Transverse Single Spin Asymmetry of Very Forward π^0 Production Using RHICf Detector in Polarized Proton-Proton Collision

理研
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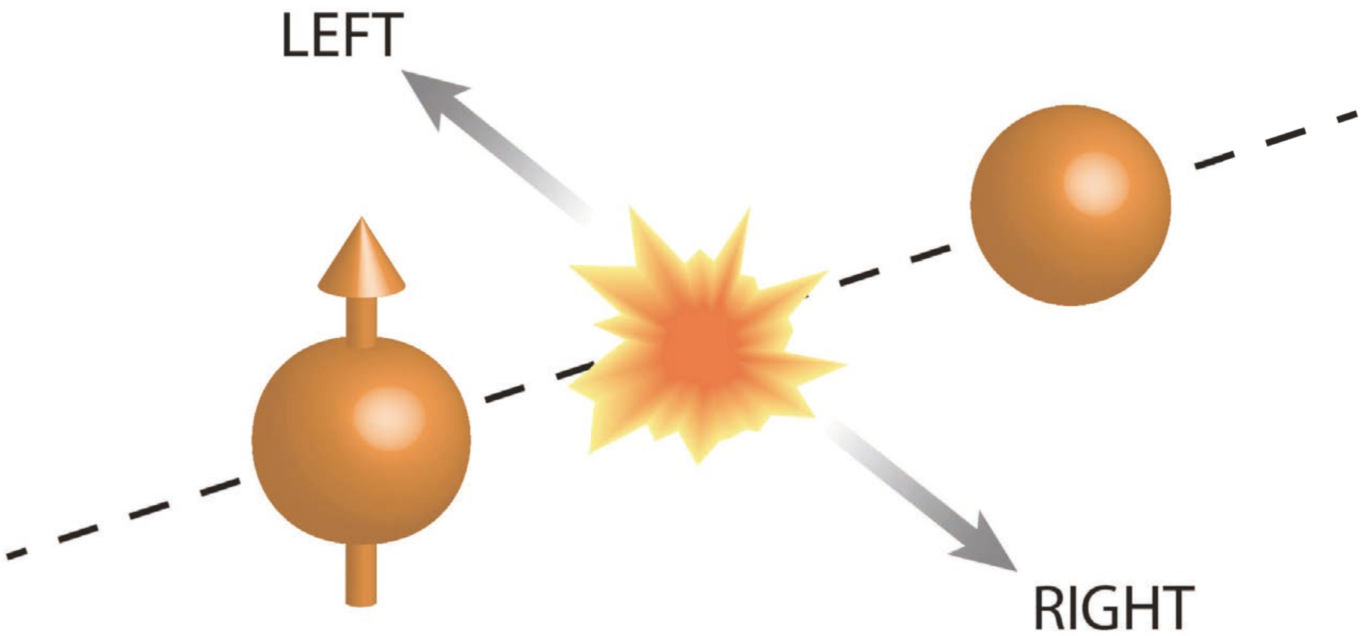
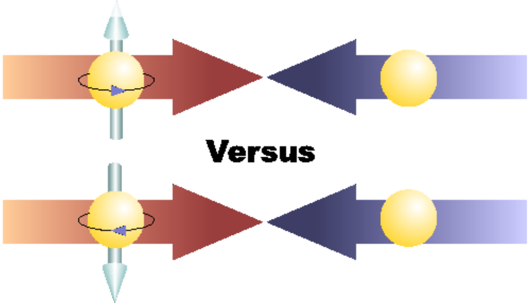
Outline

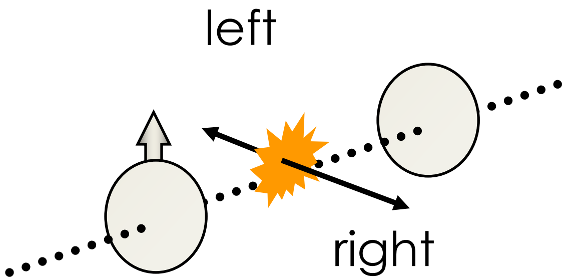
- Introduction
  - Transverse Single Spin Asymmetry
  - Proton spin decomposition (Proton spin puzzle)
- Status of the proton spin puzzle
- New RHICf experiment @ STAR
- Hypothesis to connect new and existing data and orbital angular momentum
- Physics opportunity for FoCAL at RHIC by testing above hypothesis.

Transverse Single Spin Asymmetry



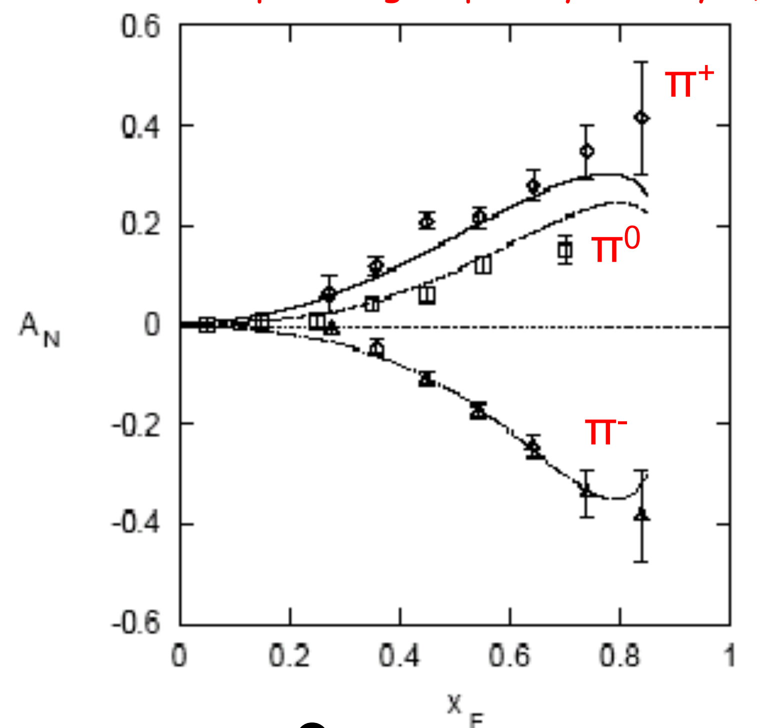


Pioneering Transverse Single Spin Assymmetry



$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

E704: pion single spin asymmetry A_N



Naïve Theory Prediction:
Small in high energy
(Kane, Pumplin, Repko, PRL 41, 1689-1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N O(10^{-4}) Theory

Experiment:
(E704, Fermi National Laboratory, 1991)

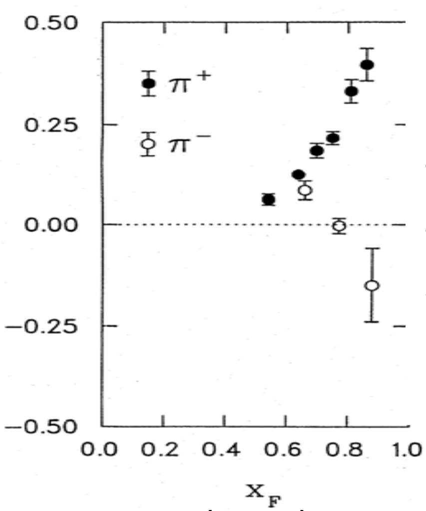
$$pp^{\uparrow} \rightarrow \pi + X$$
$$\sqrt{s} = 20 \text{ GeV}$$

A_N O(10^{-1}) Measured

$$x_F = \frac{2p_L}{\sqrt{s}}$$

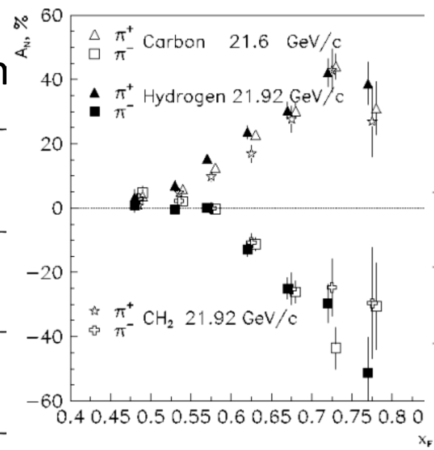
Energy Dependence of A_N

ZGS 12 GeV bean



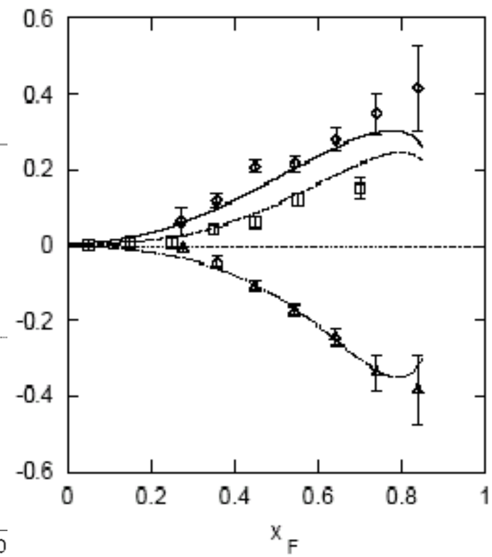
PRL36, 929 (1976)

AGS 22 GeV beam



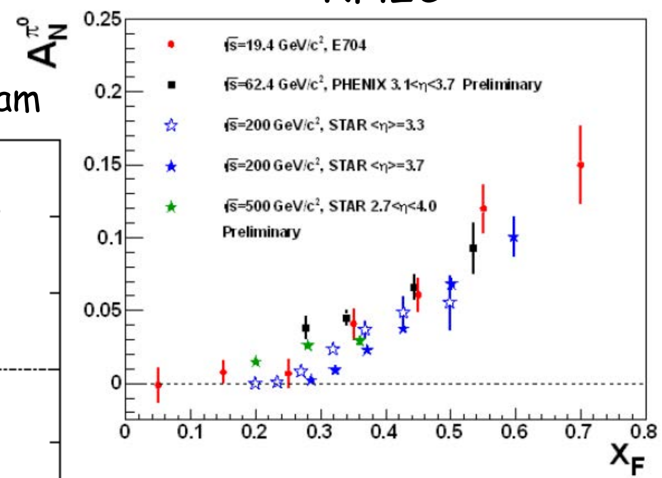
PRD65, 092008 (2002)

E704 200GeV beam



PLB261, 201 (1991)
PLB264, 462 (1991)

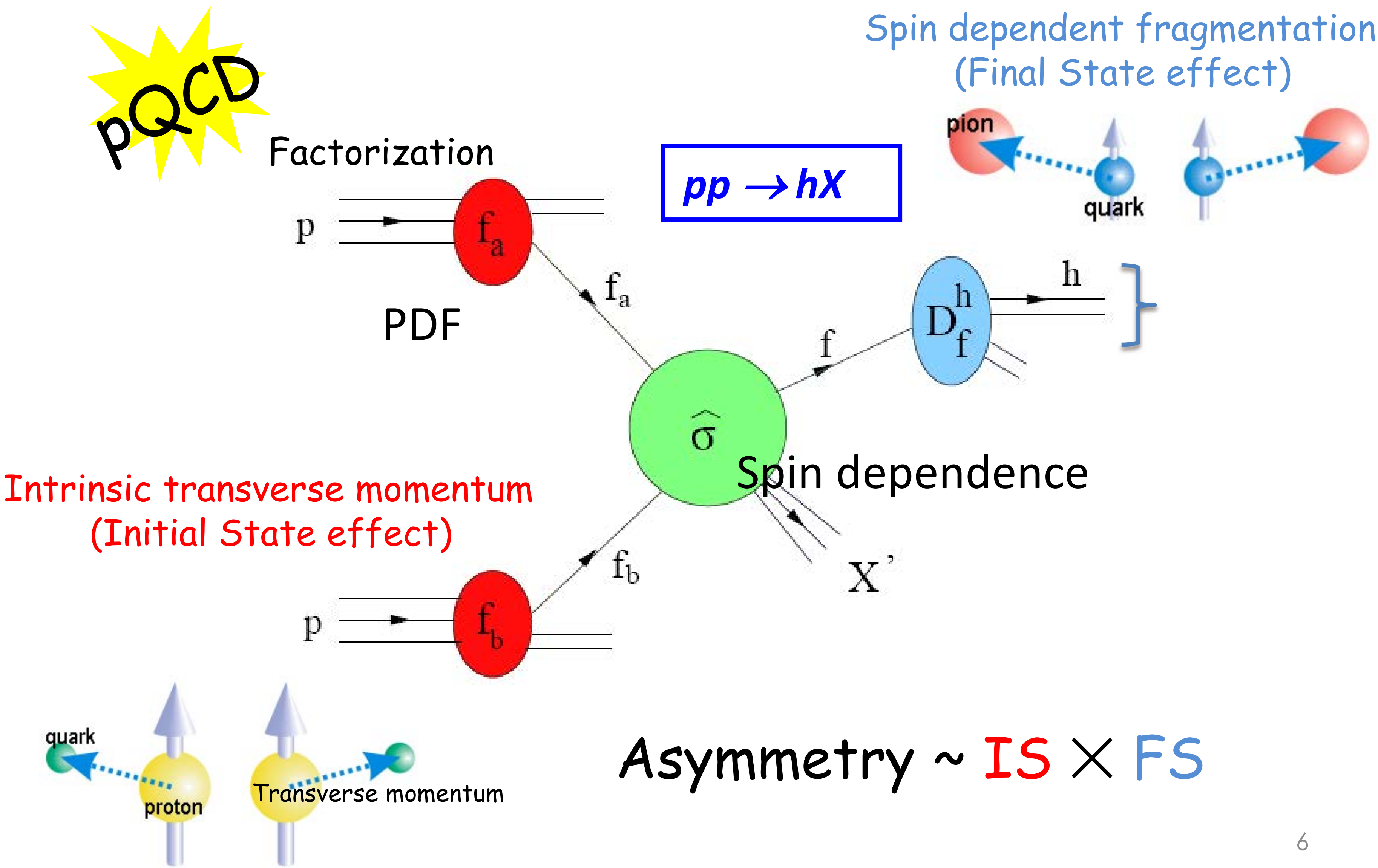
RHIC



Asymmetry still persists even in high energy!

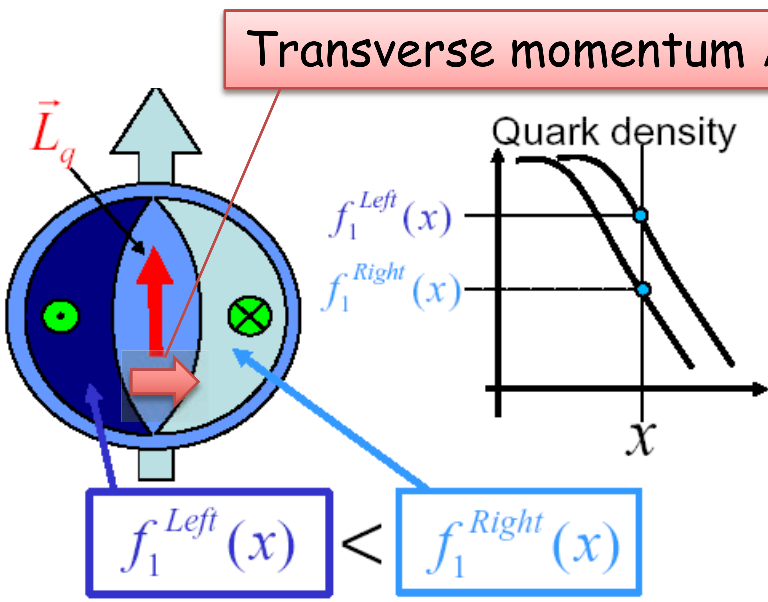
Non-perturbative ⟷ Perturbative

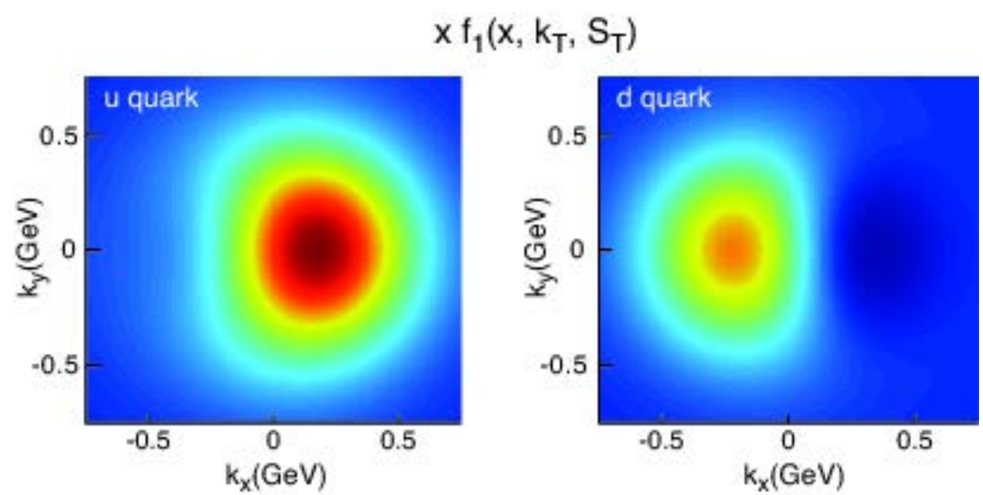
Origin of Left-Right Asymmetry



Intrinsic Transverse Momentum and Orbital Angular Momentum

If a parton has a orbital angular momentum in a nucleon, the probability to find the parton which carries the momentum fraction *x* is different between left and right sides of nucleon





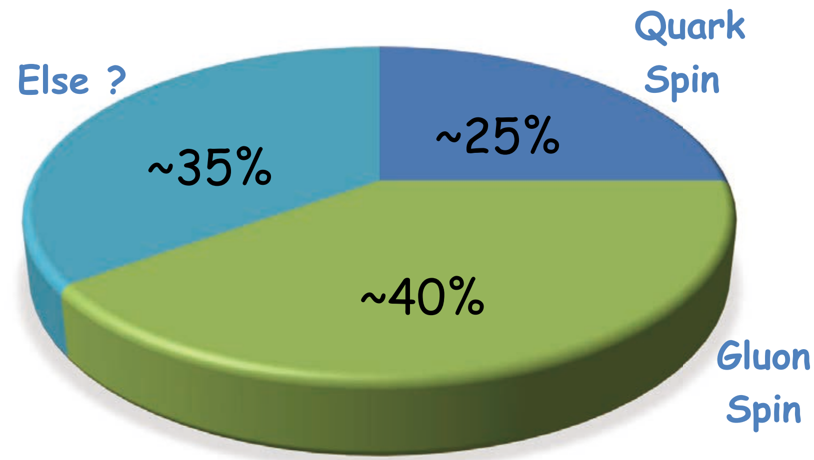
Quark transverse momentum distributions

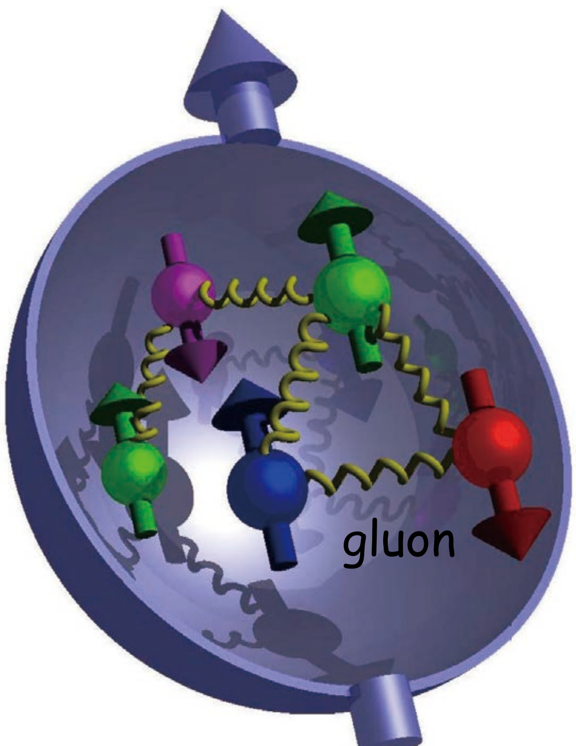
Proton Spin Puzzle

Longitudinal Spin Sum Rule

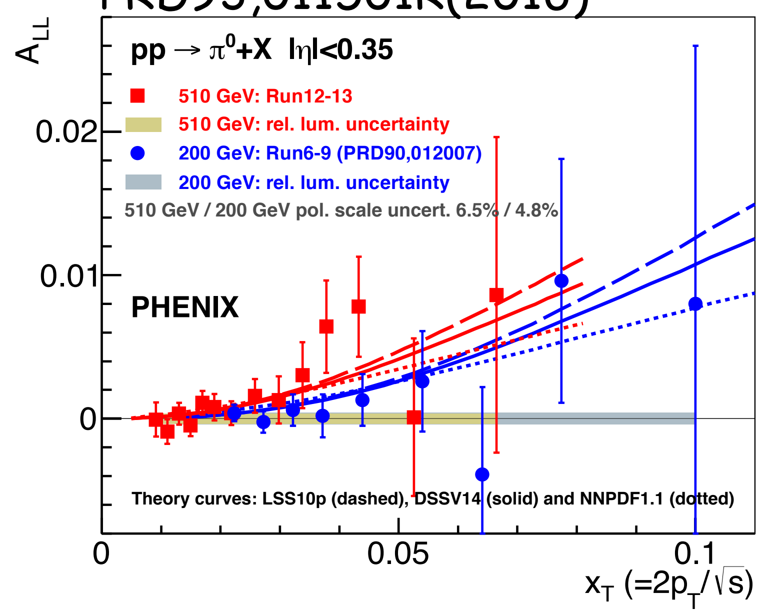
$$S_z = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

~25% ~40% ??



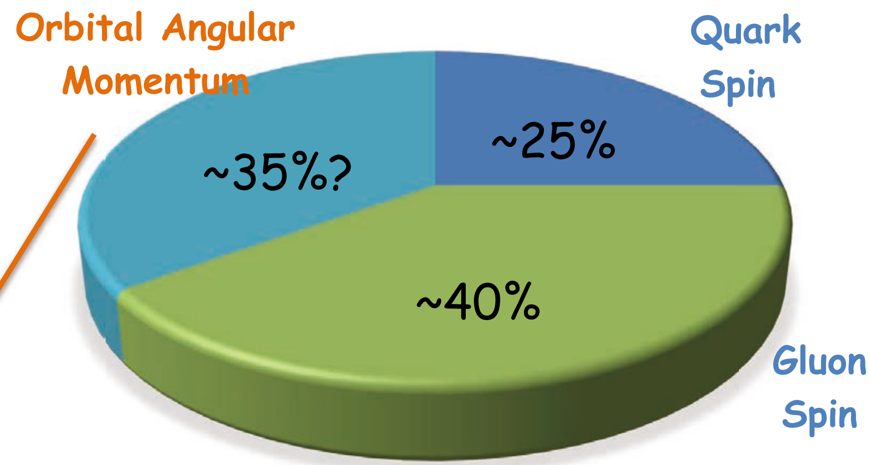


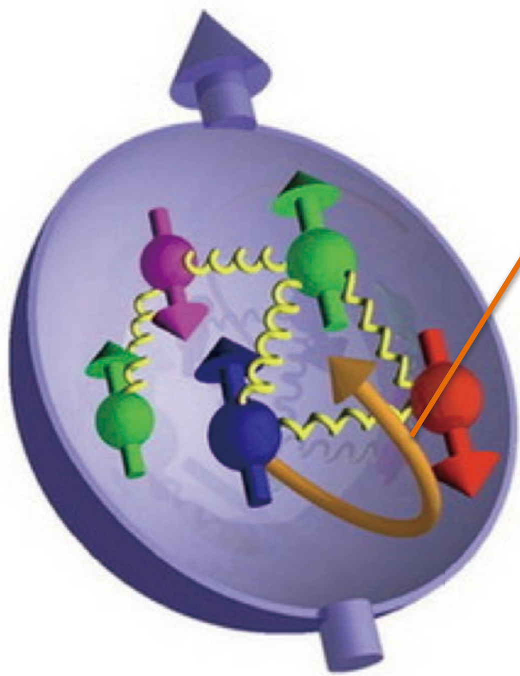
PRD93,011501R(2016)

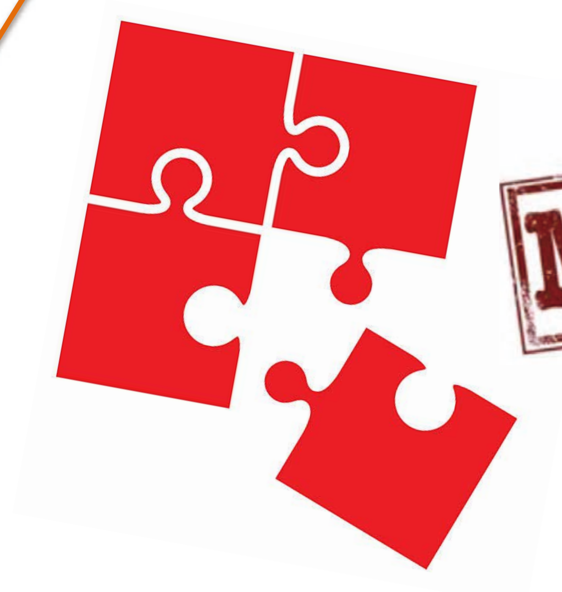


Orbital Angular Momentum

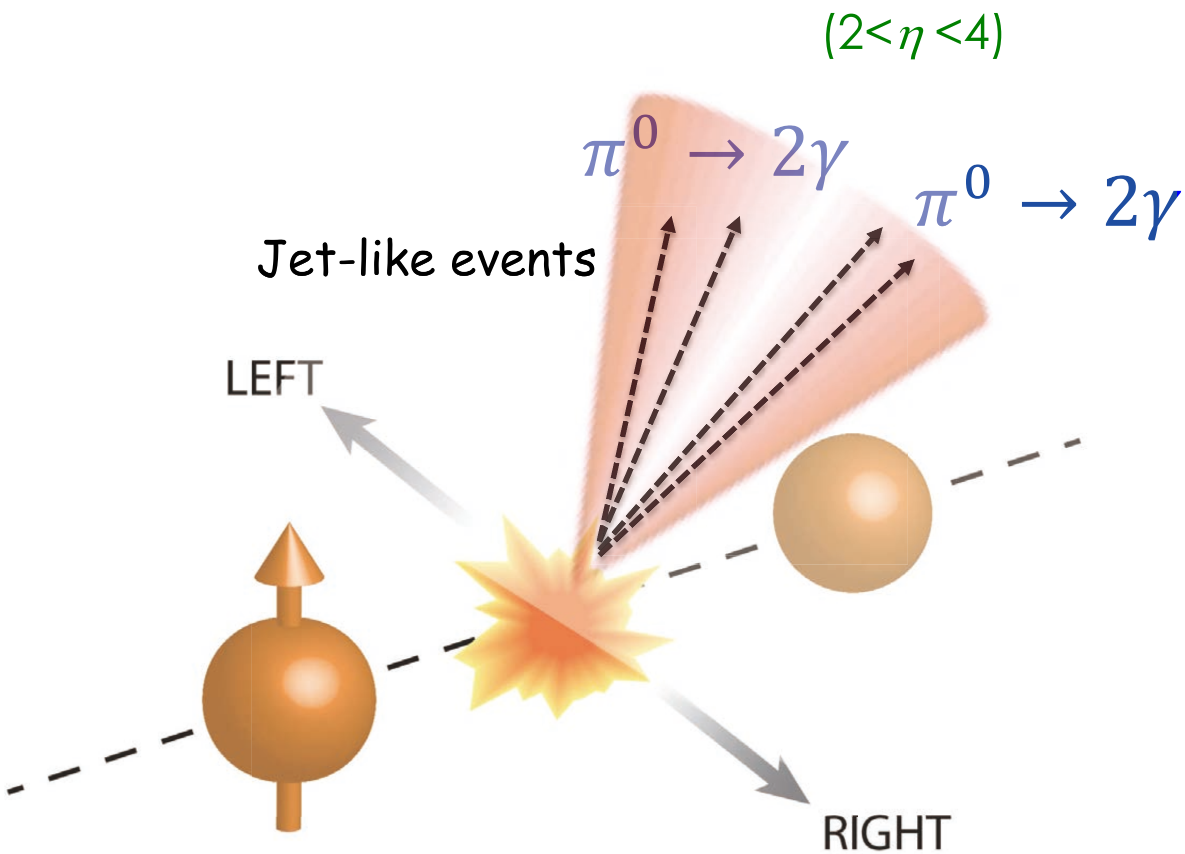
$$S_z = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$



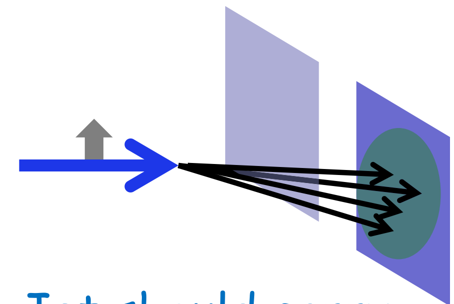




Next Generation Experiments

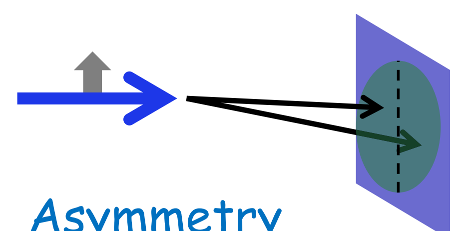


Initial state



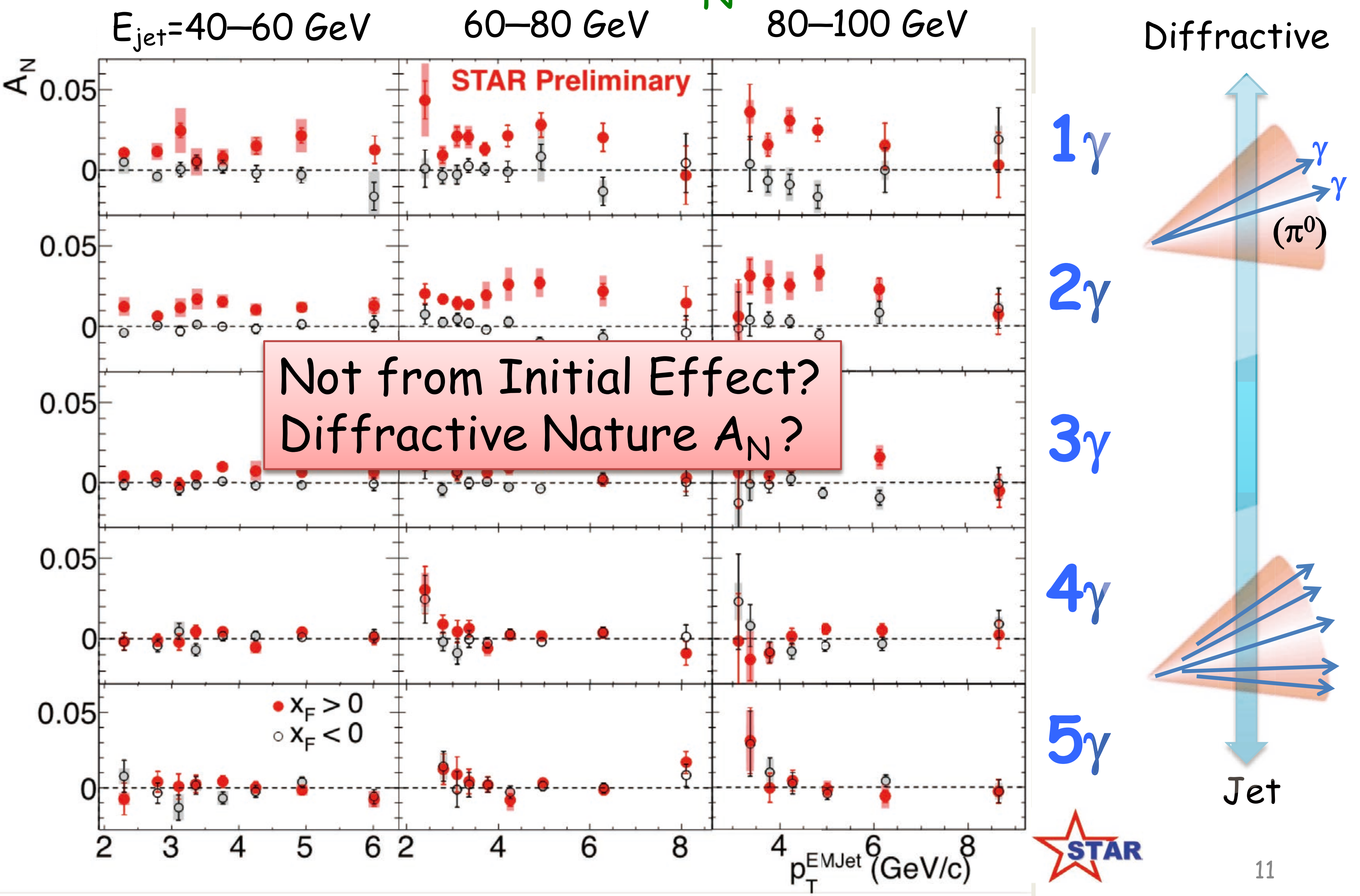
Jet should carry the asymmetry

Final state



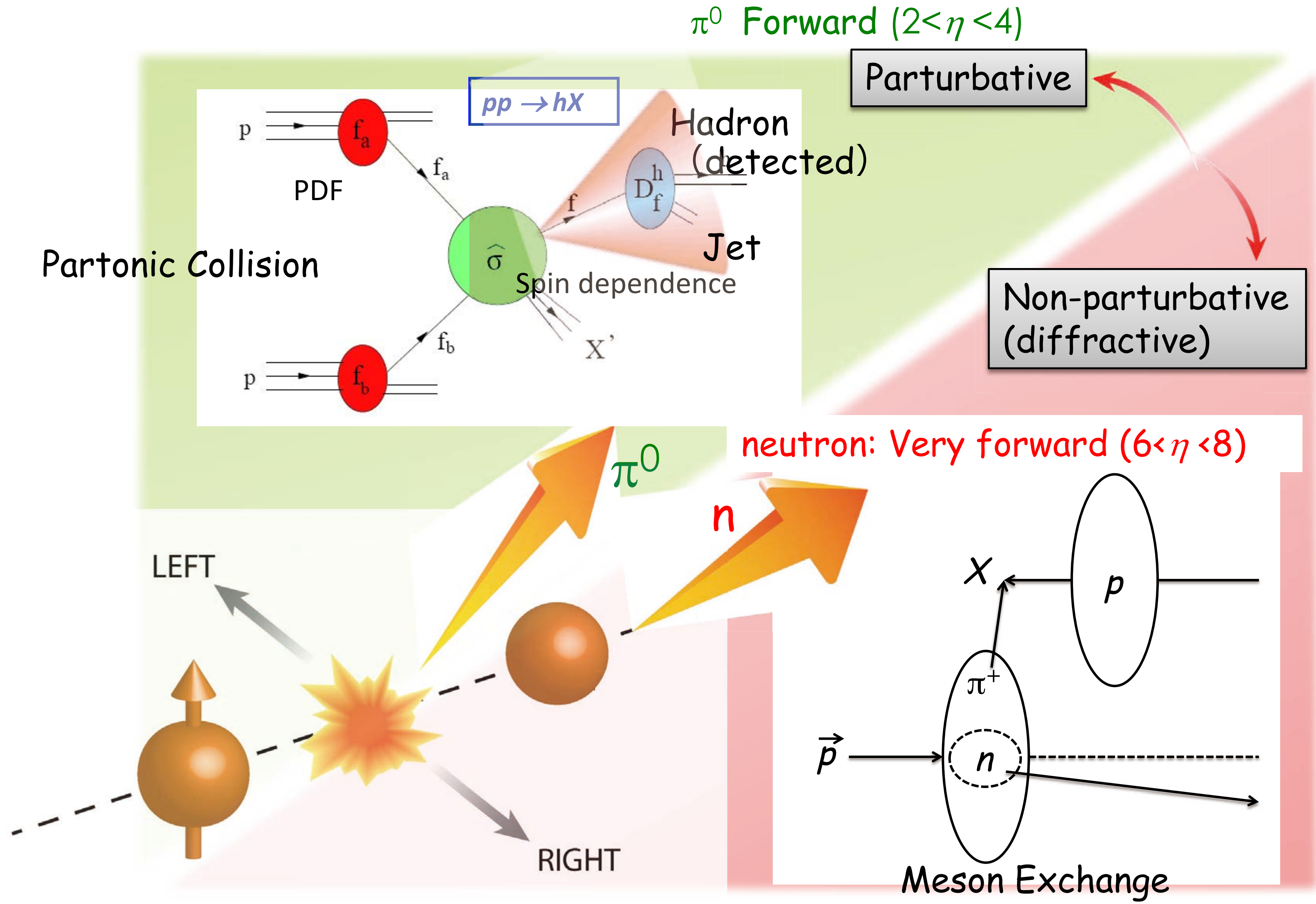
Asymmetry appears within Jet

γ-multiplicity dependence of Forward ($2<\eta<4$) π^0 A_N



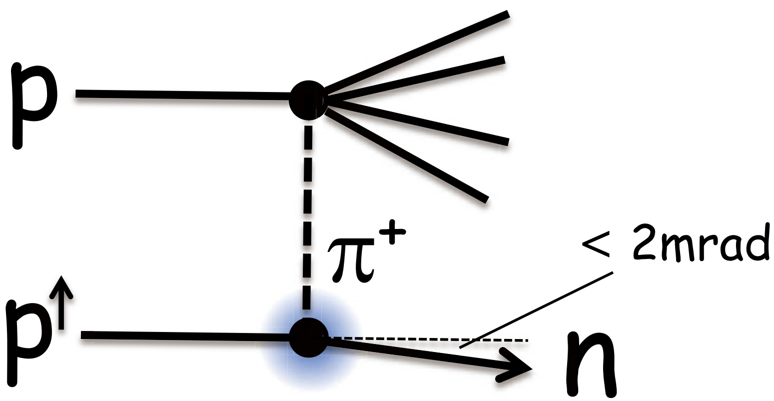
Not from Initial Effect?
Diffractive Nature A_N?

Assymmetries in Diffractive Origin



Production Mechanism of Forward Neutron

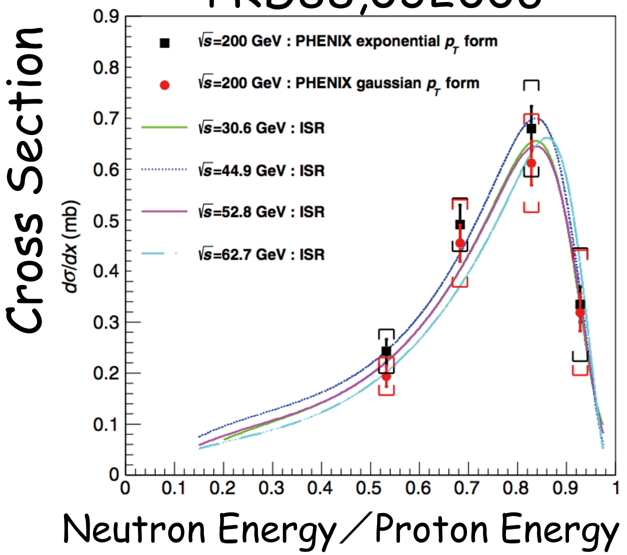
Cross Section



Momentum Transfer ~ 100MeV/c

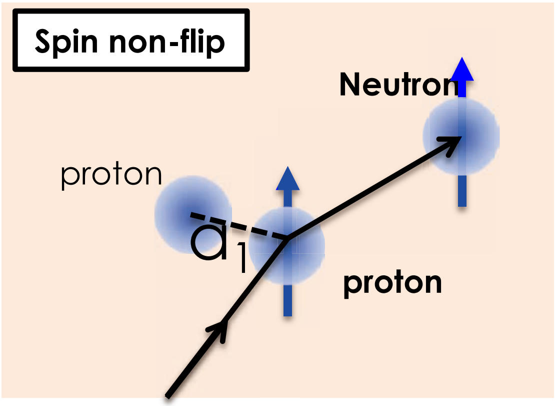
Well Explained by
One-Pion Exchange

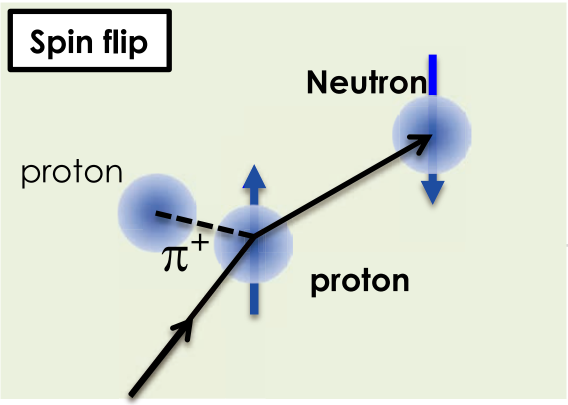
PRD88,032006



Large fraction of proton energy is carried by neutron

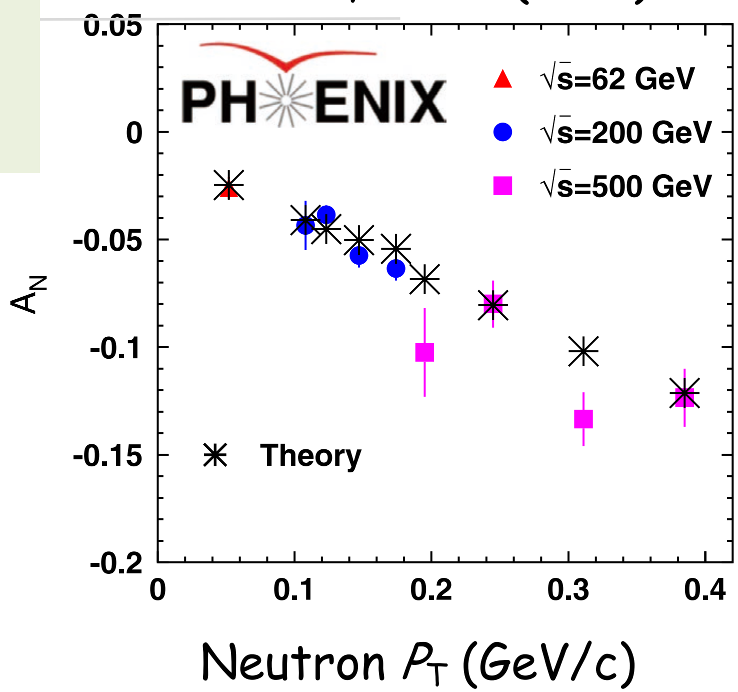
$p^{\uparrow}$+p Forward Neutron A_N





$$A_N \approx \frac{\left(\phi^*_{non-flip}\phi_{flip}\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

PRD84,114012(2011)

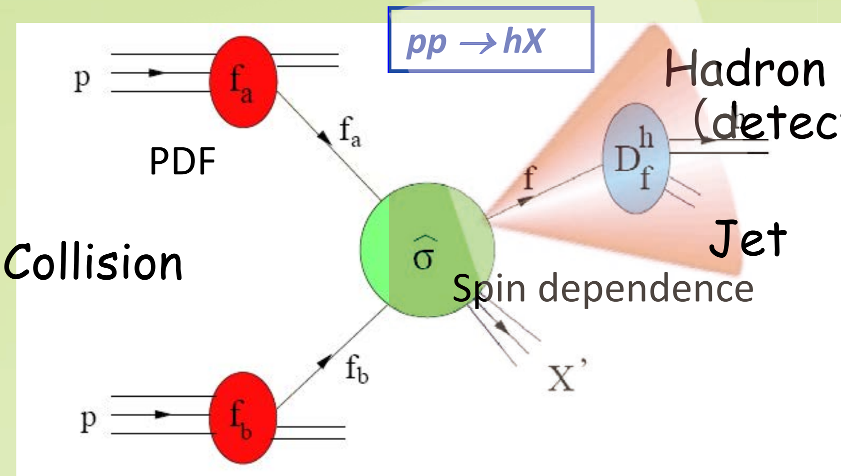


Asymmetries are well reproduced by the interference between π and a_1 Reggeon.
However, the coupling between p and a_1 is model dependent assumption

Diffractive π^0 Asymmetry?

π^0 Forward ($2<\eta<4$)

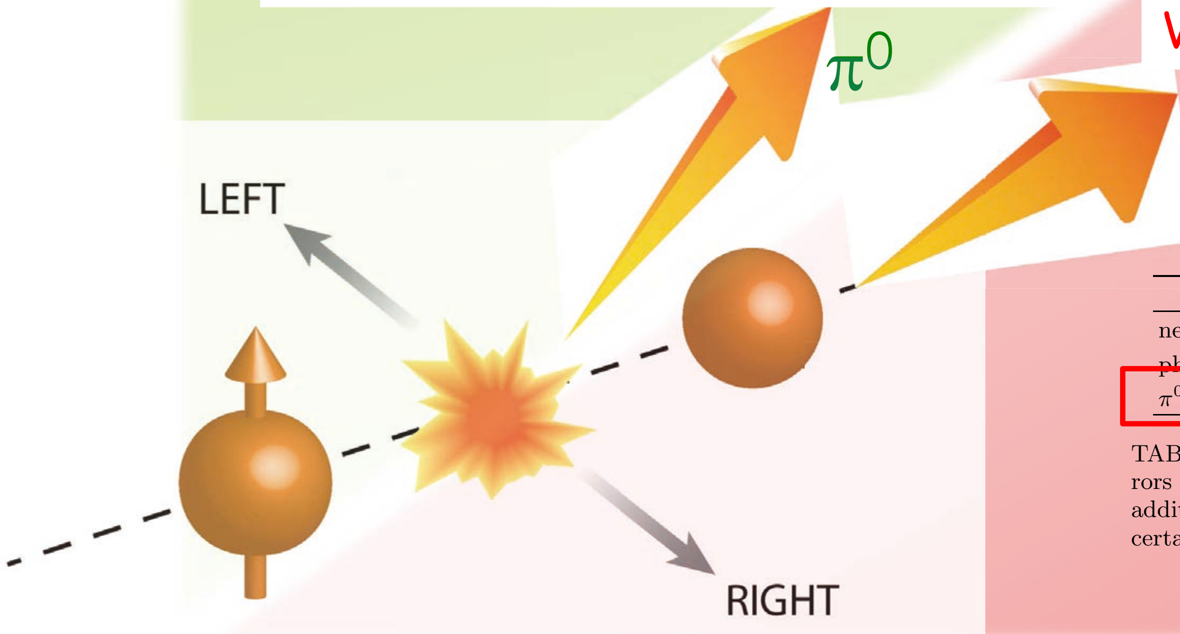
Parturbative



Partonic Collision

Non-parturbative (diffractive)

Very forward n, π^0 ($6<\eta<8$)

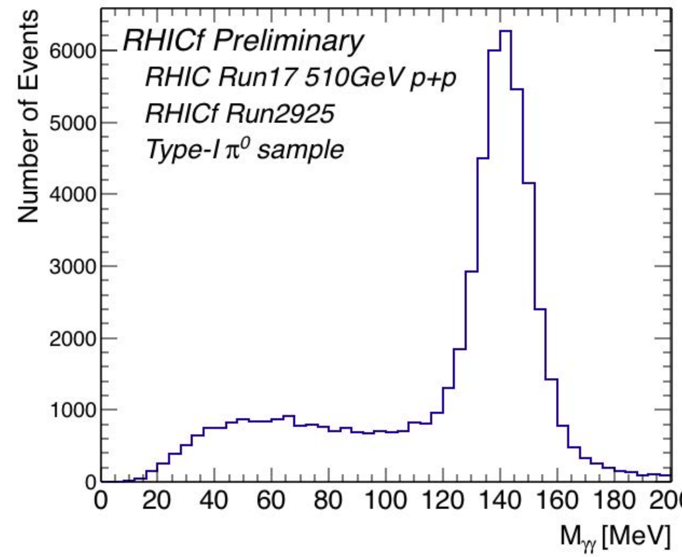


Phys. Lett. B650 (2007) 325.

	forward			backward		
neutron	−0 090	0 006	0 009	0 003	0 004	0 003
photon	−0 009	0 015	0 007	−0 019	0 010	0 003
π^0	−0 022	0 030	0 002	0 007	0 021	0 001

TABLE I: Asymmetries measured by the EMCal. The errors are statistical and systematic, respectively. There is an additional scale uncertainty, due to the beam polarization uncertainty, of $(1\ 0^{+0\ 47}_{-0\ 24})$.

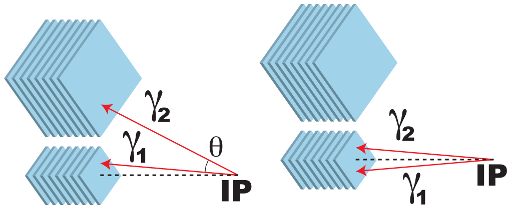
Junsang Park (SNU)



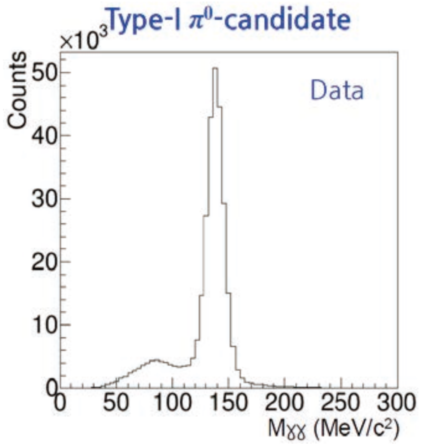
π^0 Offline Analysis

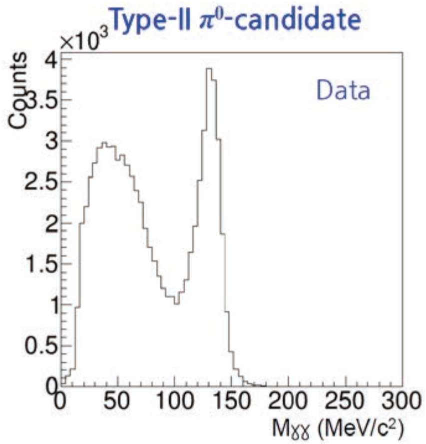
- π^0 peak with ~10 MeV/c^2 width
  - 3σ region selected as π^0 candidates
- $p_T < 1.0$ GeV/c
- $0.2 < x_F < 1.0$

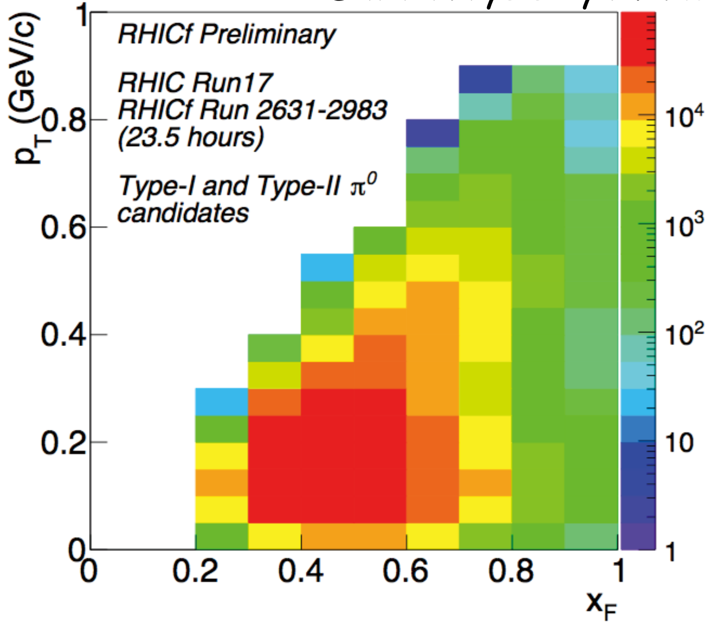
Data analysis by Minho Kim



Type-I   Type-II
(same as single high-E photon)

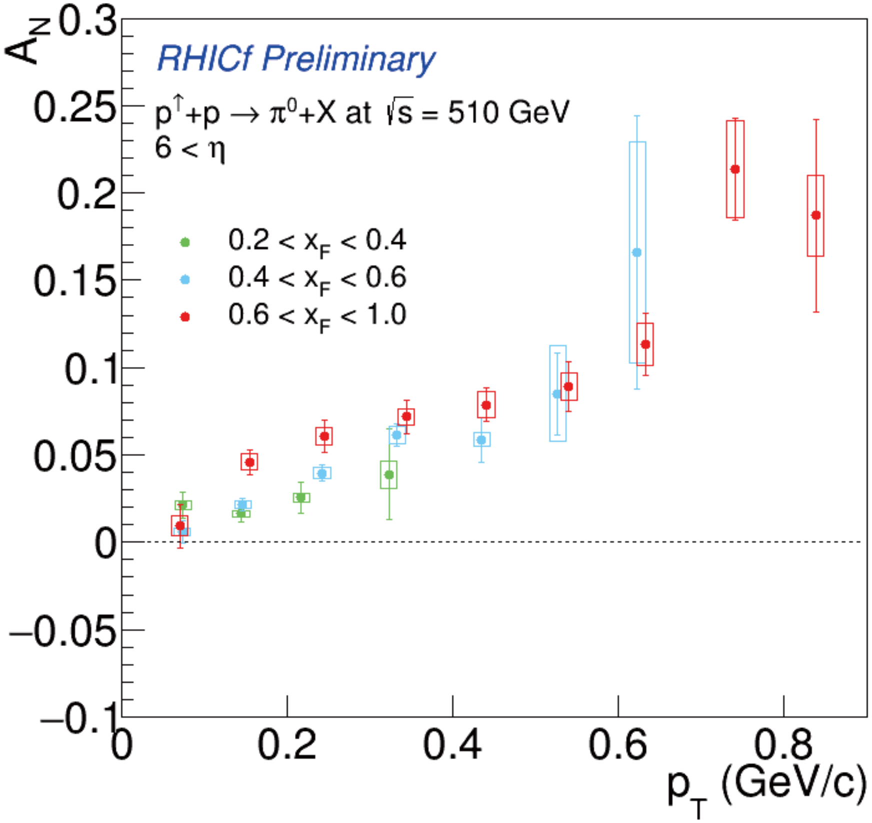


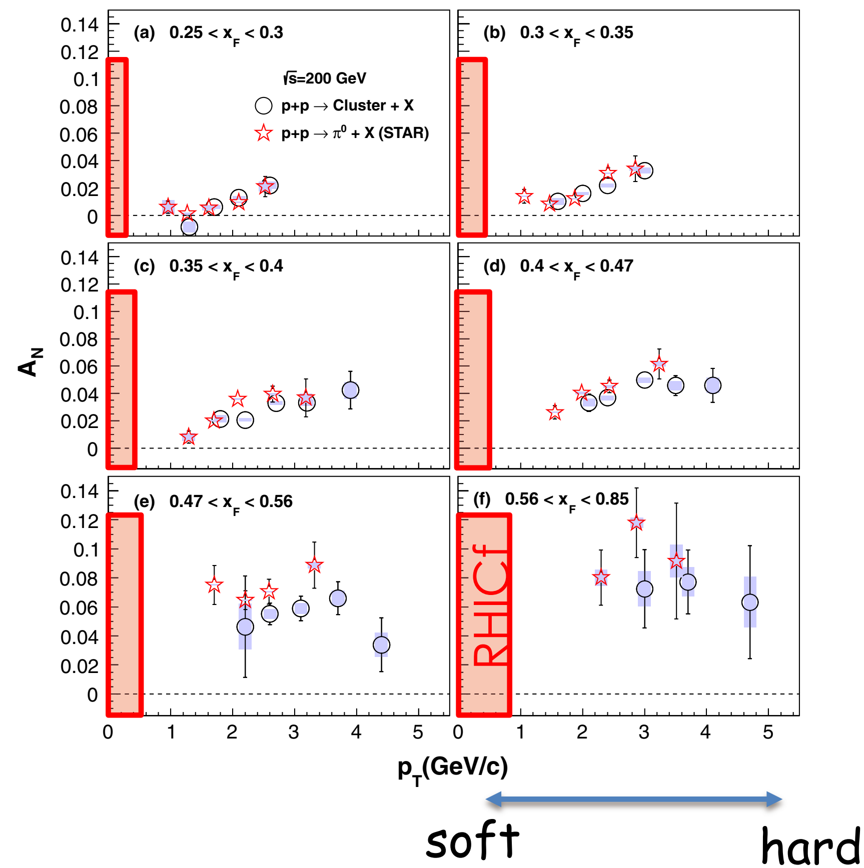




π^0 Asymmetry Preliminary Results

Phys. Rev. D **90**, 012006



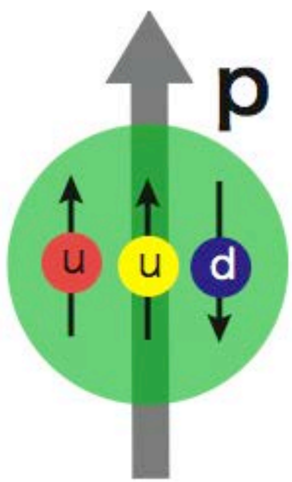


Large Asymmetry was observed p_T<1GeV

My personal hypothesis

THEORETICAL INTERPRETATION

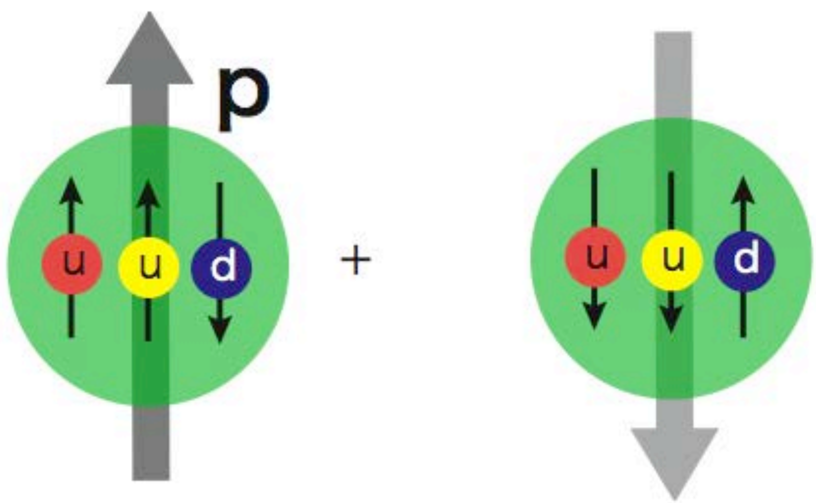
Proton Spin +1/2



$$|p\rangle$$

$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2}$$

Proton Spin +1/2

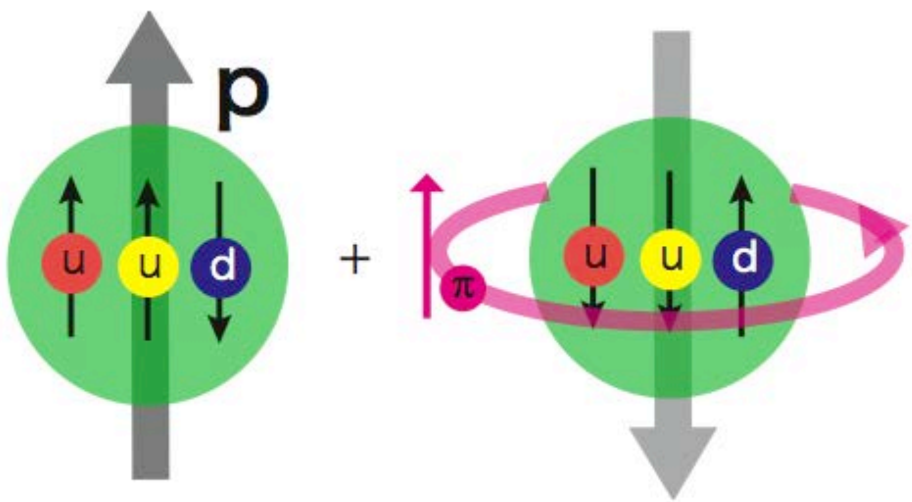


$$|p\rangle$$

$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right)$

Proton Spin +1/2

Pion cloud model

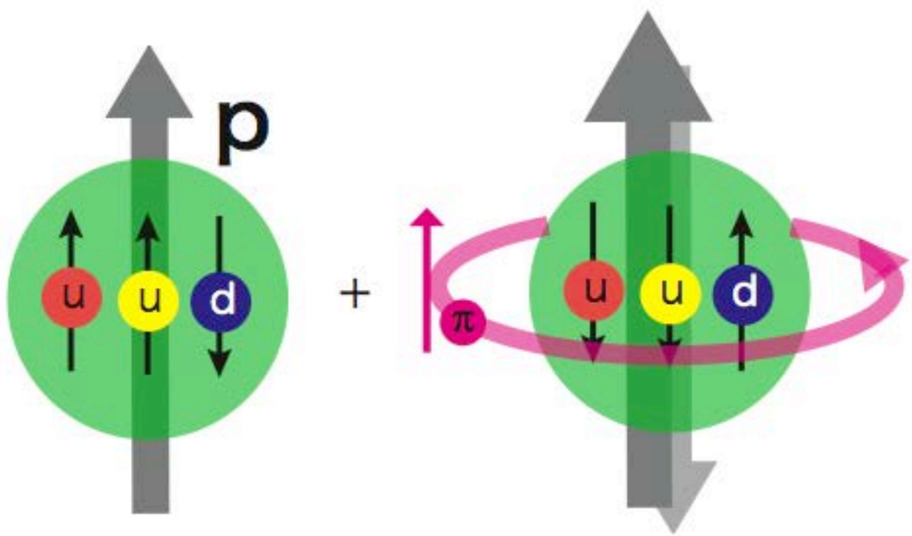


$$|p\rangle \qquad |N\pi\rangle$$

$$S+L=J \qquad +\frac{1}{2}+0=+\frac{1}{2} \qquad \left(-\frac{1}{2}+0\right)+(0+1)=$$

P-wave

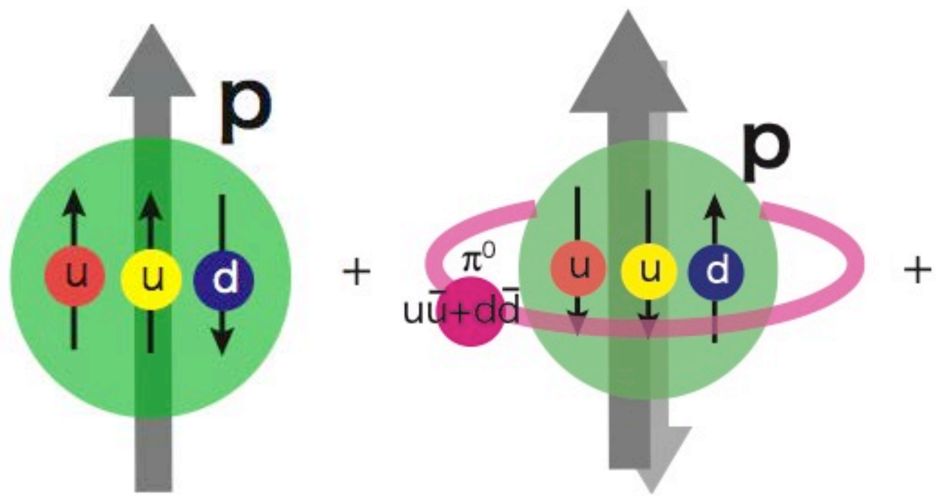
Proton Spin +1/2



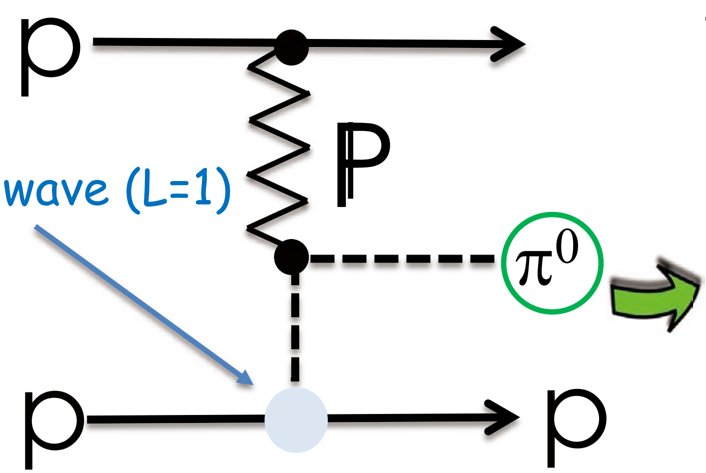
$$|p\rangle \qquad |N\pi\rangle$$

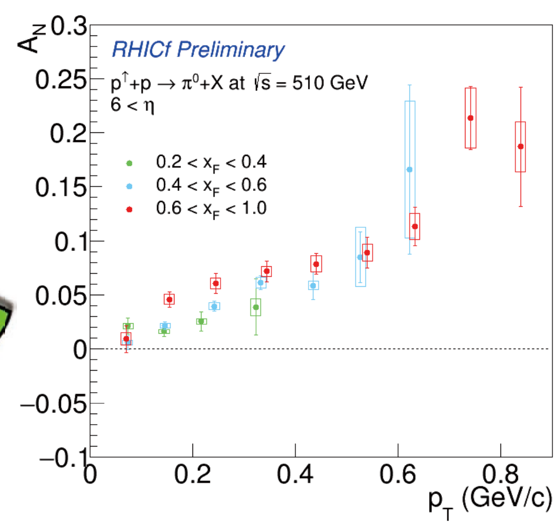
$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right) + (0 + 1) = +\frac{1}{2}$$

Proton Spin +1/2

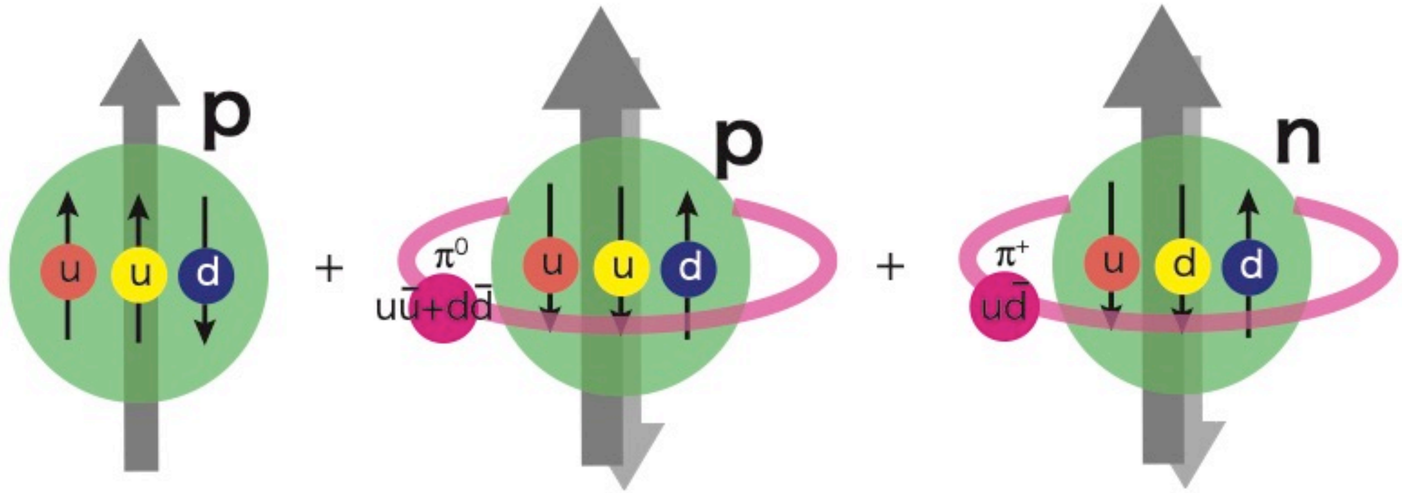


Pion cloud in p-wave (L=1)

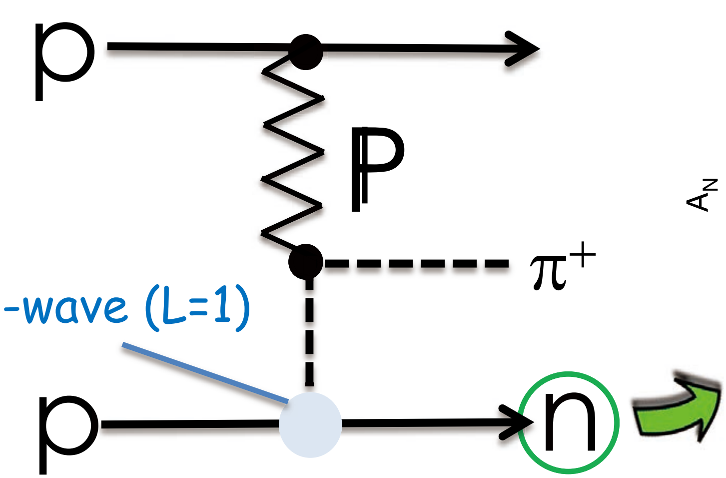


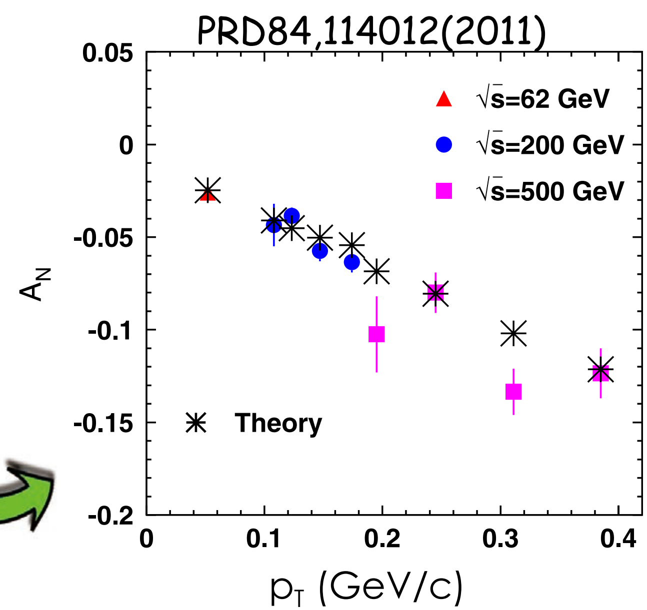


Orbital Momentum & Diffractive π^0



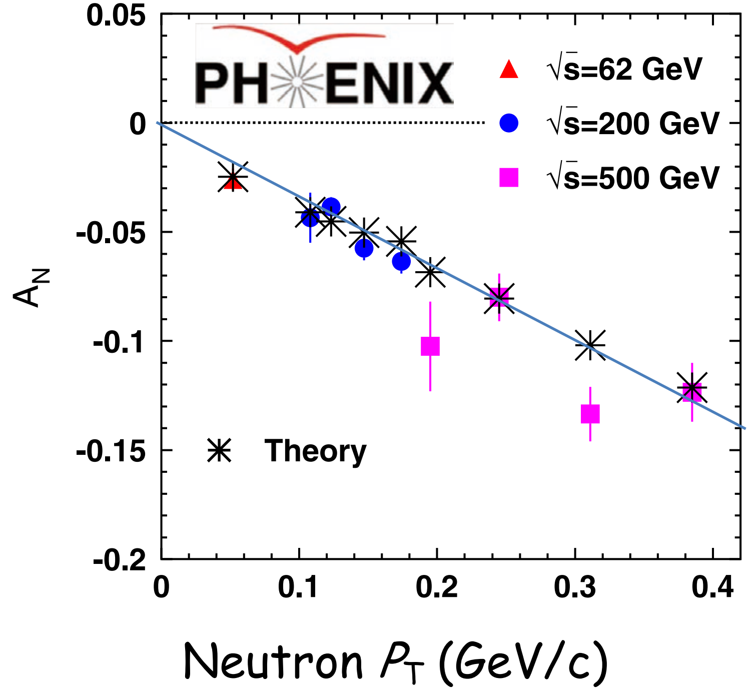
Pion cloud in p-wave (L=1)

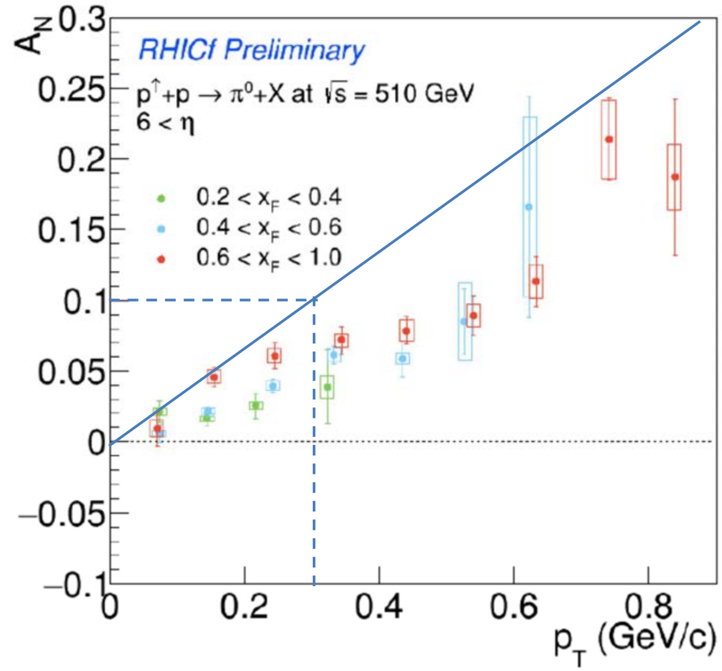




Can π^0 and neutron A_N be same origin?

PRD84,114012(2011)



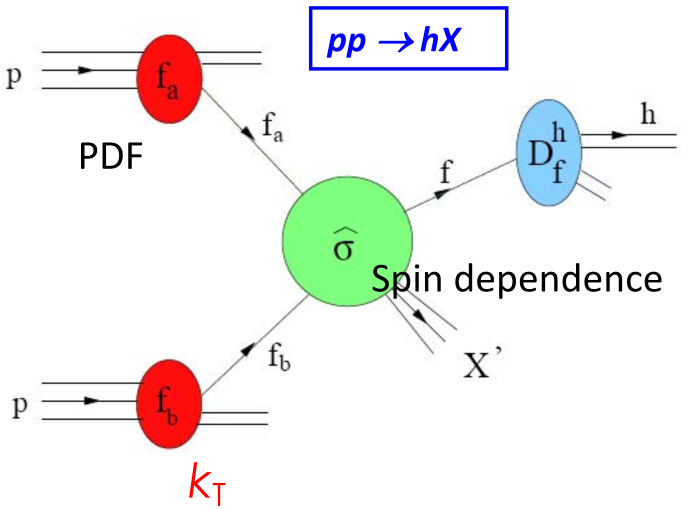


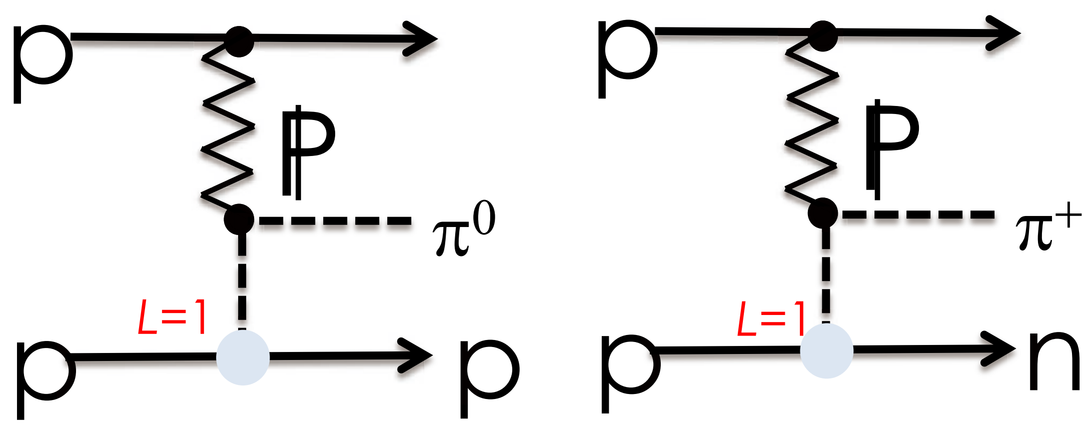
If they come from the same origin, the slope should be same but opposite sign

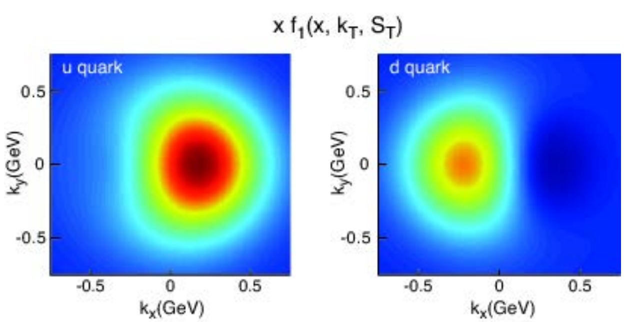
- Not sure if (pi+, pi0) suppose to have same orbital angular momentum.
- Above data are inclusive. Need to guarantee 2-body decay to require $A_N^n = -A_N^{\pi^+}$
- Kinematic conditions are not necessarily consistent between 2 measurements.
- Etc.

Intrinsic Orbital Motion via Different Means

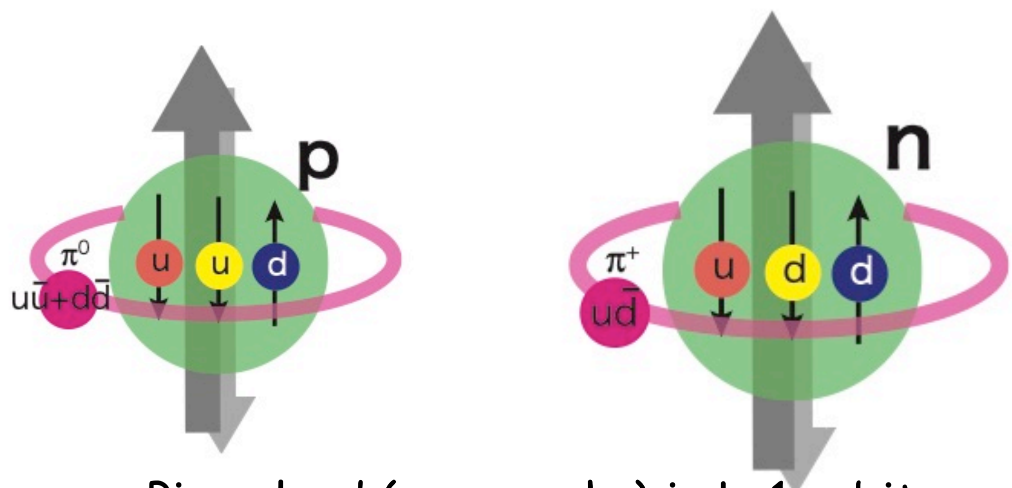
Aren't we measuring same orbital angular momentum in different scale?





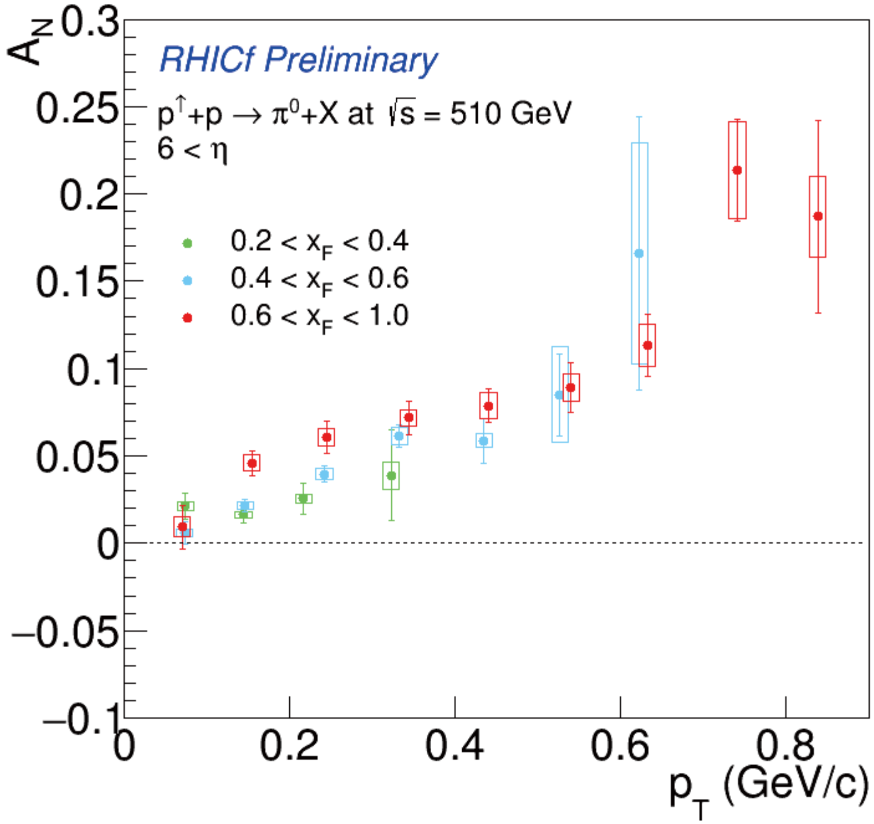


Quark transverse momentum distributions

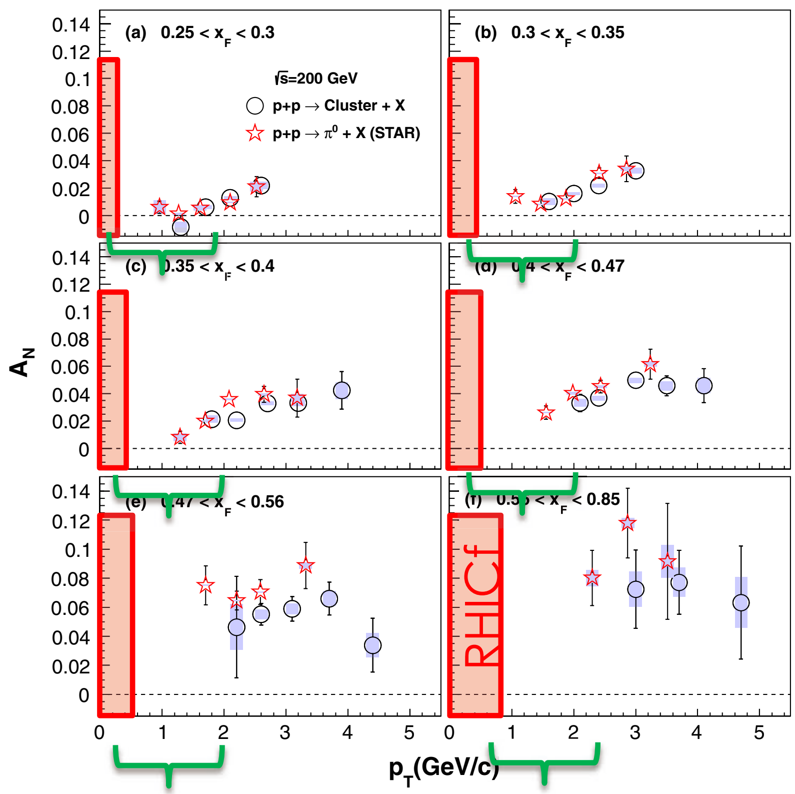


Pion cloud (sea quarks) in L=1 orbit

π^0 Asymmetry Preliminary Results



Phys. Rev. D **90**, 012006



New possible opportunity to extract physics by FoCAL?

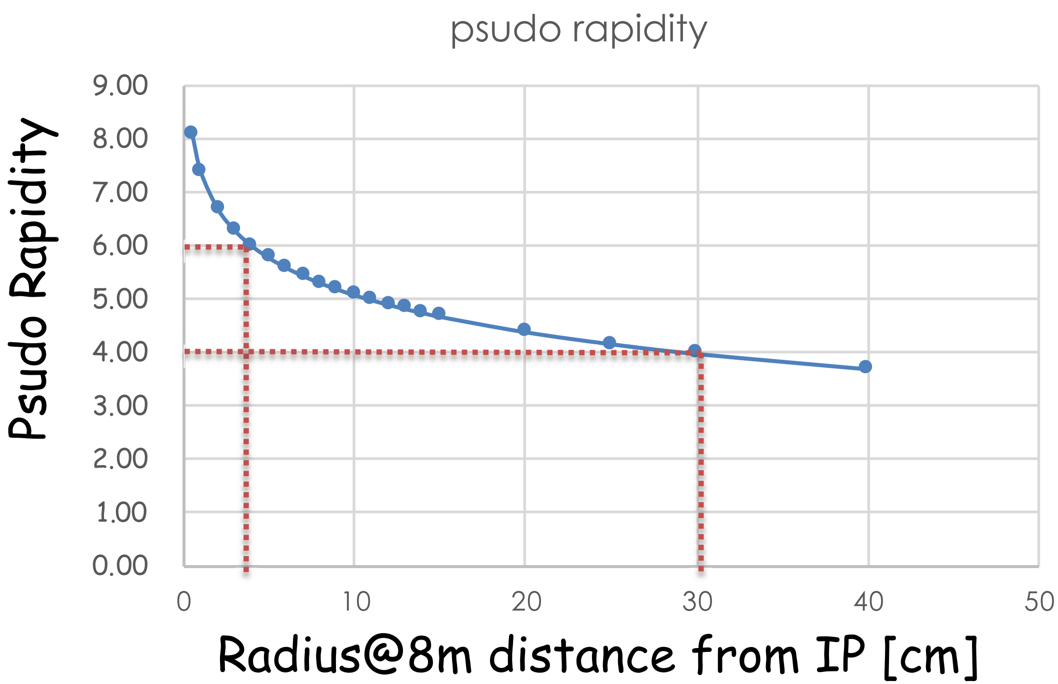
sPHENIX Running schedule

	Year	Species	Energy [GeV]	Wks	Rec. L	Samp. L	Samp. L (all-z)
2023	Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
2024	Year-2	$p+p$	200	11.5	—	48 pb^{-1}	267 pb^{-1}
		p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
2025	Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
	Year-4	$p+p$	200	23.5	—	149 pb^{-1}	783 pb^{-1}
	Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

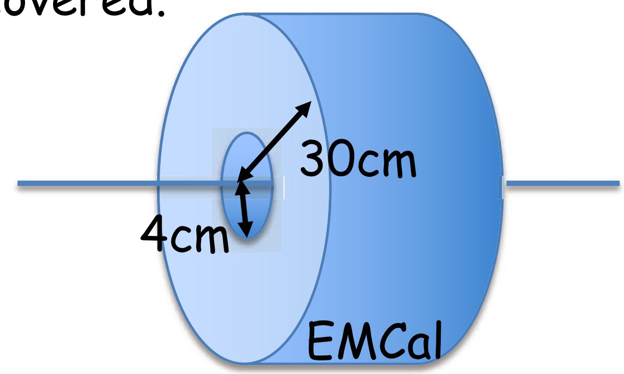
If extended (Year-4, Year-5)

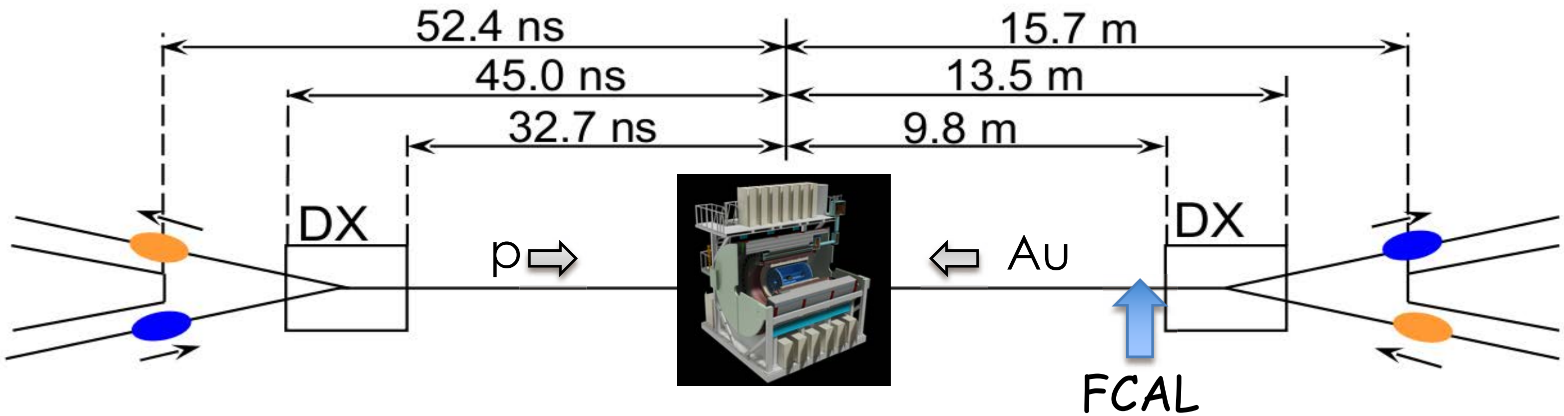
Polarized Proton Beam

Detector Location



- Rapidity of interest is 4<η<6.
- The detector position just in front of DX magnet is optimal (z~8m from IP).
- The radius 4<r<30cm is to be covered.



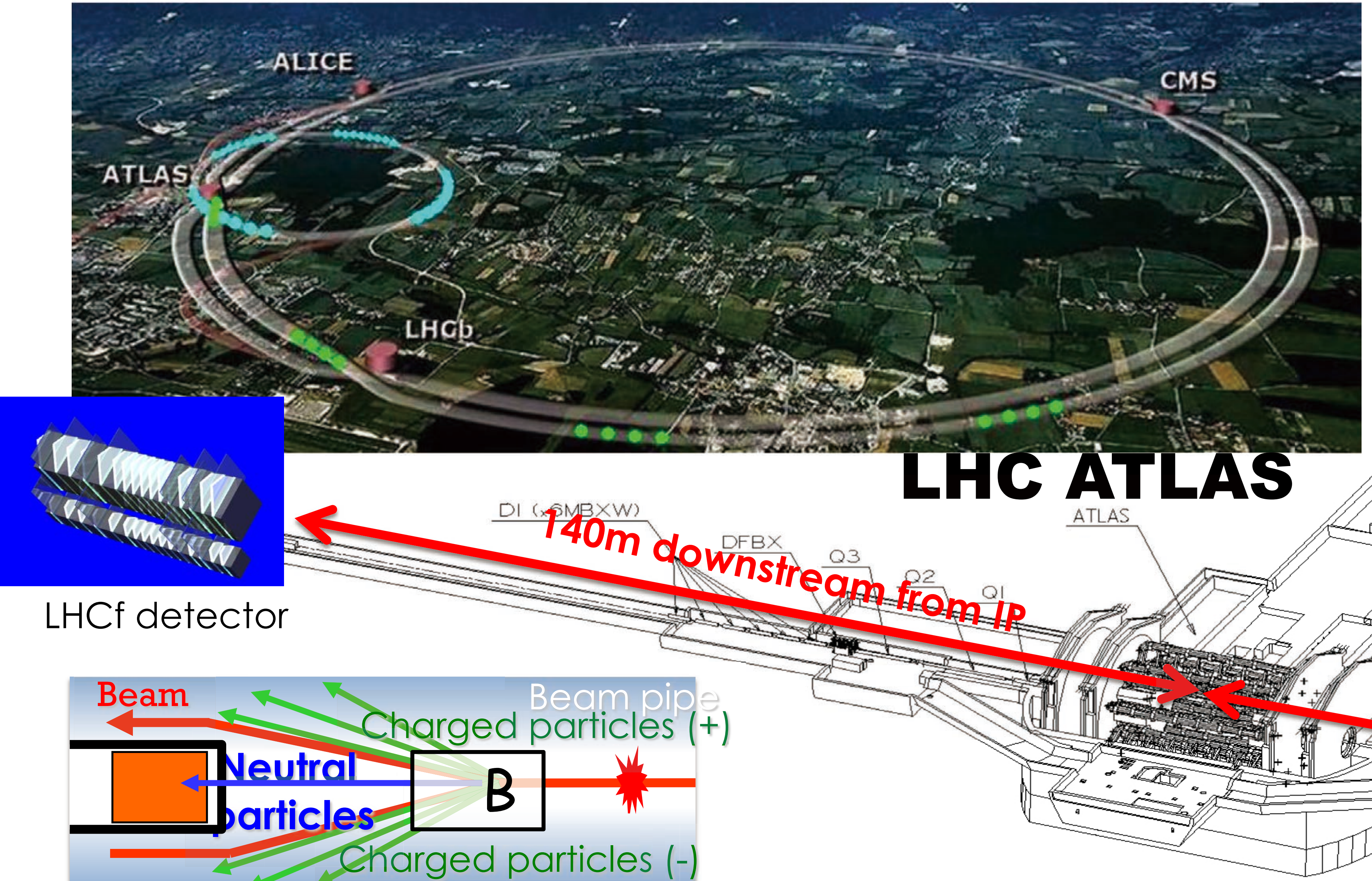


Summary

- Proton's spin sum rule has been examined
- Forward transverse single spin asymmetry has been considered to be sensitive to the orbital angular momentum.
- Forward π has been studied in pQCD framework, but recent data indicate possibility of soft process may be (partially) playing a role.
- Large observed asymmetry in RHICf indicates large asymmetry caused by diffractive mechanism.
- New experiment is necessary to interconnect asymmetries between hard (pQCD) and soft (diffractive) nature.

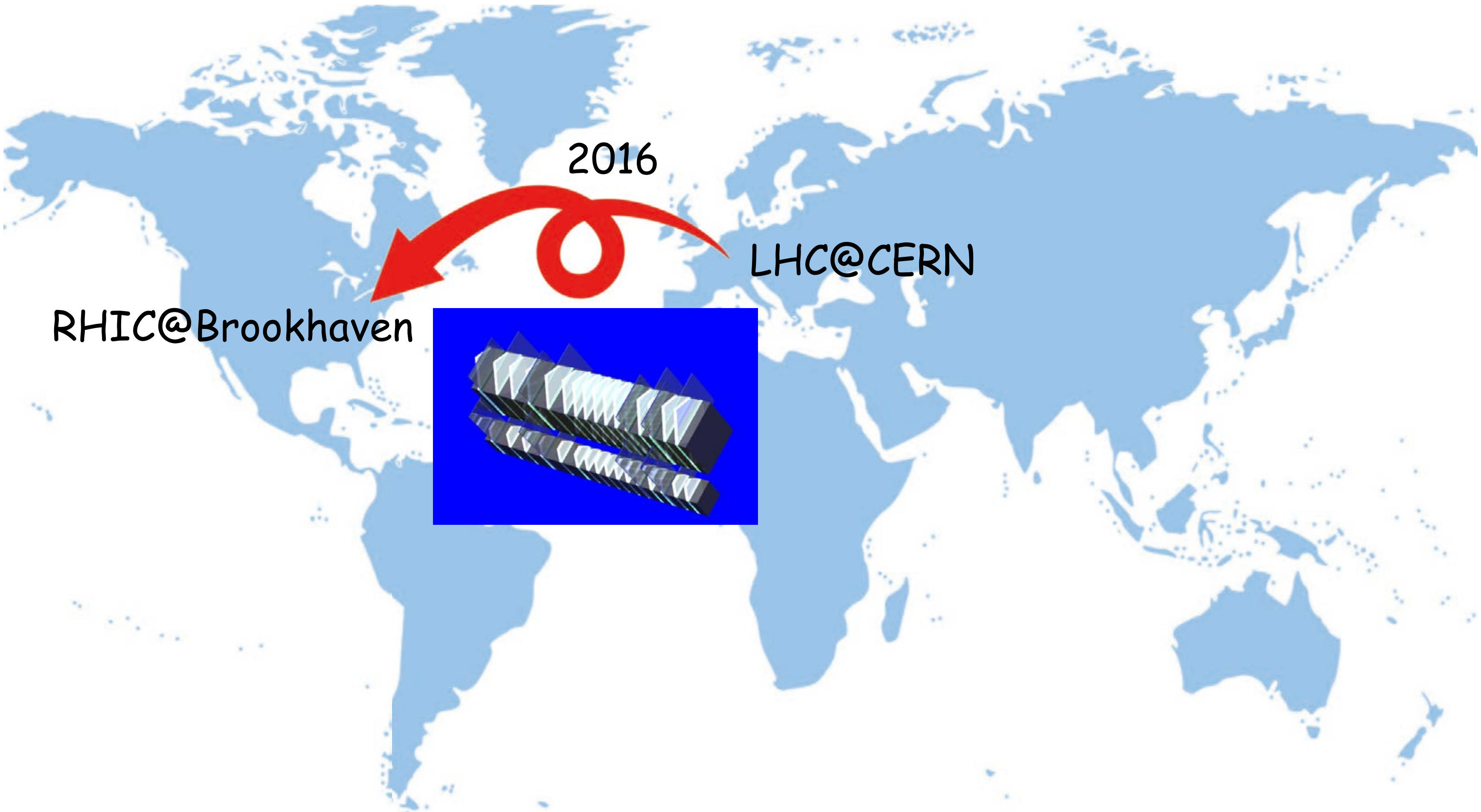
BACKUP

LHC forward (LHCf) Experiment



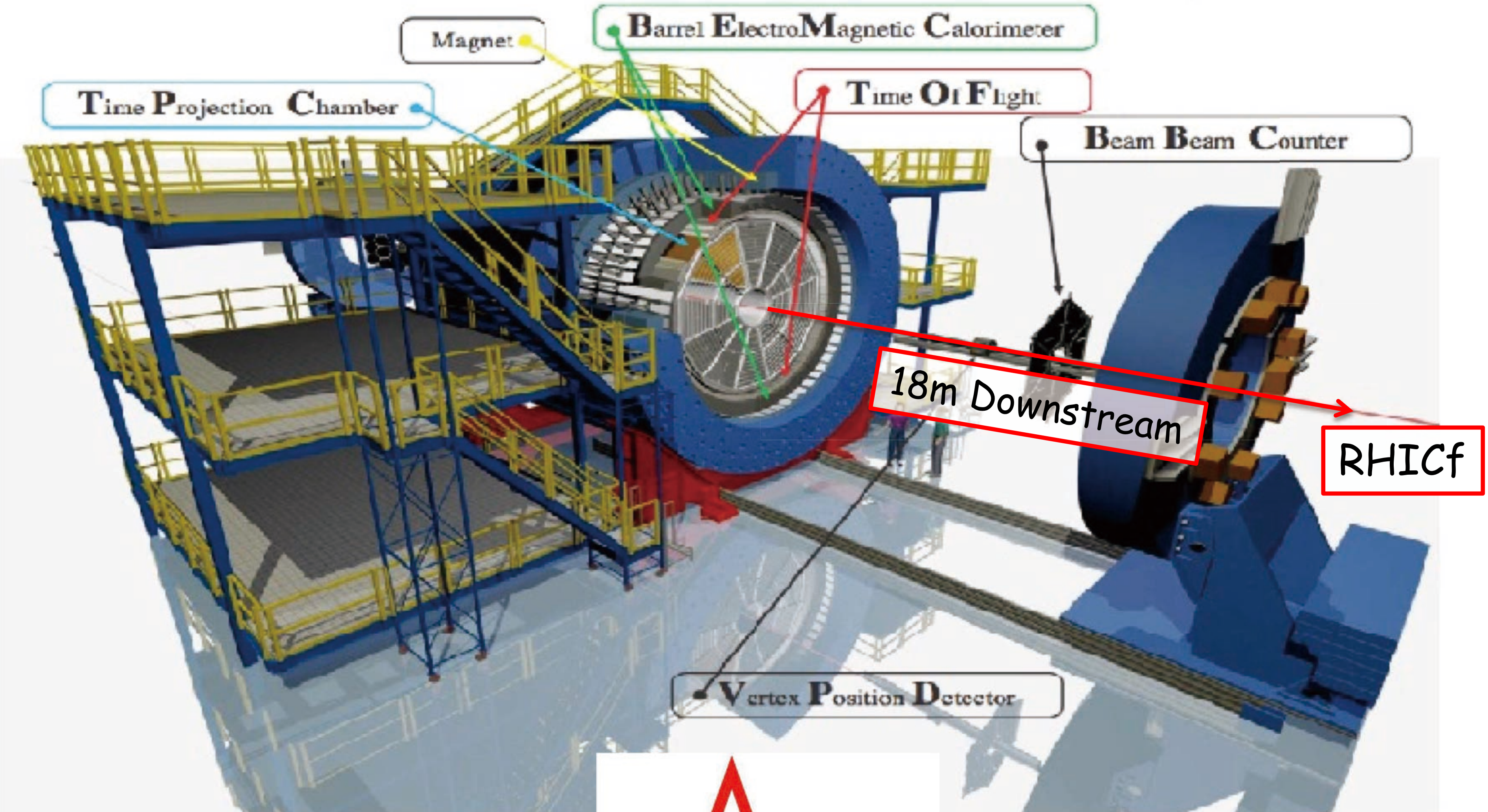
LHCf detector

LHCf -> RHICf



RHICf Collaboration

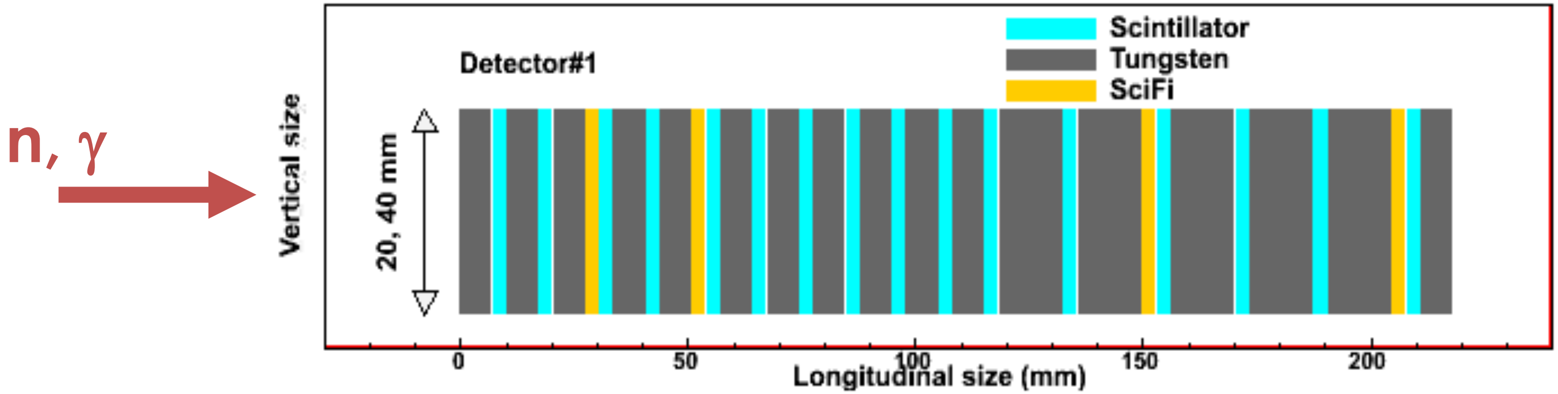
Solenoidal Tracker At RHIC : $-1 < \eta < 1, 0 < \phi < 2\pi$

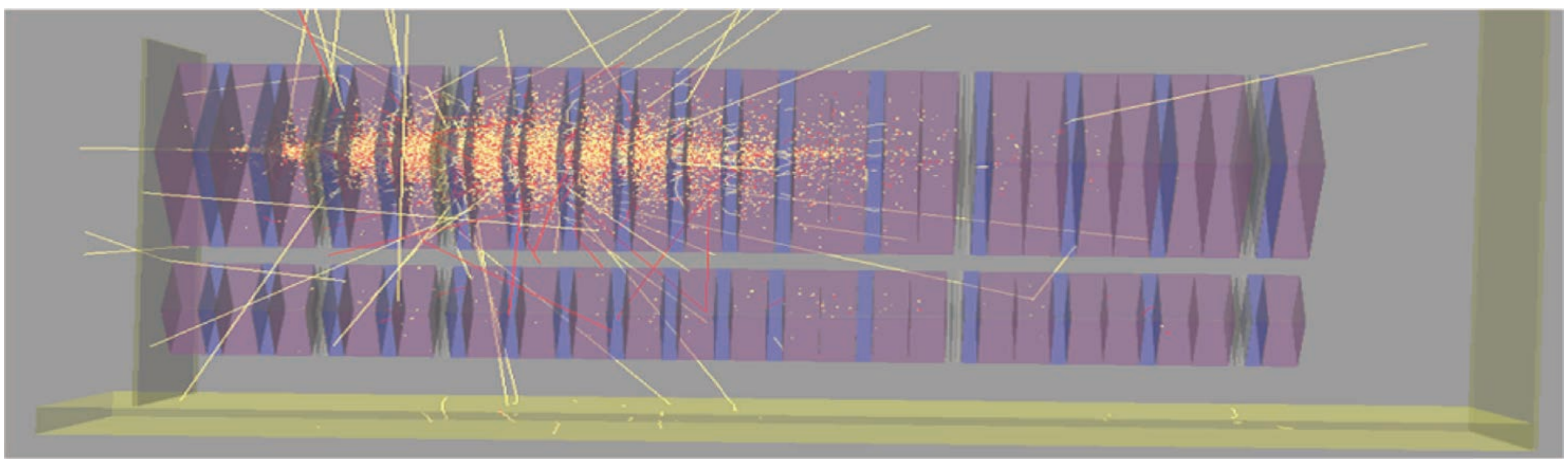


STAR


290mm
90mm

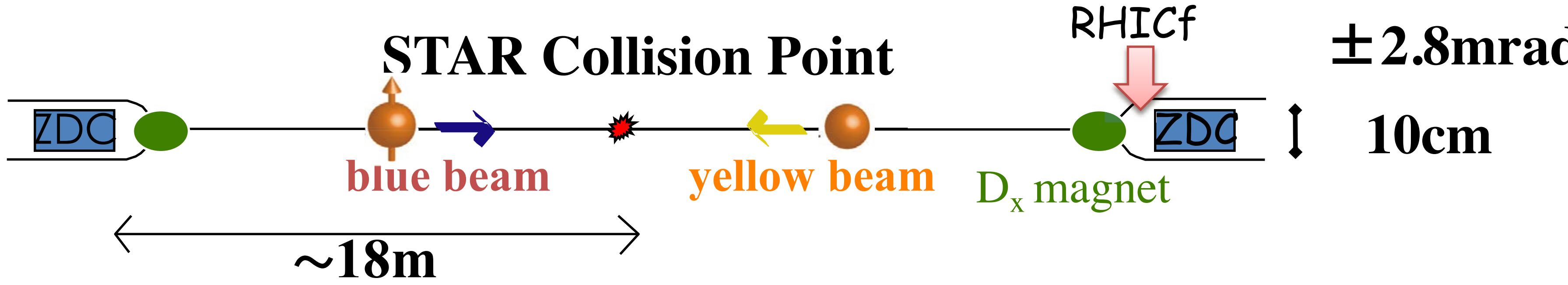
Sampling calorimeter



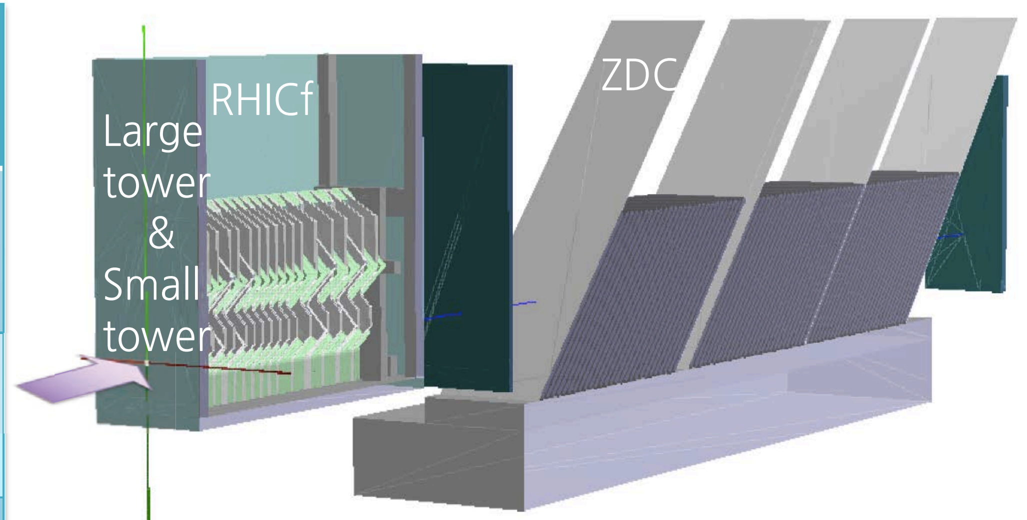


- Incident particles develop showers in Tungsten
- Deposited energy is sampled by scintillators interleaved (3% for EM showers)
- Four strip detector layers record lateral distribution of showers

RHICf Experimental Setup

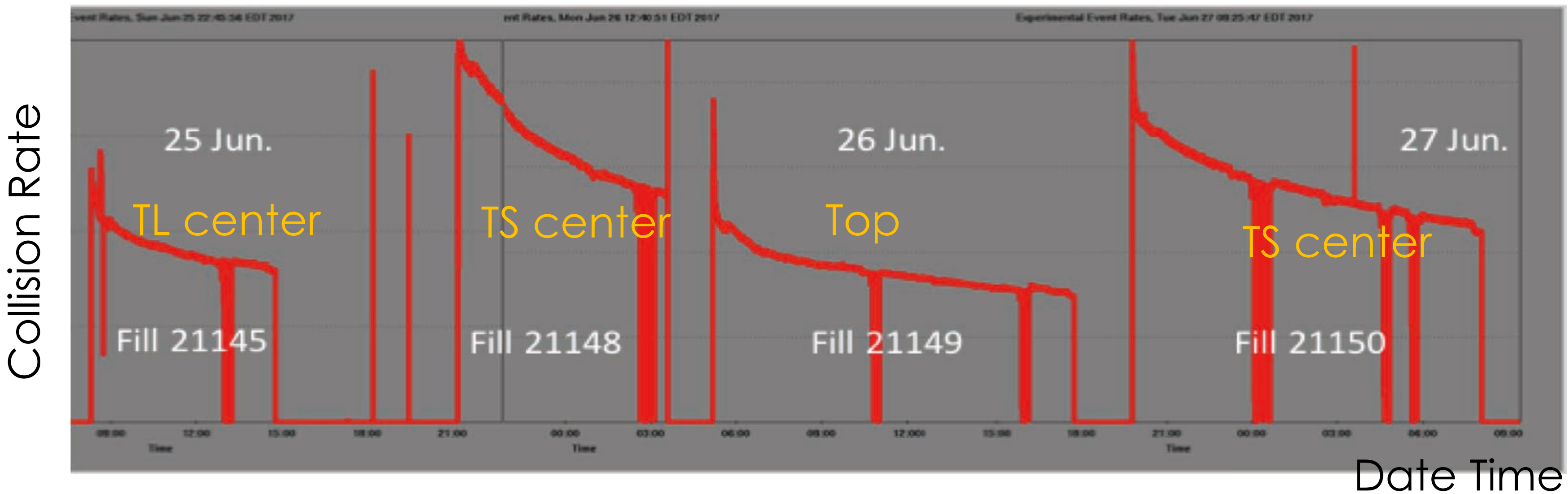


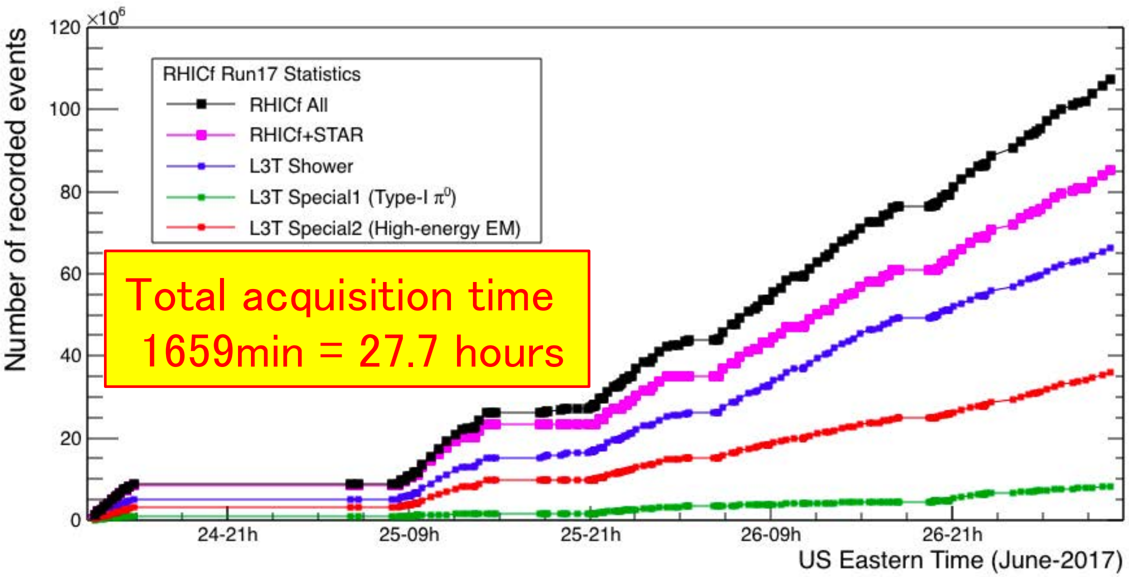
RHICf	ZDC+SMD
Sampling (λ_I=1.7)	Total Absorption (λ_I=5.1)
S=4cm × 4cm + 2cm × 2cm	S=10cm × 10cm
ΔE_n~35%	ΔE_n~18%
Δx_n~0.1cm	Δx_n~1cm



Installed new sampling calorimeter RHICf in front of existing neutron calorimeter, ZDC.

RHICf Experiment : June 2017





Total : 110M events

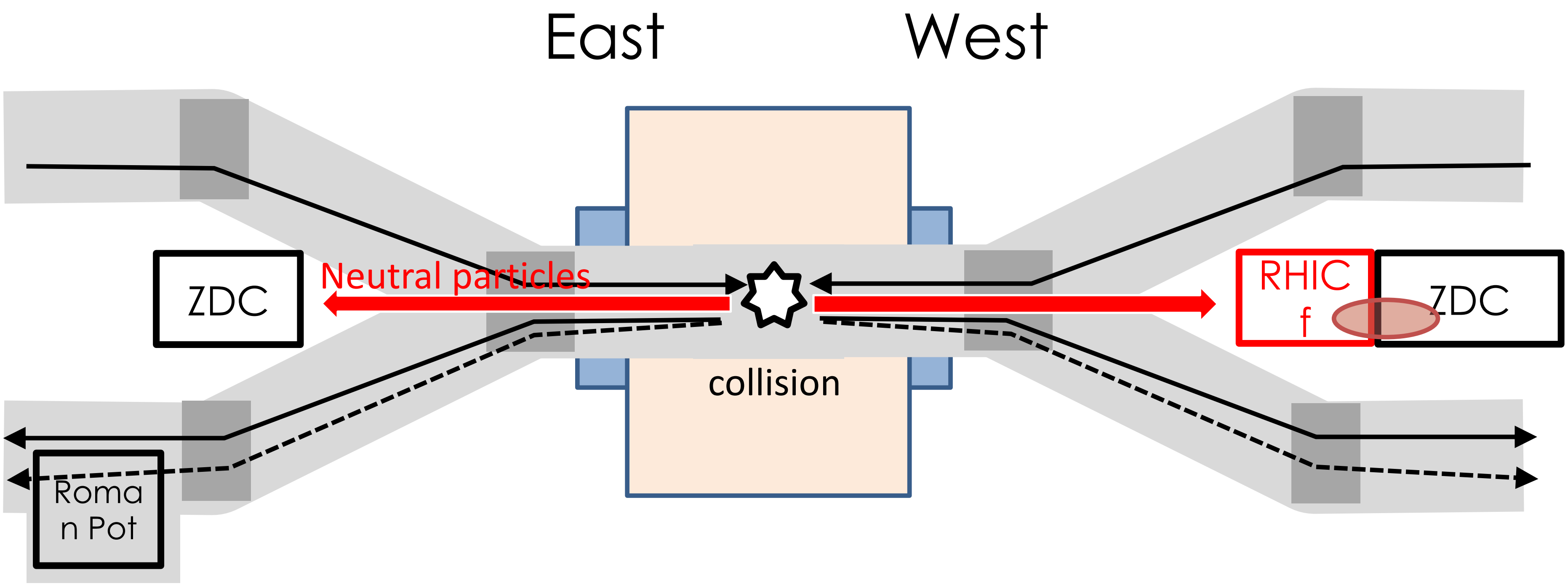
RHICf+STAR

RHICf (shower event)

RHICf (High-energy EM trigger)

RHICf (Type-I π^0 trigger)

RHICf Layout at STAR



- RHICf was installed in front of existing ZDC
- ZDC is only capable to measure neutron, not π^0
- RHICf+ZDC allows us simultaneous measurements of π^0 and neutron

Orbital Momentum & Diffractive π^0