Review of Drell-Yan Experiments

- Highlights from proton-induced DY
- Pion-induced DY
- Spin-dependent DY
- Future experiments

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International Workshop on Hadron Structure and Spectroscopy
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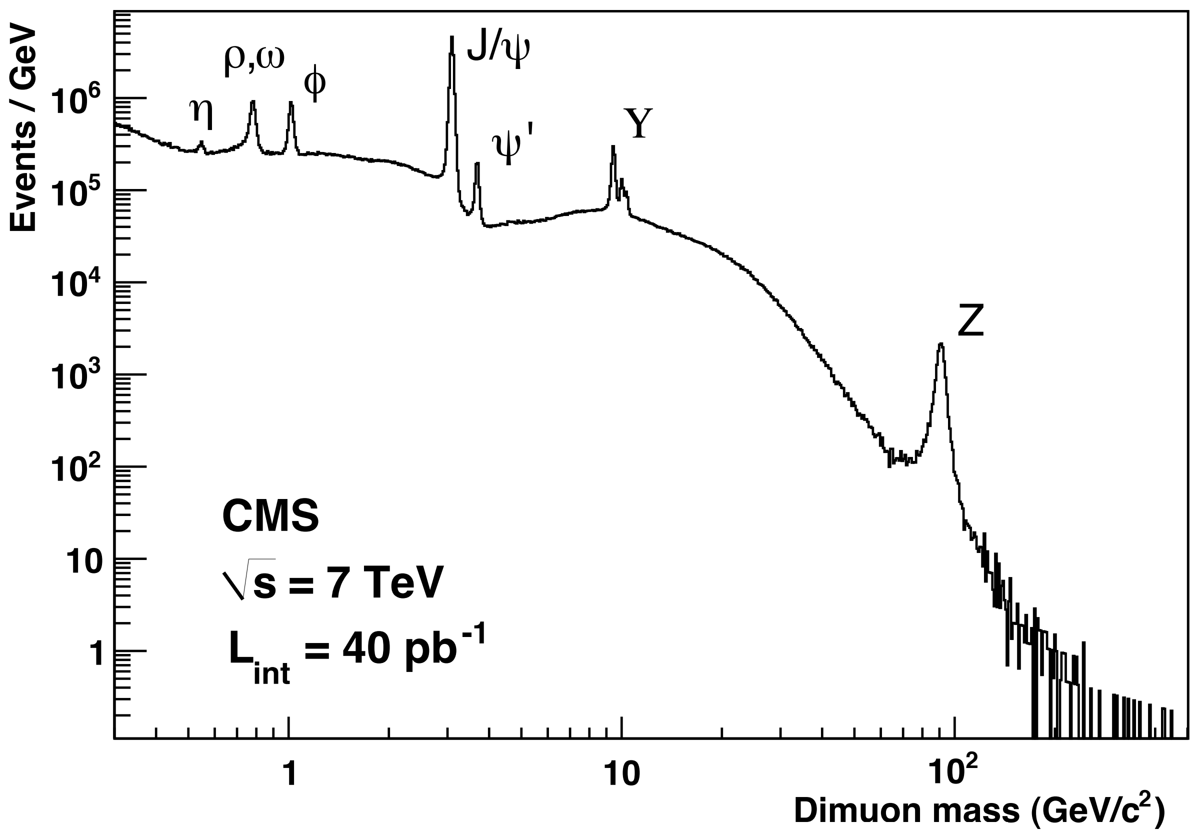
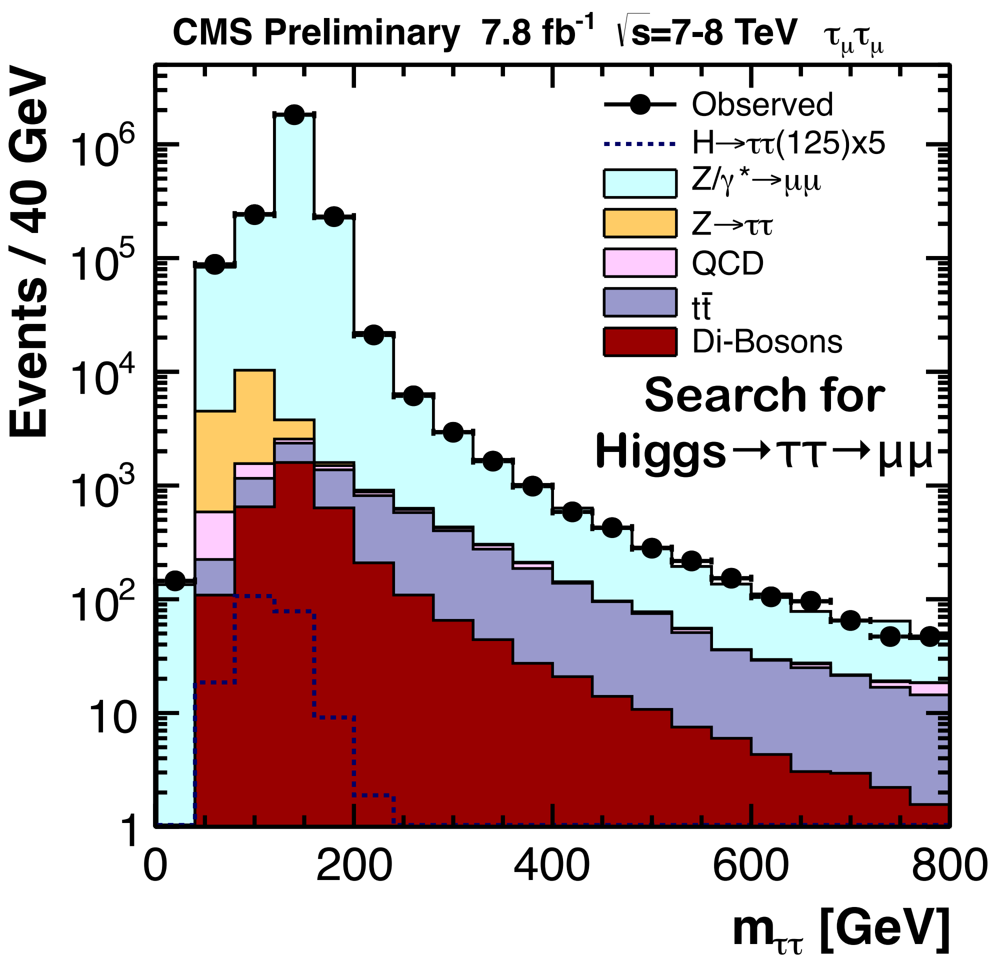
Appetizer: Drell-Yan at highest-energy pp(-) collider

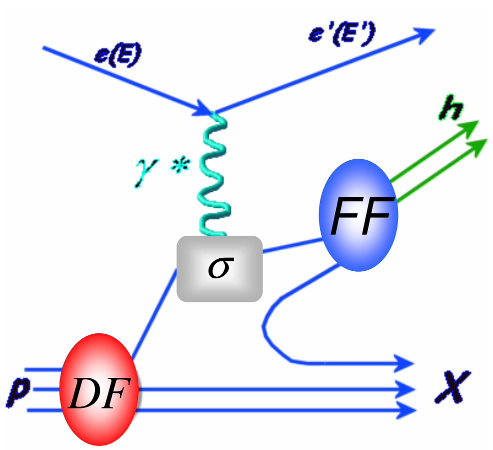




Di-muon production: pp(-)→μ+μ-X

- LHC and Tevatron: Drell-Yan widely explored
  - Major background in searches.
  - Probe for new physics,
  e.g. through angular dependences (A_{FB}).
  - Constraints on PDFs,
  e.g. s(x) in W- and Z-production.
- Studies of proton structure:
  - Dilepton-p_T ↗ √s
  - Q^2-evolution of Sivers effect
  - Cannot probe valence quarks.
- Need more than “Physics at the Terascale”

Probing the partonic structure of hadrons



Assumption: factorization applies
Caveat: might break down @high-x

Probe universality

DIS

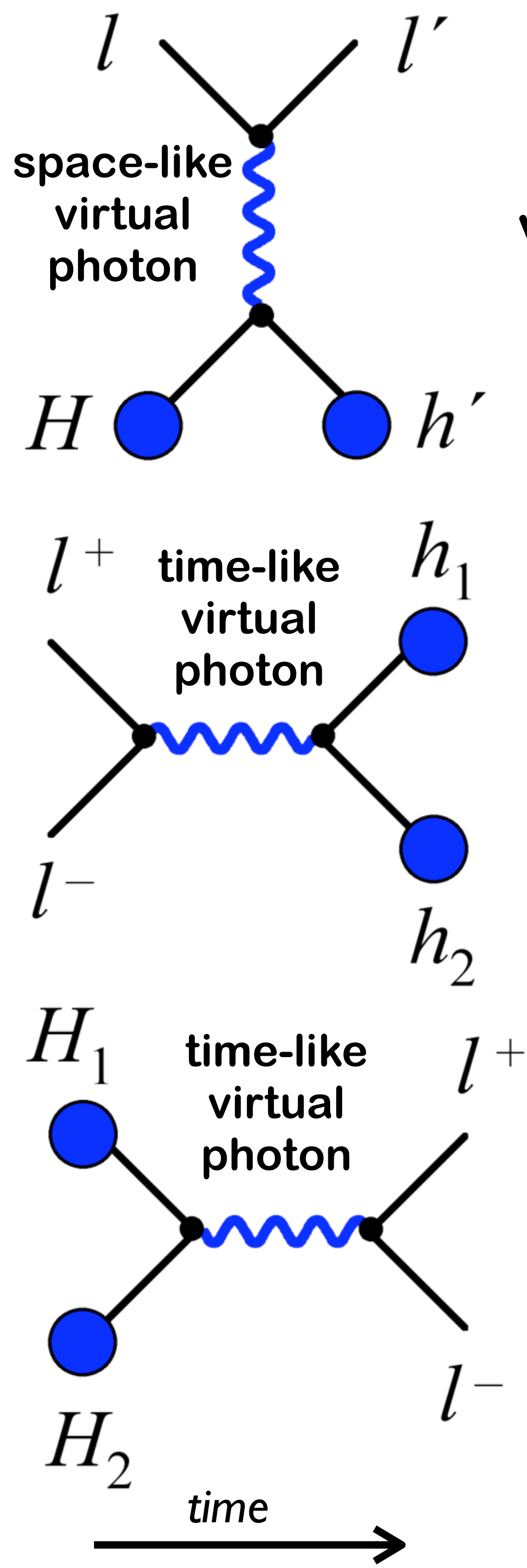
$DF \otimes FF$

electron-electron collisions

$FF \otimes FF$

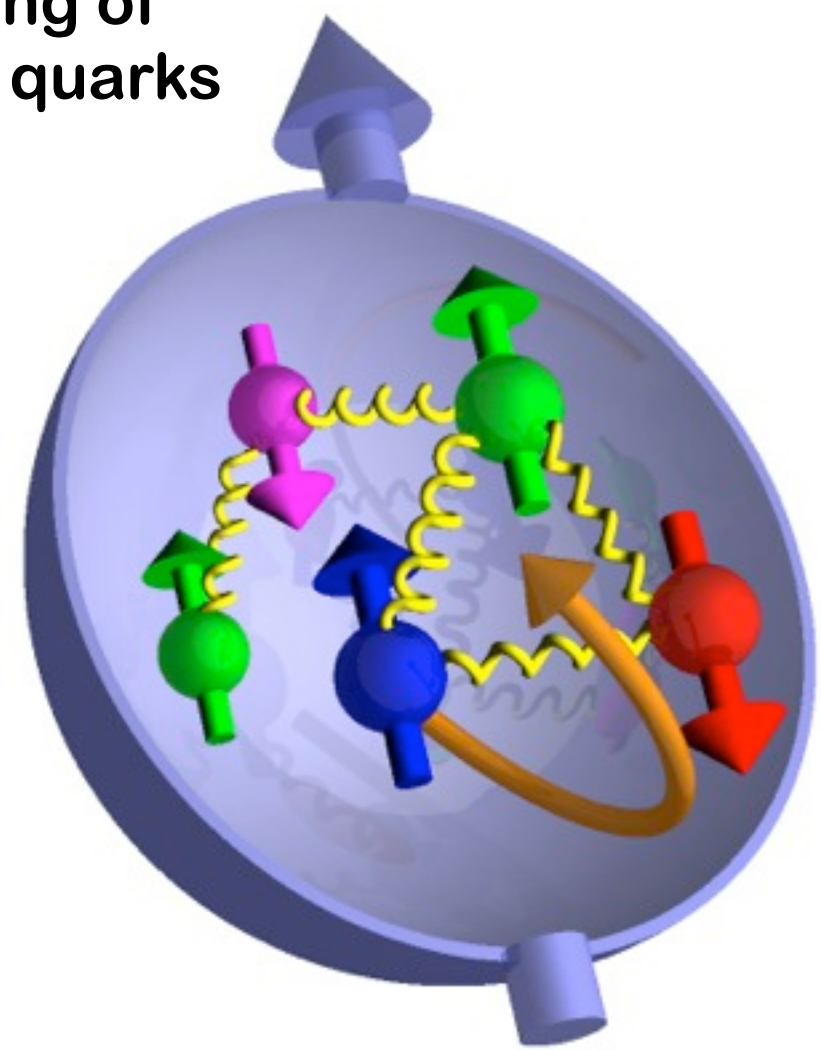
Drell-Yan (DY)

$DF \otimes DF$

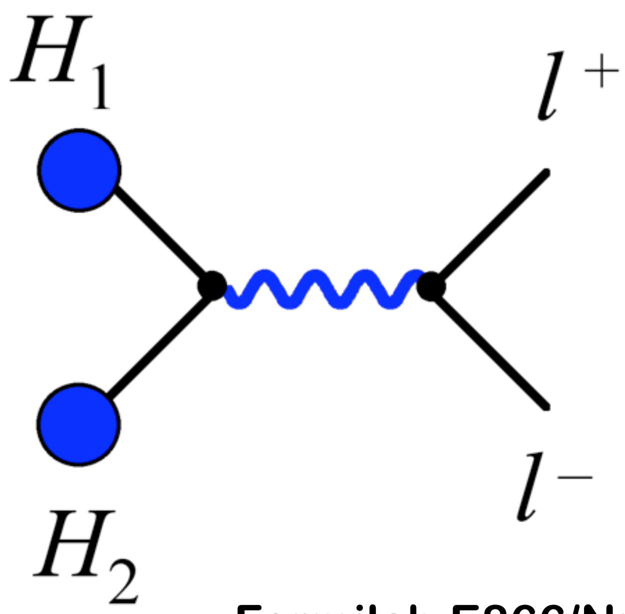


mapping of valence quarks

mapping of sea quarks



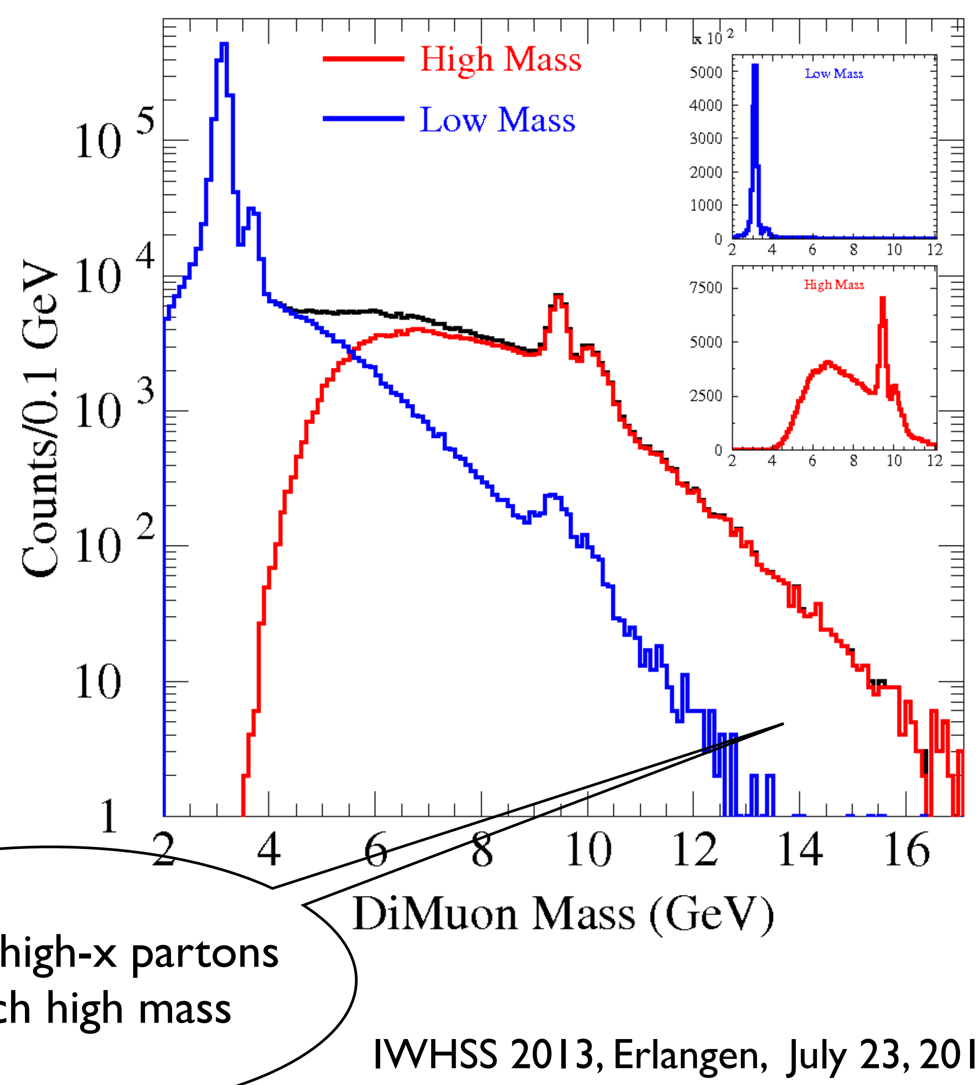
Hadron structure explored through DY scattering



- Cleanest hard hadron-hadron scattering process
- But: experimentally challenging: small cross section. Continuum varies as $\frac{d\sigma}{dm_{\mu\mu}} \approx \frac{10^{-32}}{m_{\mu\mu}^5} \cdot \frac{\text{cm}^2}{\text{GeV}^2}$
- Crucial role in studying quark structure in hadrons:
  - nucleons
  - nuclei
  - mesons
- Spin-orbit correlations, TMDs = transverse-momentum dependent PDFs
- Add polarization to our DY experiments to cover the missing spin program: spin-dependent TMDs in Drell-Yan

Milestone will be measurement of Sivers-function sign switch (?) in polarized Drell-Yan

Fermilab E866/NuSea



Drell-Yan as selective probe of sea distributions

(proton-induced Drell-Yan)

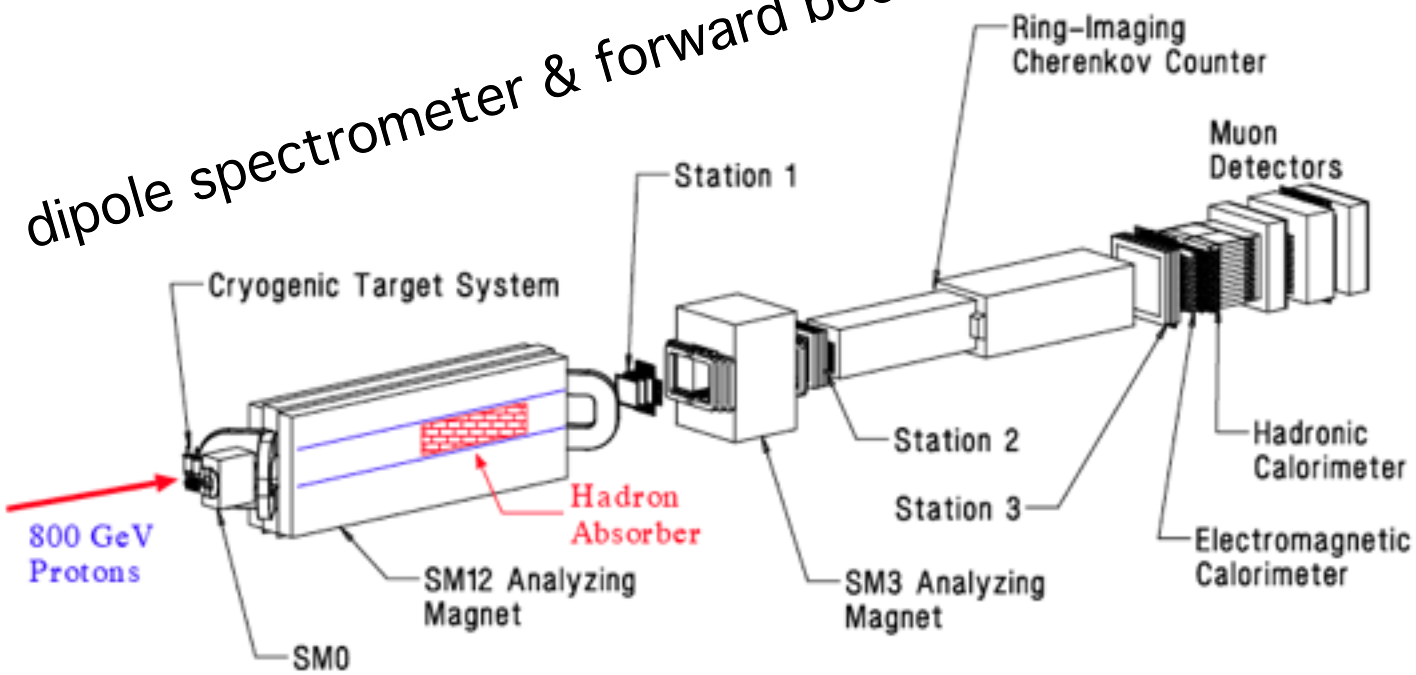
Fixed target experiment

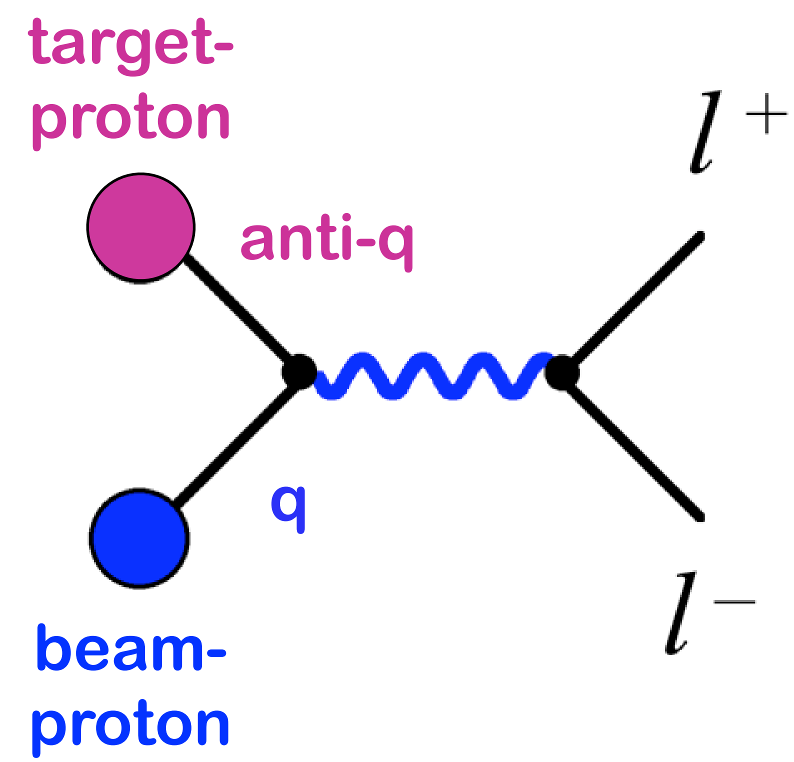
example: Fermilab di-muon spectrometer [E866]

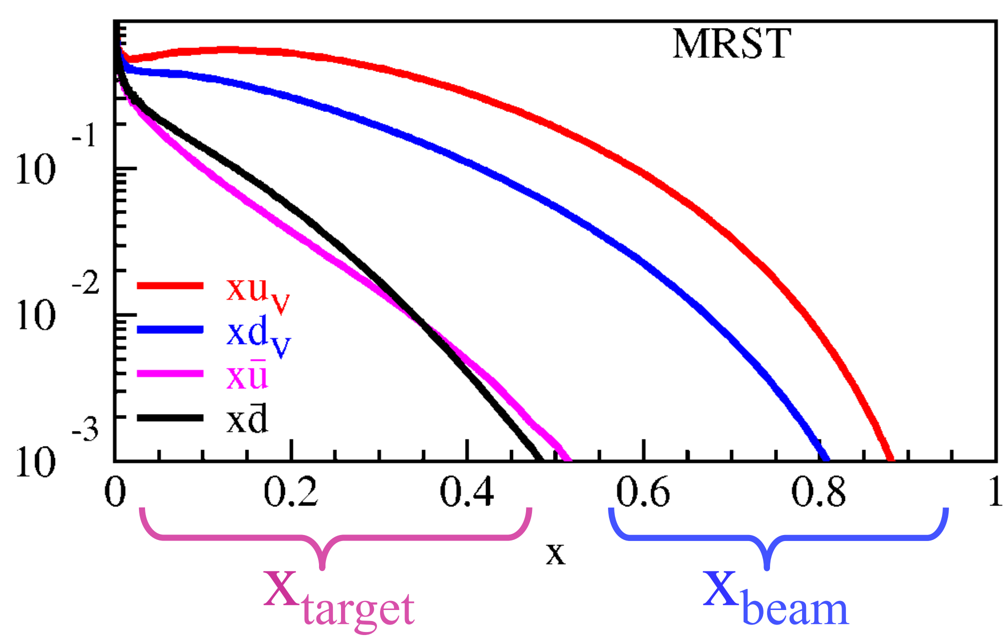
dipole spectrometer & forward boost of dileptons ⟶ favors $x_{Feynman}$ (= x_{beam} - x_{target}) ≳ 0

large x_{beam} (quark) in valence region

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







$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t s} \times \sum e^2 [\bar{q}_t(x_t) q_b(x_b) + \underbrace{\bar{q}_b(x_b) q_t(x_t)}_{\text{suppressed}}]$$

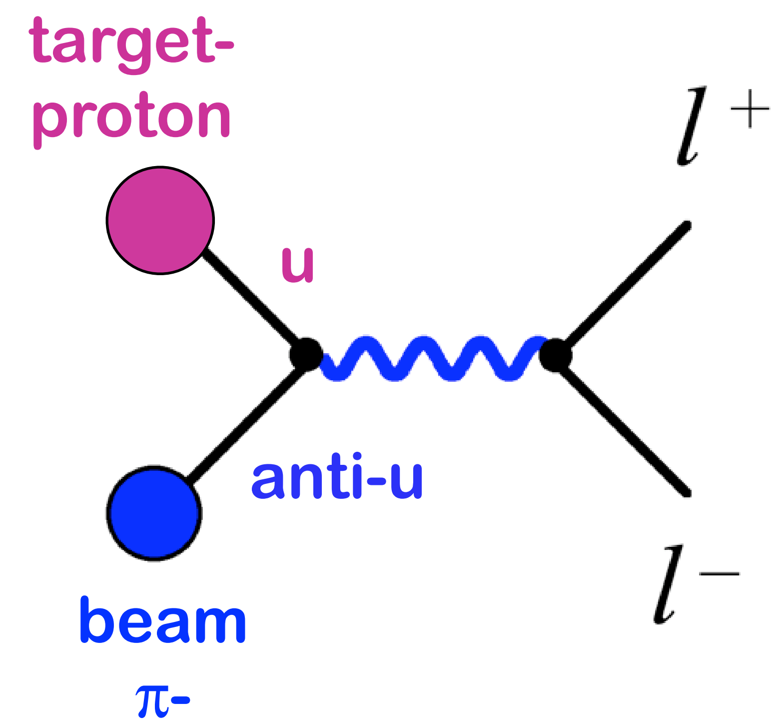
$$\frac{m_{\mu\mu}}{s} = x_b x_t$$ scaling analog to DIS

What about pion-induced Drell-Yan?

- Valence anti-u quark in the pion: allows to create large-mass dileptons.
  Proton-induced DY needs to generate the dilepton from sea-quark object with small x.

- Pions as alternative probe to test
  - nuclear models
  - meson structure – not accessible in DIS
  - "subtleties of partonic structure"

- Flavor dependence: pion (or meson in general) is specific qqbar compound

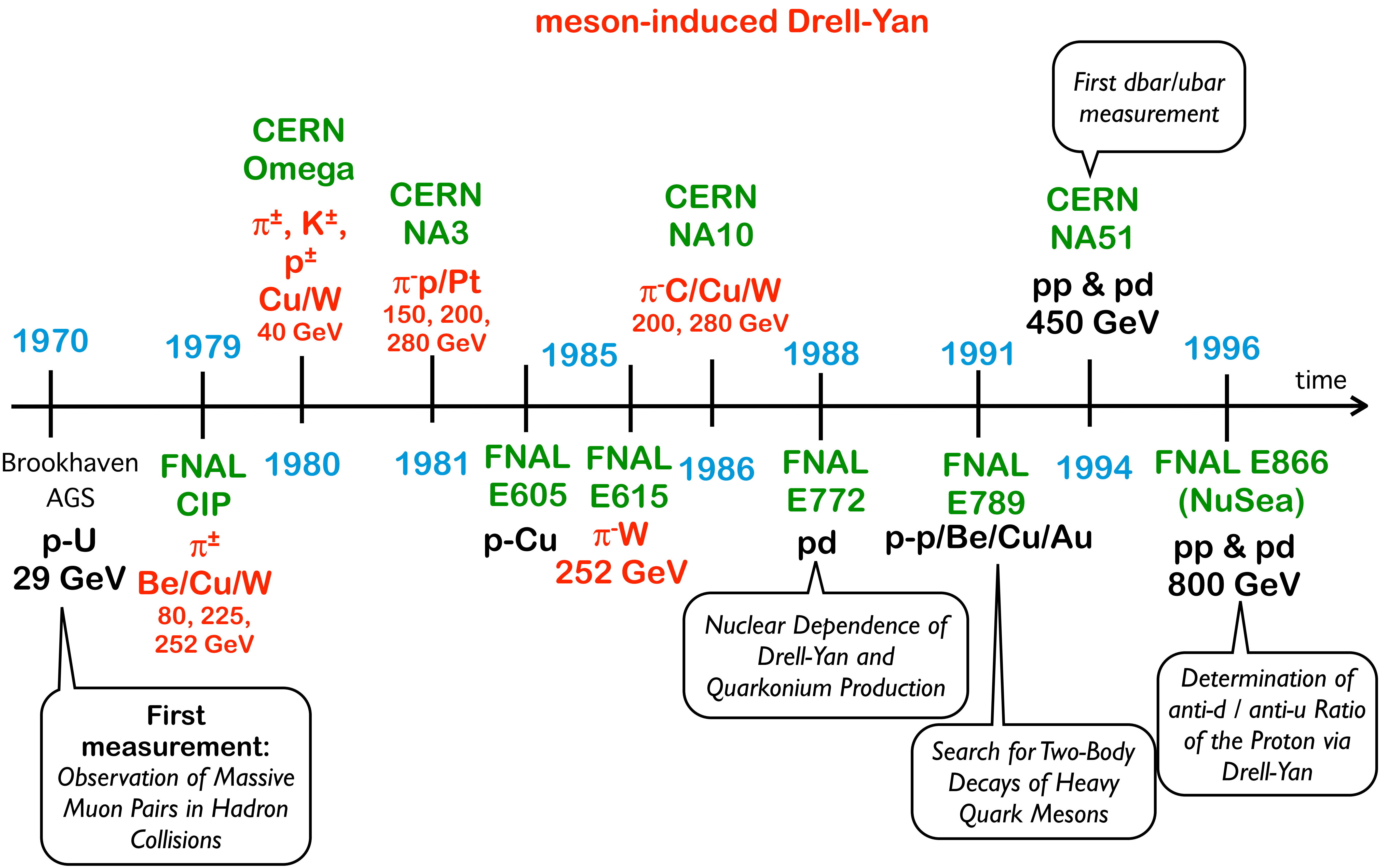


sensitive to the valence quark of the nucleon target

(anti-d d annihilation suppressed)

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

Selected Drell-Yan experiments of the past



A typical Drell-Yan experiment

Omega @ CERN (1980)

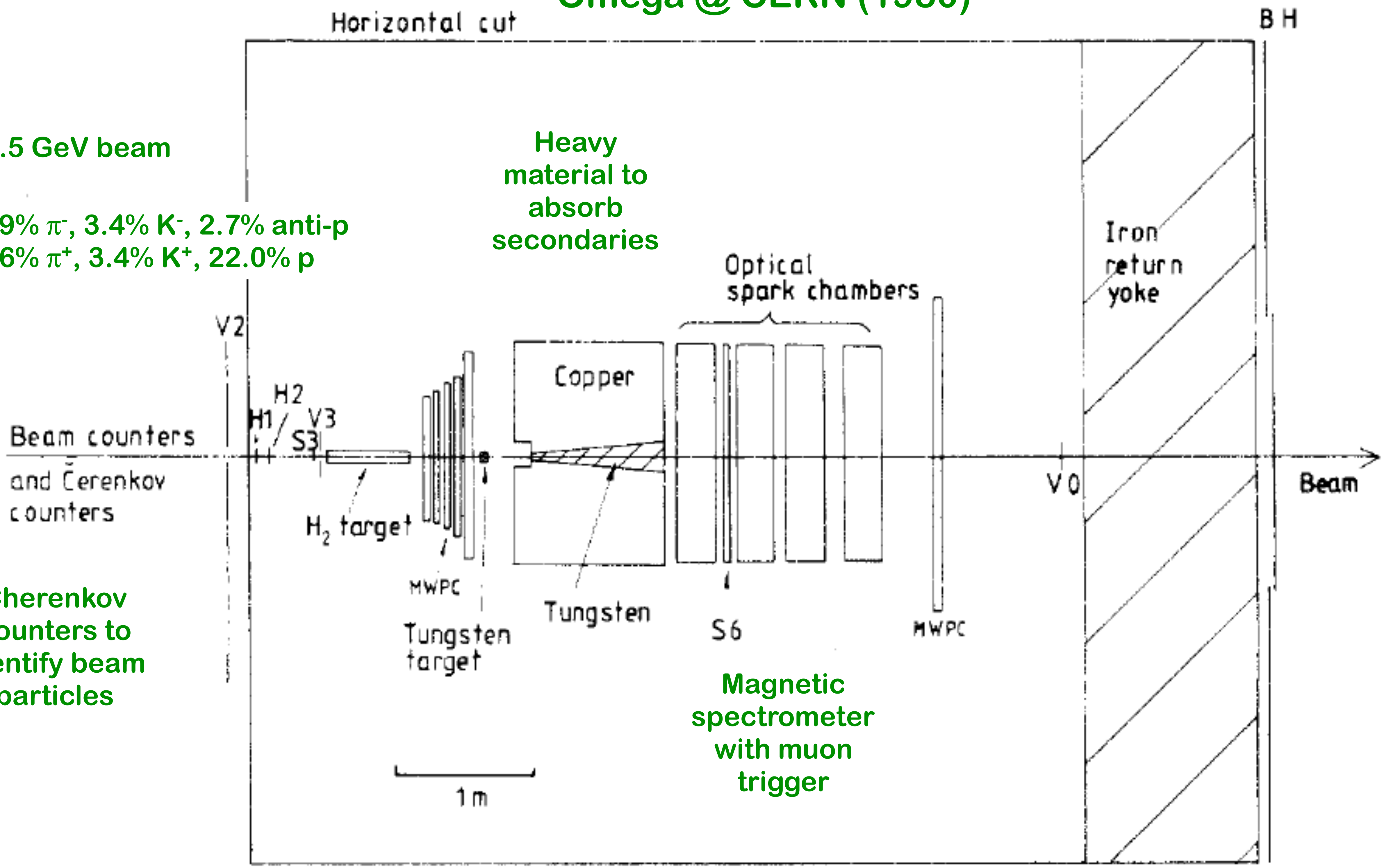
39.5 GeV beam

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

Heavy material to absorb secondaries

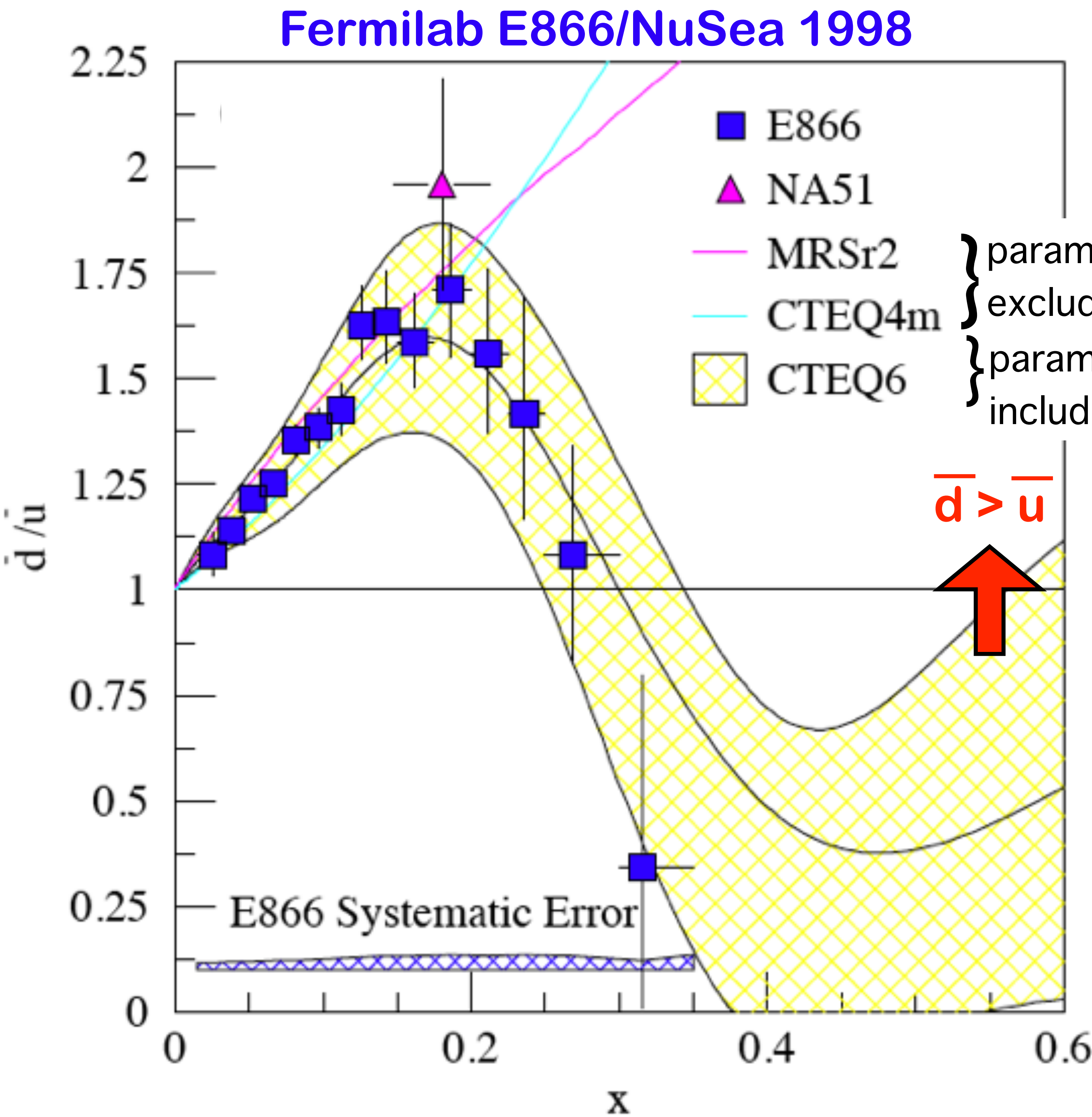
Cherenkov counters to identify beam particles

Magnetic spectrometer with muon trigger



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

Isospin symmetry violation in the anti-quark sea



- Inclusion of σ^{pd}/σ^{pp} into global fits: change of perception of sea-quark distributions in the nucleon

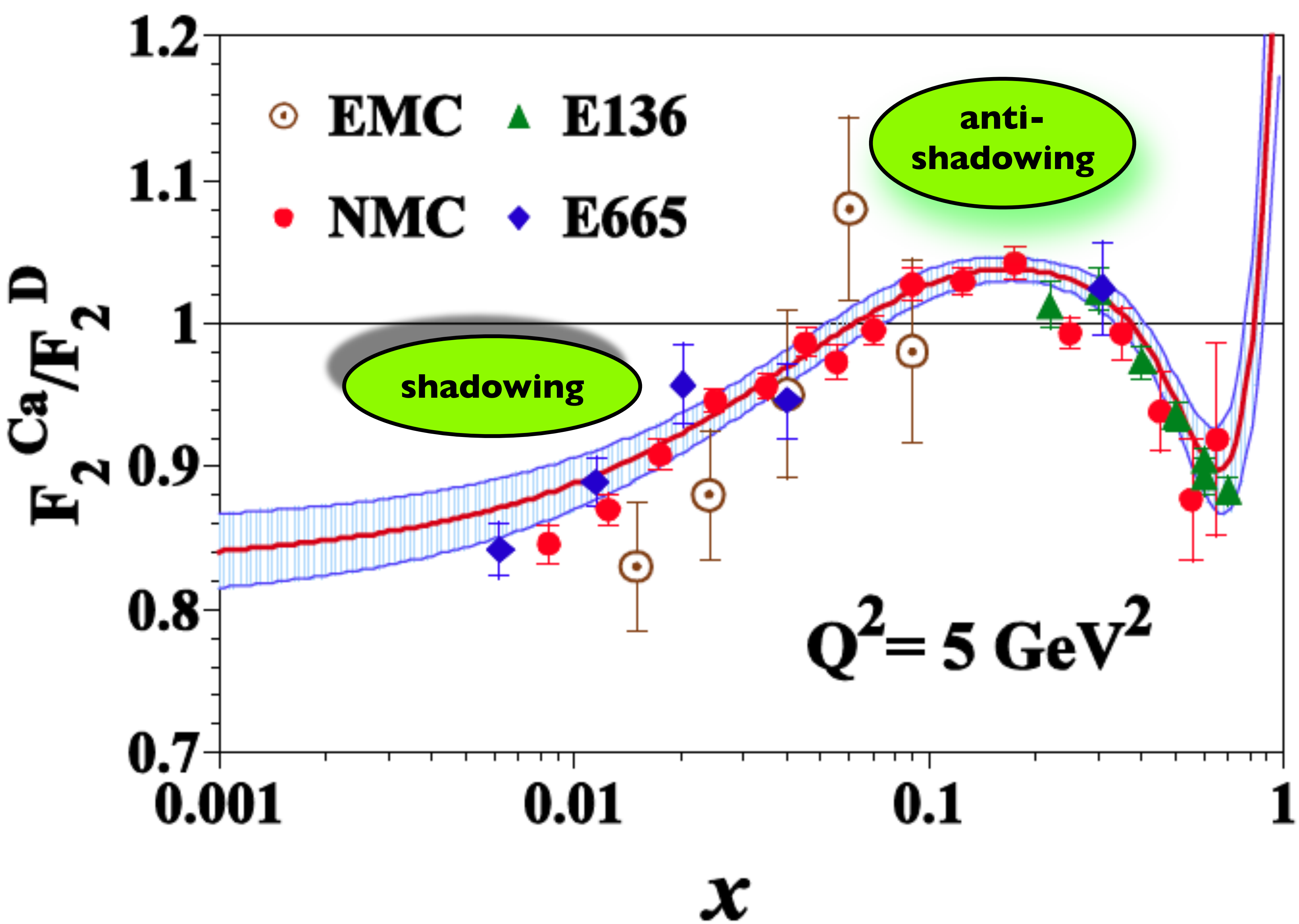
- Origin of sea quarks? g→qqbar should naively give symmetric ubar, dbar.

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

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

Nucleons in nuclei

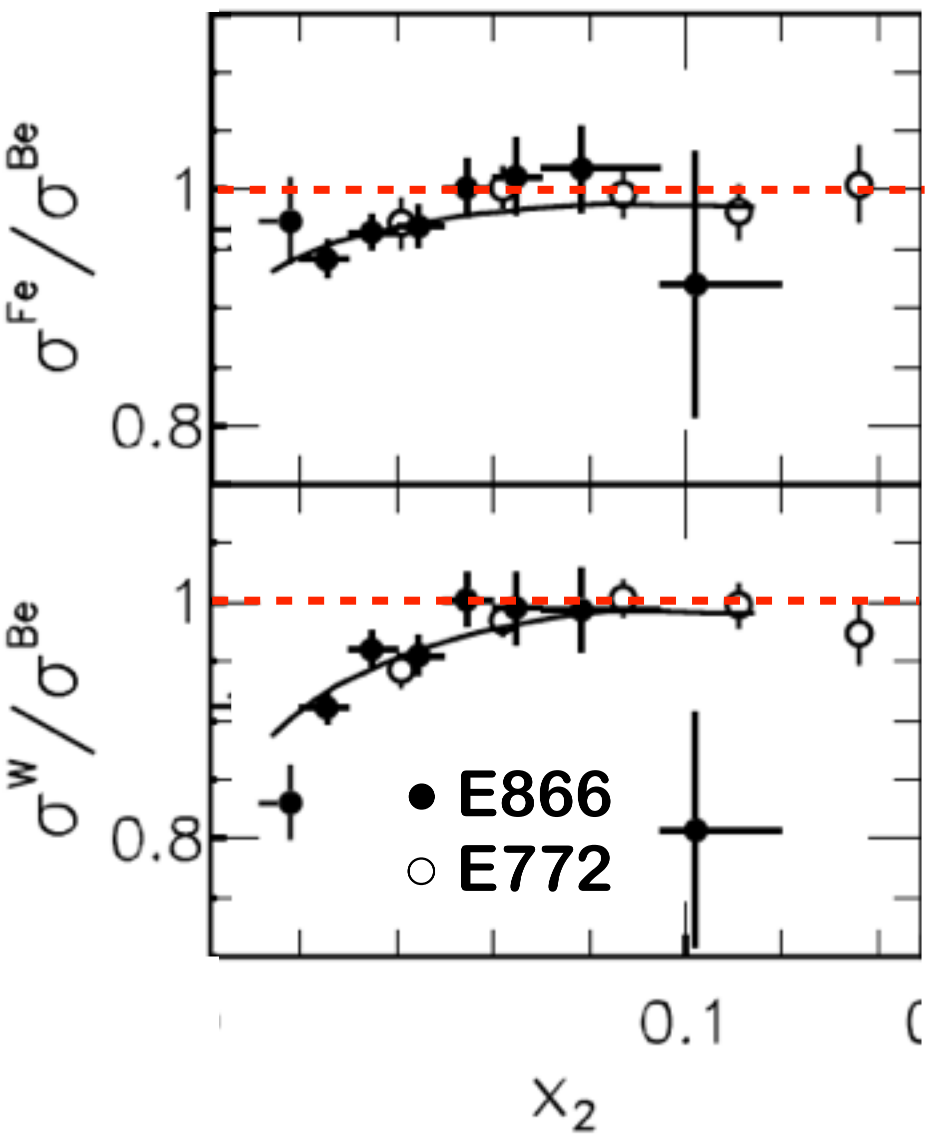
EMC effect in DIS



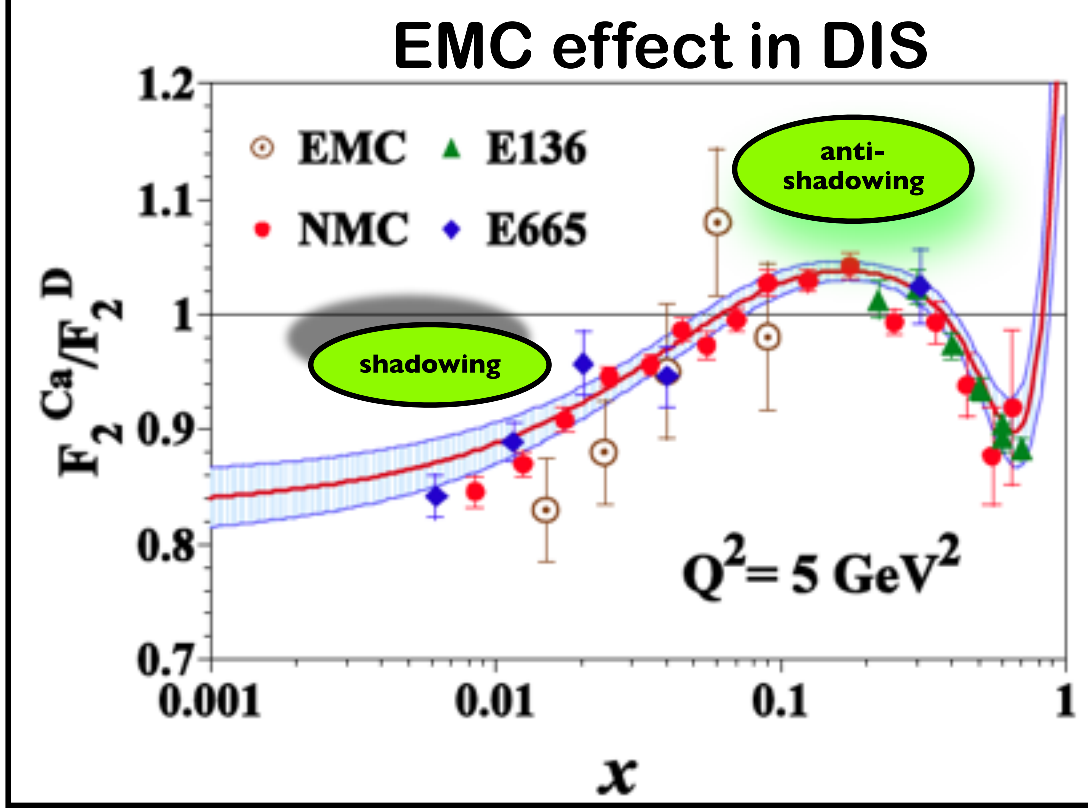
Geesaman, Saito, Thomas, The Nuclear EMC Effect
Ann. Rev. Nucl. Part. Sci. 45 (1995) 337

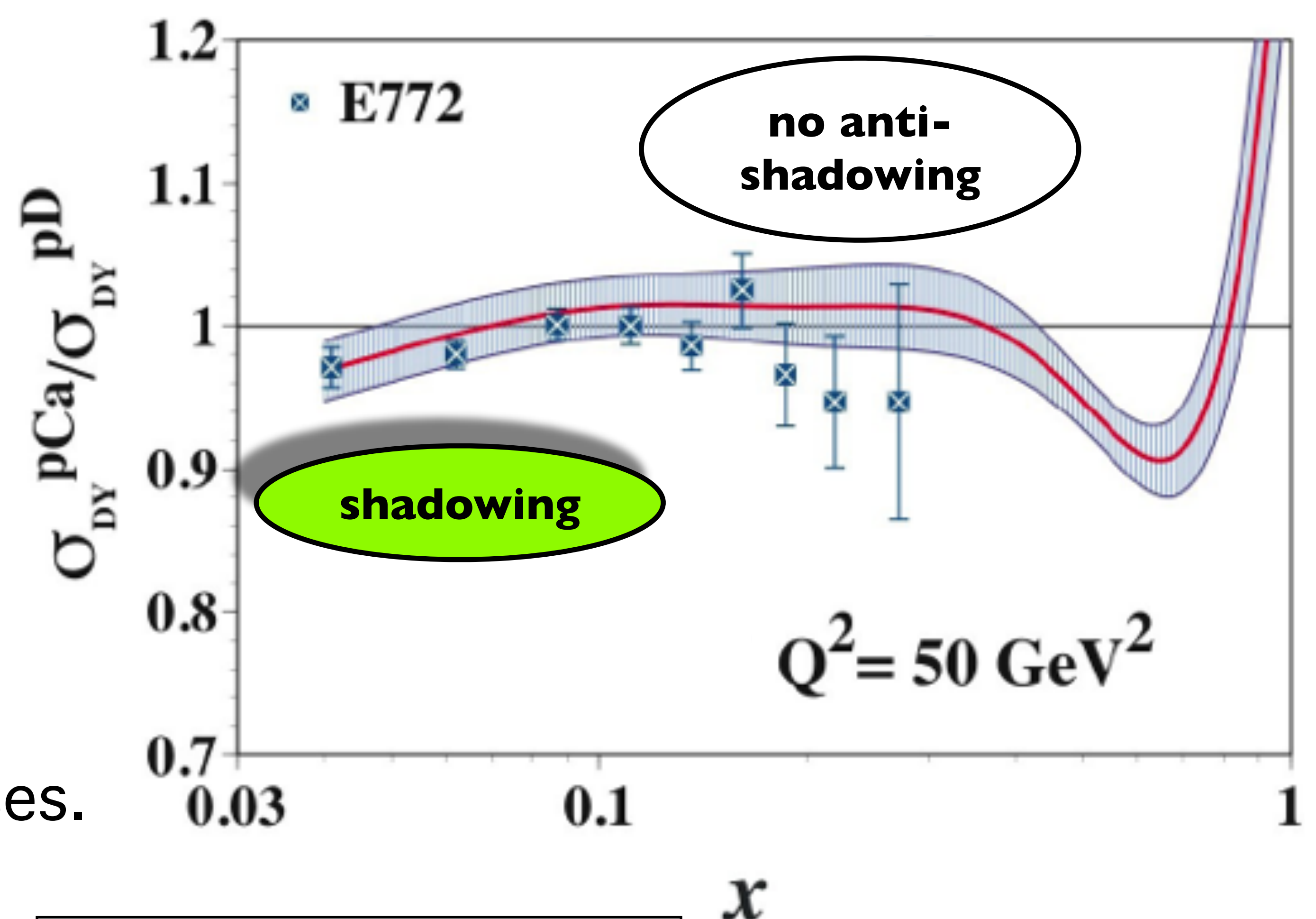
- Modification of parton distributions in nuclei?
- Can the nucleus be described in terms of quarks and gluons only?
- Explanation of EMC effect: nuclear pions?
- F_2 in DIS: charge-weighted sum of quarks and anti-quarks.
  What about the sea quarks?

EMC effect in Drell-Yan



$$\frac{\sigma^{\mathrm{pA}}}{\sigma^{\mathrm{pd}}} \approx \frac{\overline{u}_{\mathrm{A}}(x)}{\overline{u}_{\mathrm{N}}(x)}$$





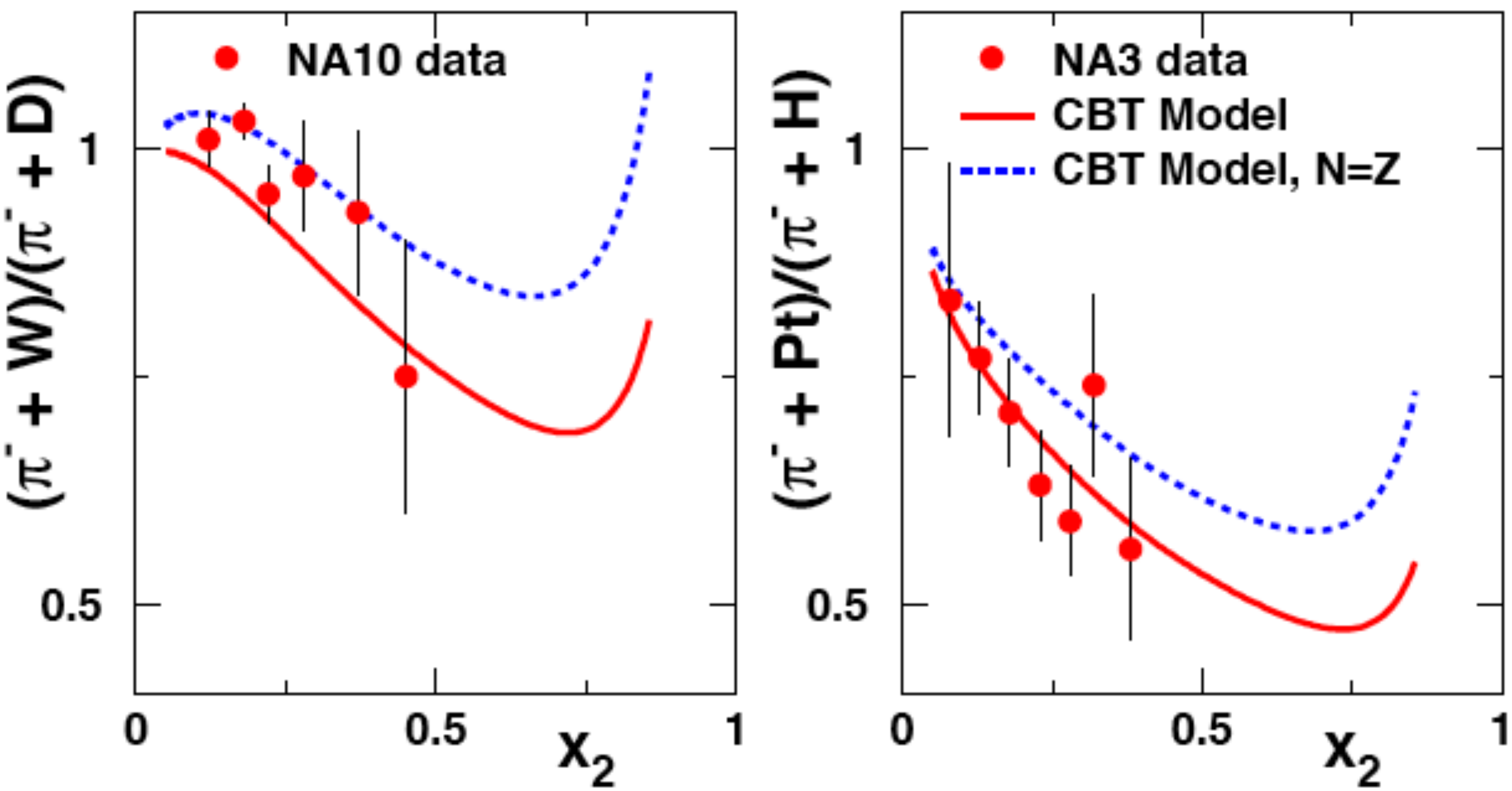
- DY: no excess pions.
Traditional meson-exchange model?
- Contemporary models:
large effects for anti-quarks as x increases.
- Needs more statistics to confirm
(e.g. Fermilab E906/SeaQuest)

E772: PRL 64 (1990) 2479
E866: PRL 83 (1999) 2304

Flavor-dependent EMC effect in pion-induced DY

- Flavor-dependent modification of quark distributions in the nuclear medium?
- Distinguish between different nuclear models
- Cloet, Bentz, Thomas (CBT) model:

isovector mean field in a N≠Z nucleus affects u- and d-quarks differently



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

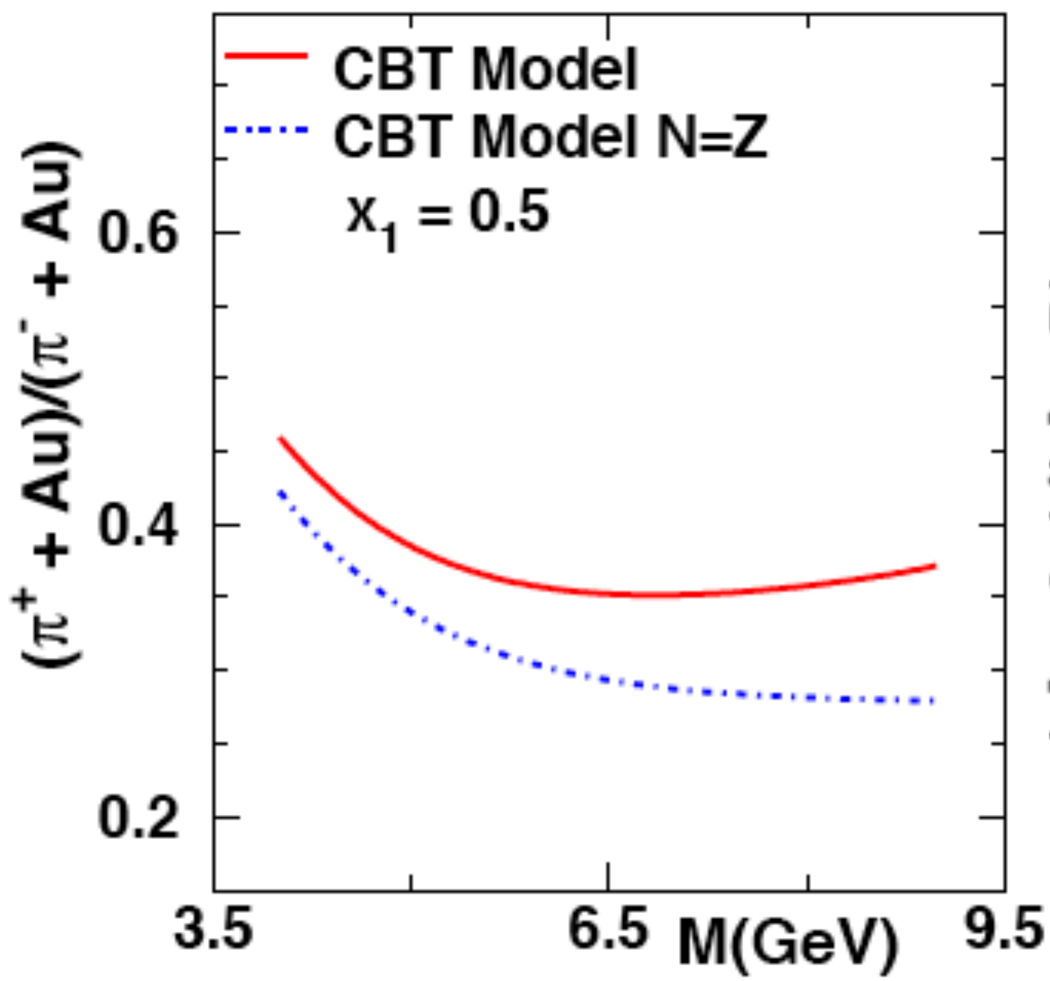
flavor-independent EMC effect

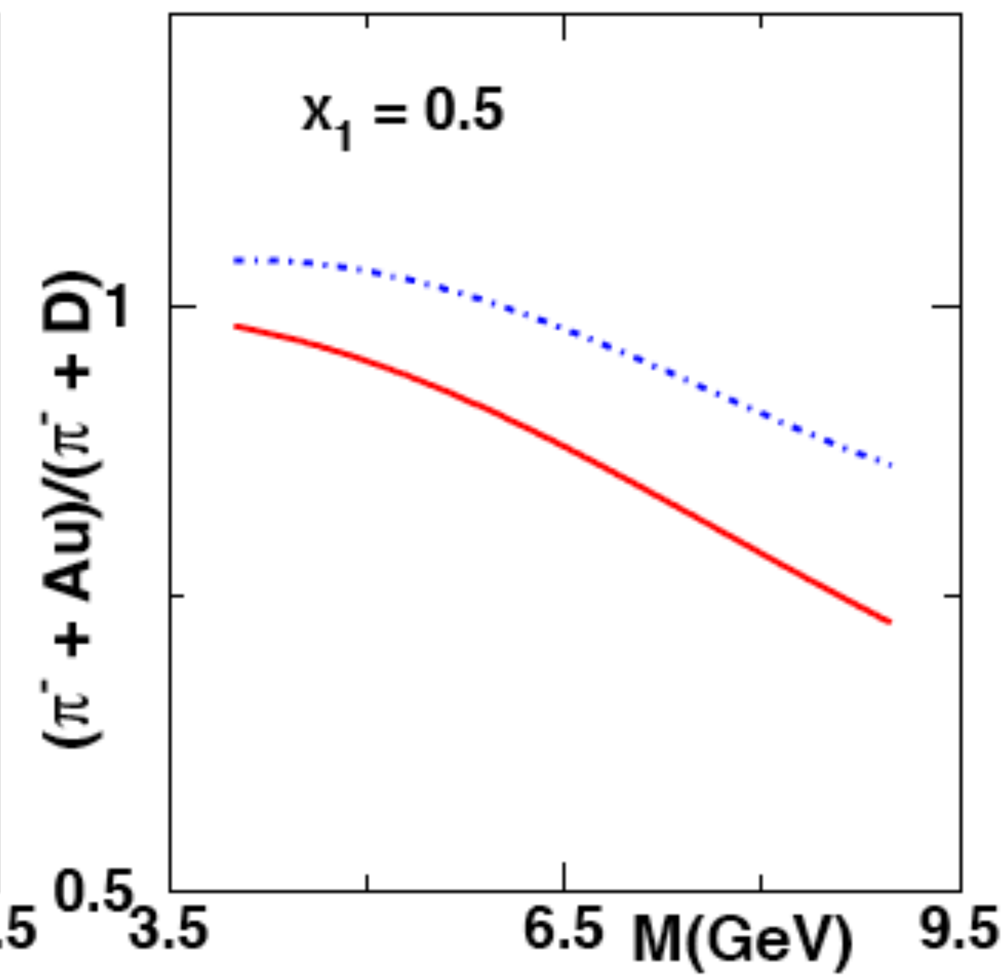
flavor-dependent EMC effect

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916

Flavor-dependent EMC effect in pion-induced DY

$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)} \qquad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$



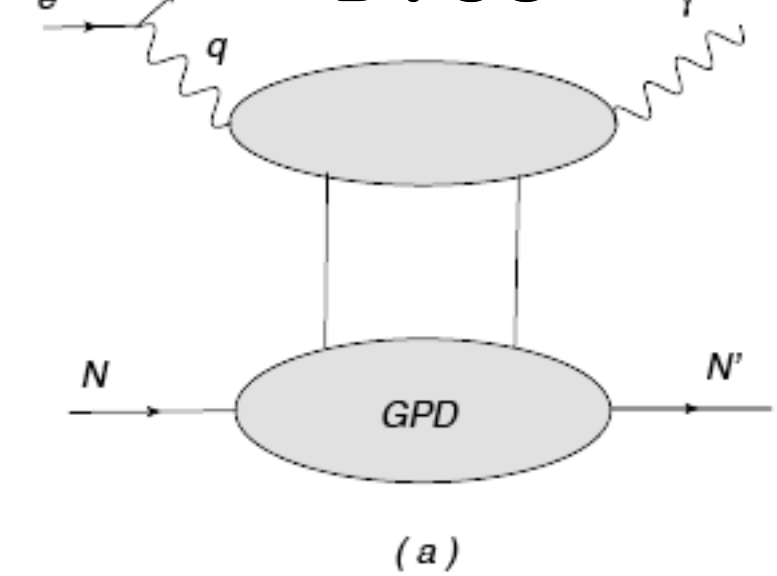


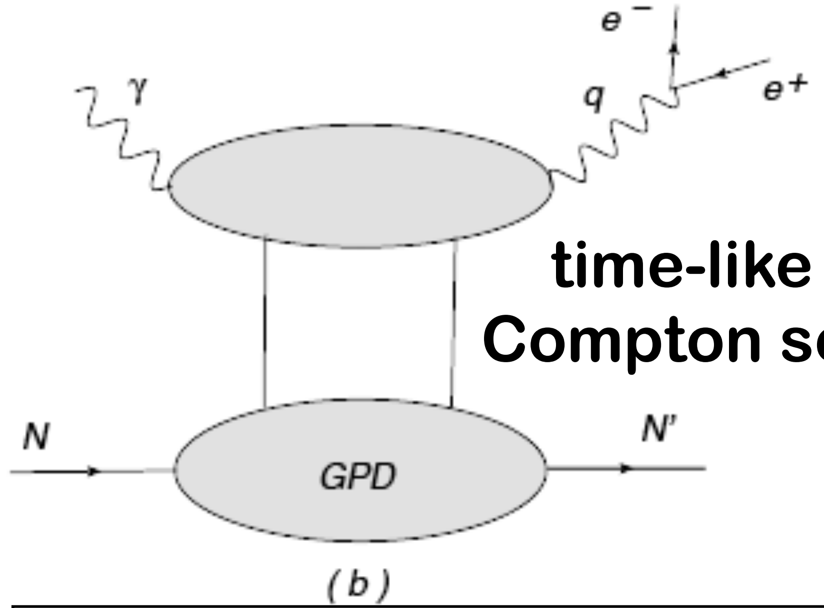
160 GeV
pion beam
@Q^2=25 GeV^2

Important new information from COMPASS-II Drell-Yan data with pion beams

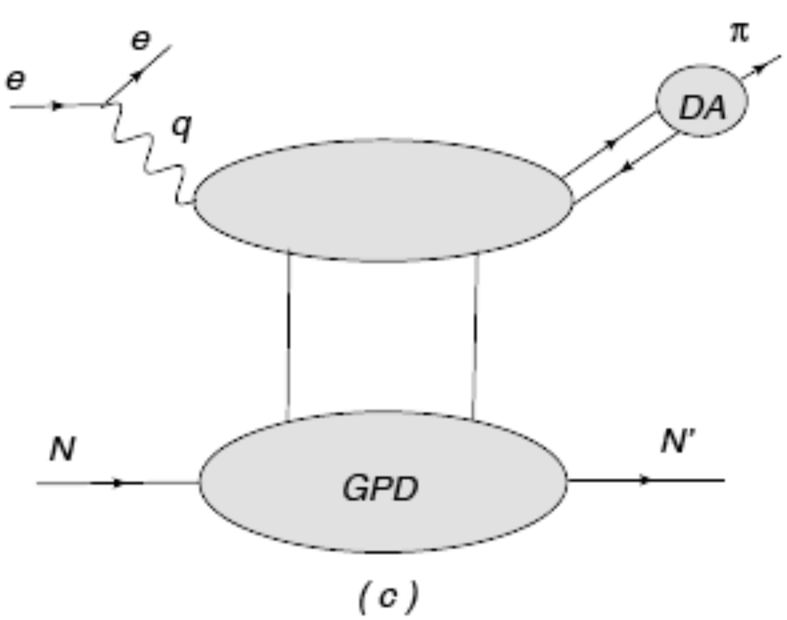
Pion-induced exclusive Drell-Yan $\pi^- N \rightarrow N' \mu^- \mu^+$

DVCS





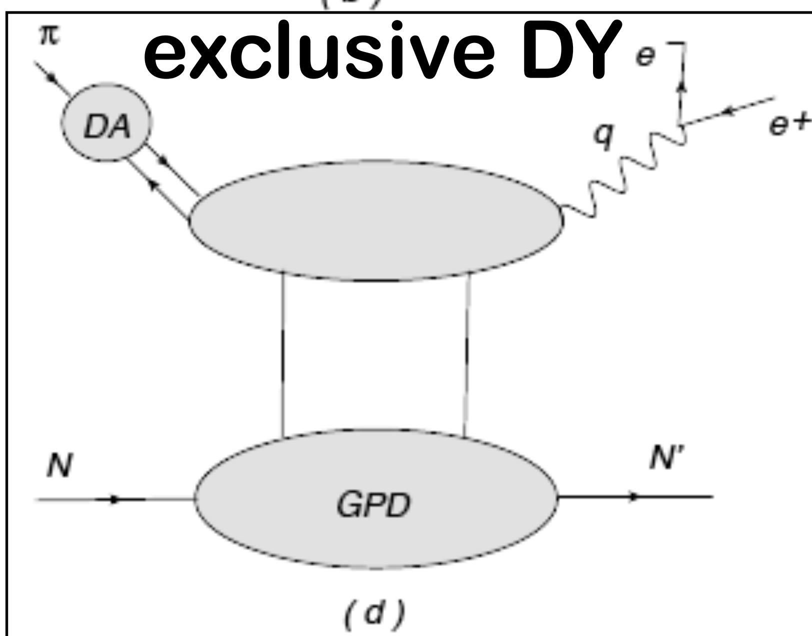
time-like virtual Compton scattering



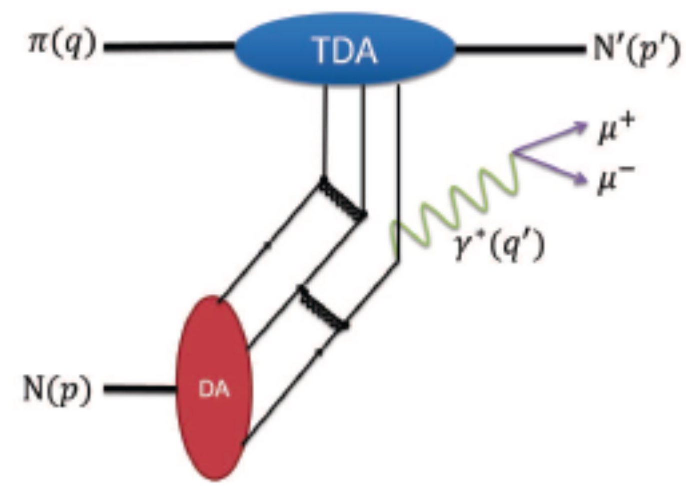
hard exclusive pion production (DVMP)

space-like

exclusive DY



Preferred @lower beam energy to enhance exclusive cross section



@larger momentum transfer to the target: involves TDA = nucleon-to-pion Transition Distribution Amplitude

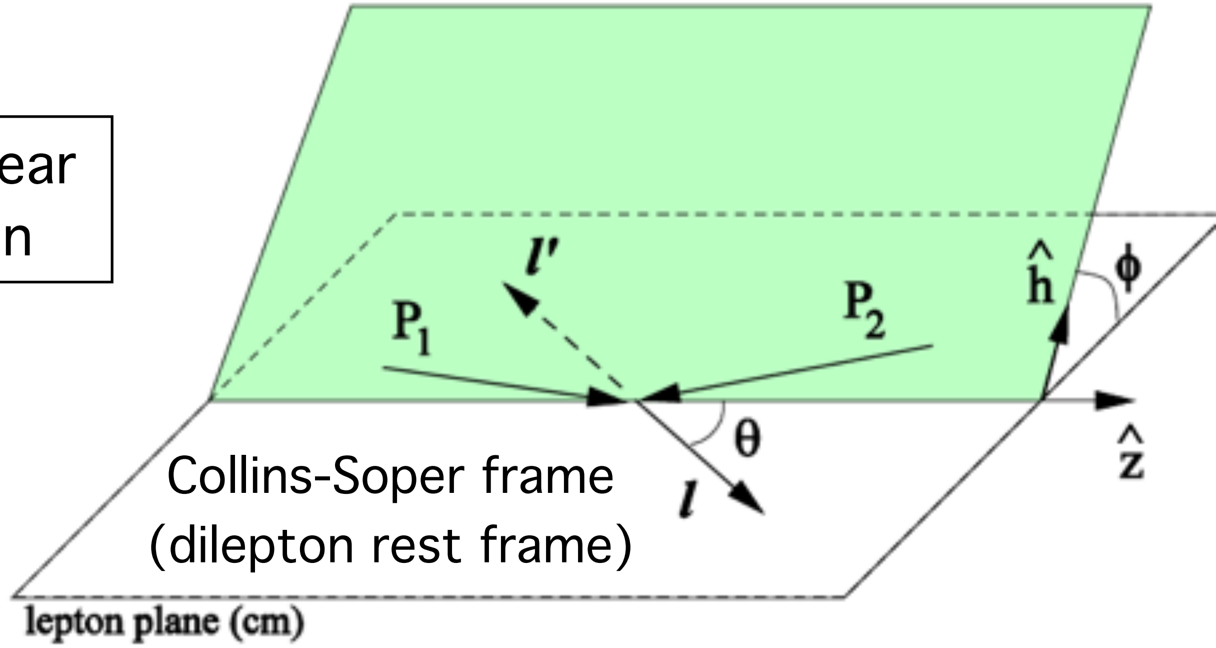
time-like

Mueller, Pire, Szymanowski, Wagner: On timelike and spacelike hard exclusive reactions, arXiv:1203.4392

Angular dependence of the (spin-integrated) DY cross section

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

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



(1+$\cos^2\theta$) “naive DY” + k_T + higher $O(\alpha_S)$:

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

Lam-Tung relation

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

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

- Basic derivation from structure-function formalism
- 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

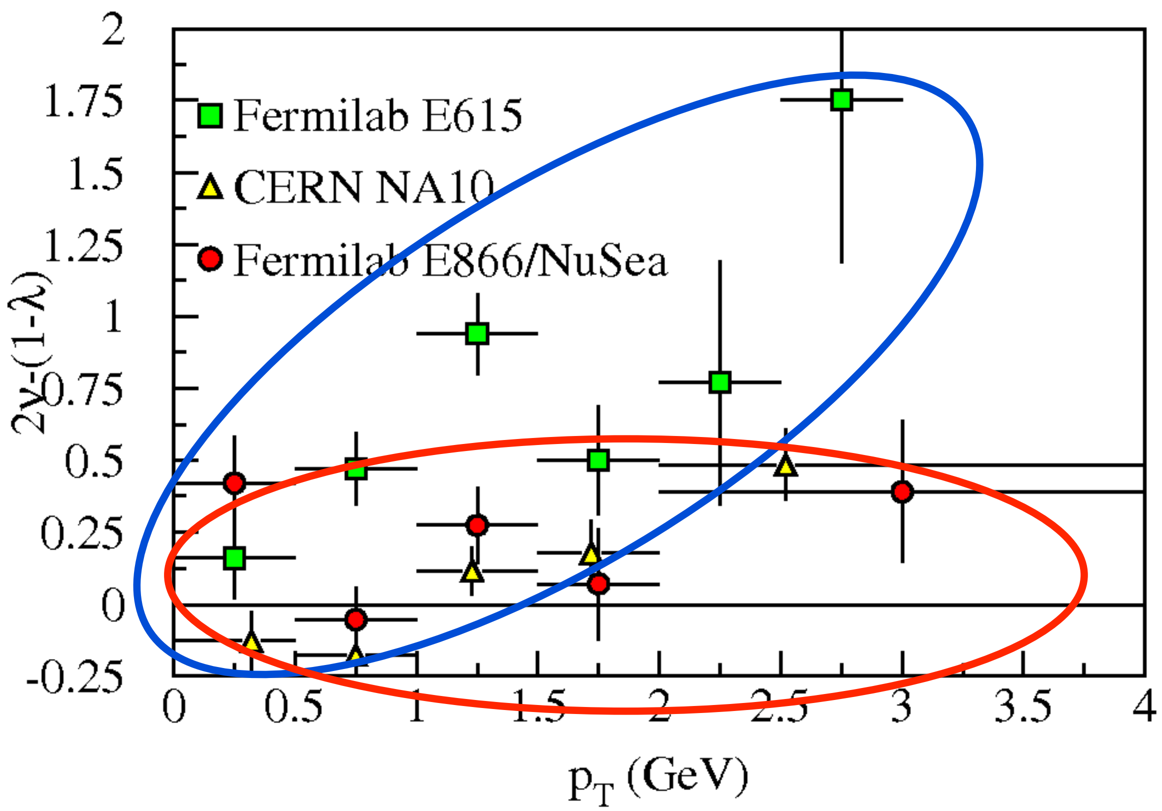
$$1 - \lambda = 2\nu$$

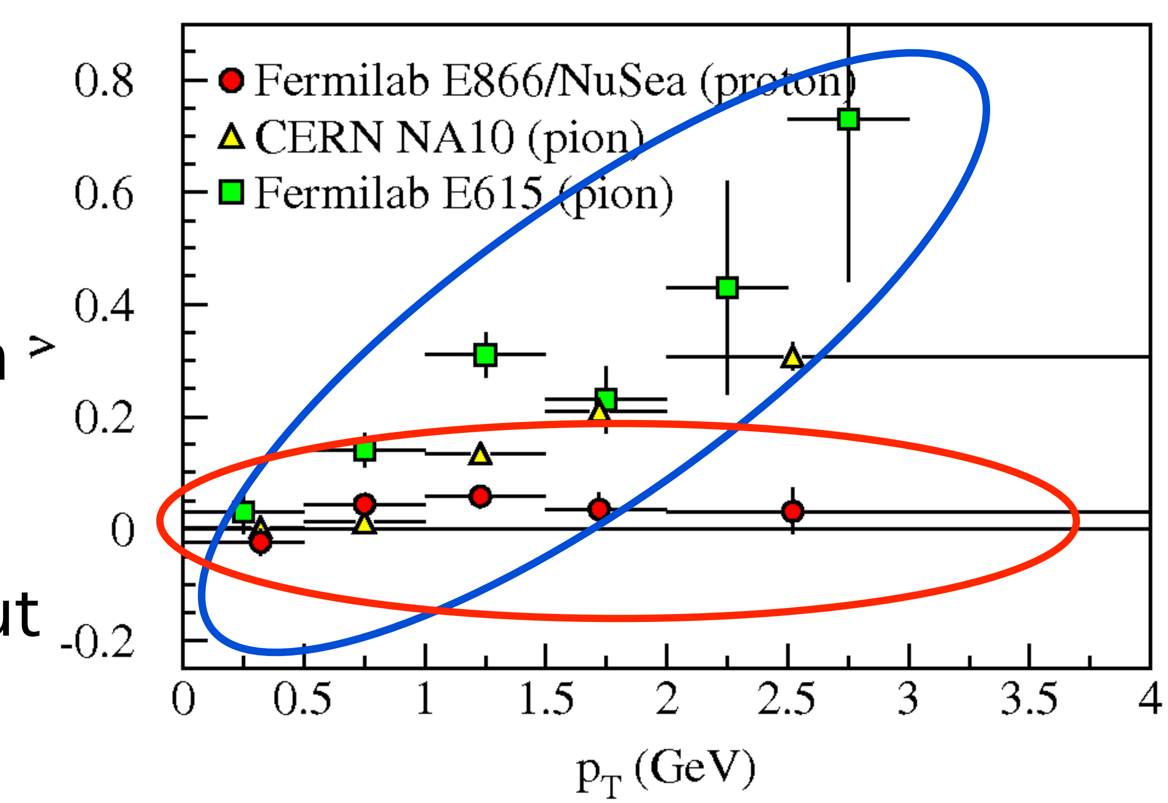
- **Proton-induced Drell-Yan (E866)**
  - consistent with LT-relation
  - no cos(2Φ) dependence
  - no p_T dependence

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

- The **Boer-Mulders (BM) TMD** enters the stage: correlation between
  - quark transverse spin &
  - quark transverse momentum

- **Pionic DY probes BM (valence),** target=proton
  Protonic DY probes BM (sea), target=proton
  - BM (sea) small compared to BM (valence)
  - from Drell-Yan, we can learn something about **spin-orbit correlations**!





see also: P. E. Reimer, Exploring the Partonic Structure of Hadrons Through the Drell-Yan Process, arXiv:0704.3621

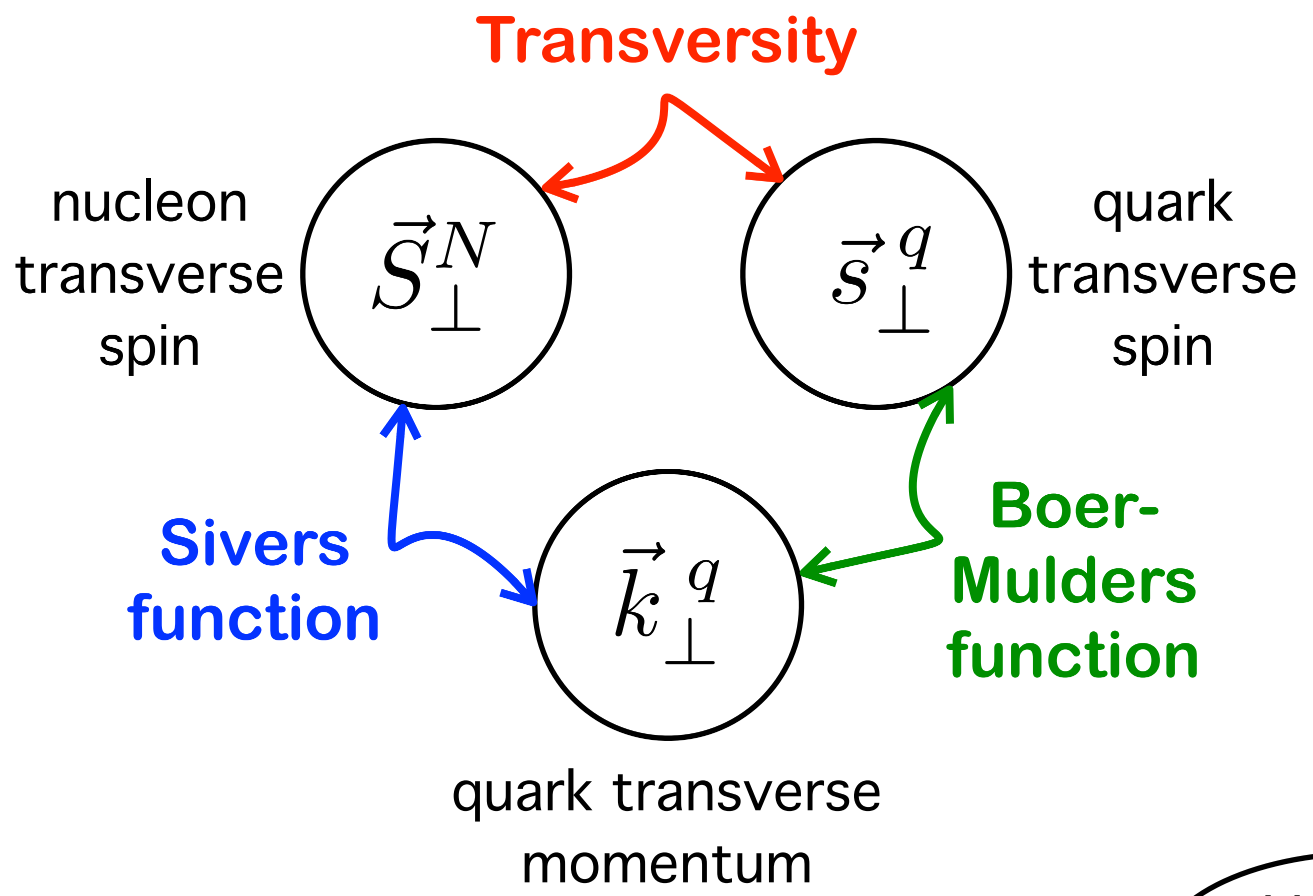
Spin-orbit correlations from Drell-Yan?

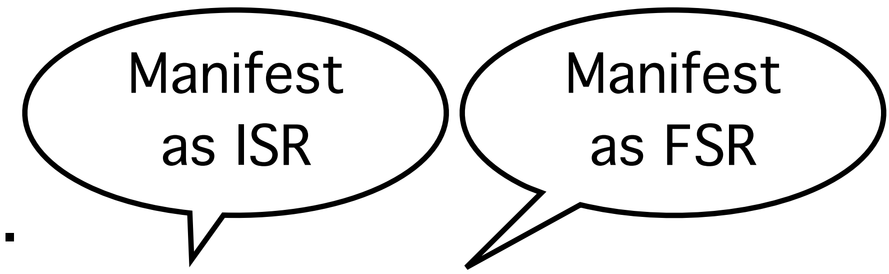
- Boer and Mulders 1998: distribution function of the unpolarized nucleon with intrinsic k_T dependence.
  - Describes correlation between quark transverse spin and momentum.
  - Induces cos(2Φ) modulation of the DY cross section.

- Other theoretical interpretations:
  - QCD higher-twist effect causes change of virtual-photon polarization from transversely (λ=1) to longitudinally (λ=-1) polarized for $x_\pi \rightarrow 1$?
    – Data taken at different $\sqrt{s}$: pion: 11 GeV and 16 GeV; proton: 39 GeV.
    – Such effect should be seen in E906/SeaQuest data.
  - Spin correlations between annihilating quark and anti-quark?
  - Glauber gluons, QCD instantons, ...

More measurements in wider kinematic range, and kaon/anti-proton beams will help to differentiate the interpretations.

The missing spin program: TMDs in spin-dependent Drell-Yan





- 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?

More details on TMDs in G. Schnell's talk
Theoretical overview in M. Radici's talk @ this workshop

Future Drell-Yan experiments

- Programs for future Drell-Yan measurements:
  nucleon-nucleon at
  - SeaQuest (Fermilab)
  - RHIC (Brookhaven)
  - J-PARC (KEK)
  - IHEP (Protvino)
  - JINR (Dubna)

  anti(p)-nucleon at
  - FAIR (GSI)

  pion-nucleon at
  - COMPASS (CERN)

  Only existing meson plan!

The story of the DY E-XYZ and NA* experiments will be continued

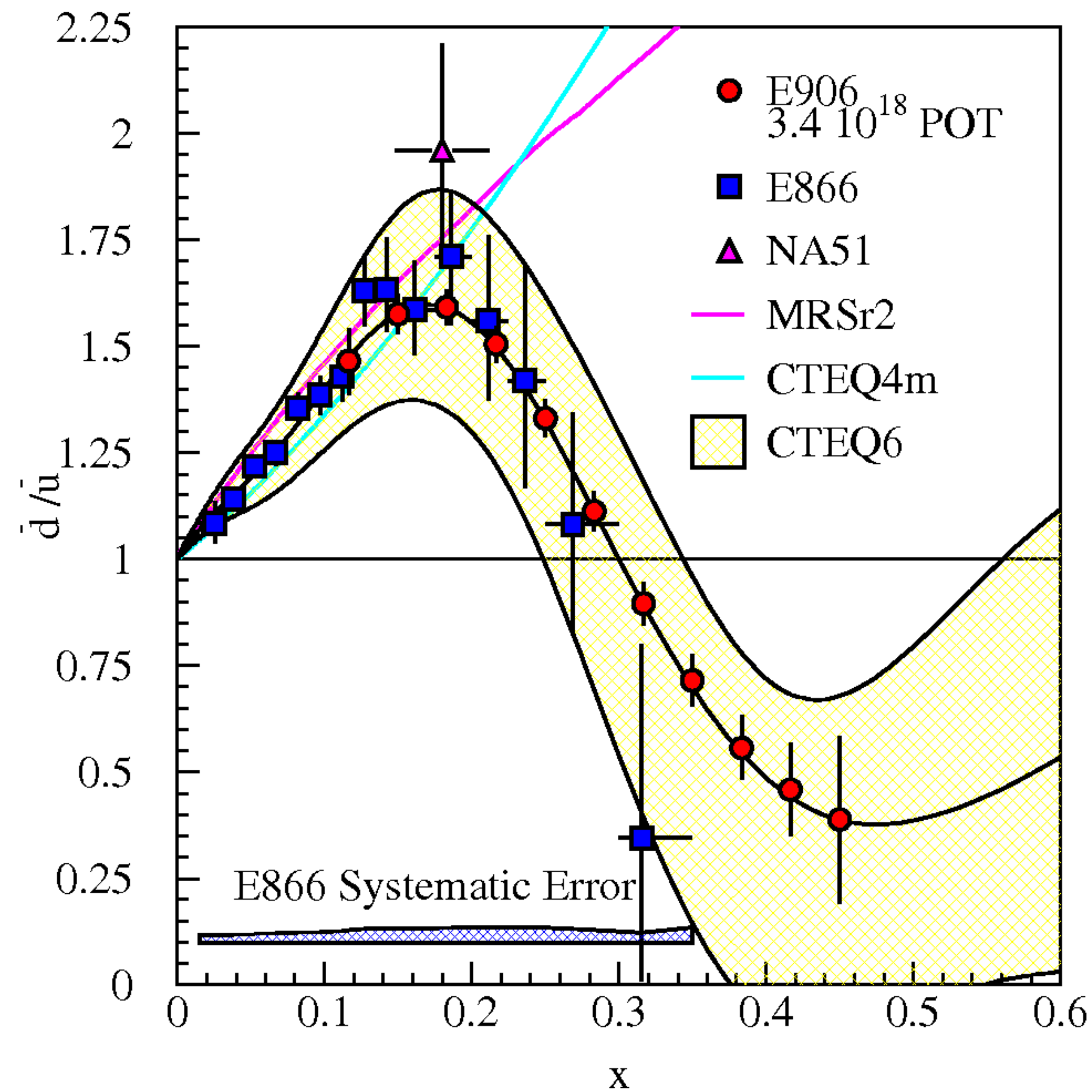
- Past measurements exclusively considered the unpolarized cross section, future ones also aim for polarization measurements.
  - transversely polarized DY: spin-dependent TMDs
  - longitudinally polarized DY: quark helicity

More details on FAIR in K. Peter's talk @ this workshop
More details on JINR in I. Savin's and A. Nagaytsev's talk
The RHIC Spin program, arXiv:1304.0079

Fermilab E906/SeaQuest

- Unpolarized proton-induced Drell-Yan
  - Significant increase in physics reach: high-x structure of the proton
  - Extend sea-quark measurements to larger x by using 120 GeV protons from Fermilab Main Injector.
  - Will start physics run in the nearest future.

- Probed physics:
  - What is dbar / ubar?
  - What are the origins of the sea quarks?
  - How are quark spin and orbital motion correlated?
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
  - Do colored partons lose energy in cold nuclear matter?

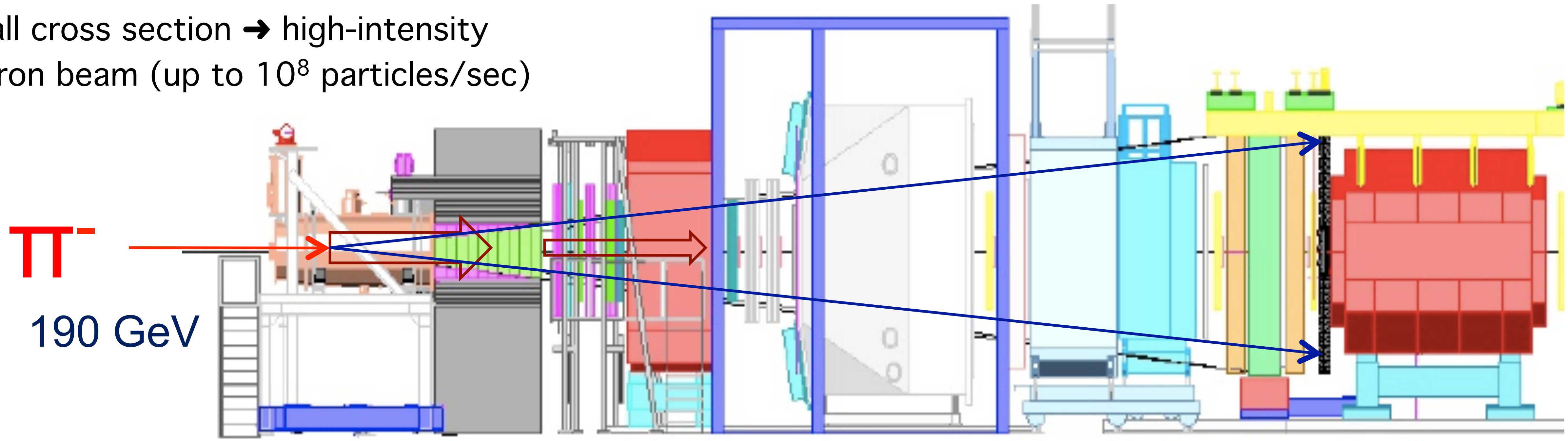


- Polarized SeaQuest: plans to polarize the proton beam and maybe even the target.

Click: Opportunities for polarized physics at Fermilab, workshop May 20-22, 2013

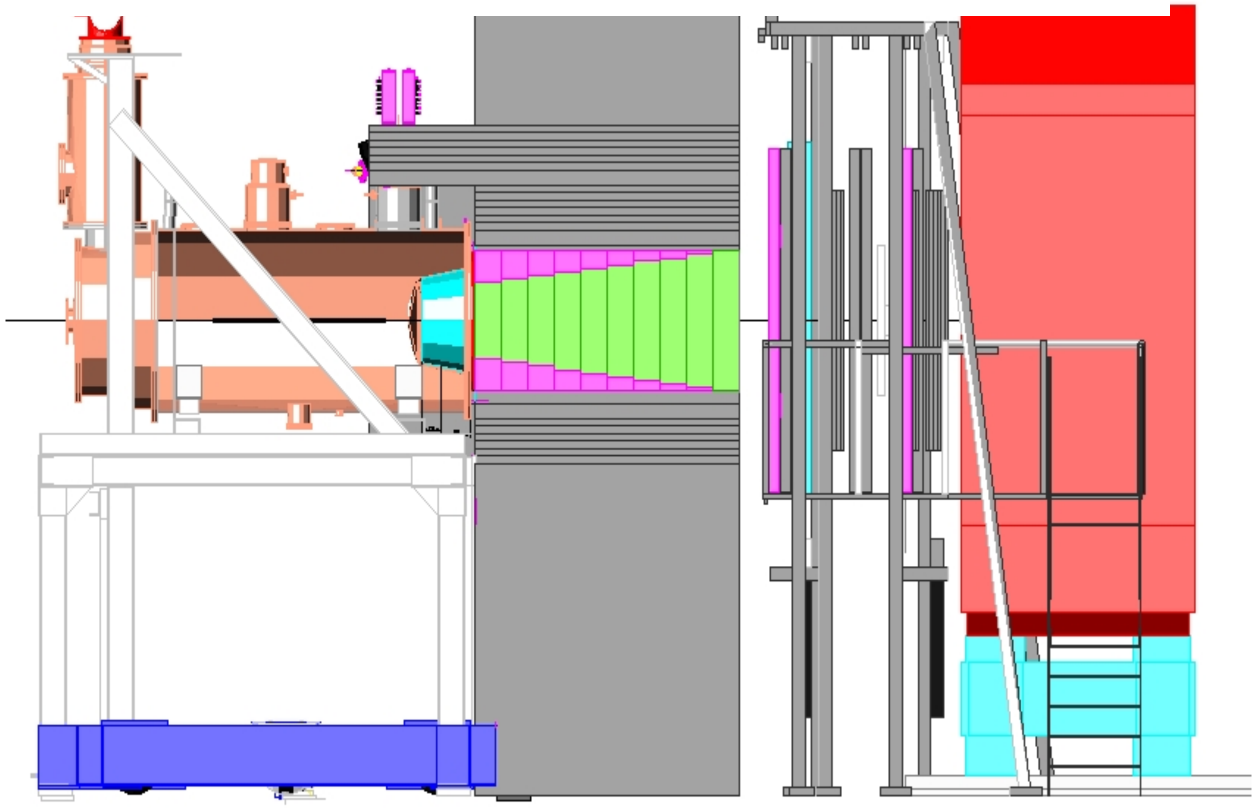
Pion-induced Drell-Yan at COMPASS-II

Small cross section ➜ high-intensity hadron beam (up to 10^8 particles/sec)



Key elements:

1. Transversely polarized NH_3 target
2. Tracking system
   (Large and Small Angle Spectrometer)
3. Muon trigger
4. RICH-I, calorimetry
5. Hadron absorber

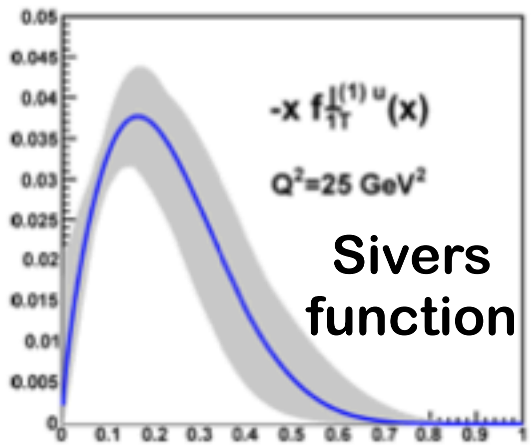


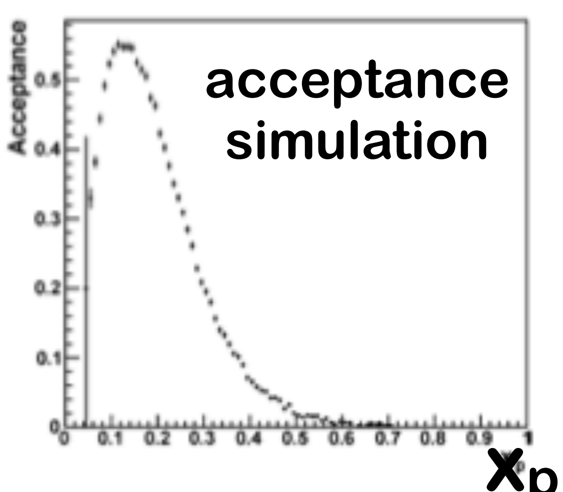
More details on COMPASS-II in A. Ferrero's talk @ this workshop

adapted from O. Denisov

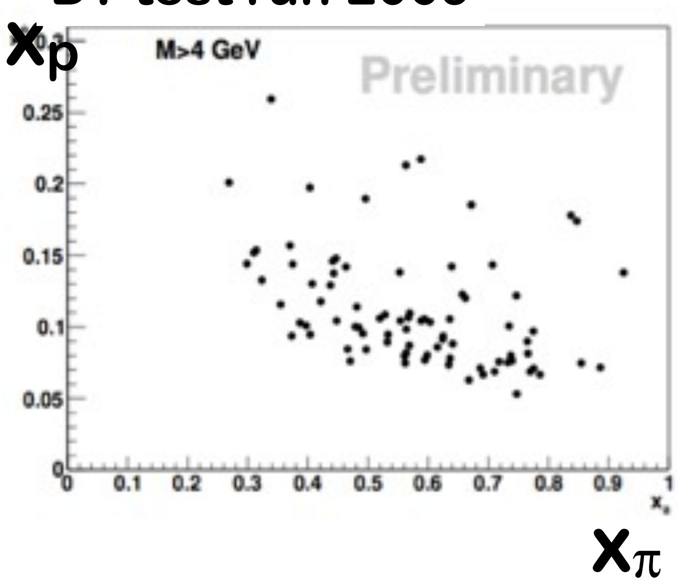
COMPASS-II TMD program

COMPASS-II DY will probe the **valence-quark region,** where the Sivers function has its largest magnitude

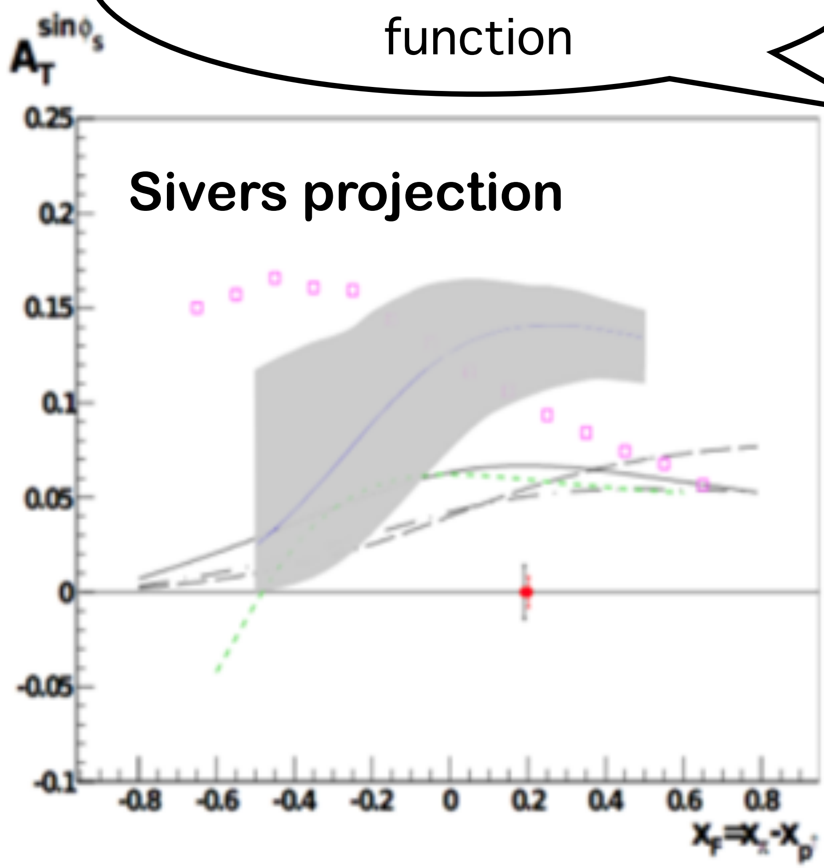




DY test run 2009



$\pi^- p \rightarrow \mu^+ \mu^- X$:
sensitivity to u-quark Sivers function



DY with <u>trans. pol. NH3 target</u>:

a) Sivers $\sin(\Phi_S)$: magnitude and sign

b) Pretzelosity $\sin(2\Phi+\Phi_S)$

c) Transversity $\sin(2\Phi-\Phi_S)$

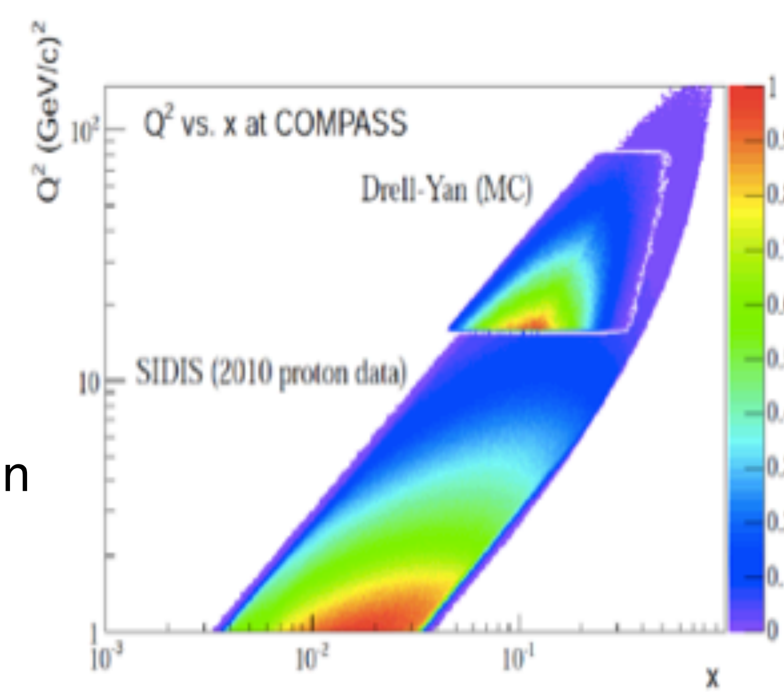
DY with <u>unpolarized NH3 target</u>:

d) Boer-Mulders $\cos(2\Phi)$

DY SSA with trans. pol. NH3 target: low-mass dimuon events to study a)-d)

Projection: 2 years running and 140 days pa, about 230k DY events above J/Psi threshold

Optimal conditions for the observation of **Sivers sign-switch:** kinematic overlap between SIDIS and DY



Drell-Yan at COMPASS-II

Possible additional physics with approved measurements:

- Modification of the λ, μ, ν parameters as x→1 (existing data are for λ only). Violation of the Lam-Tung relation as x→1.
- Dependence of <p_T> on the kinematic variables (e.g. x)
- x-dependence of the valence-quark distribution of pions.
- Low-mass, high p_T DY events as alternative for direct-photon production.

UA1 Collaboration, Phys. Lett. 209 (1988) 397

In this region, DY is related to high pT direct photon production by the electromagnetic coupling α multiplied by a factor that is essentially a measure of the virtuality of the intermediate photon.

+ if a solid nuclear target is placed in the beam:

- Quark energy loss in nuclei.
- Test of flavor-dependent EMC effect.
- Nuclear-dependence of the Boer-Mulders function.

New measurements using liquid hydrogen and liquid deuterium targets:

- Measure d/u ratios at large-x.
- Determine pion valence quark distributions.
- Test charge-symmetry-breaking of parton distributions in nucleons.
- Measure dbar/ubar at large-x using (π^+ + d) / (π^+ + p) DY ratios.

Recent review of Charge Symmetry violation: Lodergan, Peng, Thomas, Rev. Mod. Phy. 82 (2010) 2009

based on priv. comm. with Jen-Chieh Peng, 2011 / 2013

Summary

Drell-Yan: explore the flavor and spin structure of nucleons and nuclei

- Pion-induced Drell-Yan provides important additional information compared to the proton-induced case.
- To cover the full Drell-Yan program: need
  - proton, anti-proton and meson beams
  - unpolarized H, D & nuclear targets
  - polarized targets and / or desirably polarized beams

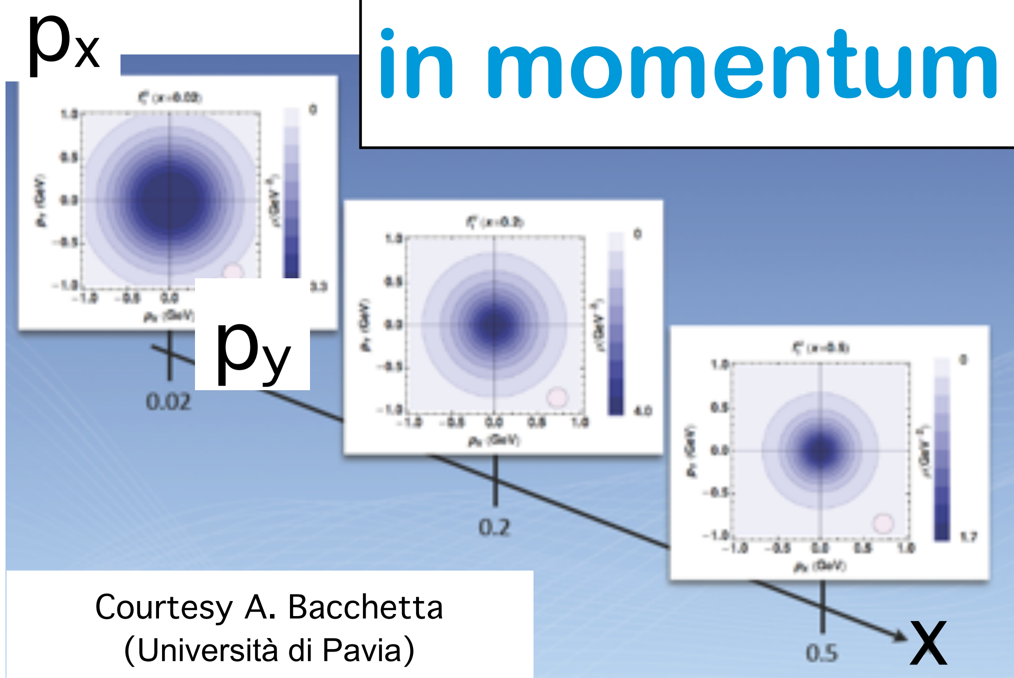
This review would not have been possible without material from Wen-Chen Chang, Jen-Chieh Peng, Paul Reimer, Wolfgang Lorenzon, Markus Diefenthaler, Oleg Denisov, and others.

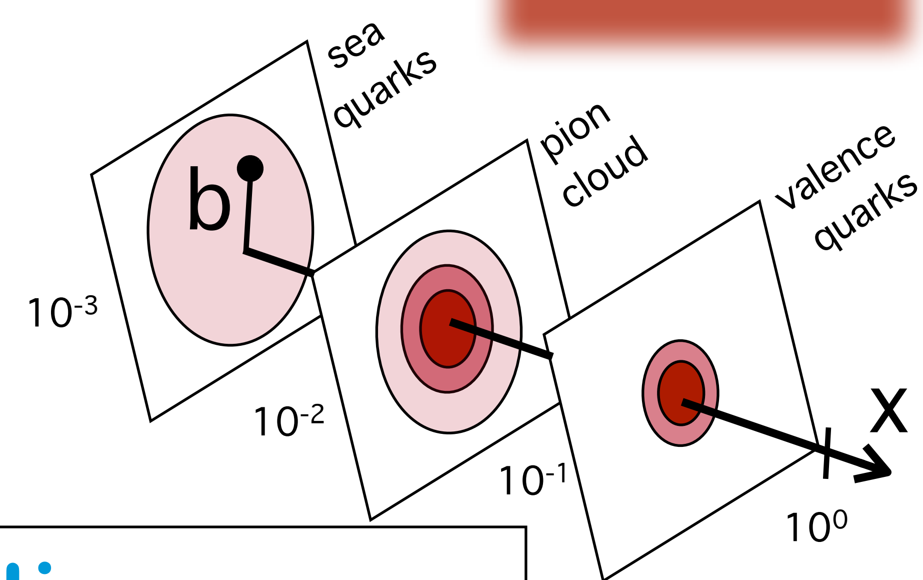
Thank you!

Backup

Nucleon Tomography in DIS

in momentum space





in position space

Correlation between **spin** and **transverse momentum** ?

Correlation between **longitudinal momentum** and **transverse position** ?

Transverse Momentum dependent PDFs

TMDs
$f(x,k_\perp)$

GPDs
$H(x,b_\perp)$
$\leftrightarrow$ FT $\leftrightarrow$ $H(x,\xi,t)$

Generalized Parton Distributions

$k_\perp$-integration

$\xi=0, t=0$

PDFs q(x), 1D:
Parton Distribution Functions

semi-inclusive measurements

inclusive measurements

exclusive measurements

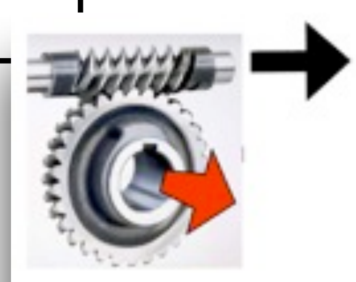
Transverse-Momentum Dependent PDFs (TMDs)

Distribution Functions (DF)

Diagonal 'survives' integration over transverse momentum k_T. "Collinear analysis"

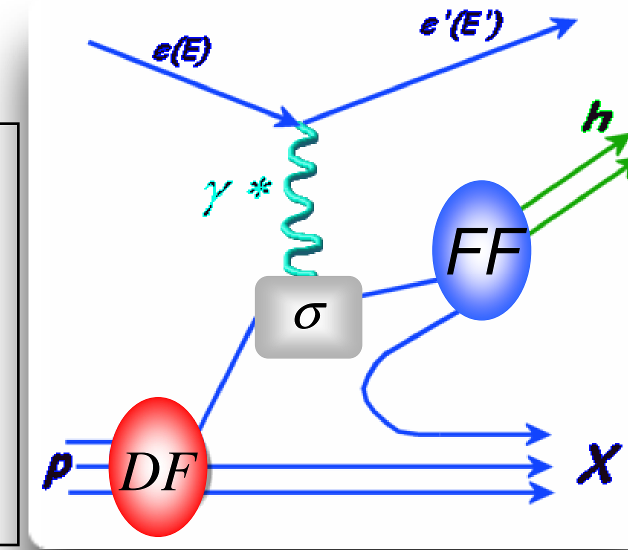
nucleon \ quark polarization	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm-gear
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear	h_1 Transversity; $h_{1T}^{\perp}$ Pretzelosity

chiral odd



factorization

$$\sigma^{ep\to ehX} = \Sigma_q (FF \otimes \sigma^{eq\to eq} \otimes DF)$$



Fragmentation Function (FF)

☛ TMDs depend on the longitudinal and transverse momentum of a parton inside a hadron.

☛ Describe strength of various spin-spin or spin-orbit correlations of the parton-hadron system.