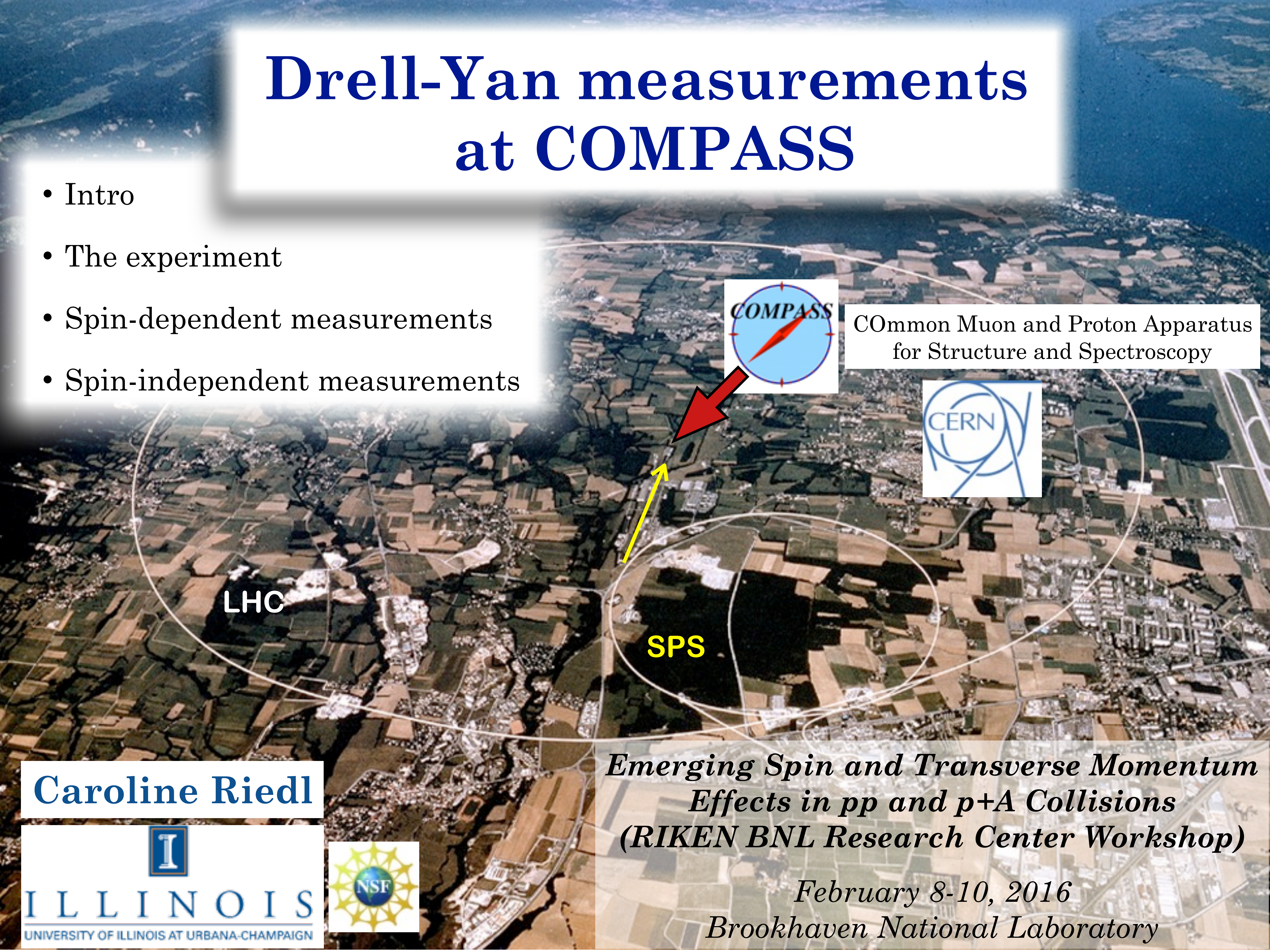
Drell-Yan measurements at COMPASS

- Intro
- The experiment
- Spin-dependent measurements
- Spin-independent measurements



COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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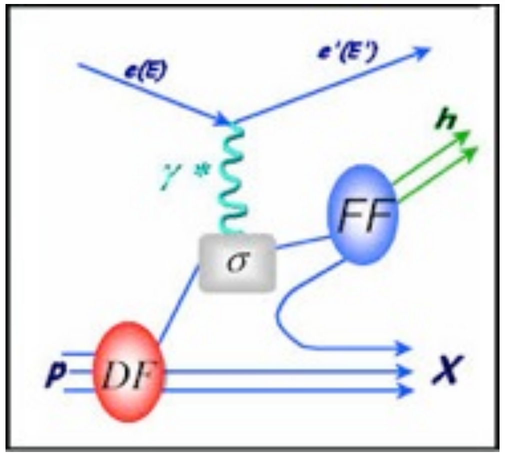
Emerging Spin and Transverse Momentum Effects in pp and p+A Collisions (RIKEN BNL Research Center Workshop)

February 8-10, 2016
Brookhaven National Laboratory

Probing the partonic structure of hadrons

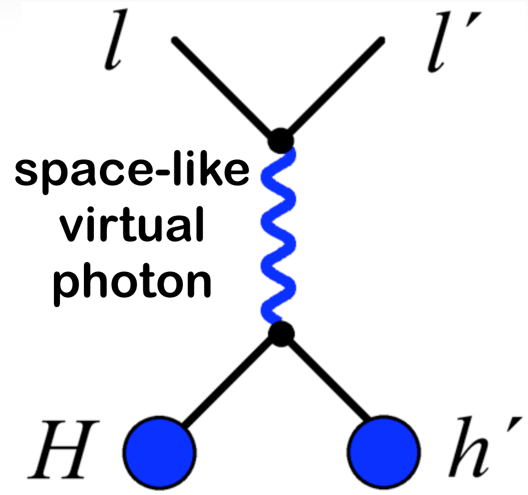


Probe universality

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

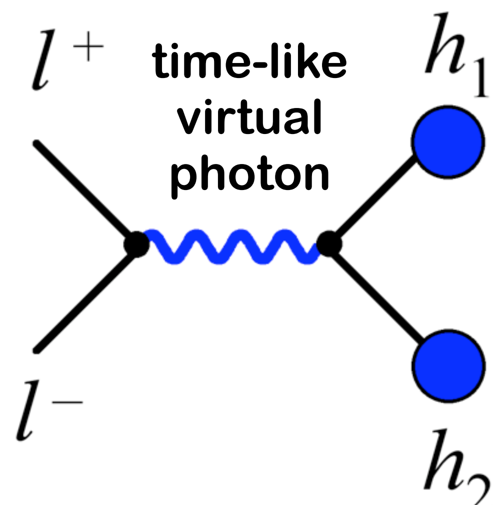
(SI)DIS

$DF \otimes FF$



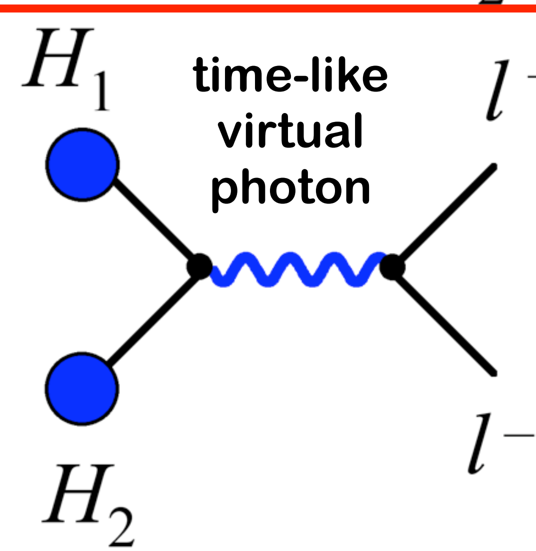
electron-positron annihilation

$FF \otimes FF$



Drell-Yan (DY)

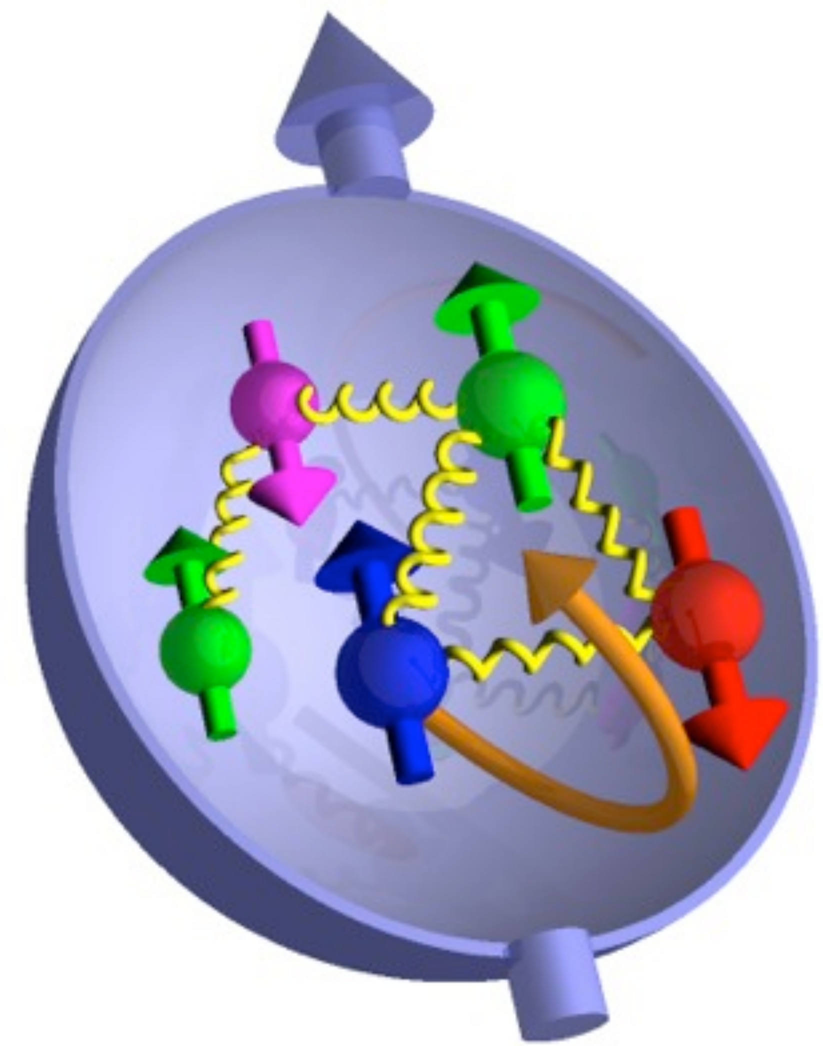
$DF \otimes DF$



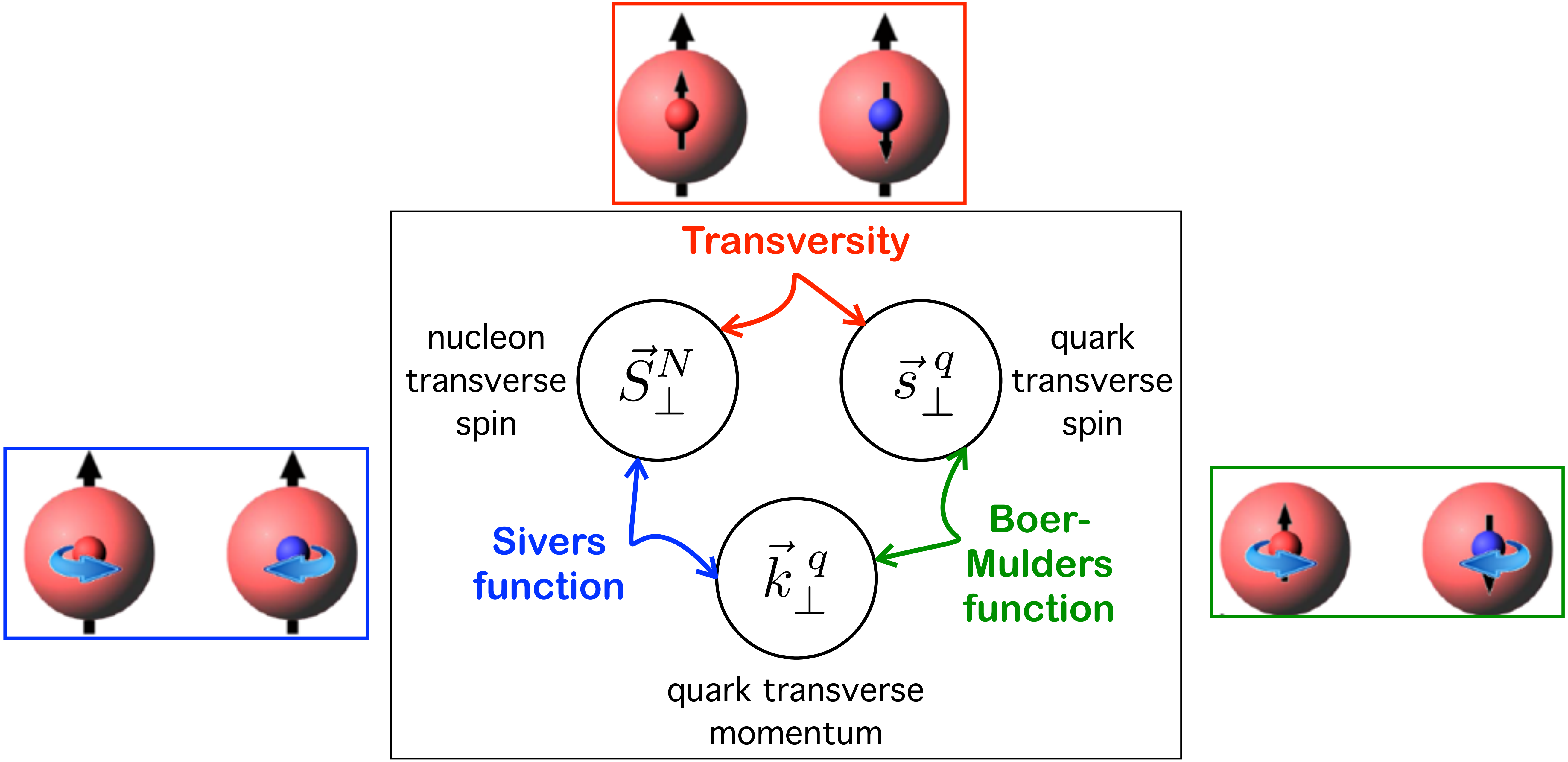
time

TMDs: Transverse-Momentum dependent PDFs

GPDs: Generalized Parton Distributions

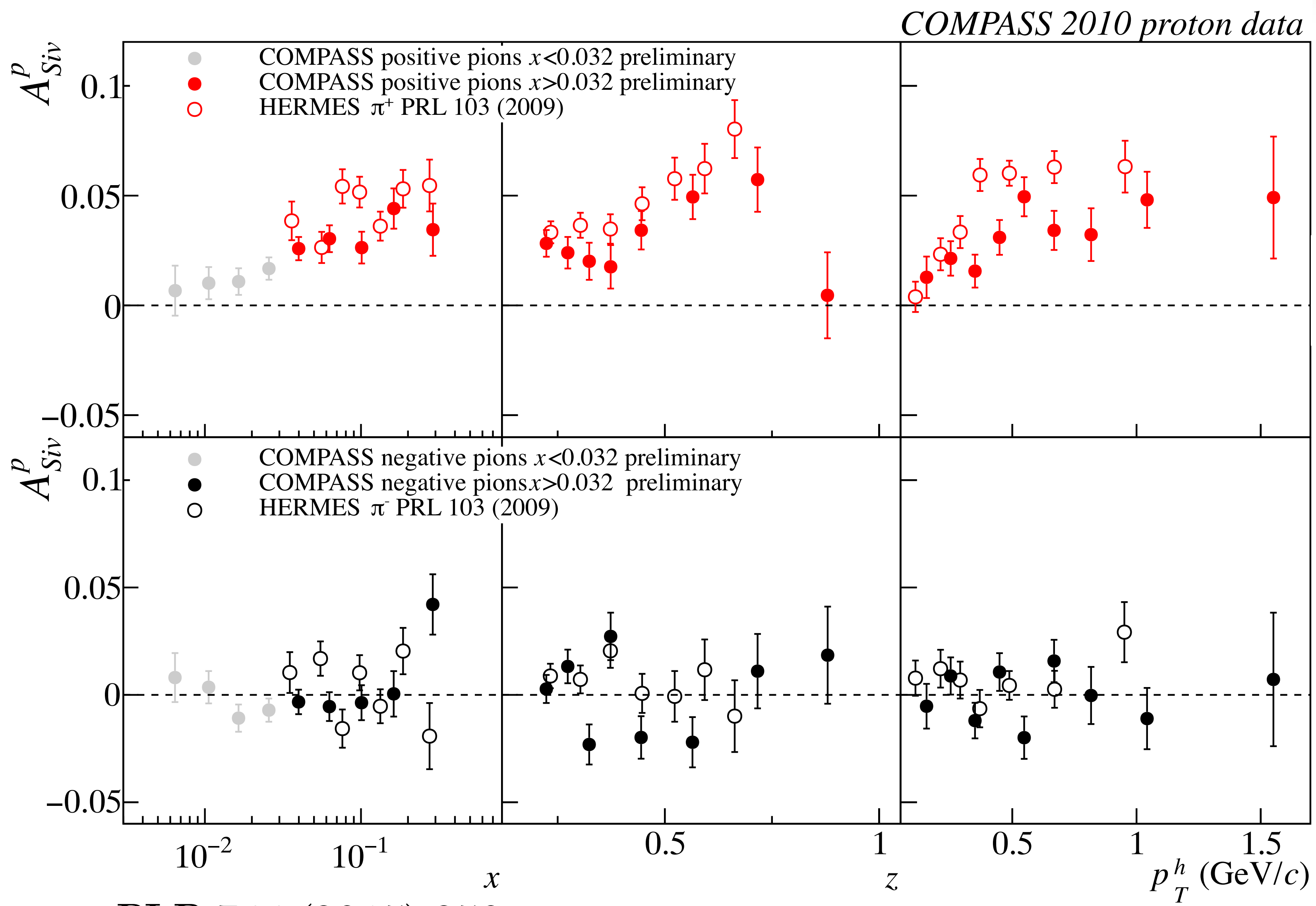


TMDs in Drell-Yan - the “missing spin program”



Test fundamental predictions by measuring TMDs in Drell Yan.

Sivers and Boer-Mulders measured in SIDIS



PLB 744 (2015) 250

π+ results clearly different from 0

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

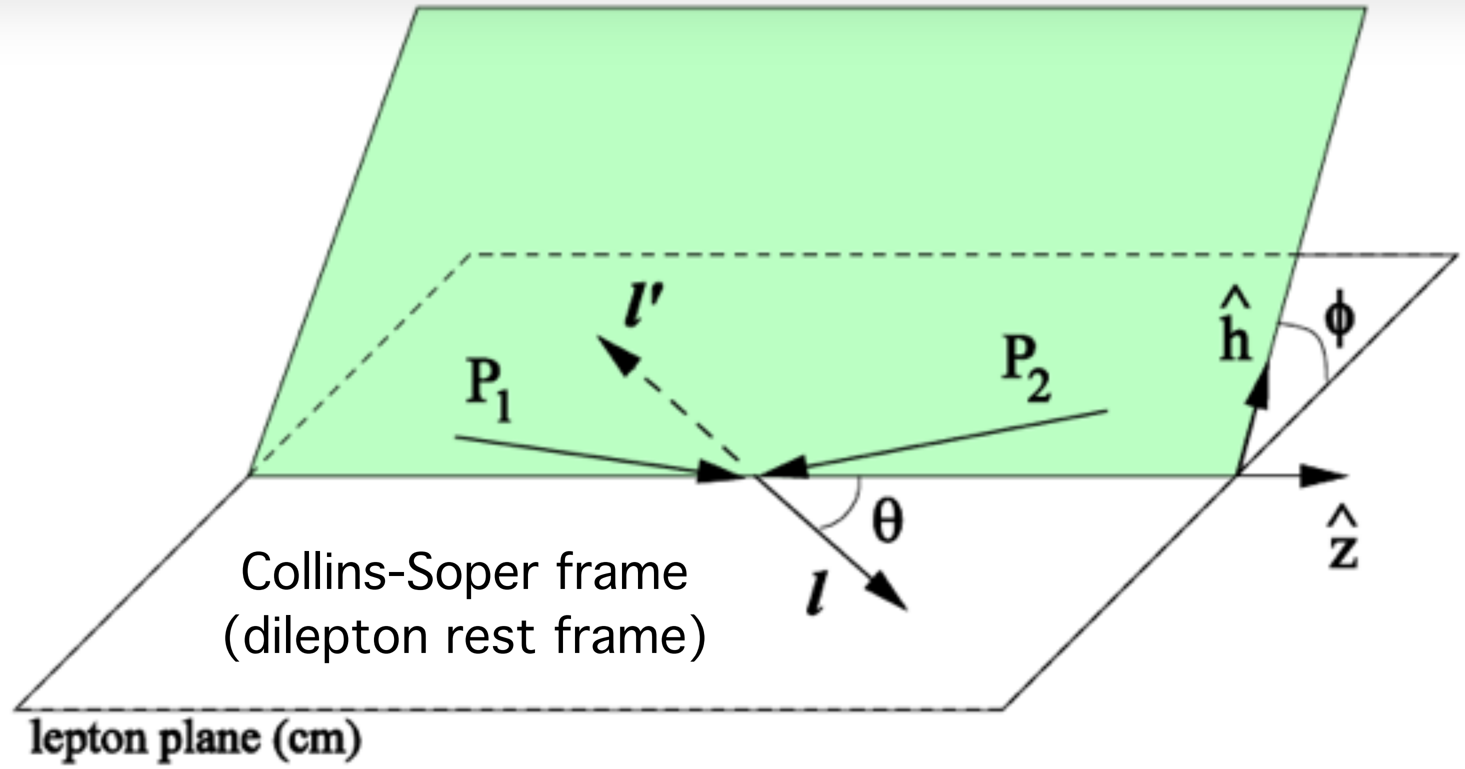
Drell Yan: QCD gluon gauge link (Wilson line) in initial state vs. **SIDIS**: final-state interactions.

Angular dependence of the Drell-Yan cross section

"no spin"
(spin integrated)

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

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



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

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

Boer-Mulders (BM) modulation

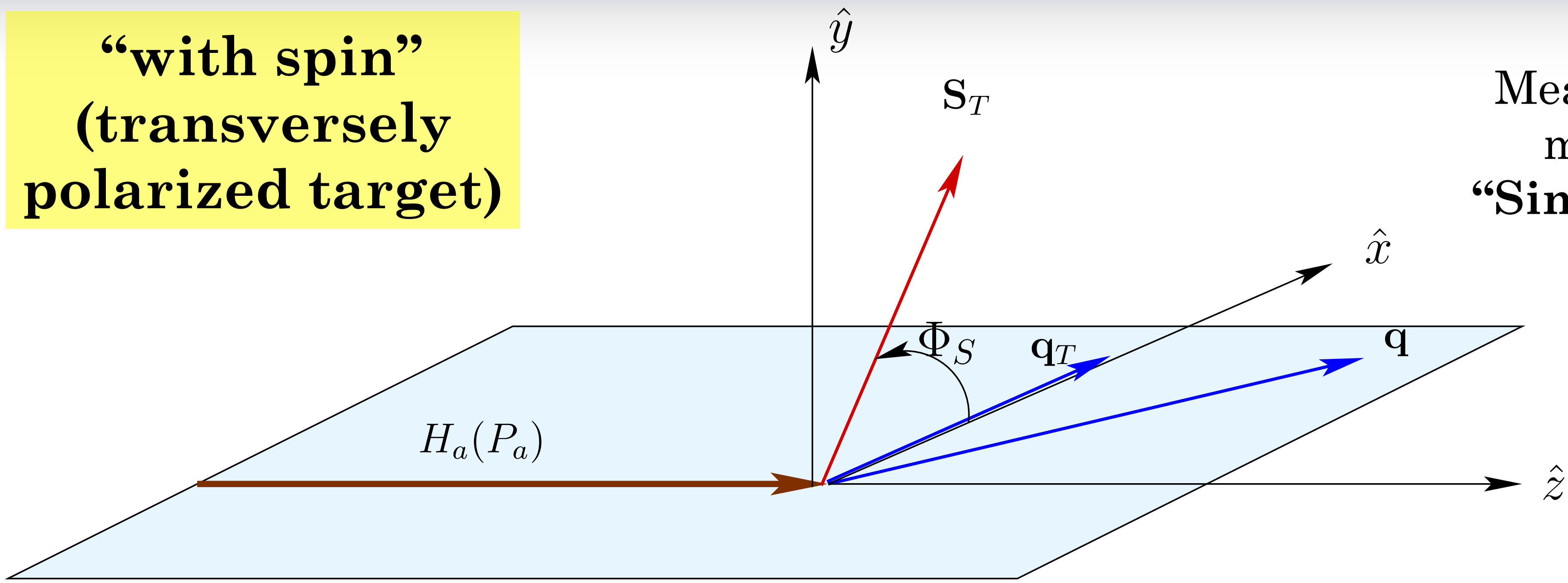
$$1 - \lambda = 2\nu$$

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

Basic derivation from structure-function formalism

Angular dependence of the Drell-Yan cross section

"with spin" (transversely polarized target)



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

	beam	target
Drell-Yan	DF	$\otimes$ DF

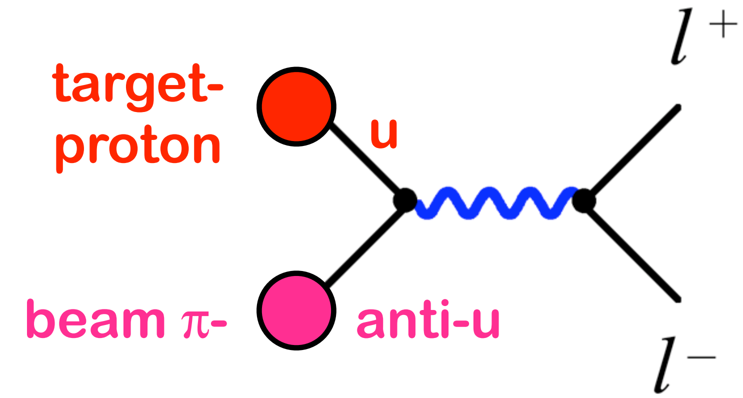
$$d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos(2\phi)$$
$$+ |S_T| \; \bar{f}_1 \otimes \bar{f}_{1T}^\perp \sin\phi_S$$
$$+ |S_T| \; \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S)$$
$$+ |S_T| \; \bar{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S)$$

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

Why a meson beam?

Drell-Yan DF ⊗ DF

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

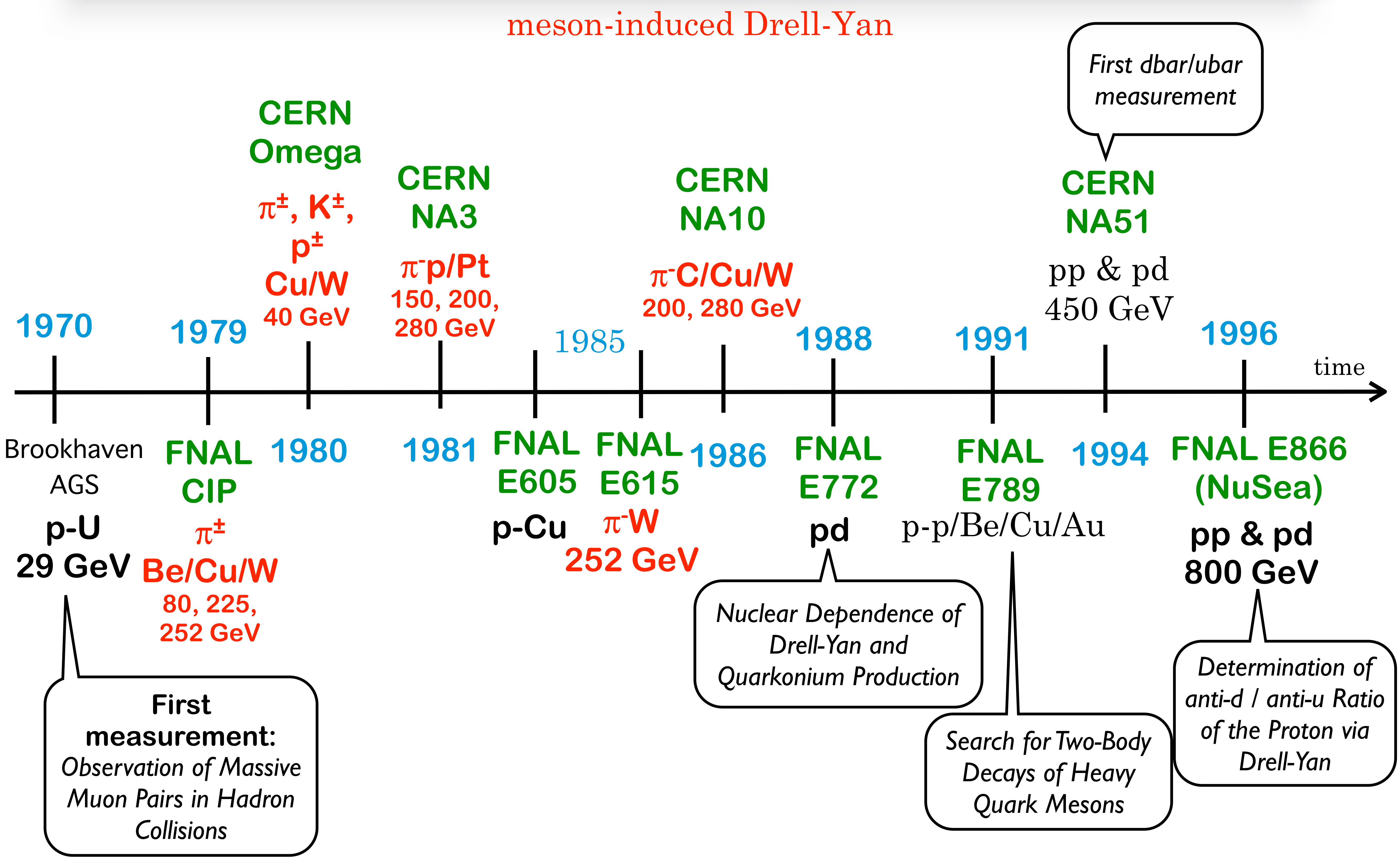


- **Flavor sensitive**: meson is specific qqbar compound
  - pi-minus on proton: selectively probes u-quark Sivers distribution of the proton
  - no cancellation effects by opposite-sign u- and d-quark Sivers contributions
- Creation of **large-mass di-lepton from valence quarks**: large x
  Proton-induced DY generates di-lepton
  from sea-quark object with small x.
- Mesons as alternative probe to **test meson structure** →
  and **nuclear models** (not accessible in DIS)

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

See also: W.-C. Chang and D. Dutta, arXiv:1306.3971,

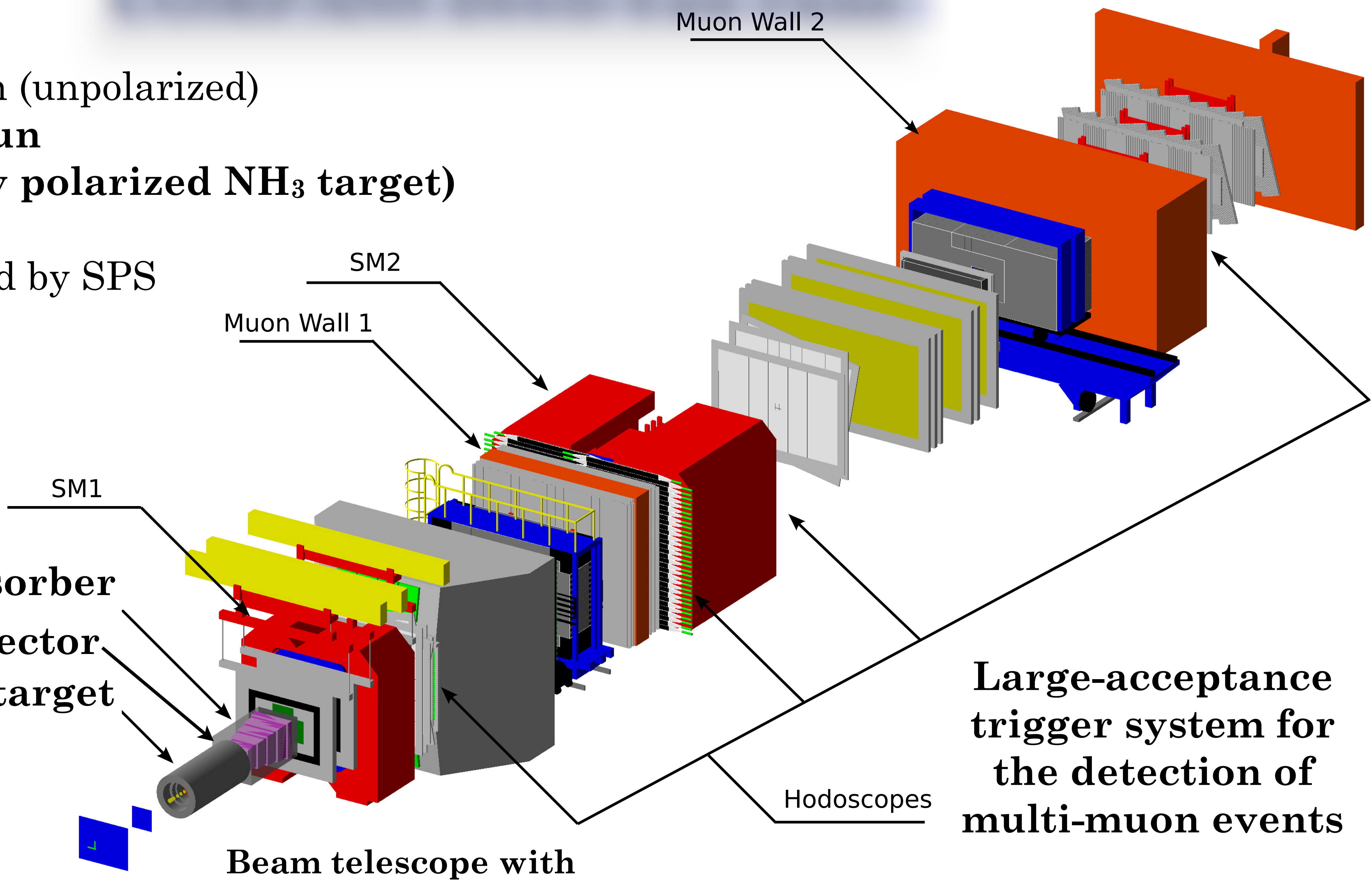
Selected Drell-Yan experiments of the past



COMPASS Drell-Yan runs

- 2008: test run
- 2014: pilot run (unpolarized)
- **2015: main run**
  (transversely polarized NH_3 target)

+ 2018 approved by SPS



190 GeV negative hadron beam (π/K/p 97/2/1%)
(from 400 GeV SPS protons onto conversion target)
Beam intensity 2015: 10^8 particles / sec

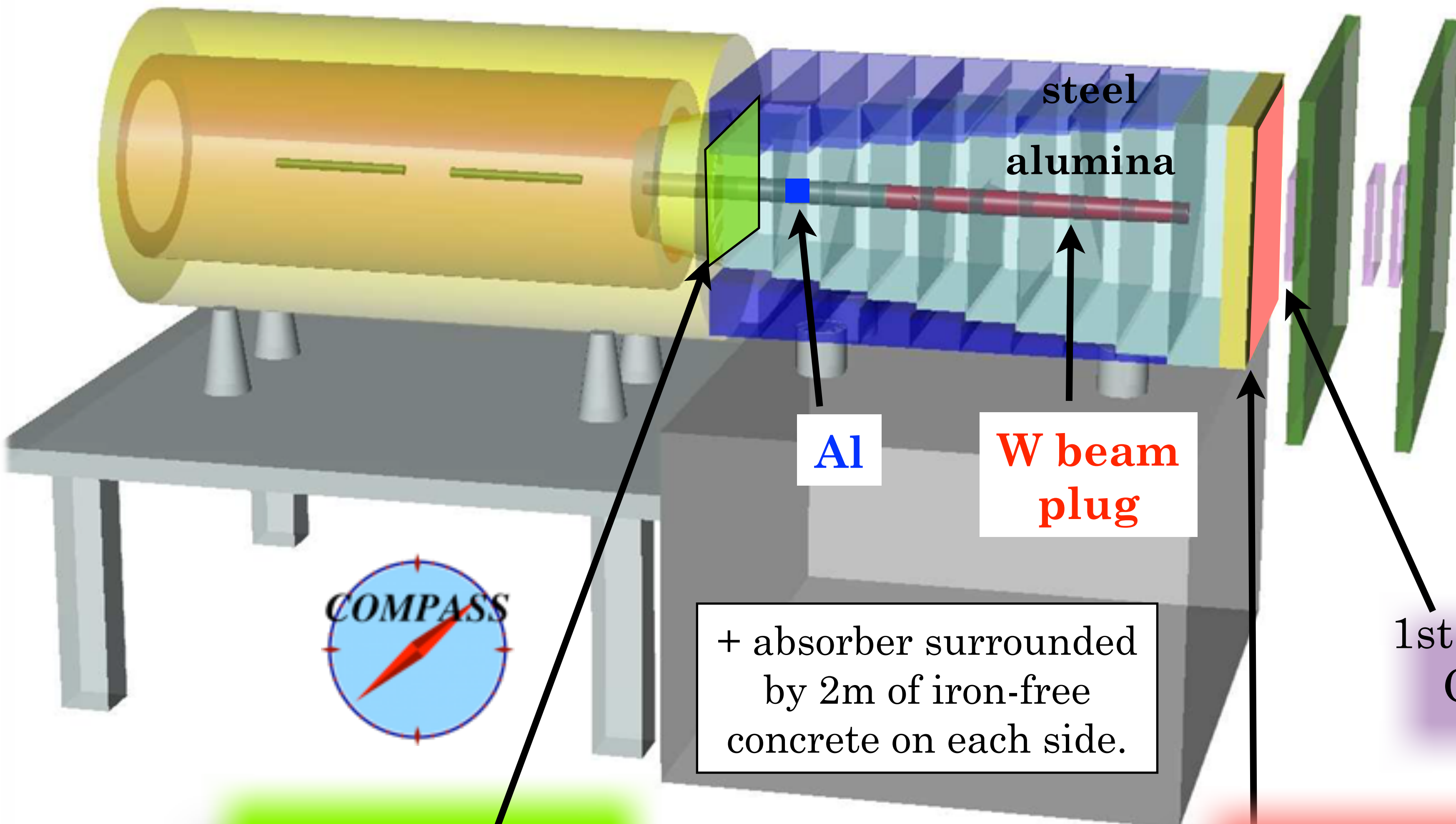
2-stage spectrometer:
"LAS": 35 mrad < θ_μ < 180 mrad
"SAS": 18 mrad < θ_μ < 35 mrad
~350 tracking planes

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

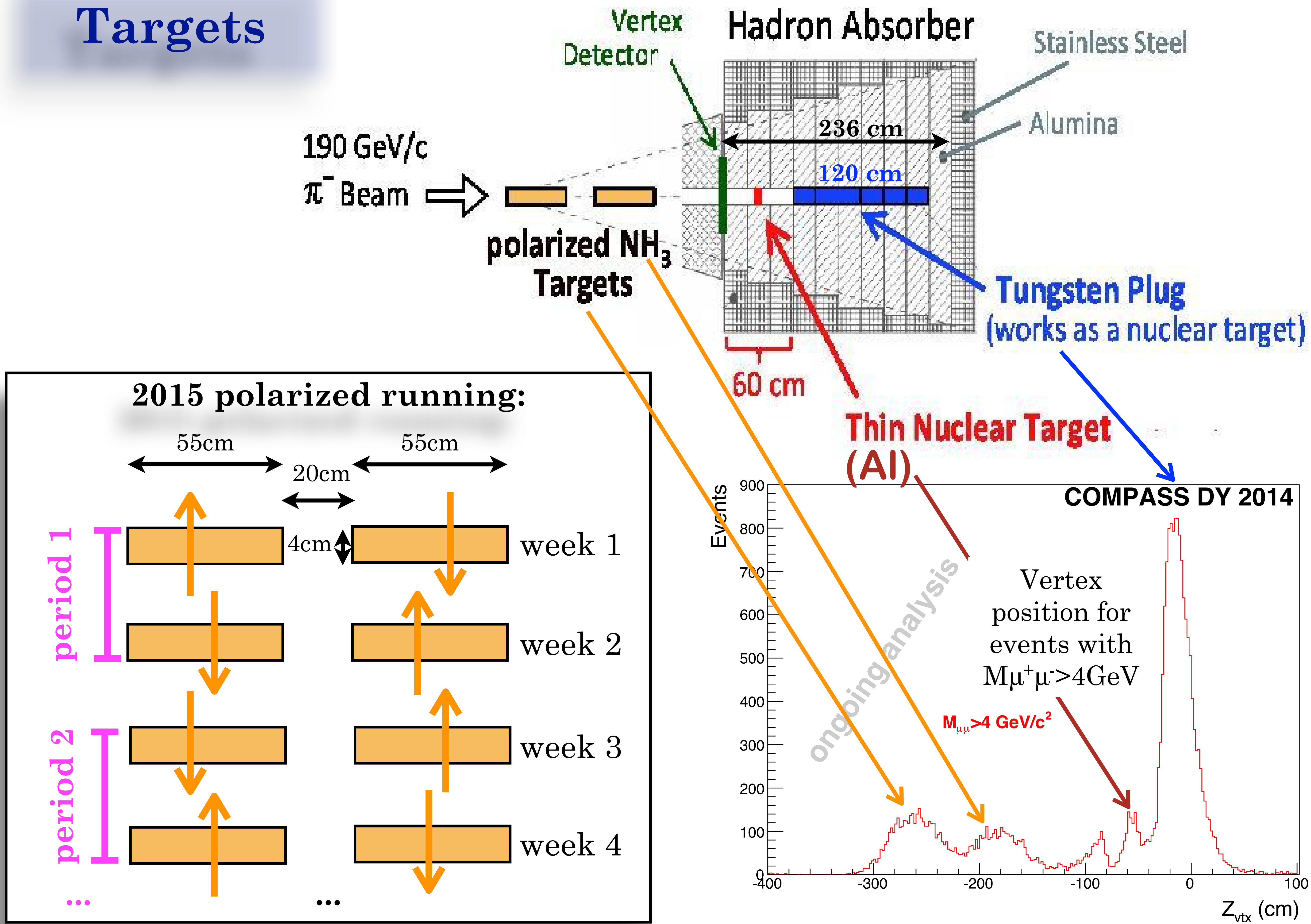
Vertex detector

to improve resolution of
- mass & angle of virtual photon
- vertex position.

^{6}Li absorber

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

Targets

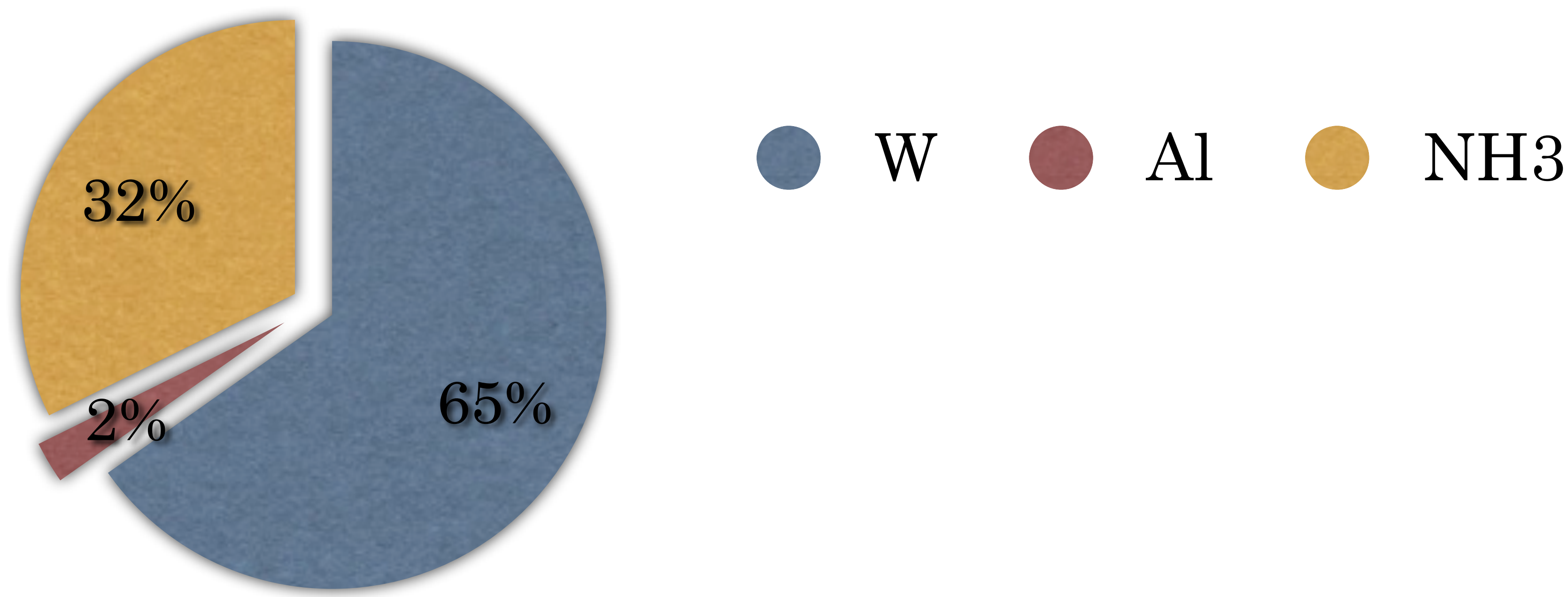


Vertex Detector
Hadron Absorber
Stainless Steel
Alumina
236 cm
120 cm
190 GeV/c
π⁻ Beam
polarized NH3 Targets
Tungsten Plug
(works as a nuclear target)
60 cm
Thin Nuclear Target
(Al)
2015 polarized running:
55cm
55cm
20cm
4cm
week 1
week 2
week 3
week 4
period 1
period 2
...
...
COMPASS DY 2014
Events
ongoing analysis
Vertex position for events with Mμ+μ->4GeV
Mμμ>4 GeV/c2
Zvtx (cm)
0
100
200
300
400
500
600
700
800
900
-400
-300
-200
-100
0
100

Existing COMPASS Drell-Yan data

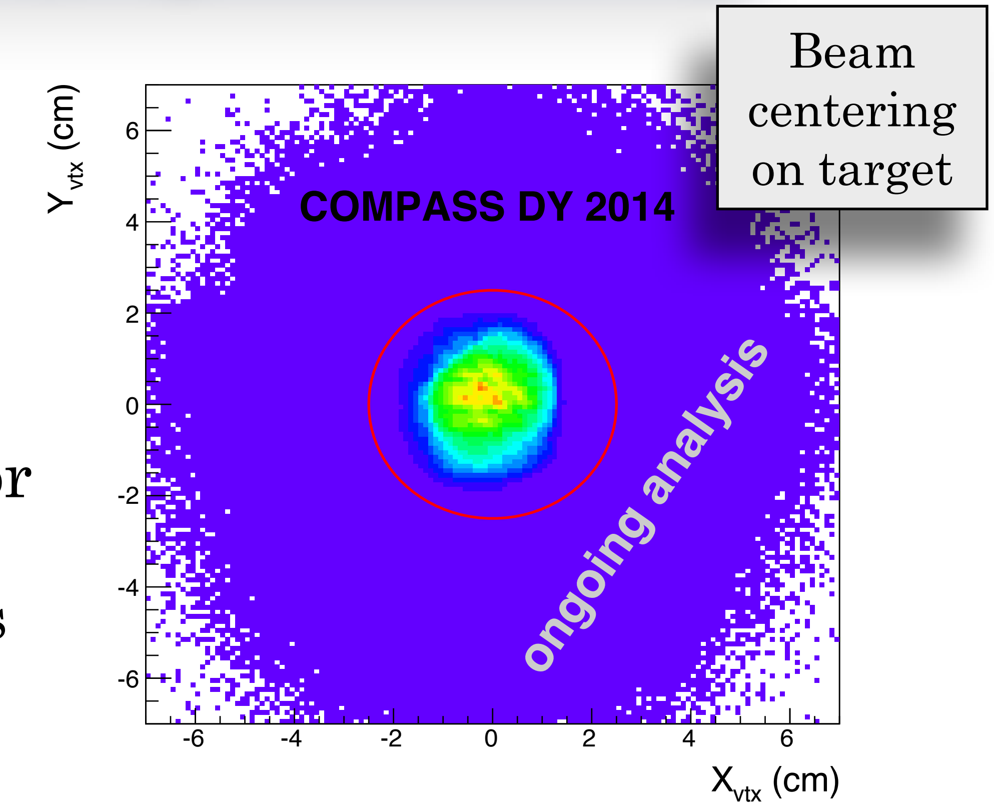
- 2014: **unpolarized proton** (mass 1), **unpolarized aluminum** (mass 27), **unpolarized tungsten** (mass ~183) → ***preliminary distributions shown today***
- 2015: **transversely polarized proton**, **unpolarized aluminum**, **unpolarized tungsten**
- Scatter off different targets and record data at the same time.

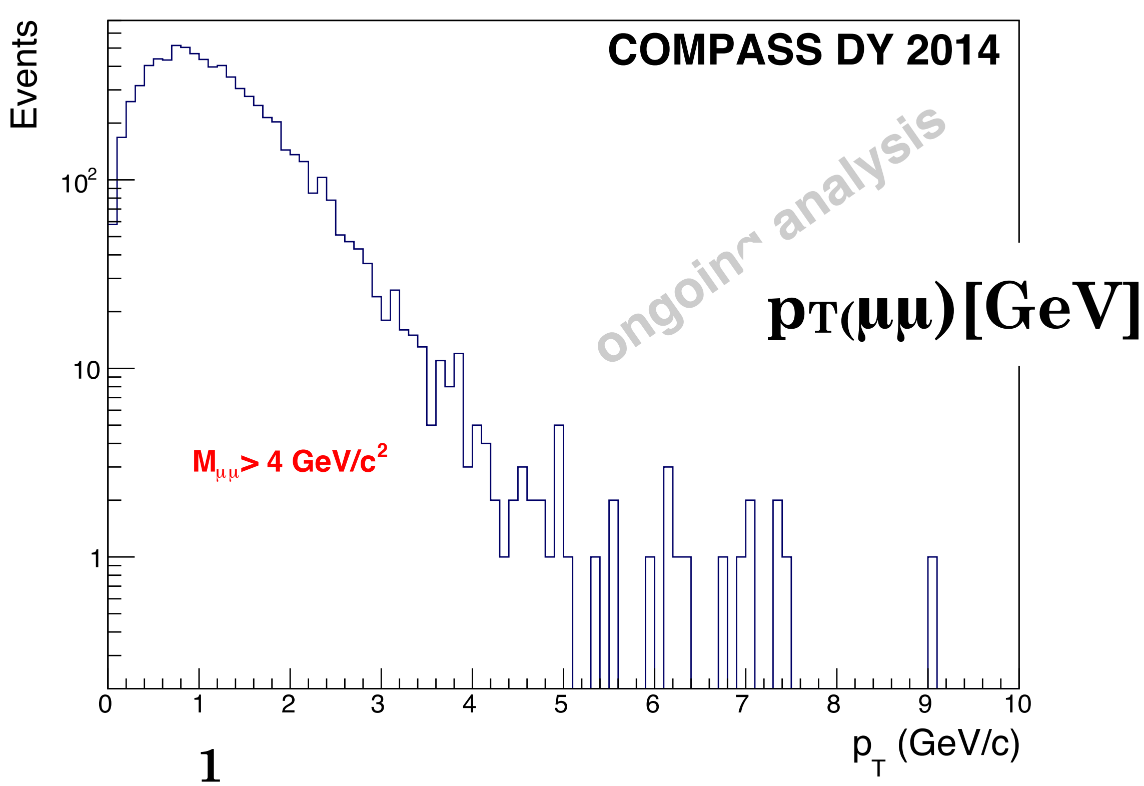
Events with oppositely charged di-muon events (Mμ+μ->4GeV):

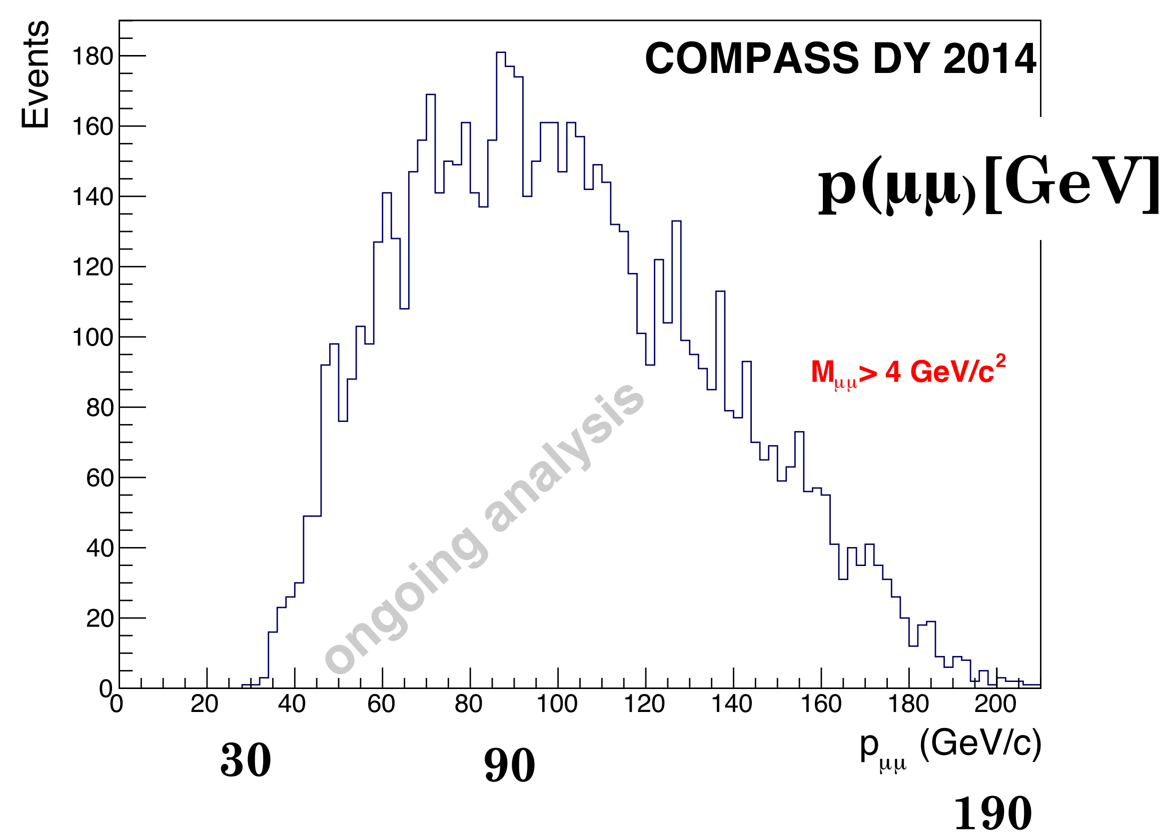


2014 data (DY pilot run) - preliminary

- ~ 2 weeks of stable data taking
- Average beam intensity: 7.3x10^7 particles /s (up to nominal 10^8/s)
- No target polarization, no (usage of) vertex detector
- Statistics (**NH_3 $M\mu^+\mu^-$>4GeV**): ~7k di-muon events (~9% of 2015 data); ~200k J/ψ.

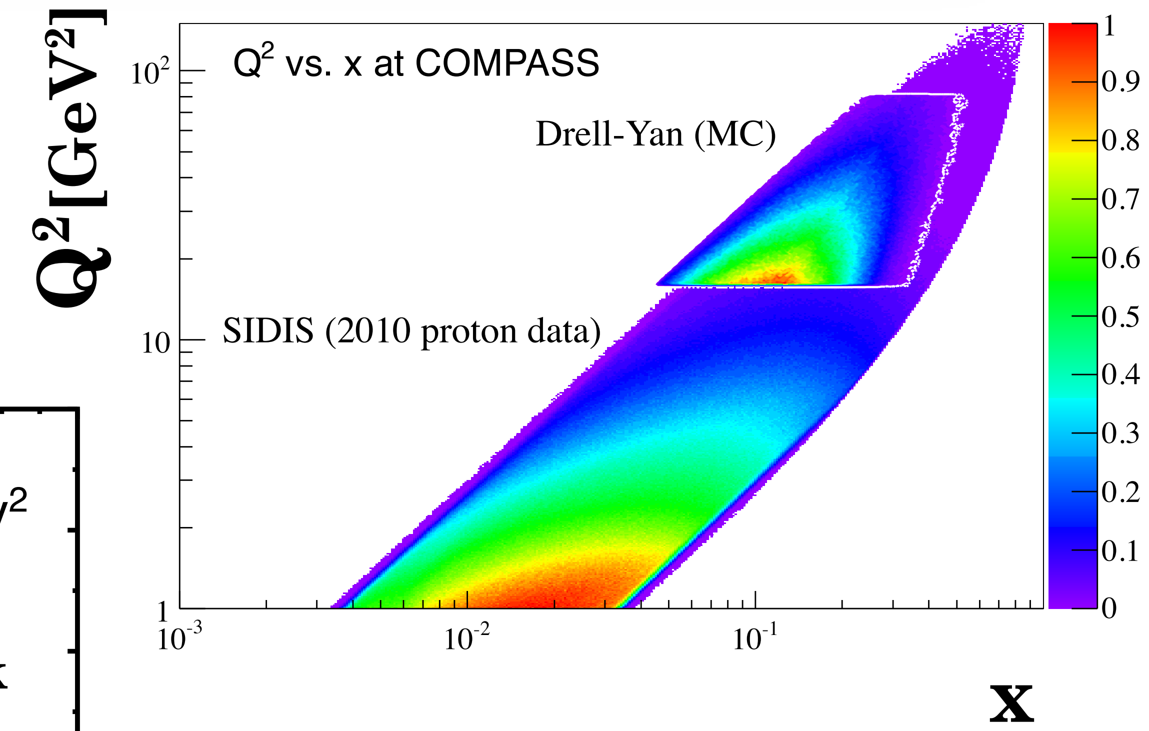


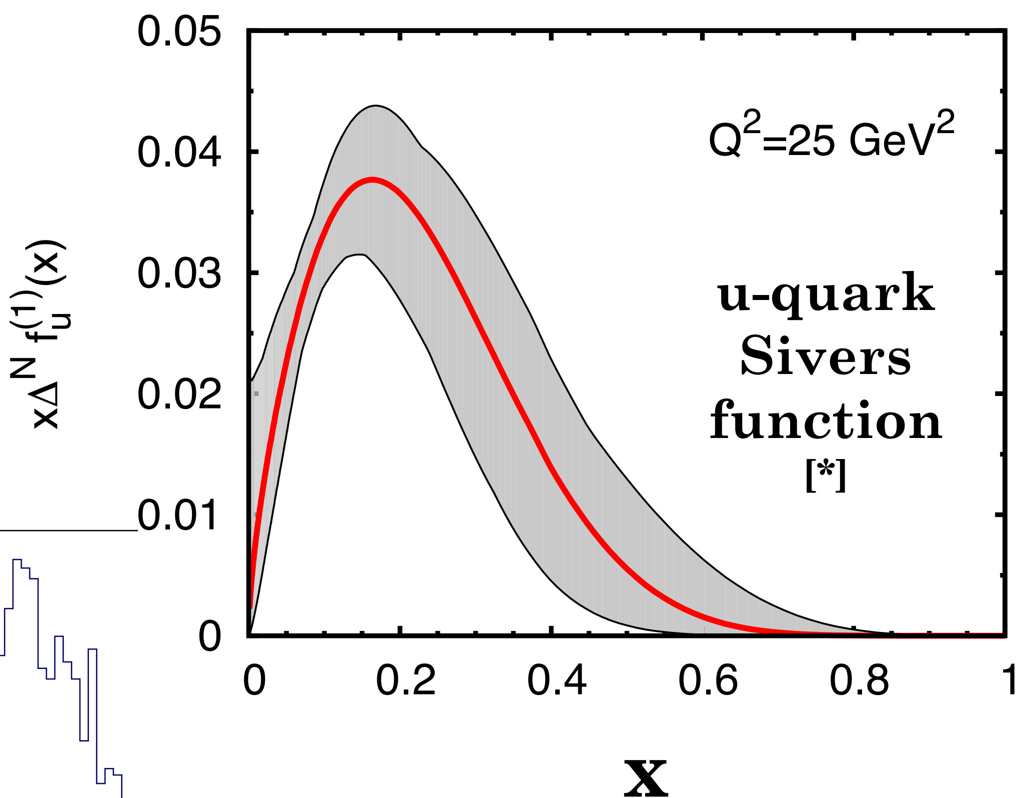




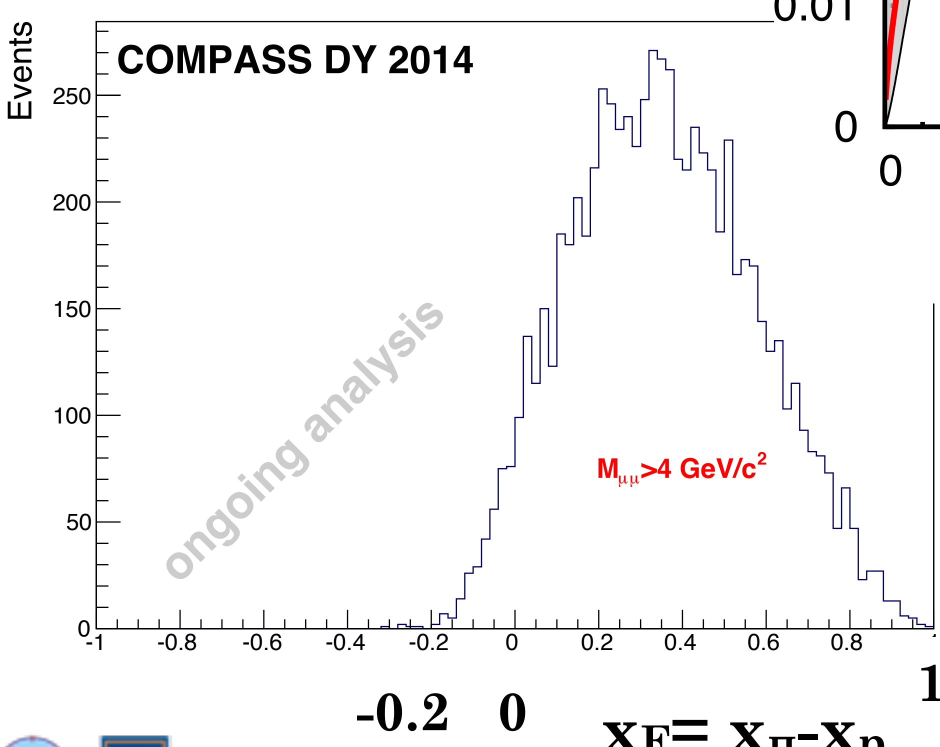
Phase space of COMPASS Drell-Yan data

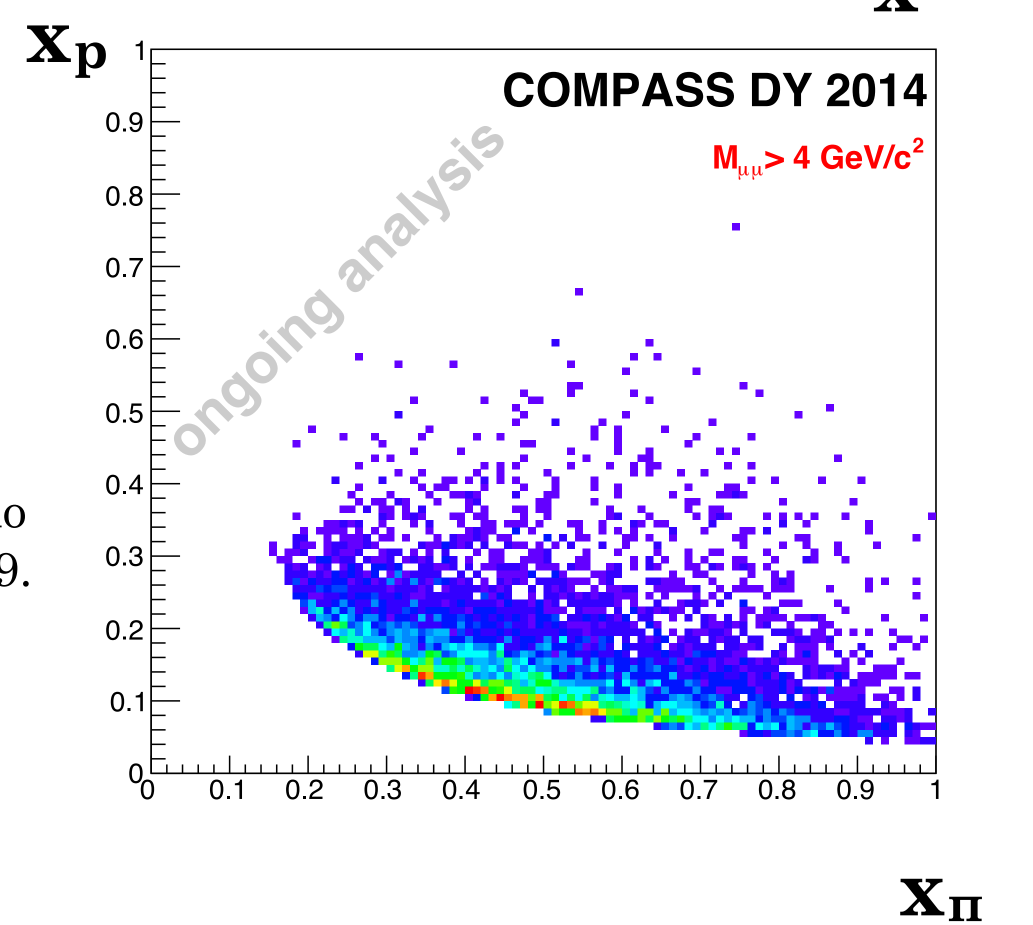
- Unique possibility of measuring **SIDIS** and **Drell-Yan** observables **at the same facility.**
- π- on proton probes **valence-quark region** ☛ Sivers function of large magnitude.



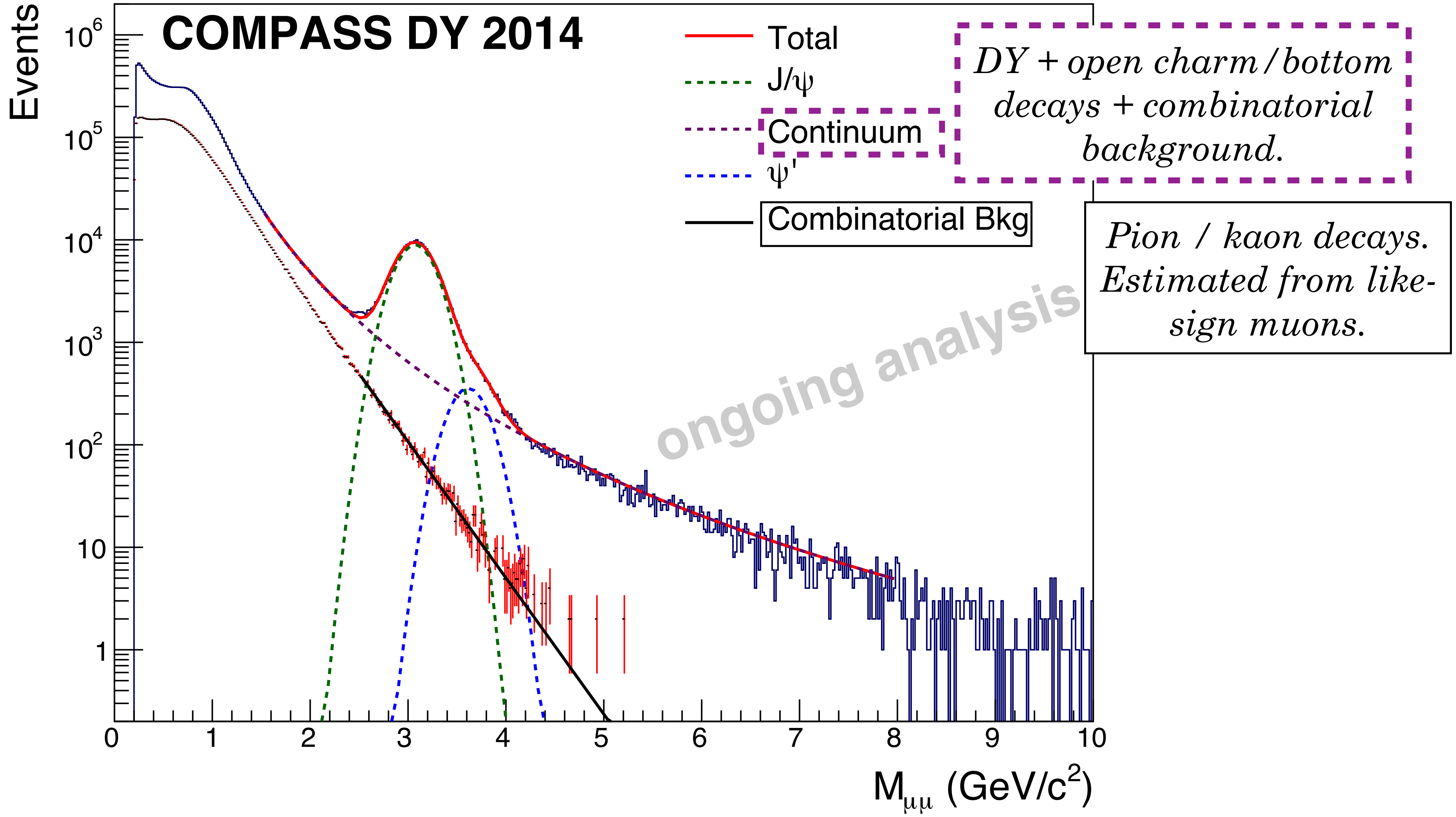


[*] calculated from: M. Anselmino et al., Eur. Phys. J. A39 (2009) 89.



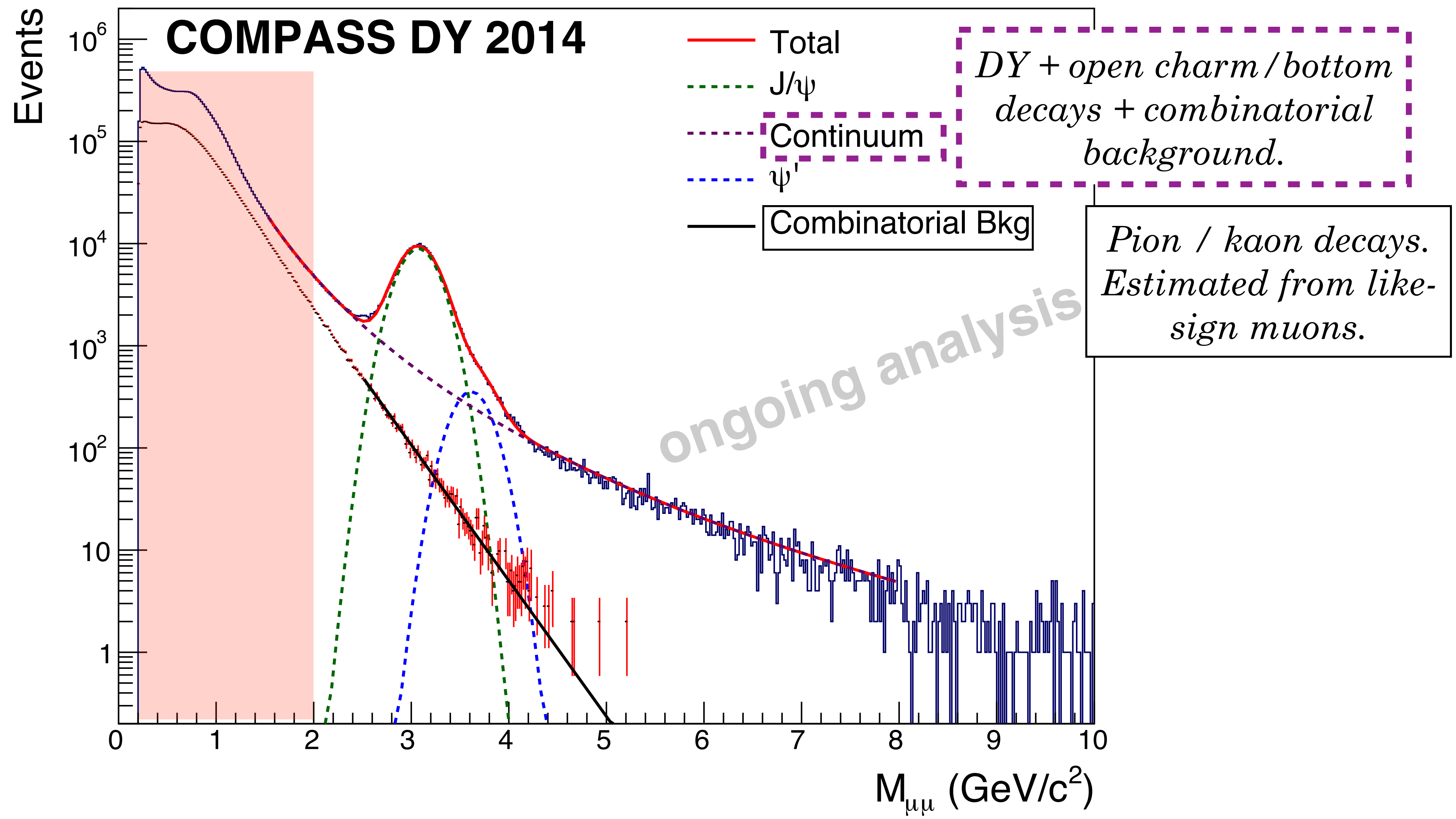


Di-muon kinematics



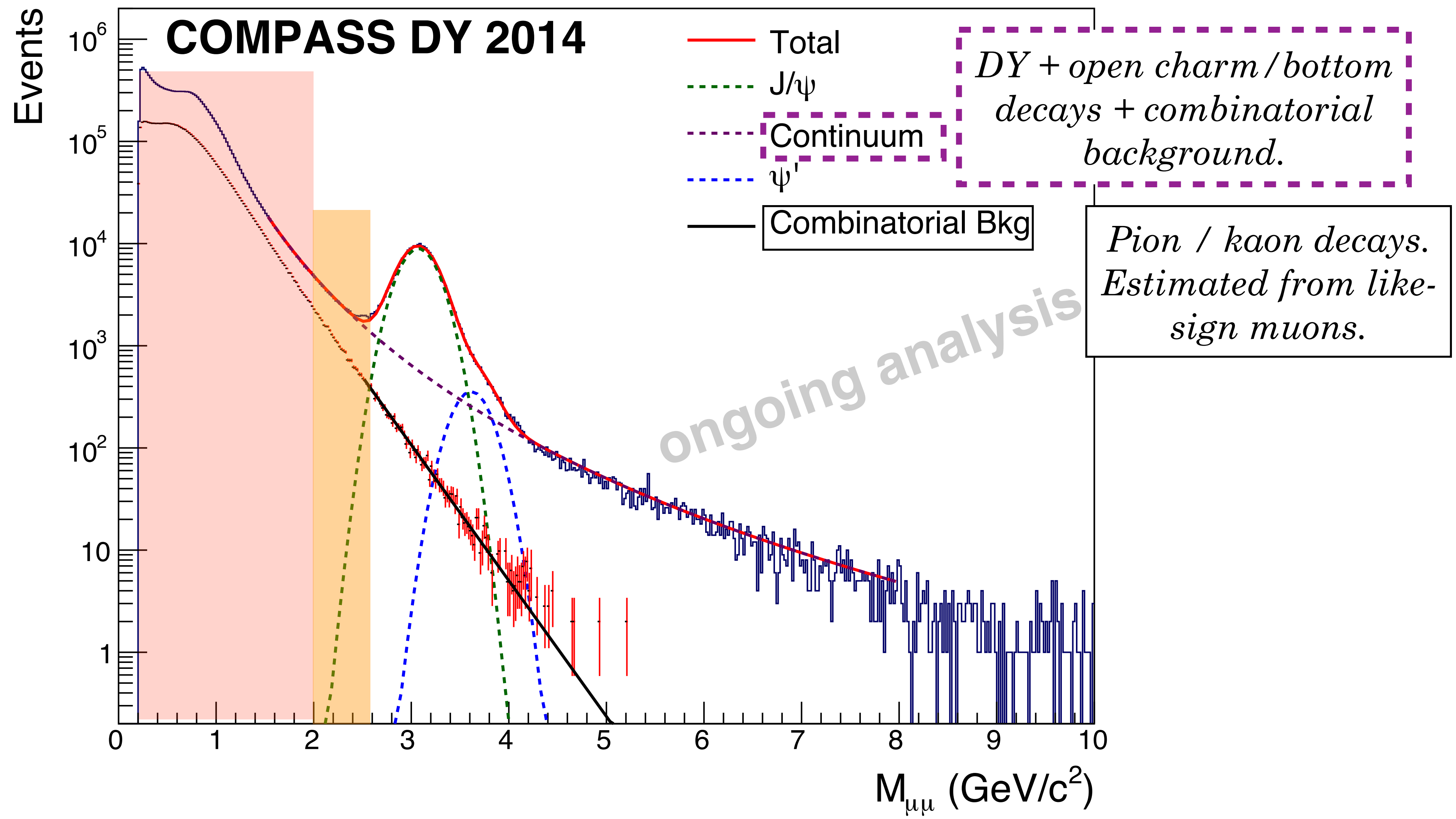
Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q^2 [GeV^2]	1-4	4-6.25	6.25-16		16-81
Region	**“DY low mass”**	**“DY medium mass”**	**“DY J/ψ”**	**“J/ψ”**	**“DY high mass”**
clean?	✘✘ >50% bg	✘	✘ ✘	✘✘	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✘
large Sivers?	✘	✘	✘	-	✔

Di-muon kinematics



Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q^2 [GeV²]	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?	✗	✗	✗	-	✔

Di-muon kinematics



Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
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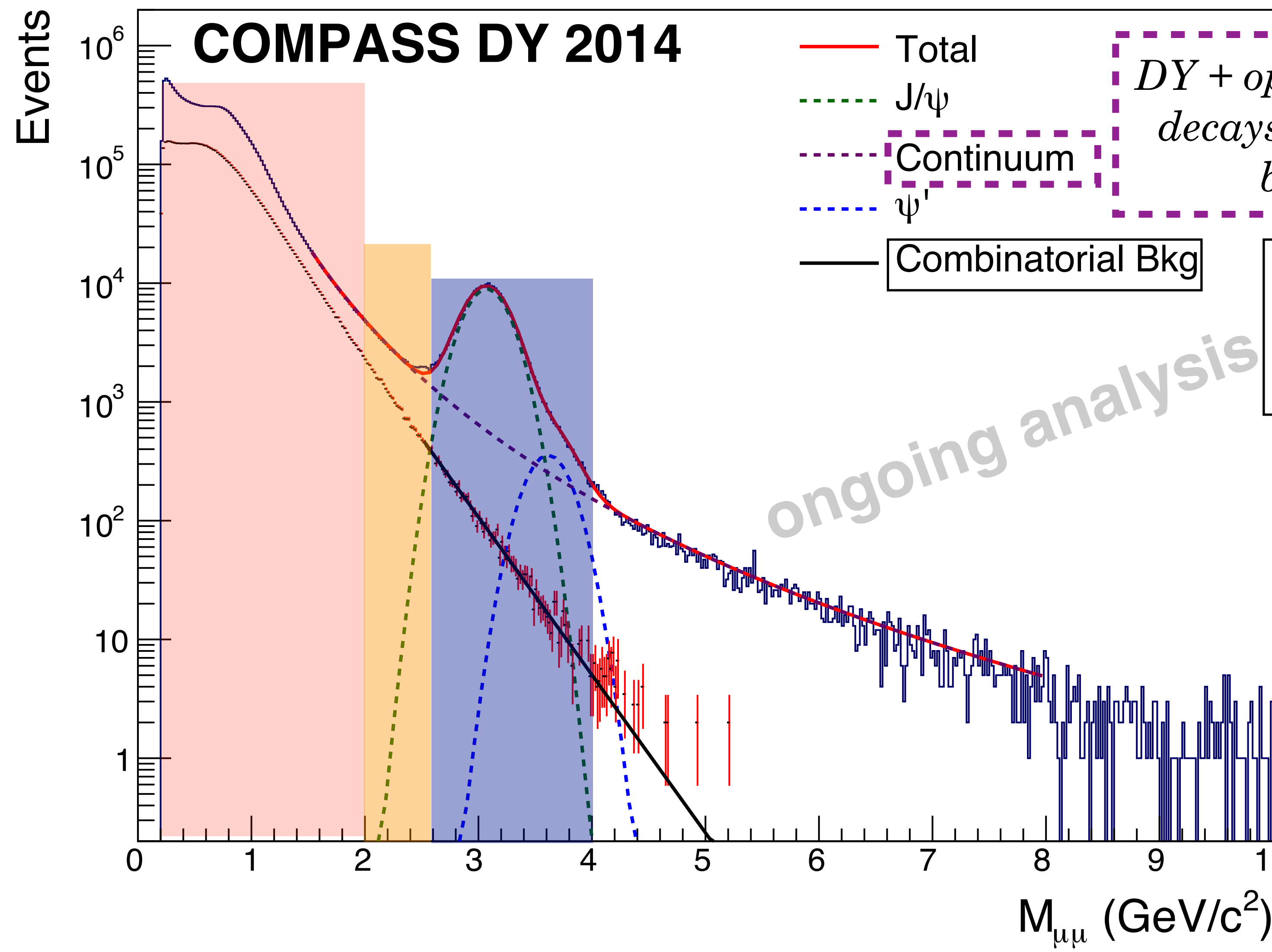
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔

Di-muon kinematics

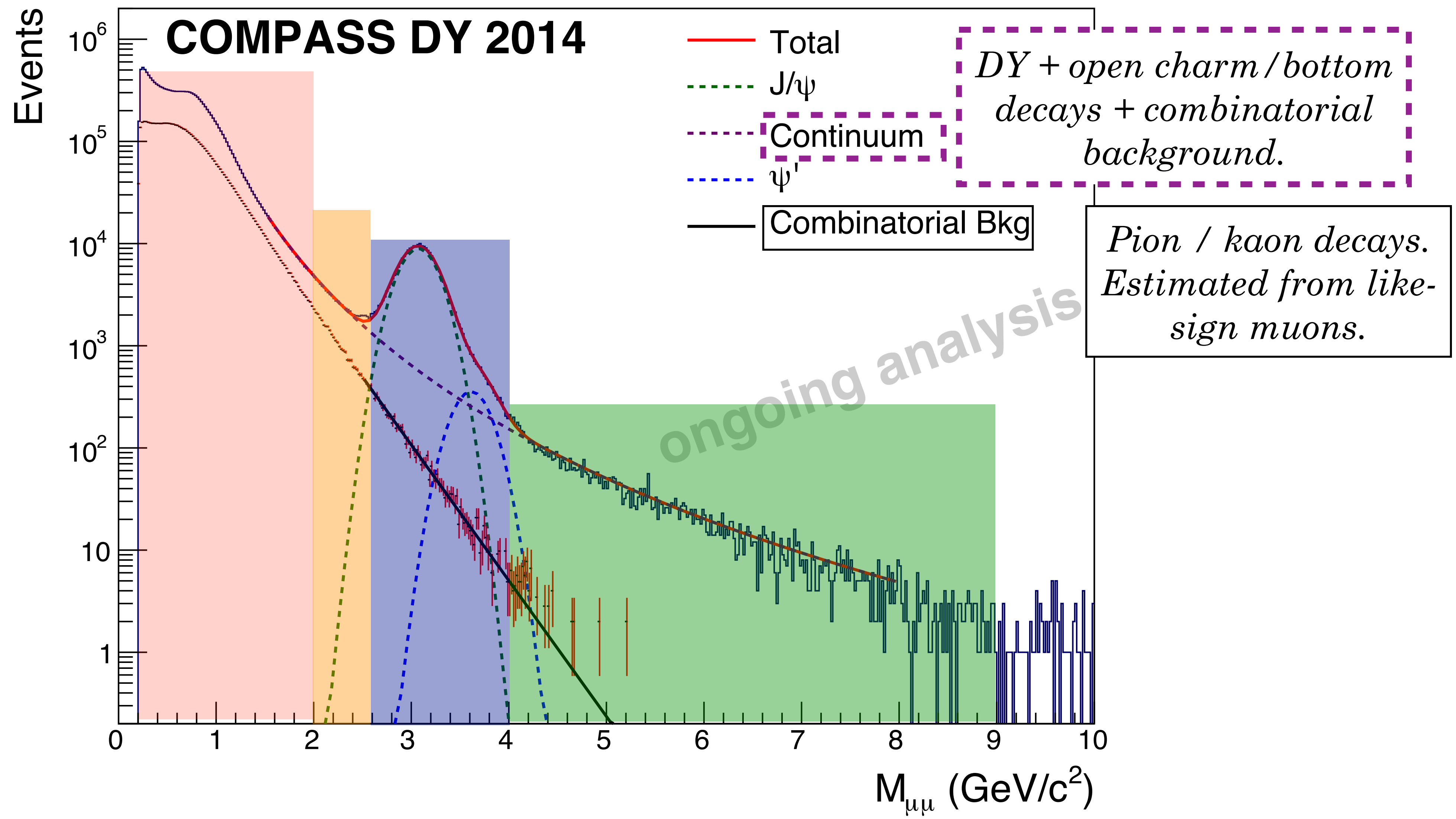


DY + open charm / bottom decays + combinatorial background.

Pion / kaon decays. Estimated from like-sign muons.

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?	✗	✗	✗	-	✔

Di-muon kinematics

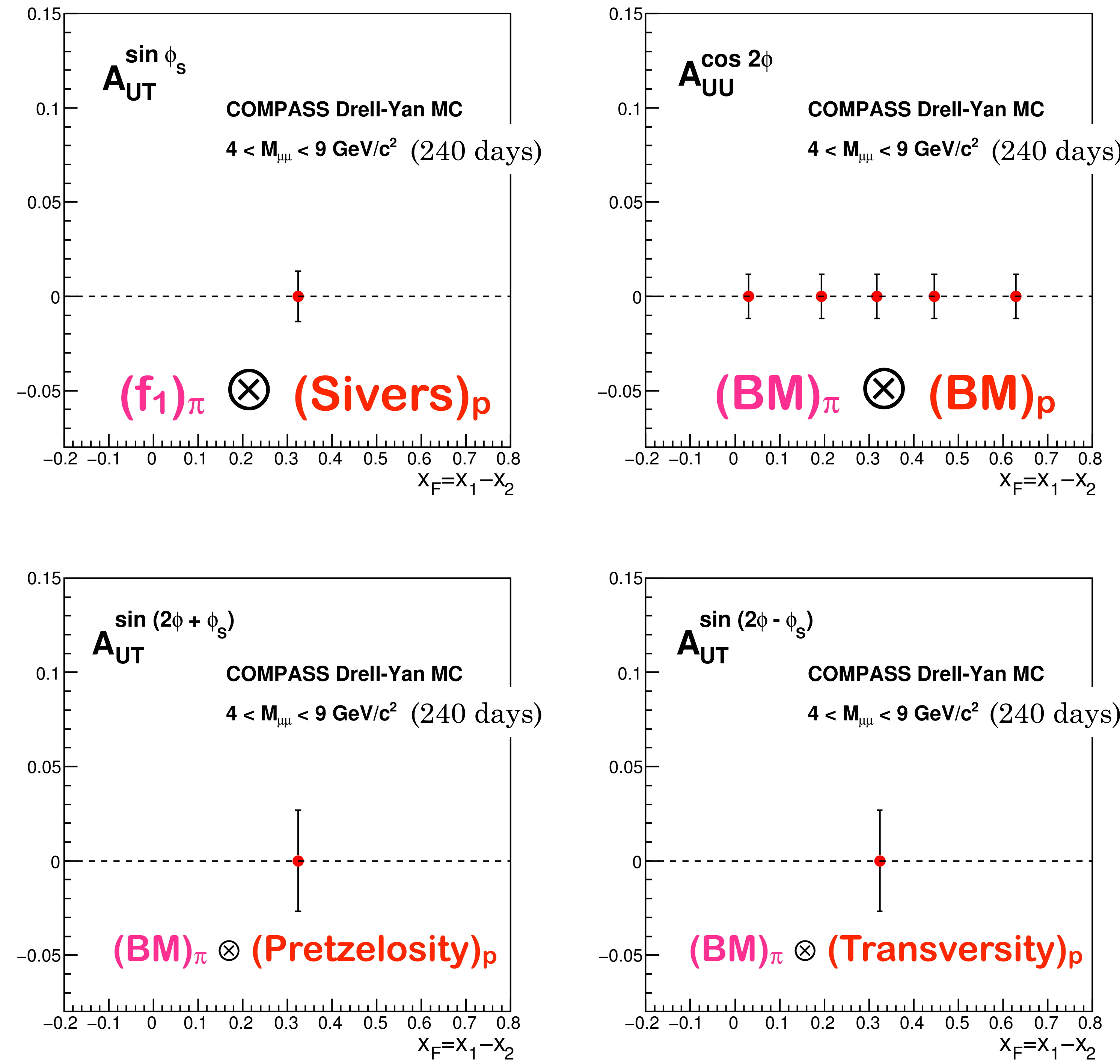


Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q² [GeV²]	1-4	4-6.25	6.25-16		16-81
Region	**"DY low mass"**	**"DY medium mass"**	**"DY J/ψ"**	**"J/ψ"**	**"DY high mass"**
clean?	✘✘ >50% bg	✘	✘ ✘	✘✘	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✘
large Sivers?	✘	✘	✘	-	✔

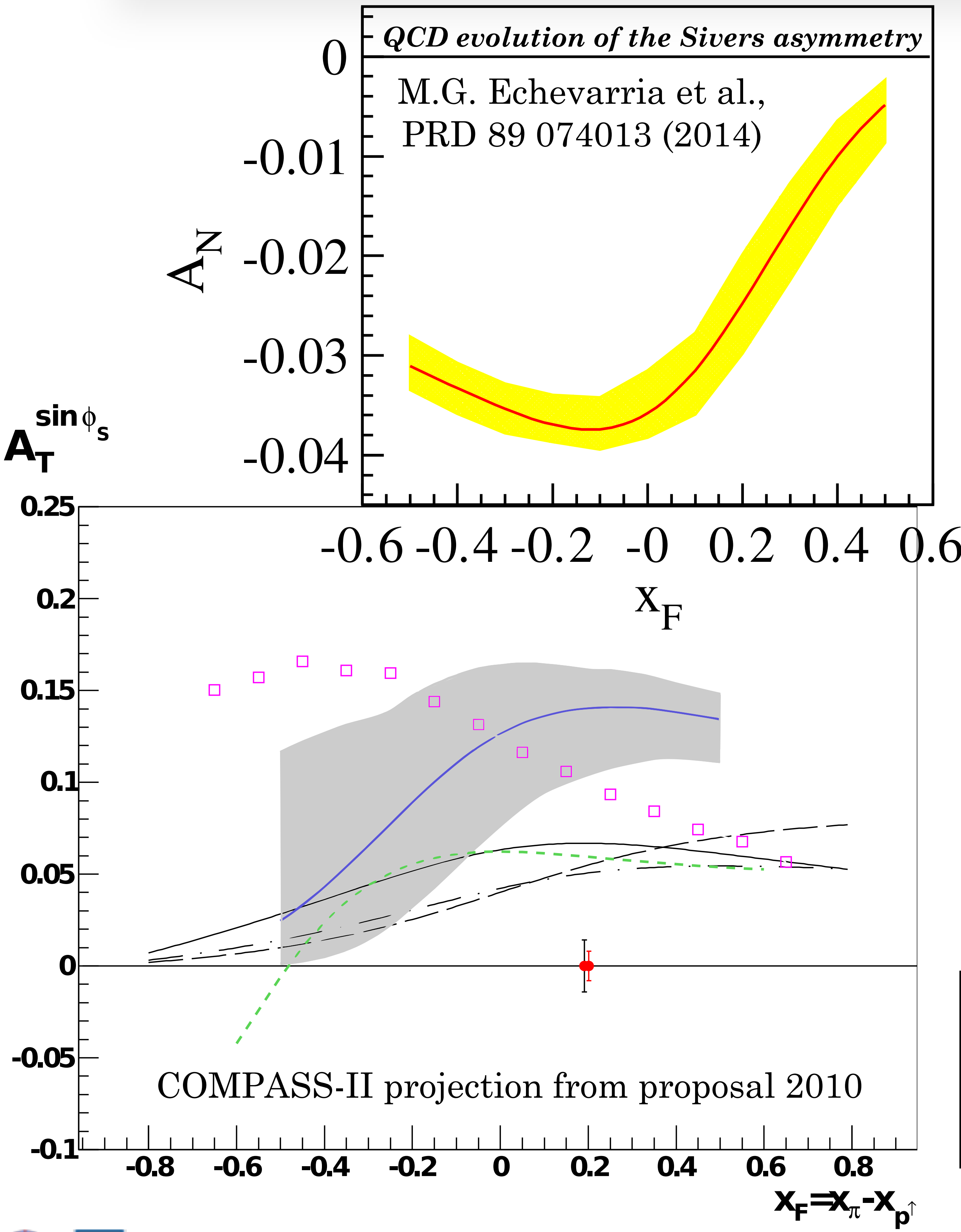
COMPASS DY projections (proton)

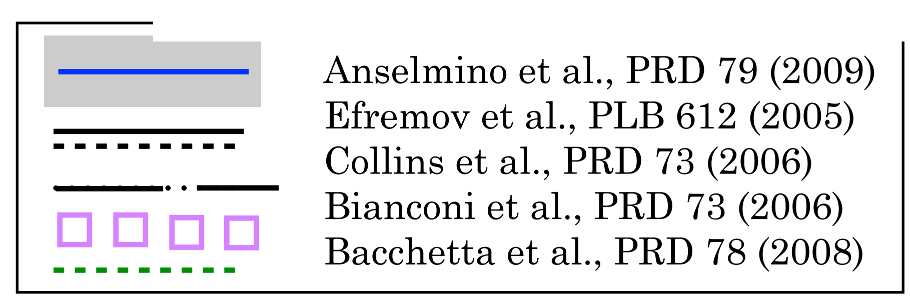
$$
\begin{aligned}
d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = \\
= 1 + \overline{h}_1^\perp \otimes h_1^\perp \cos(2\phi) \\
+|S_T|\ \overline{f}_1 \otimes \overline{f}_{1T}^\perp \sin\phi_S \\
+|S_T|\ \overline{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi+\phi_S) \\
+|S_T|\ \overline{h}_1^\perp \otimes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

beam pion   target proton



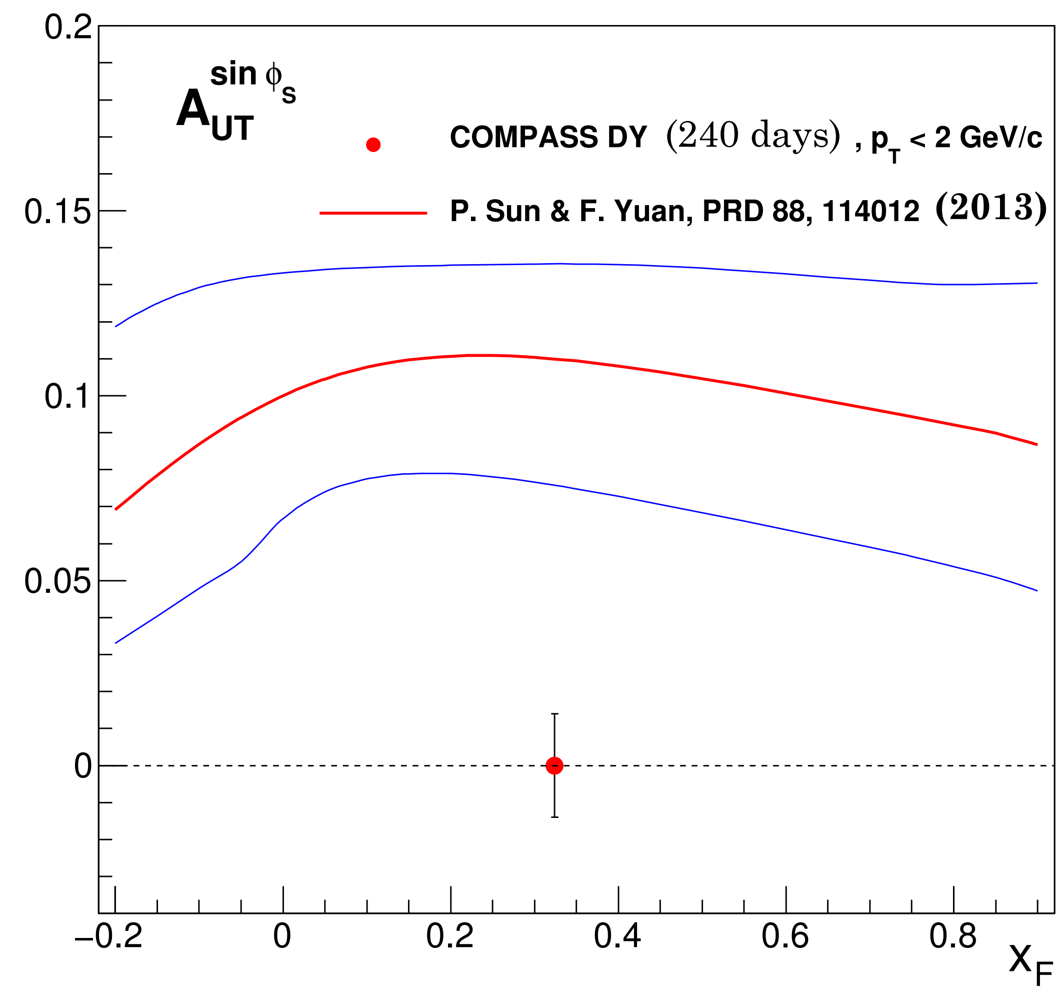
Sivers amplitude: predictions for COMPASS DY





3-15% in absolute size.

Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production

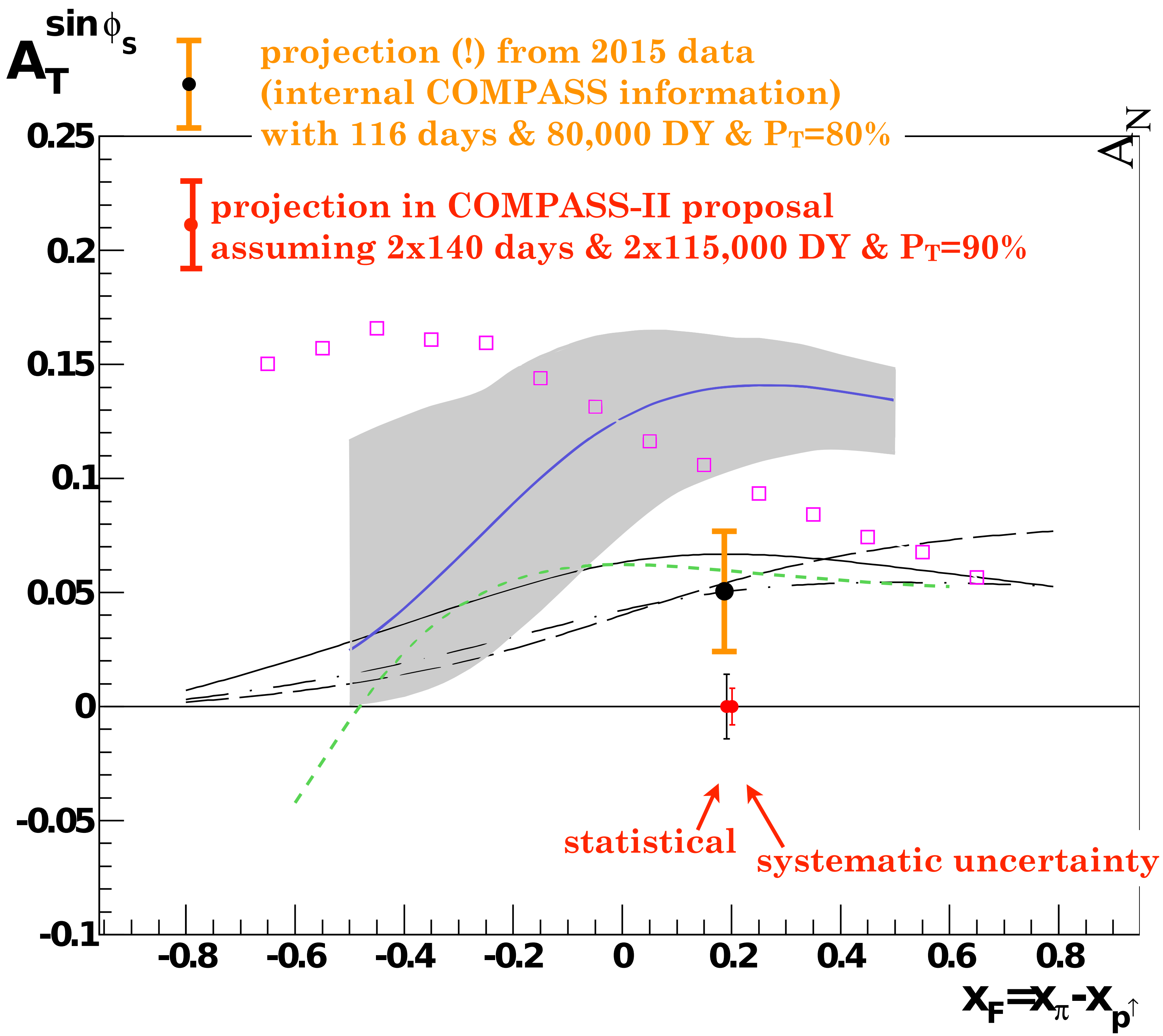


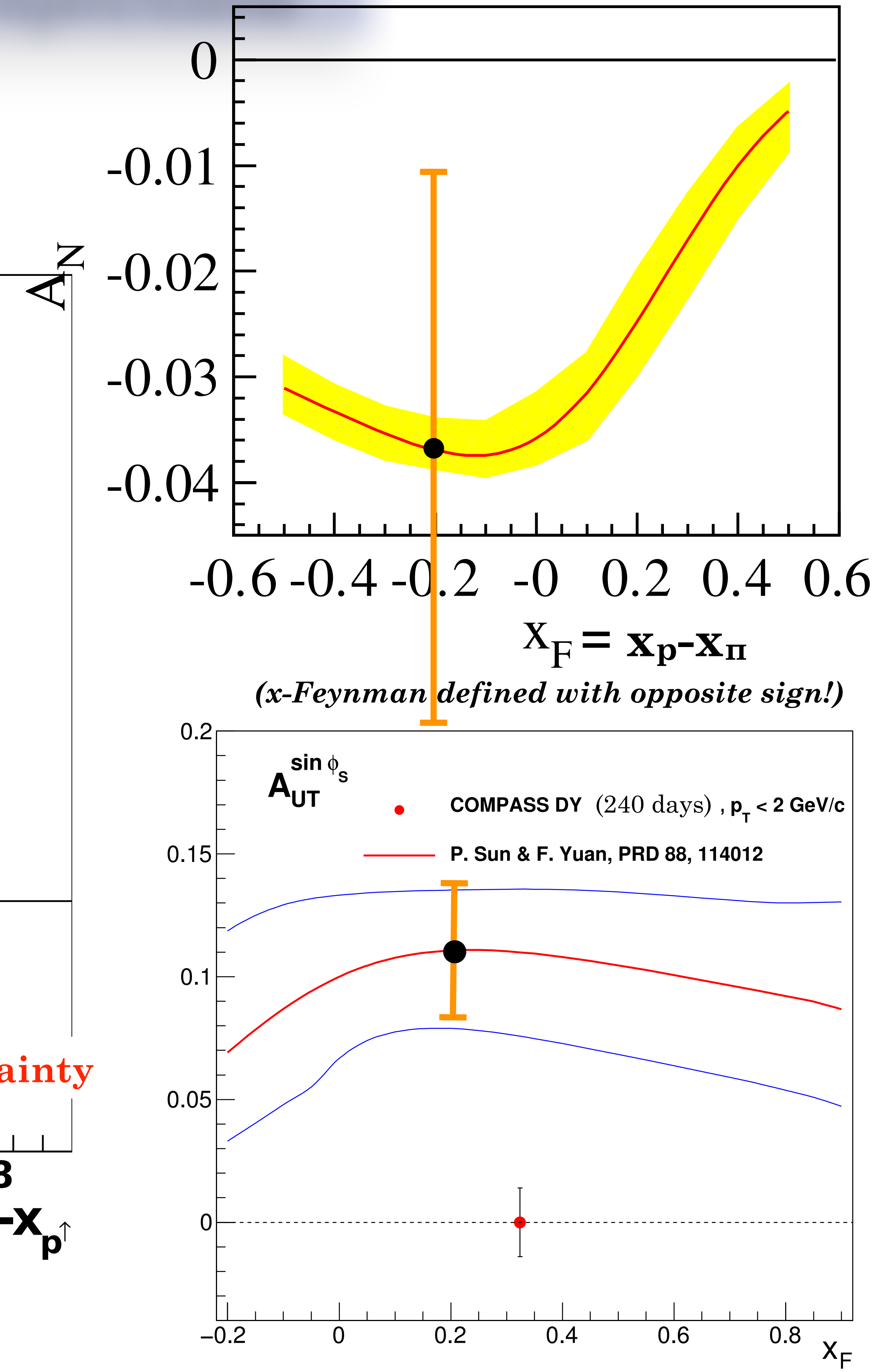
COMPASS polarized 2015 data - a first glance

- 4.5 months of physics data taking, ~ 116 days
- Transverse target polarization ~80%
- Beam intensity ~10^8 particles / second
- ~740 TB of recorded data
- ~80,000 Drell-Yan events with M>4GeV and transversely polarized target
- ⇒ expected statistical uncertainty of the Sivers amplitude $\delta A \approx 2.8\%$

Sivers amplitude: projection

From di-muon events with M>4GeV.





(complete references see earlier page)

What about the unpolarized data?

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

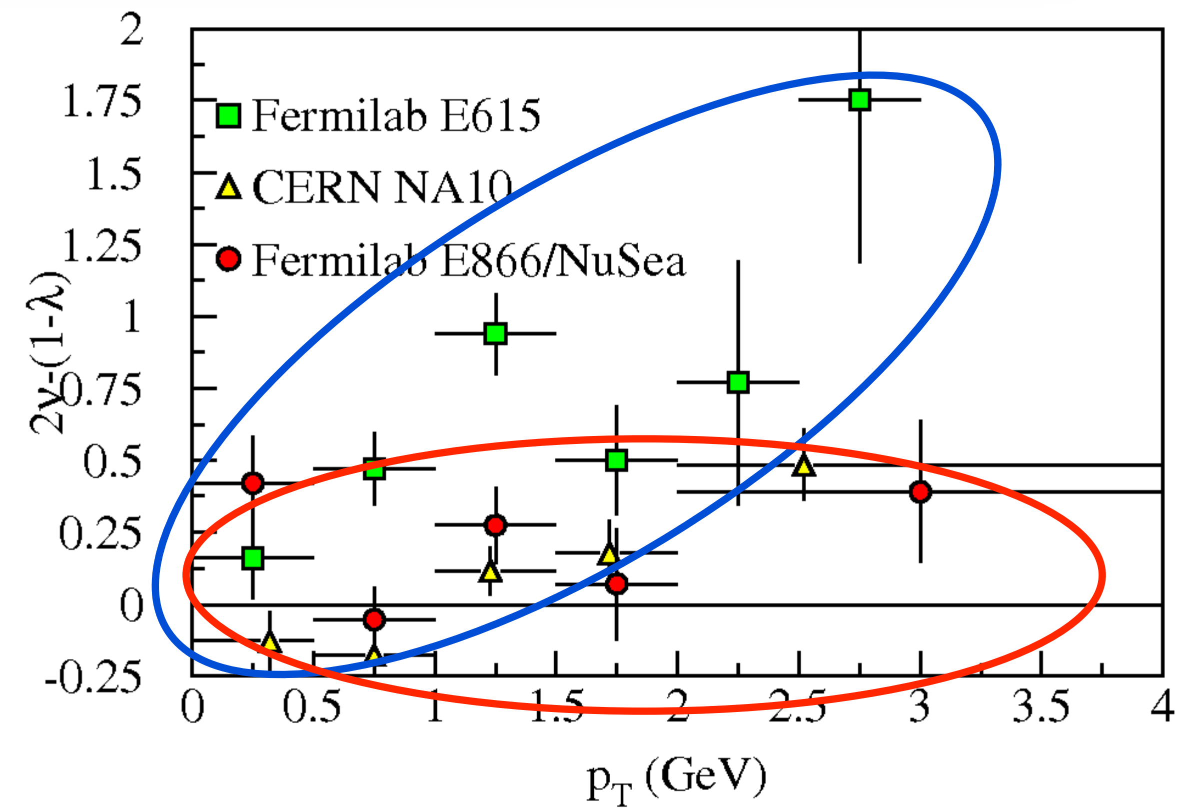
$$1 - \lambda = 2\nu$$

Lam-Tung relation

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.

Lam-Tung in proton- and pion-induced DY

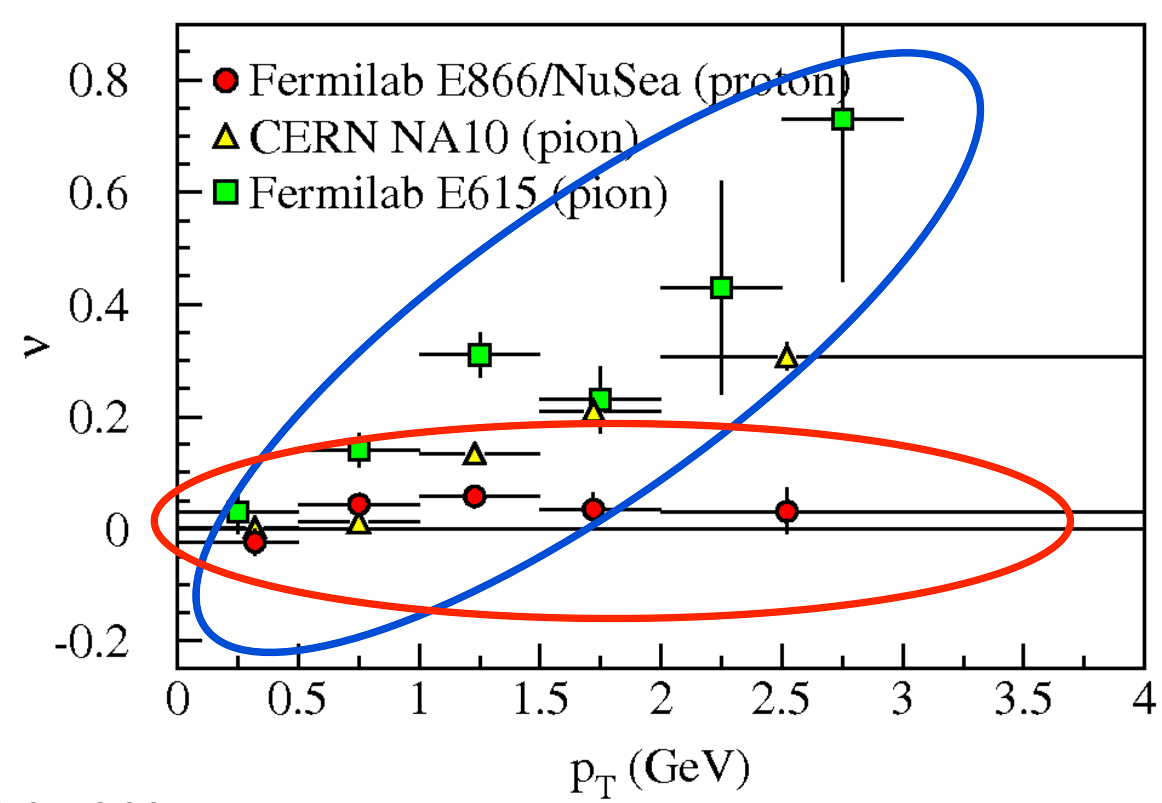
$$1 - \lambda = 2\nu$$



- 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

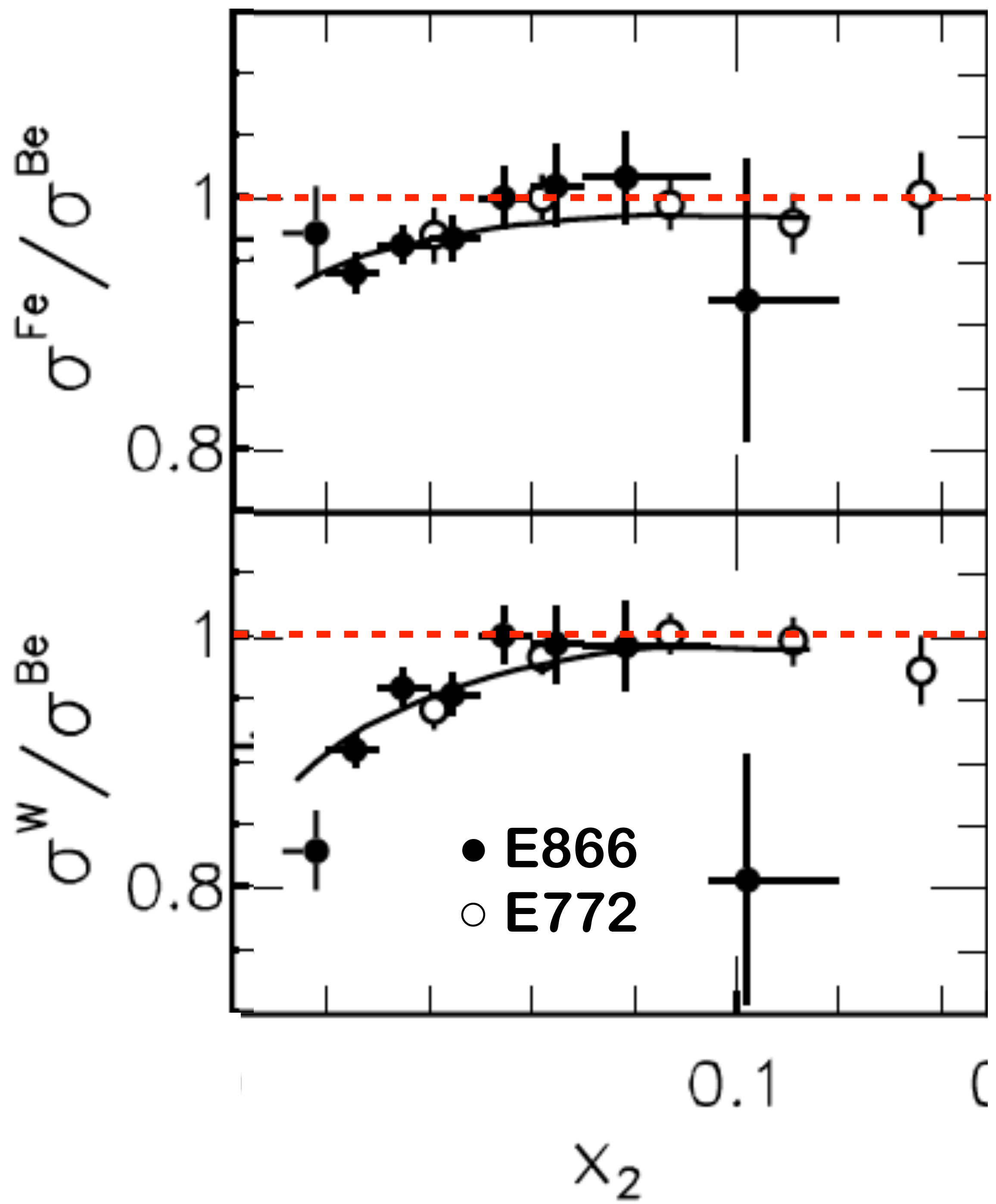
see also: P. E. Reimer, arXiv:0704.3621

EMC effect in Drell Yan

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

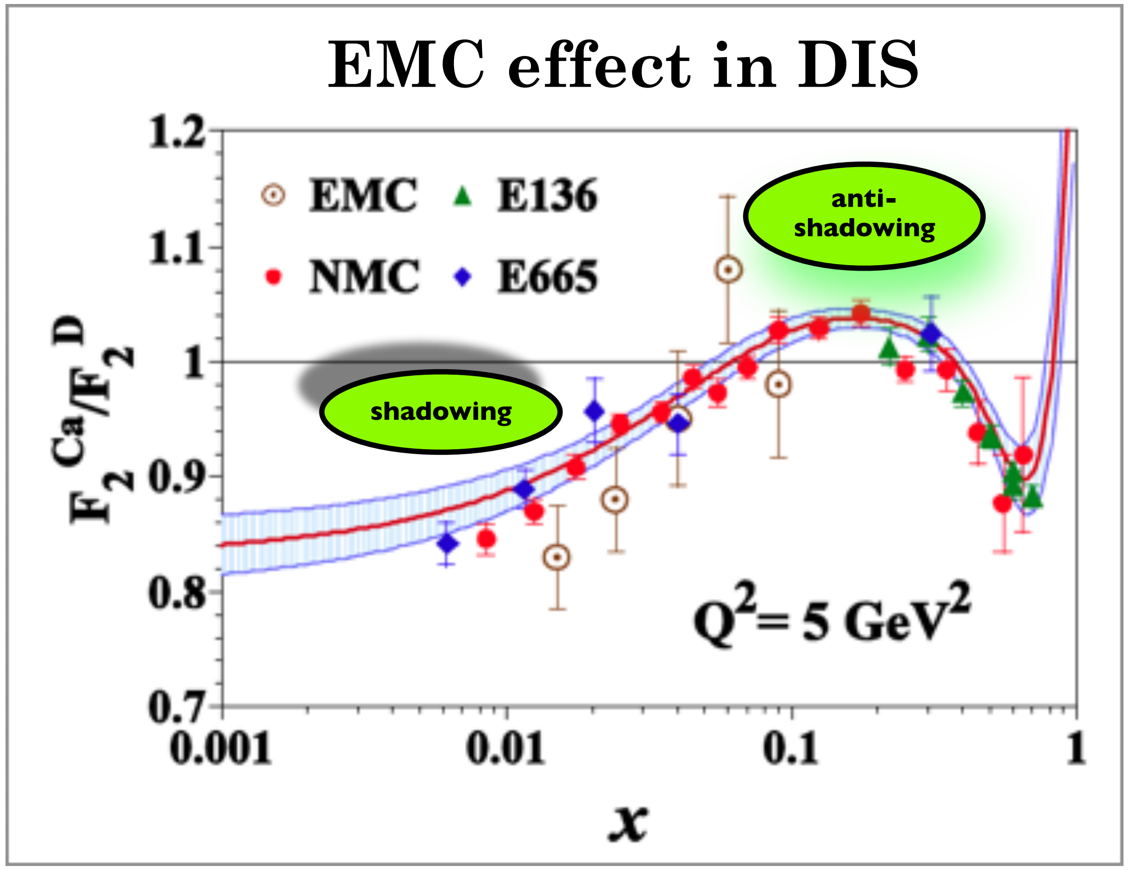
Modification of quark distributions in the nuclear medium

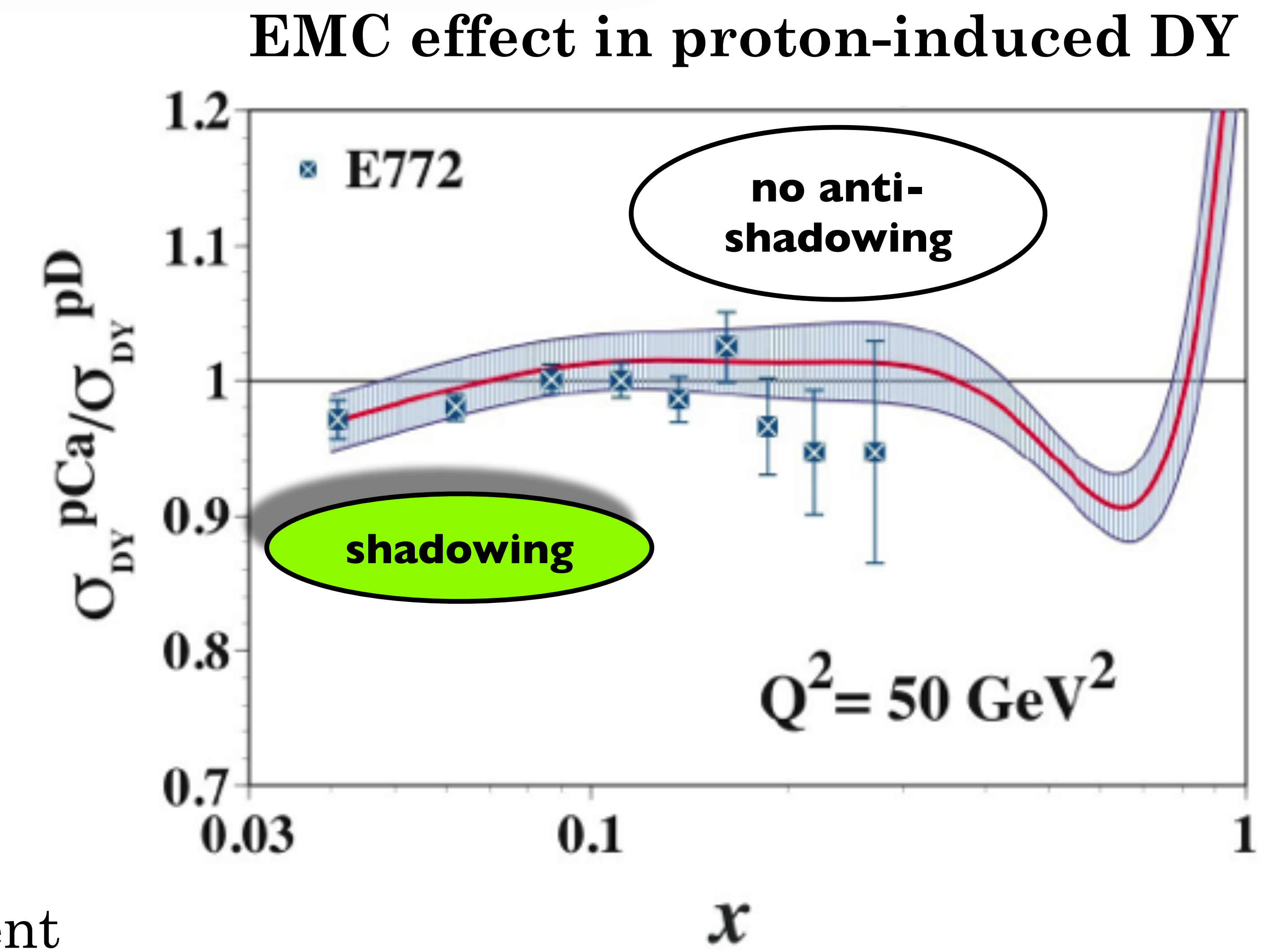
proton-induced DY



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

EMC effect in Drell Yan



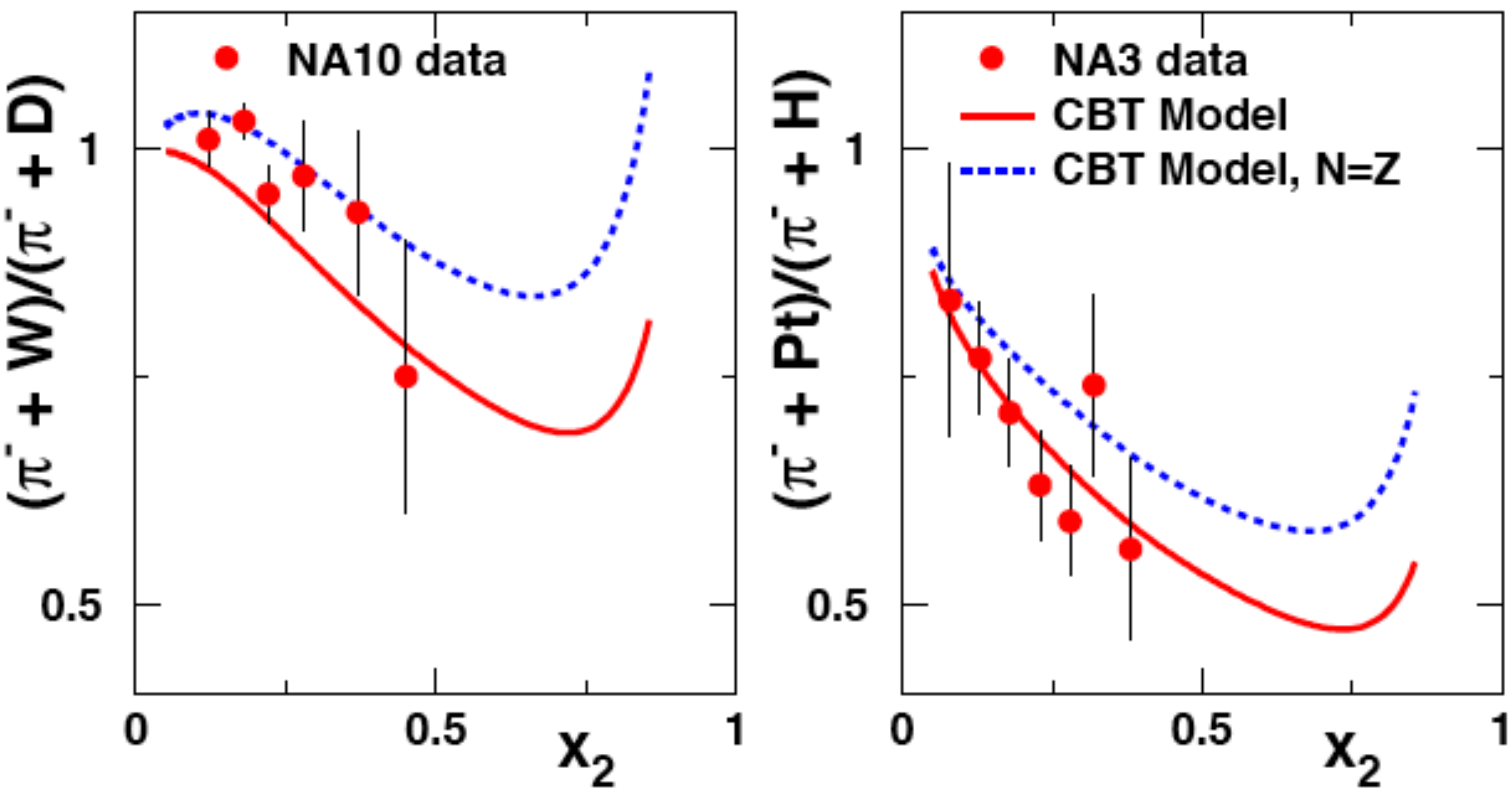


- EMC effect: many models with different input physics. DIS data sufficient as probe?
- DY: no excess pions! Traditional meson-exchange model?
- Contemporary models: large effects for anti-quarks as x increases.

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



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

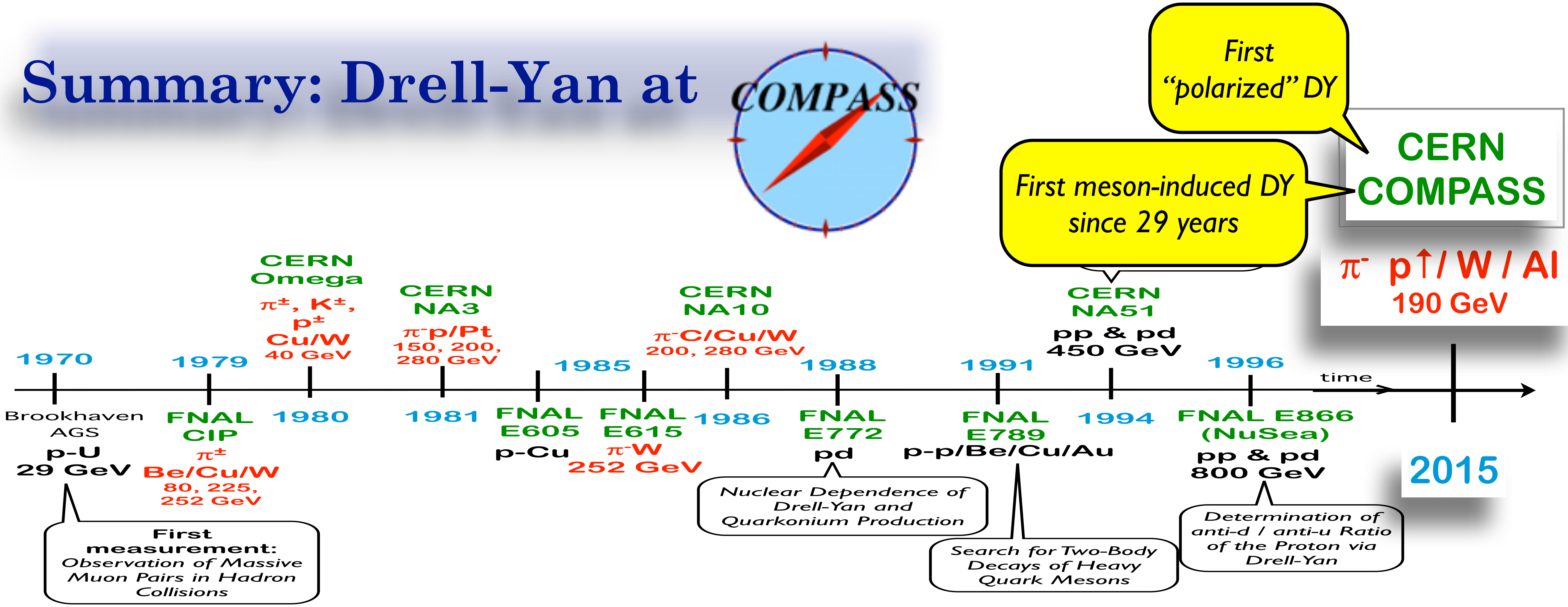
flavor-independent EMC effect

flavor-dependent EMC effect

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916

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

Summary: Drell-Yan at COMPASS



- Measure modulations of TMDs in Drell Yan.
  Sivers, Boer-Mulders: sign switch in Drell-Yan vs. SIDIS?
- Confirmation of violation of Lam-Tung relation in pionic DY?
- Flavor-dependence of EMC effect? Nuclear dependence of BM TMD?
- Outlook:
  - 2nd year of Drell-Yan @COMPASS beyond 2017 is planned.

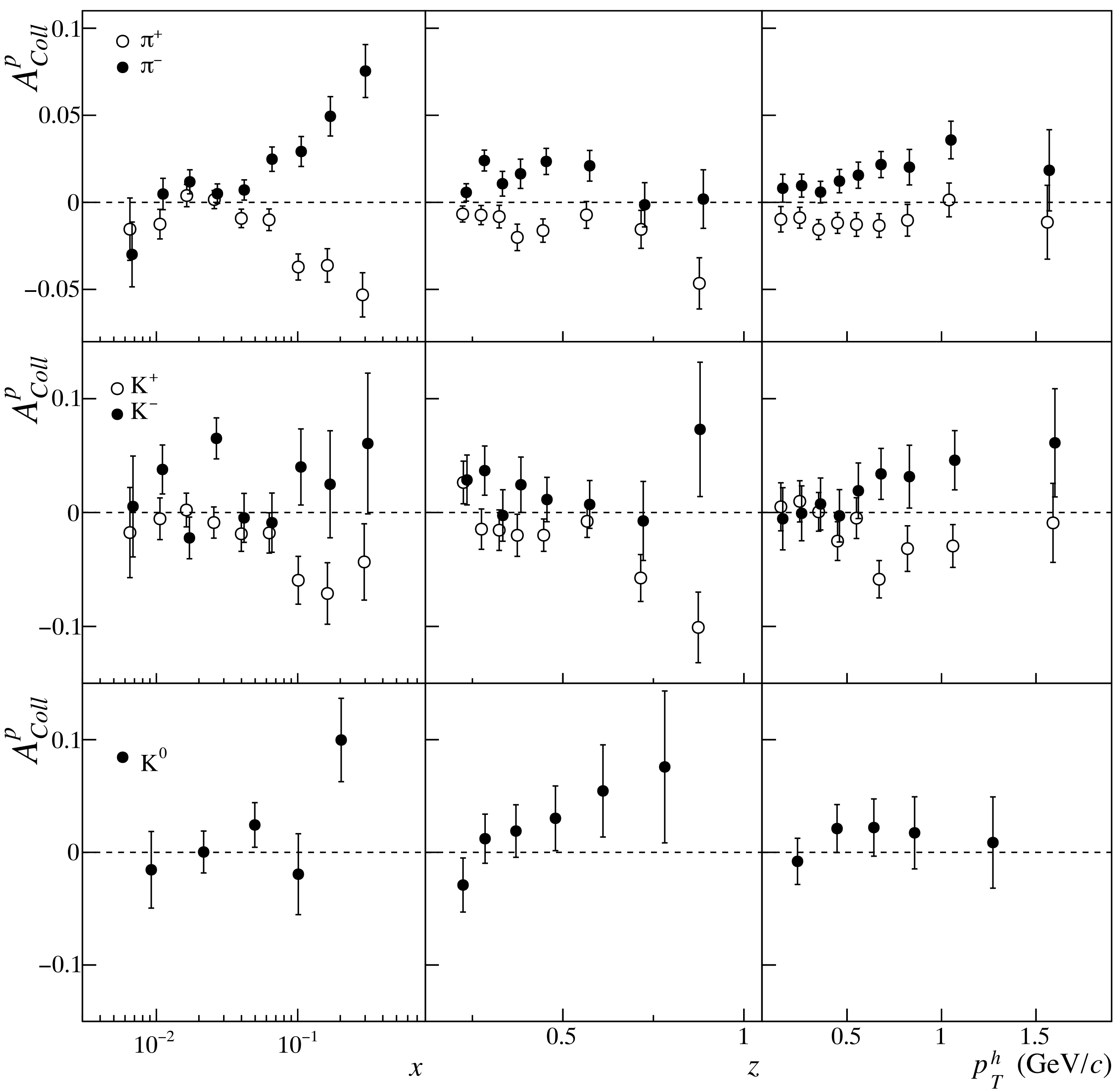
Much of the material shown in this talk is courtesy of the COMPASS collaboration. Special thanks to Catarina Quintans (DY convener), Michela Chiosso (run coordinator 2015), Marcia Quaresma (2014 analysis), and Oleg Denisov (spokesperson).

COMPASS-II 2010 proposal recommended by SPSC and approved by the Research Board for a first period of 3 years including 1 year for **Drell-Yan**.
http://wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

Backup

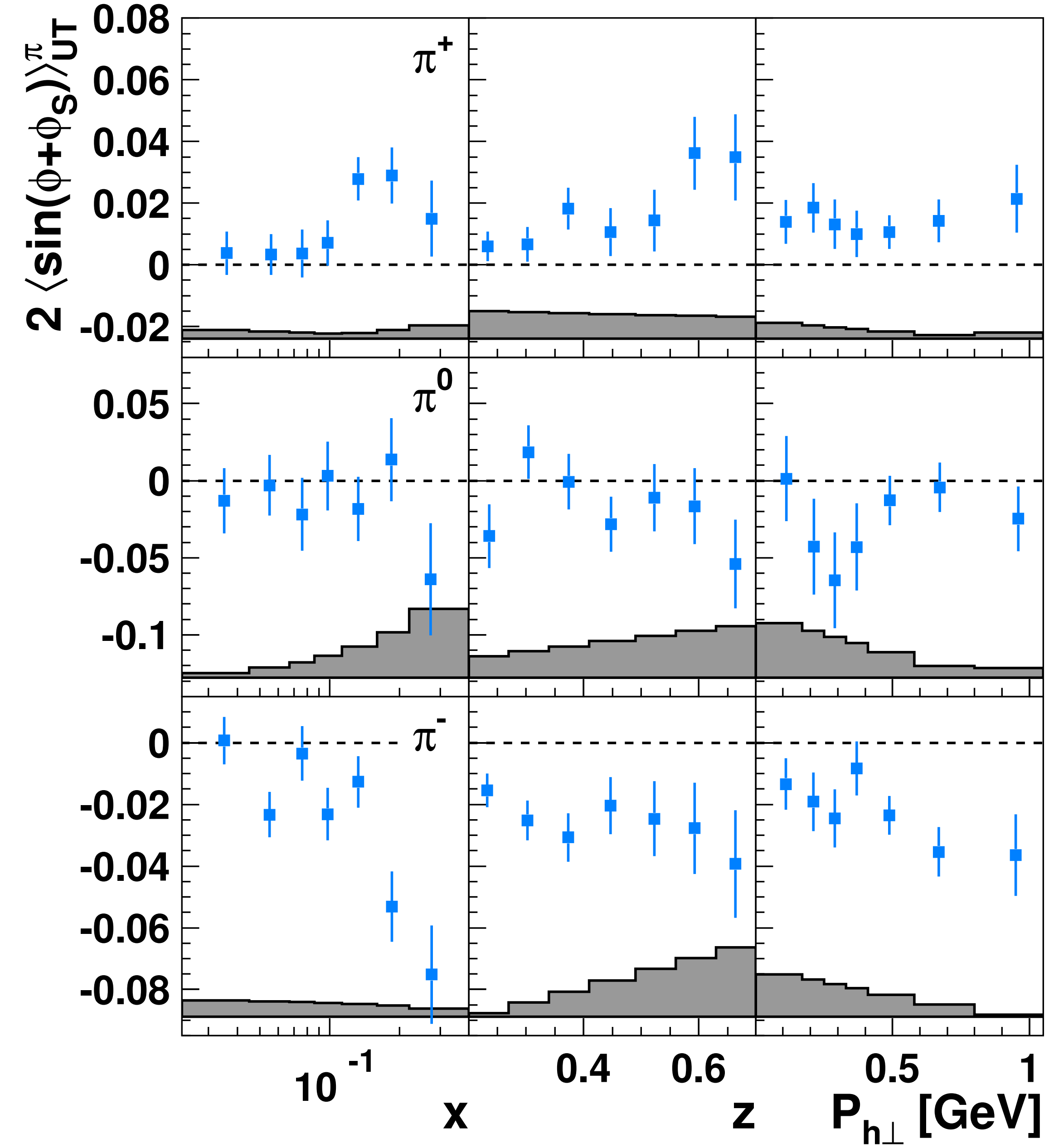
Collins amplitudes in SIDIS

COMPASS



PLB 744 (2015) 250

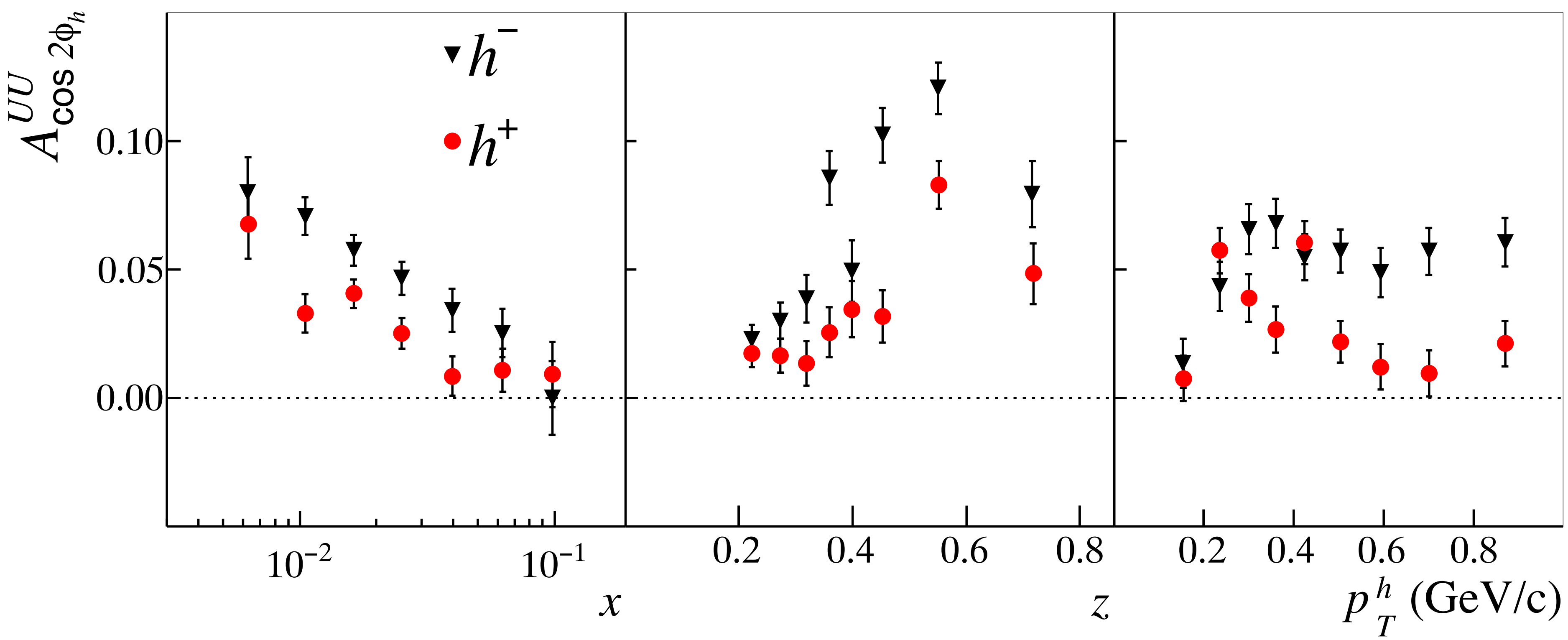
HERMES

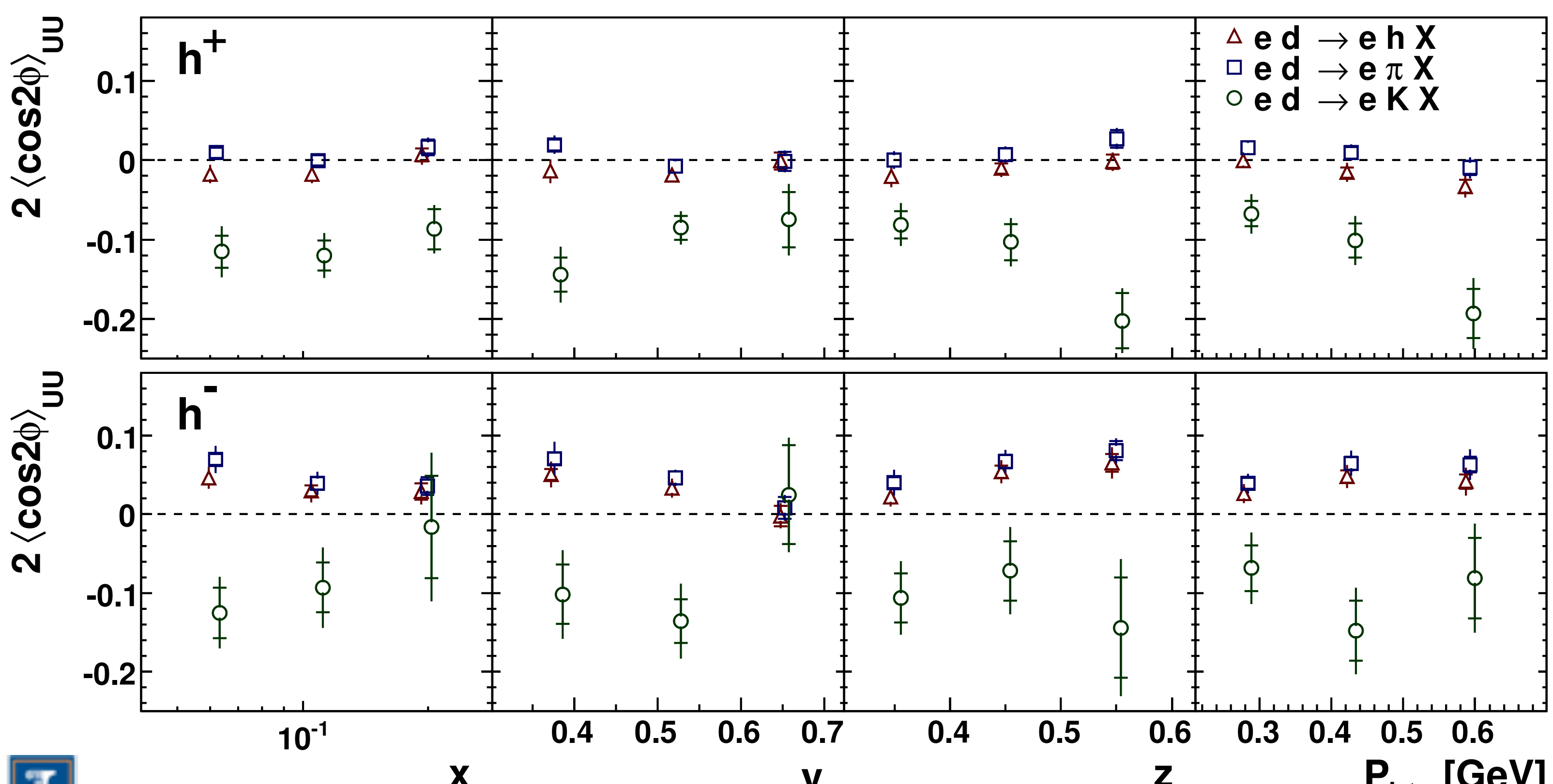


PLB 693 (2010) 11

cos(2ϕ) amplitudes (BM)

COMPASS (LiD) NPB 886 (2014) 1046



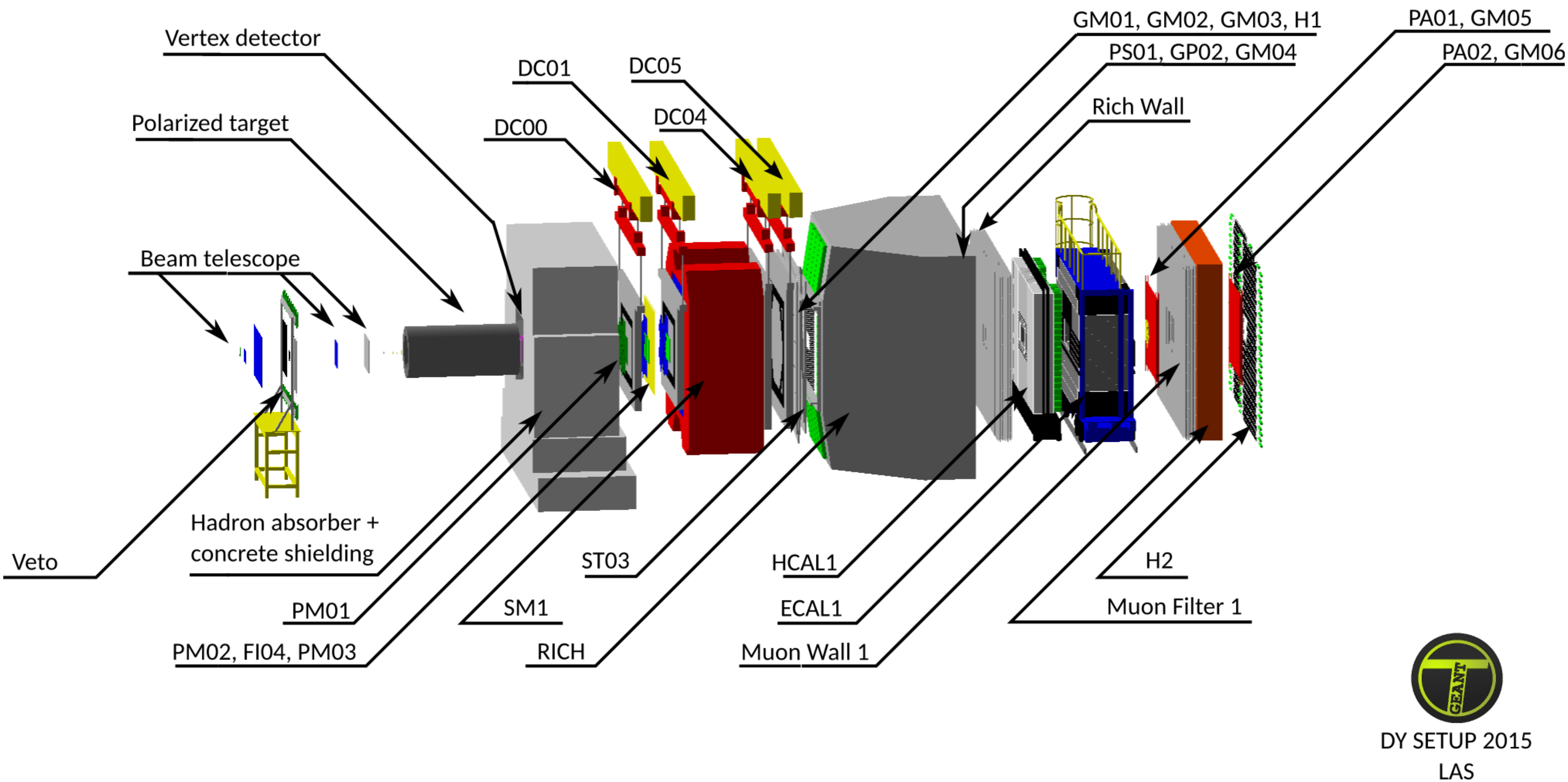


HERMES (deuteron)
Results on proton very similar.

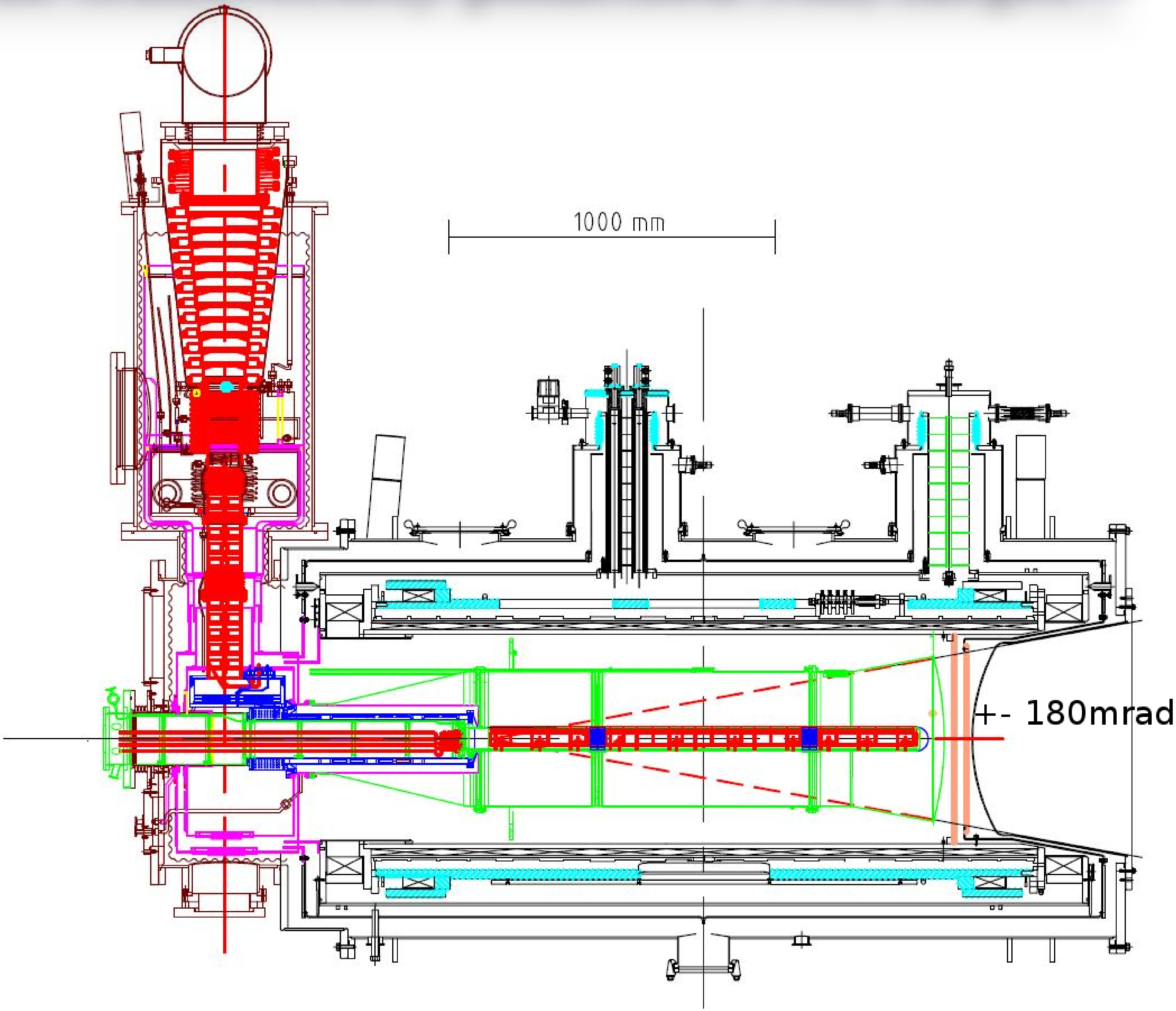
PRD 87 (2013) 012010

Red HERMES points vs. COMPASS???
h+: H=slightly negative, C=up to +0.05
h-: H=+0.05, C=+0.05

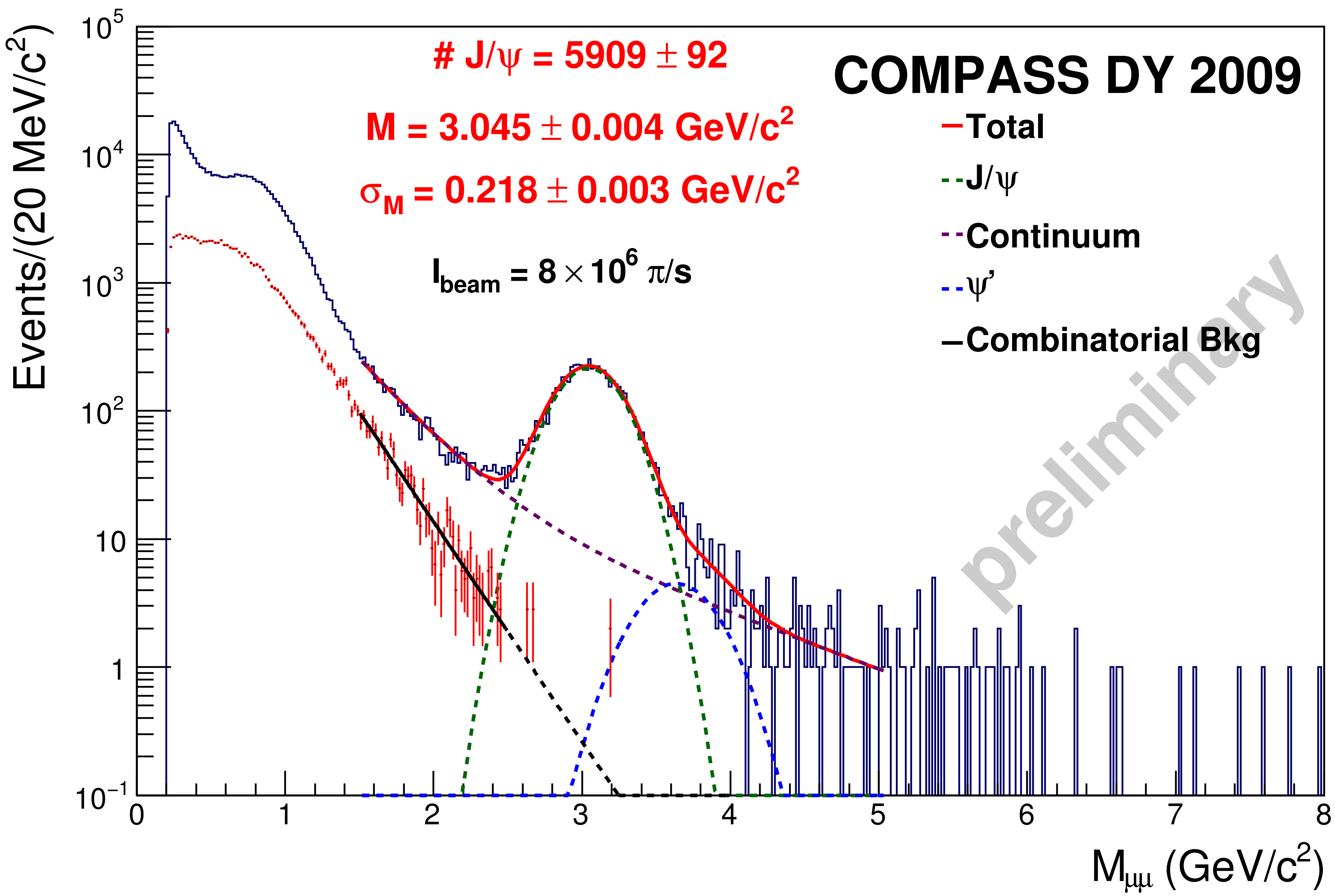
COMPASS Large Angle Spectrometer 2015



The transversely polarized NH_3 target



COMPASS beam test 2009



Beam test 2009: 190 GeV π^- beam on 2x 40cm-CH_2 cells

2014 data: technical release (2015)

Disclaimer: all plots in this talk containing COMPASS 2014 data (DY pilot run) are preliminary.

Selection criteria for muon pairs:

1. All opposite dimuons pairs with a primary vertex.
2. Dimuon trigger (Middle+LAST or Outer+LAST or LAST+LAST).
3. $\theta\mu- > 12$ mrad or $p\mu- < 100$ GeV/c, to reject pairs with the negative muon coming from the pion beam decay.
4. $-350 < Zvtx < -145$ cm, to select vertices in the ammonia target cells.
5. $rvtx < 2.5$ cm, to select vertices within the radius$\pm$0.5 cm of the ammonia cells.
6. $Zlast > 1500$ cm, to select muons with the last measured point after MF1.
7. $Zfirst < 300$ cm, to select muons with the first measured point before SM1.
8. $t\mu$ defined, muons with time defined.
9. $|t\mu1 - t\mu2| < 15$ ns, time difference between the two muons lower than 15 ns.
10. Trigger validation, requiring that the selected muons are in the geometrical acceptance of the hodoscopes of the corresponding fired trigger.
11. Image cut, requiring that the pair would be geometrical accepted if their muons have the opposite charge. This cut is a requirement to estimate the combinatorial background.

(The image cut "symmetrizes" the acceptance with respect to the muon charge.)

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!

- 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

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.

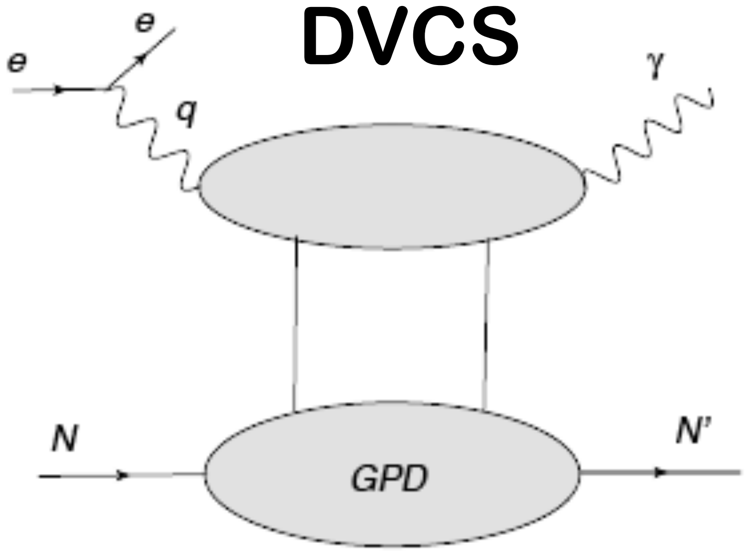
- Other theoretical interpretations:
  - QCD higher-twist effect causes change of virtual-photon polarization from transversely (λ=1) to longitudinally (λ=-1) polarized for $x_\pi \rightarrow 1$?
    - Data taken at different $\sqrt{s}$: pion: 11 GeV and 16 GeV; proton: 39 GeV.
    - Such effect should 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.

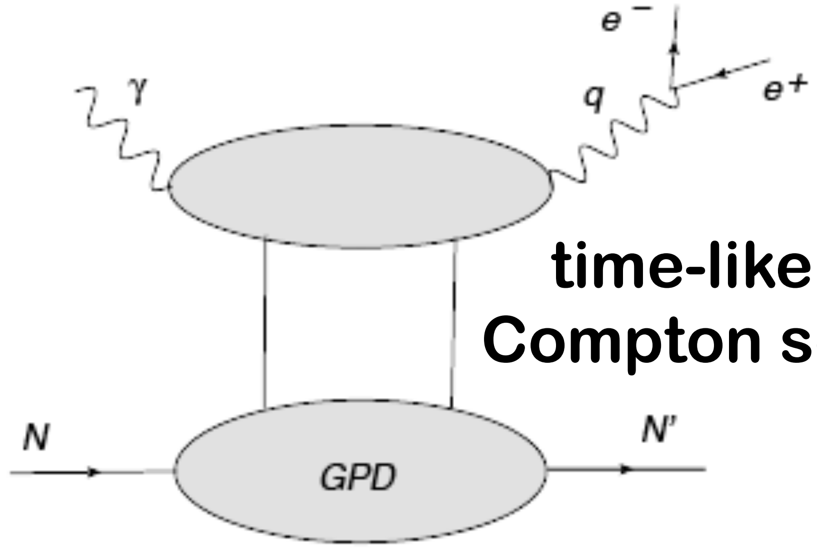
Pion-induced exclusive Drell-Yan

$\pi^- N \rightarrow N' \mu^- \mu^+$

DVCS



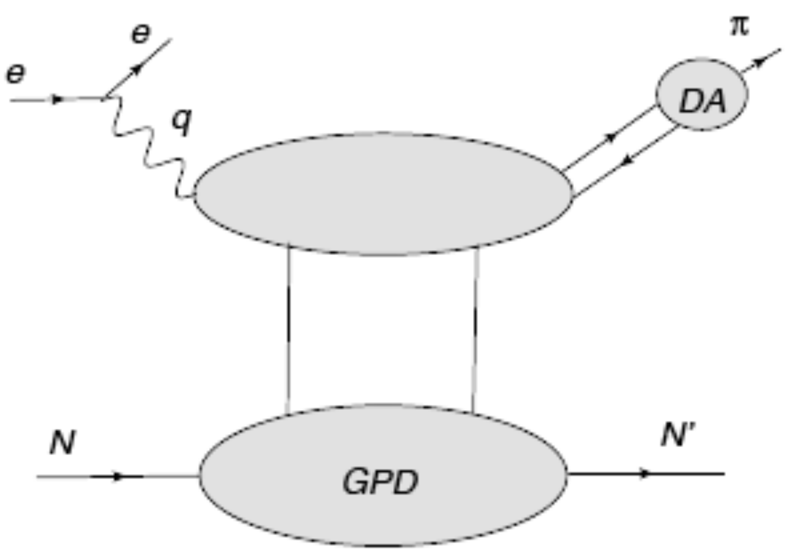
(a)



(b)

time-like virtual Compton scattering

Priv. Comm. Peter Kroll (2015): cross sections for exclusive DY at COMPASS are expected to be a factor of 1000 smaller than at J-Parc.

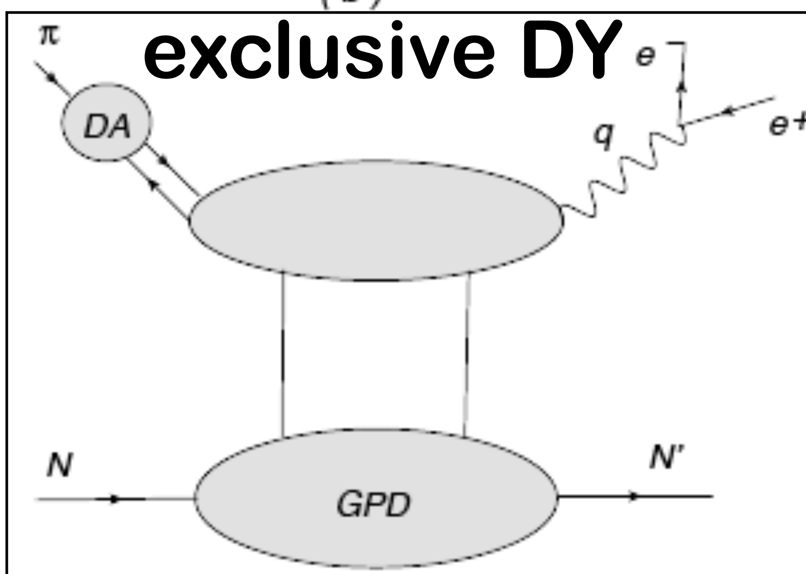


(c)

hard exclusive pion production (DVMP)

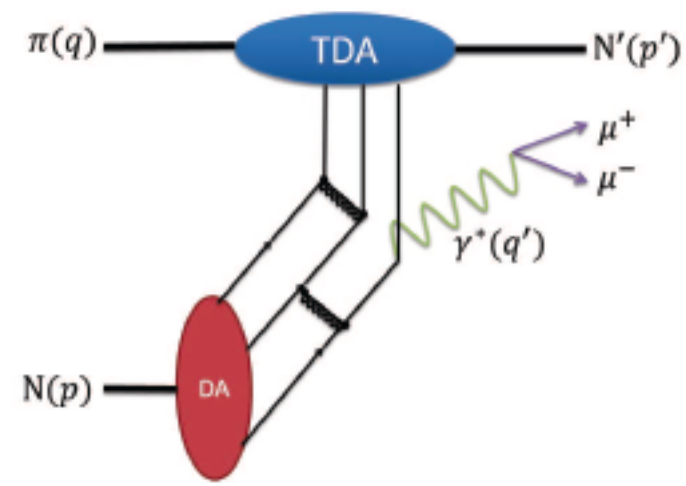
space-like

exclusive DY



(d)

Preferred @lower beam energy to enhance exclusive cross section

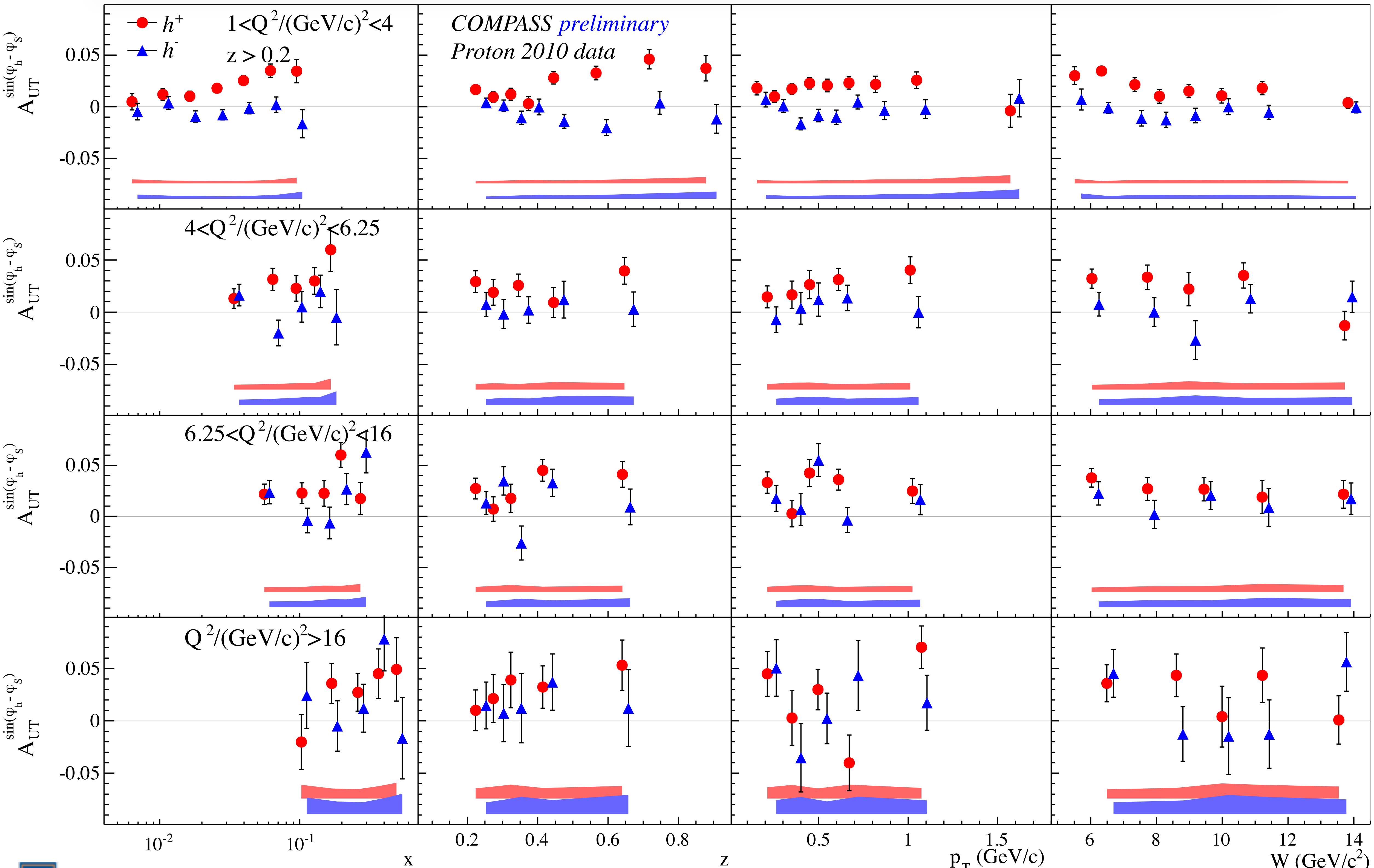


@larger momentum transfer to the target: involves TDA = nucleon-to-pion Transition Distribution Amplitude

time-like

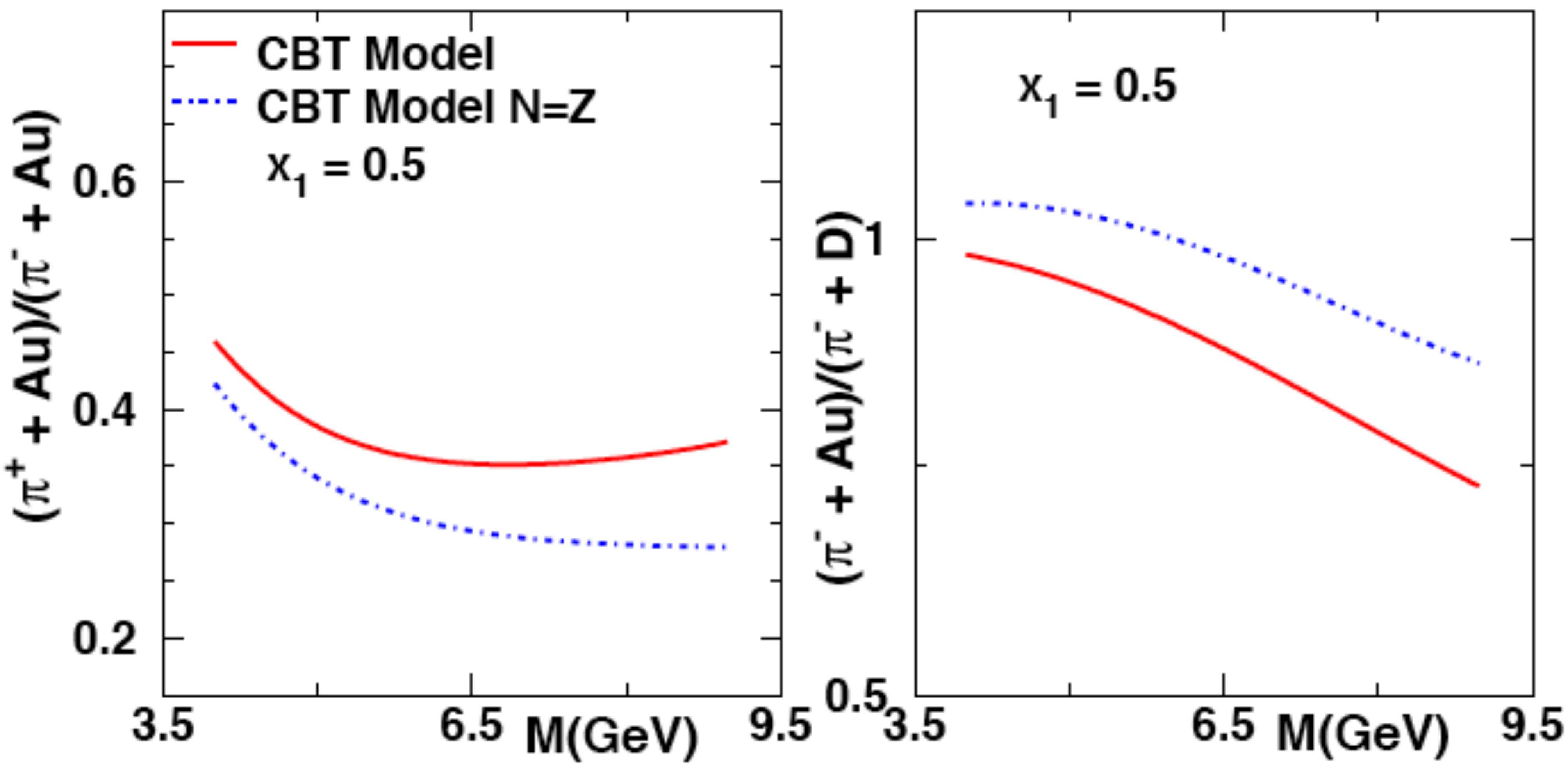
Mueller, Pire, Szymanowski, Wagner: **On timelike and spacelike hard exclusive reactions,** arXiv:1203.4392

SIDIS Sivers in DY kinematic region



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

A new drift chamber for COMPASS