LIMITS OF HADRONIC EXISTENCE

THE ROLE OF REFERENCE MEASUREMENT IN HEAVY-ION RESEARCH

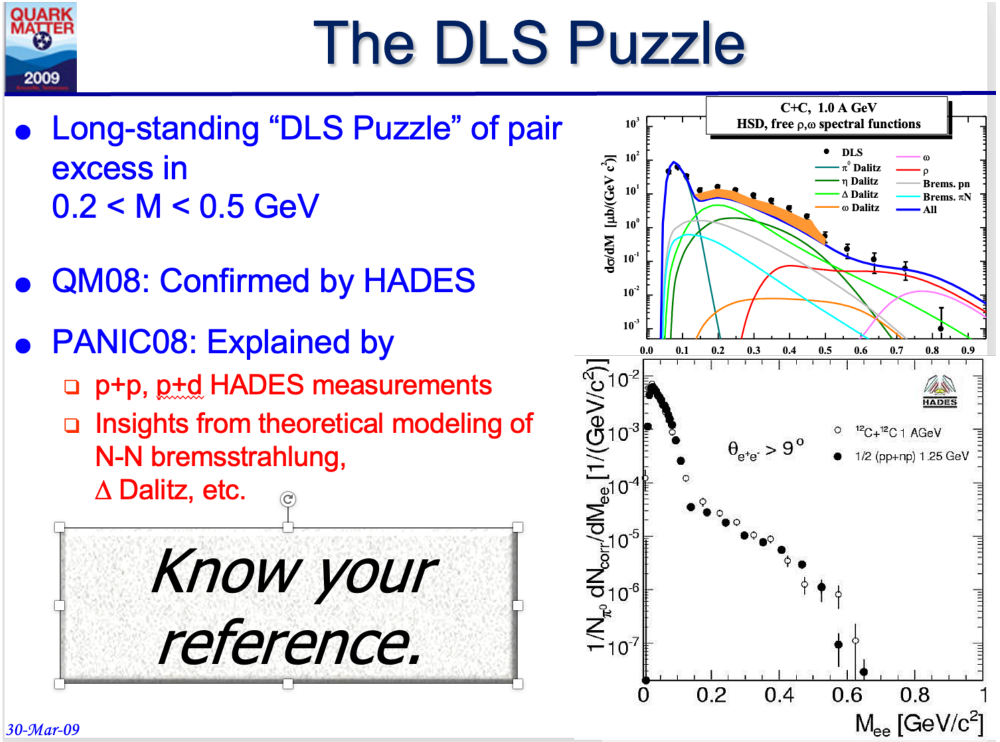
Joachim Stroth

QCD at FAIR

GSI Darmstadt

November 11–14, 2024

William (Bill) Zajc: QM 2009 in Stony Brook



Data

DLS: Phys.Rev.C 49 (1994) 314-319

DLS: Phys.Rev.Lett. 79 (1997) 1229-1232

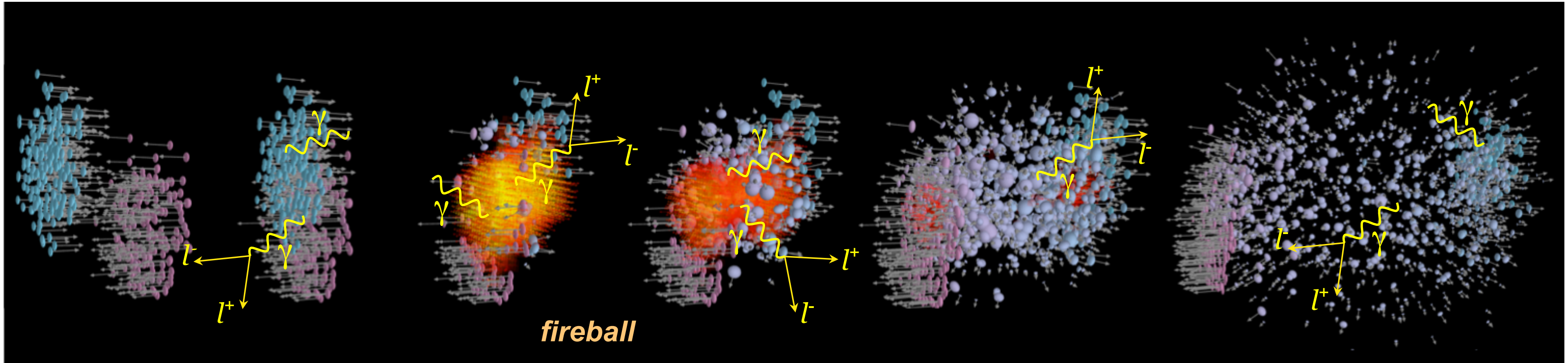
HADES: Phys.Lett.B 690 (2010) 118-122

Theory (bremsstrahlung)

Kaptari(Kämpfer:Phys.Rev.C 80 (2009) 064003

Mosel/Shyam: Phys.Rev.C 79 (2009) 035203

QCD matter under extreme conditions



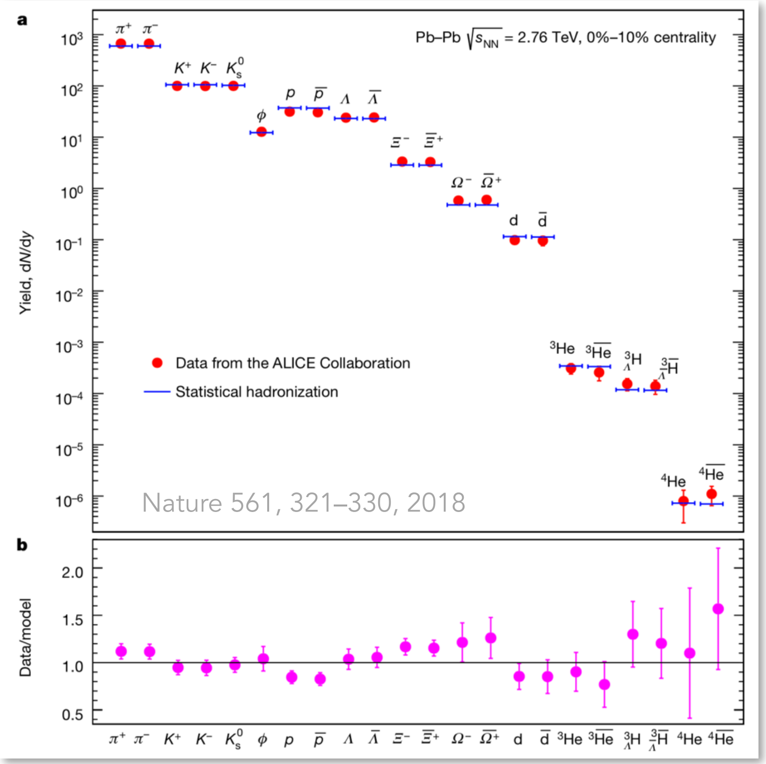
artwork by F. Seck, T. Galatyuk based on UrQMD

Enrico Fermi *[Prog. Theor. Physics 5, 570 (1950)]*

… a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space filled by the nucleons and their **surrounding pion field will suddenly be loaded with a very great amount of energy**. Since the interactions of the pion field are strong, we may expect this energy is rapidly **distributed among the various degrees of freedom** …

Freeze-out conditions from SIS18 to LHC

ALICE data

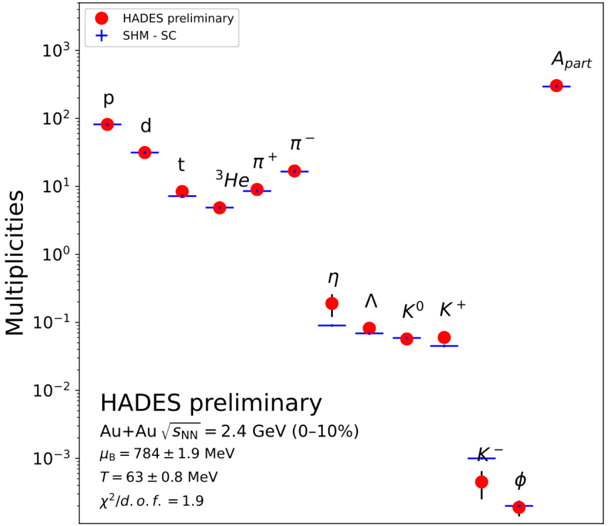


1 ppm

ALICE ($\sqrt{s}$ = 2.76 ATeV): T_{ch} = 156.5 (1.5) MeV; μ_B = 0.7 (3.8) MeV

HADES ($\sqrt{s}$ = 2.4 AGeV): T_{ch} = 63 (0.8) MeV; μ_B = 784 (1.9) MeV

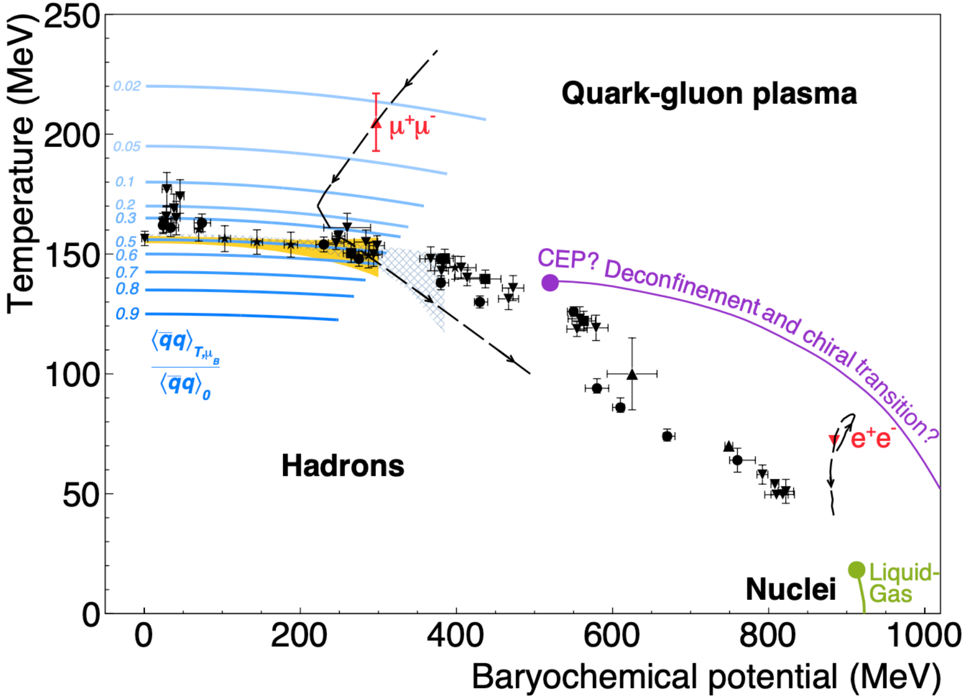
- Factor ~1000 in beam energy / factor ~2 in temperature
- Much different multiplicities for nuclear clusters



1 ppm

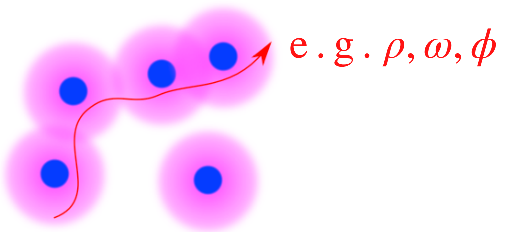
The QCD Phase Diagram

From medium-effects to novel phases of QCD matter



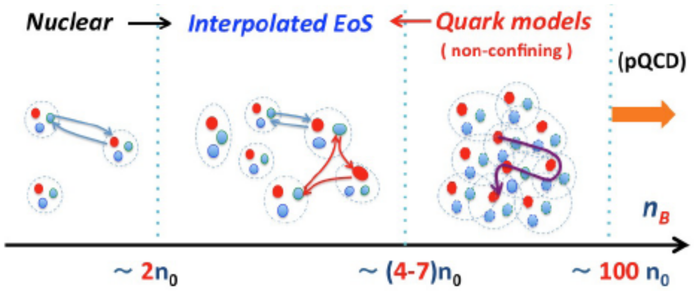
Soft deconfinement in overlapping pion clouds

K. Fukushima et al.: Phys.Rev.D 102 (2020) 9, 096017



"Quarks can be deconfined and still bound"

G. Baym, QNP2018



INITIAL STATE RADIATION
MESON-BARYON COUPLING
CHARM PRODUCTION AND PROPAGATION

INITIAL STATE RADIATION

Important for precise extraction of excess radiation

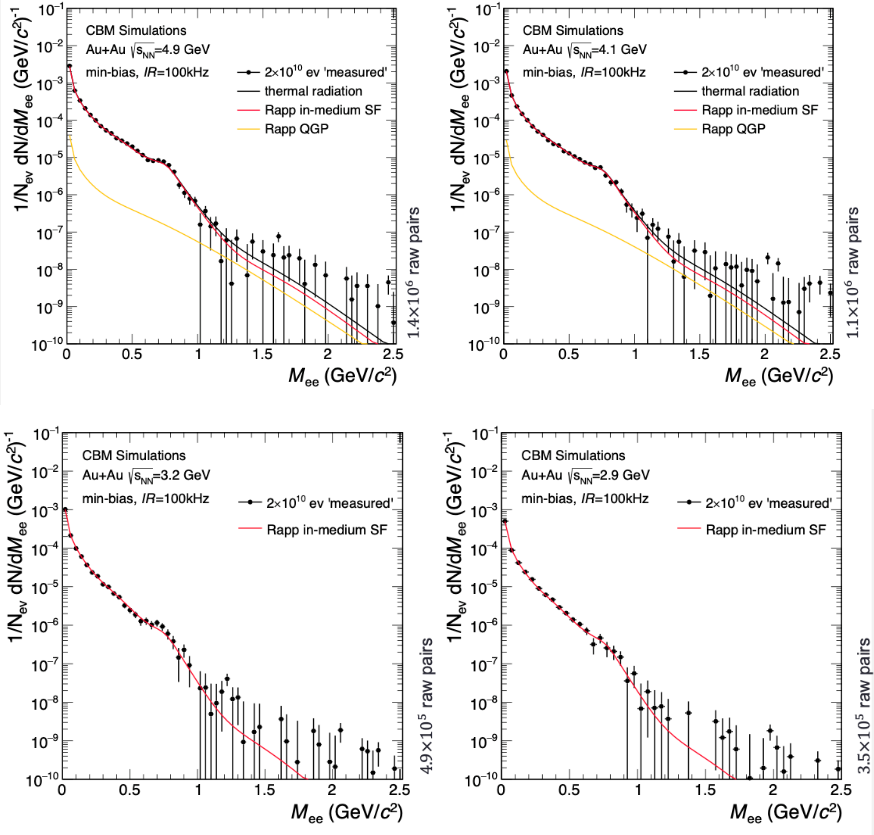
Dileptons as probe of the QCD matter

- Extraordinary probe for the microscopic structure of the matter making up the fireball
- Needs careful subtraction of pre-equilibrium and final state contribution

LMR/IMR yield:	Fireball four-volume integral
(LMR/)IMR slope:	Fireball mean temperature
dP/dM:	VM melting, chiral mixing
dP/d*α_{HX} *(polar.):	Production process, partonic vs. hadronic
dP/d*ϕ *(flow):	Emission time, pressure
v***LMR and low*** p_t***:***	Electrical conductivity of matter

➡ ***Precise reconstruction of medium (excess) radiation needed***

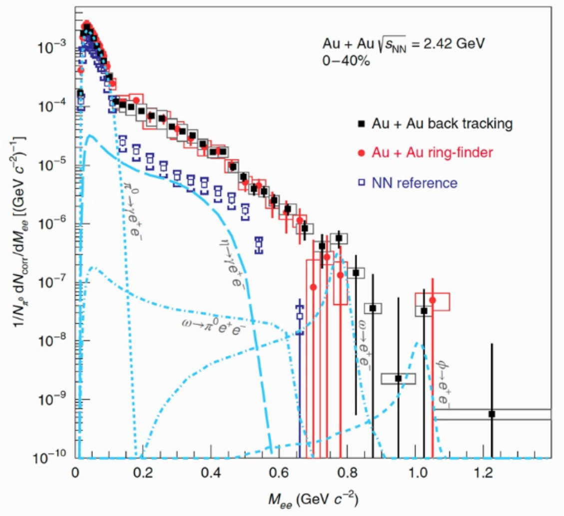
CBM simulation: Au+Au BES



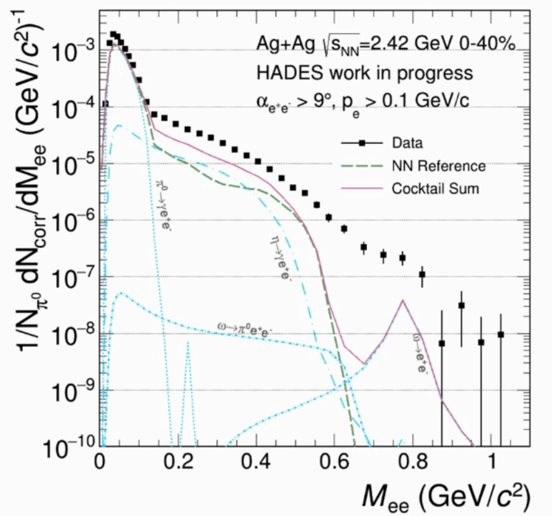
Dilepton spectra measured by HADES

- **Significant excess radiation** above contributions from initial state (from NN reference) and freeze-out (meson cocktail) visible
- Excess radiation drops by four orders of magnitude for inv. mass of 0.2 down to 1 GeV

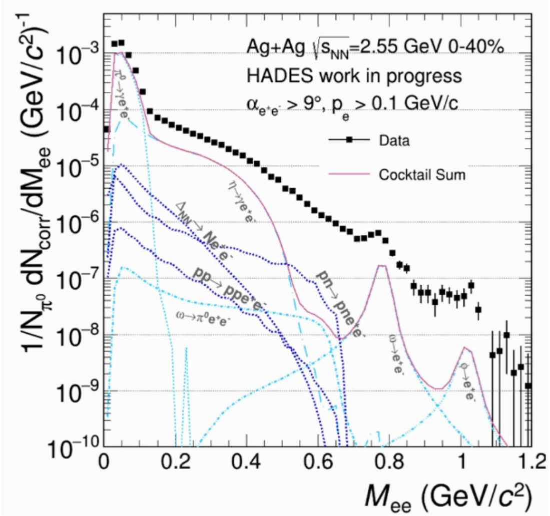
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag at $\sqrt{s_{NN}} = 2.42$ GeV

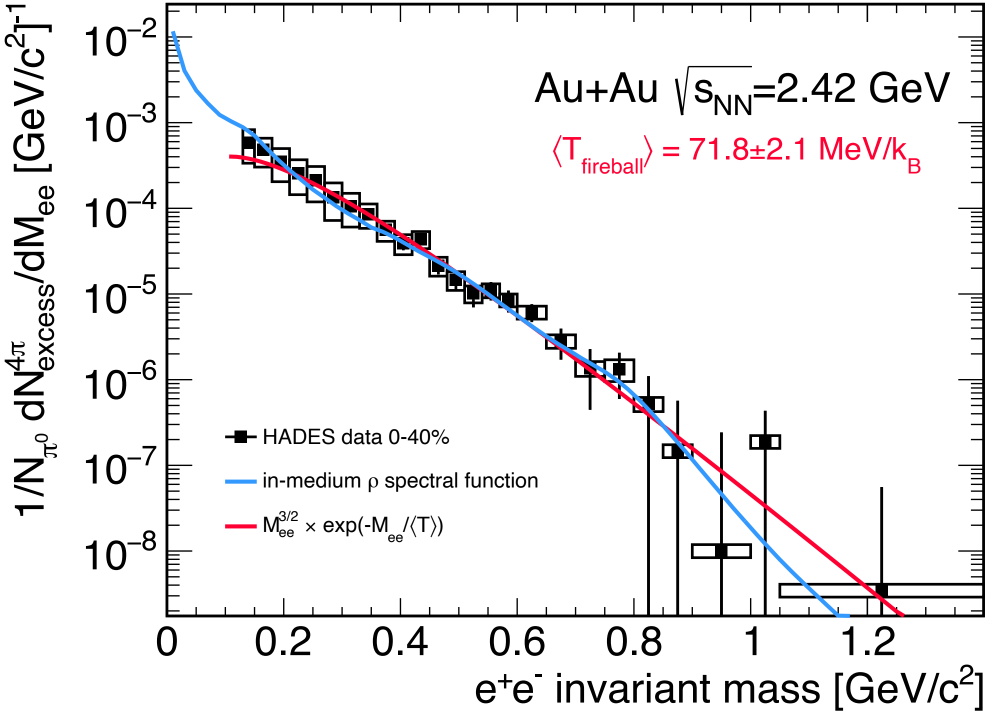


Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



HADES, Nature Phys. 2019

Thermal Dileptons from HADES Au + Au @ $\sqrt{s_{NN}} = 2.4\,\mathrm{GeV}$



HADES, Nature Phys. 2019

- Coarse-grained UrQMD(3)
  - thermal emissivity with(1)
  - in-medium propagator (4)
  - $\rho - a_1$ chiral mixing(5) (not measured so far)
- Planck radiation (two parameters only)

➡ ***Strong modification of ρ meson***

(1) Rapp, van Hees; arXiv:1411.4612v
(4) Rapp, Wambach, van Hees; arXiv:0901.3289
(5) Rapp, Hohler; arXiv:1311.2921v

MESON-BARYON COUPLING

Controls the thermal emissivity in hadronic environment

Vector-meson dominance in hot & dense matter

Generalized „Bremsstrahlung" – Fourier transform of current-current correlation function $\langle j(x), j(0)\rangle$:

$$\Pi^{\mu\nu}_{EM}(q) = \int d^4x e^{iqx}\,\Theta(x_0)\langle[j^{\mu}_{EM}(x), j^{\nu}_{EM}(0)]\rangle_T$$

L. McLerran, K. Toimela, Phys. Rev. D31 (1985)
See also: Ralf Rapp arXiv-1110-4345

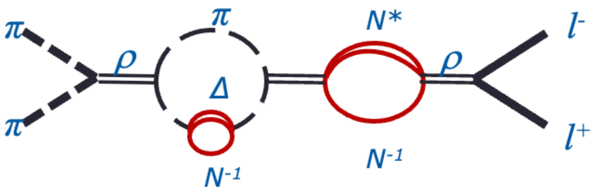
Extension of the Gounaris-Sakurai formula to a thermal pion gas: *C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65*

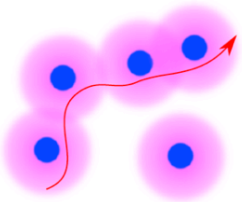
$$j^{\mu}_{EM} = \tfrac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \tfrac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \tfrac{1}{3}\bar{s}\gamma^{\mu}s \;\Longrightarrow\; \mathrm{Im}\Pi_{EM} \sim \mathrm{Im\,D}_{\rho} + \tfrac{1}{9}\mathrm{Im\,D}_{\omega} + \tfrac{2}{9}\mathrm{Im\,D}_{\phi}$$

Hadronic current can be approximated by the imaginary part of the in-medium ρ propagator.
Inclusion of meson-baryon coupling, ρ only:

$$\mathrm{Im}\Pi_{EM}(M) = \left(\frac{m_{\rho}^2}{g_{\rho}}\right)^2 \mathrm{Im}D_{\rho}(M) \qquad D_{\rho}(M, q; \mu_B, T) = \frac{1}{(M^2 - m_{\rho}^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B})}$$

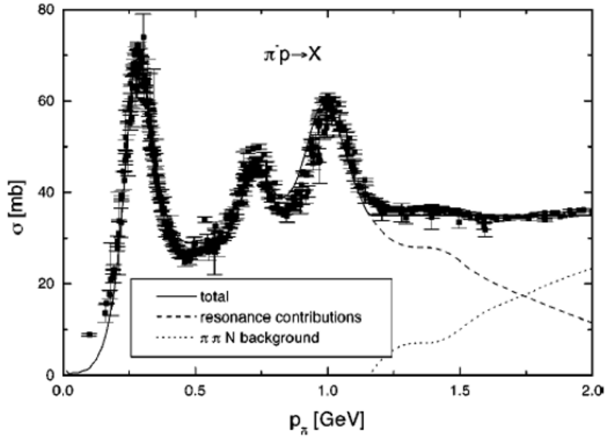
R. Rapp, J. Wambach: Adv.Nucl.Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496
M. Asakawa, C-M. Ko et al., PRC 46 (1992) R1159

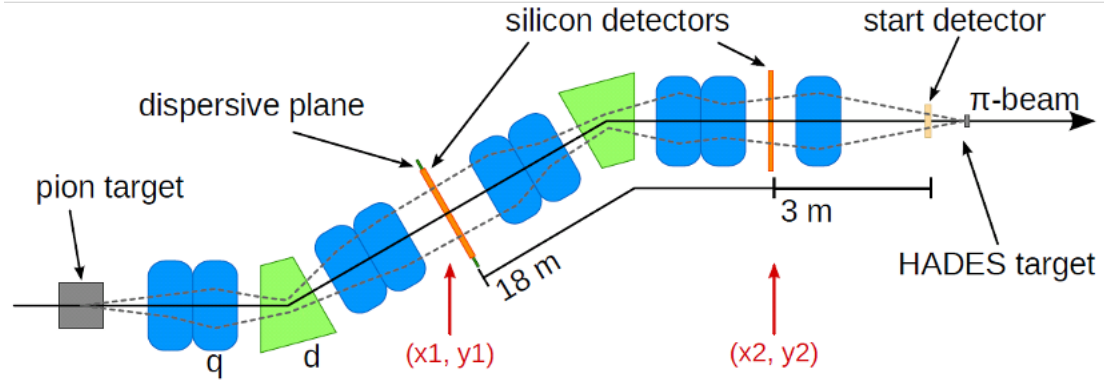


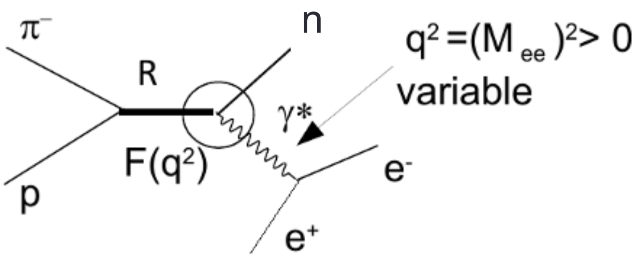


The HADES pion beam facility

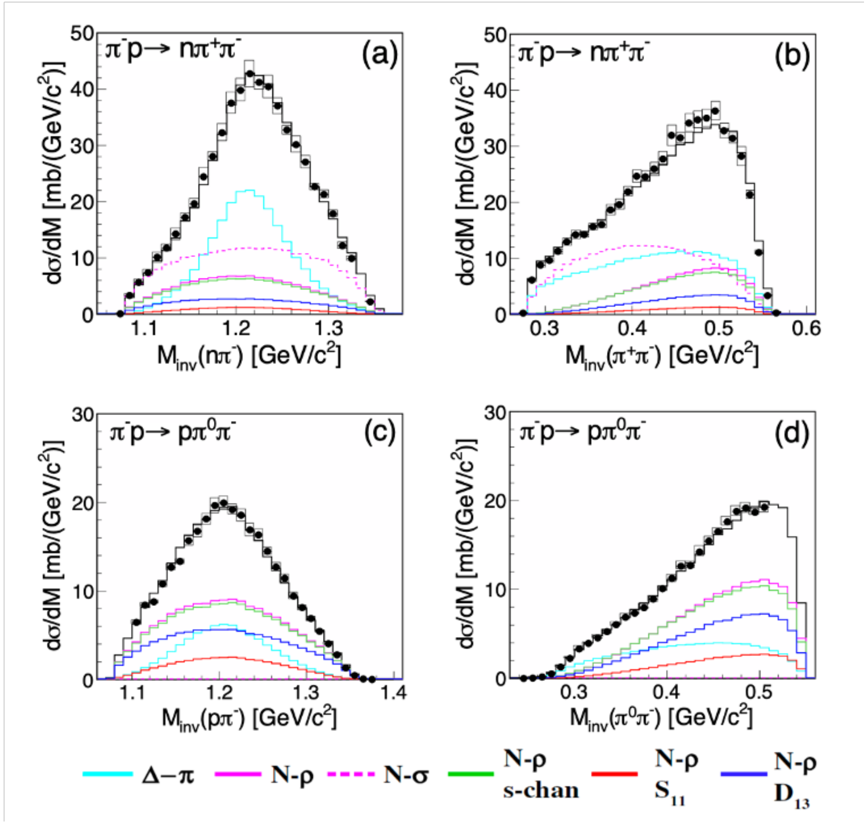
- Pion production target 40 m upstream the experiment target position
- Direct **excitation of baryon resonance** and exclusive reconstruction of final states
- Combination with dilepton spectrometer **world-wide unique**







Extraction of partial waves from two-pion channel

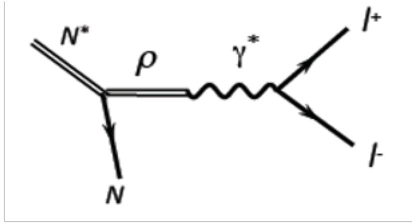


- $p_\pi = [0.66, 0.69, 0.75, 0.8]$ GeV
- $\pi^- + p \to \pi^- + \pi^+ + n$
  - Hadronic final states used in PWA (Bonn/Gatchina code)
  - Use invariant masses, and angular distribution (not shown here)
- $\pi^- + p \to e^- + e^+ + n$
  - Prediction for dilepton invariant mass assuming strict VMD
  - Comparison to two-component model by Pena & Ramalho
-

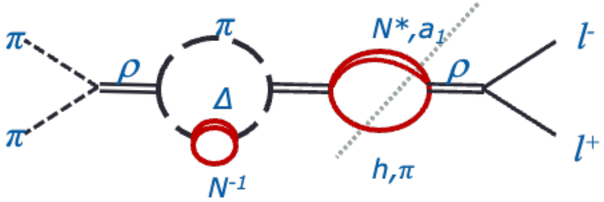
HADES arXiv:2309.13357; arXiv:2205.15914; Phys. Rev. C 102 (2020) 2, 024001

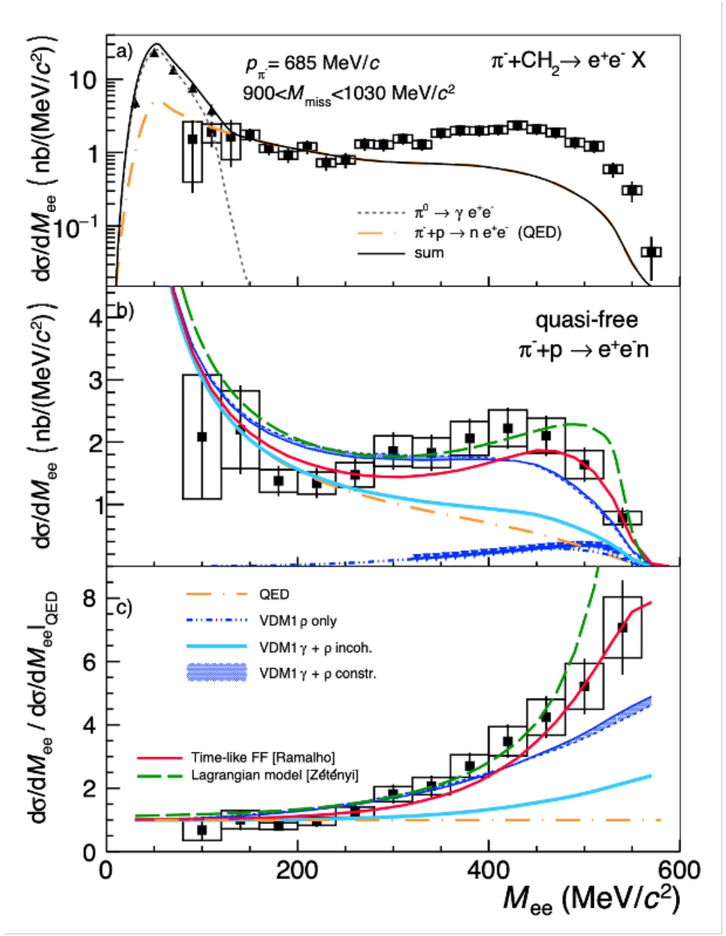
$\pi^- + p \rightarrow e^- + e^+ + n$

Resonance-Dalitz decay (a la VMD) …



… is analogous to baryonic contribution to in-medium ρ self-energy (**emissivity**)



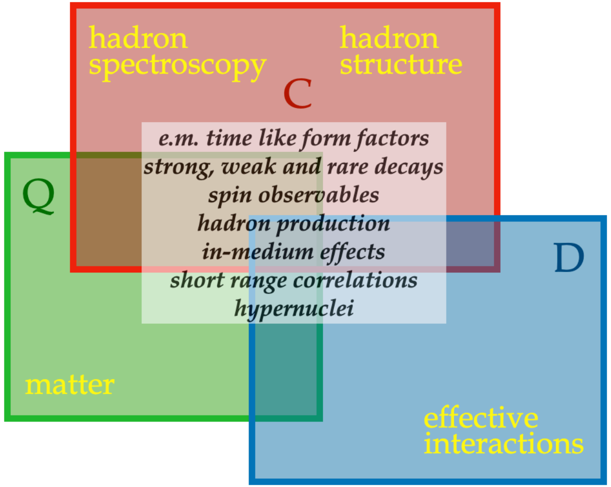


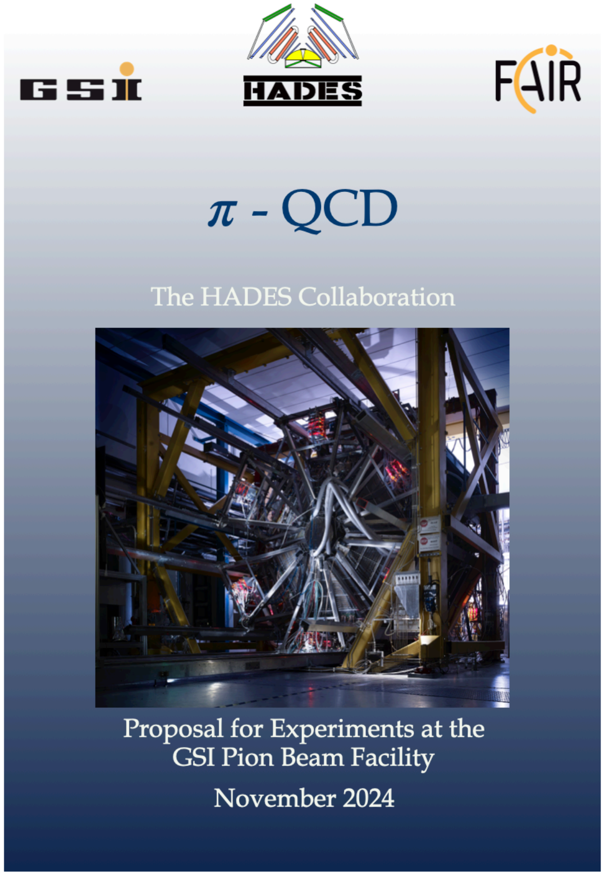
HADES arXiv:2309.13357; arXiv:2205.15914; Phys. Rev. C 102 (2020) 2, 024001

The HADES Proposal for 2026 – 2028

"Boosting the understanding of non-perturbative QCD
by combining pion beams with HADES
and involving three pillars"

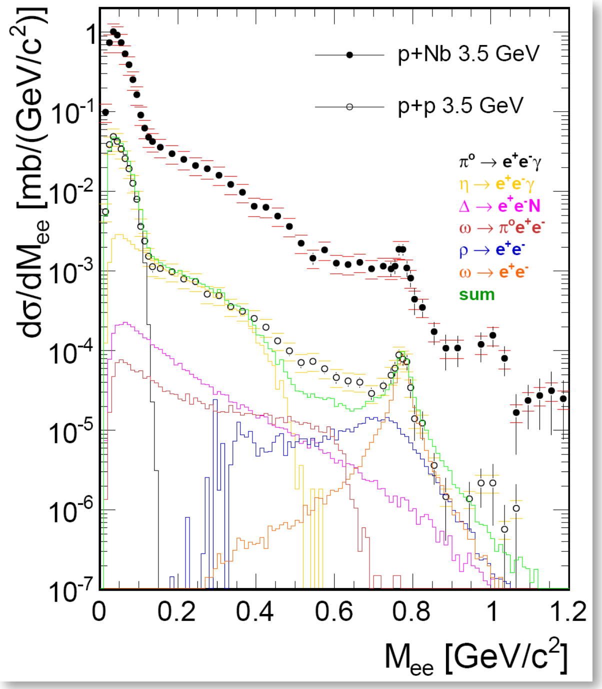
π - QCD



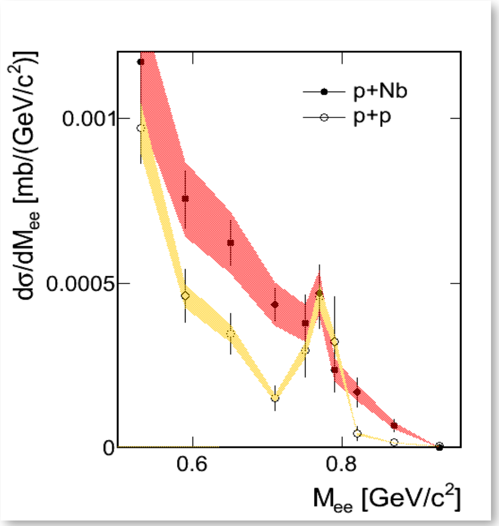


Vector mesons in cold matter

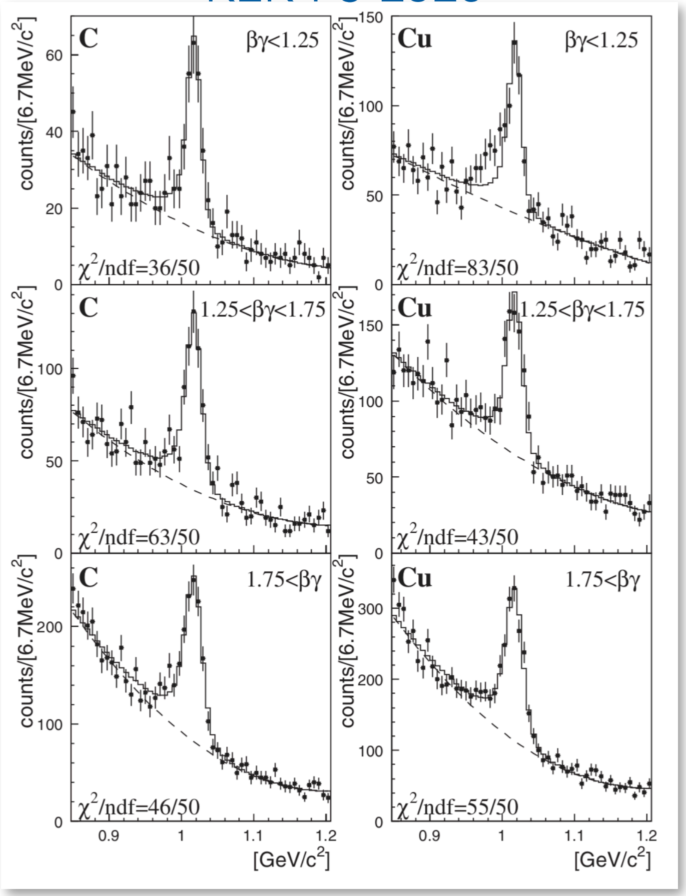
- Ideal probe to monitor medium modifications
- Low relative momentum to medium needed to increase sensitivity



HADES



KEK-PS E325



HADES, Phys.Lett.B 715 (2012)

KEK-PS E325, Phys.Rev.L. 98, 042501

CHARM PRODUCTION AND PROPAGATION

Preparing grounds for using charm as probe of compressed baryonic matter

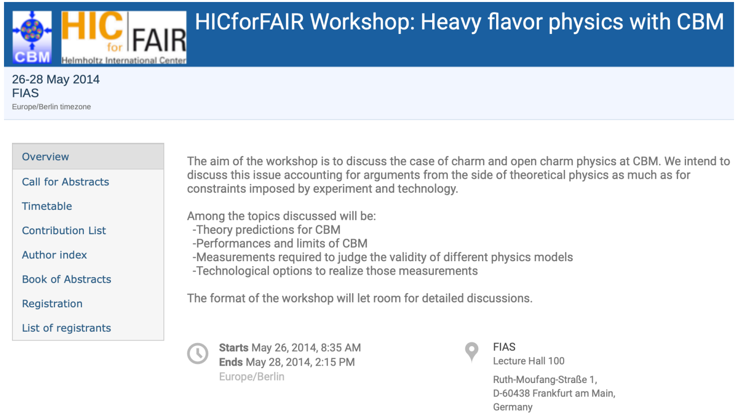
Measurement of J/Ψ via dilepton decay

CBM can provide unique opportunity for pioneering studies of

- charm production
- charmonium formation

in normal (and compressed) nuclear matter

In all cases, need p-p as reference, and all reactions should be studied at the same collision energy


HICforFAIR Workshop: Heavy flavor physics with CBM

26-28 May 2014
FIAS
Europe/Berlin timezone

Overview
Call for Abstracts
Timetable
Contribution List
Author index
Book of Abstracts
Registration
List of registrants

The aim of the workshop is to discuss the case of charm and open charm physics at CBM. We intend to discuss this issue accounting for arguments from the side of theoretical physics as much as for constraints imposed by experiment and technology.

Among the topics discussed will be:
-Theory predictions for CBM
-Performances and limits of CBM
-Measurements required to judge the validity of different physics models
-Technological options to realize those measurements

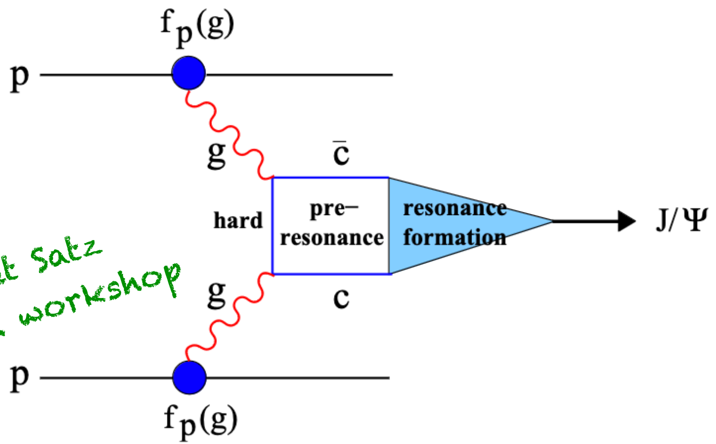
The format of the workshop will let room for detailed discussions.

Starts May 26, 2014, 8:35 AM
Ends May 28, 2014, 2:15 PM
Europe/Berlin

FIAS
Lecture Hall 100
Ruth-Moufang-Straße 1,
D-60438 Frankfurt am Main,
Germany

time evolution of J/ψ formation

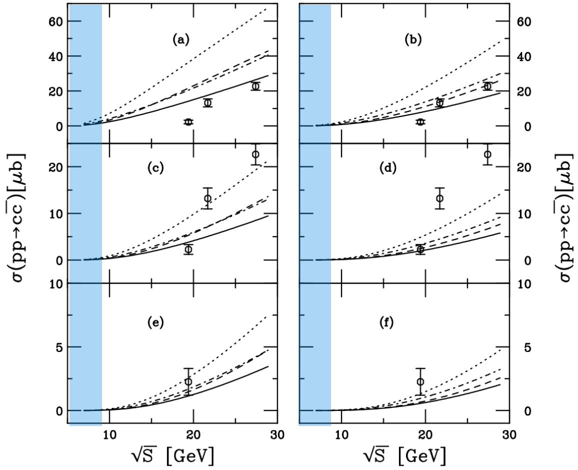
hard	0.05 fm	pre–resonance	0.25 fm	resonance
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c \Lambda_{qcd}}$	

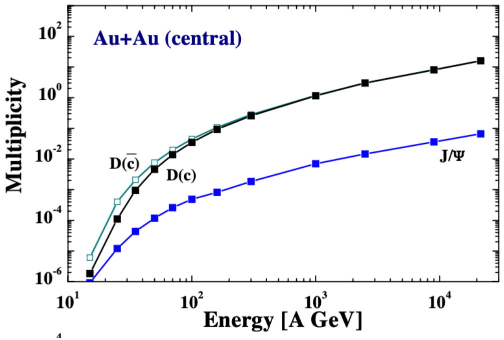


Conclusion Helmut Satz
2014 HICforFAIR workshop

Production cross section of (open) charm near threshold

- Unclear production mechanism in the non-perturbative regime. Perturbative treatment factories hard (perturbative) and soft (universal/non-perturbative) parton distributions.
- Problems below $\sqrt{s} = 20\,\mathrm{GeV}$ →use Sudakov resummation
  [R. Bonciani, et al. Nucl. Phys. B 529, 424 (1998)]
- Sparse data and large variations due to generally low statistics at “low” energies: “Uncertainties in the cross sections remain large even at NNLO-NNLL”
  [N. Kidonakis et al. Phys.Rev.D 67 (2003) 074037]
- Production modelled in transport via extrapolations of parameterization fitted to PYTHIA, see e.g. (P)HSD:
  [W. Cassing et al. Nucl.Phys.A 691 (2001) 753-77]





The CBM physics book. Lecture Notes in Physics Vol. 814. Springer

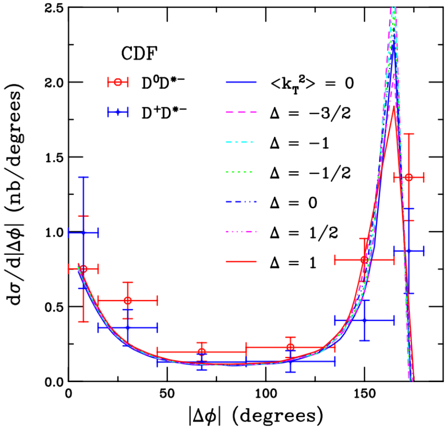
Charm correlation measurements

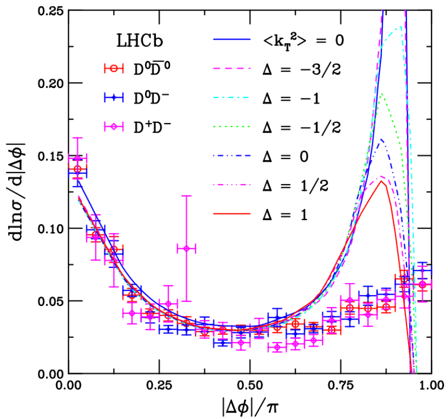
Correlated heavy quark ($\bar{Q}Q$) production. Use exclusive NLO codes to avoid problems due to improper interference treatment.

R. Vogt; Phys.Rev.C 98 (2018) 3, 034907

- $\bar{Q}Q$ produced strictly back-to-back in LO
- **Where are the limits of perturbative calculations?**

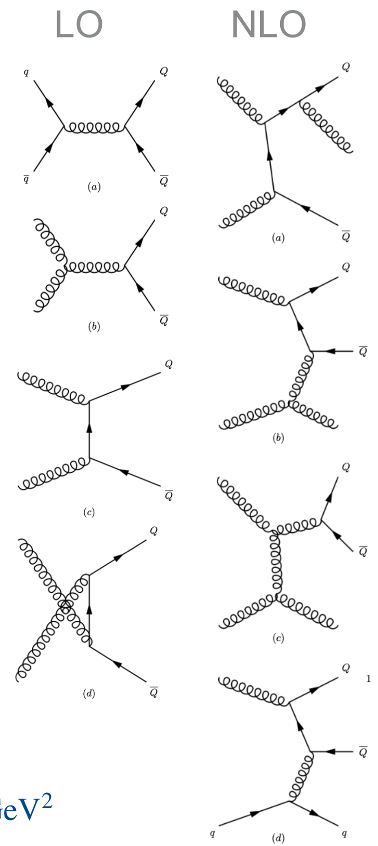
➡ Charm correlations in pp in energy scan → Modifications in cold matter (pA)





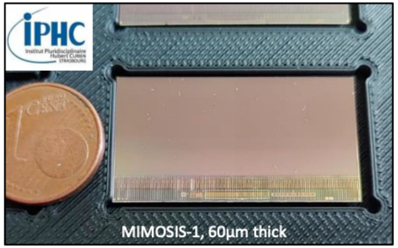
Transverse momentum broadening:

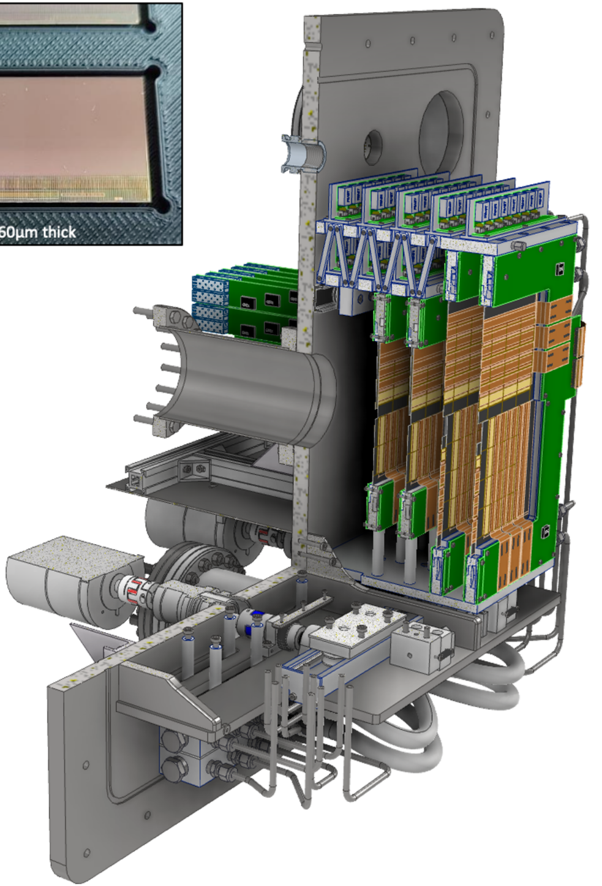
$$\langle k_T^2 = \rangle\, 1 + \frac{\Delta}{n}\left(\frac{\sqrt{s}}{20\,\mathrm{GeV}}\right)\mathrm{GeV}^2$$



Micro Vertex Detector

Enables open-charm measurements with CBM





- Four stations of MIMOSIS (CMOS) sensors with 100% fill factor positioned close to the target
- Enhanced track reconstruction efficiency for tracks with low-momentum and factor ten improved vertex resolution over STS alone.
- Operation in vacuum and in a one-Tesla magnetic field.
- Liquid cooled down to -20°C (if needed), 70 W heat extracted laterally
- Material budget of 0.2 – 0.5 % X_o /station
- 288 sensors, 148 M pixel, 200 kfps, 5 µm precision

IPHC Strasbourg, IKF Goethe University Frankfurt, GSI

CAD; F. Matejzek, Goethe University Frankfurt

SUMMARY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The heavy-ion program requires reference measurements

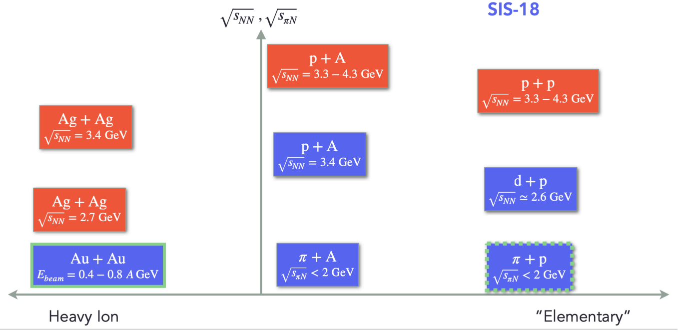
The partly stand for their own by contributing to understanding the structure of hadrons

- Beam energy scans for hadron and dilepton production off protons and nuclei
- Dedicated program at SIS18 with pion beams
- Cold matter studies of vector meson propagation (and short range correlations)
- Charm production and propagation near threshold

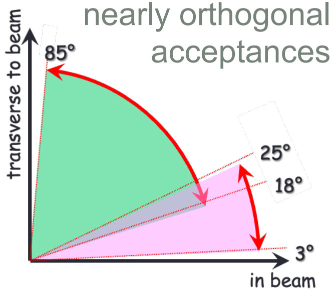
CBM runs first 3 years / Heuer commission)

Year	Setup	Reaction	Beam Energies T_{lab} [AGeV]	Days on Target	Number of events	Remarks
0	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10,max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{10}$ each	EB minBias
1	ELEHAD	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{10}$ each	minBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{11}$ each	minBias
2	MUON	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{11}$ each	minBias
2	MUON	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{11}$ each	minBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{12}$ each	minBias
3	HADR	Au+Au	2,4,6,8,10,max	12 (2 each)	$4\cdot10^{11}$ each	EB + Selector(s)
3	HADR	C+C	2,4,6,8,10,max	6 (1 each)	$8\cdot10^{11}$ each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	$2\cdot10^{10}$ each	minBias

HADES runs to come



HADES and CBM have nearly orthogonal acceptances



THANK YOU