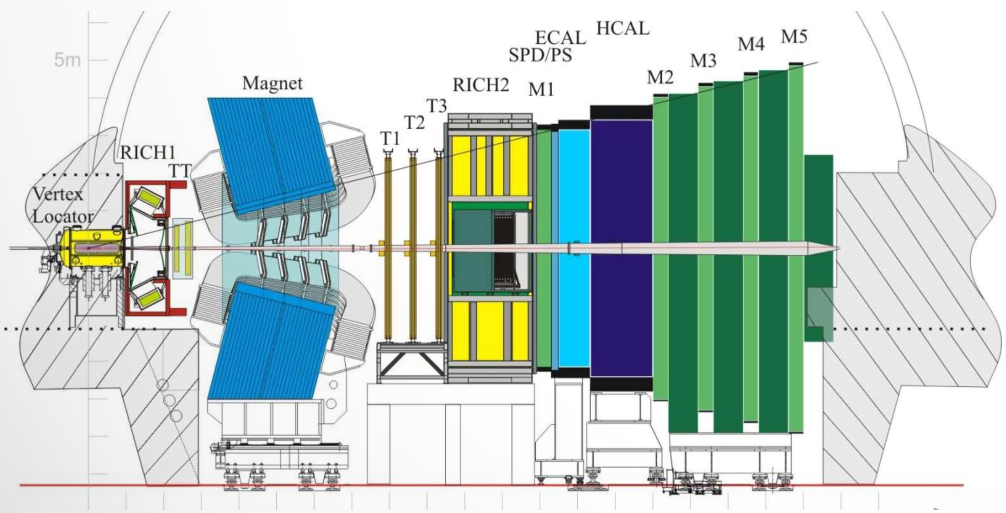
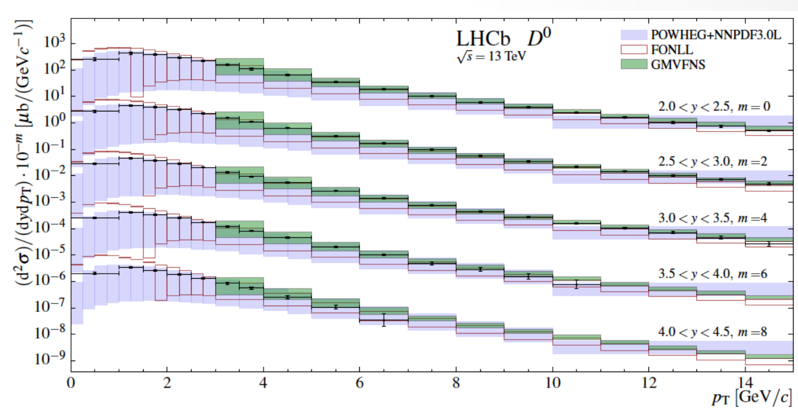
LHCb: Recent and upcoming results related to cosmic ray interactions

ISVHECRI 2018, Nagoya, Japan

Hans Dembinski[1] on behalf of the LHCb collaboration

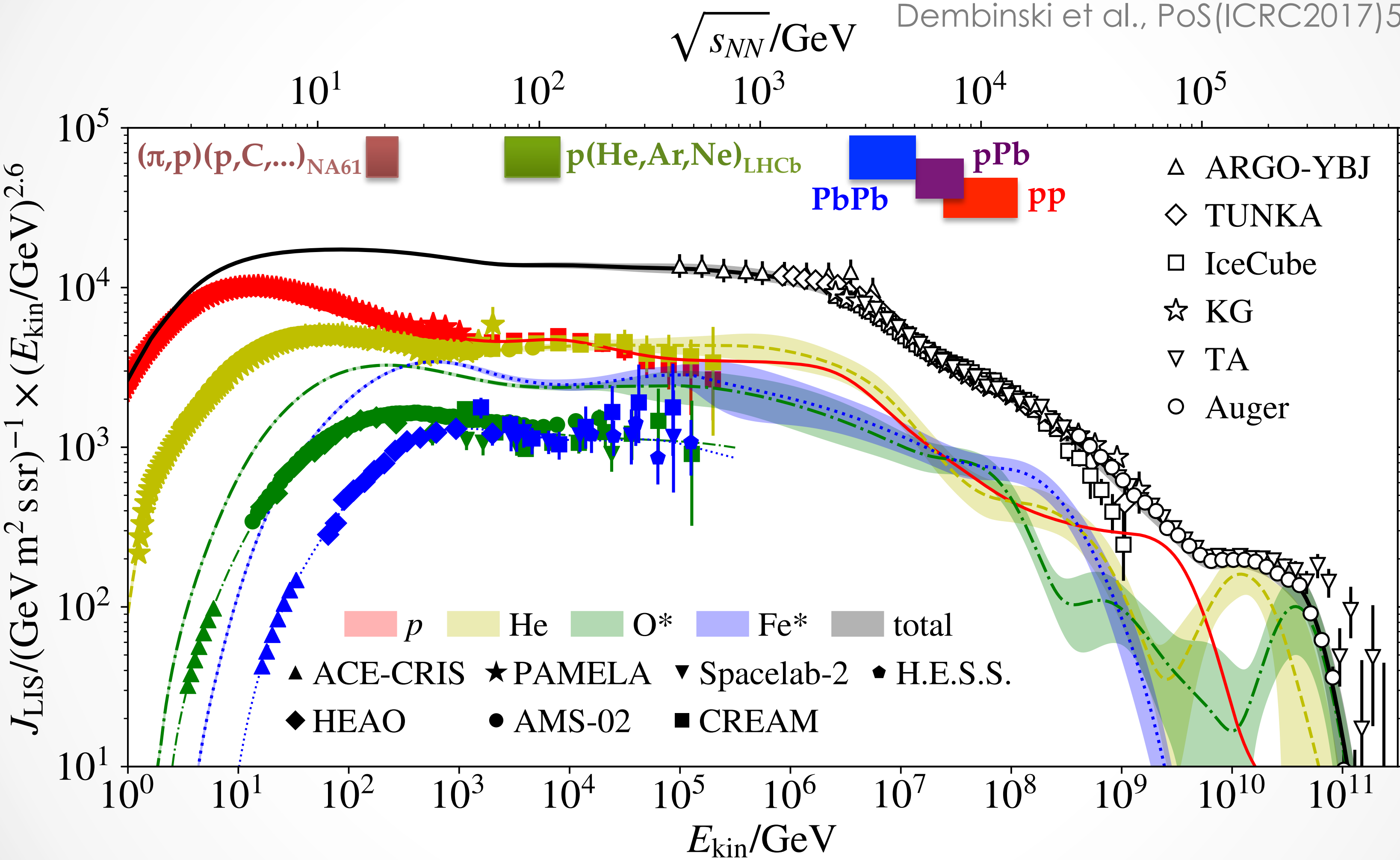
[1]Max Planck Institute for Nuclear Physics, Heidelberg





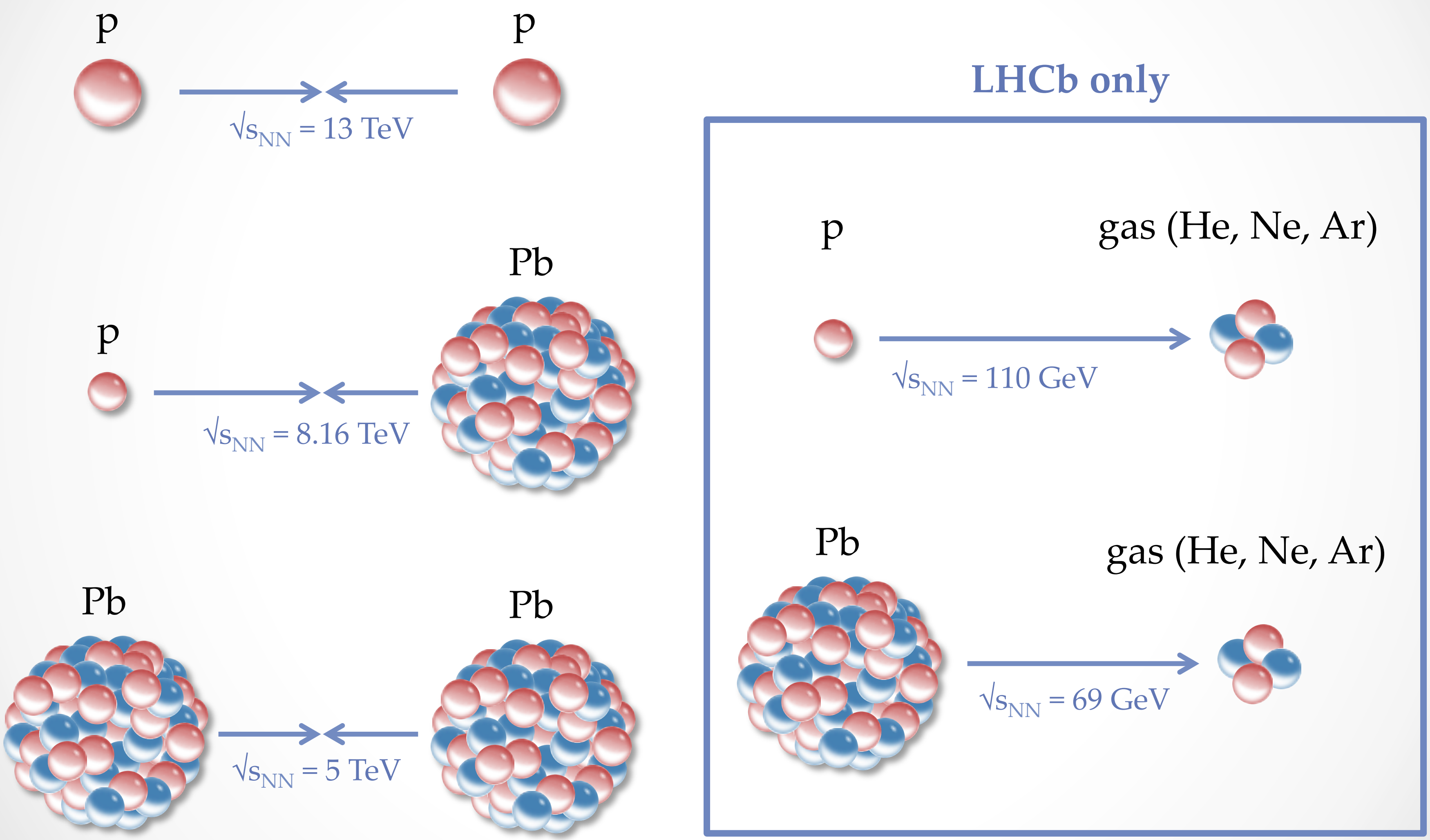
CERN and cosmic rays

Dembinski et al., PoS(ICRC2017)533



SPS (NA61) and LHC cover **three orders of magnitude** in c.m.s. energy

Collisions at the LHC



Modeling CR interactions

extrapolation to **higher energy** & **different collision systems**

Reference systems used for model tuning

LHC:
p+p @ **7** … **14** TeV
p+Pb @ **5** … **8.14** TeV
Pb+Pb @ **2.76** … **5** TeV

SPS:
p+C, π+C @ **12** GeV

Other experiments:
RHIC, Tevatron, …

Hadronic interaction models

Glauber
Gribov-Regge
pQCD

Theory & Phenomenology

Pomerons
Mini-jets
Multi-parton interactions

Systems in air showers

π+(N, O)

K+(N, O)

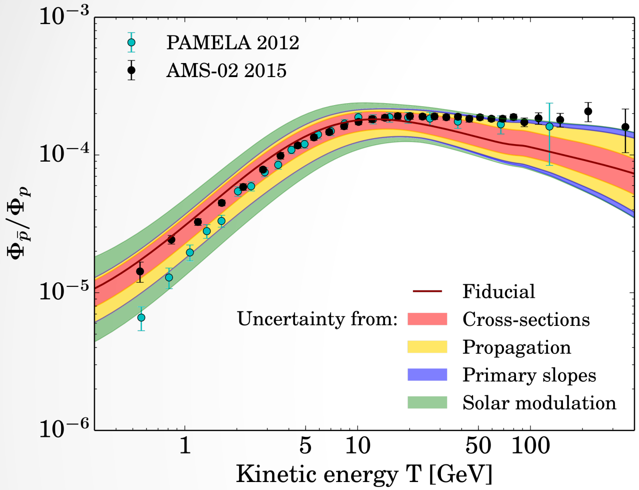
(p, n)+(N, O)
…
Fe+(N, O)

@ **1** GeV … **1000** TeV

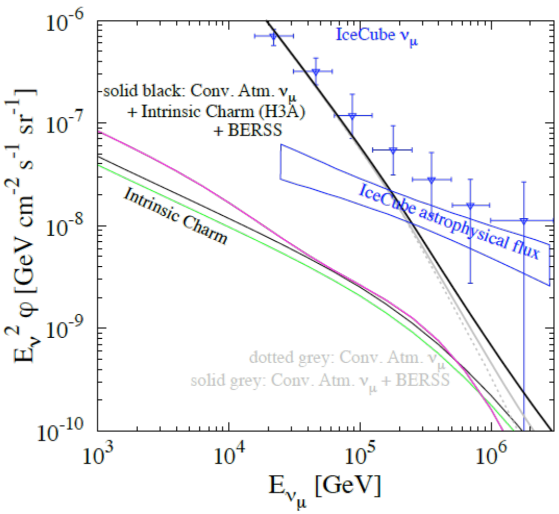
- **Light hadron production** most important
- Measurement accuracy in reference systems ~ 5-10 %
- Model deviation often larger

LHCb and CR physics

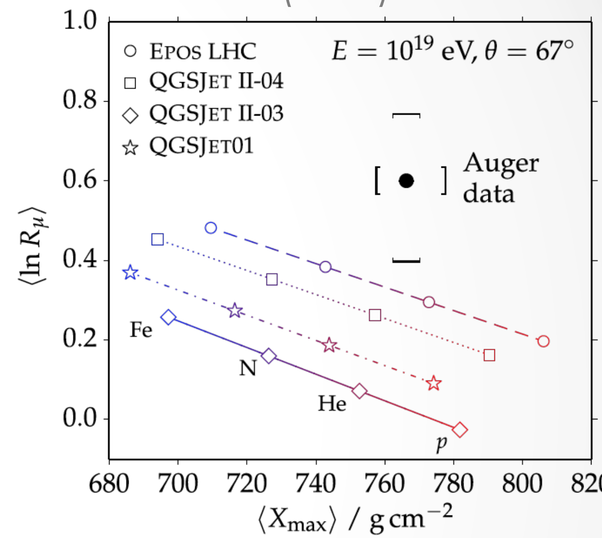
AMS, PAMELA
JCAP 1509 (2015) no.09, 023



IceCube
arXiv 1607.08240



Pierre Auger Observatory
PRD 91 (2015) 032003



LHCb can provide input to cosmic ray physics

- Anti-proton production in pHe collisions
  Most uncertain component of anti-proton flux measured by AMS-02
- Charmed meson production in pp and pPb in forward direction
  Charmed mesons in air showers produce neutrino background for IceCube
- Light hadron production in pp and pPb in forward direction
  Address muon puzzle in air showers, prevents unambiguous inference of <lnA>

Muon Puzzle and <lnA>

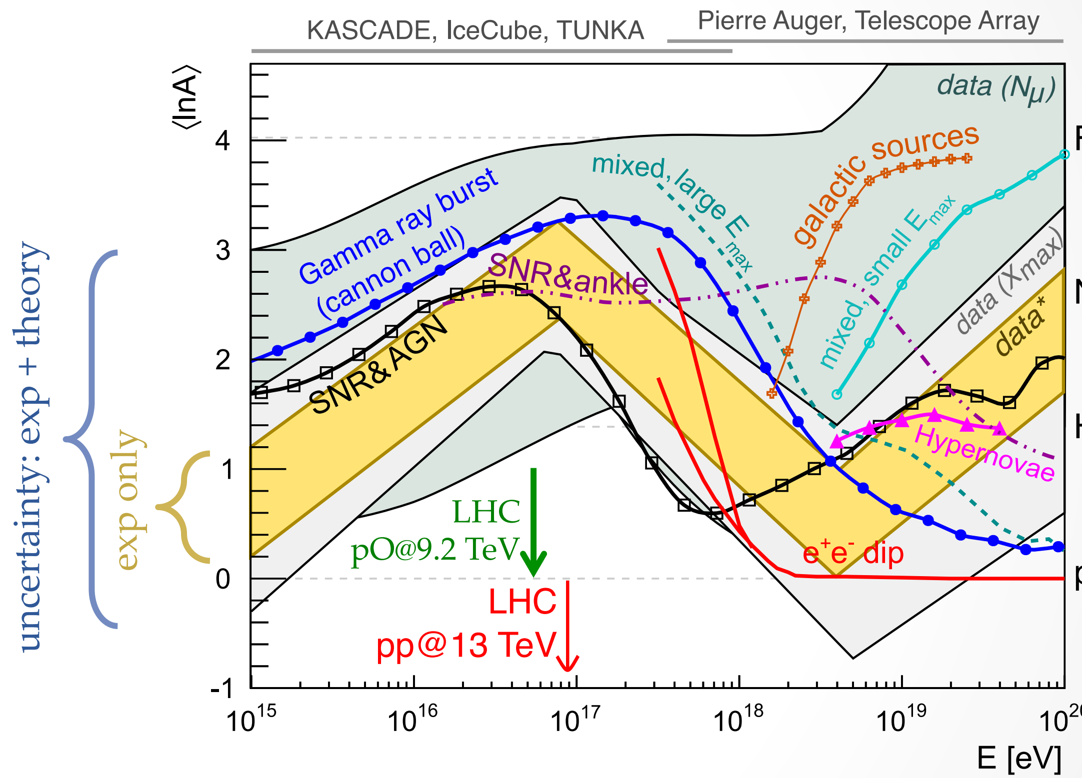
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660–678

Cosmic ray observables to test astrophysical theories

Directions
- No point sources found

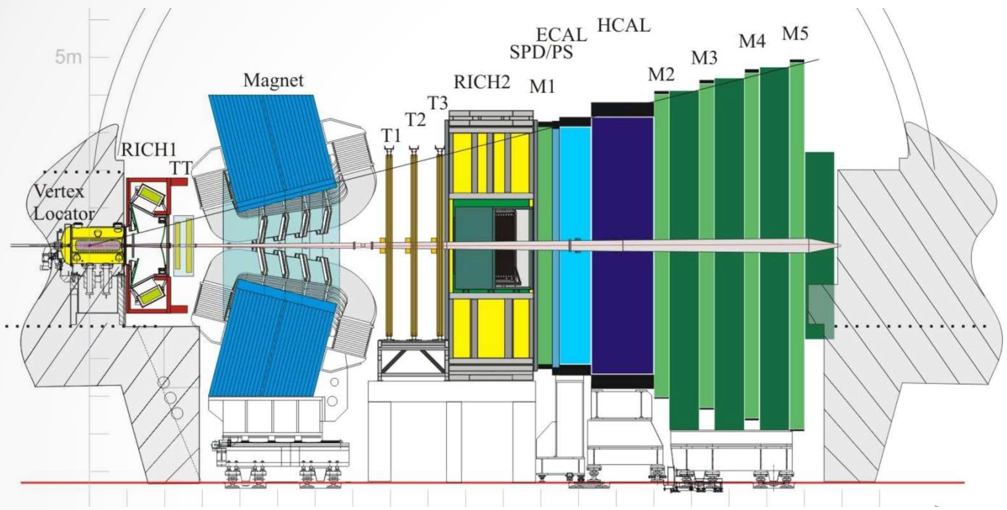
Energy spectrum
- Good accuracy
- Weakly discriminating

Mass composition
- **Poor accuracy (theoretical)**
- **Strongly discriminating**

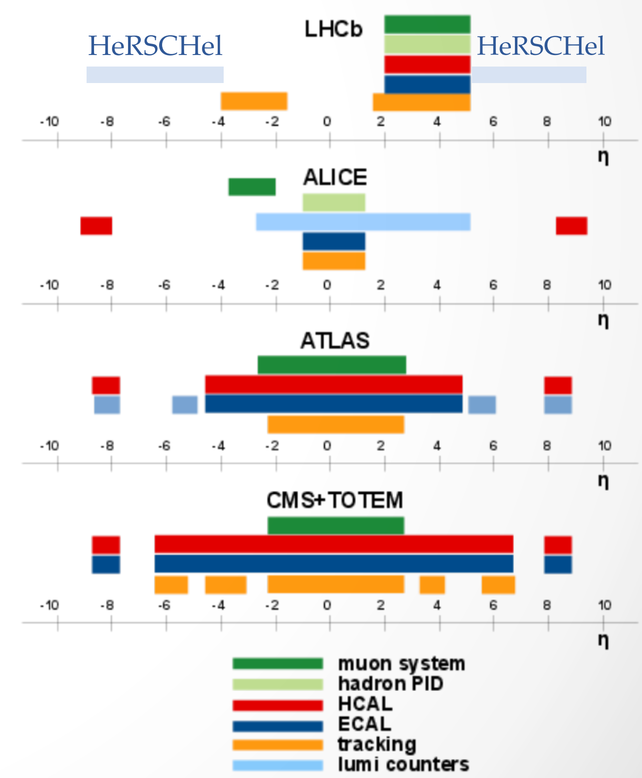


Mass composition **very sensitive** to astrophysical theories of CR origin, but accuracy of <lnA> poor because of **uncertainties in air shower models**

LHCb experiment



JINST 3 (2008) S08005
IJMP A 30 (2015) 1530022

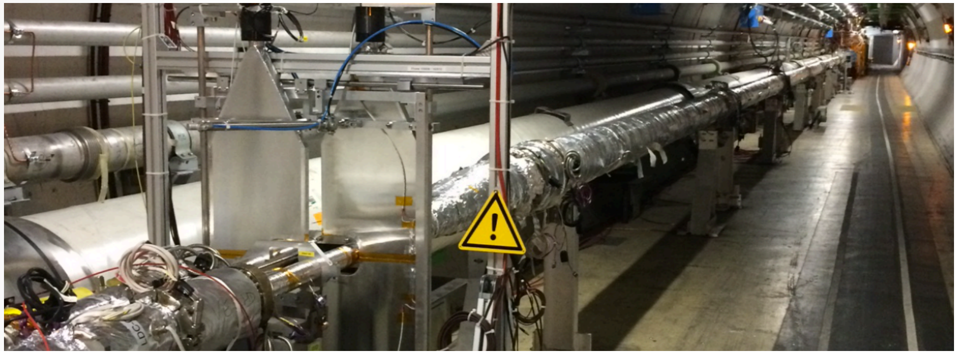


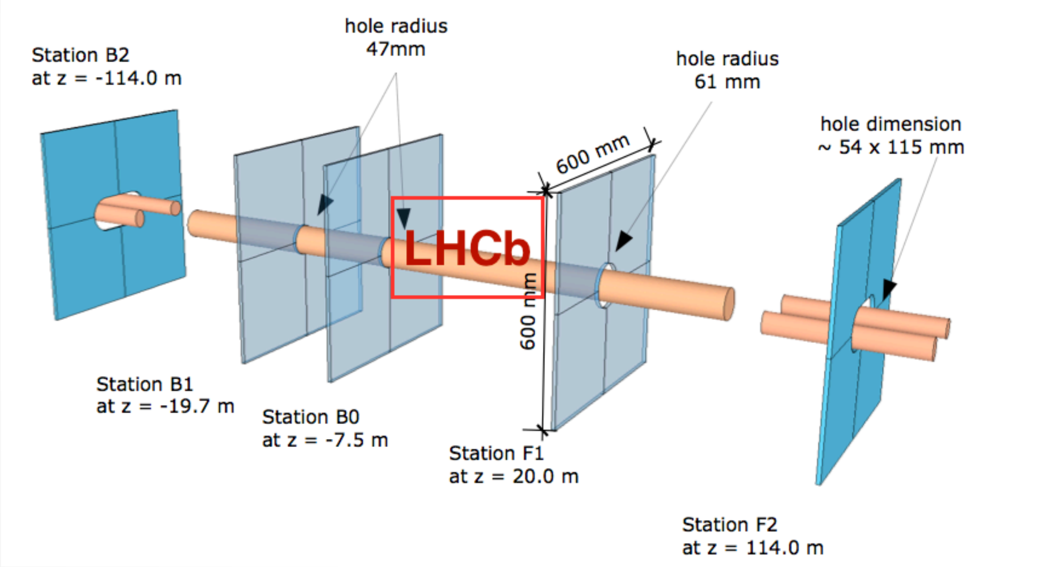
Forward spectrometer fully instrumented in $2 < \eta < 5$

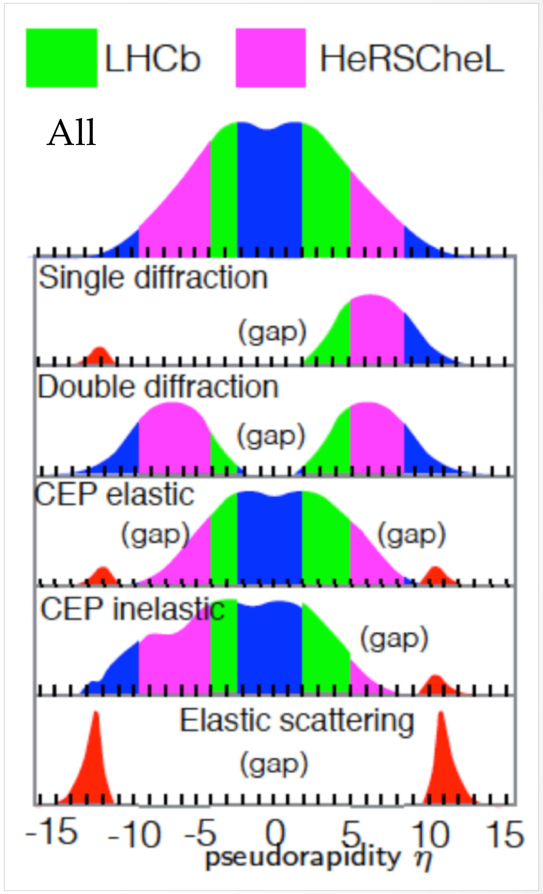
- Very good momentum and vertex resolution
  - $\delta p/p < 1$ % for $0 < p < 200$ GeV/c, $\delta x \sim 20$ μm for high p_T tracks
- Good particle identification
  - K: ~90 % efficiency, mis-ID < 5 %
  - μ: ~97 % efficiency, mis-ID ~ 1-3 %
- **Optimal:** μ, p, K^{+-}, π^{+-} produced inside Vertex Locator
- **Ok:** K^0_S, Λ^0, γ, e, π^0
- **Challenging:** stable neutral hadrons n, K^0_L

HeRSCHeL: forward scintillator

Carvalho Akiba et al. JINST 13 (2018) no.04, P04017







- Forward shower counters with acceptance $5 < |\eta| < 10$
- Better identification of diffractive events, important to identify CEP

Recent LHCb measurements

Many new high-precision results on charm

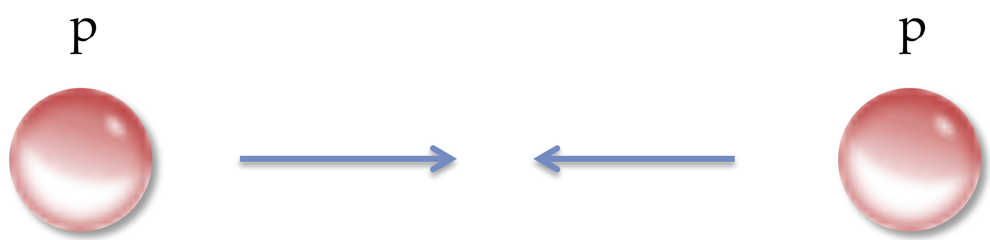
- pp @ 13 TeV
  - Inelastic cross-section: LHCb-PAPER-**2018**-003, arxiv:1803.10974
  - Prompt charm production: JHEP03(**2016**)159
  - J/ψ & J/ψ pair production: JHEP10(**2015**)172, JHEP06(**2017**)047
  - Central Exclusive Production (CEP) of J/ψ & $\psi(2S)$: LHCb-CONF-**2016**-007
  - Two-particle angular correlation: LHCb-PROC-**2017**-033
- pPb
  - @ 5 TeV - D^0 & $\psi(2S)$ production: JHEP10(**2017**)090, JHEP03(**2016**)133
  - @ 8.16 TeV
    J/ψ production: Phys. Lett. B 774 (**2017**) 159
    Two-particle angular correlation: Phys. Lett. B 762 (**2016**) 473
- Fixed target (SMOG)
  - pHe @ 110 GeV
    anti-proton spectra: LHCb-CONF-**2017**-002
  - pHe @ 86.6 GeV & pAr @ 110 GeV
    J/ψ, D^0 production: LHCb-PAPER-**2018**-023 (in prep.)

Older measurements @ 7 TeV

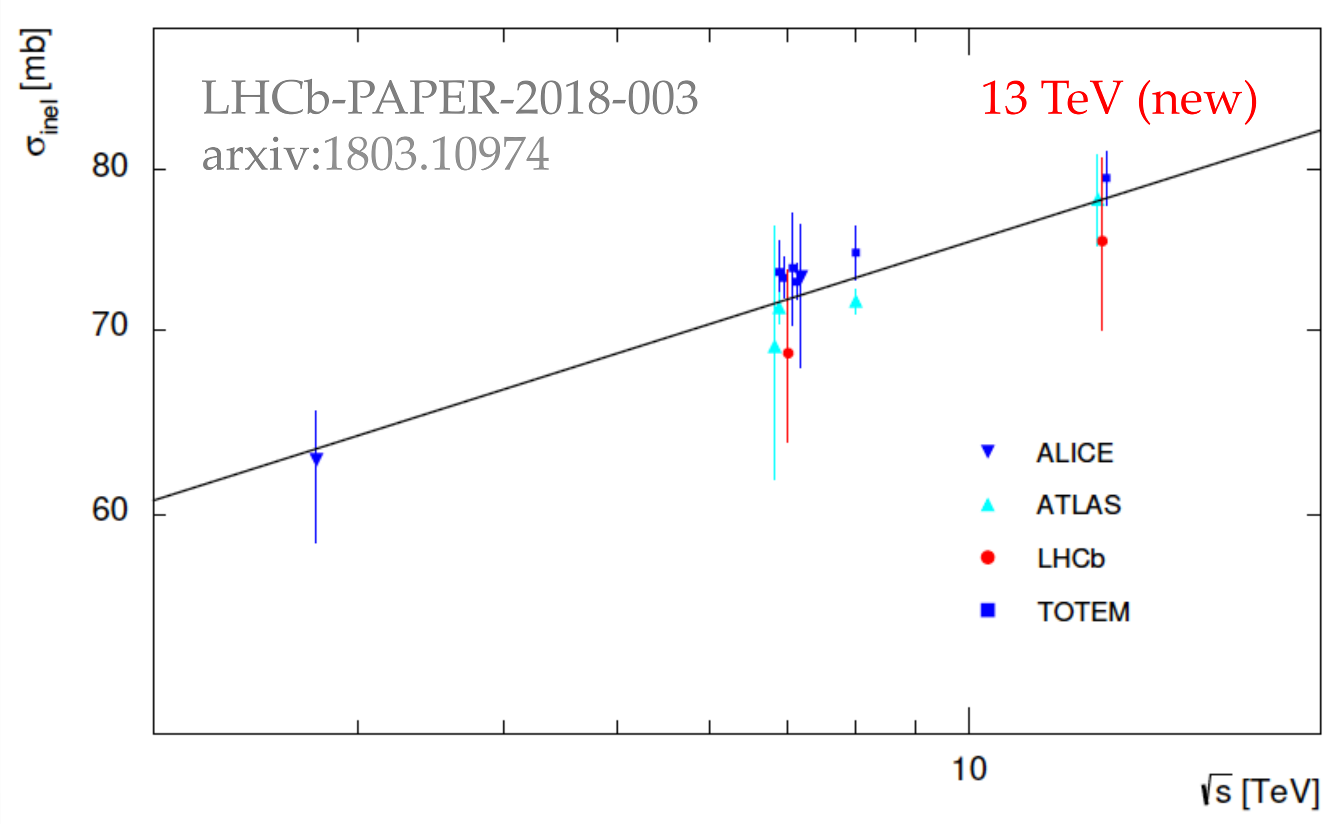
- Inelastic cross-section
- Charged particle spectra
- Multiplicities of charged particles
- Ratios of pi, K, p
- Energy flow

Eur. Phys. J. C (2012) 72:2168
Eur. Phys. J. C (2013) 73:2421
Eur. Phys. J. C (2014) 74:2888
JHEP02(2015)129

p+p collisions at 13 TeV

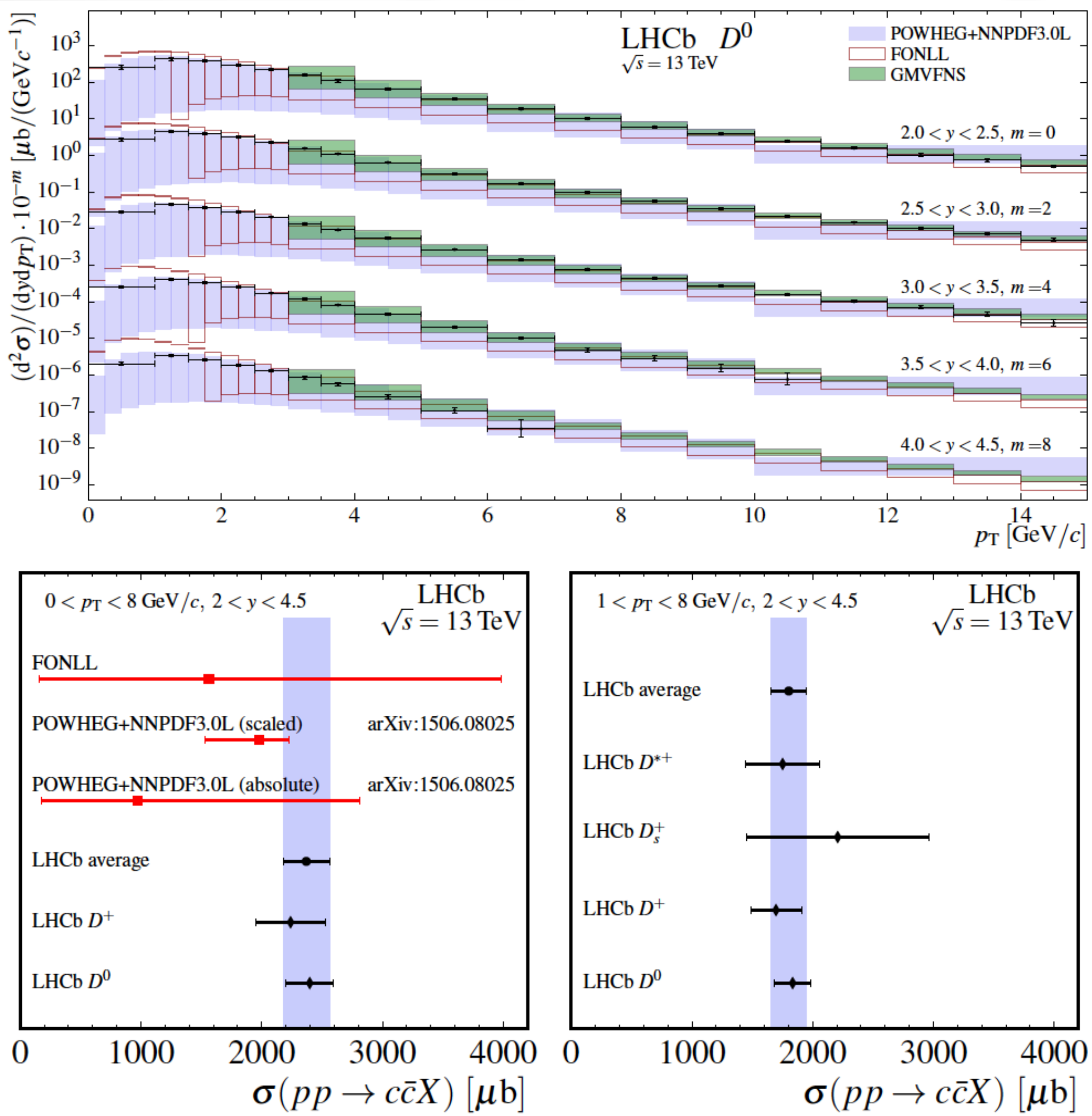


Inelastic cross-section



- New measurement using 10.7 nb^{-1} of zero-bias events at 13 TeV
- Total uncertainty 4 % (systematic)
  - Low intrinsic systematic uncertainty of analysis 0.2 %
  - Luminosity 3.9 %
- Excellent agreement with TOTEM and ATLAS results

Prompt charm production



JHEP03(2016)159
JHEP05(2017)074 (erratum)

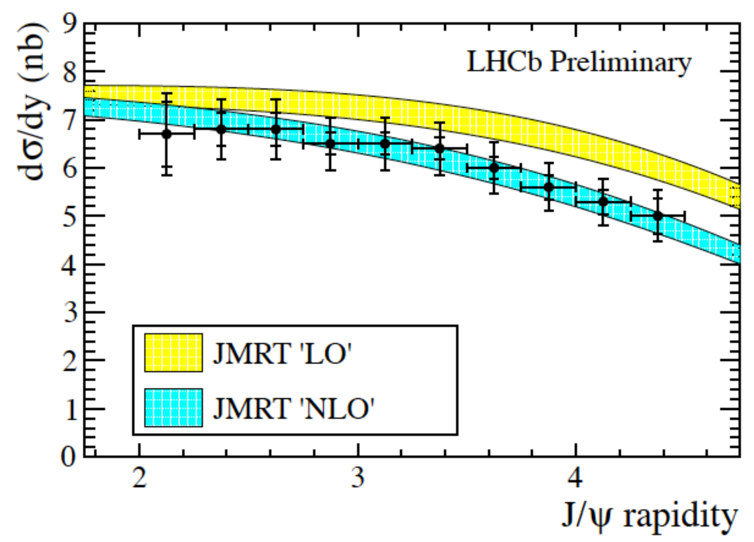
2D spectra of D^0, D^+, D_s^+, D^{*+} available, also ratios

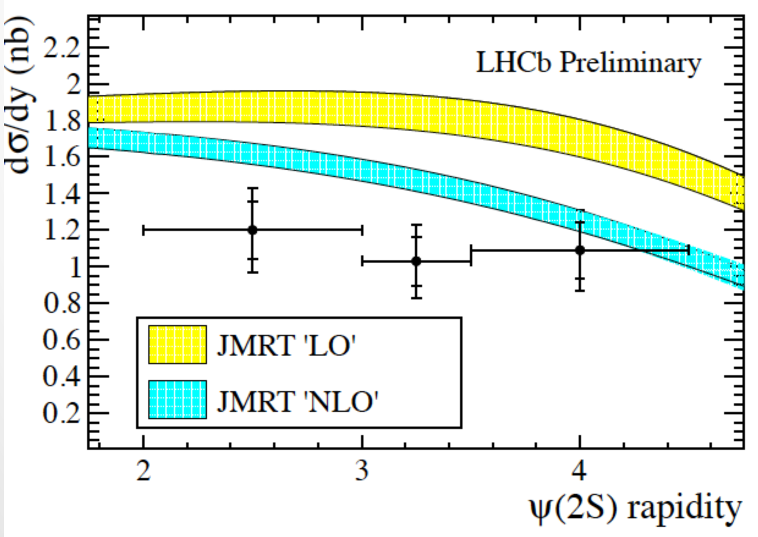
Good agreement of theory and measurement

Measurement much more accurate (5–10 %) than theory, especially at low p_T

Comparisons with CR models wanted

CEP of J/ψ and ψ(2S)



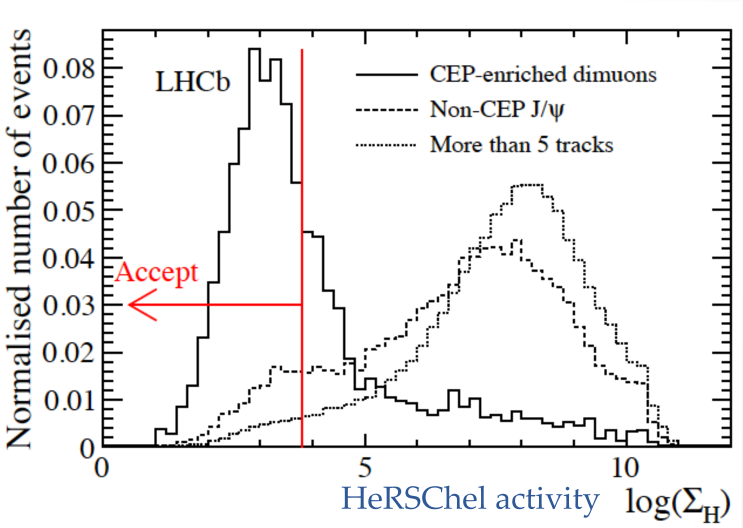


LHCb-CONF-2016-007

Central exclusive production

- Diffractive process: pp → pXp, X = meson
- Fusion of photon and pomeron
  photon (spin 1) + pomeron (spin 0) = vector meson (spin 1)
- pQCD calculations available
- Probes gluon PDF down to $x = 2\times10^{-6}$

Discrimination of CEP events with HeRSChel



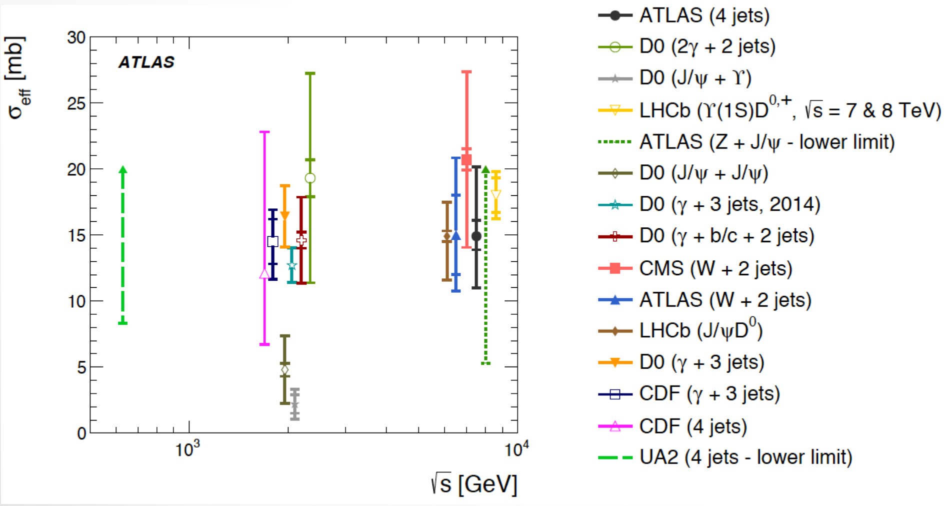
Inclusive J/ψ pair production

Probe for double-parton scattering (DPS)

$$\sigma_{\mathrm{DPS}}\,(J/\psi\, J/\psi\,) = \frac{1}{2}\frac{\sigma\,(J/\psi\,)^2}{\sigma_{\mathrm{eff}}}$$

σ_{eff} thought to be universal for all processes and energies

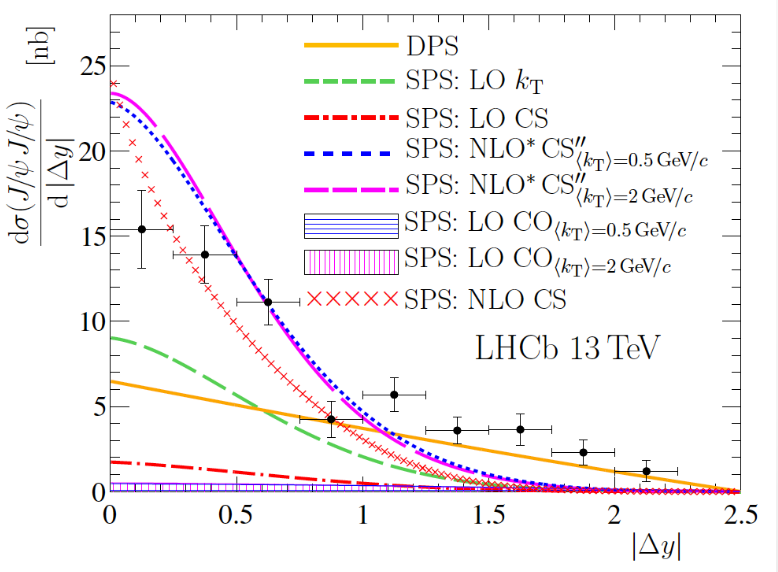
Compilation of σ_{eff} measurements



DPS process sensitive to parton structure

- parton transverse profile
- parton correlations

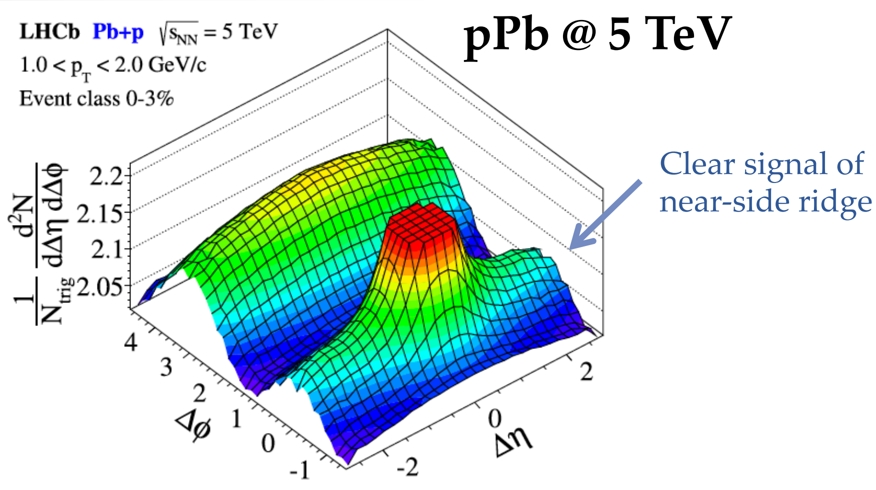
JHEP06(2017)047



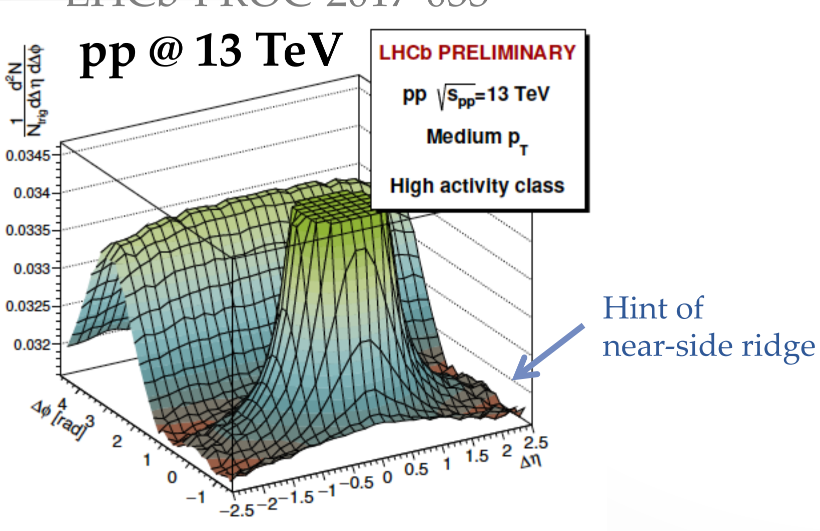
DPS contribution significant in tail of |Δy| distribution

Angular correlations

Phys. Lett. B 762 (2016) 473



LHCb-PROC-2017-033



Take pairs of charged prompt particles, bin by (Δη, Δϕ)

Structures in angular correlation plot

- Near-side peak from jets
- Away-side ridge from back-to-back jets
- Near-side ridge from interesting physics
    - Quark gluon plasma
    - Color glass condensate
    - Collective effects (e.g. flow in EPOS)

Near-side ridge in pPb @ 5 TeV

- Clear signal in central collisions

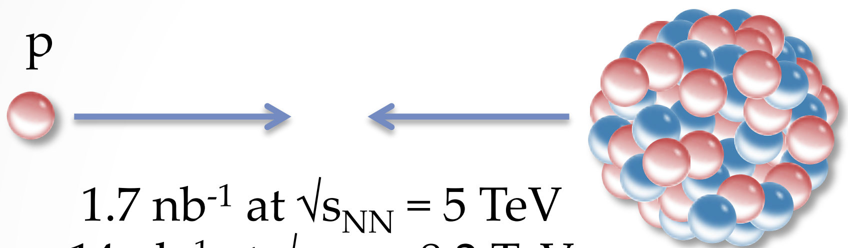
Near-side ridge in pp @ 13 TeV

- Hint of signal in high activity events
- Needs further study with more statistics

p+Pb collisions

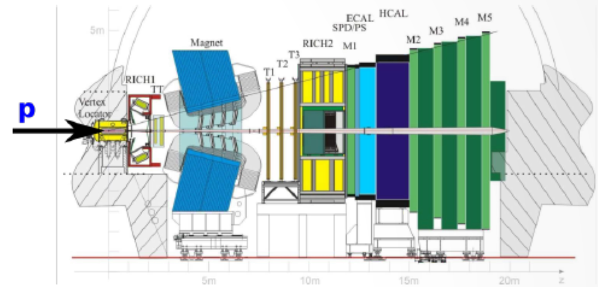
Pb

p



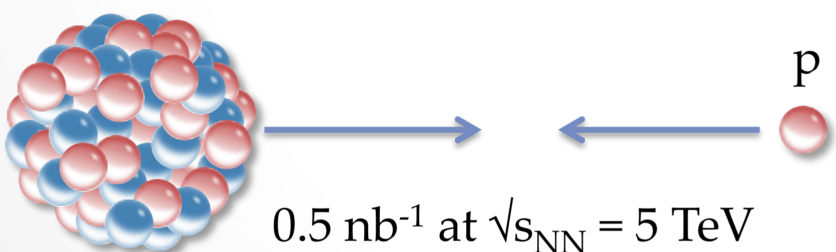
1.7 nb^{-1} at $\sqrt{s_{NN}}$ = 5 TeV
14 nb^{-1} at $\sqrt{s_{NN}}$ = 8.2 TeV
Probes low x in nuclear PDF

"forward"



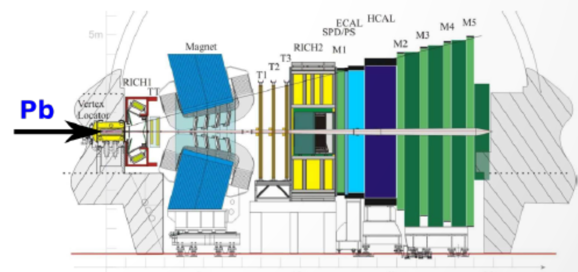
Pb

p

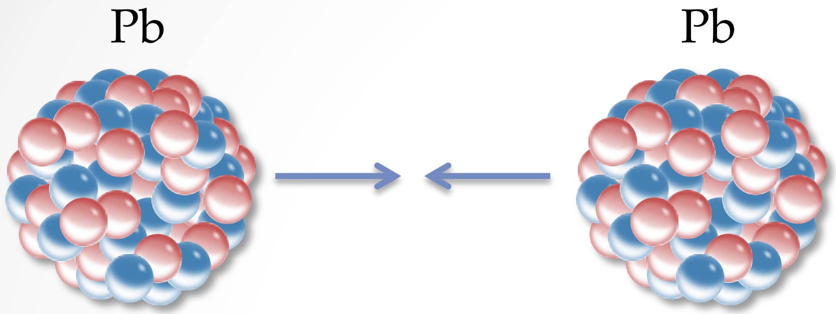


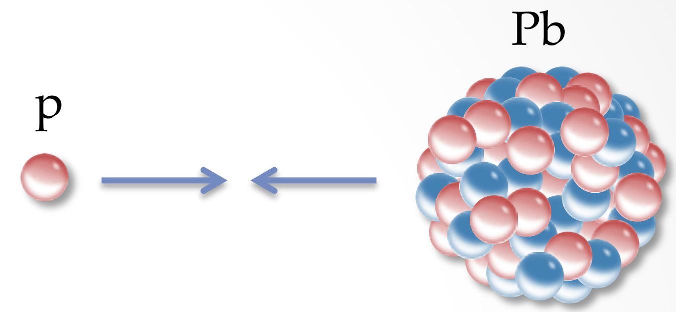
0.5 nb^{-1} at $\sqrt{s_{NN}}$ = 5 TeV
21 nb^{-1} at $\sqrt{s_{NN}}$ = 8.2 TeV
Probes high x in nuclear PDF

"backward"

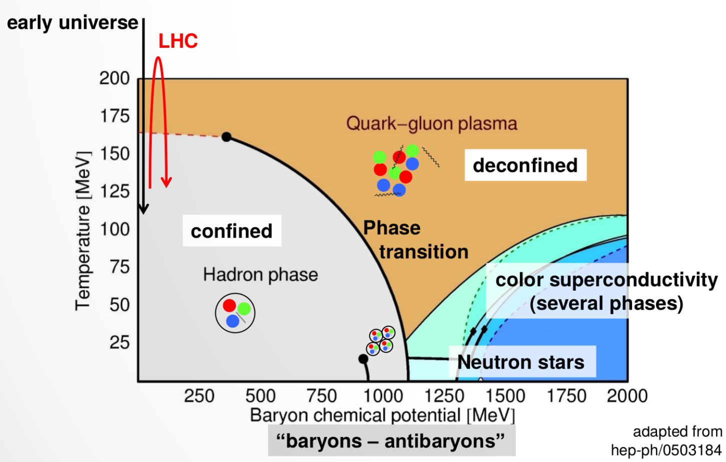


Heavy-ion physics





- Probe **Q**uark **G**luon **P**lasma (QGP)



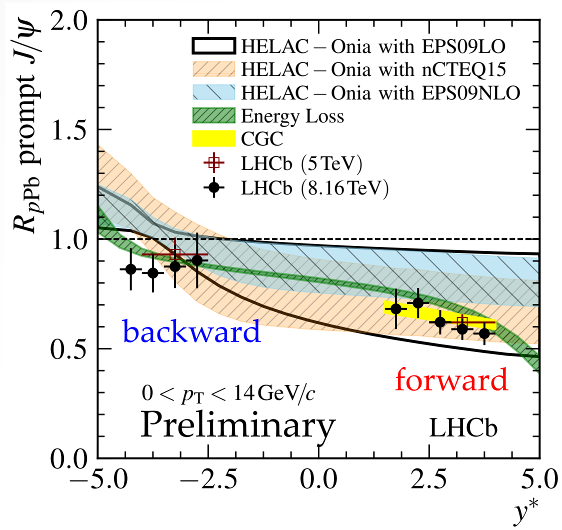
- Study cold nuclear matter effects, disentangle from QGP effects
- Study nuclear PDF at low and high x (forward, backward)
- Study absorption and coherent energy loss in nuclear medium

Nuclear modification factor

$$R_{pA} = \frac{\text{cross-section for pPb}}{\text{A x cross-section for pp}}$$

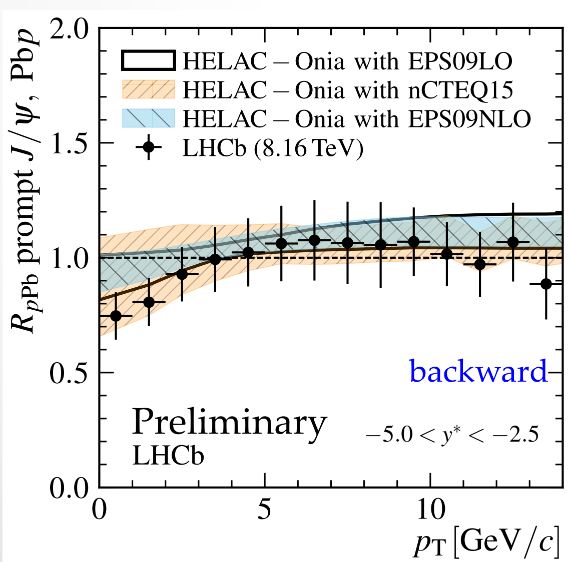
Superposition model: $R_{pA} = 1$

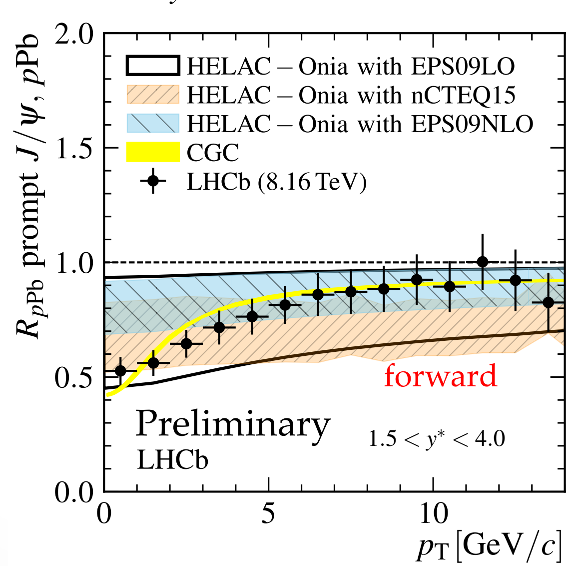
Prompt J/ψ production



LHCb-PAPER-2017-014

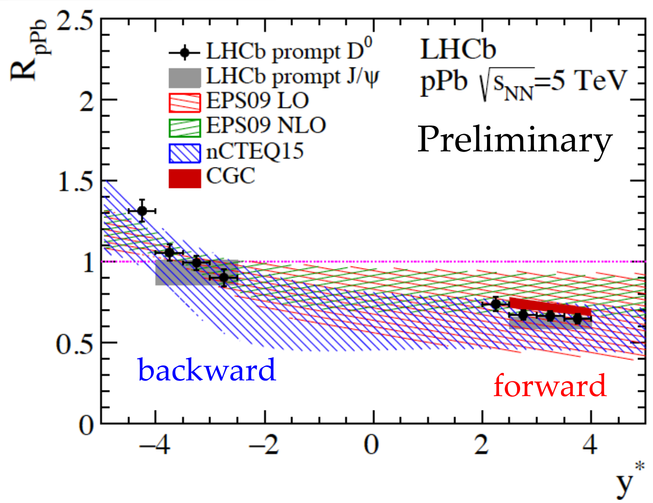
- Up to 50 % suppression in forward direction
- No visible dependence on beam energy
- Parton density models constrained
- Good agreement with Color Glass Condensate model





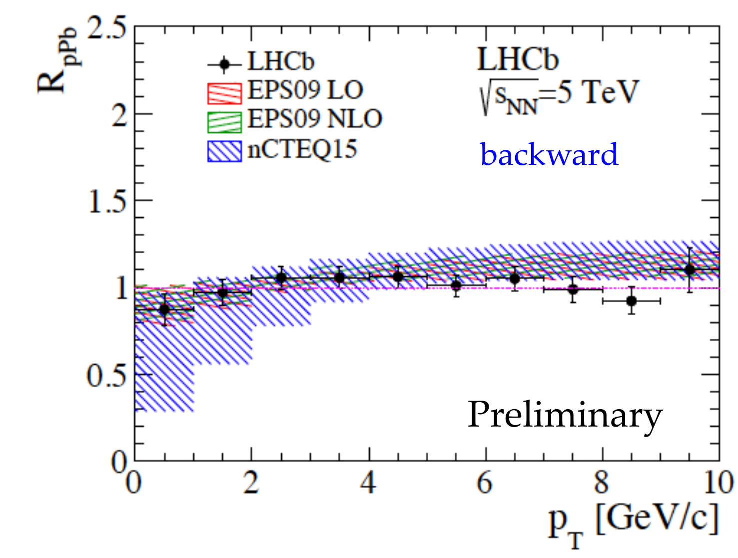
Also available:
double-differential CS
Ratio forward/backward

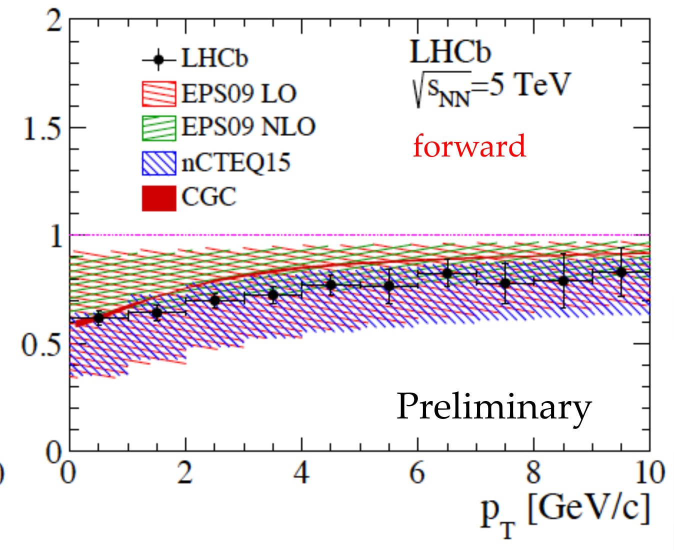
Prompt D^0 production



LHCb-PAPER-2017-015

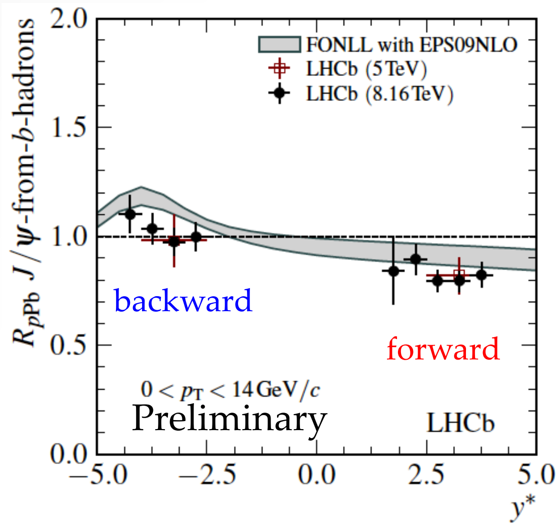
- Small excess in backward rapidity
- Overall similar to R_{pPb} for J/ψ: similar cold nuclear effects
- Parton density models constrained
- **Superposition model** ok for high x_{Pb} and p_T, but violated for low x_{Pb} and p_T





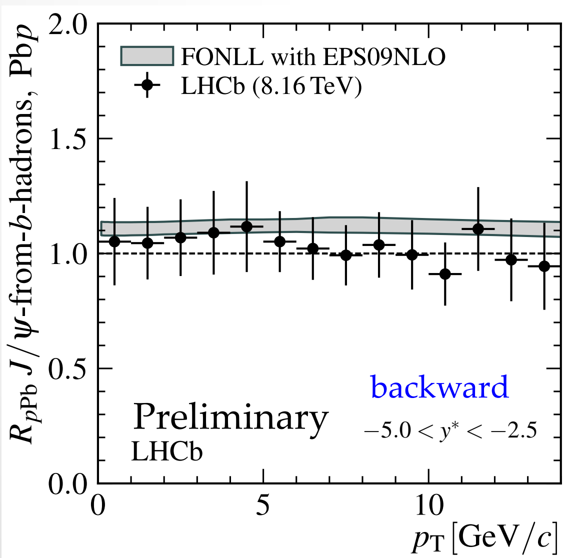
Also available:
double-differential CS
Ratio forward/backward

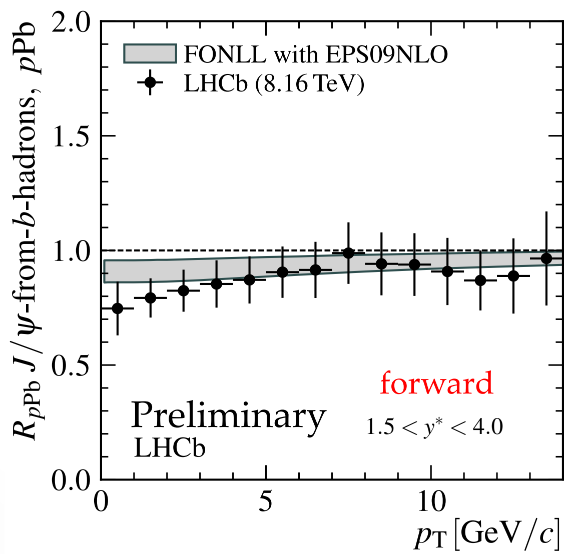
J/ψ from b-mesons



LHCb-PAPER-2017-014

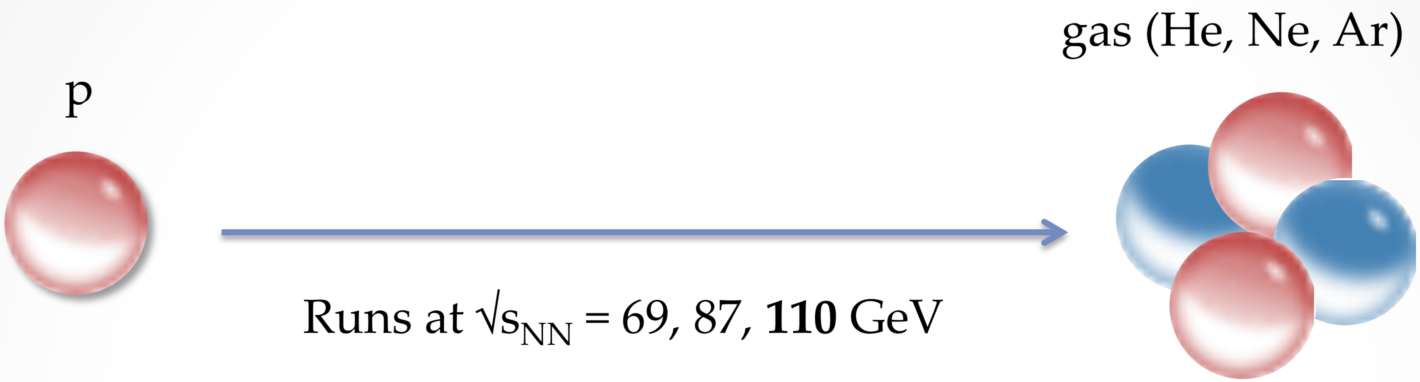
- Smaller deviations from unity
- No visible dependency on beam energy
- Good agreement with model

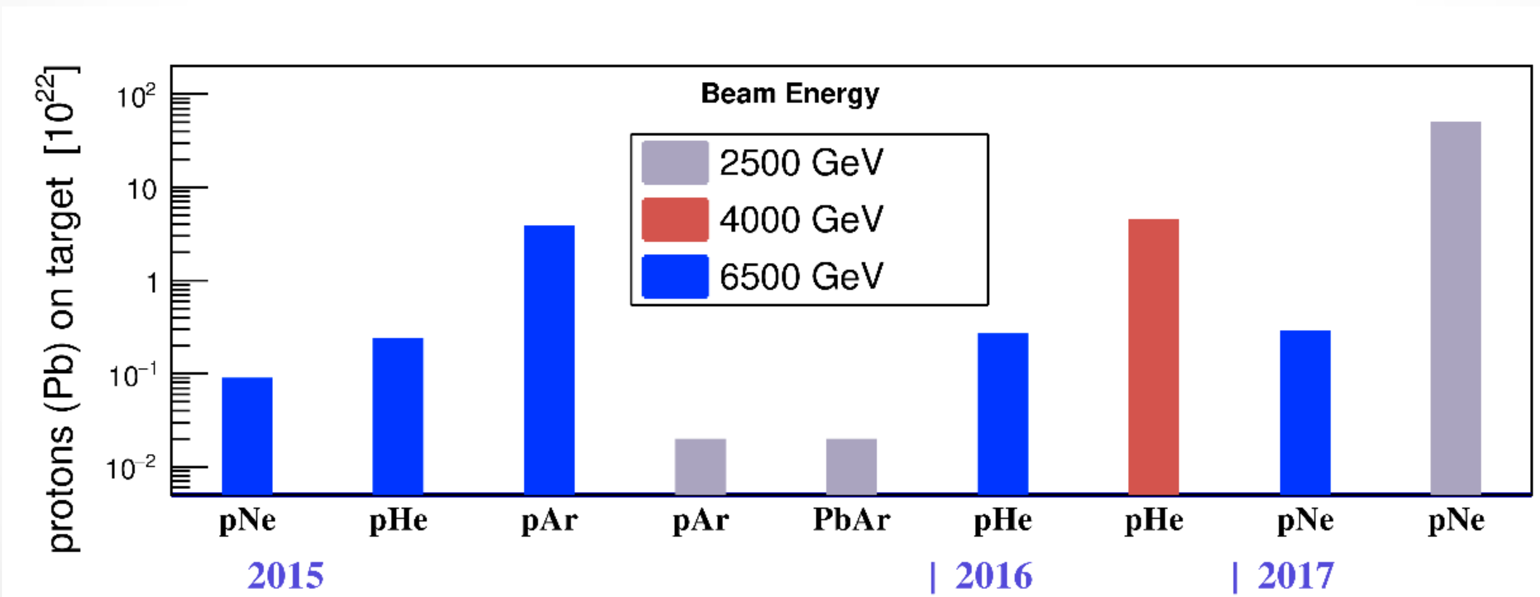




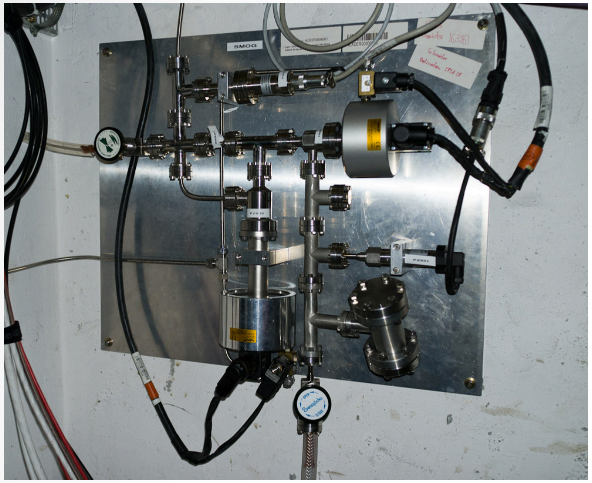
Also available:
double-differential CS
Ratio forward/backward

p+Gas collisions





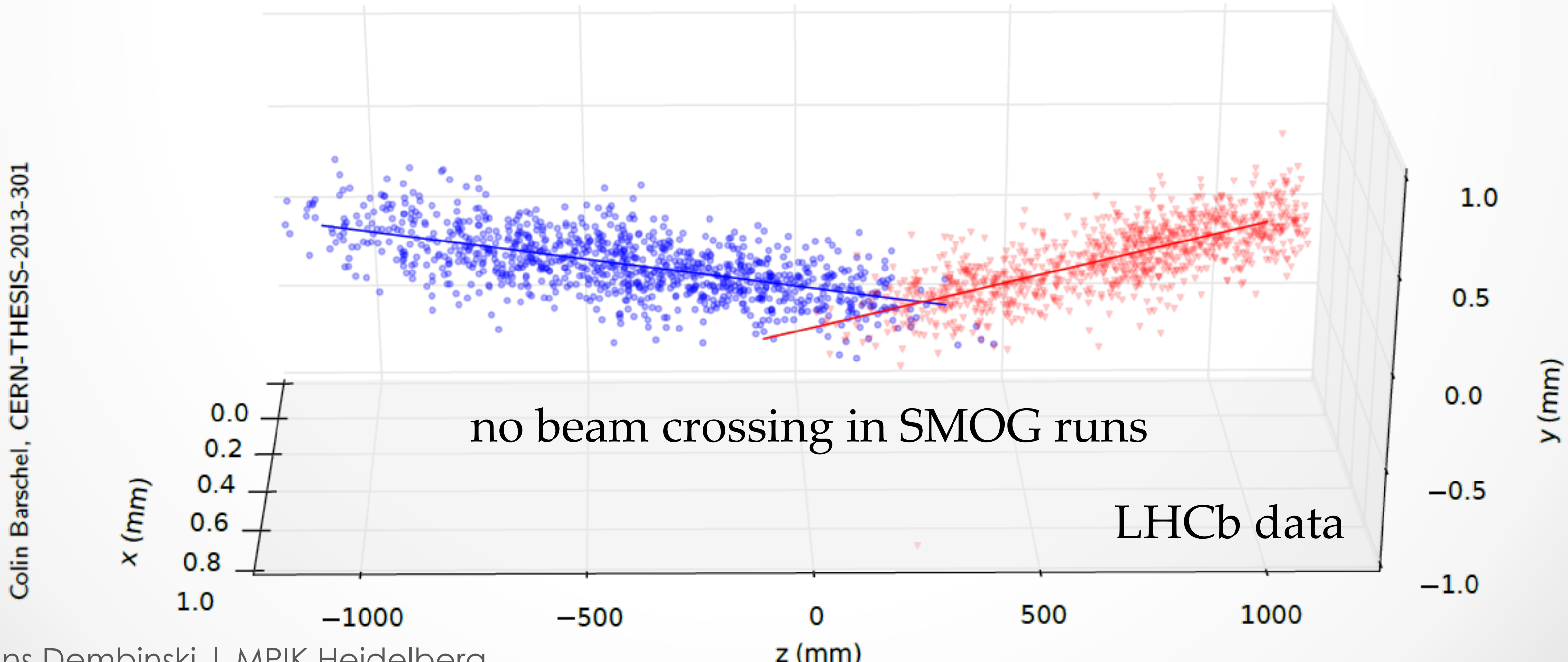
SMOG: Gas target



JINST 9 (2014) P12005

System for **M**easuring **O**verlap with **G**as

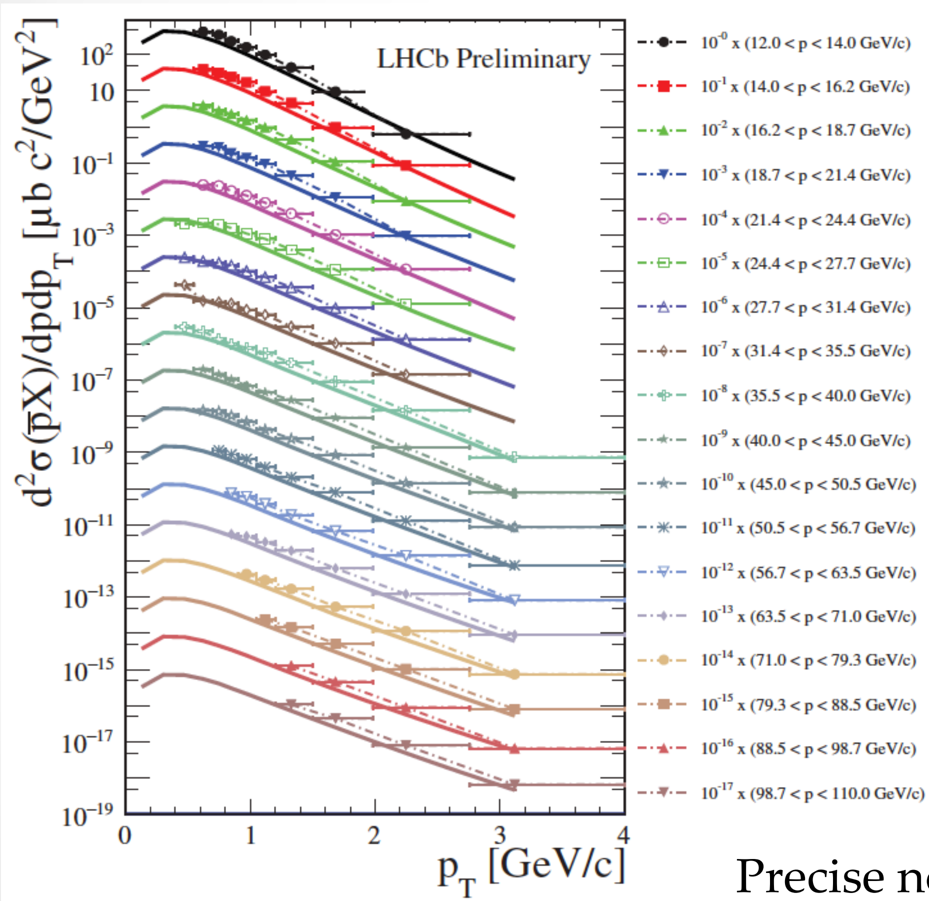
- Inject He, Ne, Ar into beam pipe at ~2x10^{-7} mbar
- Enabled best luminosity measurement at LHC
- Allows data taking in **fixed target mode**



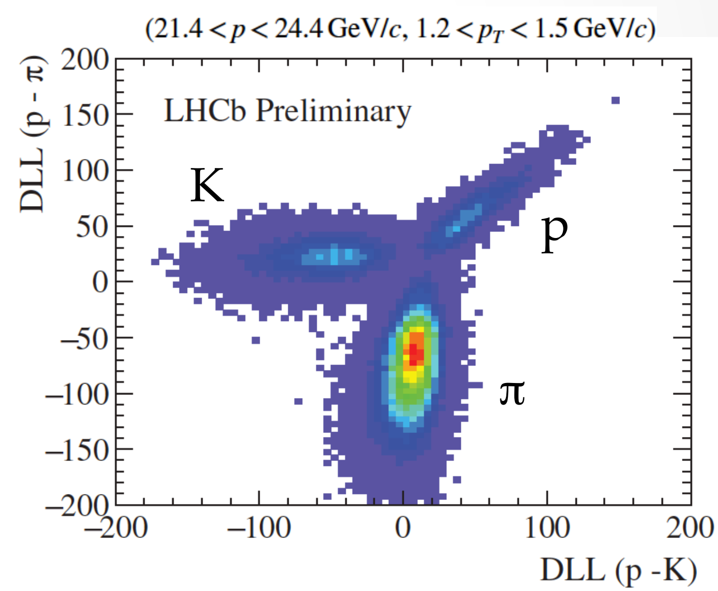
anti-p production in pHe

Prompt production at $\sqrt{s_{NN}}$ = 110 GeV

LHCb-PROC-2018-001
LHCb-CONF-2017-002



Excellent anti-proton identification
(multivariate, uses both RICH detectors)



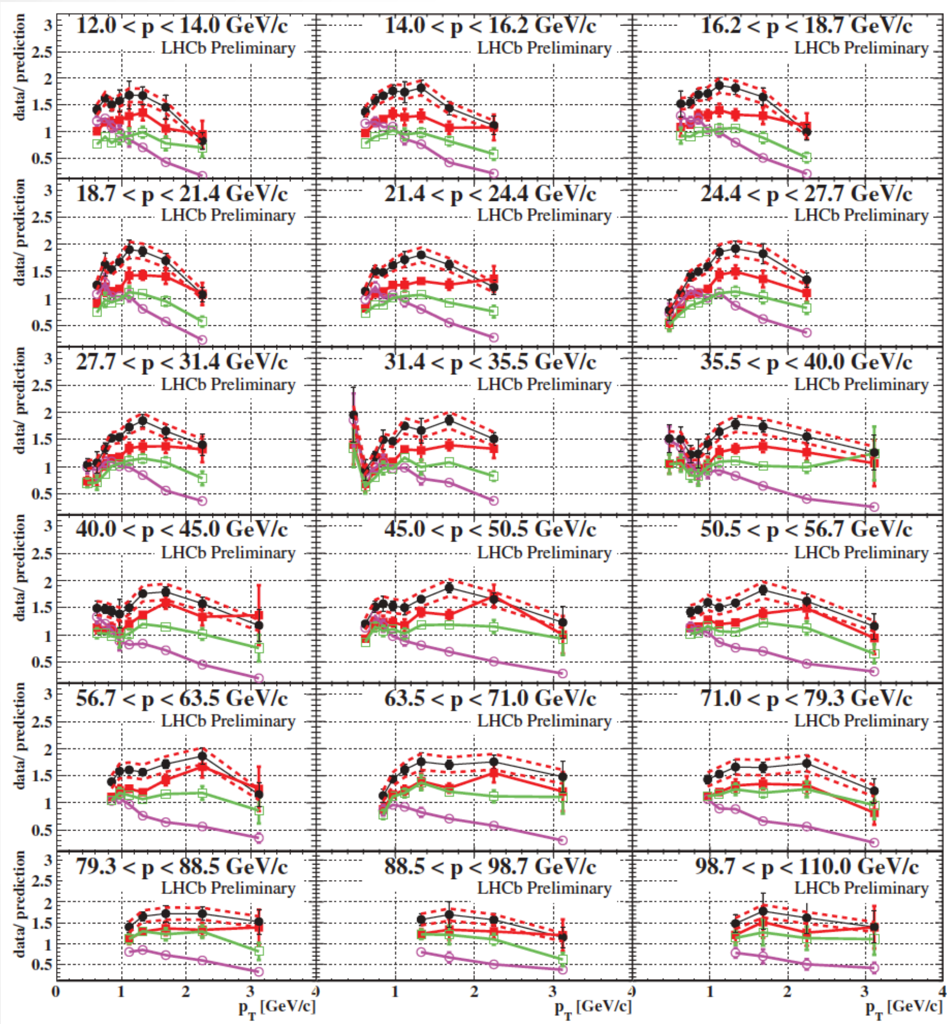
Total uncertainty < 10 %

Precise normalization of cross-section

- Reference: single electron-scattering ($p+e^-_{gas}$)
- Clear signature, backgrounds charge-symmetric
- Only **6 % uncertainty**

anti-p production in pHe

EPOS-LHC **EPOS-1.99** **HIJING** **QGSJet-II.04**



LHCb-PROC-2018-001
LHCb-CONF-2017-002

Data / model predictions

- Simulations with CRMC
  https://web.ikp.kit.edu/rulrich/crmc.html
- EPOS-LHC
  Too few anti-p by factor 1.5 to 2
  Fewer anti-p than EPOS-1.99
- HIJING
  Best overall agreement
- QGSJet-II.04
  Good at low (p, p_T)
  Too many anti-p at high (p, p_T)

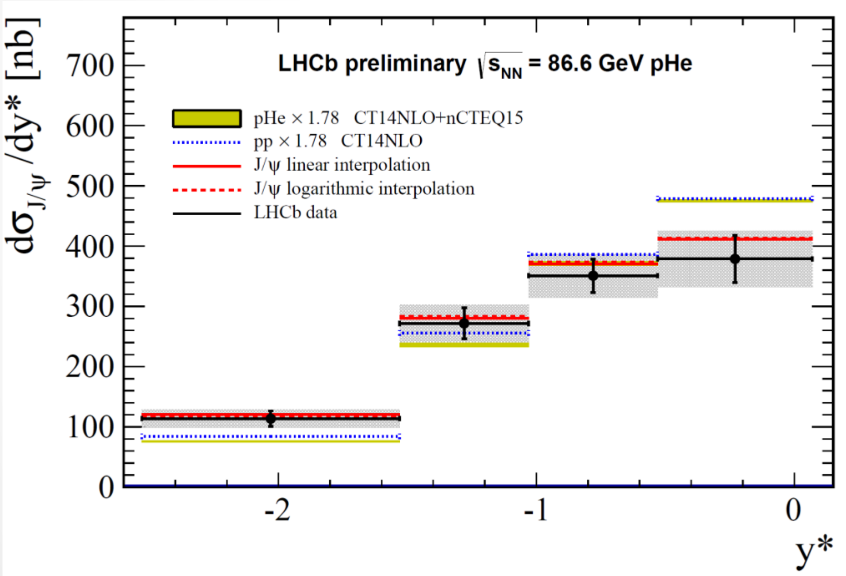
J/ψ production in p(He,Ar)

LHCb-PAPER-2018-023
in preparation

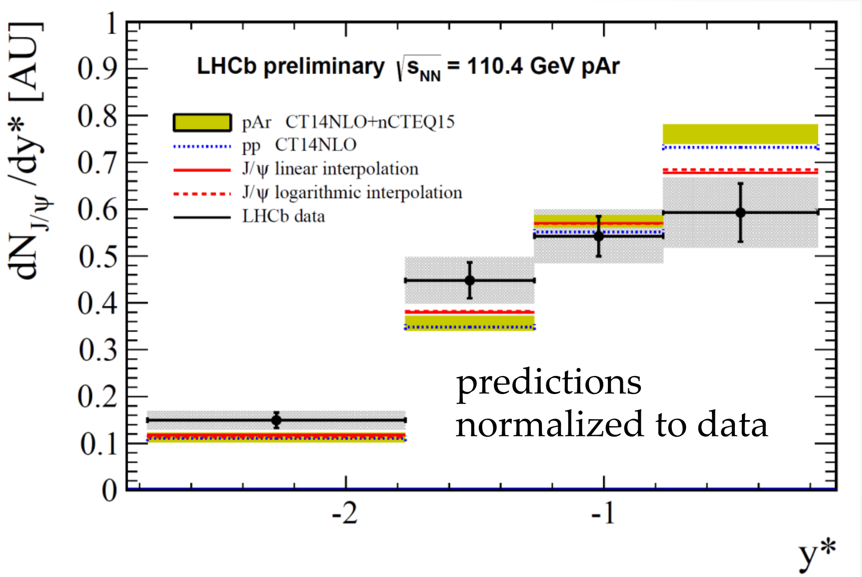
- Cross-section reported for p+He, luminosity measurement available
- Yields reported for p+Ar; no normalization information, only shape

Cross-section/yield vs. p_T also available + total cross-section for p+He

pHe: differential cross-section



pAr: differential yield (no normalization)



- Good agreement with interpolation based on PHENIX and HERA-B data
- HELAC-ONIA under-estimates p+He cross-section by factor 1.78

HELAC-ONIA: Shao & Lansberg, EPJC(2017)77: 1

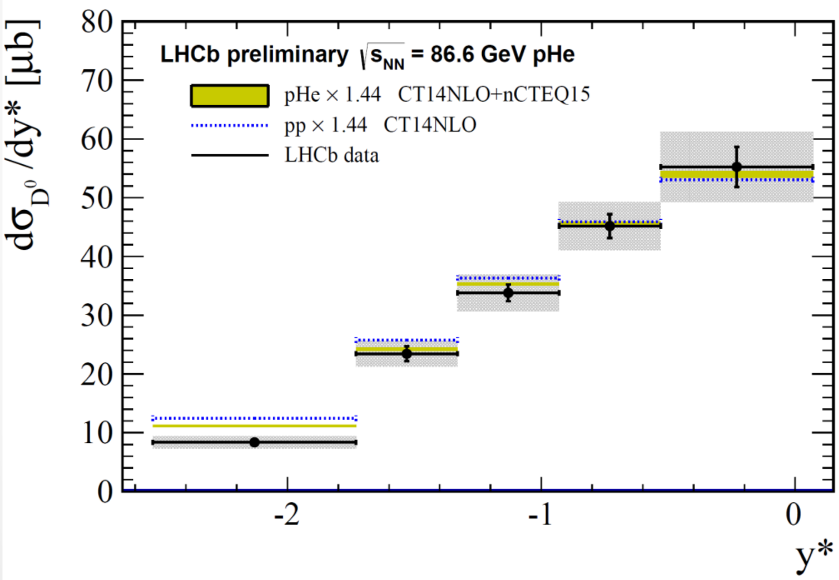
D^0 production in p(He,Ar)

LHCb-PAPER-2018-023
in preparation

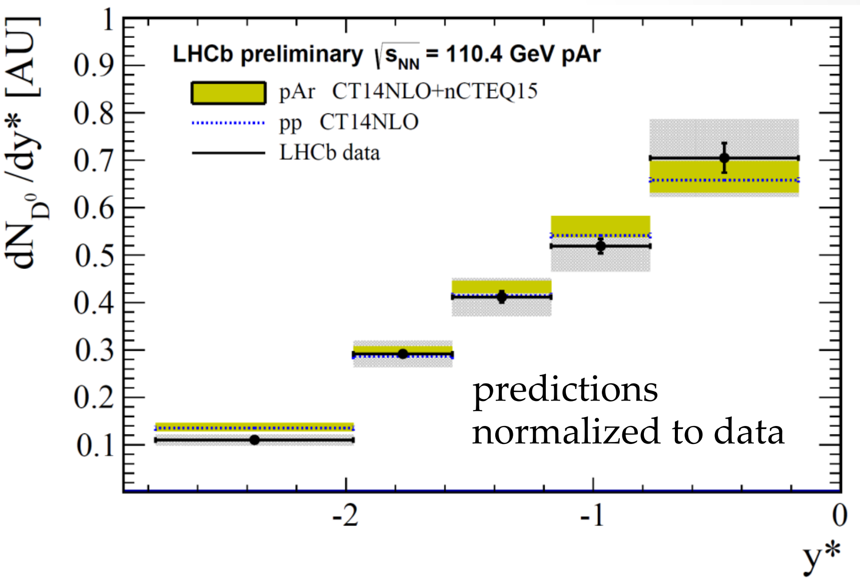
- Cross-section reported for p+He, luminosity measurement available
- Yields reported for p+Ar; no normalization information, only shape

Cross-section/yield vs. p_T also available + total cross-section for p+He

pHe: differential cross-section



pAr: differential yield (no normalization)



- Good agreement with interpolation based on PHENIX and HERA-B data
- HELAC-ONIA under-estimates p+He cross-section by factor 1.44

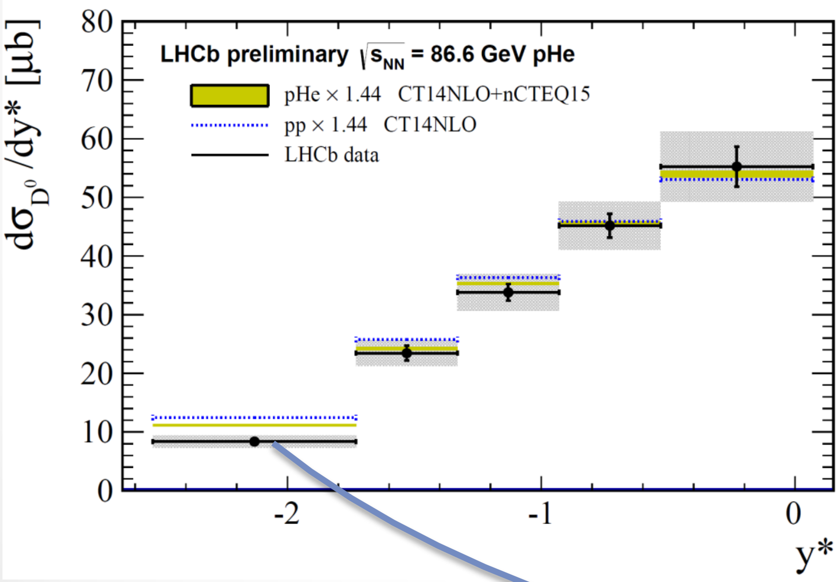
HELAC-ONIA: Shao & Lansberg, EPJC(2017)77: 1

Intrinsic charm in nucleon?

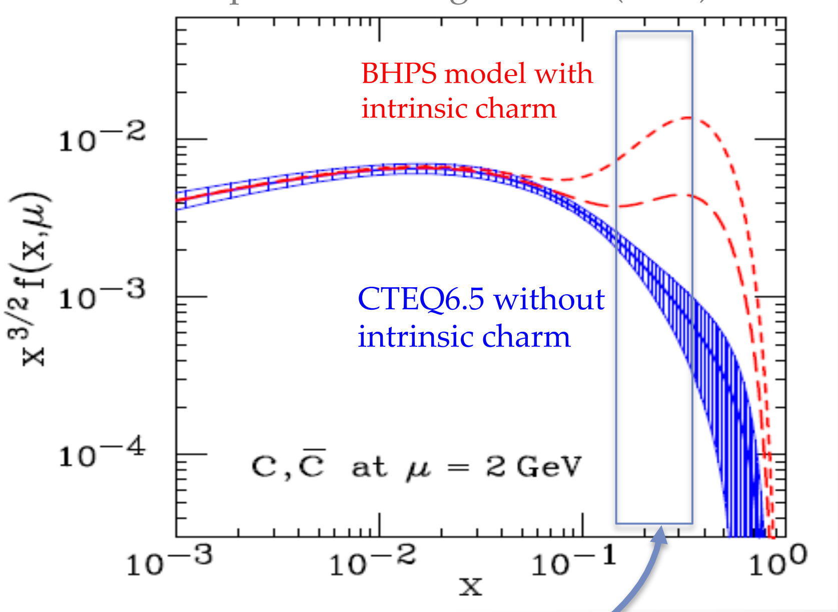
LHCb-PAPER-2018-023
in preparation

- D^0 cross-section provides first test of intrinsic charm content in the nucleon
- No sign of strong intrinsic charm contribution to nuclear PDF

pHe: differential cross-section



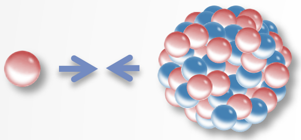
Pumplin, Lai, Tung, PRD75 (2007), 054029



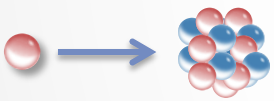
First bin probes high x region of nuclear PDF, where intrinsic charm contributes

Summary & Outlook

- QCD with p+p collisions @ 13 TeV
  - Charm production: J/ψ, D^0, D^+, D_s
  - Parton PDF: J/ψ pairs, CEP of J/ψ and $\psi(2S)$
  - Collective effects: Two-particle angular correlations
  - **Prospects**
    - Precision measurement of π, K, p spectra
    - Precision measurement of e.m., hadron energy flow



- Heavy-ion physics with p+Pb collisions @ 5 TeV and 8.16 TeV
  - Cold nuclear matter effects (test of superposition assumption): J/ψ, D^0
  - Collective effects: Two-particle angular correlations



- Light-ion physics with p+(He,Ar) collisions @ 86.6 and 110 GeV
  - Charm production and probe of nuclear PDF at high-x: J/ψ, D^0
  - Precision measurement of anti-proton production for AMS-02 and PAMELA
  - **Prospects**
    - Measure non-prompt contribution (20-30 %) to anti-proton yield from hyperon decays
    - Measurement of π, K spectra to constrain e^+ production
    - Scaling violation? Repeat analysis with p+He(gas) collisions @ 86.6 GeV

LHCb is excellent for studying CR physics. Lots of activity, more to come.

Acknowledgments

- Lead nucleus graphic from Inductiveload - Public Domain: https://commons.wikimedia.org/w/index.php?curid=2858666