Nucleon Spin Structure from Experiments using the Drell-Yan Process

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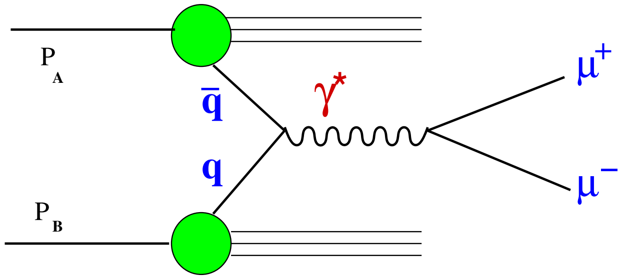
CERN/FIS-NUC/0017/2015

Drell-Yan – the origins

Drell-Yan process: proposed in **1970** to explain the **massive dilepton spectrum** from hadronic collisions, first observed at BNL.

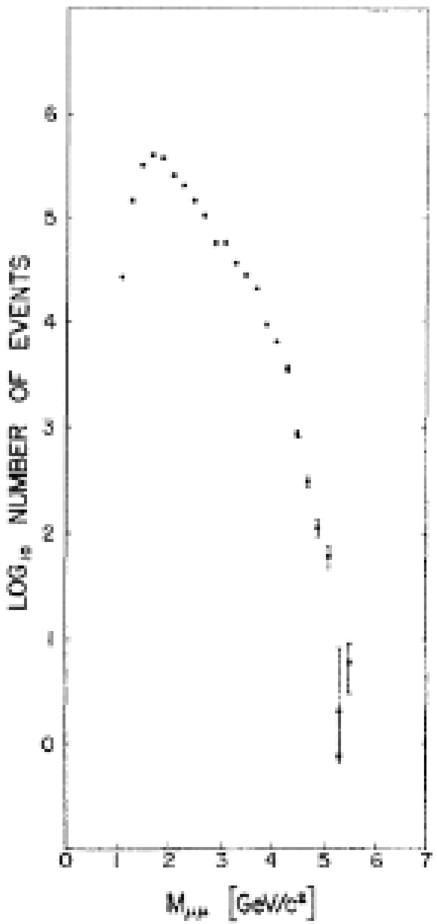
S.D. Drell and T.M. Yan, Phys.Rev.Lett. **25**, 316 (1970)



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

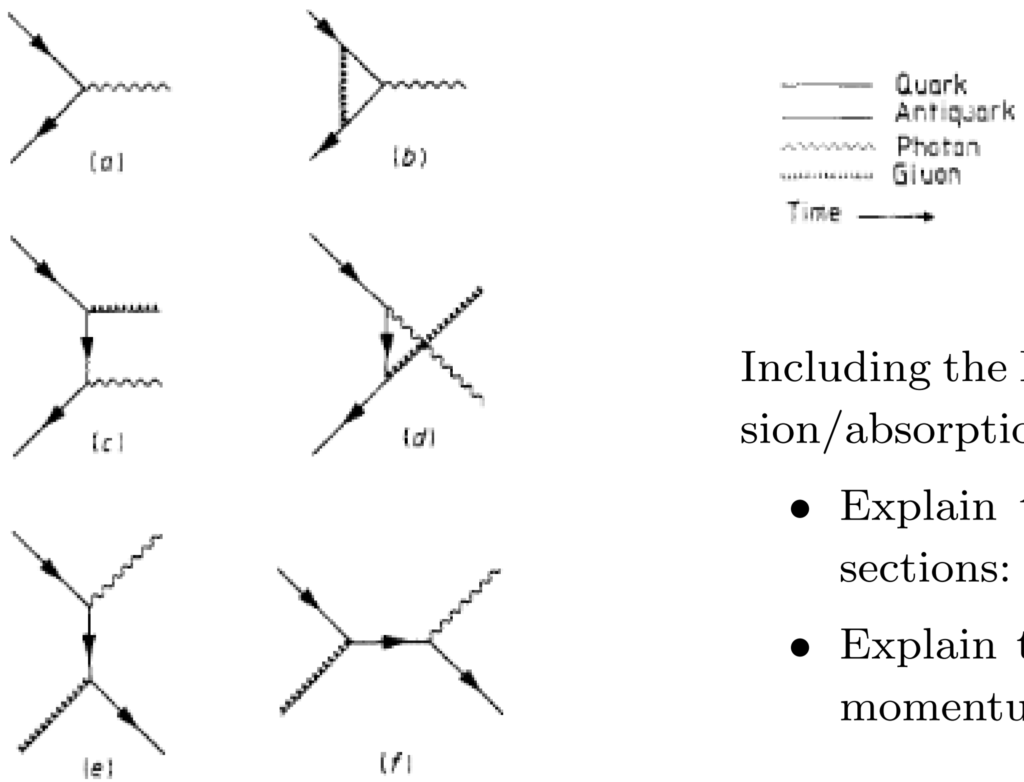
proton beam @20-30 GeV/c

Christenson et al, Phys.Rev.Lett. **25**, 1523 (1970)



Drell-Yan – well-understood process

Soon it was understood one needs to go beyond the naive parton model picture:



Including the LO QCD effects of gluon emission/absorption/scattering to fix problems:

- Explain too large experimental cross-sections: k_{DY} factor ≈ 2
- Explain too large dileptons transverse momentum

I.R. Kenyon, Rep.Prog.Phys., Vol. 45, 1982.

Nowadays, NNLO QCD calculations lead to k_{DY} factor $\approx$ 1.

Drell-Yan generalized

Same mechanism applies to having other electroweak Gauge bosons as mediators to the $q\bar{q}$ annihilation and production of lepton pair: γ, but also Z and W.

- In fixed target experiments with hadron beams
- In hadron colliders

...and spanning a wide energy range

Experiment	type	$\sqrt{s}(GeV)$	when
NA3 (CERN)	fixed target; $\pi^{\pm}$ W	16.8, 19.4, 22.9	1983
NA10 (CERN)	fixed target; π^{-} W	19.1	1985
E615 (FNAL)	fixed target; π^{-} W	21.8	1989
NA51 (CERN)	fixed target; pp, pd	29.1	1994
E866 (FNAL)	fixed target; pp, pd	38.8	1998
CDF (Tevatron)	collider; $p\bar{p}$	1960	2004-2007
STAR (RHIC)	collider; $pp^{\uparrow}$	500	2011
E906 (FNAL)	fixed target; pp, pd, pC, pW	15.1	2012
COMPASS (CERN)	fixed target; $\pi^{-}p^{\uparrow}$, pAl, pW	18.9	2014-2015
CMS (LHC)	collider; pp	8000	2010-
ATLAS (LHC)	collider; pp	8000	2010-

* List not complete.

DY cross-section

The inclusive Drell-Yan cross-section includes a **convolution of 2 PDFs**, and the short distance **partonic cross-section** of the annihilating partons, which is perturbatively calculable:

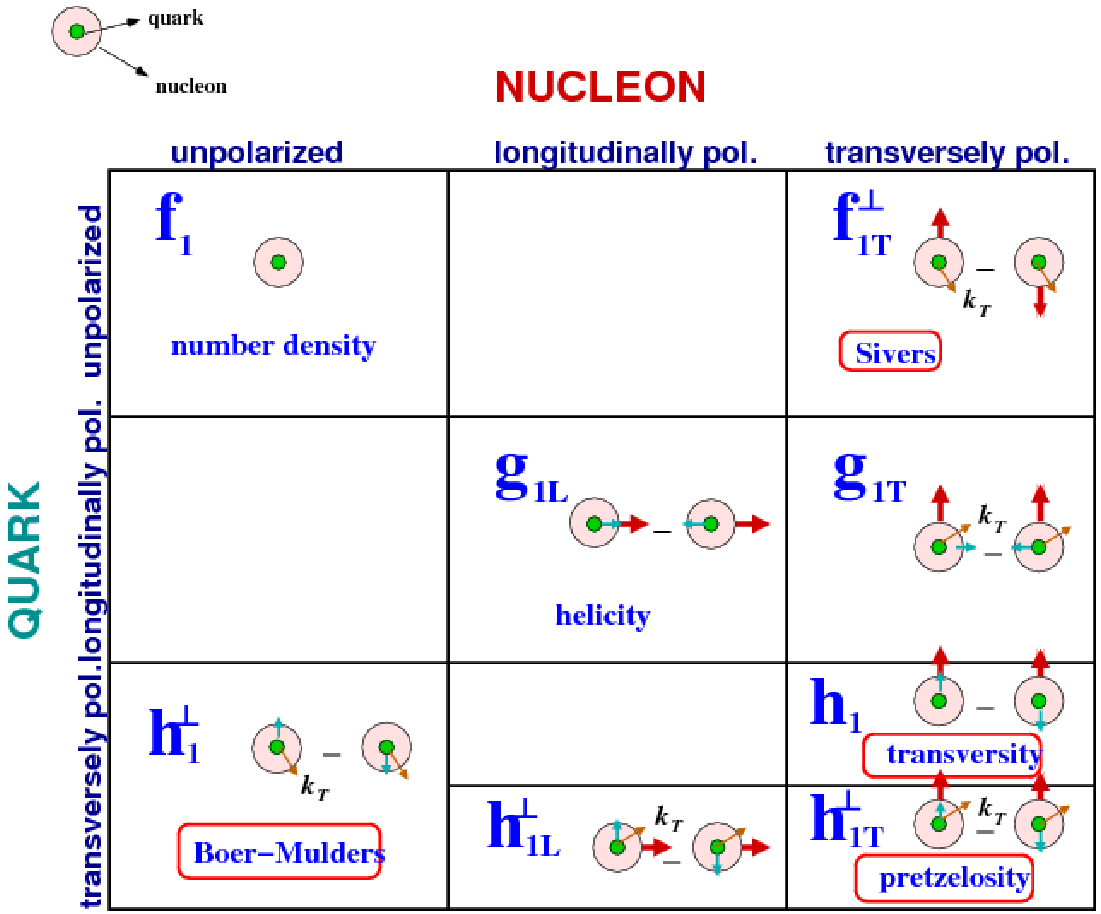
$$\frac{d\sigma_{AB\to l\bar{l}X}}{dQ^2dy} = \sum_{ab}\int_0^1 dx_a \int_0^1 dx_b\ \Phi_a^A(x_a,\mu)\ \Phi_b^B(x_b,\mu)\ \frac{d\hat{\sigma}_{ab\to l\bar{l}}(x_a,x_b,Q,\mu,\alpha_s)}{dQ^2dy}$$

The Drell-Yan cross-section is QCD factorizable, for unpolarized and also polarized cases.

↪Drell-Yan process is an optimal tool to extract information on the PDFs (and TMD PDFs) – complementary to DIS/SIDIS.

TMD PDFs

At leading-twist, if we consider the quarks k_T, 8 transverse momentum dependent PDFs are needed to describe the nucleon. If integrated in k_T, 3 PDFs remain.



Each of these TMD PDFs corresponds to a given correlation among

- polarization of the nucleon,
- transverse spin of the parton,
- intrinsic transverse momentum of the parton.

Flavor asymmetry in light quarks sea

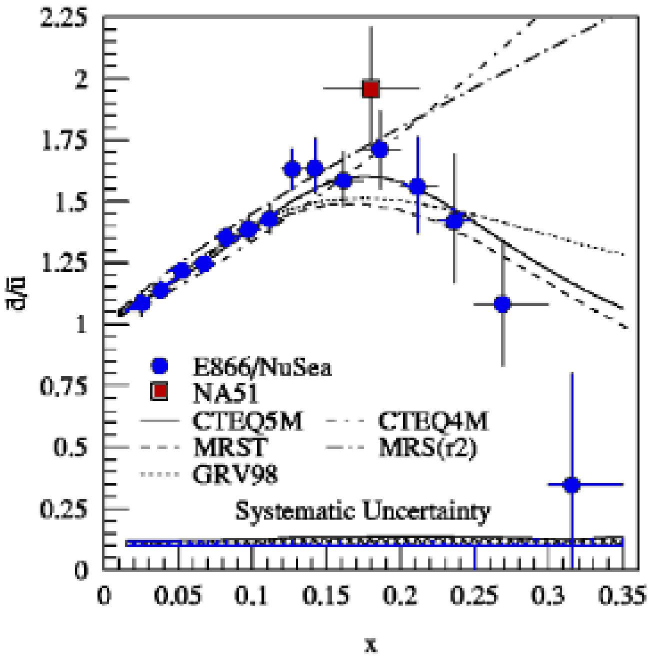
The NMC experiment at CERN was the first to obtain experimental evidence that the nucleon sea is not flavor symmetric.

The **proton induced Drell-Yan process** emerged as an alternative to DIS in measuring, in a rather direct way, the $\bar{u}/\bar{d}$ asymmetry.
S.D. Ellis and W.J. Stirling, Phys.Lett.B **256**, 258 (1991)

$\hookrightarrow$ First measured by NA51 at CERN:
pp and pd collisions, 450 GeV proton beam

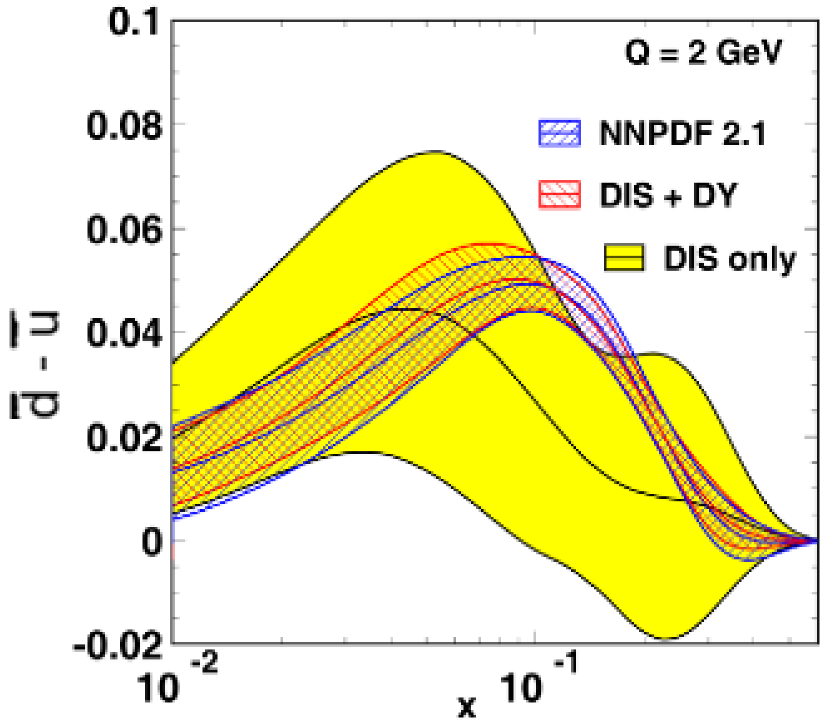
$\hookrightarrow$ Extended measurements by E866 (NuSea) at Fermilab: pp and pd collisions, 800 GeV proton beam

$$\frac{\sigma_{DY}(pd)}{2\sigma_{DY}(pp)}\Big|_{x_1 \gg x_2} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$



NA51, Phys.Lett.B **332**, 244 (1994)
E866, Phys.Rev.D **64**, 052002 (2001)

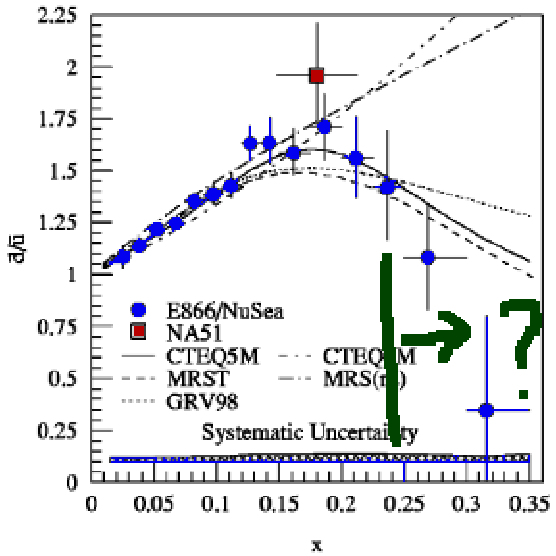
Impact to the sea quarks PDFs knowledge



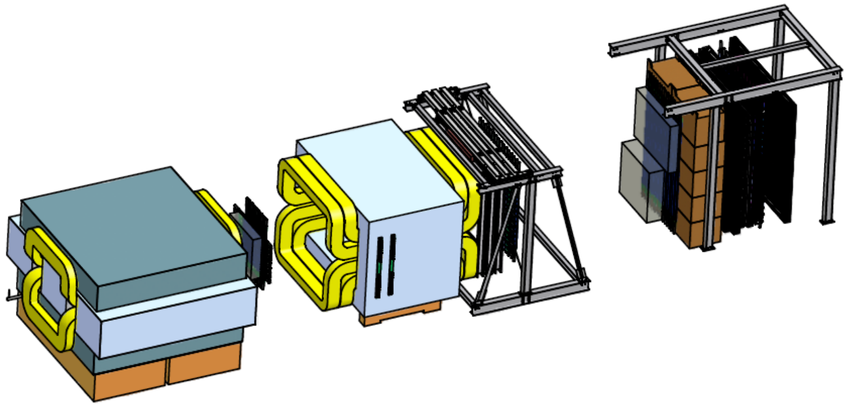
The Drell-Yan data is crucial for the precision of the light sea PDFs extraction.

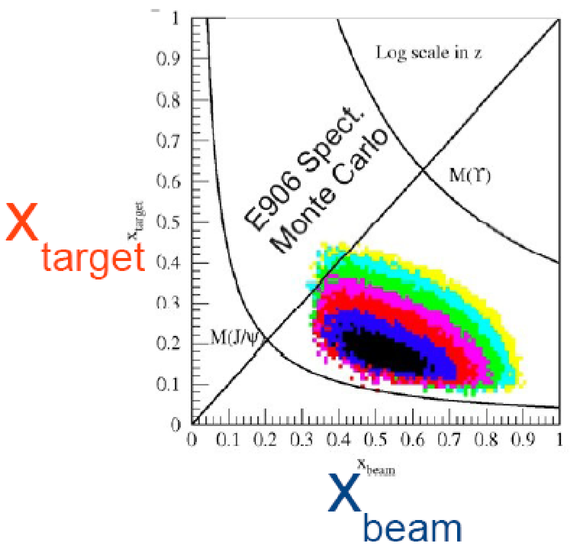
E.Perez and E.Rizvi, Rep.Prog.Phys. 76, 046201 (2013)

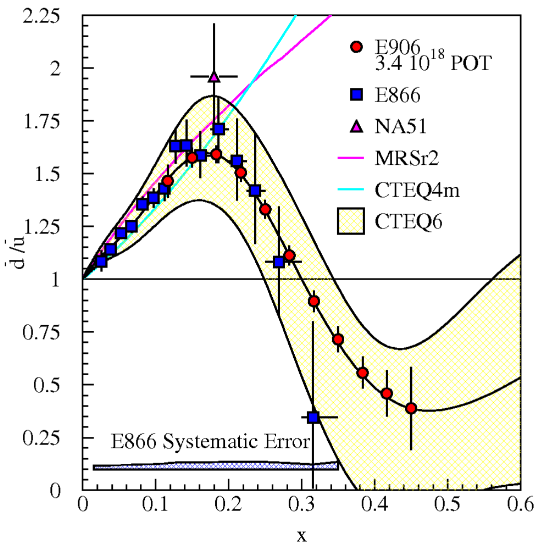
$\bar{d}/\bar{u}$ at large x_2



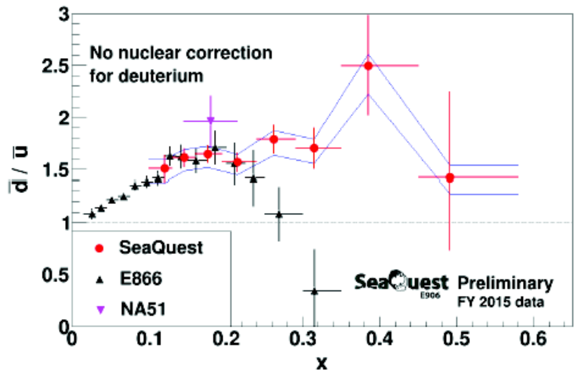
E906 (SeaQuest) experiment at Fermilab uses a 120 GeV proton beam to extend the measurement to **large** x_2.







Preliminary results: April 2016



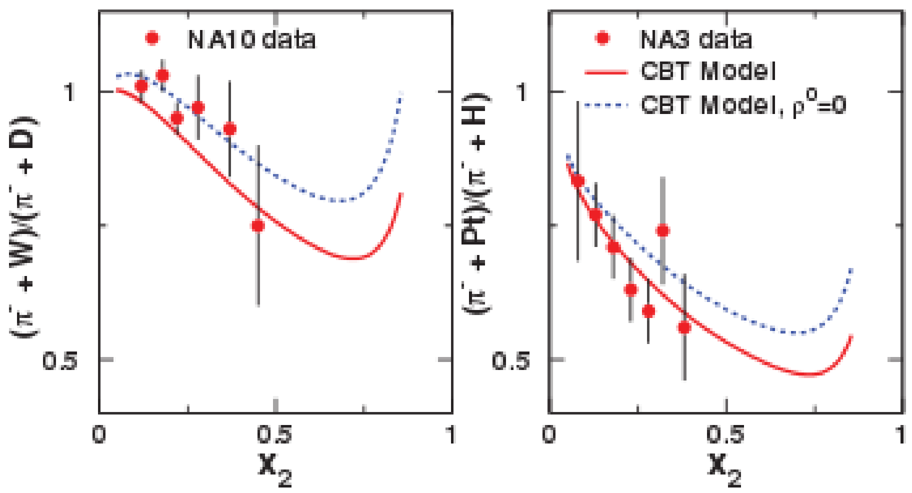
★Bryan Ramson talk, tuesday afternoon

Quark flavor dependence of EMC effect

The EMC effect was first observed in DIS, as a modification of the PDFs in nuclei. Its quark flavor dependence is still to be understood.

Another way: the **pion induced Drell-Yan processes**.

$$\frac{\sigma_{DY}(\pi^- + A)}{\sigma_{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)} \quad ; \quad \frac{D_{DY}(\pi^- + A)}{\sigma_{DY}(\pi^- + H)} \approx \frac{u_A(x)}{u_p(x)}$$



Cloet, Bentz and Thomas model (CBT): the ρ^0 mean field in a $N \neq Z$ nucleus makes that u and d quark distributions are modified differently.

Phys.Lett.B **642**, 210 (2006)

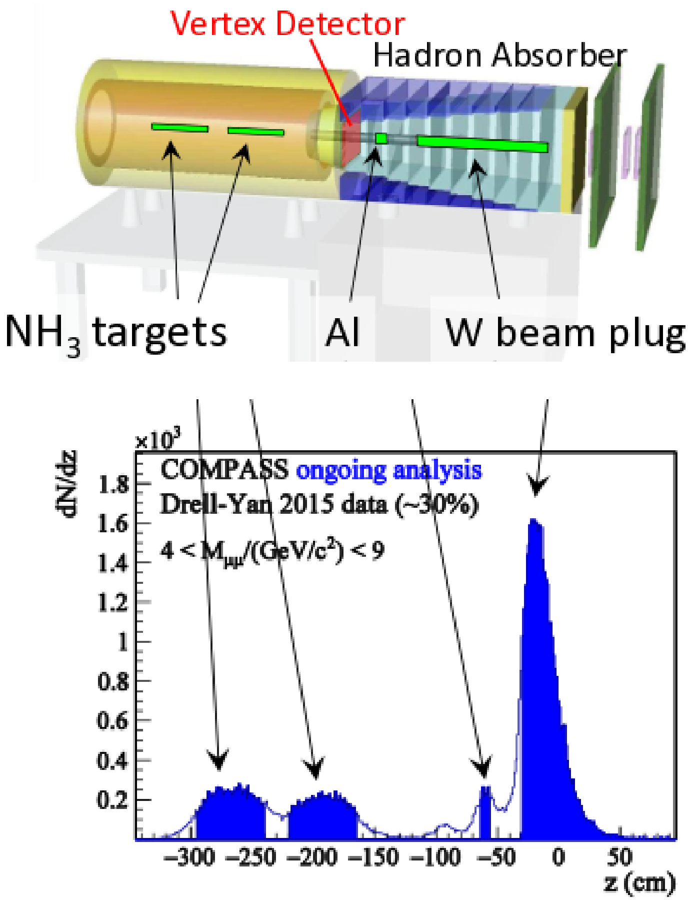
But: past data not precise enough to answer.

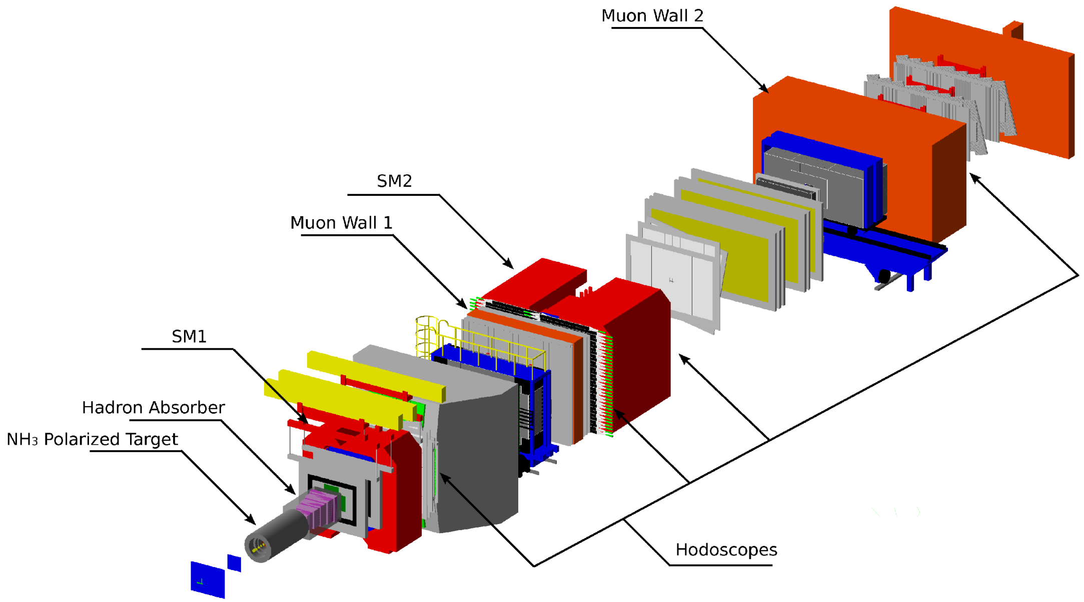
NA3, Phys.Lett.B **104**, 335 (1981)

NA10, Phys.Lett.B **193**, 368 (1987)

Quark flavor dependence of EMC effect

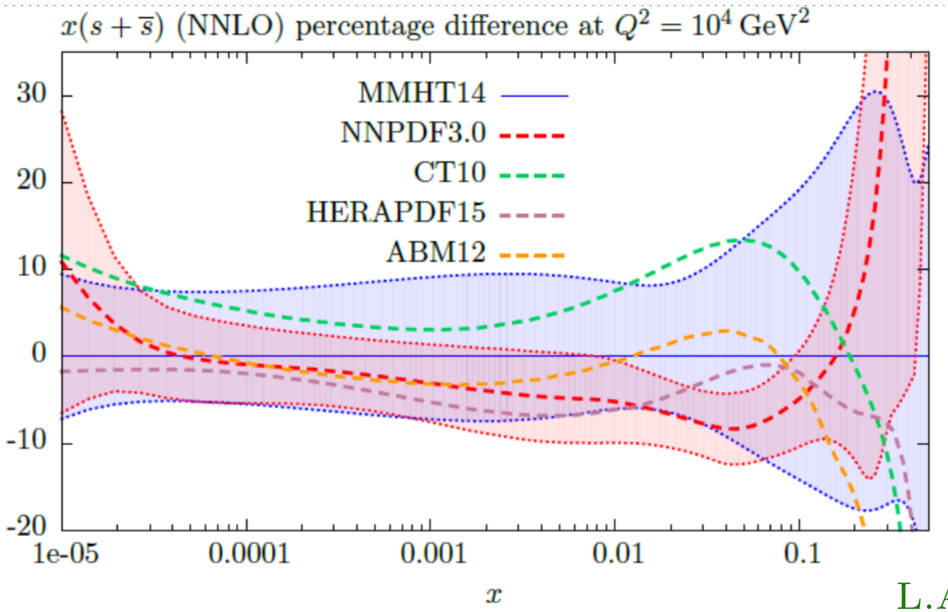
The new measurements from the COMPASS experiment at CERN, from data taken in (2014/2015) using π^- **beam** of 190 GeV on **NH_3, Al and W targets** are expected very soon.





Strange quark distribution

Still large uncertainties in the valence region. Data coming mostly from DIS (HERMES and COMPASS), but input from fragmentation functions needed.



L.A.

Harland-Lang et al, arXiv:1412.3989v2

The kaon induced Drell-Yan avoids the need for FFs.

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

$\hookrightarrow$Possible at COMPASS, where negative hadron beam contains 2.5% kaons.

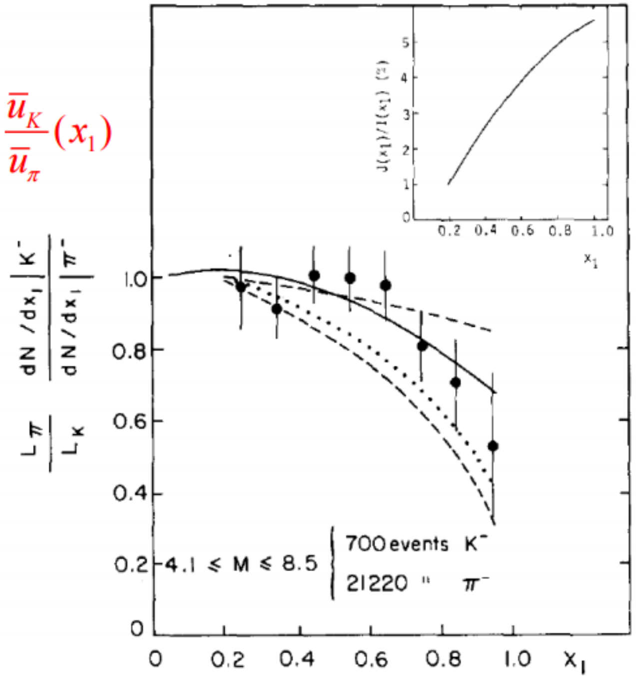
Pion and Kaon PDFs

Since more than 30 years there is no new pion induced Drell-Yan data. The new COMPASS results are expected to contribute significantly to the **pion PDFs** knowledge.

The kaon PDFs are practically unknown. The only data available is from the NA3 experiment at CERN, with very low statistics.

NA3, Phys.Lett.B 93, 354 (1980)

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



- A possible future development of COMPASS, with a kaon enriched hadron beam
- 50% K^-, 50% $\bar{p}$, via RF separation method
- Deep impact in our knowledge of the kaon PDFs

Gluon distributions

Heavy quarkonia production (J/ψ, Υ) in high energy collisions occurs mainly via the gluon-gluon fusion process. In this case:

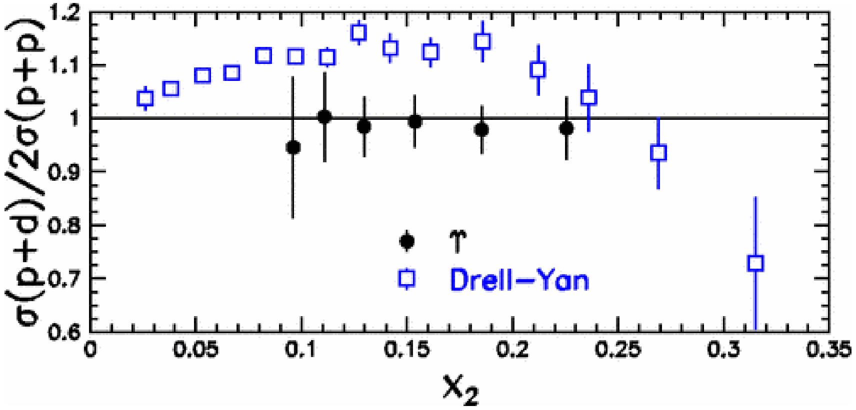
$$\frac{\sigma(p+D \to [\psi,\Upsilon]X)}{2\sigma(p+p \to [\psi,\Upsilon]X)} \approx \frac{1}{2}\left(1+\frac{g_n(x_2)}{g_p(x_2)}\right)$$

- J/ψ measurement by NA51 in $p+p$ and $p+D$ collisions at 450 GeV, integrated over x_2

NA51, Phys.Lett. B 438, 35 (1998)

- Υ measurements by E866, with proton beam at 800 GeV, as a function of x_2.

E866, Phys.Rev.Lett. 100, 062301 (2008)



Good agreement between experiments: **the gluon distributions in proton and neutron are very similar** (no charge symmetry breaking effect).

Increasing sensitivity to the gluon distributions

New measurements ongoing or planned to measure the nucleon gluon distributions from heavy quarkonia processes:

- E906/SeaQuest using $p + p$ and $p + d$ at 120 GeV, will have high statistics J/ψ and Υ samples
- COMPASS possible future measurements using $\pi^- + p$ at $\approx$ 190 GeV will produce a large J/ψ sample – but gluon-gluon fusion mechanism might not be the dominant one.
- AFTER possible future measurements using $p + p$ and $p + d$ with 7 TeV proton beam (and fixed target) would collect enourmous J/ψ and Υ samples also.

  ★ Daniel Kikola talk, thursday morning
- ... and at RHIC and LHC experiments.

Angular dependencies of the DY process

The normalized decay angle distribution for **unpolarized Drell-Yan** is:

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

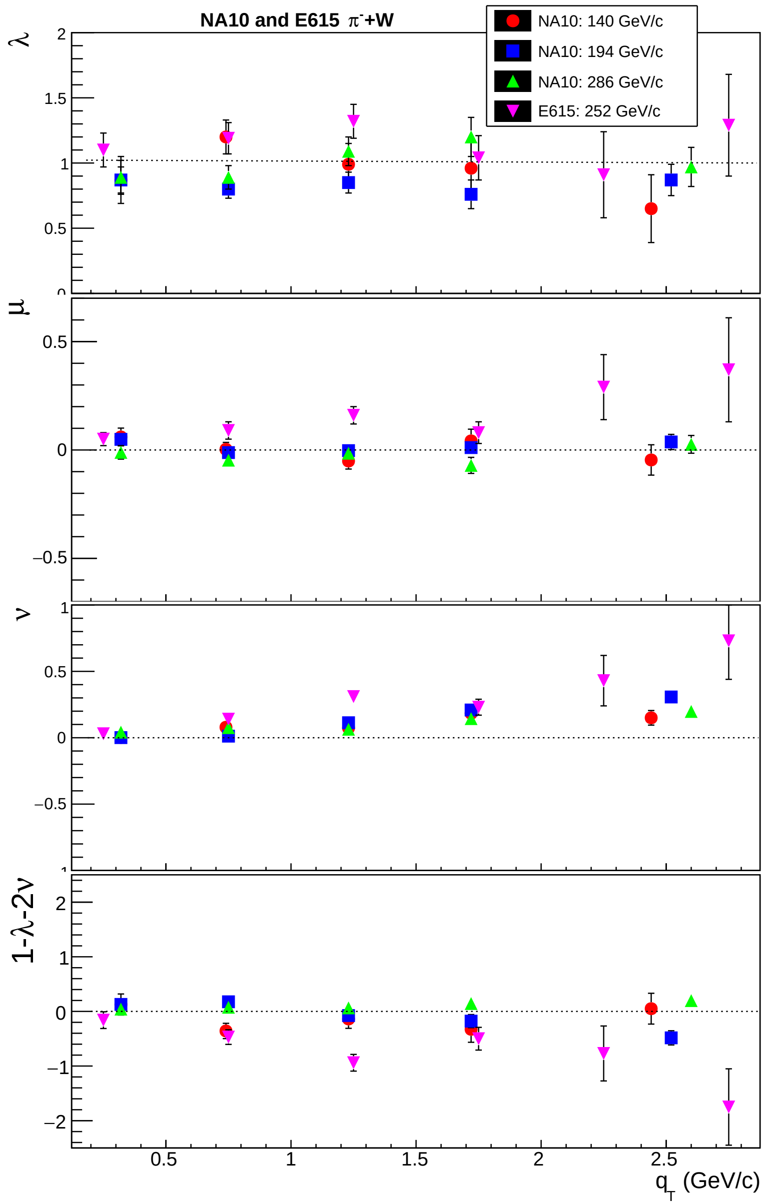
In the naive Drell-Yan model, where partons $k_T = 0$ and no QCD processes involving gluons are considered: $\lambda = 1$, $\mu = \nu = 0$.

The Lam-Tung relation, deriving from the fermion nature of quarks, predicts (even when NLO QCD effects are included):

$$\boxed{1 - \lambda - 2\nu = 0}$$

C.S. Lam and W.K. Tung, Phys.Rev. D **18**, 2447 (1978)

Violation of the Lam-Tung relation



Coefficients λ, μ and ν were first measured in the 1980's, in pion induced Drell-Yan fixed-target experiments:

NA10 at CERN: π^- beam of 140, 194 and 286 GeV/c on W target; also 286 GeV π^- beam on D.

E615 at Fermilab: π^- beam of 252 GeV/c on W target.

- Strong $\cos 2\phi$ modulation (ν) increasing with p_T, seen at both experiments
- Lam-Tung relation violated in E615, not so clear in NA10 data

NA10, Z.Phys.C 37, 545 (1988)
E615, Phys.Rev.D 39, 92 (1989)

Lam-Tung relation in pion induced DY

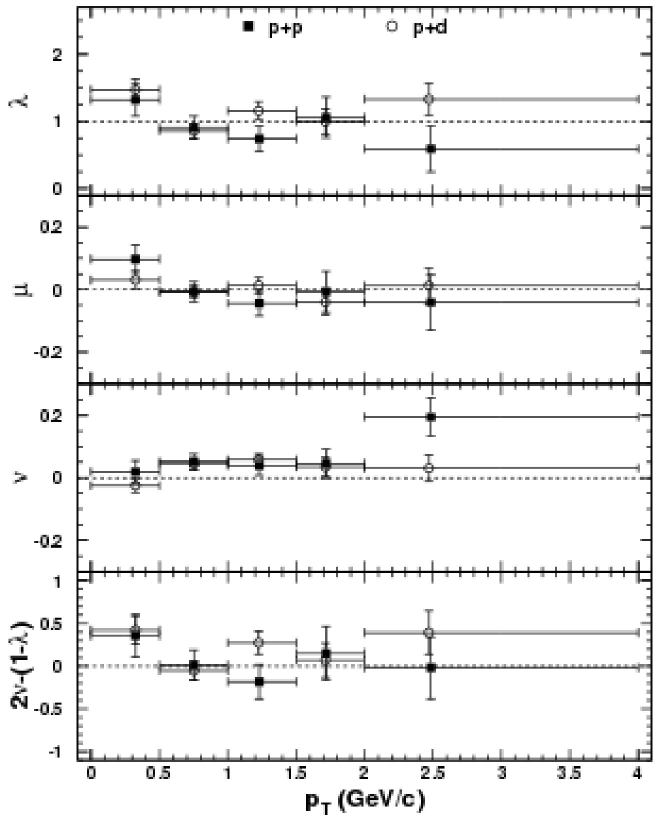
New COMPASS data on pion induced Drell-Yan, after 30 years

- Advantage over past experiments of much larger geometrical acceptance
- Two long targets (NH_3 and W)
- This kind of analysis requires a detailed Monte-Carlo, with good description of the spectrometer
- Need for multidimensional acceptance correction
- The analysis is ongoing, and results are expected in the near future.

★Luis Silva talk, tuesday afternoon

Lam-Tung relation in proton induced DY

E866 (NuSea) experiment at Fermilab also measured the angular coefficients of Drell-Yan distribution in $p + p$ and $p + d$ at 800 GeV/c.



- No significant ν values.
- No Lam-Tung violation.

While in pion induced DY there is annihilation of valence quark and antiquark, here a valence quark annihilates with a sea antiquark.

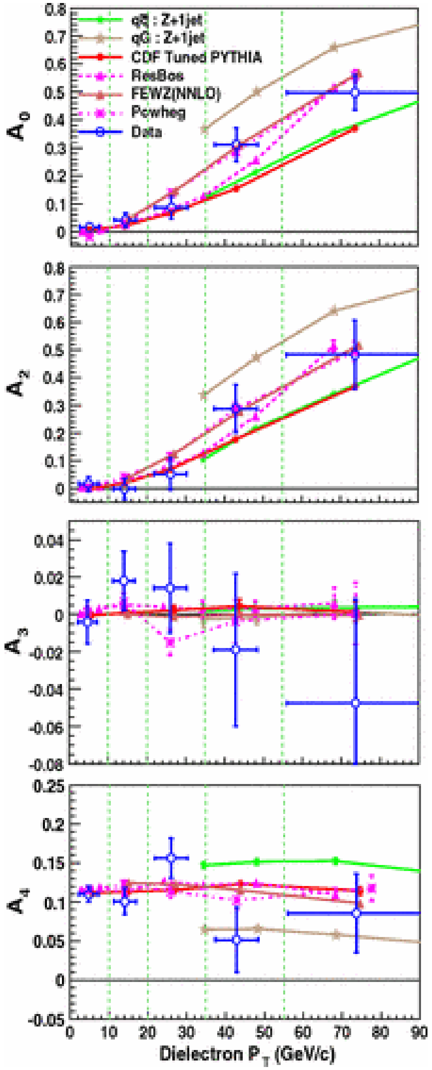
E866, Phys.Rev.Lett. **102**, 182001 (2009)

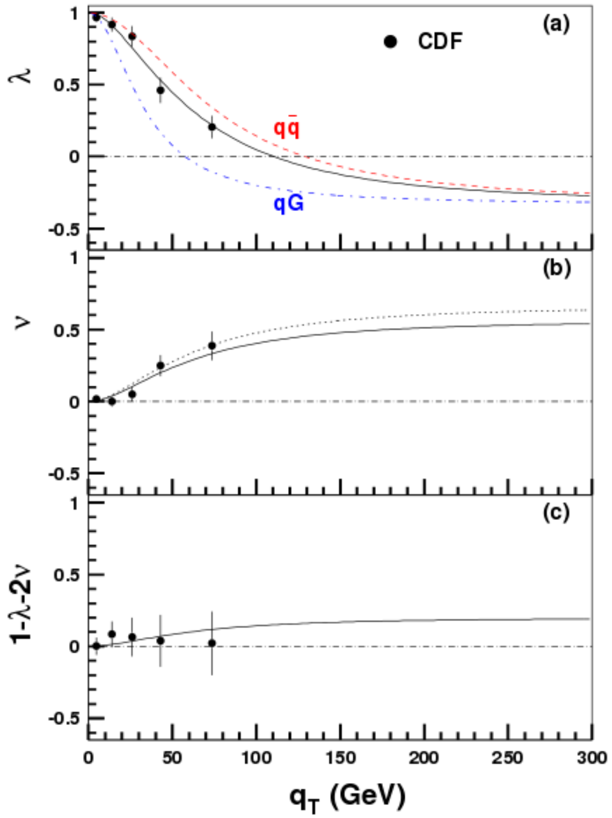
The E906 experiment is also studying the angular distributions of proton induced Drell-Yan at 120 GeV/c beam.

$\hookrightarrow$Results expected soon.

Lam-Tung relation Drell-Yan from $p\bar{p}$

The CDF experiment at Tevatron measured $p\bar{p} \to e^+e^-X$ in the **Z mass region**, at $\sqrt{s} = 1.96$ TeV. CDF, Phys.Rev.Lett. **106**, 241801 (2011)





$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

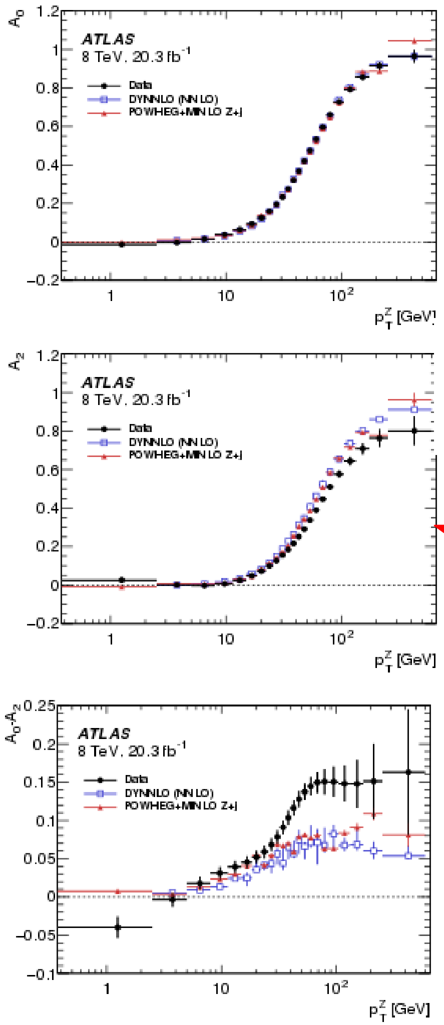
$$\frac{d\sigma}{d\phi} \propto 1 + \frac{3\pi A_3}{16}\cos\phi + \frac{A_2}{4}\cos 2\phi + \frac{3\pi A_7}{16}\sin\phi + \frac{A_5}{4}\sin 2\phi$$

- No clear violation of Lam-Tung relation ($A_0 = A_2$)
- Data can be explained with Z production from $q\bar{q}$ process at 72.5% and qg process at 27.5%

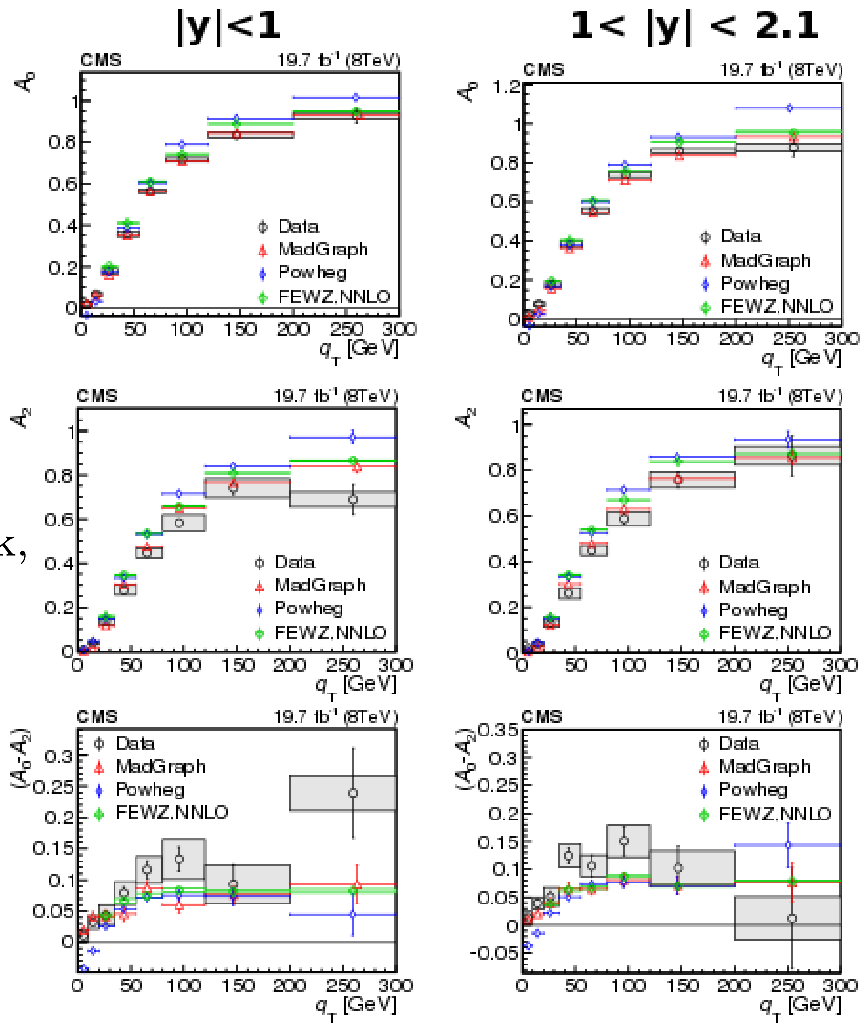
  $\hookrightarrow$ J-C. Peng et al, Phys.Lett.B **758**, 384 (2016)

Lam-Tung relation at the LHC

Both ATLAS and CMS experiments at LHC/CERN reported Drell-Yan results at the **Z mass region** showing clear violation of the Lam-Tung relation.



★Fabio Anulli talk, tuesday afternoon



ATLAS, JHEP 08(2016)159 CMS, Phys.Lett.B **750**, 154 (2015)

Lam-Tung relation violation – the old interpretations

Early NLO calculations done more than 20 years ago pointed to perturbative QCD effects to have very small impact, thus not able to explain the observed deviation from Lam-Tung.

$\hookrightarrow$Several non-perturbative QCD effects were proposed:

- Higher-twist effects in quark-antiquark binding of pions
- Factorization-breaking QCD vacuum
- Correlation between the quark k_T and its transverse spin in an unpolarized nucleon – the Boer-Mulders TMD PDF.
- ...

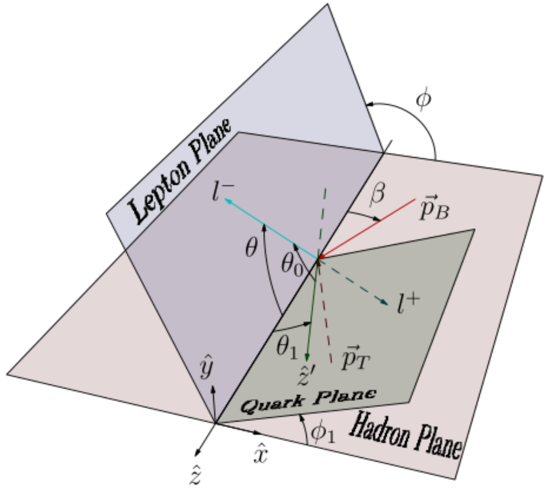
But: Recent works by J-C.Peng et al. and by M. Lambertsen and W. Vogelsang made us rethink it all.

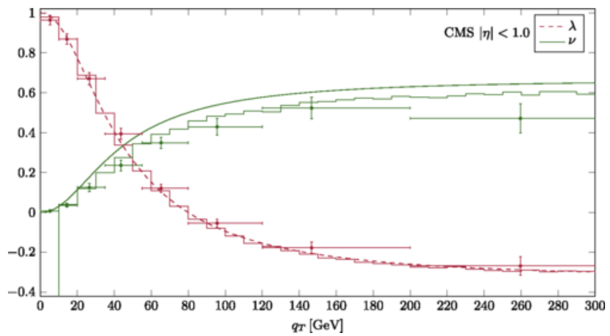
J-C.Peng, W-C. Chang, R.E. McClellan, O. Teryaev, Phys.Lett.B **758**, 384 (2016)
M. Lambertsen and W. Vogelsang, Phys.Rev. D **93**, 114013 (2016)

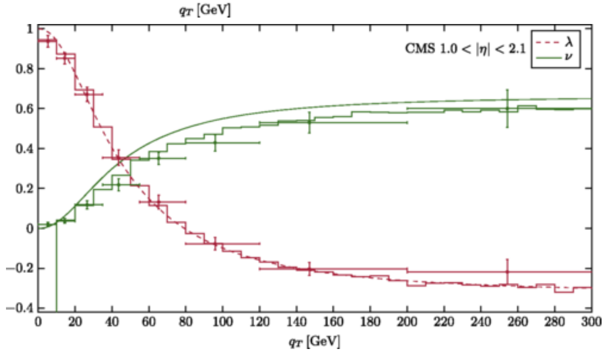
Interpretation of the Lam-Tung violation

J-C. Peng et al: the most likely reason for the violation of the Lam-Tung relation in the LHC measurements is the non-coplanarity of the axis of the incoming partons wrt the hadron plane, due to QCD radiative effects at $O(\geq \alpha_s^2)$.

★ J-C. Peng talk, tuesday afternoon







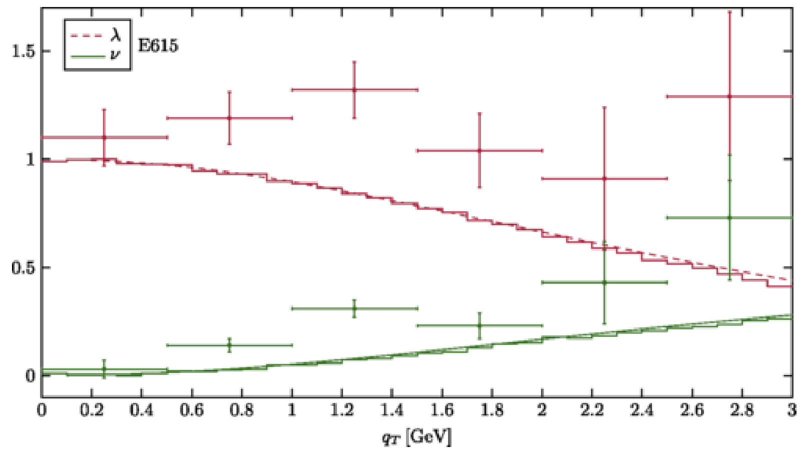
M. Lambertsen and W. Vogelsang: re-calculate NNLO QCD corrections to Drell-Yan allows to explain both the hadron collider and the fixed-target experiments angular distributions.

M. Lambertsen and W. Vogelsang, Phys.Rev. D **93**, 114013 (2016)

What about Boer-Mulders TMD PDF?

If perturbative QCD can explain the Lam-Tung relation violation and the large $\cos 2\phi$ modulations observed in unpolarized Drell-Yan, is there still "space" for a non-zero Boer-Mulders effect?

Hadron collider data were all obtained from the Z mass region, at quite large dilepton q_T. But at the typically low q_T of the dileptons at moderate energy fixed target experiments, the non-coplanarity of the $q\bar{q}$ axis could be mostly due to the intrinsic k_T of colliding partons.



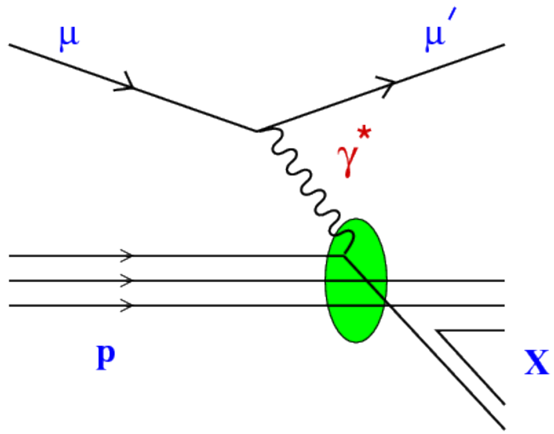
M. Lambertsen and W. Vogelsang, Phys.Rev. D **93**, 114013 (2016)

- Difficulties to describe both λ and μ, also seen for NA10 data.
- Some tension seen in data, where limit $\lambda \leq 1$ not always fulfilled.

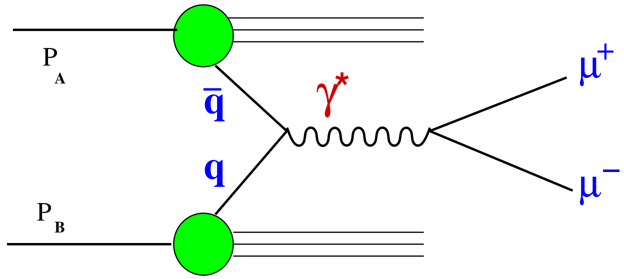
$\hookrightarrow$Check it at COMPASS, results expected soon.

T-odd TMDs: predictions

SIDIS



DY



Because the Sivers and Boer-Mulders PDFs are naive time-reversal odd, a sign change of these TMDs when measured from Semi-inclusive DIS or from Drell-Yan is predicted:

$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS) \qquad h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

$$\Downarrow$$

Test the QCD TMD factorization and the TMD approach itself.

- At COMPASS at CERN and RHIC experiments – right now
- Many future experiments propose to address the issue

Single spin asymmetries and TMDs

In polarized Drell-Yan, when there are 2 very different scales: $q_T \ll Q$, the cross-section can be factorized in terms of products of TMDs.

The single transverse spin asymmetry when the polarization of one of hadrons is reversed is: $A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

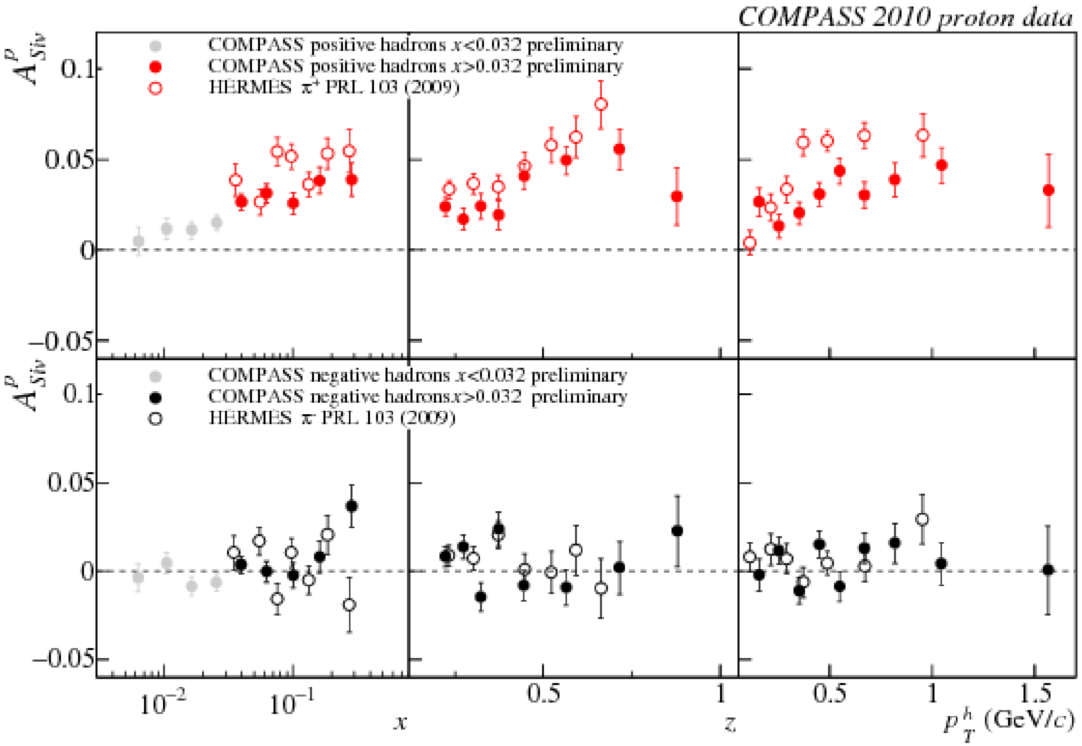
The cross-section (LO) can be written in a form evidencing the azimuthal asymmetries:

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{Fq^2} \hat{\sigma}_U \Big\{ (1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi) + |\vec{S}_T| \Big[A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \Big(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi + \phi_S) + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi - \phi_S) \Big) \Big] \Big\}$$

Sivers from SIDIS

The Sivers asymmetry A^p_{Siv}, which relates to the Sivers TMD in SIDIS, was measured by HERMES and COMPASS Collaborations using a transversely polarized proton target:

- positive asymmetry for h^+;
- asymmetry compatible with zero for h^-.



★ Anna Martin talk, monday afternoon.

★ Gunar Schnell talk, tuesday afternoon.

COMPASS, Phys.Lett.B 717 (2012)

HERMES, Phys.Rev.Lett. 103 (2009)

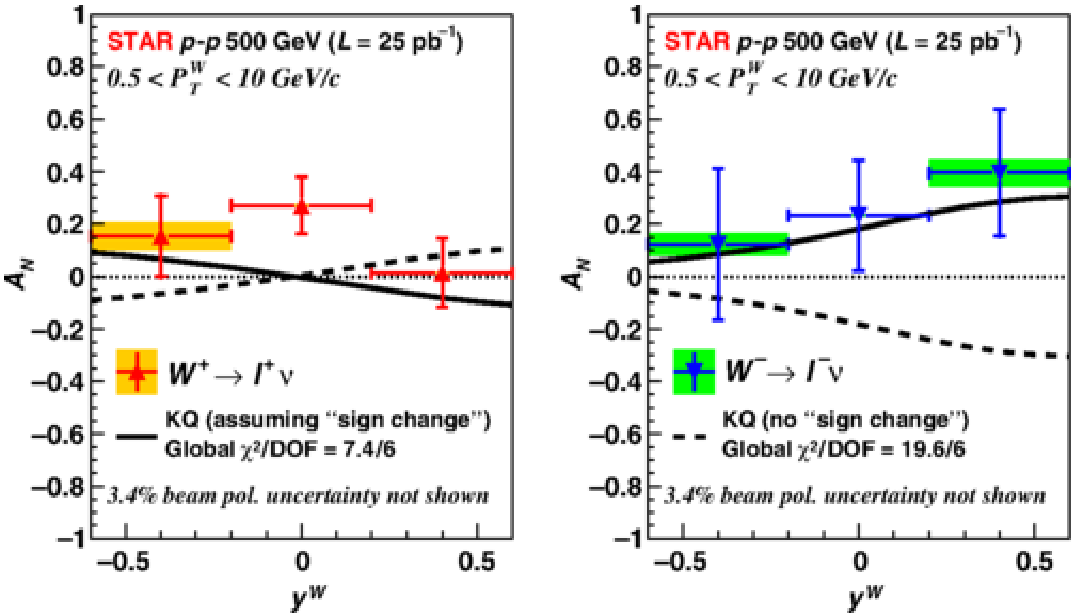
Systematic difference between the 2 experiments interpreted as sign of **scale dependence of TMDs** (Q^2 evolution).

Sivers sign change?

The STAR experiment at RHIC recently reported the measurement of A_N in $p^\uparrow + p \to W^\pm/Z^0$ at $\sqrt{s} = 500 GeV$. One of the beams is polarized ($\langle P \rangle = 53\%$)

STAR, Phys.Rev.Lett. **116**, 132301 (2016)

A_N compared to models where Sivers TMD is obtained from SIDIS data

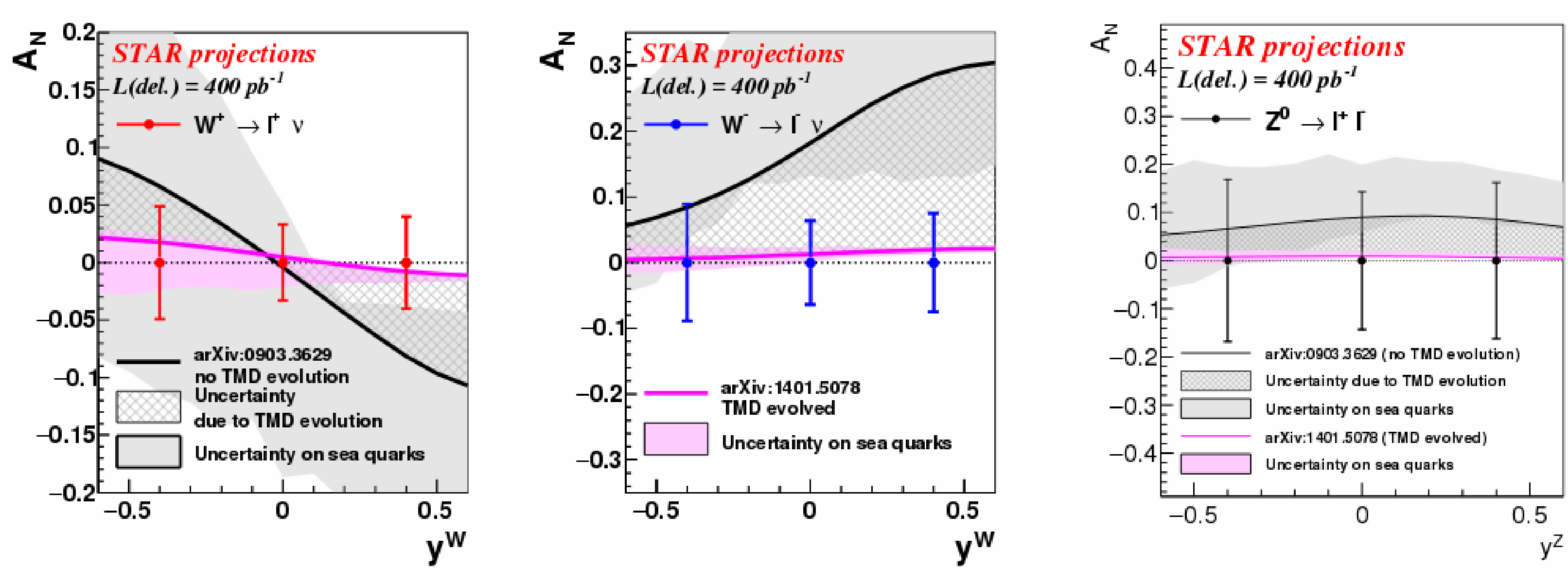


★ Devika Gunarathne talk, tuesday morning

- KQ: Z-B. Kang and J-W. Qiu, Phys.Rev.Lett. **103**, 172001 (2009)
- KQ model does not include TMD evolution effect. It does not take into account the very large difference between k_T at SIDIS and at DY.
- Data comparison with KQ model shows **preference for a sign change of Sivers TMD from DY wrt SIDIS**

STAR polarized data in 2017

The **2017** Run of the STAR experiment will be devoted to the polarized measurements, including A_N from both W and Z production.



From: S. Fazio, arXiv:1607.01676v1

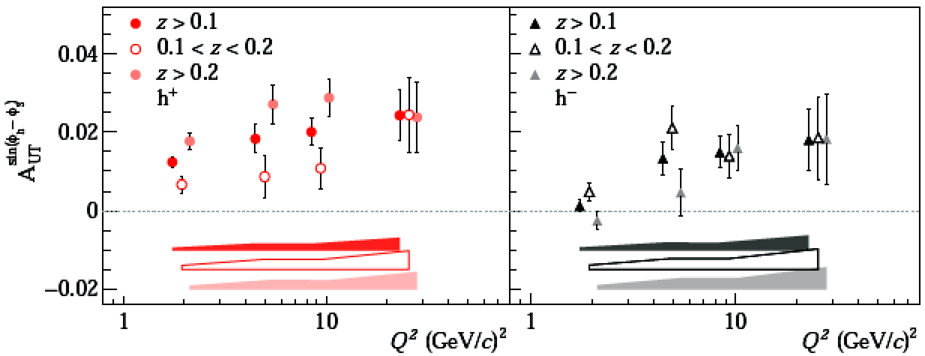
STAR $W^{\pm}$ data can constrain the sea quarks Sivers function.

Polarized Drell-Yan at COMPASS

COMPASS took data during 2015, with $\pi^- + NH_3 \rightarrow \gamma^* \rightarrow \mu^+\mu^- X$, at 190 GeV/c beam, and target polarized transversely to the beam.

- Drell-Yan in COMPASS sensitive to valence quarks (u quark dominance)
- Same COMPASS polarized target as used for the Sivers asymmetry from SIDIS
- Basically the same spectrometer (with exception of a hadron absorber downstream of target)

Ideal for checking the Sivers sign change.

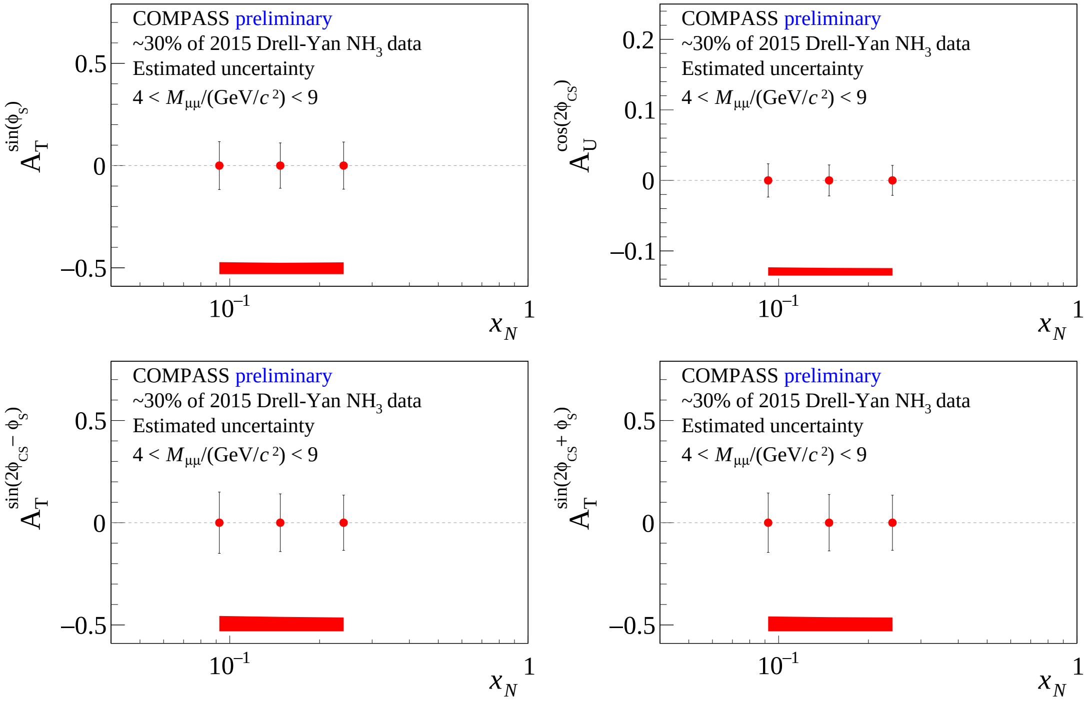


$\Longrightarrow$COMPASS SIDIS data in "almost the same" phase space as accessible from Drell-Yan, for a future direct comparison.

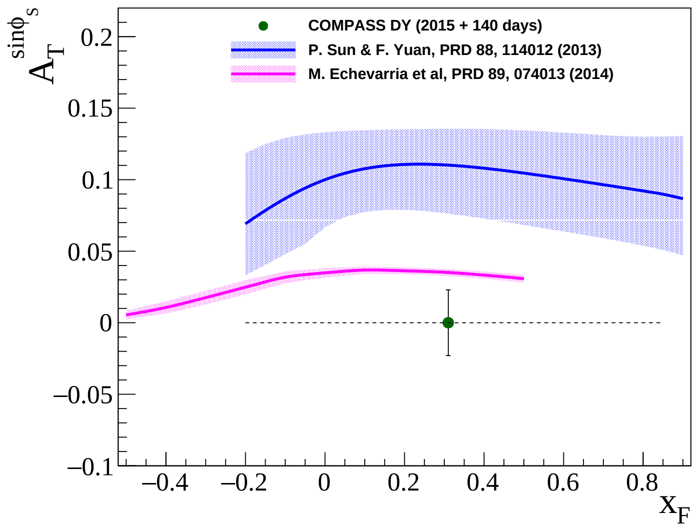
NEW: COMPASS, CERN-EP-2016-250.

COMPASS polarized Drell-Yan: TSSAs

COMPASS took polarized Drell-Yan data in 2015. At the moment, 30% of the data are processed and analysis is ongoing.



Request for another Run in 2018.



Projections for the combined statistics of the 2 years.

Predictions from P. Sun and F. Yuan, Phys.Rev.D **88**, 114012 (2013) and from M. Echevarria et al, Phys.Rev.D **89**, 074013 (2014)

★ Bakur Parsamyan talk, monday morning

TSAs from (un)polarized DY – the future

After the check of sign of Sivers TMD in Drell-Yan wrt SIDIS, a new phase will come for studying in detail dependencies and TMD evolution. It will require input from both type of processes.

Several (un)polarized Drell-Yan experiments are being planned:

Experiment	type	$\sqrt{s}(GeV)$	when
STAR (RHIC)	collider; $p^{\uparrow}p$	510	2017
COMPASS (CERN)	fixed target; $\pi^{-}\ p^{\uparrow}$, $K^{-}p^{\uparrow}$	18.9	2018
E1039 (FNAL)	fixed target; $pp\uparrow$	15	2018-2019
J-PARC (KEK))	fixed target; $\pi^{-}p$	3-5.5	>2018
NICA (JINR)	collider; $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}d^{\uparrow}$	10-26	>2018
E1027 (FNAL)	fixed target; $p^{\uparrow}p$	15	>2020
PANDA (FAIR)	fixed target; $\bar{p}p$	5.5	>2022
J-PARC (KEK)	fixed target; K^{-}p, $\bar{p}p$	2.2-4.5	>2022
AFTER (CERN)	fixed target; $pp^{\uparrow}$	115	2025
COMPASS+ (CERN)	fixed target; $K^{-}p^{\uparrow}$, $\bar{p}p^{\uparrow}$	$\approx$ 20	2025

* List possibly not complete

Some final comments

- Drell-Yan is an ideal tool to learn about the nucleon internal dynamics
- After all, NNLO QCD corrections to DY are NOT negligible. They seem to be the missing piece in the puzzle for the understanding of a long standing problem – the Lam-Tung relation violation.
- Is there still space for a significant Boer-Mulders function?
- For the first time we have data on polarized Drell-Yan – RHIC and COMPASS@CERN
  - check predicted sign change of Sivers TMD and the TMD approach itself.
  - Measure all angular modulations accessible in transversely polarized Drell-Yan

  ↪**Important results expected very soon**.
- The **many proposed new projects using the polarized Drell-Yan** process will be crucial for the next step of TMD PDFs dependencies and evolution.

Thank you!

ANNOUNCEMENT: IWHSS 2017

on behalf of COMPASS

IWHSS17

IWHSS 2017 is the 14th workshop in a series of annual workshops on Hadron Structure and Spectroscopy and for 2017 will be organized by INFN - TO

It will be held in Cortona (AR) Italy, from April 3 to 5, 2017 in the Centro Convegni Sant'Agostino.

The workshop will be devoted to the *after 2020 program for COMPASS* following the *COMPASS beyond 2020 Workshop* at CERN in march 2016 and the *Physics Beyond Colliders workshop* at CERN in september 2016.

IWHSS17
International Workshop on Hadron Structure and Spectroscopy
Cortona (Tuscany - Italy)
3-5 April 2017

The site of the conference:
Sant'Agostino Conference Centre
Cortona