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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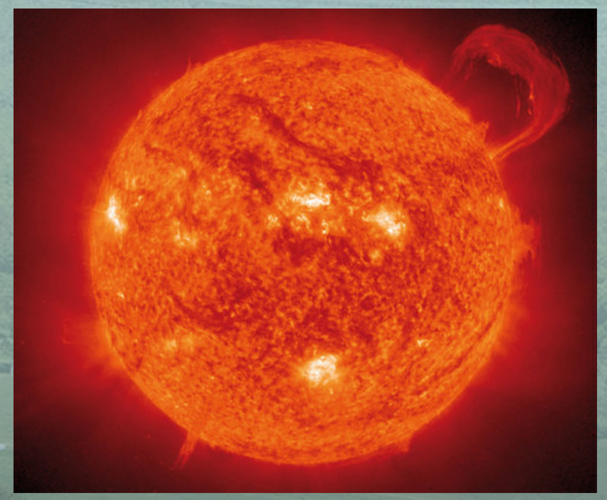

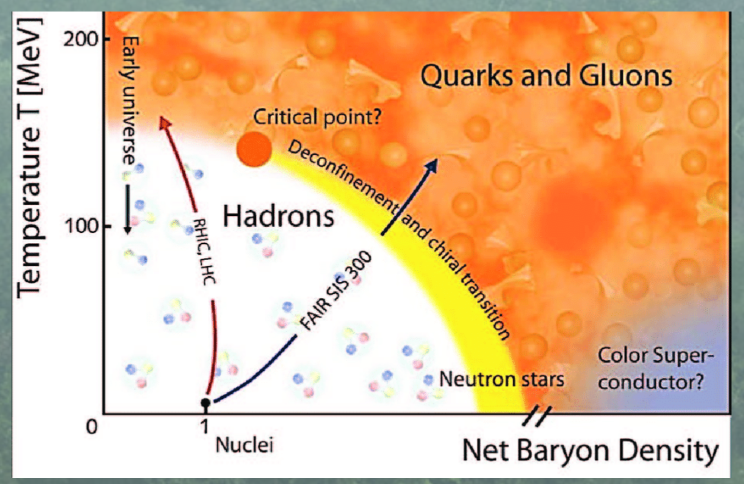

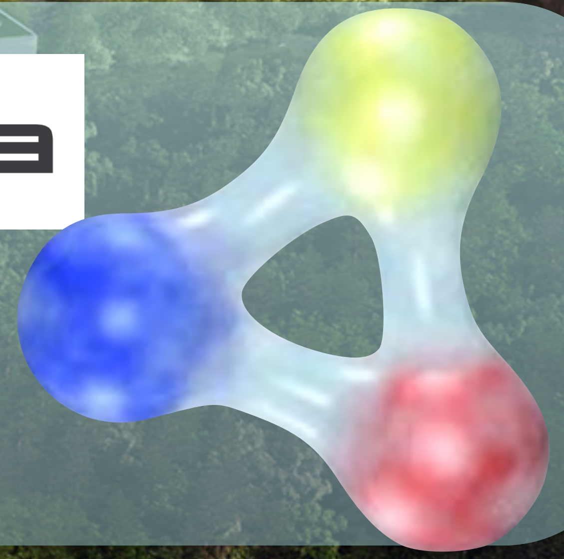

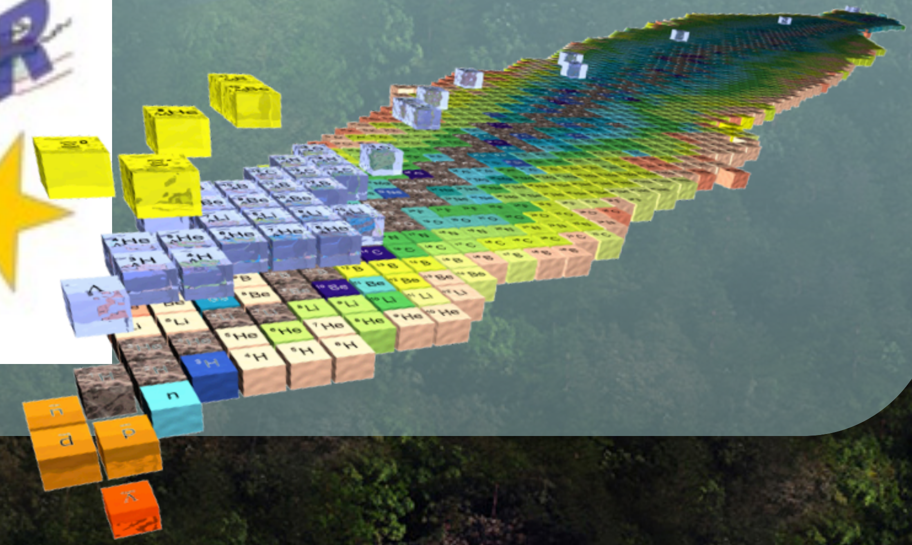

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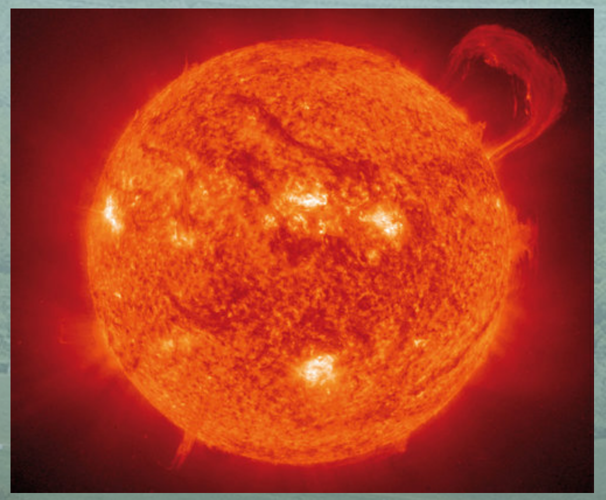
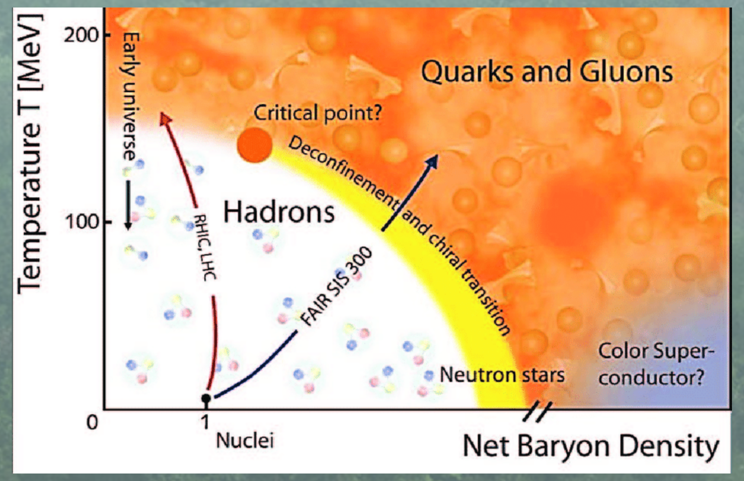
APPA

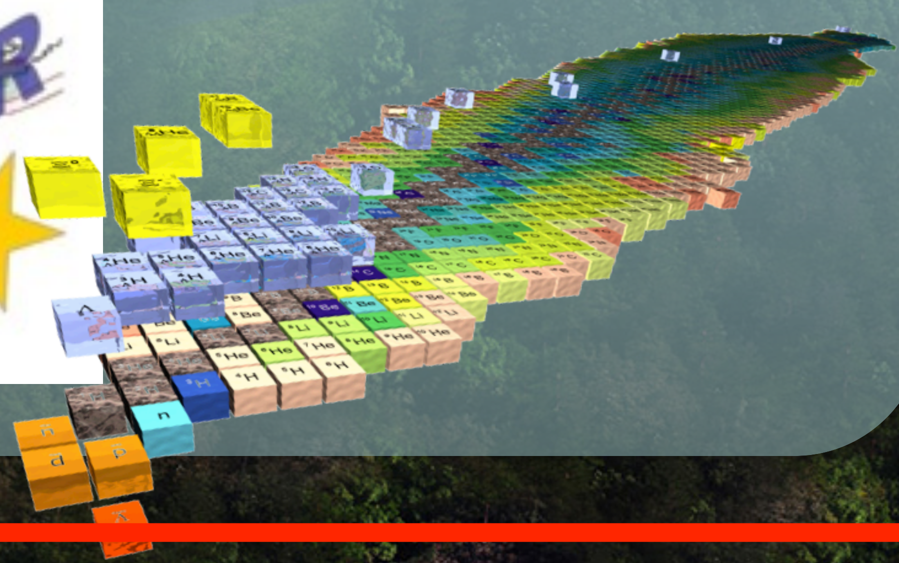


CBM



panda

NUSTAR



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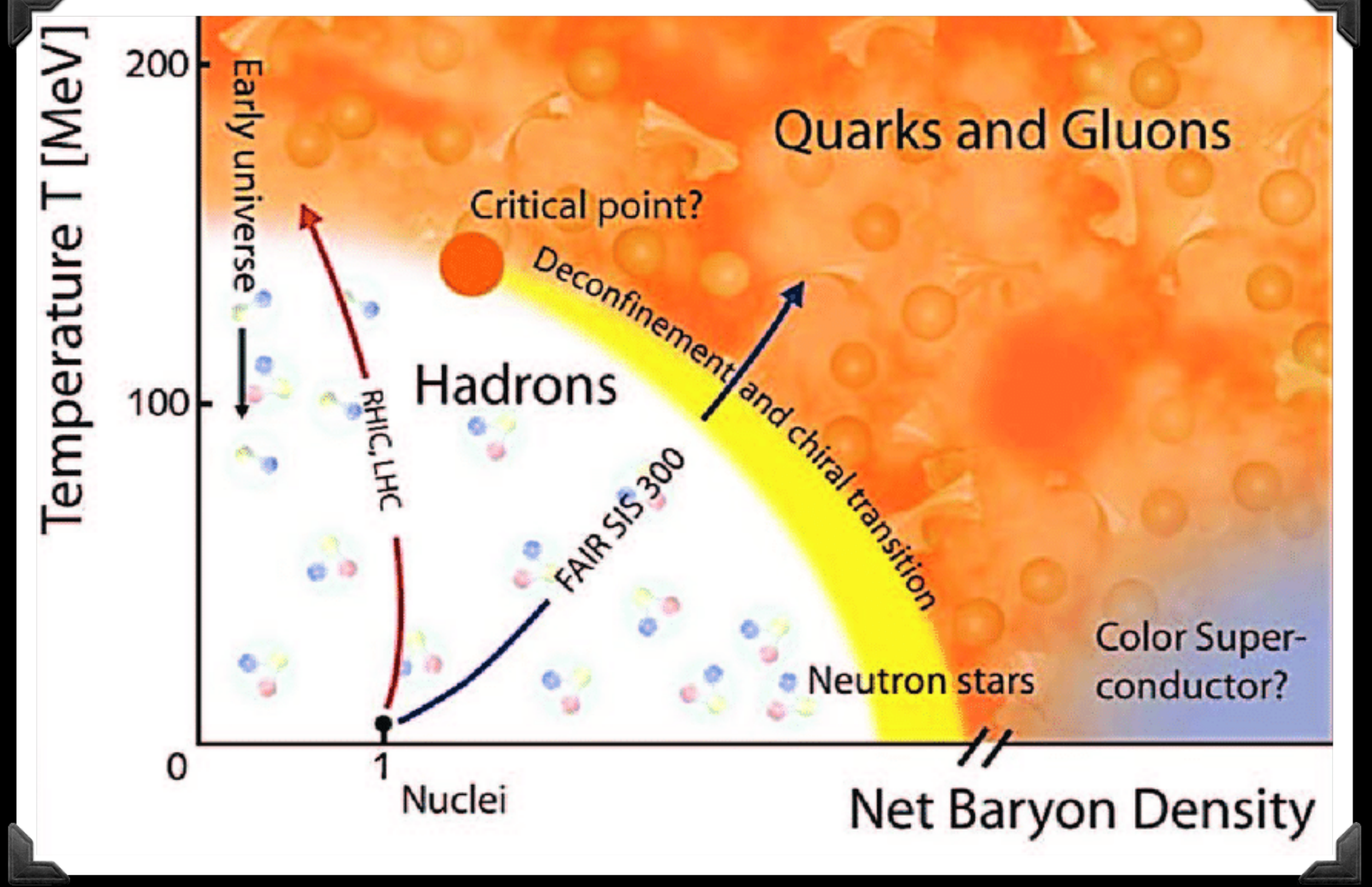
Methodologies at FAIR

...QCD matter at *extremes*

Methodologies at FAIR

...QCD matter at *extremes*



- **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

Methodologies at FAIR

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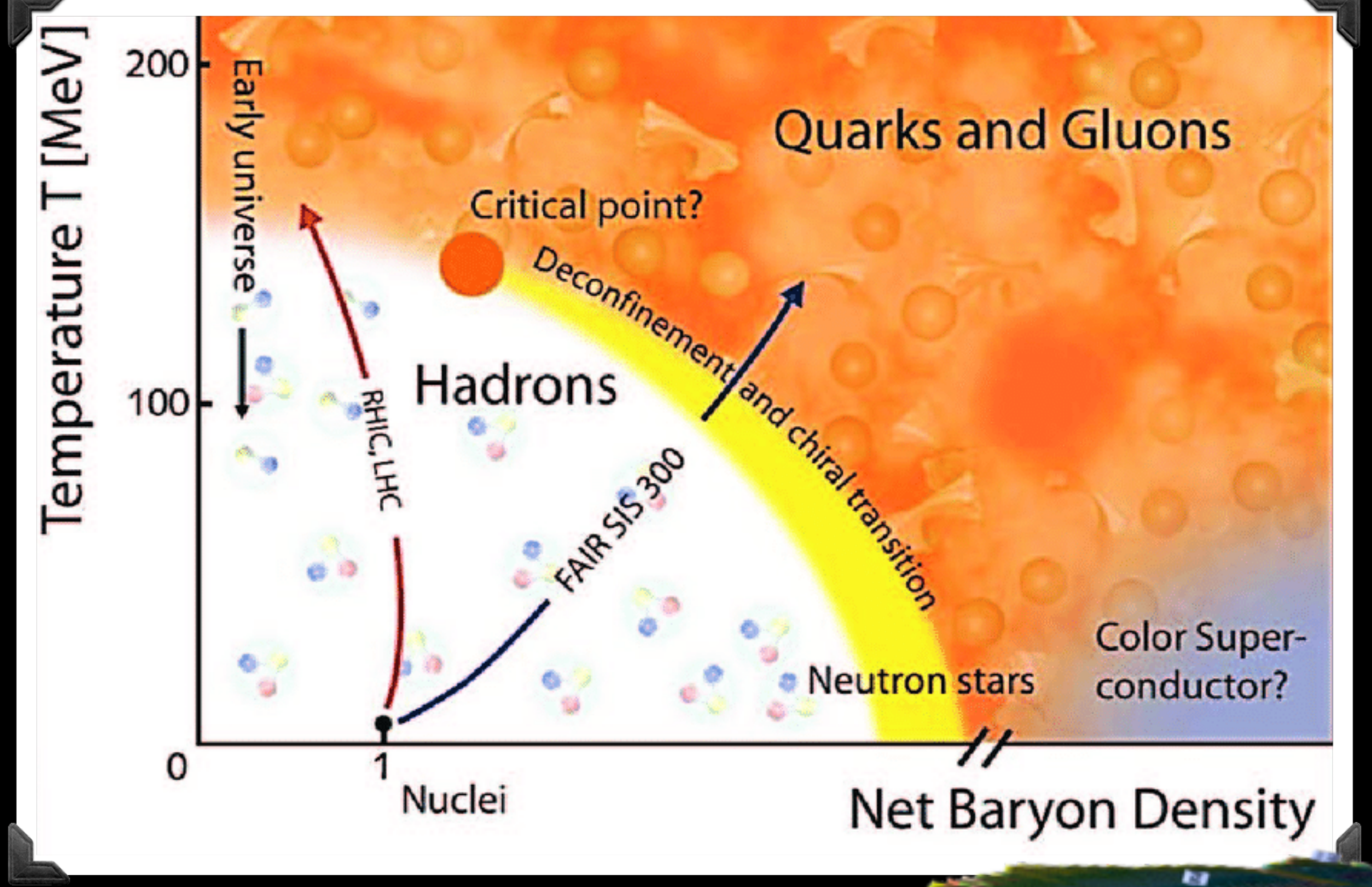

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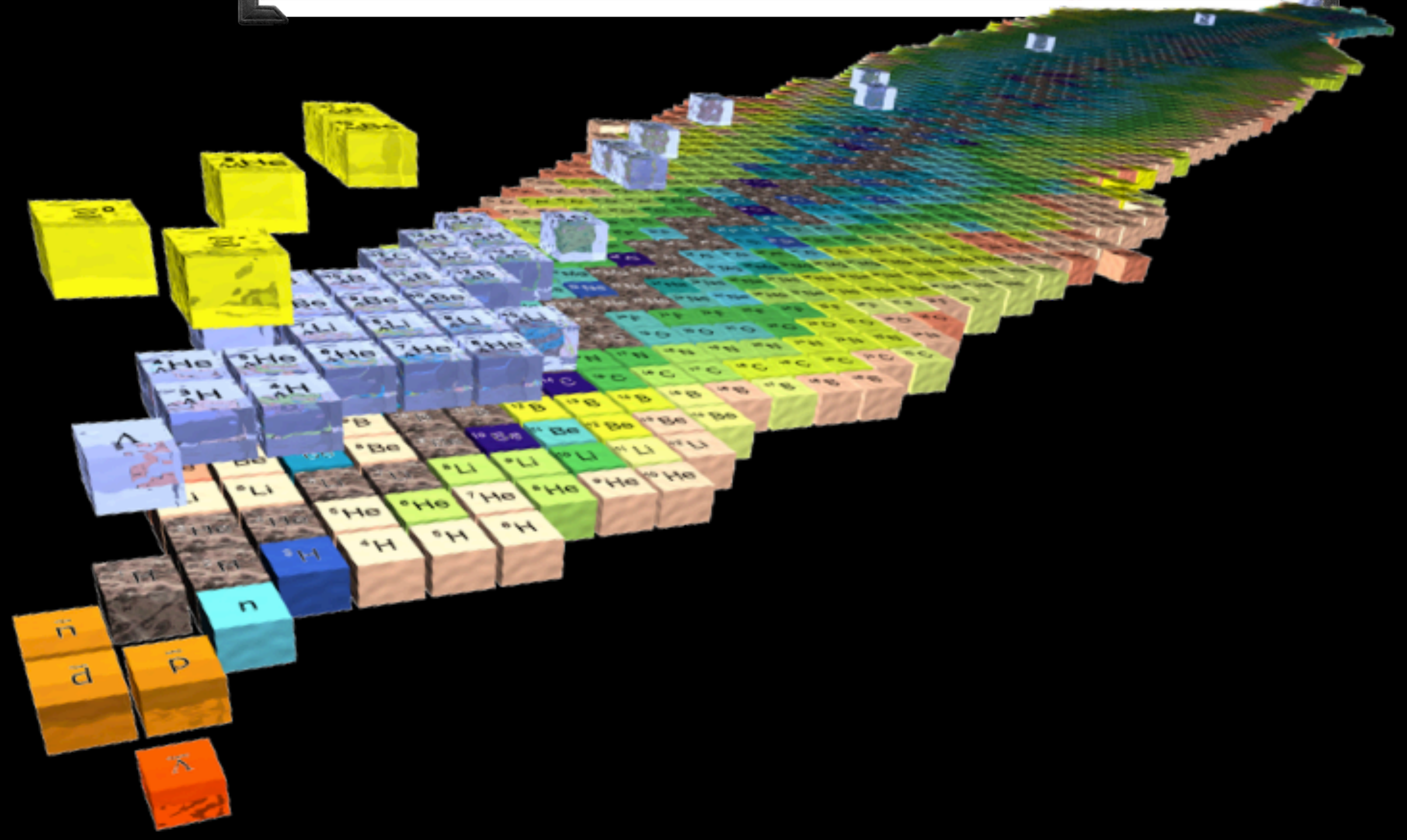

- **Nuclear physics:**
  - Map out the nuclear spectrum in isospin and strangeness
  - Properties of nuclei at the edge of stability, *e.g.* neutron-rich
  - Probe baryon/meson degrees-of-freedom in many-body systems

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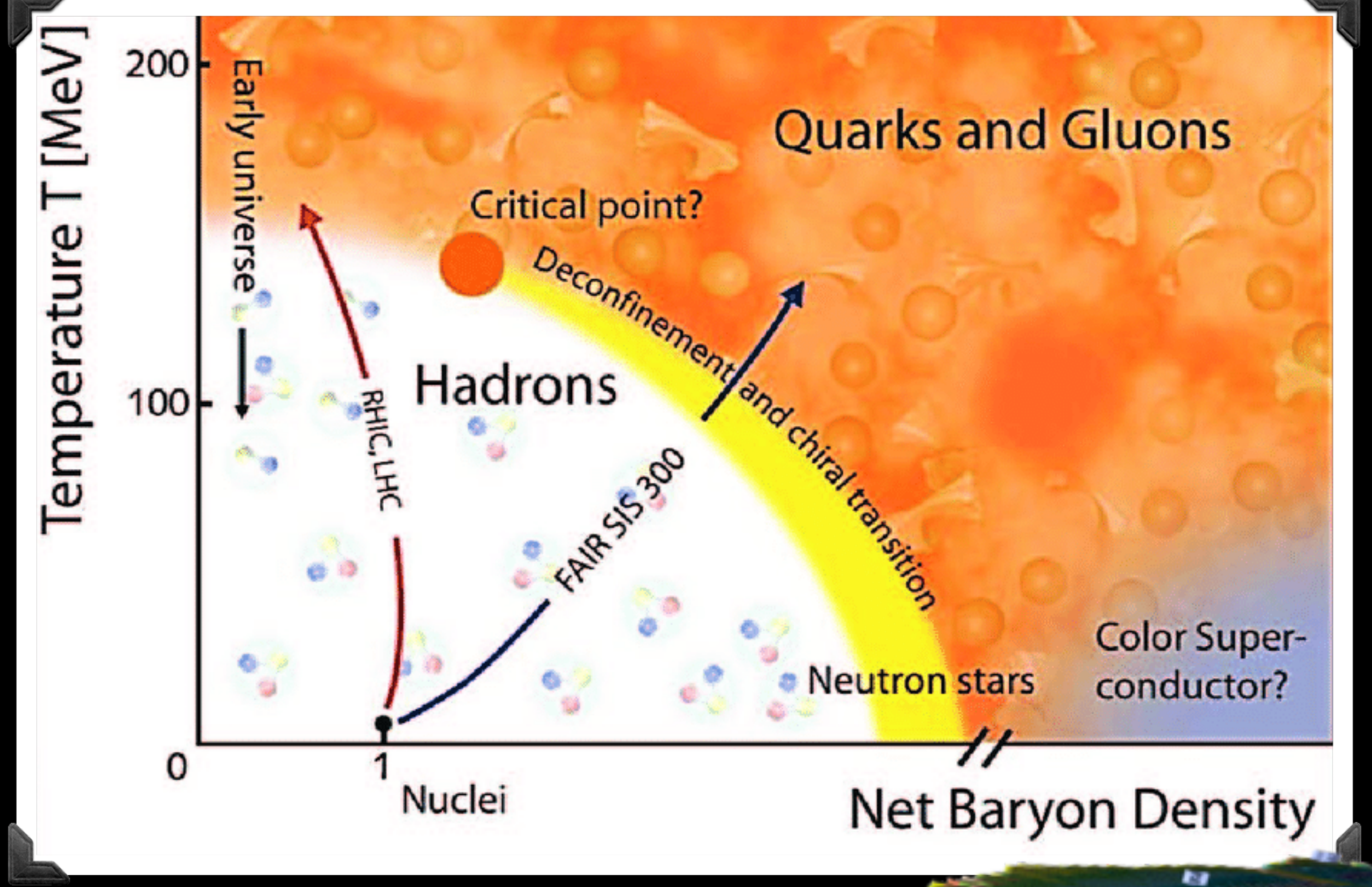

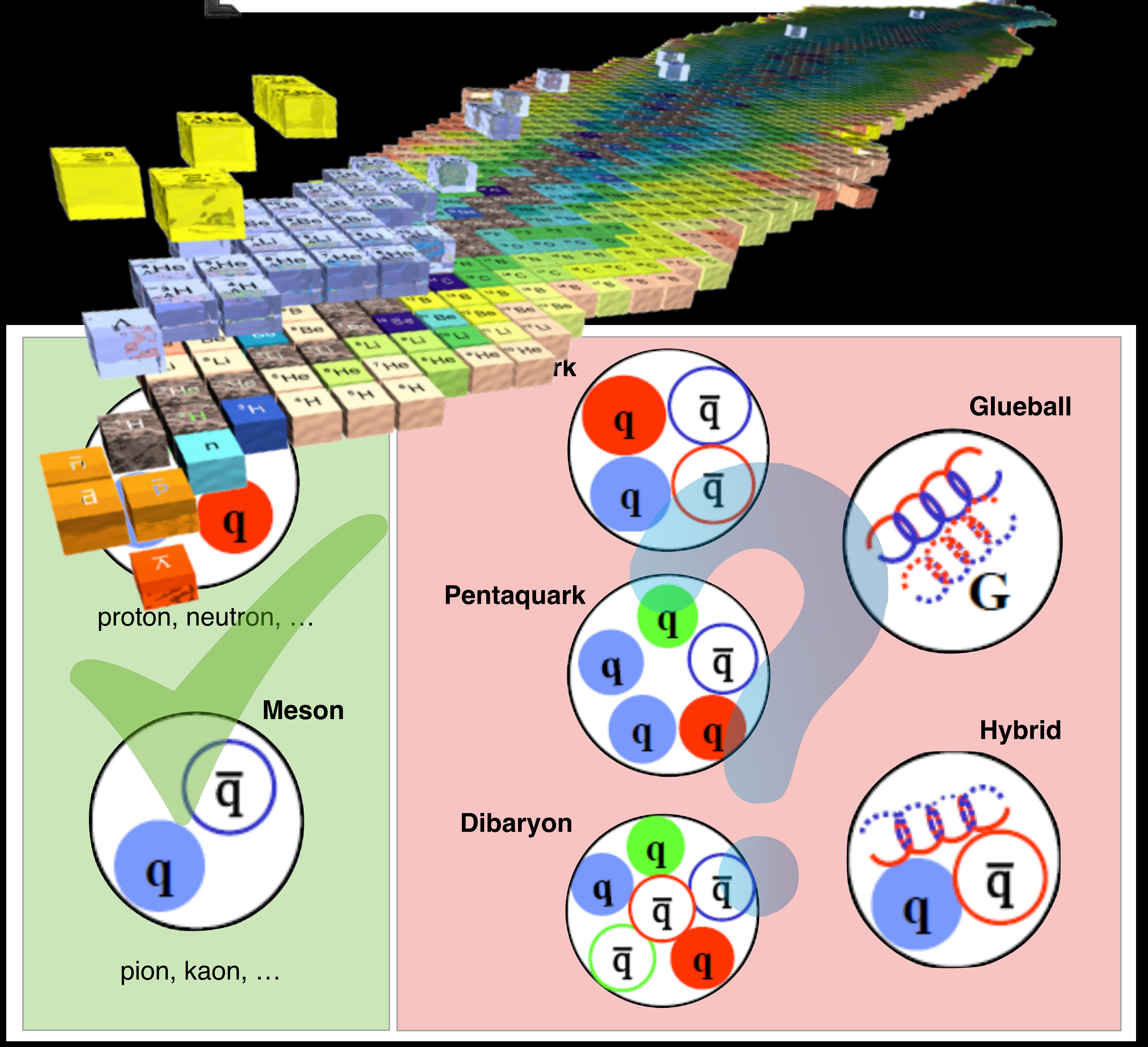

Methodologies at FAIR

...QCD matter at *extremes*

- **Heavy-ion physics:**
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Hadron interactions:
Reference for understanding medium effects

- **Nuclear physics:**
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Hadron interactions:
Provide baryon-baryon data in flavour SU(3)

- **Hadron physics:**
  - Map out the hadron spectrum
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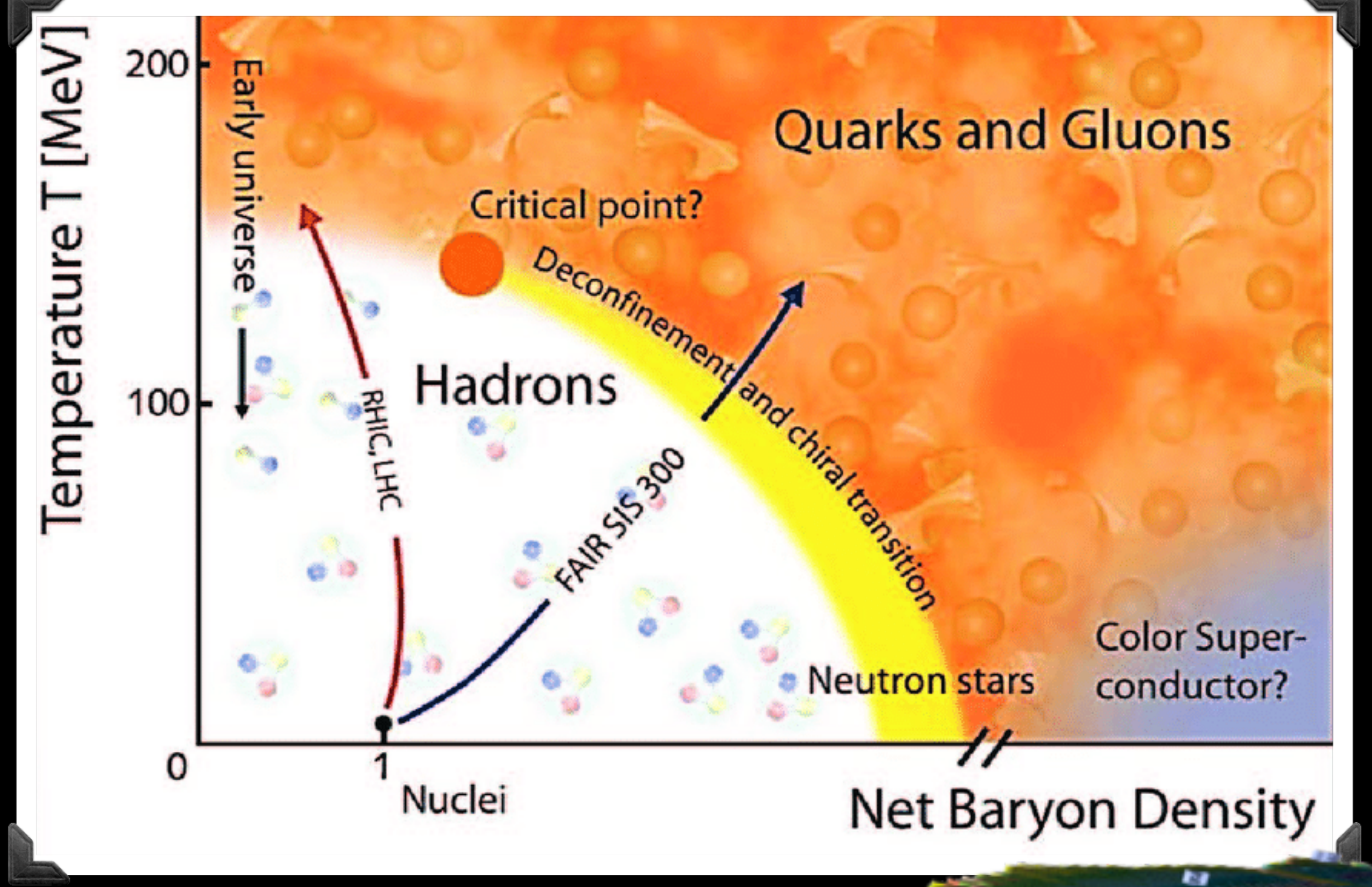
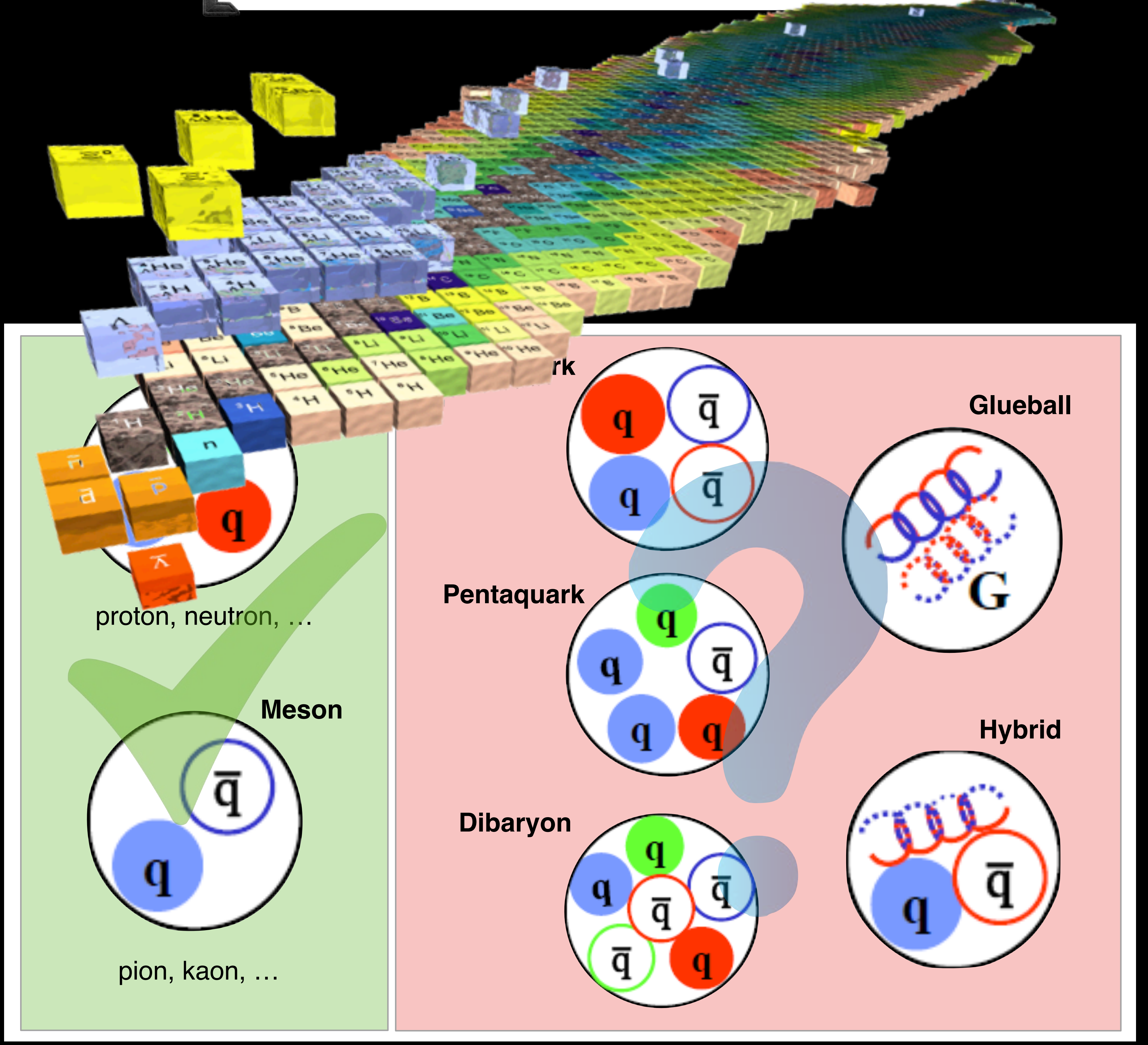
  - "Microscopic" study of hadron-hadron interactions

Hadron interactions:
Enable spectroscopy of (new) hadronic matter






Hadron Physics
Facilities at FAIR

Hadron Physics Facilities at FAIR


High Acceptance Di-Electron
Spectrometer (HADES)
(FAIR Phase Zero)
$\pi, p, d \ldots$(SIS18)
Today!
$\bar{p}, p \ldots$(HESR)
~203x
Hadron Physics
Facilities at FAIR
antiProtons ANnihilations at
DArmstadt (PANDA)

High Acceptance Di-Electron Spectrometer (HADES)
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$\pi, p, d\ldots$(SIS18)
Today!
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Compressed Baryonic Matter (CBM)
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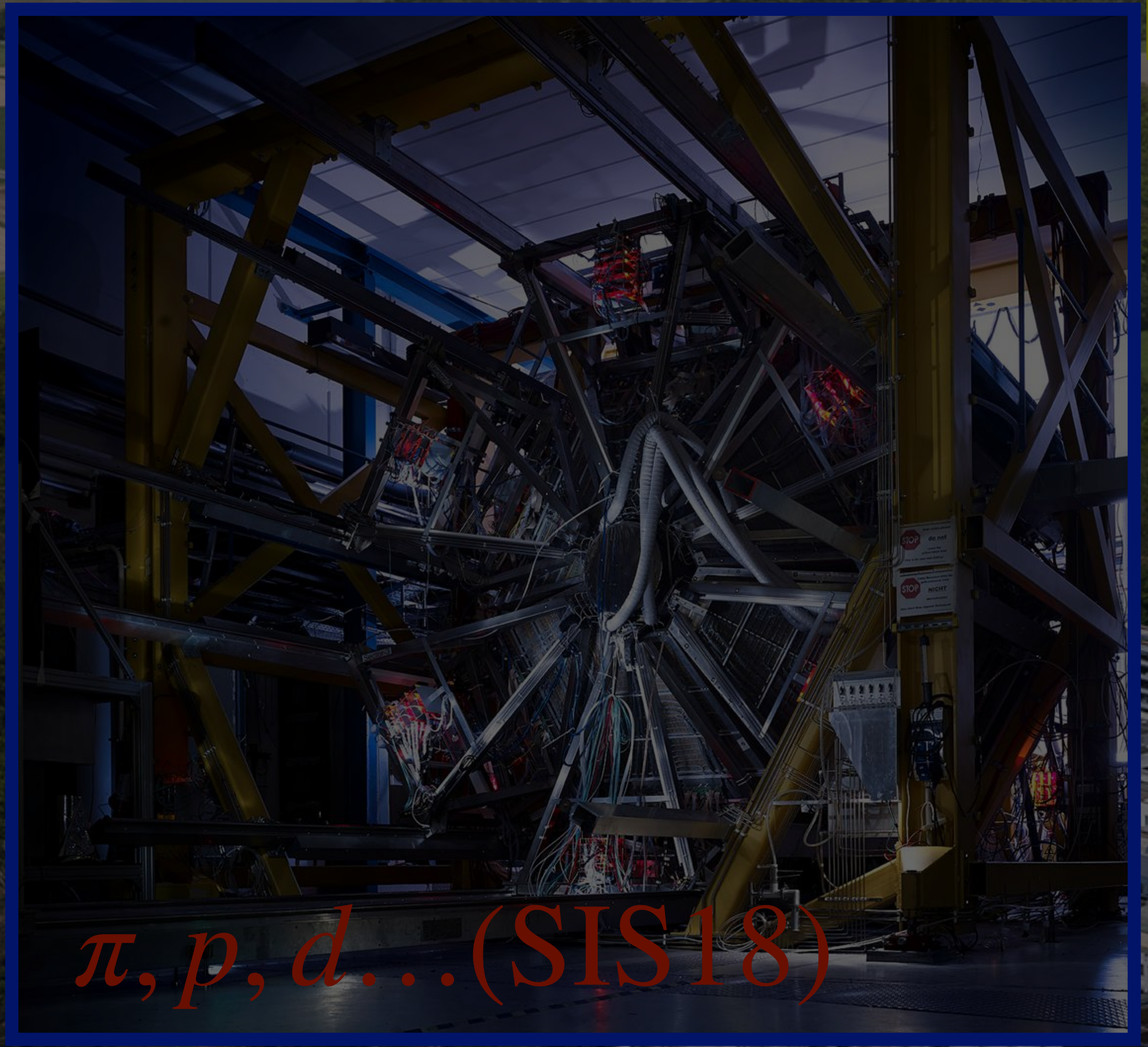
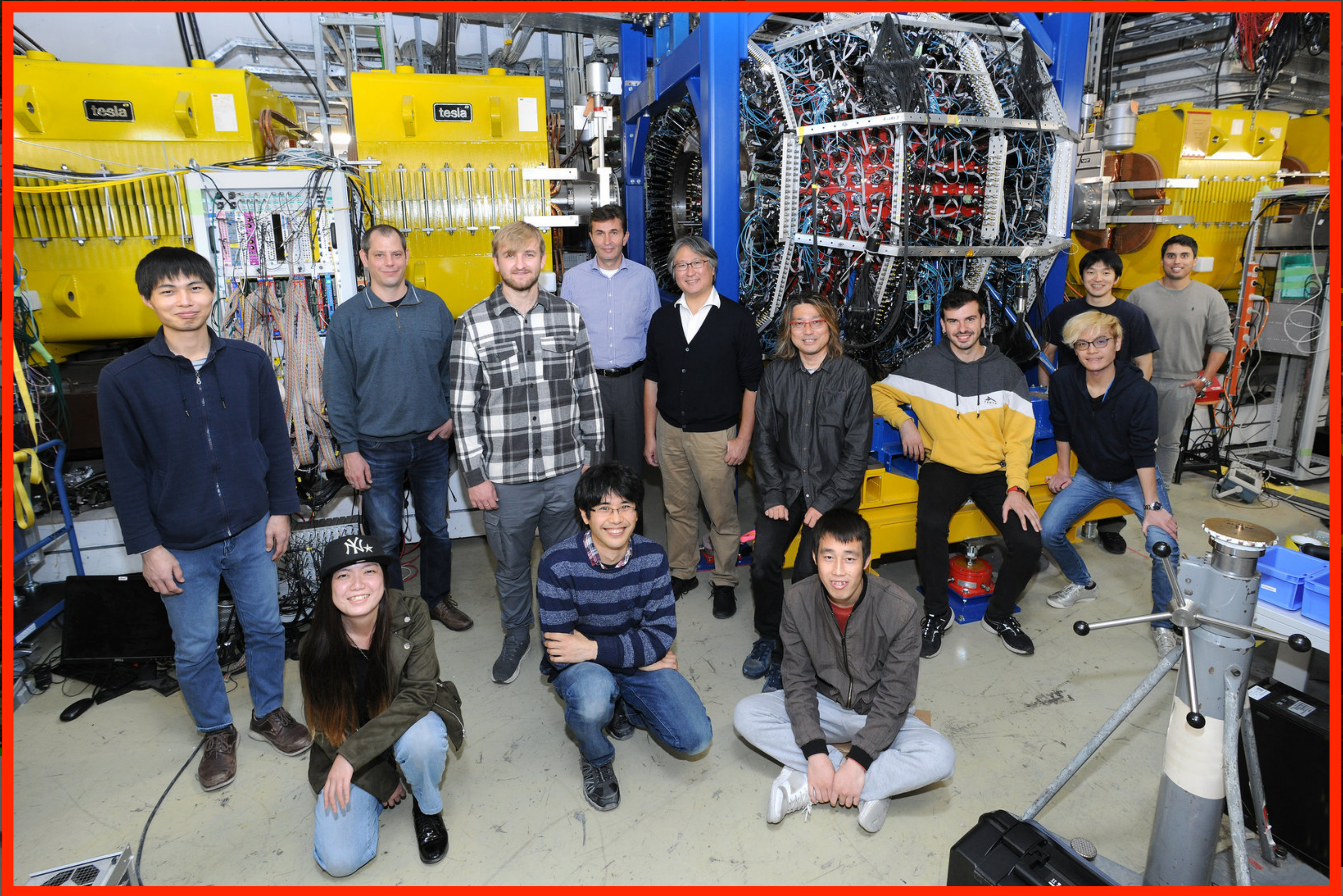


Today!

onic **Matter (CBM)**

~2028

Another goldmine in **hadron physics** at GSI!



~203x

adron Physics Facilities at FAIR

anti**P**rotons **AN**nihilations **at DA**rmstadt **(PANDA)**

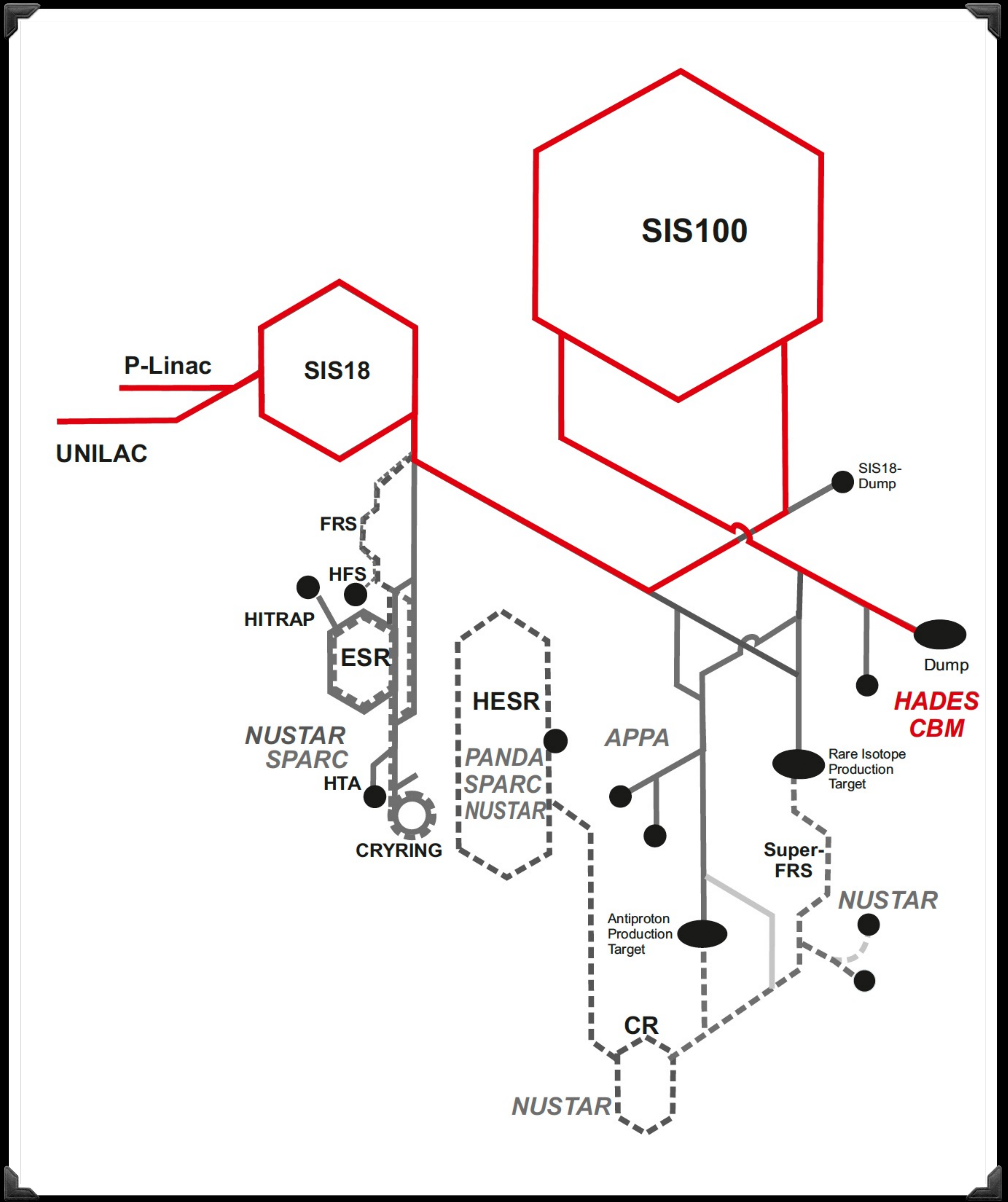
Purpose of our *white paper*

…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?



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

	reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
SIS18	$pp \rightarrow K^+\Lambda p$	2.548	1.6
	$pp \rightarrow K^+K^-pp$	2.864	2.5
	$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7
SIS100	$pp \rightarrow K^+K^+K^+\Omega^-n$	4.092	7.0
	$pp \rightarrow \Lambda\bar{\Lambda}pp$	4.108	7.1
	$pp \rightarrow \Xi^-\bar{\Xi}^+pp$	4.520	9.0
	$pp \rightarrow \Omega^-\bar{\Omega}^+pp$	5.222	12.7
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Picture credit: N. Herrmann, FAIR seminar, Krakow

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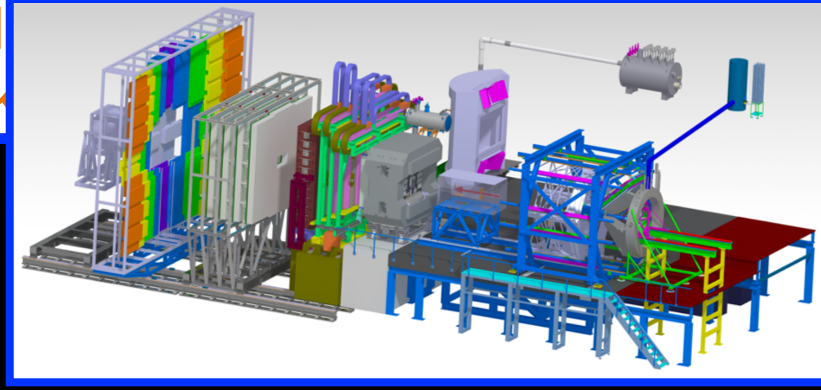
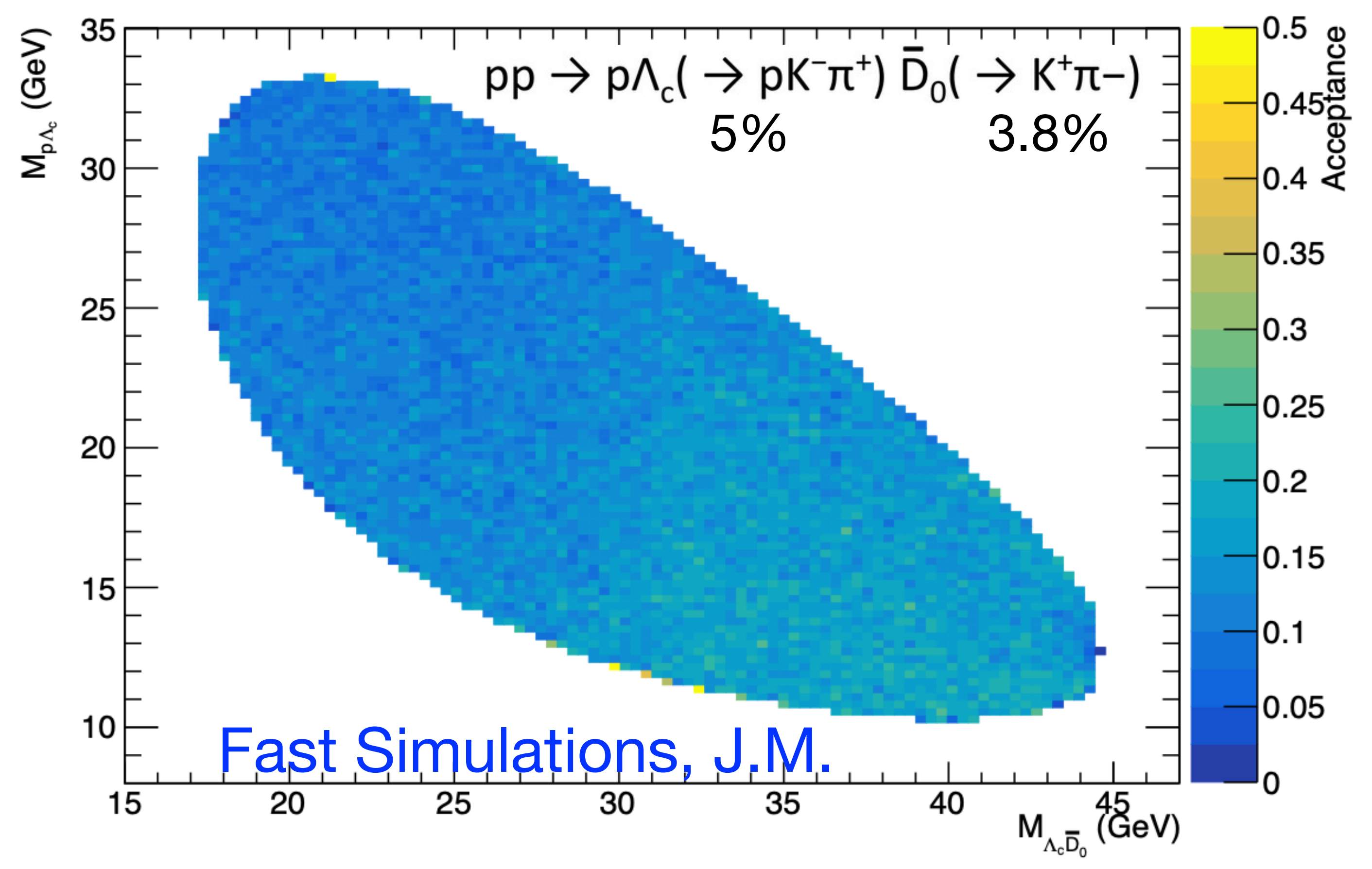
Expected reconstructed counts / Day @ 30 GeV/c for 1 MHz

$\Xi^- \rightarrow \Lambda\pi^-$	~ 40 μb	**$1.2\cdot10^9$**
$\Omega^- \rightarrow \Lambda K^-$	~ 0.6 μb	**$1.4\cdot10^7$**
p $\Lambda_C D^0$	~ 0.1 μb	**$2.7\cdot10^4$**
pp J/ψ	~ 1 nb	**$1.6\cdot10^3$**

Jenny Taylor FastSim





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  - Towards high-rate capabilities and free-streaming DAQ’s

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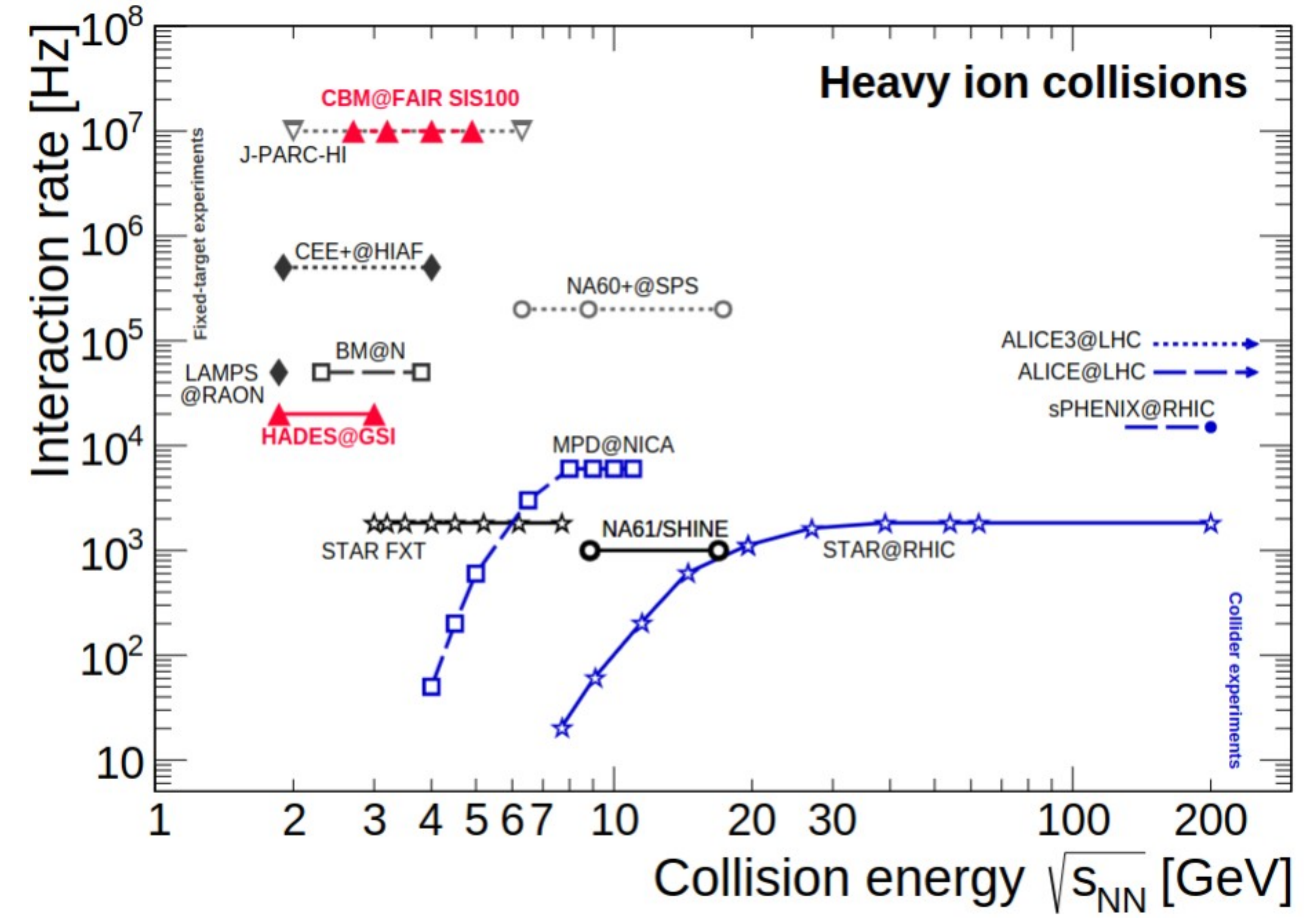

T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities

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- **Theory enrichment:**
  - Terra incognita: intellectual challenges in this energy regime!

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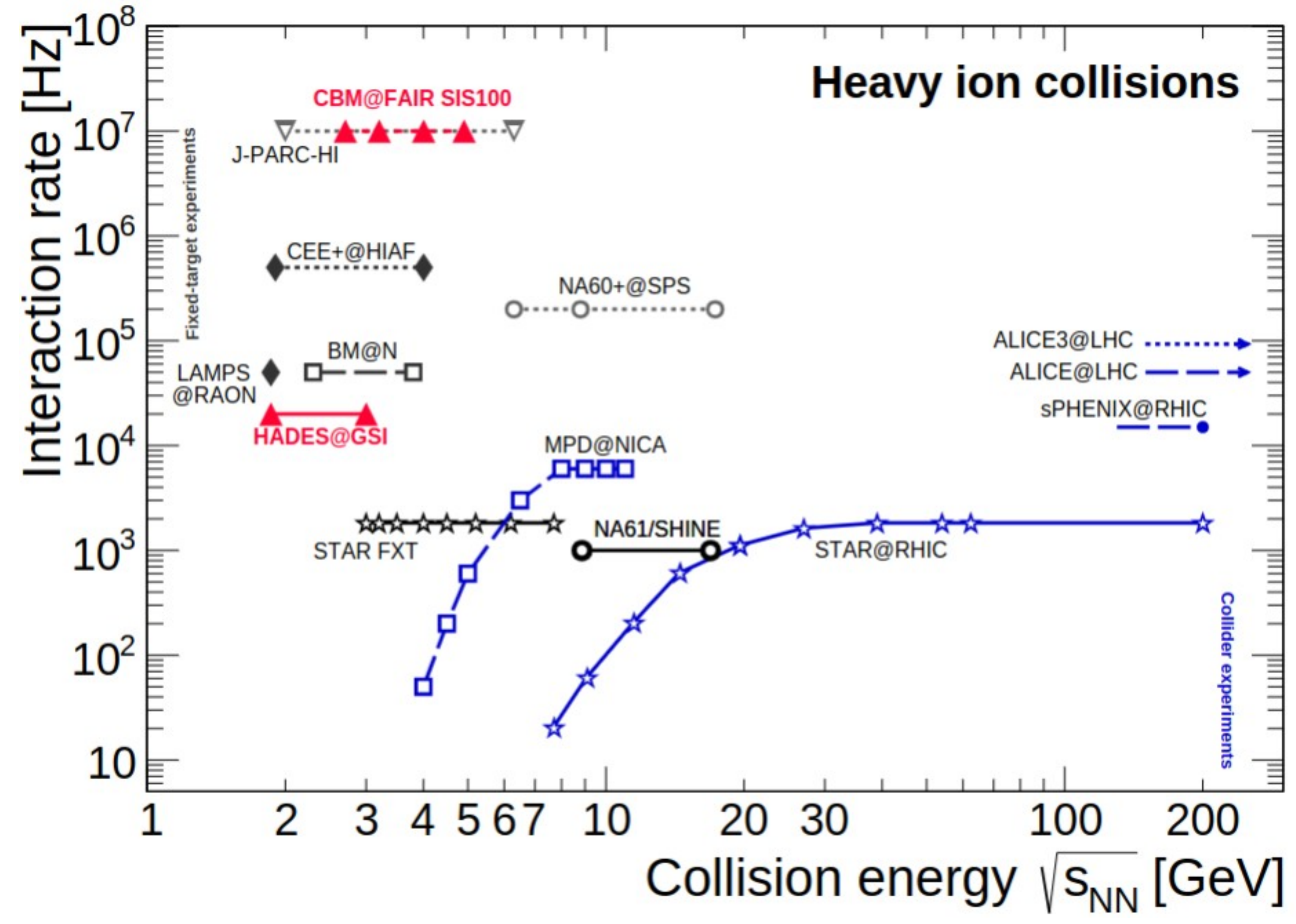

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Physics opportunities with proton beams at SIS100

6-9 February 2024
Wuppertal University
Europe/Berlin timezone

Physics opportunities with proton beams at SIS100

6-9 February 2024
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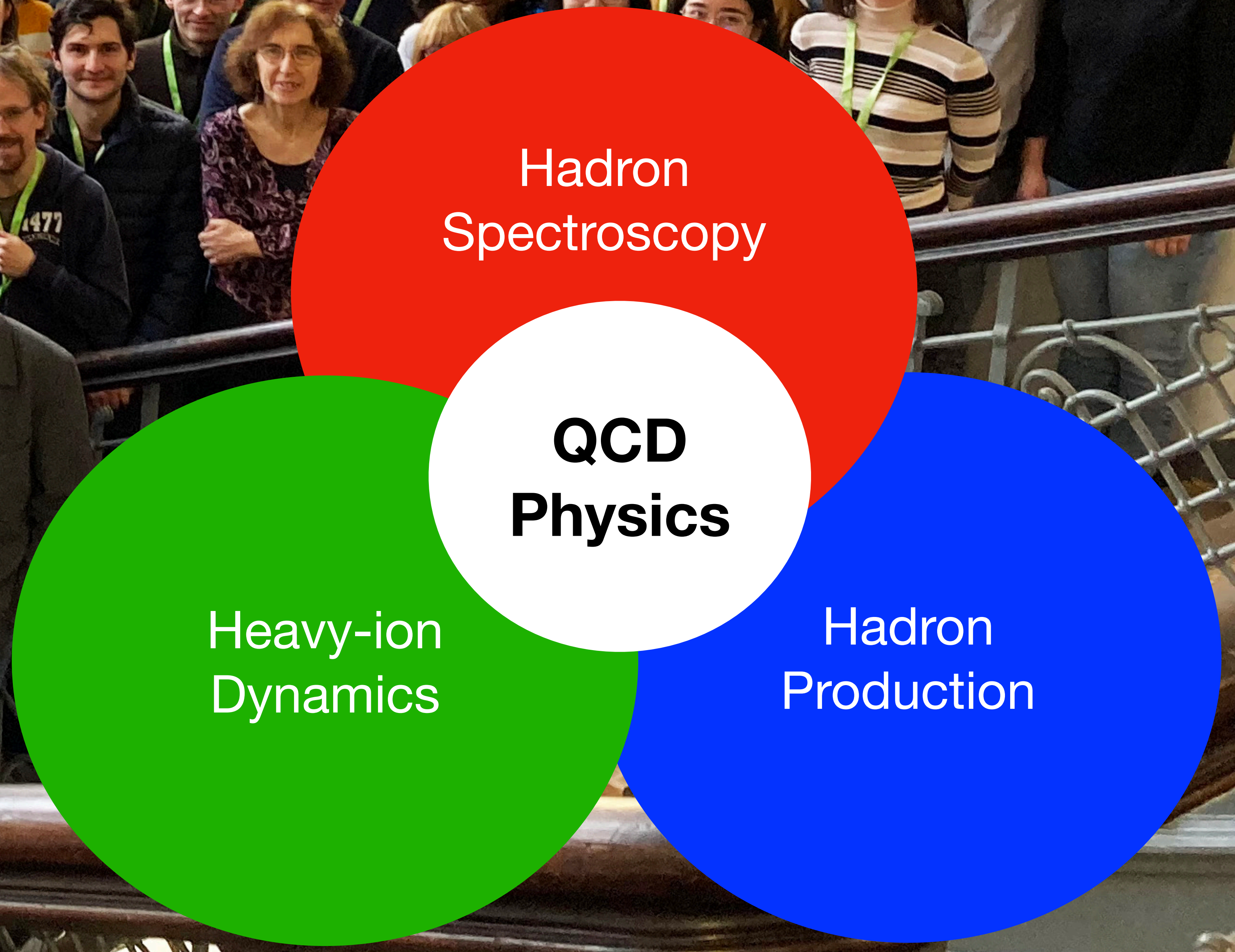
- Bring together experts from both theory and experiment
- Form a community connecting the common interest among different QCD-driven scientists
- Identify promising topics as a basis for a long-term proton-driven physics program
- Evaluate its complementarity with programs at other facilities
- Prepare towards a white-paper



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

6-9 February 2024
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Take away:
- 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

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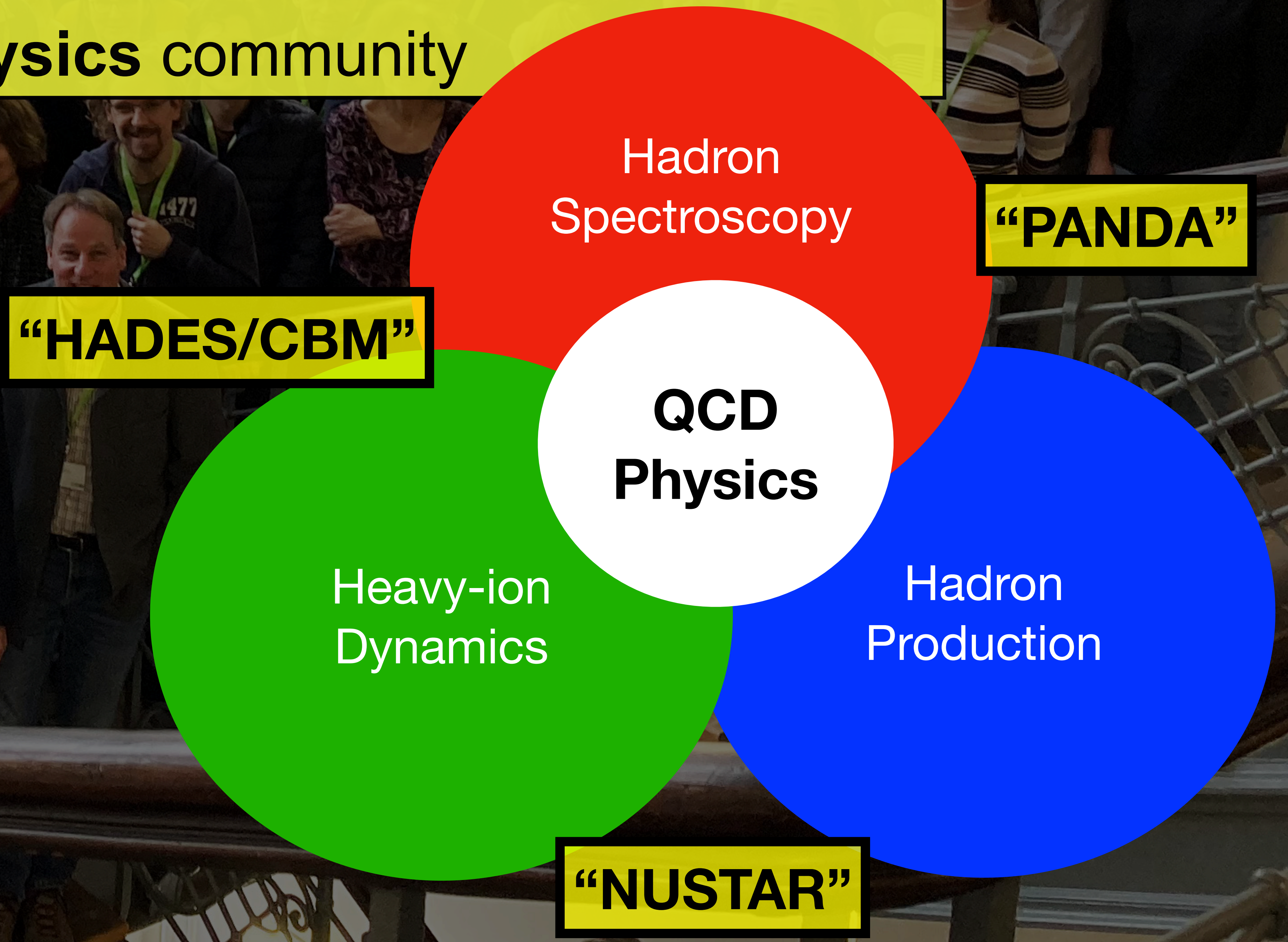


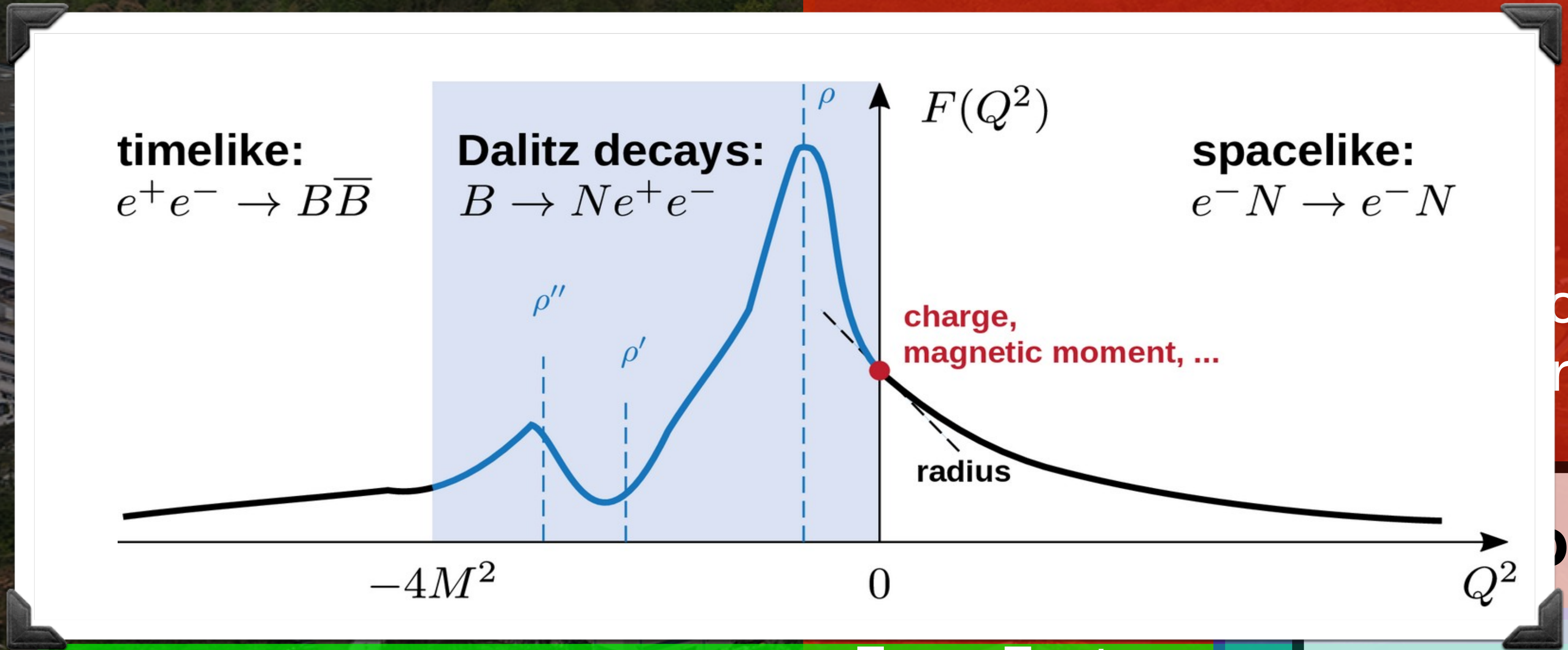
A comprehensive QCD program at GSI/FAIR!

A comprehensive QCD program at GSI/FAIR!

Composition of hadrons

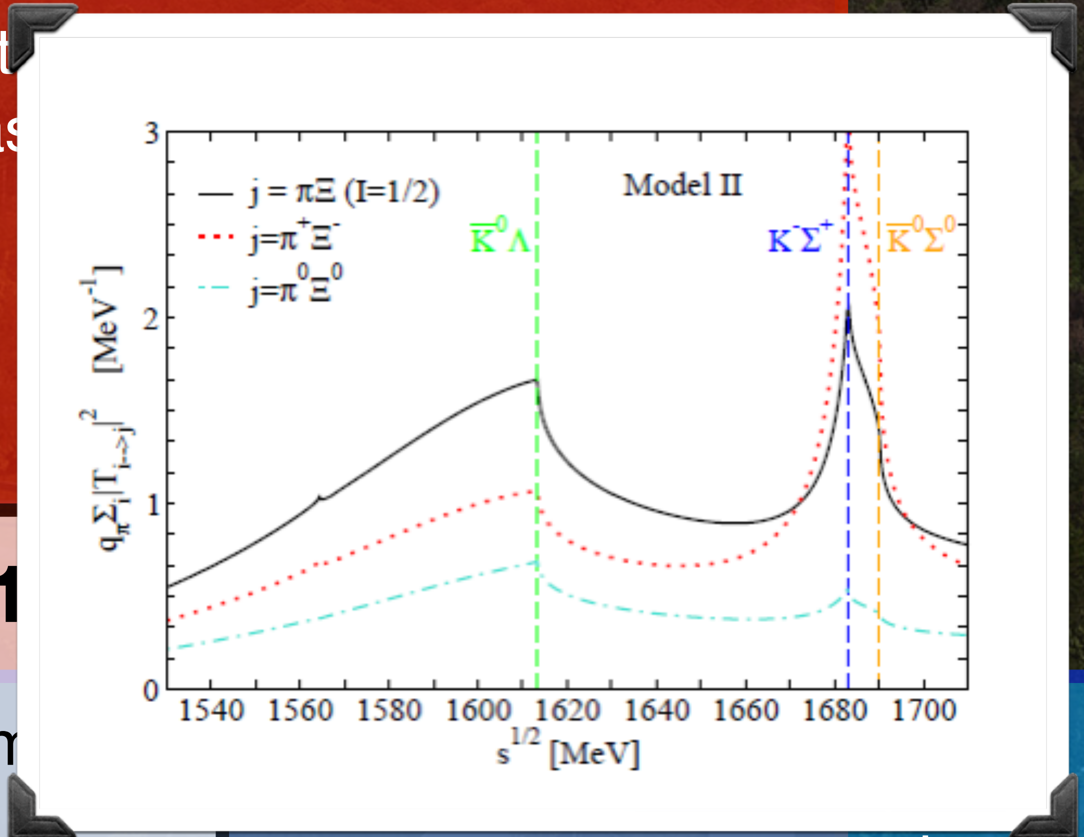
Hadron structure

Hadron spectroscopy



Emergent
Mas

charm of
roton



ns@SIS1

Form Factors of hyperons

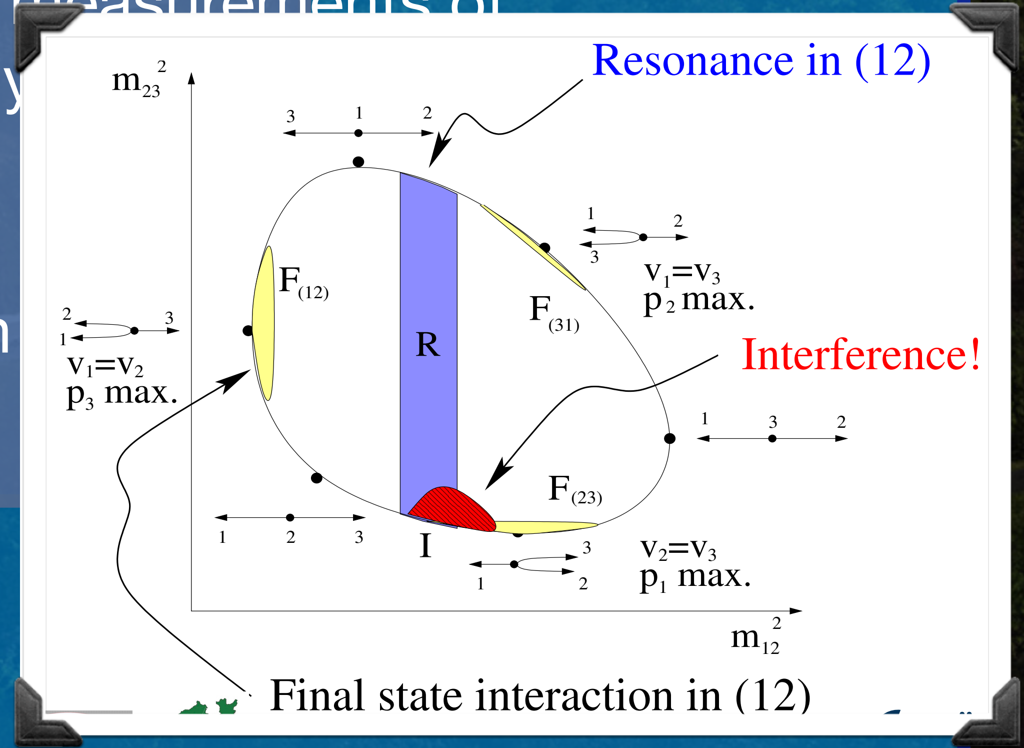
Polarisation

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

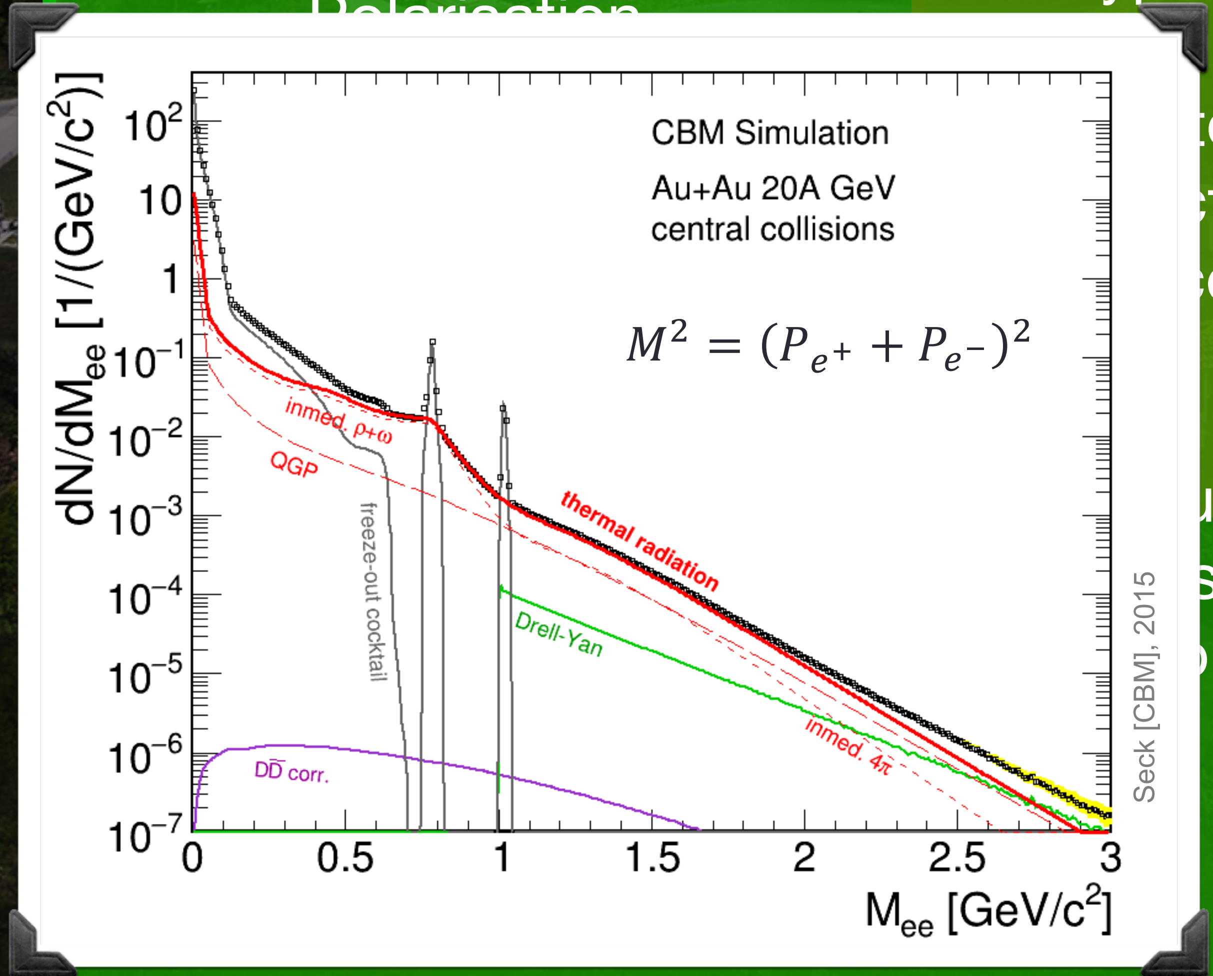
measurements of
hy

-nucleon
actions

l-state
actions
using PWA



Reference measurements for p+A,A+A



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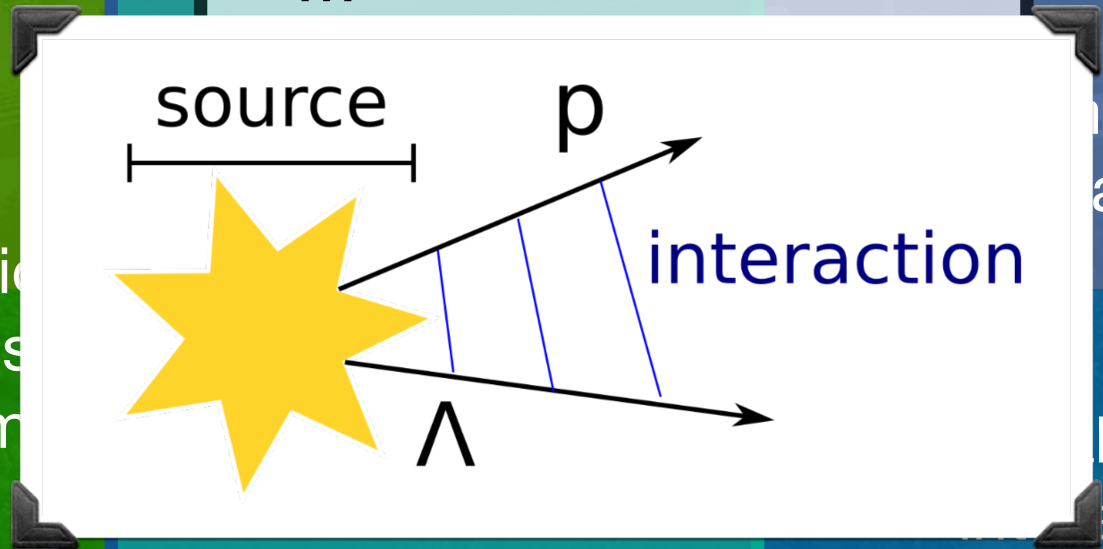


Few-body interactions

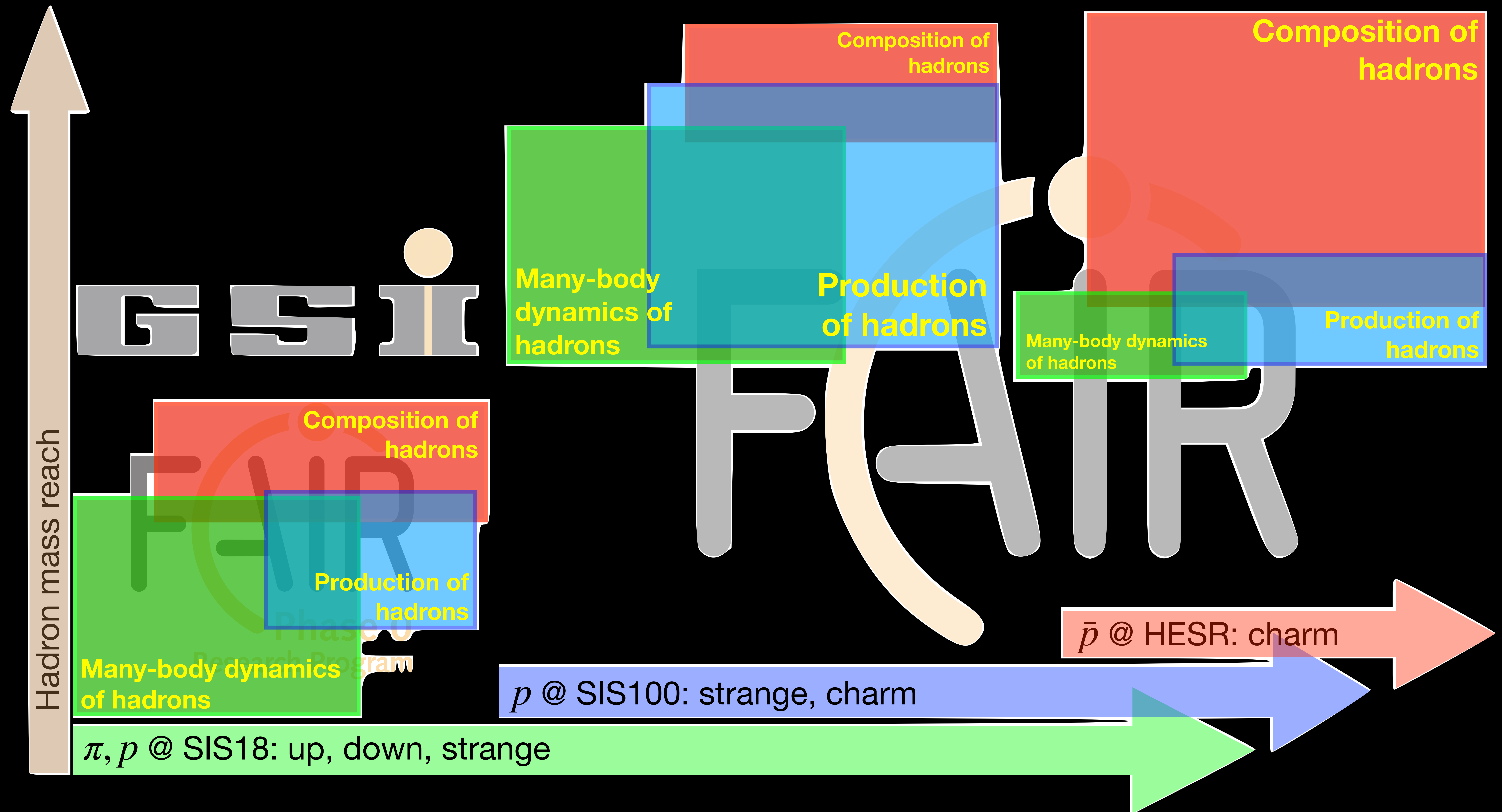
Hadron production

Production *mechanisms* of hadrons

Heavy-ion dynamics

Microscopic study of 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

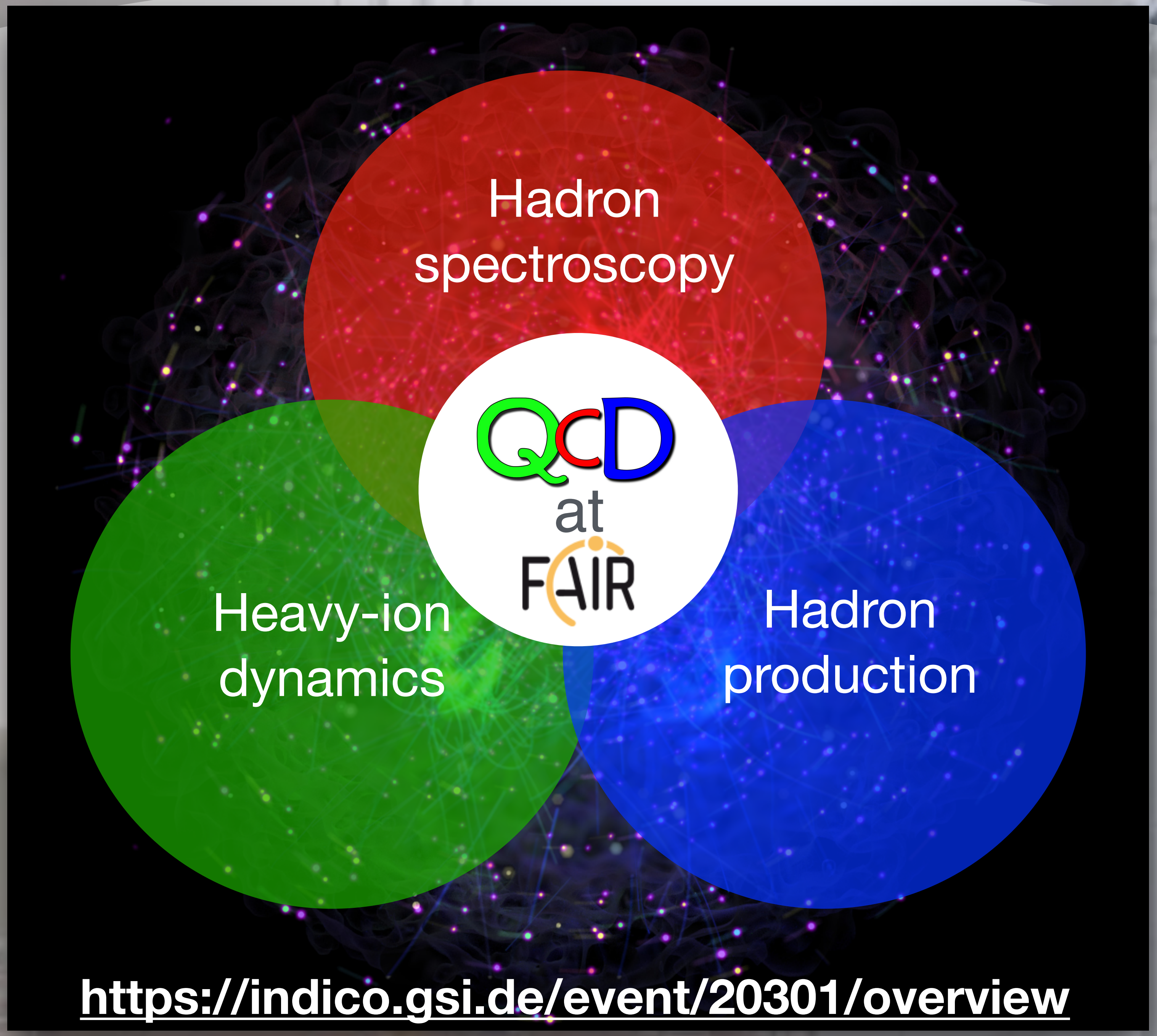
Contents

Convenors:

Editors: Frank Nerling, Johan Messchendorp

Coming up soon!

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

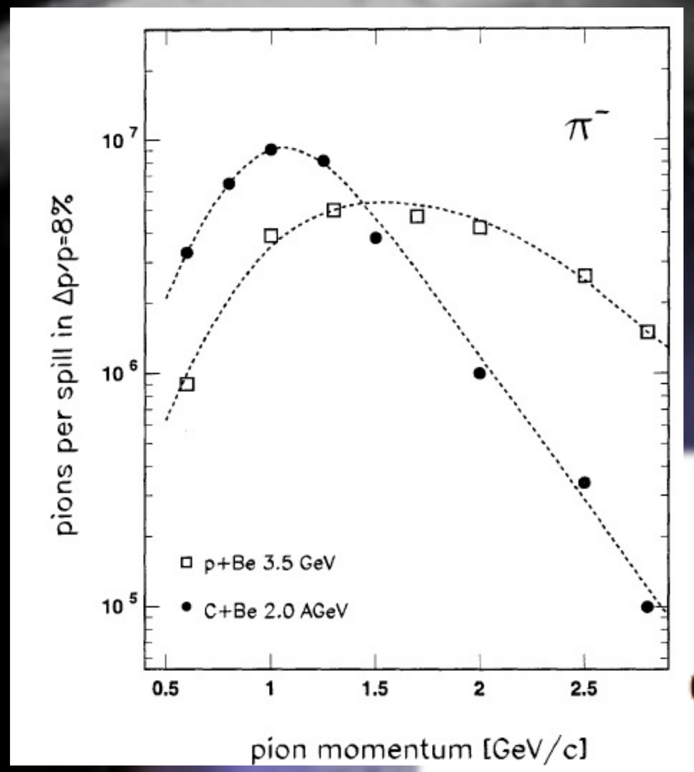


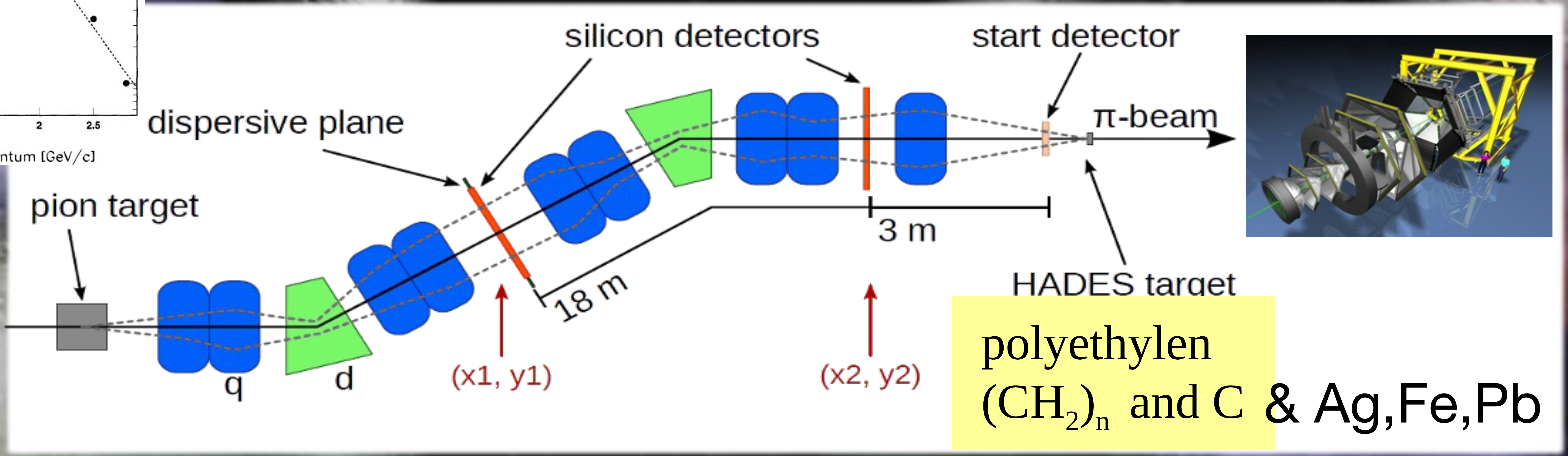
Welcome

Pion beams at GSI/FAIR

***The* focus of HADES for next years!**

π

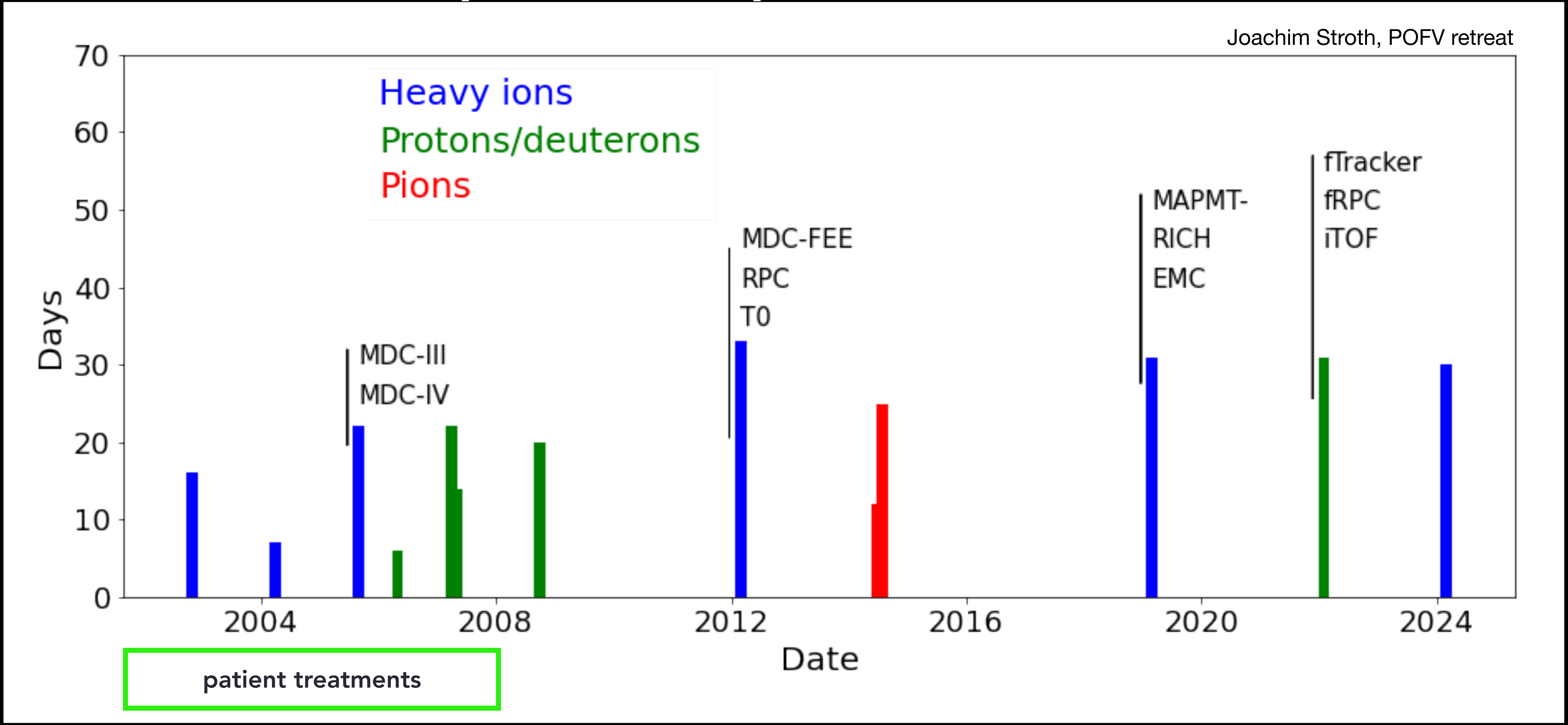




polyethylen $(CH_2)_n$ and C & Ag,Fe,Pb

HADES and its pion beams

… sort of an *all-time* personal inspiration



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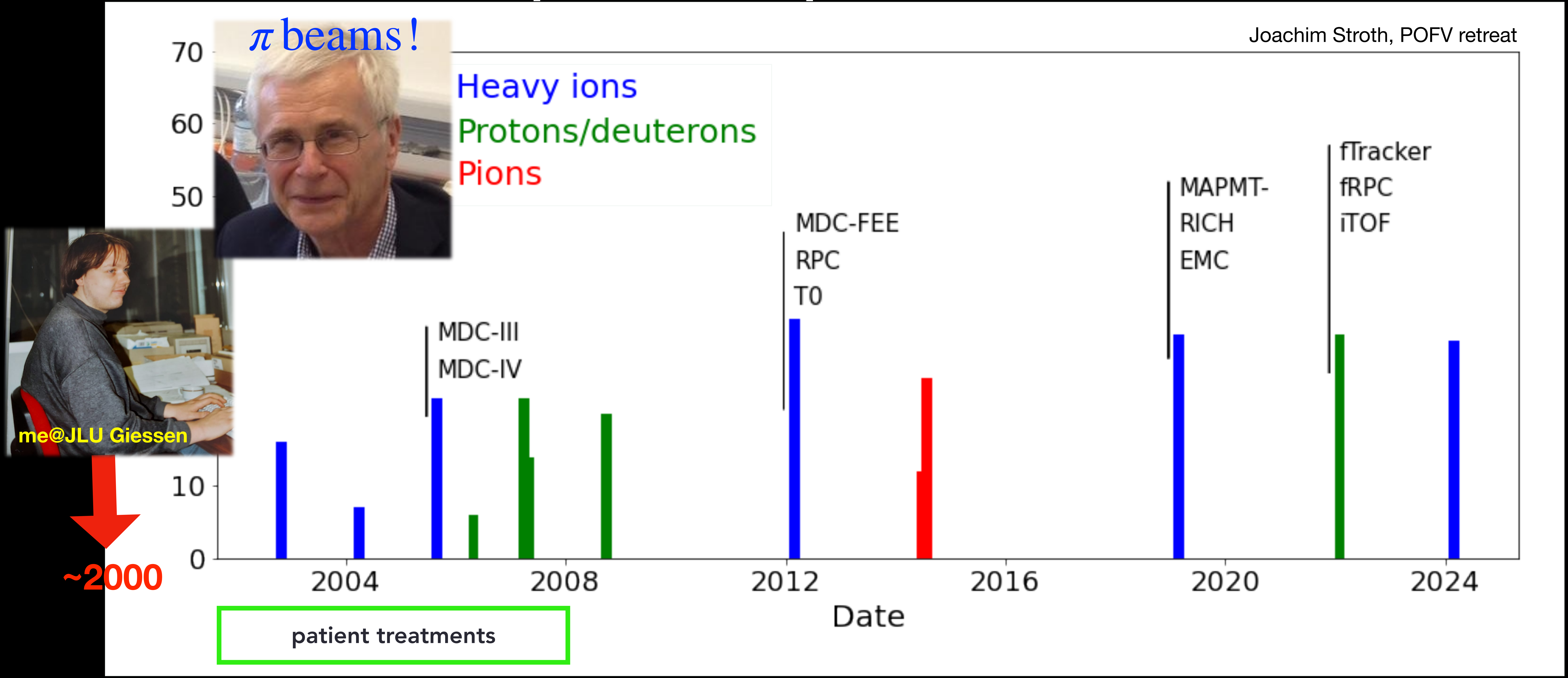

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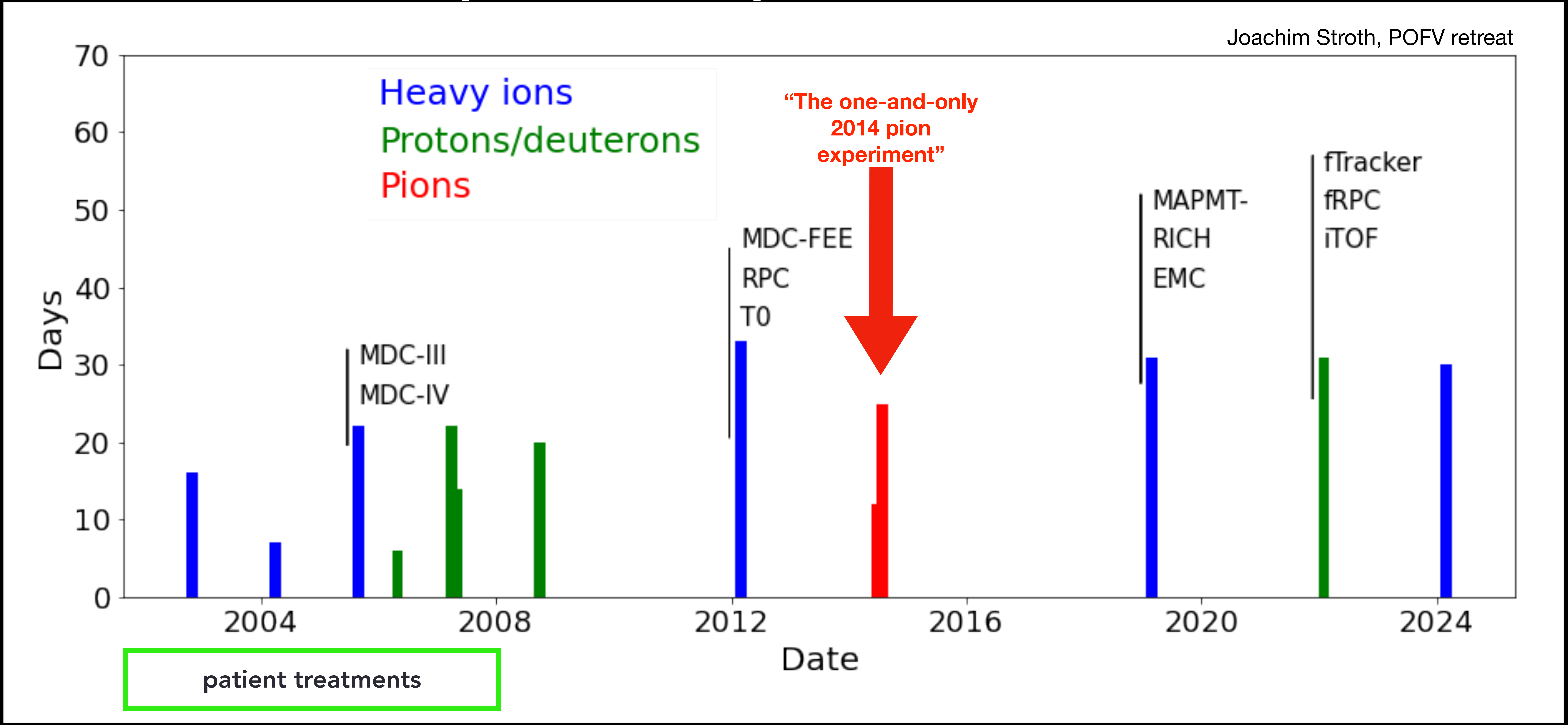

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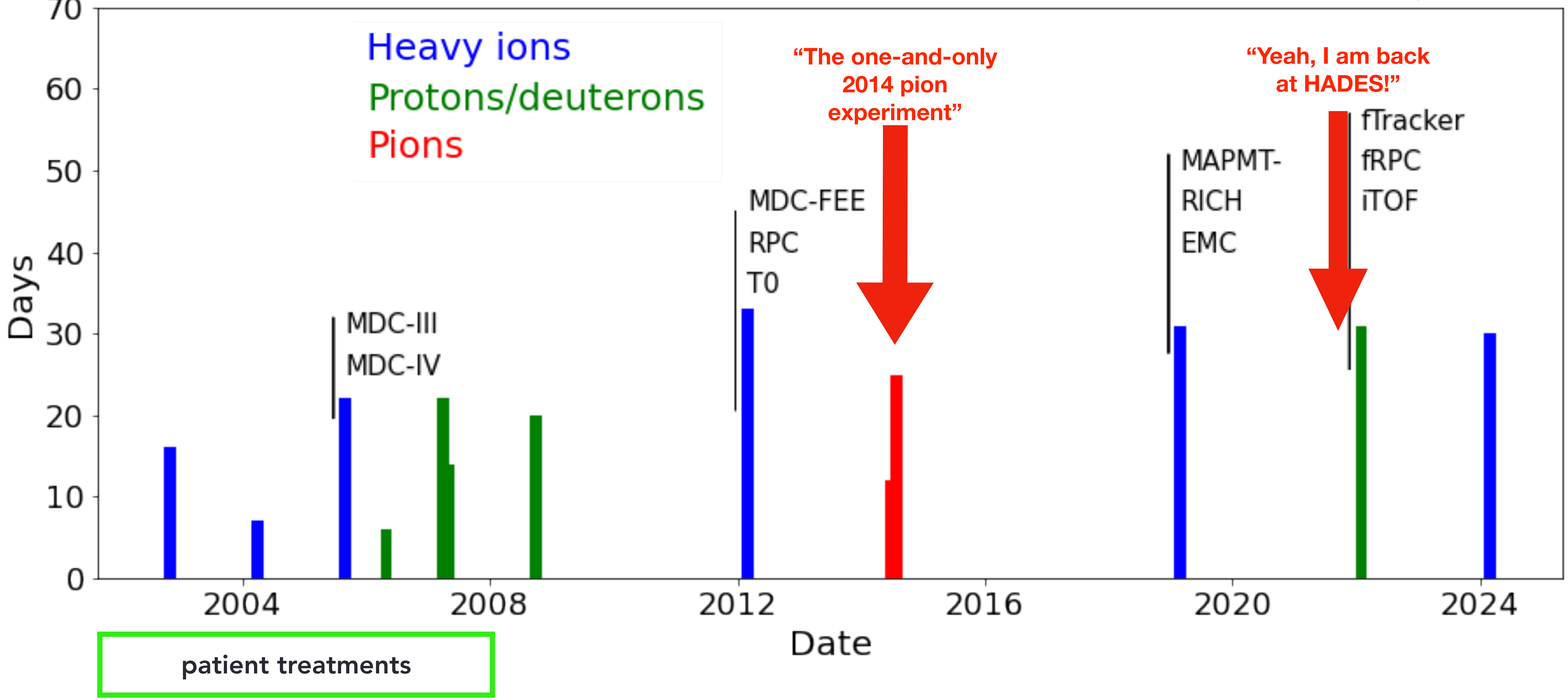
Joachim Stroth, POFV retreat



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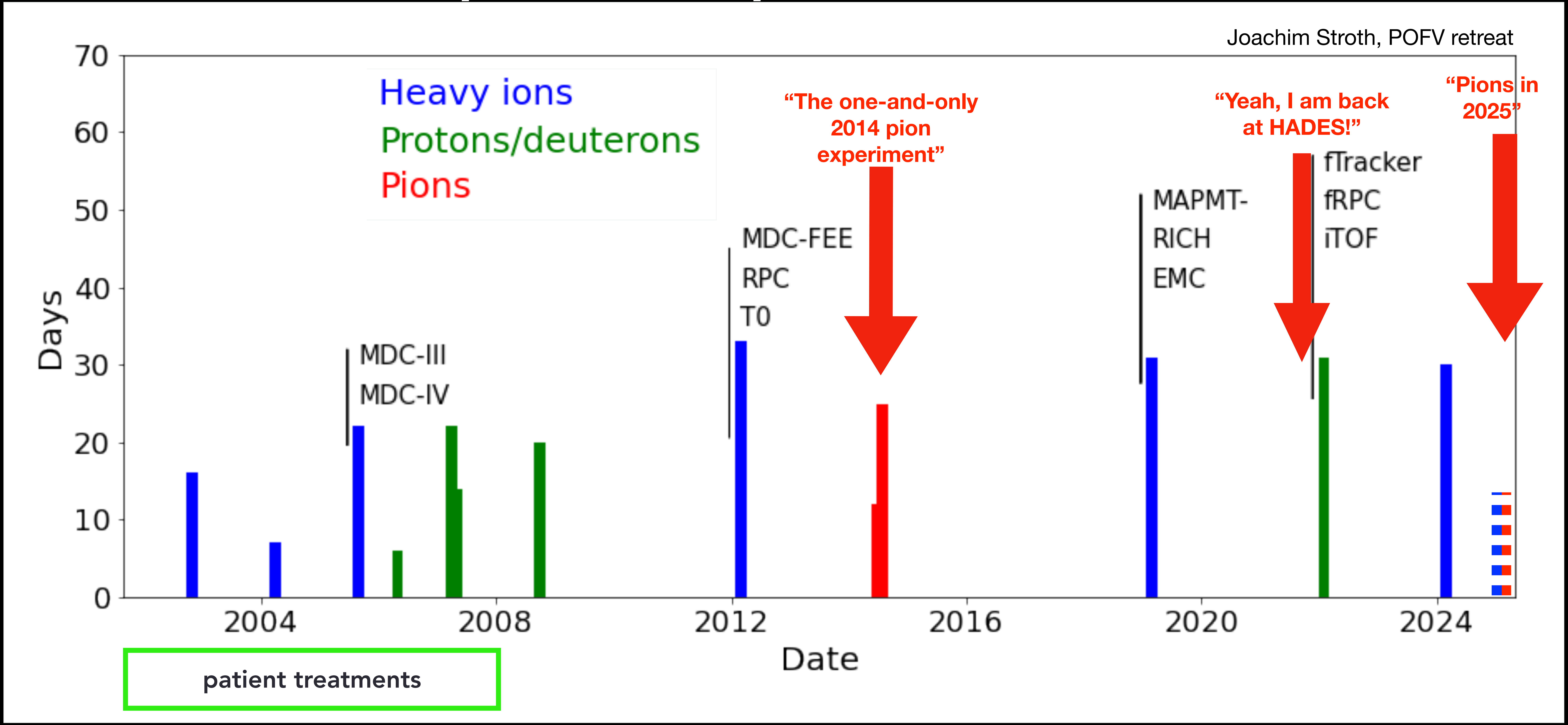

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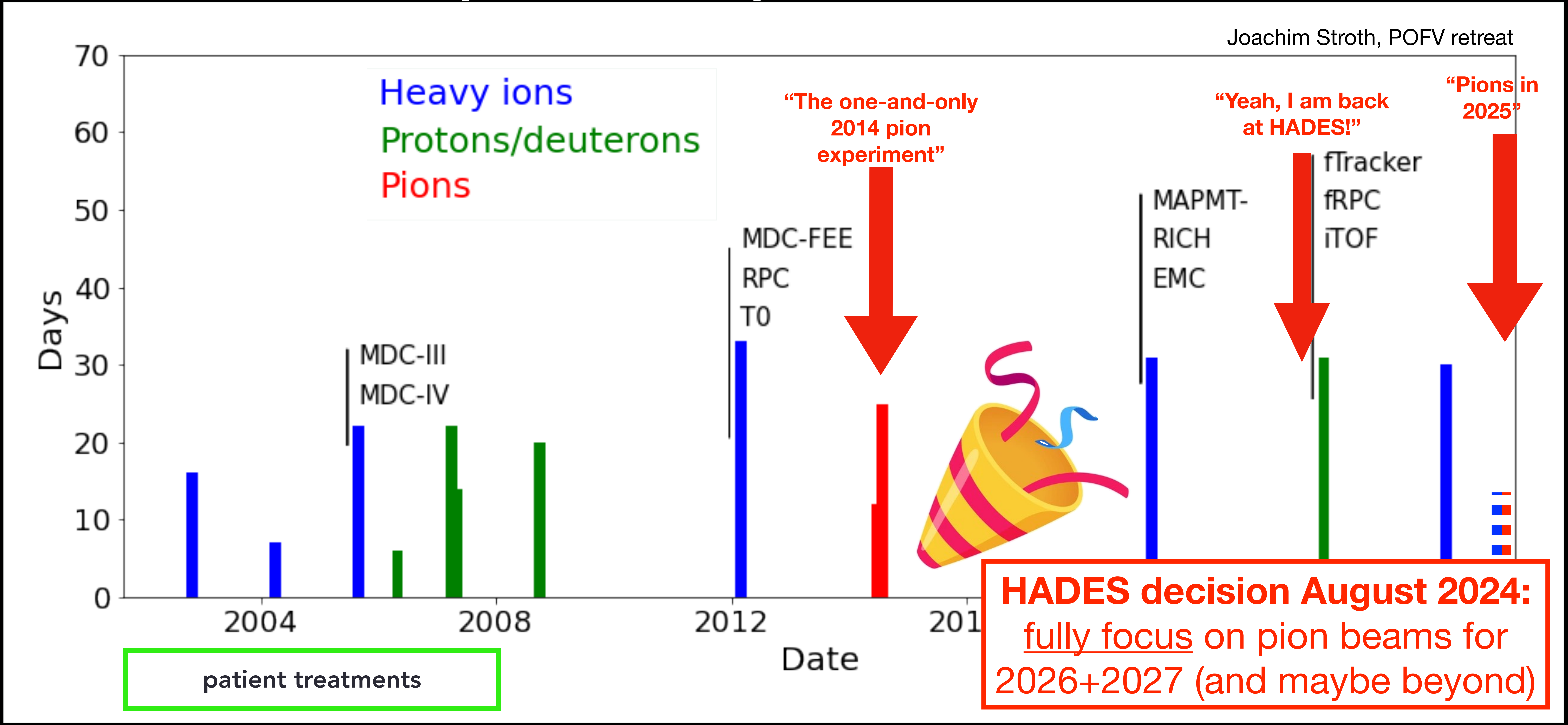
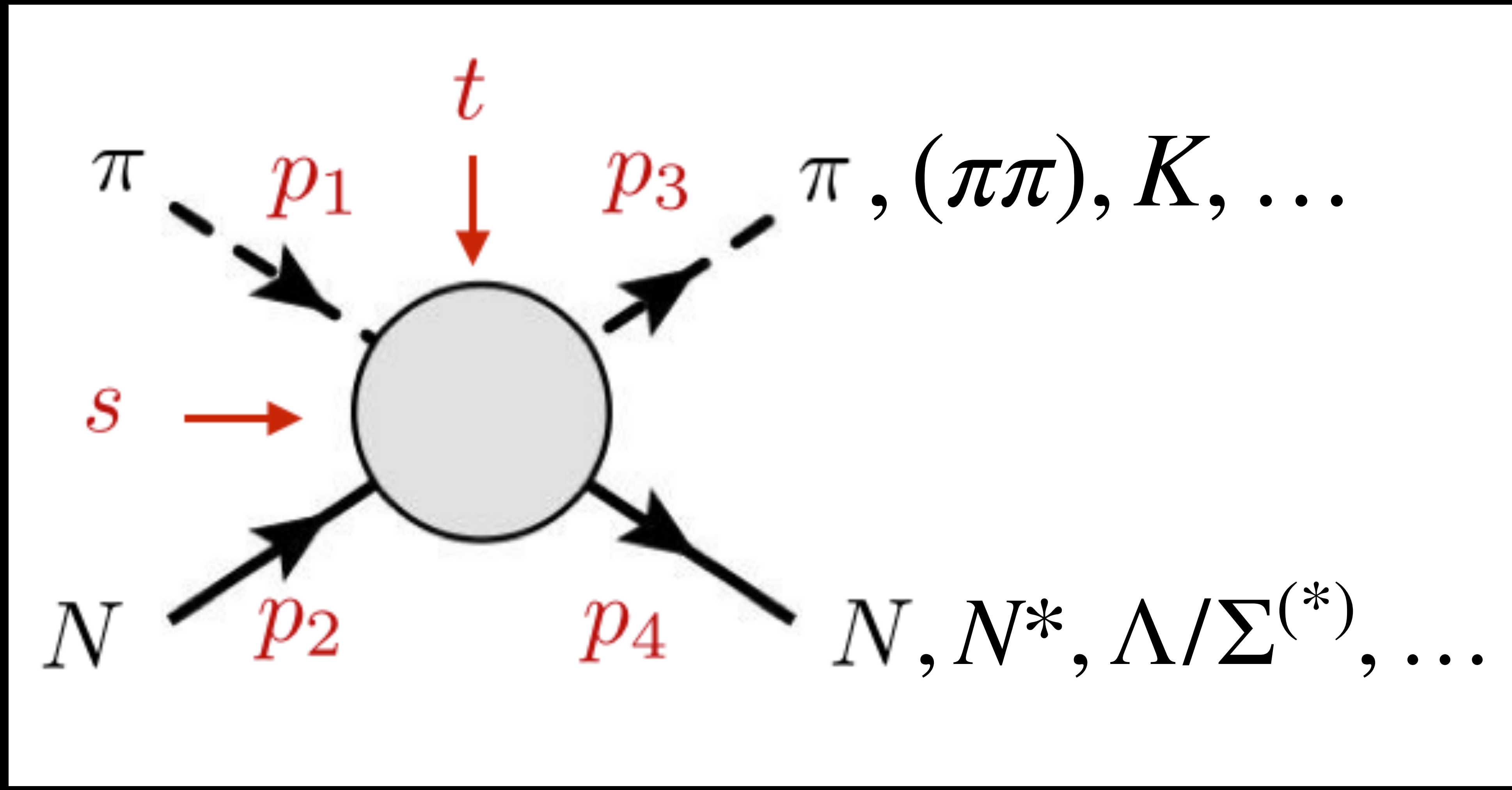


What makes $\pi + p/A$ interactions so appealing?

….precision probe in subatomic physics!



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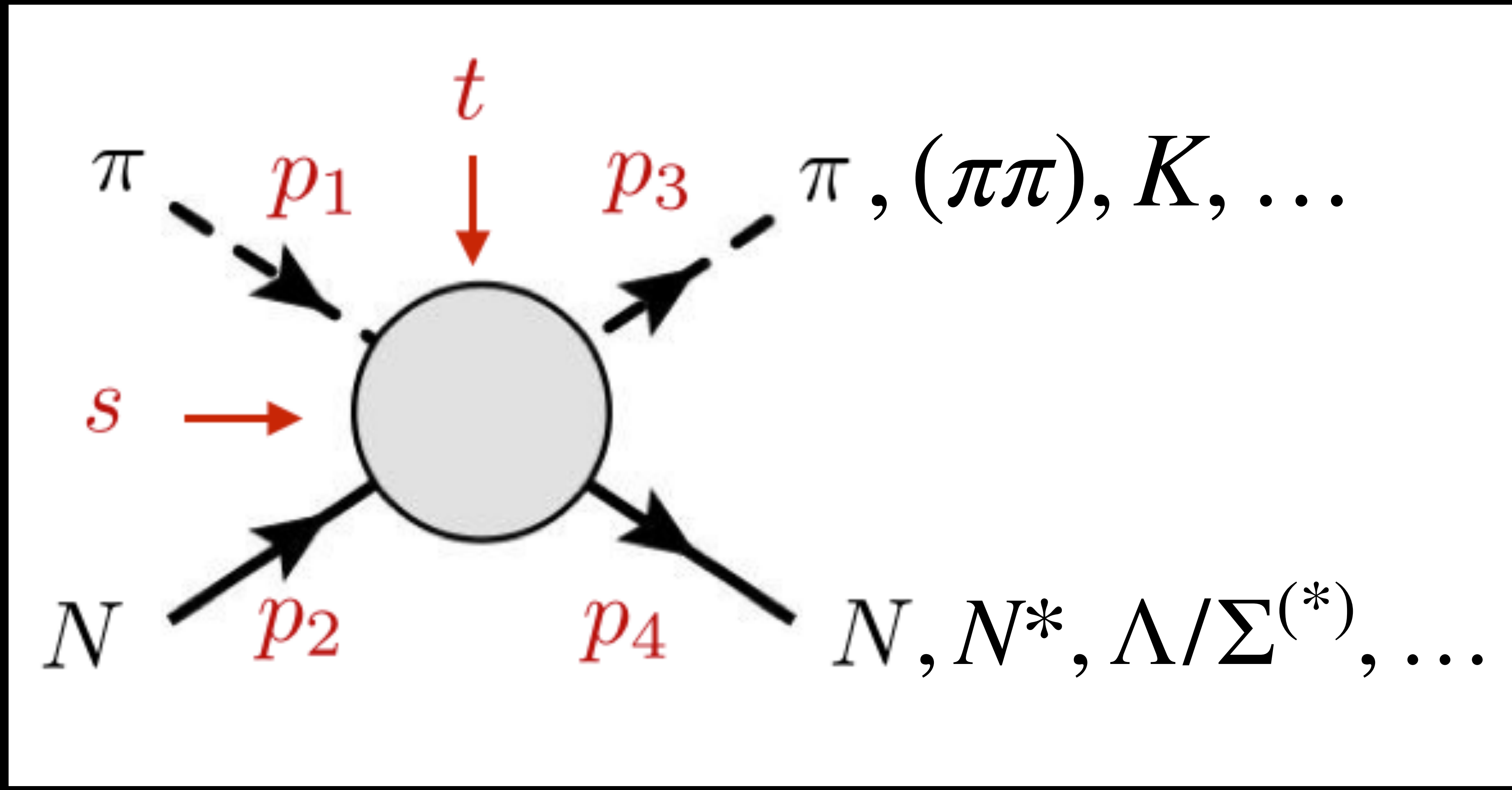
- 'Simple' initial state with spin-zero Goldstone boson; 'Simple' final states, 2/3-bodies



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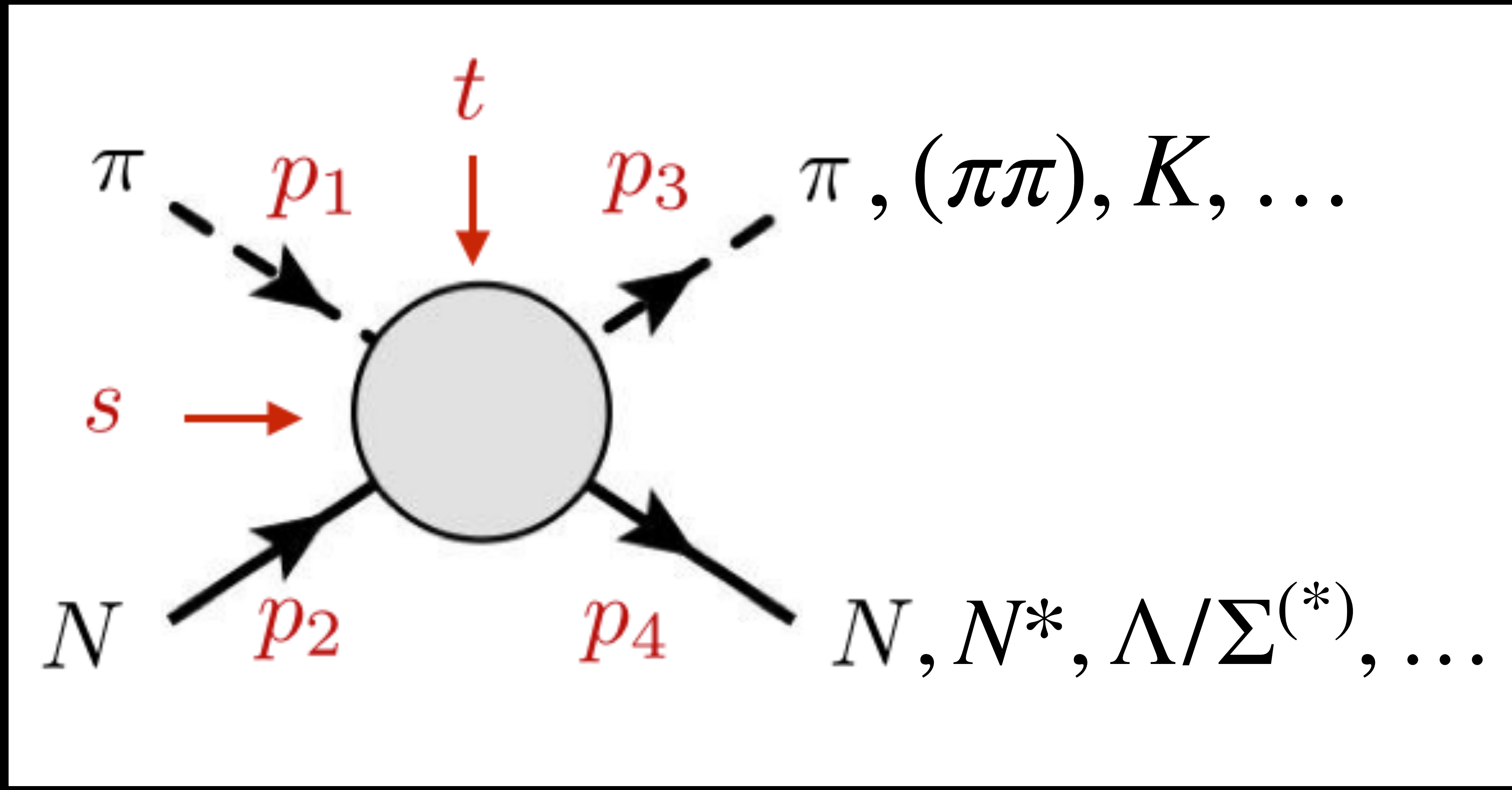
- 'Simple' initial state with spin-zero Goldstone boson; 'Simple' final states, 2/3-bodies
- Theory: Lattice-QCD, (χ)EFT in $SU(3)_F$, Dyson-Schwinger BS: close to first principles of QCD!
- Experiment: sizeable cross sections w.r.t. electromagnetic beams, simple final states —> high acceptance, enable PWA, etc. …

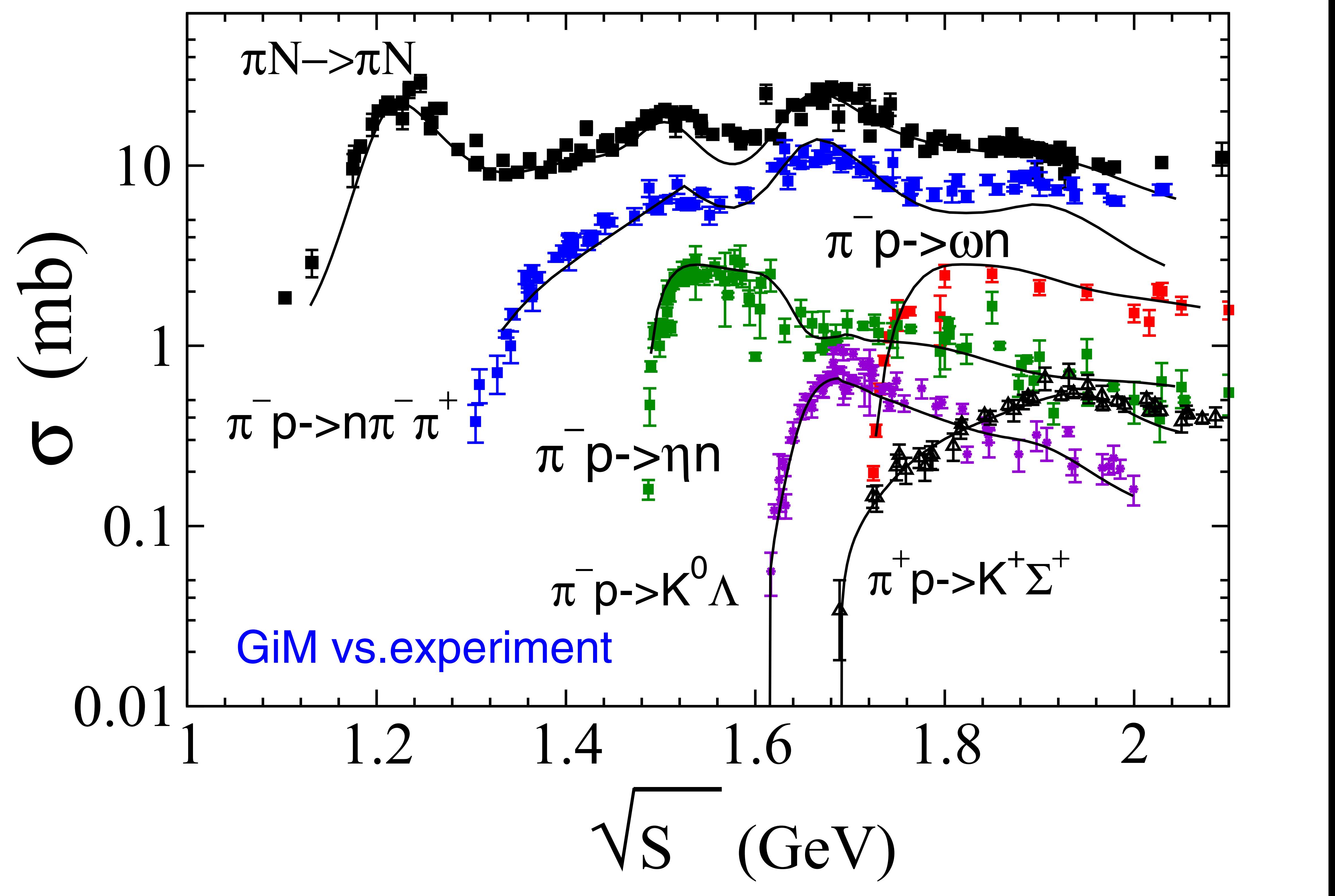


The power of pion beams *at GSI*

…what makes us competitive & complementary?

- 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 exps
- Respectable intensities beyond 10^6/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

Shklyar, Lenske, Mosel, PRC93, 045206 (2016)



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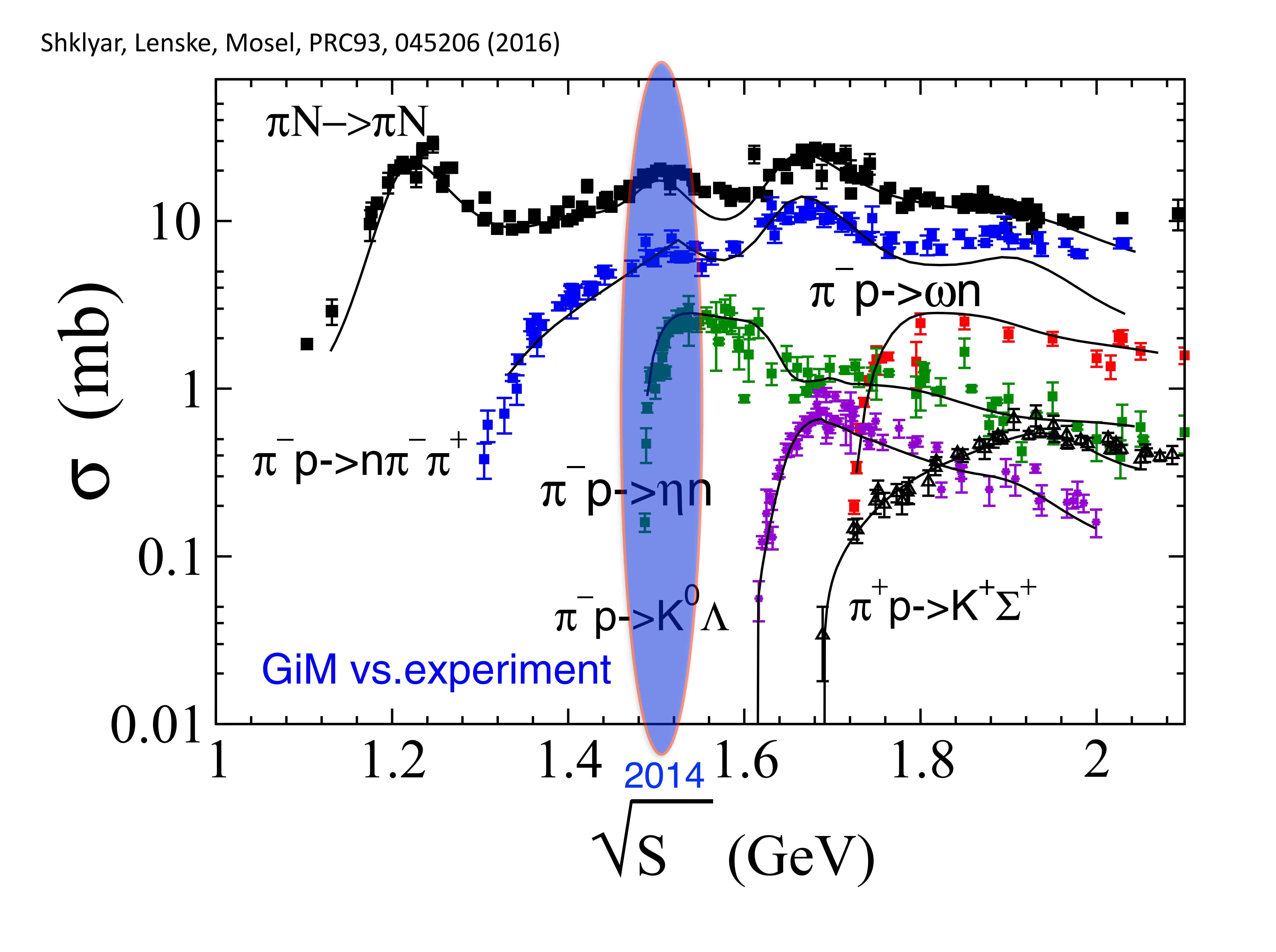

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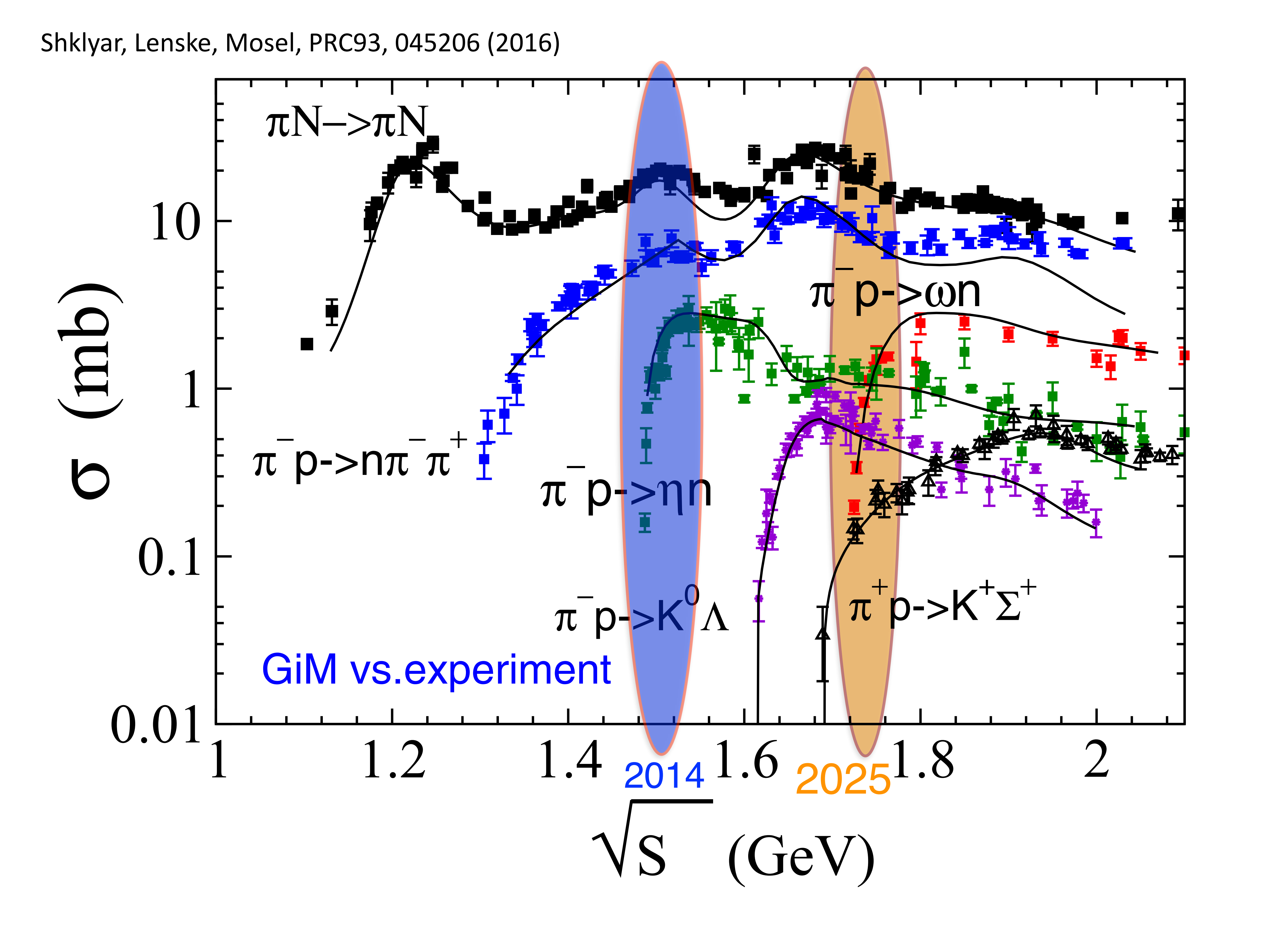

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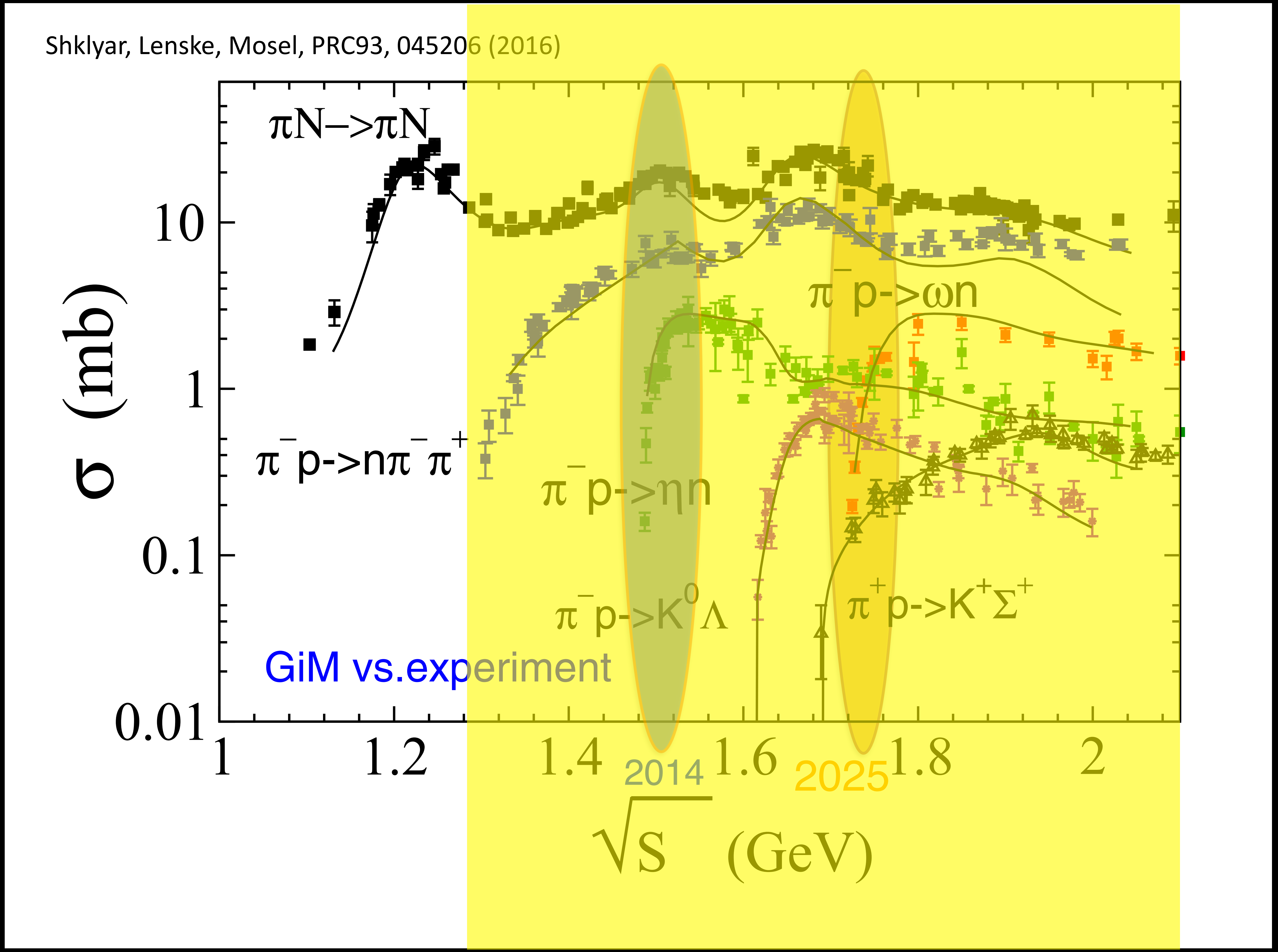


HADES GPAC proposal for 2026 + 2027, …

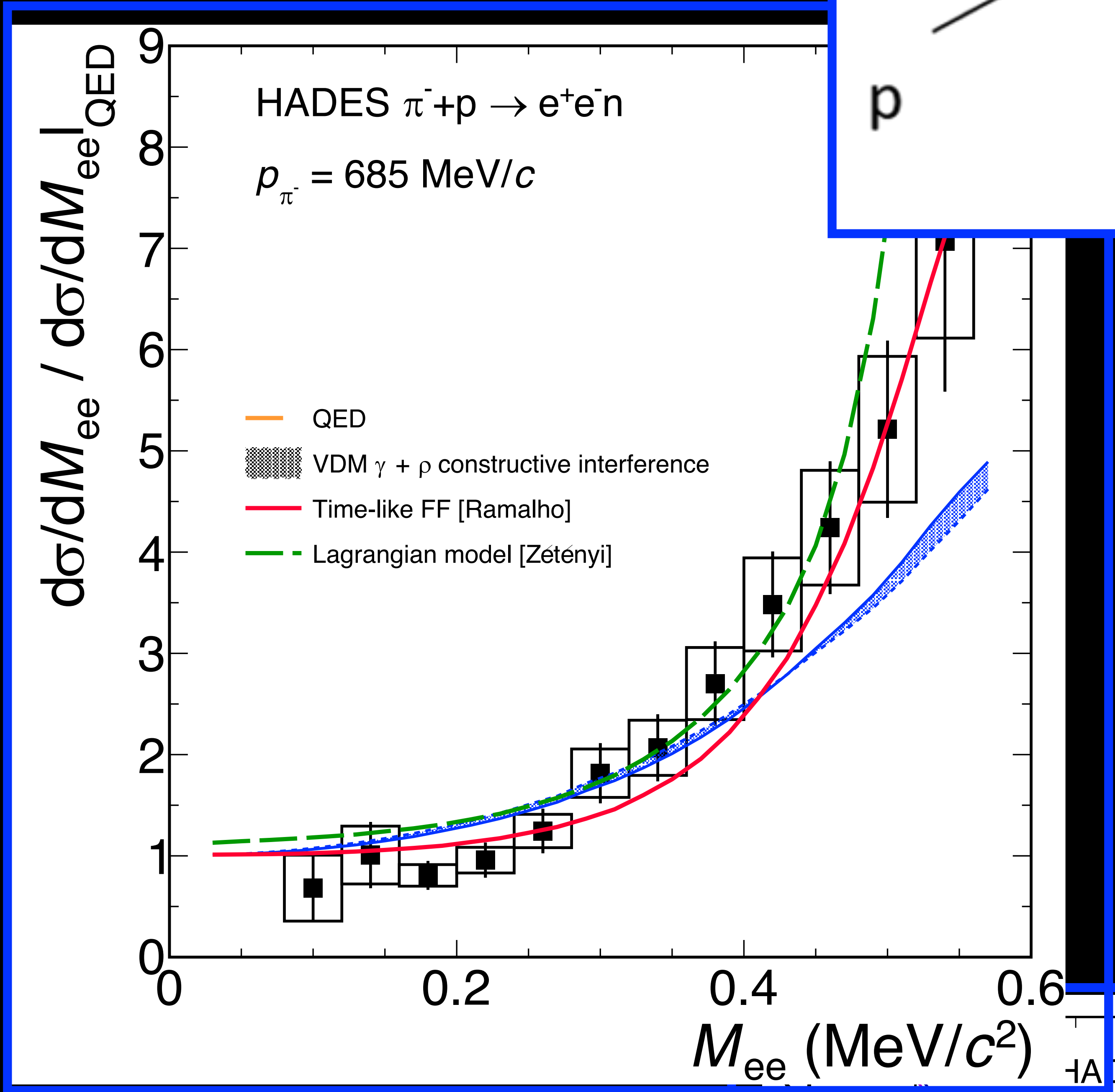
Pion beam program

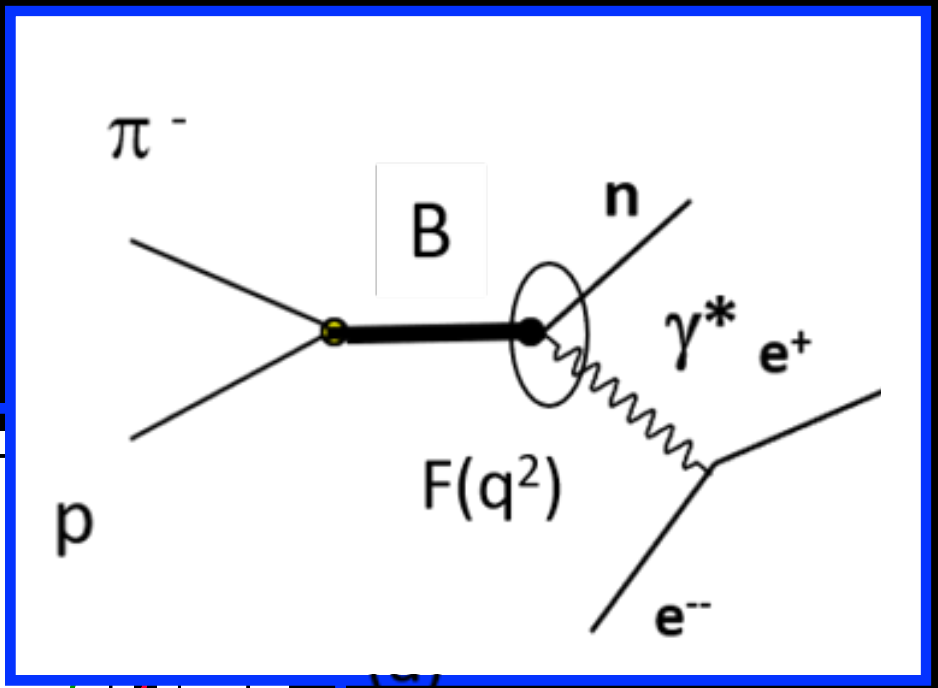
… *wide physics opportunities*

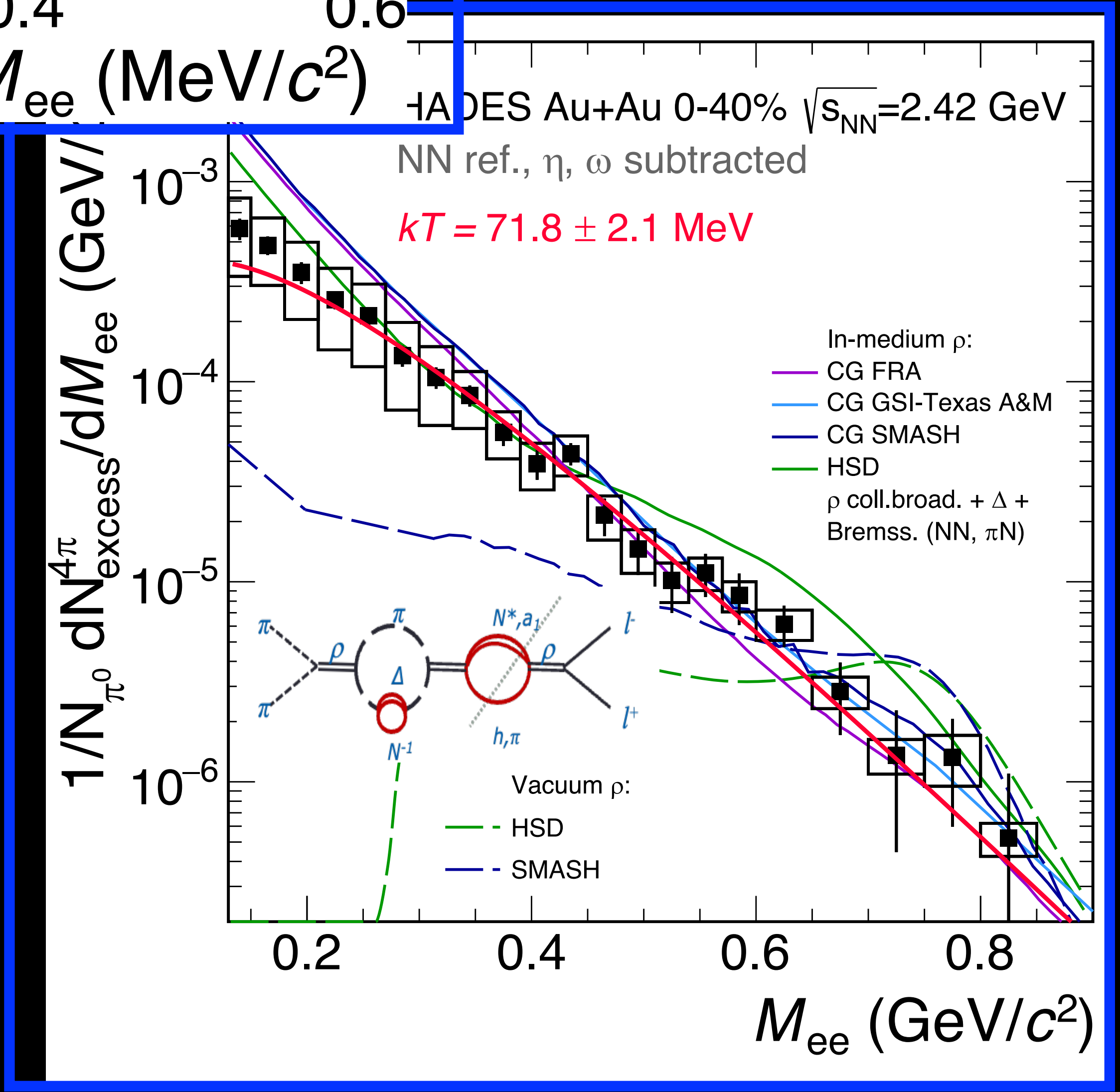
Hadron Physics

- Baryon |S|=0,1 spectroscopy in *formation* and *production*, f.e. N^* up to 3rd resonance regions, meson-baryon couplings
- Polarisation studies in hyperon production: $\pi^- p \rightarrow \overrightarrow{\Lambda} K^0 / \overrightarrow{\Sigma}^0 K^0 / \ldots$ (self-analysing weak decay)
- Vector-meson production: $\pi^- p \rightarrow \rho/\omega/\phi N$; SDME's extraction ($\omega \rightarrow e^+e^-/\pi^+\pi^-\pi^0$ topologies)
- Strangeness production, e.g. $\Lambda(1405{,}1520), \Xi, \ldots$
- Electromagnetic structure of |S|=0,1 baryons, *e.g.* $N^* \rightarrow Ne^+e^-/\Lambda(1405{,}1520), \Sigma(1385) \rightarrow \Lambda e^+e^-, \ldots$
- Light meson dynamics, f.e. in $\pi\pi, K\bar{K}, K\pi, \eta\pi, \ldots$
- Rare (BSM) decays of mesons, f.e. X(17) with η decays

"2014" highlight!







HADES, arXiv:2205.15914 + PRC102, 024001 (2020)

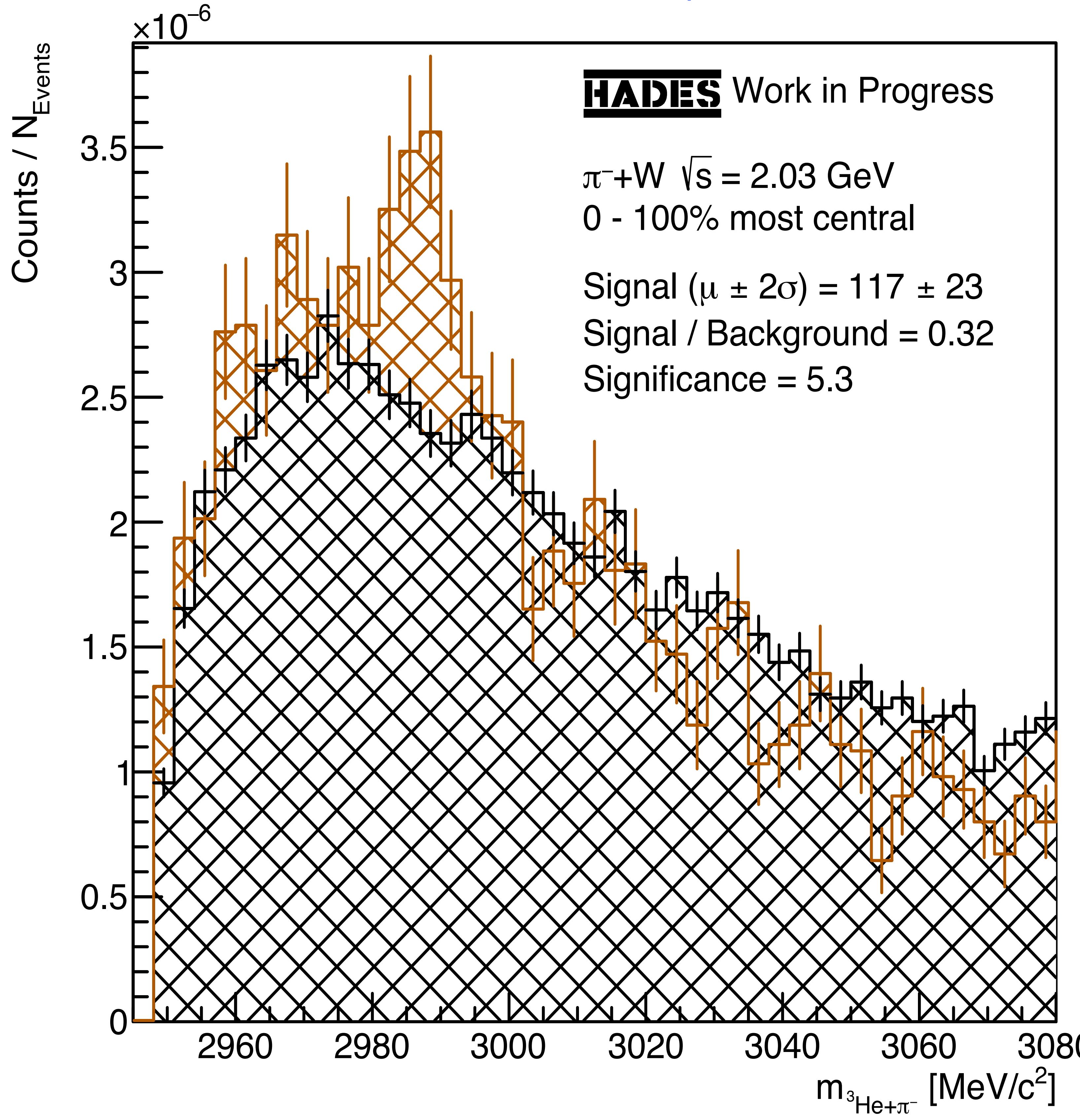
Pion beam program

… *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!
- $\overrightarrow{Y}N \to \overrightarrow{Y}N$ interactions
- Particle production xsection data for neutrino energy reconstruction in T2K, DUNE experiments

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



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?

Backup

“Facilities exploiting exclusive hyperon studies”

Timeline	2025	2028	2032
Probe:	FAIR **Phase 0**	**FS+**	**MSVc**
$\pi + p/A$	HADES Stage 1	HADES Stage 2	HADES available? Stage 3
	JPARC		
$p + p/A$	HADES@SIS18		CBM / HADES@SIS100
	CERN / JPARC / NICA		
$\bar{p} + p/A$			PANDA?
$K + p/A$		KLF	
	JPARC		
$\gamma^{(*)} + p/A$	MAMI/ELSA/GLueX/CLAS12		EIC
$e^+ + e^-$	BESIII/BelleII		BelleII/...

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

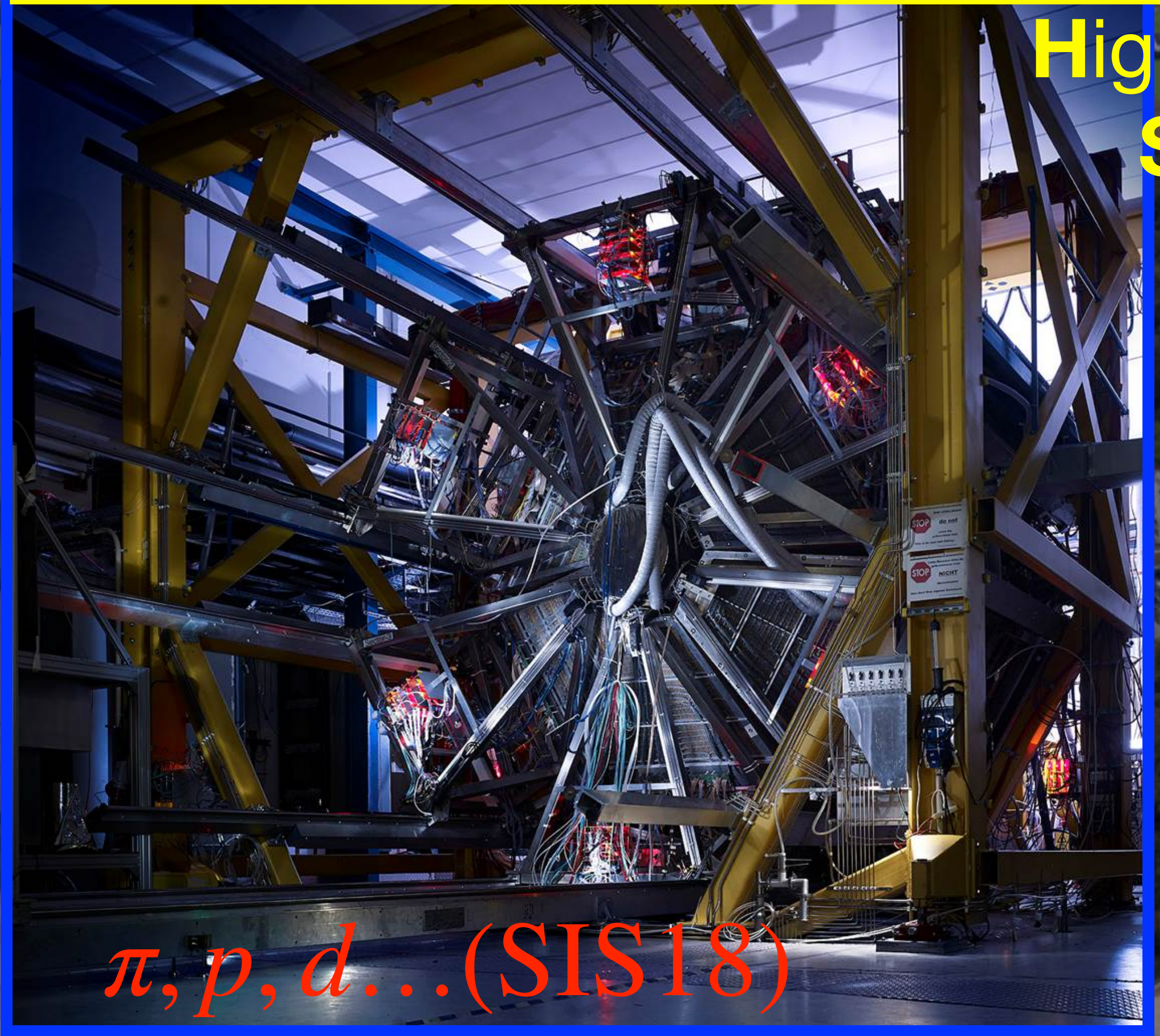
- Probing electromagnetic *and* hadronic aspects in pion-produced matter is unique

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

HADES/PANDA@FAIR-Phase-0:
“Hadron physics meets heavy-ion physics”



October 2023

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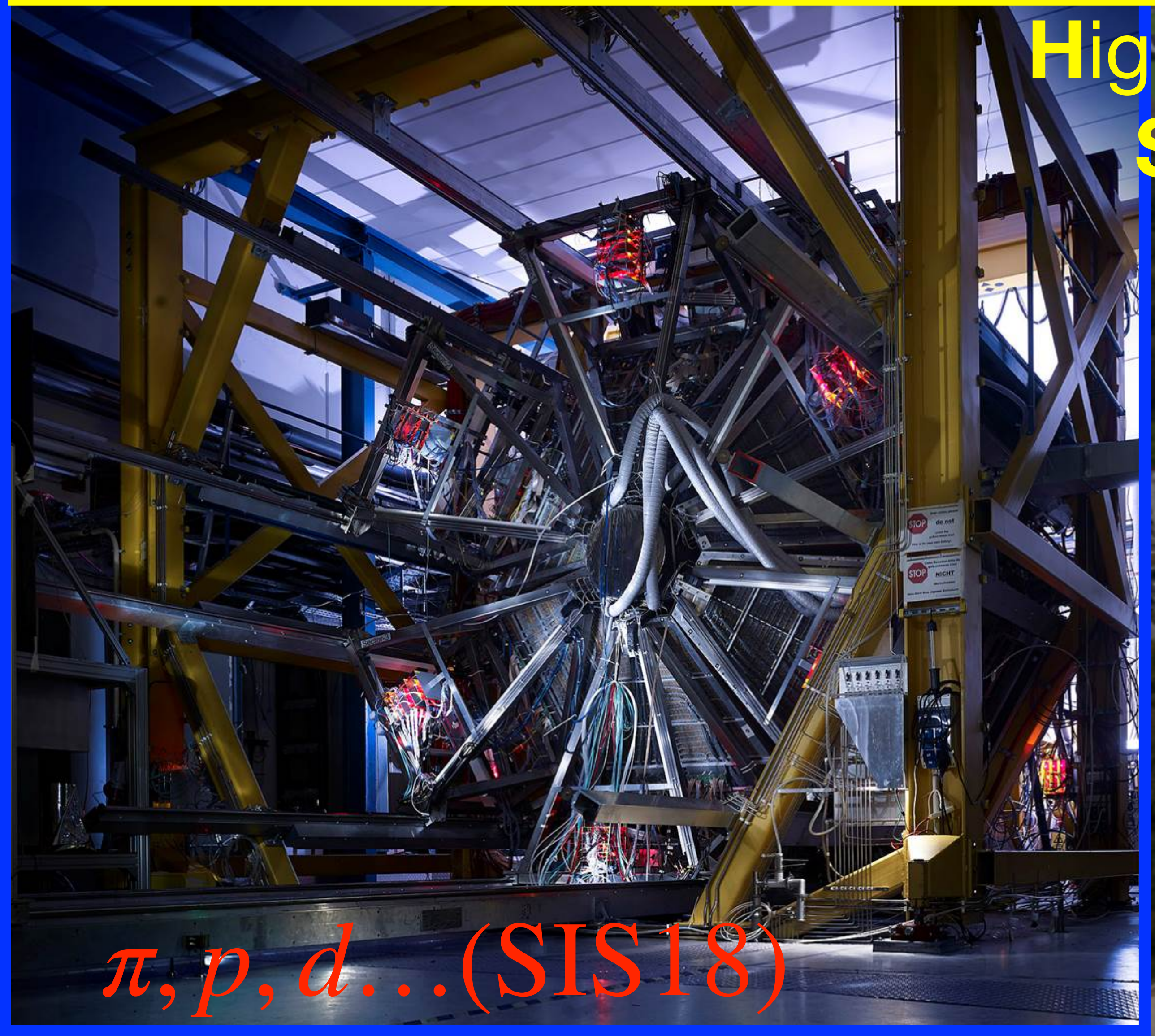
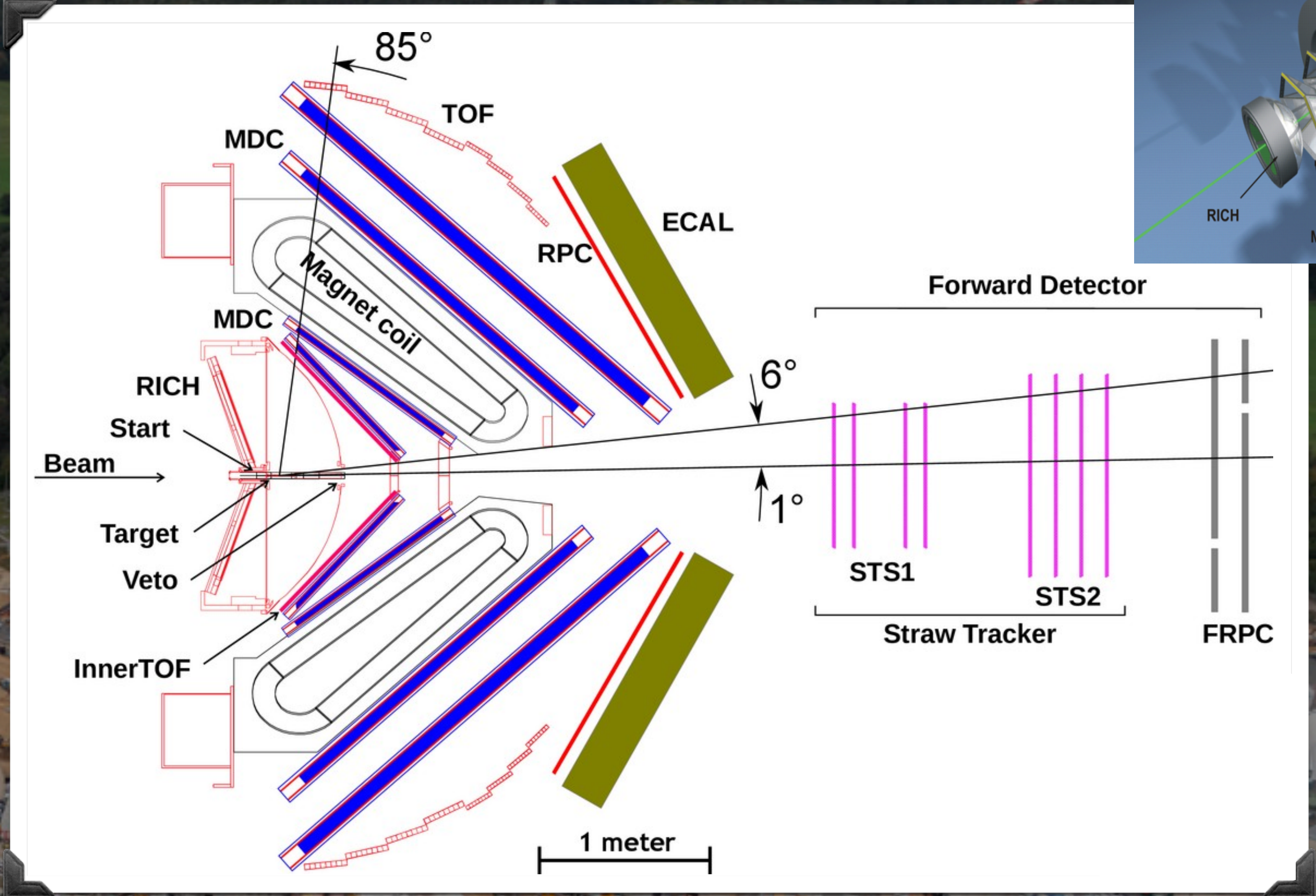
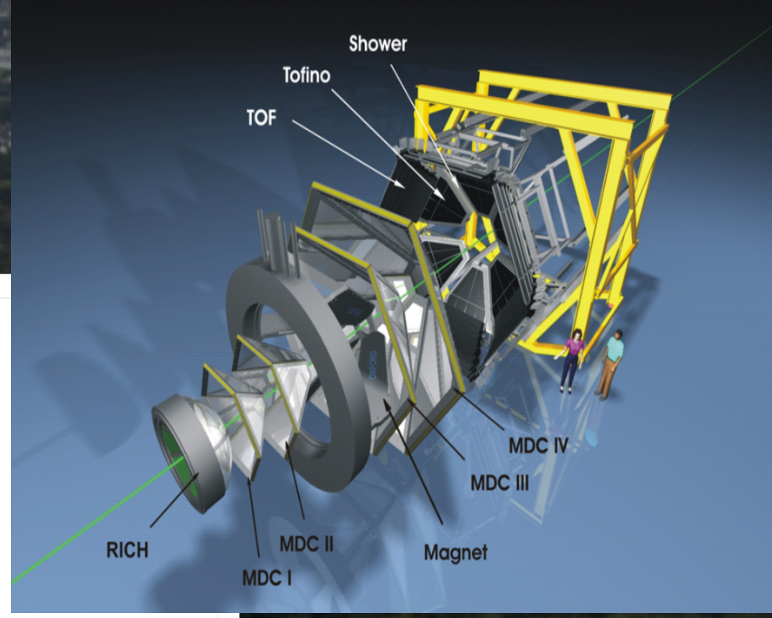


High **A**cceptance **D**i-**E**lectron **S**pectrometer **(HADES)**





- **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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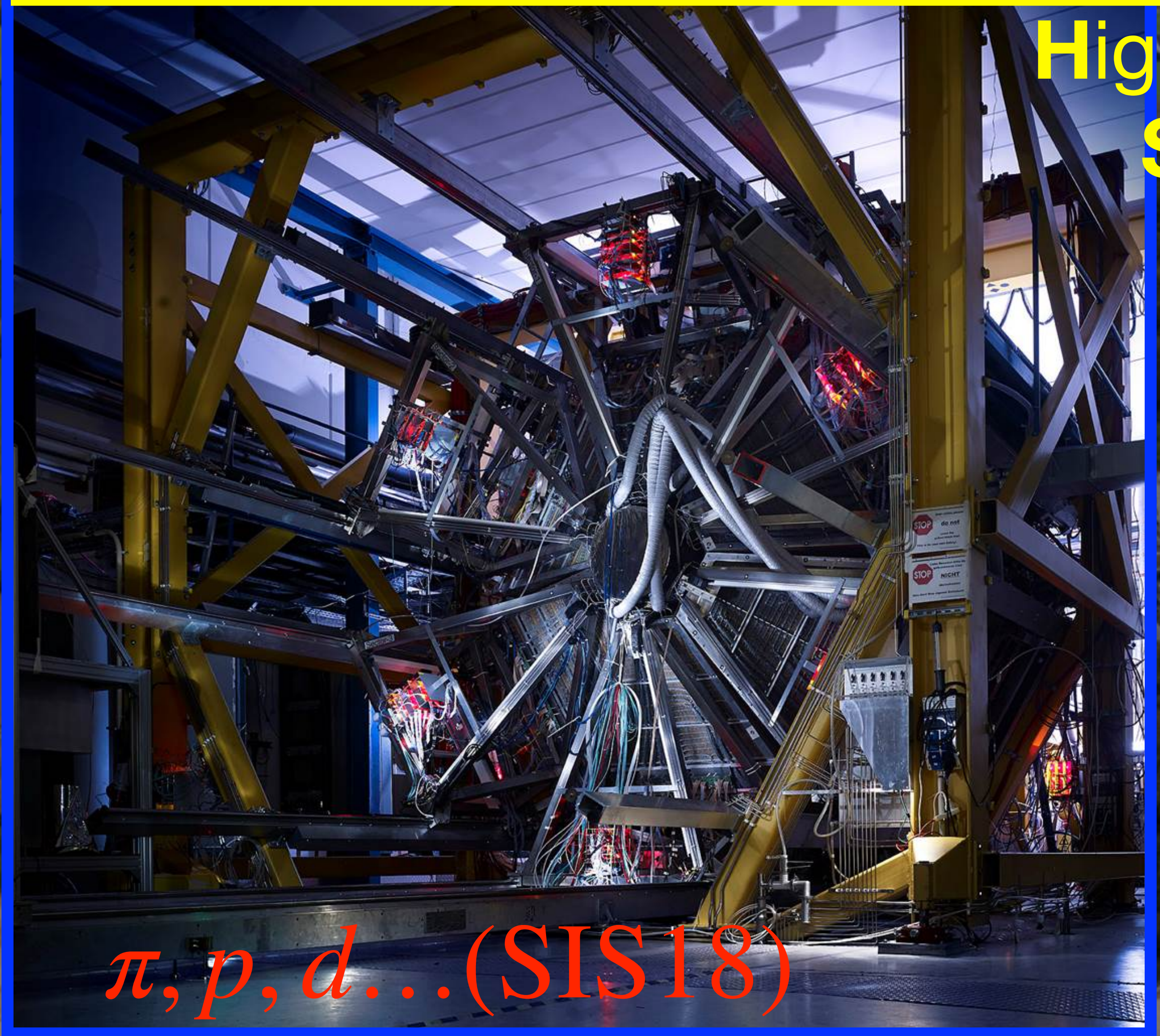

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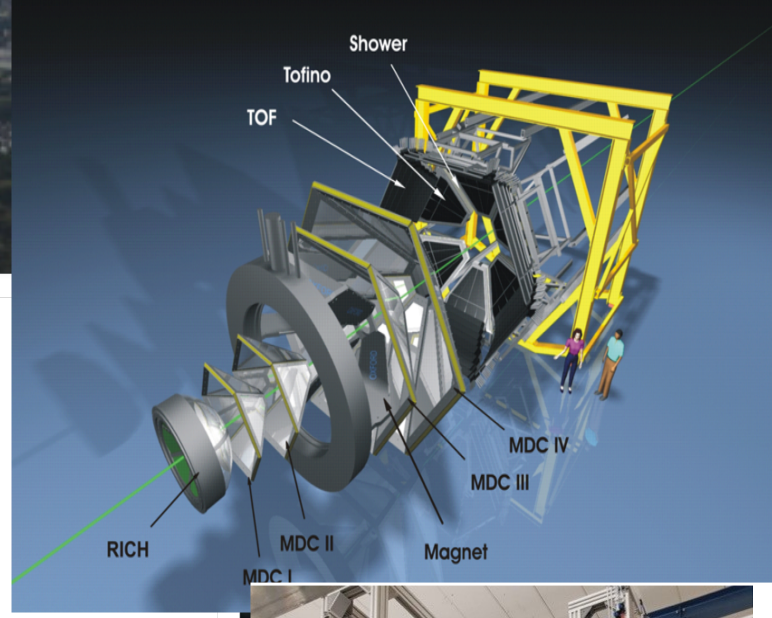

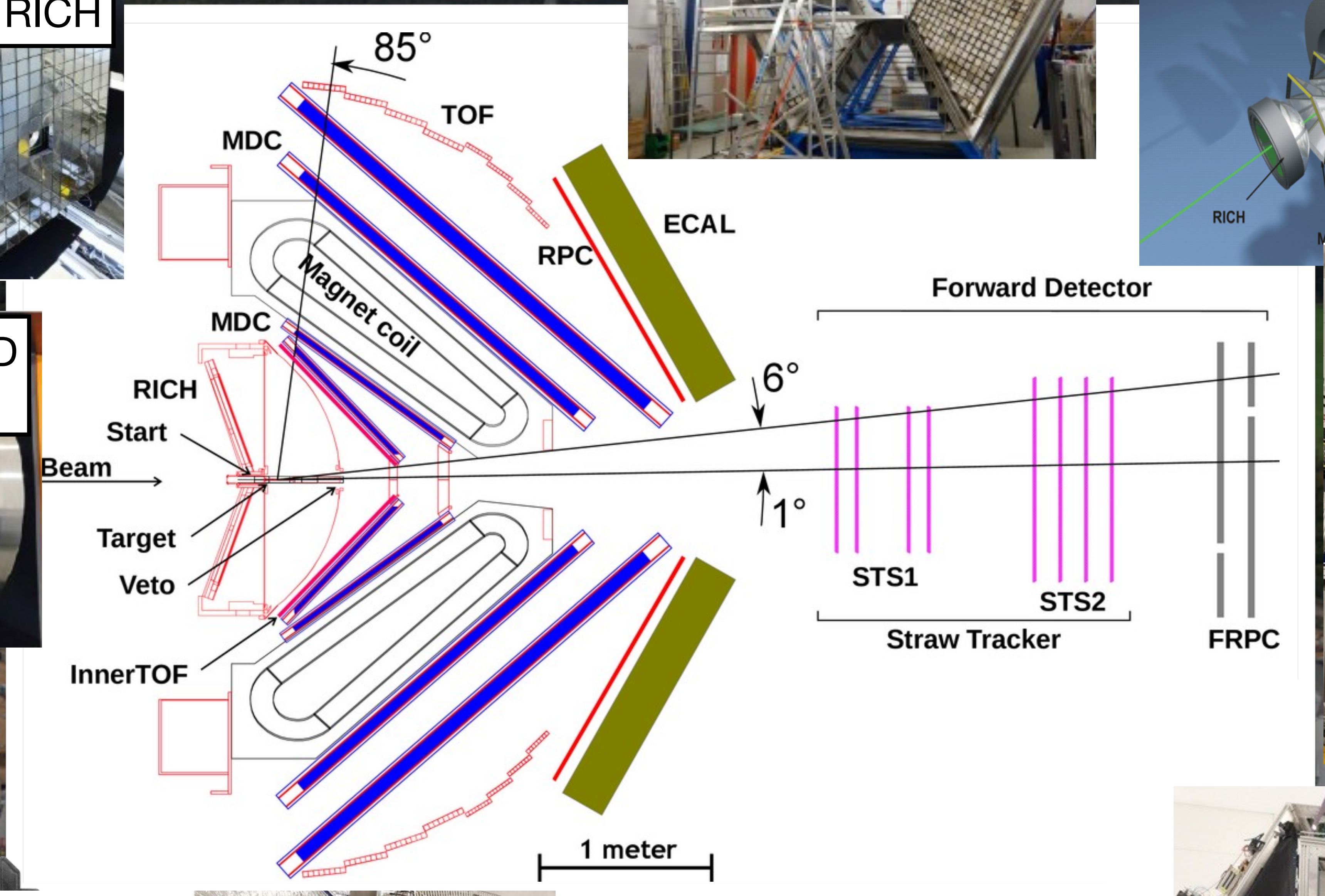

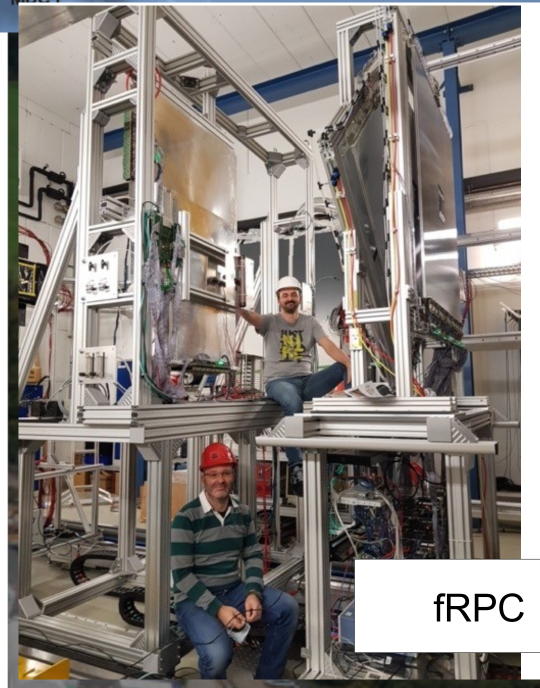

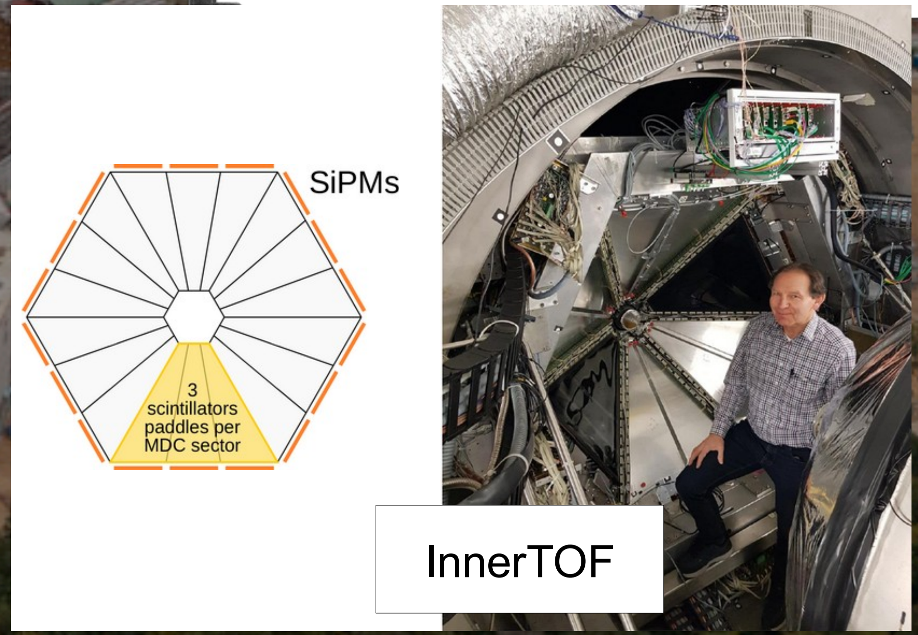

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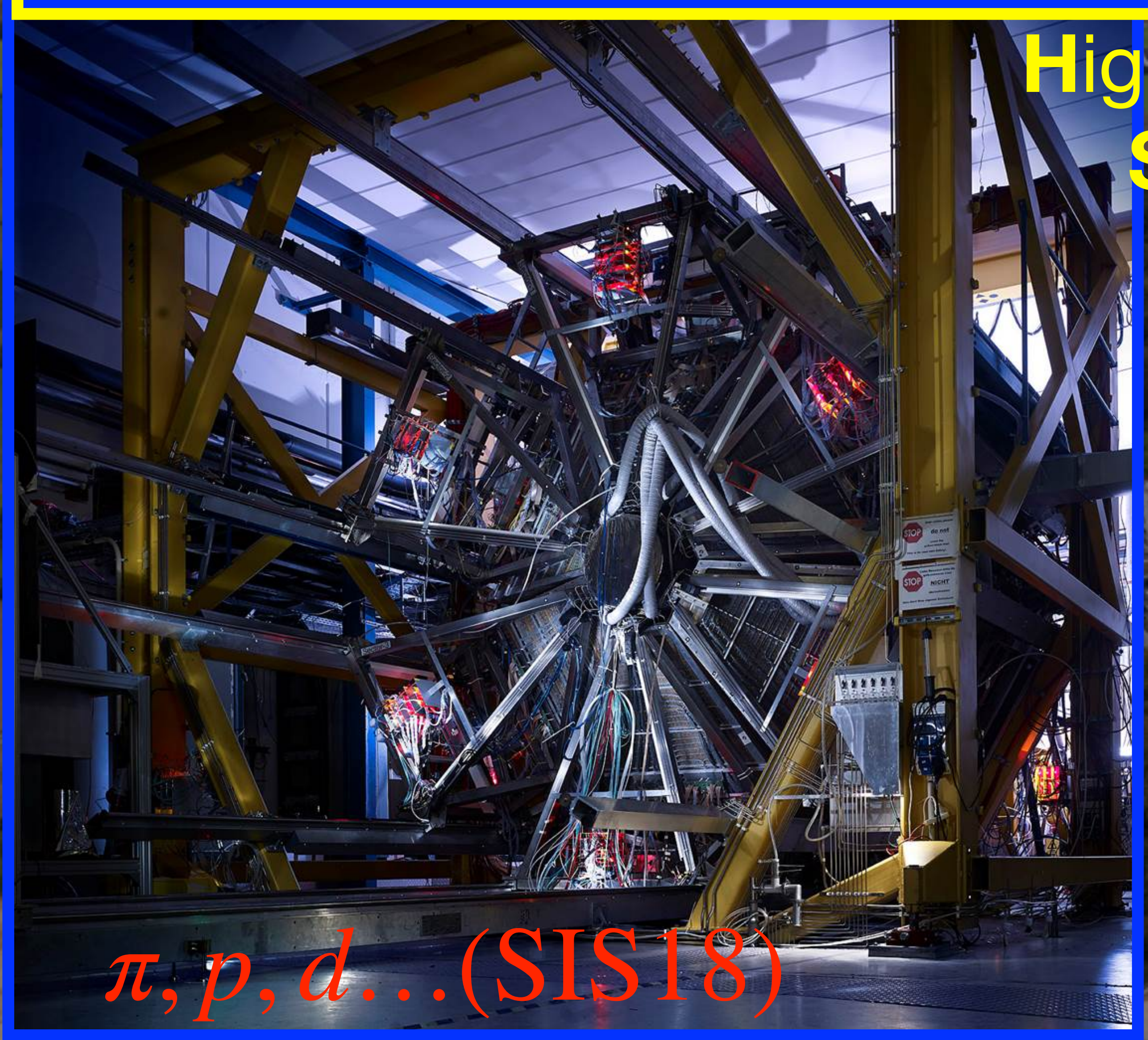

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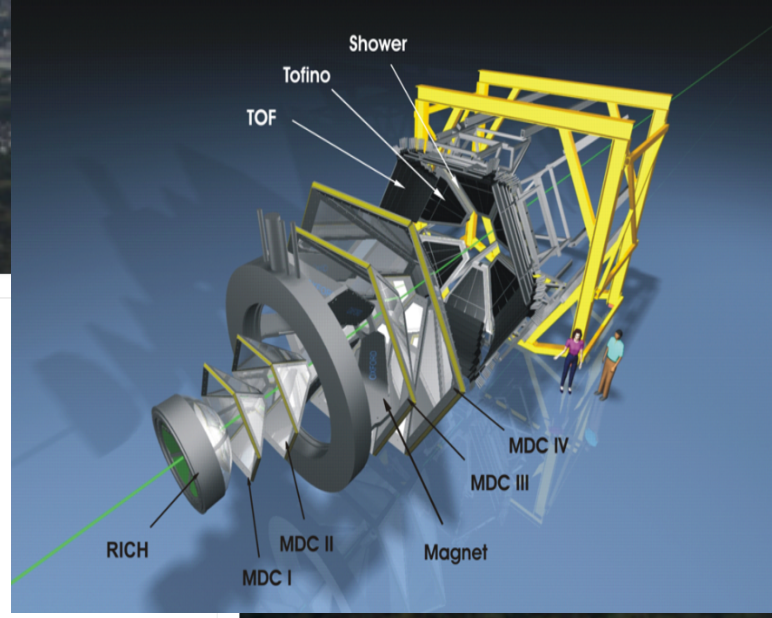

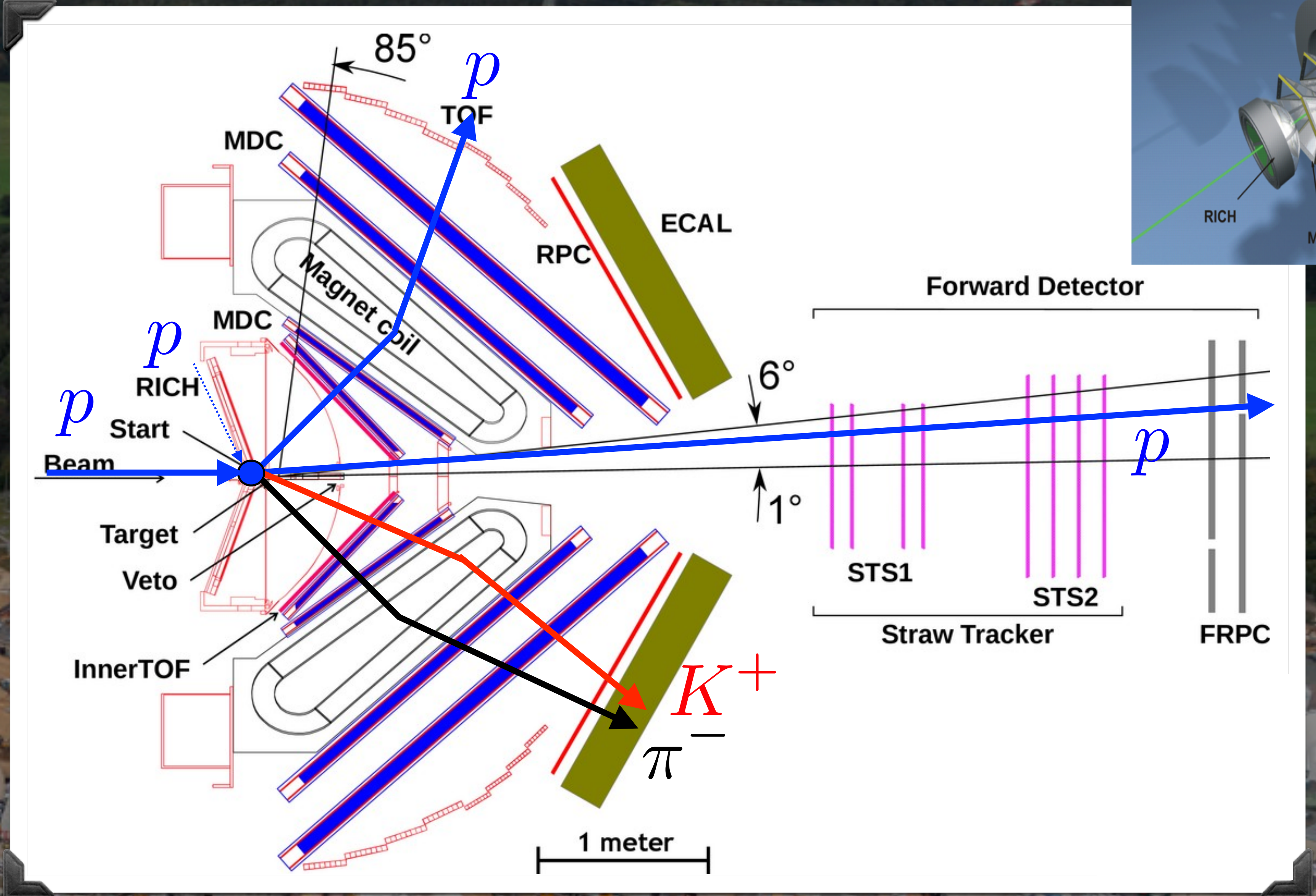

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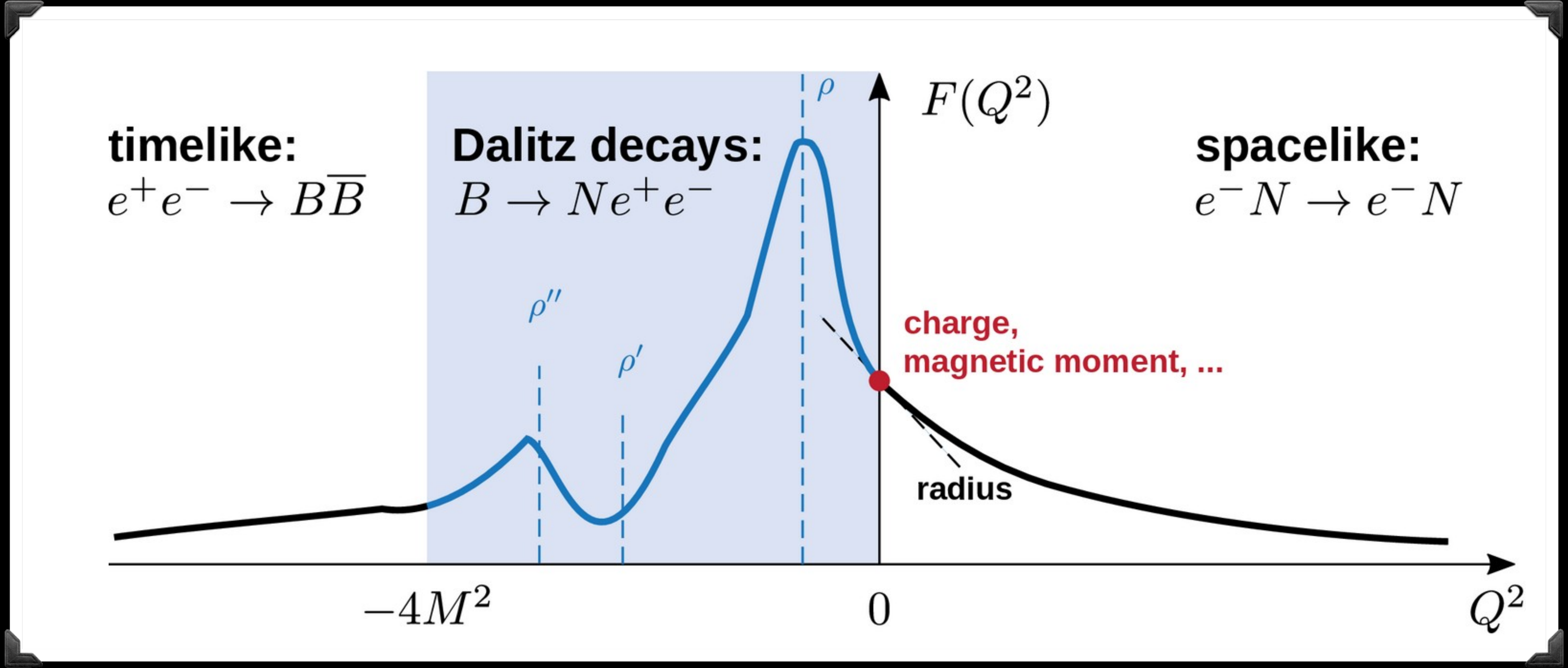
“exclusive” reactions!!

[Case study: Feb. 2022 run with 4.5 GeV protons]

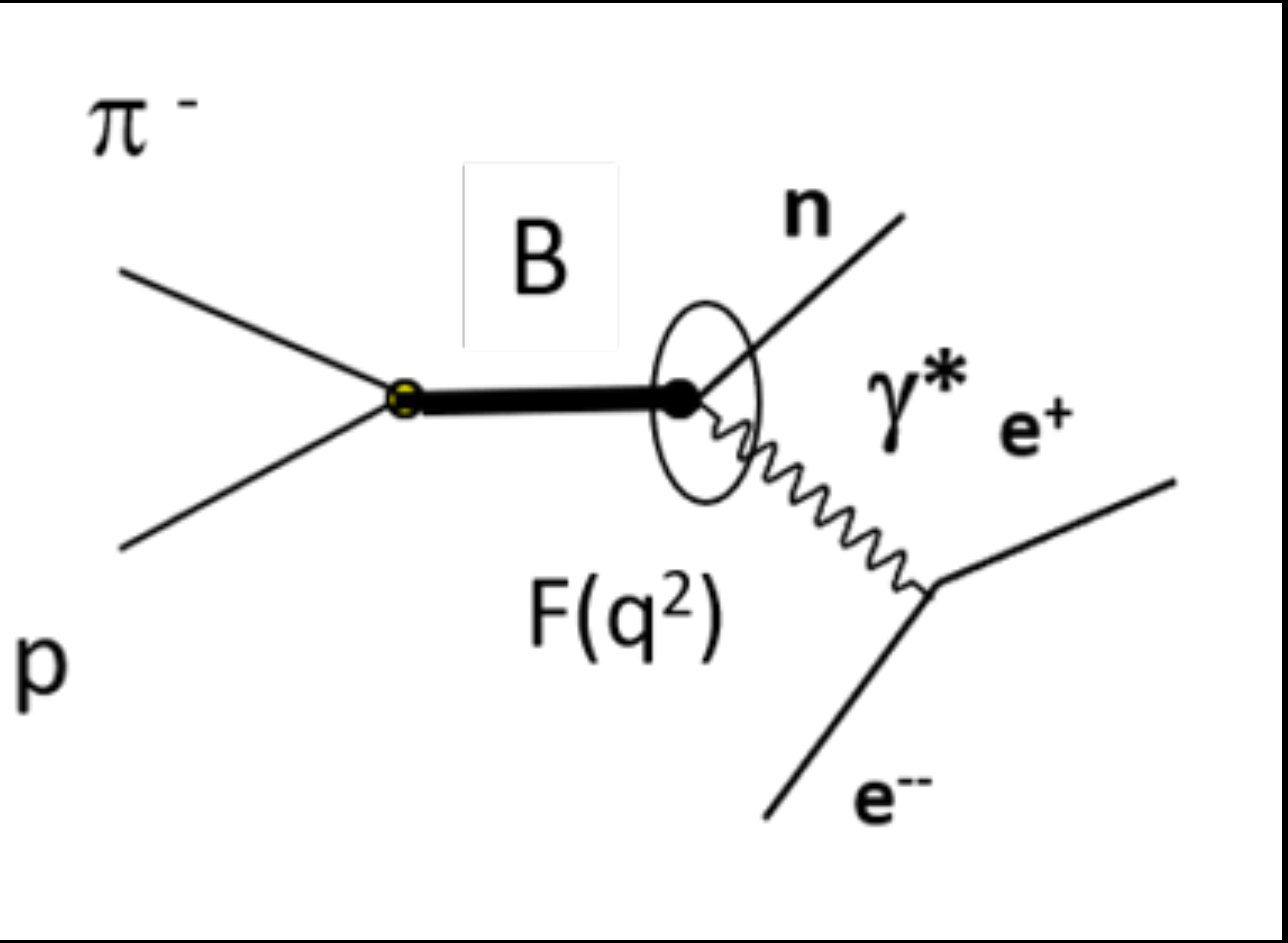
The power of pion beams

...and why being so obsessed about it?



Role of meson cloud?

Validity of Vector Meson Dominance?



Measure $d\sigma/dM_{ee}$ w.r.t. QED model

Combine with $\pi^+\pi^-$ data providing $N^*N\rho$ couplings (PWA)

Extract Spin Density Matrix Elements

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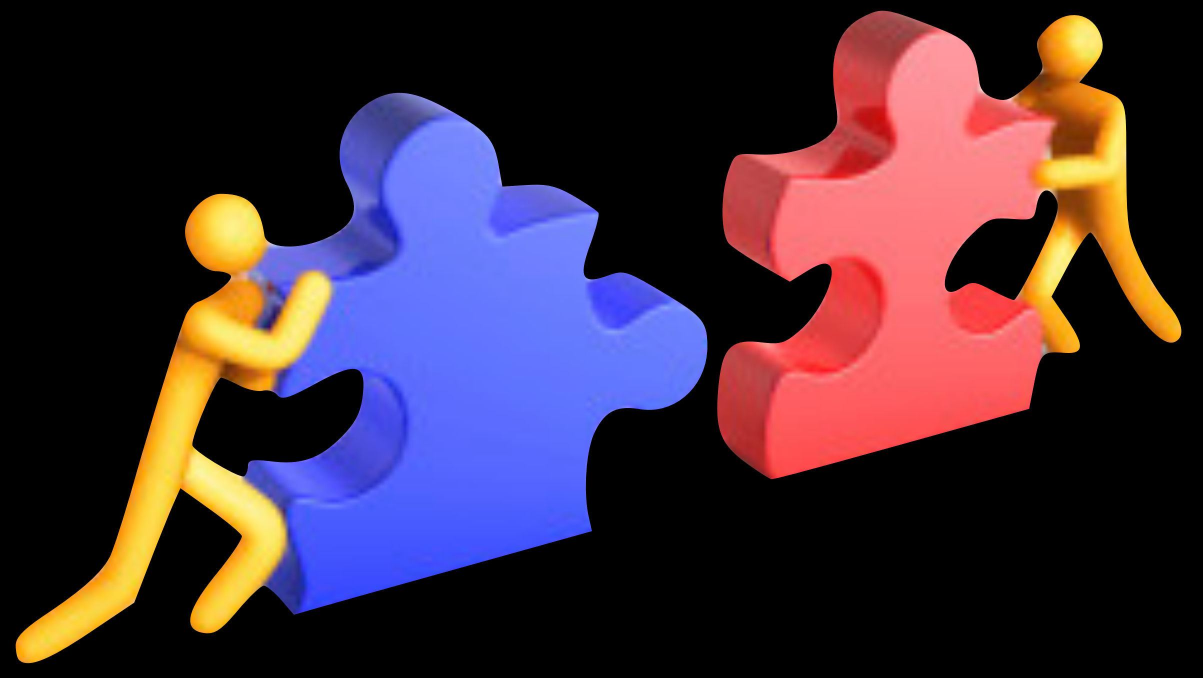
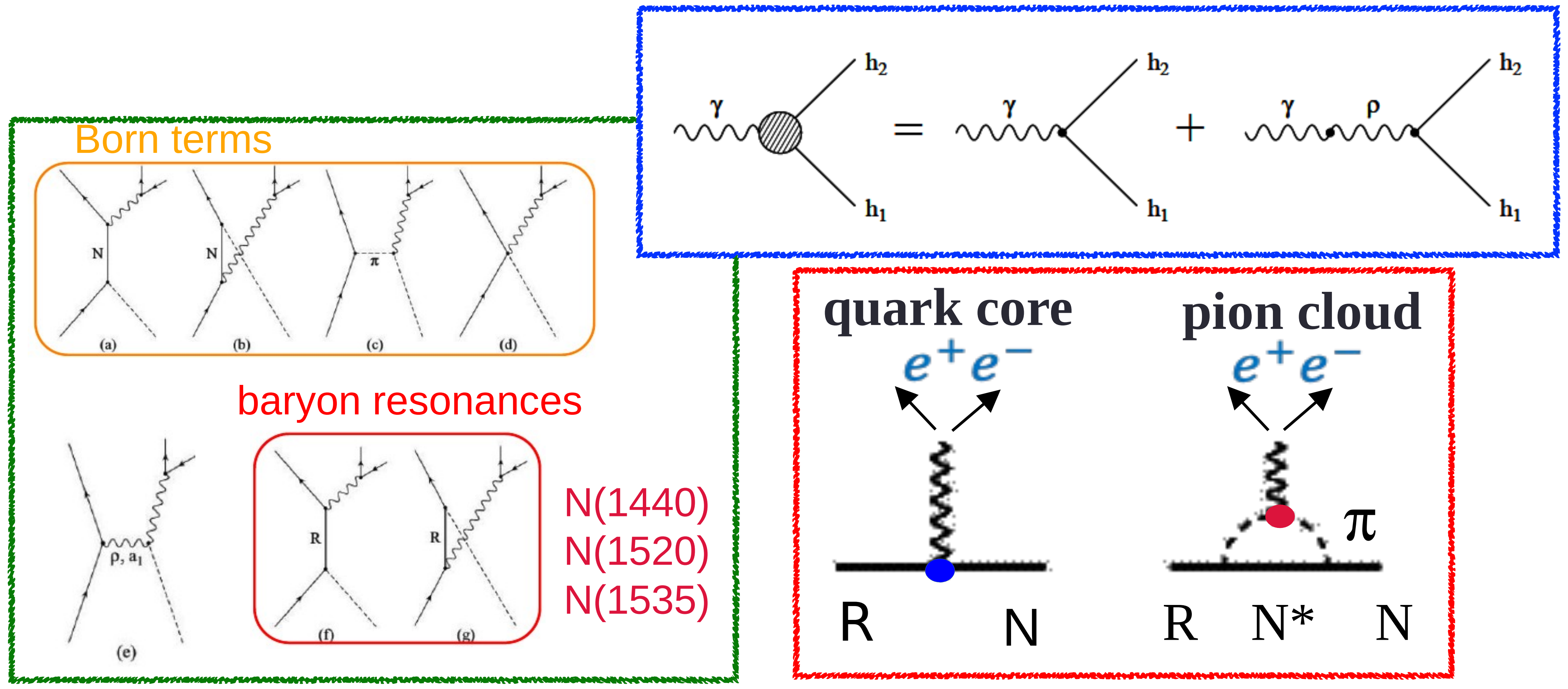
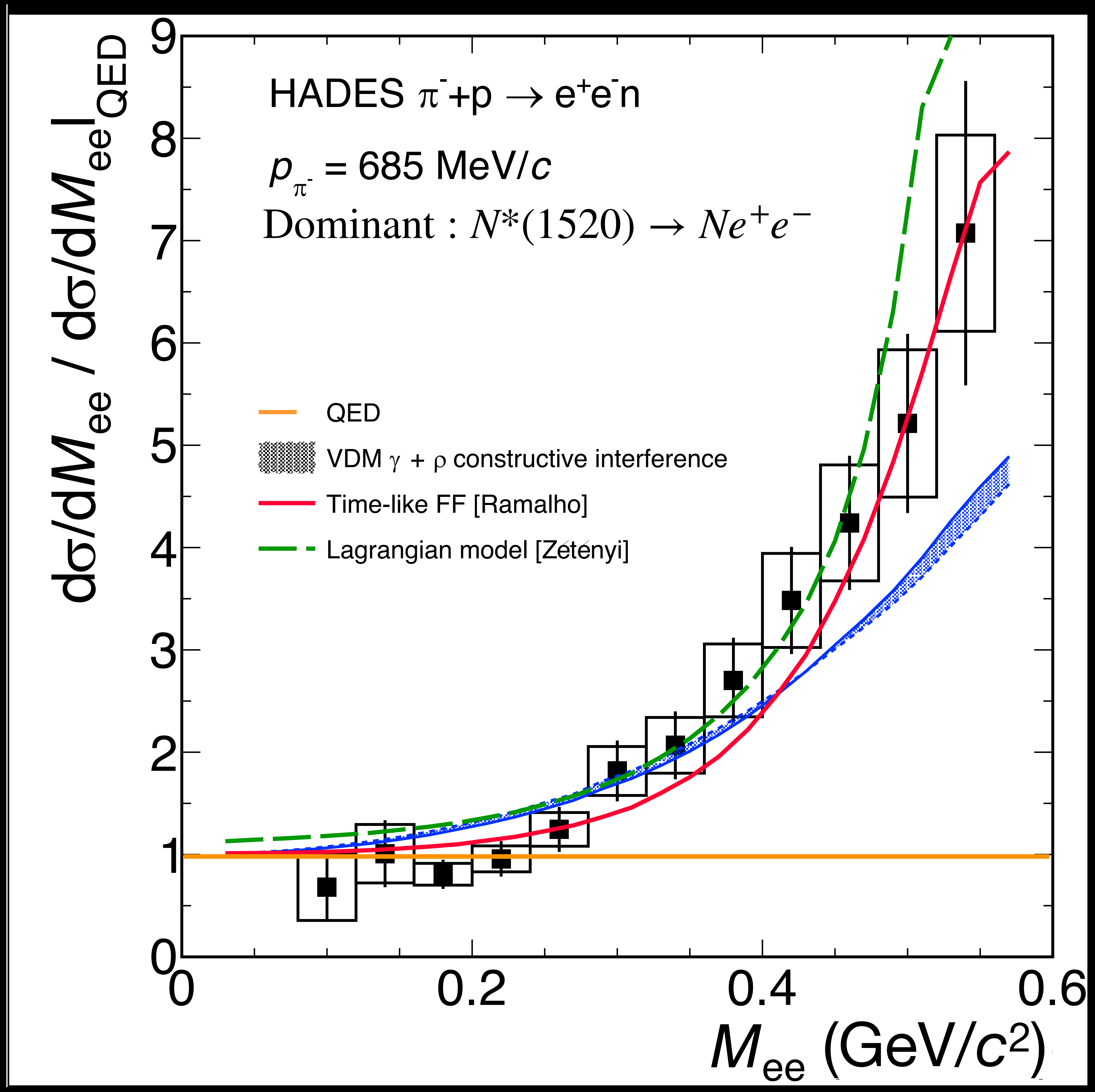


- 2-component VMD (VMD1) gives reasonable description
- Lagrangian model – very promising
- Time-like FF - dominant pion cloud contribution (pion emFF)





HADES, arXiv:2205.15914 + PRC102, 024001 (2020)

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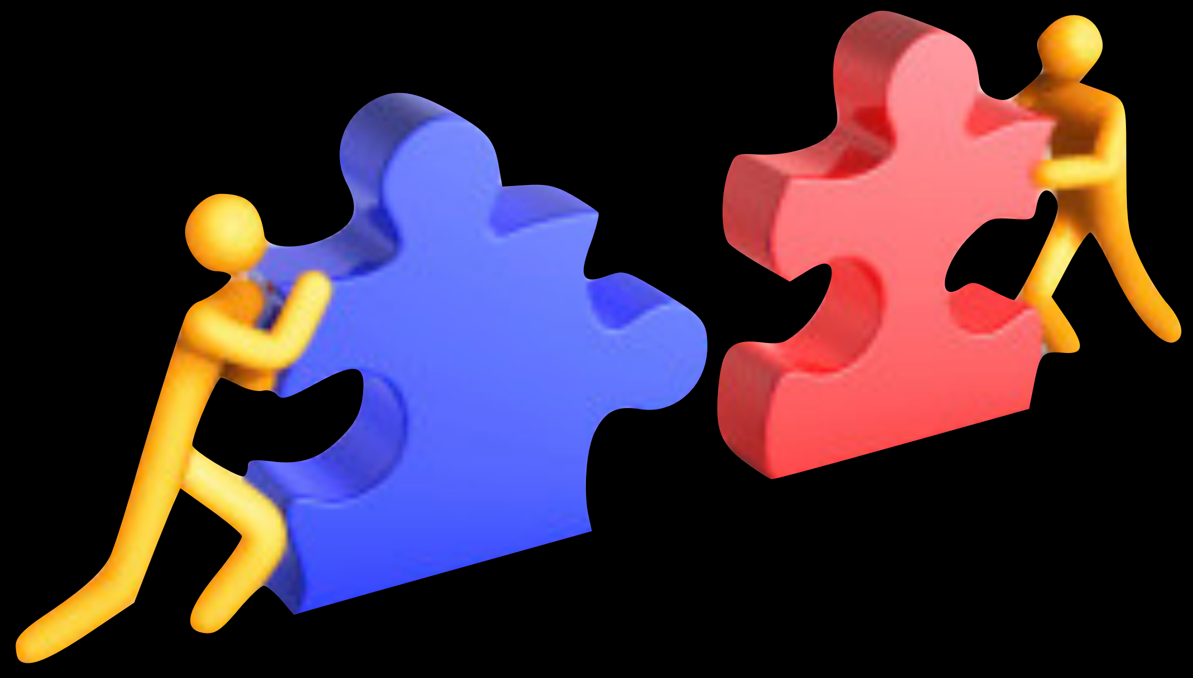
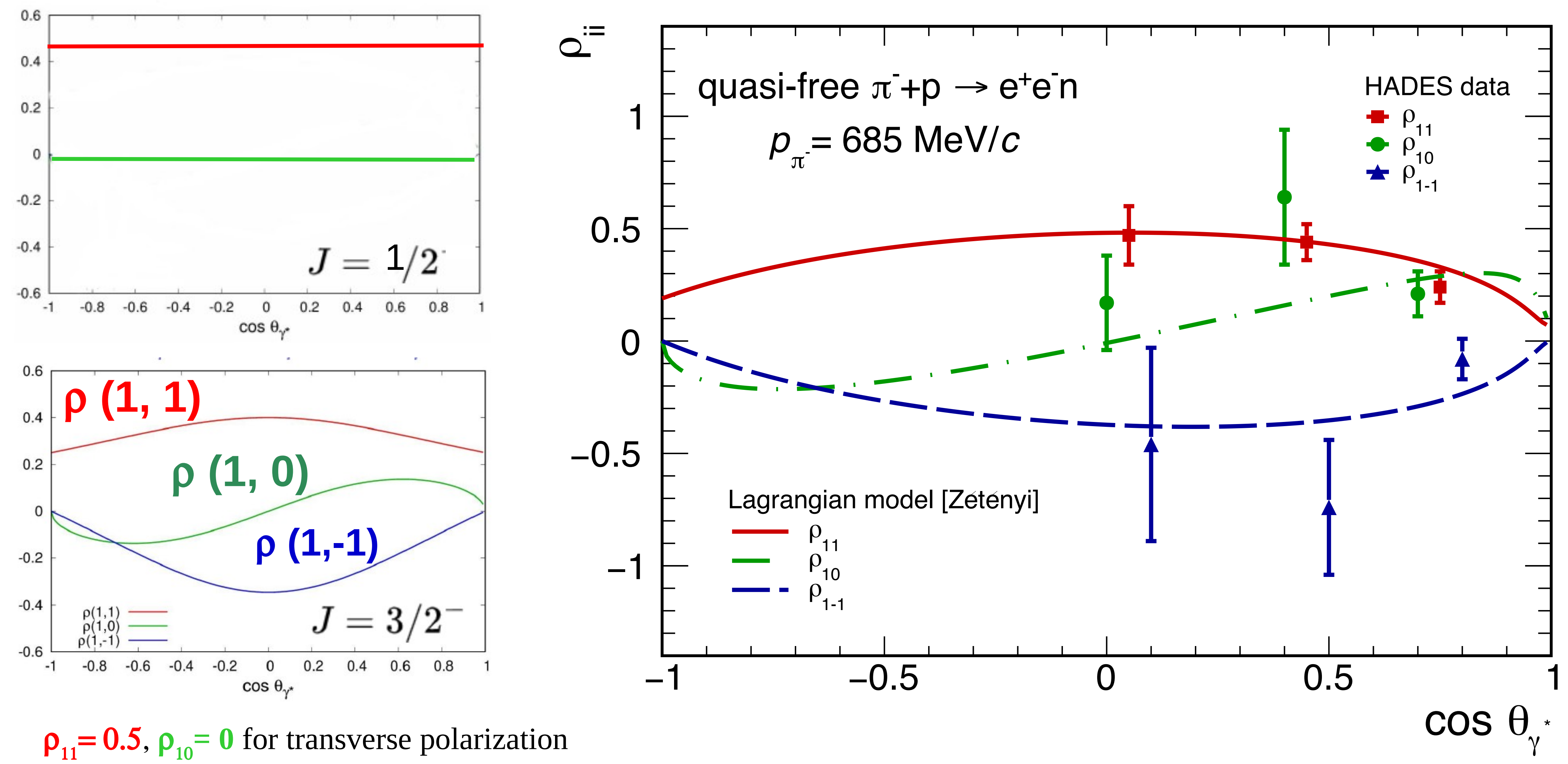


$$|A|^2 \propto 8k^2\left[1-\rho_{11}+(3\rho_{11}-1)\cos^2\Theta+\sqrt{2}Re\rho_{10}\sin 2\Theta\cos\phi+Re\rho_{1-1}\sin^2\Theta\cos 2\phi\right]$$



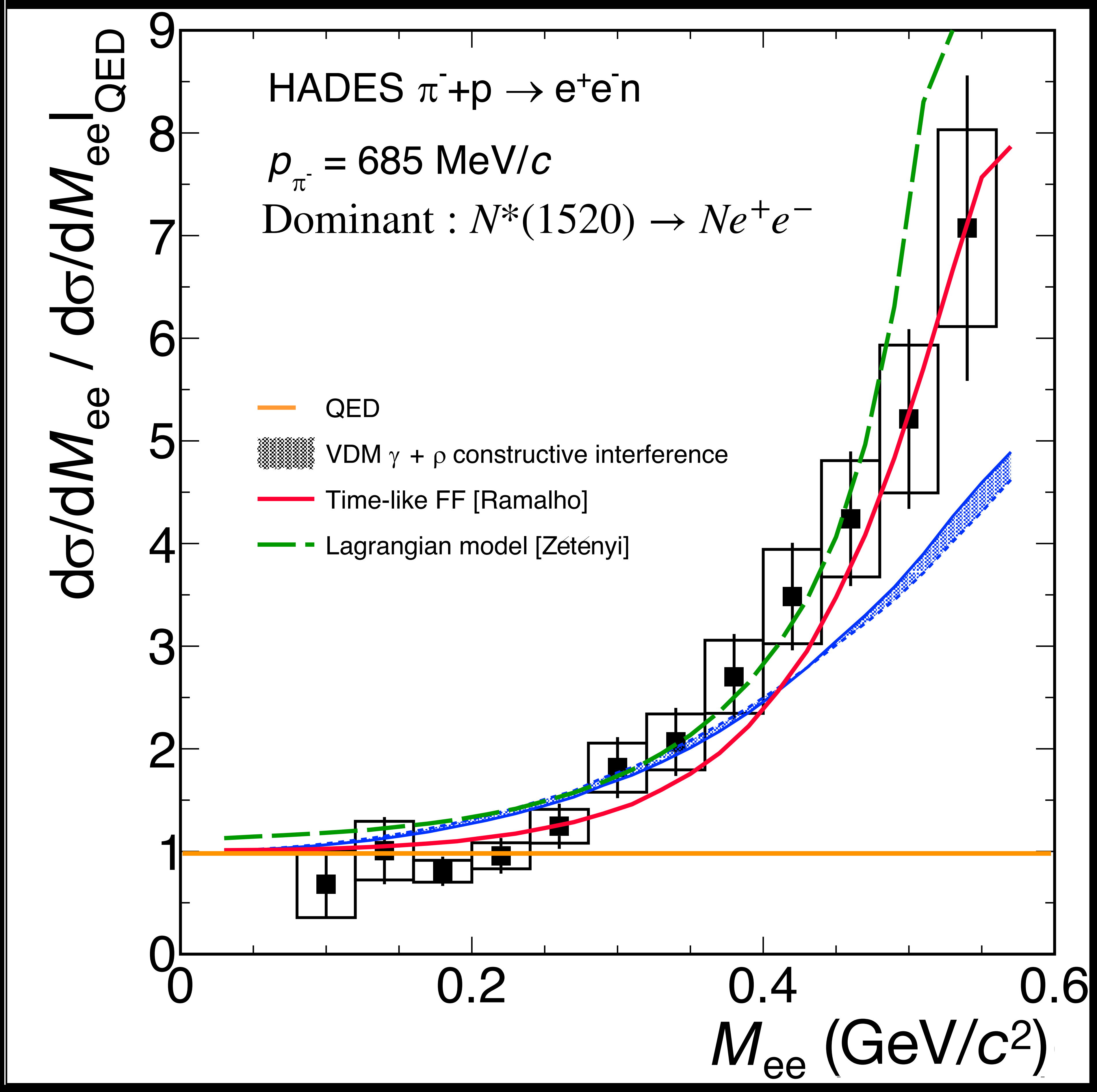
$\rho_{11} = 0.5$, $\rho_{10} = 0$ for transverse polarization (real photon) => contribution from virtual photon angular dependence

→ contributions of spins larger than ½: N(1520) resonance

more precise data needed !

Spin Density Matrix Elements

Adapted from I. Ciepal



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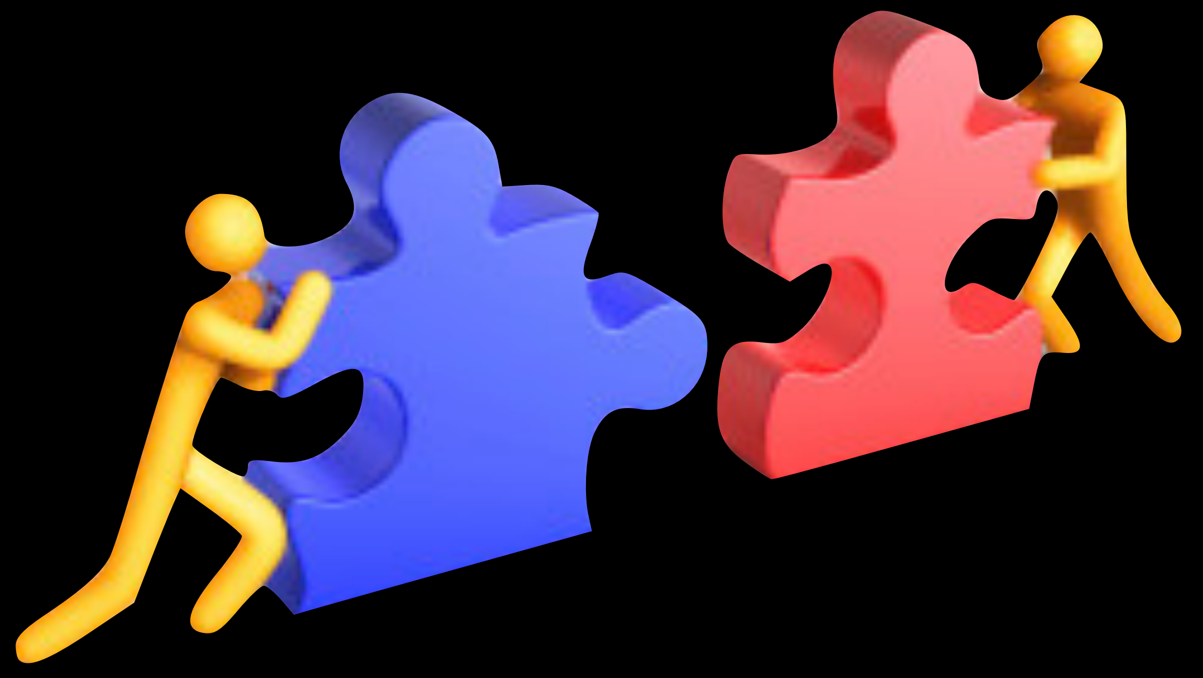
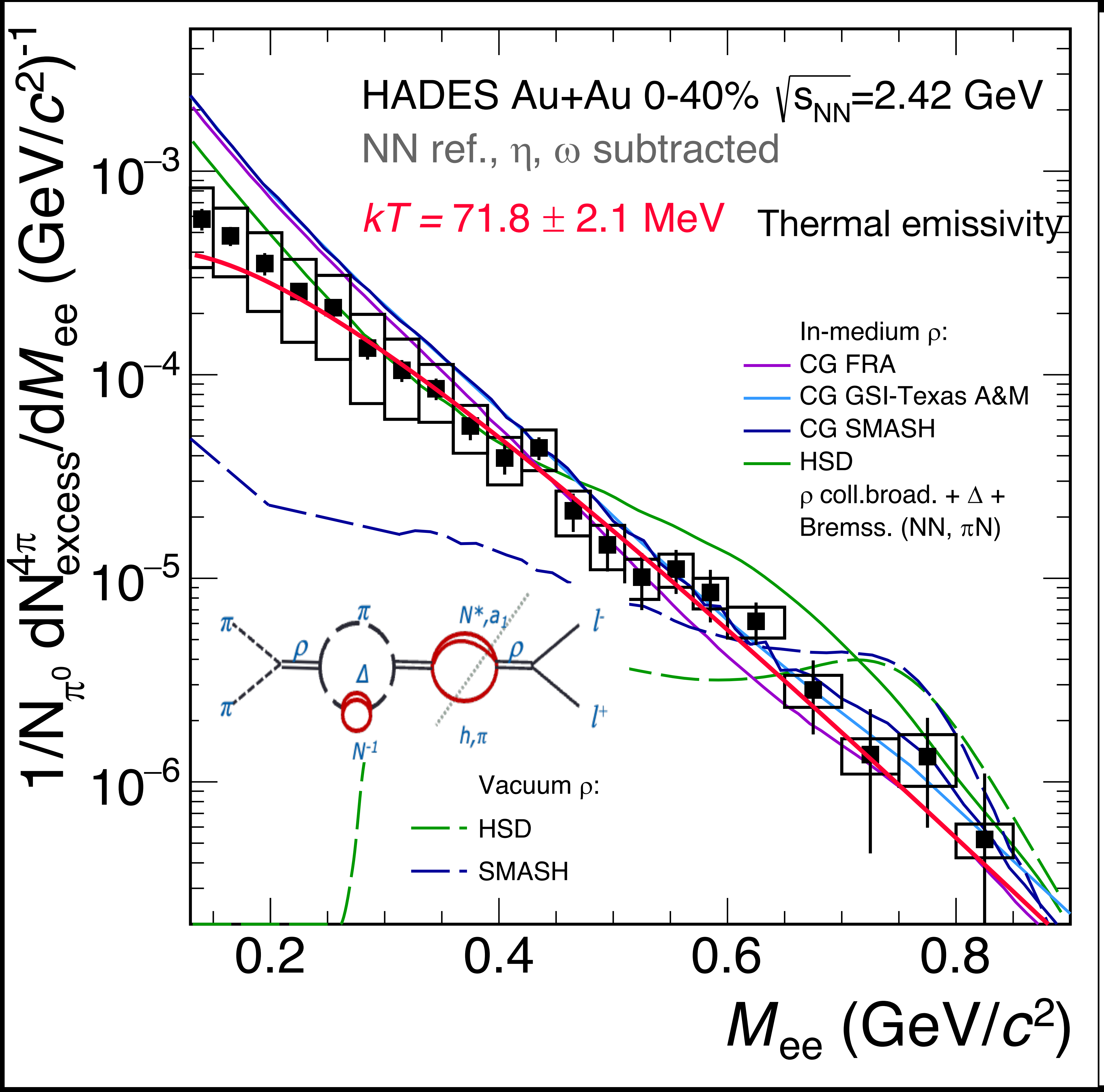
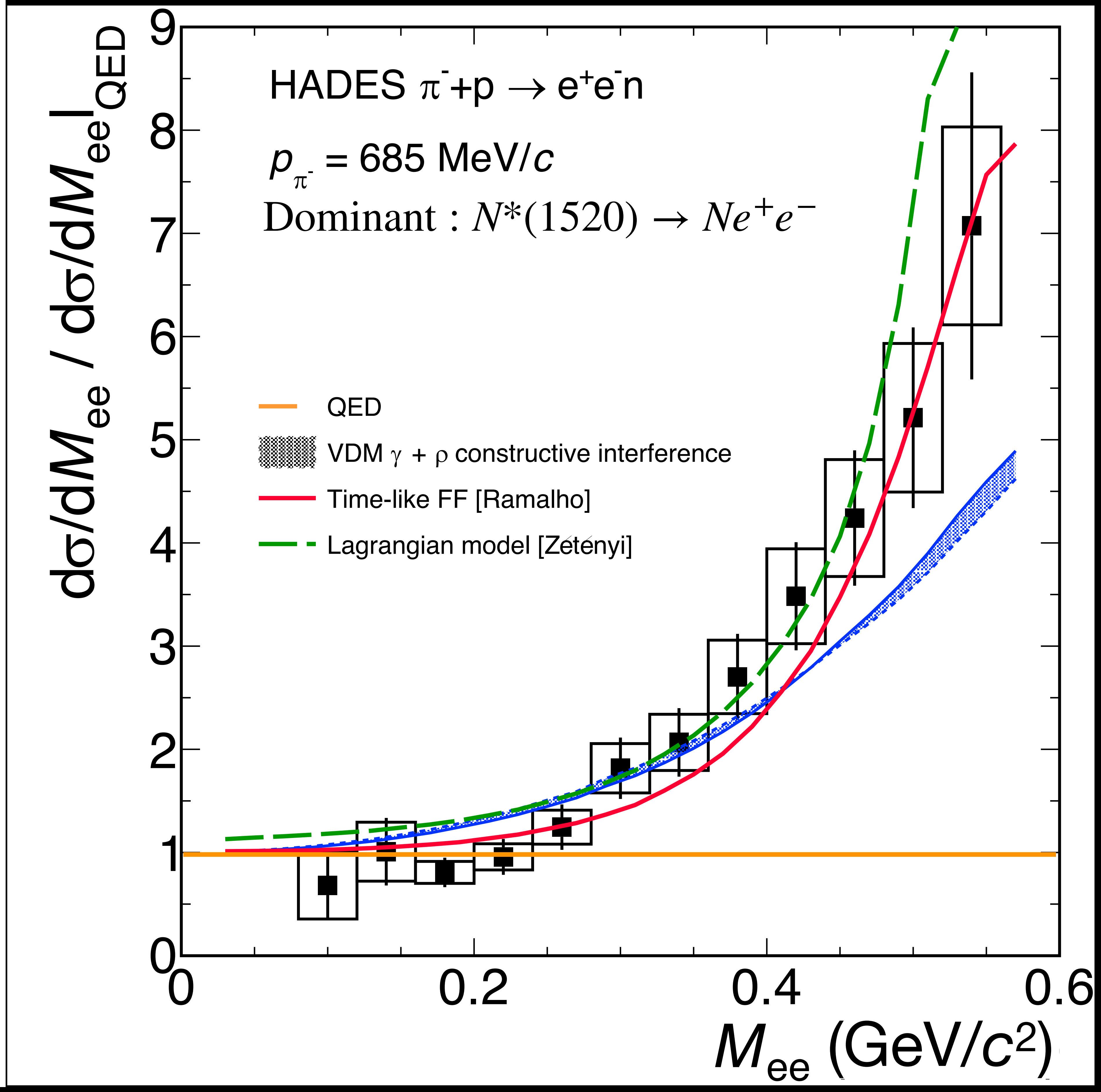


Happy "heavy-ion" and "hadron" physicists!!!



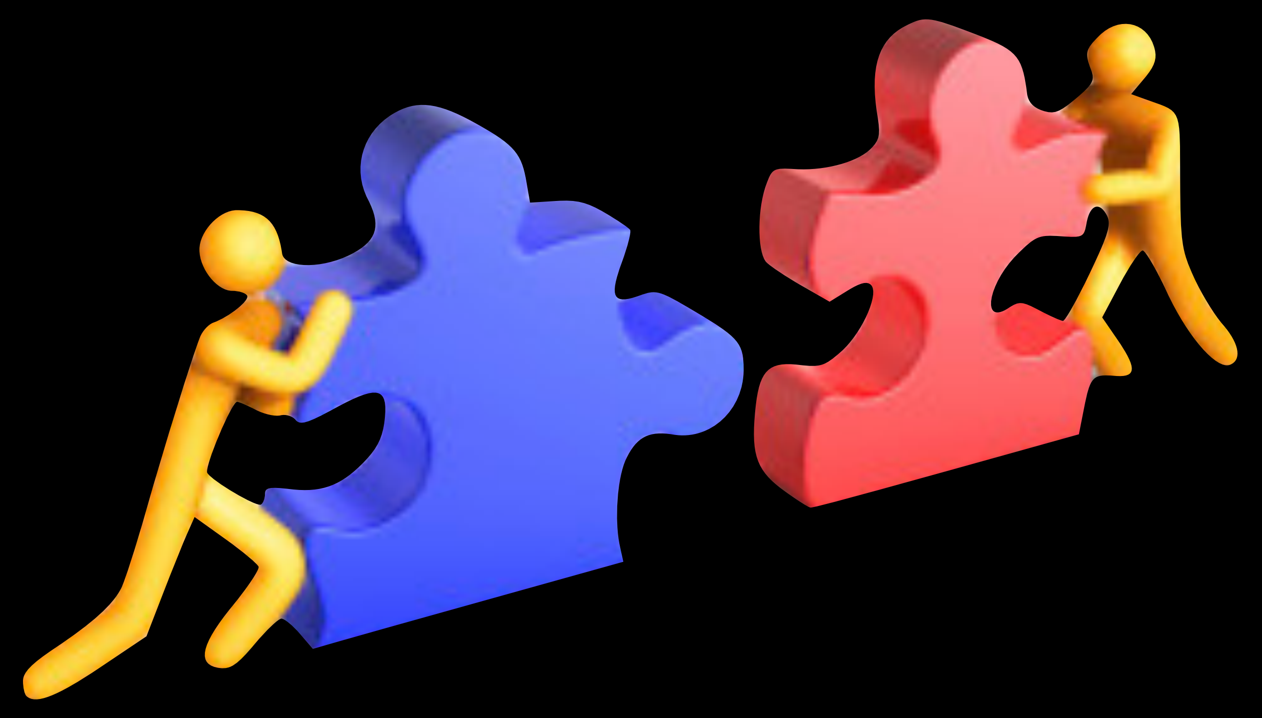


HADES, Nature Phys. 15 (2019), 10, 1040

HADES, arXiv:2205.15914 + PRC102, 024001 (2020)

Hadron-driven “QCD” physics at FAIR?

…a win-win-win situation



Hadron-driven “QCD” physics at FAIR?

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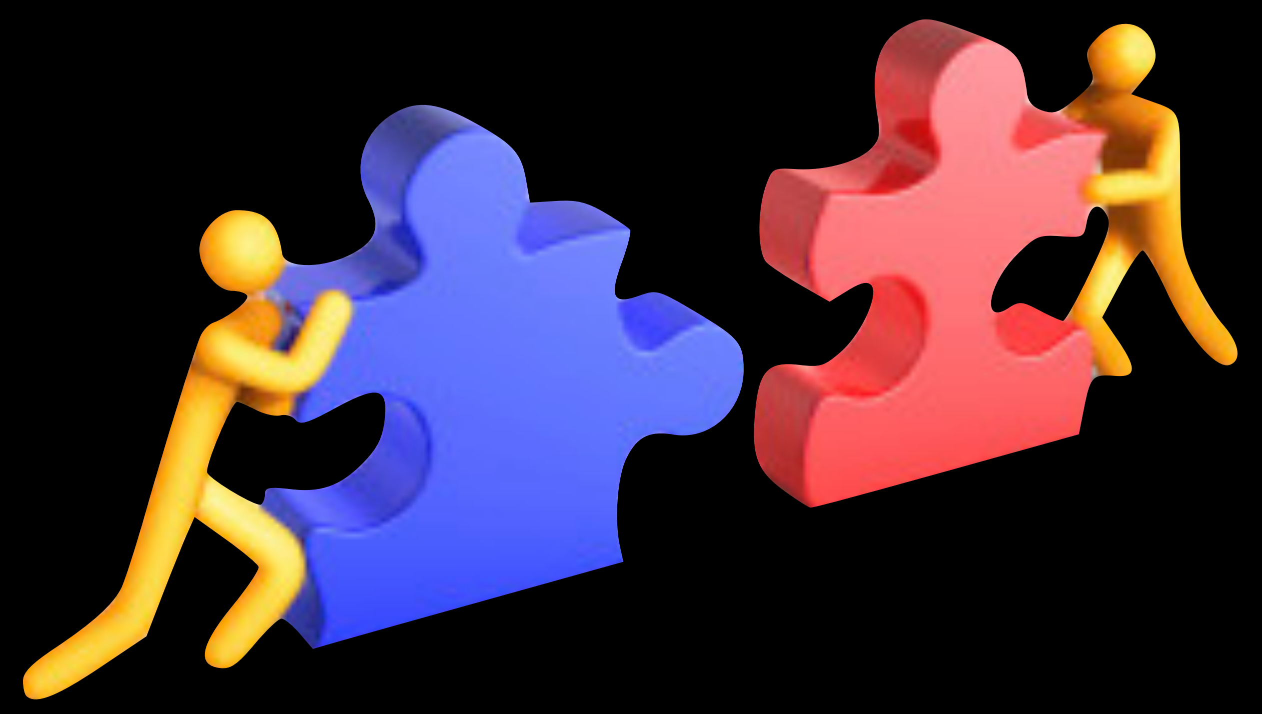
- **From heavy-ion perspectives:**
  - Necessary reference to heavy-ion reactions
  - Detailed information on baryon resonances and meson-baryon couplings



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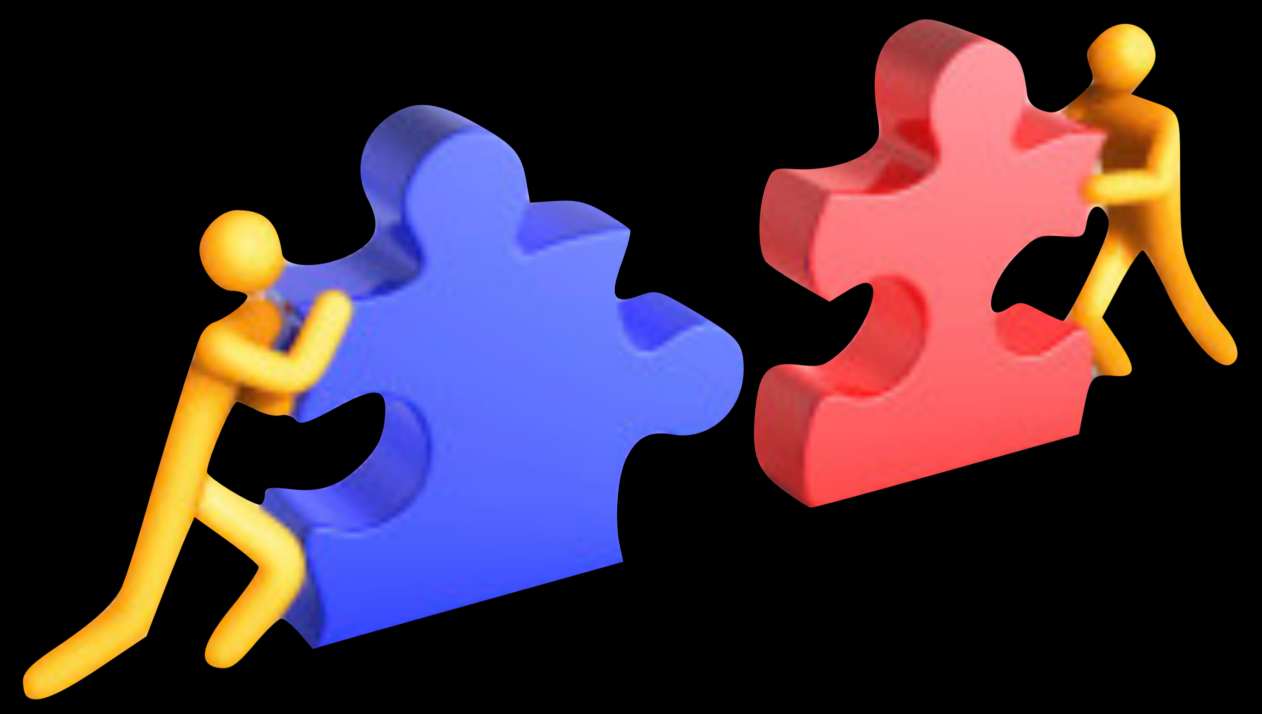
- **From nuclear perspectives:**
  - (Ab-initio) baryon-baryon data in flavour SU(3)



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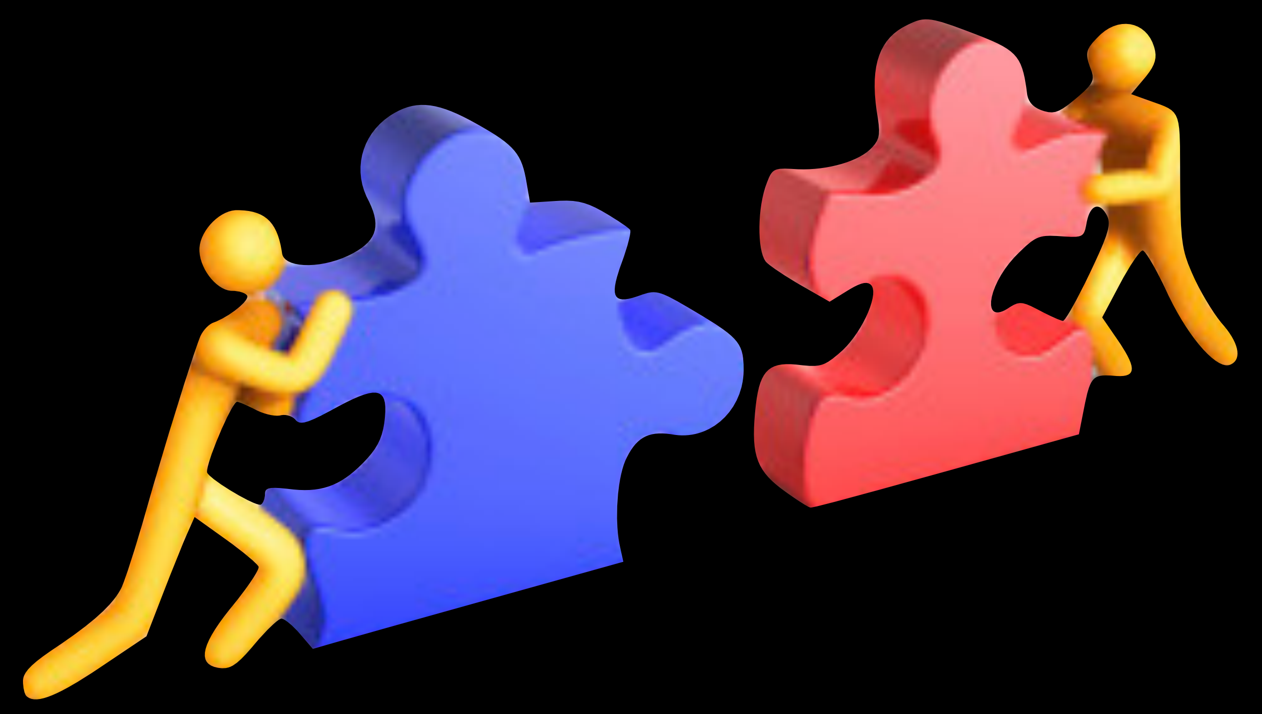
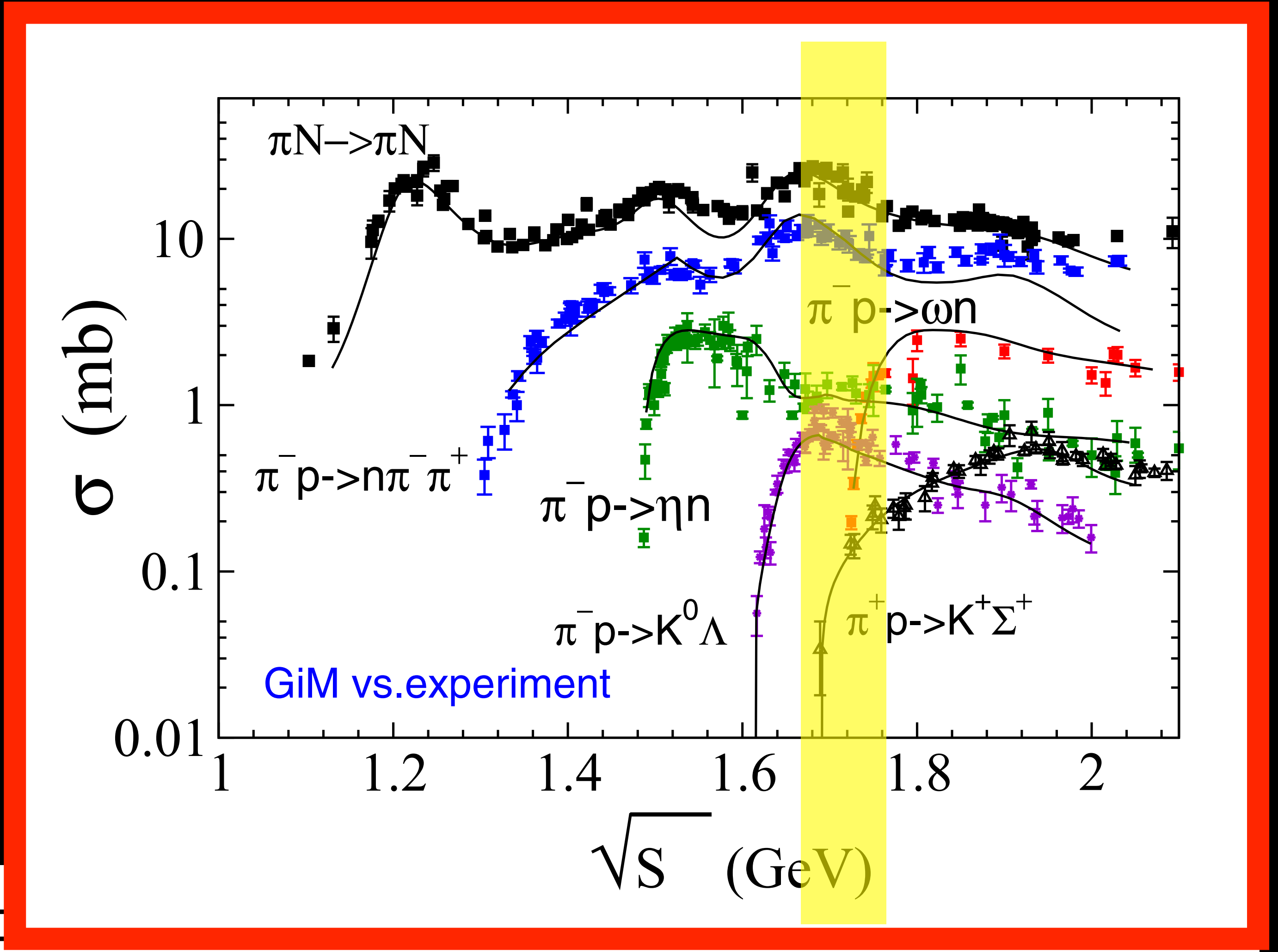


- **From hadron perspectives:**
  - Controllable tool for hadron spectroscopy & structure studies in u,d,s,c sectors
  - Intermediate physics program with pions & protons towards antiprotons

The power of pion beams *at GSI*

...what makes us competitive & complementary?



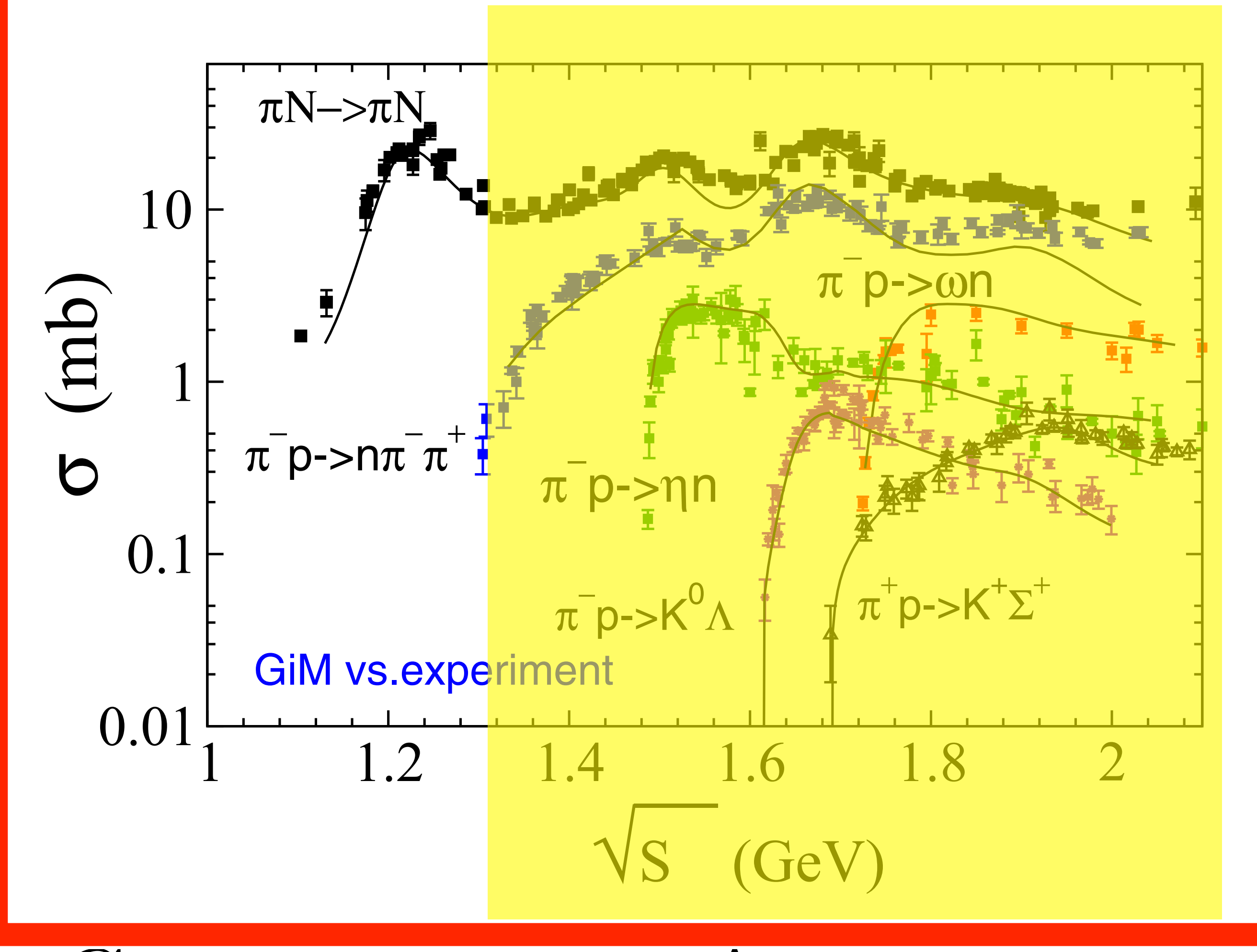
"2020" proposal (143 shifts)

channel	ε_{AR}	σ_H (mb)	σ_C (mb)	σ_{Ag} (mb)	BR	C_2H_4 target $\dot{N}_H/\dot{N}_{tot}$ (shift^{-1})	C target $\dot{N}_C$(shift^{-1})	Ag target $\dot{N}_{Ag}$(shift^{-1})
$\pi^-\pi^+$ n	0.14	10	16	63	1	$3.4\times10^6/6.1\times10^6$	3.8×10^6	2.0×10^6
$\pi^-\pi^0$ p	0.09	6.5	10.4	41	1	$1.4\times10^6/2.6\times10^6$	1.6×10^6	8.6×10^5
$\pi^0\pi^0$ p	0.01	2	3.2	13	1	$4.9\times10^4/8.8\times10^4$	5.4×10^4	2.9×10^4
$K^0\Lambda$	0.04	0.56	1.85	7.3	0.35	$1.9\times10^4/5.0\times10^4$	4.3×10^4	2.4×10^4
$K^0\Sigma^0$	0.04	0.24	0.79	3.1	0.35	$8\times10^3/2.2\times10^4$	1.9×10^4	1.0×10^4
$K^+\Sigma^-$	0.13	0.23	0.76	3.0	1	$7.2\times10^4/1.9\times10^5$	1.7×10^5	9.0×10^4
ηn	0.01	1.2	3.96	15.6	0.39	$1.2\times10^4/3.1\times10^4$	2.6×10^4	1.4×10^4
ωn	0.015	1.5	4.95	19.5	0.89	$4.9\times10^4/1.3\times10^5$	1.1×10^5	4.0×10^4
$\rho\to e^+e^-$	0.25	2.1	6.93	90.3	$6\,10^{-5}$	78/204	176	95
$\omega\to e^+e^-$	0.31	1.7	5.61	73.1	$7.4\,10^{-5}$	84/222	190	104

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

The power of pion beams *at GSI*

...what makes us competitive & complementary?



"2020" proposal (143 shifts)

channel	ε_{AR}	σ_H (mb)	σ_C (mb)	σ_{Ag} (mb)	BR	C_2H_4 target $\dot{N}_H/\dot{N}_{tot}$ (shift^{-1})	C target $\dot{N}_C$ (shift^{-1})	Ag target $\dot{N}_{Ag}$ (shift^{-1})
$\pi^-\pi^+$ n	0.14	10	16	63	1	$3.4\times10^6/6.1\times10^6$	3.8×10^6	2.0×10^6
$\pi^-\pi^0$ p	0.09	6.5	10.4	41	1	$1.4\times10^6/2.6\times10^6$	1.6×10^6	8.6×10^5
$\pi^0\pi^0$ p	0.01	2	3.2	13	1	$4.9\times10^4/8.8\times10^4$	5.4×10^4	2.9×10^4
$K^0\Lambda$	0.04	0.56	1.85	7.3	0.35	$1.9\times10^4/5.0\times10^4$	4.3×10^4	2.4×10^4
$K^0\Sigma^0$	0.04	0.24	0.79	3.1	0.35	$8\times10^3/2.2\times10^4$	1.9×10^4	1.0×10^4
$K^+\Sigma^-$	0.13	0.23	0.76	3.0	1	$7.2\times10^4/1.9\times10^5$	1.7×10^5	9.0×10^4
ηn	0.01	1.2	3.96	15.6	0.39	$1.2\times10^4/3.1\times10^4$	2.6×10^4	1.4×10^4
ωn	0.015	1.5	4.95	19.5	0.89	$4.9\times10^4/1.3\times10^5$	1.1×10^5	4.0×10^4
$\rho\rightarrow e^+e^-$	0.25	2.1	6.93	90.3	$6\,10^{-5}$	78/204	176	95
$\omega\rightarrow e^+e^-$	0.31	1.7	5.61	73.1	$7.4\,10^{-5}$	84/222	190	104

Existing "2020": $\sqrt{s} = 1.67 - 1.79\,\mathrm{GeV}$ ➡ New "**2024**": $\sqrt{s} = 1.37 - 2.3\,\mathrm{GeV}$