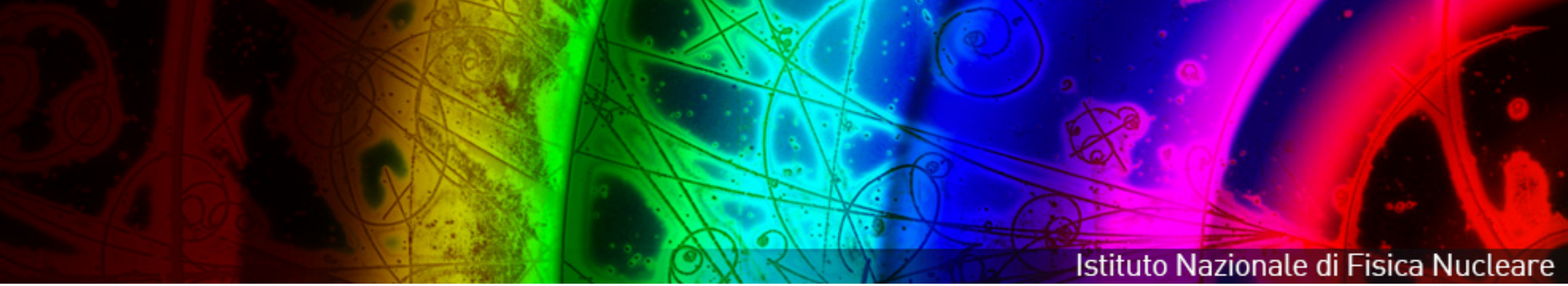


LHCb fixed target results and prospects

Pasquale Di Nezza

INFN LNF Istituto Nazionale di Fisica Nucleare

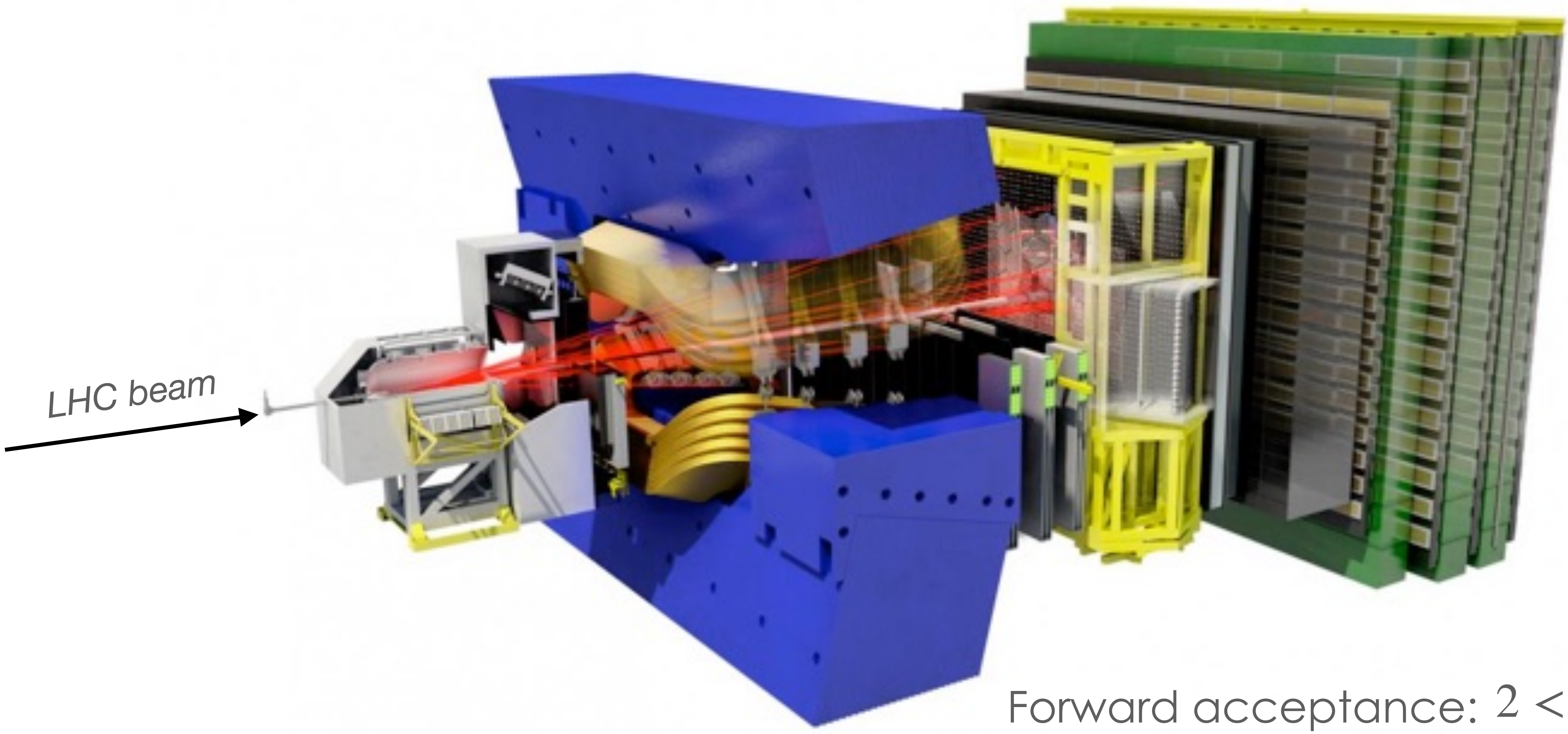
on behalf of LHCb

IS2019 NYC

26/06/19

LHCb, a single-arm forward spectrometer perfectly suited for fixed target collisions

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



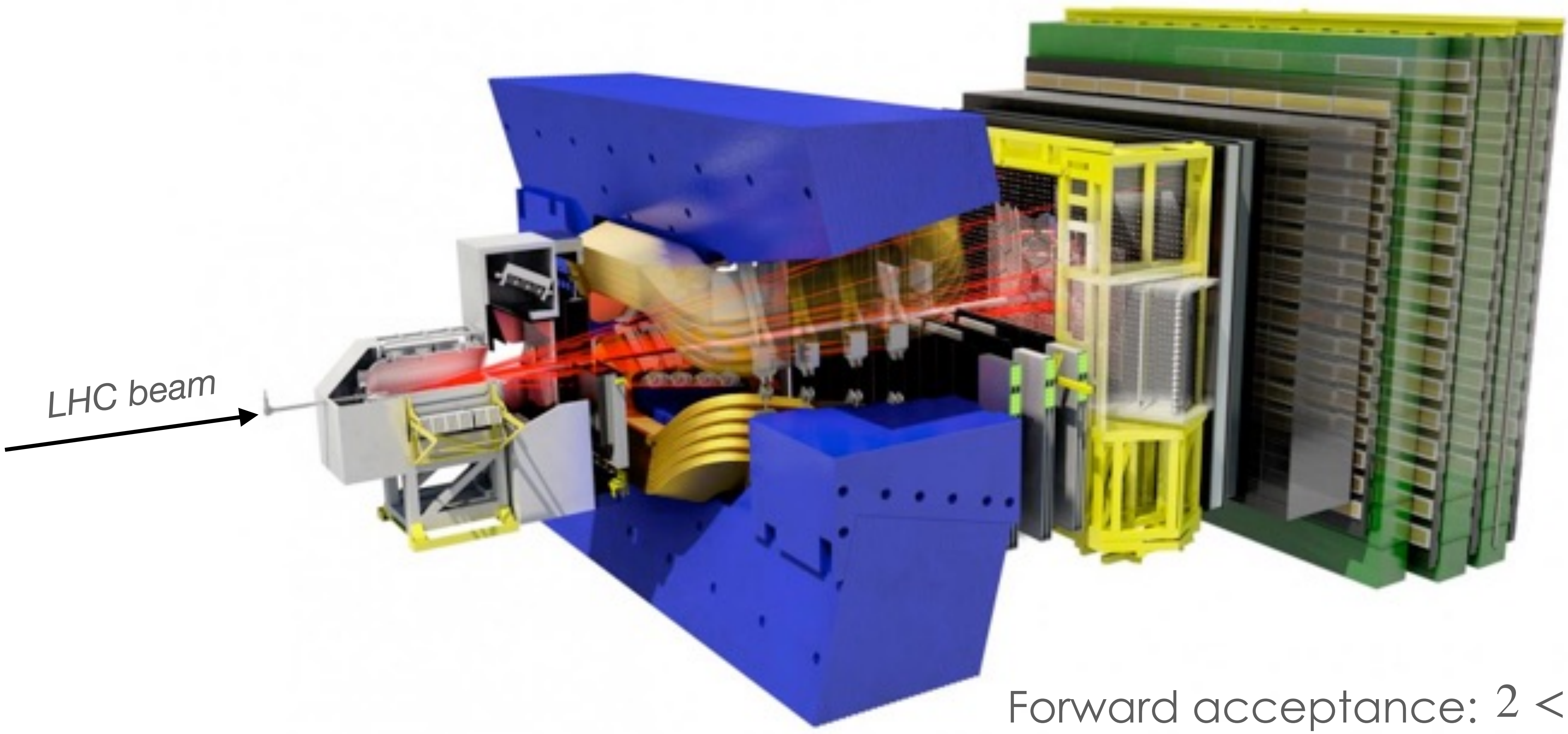
Forward acceptance: $2 < \eta < 5$

Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

optimised for studying particles containing c- and b-quarks

LHCb, a single-arm forward spectrometer perfectly suited for fixed target collisions

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



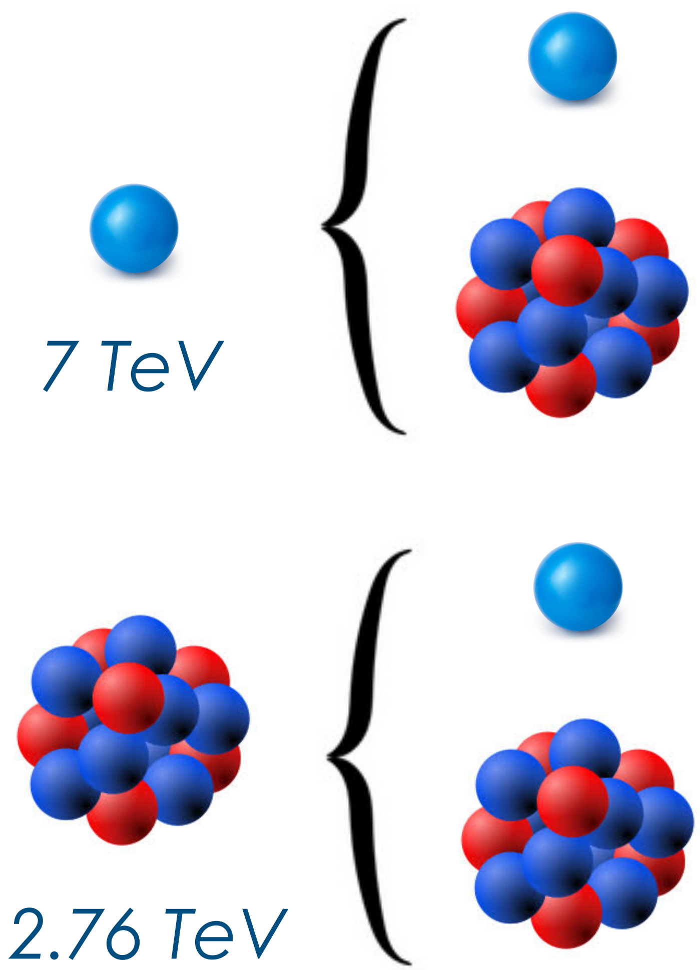
Forward acceptance: $2 < \eta < 5$

Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

optimised for studying particles containing c- and b-quarks

LHCb is the only experiment able to run both in collider and in <u>fixed-target</u> mode

Kinematics on fixed target



pp or pA collisions: 7 TeV beam on fixed target

$$\sqrt{s} = \sqrt{2m_N E_p} \simeq 115\ GeV$$

$$-3.0 \leq y_{CMS} \leq 0 \ \rightarrow \ 2 \leq y_{lab} \leq 5$$

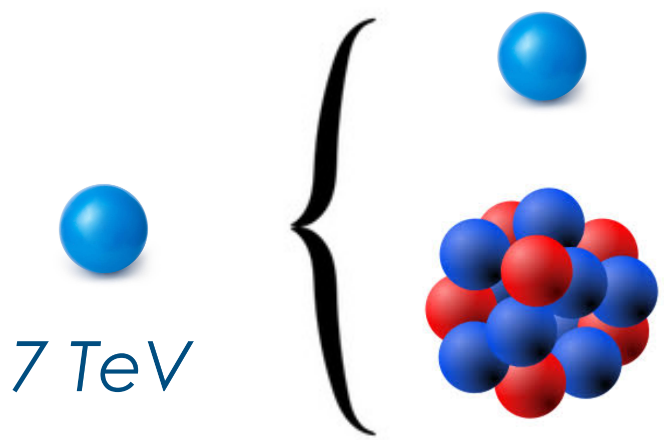
between SPS & RHIC

AA collisions: 2.76 TeV beam on fixed target

$$\sqrt{s_{NN}} \simeq 72\ GeV$$

$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

Kinematics on fixed target

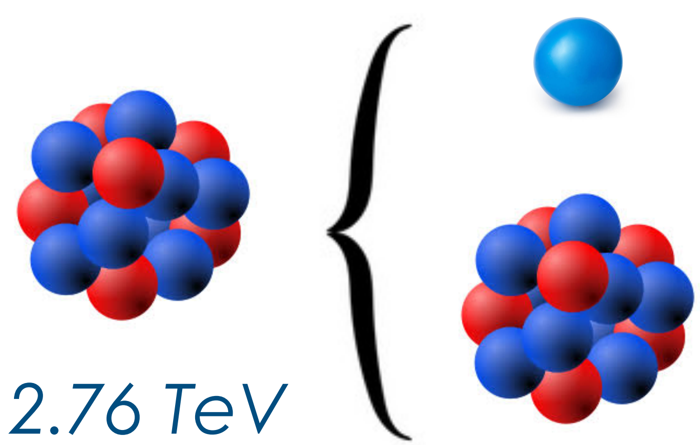


pp or pA collisions: 7 TeV beam on fixed target

$$\sqrt{s} = \sqrt{2m_N E_p} \simeq 115\ GeV$$

$$-3.0 \leq y_{CMS} \leq 0 \ \rightarrow \ 2 \leq y_{lab} \leq 5$$

between SPS & RHIC



AA collisions: 2.76 TeV beam on fixed target

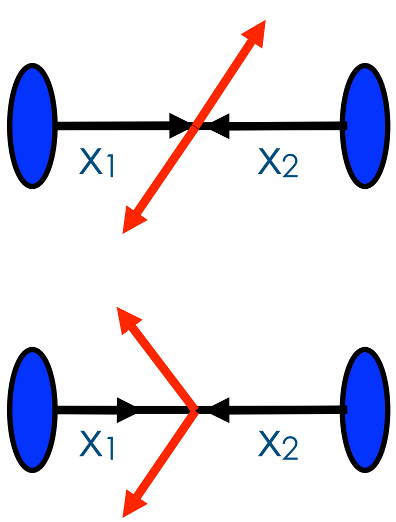
$$\sqrt{s_{NN}} \simeq 72\ GeV$$

$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

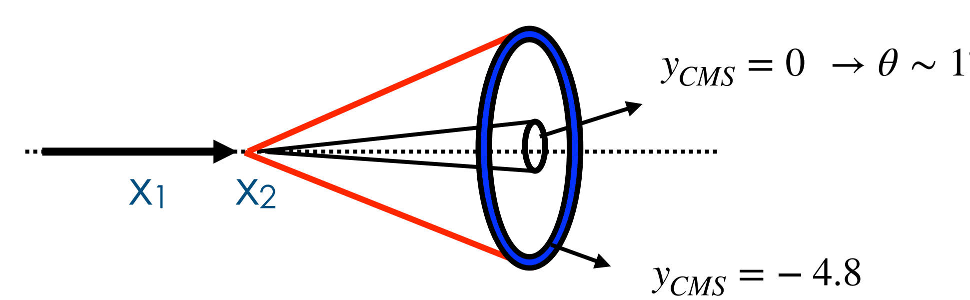
Boost effect $\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$ → access to large x_2 physics (x_F<0)

$x_1 \sim x_2$

$x_1 << x_2$



CMS → **Target rest frame**

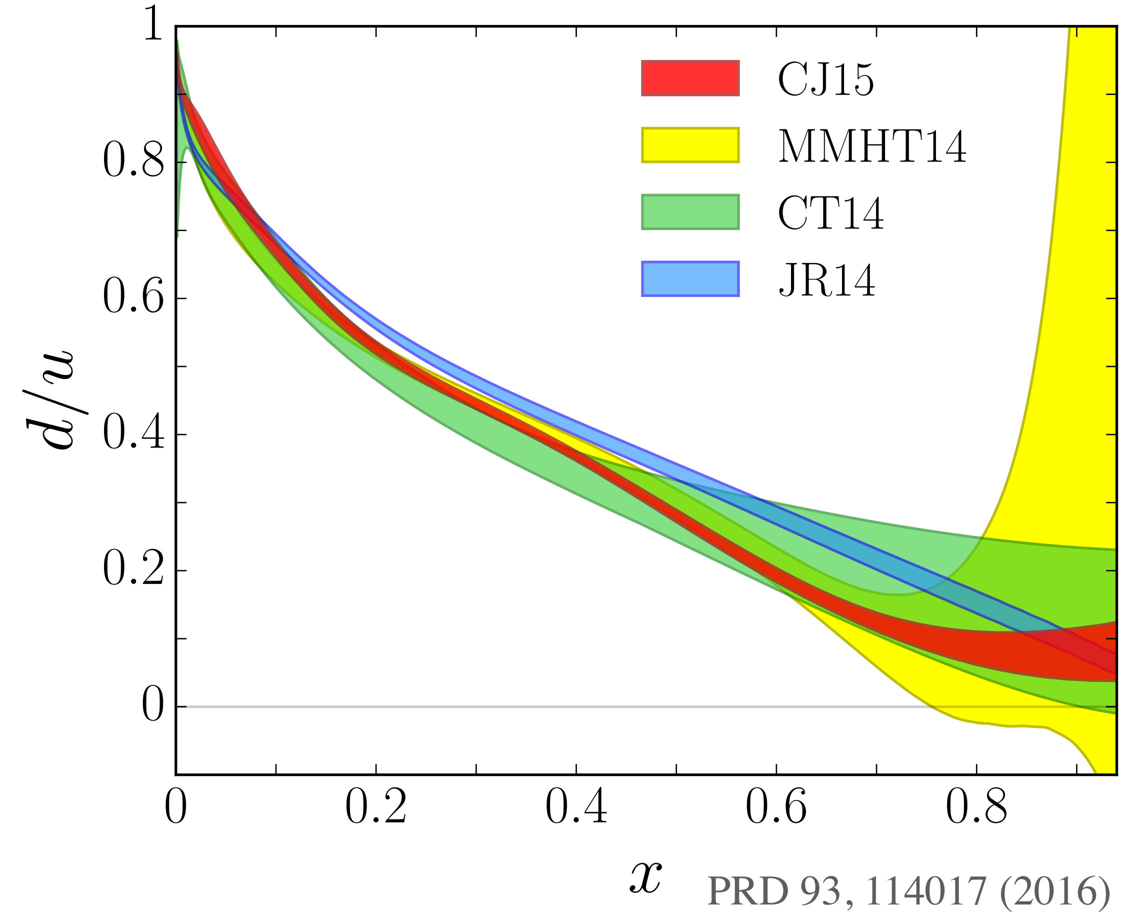


Physics Motivations
(non exhaustive list)

High-x physics

Smaller uncertainty could better constraint models on hadron structure, e.g. for x—>1

- d/u —> 1/2 : SU(6) spin-flavour symmetry
- d/u —> 0 : scalar diquark dominance
- d/u —> 1/5 : pQCD power counting
- d/u —> 0.42 : local quark-hadron duality

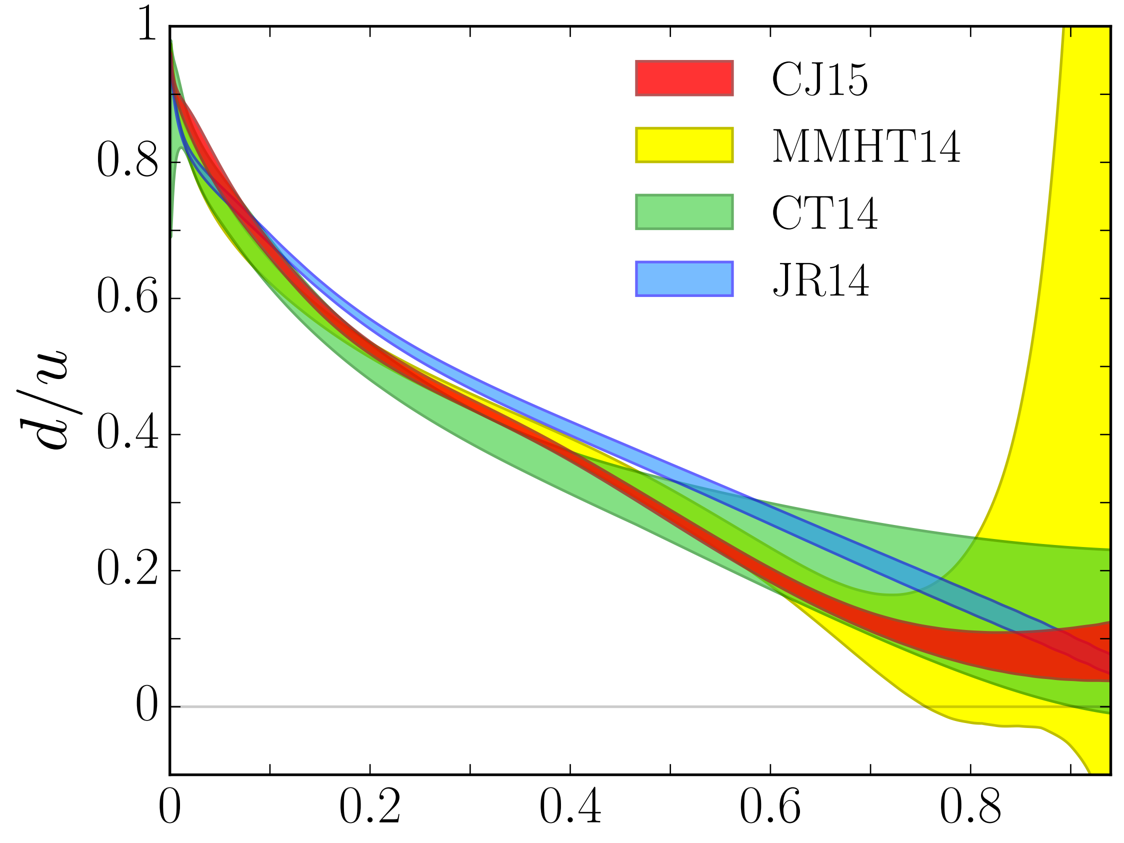


PRD 93, 114017 (2016)

High-x physics

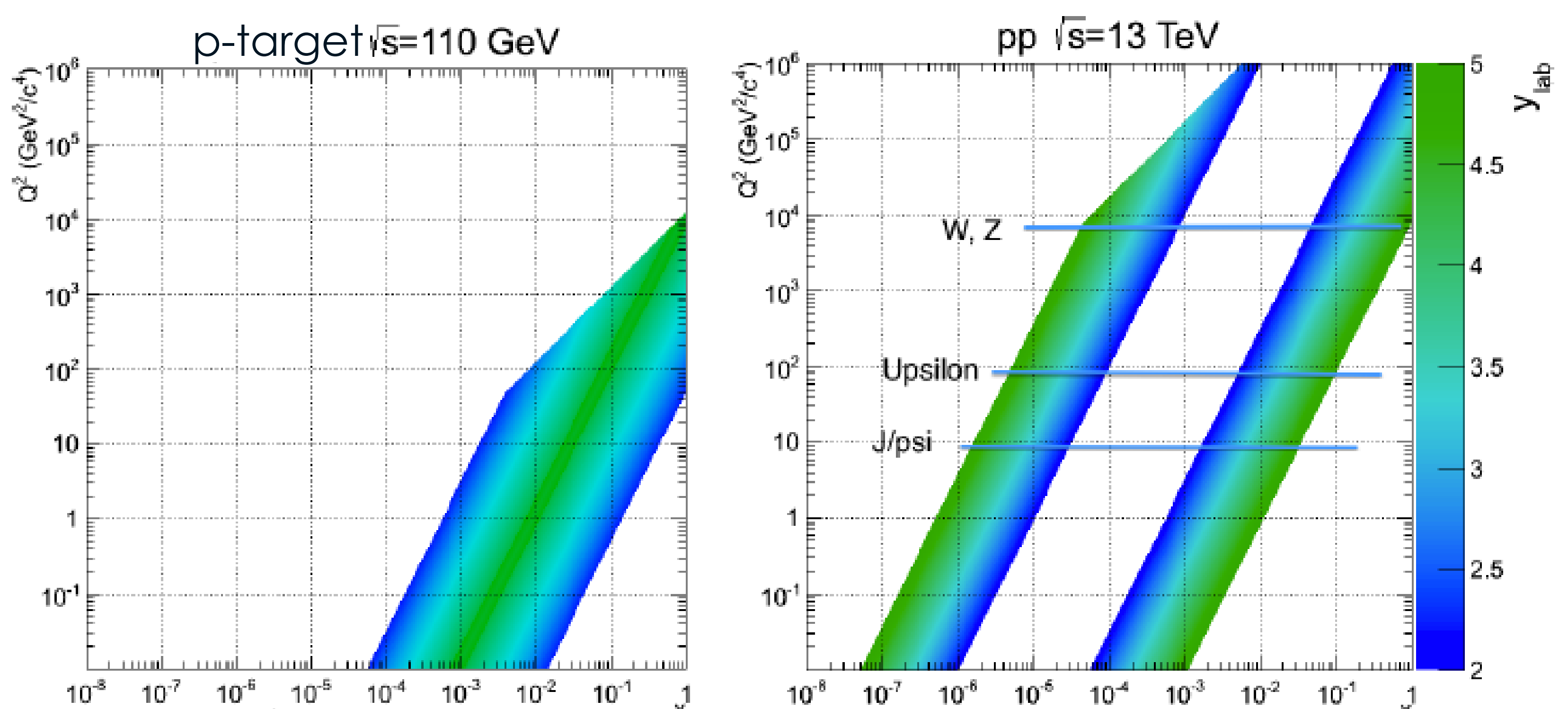
Smaller uncertainty could better constraint models on hadron structure, e.g. for x—>1

- d/u —> 1/2 : SU(6) spin-flavour symmetry
- d/u —> 0 : scalar diquark dominance
- d/u —> 1/5 : pQCD power counting
- d/u —> 0.42 : local quark-hadron duality



PRD 93, 114017 (2016)

At the LHC fixed target pp, pA, Pb-p or Pb-A collisions one has unique kinematic conditions at the poorly explored energy of √s ~ 100 GeV

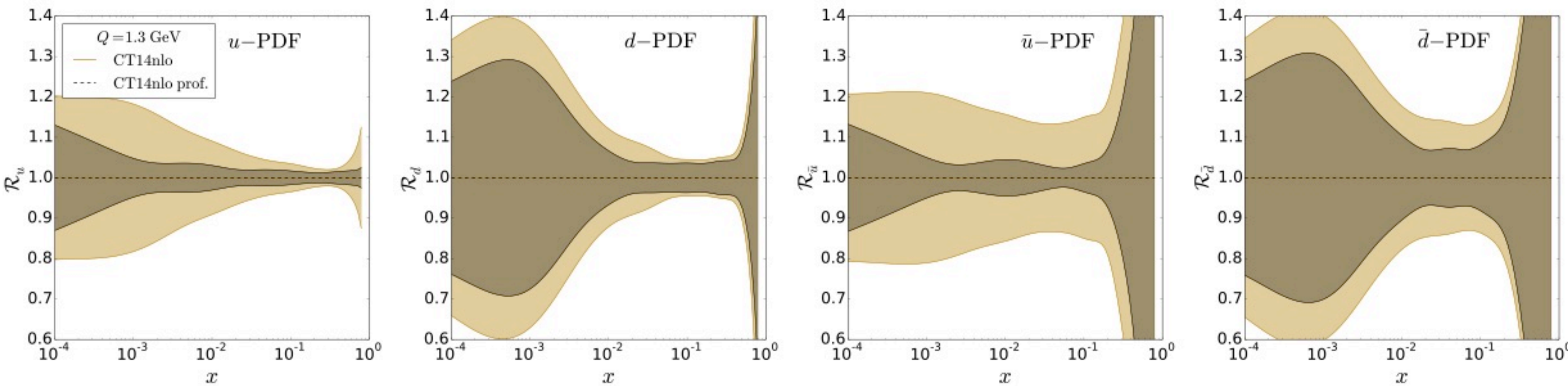


Fermi motion in the nucleus can allow to access the exotic $x > 1$ region, where parton dynamics depends on the interaction between the nucleons within the nucleus.

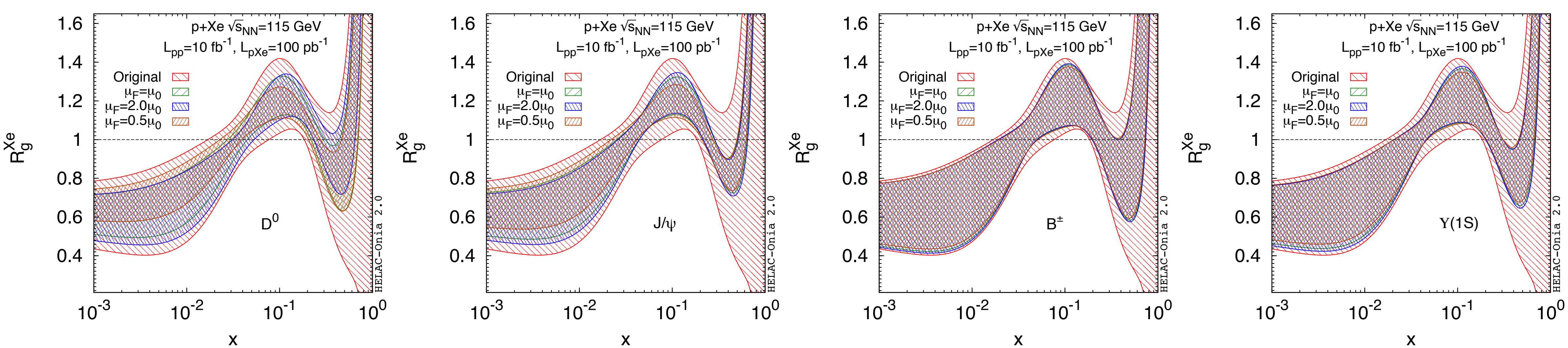
A bridge between QCD and nuclear physics

Parton Distribution Functions

arXiv:1807.00603



PDF



nPDF (gluon)

Substantial improvement of the uncertainties

estimation with 10 fb^{-1}

- Intrinsic heavy-quark:

-recent global QCD analyses support the existence of non-perturbative intrinsic charm

-5-quark Fock state (uudQQ) of the proton may appear at high x

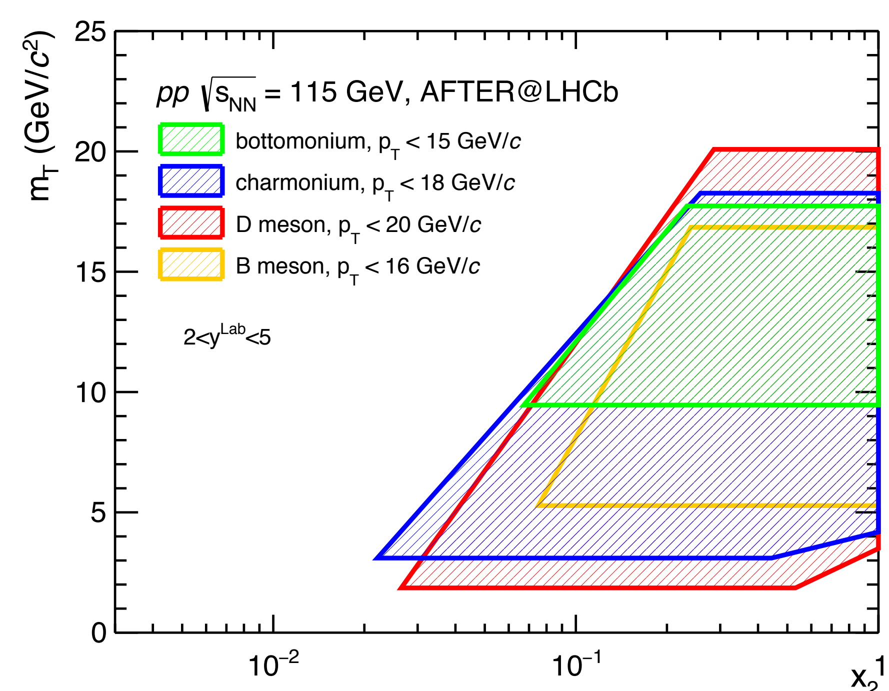
-charm PDFs at large x could be larger than obtained from conventional fits

- $W^{\pm}$ boson production near threshold

-strongly dependent on quark PDFs at large x

-search for heavy partners of the gauge bosons (predicted by many extensions to SM)

arXiv:1807.00603



- Complementary D and B-physics done at high energies

- Transverse Momentum Distribution functions (TMDs)

- Measurements relevant for astroparticle and cosmic ray physics

- pA collisions:

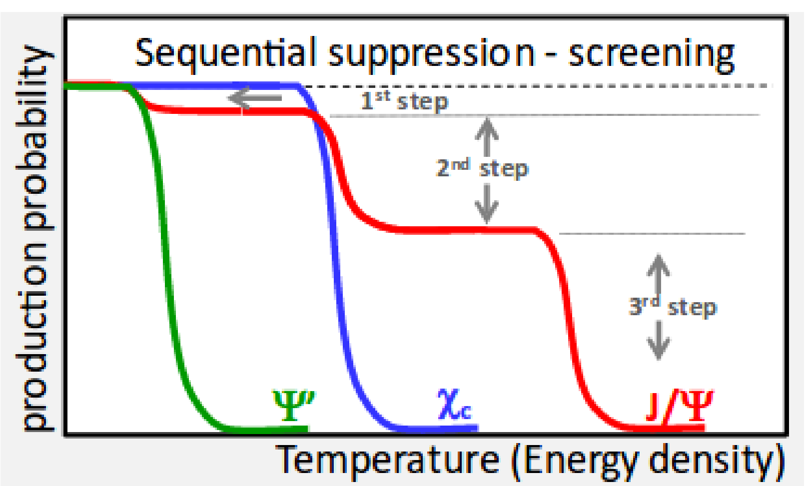
-nuclear matter effects on PDFs (special sensitivity to high-x, e.g. poorly known anti-shadowing)

-studies of parton energy-loss and jet-quenching in cold nuclear matter

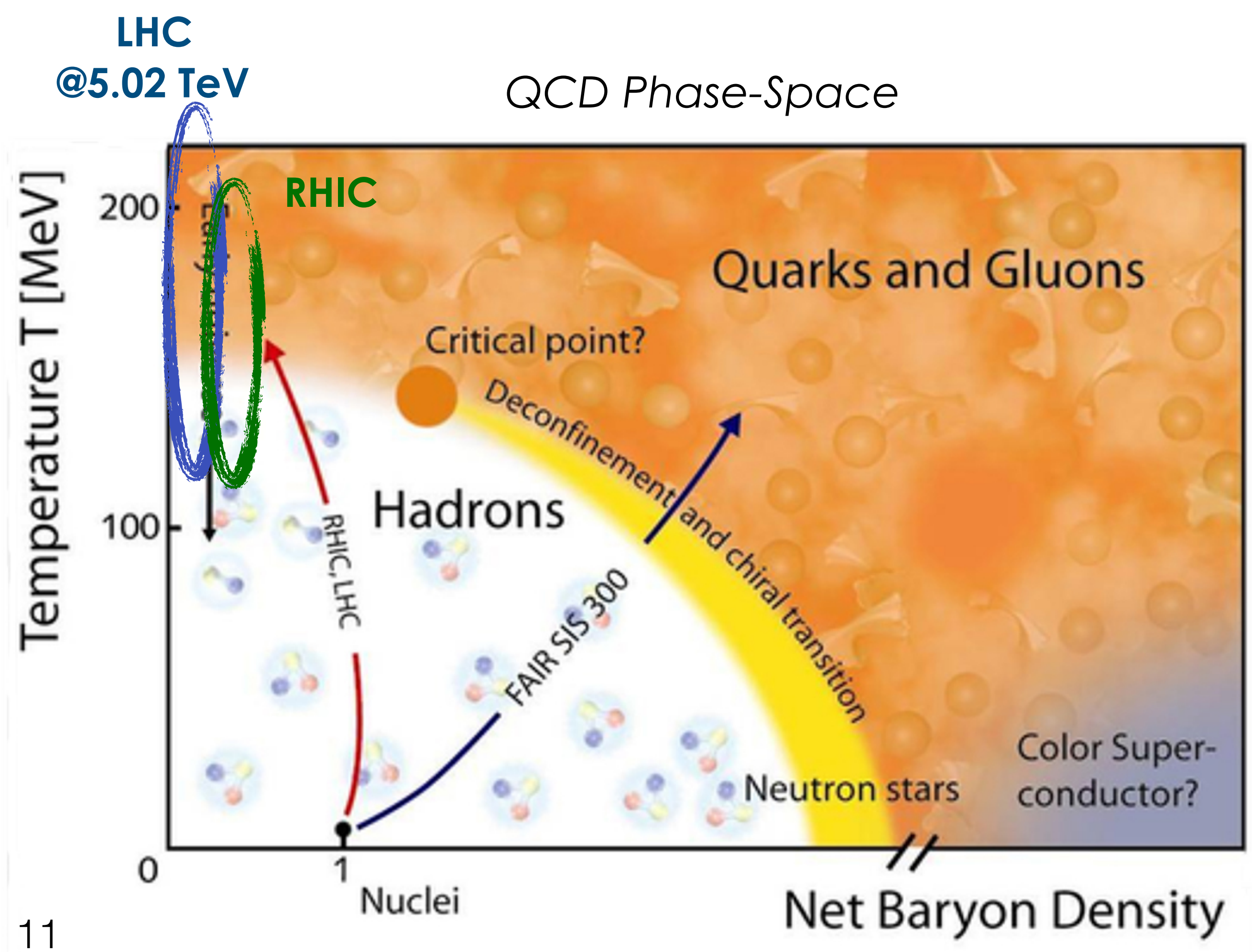
- PbA collisions at $\sqrt{s_{NN}} \approx 72$ GeV

-study of QGP formation (quarkonium suppression, jet-quenching in hot nuclear matter)

-fixed target kinematics allows to study the nucleus remnants in its rest frame (after QGP formation)

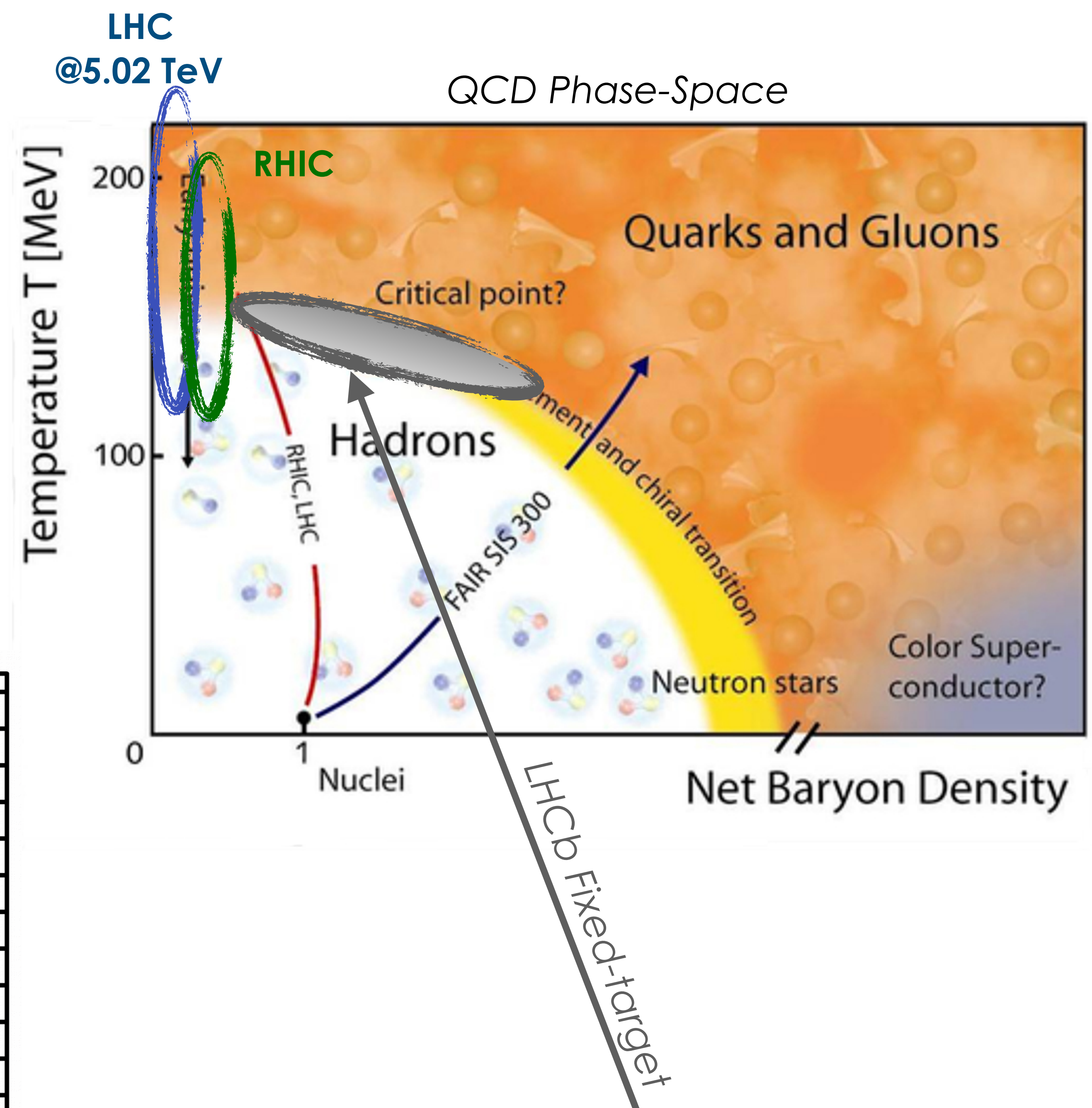


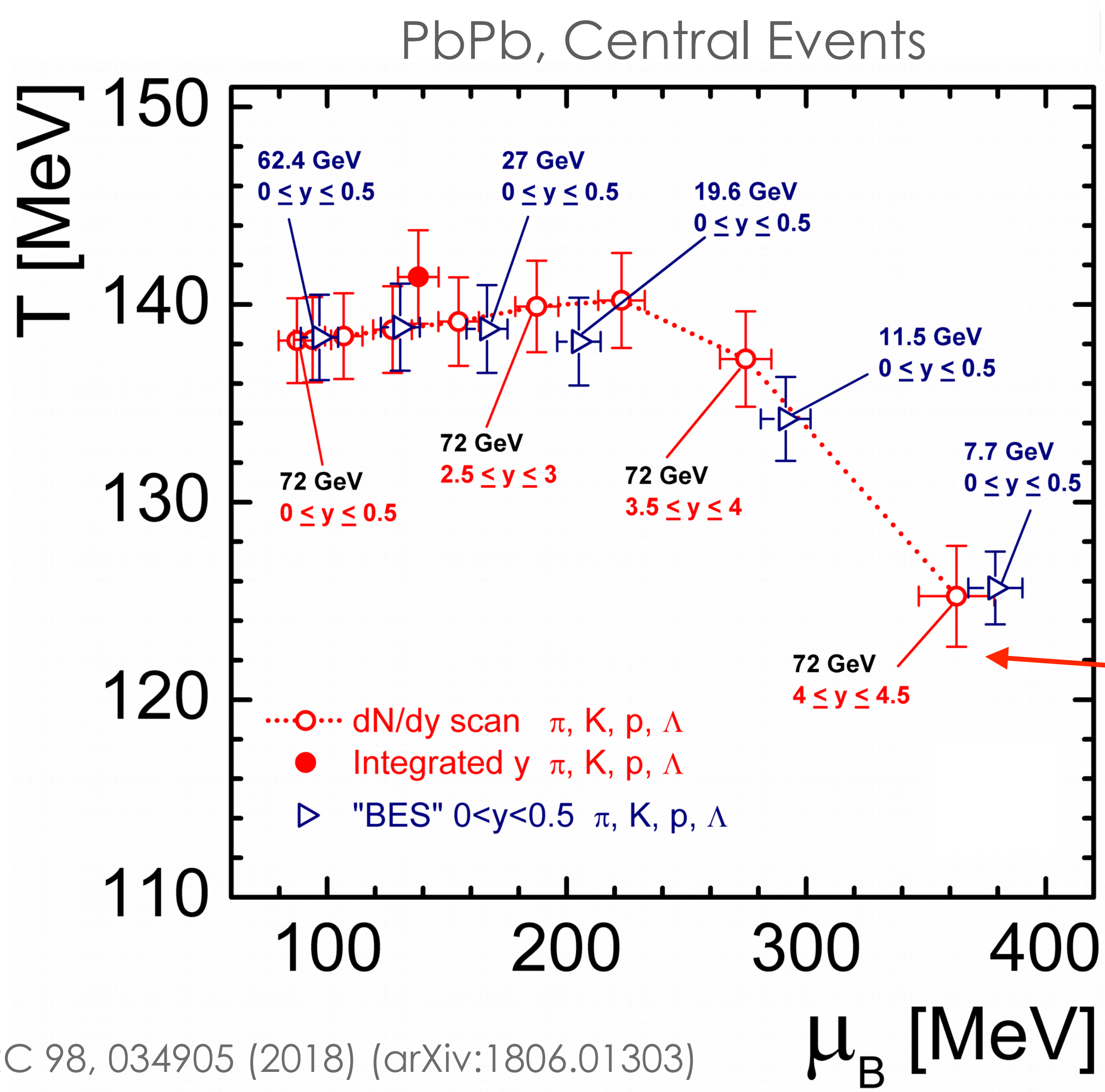
$c\bar{c}$ bound states: J/ψ, χ_C , ψ′, …
different binding energy,
different dissociation
temperature



AA collisions (QGP)

Searching for the Triple Point and the transition





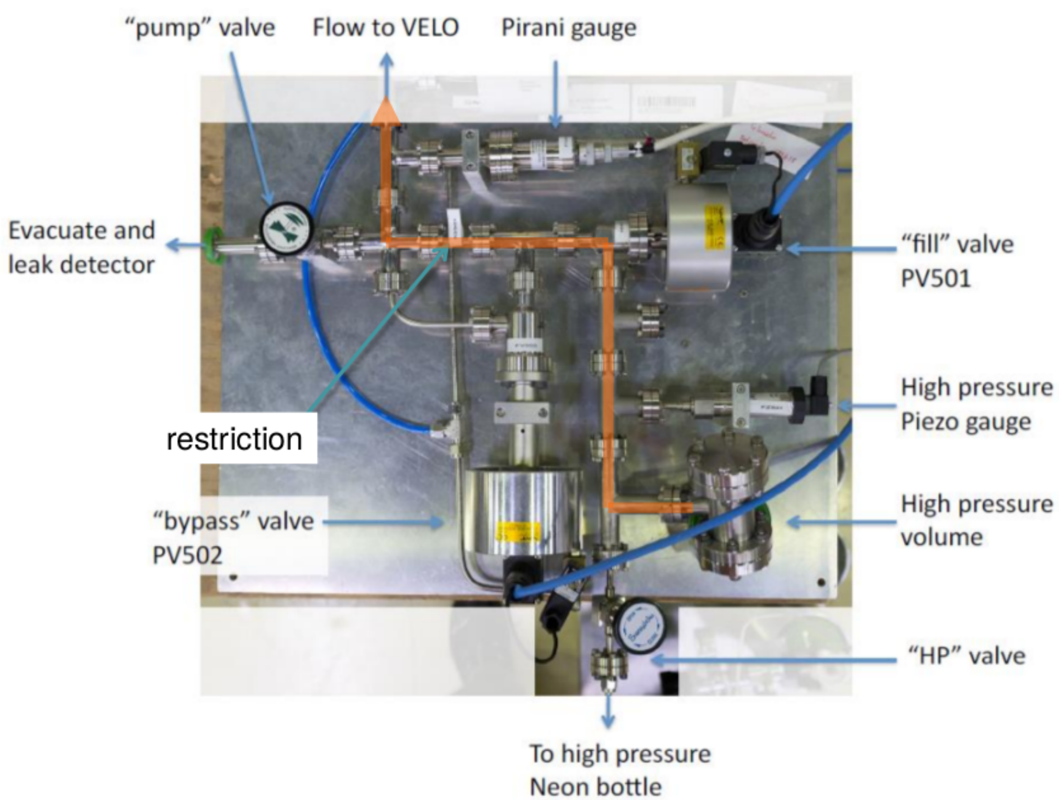
Moving on the μ_B-T plane at fixed energy but scanning in rapidity (contrary to RHIC where it was possible to scan in energy at fixed rapidity)

LHCb can go from y~2 (at the plateau) to y~5 (on the slope)

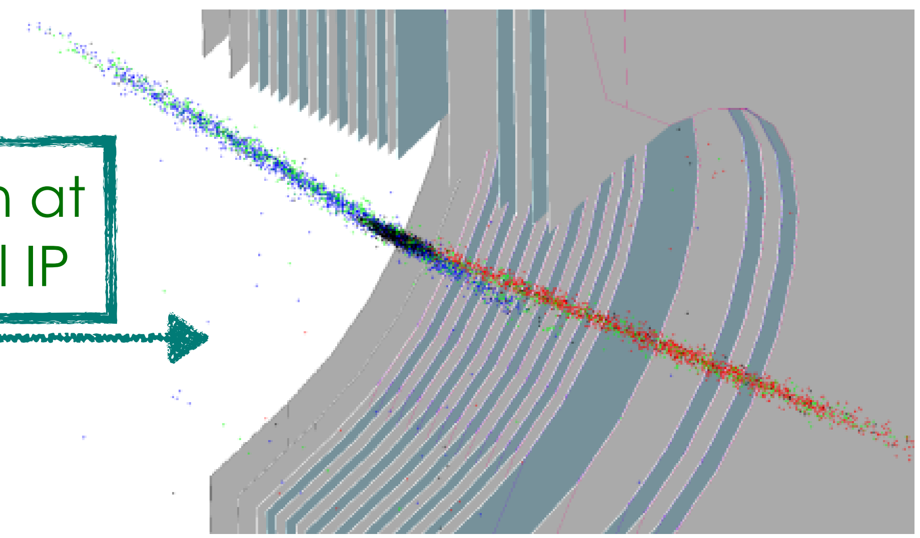
PRC 98, 034905 (2018) (arXiv:1806.01303)

SMOG, a successful idea and a pseudo-target

System for Measuring Overlap with Gas (SMOG) has been thought for precise luminosity measurements by beam gas imaging, but then it served as a "pseudo-target" producing interesting results

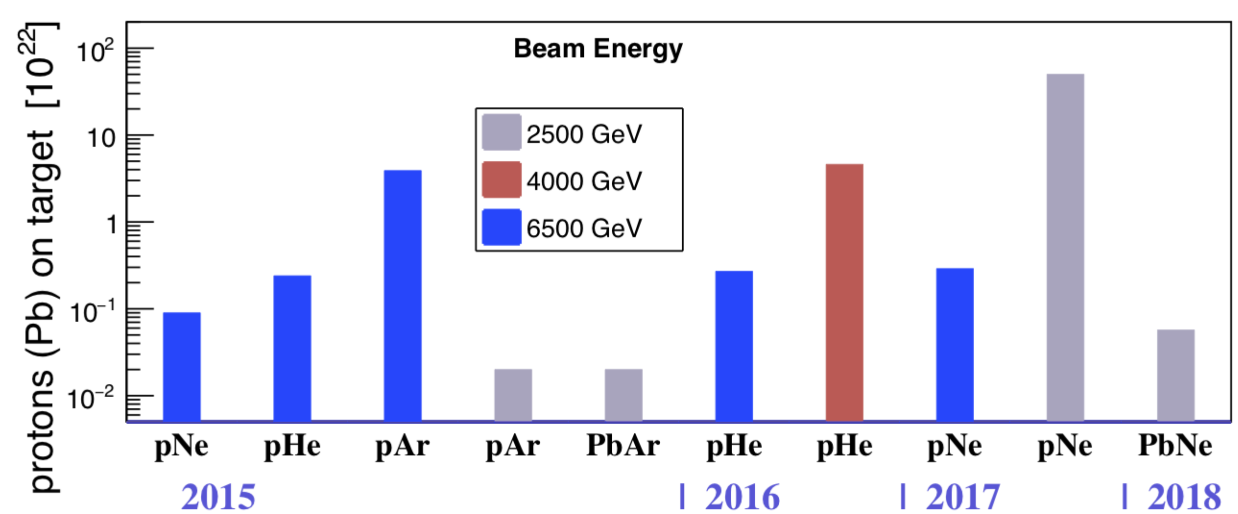


gas injection at the nominal IP



- Low intensity noble gas injected in the VELO vessel (~10^{-7} mbar)
- Gas pressure 2 orders or magnitude higher than LHC vacuum

Data taking SMOG 2015-2018



2 papers published on PRL:
-antiproton production in p-He collisions @ 110 GeV PRL121,222001(2018) (arXiv:1808.06127)
-First measurement of charm production in fixed-target configuration at the LHC - PRL122,132002(2019) (arXiv:1810.07907)

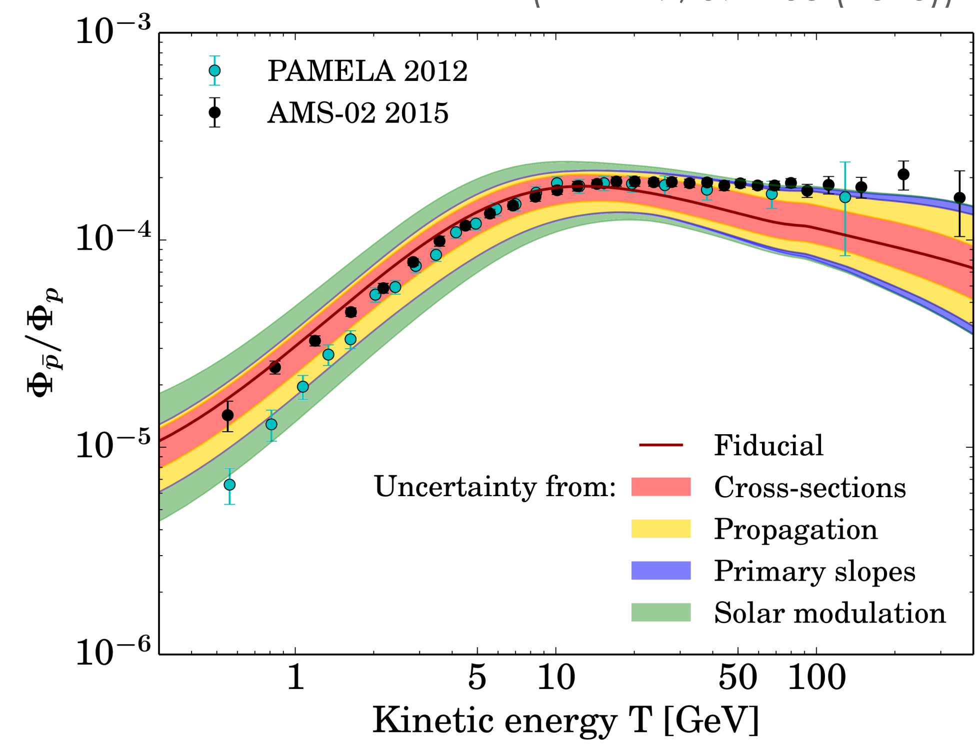
Antiproton production in p-He collisions

… a very interesting aspect

The antiproton fraction in cosmic rays is a sensitive indirect probe for exotic astrophysical sources of antimatter, such as DM annihilation

(PRL 117, 091103 (2016))

An excess of antiprotons over current predictions based on spallation of primary cosmic rays on interstellar medium (H and He) has been recently observed by the space-borne PAMELA and AMS-02 experiments

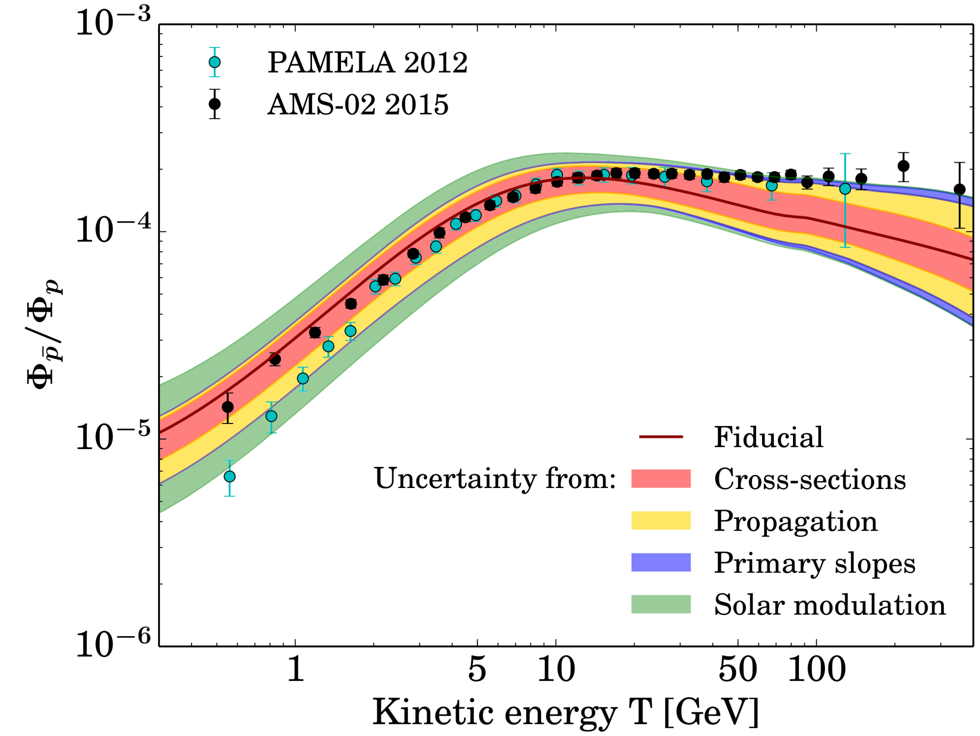


… a very interesting aspect

The antiproton fraction in cosmic rays is a sensitive indirect probe for exotic astrophysical sources of antimatter, such as DM annihilation

(PRL 117, 091103 (2016))

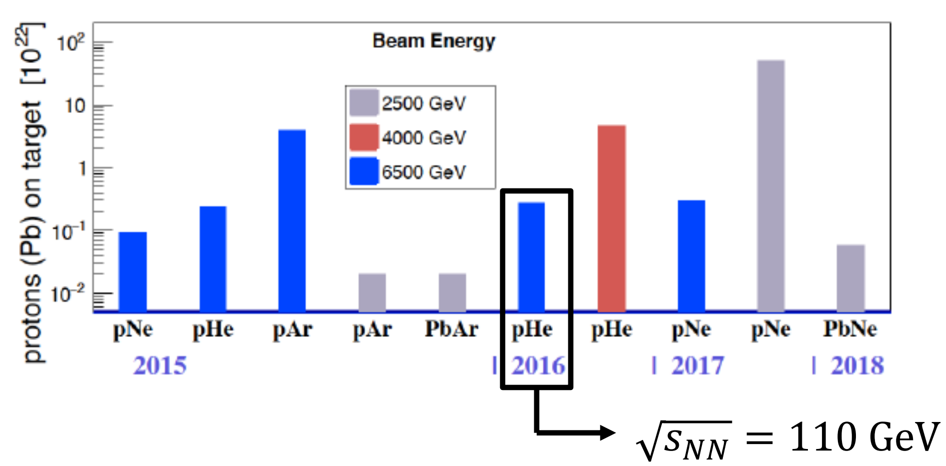
An excess of antiprotons over current predictions based on spallation of primary cosmic rays on interstellar medium (H and He) has been recently observed by the space-borne PAMELA and AMS-02 experiments

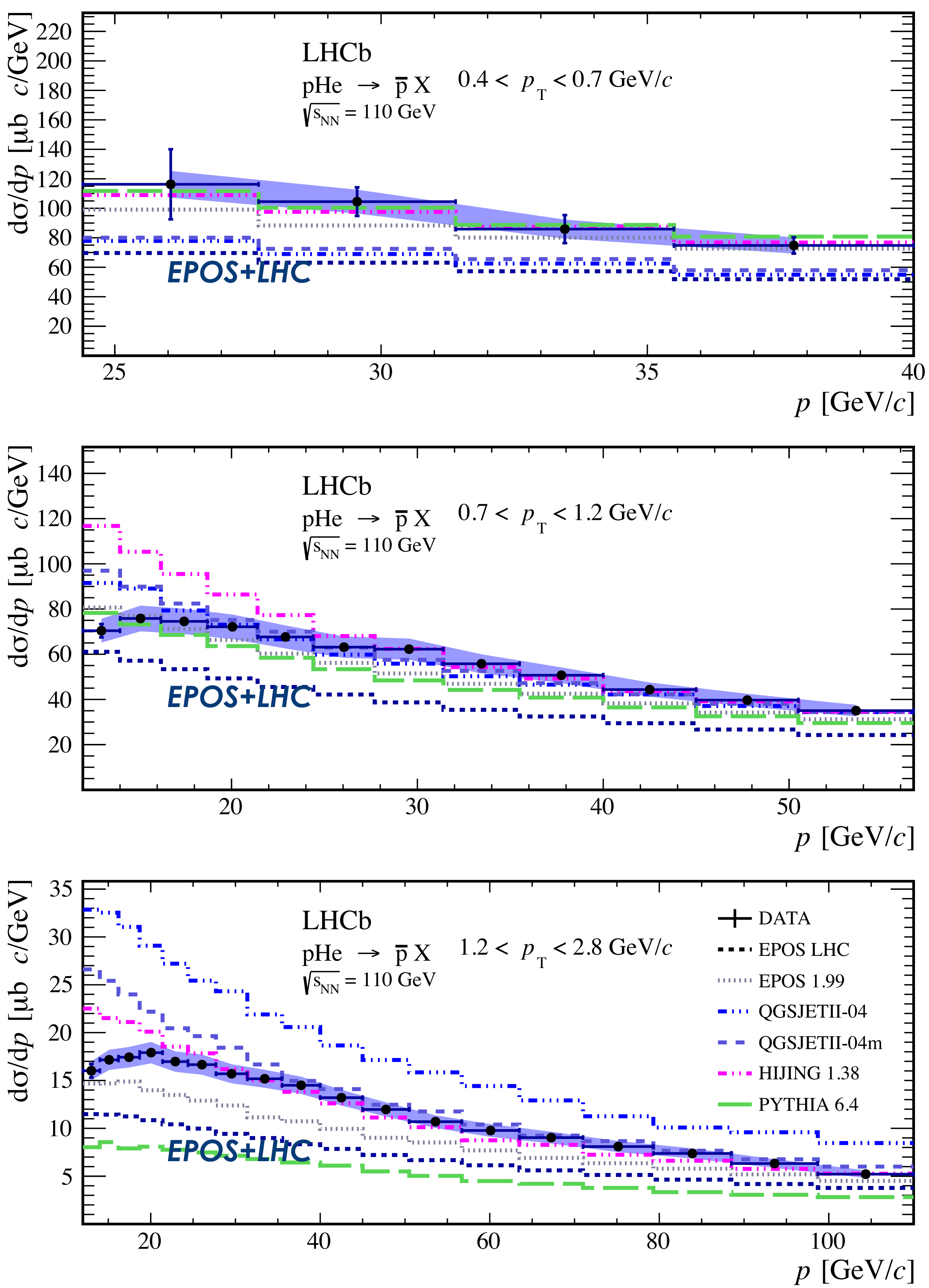


However, present predictions for $\bar{p}$/p flux ratio from the known production sources are limited by large uncertainties on $\bar{p}$ production cross sections (especially from He)

LHCb has provided the first direct measurement of $\bar{p}$ production in fixed-target p-He collisions

Empirical parameterizations are mostly based on SPS pp data, but no previous measurement of $\bar{p}$ production in p-He





Phys. Rev. Lett. 121 (2018), 222001 (arXiv:1808.06127)

- Uncertainties are smaller than model spread
- EPOS+LHC_tuning underestimate the $\bar{p}$-production
- … but then the visible inelastic cross section is compatible with EPOS-LHC:

$$\sigma_{\rm vis}^{\rm LHCb}/\sigma_{\rm vis}^{\rm EPOS-LHC} = 1.08 \pm 0.07 \pm 0.03$$

→ discrepancy: $\bar{p}$ yield/event

Fundamental contribution able to shrink the background uncertainties in dark matter searches in space

Natural pHe extensions:

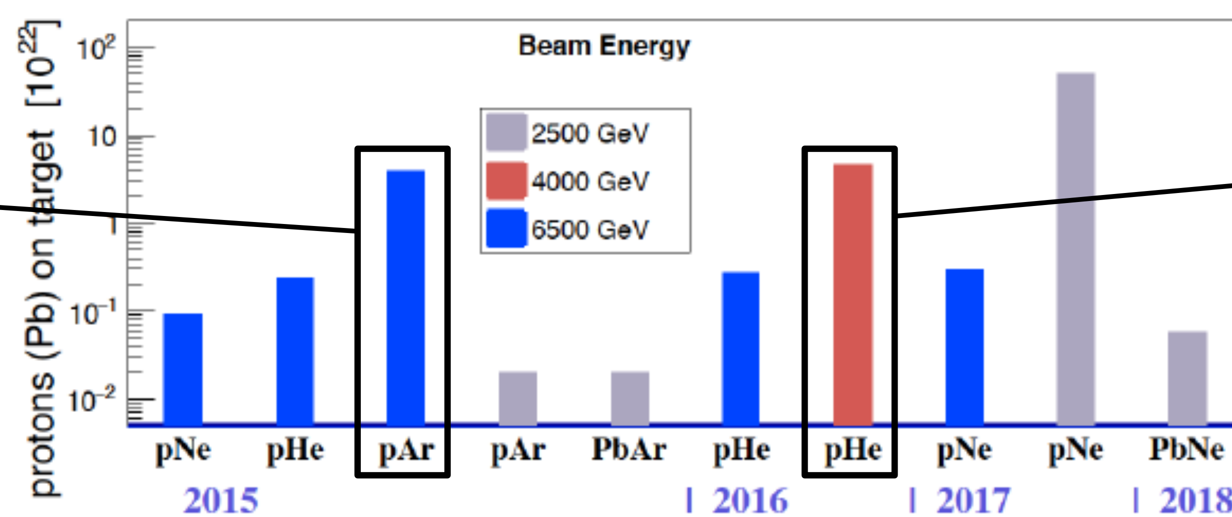
- inclusive $\bar{p}$ from hyperon decays

-charged π,*K*,*p* spectra

-$\sqrt{s_{NN}}$=87 GeV data

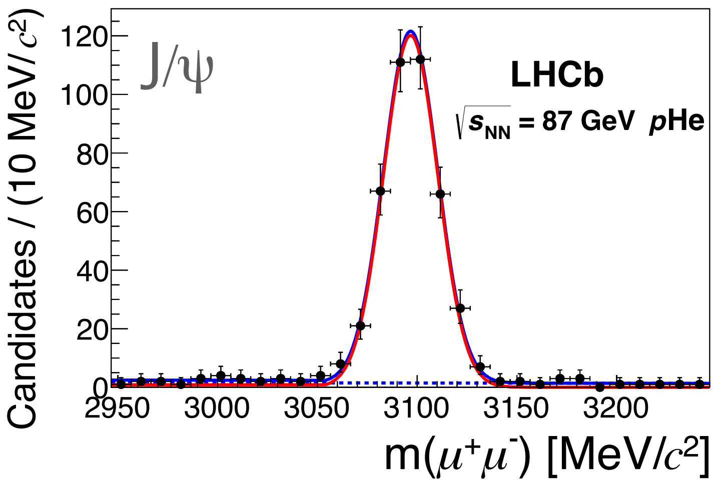
Charm production in fixed targets

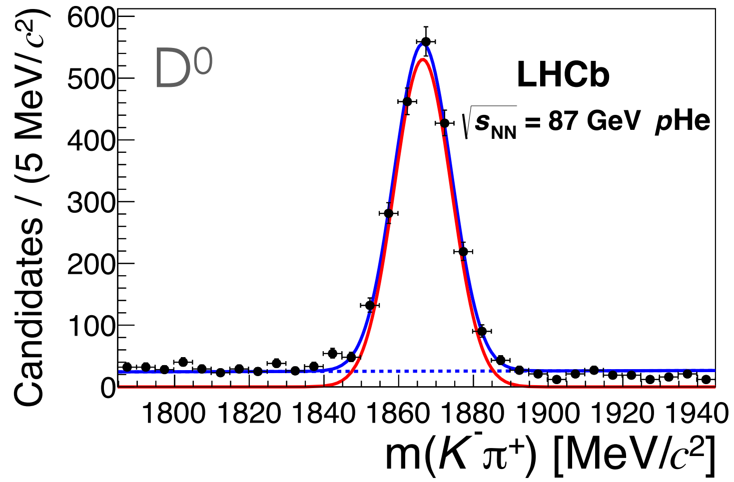
$\sqrt{s_{NN}} = 110$ GeV



$\sqrt{s_{NN}} = 87$ GeV

Charm production in fixed targets



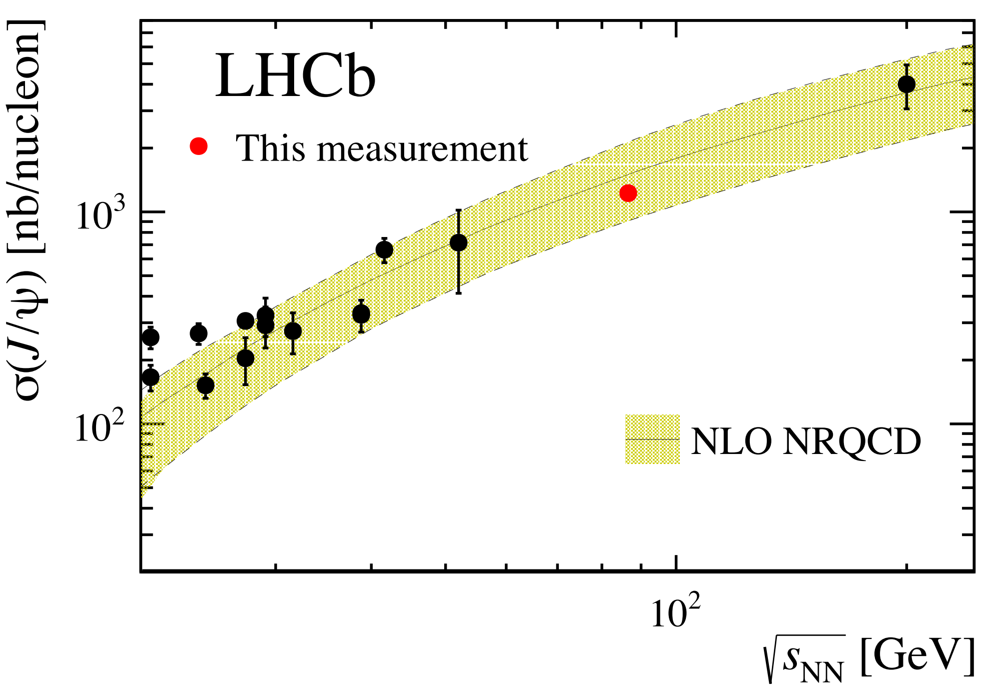


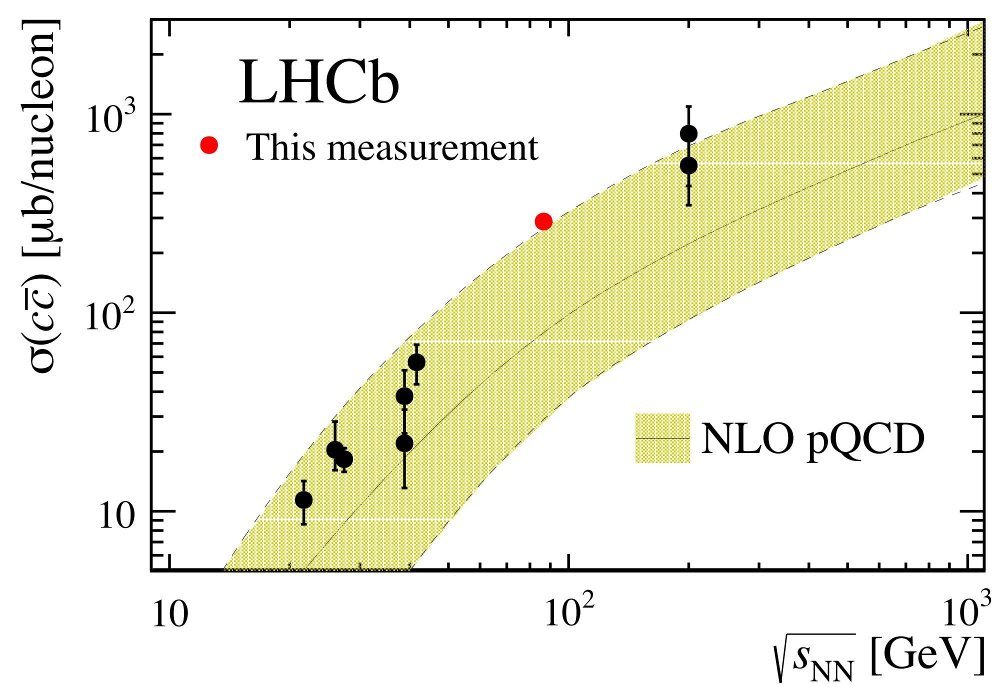
PRL 122, 132002 (2019) (arXiv:1810.07907)

First LHCb charm samples from:

pHe@87 GeV (7.6 ± 0.5 nb^{-1}) and

pAr@110 GeV (few nb^{-1})



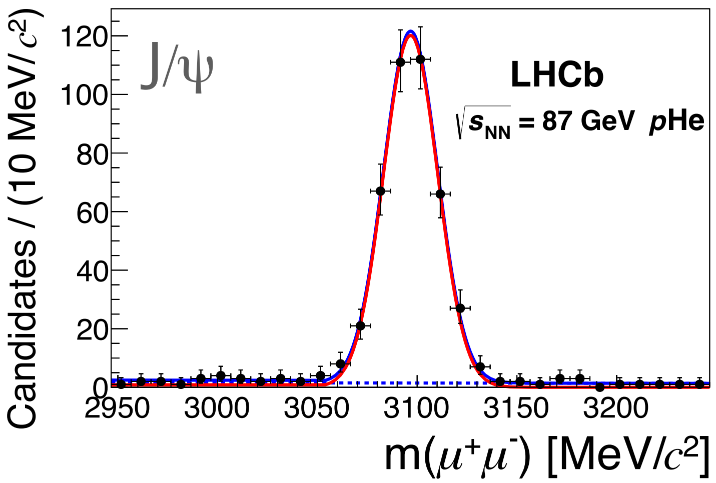


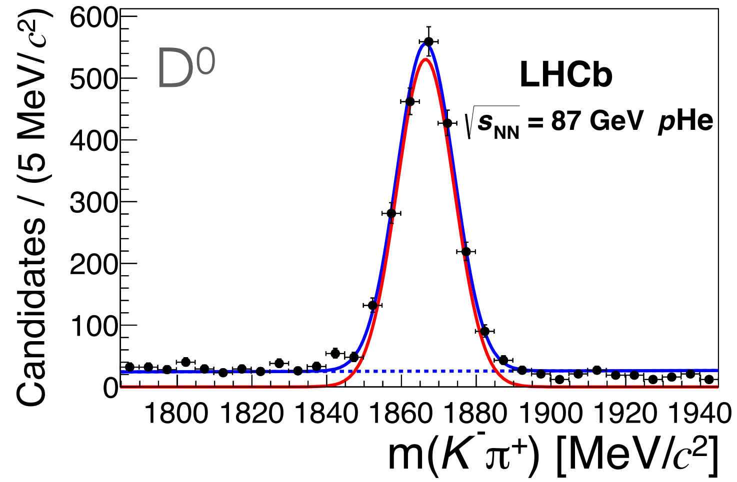
First determination of $c\bar{c}$ cross-section at this energy scale

LHCb results are in good agreement with NLO NRQCD fit (J/ψ, left) and NLO pQCD predictions ($c\bar{c}$, right) and other measurements

Charm production in fixed targets

PRL 122, 132002 (2019) (arXiv:1810.07907)

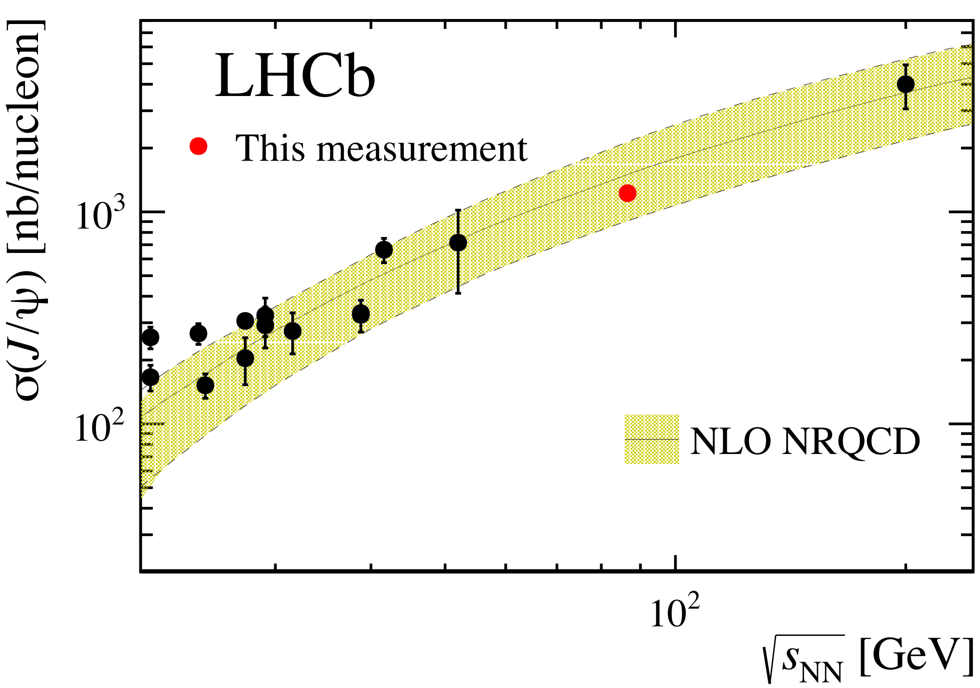


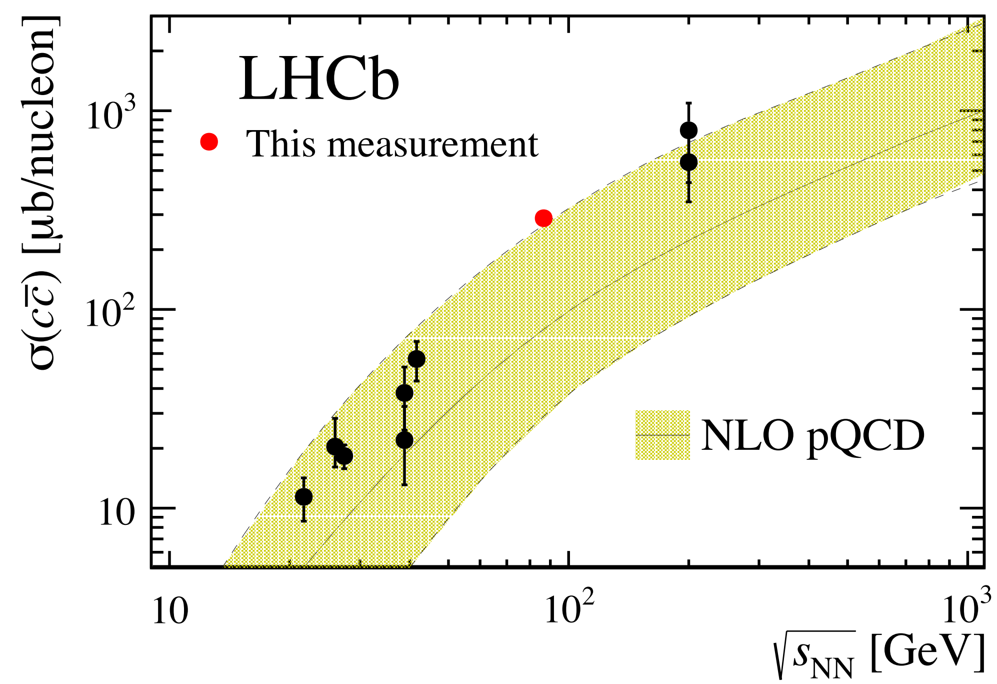


First LHCb charm samples from:

pHe@87 GeV (7.6 ± 0.5 nb^{-1}) and

pAr@110 GeV (few nb^{-1})





Integrated cross-sections

$$\left.\begin{array}{l}\sigma_{J/\psi} = 652 \pm 33\,(stat) \pm 42\,(syst)\quad nb/nucleon \\ \sigma_{D^0} = 80.8 \pm 2.4\,(stat) \pm 6.3\,(syst)\quad nb/nucleon\end{array}\right]\quad y \in [2.0, 4.6]$$

Extrapolated to the full phase-space (using PYTHIA8)

$$\sigma_{J/\psi} = 1225.6 \pm 100.7 \quad nb/nucleon$$

$$\sigma_{D^0} = 156.0 \pm 13.1 \quad nb/nucleon$$

Then, using the $f(c \to D^0)$ FF, the $c\bar{c}$ production cross section is

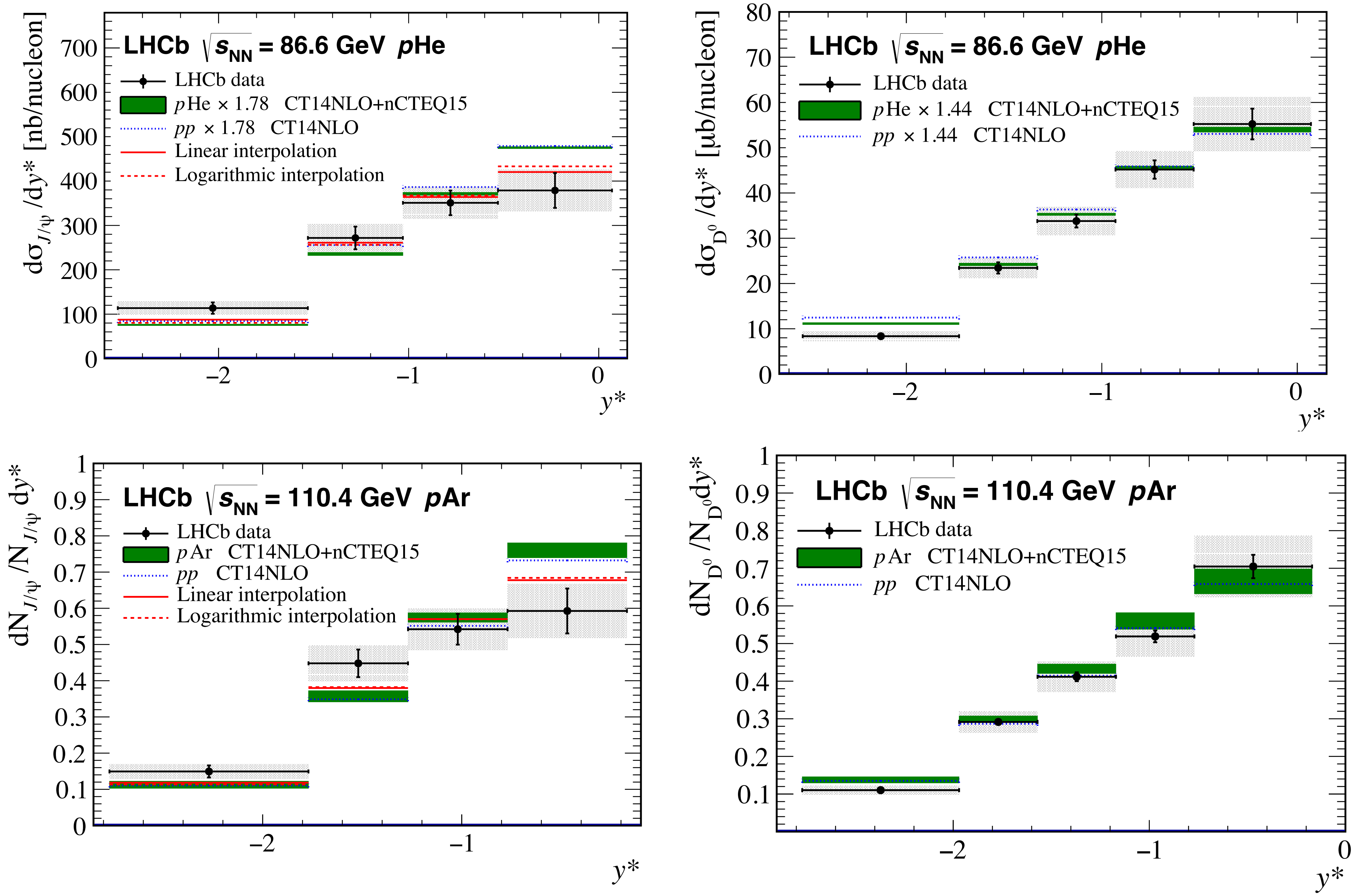
$$\sigma_{c\bar{c}} = 288.0 \pm 24.2 \pm 6.9 \quad nb/nucleon$$

J/ψ D^0

PRL 122, 132002 (2019) (arXiv:1810.07907)

He

Ar



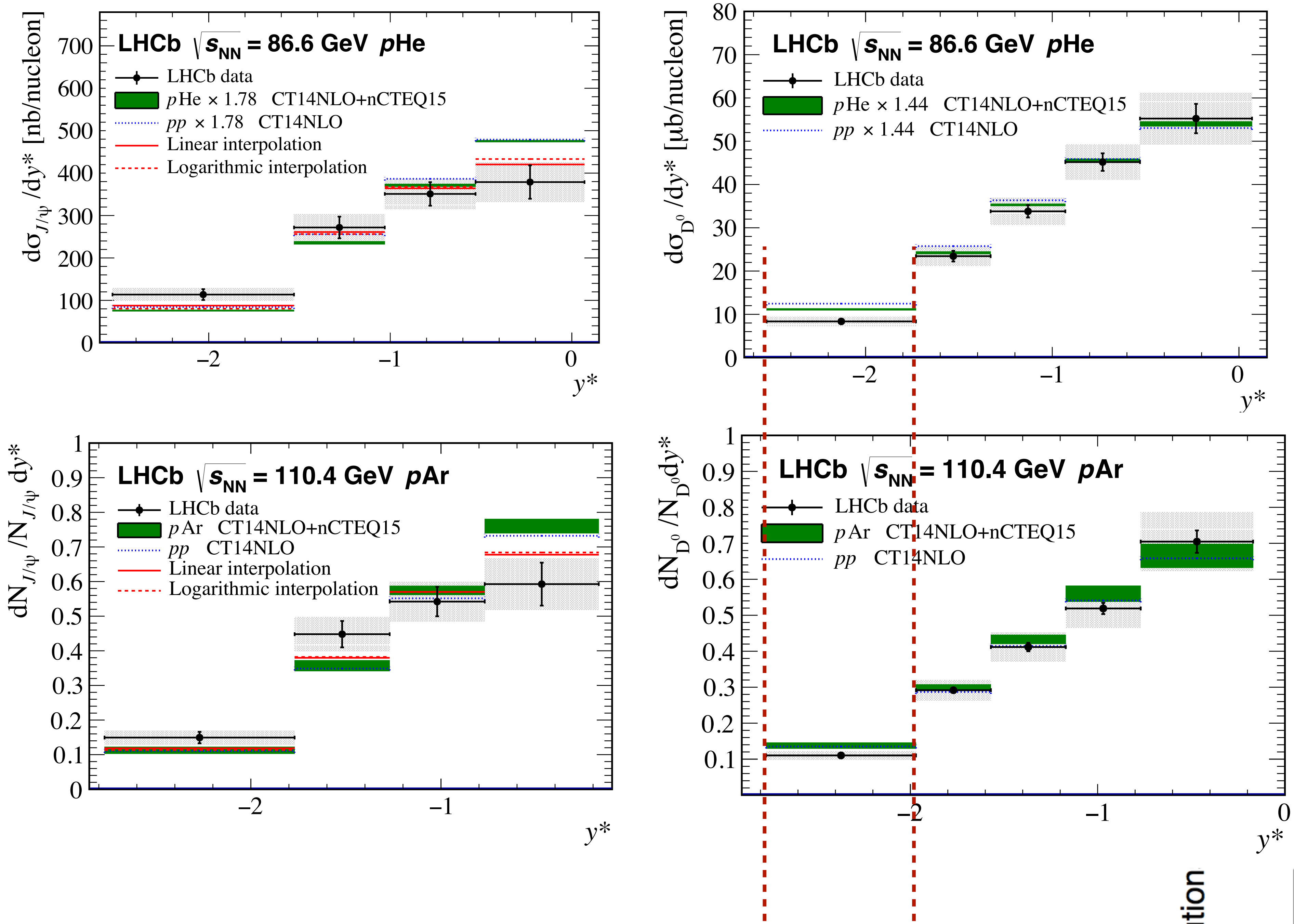
- Good agreement of phenomenological predictions with y*-shape, poor in p_T (not shown here) … gluon dominance?
- HELAC-ONIA, designed and tuned for collider data, underestimate the J/ψ (D^0) pHe-cross section by a factor 1.78 (1.44)

PRL 122, 132002 (2019) (arXiv:1810.07907)

J/ψ | D^0

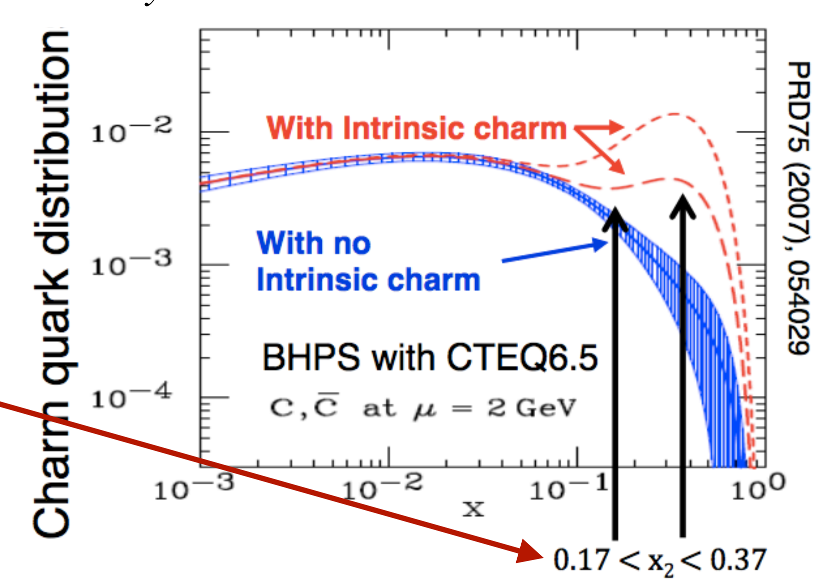
He

Ar



$-2.53 < y^* < -1.73$

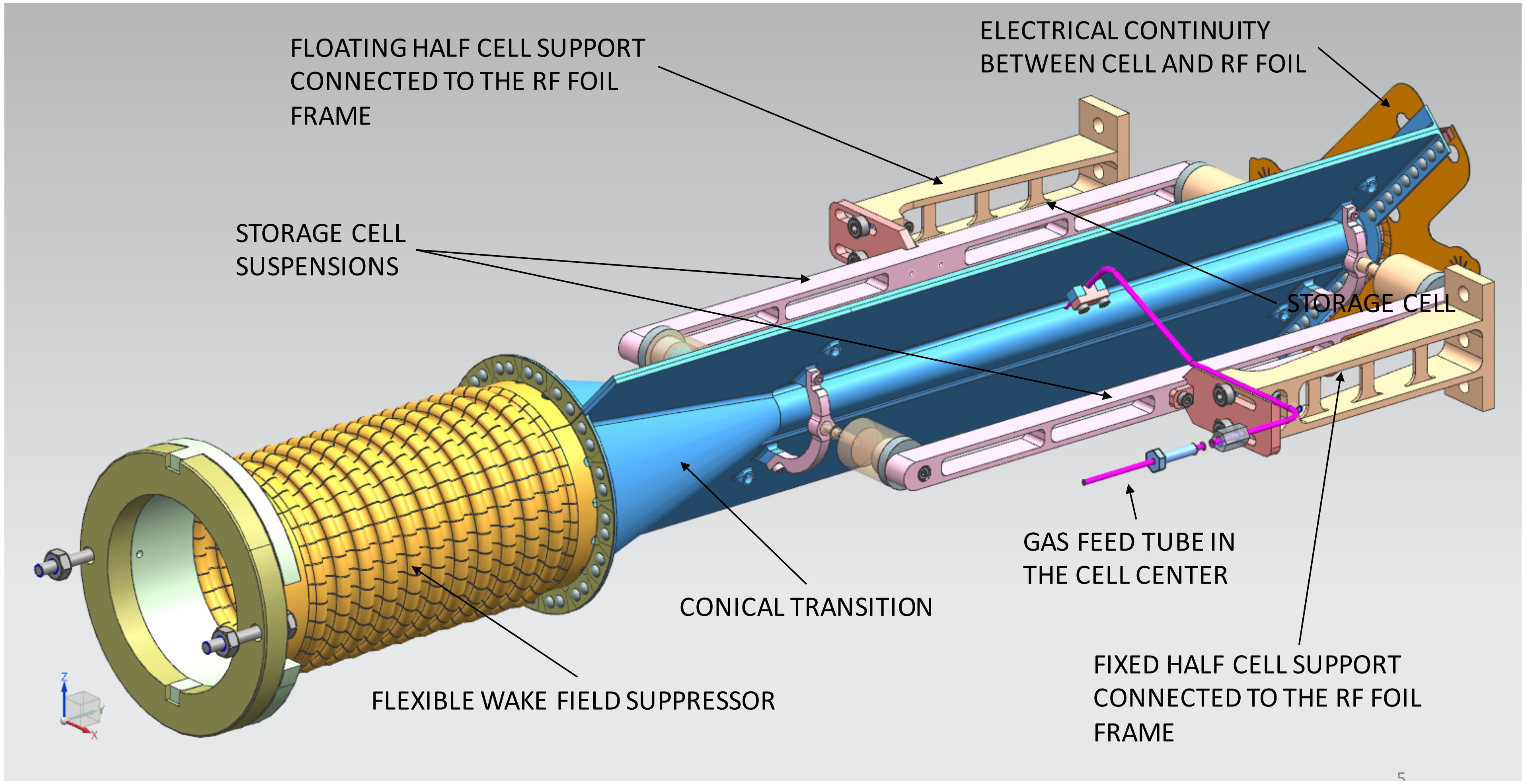
$0.17 < x_2 < 0.37$



- HELAC-ONIA does not contain intrinsic charm contribution
- No evidence for sizeable valence-like intrinsic charm contribution

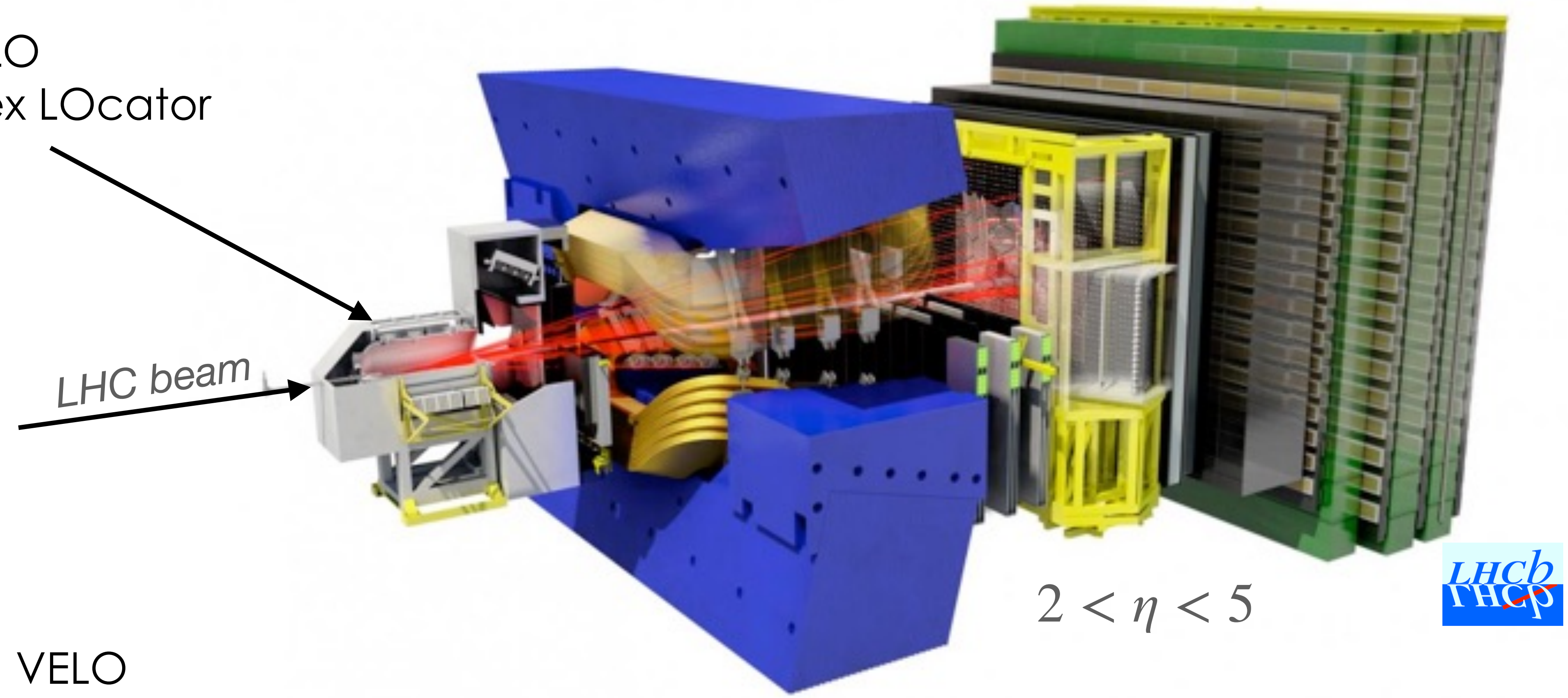
SMOG2

Towards the installation of a real storage cell



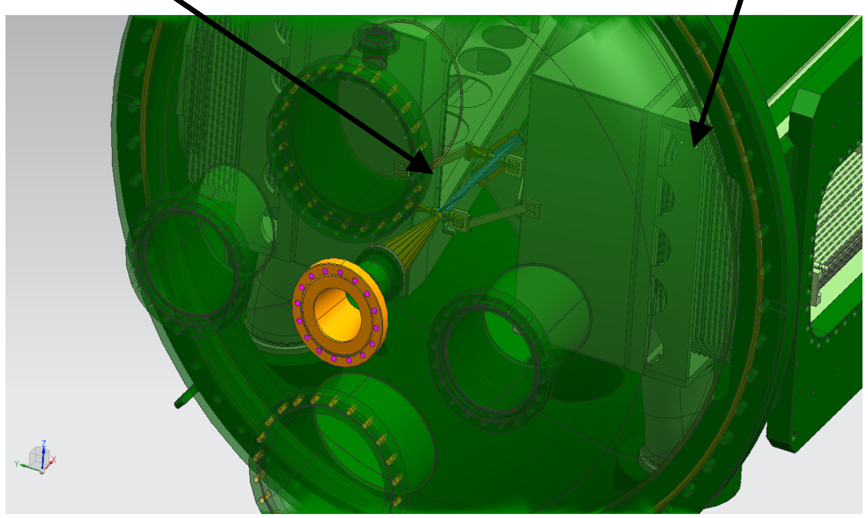
SMOG2

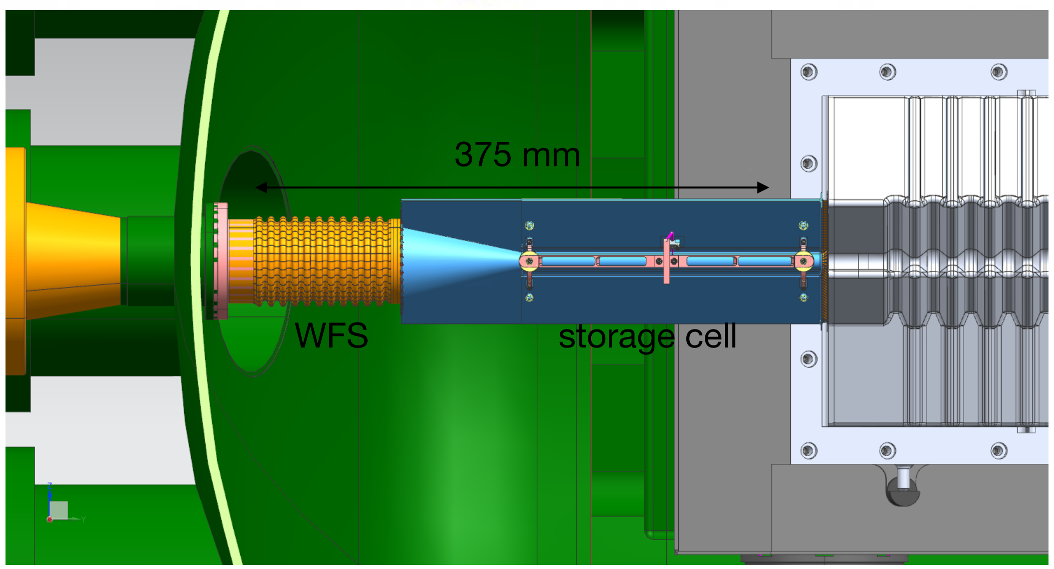
VELO
silicon VErtex LOcator



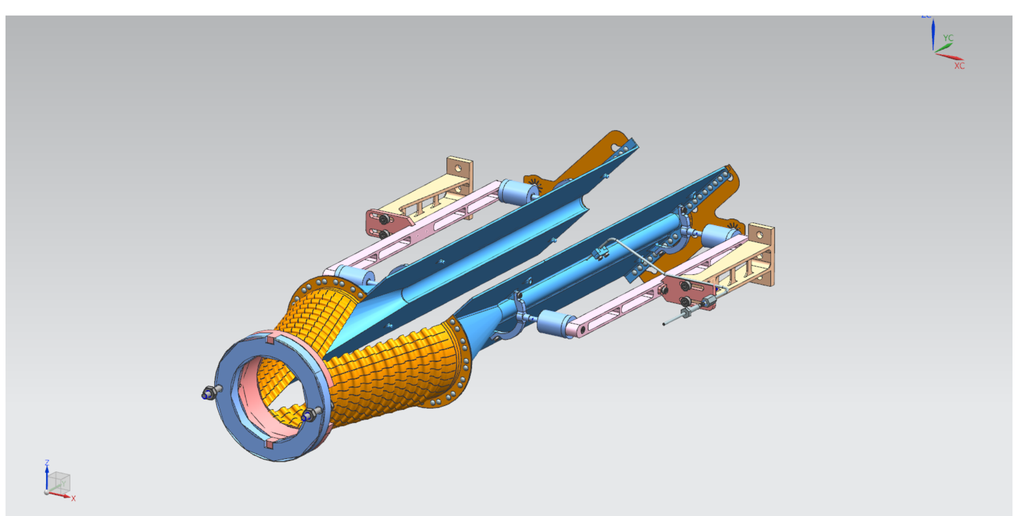
SMOG2

VELO

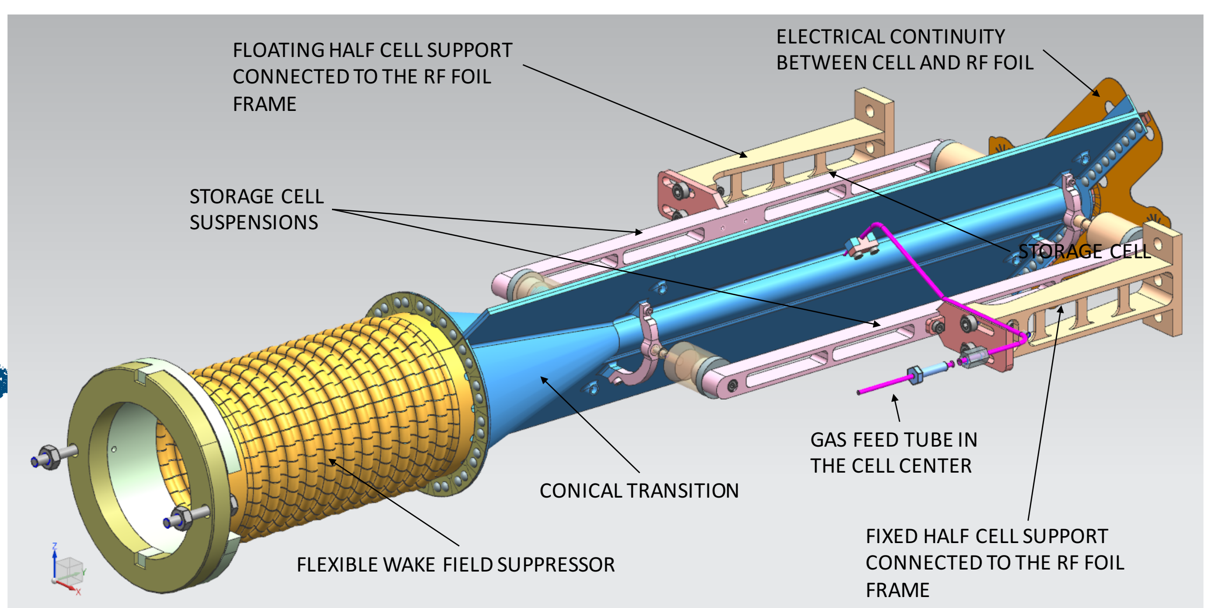




Internal side view



openable storage cell



SMOG2 vs SMOG

- Increase of the luminosity by up to 2 orders of magnitude using the same gas load of SMOG
- Injection of $H_2, D_2, {}^{3,4}He, N_2, Ne, Ar, Kr, Xe$
- New Gas Feed System. Gas density (luminosity) measured with high precision
- Well defined interaction region upstream the IP@13TeV:
    - strong background reduction,
    - no mirror charges effect,
    - possibility to use all the bunches,
    - possible simultaneous data taking with pp interactions @13 TeV

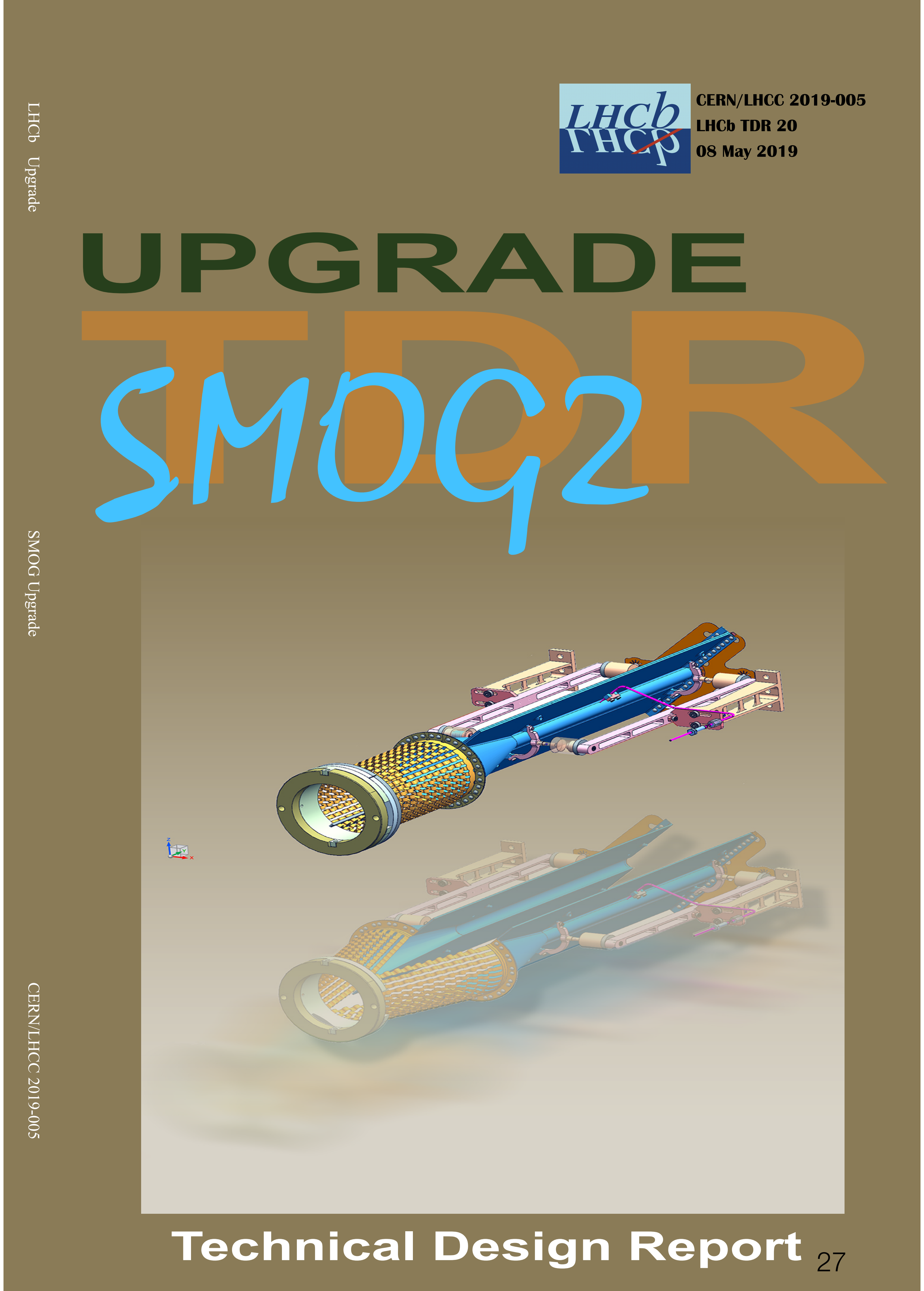
Statistics in full synergy mode (1 yr data taking)

CERN-LHCC-2019-005 ; LHCB-TDR-020

Storage cell assumptions	gas type	gas flow (s^{-1})	peak density (cm^{-3})	areal density (cm^{-2})	time per year (s)	int. lum. (pb^{-1})
SMOG2 SC	He	1.1×10^{16}	10^{12}	10^{13}	3×10^{3}	0.1
	Ne	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	Ar	2.4×10^{15}	10^{12}	10^{13}	2.5×10^{6}	80
	Kr	8.5×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	Xe	6.8×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	H_2	1.1×10^{16}	10^{12}	10^{13}	5×10^{6}	150
	D_2	7.8×10^{15}	10^{12}	10^{13}	3×10^{5}	10
	O_2	2.7×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	N_2	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1

SMOG2 example pAr @115 GeV

Int. Lumi.		80/pb
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k



Installation scheduled in the second half of November 2019

R&D

arXiv:1901.08002

SMOG2

not only a project itself

LHCspin

Phase II transversely polarised H and D target

The R&D is going on, we aim for the installation during the LHC LS3 (2024-2026)

... at LHCb

Conclusions

- LHCb developed a lively and fast growing fixed-target physics program, with very specific capabilities and unique acceptance at a hadron collider
- Much more data from Run2 to be analyzed and substantial development of the program in the near future with an upgraded spectrometer and a real storage cell (SMOG2)

Conclusions

- LHCb developed a lively and fast growing fixed-target physics program, with very specific capabilities and unique acceptance at a hadron collider
- Much more data from Run2 to be analyzed and substantial development of the program in the near future with an upgraded spectrometer and a real storage cell (SMOG2)

Fixed-Target collisions at LHCb offer a unique opportunity for *a laboratory for QCD and astroparticle* in unexplored kinematic regions