Transverse-Momentum-Dependent Distributions and Color Entanglement in QCD

Lecture 3 – Experimental Processes and Facilities

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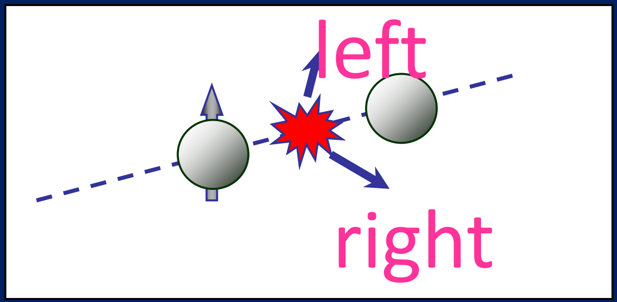

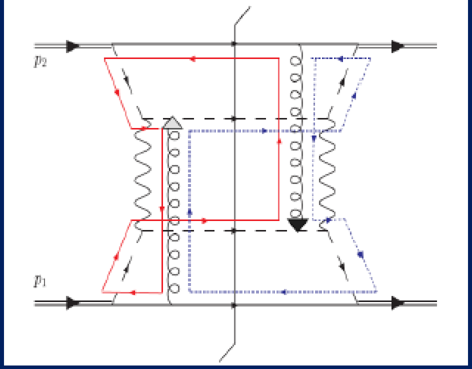

Hampton University Graduate Studies Program
Jefferson Lab
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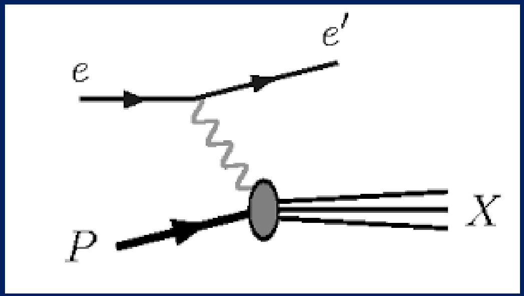
Overview of processes

- Inclusive deep-inelastic lepton-nucleon scattering (DIS)
- Semi-inclusive deep-inelastic lepton-nucleon scattering (SIDIS)
- Electron-positron annihilation to hadrons
- Quark-antiquark annihilation to leptons (Drell-Yan)
- Hadron-hadron collisions to final states involving hadrons

QED processes involving hadrons

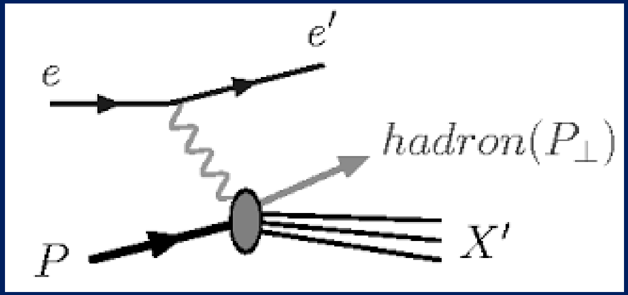
Inclusive DIS



- Inclusive deep-inelastic lepton-nucleon (or lepton-nucleus) scattering
  - “Inclusive” – measure *only* energy and angle of scattered lepton
  - “Deep-inelastic” – probe the nucleon with high enough energies to break it up. Effectively *elastic* scattering off of a quark or antiquark inside the nucleon
  - Gluons only involved at higher orders—can gain information on gluons via Q^2 dependence
- Measured cross sections depend on nucleon structure functions—probe nucleon structure

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$

Semi-inclusive DIS

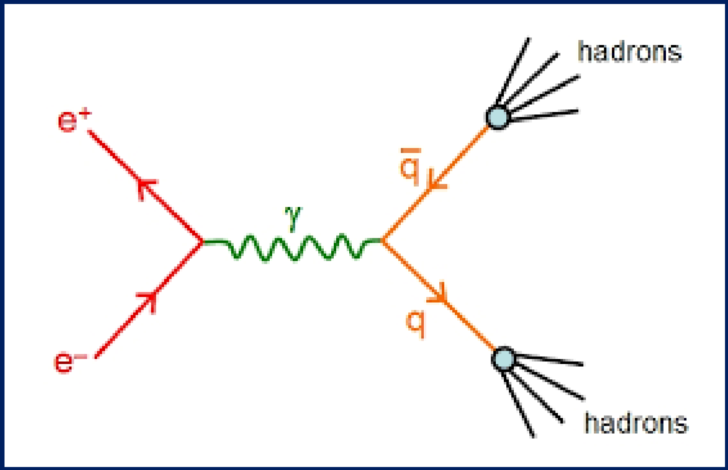


- Semi-inclusive deep-inelastic lepton-nucleon scattering (SIDIS)
  - Measure energy and angle of scattered lepton *and* at least one final-state produced hadron—more information
  - Can study nucleon structure *and* hadronization
  - Measuring scattered lepton and one hadron gives enough vectors to probe transverse-momentum-dependent functions in the nucleon and/or in hadronization

- (“Exclusive” processes – measure *entire* final state, useful e.g. for accessing Generalized Parton Distribution Functions – Julie Roche’s lectures)

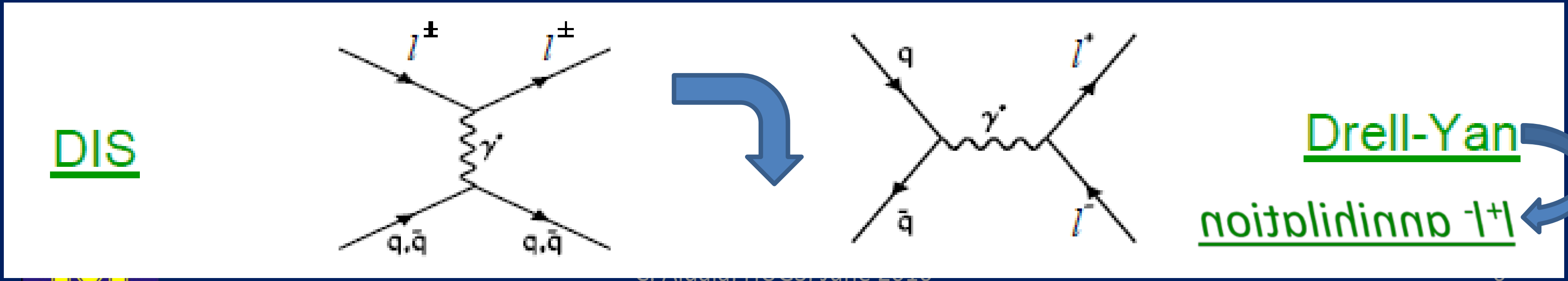
Electron-positron annihilation to hadrons

- e+e- → $q\bar{q}$, measure one or more final-state hadrons
  - "Single-inclusive annihilation" (SIA) – measure only a single produced hadron
  - Study hadronization



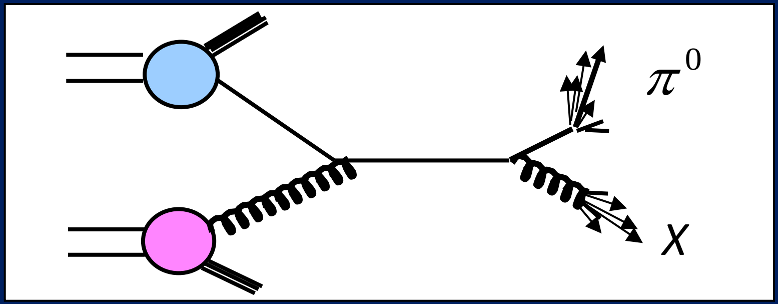
Quark-antiquark annihilation to leptons

- "Drell-Yan" process – Drell and Yan, PRL 25, 316 (1970); Erratum PRL 25, 902 (1970)
- Pion (typically π-, $\bar{u}d$), antiproton, or proton on proton or nucleus
- Also Drell-Yan-like processes of quark-antiquark annihilation or scattering to produce a Z or W boson
- Purely electroweak final state—no observed hadrons
- Study hadron structure
- *Definitively tag antiquarks*
- Related to DIS (inclusive or semi-inclusive) by rotation of the Feynman diagram – Drell-Yan the *s*-channel process, DIS the *t*-channel process
- Related to electron-positron annihilation by time reversal



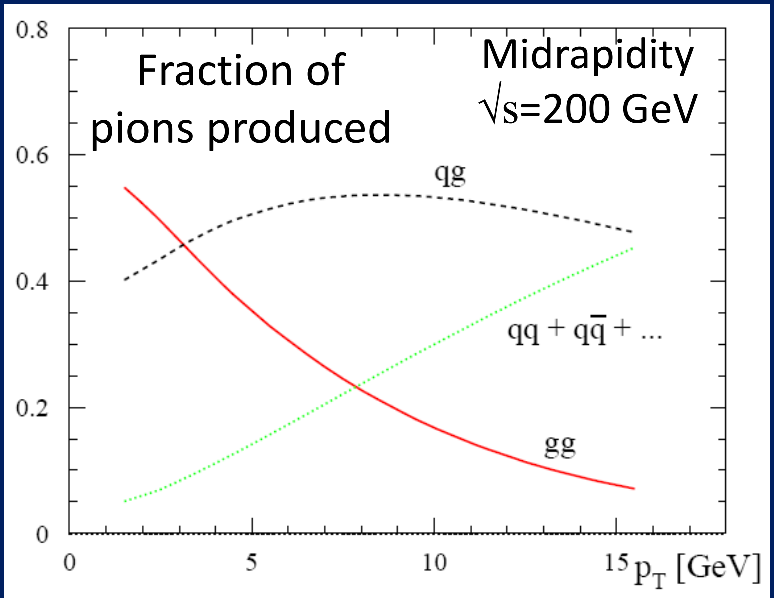
Hadronic collisions to hadrons

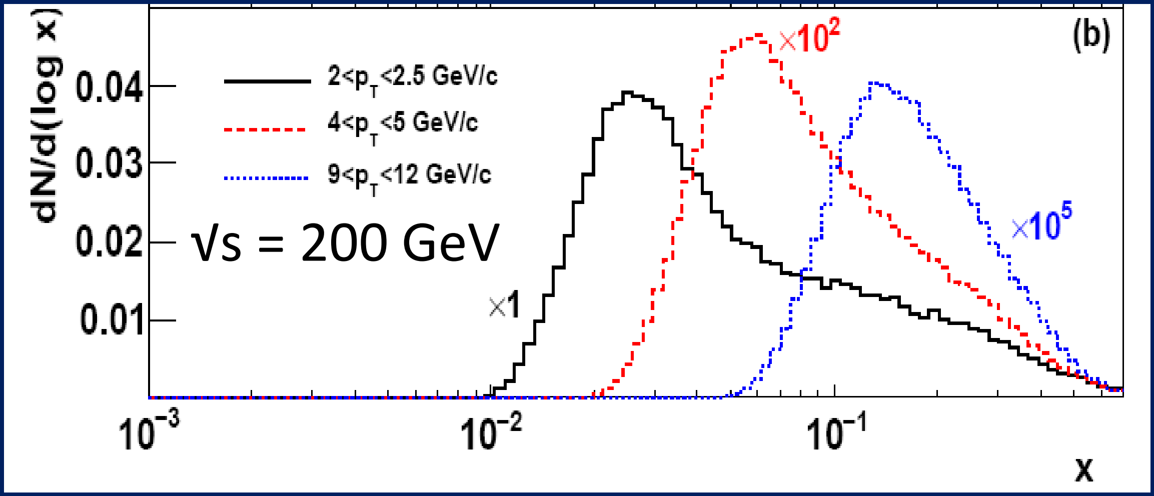
- Quantum *chromo*dynamics process at leading order—gluons can interact directly
- Study structure *and* hadronization
- Two composite objects colliding—in general don't know the exact parton kinematics
  - Measuring a single final-state particle samples from a range of partonic x values and fragmentation z values
  - Fully reconstructing the jet formed by a hadronizing quark or gluon gives access to that outgoing parton's total momentum



$p+p \rightarrow \pi^0 + X$ at RHIC: p_T vs. x

Correlation between p_T of produced pion and *x* of interacting gluon
- Based on simulation using NLO pQCD as input



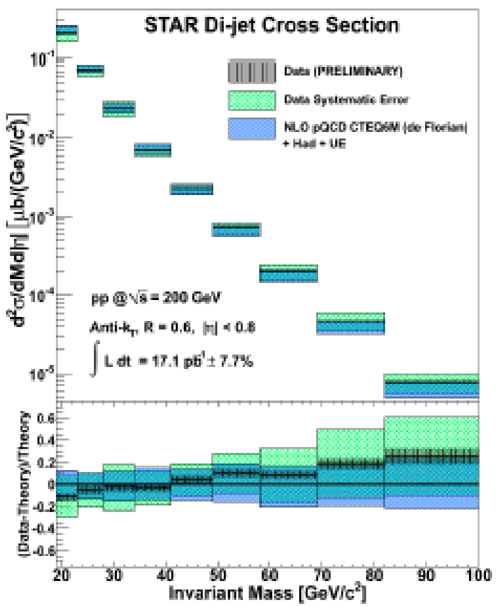


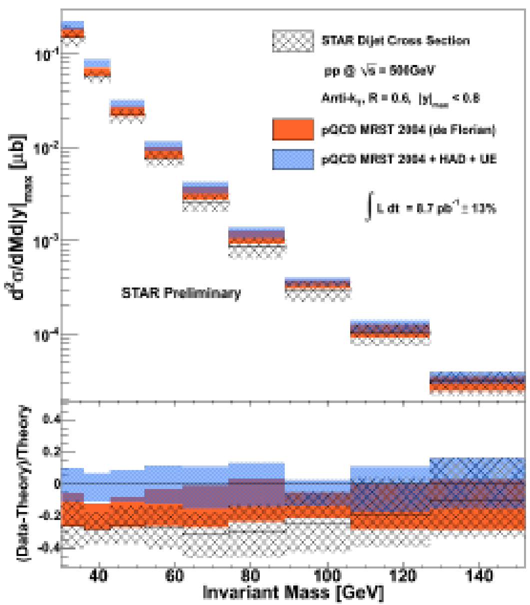
PRL 103, 012003 (2009)

p+p → dijets: Access to full partonic kinematics

- Di-jet permit event by event calculations of x_1 and x_2 at leading order .
- Di-jet cross section is well-described by NLO pQCD with corrections for hadronizations and underlying event.

STAR 2009 di-jet cross section results





$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4}\right)$$

$$M = \sqrt{x_1 x_2 s}$$

$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

$$|\cos\theta^*| = \tanh\frac{|\eta_3 - \eta_4|}{2}$$

From D. Gunarathne

- Di-jet cross section results are well described by the NLO pQCD calculations.

Experiments

- DIS, SIDIS
  - H1 and ZEUS at HERA electron-proton and positron-proton collider, DESY (1992-2007)
  - HERMES electron or positron beam on polarized proton, polarized deuterium, or nuclear targets, DESY (1995-2007)
  - COMPASS muon beam on various targets, e.g. polarized NH_3, polarized deuterium, CERN (2002-present)
  - JLab 6 and now 11-12 GeV electron beam on various targets (1994-present)
  - Future Electron-Ion Collider

- Electron-positron annihilation
  - BaBar at SLAC (1999-2008)
  - Belle at KEK (1999-present)
  - BES III at the Beijing Electron-Positron Collider (2008-present)
  - With Higgs mass ~125 GeV, an e+e- “Higgs factory” with center-of-mass a few hundred GeV could be very interesting for hadronization studies at complementary scales to B factories. . .
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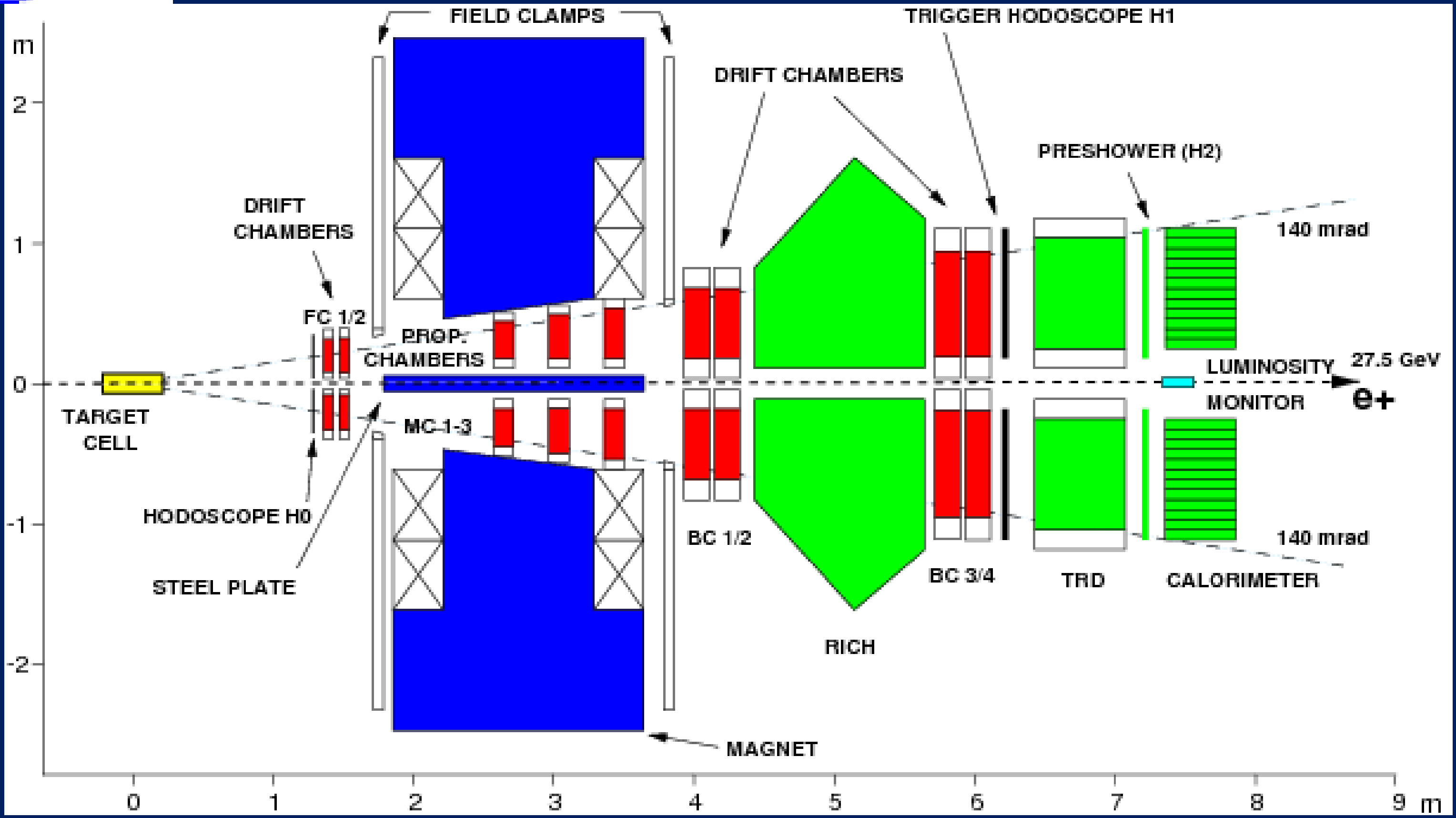
Experiments (cont.)

- Drell-Yan
  - CDF and D0 at Tevatron, antiproton-proton collider, Fermilab (1987-2011)
  - Fermilab E866/NuSea, proton beam on hydrogen, deuterium, and nuclear targets (1994-1996)
  - Fermilab E906/SeaQuest, proton beam on hydrogen, deuterium, and nuclear targets (2014-present)
  - COMPASS, π- beam on polarized NH_3 (2014-present with pion beam)
  - PHENIX, STAR at RHIC, polarized proton-proton collider, BNL (2001-present)
  - CMS, ATLAS, LHCb at LHC, proton-proton collider, CERN (2009-present)

- Hadronic-collisions to hadrons
  - PHENIX, STAR, BRAHMS at RHIC – polarized p+p, nuclear collisions
  - CMS, ATLAS, ALICE, LHCb at LHC p+p and nuclear collisions
  - COMPASS - π- beam on various targets (for hadron spectroscopy)
  - NA61/SHINE at CERN – pions, protons, and nuclear beams on various nuclear targets (2007-present)
  - J-PARC facility – proton, pion, kaon, neutron beams on various targets (2008-present)
  - CDF and D0 at Tevatron, antiproton-proton collider, Fermilab
  - Various other experiments longer ago . . .

HERMES at DESY

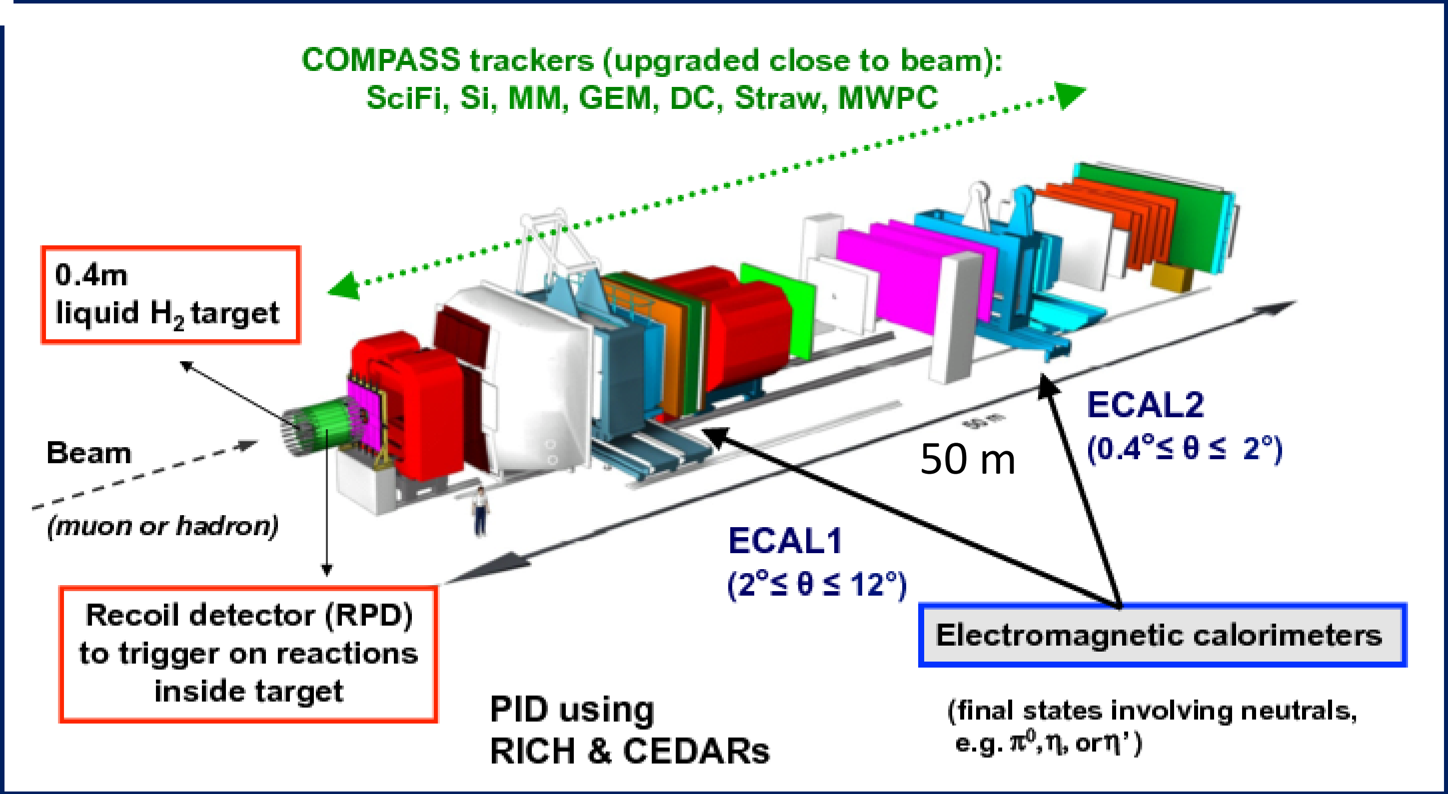


- 27 GeV e- or e+ beam from HERA, longitudinally polarized "naturally" via the Sokolov-Ternov effect

HERMES at DESY

Beam

COMPASS at CERN



- 160 GeV muon beam from SPS (proton beam on Be produces pions, which decay to muons), polarized “naturally” via the weak force

SIDIS angular-dependent cross section in terms of structure functions

From C. van Hulse

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2\,d\phi_S} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_h)F_{UU}^{\cos(\phi_h)} + \epsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}$$

beam polarization

$$+\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h)F_{LU}^{\sin(\phi_h)}$$

longitudinal target polarization

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h)F_{UL}^{\sin(\phi_h)} + \epsilon\sin(2\phi_h)F_{UL}^{\sin(2\phi_h)}\right]$$

$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h)F_{LL}^{\cos(\phi_h)}\right]$$

transverse target polarization

$$+S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\ \epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\ \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)}$$

$$+\ \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

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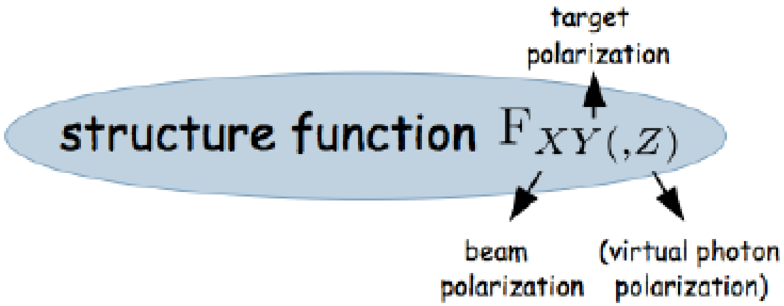
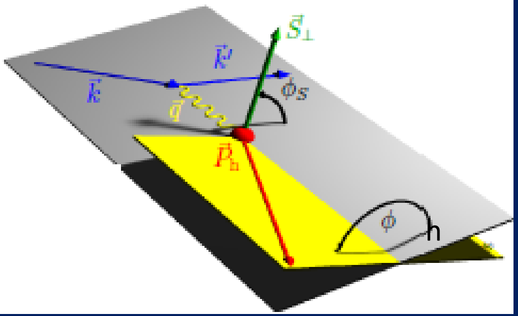




SIDIS angular-dependent cross section in terms of TMD pdfs and FFs

From J.-C. Peng

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$f_1 =$

Boer-Mulders $h_1^\perp =$

$h_{1L}^\perp =$

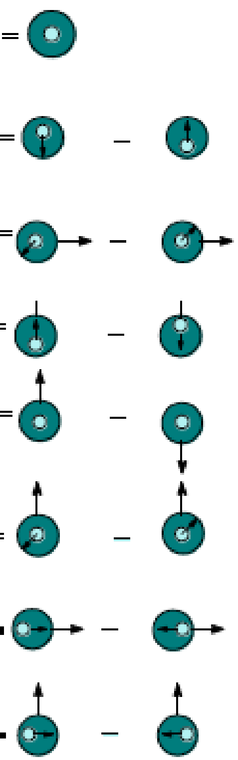
Transversity $h_{1T} =$

Sivers $f_{1T}^\perp =$

$h_{1T}^\perp =$

$g_{1L} =$

$g_{1T} =$



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Polarzied beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z, P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

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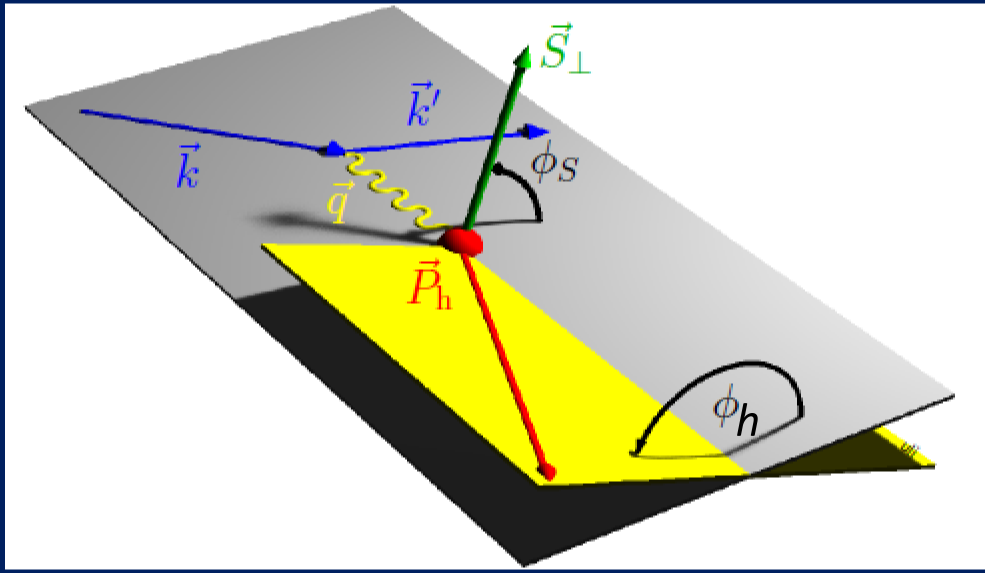
SIDIS vector diagram for a transversely polarized target

- The grey plane is defined by the $\vec{k}$ and $\vec{k}'$ vectors, which are the incoming and outgoing lepton momenta
- The yellow plane is defined by the produced hadron momentum and the virtual photon momentum (experimentally known via the difference $\vec{k} - \vec{k}' = \vec{q}$)
- Angle ϕ_S between lepton plane and spin vector
- Angle ϕ_h between lepton plane and hadron plane
  - Note: ϕ_h also just denoted ϕ sometimes



See the "Trento Conventions" for a definition of angles: PRD70, 117504 (2004)

A SIDIS TMD pdf measurement

- Sivers amplitudes – function of $\sin(\phi_h-\phi_S)$, for unpolarized lepton beam on transversely polarized target
- Can directly relate to structure functions
- Structure functions can in turn be related to pdfs and FFs, here Sivers TMD pdf convoluted with unpolarized TMD FF

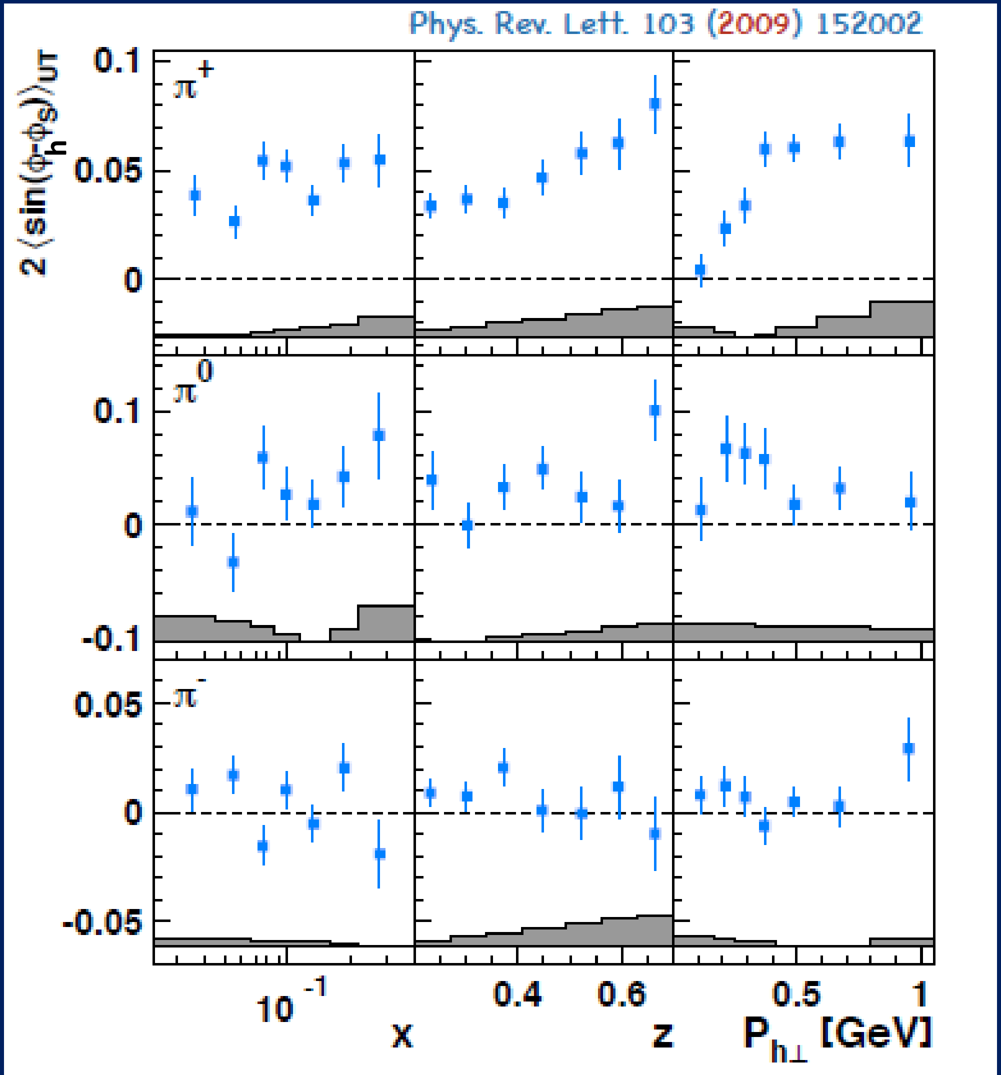
$$F_{UU}^{\cos\phi_h} \propto f_1 \otimes D_1,$$

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

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

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

$$\ldots$$



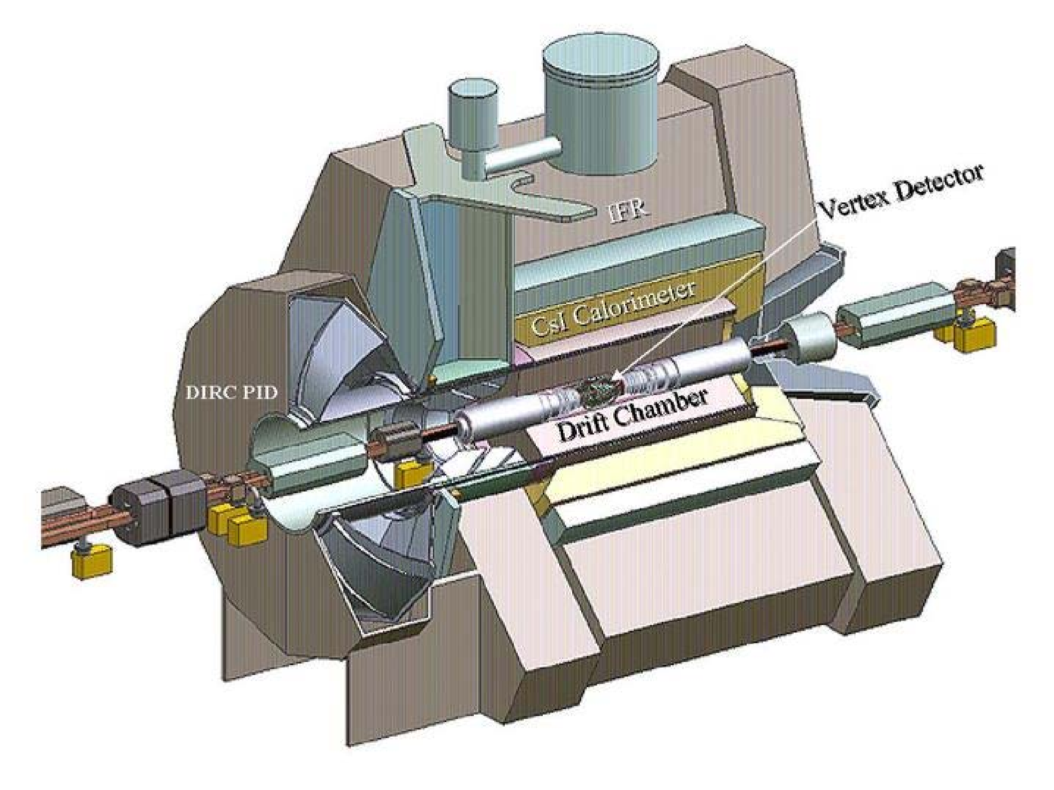
Another way of looking at the Sivers TMD pdf

- pdf describing correlation between spin of transversely polarized proton and transverse momentum of quark inside it
- Can think of the TMD pdf for an unpolarized quark in a transversely polarized proton and decompose it into polarized and unpolarized parts

$$f_{1T}(\mathrm{x}, k_T) = f_1(\mathrm{x}, k_T) + \frac{1}{2} f_{1T}^{\perp}(\mathrm{x}, k_T) \boldsymbol{S} \cdot (\boldsymbol{P} \times \boldsymbol{k}_T)$$

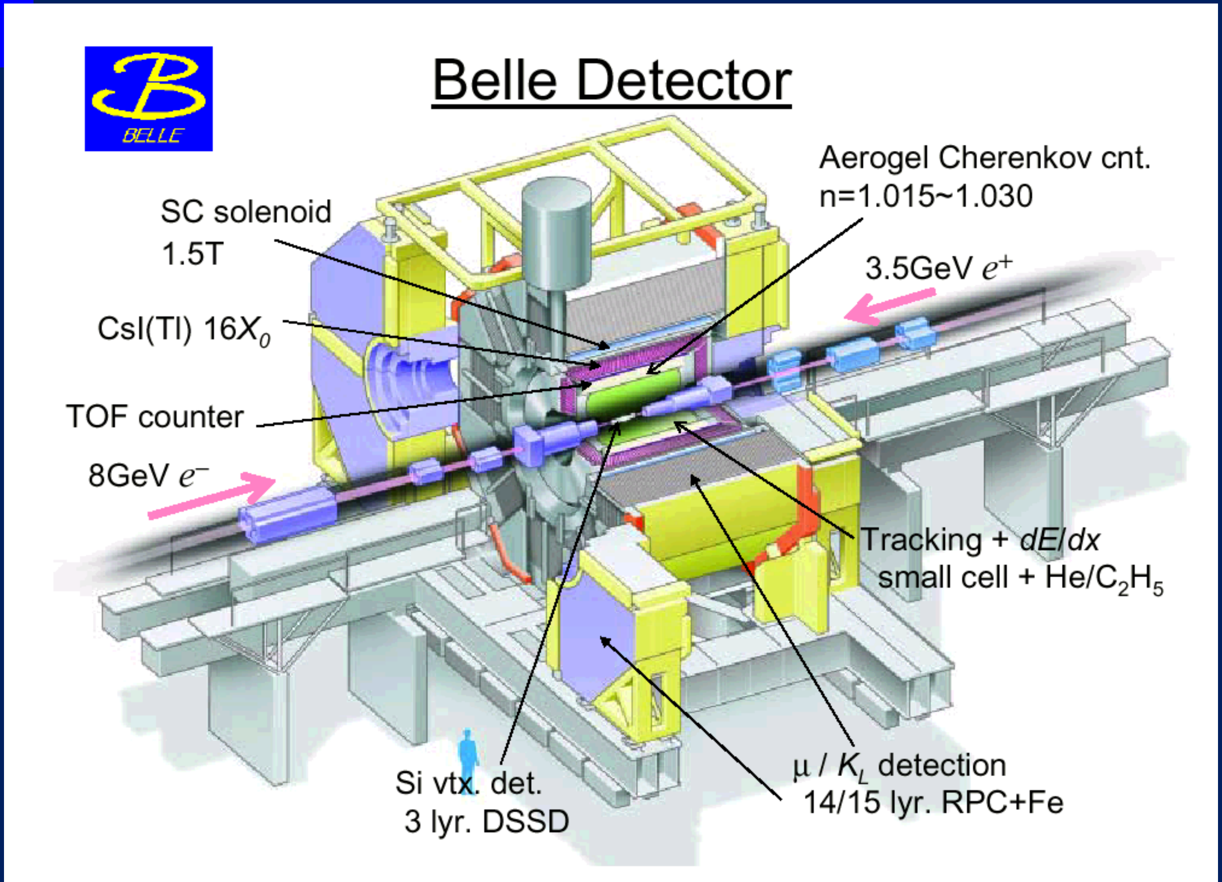
Unpolarized TMD pdf Sivers TMD pdf

BaBar at SLAC



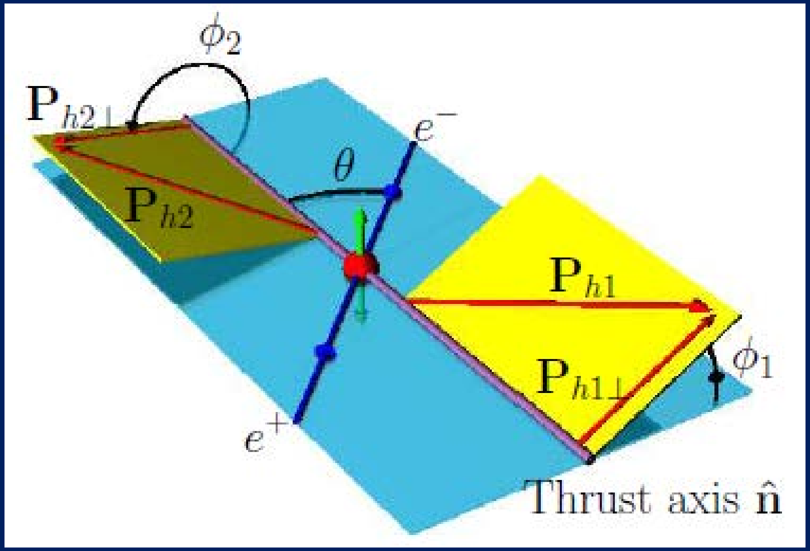
- 9.0 GeV electron beam colliding with 3.1 GeV positron beam
  - Asymmetric so that produced particles are boosted in the lab frame and travel farther before decaying
  - Designed as a B meson factory to study CP violation

Belle at KEK



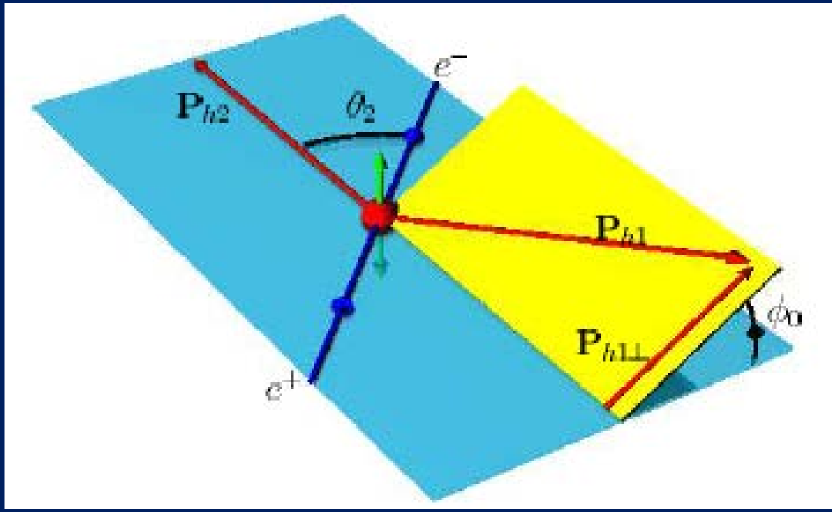
- 8 GeV e- beam on 3.5 GeV e+ beam

e+e- vector diagram to measure the Collins TMD FF



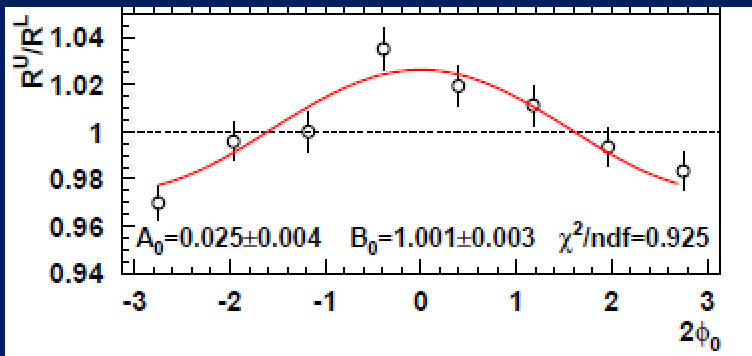
- ϕ_i defined as angle between plane spanned by lepton momenta and thrust axis, and the plane spanned by the thrust axis and the hadron momentum
  - Thrust axis an experimental quantity – proxy for the axis of the produced q-qbar pair
  - Expect a $\cos(\phi_1+\phi_2)$ modulation

Alternative e+e- vector diagram to measure the Collins TMD FF



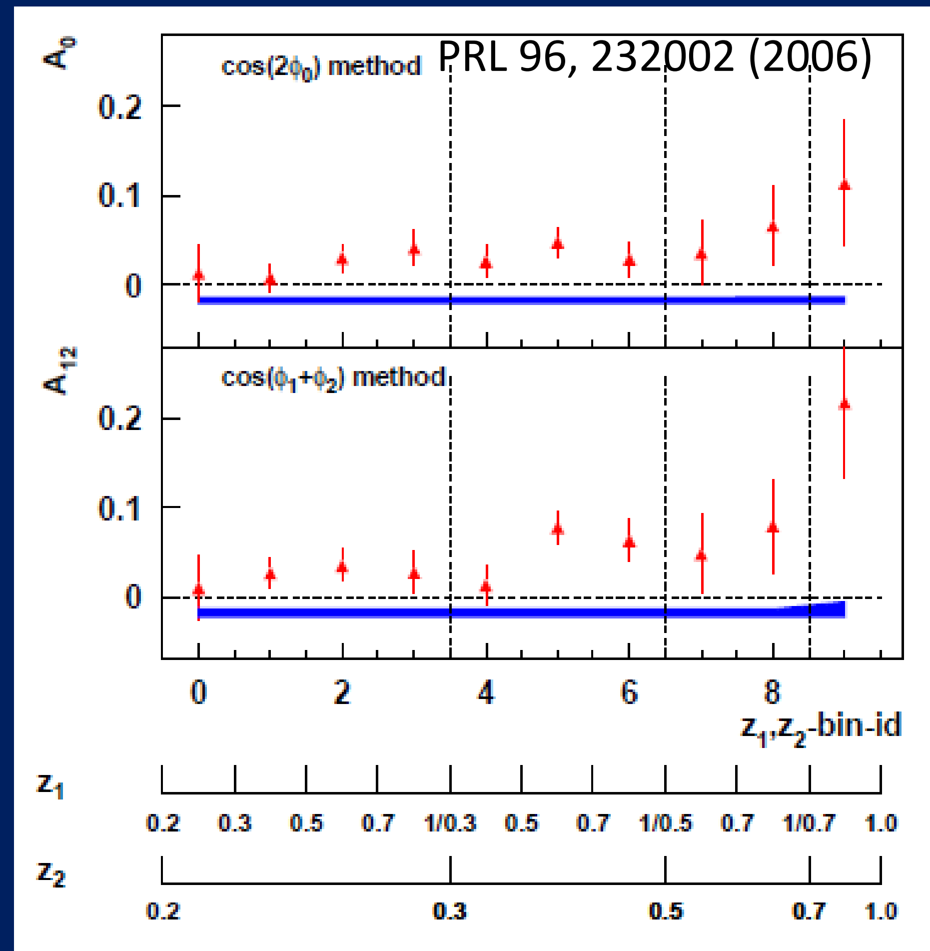
- ϕ_0 defined as angle between plane spanned by lepton momenta and the first hadron, and the plane spanned by lepton momenta and second hadron's transverse momentum with respect to the first
  - Doesn't depend on thrust axis
  - Expect a $\cos(2\phi_0)$ modulation

An e+e- TMD measurement



- Cosine fit to ratio of unlike-sign to like-sign hadron pairs as function of ϕ_0 gives A_0

$$R_0^U/R_0^L = 1 + \cos(2\phi_0)\frac{\sin^2\theta}{1+cos^2\theta} \times \left\{ \frac{f\left(H_1^{\perp,fav}\overline{H}_1^{\perp,fav} + H_1^{\perp,dis}\overline{H}_1^{\perp,dis}\right)}{\left(D_1^{fav}\overline{D}_1^{fav} + D_1^{dis}\overline{D}_1^{dis}\right)} - \frac{f\left(H_1^{\perp,fav}\overline{H}_1^{\perp,dis}\right)}{\left(D_1^{fav}\overline{D}_1^{dis}\right)} \right\};$$



Similar for other method using A_{12}

Another way of looking at the Collins TMD FF

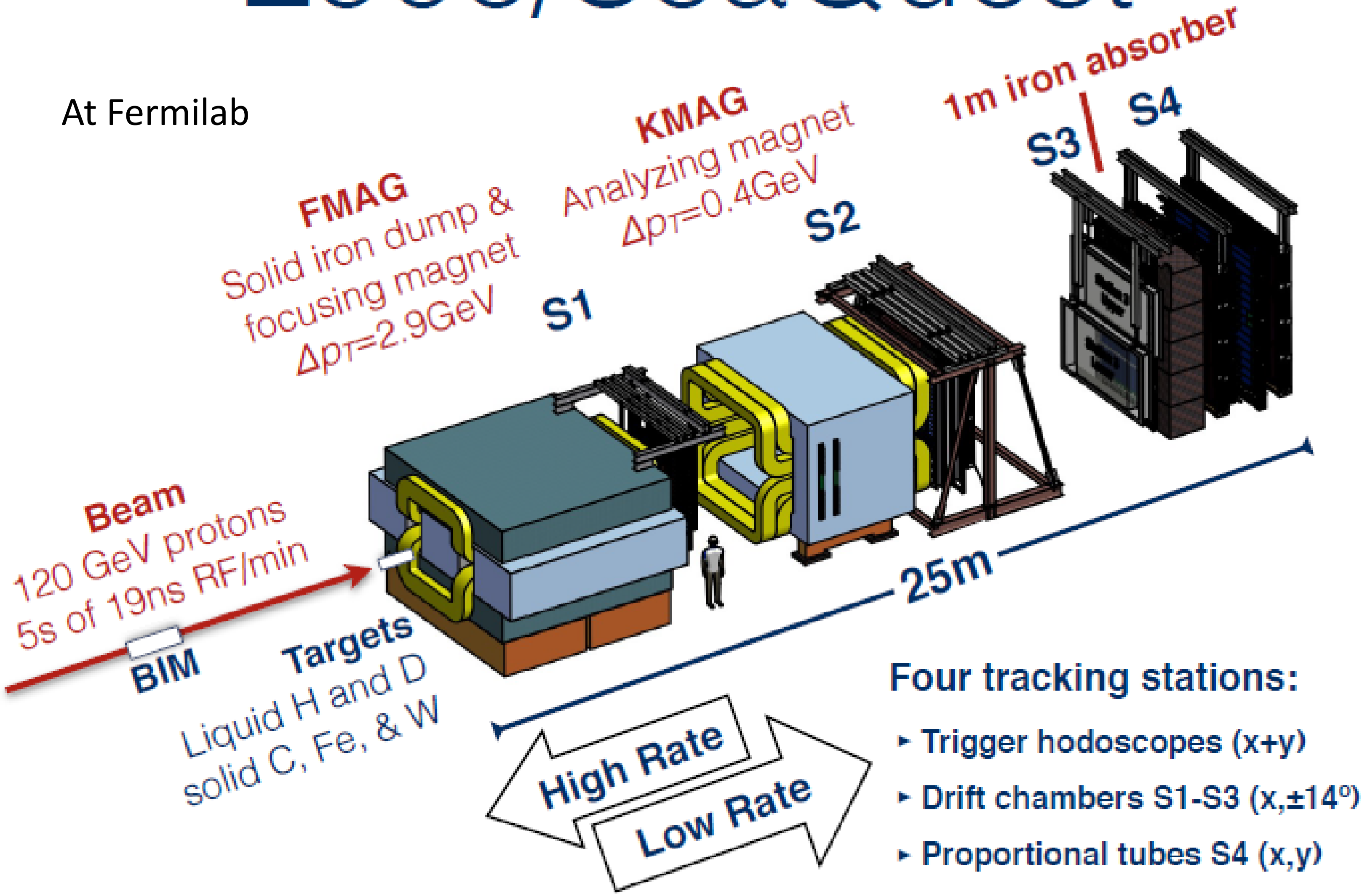
- FF describing correlation between transversely polarized quark and transverse momentum of hadron fragmenting from it
- Can decompose number density for finding hadron *h* with transverse momentum $p_{\perp h}$ from a transversely polarized quark as follows

$$D_{q^\uparrow}^{h}(z,\vec{p}_{h\perp}) = \underbrace{D_1^{q,h}(z)}_{\text{unpolarized FF}} + \underbrace{H_1^{\perp q,h}(z,p_{h\perp}^2)}_{\text{Collins FF}} \frac{\left(\hat{k}\times\vec{p}_{h\perp}\right)\cdot\vec{s}_q}{zM_h}$$

(unpolarized FF should really include transverse momentum as well)

E906/SeaQuest

At Fermilab



Drell-Yan angular-dependent cross section in terms of structure functions

$$
\begin{aligned}
\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha_{em}^2}{F\, q^2} \times \\
& \Big\{ \Big((1+\cos^2\theta)\, F_{UU}^1 + (1-\cos^2\theta)\, F_{UU}^2 + \sin 2\theta \cos\phi\, F_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UU}^{\cos 2\phi} \Big) \\
& + S_{aL} \Big(\sin 2\theta \sin\phi\, F_{LU}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{LU}^{\sin 2\phi} \Big) \\
& + S_{bL} \Big(\sin 2\theta \sin\phi\, F_{UL}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{UL}^{\sin 2\phi} \Big) \\
& + |\vec{S}_{aT}| \Big[\sin\phi_a \Big((1+\cos^2\theta)\, F_{TU}^1 + (1-\cos^2\theta)\, F_{TU}^2 + \sin 2\theta \cos\phi\, F_{TU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{TU}^{\cos 2\phi} \Big) \\
& \qquad + \cos\phi_a \Big(\sin 2\theta \sin\phi\, F_{TU}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{TU}^{\sin 2\phi} \Big) \Big] \\
& + |\vec{S}_{bT}| \Big[\sin\phi_b \Big((1+\cos^2\theta)\, F_{UT}^1 + (1-\cos^2\theta)\, F_{UT}^2 + \sin 2\theta \cos\phi\, F_{UT}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UT}^{\cos 2\phi} \Big) \\
& \qquad + \cos\phi_b \Big(\sin 2\theta \sin\phi\, F_{UT}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{UT}^{\sin 2\phi} \Big) \Big] \\
& + S_{aL}\, S_{bL} \Big((1+\cos^2\theta)\, F_{LL}^1 + (1-\cos^2\theta)\, F_{LL}^2 + \sin 2\theta \cos\phi\, F_{LL}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{LL}^{\cos 2\phi} \Big) \\
& + S_{aL}\, |\vec{S}_{bT}| \Big[\cos\phi_b \Big((1+\cos^2\theta)\, F_{LT}^1 + (1-\cos^2\theta)\, F_{LT}^2 + \sin 2\theta \cos\phi\, F_{LT}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{LT}^{\cos 2\phi} \Big) \\
& \qquad + \sin\phi_b \Big(\sin 2\theta \sin\phi\, F_{LT}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{LT}^{\sin 2\phi} \Big) \Big] \\
& + |\vec{S}_{aT}|\, S_{bL} \Big[\cos\phi_a \Big((1+\cos^2\theta)\, F_{TL}^1 + (1-\cos^2\theta)\, F_{TL}^2 + \sin 2\theta \cos\phi\, F_{TL}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{TL}^{\cos 2\phi} \Big) \\
& \qquad + \sin\phi_a \Big(\sin 2\theta \sin\phi\, F_{TL}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{TL}^{\sin 2\phi} \Big) \Big] \\
& + |\vec{S}_{aT}|\, |\vec{S}_{bT}| \Big[\cos(\phi_a+\phi_b) \Big((1+\cos^2\theta)\, F_{TT}^1 + (1-\cos^2\theta)\, F_{TT}^2 + \sin 2\theta \cos\phi\, F_{TT}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{TT}^{\cos 2\phi} \Big) \\
& \qquad + \cos(\phi_a-\phi_b) \Big((1+\cos^2\theta)\, \bar{F}_{TT}^1 + (1-\cos^2\theta)\, \bar{F}_{TT}^2 + \sin 2\theta \cos\phi\, \bar{F}_{TT}^{\cos\phi} + \sin^2\theta \cos 2\phi\, \bar{F}_{TT}^{\cos 2\phi} \Big) \\
& \qquad + \sin(\phi_a+\phi_b) \Big(\sin 2\theta \sin\phi\, F_{TT}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{TT}^{\sin 2\phi} \Big) \\
& \qquad + \sin(\phi_a-\phi_b) \Big(\sin 2\theta \sin\phi\, F_{TT}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{TT}^{\sin 2\phi} \Big) \Big] \Big\}. \qquad (57)
\end{aligned}
$$

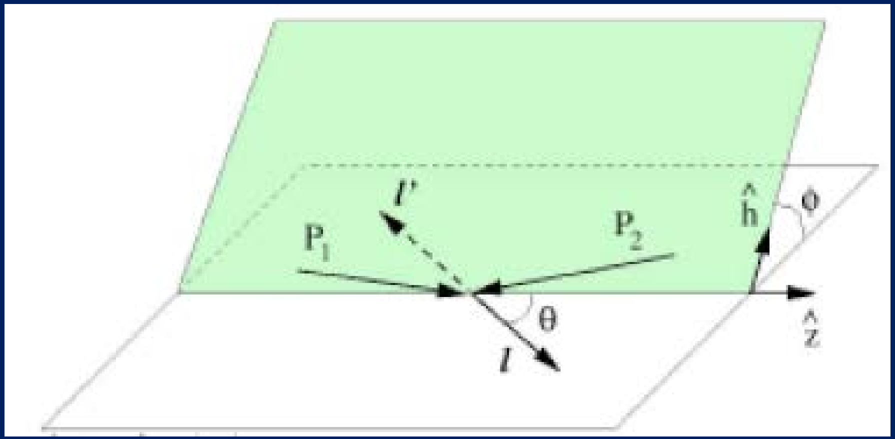
Arnold, Metz, + Schlegel, PRD79, 034005 (2009)

For any dilepton rest frame

Lots of terms!!

Drell-Yan vector diagrams for TMD pdf measurements

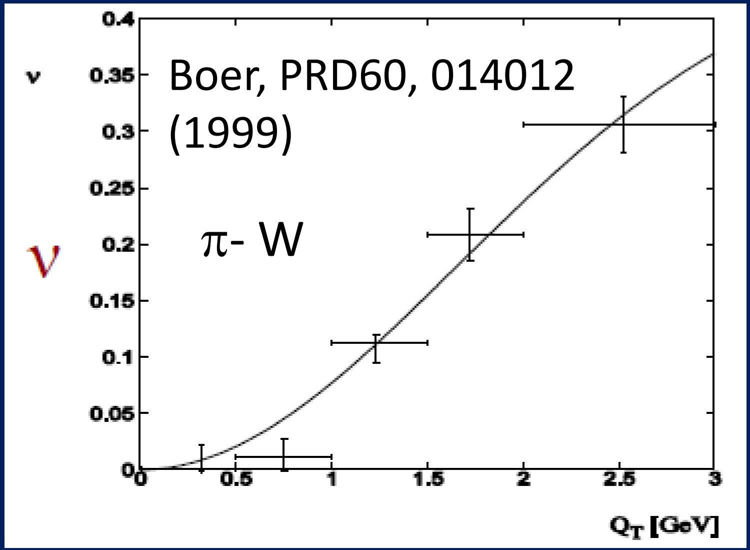
- One plane formed by produced lepton pair; other by incoming quark and antiquark
  - Incoming quark and antiquark cannot be collinear, otherwise can't define a plane!



Dilepton rest frame

A Drell-Yan TMD measurement

- No polarized Drell-Yan measurements so far!



General expression for angular dependence of *unpolarized* Drell-Yan:

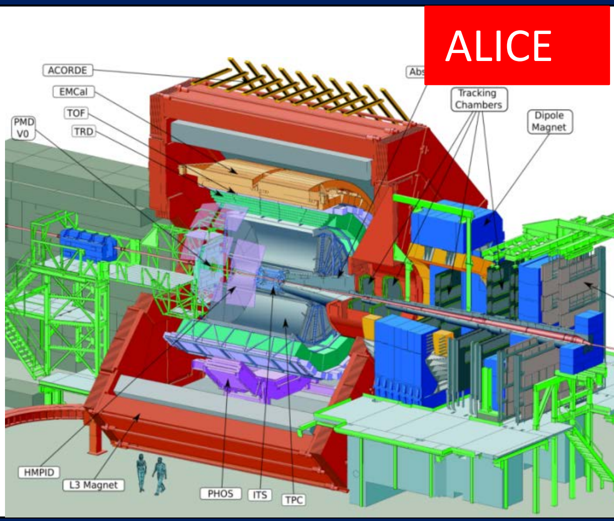
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi\right]$$

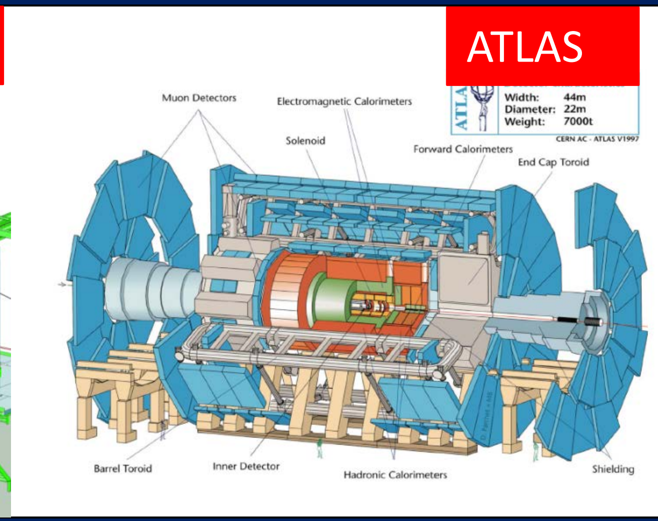
Boer-Mulders TMD pdf leads to cos 2ϕ dependence

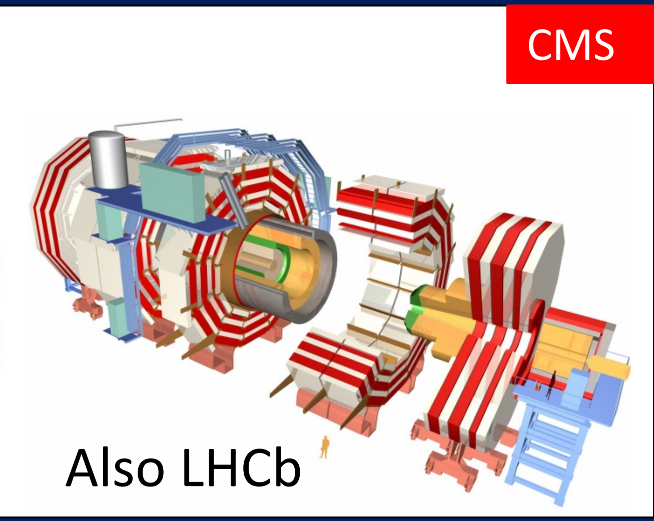
Correlation between transverse spin of (anti-)quark and its own transverse momentum

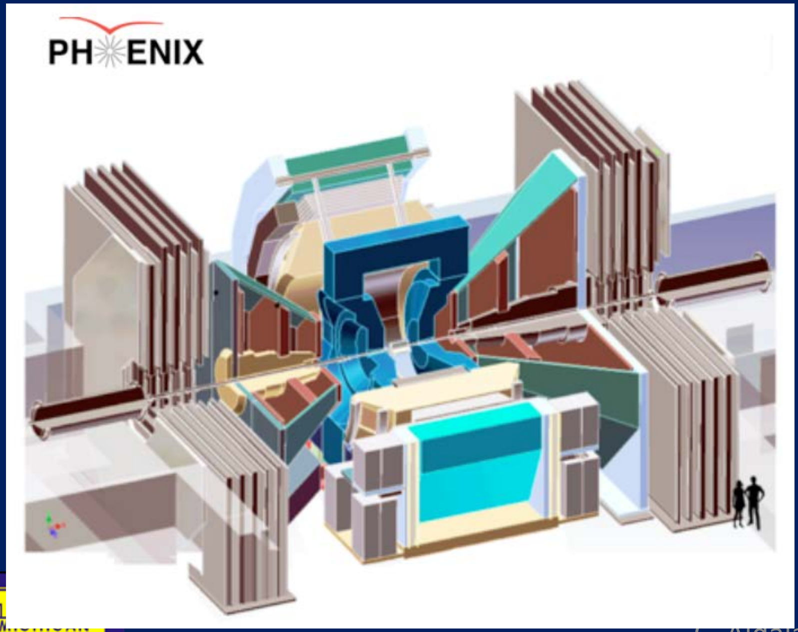
$$\nu \propto \left(\frac{h_1^\perp}{f_1}\right)\left(\frac{\bar{h}_1^\perp}{\bar{f}_1}\right)$$

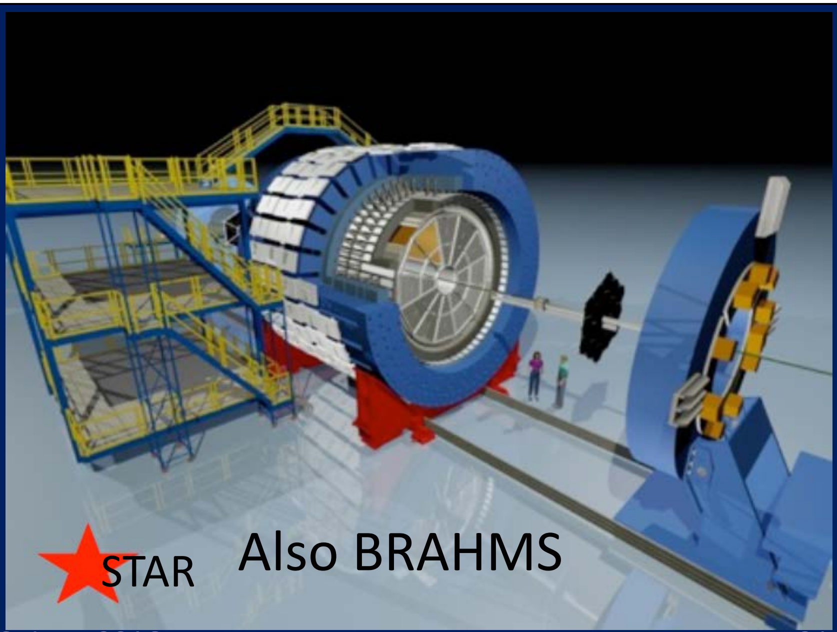
Hadronic collision to hadrons: RHIC and the LHC





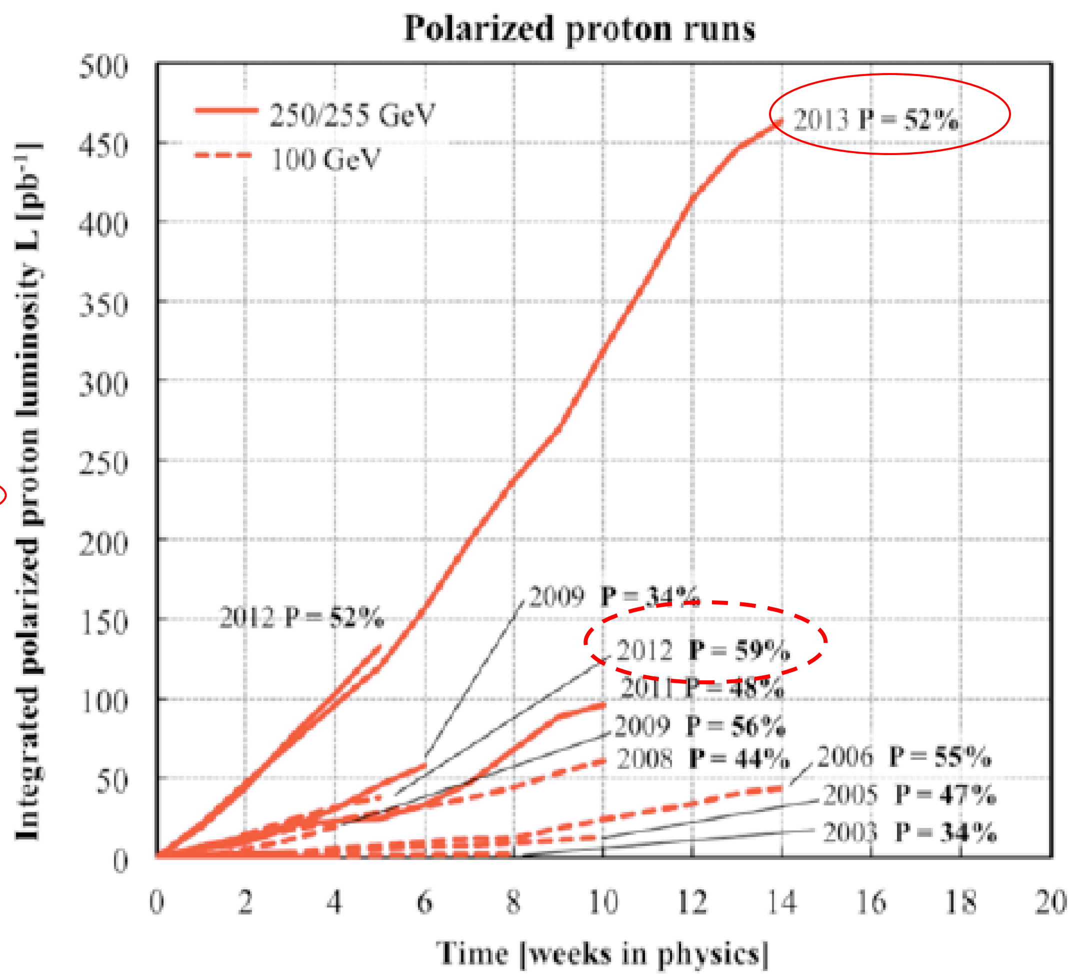






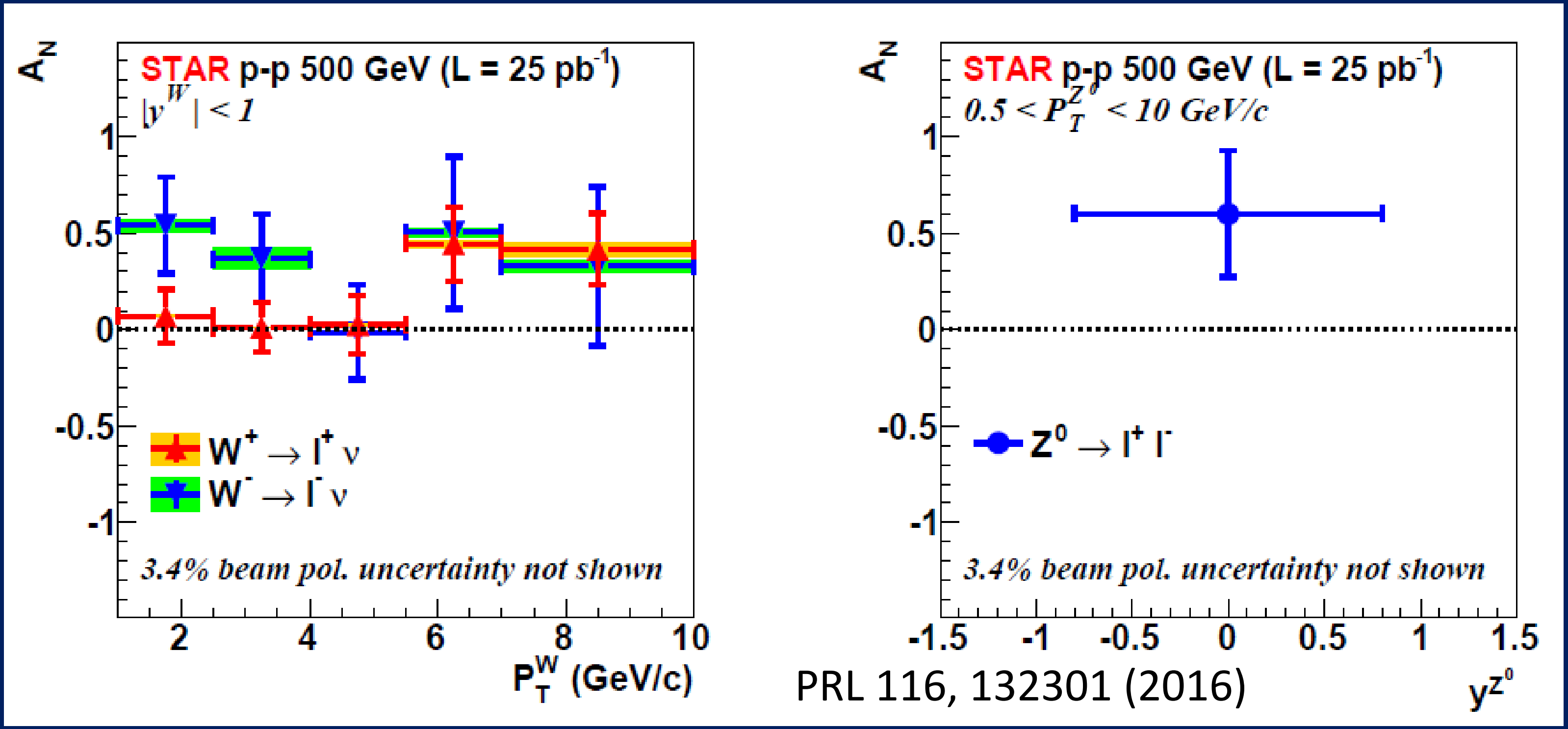
RHIC performance for polarized protons

Longitudinal data	**STAR**
$\sqrt{s}$ = **200 GeV**	
2005	3 pb^{-1}
2006	7 pb^{-1}
2009 (2015)	35 pb^{-1} (50 pb^{-1})
$\sqrt{s}$ = **500 GeV** or 510 GeV	
2009	10 pb^{-1}
2011	12 pb^{-1}
2012	82 pb^{-1}
2013	300 pb^{-1}
Transverse data	
$\sqrt{s}$ = **200 GeV**	
2006	9 pb^{-1}
2008	8 pb^{-1}
2012 (2015)	22 pb^{-1} (50 pb^{-1})
$\sqrt{s}$ = **500 GeV**	
2011 (2016)	25 pb^{-1} (400 pb^{-1})



Also ran at 62.4 GeV in 2006

Measurements of TMD functions at RHIC

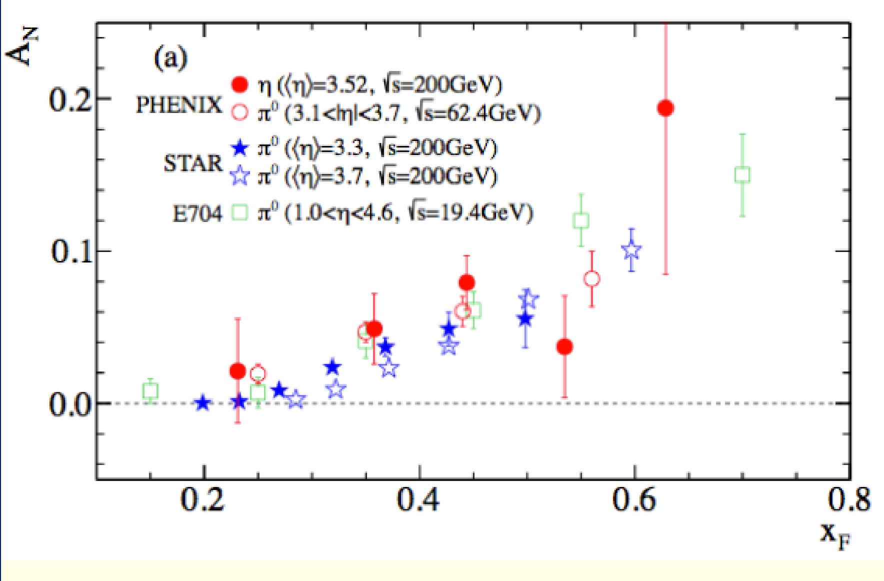


- Sensitive to Sivers TMD pdf – correlation between proton transverse spin and quark transverse momentum
- With more statistics from 2017, may be able to test relative sign difference between SIDIS and Drell-Yan-like processes

Measurements of TMD functions at RHIC

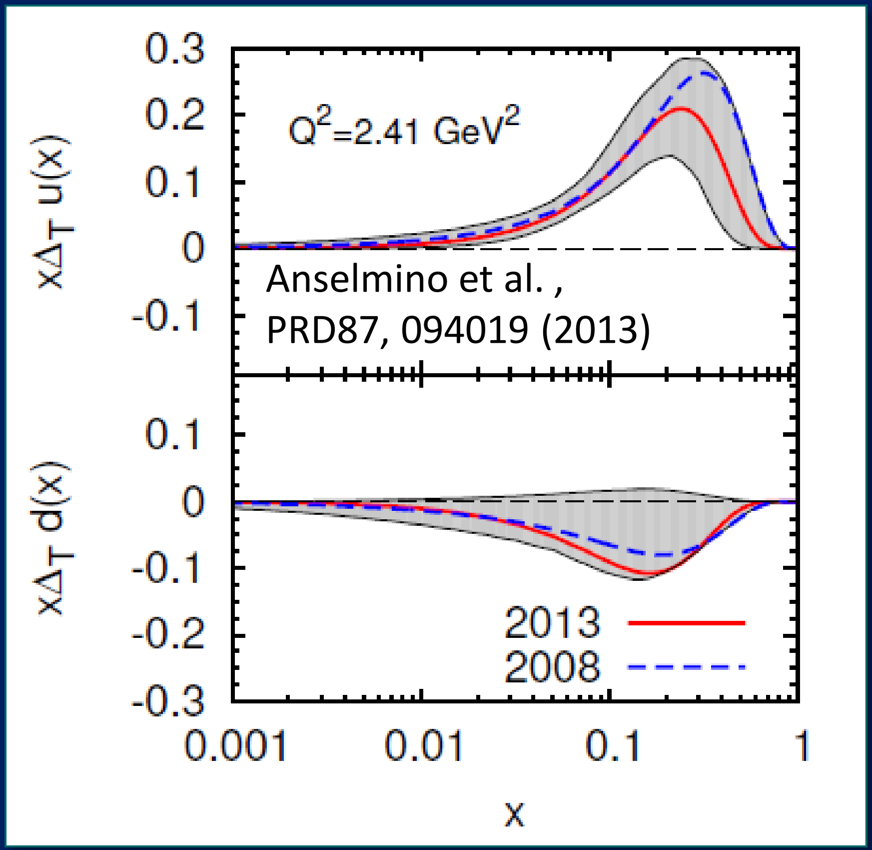
PRD90, 072008 (2014)

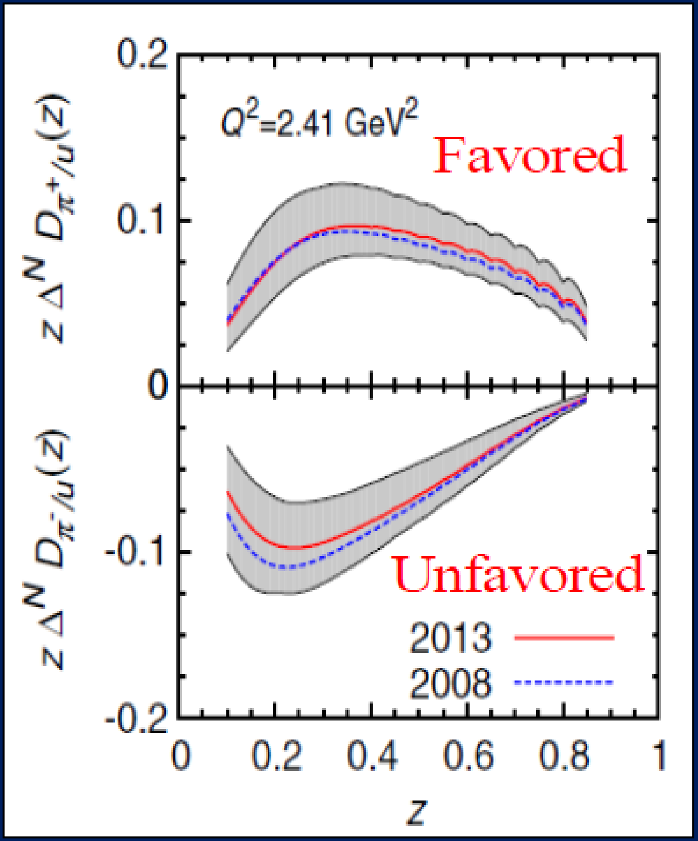
- Large spin-momentum correlations measured for production of hadrons at RHIC
  - But might be probing physics even more interesting than TMD pdfs and FFs! See next lectures . . .



Large η A_N observed by STAR and PHENIX (and Fermilab E704), similar in magnitude to π^0

Simultaneous extraction of functions: Example - transversity pdf and Collins FF





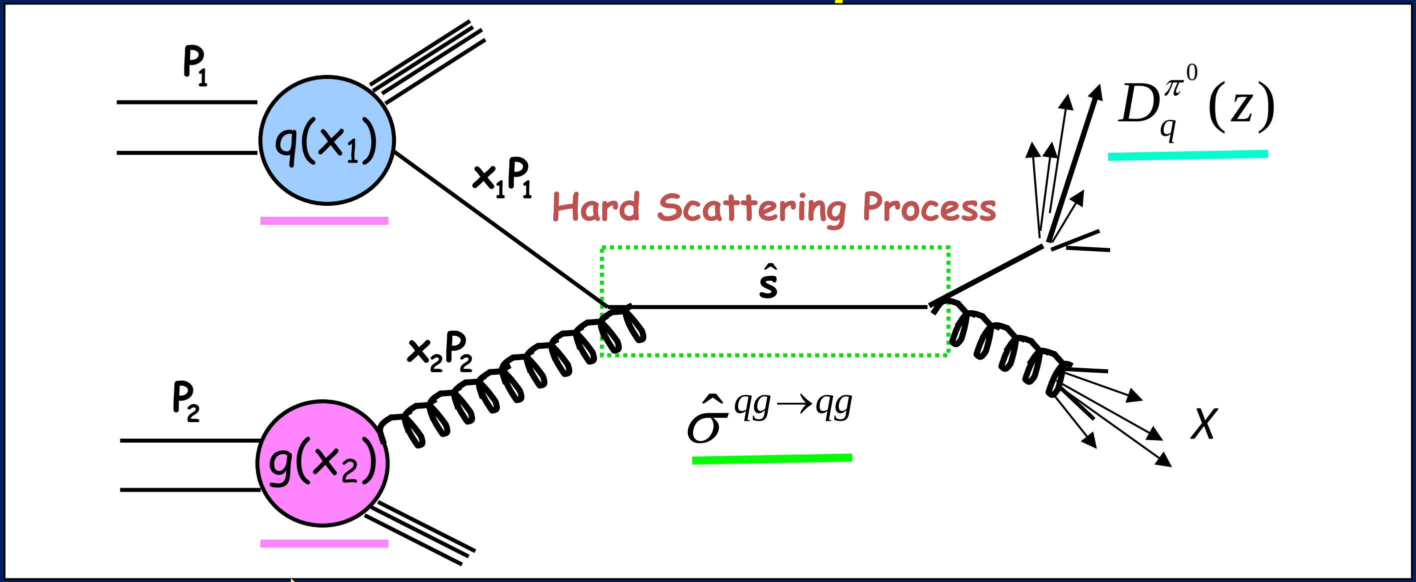
- Extracted from simultaneous fit to HERMES and COMPASS SIDIS data and BELLE e+e- data.

Summary: Lecture 3

- Different processes provide complementary information on (transverse-momentum-dependent) nucleon structure and hadronization
- Success of simultaneous fits to measurements of multiple processes provides evidence that we're uncovering *universal* descriptions of partonic behavior in the nucleon

Extra

Parton distribution functions in perturbative QCD calculations of observables



$$\sigma\left(pp \to \pi^0 X\right) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg \to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

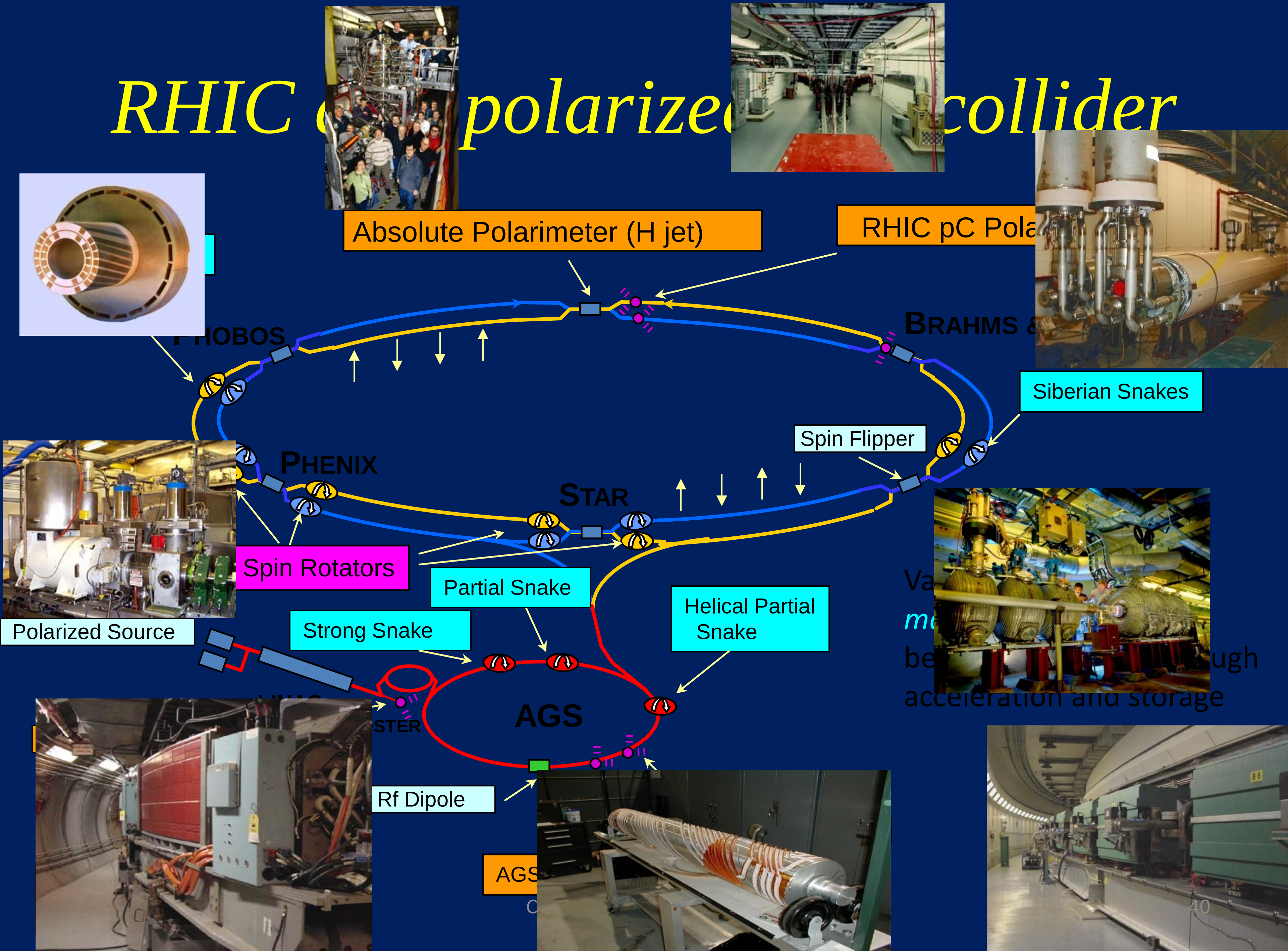
High-energy processes have predictable rates given:

- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (experiment or lattice)
- Fragmentation functions (experiment or lattice)

} **Universal non-perturbative factors**

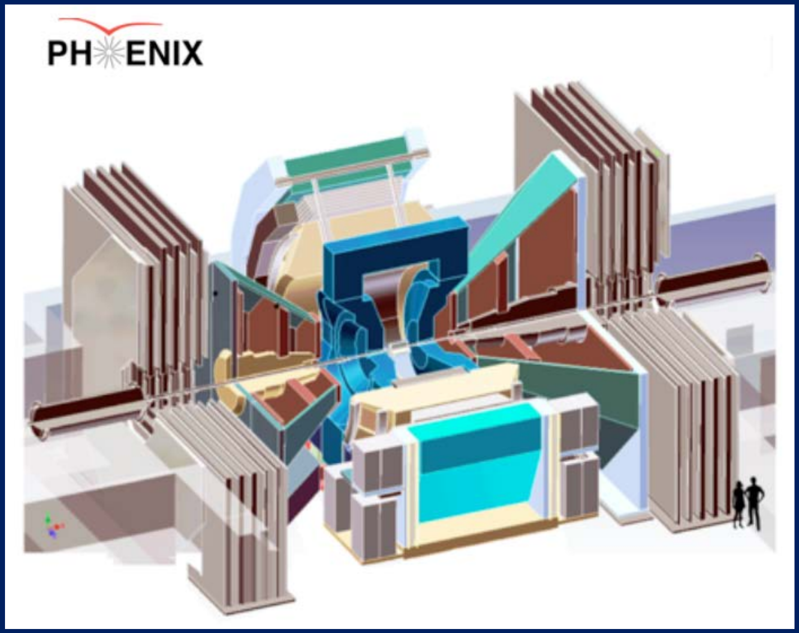
Long history of fixed-target Drell-Yan at Fermilab

- E288 – 200, 300, and 400 GeV p beams on Be, Cu, and Pt targets
- E325 – 200, 300, and 400 GeV p beams on Cu target
- E326 – 225 GeV π- beam on W target
- E439 – 400 GeV p beam on W target
- E444 – 225 GeV, π+/-, K+, proton/antiproton beams on C, Cu, W targets
- E537 – 125 GeV antiproton and π^- beams on W target
- E605 – 800 GeV p beam on Cu target
- E615 – 252 GeV π- beam on W target
- E772 – 800 GeV p beam on deuterium, C, Ca, Fe, W targets
- E866/NuSea – 800 GeV p beam on hydrogen, deuterium targets
- *E906/SeaQuest – 120 GeV p beam on hydrogen, deuterium, C, Fe, W targets – Currently running!*



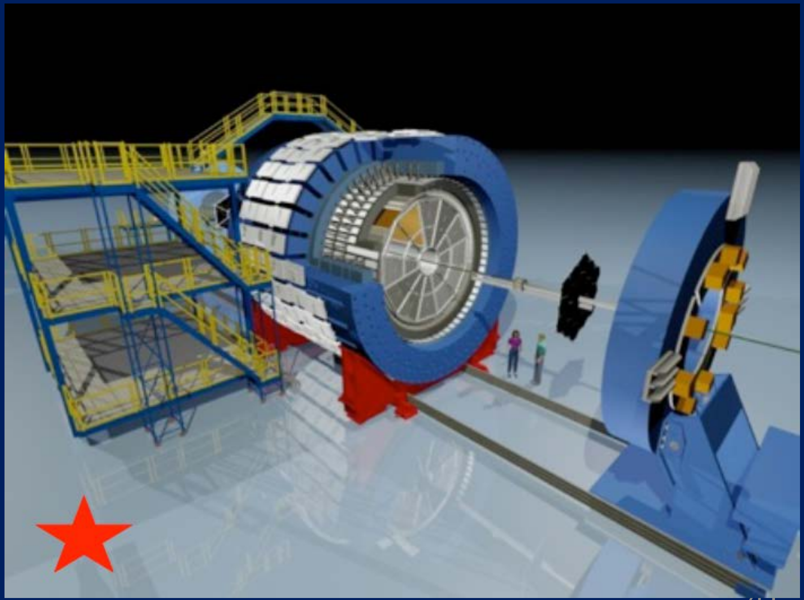
RHIC
polarize
collider
Absolute Polarimeter (H jet)
RHIC pC Pola
HOBOS
BRAHMS &
Siberian Snakes
Spin Flipper
PHENIX
STAR
Spin Rotators
Partial Snake
Helical Partial Snake
Strong Snake
Polarized Source
AGS
STER
Rf Dipole
AGS
acceleration and storage
40

RHIC's current main experiments



PHENIX:

- High resolution; high rate capabilities for rare probes
- Central arms $|\eta|<0.35$, $\Delta\phi\sim2\pi$ with key strength measuring EM probes
- Muon arms $1.2<|\eta|<2.4$
- Forward EM calorimetry



STAR:

- Key strengths jets + correlations
- Full acceptance including PID for $|\eta|< 1$, $\Delta\phi\sim2\pi$
- Forward EM calorimetry