“Prospects with measurement of heavy baryons polarization and MDMs”

Elisabeth Niel

Laboratoire de l’Accélérateur Linéaire, Orsay.

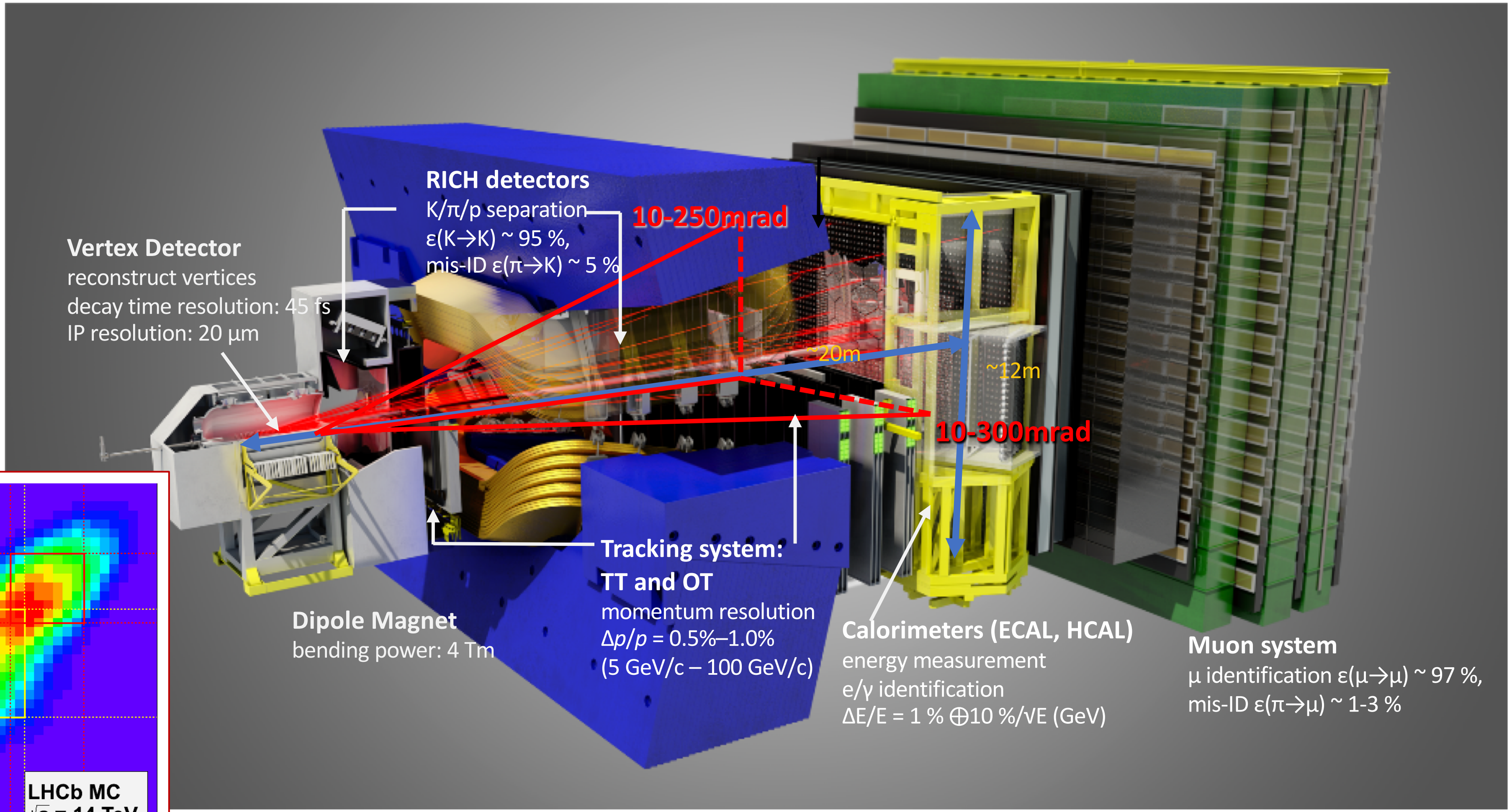
FTE@LHC Kick-off meeting

7-8 November, CERN

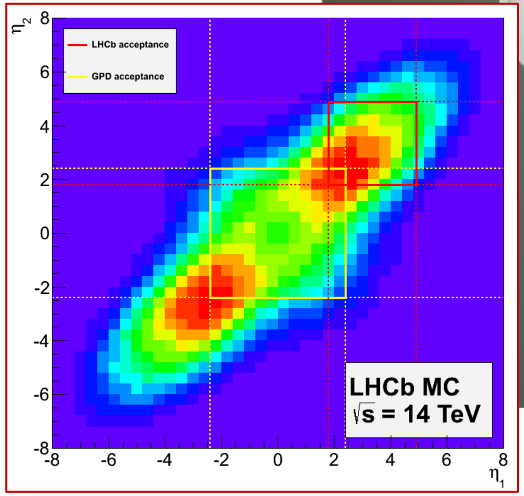
Outline

1. Fixed-target mode at LHCb
2. Charm production in fixed-target collisions
3. MDM and polarization measurement
4. First preliminary selections
5. Conclusions

The LHCb experiment



$b\bar{b}$ acceptance

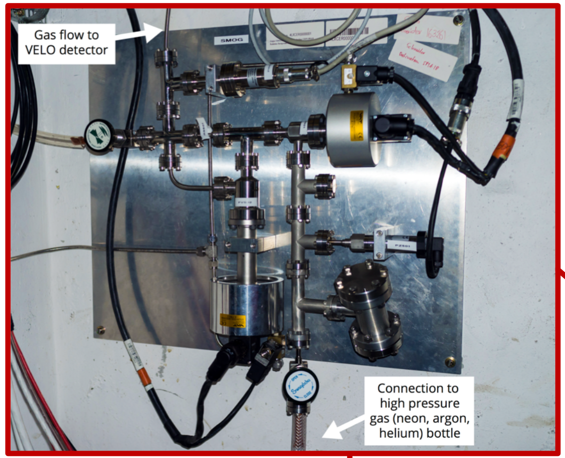


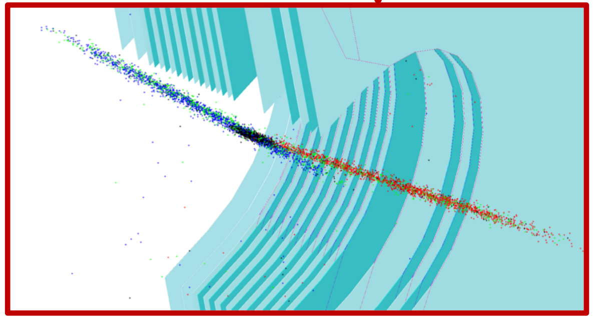
[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

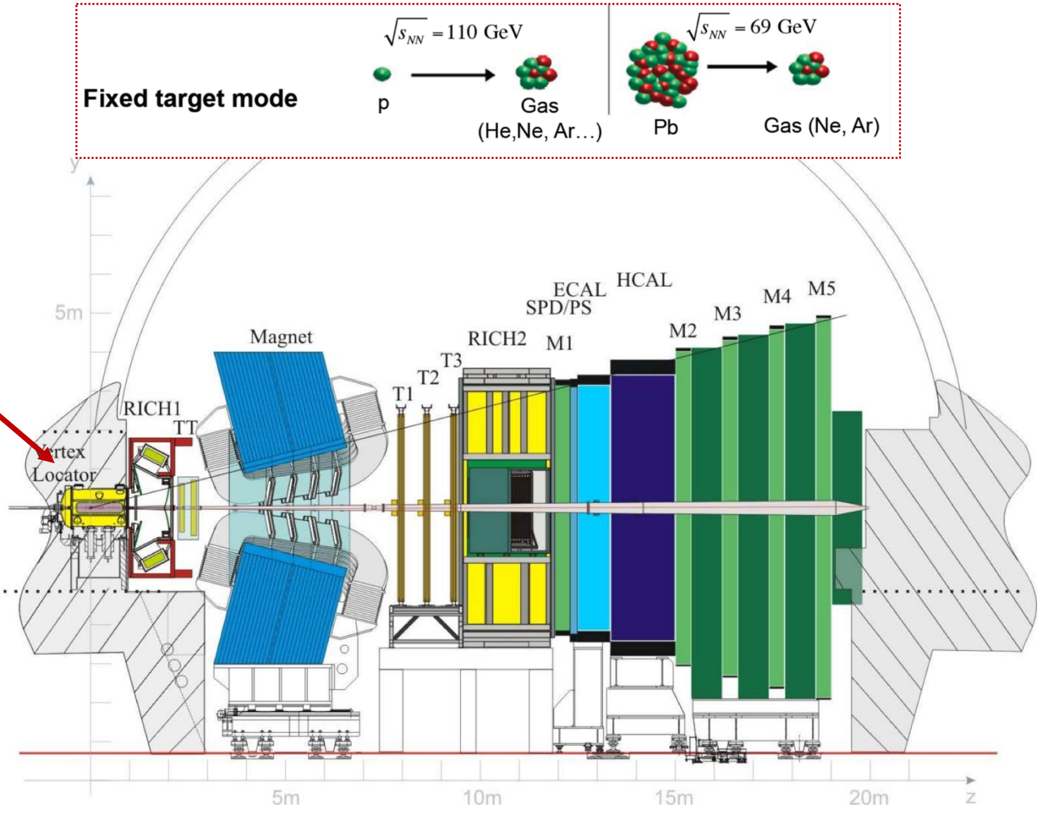
Single arm forward spectrometer with excellent vertexing, tracking, PID (acceptance $2 < \eta < 5$)

Fixed-target mode at LHCb

SMOG (The System for Measuring Overlap with Gas) enables injection of gas (He, Ne, Ar…) in the beam pipe section crossing the VELO (unique at LHC).







Fixed-target mode at LHCb

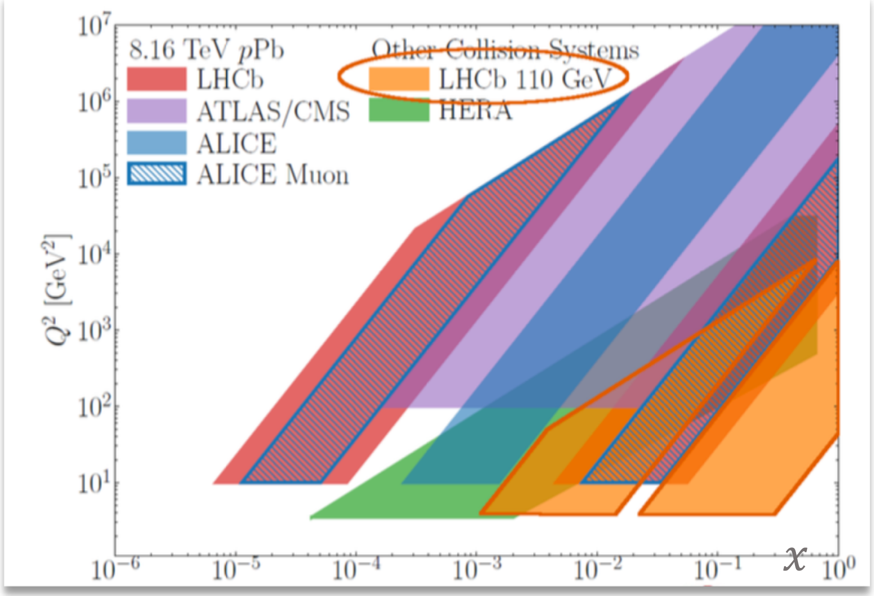
- Gas pressure : 10^{-7} to 10^{-6} mbar, which corresponds to a luminosity of $6 \times 10^{29} cm^{-2} s^{-1}$
- Luminosity measured using proton-electron scatterings since the gas density is not known precisely
- Collisions at: $\sqrt{s_{NN}} = \sqrt{2E_N m_N} = 41 - 115\ GeV$ with $E_N = 0.9 - 7\ TeV$

  → energy scale between SPS and LHC
- $y_{cm} = \sinh^{-1}(\sqrt{E_N/2M_N})$ → $3.8 < y_{cm} < 4.8$. Hence @7 TeV $-2.8 < (y^{*} = y_{Lab} - y_{cm}) < 0.2$.
  LHCb acceptance covers the backward rapidity region in the c.o.m frame.

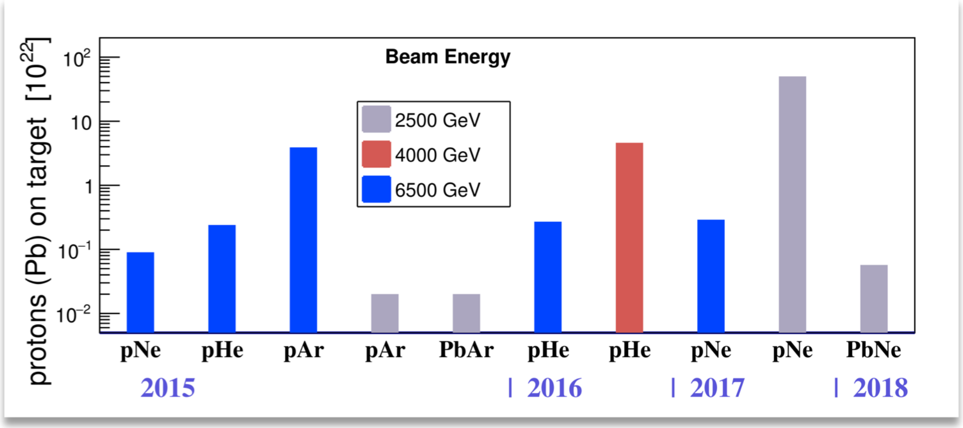
- Can observe particle carrying a large fraction of the initial longitudinal momentum of the target nucleon in the c.o.m. frame: $x_F \equiv p_L^{*}/|\max(p_L^{*})| \cong \frac{2}{\sqrt{s_{NN}}}\sqrt{M^2 + p_T^2}\,\sinh(y^{*})$

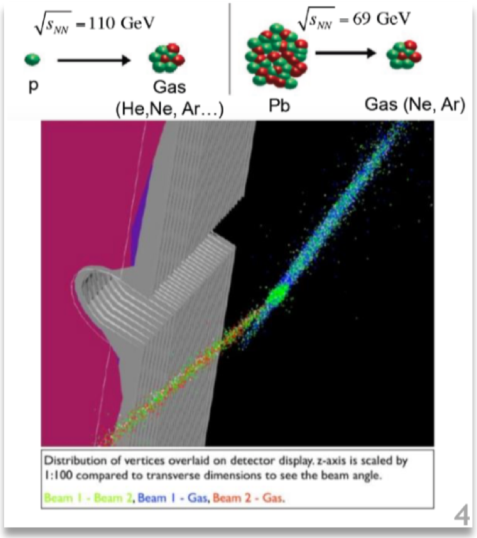
- Can access large Bjorken-x value in target nucleon ($x_F \sim x_1 - x_2$), which are accessible in beam-beam collisions only at much larger Q^2.

- Can use differents targets hence tests differents systems and study a wide range of different topics.
  (e.g. light/heavy particles production, interesting for cosmic rays physics)



Fixed-target mode at LHCb: current status





- Pilot runs 2012 (pNe) and 2013 (PbNe) + small amount of data with three gas species in 2015
- 2016: dedicated to the study of proton-helium collisions, motivated by the antiproton production measurement

- To avoid background from pp collisions, events recorded with a bunch in beam1 and empty for beam2.
  Collected during special runs at low beam intensity (Van der Meer scans, LHC MD periods)

- Special case: pp data taking at $\sqrt{s} = 5\ TeV$ at the end of 2017, the SMOG device was operated continuously and **pNe collisions at** $\boldsymbol{\sqrt{s_{NN}} = 69\ GeV}$ was collected at the same time (integrated luminosity $\sim 100\ nb^{-1}$).
- Ions-target samples also available since 2018: e.g. pNe vs PbNe comparison possible

Charm production in fixed-target collisions

First fixed-target programs at FermiLab in the 90's. These experiments cover a variety of beam particle types at a range of energies with different target materials.

Production mechanism:

Wheather you are colliding neutrinos, photons or hadrons a single process tends to dominates.

- neutrino-strange-quark charged current scattering (neutrinos + target)
- photo-gluon fusion (photons + target)
- gluon-gluon fusion (hadrons + target)

Experiment	Beam Momentum (GeV/c)	Beam Particle	Target Material
E690	800	p	LH_2
E771	800	p	Si
E866/NuSea, E789 and E772	800	p	LH_2, LD_2, C, Ca, Fe, W Ag, Au, and Cu dump
E769	250	$\pi^\pm$, $K^\pm$, and p	Be, Al, Cu, and W
E781/SELEX	600 572	Σ^- and π^- p	C and Cu C and Cu
E791	500	π^-	C and Pt
E815/NuTeV	20 to 400	ν_μ, $\overline{\nu}_\mu$	Fe
E687	220	γ	Be
E831/FOCUS	170	γ	BeO and Si
WA89	340	Σ^- and π^-	C and Cu
WA82	340 370	π^- p	Si, Cu, and W Si and W
WA92/Beatrice	350	π^-	Cu and W

Experiment	Measurement
E690	Diffractive Production of D^*
E771	c and b Production by Protons
E791	D^* Production: x_F, p_t^2, Polarization, Asymmetry
E791	Λ_c Production Polarization and Asymmetry
E781/SELEX	Production Asymmetries
E831/FOCUS	Charm Particle Correlations
E815/NuTeV	Neutrino Production of Charm
E866	$J/\psi, \psi'$, and Υ Production and A-Dependence

More details on charm production see talk from Felipe Garcia

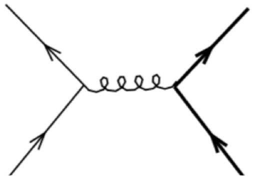
Jeffrey A. Appel : https://cds.cern.ch/record/478924/files/0011101.pdf

Charm production in fixed-target collisions

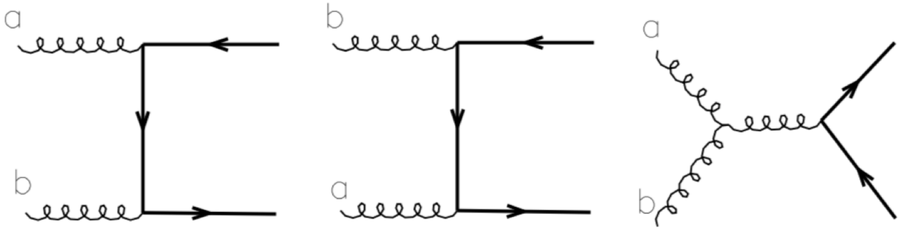
How does QCD describe the charm production? → perturbative calculations

Two processes are responsible for heavy-quark hadro-production at the LO in perturbation theory:

$q\bar{q} \rightarrow Q\bar{Q}$

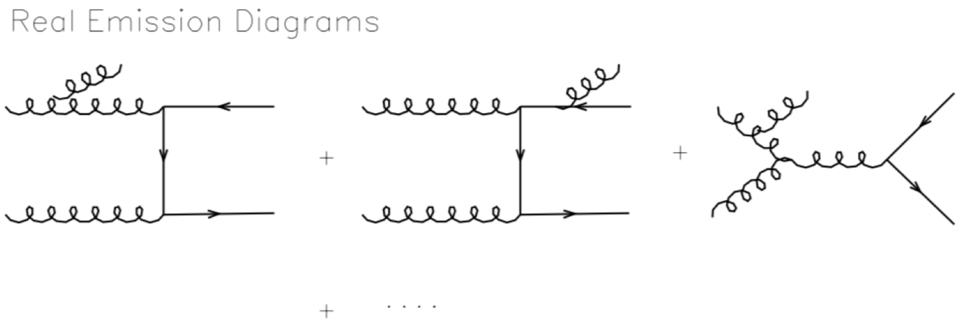


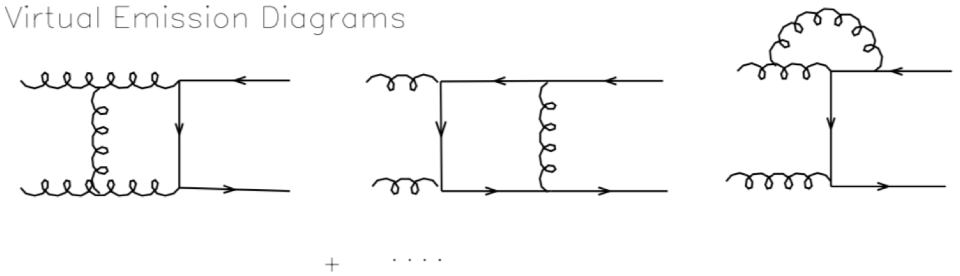
$gg \rightarrow Q\bar{Q}$



dominant at the LHC (~ 85% at $\sqrt{S} = 14\ TeV$).

Next-to-leading-order (NLO) corrections come from two sources of O(α_S^3) diagrams:





What about hadronization effects? → These effects are usually described in terms of a non-perturbative fragmentation function.

arXiv:hep-ph/9711337

MDM measurement

Motivations:

- MDMs have never been measured for short-lived charmed, beauty baryons and tau leptons.
- Measuring MDMs of baryons is a good test for new physics e.g. test for non-perturbative QCD, study the substructures of baryons, probe compositeness of quarks.

Today's status:

- First hints from the g-2 measurements for muons and electrons: [g-2 collaboration]
  → A lot of effort from the theory side : [g-2 theory initiative]

- For baryons it's harder due to the shorter lifetime $c\tau \sim 60\ \mu$m , lifetime $\sim 10^{-13} s$
  → Feasibility studies : arXiv:1705.03382v4 , arXiv:1612.06769v1
  Predictions for Λ_c^+ give a range for $\mu(\Lambda_c^+)$:

$$\frac{\mu(\Lambda_c^+)}{\mu_N} = 0.37\text{–}0.42, \qquad g(\Lambda_c^+) = 1.80\text{–}2.05.$$

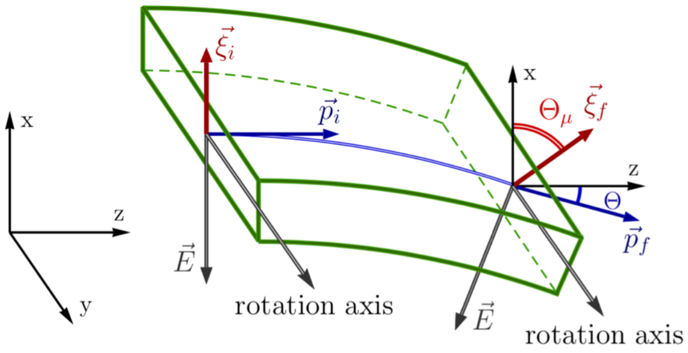
  Hence this measurement could help distinguish between different theoretical approaches

- Preliminary studies going on for τ g-2 measurement: [arxiv:1810.06699]

More details on (g-2) τ ,
see [talk from Alex Fomin]

MDM measurement

How to access the MDMs: To obtain the magnetic moment of the particle, we need to measure the precession angle Θ_μ which is directly linked to the gyromagnetic factor g :



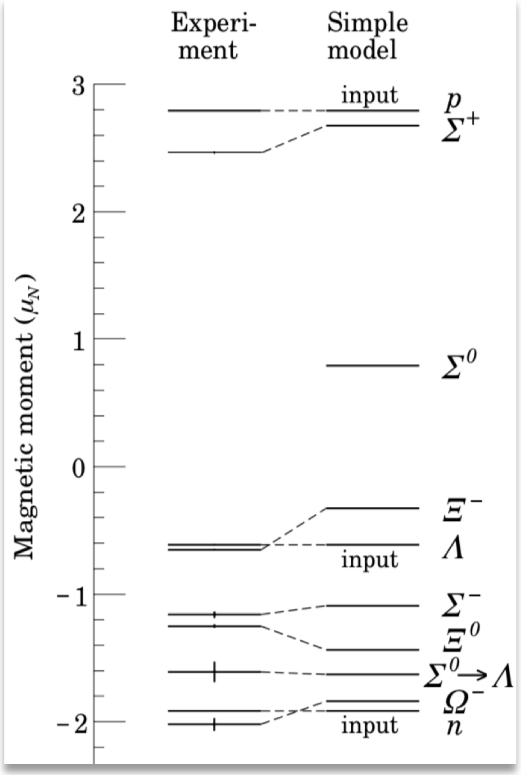
arXiv:1705.03382v4

$$\Theta_\mu \approx \gamma\left(\frac{g}{2} - 1\right)\Theta$$

From Θ_μ we can infer the **MDM** ($\vec{\mu}$) of the particle defined as

$$\vec{\mu} = \frac{g}{2}\frac{q}{mc}\vec{S}$$

The value $|g| \approx 2$ corresponds to a Dirac particle, whereas $|g| \neq 2$ would suggest the presence of MDM anomalies.



Present measurements:

Particle	MDM measurement $[\mu_N]$
p	$2.7928473446 \pm 8.2 \times 10^{-10}$
Σ^+	$2.40 \pm 0.46 \pm 0.40$
Λ	-0.6138 ± 0.0047
Ξ^-	-0.6507 ± 0.0025

Particle	MDM measurement $[\mu_N]$
Σ^-	-0.89 ± 0.14
Ξ^0	-1.250 ± 0.014
n	$-1.9130427 \pm 4.5 \times 10^{-7}$
Ω^-	-2.02 ± 0.05

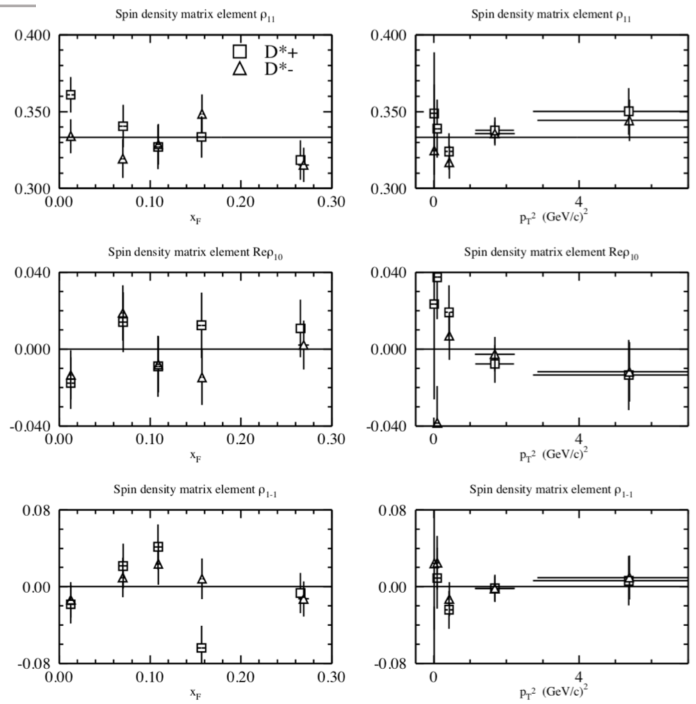
More details on crystals, see talk from Alex Fomin

Measured in units of the nuclear magneton $\mu_N \equiv \frac{e\hbar}{2m_p c}$.

Polarization measurement

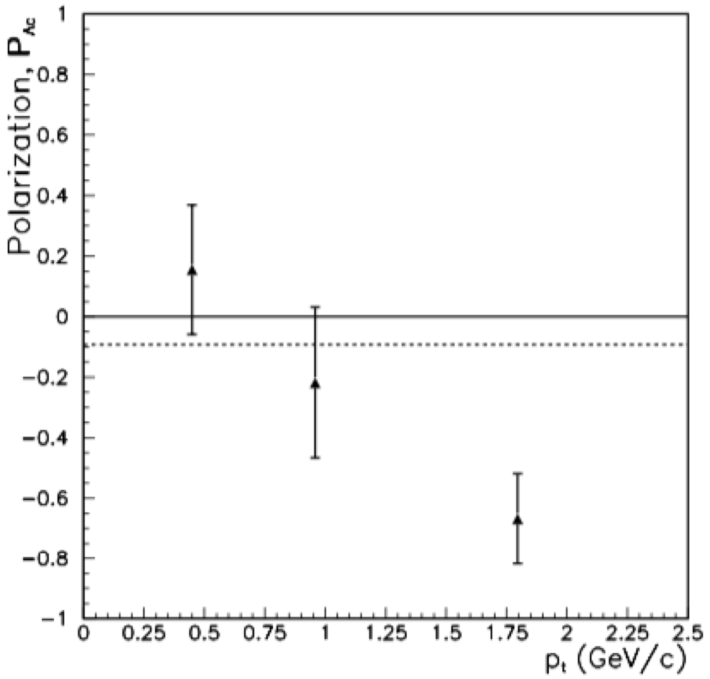
- Firs measurements of the production polarisation of heavy-quark particles E791 for Λ_c^+ , D^* and -onium.
- Knowing the polarization is usefull for better understanding QCD (Ex. J/psi to distinguish between color-octet and color-singlet models) and evaluate the sensitivity to future MDM/EDM measurements.

arXiv:hep-ex/0205099



D^* spin-density matrix elements as functions of x_F and p_t^2

arXiv:hep-ex/9912003



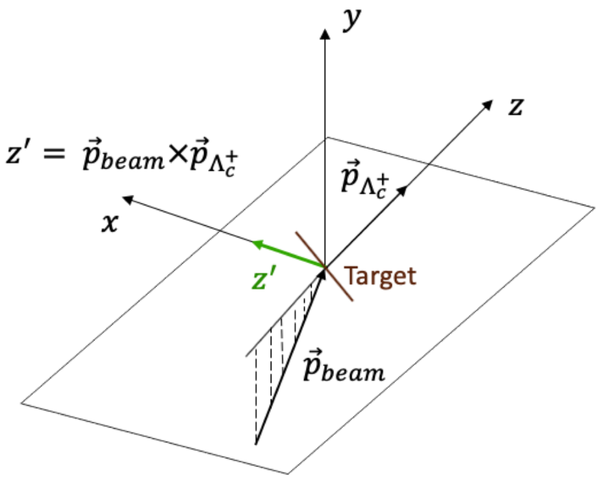
Λ_c^+ polarization as a function of p_T

Polarization measurement

- Polarization is expected to be perpendicular to the production plan due to parity conservation in strong interaction.
- Helicity formalism is used to describe the amplitude: 5 dimensional analysis, 2 masses ($m_{pK}^2, m_{p\pi}^2$) and 3 angles ($\theta_p, \varphi_p, \chi$)

- Spin density matrix

$$\rho = \begin{pmatrix} \rho_{\frac{1}{2},\frac{1}{2}} & \rho_{\frac{1}{2},-\frac{1}{2}} \\ \rho_{-\frac{1}{2},\frac{1}{2}} & \rho_{-\frac{1}{2},-\frac{1}{2}} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{pmatrix}$$



- Complete amplitude

$$\Gamma = \rho_{\frac{1}{2},\frac{1}{2}}\left(|\mathcal{A}_{\frac{1}{2},\frac{1}{2}}|^2 + |\mathcal{A}_{\frac{1}{2},-\frac{1}{2}}|^2\right) + \rho_{\frac{1}{2},-\frac{1}{2}}\left(\mathcal{A}_{\frac{1}{2},\frac{1}{2}}\mathcal{A}^*_{-\frac{1}{2},\frac{1}{2}} + \mathcal{A}_{\frac{1}{2},-\frac{1}{2}}\mathcal{A}^*_{-\frac{1}{2},-\frac{1}{2}}\right)$$

$$+ \rho_{-\frac{1}{2},\frac{1}{2}}\left(\mathcal{A}_{-\frac{1}{2},\frac{1}{2}}\mathcal{A}^*_{\frac{1}{2},\frac{1}{2}} + \mathcal{A}_{-\frac{1}{2},-\frac{1}{2}}\mathcal{A}^*_{\frac{1}{2},-\frac{1}{2}}\right) + \rho_{-\frac{1}{2},-\frac{1}{2}}\left(|\mathcal{A}_{-\frac{1}{2},\frac{1}{2}}|^2 + |\mathcal{A}_{-\frac{1}{2},-\frac{1}{2}}|^2\right)$$

→ By parity conservation in strong interaction

$\Lambda_c^+ \to (K^{*0}(890) \to K^-\pi^+)\, p$
$\Lambda_c^+ \to (\Delta^{++}(1232) \to p\pi^+)\, K^-$
$\Lambda_c^+ \to (\Lambda\,(1520) \to pK^-)\, \pi^+$

- One chain $\Lambda_c^+ \to (K^{*0}(890) \to K^-\pi^+)\, p$

$$A_{K^{*0}}(m,\lambda_p) = B_{K^{*0}}(M_{K\pi}) \times \sum_{\lambda_{K^{*0}}=-1,0,1} D^{1*}_{\lambda_{K^{*0}},0}(\phi'_K, \theta'_K, -\phi'_K)\, D^{\frac{1}{2}*}_{m,\lambda_{K^{*0}}-\lambda_p}(\phi_{K^{*0}}, \theta_{K^{*0}}, -\phi_{K^{*0}})\, ba_{\lambda_{K^{*0}},\lambda_p}$$

Relativistic Breit-Wigner

Angular dependence

Helicity amplitude

Polarization measurement

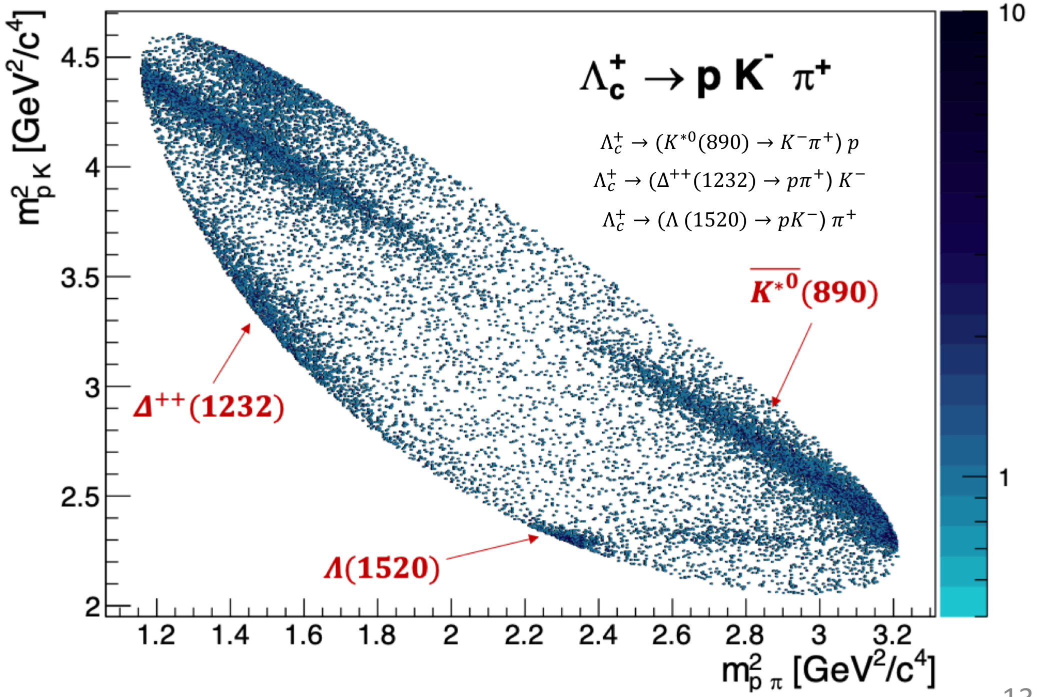
- Here helicity amplitudes including 3 resonances used, to be tuned using *pp* Data.

$$d\Gamma \sim \frac{1+P_a}{2}\left(\left|\sum_r B_r(m_r)\alpha_{r,\frac{1}{2},\frac{1}{2}}\right|^2 + \left|\sum_r B_r(m_r)\alpha_{r,\frac{1}{2},-\frac{1}{2}}\right|^2\right) + \frac{1-P_a}{2}\left(\left|\sum_r B_r(m_r)\alpha_{r,-\frac{1}{2},\frac{1}{2}}\right|^2 + \left|\sum_r B_r(m_r)\alpha_{r,-\frac{1}{2},-\frac{1}{2}}\right|^2\right)$$

- Model based on E791 already available in LHCb software (EvtGen).
- More Λ's resonances can be added to improve the model
- A measurement of the 2 other components of the polarization can be performed as a cross-check.

Resonance	Mass (approx)[MeV/c^2]	Width (approx)[MeV/c^2]	J^P	PDG status
pK channel				
Λ (1405)	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	$1/2^-$	Certain(*)
Λ (1520)	1517 ± 4	15^{+10}_{-8}	$3/2^-$	Certain
Λ (1600)	1544 ± 3	112^{+12}_{-2}	$1/2^+$	Likely
Λ (1670)	1669^{+3}_{-8}	19^{+18}_{-2}	$1/2^-$	Certain
Λ (1690)	1697 ± 6	65 ± 14	$3/2^-$	Certain
Λ (1800)	1720-1850	200-400	$1/2^-$	Likely
Λ (1810)	1750-1850	50-250	$1/2^+$	Likely
Λ (1820)	1824^{+2}_{-1}	77 ± 2	$5/2^+$	Certain
Λ (1830)	1899 ± 40	80^{+100}_{-34}	$5/2^-$	Certain
Λ (1890)	1850-1910	60-200	$3/2^+$	Certain
Λ (2100)	2090-2110	100-250	$7/2^-$	Certain
Λ (2110)	2090-2140	150-250	$5/2^+$	Likely
Λ (2350)	2340-2370	100-250	$9/2^+$	Likely(*)

EvtGen simulation

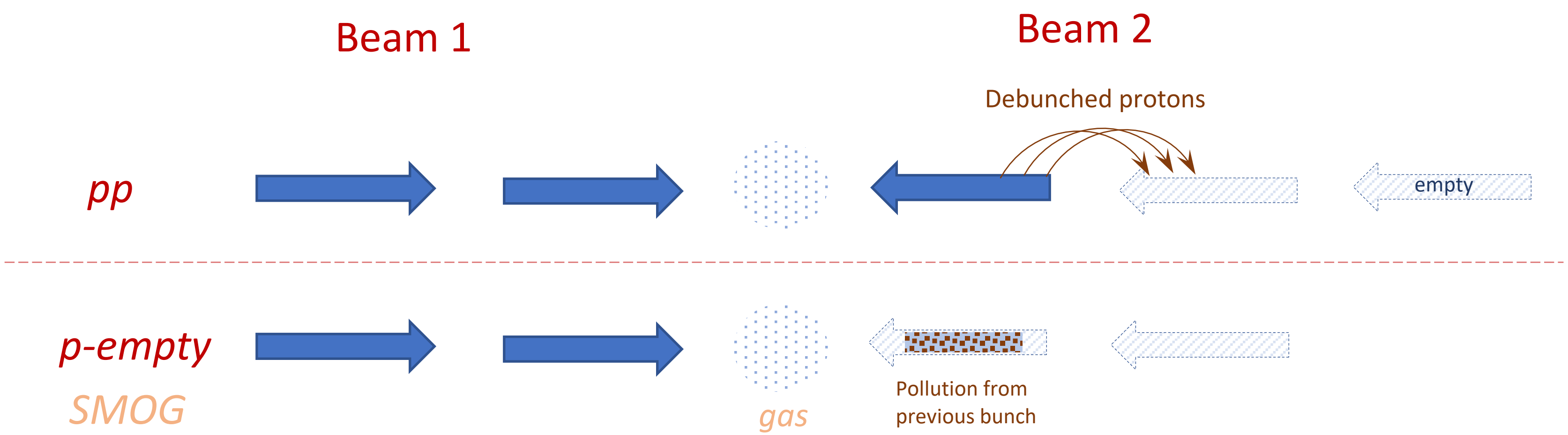


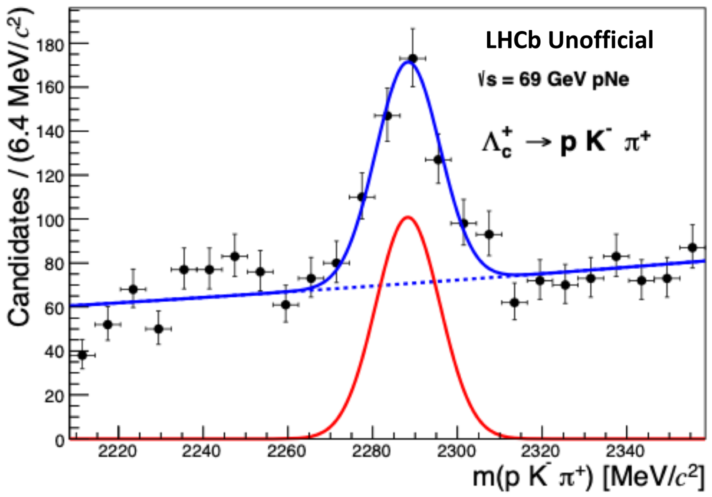
pNe $\Lambda_c^+ \to pK^-\pi^+$ sample at center-of-mass energy $\sqrt{s_{NN}} = 68.6\,GeV$

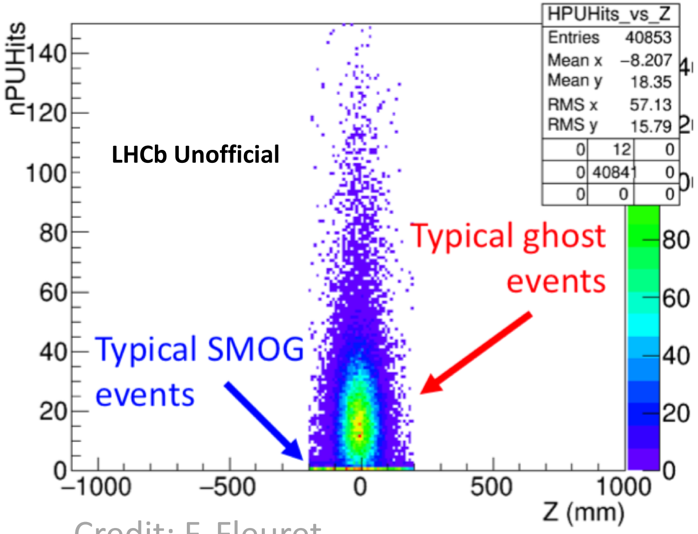
The number of expected events is ~ 200
Major problem: pollution from pp collisions « ghost charges ».

- In the pNe data sample, SMOG is operating continuosly, no special runs.
- *pp* and *p*-Gas data are taken at the same time alternating full and empty bunches.

Some debunched protons from the previous beam goes to the following bunch which is supposed to be empty.







Credit: F. Fleuret

First preliminary selections

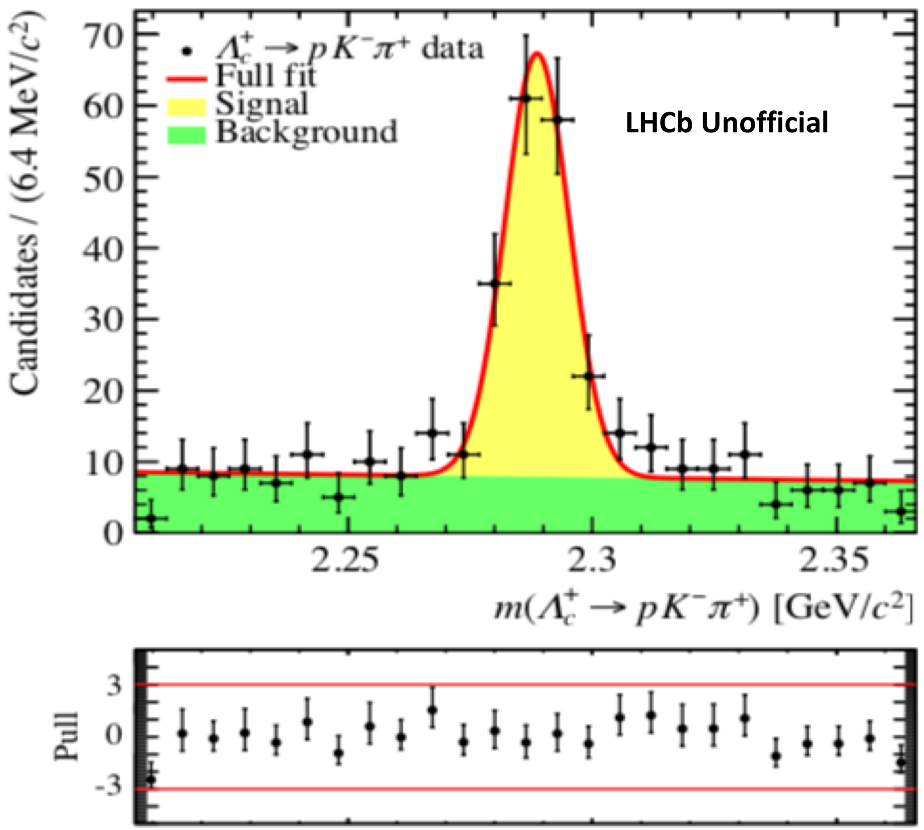
First selection with basic cuts based on (PID, Impact Parameter, Vertex position)

Signal & background yields:

- $S = 153 \pm 15, B = 197 \pm 16$ width ≈ $6.6\ MeV$
- bkg fraction ≈ 19% in $\pm 15\ GeV$ signal region

- Significance $S/\sqrt{S+B} = 11.1$

Credit: D. Marangotto



First preliminary selections

Improve the selection using the $D^+ \rightarrow K^-\pi^+\pi^+$ *p*Ne sample to train a BDT using topological variables.

- higher statistics
- similar 3-body decay topology (but $\tau(D^+) \approx 5\,\tau(\Lambda_c^+)$)
- At the end one may reweight the events according to the $\tau(D^+)/\,\tau(\Lambda_c^+)$ ratio (to be studied)

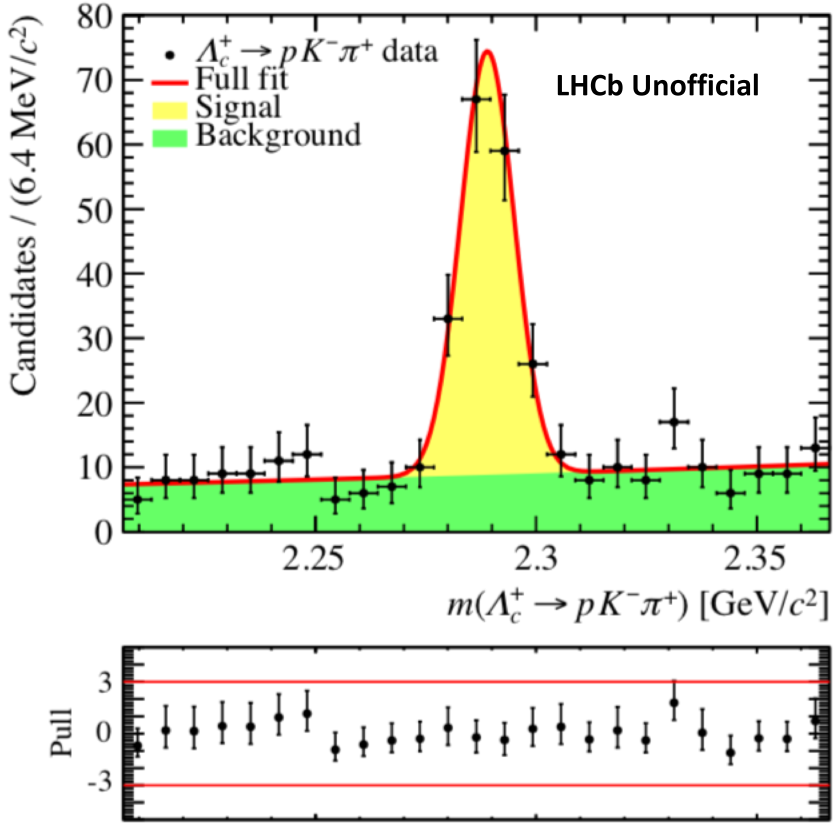
→ Preselection + loose BDT

Signal & background yields:

- $S\ = 356 \pm 24, B\ = 1104 \pm 37$ width $\approx\ 5.3 \pm 0.4\ MeV$
- bkg fraction $\approx\ 37\%$ in $\pm 15\ GeV$ signal region

- Significance $S/\sqrt{S+B} = 15.0$

Credit: D. Marangotto



Perspectives: SMOG2

- New geometry + increase in the target gas pressure
- Ex. *Neon* target: $\sim 2 \times 10^{-5} mbar$ → 100 times larger than SMOG and 0.4 collisions per bunch (pp has 7.6)

Table 2: Expected yields of reconstructed events for selected processes using fixed-target data samples acquired with SMOG during the LHC Run 2, and possible with SMOG2 during Run 3 (using as an example the pAr sample according to the scenario in Table 1).

	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass Drell-Yan yield	negl.	5	9k

CERN-LHCb-PUB-2018-015

Conclusions

- Fixed-target sample taken by SMOG can be used to measure initial polarization of Λ_c^+
- Implementation of the fit has been done with 2 different frameworks: Tensorflow (Daniele Marangotto and Louis Henry) and RooFit (Elisabeth Niel), hence the results on the polarization measurement can be cross-checked to have a robust measurement.
- The high statistics pp data allow to measure the amplitude parameters with good accurancy and fix them when measuring the polarization to p-gas data to compensate for the low statistics.

Future steps:

- Optimise the signal extraction for $\Lambda_c^+ \to pK^-\pi^+$ in pNe: clean the signal from « ghosts charges » and apply an optimised BDT trained on a bigger MC sample.
- Make an estimate of the sensitivity to the polarization in Dalitz plot bins as a function of the number of events
- Expected large improvement with SMOG2!

Thank you

BACKUP →

Charm production in fixed-target collisions

Factorization of the process :

$$A + B \to X + H$$

$$d\sigma = \sum_{i,j,k} f_i^A(x_1) \otimes f_i^B(x_2) \otimes d\sigma(ij \to kX) \otimes D_k^H(z)$$

incident partons : parton distribution functions, non perturbative (long distance)

inelastic interaction producing heavy quarks: hard scattering cross section, computable perturbative

hadronization process of these quarks: fragmentation functions, non perturbative

Factorisation scale μ_F → separates the long and short-distance physics.

Charm production in fixed-target collisions

First fixed-target programs at FermiLab in the 90's. These experiments cover a variety of beam particle types at a range of energies with different target materials.

Motivation for studying heavy-quark production:

- Can study a single quark from its production to its complete hadronisation (not affected by other QGP related effects since their masses are much highers than the QCD critical temperature $\sim 156\ MeV$)
- Allows the investigation of the gluon content of hadrons since the productions is dominated by gluon processes
- Can probe: intrinsic charm, sea-quark ditribution, quark anti-quark asymmetries (and more… particle-antiparticle correlations, fragmentation functions, color-octect model..etc) .

Experiment	Beam Momentum (GeV/c)	Beam Particle	Target Material
E690	800	p	LH_2
E771	800	p	Si
E866/NuSea, E789 and E772	800	p	LH_2, LD_2, C, Ca, Fe, W Ag, Au, and Cu dump
E769	250	$\pi^{\pm}$, $K^{\pm}$, and p	Be, Al, Cu, and W
E781/SELEX	600 572	Σ^- and π^- p	C and Cu C and Cu
E791	500	π^-	C and Pt
E815/NuTeV	20 to 400	ν_μ, $\overline{\nu}_\mu$	Fe
E687	220	γ	Be
E831/FOCUS	170	γ	BeO and Si
WA89	340	Σ^- and π^-	C and Cu
WA82	340 370	π^- p	Si, Cu, and W Si and W
WA92/Beatrice	350	π^-	Cu and W

First fixed-target programs at FermiLab in the 90's. These experiments cover a variety of beam particle types at a range of energies with different target materials.

Motivation for studying heavy-quark production:

- Can study a single quark from its production to its complete hadronisation (not affected by other QGP related effects since their masses are much highers than the QCD critical temperature $\sim 156\ MeV$)
- Allows the investigation of the gluon content of hadrons since the productions is dominated by gluon processes
- Can probe: intrinsic charm, sea-quark ditribution, quark anti-quark asymmetries (and more… particle-antiparticle correlations, fragmentation functions, color-octect model..etc) .

Jeffrey A. Appel : https://cds.cern.ch/record/478924/files/0011101.pdf

Charm production in fixed-target collisions

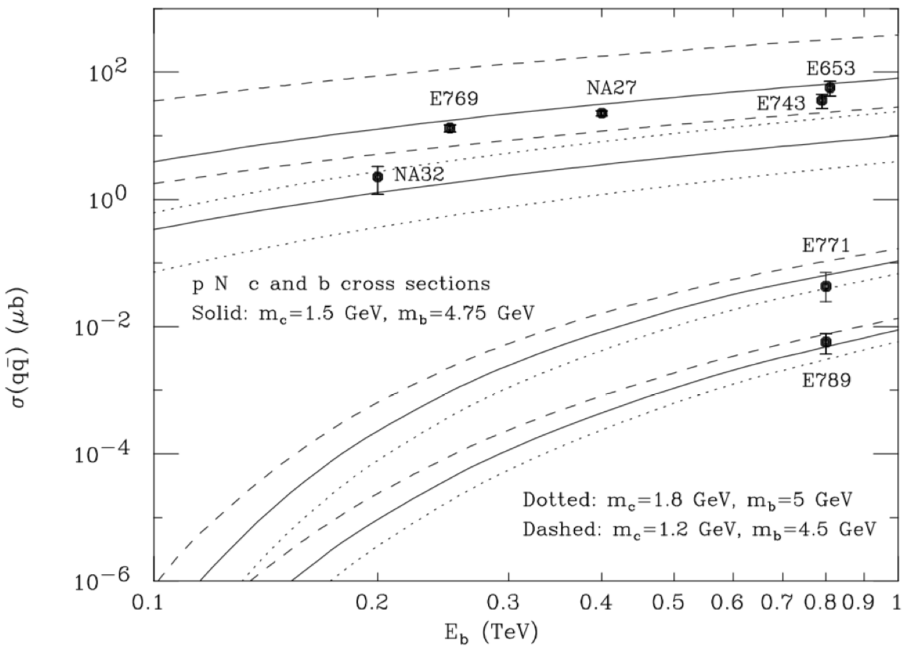


Figure 2: *Pair cross sections for b and c production in pN collisions versus experimental results.*

Most of the available data are on charmed-hadron production since the $b\bar{b}$ cross section is small at these energies.

The theoretical apparatus of perturbative QCD is in this case at its very limit of applicability, because the charm mass is very close to typical hadronic scales.

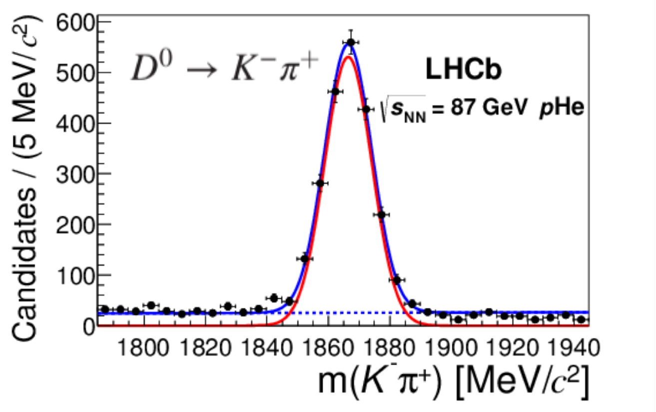
Thus, effects of non-perturbative origin will very likely play an important role and they can be better studied.

Fixed-target experiments can sheld lights on QCD calculations.

arXiv:hep-ph/9702287

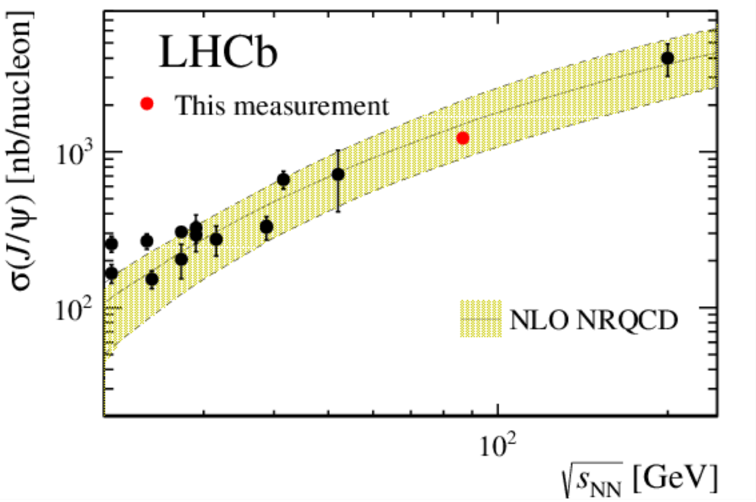
Charm production in fixed-target collisions

First measurement of charm production in fixed target mode has been performed by LHCb:[Phys. Rev. Lett. 122, 132002 (2019) LHCb-PAPER-2018-023]: Measurement of J/ψ and D^0 production cross section in pHe collisions in the rapidity range [2,4.6] at $\sqrt{s_{NN}} = 86.6\ GeV$ and $110.4\ GeV$



Motivations:

- The production of D^0 mesons allows to study the charm production mechanism
- In proton-nucleus collisions one can study the the behaviour of $c\bar{c}$ pairs, parton shadowing in the target modifying the charmonium production, saturation effects and parton energy loss.



Results:

LHCb results in good agreement with NLO NRQCD fit (J/ψ) and other experimental measurements at various energies

Rk: $c\bar{c}$ not shown here, a correction is being implemented and it is not official yet.