12 GeV Upgrade
Future Science at Jefferson Lab

SoLID SIDIS Program

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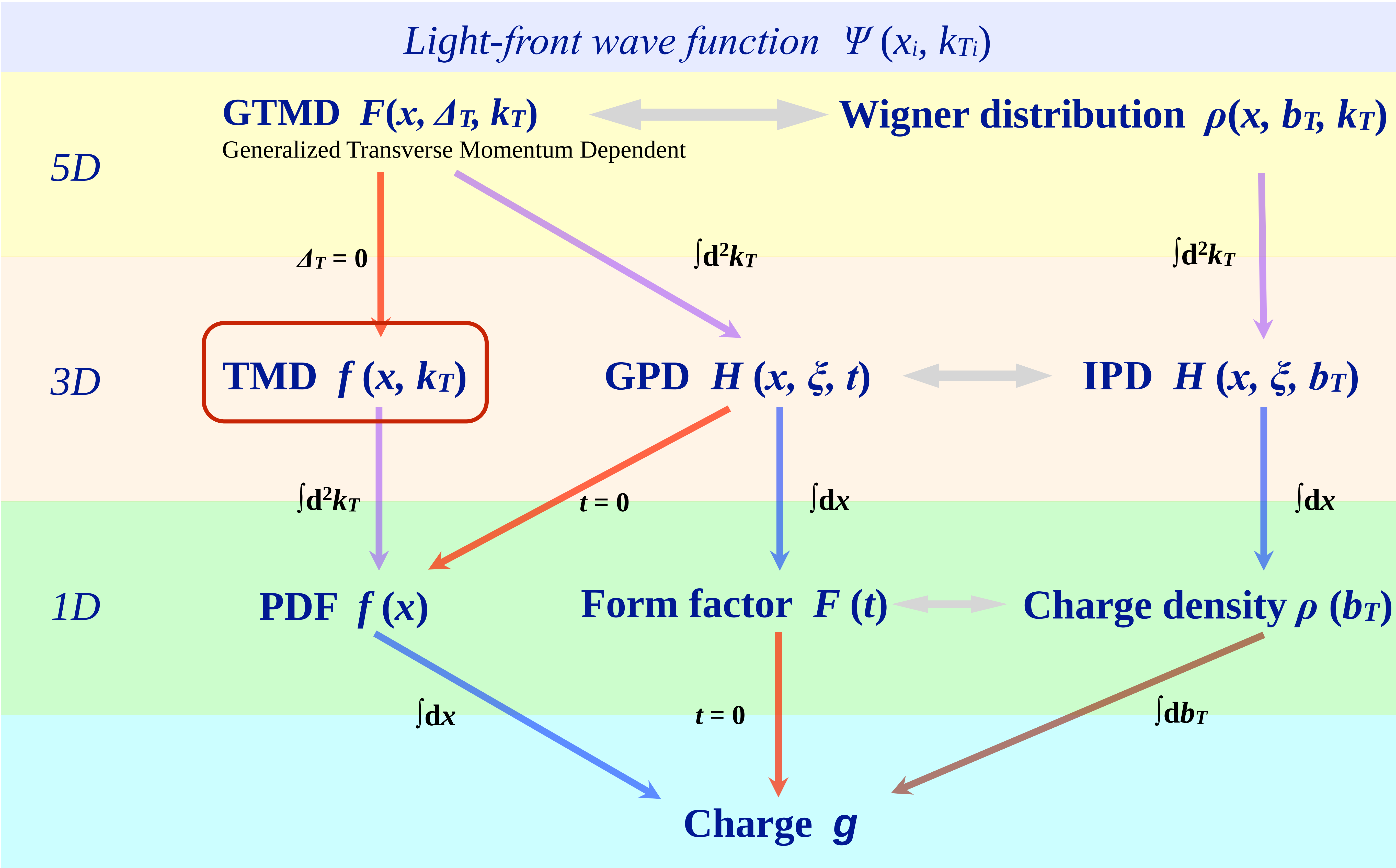
EXPLORING THE NATURE OF MATTER

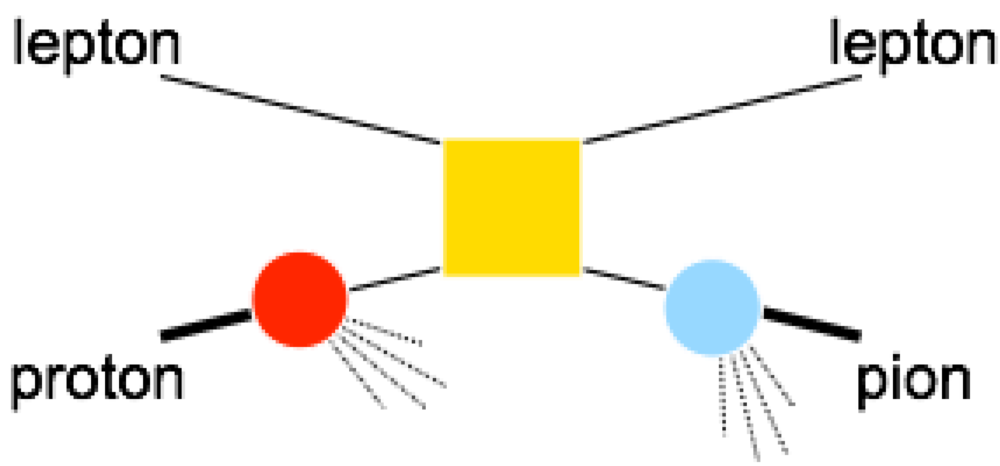
Unified View of Nucleon Structure



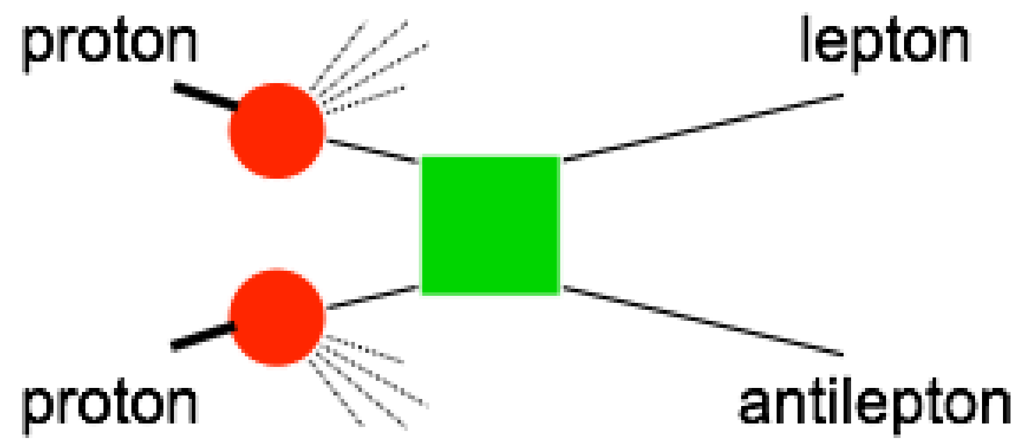
Leading Twist TMDs

		Quark Polarization		
		U	L	T
Nucleon Polarization	U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity (worm-gear)
	T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^\perp$ pretzelosity

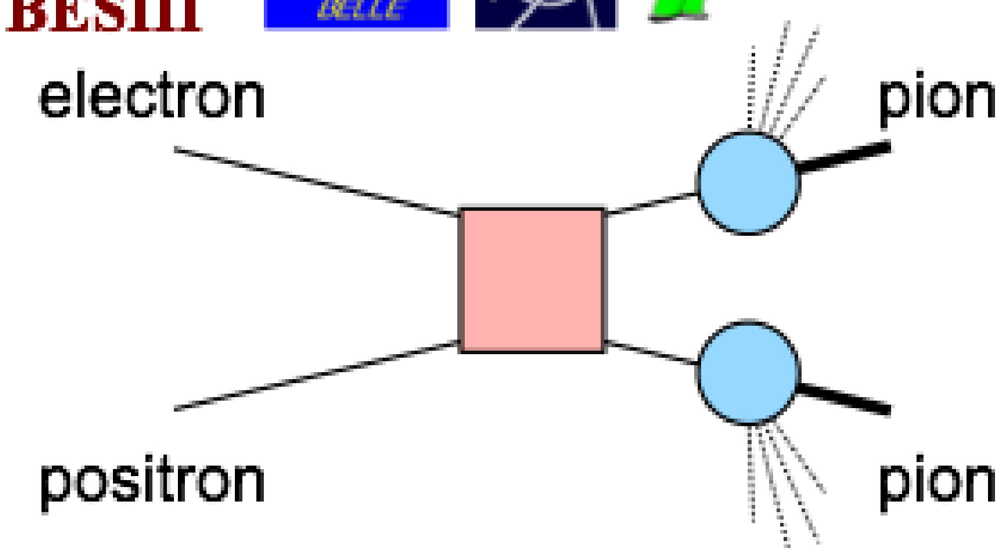
Access TMDs through Hard Processes



SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions

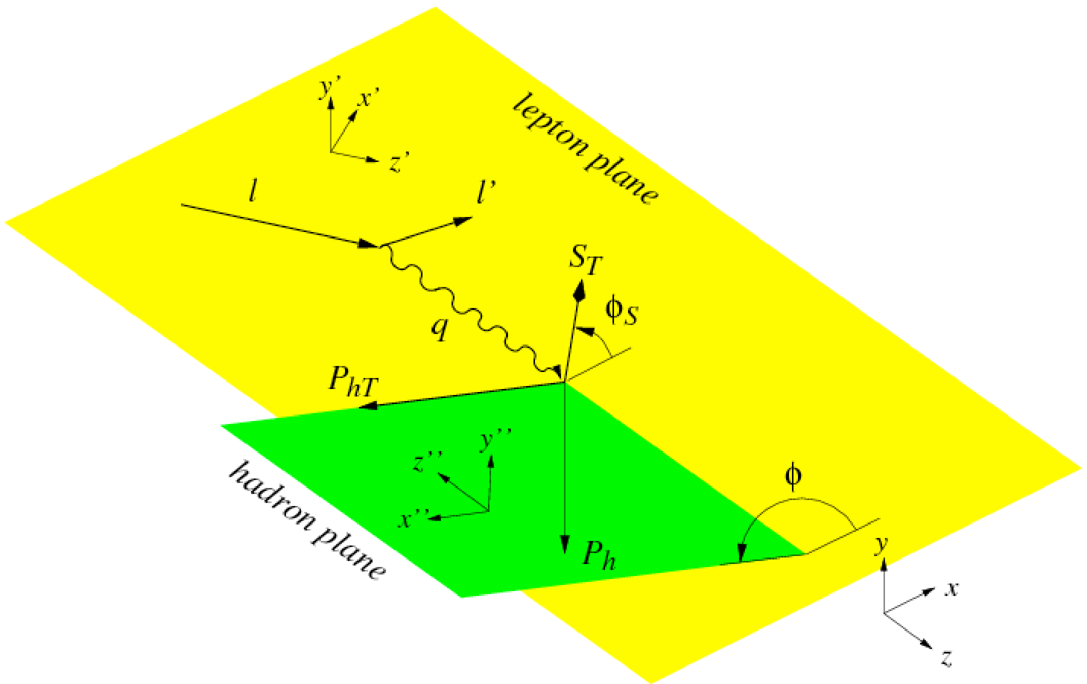
Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

SIDIS Process

SIDIS differential cross section



[Diehl&Sapeta EPJC2005]

18 structure functions $F(x, z, Q^2, P_T)$,
model independent. (one photon exchange approximation)

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} \\
&= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
&\times\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h \\
&+ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\Big] + \lambda_e S_L\Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\Big] \\
&+ S_T\Big[\big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
&\qquad + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big] \\
&+ \lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
&\qquad + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}
\end{aligned}
$$

In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs and Fragmentation functions.

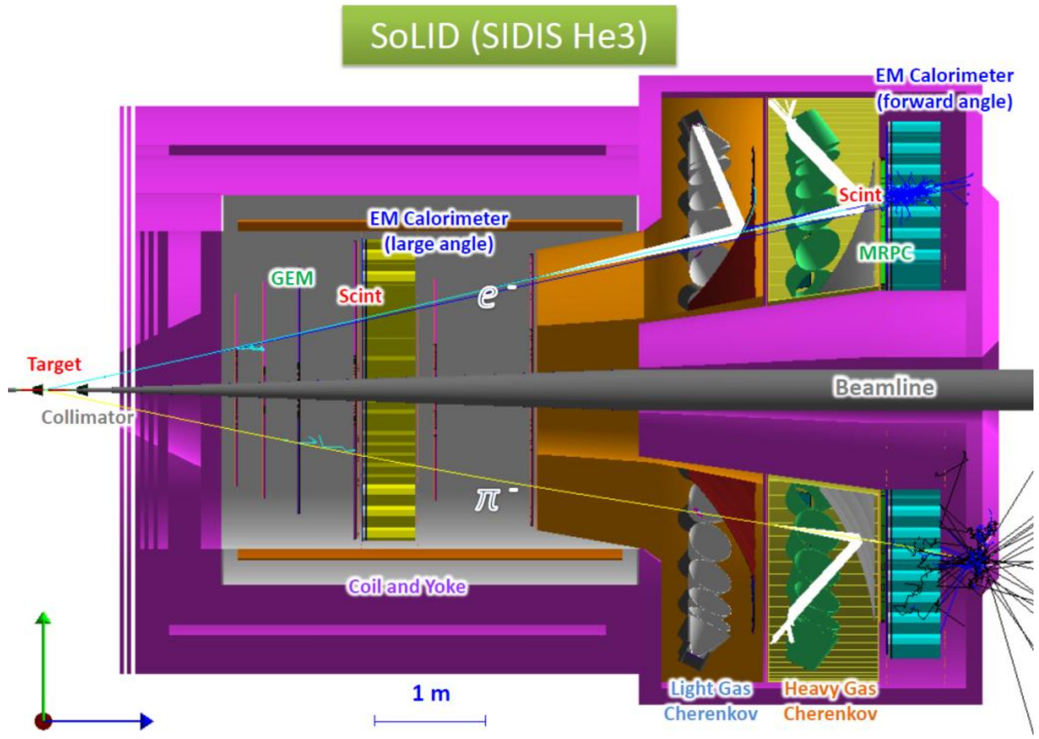
SIDIS Program at SoLID

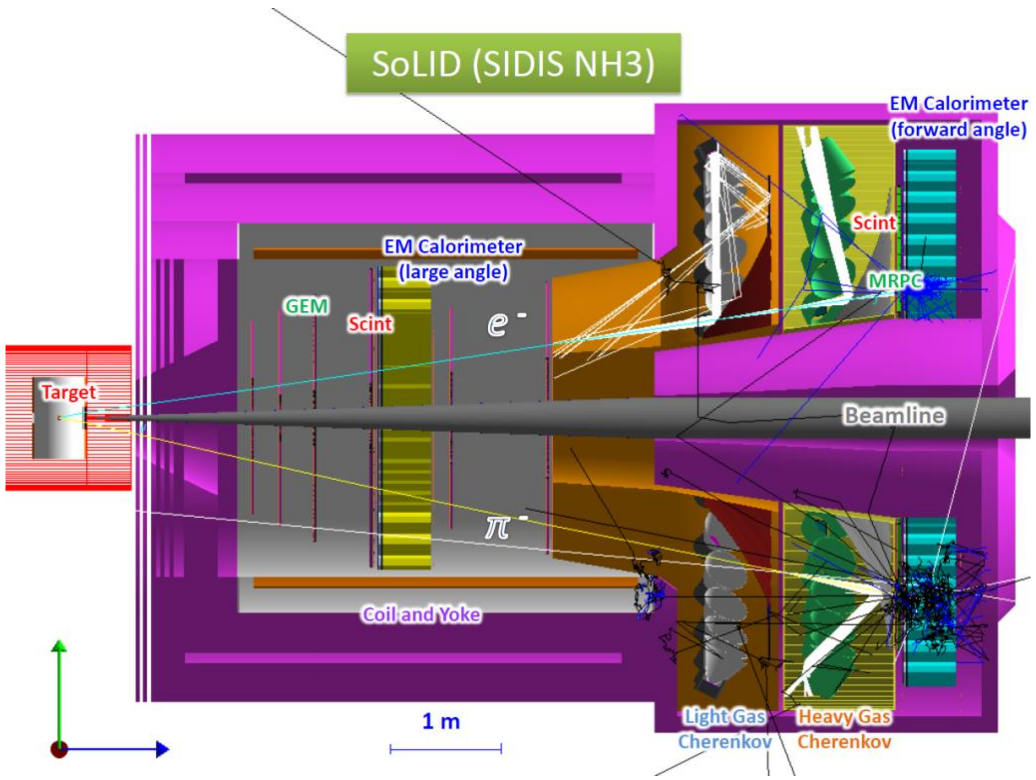
Key feature: large acceptance and high luminosity enable wide coverage in all 4 kinematic bins with well controlled systematics

- E12-10-006: Single Spin Asymmetry on transversely polarized ^{3}He, 90 days, **rated A**
- E12-11-007: Single and Double Spin Asymmetries on longitudinally polarized ^{3}He, 35 days, **rated A**

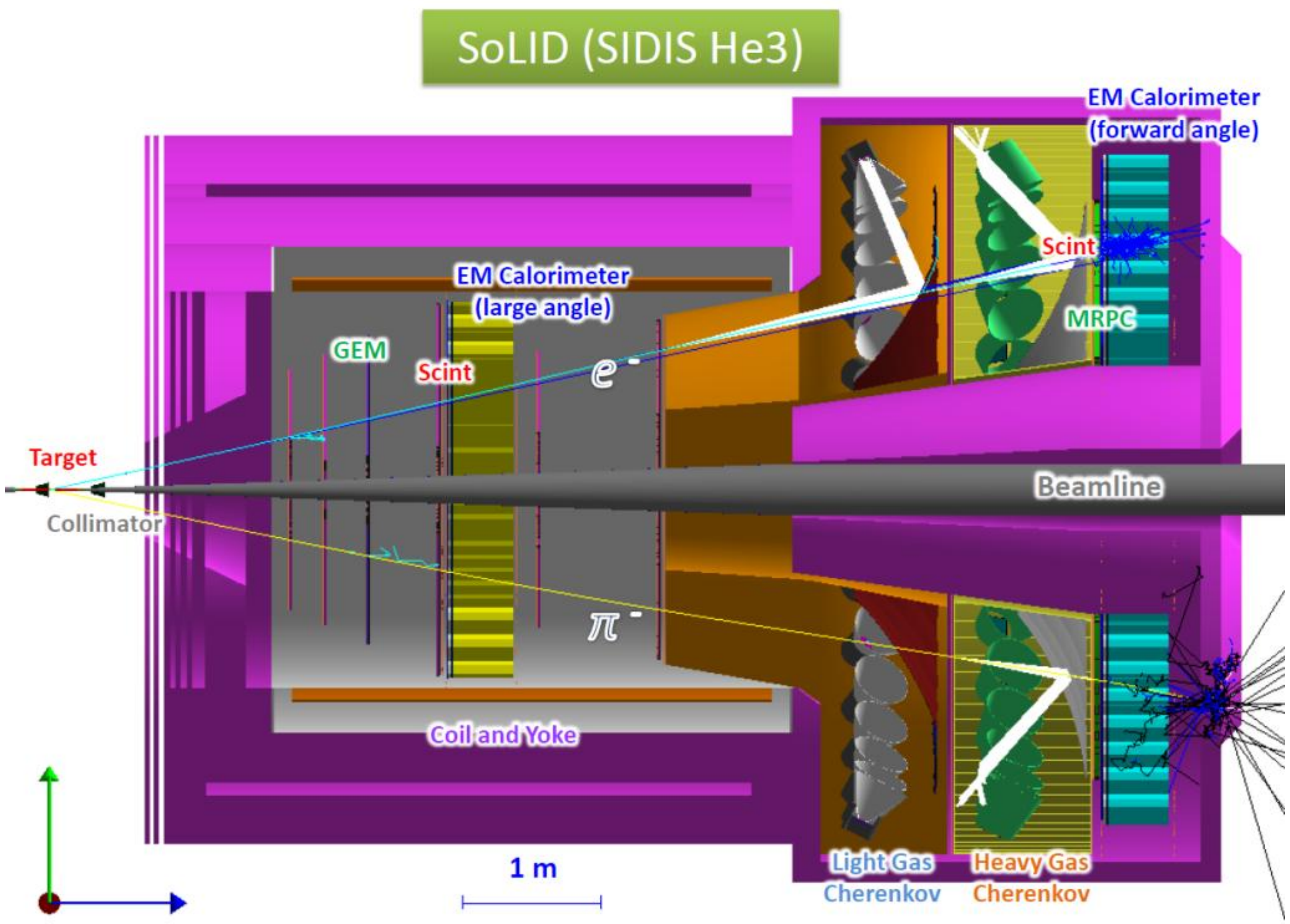
- run group
  - Dihadron process
  - Ay inclusive

- E12-10-008: Single Spin Asymmetry on transversely polarized proton (NH_3), 120 days, **rated A**



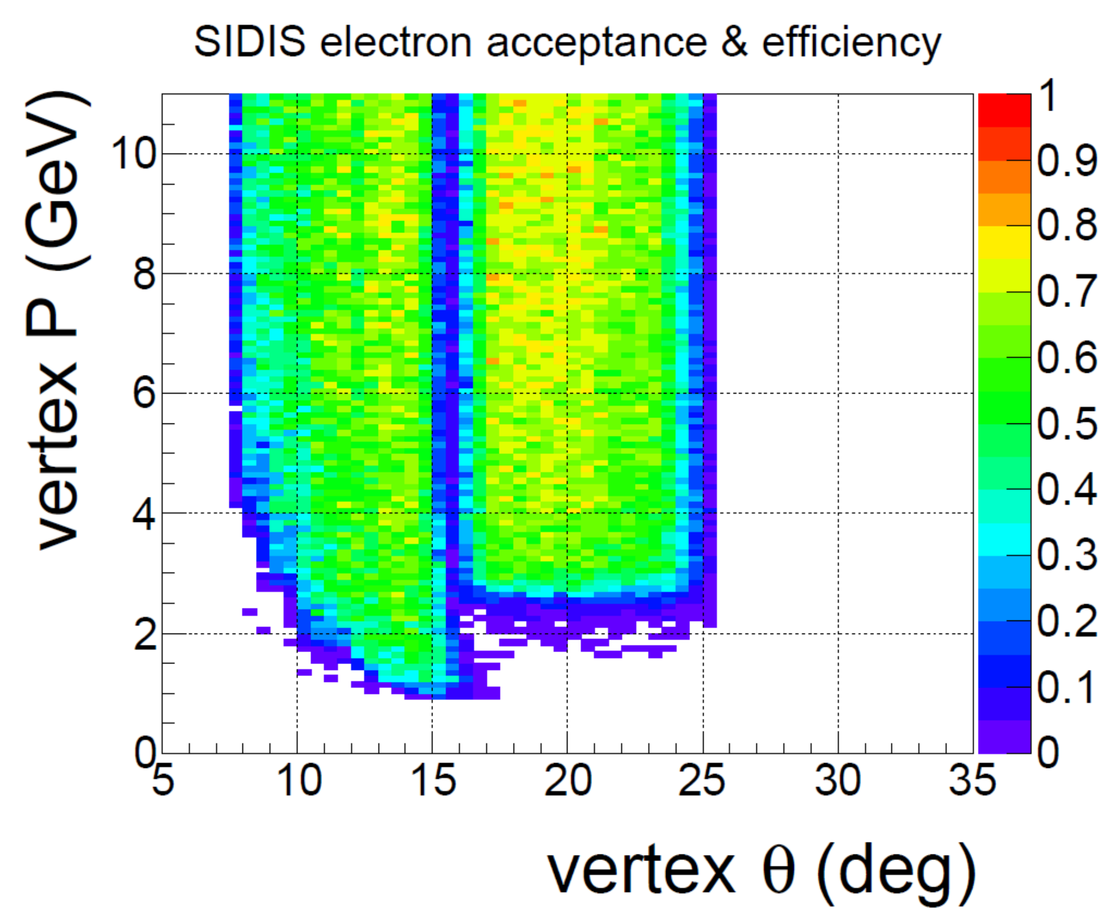


SoLID He3 Setup



Detection

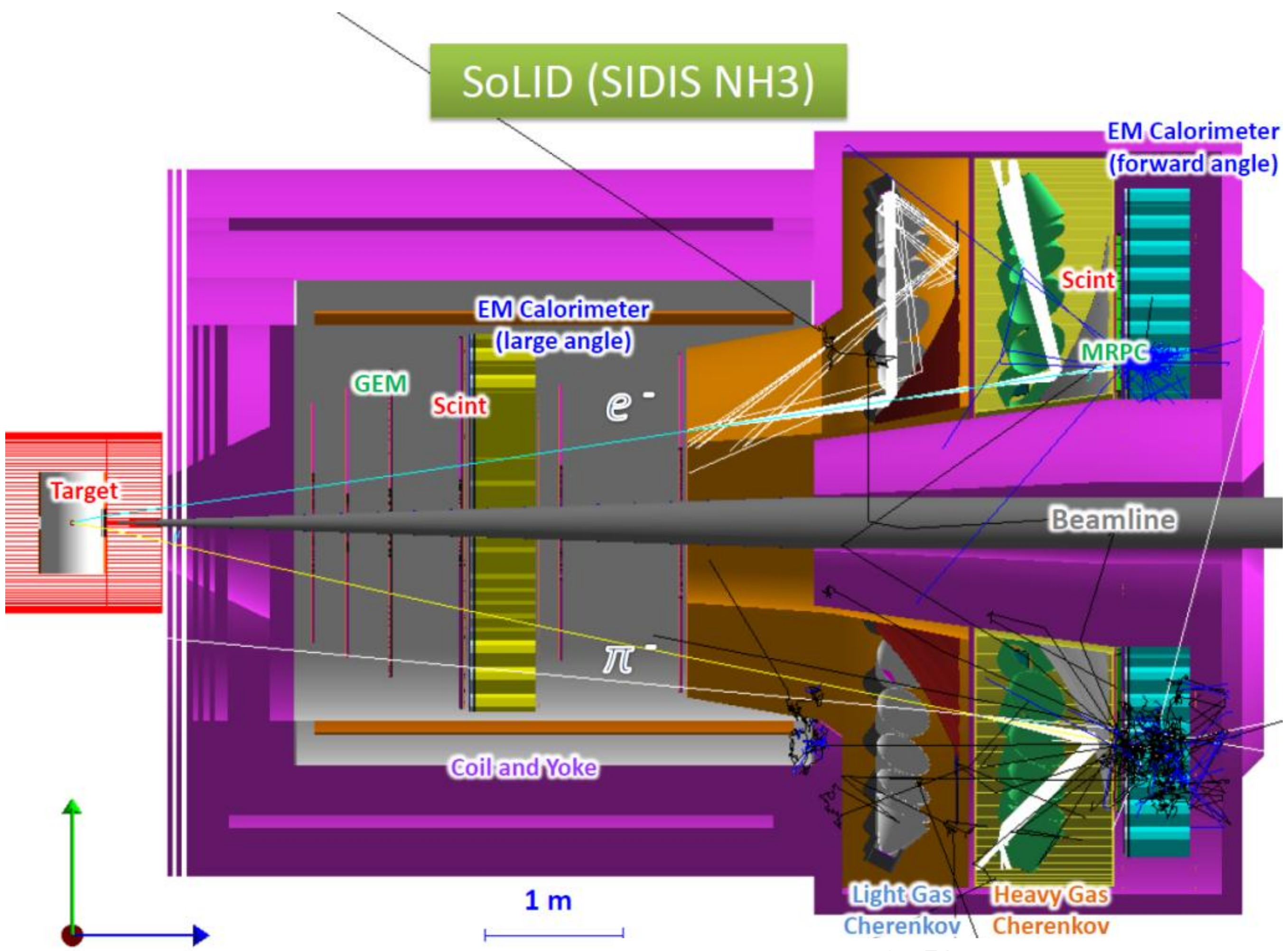
- e- at forward angle with EC and Cerenkov to reject pions
- e- above 3GeV detected at large angle with EC to reject pions
- pions detected at forward angle with TOF and Cerenkov to suppress kaons
- GEM for tracking and Scintillator for photon rejection, MRPC and Scintillator for TOF



Coverage

- Polar angle: e^- 8-24 deg, π^-/π^+ 8-15deg
- Azimuthal angle: full
- Mom: 1-7GeV

SoLID NH3 Setup

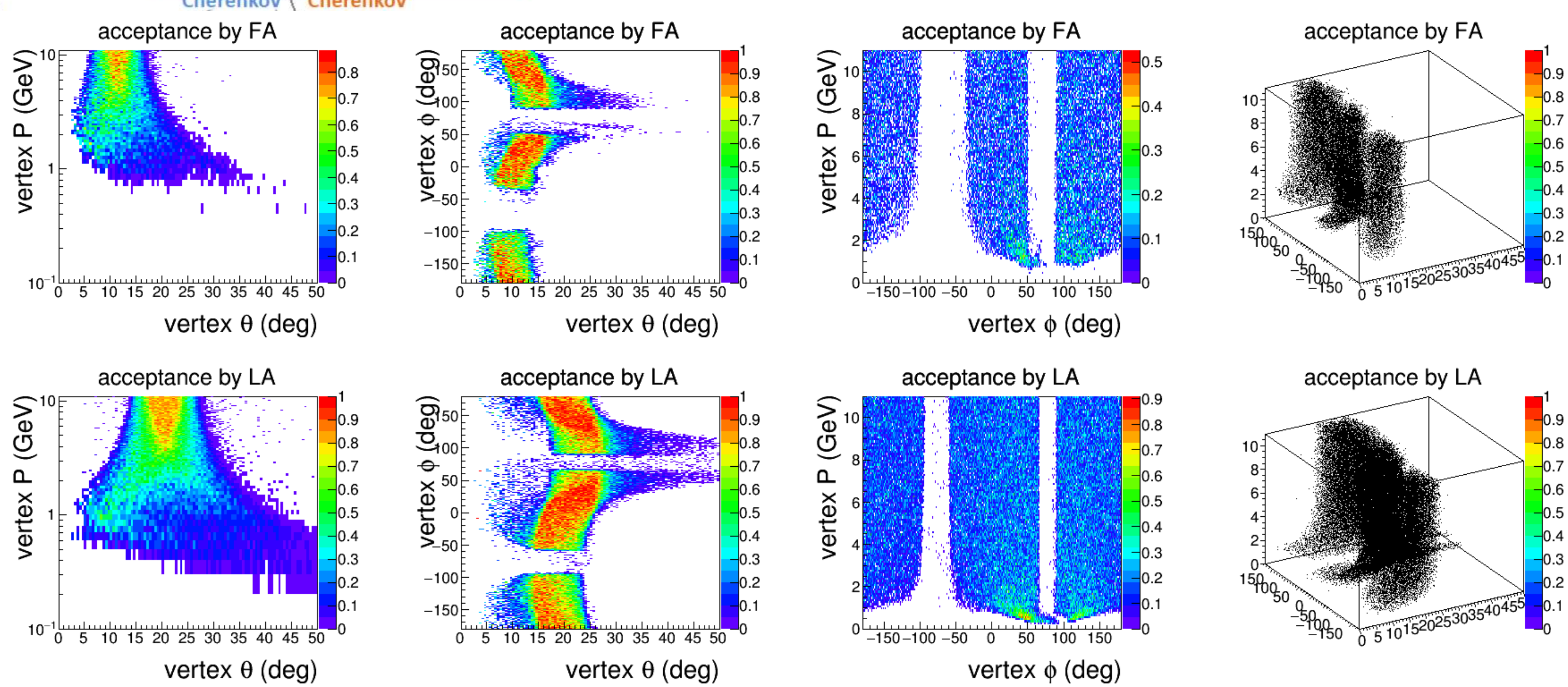


Detection is similar to He3 setup

Coverage is similar to He3 setup except some distortion from the target field

5T transverse target field
strong effect on acceptance
High radiation sheet of flame areas are cut away

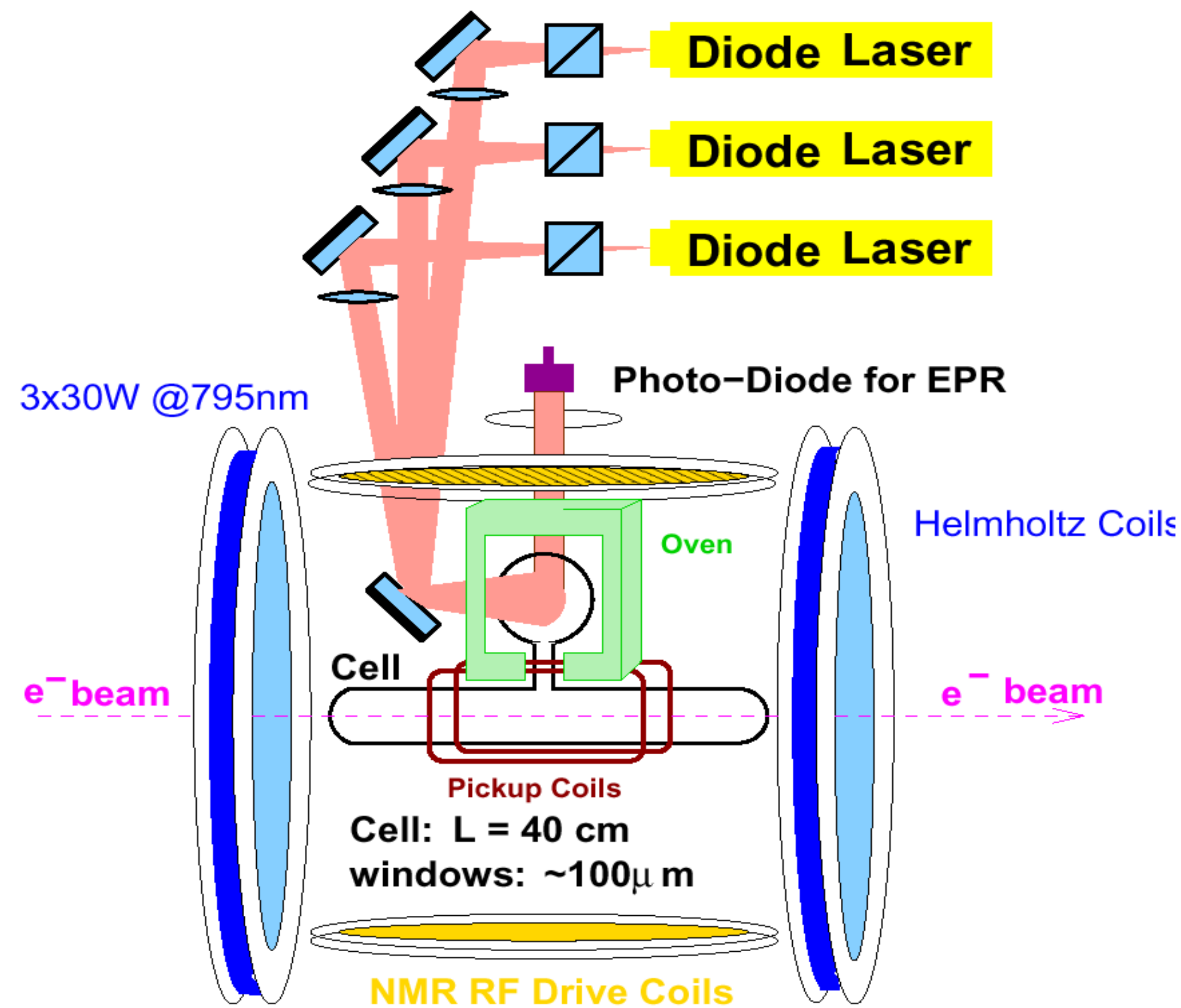
e- acceptance shown
π^- acceptance is similar
π^+ acceptance is reversed along phi=0 plane



Polarized Target and Luminosity

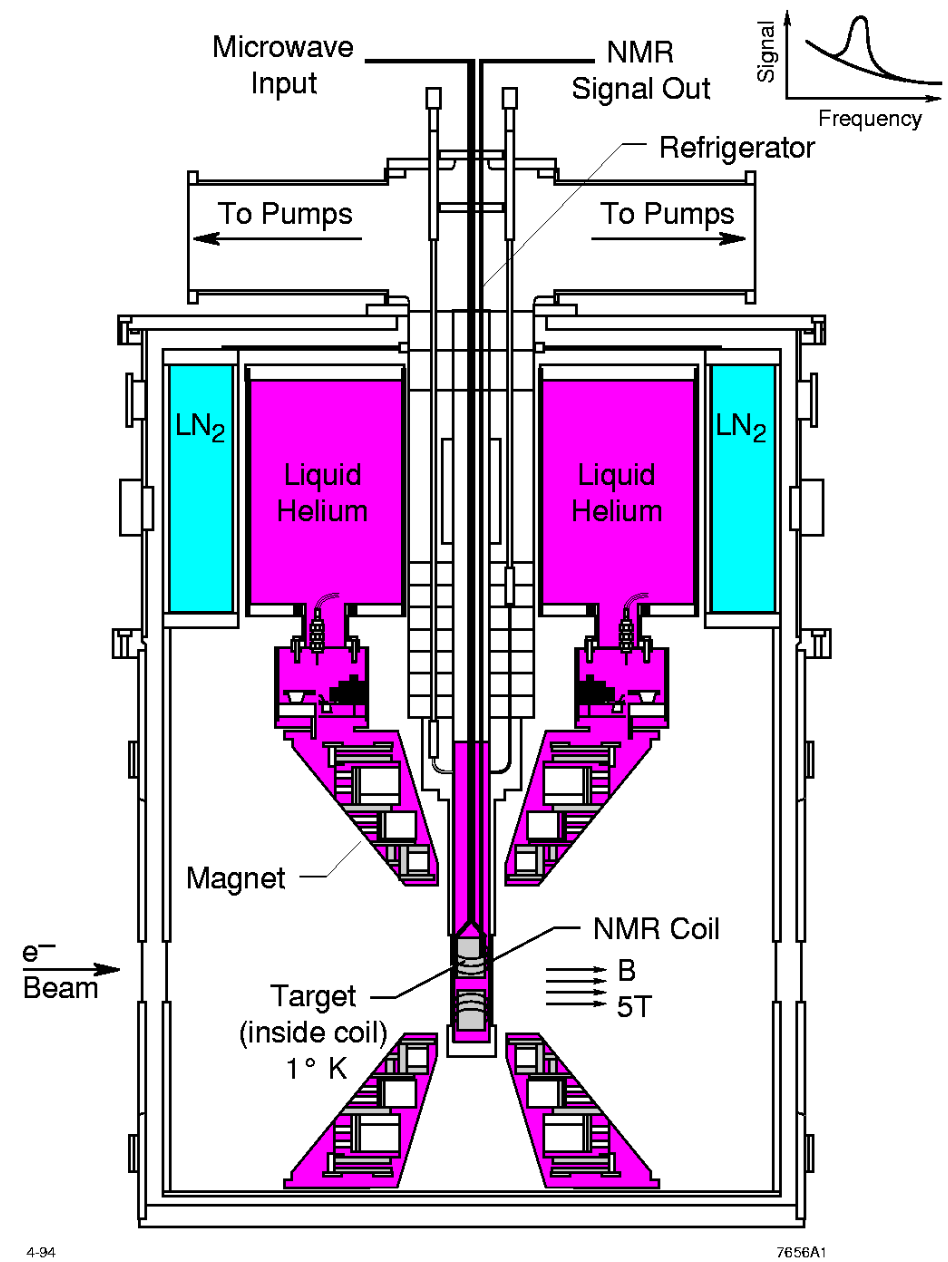
polarized ^{3}He target

Pol luminosity ~10^{36}/cm^2/s (world record)
High in-beam polarization ~ 60%



polarized NH_3 target

Pol luminosity ~10^{35}/cm^2/s
High in-beam polarization ~ 70%

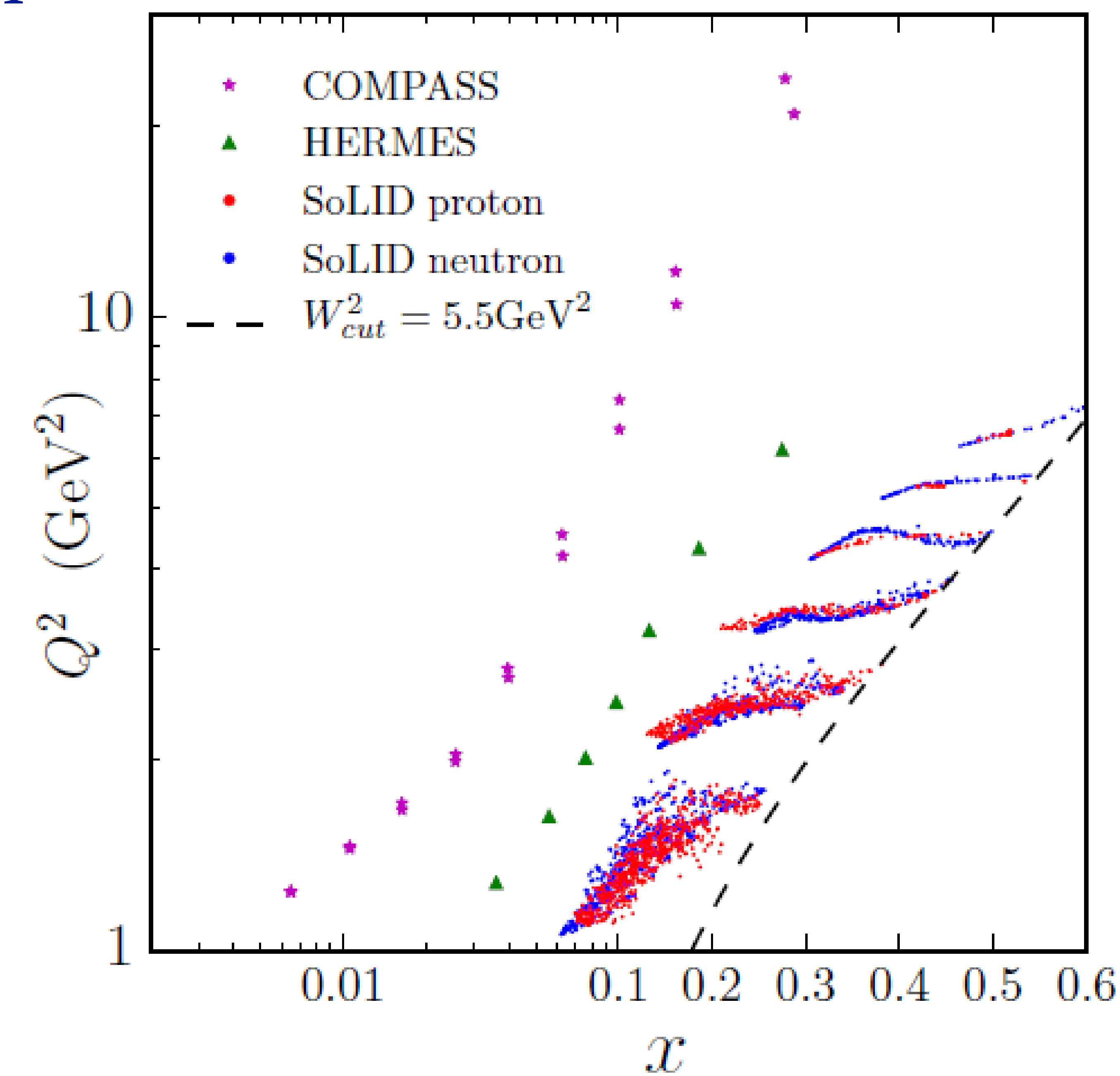


SoLID SIDIS Kinematic Coverage

With 8.8 and 11GeV beam

$0.05 < x < 0.6$
$1 < Q^2 < 8\text{GeV}$
$0.3 < z < 0.7$
$0 < P_T < 1.6\text{GeV}$

~ 2000 bins for n
~ 1000 bins for p



SoLID SIDIS Resolution and Error

	θ angle (mrad)	ϕ angle (mrad)	Vertex z (cm)	p (%)
SIDIS ^{3}He fwd angle (e)	1.3	5.7	0.9	1.7
SIDIS ^{3}He fwd angle (π)	1.2	5.2	0.9	1.1
SIDIS ^{3}He large angle (e)	1.0	1.7	0.5	1.2
PVDIS (e)	0.8	1.7	0.3	1.2

Table 21: Averaged resolutions by track fitting with most of material energy loss and without background

$E_{\rm beam}$ (GeV)	x	z	Q^2(GeV^2)	$P_{h\perp}$(GeV)	ϕ_h(rad)	ϕ_S(rad)
11	0.002	0.003	0.02	0.006	0.015	0.006
8.8	0.002	0.004	0.02	0.006	0.018	0.006

Table 23: Resolution of kinematical variables (in the Trento convention) with the ^{3}He target setup.

$P_{h\perp}$(GeV/c)	[0.0, 0.2]	[0.2, 0.4]	[0.4, 0.6]	[0.6, 0.8]	[0.8, 1.0]	[1.0, 1.2]
11 GeV beam (π^+)	110	160	150	105	75	40
11 GeV beam (π^-)	120	160	140	90	70	50
8.8 GeV beam (π^+)	75	95	80	50	45	
8.8 GeV beam (π^-)	65	95	75	50	45	

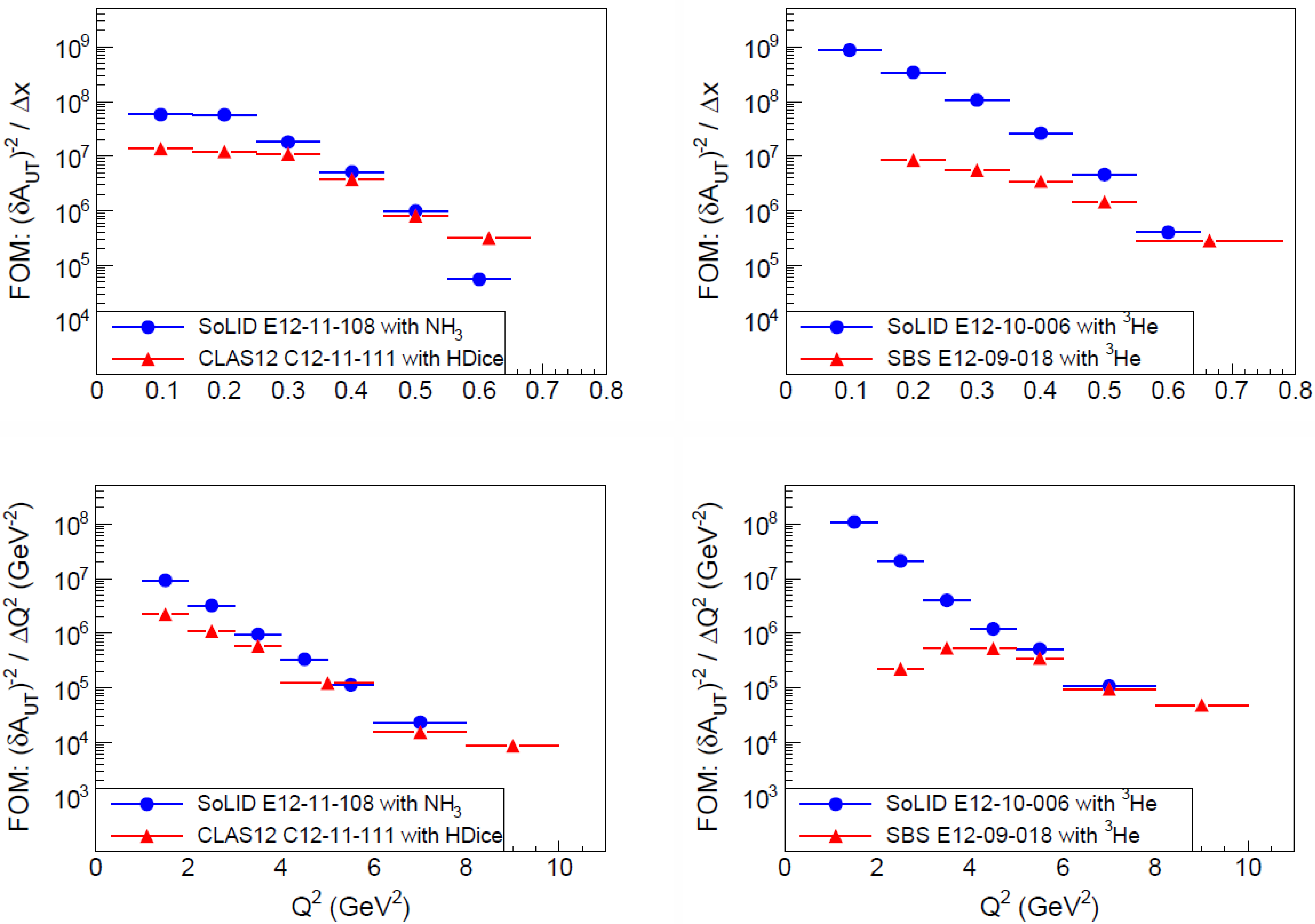
Table 24: The ratio of SIDIS signal and random coincidence background within 6 ns. These values are estimated with the ^{3}He target. Similar results are obtained for the proton target.

Systematic (abs.)		Systematic (rel.)	
Raw asymmetry	0.0014	Target polarization	3%
Detector resolution	< 0.0001	Nuclear effect	$(4-5)\%$
		Random coincidence	0.2%
		Radiative correction	$(2-3)\%$
		Diffractive meson	3%
Total	0.0014	Total	$(6-7)\%$

Table 25: The systematic uncertainties on the asymmetry measurements of SIDIS.

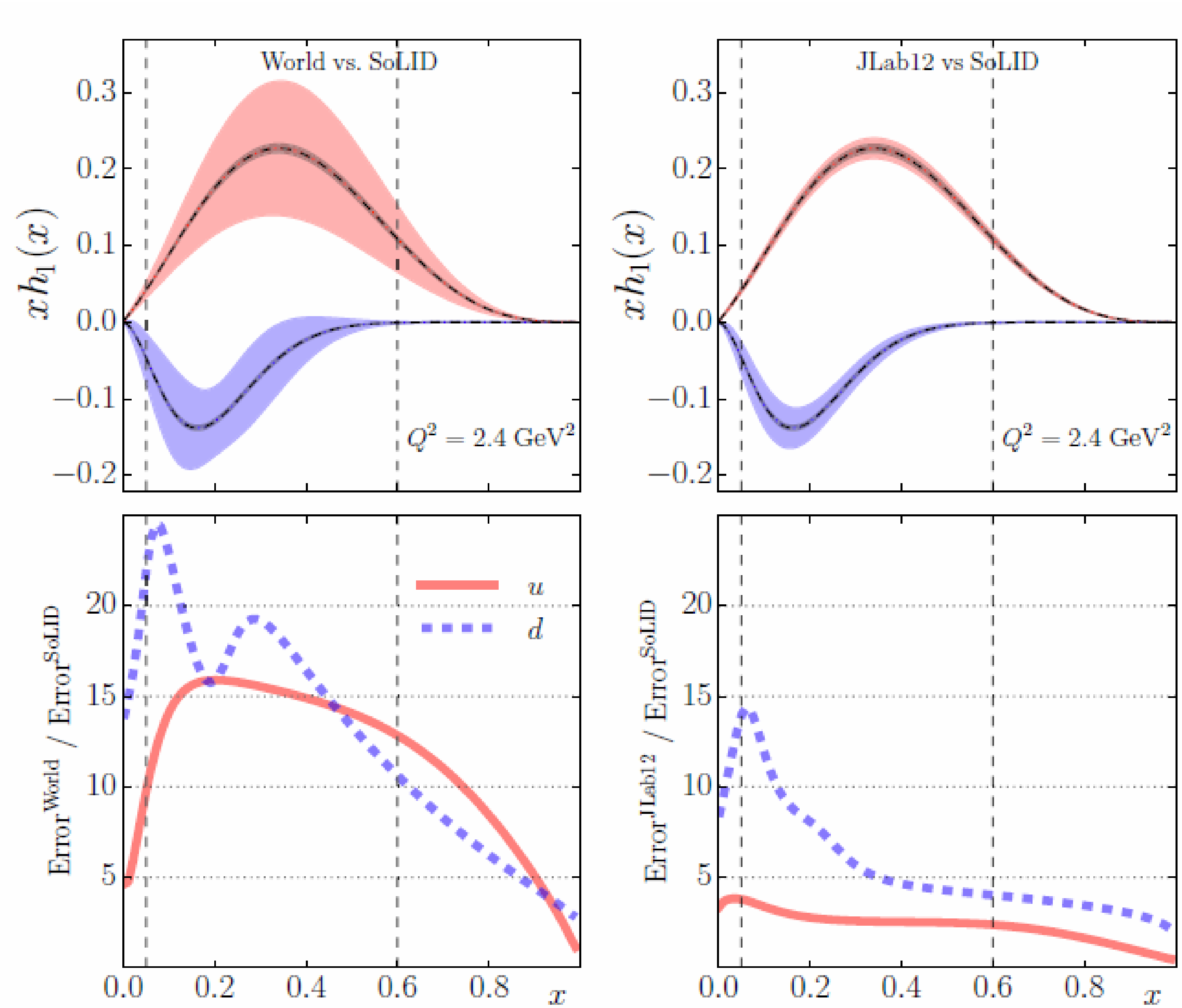
SoLID SIDIS FOM

$W > 2.3$ GeV $\quad 0.3 < z < 0.7$



Transversity Projection and Impact

Collins Asymmetries ~ Transversity (x) Collin Function
Transversity: chiral-odd, not couple to gluons, valence behavior, largely unknown



Measured: [0.05, 0.6] improvement

	SoLID vs. World	SoLID vs. JLab12
u	16	2.8
d	17	9.3

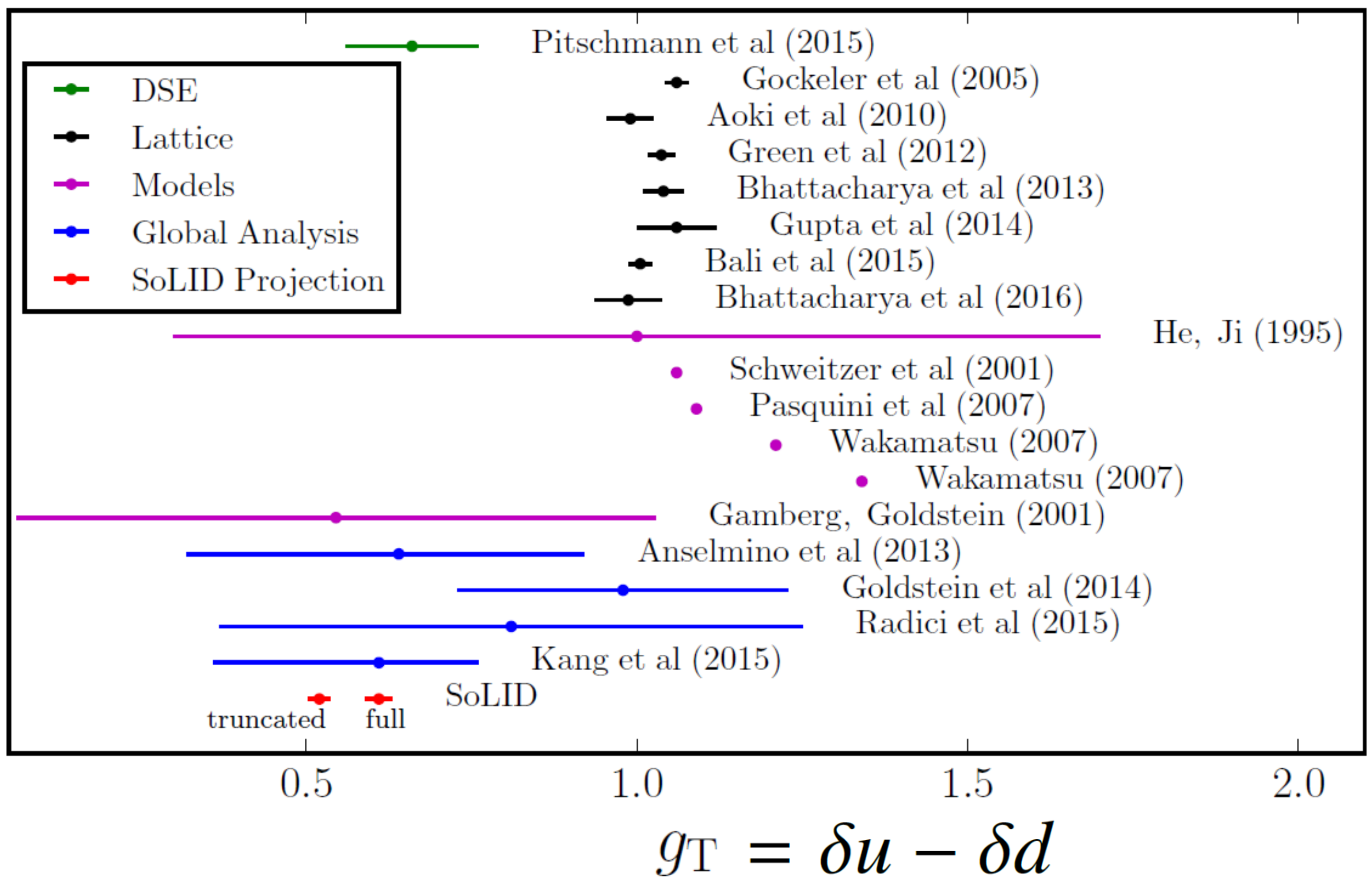
Full: [0, 1] improvement

	SoLID vs. World	SoLID vs. JLab12
u	16	3.0
d	17	10

Tensor Charge Projection and Impact

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q \bar{u}(P,S) i\sigma^{\mu\nu} u(P,S) \quad \delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$

Tensor charge: matrix element of local operators, 0th moment of transversity
Fundamental property of nucleon, valence quark dominant
Direct QCD comparison: Lattice QCD,Bound-State QCD (Dyson-Schwinger), Light-cone Quark Models, …



	World vs. SBS+CLAS12	World vs. SoLID	SBS+CLAS12 vs. SoLID	World vs. SoLID including systematics
$\delta u^{\text{measured}}$	6.1	16	2.8	6.7
$\delta d^{\text{measured}}$	1.9	17	9.3	11
δu^{full}	5.4	16	3.0	5.9
δd^{full}	1.8	17	10	10

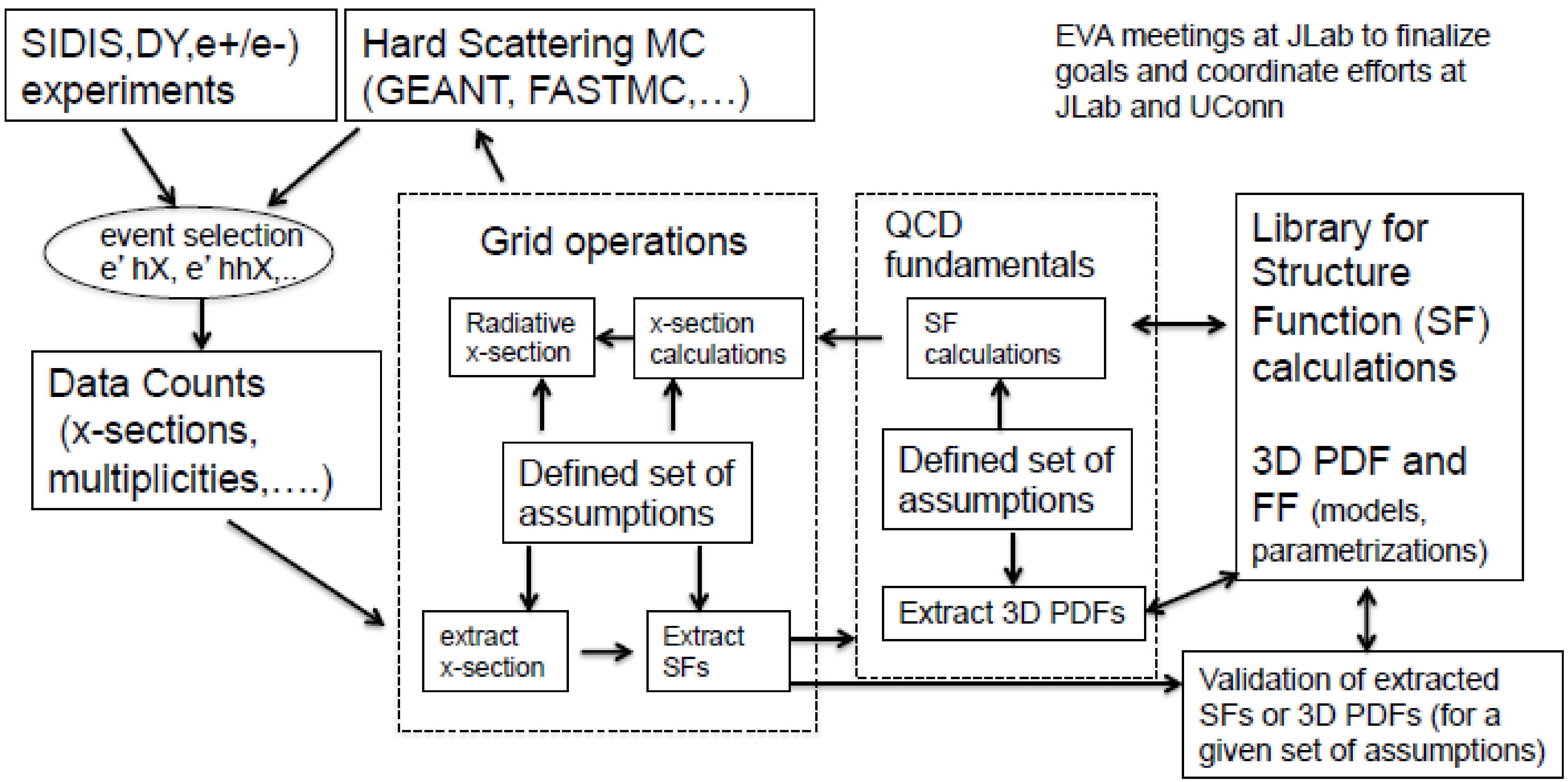
Sivers Projection and Impact

See Tianbo’s talk

Physics Extraction

Working with theorist and be part of framework

3D PDF Extraction and VAlidation (EVA) framework



Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

Summary

- SoLID: unique combination of large acceptance and high luminosity – truly utilize 12-GeV upgrade to its full potential, no competition for SIDIS physics
- SoLID SIDIS: comprehensive program with both proton and "neutron" targets in the same setup allows for flavor separation with better control of systematics
- Multi-dimensional binning of the data with high precision help reduce theoretical uncertainties in extracting TMDs
- Apart from three approved experiments, two ``bonus" experiments will accumulate data without additional beam

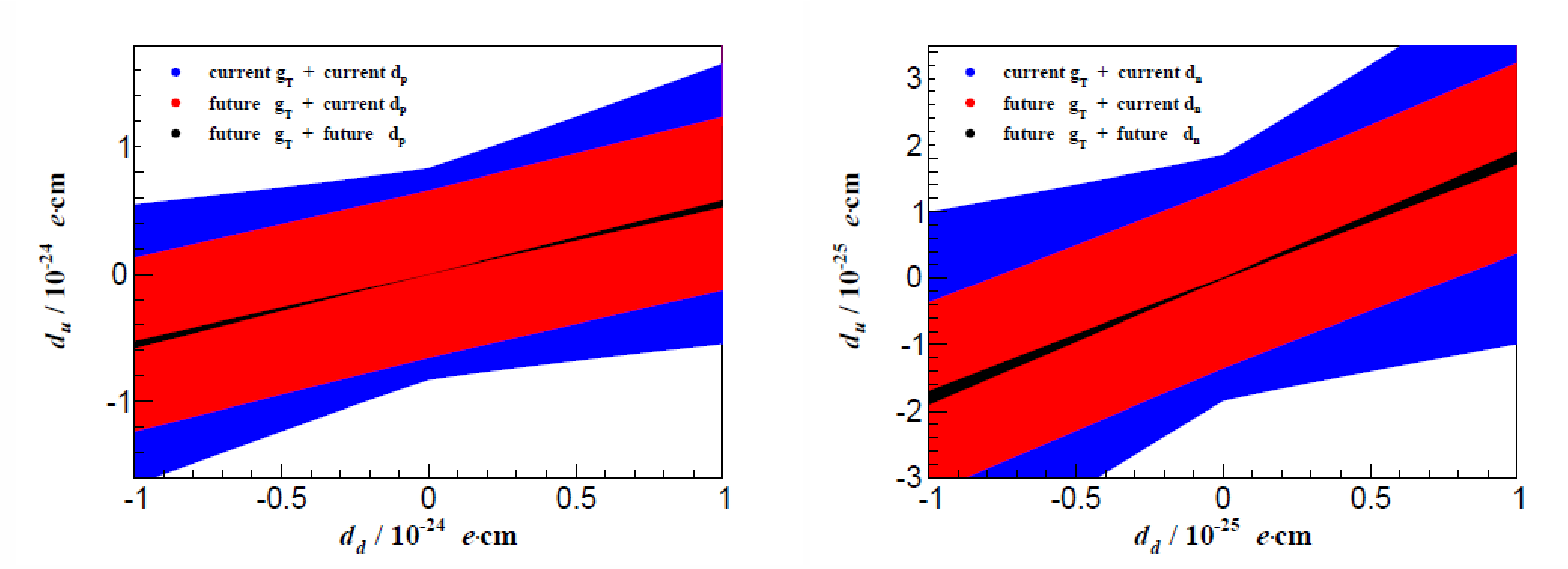
backup

Tensor Charge and Nucleon EDM

Electric **D**ipole **M**oment

Tensor charge and EDM

$$d_n = \delta_T u\, d_u + \delta_T d\, d_d + \delta_T s\, d_s$$



tensor charge precision	nucleon EDM limit	d_u limit	d_d limit
current	current	1.73×10^{-24}	1.34×10^{-24}
future	current	1.05×10^{-24}	6.83×10^{-25}
current	future	1.50×10^{-27}	1.96×10^{-27}
future	future	7.56×10^{-28}	1.19×10^{-27}