The Transverse Spin Structure of the Nucleon

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Jefferson Lab

29th Annual Hampton University Graduate Studies Program Jefferson Lab - June 3-5, 2014

Lessons Scheme

LECTURES 1 & 2

- Introduction
- Deep Inelastic Scattering and 1D parton distribution functions
- From 1D to 3D nucleon structure: Transverse Momentum Dependent (TMD) parton distribution functions
- TMD Measurements @ Jlab in Hall B

LECTURES 3 & 4

- Data analysis
- Monte Carlo simulations
- Asymmetries extraction
- TMDs extraction

LECTURE 5

- Where are we? What's next

Where are we
and where are we going?

Exploration

Consolidation

Precision


WEST VIRGINIA
CHARLESTON
WASHINGTON
ANNAPOLIS
MARYLAND
RICHMOND
Chesapeake Bay
Appalachian Mountains
Allegheny Mountains
Shenandoah Mts
Blue Ridge
Massanutten Mt
Morgantown
Fairmont
Grafton
Clarksburg
Parkersburg
Buckhannon
Elkins
Keyser
Winchester
Front Royal
Leesburg
Rockville
Arlington
Alexandria
Manassas
Warrenton
Culpeper
Harrisonburg
Staunton
Charlottesville
Lexington
Covington
Oak Hill
Beckley
Princeton
Salem
Roanoke
Bedford
Lynchburg
Christiansburg
Pulaski
Wytheville
Marion
Abingdon
Mt Rogers
Martinsville
Danville
Farmville
Emporia
Williamsburg
Newport News
Hampton
Norfolk
Virginia Beach
Chesapeake
Salisbury
La Plata
Cambridge
Elizabeth City
Edenton
Albemarle Sound
Henderson
Roxboro
Oxford
Tarboro
Williamston
Winston-Salem
Greensboro
Boone
VIRGINIA
0 km 25 50 75 km
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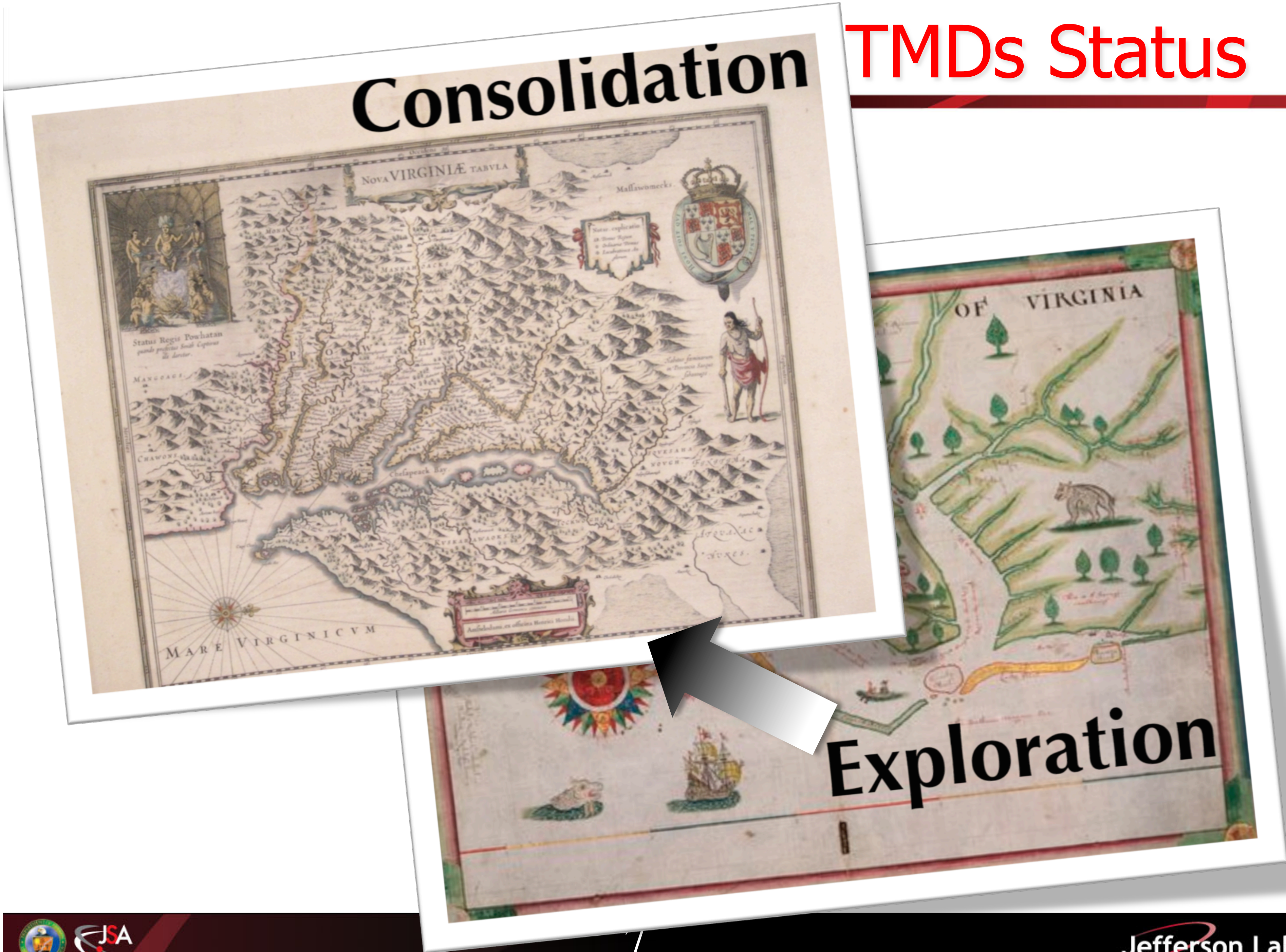
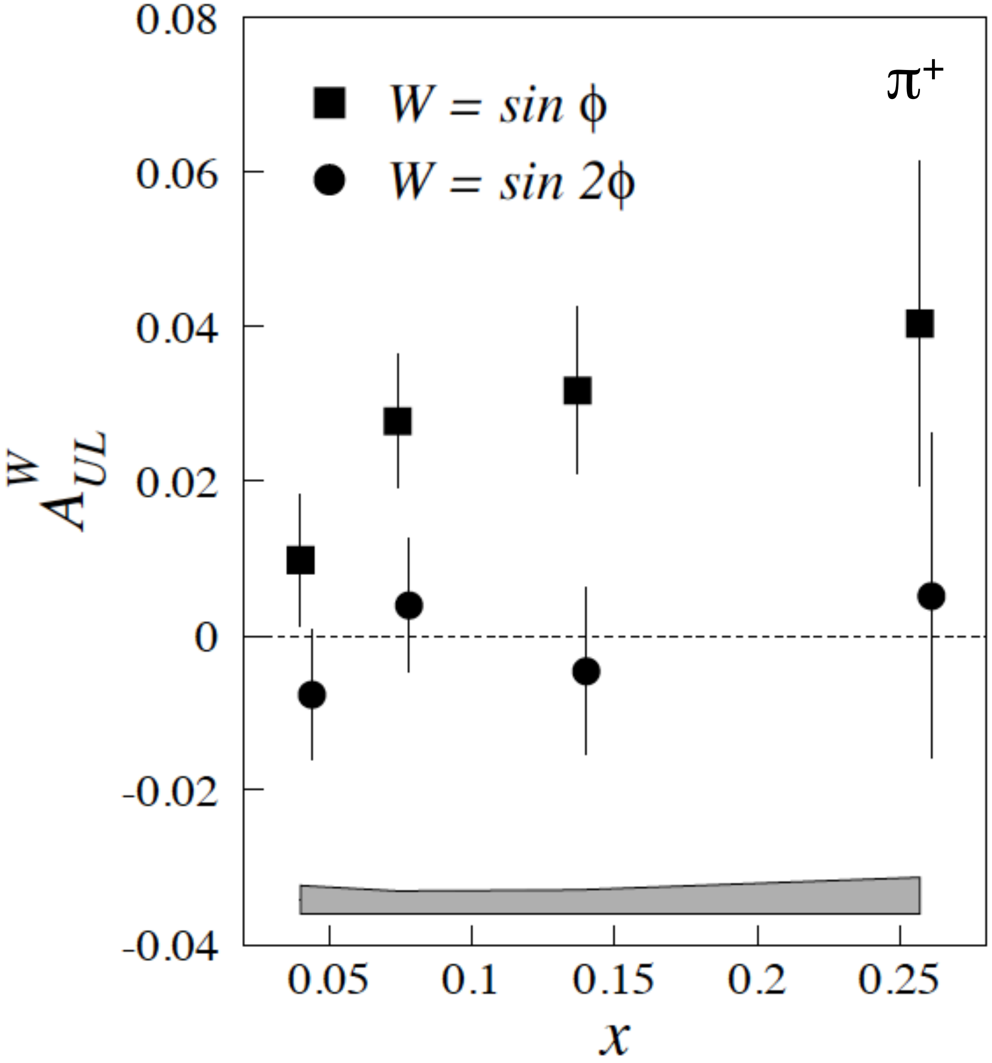
TMDs Status


Consolidation
NOVA VIRGINIÆ TABVLA
MARE VIRGINICVM
OF VIRGINIA
Exploration

Exploration



hermes

First Observation of a Single-Spin Azimuthal Asymmetry in Semi-Inclusive Pion Electro-Production

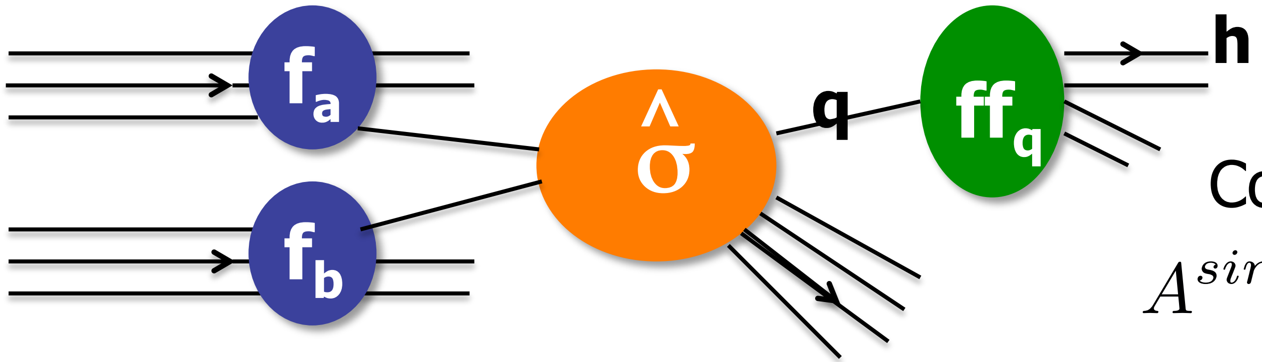
A. Airapetian et al, Phys. Rev. Lett. 84 ***(2000)*** *4047-4051*

TMDs in SIDIS

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

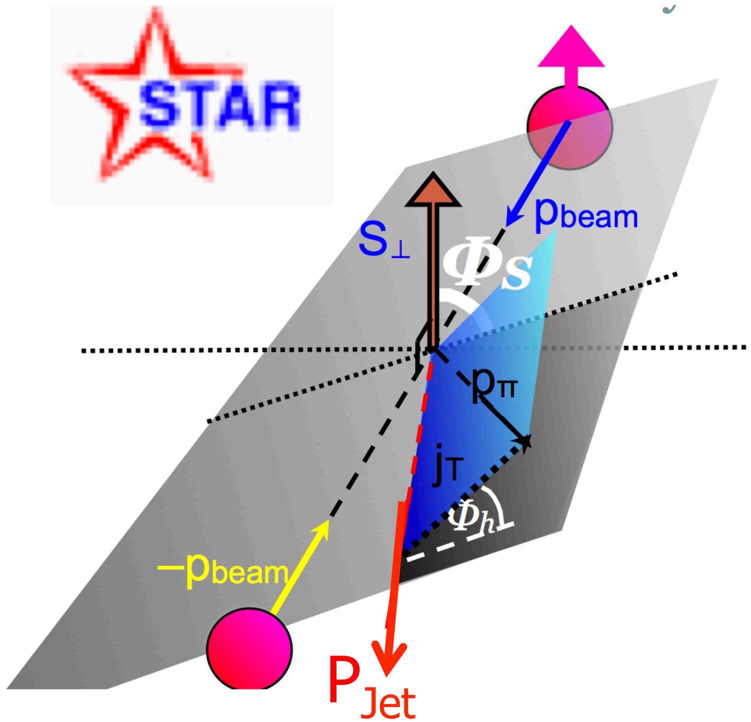
- Many consistent measurements from HERMES, COMPASS, JLAB
- All leading twist TMDs have been "explored"

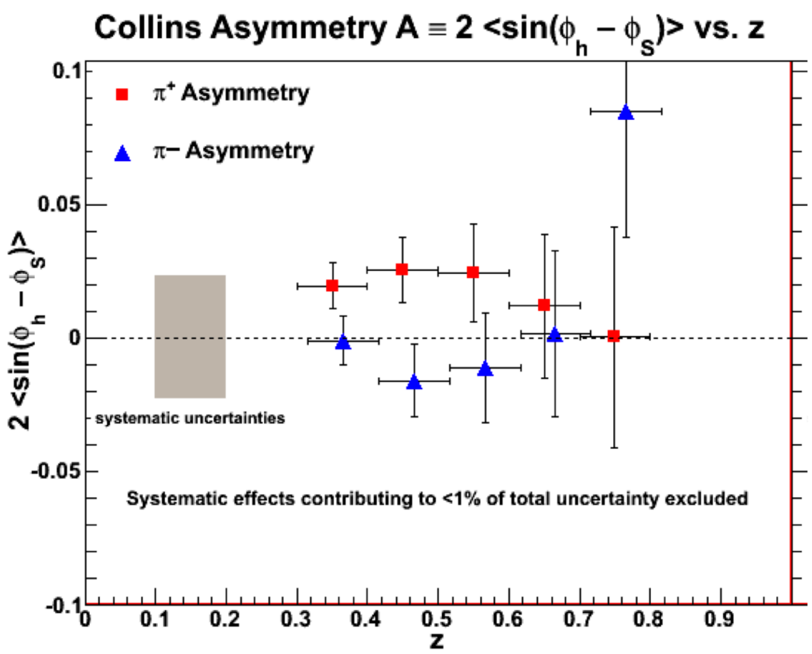
TMDs in p+p



Collins Asymmetries

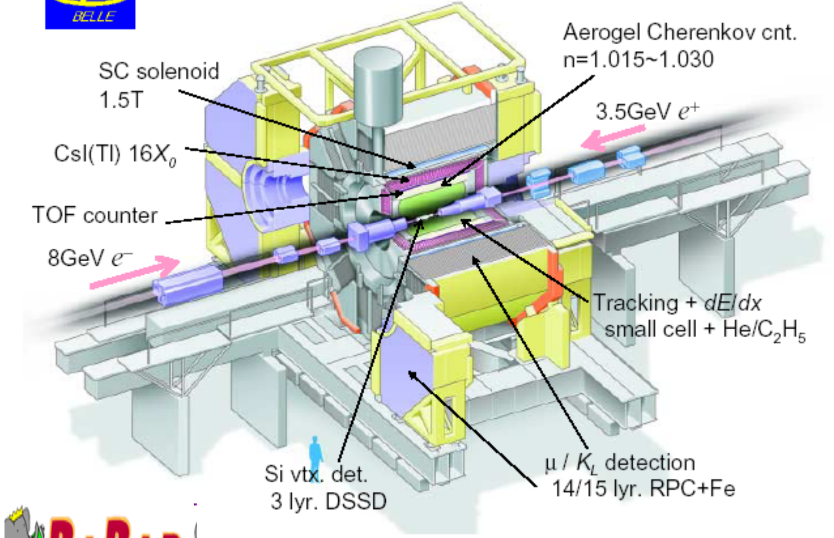
$$A^{sin(\phi_h - \phi_S)} \propto h_1 \otimes H_1$$



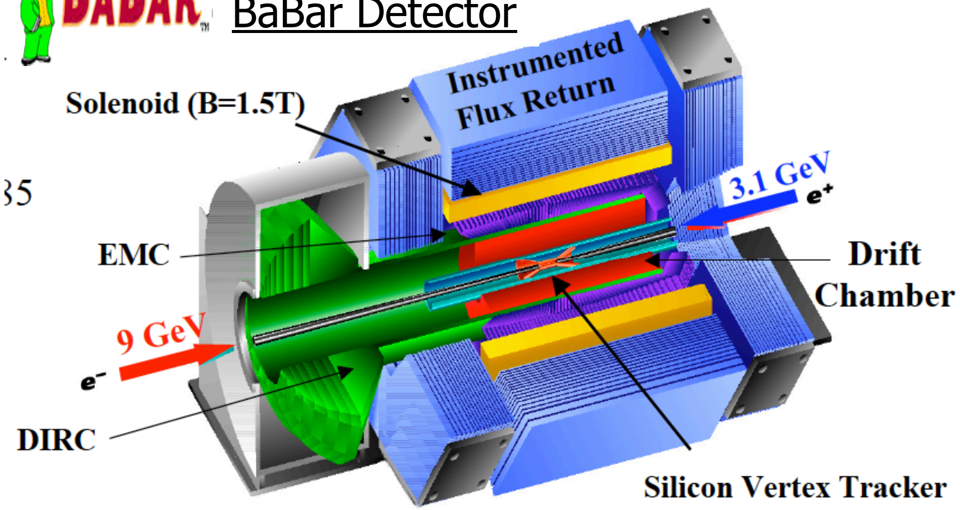


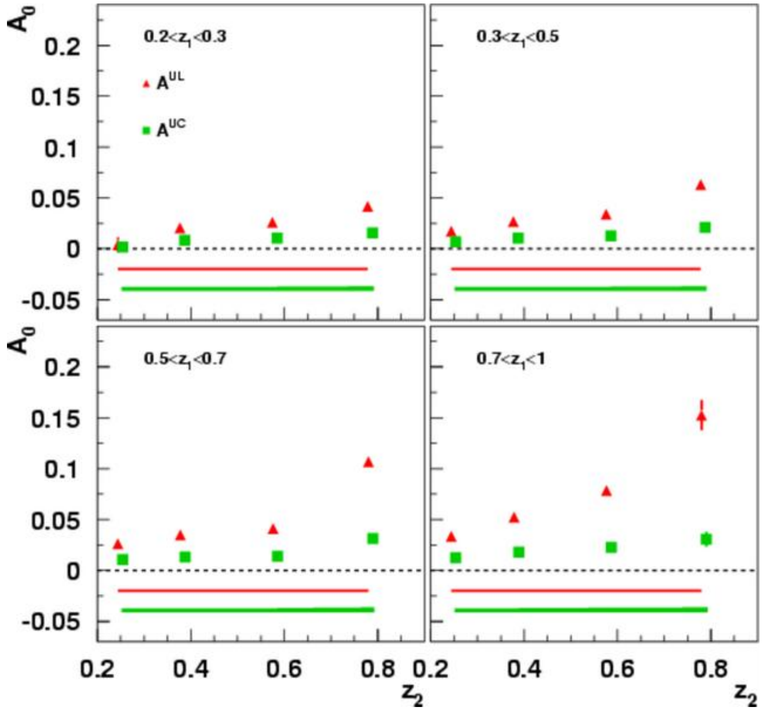
e^+e^- : $H_1^\perp$

Belle Detector



BaBar Detector

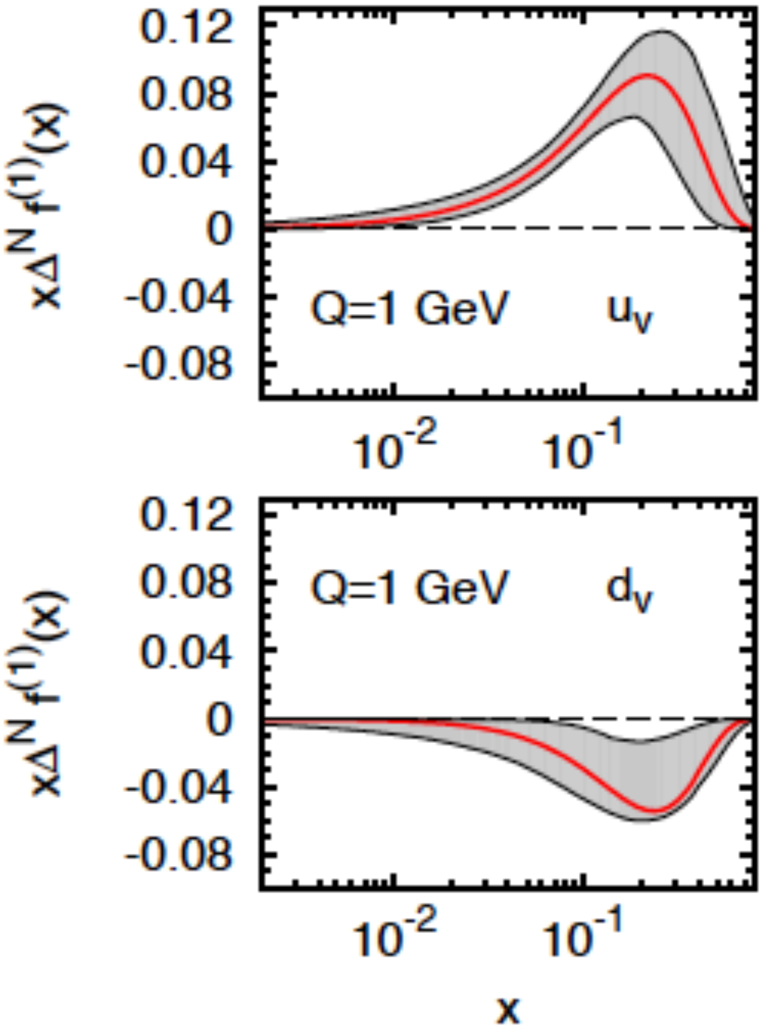




Phys.Rev.D78:032011,2008

Significant Collins effect measured at Belle and confirmed by BaBar

Transversity

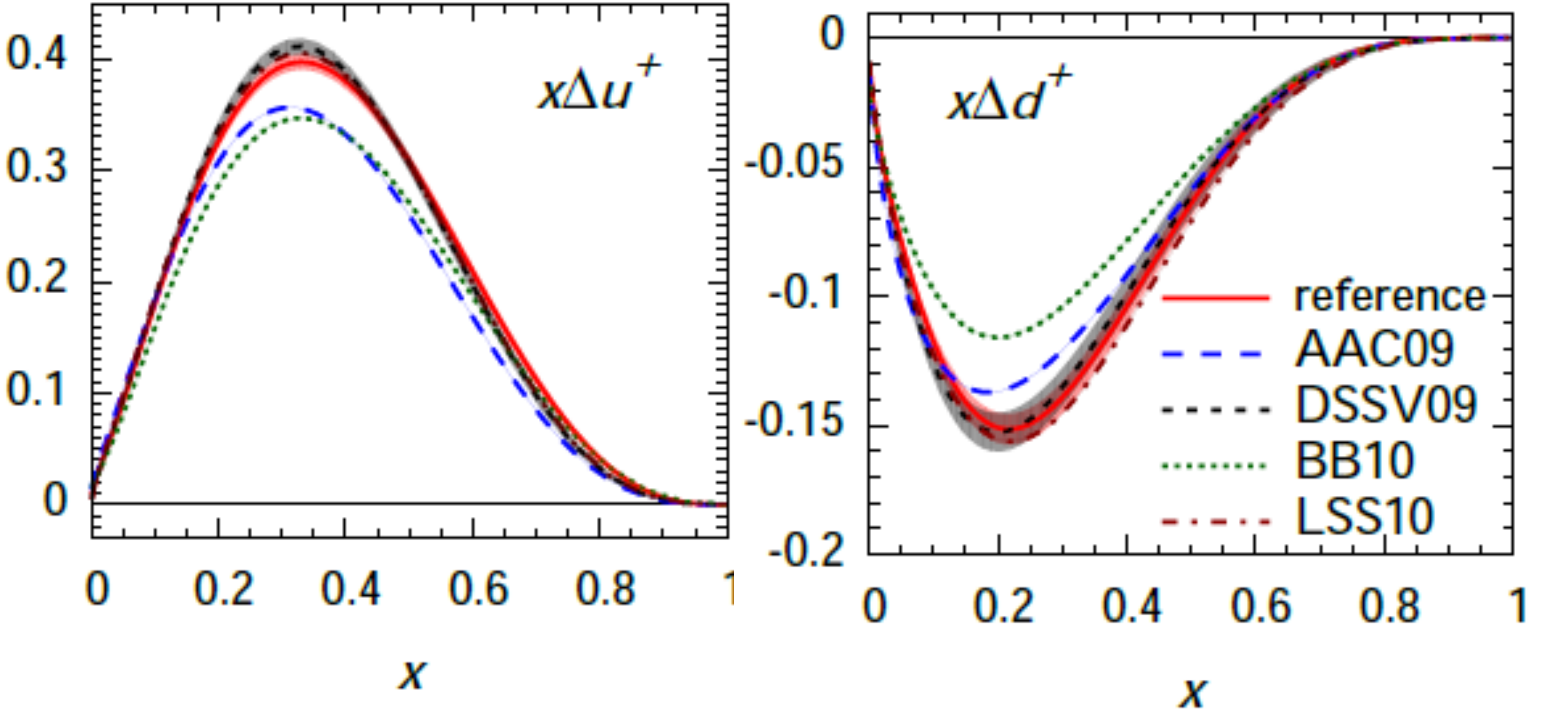


$$xh_1(x)$$

$$xh_1(x, k_T^2)?$$

(M. Anselmino et al arX:1204.1239)

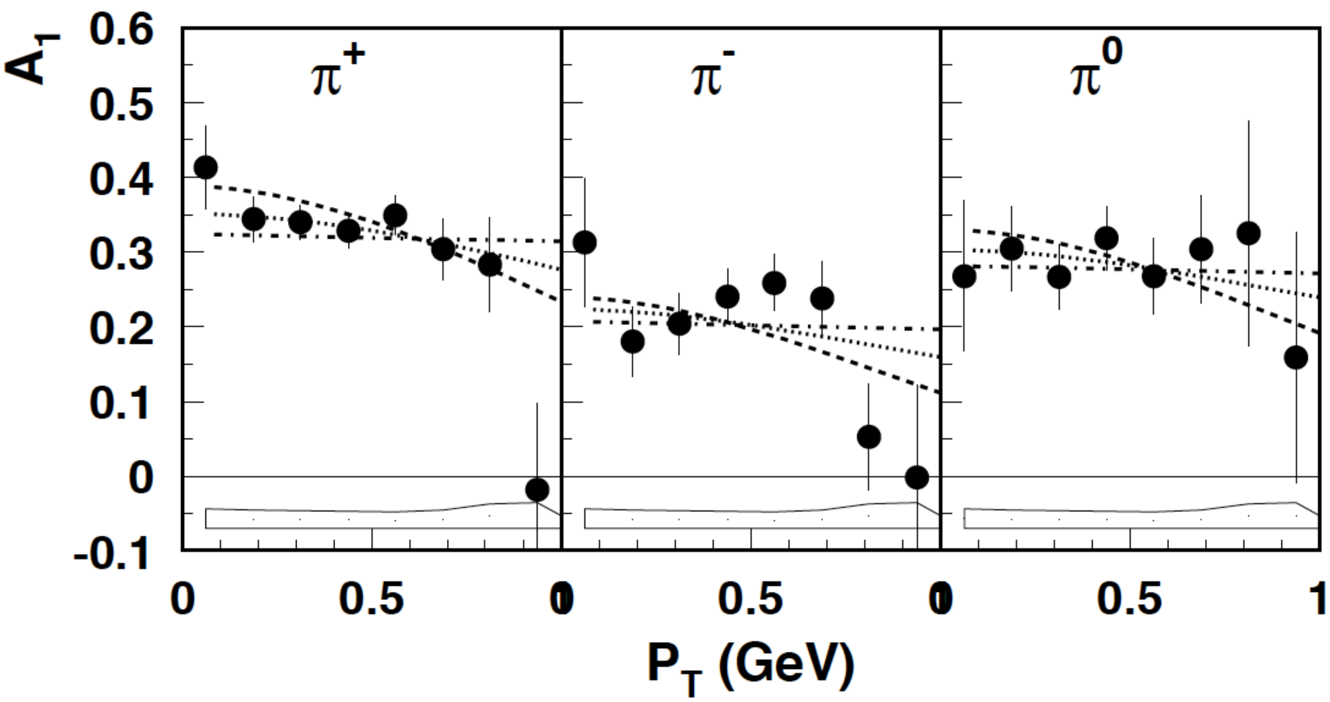
$g_1(x)$



Relatively good knowledge

$g_1(x,k_T)$

JLab-CLAS: H. Avakian et al. Phys.Rev.Lett.105:262002,2010



$$R = \frac{k_T\ width\ g_1 dist.}{k_T\ width\ f_1 dist.}$$

R=0.40
R=0.68
R=1.0

f_1=0.25 GeV^2

Data shows slight preference for R< 1

wider k_T distributions for f_1 than for g_1

Theory

Factorization proven

- for small k_T (Ji, Ma, Yuan P.L.**B597** (2004) 299)
- Drell-Yan (Collins, Soper, Sterman, N.P. **B250** (1985) 199

Complete definition of TMDs

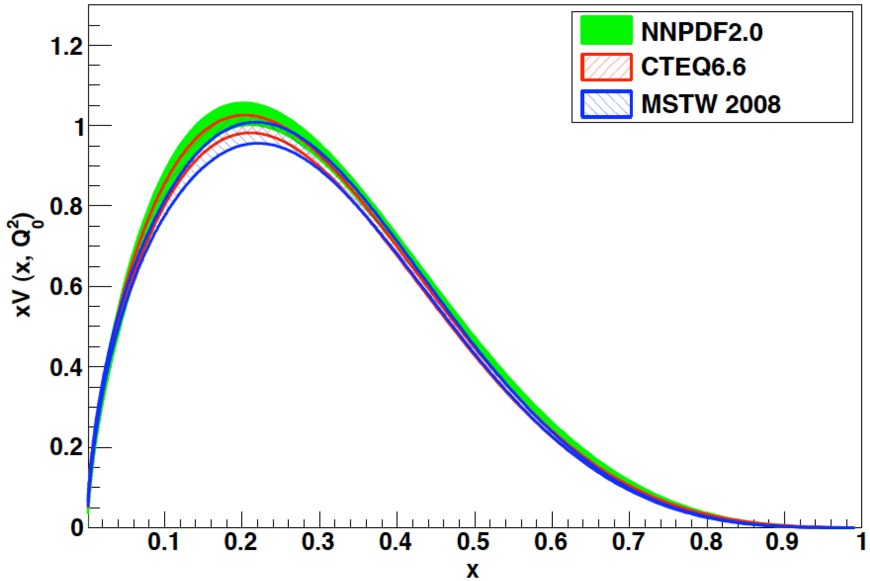
- Collins 2011 "Foundation of Perturbative QCD")

Evolution of TMDs

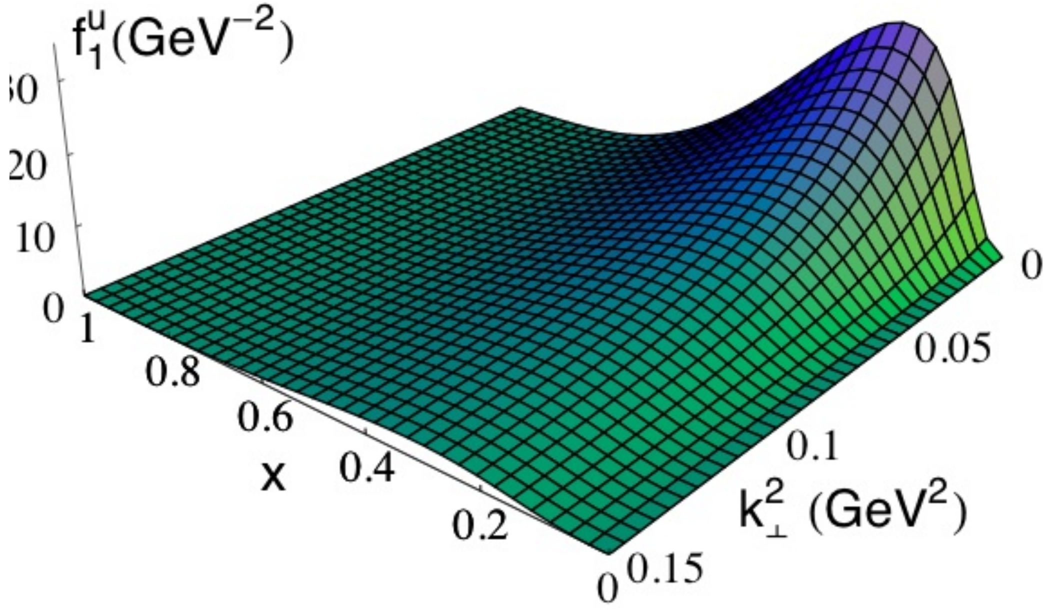
- Collins, Aybat, Rogers arX:1110.6428

Phenomenological Models

$xf_1\,(x)$: Well known

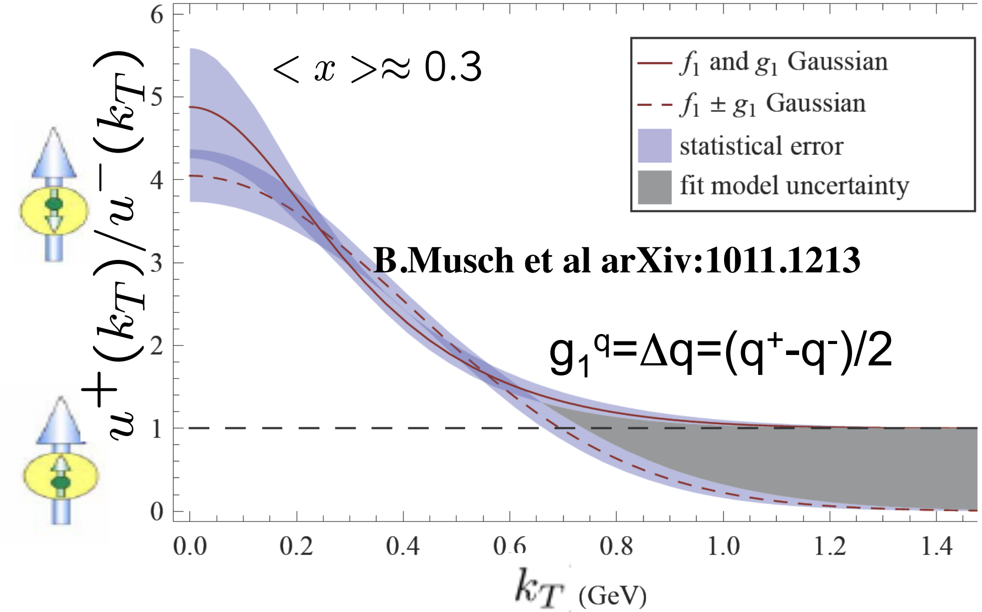


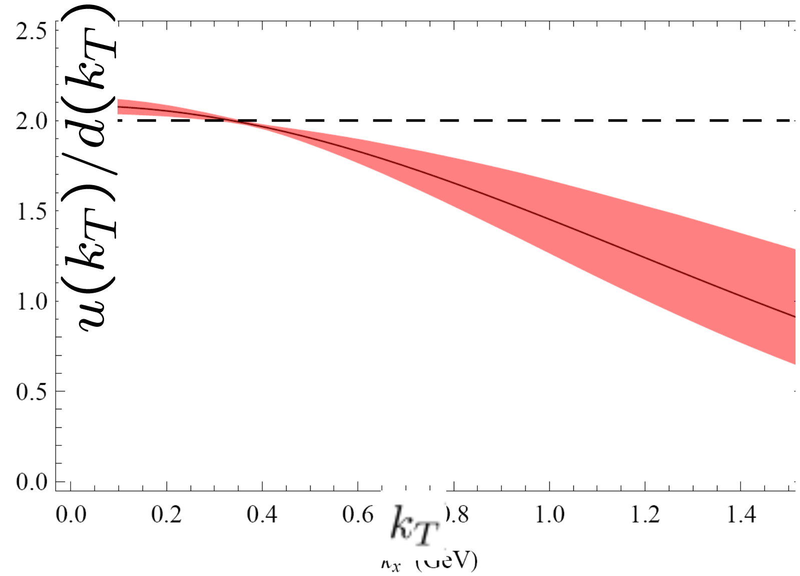
$xf_1\,(x, k^2{}_T)$: poorly known

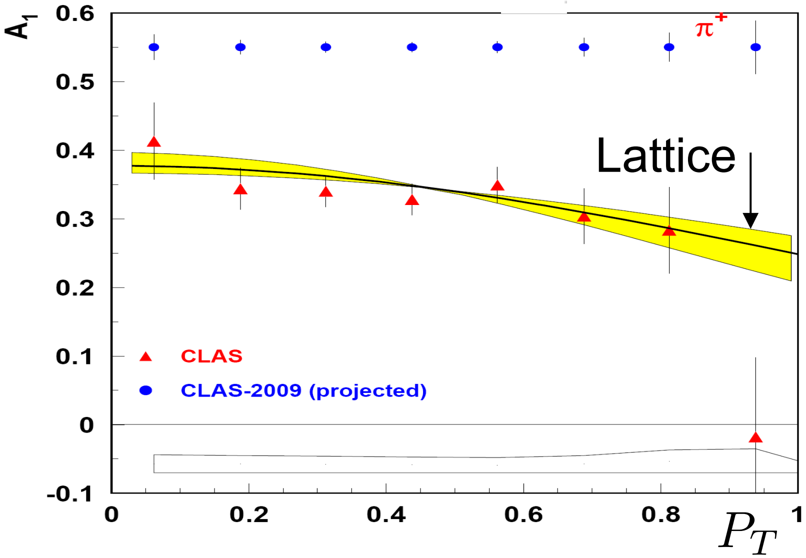


Light-cone quark model calculation
Boffi et al.

Lattice: flavor and spin effects on k_T



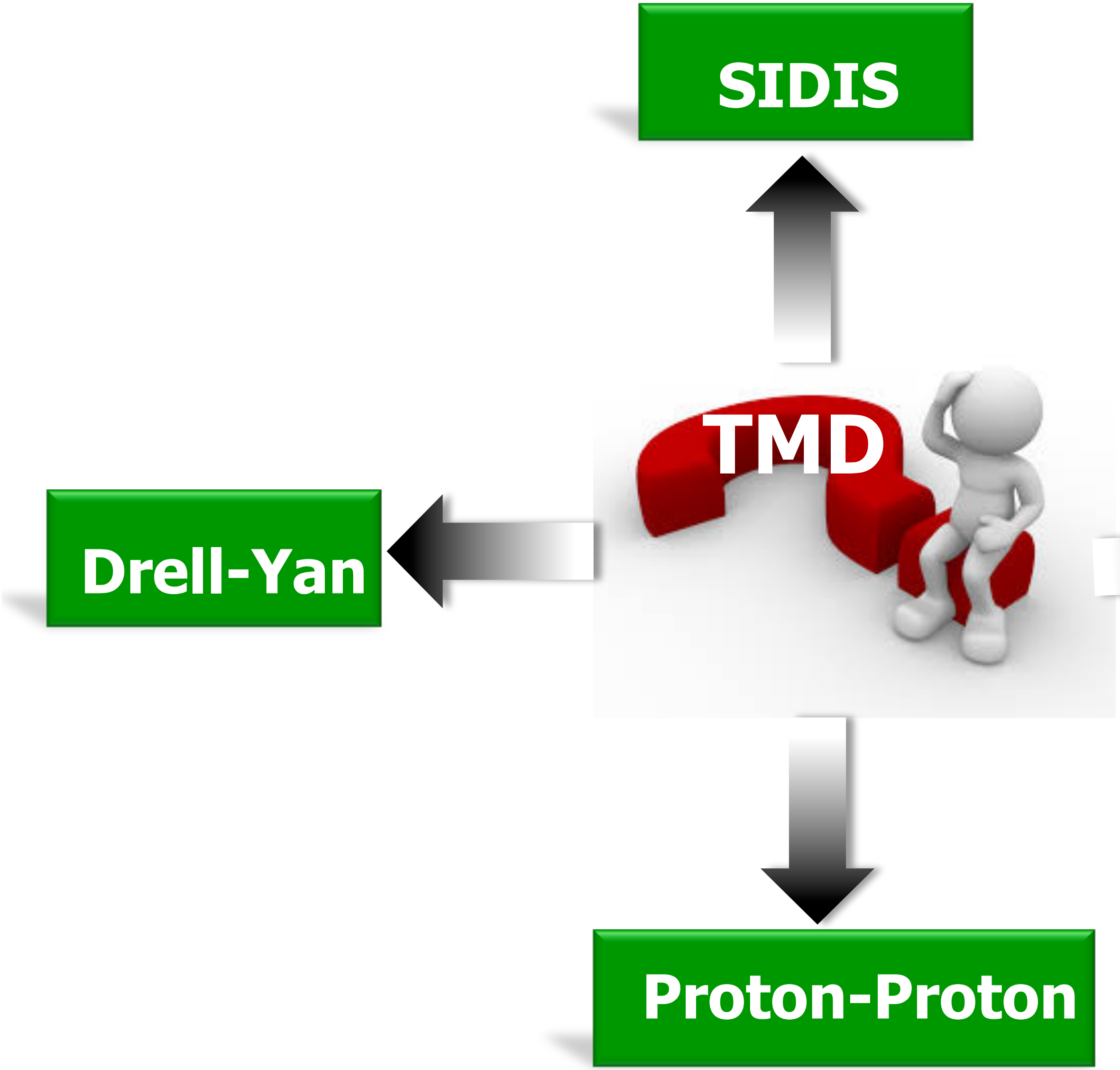




- more d-quarks at large k_T

- Double spin asymmetries from CLAS@JLab consistent with wider k_T distributions for f_1 than for g_1

TMD Extraction



We need to develop reliable and model independent techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables

Milestones for future measurements

Evolution

Factorization

Universality
&
QCD gauge-formalism

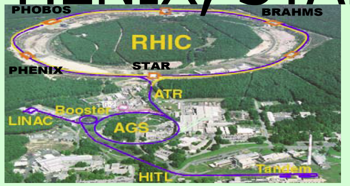
Large variety of reactions is essential in order to meet the goals

Robust procedure for extractions
Isolate each contribution
Both in PFD&FF

Flavor separation

Where?

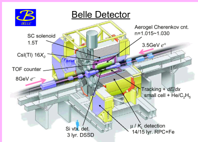
BNL: RHIC, PHENIX, STAR



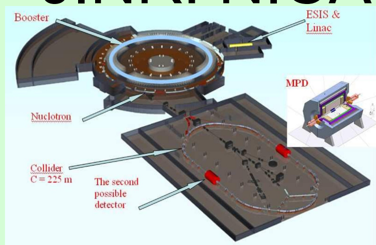
FAIR: PANDA

CERN: COMPASS

KEK: BELLE



JINR: NICA



FERMILAB

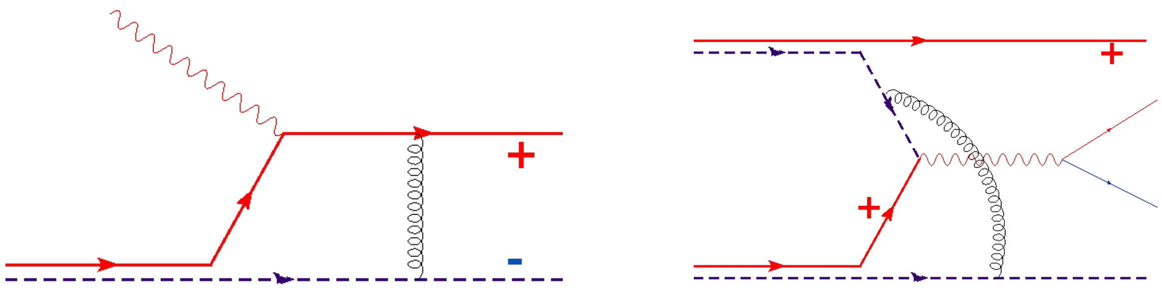
Future Electron-Ion Collider

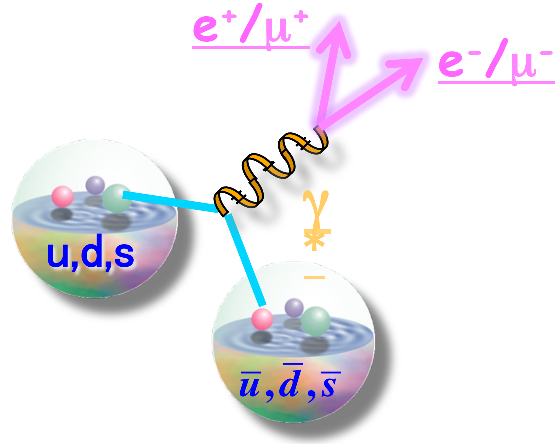
JLAB: HALL A,B,C

Drell-Yan Process

Colored objects are surrounded by gluons

Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)





$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

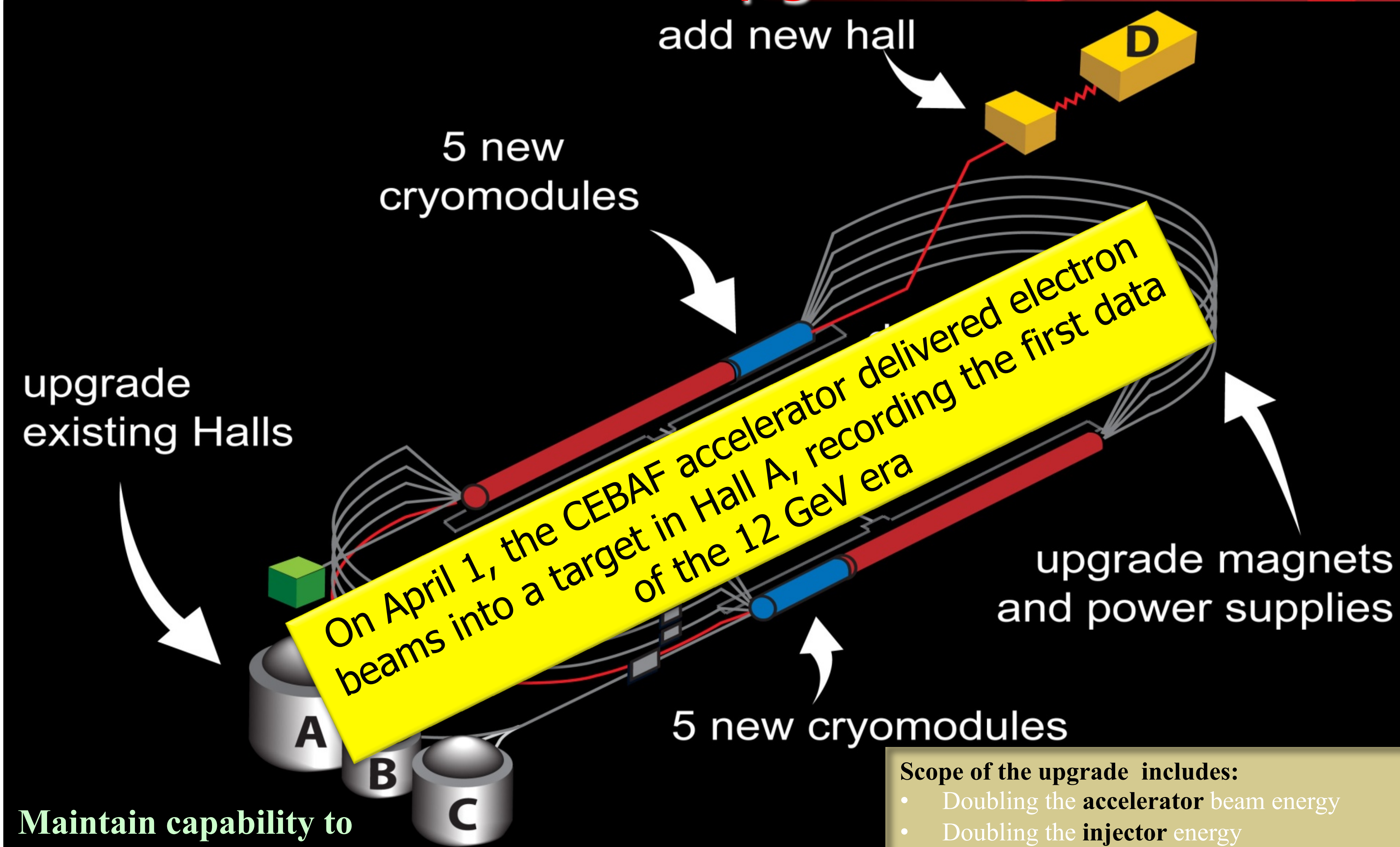
Brodsky,Hwang, Schmidt
Belitsky,Ji,Yuan
Collins
Boer,Mulders,Pijlman,
Kang, Qiu, AP
etc

One of the main goals is to verify this relation.
It goes beyond "just" check of TMD factorization but also universality test.
Motivates Drell-Yan experiments:
AnDY, COMPASS, JPARC, PAX, FERMILAB etc

Measurements @ JLab 12

CEBAF Upgrade

Shut Down May 18, 2012



Maintain capability to deliver lower pass beam energies : 2.2, 4.4, 6.6,….

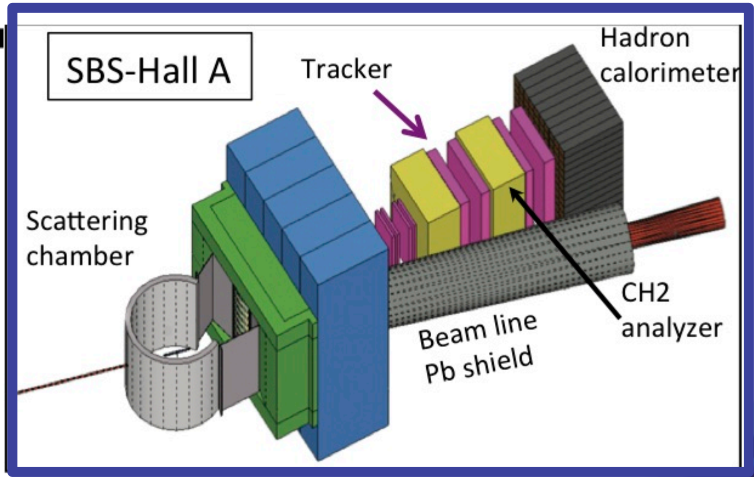
Scope of the upgrade includes:

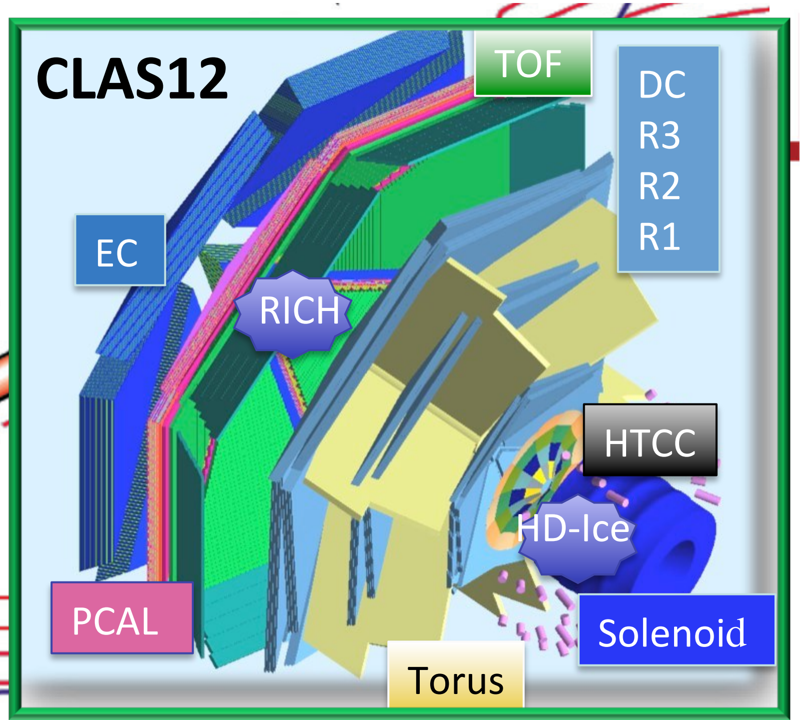
- Doubling the **accelerator** beam energy
- Doubling the **injector** energy
- **New Hall** and beam-lines
- **Upgrades** to existing Experimental Halls (**Increase of Luminosity 10^{35} - ~10^{39} cm^{-2}s^{-1}**)

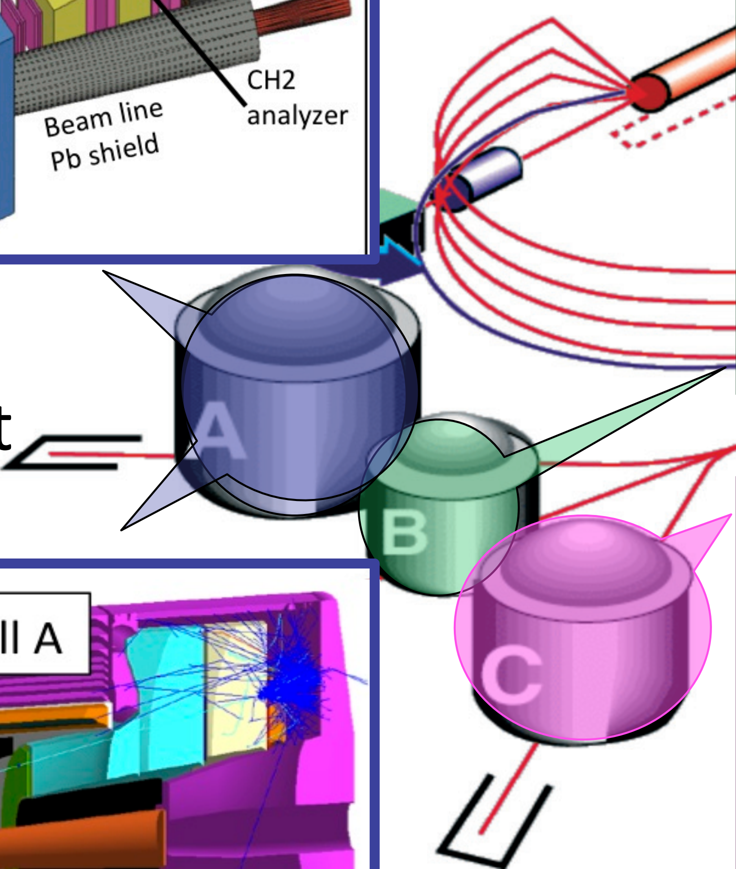
JLab: 21st Century Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range N-N correlations and the partonic structure of nuclei?
- Can we discover evidence for physics beyond the standard model of particle physics?

TMD program @ 12 GeV

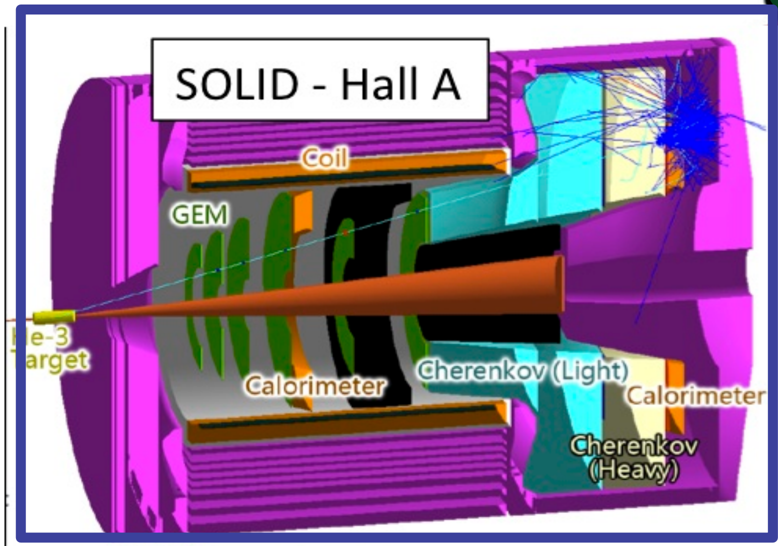


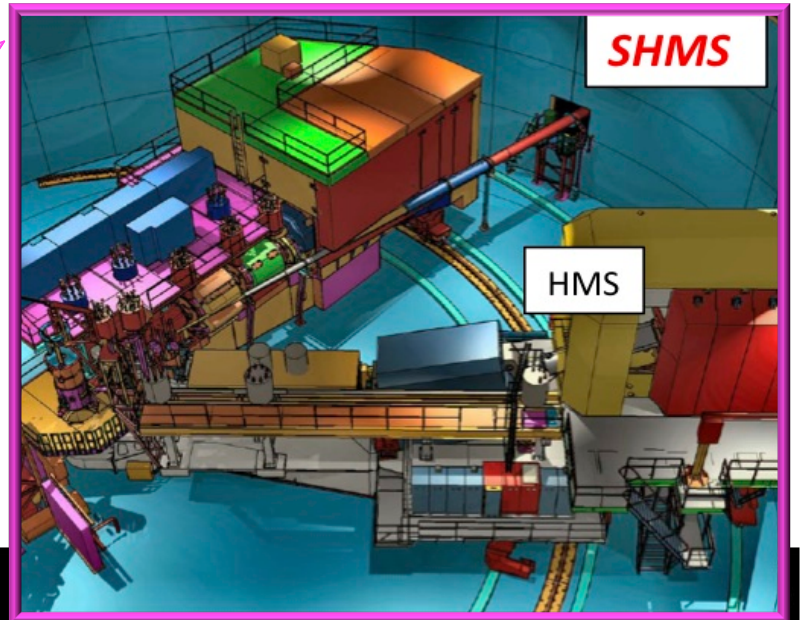


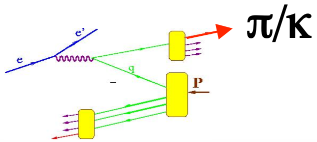


proposed
equipment

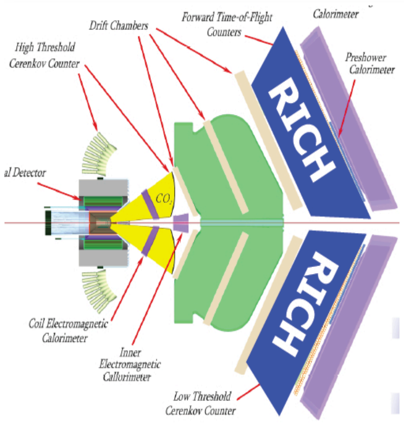
base equipment







SIDIS at JLab12



CLAS12

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-, K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+, K^-, K^0

C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

Proton

Quark spin polarization

Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C | Hall A

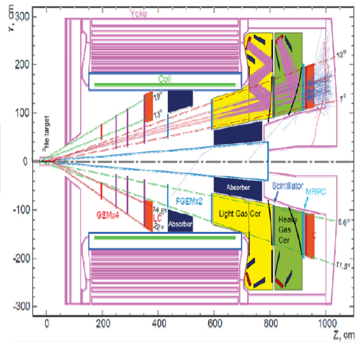
E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS SHMS

C12-11-108: π^+,π^-

Solid

H_2 | NH_3

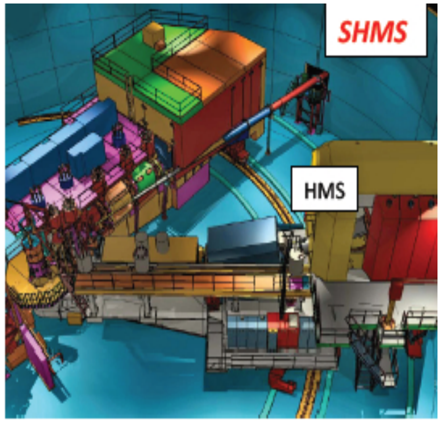


CLAS12

E09-008: π^+,π^-,π^0 K^+, K^-, K^0

E07-107: π^+,π^-,π^0
E09-009: K^+, K^-, K^0

D_2, ND_3



D_2

Quark spin polarization

Nucleon polarization

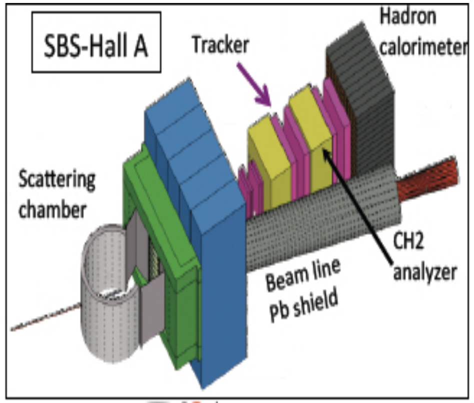
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS SHMS

D_2



^3He

Quark spin polarization

Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall A

E12-07-007: π^+, π^-

Solid

E10-006: π^+,π^-
E12-09-018: π^+,π^-, K^+,K^-

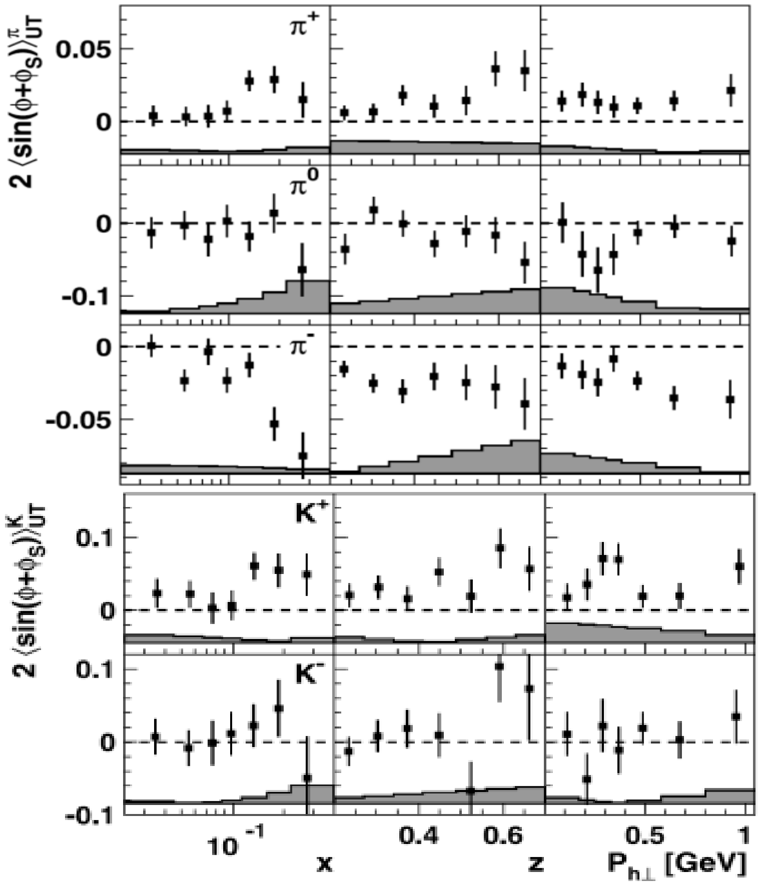
Solid

SBS

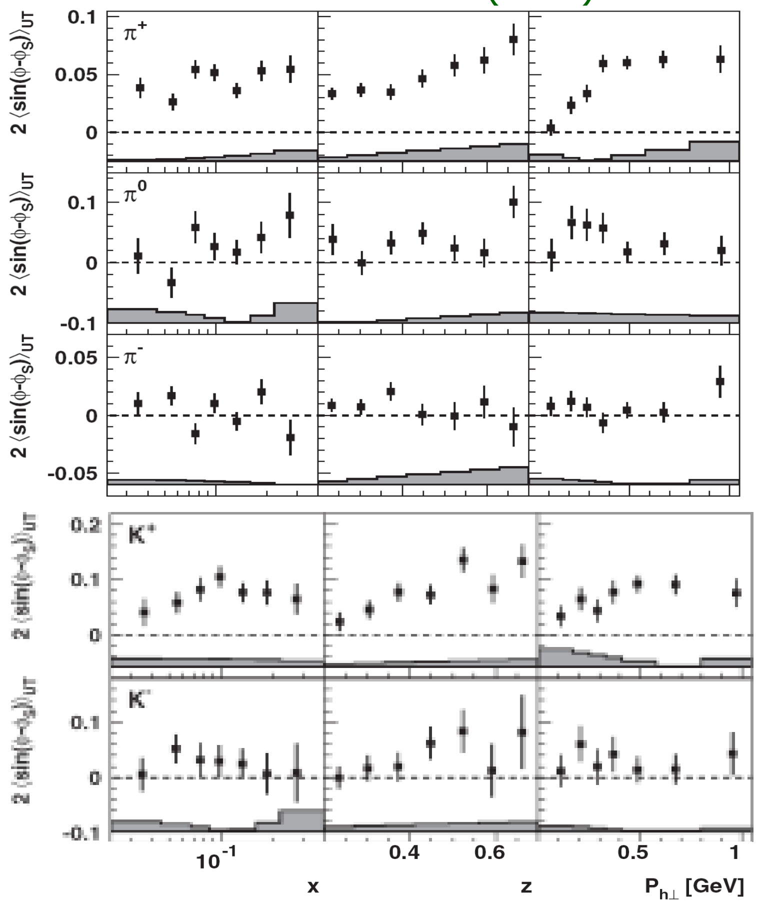
^{3}He

The Kaon puzzle

PLB 693 (2010) 11



PRL 103 (2009) 152002



- K^+ ampl. > π^+ ampl. Unespected from u-quark dominance
- role of s quarks?

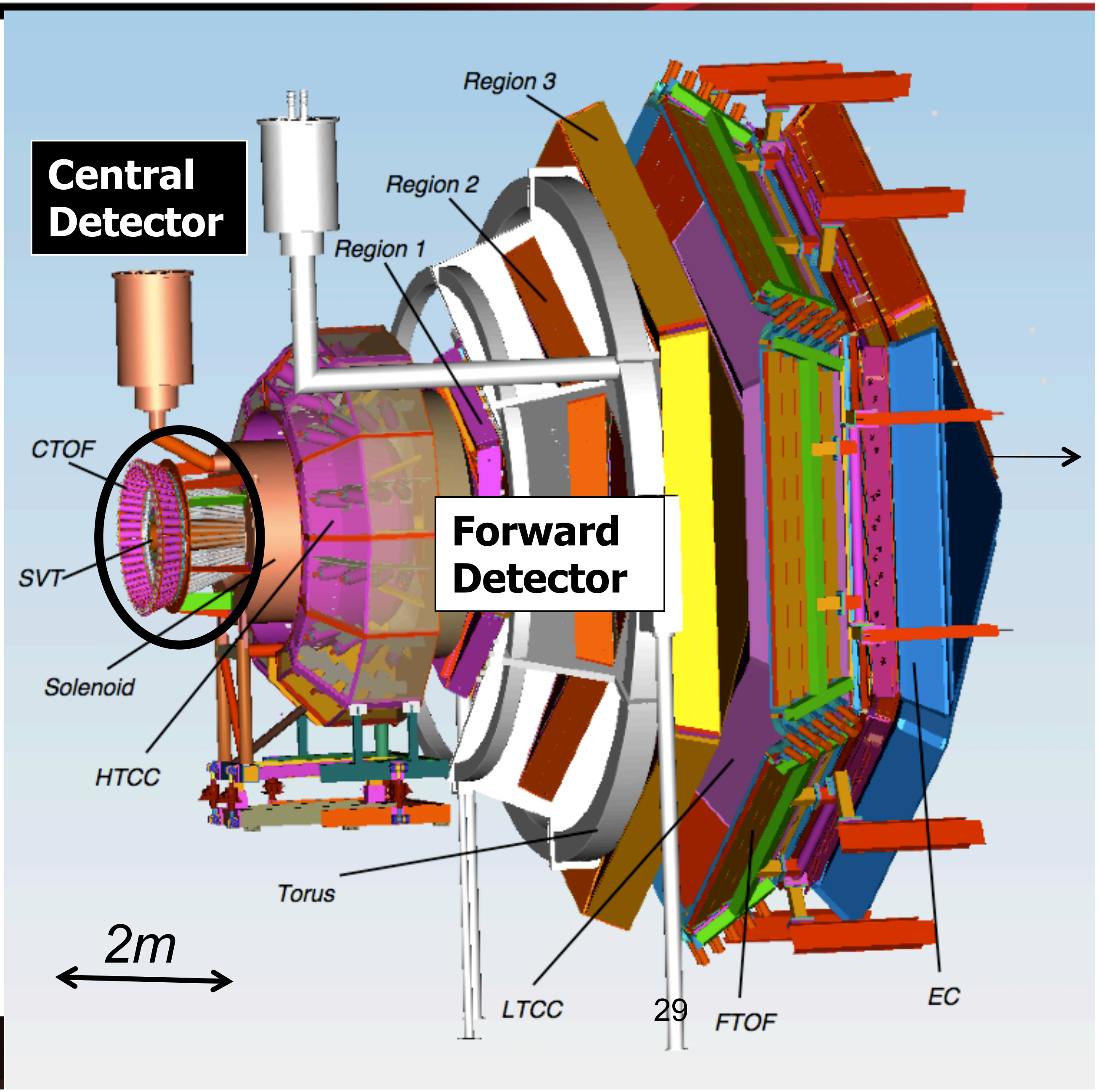
Flavour separation needs good PID: RICH detector for CLAS12

CLAS12

Cebaf
Large
Angle
Spectrometer

for fixed target electron scattering experiments

Polarized beam



broad kinematical range

$5° < \theta < 140°$

high luminosity

$L = 10^{35}$

H, D and nuclear targets

Cherenkov Detector

Threshold: $$\beta_{\mathrm{thres}} = \frac{V_{\mathrm{thres}}}{c} = \frac{1}{n}$$

Two cases:

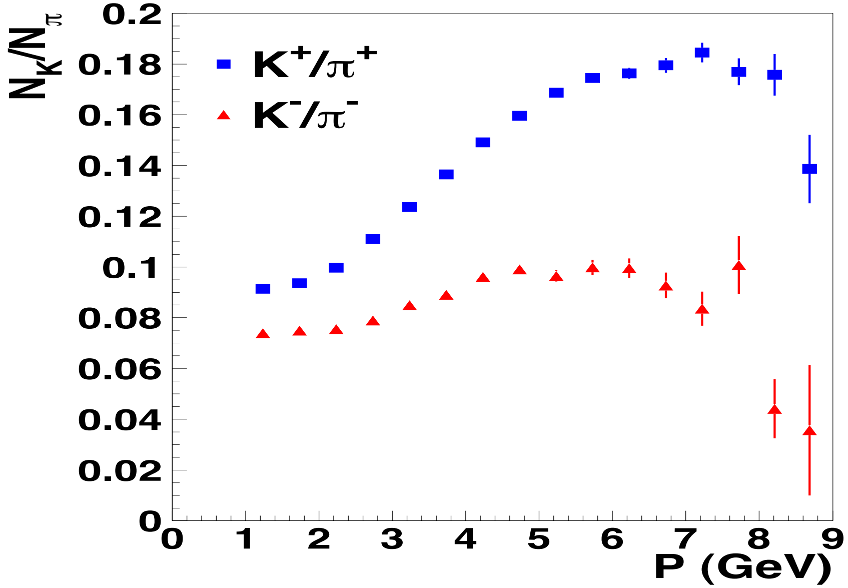
$\beta < \beta_t$: no Cherenkov light is emitted

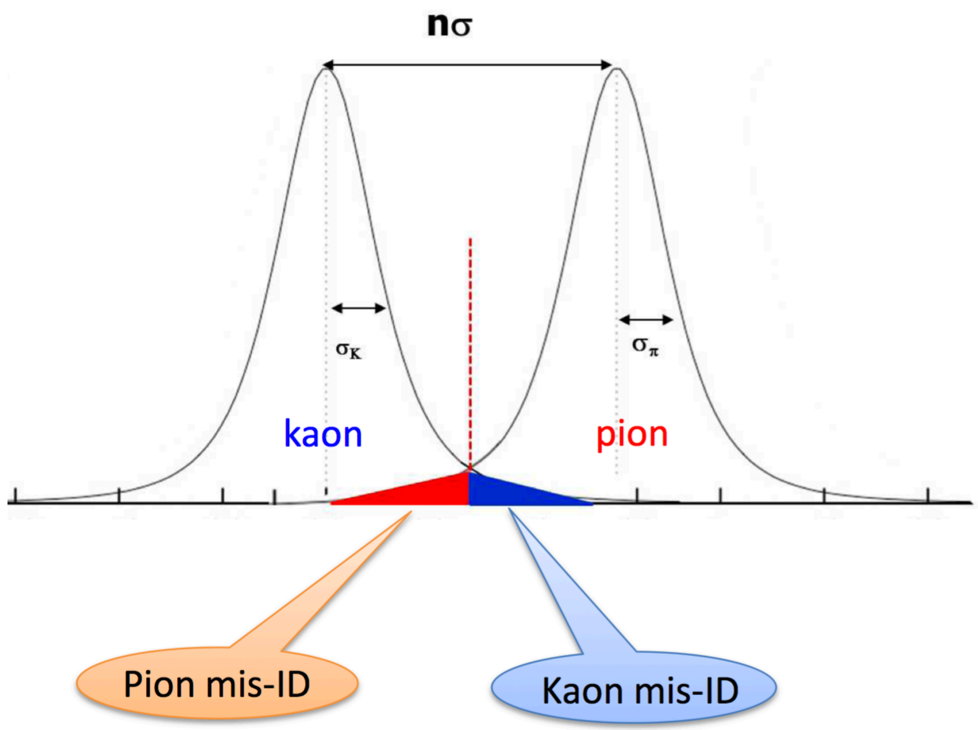
$\beta > \beta_t$: Cherenkov light is emitted

- Threshold Cherenkov detectors make a yes/no decision based on wether the particle is above or below the threshold velocity β_t = 1/n
- It is important to detect only the total NUMBER of Cherenkov photons

	P_π (GeV/c)	p_K(GeV/c)	P_p (GeV/c)
LTCC C_4F_{10} n=1.00153	2,52	8,92	16,94
HTCC CO_2 n=1.00041	4,87	17,23	32,76

SIDIS Kinematics for π & k





A pion rejection factor of 1:500 for a 90% kaon efficiency corresponds to a 4σ separation in the angular Cherenkov distributions

RICH Detector

- The more powerful use of Cherenkov radiation comes from measuring the ring-correlated angle of emission of Cherenkov photons in a **Ring Imaging Cherenkov Counter (RICH)**

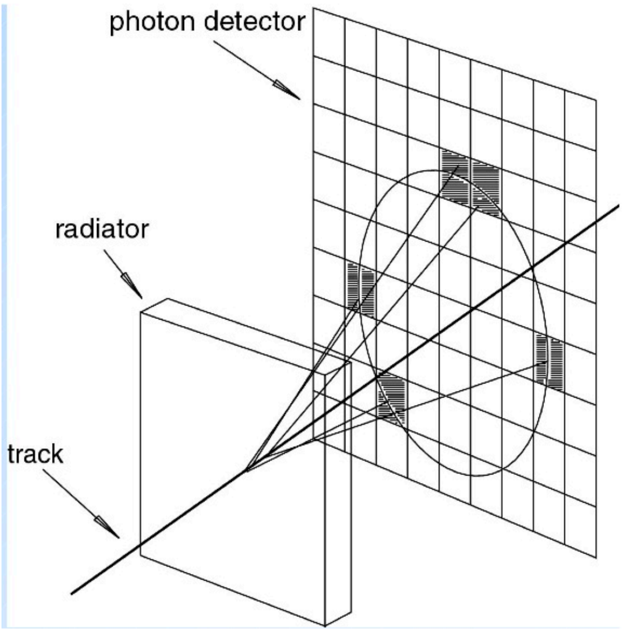
Light emission angle: $\cos\theta_C = \frac{1}{\beta n}$

Idea: transform the direction into a coordinate

→ ring on the detection plane

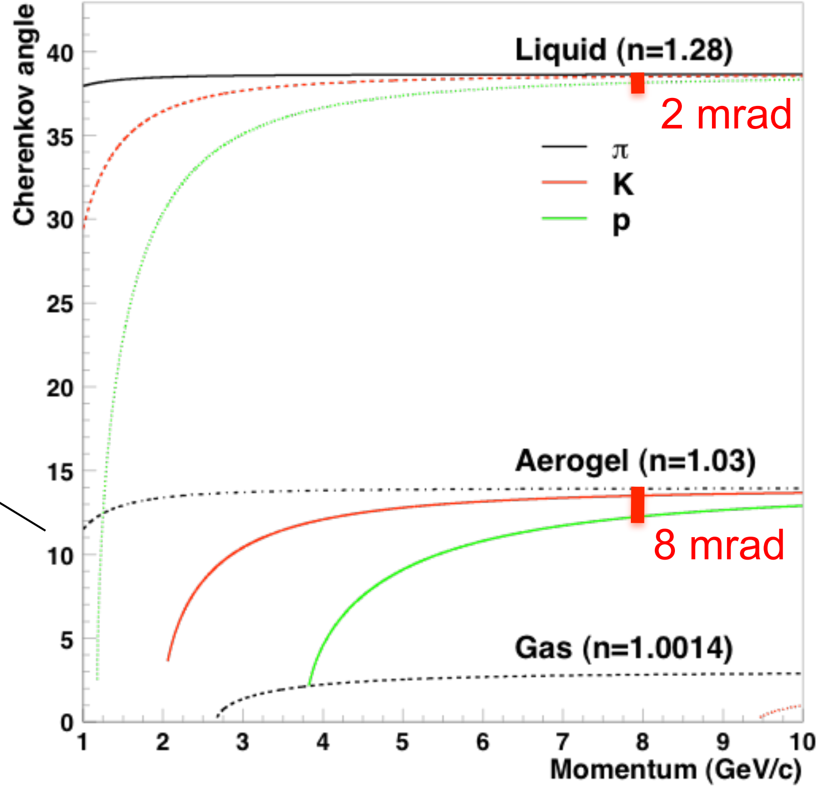
→ Ring Imaging Cherenkov

- It is important not only to detect the total NUMBER of Cherenkov photons but also the POSITION and DIRECTION of the impact point of each photon on the detector surface with high resolution



Radiator

- Aerogel mandatory to separate hadrons in the 3-8 GeV/c momentum range with the required large rejection factors
  - Collection of visible Cherenkov light
  - Use of PMTs
- Challenging project, need to minimize detector area covered with expensive photodetectors



•Solid, very light and transparent material consisting essentially of silica (SiO2)

•Very low density (0.003-0.35 g/cm^3) typically ~ 0.1 g/cm^3)
•→ n (refr. index) close to unity

- Early 1980s first application to particle physics

Errors on β

Error on the particle velocity β measured with a RICH

$$\frac{\sigma_\beta}{\beta} = \frac{\tan\theta_c}{\sqrt{N_\gamma^{det}}}\sigma_\theta$$

Depends on:

- Number of detected photons
- Error on the Cherenkov angle of the emitted photons σ_ϑ

$$\sigma_\theta = \sqrt{\Delta\theta_e^2 + \Delta\theta_c^2 + \Delta\theta_p^2}$$

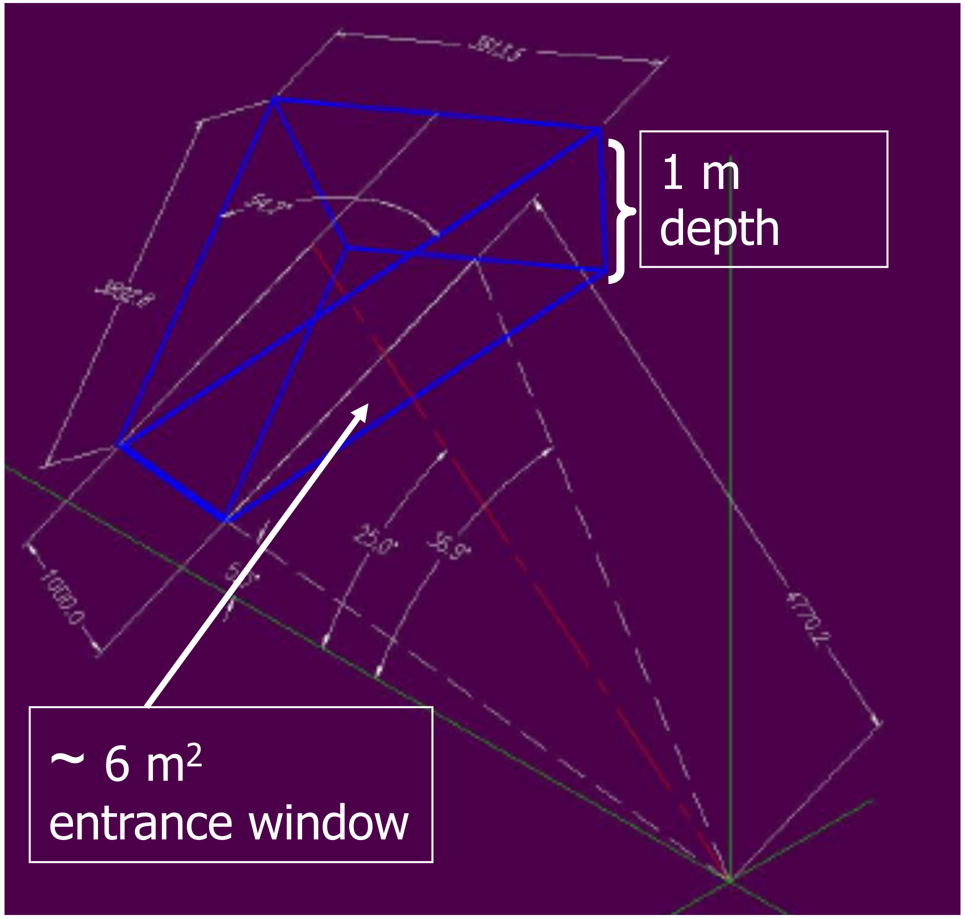
Emission point uncertainty

Chromatic error
Dispersion: $1/\beta = n(\lambda)\cos\theta$

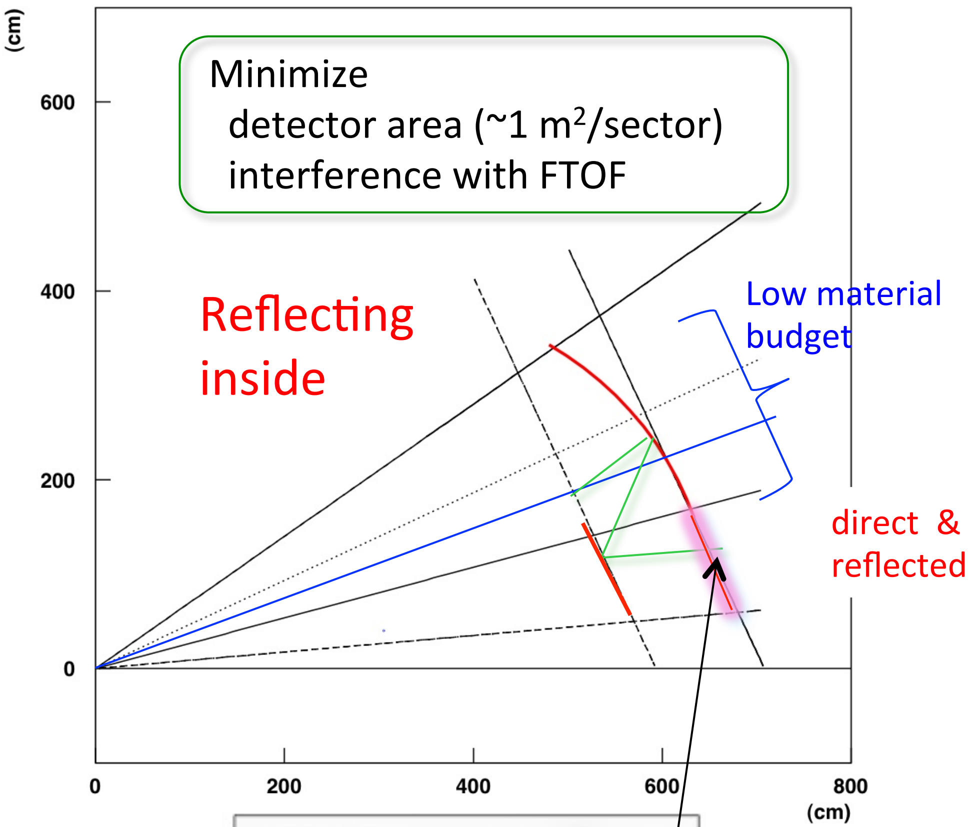
Photon impact point resolution (~photon detector granularity)

The main parameters

- Radiator thickness
  - Larger the thickness, higher the number of photons, higher the uncertainties on photon emission
- Gap length
  - Larger the gap, better the ‘focusing’, but larger must be the detection plane
- Pad size
  - Smaller the pad size smaller the uncertainties on photon detection but higher the number of photon detectors



The focusing Mirror System

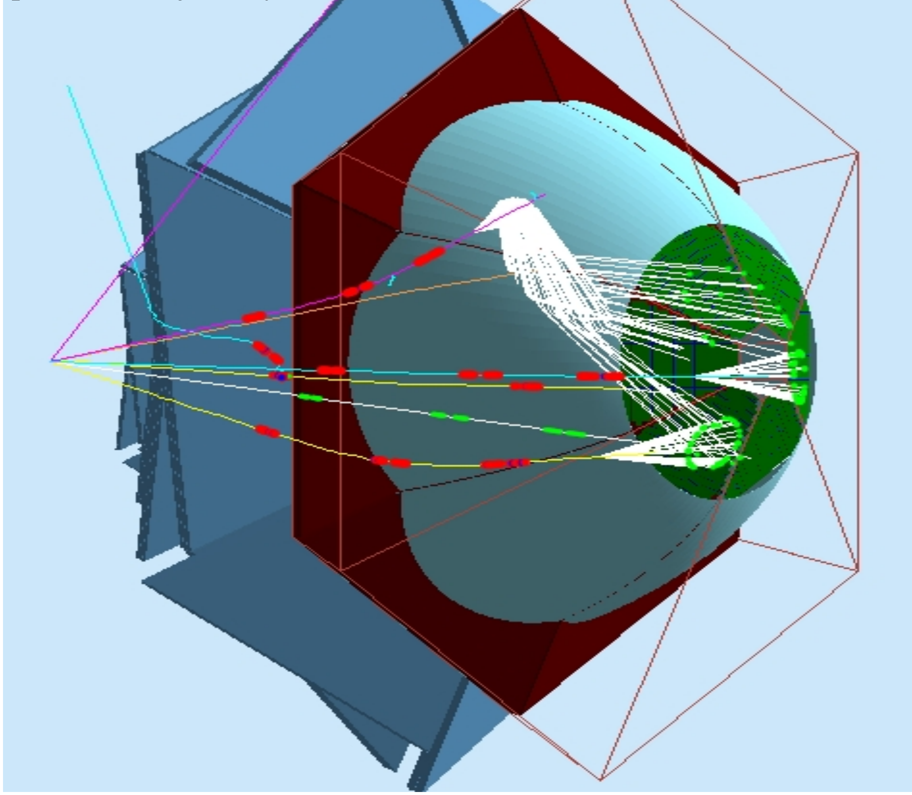


Hamamatsu- H8500

52x52x28 (mm³)

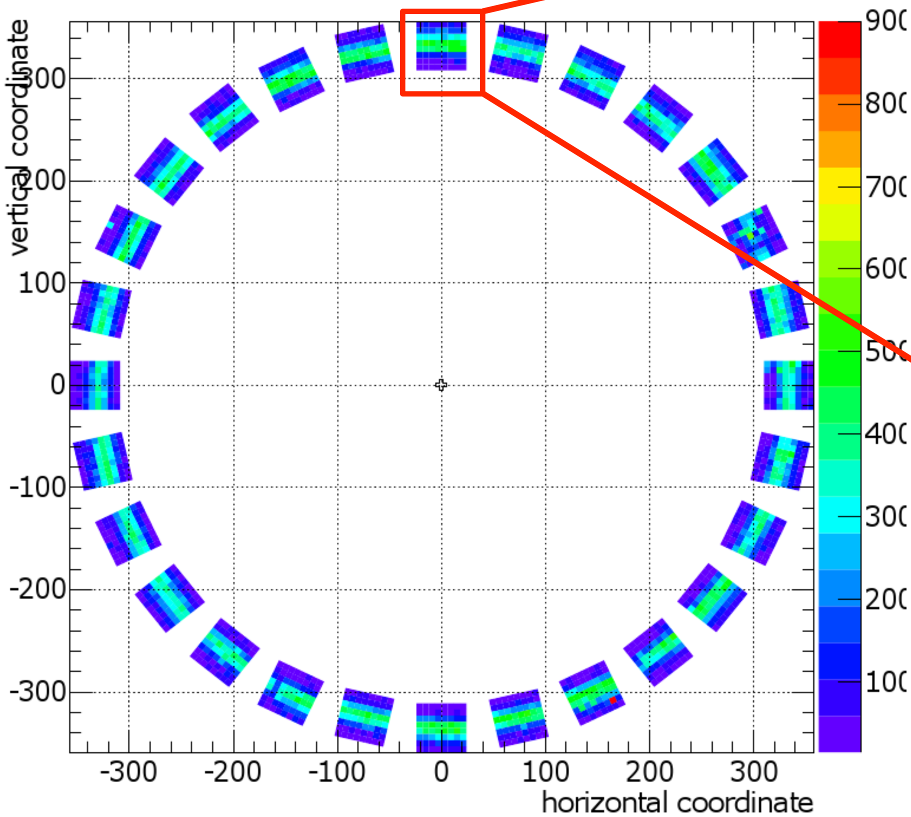
Left: H8500, Right: H8500B

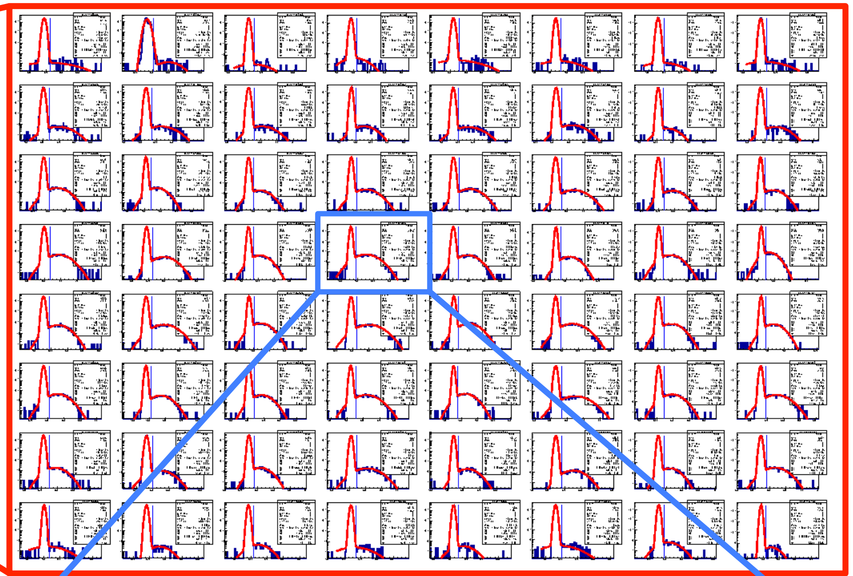
- spherical (elliptical) mirror within gap volume for backward refl.
- plane mirror just beyond radiator for forward reflections

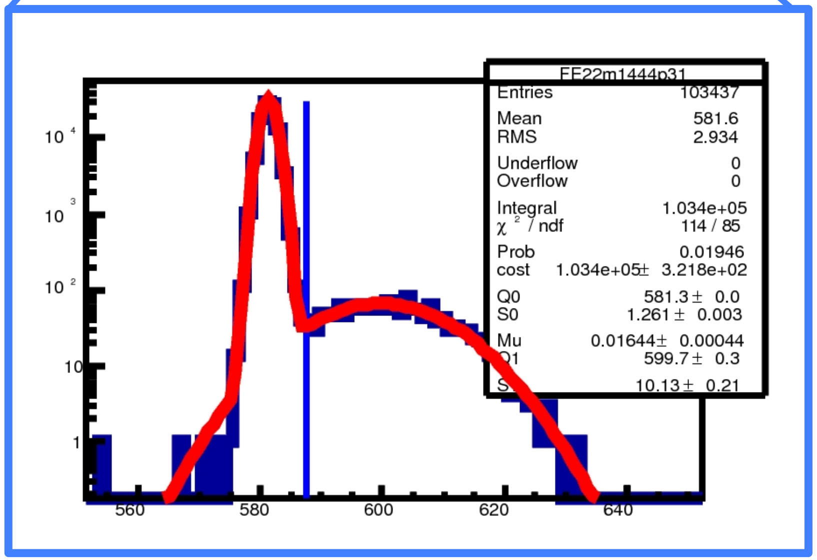


Cherenkov Ring

On-line event display



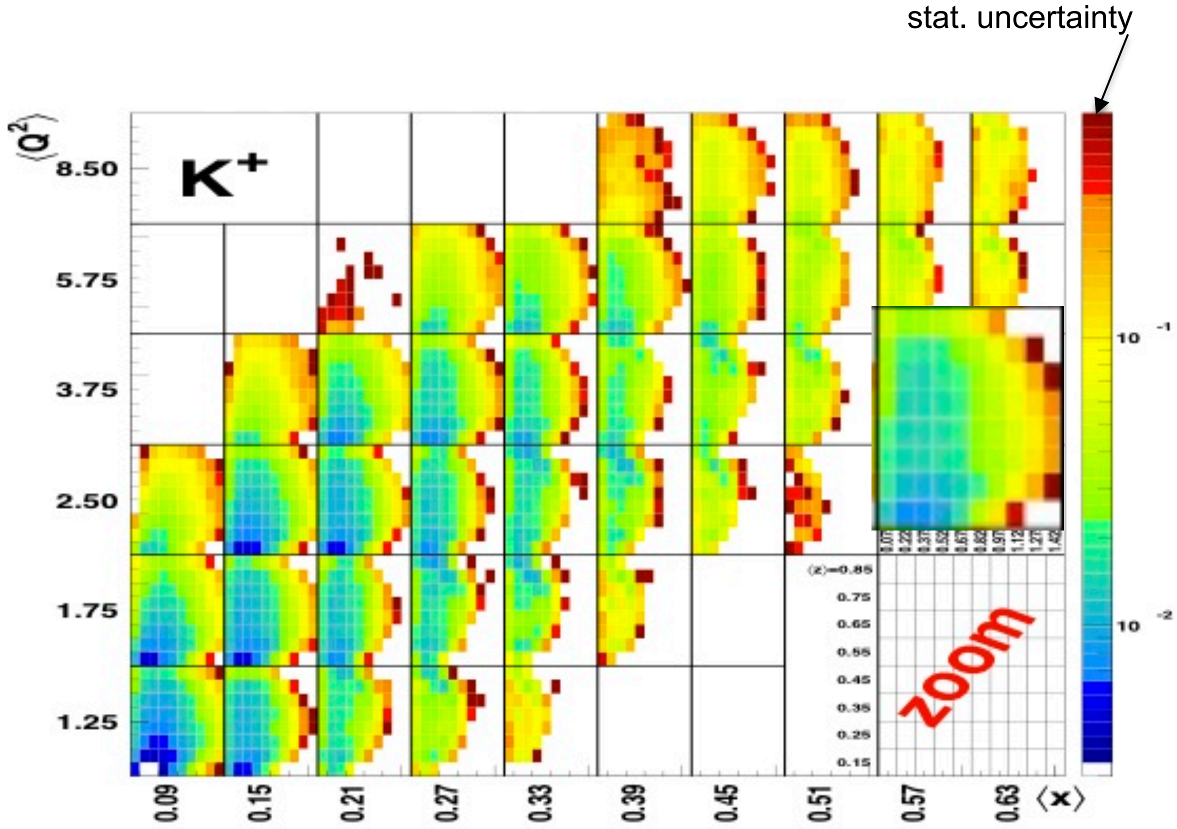




Cherenkov ring measured with the RICH prototype

37

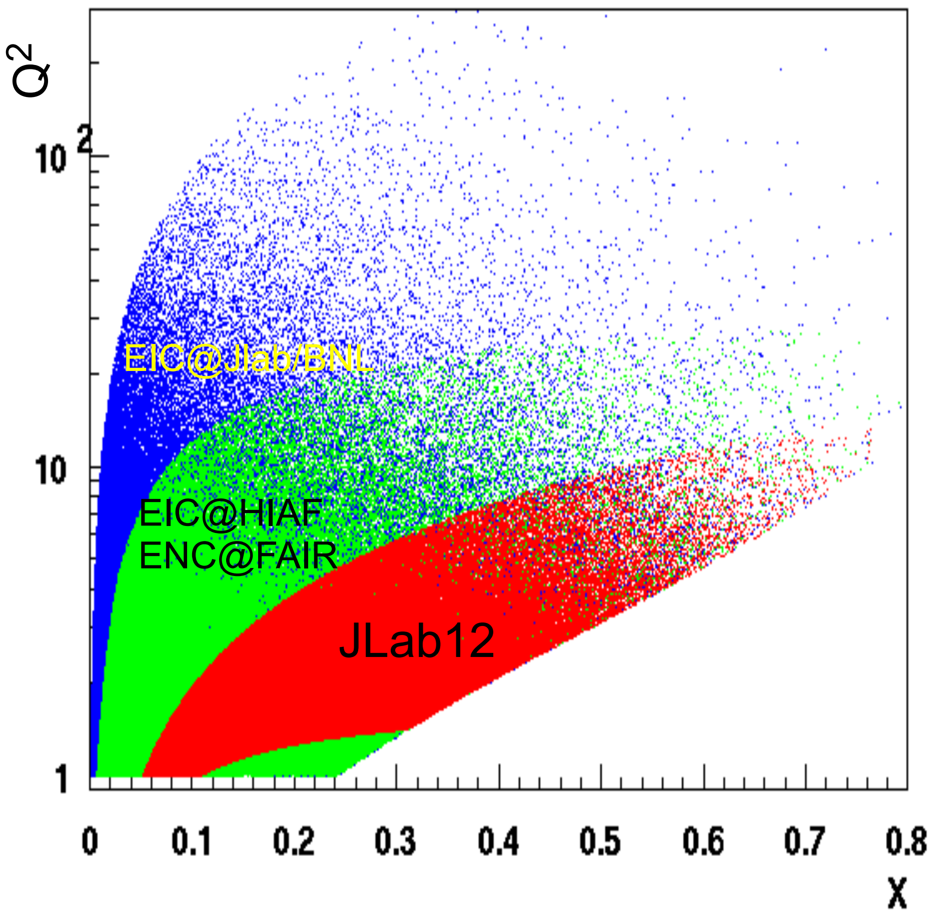
CLAS12: $h_{1L}^{\perp} \otimes H_1^{\perp}$ for kaons



CLAS12+RICH
E_e = 11GeV
Target: Long. Pol. NH3
(P=85%)

CLAS12+RICH experiment, providing multidimensional binning to study SSAs , can shed light on the "kaon puzzle" and in general on the structure of the nucleon

From JLab12 to EIC

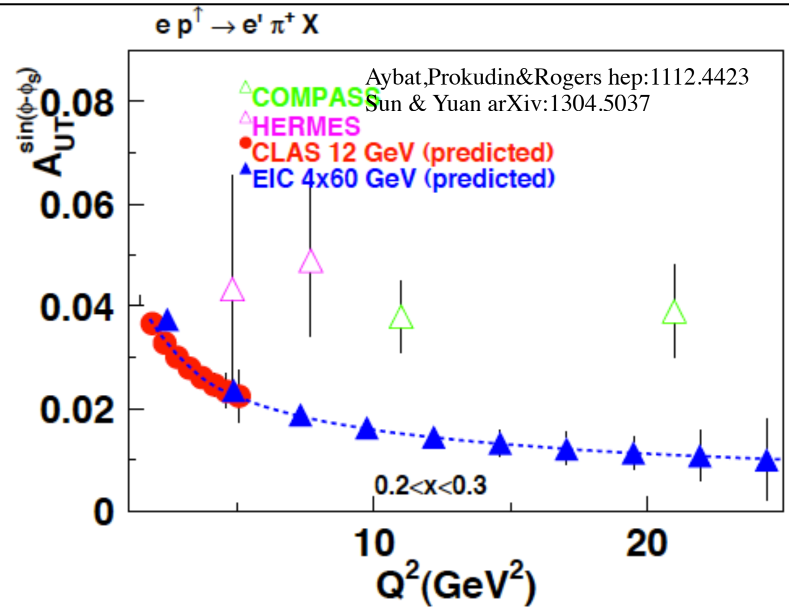


JLab@12GeV (25/50/75)

→ $0.1<x_B<0.7$: valence quarks

EIC $\sqrt{s}$ = 140, 50, 15 GeV

→ $10^{-4}<x_B<0.3$: gluons and quarks, higher P_T and Q^2.

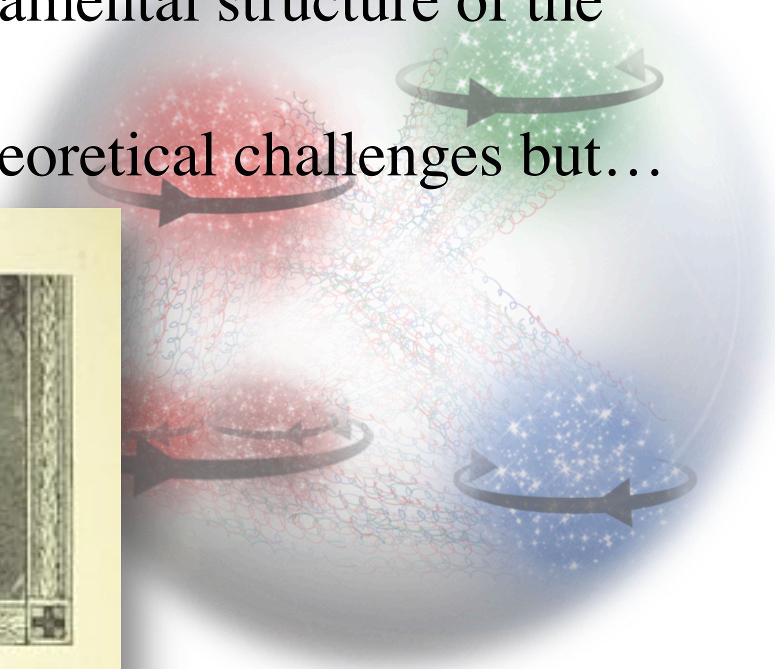


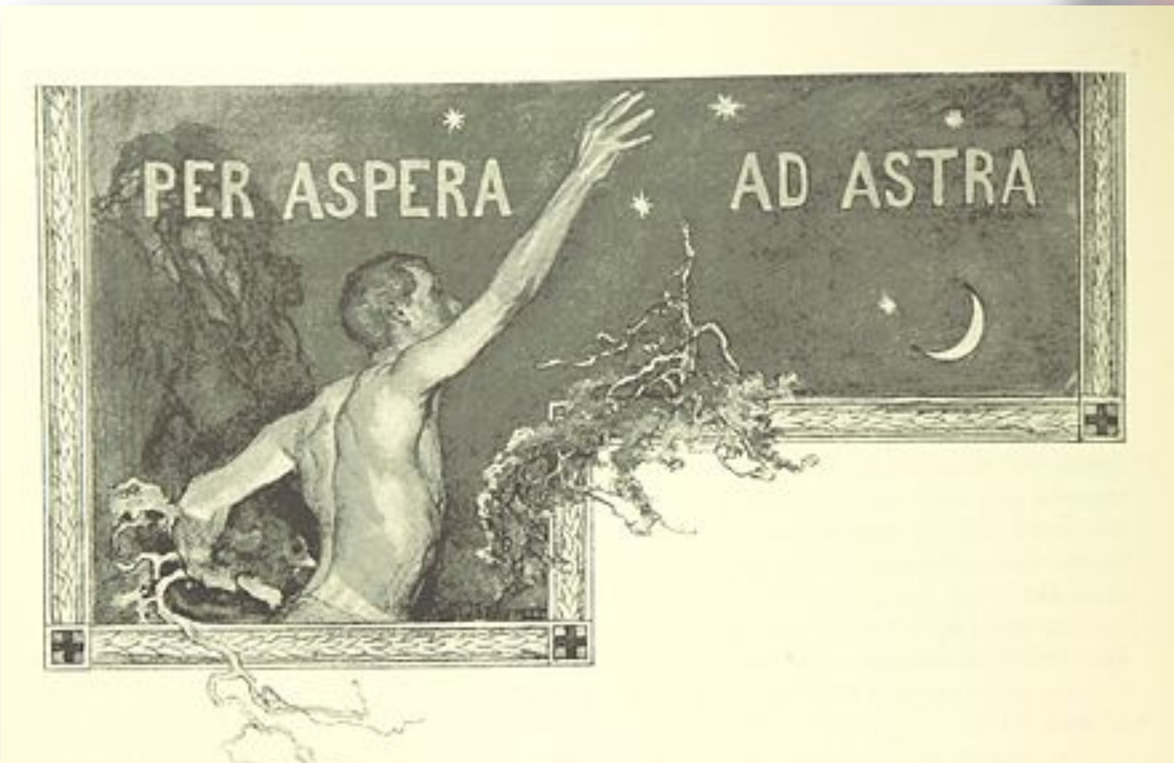
- Study of high **x** domain requires high luminosity, low **x** higher energies
- Wide range in Q^2 is crucial to study the evolution
- Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

Conclusions

Transverse Momentum Dependent parton distribution functions **open new avenues** to understanding the fundamental structure of the nucleon.

They present many experimental and theoretical challenges but…





through hardships to the stars