"Λ_c^+ polarization with SMOG"

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Joint Workshop

« GDR-QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOAccess »

3rd of June 2020, Virtual

JOINT WORKSHOP "GDR-QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOACCESS"

May 31 to June 4 2021

Visioconference

Groupement de recherche

QCD Chromodynamique quantique

Chromodynamique quantique

Motivations

1. Few measurements in fixed-target mode for hyperons, giving intruiguing results

2. For charmed baryons one measurement performed in the 90's at Fermilab E791

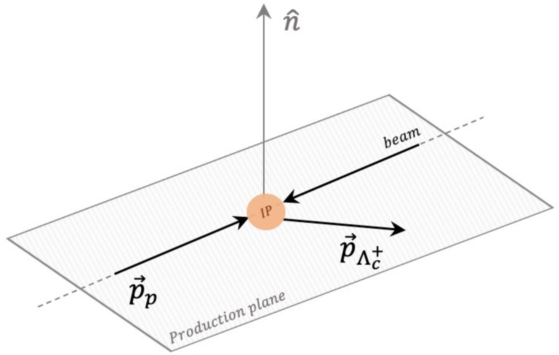
3. Polarization in fixed target needed for MDM and EDM measurements with crystals, see talks:

   - Alex Fomin https://indico.ijclab.in2p3.fr/event/7201/contributions/22630/
   - Federico Benedetti https://indico.ijclab.in2p3.fr/event/7201/contributions/22631/
   - Andrea Merli https://indico.ijclab.in2p3.fr/event/7201/contributions/22625/

4. SMOG offers the unique opportunity to preform a measurement of baryon polarization in fixed-target mode at the LHC

How to measure polarization

- Polarization P: projection of the spin on an arbitrary axis,
  → to choose the polarization axis exploit symmetries:
  for strongly produced baryons the polarization must be perpendicular to the production plane



- Need a decay that allow to measure the polarization, angular distribution for $B \rightarrow 1 + 2$:

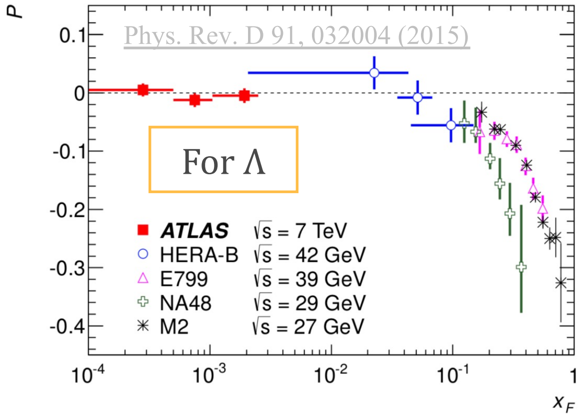
$$\frac{d\Gamma}{d\Omega} \propto (1 + \alpha_{\mathrm{B}}\, P \cos\theta)$$

  - θ is the angle between the particle 1 momentum and the baryon spin/polarization axis
  - P is the magnitude of the baryon polarization
  - α_{B} is the decay asymmetry parameter, defined as:

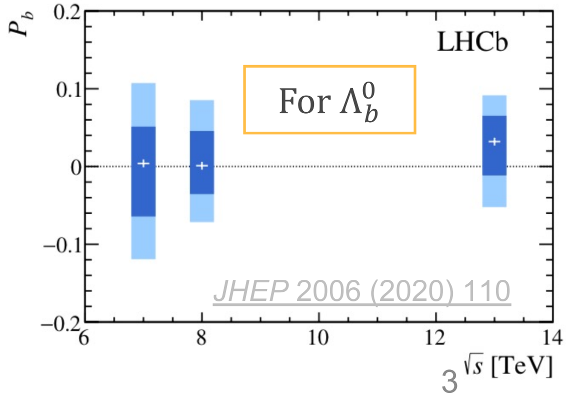
    A_+, A_- are the parity-even and parity-odd amplitudes

$$\alpha_{\mathrm{B}} = \frac{2Re(A_+^* A_-)}{|A_+|^2 + |A_-|^2}$$

  → Need parity violating decay to be sensitive to the polarization



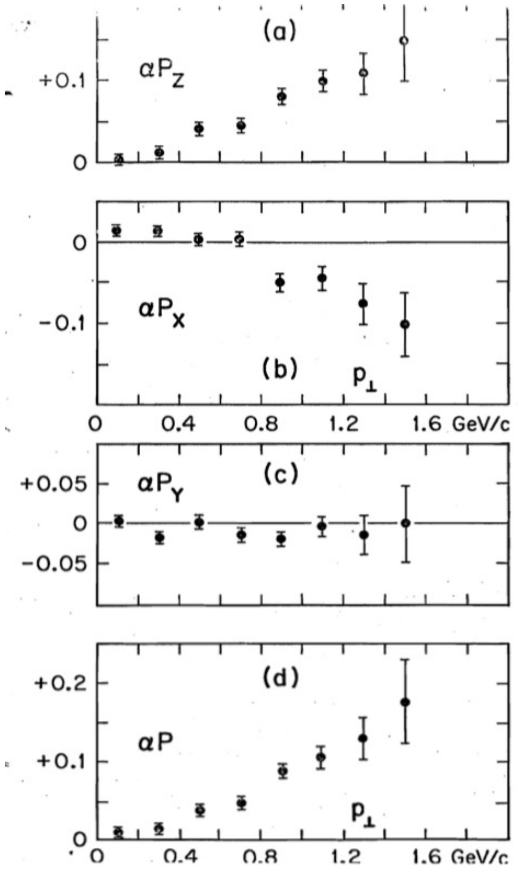
- Degree of polarization depend on the production mechanism involved:
  - In *pp* at the LHC energies: expected zero polarization for promptly produced baryons based on prevous measurements for Λ and Λ_b^0
  - Fixet-target: a polarization has been observed



Hyperon polarisation: first measurements

I. 1976: 300 GeV protons on Be target FERMILAB-PUB-76-157-E
   - ❖Measured the three components of the polarization independently
   - ❖Unexpected result: 28% polarization (not predicted by pQCD)

I. Polarisation vs transverse momentum



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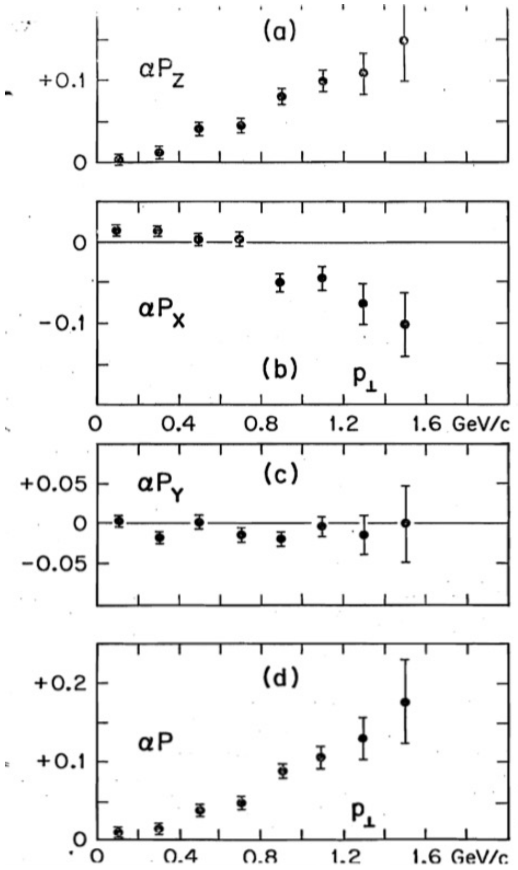

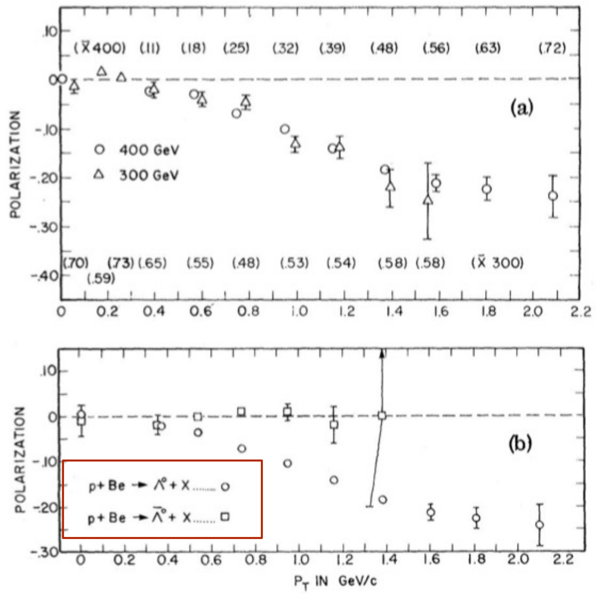

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III. Other hyperons:
   1. Σ^+ 1993, A. Morelos , p-Cu p at 800 GeV
   2. Ξ^- 1990, P. M. Ho, et. al., p+Be, p at 800 GeV
   3. Ω^- 1993, K. B. Luk, et. Al, p+Be, p at 800 Ge

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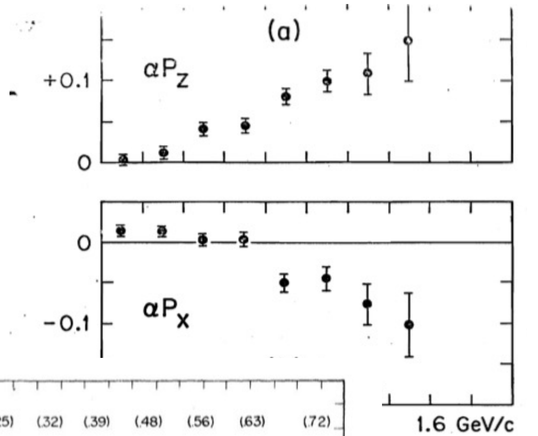
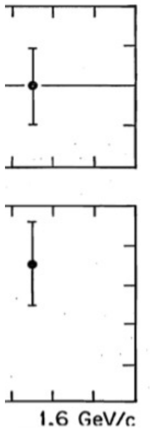
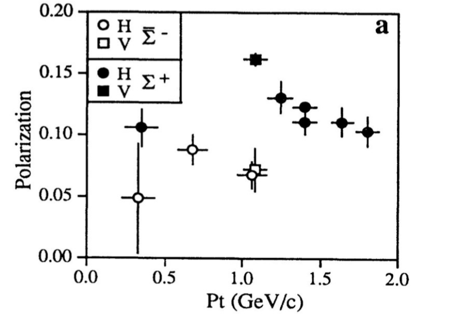
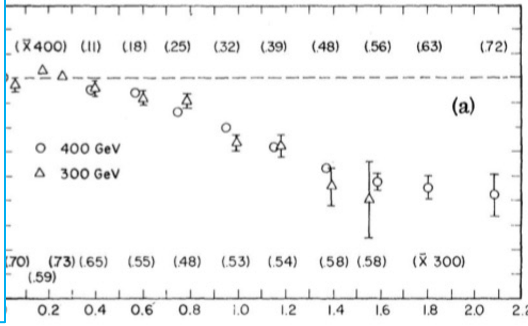
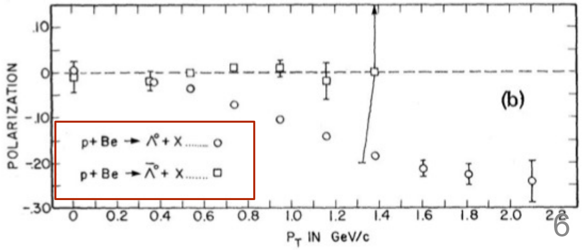


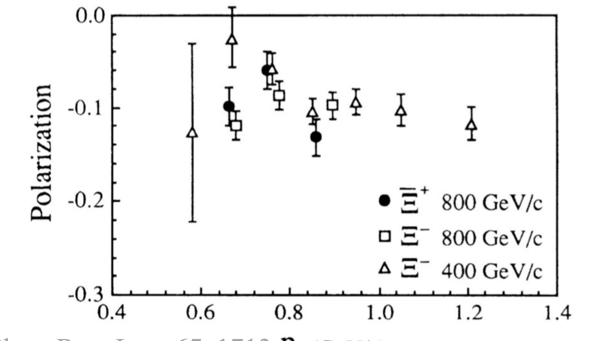


Phys. Rev. Lett. 71, 2172 (1993)

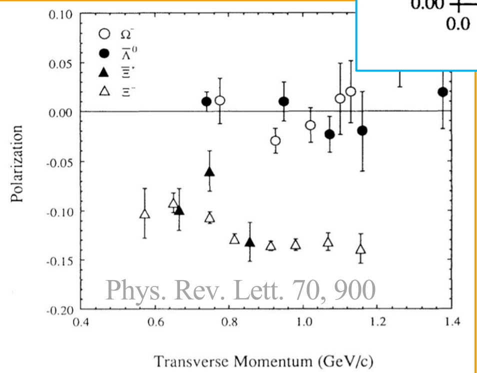








Phys. Rev. Lett. **65**, 1713 p_t (GeV/c)



Phys. Rev. Lett. 70, 900

Baryon polarisation: first measurements

In summary, it seems that:

1. Polarization increase with transverse momentum
2. It depends on the type of baryon

Other measurements have been performed in

- e^+e^- collisions:
  1. BES III at the BEPCII accelerator : $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ where $\Lambda \to p\pi^-$, polarization up to 25 %

     Nature Physics, 15(7):631–634, May 2019

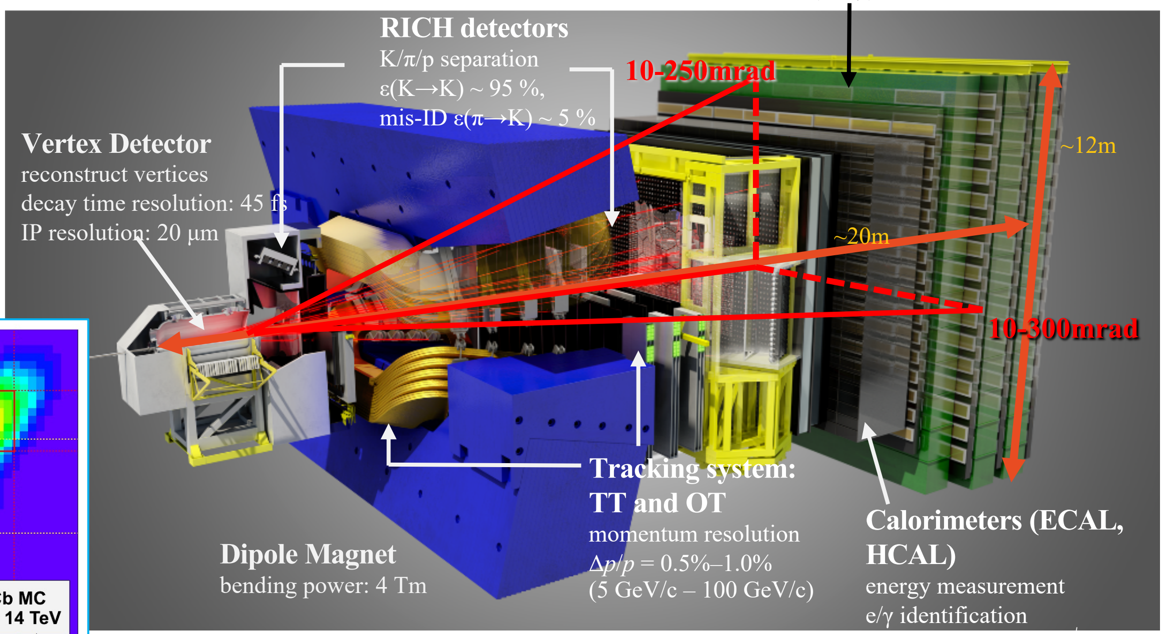
  2. BELLE: $e^+e^- \to \Lambda(\bar{\Lambda})X$, $800.4\ fb^{-1}$ collected at or near a center-of-mass energy of 10.58 GeV , significant polarisation that rises with the fractional energy carried by the $\Lambda/\bar{\Lambda}$ hyperon *Phys. Rev. Lett.*, 122(4):042001, 2019
- Ion-ion collisions
  1. Λ and $\bar{\Lambda}$ polarization compatible with zero in Pb-Pb collisions at 2.76 and 5.02 TeV *Phys. Rev. C*, 101(4):044611, 2020

Polarization measuremetns in fixed-target systems

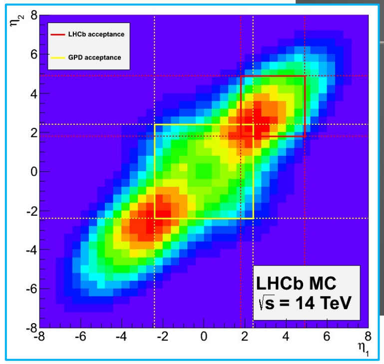
Baryon	System	Beam energy [GeV]	Result	p_T range [GeV/c]	Experiment
Λ^0	pBe	300	18%	1.5	[41]
	pBe	400	24%	2.1	[42]
	pC and pW	920	~ 0	~ 0.8	[49]
	pN	450	up to 0.29%	0.86	NA48 [50]
$\bar{\Lambda}^0$	pBe	400	0	up to 1.2	[42]
	p-X	400	0	up to 2.4	[46]
Ω^-	pBe	800	~ 0	[0.5, 1.3]	[47]
Σ^+	pCu	800	16%	1.	E761 [48]
Ξ^0	pCu and pBe	400	$\sim 20\%$	1.6	[51]
Ξ^+	pBe	800	up to 0.09%	0.76	[54]
Ξ^-	pBe	400	up to 10%	1.21	[52]
	pCu	400	up to 0.07%	0.63	[53]
	pBe	800	up to 0.1%	>0.8	[55]

The LHCb detector

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

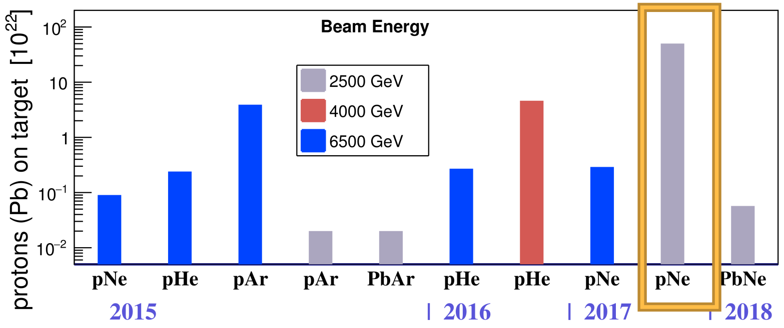


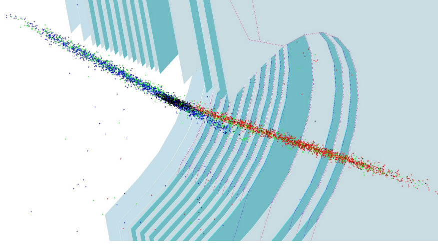
$b\bar{b}$ acceptance



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

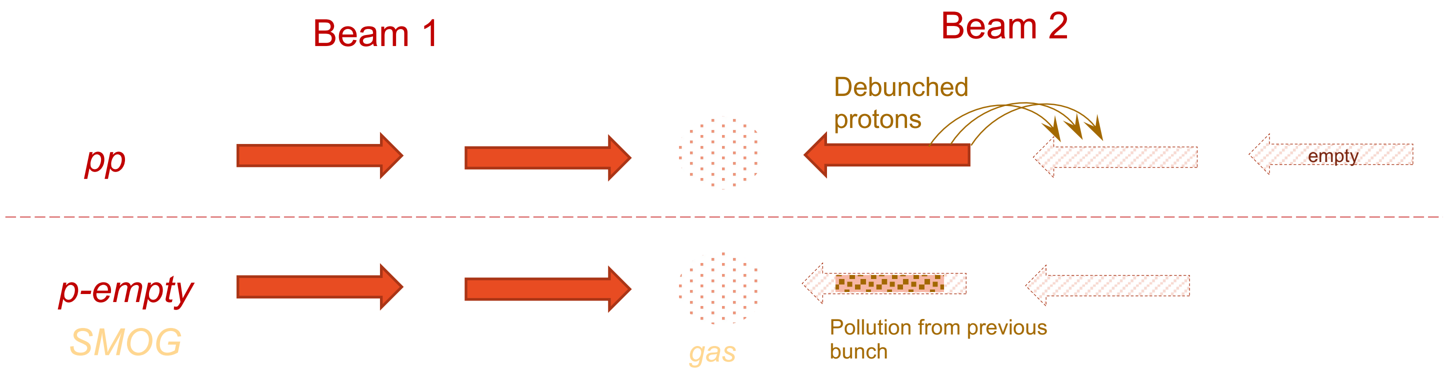
- Excellent performances
- It is a "charm factory": for pp collisions,
  - $4 \times 10^{32}\ cm^{-2}s^{-1}$ luminostiy for Run 2: the rate of $c\bar{c}$ pairs is 0.96 MHz
  - The rate of Λ_c^+ seen by the LHCb detector is 602 Hz
- Unique system to inject gas (SMOG) originally designed for luminosity measurements. Re-used to transform LHCb in a fixed-target experiment. See talk form Pasquale.
- Recent interesting physics results, see talk from Benjamin
- Data Samples:





SMOG pollution

- Data sample: 2.5 TeV protons on Neon, center of mass energy of 68.9 GeV
- Data are taken simultaneously wit *pp* collisions at 5 TeV, no special runs.
- Major problem: pollution from pp collisions « ghost charges ».
    - ❖ pp and p-Gas data are taken at the same time alternating full and empty bunches.
    - ❖ Some debunched protons from the previous beam go to the following bunch which is supposed to be empty.

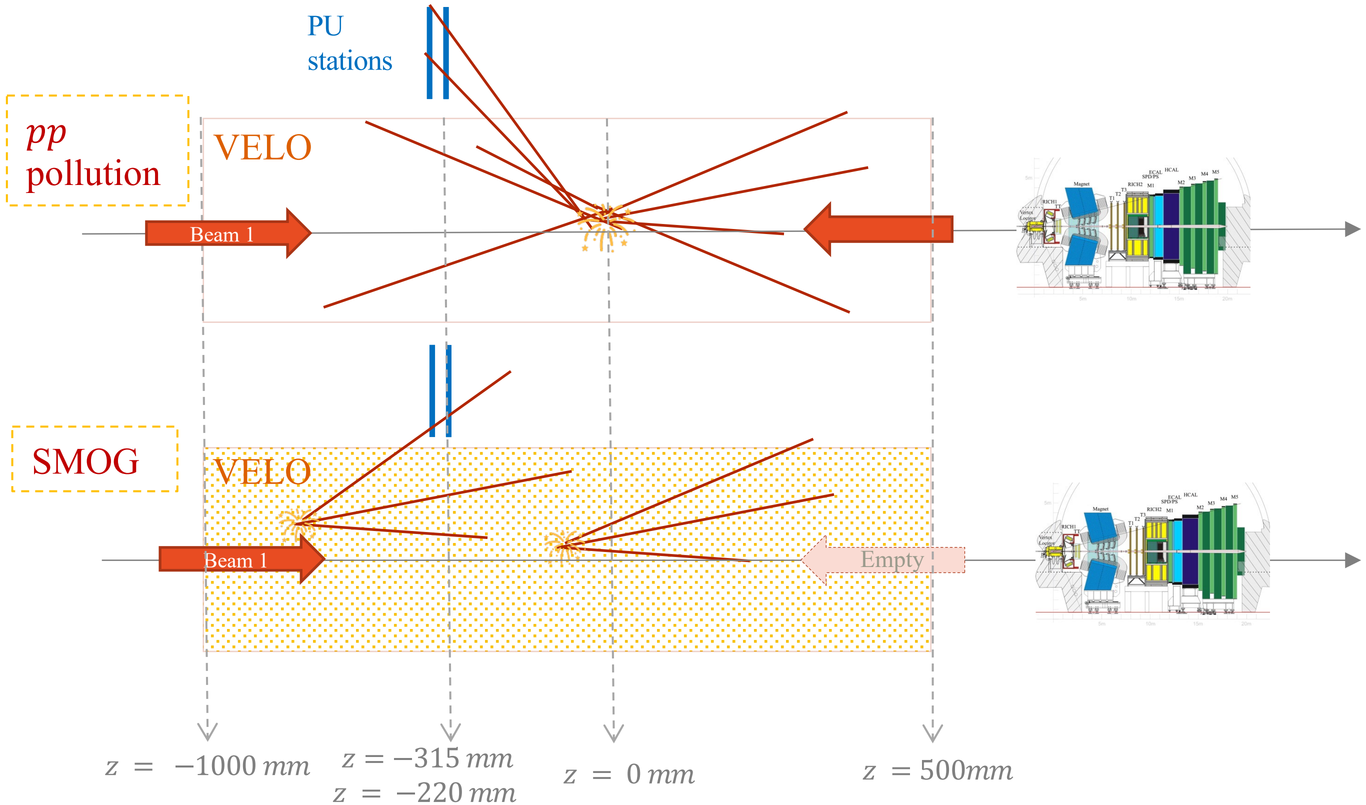


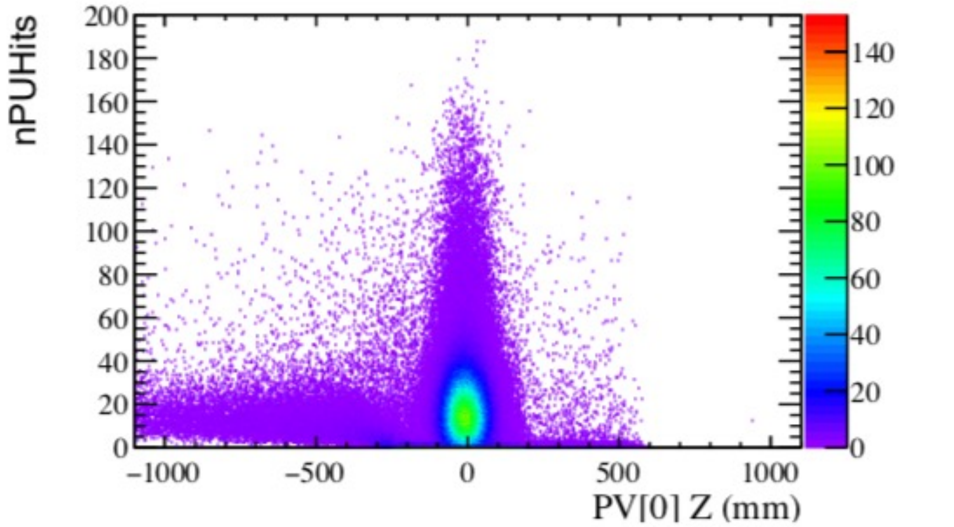
SMOG pollution

Global event cuts for 2017 pNe SMOG data. Technical report, CERN, Geneva, Jun 2020. https://cds.cern.ch/record/2720461.
By Frédéric, Benjamin, Felipe and Emilie

Cleaning using the event topology:

- Z coordinate of the PV: SMOG has a larger PVZ region
- Number of hits in the Pile Up stations of VELO at z = −315 and z = −220 mm
  → small for smog events which are forward
- Number of reconstructed tracks (nTracks) pointing opposite to the LHCb detector



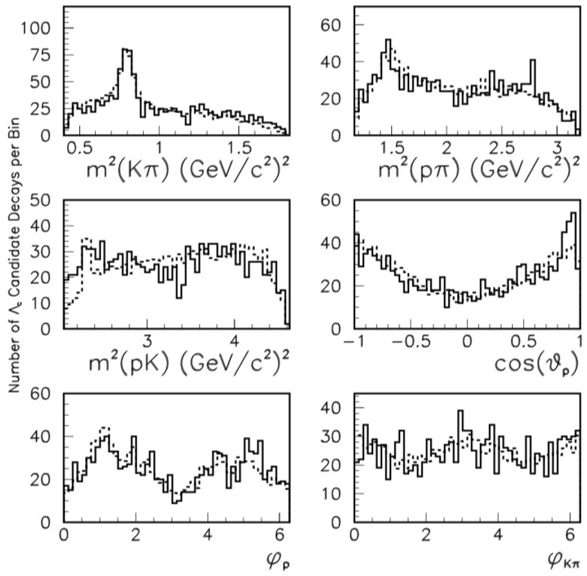


	$-200 < Z_{PV} < -100$	$-100 < Z_{PV} < +100$	$+100 < Z_{PV} < +200$
nPUHits=0 - GC	$(0.64 \pm 0.31)\%$	$(8.93 \pm 3.27)\%$	$(0.57 \pm 0.34)\%$
nPUHits=0 - SL	$(24.32 \pm 1.16)\%$	$(31.26 \pm 0.88)\%$	$(21.35 \pm 1.28)\%$
Correction factor	1.235 ± 0.012	1.195 ± 0.044	1.207 ± 0.013
nPUHits<3 - GC	$(2.25 \pm 0.47)\%$	$(29.44 \pm 4.77)\%$	$(1.84 \pm 0.56)\%$
nPUHits<3 - SL	$(14.86 \pm 0.91)\%$	$(24.32 \pm 0.77)\%$	$(14.23 \pm 1.04)\%$
correction factor	1.123 ± 0.010	0.877 ± 0.060	1.121 ± 0.012
nPUHits<5 - GC	$(4.69 \pm 0.62)\%$	$(49.08 \pm 5.35)\%$	$(3.76 \pm 0.78)\%$
nPUHits<5 - SL	$(11.91 \pm 0.81)\%$	$(21.79 \pm 0.73)\%$	$(12.17 \pm 0.96)\%$
correction factor	1.067 ± 0.010	0.620 ± 0.065	1.080 ± 0.013

Table 7: GC: Fraction of Ghost-Charge residual contamination after nPUHits cut; SL: fraction of fixed-target Signal Loss after nPUHits cut. Correction factor is given by $(1 - GC) \times (1 + SL)$

Charmed baryons: Λ_c^+ at Fermilab E791

- 1999 Phys.Lett.B471:449-459, 2000
- 500 GeV/c π^- N interactions by Fermilab experiment E791
- First five-dimensional resonant amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ with **946 ± 38** events

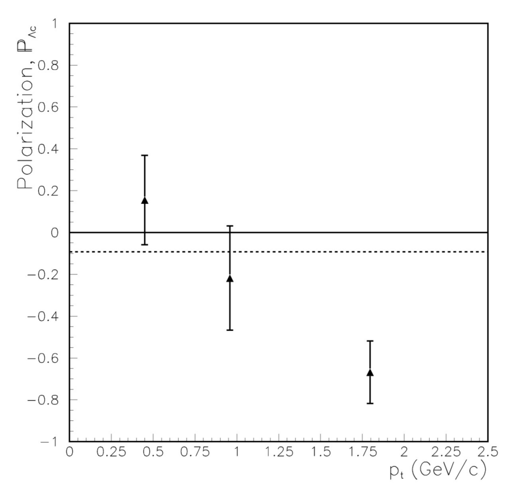


$\Lambda_c^+ \to p\, K^-\pi^+$	non resonant
$\Lambda_c^+ \to (K^* \to K^-\pi^+)\, p$	K^* chain
$\Lambda_c^+ \to (\Delta^{++} \to p\pi^+)\, K^-$	Δ chain
$\Lambda_c^+ \to (\Lambda \to pK^-)\, \pi^+$	Λ chain

Λ_c branching ratios relative to the inclusive $\Lambda_c^+ \to pK^-\pi^+$ branching fraction. The NA32 and ISR values were calculated from one-dimensional projections only.

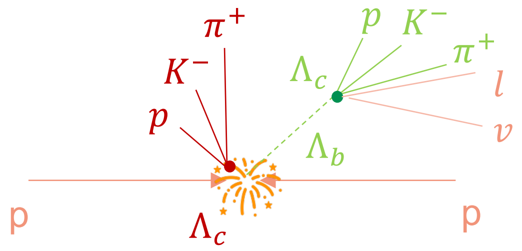
Mode	E791	NA32[16]	ISR[17]
$p\overline{K}^{*0}(890)$	0.29±0.04±0.03	$0.35^{+0.06}_{-0.07}$±0.03	0.42±0.24
$\Delta^{++}(1232)K^-$	0.18±0.03±0.03	$0.12^{+0.04}_{-0.05}$±0.05	0.40±0.17
$\Lambda(1520)\pi$	0.15±0.04±0.02	$0.09^{+0.04}_{-0.03}$±0.02	
Nonresonant	0.55±0.06±0.04	$0.56^{+0.07}_{-0.09}$±0.05	

- evidence for an increasingly negative polarization of the Λ_c^+ baryons as a function of p_T
- Additional data are needed in order to conclusively demonstrate the presence of additional resonances
- Today we know that the amplitude model used by E791 was incomplete



Charmed baryons: Λ_c^+ at LHCb

- Preliminary amplitude model for the polarization measurement is build using the high statistics sample from Run II, *pp* collisions at 13 TeV
- Model: iosbar decomposition with helicity amplitudes for spin factors and relativitic Breit-Wigners for (almost all) the intermediate resonances
- Include polarisation using density matrix (for spin ½)



$$\rho = \frac{1}{2}(\mathcal{I} + \mathbf{P}\cdot\boldsymbol{\sigma}) = \begin{pmatrix} \rho_{\frac{1}{2},\frac{1}{2}} & \rho_{\frac{1}{2},-\frac{1}{2}} \\ \rho_{-\frac{1}{2},\frac{1}{2}} & \rho_{-\frac{1}{2},-\frac{1}{2}} \end{pmatrix}$$

$$d\Gamma(\Omega) \propto \sum_{m,m'} \rho_{m,m'} \mathscr{A}_{m,\lambda_1,\lambda_2,\lambda_3} \mathscr{A}^*_{m',\lambda_1,\lambda_2,\lambda_3}$$

- Finding a model describing the data is a big challenge!

Particle	J^P	Overall status	$N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$
$\Lambda(1116)$	1/2+	****		F	
$\Lambda(1405)$	1/2−	****	****	o	****
$\Lambda(1520)$	3/2−	****	****	r	****
$\Lambda(1600)$	1/2+	***	***	b	**
$\Lambda(1670)$	1/2−	****	****	i	****
$\Lambda(1690)$	3/2−	****	****	d	****
$\Lambda(1800)$	1/2−	***	***	d	**
$\Lambda(1810)$	1/2+	***	***	e	**
$\Lambda(1820)$	5/2+	****	****	n	****
$\Lambda(1830)$	5/2−	****	***	F	****
$\Lambda(1890)$	3/2+	****	****	o	**
$\Lambda(2000)$		*		r	*
$\Lambda(2020)$	7/2+	*	*	b	
$\Lambda(2100)$	7/2−	****	****	i	
$\Lambda(2110)$	5/2+	***	**	d	
$\Lambda(2325)$	3/2−	*	*	d	
$\Lambda(2350)$		***	***	e	
$\Lambda(2585)$		**	**	n	

Not public

Not public

Moving towards SMOG measurement

- To measure the polarization: fix the helicity couplings to the values obtained in pp data, let only the polarization vary
- Expected number of $\Lambda_c^+ \rightarrow p\, K^-\pi^+$ events after cleaning with an handmade selection: **~200-300 signal events**
- Increase of the number of events using machine learning technique to optimise the selection: **~400 signal events**
- Simplified model, not all the resonances seen in pp data, for now only: $K^*(890), \Lambda^*(1520), \Delta^{++}(1232)$.
- Conclusion from toy studies: the measurement can be performed with a **statistical error ~0.12**
- The statistics will be improved during Run 3 thanks to SMOG2: **statistical error ~0.004 ,** systematics uncertainties will dominate

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

Nb signal events	Statistical error
200	0.144
300	0.118
400	0.103
SMOG2	
300 000	0.004

Conclusions and prospects

1. Baryon's polarisation has been studied starting from the first puzzling results on hyperon polarisation
2. LHC experiments can perform precise measurements on baryons (and not only) polarization and asymmetry parameters with complex multi-dimensional analyses
3. The interplay of pp and SMOG data will allow to measure Λ_c^+ polarization with a statistical (dominant) error around ~0.14 for 200 events (worst case scenario)
4. SMOG allows to performs a first measurement of Λ_c^+ polarization and SMOG2 wil allow to increase the precision significantly

Thank you

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