COMPASS Drell-Yan

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TMD ECT* Workshop
11-15 April 2016

"What we especially like about these theoretical types is that they don't tie up thousands of dollars worth of equipment."

Outline

Single polarized Drell-Yan at COMPASS

DY vs SIDIS at COMPASS

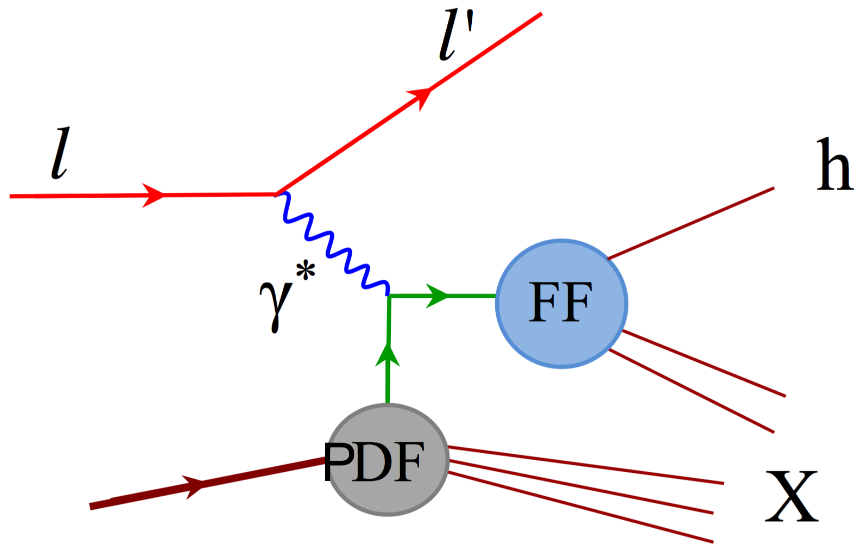
Experimental setup

Spin-dependent measurements

Spin-independent measurements

What about the future?

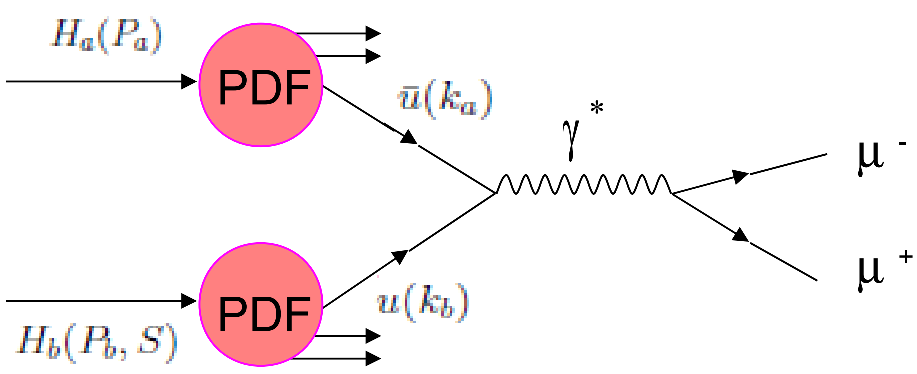
Accessing TMDs @ COMPASS



SIDIS

PDF ⊗ FF

Probe Universality

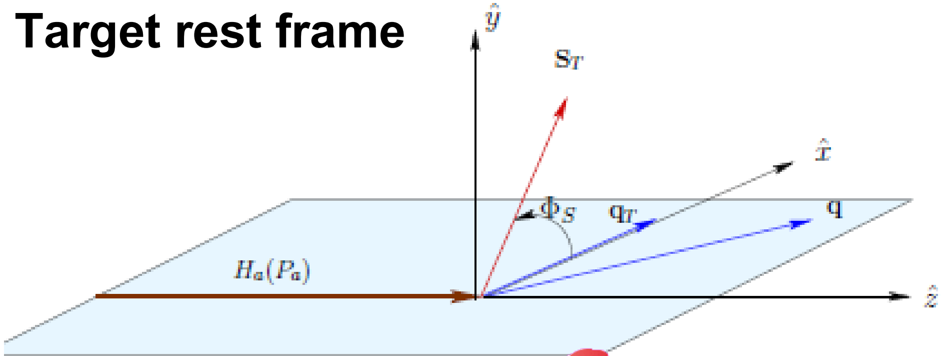


Drell-Yan (DY)

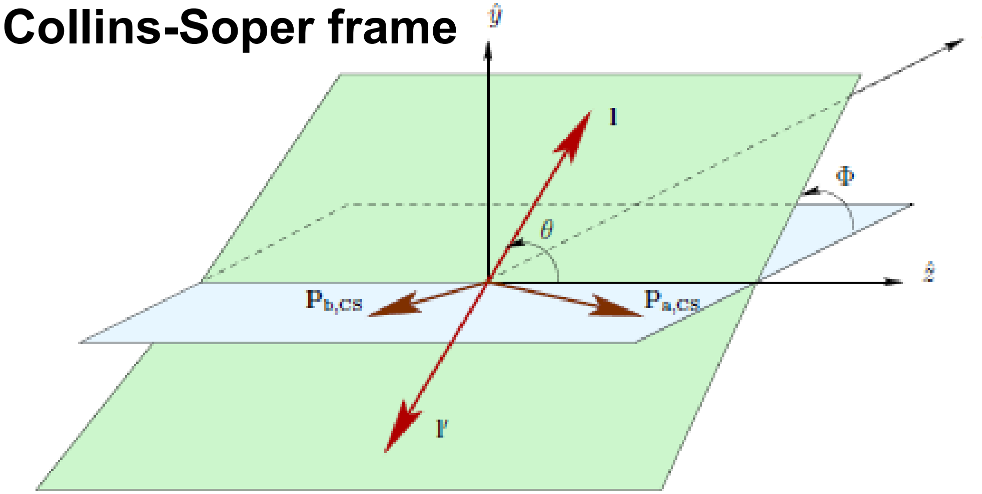
PDF ⊗ PDF

Single polarized DY

Target rest frame



Collins-Soper frame



Measure magnitude of azimuthal modulations in cross section: "Single-Spin Asymmetries"

beam target

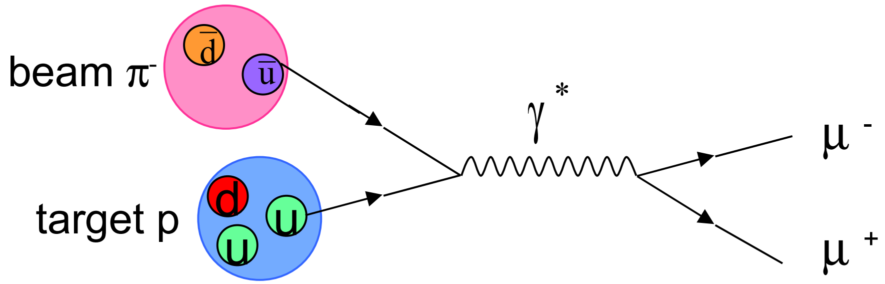
$$\boxed{\mathrm{DF} \otimes \mathrm{DF}}$$

At LO:

$$
\begin{aligned}
d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = 1 &+ \boxed{\overline{h}_1^\perp} \otimes \boxed{h_1^\perp} \cos(2\phi) \\
&+ |S_T| \boxed{\overline{f}_1} \otimes \boxed{f_{1T}^\perp} \sin\phi_S \\
&+ |S_T| \boxed{\overline{h}_1^\perp} \otimes \boxed{h_{1T}^\perp} \sin(2\phi + \phi_S) \\
&+ |S_T| \boxed{\overline{h}_1^\perp} \otimes \boxed{h_1} \sin(2\phi - \phi_S)
\end{aligned}
$$

beam		target
(BM)	$\otimes$	**(BM)**
(f_1)	$\otimes$	**(Sivers)**
(BM)	$\otimes$	**(Pretzelosity)**
(BM)	$\otimes$	**(Transversity)**

Meson induced DY process



beam target

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

$$\sigma^{\mathrm{DY}} \propto f_{\overline{u}|\pi} \otimes f_{u|p}$$

Flavor sensitive: meson is specific qqbar compound

pi-minus on proton: selectively probes u-quark Sivers distribution of the proton

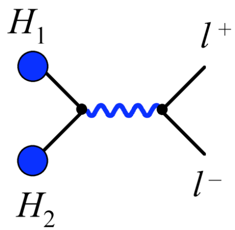
no cancellation effects by opposite-sign u- and d-quark Sivers contributions

Creation of large-mass di-lepton from valence quarks: large x
Proton-induced DY generates di-lepton from sea-quark: small x

test meson structure and nuclear models

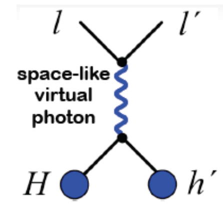
pion		proton
$(\mathrm{BM})_\pi$	$\otimes$	$(\mathrm{BM})_p$
$(f_1)_\pi$	$\otimes$	$(\mathrm{Sivers})_p$
$(\mathrm{BM})_\pi$	$\otimes$	$(\mathrm{Pretzelosity})_p$
$(\mathrm{BM})_\pi$	$\otimes$	$(\mathrm{Transversity})_p$

DY-SIDIS Bridge



DY

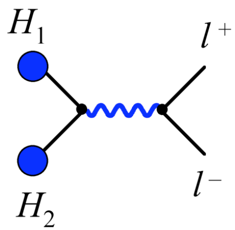
SIDIS



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1+\cos^2\theta + \sin^2\theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} + S_T \left[\begin{array}{l} \left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} \\ +\sin^2\theta \left(\begin{array}{l} \sin\left(2\varphi_{CS}+\varphi_S\right) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ +\sin\left(2\varphi_{CS}-\varphi_S\right) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right] \right\}$$

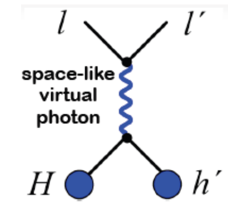
$$\frac{d\sigma_{SIDIS}^{LO}}{dxdydzdp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x}\right) \right] \times \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \left\{ 1 + \cos 2\phi_h \left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) + S_T \left[\begin{array}{l} \sin\left(\phi_h - \phi_S\right)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right) \\ + \sin\left(\phi_h+\phi_S\right)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right) \\ + \sin\left(3\phi_h-\phi_S\right)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right) \end{array} \right] \right.$$

DY-SIDIS Bridge



DY

SIDIS



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \Big\{ 1+\cos^2\theta + \sin^2\theta \cos$$

$$+ S_T \Big[\left(1+\cos^2\theta\right) \sin\varphi_S A_T^{\sin\varphi_S}$$

$$\frac{d\sigma_{SIDIS}^{LO}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$+ \varepsilon F_{UU,L}\Big) \Big\{ 1 + \cos 2\phi_h \left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)$$

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

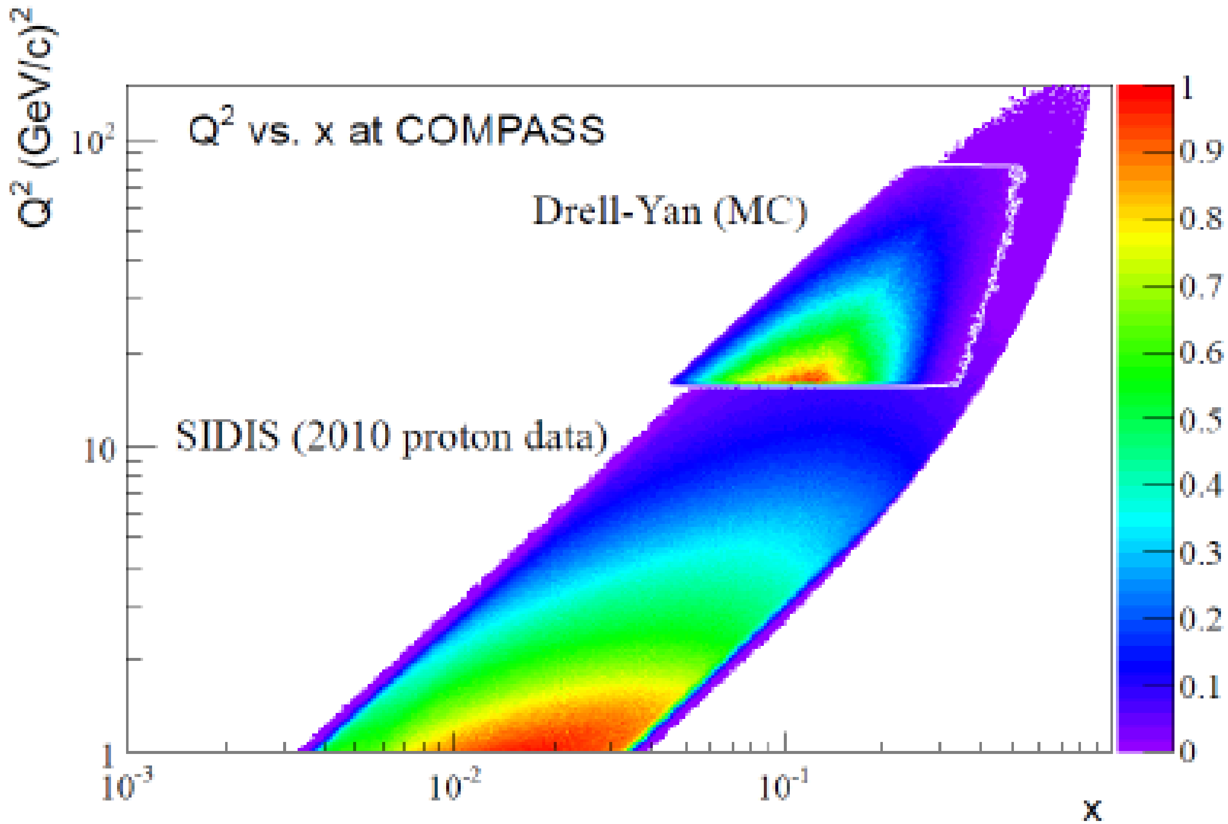
$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

DY-SIDIS Bridge



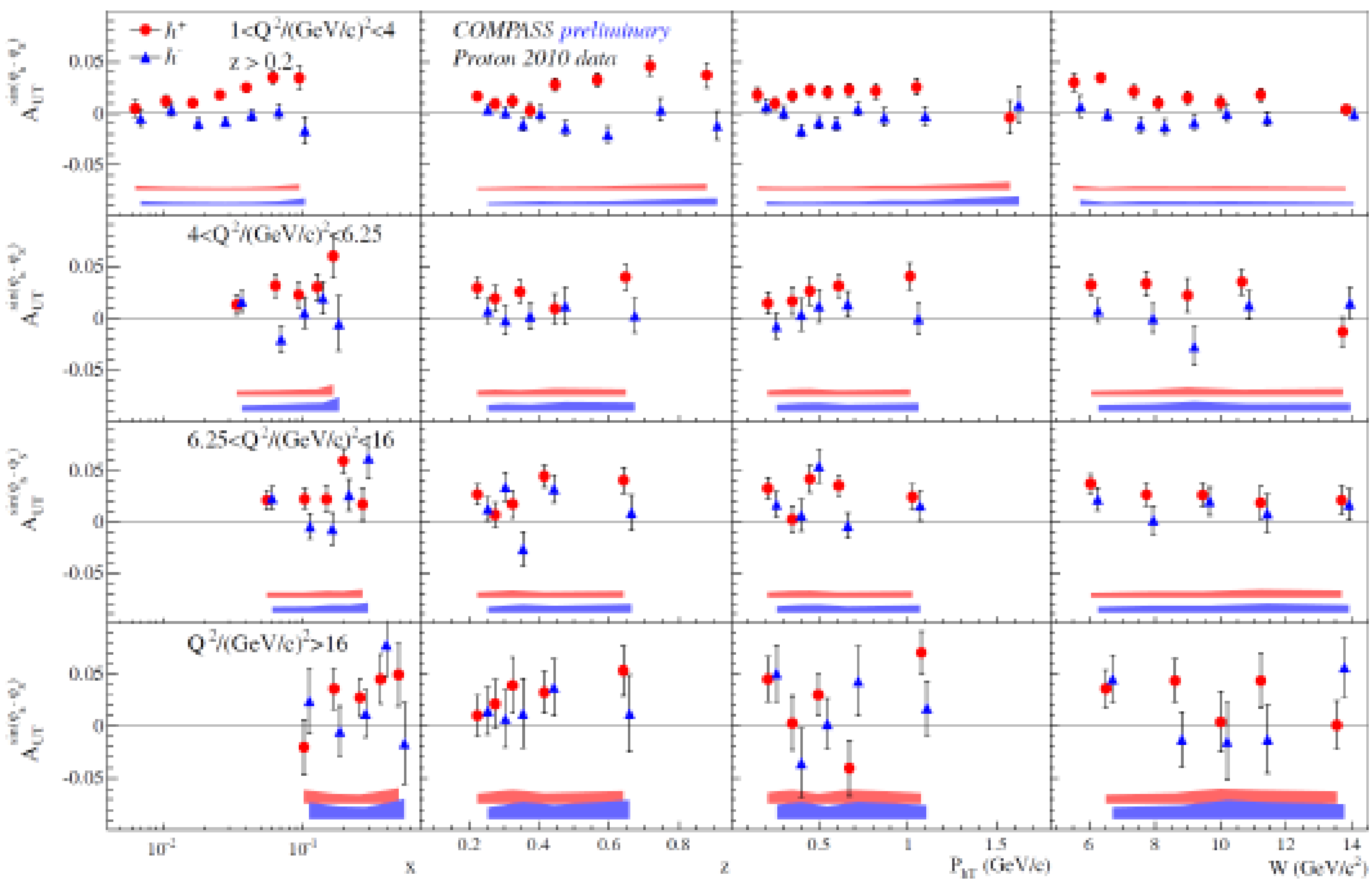
Universality: these naïve time-reversal-odd TMDs are expected to have the same magnitude but opposite sign in Drell Yan.

$$h_1^{q\perp}\Big|_{DY} = -h_1^{q\perp}\Big|_{SIDIS}$$

$$f_{1T}^{q\perp}\Big|_{DY} = -f_{1T}^{q\perp}\Big|_{SIDIS}$$

DY-SIDIS Bridge

COMPASS SIDIS 2010 proton Data Sivers in DY- Q^2 range: z > 0.2



COMPASS for DY

Most important features:

Solid state transversely polarised target (NH3) as well as nuclear targets

Hadron absorber

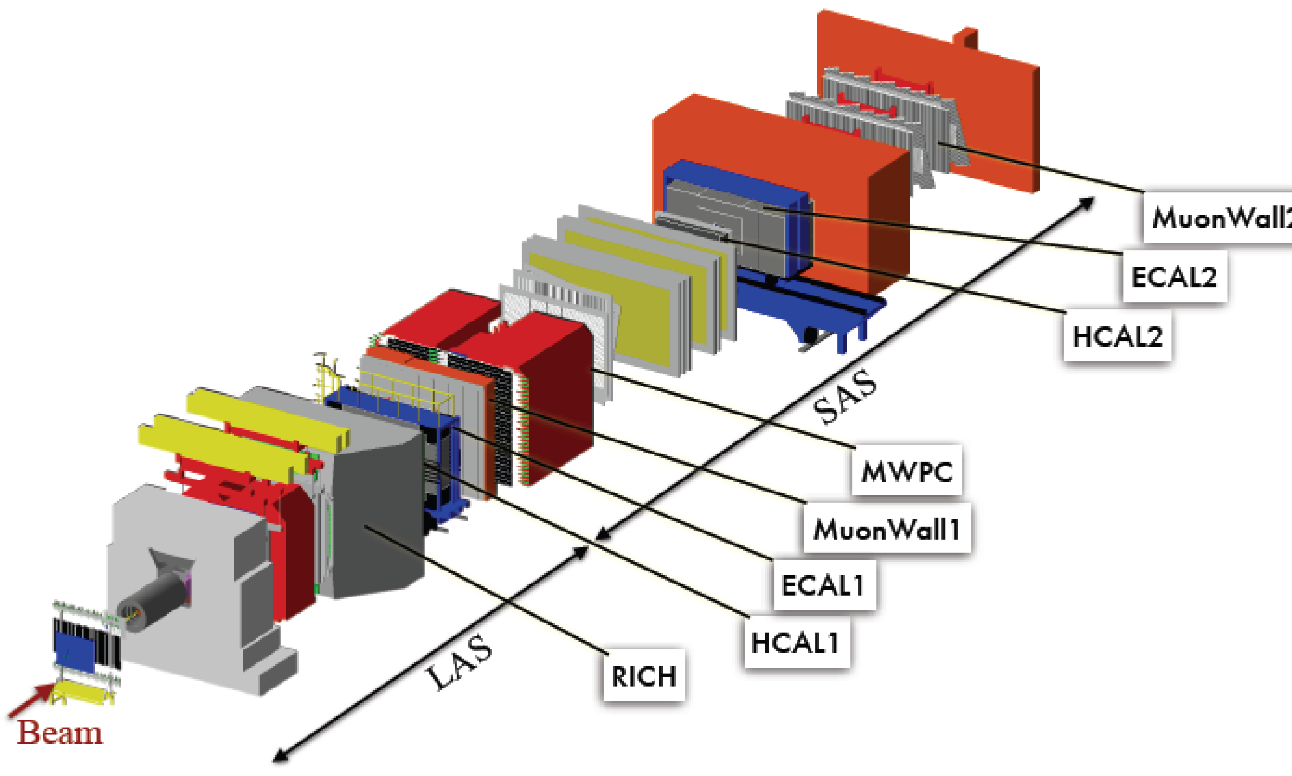
Vertex Detector

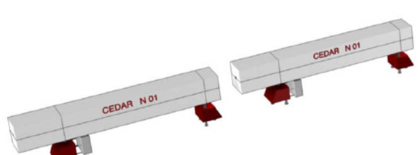
Powerful tracking system:
350 planes

Muon identification – Muon walls

A high momentum resolution for charged particles provided by a two-stage magnetic spectrometer

Large-acceptance trigger system for the detection of multi-muon events





CEDARs

DY Runs

2009: test beam for feasibility study
2014: pilot run
2015: main run
(transversely polarized NH3 target)

COMPASS for DY: hadron beam

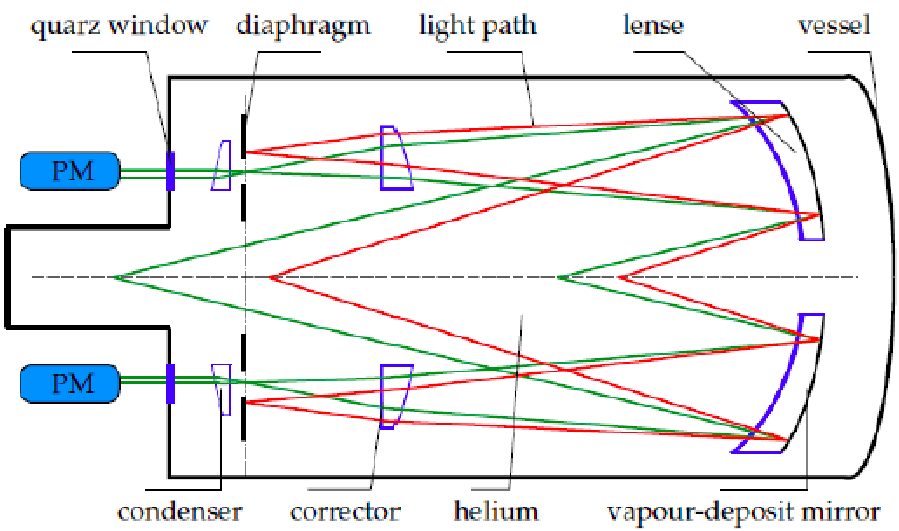
50-280 GeV/c hadron beam

Momentum (GeV/c)	Positive beams π^+	K^+	p	Negative beams π^-	K^-	$\bar{p}$
100	0.618	0.015	0.367	0.958	0.018	0.024
160	0.360	0.017	0.623	0.966	0.023	0.011
190	0.240	0.014	0.746	0.968	0.024	0.008
200	0.205	0.012	0.783	0.969	0.024	0.007

negative hadron beam (π/K/p 97/2/1%)
(from 400 GeV/c SPS protons onto conversion target)
Average Beam Intensity 2015: 10^8 particles / sec
Average Beam Intensity 2014: 7.3×10^7 particles / sec

190 GeV/c π^- beam

Two CEDARs designed to provide fast beam particle identification at high rates for particle momenta up to 300 GeV/c



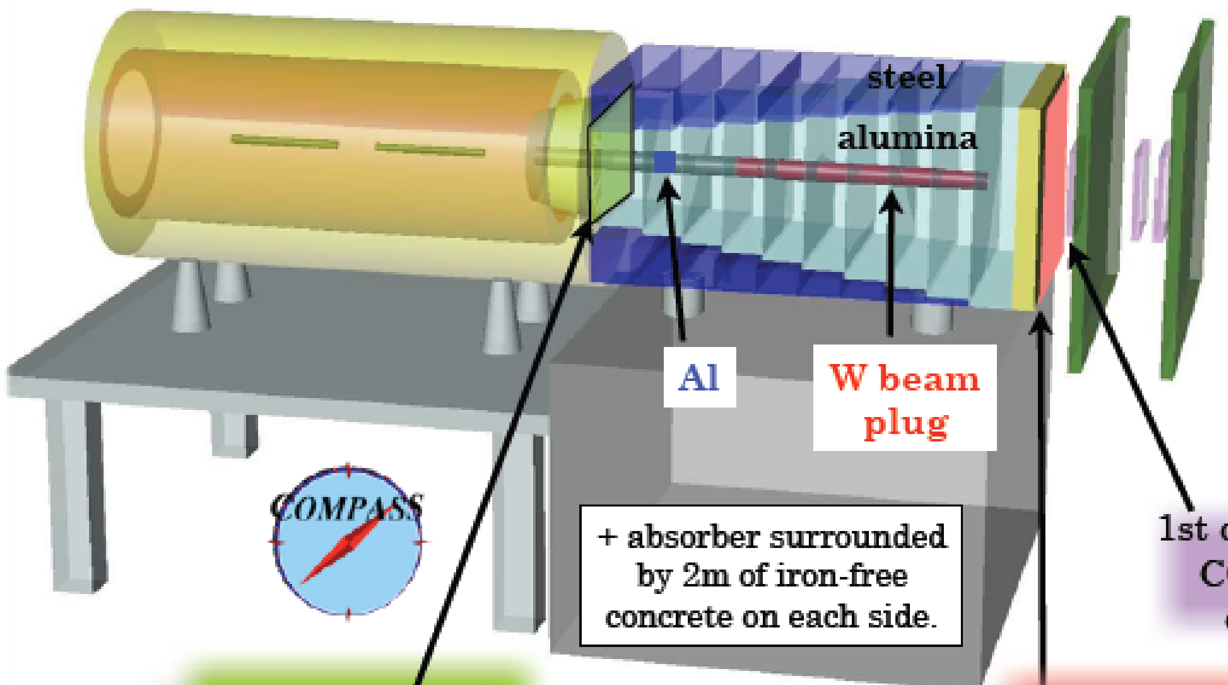
COMPASS for DY: target region

Transversely polarized NH_3 target & **Hadron absorber**

To minimize multiple scattering of muons and to maximize stopping power for hadrons.

1. Long. pol.: DNP & 2.5T solenoid
2. Trans. pol: 0.6T dipole

Ammonia beads immersed into liquid helium; dilution factor=0.22



1st downstream COMPASS detector

Vertex detector

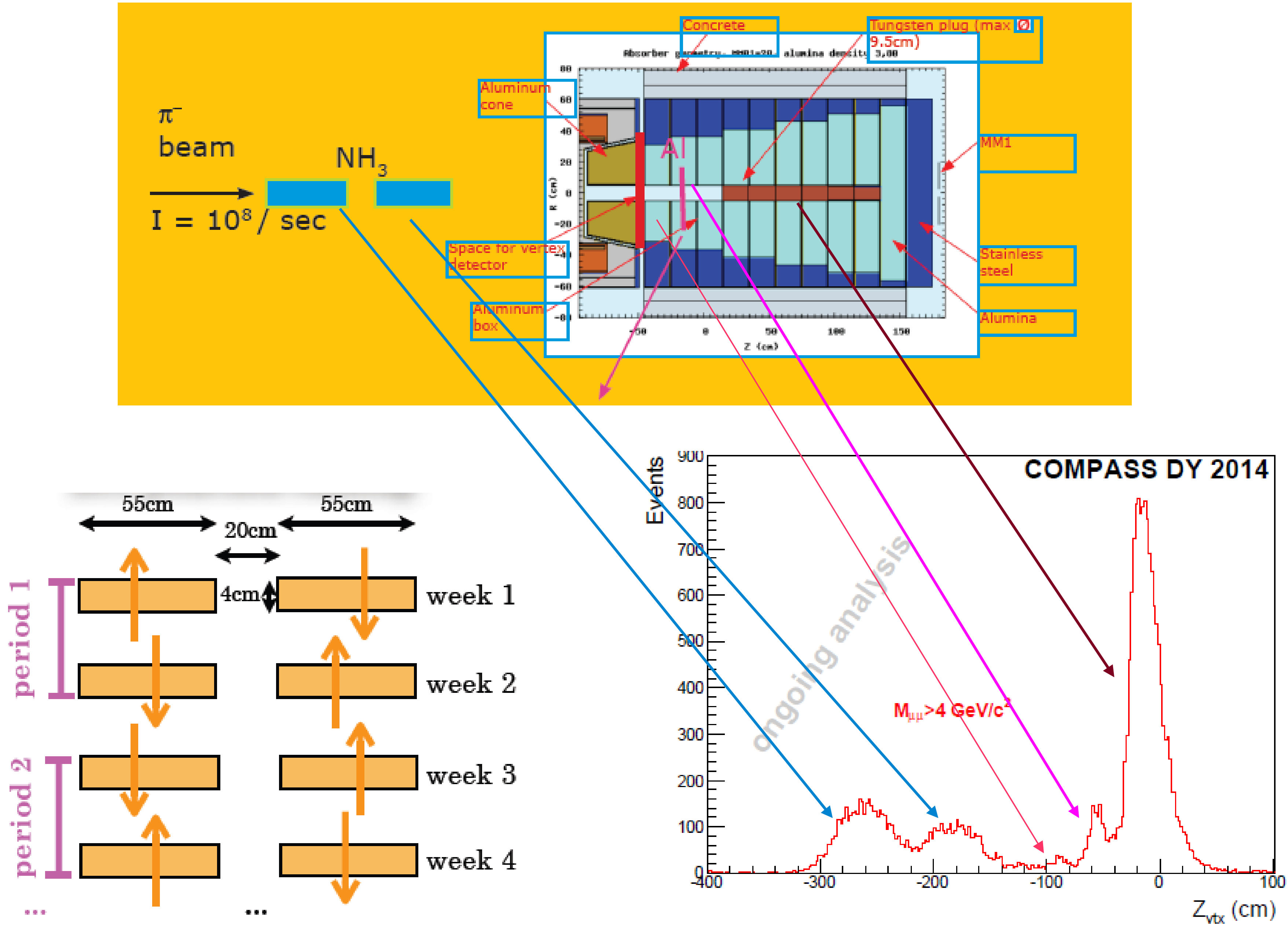
to improve resolution of

- vertex position.

^{6}Li absorber

to prevent flooding of very upstream detectors with charged particles from capture of spallation neutrons ($\Rightarrow \gamma \Rightarrow e^+e^-$)

COMPASS for DY: targets



Vertex position: $M\mu^+\mu^- > 4\,\mathrm{GeV}/c^2$

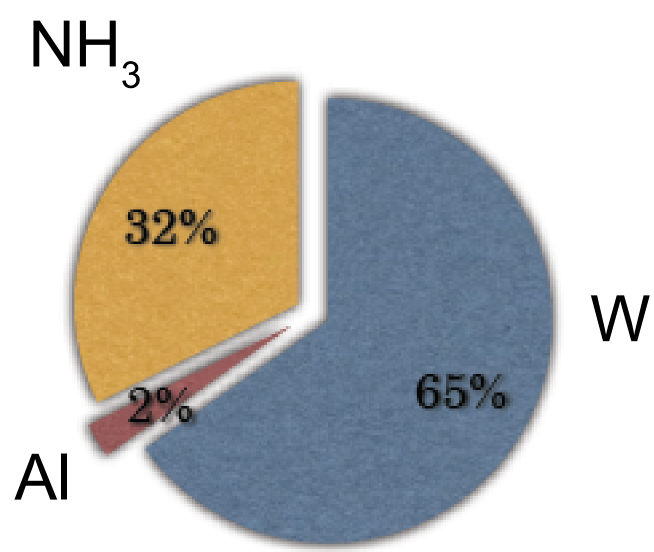
Existing COMPASS DY data

2014: unpolarized proton (mass 1),
unpolarized aluminum (mass 27),
unpolarized tungsten (mass ~183)

2015: transversely polarized proton,
unpolarized aluminum,
unpolarized tungsten

Scatter off different targets and record data at the same time

$M_{\mu^+\mu^-} > 4 GeV/c^2$ →



2014 DY data (preliminary)

6 October – 15 December 2014

~ 3 weeks of stable data taking

> 80 million opposite sign muon pairs were analysed which associate to a primary vertex with beam track

Average beam intensity: 7.3×10^{7} particles / sec
(up to nominal 10^{8}/s)

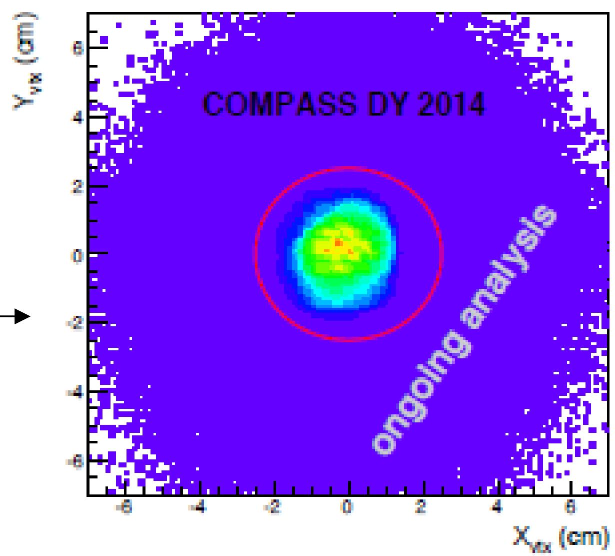
No target polarization

Statistics:

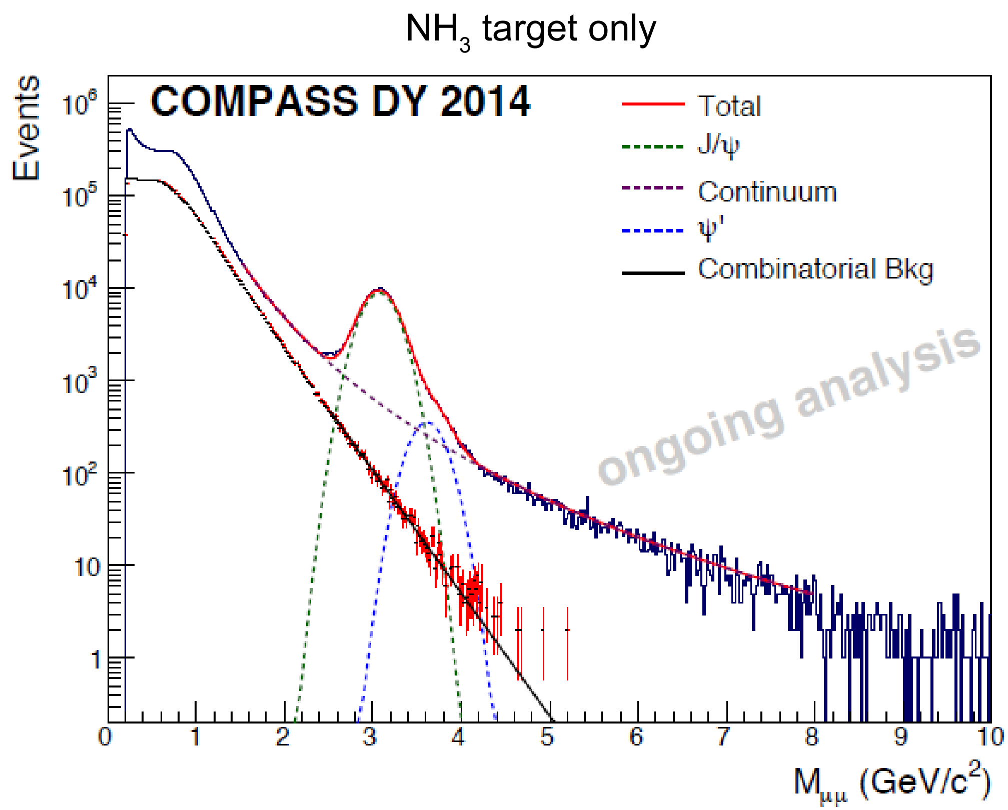
DY events ($M_{\mu^{+}\mu^{-}} > 4\,\mathrm{GeV}/c^{2}$): ~ 7k
J/ψ events: ~ 200k

Reconstructed primary vertices with 2 opposite charge muons and a beam, originated in the NH3 target region:

transverse centering with the target cells



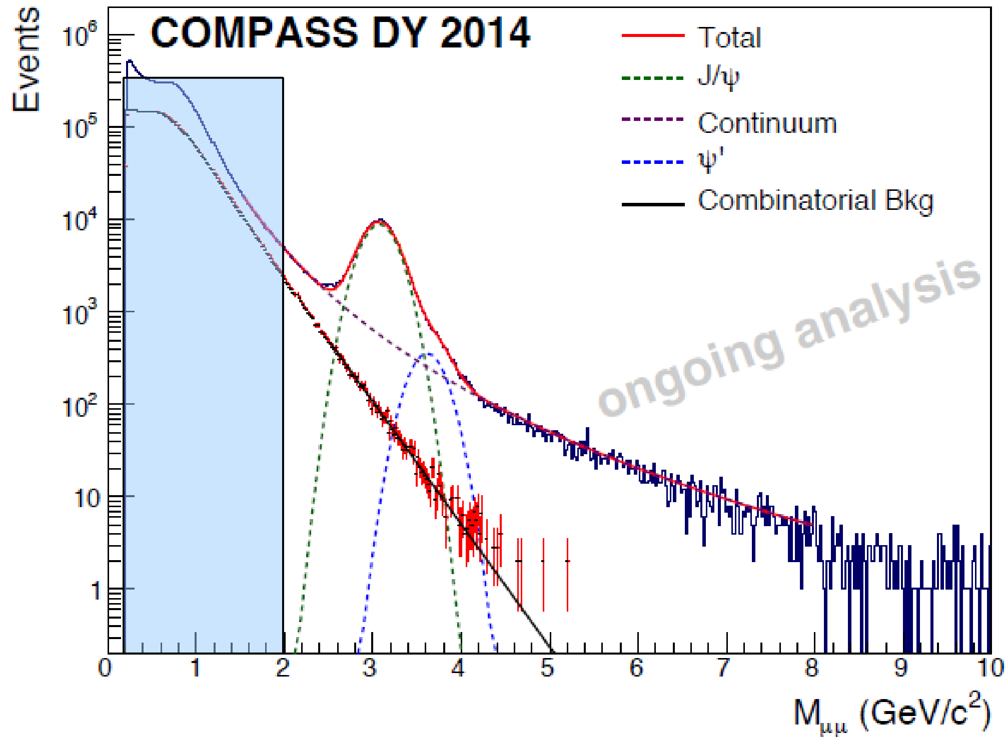
2014 DY: dimuon invariant mass spectrum



Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q^2 [GeV^2]	1-4	4-6.25	6.25-16		16-81
Region	"DY low mass"	"DY medium mass"	"DY J/ψ"	"J/ψ"	"DY high mass"
clean?	✘✘ >50% bg	✘	✘ ✘	✘✘	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✘
large Sivers?	✘	✘	✘	-	✔

2014 DY: dimuon invariant mass spectrum

NH$_3$ target only



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high DY x-section?	✔ ✔	✔	✔	-	✘
large Sivers?	✘	✘	✘	-	✔

2014 DY: dimuon invariant mass spectrum

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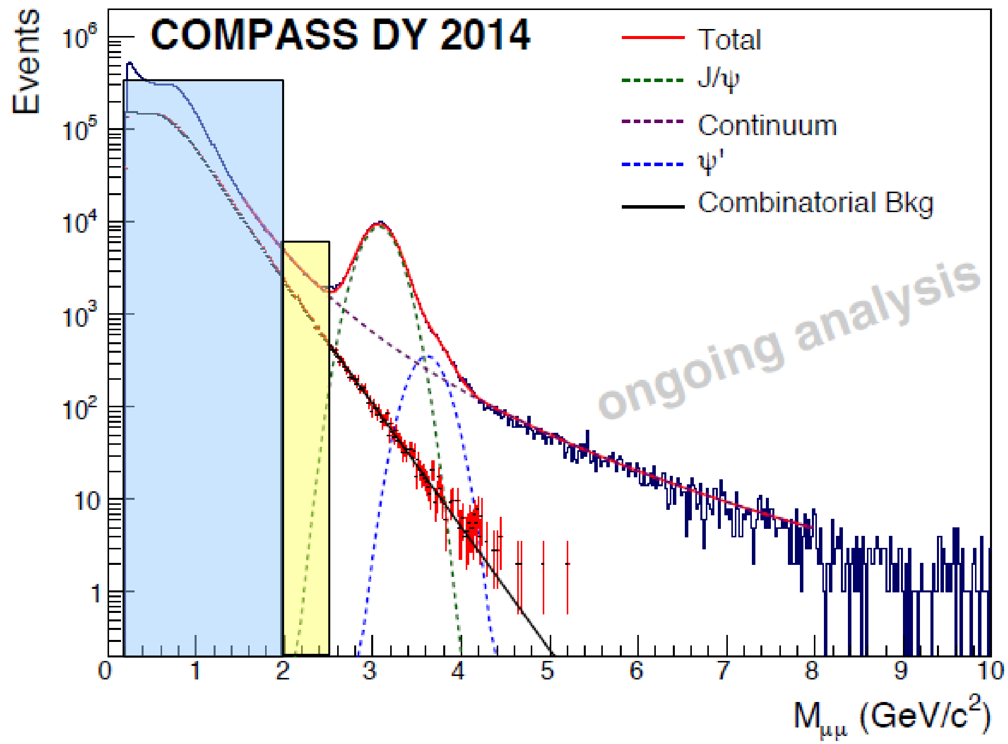

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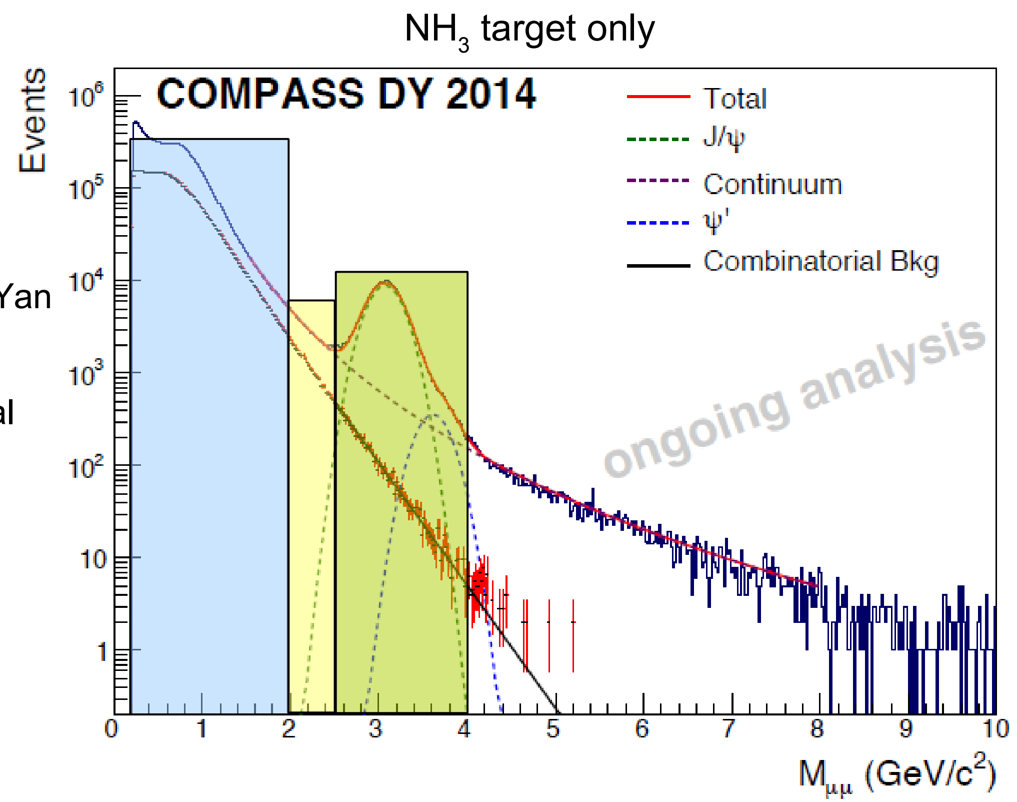
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔

2014 DY: dimuon invariant mass spectrum

Continuum:
sum of different physics contributions, namely Drell–Yan and a small amount of semi-leptonic open charm decays and the combinatorial background

x



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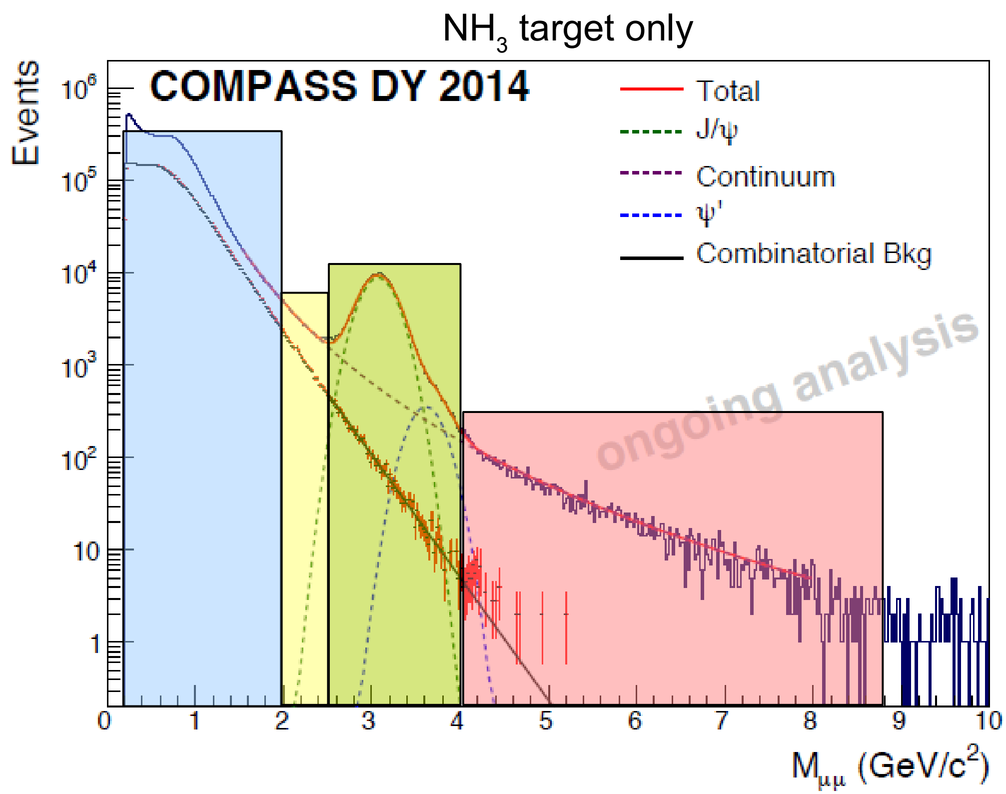
Region	"DY low mass"	"DY medium mass"	"DY J/ψ"	"J/ψ"	"DY high mass"
clean?	✗✗ >50% bg	✗	✗✗	✗✗	✔✔ <10% bg
high DY x-section?	✔✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔

2014 DY: dimuon invariant mass spectrum

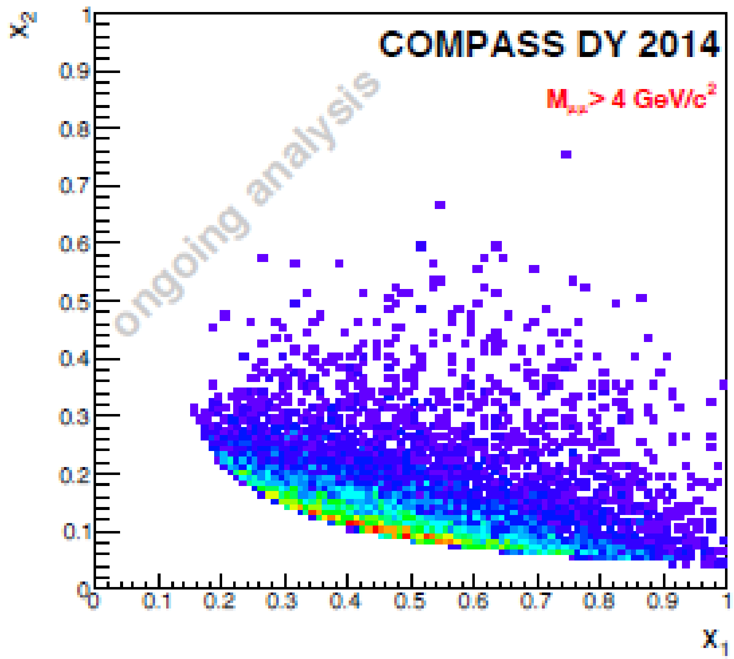


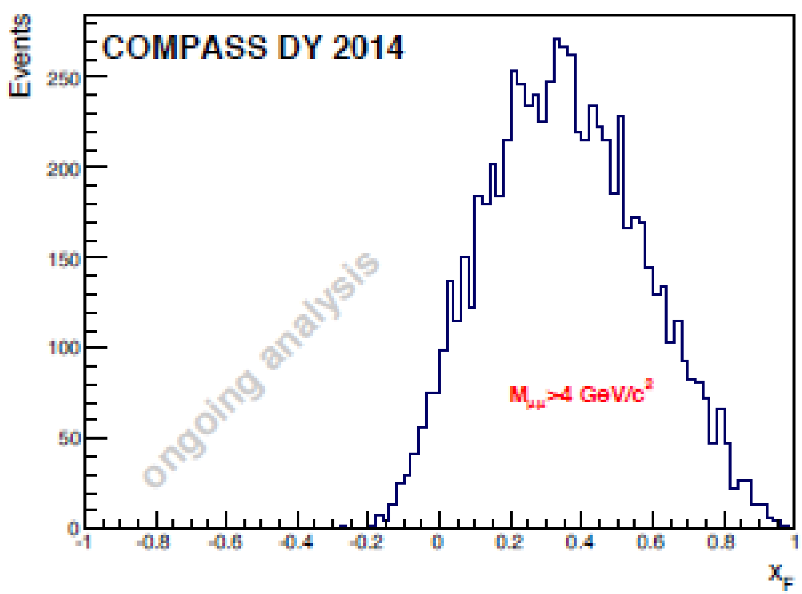
combinatorial of uncorrelated opposite-sign muon pairs obtained from the like-sign samples, after symmetrization on charges acceptance:

negligible for M > 4.5 GeV/c^2

Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q^2 [GeV^2]	1-4	4-6.25	6.25-16		16-81
Region	"DY low mass"	"DY medium mass"	"DY J/ψ"	"J/ψ"	"DY high mass"
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔

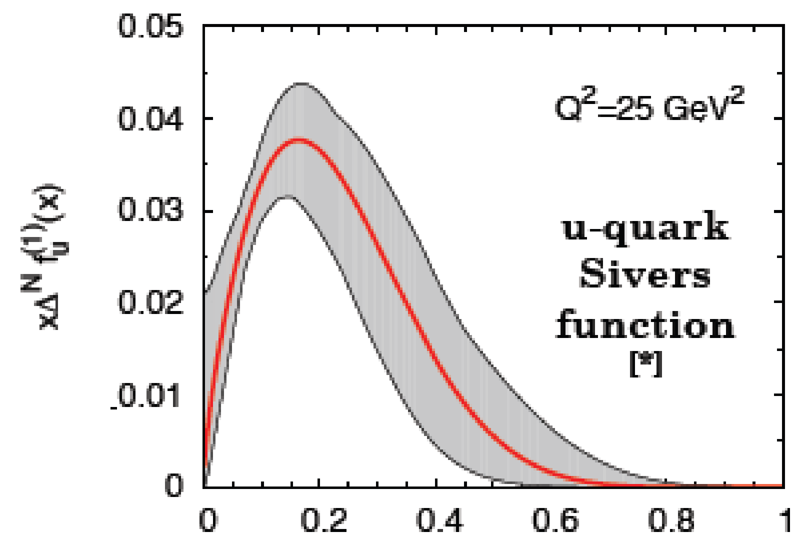
2014 DY: phase space coverage





$$= x_\pi - x_p$$

phase-space accessed is the proton and pion valence quarks one, where Sivers PDF is expected to be of large magnitude



[*] calculated from: M. Anselmino et al., Eur. Phys. J. A39 (2009) 89.

2015 DY data

4.5 months of physics data-taking

~ 116 days (excluded MD)

Transverse target polarization ~80%

Beam intensity ~10^8/second

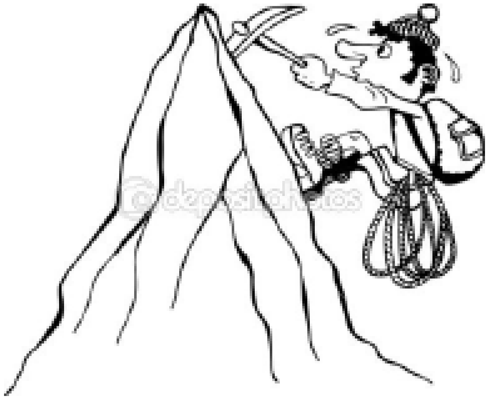
~ 740 TB of recorded data

9 periods

Estimated Statistics:

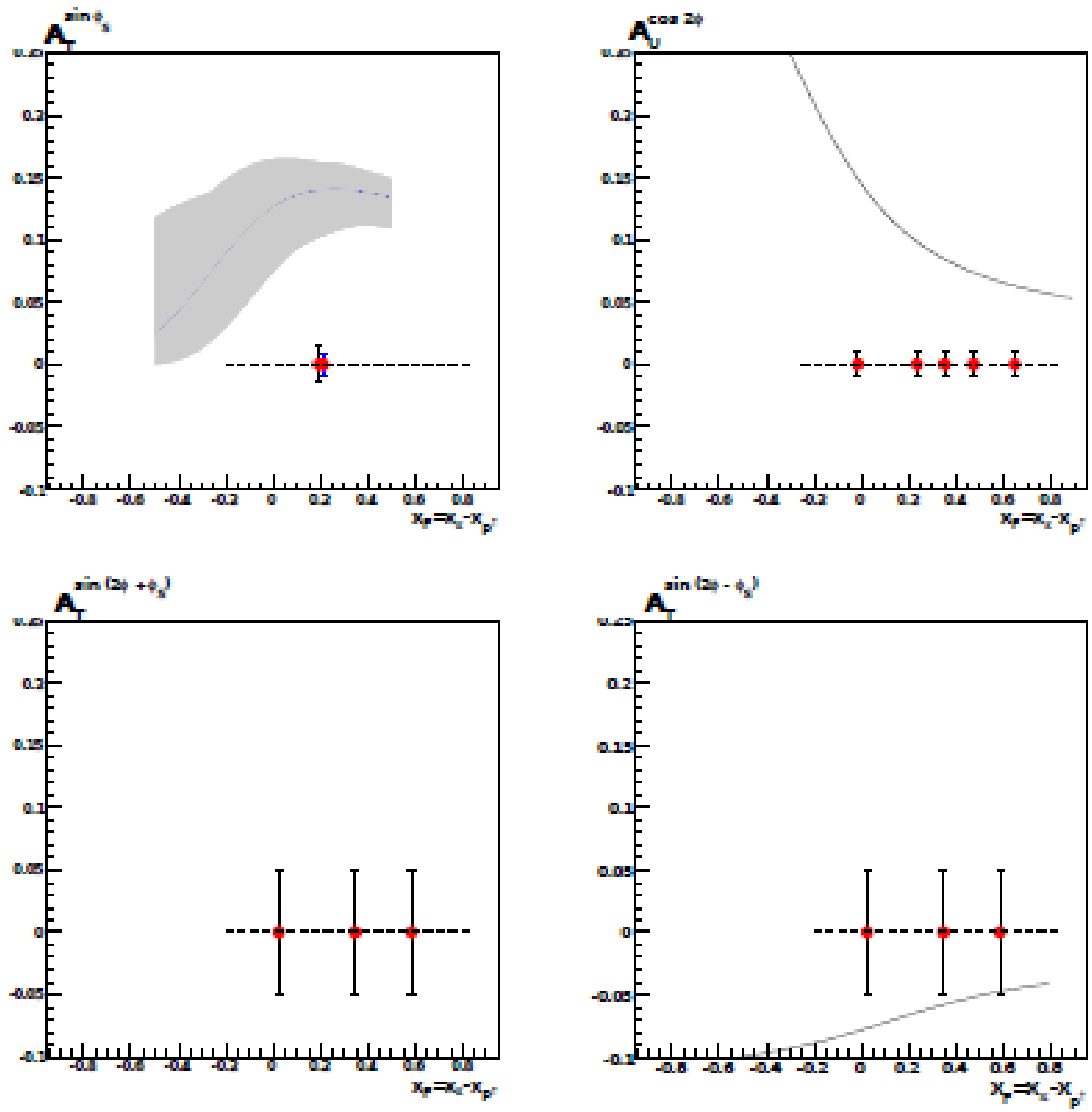
DY events ($M_{\mu^+\mu^-} > 4 GeV/c^2$): ~ 80.000
J/ψ events: ~ 2.000.000

Proposal



COMPASS DY projections (NH_3)

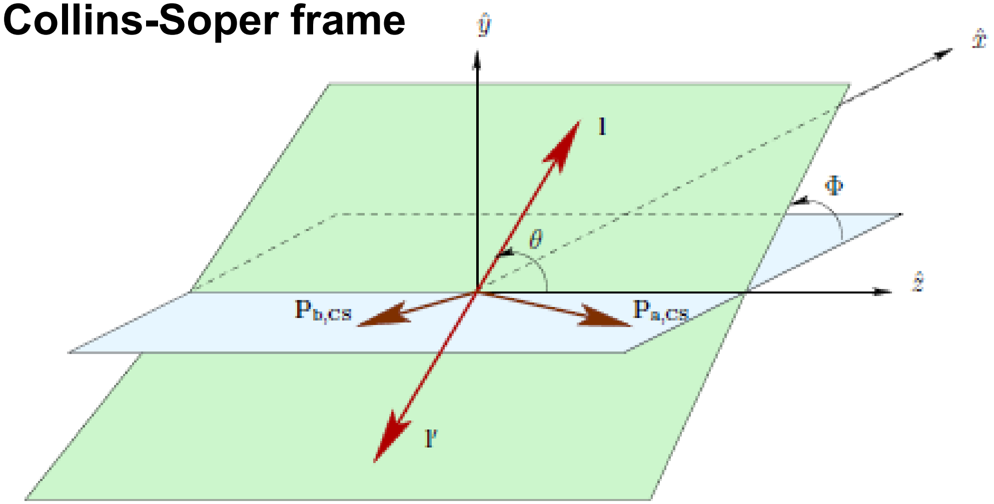
Projections: from $M_{\mu^+\mu^-} > 4 GeV/c^2$ 240 days of data taking



Analysis ongoing on first produced 2015 DY data

What about unpolarized data?

Collins-Soper frame



At NLO:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \left\{(1 + \mathrm{A}_U^1 cos^2\theta + \sin(2\theta)\ \mathrm{A}_U^{cos\phi} cos\phi + \sin^2\theta\ \mathrm{A}_U^{cos2\phi} cos(2\phi)\ )\right.$$

$$\lambda = A_U^1;\ \mu = A_U^{\cos\phi};\ \nu = 2A_U^{\cos 2\phi}$$

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q} \longrightarrow \underset{\text{pion}}{(\mathrm{BM})_\pi} \otimes \underset{\text{proton}}{(\mathrm{BM})_\mathrm{p}}$$

Lam-Tung relation $1 - \lambda = 2\nu$

Unpolarized asymmetries: acceptance corrections needed Acc(θ_{CS}; ϕ_{CS})

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

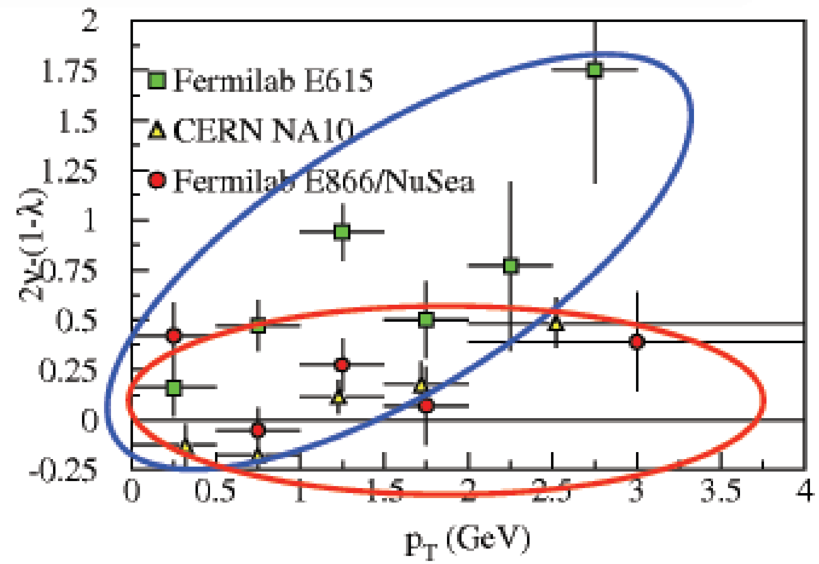
- Pion-induced Drell-Yan (NA10, E615)
  - violates LT-relation
    (independent of nucleus - no nuclear effect)
  - large cos(2Φ) dependence
  - strong with p_T

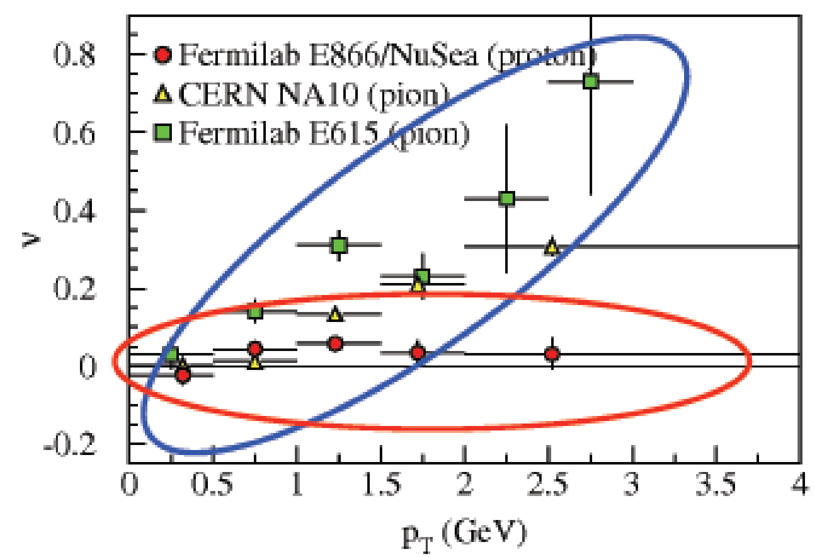
☛ **One candidate to explain LT violation: BM function**

- Pionic DY probes BM (valence), target=proton
  Protonic DY probes BM (sea), target=proton

  BM (sea) ≪ BM (valence)

☛ study of spin-orbit correlations





Lam -Tung in proton and pion induced DY

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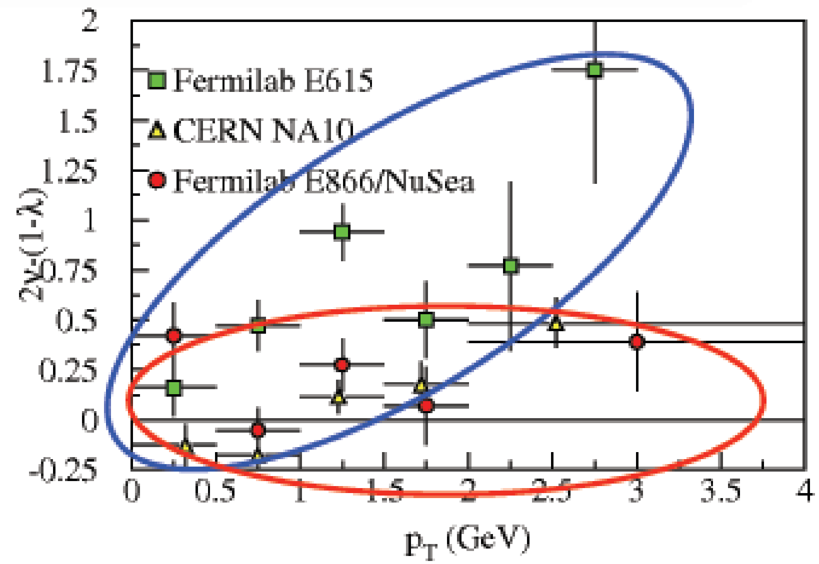
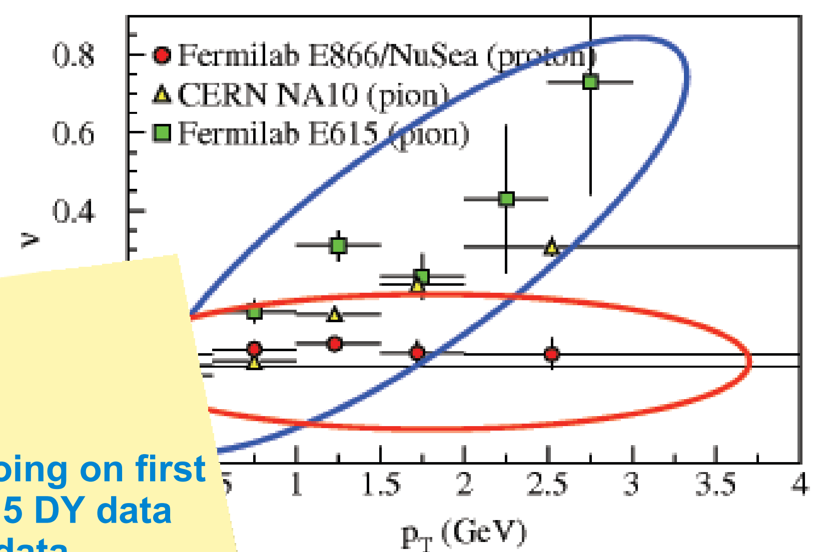
☛ study of spin-orbit correlations





Analysis ongoing on first produced 2015 DY data and 2014 DY data

What about the near and the far future?

2018
second year (un-)polarized Drell-Yan measurements with NH3 target

TMD opportunities with hadron beams beyond 2020

pion beam and the transversely polarised deuteron (^{6}LiD) target → perform complete flavour separated TMDs analysis

With Radio Frequency separated beam
DY on liquid hydrogen and liquid deuteron targets:

Improve significantly our knowledge of pion and kaon PDFs

nucleon strange quark structure

detailed study of the fundamental Lam-Tung relation violation

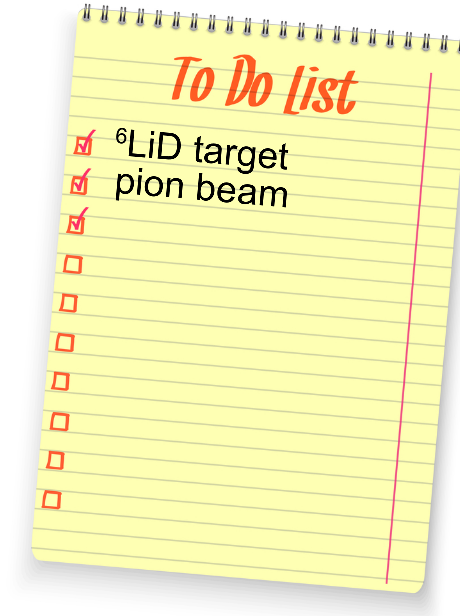
Drell Yan extraction of proton transversity

What about the near and the far future?

WISH LIST

- Polarized ^{6}LiD target
- Very Long LH2/LD2 target
- Many nuclei targets
- High-intensity pion beam
- High-intensity kaon beam
- High-intensity antiproton beam

Flavor Separation



Measure Sivers Asymmetry at Higher Q^2 in Drell-Yan
with ^{6}LiD target

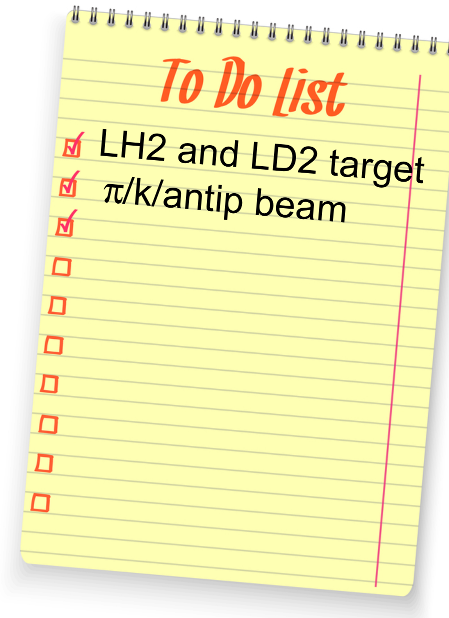
Combine with COMPASS NH_3 measurement to determine flavor dependent Sivers

Additional data at higher Q^2 for testing evolution

with pion-BM from DY on proton target:
extract proton transversity using NH_3 and ^{6}LiD runs

Provides important cross check for Collins based extraction of proton transversity (magnitude of flavor contributions)

Radio-Frequency separated beam?



Possibility of Radio-Frequency separated beam
pion, kaon and antiproton
increase by a factor of two the maximum kaon/antiproton flux actually achievable

kaon and anti-protons flux possibly reaching 10^7p/s

possibility to measure proton TMDs and transversity function in completely model-independent way and to collect unique kaon-induced DY data in order to study with high accuracy the kaon PDFs

with p-BM from SIDIS solve for pion and kaon beam BM
Use anti—protons and proton target to get p-BM and compare!

Combination of unpolarized pion and kaon-PDF and pion- and kaon-BM will provide greatly **increased knowledge of meson structure**
Eg. comparison of Meson and Baryon BM and first comparison of BM for different mass mesons

beam target

$$\boxed{(\mathrm{BM}) \otimes (\mathrm{BM})}$$

$$(f_1) \otimes (\mathrm{Sivers})$$

$$(\mathrm{BM}) \otimes (\mathrm{Pretzelosity})$$

$$(\mathrm{BM}) \otimes (\mathrm{Transversity})$$

What about the future?

COMPASS
BEYOND2020
Workshop

21 – 22 March 2016
CERN

https://indico.cern.ch/event/502879/

Gluon TMDs ?

http://www.epj-conferences.org/articles/epjconf/pdf/2015/04/epjconf_tv2014_02006.pdf

Gluon contribution to the Sivers effect. COMPASS results on deuteron target.
Adam Szabelski
on behalf of the COMPASS Collaboration

DY Run 2015 just ended...

Looking forward to present first ever polarized DY data...analysis is ongoing

Stay tuned!

**End of Run...
Party!**

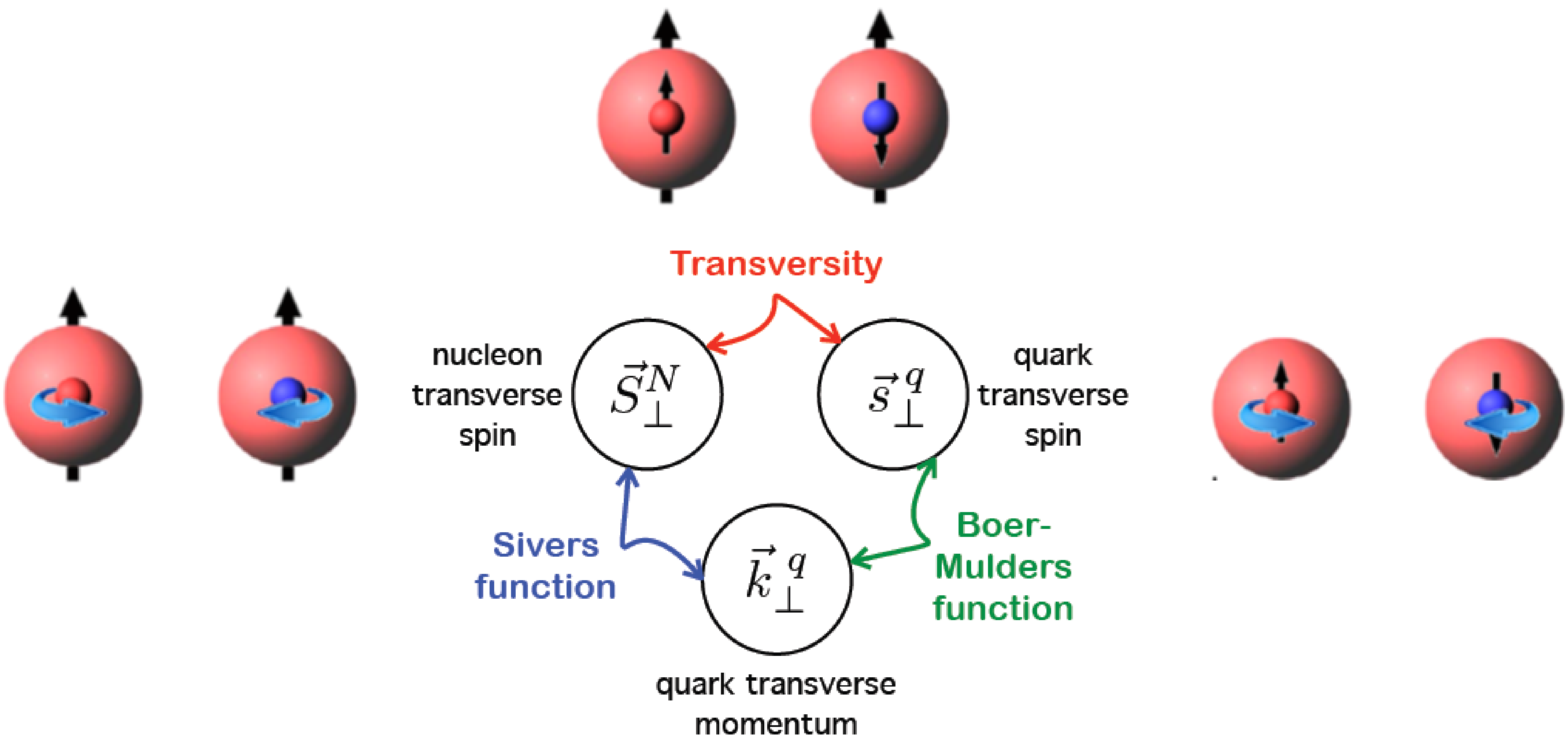
End of Run 2015...

Spare Slides

Michela Chiosso, University of Torino and INFN

TMDs in DY processes

Test fundamental predictions by measuring TMDs in Drell Yan.



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 specific
Quark-flavor dependence	Yes	No	No
Hadron dependence	Yes	No	Yes
Large P_T limit	0	Nonzero	0
Violation for πp	Yes (valence quarks involved)	Yes	Yes
Violation for Kp	Yes (valence quarks involved)	Yes	Yes/No
Violation for $\bar{p}p$	Yes (valence quarks involved)	Yes	No
Violation for pp	No (sea quarks involved)	Yes	No
References	PRD 60, 014012 (1999)	Z. Phy. C 60,697 (1993)	PLB 726, 262 (2013)

Measurements with different beams $\pi, p, K, \bar{p}$ over wide kinematical ranges would help differentiating the origin of Lam-Tung violation.

TMDs in DY processes

Brandenburg et al. (PRL 73, 939 (1994)): Pion/Kaon/Antiproton Distribution Amplitude

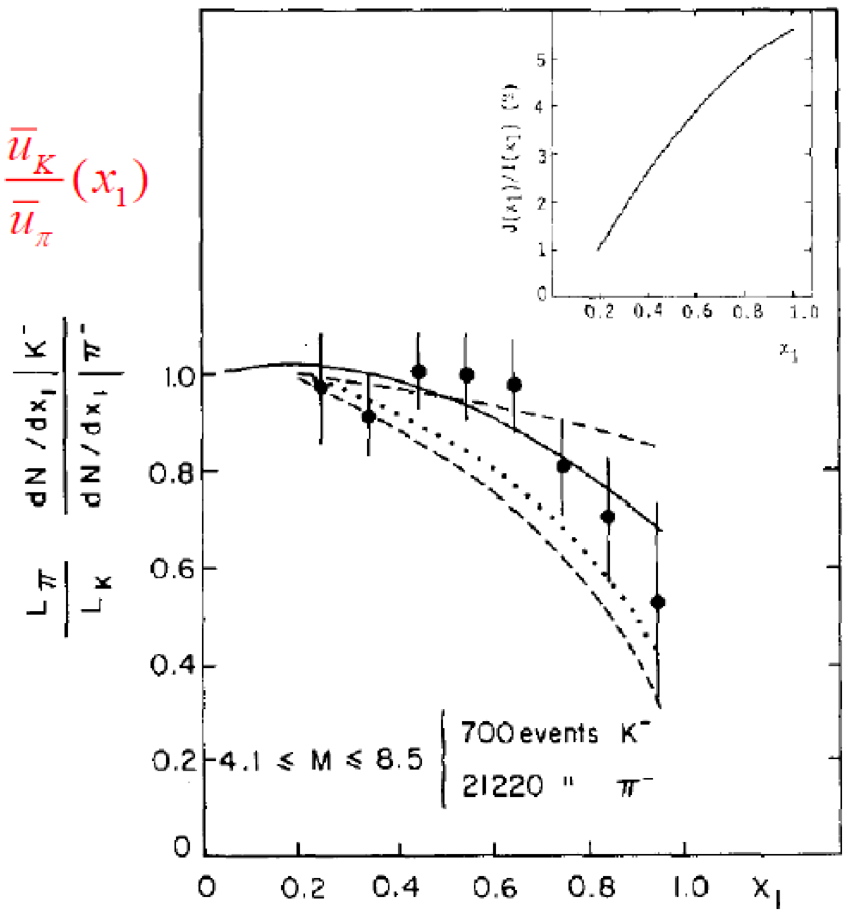
The coefficient functions λ, μ, and ν are large $x > 0.5$ are very sensitive to the shape of the projectile's distribution amplitude $\phi(z, \tilde{Q}^2)$, the basic hadron wave function which describes the distribution of light-cone momentum fractions in the lowest-particle number valence Fock state. Measurements of meson form factors [12] and other exclusive and semiexclusive processes [16] at large momentum transfer can only provide global constraints on the shape of $\phi(z, \tilde{Q}^2)$; in contrast, the angular dependence of the lepton pair distributions can be used to provide local measurements of the shapes of these hadron wave functions. Detailed measurements of the angular distribution of leptons as a function of both x and Q_T for the reactions $Hp \to l + l^- X$ for the whole range of fixed target beams $H = \pi, K, \bar{p}, p$, and n will open up a new window on the structure of hadrons at the amplitude level.

Kaon and antiproton beams

Kaon Partonic Structure

NA3 Collaboration, PLB 93, 354 (1980)

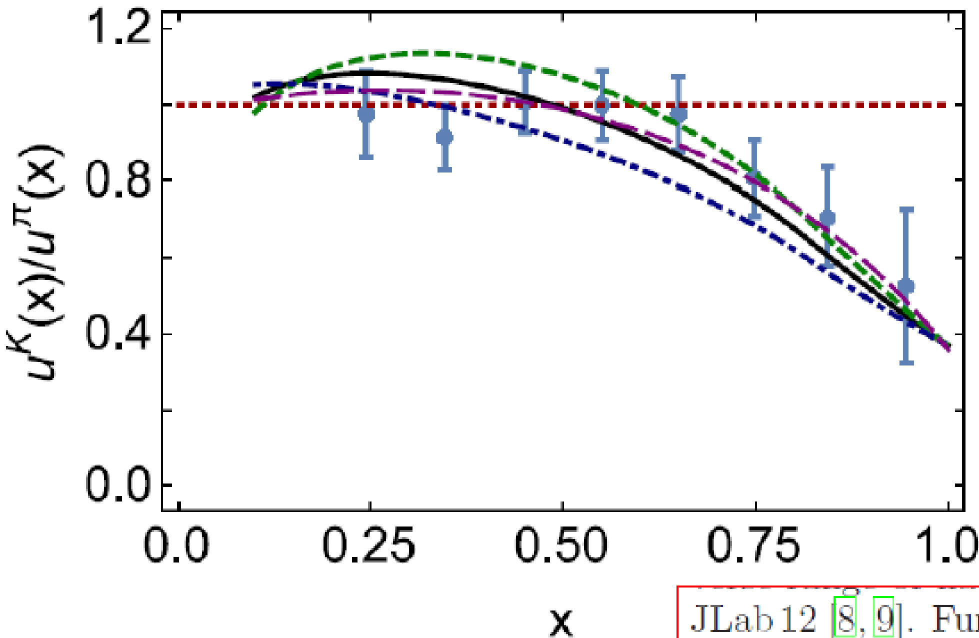
$$\frac{d\sigma^{K-}/dx_1}{d\sigma^{\pi-}/dx_1} = \frac{\bar{u}_K}{\bar{u}_\pi}(x_1)$$



TMDs in DY processes

Valence-quark distribution functions in the kaon and pion

Chen, et al., arXiv:1602.01502



JLab 12 [8, 9]. Furthermore, new mesonic Drell-Yan measurements at modern facilities could yield valuable information on π and K PDFs [10, 11], as could two-jet experiments at the large hadron collider [12]; and, looking further ahead, an electron ion collider would be capable of providing access to pion and kaon structure functions through measurements of forward nucleon structure functions [13, 14].

Kaon-induced Drell-Yan Process:

Avoiding Fragmentation Functions Uncertainty

$$K^{+}p(x_f) = u^{K}(x_1)\bar{u}^{p}(x_2) + \bar{s}^{K}(x_1)s^{p}(x_2)$$

$$K^{-}p(x_f) = \bar{u}^{K}(x_1)u^{p}(x_2) + s^{K}(x_1)\bar{s}^{p}(x_2)$$

Kaon-induced Drell-Yan cross sections will determine

- nucleon strange quark structure
- kaon PDFs

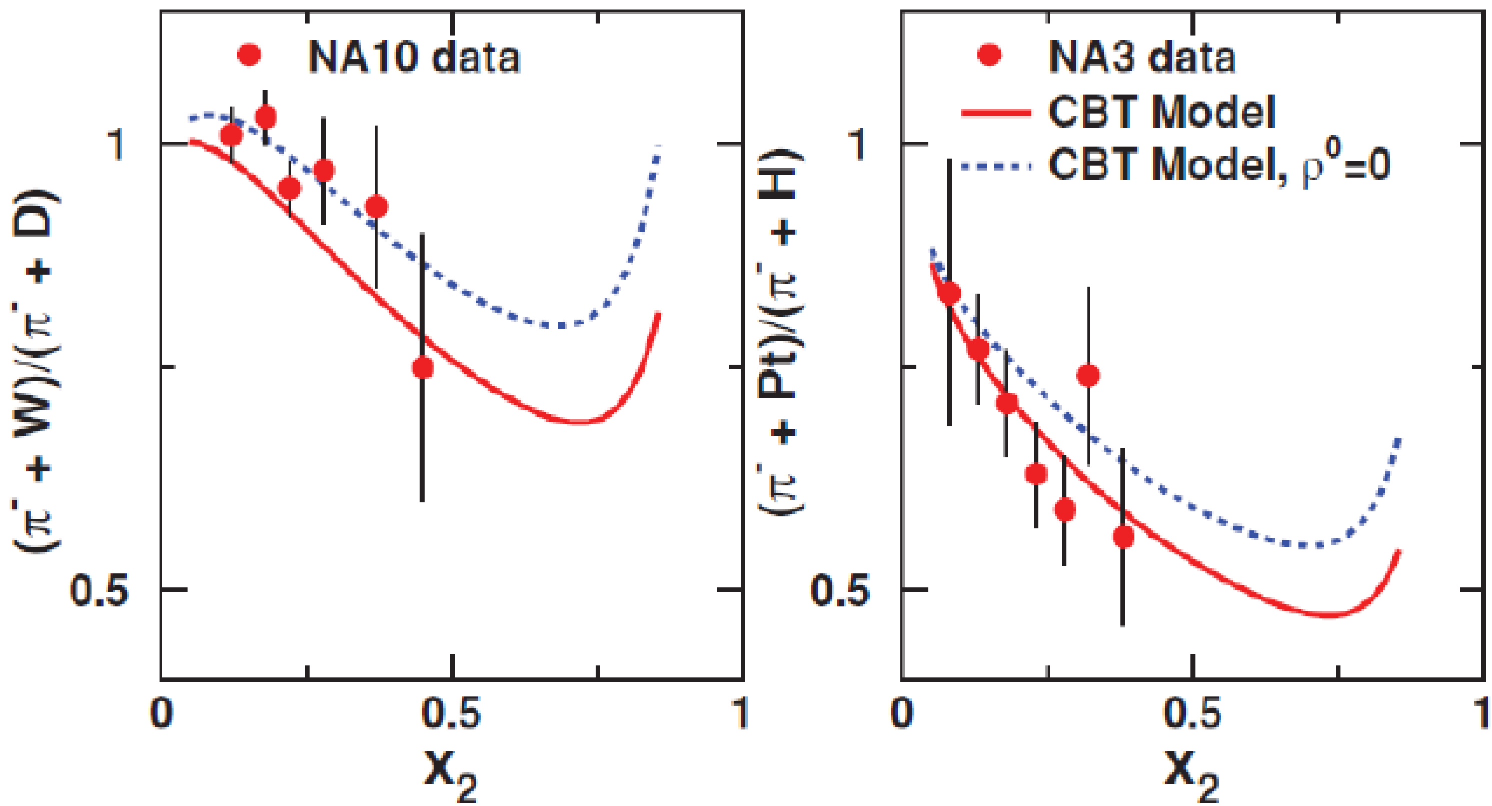
Kaon beam and LH_2 target

EMC effect

Dutta et al. (PRC 83, 04220, 2011):

Pion-induced Drell-Yan and the flavor-dependent EMC effect

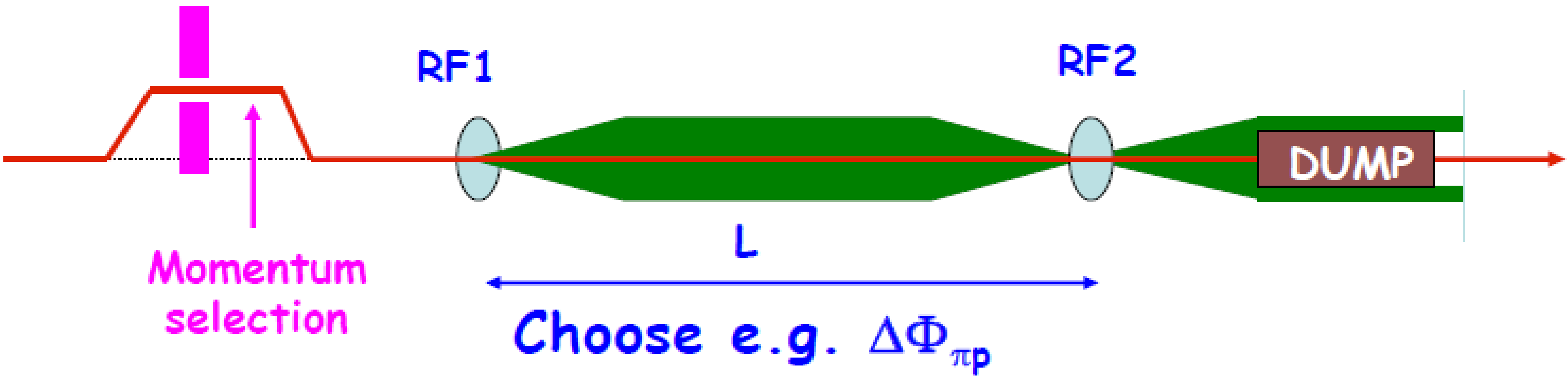
$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$



WHAT ABOUT A RF SEPARATED $\bar{p}$ BEAM ???

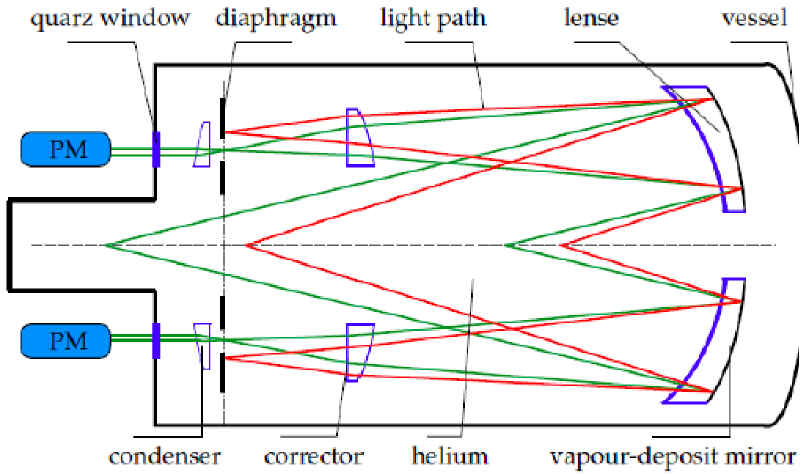
First and very preliminary thoughts, guided by
- recent studies for P326
- CKM studies by J.Doornbos/TRIUMF, e.g.
  http://trshare.triumf.ca/~trjd/rfbeam.ps.gz

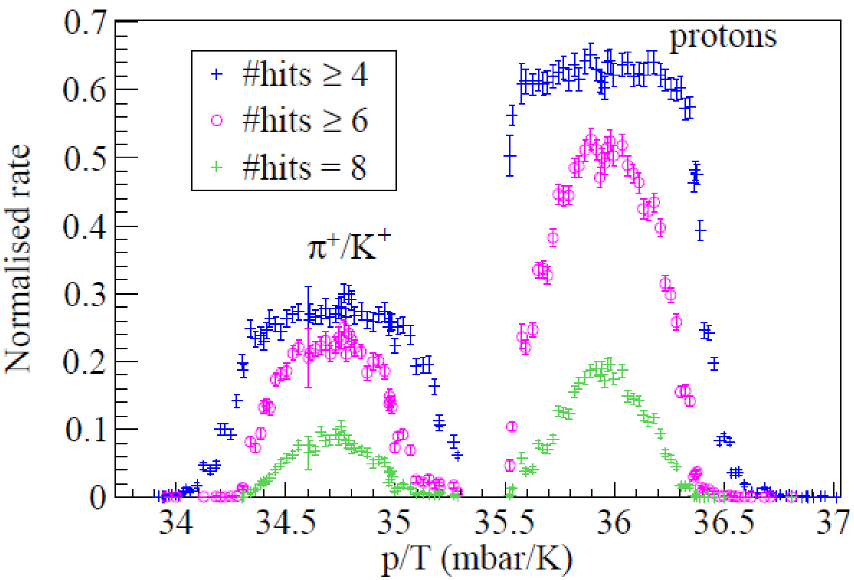
E.g. a system with two cavities:



$$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1}) \text{ with } \beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$$

Proton tagging with CEDARs





Nominal Beam intensity: of **5 x 10^6 s^{-1} (2009)**
If one assume 70% efficiency of the CEDARs proton tagging
we can expect up to ≈ 2.5 x 10^6 p s^{-1}

M2 beam line secondary beams

Particle production at 0 mrad