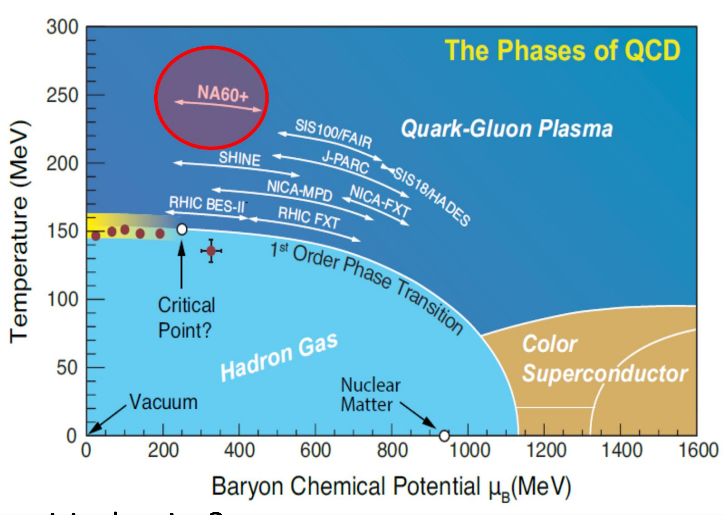
Performance studies of strangeness production in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 8.8 GeV with the NA60+ experiment at the CERN SPS

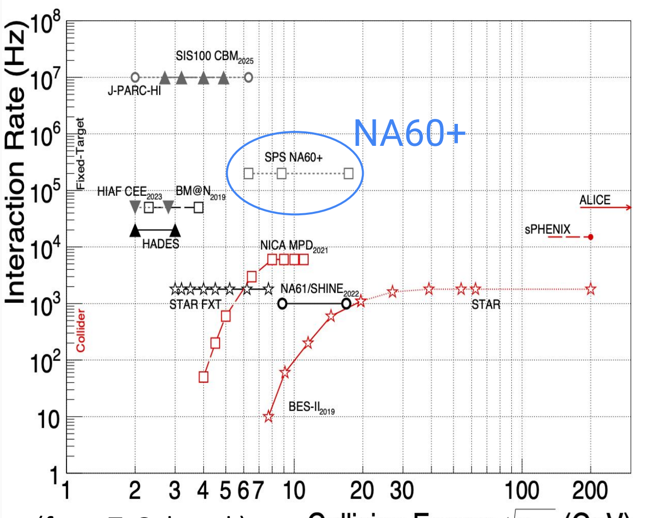
Giacomo Alocco (Università & INFN of Cagliari) for the NA60+ collaboration

NA60+

- NA60+ is a proposed experiment at the CERN SPS:
  - **explore the Quantum ChromoDynamic phase diagram** at large baryochemical potential (μ_B)



- NA60+ will perform a beam **energy scan in the range $\sqrt{s_{NN}}$ ~ 5-17 GeV** with an **high interaction rates** (~100 kHz)



(from T. Galatyuk)

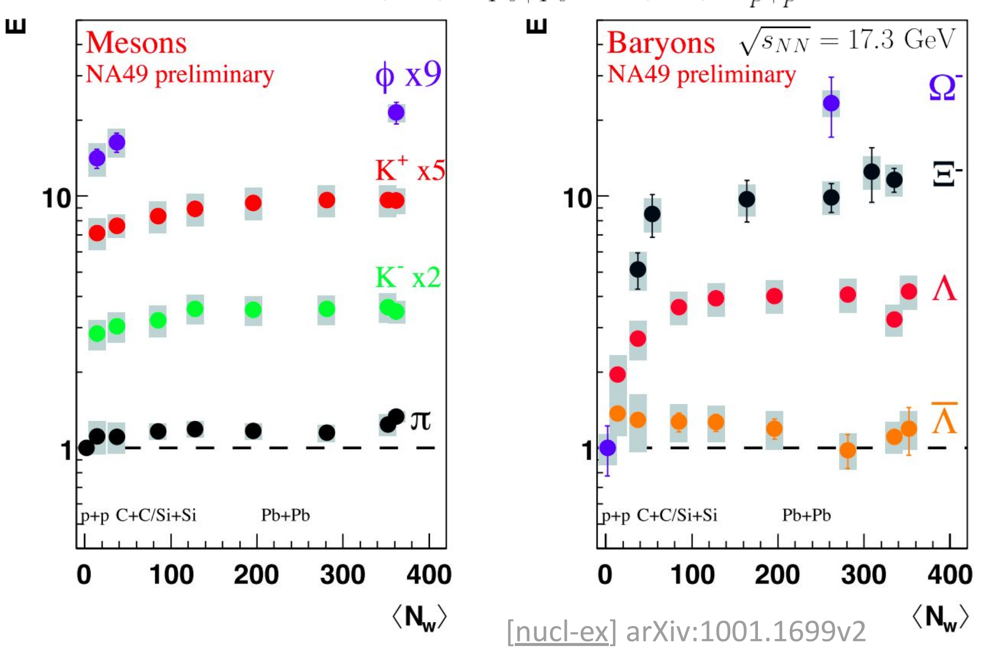
- **Main topics:**
  - Presence of a critical point?
  - First order phase transition at large μ_B?
  - Restoration of the chiral symmetry?
  - Properties of the QGP at large μ_B
- Ongoing studies at RHIC and NA61/SHINE, but the results are mostly on soft processes. NA60+ higher rates allow the study of:
  - **Hard processes**
  - **Electromagnetic processes**
  - **Strangeness production**

- Hadrons containing more than one strange quark (Ξ, Ω and ϕ) are particularly interesting:
  - Strangeness is not present in the valence content of the colliding nuclei ➞ produced in the hard scattering or in the hadronization process
  - Copiously produced at the SPS energies ➞ allow precise measurements

- Strangeness enhancement was first observed at the SPS, confirmed at RHIC and further scrutinized at the LHC

- The enhancement is proportional to the strangeness content:
  - $\Omega > \Xi > \Lambda \sim K^0_S$

$$E = \left(\frac{Yield}{\langle N_w \rangle}\right)_{Pb+Pb} / \left(\frac{Yield}{\langle N_w \rangle}\right)_{p+p}$$



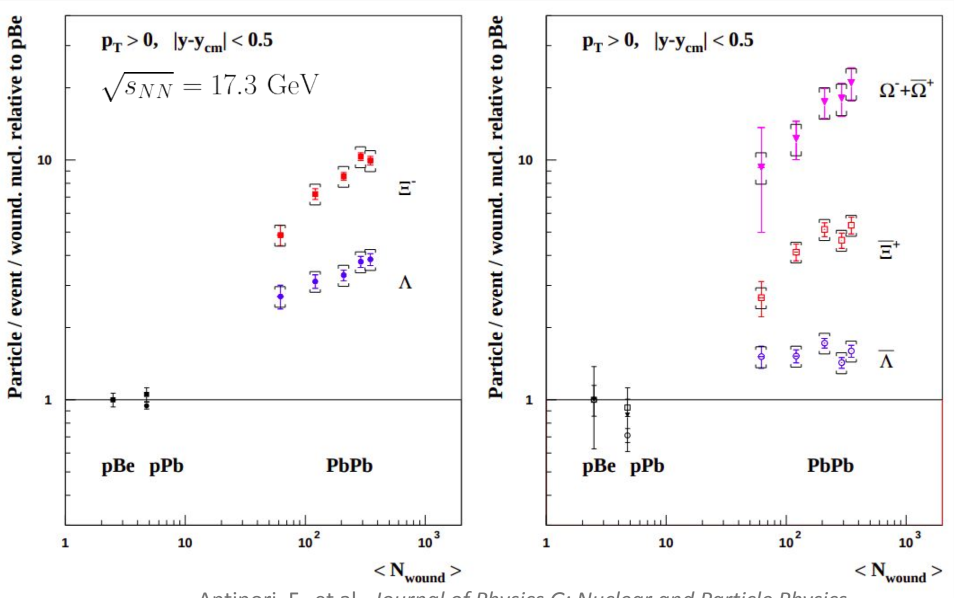
[nucl-ex] arXiv:1001.1699v2

Strangeness measurement: physics motivation

$$E = \left(\frac{Yield}{\langle N_w \rangle}\right)_{Pb+Pb} / \left(\frac{Yield}{\langle N_w \rangle}\right)_{p+Be}$$

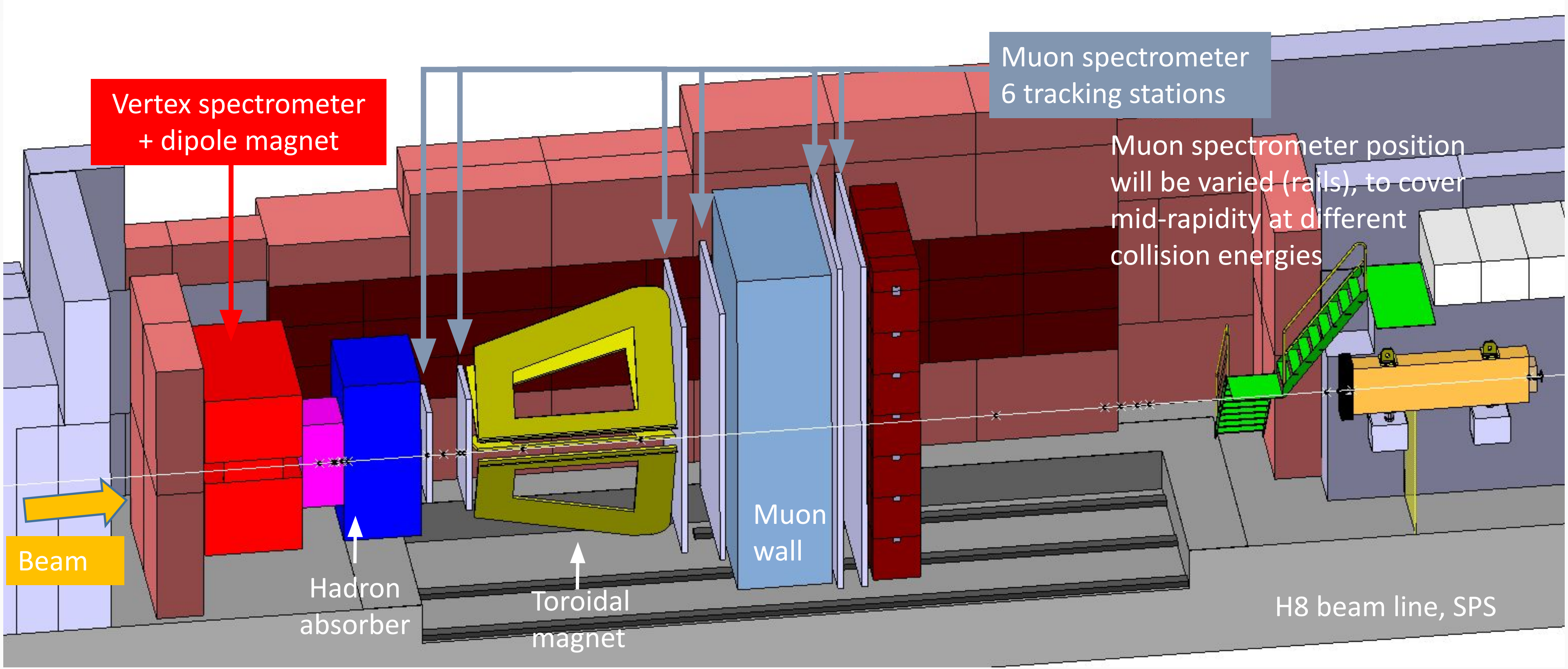
- Matter/anti-matter imbalance rate would allow a precise determination of the baryochemical potential ➞ probe production probabilities in an energy region where baryon number conservation depletes anti-particle yields

- **NA60+ could complete the measurement of the strangeness enhancement carried by NA49 and NA57** with precise measurements of:
    - K^0_S, ϕ, $\Xi^\pm$, and $\Omega^\pm$
    - The high number of events collected could allow the study of the elliptic flow of strange particles at SPS energies



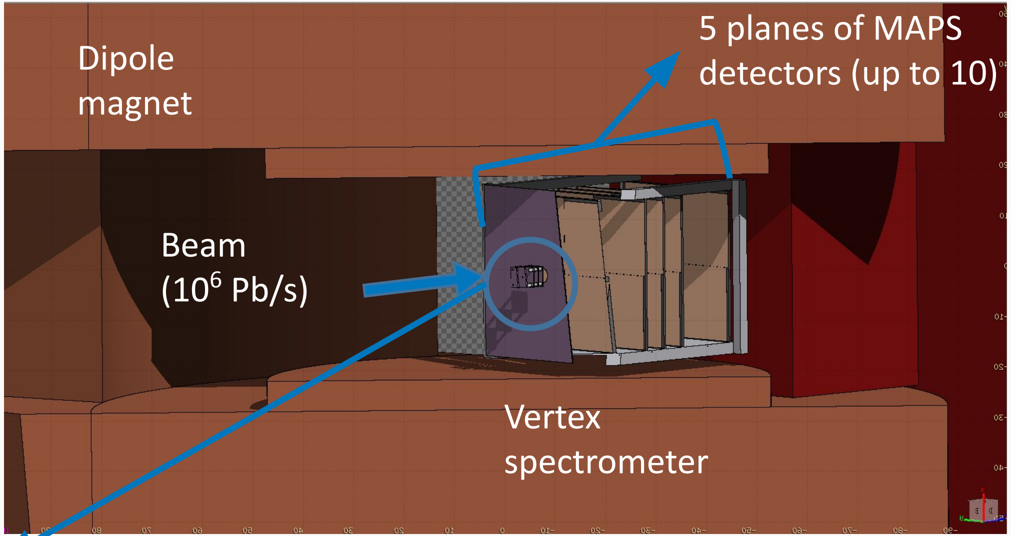
Antinori, F., et al. *Journal of Physics G: Nuclear and Particle Physics* 37.4 (2010): 045105.

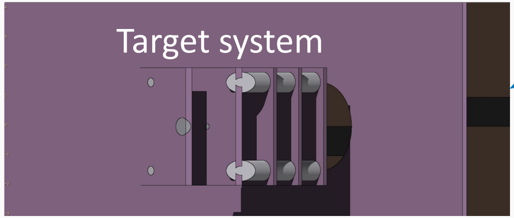
NA60+: experimental setup



NA60+: vertex region

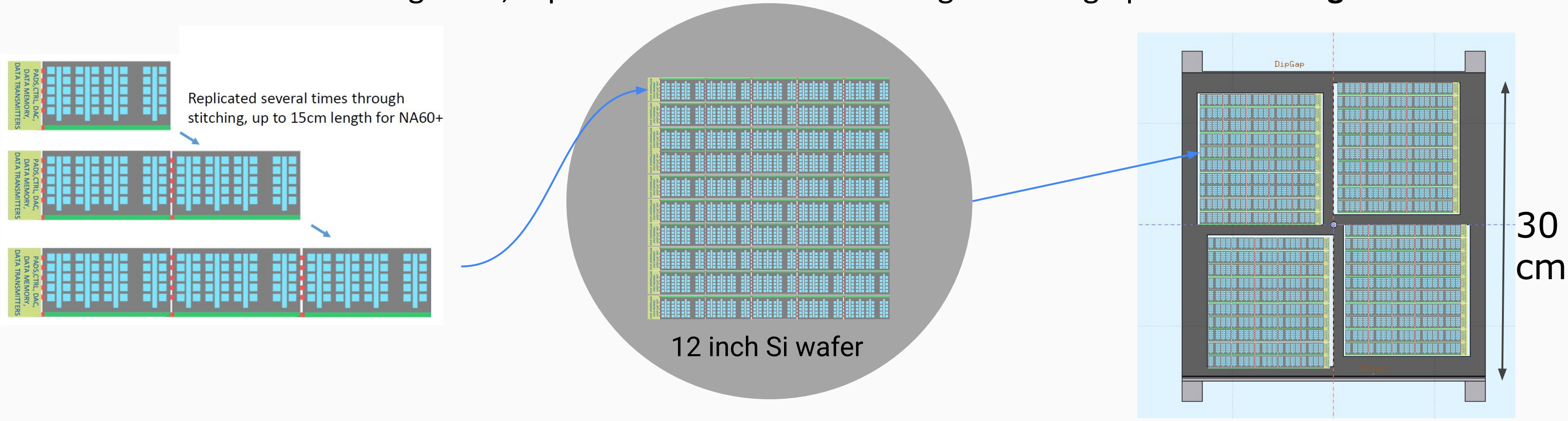
- Target system: 5 plates of 1.5 mm thick Pb
- Vertex spectrometer: from 5 to 10 layers of large area pixel sensors
- Vertex spectrometer embedded in a 1.5 T Magnetic field along the beam line ➞ MEP48 is already available at CERN





NA60+: vertex spectrometer

- High charged particle multiplicity in Pb-Pb collisions (up to $dN_{ch}/dy = 450$) requires:
  - High granularity, fast and radiation hard detectors in the vertex region
- Use of **state-of-the-art Monolithic Active Pixel Sensors**
- Synergy with **ALICE ITS3**
- Sensor based on 25 mm long units, replicated several times through stitching up to **15 cm length** for NA60+



4 sensors per station

- Few tens of microns of silicon ➞ material budget **< 0.1% X_0**
- Spatial resolution **≲ 5 µm**

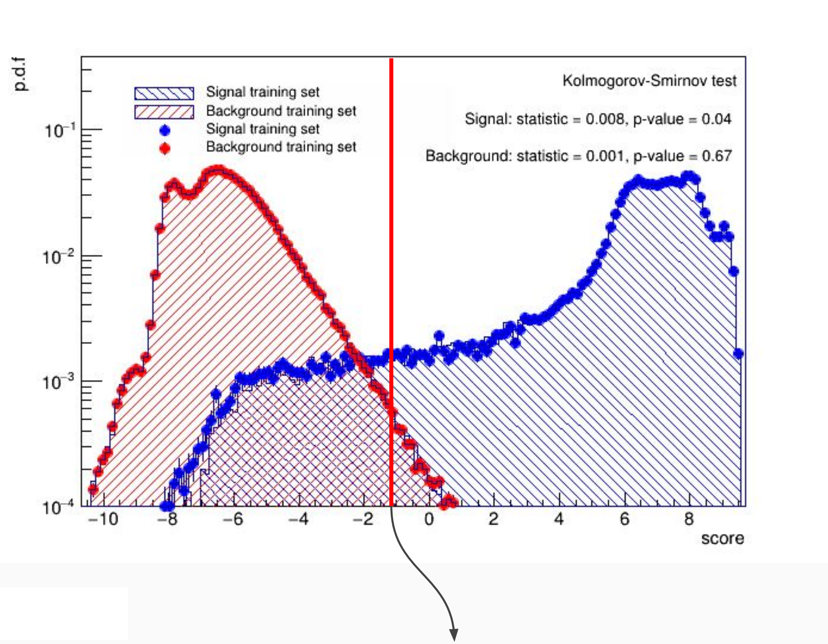
Decay channels and Simulation framework

- Decay channels studied:
  - $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p\pi^-$ + c.c., $\phi \rightarrow K^+K^-$, $\Xi^- \rightarrow \Lambda^0\pi^-$ + c.c., $\Omega^- \rightarrow \Lambda^0 K^-$ + c.c.,
- **Semi-analytical fast simulation and reconstruction code**:
  - Approximate detector response and ideal B assumed
  - Detector configuration: set of Z-ordered active or passive disks
- Simulation of Pb-Pb central collisions, the prompt particles **kinematics from NA49 measurements**[1][2][3], the K^0_S kinematics is the average of the K^+ and K^-
- **Dataset of ~10M central Pb-Pb collisions** at $\sqrt{s_{NN}}$=8.8 GeV:
  - Signal candidates built from p, $\pi^\pm$, $K^\pm$ prompt and from K^0_S, ϕ, $\Xi^\pm$, $\Omega^\pm$, (anti-)Λ^0 decays
- The results are rescaled to show the expected measurement after a month of data taking at 75 kHz

[1] Afanasiev, S. V., et al. *Physical Review C* 66.5 (2002): 054902.
[2] Alt, C., et al. *Physical Review C* 78.4 (2008): 044907.
[3] Alt, C., et al. " *Physical Review C* 78.3 (2008): 034918.

- **NA60+ will study the production of strange particles using the vertex spectrometer:**
  - Geometrical selections on the displaced decay-vertex topology to enhance the S/B (except for the ϕ)

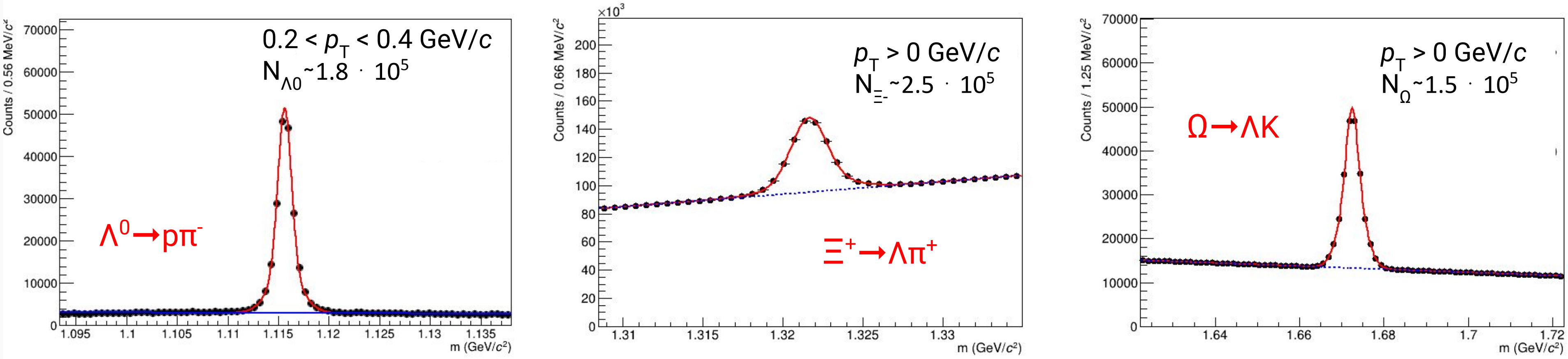
- **Boosted Decision Trees** (BDT) used for the classification
- 9M events are used for actual analysis
- ~1M events are used for the training and the testing of the BDT
- A different model is trained for each p_T interval
- The BDT output is a number called score
- The chosen **BDT score selection is the one that maximize the expected significance**



The analysis became a selection on the BDT score

Strangeness measurements

- BDTs selections have been used to enhance the S/B of the K^0_S, Λ^0, Ξ and Ω

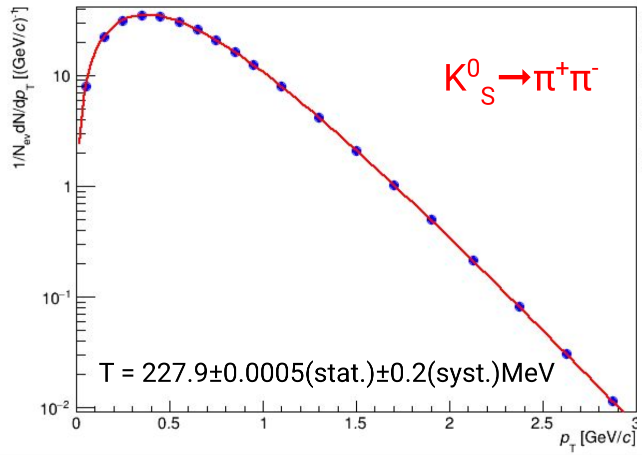


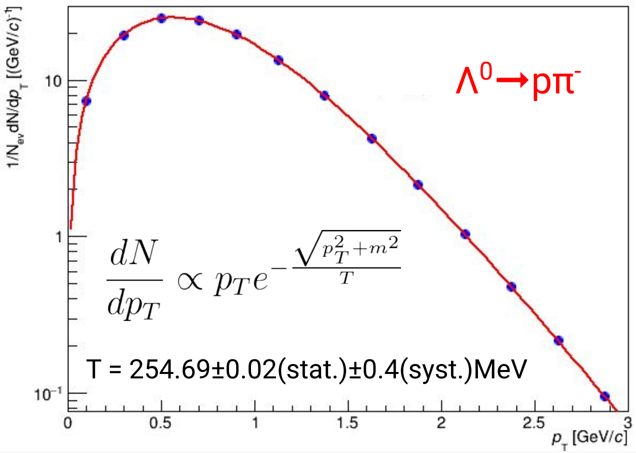
- Very large significances ➞ **Allows for differential studies of yield and v_2 vs p_T, y and centrality**

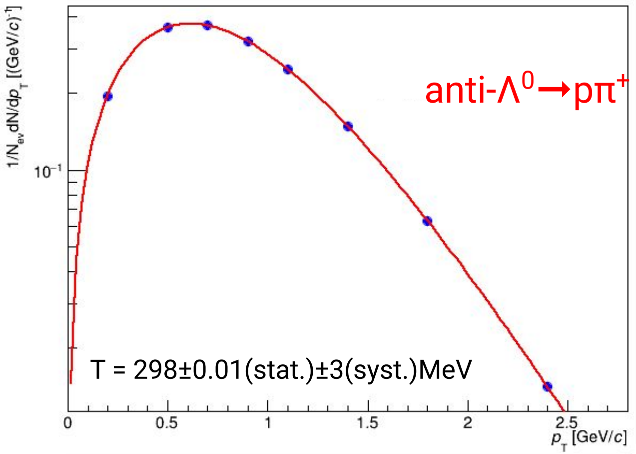
- The ϕ meson has a very short lifetime (τ = 1,55 x 10^{-22} s):
  - The decay vertex cannot be distinguished from the primary
  - It is not possible to extract the signal using topological selections

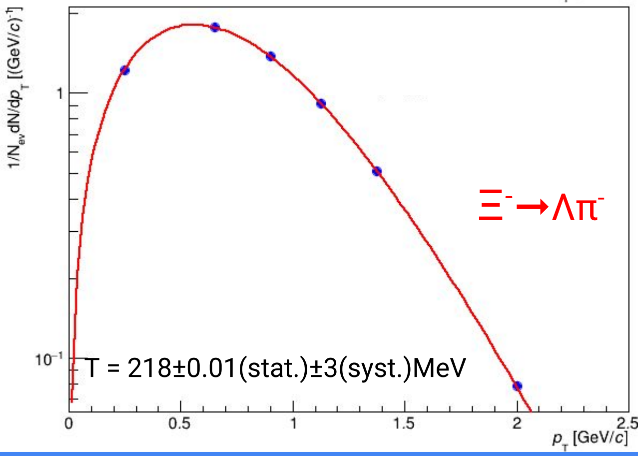
Physics performance: p_T spectra

- After the BDT selection and the signal extraction signal counts in each p_T interval









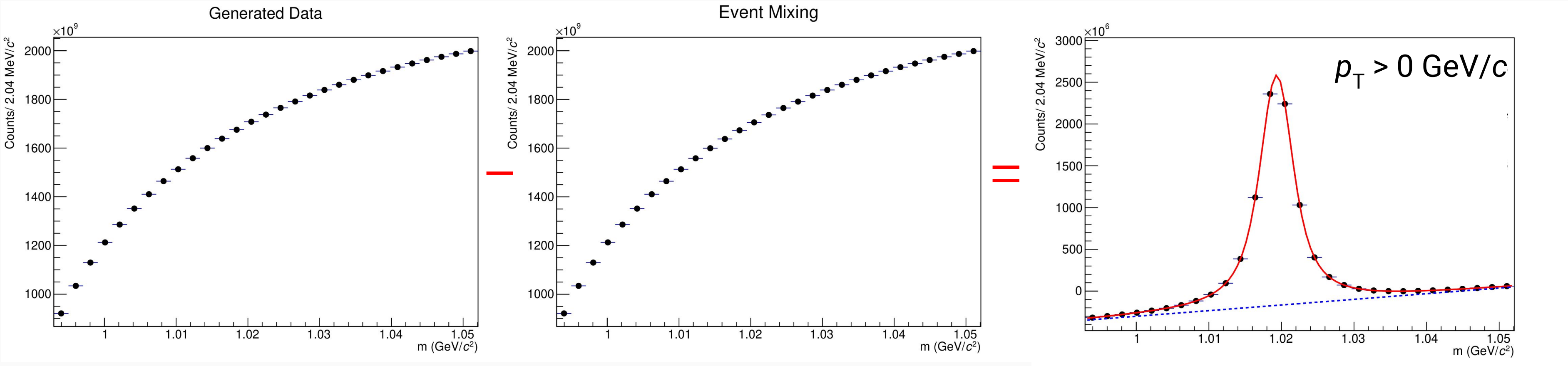
- Systematic uncertainties due to the BDT score choice and background model were taken into account

- Very **small statistical uncertainty**:
    - Several orders of magnitude lower than what was achieved by NA49 and NA57

- The **systematic uncertainties** are expected to be **dominant**

ϕ → K^+K^- : background subtraction

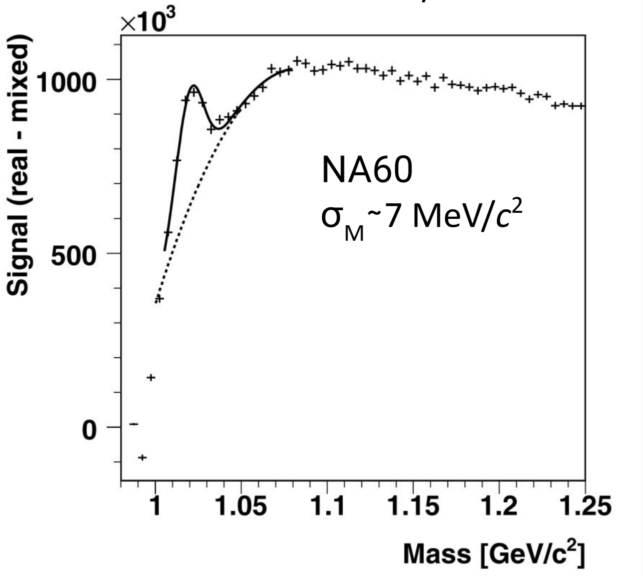
- **It is not possible to discriminate the background from the ϕ signal through topological selections**
- The **background** has been **reproduced using the event mixing**:
  - Candidates ϕ are built pairing the tracks from one event with the tracks of the next four events

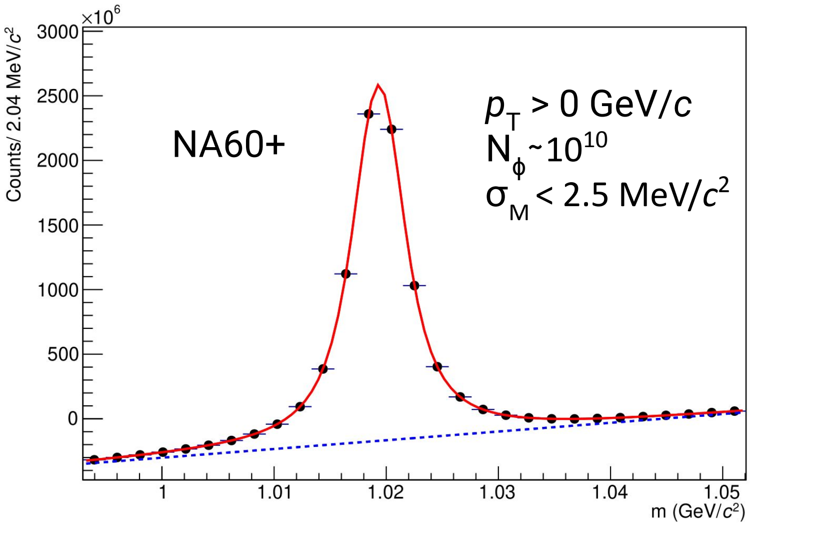


- The background has been normalized to the counts in 0.98 < m < 0.99 GeV/c^2 and 1.04 < m < 1.06 GeV/c^2

$\phi \to K^+K^-$: comparison with NA60

- NA60 measured ~ 15·10^5 ϕ [1] in In-In collisions, integrating on all the centrality classes, $p_T > 0.9$ GeV/c with mass resolution of ~7 MeV/c^2





- NA60+ will reconstruct ~10^{10} ϕ just in the 0-5 % centrality class, with a much better resolution then NA60
- **The resolution on the invariant mass is smaller than the width of the resonance:**
  - $1 < \sigma_m < 2.5$ MeV, $\Gamma_\phi = 4.26$ MeV
  - The high resolution and statistics could allow to observe modification of the mass that may be induced by the medium

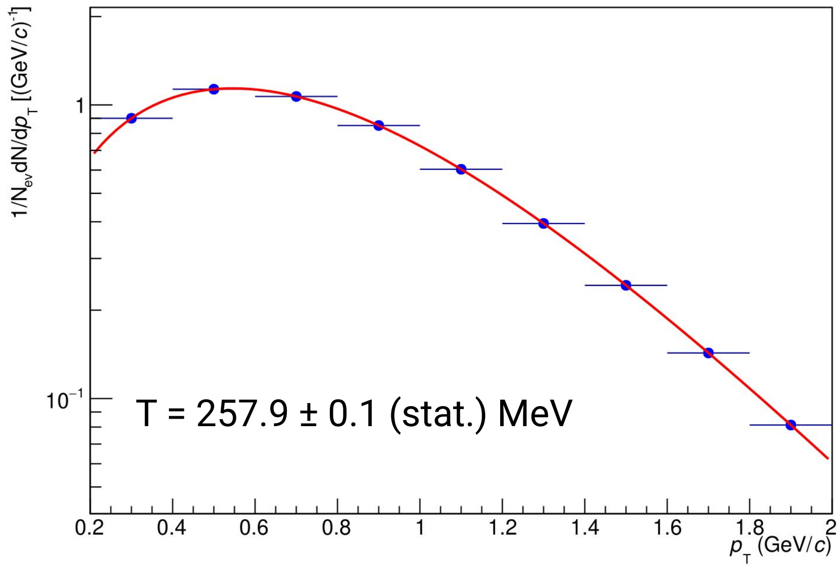
[1] De Falco, Alessandro, and NA60 collaboration. *Nuclear Physics A* 830.1-4 (2009): 753c-756c.

$\phi \rightarrow K^+K^-$: p_T spectrum

- The **possibility of extracting the signal in a wide range of p_T** looks promising

- The signal 10M events is was possible to extract the signal from $0.2 < p_T < 2.0$ GeV/c:
  - With full statistics the data this range can be expanded even further

- Kaon absorption and rescattering in the medium can result in a loss of signal that reduces the observed yield:
  - Effect at low p_T ➞ hardening of the p_T spectrum of $\phi \rightarrow K^+K^-$ w.r.t. $\phi \rightarrow \mu^+\mu^-$
  - Extracting the signal at low p_T is essential to study this effect



Conclusion

- We expect to collect ~10^{11} Pb-Pb collisions in one month of data taking with an energy beam scan in the range $\sqrt{s_{NN}}$ ~ 5-17 GeV

- The performance of the measurement of strange particles into their principal decay channel using the vertex spectrometer have been investigated

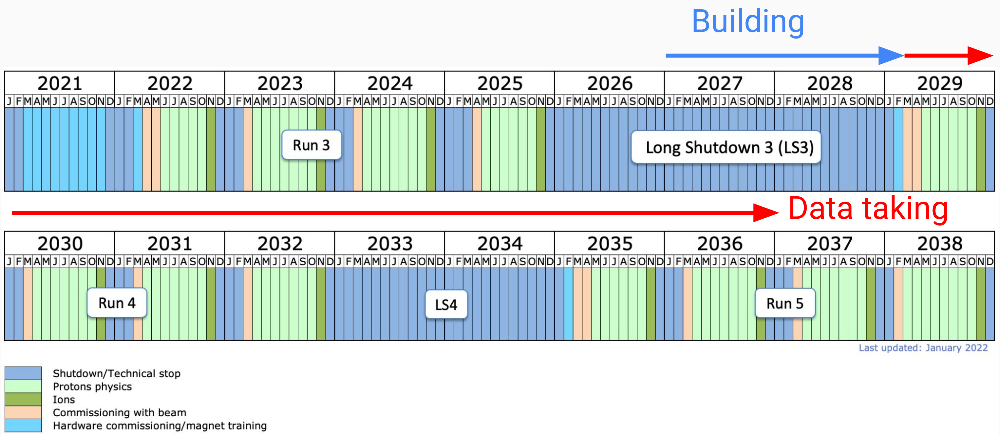
- Very large statistical significance for K^0_S, Λ^0, ϕ, $\Xi^\pm$ and $\Omega^\pm$ hyperons:
  - **Large improvement in their measurement w.r.t. the NA49 and NA57 measurements**
  - Possibility to perform the studies of the elliptic flow of strange particles at the SPS energies

- The project is part of the **Physics Beyond Colliders** CERN initiative since 2016 (QCD study group) and receives a substantial support on several technical aspects, including integration, RP and beam studies, and the project of the toroidal magnet

- An **Expression of Interest** (https://cds.cern.ch/record/2673280) was submitted in 2019 to the CERN SPSC

- A **Letter of Intent** is currently in (advanced) preparation ➞ to be submitted in 2022

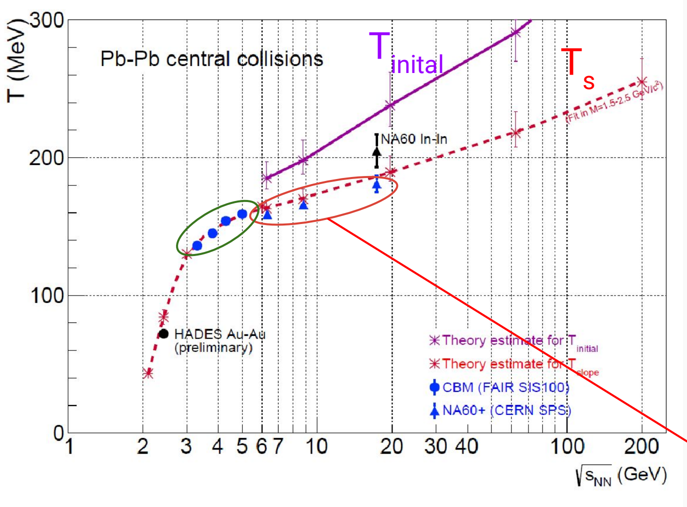
- Goal:
  - Obtain the CERN approval and build the experiment for data taking not later than the **end of LHC Long Shutdown 3** (2029)
  - Foresee **at least 5-6 yrs** of data taking (one energy point per year with p-A and Pb-Pb)



Backup

NA60+: physics motivation

- Measure:
  - **Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition**
  - **ρ-a_1 modifications: chiral symmetry restoration**



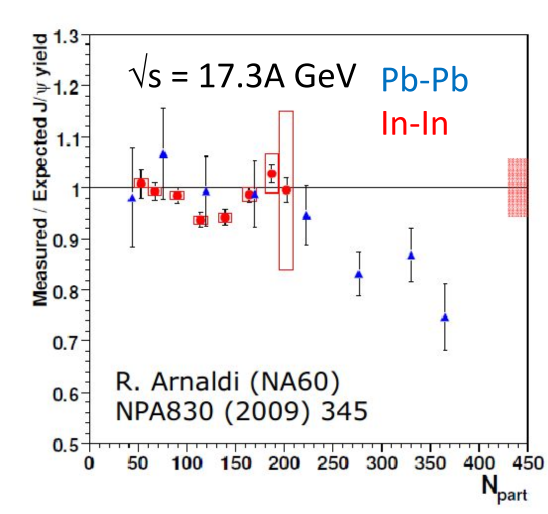
Compilation T. Galatyuk, QM2018
Hades,Nature Phys, 15(2019) 1040
√s>6 GeV, R. Rapp, PLB 753 (2016) 586
√s<6 GeV, T. Galatyuk, EPJA 52 (2016) 131

- **Extract temperature via fit** the dimuon mass:
  - $dN/dM \propto M^{3/2} \exp(-M/T_s)$
  - Possible flattening in √s-dependence of T_s
- Reach T at which the chiral symmetry may be restored:
  - observation of **ρ-a_1 mixing**

$\sqrt{s_{NN}}$ range covered by NA60+
→ complementarity with **CBM**

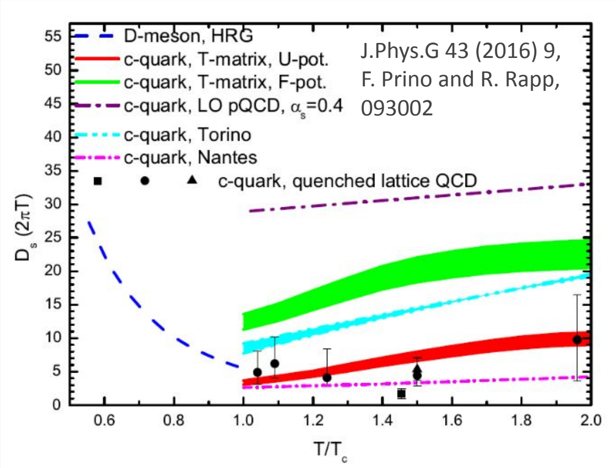
NA60+: physics motivation

- Measure:
  - **Quarkonium suppression: signal of deconfinement**
  - **Hadronic decays of charmed hadrons: QGP transport coefficients**



- NA50/NA60 experiments detected an **anomalous J/ψ suppression ➞** not explainable by cold nuclear matter effects
  - NA60+ can explore the centrality dependence of **J/ψ suppression vs √s**

- Measure 2 and 3 prong decays of charmed mesons and baryons:
  - R_{AA},v_2 : **transport coefficients**
  - Λ_c,D, D_s : study **hadronization mechanisms**

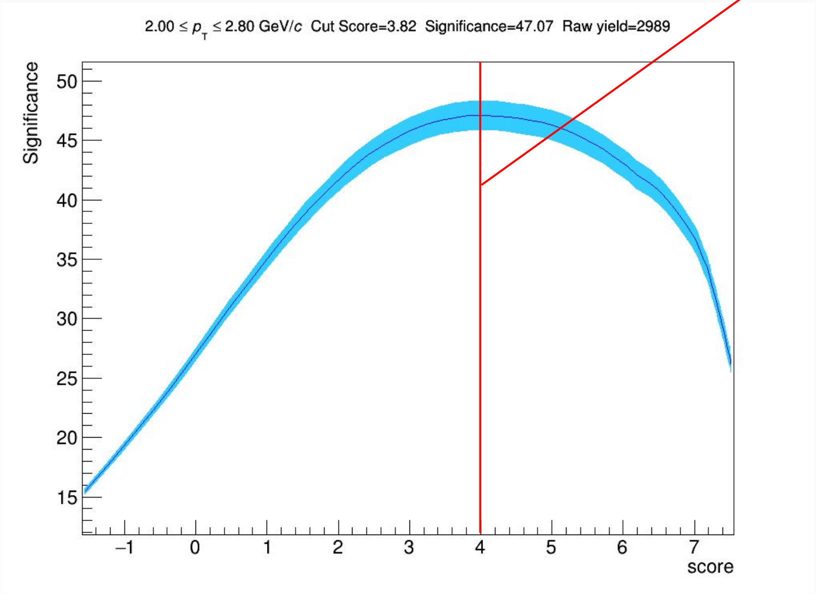


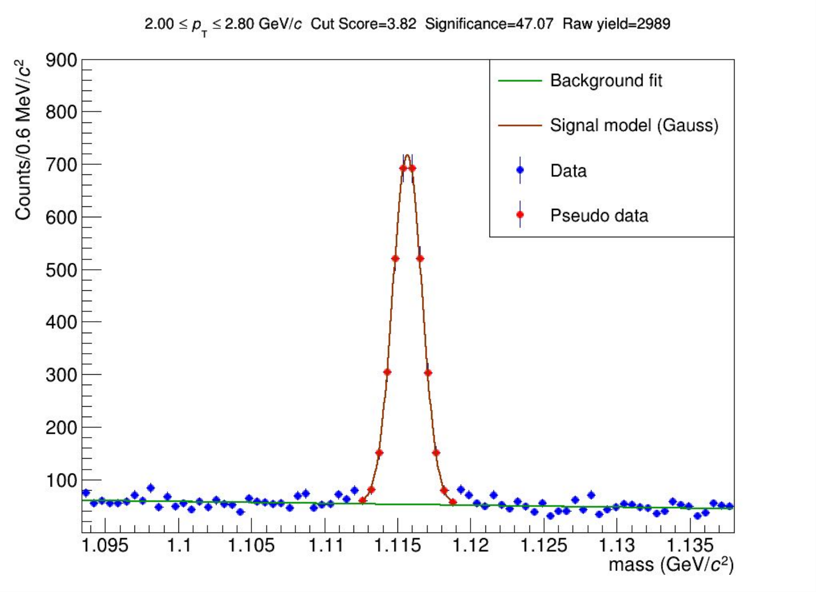
Preselection cuts

- Selections on the cosine of the pointing angle (cosp):
  - K^0_S: cosp > 0.9994
  - Λ^0 : cosp > 0.9998
  - anti-Λ^0, $\Xi^\pm$, $\Omega^\pm$: cosp > 0.9999 cuts needed to reduce the size of the trees under 100 Gb (for 9M events)
- $\Xi^\pm$ required further selections:
  - Selections on candidates (anti-) Λ^0, both prompt and non-prompt:
    - $\alpha < 0$ for anti-Λ^0 and $\alpha > 0$ for Λ^0 where α is the Armenteros α
  - Further selection on the non prompt (anti-)Λ:
    - Mass of the candidates: $m_\Lambda - 5\sigma < m < m_\Lambda + 5\sigma$ where $\sigma = 0.0007$ GeV/c^2
- For both $\Xi^\pm$ and $\Omega^\pm$:
    - Rejected if |decay vertex Λ| < |decay vertex $\Xi^\pm$ (Ω)|

- The expected signal is given by: $$S_{exp} = \int_{p_{Tmin}}^{p_{Tmax}} \frac{dN}{dp_T} dp_T \cdot \epsilon_{rec} \cdot \epsilon_{BDT} \cdot BR$$
- The background is given by the fit of the candidates that survive the BDT selection outside the peak region

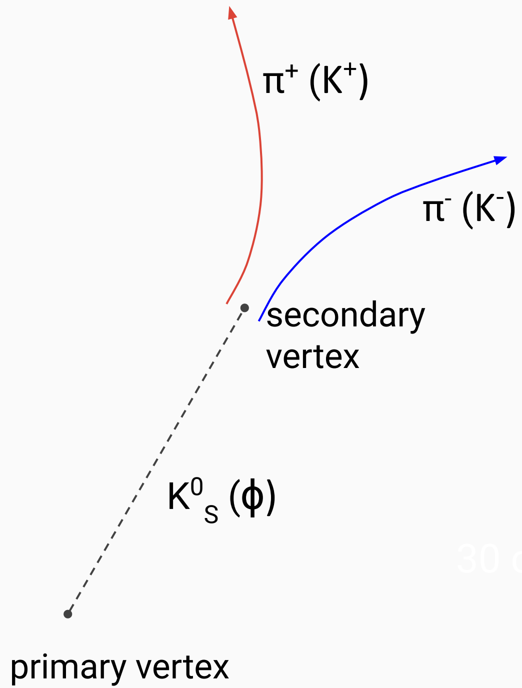
Optimal score selection





Unstable particle reconstruction

- The K^0_S, ϕ, and Λ^0 are neutral particles:
  - No signal left in the detector
  - Detected through their decay daughters
- The tracks of the charged particles produced in the collisions are reconstructed:
  - The vertex telescope is embedded in a magnetic field along the beam axis:
    - The momentum and the charge are obtained from the curvature of the trajectory
- The candidate K^0_S, ϕ, and Λ^0 are reconstructed summing the 4-momenta of every possible opposite charge pair of particles:
  - High charged particle multiplicity ➞ huge combinatorial background
- $\Xi^\pm$, $\Omega^\pm$ are also reconstructed through their decay daughter:
  - First is reconstructed the (anti)-Λ^0 then then the $\Xi^\pm$, $\Omega^\pm$ candidates



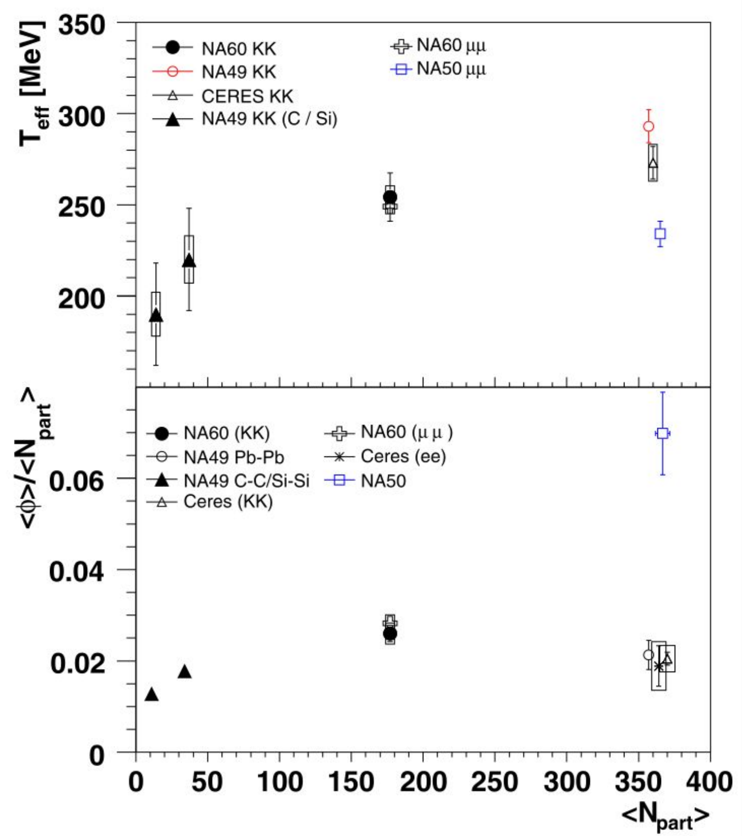
ϕ puzzle

- "ϕ puzzle":
  - NA49 detected the ϕ through its decay into K^+K^- pairs, while NA50 studied the $\phi \rightarrow \mu^+\mu^-$ channel in Pb-Pb collision ➞ discrepancies both in the yield and in the slope of the m_T spectra

- NA50 acceptance was limited to high p_T , while NA49 was dominated by low p_T

- In-medium effects may affect the spectral function of the ϕ ➞ modification of its mass and partial decay widths

- Kaon absorption and rescattering in the medium can result in a loss of signal in the region that reduces the observed yield:
  - Effect at low p_T ➞ hardening of the p_T spectrum of $\phi \rightarrow K^+K^-$
  - The yield in lepton pairs is expected to exceed the one in kaon pairs by about 50% (less than what was observed)



De Falco, Alessandro, and NA60 collaboration. "NA60 results on ϕ production in the hadronic and leptonic channels in In-In collisions at 158 GeV." *Nuclear Physics A* 830.1-4 (2009): 753c-756c.

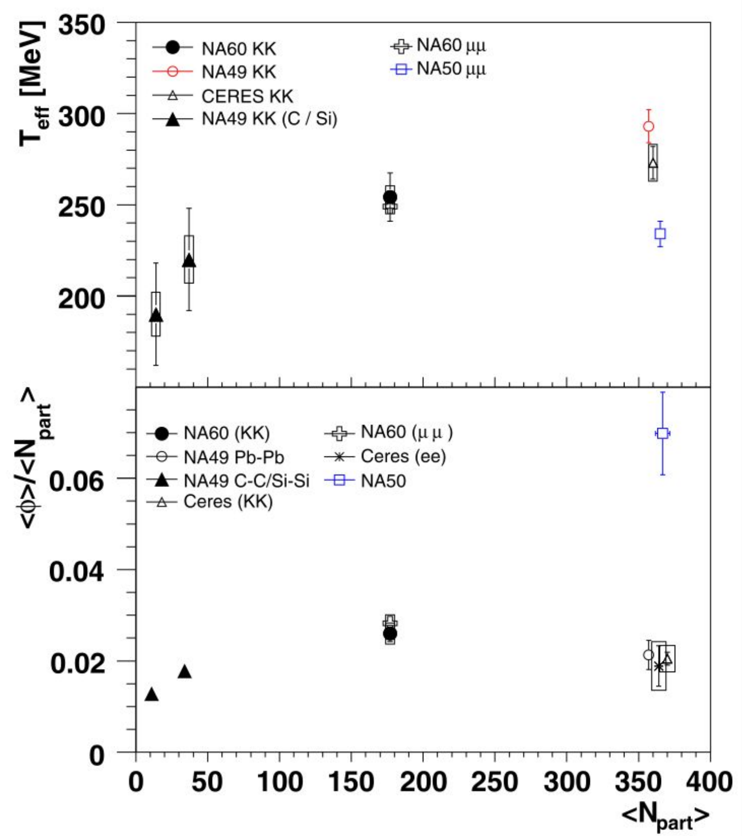
ϕ puzzle

- CERES experiment at the SPS studied ϕ production in Pb-Pb collisions both in the K^+K^- and dielectron channels finding agreement with the NA49 results, but the measurement is affected by a large statistical error

- The yield per participant measured in In-In exceeds the one observed in Pb-Pb in the hadronic channel (both NA49 and CERES) by about 30%:
    - Suggest a suppressing mechanism for the kaon channel, below experimental sensitivity in In-In, which shows up in Pb-Pb

- ϕ multiplicity in central Pb-Pb is smaller than in central In-In ➞ possible suppression mechanism

- Hint for a possible physics mechanism leading to a difference in the two channels in Pb-Pb collisions, while producing no remarkable difference in In-In collisions



De Falco, Alessandro, and NA60 collaboration. "NA60 results on ϕ production in the hadronic and leptonic channels in In-In collisions at 158 GeV." *Nuclear Physics A* 830.1-4 (2009): 753c-756c.

Expected statistical uncertainties:

- The statistical uncertainties goes as:

$$\sigma \propto \frac{1}{\sqrt{N_{ev}}}$$

- The expected uncertainties are computed as:

$$\sigma_{exp} = \frac{\sqrt{N_{sim}}}{\sqrt{N_{exp}}} \times \sigma_{sim} = 0.03 \times \sigma_{sim}$$

events used for the simulations (9M)

uncertainty from the simulation

uncertainty after one month of data taking

events after one month of data taking

K^0_S selections:

- Preselection cuts applied to K^0_S candidates:
  - cosp > 0.9994

- Variables used by the BDT:
  - cosp of the candidate
  - decay distance of the candidate
  - dca of the candidate to the primary vertex
  - product of distance of the candidate decay daughters tracks to primary vertex on the xy plane with sign
  - rapidity of the candidate

Λ^0 selections:

- Preselection cuts applied to Λ^0 candidates:
  - cosp > 0.9998

- Variables used by the BDT:
  - cosp of the candidate
  - decay distance of the candidate
  - dca of the candidate to the primary vertex
  - product of distance of the candidate decay daughters tracks to primary vertex on the xy plane with sign
  - rapidity of the candidate

(anti-)Λ^0 selections:

- Preselection cuts applied to anti-Λ^0 candidates:
  - cosp > 0.9999

- Variables used by the BDT:
  - cosp of the candidate
  - decay distance of the candidate
  - dca of the candidate to the primary vertex
  - product of distance of the candidate decay daughters tracks to primary vertex on the xy plane with sign
  - rapidity of the candidate

Ξ^- selections:

- Preselection cuts applied to Ξ^- candidates:
  - cosp > 0.9999
  - $1.11075 < m_{\Lambda 0} < 1.12065$ GeV/c^2

- Variables used by the BDT:
  - cosp of the Λ^0 candidate
  - product of distance of the Λ^0 candidate decay daughters tracks to primary vertex on the xy plane with sign
  - product of distance of the candidate decay daughters tracks to primary vertex on the xy plane with sign
  - dca of the candidate to the primary vertex
  - dca of the Λ^0 candidate to the primary vertex
  - decay distance of the candidate
  - rapidity of the candidate

Ξ^+ selections:

- Preselection cuts applied to Ξ^+ candidates:
  - cosp > 0.9999
  - $1.11075 < m_{anti\text{-}\Lambda 0} < 1.12065$ GeV/c^2

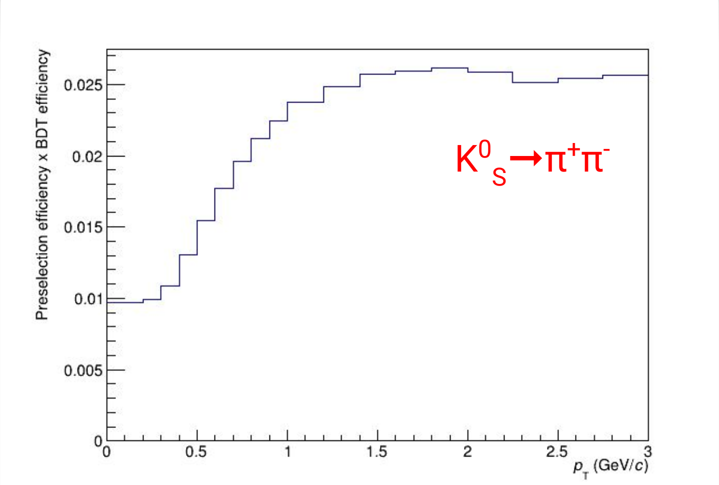
- Variables used by the BDT:
  - cosp of the candidate
  - product of distance of the Λ^0 candidate decay daughters tracks to primary vertex on the xy plane with sign
  - product of distance of the candidate decay daughters tracks to primary vertex on the xy plane with sign
  - dca of the candidate to the primary vertex
  - dca of the Λ^0 candidate to the primary vertex
  - decay distance of the candidate
  - rapidity of the candidate

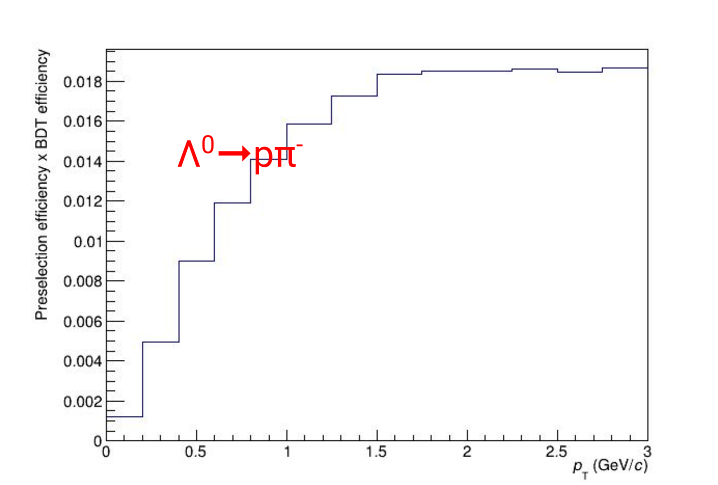
Ω^{-}+Ω^{+} selections:

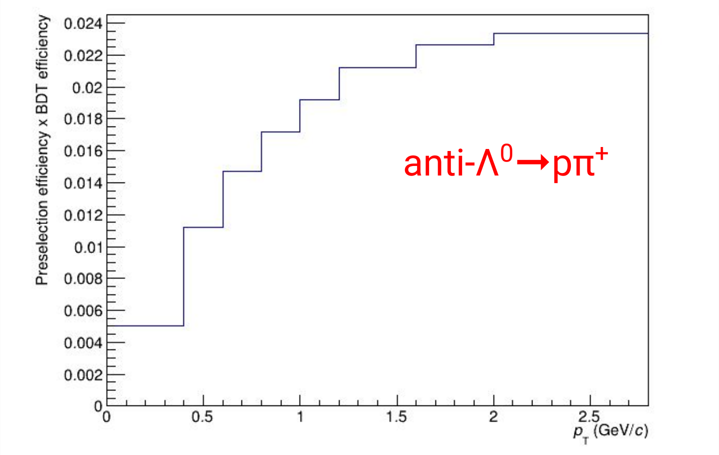
- Preselection cuts applied to $\Omega^{\pm}$ candidates:
  - $p_T > 0.9$ GeV/c
  - cosp > 0.99999
  - decay distance of the Λ^0 candidate > 0.2 cm
  - dca to the primary vertex < 0.003 cm
  - dca to the primary vertex of the Λ^0 candidate < 0.002 cm
  - $1.1145 < m_{\Lambda 0} < 1.117$ GeV/c^2

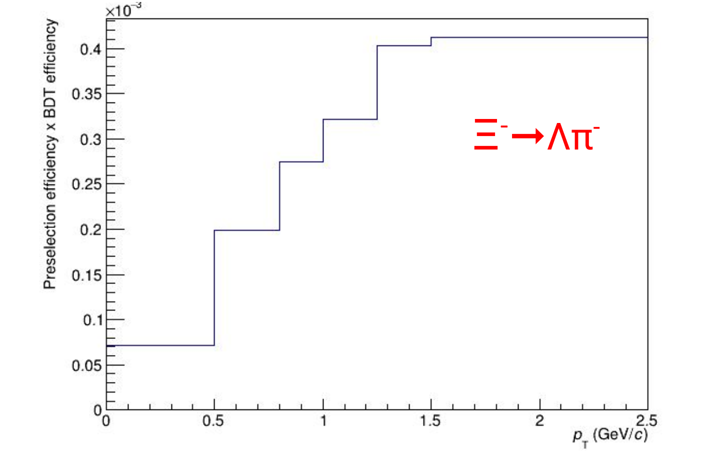
- Variables used by the BDT:
  - cosp of the Λ^0 candidate
  - impact parameter of the Λ^0 candidate
  - impact parameter of the candidate
  - decay distance of the candidate
  - rapidity of the candidate

Efficiency x Acceptance before the BDT selection









Comparison of the statistical uncertainties with NA49

	NA60+			NA49	
Particle	σ_T / T	σ_{Yield}/Yield	σ_{Mass} /Mass	σ_T / T	σ_{Yield}/ Yield
K^0_S	10^{-6}	$2 \cdot 10^{-5}$	Not measured	No measurements	No measurements
Λ^0	$3 \cdot 10^{-6}$	$2 \cdot 10^{-5}$	Not measured	0.04	0.04
anti-Λ^0	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	Not measured	0.06	0.05
Ξ^-	$3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	Not measured	0.04	0.07
Ξ^+	Not measured	$4 \cdot 10^{-3}$	Not measured	0.09	0.08
$\Omega^+ + \Omega^-$	Not measured	Not measured	Not measured	0.2	0.2
Φ	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-6}$	0.07	0.04

NA60+ expression of interest

https://na60plus.ca.infn.it/

Signed by 82 physicists from France, Germany, India, Italy, Japan, Switzerland, USA

The NA60+ Collaboration

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- Observables
- Requirements
- Experimental layout
- Detectors
- Physics performances
- Competition with other measurements

http://cds.cern.ch/record/2673280

Expression of Interest for a new experiment at the CERN SPS: NA60+

CERN-SPSC-2019-017 / SPSC-EOI-019
03/05/2019

NA60+ Collaboration

Abstract

The exploration of the phase diagram of Quantum ChromoDynamics (QCD) is carried out by studying ultrarelativistic heavy-ion collisions. The energy range covered by the CERN SPS ($\sqrt{s_{NN}} \sim$ 5–17 GeV) is ideal for the investigation of the region of the phase diagram corresponding to finite baryochemical potential (μ_B), and has been little explored up to now. In this Expression of Interest, we describe the physics motivations and the exploratory studies for a new experiment, NA60+, that would address several observables which are fundamental for the understanding of the phase transition between hadronic matter and a Quark–Gluon Plasma (QGP) at SPS energies. In particular, we propose to study, as a function of the collision energy, the production of thermal dimuons from the created system, from which one would obtain a caloric curve of the QCD phase diagram that is sensitive to the order of the phase transition. In addition, the measurement of a ρ–a_1 mixing contribution would provide crucial insights into the restoration of the chiral symmetry of QCD. In parallel, studies of heavy quark and quarkonium production would also be carried out, providing sensitivity for transport properties of the QGP and the investigation of the onset of the deconfinement transition. The document defines an experimental set-up which couples a vertex telescope based on monolithic active pixel sensors (MAPS) to a muon spectrometer with tracking (GEM) and triggering (RPC) detectors within a large acceptance toroidal magnet. Results of physics performance studies for most observables accessible to NA60+ are discussed, showing that the results of the experiment would lead to a significant advance of our understanding of (non-perturbative) strong interaction physics. It is also shown that beam intensities of the order of 10^7 lead ions/s are required in order to obtain meaningful results on the various physics topics. Such intensities can presently be reached only in the ECN3 underground hall of the SPS. In addition, the support and engagement of CERN for the development, construction and operation of the toroidal magnet is considered crucial for the success of the project.

May 3, 2019