Discussion session: fixed target physics case for forward detector

See also my presentation at last LHCb U2 heavy-ions: tracker and physics workshop (12th -13th April 2022) : https://indico.ijclab.in2p3.fr/event/8156/contributions/25479/attachments/18651/24999/WorkshopLHCb.pdf

Which setup?

- Data taking with proton/Pb beams?
- Target versatility? From H to heavy nuclei?
- Luminosity that can be collected?
- Possibility for polarized target ?
- Particle detection only in the forward region in the lab? Extension to mid-rapidity in the lab?

Fixed target mode at LHC: kinematics

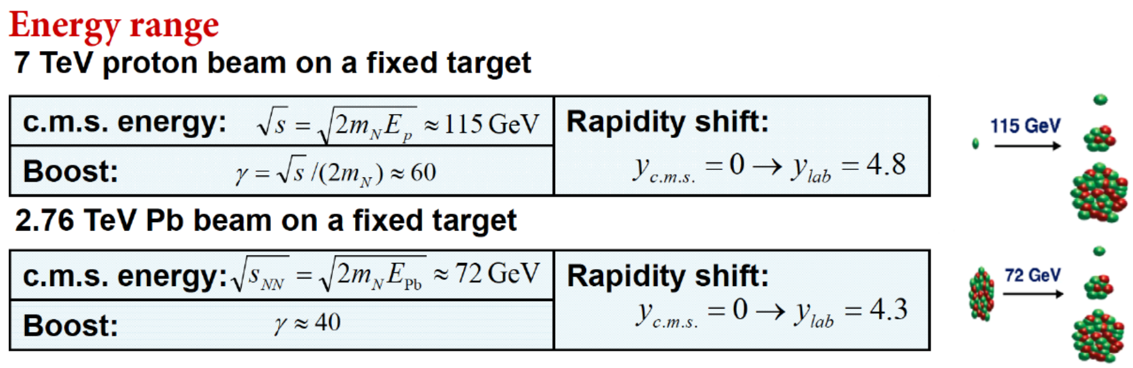
- ❑ New energy range with the same LHC accelerator
  - ➢ Same $\sqrt{s_{NN}}$ for pH, pA → interesting for R_{pA}
  - ➢ Same $\sqrt{s_{NN}}$ for PbH, PbA in between SPS and RHIC top energies

- ❑ Access to the high Feynman-x_F domain (access to partons with $x_2 \rightarrow 1$ in the target)
  - ➢ Backward physics accessible with forward detectors in the lab. Caveat: end of phase space slightly outside LHCb acceptance for J/ψ and D mesons

- ❑ Target species versatility: atomic number dependence of nuclear effects, isospin study with Deuteron and ^{3}He targets

- ❑ Target polarization and spin physics programme

- ❑ Outstanding luminosities as large as collider case with dense targets



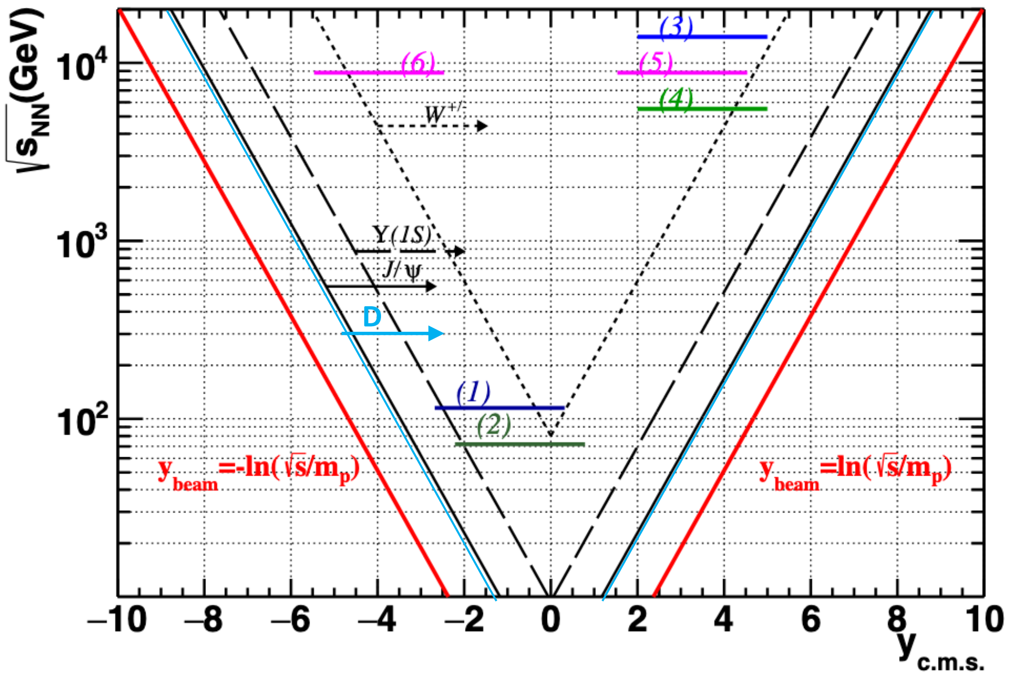
Energy range

7 TeV proton beam on a fixed target

c.m.s. energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\text{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost: $\gamma = \sqrt{s}/(2m_N) \approx 60$	

2.76 TeV Pb beam on a fixed target

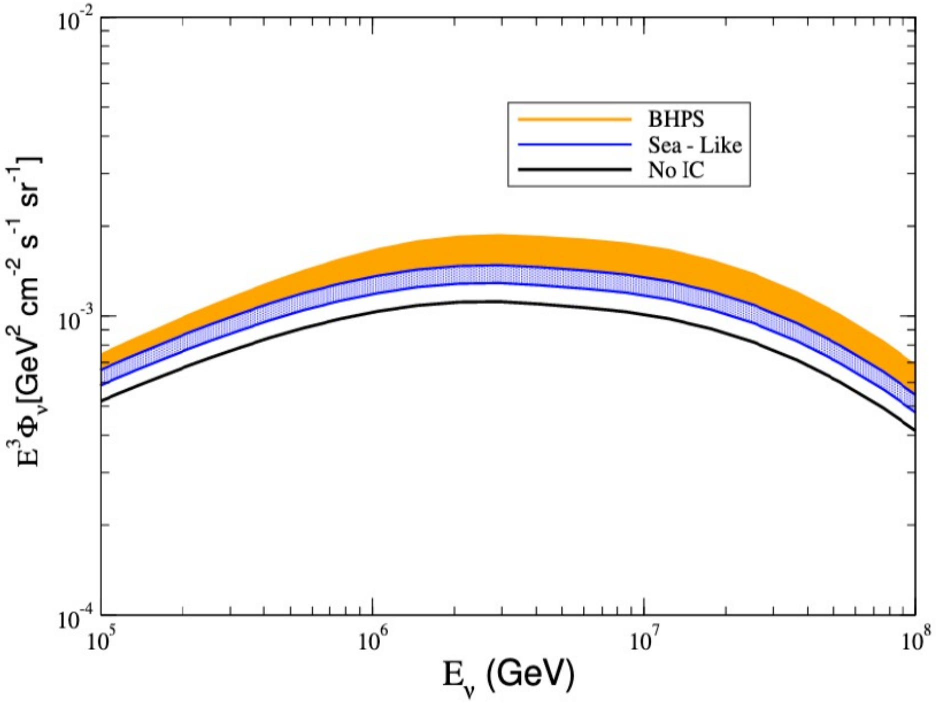
c.m.s. energy: $\sqrt{s_{NN}} = \sqrt{2m_N E_{\text{Pb}}} \approx 72\,\text{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost: $\gamma \approx 40$	



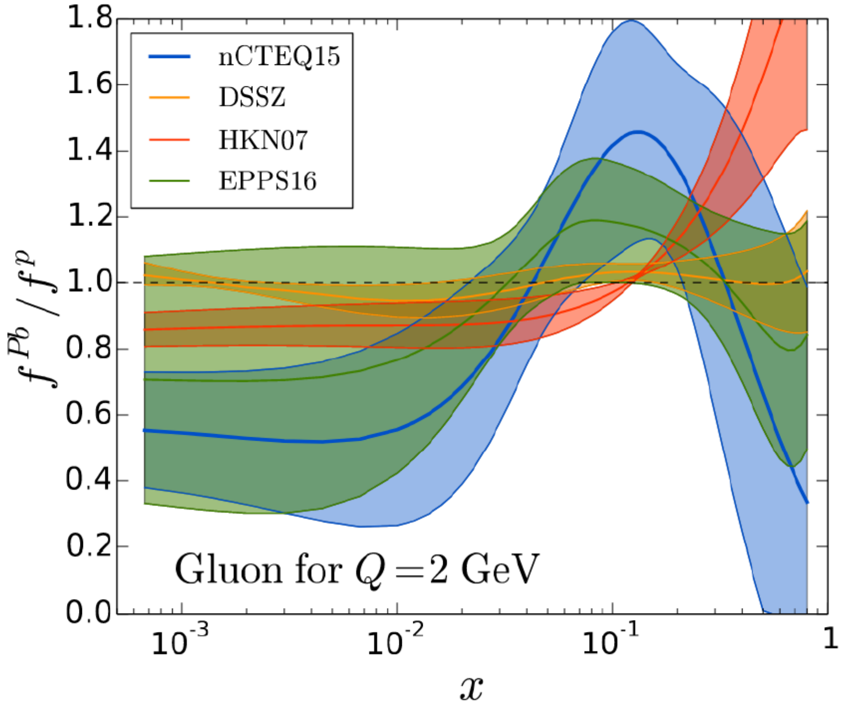
Nucleon and nuclear structure at large-x

1/ The exploration of the high-momentum (x) frontiers in nucleon and nuclei with specific emphasis on the sea quark, gluon and heavy quark content, together with implications for astrophysics

- Structure of nucleon and nuclei at high-x poorly known
- The origin of the EMC effect in nuclei is still not understood → Study a possible gluon EMC effect ?
- The Existence of a possible non-perturbative source of *c* or *b* quarks in the proton → Important for HE neutrino and CR physics



Impact of uncertainties on charm content of the proton on neutrino flux atmospheric neutrino fluxes is main background for observation of cosmic neutrino in the PEV range

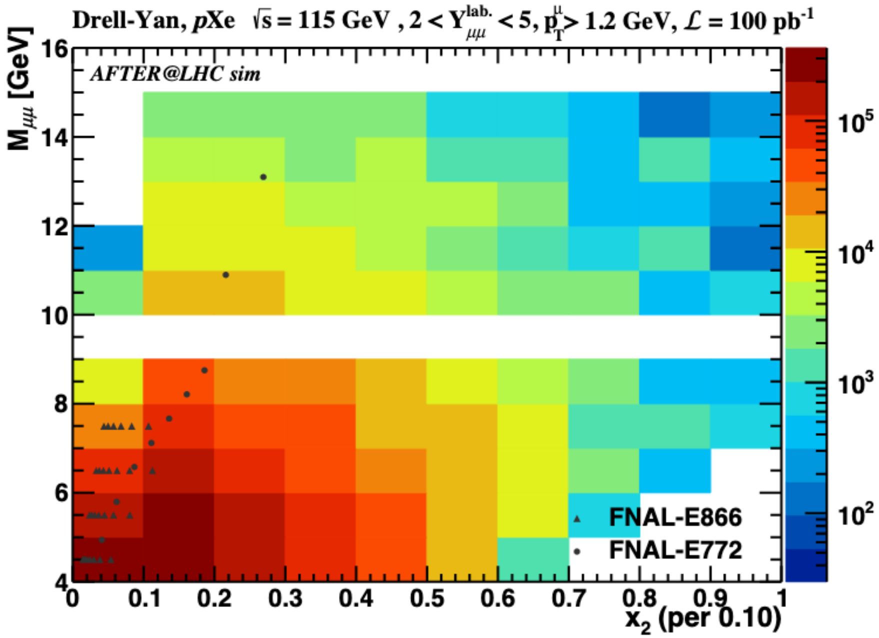


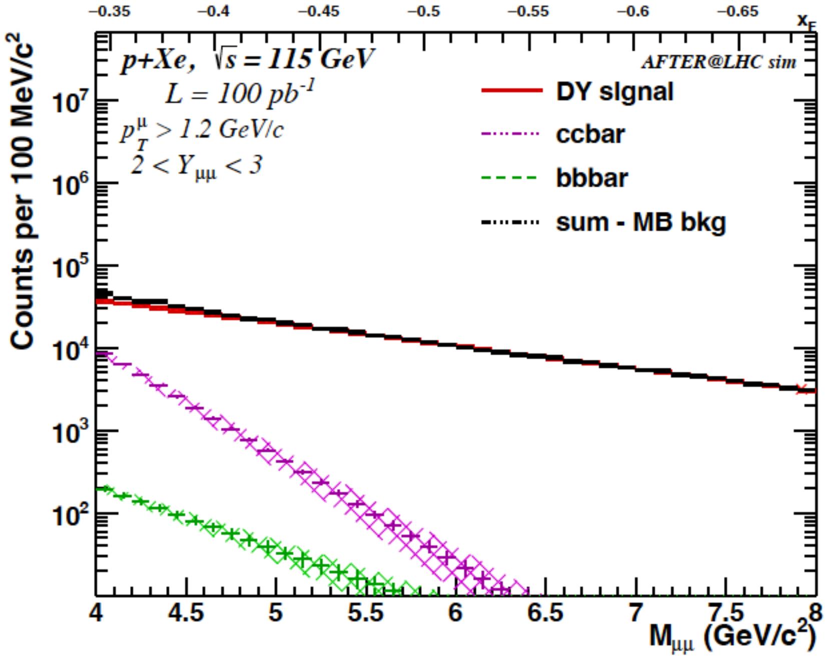
Compilation of gluon nPDFs uncertainties

→ + Explore A-dependence with several target types

Drell-Yan to probe nuclear PDFs

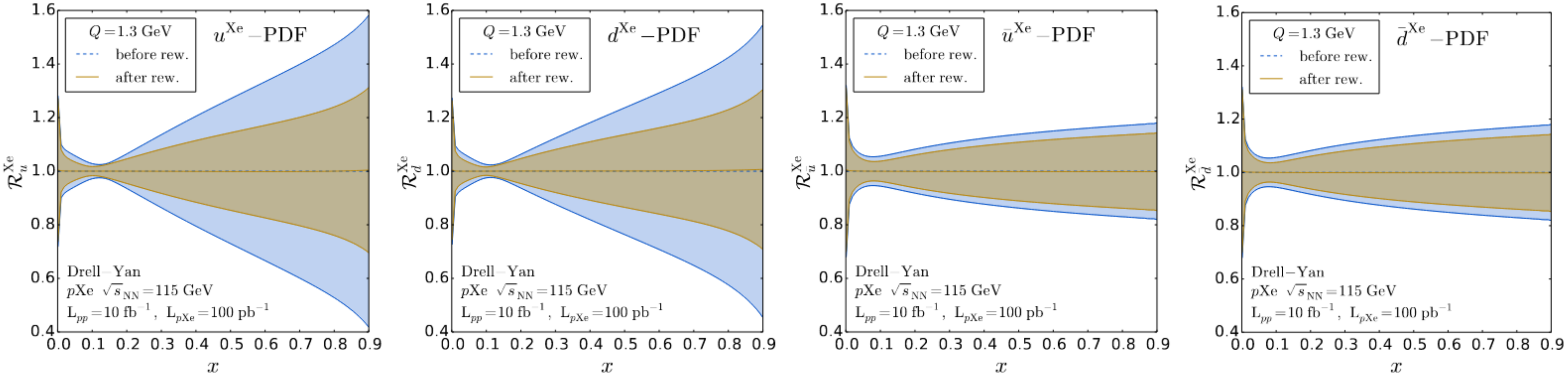
- ☐ In pA FT collisions, similar kinematic coverage as for pp case
- ☐ Unique acceptance of LHCb compared to existing DY pA data (E866 & E772 @ Fermilab) used for nPDF fit
- ☐ pXe simulation at $\sqrt{s_{NN}}$ = 115 GeV, L_{int} = 100 pb^{-1}, very large yields up to $x_2 \rightarrow 1$
- ☐ DY contribution dominates over $c\bar{c}$ and $b\bar{b}$ production at backward rapidity (com. Back subtracted via evt. mix.)





Drell-Yan to probe nuclear PDFs

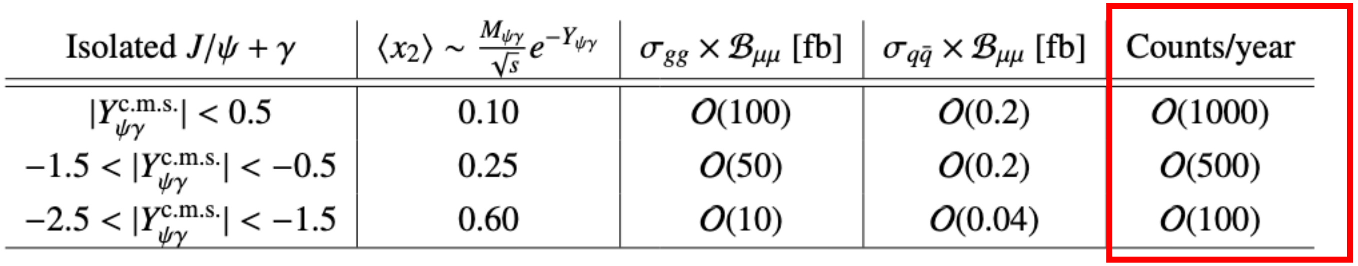
- ☐ Impact from DY measurements on nPDFs evaluating via reweighting using R_{pXe} pseudo-data $\sqrt{s_{NN}}$ = 115 GeV
- ☐ Significant decrease of nPDFs uncertainties for up and down quark at large-x



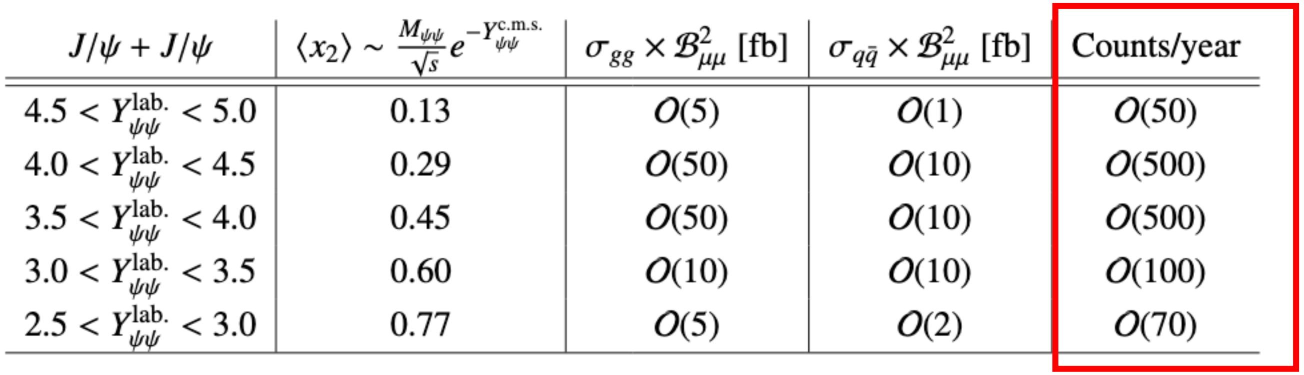
Uncertainty on nCTEQ15 nPDFs before and after reweighting using R_{pXe} pseudo-data

Associated J/**ψ**+**γ**, J/**ψ**+ J/**ψ** production and gluon PDF

- ☐ Limited knowledge of gluon PDFs for x > 0.5
- ☐ Abundant production of open heavy flavour and quarkonia expected at large-x to probe gluon PDF
- ☐ Associated J/**ψ**+**γ** and J/**ψ**+ J/**ψ** production dominated by gluon-gluon subprocess at large-x, probes requiring large luminosities, while single inclusive quarkonium production presumably dominated by heavy quark induced channels

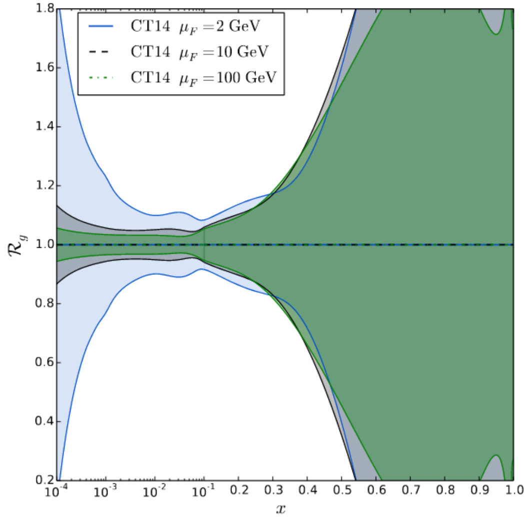


Isolated $J/\psi + \gamma$	$\langle x_2 \rangle \sim \frac{M_{\psi\gamma}}{\sqrt{s}} e^{-Y_{\psi\gamma}}$	$\sigma_{gg} \times \mathcal{B}_{\mu\mu}$ [fb]	$\sigma_{q\bar{q}} \times \mathcal{B}_{\mu\mu}$ [fb]	Counts/year
$\lvert Y^{\text{c.m.s.}}_{\psi\gamma} \rvert < 0.5$	0.10	$\mathcal{O}(100)$	$\mathcal{O}(0.2)$	$\mathcal{O}(1000)$
$-1.5 < \lvert Y^{\text{c.m.s.}}_{\psi\gamma} \rvert < -0.5$	0.25	$\mathcal{O}(50)$	$\mathcal{O}(0.2)$	$\mathcal{O}(500)$
$-2.5 < \lvert Y^{\text{c.m.s.}}_{\psi\gamma} \rvert < -1.5$	0.60	$\mathcal{O}(10)$	$\mathcal{O}(0.04)$	$\mathcal{O}(100)$



$J/\psi + J/\psi$	$\langle x_2 \rangle \sim \frac{M_{\psi\psi}}{\sqrt{s}} e^{-Y^{\text{c.m.s.}}_{\psi\psi}}$	$\sigma_{gg} \times \mathcal{B}^2_{\mu\mu}$ [fb]	$\sigma_{q\bar{q}} \times \mathcal{B}^2_{\mu\mu}$ [fb]	Counts/year
$4.5 < Y^{\text{lab.}}_{\psi\psi} < 5.0$	0.13	$\mathcal{O}(5)$	$\mathcal{O}(1)$	$\mathcal{O}(50)$
$4.0 < Y^{\text{lab.}}_{\psi\psi} < 4.5$	0.29	$\mathcal{O}(50)$	$\mathcal{O}(10)$	$\mathcal{O}(500)$
$3.5 < Y^{\text{lab.}}_{\psi\psi} < 4.0$	0.45	$\mathcal{O}(50)$	$\mathcal{O}(10)$	$\mathcal{O}(500)$
$3.0 < Y^{\text{lab.}}_{\psi\psi} < 3.5$	0.60	$\mathcal{O}(10)$	$\mathcal{O}(10)$	$\mathcal{O}(100)$
$2.5 < Y^{\text{lab.}}_{\psi\psi} < 3.0$	0.77	$\mathcal{O}(5)$	$\mathcal{O}(2)$	$\mathcal{O}(70)$

CT14nlo gluon relative PDF uncertainty in proton



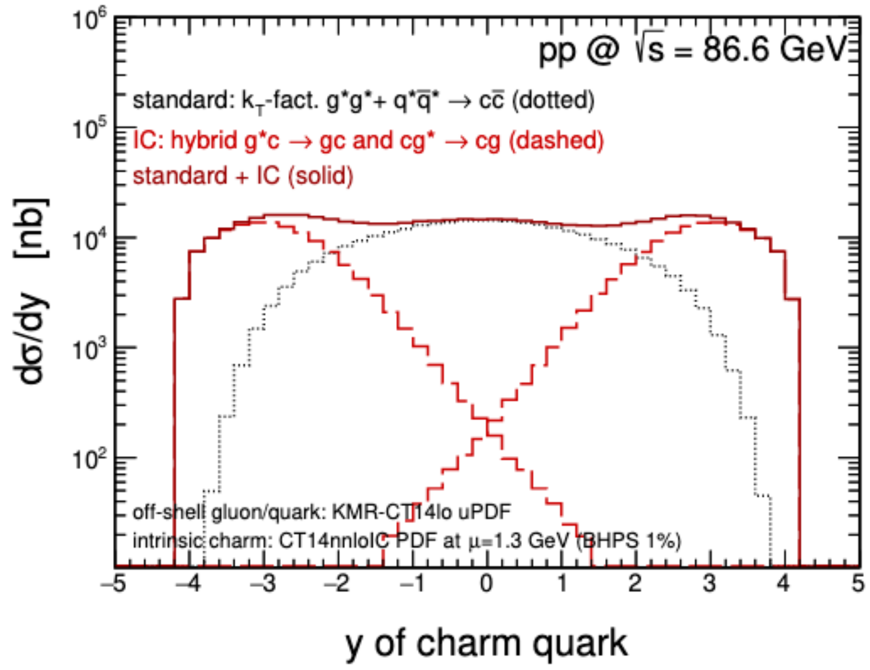
intrinsic charm in the proton

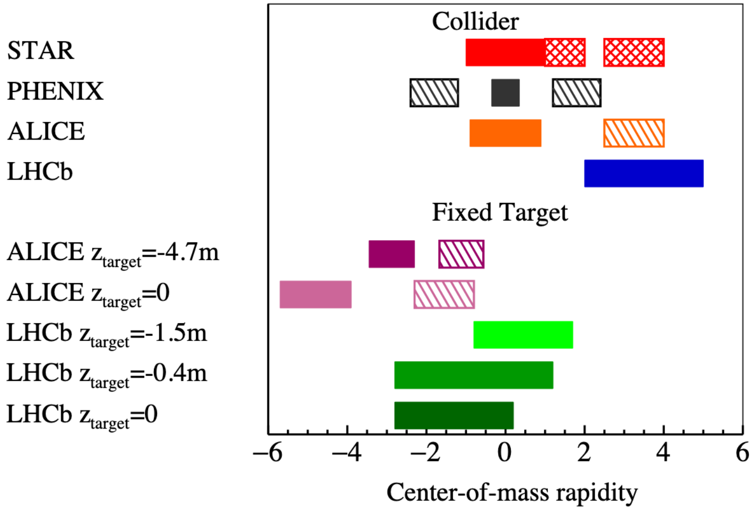
R. Maciula, talk at QCD@LHC 2022

- ❑ Search for existence of non-perturbative source of charm (and beauty) quark in nucleon and nucleus, carrying a relevant fraction of its momentum (possible evidence in Z+charm production at LHCb in pp collider mode, Giacomo Magni talk at QCD@LHC 2022)

→ Relevant for PDFs/nPDFs relying on assumption that charm and beauty PDFs pertubatively generated by gluon splitting

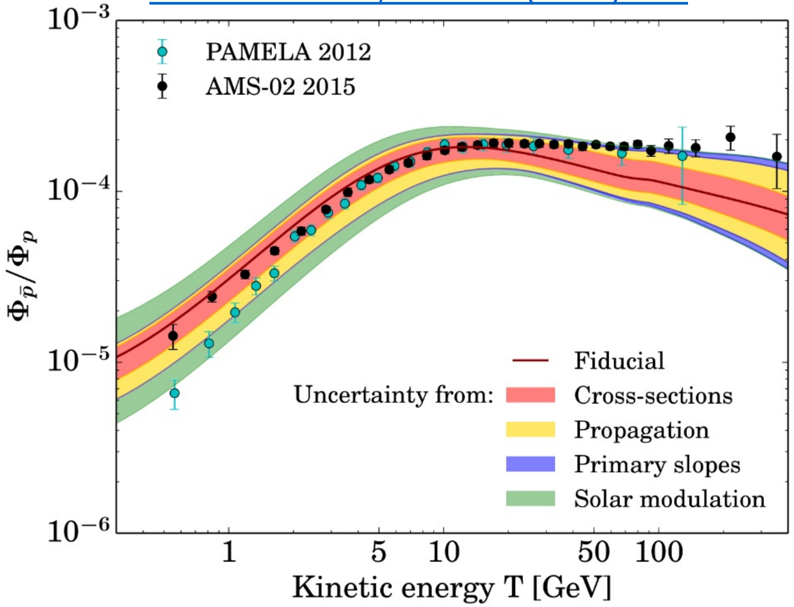
- ❑ Intrinsic charm modify the rate of several processes (eg. D mesons) at LHC energies in fixed-target mode, especially at large-x in a region where perturbative charm is suppressed



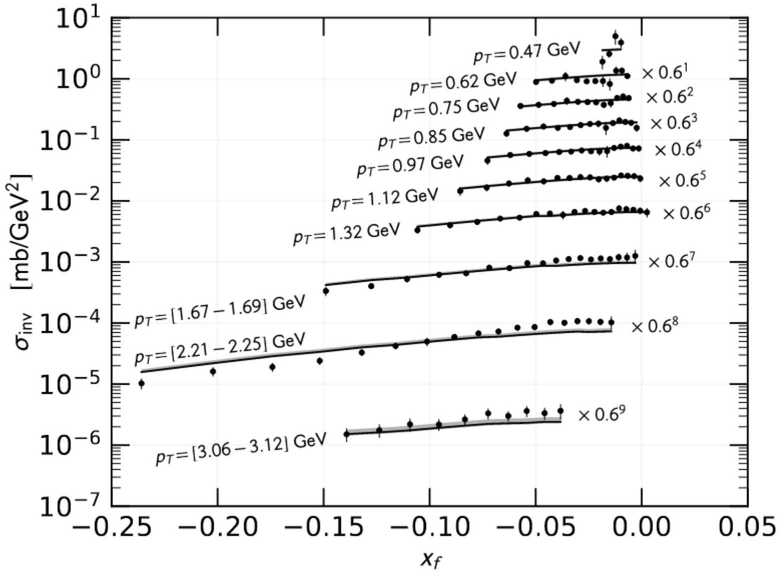


Antiproton measurements to constrain models for Dark Matter searches

G. Giesen et al., JCAP 09 (2015) 023



M. Korsmeier et al, Phys. Rev. D 97, 103019 (2018)

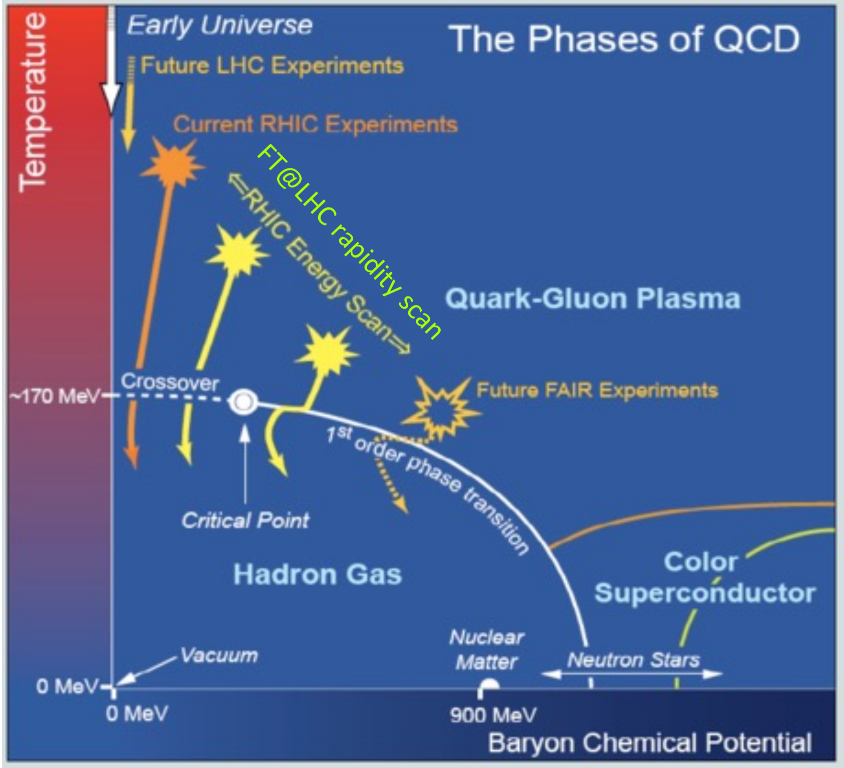


LHCb data now used to constrain models

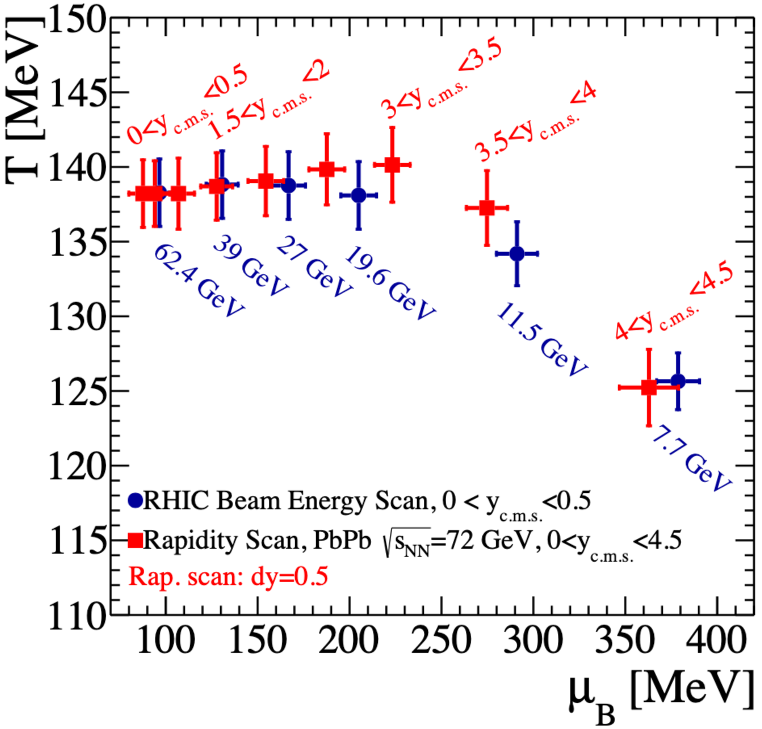
- ☐ Antiproton cross section measurements in the GeV range useful to constrain modeling of conventional astrophysical sources, which are background for Dark Matter searches
- ☐ Good precision now from AMS measurements in 1- 400 GeV range
- ☐ Need to reduce theoretical uncertainties on secondary antiproton production (created by high energy scatterings between interstellar matter and primary cosmic rays)

The study of the hot medium created in ultrarelativistic heavy-ion collisions with novel quarkonium and heavy-quark observables in a new energy domain, and with identified light hadrons down to the target-rapidity region

- Systematic studies of the medium properties with three experimental degrees of freedom : rapidity scan, different colliding systems, centrality dependence
- Rapidity scan at $\sqrt{s_{NN}}$ = 72 GeV with FT@ALICE can complement the RHIC beam energy scan from $\sqrt{s_{NN}}$ = 62.4 GeV down to 10-20 GeV
- A novel way to search for the QCD critical point and probe the nature of the phase transition to confined partons



ALICE (Z = -4.7m)

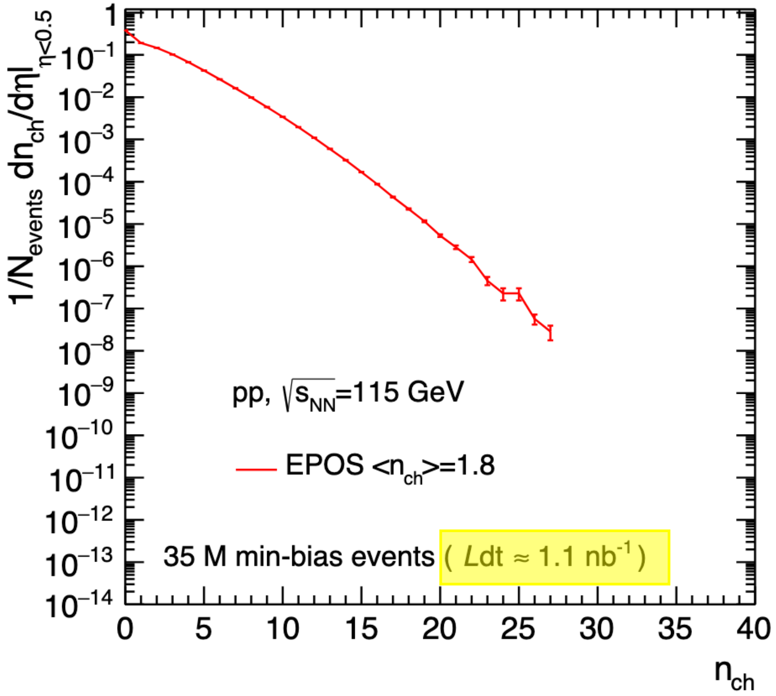


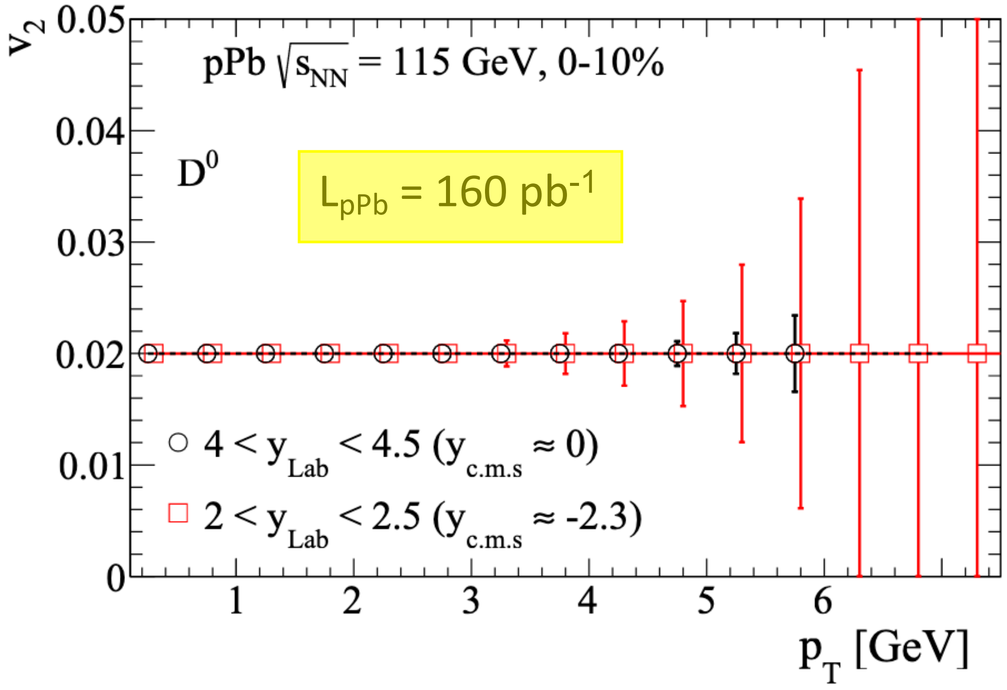
V. Begun et al., Phys. Rev. C98 n°3 (2018) 034905

+ collectivity in small systems with heavy quarks, factorization of CNM effects from pA to AA with Drell-Yan…

Search for collectivity in small systems at low energy

- ☐ Order of magnitude luminosity larger than at RHIC → access to very high multiplicity events in pH collisions
- ☐ With $L_{int} = 1.1\ nb^{-1}$, reaching already events with 15 times the average pp multiplicity (MPI + collective studies for heavy quarks)
- ☐ Statistical precision on the D^0 meson v_2 in pPb at $\sqrt{s_{NN}} = 115$ GeV already at the sub-percent level for $p_T < 3$ GeV/c

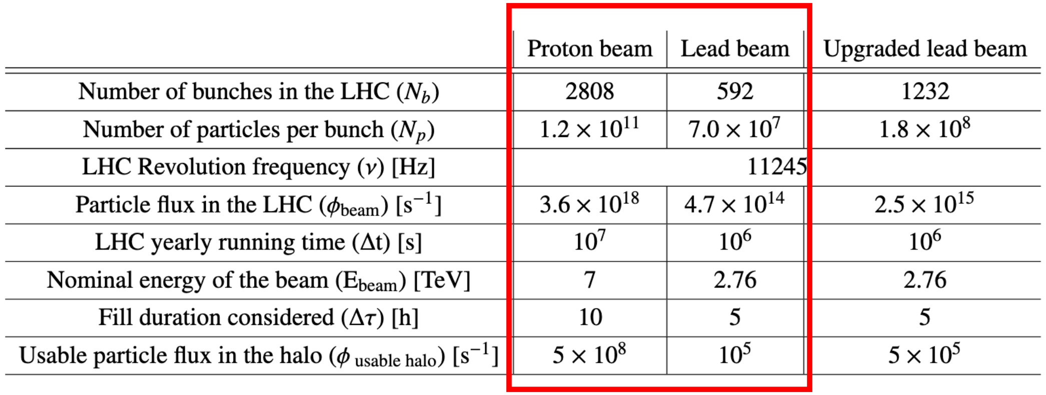




Back up

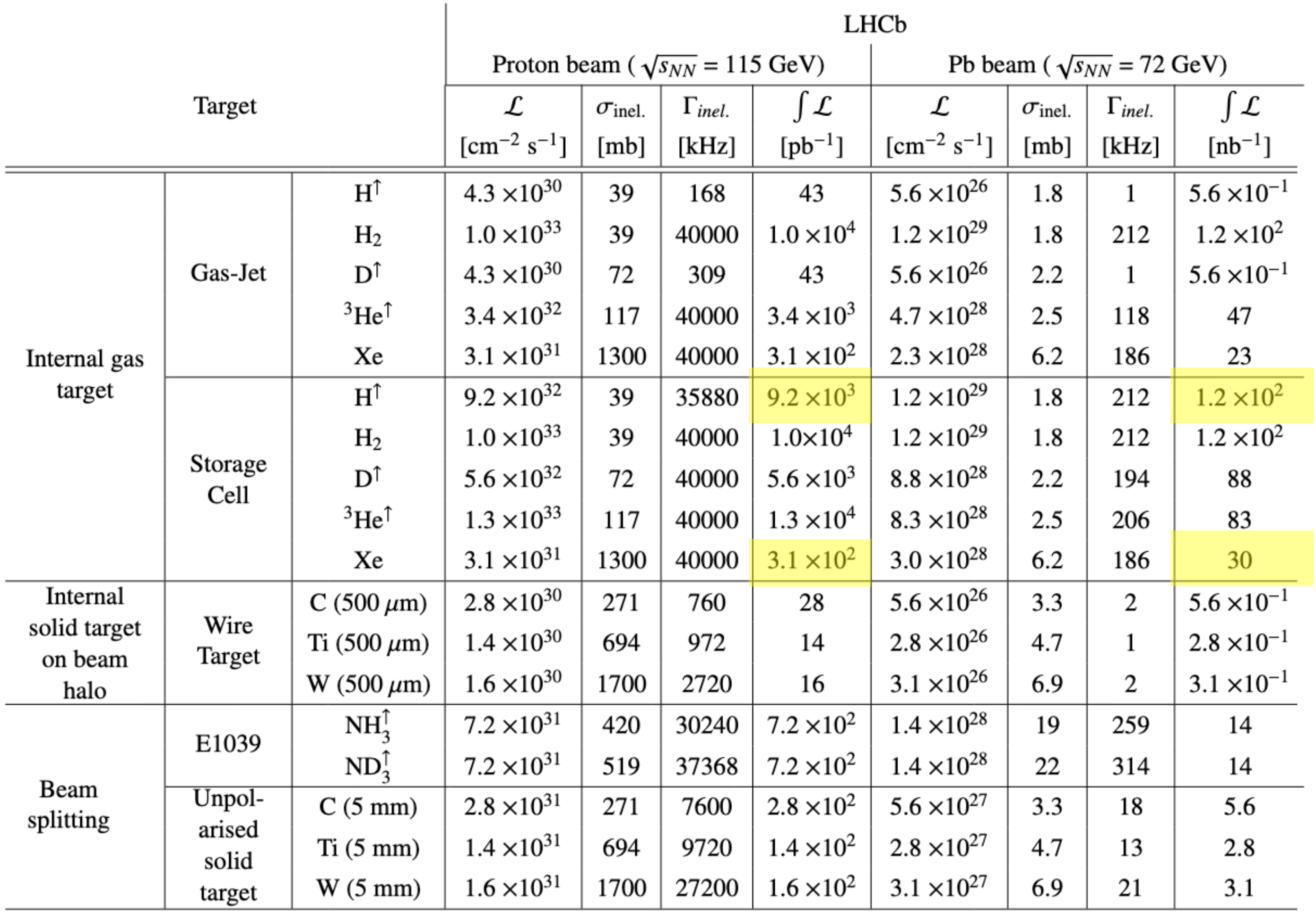
Considerations about luminosities

- ☐ LHC parameters assumptions for the computation of the beam flux on target



	Proton beam	Lead beam	Upgraded lead beam
Number of bunches in the LHC (N_b)	2808	592	1232
Number of particles per bunch (N_p)	1.2×10^{11}	7.0×10^{7}	1.8×10^{8}
LHC Revolution frequency (ν) [Hz]	11245		
Particle flux in the LHC (ϕ_{beam}) [s^{-1}]	3.6×10^{18}	4.7×10^{14}	2.5×10^{15}
LHC yearly running time (Δt) [s]	10^{7}	10^{6}	10^{6}
Nominal energy of the beam (E_{beam}) [TeV]	7	2.76	2.76
Fill duration considered ($\Delta\tau$) [h]	10	5	5
Usable particle flux in the halo ($\phi_{\text{usable halo}}$) [$s^{-1}$]	5×10^{8}	10^{5}	5×10^{5}

- ☐ 1m long storage cell
- ☐ Gas flux levelled with Pb beam (considering no more than a 15% consumption of the beam)
- ☐ Assuming 40MHz max interaction rate in pp and 5MHz in PbPb for LHCb
- ☐ Max yearly luminosity reachable : L_{int} pH = 10 fb^{-1}, L_{int} pXe = 310 pb^{-1}, L_{int} PbH = 120 nb^{-1}, L_{int} PbXe = 30 nb^{-1}
- ☐ SMOG2 expectations: L_{int} pH = 150 pb^{-1}, L_{int} pXe = 22 pb^{-1}, L_{int} PbH = 10 nb^{-1}, L_{int} PbAr = 60 nb^{-1}



Target			LHCb							
			Proton beam ($\sqrt{s_{NN}}$ = 115 GeV)				Pb beam ($\sqrt{s_{NN}}$ = 72 GeV)			
			$\mathcal{L}$ [$cm^{-2}\ s^{-1}$]	$\sigma_{\text{inel.}}$ [mb]	$\Gamma_{inel.}$ [kHz]	$\int \mathcal{L}$ [pb^{-1}]	$\mathcal{L}$ [$cm^{-2}\ s^{-1}$]	$\sigma_{\text{inel.}}$ [mb]	$\Gamma_{inel.}$ [kHz]	$\int \mathcal{L}$ [nb^{-1}]
Internal gas target	Gas-Jet	$H^{\uparrow}$	4.3×10^{30}	39	168	43	5.6×10^{26}	1.8	1	5.6×10^{-1}
		H_2	1.0×10^{33}	39	40000	1.0×10^{4}	1.2×10^{29}	1.8	212	1.2×10^{2}
		$D^{\uparrow}$	4.3×10^{30}	72	309	43	5.6×10^{26}	2.2	1	5.6×10^{-1}
		$^3He^{\uparrow}$	3.4×10^{32}	117	40000	3.4×10^{3}	4.7×10^{28}	2.5	118	47
		Xe	3.1×10^{31}	1300	40000	3.1×10^{2}	2.3×10^{28}	6.2	186	23
	Storage Cell	$H^{\uparrow}$	9.2×10^{32}	39	35880	9.2×10^{3}	1.2×10^{29}	1.8	212	1.2×10^{2}
		H_2	1.0×10^{33}	39	40000	1.0×10^{4}	1.2×10^{29}	1.8	212	1.2×10^{2}
		$D^{\uparrow}$	5.6×10^{32}	72	40000	5.6×10^{3}	8.8×10^{28}	2.2	194	88
		$^3He^{\uparrow}$	1.3×10^{33}	117	40000	1.3×10^{4}	8.3×10^{28}	2.5	206	83
		Xe	3.1×10^{31}	1300	40000	3.1×10^{2}	3.0×10^{28}	6.2	186	30
Internal solid target on beam halo	Wire Target	C (500 μm)	2.8×10^{30}	271	760	28	5.6×10^{26}	3.3	2	5.6×10^{-1}
		Ti (500 μm)	1.4×10^{30}	694	972	14	2.8×10^{26}	4.7	1	2.8×10^{-1}
		W (500 μm)	1.6×10^{30}	1700	2720	16	3.1×10^{26}	6.9	2	3.1×10^{-1}
Beam splitting	E1039	$NH_3^{\uparrow}$	7.2×10^{31}	420	30240	7.2×10^{2}	1.4×10^{28}	19	259	14
		$ND_3^{\uparrow}$	7.2×10^{31}	519	37368	7.2×10^{2}	1.4×10^{28}	22	314	14
	Unpol-arised solid target	C (5 mm)	2.8×10^{31}	271	7600	2.8×10^{2}	5.6×10^{27}	3.3	18	5.6
		Ti (5 mm)	1.4×10^{31}	694	9720	1.4×10^{2}	2.8×10^{27}	4.7	13	2.8
		W (5 mm)	1.6×10^{31}	1700	27200	1.6×10^{2}	3.1×10^{27}	6.9	21	3.1

Spin and 3D nucleon structure

❑ **Advance our understanding of the dynamics and spin of quarks and gluons inside (un)polarised nucleons**

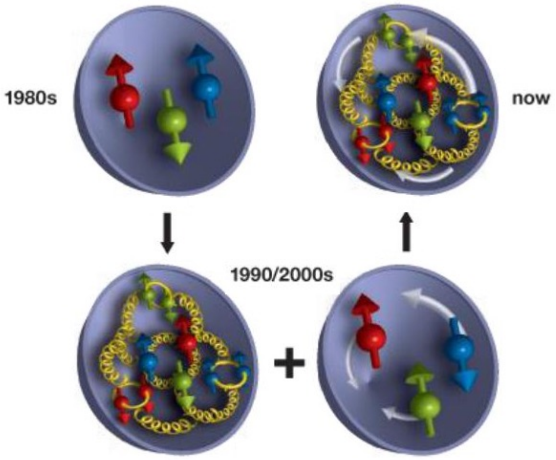
- ➢ From the spin crisis to the spin puzzle
- ➢ For longitudinally polarised nucleon, with helicity +1/2:

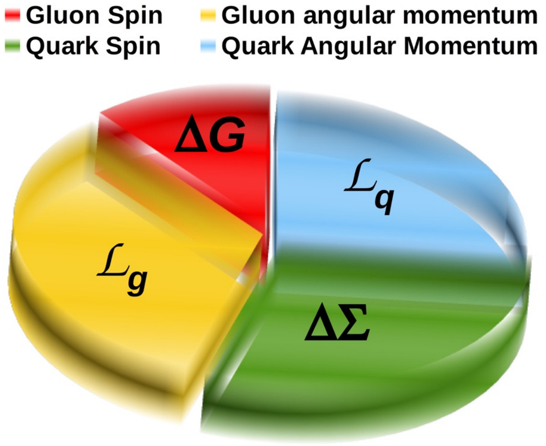
$$\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G+\underbrace{\ell_g+\ell_q}$$

Spin of quarks and antiquarks

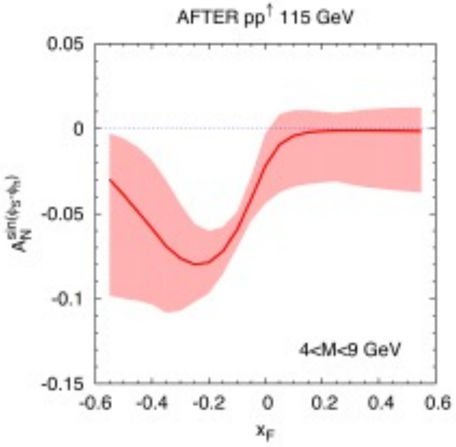
Spin of gluons

Orbital angular momentum of quarks and gluons





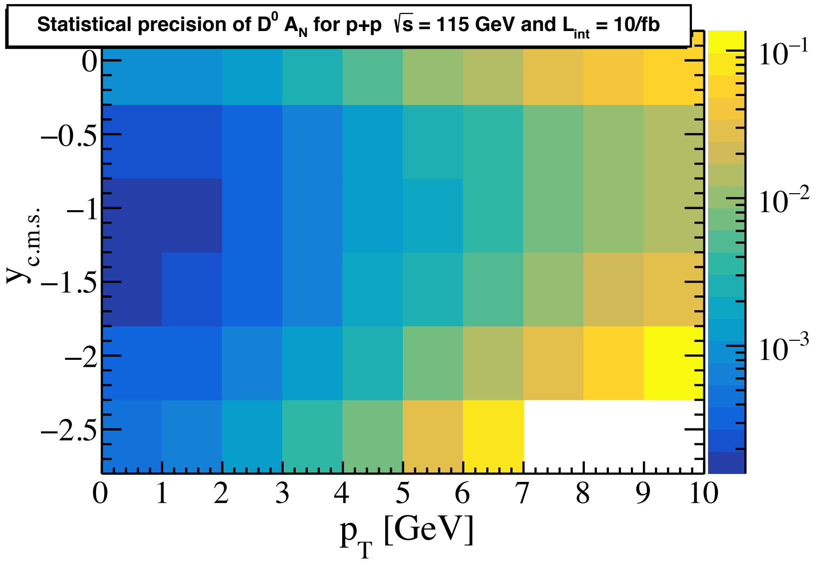
M. Anselmo, Feb. 2013(Courtesy U. d'Alessio)

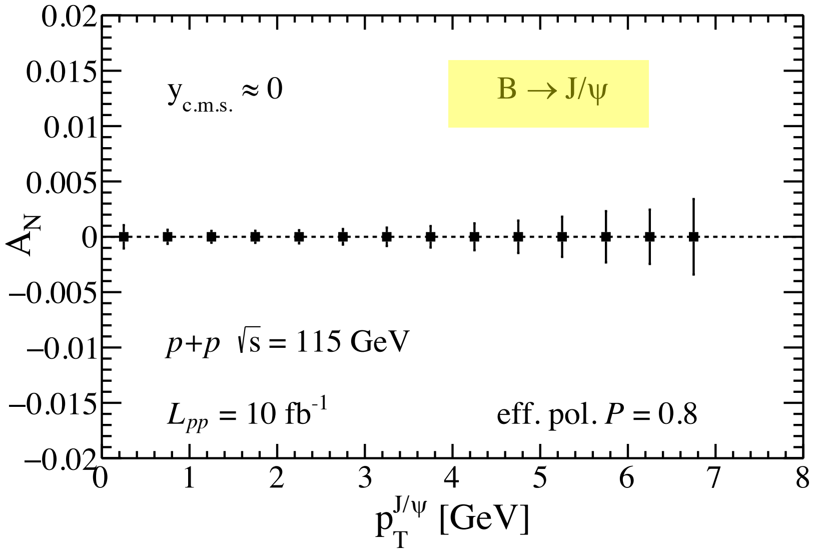


- ➢ First hint by COMPASS that $\ell_g \neq 0$
- ➢ Access information on the orbital motion of the partons inside bound hadrons via Single Spin Asymmetries (Sivers effect)
  - Sivers effects : correlation between the parton transverse momentum k_T and the proton spin
    - Gluon Sivers effect at large x_F with gluon sensitive probes
    - Quark Sivers effect at large x_F with Drell-Yan
- ➢ Test TMD factorization formalism → sign change of A_N between SIDIS and DY

Probing the gluon Sivers effect: Open Heavy Flavours

- **Gluon Sivers effect: correlation between the gluon transverse momentum k_T and the proton spin**
- No analogous process to DY to probe the gluon content, being both experimentally clean and theoretically well-controlled
- Large yields in FT@LHC for several gluon sensitive probes (Open HF, quarkonia ~ 10^6 Υ and 10^9 J/Ψ per year)
- Gluon TMDs more « universal », gluon Sivers functions can be reduced to 2 independent ones

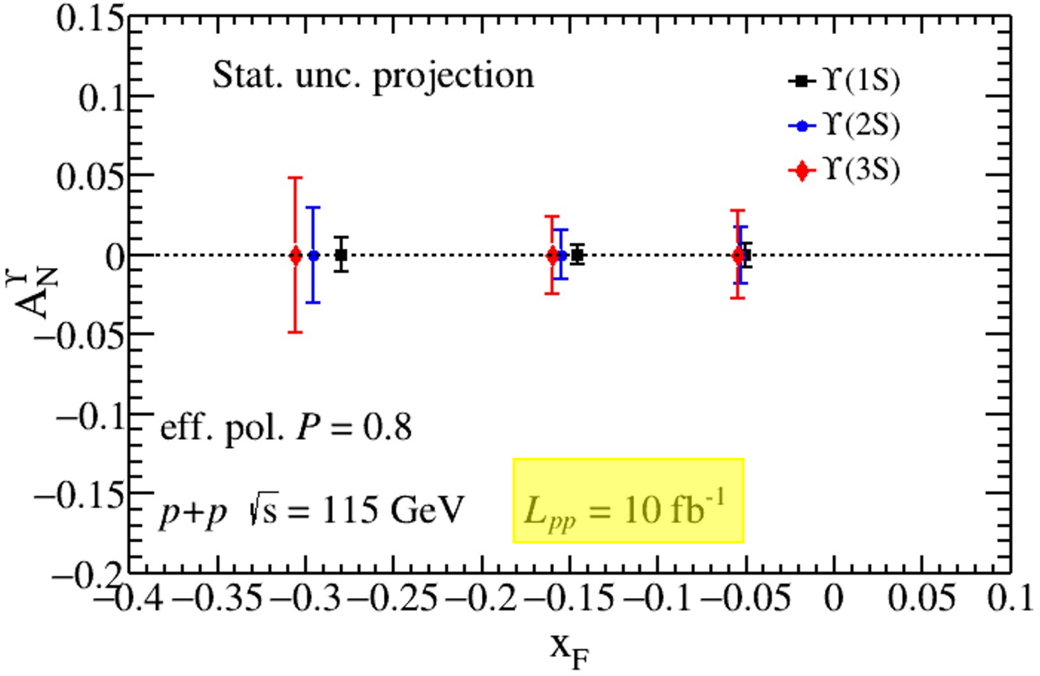


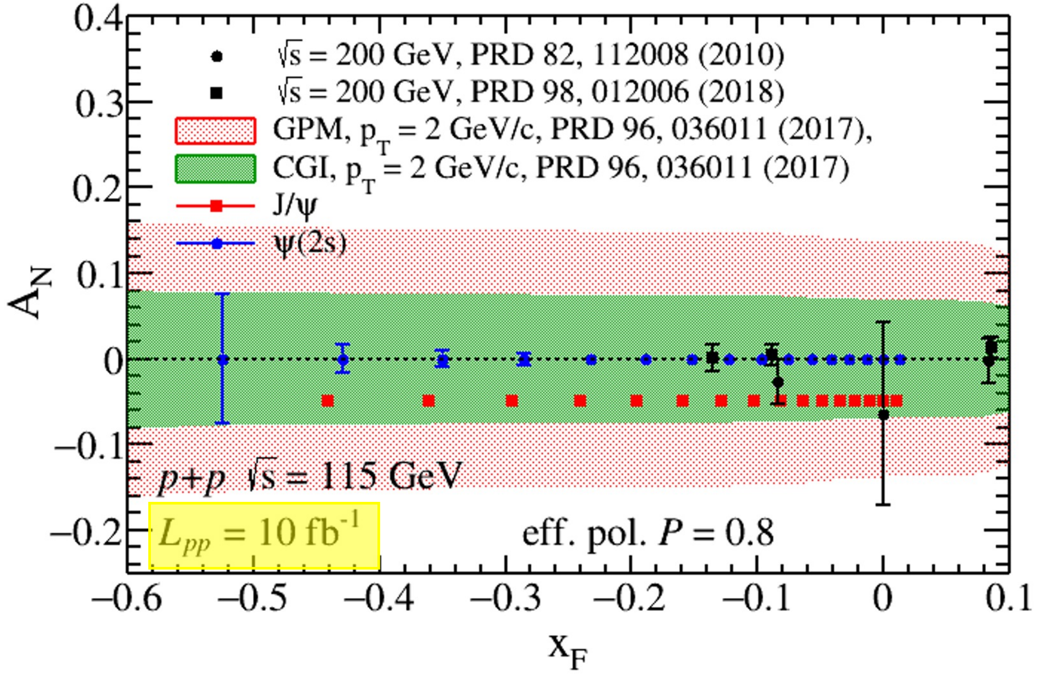


- « LHCb-like detector », precision at percent level on D^0 A_N for $p_T \leq 5$ GeV/c, similar conclusion for B → J/ψ

Probing the gluon sivers effect: Quarkonium

- ❑ Measurement of bottomonium A_N statistically doable with FT@LHC
- ❑ Large charmonium yields → precise access to gluon content of the proton over a much wider x-range than at RHIC
- ❑ Several possible explanations for current A_N measurements compatible with zero (gluon Sivers function might be zero, J/Ψ production mechanism via colour-octet transitions…) → new precise measurements needed





- ❑ Comparison with 2 models ; Generalised parton model (GPM), Color Gauge invariant version of GPM model (CGI)
- ❑ Study can be extended to : C-even quarkonium (access to tri-gluon correlation functions with η_c)
  Quarkonium associated production (TMD evolution by tuning the mass of the final state)

Exclusive quarkonium photoproduction to probe the GPDs

- Exclusive photoproduction studied in « UPC » probes the internal structure of hadrons in terms of GPDs → related to the OAM carried by quarks and gluons via Ji’s sum rule

- Exclusive J/Ψ production sensitive to gluon GPDs, STSA sensitive to yet unknown GPD E_g (importance piece of spin sum rule)

- Enough precision at FT@LHC to perform a first extraction of E_g