Semi Inclusive Deep Inelastic Scattering with Super BigBite Spectrometer

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Hall A collaboration meeting
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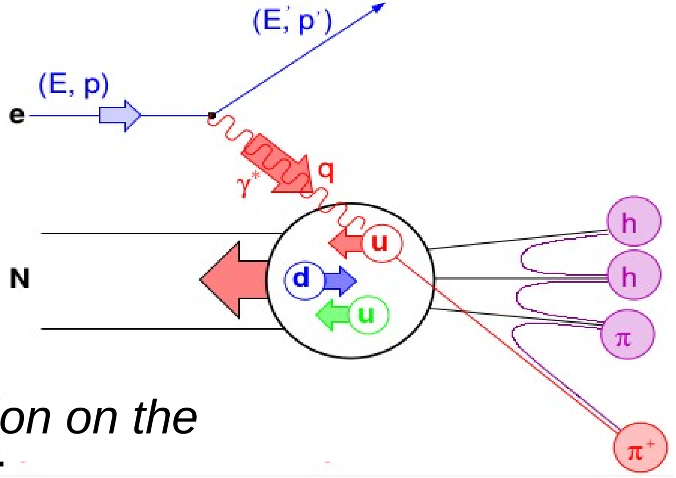
Semi-Inclusive DIS and
Transverse Momentum Distribution functions

Semi-inclusive Deep Inelastic Scattering (SIDIS):

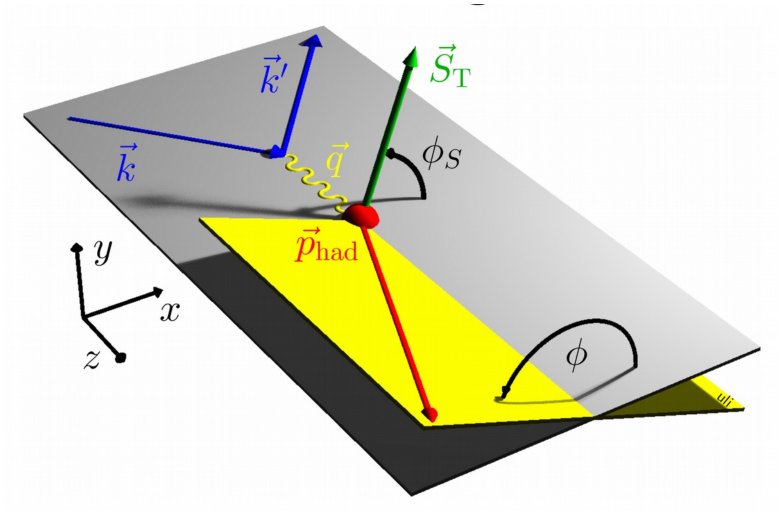
virtual photon strikes a quark (*large* Q^2, W, *finite* x);
Quark hadronizes
($z = E_h/\nu$, P_{hT} moderate;
$P_{hT}/z << Q^2$);

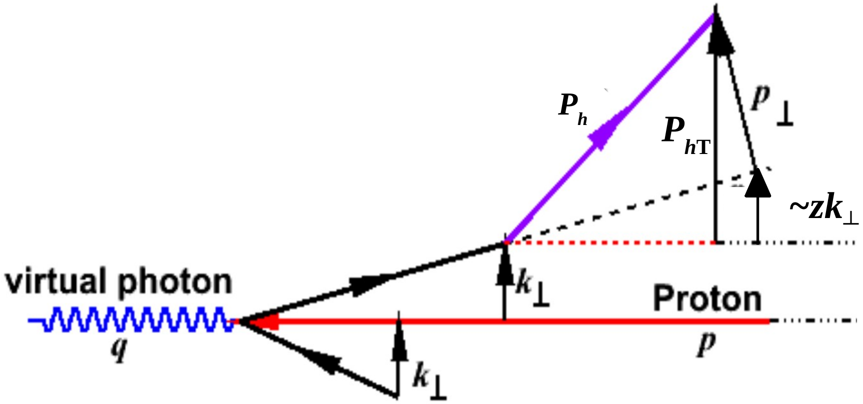


Observables accessed w/ harmonics of hadron azimuthal angle ϕ_h;

Knowledge of lepton, nucleon polarization necessary to access all observables;

Detected hadron carries *information on the transverse momentum of partons*;
=> **Transverse Momentum Distributions (TMDs)** of partons (Of course, this info is blended in with the parton hadronization – Fragmentation functions)





SIDIS observables and TMDs

Twist-2 **SIDIS observables**	**TMDs**

$$F_{UU,T} \propto f_1^q \otimes D_1^q$$

$$F_{UU}^{\cos(2\phi_h)} \propto h_1^{q\perp} \otimes H_1^{q\perp}$$

$$F_{UL}^{\sin(2\phi_h)} \propto h_{1L}^{q\perp} \otimes H_1^{q\perp}$$

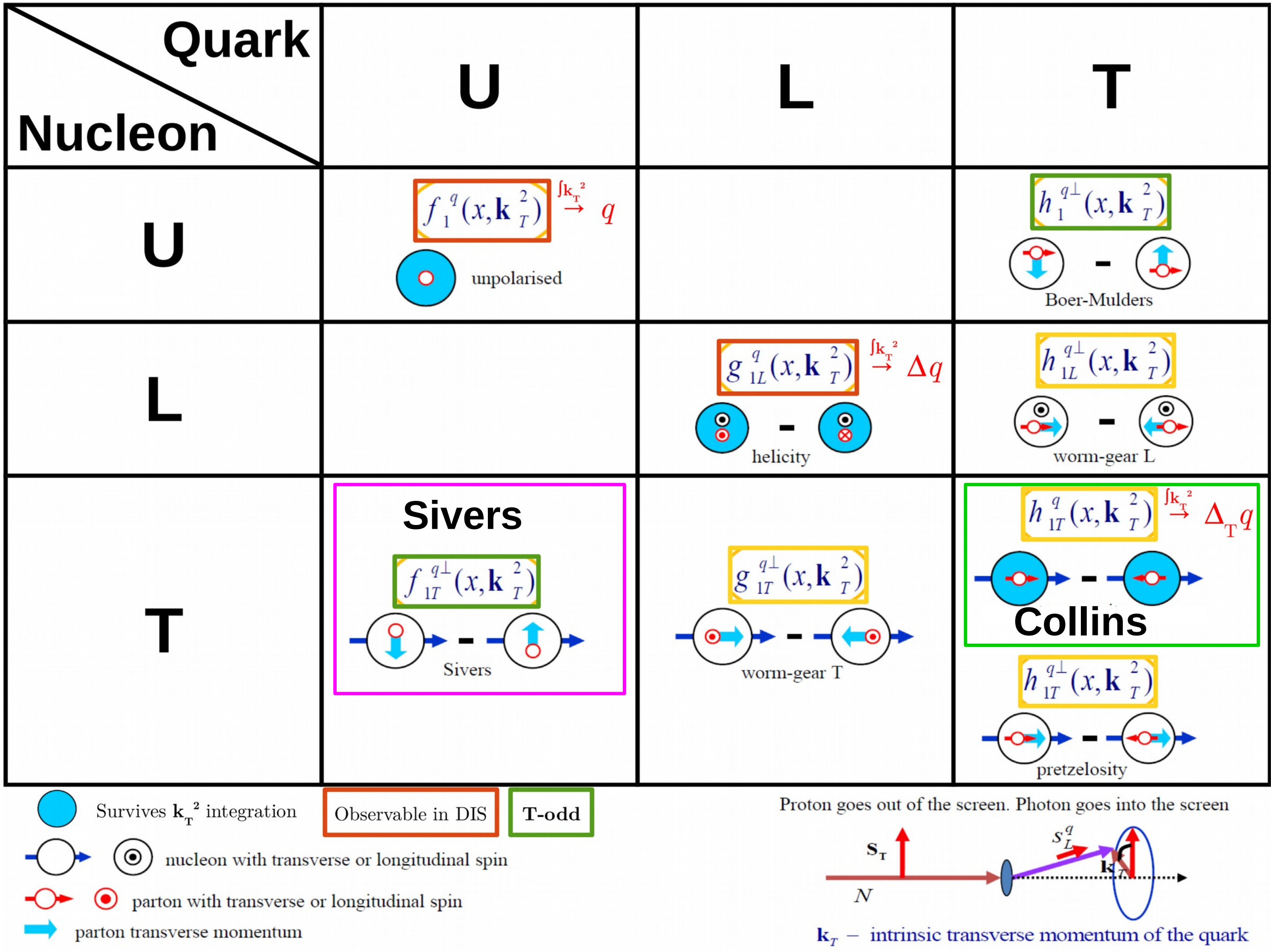
$$F_{LL} \propto g_{1L}^q \otimes D_1^q$$

$$\boxed{F_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^{q\perp} \otimes D_1^q}$$

$$\boxed{F_{UT}^{\sin(\phi_h + \phi_S)} \propto h_1^q \otimes H_1^{q\perp}}$$

$$F_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_{1T}^{q\perp} \otimes H_1^{q\perp}$$

$$F_{LT}^{\sin(\phi_h - \phi_S)} \propto g_{1T}^q \otimes D_1^q$$



Quark / Nucleon	U	L	T
U	$f_1^q(x,\mathbf{k}_T^2) \xrightarrow{\int \mathbf{k}_T^2} q$ unpolarised		$h_1^{q\perp}(x,\mathbf{k}_T^2)$ - Boer-Mulders
L		$g_{1L}^q(x,\mathbf{k}_T^2) \xrightarrow{\int \mathbf{k}_T^2} \Delta q$ - helicity	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ - worm-gear L
T	**Sivers** $f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ - Sivers	$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ - worm-gear T	$h_{1T}^q(x,\mathbf{k}_T^2) \xrightarrow{\int \mathbf{k}_T^2} \Delta_T q$ - **Collins** $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ - pretzelosity

● Survives $\mathbf{k}_T^2$ integration

Observable in DIS

T-odd

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

Proton goes out of the screen. Photon goes into the screen

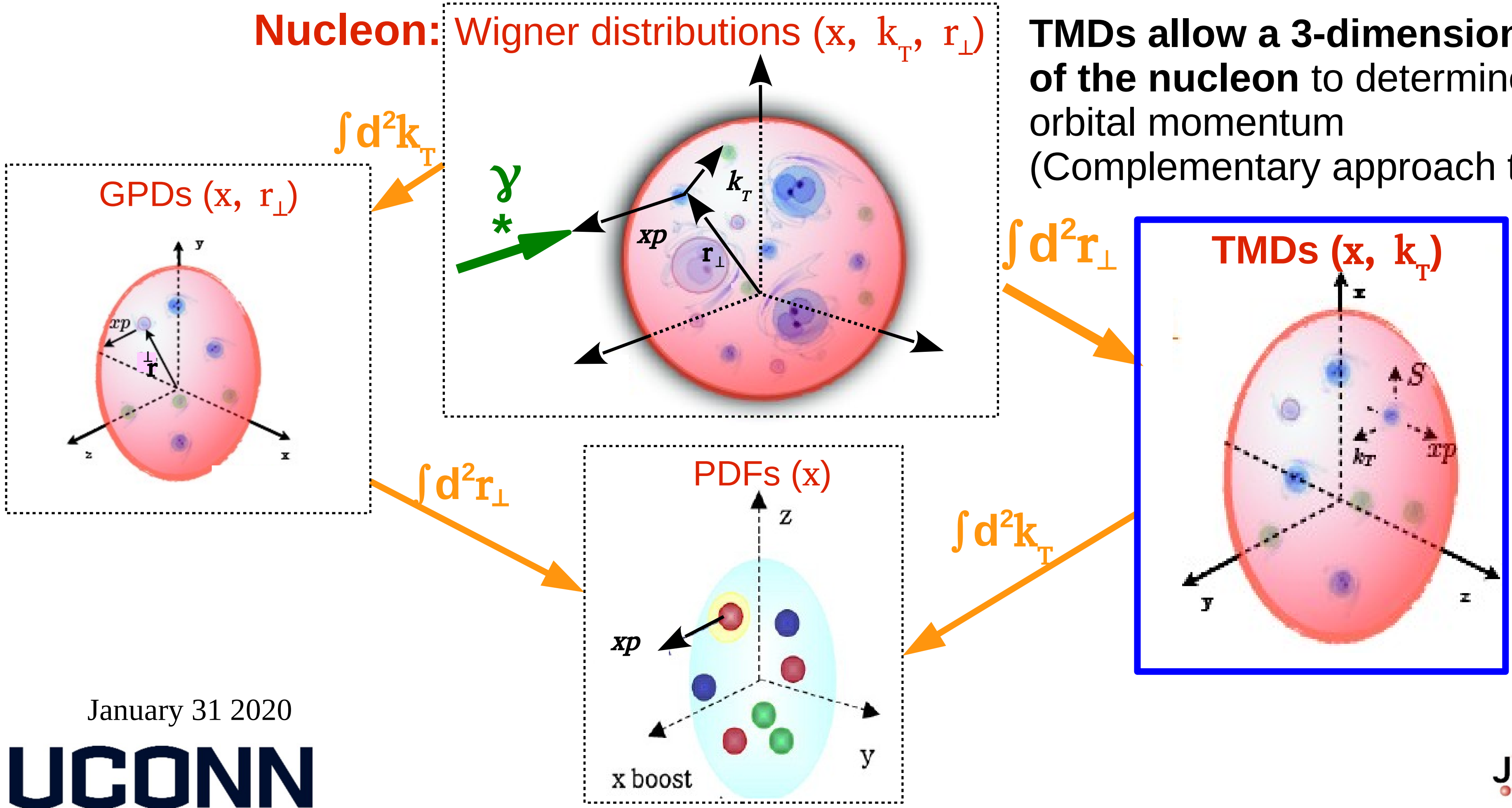
$\mathbf{k}_T$ – intrinsic transverse momentum of the quark

$D_1^q(z, Q^2, P_{hT})$ Unpolarized Fragmentation Function

$H_1^{q\perp}(z, Q^2, P_{hT})$ Collins Fragmentation Function

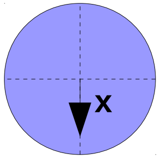
TMDs and the nucleon structure

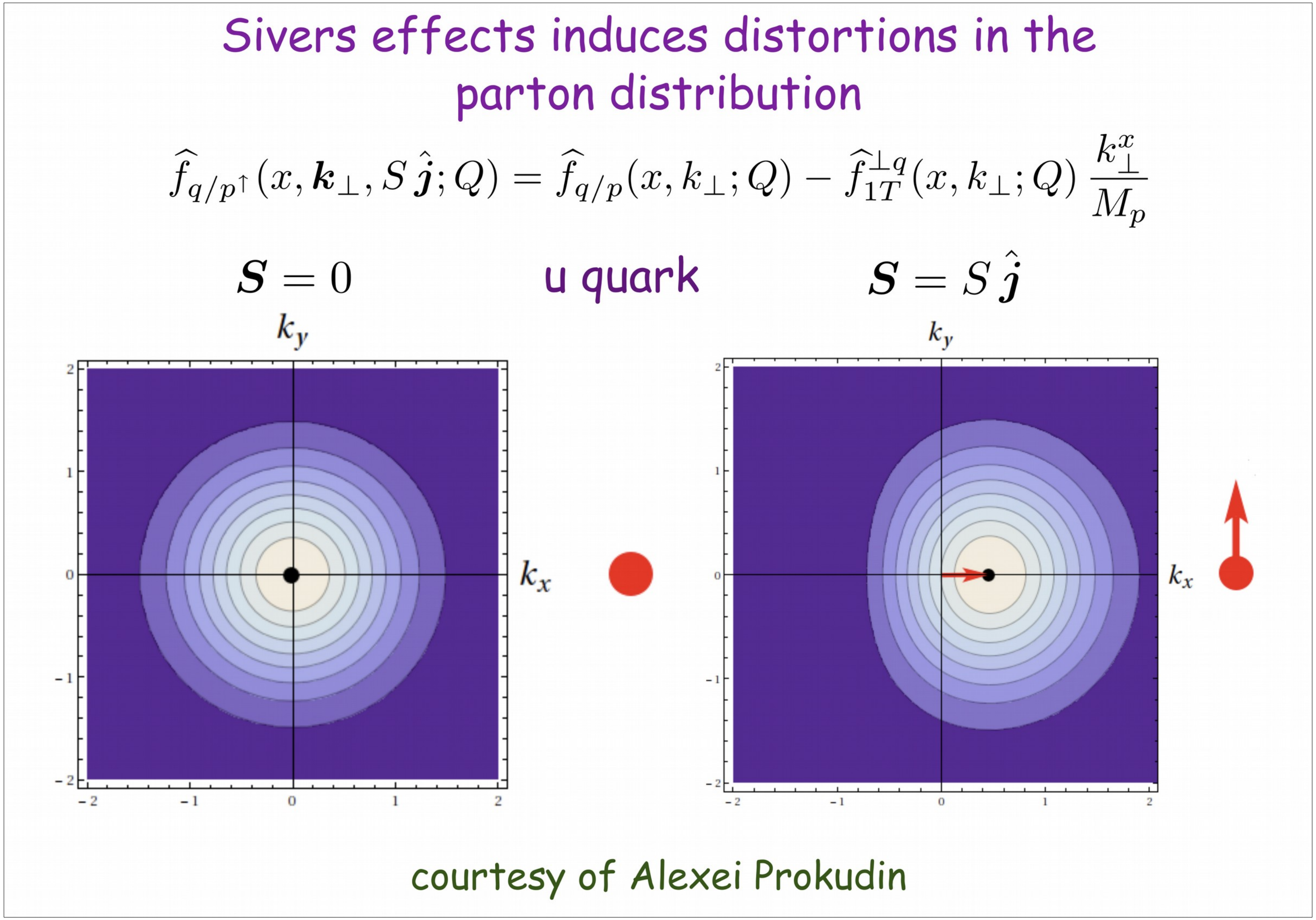
Nucleon “spin puzzle”: $$S_N = \tfrac{1}{2} = \underset{\text{Well known}}{\boxed{\tfrac{1}{2}\,\Delta\Sigma}} + \underset{\text{known}}{\boxed{\Delta G}} + \underset{\text{unknown}}{\boxed{L_q + L_g}}$$



TMDs allow a 3-dimensional imaging of the nucleon to determine the quark orbital momentum
(Complementary approach to GPDs)

TMDs and the nucleon structure
Quark OAM on transversely polarized target



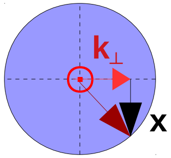


Sivers effects induces distortions in the parton distribution

$$\widehat{f}_{q/p^\uparrow}(x,\boldsymbol{k}_\perp,S\,\hat{\boldsymbol{j}};Q)=\widehat{f}_{q/p}(x,k_\perp;Q)-\widehat{f}_{1T}^{\perp q}(x,k_\perp;Q)\,\frac{k_\perp^x}{M_p}$$

$\boldsymbol{S}=0$ u quark $\boldsymbol{S}=S\,\hat{\boldsymbol{j}}$

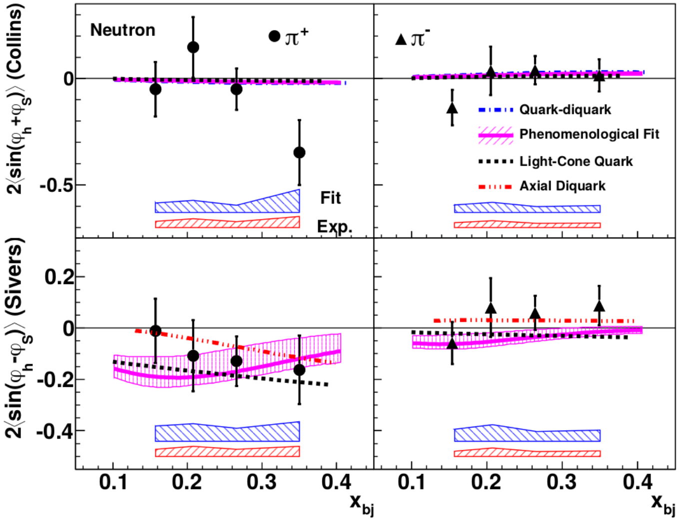
courtesy of Alexei Prokudin



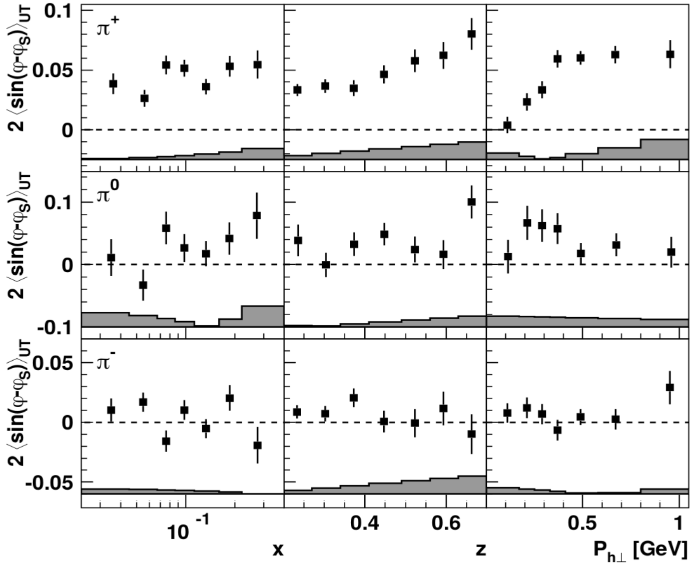
Slide from M. Anselmino, POETIC 6, 2015

Current knowledge about TMDs
Selected transversely polarized target data

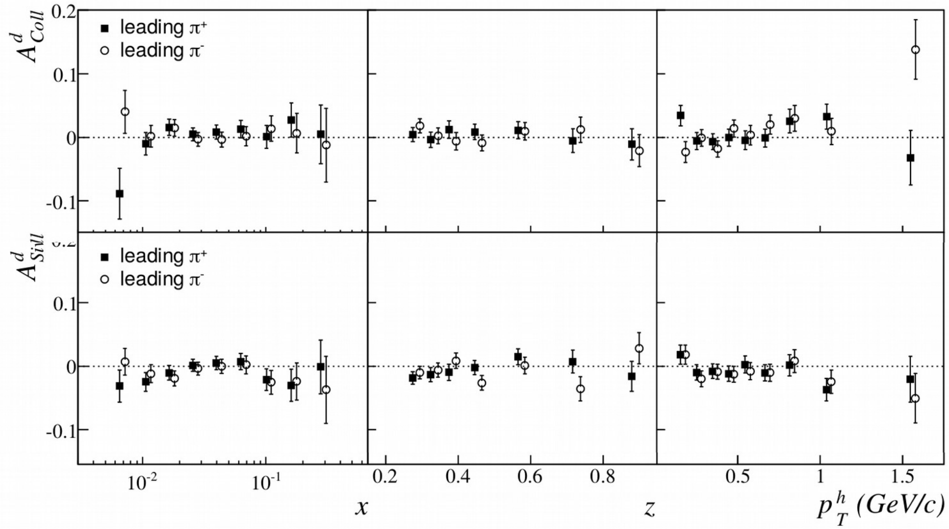
***Neutron*:**
[Qian et al.,
Phys. Rev. Lett., **107** (2011) 072003.
arXiv:1106.0363]



***Proton*:**
[A. Airapetian et al. (HERMES Collaboration),
Phys. Rev. Lett. 103, 152002 (2009)
arXiv:0906.3918]



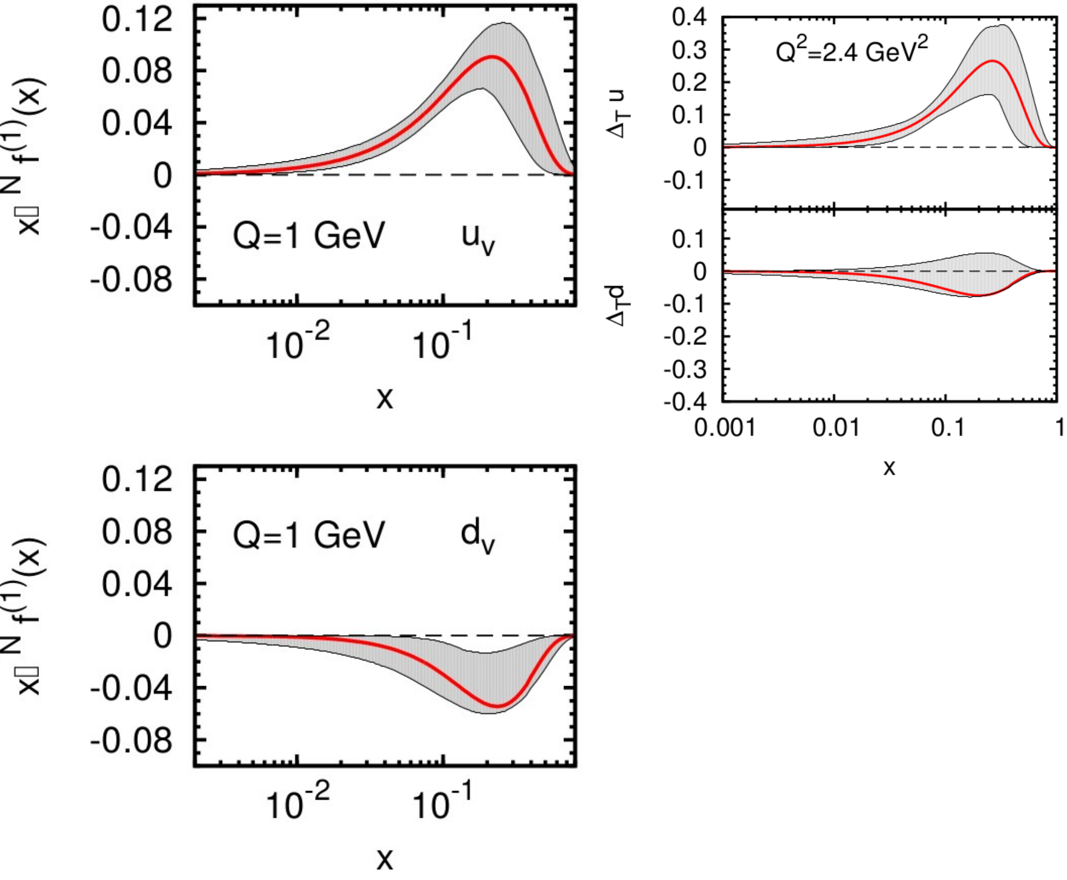
***Polarized D*:**
[M. Alekseev et al.
(COMPASS Collaboration),
Phys. Lett. **B 673**, 127 (2009),
arXiv:0802.2160]



Current knowledge about TMDs
Fits over transversely polarized target data

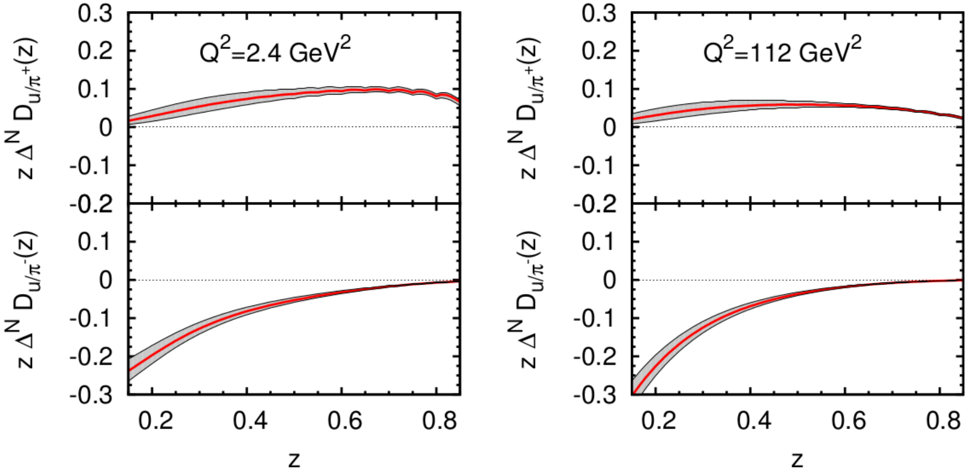
Sivers function:

[Anselmino et al., Phys. Rev. **D 86** (2012) 014028, arXiv:1204.1239]



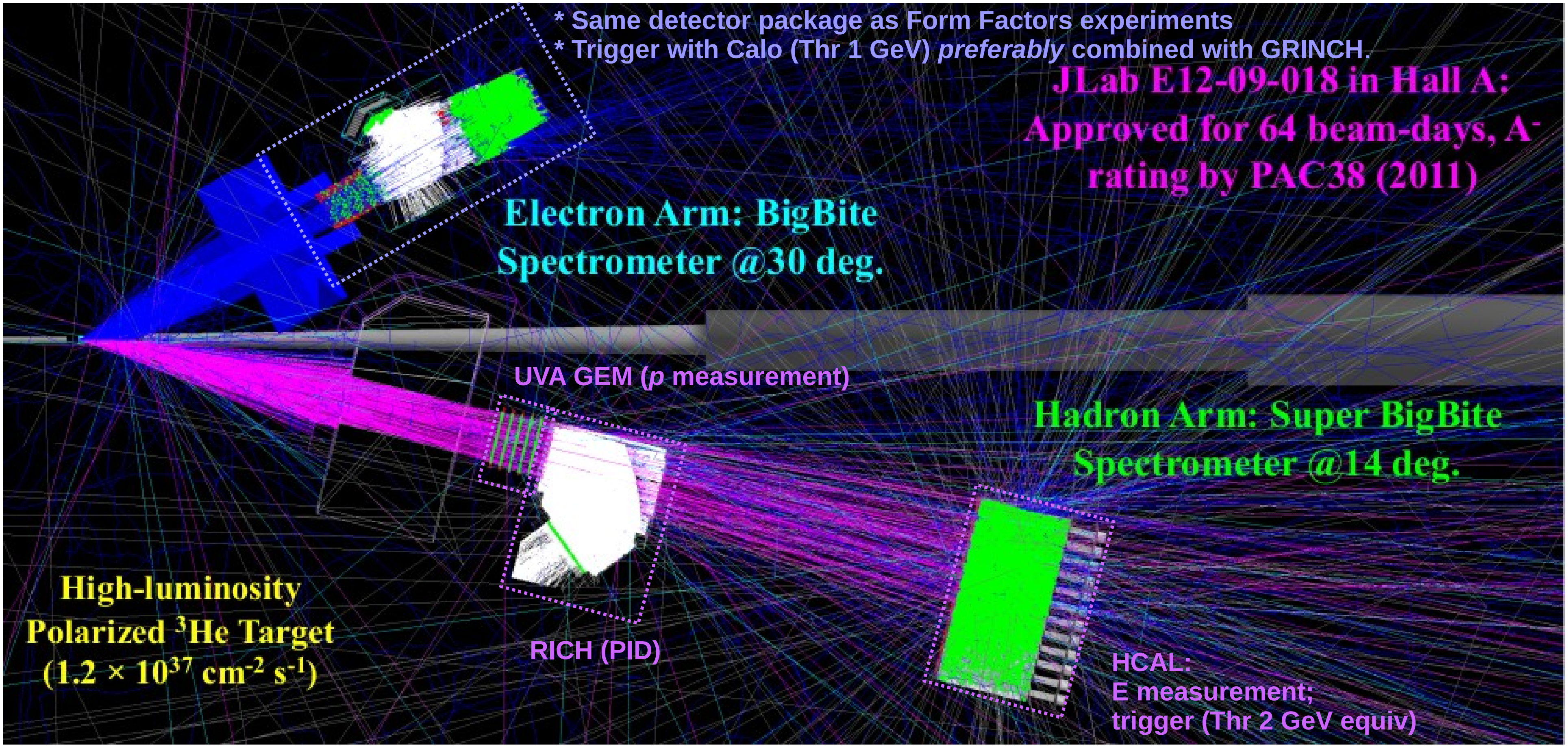
Collins function:

[Anselmino et al., Phys. Rev. **D 92**, (2015) 114023 arXiv:1510.05389]



SIDIS with Super BigBite Spectrometer
Setup for experiment E12-09-018

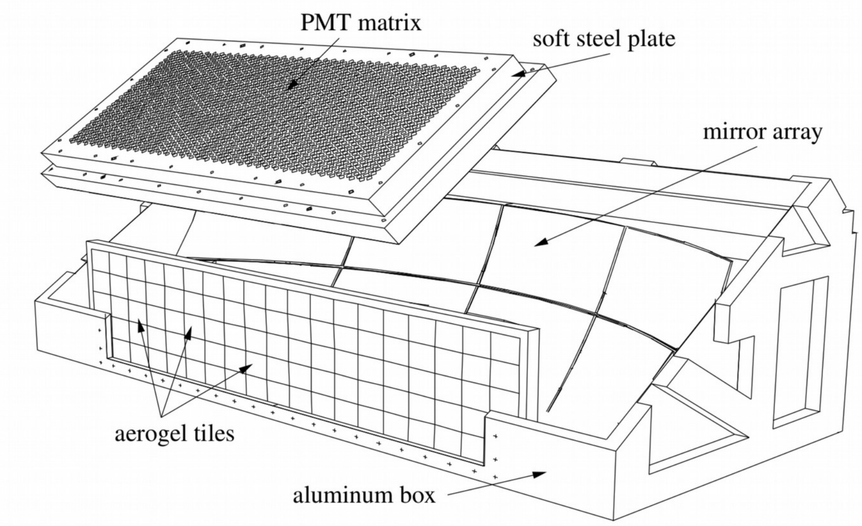
The SBS SIDIS experiment will use the SBS-BigBite Pair (below)

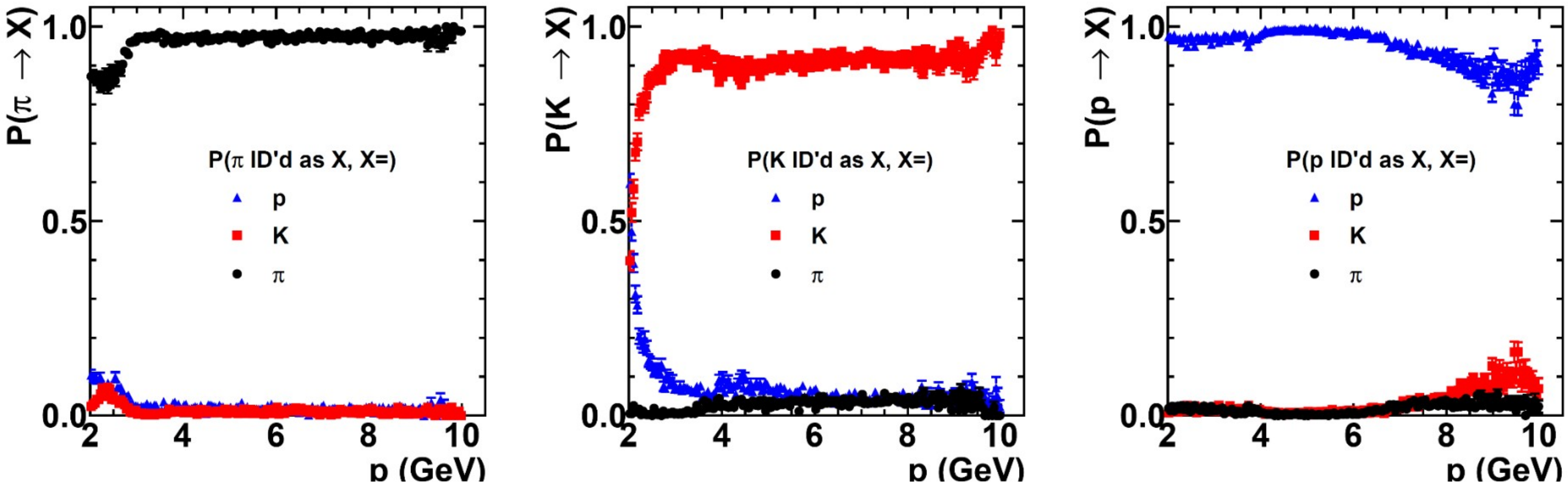


Most systems will already be built for other SBS experiments (refer to all SBS talks in this session), except for the RICH and the target

SIDIS with SBS
A word on Ring Imaging CHerenkov

RICH: Purpose: Particle ID
 * Heavy gas Cherenkov (C4F8 n = 1.00132) + Aerogel tiles (n = 1.0304)
 * Combination of the two offers π/K/p separation over a wide momentum range



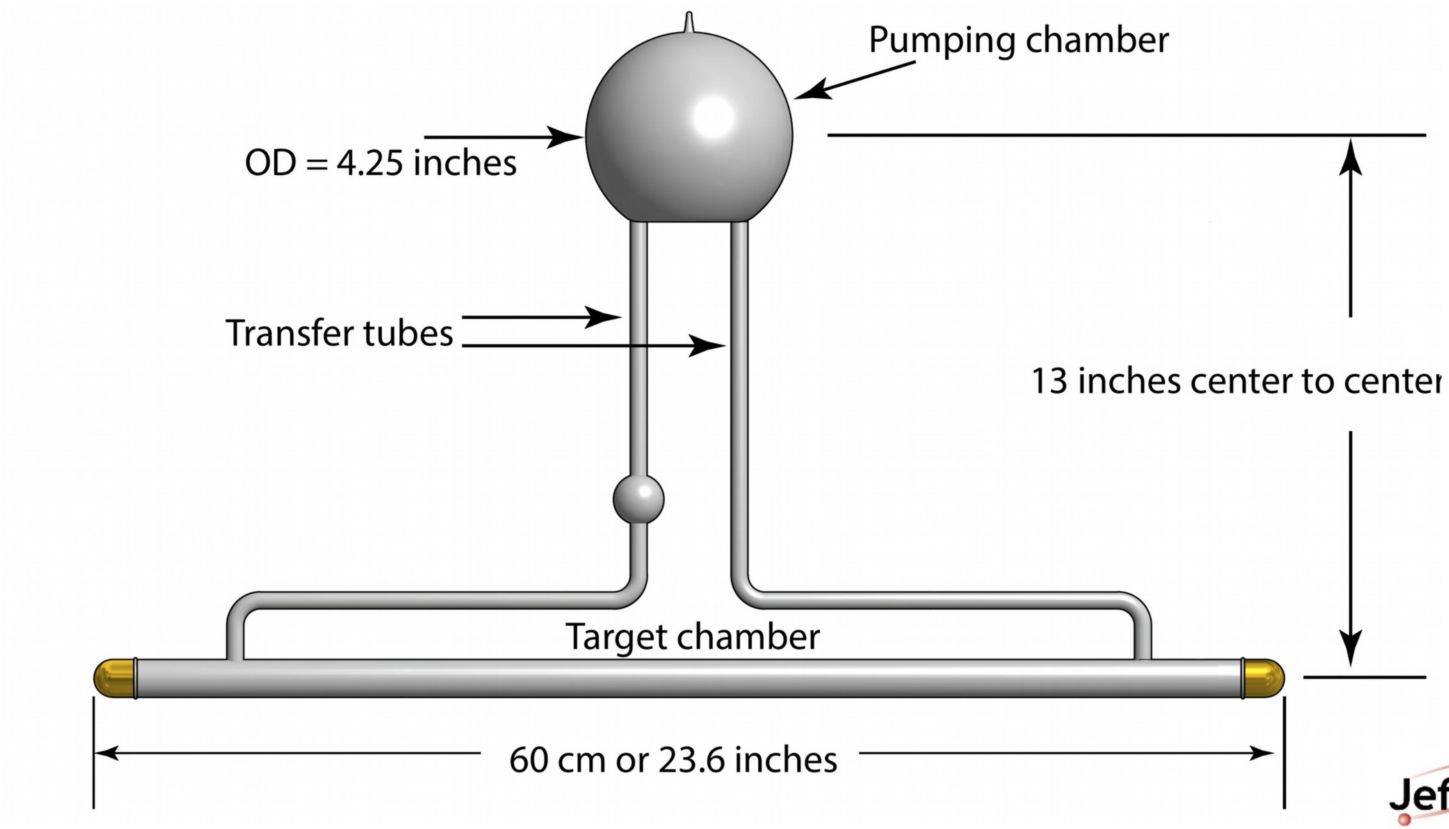


Plot credit: Andrew Puckett

SIDIS with SBS
Another word on the polarized target

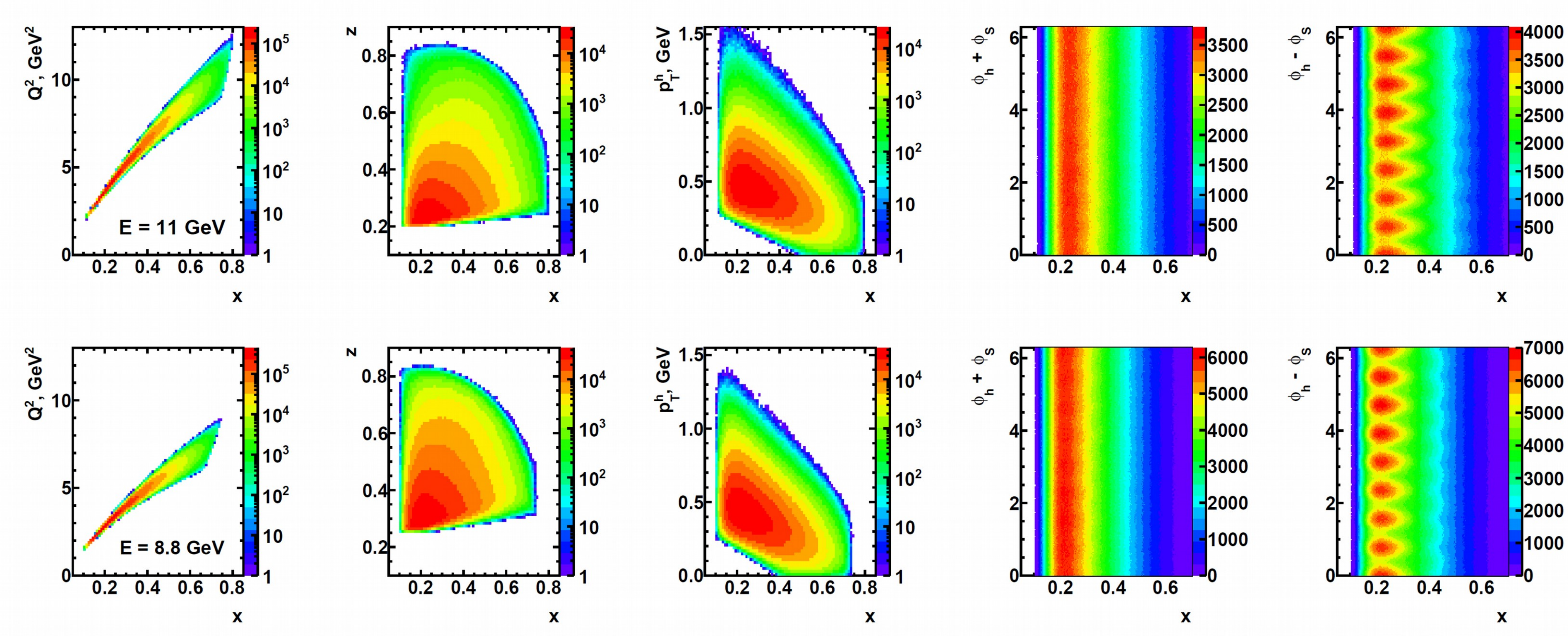
Polarized ^{3}He target: (more details in Gordon’s talk)
- 60 cm long, filled with 10 atm of 3He;
- Metal ends to sustain high beam currents (>40μA);

=> Luminosity > 10^{37}cm^{-2}s^{-1}
- SIDIS will nominally require more polarization directions:
  - → Proposal: 8 spin orientations, equally spaced at 45-degree intervals perp. to beam direction
  - → need *at least* 4: ±horizontal and ±vertical;
  - → vertical polarization the most challenging to obtain – may require redesign



SIDIS with SBS
Kinematic coverage

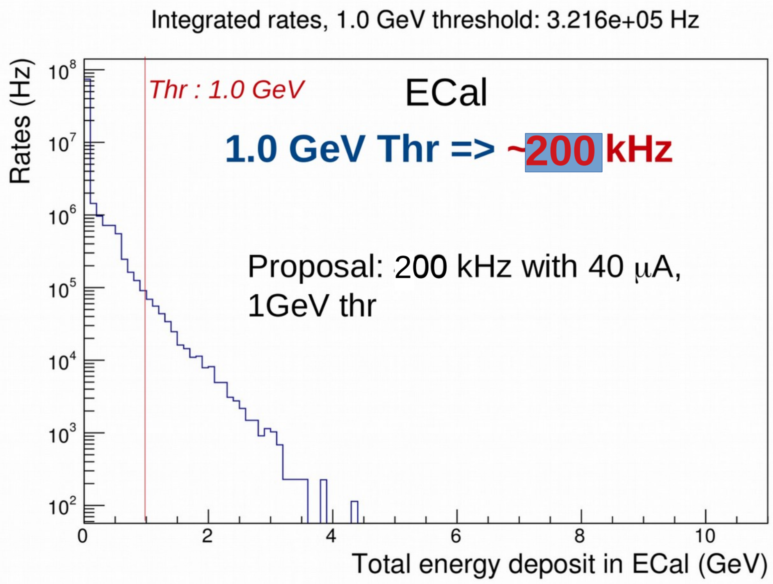
2 beam energies, same detector settings:
BB at 30 degrees, 1.55m from target
SBS at 14 deg, 2.5m (HCal at 8.5 m)
$Q^2 > 1$ GeV^2 , $W > 2$ GeV, $P_h \geq 2$ GeV, $M_X \geq 1.5$ GeV, $y \leq 0.9$



Plots credit: Andrew Puckett

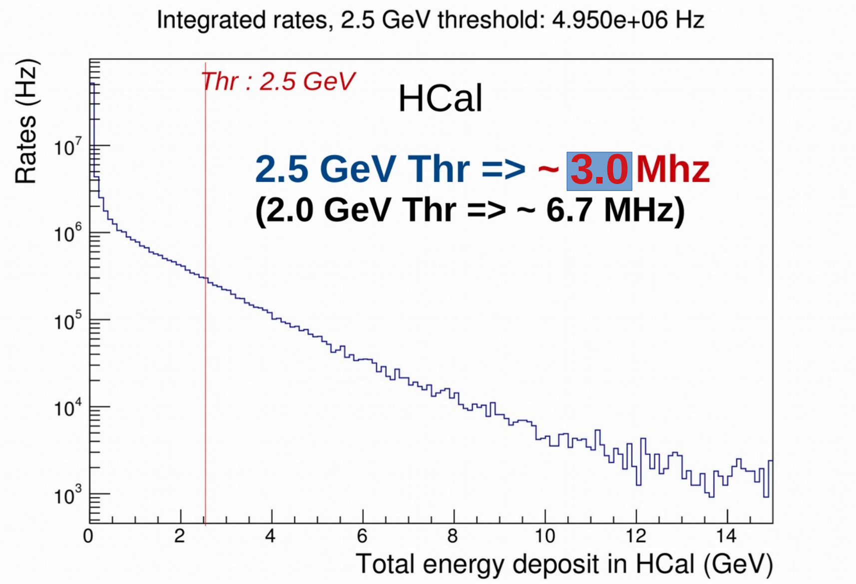
SIDIS with SBS
Trigger projections

Pythia full response with SIDIS **(50μA on 60cm ^{3}He)** *Circa 2016, with updated raw rates*



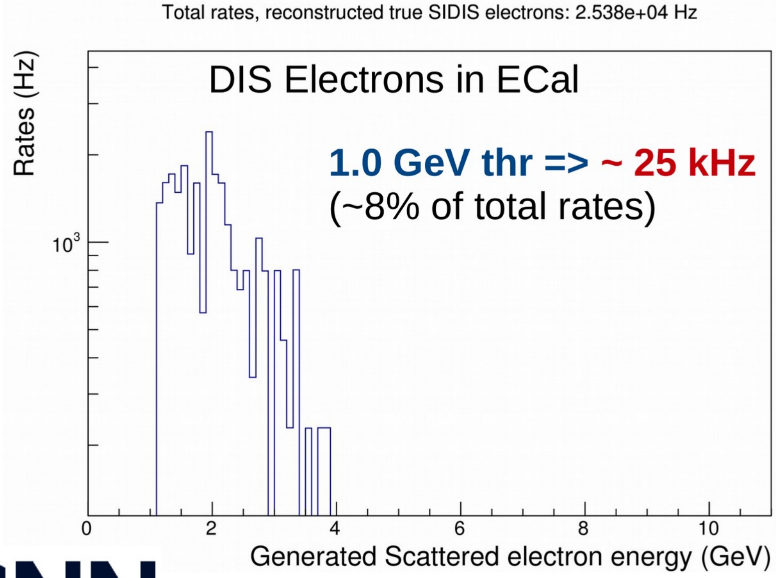
1.0 GeV Thr => ~200 kHz

Proposal: 200 kHz with 40 μA, 1GeV thr



2.5 GeV Thr => ~ 3.0 Mhz

(2.0 GeV Thr => ~ 6.7 MHz)



1.0 GeV thr => ~ 25 kHz

(~8% of total rates)

Trigger combining ECal and HCal singles, in a 30ns window: **20kHz** (too high!)

Particle energies E_p determined with :

E_p = Np.e. * C_Npe2Edep (* HCal_sampl_frac);

Np.e. : number of p.e. collected in PMTs of calos ;
C_Npe2Edep : coefficient to convert Np.e. to energy deposit ;
Hcal_sampl_frac : sampling fraction of HCal (ratio of E_p /E_dep)

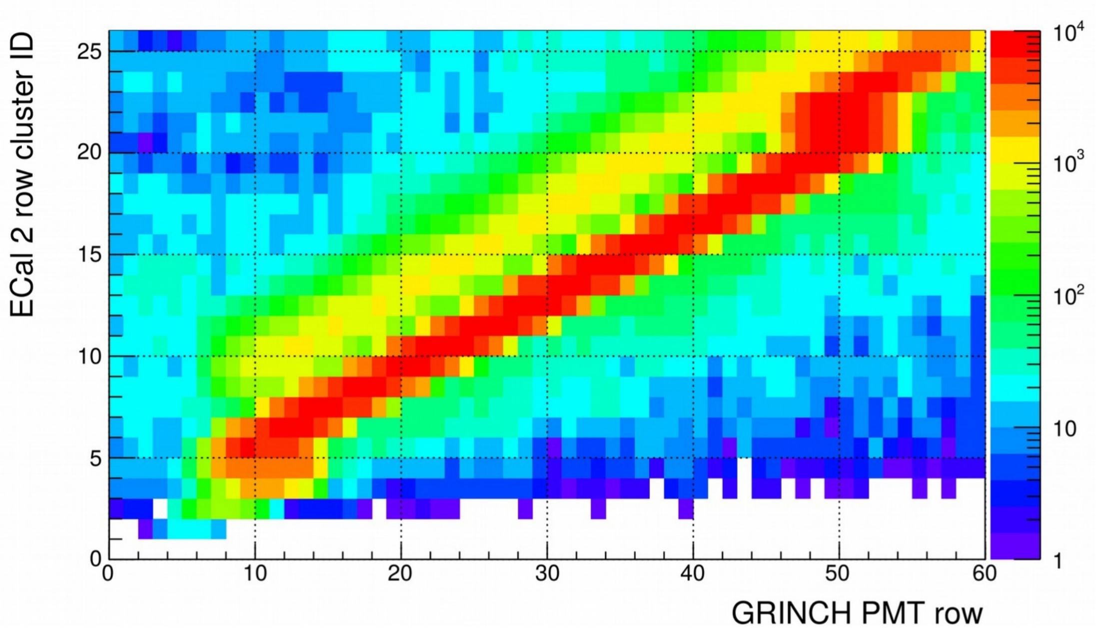
(determination of C_Npe2Edep, Hcal_sampl_frac explained in backup)

*Either lower luminosity, raise thresholds, **or**...*

SIDIS with SBS
Trigger projections

Using BB ECal/ GRINCH correlation in trigger logic lowers the electron rates

Circa 2016, with updated raw rates

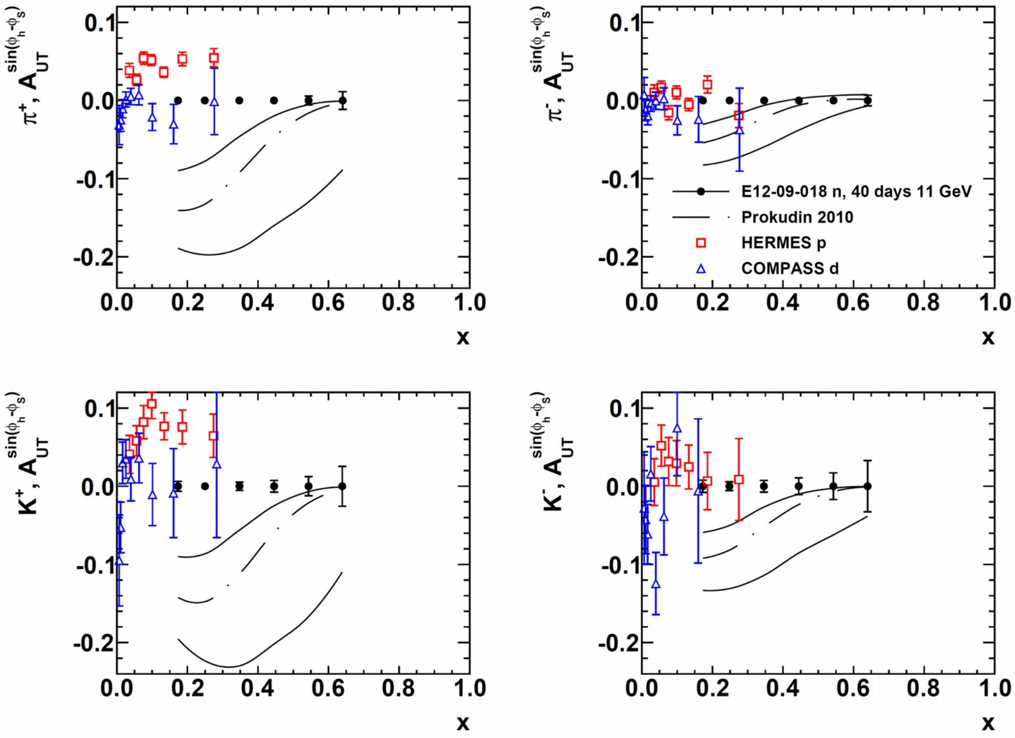


Electron arm total rates (Signal + Background): <**35 kHz** (down from 200kHz)
Δt = 30ns coincidence with HCal single rates (3 MHz):
Total SIDIS trigger rates: <**5 kHz** (down from ~20kHz)

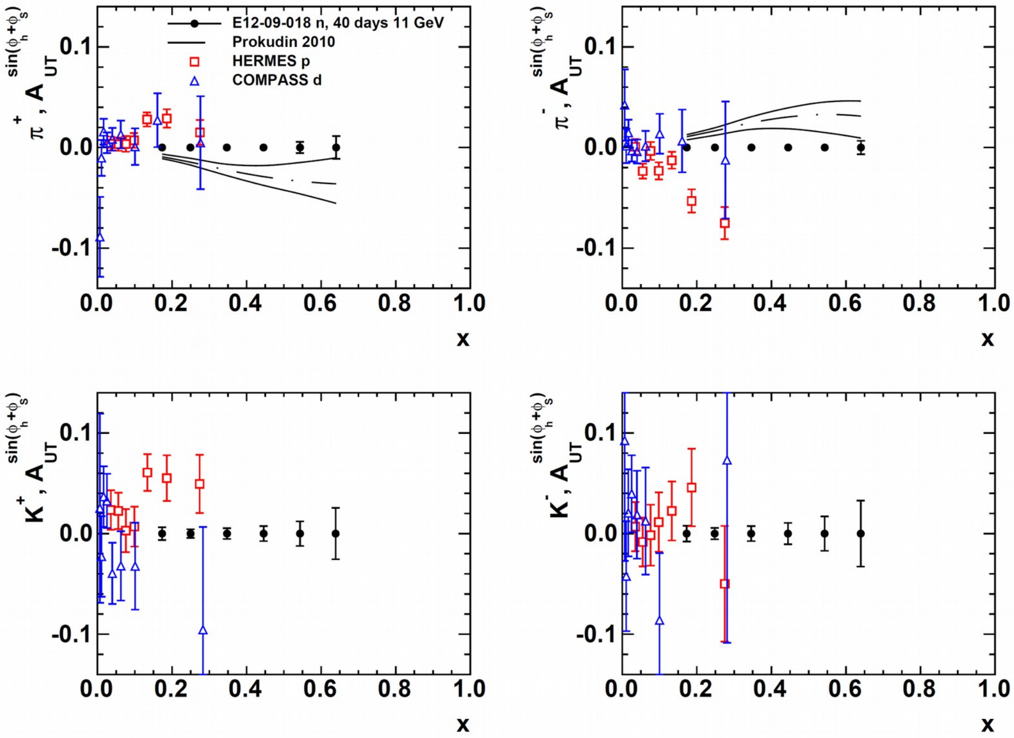
SIDIS with SBS
Projected observables

Overall statistical F.O.M:
- 100 times better than HERMES data;
- 1000 better than Hall A SIDIS @ 6 GeV;

Great extension of dataset at higher x



Projected A_{UT}^{Sivers} vs. x (11 GeV data only)



Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

Plots credit: Andrew Puckett

SIDIS with SBS
Extraction of SIDIS SSA with SBS

Example results for 2D/3D binning (x, z, p_T)

E = 11 GeV, 40 days:

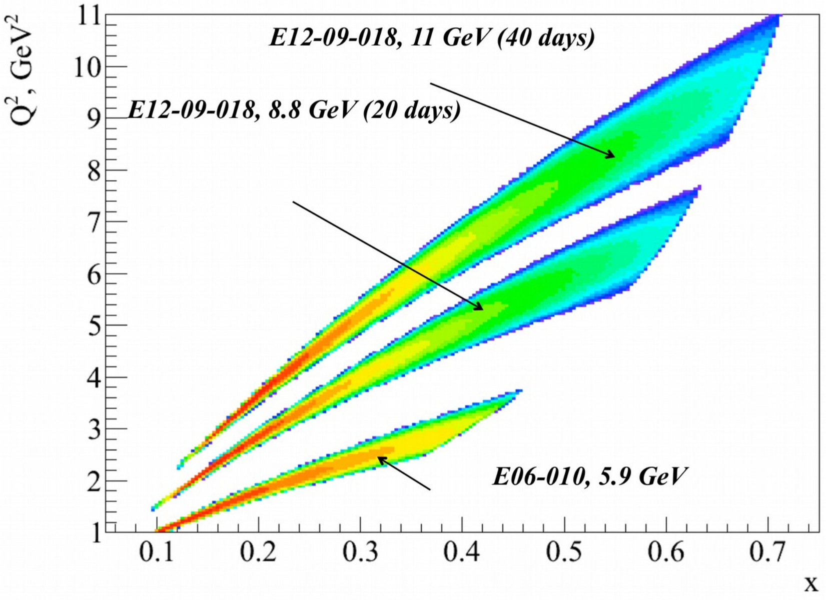
$A_{UT}^{\sin(\phi_h - \phi_S)}$ for $\mathbf{n}(e, e' \pi^+)X$:

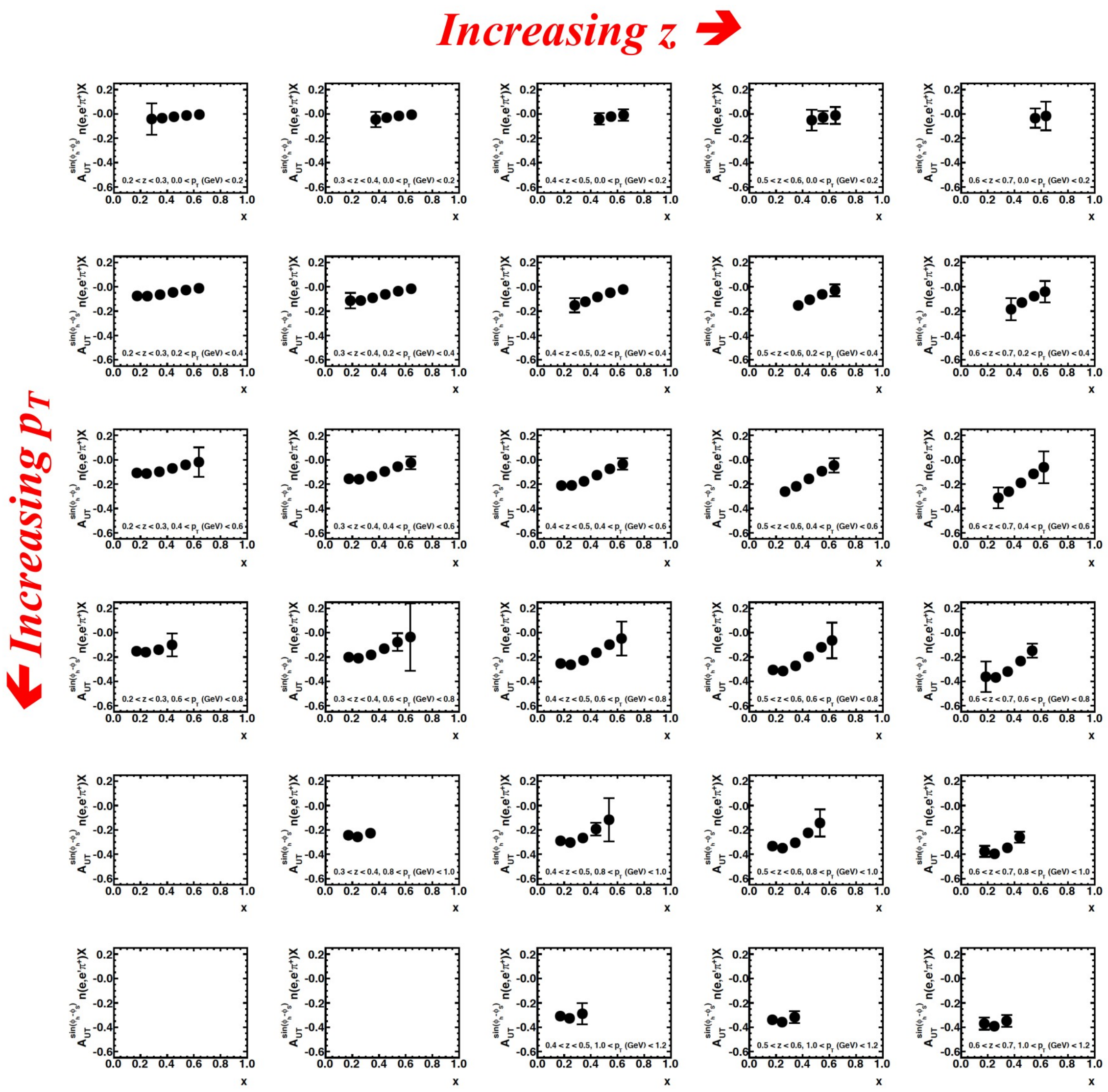
$0.1 < x < 0.7, \Delta x = 0.1$

$0.2 < z < 0.7, \Delta z = 0.1$

$0.0 < p_T$ (GeV) $< 1.2, \Delta p_T = 0.1$ GeV

"4D" with Q^2 dependence from 20 days at 8.8 GeV:




Increasing z ➔

Increasing p_T

Plots credit: Andrew Puckett

Summary

* SIDIS measurements grant access to TMDs, which in turn provide insight on the nucleon content

* The planned SIDIS experiment with SBS on a *transversely polarized helium-3* target will provide a premium insight on the quark orbital angular momentum of the neutron;

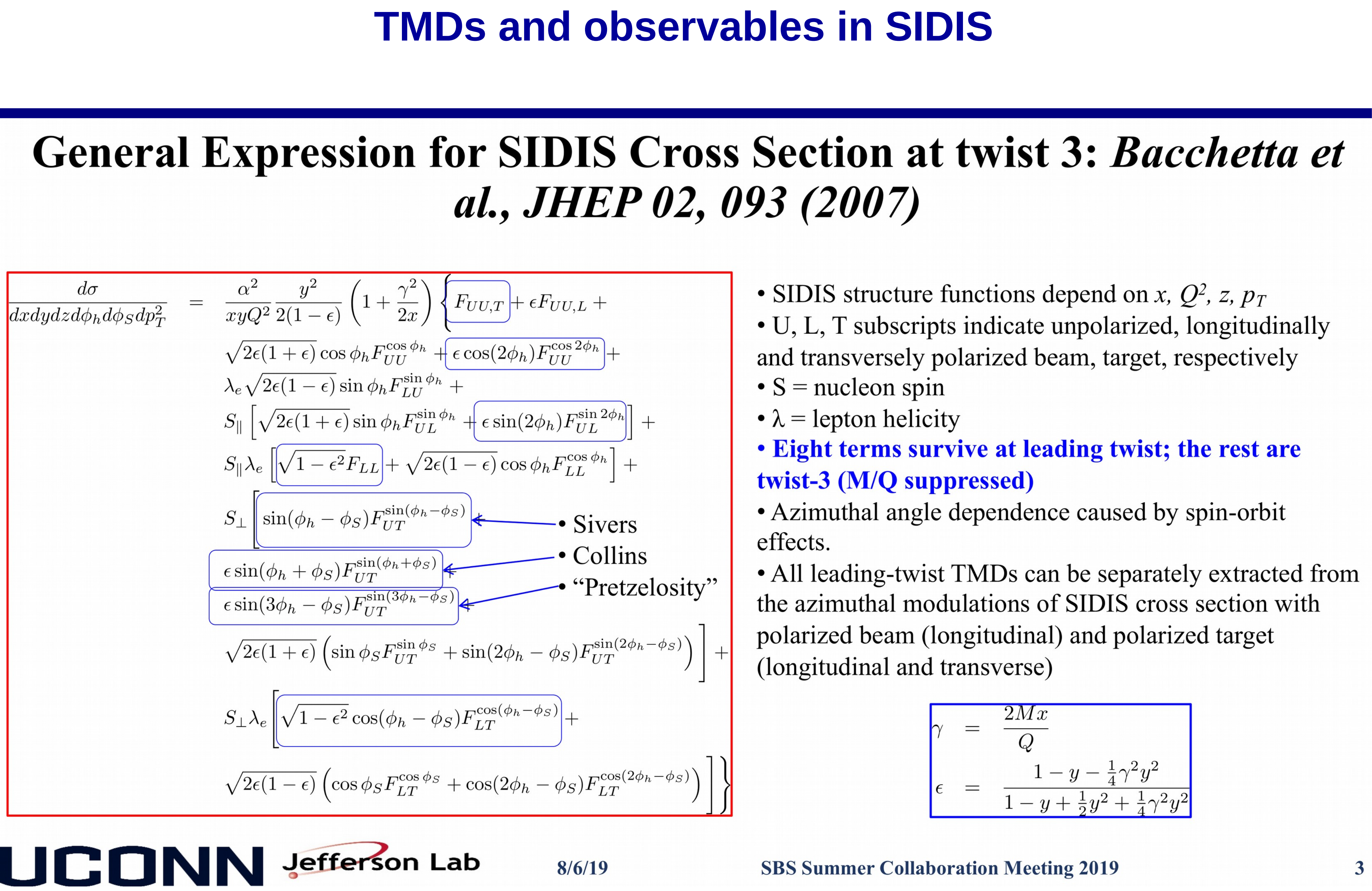
* this experiment will increase statistical figure-of-merit of existing measurements by a factor 100 to 1000, and will *greatly extend x coverage*;

* sharing most of its equipment with the other SBS experiments, and requiring “modest” dedicated effort (see below), it is also reasonably cost effective in terms of development;

** dedicated efforts necessary (=TODO):*

- RICH DAQ update and commissioning;
- polarized target (esp vertical polarization);
- GRINCH integration into BigBite trigger logic;

Thank you for your attention !



TMDs and observables in SIDIS

General Expression for SIDIS Cross Section at twist 3: *Bacchetta et al., JHEP 02, 093 (2007)*

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,d\phi_S\,dp_T^2} = \; & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{\boxed{F_{UU,T}}+\epsilon F_{UU,L}+ \\
& \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}+\boxed{\epsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}}+ \\
& \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}+ \\
& S_\parallel\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\boxed{\epsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}}\right]+ \\
& S_\parallel\lambda_e\left[\boxed{\sqrt{1-\epsilon^2}F_{LL}}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]+ \\
& S_\perp\Bigg[\boxed{\sin(\phi_h-\phi_S)F_{UT}^{\sin(\phi_h-\phi_S)}} \leftarrow \text{• Sivers} \\
& \boxed{\epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}} \leftarrow \text{• Collins} \\
& \boxed{\epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}} \leftarrow \text{• “Pretzelosity”} \\
& \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{UT}^{\sin\phi_S}+\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\right)\Bigg]+ \\
& S_\perp\lambda_e\Bigg[\boxed{\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}}+ \\
& \sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LT}^{\cos\phi_S}+\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\right)\Bigg]\Bigg\}
\end{aligned}
$$

- SIDIS structure functions depend on x, Q^2, z, p_T
- U, L, T subscripts indicate unpolarized, longitudinally and transversely polarized beam, target, respectively
- S = nucleon spin
- λ = lepton helicity
- **Eight terms survive at leading twist; the rest are twist-3 (M/Q suppressed)**
- Azimuthal angle dependence caused by spin-orbit effects.
- All leading-twist TMDs can be separately extracted from the azimuthal modulations of SIDIS cross section with polarized beam (longitudinal) and polarized target (longitudinal and transverse)

$$
\boxed{\begin{aligned}
\gamma &= \frac{2Mx}{Q} \\
\epsilon &= \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}
\end{aligned}}
$$

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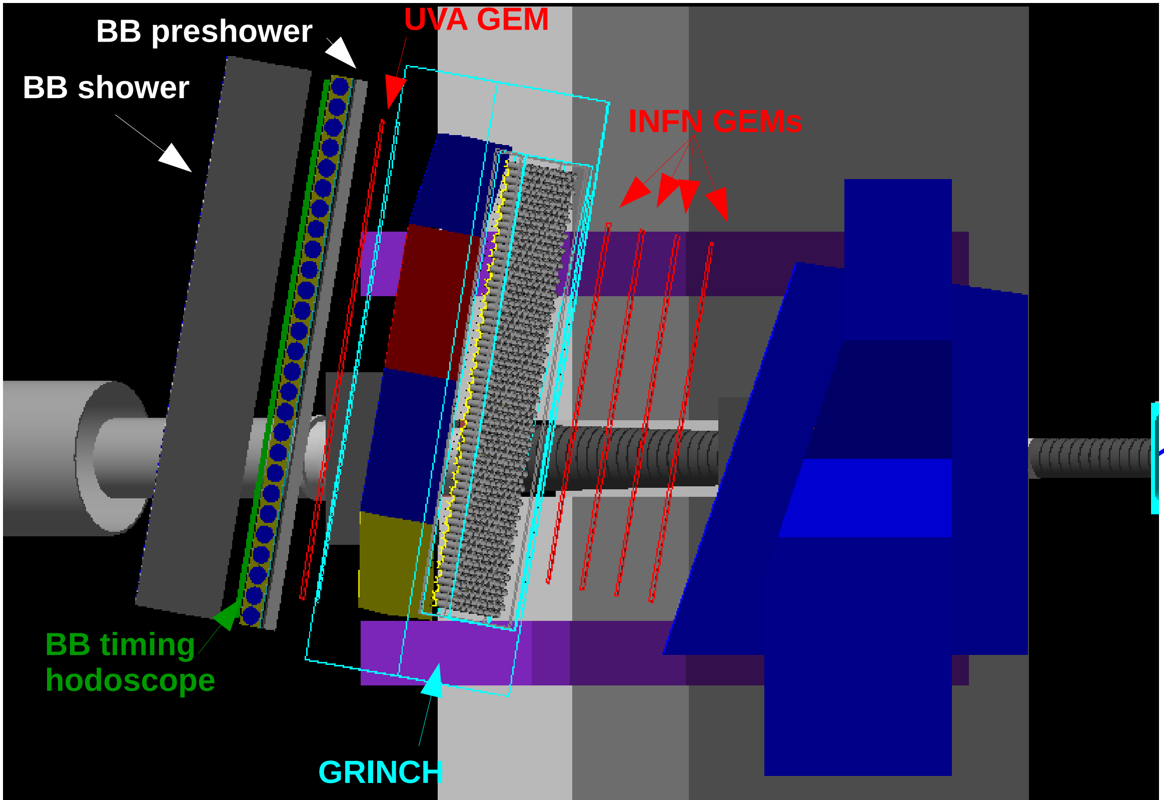
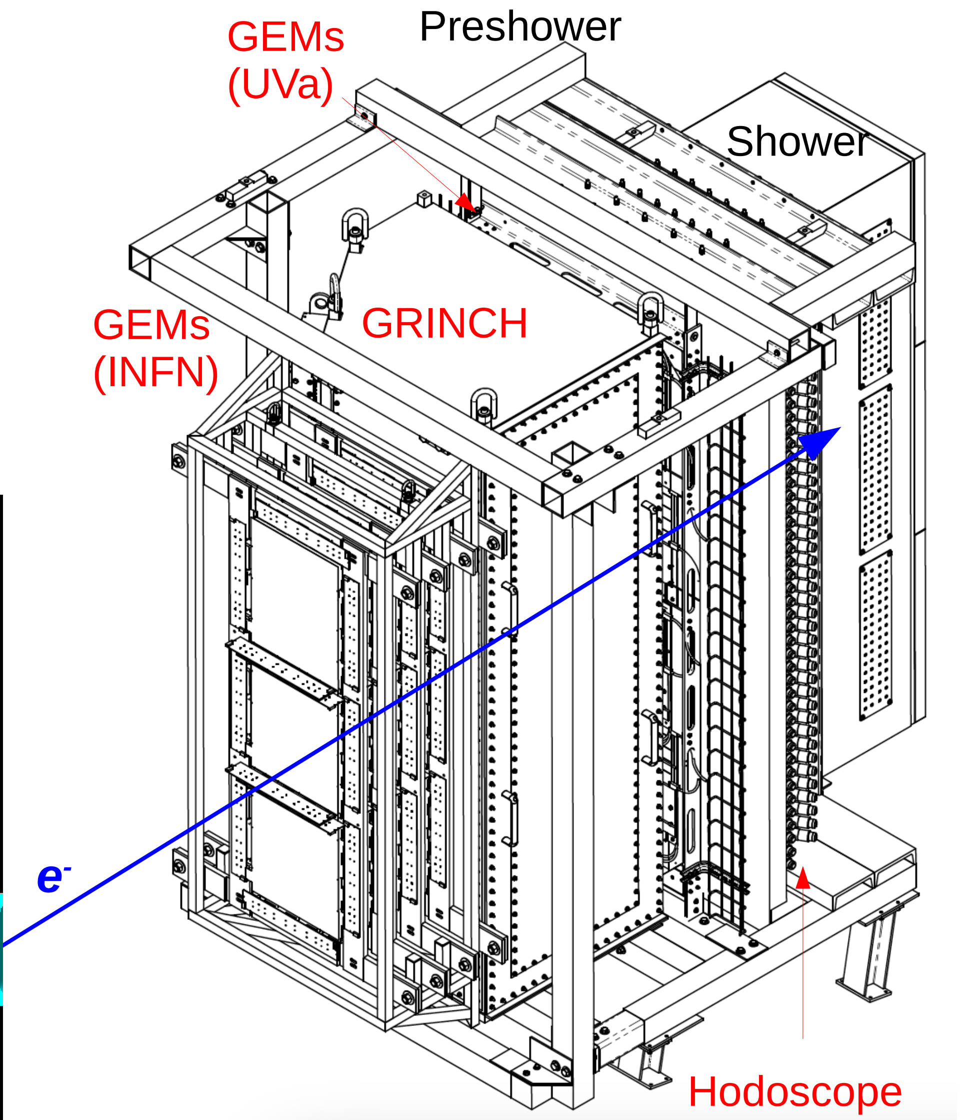
Slide taken (shamelessly) from Andrew, from last SBS collaboration meeting...

SIDIS with SBS

Experimental setup: Electron arm

BigBite:
 * Same detector package as for Form Factors experiments (see Brian and William’s talks for more details);
 * Calorimeter threshold 1 GeV;
 * Trigger logic will have to use calo combined with GRINCH.





SIDIS with SBS

Experimental setup: Hadron arm

SBS:

- 5 planes of UVA GEM (momentum measurement);
- RICH (particle ID);
- HCal (energy measurement+trigger – 2 GeV equiv. thr);
- optional Large Angle Calorimeter in front of HCal for better energy resolution