PRODY
Precision Research on Origins of Drell-Yan:

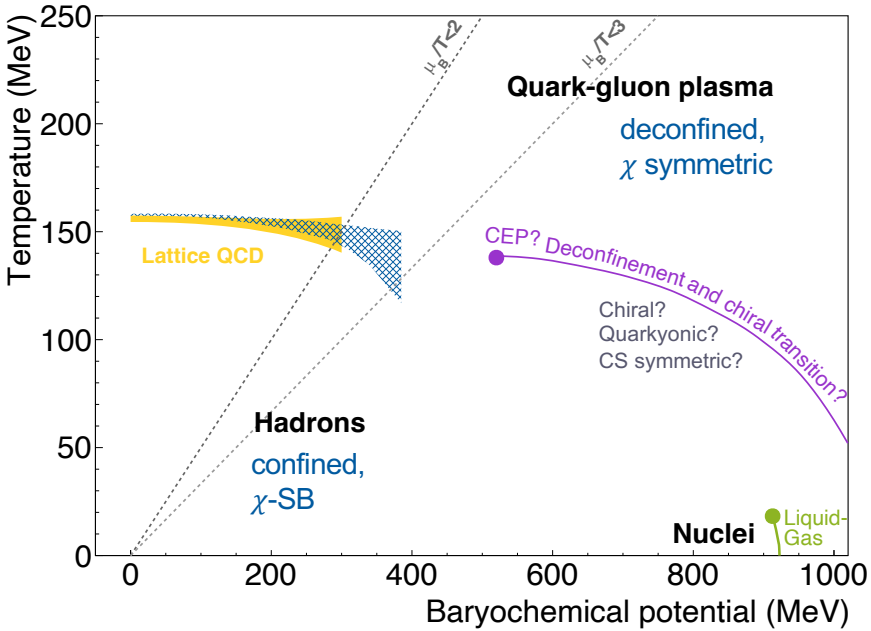
understanding the fundamental particle interaction process ranging from pQCD to non-perturbative regime, from LHC-to-SPS-to-SIS

Town Meeting, Hadron Physics in Horizon Europe

July 1-2, 2025, Nantes, France

Hot and dense QCD: Mission

Decode the phases of strong-interaction matter in the non-perturbative regime of QCD



Vanishing μ_B, high T (lattice QCD):

- **crossover** between hadronic and partonic medium
  - $T_{pc} = 156.5 \pm 1.5$ MeV ($T_c = 132^{+3}_{-6}$ MeV at chiral limit)
- **no 1st order transition** found by lQCD for $\boldsymbol{\mu_B^{CEP}/T_c < 3}$

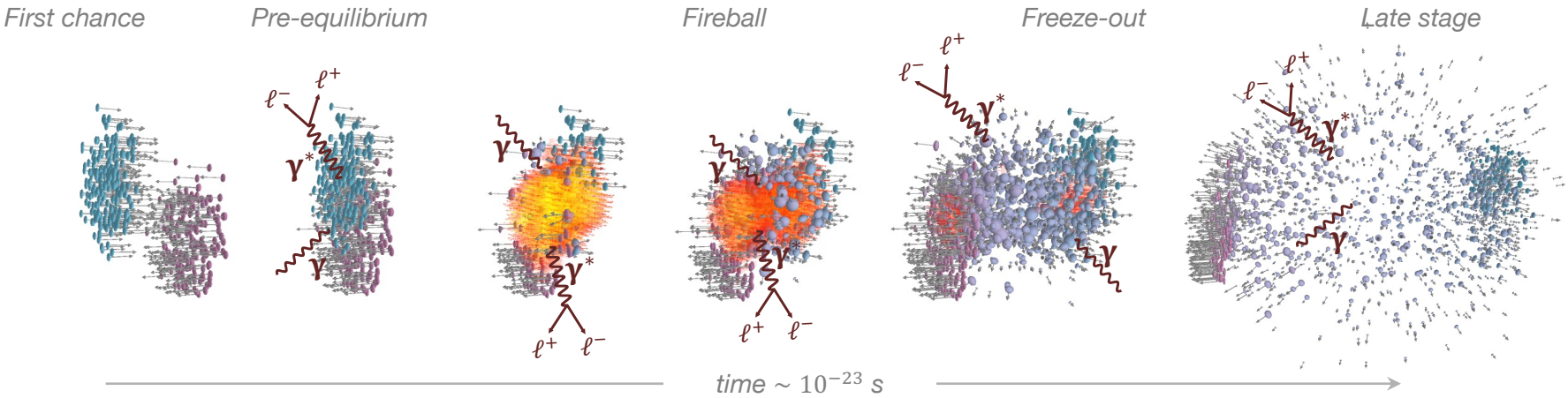
Large μ_B, moderate T (lattice QCD inspired effective theories):

- limits of hadronic existence?
- 1st order transition?
- QCD critical point?
- equation-of-state of dense matter?

„If you want to detect something new, build a dilepton spectrometer“

Samuel Chao Chung Ting

Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation (γ, γ^*)

Reflect the whole history of a collision

No strong final state interaction
↝ leave reaction volume undisturbed

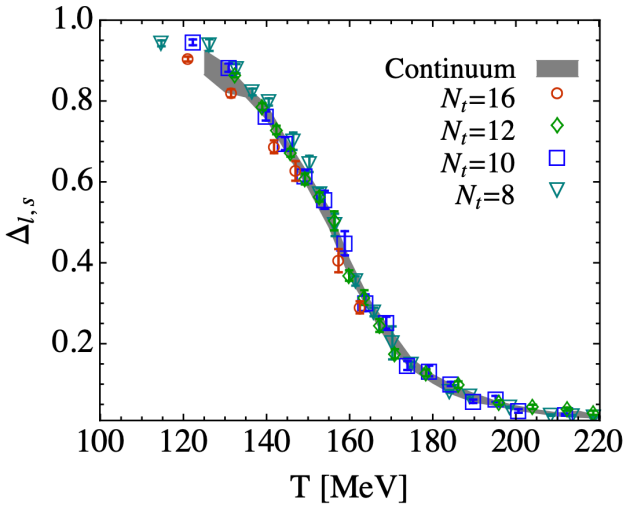
Encodes information about matter properties which enables unique measurements

- Degrees of freedom of the medium,
- Fireball lifetime, temperature, acceleration, polarization,
- Transport properties,
- **Restoration of chiral symmetry.**

Dileptons and chiral symmetry of QCD

Spontaneously broken in the vacuum
$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$

Condensates $\langle \bar{q}q \rangle$ calculated by lattice QCD

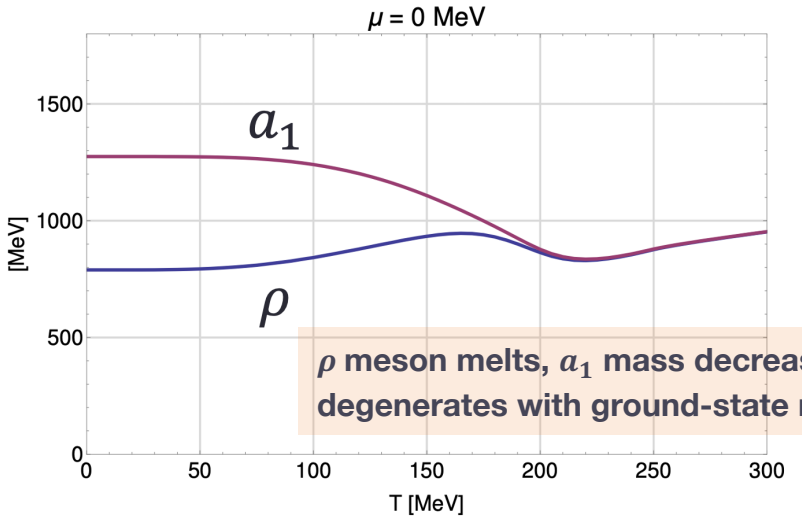


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

Restoration at finite T and μ_B manifests itself through mixing of vector and axial-vector correlators

S. Weinberg, PRL 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi}\left[\Pi_V(s) - \Pi_{AV}(s)\right] = m_\pi^2 f_\pi^2 = -2m_q\langle \bar{q}q \rangle$$

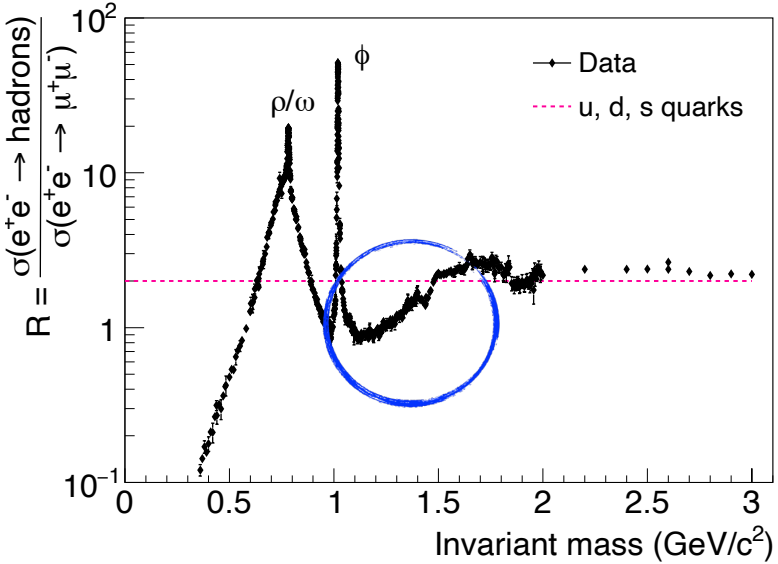


ρ meson melts, a_1 mass decreases and degenerates with ground-state mass

Hadronic many-body theory Hohler and Rapp, PLB 731 (2014)
FRG Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
Light mesons and baryons from lattice QCD, Aarts, QM2022, April 2022

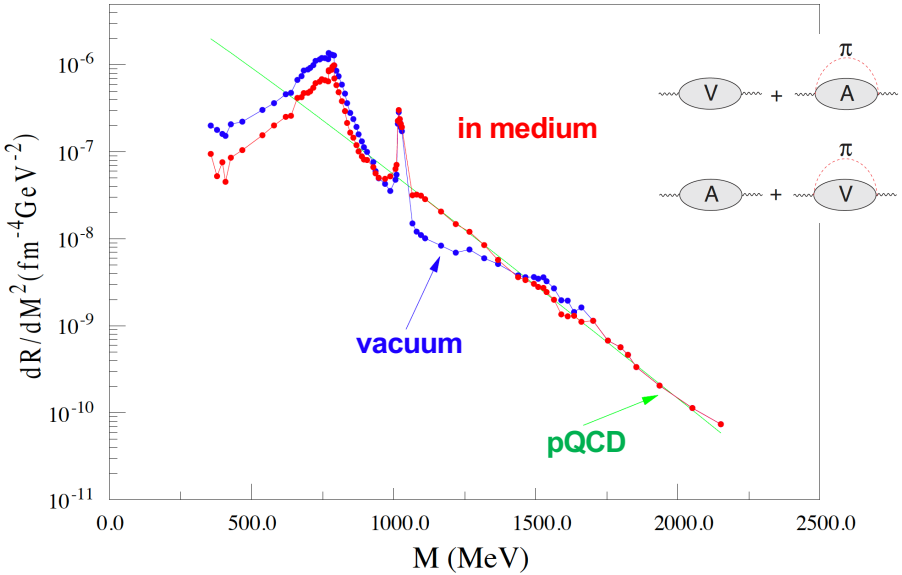
Signature for chiral symmetry restoration

Electromagnetic correlator **in the vacuum accurately known** from e^+e^-annihilation



Beringer *et al.* (PDG), Phys. Rev. D (2012) 010001

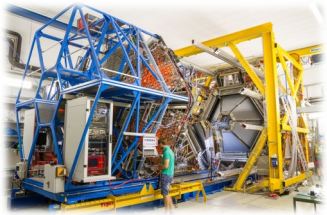
In the medium - changes in yield and shape at $M_{ee} > 1.1$ GeV/c^2 due to **chiral $\rho - a_1$ mixing**



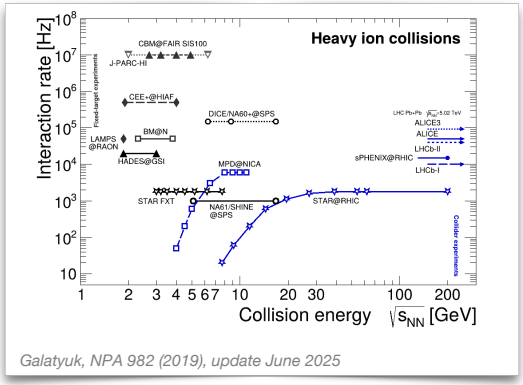
Dey, Eletsky and Ioffe, Phys.Lett. B252 (1990)
Rapp and Wambach, Adv.Nucl.Phys. 25 (2000)

Current and future extreme matter dilepton instruments

HADES at SIS18

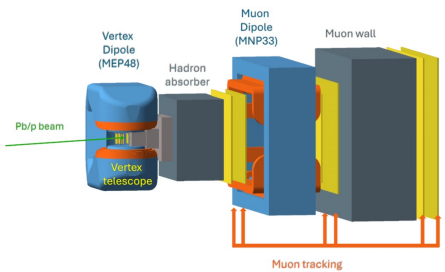


CBM at SIS100



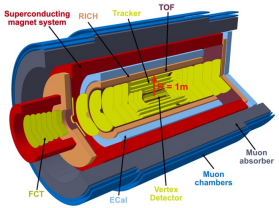
Galatyuk, NPA 982 (2019), update June 2025

DiCE/NA60+ at SPS

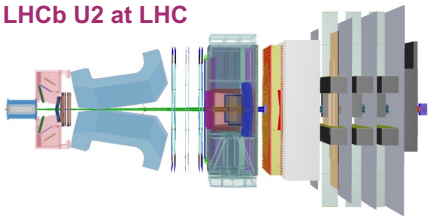


ALICE at LHC

ALICE3 at LHC

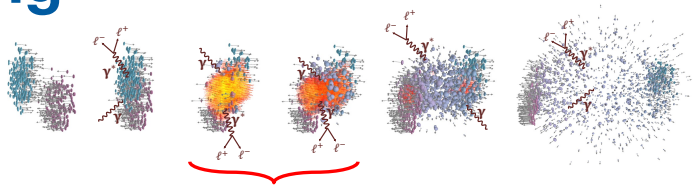


LHCb U2 at LHC

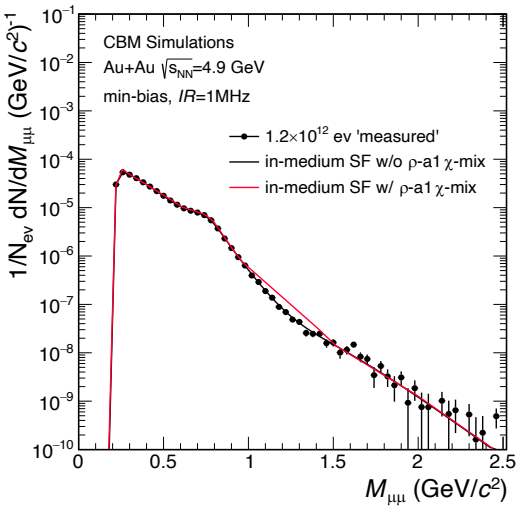


Prospects for detecting chiral mixing

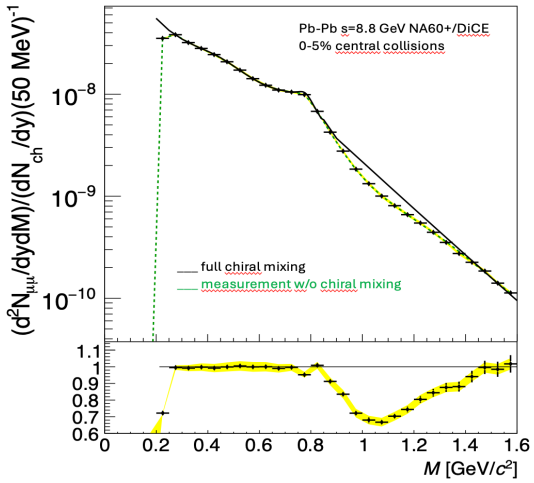
CBM, DiCE/NA60+ and **ALICE3 sensitivity**
to detect a signal is **demonstrated**



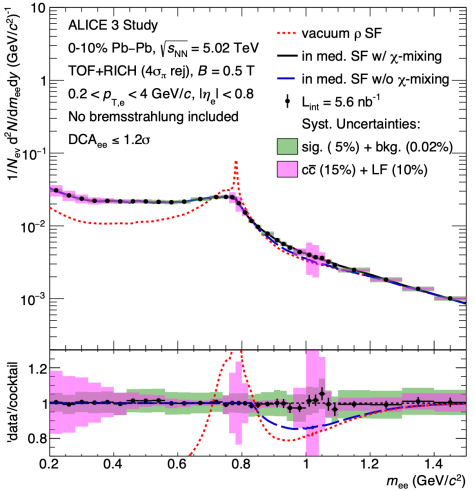
SIS100



SPS



LHC



Prospects for detecting chiral mixing

CBM, DiCE/NA60+ and **ALICE sensitivity**
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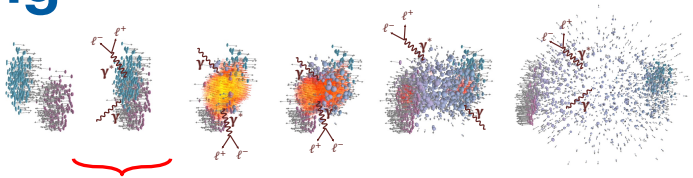
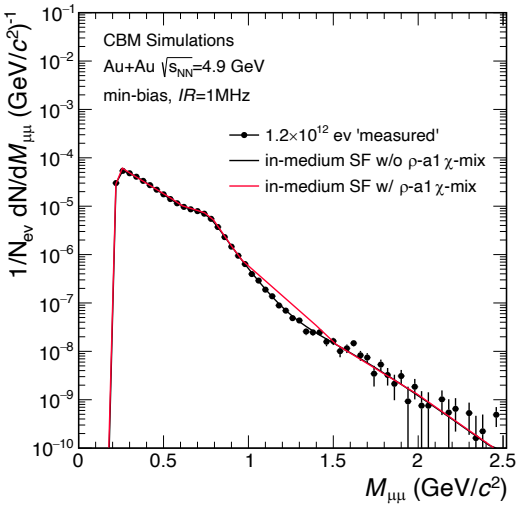
HOWEVER, significantly depends on knowledge of contributions from pre-equilibrium radiation, open charm and hadron decay contributions



?

purely known

SIS100



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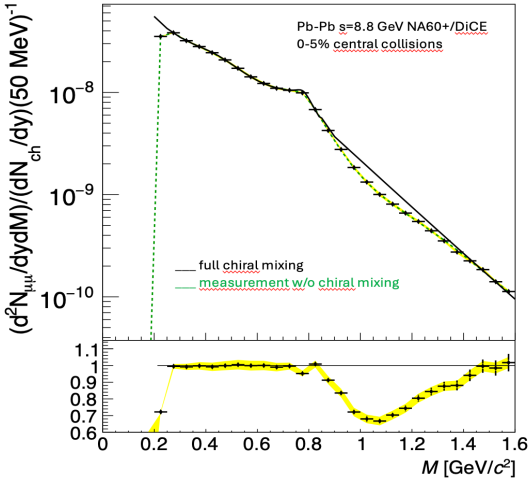

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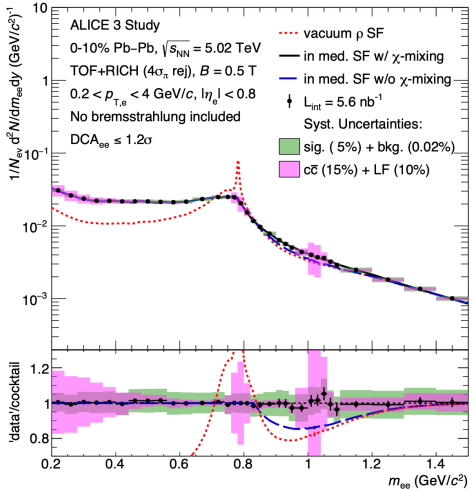
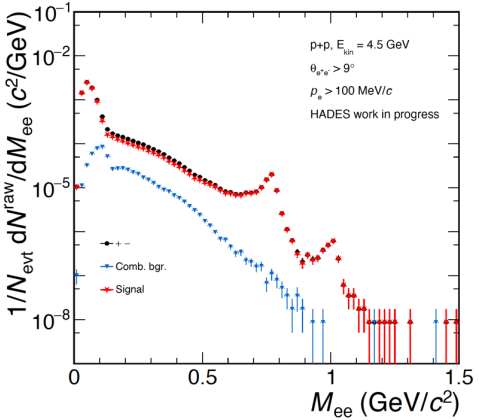
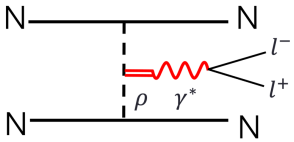


Assessment of “early stage” radiation

hadronic

SIS18



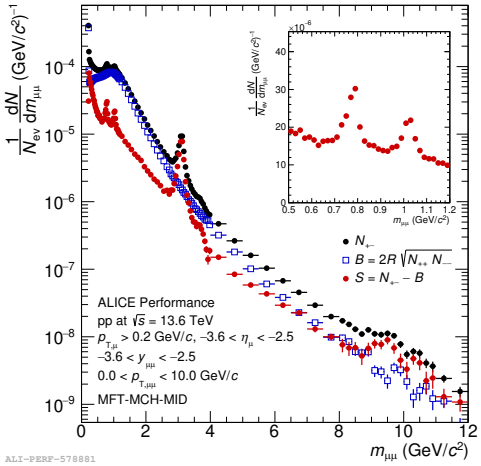


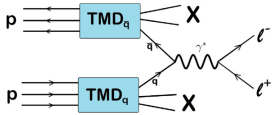
- DY-like process, hadronic degrees of freedom
  - example: one boson exchange effective Lagrangian based approach (π^+, π^- annihilation)

→ constrain theory calculations using existing high quality HADES data

partonic

LHC





+ NLO DY production

$gq \to \gamma^* q,\ q\bar{q} \to \gamma^* g$

- Parton distribution functions (PDFs) non perturbative quantities
  - there is no data in the low x region between 10^{-4} -10^{-6}
- In the limit of $q_T \ll Q$, DY probes transverse momentum distributions (TMDs)

→ determine PDFs and access TMDs using existing high quality dileptons measurements from ALICE, LHCb

Assessment of “early stage” radiation

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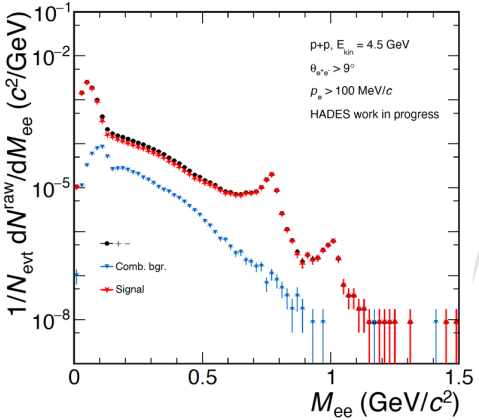
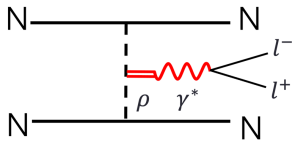


SIS100 $\sqrt{s_{NN}} = 2 - 5$ GeV

SPS $\sqrt{s_{NN}} = 6 - 17$ GeV

- Transition between perturbative and hadronic regimes
- No guidance from theory
- No measurements



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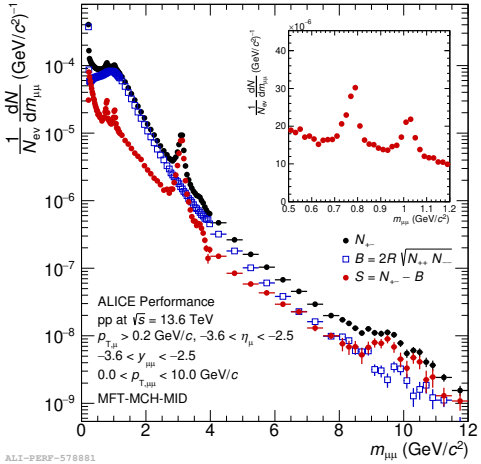

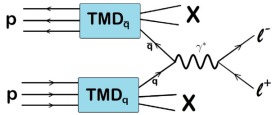

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PRODY
Precision Research on Origins of Drell-Yan:

On the theory side, we aim to:

(i) Push perturbation theory to its limits and identify the transition between perturbative and non-perturbative regimes;

(ii) Understand the nature of non-perturbative DY-like processes using dedicated non-perturbative methods;

(iii) Compute differential observables such as M_{ll}, p_T and polarization observables of DY and DY-like pairs across a wide energy range — from the LHC down to SPS and SIS energies.

On the experimental side, we will:

(iv) Develop advanced analysis techniques to isolate thermal radiation from non-equilibrium dilepton sources;

(v) Apply these techniques to existing datasets from HADES, ALICE, and LHCb;

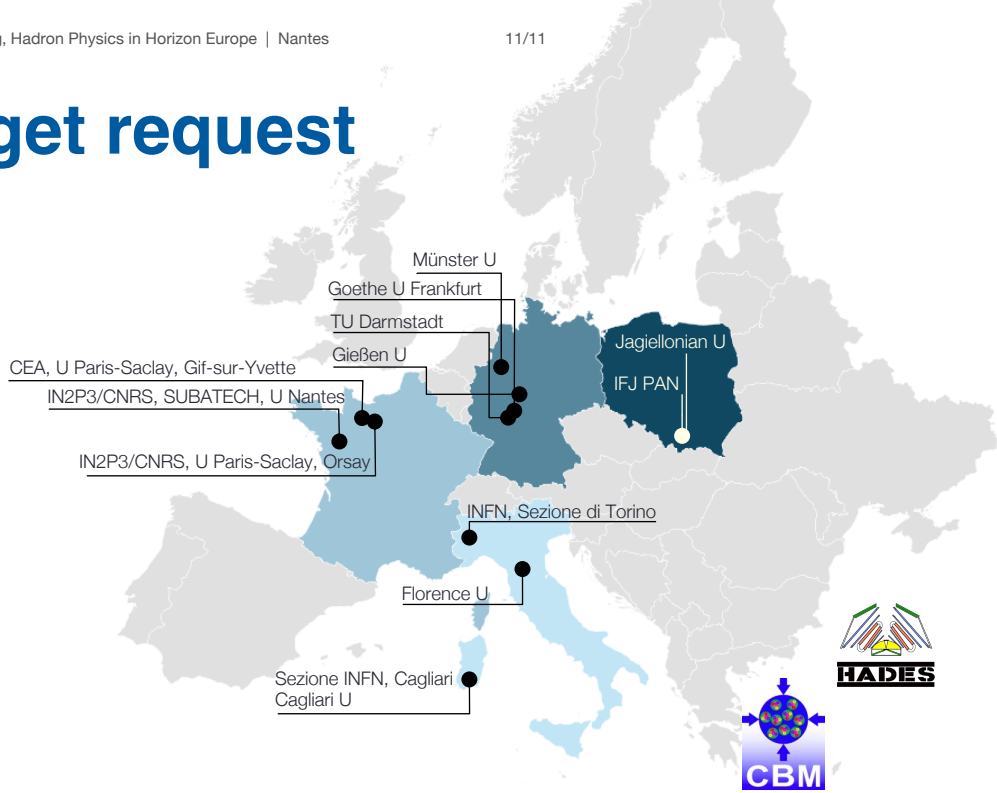
(vi) Conduct feasibility studies for upcoming experiments at CBM and DiCE/NA60+.

A particular emphasis will be placed on photon polarization observables, which offer additional sensitivity to the production mechanisms. All studies will be performed for both proton-proton (pp) and proton-nucleus (pA) collisions.

Spin-off study: **charm quark content of the proton.** Low-energy nuclear collisions, particularly through the study of open charm hadrons ($D/\bar{D}$) and charmonium states such as J/ψ, provide an optimal testing ground for intrinsic charm.

Network, estimated budget request

Category		Amount
Personnel	PhD (40k €/year) PhD (40k €/year) PhD (30k €/year) PhD (30k €/year)	120k € 120k € 90k € 90k €
Travel/ organisation	Workshops, conferenences	100k €
Total		**520k €**



ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

GSI

FAIR

CERN

INFN

Connection to TA and VA

DiCE/NA60+

ALICE

LHCb

AMBER
Apparatus for Meson and Baryon Experimental Research

Embedded within large-scale international collaborations

Thank you for your attention!

Project leaders: A. Andronic[1], H. Appelshäuser[2], R. Arnaldi[3], V. Bertone[4], G. Bozzi[5], U. D'Alesio[5], S. Diehl[6], **T. Galatyuk**[7,8], P. Gasik[7,8], S. Harabasz[9], M. Klasen[1], R. Maciula[10], L. Motyka[11], J. Otwinowski[10], P. Salabura[11], E. Scomparin[3], E. Speranza[12], J. Stroth[2,8], A. Szczurek[10], G. Usai[5], **M. Winn**[9]