pA Physics at LHCb and HERA-B

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Outline

- Introduction
- The LHCb Experiment
- The HERA-B Experiment
- Summary

AFTER @ LHC

Ecole de Physique des Houches

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1. INTRODUCTION

➜ *common features of LHCb and HERA-B*

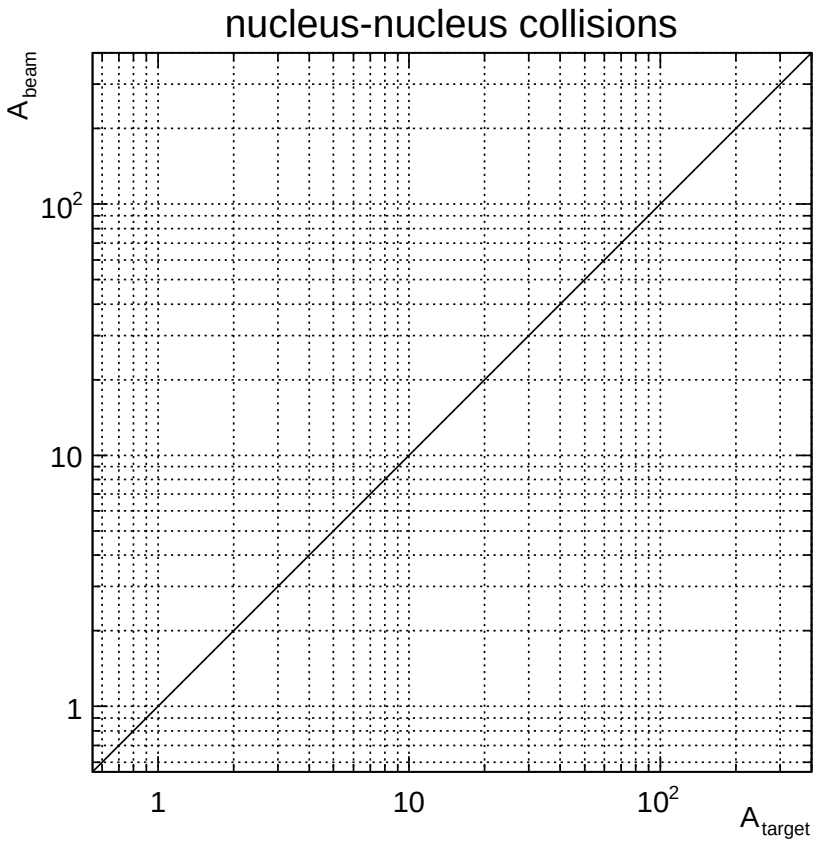
- single-arm forward spectrometer at a hadron machine
- high-rate experiments in hadronic environment
- designed to do heavy flavour physics
  - ➜ CP-violation
  - ➜ rare decays
- able to do also electroweak measurements and QCD studies
  - ➜ access to different types of hadron-hadron interactions
  - ➜ different kinematic regimes
  - ➜ study of exclusive and diffractive processes
  - ➜ particle production in different types of hadronic interactions

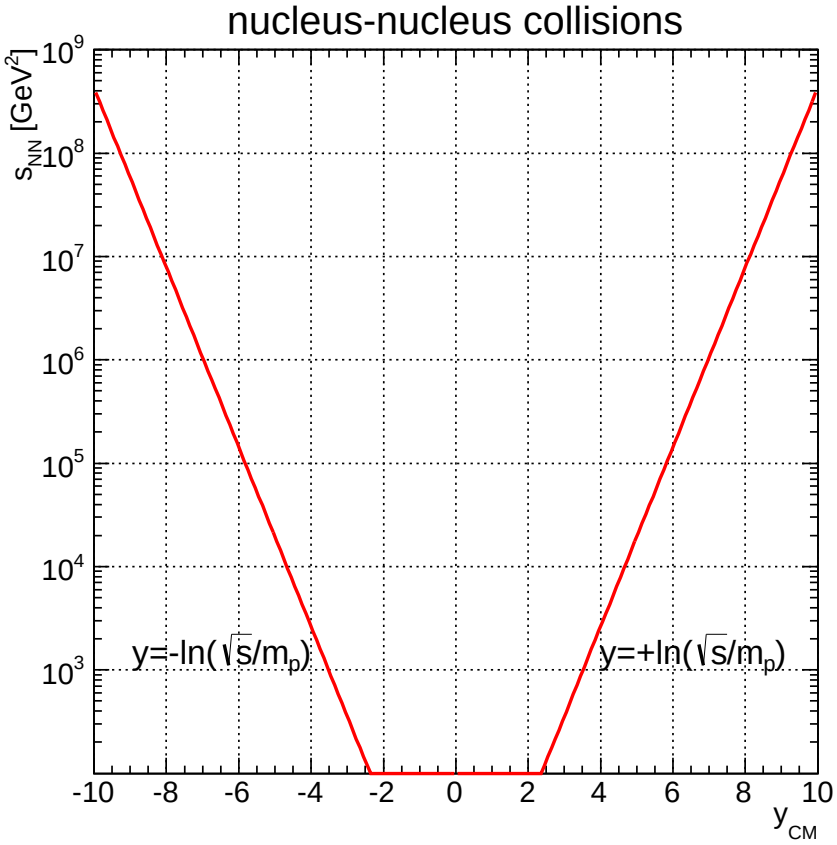
❖ highest $\sqrt{s_{NN}}$ of lab-experiments with matter-matter collisions!

➜ physics reach

Configuration spaces

➜ *the "x-Q^2"-planes of hadronic interactions*





- collisions partners: $A_{\mathrm{beam}} \leq A_{\mathrm{target}}$ – "beam" defines positive rapidity
- kinematically allowed range for final state particles

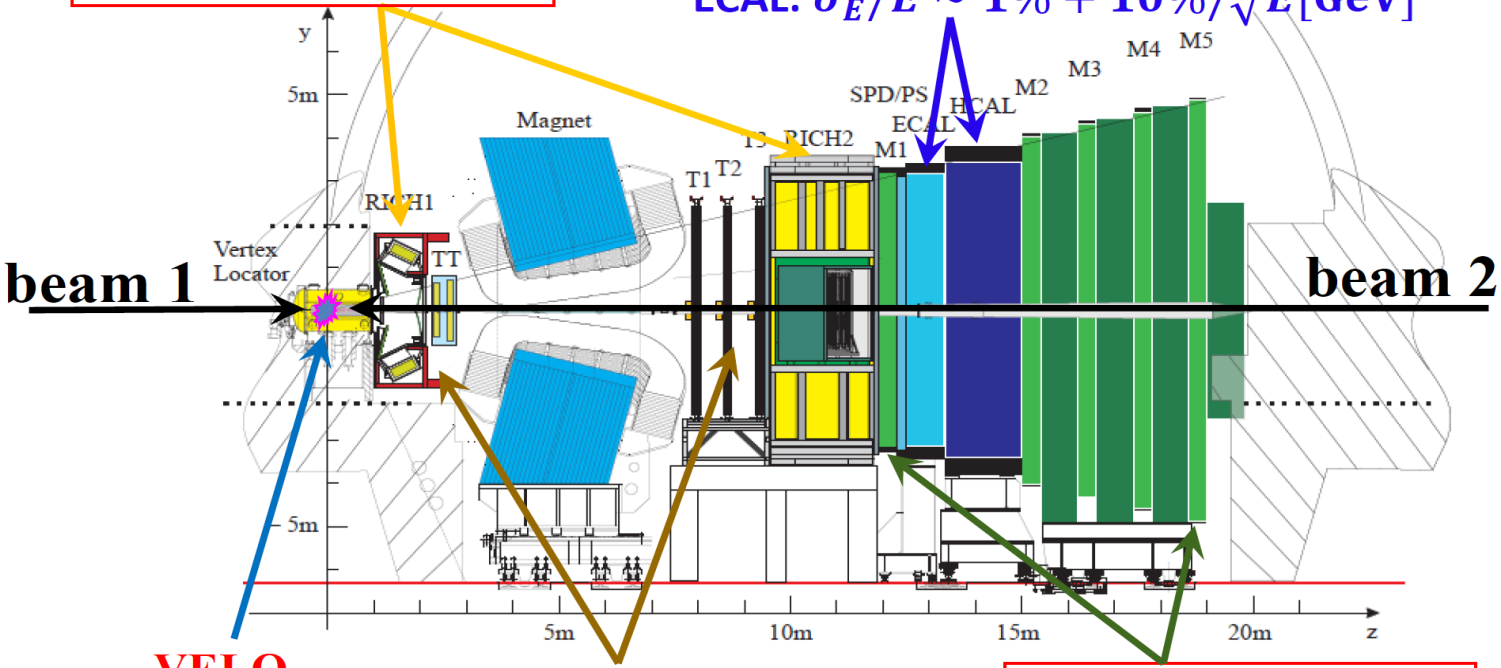
2. The LHCb Experiment

JINST 3 (2008) S08005

Pseudorapidity acceptance
$2 < \eta < 5$

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\text{GeV}]}$

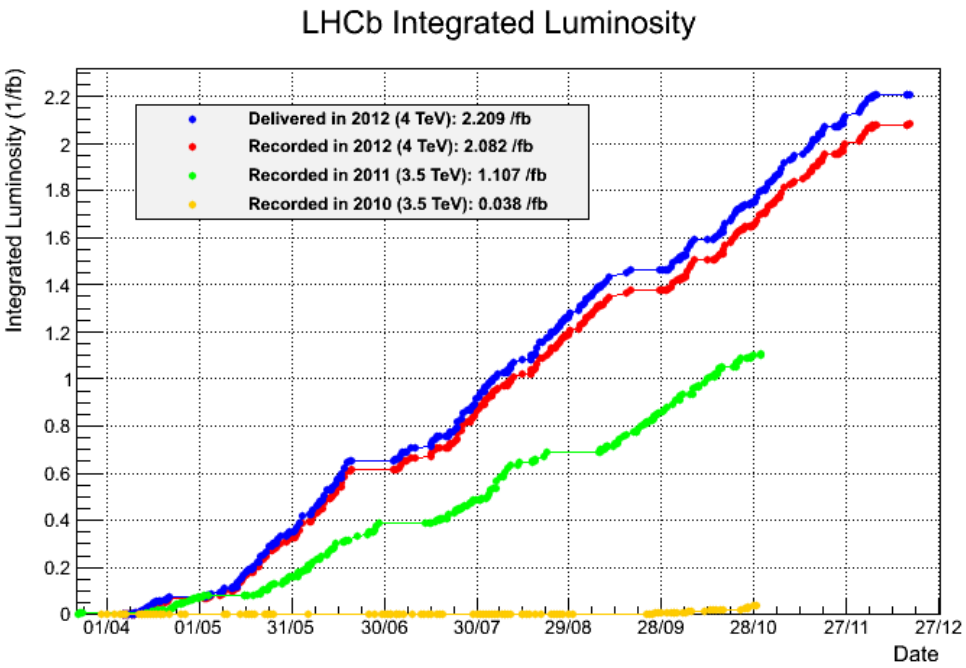


VELO
$\sigma_{IP} \sim 20\ \mu m$
for high-p_T tracks
bwd acc. $-4 < \eta < -1.5$

Tracking System
$\Delta p/p = 0.4\%@5\ \text{GeV}/c$
to $0.6\%@100\ \text{GeV}/c$

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ mis-id: $1 \sim 3\%$

Data taking history

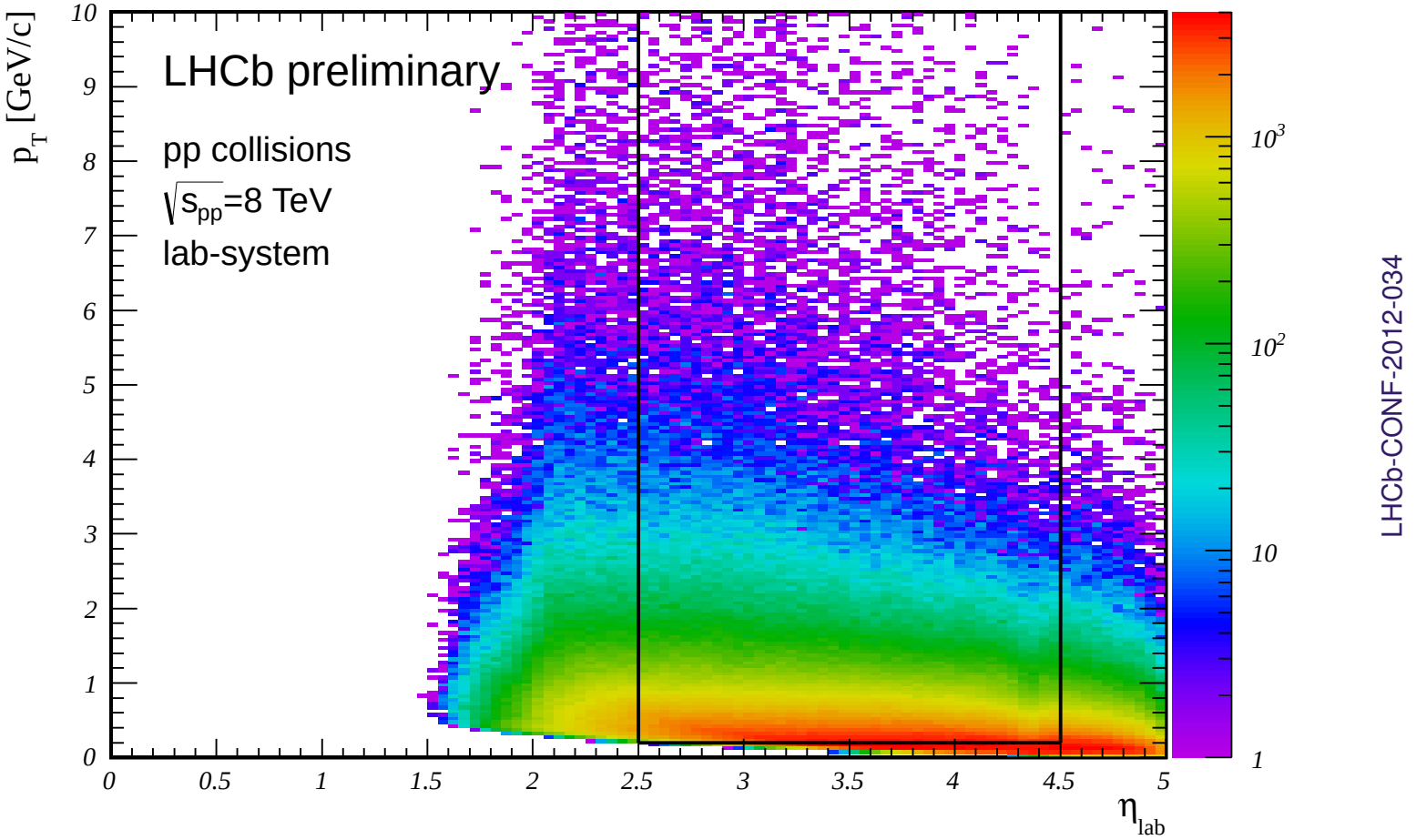


year	int.luminosity	E[TeV]
2009	6.8 μb^{-1}	0.9
2010	0.3 nb^{-1}	0.9
2010	37 pb^{-1}	7
2011	0.1 pb^{-1}	2.76
2011	1 fb^{-1}	7
2012	2 fb^{-1}	8
2013	1.3 nb^{-1}	5 (pA)
2013	0.6 nb^{-1}	5 (Ap)
2013	3 pb^{-1}	2.76

- DAQ efficiency $\approx 95\%$
- instantaneous luminosity up to $L = 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
  - ➜ twice design value at double the nominal bunch spacing
  - ➜ luminosity leveling for LHCb by beam steering
- a total of about 2×10^{14} pp-collisions scrutinized

Kinematic coverage of LHCb

➜ *particle flux in minimum-bias pp-interactions at $\sqrt{s} = 8$ TeV*



examples illustrating the physics potential ➜

Production of light flavors

➜ *particle production ratios as a function of y and p_T*

- antiparticle/particle ratios and ratios of different particle species

$$\frac{\pi^-}{\pi^+}\,,\ \frac{K^-}{K^+}\,,\ \frac{\bar{\Lambda}}{\Lambda} \quad \text{and} \quad \frac{p+\bar{p}}{\pi^+ + \pi^-}\,,\ \frac{K^+ + K^-}{\pi^+ + \pi^-}\,,\ \frac{\bar{\Lambda}}{K^0_S}$$

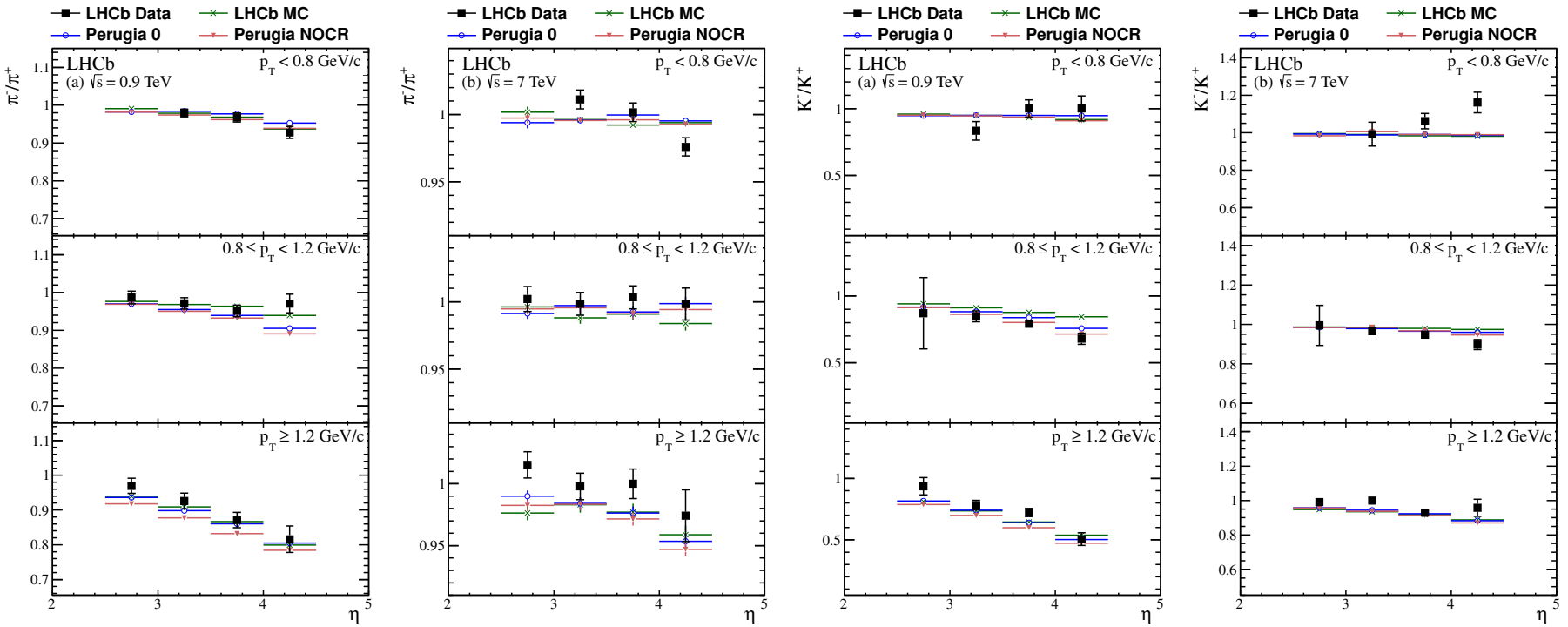
- many systematic uncertainties cancel
- lots of information about the hadronization process, for example:
  - ➜ baryon suppression from baryon/meson ratios
  - ➜ strangeness suppression from kaon/pion ratios
  - ➜ baryon number transport from antibaryon/baryon ratios

❖ experimental aspects:

- ➢ results based on $0.3\,\text{nb}^{-1}$ at $\sqrt{s} = 0.9\,\text{TeV}$ and $1.8\,\text{nb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$
- ➢ PID efficiencies from $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$ and $\phi \to K^+K^-$
- ➢ dominant uncertainties from PID due to limited size of calibration sample

Antiparticle/particle ratios

π^-/π^+ $\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$ K^-/K^+ $\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$

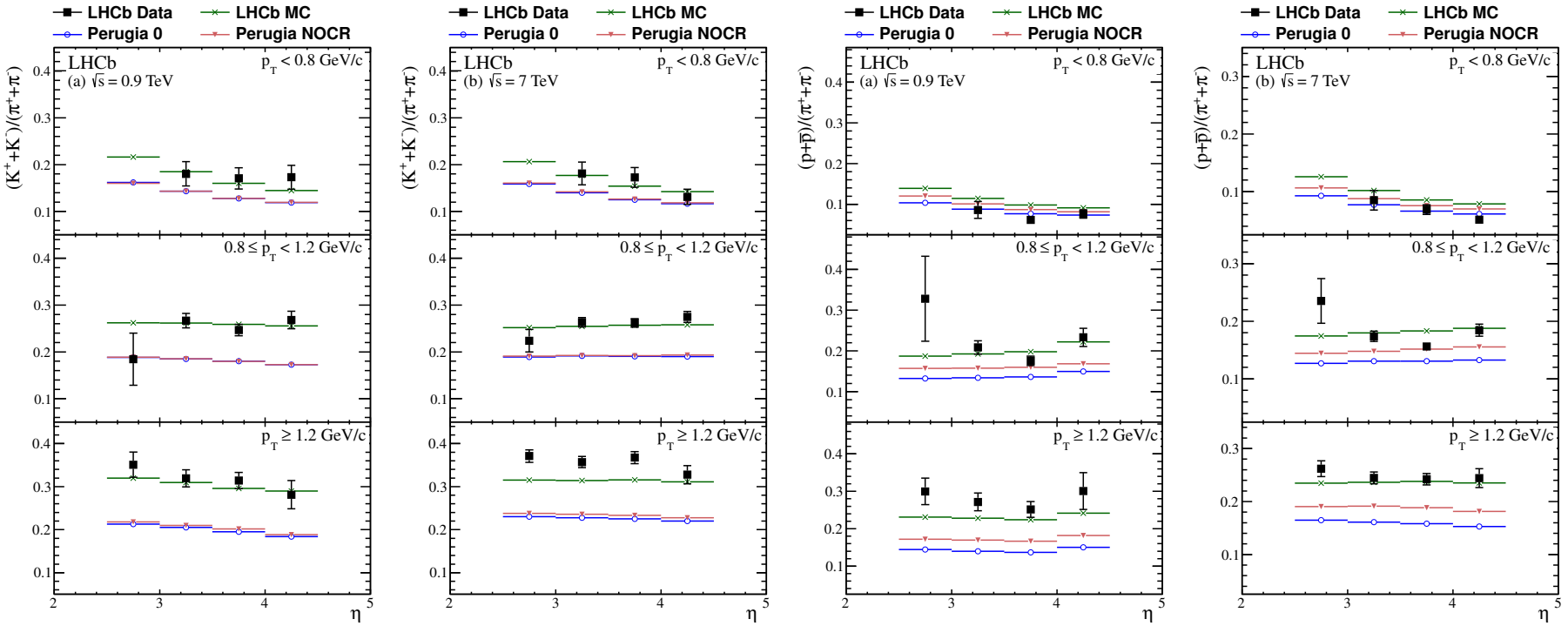


Eur.Phys.J.C72(2012)2168

- charge ratio drops towards larger rapidities (proton beam)
- effect more pronounced at higher p_T
- general behaviour reproduced by PYTHIA tunes

Ratios between particle species

$(K^+ + K^-)/(\pi^+ + \pi^-)$ $\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$ $(\bar{p} + p)/(\pi^+ + \pi^-)$ $\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$

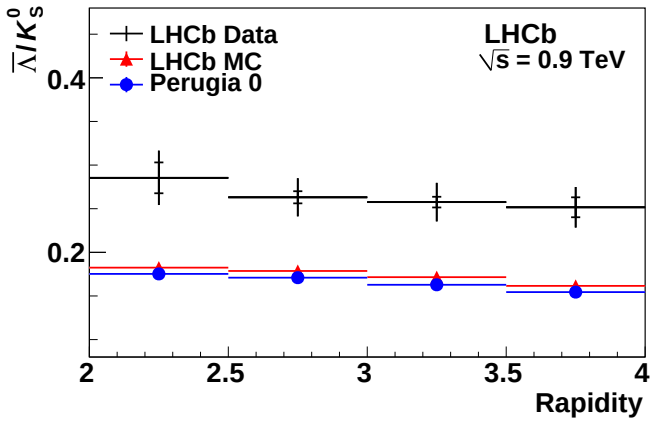


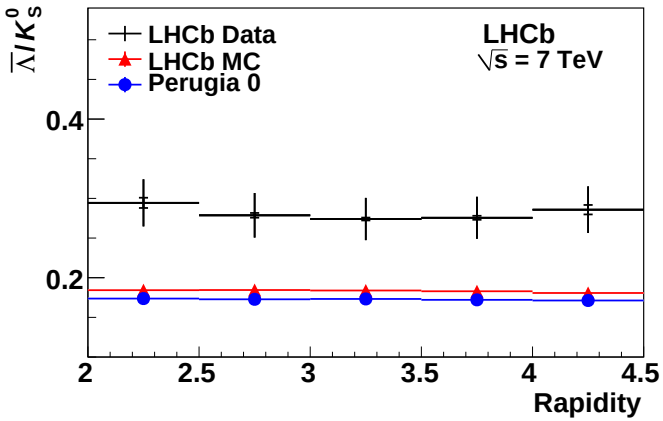
Eur.Phys.J.C72(2012)2168

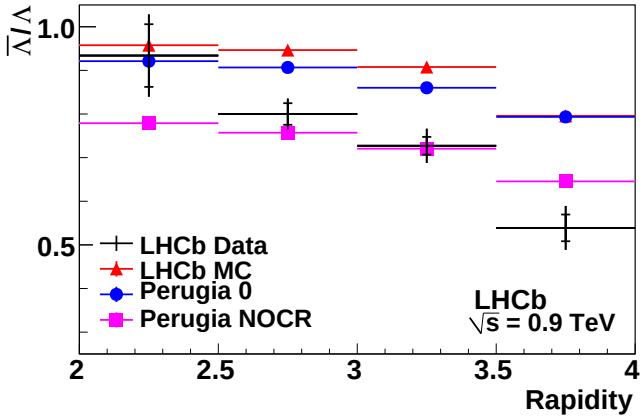
- strangeness suppression very similar to baryon suppression
- less suppression at larger p_T
- data best described by LHCb-tune of PYTHIA

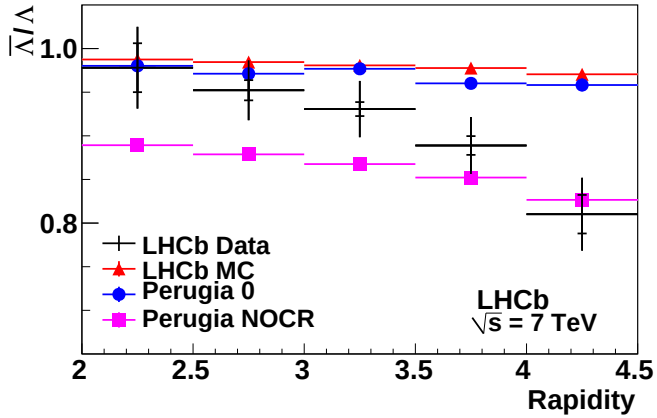
Production of strange baryons

$\sqrt{s} = 0.9\,\text{TeV}$	$\sqrt{s} = 7\,\text{TeV}$







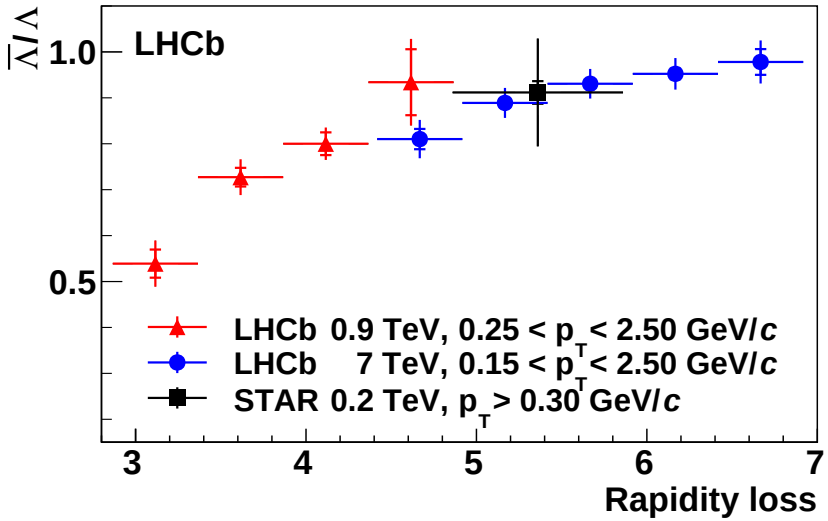


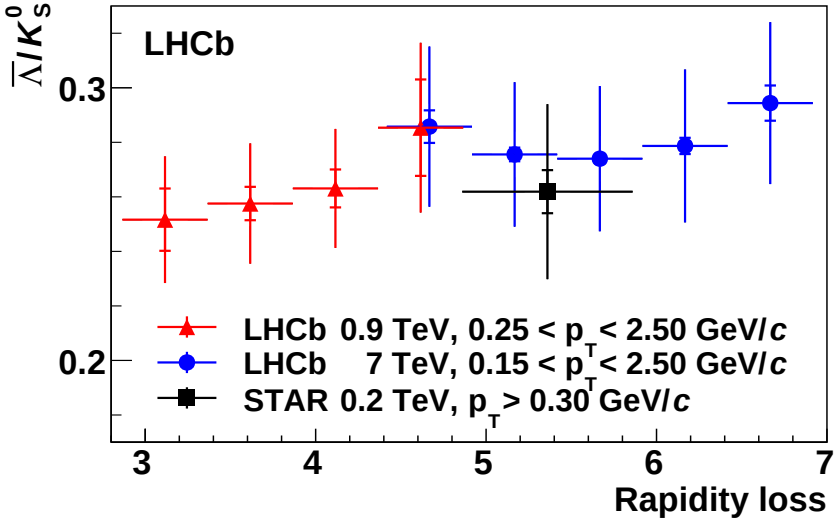
JHEP08(2011)034

- ➜ simulation overestimates baryon suppression in fragmentation
- ➜ rapidity dependence (baryon number transport) not described

Baryon number transport

➜ V^0 particle ratios as a function of rapidity loss



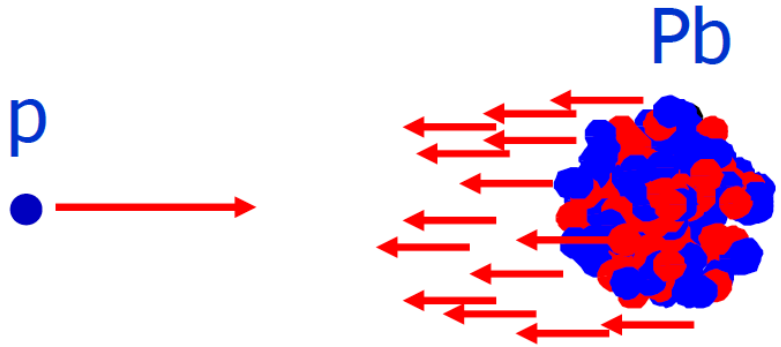


JHEP08(2011)034

- scaling behavior for baryon number transport and baryon suppression
- no dependence on center-of-mass energy within experimental errors
- weak dependence of fragmentation ($\bar{\Lambda}/K^0_S$) as a function of rapidity loss
- drop in $\bar{\Lambda}/\Lambda$ for $\Delta y \to 0$ dominated by baryon number transport

Proton-nucleus collisions

➜ *exploit the capability of LHC to store also heavy ions*



➜ *additional extremely rich physics program, e.g.*

- study of particle production
  - ➜ light flavors, strangeness, charm
- study of cold nuclear effects
  - ➜ needed for the interpretation of QGP signatures in heavy-ion collisions
  - ➜ compare J/ψ production in pA and pp
  - ➜ differentiate between prompt J/ψ and J/ψ from b as a possible handle to disentangle shadowing and energy loss effects

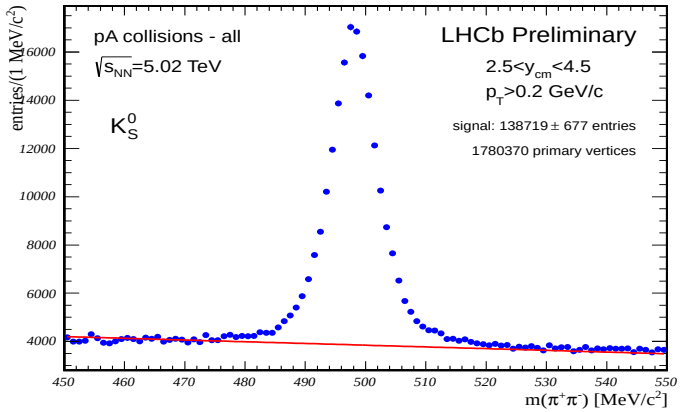
➜ *exploratory analysis of the pPb pilot run data*

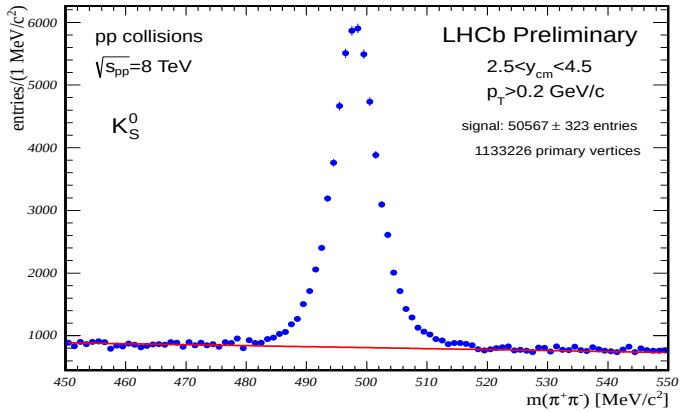
- integrated luminosity $L_{\rm int} \sim 1\,\mu{\rm b}^{-1}$
- look at $K^0_S, \Lambda, \bar{\Lambda}, \phi, D^0$-production
- kinematic range $2.5 < y_{\rm CM} < 4.5$ and $p_T > 0.2\,{\rm GeV}/c$
- compare pPb collisions to minimum bias pp interactions at $\sqrt{s} = 8\,{\rm TeV}$

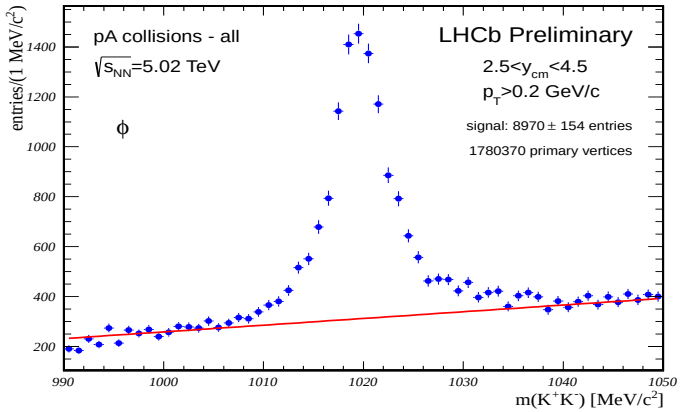
$$\text{determine:} \qquad R(X) = \frac{N(X)/\text{pPb interaction}}{N(X)/\text{pp interaction}}$$

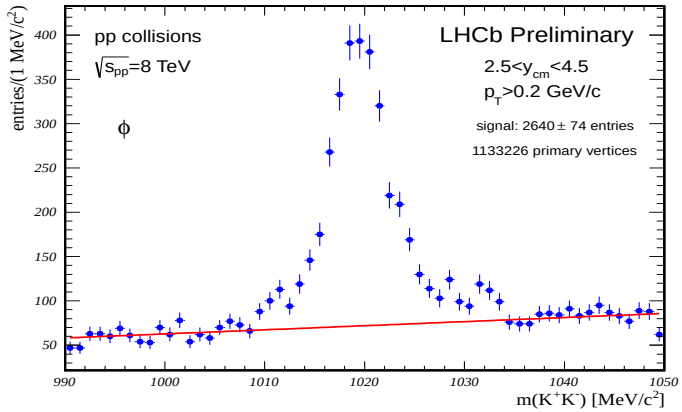
- note: at present only statistical errors, no correction for . . .
  - ➜ spurious- or multiply reconstructed tracks
  - ➜ tracks from decays and secondary interactions
  - ➜ tracking efficiencies
  - ➜ different kinematics in lab-system
  - ➜ different nucleon-nucleon center-of-mass energies
- expect the corrections to increase $R(X)$ by $O(7\%)$

K^0_S and ϕ-meson production







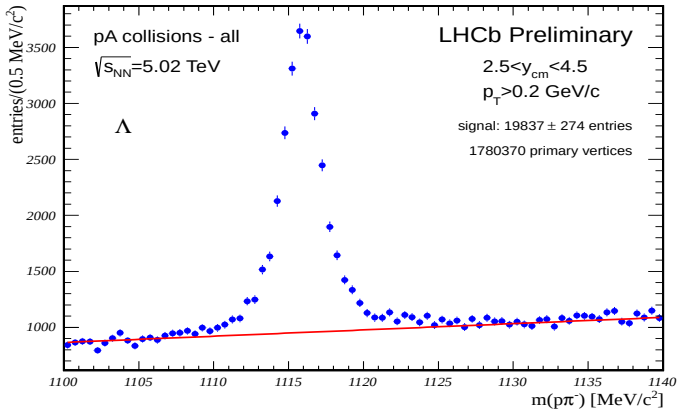


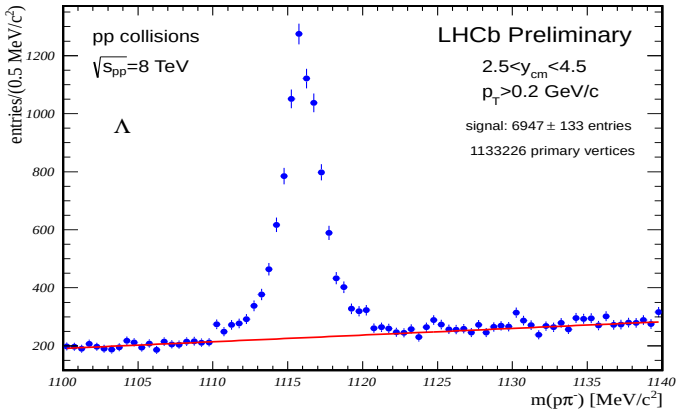
LHCb-CONF-2012-034

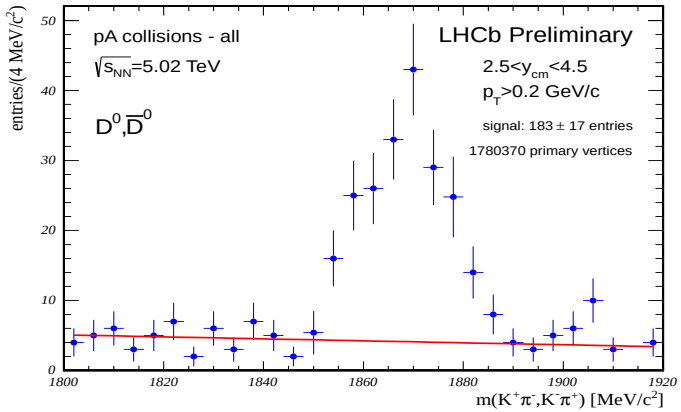
$$R(K^0_S) = 1.745 \pm 0.014_{\text{stat}}$$

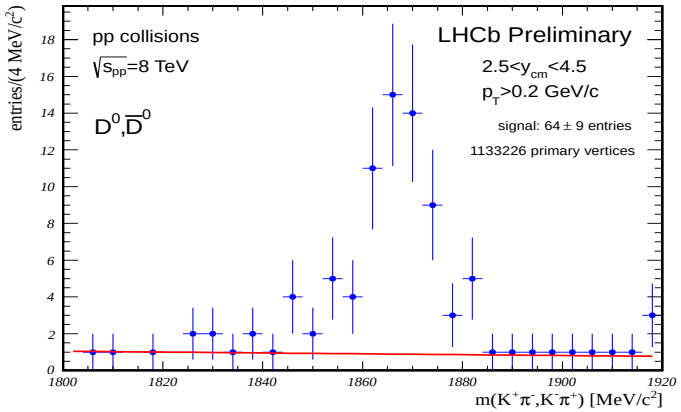
$$R(\phi) = 2.163 \pm 0.071_{\text{stat}}$$

Strange baryon & open charm production









LHCb-CONF-2012-034

$$R(\Lambda) = 1.818 \pm 0.043_{\text{stat}} \quad \text{and} \quad R(\bar{\Lambda}) = 1.827 \pm 0.047_{\text{stat}}$$

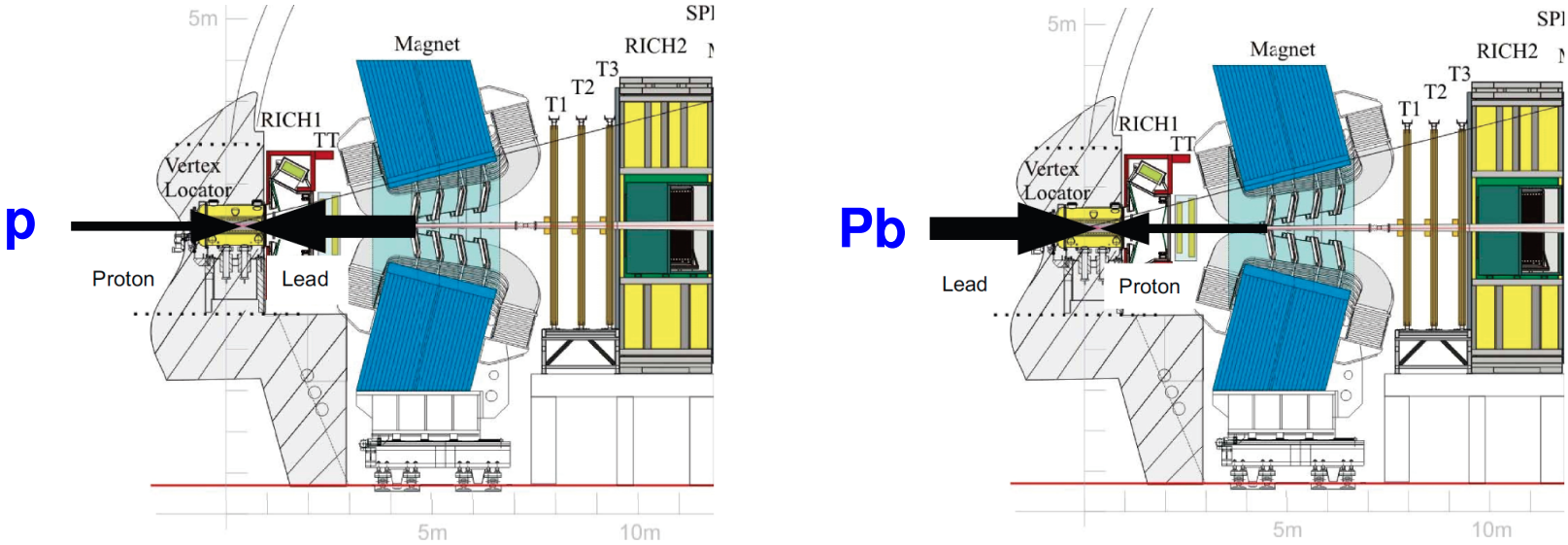
$$R(D^0) = 1.820 \pm 0.307_{\text{stat}}$$

Study of cold nuclear effects

➜ *measurement of the nuclear modification factor*

$$R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy}$$

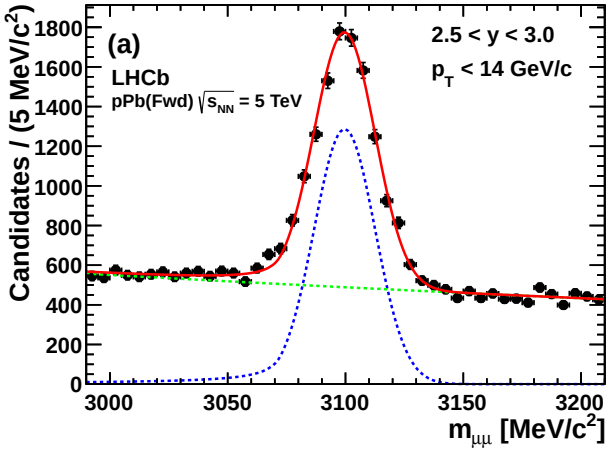
- positive rapidity in direction of the proton
- exploit asymmetric layout of LHCb to measure forward and backward

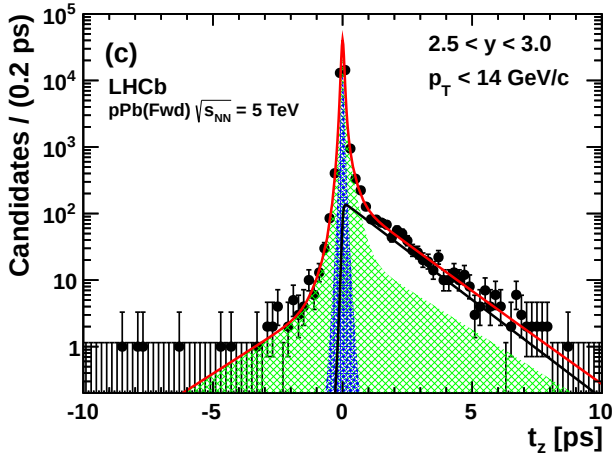


results from $1.6\,\mathrm{nb}^{-1}$ pPb-data recorded in 2013 ➜

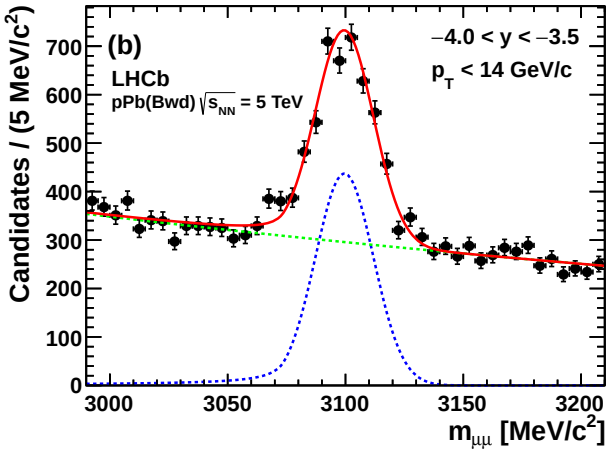
Separating prompt & delayed J/ψ-decays

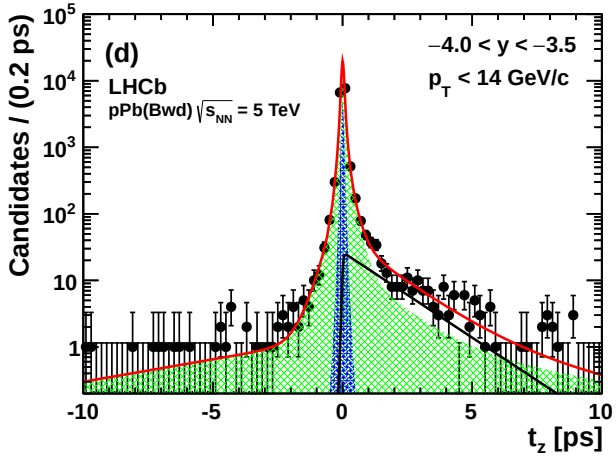
❖ simultaneous fit of mass and pseudo-proper-time $t_z = (z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}/p_z$





pA collisions:
forward hemisphere
$2.5 < y < 3.0$
$p_T < 14\,\text{GeV}/c$



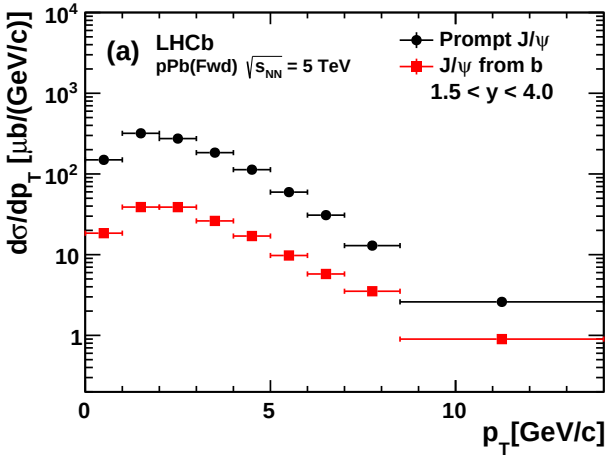


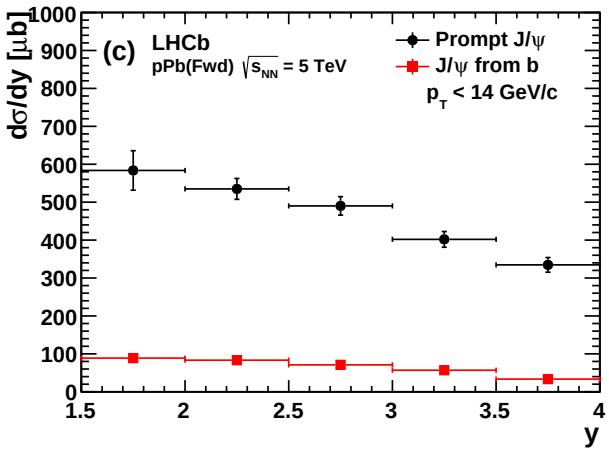
Ap collisions:
backward hemisphere
$-4.0 < y < -3.5$
$p_T < 14\,\text{GeV}/c$

arXiv:1308.6729

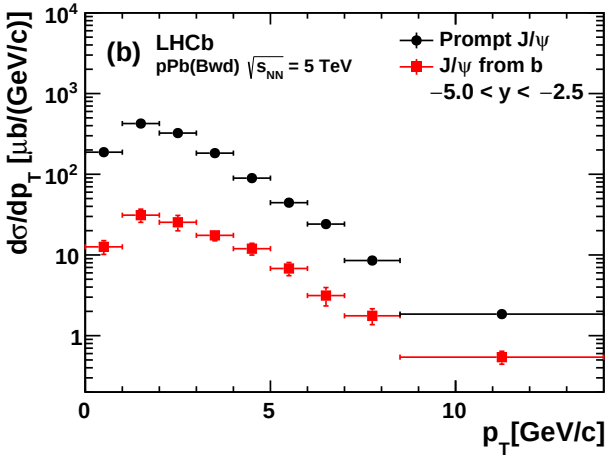
Single differential cross-sections

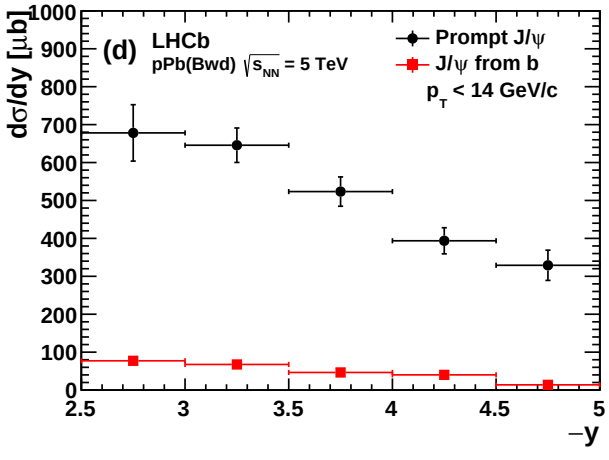
❖ center-of-mass energy $\sqrt{s} = 5\,\text{TeV}$, transverse momentum $0 < p_T < 14\,\text{GeV}/c$





pA collisions:
forward hemisphere
$1.5 < y < 4.0$



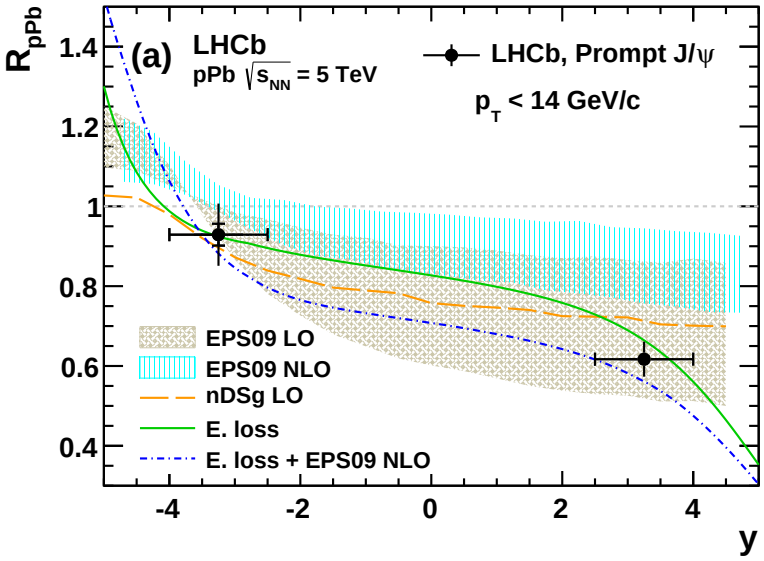


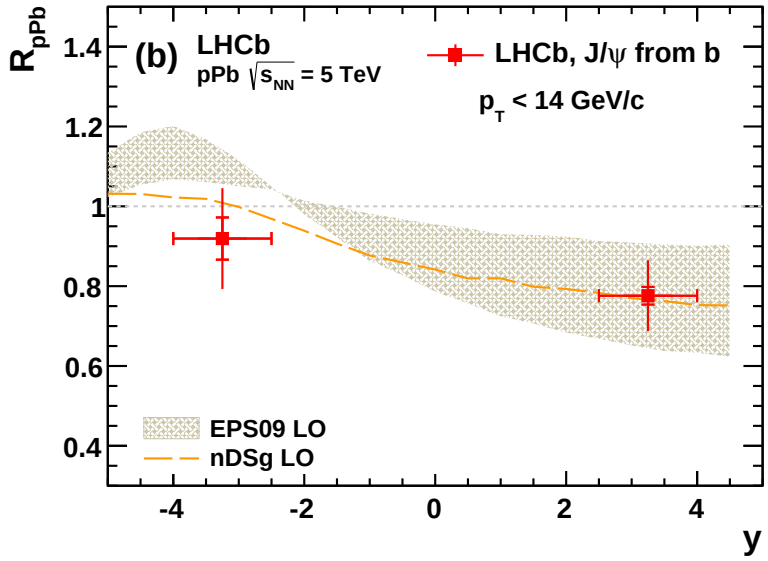
Ap collisions:
backward hemisphere
$-5.0 < y < -2.5$

arXiv:1308.6729

Results: nuclear modification factors

➜ *common range of fwd- and bwd acceptance:* $2.5 < |y| < 4.0$

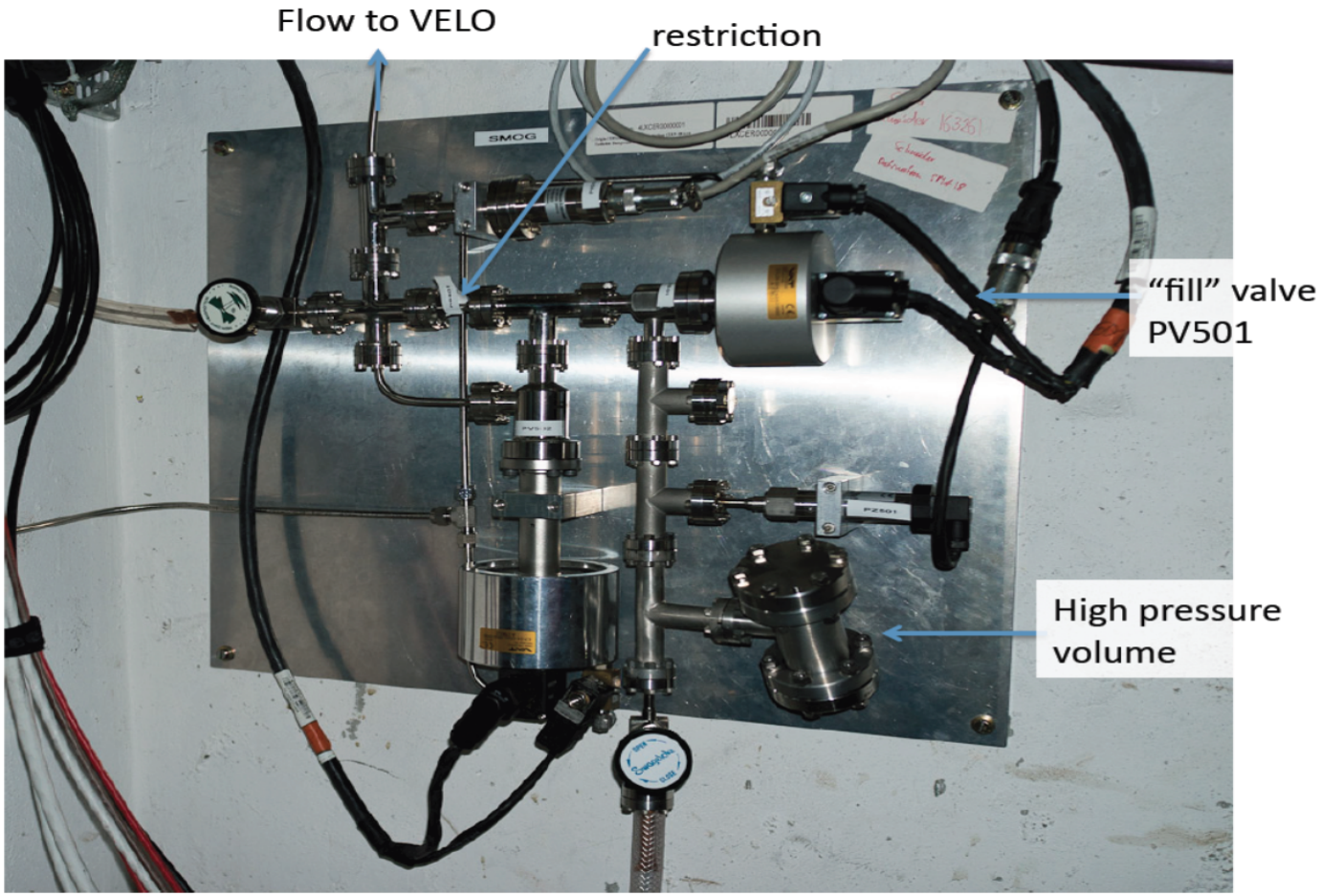




arXiv:1308.6729

- results require interpolation of pp cross-section to $\sqrt{s} = 5\,\text{TeV}$
- $R_{pPb} \neq 1$: the nucleus is not a loose collection of independent nucleons
- B-mesons less affected than prompt J/ψ: smaller systems less affected
- energy loss and shadowing are about equally important
- J/ψ data agree with “energy loss + NLO shadowing”

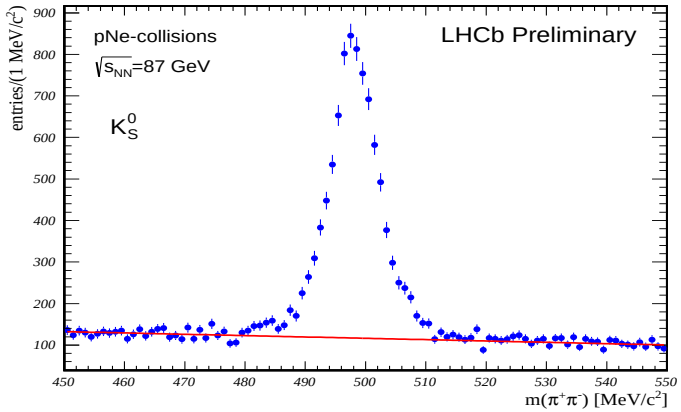
SMOG: System for Measuring Overlap with Gas

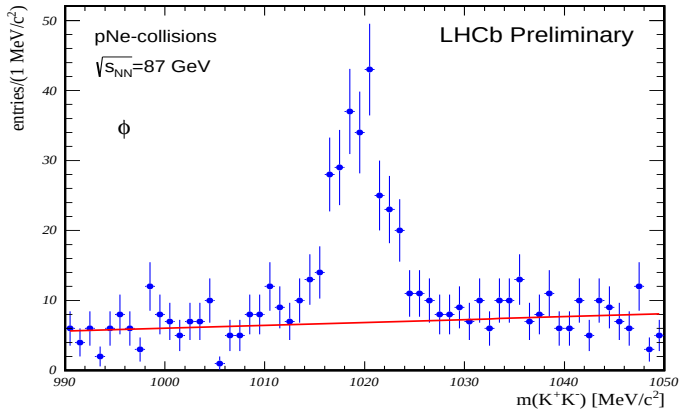


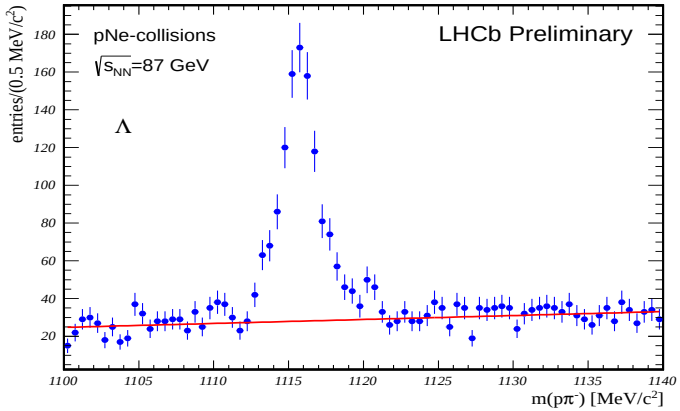
➜ injection of Ne-gas into VELO

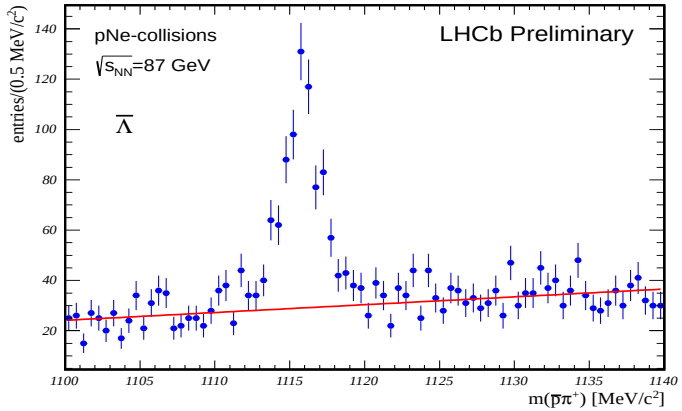
➜ *proton-Neon collisions*

- $\sqrt{s_{NN}} = 87\,\text{GeV}$, boost to center-of-mass $\Delta y \approx 4.5$
- LHCb: backward direction in the nucleon-nucleon center-of-mass





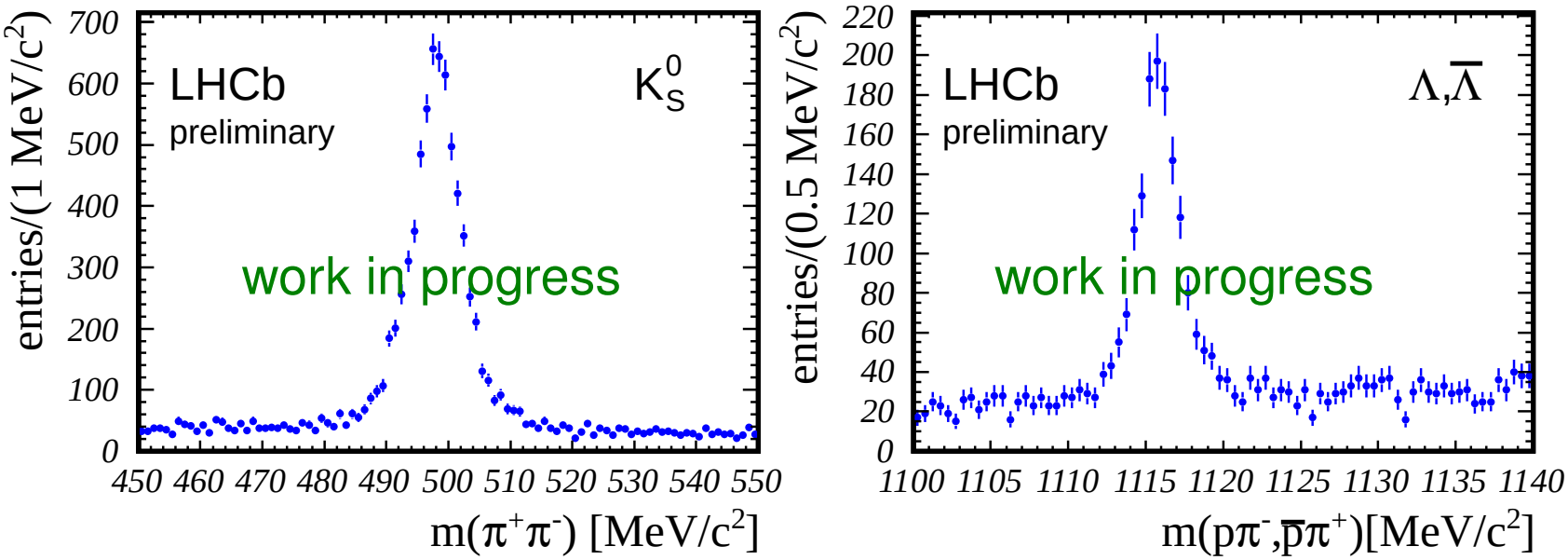




LHCb-CONF-2012-034

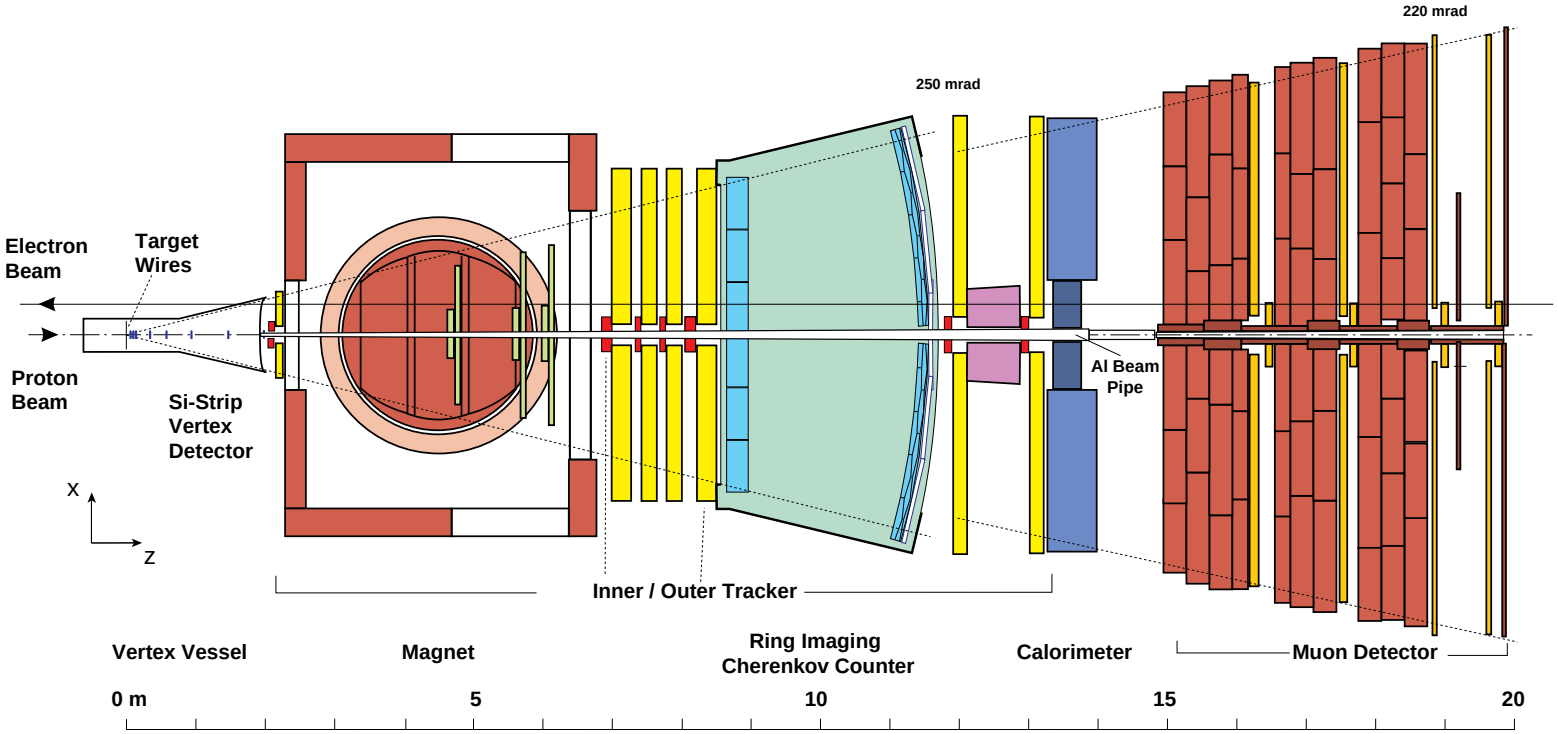
➜ *a first look at PbNe collisions*

PbNe-interactions - $\sqrt{s_{NN}}$=54.4 GeV



- 40 min data taking with PbNe interactions
- plots based on 1/4 of available statistics

3. THE HERA-B EXPERIMENT



- fixed target experiment at the HERA proton ring
- C, (Al,) Ti, W target wires in the beam halo
- forward spectrometer - layout similar to LHCb, except . . .
  - ➜ only one RICH detector behind the magnet
  - ➜ ECAL system with PS/SPD detector
  - ➜ no HCAL

Kinematics

- angular coverage $10 - 220$ mrad
  - ➜ pseudorapidity very similar to range covered by LHCb

$$\eta = -\ln\tan\frac{\theta}{2} \sim [2.2 - 5.2] \sim 3.7 \pm 1.5$$

- energy of the proton beam $E = 920$ GeV
  - ➜ nucleon-nucleon center-of-mass energy

$$\sqrt{s_{NN}} = \sqrt{2 m_N E} \approx 42 \text{ GeV}$$

  - ➜ boost of center-of-mass system

$$\gamma = \frac{E}{M} \approx \frac{920}{42} \approx 22$$

  - ➜ rapidity of center-of-mass system

$$y = \frac{1}{2}\ln\frac{E+p}{E-p} = \frac{1}{2}\ln\frac{(E+p)^2}{(E+p)(E-p)} \approx \ln\frac{2E}{M} \approx \ln\frac{2\cdot 920}{42} \approx 3.8$$

- HERA-B was a central detector !
- study of pA collisions at $\sqrt{s_{NN}} = 42$ GeV

The HERA-B physics programme

➜ *topics covered*

- measurement of V^0 production cross-sections
- K^{*0} and ϕ-meson production
- measurement of $b\bar{b}$ production cross-section
- charm, beauty and charmonium production
- nuclear effects in J/ψ production
- J/ψ and Λ polarization measurements
- searches for pentaquarks and for the FCNC decay $D^0 \to \mu^+\mu^-$

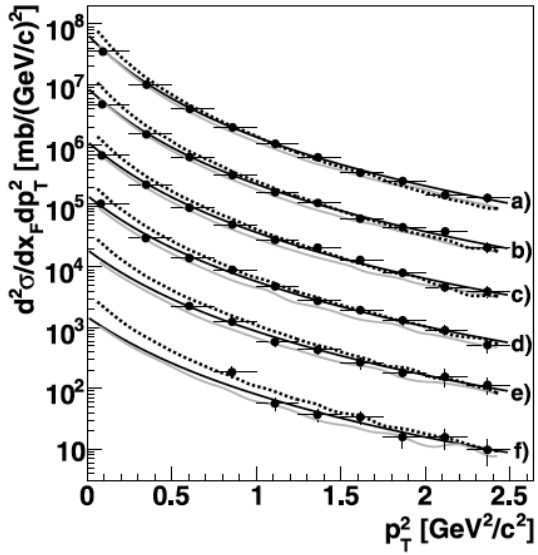
➜ *data samples for the final analyses*

- C, Ti and W targets
- 2.0×10^8 minimum bias events
- 1.4×10^8 lepton triggered events

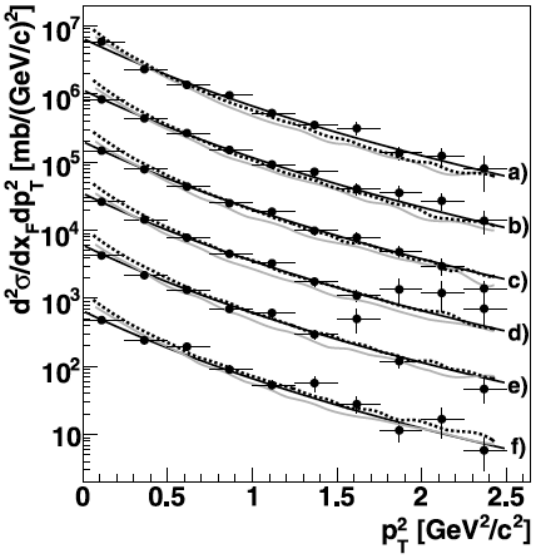
➜ some examples

V^0 production measurements

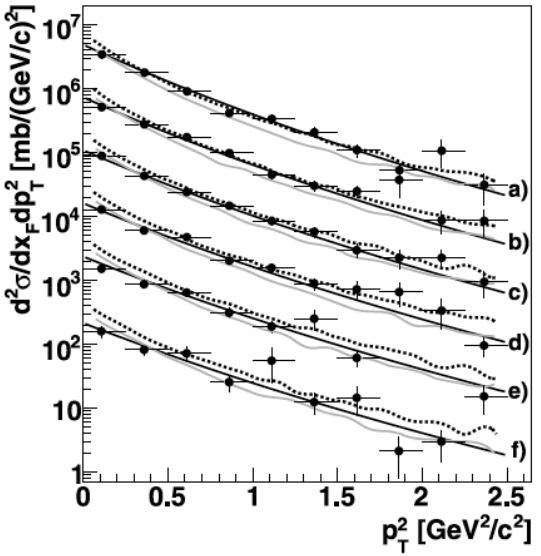
➜ *based on* 2×10^8 *minimum bias events*



(d) $p + Ti \to K_S^0 + X$



(e) $p + Ti \to \Lambda + X$



(f) $p + Ti \to \bar{\Lambda} + X$

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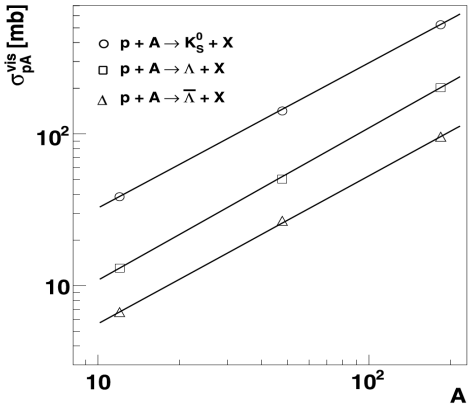
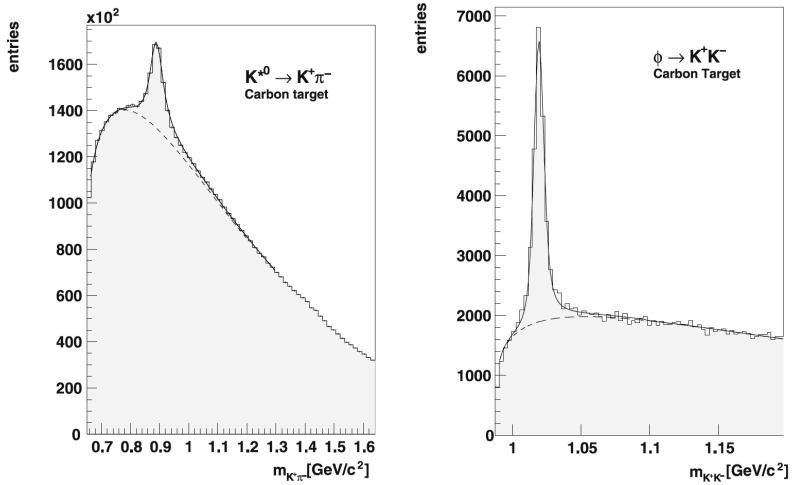


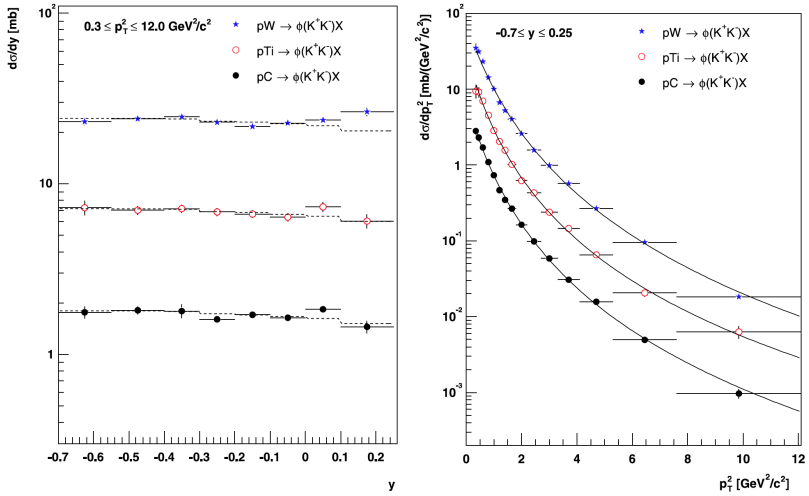
➜ A-dependence of visible V^0 cross-sections and, as an example, V^0 cross-sections vs p_T^2 on Ti for $-0.12 < x_F < -0.02$ compared to a heuristic parameterization (dark), Pythia (light) and EPOS (dashed) (subsequent curves are scaled)

Vector meson production

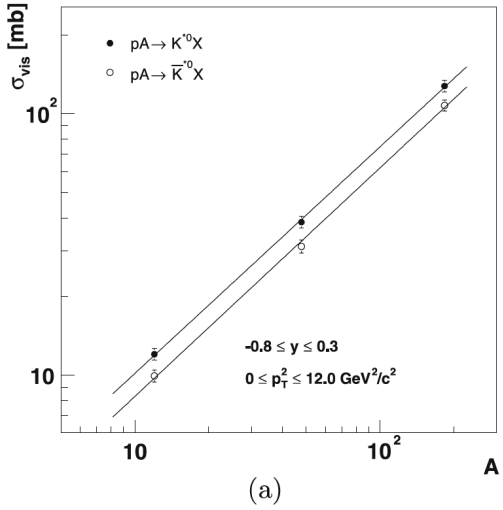
➜ K^{0*} and ϕ-meson signals

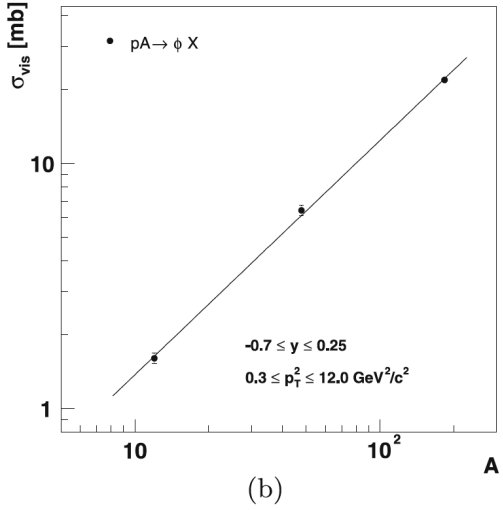


➜ ϕ-meson cross-sections



➜ A-dependence





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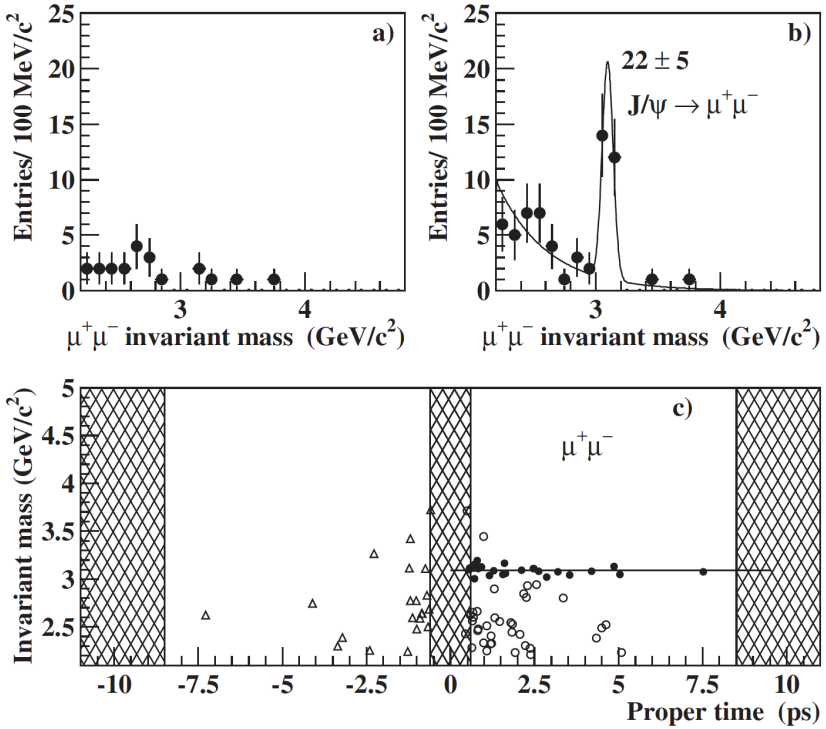
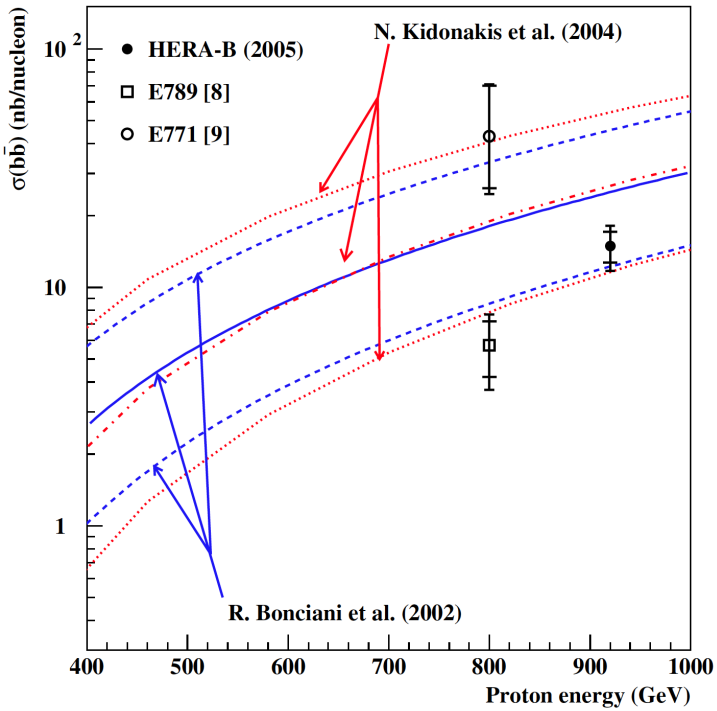
Measurement of the $b\bar{b}$ cross-section

➜ *analysis of detached J/ψ decays*



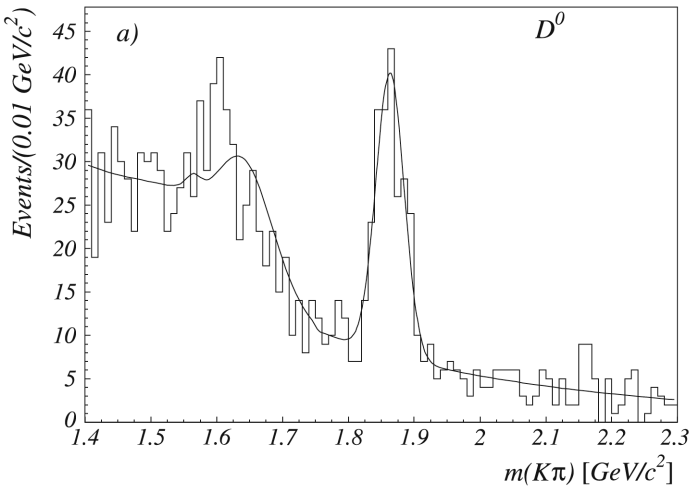


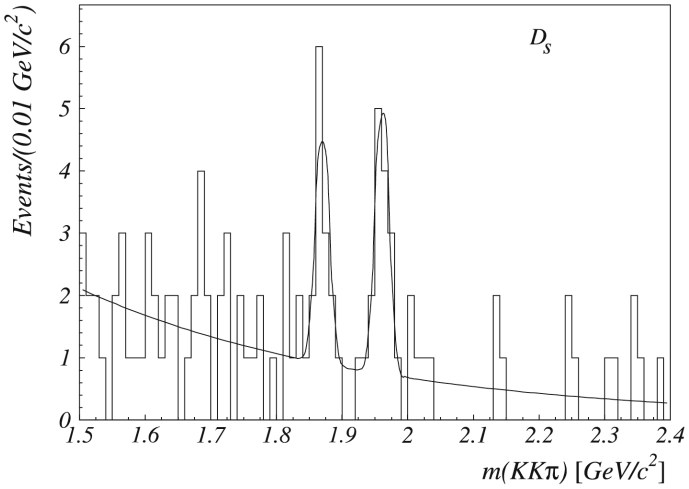
PRD73(2006)052005

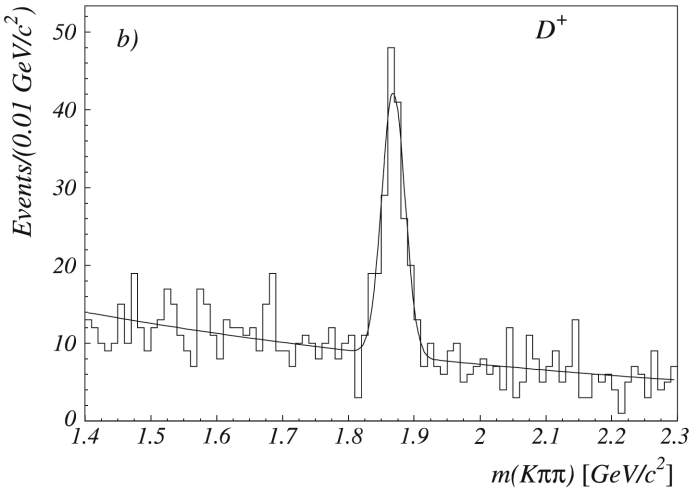
- clean finite-lifetime signal downstream of primary vertex
- low statistics measurement
- best cross-section measurement at $\sqrt{s} = 42\,\text{GeV}$

Charm production

➜ *minimum bias event sample with 3 target materials*







- clean signals
- low statistics

❖ yields

Table 3. Number of reconstructed D mesons

sample	D^0	D^+
total	174.8±16.8	130.5±14.7
particle	75.9±10.9	54.5±9.3
anti-particle	99.0±11.9	75.8±10.5
C	66.1±9.6	43.1±7.7
W	92.3±11.7	72.4±10.6
Ti	17.4±5.7	14.9±5.0
sample	D_s^+	D^{*+}
total	11.4±4.0	61.3±13.0
particle	4.9±2.6	21.0±6.6
anti-particle	6.7±2.8	40.6±8.3
C	4.2±2.2	26.6±6.4
W	6.7±3.0	24.8±7.5
Ti	0.4±1.0	9.6±4.0

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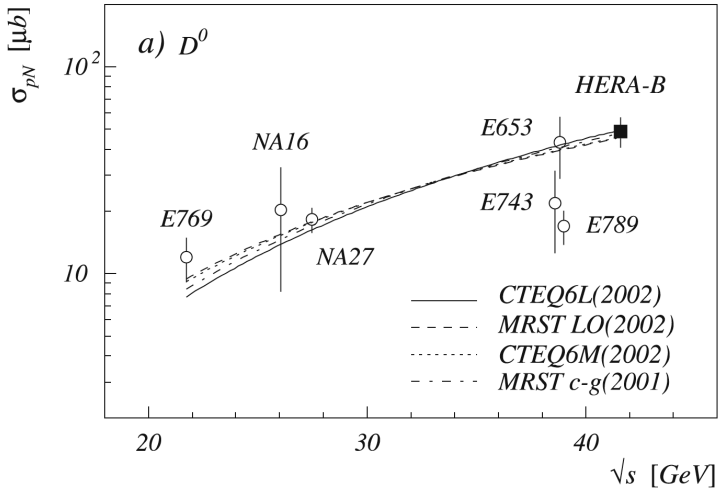
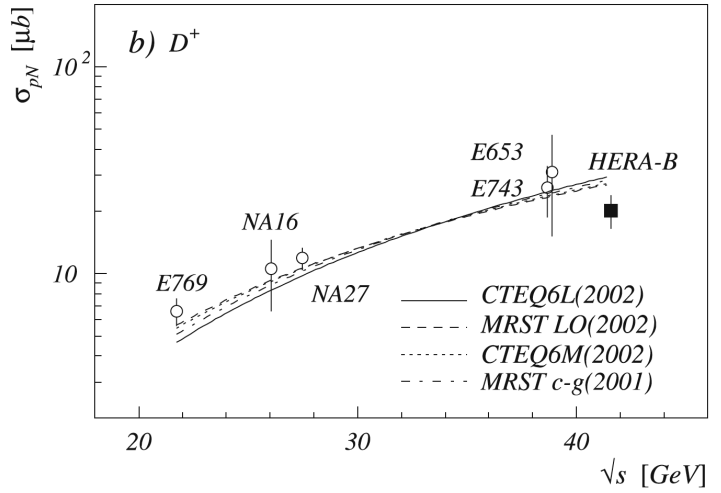
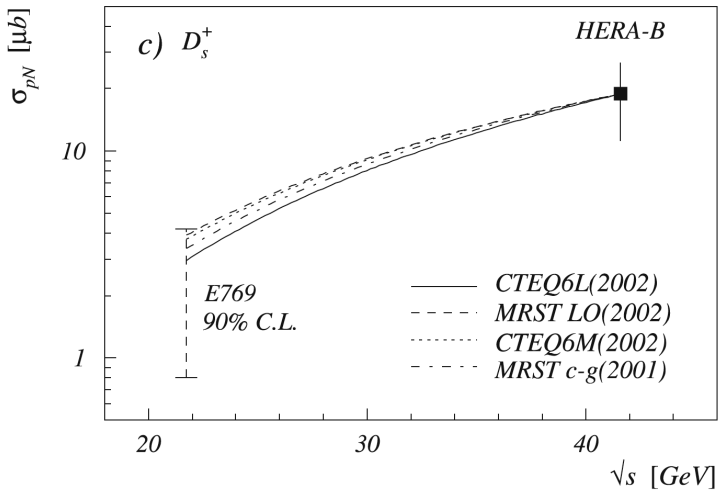
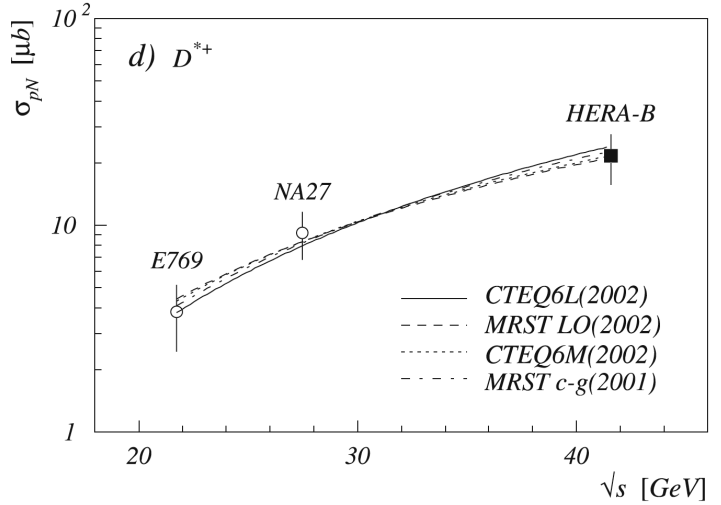
Open charm cross-sections

➜ *very competitive measurements . . .*









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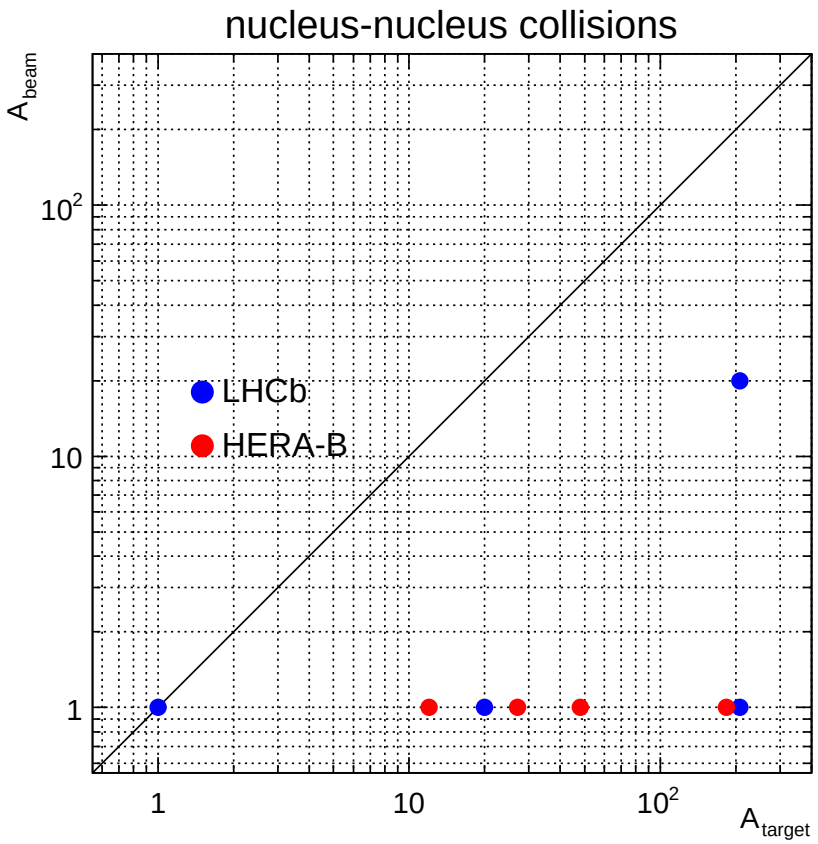
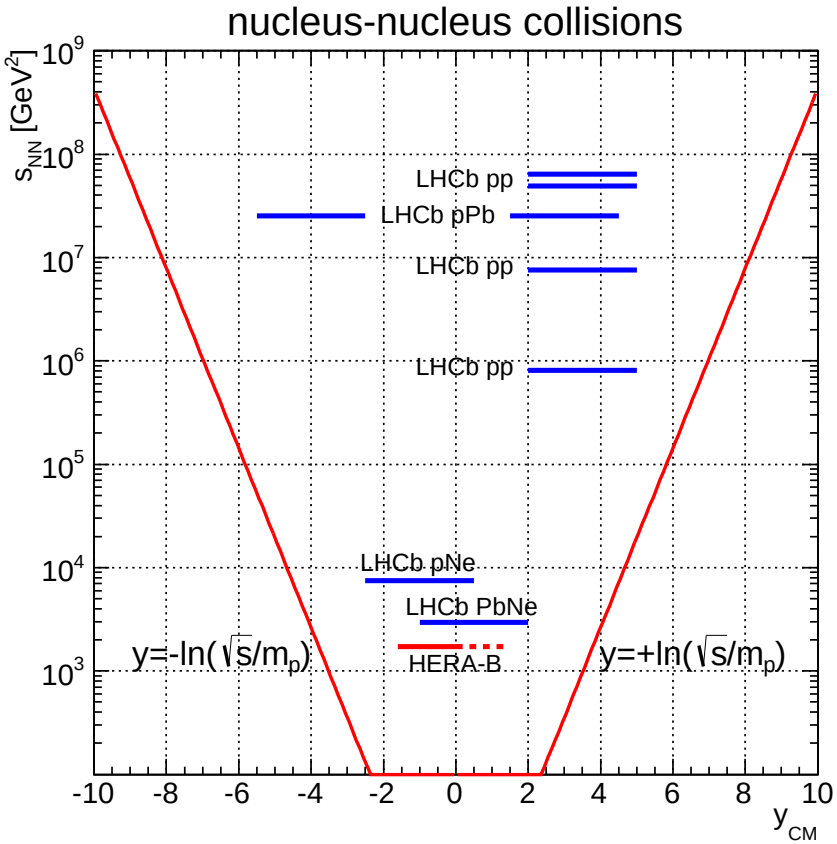
4. SUMMARY

- HERA-B was the highest energy proton-nucleus experiment before LHC
  - ➜ large data samples of $O(10^8)$ events are available
  - ➜ backward-central region covered by tracking and PID
  - ➜ published results of strangeness, charm and beauty production
  - ➜ multiplicities and inclusive cross-section and particle ratios not yet done
- QCD studies at the highest energies: LHC
  - ➜ currently 7 experiments to exploit the physics potential
- LHCb can be operated in fixed target and collider mode
  - ➜ different combinations of beam and target nuclei
  - ➜ central detector in fixed target operation
  - ➜ mid-forward coverage in collider mode
  - ➜ many measurements already done
  - ➜ potential to do much more

current score by HERA-B and LHCb ➜

Phase space coverage by LHCb & HERA-B





- additional beam-target combinations from RHIC and ALICE/ATLAS/CMS
- fwd-coverage at lower s_{NN} by fixed target experiments at CERN & Fermilab
- more data about $p\bar{p}$ from $Sp\bar{p}S$ and Tevatron
- full phase space covered by cosmic ray experiments