STAR Forward Tracking

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Outline

• Introduction & History
• STAR Forward Detectors
• Tracking Concepts
• Track Finding and Fitting
• Performance
• Conclusions
• HW Questions
Detector Technology through the years

1906: Geiger Counter, H. Geiger, E. Rutherford
1910: Cloud Chamber, C.T.R. Wilson
1912: Tip Counter, H. Geiger
1928: Geiger-Müller Counter, W. Müller
1929: Coincidence Method, W. Bothe
1930: Emulsion, M. Blau
1940-1950: Scintillator, Photomultiplier
1952: Bubble Chamber, D. Glaser
1962: Spark Chamber
1968: Multi Wire Proportional Chamber, C. Charpak
1970es: Silicon era

[lecture notes Erika Garutti]
Discovery of the $\pi$

Discovery of the pion
Nuclear emulsion technique

[Powell 1947; Nobel prize 1950]

- Pion decays to a muon and an unseen particle, hence the sharp bend to the track

\[ \pi \rightarrow \mu^- \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]
The Neutrino Event

• Observation of a neutrino in a hydrogen bubble chamber - 1970

• Neutrino strikes a proton, converts into a muon

• It looks like 3 particles coming from nothing!

• Tracks were drawn by hand on photos of every event
Particle Detectors have come a long way

Modern detectors are fully electronic with several special purpose sub-detectors
The STAR Forward Upgrade

Coverage: $2.5 < \eta < 4.0$

Forward Tracking System
- Silicon microstrip sensors
- small-Strip Thin Gap Chambers

Forward Calorimetry System
- Hadronic Calorimeter
- Electromagnetic Calorimeter
**Forward Rapidity Physics Program**

Measurements planned for 2021+ with the STAR forward upgrade

→ Address important topics in **hot & cold** QCD

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### Forward Tracking System

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum Resolution</td>
<td>&lt; 30%</td>
</tr>
<tr>
<td>Tracking Efficiency</td>
<td>&gt; 80% @ 100 tracks / event</td>
</tr>
<tr>
<td>Charge Separation</td>
<td>–</td>
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**Beam:**
- 500 GeV: p+p
- 200 GeV: p+p and p+A

**Physics Topics:**
- TMD measurements at high $x$ transversity $\rightarrow$ tensor charge
- Improve statistical precision for Sivers through Drell-Yan
- $\Delta g(x, Q^2)$ at low $x$ through di-jets
- Gluon PDFs for nuclei $\rightarrow$ $R_{pA}$ for direct photons & DY
- Test of Saturation predictions through di-hadrons, g-Jets

**Beam:**
- 200 GeV: Au+Au

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### Forward Calorimeter System

<table>
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<tr>
<th>Detector</th>
<th>Resolution p+p and p+A</th>
<th>Resolution A+A</th>
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<tr>
<td>ECal</td>
<td>$\sim 10%/\sqrt{E}$</td>
<td>$\sim 20%/\sqrt{E}$</td>
</tr>
<tr>
<td>HCal</td>
<td>$\sim 50%/\sqrt{E} + 10%$</td>
<td>–</td>
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Let's review the technology used for the tracking detectors.
STAR Forward Silicon Tracker

- Full installation: 3 identical disks
  - Acceptance:
    - $0 < \phi < 2\pi$, $2.5 < \eta < 4.0$
- 12 wedge modules / disk
- APV25 frontend readout chips
- Flexible hybrid
- Precise $\phi$, imprecise R measurement
STAR Forward Silicon Tracker - Prototype Module

- cooling tubes
- T-board
- outer hybrid
- inner hybrid
- APV25 chips
- outer silicon sensor
- inner silicon sensor
- mechanical structure
Small-Strip Thin Gap Chambers (sTGC)

Detector:
- Based on ATLAS sTGC design
- 4 layers in total
  - 4 modules/layer
  - 2 chambers/module
- Pentagon shape formed from identical modules
- Shandong University: sTGC R&D and production
- **Position resolution: ~100 μm**

Wire: Au-plated tungsten wire
- Ø 50μm, 1.8mm pitch
Copper strip: 3.2mm pitch
Height of one layer: 5.8mm
Gas: 55% n-pentane+45%CO2
HV: 2900V

Requires dedicated gas system
## Forward Tracking System

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### Silicon mini-strip disks ×3
- Location: z = 90, 140, 187 cm from interaction point
- **Build on and utilize STAR experience of successful Intermediate Silicon Tracker (IST) detector**
- minimal material (≤1% X0/layer) in the acceptance

### Small-Strip Thin Gap Chamber (sTGC) ×4
- Location: z = 270, 300, 330, 360 cm from interaction point
- **Significant reduction in cost (compared to all silicon)**
- Prototype at BNL, testing in STAR during 2019 run

Basics of Tracking

1. Find track candidates
   • Input: unsorted hits from detectors
   • Output: Possible tracks and their associated hits

2. Resolve ambiguities / conflicts
   • Input: Possible tracks (maybe with shared hits)
   • Output: Set of ”BEST” tracks
   • Considerations :
     • Can one hit be used by several tracks?
     • If so, how many shared hits are allowed?
     • If conflicts exists, what metric defines the “BEST” track?

3. Fit track model
   • Input: Set of tracks and their associated hits
   • Output: Momentum and charge information
   • Procedure : Fit points ( + Primary Vertex?) to track model
     • Track Model in uniform $\vec{B} =$ Ideal helix
     • Track Model in non-uniform $\vec{B} =$ helix modified by magnetic field variations (including zero field)
Track Finding Procedure

• How do we go from this:

Naïve approach: make all possible connections
  o Very slow due to combinatorial blow up
  o Still need to distinguish real track segments from combinatorial

Cellular Automation
  o Use simple “criteria” to build up longer segments of hits
  o Build small segments, then grow them according to additional criteria
  o Very performant & easily parallelized

• To this:
Tracking in the STAR TPC (with iTPC upgrade)

• Thousands of tracks per event (central collisions)
Conway’s Game of Life

• Cellular Automation
  • System is in discrete states
  • “Update” state based on simple rules
  • Simple initial conditions and simple rules → complex emergent behavior

• But how can we use this for particle tracking?

A “glider” gun (Wikipedia)
Apply Cellular Automation to Tracking?

- How to apply Cellular Automation?
- How to express states of the system?
- How do we “update” to grow our tracks?
Apply Cellular Automation to Tracking?

• First look at “hit pairs”
• Hits on neighboring detector planes
• How to distinguish “real” pairs (from a single particle track) from “fake” pairs?

• Can we apply simple criteria for this?
Criteria for Finding Track Segments

Criteria DeltaPhi :
\[ \Delta \phi = \phi_A - \phi_B \]

Two-Segment Criteria :
- \( 0.2 < p_T < 5 \text{ GeV/c} \)
- 5 tracks / event
- Uniform B field

Hits at GEN level precision
\( (\sigma_x = \sigma_y = 0) \)
Criteria for Finding Track Segments

Criteria DeltaRho:

\[
\rho = \sqrt{x^2 + y^2}
\]

\[
\Delta \rho = \rho_A - \rho_B
\]

Two-Segment Criteria: \(\Delta \rho < 5 \text{ GeV/c}\)

\[0.2 < p_T < 5 \text{ GeV/c}\]

5 tracks / event

Uniform B field

Hits at GEN level precision

\((\sigma_x = \sigma_y = 0)\)
Criteria for Finding Track Segments

Criteria RZRatio:

\[
\left( \frac{\Delta R}{\Delta z} \right)^2 = \frac{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}{(\Delta z)^2}
\]

Strong discriminator for forward tracks

Hits at GEN level precision 
\((\sigma_x = \sigma_y = 0)\)
Criteria for Finding Track Segments

Criteria

StraightTrackRatio:

\[
\frac{\rho_A \cdot Z_B}{\rho_B \cdot Z_A}
\]

Strong discriminator for forward tracks

Hits at GEN level precision
\((\sigma_x = \sigma_y = 0)\)
Apply Cellular Automation to Tracking?

• Next look at “hit triplets”
• Hits on neighboring detector planes connected by one hit
• How to distinguish “real” pairs (from a single particle track) from “fake” pairs?
• Can we apply simple criteria for this?
Criteria for Finding Track Segments

Three-Segment Criteria: 2DAngle

Criteria 2DAngle:

\[
\Delta x_1 = x_B - x_A \\
\Delta y_1 = y_B - y_A
\]

\[
\Delta x_2 = x_C - x_B \\
\Delta y_2 = y_C - y_B
\]

\[
u = (\Delta x_1)^2 + (\Delta y_1)^2
\]

\[
v = (\Delta x_2)^2 + (\Delta y_2)^2
\]

\[
\cos^2(\theta) = \frac{\Delta x_1 \cdot \Delta x_2 + \Delta y_1 \cdot \Delta y_2}{u \cdot v}
\]

Hits at GEN level precision
\((\sigma_x = \sigma_y = 0)\)
Criteria for Finding Track Segments

Criteria ChangeRZH: 

$$\Delta Z = \left( \frac{\Delta R}{\Delta z} \right)^2_{BA} - \left( \frac{\Delta R}{\Delta z} \right)^2_{BC}$$

Hits at GEN level precision

$$\sigma_x = \sigma_y = 0$$

0.2 < p_T < 5 GeV/c
5 tracks / event
Uniform B field
Cleaning the Cellular Automata output

• After Cellular automata, we have all possible tracks
• Use Hopfield Neural Network to find “Best Tracks”

Hopfield Recurrent Artificial Neural Network

• Can process “corrupt” data, reconstructing true data
• Recurrent network – exhibits temporal behavior “memory”
• For tracking, ideal for finding unique tracks
• It is generally a good assumption that real tracks do not share any hits
Cleaning the Cellular Automata output

- After Cellular automata, we have all possible tracks
- Use Hopfield Neural Network to find “Best Tracks”

- Can process “corrupt” data, reconstructing true data
- Recurrent network – exhibits temporal behavior “memory”
- For tracking, ideal for finding **unique tracks**
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Hopfield Recurrent Artificial Neural Network
Goal of Track Finding

1. Efficiency
   • Find every track that exists – criteria cannot be too specific or inflexible

2. Purity
   • Don’t find tracks that shouldn’t be there
   • Caused by mismatching hits from one track with hits from another (previous slides)
   • Ghost hits!
sTGC Ghost hits

sTGC ghost hits

- sTGC is basically a sandwich of two 1 dimensional detectors
- Ambiguity exists when multiple hits occur
- Leads to “ghost” hits
- Major problem for high multiplicities
Reduce Ghost hits with Diagonal strips

Split strip

Diagonal strip
Reduce Ghost hits with Diagonal strips

Split strip

Diagonal strip
Reduce Ghost hits with Diagonal strips

Significant reduction of ghost hits
Challenges: Magnetic Field in Forward Region

Magnet steel end plane
Uniform B-field
Forward Tracking

Unique Challenges:

- Combination of detector technologies: Silicon & sTGC
- Changing magnetic field
- Large hit density

- Track finding:
  - Cellular Automata

- Track Fitting:
  - GENFIT2 (a multi-experiment tracking framework)
Tracking Efficiency

Evaluate performance under ideal conditions

- Track finding efficiency (perfect 4/4 correct hits) is ≈ 98%
- Track finding efficiency (3/4 or more correct hits) is ≈ 99.5%
- Full material effects
- Real STAR B-field

GENERATOR (“GEN” or “MC” hits):

- $1 \mu^+ / \text{Event}$
- $2.45 < |\eta| < 4.05$
- $0.2 < p_T < 5 \text{ GeV/c}$
- B Field: REAL (StarMagField)
- Primary Vertex distribution $\mu = (0, 0, 0)$, $\sigma = (0.05, 0.05, 5) \text{ cm}$.
- CA Track finding uses sTGC only, fast & generic

Efficiency within acceptance

- Efficiency (Quality = 4/4)
- Efficiency (Quality >= 3/4)
Tracking Algorithm

Track Finding
- Cellular Automata based
- Uses hits from sTGC detector

Track Fitting procedure
1. Fit primary vertex + sTGC hits
2. Swim along track, find hits in Si planes
3. Refit with primary vertex + Si + sTGC
Track Fitting and performance

1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

Primary Vertex $\sigma_{XY} = 500 \, \mu m$

- Beamline constraint should provide $\sigma_{XY} = 500 \, \mu m$ or better
Track Fitting and performance

1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

Primary Vertex $\sigma_{XY} = 500 \, \mu m$
- Beamline constraint should provide $\sigma_{XY} = 500 \, \mu m$ or better
- Combine projected R-position @ silicon with very high-precision phi-measurement
Example single track fit

Primary Vertex

Hits in Silicon Detector

Hits in sTGC Detector

GENFIT2 Display
Track Fitting and performance

1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

Primary Vertex $\sigma_{XY} = 500 \mu m$
- Beamline constraint should provide $\sigma_{XY} = 500 \mu m$ or better
- Refit with Si provides significantly improved momentum resolution (x2) + charge identification (especially at higher pT)
Understanding the track fitting

• Study track FITTING only → assume PERFECT track finding, i.e.

• Why do this: Study track fitting independent of track finding

• If we have perfect information of track hits, how well can we determine track momentum and charge?
MC Closure test: verify the tracking procedure

MC Closure to prove that the tracking code “works”

1. Generate tracks / propagate with GEANT
   ➢ Physics_OFF = Multiple scattering, hadronic interactions, etc. turned OFF
2. Use GEANT hits, blur position by $\sigma_{XY} = 1 \mu m$ (could be anything)
3. Assign hit covariance matrix according to $\sigma_{XY}$
4. Fit tracks using GENFIT2 implementation

Thank you to Jason / Victor for help turning OFF multiple scattering etc.
GEN Level (Physics_off) $\sigma_{XY} = 0.1 \mu m$

Physics_off = leave hit in detector, otherwise no interaction with material

Healthy correlation

Perfect Charge ID

Inverse Momentum Resolution Better than 1%

Proves tracking software works as expected

Daniel Brandenburg | BNL
GEN Level (Physics_off) $\sigma_{XY} = 1\mu$m

**Healthy correlation**

**Inverse Momentum Resolution**
Better than 10%

**$p_T^{-1}$ Resolution**
Minimal/Healthy Momentum dependence

Proves tracking software works as expected
GEN level $\pm 1\mu m$ (Physics ON)

charge id good, but a little worse

No $p_T$ dependence, dominated by interactions
High Multiplicity Tracking

• Naïve CA implementation is very slow for high-mult events.
  • Scales with combinatorial pairs
  • Problem will be worse with ghost hits from sTGC in high-mult events

• CA is easily parallelizable / separable
  • Simplest approach: split hits from each station into slices in $\phi$

  • Reduces combinatorial pairs
  • May reduce efficiency for low $p_T$ tracks
    ✓ Multiple iterations to recover hard-to-find track candidates
Tracking Performance at higher multiplicities

**Tracking Performance:**

- Split/Parallelize high multiplicity events – speedup $\sim x1000$
- Track finding shows healthy behavior trending towards higher multiplicity
- Detailed studies will be needed with ghost hits and diagonal strips
- Preliminary study: momentum resolution peripheral Au+Au $<$ 30%, meeting goals for physics in AA
  - Note: resolution depends on $\eta, p_T$ and multiplicity
Track Finding Efficiency vs. Multiplicity

- Healthy behavior with increased multiplicity
- Duration for high-multiplicity event ~ 400 ms / Event
Conclusions

• Detector technology as been crucial for advancing our experiment reach and physical understanding

• STAR Forward upgrade uses modern tracking technology to achieve tracking in challenging situations: non-uniform B-field, various detector technologies...

• Tracking requires cutting edge mathematical algorithms for finding “real” tracks in the sea of background
Homework

• Read about particle detectors:
  • https://www2.physics.ox.ac.uk/sites/default/files/Detectors.pdf

• Read about track finding using machine learning:

• Derive the relation between track curvature and the track momentum in a given B-field

• Write a ROOT/python code to compute/plot the number of ghost hits vs. real hits for an sTGC like detector. Can you come up with a mathematical expression for this?
  • If you break the area into 4 smaller independent detectors, how would that change the number of ghost hits?