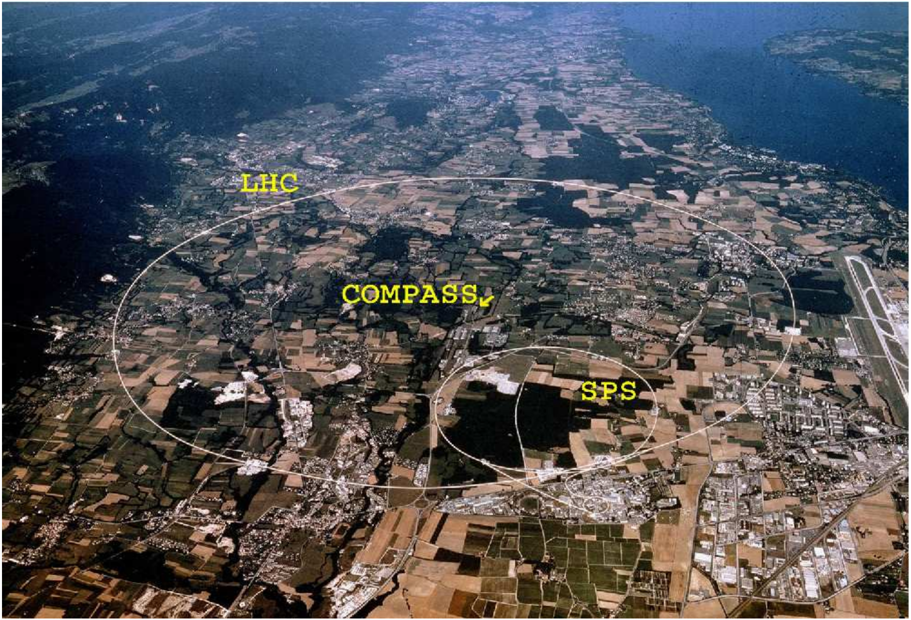
LIP activities in COMPASS experiment at CERN

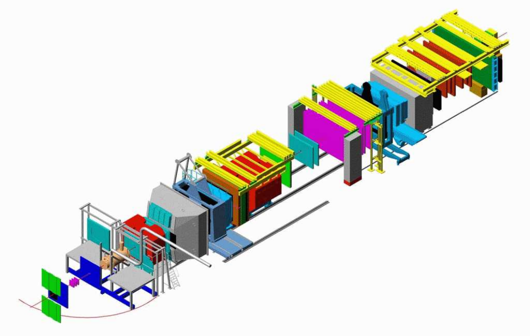
M. Stolarski & M. Quaresma
on behalf of the COMPASS LIP group

15-II-2020

COMPASS at CERN



- **CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



- Fixed target experiment, with muon and hadron beam
- Collaboration of 12 countries and about 220 physicists
- PHASE-I data taking in 2002-2011
- Currently PHASE-II ongoing (last data taking in 2021)
- Possible Extension: COMPASS++/AMBER 2021+

Physics Goals

- Phase I
  - Muon beam program
    - gluon polarisation in the nucleon
    - spin dependent structure functions
    - polarised quark distributions
    - unpolarized fragmentation functions
  - Hadron beam program
    (pion polarizability, hadron spectroscopy, exotics searches)
- Phase II
  - **T**ransverse **M**omentum **D**ependent functions (TMDs)
    - with hadron and muon beams!
  - **G**eneralized **P**arton **D**istribution functions (GPDs)
  - Unpolarized fragmentation functions

RED - Present LIP activities, BLUE - Past LIP activities

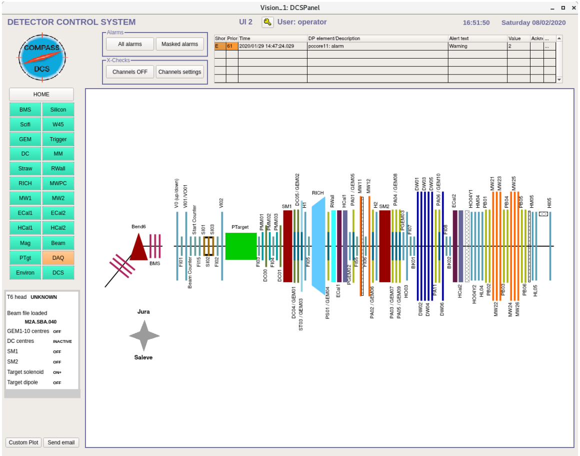
COMPASS LIP group

- Researchers:
  - Catarina Quintans (group leader)
  - Celso Franco
  - Pietro Faccioli
  - Marcia Quaresma
  - Marcin Stolarski

- Post-docs:
  - Ana Sofia Nunes (Left to BNL in Jan 2019)
- Students:
  - In the course of the two years there were 4 students from Italy (ERASMUS+), and 5 students on LIP internships
- Engineer:
  - Christophe Pires

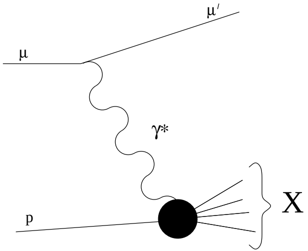
LIP Activities - Detector Control System

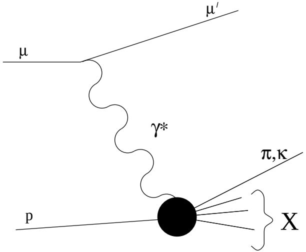
- LIP group has full responsibility of COMPASS Detector Control System
- New equipments have to be integrated
- Standards continuously evolve, thus the system has to be kept up-to-date
- During data taking, DCS on-call must be guaranteed non-stop for 6 months



LIP group Activities - Fragmentation Functions

- FF are needed in analyses which deal with a hadron(s) in the final state
- IDEA: K^+ $(u\bar{s})$ has different probability to originate from d-quark than π^- $(d\bar{u})$
- In Leading Order QCD Fragmentation Function D_q^h describes probability density for a quark of flavour q to fragment into hadron of type h
- Fragmentation functions are measured via. Hadron Multiplicities, *i.e.* number of observed hadrons divided by a number of DIS events
- Measured hadron multiplicities need to be corrected for various effects e.g.
    - spectrometer acceptance & reconstruction program efficiency
    - RICH efficiency & purity (for π and K)
    - radiative corrections





Kinematic Variables

Q^2:

- negative four-momentum transfer from lepton to nucleon
- Q^2 is a photon resolution
- $Q^2 \approx 1\text{GeV}^2 \rightarrow \delta r \approx 1$ fm
- DIS: $Q^2 > 1$ GeV^2 - the perturbative region

Bjorken x:

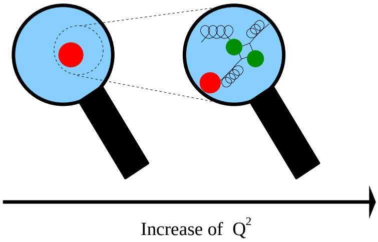
- in the frame of the proton infinite momentum, x is the fraction of the proton momentum carried by the quark (parton)

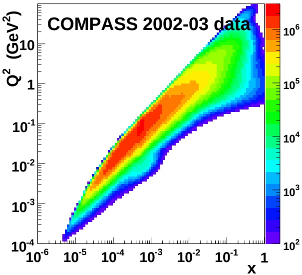
ν :

- photon energy $\nu = Q^2/2Mx$

hadron z

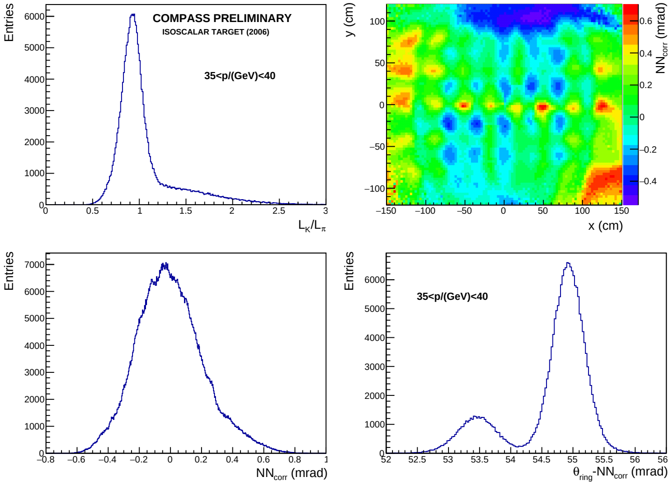
- the energy ratio of the hadron to the virtual photon
- variable used in SIDIS





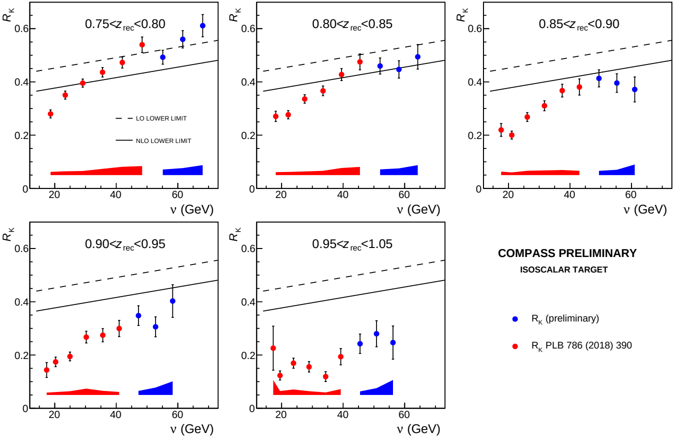
Improvement of RICH PID (done fully at LIP)

- Originally Likelihood was used to separate π from K
- We used NN to correct internal description of the RICH optical system, effectively correcting θ angle of the emmited Chernkov light.



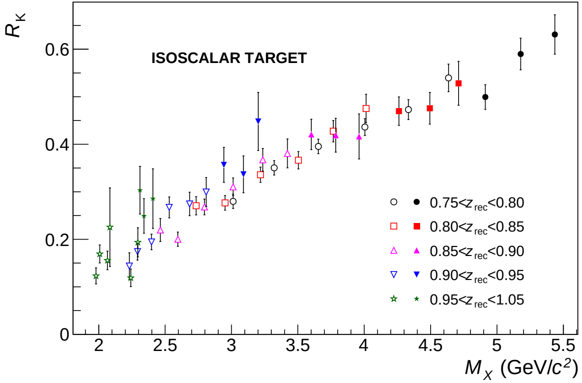
Multiplicities Ratios K^-/K^+ and $\bar{p}/p$

- In the multiplicity ratio many experimental and theoretical uncertainties cancel
- In LO pQCD one can calculate a lower limit for the ratios, $R_{K,(p)} = M^{K(p)^-}/M^{K(p)^+}$
- $R_{K,p} > \frac{\bar{u}+\bar{d}}{u+d}$; isoscalar target (note lack of D_q^h in the limit!)



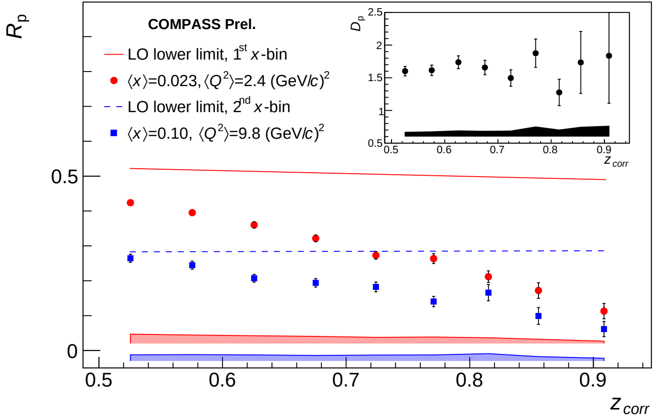
R_K vs Missing mass

- High-z kaon $\rightarrow$ reduced phase space for other particles
- But conservation laws need to be fulfilled (strangeness, baryon number)
- Natural variable to study such effect is a missing Mass, M_{X}
- $M_{\mathrm{X}} \approx \sqrt{M_{\mathrm{p}}^2 + 2M_{\mathrm{p}}\nu(1-z) - Q^2(1-z)^2}$
- Indeed R_K vs M_{X} shows a smooth trend!



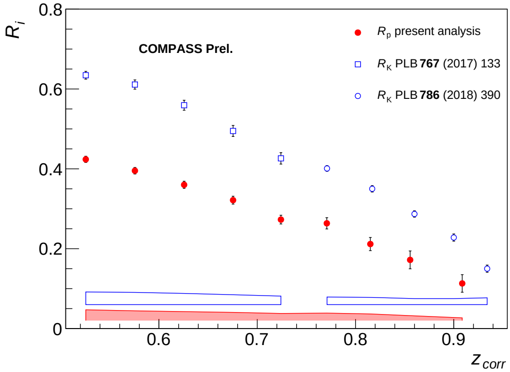
Ratio $\bar{p}/p$ for isoscalar target

- Results are below the lower limit predicted by LO pQCD



R_p vs. R_K

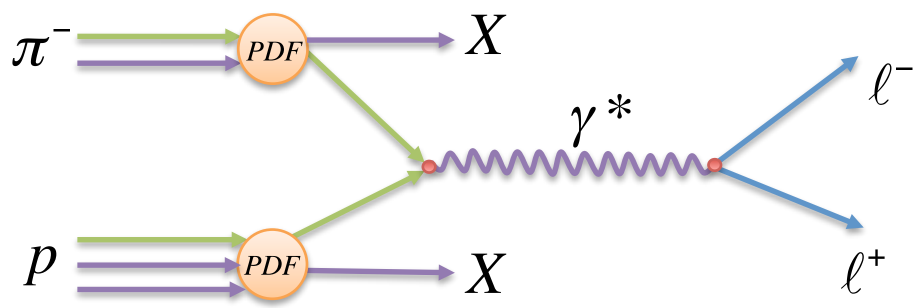
- R_p and R_K lower limits are the same in LO pQCD
- We expect $R_K/R_p \approx 1.10 \pm 0.05$
- Clearly very different results seen in data

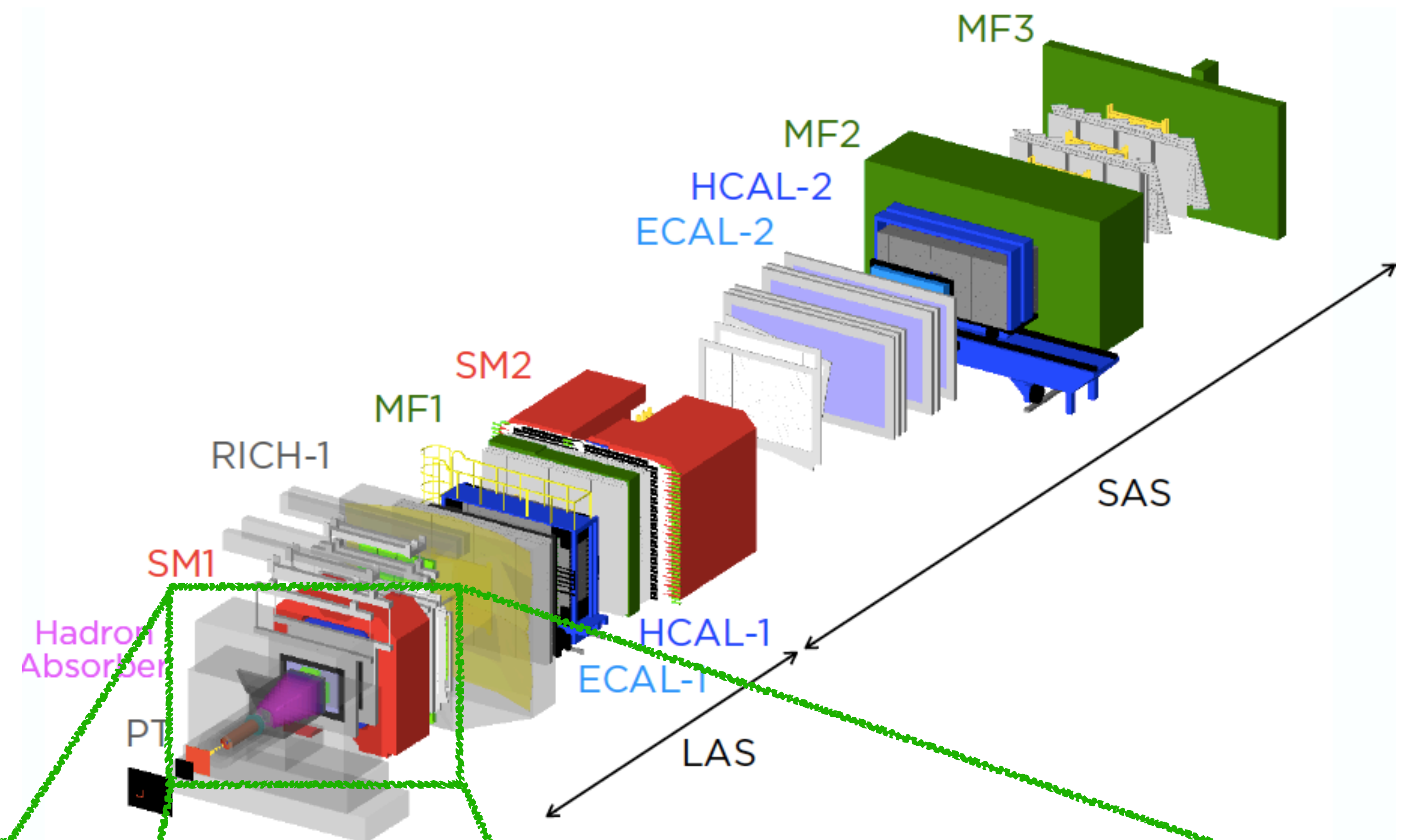


COMPASS is the first to observe all these effects, which are important to be taken into account by theorists

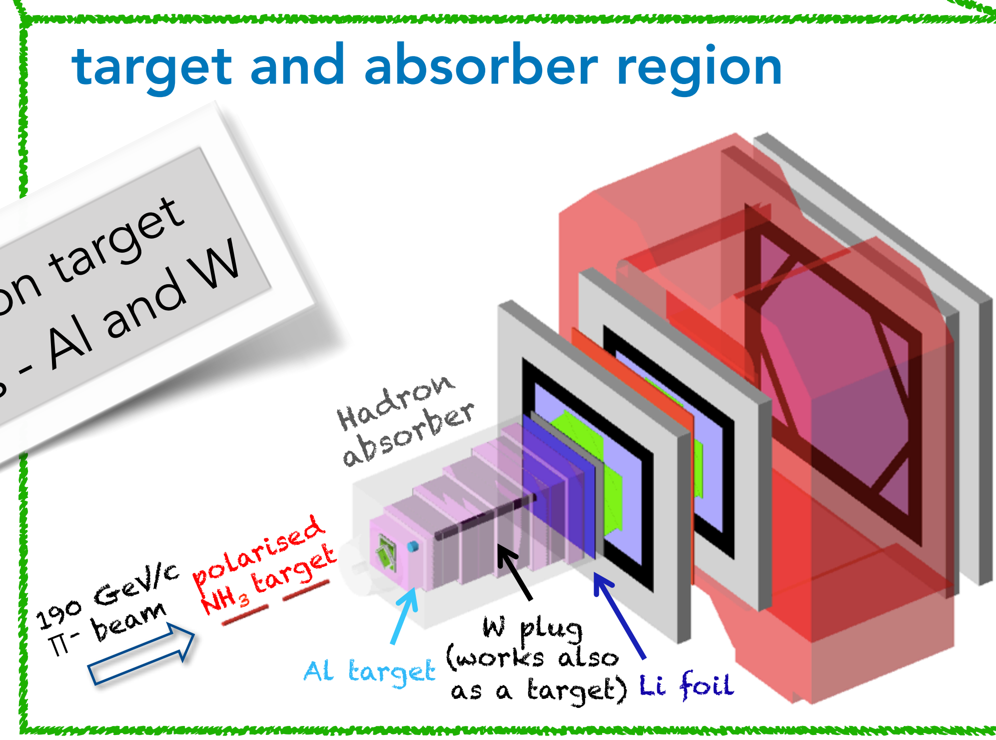
pion induced Drell-Yan

2 years of data-taking - 2015/2018

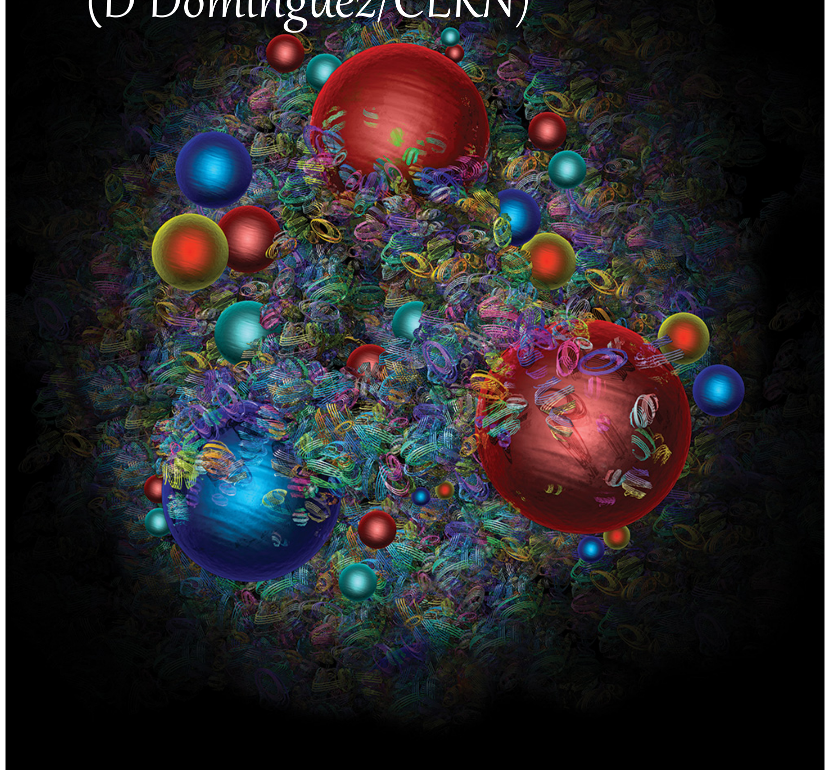




polarised proton target
nuclear targets - Al and W



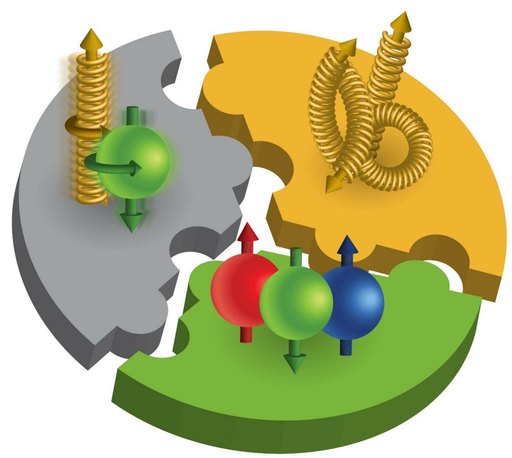
Motivation for the Drell-Yan programme

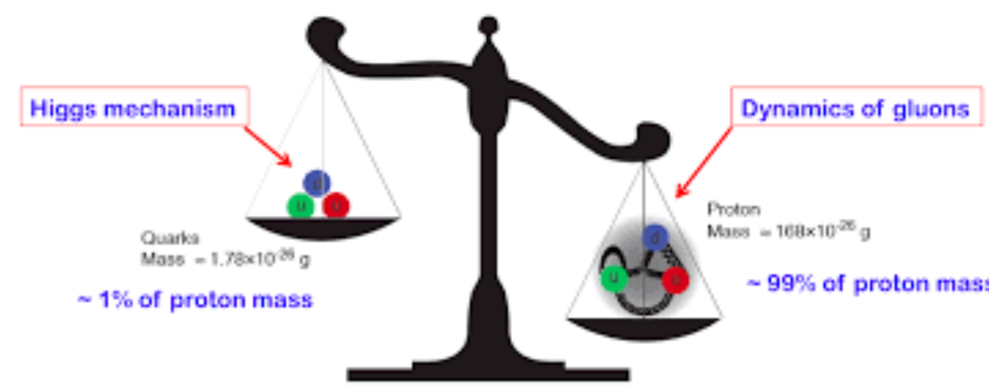


artistic picture of the proton
(D Dominguez/CERN)

proton is a very complex object:
study the constituents of the proton (quarks and gluons)
understand the forces between them

what is the **origin of the proton properties**
such as **spin** and **mass**?





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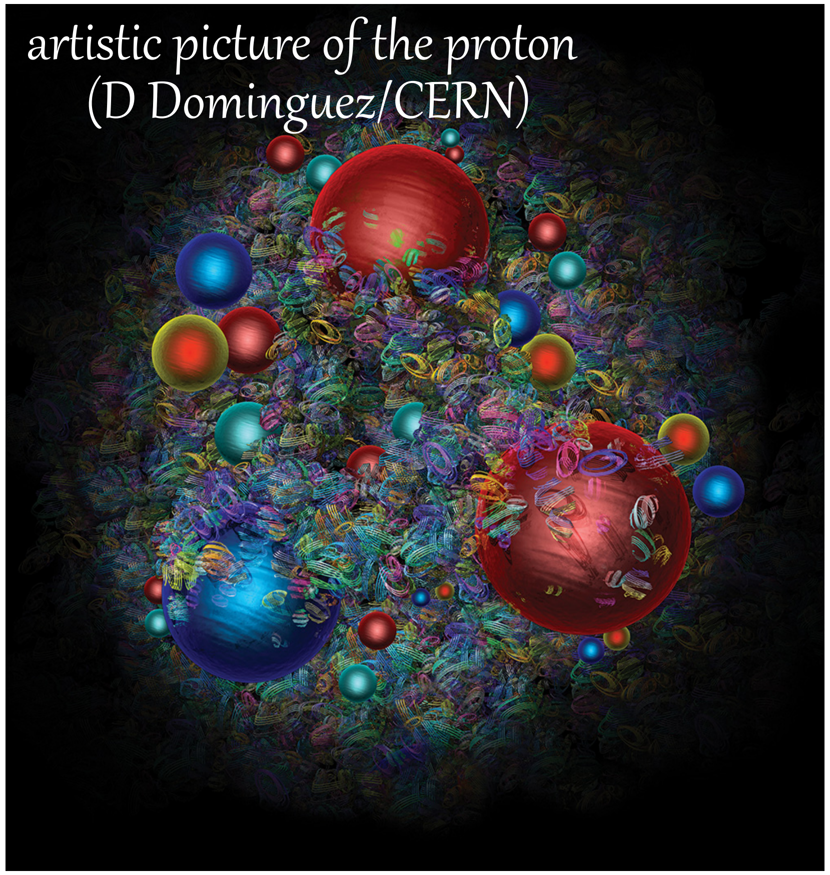

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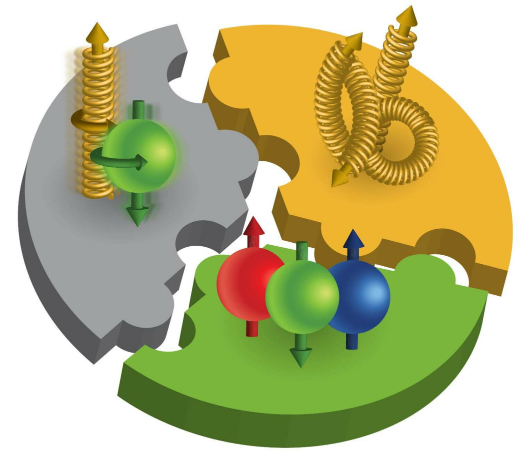
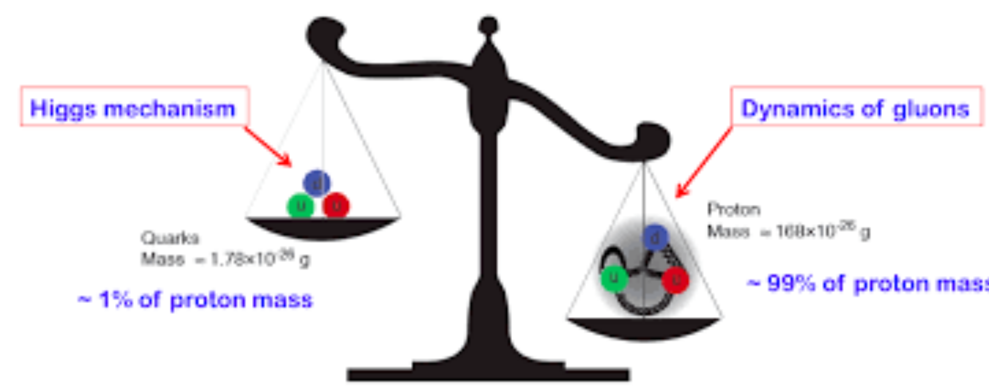
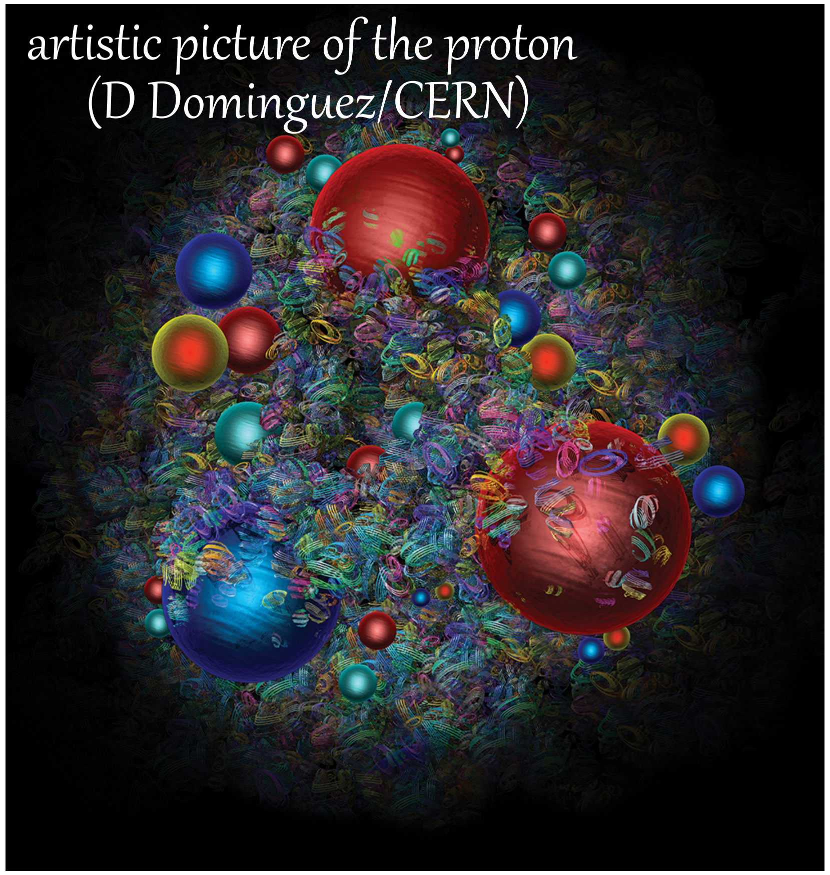




why is it important to study the **transverse structure of the proton**?
Connection with the **orbital angular momentum of partons**

Motivation for the Drell-Yan programme



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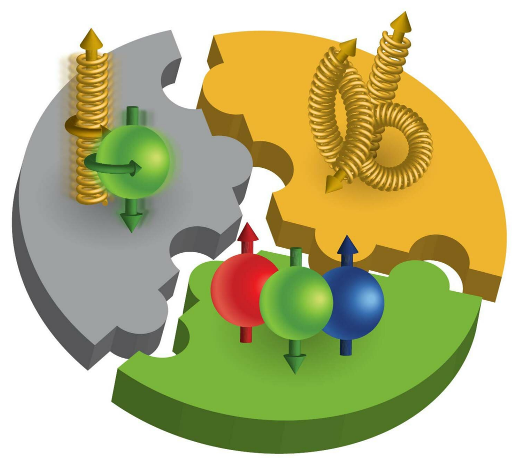
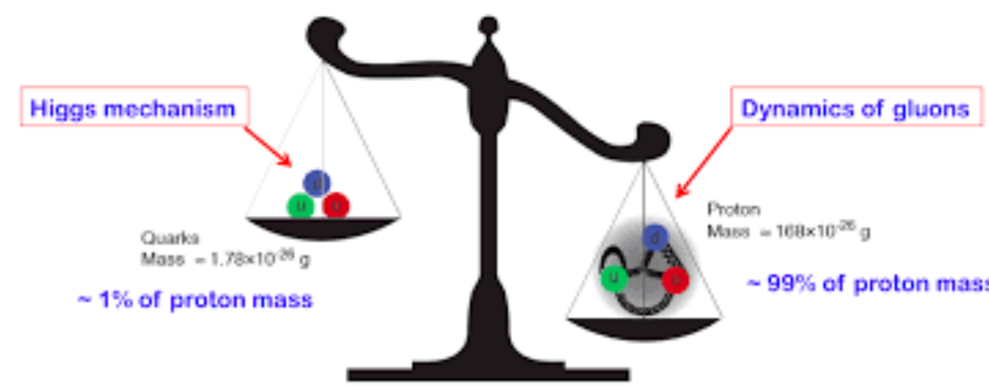




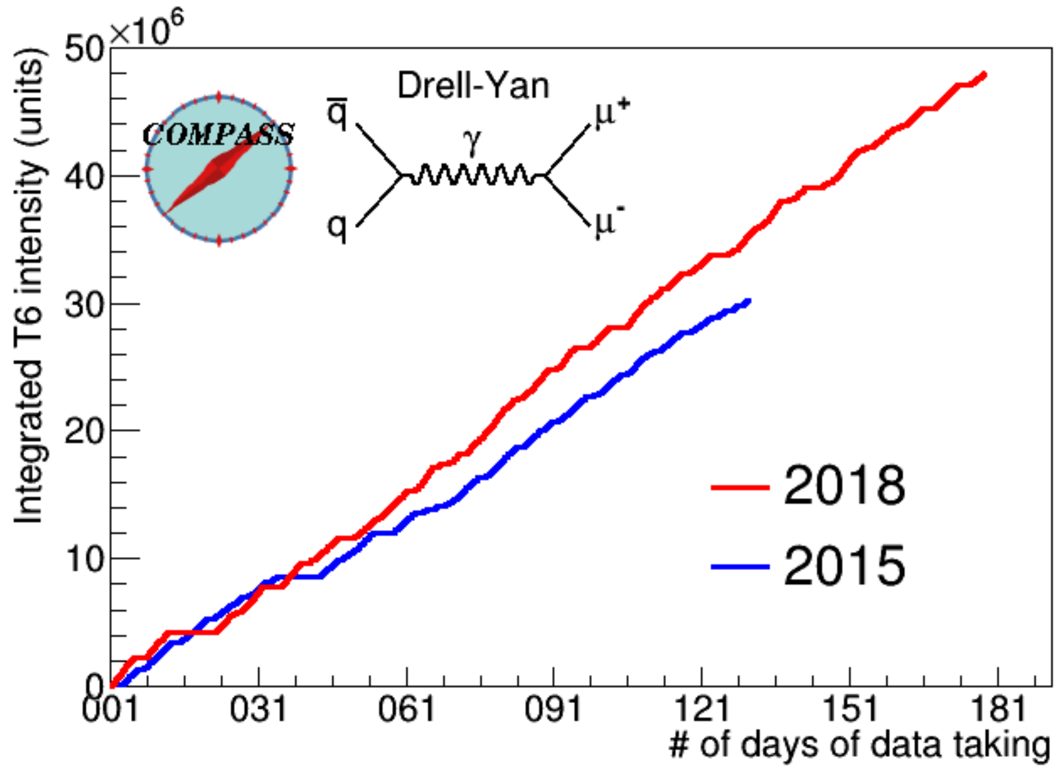
Drell-Yan is an excellent process to study the **nucleon** and the **meson structure**
by measuring the parton distributions inside those hadrons

using different beam particles ⟶ access **different quark flavours** in **different hadrons** (i.e. protons, pions, kaons)

using polarised targets ⟶ access the **spin dependent** hadron structure

2018 data-taking

Successful data-taking with major contributions from our group



From April to November 2018:

217 days of beam

rather smooth data-taking

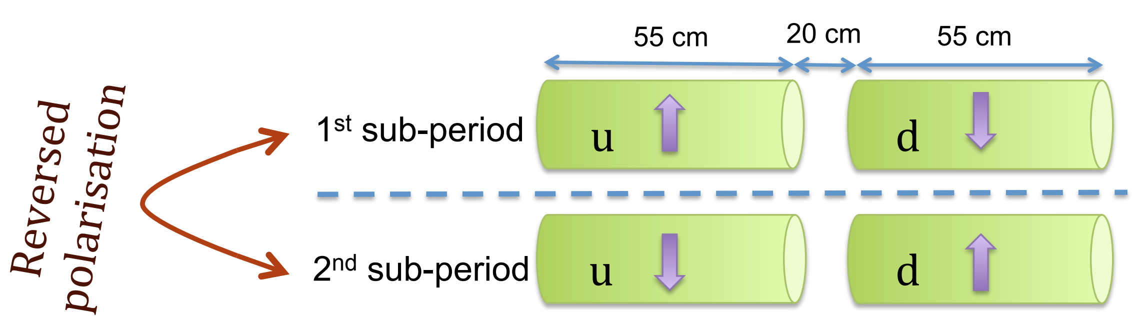
LIP helpful quasi-online analysis

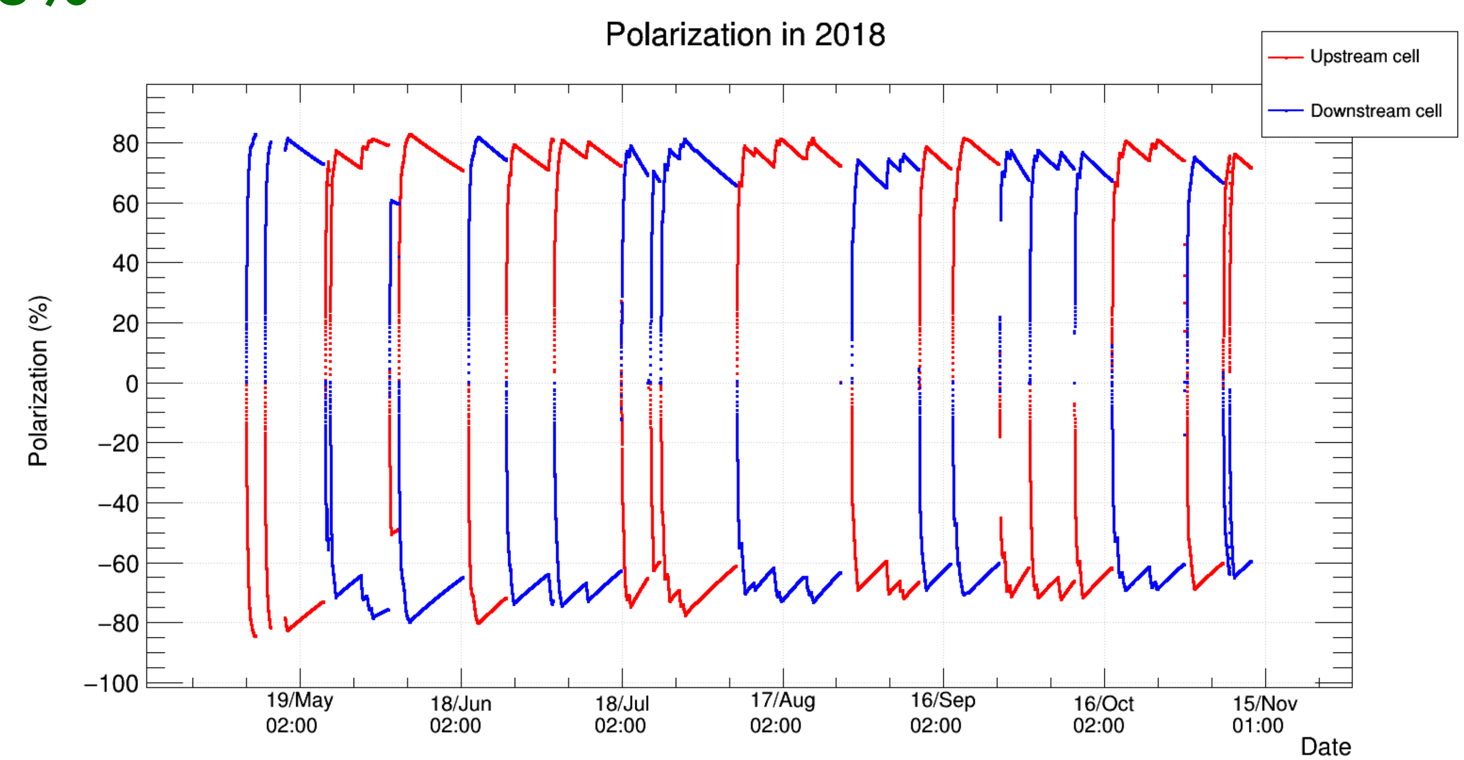
Preliminary production of all data collected (1.8PB)

Optimisation of events reconstruction os ongoing

Average target proton polarisation ~73%

Two NH_3 target cells oppositely polarised





several analyses ongoing

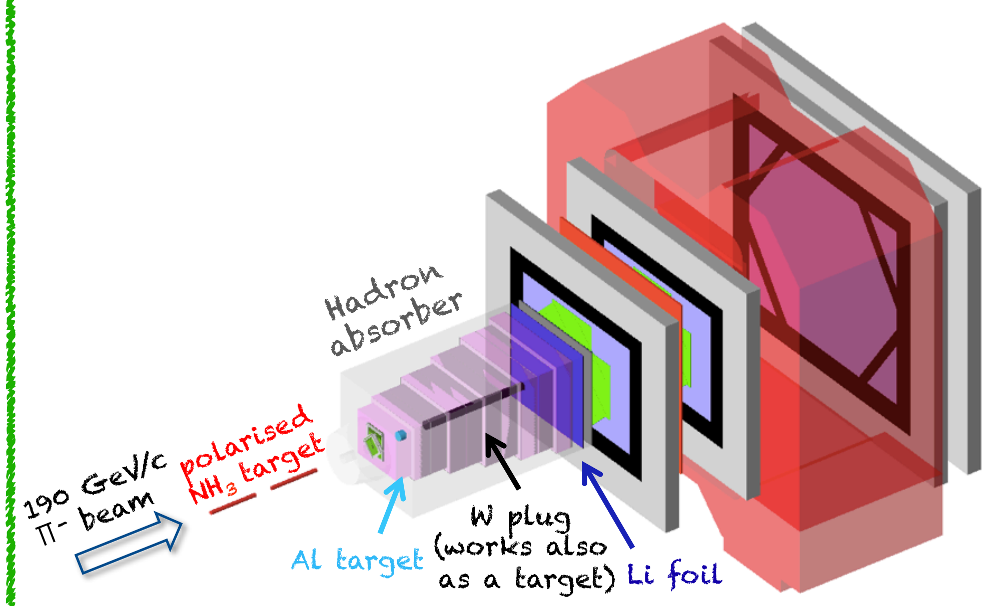
Polarised data (NH3):

- Transverse Spin Asymmetries

Unpolarised data (NH3, Al, W):

- unpolarised Asymmetries
- cross-sections
- nuclear dependences

target and absorber region



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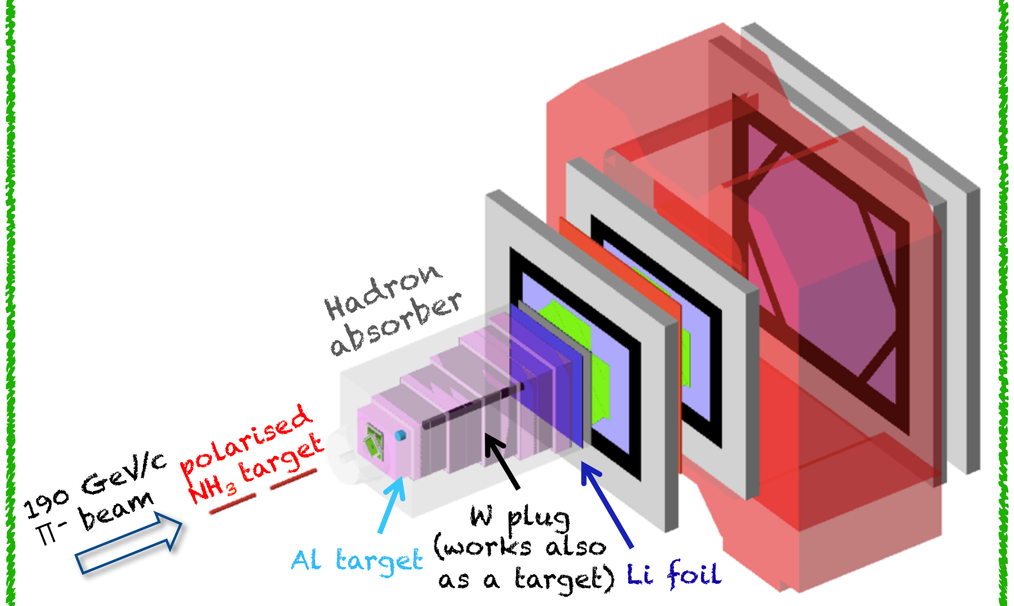

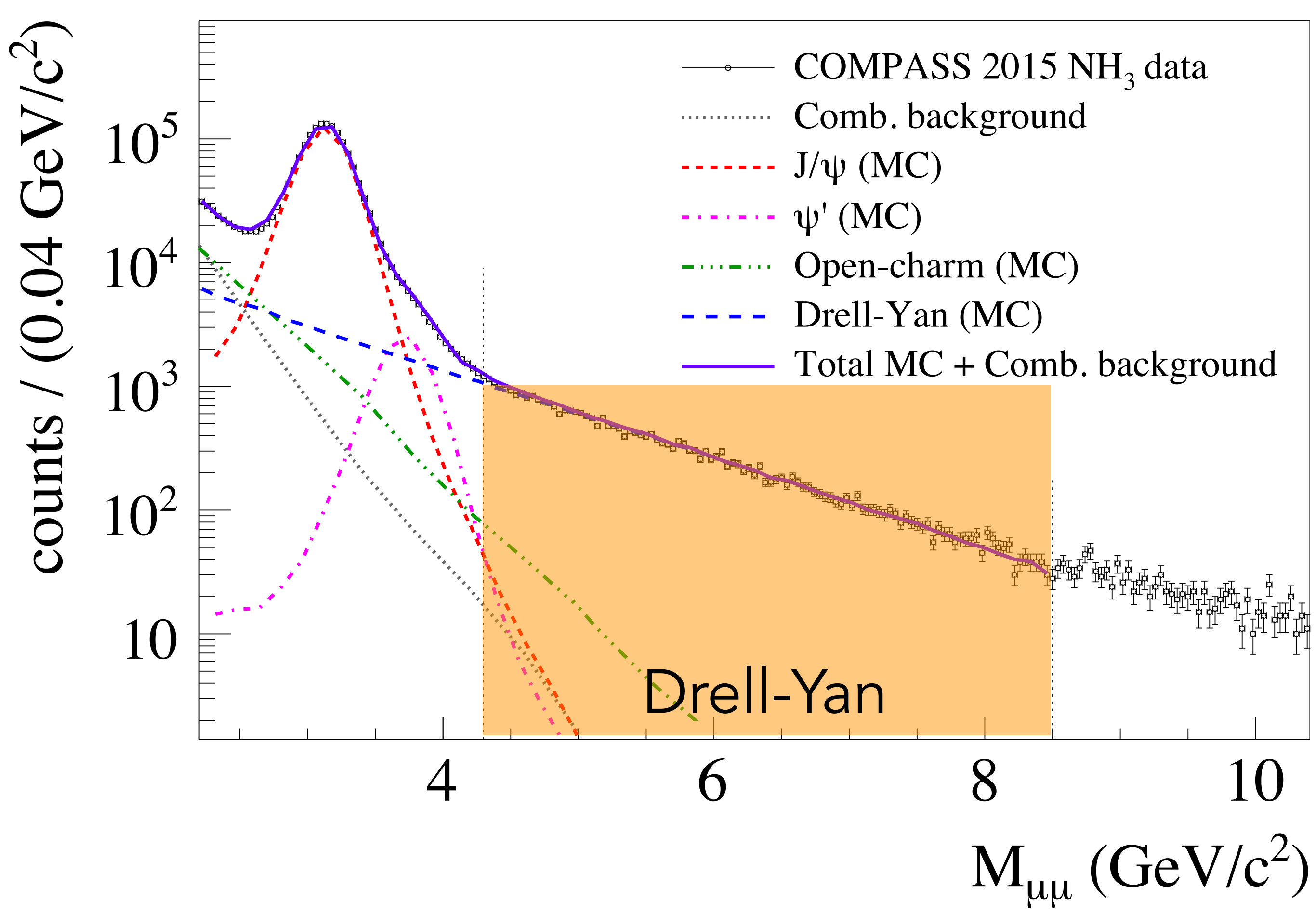

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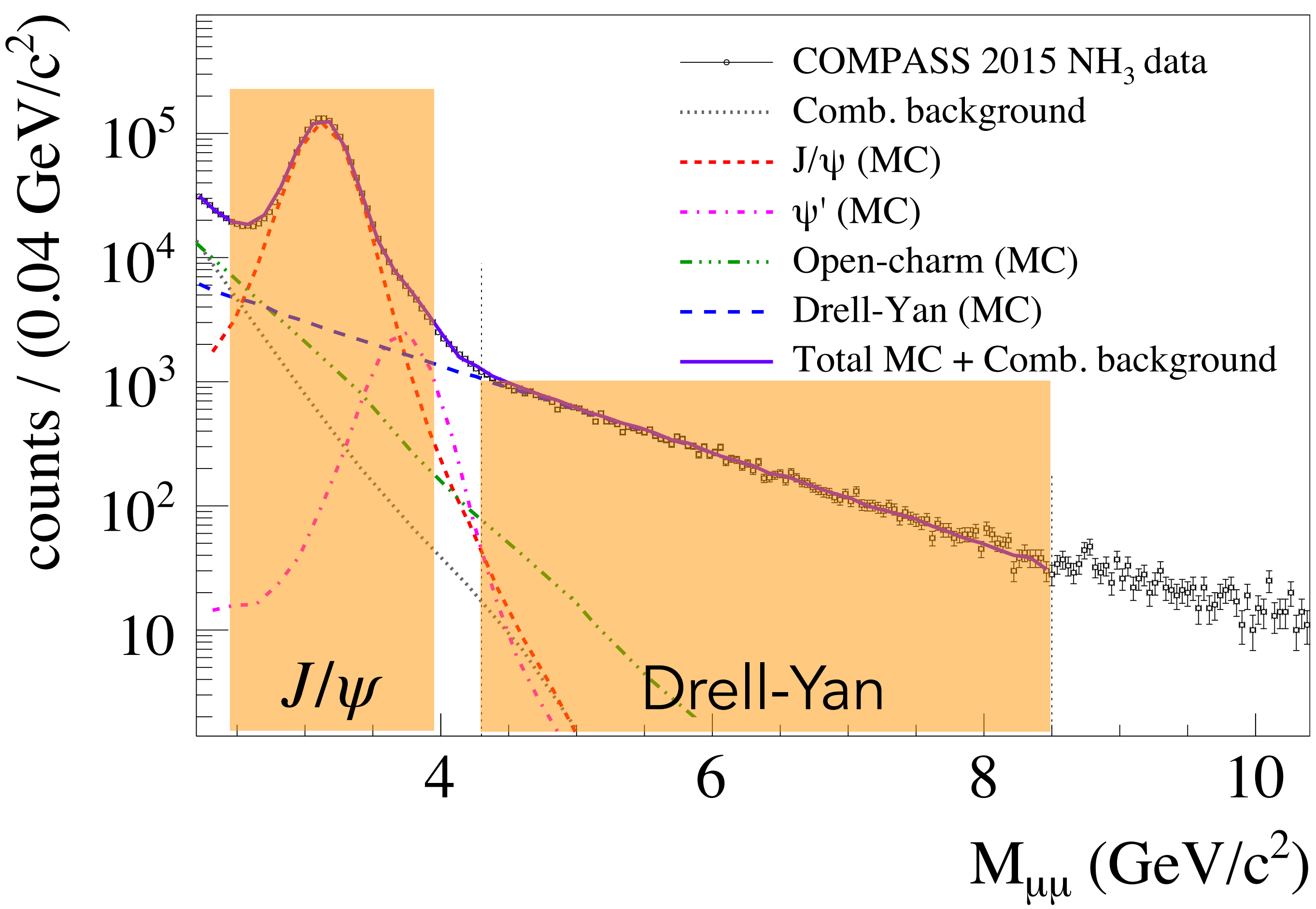

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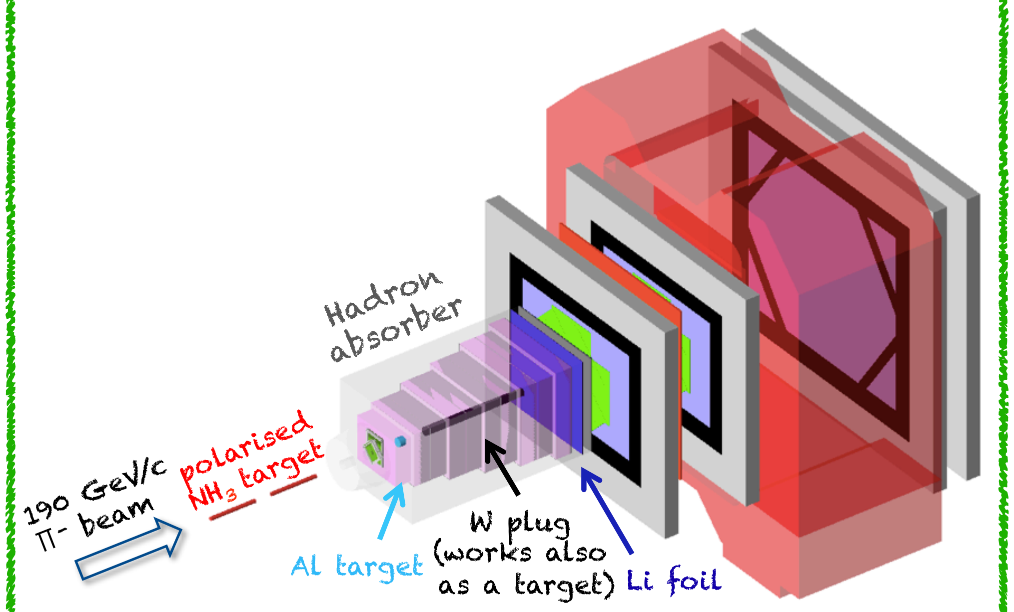

Our group is leading the studies on the machine learning techniques for background rejection in the Drell-Yan analyses

Drell-Yan data

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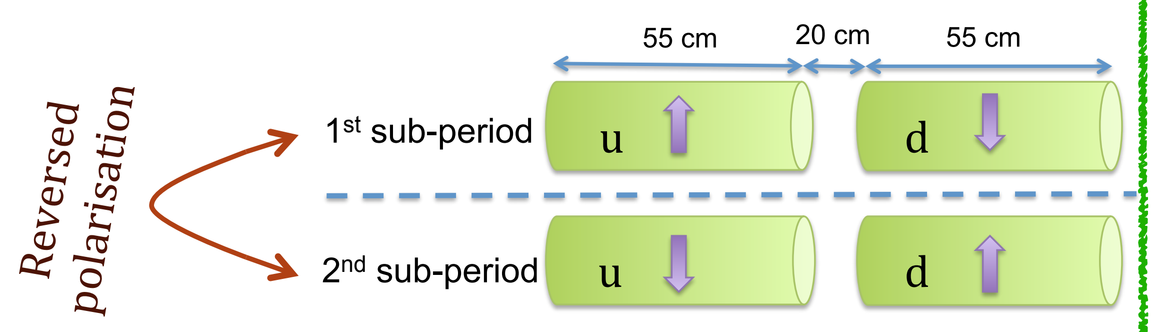
Acceptance corrections cancel

Better control of **systematics**

Two NH_3 target cells oppositely polarised



$$Asym(\phi_S, \phi_{CS}) \propto \frac{N_u^{\uparrow} N_d^{\uparrow}}{N_u^{\downarrow} N_d^{\downarrow}}$$

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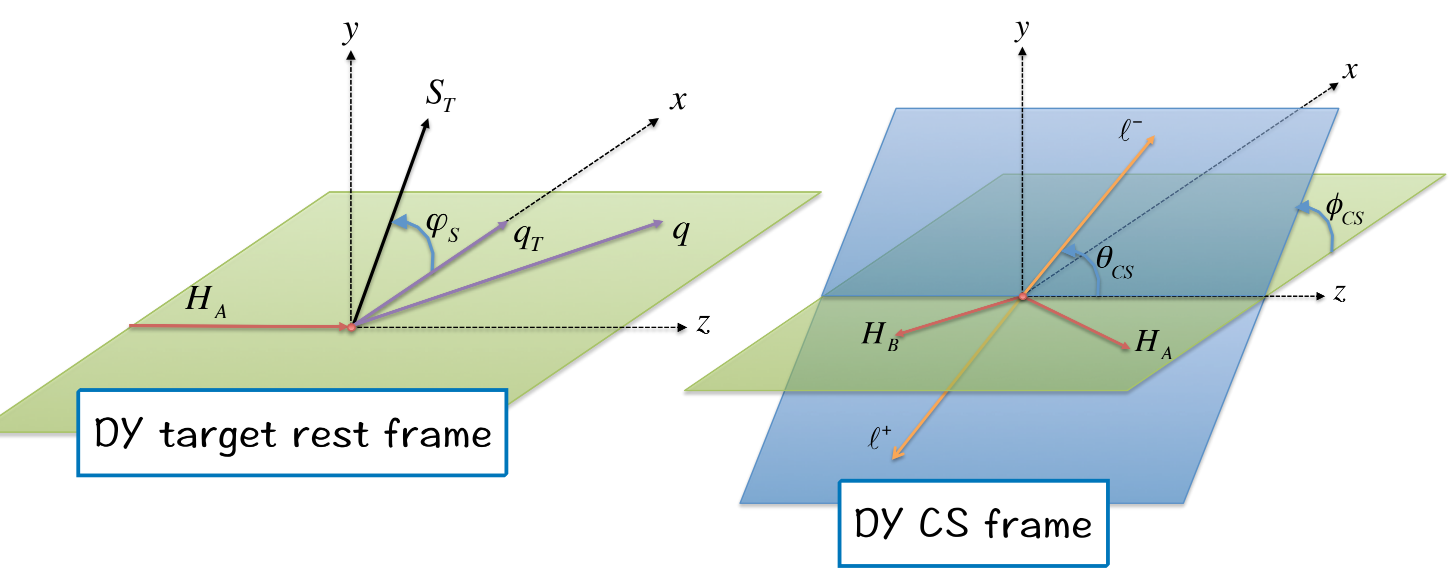
$Asym(\phi_S, \phi_{CS})$



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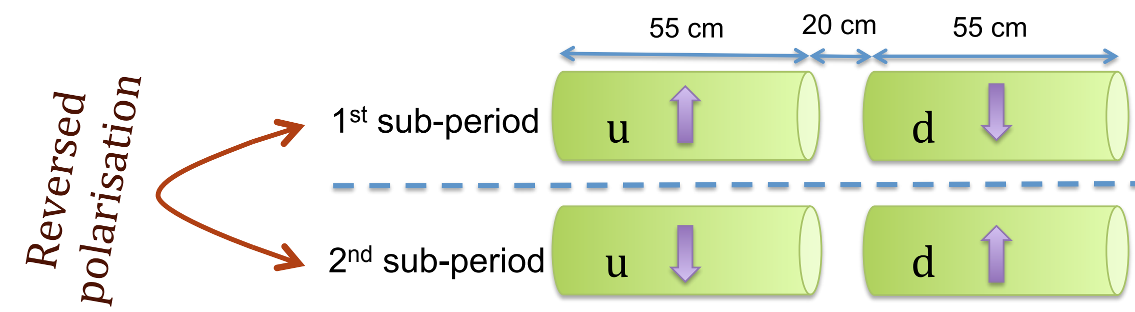

$$Asym(\phi_S, \phi_{CS}) \propto \frac{N_u^{\uparrow} N_d^{\uparrow}}{N_u^{\downarrow} N_d^{\downarrow}}$$

For single transversely polarised LO DY:

$$d\sigma^{DY} \propto \left(1 + \lambda \cos^2(\theta_{CS}) + \sin^2(\theta_{CS}) A_{UU}^{\cos(2\phi_{CS})} \cos(2\phi_{CS})\right) + S_T \left[(1 + \cos^2(\theta_{CS})) A_{UT}^{\sin(\varphi_S)} \sin(\varphi_S) + \sin^2(\theta_{CS}) \left(A_{UT}^{\sin(2\phi_{CS}-\varphi_S)} \sin(2\phi_{CS} - \varphi_S) + A_{UT}^{\sin(2\phi_{CS}+\varphi_S)} \sin(2\phi_{CS} + \varphi_S)\right)\right]$$

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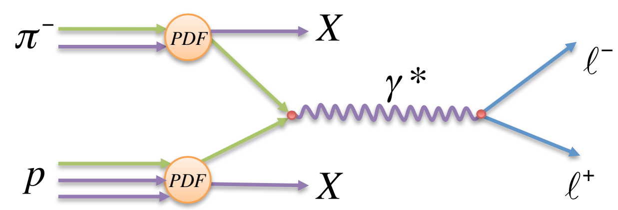


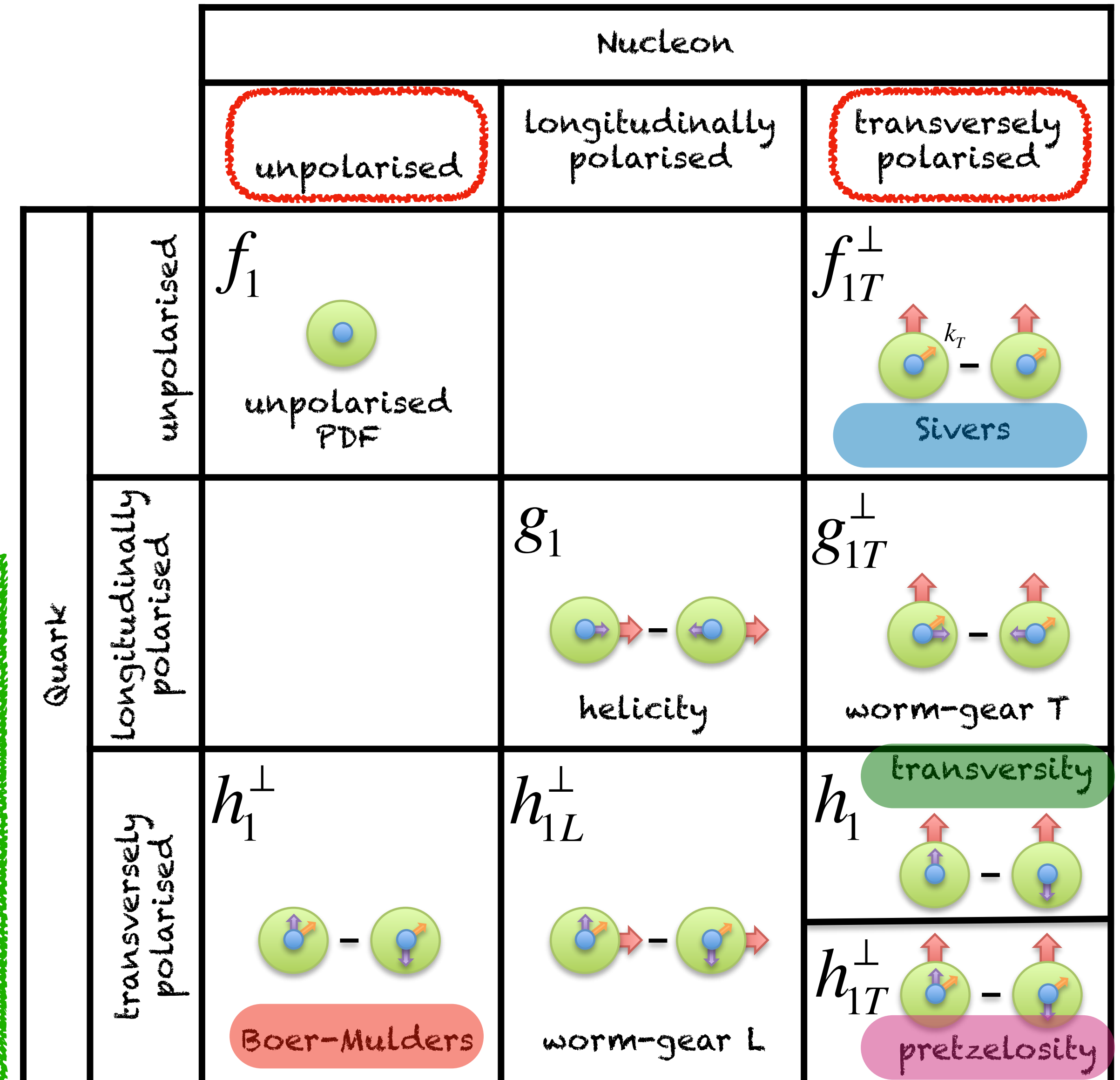
Transverse Momentum Dependent PDFs

$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$ Boer-Mulders

$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$ Sivers

$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ transversity

$A_{UT}^{\sin(2\phi+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$ pretzelosity



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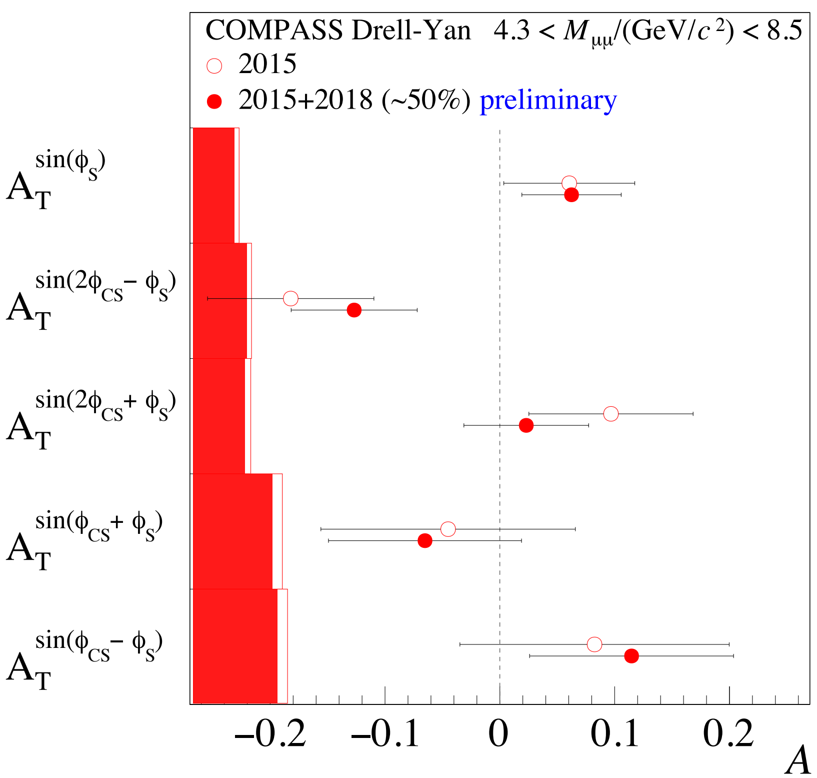
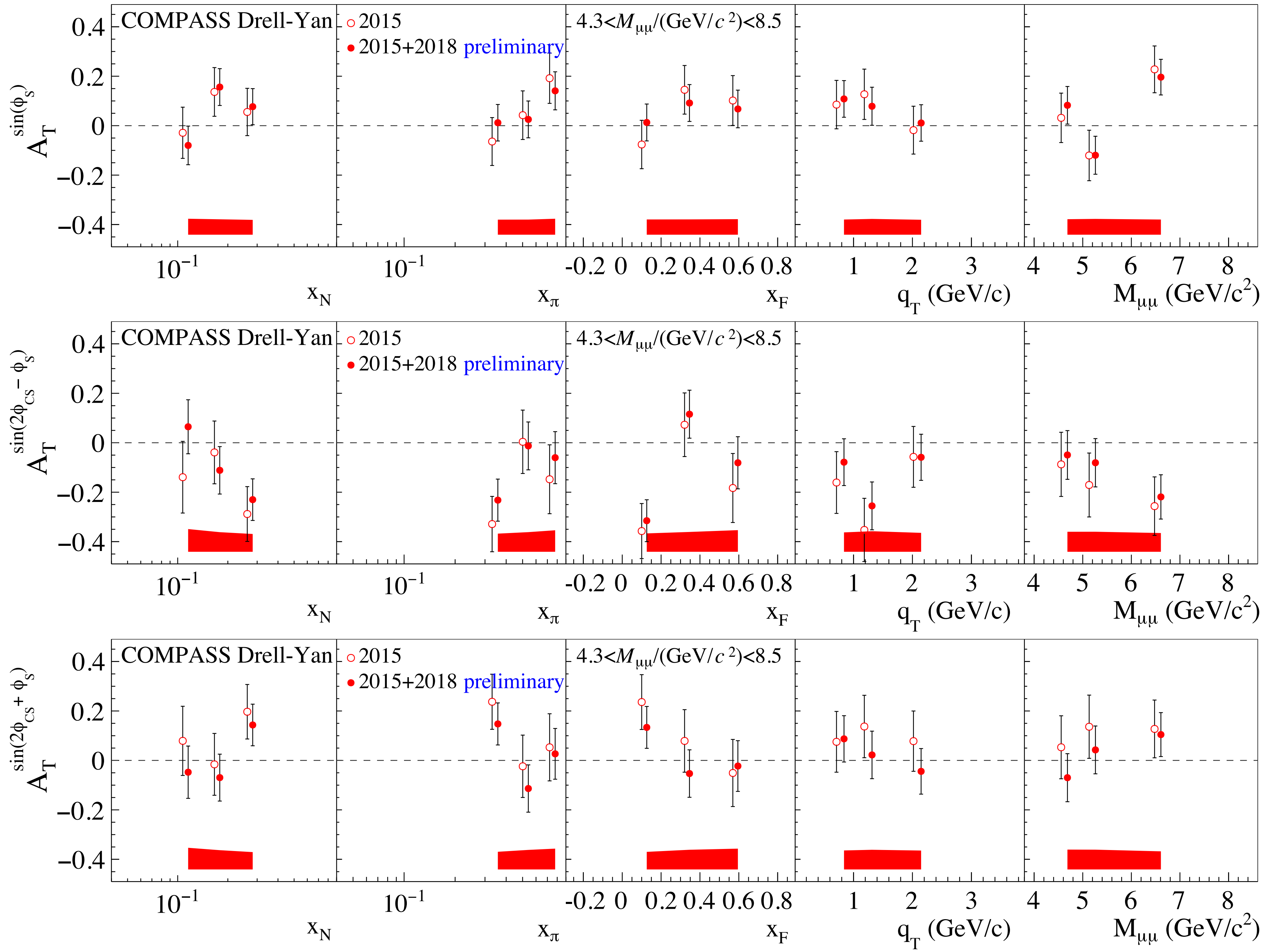
○ 2015 data - PRL 119 (2017) 112002

● 2015 + 2018 data - 50% of 2018 preliminary





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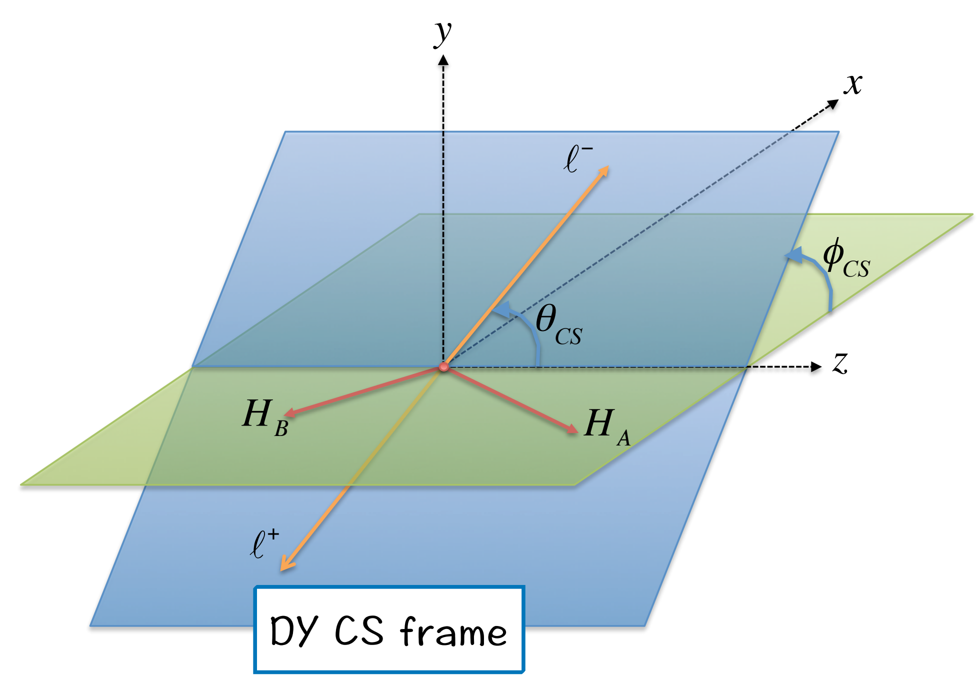
Acceptance corrections mandatory
Monte-Carlo dependence

Our group is contributing for the improvement of the MC description of the apparatus and the detectors and trigger efficiencies

For unpolarised DY:

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



Naive LO process: $\lambda = 1,\ \mu = \nu = 0$

The Lam-Tung relation **PRD 18 (1978) 2447**:

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

should still be valid when we include higher order corrections

Drell-Yan data

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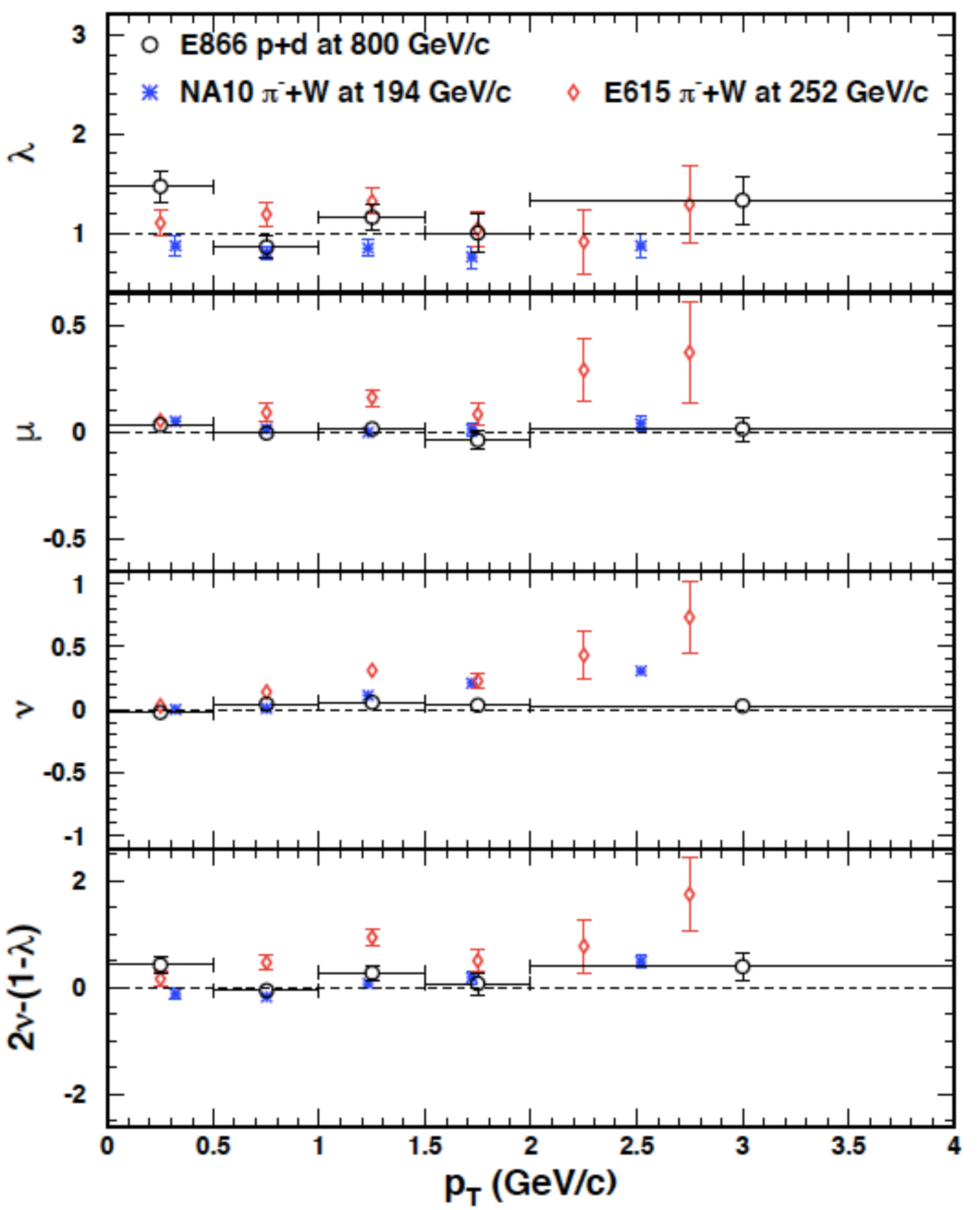
PRL 99 (2007) 082301



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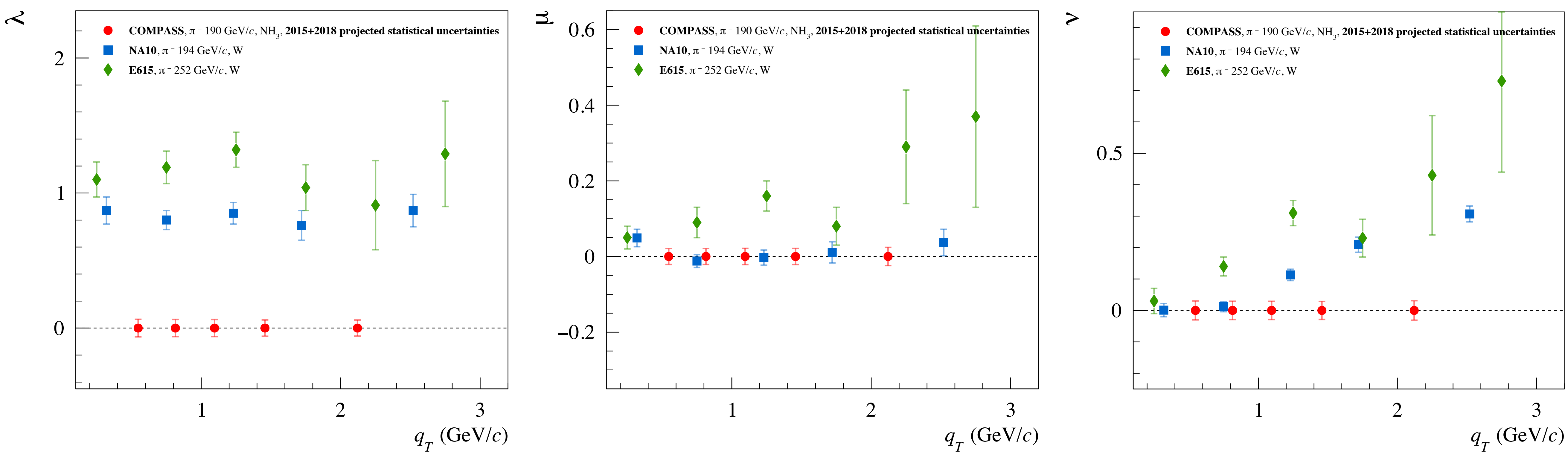
Statistical projections from COMPASS:



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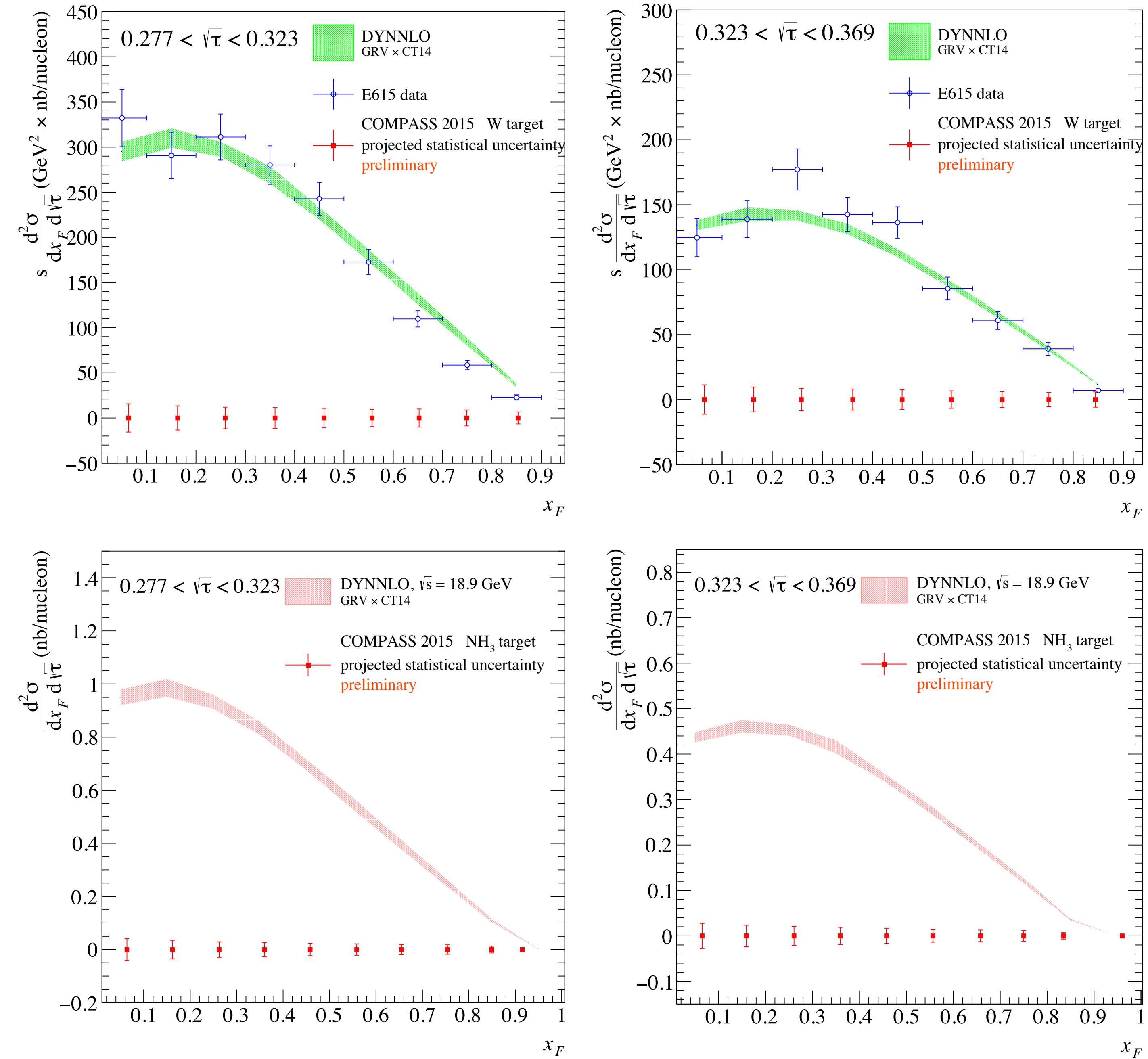

<u>Fundamental for global analysis:</u>

- For the extraction of the PDFs
- For studies on the transverse momentum dependences

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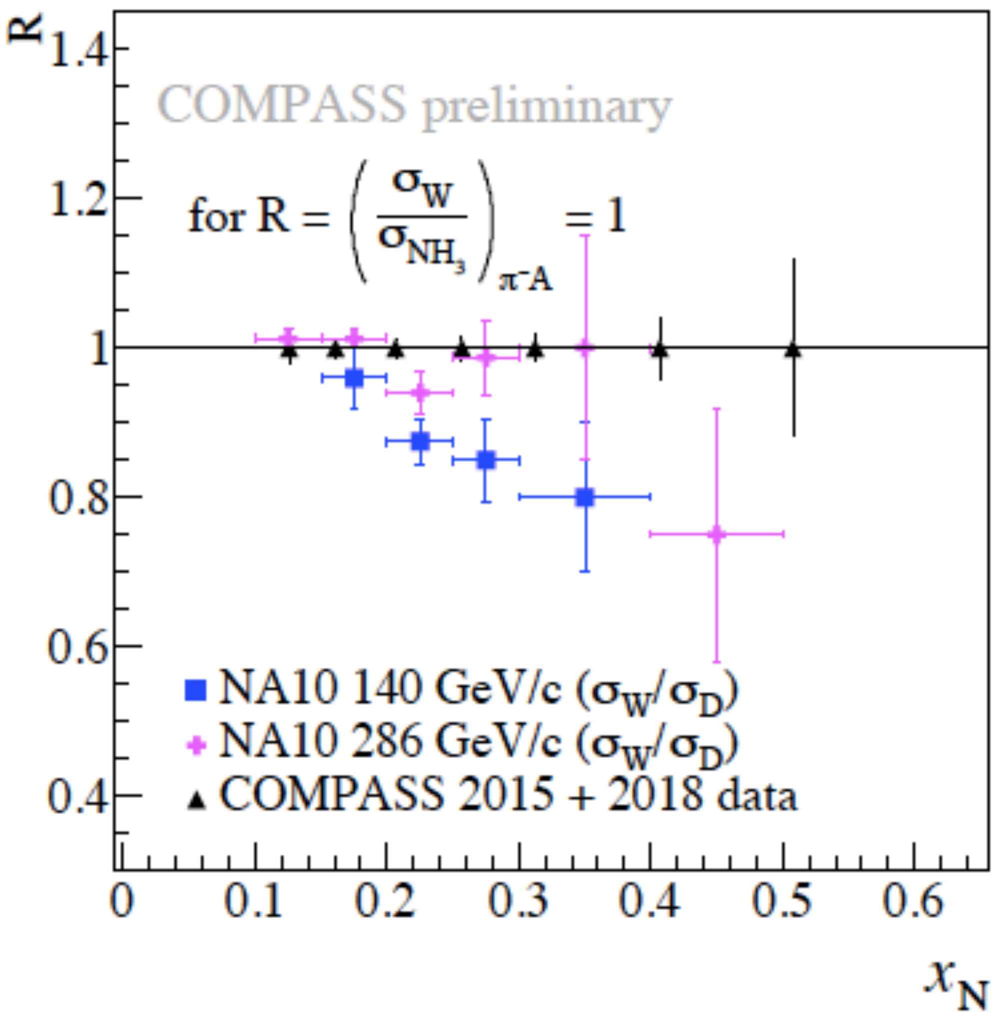
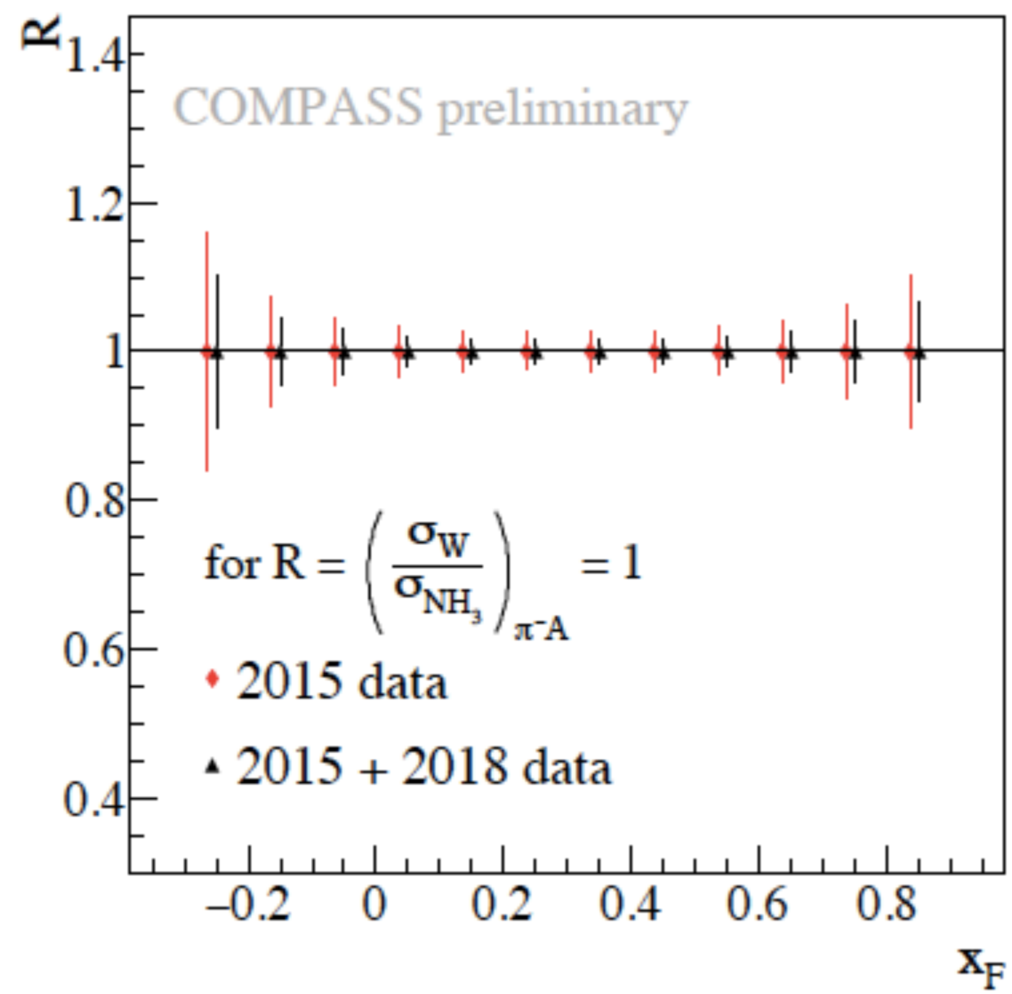
How are the parton distributions in nuclei with respect to nucleon?

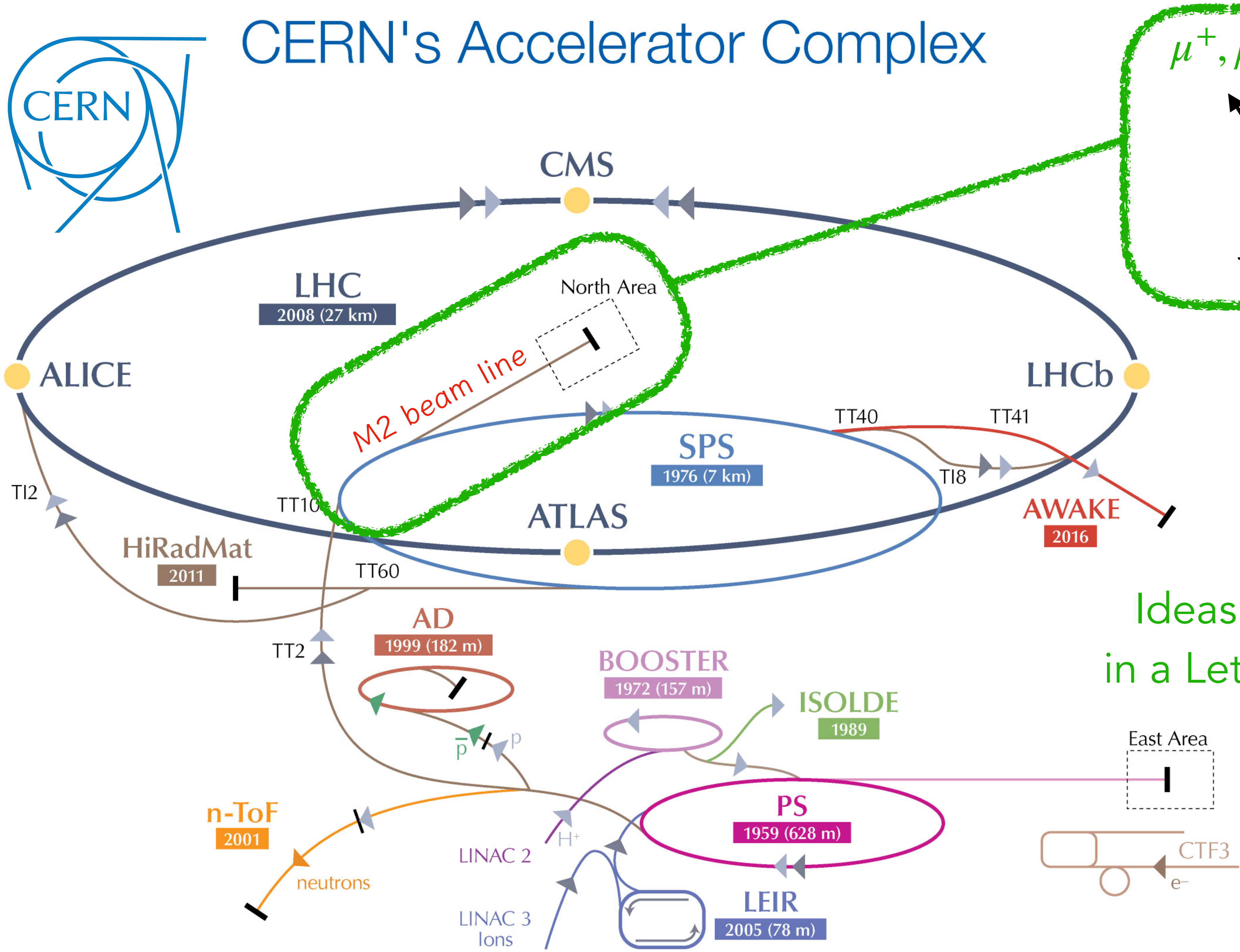
Expect an impact to the nuclear PDFs extraction at large x_F





AMBER experiment at CERN

End of COMPASS experiment (last run in 2021) ➡ Still many ideas for QCD studies



μ^+, μ^- $\quad$ $\pi^+, \pi^-, p, \bar{p}, K^+, K^-$

muon and hadron beams from the same beam line

UNIQUE WORLDWIDE

Ideas for AMBER are collected in a Letter of Intent (January 2019)

CERN-SPSC-2019-003 (SPSC-I-250)

Apparatus for Meson and Baryon Experimental Research

AMBER physics programme

In the Letter of Intent:

1. Hadron physics with standard muon beams
2. Hadron physics with standard hadron beams
3. Hadron physics with RF-separated beams

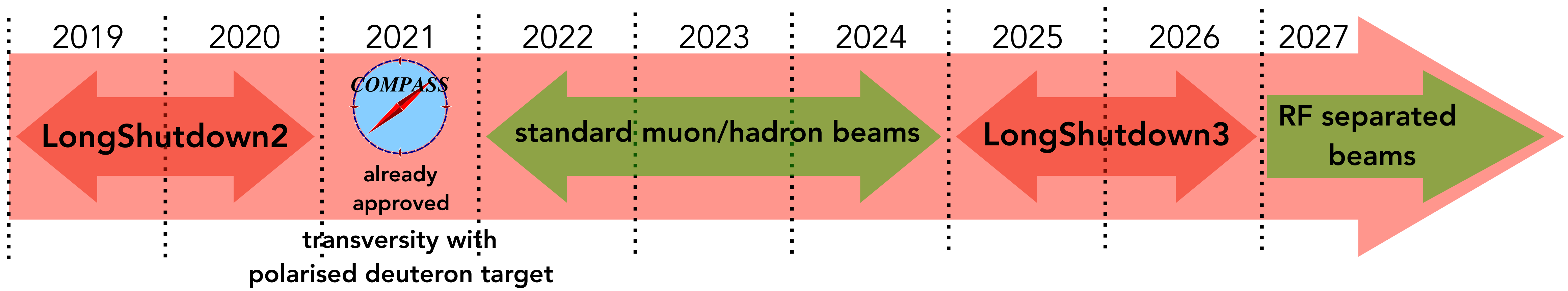
CERN-SPSC-2019-022 (SPSC-P-360)

1st phase proposal (May 2019):

1. Proton-radius measurement using elastic muon-proton scattering
2. Drell-Yan and Charmonium production using conventional hadron beams (both charges)
3. Measurement of antiproton production cross sections for dark matter search

Far future - after LS3:

1. Kaon spectroscopy
2. Kaon structure via the Drell-Yan process
3. Study of the gluon distribution in the kaon via prompt-photon production
4. Kaon polarizabilities via the Primakoff reactions
5. Vector-meson production off nuclei by pion and kaon beams



AMBER physics programme

In the Letter of Intent:

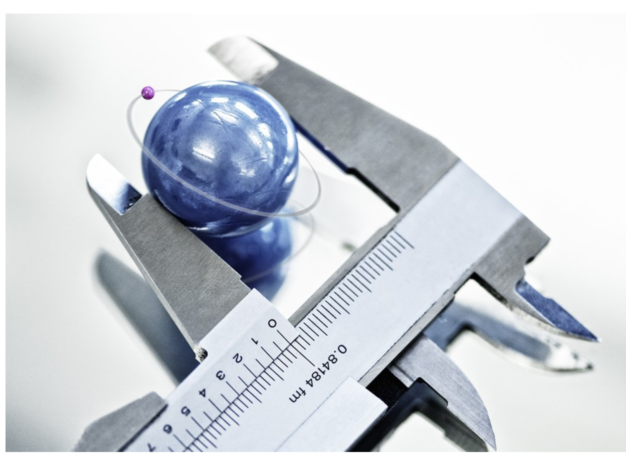
1. Hadron physics with standard muon beams
2. Hadron physics with standard hadron beams
3. Hadron physics with RF-separated beams

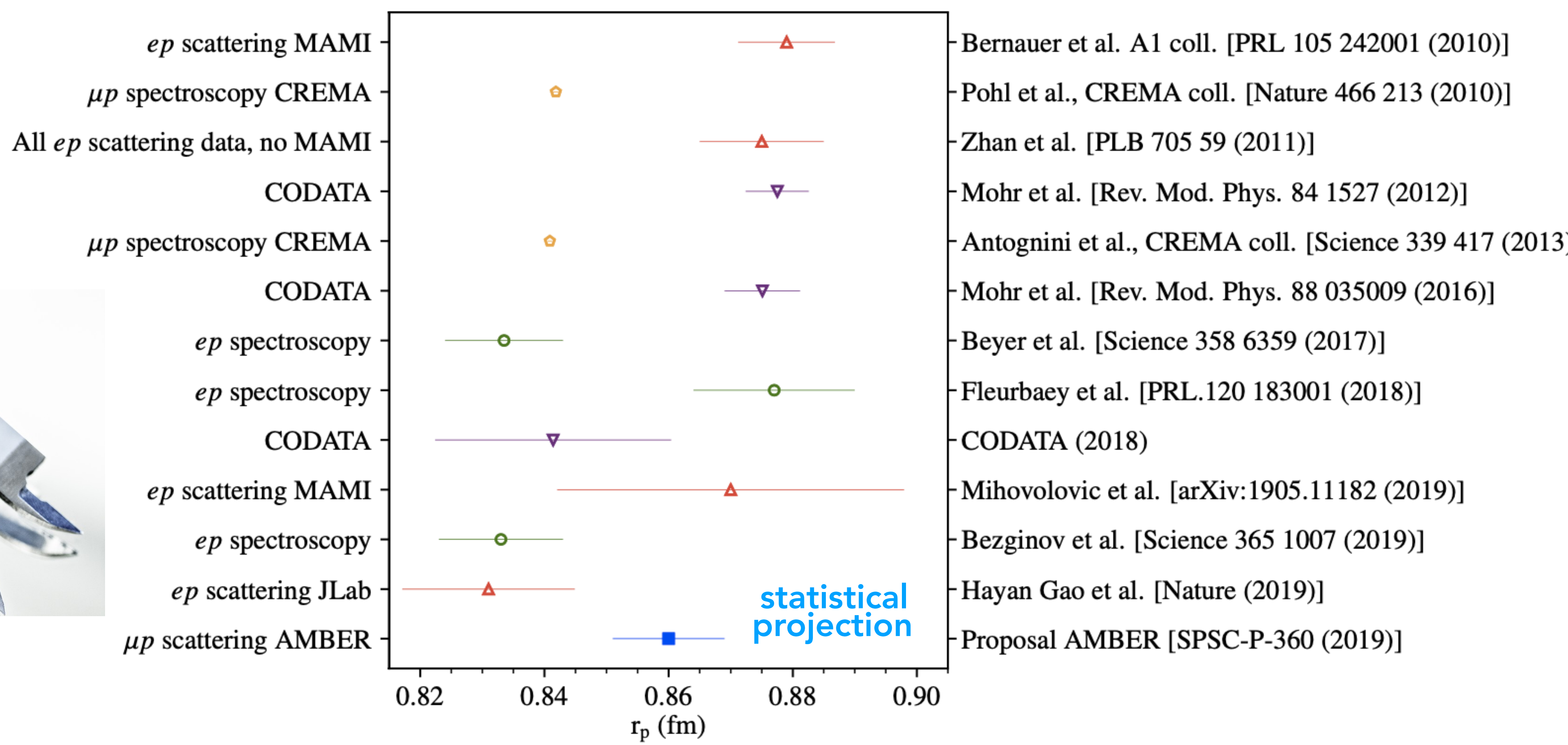
CERN-SPSC-2019-022 (SPSC-P-360)

1st phase proposal (May 2019):

1. Proton-radius measurement using elastic muon-proton scattering

proton radius puzzle





$r_p^{spectroscopy} \approx 0.84\ fm$ $\qquad$ $r_p^{elastic\ scattering} \approx 0.88\ fm$

AMBER physics programme

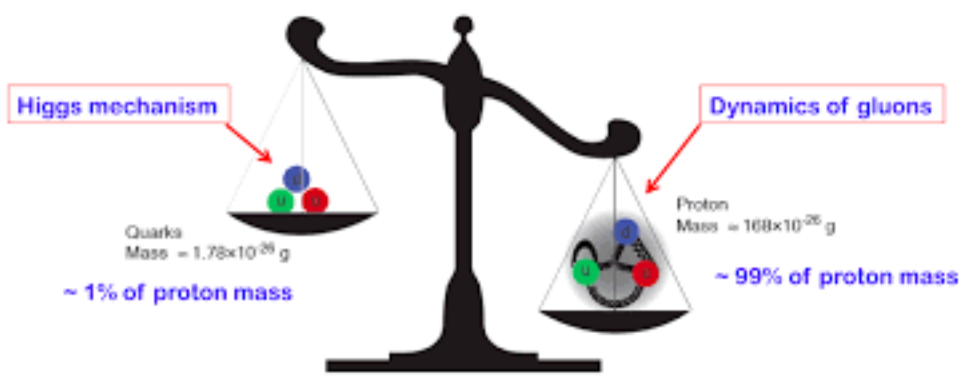
In the Letter of Intent:

1. Hadron physics with standard muon beams
2. Hadron physics with standard hadron beams
3. Hadron physics with RF-separated beams

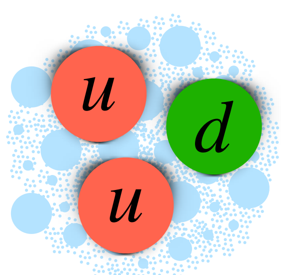
CERN-SPSC-2019-022 (SPSC-P-360)

1st phase proposal (May 2019):

1. Proton-radius measurement using elastic muon-proton scattering
2. Drell-Yan and Charmonium production using conventional hadron beams (with beam PID)

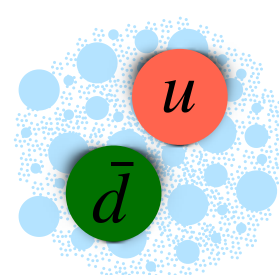


Our group is already involved on the simulations and projections/predictions for the future



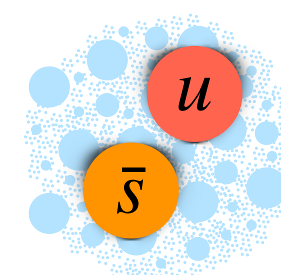
$M_p \sim 940\ MeV/c^2$

Three light valence quarks



$M_\pi \sim 140\ MeV/c^2$

Two light valence quarks



$M_K \sim 490\ MeV/c^2$

One light valence quark
plus
one "heavy" valence quark

The **nucleon** and the **meson PDFs** are fundamental to **understand the hadrons mass** budget

Summary

- COMPASS had 2 years of Drell-Yan data-taking in 2015 and in 2018
- Our group is deeply involved in several analyses, both with polarised and unpolarised samples
- These results are of fundamental interest for our understanding of the proton and pion structures
- AMBER is being proposed as a new fixed target experiment at CERN
- Possibility to start measurements in 2022, with a COMPASS-like spectrometer and a new TPC detector as active target, to measure the proton charge radius
- kaon induced Drell-Yan: first ever dedicated measurement of kaon structure

For more details on AMBER experiment
see Rita Silva poster today in the poster session 2

THANK YOU
FOR YOUR
ATTENTION