Prospects for cold nuclear matter effects studies with SMOG/SMOG2

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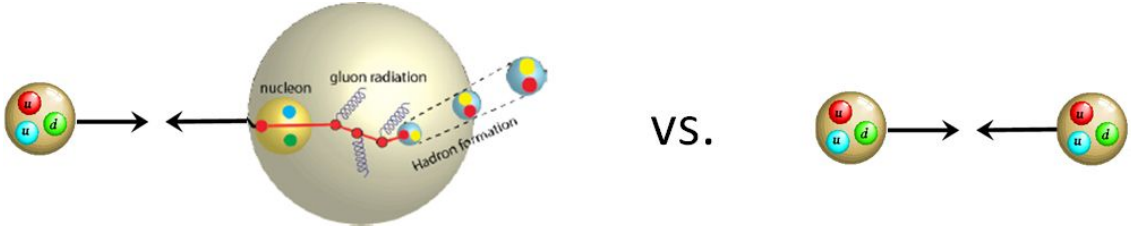
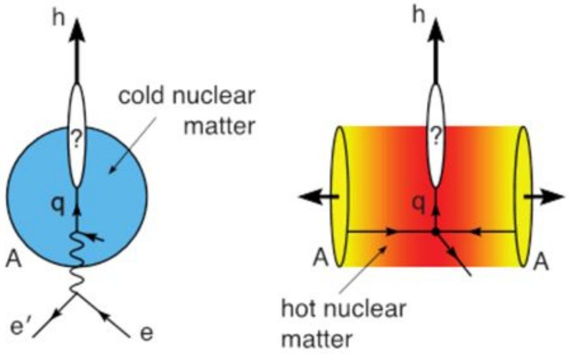
Cold Nuclear Matter effects in hadronic collisions

Medium-induced modification of high p_T particle production in nucleus-nucleus collisions (pA, AA) relative to the baseline binary pp collisions is a powerful probe of the properties of dense QCD matter.



Cold Nuclear Matter (CNM) effects encode the rich phenomenology non-trivial QCD dynamics in pA reactions, which constitutes the baseline for the interpretation of the modification of particle formation and propagation in the QGP medium created in ultra-relativistic heavy-ion collisions ("Hot Nuclear Matter effects").



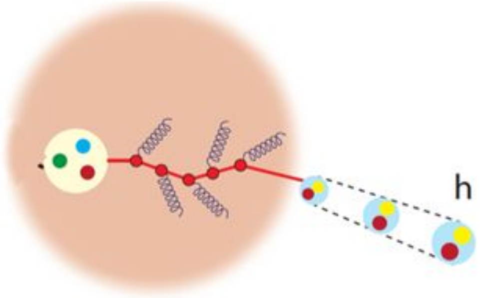
Cold Nuclear Matter effects in hadronic collisions

Initial-State CNM effects [arXiv:hep-ph/0212148v2]:

- **Nuclear modification of the PDFs (nPDFs)**
- **IS parton energy loss**
- **Cronin effect (p_T broadening)**

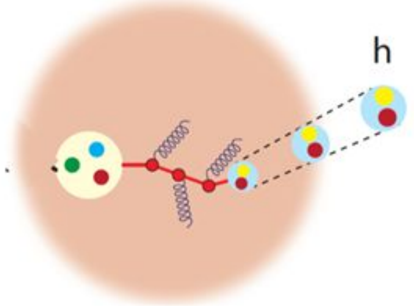
Final-State CNM effects [Phys. Rev. Lett. 93, 082302]:

- **FS energy loss**
- **FS rescattering**
- **absorption**



Hadronization occurs outside the nucleus:

While propagating through the target nucleus, quarks lose energy via **radiative gluonic emissions** and **collisions** with the medium constituents, enhancing in average their p_T



Hadronization occurs inside the nucleus:

The interaction of the formed hadron with the surrounding hadronic medium may also cause an increased transverse momentum compared to hadron production in pp collisions.

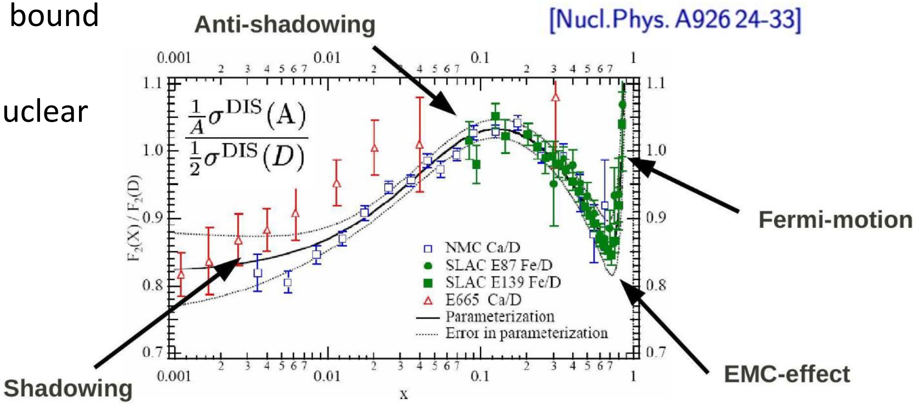
- Both the **radiative energy loss** and the **transverse momentum of the parton** increase with the path length of the quark in the nuclear medium before the hadron formation, i.e. with the nucleus mass ($R \propto \sqrt[3]{A}$).
- A precise understanding of all these effects is mandatory in order to pin down the role of parton energy loss effects in the QGP environment.

Cold Nuclear Matter effects in hadronic collisions

- In the nuclear environment the partonic contents of the bound nucleons are modified
- These modifications are encoded in terms of universal nuclear parton distribution functions (nPDFs)
- A rich phenomenology is observed through the ratio

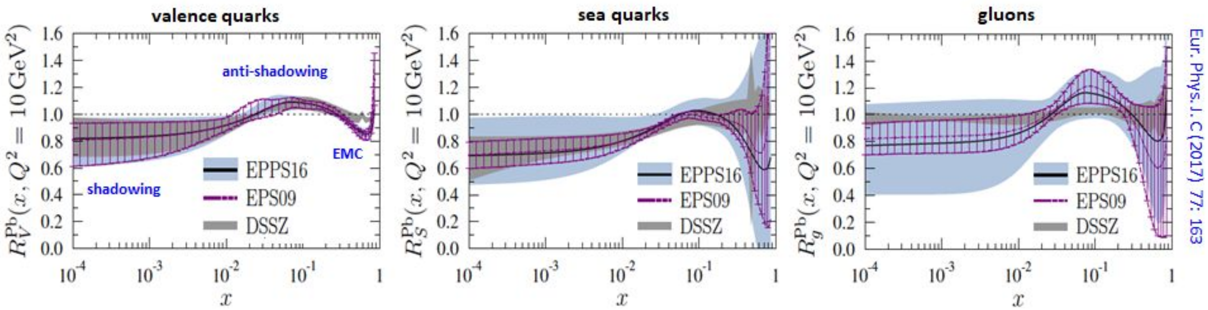
$$R_i^A(x,Q^2) = \frac{f_i^{p/A}(x,Q^2)}{f_i^{p}(x,Q^2)}$$

in different x-Bjorken regimes



- **Nuclear antishadowing** is particularly pronounced at fixed-target LHC kinematics

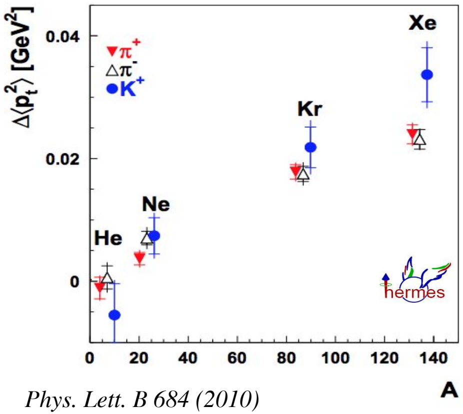
Recent results from Global fits:



Nuclear Modification Factor - Cronin Effect

Cronin effect [J.W.Croninetal.,Phys.Rev.D11,3105(1975)]: high-p_T hadron production is enhanced in pA collisions (compared to pp collisions) as a result of the multiple interactions with the nuclear medium constituents. This is observed experimentally e.g. through the broadening of the transverse momentum of the produced hadrons as a function of the nuclear mass.

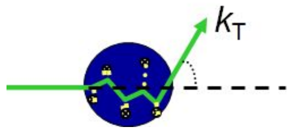
$$\Delta\langle p_t^2\rangle_A^h = \langle p_t^2\rangle_A^h - \langle p_t^2\rangle_D^h$$



Phys. Lett. B 684 (2010) 114-118

There are several possible contributions to the transverse momentum of the hadrons produced in pA collisions:

1. primordial parton transverse momentum
2. gluon radiation of the propagating quark
3. Fragmentation process
4. rescattering of the formed hadron with the surrounding medium



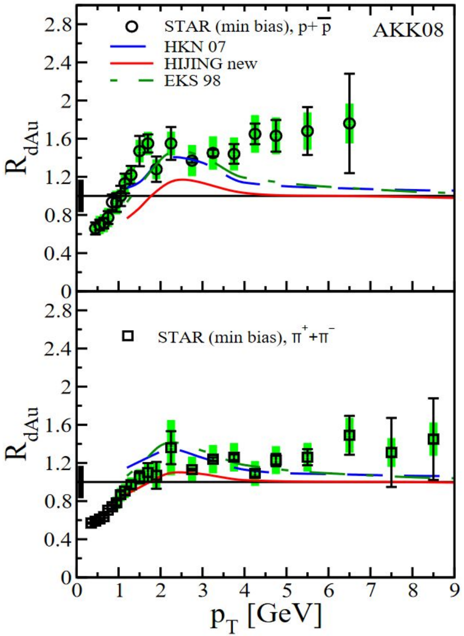
A very intriguing experimental observation in both pA and AA collisions is the much larger magnitude of the Cronin effect observed on baryons compared to mesons (**baryon/meson anomaly**).

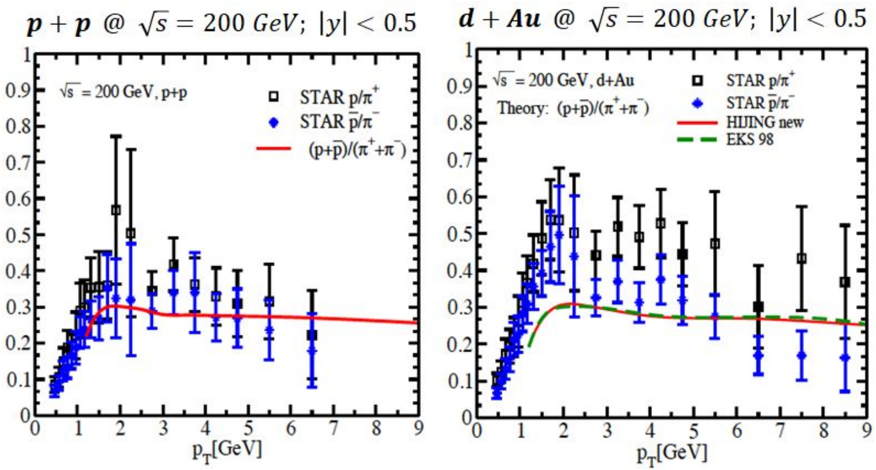
A clear explanation is still lacking $\Longrightarrow$ "very interesting to study protons/pions ratios is pp and pA collisions"!

A benchmark processes for studying these effects is **inclusive light particle production in hadronic collisions** which, at low p_T regime (p_T <Q), can only be described by non-collinear pQCD factorization. i.e. by taking into account the intrinsic transverse momentum of the incoming partons.

Nuclear Modification Factor

$$R_{pA} = \frac{\frac{d\sigma^{pA\to h+X}}{dyd^2p_T}}{\langle N_{binary}\rangle \frac{d\sigma^{pp\to h+X}}{dyd^2p_T}}$$





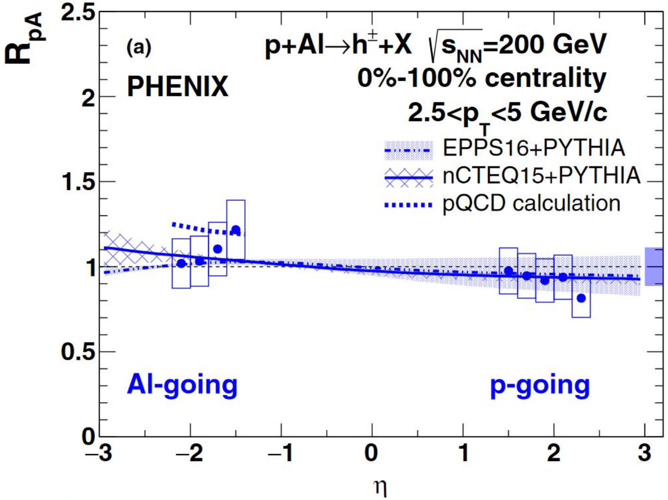
J. Adams *et al.*, (STAR Collaboration), Phys. Lett. **B637**, 161 (2006)

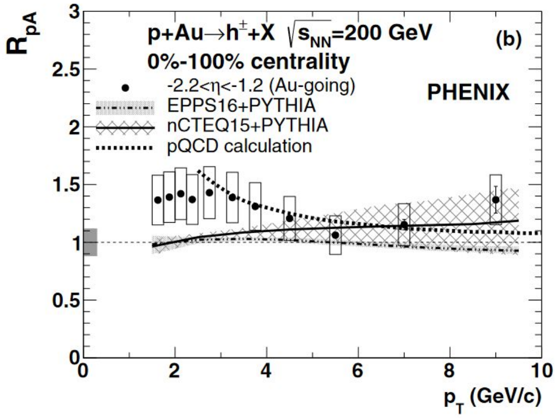
Theory curve by: A.H. Rezaeian and Z. Lu: [arXiv:0810.4942]

- Only accounts for IS effects (Cronin effect + nPDFs)
- Underestimate of d+Au data might indicate importance of FS effects not taken into account

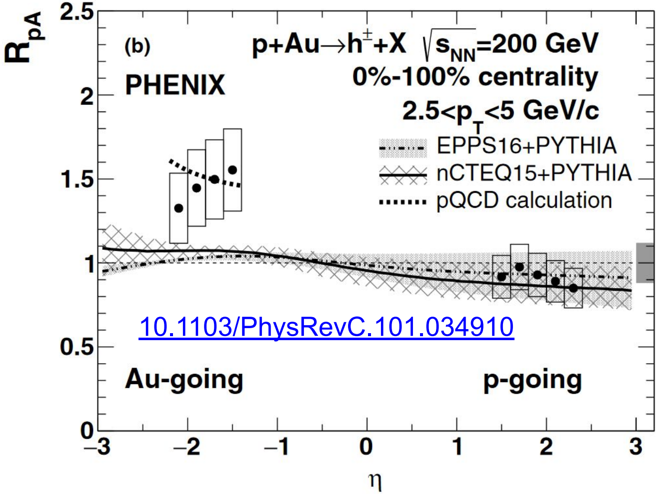
Nuclear Modification Factor
Forward and backward rapidity regions

- Enhancement in backward region has a clear ***A-dependence***
- pQCD calculation considering incoherent multiple scatterings inside the nucleus can describe data in backward region [Phys. Rev. D 88, 054010]
- calculations using nuclear parton distribution functions predict data in the forward region





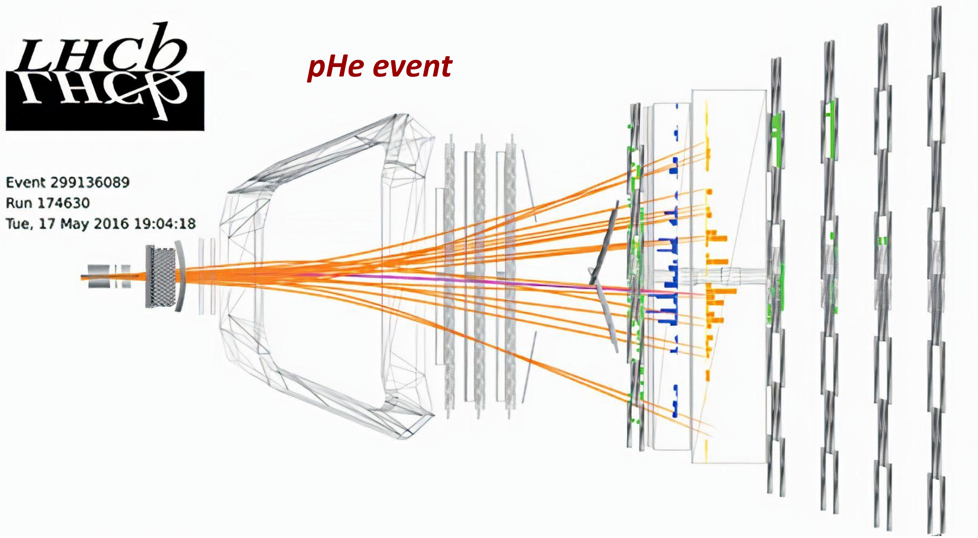
$$R_{pA} = \frac{dY^{pA}/dp_T d\eta}{dY^{pp}/dp_T d\eta} \cdot \frac{1}{\langle N_{\mathrm{coll}} \rangle}$$



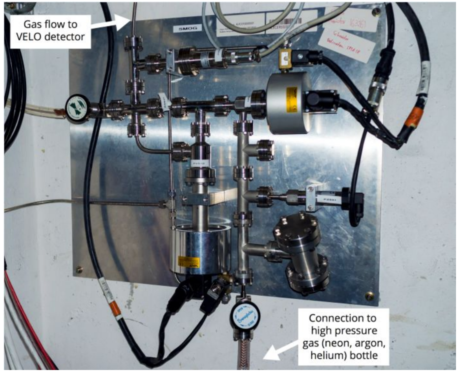
10.1103/PhysRevC.101.034910

SMOG (System for Measuring Overlap with Gas)

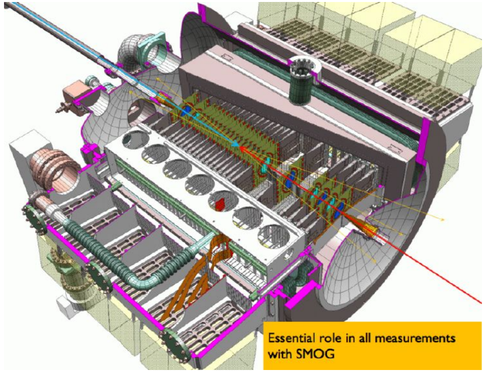
LHCb offered the unique opportunity to operate an LHC experiment in ***fixed-target mode*** through the ***SMOG*** system by injecting noble gases into the vacuum in the LHCb beam pipe around the pp interaction point



Injection System



Gas injected through a ***Gas Feed System*** with a pressure of 2×10^{-7} mbar, two order of magnitude higher than LHC vacuum.



The fixed target program in LHCb allows the study of CNM effects from the initial state, such as Cronin enhancement and nuclear antishadowing:

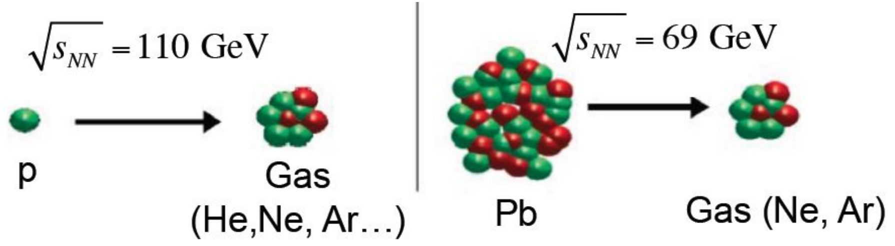
- result in a modification of the production cross section
- provide crucial tests of predictions from perturbative QCD

Fixed target Collisions with SMOG/SMOG2

$$E_p \in [0.9,\ 7]\ TeV$$

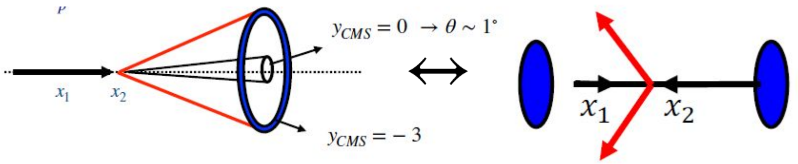
$$\sqrt{s_{NN}} = \sqrt{2E_p M_N} \in [40,\ 115]\ GeV$$

$$\gamma = \frac{\sqrt{s}}{2m_p} \approx 60 \qquad E_p = 7\text{ TeV}$$



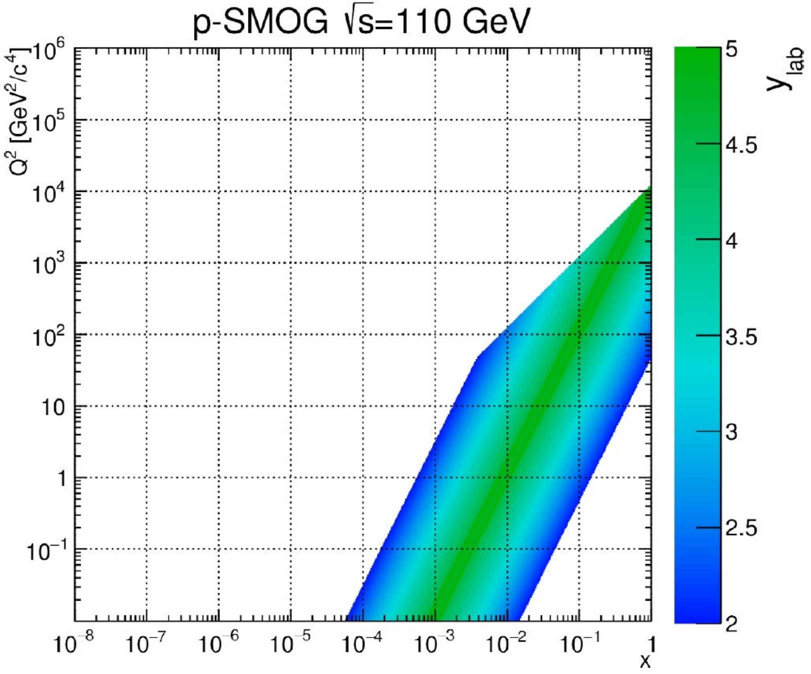
- the cm of the system is strongly boosted in the lab frame → ***backward rapidity region*** in the cm frame

$$2 \lesssim y_{lab} \lesssim 5 \quad \leftrightarrow \quad -3.0 \lesssim y^* \lesssim 0$$

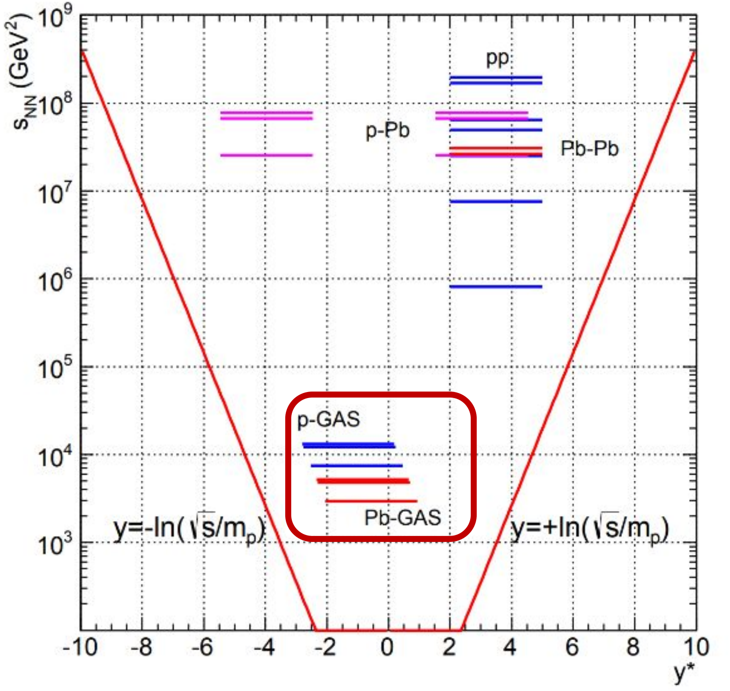


Fixed target Collisions with SMOG

$$x = e^{\pm y}\frac{Q}{\sqrt{s}}$$



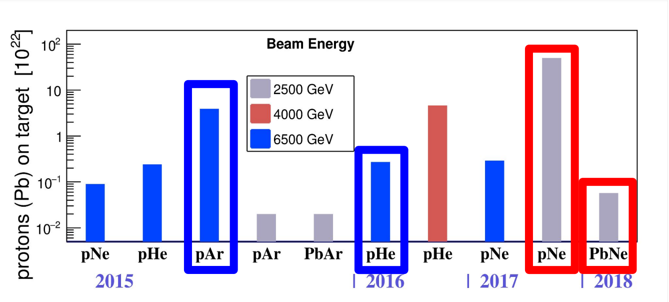
$$x_F = \frac{p_L^*}{|max(p_L^*)|} \sim x_1 - x_2 < 0$$



Cold Nuclear Matter studies with SMOG data

Measurement: ***prompt*** Pions, kaons and protons production in MB events in

- Light systems : pHe vs. pAr collisions @ $\sqrt{s_{NN}}$ = 110 GeV
- heavier systems : pNe vs. PbNe collisions @ $\sqrt{s_{NN}}$ = 69 GeV



Physics observables:

- $p/\pi^+, \bar{p}/\pi^-$ ratios (vs p_T, η and multiplicity)
- Double ratios:

$$\frac{< N_{pHe} > \dfrac{d^2\sigma^{pAr \to h+X}}{dp_T\, d\eta}}{< N_{pAr} > \dfrac{d^2\sigma^{pHe \to h+X}}{dp_T\, d\eta}} \qquad \frac{< N_{PbNe} > \dfrac{d^2\sigma^{PbNe \to h+X}}{dp_T\, d\eta}}{< N_{pNe} > \dfrac{d^2\sigma^{pNe \to h+X}}{dp_T\, d\eta}}$$

- Strangeness effects combined with nuclear matter effects?

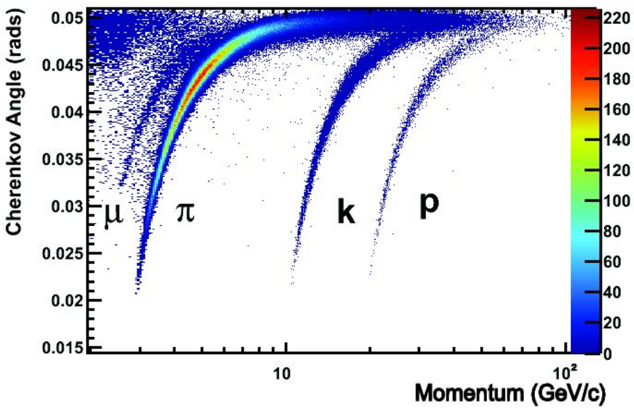
  → possibility to look also at kaon production in the ratios

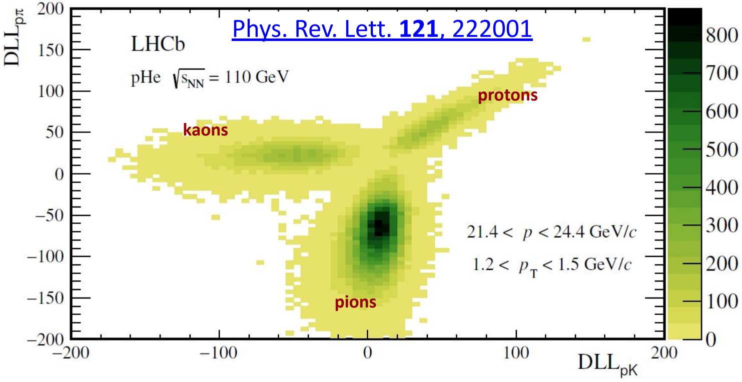
Particle Identification in LHCb

Excellent discrimination between ***K***, ***π*** and ***p*** provided by the RICH subdetectors.

- information encoded in a DLL variable which provides the difference in the log-likelihood between the kaon (or proton) hypothesis and the pion hypothesis
- dedicated SMOG tools based on NN developed to perform a data-driven PID using data calibration samples:

$K^0_S \to \pi^-\pi^+$ $\Lambda \to p\pi$ $\phi \to K^-K^+$



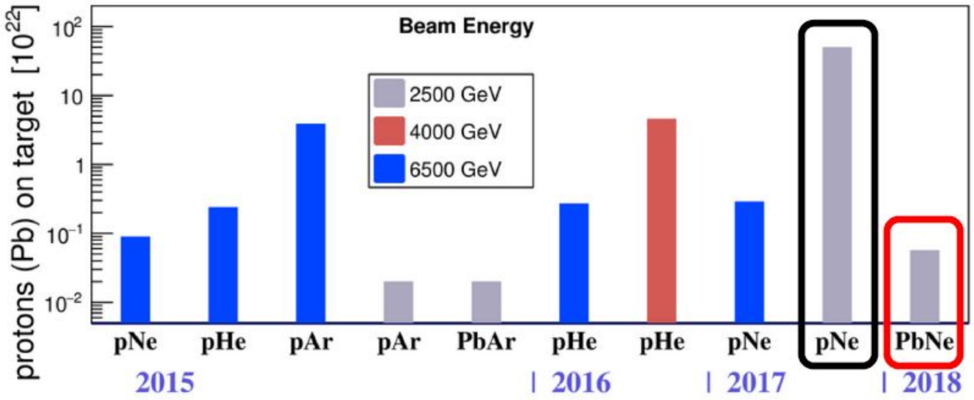


SMOG as a bridge between Cold Nuclear Matter and QGP

SMOG and SMOG2 data can establish a smooth transition between CNM behaviour and QGP effects comparing quantities related to light hadron and strangeness production at a fixed CoM energy.

Since in pA collisions no hot and dense medium is expected to be created, a ***pA run at the same nucleon-nucleon energy as in nucleus-nucleus (AA) collisions*** is of major importance to test the theoretical models and to have reliable baseline spectra for the extraction of novel physical effects

With SMOG data already available this kind of direct comparison between ***light hadron production*** yields can be performed, together with measurements involving ***strangeness enhancement***



pNe (2017) $\sqrt{s_{NN}} = 68.6\ GeV$ $L \sim 200\ nb^{-1}$

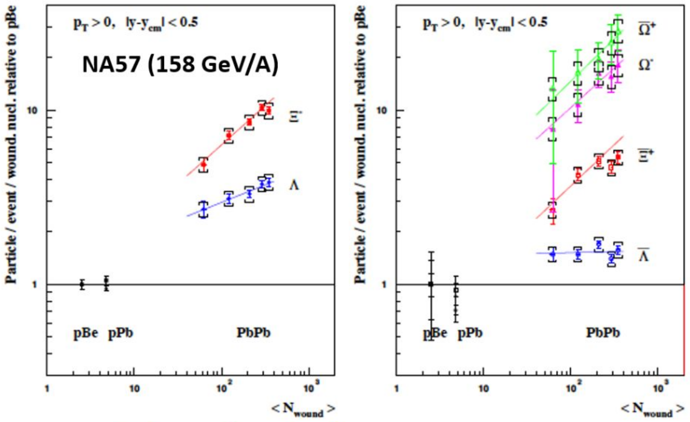
PbNe (2018) $\sqrt{s_{NN}} = 68.6\ GeV$ $L \sim 0.3\ nb^{-1}$

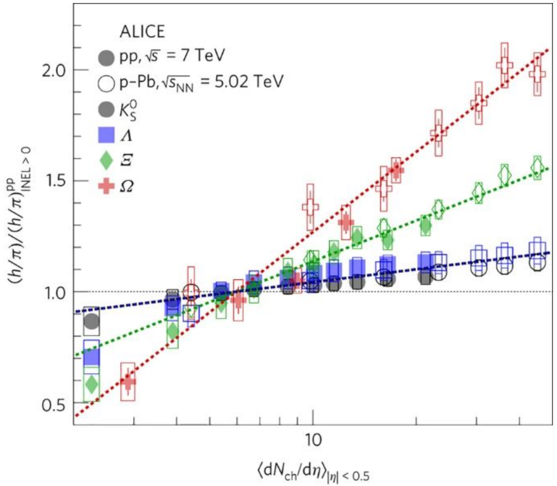
For comparison:

1. AuAu @ AGS: $\sqrt{s_{NN}} = 4.4\ GeV$
2. PbPb @ SPS: $\sqrt{s_{NN}} = 16.8\ GeV$
3. AuAu @ RHIC: $\sqrt{s_{NN}} = 62 - 500\ GeV$
4. PbPb @ LHC: $\sqrt{s_{NN}} = 5500\ GeV$

Strangeness enhancement as test of QGP formation

$$E = \frac{2}{\langle N_{part} \rangle} \left[\frac{dN(Pb+Pb)}{dy}\bigg|_{y=0} \Big/ \frac{dN(p+Be)}{dy}\bigg|_{y=0} \right]$$





Interesting hadrons

- Non-strange hadrons: $\pi^+, \pi^-, p, \bar{p}$
- Single-strange mesons: K^+, K^-, K^0_s
- Single-strange baryons: $\Lambda, \bar{\Lambda}$
- $s\bar{s}$ mesons: ϕ
- Double-strange baryons: $\Xi^-, \bar{\Xi}^+$
- Triple-strange baryons: $\Omega^-, \bar{\Omega}^+$

Main decay modes:

- $K^0_s \to \pi^+\pi^-$ $(BR = 69.2\%)$
- $\Lambda \to p\pi$ $(BR = 63.9\%)$
- $\phi \to K^+K^-$ $(BR = 49.2\%)$
- $\Xi \to \Lambda\pi$ $(BR = 99.9\%)$
- $\Omega \to \Lambda K$ $(BR = 67.8\%)$

Strangeness enhancement as test of QGP formation

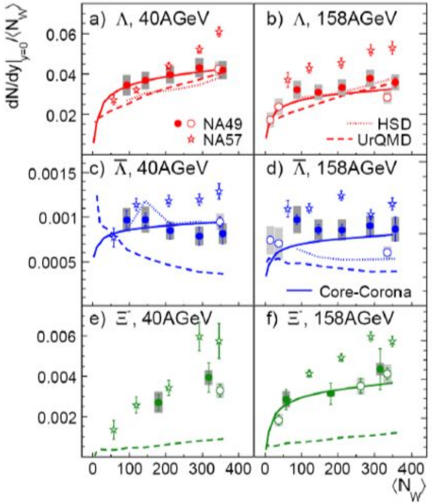
Measurements :

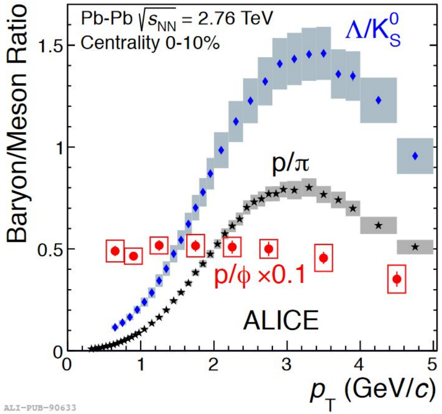
- **Strange hadron production :**
  - multiplicity distributions: diff. yields vs. event-multiplicity
  - η distributions: differential yields vs. η
  - p_T distributions: differential yields vs. p_T

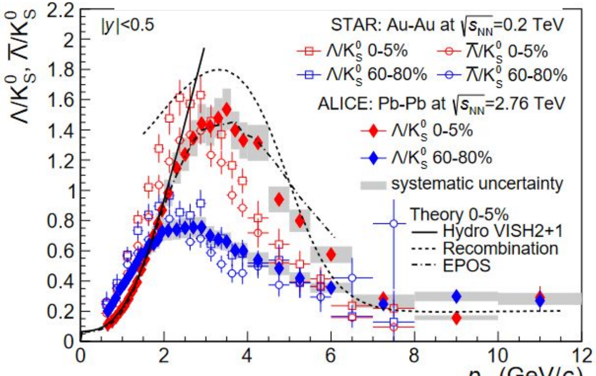
- **Strange/non-strange hadron ratios vs. event multiplicity and p_T :**
  - K/π
  - $K_S^0/(\pi^+ + \pi^-)$
  - $(\Lambda + \bar{\Lambda})/(\pi^+ + \pi^-)$
  - $(\Xi^- + \bar{\Xi}^+)/(\pi^+ + \pi^-)$
  - $(\Omega^- + \bar{\Omega}^+)/(\pi^+ + \pi^-)$

- **Baryon/meson ratios :**

  $p/\pi, \Lambda/K, \Lambda/\phi, \Omega/\phi, \ldots$



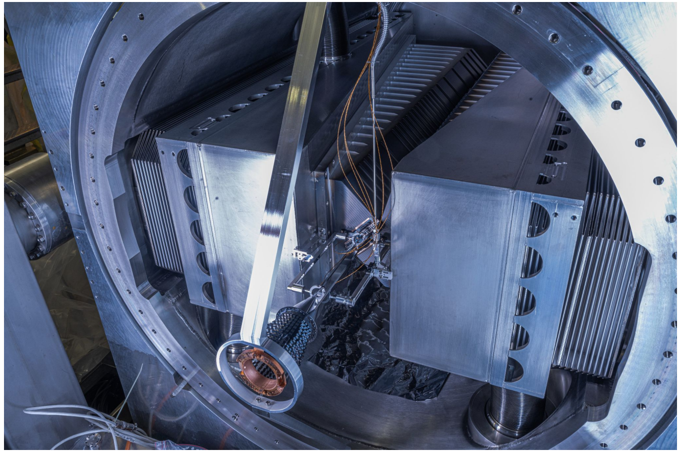




10.1103/PhysRevLett.111.222301

SMOG2

Talk by Pasquale



SMOG2 will greatly increase the opportunities offered by the fixed-target program :

- ***precise luminosity determination*** → cross sections
- wide choice of targets
  - access to ***heavy*** nuclei
  - possibility to study the physics properties of CNM as a function of number of nucleons in target

$H_2, D_2, \boxed{He}, N_2, O_2, \boxed{Ne}, \boxed{Ar}, Kr, Xe$

gas already used with SMOG

Early measurements → possibility to collect interesting data during commissioning exploiting the very first beams circulating in 2022 and using different gas types

- considering 6h ✕ 7 days → ∼2.2 pb^{-1}
- enough data to perform an inclusive hadron production analysis

Fixed target in LHCb is a unique QCD laboratory at an unexplored $\sqrt{s}$ and physically interesting kinematics regions :

- ‘small’ system such as proton-nucleus collisions are dominated by initial state effects → ideal probes for Cold Nuclear Matter effects
- bridge between CNM effects and QGP formation
    - question whether a locally equilibrated Quark Gluon Plasma could be formed even in small collision systems
    - strangeness enhancement
- modeling of initial conditions in nuclear collisions

- SMOG2 will offer a wide choice of targets in combination with proton and ion beams and the significantly higher luminosity compared to SMOG will greatly increase the statistical precision

Strangeness enhancement as test of QGP formation

Strangeness enhancement is expected due to:

- high gluon density in the QGP
- dominance of the gluonic production channel for strangeness in the QGP
- mass of the s quark being similar to the critical temperature T for the QCD phase transition (~ 150 MeV)
- strangeness formation time similar to the expected lifetime of the QGP
    - strangeness chemical equilibrium in QGP is possible, leading to abundant strange quark density in QGP