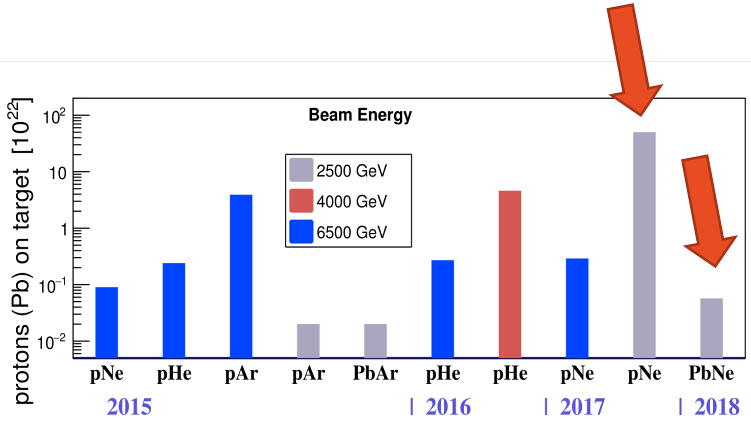
Charm with fixed-target LHCb

Elisabeth Maria Niel

École polytechnique fédérale de Lausanne

Rencontres QGP France 2022

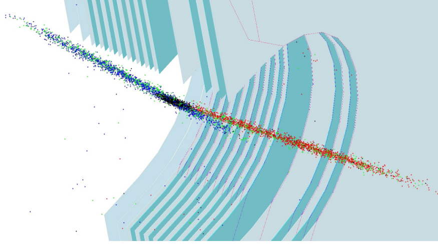
2-5 May 2022



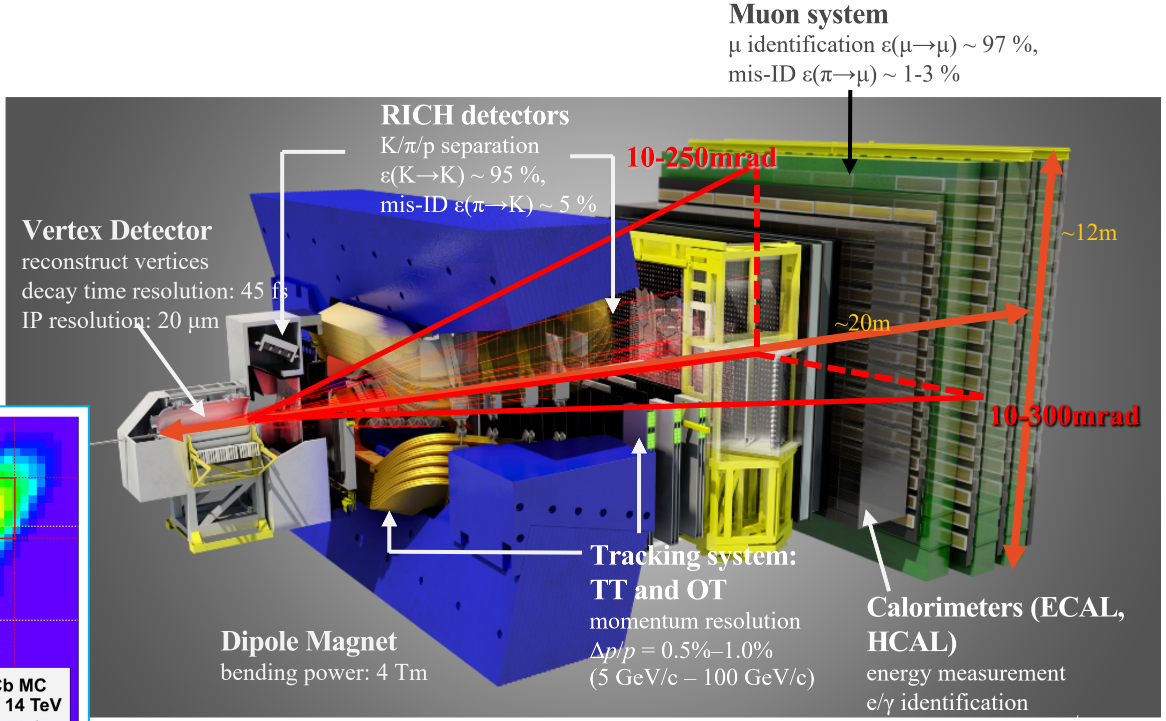
Irène Joliot-Curie

Laboratoire de Physique des 2 Infinis

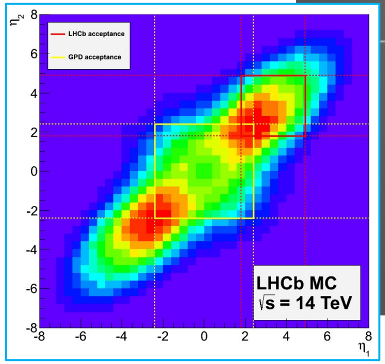
The LHCb detector



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

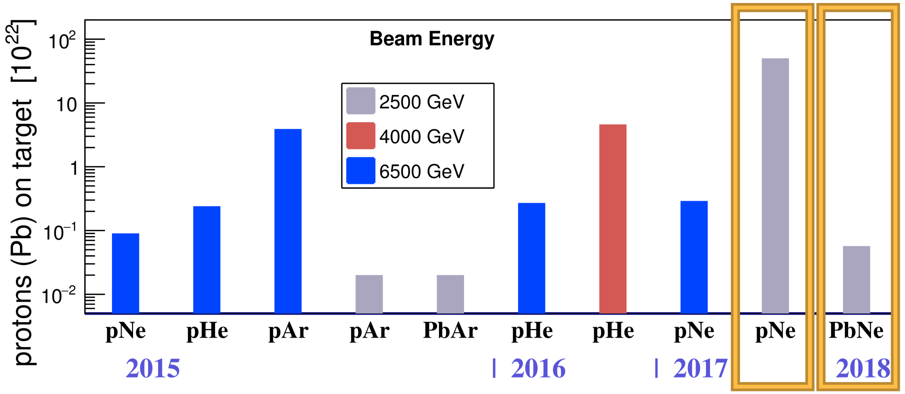


$b\bar{b}$ acceptance



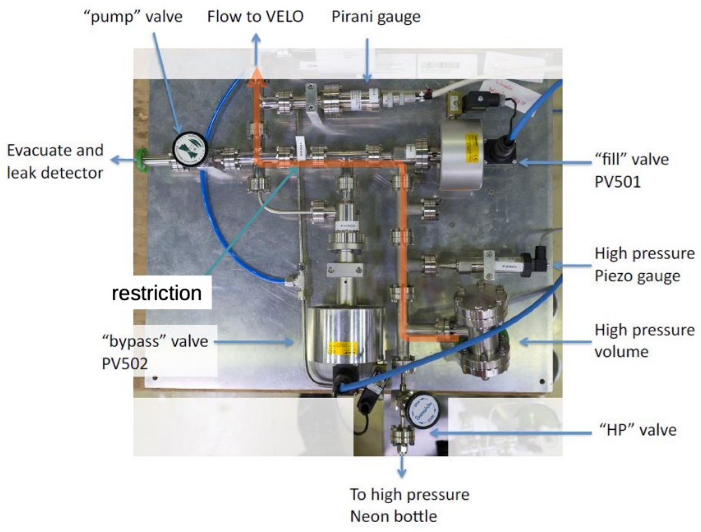
Single arm forward spectrometer with excellent vertexing, tracking, PID (acceptance $2 < \eta < 5$)

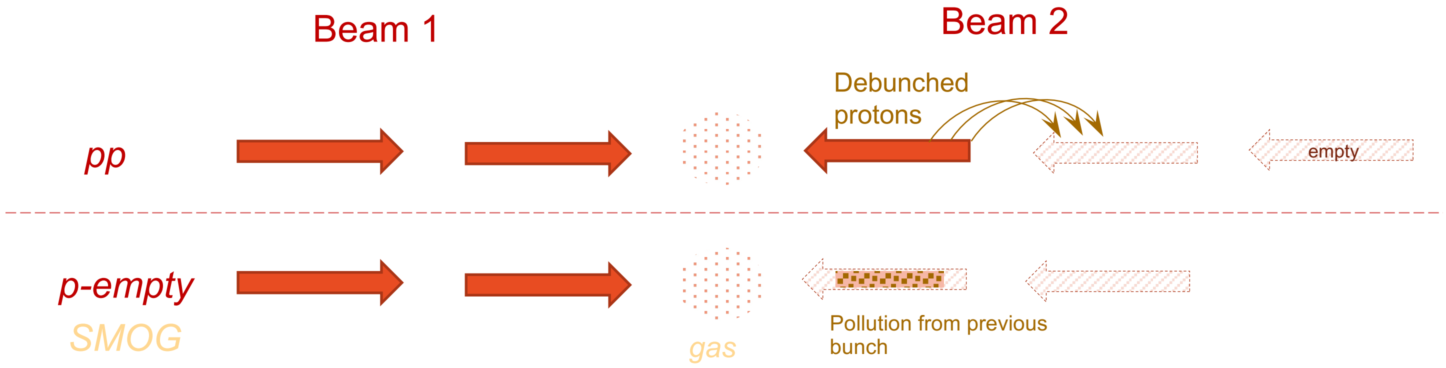
- Excellent performances
- It is a "charm factory": for *pp* collisions,
  - $4 \times 10^{32}\ cm^{-2}s^{-1}$ luminostiy for Run 2: the rate of $c\bar{c}$ pairs is 0.96 MHz
  - The rate of Λ_c^+ seen by the LHCb detector is 602 Hz
- Unique system to inject gas (SMOG) originally designed for luminosity measurements. Re-used to transform LHCb in a fixed-target experiment. [JINST 9 (2014) P12005]
- Data Samples SMOG:



SMOG pollution

- Data sample: 2.5 TeV protons on Neon, center of mass energy of 68.9 GeV
- Data are taken simultaneously with *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.



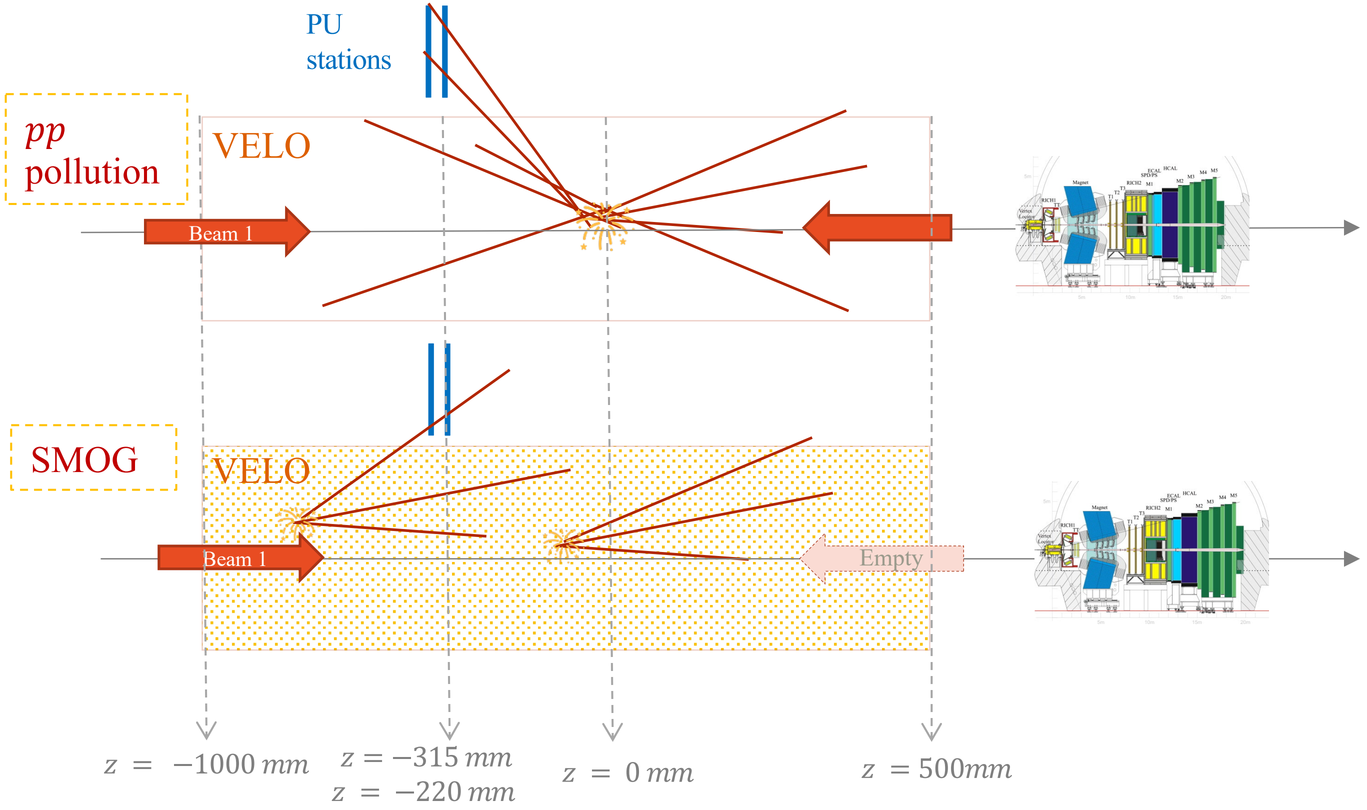


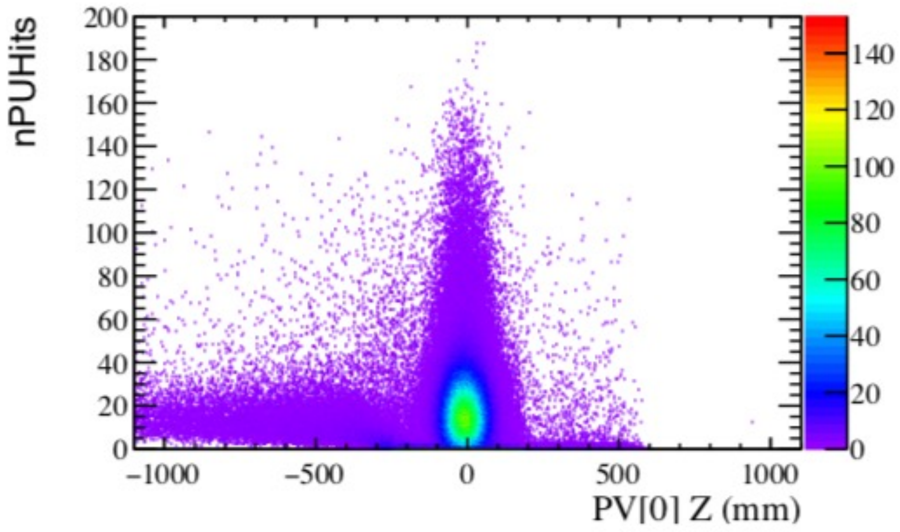
SMOG pollution

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 LHCb





	$-200 < Z_{PV} < -100$	$-100 < Z_{PV} < +100$	$+100 < Z_{PV} < +200$
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 $(1 - GC) \times (1 + SL)$

Charm production as a probe for QCD

Charmonium production

T. Matsui, H. Satz, Physics Letters B 178 (1986), no. 4 , *Phys.Rev.D* 64 (2001) 094015

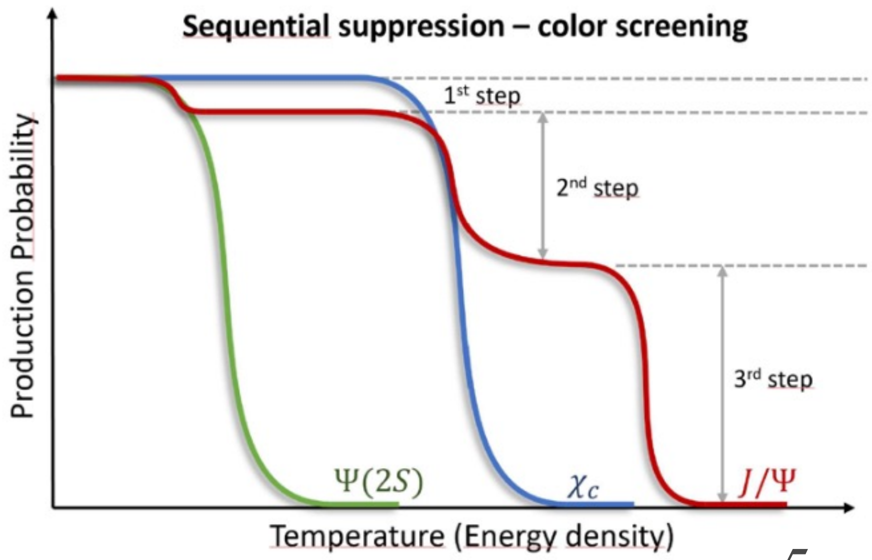
1. It's a smoking gun of QGP production via the color screen mechanism
2. J/ψ suppression has been studied in several fixed-target experiment, however the underlying mechanism is still not fully understood→ new measurements in different colliding systems are fundamental to constraint cold nuclear matter effects
3. Suppression compensated by statistical recombination at high $\sqrt{s}_{NN}$
4. Other charmonium states also affected : $\psi(2S)$ and χ_c with lower binding energy (suppressed at lower temperature). For J/ψ produced from excited states → sequential suppression.

Why Open Charm?

1. D^0 open charm, not affected by QGP and gives an estimate of the total amount of $c\bar{c}$ pairs
2. Compare the ratio J/ψ to D^0 in pNe and PbNe systems
3. Cross-section and asymmetry relevant to study the nucleon content

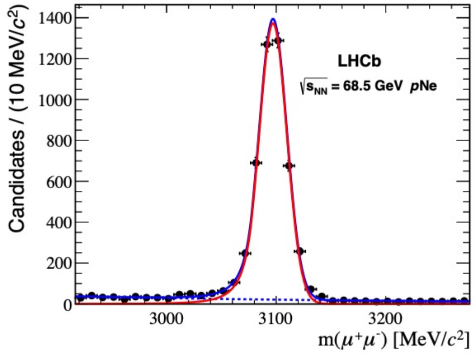
Measurement with pNe LHCb data:

1. J/ψ cross-section (integrated and as a function of p_T and y^*)
2. J/ψ / $\psi(2S)$ ratio using di-muon decay
3. D^0 ratio , using $D^0 \to K^-\pi^+$
4. D^0 production asymmetry

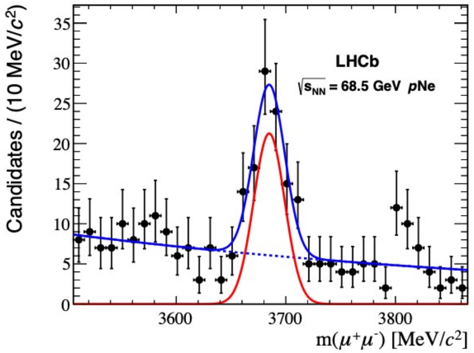


Charmonium production

$N_{sig} = 4\ 542\ J/\psi \rightarrow \mu^+\mu^-$



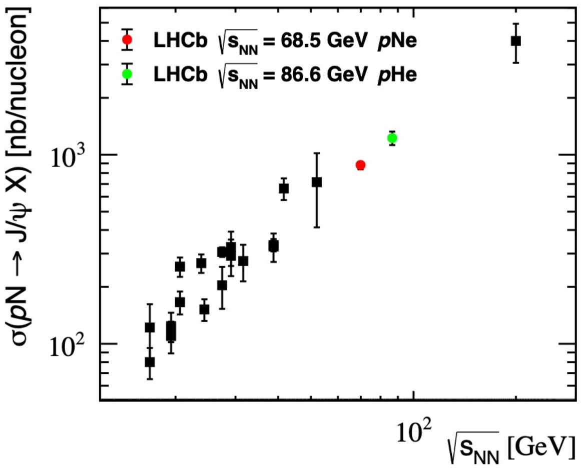
$N_{sig} = 76\ \psi(2S) \rightarrow \mu^+\mu^-$



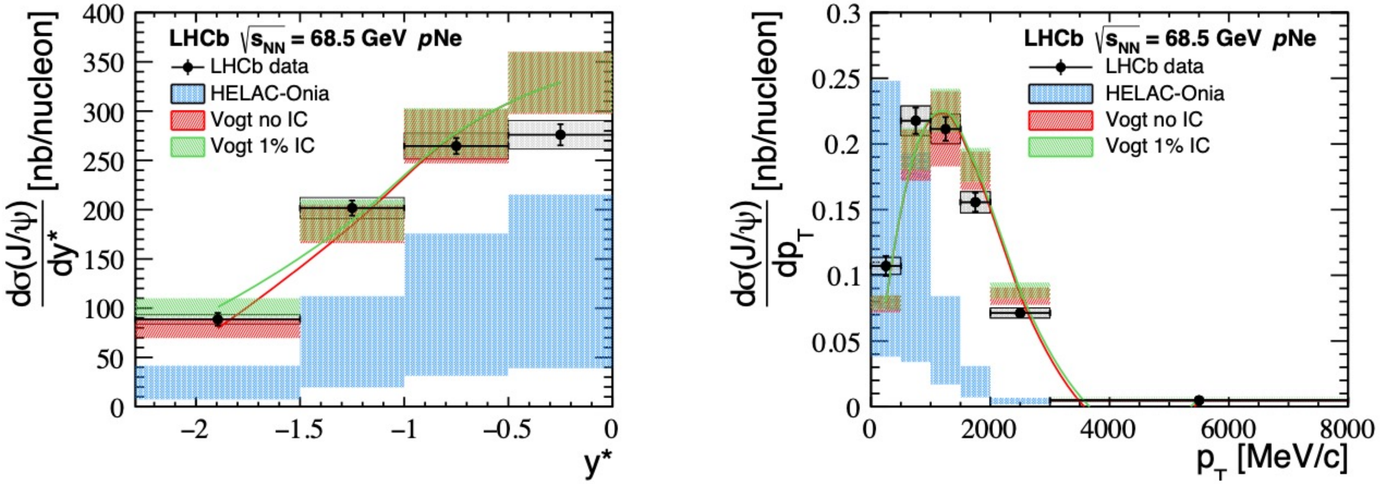
$$\sigma = \frac{N_{\text{Signal}}^{\text{After correction}}}{\mathcal{L} \times A_{\text{nucleus}} \times BR}$$

$$\sigma^{J/\psi}_{y* \in [-2.29,0]} = 444.1 \pm 6.9\ (\text{stat})\ \pm 4.5\ (\text{uncorr syst})\ \pm 21.2\ (\text{corr syst}) \text{nb/A}.$$

1. J/ψ cross section measurement:



- Total cross-section: extrapolation to full phase space using Pythia8+CT09MCS PDF
- power-law dependency with $\sqrt{s_{NN}}$



- HELAC-ONIA using CT14NLO and nCTEQ15 under shoot the data
- Good agreement with predictions with (1%) and without an Intrinsic Charm contribution

Charmonium production

- Ratio $J/\psi\ /D^0$

[redacted]

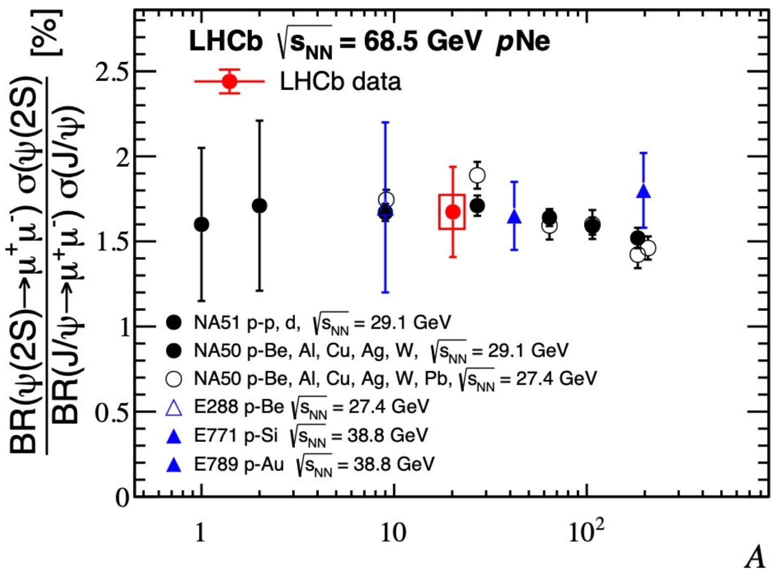
- Benchmark for $c\bar{c}$ suppression in PbNe
- Strong dependency in p_T
- Integrated:

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = 0.0106 \pm 0.0005(\text{stat} + \text{uncorr}) \pm 0.0008(\text{corr})$$

- Ratio $\psi(2S)/\ J/\psi$ first measurement in SMOG:

In line with other measurements for different values of target atomic mass number (A)

$$\frac{Br_{\psi(2S)\to\mu^+\mu^-}\sigma_{\psi(2S)}}{Br_{J/\psi\to\mu^+\mu^-}\sigma_{J/\psi}} = 1.67 \pm 0.27\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \%,$$



Open charm results

[redacted]

$\sigma^{D^0}_{y*\in[-2.29,0]} =$ [redacted] $\pm 0.3(\text{stat.}) \pm 0.4(\text{uncorr. syst.}) \pm 2.8(\text{corr. syst.})\ \mu\text{b/A}.$

$\sigma^{D^0}_{4\pi} =$ [redacted] $\pm 0.6\ (\text{stat})\ \pm 0.7\ (\text{uncorr syst})\ \pm 5.7\ (\text{corr syst})\ \mu\text{b/A}.$

[redacted]

1. Previous measurement in pHe/pAr no strong evidence of intrinsic charm in the nucleon was observed in the large bjorken-x region: Phys. Rev. Lett. 122 (2019) 132002

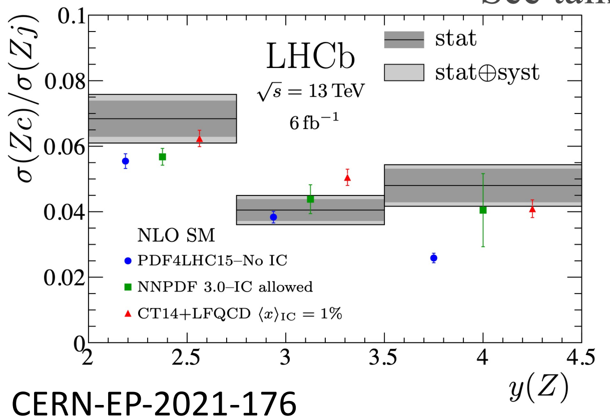
$$x \simeq \frac{2m_c}{\sqrt{s_{\text{NN}}}}\exp(-y^*)$$

2. Here the IC component should enhance the D^0 production for negative y*

3. A contribution at the 1% level of valence-like IC improves the agreement between data and theoretical predictions

4. Even more relevant, Z jets measurement pp:

See talk from Oscar



CERN-EP-2021-176

Open charm results

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

Asymmetry:

$$\mathcal{A}_{\text{prod}} = \frac{\sigma(D^0) - \sigma(\overline{D}^0)}{\sigma(D^0) + \sigma(\overline{D}^0)}$$

- Asymmetry measured in fixed target for D^+ (pion beam) and D_s^+ (Σ beam)
- Beam hadron shares a quark with only one of the charged states leading particle effect

D^+: $c\bar{d}$

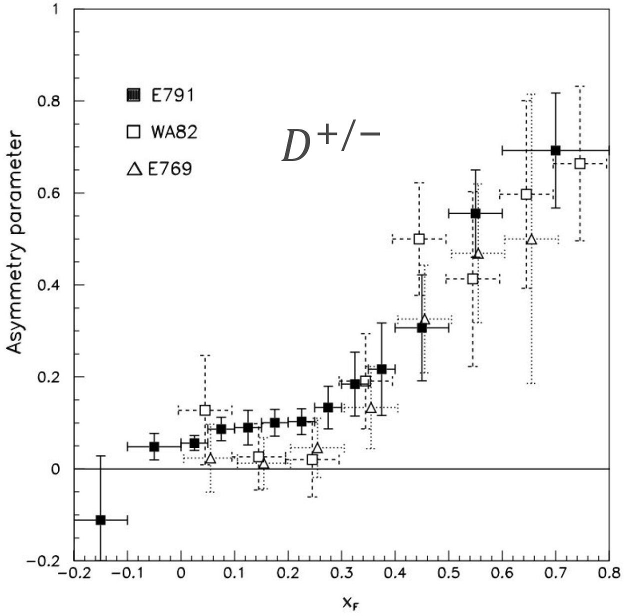
D^-: $d\bar{c}$

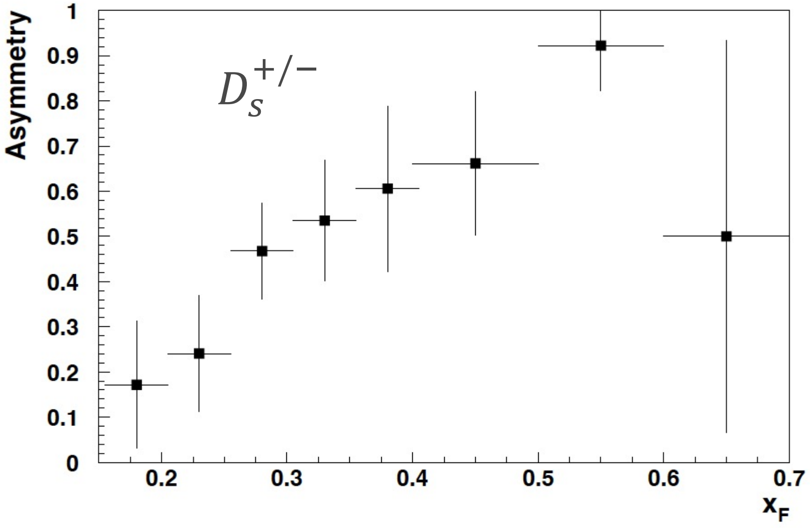
D^0: $c\bar{u}$

$\overline{D}^0$: $u\bar{c}$

D_s^+: $c\bar{s}$

D_s^-: $s\bar{c}$





$$A \equiv \frac{N_{D_s^-} - N_{D_s^+}}{N_{D_s^-} + N_{D_s^+}}$$

Phys Rev Lett. 72 (1994), no. 06 812.

Phys. Lett. B 558 (2003) 34, arXiv:hep-ex/0302039.

Open charm results

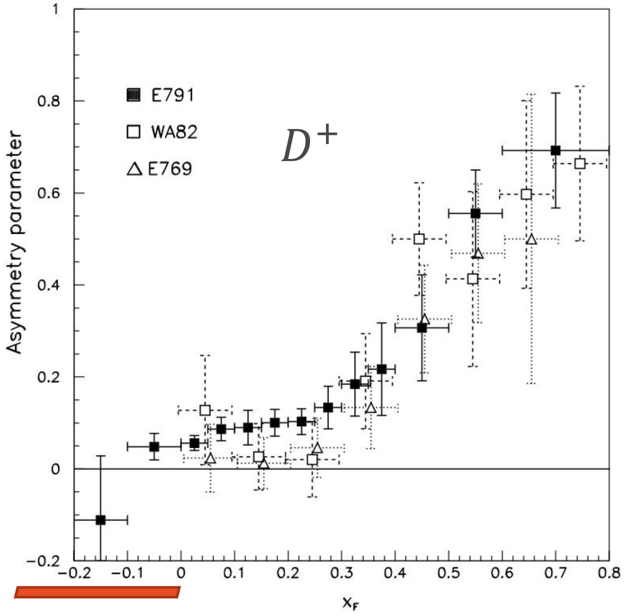
Asymmetry:

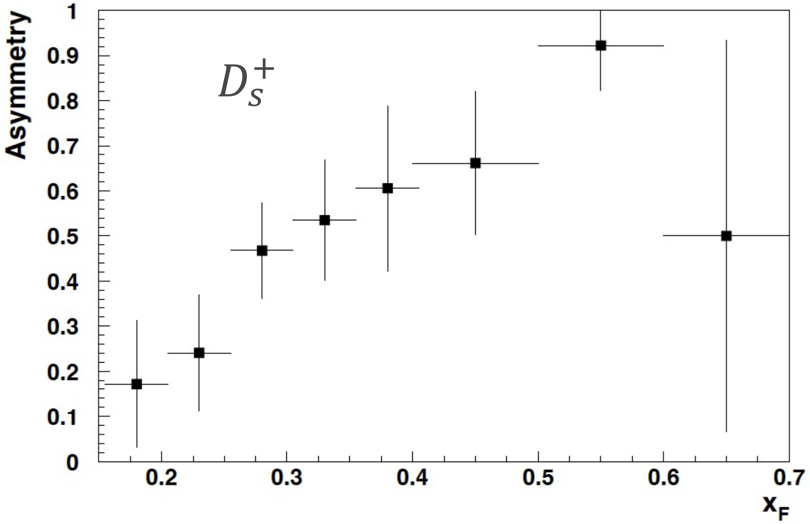
$$\mathcal{A}_{\text{prod}} = \frac{\sigma(D^0) - \sigma(\overline{D}^0)}{\sigma(D^0) + \sigma(\overline{D}^0)}$$

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	$\nu_\mu, \overline{\nu}_\mu$	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

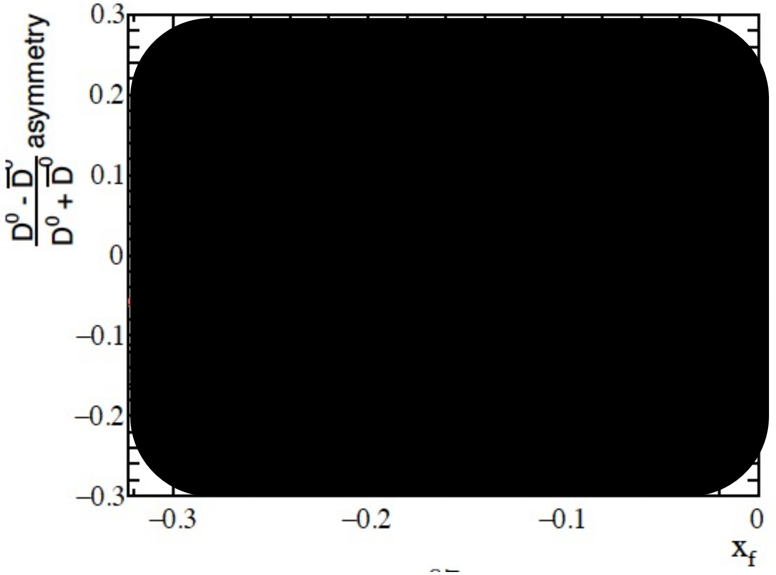
- Asymmetry measured in fixed target for D^+ (pion beam) and D_s^+ (Σ beam)
- Beam hadron shares a quark with only one of the charged states leading particle effect

$$x_F = 2\sinh y^* \sqrt{\frac{m^2 + p_T^2}{s_{NN}}}$$





SMOG pNe



Open charm results

Asymmetry:

$$\mathcal{A}_{\text{prod}} = \frac{\sigma(D^0) - \sigma(\overline{D}^0)}{\sigma(D^0) + \sigma(\overline{D}^0)}$$

[redacted]

LHCb observes a negative asymmetry, up to -15%, with a clear y*-dependency

1. Pythia predicts a negative asymmetry, independent of y*
2. This production asymmetry shows the x_F dependency, where the asymmetry increases when reaching the valence quark region (i.e x_F ~ -0.3).

Does this come from the quark content of the target Ne? What about other charm hadrons ?

D^+: $c\bar{d}$
D^-: $d\bar{c}$
D^0: $c\bar{u}$
$\overline{D}^0$: $u\bar{c}$
D_s^+: $c\bar{s}$
D_s^-: $s\bar{c}$

We would expect smaller D+/D- asymmetry, opposite Ds/Dsbar and Lc/Lcbar asymmetries→ to be confirmed!

Charm baryons cross section measurement: Λ_c^+ and Ξ_c^+

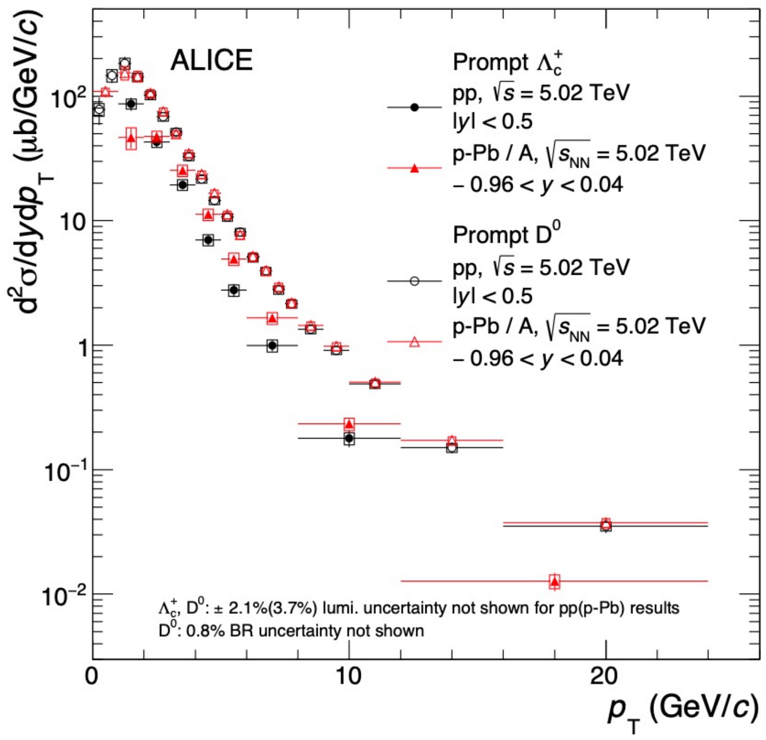
- Since the luminosity for the *p*Ne sample is measured, absolute cross section measurement is possible

  For PVZ in [-200,-100] and [100,150] mm 24.9 +/- 0.3 +/- 1.6 nb^{-1}
  (by Giacomo Graziani, used in open charm and charmonium analysis)

- Measure differential cross section as a function of y^* and p_T

Motivation (similarly to the D^0 and J/ψ analysis) :

1. First measurement of baryon cross-section in SMOG
2. Compare with theory prediction (heavy quark production in pQCD)
3. Compare to D^0 as in pPb for ALICE
4. Λ_c^+ polarization measurement

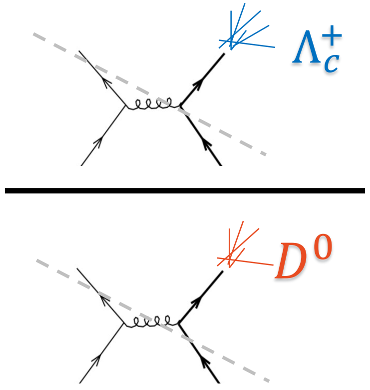


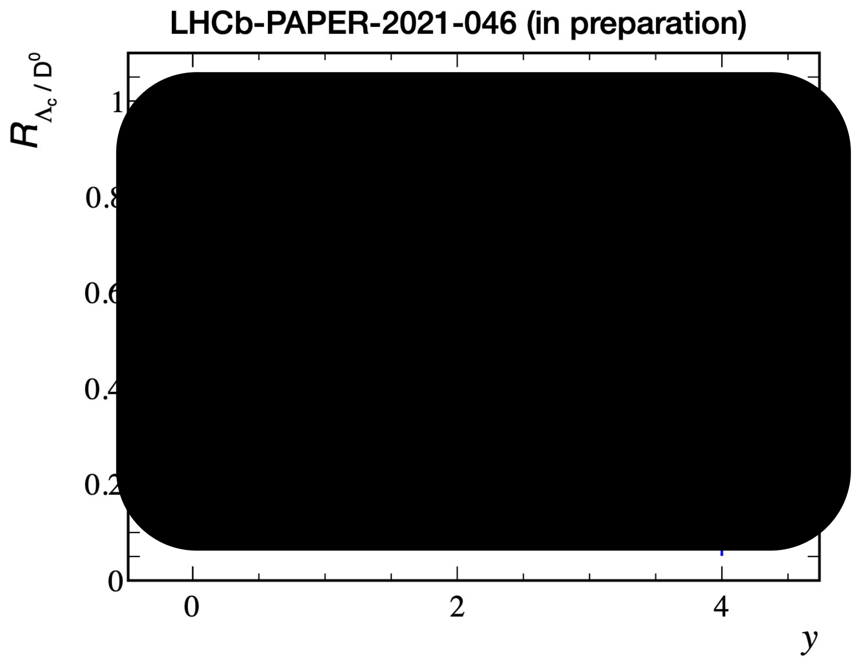
https://arxiv.org/pdf/2011.06078.pdf

Ratios baryons/mesons

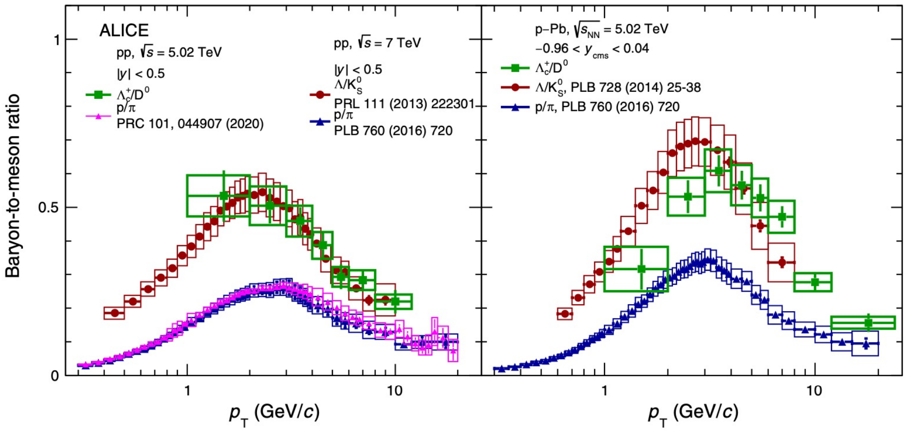
- It is even more interesting to study ratios of: Lc/D0, Lc/D+, Lc/Ds
- Heavy-flavours can be used to test pQCD
- Common part for baryons and mesons = production→cancels in the ratio
- Ratios allow to study heavy quark **coalescence** :
  if colaescence happens, then $p_T^{\Lambda_c^+} \gg p_T^{D^0}$
  → enhanced Λ_c^+ production (w.r.t. heavy quark fragmentation)
- For SMOG:
  1. Different energy or multiplicity
  2. Do we have more/less coalescence?
  3. We could even compare with strange baryon/meson ratio, is it the same for s and c quarks?

$R(\Lambda_c^+/ D^0) =$





https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.127.202301



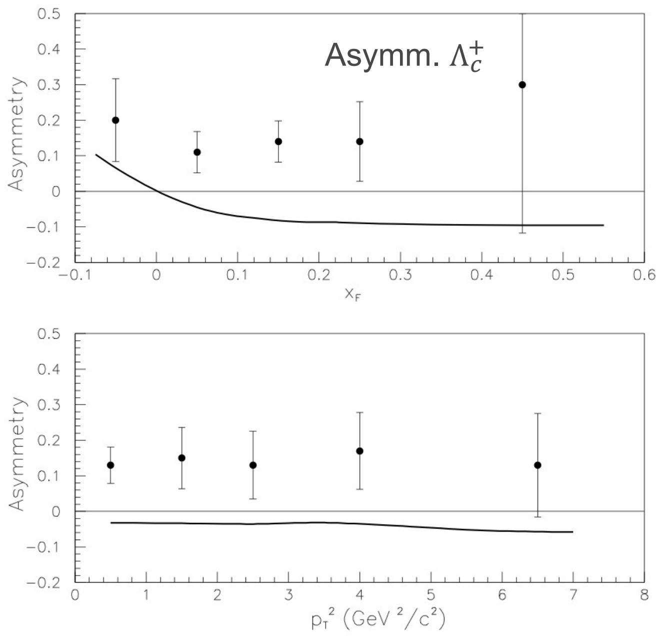
The puzzling asymmetries

- Asymmetry:

$$\mathcal{A}_X = \frac{N(X) - N(\bar{X})}{N(X) + N(\bar{X})}$$

- There is one (non conclusive) measurement from FermiLab (E791) for Λ_c^+ asymmetry, compatible with no asymmetry or with increasing at $x_F = 0$.
- There is also a measurement from SELEX, with different beams

Phys.Lett.B495:42-48,2000



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, $\bar{\nu}_\mu$	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

Questions we would like to answer after seeing this large asymmetry for charm mesons:

1. How is the $c/\bar{c}$ hadronization asymmetry changing for Λ_c^+(udc): same trend? Inverted trend?
2. At y^* (very) negative, valence region→ more u/d quarks available→ do we produce more Λ_c^+ ?
3. Compare the different charm asymmetries in SMOG

SMOG could largely improve this!

LHCb-INT-2017-011
JHEP 08 (2017)
EPJC-C (80) (2019)
EPJC 77 (2017)
JHEP 1708:120 (2017)
EPJC 77 (2017) 828
EPJ C 80 (2020) 10, 929
arxiv:2010:11902

Polarisation in SMOG

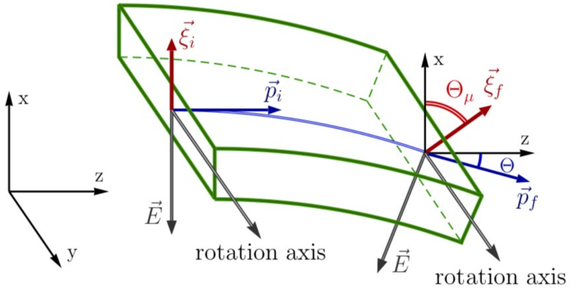
First polarisation measurement in fixed-target

Why: Proposal for **MDM measurement** of charm baryons at LHCb.
The combined measurements of MDMs of Ξ_c^+ and Λ_c^+ can help understand the g-factor of the charm quark

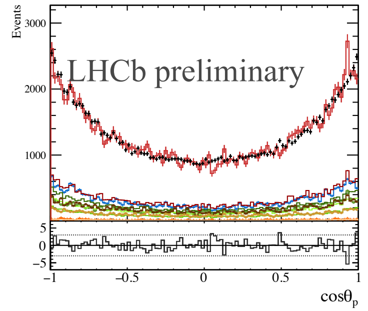
The idea: crystal 1 deflect the beam→ target + bending crystal

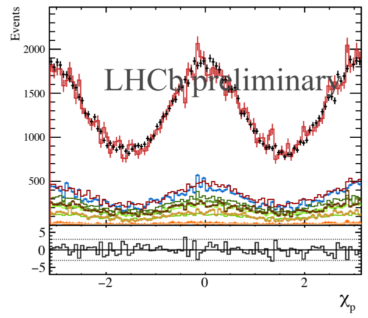
- crystals will be placed upstream of LHCb (used to analyze the decay products)
- already used for Σ^+ MDM measurement $c\tau \sim 2.4\ cm$ (E761, Fermilab, D.Chen, PhD thesis, SUNY, Albany, 1992).
- For Λ_c^+ harder due to shorter $\boldsymbol{c\tau \sim 60\ \mu m}$

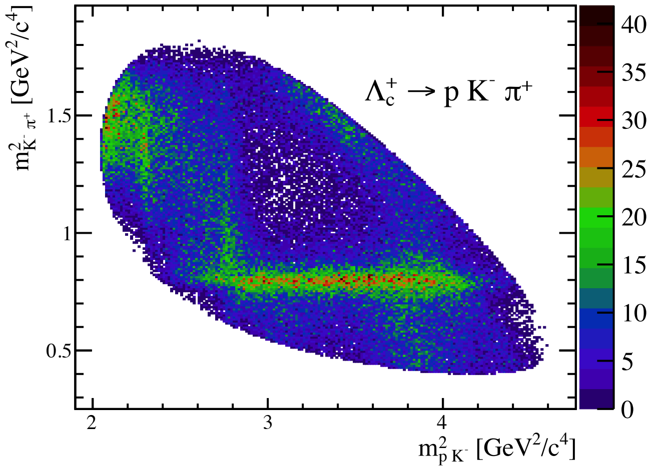
- Preliminary measurement in pp collisions to fix the amplitude model performed



Λ_c^+ precession in a crystal







[redacted]

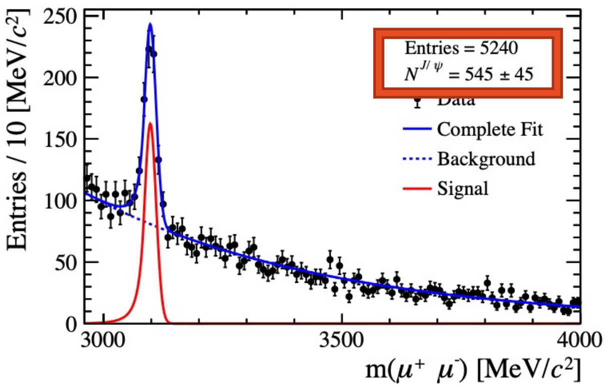
m^2_{pK} [GeV^2/c^4] $m^2_{K^-\pi^+}$ [GeV^2/c^4]

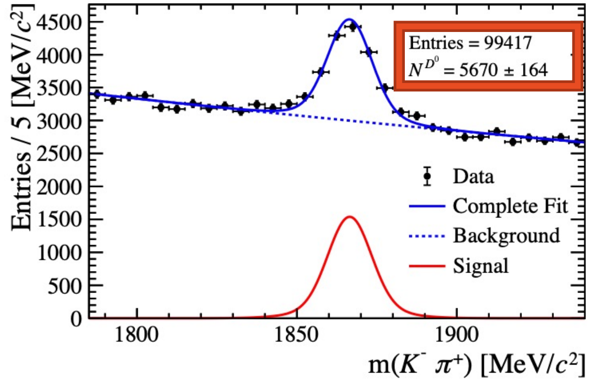
https://www.theses.fr/2021UPASP075

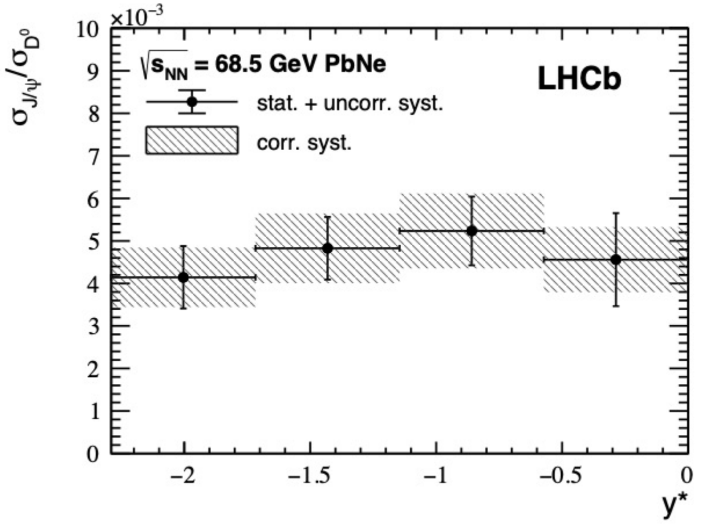
D^0 and J/ψ in PbNe collisions

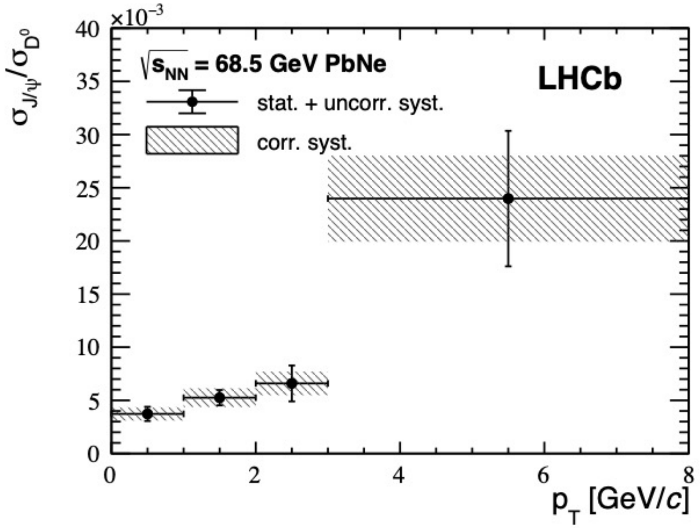
- First measurement of J/ψ and D^0 in fixed target nucleus-nucleus collisions
- Centrality determined by energy deposit in electromagnetic calorimeter arXiv:2111.01607
- The ratio of J/ψ over D0 is evaluated integrated and binned in y, pT, and nSPDHits.
- Luminosity measurement still missing, no absolute cross section available yet
- Ratio integrated:

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = (5.1 \pm 0.4 \pm 0.9) \times 10^{-3},$$









➢ No dependence on rapidity

➢ Strong dependence on p_T

Charm in pNe vs PbNe

- Evaluate suppression as a function of the nucleons participating to the collision N_{par} and the nb of binary nucleon-nucleon collisions N_{coll} (estimated from Glauber model to the actual data)
- pNe collisions = very peripheral PbNe collisions , ratio in pNe:

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = \text{[redacted]} \pm 0.0005(\text{stat} + \text{uncorr}) \pm 0.0008(\text{corr})$$

- Ratio for PbNe and pNe vs N_{coll} fitted with a power law:
  - D^0 not suppressed due to CNM effects or QGP → $\sigma_{\mathrm{AB}}^{D^0} \propto N_{\mathrm{coll}}$
  - whereas J/ψ could be → $\sigma_{\mathrm{AB}}^{J/\psi} \propto N_{\mathrm{coll}}^{\alpha'}$

$$\sigma^{J/\psi}/\sigma^{D^0} \propto N_{\mathrm{coll}}^{\alpha'-1}$$

$\alpha' =$ [redacted].05

→ J/ψ suppressed by additional nuclear effects compared to D^0

$\sigma_{J/\psi}/\sigma_{D^0}$

10

[redacted]

- product of the mass number of the nuclei A and B: pNe = 20 , PbNe = 4160
- $\alpha =$ [redacted].04 close with the v[redacted] littérature ~0.92

Phys. Rev. Lett. 84 (2000) 3256.
Physics Letters B 466 (1999) 408.

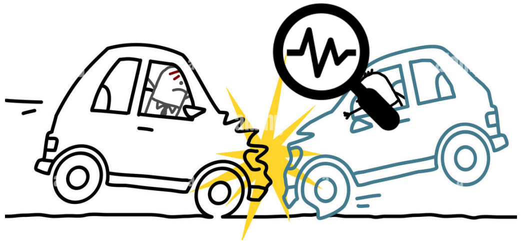
The European Physical Journal C - Particles and Fields 33 (2004) 31.

Phys. Lett. B 410 (1997) 337

Conclusions

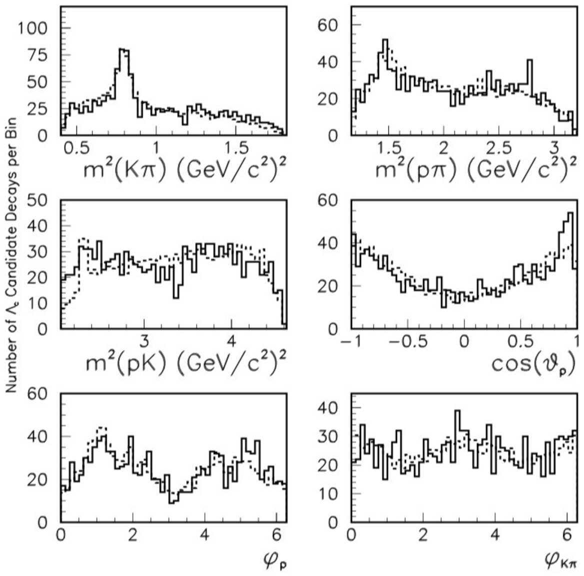
- SMOG data have produced unique results and more results are to come!
- Today : Open charm and charmonium production in pNe and PbNe
- Future: charm baryons (Λ_c^+ and Ξ_c^+) polarization, production cross-section and asymmetry
- SMOG2 successfully installed, first runs are coming soon!

Ready to collide???



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 $\pm$ 38** events

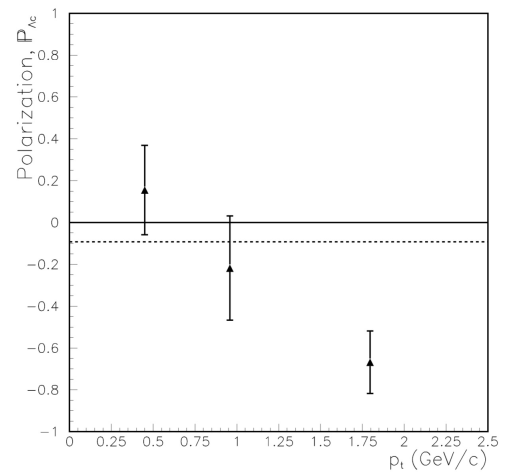


$\Lambda_c^+ \to p\, K^-\pi^+$	non resonant
$\Lambda_c^+ \to (K^* \to K^-\pi^+)\, p$	K^* chain
$\Lambda_c^+ \to (\Delta^{++} \to p\pi^+)\, K^-$	Δ chain
$\Lambda_c^+ \to (\Lambda \to pK^-)\, \pi^+$	Λ chain

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



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 ,** systematic 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

Initial plan

Measure Λ_c^+ polarization in the pNe sample (2017) using $\Lambda_c^+ \to p K^- \pi^+$

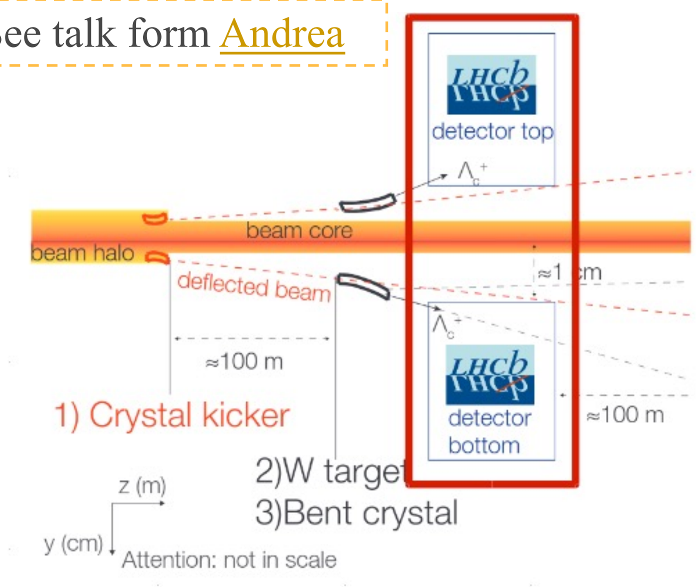
See talk form Andrea

- **Why:** Proposal for MDM and EDM measurement of charm baryons at LHCb. The combined measurements of MDMs of Ξ_c^+ and Λ_c^+ can help understand the g-factor of the charm quark

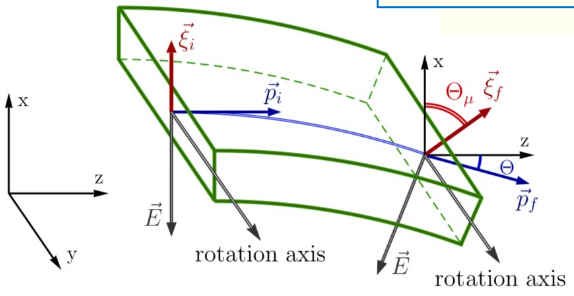
- **The idea:** crystal 1 deflect the beam→ target + bending crystal

    - crystals will be placed upstream of LHCb (used to analyse the decay products)
    - already used for Σ^+ MDM measurement $c\tau \sim 2.4\ cm$ (E761, Fermilab, D.Chen, PhD thesis, SUNY, Albany, 1992). For Λ_c^+ harder due to shorter $\boldsymbol{c\tau \sim 60\ \mu m}$

  → Need the polarization in fixed-target collision as input of MDM measurements.



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



Λ_c^+ precession in a crystal

- Fixed-target pNe sample collected at LHCb in 2017 is too small, need to perform a preliminary analysis in the pp collision system to fix the amplitude model and fit the amplitude parameters.

- Final step: use the model obtained in *pp* collisions to measure the polarization in the fixed-target sample (well advanced)

LHCb-INT-2017-011
JHEP 08 (2017)
EPJC-C (80) (2019)
EPJC 77 (2017)
JHEP 1708:120 (2017)
EPJC 77 (2017) 828
EPJ.C 80 (2020) 10, 929
arxiv:2010:11902

Previous SMOG results

1. Charm production in *p*Ar, *p*He collisions Phys. Rev. Lett. 122 (2019) 132002
2. Prompt antiproton in *p*He collisions at 110 GeV Phys. Rev. Lett. 121 (2018) 222001

New Technical publications

1. A Neural-Network-defined Gaussian Mixture Model for PID with SMOG data JINST 17 (2022) P02018
2. Centrality determination in heavy-ion collisions with the LHCb detector arXiv:2111.01607