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Nucleon Partonic Spin Structure to be explored by the Unpolarized Drell-Yan Program in the COMPASS-II Experiment at CERN

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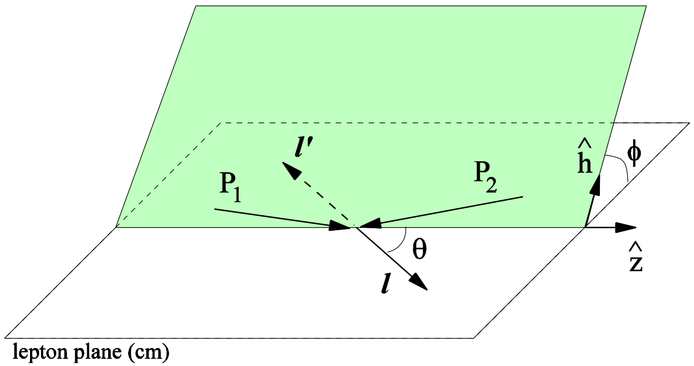
Outline

- Violation of Lam-Tung relation in π-induced Drell-Yan reaction.
- Boer-Mulders functions: TMD PDF accessed by the unpolarized Drell-Yan reaction.
- Unpolarized DY program in COMPASS-II at CERN: π, K and $\bar{p}$ beam
- Summary

Drell-Yan decay angular distributions



θ and ϕ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta+\mu\sin2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi)$$

$$\propto (W_T(1+\cos^2\theta)+W_L(1-\cos^2\theta)+W_\Delta\sin2\theta\cos\phi+W_{\Delta\Delta}\sin^2\theta\cos2\phi)$$

$q\bar{q}$ annilation parton model:

$O(\alpha_s^0)$ λ=1, $\mu=\nu$=0; $W_T=1, W_L=0$

Lam-Tung relation (1978)

Collinear pQCD: $O(\alpha_s^1)$, $W_L=2W_{\Delta\Delta}$; $1-\lambda-2\nu=0$

Angular Distributions of Drell-Yan Events

I.R. Kenyon, Rep. Prog. Phys. 45 (1982) 1261

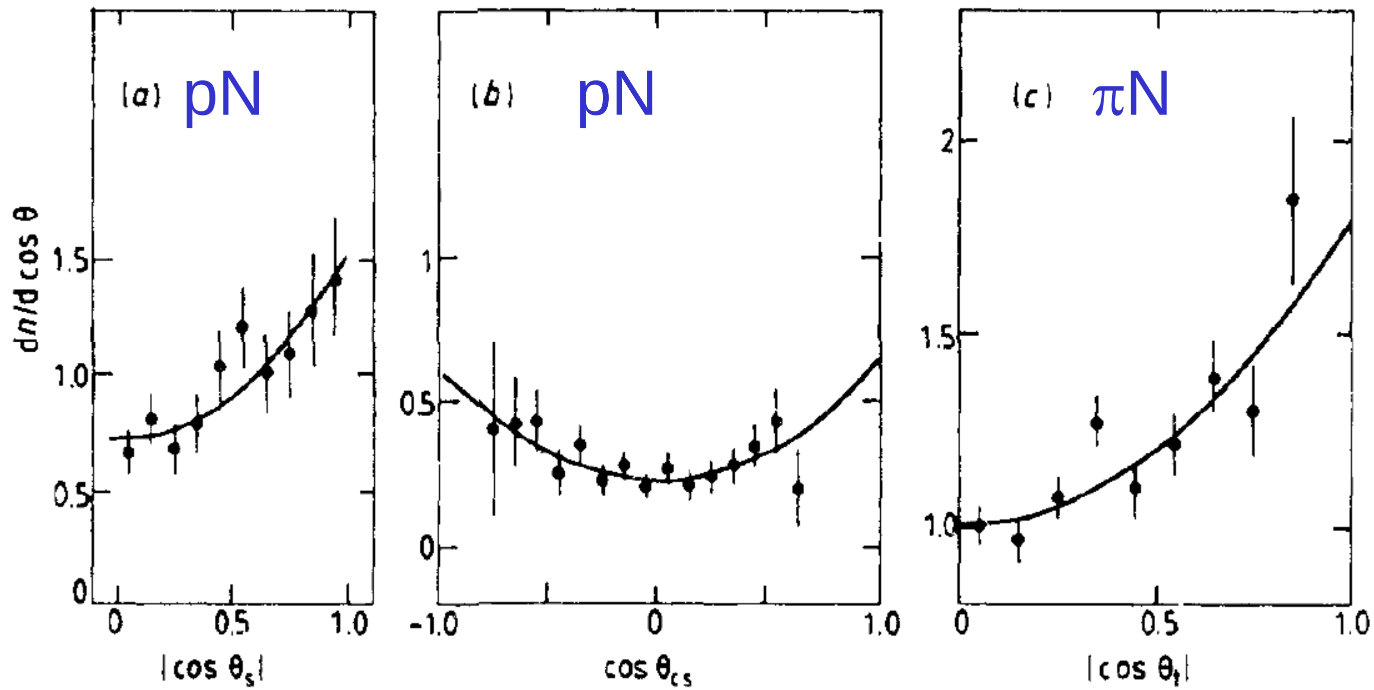
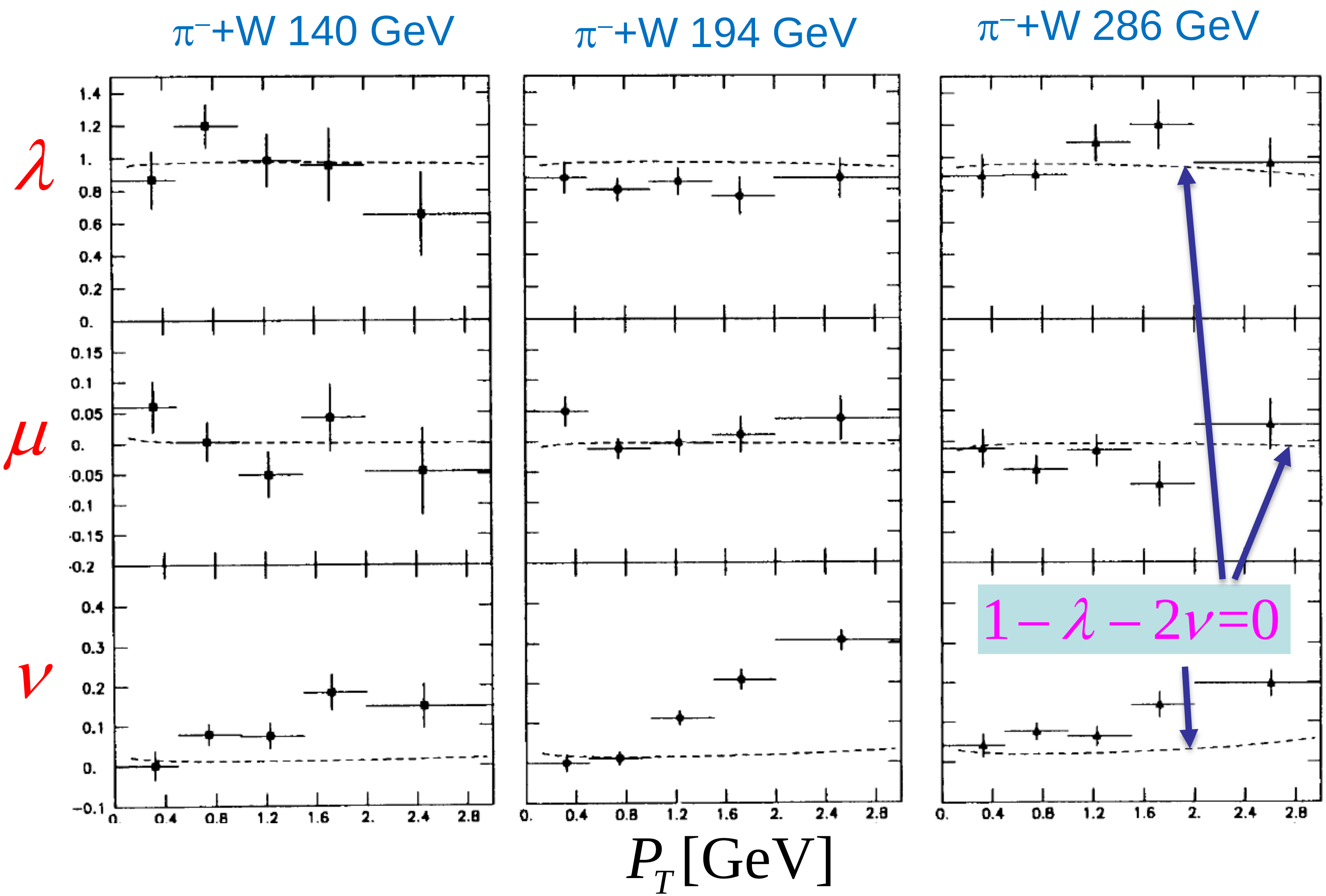


Figure 17. Measurements of the decay angular distribution of lepton pairs by Kourkoumelis *et al* (1980), Antreasyan *et al* (1980) and Badier *et al* (1980a). Fits to the form $1+\alpha\cos^2\theta$ are shown as full curves and are discussed in the text. (*a*) ISR ABCS, $4.5<M<8.7$ GeV, (*b*) ISR CHFMNP, $6<M<8$ GeV, (*c*) NA3, π^- 200 GeV, $4<M<6$ GeV, $p_t<1$ GeV.

$$d\sigma(\Omega) \propto (1+\cos^2\theta)$$

NA10 @ CERN: Violation of LT Relation

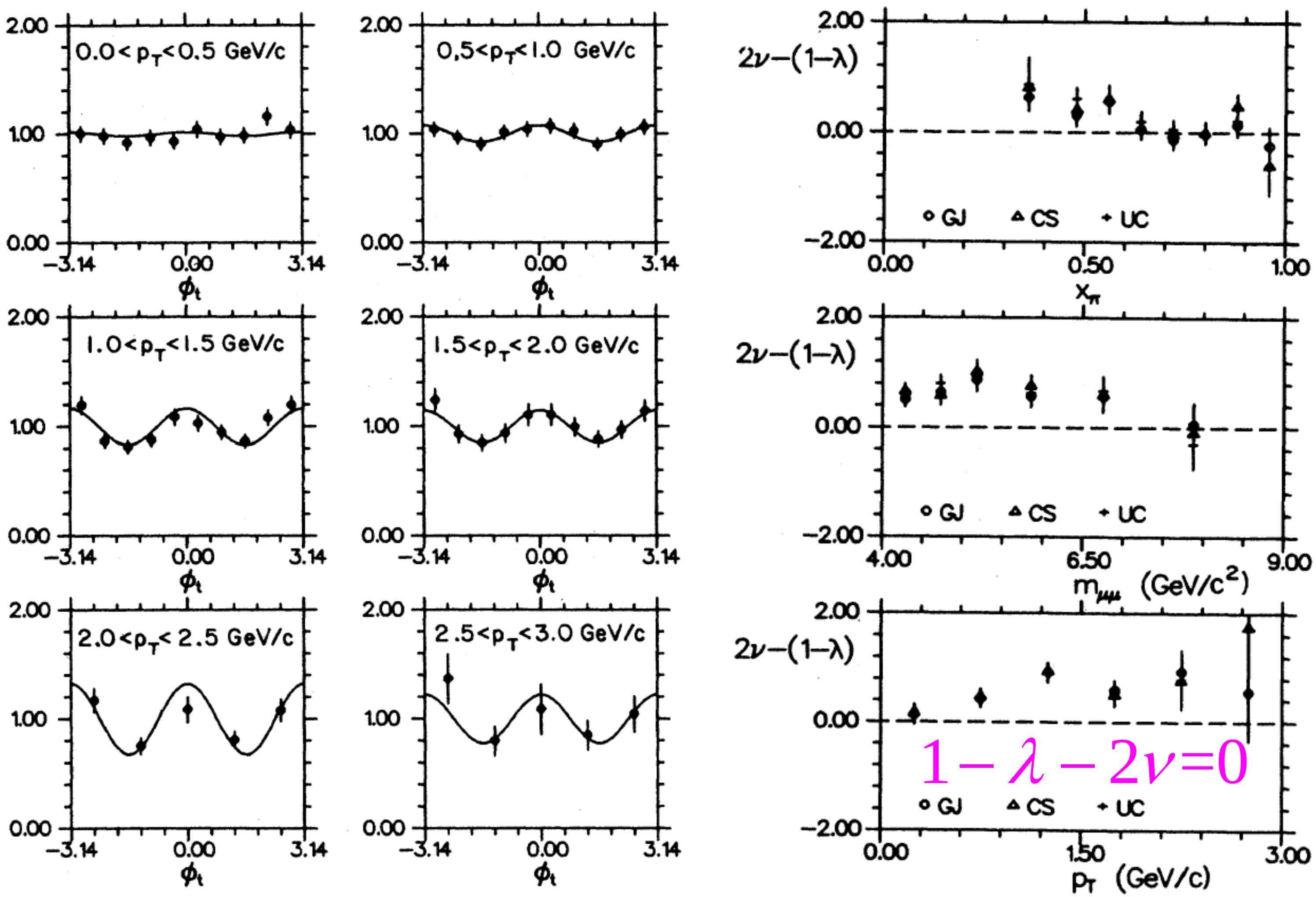
Z. Phys. 37 (1988) 545



E615 @ FNAL: Violation of LT Relation

PRD 39, 92 (1989)

252-GeV π^{-}+W



$1-\lambda-2\nu=0$

$\cos 2\phi$ modulation at large p_T

Azimuthal Asymmetries Require Nontrivial Spin Correlation

The most general $q\bar{q}$ spin density matrix

$$\rho^{(q,\bar{q})} = \frac{1}{4}\{1\otimes 1 + F_j(\vec{\sigma}\bullet\vec{e}_j)\otimes 1 + G_j 1\otimes(\vec{\sigma}\bullet\vec{e}_j) + \mathrm{H}_{ij}(\vec{\sigma}\bullet\vec{e}_i)\otimes(\vec{\sigma}\bullet\vec{e}_j)\}$$

$$\text{Violation of LT relation: } \kappa = -\frac{1}{4}(1-\lambda-2\nu) \approx \left\langle \frac{H_{22}-H_{11}}{1+H_{33}} \right\rangle$$

$$\text{Collinear case: } H_{11} = H_{22},\ H_{23} = H_{32} = 0,\ \kappa = 0$$

Brandenburg, Nachtmann & Mirkes, ZPC 60 (1993) 697

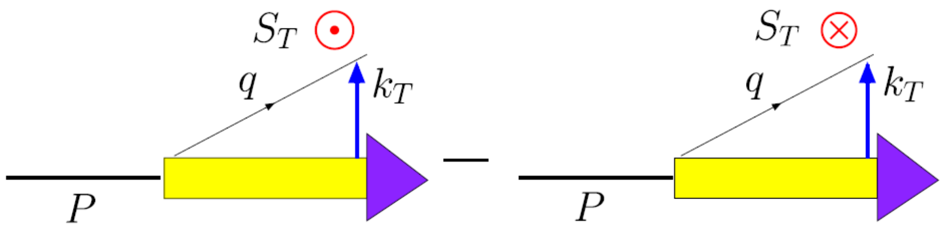
Nonzero κ requires *the correlation of the spins of quark and antiquark.*

What will be the mechanism?

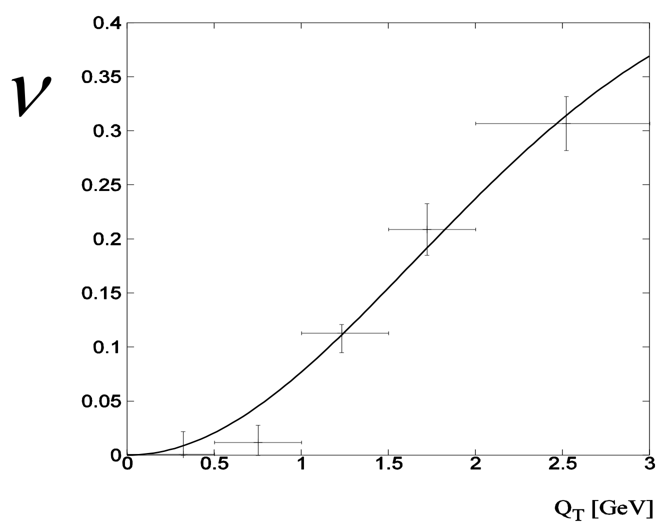
D. Boer (PRD 60, 014012 (1999))
Hadronic Effect, Boer-Mulders Functions

Spin-orbit correlation of transversely polarized *noncollinear partons* inside an unpolarized hadron

$h_1^{\perp} =$



- Boer-Mulders Function $h_1^{\perp}$: a correlation between quark's k_T and transverse spin S_T in an unpolarized hadron
- $h_1^{\perp}$ can lead to an azimuthal dependence with $\frac{\nu}{2} \propto h_1^{\perp}(N)\overline{h}_1^{\perp}(\pi)$



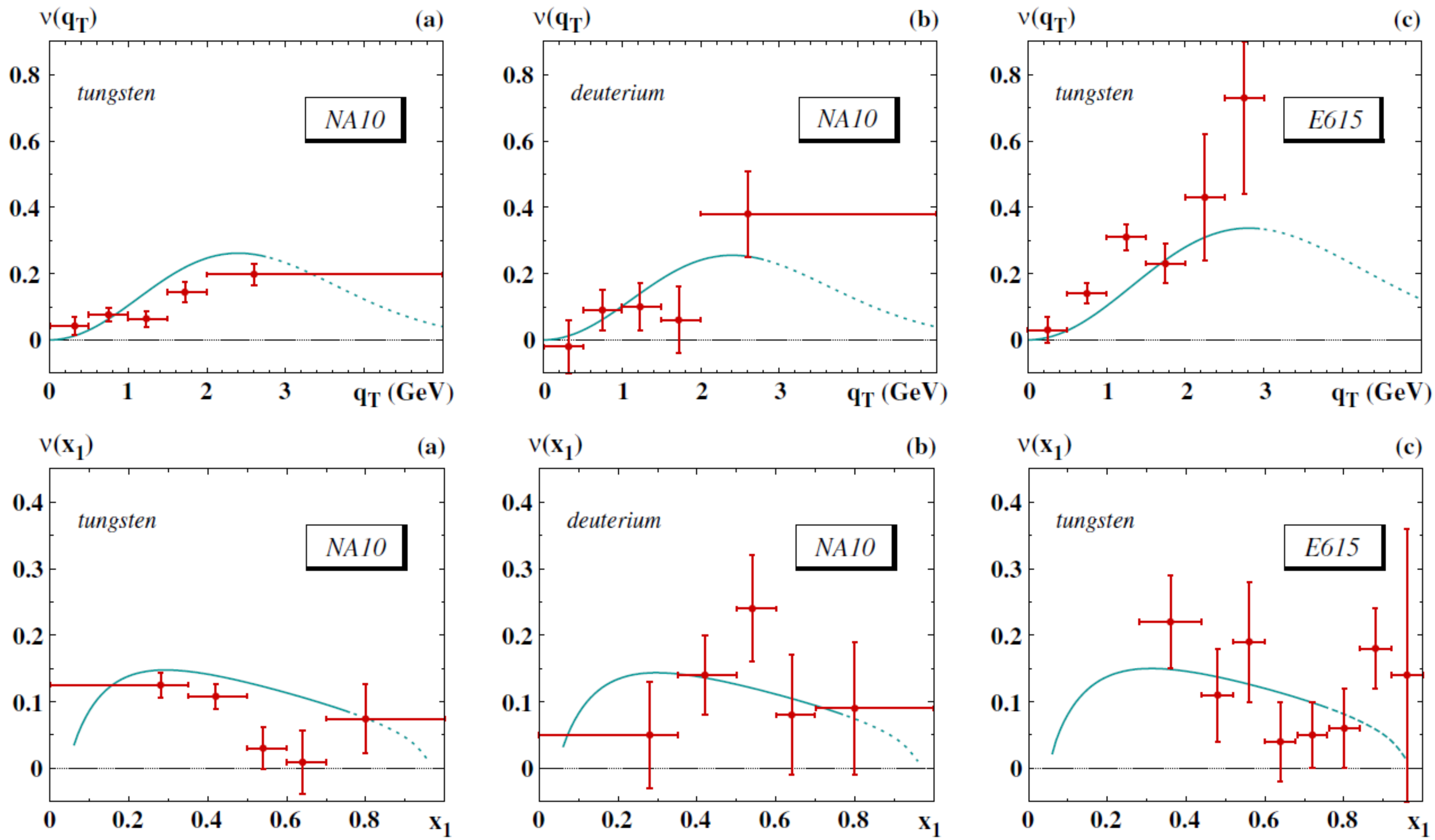
$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad \kappa_1 = C_{H_1} C_{H_2}/2$$

$$\kappa = \frac{\nu}{2} \rightarrow 0 \text{ for large } |k_T|$$

Consistency of factorization in term of TMDs

Pasquini and Schweitzer (PRD 90, 014050 (2014))
Boer-Mulders Functions of Pion and Proton in Light-Front Constituent Model



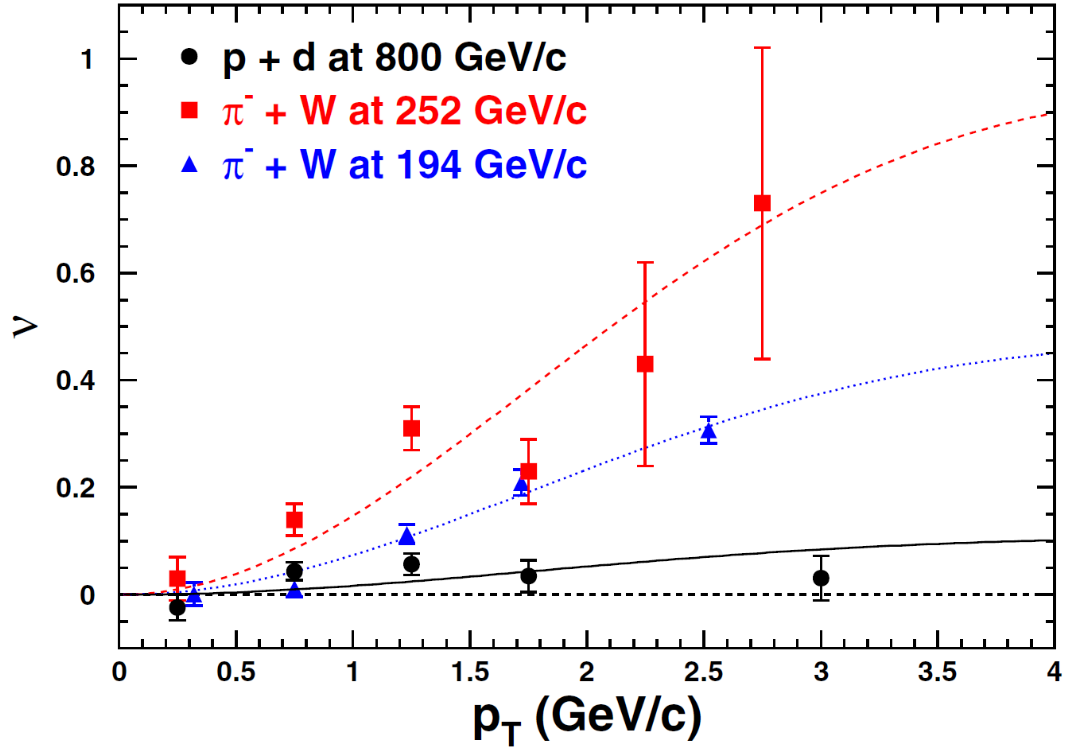
Theoretical Interpretations of Lam-Tung Violation in pion-induced DY

	Boer-Mulders Function	QCD chromo-magnetic effect	Glauber gluon
Origin of effect	Hadron	QCD vacuum	Pion specifically
Quark-flavor dependence	Yes	No	No
Hadron dependence	Yes	No	Yes
Large P_T limit	0	Nonzero	0
Reference	PRD 60, 014012 (1999)	Z. Phy. C 60,697 (1993)	PLB 726, 262 (2013)

Measurements with different beams $\pi^{\pm}, p, K^{\pm}, \bar{p}$ over a wide kinematical range would help differentiating the origin.

Azimuthal cos2ϕ Distribution in proton-induced DY

E866, PRL 99, 082301 (2007)



$$h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2},$$

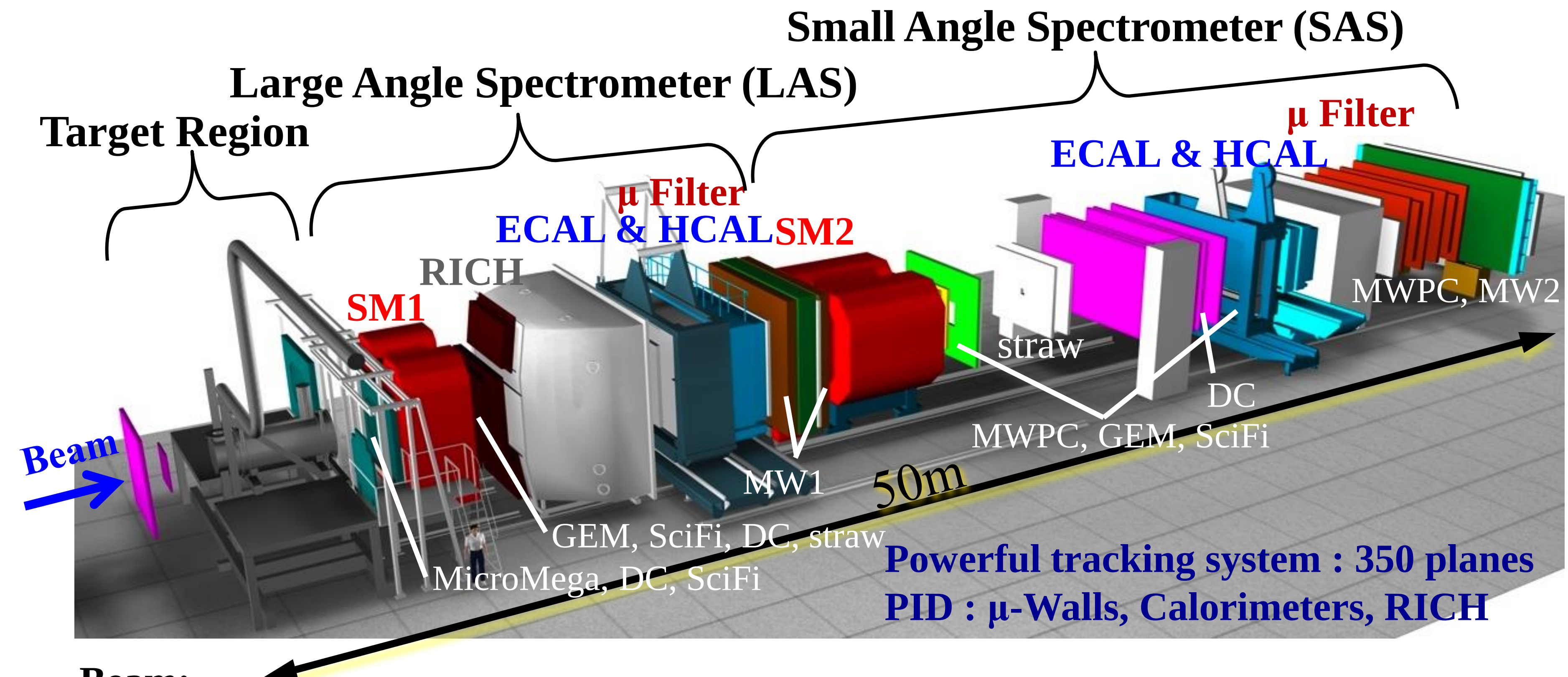
$$\kappa_1 = C_{H_1} C_{H_2}/2$$

$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

$\nu(pd \rightarrow \mu+\mu- X) \sim$ [valence $h_1^\perp(p)$] * [sea $h_1^\perp(p)$]

Sea-quark BM functions are much smaller than valence quarks

COMPASS Setup



Beam:

Polarized lepton beam : μ^+, μ^- 50-280 GeV/c

Hadron beam : π^+, π^+, K^+, K^-, p

Target:

Polarized NH_3 and ^6LiD target

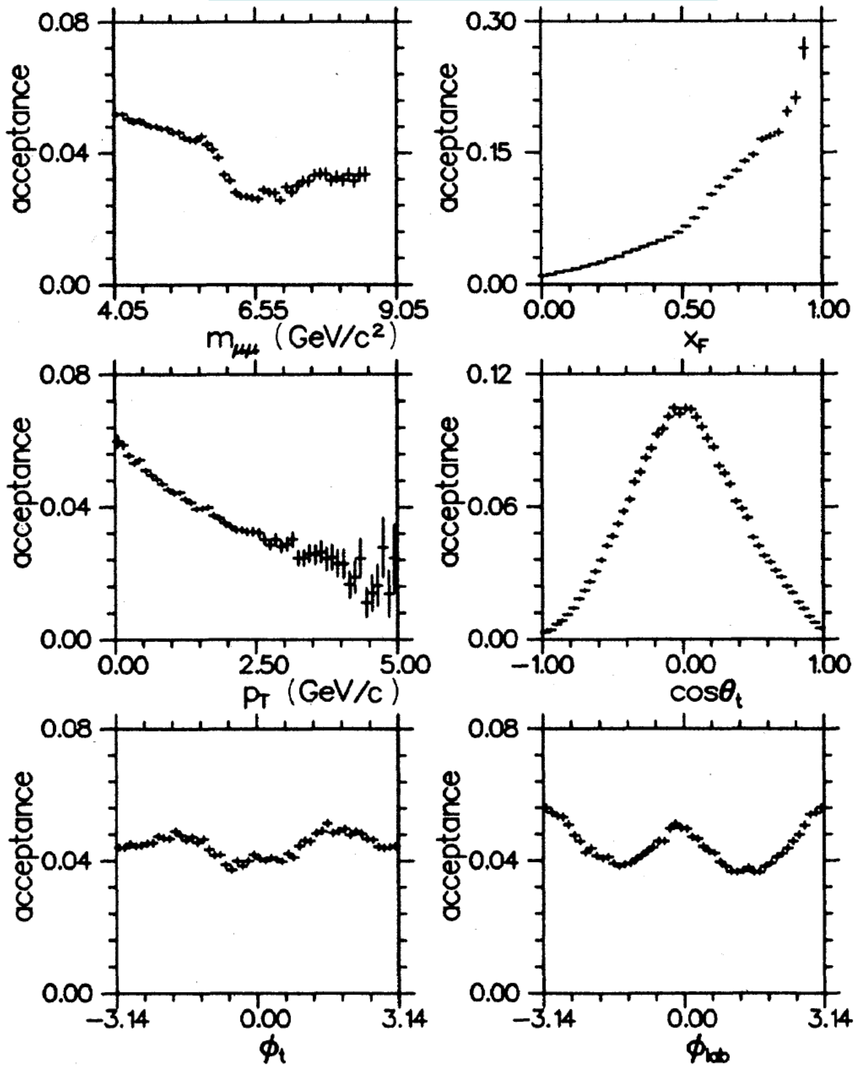
Liquid hydrogen target

Nuclear target

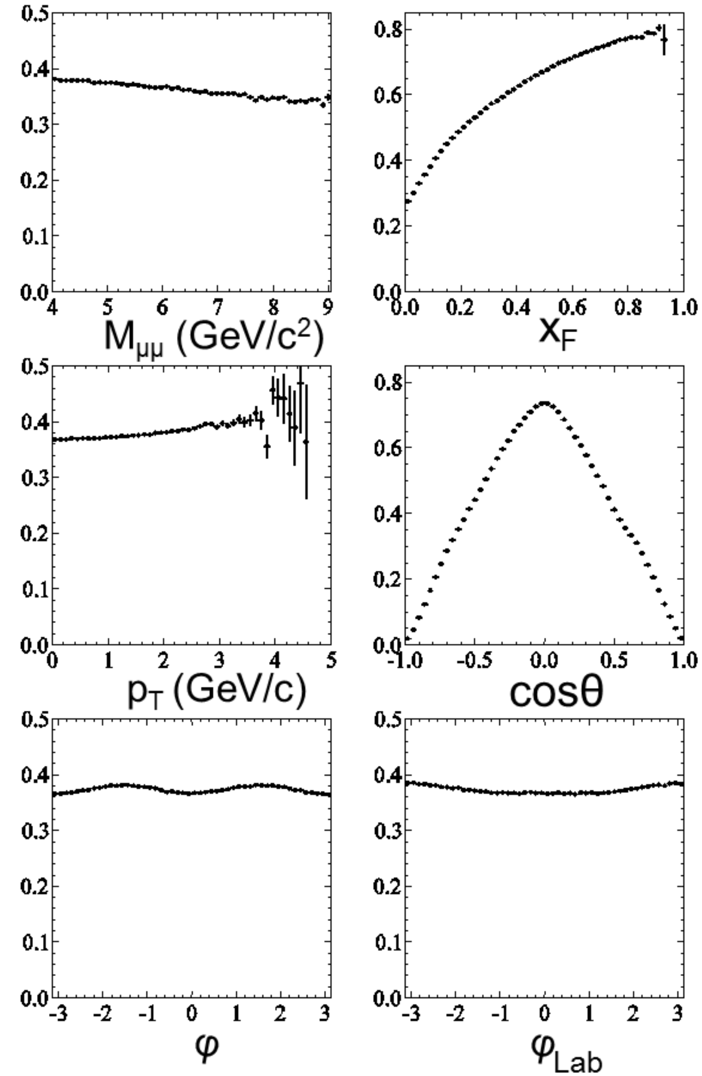
Various Combinations of Beam & Target

Dimuon Acceptance

E615 @ FNAL (1989)

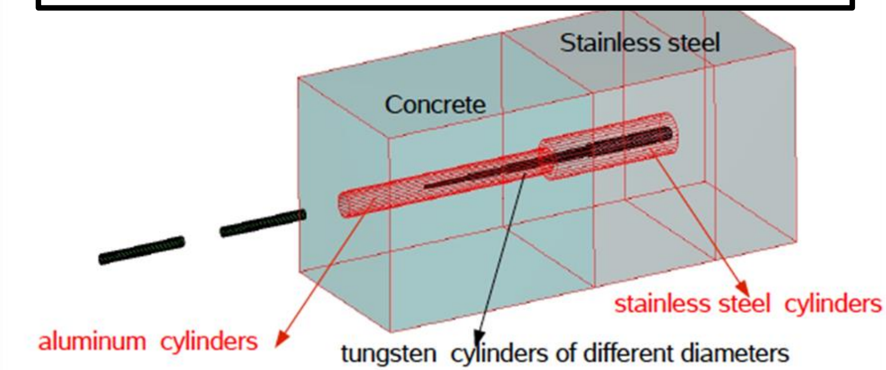


COMPASS @ CERN (2014)

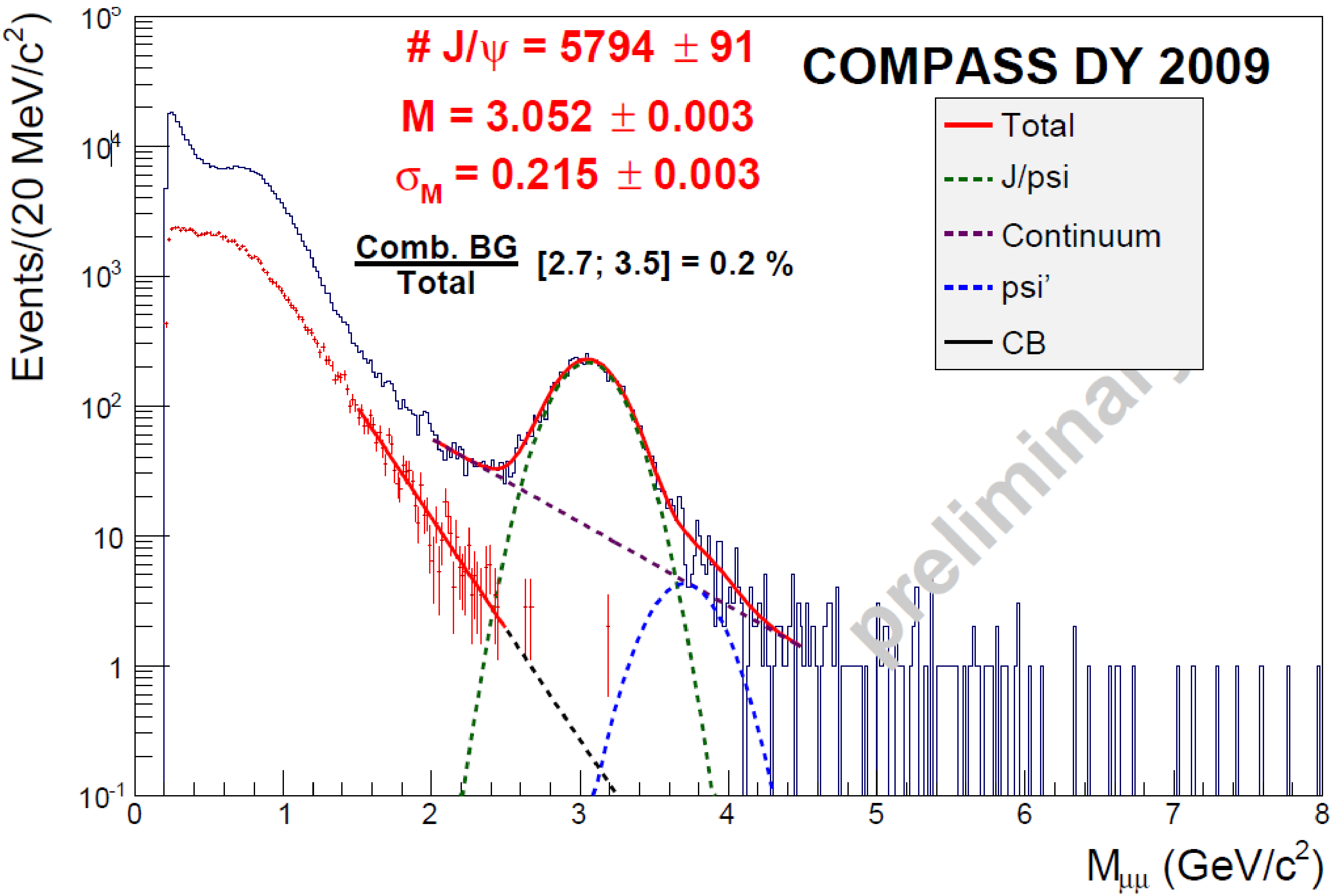


DY Feasibility @COMPASS: Beam Test 2009

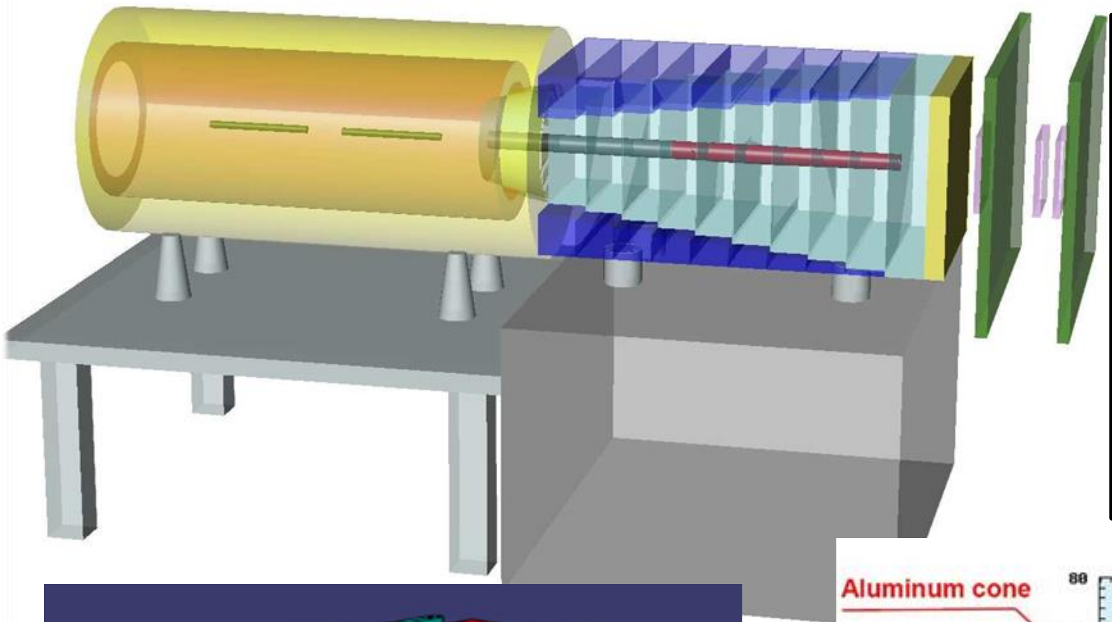
- 160 GeV/c π- beam
- 2 cells polyethylene target
- Prototype hadron absorber and beam plug
- 3 days of data taking



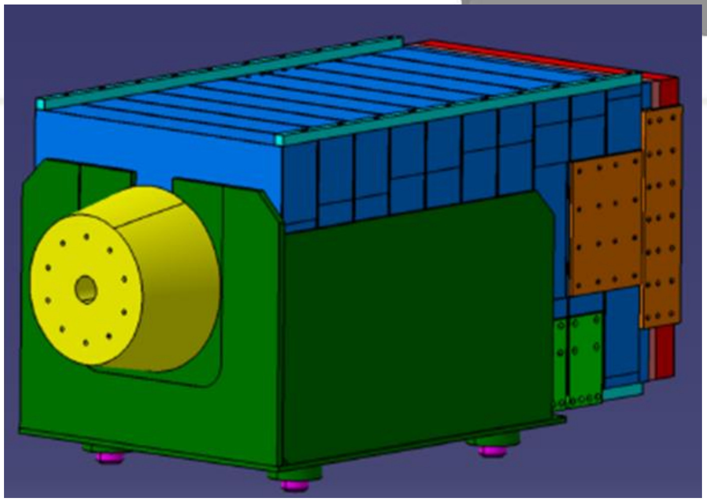
DY Feasibility @COMPASS: Beam Test 2009

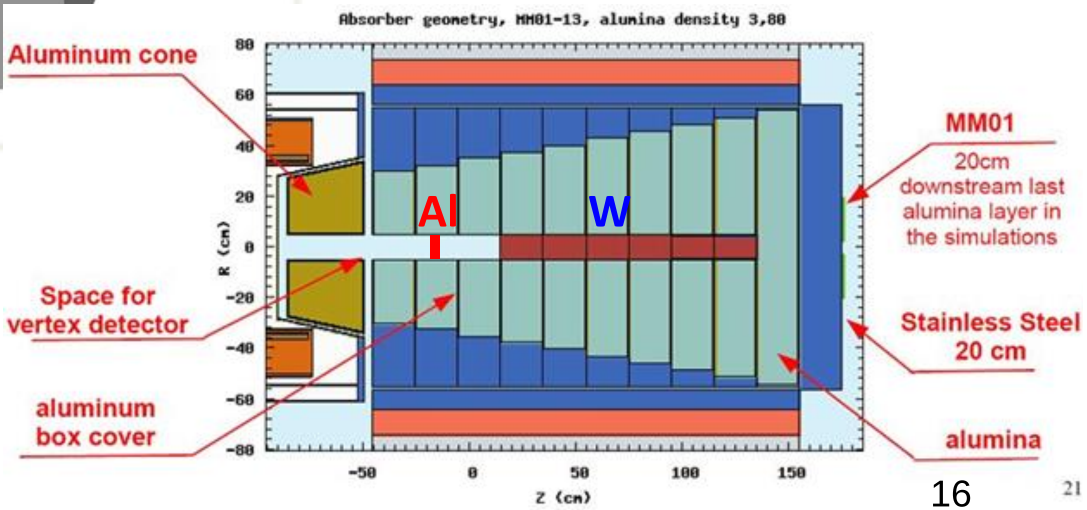


Hadron Absorber & Nuclear Targets



- Absorber: 236 cm long, made of Al_2O_3.
- Beam plug: 120 cm long, made of tungsten.
- Radiation lengths (multiple scattering for μ): $x/X_0 = 33.53$
- Hadronic interaction lengths (stopping power for π): $x/\lambda_{int} = 7.25$
- 7cm Al target





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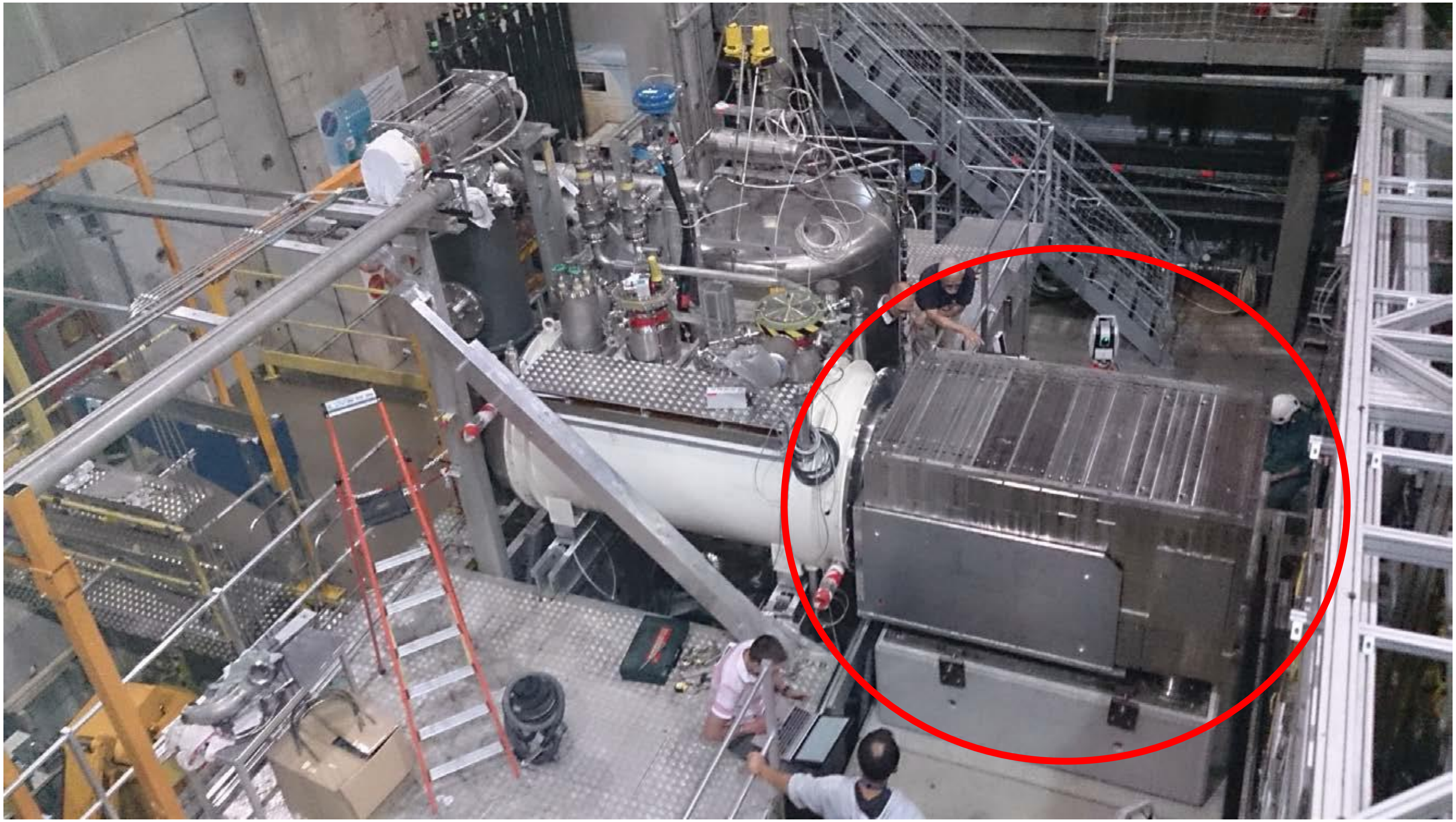
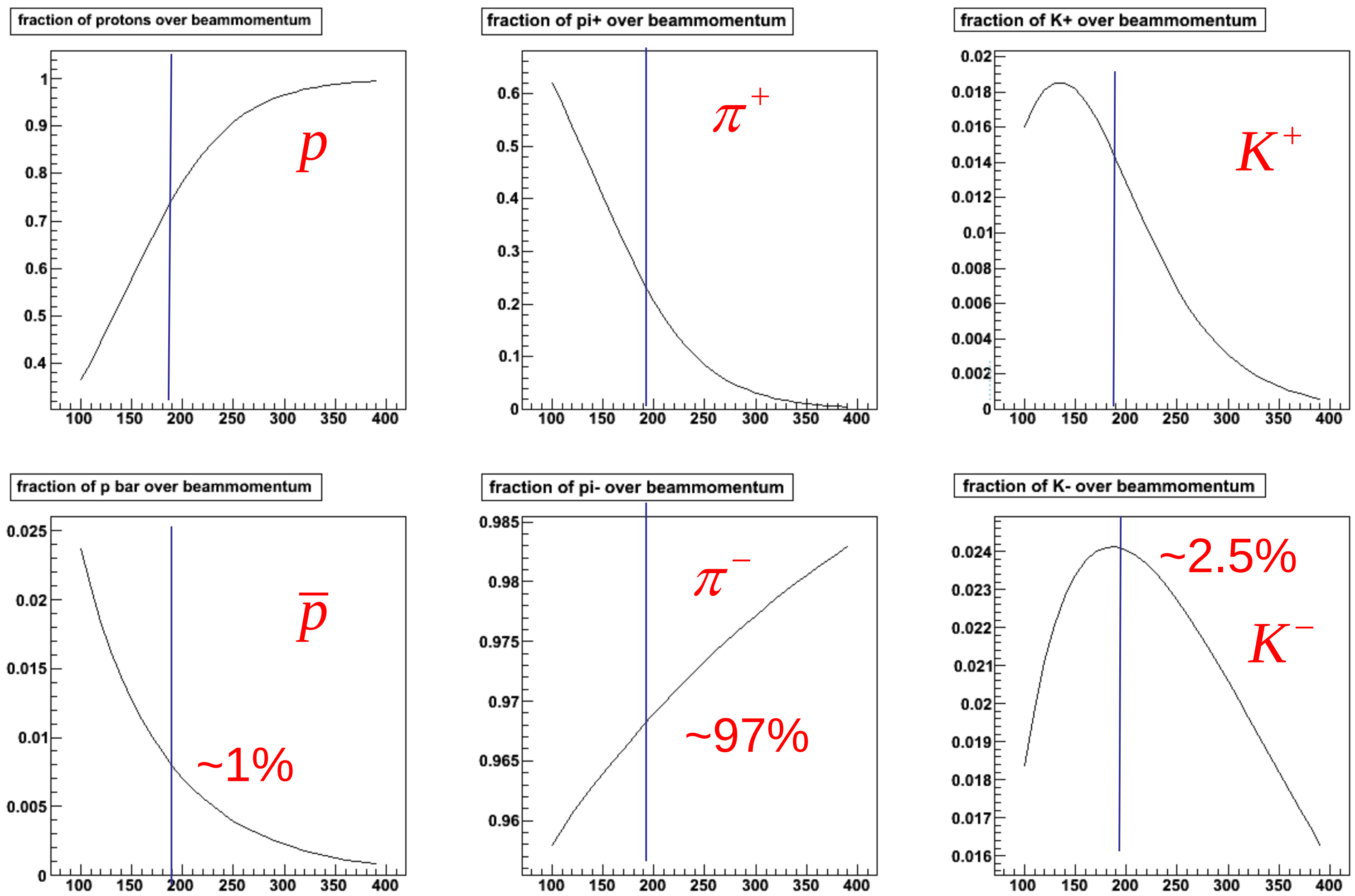
Hadron Absorber & Nuclear Targets (2014)



Fraction of Hadrons in M2-Hadron-beam at COMPASS target

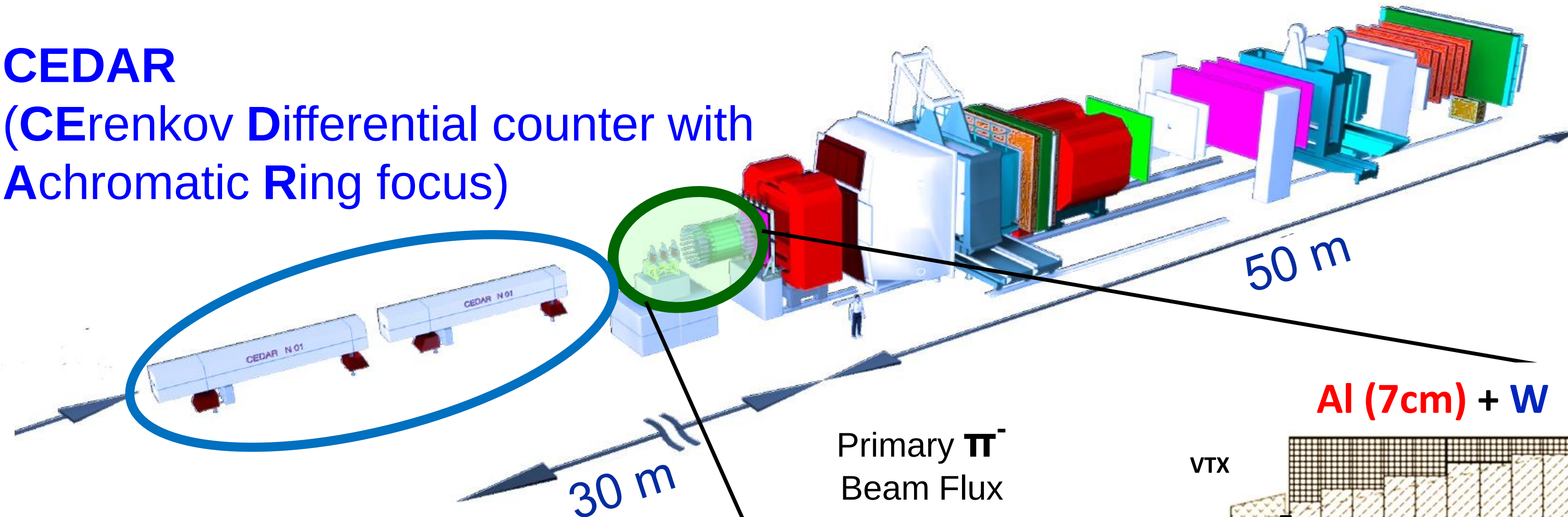
http://www.staff.uni-mainz.de/jasinsk/index.htm

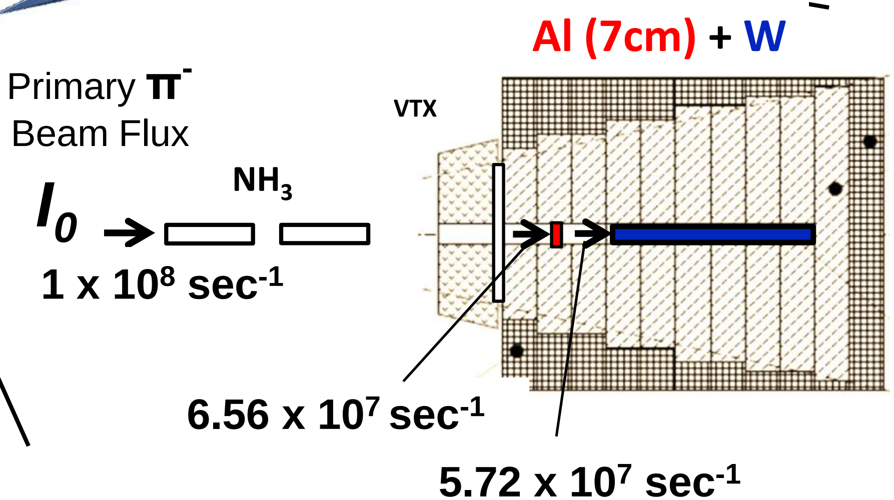


Beam momentum

Beam PID & Nuclei Targets

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.

Expected Statistics of Unpolarized Drell-Yan Events

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

	NH_3	Al (7cm)	W
π^- beam	285,000	55,100	549,000
K^- beam	3,570	710	7,570
$\bar{p}$ beam	2,570	450	3,640

	NA3	E537	E615
π^- beam	21,220		27,977
K^- beam	700		
$\bar{p}$ beam		387	

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

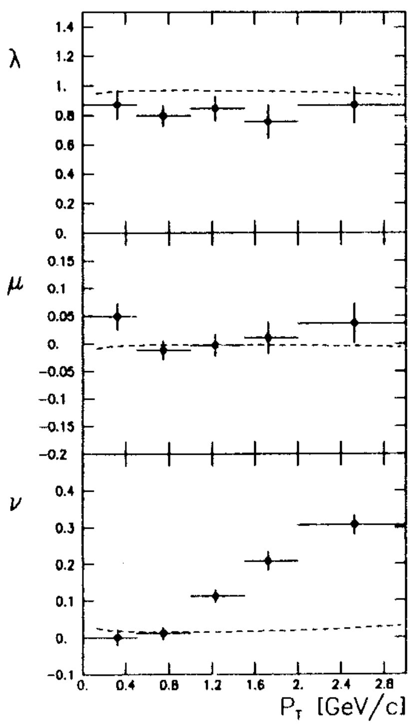
Expected Statistical Precision of Dimuon Angular Distributions

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

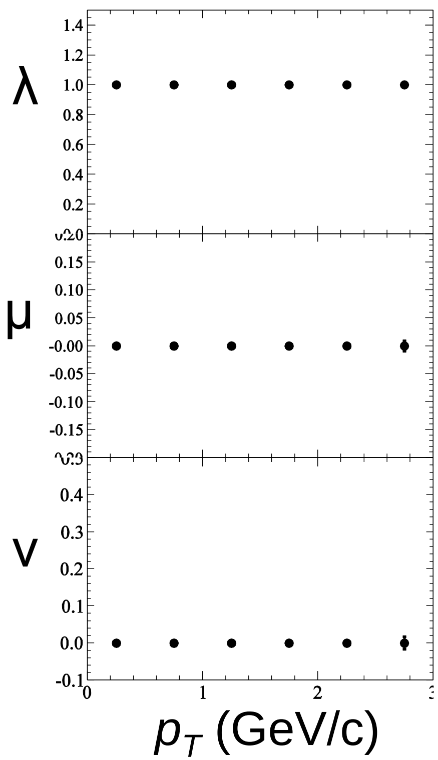
COMPASS, DY on **W target**, 140-day data taking

NA10

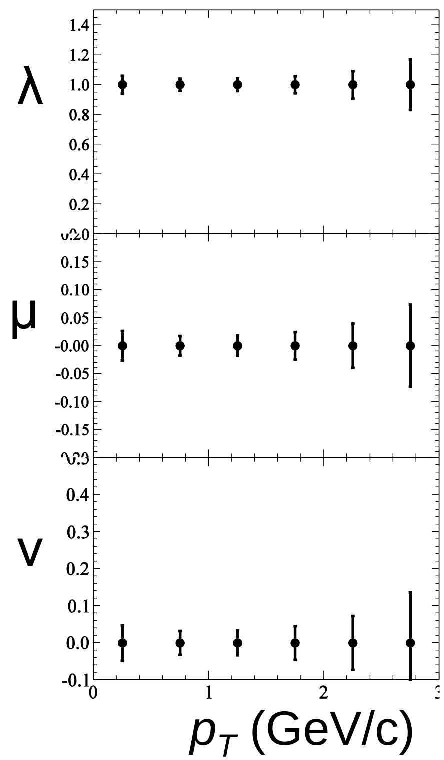
194 GeV/c



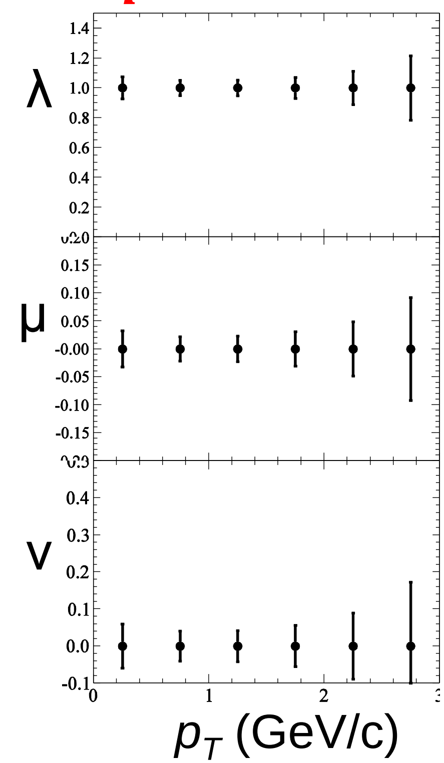
$\pi^- W$



$K^- W$



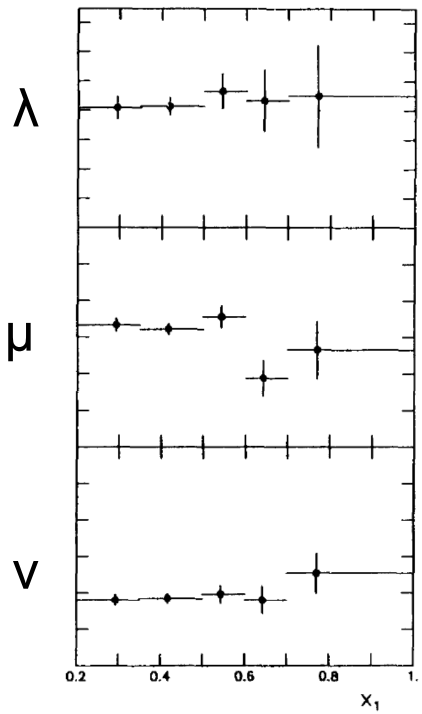
$\bar{p}$ W



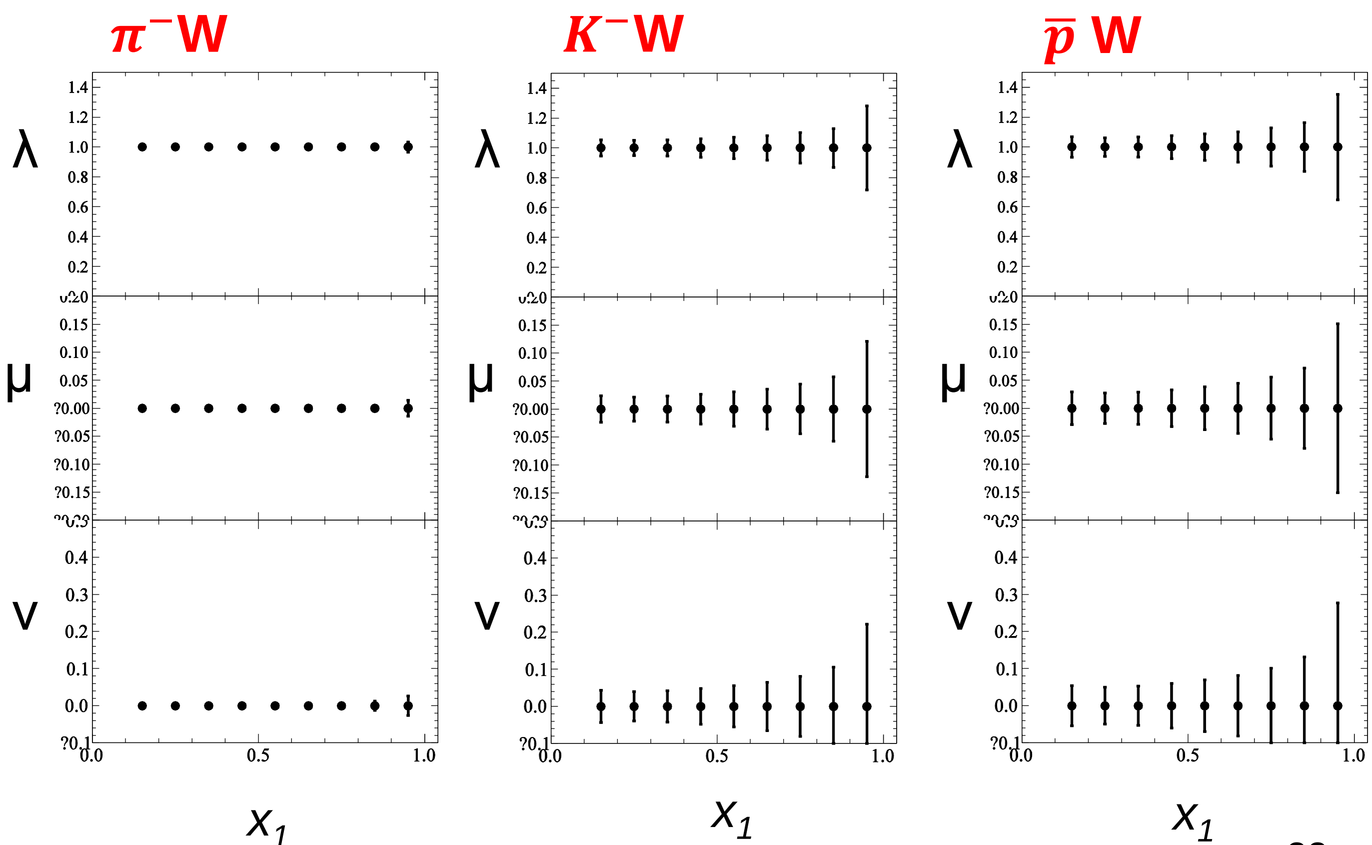
Expected Statistical Precision of Dimuon Angular Distributions

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

NA10



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



COMPASS-II Drell-Yan Program

- 2014-2018 short-term plan:
  - Commissioning of **polarized Drell-Yan** experiment started in mid-October 2014.
  - Physics runs will take place for year 2015.
  - 2016-2017: **DVCS** program.
  - 2018: **Polarized Drell-Yan** program (to be approved)
- 2020-2024 medium-term plan (under planning) :
  - **Polarized ^{6}LiD target**: flavor separation of TMD SSAs.
  - **Long LH_2 and nuclei targets**: unpolarized pion-induced DY.
- >2025 long-term plan (under planning) :
  - Extracted high intensity RF separated antiproton/kaon beam: (un)polarized antiproton/kaon-induced DY.

Summary

- TMD Boer-Mulders function, the spin-orbit correlation of transversely polarized partons, serves as a reasonable interpretation of violation of Lam-Tung relation in pion-induced DY process.
- COMPASS-II experiment will carry out the measurement of unpolarized DY process using π, K and $\bar{p}$ beam over a wide kinematical range. The expected statistics for a successful data taking in 2015 will be more than 10 times larger than the existing world data.
- COMPASS-II unpolarized DY program will hopefully bring further understanding on the origin of Lam-Tung violation and also the partonic structures of protons and pions.