Azimuthal Transverse Single-Spin Asymmetries of Charged Hadrons within Jets from Polarized p+Au Collisions at $\sqrt{s} = 200$ GeV

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CNFS Student Seminar Presentation

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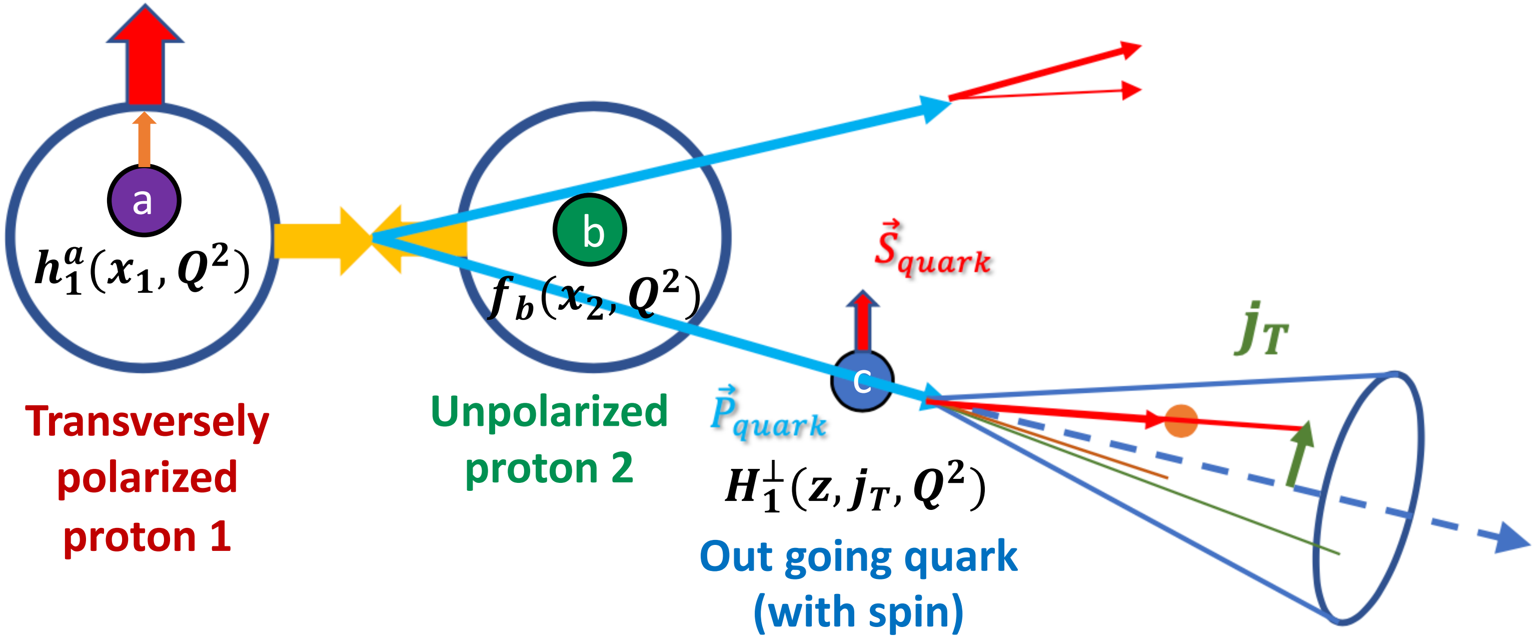
The Collins Effect

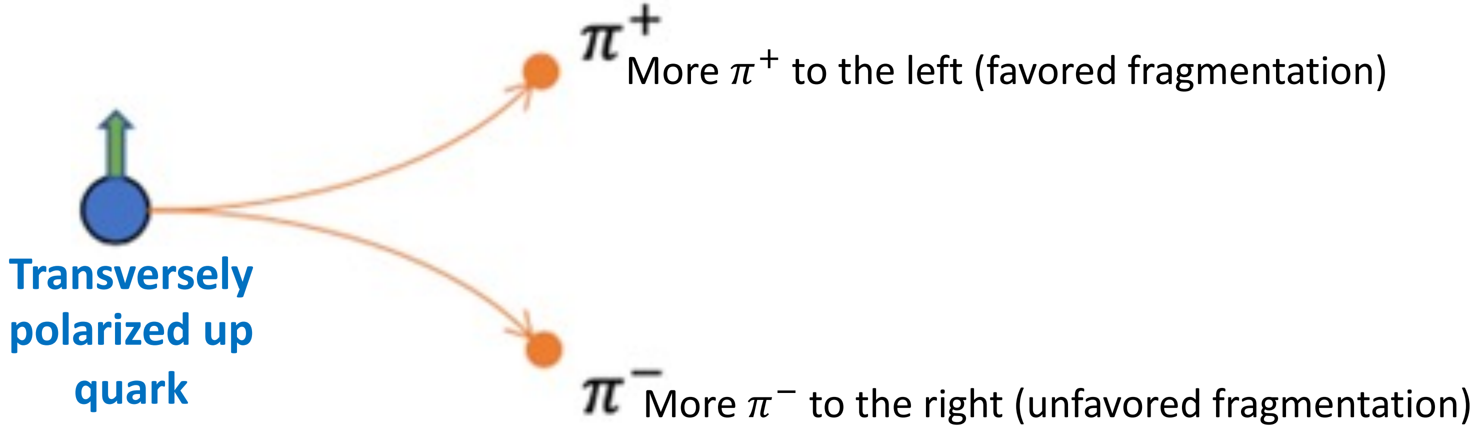


Transversely polarized proton 1

Unpolarized proton 2

Out going quark (with spin)

Figures by Ting Lin



More π^+ to the left (favored fragmentation)

More π^- to the right (unfavored fragmentation)

Transversely polarized up quark

- **It is the relationship between leading twist (twist 2) collinear transversity, $h_1^a(x_1, Q^2)$, and the transverse momentum dependent (TMD) Collins fragmentation function $H_{1\,\pi/c}^{\perp}(z_\pi, j_T, Q^2)$.**
- **This effect manifest itself experimentally as a final state effect where hadrons produced from the fragmenting quark are azimuthally distributed about the axis of the parent jet (from the fragmenting quark).**

Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B **774**, 635 (2017), arXiv:1707.00913 [hep-ph].
Z.-B. Kang, X. Liu, F. Ringer, and H. Xing, J. High Energy Phys. **11**, 068 (2017), arXiv:1705.08443 [hep-ph].

Experimental Measurement of the Collins Effect

Relative difference of the spin-dependent cross section:

U. D'Alesio, F. Murgia, and C. Pisano, Phys. Rev. D1626 83, 034021 (2011), arXiv:1011.2692 [hep-ph].

$$\frac{d\sigma^{\uparrow}(\phi_S,\phi_H)-d\sigma^{\downarrow}(\phi_S,\phi_H)}{d\sigma^{\uparrow}(\phi_S,\phi_H)+d\sigma^{\downarrow}(\phi_S,\phi_H)}$$
$$\propto A_{UT}^{\sin(\phi_S)}\sin(\phi_S)$$
$$\boxed{+A_{UT}^{\sin(\phi_S-\phi_H)}}\sin(\phi_S-\phi_H)$$
$$+A_{UT}^{\sin(\phi_S-2\phi_H)}\sin(\phi_S-2\phi_H)$$
$$+A_{UT}^{\sin(\phi_S+\phi_H)}\sin(\phi_S+\phi_H)$$
$$+A_{UT}^{\sin(\phi_S+2\phi_H)}\sin(\phi_S+2\phi_H)$$

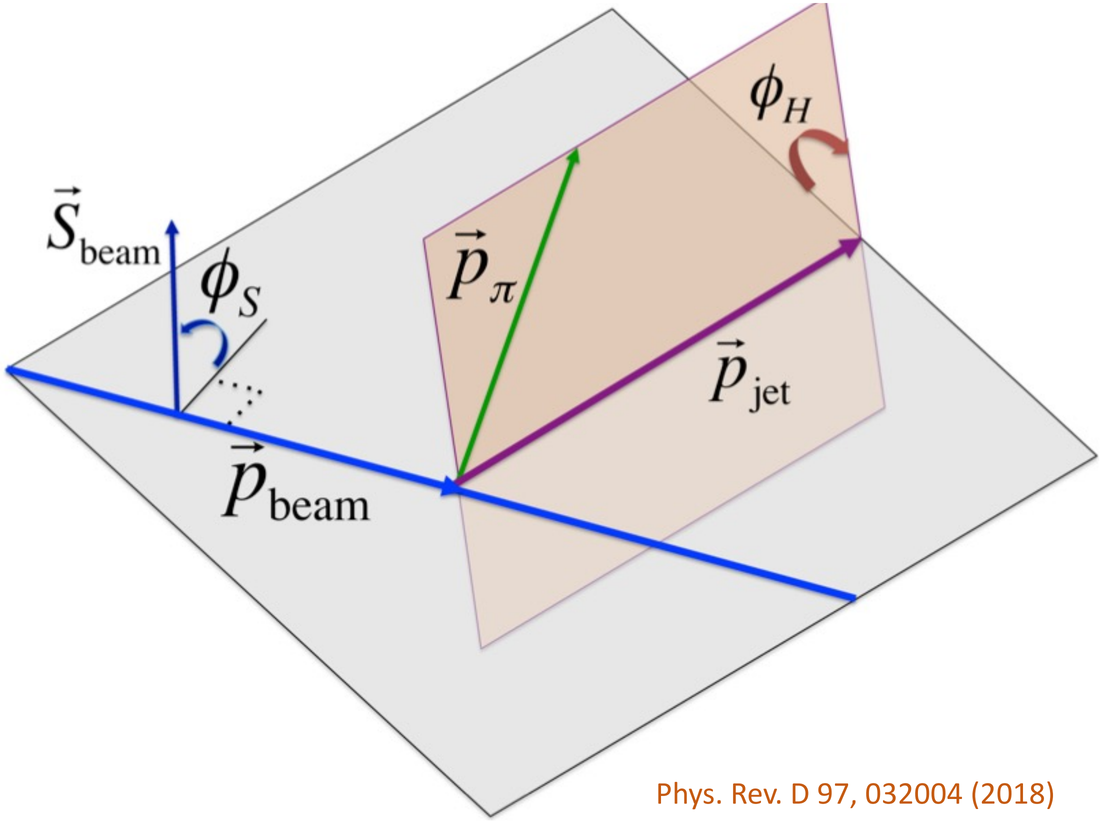
Experimentally observed Collins asymmetry sensitive to quark transversity and Collins fragmentation functions

Experimentally:

$$A_{UT}\sin(\emptyset)=\frac{1}{P}\cdot\frac{\sqrt{N_{\alpha}^{\uparrow}N_{\beta}^{\downarrow}}-\sqrt{N_{\alpha}^{\downarrow}N_{\beta}^{\uparrow}}}{\sqrt{N_{\alpha}^{\uparrow}N_{\beta}^{\downarrow}}+\sqrt{N_{\alpha}^{\downarrow}N_{\beta}^{\uparrow}}}$$

G. G. Ohlsen and P. W. Keaton, Nucl. Instrum. Meth. 109, 41 (1973).

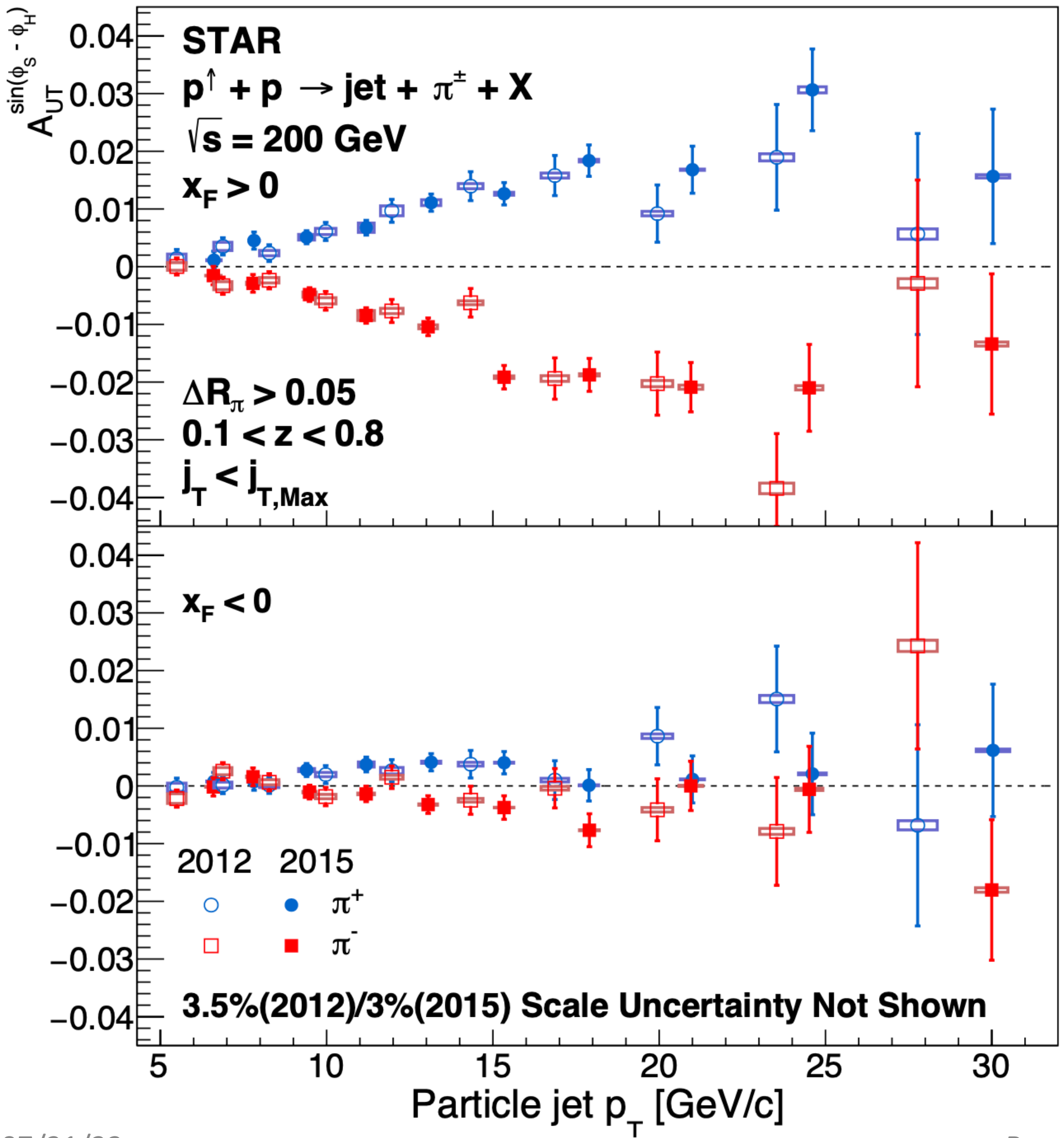
- $N^{\uparrow(\downarrow)}$ is the number of $h^{+}(h^{-})$ in the jet when beam polarization is ↑ (↓) in the given detector half α (up) or β (down) weighted by the average beam polarization P.

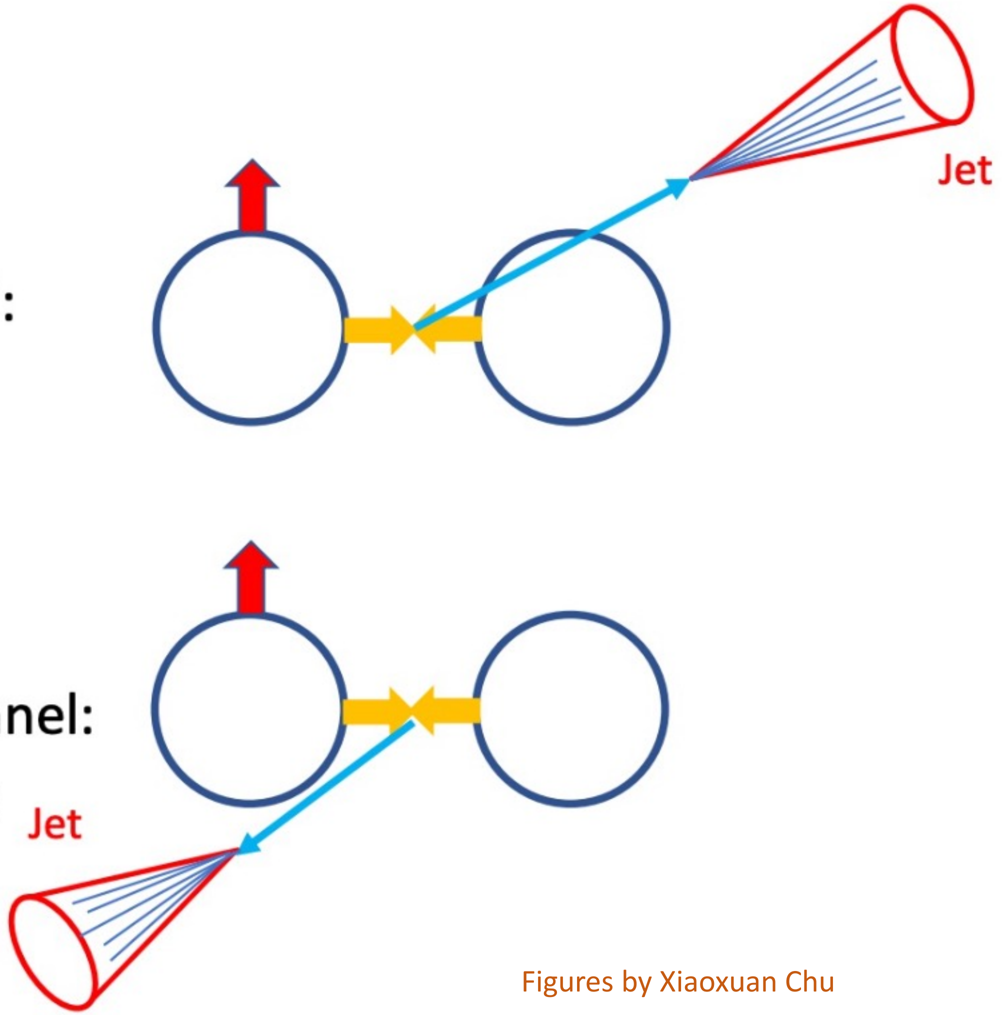


Phys. Rev. D 97, 032004 (2018)
Phys. Rev. D 83, 034021 (2011)

Collins Asymmetry in Polarized *pp* at $\sqrt{s_{NN}} = 200$ GeV

STAR: arXiv:2205.11800v1





Top panel:

$x_F > 0$

Bottom panel:

$x_F < 0$

Figures by Xiaoxuan Chu

Motivation For Collins Effect Measurement

Why Collins effect in pAu?

- Maximize the opportunity for **TMD factorization breaking** by having very large color field from the Au nucleus where the active quarks (quarks participating in the hard scattering) have ample opportunities to interact with the gold remnants which will yield to **factorization breaking**.
- Since the TMD Collins fragmentation function is involved in the Collins effect, it will give us an insight into the universality of TMD functions.
- Gives us insight into the energy evolution of TMD functions.

What is the usefulness of transversity?

- Integral gives tensor charge, which is a critical input for low-energy beyond the Standard Model calculations
- Difference between helicity and transversity directly related to parton orbital angular momentum

$h_1^q(x) \approx$

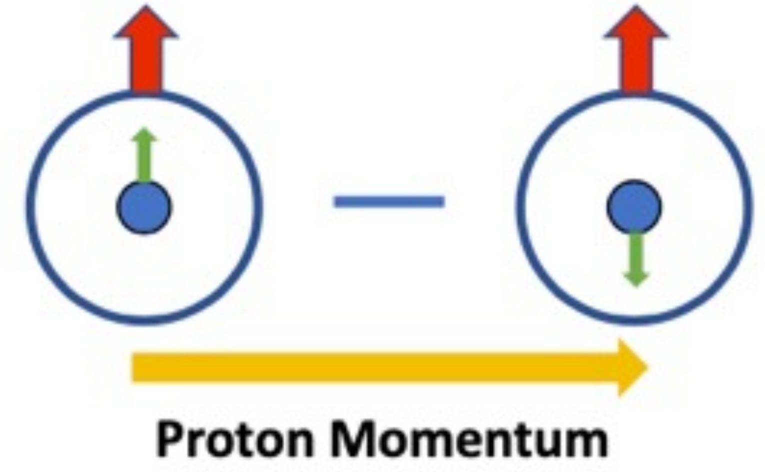
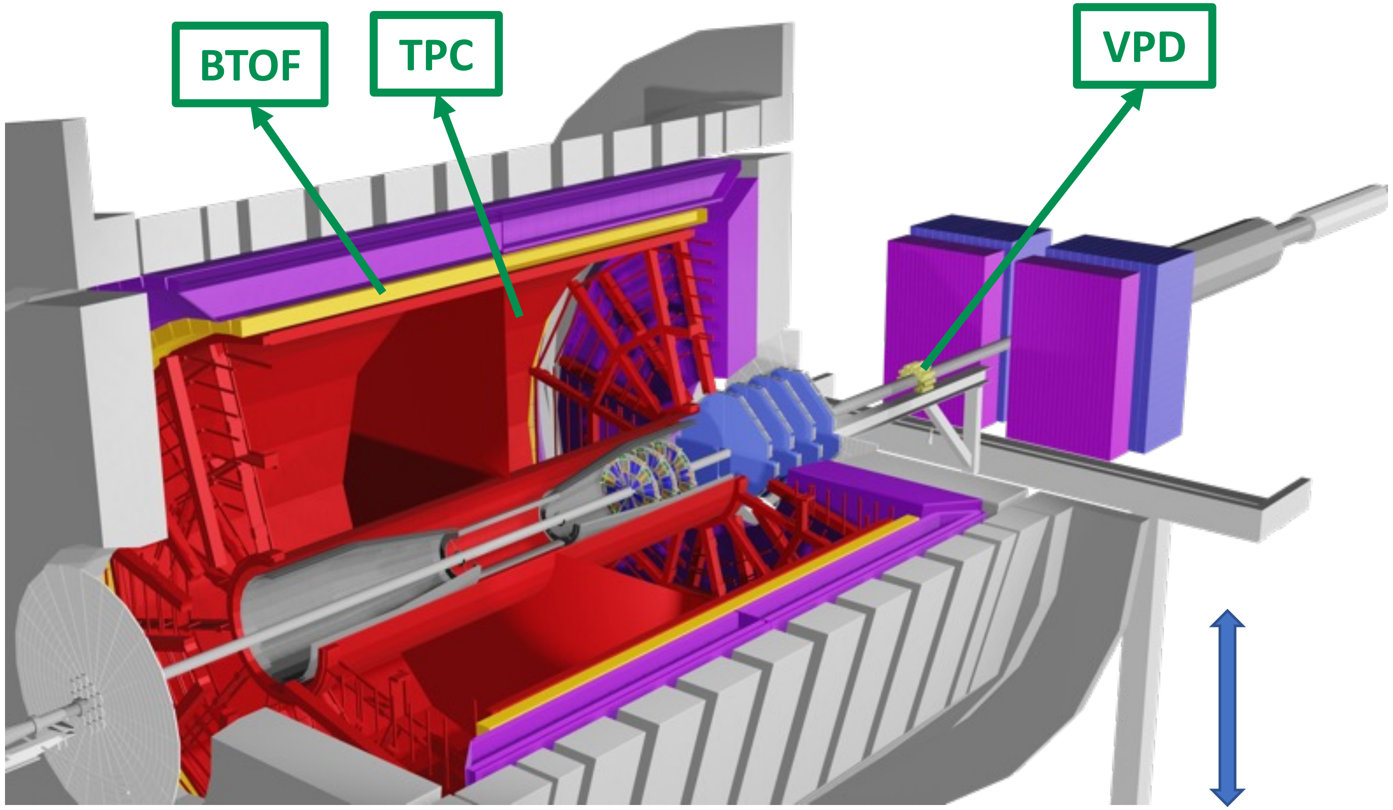


Figure by Ting Lin

Proton polarization
Quark polarization

STAR: Solenoidal Tracker At RHIC



Human size compared to STAR

RHIC:

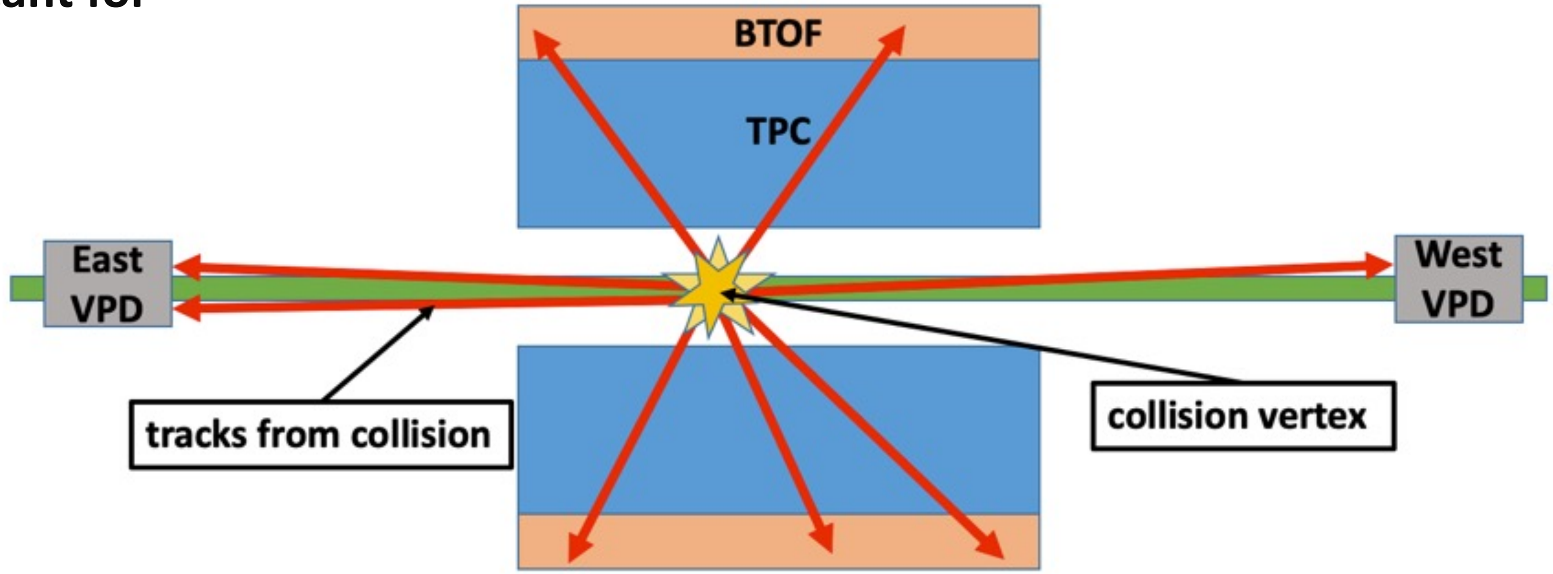
- **The only machine in the world capable of colliding high-energy beams of polarized protons**
- **The beams travel in opposite directions around RHIC's 3.86 km two-lane racetrack**

Relevant STAR detectors for this talk:

- **TPC:** Time Projection Chamber
- **BTOF:** Barrel Time-of-Flight
- **VPD:** Vertex Position Detector

Time-of-Flight (TOF) System

- **Particle identification is very important for Collins Asymmetry measurements**



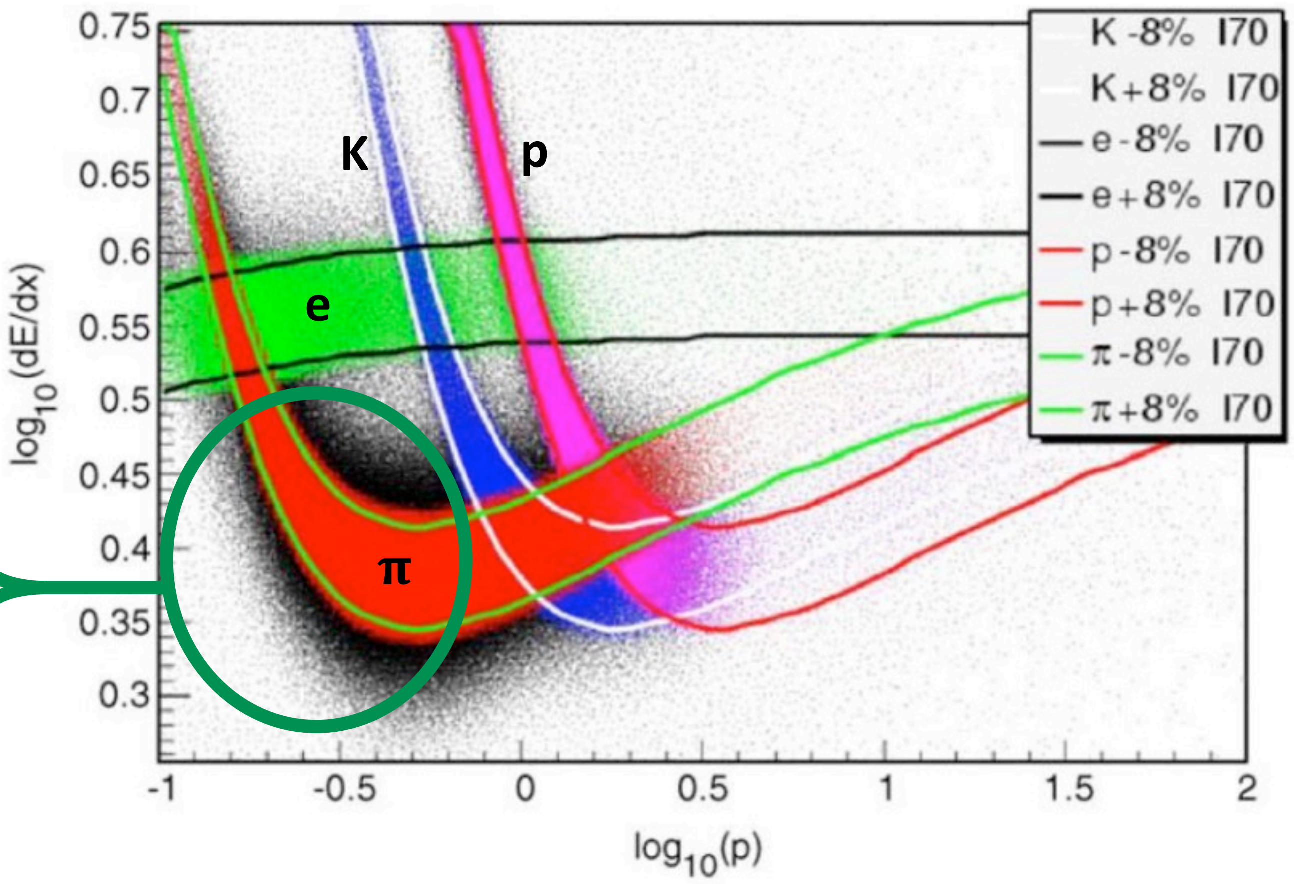
- “regular” TOF:
  - VPD: Event start time
  - BTOF: Event stop time
- **Start-less TOF:**
  - **Originally developed for studying Au+Au collisions at low energies due to low VPD efficiency**
    - **It has never been used before to study collisions involving protons**
  - **BTOF is used to obtain the stop time**
  - **Well-identified tracks with BTOF hits are used to calculate the start time**
    - **Low momentum pions end up providing the highest number of such tracks**
    - **The start time of a track is inferred based on the mass, momentum, and track length of the track**

Selecting Pions With High Purity Using dE/dx

- **Default start-less TOF high purity pion selection cuts:**
  - $0.2 < p < 0.6$ GeV/c
  - $|N_\sigma(pi)| < 2.0$, where N_σ is the dE/dx for a given particle in normalized units

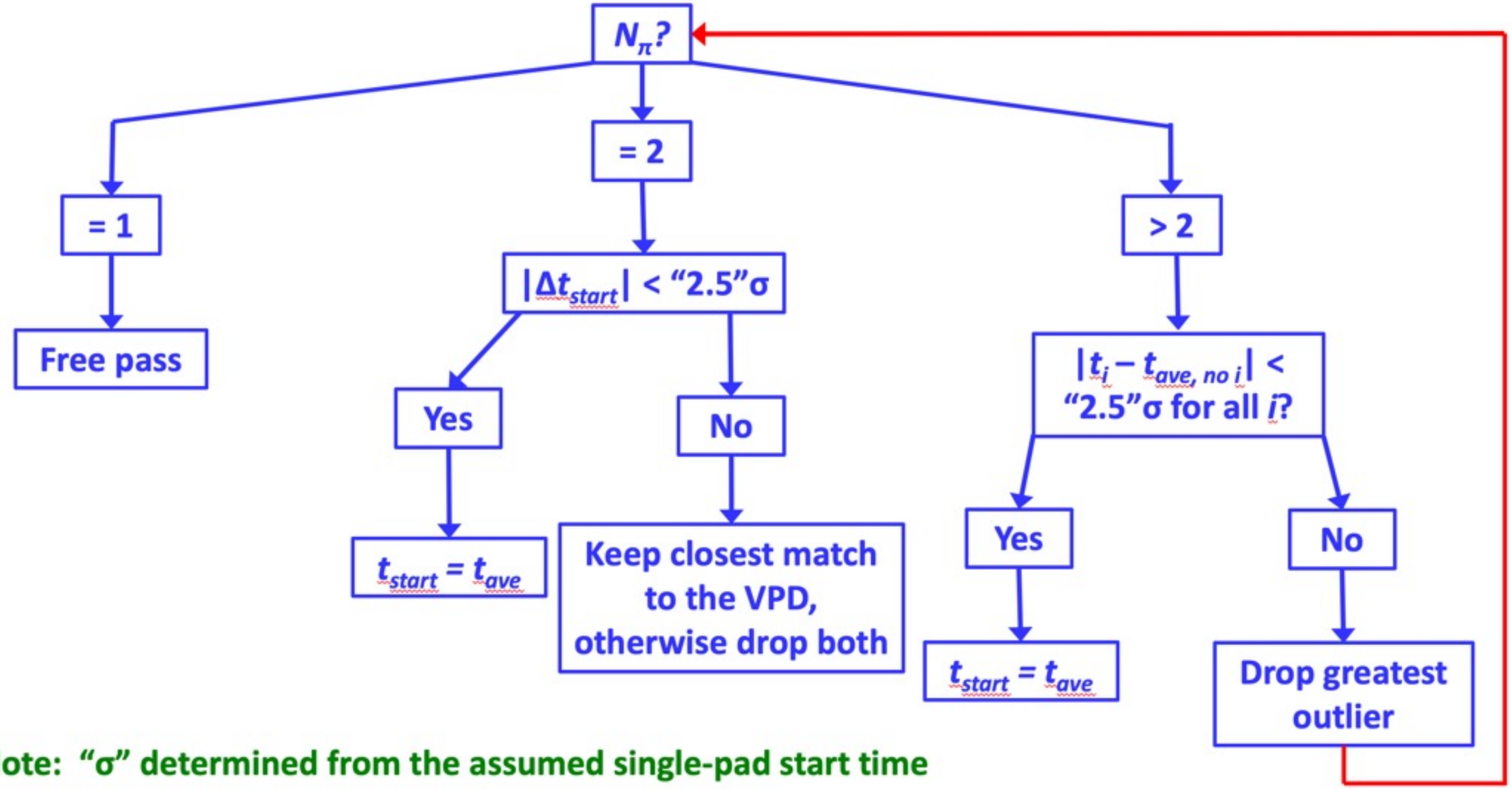
- **Optimized start-less TOF high purity pion selection cuts:**
  - $0.2 < p < 0.7$ GeV/c
  - $|N_\sigma(pi)| < 2.0$

  - $N_\sigma(e) < -3.0$ and $N_\sigma(K) < -3.0$
  - Track cuts to have good quality tracks:
    - nHitsFit > 20
    - nHitsFit/nHitsPoss > 0.51
    - nHitsdEdx > 0.5 * nHitsFit
  - Avoid tracks tangent to BTOF trays:
    - $p_T > 0.18$ GeV/c
  - Vertex pointing accuracy to reduce contamination from secondary particles and decays in flight:
    - 2 cm global DCA cut



Improved BTOF Outlier Rejection Algorithm

The outlier rejection algorithm prunes through the candidate pions to remove ones with anomalous start time w.r.t. the remaining pions



N_π?

= 1

Free pass

= 2

$|\Delta t_{start}| <$ "2.5"σ

Yes

$t_{start} = t_{ave}$

No

Keep closest match to the VPD, otherwise drop both

> 2

$|t_i - t_{ave,\, no\ i}| <$ "2.5"σ for all i?

Yes

$t_{start} = t_{ave}$

No

Drop greatest outlier

Note: "σ" determined from the assumed single-pad start time resolution and the number of pads in the calculation

The default algorithm had a few issues, including:

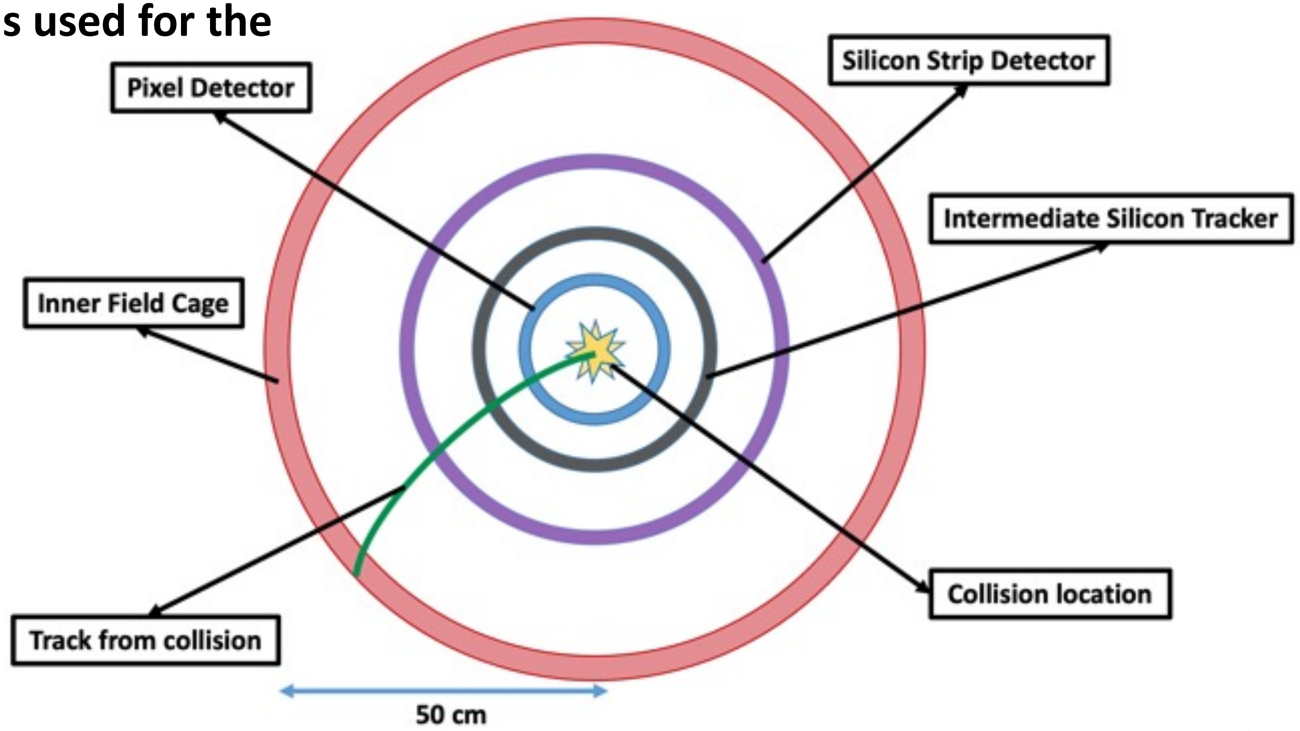
- A single-pass loop only
- Order dependent
- Allowed a wide time window

The new and imporved BTOF outlier rejection algorithm addresses all these issues!

Energy Loss (dE/dx) Time Correction

- **The pion momentum used for start-time calculation is the momentum at the collision point, but:**
  - The particle loses energy and slows down as it passes through material
  - This leads to a measured TOF that is longer than the calculated TOF for a pion of momentum p

- **Based on the geometry of STAR we introduced a simple and effective dE/dx correction to the start time calculation of candidate pions used for the determination of start time for a given event**
  - This dE/dx correction includes an empirically tuned fudge factor (FF)
  - Depends on the configuration of STAR for a given run
  - When dE/dx correction is included, we obtain a better BTOF time resolution and a higher number of candidate pions for start time calculations



Results

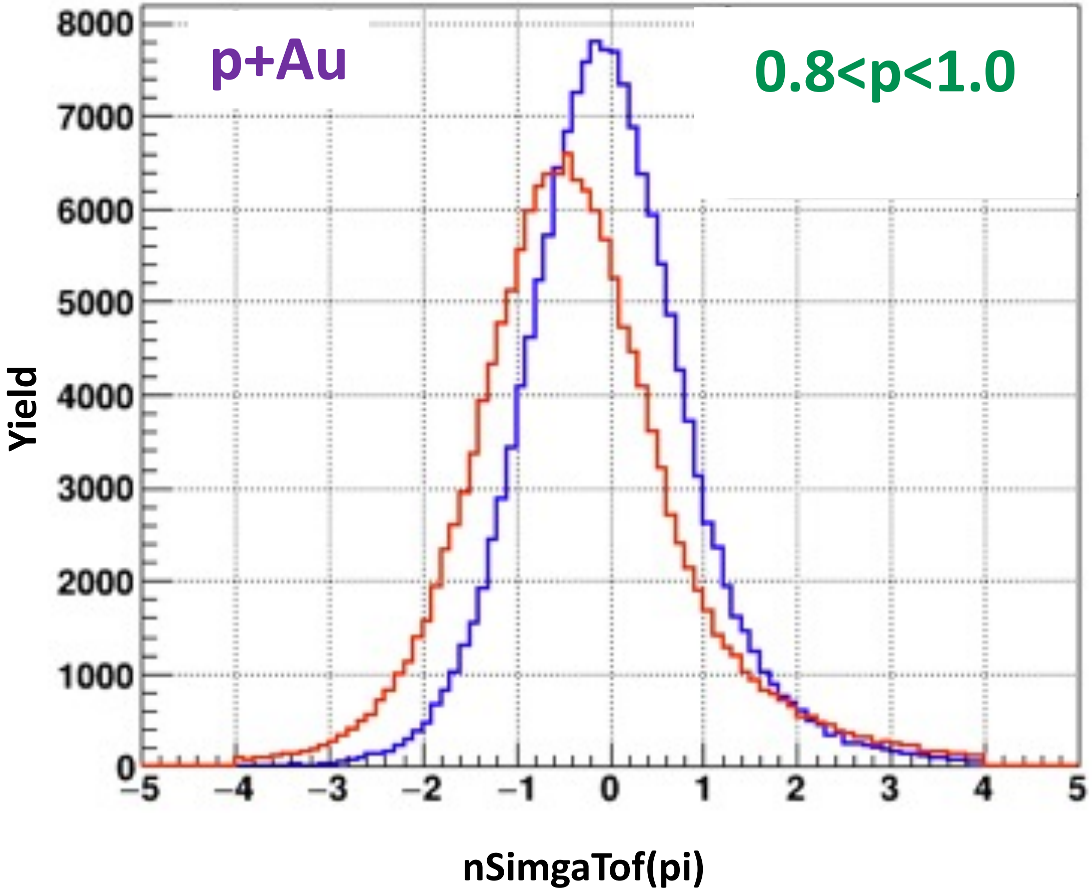
- **We define a new quantity for particle identification:**

$$N_{\sigma\,TOF}(\pi) = \frac{TOF_{meas} - {}^{L}/_{c\beta_{\pi}(p)}}{\sigma_{eff}}$$

Where σ_{eff} accounts for start-time resolution, stop-time resolution, and path-length uncertainty

- **When optimized Start-Less TOF is compared to default start-less TOF, we notice:**
  - **Integrated yield is increased by ~ 2%**
  - **RMS decreases by~19%**
    - **$\sigma_{BTOF} = \sim$75 ps**
  - **Small improvement in efficiency, and significant improvement in resolution**
  - **dE/dx correction shifts the centroid to zero**

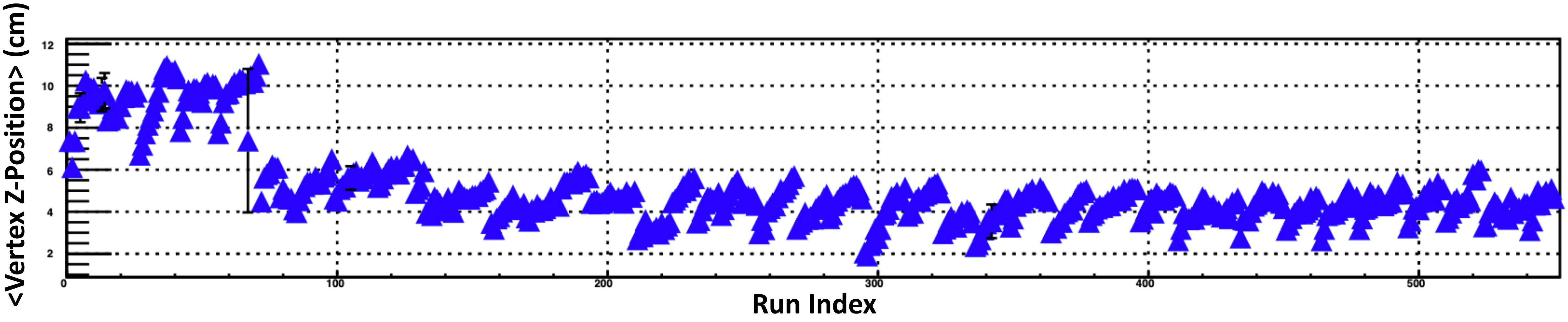
Default Start-Less TOF compared to Optimized Start-Less TOF



Towards a Collins Asymmetry Measurement in pAu

- **The Collins analysis will depend on analyzing data stored in ROOT jet trees**
    - **To utilize our improvements from start-less TOF, we needed to implement the new event and track level information in jet tree codes**

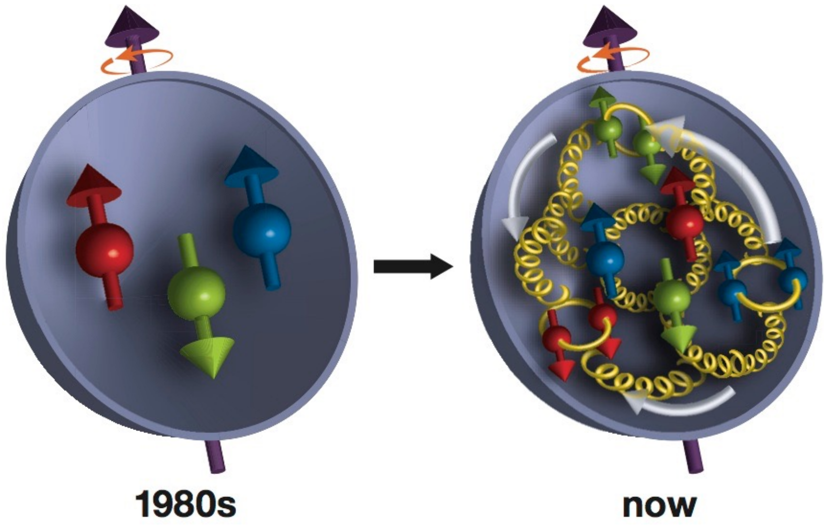
- **Performed quality assurance (QA) analysis on the 2015 p+Au dataset that will be used for the Collins analysis**



- **Currently working on the initial steps in the maximum likelihood method for particle identification**

Back up

Introduction



In the leading twist (collinear twist-2) formulation, the structure of the proton can be fully described by three parton distribution functions (PDF's):

Unpolarized PDF: $f_1(x)$

Helicity PDF: $\Delta f_1(x)$

Transversity PDF: $h_1^q(x)$

our focus

$h_1^q(x) \approx$

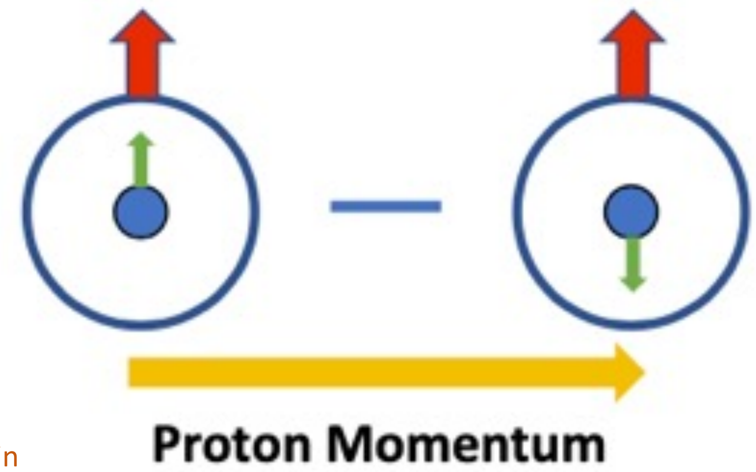


Figure by Ting Lin

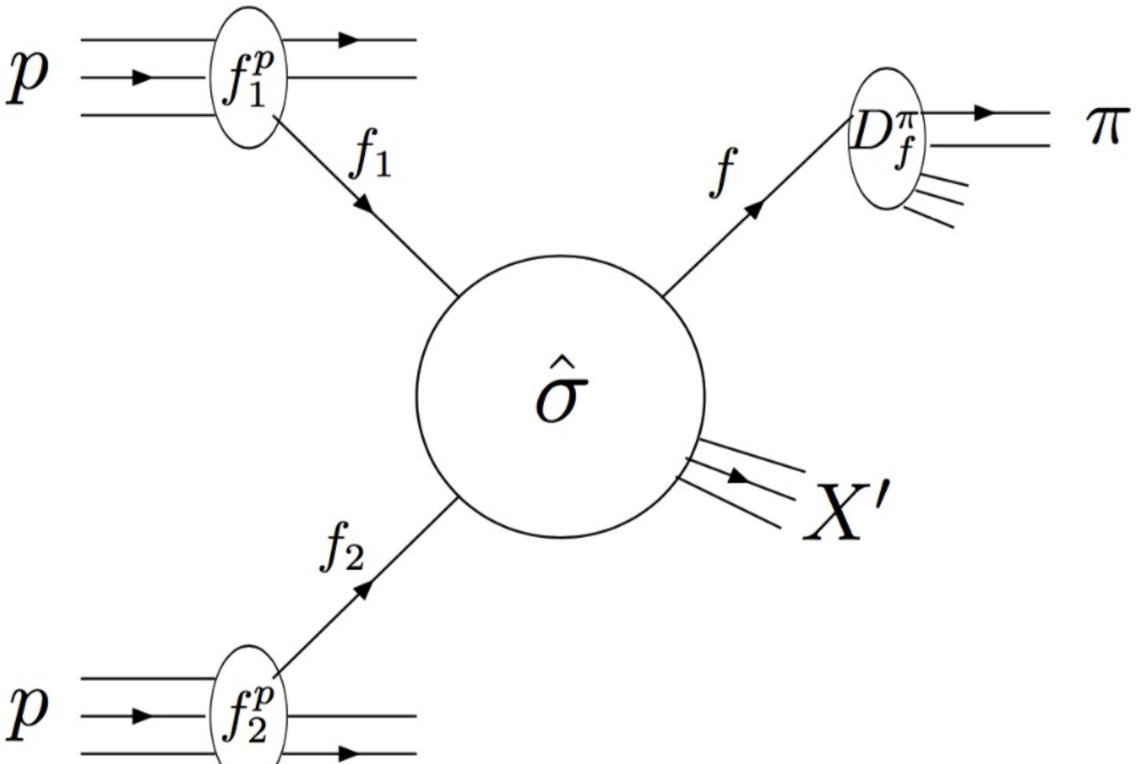
Proton polarization

Quark polarization

Factorization Using an Example

$$d\sigma^{pp\to\pi X} = \sum_{f_1,f_2,f}\int dx_1 dx_2 dz \boxed{f_1^p\left(x_1\right) f_2^p\left(x_2\right)} \times \boxed{d\hat{\sigma}^{f_1 f_2\to fX'}\left(\hat{s},\hat{t},\hat{u}\right)} \boxed{D_f^\pi\left(z\right)}$$

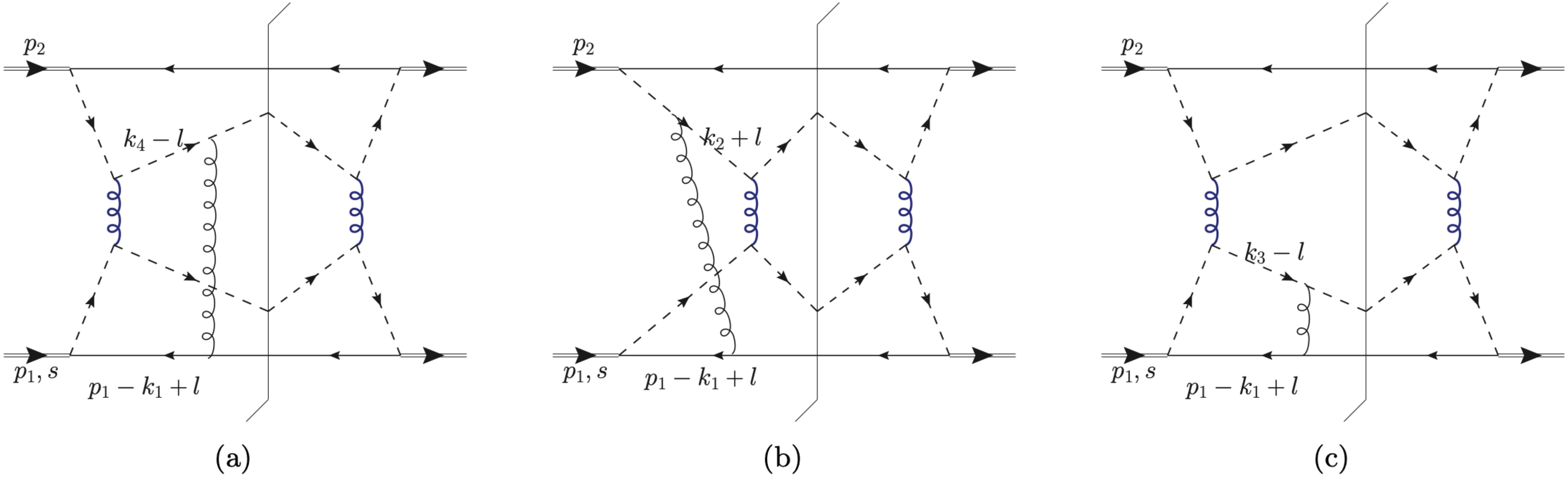
non-perturbative QCD perturbative QCD non-perturbative QCD



- **When calculating the cross-section for a process, factorization allows us to separate the perturbative QCD portion of the calculation, $\hat{\sigma}^{f_1 f_2\to fX'}$, from the non-perturbative portion of the calculation, the PDF's $f_1^p(x_1)$ and $f_1^p(x_2)$ and the fragmentation function $D_f^\pi(z)$.**
- **$f_1^p(x_1)$, $f_1^p(x_2)$, and $D_f^\pi(z)$ are extracted from observables in experimental data**

Adkins, J. K. (2017). *STUDYING TRANSVERSE MOMENTUM DEPENDENT DISTRIBUTIONS IN POLARIZED PROTON COLLISIONS VIA AZIMUTHAL SINGLE SPIN ASYMMETRIES OF CHARGED PIONS IN JETS*. Retrieved November 16, 2021.

TMD Factorization Breaking in Hadron Production (in principle)



- **In principle, TMD factorization breaking is predicted in hadron-production due to color entanglement**
  - **Because of gluon exchanges between active quarks from one proton (quark participating in the scattering process) and remnant from the other proton**
  - **No longer able to separate, or factorized, the PDF's and fragmentation functions because now the quarks in the scattering process are correlated with both protons**
- **Within uncertainty, this has not been observed experimentally.**

J. Collins and J.-W. Qiu, Phys. Rev. D 75, 114014 (2007); J. Collins, arXiv:0708.4410.

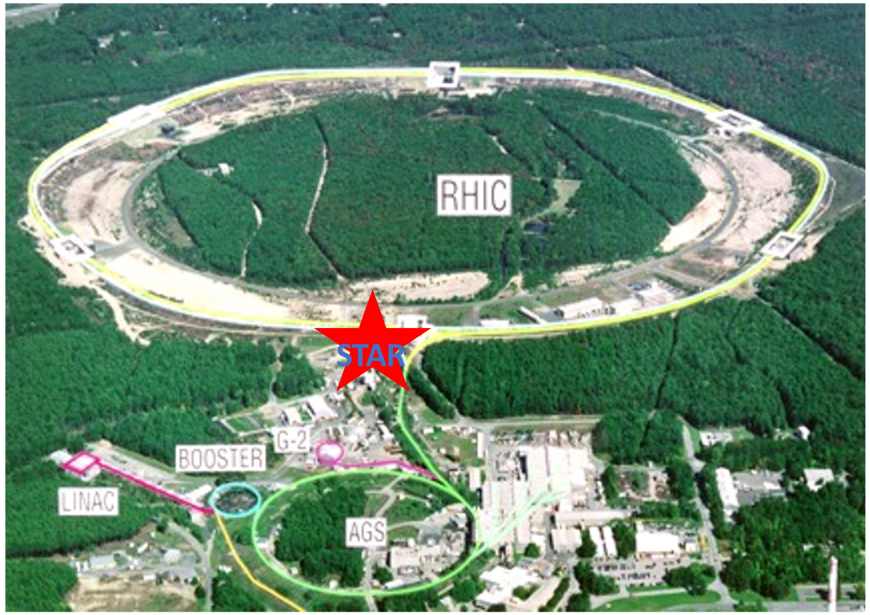
Why Collins Effect in *p*Au?

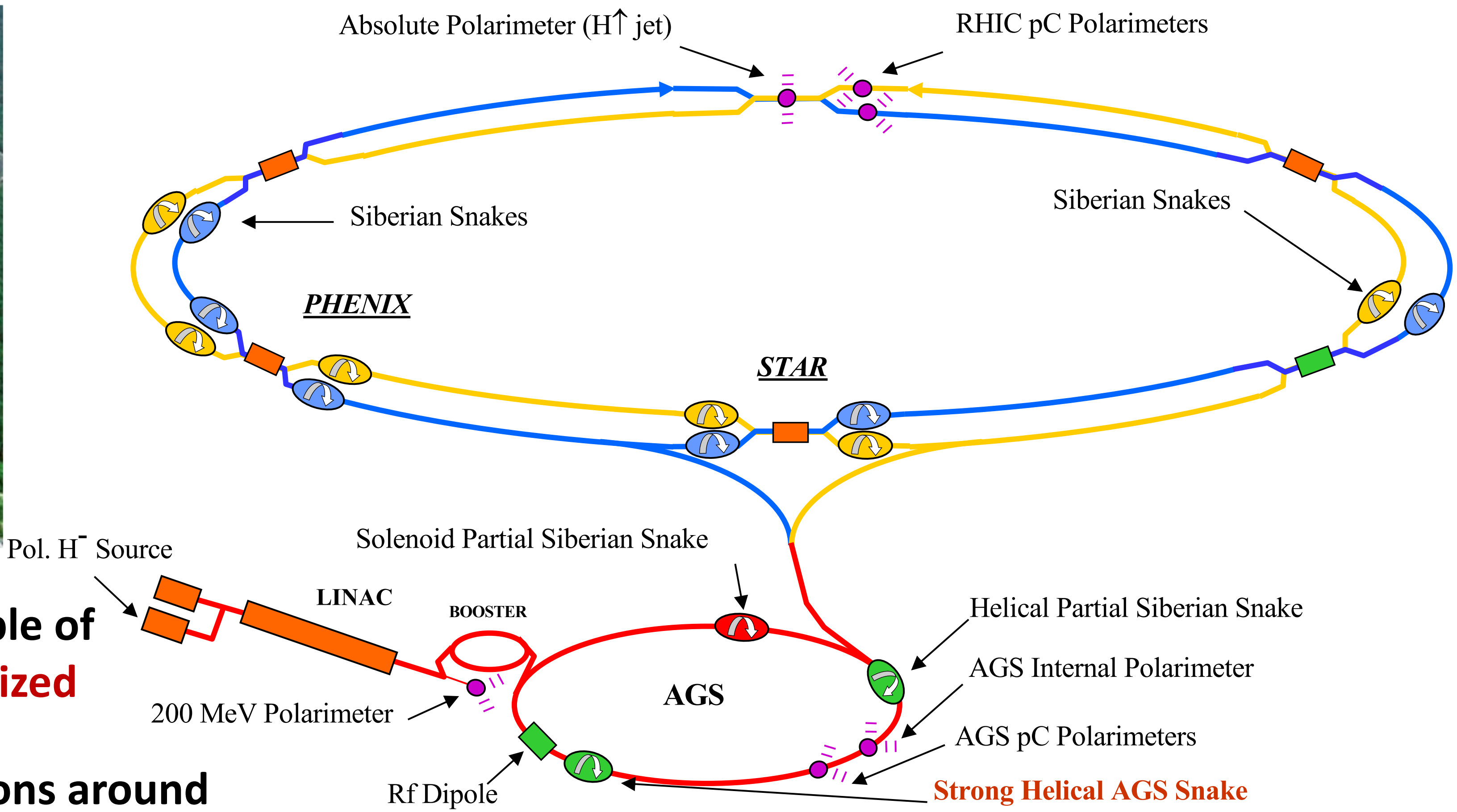
- **Maximize the opportunity for TMD factorization breaking by having very large color field from the Au nucleus where the active quarks (quarks participating in the hard scattering):**
    - **have a lot of opportunities of interacting with the gold remnants in the final state, which will break factorization**
    - **interact with the gold nucleus in the initial state before scattering, which will also break factorization**

- **Since the TMD Collins fragmentation function is involved in the Collins effect, it will give us an insight into the universality of the Collins fragmentation function.**

- **Gives us insight into the energy evolution of TMD functions.**

RHIC: Relativistic Heavy Ion Collider





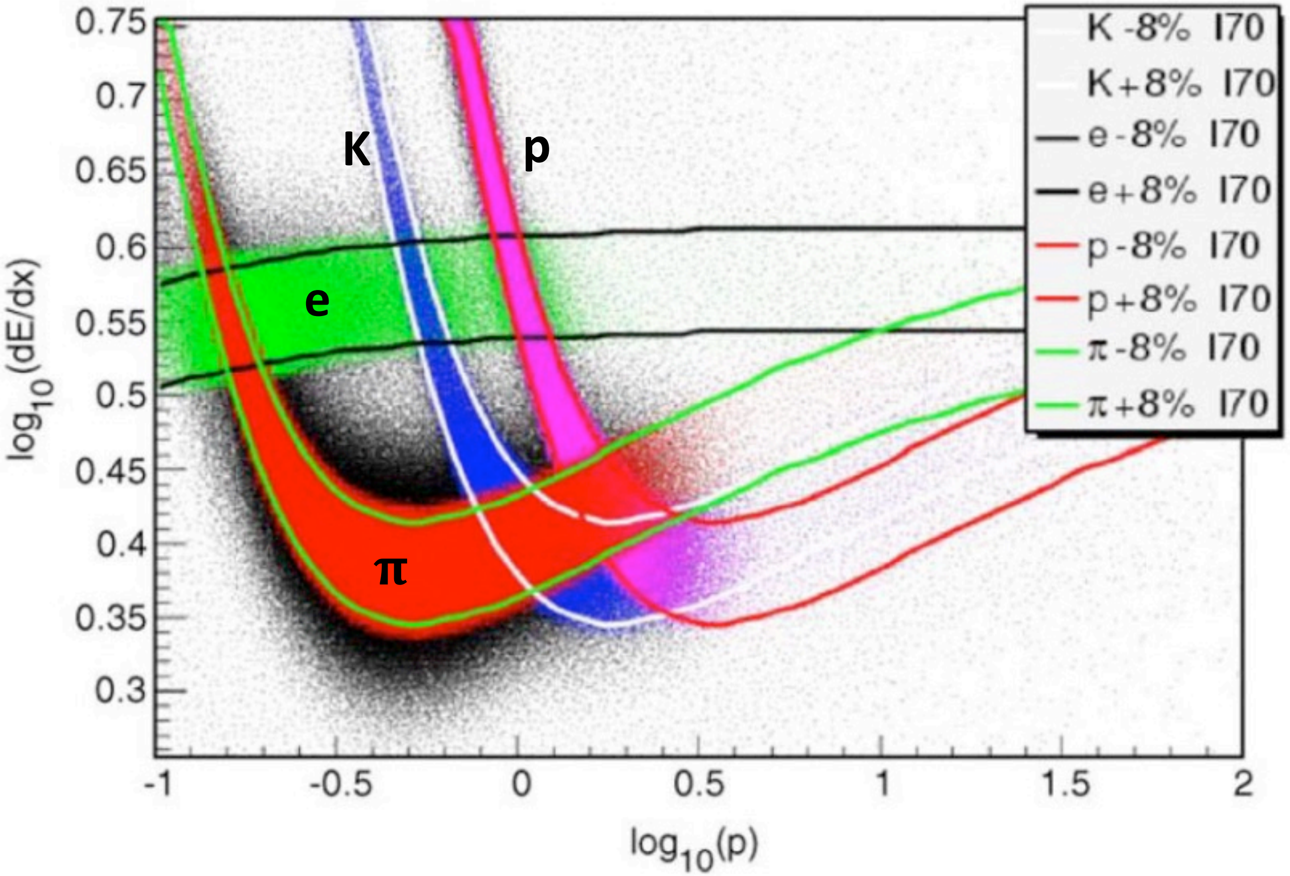
- **The only machine in the world capable of colliding high-energy beams of polarized protons**
- **The beams travel in opposite directions around RHIC's 3.86 km two-lane racetrack**
- **Provides a tool to research and study the state of matter known as Quark-Gluon Plasma**
- **Enables us to explore the different properties of protons**

Particle Identification at STAR

- **STAR primarily relies on dE/dx information from the TPC for particle identification (PID):**
    - This is powerful because it is available for every reconstructed track using the TPC

- **In certain momentum ranges, dE/dx bands overlap and its PID power is reduced**

- **In the following slides, I will show work to optimize a PID tool that is complementary to dE/dx, and particularly where the dE/dx vs. p bands for different particle types are close or cross each other**



A Conceptional Problem With The Default Outlier Rejection

- **The outlier rejection algorithm prunes through the candidate pions to remove ones with anomalous start time w.r.t. the remaining pions:**
  - **But the result depends on the order of the candidate pions**

Consider the following hit times:

- **4.8 ns, 5.0 ns, 5.2 ns, and 21 ns**

- **From the above time values, it is expected that 21 ns seconds would be the hit with the outlier time value and the time average to be 5 ns**

Example:

Order	t_ave	Tot Prob
x,y,21,4.8	4.8	1/12
5.2,21,y,z	4.9	1/12
21,x,y,z	5	5/12
5.0,21,x,y	5	
x,y,21,5.0	5	
4.8,21,x,y	5.1	1/12
x,y,21,5.2	5.2	1/12
x,y,z,21	21	1/4 !!!!

dE/dx Time Correction

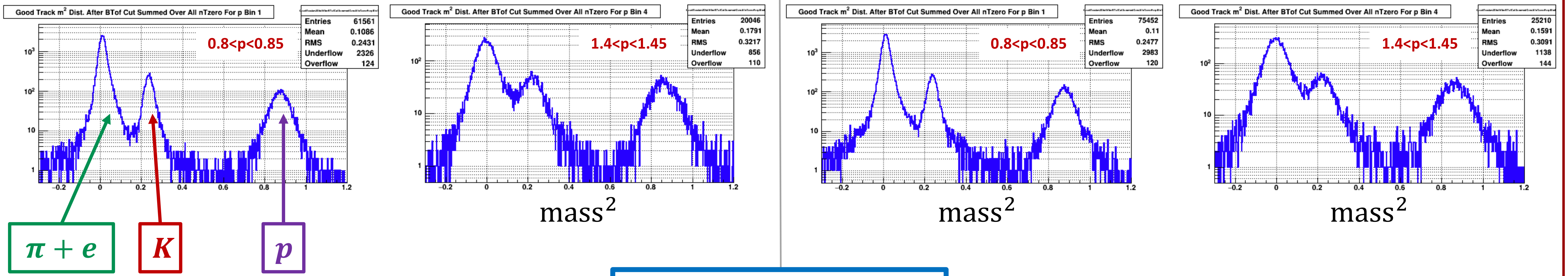
- We start by looking at $\Delta t = \frac{L}{c}\Delta\left(\frac{1}{\beta}\right)$
- The change in $\frac{1}{\beta}$ is given by: $\Delta\left(\frac{1}{\beta}\right) = -\frac{\mathrm{m}^2}{\mathrm{p}^3}\Delta\mathrm{E}$
- From the Bethe-Bloch equation, we have: $\frac{dE}{dx} = \frac{const}{\beta^2}\left[\ln\left(\frac{2\gamma^2 m_e \beta^2}{I_{avg}}\right) - \beta^2\right]$
    - const depends on the material in STAR
- The product of these terms implies $\Delta\left(\frac{1}{\beta}\right)$ is nearly a factor of 50 larger for ptot=0.2 GeV/c than for ptot=0.7 GeV/c
- If we assume that STAR is cylindrically symmetric with radius R, we get: const = $\mathrm{const(r)}$
    - Not a good assumption for 2015, but let's try it anyway
- Furthermore, if we assume a small change in β over the track length, then the integral portion in the Bethe-Bloch equation for a particle at $\eta = 0$ is given by: $\int_0^{\mathrm{BTOF}} \mathrm{const(r)dr}$
    - For a track at $\eta \neq 0$, the energy loss scales with $\frac{\mathrm{L}}{\mathrm{R}}$, so we get: $\frac{\mathrm{L}}{\mathrm{R}}\int_0^{\mathrm{BTOF}} \mathrm{const(r)dr}$
- Introduce an empirically tuned fudge factor to account for $\frac{1}{\mathrm{R}}\int_0^{\mathrm{BTOF}} \mathrm{const(r)dr}$ and its radial dependence

mass^2 Distributions Before and After Optimizing Start-less TOF

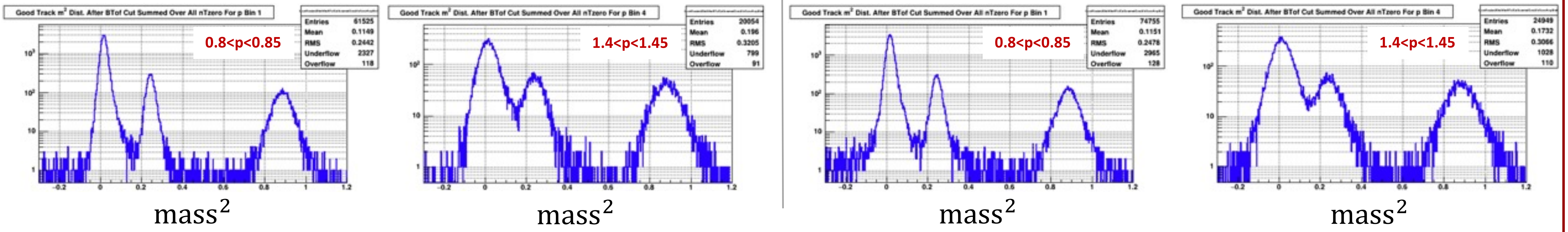
p + Au

Default Start-Less TOF

p + p



Optimized Start-Less TOF



- **15-20% improvement in resolution**
- **1-2% increase in signal yield**