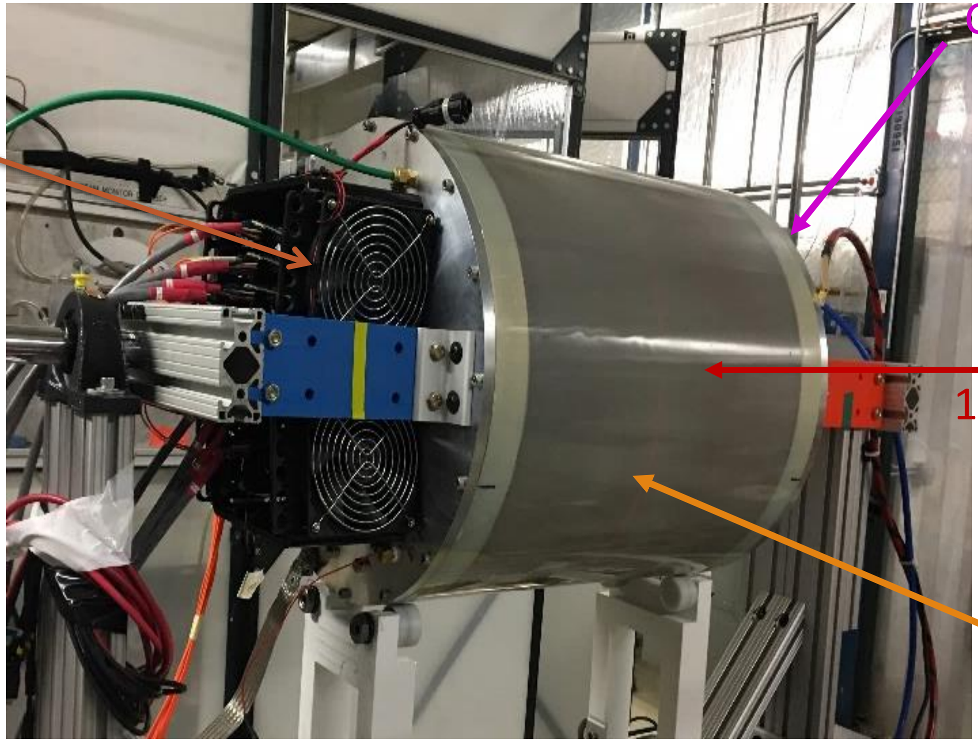


Test Beam Results

- Prototype TPC introduced to 120 GeV/c proton beam at FNAL
- 40-cm one sided TPC with one full readout module (4 GEMs + pad plane + real front-end electronics)
- 3-D position controlled to mimic tracks at different angles, drift lengths



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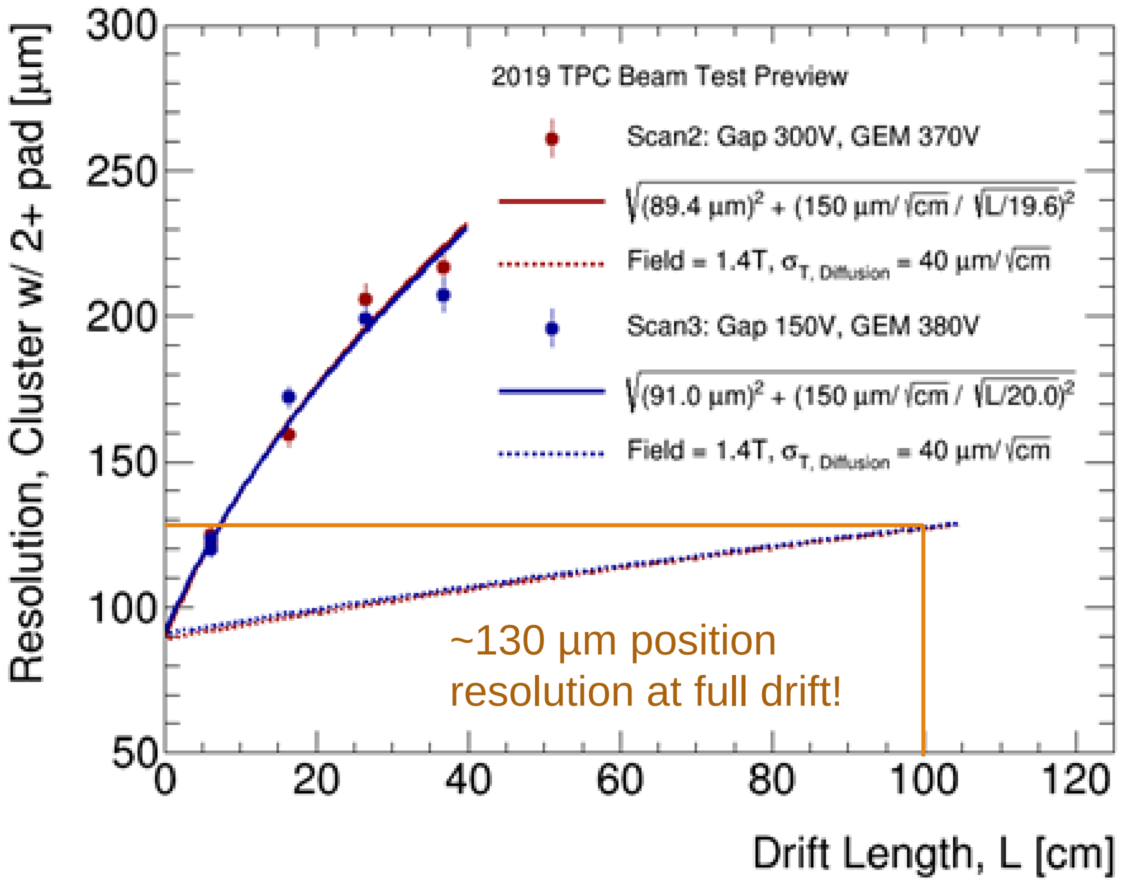


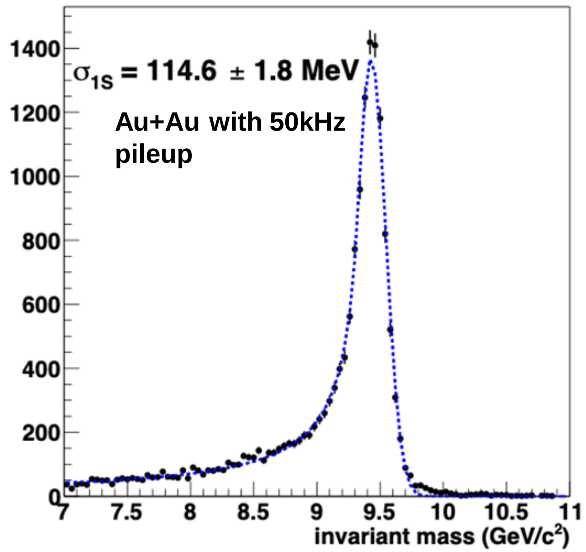
Test Beam Results (Cont.)

- Tracks with shorter drift will have higher resolution due to decreased diffusion in gas

Decreased L improves σ_x

$$\sigma_x^2 = \sigma_{pad}^2 + \frac{D_T^2 L}{N_{eff}} + \sigma_{sc}^2$$

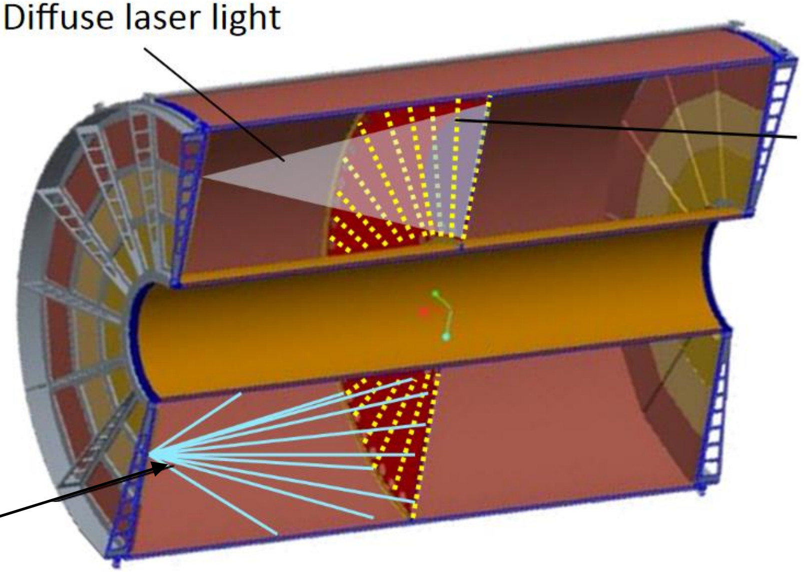
- Integrated over $\frac{dN}{d\eta}$ and η, average drift length is 75 cm, position resolution is 115 µm, invariant mass resolution of TPC alone is ~103 MeV/c^2

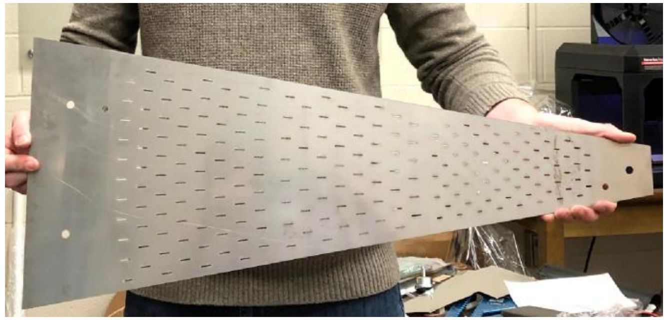


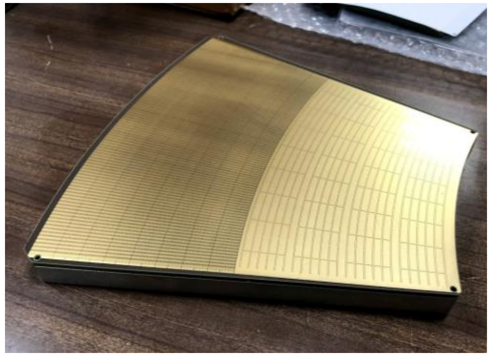
- **Preliminary result corresponds to a momentum resolution of $\frac{\Delta p}{p} \approx 0.2\% * p$**

Space Charge Correction

- Two laser systems have been designed to provide measurement of space-charge
- "Line-laser" system to ionize the gas, producing straight "tracks"
  - Provides information about distortions due to E, B field anisotropy
- "Diffuse-laser" frees electrons from aluminum strips on central membrane
  - Fires often, provides information on integrated field distortions
- Instrument from 30 cm onwards, 10 cm for charge monitoring
- Physics tracks themselves can also be used to measure distortions

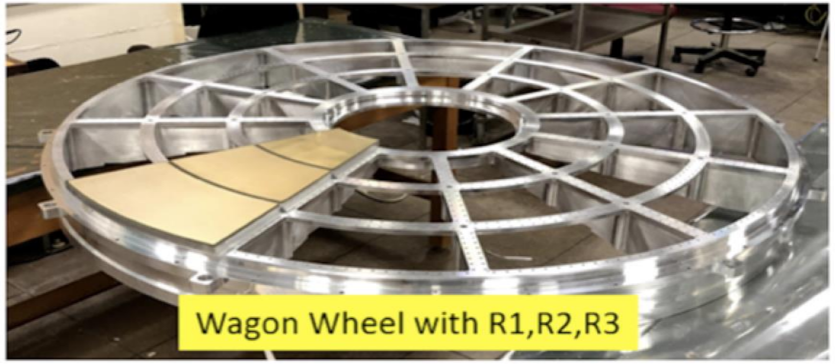


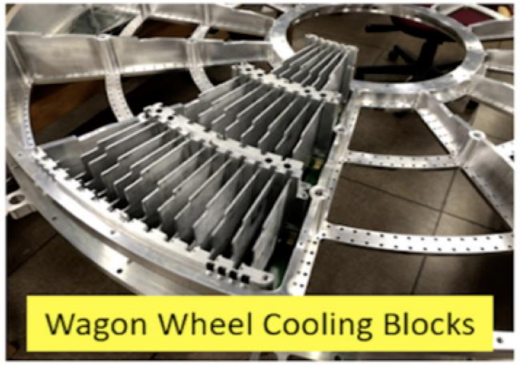




Construction Status

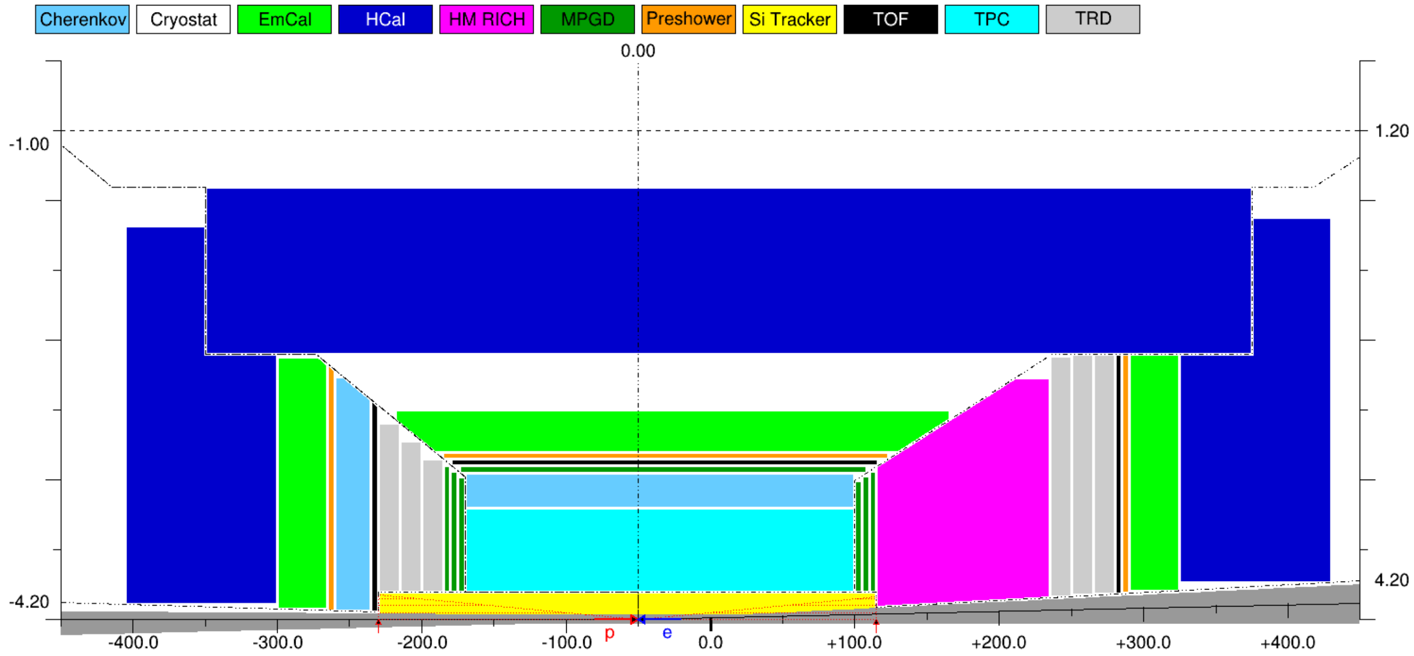
- Scheduled for installation mid-2022
- Field cage construction almost complete at SBU
- Pad-planes designed + in-hand
- Endcap aluminum support structures (Wagon wheels) ready for readout module installation
- GEMs from CERN being framed at WSU, VU, WIS, TU
- Full readout module construction + testing to begin soon



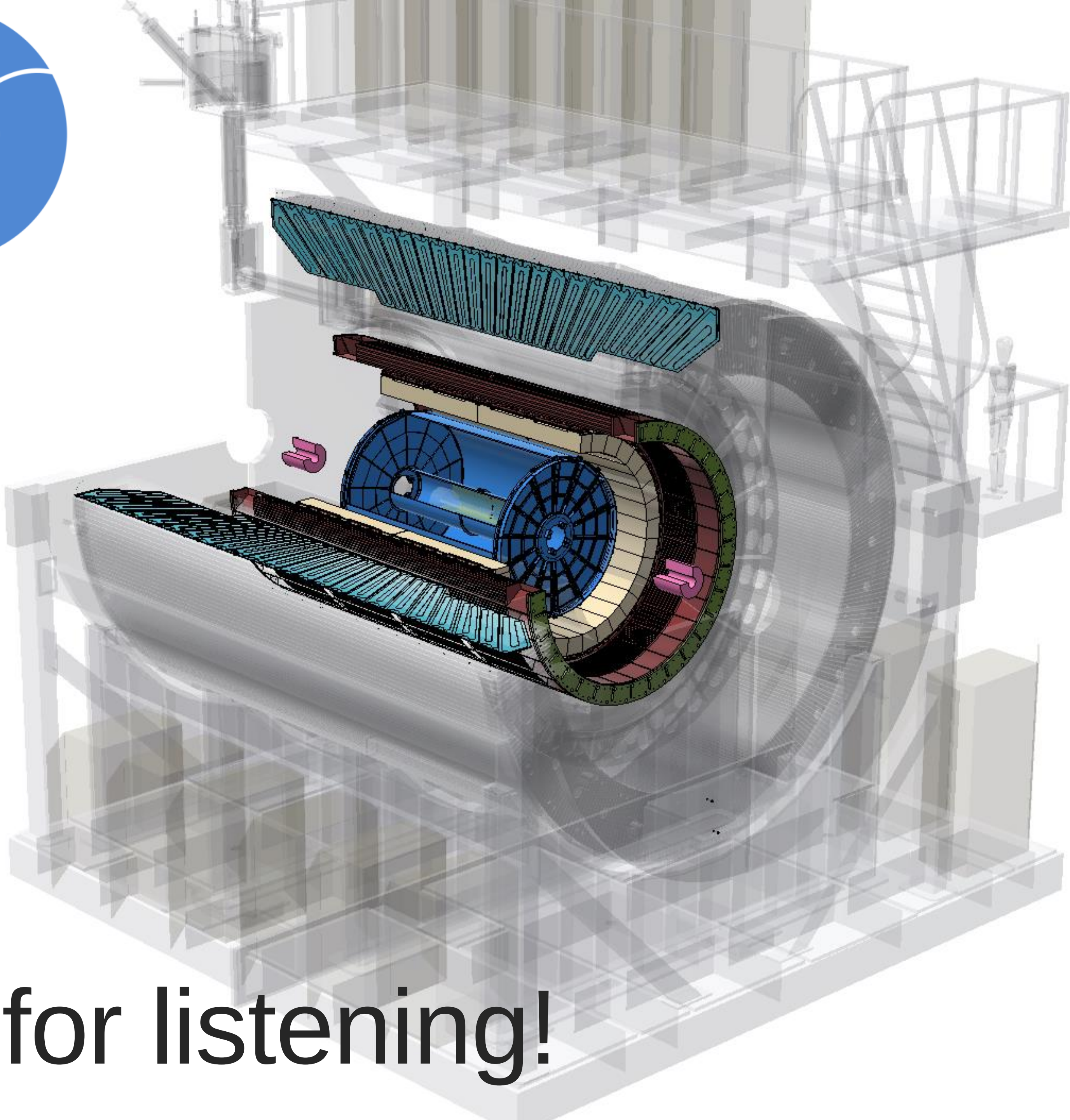


EIC TPC?

- With some slight modifications, the sPHENIX TPC could be the barrel tracker for a hermetic EIC detector
- Similar event rate (~15 kHz), but much lower multiplicity O(10) vs. O(400)
  - Less IBF, gas could be optimized to provide better dE/dx and position resolution
- Could possibly be altered to be one-sided
  - Reduce material budget in electron-going direction
- 3T magnetic field is an option
  - Would improve momentum resolution, greater bending and less diffusion

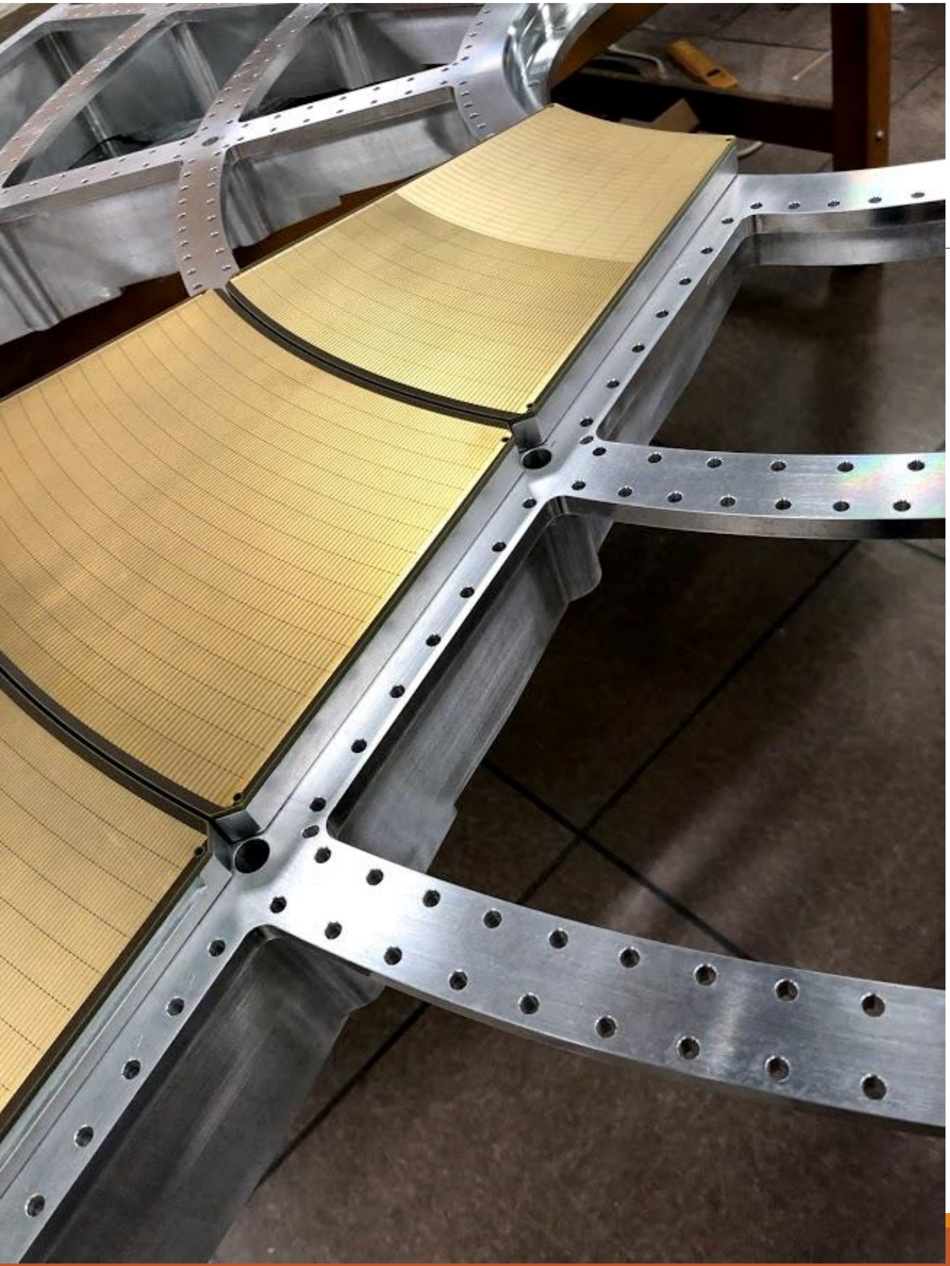


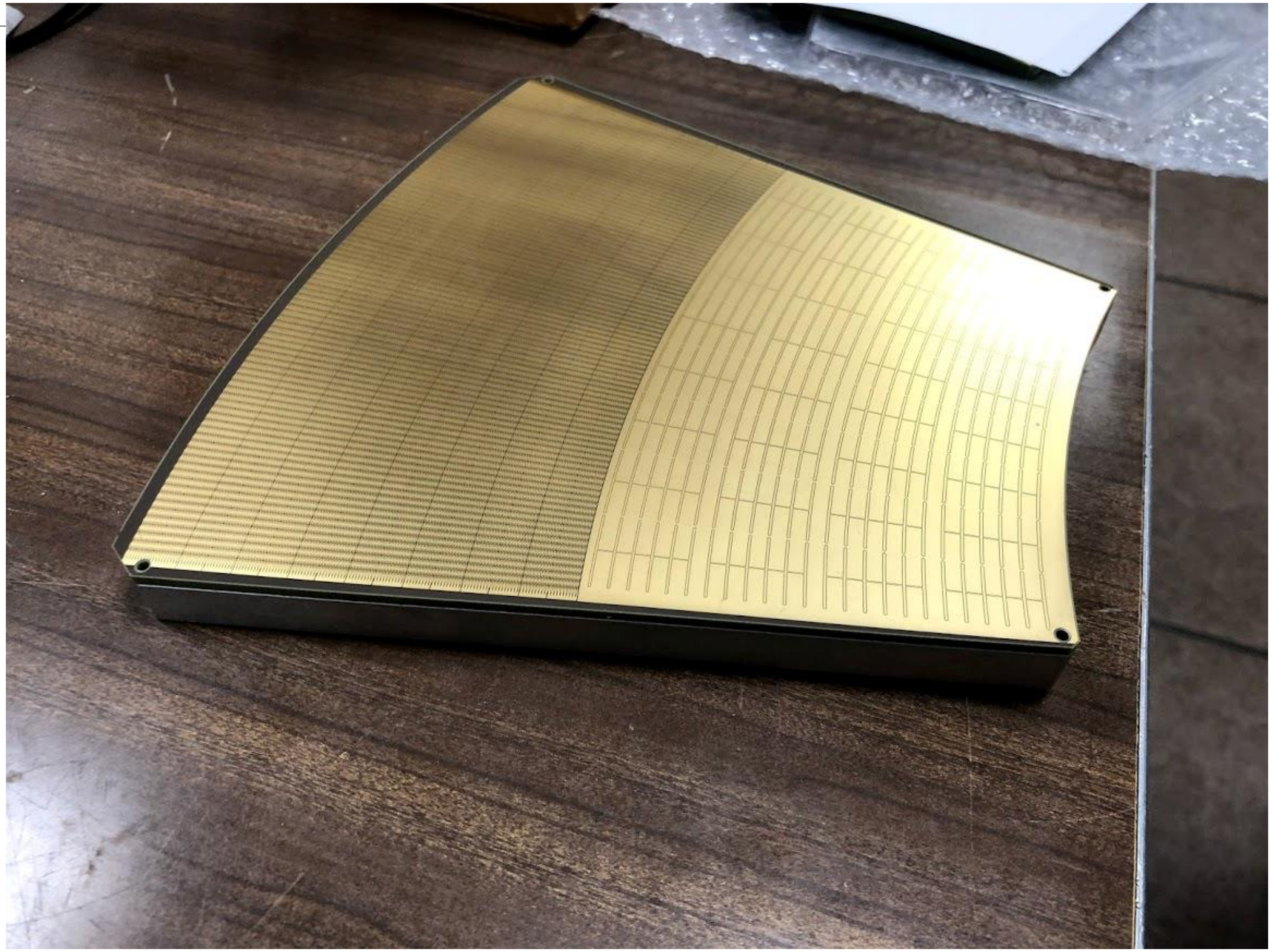
Example of a possible EIC detector configuration sPHENIX



Thanks for listening!

Backup





Position to momentum resolution

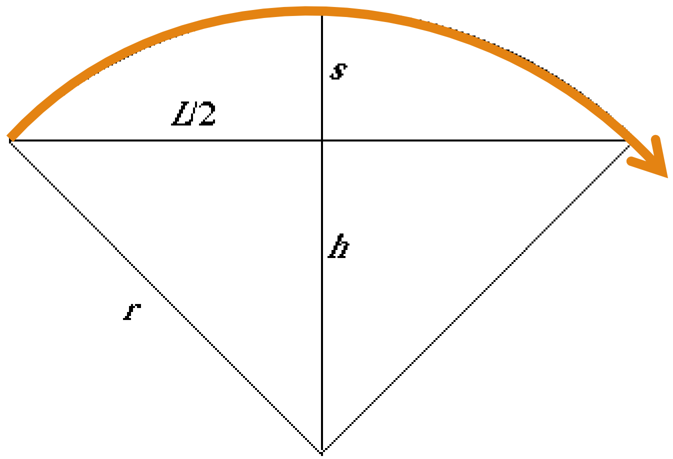
- In a homogenous magnetic field: $\rho = \frac{p_T}{q \cdot B}$

$$\boxed{\frac{\sigma_p}{p} \propto \sigma_x * \frac{p_T}{BL^2\sqrt{N_{Pad\ Rows}}}}$$

Gluckstern, 1963

- sPHENIX TPC has 48 pad rows in r – ideally yields 48 precise measurements of position

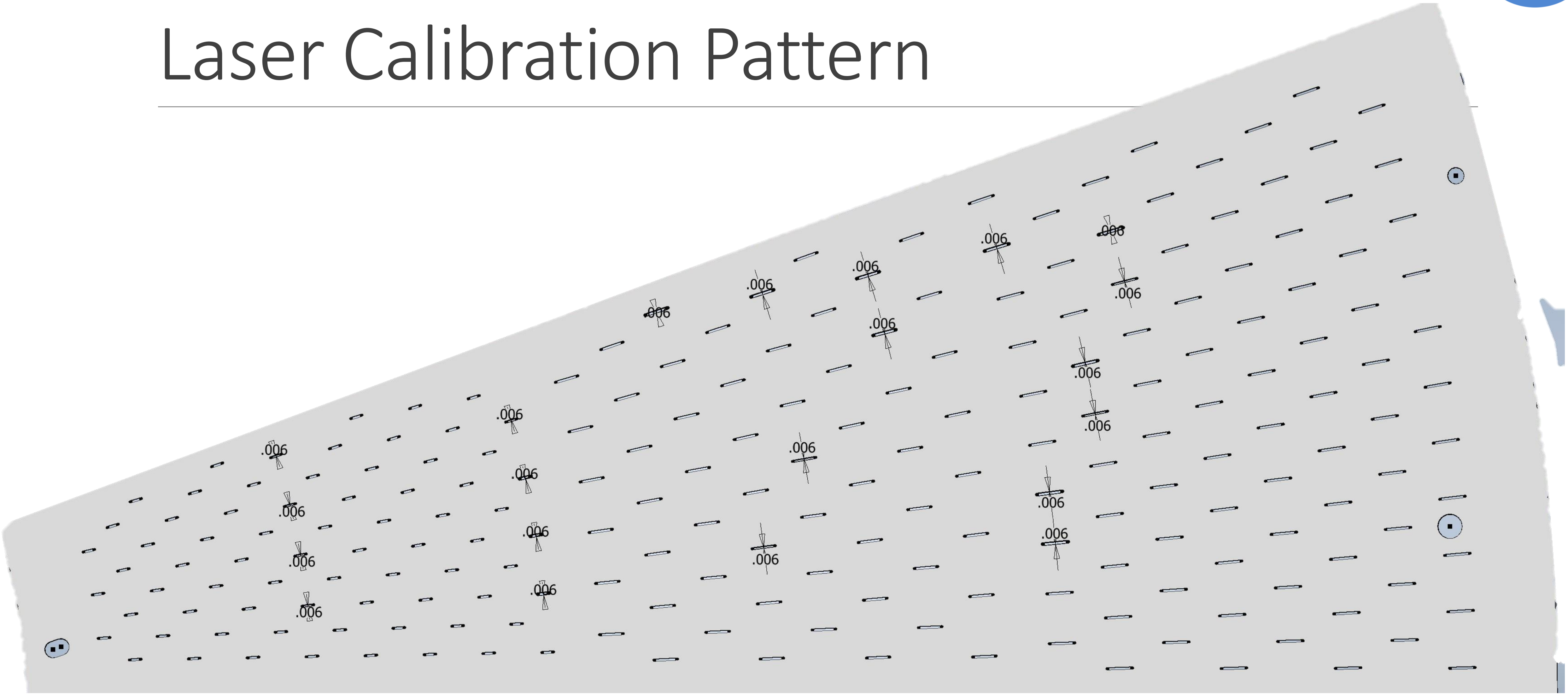
- Due to size constraints, L and $N_{\text{pad rows}}$ are smaller than STAR, ALICE, difference compensated in B, σ_x



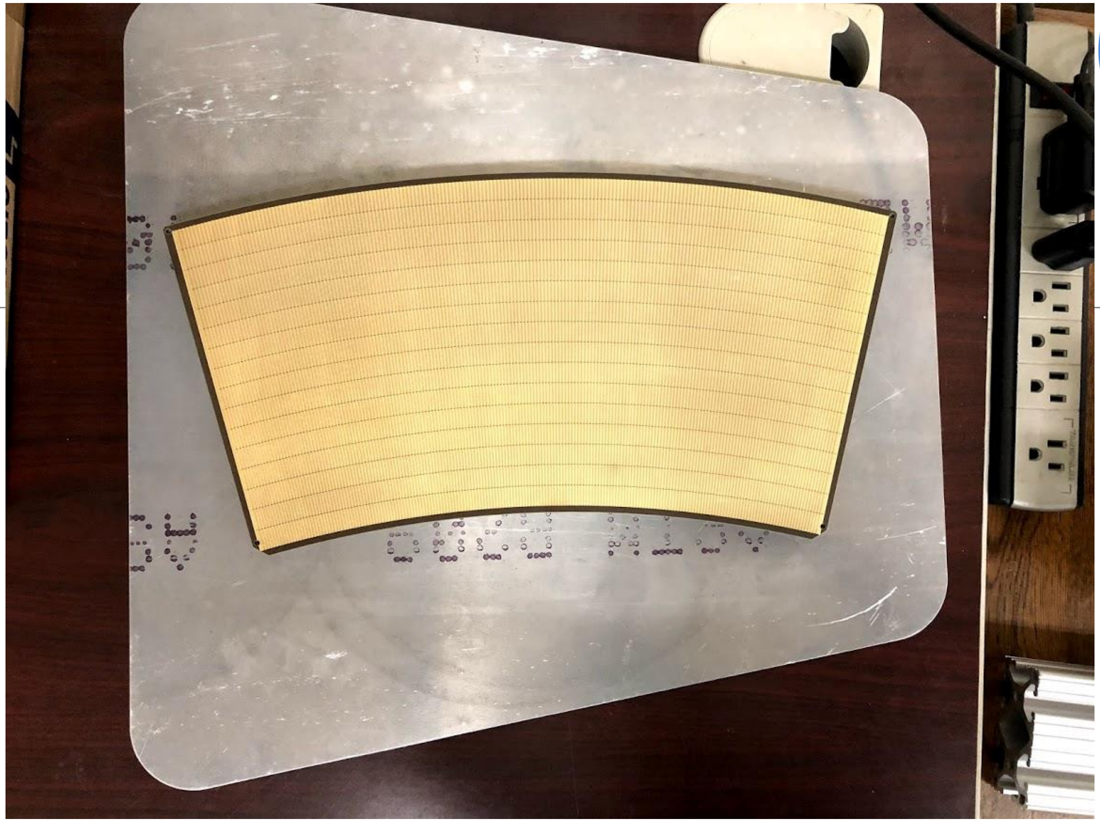
p_T error ∝ error in measurement of s (Sagitta of curve)

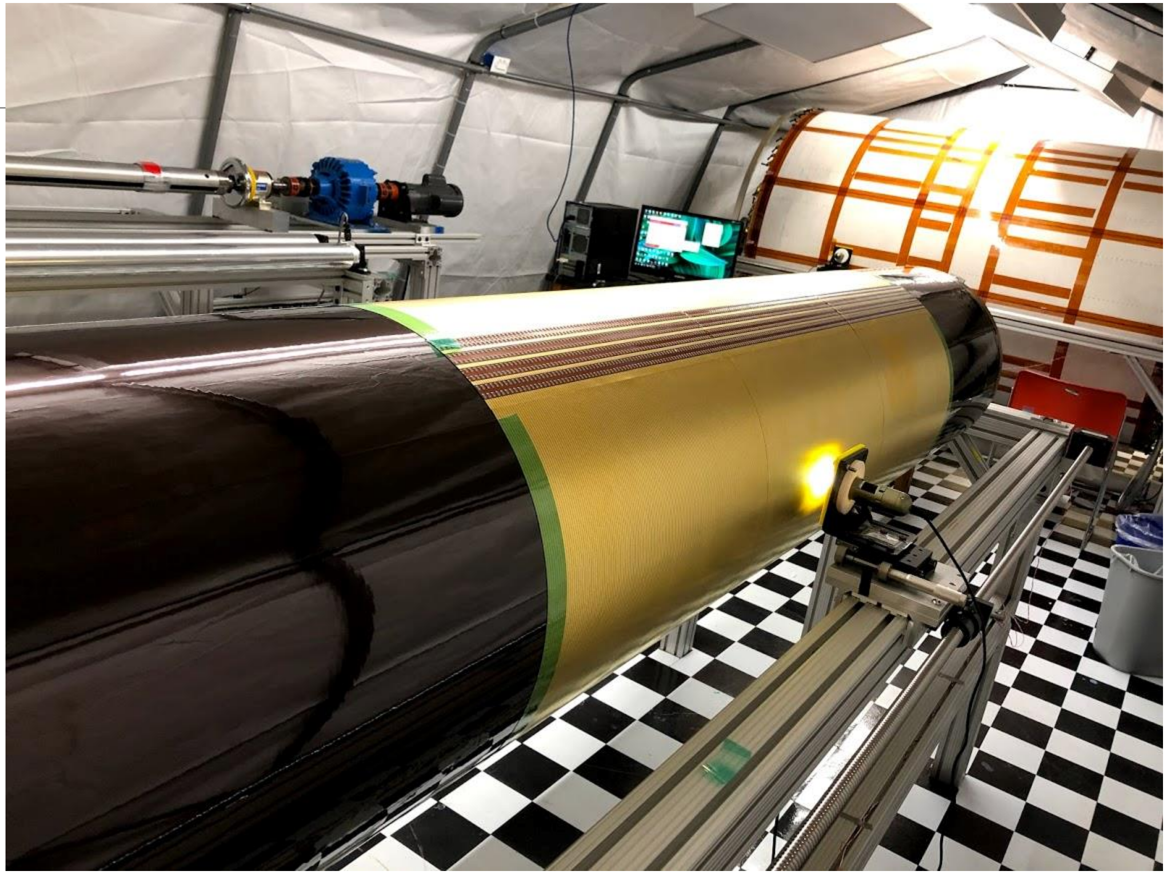
Parameters	sPHENIX (Au+Au 200 GeV)	ALICE (Pb+Pb 5.5 TeV)
dN/dy (Minbias)	180	500
η coverage of TPC	2.2 ($\|\eta\|$ <1.1)	1.8 ($\|\eta\|$ <0.9)
# of tracks in TPC	396	900
Effective # of tracks in TPC (accounted for r-dep. η coverage change)	560	1690
Effective factor for track # increase for accounting albedo background	2	2
# of measurements in r	40	159
# of samples in ϕ	3	2
# of samples in timing	5	10
# of bits of each sample	10	10
Data volume increase factor by SAMPA header	1.4	1.4
Data volume/event (bits)	9.41×10^6	1.50×10^8
Data volume/event (bytes)	1.18×10^6	1.88×10^7
Collision rate [kHz]	100	50
Total data rate (bits/sec)	9.41×10^{11}	7.52×10^{12}
Total data rate (bytes/sec)	1.18×10^{11}	9.41×10^{11}

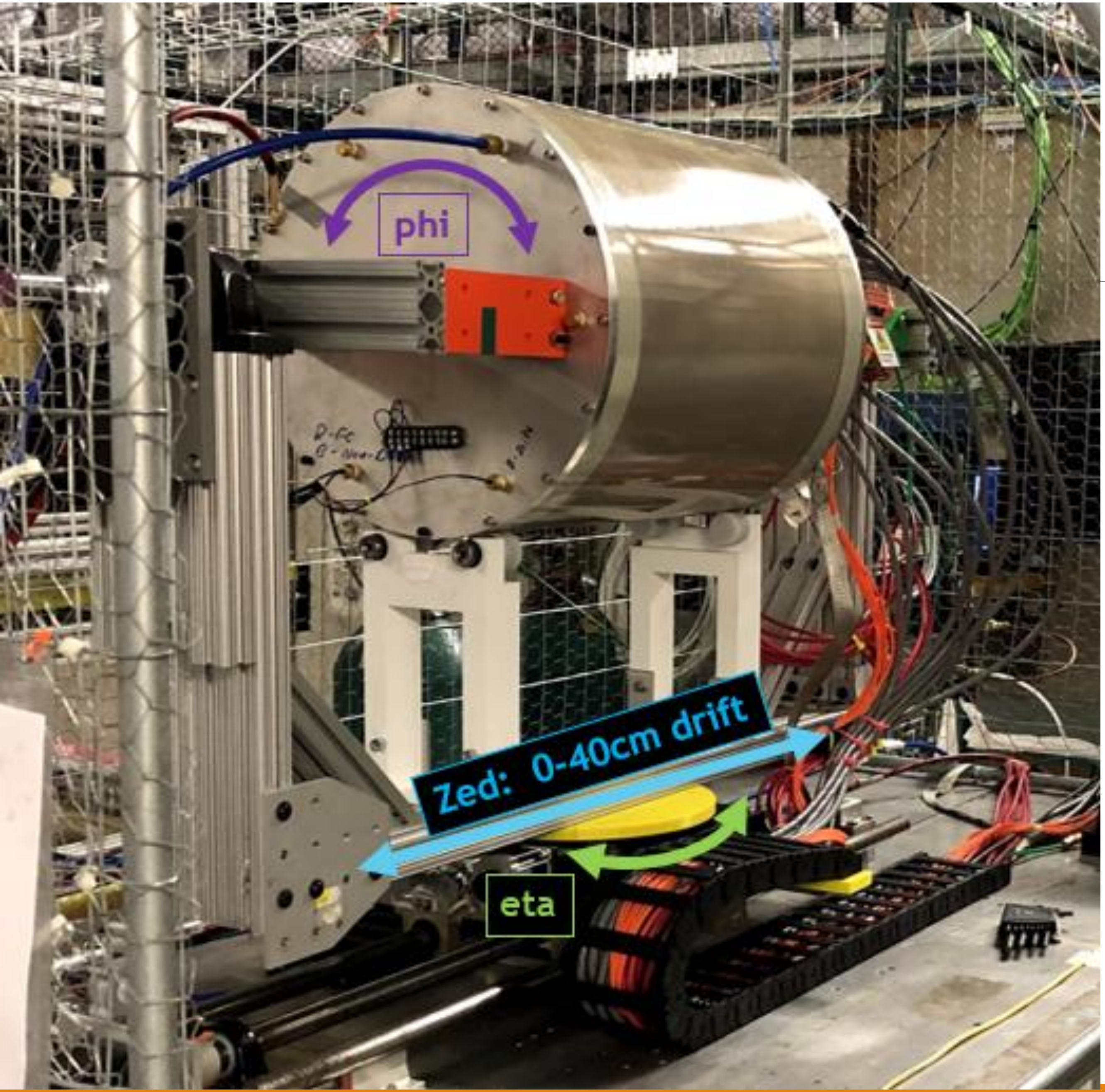
Laser Calibration Pattern

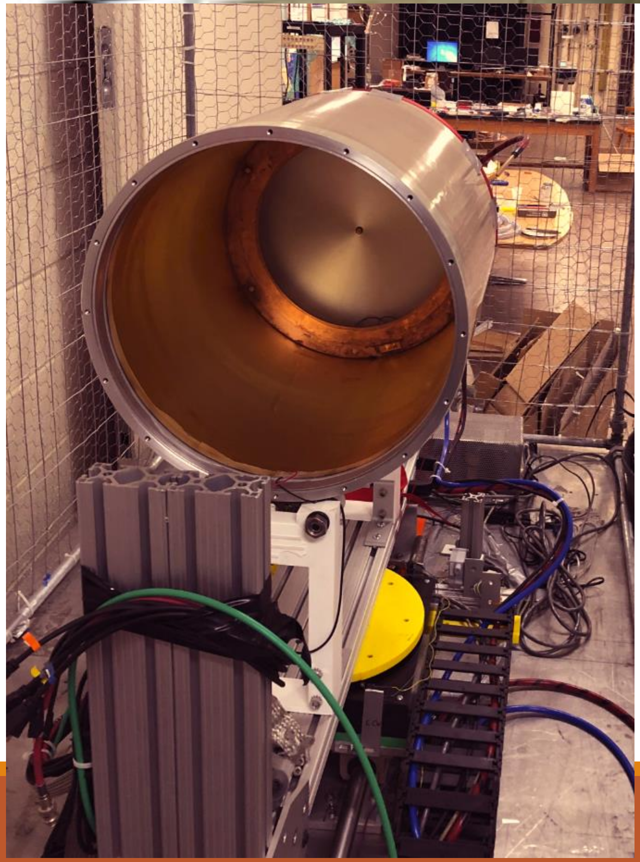


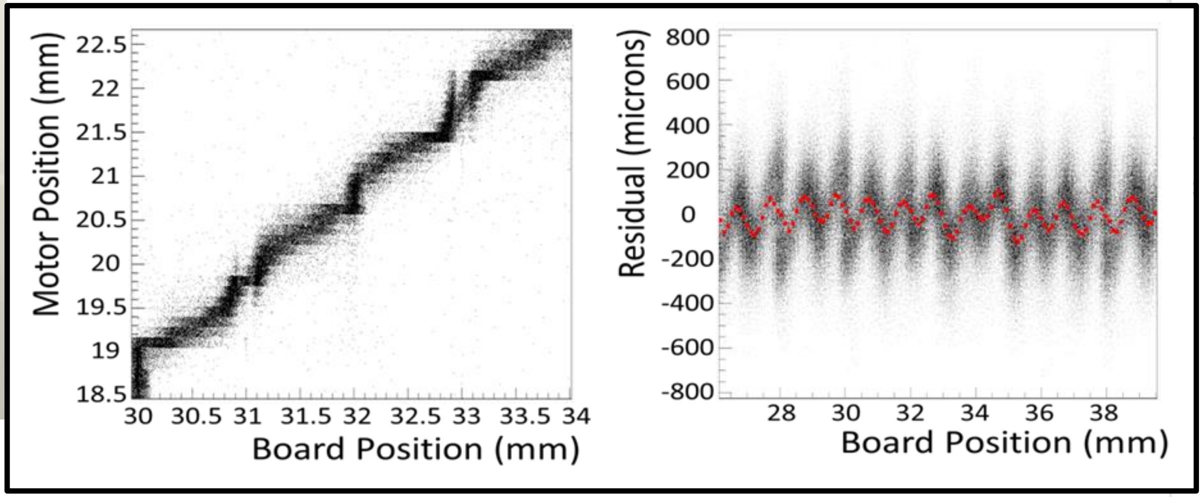
Assembling Large Field Cage



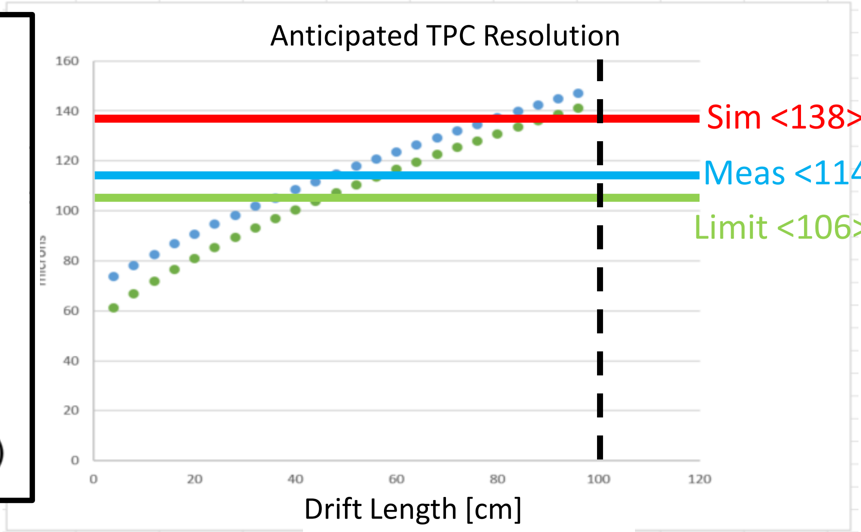



phi
Zed: 0-40cm drift
eta





Motor Position (mm)
22.5
22
21.5
21
20.5
20
19.5
19
18.5
30 30.5 31 31.5 32 32.5 33 33.5 34
Board Position (mm)
Residual (microns)
800
600
400
200
0
-200
-400
-600
-800
28 30 32 34 36 38
Board Position (mm)



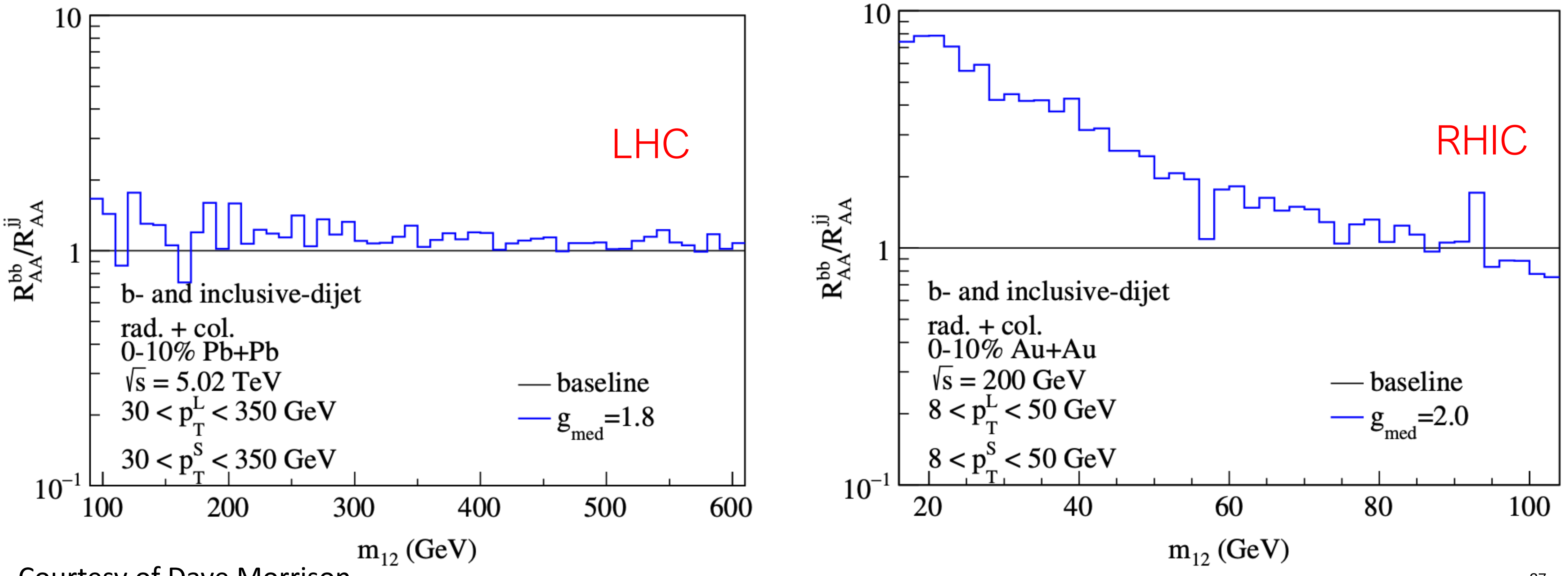
Anticipated TPC Resolution
160
140
120
100
80
60
40
20
0
0 20 40 60 80 100 120
Drift Length [cm]
Sim <138>
Meas <114
Limit <106>

	Ne:CF4 - 90:10	Ne:CF4 - 50:50	Comment
$v_{drift}\left(\frac{\mu m}{ns}\right)$	78	80	Improvement
$D_{Transverse}\left(\frac{\mu m}{\sqrt{cm}}\right)$	65	40	Improvement
$D_{Longitudinal}\left(\frac{\mu m}{\sqrt{cm}}\right)$	160	110	Improvement
$N_{primary}\left(\frac{e}{cm}\right)$	16	31.5	Improvement
$N_{total}\left(\frac{e}{cm}\right)$	48.7	71.5	Improvement
Space Charge (arb)	1.00	1.42	Max 3mm → 4.25mm Likely Tolerable

Sensitivity of novel heavy flavor jet observables

Z-B Kang, J Reiten, I Vitev, B Yoon, "Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions", Phys. Rev. D99 034006 (2019)

strong coupling to the medium near T_c ⇔ pronounced b-dijet effect at RHIC



Courtesy of Dave Morrison