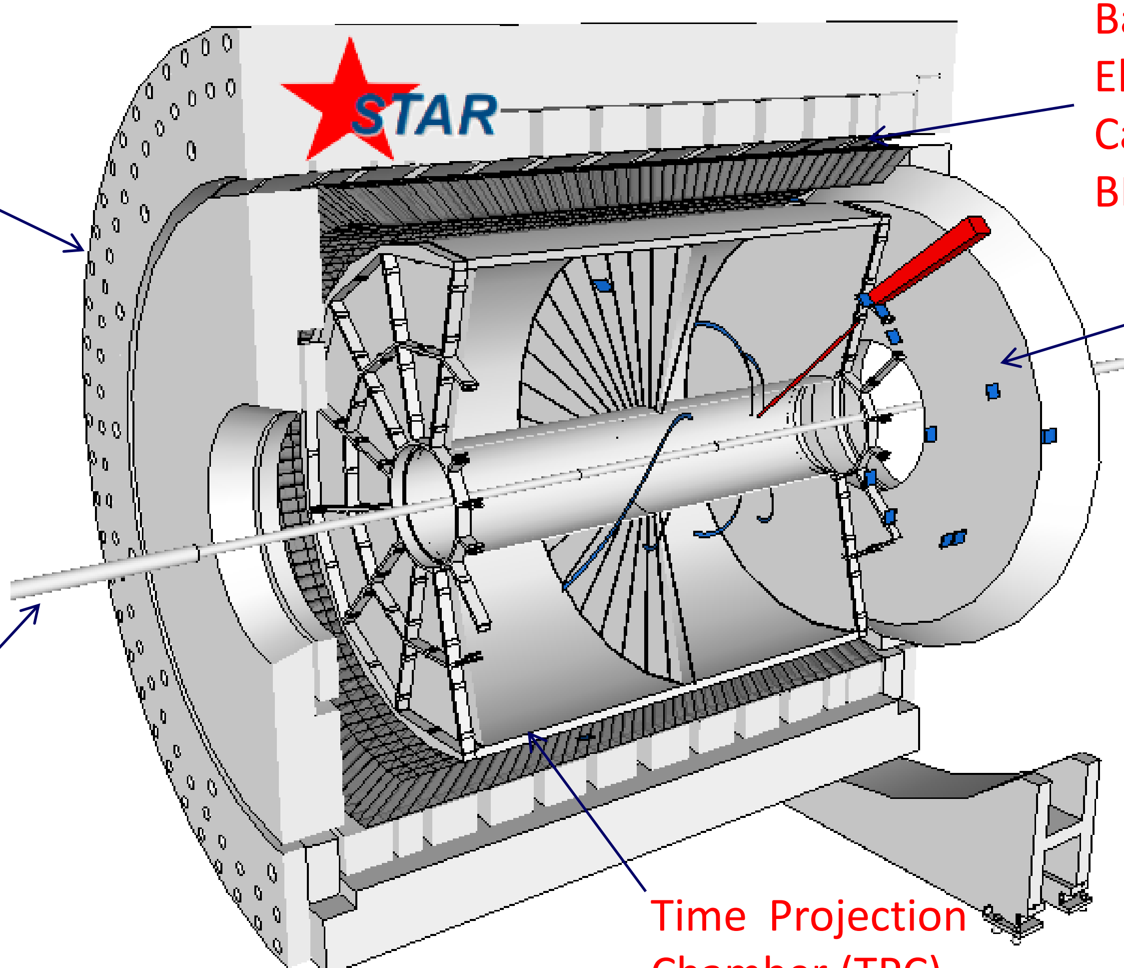
The Star Transverse Spin Program



George Igo
for STAR Collaboration

Introduction

- The over-all goal of the STAR Collaboration's spin program at RHIC is to understand the origin of the proton spin in terms of intrinsic quark and gluon spin and orbital angular momentum:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Inclusive polarized deep-inelastic scattering (DIS) experiments have shown that only approximately 25% of the spin of the proton is attributable to the intrinsic polarization of the quarks and the anti-quarks.

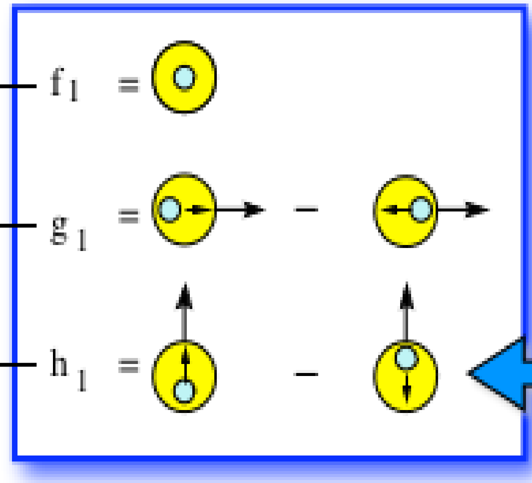
Recent measurements in the medium x-range [0.05-0.2] at STAR suggest that the contribution due to the intrinsic polarization of the gluons, ΔG, is of the same order of magnitude or less.

- To have a complete picture of PDFs at leading order/'twist'

unpolarized PDF, well-known
--upolarized DIS

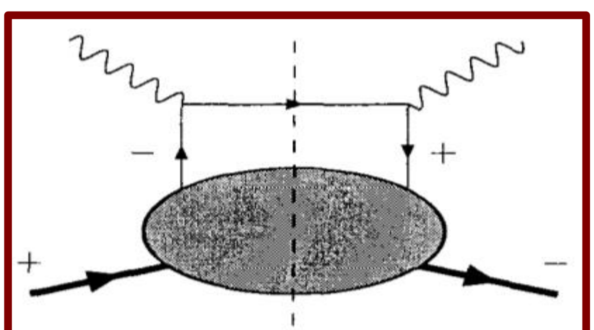
helicity PDF ,known
--polarized DIS, pp

transversity, chiral-odd,
poorly constrained,
inaccessible through
inclusive DIS



$\Delta G,$

transversity



helicity conservation

Transverse SSA at STAR

- **To access proton transversity**
  - ***a) Mid-rapidity hadron-jet correlations***
  - ***b) Mid-rapidity di-hadron production***

- **Verify twist-3 models & connection to TMD PDFs**
  - ***forward rapidity inclusive hadron production***

Motivation , contd

Furthermore, the left-right asymmetries of pions produced in transversely polarized collisions were found to be several Oom larger than predicted by pQCD calculations. This <u>discovery</u> encouraged the expansion of the collinear framework used to define and extract the spin dependent distribution functions.

The introduction of distribution functions that depend on the <u>*transverse momentum*</u> of the partons (k_T) <u>inside the proton</u> & *fragmentation functions* that depend on the transverse momentum of the hadronization products of the partons (j_T) implies that the proton has a much richer spin dependent substructure than originally envisioned.

Motivation, contd

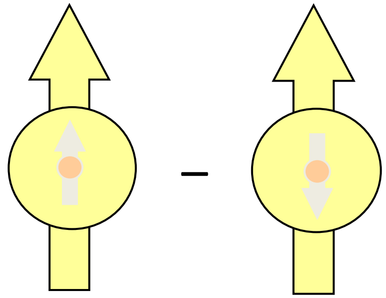
The introduction of j_T dependent fragmentation functions (Collins Functions, $\Delta D(z)$) and di-hadron fragmentation functions (IFF) in turn, facilitated the experimental measurement of the least known distribution function (the *transversity*) within the k_T integrated framework.

The transversity distribution characterizes the number density of transversely polarized partons inside a transversely polarized nucleon. The momentum $f(x)$, helicity $\Delta f(x)$ and transversity $\Delta_T f(x)$ distributions completely describe the momentum and spin structure of the proton at leading twist within a collinear framework. Unlike $f(x)$ and $\Delta f(x)$, $\Delta_T f(x)$ is chiral odd and can be measured only when coupled with another chiral odd operator, such as $\Delta D(z)$, the *Collins fragmentation function*.

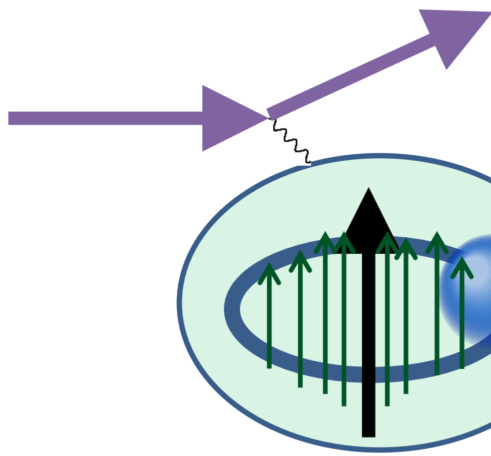
Introduction, cont’d

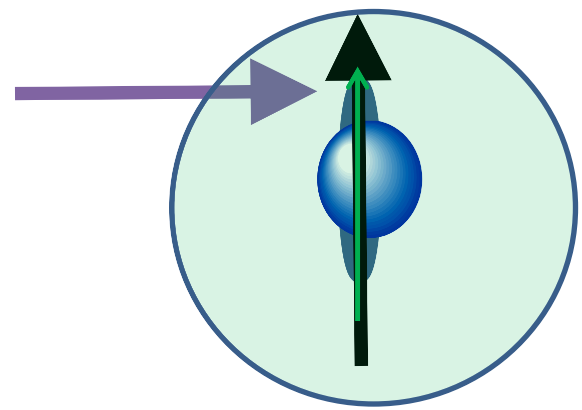
The quark transversity distribution (QTD) is closely associated with the orbital angular momentum (OAM) of the quarks and its contribution to the spin of the proton. We have little knowledge of OAM at the present time.

The QTD is the quark distribution when the nucleon is <u>transversely polarized</u>. Unlike the polarized quark distribution in a longitudinally polarized nucleon, the QTD is difficult to measure because it is a chiral odd distribution.

Why is  so hard to measure?

- Boost suppresses transverse spin vector
- Semi-classic picture: Rotating charge





- Leptonic probe is ‘too fast’ to see transverse spin
- To probe: knock out quark and use effect generated by angular moment conservation

New Results

Since last year, STAR has released new mid-rapidity measurements of QTD related experimental quantities:

Collins effect in jets

Interference Fragmentation Functions (IFFs)

First clear signatures of quark transversity in p+p collisions at RHIC!

We will discuss these next, beginning with *Collins effect in jets.*

Motivation, contd

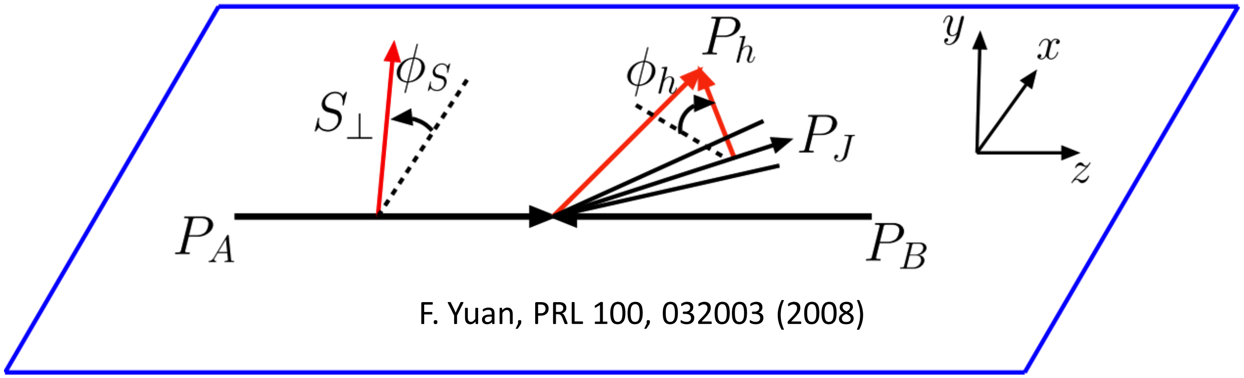
Yuan [Phys. Rev. Lett. *100, 032003 (2008)*] proposed that the azimuthal distribution of charged pions within a jet in hadronic collisions could provide sensitivity to the $\Delta_T f(x) \otimes \Delta D(z)$ distribution.

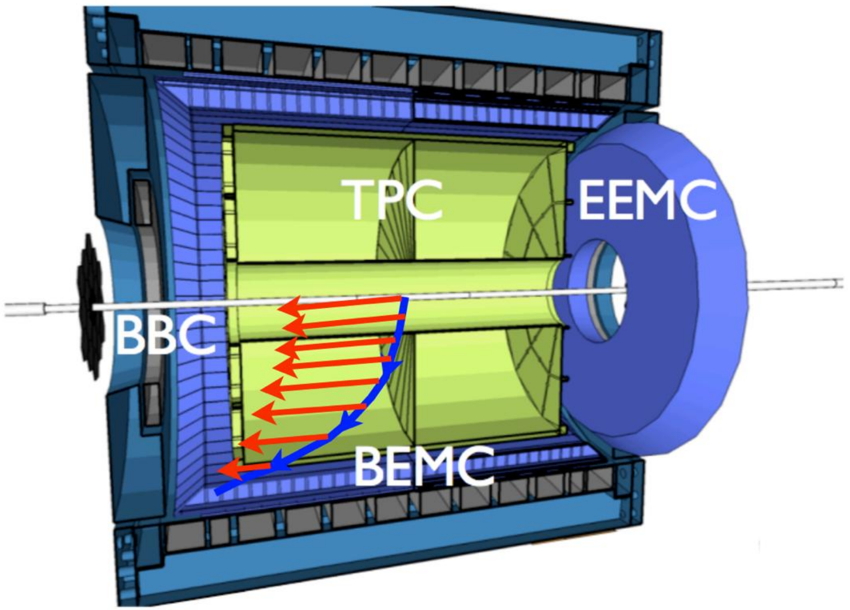
A quark from a transversely polarized proton scatters off a parton from an unpolarized proton beam. The quark from the polarized proton will carry a spin orientation preference associated with the proton spin. When the quark fragments, the emerging hadron's j_T is correlated with the spin direction of the quark. This combination of effects will produce an asymmetric distribution of pions within a reconstructed jet that depends on the initial spin orientation of the parent proton. The differential cross section for this process can be written in terms of the unpolarized cross section and a sine weighted moment associated with the Collins function:

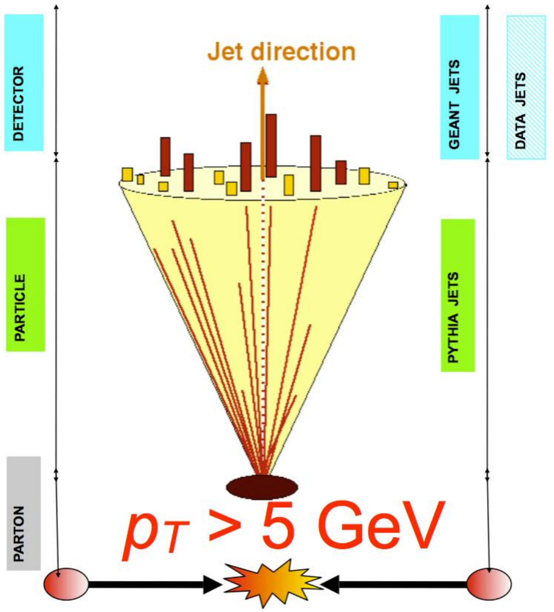
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{unpol}}{d\Omega}(1 + A_n \sin[\phi_H - \phi_S])$$

Midrapidity jet Collins: A_N is related to $\Delta_T f(x) \otimes \Delta D(z)$!

- Measure an azimuthal modulation of a π in a jet





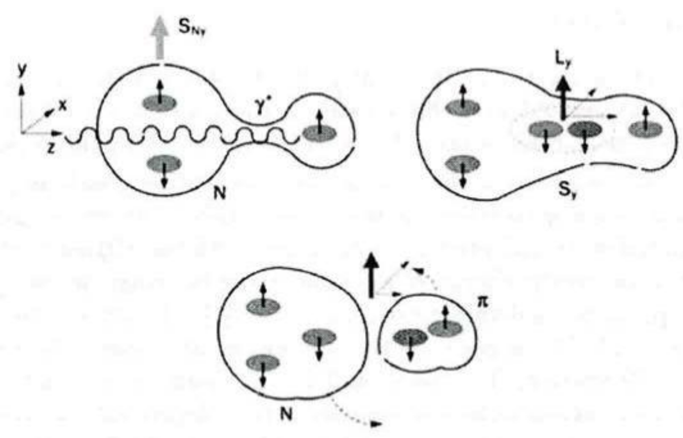


Artru Model for Collins Fragmentation

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

Proton spin
is pointing up!

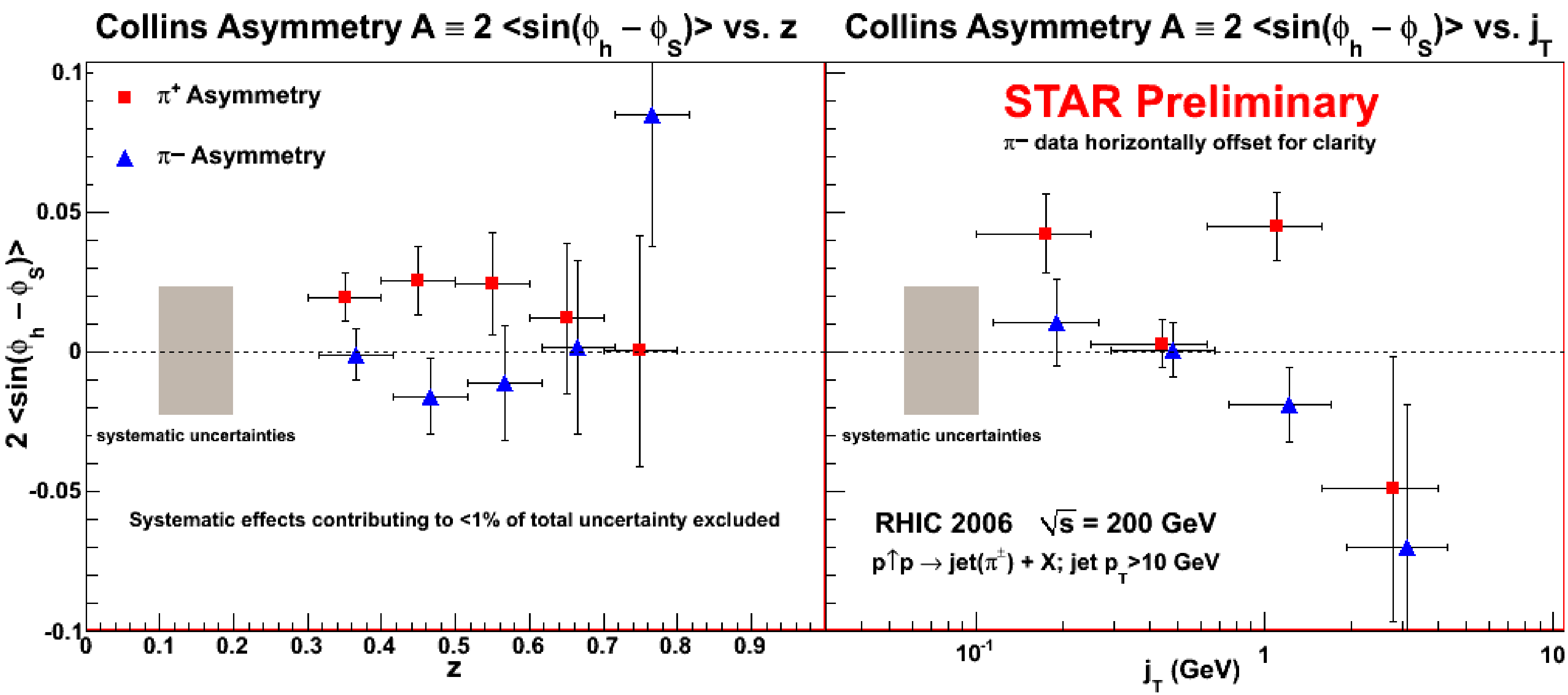
u-quark absorbs
photon/gluon .



String breaks and
a dd-pair with spin
1 is inserted.

π^+ picks up L_y=+1 to
compensate for the
pair S=1(S_z=-1).

A clear signature of the observation of quark transversity in p+p collisions at RHIC.

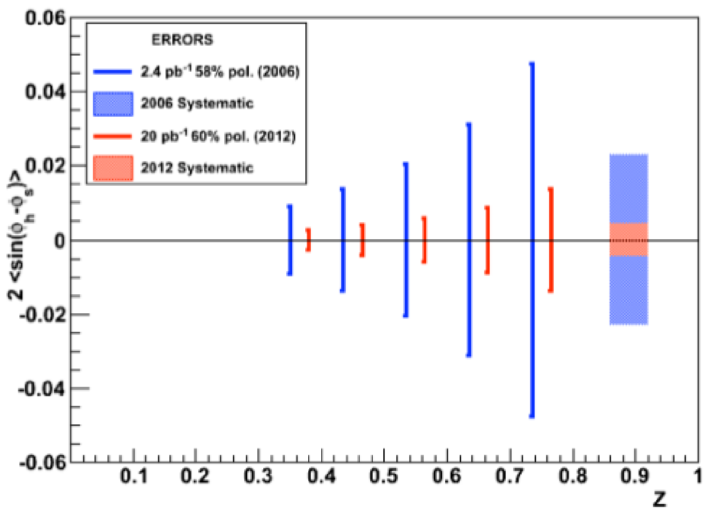


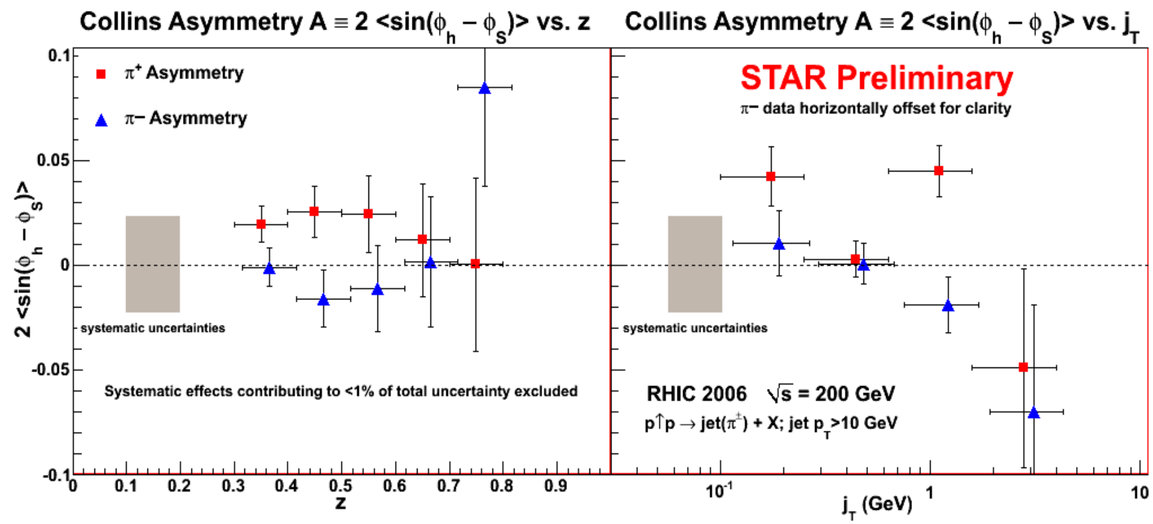
Mid-rapidity hadron-jet correlations, contd

STAR Run12 projection

reduced systematic errors

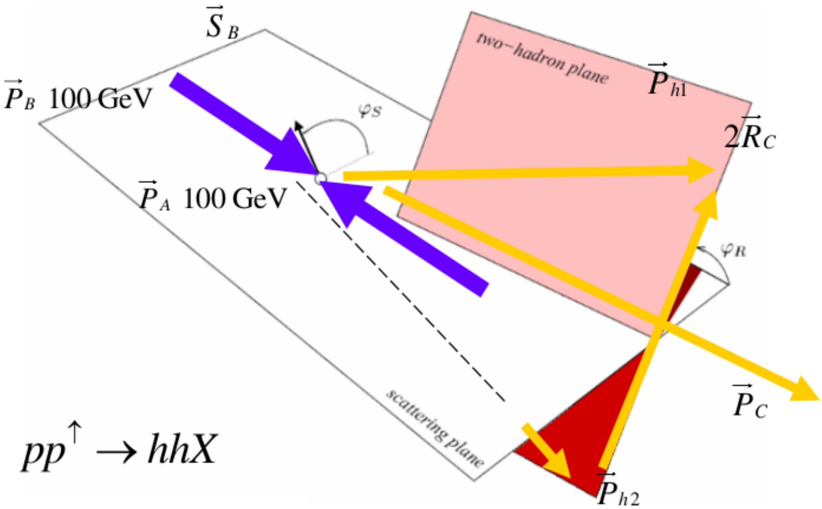
analysis underway





Mid-rapidity di-hadron production

extract proton transversity through its coupling with chiral-odd Interference Fragmentation Function



$pp^{\uparrow} \rightarrow hhX$

$$d\sigma_{UU} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \int \frac{dx_a dx_b}{4\pi^2 z_c} \boxed{f_1^a(x_a)\, f_1^b(x_b)} \boxed{\frac{d\hat{\sigma}_{ab\rightarrow cd}}{d\hat{t}}} \boxed{D_{1,oo}(\bar{z}_c, M_C^2)}$$

Unpolarized quark distribution
Known from DIS

Transversity
to be extracted

Hard scattering cross section
from pQCD

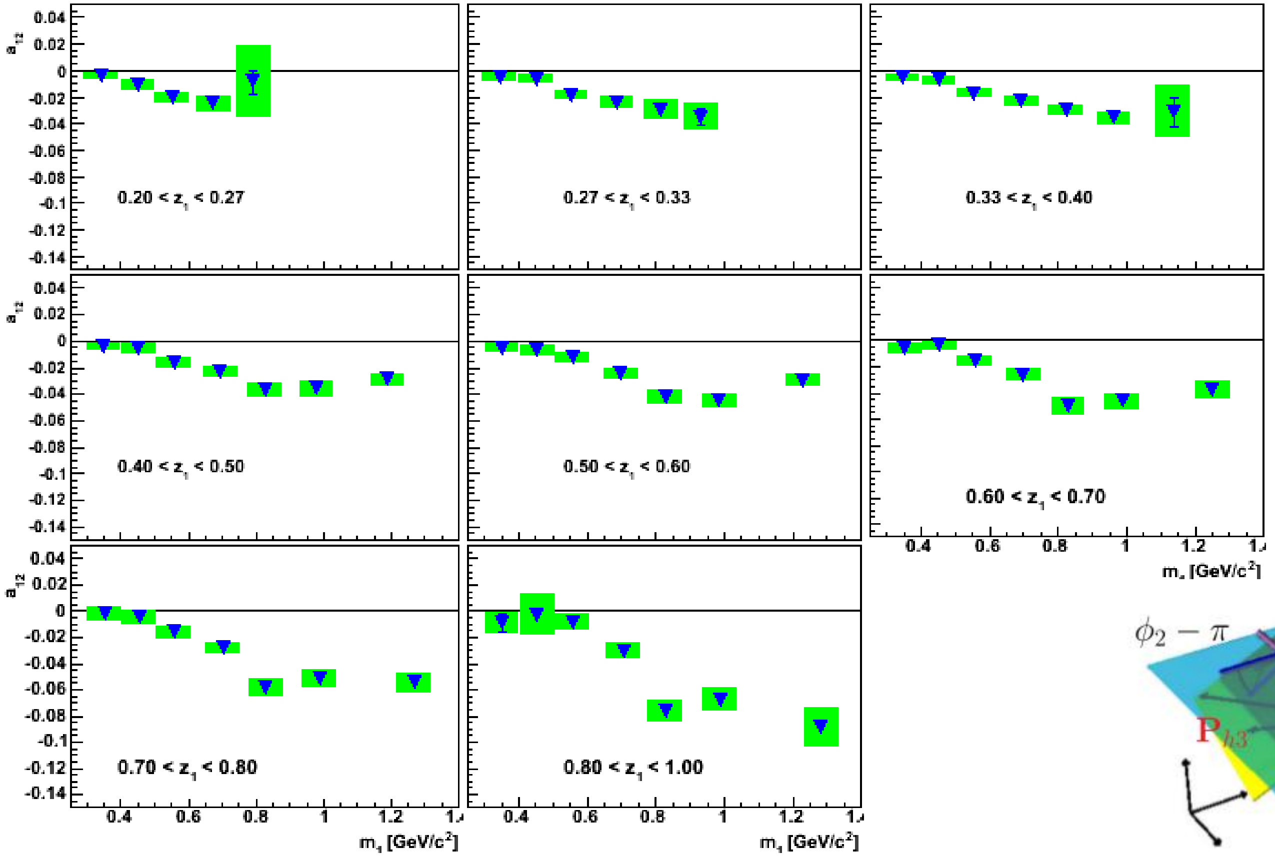
IFF + Di-hadron FF
measured in e+e-

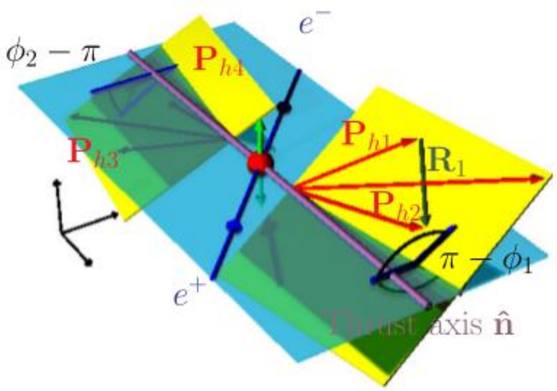
$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C} |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} \boxed{f_1^a(x_a)} \boxed{h_1^b(x_b)} \boxed{\frac{d\Delta\hat{\sigma}_{ab^\uparrow\rightarrow c^\uparrow d}}{d\hat{t}}} \boxed{H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)}$$

Collinear factorization is preserved

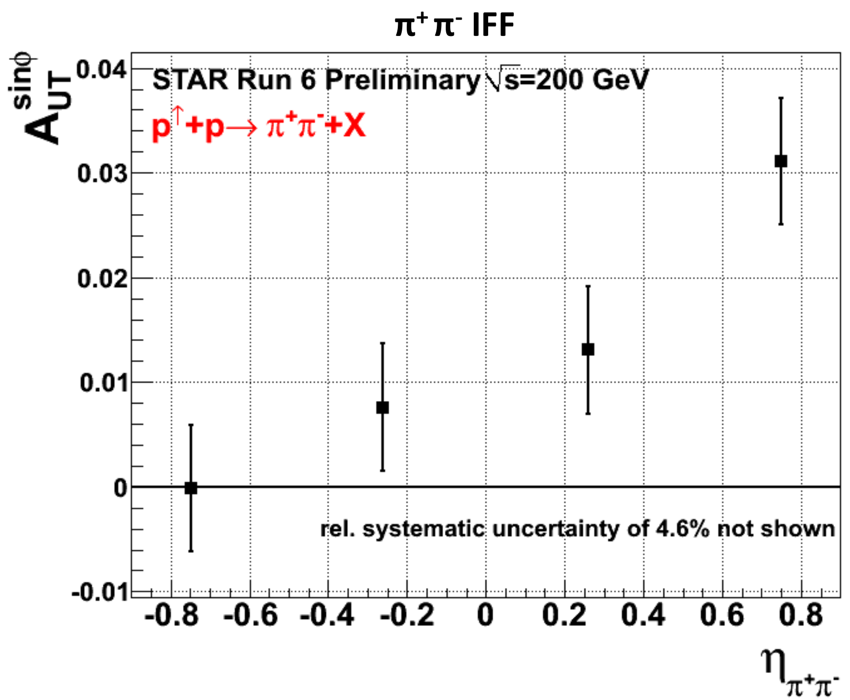
Mid-rapidity di-hadron production

Interference Fragmentation Function measured in e^+e^- annihilation at the Belle facility at KEK, Japan





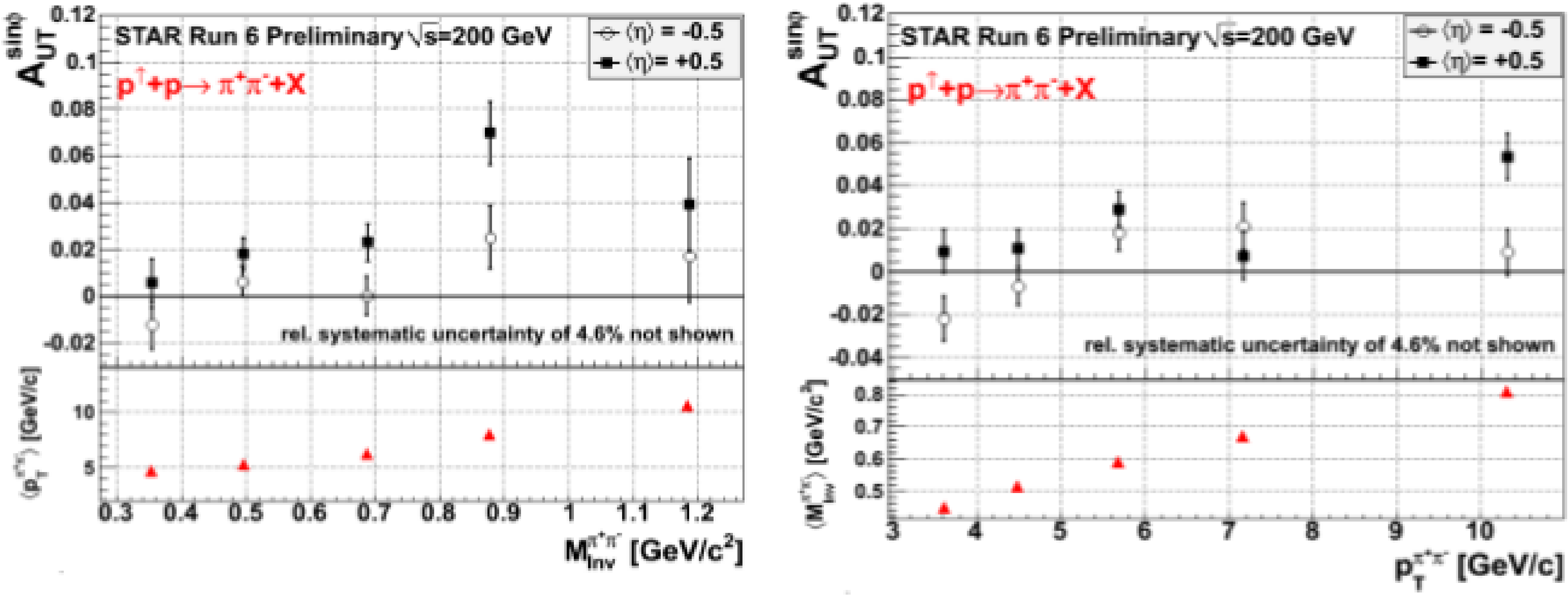
We have additional data (pi+pi- IFF, Collins Effects in Jets) in the can from Run 12



- Recorded >~10 times the figure-of-merit during the 200 GeV pp part of Run 12, with less biased triggers than we had during Run 6
- Big advantage in pushing transversity measurements more forward
  - Large increase in the polarization transfer coefficient
  - See the increasing signal very clearly in the IFF measurement
  - Also: TPC inner sector upgrade, combined with the FGT and EEMC, will extend these studies to η = 2

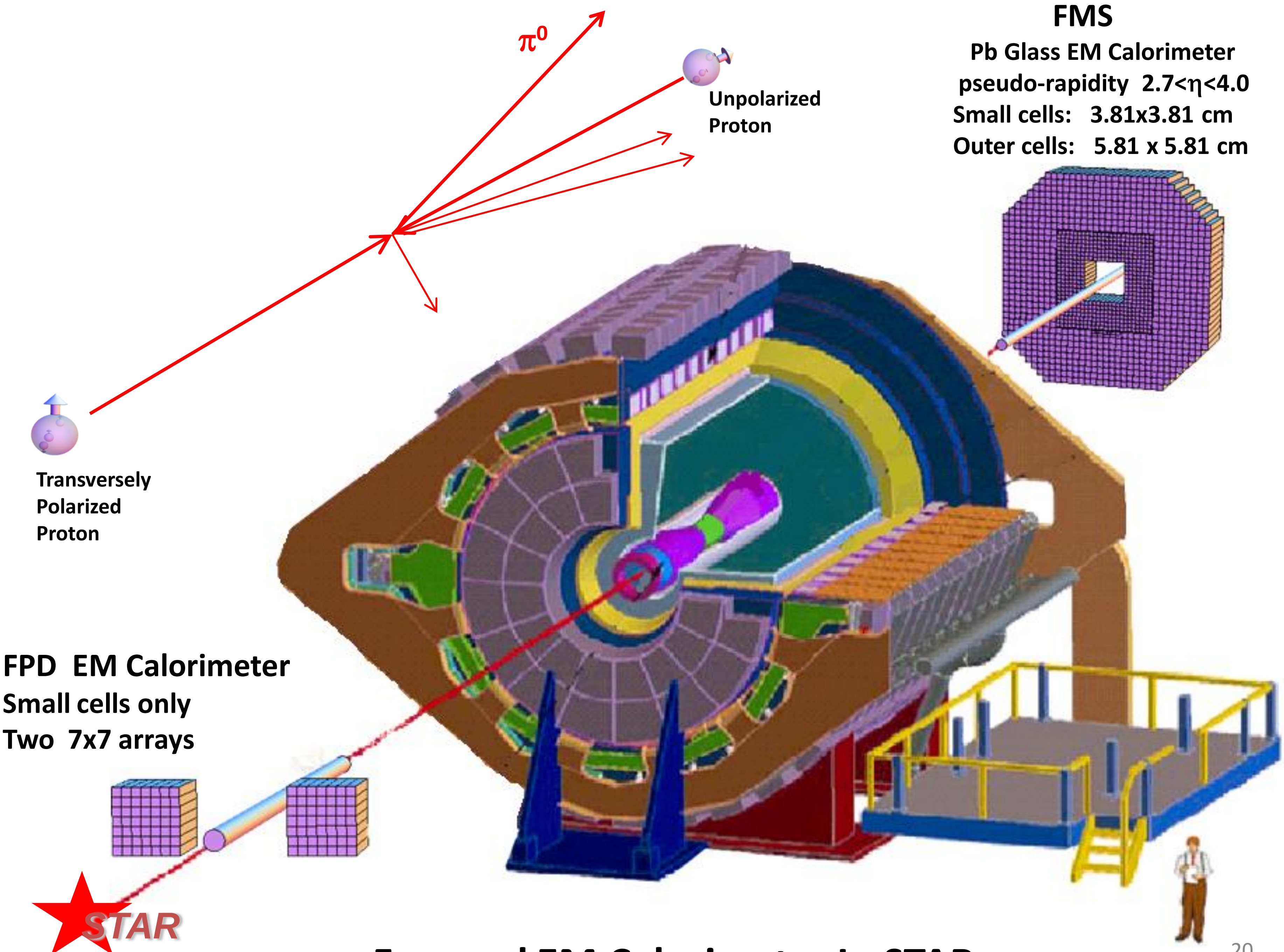
Mid-rapidity di-hadron production

STAR shows significant signal in di-hadron asymmetries

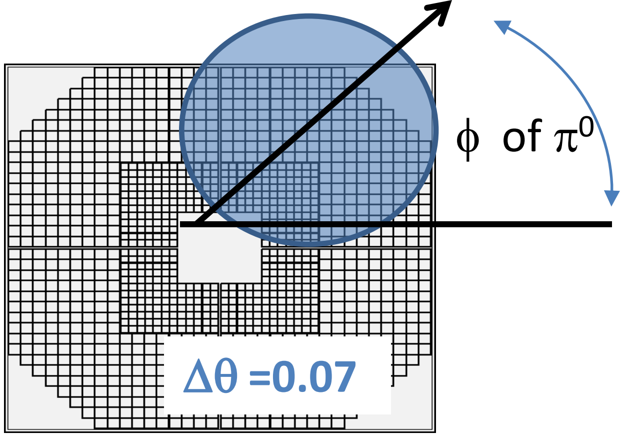


And yet another new transverse spin result from *STAR!*

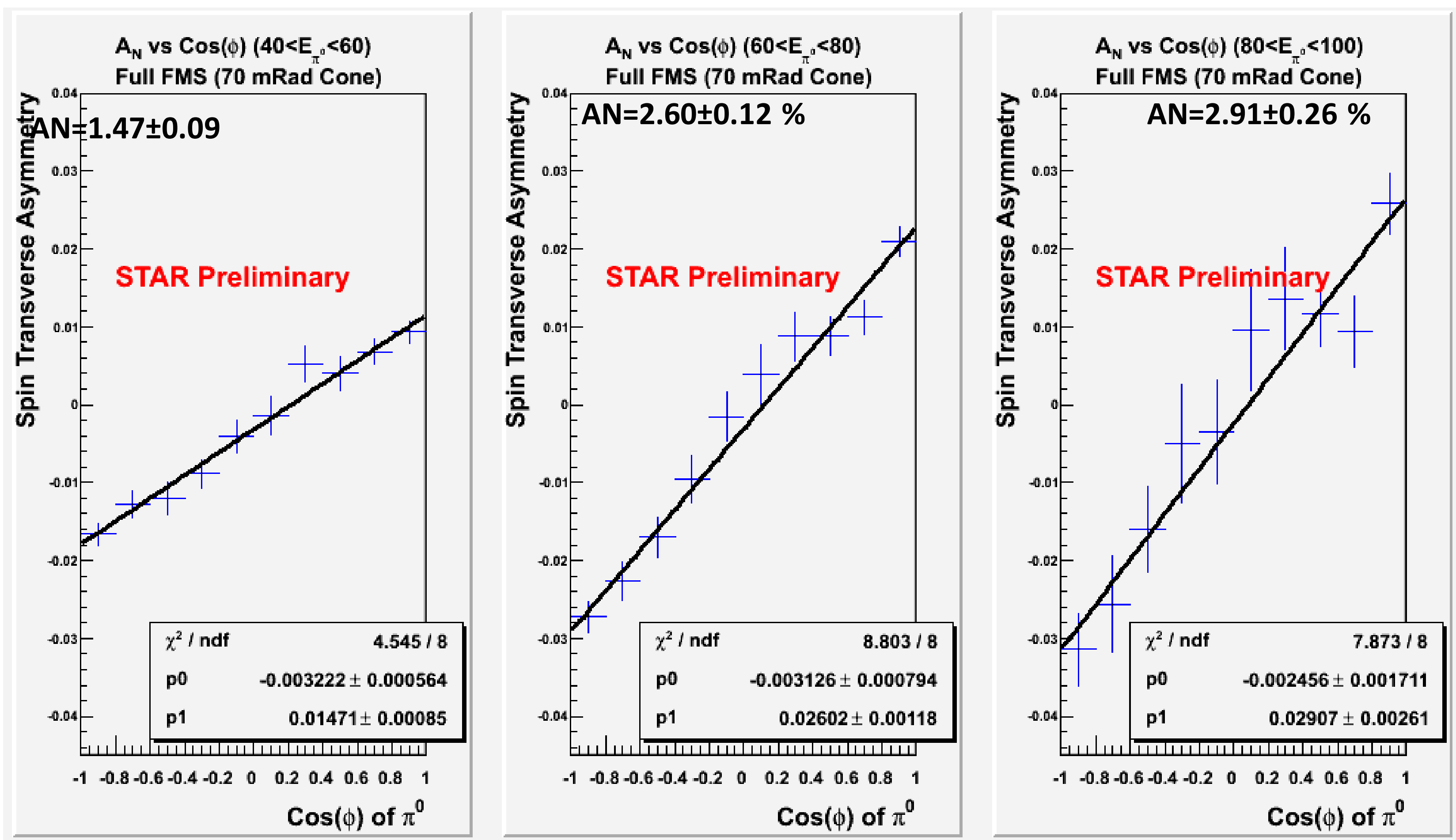
Measured with the FMS (Forward Meson Spectrometer) in Run 11, pi0 A_n asymmetries are found to extend to very high p_T .



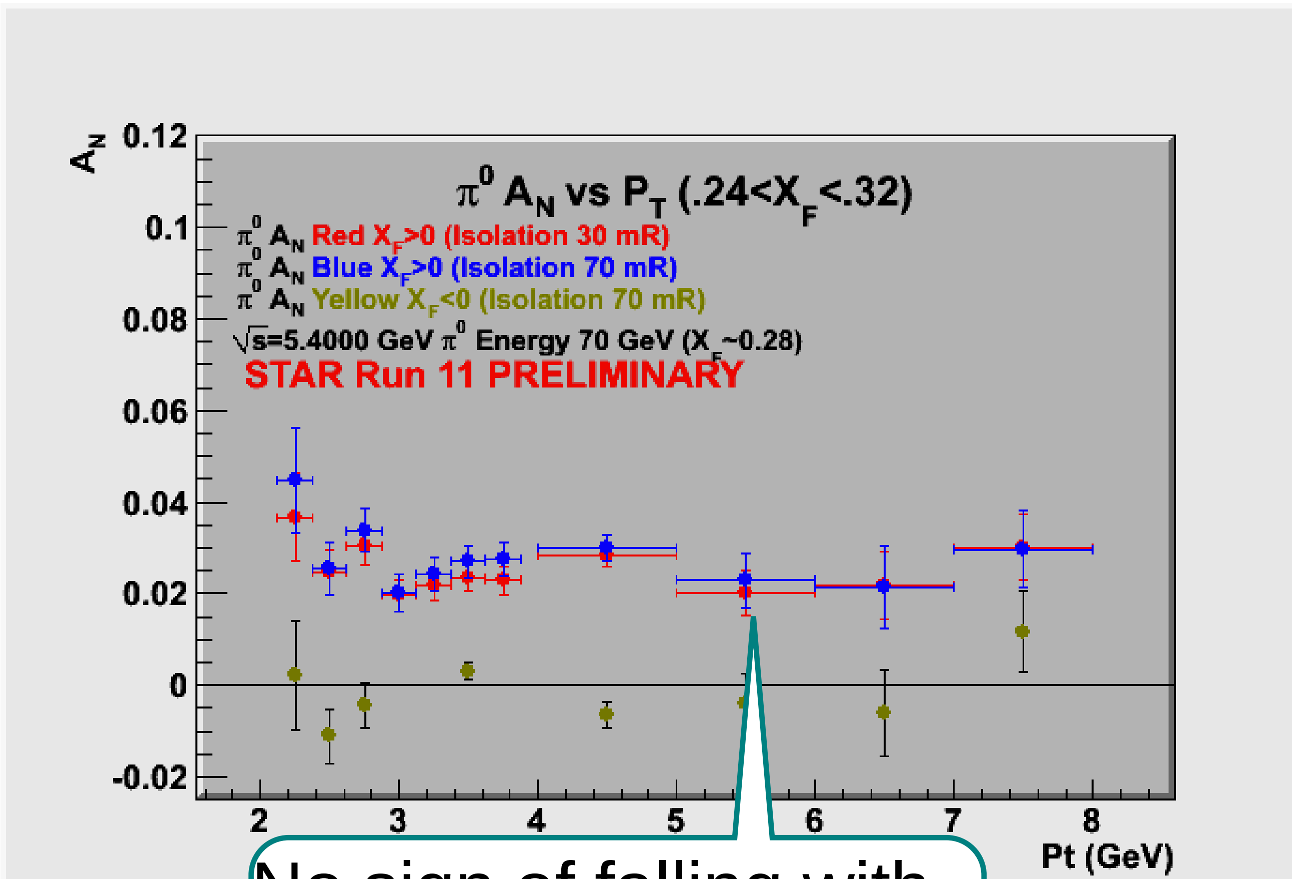
Forward EM Calorimetry In STAR.



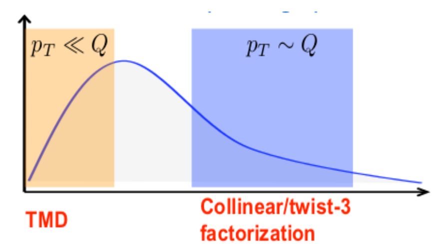
Blue Beam A_N
The raw asymmetry
can be plotted as a function of Cos(ϕ)
(with polarization axis at Phi=$\pi/2$)
Slope =A_N



2011 forward pi0



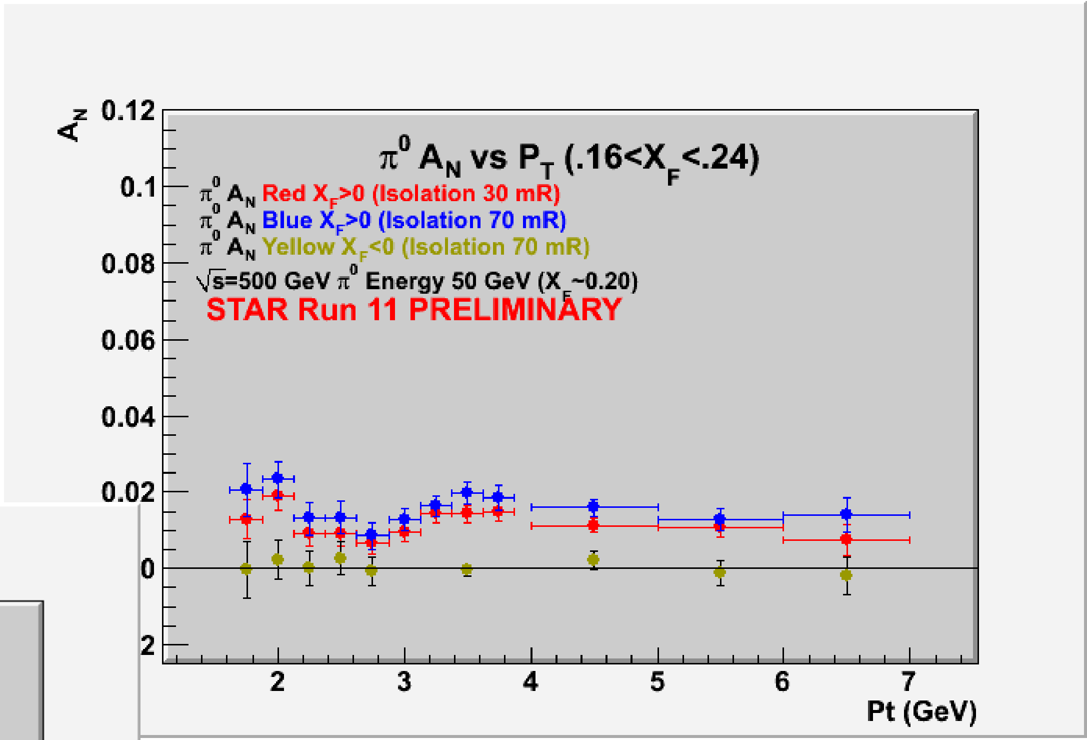
No sign of falling with pT - not what we expect from pQCD

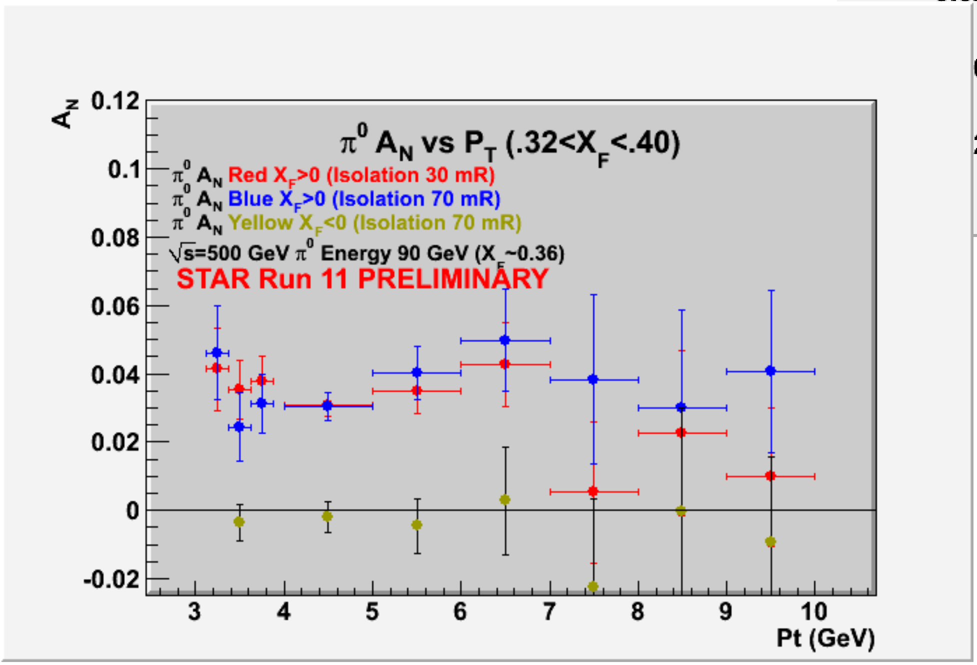


Expectation from pQCD:
A_N ~ 1/pT

π^0 A_N vs p_T

same trend observed for different $x_{F\ values}$





Summary

a) Transverse SSA is a powerful tool that helps us to understand the spin structure of the proton

b) Transverse SSA also provides a critical test of our knowledge of the non-perturbative regime of QCD

c) STAR is actively involved in Transverse SSA measurements through multiple approaches. With a future forward detector upgrade, STAR will be able to access new kinematic regions and more critical observables

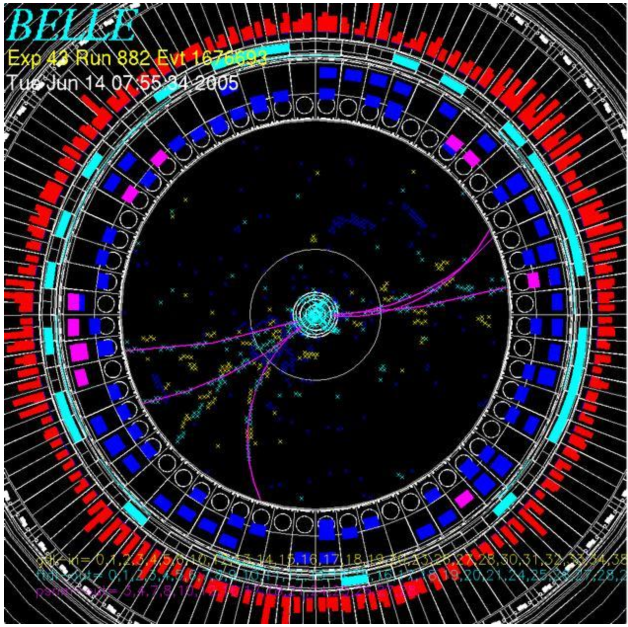
Backup

Measurement of Spin Dependent Fragmentation Functions in e^+e^- Annihilation at the KEK B-Factory

Electromagnetic Interactions with Nucleons and Nuclei

8th European Research Conference, Milosm September 27th - October 2nd 2009

M. Grosse Perdekamp UIUC
M. Leitgab UIUC
A. Ogawa BNL and RBRC
R. Seidl RBRC
A. Vossen UIUC



for the Belle Collaboration

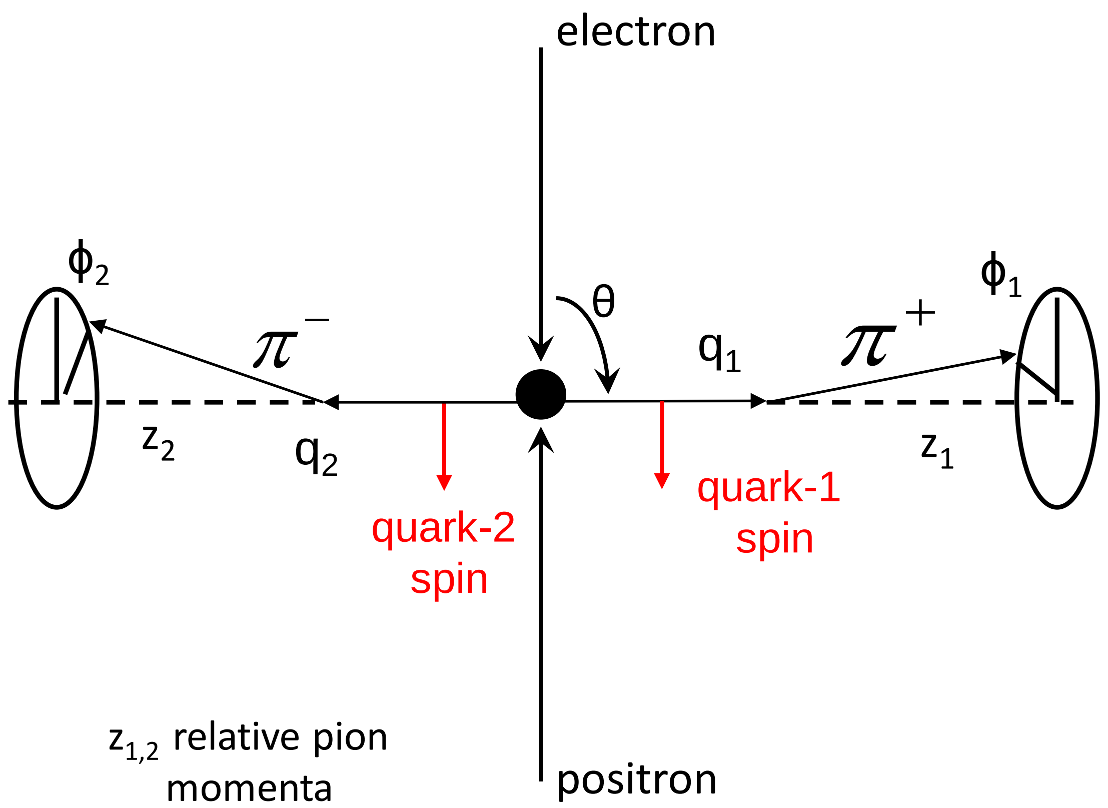
CFF or IFF in e^+e^- : Need Correlation between Hemispheres !

- Quark spin direction unknown: measurement of CFF or IFF in one hemisphere is not possible as the azimuthal modulation will average out.

- Example, correlation between two back-to-back hemispheres $\sin \varphi_i$ single spin asymmetries for CFF results in $\cos(\varphi_1+\varphi_2)$ modulation of the observed di-hadron yield.

⇒ Measurement of azimuthal correlations for pion pairs (CFF) or pairs of pion pairs (IFF) around the jet axis in events with back-to-back jets!

Collins Effect in di-Hadron Correlations In e^+e^- Annihilation into Quarks!



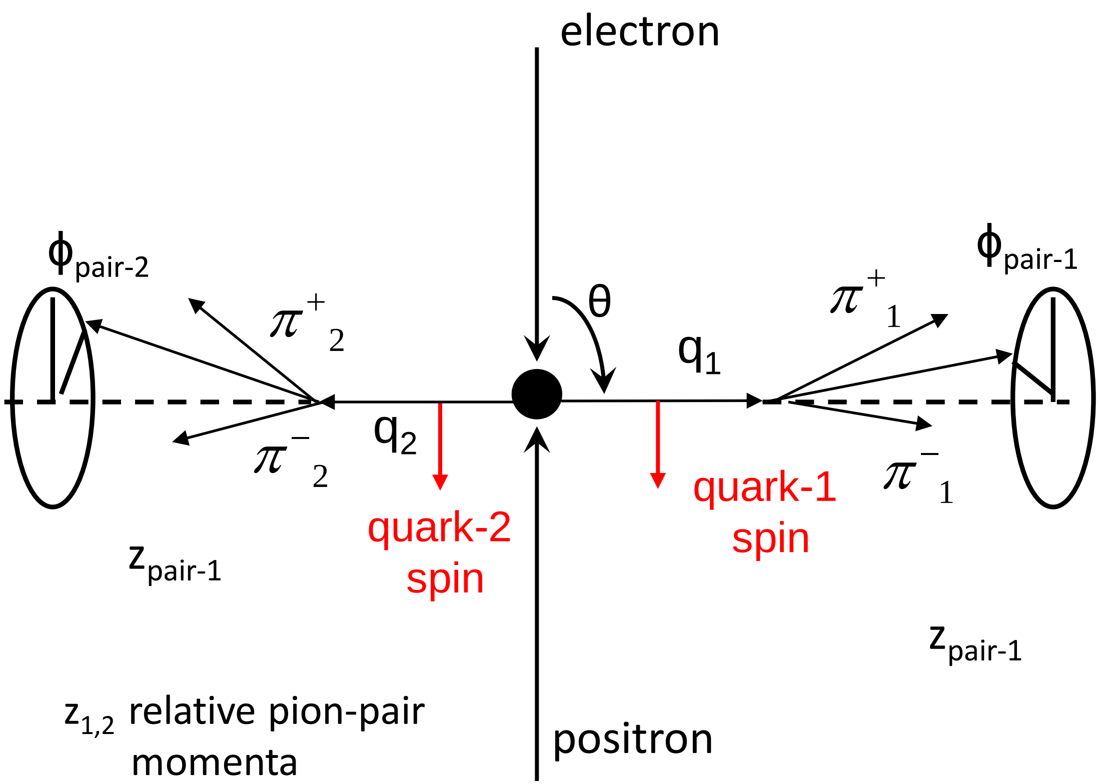
Collins effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements:

$$N_{\pi_1,\pi_2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$$

Experimental requirements:

- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets

IFF in Correlation of di-Hadron Pairs in e^+e^- Annihilation into Quarks!



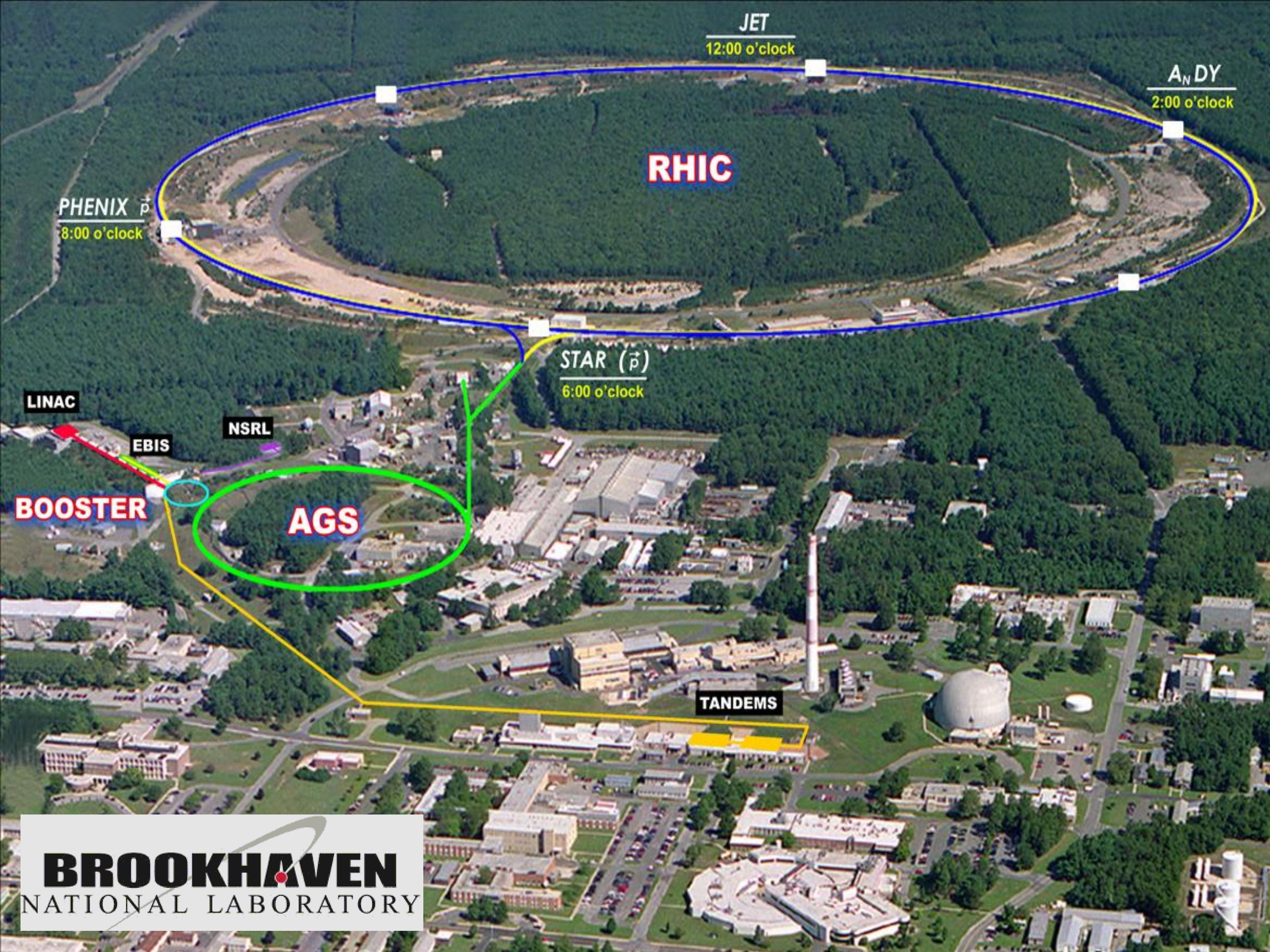
$$a_{12} \sim \frac{\sin^2\theta}{1+\cos^2\theta} H_1^{\sphericalangle}(z_{pair-1}, M^2_{pair-1}) H_1^{\sphericalangle}(z_{pair-2}, M^2_{pair-2})$$

IFF in e^+e^- quark fragmentation leads to azimuthal asymmetries in the correlation of two hadron pairs:

$N_{pair_1, pair_2}(\phi_{pair-1}+\phi_{pair-2}) \sim a_{12}\cos(\phi_{pair-1}+\phi_{pair-2})$

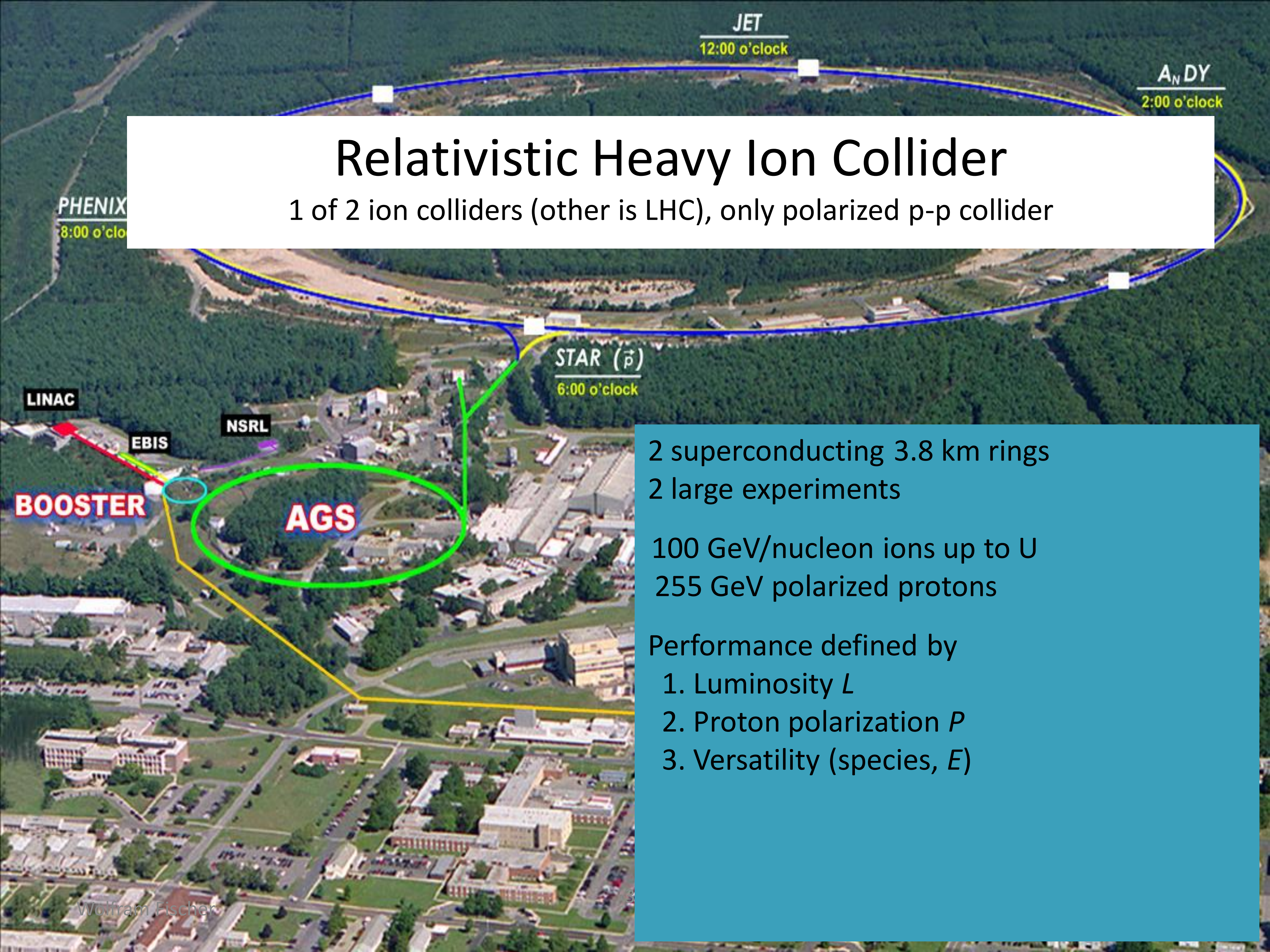
Experimental requirements:

- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets


JET
12:00 o'clock
A_N DY
2:00 o'clock
RHIC
PHENIX $\vec{p}$
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
LINAC
NSRL
EBIS
BOOSTER
AGS
TANDEMS
BROOKHAVEN
NATIONAL LABORATORY

Relativistic Heavy Ion Collider

1 of 2 ion colliders (other is LHC), only polarized p-p collider



2 superconducting 3.8 km rings
2 large experiments

100 GeV/nucleon ions up to U
255 GeV polarized protons

Performance defined by

1. Luminosity *L*
2. Proton polarization *P*
3. Versatility (species, *E*)

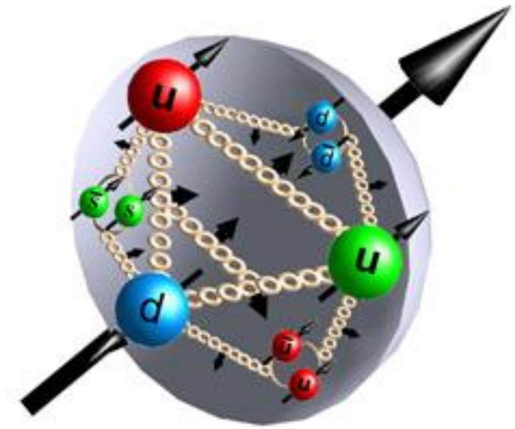
- **Run-12 overview** (= status, operation in all modes possible)
- Polarized protons, $\sqrt{s}$ = 200, 510 GeV
- Uranium-uranium $\sqrt{s_{NN}}$ = 193 GeV, copper-gold $\sqrt{s_{NN}}$ = 200 GeV

- **Heavy ion upgrades**
- Luminosity with stochastic cooling

- **Polarized proton upgrades**
- Polarization and luminosity with source upgrade

- R&D for polarized ^{3}He

2012 RHIC Run (23 weeks of cryo ops) – most varied to date



•100 GeV polarized protons
- new records for L_{peak} (1), L_{avg} (2), P (3)

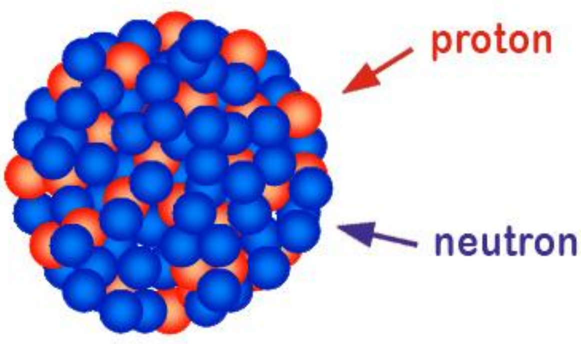
•255 GeV polarized protons
- highest energy polarized proton beam (4)
- new records for L_{peak} (5), L_{avg} (6), P (7)

96.4 GeV/nucleon uranium-uranium

heaviest element in collider (8),

3D stochastic cooling: 1st time in hadron collider! (9)

all ions lost through burn-off 1st time in hadron collider! (10)

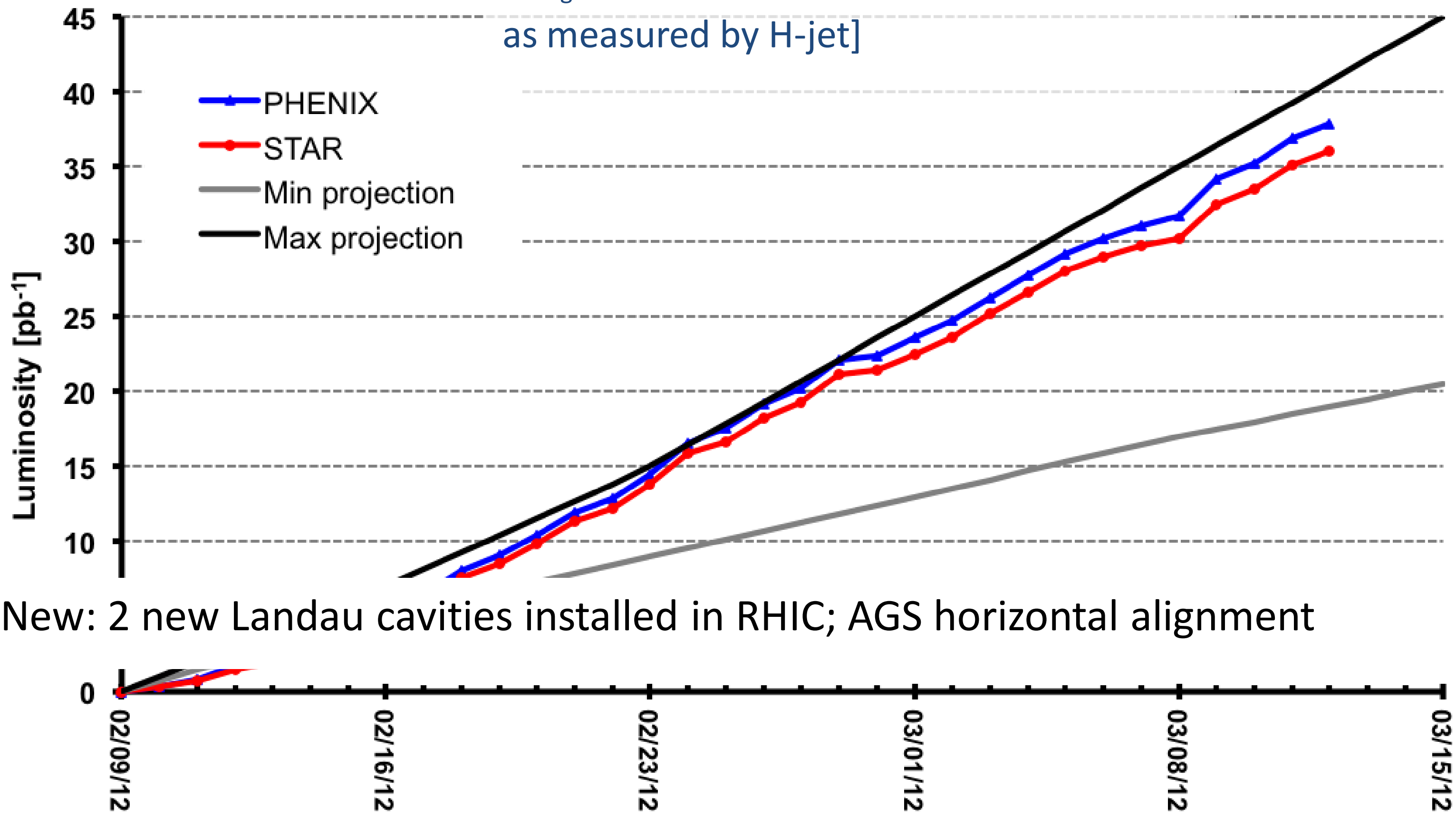


Uranium Nucleus

Run-12 – Polarized protons 100 GeV

$P_{avg,B}$ = 61.8% (2009: 56%)
$P_{avg,Y}$ = 56.6% (2009: 57%)

[P_{avg} – average over intensity and time, as measured by H-jet]

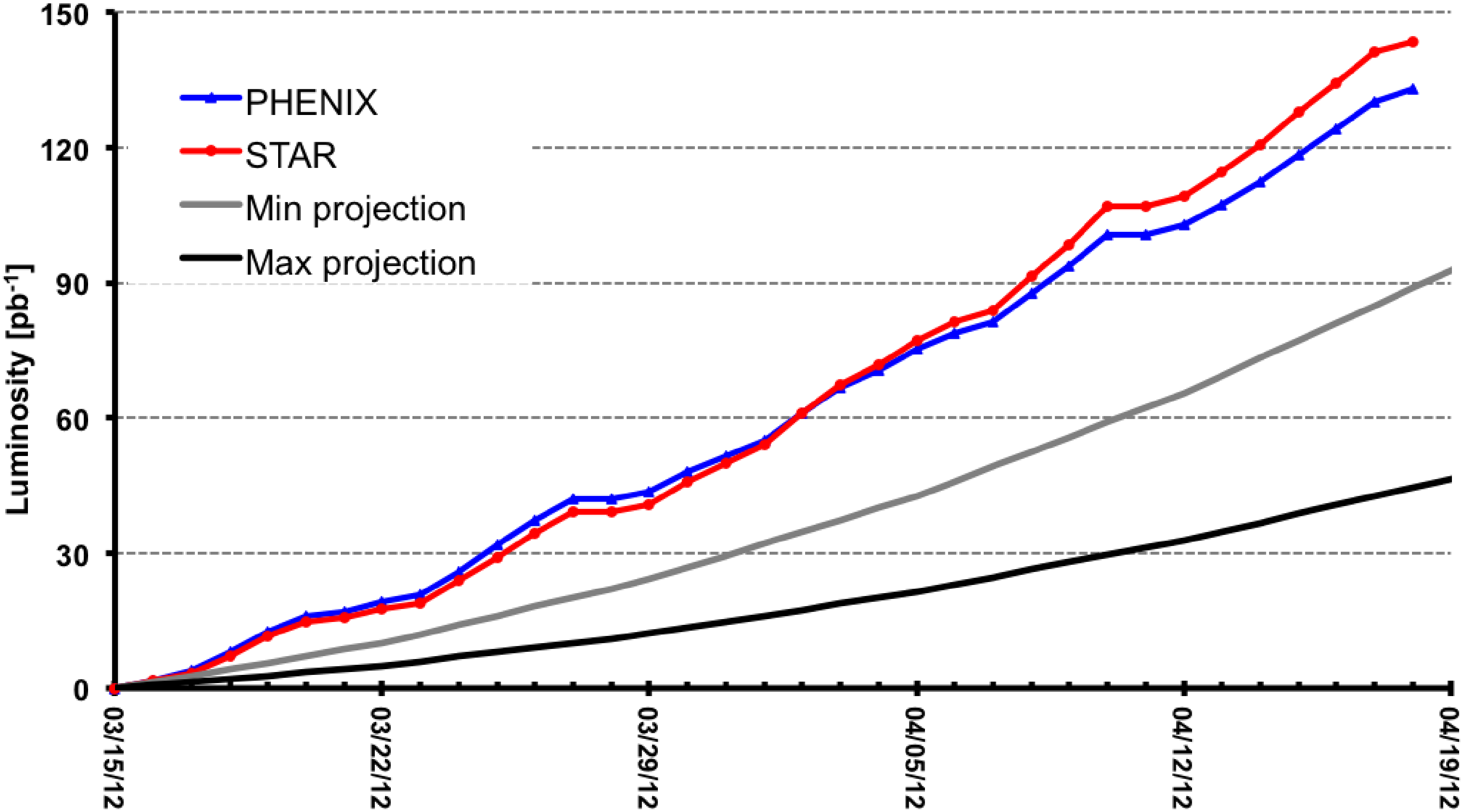


5 weeks

New: 2 new Landau cavities installed in RHIC; AGS horizontal alignment

Run-12 – Polarized protons 255 GeV

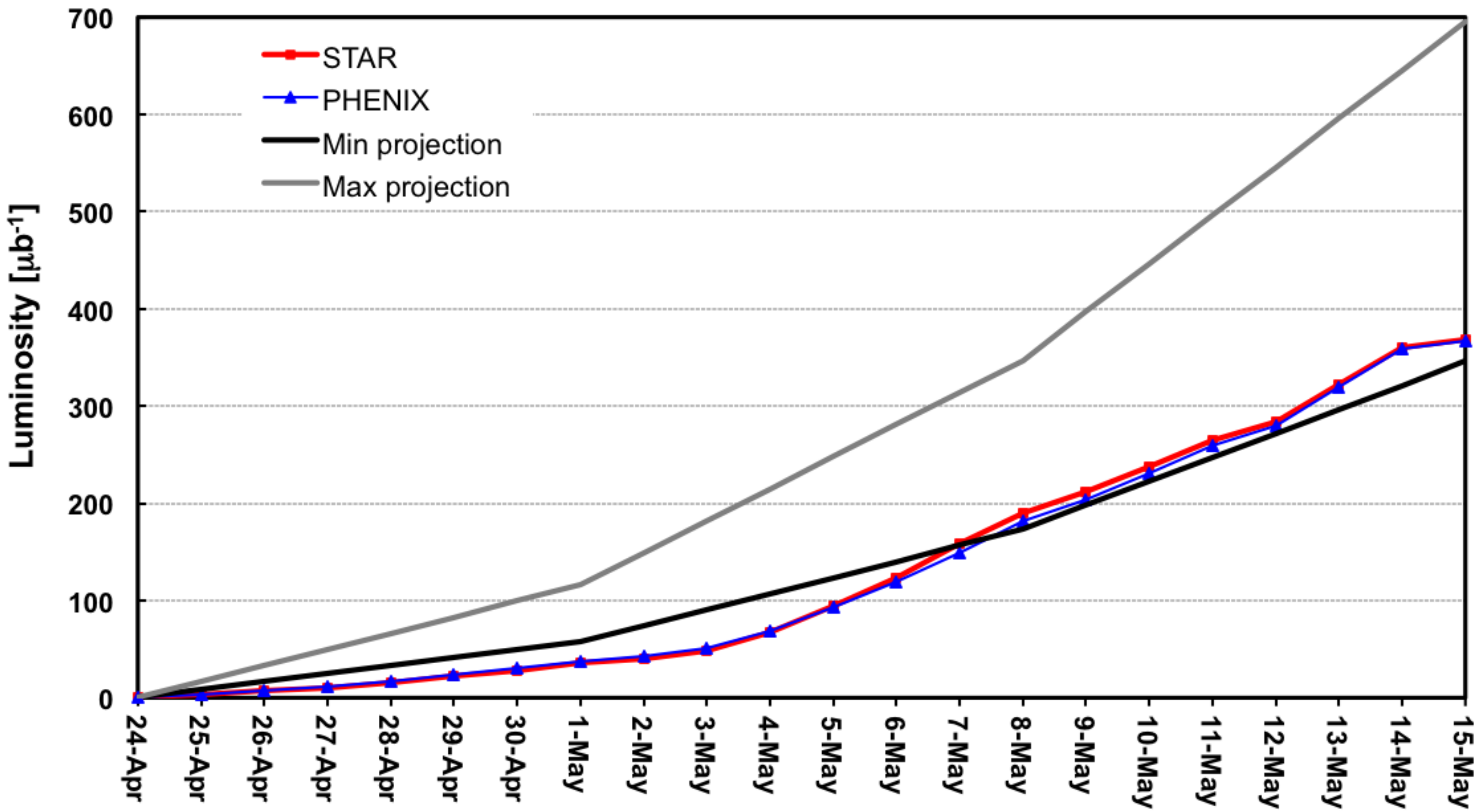
$P_{avg,B}$ = 50.3% (2011: 48%)
$P_{avg,Y}$ = 53.5% (2011: 48%)



5 weeks

New: same as for 100 GeV; also increased store energy to increase polarization lifetime.

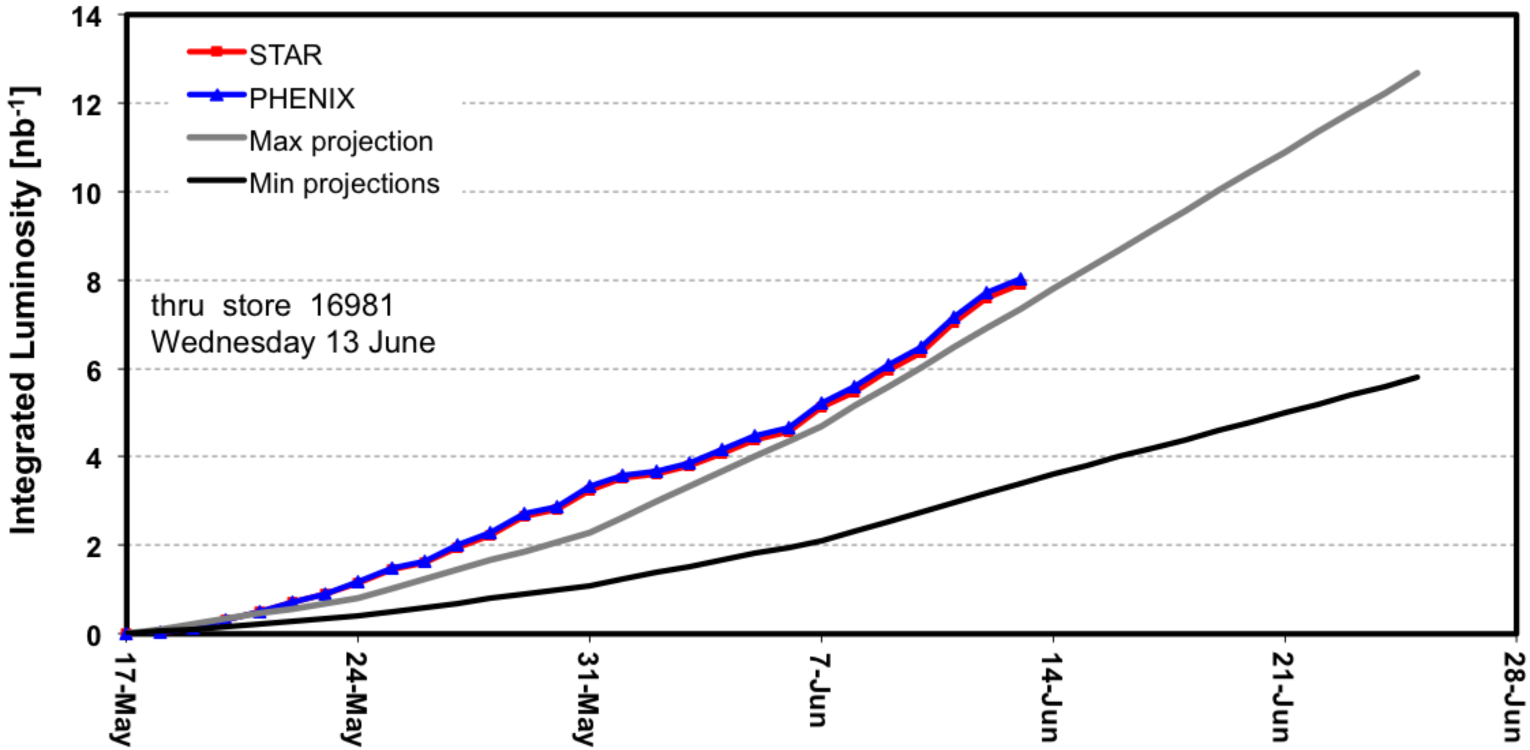
Run-12 – Uranium-uranium 96.4 GeV/nucleon



3 weeks

New: first use of EBIS for RHIC operation; first U-U operation in a collider; used standard lattice to increase off-momentum dynamic aperture; first use of Blue and Yellow horizontal stochastic cooling (resulting in 3D cooling in both rings); due to small beam size need micro-vernier scan every 1/2 h

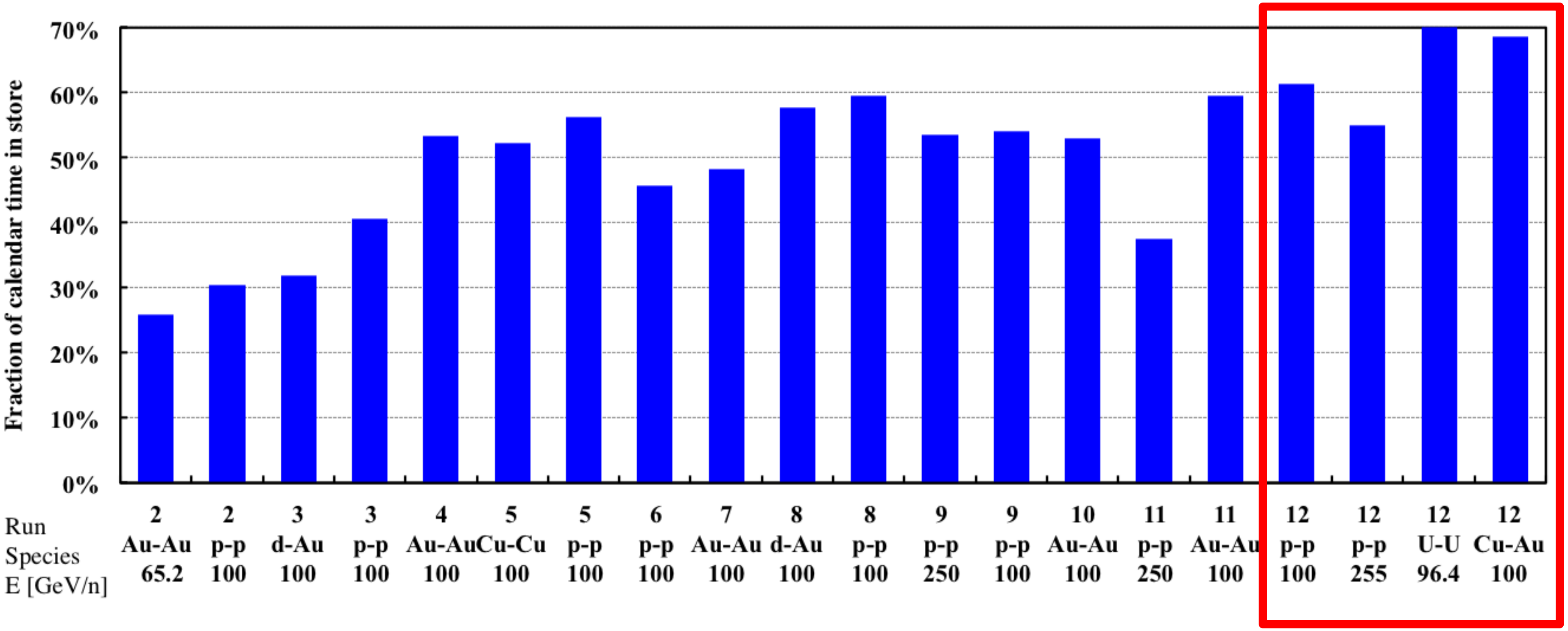
Run-12 – Copper-gold 100 GeV/nucleon (still running)



~6 weeks

New: first Cu-Au operation in a collider; used <u>standard lattice to increase off-momentum dynamic aperture</u>; <u>first use of Blue and Yellow horizontal stochastic cooling (resulting in 3D cooling in both rings)</u>

Time-in-store as fraction of calendar time



As of 06/14/12

- Run-12 with low failure rates in all systems
- Highest time-in-store ratios to date
  (even with increased APEX time during 255 GeV protons compared to Run-11)

RHIC ions – 6 species and 15 energies to date

- $^{238}U^{92+}$–$^{238}U^{92+}$ first time in 2012, 3 weeks physics, complete
- 96.4 GeV/nucleon
- $^{197}Au^{79+}$–$^{197}Au^{79+}$
- 3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 27.9, 31.2, 65.2, 100.0 GeV/nucleon
- $^{63}Cu^{29+}$–$^{197}Au^{79+}$ first time in 2012
- 99.9/100.0 GeV/nucleon
- $^{63}Cu^{29+}$–$^{63}Cu^{29+}$
- 11.2, 31.2, 100.0 GeV/nucleon
- d–$^{197}Au^{79+}$
- 100.7/100.0 GeV/nucleon

Can collide any species from protons (polarized) to uranium
– with each other or with another species