Spin physics opportunities with A Fixed Target ExpeRiment at the LHC (AFTER@LHC)

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Outline

- A fixed-target experiment with LHC beams: main kinematic features
- Physics motivations for a high-luminosity fixed-target experiment at the LHC: nucleon and nuclear structure at large-x, spin and Quark Gluon Plasma physics
- Possible technical implementations and achievable luminosities
- A selection of projected performances

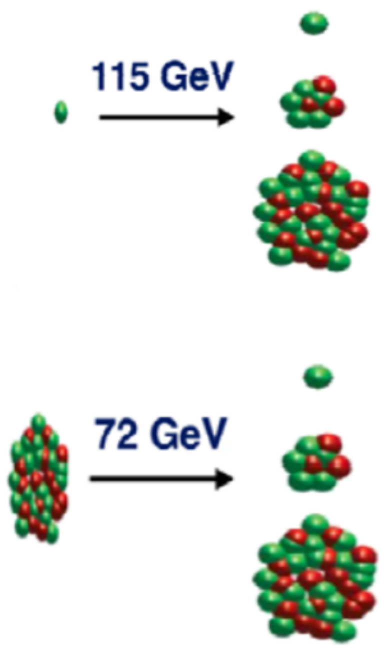
A fixed-target experiment at the LHC

Main kinematic features:

Energy range

- 7 TeV proton / 2.76 Pb beam on a fixed target

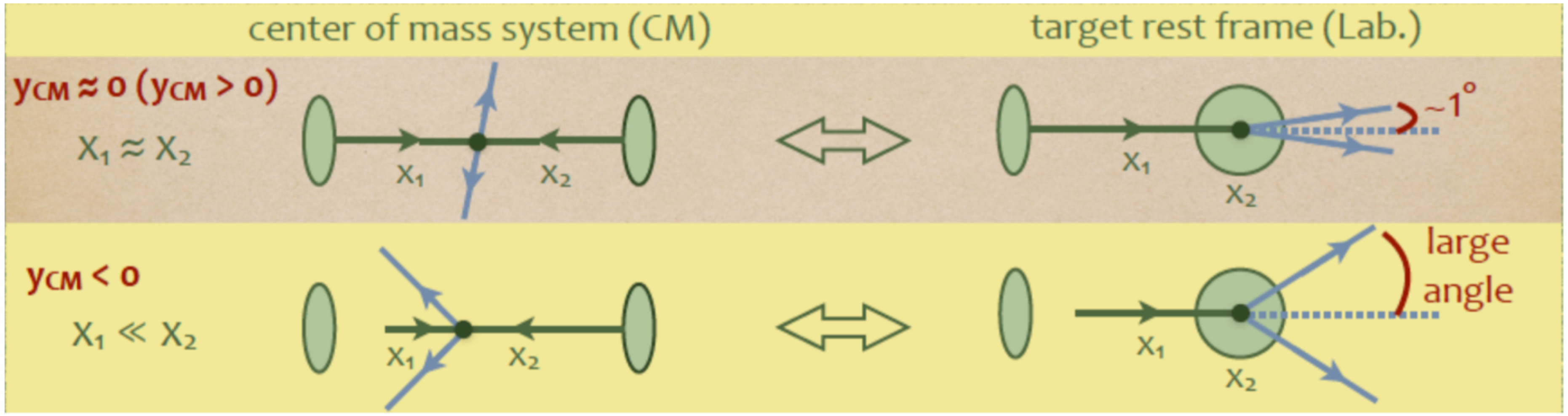
beam type	CM energy $\sqrt{s_{(NN)}}$	boost $\gamma=\sqrt{s}/2m$	rapidity shift
proton (E = 7 TeV)	115 GeV	61	4.8
lead (E = 2.76 TeV)	72 GeV	38	4.2



→ center-of-mass energy in-between SPS at CERN and nominal RHIC

Rapidity range

- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Easy access to (very) large backward rapidity range ($y_{CM} < 0$) and large parton momentum fraction in the target (x_2)

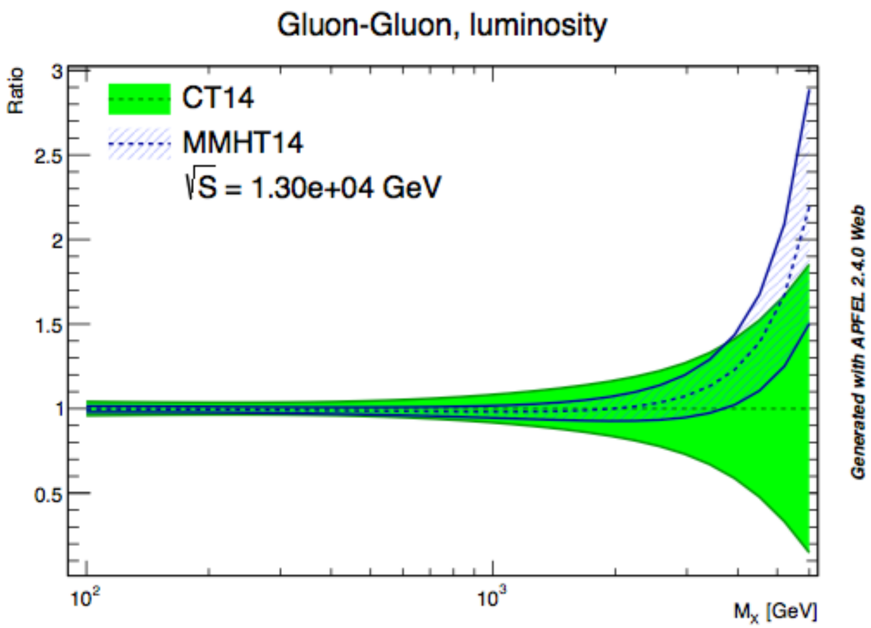


A fixed-target experiment at the LHC

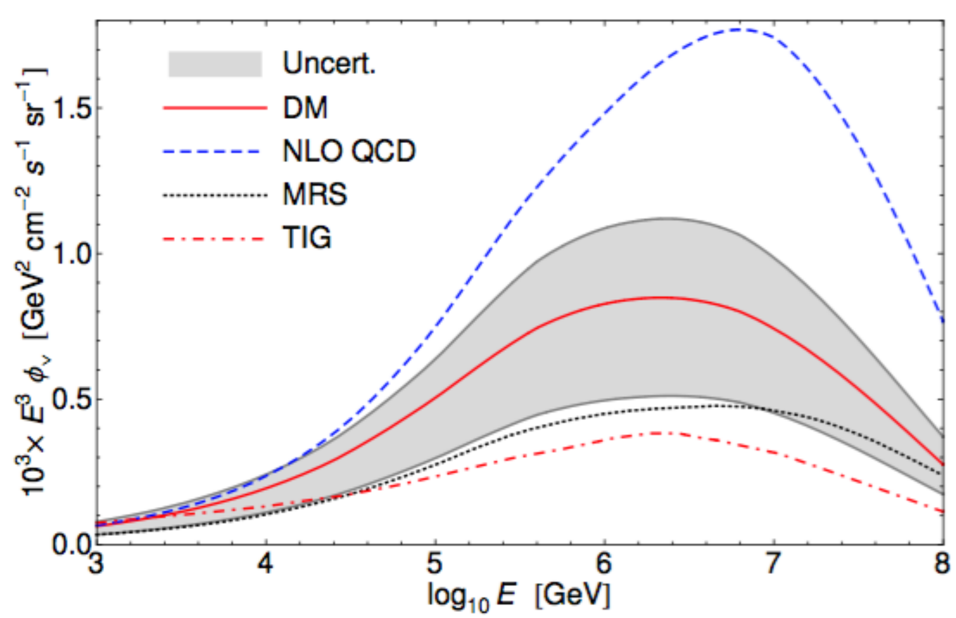
- Several advantages of fixed-target mode:
  - Accessing **high-*x* frontier** ($y_{CM} < 0$ and parton momentum fraction $x > 0.5$)
  - Achieving **high luminosity**
  - Varying **atomic mass number** of the target
  - **Polarising** the target
- This can be realized at LHC in a parasitic mode!
- Fixed-target mode started at LHCb with a low density gas-target (by using SMOG)

Physics motivations: nucleon and nuclear structure at large-x

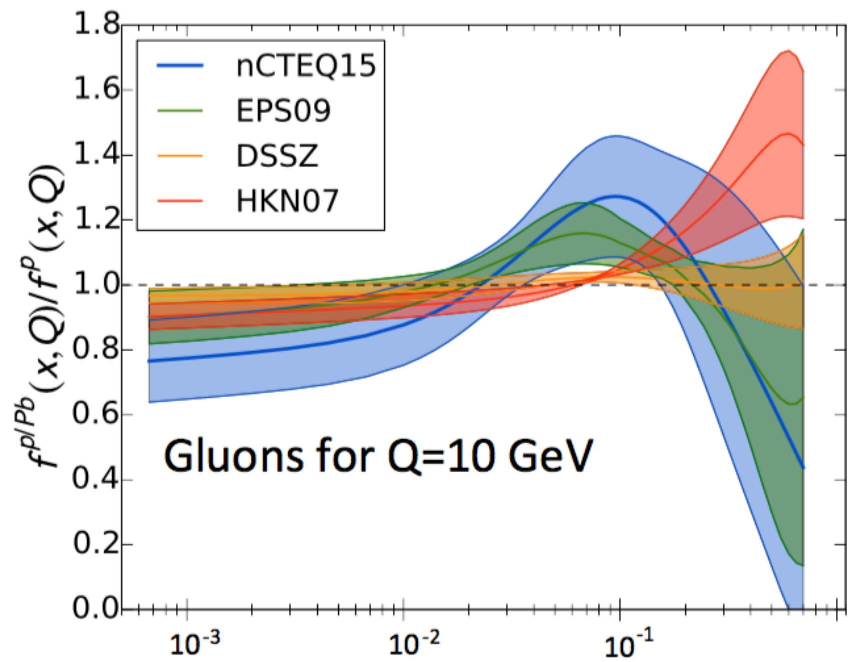
- Advance our understanding of the high-x gluon, antiquark and heavy-quark content in the nucleon and nucleus
    - Structure of nucleon and nuclei at high-x are poorly known ($x > 0.5$)
    - Some longstanding puzzles:
        - Proton charm content (important for high-energy neutrino and cosmic-ray physics)
        - Origin of nuclear EMC effect: studying a possible gluon EMC effect
    - Search and study rare proton fluctuation where one gluon carries most of the proton momentum: test QCD in a new limit never explored



Uncertainty on the gluon-gluon luminosity



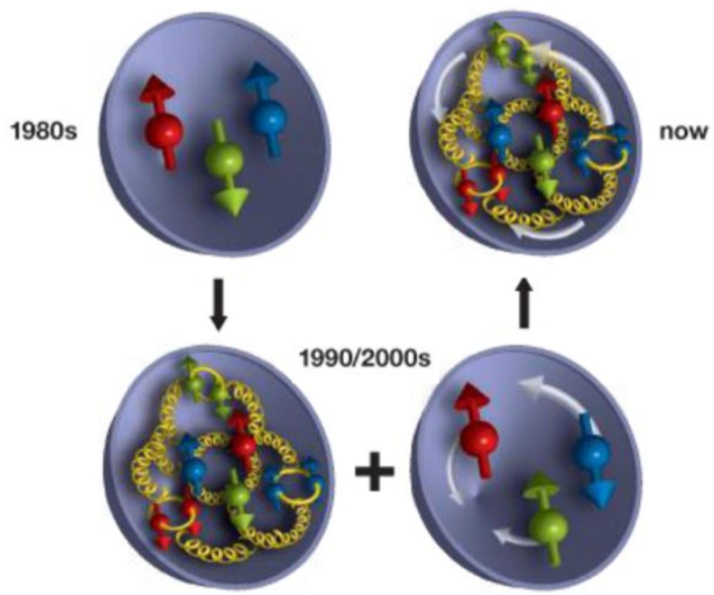
Energy spectrum of neutrino flux



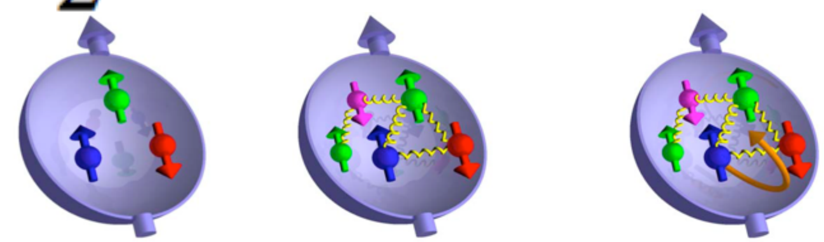
Gluon density in Pb nuclei

Physics motivations: spin physics

- Unraveling the spin of the nucleon



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$



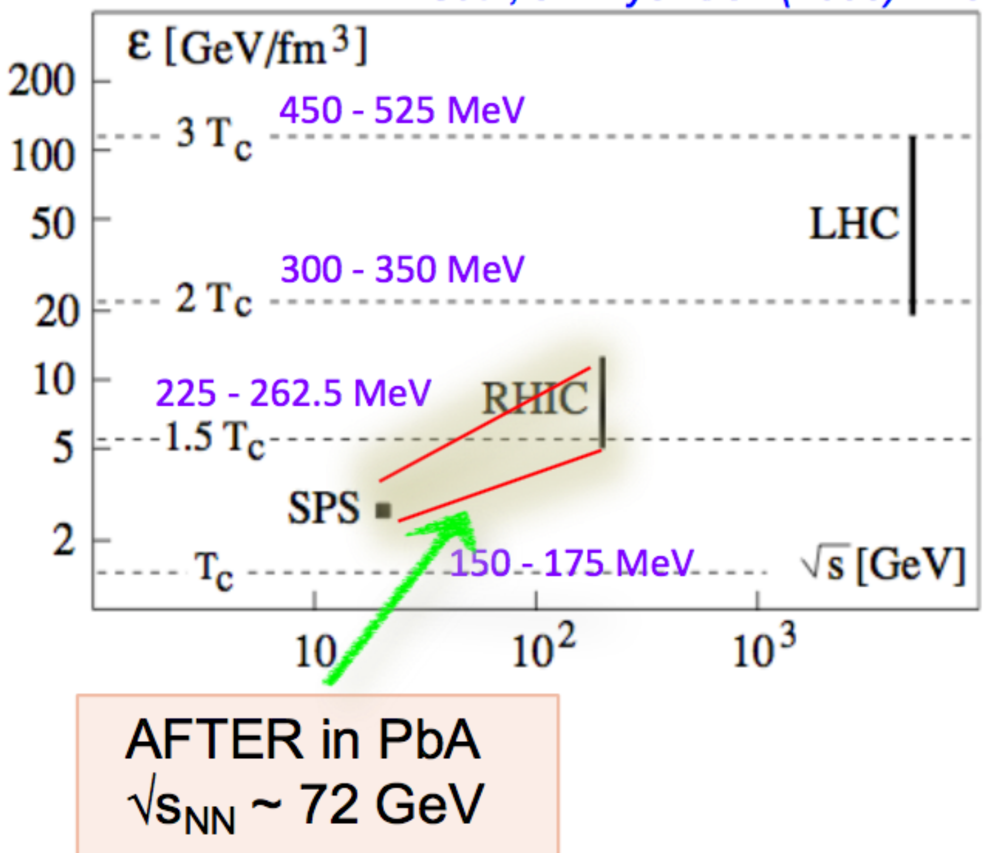
quark spin 25% | gluon spin | quark and gluon OAM

- Missing knowledge on the contribution of the orbital angular momentum (OAM) L_g and L_q to the proton spin
- Access information on the orbital motion of partons bound inside hadrons via Transversally Single Spin Asymmetries (TSSA): Sivers effect with transversally polarised target
- Test TMD (Transverse Momentum Dependent functions) factorization formalism: sign change of A_N between semi-inclusive DIS and Drell-Yan
- Determination of linearly polarised gluons in an unpolarised proton (Boer-Mulders effect)

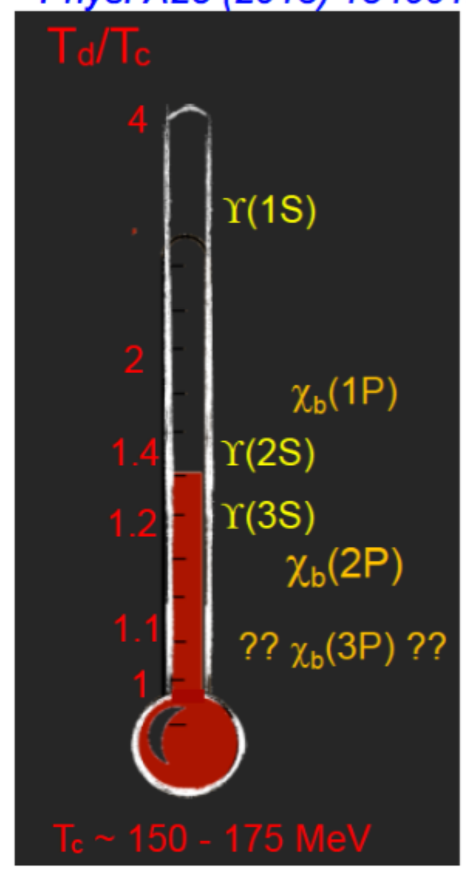
Physics motivations: quark gluon plasma

- QGP studies between SPS and nominal RHIC energies (e.g. with quarkonia)

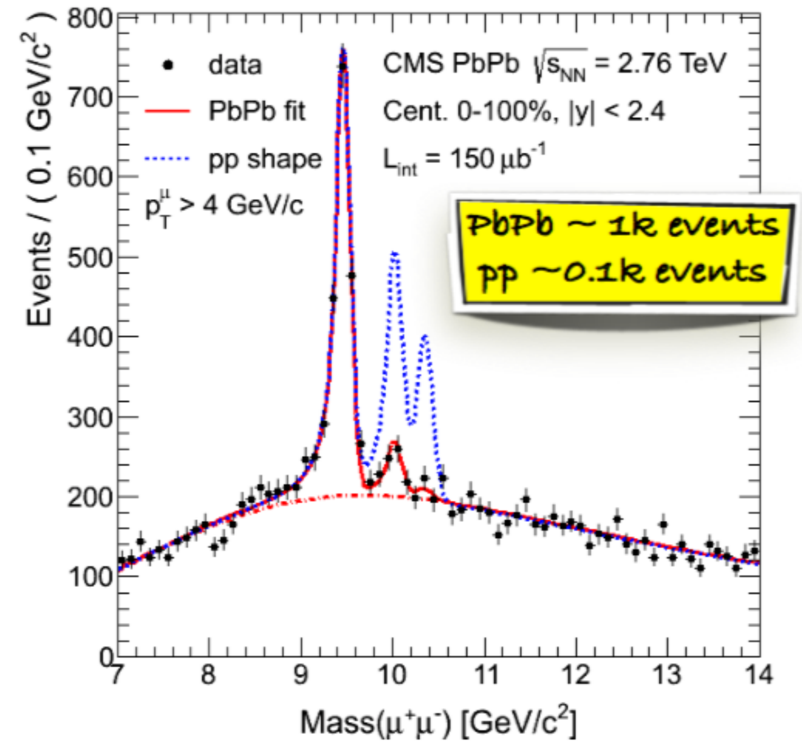
Satz, J. Phys. G32 (2006) R25



Mocsy et al, Int. J. Mod. Phys. A28 (2013) 1340012



Dissociation temperature from lattice QCD (+hydro)



Phys. Rev. Lett. 109 (2012) 222301

- A complete set of open and hidden heavy-flavour studies (vs system size and rapidity)
- E.g.: at 72 GeV, Y(3S) and Y(2S) are expected to melt: perform the same study as CMS at low energy

Possible fixed-target implementations

– Internal gas target similar to SMOG at LHCb / inspired by HERMES at HERA, RHIC polarimeter

- Full LHC proton flux: 3.4×10^{18} p/s and Pb flux: 3.6×10^{14} Pb/s on internal gas target
- Currently used by the LHCb collaboration via the luminosity monitor (SMOG) at low gas density

→ high intensity beam on gas target

– Internal wire/foil target as in HERA-B, STAR

- Beam halo is recycled directly on internal solid targets

– Beam line extracted with a bent crystal

- Beam halo is deflected by a bent crystal
- Expected proton flux $\sim 5 \times 10^{8}$ p/s, Pb flux $\sim 2 \times 10^{5}$ Pb/s
- Provides a new facility with 7 TeV proton and 2.76 lead beams
- Civil engineering required

– Beam "split" by a bent crystal

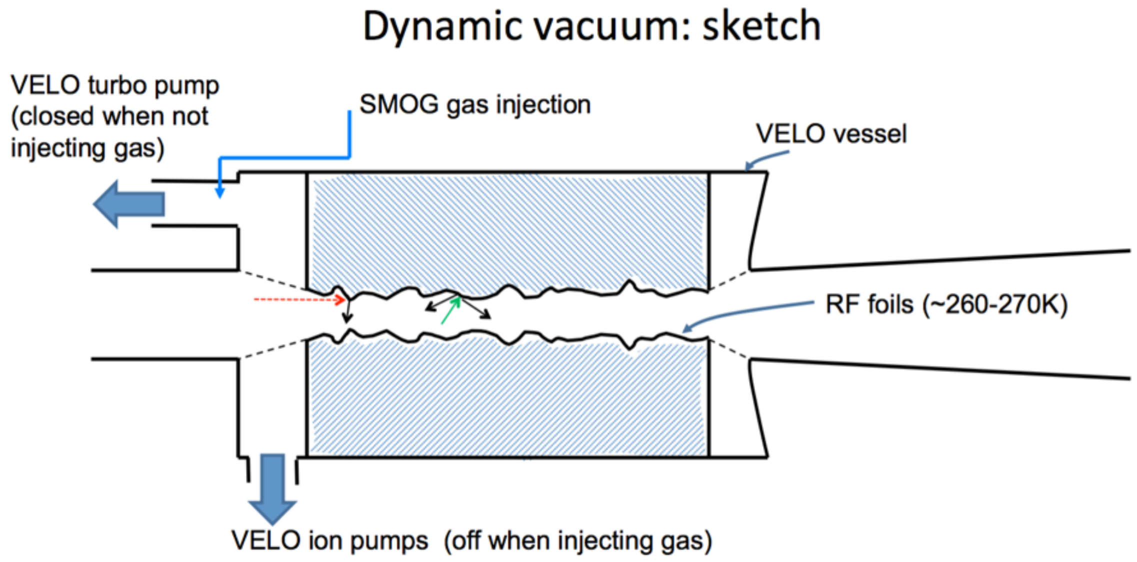
- Beam halo is deflected on a solid target internal to the LHC beam pipe
- Similar fluxes as for beam extraction
- Compatible with an existing experiment

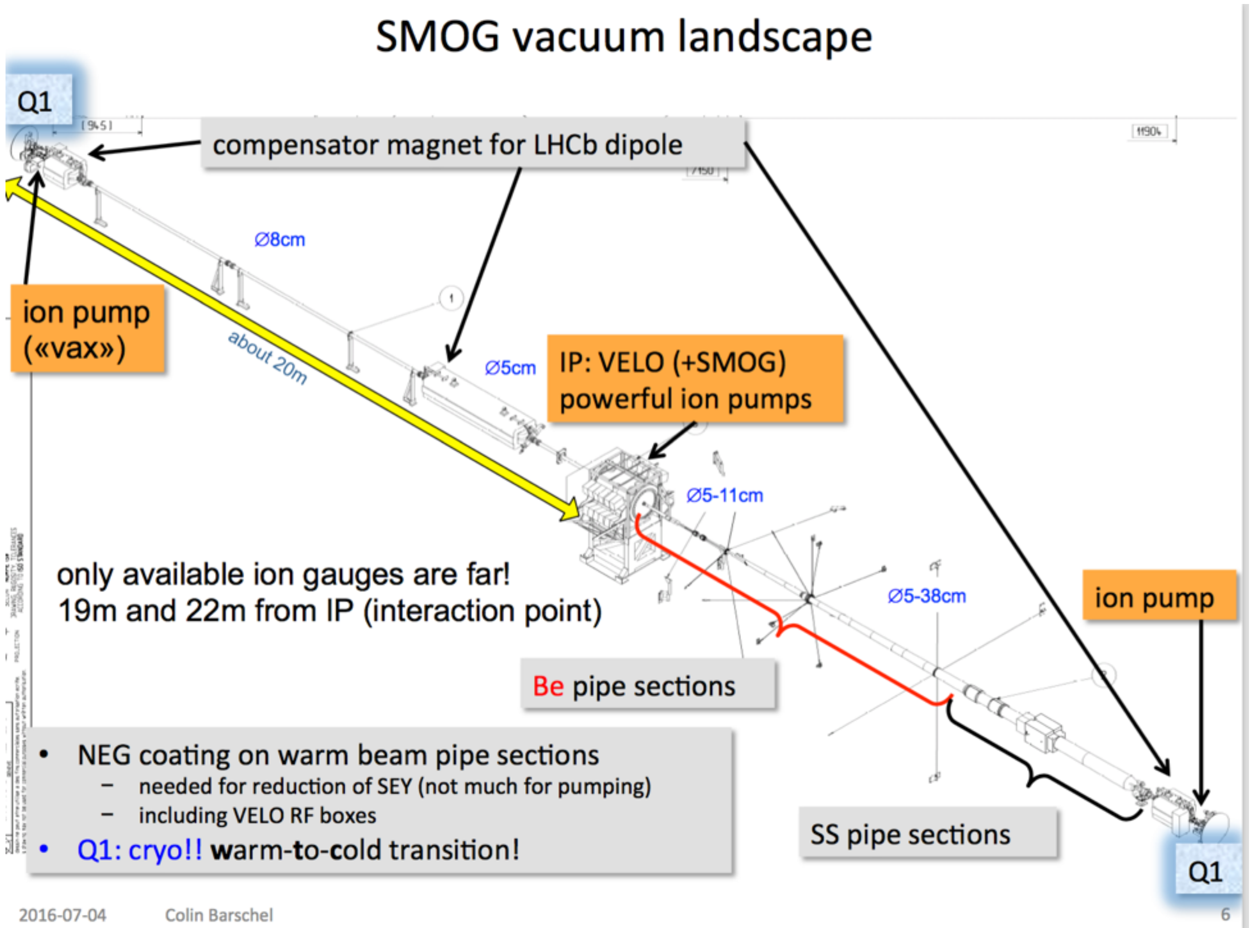
→ beam halo on dense target

Similar luminosities obtained with internal solid target and high-density gas targets
Internal gas and solid targets can be coupled with an existing LHC detector

Internal gas target: SMOG in LHCb

VELO (+SMOG)





SMOG/LHCb (System for Measuring the Overlap with Gas)

– Gas injecting into Vertex Locator (VELO) vacuum chamber: P ~1.5 10^{-7} mbar
– LHC vacuum ion pump stations located ±20m on both sides
– Noble gas already injected: He, Ne, Ar
– Use full intensity of the LHC proton and lead beam without decrease of the beam lifetime
– Limited running time: so far, at most 1 week
– Typical integrated luminosities: pAr, 17h of data-taking: L_{int} ~ 3.75/nb

Internal gas target: gas-jet

Polarised H-jet polarimeter at RHIC-BNL ***Zelenski et al. NIM A 536 (2005) 248***
- Used to measure the proton beam polarisation at RHIC
- 9 vacuum chambers: 9 stages of differential pumping
- Polarised gas: free atomic beam source (ABS) crossing the RHIC beam: H, D and $_3$He possible
- Holding field in the target vacuum chamber
- Diagnostic system: Breit-Rabi polarimeter

Density
- Polarised inlet $H_{\uparrow}$ flux: 1.3 10^{17} H/s
- Areal density $\vartheta_{H\uparrow} = 1.2\ 10^{12}$ atoms/cm^2 (7-15 × SMOG)
- Higher flux can be obtained for $^3He_{\uparrow}$ (x100) and H_2 (x1000)
- Gas target profile at interaction point: gaussian with a full width of ~6 mm

Luminosity
- Using nominal LHC bunch number [2808 bunches for proton and 592 for lead] and for 1 LHC year [10^7s proton beam and 10^6s lead beam]
- $\mathscr{L}_{p\text{-}H\uparrow} = 4.5\ 10^{30}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H\uparrow}$ = 45/pb]
- $\mathscr{L}_{p\text{-}H2} = 10^{33}\text{-}10^{34}$ cm^{-2}s^{-1} [t = 10^7: $\mathscr{L}_{p\text{-}H2}$ = 10-100/fb]

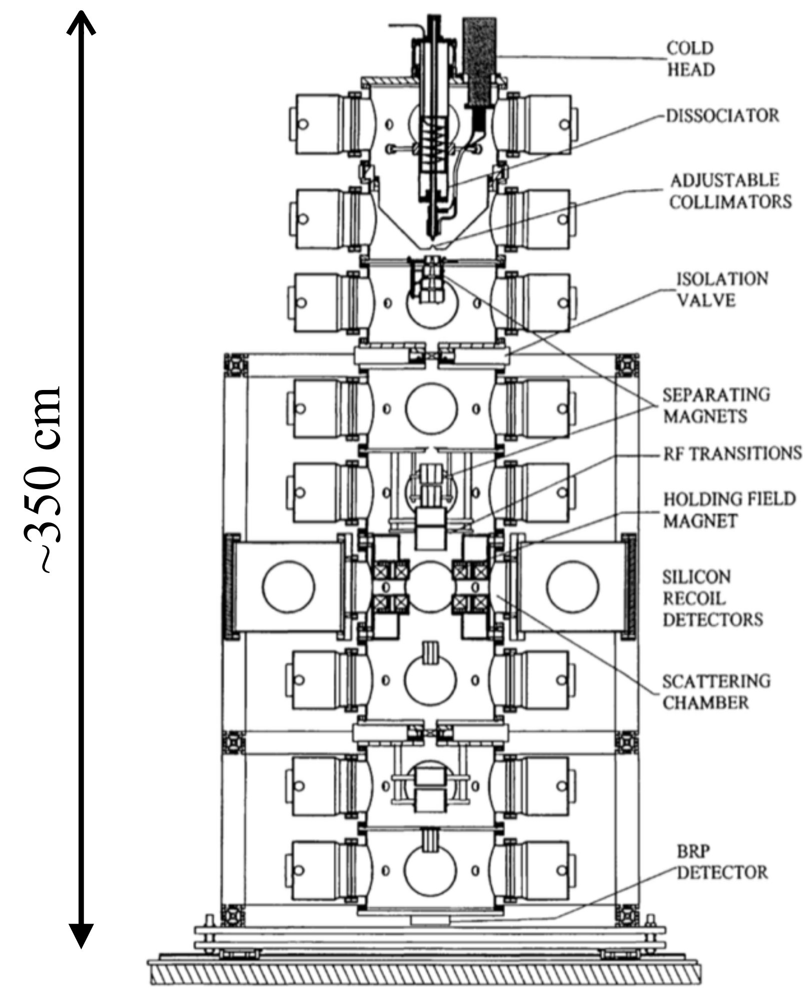
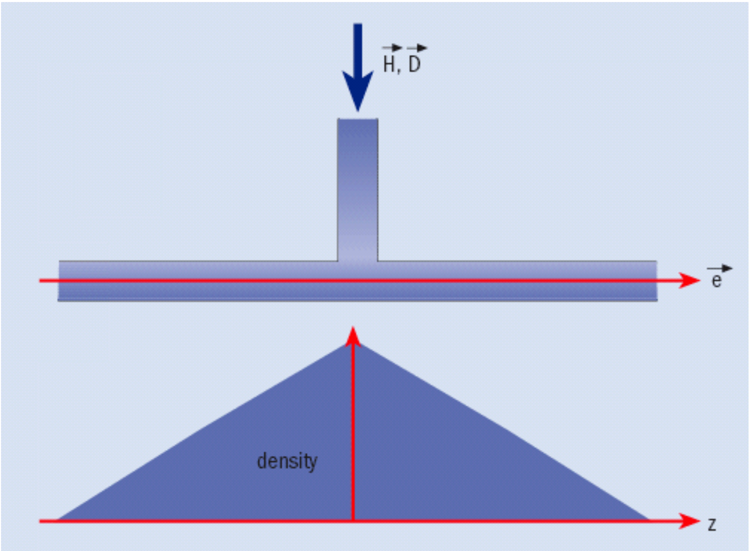


Fig. 1. H-jet polarimeter general layout.

Internal gas target: storage cell

HERMES/DESY T-shape internal storage cell target:

- Vacuum chamber target ~ 72 cm x 50 cm and pumping system
- Polarised gas: atomic beam source
- Holding field in the target chamber
- Diagnostic systems: target gas analyzer and polarimeter
- Unpolarized gas via capillary
- Proposal for LHC using an openable storage cell of 1m long and 2.8 cm wide: *C. Barschel et al. Adv.High Energy Phys. 2015 (2015) 463141*

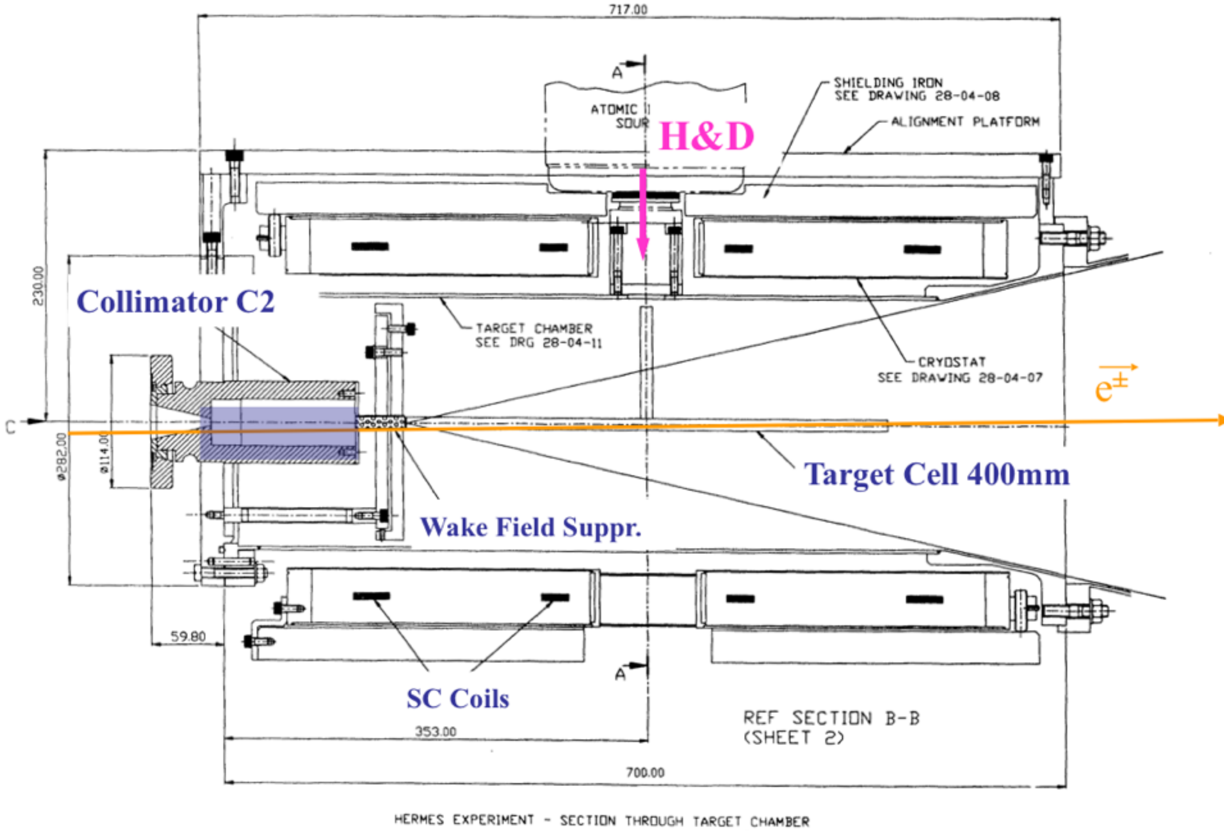


Density

- Polarised inlet $H_\uparrow$ flux: $6.5\ 10^{16}\ H_\uparrow/s$
- Areal density $\vartheta_{H\uparrow} = 2.5\ 10^{14}$ atoms/cm^2 (~100 × gas jet)
- Unpolarised gas pressure limited by beam lifetime

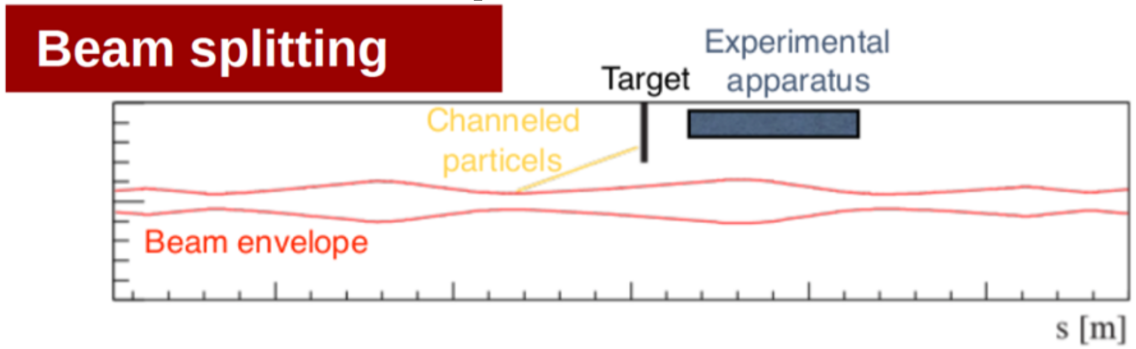
Luminosity

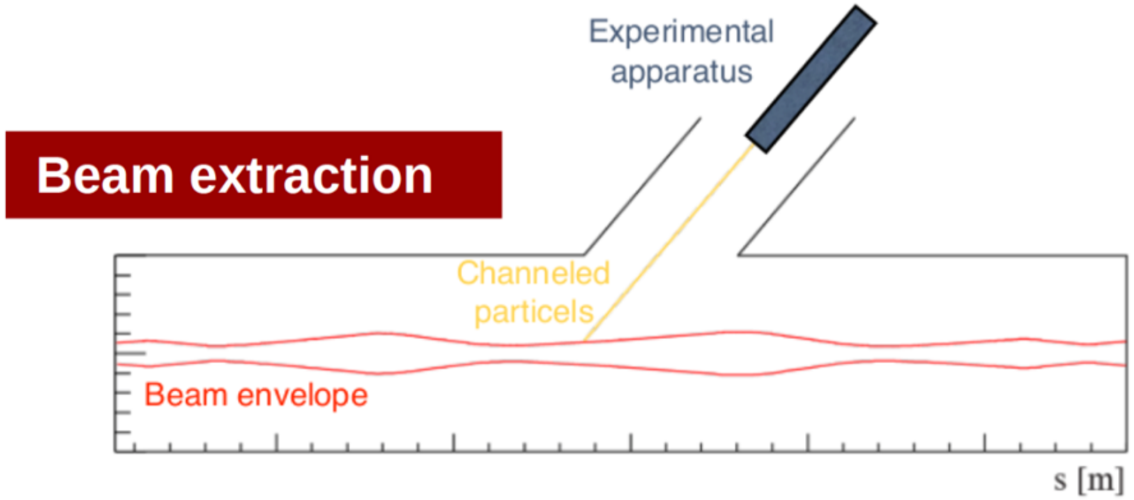
- $\mathscr{L}_{p\text{-}H\uparrow} = 0.9\ 10^{33}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}H\uparrow} = 9/fb$]
- $\mathscr{L}_{p\text{-}H2} = 5.8\ 10^{33}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}H2} = 58/fb$]
- $\mathscr{L}_{Pb\text{-}Xe} = 3\ 10^{28}\ cm^{-2}s^{-1}$ [$t = 10^6 s$: $\mathscr{L}_{Pb\text{-}Xe} = 30/nb$]



Slow beam extraction using bent crystal

S.Redaelli, *Physics Beyond Collider Kickoff workshop*, CERN, Sept. 2016





Bent crystals studied by UA9
- For collimation purpose at the LHC
- Beam extraction: new beam line possible (long-term projet)
- Beam splitting
  - Crystal located ~100 m downstream the target
  - Solid target internal to the beam pipe close to an existing experimental apparatus
  - Absorber ~100 m upstream the detector

Extracted proton and lead flux
- Proton flux ~5 x 10^8 p/s (LHC beam loss: ~10^9 p/s)
- Lead flux ~2 x 10^5 Pb/s

Luminosity
- Assuming 5 mm target length
- $\mathscr{L}_{\text{p-H}} = 1.3\ 10^{31}\ \text{cm}^{-2}\text{s}^{-1}$ [$t = 10^7$s: $\mathscr{L}_{\text{p-H}} = 0.1$/fb]
- $\mathscr{L}_{\text{Pb-W}} = 3\ 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$ [$t = 10^6$s: $\mathscr{L}_{\text{Pb-Xe}} = 3$/nb]
- Similar luminosities as the internal storage cell if larger target thickness

Luminosity if slow beam extraction is coupled with polarised target e.g. COMPASS NH_3
- $\mathscr{L}_{\text{p-NH3}\uparrow} = 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ [$t = 10^7$s: $\mathscr{L}_{\text{p-H}} = 1$/fb]

Figure of Merit for spin physics

Expected luminosities and spin figure of merit ($\mathcal{F}$) for current or planned experiments

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$\mathcal{P}_{\text{eff}} = p_T^2 f^2$: effective pol.

$\mathcal{F} = \mathcal{P}_{\text{eff}} \times \mathcal{L}$

Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^{\uparrow}$	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ ($cm^{-2}s^{-1}$)
AFTER@LHCb	$p + p^{\uparrow}$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^3He^{\uparrow}$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_{\mu}$	$p + p^{\uparrow}$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	190	19	$0.2 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^{\uparrow}$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^{\uparrow} + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^{\uparrow} + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

New beam line:

- Slow beam extraction + Compass $NH_{3\uparrow}$: $\mathcal{F} = 2.5\ 10^{31}$ /cm^2/s
- Slow beam extraction + E1039 $NH_{3\uparrow}$: $\mathcal{F} = 1.5\ 10^{30}$ /cm^2/s

In an existing LHC experimental cavern:

- LHC beam + storage-cell $H_{\uparrow}$: $\mathcal{F} = 6.4\ 10^{32}$ /cm^2/s
- LHC beam + gas-jet $H_{\uparrow}$: $\mathcal{F} = 3.4\ 10^{30}$ /cm^2/s

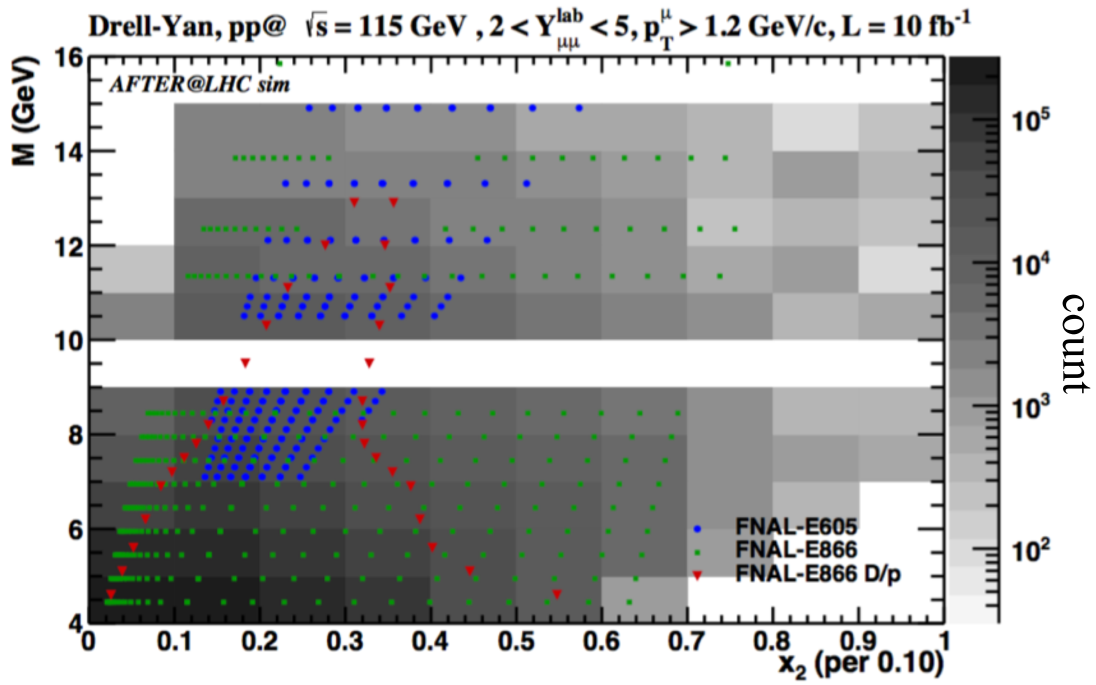
A selection of projected performances

– Nucleon and nuclear structure with Drell-Yan and open charm
– Quark and gluon Sivers effect using a polarised target
– Projected performances are obtained with a LHCb-like detector ($2 < \eta < 5$, vertex detector, PID capabilities)
– Luminosities: $L_{pp} \sim 10$/fb, $L_{pA} \sim 100$/pb

Not covered:
– Quark Gluon Plasma physics case
– Photon related observables
– W boson
– Antiproton measurements for astroparticle physics
– Associated production of hard probes
– Ultra-peripheral collisions
– …

Nucleon structure with Drell-Yan

– Extension of the coverage of the existing Fermilab Drell-Yan data to **large *x*-value** → **1** by probing laboratory rapidities down to 2
– At least 30 events per bin in (M, *x*)
– Impact of Drell-Yan measurements on Parton Distribution Function (PDF) evaluated with generation of pseudo-data and profiling analysis
– Large statistical sample in pp@115 GeV allow to constrain valence and light sea quarks PDF, as well as valence quarks PDF at $x > 0.4$



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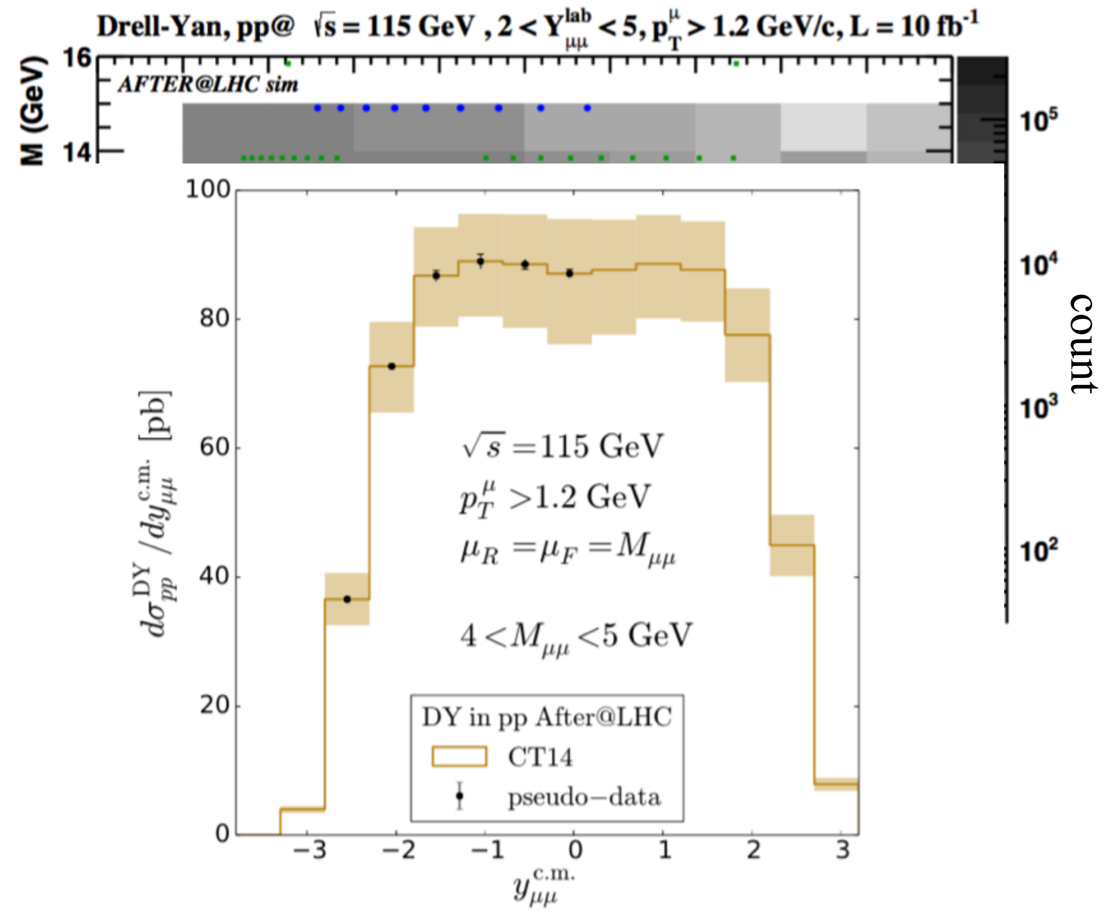

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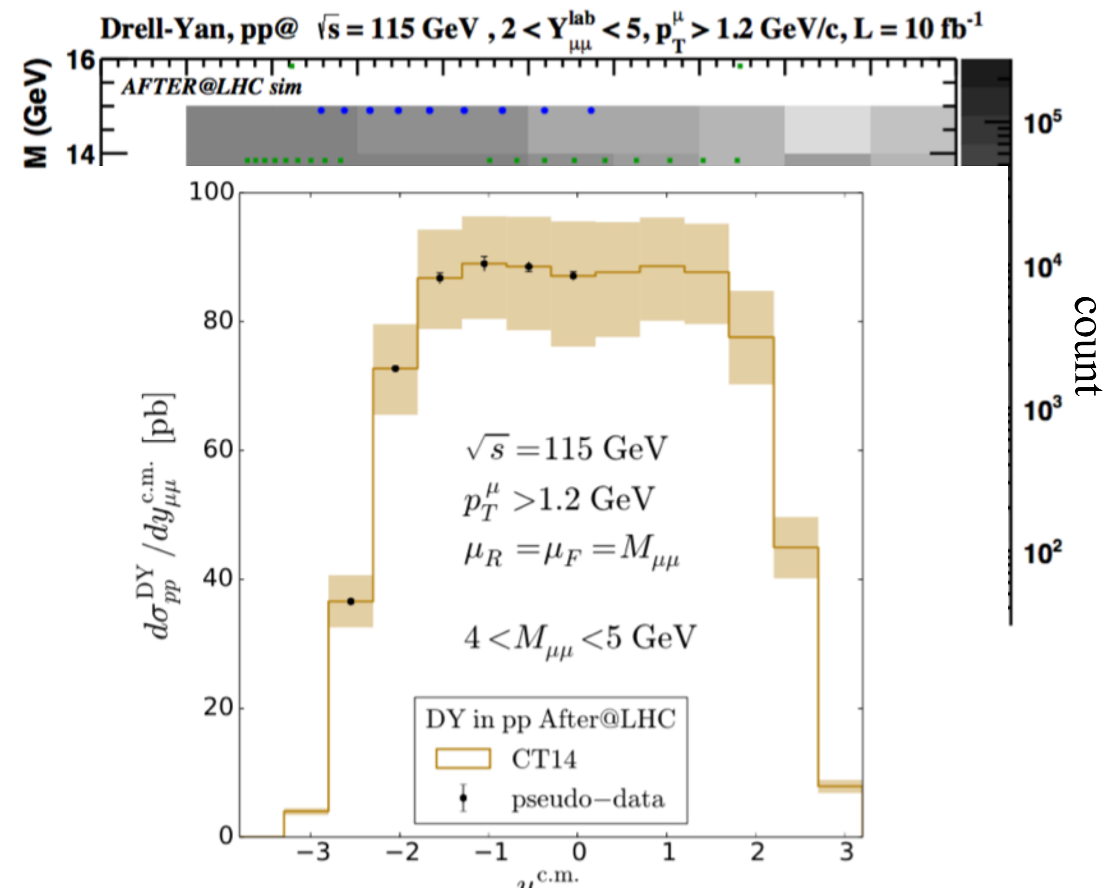
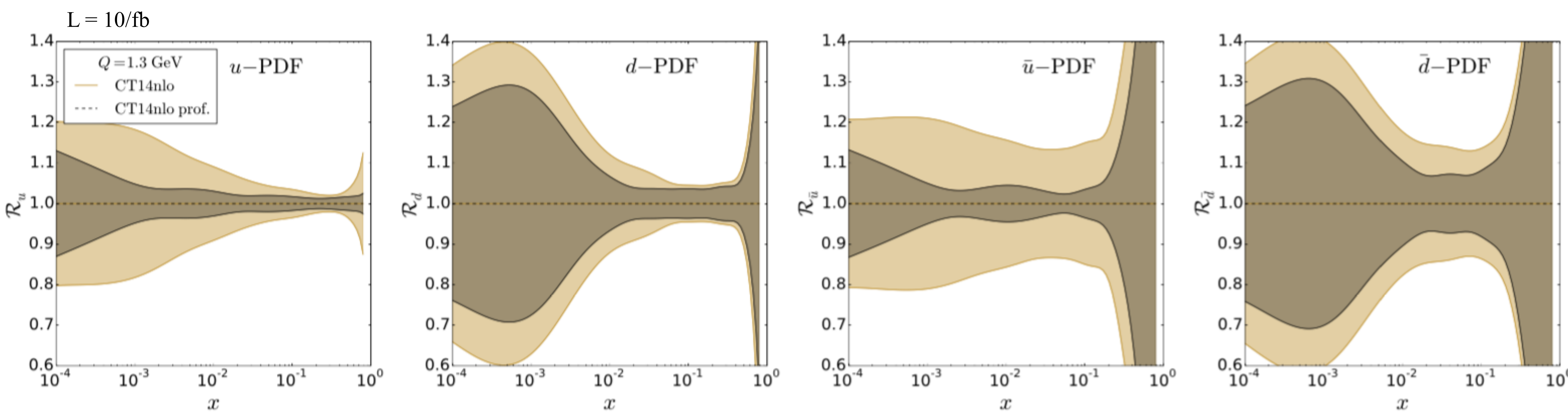
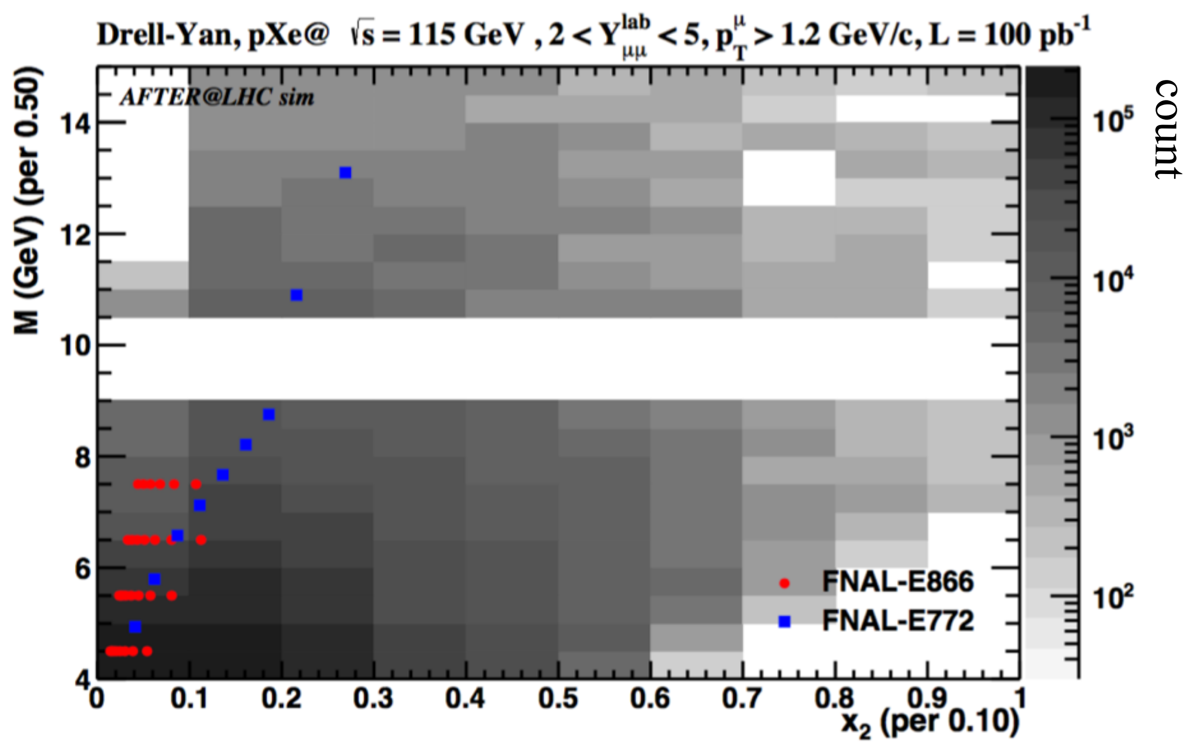
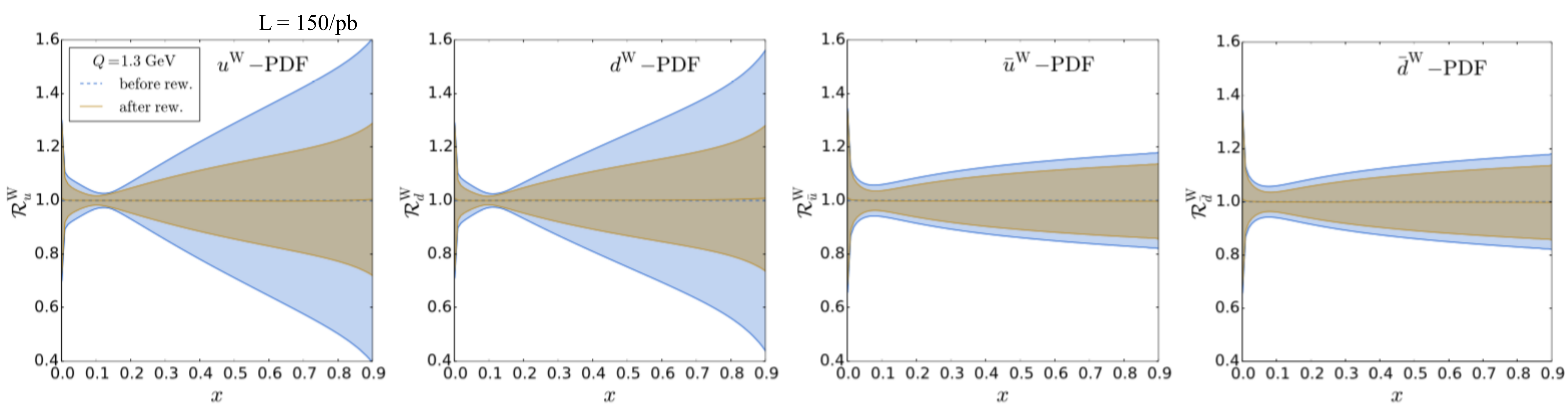




Nuclear structure with Drell-Yan

- Much larger kinematical coverage in pA@115 GeV than Drell-Yan Fermilab measurements used for nPDF fit
- Impact of Drell-Yan measurements on nPDF evaluated by using pseudo data on nuclear ratio R_{pA} with reweighting analysis
- Example with L=150/pb for pW@115 GeV: significant decrease of the uncertainties for u and d quark nPDF at large x





Drell-Yan for spin physics

Transverse Single Spin Asymmetry: $A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

- Drell-Yan pair production on a transversally polarised target can probe the quark Sivers TMD function, related to quark OAM L_q
- Test the TMD factorization formalism: sign change of A_N between semi-inclusive DIS and Drell-Yan
- With polarised H or ^{3}He targets (storage-cell gas target): high spin figure of merit and precise measurement possible

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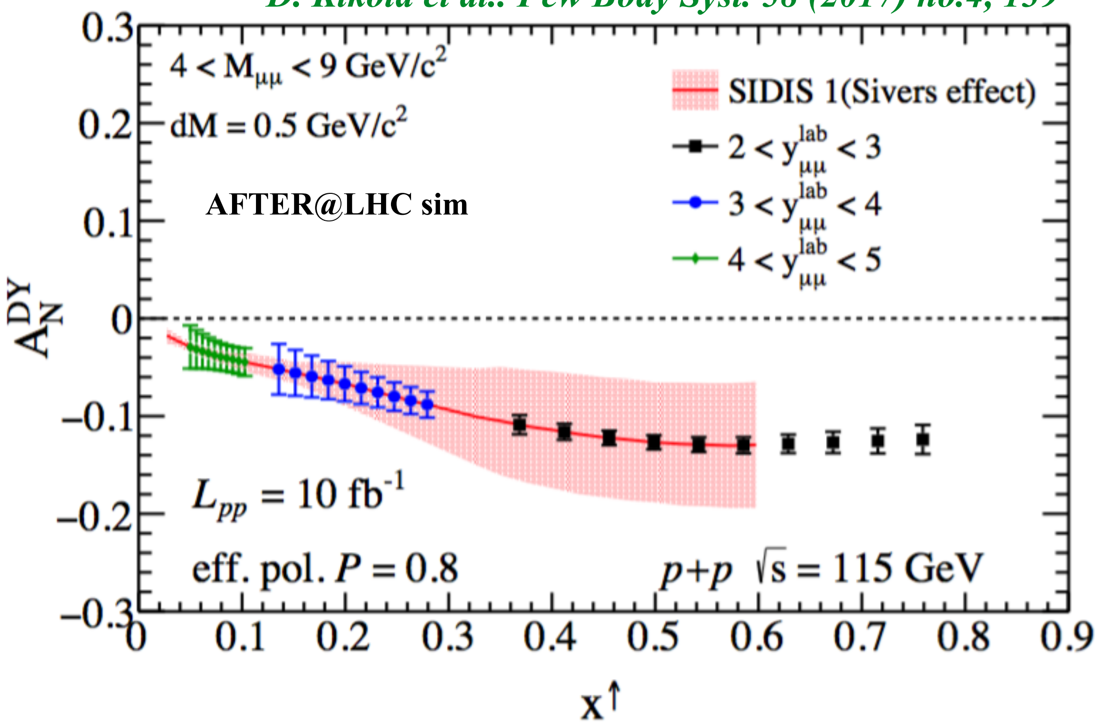
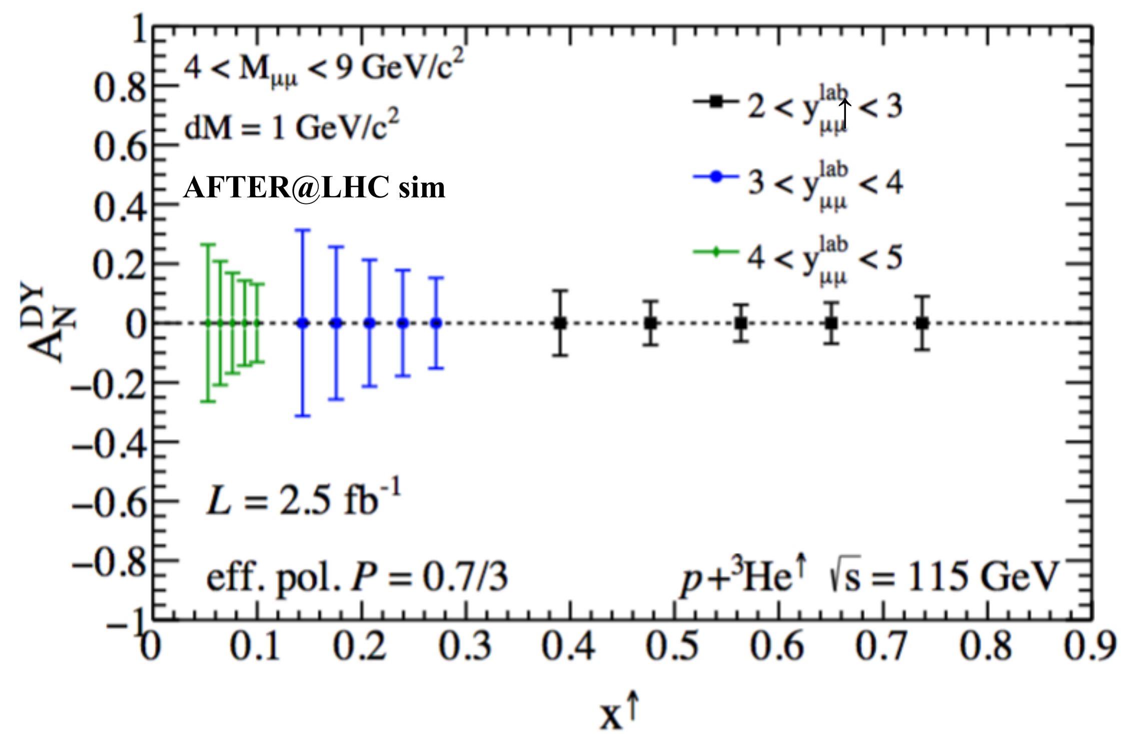


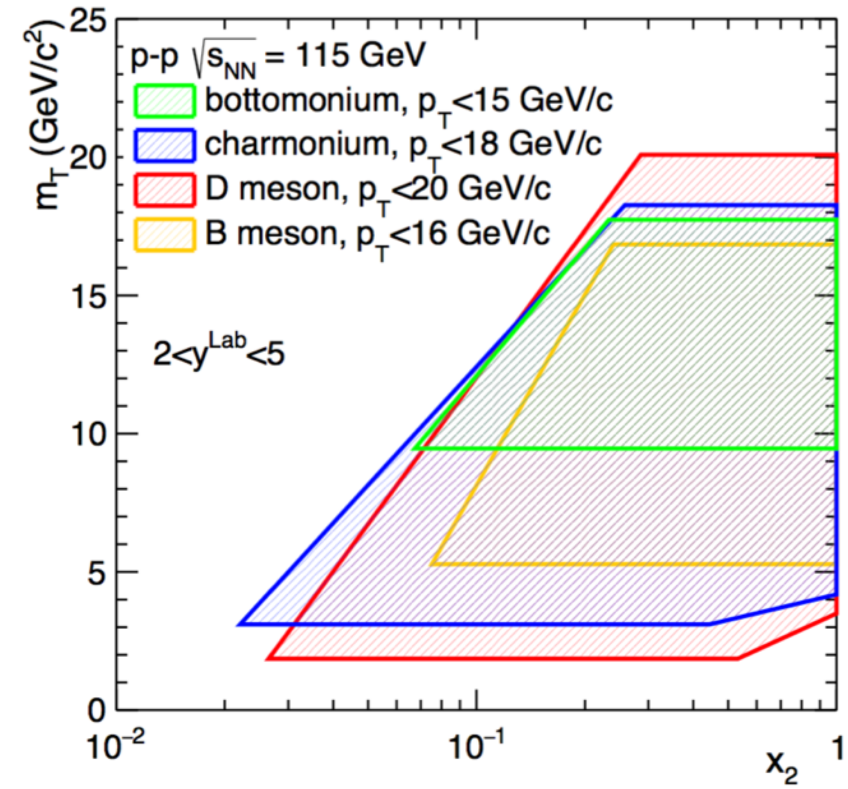


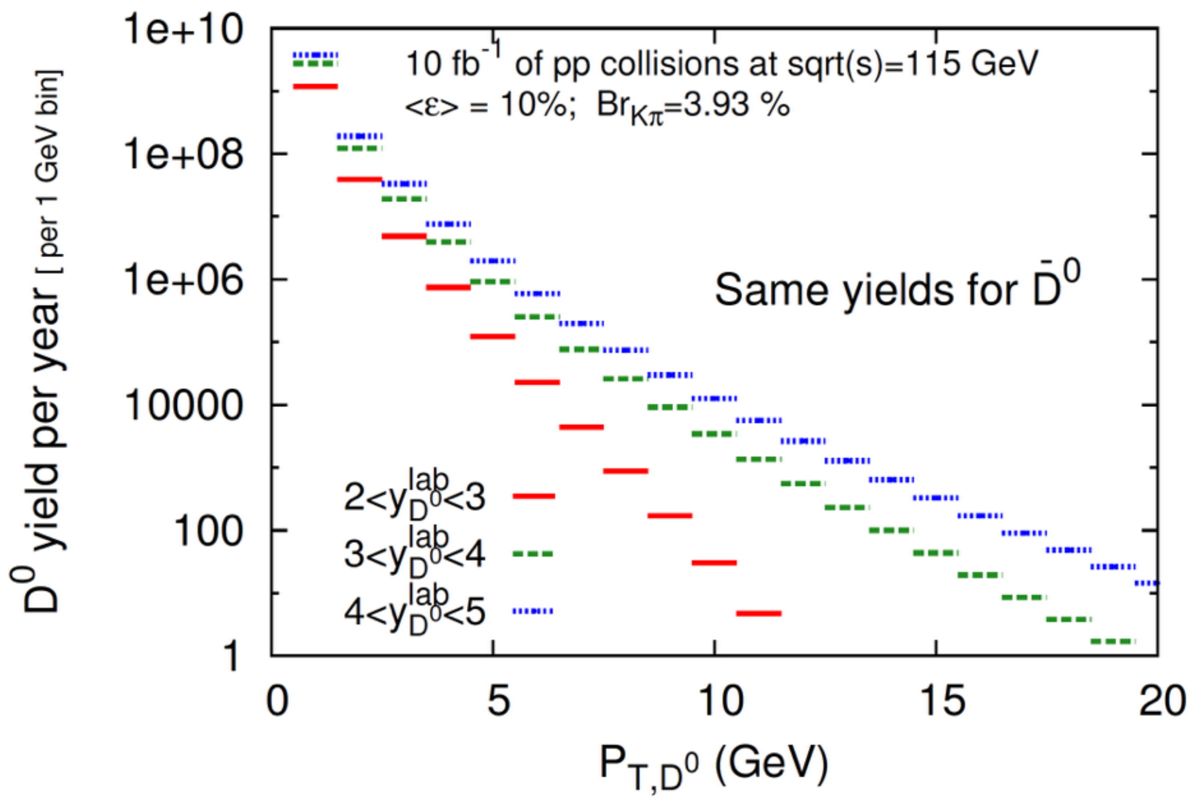
- Uncorrelated background estimated with like-sign μ pair
- Large statistics and high S/B ratio result into small statistical uncertainties for A_N and $x_{\uparrow} > 0.3$
- $H_{\uparrow}$ target: large A_N predicted *M. Anselmino et al. Adv. High Energy Phys. 2015 (2015) 475040*

$^3He_{\uparrow}$ target: quark Sivers effect in the neutron

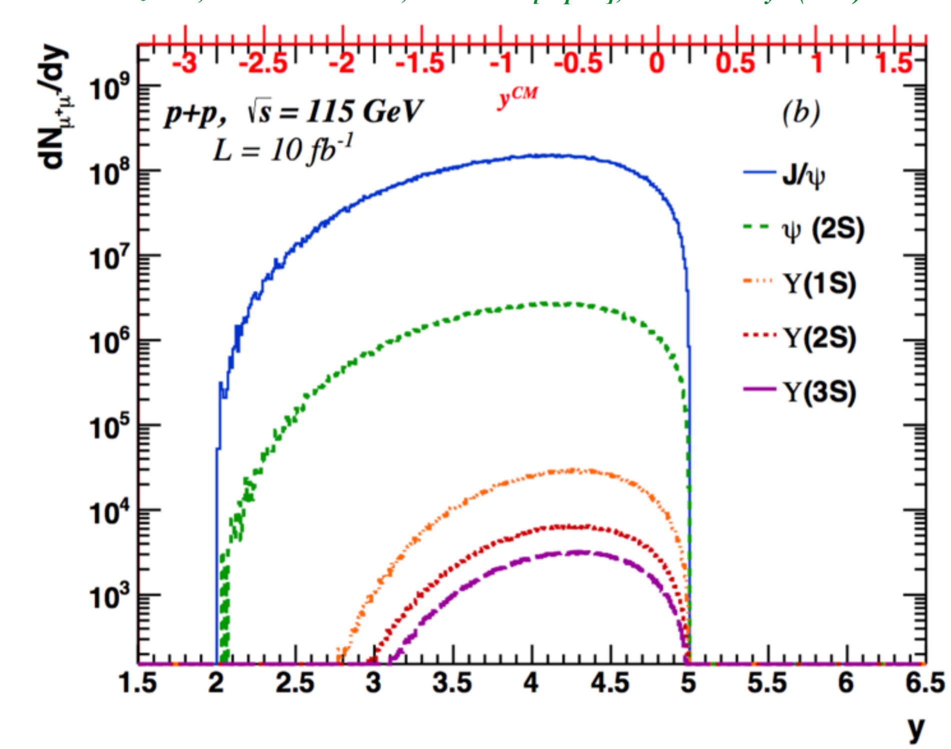
Open and hidden heavy-flavour

- Open heavy-flavour and quarkonia as probe of gluon content in a nucleon
- High statistical precision and wide rapidity coverage expected in in pp@115 GeV for open and hidden heavy-flavour
- At forward rapidity with typical forward detector, possibility to reconstruct those particles down to low p_T → total cross-section measurement



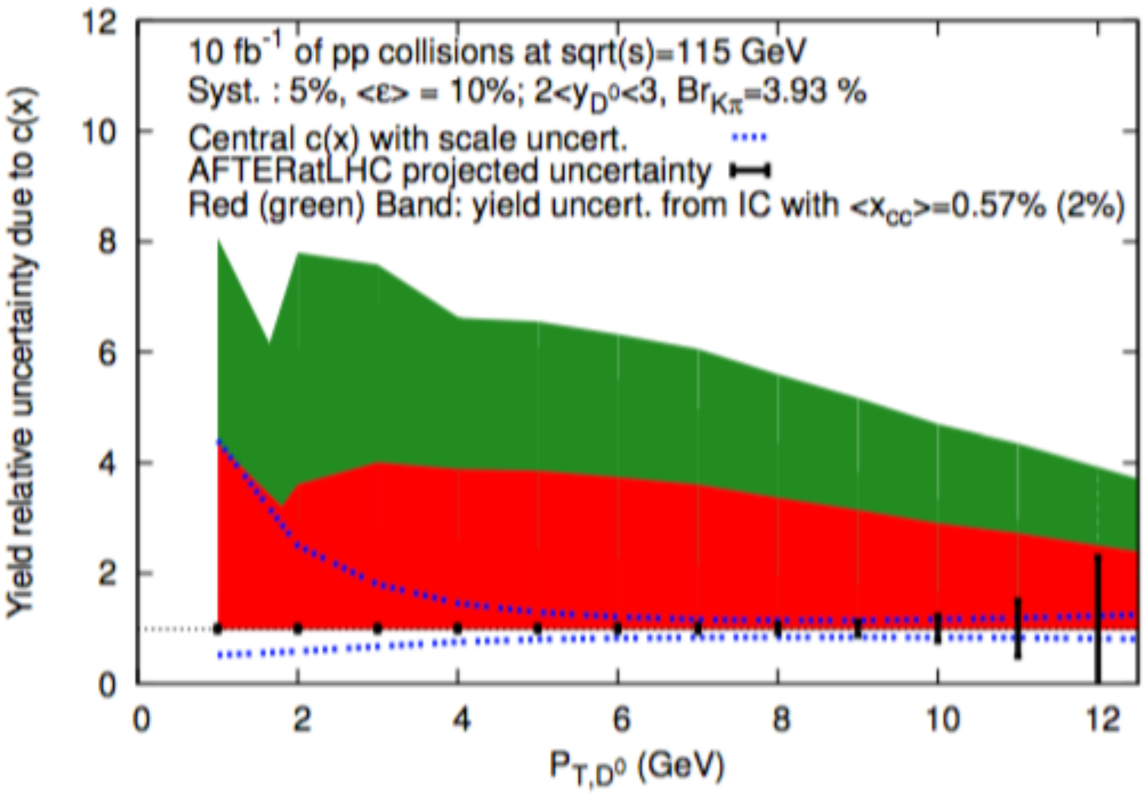


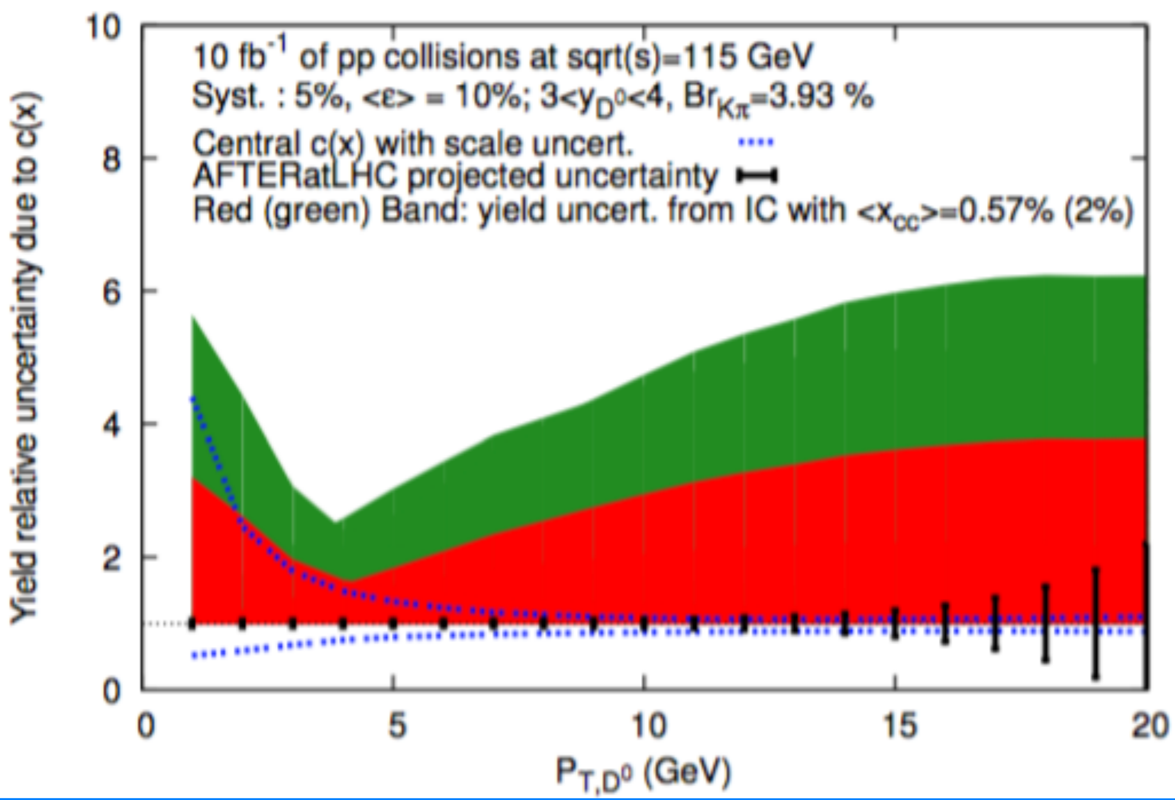
B. Trzeciak, L. Massacrier et al., 1504.05145 [hep-ex], Adv.Hi.En.Phys. (2015) 986348

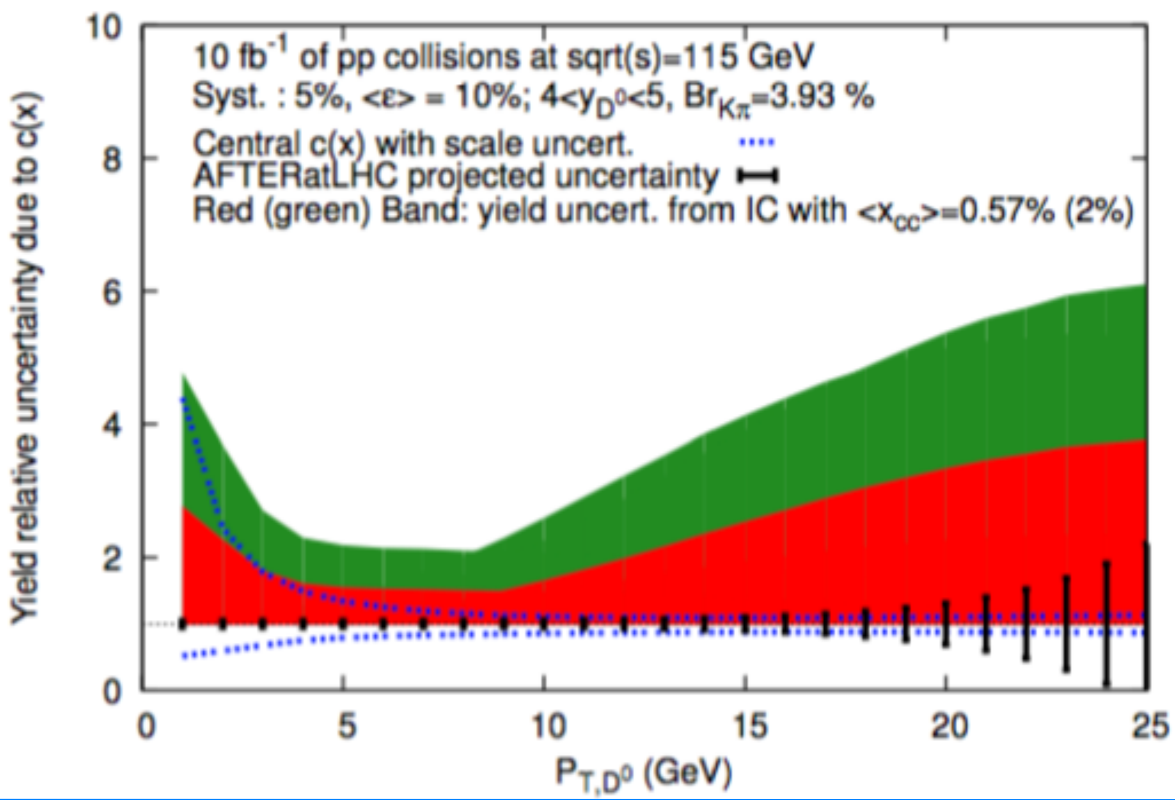


Charm content of the nucleon at large x

- At large-$\boldsymbol{x}$ > 0.1, very large charm PDF uncertainties (perturbative via gluon splitting vs non-perturbative from intrinsic charm): longstanding debate in the QCD community
- Enveloppe of several charm distributions (red and green band) shows up to a factor 8 relative uncertainties on D meson yield within $2 < y_D < 5$ in pp@115 GeV
- One can easily probe charm content of nucleon at large x for D meson with $p_T < 15$ GeV/c
- Impact on neutrino flux and cosmic-ray physics







Open charm for spin physics

- D mesons can also be collected with a transversely polarised target: no existing measurement
- It gives access to the tri-gluon correlation and the gluon Sivers effect (related to L_g)
- Differences in D and $\overline{D}$ gives access to C-odd correlators
- Feynman $x_F = x_1 - x_2 < 0$

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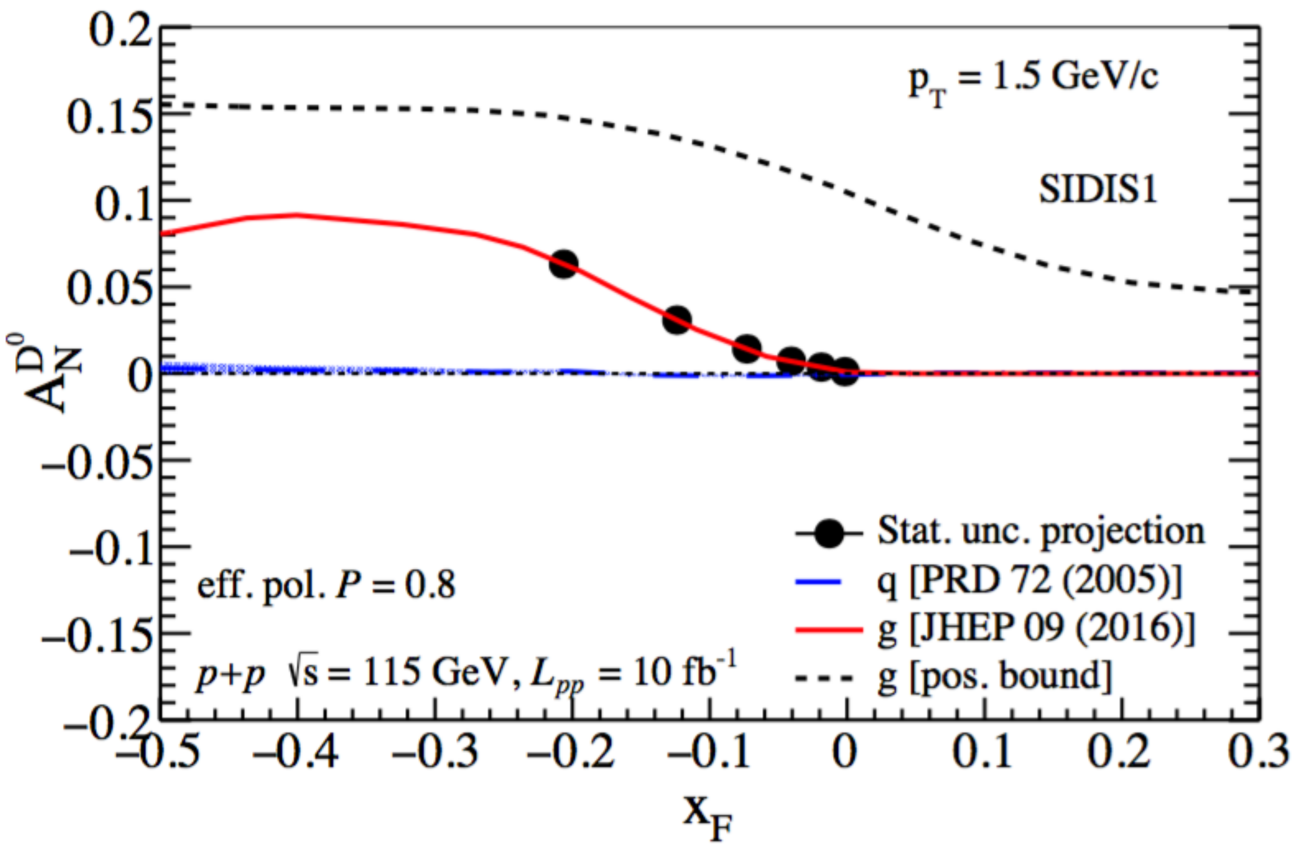
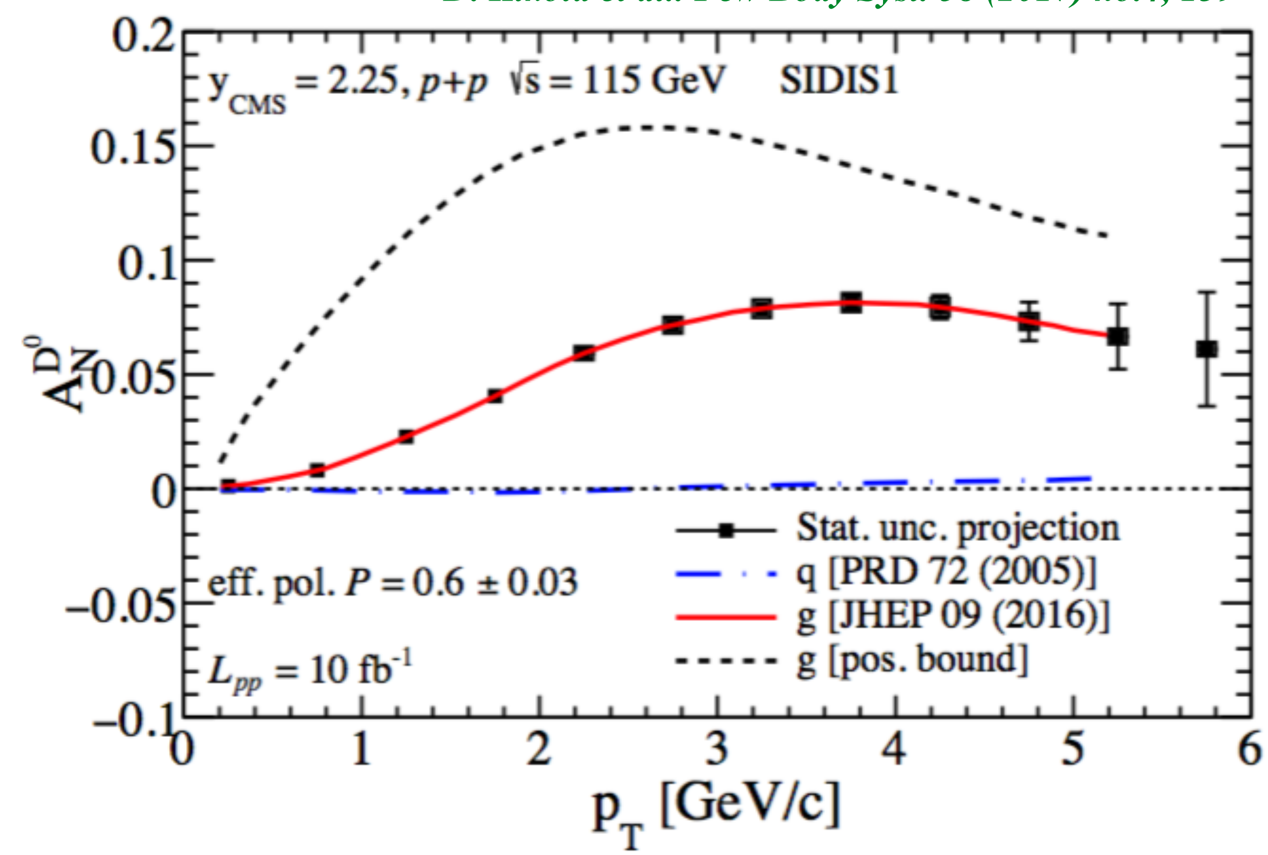
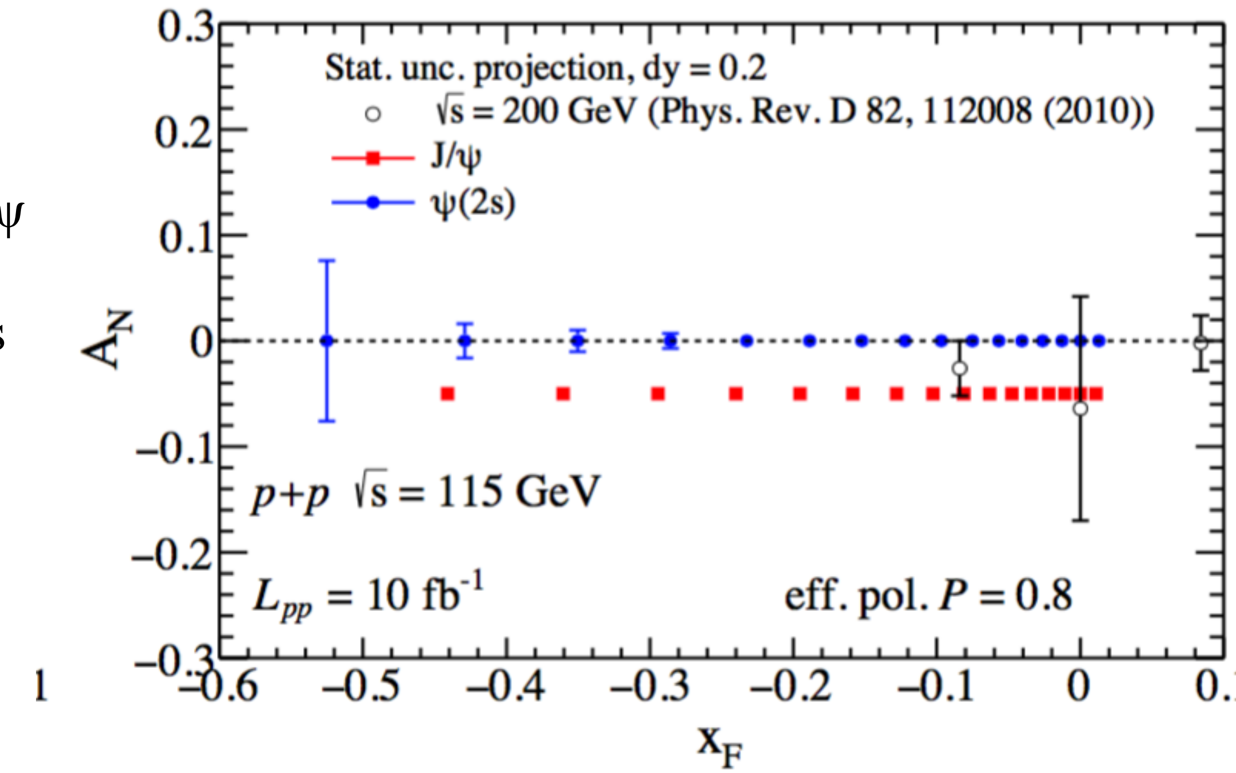




Quarkonium production

– Large yield expected for quarkonia: possibility to measure the charmonium and bottomonium family
– e.g. statistical uncertainty projection on A_N for Υ(nS), J/ψ and ψ(2S)
– Also access on polarised neutron $^3He_{\uparrow}$ with uncertainties at the percent level
– So far only J/ψ measurements at RHIC with large uncertainties
– Asymmetry sensitive to gluon Sivers effect



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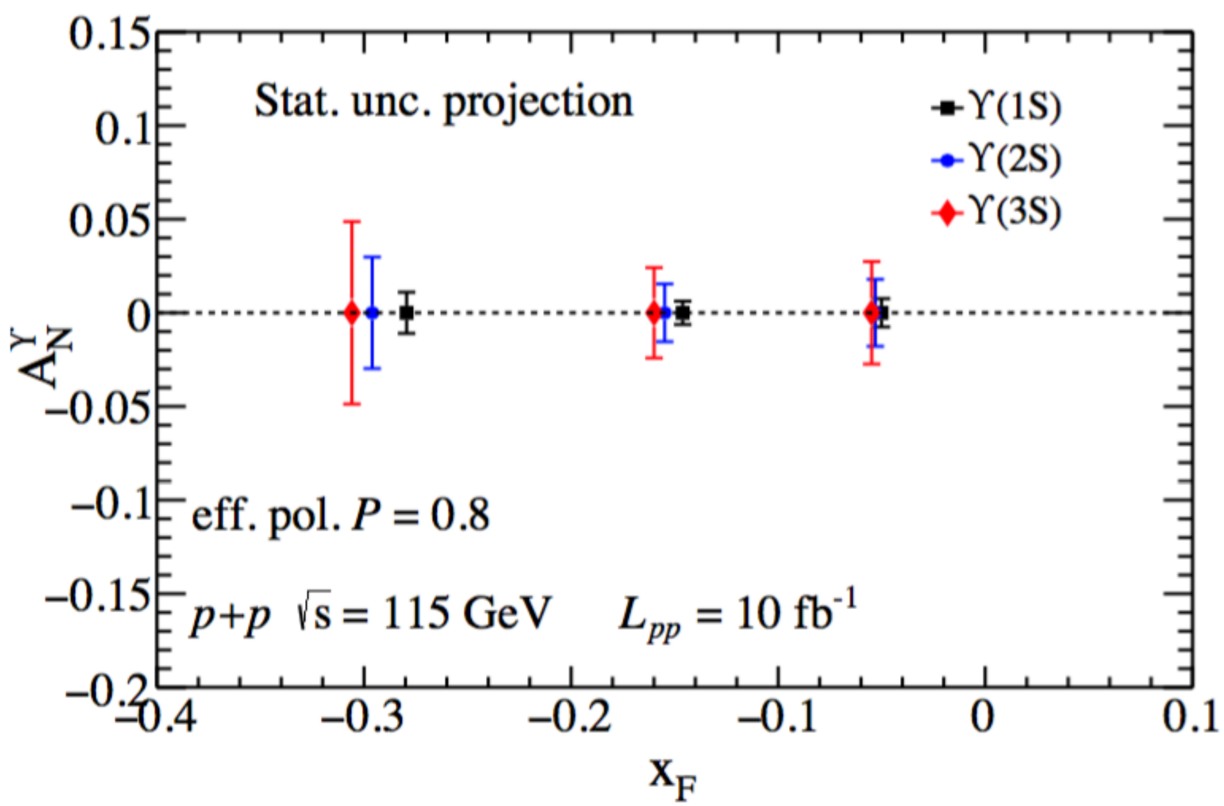
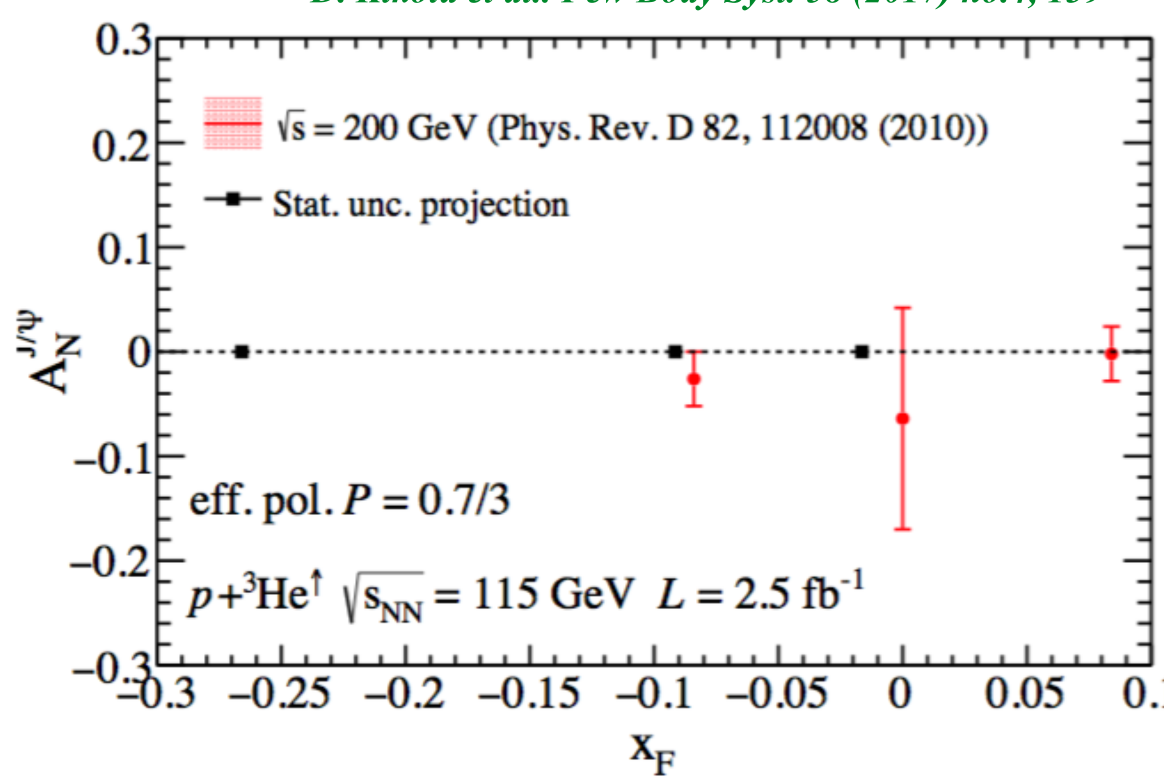
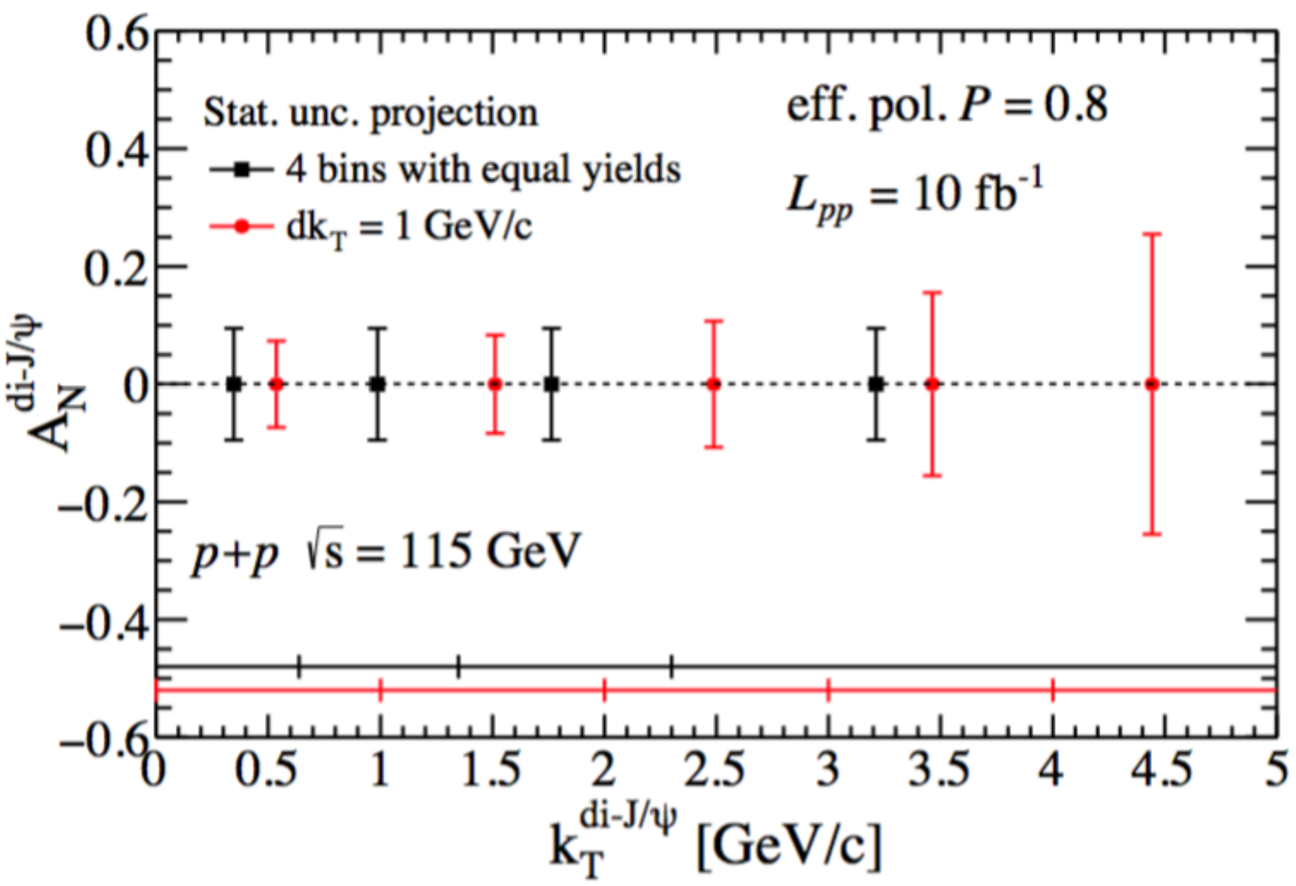




Double J/ψ production

– A_N of double J/ψ production never measured earlier
– It allows one to study the k_T dependence of the gluon Sivers function



Summary

- Three main physics motivations for a high-luminosity fixed-target program at the LHC:
  - –the high-*x* frontier: nucleon and nuclear structure and connections with astroparticles
  - –the nucleon spin and the transverse dynamics of partons
  - –the Quark Gluon Plasma
- Two possible technical implementations without interfering with other experiments:
  - –an internal gas-target inspired from SMOG/RHIC/HERMES
  - –a slow beam extraction with bent crystal on a solid target
- Technical implementations of fixed-targets currently discussed within the Physics Beyond Collider working group (http://pbc.web.cern.ch/). Next general meeting: November 2017 (https://indico.cern.ch/event/644287)

back-up slides

Beam splitting using bent crystal

Luminosities considering 5 mm thick targets (compatible with both beam splitting or extraction)

LHC beam	Target species	Density ρ [g cm^{-3}]	M [g mol^{-1}]	Thickness [mm]	θ_{Target} [cm^{-2}]	beam flux [s^{-1}]	$\mathcal{L}$ [cm^{-2}s^{-1}]
p	Solid H	0.088	1	5	$2.6 \cdot 10^{22}$	5×10^8	$1.3 \cdot 10^{31}$
p	C	2.25	12	5	$5.6 \cdot 10^{22}$	5×10^8	$2.8 \cdot 10^{31}$
p	Ti	4.43	48	5	$2.8 \cdot 10^{22}$	5×10^8	$1.4 \cdot 10^{31}$
p	W	19.25	184	5	$3.1 \cdot 10^{22}$	5×10^8	$1.6 \cdot 10^{31}$
Pb	Solid H	0.088	1	5	$2.6 \cdot 10^{22}$	10^5	$2.6 \cdot 10^{27}$
Pb	C	2.25	12	5	$5.6 \cdot 10^{22}$	10^5	$5.6 \cdot 10^{27}$
Pb	Ti	4.43	48	5	$2.8 \cdot 10^{22}$	10^5	$2.8 \cdot 10^{27}$
Pb	W	19.25	184	5	$3.1 \cdot 10^{22}$	10^5	$3.1 \cdot 10^{27}$

- Typical luminosities integrated over a month (10^6s): L_{PbW} (72 GeV) = 3/nb
- Large luminosities depending on target thickness