A cross-community-driven hadron physics program at GSI/FAIR

Towards a white paper!

Frank Nerling & Johan Messchendorp, Super-FRS EC Meeting, October 30, 2024



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- Heavy-ion physics:
 - Exploring dense QCD matter
 - Probe strongly-interacting many-body systems
 - Hadrons as probes of the medium
 - Properties of hadrons in a dense environment



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• Nuclear physics:

- Map out the nuclear spectrum in isospin and strangeness
- Properties of nuclei at the edge of stability, e.g. neutron-rich
- Probe baryon/meson degrees-of-freedom in many-body systems

[MeV] 200 Quarks and Gluons Critical point? Tempera Hadrons Color Super-Neutron stars conductor Nucle Net Baryon Density



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Hadron physics: ightarrow

- Map out the hadron spectrum
- Search for "exotic" forms of hadrons
- "Microscopic" study of hadron-hadron interactions



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- Hadron physics: lacksquare
 - Map out the hadron spectrum
 - Search for "exotic" forms of hadrons *Enable spectroscopy of (new)*
 - "Microscopic" study of hadron-hadron meracuons \bullet

Hadron interactions: Reference for understanding *medium effects*

> **Hadron interactions:** in flavour SU(3)

Provide baryon-baryon data

eV 200 Quarks and Gluons Critical point? Hadrons Color Super-Neutron stars conductor? Nucle Net Baryon Density

Hadron interactions: hadronic matter







Hadron Physics Facilities at FAIR





Hadron Physics Facilities at FAIR

antiProtons ANnihilations at DArmstadt (PANDA)

~203x



High Acceptance Di-Electron Spectrometer (HADES) (FAIR Phase Zero)

Today!

Hadron Physics Facilities at FAIR

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 $\bar{p}, p...(\text{HESR})$



High Acceptance Di-Electron Spectrometer (HADES) (FAIR Phase Zero)

Today!

 $\bar{p}, p...(\text{HESR})$

p,*d*...(SIS100)

Compressed Baryonic Matter (CB



Hadron Physics Facilities at FAIR

antiProtons ANnihilations at **DArmstadt (PANDA)**



High Acceptance Di-Electron Spectrometer (HADES) (FAIR Phase Zero)

Another goldmine in hadron physics at GSI!



~203x

Today!

p,*d*...(SIS100)

onic Matter (CBM)

Facilities at FAIR

antiProtons ANnihilations at DArmstadt (PANDA)

Purpose of our white paper ...how it all started

- Initiative from FAIR-motivated group from within various collaborations, such as CBM, HADES, PANDA
- Promote the realisation of First Science+ (FS+) at FAIR
- Identify a QCD-inspired physics program with proton beams
- Strengthen collaborations among hadron-, nuclear- and heavy-ion communities
- Reach out for new collaborators from both experiment and theory!

From SIS18 to SIS100 ...what could that add in hadron physics with protons?

	CBM ^{VIII} Experiment requirements									
			CBMVIII	Experiment	requiren	nents				
					lor	n type ^{ix}				
eam Parameters	р	⁴⁰ Ar	⁵⁸ Ni	¹⁰⁷ Ag	¹⁹⁷ Au	р	¹⁴ N	⁴⁰ Ar	⁵⁸ Ni	
		Operation in MS								
Time structure	slow extraction									
Spill length [s]	5			10		5			10	
per of ions per cycle	1010	4x:	10 ⁸	2x10 ⁸	10 ⁸	10 ¹²	1011	4x1	. 0 ¹⁰	
gy range [GeV/u] ^x	5-11, 14- 29	3-11, 12.4- 12.6	2-11, 12-14	2-1:	1	5-11, 14- 29	3-11, 12-14	3-11, 12- 12.6	2-11 12- 13.6	
f. energy <mark>[</mark> GeV/u]	29			11		29			11	
nsverse emittance 4σ) [mm mrad]	1 x 0.6									
entum spread (2σ)					5	x 10 ⁻⁴				
spot radius on tar- get [mm]						1				

From SIS18 to SIS10 ...what could that add in hadron physics with

- **Energy upgrade:**
 - From max 4.7 GeV (SIS18) to 29 GeV (SIS100) proton \bullet 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 ightarrow

ן	protons?

	reaction	\sqrt{s} (GeV)	T _{lab} (
	$pp \to K^+ \Lambda p$	2.548	1.6
SIS18	$pp \rightarrow K^+ K^- pp$	2.864	2.5
	$pp \rightarrow K^+ K^+ \Xi^- p$	3.247	3.7
	$pp \to K^+ K^+ K^+ \Omega^- n$	4.092	7.0
SIS100	$pp \rightarrow \Lambda \bar{\Lambda} pp$	4.108	7.1
	$pp \rightarrow \Xi^- \overline{\Xi}^+ pp$	4.520	9.0
\checkmark	$pp \rightarrow \Omega^- \overline{\Omega}^+ pp$	5.222	12.7
	$pp \rightarrow J/\Psi pp$	4.973	12.2

Picture credit: N. Herrmann, FAIR seminar, Krakow

GeV)	

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Intensity upgrade:

- From max #protons/cycle of 10¹² (SIS18) to 2x
- Even during "commissioning" (10¹⁰ protons/cy LH₂ target: ~10 pb⁻¹ day⁻¹

				read	ction		\sqrt{s} (GeV)	T _{lab} (G
				pp	$\rightarrow K^+ \Lambda p$		2.548	1.6
n protons?		S	SIS18	pp ·	$\rightarrow K^+K^-pp$		2.864	2.5
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		SIS	5100	pp ·	$\rightarrow \Lambda \bar{\Lambda} pp$		4.108	7.1
proton				pp	$\rightarrow \Xi^- \overline{\Xi}^+ pp$		4.520	9.0
				pp	$\rightarrow \Omega^{-} \overline{\Omega}^{+} p p$		5.222	12.7
				pp	$\rightarrow J/\Psi pp$		4.973	12.2
s and even	Expected r @ 30 GeV/	econ / <i>c</i> for	structed 1 MHz	coui	nts / Day	. H (rał E		
erons	$\Xi^{-} ightarrow \Lambda \pi^{-}$	_	~ 40 µ	Jp	1.2·10 ⁹	astSi		
	$\Omega^{-} \to \Lambda K$		~0.6	μb	1.4·10 ⁷	ylor Fa		
(10^{13})	$p \Lambda_C^0 D^0$		~0.1	μb	2.7·10 ^₄	iny Ta		
	pp J/ψ		~ 1 r	ıb	1.6·10 ³	Jer		
cie) and 5 cm			() ³⁵ 		$bb \rightarrow k$	$h^{-}(\rightarrow 5)$	pK ⁻ π^+) \overline{D}_0 (\rightarrow K % 3.8	, , , , , , , , , , , , , ,

Fast Simulations, J.M.

45 M_{Λ₀Đ₀} (GeV)

40

From SIS18 to SIS100what could that add in hadron physics with protons?

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Intensity upgrade:

- From max #protons/cycle of 10^{12} (SIS18) to 2×10^{13} (SIS100) lacksquare
- Even during "commissioning" (1010 protons/cycle) and 5 cm LH₂ target: ~10 pb⁻¹ day⁻¹

Detector enrichments:

Towards high-rate capabilities and free-streaming DAQ's ightarrow

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Picture credit: N. Herrmann, FAIR seminar, Krakow

T. Galatyuk, NPA 982 (2019), update 2023 https://github.com/tgalatyuk/interaction_rate_facilities

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- **Detector enrichments:**
 - Towards high-rate capabilities and free-streaming DAQ's ightarrow
- Theory enrichment:
 - Terra incognita: intellectual challenges in this energy regime!

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	Picture credit: N. Hei	rmann	

FAIR seminar, Krakow

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6-9 February 2024

Physics opportunities with proton beams at SIS100

 \bullet

Physics opportunities with proton beams at SIS100

6-9 February 2024 Wuppertal University

Europe/Berlin timezone

- Bring together experts from both theory and experiment
- Form a community connecting the common interest among different QCDdriven scientists
- Identify promising topics as a basis for a long-term proton-driven physics program
- Evaluate its complementarity with programs at other facilities
 - Prepare towards a white-paper

Physics opportunities with proton beams at SIS100 p, d, π, \bar{p} GSI/FAIR

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- Promising comprehensive physics program Strong support both theoretically and experimentally Provide a roadmap as basis for long-term endeavour Include the perspectives of *pion beams* at GSI/FAIR Involve the nuclear physics community

A comprehensive **CCD** program at GSI/FAIR!

Hadron structure

Mass-radius of the proton

E.m.+weak transition Form Factors of hyperons

Dilepton production sources

Production mechanisms axial and vector mesons

> Few-body interactions

Reference measurements for p+A,A+A

Polarisation sources

Near-threshold (anti) strange and charm production

Nuclear modification factors

Heavy-ion dynamics

Composition of hadrons

Hadron spectroscopy

Emergent Hadron Mass

Intrinsic charm of the proton

protons@SIS100

Strange and charm High intensity Versatile detectors High-rate capabilities SU(3) baryon-like spectroscopy

 $N \rightarrow N/\Delta$ GPDs via 2->3 hadronic reactions

> Line-shape measurements of hyperon resonances

Femtoscopy

Hypernuclei via spallation Charm-nucleon interactions

> **Final-state** interactions using PWA

Search for exotic form of hadrons

> Hadron production

Production mechanisms of hadrons

Microscopic study of hadron-hadron interactions

A comprehensive **CCD** program at GSI/FAIR!

Hadron

structure

Reference measurements for p+A,A+A

dynamics

Composition of hadrons

hadron-hadron interactions

A roadmap towards a **QCD** program at FAIR!

White paper:

- Paper is in the making!
- ~75 contributors so far!
- Including leading theorists and experimentalist from strong-QCD communities
- Publication ~spring 2025

Hadron Physics at GSI and FAIR: Prospects for the Next Decade

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Editors: Frank Nerling, Johan Messchendorp

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Coming up soon!

- White-paper workshop
- <u>November 11-14, 2024</u>, **GSI**
- Open plenary sessions with highlight talks
- Closed (parallel) working sessions

TUB

https://indico.gsi.de/event/20301/overview

Pion beams at GSI/FAIR *The* focus of HADES for next years!

Joachim Stroth, POFV retreat

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What makes $\pi + p/A$ interactions so appealing?precision probe in subatomic physics!

What makes $\pi + p/A$ interactions so appealing?precision probe in subatomic physics!

- The pion-nucleon system elementary in hadron, nuclear, and heavy-ion physics Proven valuable probe of strong QCD, both
- theoretically and experimentally
- 'Simple' initial state with spin-zero Goldstone boson; 'Simple' final states, 2/3-bodies

What makes $\pi + p/A$ interactions so appealing?precision probe in subatomic physics!

- The pion-nucleon system elementary in hadron, nuclear, and heavy-ion physics • Proven valuable probe of strong QCD, both
- theoretically and experimentally
- 'Simple' initial state with spin-zero Goldstone boson; 'Simple' final states, 2/3-bodies
- Theory: Lattice-QCD, (χ) EFT in SU(3)_F, Dyson-Schwinger BS: close to first principles of QCD!
- Experiment: sizeable cross sections w.r.t. electromagnetic beams, simple final states -> high acceptance, enable PWA, etc. ...

- Unique combination of pion beam and dilepton spectrometer + much more!
- Large phase space coverage + wide particle reconstruction capabilities
- \sqrt{s} coverage and scan up to ~2 GeV, complementary photo-production exp^s
- Respectable intensities beyond 10⁶/s
- Sizeable xsecs for strangeness production w.r.t. light hadrons, strangeness factory!
- Access to many observables: xsections, BF's, SDMEs, self-polarisation weak decay
- Precision studies combining hadron dynamics and electromagnetic structure

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Pion beam program ... wide physics oppor Ū **Hadron Physics**

- Baryon |S|=0,1 spectroscopy in fo f.e. N* up to 3rd resonance regions
- Polarisation studies in hyperon pr $\pi^- p \rightarrow \overrightarrow{\Lambda} K^0 / \overrightarrow{\Sigma}^0 K^0 / \dots$ (self-ana **•** 10⁻⁶
- Vector-meson production: $\pi^- p$ -0.2 extraction ($\omega \rightarrow e^+ e^- / \pi^+ \pi^- \pi^0$ topologies)
- Strangeness production, e.g. $\Lambda(1405, 1520)$
- Electromagnetic structure of |S|=0,1 baryons, $N^* \rightarrow Ne^+e^-/\Lambda(1405, 1520), \Sigma(1385) \rightarrow Ne^+e^-/\Lambda(1405, 1520)$
- Light meson dynamics, f.e. in $\pi\pi$, $K\overline{K}$, $K\pi$, $\eta\pi$, ...
- Rare (BSM) decays of mesons, f.e. X(17) with η decays lacksquare

Pion beam program ... wide physics opportunities **Nuclear and Heavy-ion Physics**

- Vector meson properties in dense matter including study of $\rho - a_1$ mixing, ϕ meson!
- Line-shape, transparency ratios, A-dependence,... (towards low momenta with high sensitivity)
- Hidden & open strangeness production in $\pi + p/A$
- Precision data for transport models
- Hypernuclei studies, factory!
- $\overrightarrow{YN} \rightarrow \overrightarrow{YN}$ interactions
- Particle production xsection data for neutrino energy reconstruction in T2K, DUNE experiments

A "cold matter" *highlight* from 2014 pion beam at $\sqrt{s} = 2 \,\text{GeV}$

Latest work of Simon Spies

A cross-community-driven hadron physics program at GSI/FAIR ...with pion and proton beams from SIS18+SIS100

- Ambition: long-term physics program inspired by strong-QCD and connecting hadron, nuclear, and heavy-ion communities
- Exploiting pion & proton beams (SIS18/100) together with available facilities: HADES, CBM, WASA(?) and interested researchers from all communities!
- Invitation to nuclear physics community to take part in the white-paper discussions and contribute!
- GPAC proposal: strengthen the pion-beam facility and corresponding physics program! Strategy involving WASA?

"Facilities exploiting exclusive hyperon studies"

Timolino			
	2025		2028
Probe:	FAIR	Phase 0	
$\pi + n/A$		Stage 1	HADES
			JF
n + n/A		HADES	@SIS18
			CERN ,
$\bar{p} + p/A$			
K + p/A			JPAR
$\gamma^{(*)} + p/A$	N	1AMI/ELSA/GLue	X/CLAS12
$e^+ + e^-$		BESIII/B	ellell

J-PARC ... competition, complementarity, collaboration? Key selling features of pion-beam facility at GSI

- Combination of a pion beam with a versatile setup with high acceptance and capabilities
- Broad applicability with multifaceted and efficient data collection enabling a program connecting physics topics from different fields (hadron, nuclear, heavy-ion) with(in) one setup/ collaboration/beam-time period
- Probing electromagnetic and hadronic aspects in pion-produced matter is unique

The process ...activities in the past years

- Many preparatory activities ongoing since 2023
- Discussions among physicists from various FAIR collaborations
- Kick-off satellite event at MESON2023 in June 2023
- Feasibility studies using Monte Carlo simulations
- Presentations at FAIR advisory boards ECE/ECSG/JSC at workshops, conferences, etc.
- Workshop "physics opportunities with proton beams at SIS100" in Wuppertal, February 2024
- Setup structure white paper, identify convenors, contributors, setup working groups, overleaf, mailinglists, etc.
- White paper workshop, 11-14th November, 2024 at GSI

October 2023

- HADES = high-acceptance dilepton spectrometer and much more!
- Outstanding in dilepton spectrometry
- Excellent tracking & PID capabilities
- Modular at forward angles
- Additional photon detection
- Good angular coverage
- Designed for various SIS18 beams
- Including pion beams!

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"exclusive" reactions!! [Case study: Feb. 2022 run with 4.5 GeV protons]

Extract Spin Density Matrix Elements

KEENGEENWEIER UNIFORWAARI $\pi N \rightarrow 2\pi N$ SCATTERING

A. The issue of unitarity rone de Gay mp 6 and key issues i . This constraint is maintained it nent of the scattering problem. The α including $\alpha \rightarrow \alpha$, $\alpha \rightarrow \alpha$ including α include α include α

HADES data

- contribution (pion emFF)

KEEncleenweith Uniforwardi $\pi N \rightarrow 2\pi N$ SCATTERING

rone de Gay mponant key issues i . This constraint is maintained it nent of the scattering problem. The $\frac{1}{2}$

$\pi N \rightarrow 2\pi N$ SCATTERING

 $\frac{1}{2}$

- From heavy-ion perspectives:
 - Necessary reference to heavy-ion reactions

Detailed information on baryon resonances and meson-baryon couplings

- From heavy-ion perspectives:
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- From nuclear perspectives:
 - (Ab-initio) baryon-baryon data in flavour SU(3)

Detailed information on baryon resonances and meson-baryon couplings

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 - Necessary reference to heavy-ion reactions
 - Detailed information on baryon resonances and meson-baryon couplings
- From nuclear perspectives:
 - (Ab-initio) baryon-baryon data in flavour SU(3)
- From hadron perspectives:
 - Controllable tool for hadron spectroscopy & structure studies in u,d,s,c sectors
 - Intermediate physics program with pions & protons towards antiprotons

The ba	pov t mak	Ver (es us	of p s com	bion petit	beal ive & co	ms at GSI omplementary	$2^{0} \qquad 0.1^{10} \qquad \pi^{N->\pi N} \qquad \pi^{n} \qquad \pi^{n$	$\pi p \rightarrow M^{0} \Lambda$ $\pi p \rightarrow K^{0} \Lambda$ $\pi p \rightarrow K^{0} \Lambda$ $\pi p \rightarrow K^{0} \Lambda$
"2020	" pro	posa	1 (143	Shift	S)		0.01 - 1.2	$1.4 \qquad 1.6 \qquad 1.8$ $\sqrt{S} (GeV)$
channel	ε_{AR}	$\sigma_H \ ({ m mb})$	σ_C (mb)	$\sigma_{Ag} \ ({ m mb})$	BR	$\frac{C_2 H_4 \text{ target}}{\dot{N}_H / \dot{N}_{tot} \text{ (shift}^{-1})}$	$ \begin{array}{c} \hline C \text{ target} \\ \dot{N}_C(\text{shift}^{-1}) \end{array} $	$egin{array}{c} { m Ag targe} \ \dot{N}_{Ag} ({ m shift}^{-}) \end{array}$
$\pi^-\pi^+$ n	0.14	10	16	63	1	$3.4 imes 10^6 / 6.1 imes 10^6$	3.8×10^{6}	2.0×10
$\pi^-\pi^0~{ m p}$	0.09	6.5	10.4	41	1	$1.4~ imes 10^{6}/2.6~ imes 10^{6}$	1.6×10^{6}	$8.6 \times 10^{\circ}$
$\pi^0\pi^0~{ m p}$	0.01	2	3.2	13	1	$4.9 \ imes 10^4 / 8.8 \ imes 10^4$	5.4×10^{4}	$2.9\! imes\!10^4$
$\mathrm{K}^{0}\Lambda$	0.04	0.56	1.85	7.3	0.35	$1.9\times10^4/5.0\times10^4$	$4.3 imes 10^4$	2.4×10
$\mathrm{K}^{0}\Sigma^{0}$	0.04	0.24	0.79	3.1	0.35	$8\times 10^3/2.2\times 10^4$	1.9×10^4	1.0×10
$K^+\Sigma^-$	0.13	0.23	0.76	3.0	1	$7.2\times10^4/1.9\times10^5$	$1.7 imes 10^5$	9.0 imes 10
ηn	0.01	1.2	3.96	15.6	0.39	$1.2\times 10^4/3.1\times 10^4$	$2.6 imes 10^4$	1.4×10
ωn	0.015	1.5	4.95	19.5	0.89	$4.9\times10^4/1.3\times10^5$	1.1×10^5	4.0×10
$ ho ightarrow { m e}^+ { m e}^-$	0.25	2.1	6.93	90.3	610^{-5}	78/204	176	95
$\omega \rightarrow e^+e^-$	0.31	1.7	5.61	73.1	7.410^{-5}	84/222	190	104

Existing "2020": $\sqrt{s} = 1.67 - 1.79 \,\text{GeV}$

The <i>wha</i> <i>"</i> 2020	pov t mak	Ver (es us posa	of r s com	Dion opetit S shift	bear ive & co	ms at GSI omplementary	$2^{2} = 0.1^{10} = 0.1^{10} = 1.2^{10}$	$\pi p \rightarrow \eta n$ $\pi p \rightarrow \kappa^{0} \Lambda$
channel	ε_{AR}	σ_H	σ_C	σ_{Ag}	BR	C_2H_4 target	C target	Ag targe
		(mb)	(mb)	(mb)		$\dot{N}_H / \dot{N_{tot}}$ (shift ⁻¹)	$\dot{N}_C(\mathrm{shift}^{-1})$	$\dot{N}_{Ag}(\mathrm{shift})$
$\pi^-\pi^+$ n	0.14	10	16	63	1	$3.4 \ imes 10^6 \ / 6.1 \ imes 10^6$	3.8×10^{6}	$2.0 \times 10^{\circ}$
$\pi^-\pi^0~{ m p}$	0.09	6.5	10.4	41	1	$1.4 \ imes 10^{6} / 2.6 \ imes 10^{6}$	1.6×10^{6}	8.6×10^{-10}
$\pi^0\pi^0~{ m p}$	0.01	2	3.2	13	1	$4.9 \times 10^4 / 8.8 \times 10^4$	5.4×10^4	$2.9\! imes\!10^4$
${ m K}^0 \Lambda$	0.04	0.56	1.85	7.3	0.35	$1.9 imes10^4/5.0 imes10^4$	$4.3 imes 10^4$	2.4 imes 10
$\mathrm{K}^{0}\Sigma^{0}$	0.04	0.24	0.79	3.1	0.35	$8\times 10^3/2.2\times 10^4$	1.9×10^4	$1.0 \times 10^{\circ}$
$K^+\Sigma^-$	0.13	0.23	0.76	3.0	1	$7.2\times10^{4}/1.9\times10^{5}$	$1.7 imes 10^5$	9.0 imes 10
ηn	0.01	1.2	3.96	15.6	0.39	$1.2 imes10^4/3.1 imes10^4$	$2.6 imes 10^4$	$1.4 \times 10^{\circ}$
ωn	0.015	1.5	4.95	19.5	0.89	$4.9 imes 10^4 / 1.3 imes 10^5$	1.1×10^5	$4.0 \times 10^{\circ}$
$ ho ightarrow e^+ e^-$	0.25	2.1	6.93	90.3	610^{-5}	78/204	176	95
$\omega \rightarrow e^+e^-$	0.31	1.7	5.61	73.1	7.410^{-5}	84/222	190	104

Existing "2020": $\sqrt{s} = 1.67 - 1.79 \,\text{GeV}$

New "2024": $\sqrt{s} = 1.37 - 2.3 \,\text{GeV}$

