Hadron Structure from the Drell-Yan Process

- ✓ Probing Hadron Structure with Drell-Yan
- ✓ Proton induced Drell-Yan
- ✓ Pion induced DY
- ✓ DY with polarized protons
- ✓ Future Experiments

Matthias Grosse Perdekamp, UIUC

Probing the Quark Structure of Hadrons with Electro Weak Probes

DIS

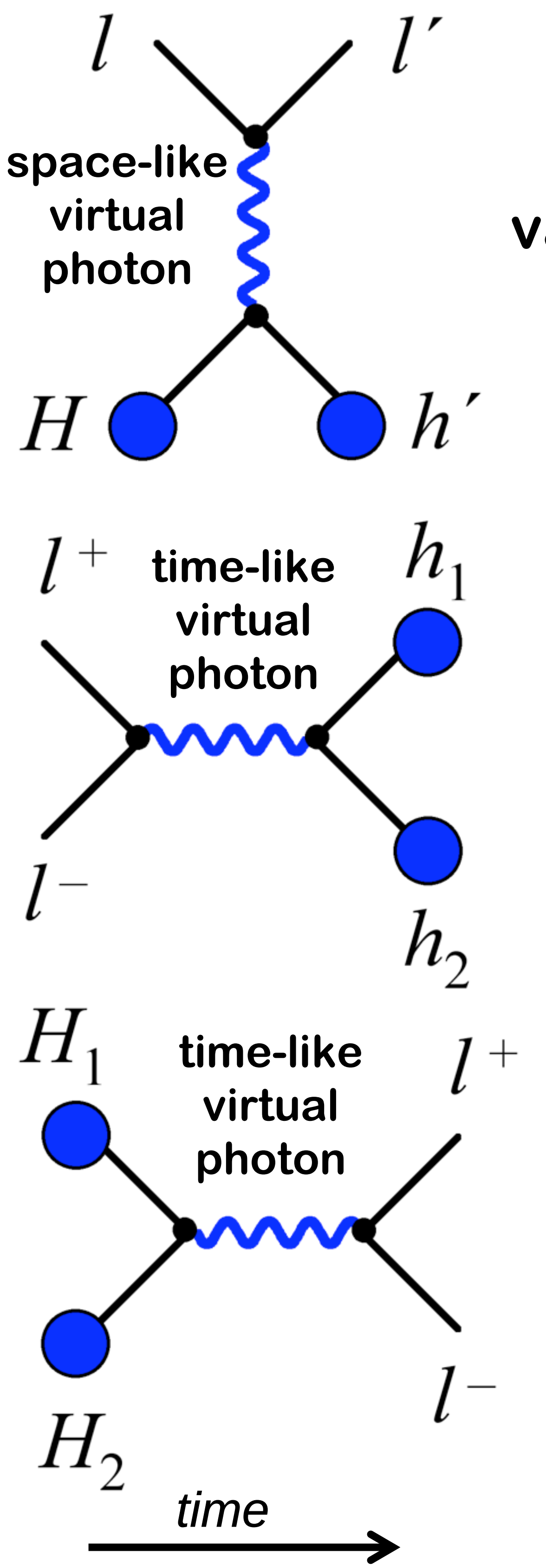
$\mathrm{DF} \otimes \mathrm{FF}$

electron-electron collisions

$\mathrm{FF} \otimes \mathrm{FF}$

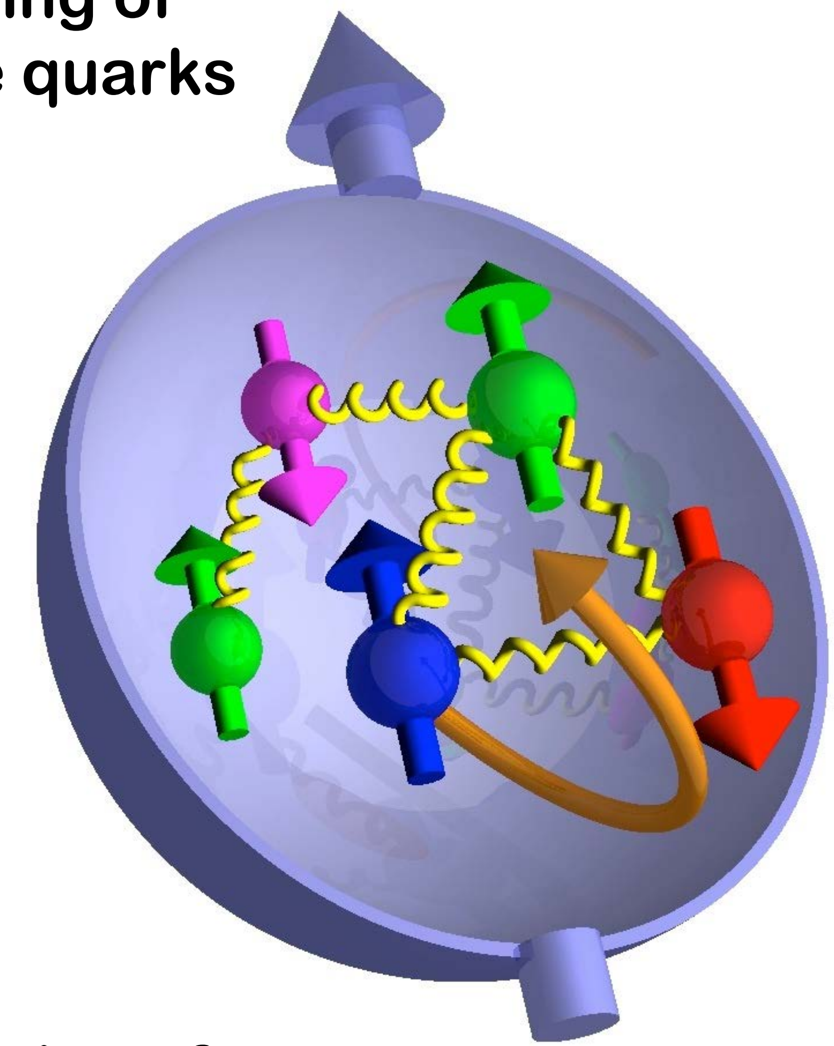
Drell-Yan (DY)

$\mathrm{DF} \otimes \mathrm{DF}$



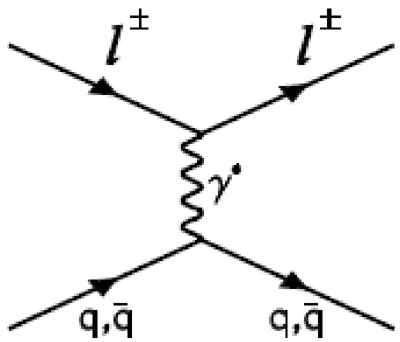
mapping of valence quarks

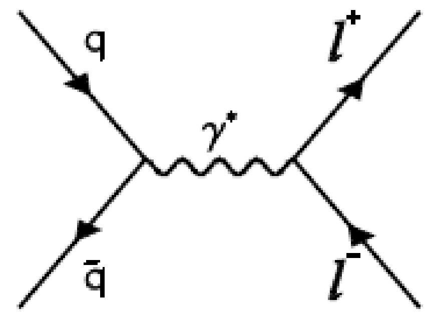
mapping of sea quarks



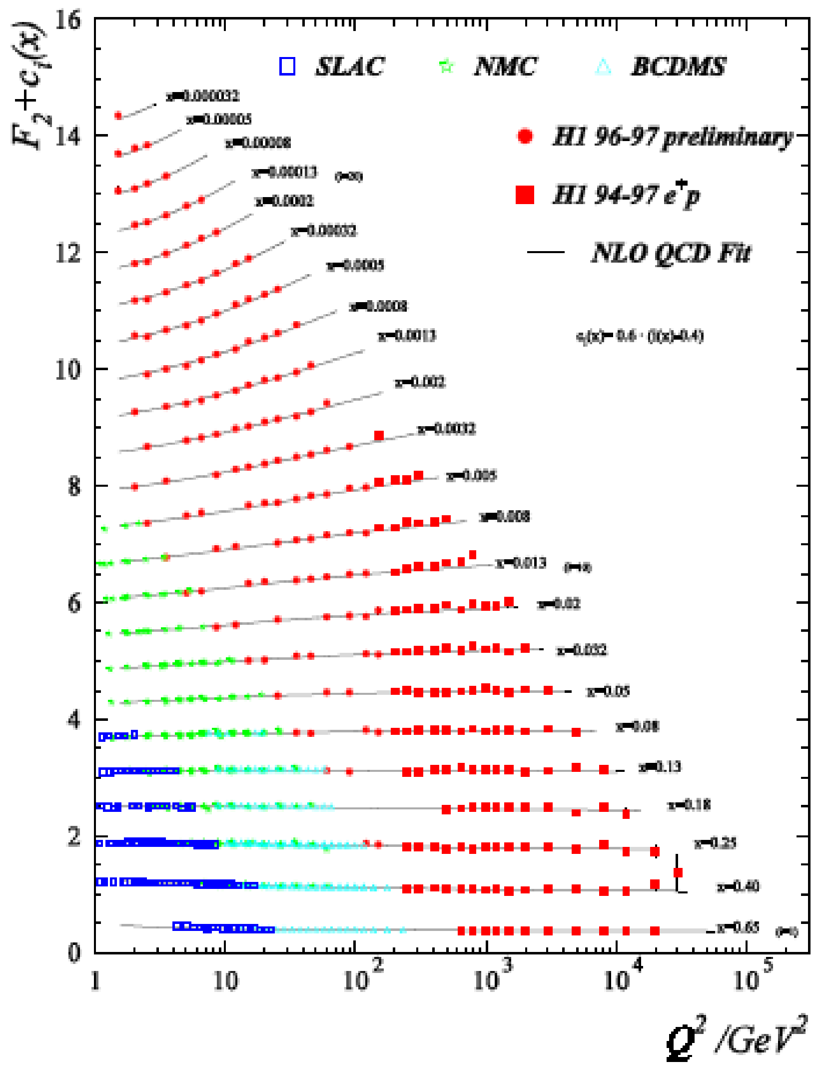
Complementarity Between DIS and Drell-Yan

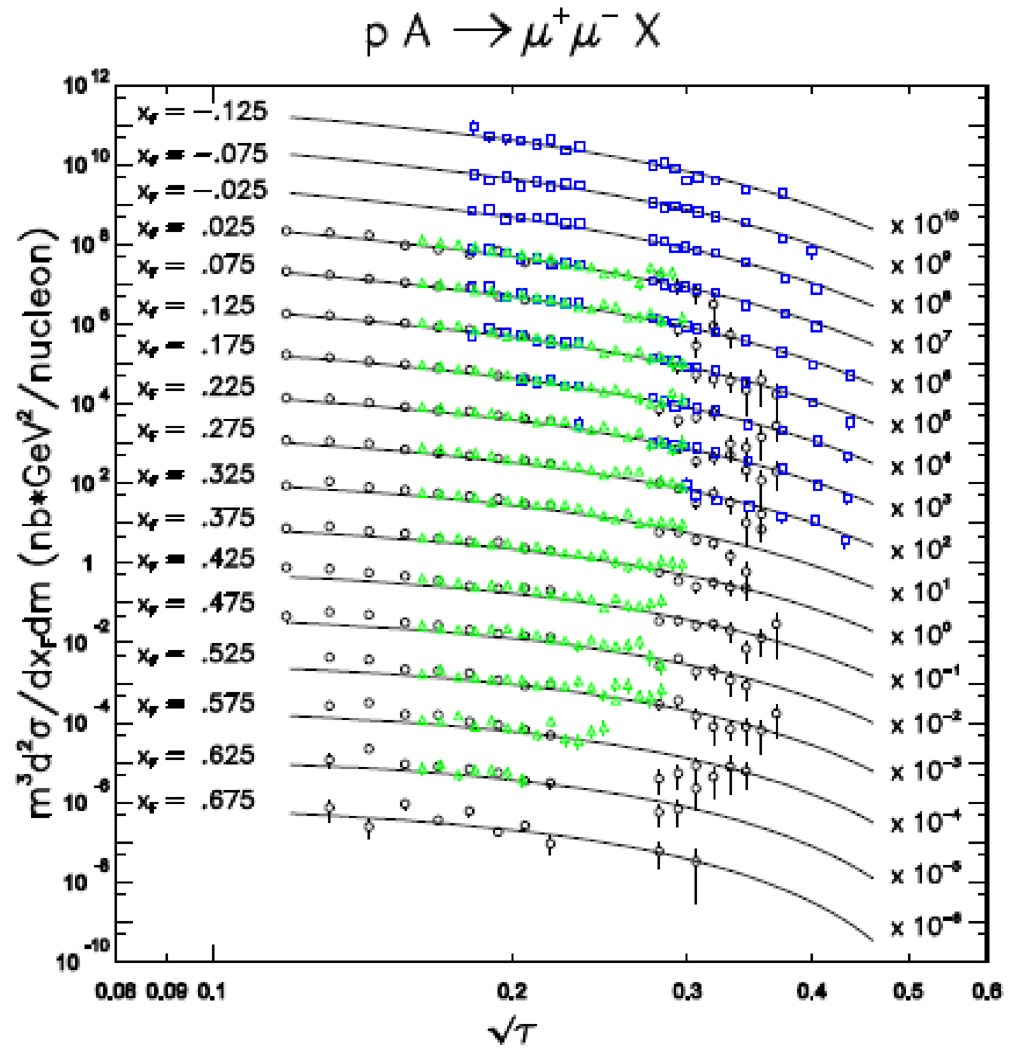
DIS





Drell-Yan





Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both DIS and Drell-Yan processes are tools for probing the quark and anti-quark structure of hadrons. The data stretch over a wide range in Q^2 and test evolution.

Lepton-pair production provides unique information on parton distributions

$p + W \rightarrow \mu^+ \mu^- X$

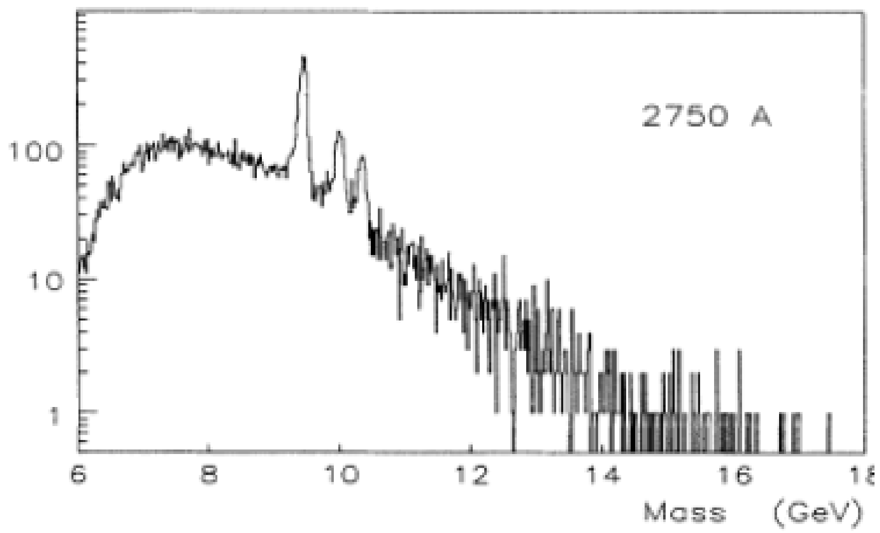
800 GeV/c

$\pi^- + W \rightarrow \mu^+ \mu^- X$

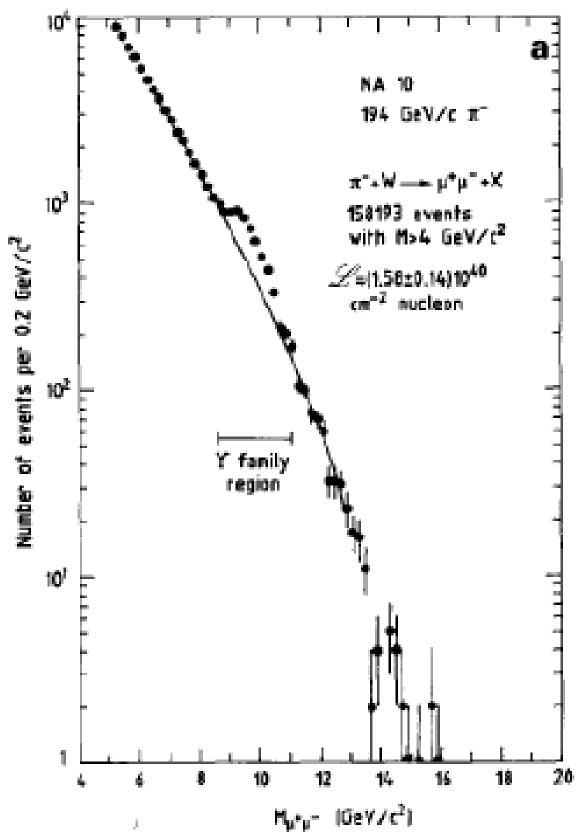
194 GeV/c

$\bar{p} + p \rightarrow l^+ l^- X$

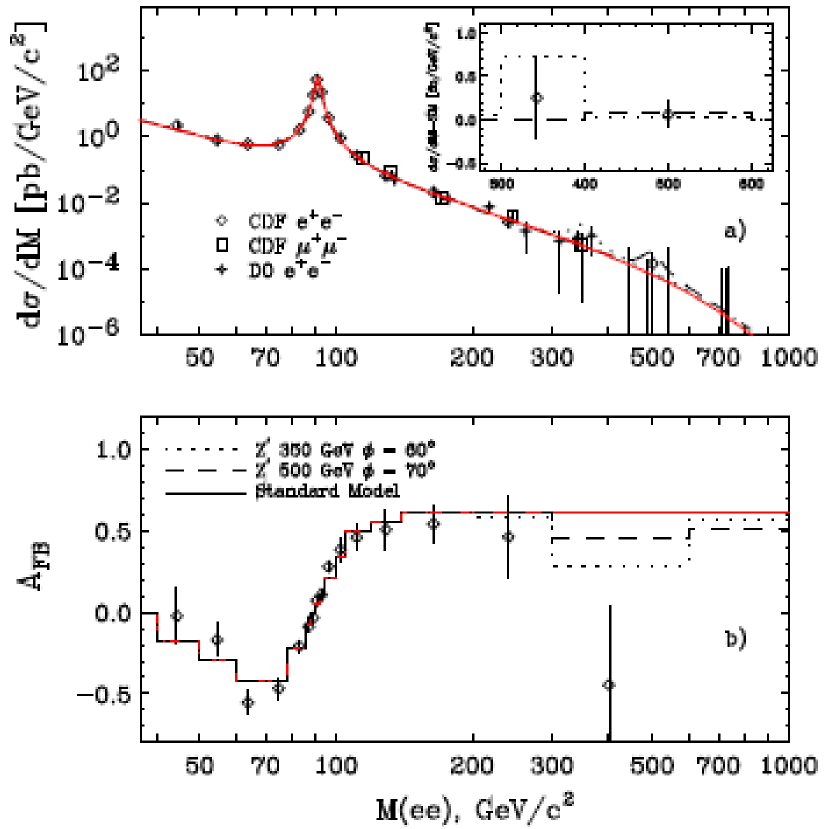
1.8 TeV



Probe antiquark distribution in nucleon



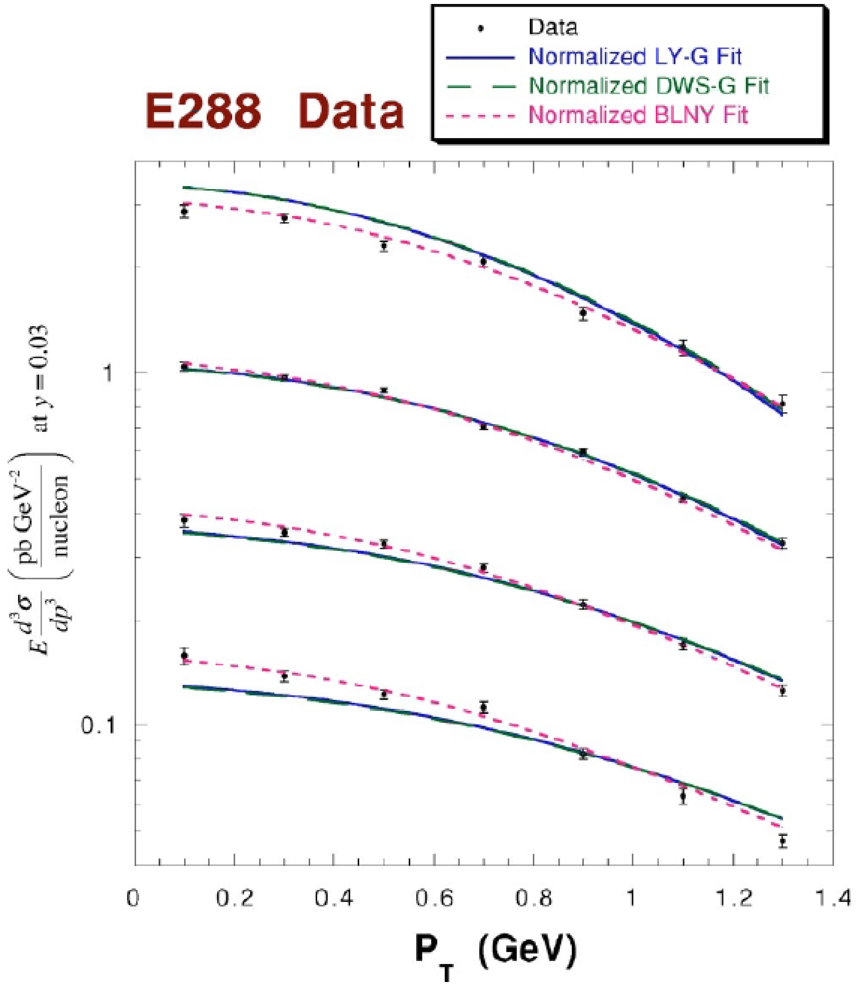
Probe antiquark distribution in pion

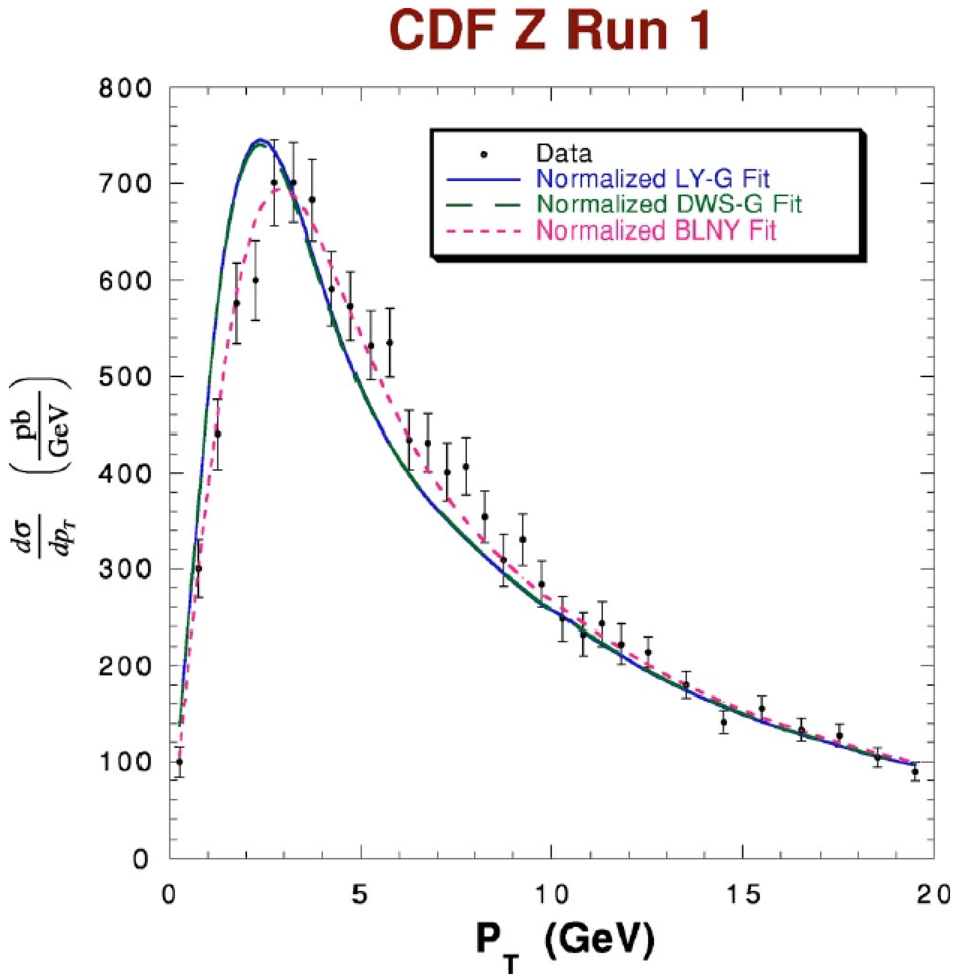


Probe antiquark distributions in antiproton

Unique features of D-Y: antiquarks, unstable hadrons…

DY p_T Dependence for Different Q^2



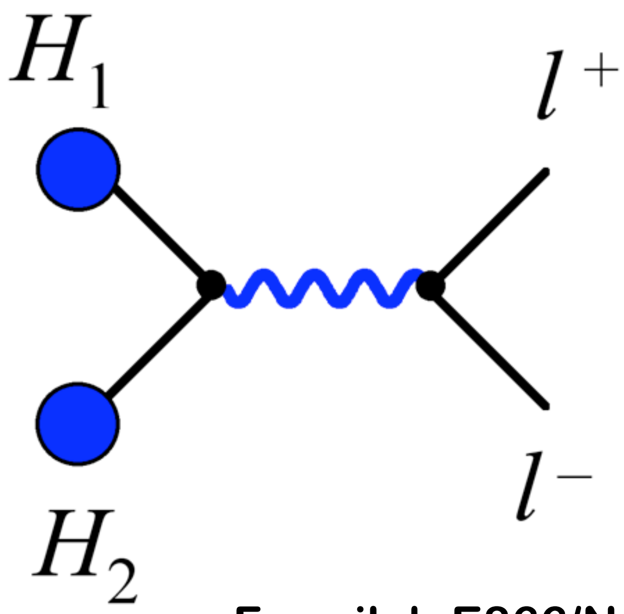


Important input for the phenomenology of transverse momentum dependent quark distributions (TMDs) and their evolution.

Hadron Structure Explored Through Drell-Yan Scattering

- Cleanest hard hadron-hadron scattering process

- But: experimentally challenging: small cross section. Continuum varies as $$\frac{d\sigma}{dm_{\mu\mu}} \approx \frac{10^{-32}}{m_{\mu\mu}^5} \cdot \frac{\text{cm}^2}{\text{GeV}^2}$$



- Important role in studying quark structure in hadrons: - nucleons
  - Parton Distribution Functions (PDFs) in nuclei
  - PDFs in mesons

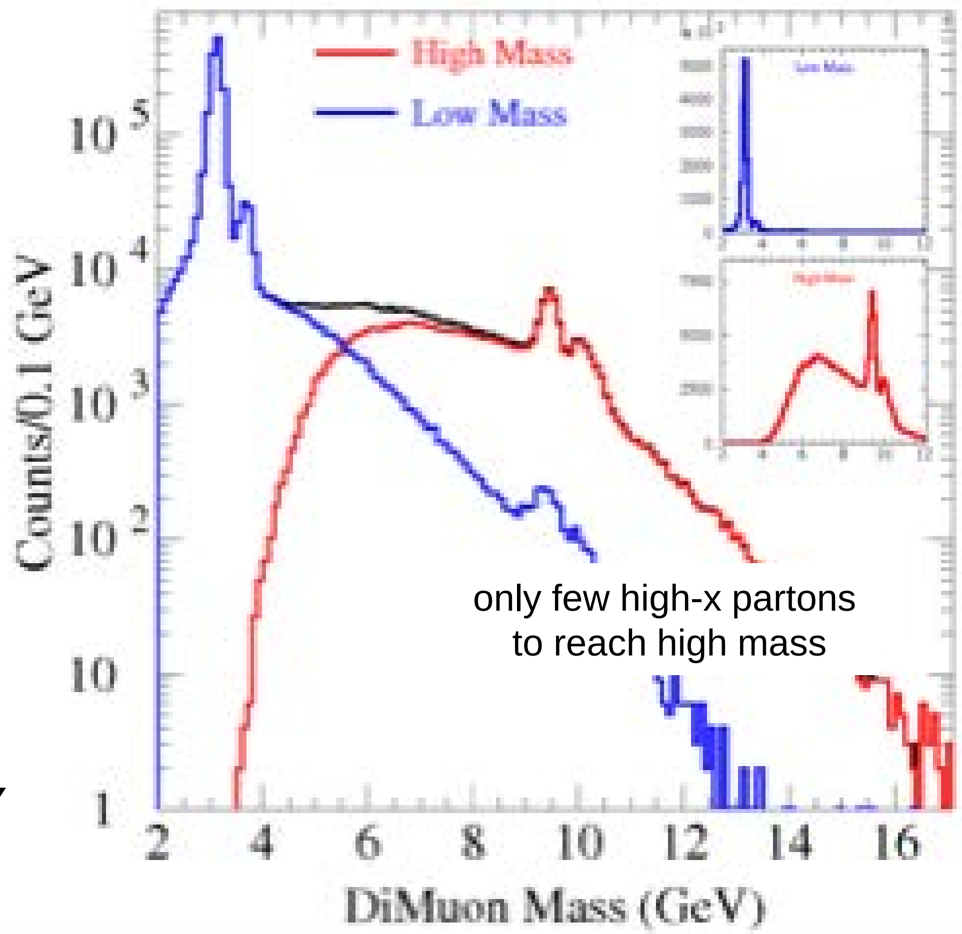
- Provides access to transverse-momentum dependent PDFs (TMDs)

- Interesting current focus: DY experiments with polarized protons

  ➔ complete understanding of the origin of large single transverse spin asymmetries in SIDIS and pp

  Milestone: measurement of sign switch between DY and SIDS for Sivers asymmetry

Fermilab E866/NuSea



Typical Fixed Target Muon Drell-Yan Experiment

Omega @ CERN (1980)

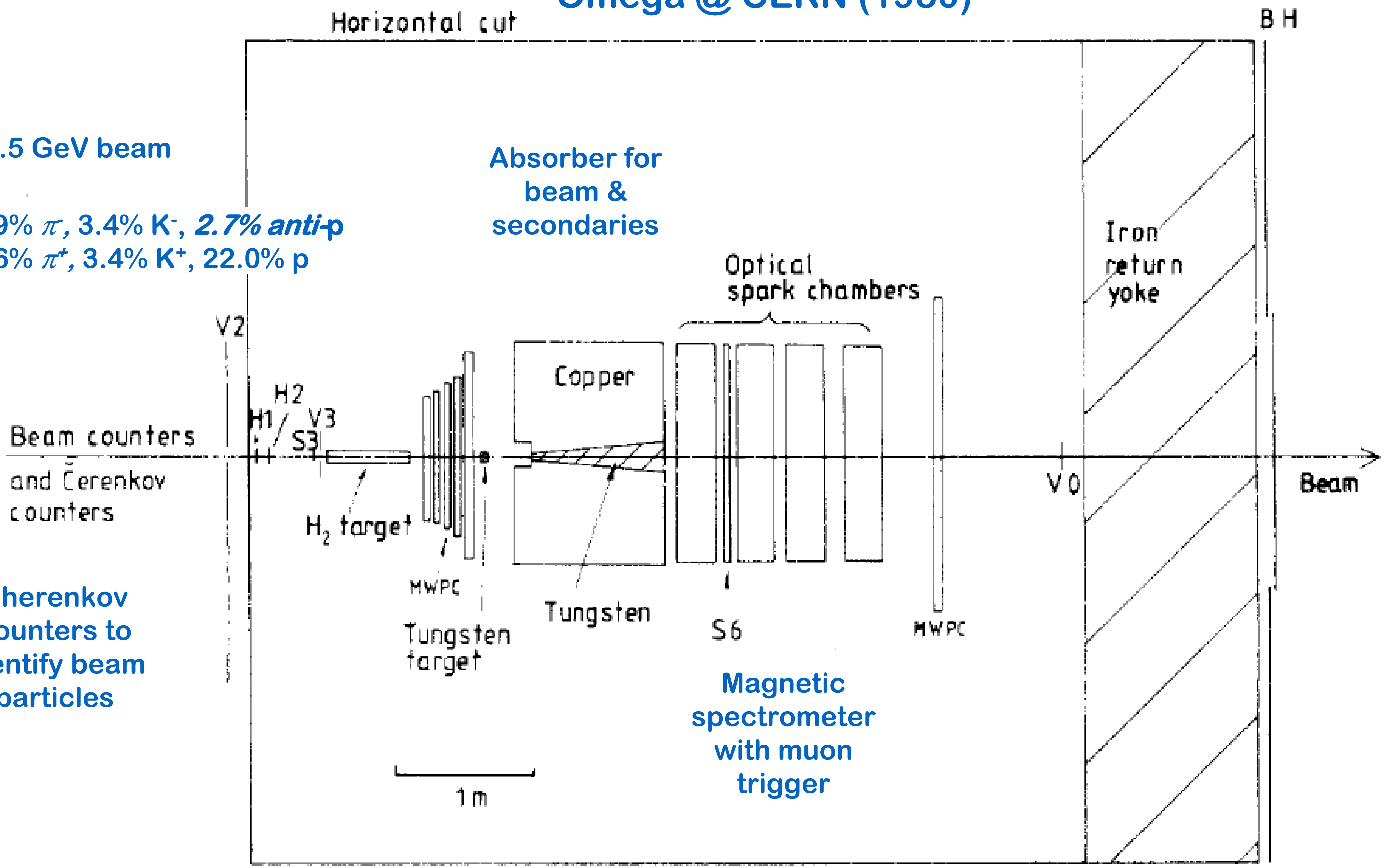
39.5 GeV beam

93.9% π^-, 3.4% K^-, *2.7% anti-p*
74.6% π^+, 3.4% K^+, 22.0% p

Absorber for beam & secondaries

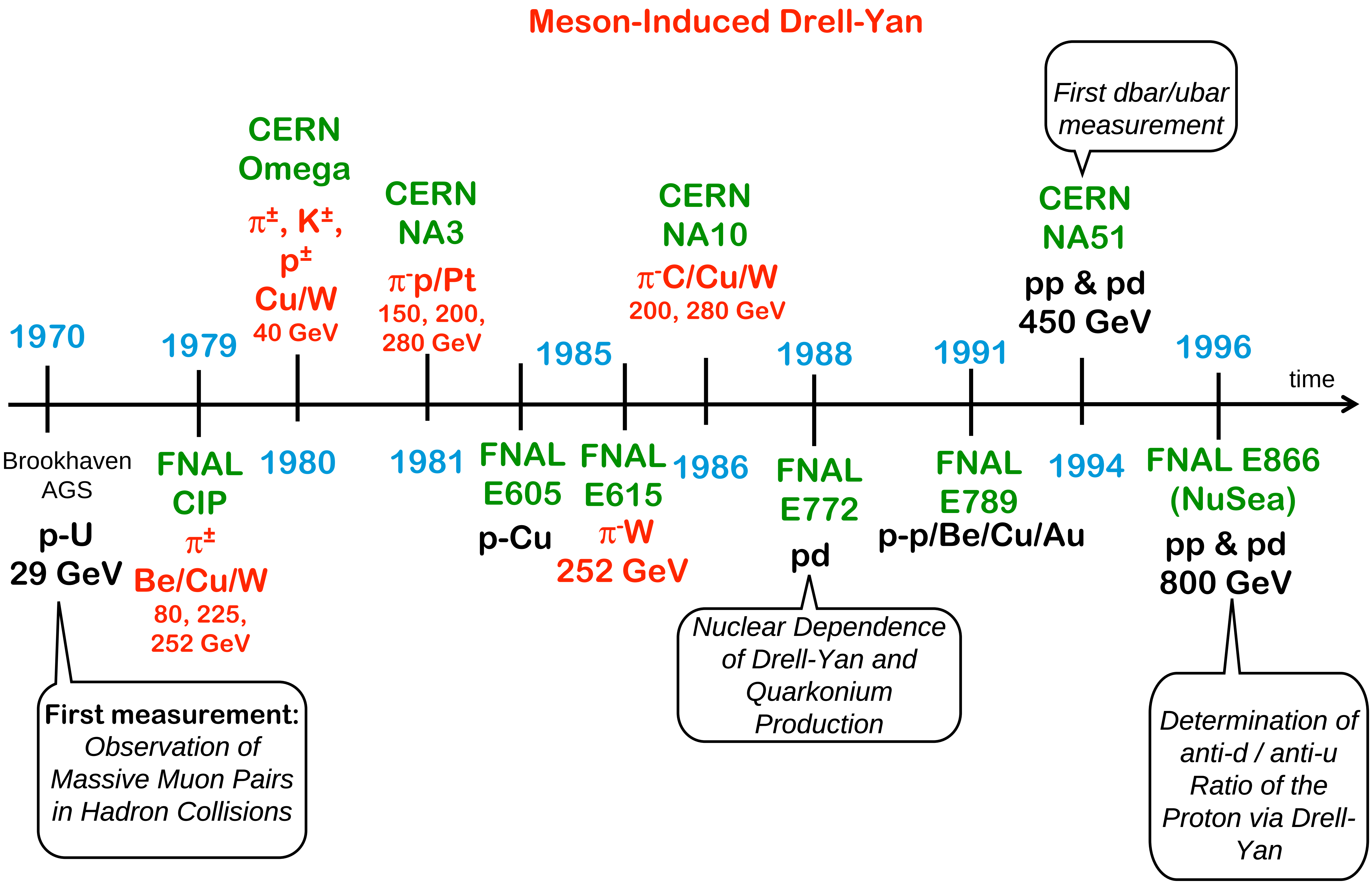
Cherenkov counters to identify beam particles

Magnetic spectrometer with muon trigger



From the review: I. R. Kenyon, The Drell-Yan Process, Rep. Pos. Phys. Vol 45 (1982)

Selected Past Drell-Yan Experiments

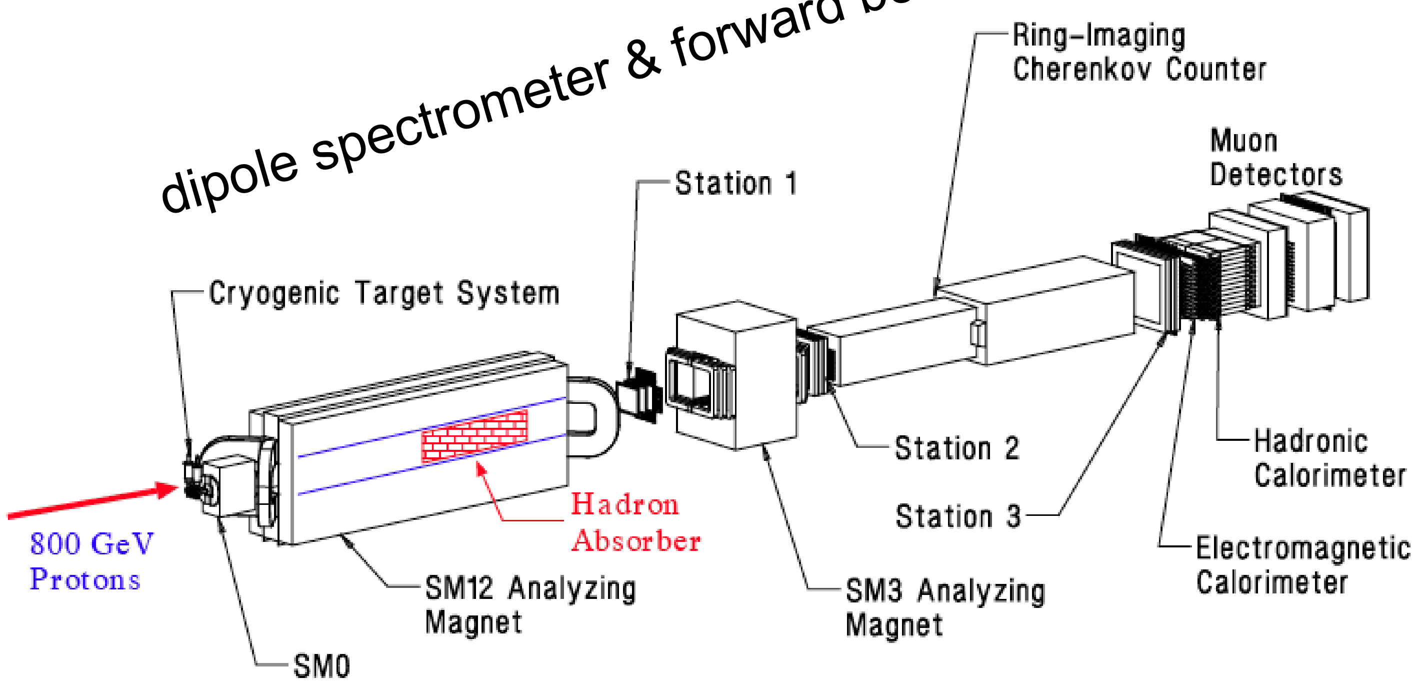


Proton Induced DY as Probe of Sea Quark Distributions

Fixed target experiment

example: Fermilab di-muon spectrometer [E866]

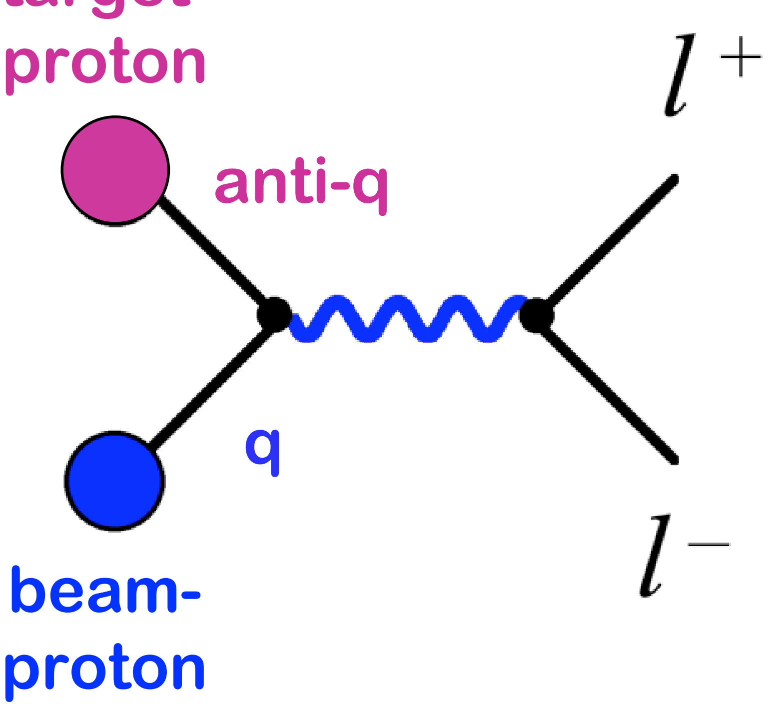
dipole spectrometer & forward boost of dileptons → selectsPhys. Rev. D 84, 112002 (2011)

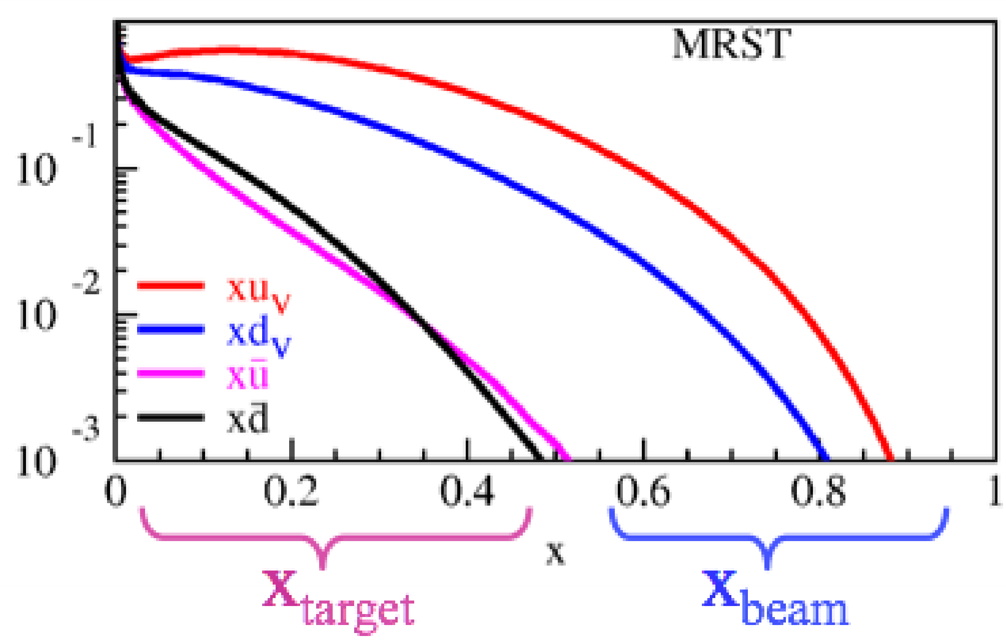


$x_{Feynman}$ (= x_{beam} - x_{target}) $\gtrsim 0$

large x_{beam} (quark) in valence region

small x_{target} (anti-quark) in sea region





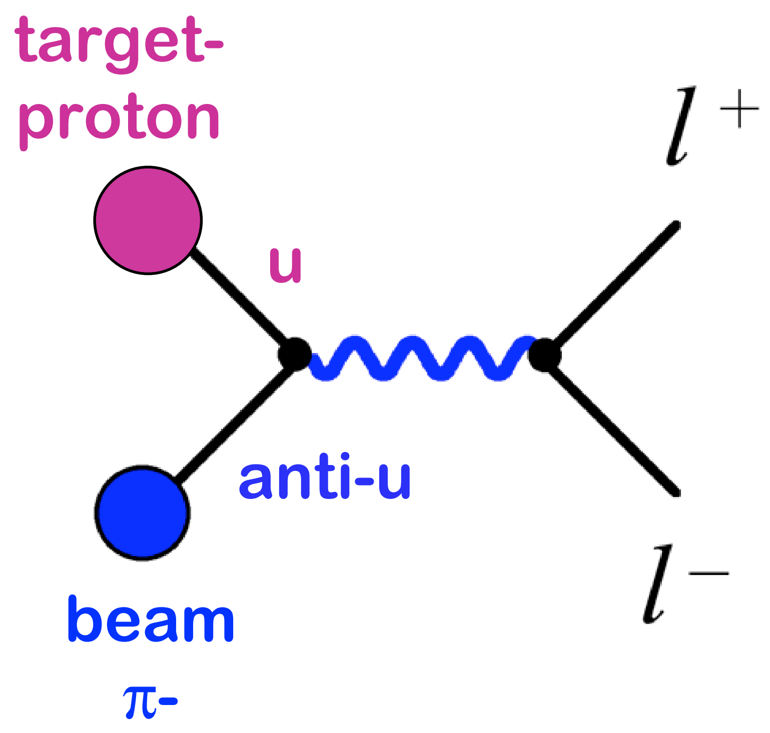
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9 x_b x_t s} \times$$

$$\sum e^2 [\underline{\bar{q}_t(x_t)} \, \underline{q_b(x_b)} + \underbrace{\bar{q}_b(x_b) q_t(x_t)}_{\text{suppressed}}]$$

$$\frac{m_{\mu\mu}}{s} = x_b x_t$$ scaling analog to DIS

Pion-Induced Drell-Yan Probes Valence Quark Distibution in Target:

- Proton-induced DY needs to generate the di-lepton from sea-quark object with small x.
- Valence anti-u quark in the pion: allows to create large-mass dileptons with valence u-quark in the target!
- Pions are complementary probe to probe
  - valence structure
  - nuclear effects at high x
  - meson structure – not accessible in DIS
- Flavor dependence: meson quark composition pics specific q-flavor in the target

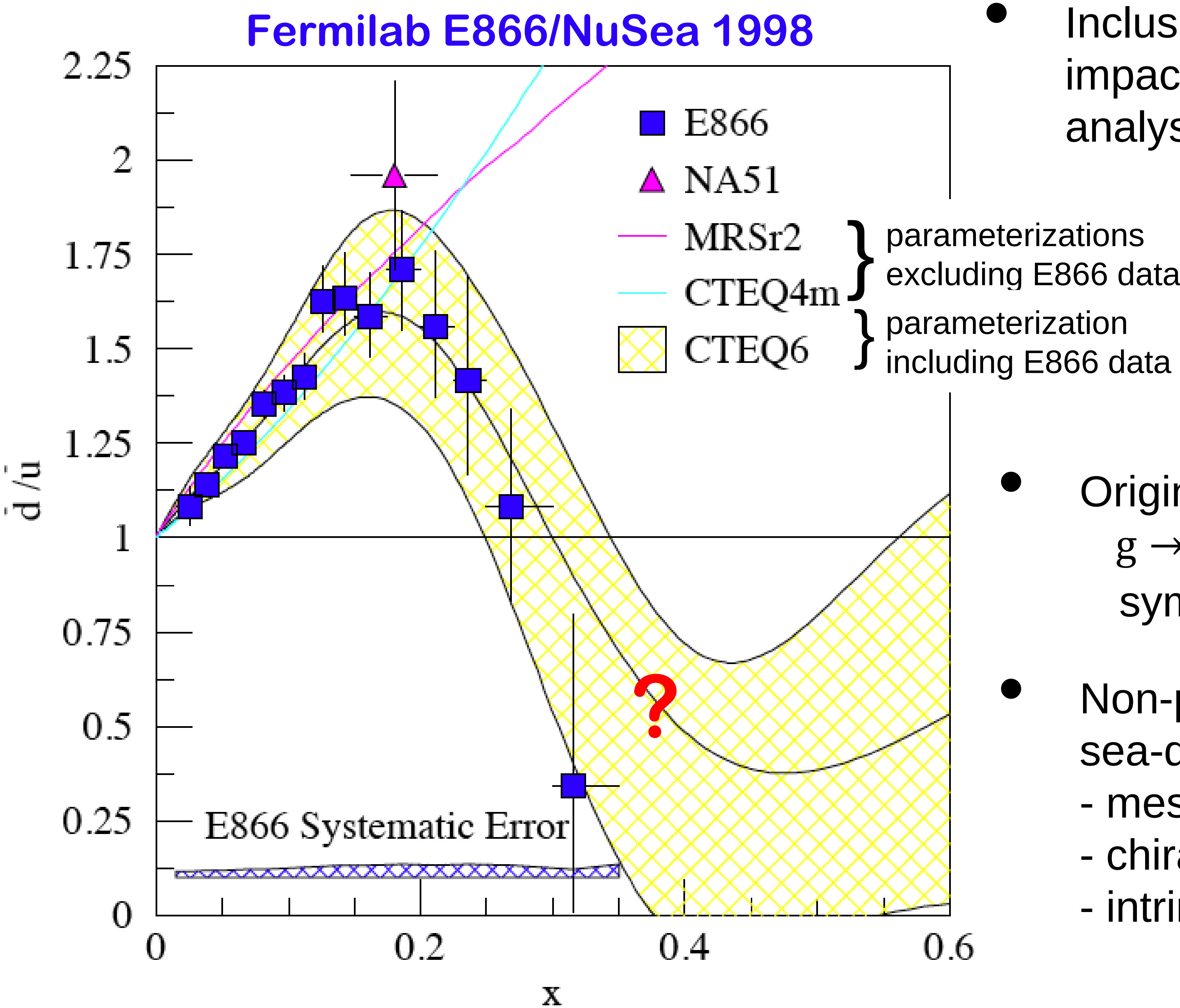


sensitive to the valence quark of the nucleon target

(anti-d d annihilation suppressed)

Recent review: arXiv:1306.3971
W.-C. Chang and D. Dutta,
The pionic Drell-Yan process: a brief survey

E866 Isospin Symmetry Broken in the Anti-Quark Sea



- Inclusion of E866 σ^{pd}/σ^{pp} into global fits: impact of sea-quark dis. from QCD analysis of hard scattering data!

- Origin of sea quarks?
  $g \rightarrow q\bar{q}$ should naively give symmetric $q\,\bar{q}$.

- Non-perturbative contributions to sea-quark distributions:
  - meson-cloud model
  - chiral perturbation theory
  - intrinsic quark sea

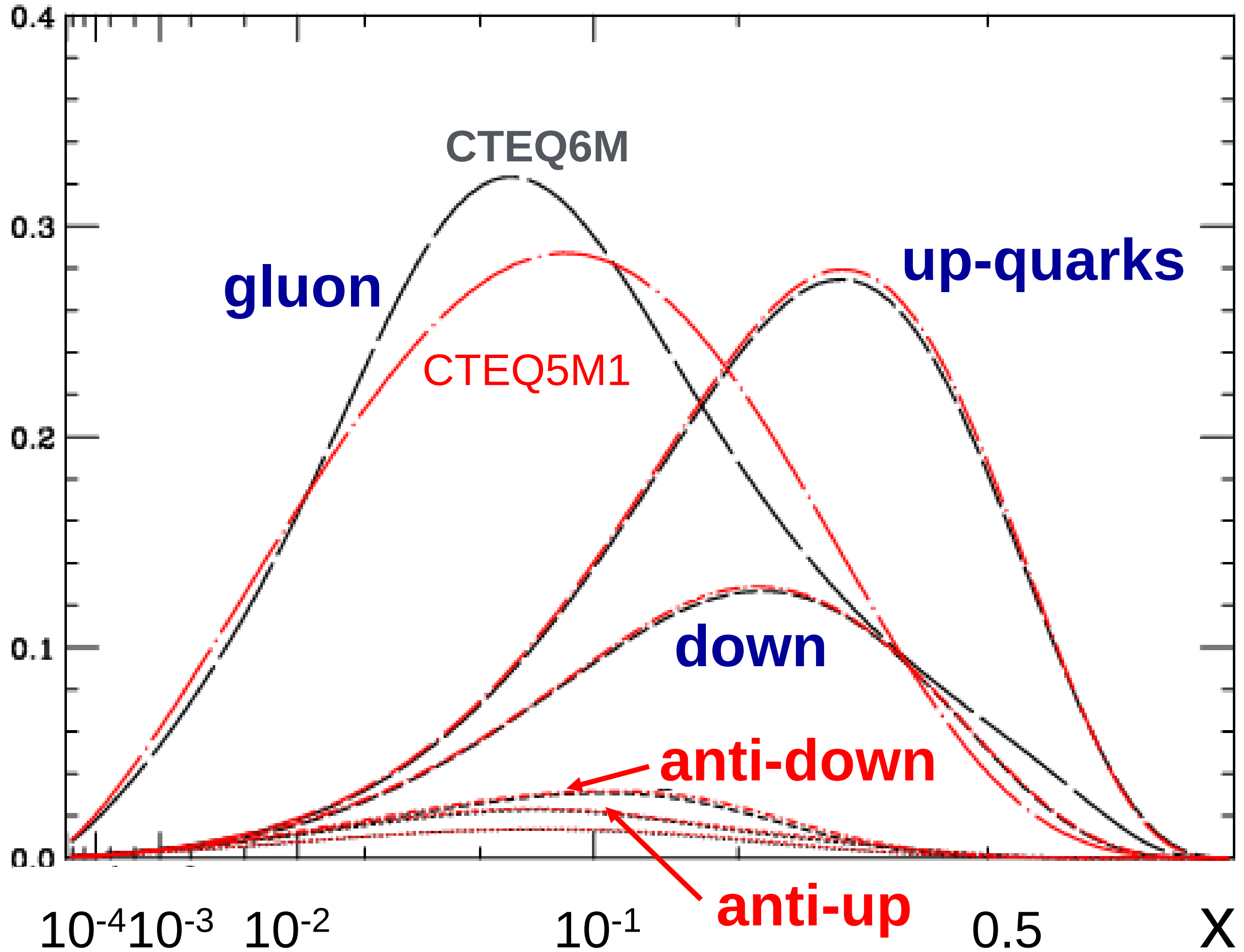
Reviews: Kumano: hep-ph/9702367; G.T. Garvey, J.-C. Peng: nucl-ex/0109010

CTEQ Global Analysis for $G(x,Q^2)$, $q(x,Q2)$ and $\bar{q}(x,Q^2)$

J. Pumplin et.al JEHP 0207:012 (2002)

CTEQ6: first use of E866 data constraining anti-quark distributions

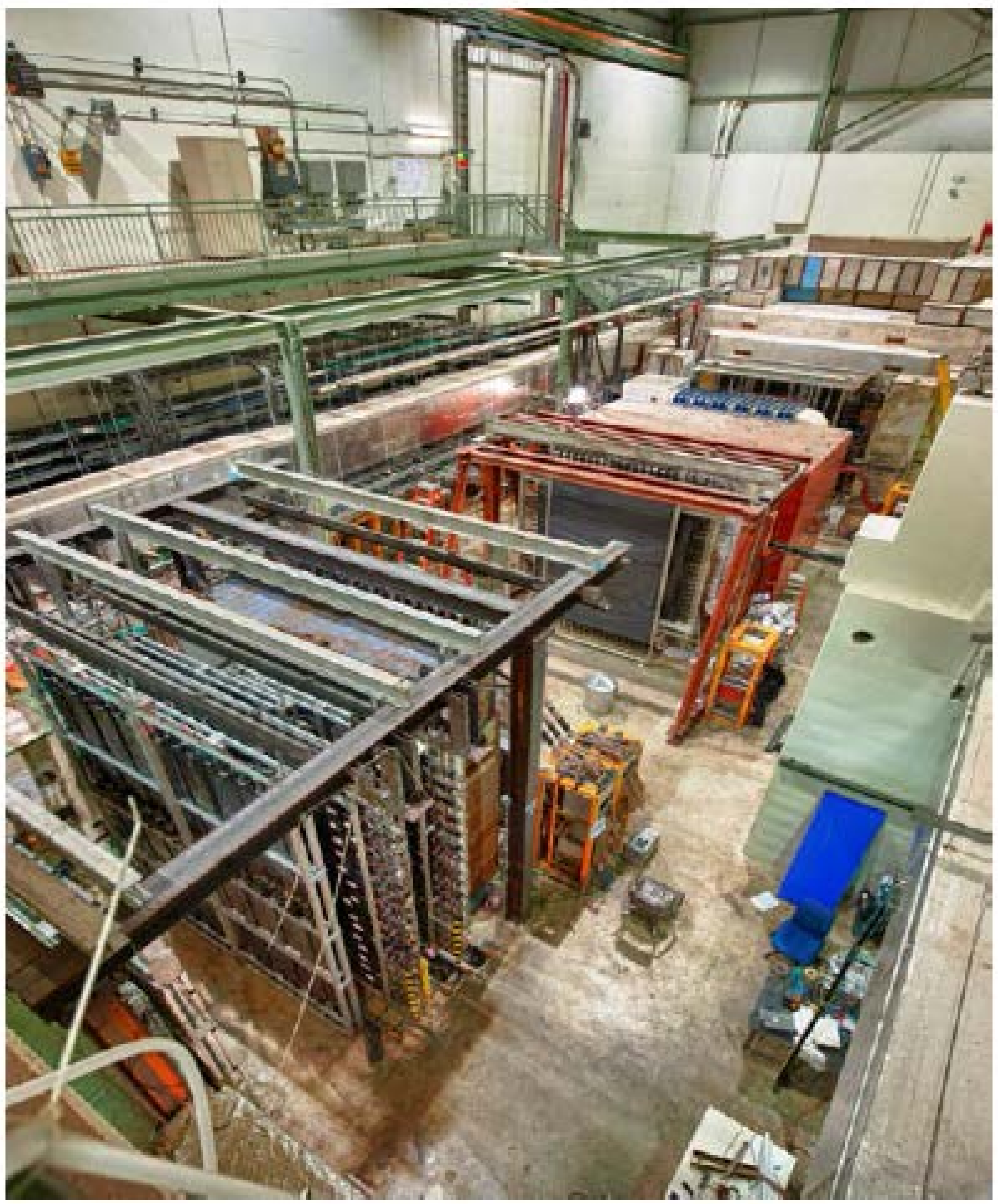
Quark, Anti-Quark and Gluon Distributions

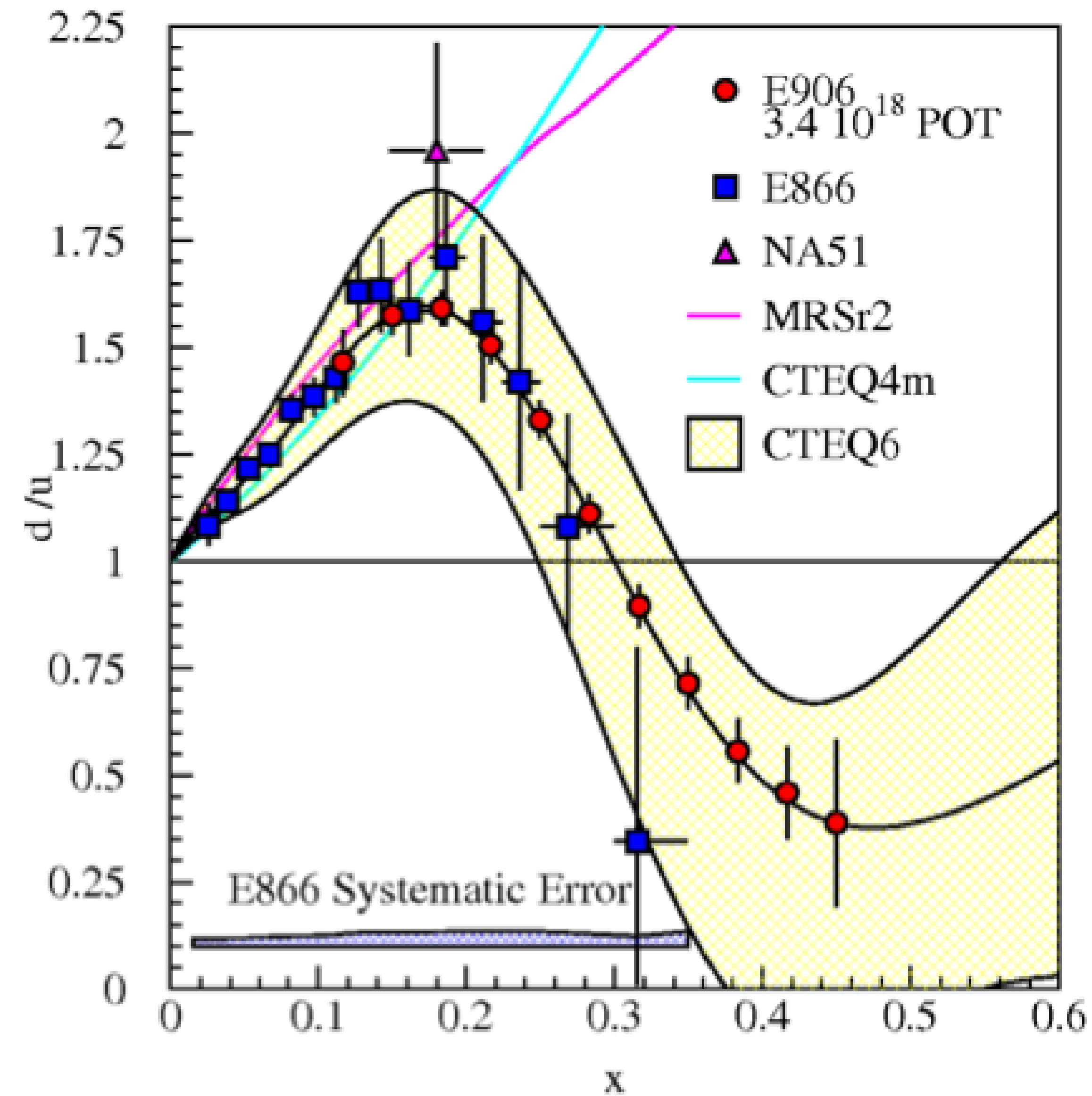


Data in fit:
- o DIS: HERA + earlier fixed target
- o Tevatron pp
- o E866 Drell Yan
- …

Current Fermilab E906/SeaQuest

Will extend sea-quark measurements to larger x by using 120 GeV protons from Fermilab Main Injector.





SeaQuest Update at DIS 2015, Kun Liu – Los Alamos

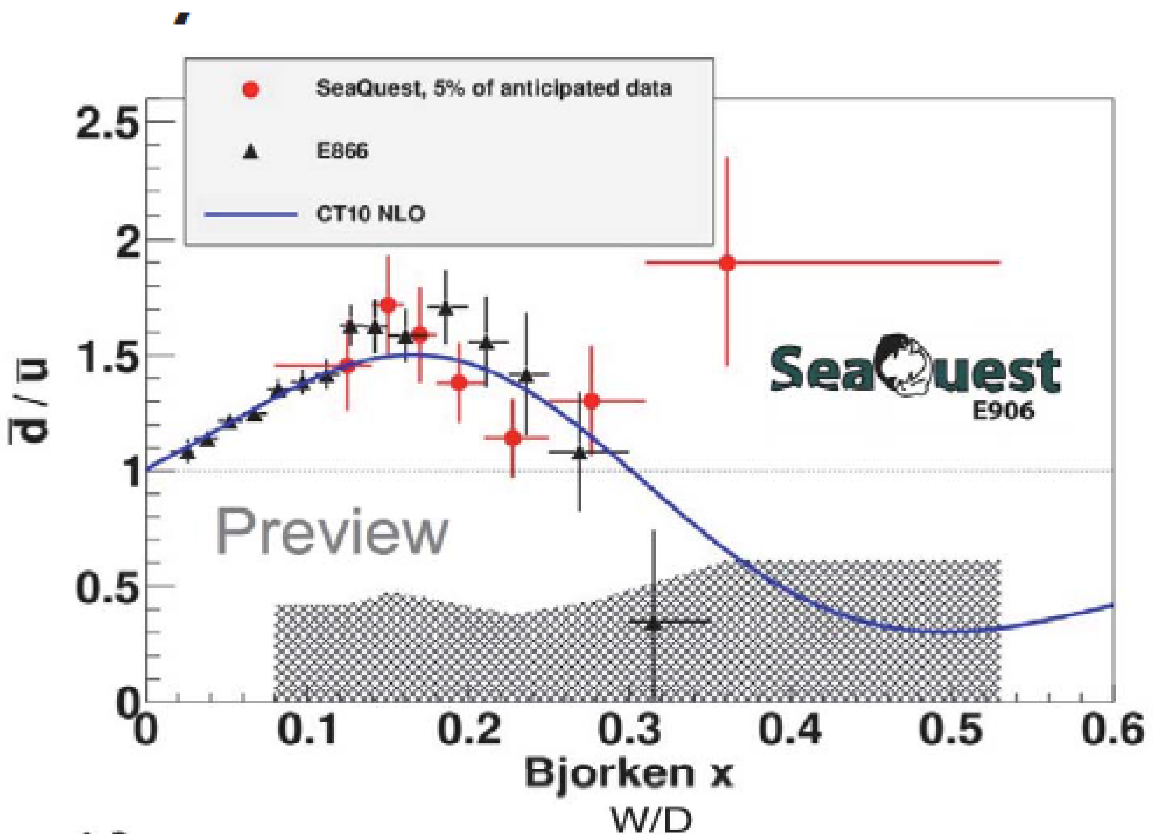
Run-II: 5% of total statistics:

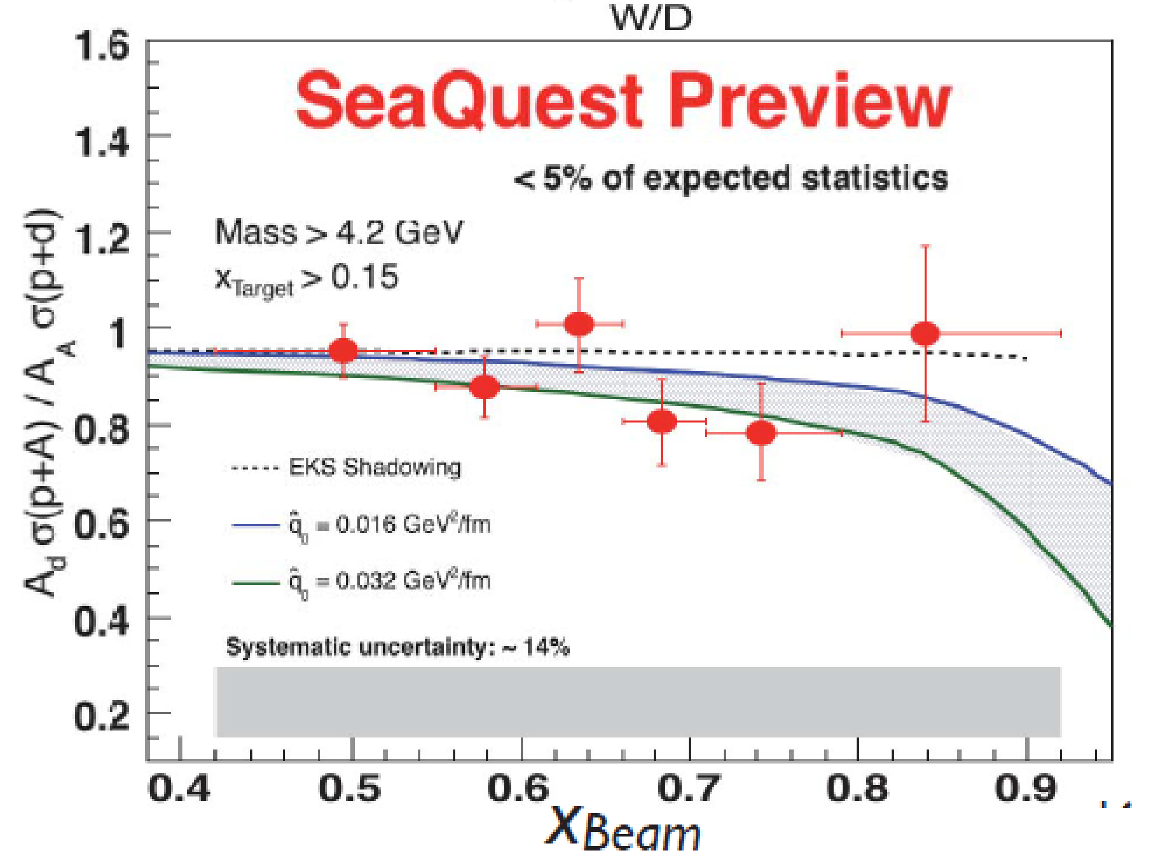
- confirmed the large light sea quark asymmetry at $x_2 \sim 0.15$, while the sign change at $x_2 > 0.3$ still waits for more statistics
- observed a negative slope beyond the extent of shadowing

Ongoing Run-III: ~20x of Run-II statistics

Other ongoing physics analysis:

- EMC effect in Drell-Yan
- Transverse momentum broadening
- Difference between J/ψ and ψ' suppression in pA
- Search for double J/ψ production
- Search for dark photons





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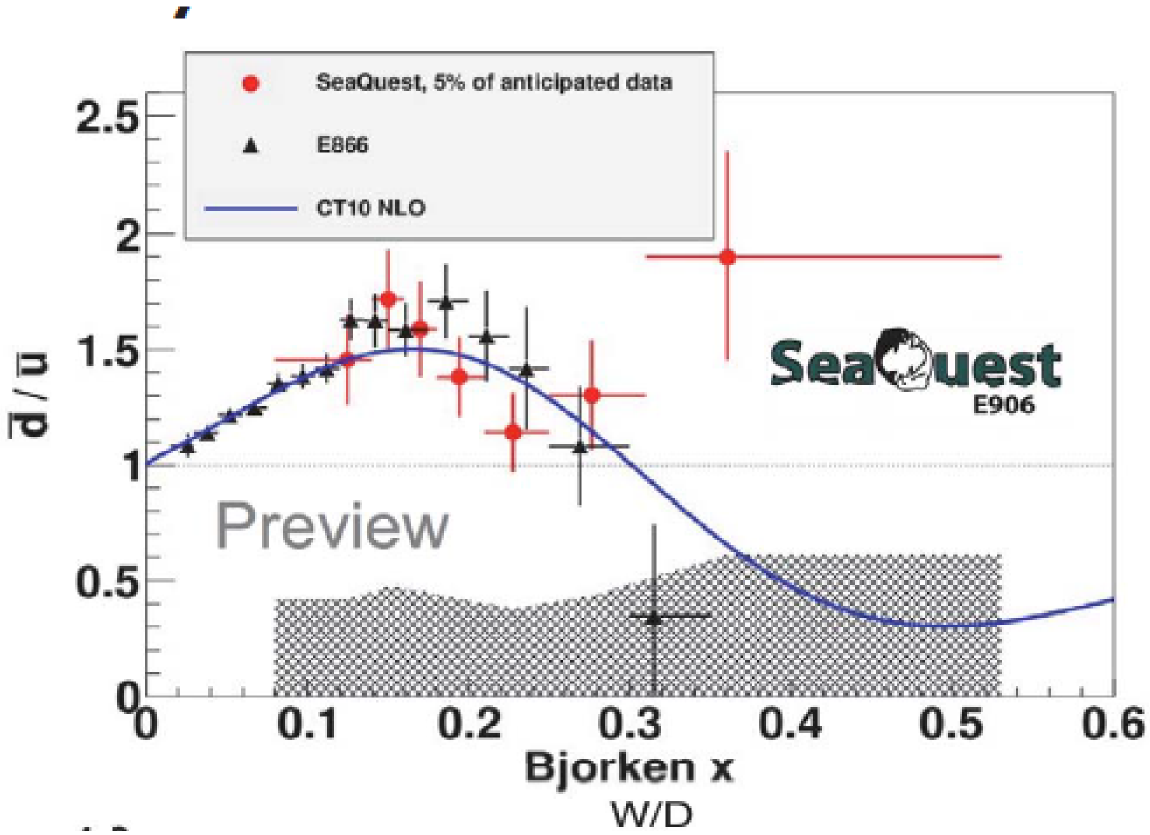
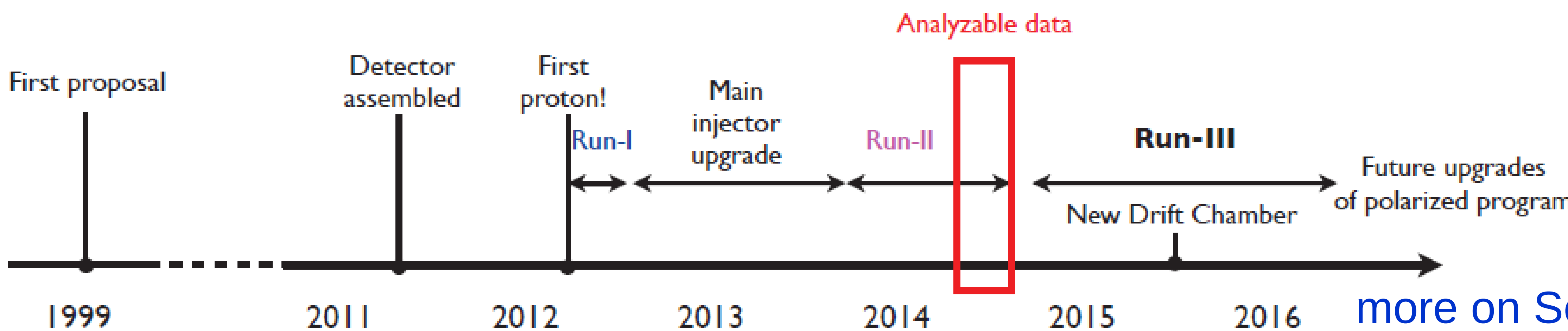


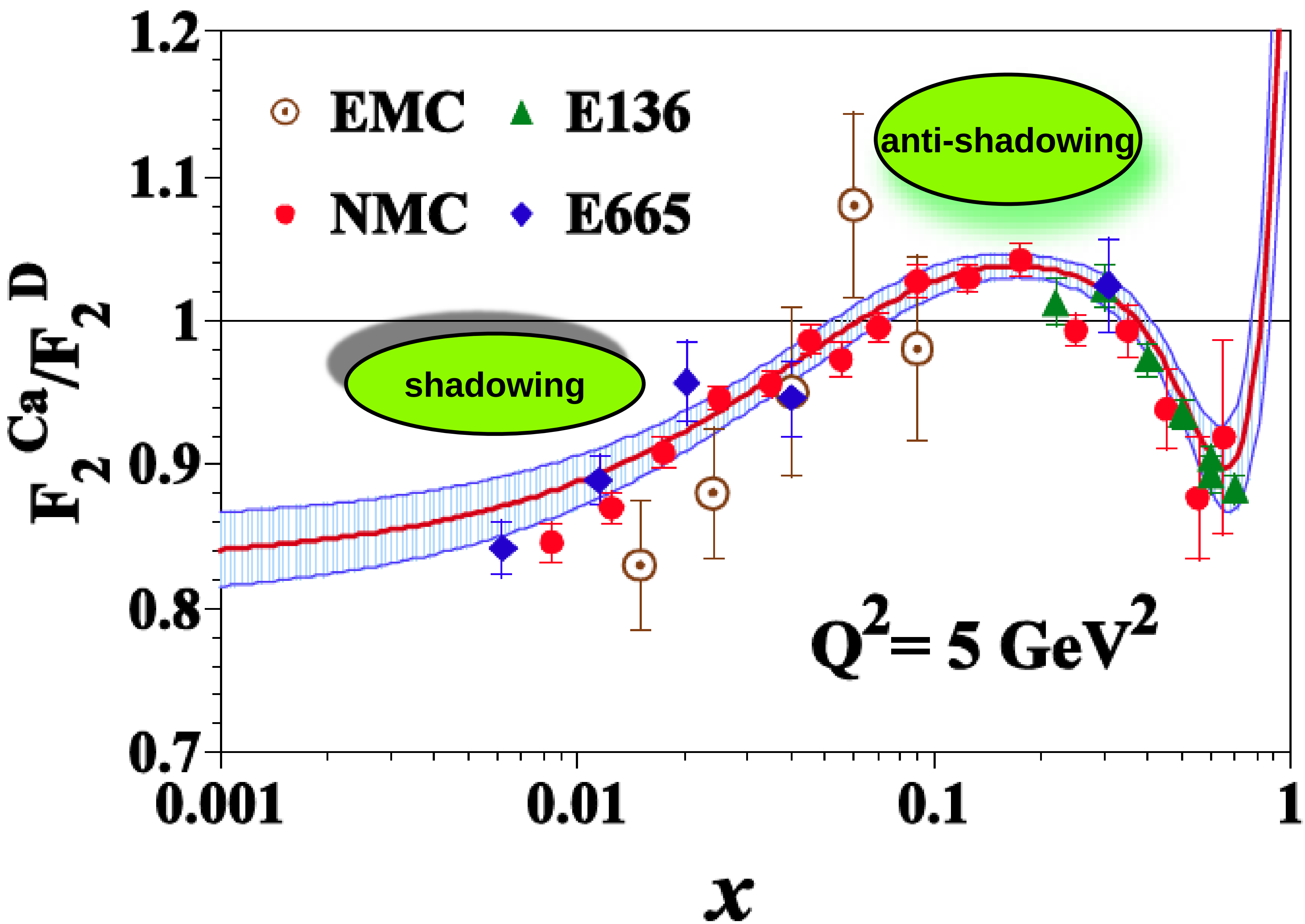
Timeline and milestones of SeaQuest



more on SeaQuest in Dr. Aidala's talk!

Nuclear Effects in Nucleon Structure

EMC effect in DIS 1983, EMC at CERN

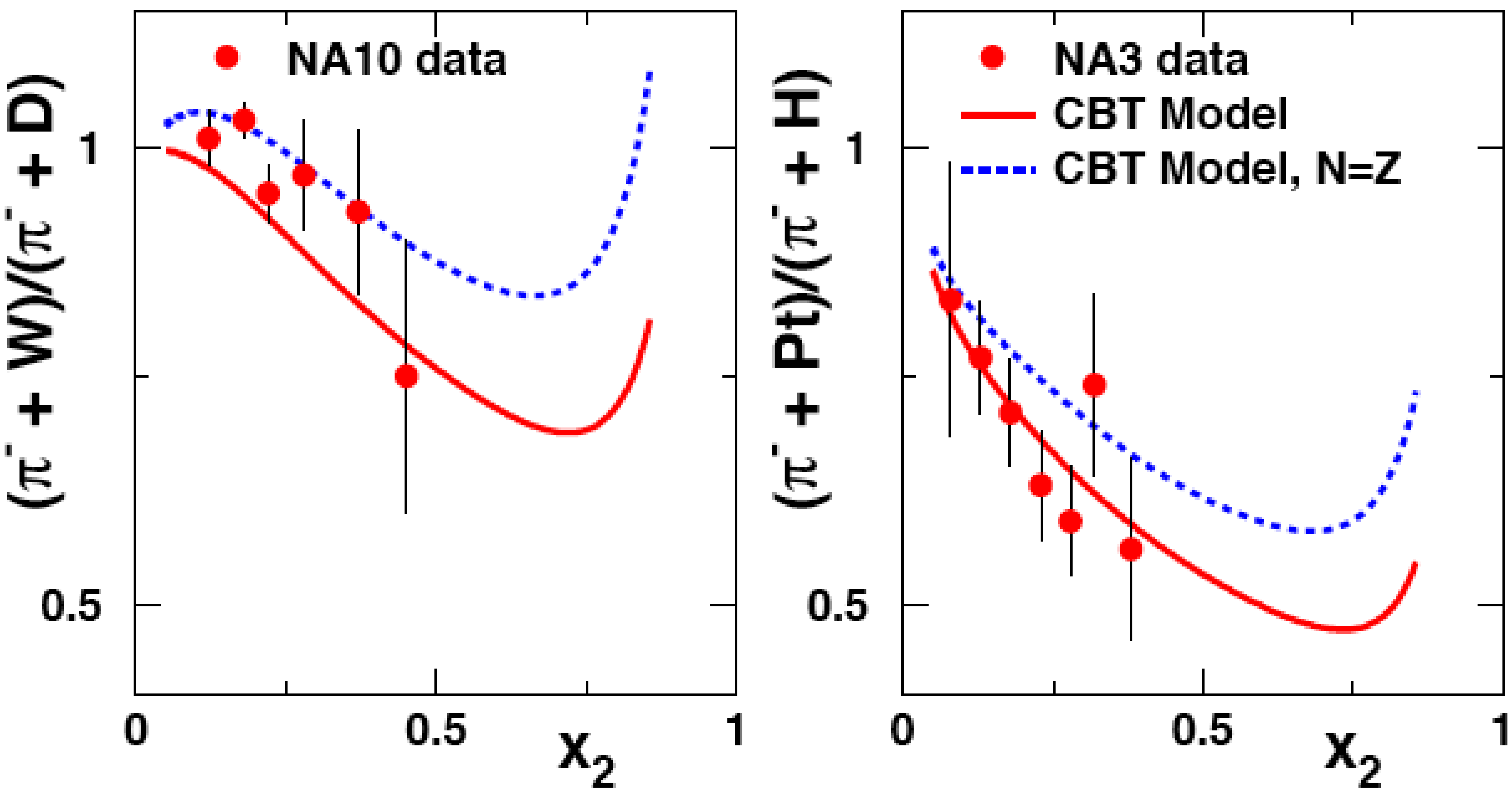


Geesaman, Saito, Thomas, The Nuclear EMC Effect
[Ann. Rev. Nucl. Part. Sci. 45 (1995) 337]

- Modification of parton distributions in nuclei?
- F_2 in DIS: charge-weighted sum of quarks and anti-quarks.
  Are there nuclear effects for sea quarks?
- Drell-Yan !

Flavor-Dependent EMC Effect in Pion-Induced DY

- Flavor-dependent modification of quark distributions in the nuclear medium?
- Distinguish between different nuclear models
- **<u>Cloet, Bentz, Thomas (CBT) model:</u>**
- isovector mean field in a N≠Z nucleus affects u- and d-quarks differently



$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

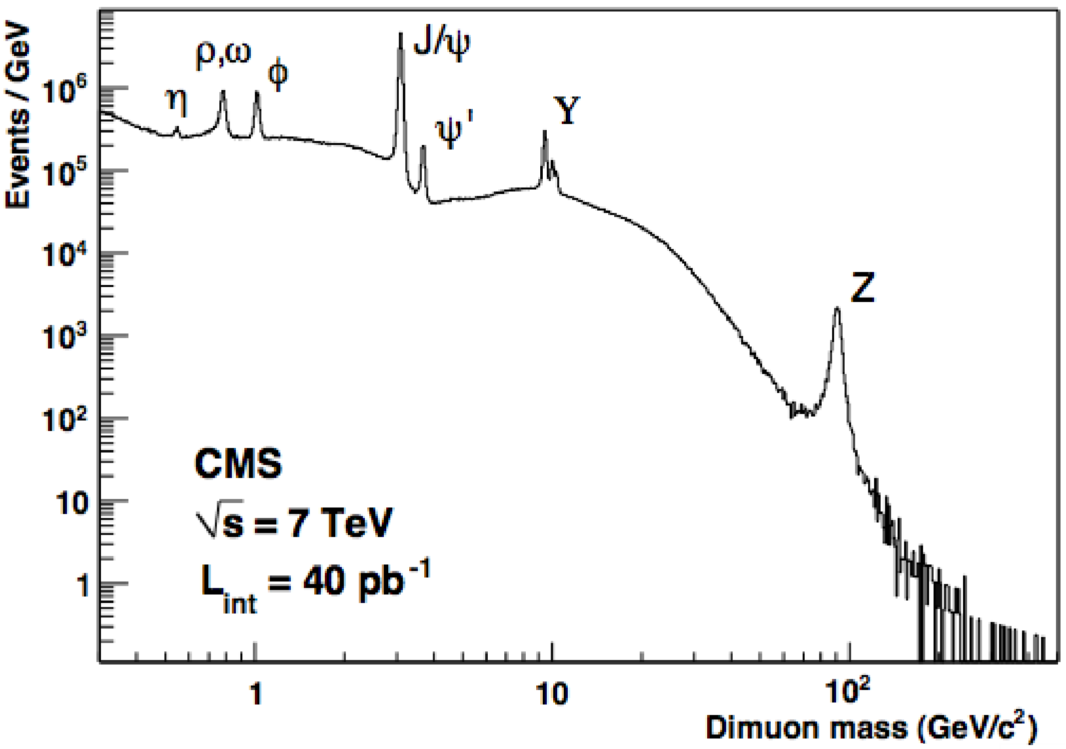
flavor-independent EMC effect

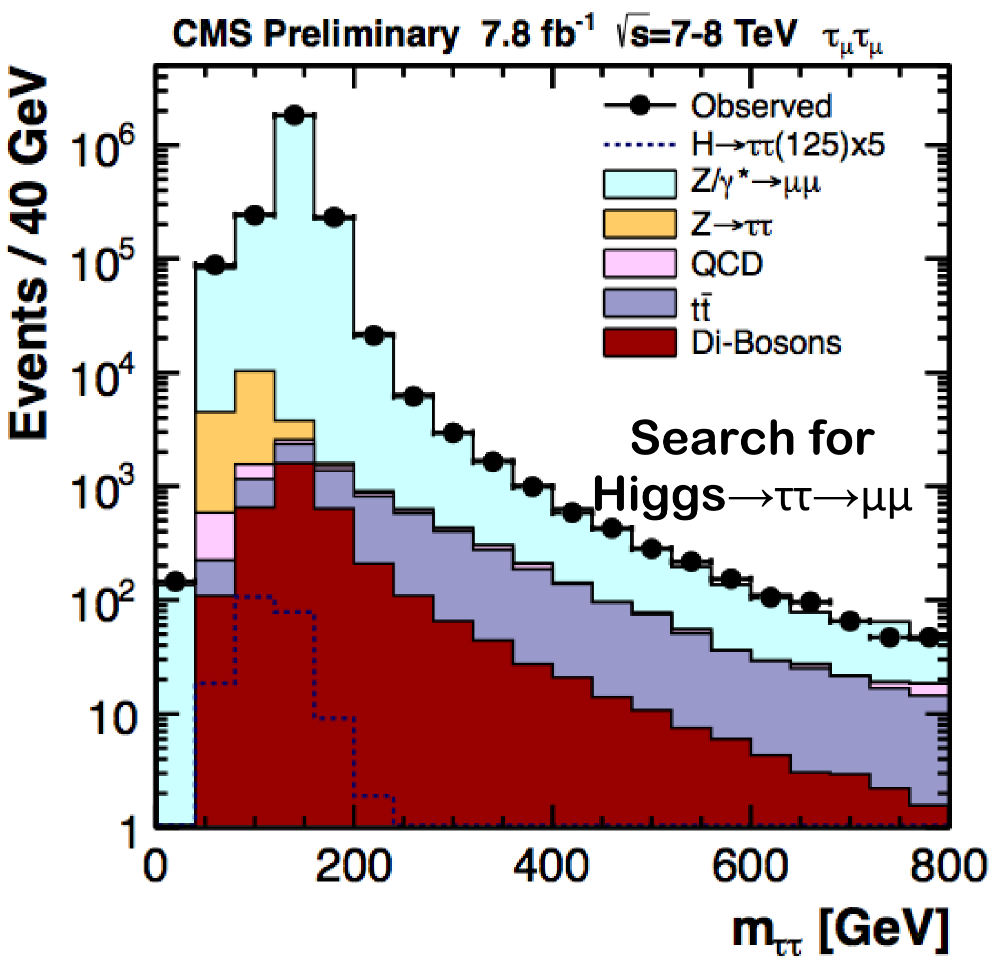
flavor-dependent EMC effect

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916

Experimental possibilities in p-Pb at LHC ?!

Drell-Yan at Highest-Energy pp($\bar{p}$) Colliders



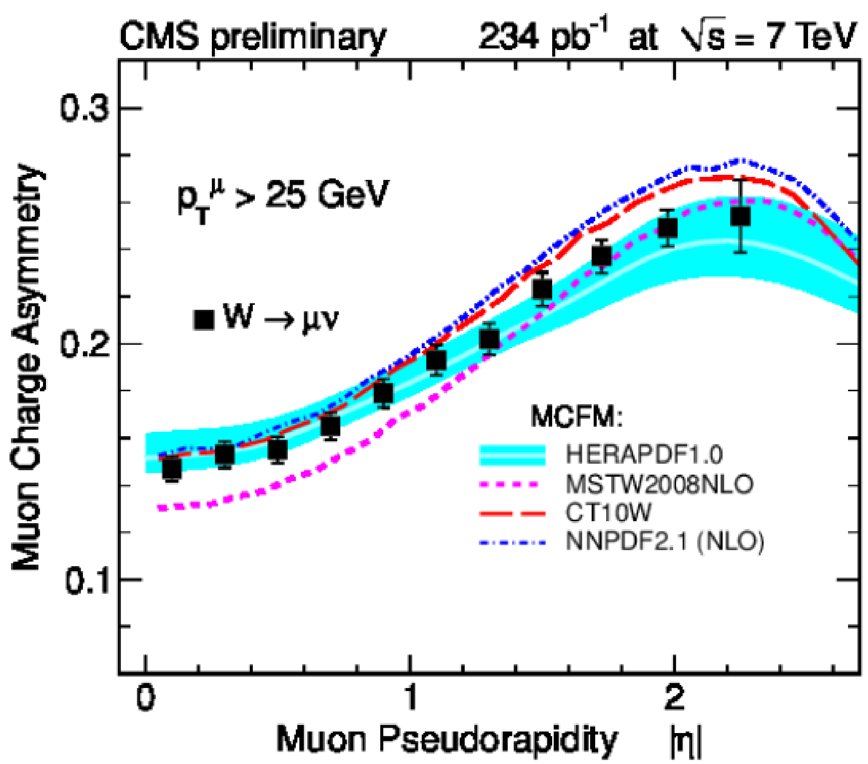


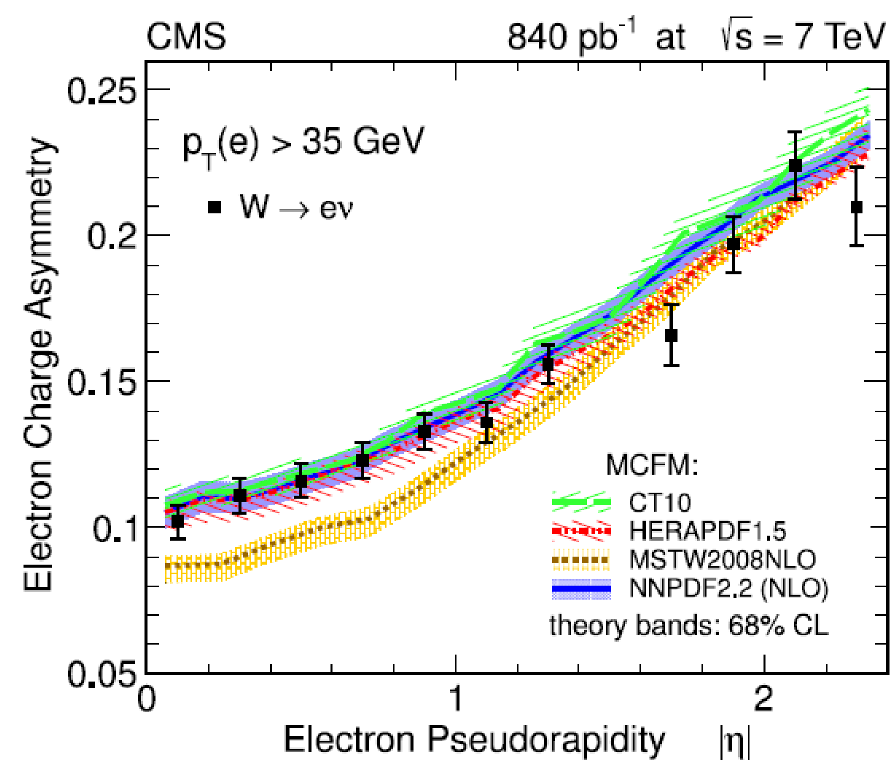
Di-muon production: pp$\overline{(p)}$→$\mu^+\mu^-$X

- LHC & Tevatron: Drell-Yan widely explored
- Major background in searches.
- Constraints for PDFs
- Probe for new physics/precision test of SM: measurement of A_{FB}

Impact of Charged Current Ratio on PDFs

$$A(\eta) = \frac{d\sigma/d\eta(W^+) - d\sigma/d\eta(W^-)}{d\sigma/d\eta(W^+) + d\sigma/d\eta(W^-)}$$

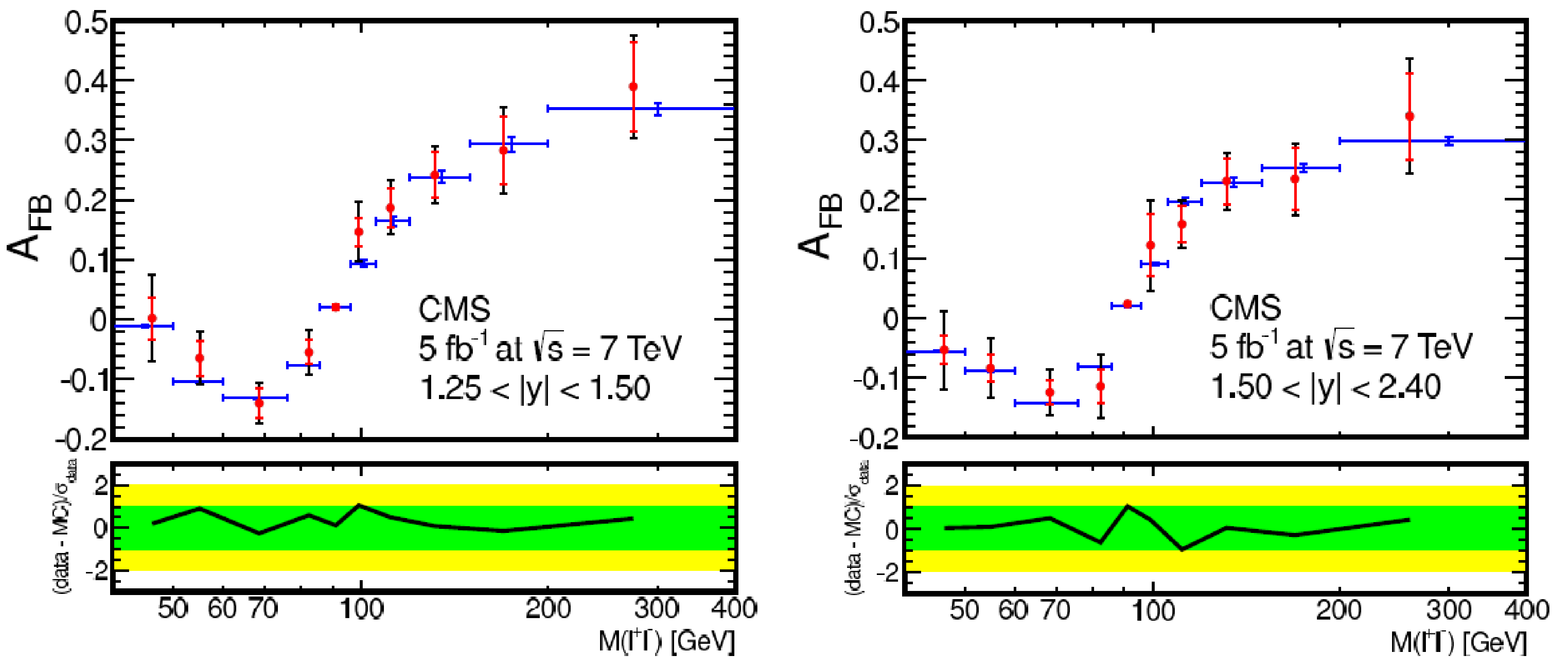




Input for constraining u/d and anti-quark distributions in PDF fits

Measurement of Forward-Backward Asymmetry in DY in CMS

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



Weak mixing angle from multi-variant analysis of DY production vs m, y, cosθ to 0.1%:

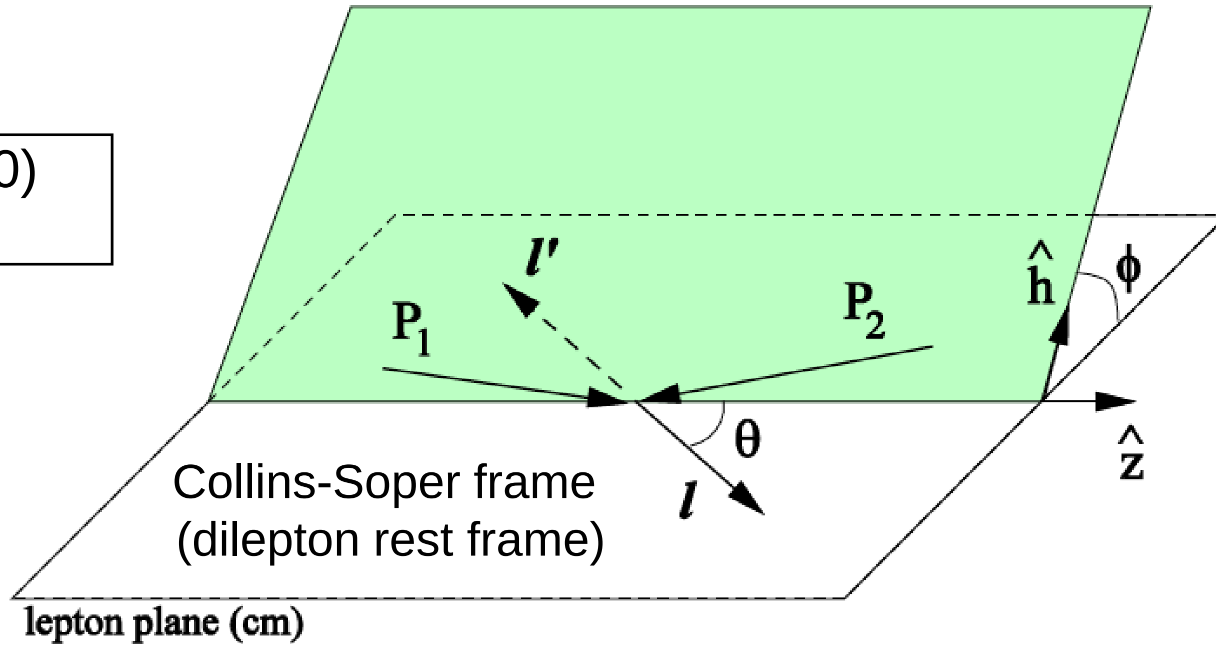
$$\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0020\ (\text{stat.}) \pm 0.0025\ (\text{syst.})$$

Phys. Rev. D 84, 112002 (2011)

Angular Dependence of the (Spin-Integrated) DY Cross Section

$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta$$

Drell-Yan in collinear (k_T=0)
qqbar annihilation



($1+\cos^2\theta$)
+ k_T + higher O(α_S):

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin(2\theta)\cos\phi + \frac{\nu}{2}\sin^2\theta\cos(2\phi)$$

Lam-Tung relation

$$1 - \lambda = 2\nu$$

C.S. Lam and W.K. Tung, PRD 18 (1978) 2447

- Reflects spin-½ nature of quarks (DIS-Callan-Gross-like)
- Widely insensitive to QCD corrections
- “unique opportunity to test the QCD-improved quark-parton model”

Lam-Tung in Proton- and Pion-Induced DY

- **Proton-induced Drell-Yan (E866)**
  - consistent with LT-relation
  - no cos(2Φ) dependence
  - no p_T dependence

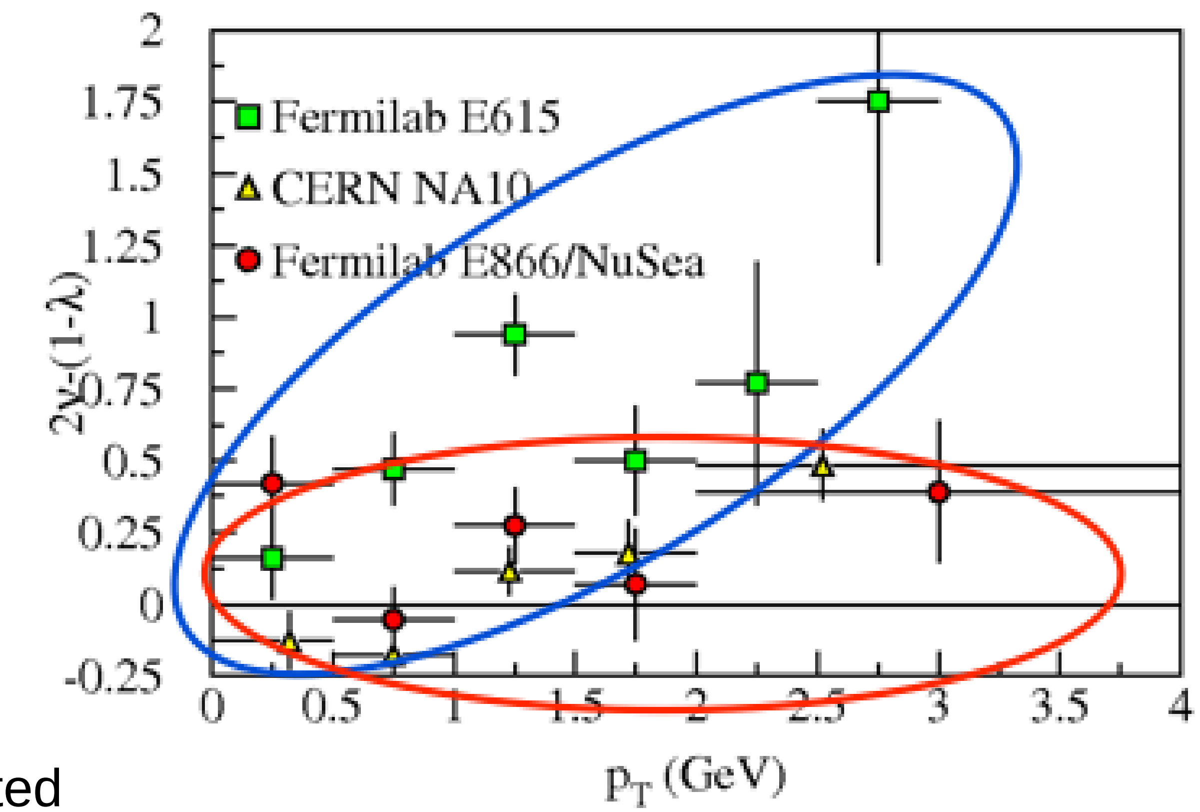
- **Pion-induced Drell-Yan (NA10, E615)**
  - violates LT-relation
    (independent of nucleus - no nuclear effect)
  - large cos(2Φ) dependence
  - strong with p_T

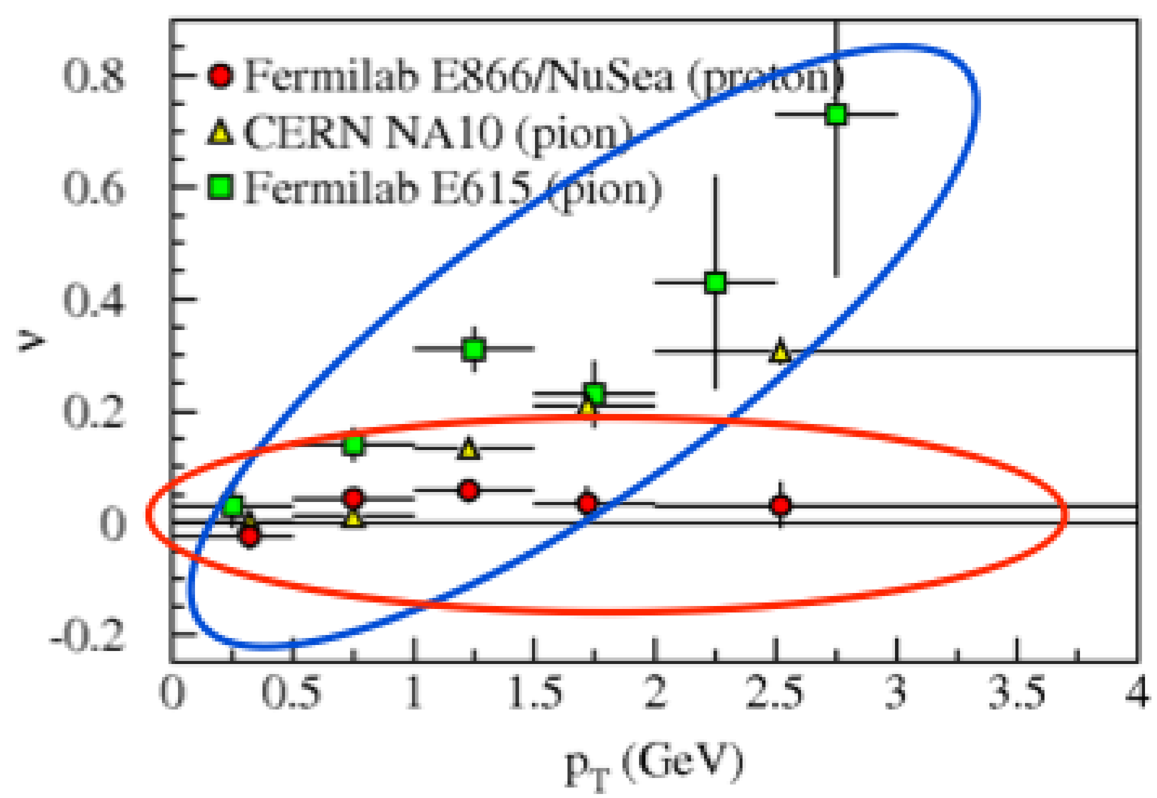
- **Explanations**
  - Boer-Mulders (BM) TMD ➔quark transverse spin correlated with quark transverse momentum ?
  - higher twist
  - spin effects in QCD vaccum

- **Pionic DY probes BM (valence),** target=proton
  Protonic DY probes BM (sea), target=proton
  - BM (sea) small compared to BM (valence)

- Drell-Yan may be sensitive to **spin-transverse momentum correlations**!

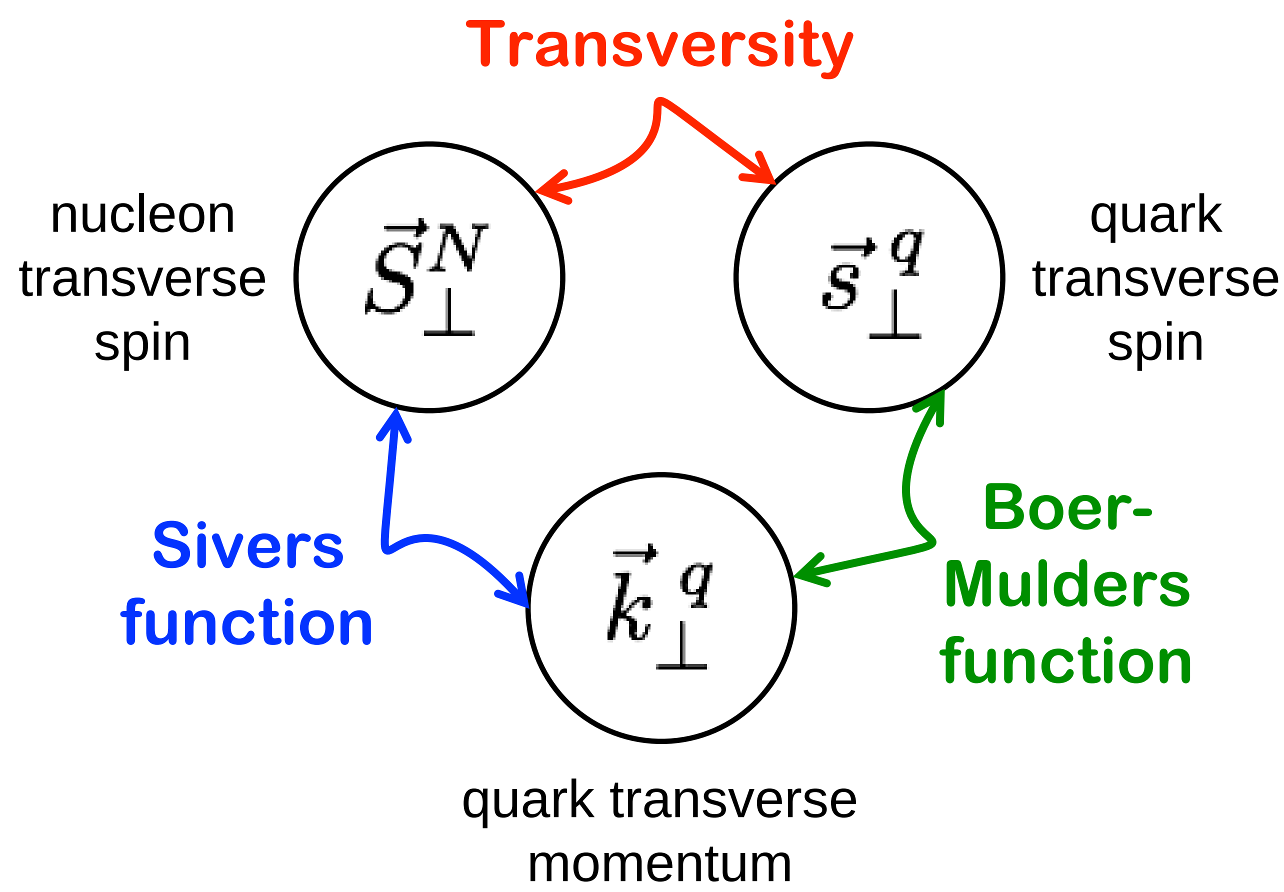
$$1 - \lambda = 2\nu$$





TMDs in Spin-Dependent Drell-Yan

Correlations between transverse nucleon spin, quark spin and quark transverse momentum



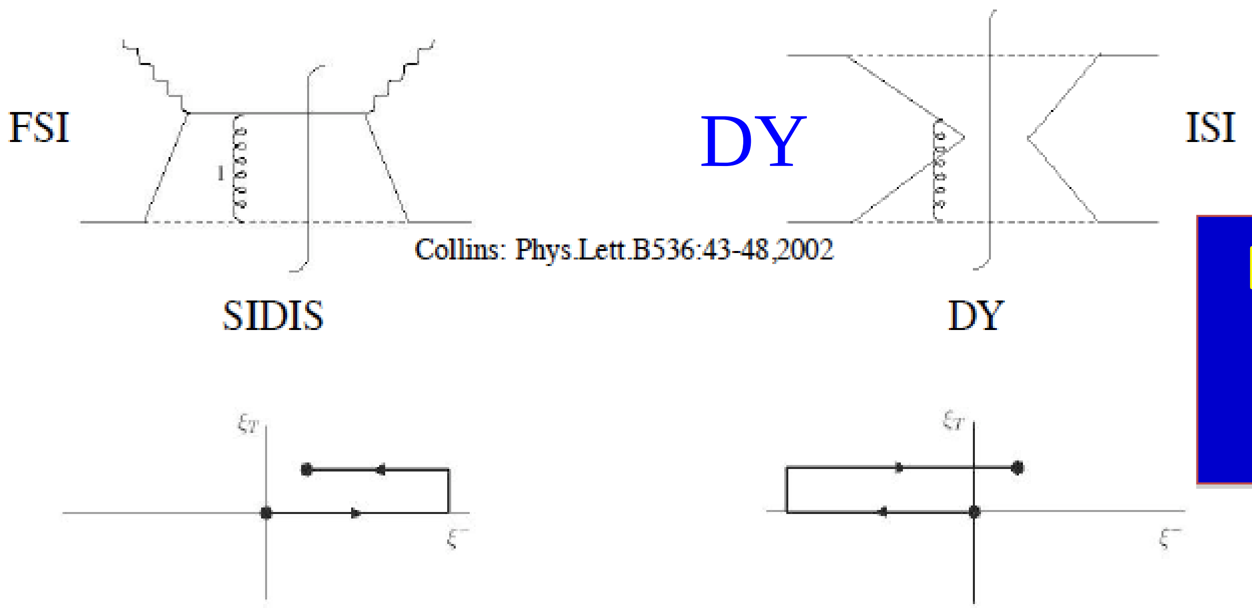
- Are Sivers function and Boer-Mulders **universal**?
  - *Observed to be clearly different from zero in SIDIS.*
  - Expect **sign switch** of these time-reversal-odd TMDs in DY wrt SIDIS: fundamental QCD prediction due to gauge invariance

- Experimental verification: crucial test of non-perturbative QCD and TMD physics
  - origin of large SSAs?
  - validity of QCD factorization?

Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and DY

SIDIS

DY



Direction of the gauge-link integrals of k_T dep. pdfs is process-dependent and changes its sign between SIDIS and DY

Sivers $$f_{1T}^{\perp}(x, \mathbf{k}_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x, \mathbf{k}_T)\Big|_{DY}$$

Boer-Mulders $$h_1^{\perp}(x, \mathbf{k}_T)\Big|_{SIDIS} = -h_1^{\perp}(x, \mathbf{k}_T)\Big|_{DY}$$

Sign reversal between polarized SIDIS and Drell-Yan is to be tested!

TEST proposed process dependence of TMD pdfs!

Predictions for the size of asymmetries depend on Q2 of the experiment and knowledge of TMD evolution

Current Polarized Drell-Yan Experiments

pion-nucleon

- COMPASS (CERN)

Proposed future Polarized Drell Yan Experiments

proton-proton

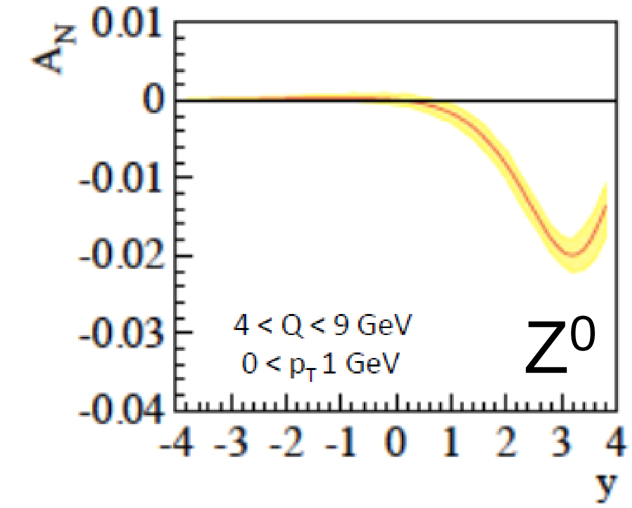
- SeaQuest (Fermilab)
- RHIC (Brookhaven)
- J-PARC (KEK)
- IHEP (Protvino)
- JINR (Dubna)

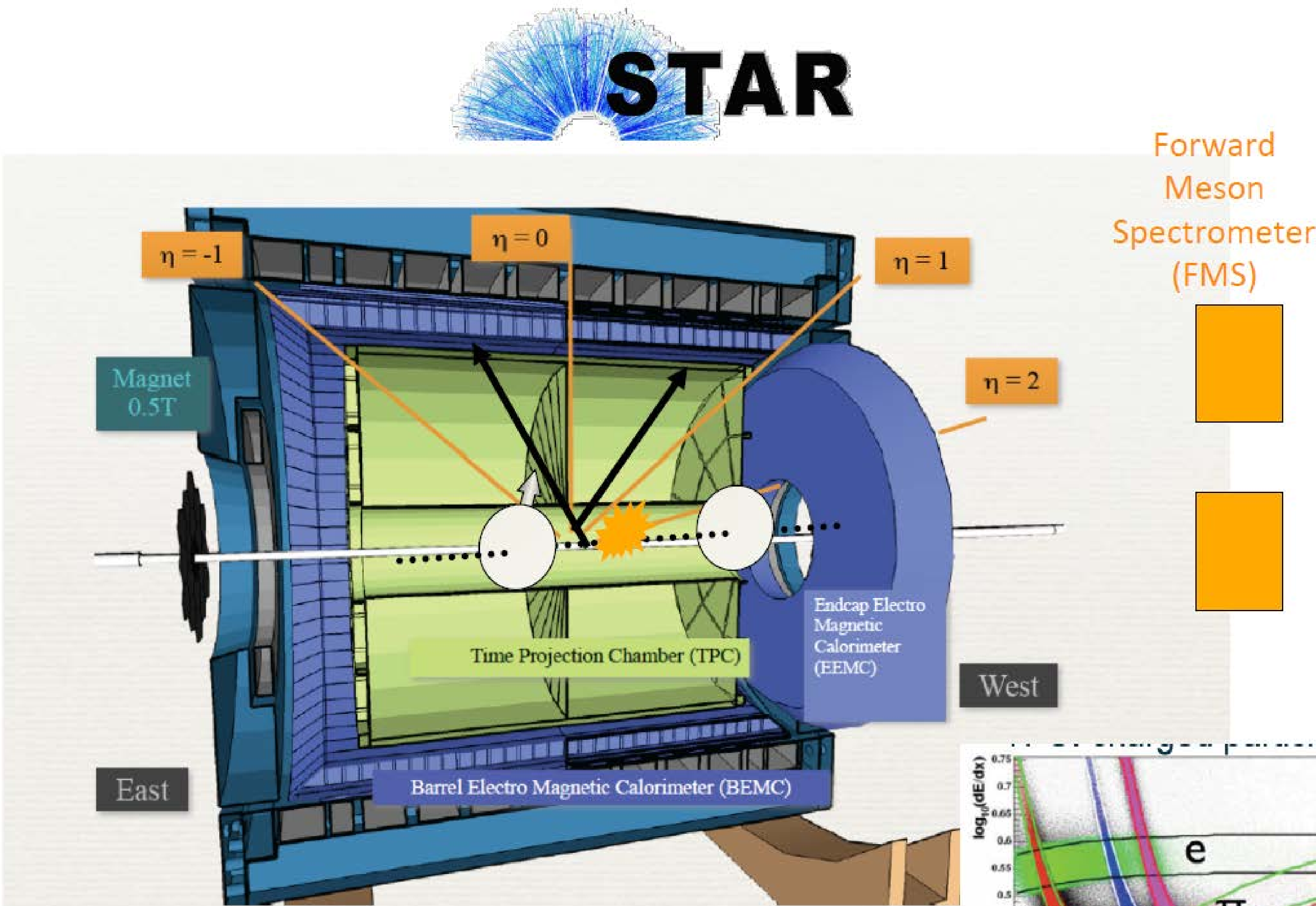
anti(p)-proton

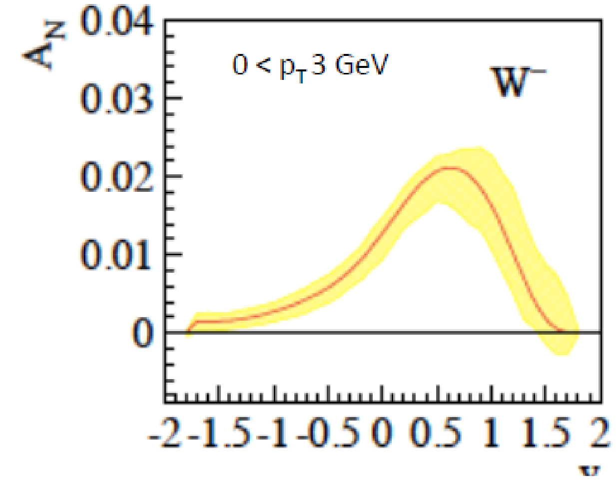
- FAIR (GSI)

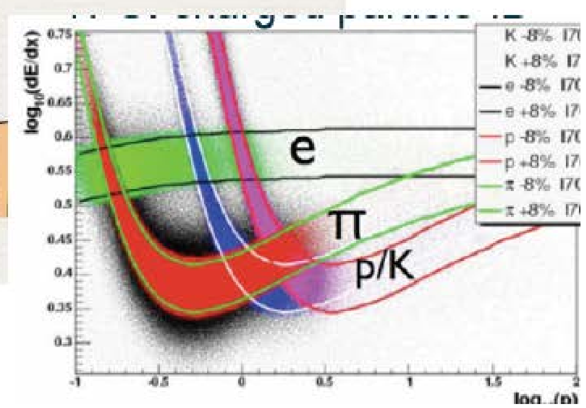
A_N for direct-photon, DY, W and Z^0 from STAR at RHIC

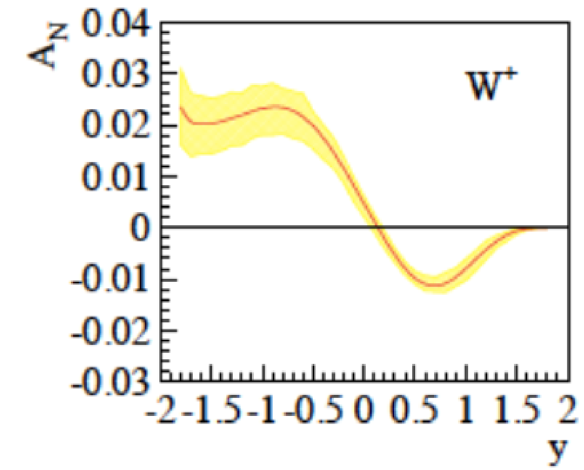
Z. Kang et al. arXiv:1401.5078v1









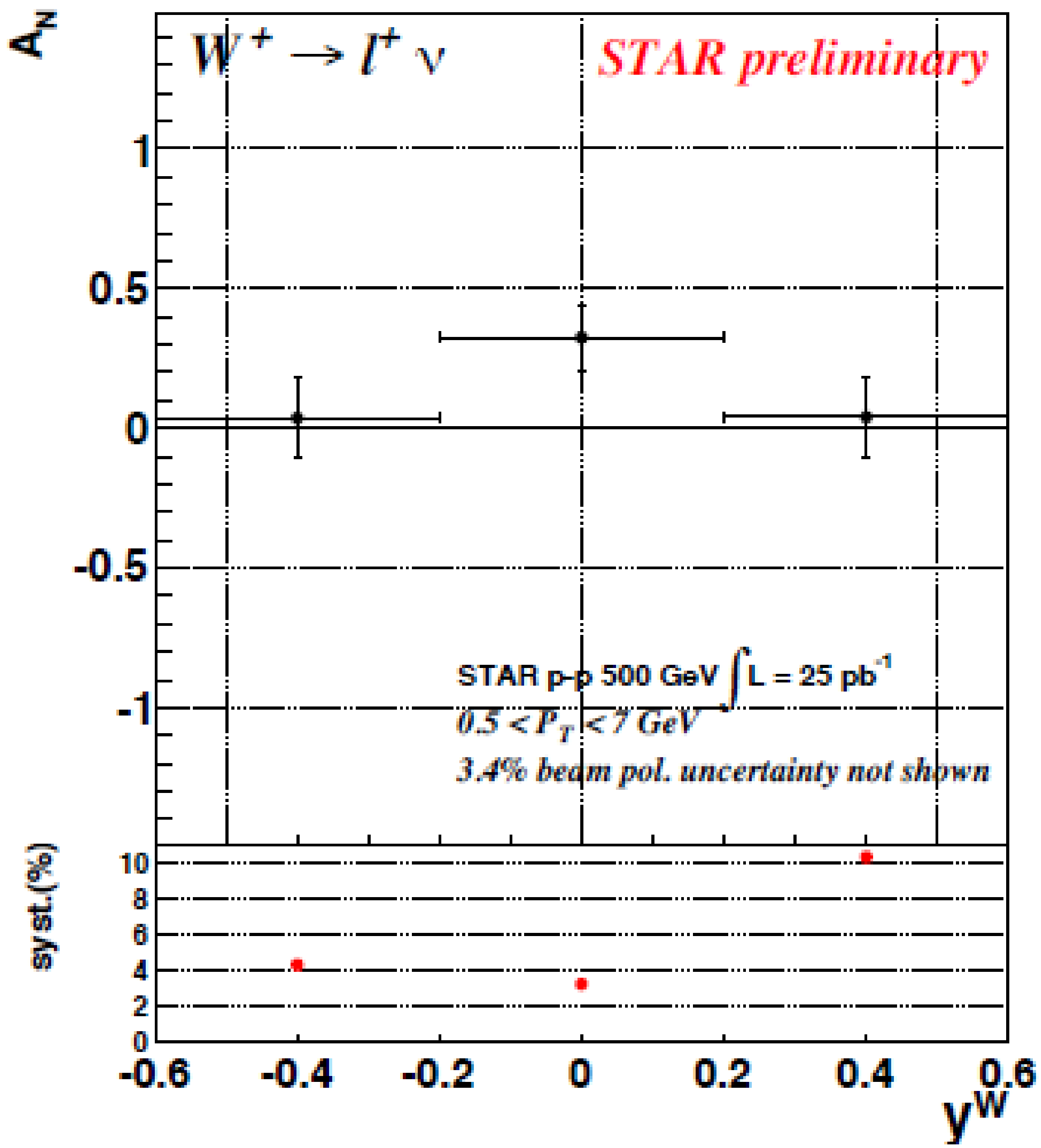


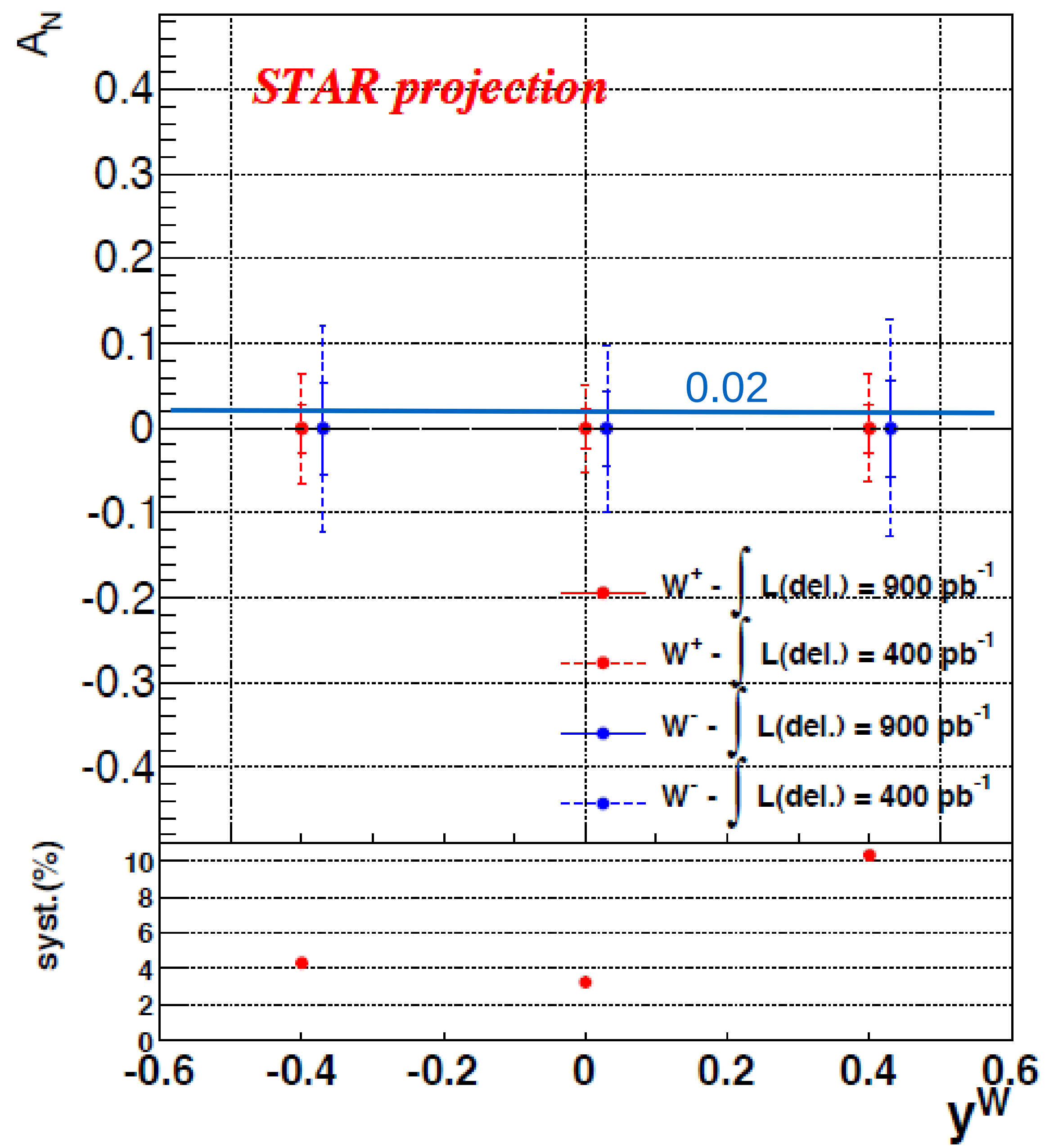
$$\eta = -log(tan\frac{\theta}{2})$$

ϕ : azimuthal angle

From A. Vossen's talk at Transversity 2014

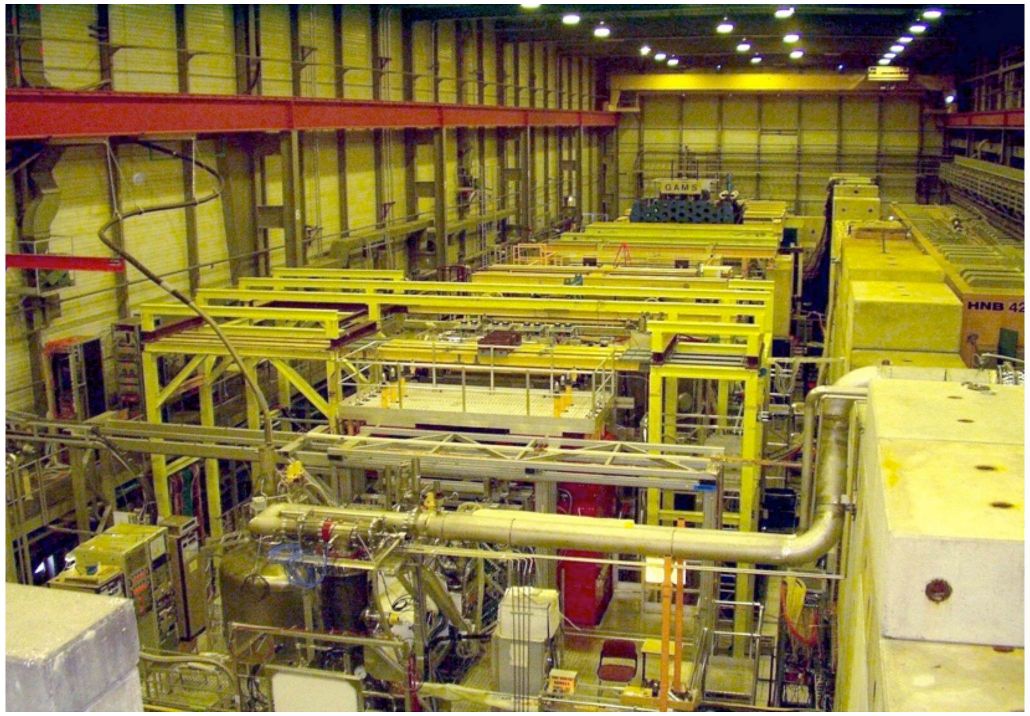
STAR $A_N(W^+)$: 2011data vs 2016 Projections

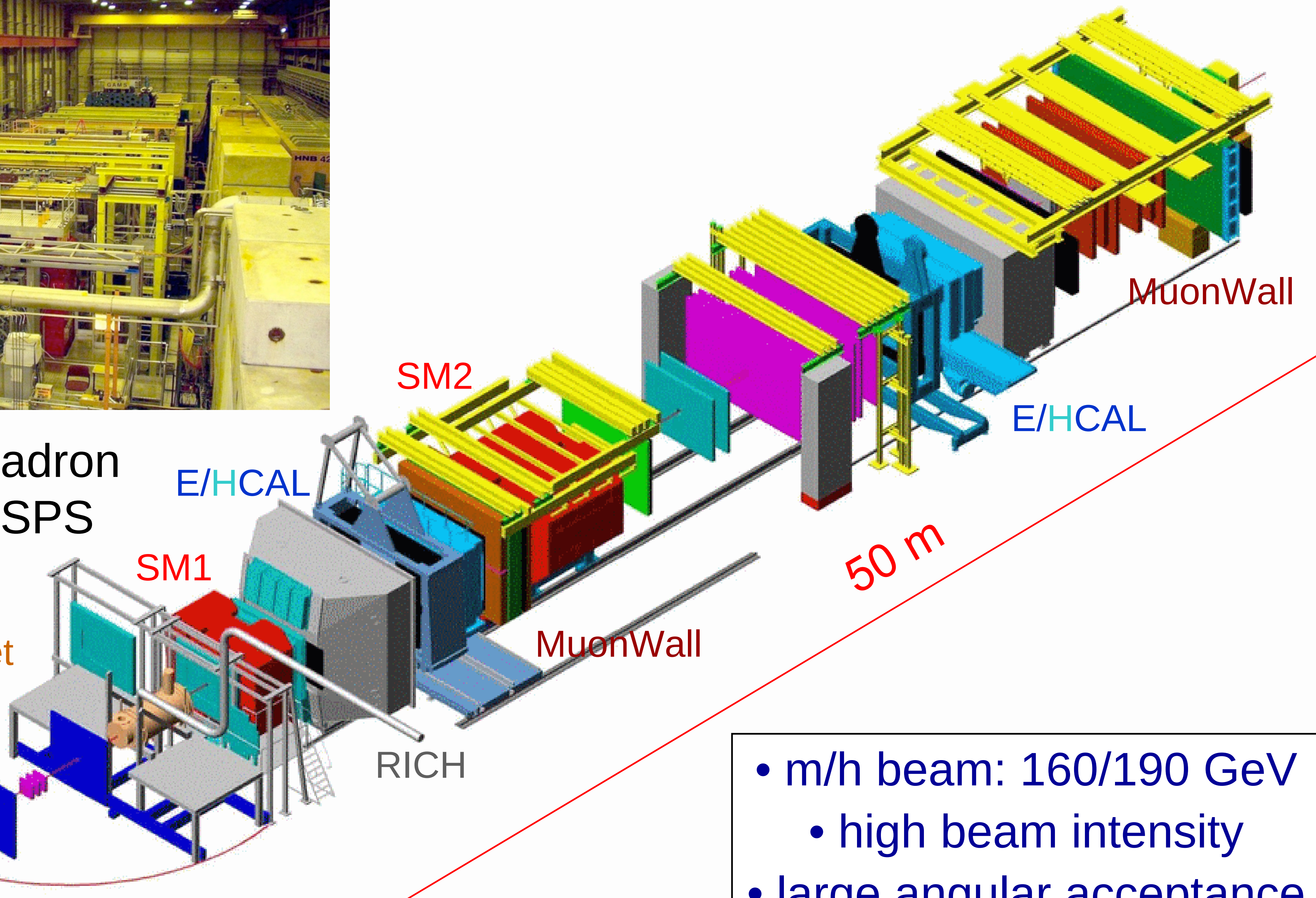




From A. Vossen's talk at Transversity 2014

The COMPASS Spectrometer



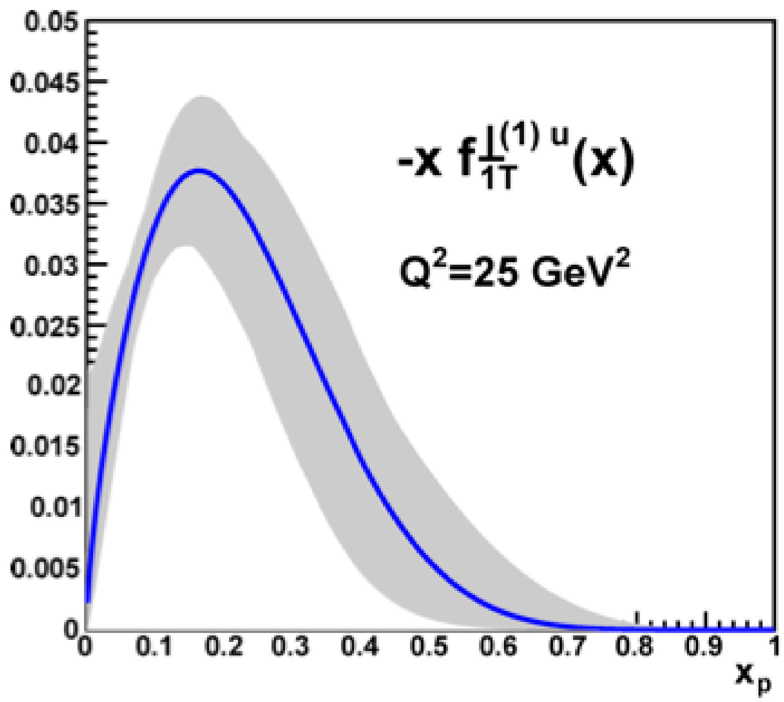


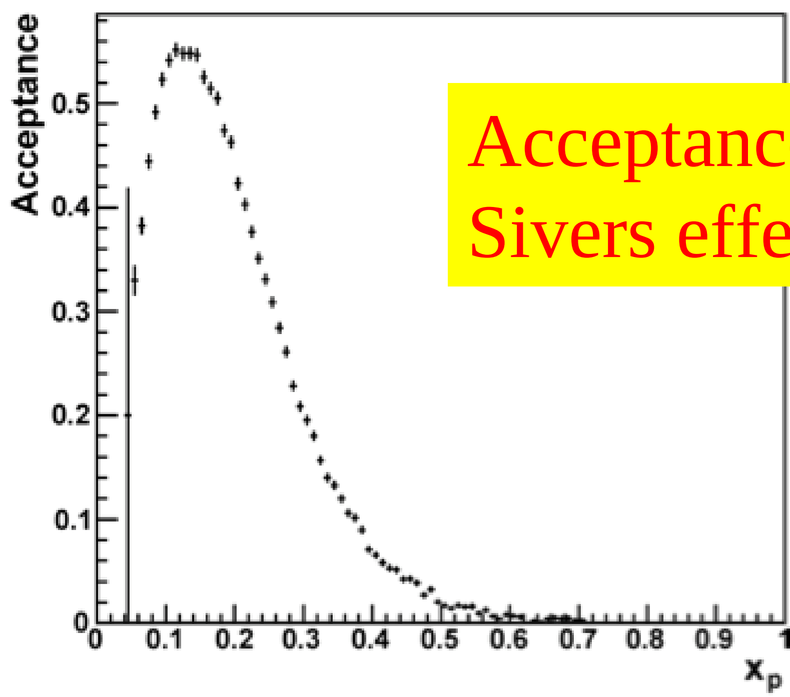
Secondary hadron beam from SPS

two stage spectrometer
to cover a large kinematic range

- m/h beam: 160/190 GeV
- high beam intensity
- large angular acceptance
- broad kinematical range

Kinematics $4 < M_{uu} < 9$ GeV/c^2 at COMPASS

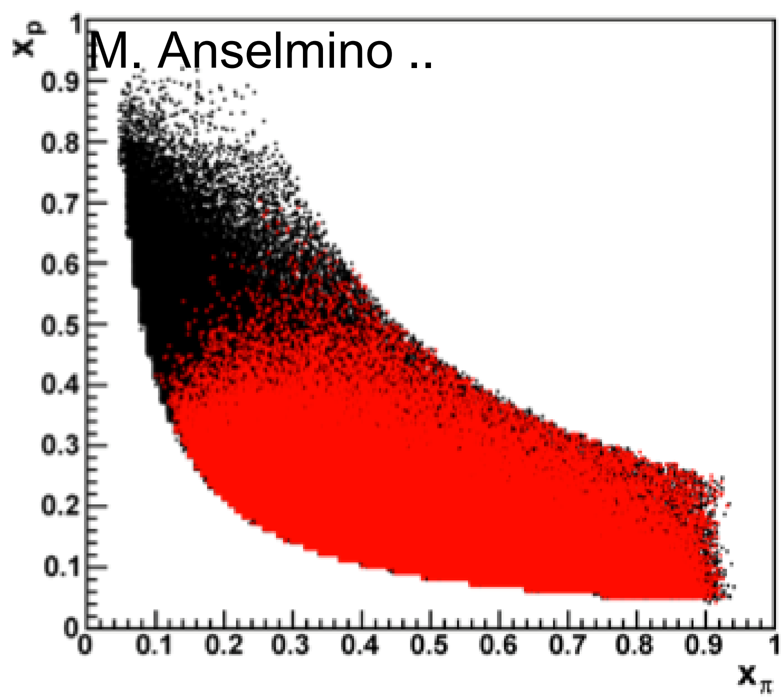


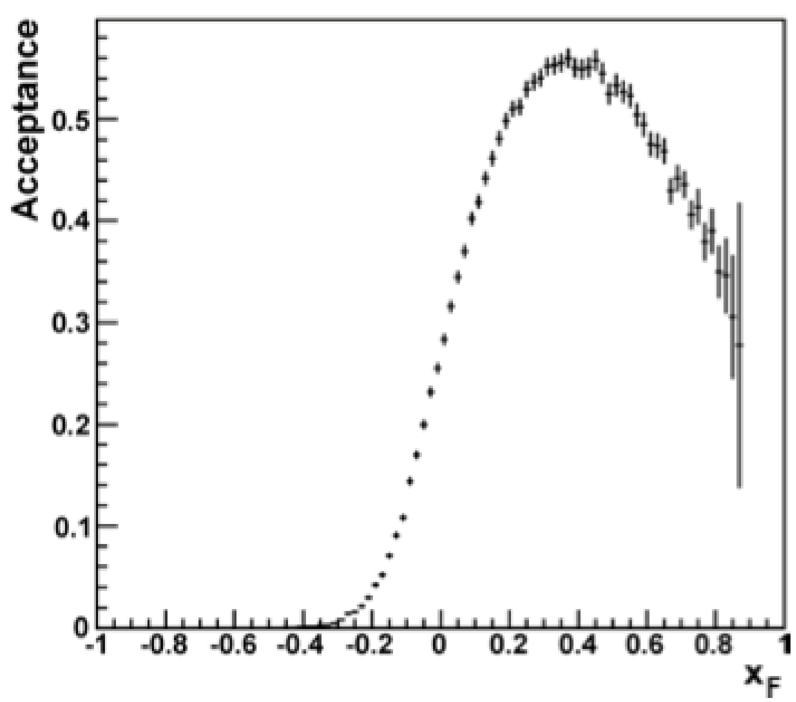


Acceptance is largest where
Sivers effect is known to be largest

Phys.Rev.D79:054010, 2009

M. Anselmino ..



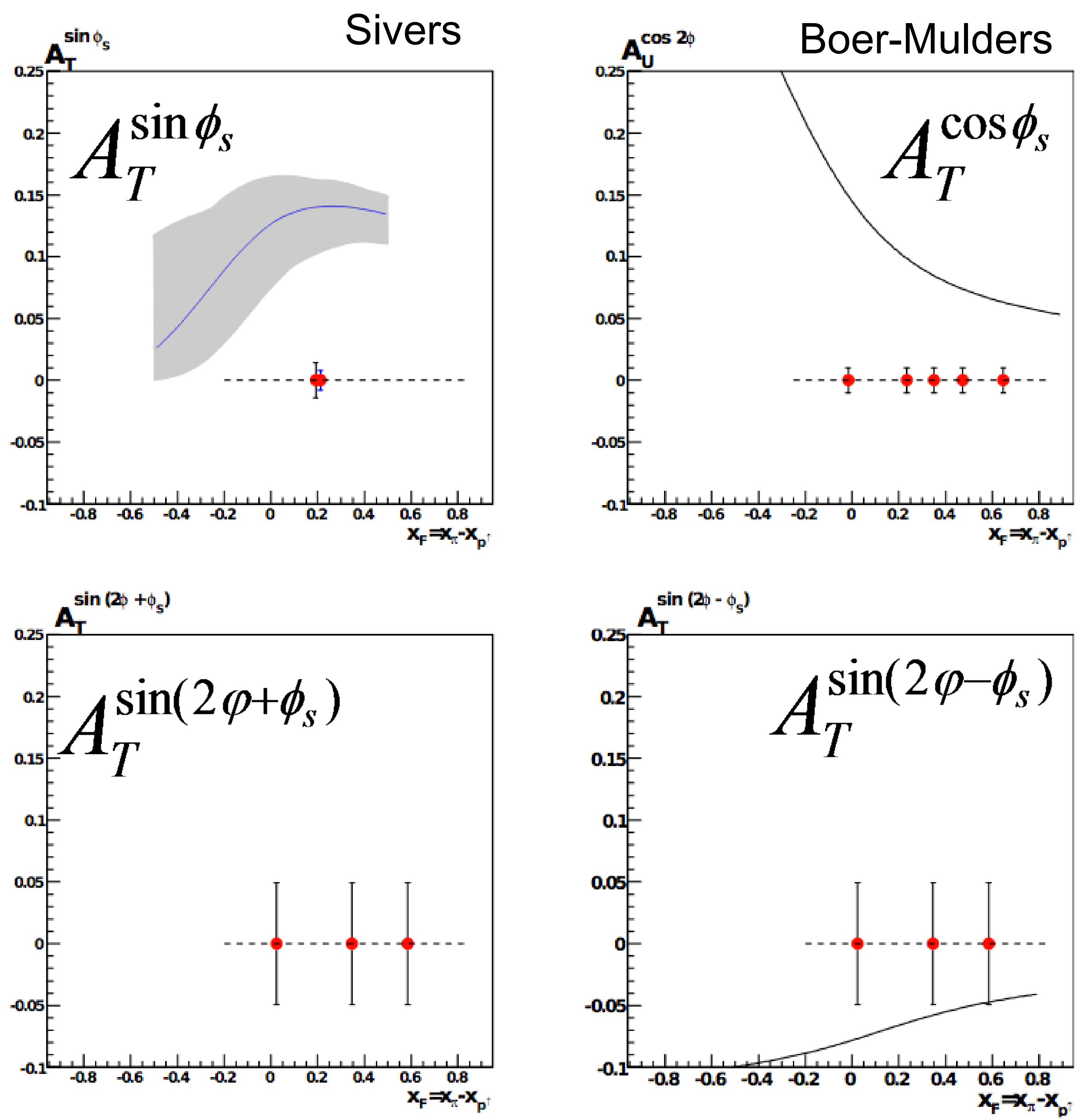


Valence range (x~> 0.1) for both quarks (➔ u-ubar annihilation)

P_T dimuon is about 1GeV/c where TMD effects are dominant

COMPASS A_T Statistical Precision

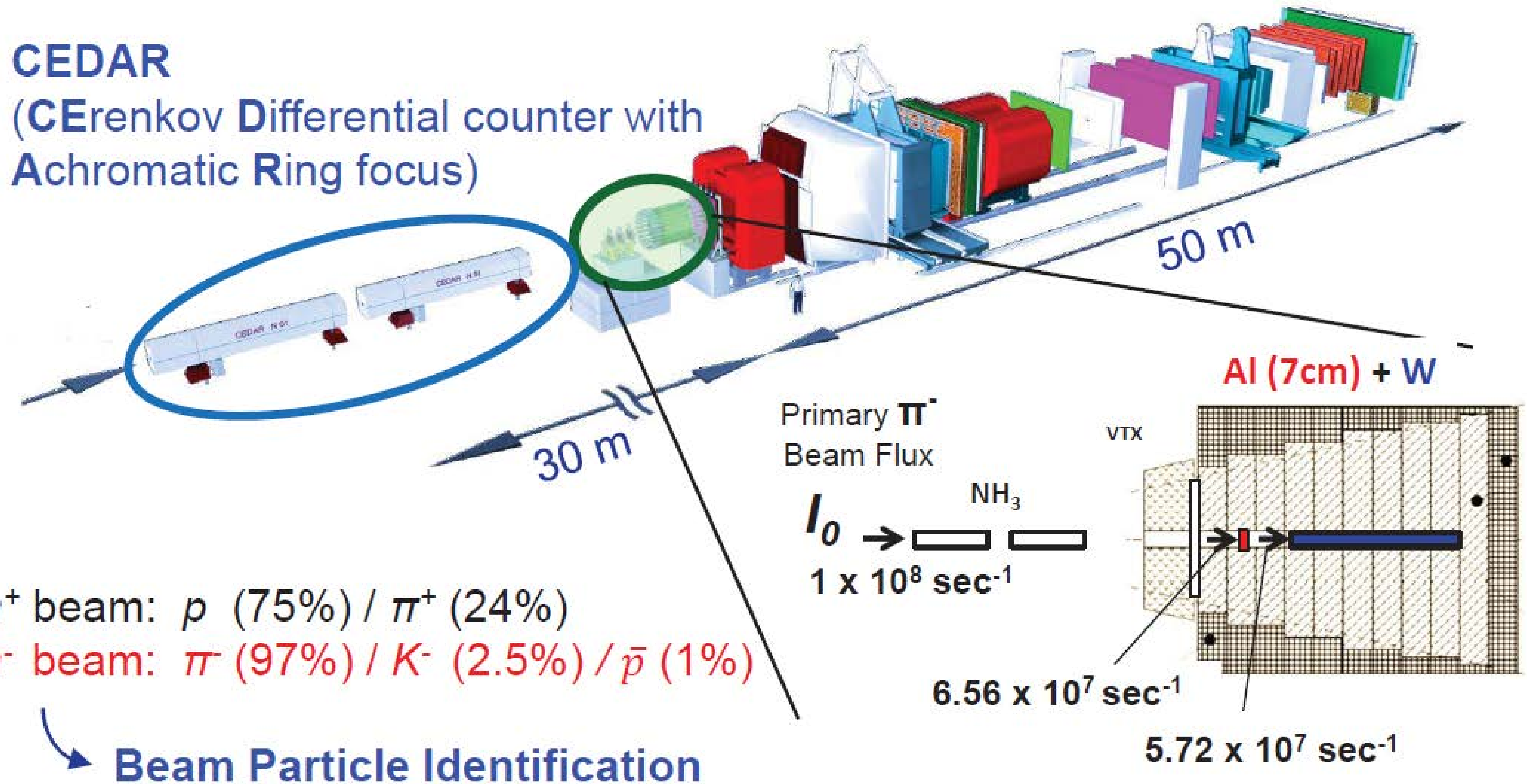
$4 < M_{\mu\mu} < 9$ GeV/c^2



Details will be given in the presentation by Robert Heitz following this talk!

COMPASS Drell Yan With Nuclear Targets and PID in the Negative Hadron Beam

CEDAR
(**CE**renkov **D**ifferential counter with **A**chromatic **R**ing focus)



h^+ beam: p (75%) / π^+ (24%)
h^- beam: π^- (97%) / K^- (2.5%) / $\bar{p}$ (1%)

→ **Beam Particle Identification**

COMPASS could study the beam- and target-dependence of Drell-Yan process.

from Wen-Chen Chang at Spin 2014

COMPASS Drell Yan With Nuclear Targets Projections for Number of Drell Yan Pairs

DY ($4 < M_{\mu\mu} < 9$ GeV/c^2) 140-day data taking

	NH_3	Al (7cm)	W	NA3	E537	E615
π^- beam	285,000	55,100	549,000	21,220		27,977
K^- beam	3,570	710	7,570	700		
$\bar{p}$ beam	2,570	450	3,640		387	

COMPASS could improve the existing statistics of π, K and $\bar{p}$-induced DY by more than one order of magnitude!

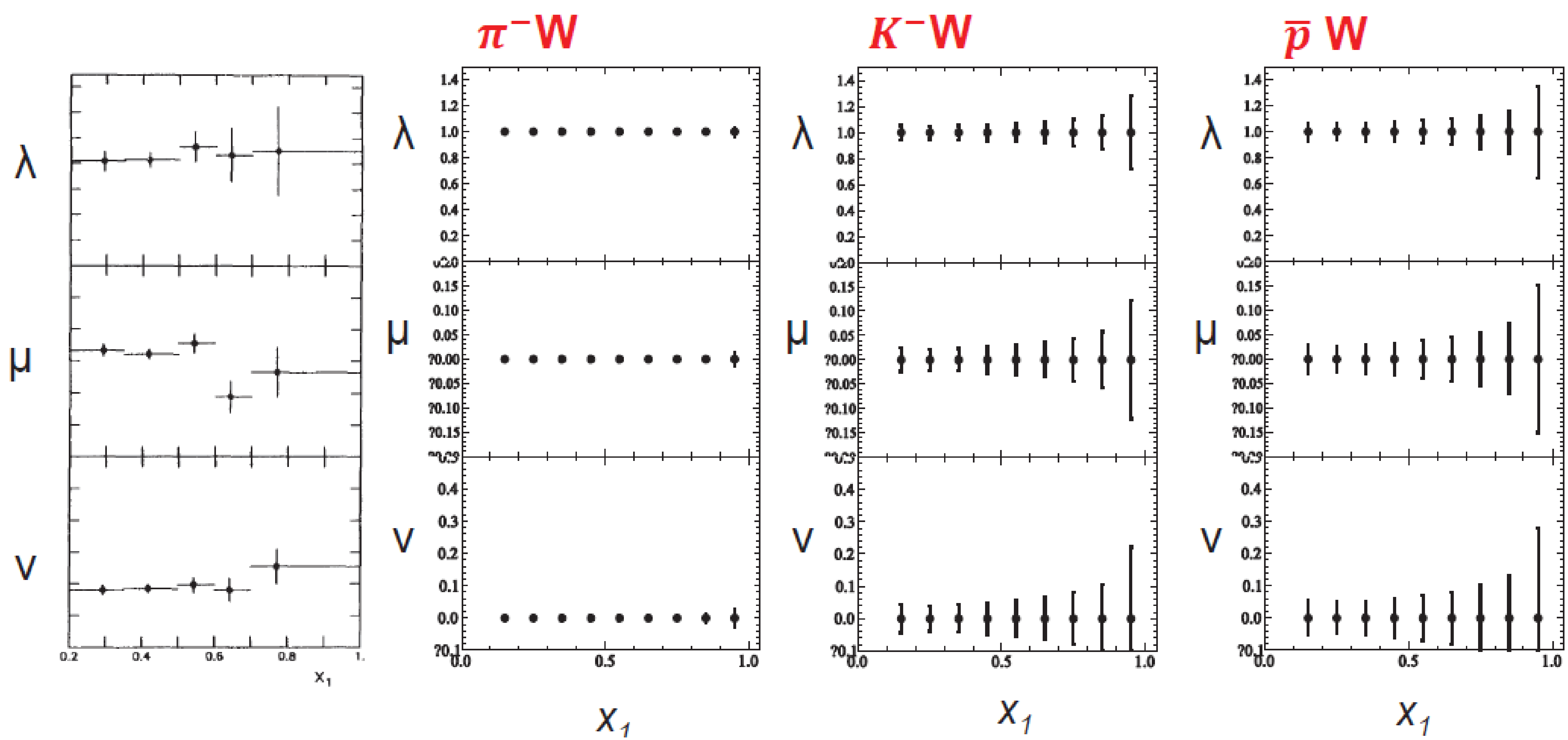
from Wen-Chen Chang at Spin 2014

COMPASS Drell Yan With Nuclear Targets Expected Precision for Lam-Tung Relation

$4 < M_{\mu\mu} < 9\ GeV/c^2$

NA10

COMPASS, DY on **W target**, 140-day data taking



from Wen-Chen Chang at Spin 2014

Summary

Large body of Drell-Yan data available constraining:

o nucleon and meson pdfs
o flavor dependence
o nuclear effects in hadron structure
o TMD evolution through p_T dependence
o spin – k_T correlations in hadrons

Future experiments are being prepared with polarized Targets and polarized beams to study single transverse spin asymmetries and the related spin dependent TMD distribution functions of the hadron