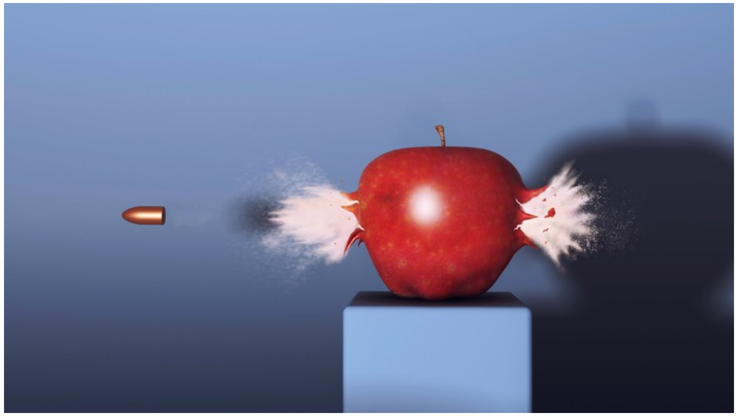
UNIVERSITÀ DEGLI STUDI DI FERRARA
- EX LABORE FRUCTUS -

INFN Istituto Nazionale di Fisica Nucleare

Perspectives for a polarized fixed target at LHC



L. L. Pappalardo

2nd Italian Workshop on Hadron Physics and Non-Perturbative QCD

Pollenzo (CN), May 22-24 2017

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- backward CM rapidity region ➔ very high x-Bjorken!

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- ✓ **Polarized gas target technology well established (10 years @ HERMES)**
- ✓ **Very high performances ($P \sim 80\%$)**

Kinematics for a fixed target @ LHC

Kinematic conditions for a fixed target at LHC

7 TeV proton beam on a fixed target proton:

- $\sqrt{s} \approx 115\ GeV$ **(between SPS & RHIC)**
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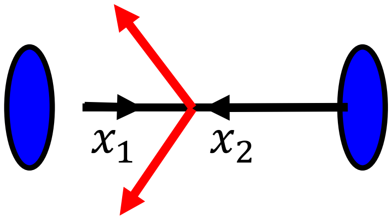
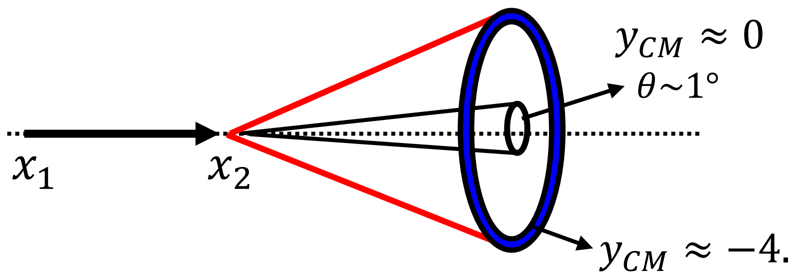
CM system

CM backward rapidity region ($-4.8 < y_{CM} < 0$)



Target rest frame (Lab system)



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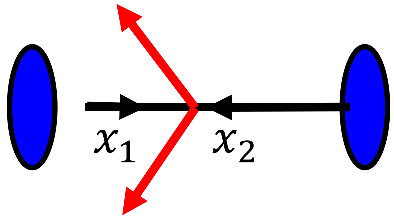

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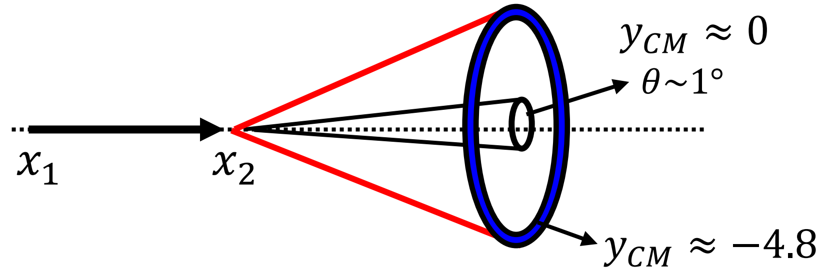

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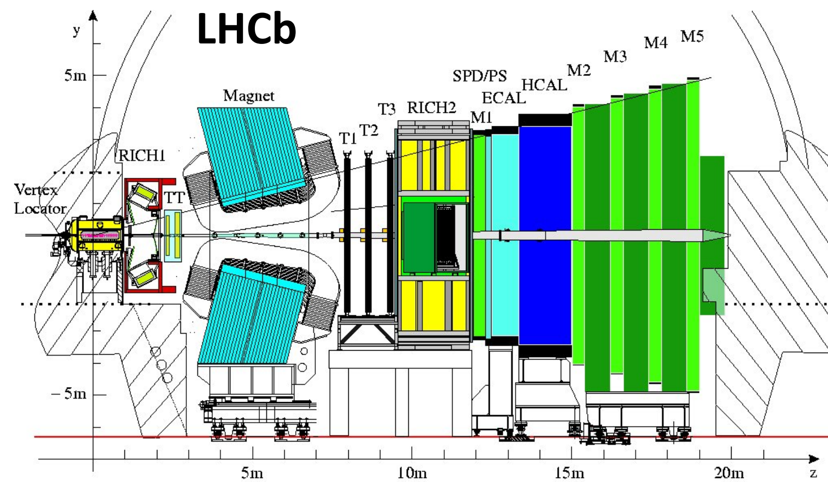
- **LHCb** acceptance and detector performance perfectly suitable!



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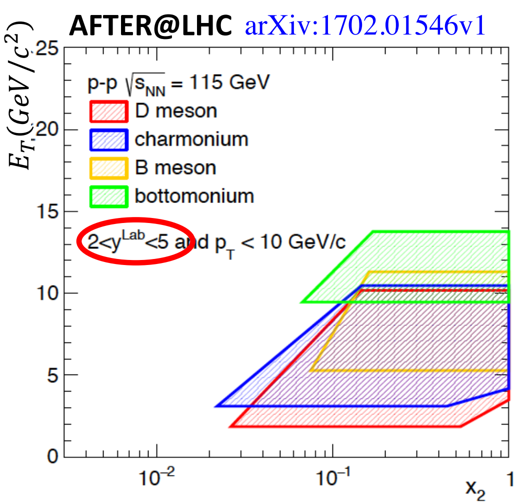
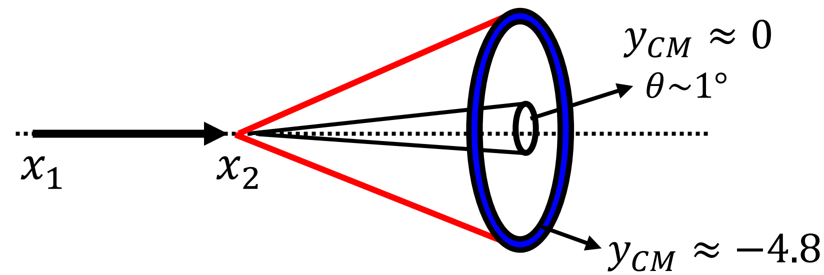
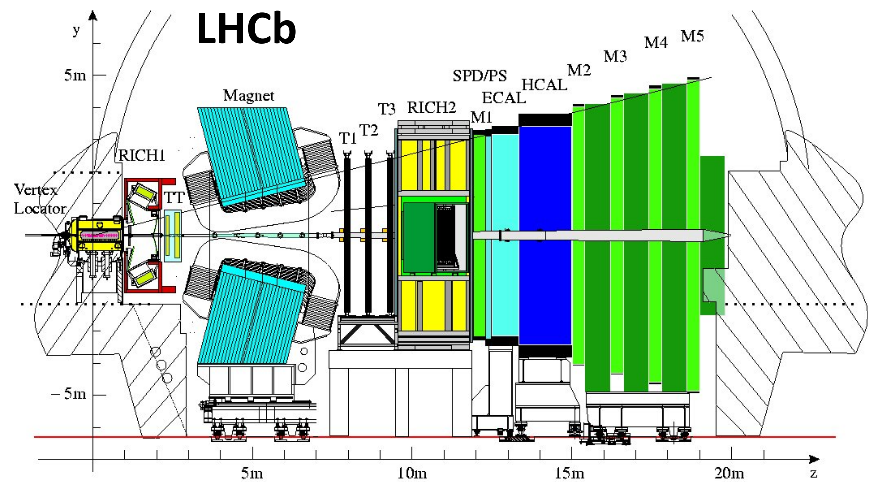


$$x_2 = \frac{E_T}{\sqrt{s}} e^{-y_{CM}}$$

$$E_T = \sqrt{p_T^2 + m^2}$$

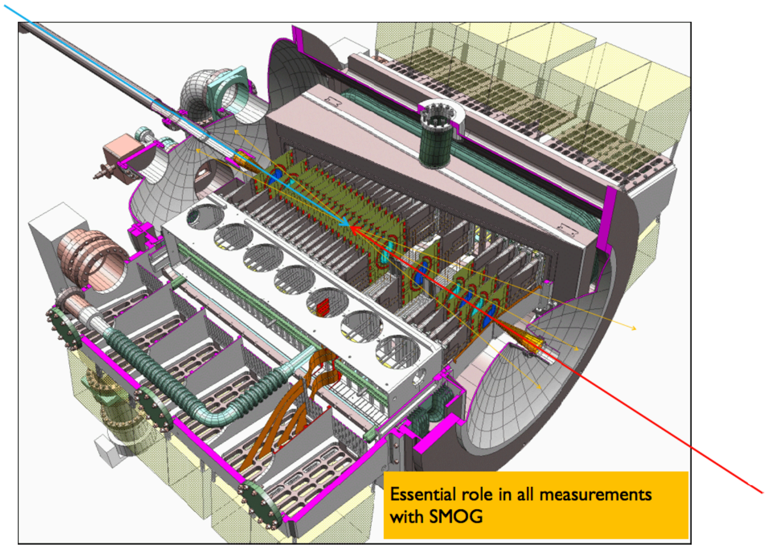


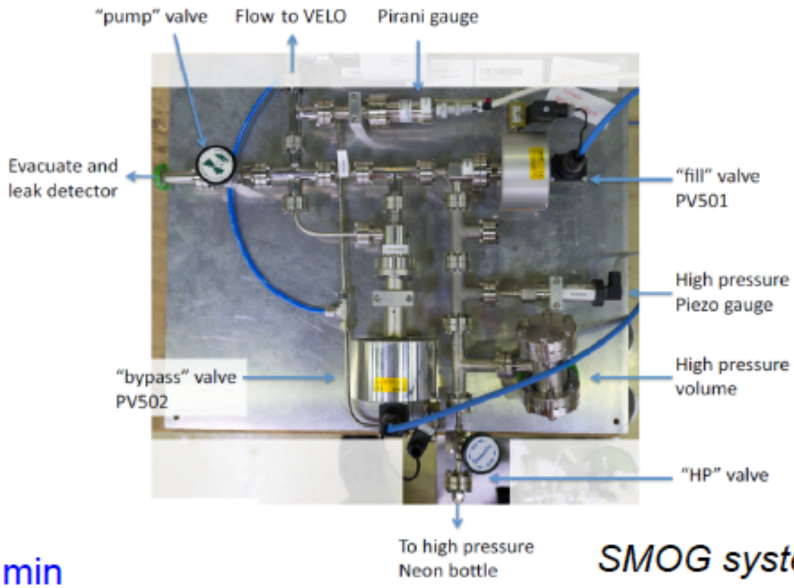


- Sensitive to x_2 **up to 1** (**very high x ➔ unexplored**!)
- Access to **target-fragmentation region** $(x_F = |P_z|/P_{z\,max} \to -1)$

SMOG: the present unpolarized fixed target experiment @ LHCb

→ SMOG: System for Measuring Overlap with Gas:
- Main use so far for precise **luminosity determination**
- Low density noble gas injected in the VELO, in the interaction region
- Only local temporary degradation of LHC vacuum





SMOG system

- ❑ pNe pilot run at $\sqrt{s_{NN}}$ = 87 GeV (2012) ~ 30 min
- ❑ PbNe pilot run at $\sqrt{s_{NN}}$ = 54 GeV (2013) ~ 30min
- ❑ pNe run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 12h
- ❑ pHe run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 8h
- ❑ pAr run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 3 days
- ❑ pAr run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ few hours
- ❑ PbAr run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ 1.5 week
- ❑ pHe run at $\sqrt{s_{NN}}$ = 110 GeV (2016) ~ 2 days

Preferred target Gas

	He	Ne	Ar	Kr	Xe
A	4	20	40	84	131

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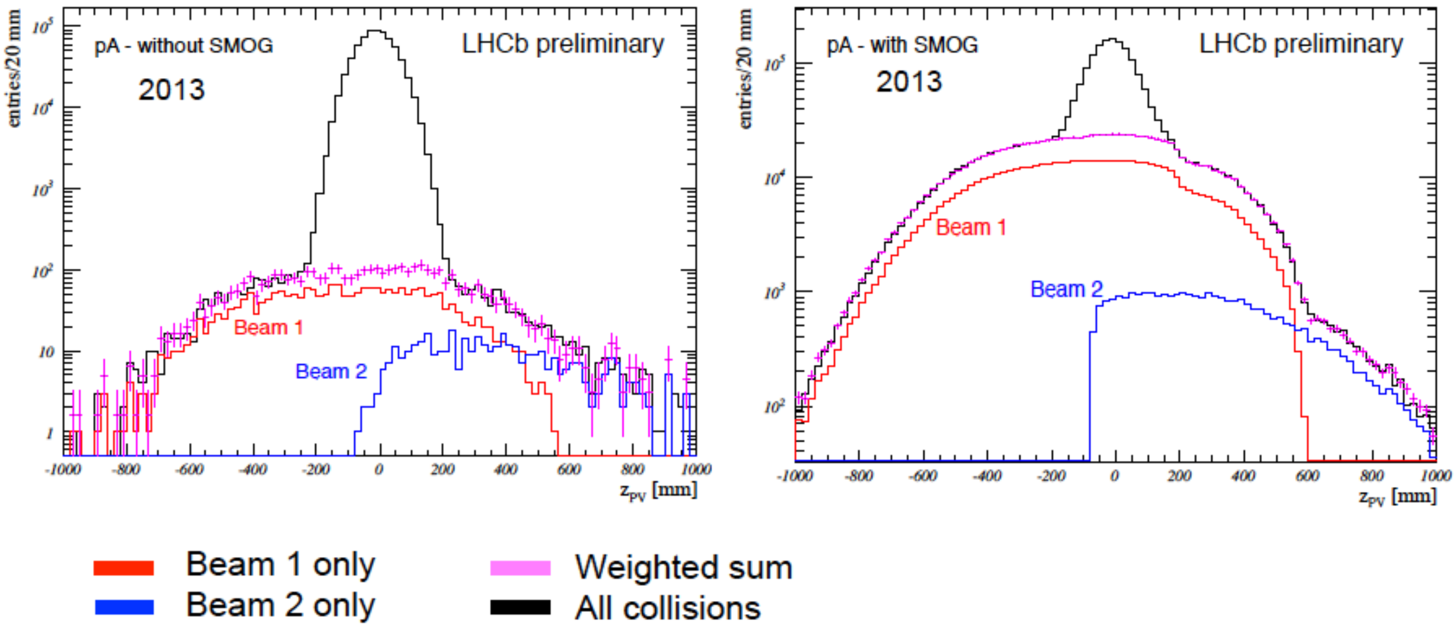
LHCb-CONF-2012-034



- Gas pressure ($\sim 10^{-7} mbar$) is 2 orders of magnitude larger than LHC vacuum pressure
- SMOG increases the beam-gas collision rate by 2 orders of magnitude
- Precise vertexing (and LHC filling scheme) allows to separate beam-beam and beam-gas contributions → **Fixed target collisions can be isolated from regular collider collisions**

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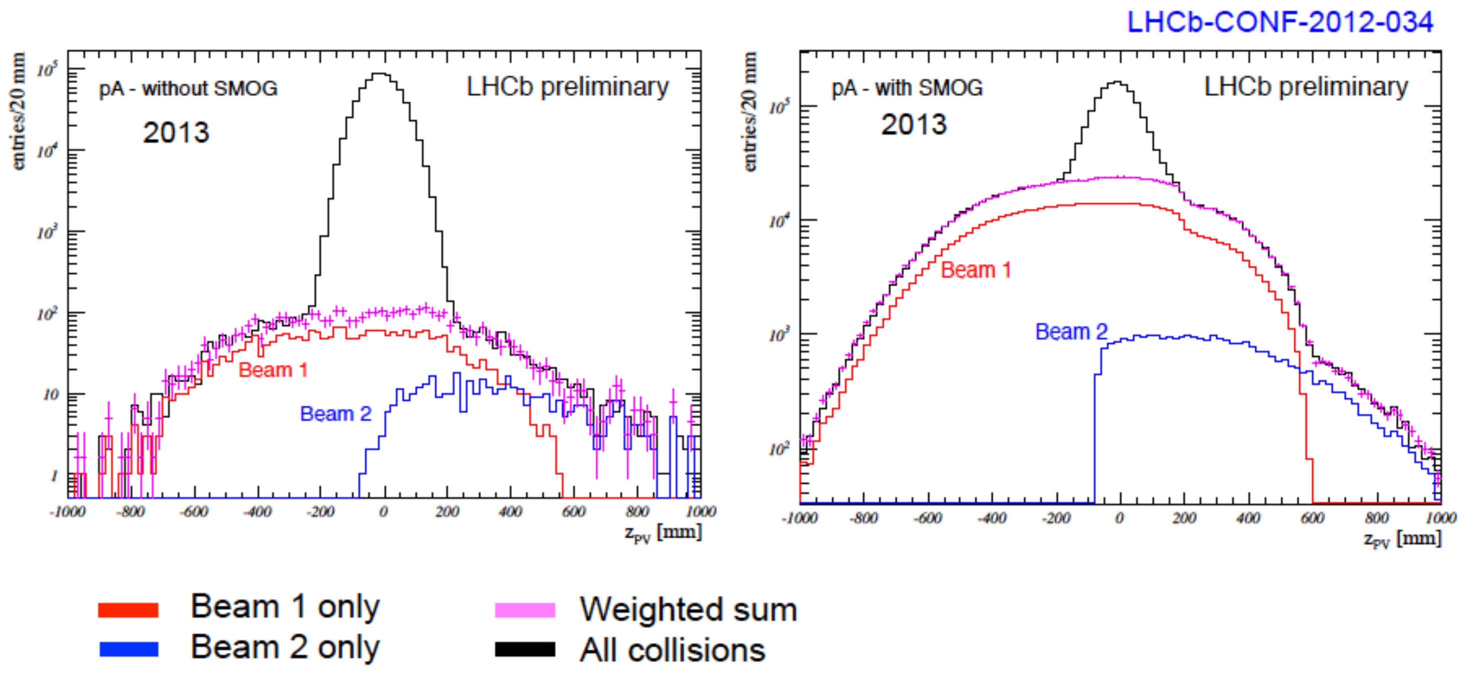

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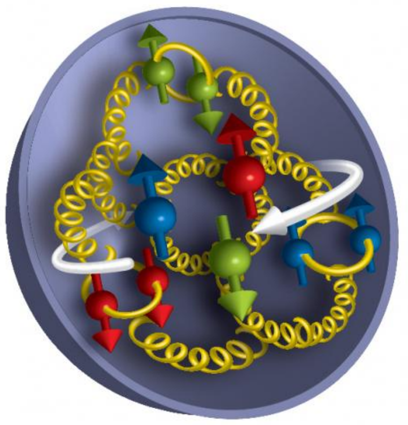
A recent idea of installing a **storage cell inside the VELO** is presently under discussion and would constitute an R&D for a future polarized target system at LHCb!

Physics opportunities with a polarized target @ LHC

The proton as a laboratory for QCD

The study of the hadrons structure is a fundamental step towards the understanding of **confinement**, and more in general, of strong interactions in the **non-perturbative QCD**.



The proton is an ideal laboratory for studying the complex dynamics of quarks and gluons and to **test fundamental predictions of QCD**: **Universality, Q^2 evolution, factorization,…**

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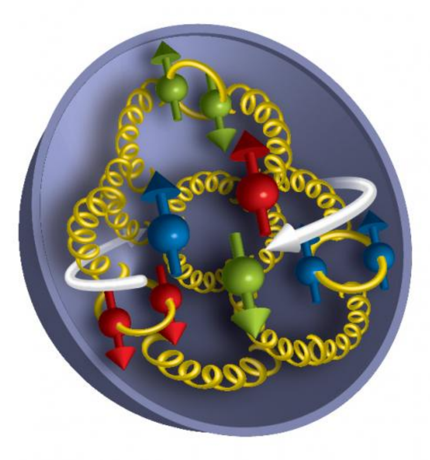
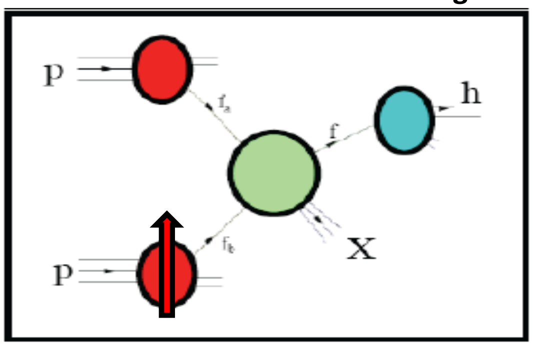
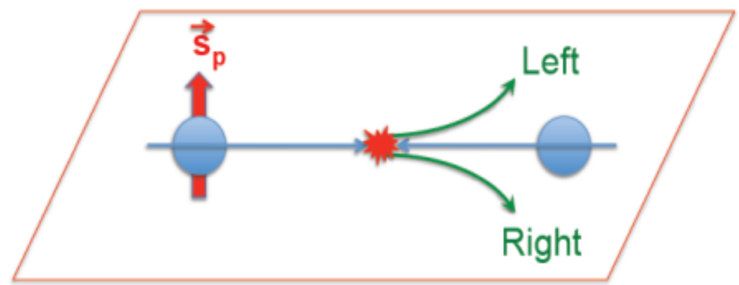


Polarized inclusive hard scattering





Main spin observables in hadron collisions:
Single Transverse Spin Asymmetries (STSAs)

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow}-N_h^{\downarrow}}{N_h^{\uparrow}+N_h^{\downarrow}}$$

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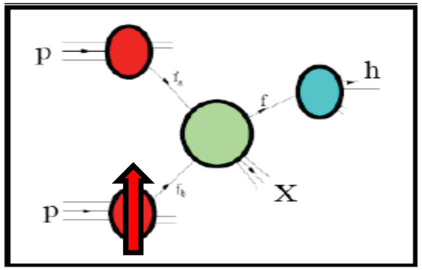

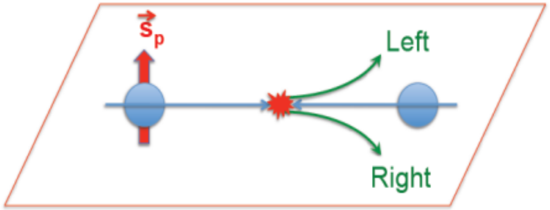

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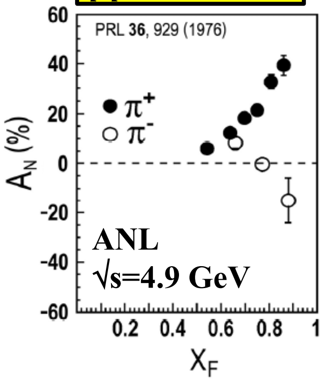
LO collinear pQCD predicts $A_N \sim O(10^{-4})$ but **asymmetries as large as 40%** have been measured!

$pp^{\uparrow} \rightarrow \pi + X$



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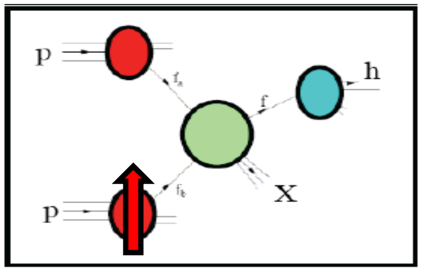

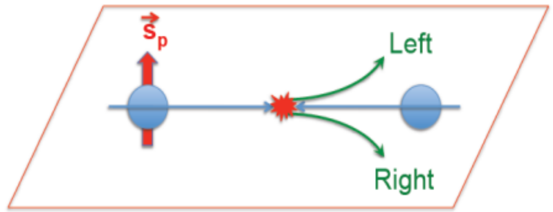

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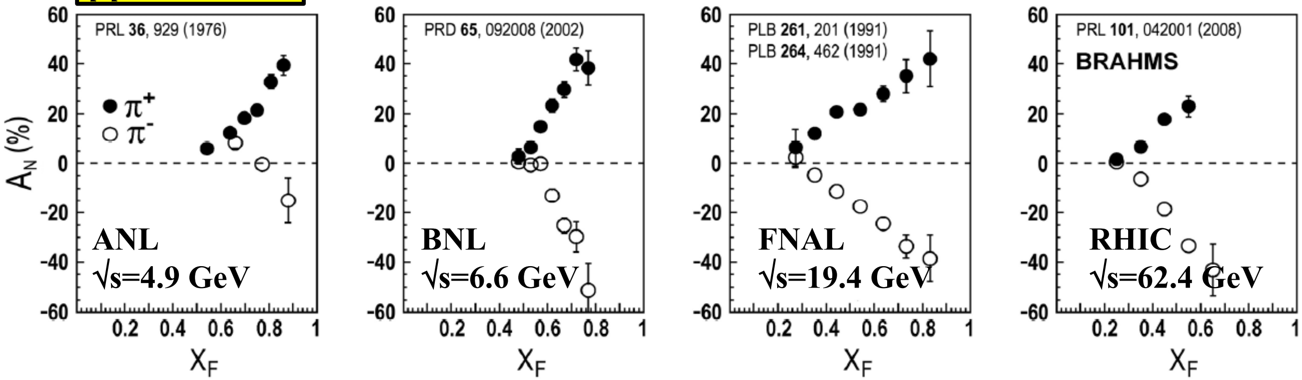

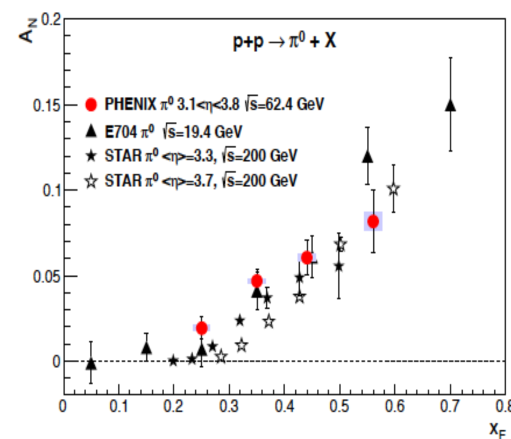

- **Very large asymmetries persistent with energy !**
- Reproduced by various experiments over 40 years!
- Large asymmetries also for π^0 at high-energies ($\sqrt{s} = 200\ GeV, p_T > 2\ GeV$), where the applicability of pQCD is well established.

STSAs in pp collisions

Collinear (twist-3) approach: (Efremov-Taryaev, Qiu-Sterman, Kanazawa-Koike)

- based on collinear QCD factorization (1 hard scale: works for $p_T, Q \gg \Lambda_{QCD}$)
- exchange of a gluon between the active parton and the color field of the IS or FS hadron
- gluon exchange generates the interference between different partonic scattering amplitudes
- this interference, described by a **3-parton (e.g. qgq, ggg) correlation function**, generates the SSA
- interestingly, the Qiu-Sterman correlator $T_{q(G)}(x,x)$ can be related at tree level to the first transverse moment of the **quark (or gluon) Sivers function**:

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Non-collinear (leading-twist) approach: (Anselmino, D'Alesio et al.)
- involves TMD PDFs and FFs
- works in the limit $p_T \ll$ Q (2 energy scales), but is not supported by TMD factorization
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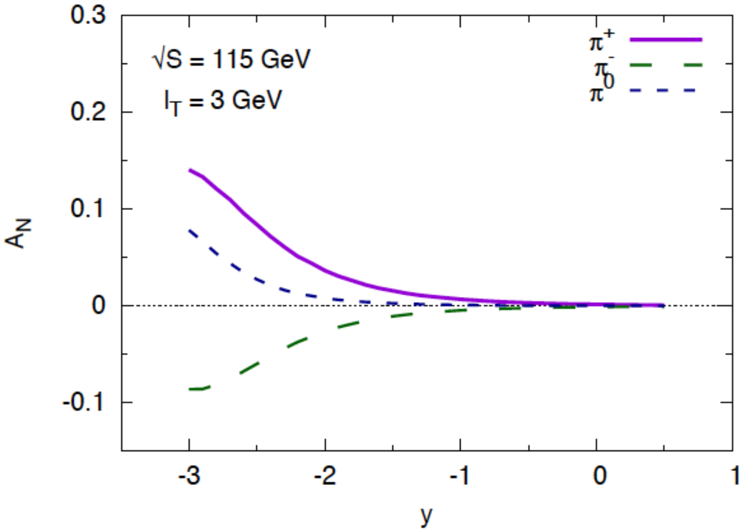
➢ **The two approaches correspond exactly** in the overlap region $\Lambda_{QCD} \ll p_T \ll Q$ (proved for SSAs in Drell-Yan: Ji, Qiu, Vogelsang, Yuan, PRL, 2006)

➢ …but very little is presently known about **tri-gluon correlation functions** and **gluon TMDs**.

Physics potentiality with a polarized target @LHCb

Collinear (twist-3) approach: **Kanazawa et al.** arXiv:1502.04021v3



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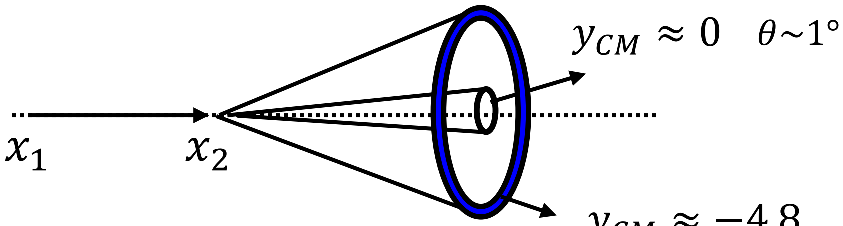
- The effect increases with more negative CM rapidity
- Accessible by LHCb acceptance with fixed target!



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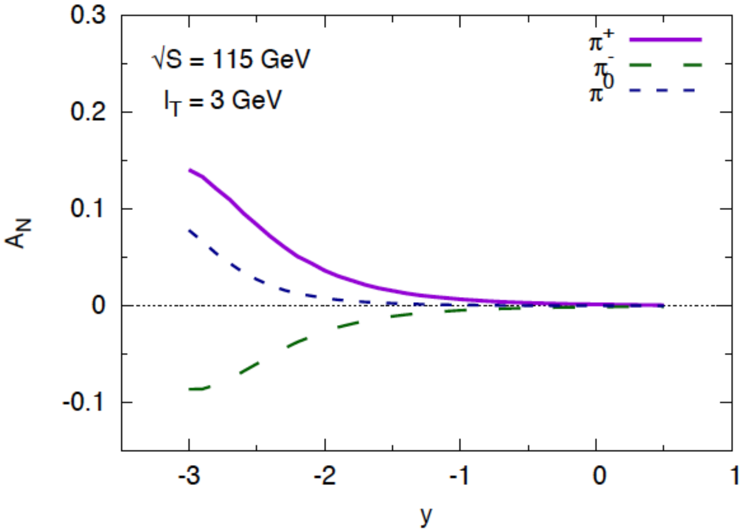

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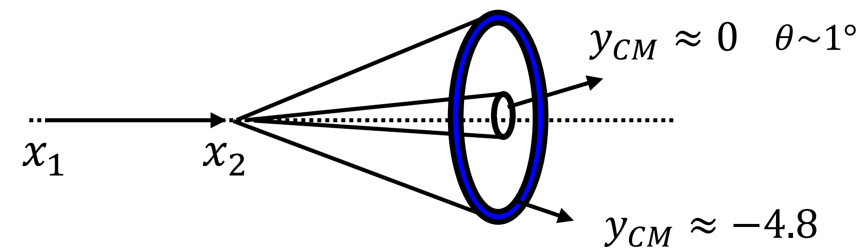

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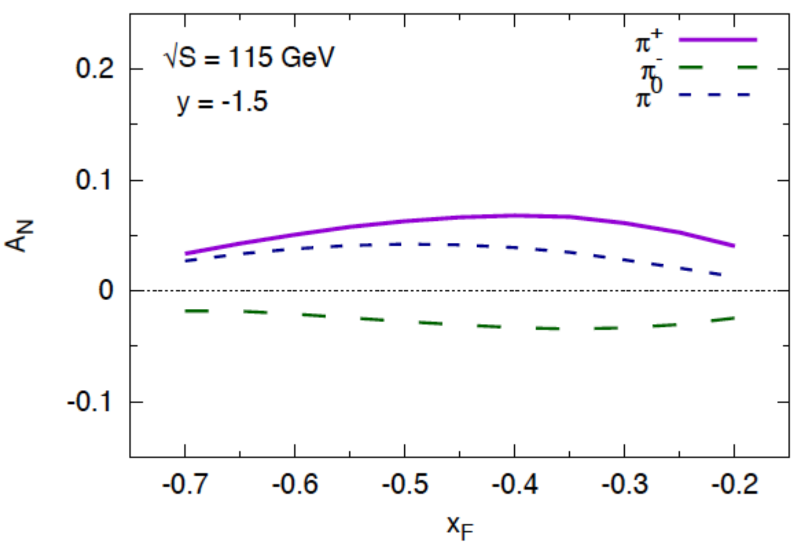

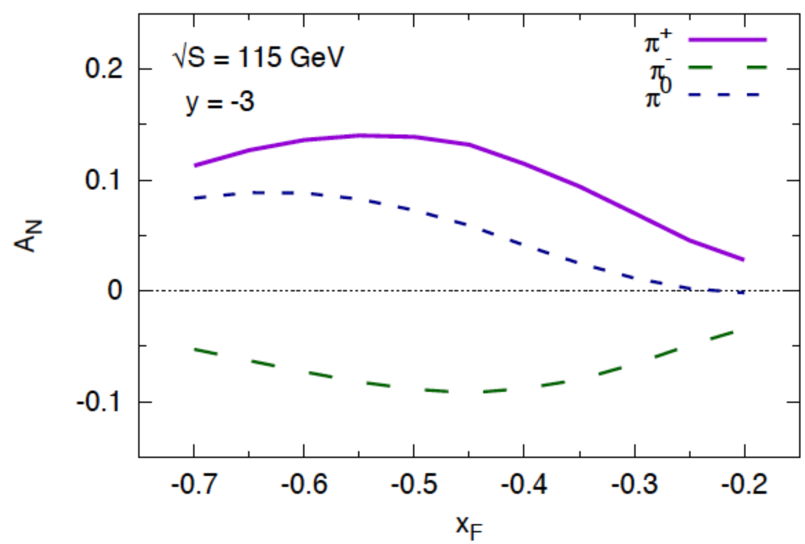

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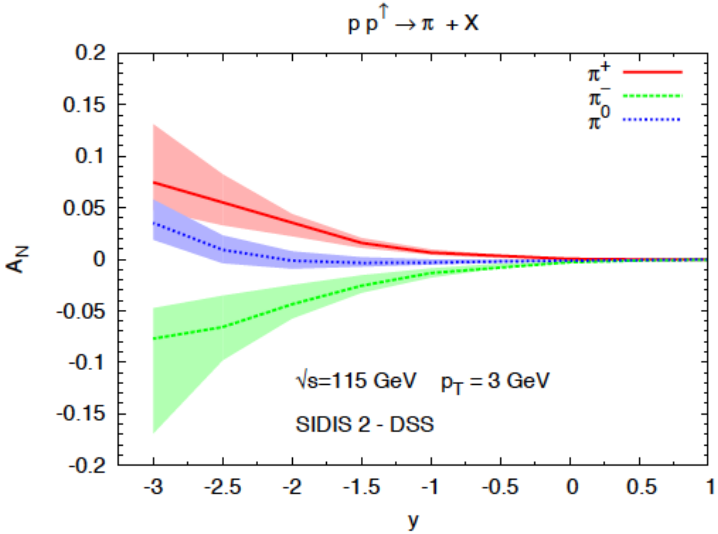

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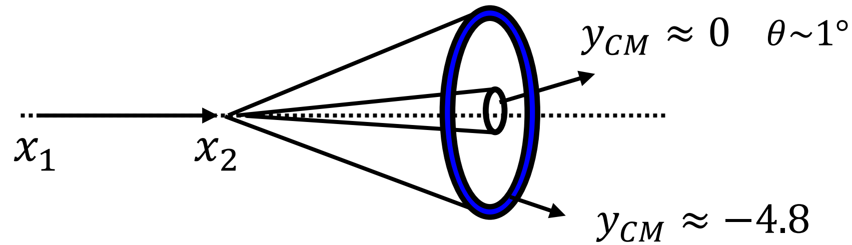

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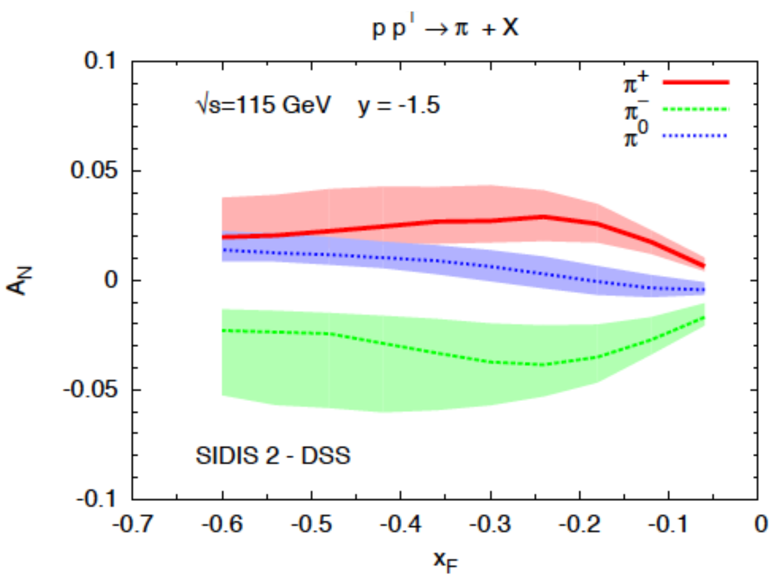

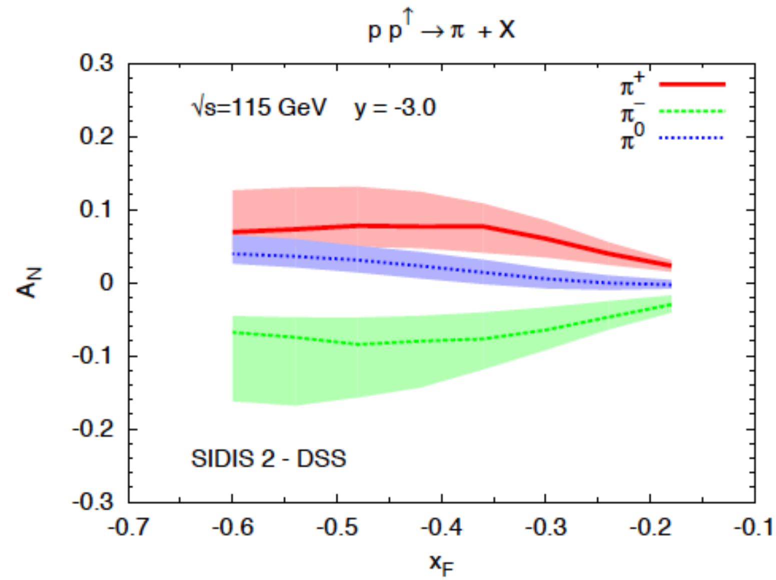

Probing the gluon PDFs

Inclusive pion production provides sensitivity to the quark pdfs, but a fixed polarized target at LHC can also open the way to the **extraction of gluon PDFs!**

- being heavy quarks dominantly produced through gluon-gluon interactions, one can probe the gluon dynamics within the proton by measuring **heavy-flavor observables**
- At LHC quarkonia production dominated by **gluon fusion**
- **Heavy quarks and quarkonium production** (e.g. in $pp^{\uparrow} \rightarrow J/\psi X$) turns out to be an ideal **gluon-sensitive observable!**

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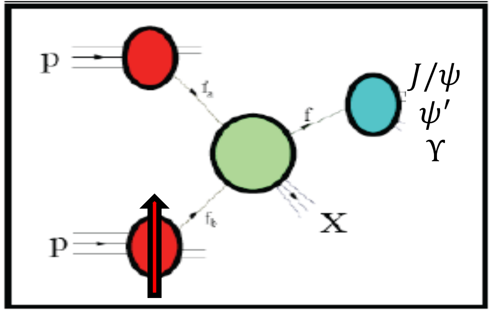

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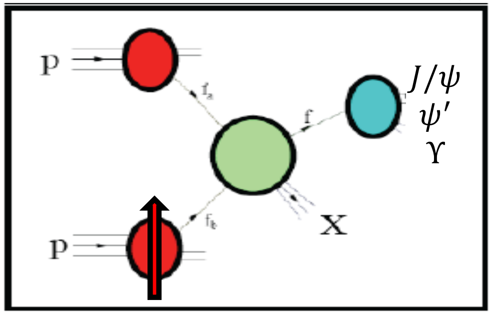

One main achievement would be accessing the **gluon Sivers function at high $x_2^{\uparrow}$ through STSAs:**

- basically unknown!
- shed light on spin-orbit correlations of gluons inside the proton
- sensitive to gluon orbital angular momentum!

Probing the gluon PDFs

Inclusive pion production provides sensitivity to the quark pdfs, but a fixed polarized target at LHC can also open the way to the **extraction of gluon PDFs!**

- being heavy quarks dominantly produced through gluon-gluon interactions, one can probe the gluon dynamics within the proton by measuring **heavy-flavor observables**
- At LHC quarkonia production dominated by **gluon fusion**
- **Heavy quarks and quarkonium production** (e.g. in $pp^{\uparrow} \rightarrow J/\psi X$) turns out to be an ideal **gluon-sensitive observable!**

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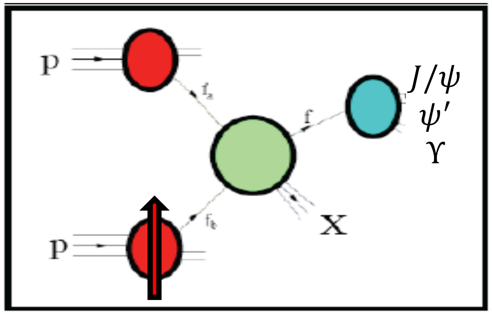

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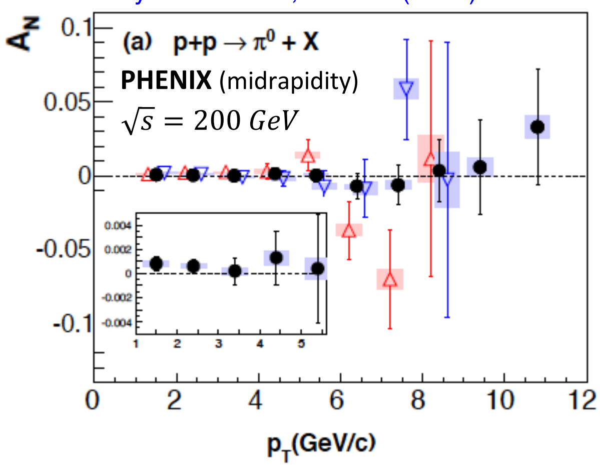
The measured STSAs can be related (GPM) to the convolution of the gluon Sivers function for the target proton and the unpolarized gluon pdf for the beam proton:

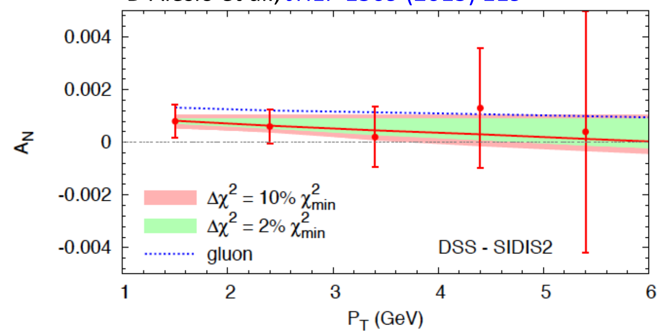
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}} \propto f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg \rightarrow J/\psi g}$$

Probing the gluon PDFs (from RHIC data)

Phys. Rev. D 90, 012006 (2014)

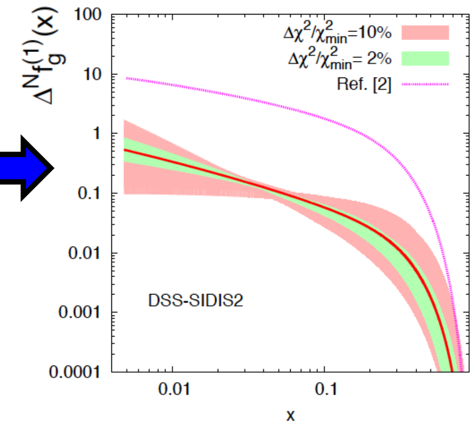


D'Alesio et al., JHEP 1509 (2015) 119



A_N estimate in the frame of GPM, based on param. from SIDIS data + FFs from DSS

First $k_\perp$-moment of the gluon Sivers function



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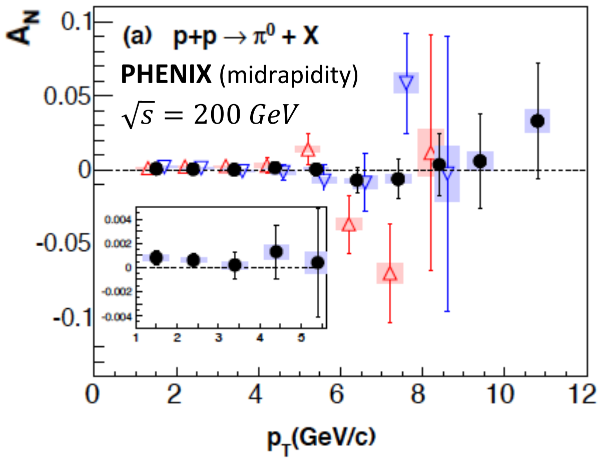

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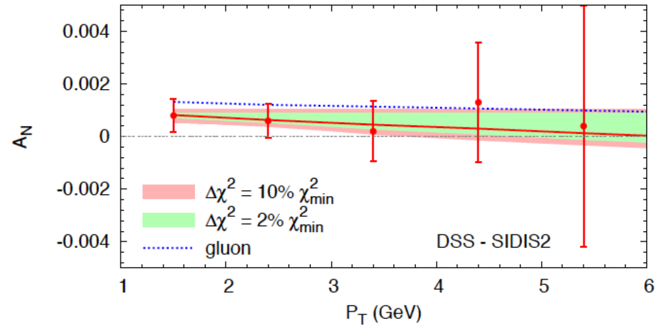

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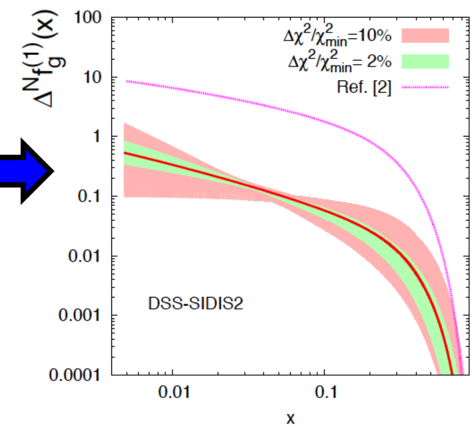
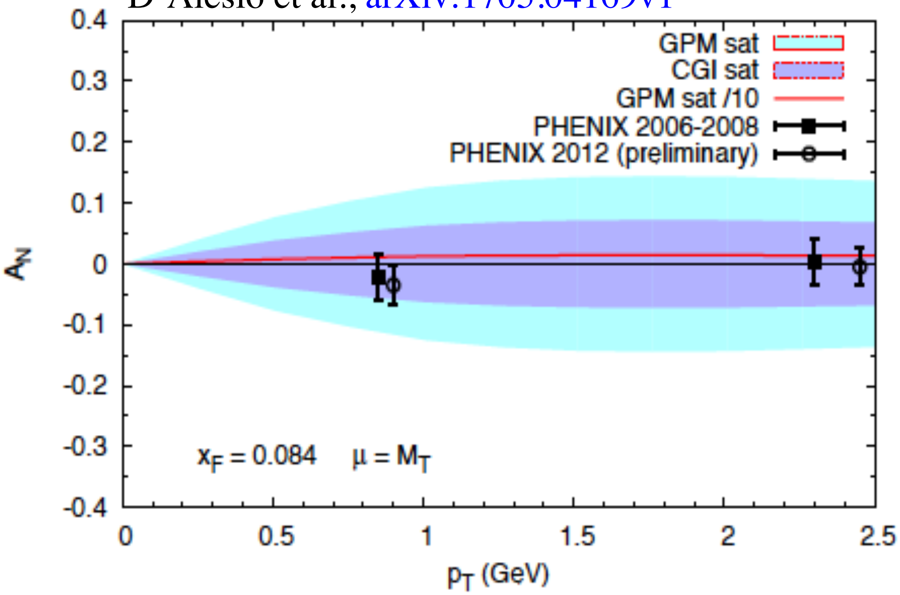
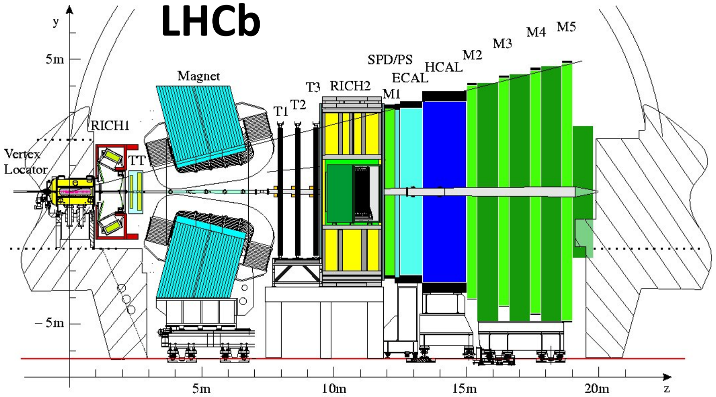


D'Alesio et al., arXiv:1705.04169v1



- **Existing quarkonia results only from PHENIX**
- First measurement of A_N for $pp^{\uparrow} \rightarrow J/\psi X$
- A very recent prediction of A_N from 2 models:
- Generalized Parton Model (**GPM**)
- Color-Gauge Invariant GPM **(CGI-GPM)**: takes into account the process dependence of the Sivers funct. including the effects of ISI and FSI
- two independent Sivers functions are needed:
  - ***f-type*** (color antisymmetric), relevant here
  - ***d-type*** (color symmetric), vanishing here but dominant in $pp^{\uparrow} \rightarrow DX$

Physics potentiality with a polarized target @LHCb



- LHCb can measure nearly all quarkonia states (including C-even η_c, χ_c, χ_b) with high precision!

- Expected yields much larger than previous fixed-target experiments
- Υ-mesons is a unique observable, poorly accessible from other hadron-hadron experiments

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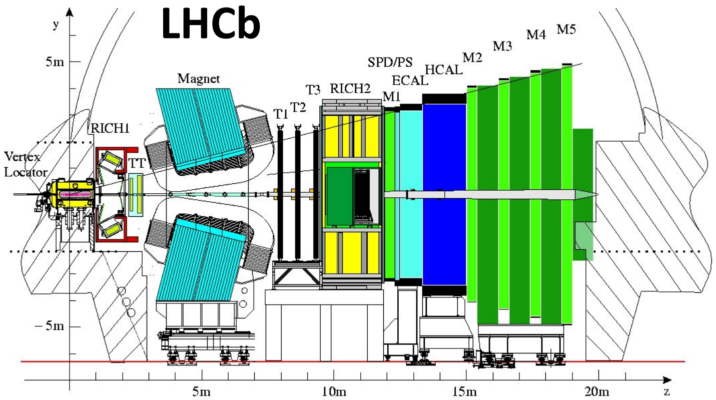

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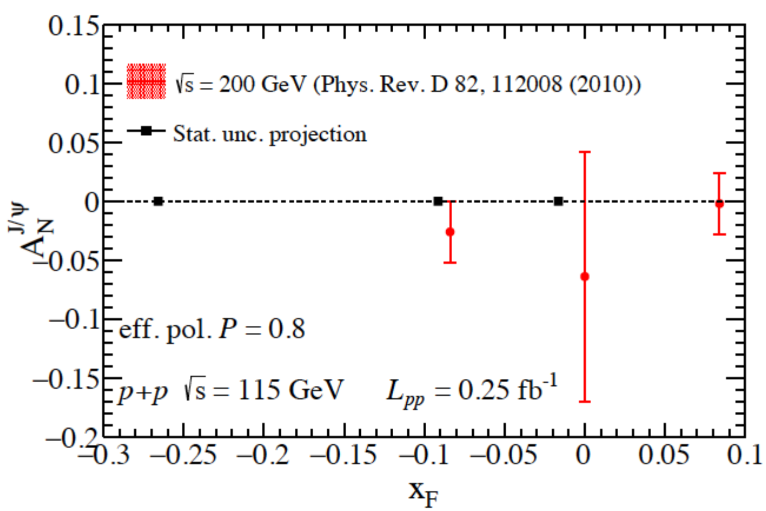
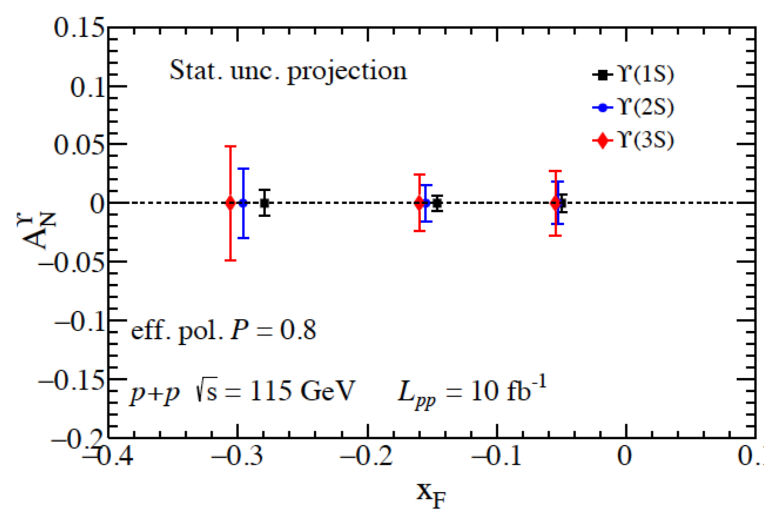
(projected results from **AFTER@LHC** arXiv:1702.01546v1)





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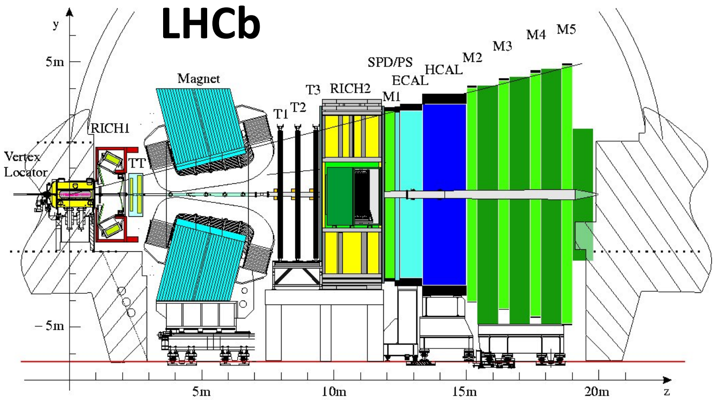

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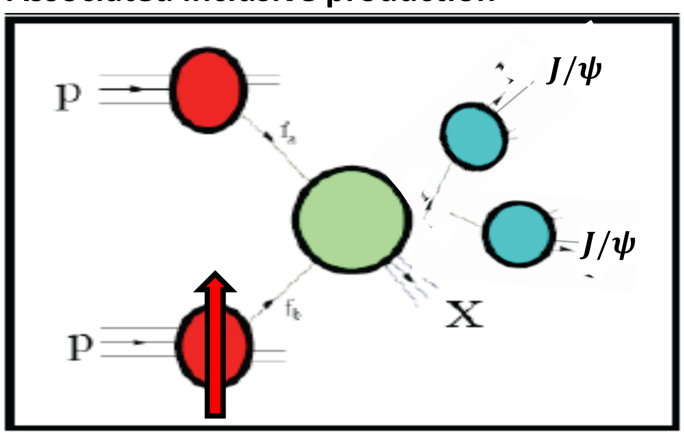
- Associated-production channels (e.g. J/ψ - J/ψ, J/ψ - γ, Υ - γ) can shed light on the p_T dependence of the gluon Sivers function

Associated inclusive production



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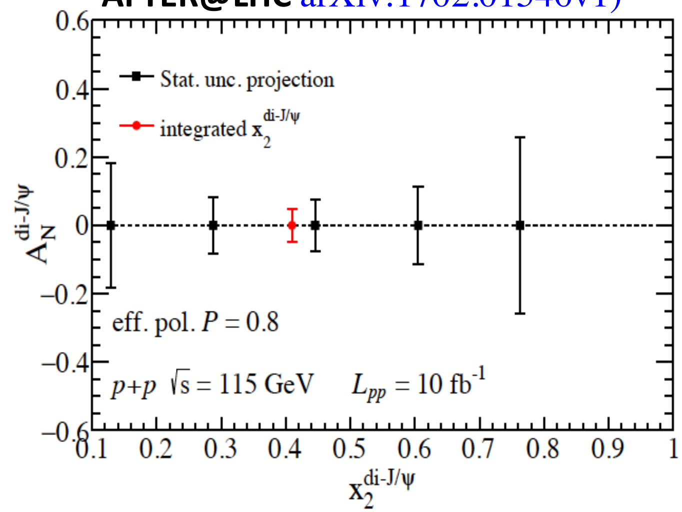
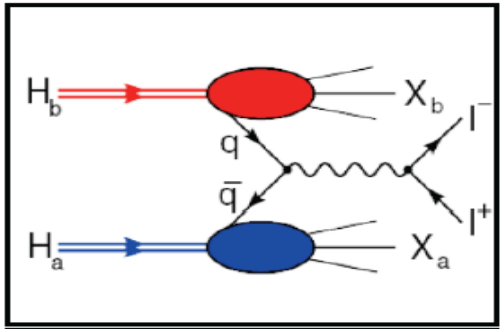


What about quark PDFs ?

Drell-Yan



LHCb has excellent capabilities for $\mu\mu$ channel!

- Drell-Yan process is very interesting even without polarization, as it provides a way to access the **antiquark content of the proton**.

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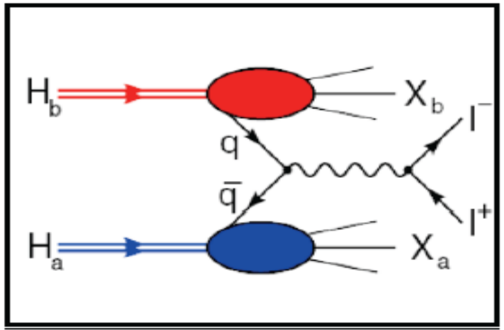

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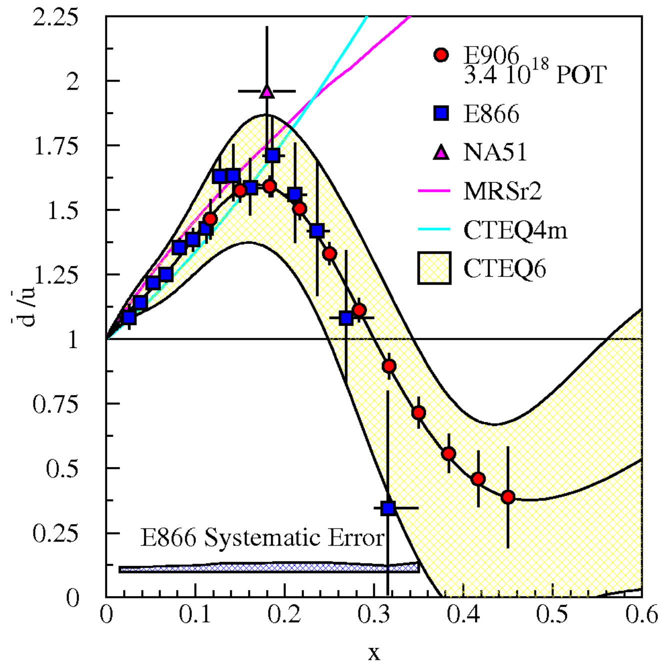

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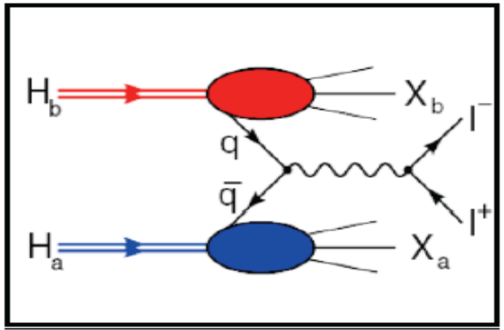

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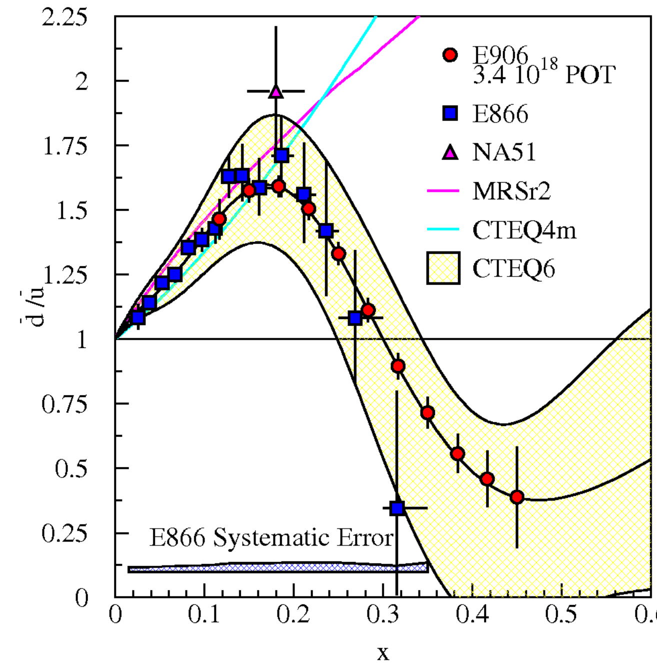

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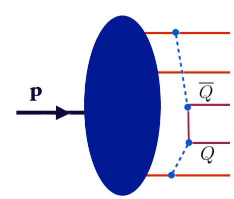
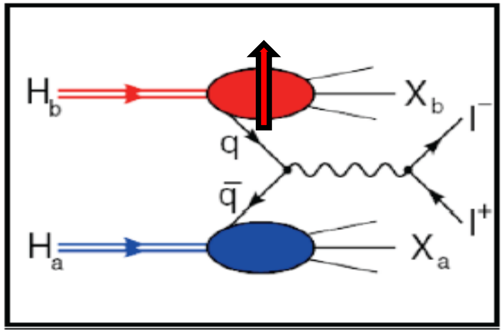
- 5-quark Fock state may contribute at high x!



S.J. Brodsky et al.,
Adv.High Energy Phys. 2015 (2015) 231547

What about quark PDFs ?

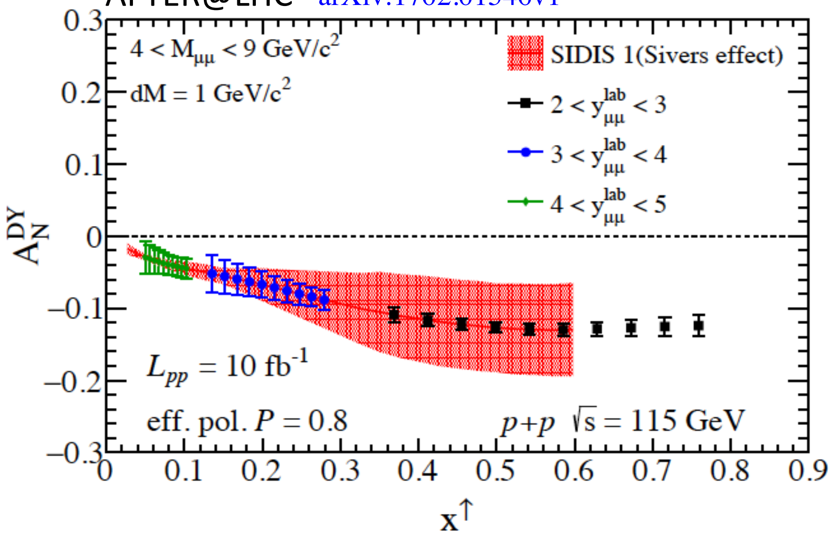
Polarized Drell-Yan

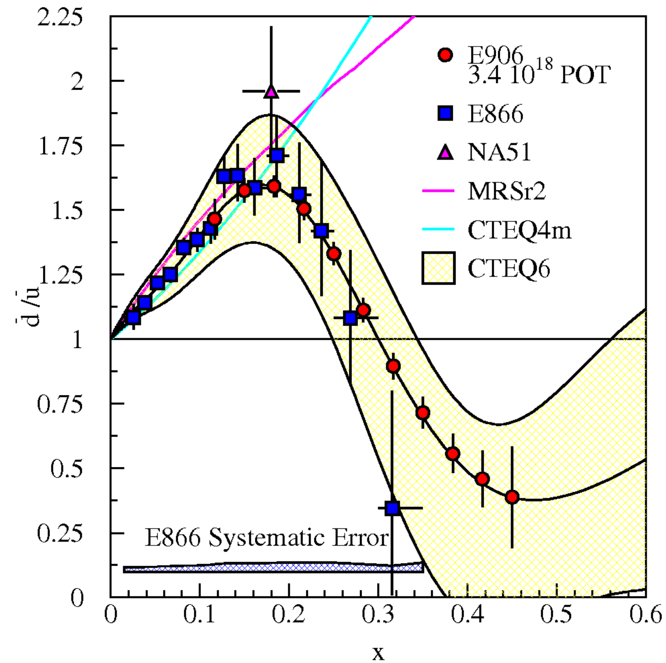


LHCb has excellent capabilities for $\mu\mu$ channel!

Quark Sivers and Boer-Mulders functions measurable in Drell-Yan up to very high $x_2^{\uparrow}$

AFTER@LHC arXiv:1702.01546v1





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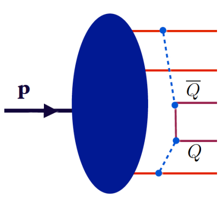

S.J. Brodsky et al., Adv.High Energy Phys. 2015 (2015) 231547

Physics reach with an unpolarized fixed target
(can already be addressed at LHCb with **SMOG**)

- **Intrinsic heavy-quark** at large x_F associated with higher Fock states of the proton
  - Recent global QCD analyses supports existence of non-perturbative intrinsic charm in the proton
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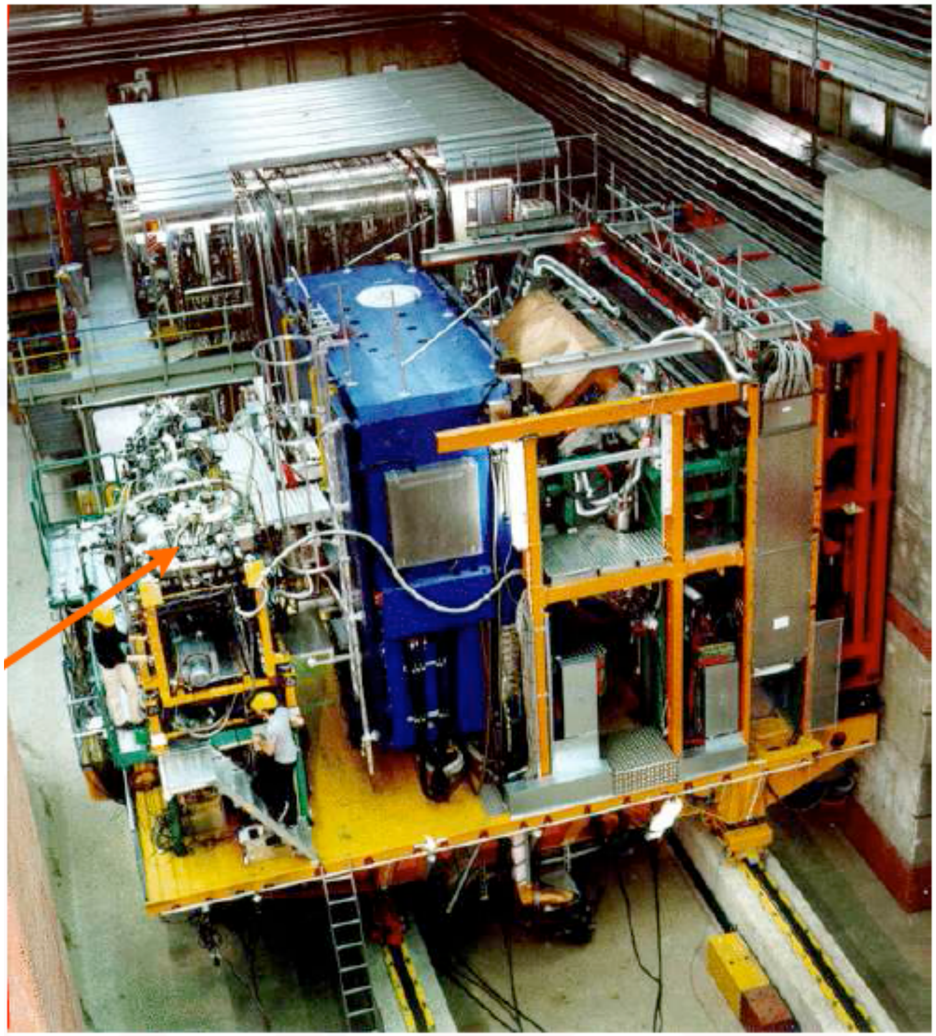
- **$W^{\pm}$ boson production near threshold**
  - small cross-section, but yields strongly dependent on quark PDFs at large x
  - search for **heavy partners of the gauge bosons** (predicted by many extensions to SM)
- **Complementary D and B-physics at fixed target kinematics** (exploiting the large boost $\gamma \approx 60$)
- …

The polarized target Setup

The Hermes experiment at HERA

- -Gas target
- -Silicon vertex
- -Tracking chambers
- -Dipole
- -Tracking chambers
- -RICH
- -Tracking chambers
- -Preshower
- -Calorimeter
- -Muon tracker

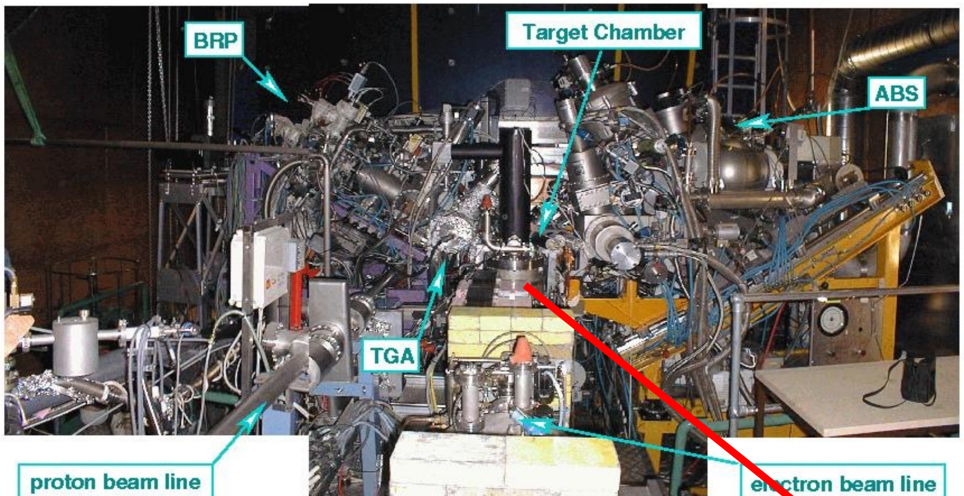
... a mini LHCb



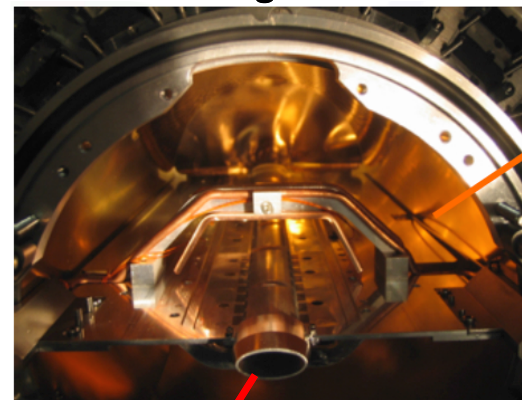
A ground-breaking experiment in polarized hadron physics!!!

The Hermes experiment at HERA

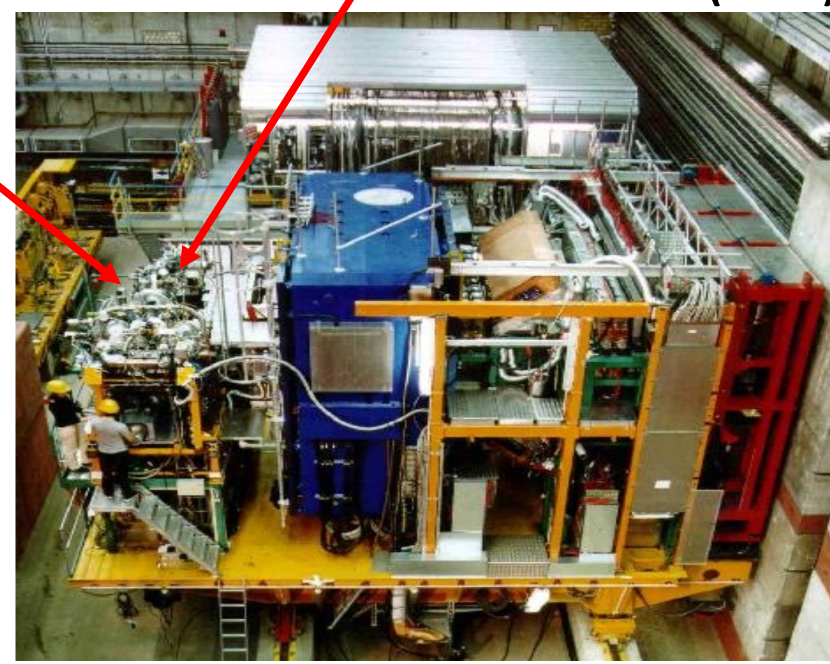
Polarimeter **Atomic Source**

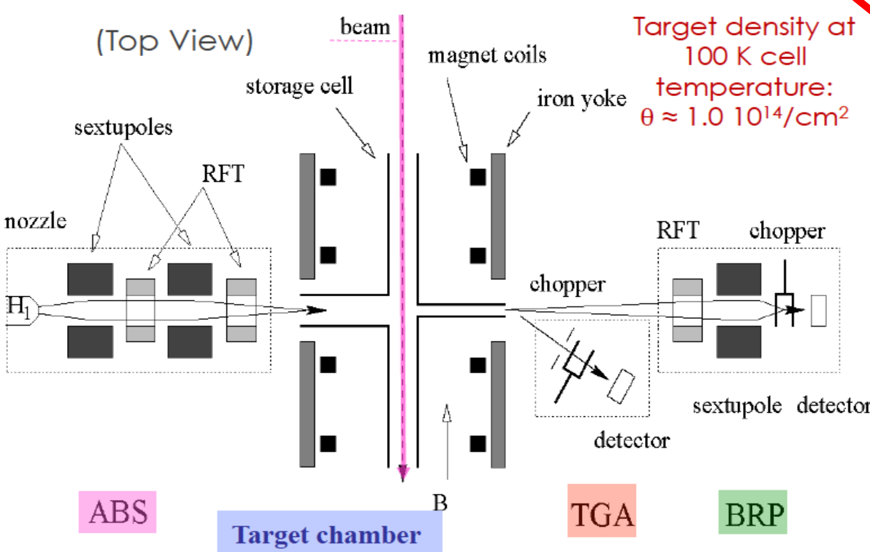


storage cell



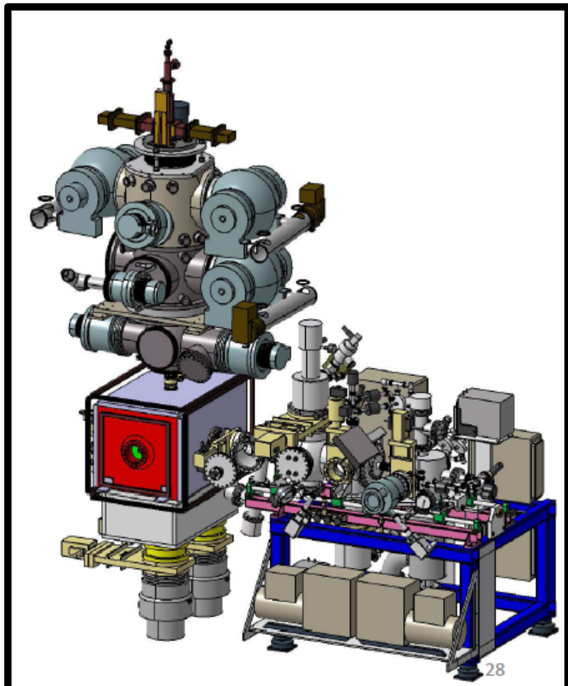
HERMES (DESY)



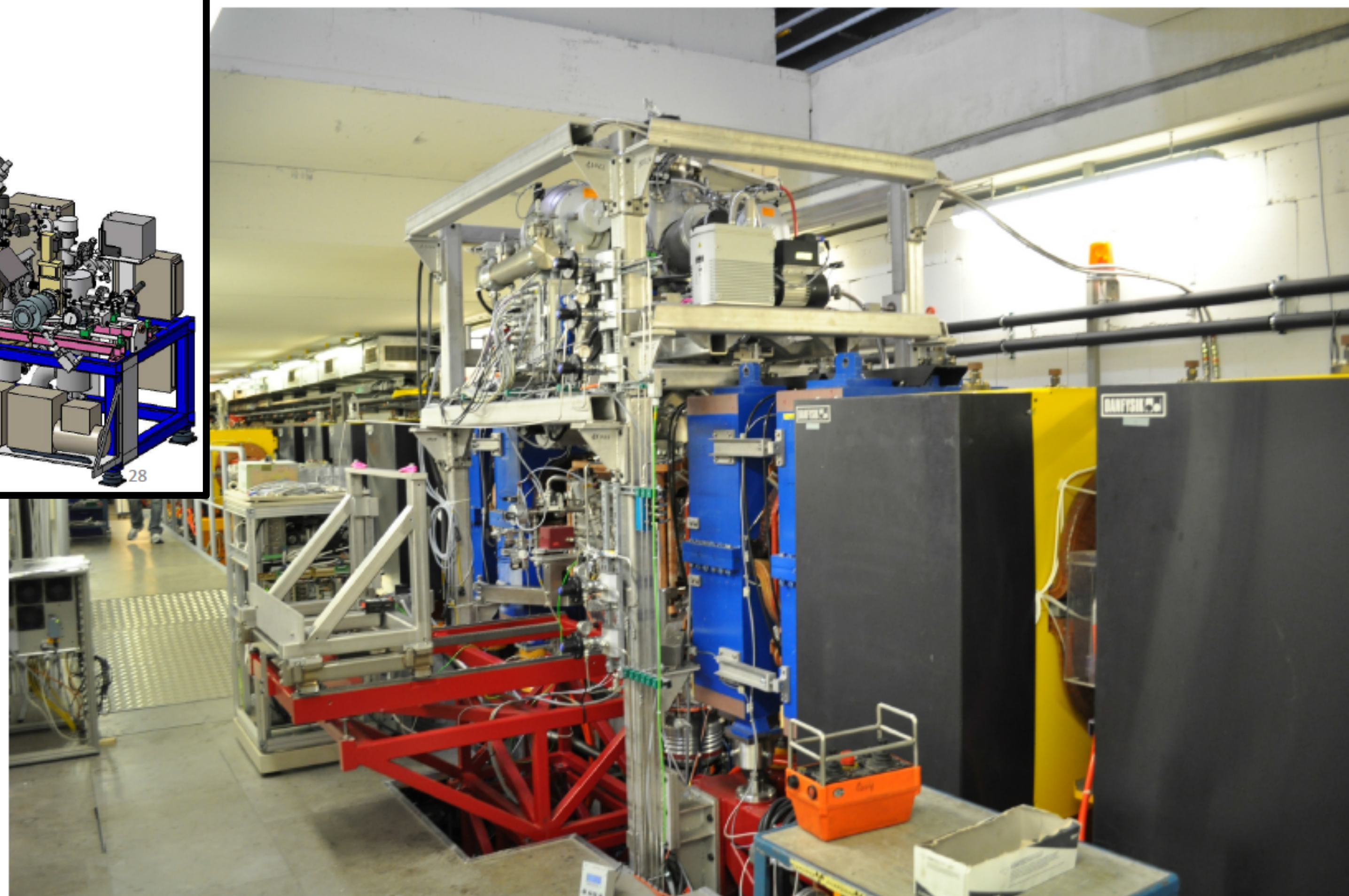


Target density at 100 K cell temperature: $\theta \approx 1.0\ 10^{14}/cm^2$

The second life of the HERMES target

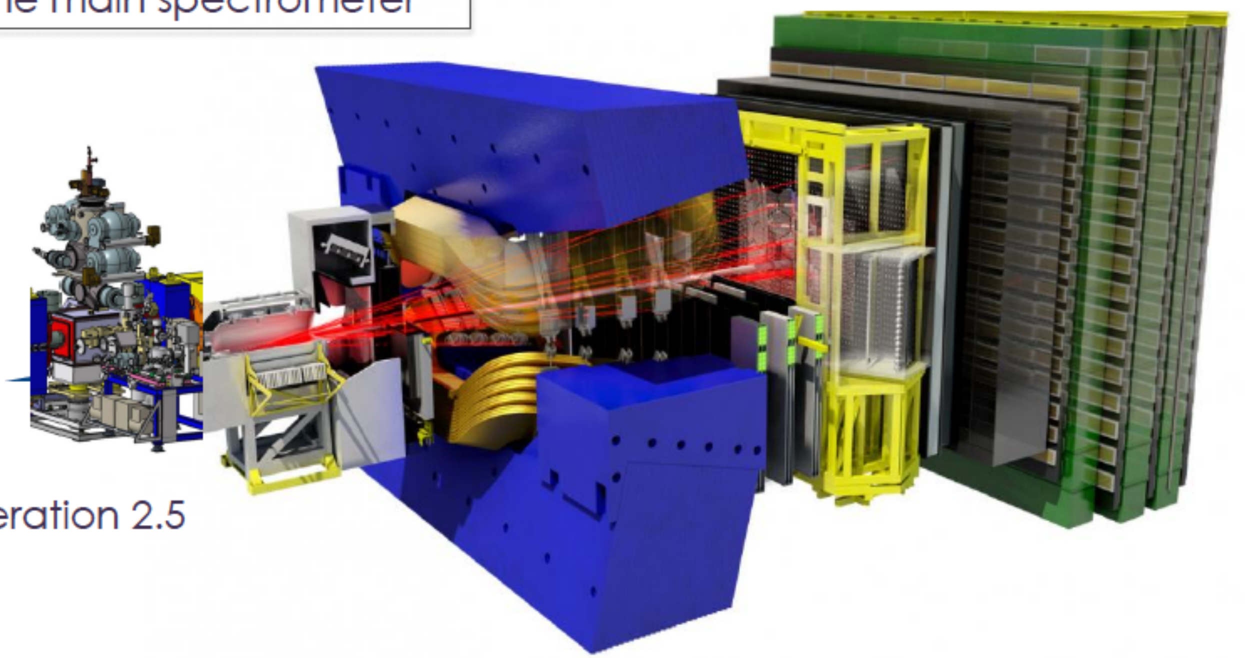


PAX experiment @ COSY (Julich)



The future for the HERMES target ?

N.B. No changes are requested to the main spectrometer

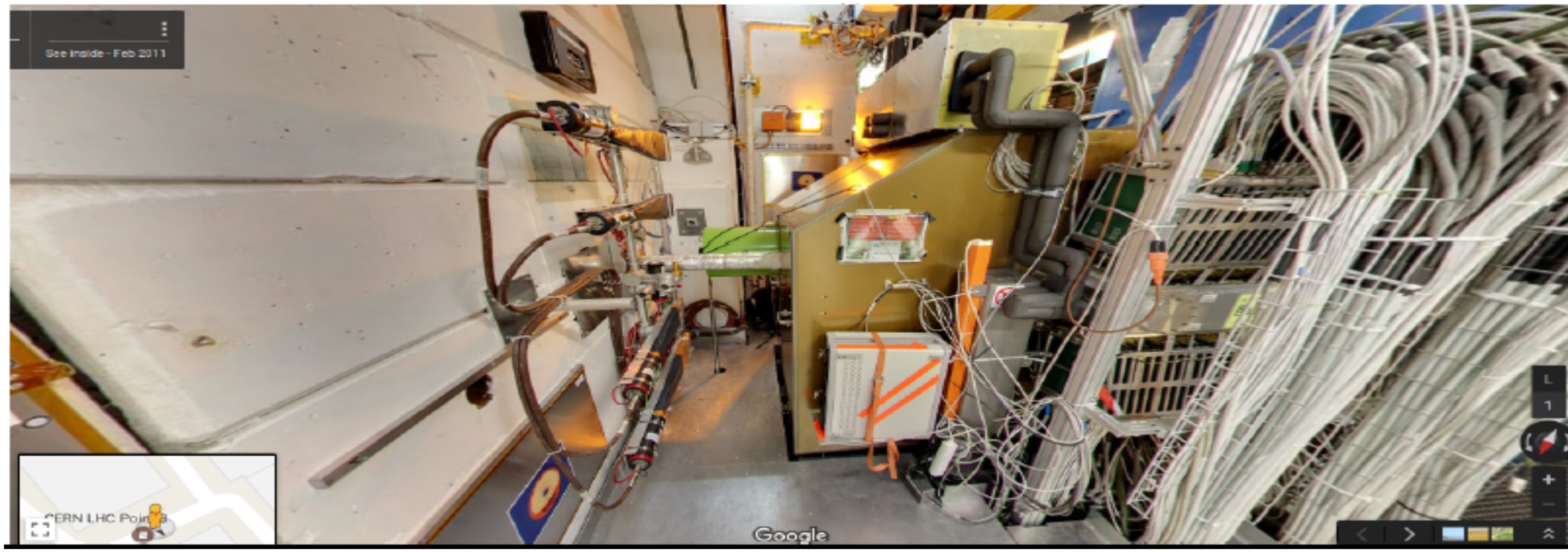


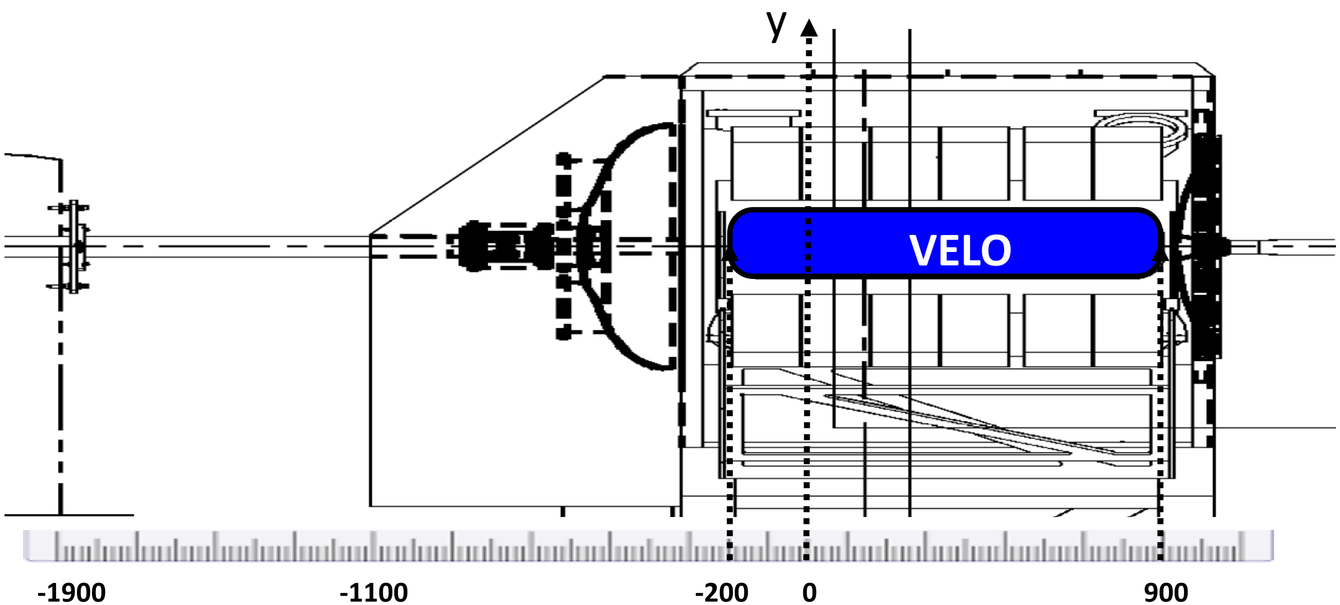
Target generation 2.5

The target can provide polarised: Hydrogen, Deuterium and, with substantial changes, ^{3}He

Advances in High Energy Physics Volume 2015, Article ID 463141, 6 pages http://dx.doi.org/10.1155/2015/463141

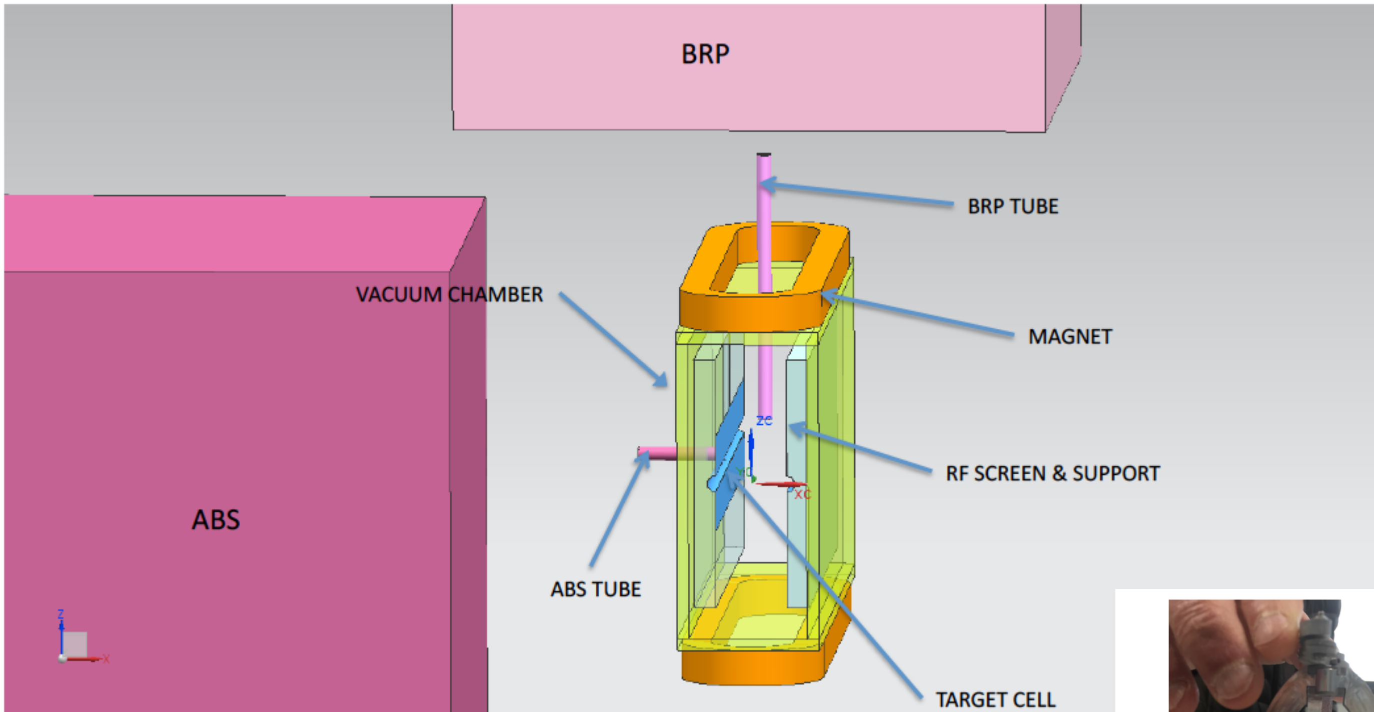
There is some room beyond the VELO…

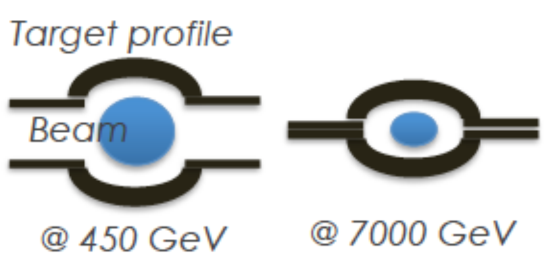


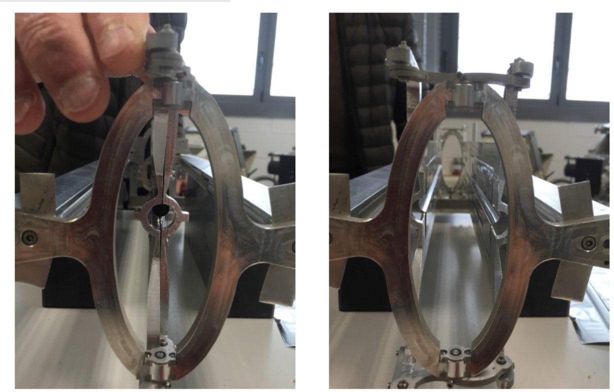


A new design for a compact polarized target

Draft-0 of the target 3D model

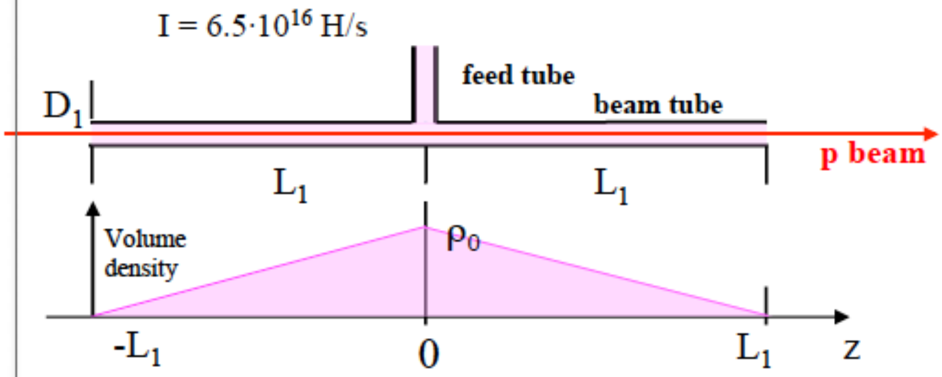






R&D already on going following the VELO drawings for the movement

Interference with the LHC beam



L_{total}=50 cm, d=1.4 cm

Central density: ρ_0=1.04 x 10^{13} /cm^3
Areal density:

- θ_{100K}= $\rho_0 L/2$ = 2.60 x 10^{13} /cm^3
- θ_{300K}= $1/\sqrt{3}\ \rho_0 L/2$ = 1.50 x 10^{13} /cm^3

Lumi (pA)=
$I\ \theta_{100K}$ = 0.94 $nb^{-1}s^{-1}$

$I\ \theta_{300K}$ = 0.54 $nb^{-1}s^{-1}$

- The pressure in the LHC beam pipe outside the target region would be $\sim 10^{-7}$mbar, one order of magnitude lower than the maximum pressure allowed by LHC
- Parallel operation causes small reduction of half-life (< 10%) keeping the beam-life $\sim 10\ h$

Conclusions: the physics

- A polarized fixed target at LHC will provide unique kinematic conditions for a broad and ambitious physics program!
- The **LHCb** spectrometer is perfectly suitable to host the target
- The LHCb high luminosity, excellent tracking and PID performances will allow to push the STSAs for quarkonia to a precision era, opening the way to the extraction of the **gluon PDFs** (e.g. unknown **gluon Sivers function**)
- The (sea)quark TMDs can be probed in (polarized) Drell-Yan
- A rich physics program with (high-density) unpolarized gas is also envisaged
- …New ideas from the theory community are welcome!

Conclusions: the project

- The idea of a polarized target is being taken into serious consideration by the LHCb Collaboration and LHC machine experts!
- A review process has been initiated inside the LHCb Collaboration
- The installation of a storage cell inside the VELO is presently under discussion within the Collaboration and would constitute a R&D for the polarized target system
- Simulation studies are ongoing (acceptance, resolutions, backgrounds, etc)
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We are working to bring spin physics at the most powerful particle accelerator!

Anyone interested to contribute to this fascinating challenge is more than welcome!!

Backup

A couple of words on the proponents

Referent Persons

Physics Case
Pasquale Di Nezza
(LHCb Frascati)

Experimental Implementation
Paolo Lenisa
(INFN, Univ.Ferrara)

Study Group

- Polarised Target and Polarimeter
E.Steffens (Univ.Erlangen), A.Nass (Juelich), G.Ciullo (Ferrara)

- Target holding field and depolarisation studies
M.Statera (Milano), D.Reggiani (PSI)

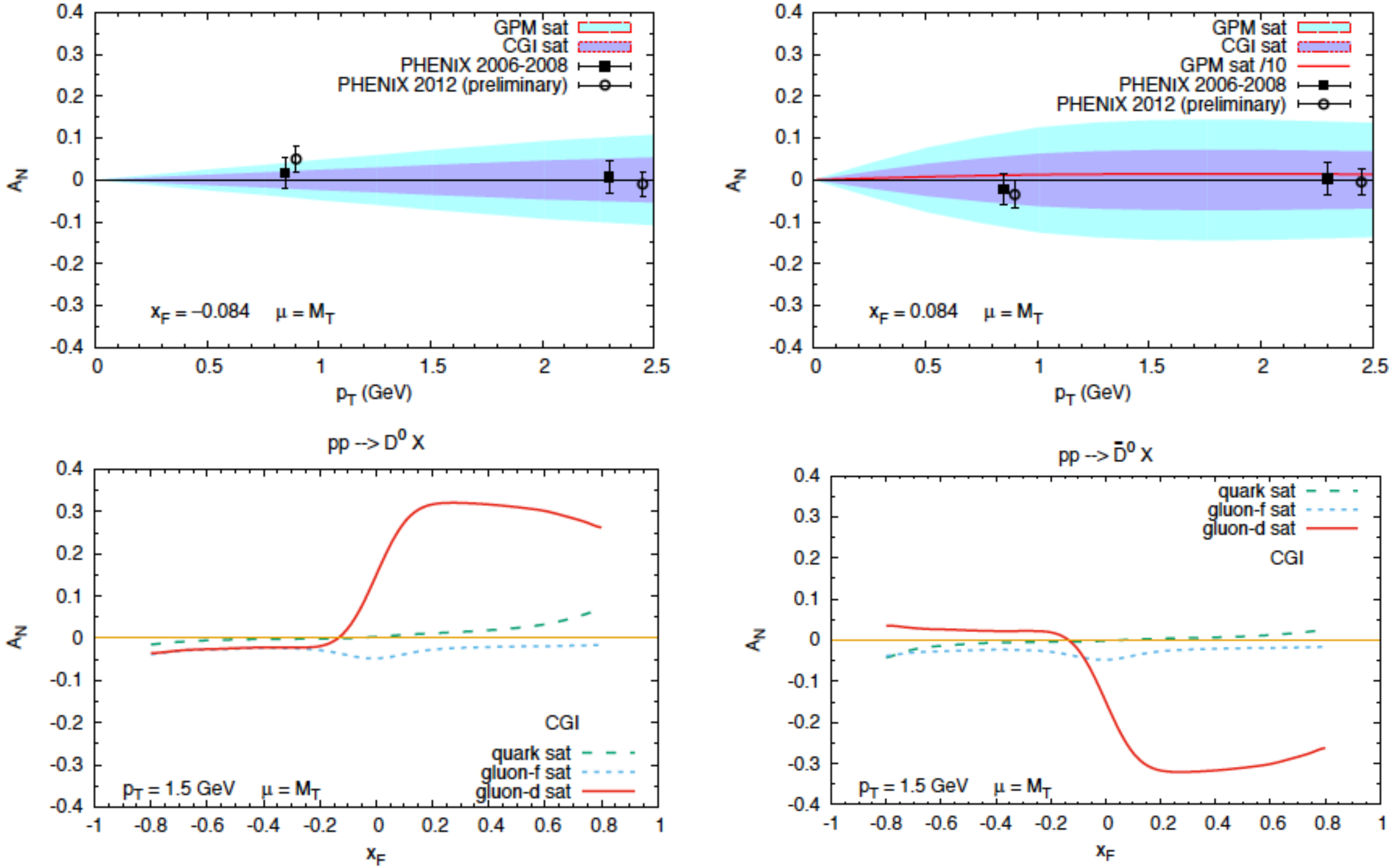
- Openable storage cell design
V.Carassiti (Ferrara)

- MC Simulations
L.Pappalardo (Ferrara)

- Accelerator related issues
F.Rathmann (Juelich), B.Lorentz (Juelich)

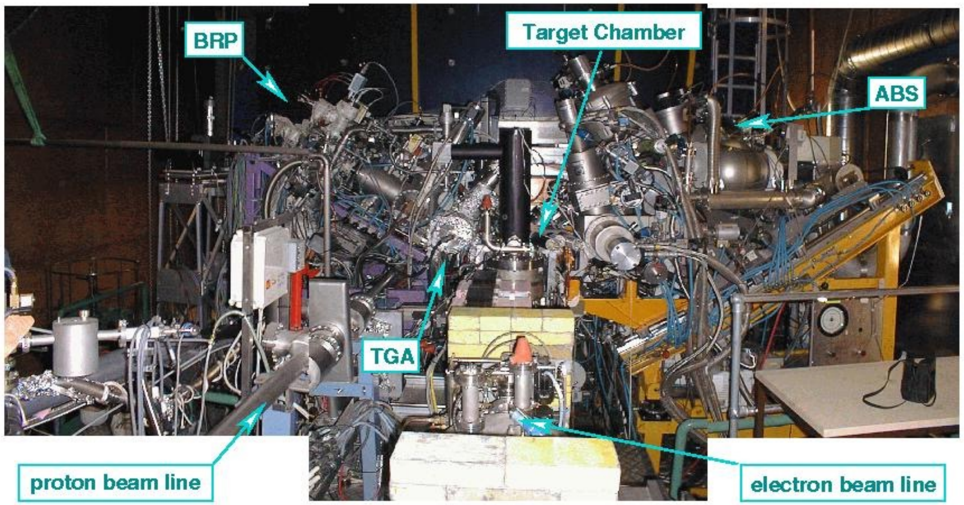
Probing the gluon PDFs (from RHIC data)

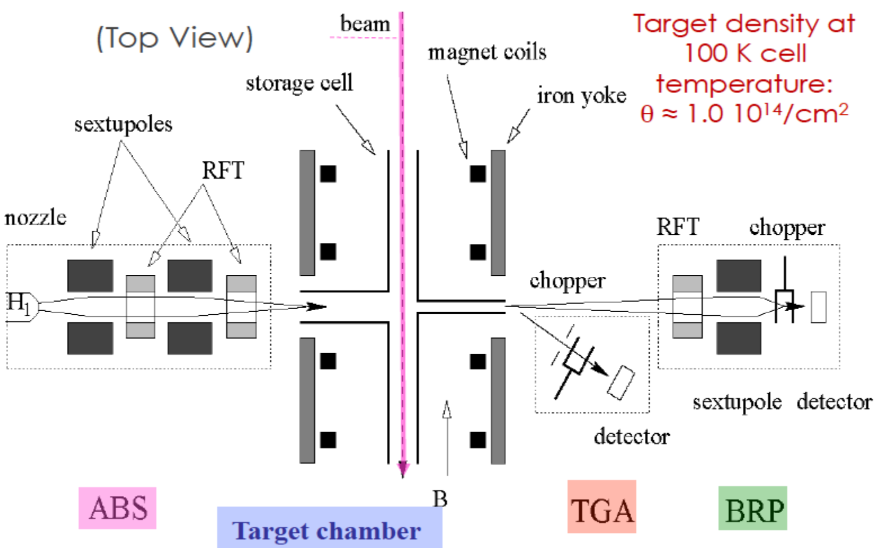
D'Alesio et al., arXiv:1705.04169v1



How does it work?

Polarimeter **Atomic Source**





- **ABS** (Atomic Beam Source): Dissociator with cooled nozzle and differential pumping; permanent 6-poles and RF transitions
- **Target chamber** with cell, holding field coils, beam and sample tubes
- **TGA** (Target Gas Analyzer): Measurement of dissociation degree α
- **BRP** (Polarimeter for atoms): Measurement of substate population of atoms → electron pol. P_e and nuclear pol. P_n !