

“QCD at FAIR” – A Hadron Physics driven campaign towards FAIR completion

15^h Intern. Workshop on the Physics of Excited Nucleons,
NSTAR 2026, Sevilla, Spain, September 7–11th, 2026

Frank Nerling

HFHF, GU Frankfurt & GSI Darmstadt

on behalf of



“QCD at FAIR” – White Paper: “Hadron Physics Opportunities at FAIR”

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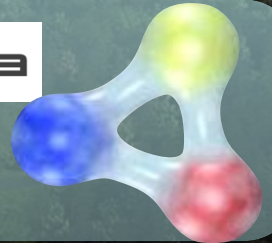
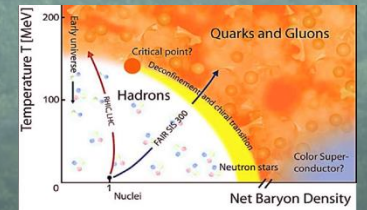
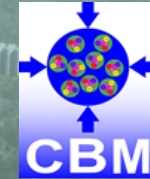
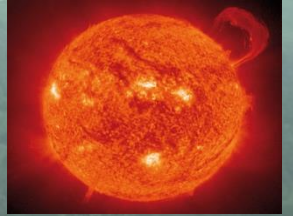
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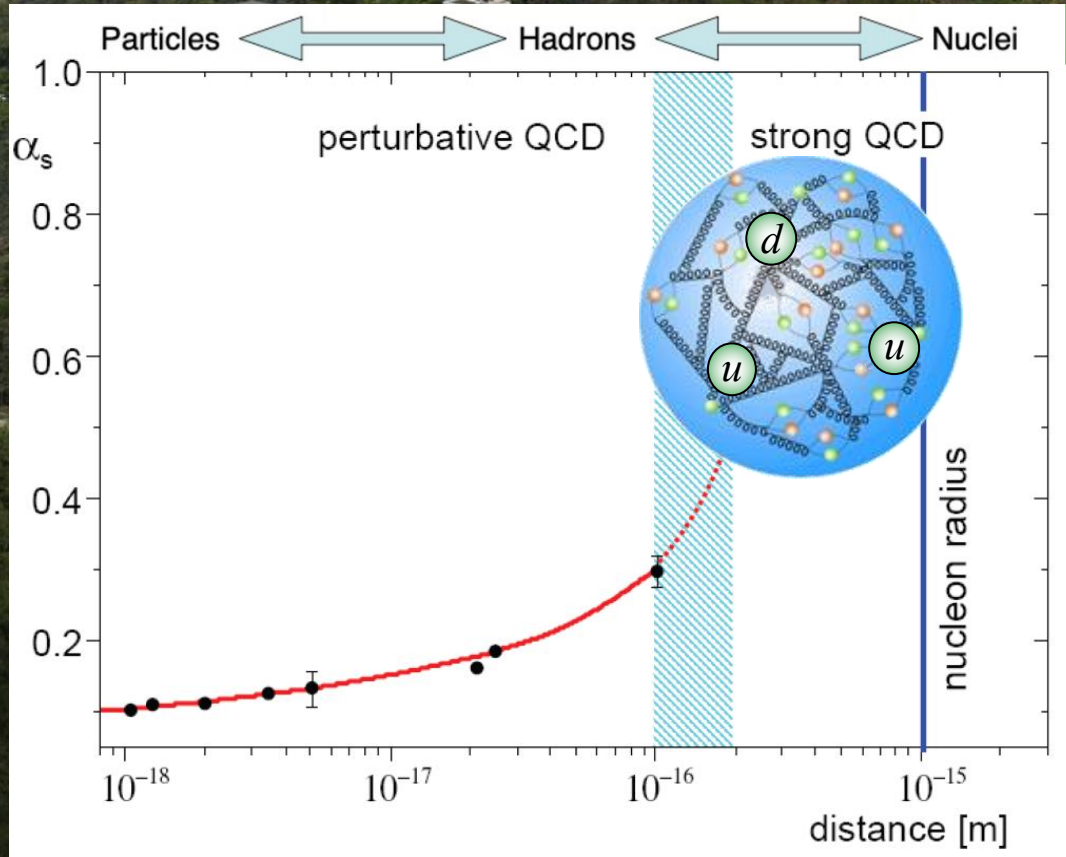




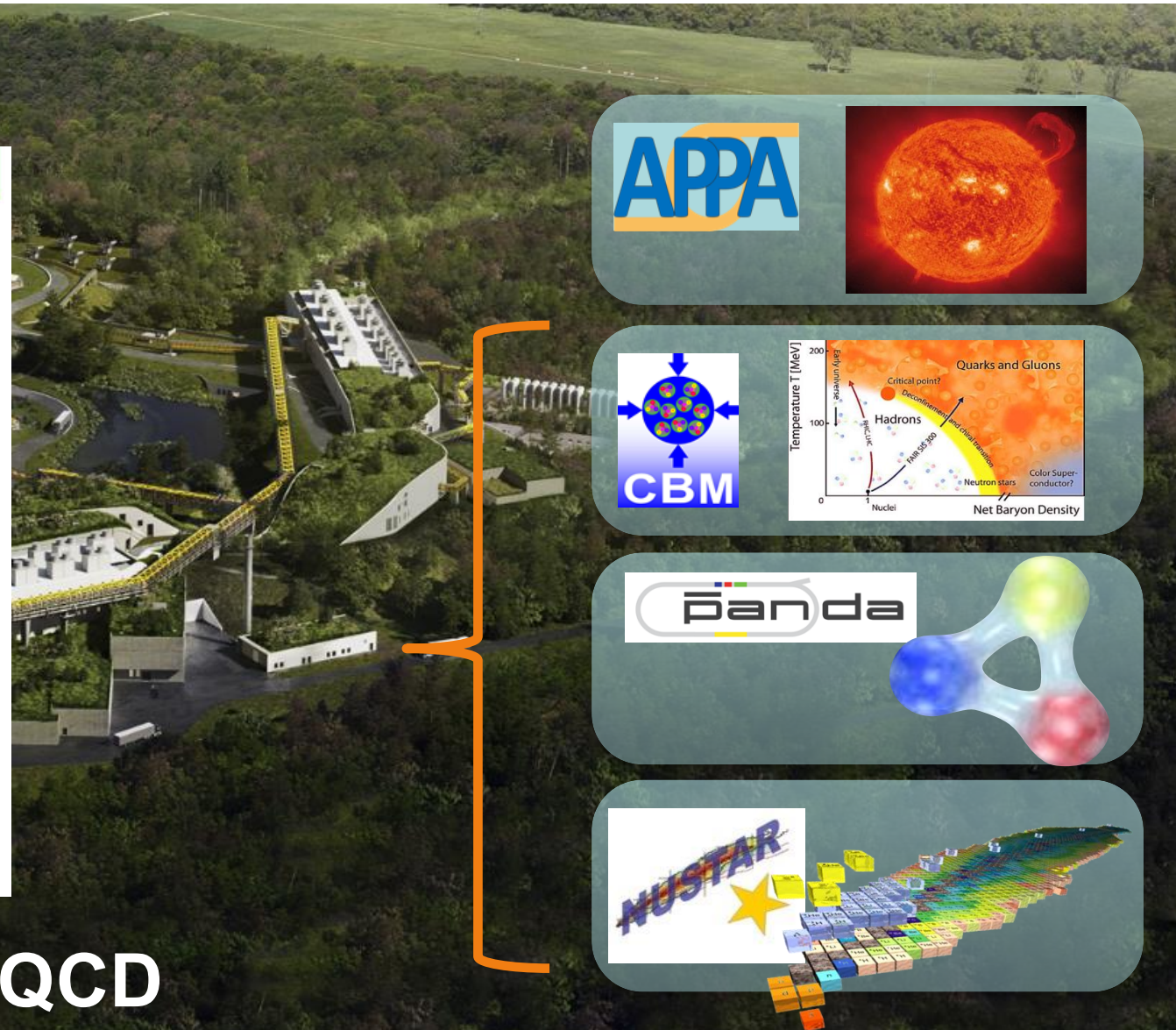
FAIR – The Facility to study QCD

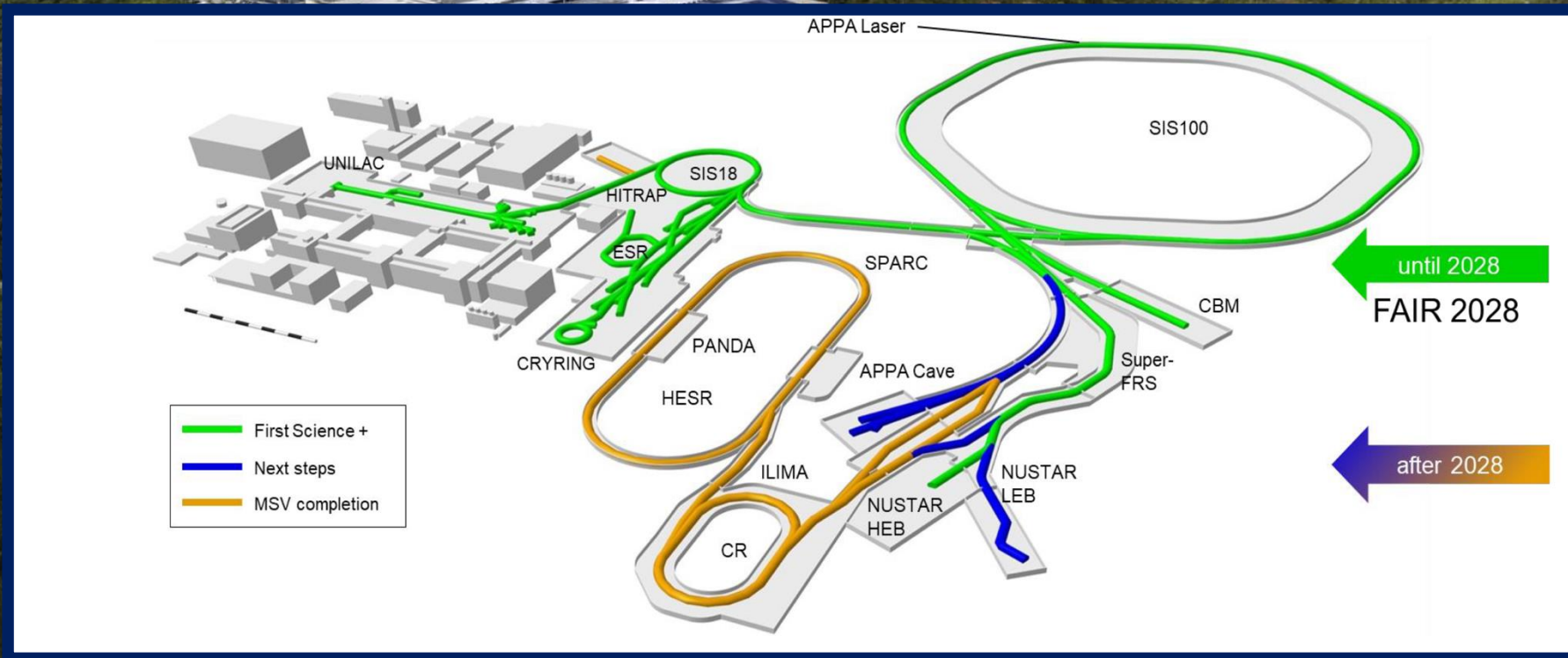


FAIR – The Facility to study QCD

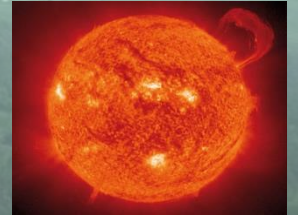


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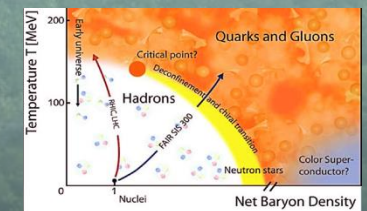




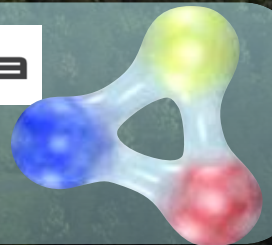
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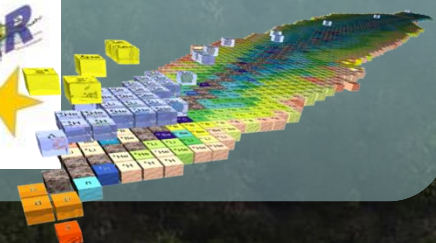
CBM



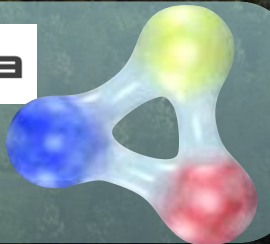
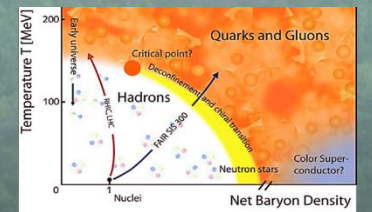
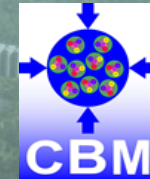
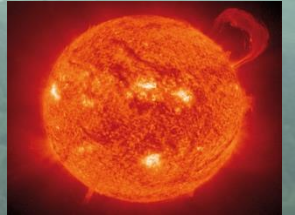
panda



NUSTAR



FAIR – The Facility to study QCD

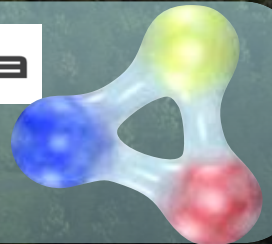
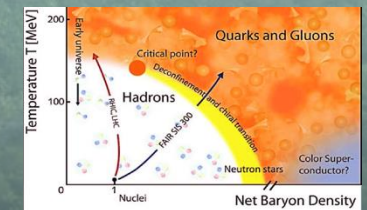
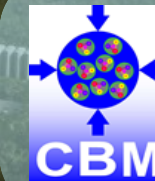
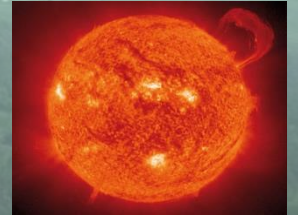


Hadron Physics Facilities at FAIR



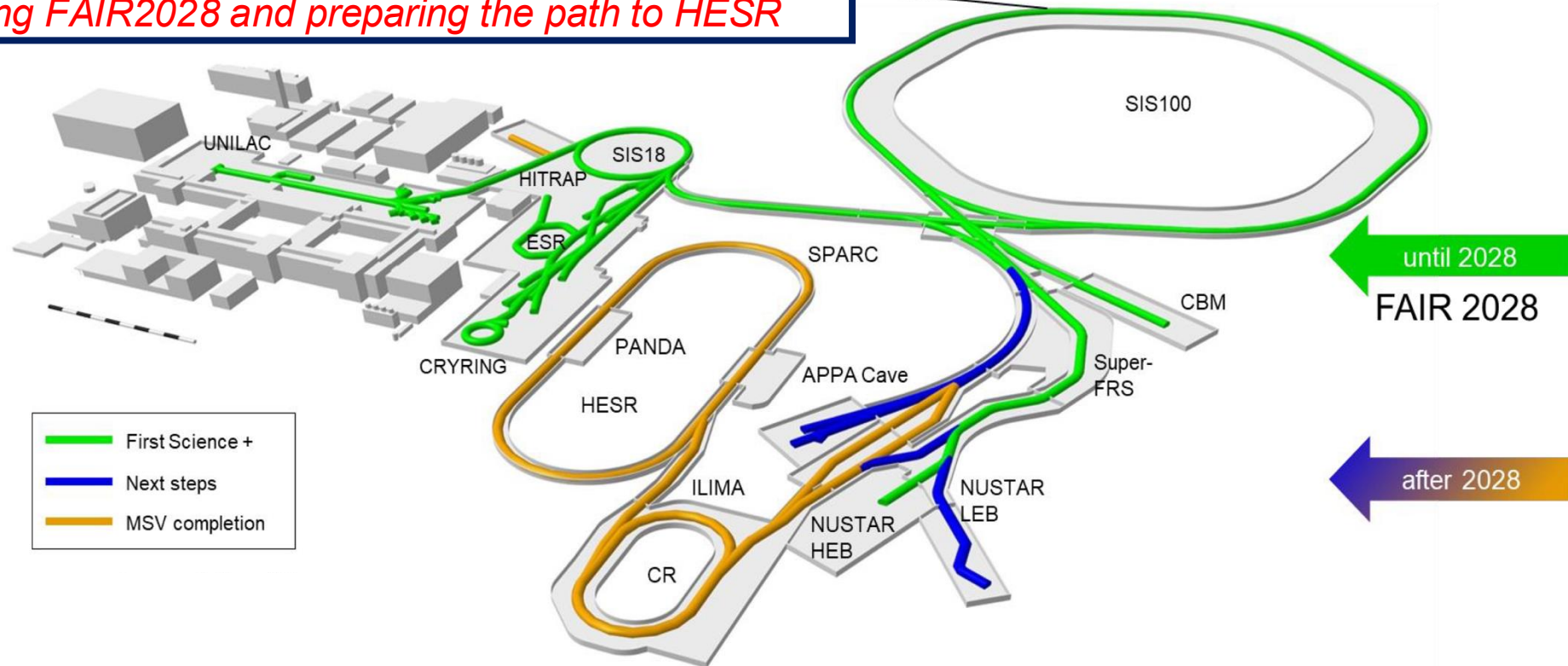
Overcome and bridge delay:

→ Cross-community strong QCD- driven
Hadron Physics program at GSI/FAIR



Hadron Physics Facilities at FAIR

Maximise FAIR potential for Hadron Physics
→ *Enriching FAIR2028 and preparing the path to HESR*



FAIR – The Facility to study QCD



Hadron Physics Facilities at FAIR

HADES

Today

$\pi, p, d \dots$



WASA

SIS18

→ e.g. η/η' physics & hypernuclei

FRS



Hadron Physics Facilities at FAIR

HADES

Today

$\pi, p, d \dots$

SIS18

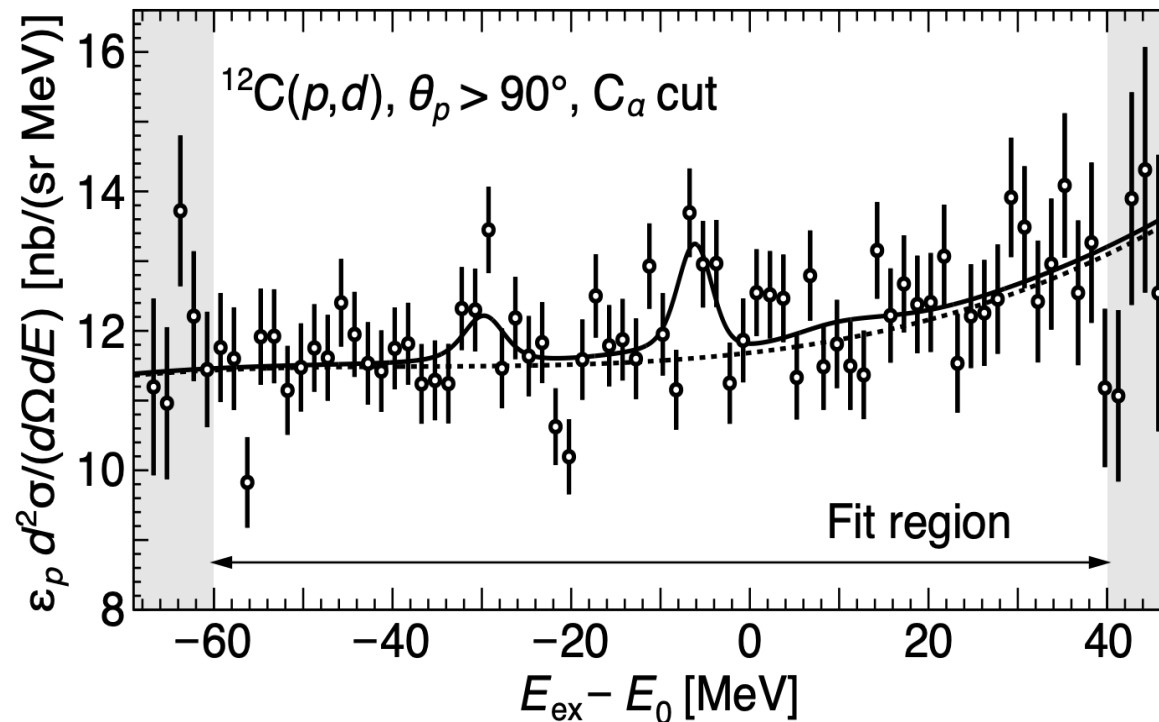
→ e.g. η/η' physics & hypernuclei

WASA FRS



NEW! $\eta' - {}^{11}\text{C}$ nuclei?

[PRL 136 (2026) 142501]



Hadron Physics Facilities at FAIR

→ cf. Talk by Kenta Itahashi

HADES

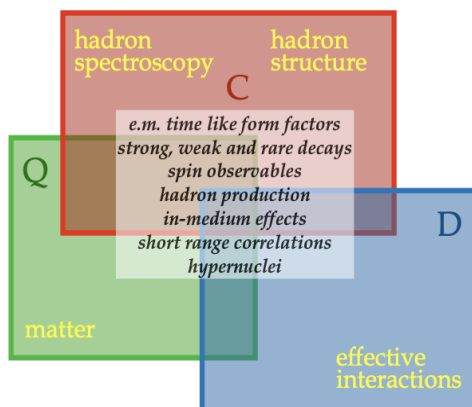
Today

$\pi, p, d \dots$

SIS18

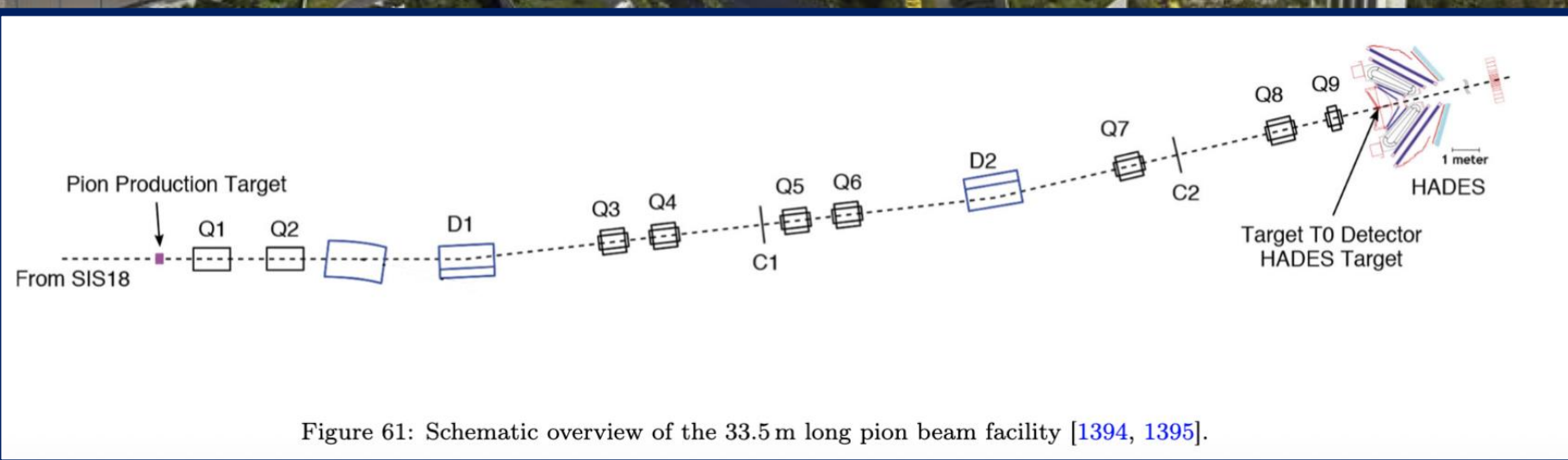
WASA FRS

π - QCD



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

→ Supplement material for GPAC (beam-time proposals)



Hadron Physics Facilities at FAIR

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$\pi, p, d \dots$



WASA

SIS18

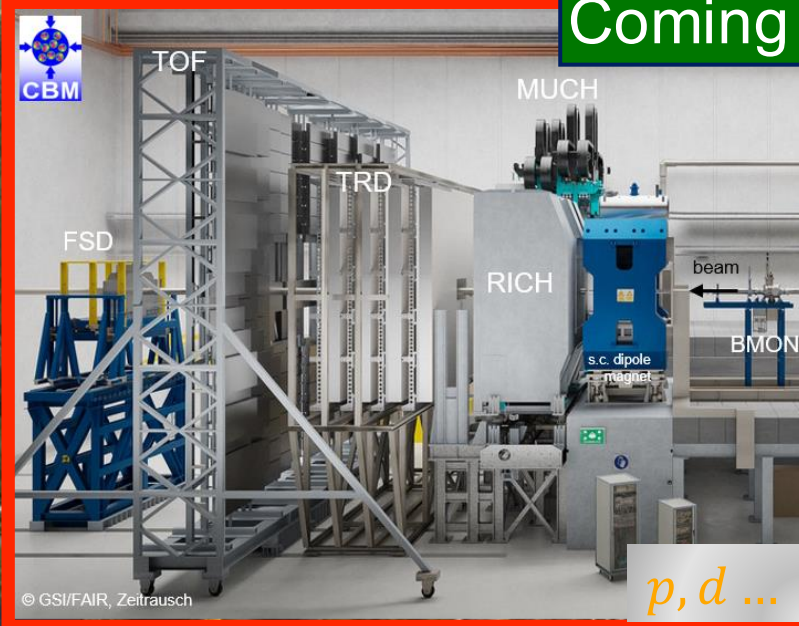
FRS

CBM
SIS100



© GSI/FAIR, Zeitrausch

Coming soon



$p, d \dots$

Hadron Physics Facilities at FAIR

HADES

Today

$\pi, p, d \dots$

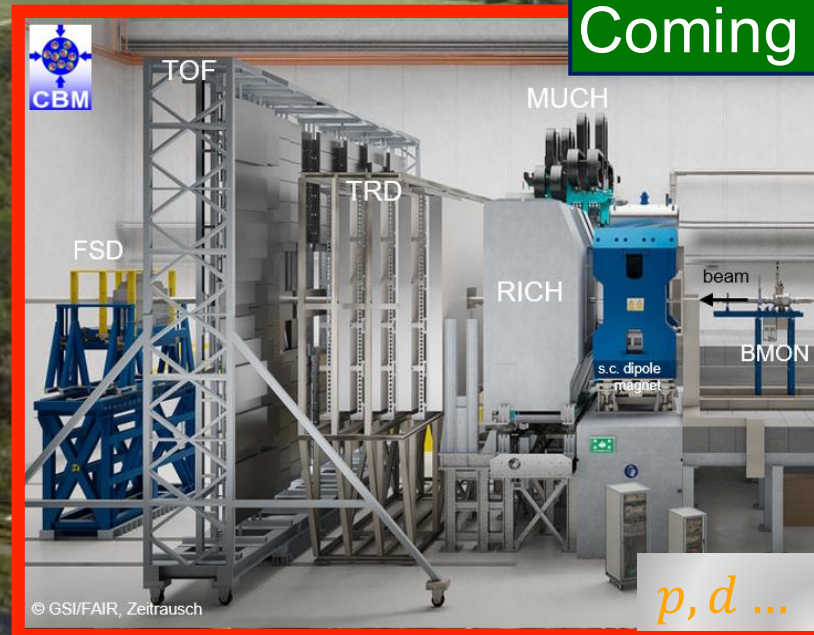


WASA

SIS18

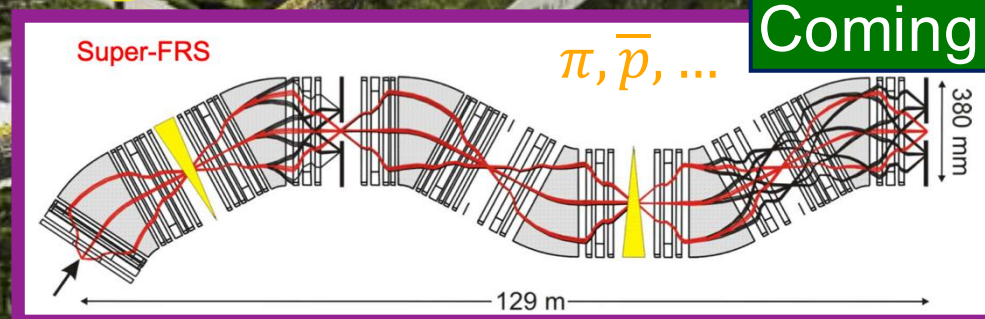
FRS

CBM
SIS100



Coming soon

$p, d \dots$



Coming soon

e.g. ASuCA at Super-FRS

Hadron Physics Facilities at FAIR

HADES

Today

$\pi, p, d \dots$

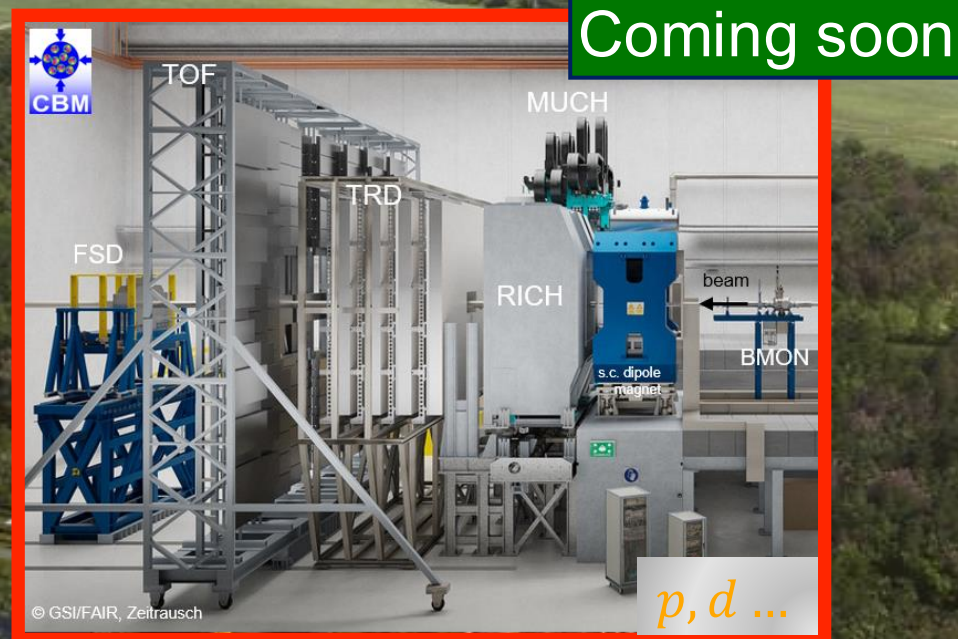


WASA

SIS18

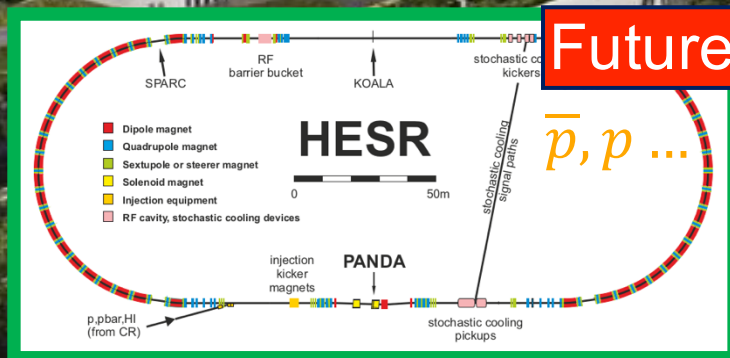
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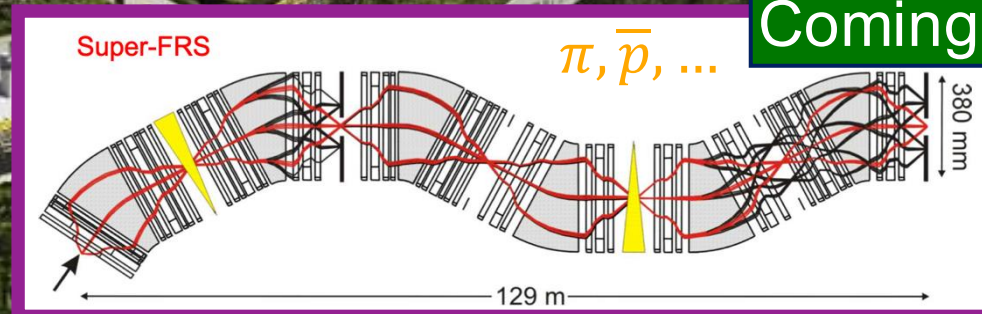
Coming soon

$p, d \dots$



Future

$\bar{p}, p \dots$



Coming soon

(Anti-) proton experiments at
HESR

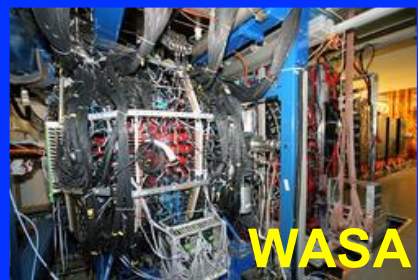
e.g. ASuCA at Super-FRS

Hadron Physics Facilities at FAIR

HADES

Today

$\pi, p, d \dots$



WASA

SIS18

FRS

CBM
SIS100



© GSI/FAIR, Zeitrausch

Coming soon



$p, d \dots$

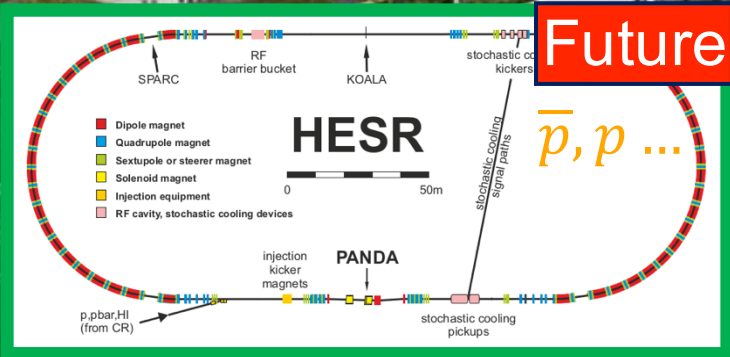
Data processing, AI, ...

Today



Green-IT Cube

Future



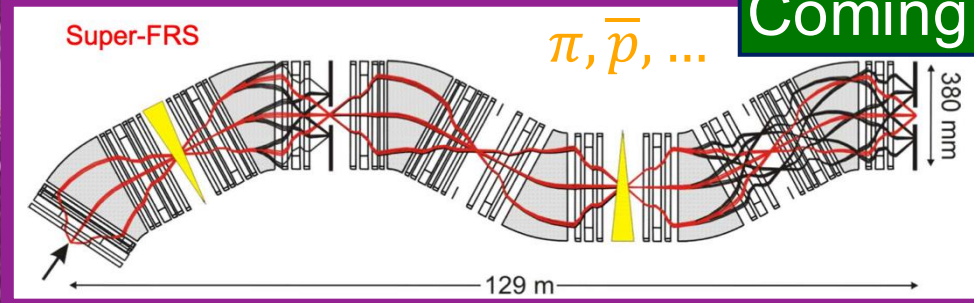
$\bar{p}, p \dots$

(Anti-) proton experiments at
HESR

Super-FRS

$\pi, \bar{p}, \dots$

Coming soon



e.g. ASuCA at Super-FRS

Hadron Physics Facilities at FAIR

HADES

SIS18

Today

$\pi, p, d \dots$

CBM
SIS100

Coming soon



- Outstanding spectrometer (toroid)
- Excellent tracking & PID capabilities
- Additional photon detection
- Large angular coverage
- Designed for various SIS18 beams including *pion* and *proton beams*!
=> Study *exclusive hadronic final states*

- Outstanding spectrometer (dipole)
- Excellent tracking & PID capabilities
- High-rate capabilities
- Excellent forward-angular coverage
- Designed for various SIS18 beams including *proton beams*!
=> Study *exclusive hadronic final states*

Hadron Physics Facilities at FAIR

HADES

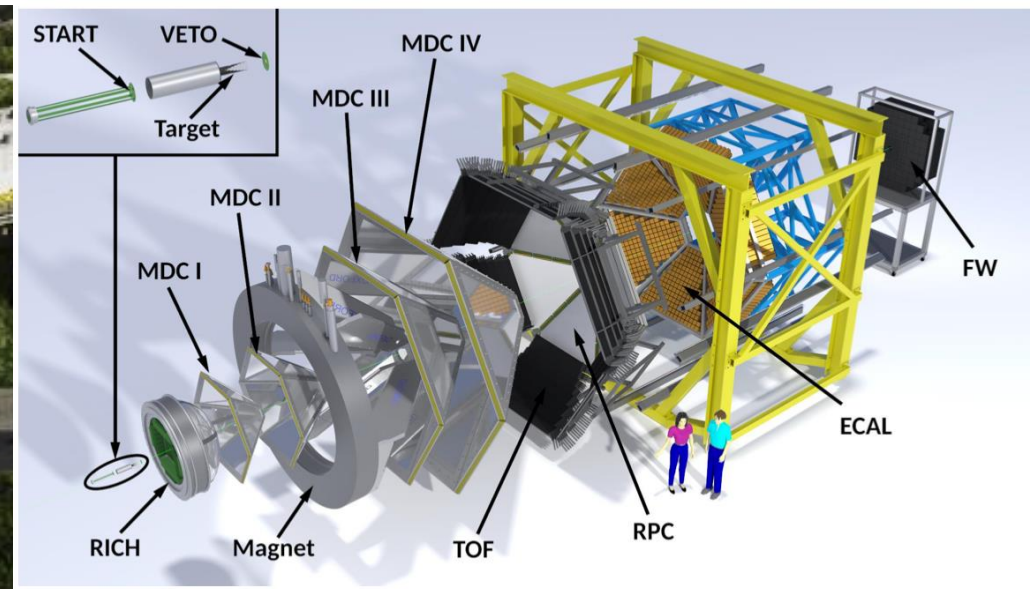
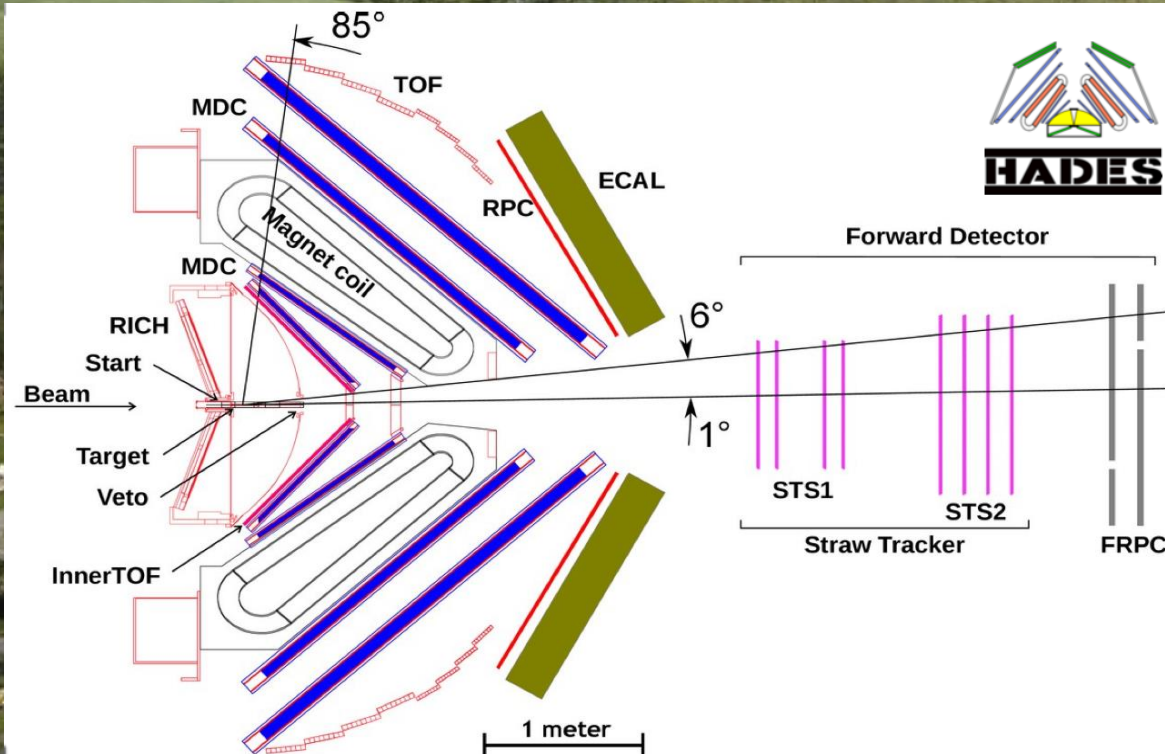
SIS18

Today

$\pi, p, d \dots$

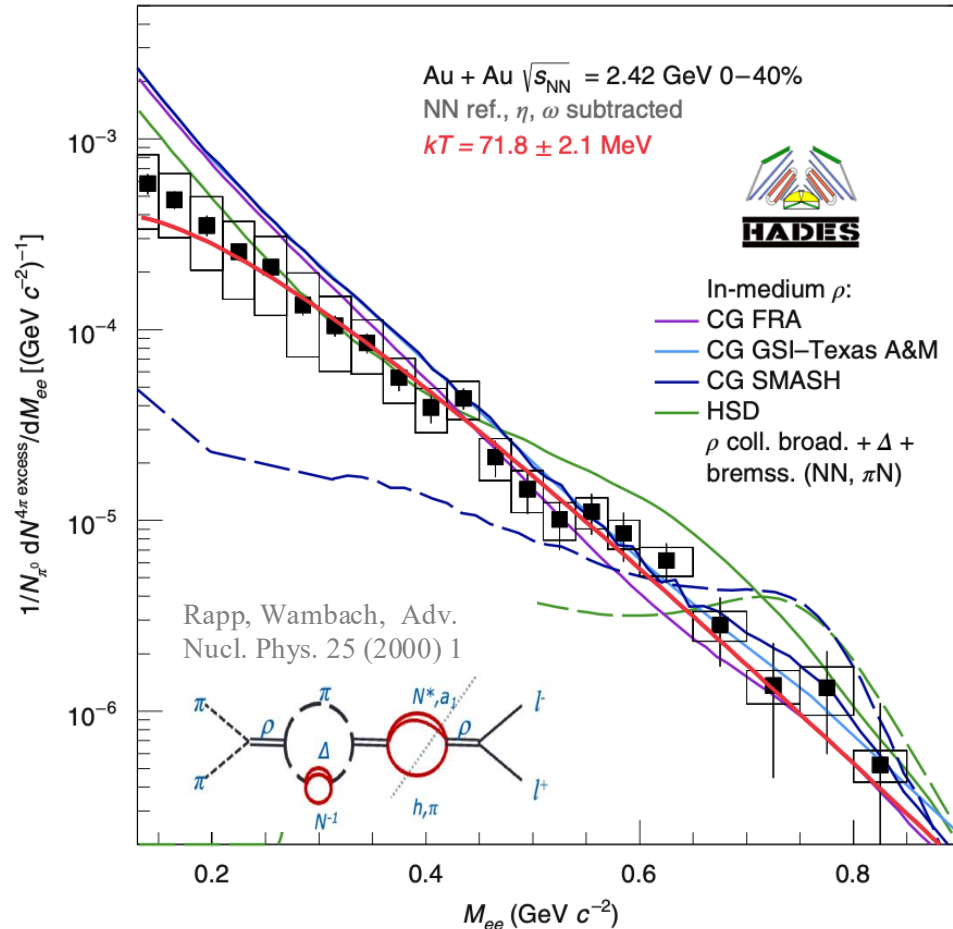
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Hadron Physics Facilities at FAIR



Heavy-ion beam physics, example

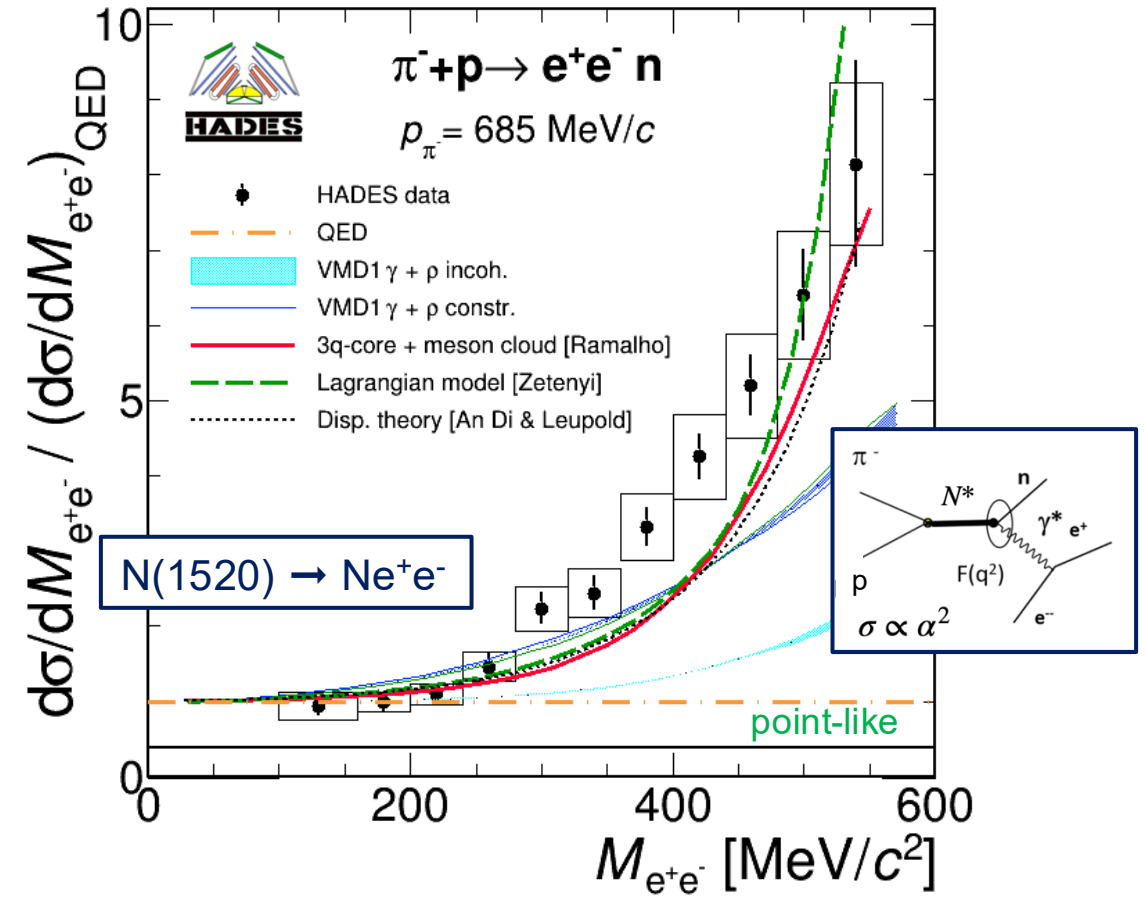
[HADES, Nature Phys. 15 (2019), 10, 1040]



→ **Di-lepton spectrum: Heavy-ion Dynamics**

Pion-beam physics, example

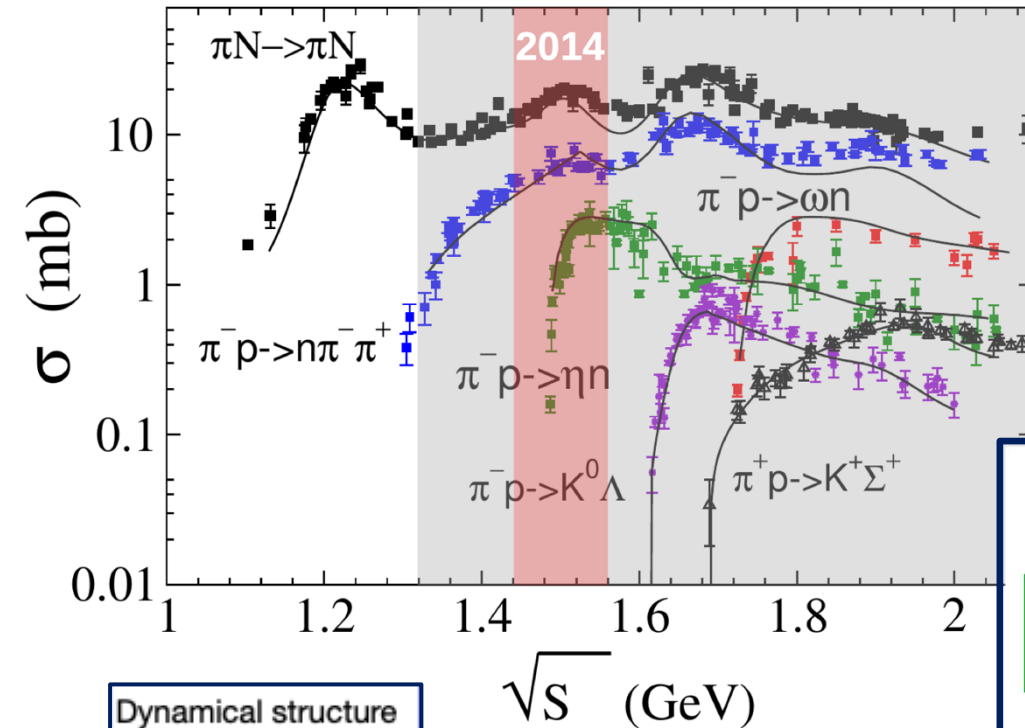
[PLB861, 139267 (2025), PRC102, 024001 (2020),
arXiv:2309.13357, PRC111, 024908 (2025)]



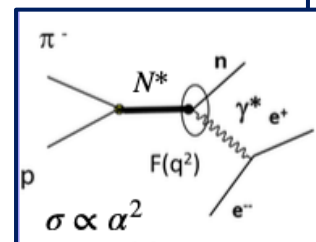
→ **Di-lepton spectrum: Hadron Structure**

Physics with pion beam

- The pion-nucleon system elementary in hadron, nuclear, and heavy-ion physics
- ‘Simple’ initial state with spin-zero boson; ‘Simple’ final states, 2/3-bodies
- $\sqrt{s}$ coverage and scan up to ~ 2 GeV
- Access to many observables
- Precision studies combining hadron dynamics and electromagnetic structure
- HADES committed to near-future πp & πA studies (“ π -QCD” program)



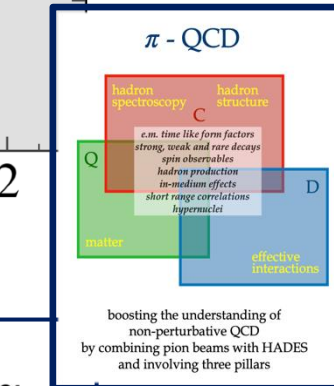
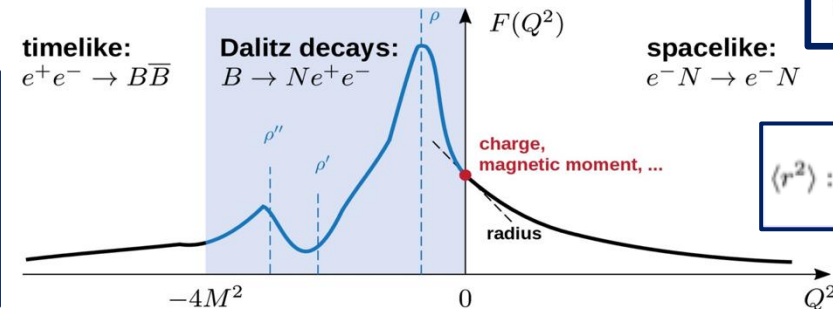
Dynamical structure of resonances



timelike:
 $e^+e^- \rightarrow B\bar{B}$

Dalitz decays:
 $B \rightarrow Ne^+e^-$

spacelike:
 $e^-N \rightarrow e^-N$



$$\langle r^2 \rangle := \frac{6}{F(0)} \frac{dF(q^2)}{dq^2} \Big|_{q^2=0}$$

HADES

SIS18

Today

$\pi, p, d \dots$

- Outstanding spectrometer (toroid)
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- Additional photon detection
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- Designed for various SIS18 beams including *pion* and *proton beams*!
=> Study *exclusive hadronic final states*

CBM
SIS100

Coming soon



Compressed **Baryonic Matter**

- Outstanding spectrometer (toroid)
- Excellent tracking & PID capabilities
- High-rate capabilities
- Excellent forward-angular coverage
- Designed for various SIS18 beams including *proton beams*!
=> Study *exclusive hadronic final states*

Hadron Physics Facilities at FAIR

From SIS18 to SIS100 – Hadron physics from pions to protons

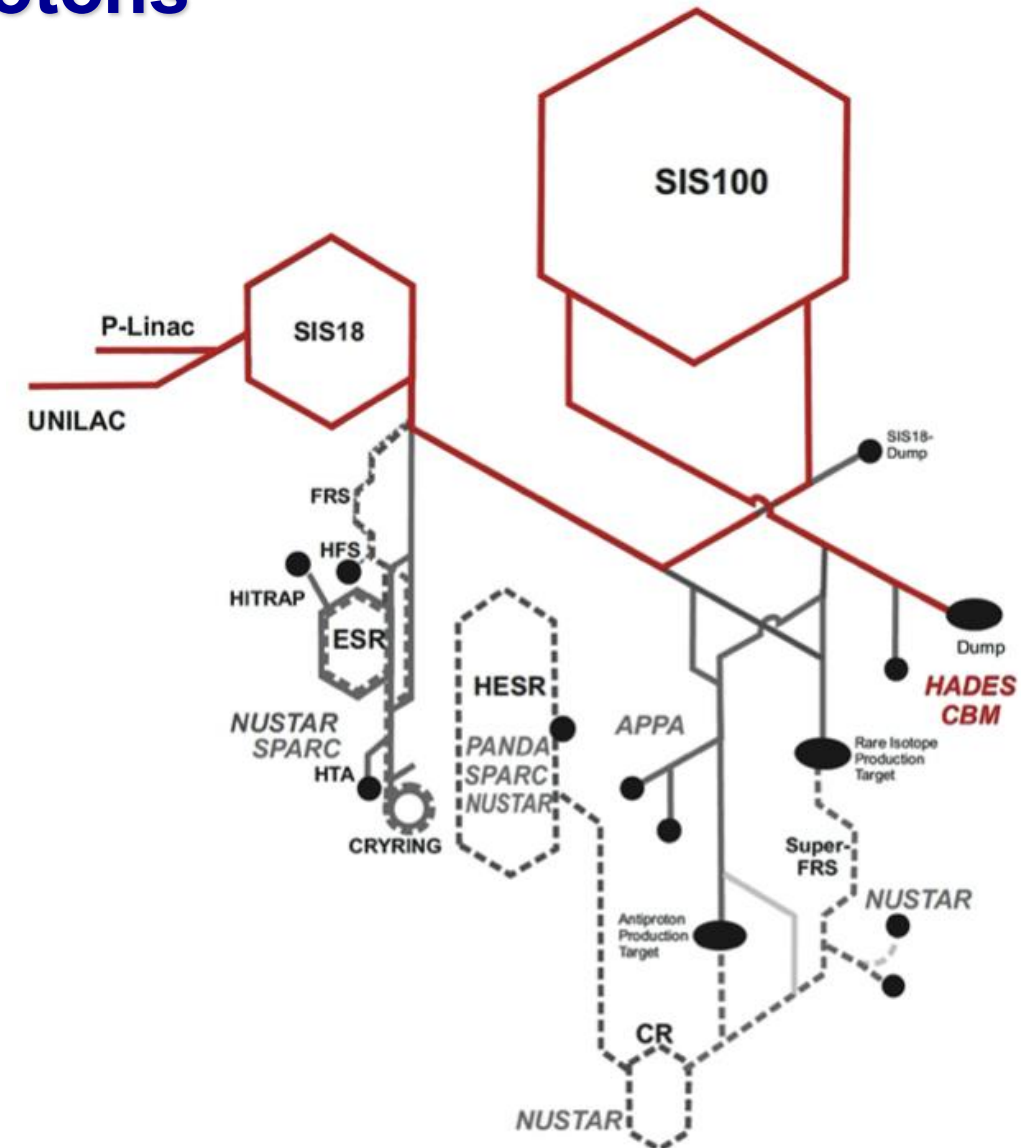
Energy upgrade:

- From max 4.7 GeV (SIS18) to 29 GeV (SIS100)
proton energy: $\sqrt{s_{NN}} \approx 3.5 \text{ GeV} \rightarrow 7.6 \text{ GeV}$
- Opening new realm: double & triple strangeness and even charm baryons and mesons!
- Significant increase in production yield of hyperons

Intensity upgrade:

- From max protons/s of 10^{11} (SIS18) to 10^{13} (SIS100)
- Even during “commissioning” (10^8 protons/s) with 5 cm LH2 target (Interaction rate: 1 MHz $\rightarrow$ >100 MHz)

Production per day at 10 MHz pp interaction rates at 30 GeV/c		
$\Xi^- \rightarrow \Lambda \pi^-$	$\sim 40 \text{ } \mu\text{b}$	7×10^8
$\Omega^- \rightarrow \Lambda K^-$	$\sim 0.6 \text{ } \mu\text{b}$	7×10^6



From SIS18 to SIS100 – Hadron physics from pions to protons

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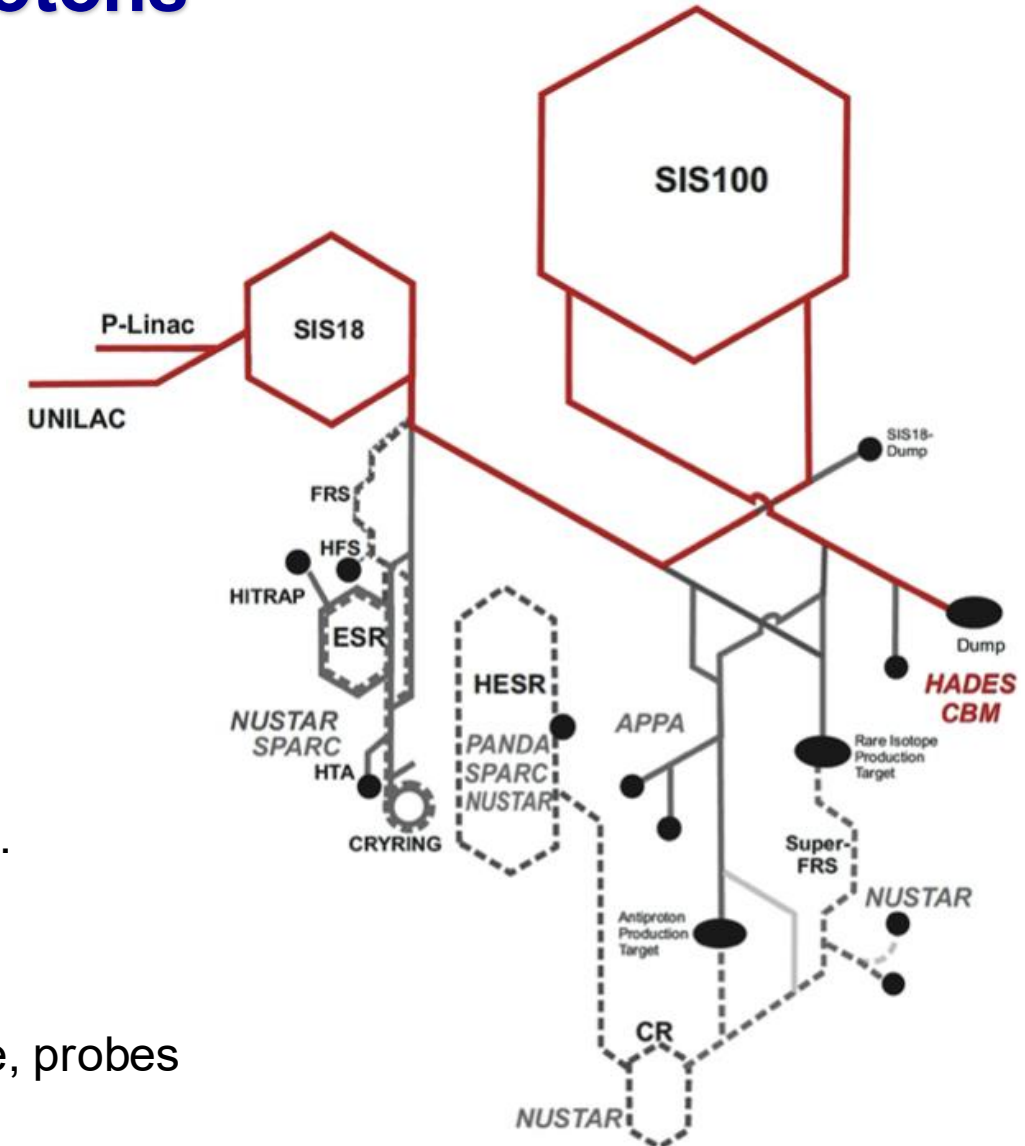
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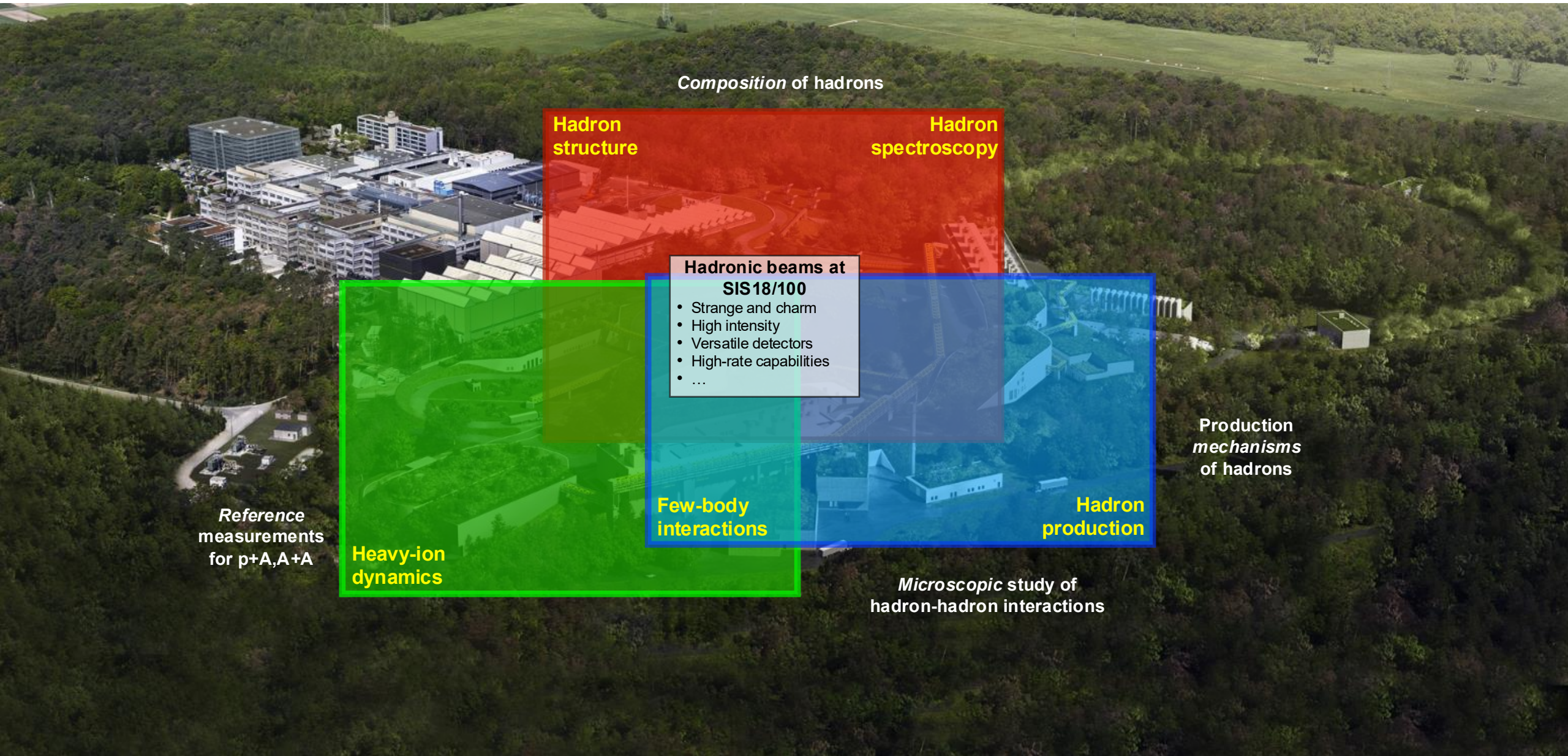
Detector enrichment:

- Towards high-rate capabilities and free-streaming DAQ's etc.

Theory enrichment:

- “Terra incognita”: attention refocussed for this energy regime, probes





Composition of hadrons

Hadron
structure

Hadron
spectroscopy

Hadronic beams at
SIS18/100

- Strange and charm
- High intensity
- Versatile detectors
- High-rate capabilities
- ...

Reference
measurements
for p+A, A+A

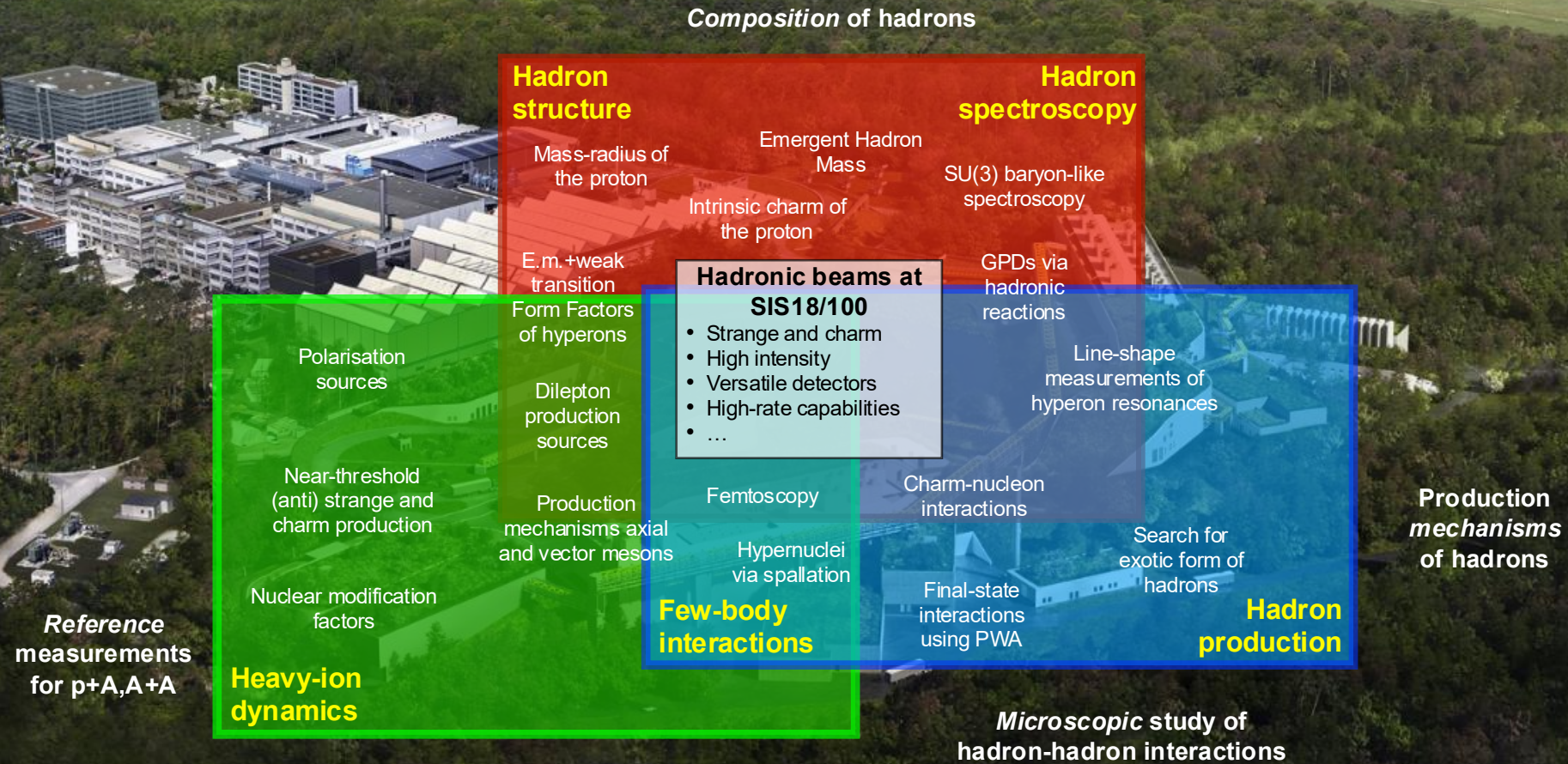
Heavy-ion
dynamics

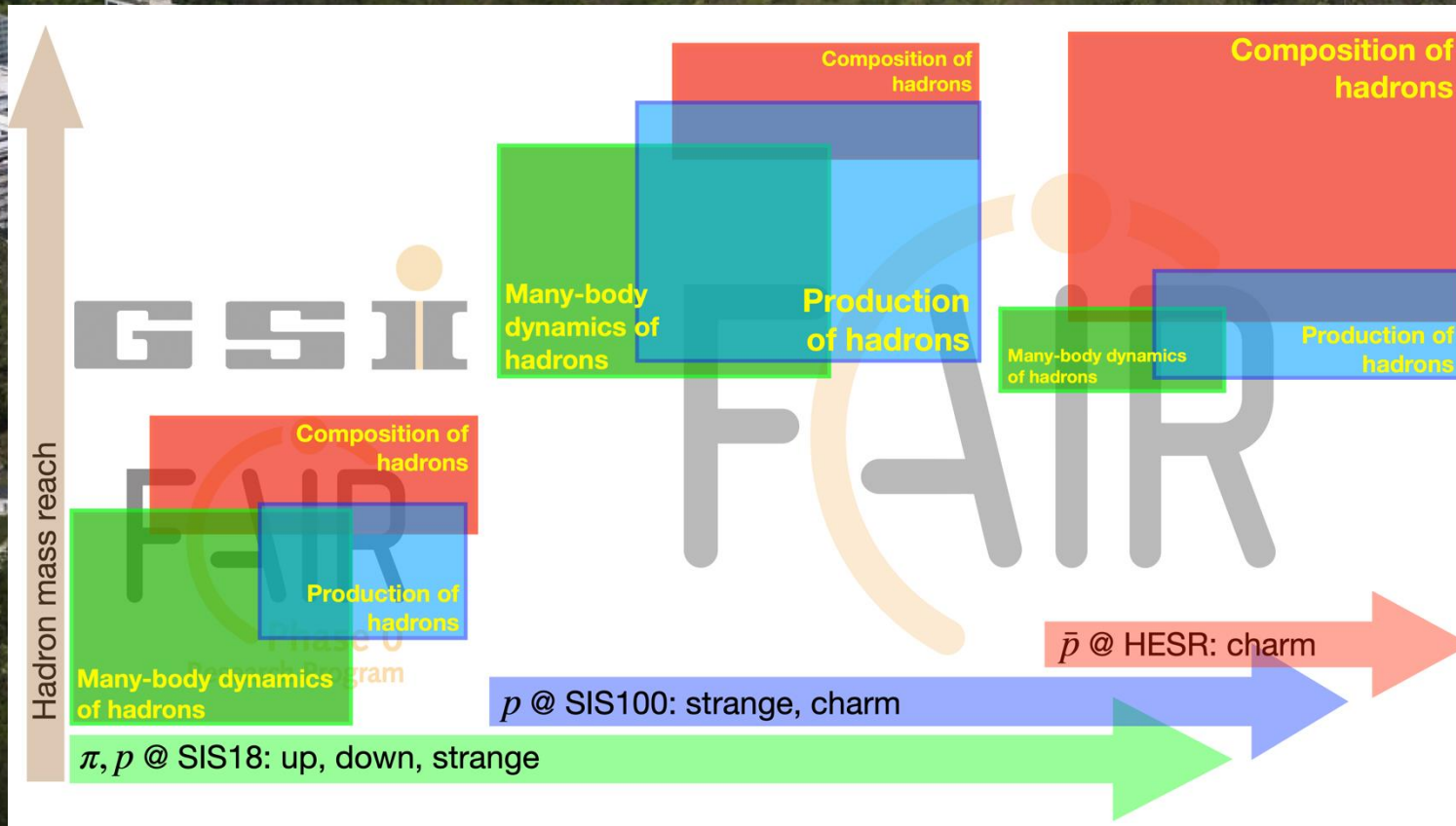
Few-body
interactions

Hadron
production

Production
mechanisms
of hadrons

Microscopic study of
hadron-hadron interactions



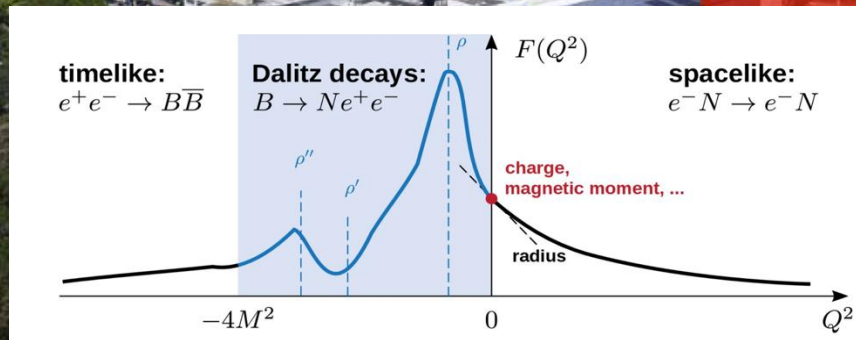


A comprehensive QCD program at GSI/FAIR – Hadron Structure

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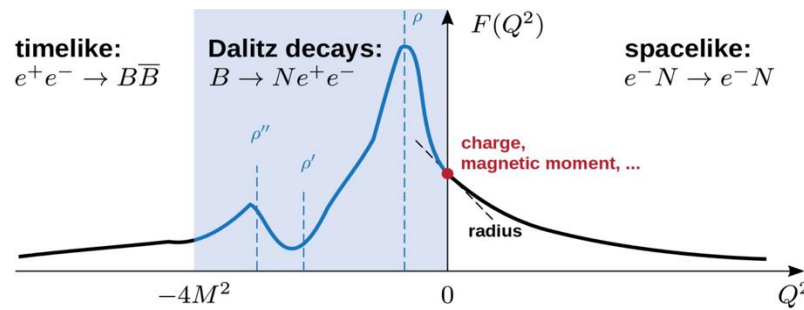
Microscopic study of
hadron-hadron interactions

A selection of feasibility studies – Hyperon Structure

Composition of hadrons

Hadron structure

Hadron spectroscopy



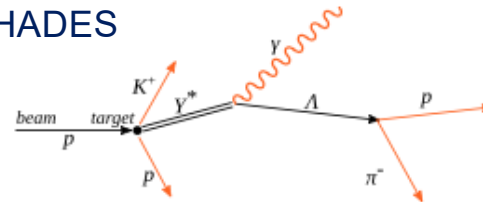
Hadronic beams at SIS18/100

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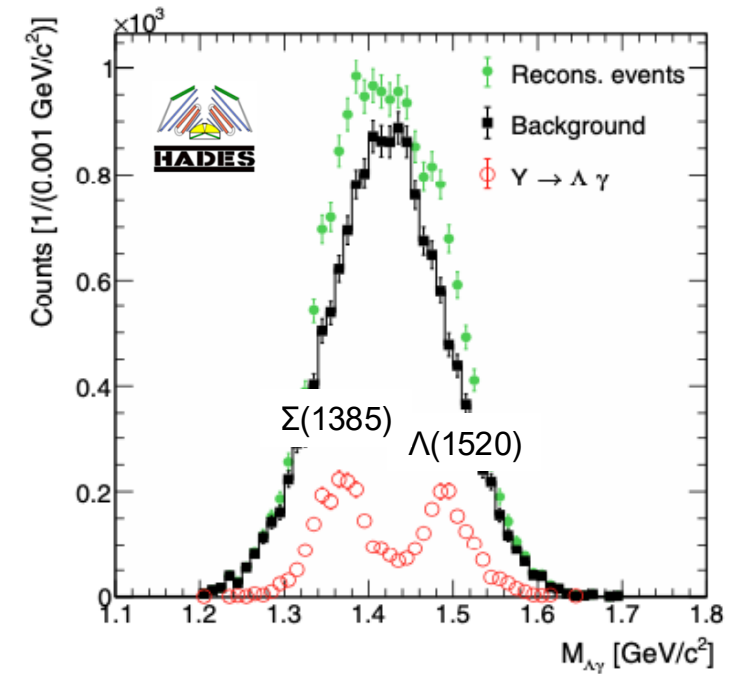
Reference measurements for $p+A, A+A$

Heavy-ion dynamics

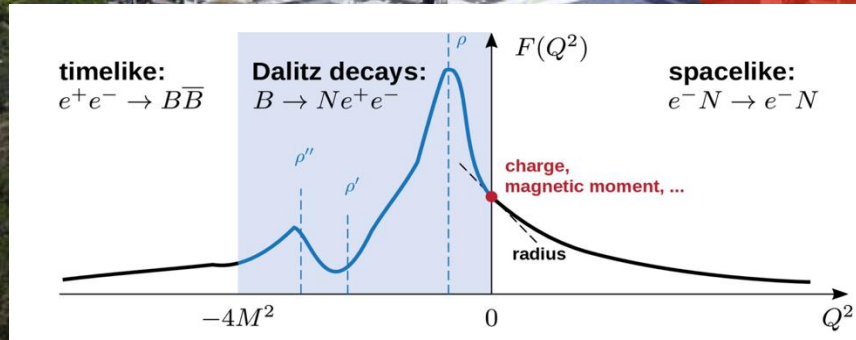
HADES



[HADES, Eur. Phys. J. A (2021) 57:138]



A selection of feasibility studies – Hyperon Structure



Composition of hadrons

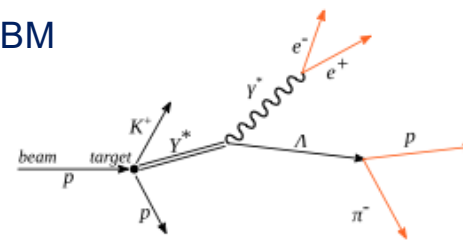
Hadron structure

Hadron spectroscopy

Hadronic beams at SIS18/100

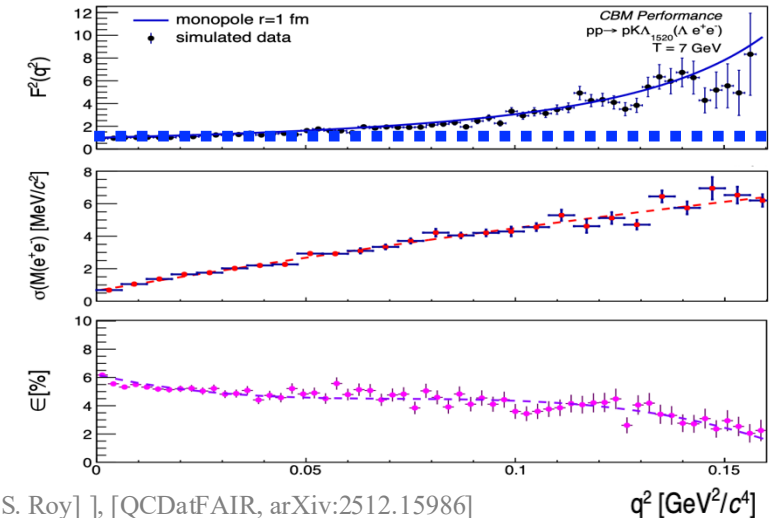
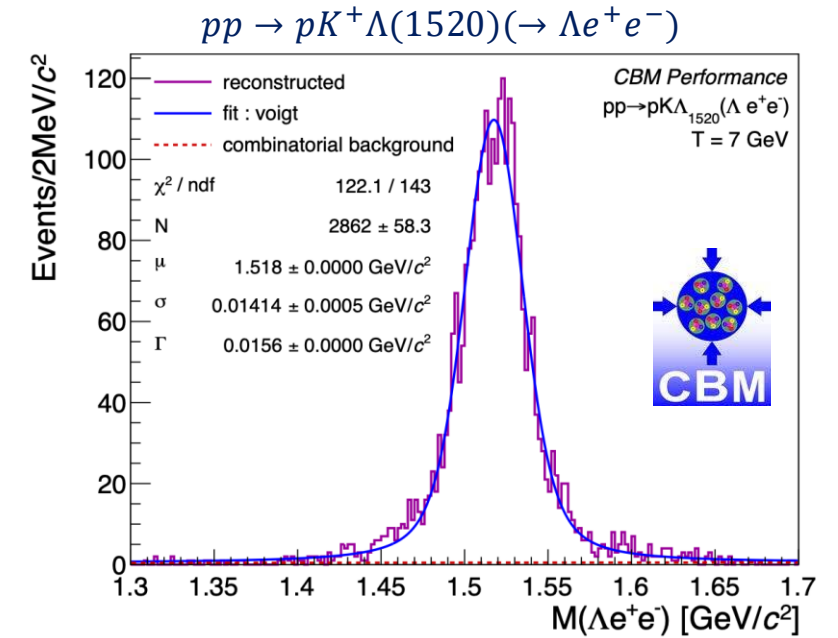
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CBM



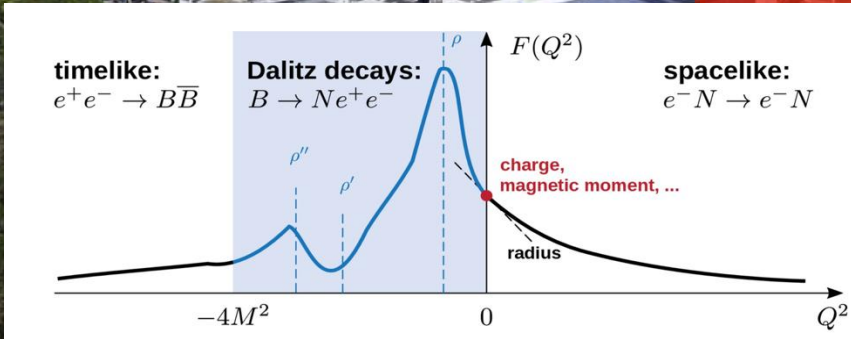
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Heavy-ion dynamics



[S. Roy]], [QCDatFAIR, arXiv:2512.15986]

A selection of feasibility studies – Hyperon Structure



Composition of hadrons

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Hadronic beams at
SIS18/100

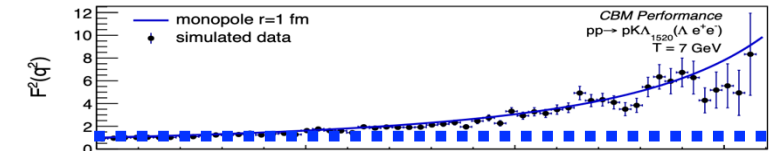
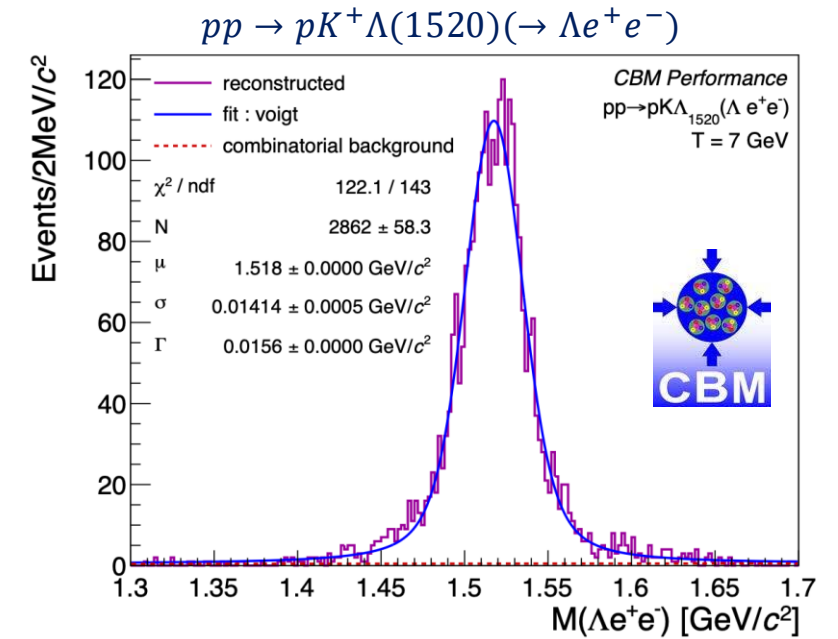
- Strange and charm
- High intensity
- Versatile detectors
- High-rate capabilities
- ...

Few-body interactions

Reference measurements

✓ Electromagnetic & weak transition form factors

Microscopic hadron-hadron



→ Physics results – after commissioning, interaction rate 1 MHz, 10 days

[S. Roy], [QCDataFAIR, arXiv:2512.15986]

q^2 [GeV²/c⁴]

A comprehensive QCD program at GSI/FAIR

-- |S| = 2,3 hyperon dynamics at CBM/SIS100

Composition of hadrons

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SIS18/100

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Hadron
production

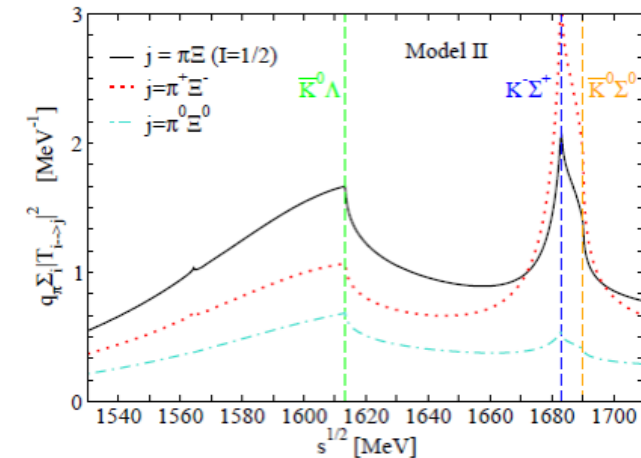
Reference
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✓ Electromagnetic & weak transition form factors

Microscopic study of
hadron-hadron interactions

mechanisms
of hadrons

[A. Feijoo et al., Phys. Lett. B 841, 137927 (2023)]



Coupled meson-baryon channels in neutral S=-2:
 $\pi^0\Xi^0$, $\pi^+\Xi^-$, $K^-\Sigma^+$, $K^0\Sigma^0$, $\eta\Xi^0$

A comprehensive QCD program at GSI/FAIR

-- |S| = 2,3 hyperon dynamics at CBM/SIS100

|S| = 2,3 hyperon dynamics at CBM at SIS100:

- Υ^* composition: spectroscopy & structure

- Excited Ξ^*, Ω^* spectroscopy
- Unconventional states, e.g. $\Xi(1620, 1690)$
- Line-shape measurements

- Experimental studies...

- LHCb, e.g. $\Xi_b^- \rightarrow J/\psi + \Lambda K^-$
- Belle, e.g. $\Xi_c^+ \rightarrow \pi^{++} \Xi^- \pi^+$
- GlueX, e.g. $\gamma p \rightarrow K^+ K^{(+)0} + \Lambda \bar{K}$
- ALICE, e.g. femtoscopy $\bar{K} N$
- ...
- **CBM**, e.g. $pp \rightarrow p K^+ K^+ + \Xi^- \pi^+ / \dots$

for p+A, A+A

Heavy-ion
dynamics

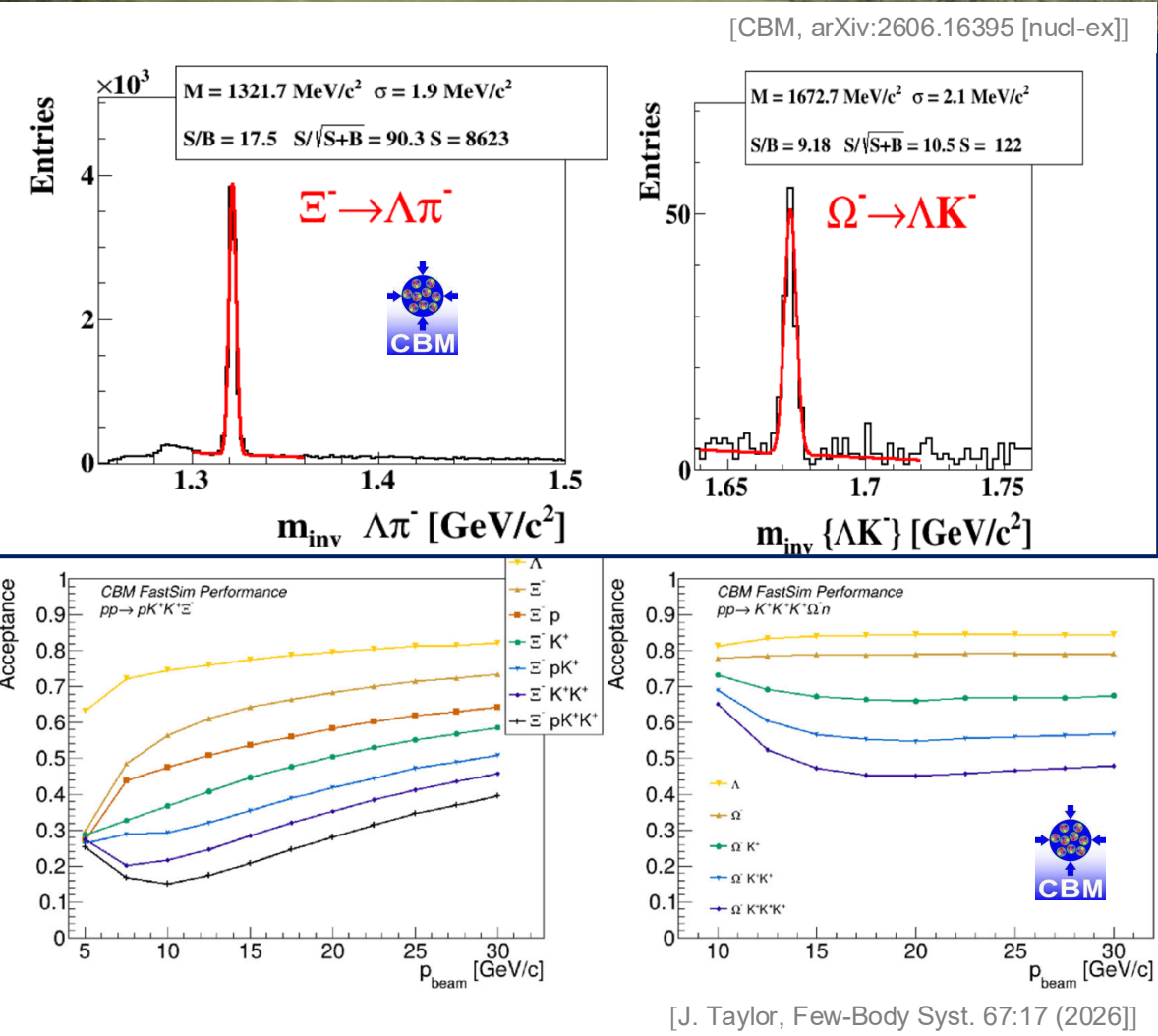
Composition of

dronic beam

SIS18/100

range and char
gh intensity
rsatile detector
gh-rate capabili

body
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[J. Taylor, Few-Body Syst. 67:17 (2026)]

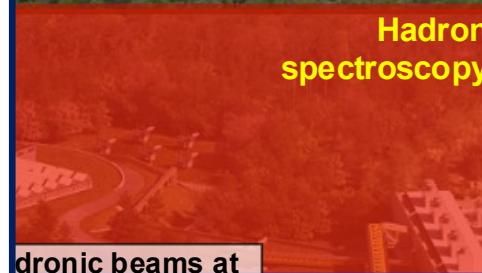
A comprehensive QCD program at GSI/FAIR

-- |S| = 2,3 hyperon dynamics at CBM/SIS100

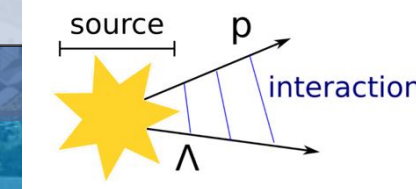
|S| = 2,3 hyperon dynamics at CBM at SIS100:

- Y^* composition: spectroscopy & structure
 - Excited Ξ^*, Ω^* spectroscopy
 - Unconventional states, e.g. $\Xi(1620, 1690)$
 - Line-shape measurements
- Experimental studies...
 - LHCb, e.g. $\Xi_b^- \rightarrow J/\psi + \Lambda K^-$
 - Belle, e.g. $\Xi_c^+ \rightarrow \pi^{++} \Xi^- \pi^+$
 - GlueX, e.g. $\gamma p \rightarrow K^+ K^{(+0)} + \Lambda \bar{K}$
 - ALICE, e.g. femtoscopy $\bar{K} N$
 - ...
 - **CBM**, e.g. $pp \rightarrow p K^+ K^+ + \Xi^- \pi^+ / \dots$
- Additional opportunities...
 - Strong phase studies via $\pi\Lambda$ FSI (input to CPV)
 - **Low-energy scattering** params in $\Lambda\Lambda, \Sigma\Sigma$ FSI via dispersion and femtoscopy

Composition of hadrons



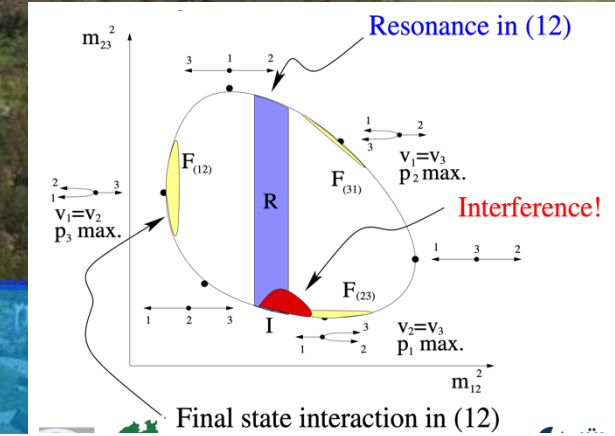
range and charm
high intensity
versatile detectors
high-rate capabilities



body
ctions

Hadron
production

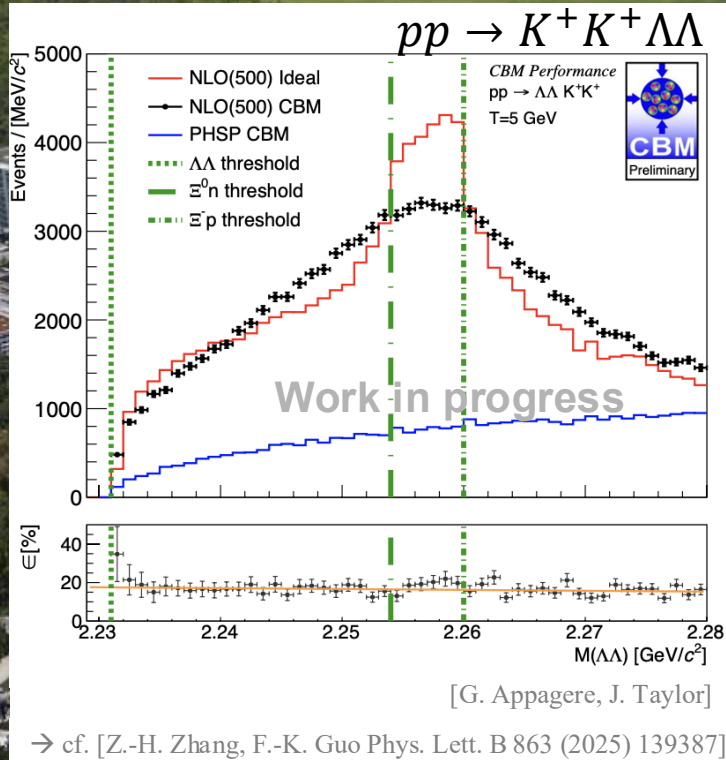
Microscopic study of
hadron-hadron interactions



Production
mechanisms
of hadrons

A selection of feasibility studies

– Low-energy scattering parameters, $S = -2$



Reference
measurements

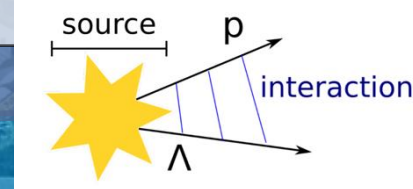
Composition of hadrons

Hadron
spectroscopy

Hadronic beams at
SIS18/100

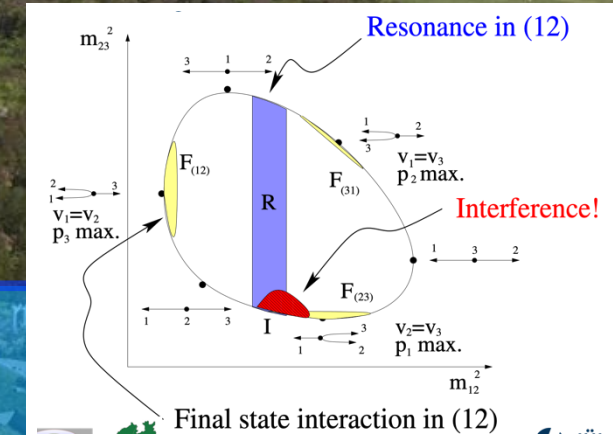
- Strange and charm
- High intensity
- Versatile detectors
- High-rate capabilities
- ...

Few-body
interactions



Hadron
production

Production
mechanisms
of hadrons

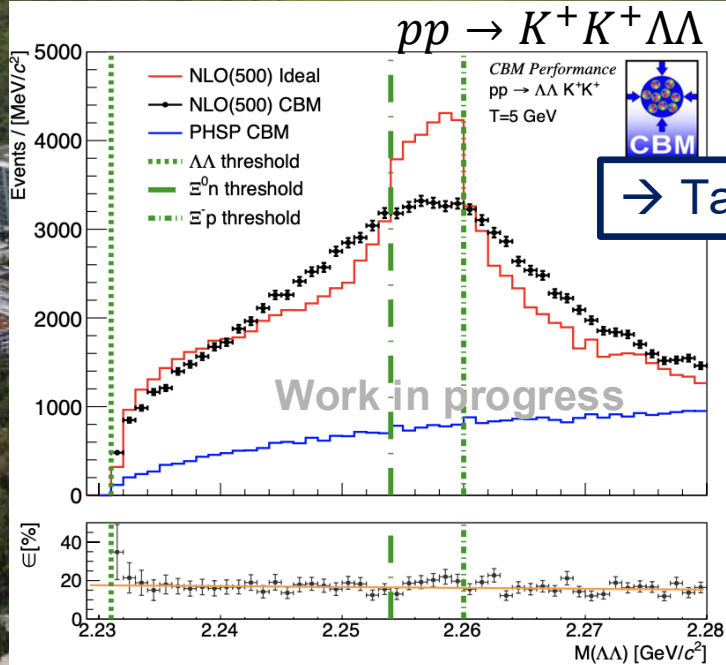


- ✓ Electromagnetic & weak transition form factors
- ✓ $|S| = 2, 3$ hyperon dynamics
- ✓ Scattering parameters from short-range correlations

→ „First“ Physics results – after commissioning,
interaction rate 1 MHz, 10 days

A selection of feasibility studies

– Low-energy scattering parameters, $S = -2$



[G. Appagere, J. Taylor]

interdisciplinary connection to astro-
physics, via hyperon puzzle (EoS, NS)
"The Universe in the Lab"

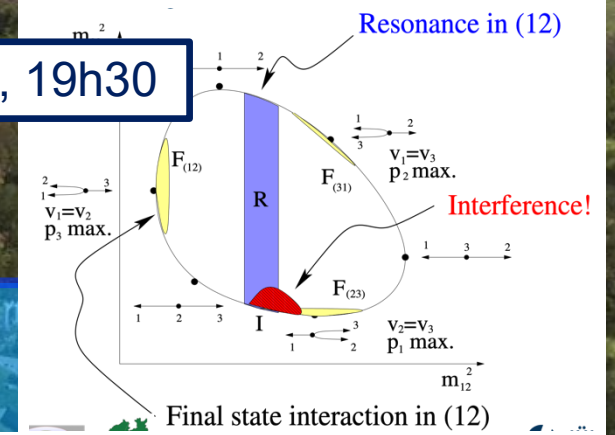
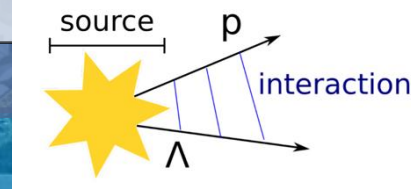
- ✓ Electromagnetic transition form factors
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Composition of hadrons

→ Talk by Gandharva Appagere, Tue, 19h30

Hadronic beams at
SIS18/100

- Strange and charm
- High intensity
- Versatile detectors
- High-rate capabilities
- ...



Production
mechanisms
of hadrons

Hadron
production

Mi
hadro

→ „First“ Physics results – after commissioning,
interaction rate 1 MHz, 10 days

A comprehensive QCD program at GSI/FAIR

– From strange to charm

Composition of hadrons

Hadron structure

Hadron spectroscopy

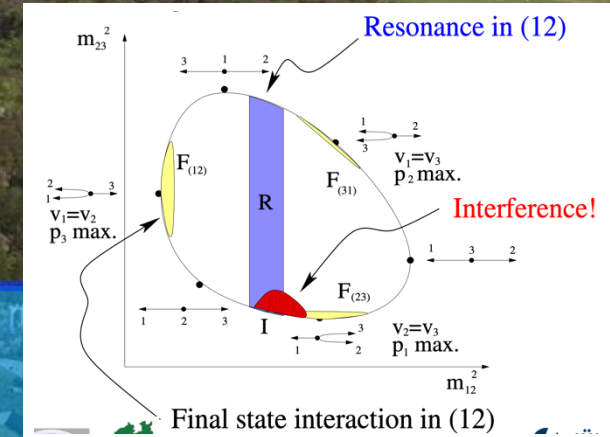
Hadronic beams at
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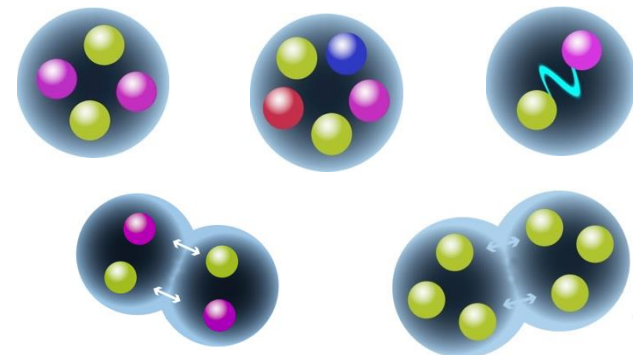
Reference measurements

Few-body interactions

Microscopic hadron-hadron



Exotic hadrons



- ✓ Electromagnetic & weak transition form factors
- ✓ $|S| = 2,3$ hyperon dynamics
- ✓ Scattering parameters from short-range correlations

A selection of feasibility studies – Strange exotic candidates

The $\Lambda(1405)$ case:

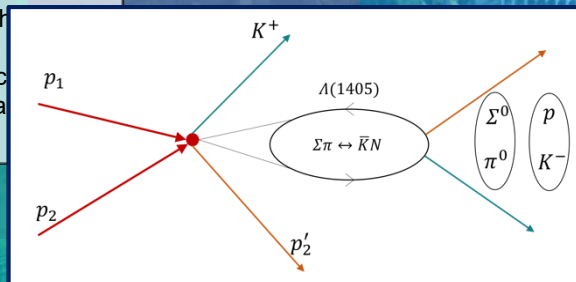
- Dalitz & Tuan [PRL2, 425 (1959)]
- $I(J^P)=0(1/2^-)$ [CLAS, PRL112, 082004 (2014)]
- Coupling to $\pi\Sigma$ and $\bar{K}N$
- Internal structure: two poles? First two-pole structure in LQCD: [Bulava et al., PRL132, 051901 (2024)]
- Molecular state dynamically generated by $\bar{K}N - \pi\Sigma$ interactions?

Composition of hadrons

Hadron spectroscopy

Hadronic beams at
SIS18/100

- Strange and charm
- High intensity
- Versatile detection
- High-rate capability
- ...



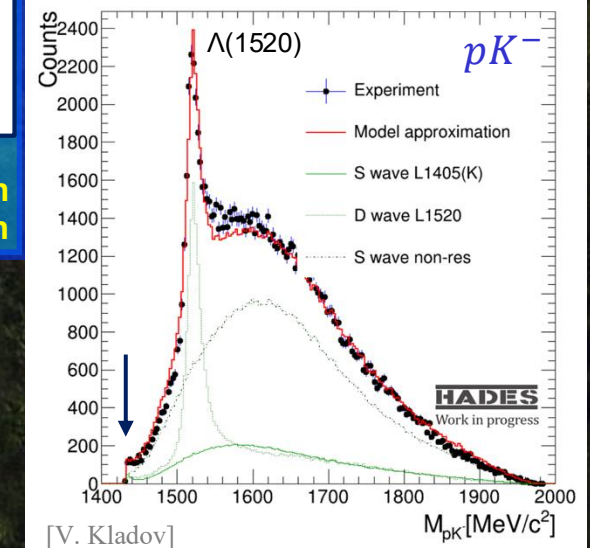
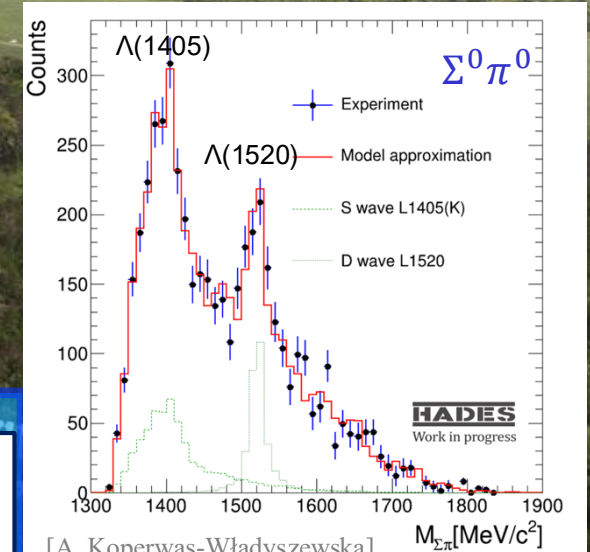
Few-body interactions

Hadron production

*Microscopic study of
hadron-hadron interactions*

Reference
measurements
for $p+A, A+A$

**Heavy-ion
dynamics**



A selection of feasibility studies – Strange exotic candidates

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→ cf. Talk by Colin Morningstar, also John Bulava

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Heavy-ion
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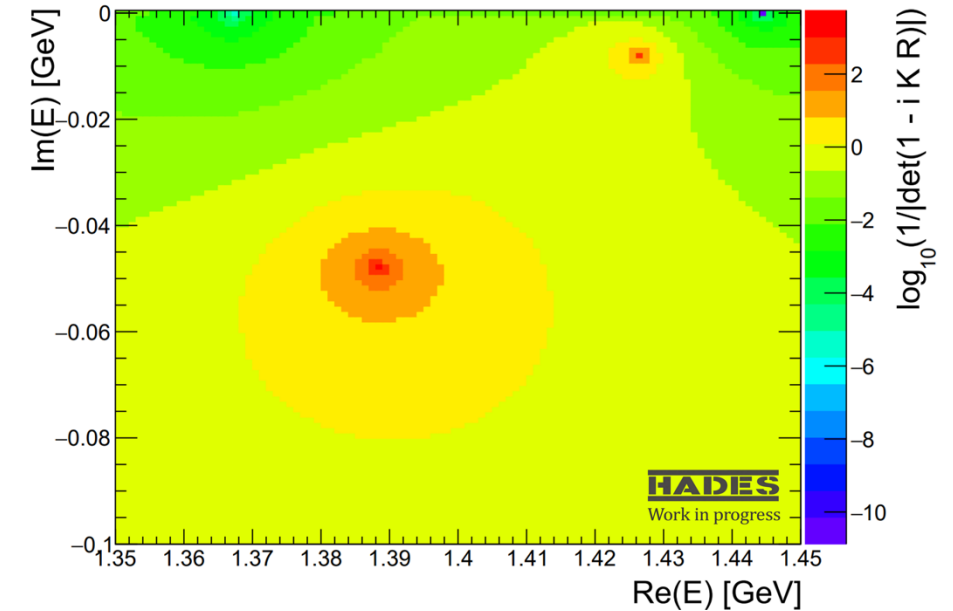
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Composition of hadrons

Hadron
spectroscopy

Hadronic beams at
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Strange and charm
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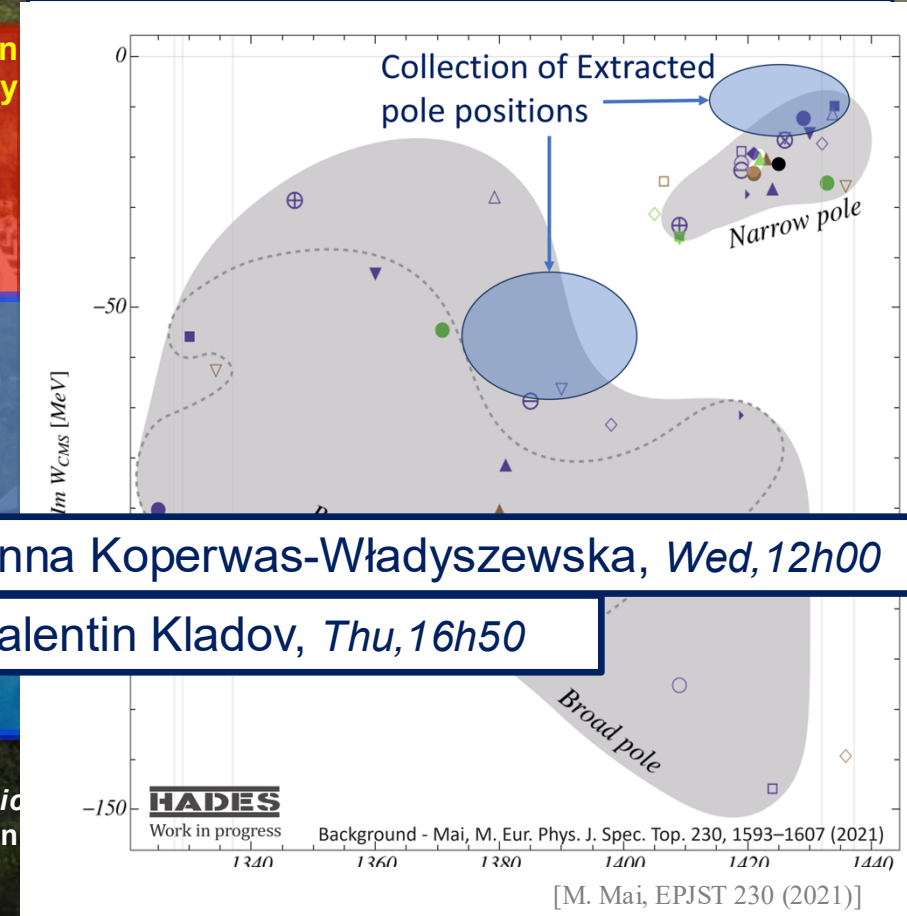
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- ...

Few-body interactions

Heavy-ion dynamics

Reference measurements for p+A, A+A

Microscopic hadron-hadron



→ Talk by Anna Koperwas-Władyszewska, Wed, 12h00

→ Talk by Valentin Kladov, Thu, 16h50

A selection of feasibility studies – Strange exotic candidates

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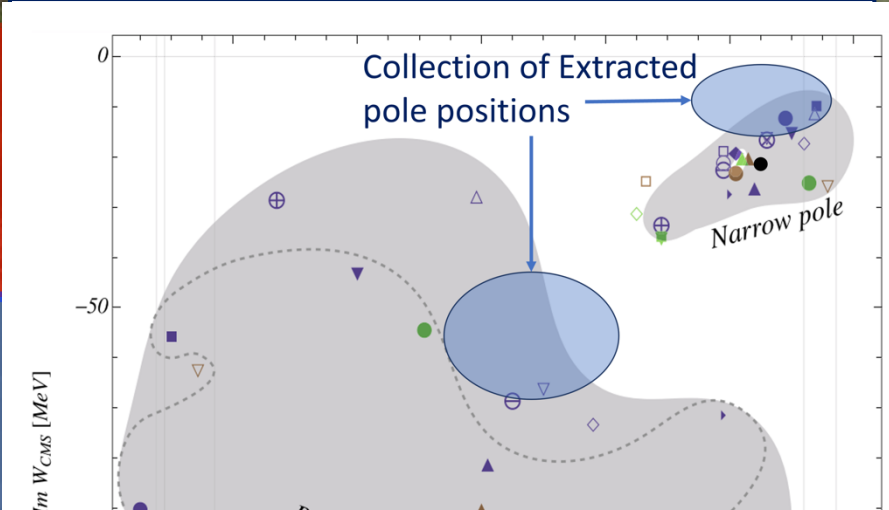
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- ✓ Electromagnetic & weak transition form factors
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- ✓ Scattering parameters from short-range correlations
- ✓ Exotic strange states

Microscopic hadron-hadron

HADES
Work in progress

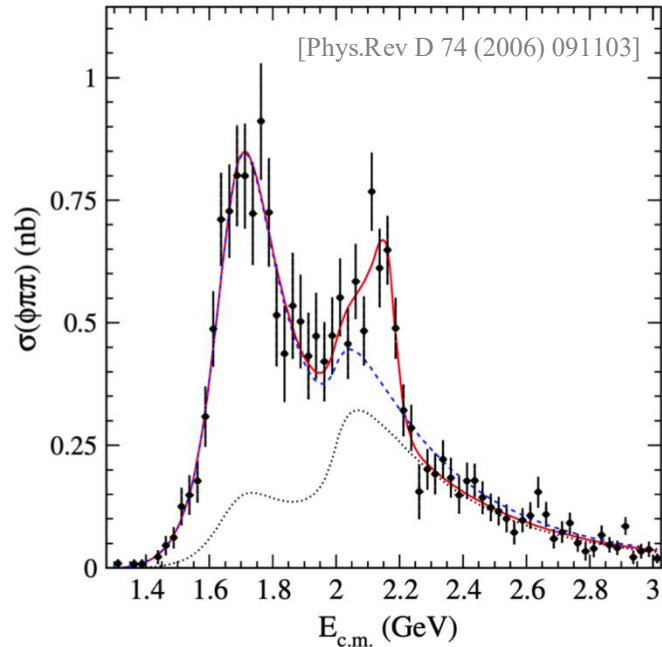
Background - Mai, M. Eur. Phys. J. Spec. Top. 230, 1593–1607 (2021)
EPJST 230 (2021)]

→ Talk by Ahmed Foda (PWA), Mon, 16h40

→ Talk by Saket K. Sahu (excl. π prod. in pp), Tue, 16h30

A selection of feasibility studies – Exotic hadrons, multiquark states

Tetraquark candidate $\phi(2170)$ (BaBar)



measurements
for p+A, A+A

**Heavy-ion
dynamics**

Composition of hadrons

**Hadron
structure**

**Hadron
spectroscopy**

**Hadronic beams at
SIS18/100**

- Strange and charm
- High intensity
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- ...

**Few-body
interactions**

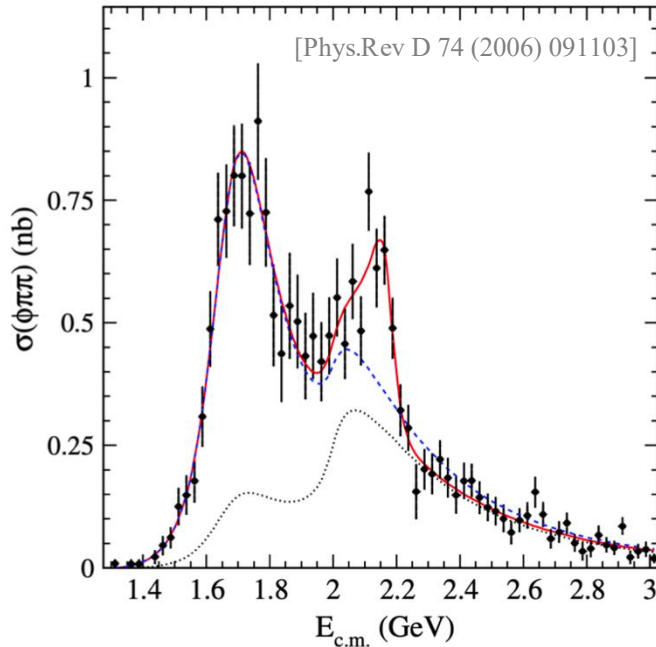
**Hadron
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**Production
mechanisms
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*Microscopic study of
hadron-hadron interactions*

A selection of feasibility studies – Exotic hadrons, multiquark states

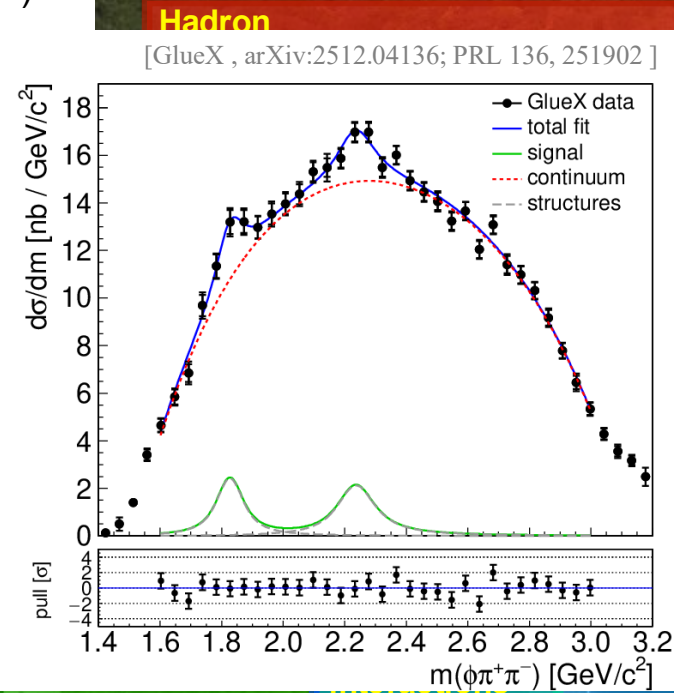
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Composition of hadrons



→ cf. Talk by Will Imoehl

Hadron
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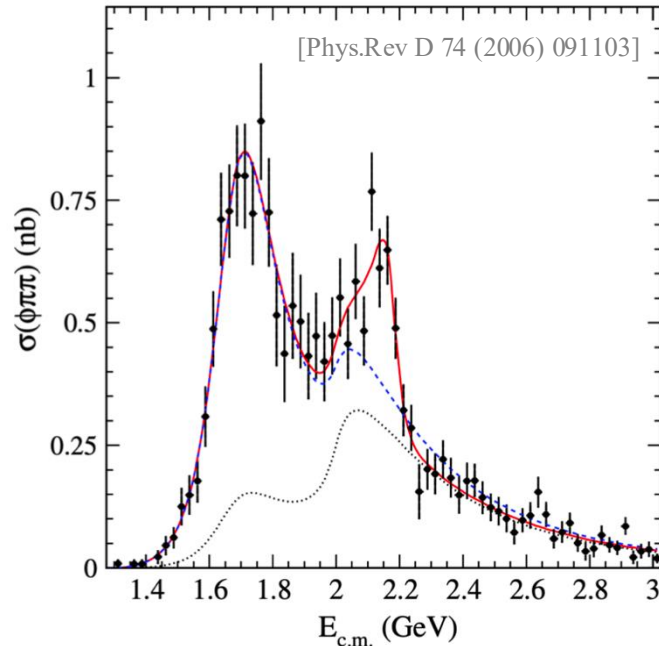
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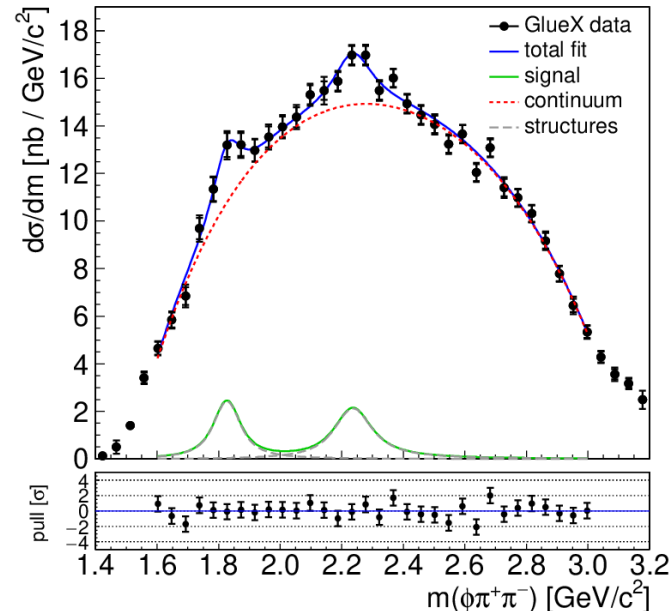


measurements

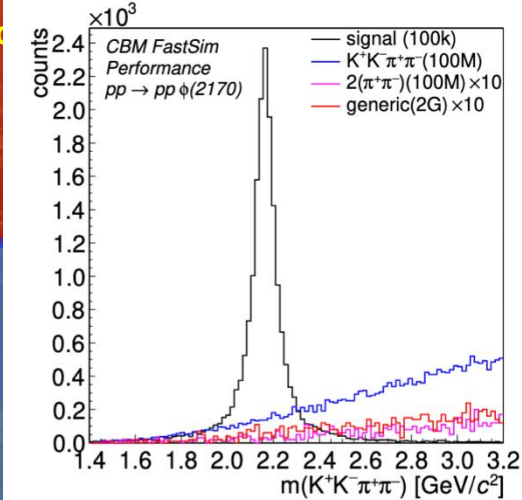
Composition of hadrons

Hadron

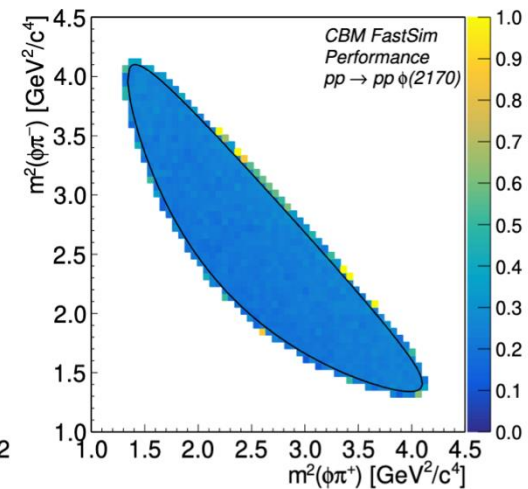
[GlueX, arXiv:2512.04136; PRL 136, 251902]



spect



[K. Götzen, F. Nerling]



[QCDAFAIR, arXiv:2512.15986]

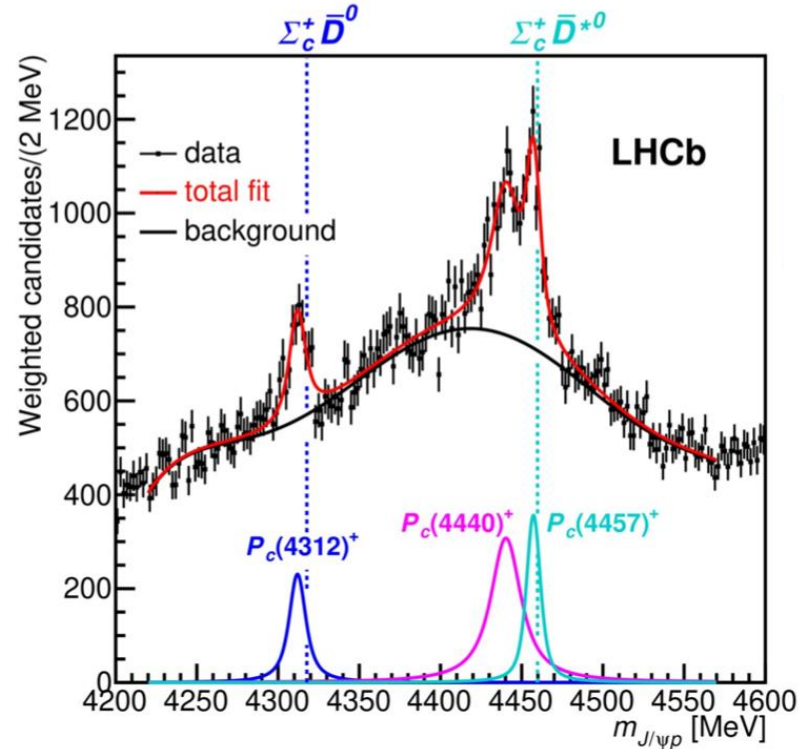
**Hadron
production**

- ✓ Electromagnetic & weak transition form factors
- ✓ $|S| = 2,3$ hyperon dynamics
- ✓ Scattering parameters from short-range correlations
- ✓ Exotic (hidden-) strange states

*Microscopic study of
hadron-hadron interactions*

A selection of feasibility studies – Exotic hadrons, multiquark states

Pentaquark states P_{cc} (LHCb)



Composition of hadrons

Hadron spectroscopy

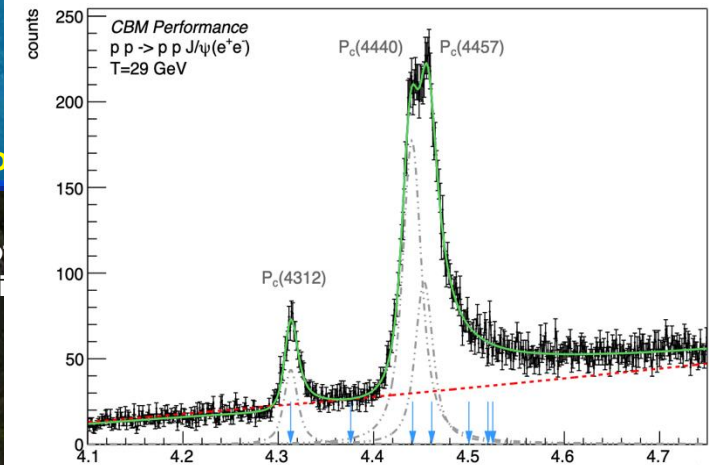
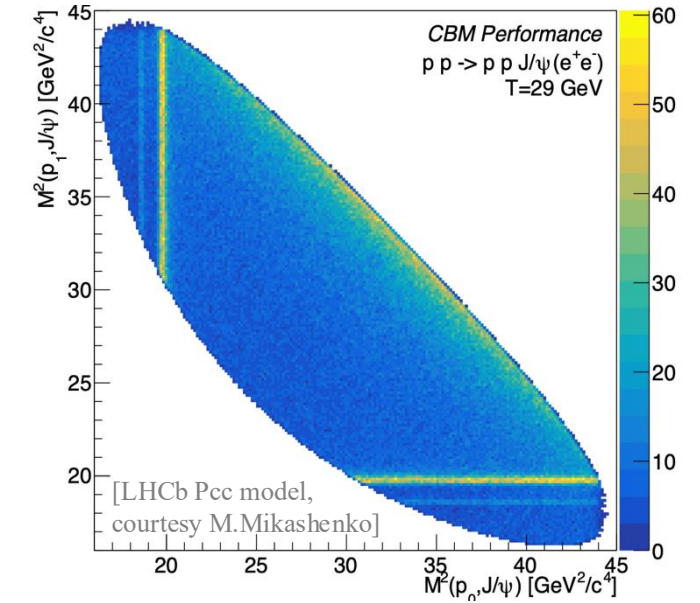
Hadronic beams at
SIS18/100

- Strange and charm
- High intensity
- Versatile detectors
- High-rate capabilities
- ...

Few-body interactions

Microscopic study of
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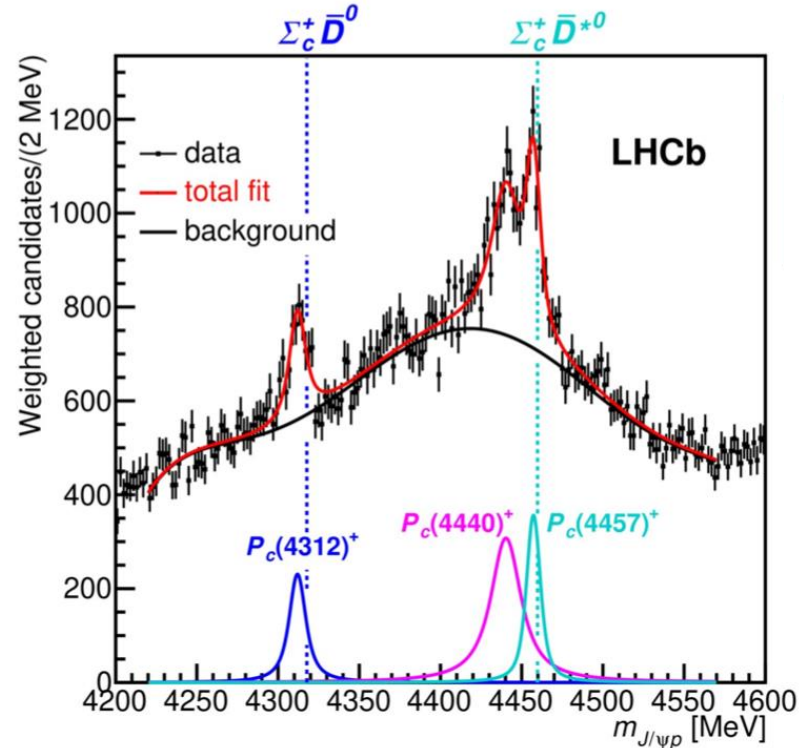
[R. Kliemt, S. Roy]

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A selection of feasibility studies – Exotic hadrons, multiquark states

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Composition of hadrons

Hadron spectroscopy

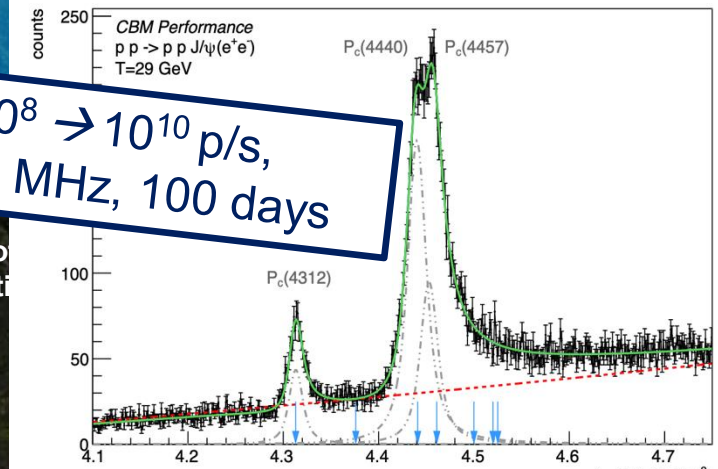
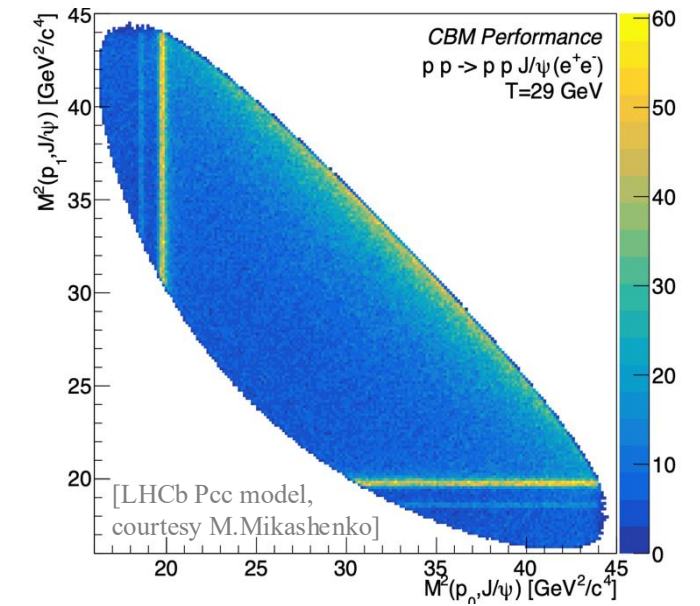
Hadronic beams at
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- Strange and charm
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- ...

Few-body interactions

→ Charm Physics – $10^8 \rightarrow 10^{10}$ p/s,
interaction rate 100 MHz, 100 days

Pentaquark states P_{cc} (LHCb)



[R. Kliemt, S. Roy]

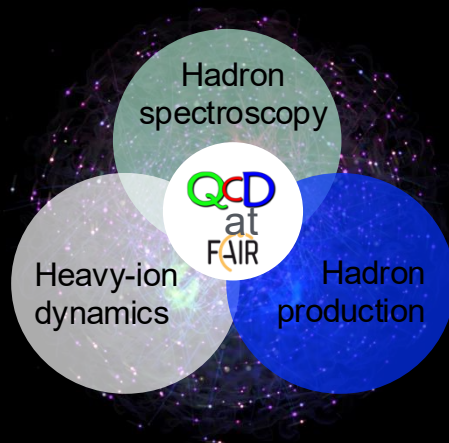
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- ✓ Electromagnetic & weak transition form factors
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- ✓ Exotic (hidden-) strange & (hidden-) charm multiquark states

....



Towards a long-term programme supported by a network & community ...



White Paper

Purpose:

- Bring together experts from experiment and theory
- Involve hadron, nuclear and heavy-ion (QCD) communities
- Develop hadron physics program for next decade at GSI/FAIR

Preparatory workshops

- Cracow, June 21, 2023
- Wuppertal, February 6-9, 2024
- GSI, November 11-14, 2024
- Italy, June, one week, 2025

Eds.: Johan Messchendorp & Frank Nerling

Cracow, MESON, Satellite-workshop. June 21, 2023



Wuppertal, Feb 6-9, 2024



GSI Darmstadt, Nov 11-14, 2024



Cantania, Jun, 22-27, 2025





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Hadron spectroscopy

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Hadron Physics Opportunities at FAIR

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- 2.2 Roadmap – Hadron physics from GSI, FAIR Phase-0 to
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- 3.2 Remarks on hadronic systems
- 3.2.1 Meson-meson systems
- 3.2.2 Meson-baryon interactions
- 3.2.3 Baryon-baryon interactions
- 3.2.4 Baryon-baryon bound and virtual states (dibaryon)
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- 3.3.3 Dispersive analysis of short ranged production reactions
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Acknowledgments

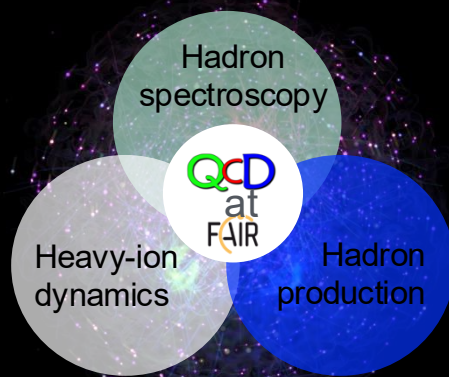
References

Glossary of abbreviations





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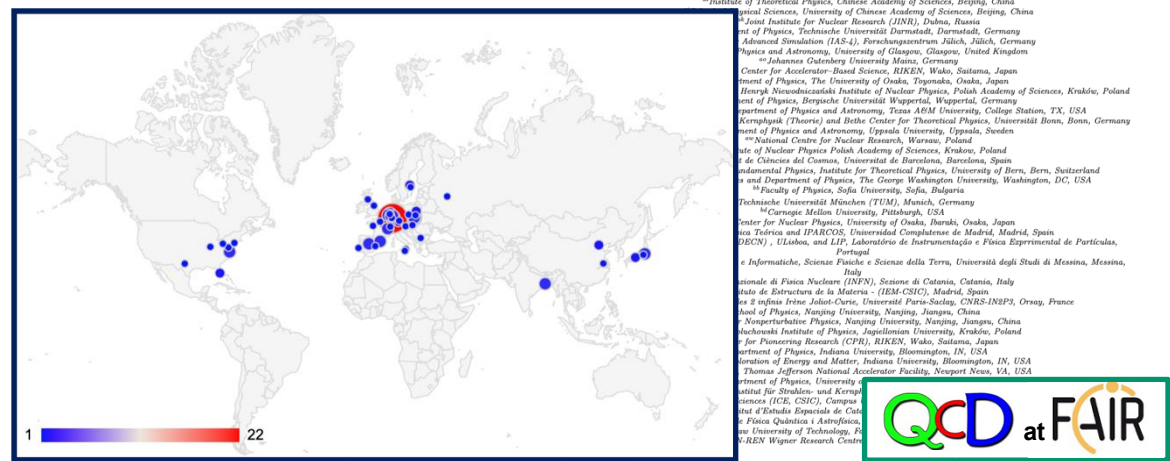
Eds.: Johan Messchendorp & Frank Nerling

Hadron Physics Opportunities at FAIR

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“QCD at FAIR” established – A win-win-win situation!

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 - Common interests and (overlap in) topics
 - Synergies and complementary expertise
 - Future completion of MSV ...
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 - HADES, CBM, WASA, ...
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 - Dedicated Physics Working Groups formed
- **Hadron physics perspectives:**
 - Hadron spectroscopy & structure studies in u,d,s sectors, also charm
 - Intermediate **physics program** with **pions & protons** towards **antiprotons**
 - Interdisciplinary connections to astro-(particle) physics

EMMI Collaboration Meeting: QCD at FAIR Workshop 2025
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=> White paper submitted to PPNP

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**Thank you very much
for your attention!**