山形大学
Yamagata University

AMBER
Apparatus for Meson and Baryon Experimental Research

Polarized solid target for possible future AMBER program at CERN

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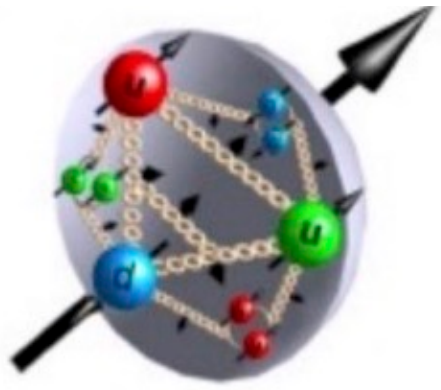
SPIN2025 in 青島

Nucleon Spin Structure



Nucleon spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{z,q} + L_{z,g}$$

$\Delta\Sigma$: Quark spin
EMC、SMC、HERMES

ΔG : Gluon spin
COMPASS、PHENIX

$L_{z,q}$: Quark OAM
HERMES、COMPASS、
SeaQuest、PHENIX

$L_{z,g}$: Gluon OAM
COMPASS, PHENIX

Precision measurements in 1990s
20-30 % by global analysis

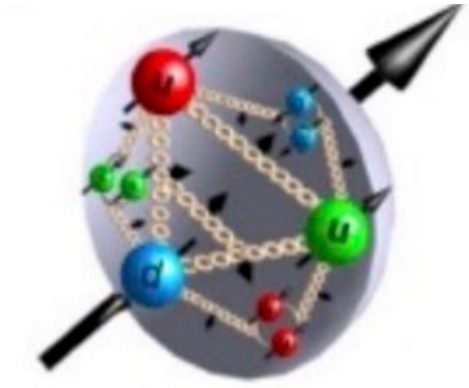
Measurements in 2000s
It does not explain the nucleon spin.

TMD PDFs measurements since 2000s
Supporting OAM contribution

Just started. Precision measurements will be carried out.

Nucleon Spin Structure

Apparatus for Meson and Baryon Experimental Research



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Spin of π
S=0

Spin structure of π and K

AMBER Drell-Yan

- π,K (TMD) PDFs
- Quark OAM in π, K
- Valence and Sea quark
- Gluon PDF

CERN & AMBER

AMBER

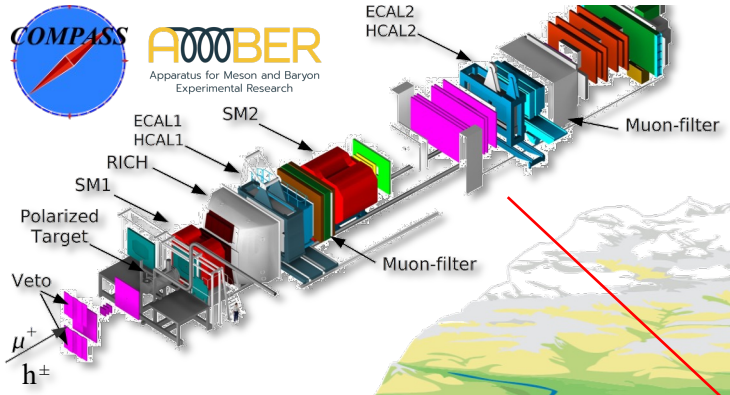
Secondary beam

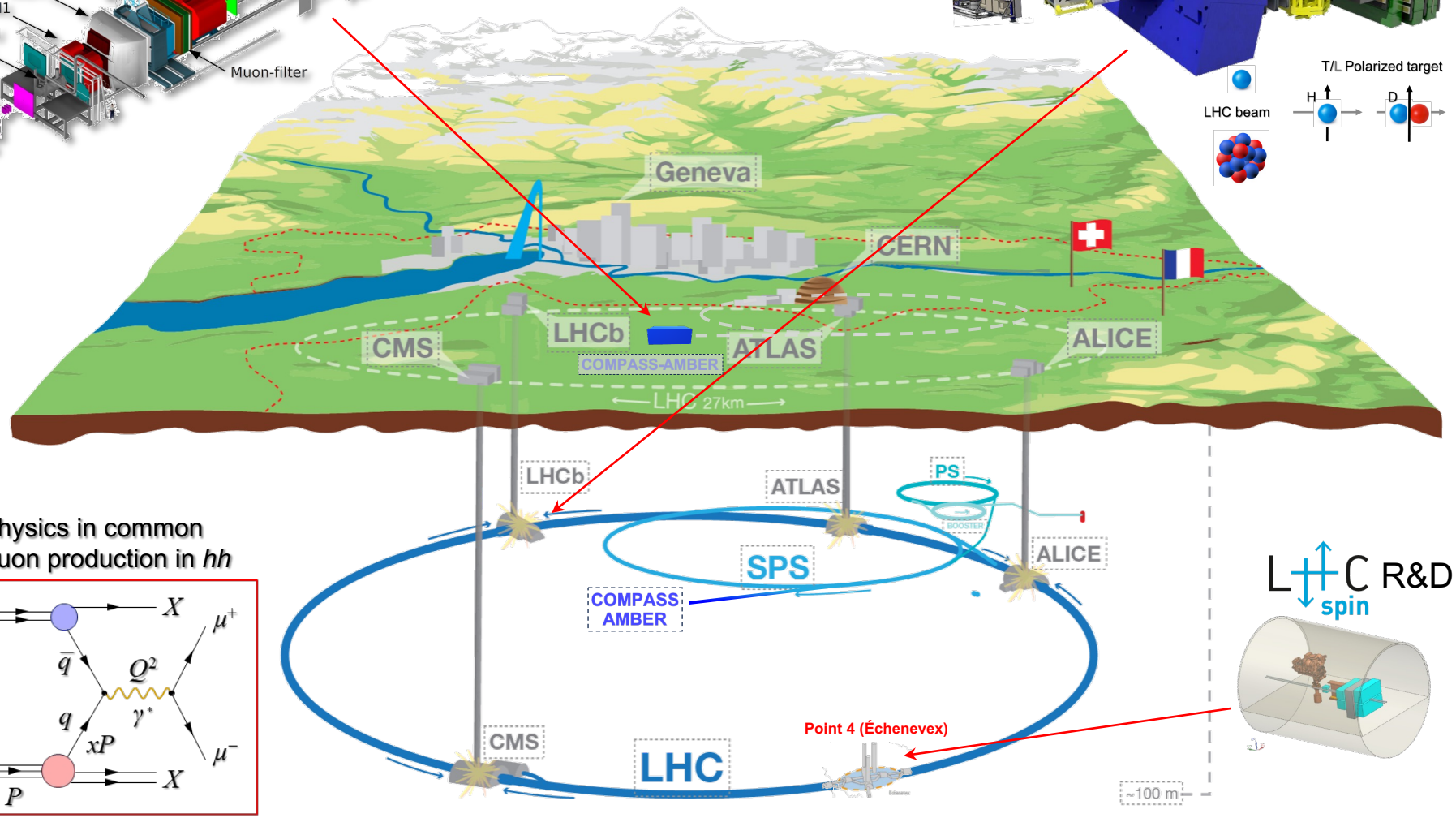
$\mu^{\pm}, \pi^{\pm}, K^{\pm}, p, \bar{p}$

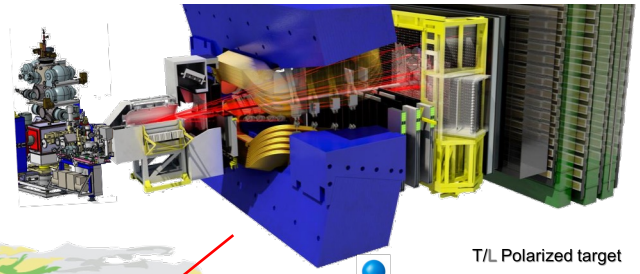
Fixed target

Polarized solid target
Liquid H_2/D_2 target

$\pi^{\pm}$ beam + PT
$\mu^{\pm}$ beam + PT
→ powerful tool for spin physics



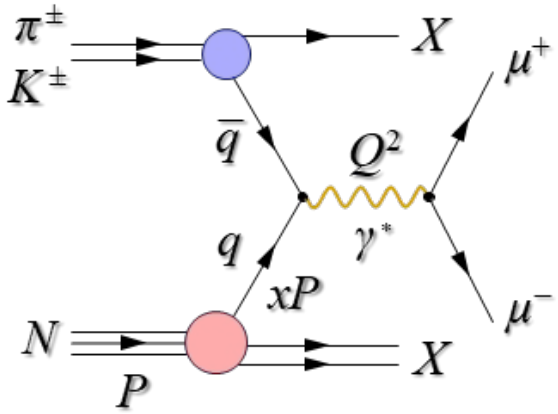




physics in common
dimuon production in *hh*

Drell-Yan and SIDIS

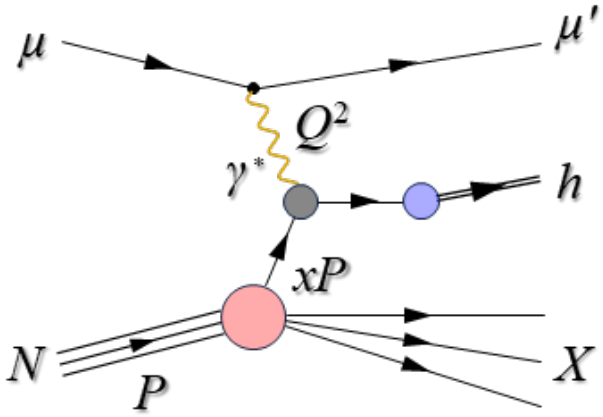
Drell-Yan Process



- Quark-Antiquark annihilation
  - two leptons in the final state
- Small cross section
- Structure functions entering the cross section given as convolutions of hadron PDFs

$$(PDF) \otimes (PDF)$$

Semi-Inclusive DIS process



- Structure functions given as convolutions of PDFs and FFs
- Higher cross section
- Requires knowledge of FFs (e.g. from e^+e^- data)

$$(PDF) \otimes (FF)$$

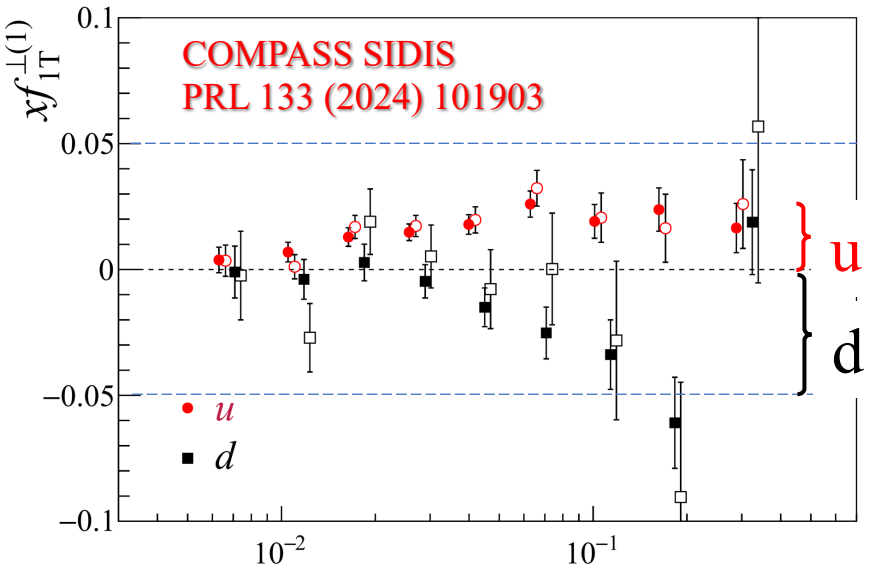
COMPASS SIDIS results (muon beam of 160 GeV)

Transversely polarized deuteron target (6LiD) : 2002-2004, 2022
Transversely polarized proton target (NH3) : 2007, 2010

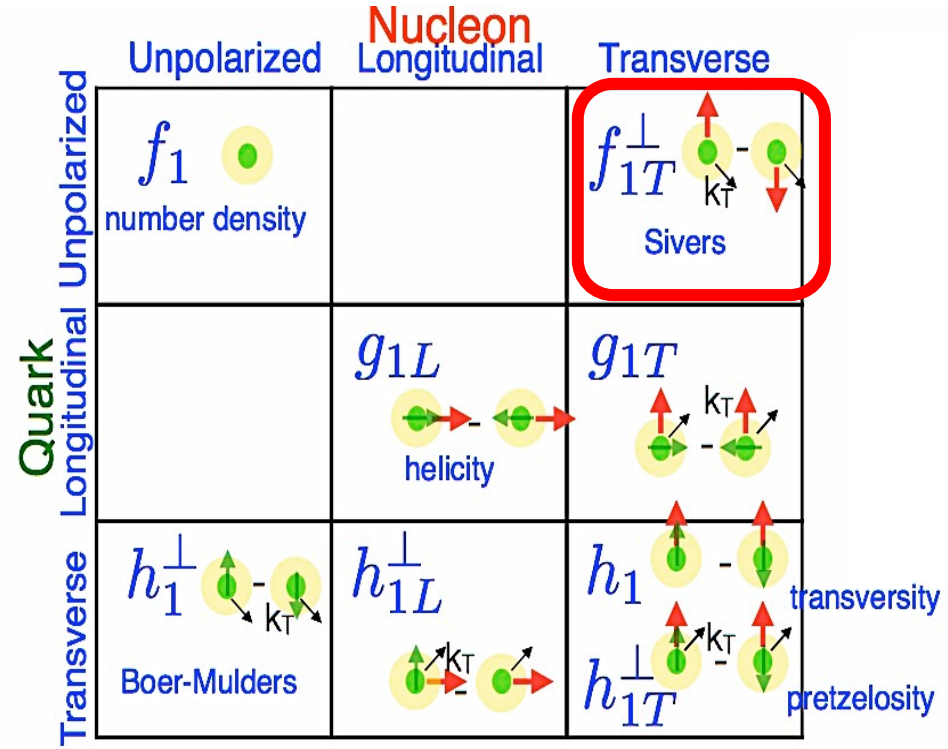
COMPASS 2022 data

- Much smaller uncertainties for d-quark
- d-quark Sivers TMD PDF larger than u-quark?
- In agreement with recent global fits

Sivers TMD PDF



Quark TMD PDFs



Sivers, BM : related to quark OAM

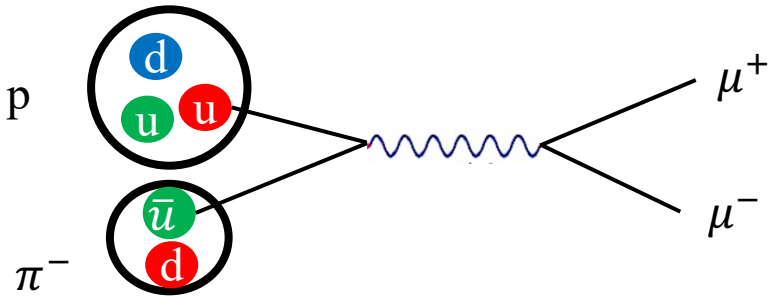
New physics motivation with DY at AMBER

First measurement of polarized DY in 2015 (polarized proton target with π^-beam)

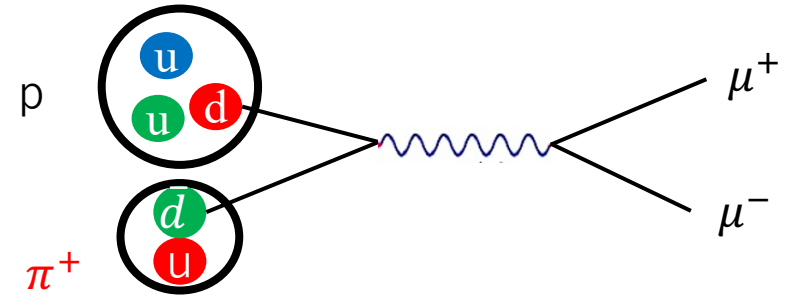
Interesting possibilities for AMBER

- π^+beam instead of π^-(larger effect)
- Beam energy 190 GeV
- Higher intensity (+>50 % statistics)
- Triggerless readout (+20 % statistics)

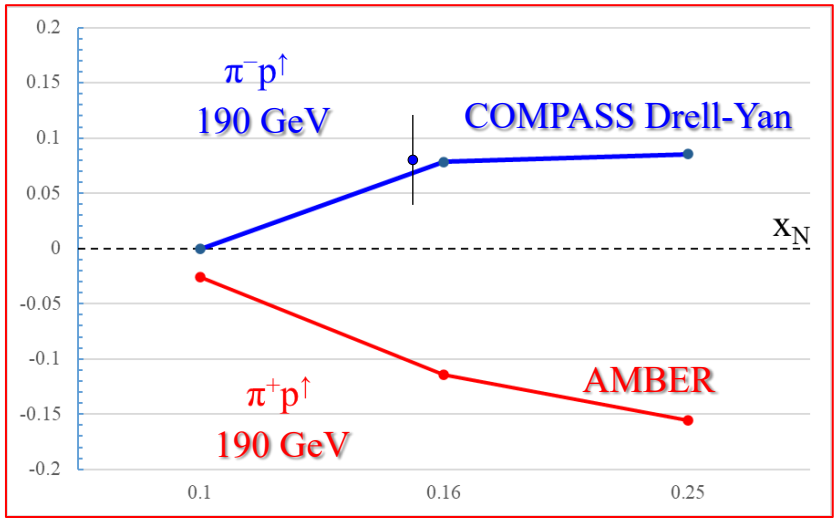
DY in 2015 and 2018



DY for new program



Sivers TMD PDF



Dynamic Nuclear Polarization（DNP)

Polarization P of spin ½ at thermal equilibrium (Boltzmann distribution)

$$P = tanh\left(\frac{\mu B}{K_B T}\right)$$

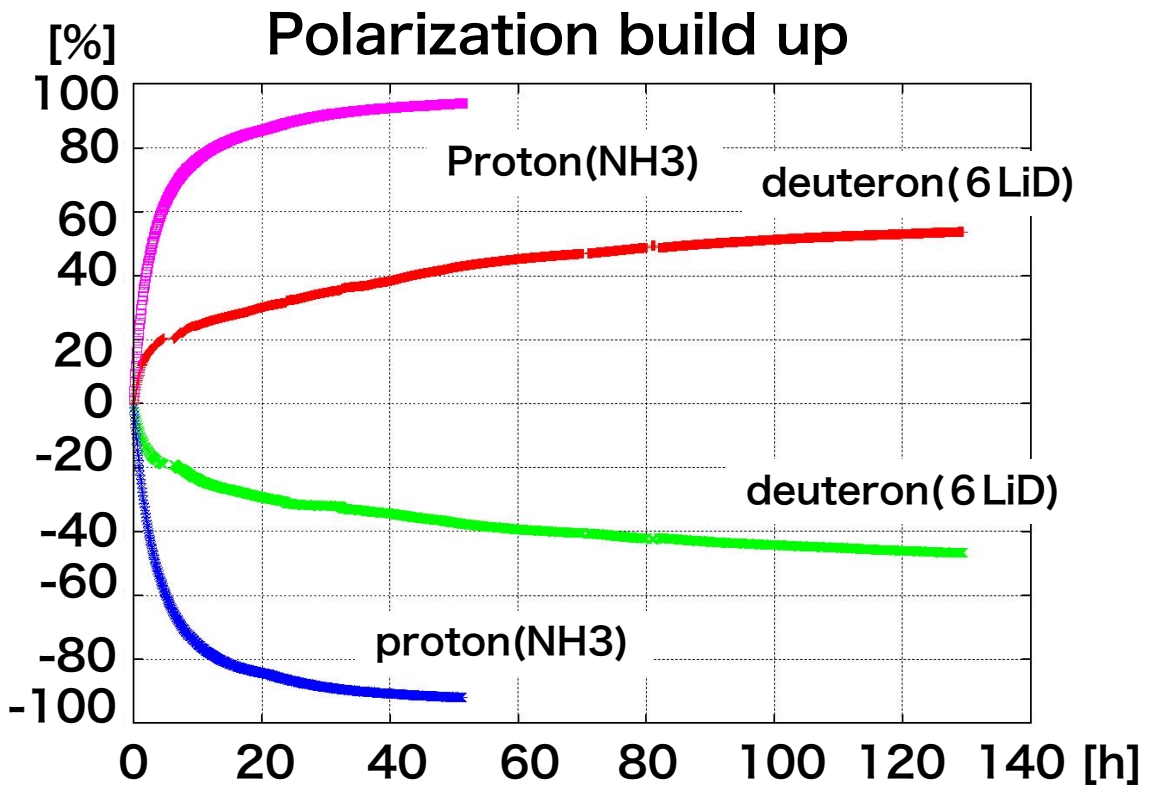
μ : magnetic moment
B : magnetic field
K_B : boltzmann constant
T : temperature

Polarization at thermal equilibrium@2.5T

	electron	proton	deuteron
4.2 K	66.4 %	0.061 %	0.012 %
1.0 K	99.8 %	0.26 %	0.052 %
0.1 K	99.9 %	2.6 %	0.52 %

DNP: Transfer the high electron polarization to nucleon by MW

- Free radical dope to Material (NH_3、 ^{6}LiD)
- Electron spin relaxation ＜ Nucleon spin relaxation



DNP(@2.5T)
Polarizing
longitudinally

→ Data taking(@0.6T)
Transversal position

COMPASS PT system

Dilution refrigerator

- 50mK
- 350mW cooling power at 300mK

Magnet

- 2.5T solenoid（Polarization、longitudinal）50 ppm homogeneity
- 0.6T dipole（Transverse）
- 180mrad acceptance (400 mm in diameter)

Target cell

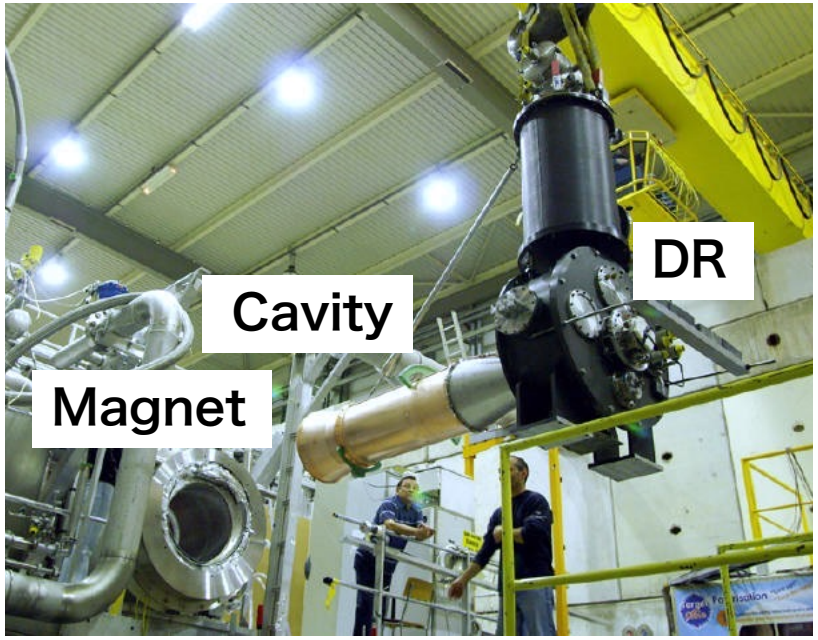
- 3 cells (30, 60, 30cm long)
  or 2 cells (55, 55 cm long)
- Diameter 3 or 4 cm

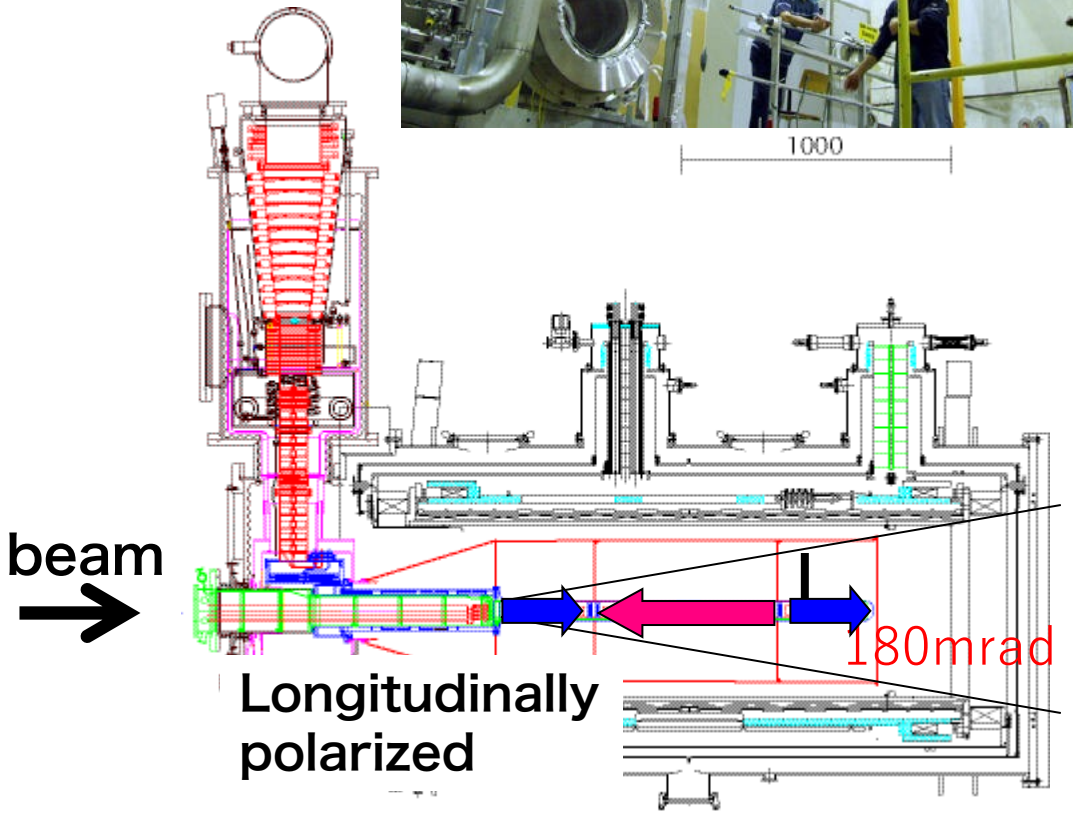
Microwave

- 2 sets of EIO (20W)
- 3 sets of Gunn Diode (3W)

NMR

- 10 cannels (3, 4, 3) or (5,5)





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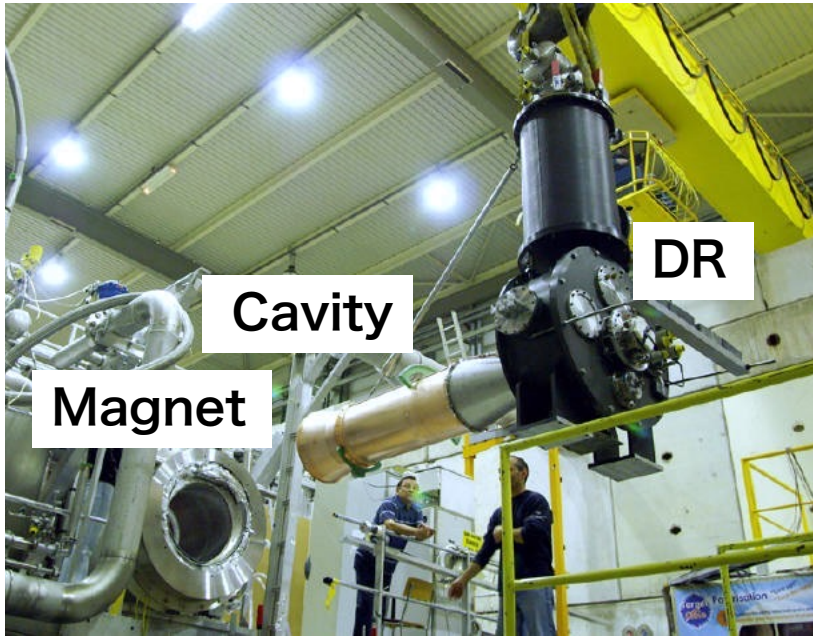
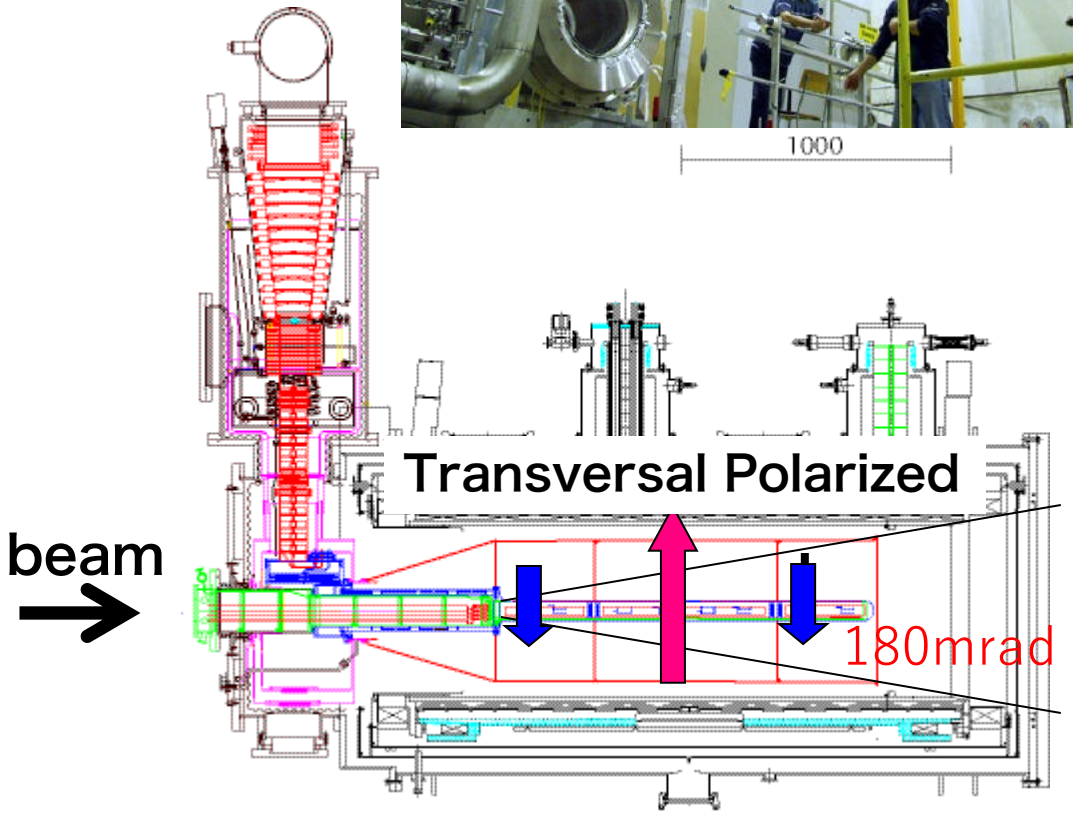
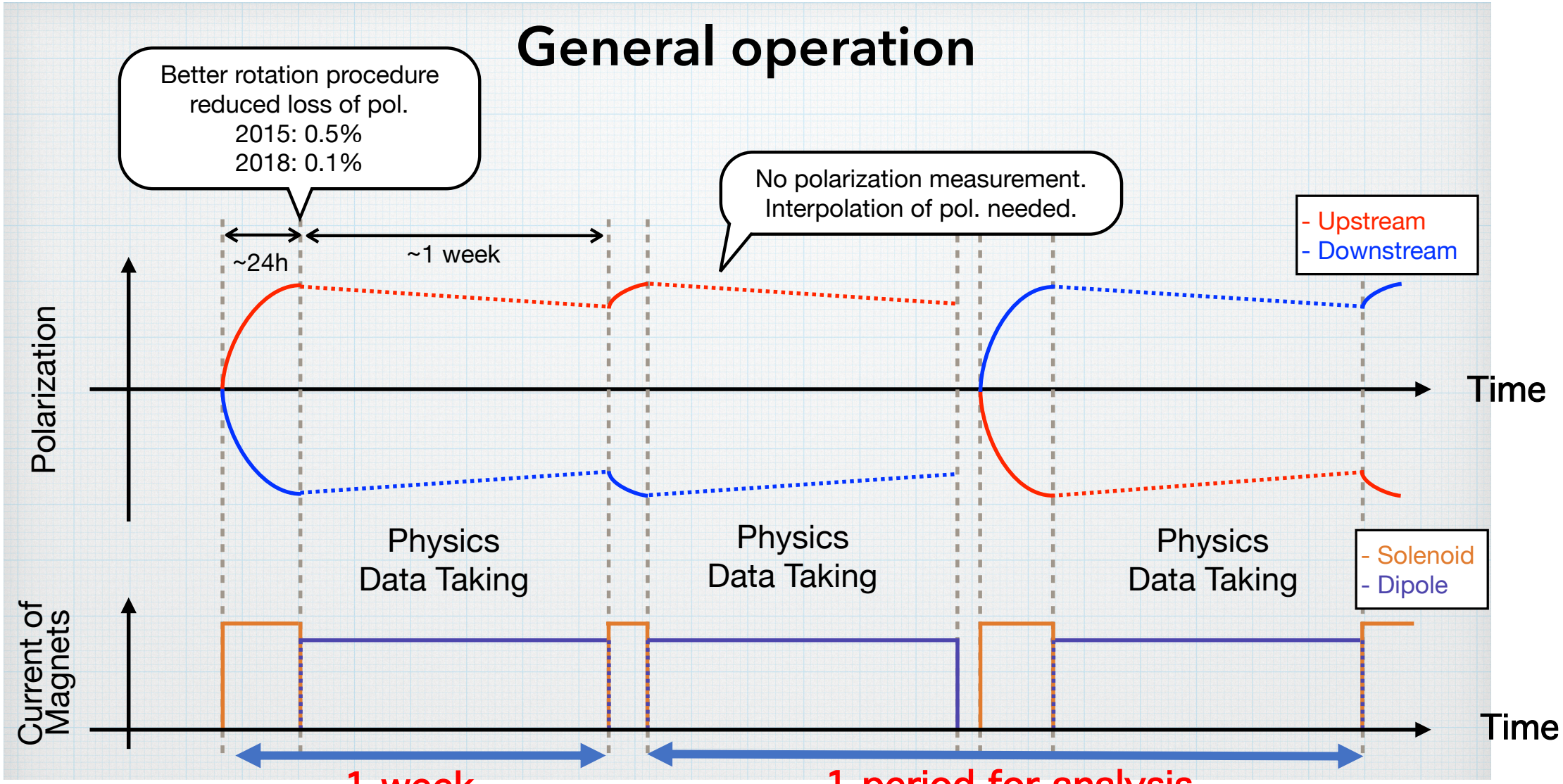




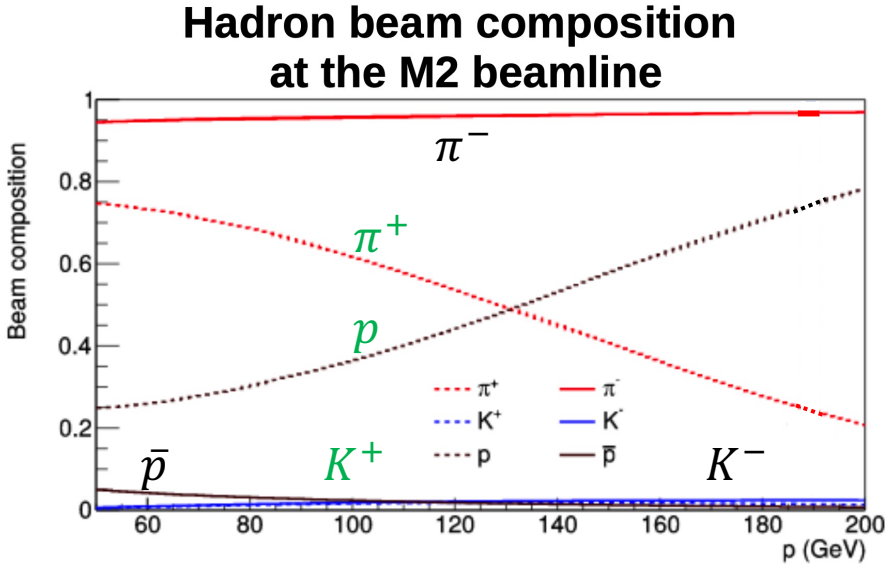
General operation



Beam intensity : 10^8 /s for 5 s and then no beam for 10 s or more

Polarized target and beam for Drell-Yan process

- Transversal polarized target
- COMPASS in 2022 with SIDIS
  - Muon beam + polarized deuteron target (^{6}LiD)
  - SIDIS process
- Target material choice for Drell-Yan
  - Hadronic scattering
    -- Energy deposition in the material
  - Radiation damage of the target material
    -- Ammonia is the best. (NH3 or ND3)
  - Shorter relaxation time because of the heat and the radiation damage
    -- DY is more difficult than SIDIS.
- Pion beam at M2 beam line
  - Beam intensity in 2015 and 2018 : 1 x 10^8 /s → 50 % more for the future?
    π^+ beam instead of π^- : longer beam time required (under evaluation)
    → Target polarization improvement will help.



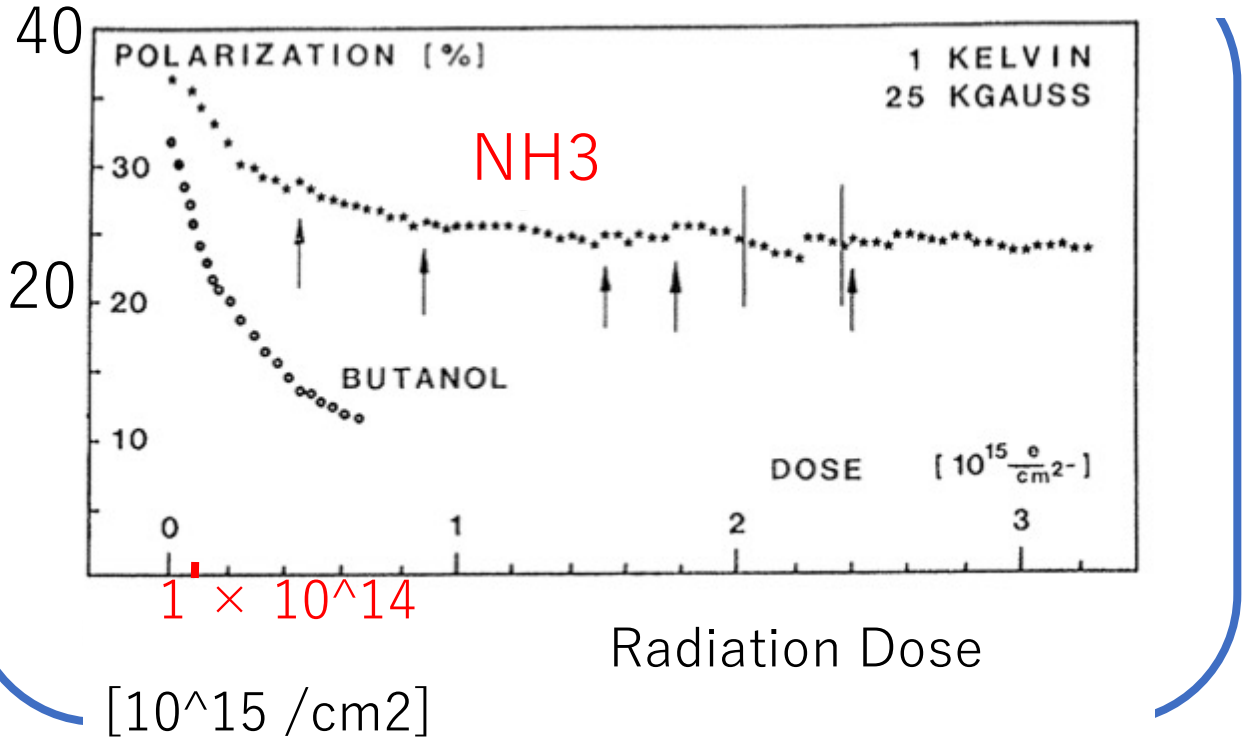
Radiation damage

Additional radicals are produced by beam.

W. Meyer et. al., Proceedings of the 4th international workshop on Polarized target materials and techniques (1984)

The polarization drops to 1/e of maximum polarization is 7 × 10^15 particles/cm2 (electrons) for ammonia

Radiation effect to polarization at 1K and 2.5T

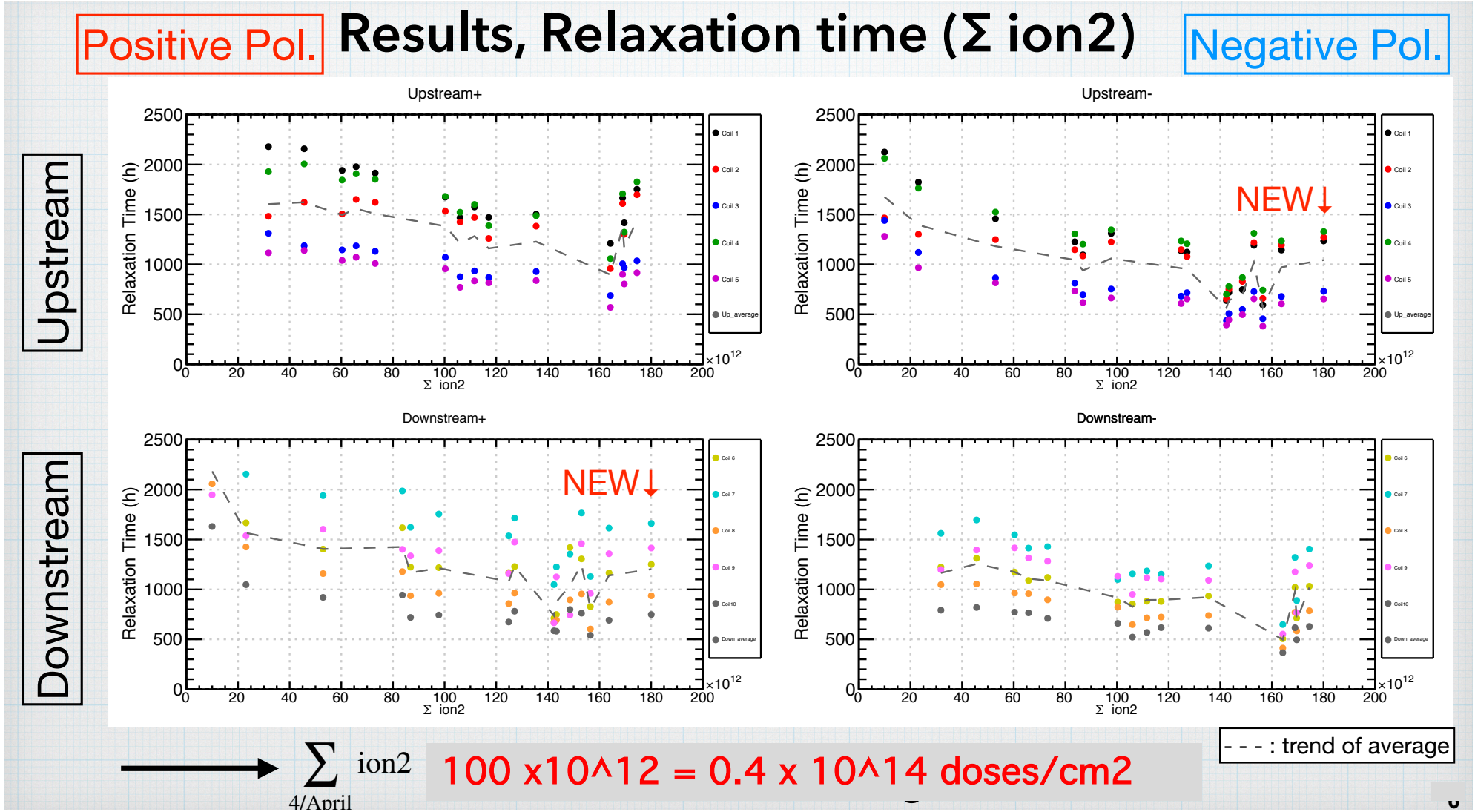


Accumulated doses in 2018 : 0.7 × 10^14 /cm2

Relaxation time in 2018 vs accumulated doses

0.7 x 10^14 doses/cm^2 in 2018

Positive Pol. **Results, Relaxation time (Σ ion2)** Negative Pol.



→ $\sum$ ion2 4/April

100 x10^12 = 0.4 x 10^14 doses/cm2

Target system for DY -- CERN vs USA

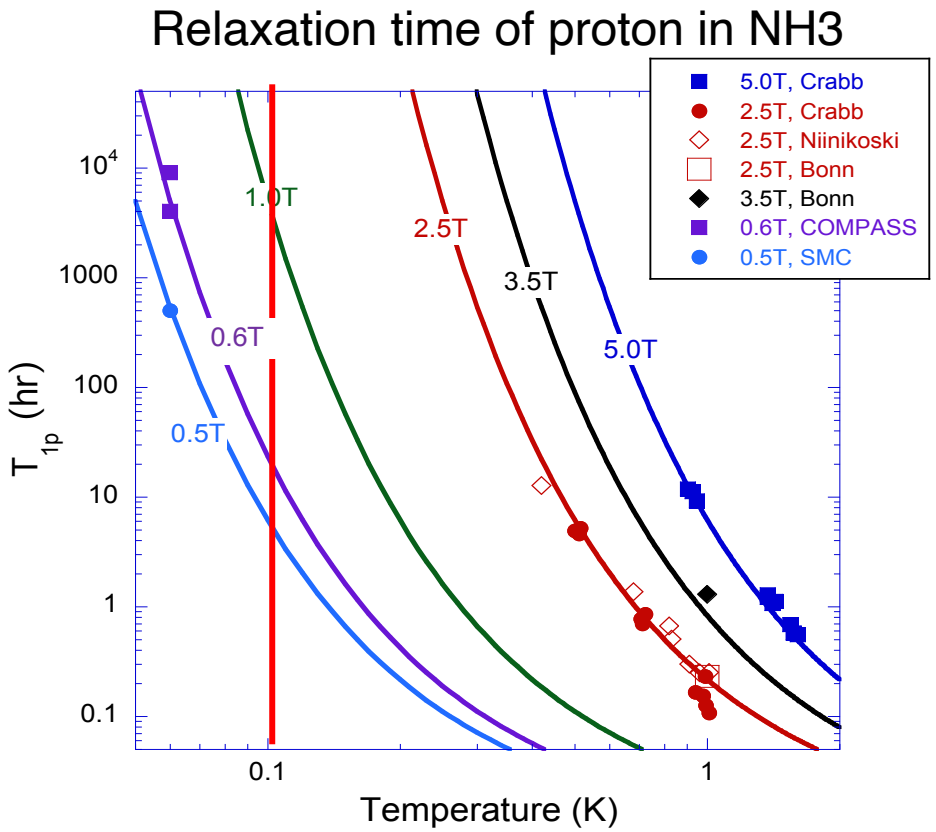
	CERN (SMC, COMPASS)	USA (SpinQuest, JLab)
Magnetic filed	2.5 T solenoid 0.6 T dipole	5 T dipole
Refrigerator	50 mK, 3He/4He dilution refrigerator	1 K, 4He refrigerator
Target size (length)	55cm – 55 cm (20 cm gap)	8 cm
Target Material	NH3	NH3 (ND3)
Polarizing	DNP at 2.5 T and frozen mode at 0.6 T dipole	Continuously DNP at 5 T
Average polarization	About 75 %	90 %

$$FoM = n_t \cdot P_t^2 \cdot f^2$$

USA Target FoM is 40% higher.

Possible scenario of PT system

- 2.5 T dipole magnet with 100 ppm homogeneity for 130 cm long
  - 100 mK refrigerator
- 5 T dipole magnet with 100 ppm homogeneity for 130 cm long
  - 1 K refrigerator (easier operation)
  - The beam is kicked out.
- 2.5 T solenoid + 1.0 T or more dipole
  - 100 mK refrigerator
  - longer relaxation time in frozen spin mode with the dipole magnet



C. Keith, Boppard 2022

Summary

- π^+ induced polarized Drell-Yan program
  - just started studying feasibility
- Different beam energies being considered
  - large proton contamination at CERN-M2 beam line
  - larger enhancement of Sivers expected
- NH3: one of the candidate materials
- Target magnet improvement required
  - 3 scenarios shown
- Please contact us if you are interested

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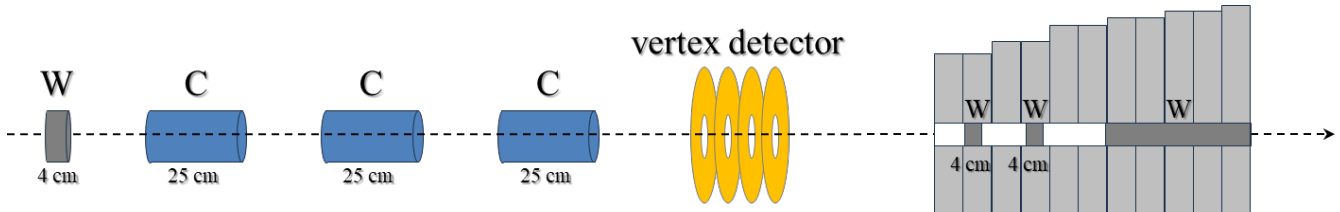
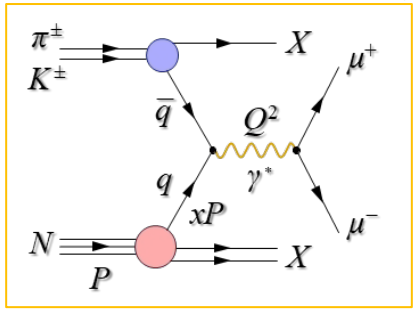
AMBER – $\pi^{\pm}$, $K^{\pm}$ induced dimuon production on C/W





Compared to COMPASS

- Light isocalar target (carbon) instead of NH_3-He mix
- Improved mass resolution (~ 100 MeV/c^2)
  - Lower background → enlarge DY mass range
  - J/ψ and ψ(2S) studies
- Wider beam choice: $\pi^{\pm}$, $K^{\pm}$, p / $\bar{p}$, CEDARs (PID)
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$
- Higher beam intensity (RP upgrades)
- Revised spectrometer, Triggerless DAQ