Pion- and (anti)proton-induced QCD studies at GSI/FAIR

...from SIS18 to SIS100

Johan Messchendorp

NSTAR2024, June 17-21 2024, York, UK

Facility for Antiproton and Ion Research -
“The Universe in the Laboratory”

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{q}\,(\,i\gamma_\mu D^\mu - m_q\,)\,q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

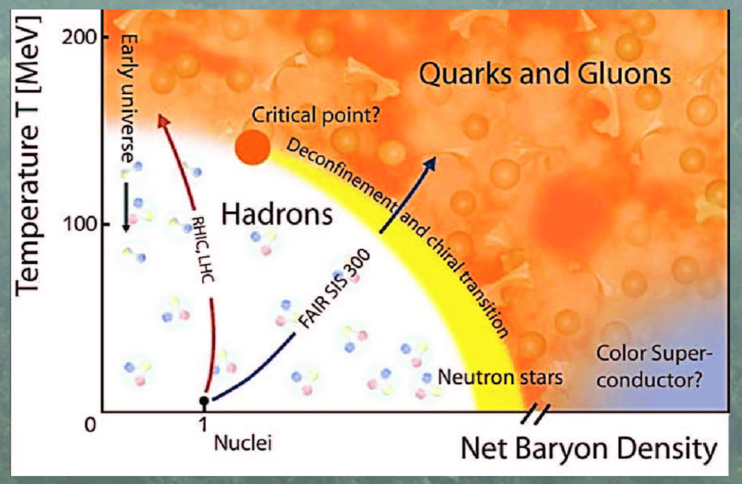
Properties of strongly interacting matter

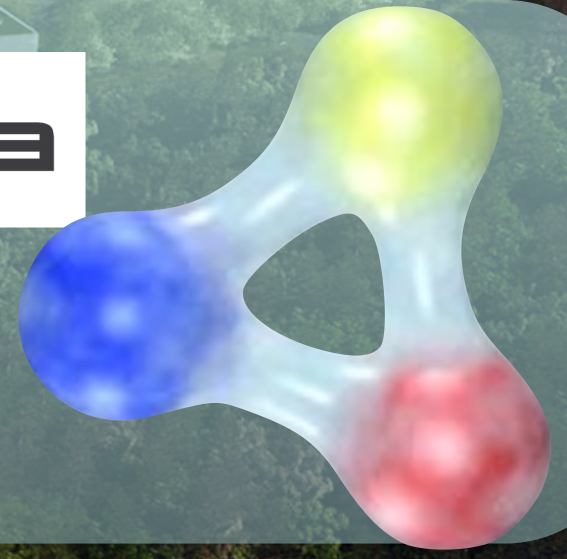
Formation of hadronic matter

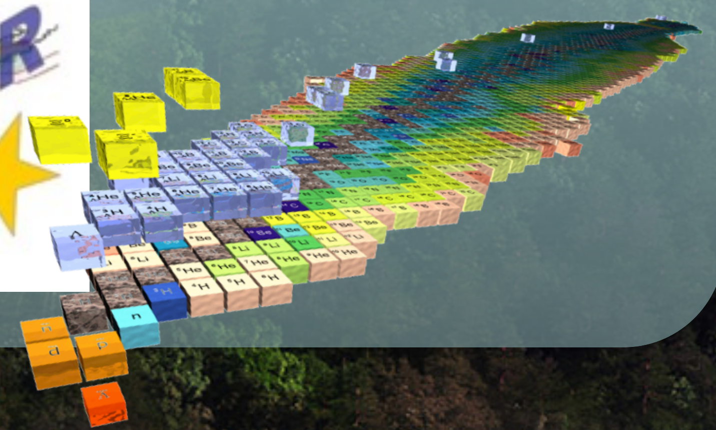
Underlying symmetries

Degrees of freedom: from quarks/gluons to baryons/mesons

Origin of mass







Hadron Physics Facilities at FAIR

Hadron Physics Facilities at FAIR

antiP**rotons** AN**nihilations at**
DArmstadt **(PANDA)**

$p, d \ldots$(SIS100)
Compressed Baryonic Matter (CBM)
$\bar{p}, p \ldots$(HESR)
Hadron Physics Facilities at FAIR
antiProtons ANnihilations at DArmstadt (PANDA)


HADES/PANDA@FAIR-Phase-0:
"Hadron physics meets heavy-ion physics"
High **A**cceptance **D**i-**E**lectron **S**pectrometer **(HADES)**
Hadron Physics Facilities at FAIR
October 2023
$\pi, p, d \ldots$(SIS18)

HADES/PANDA@FAIR-Phase-0:
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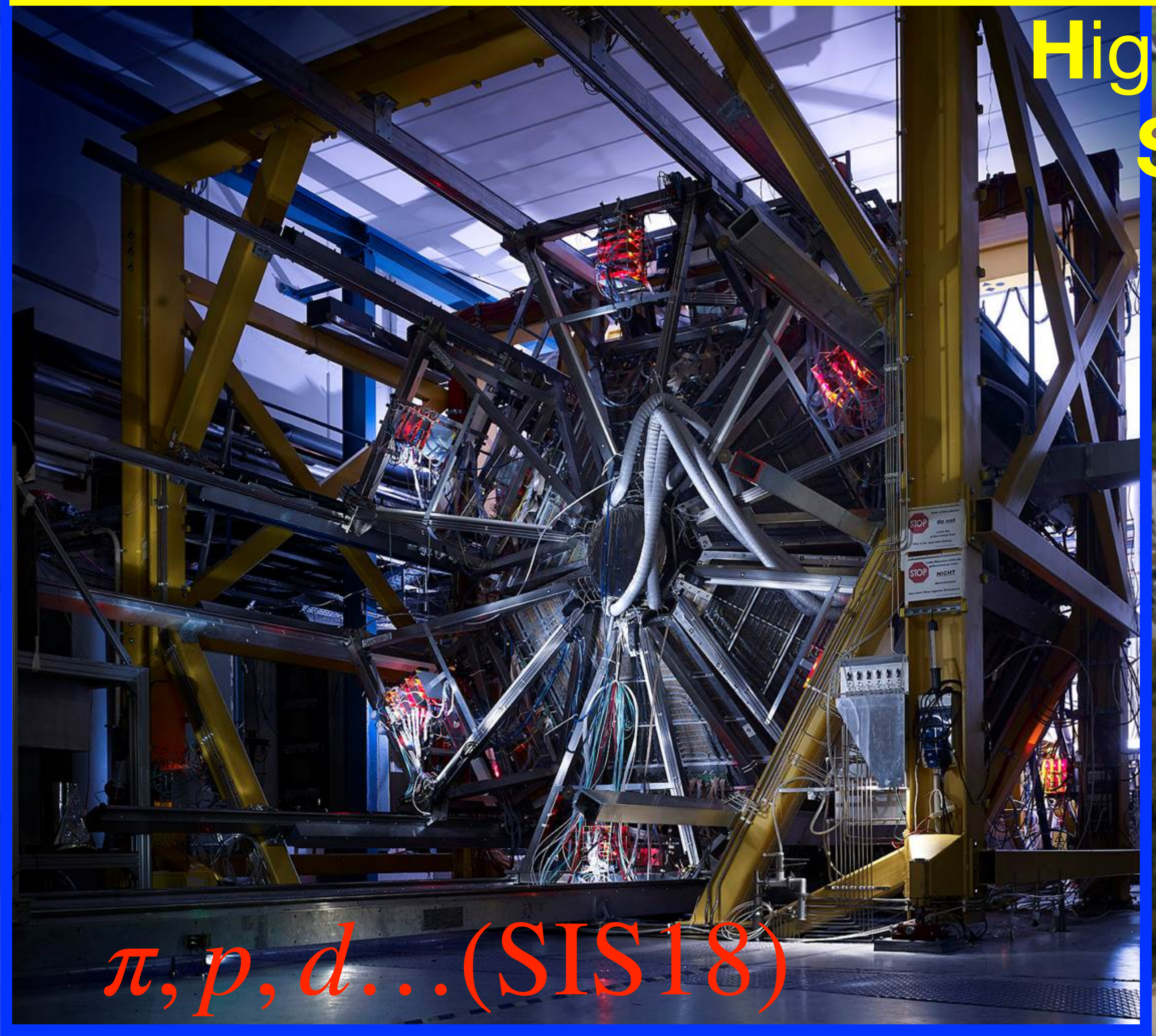
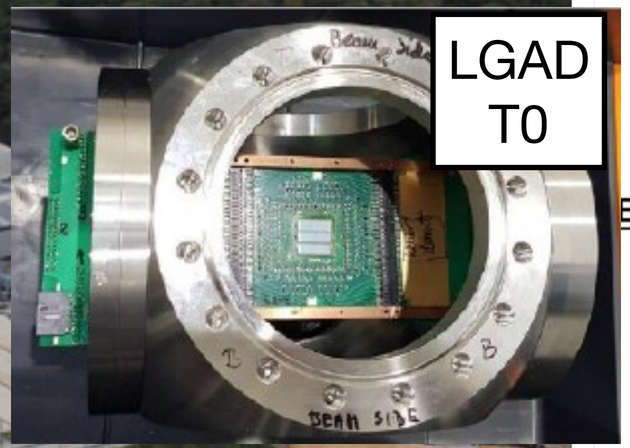
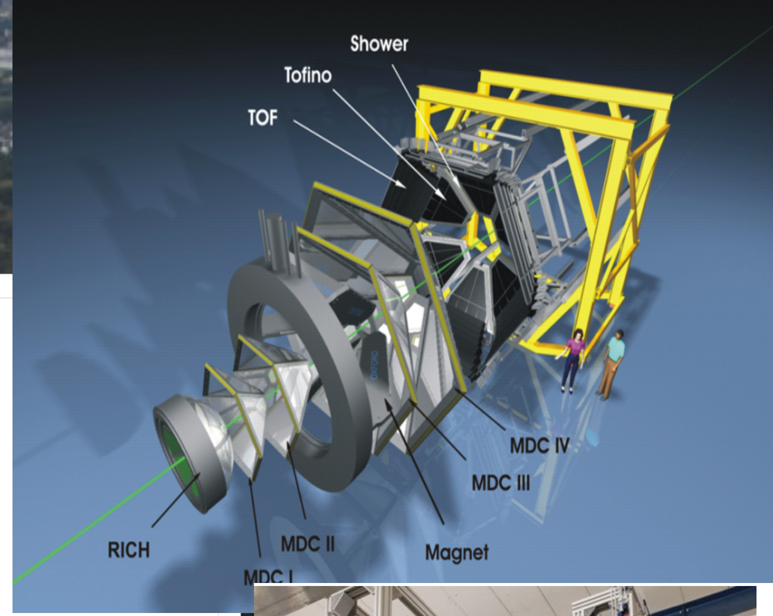
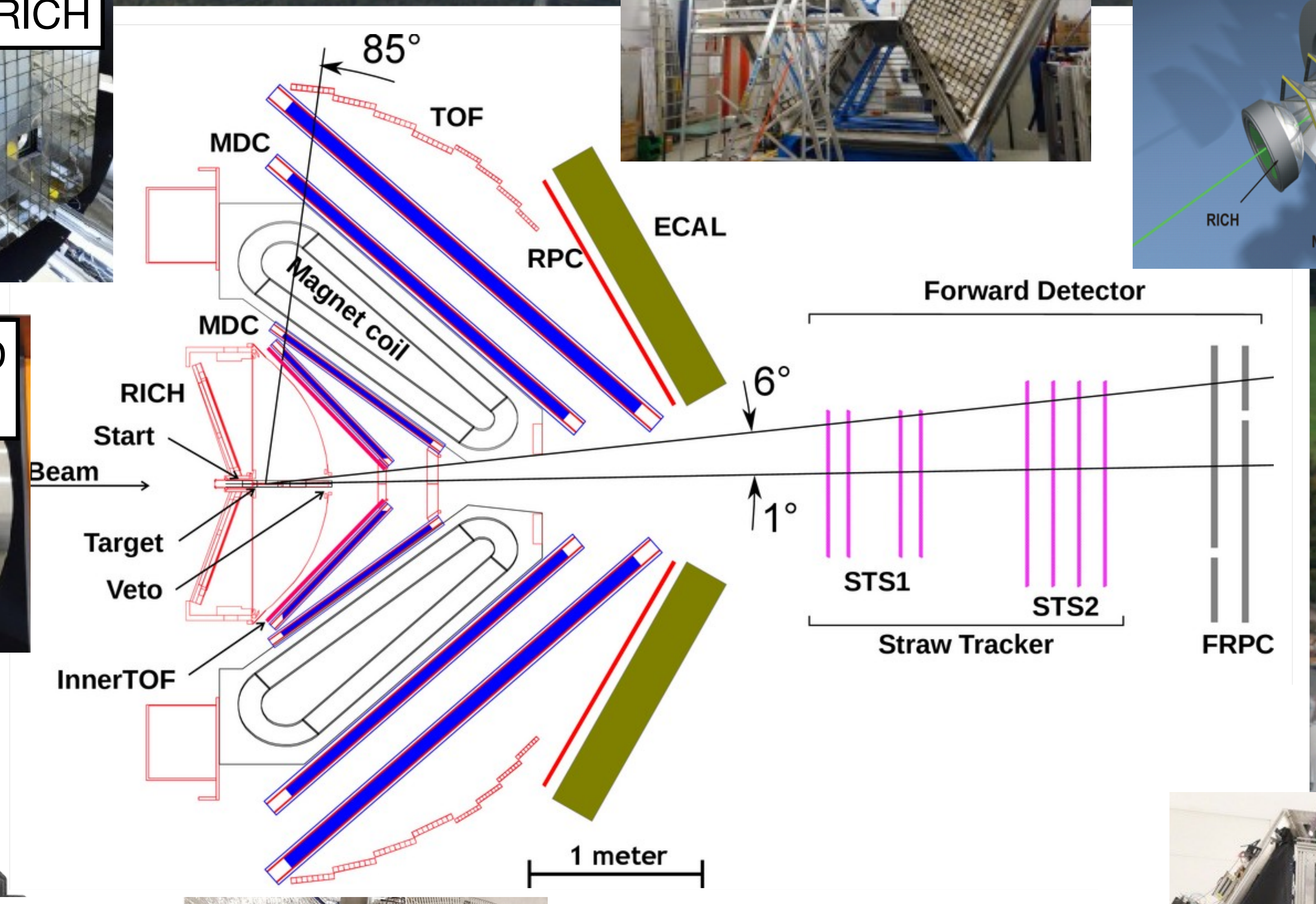
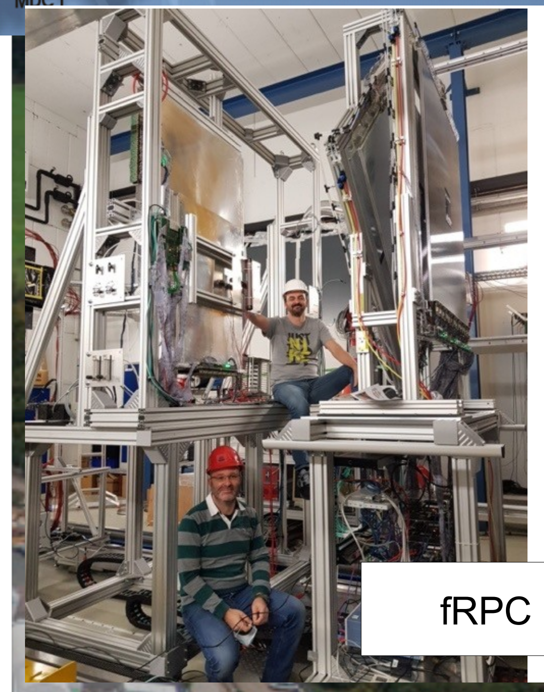
High **A**cceptance **D**i-**E**lectron **S**pectrometer **(HADES)**

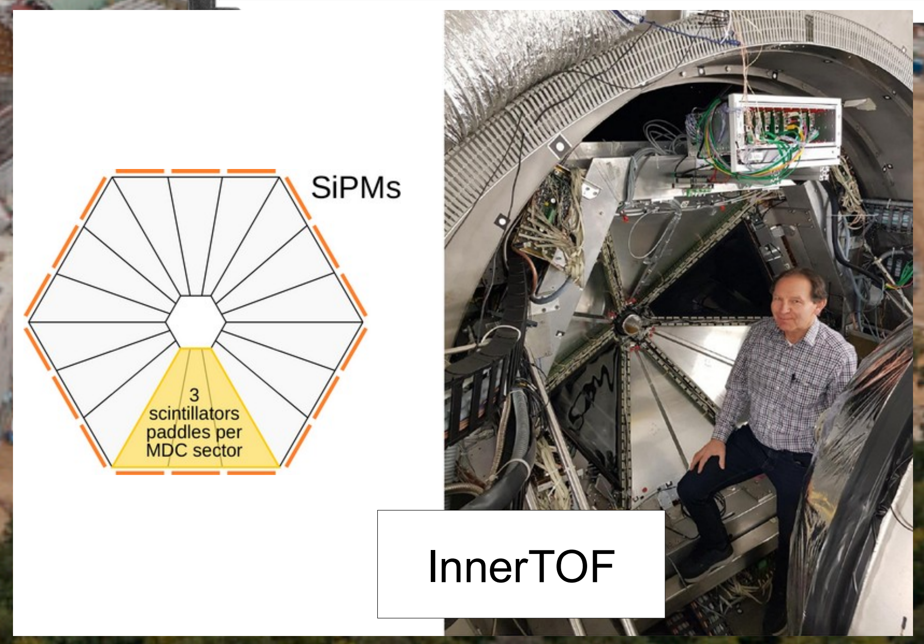












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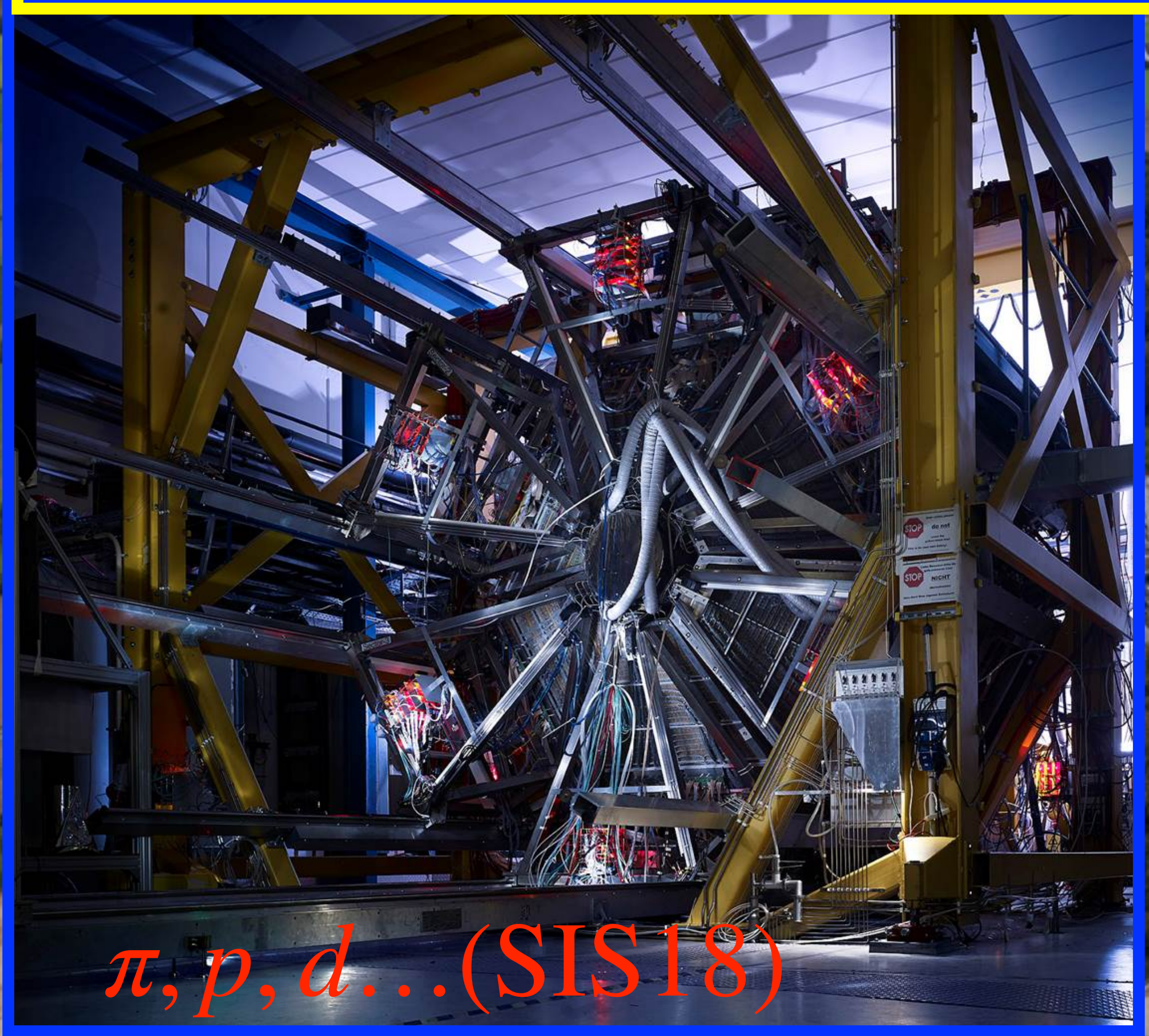
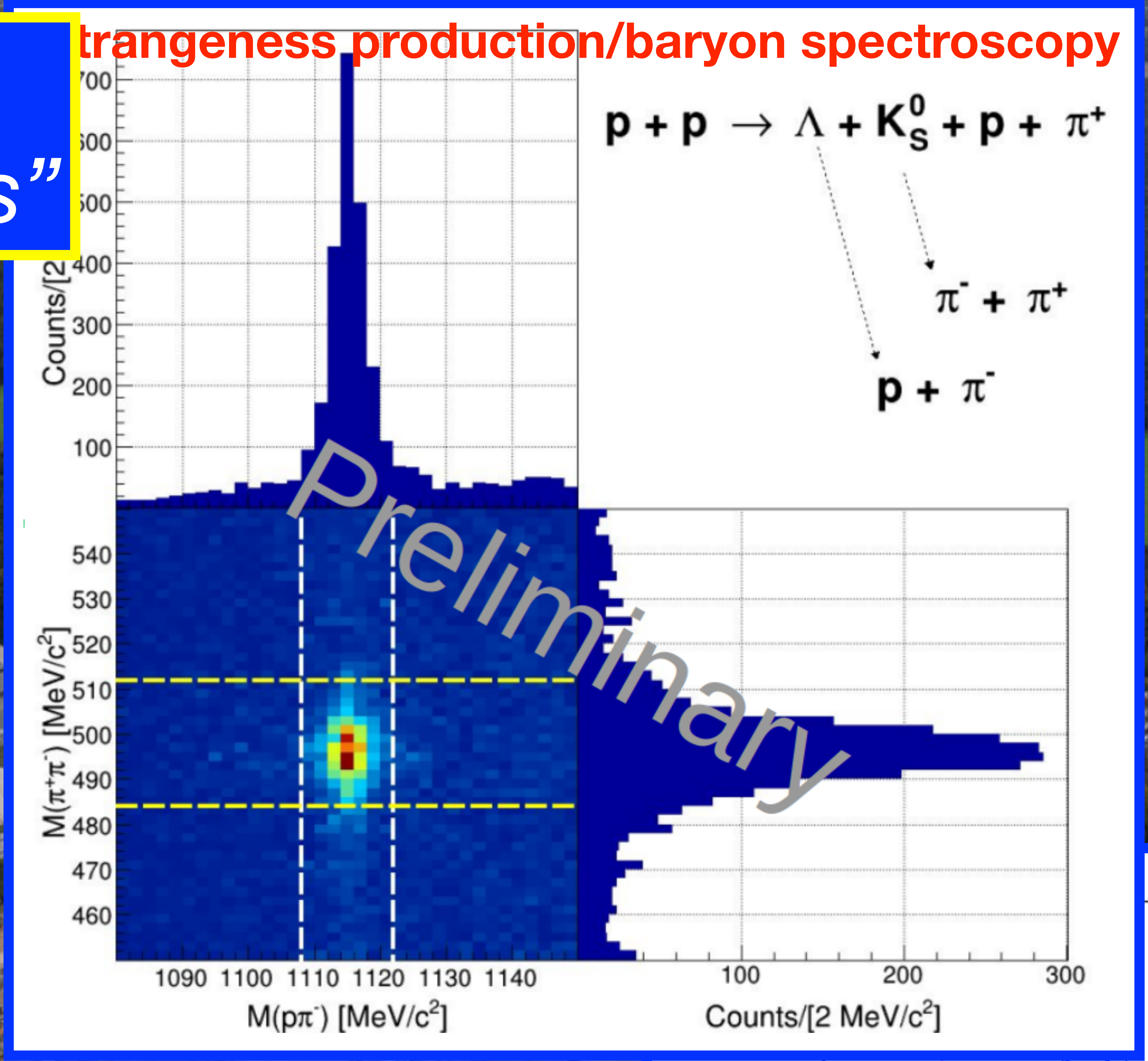
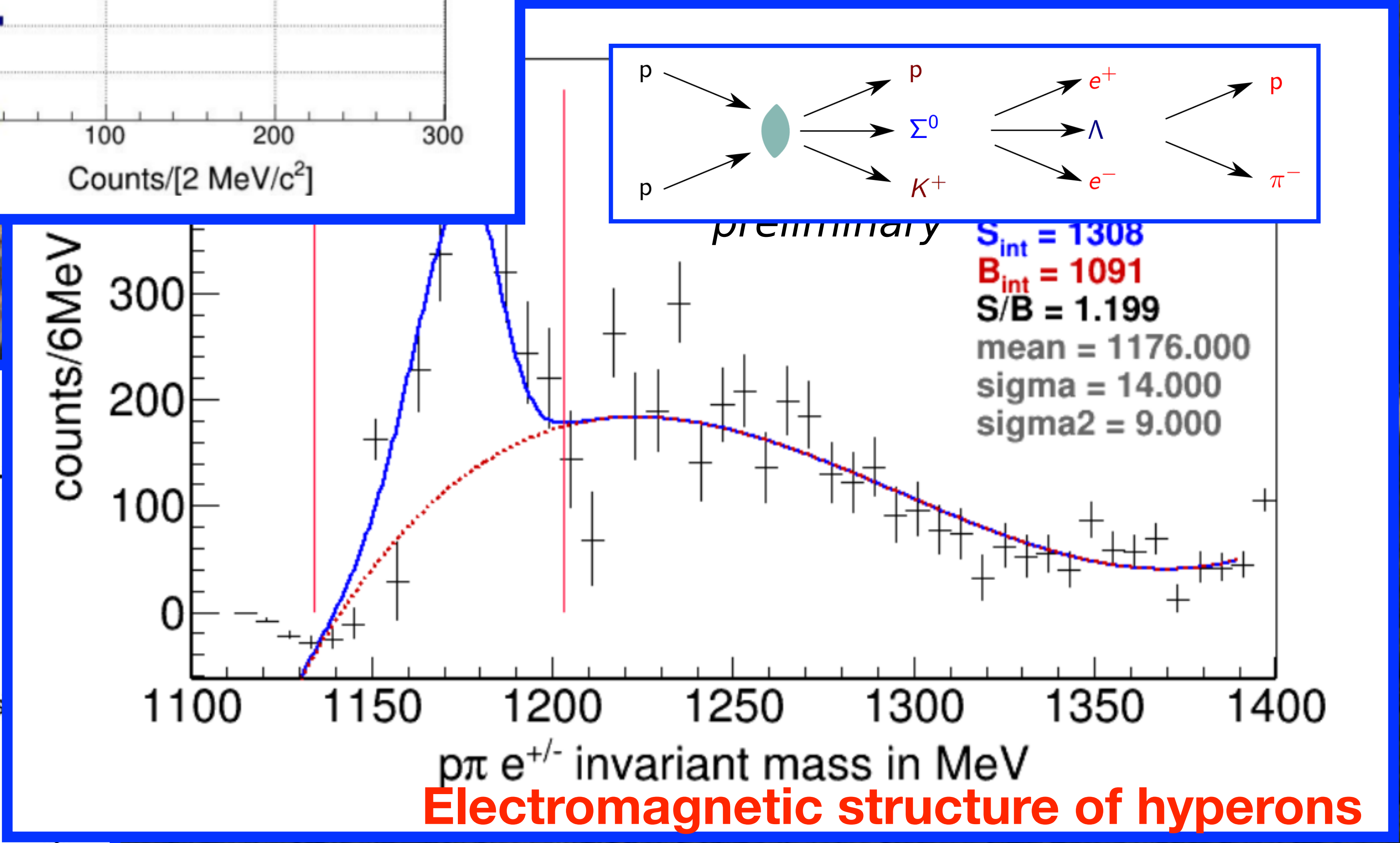
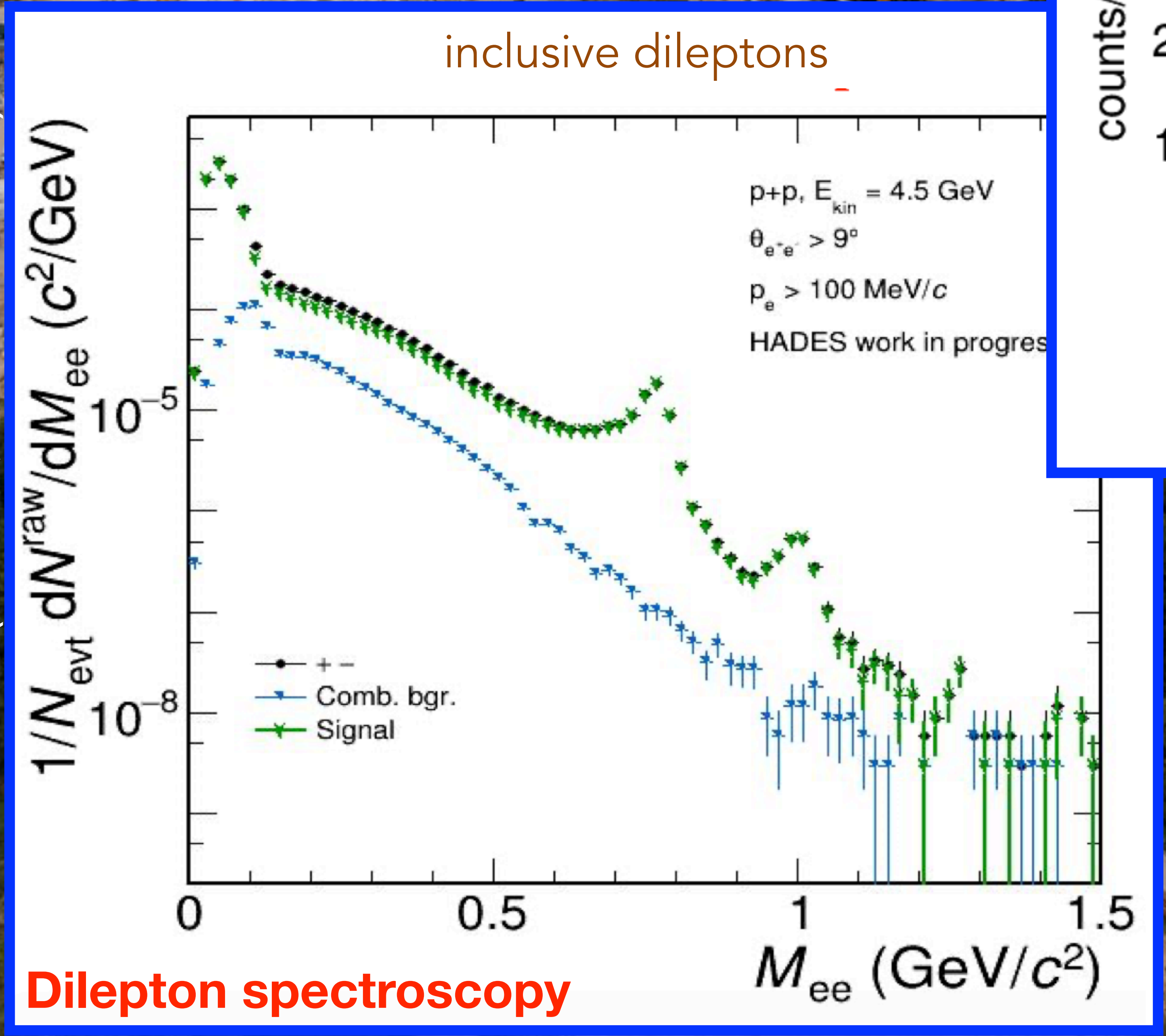




S. Pattnaik (GSI)



J. Rieger (Uppsala)



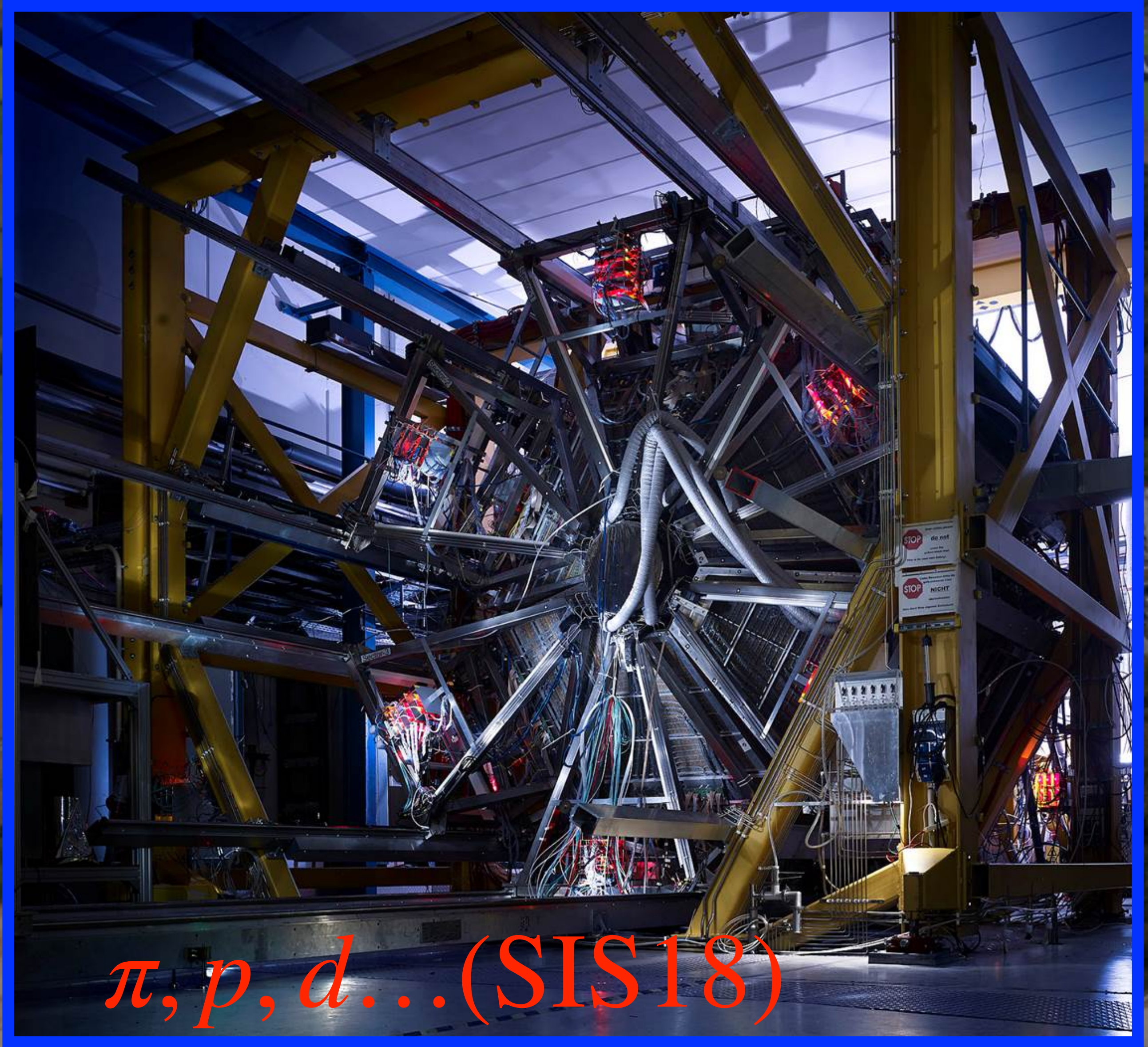
R. Abou Yassine (UCLab, TU Darmstadt)

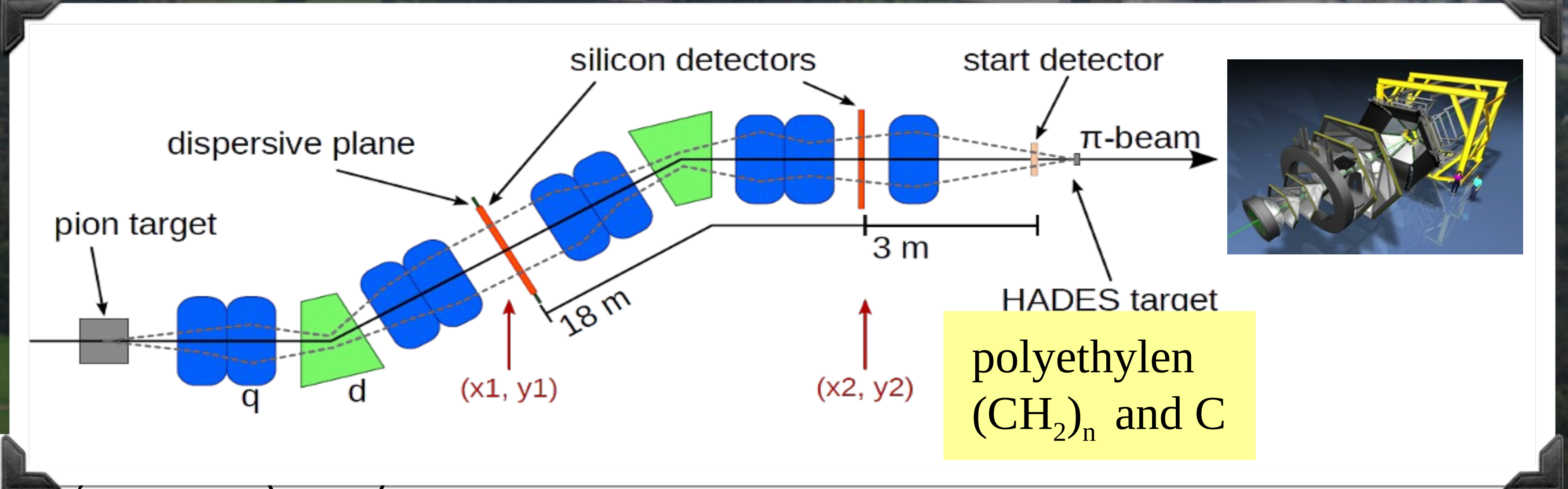
See talks at this conference:

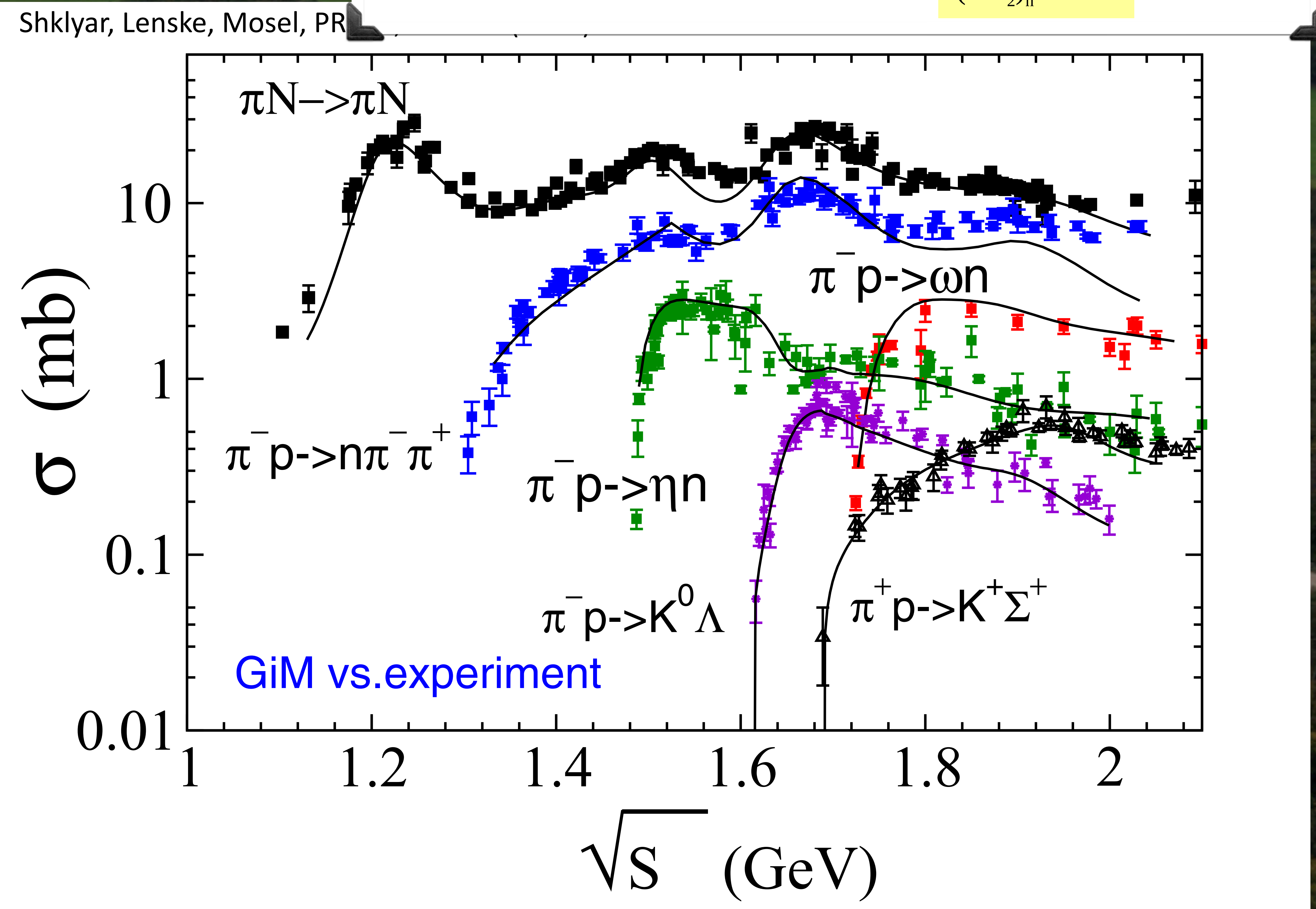
- **Szymon Harabasz**, Monday 13:30
- **Iza Ciepal**, Tuesday 9:30
- **Jana Rieger**, Tuesday 14:25

Recent p+p studies at T=4.5 GeV
Analysis in progress!
[EPJA57, 138 (2021)]

Pion-beam facility!







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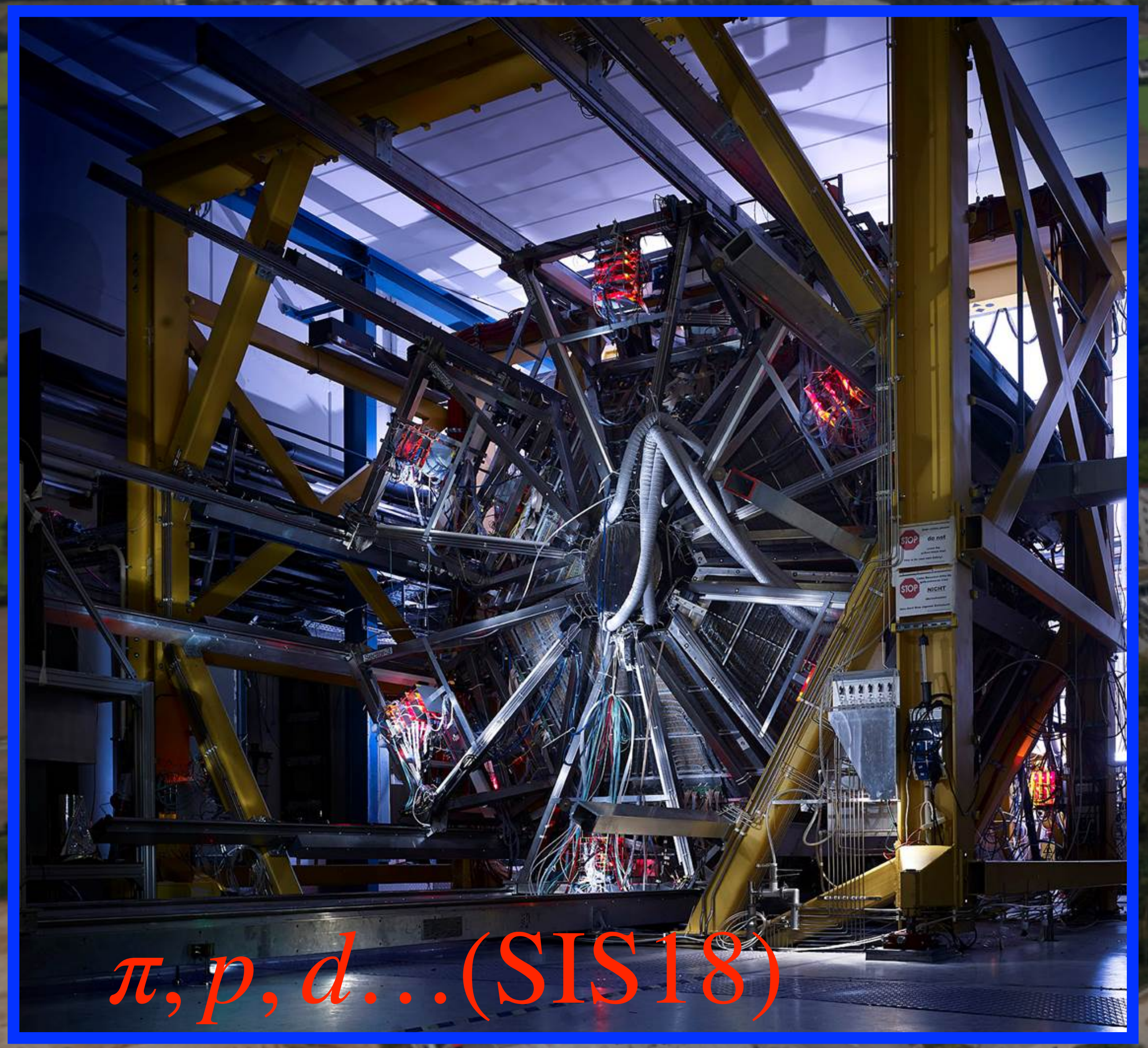

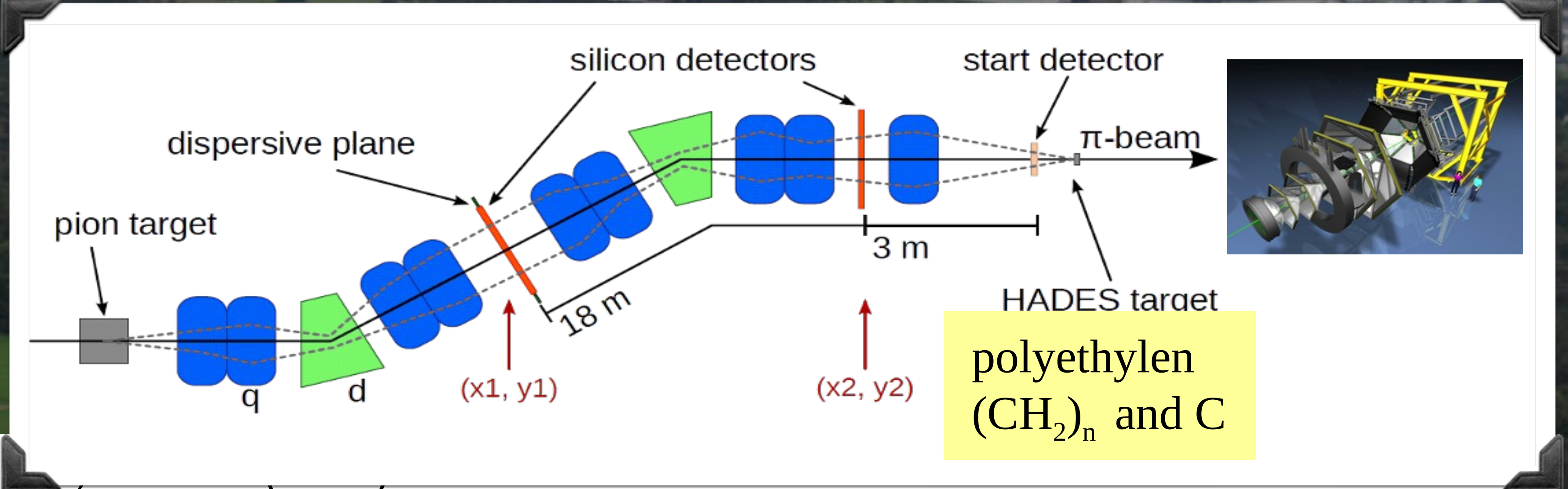

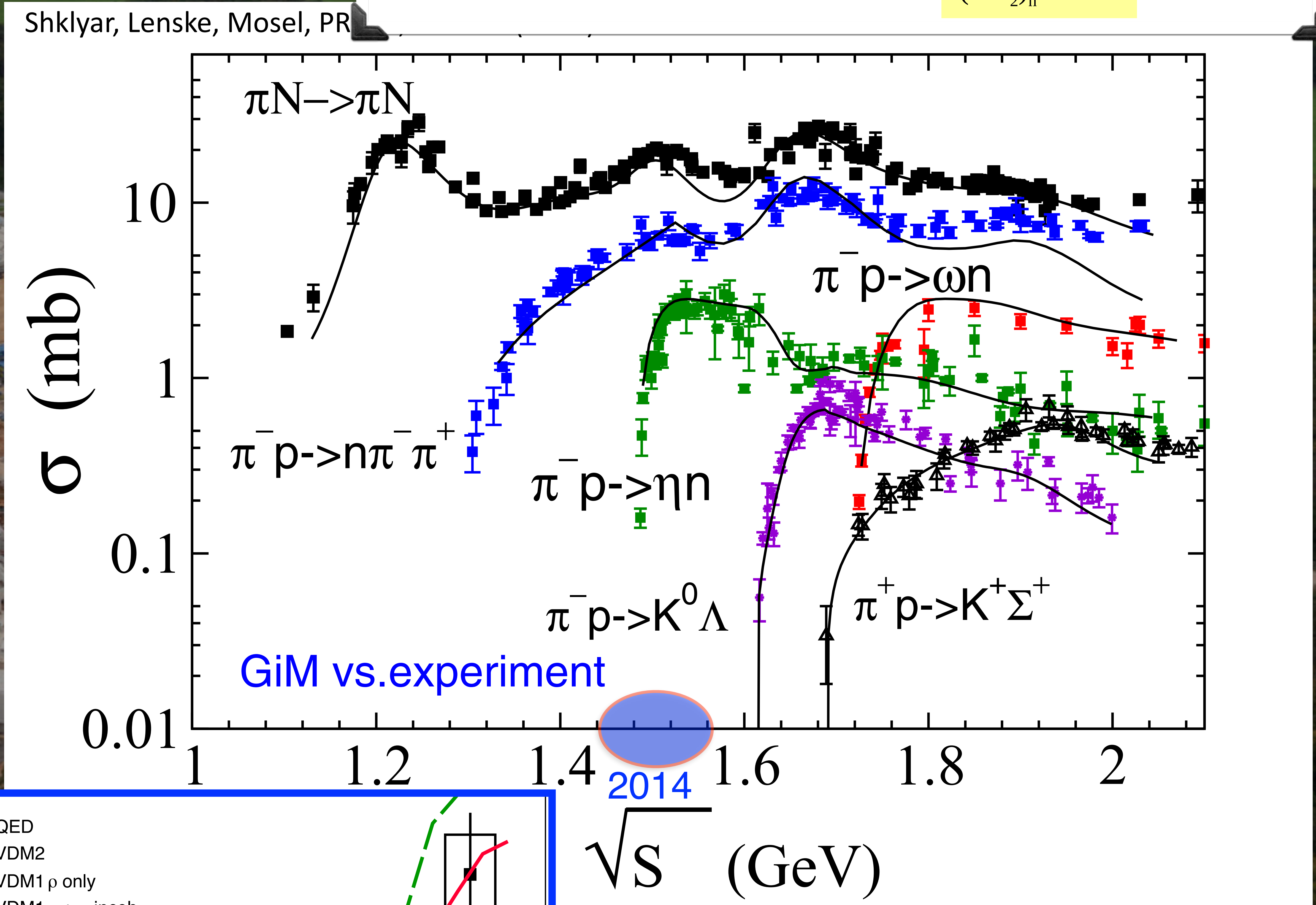

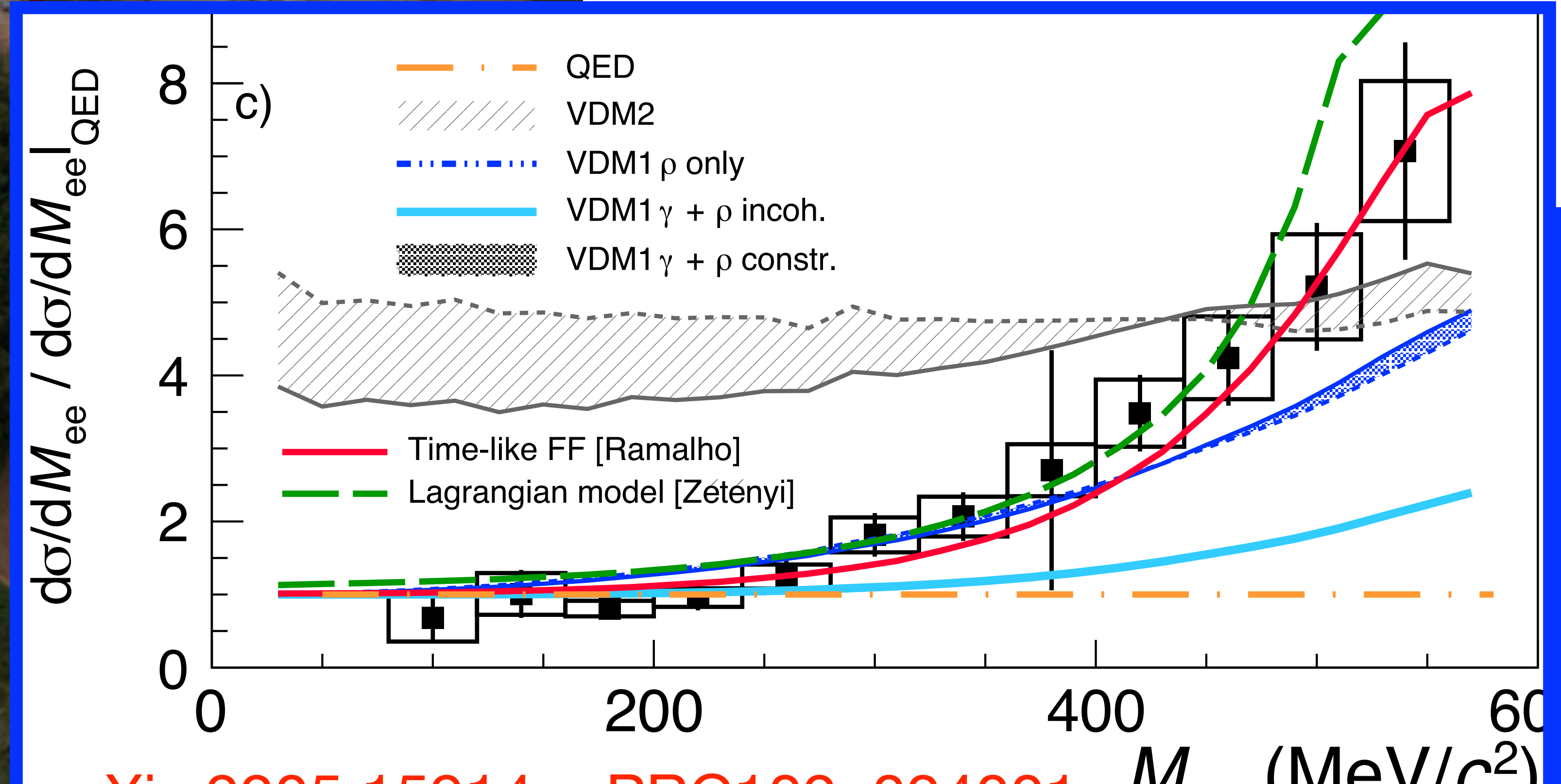

arXiv:2205.15914 + PRC102, 024001

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"2014" highlights:

- **PWA** $\pi^- p \to N\pi\pi$
- **8 PDG** entries on N(1440,1520,1535)
- E.m. transition form factor $N(1520) \to Ne^+e^-$
- Unique test of VMD models!

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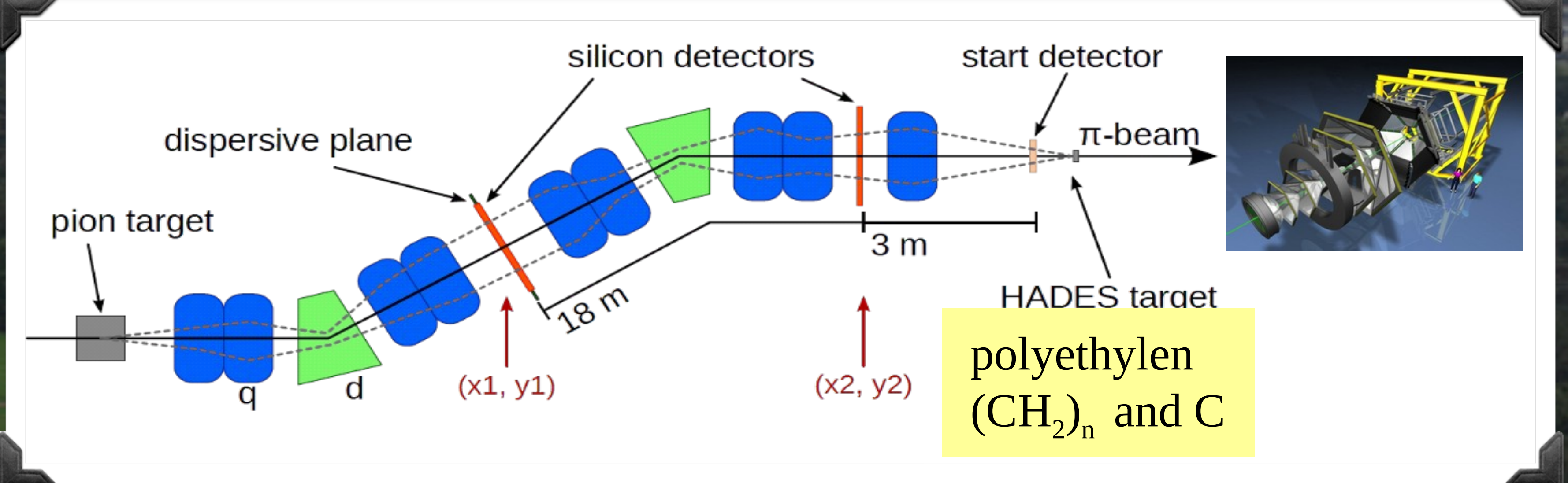
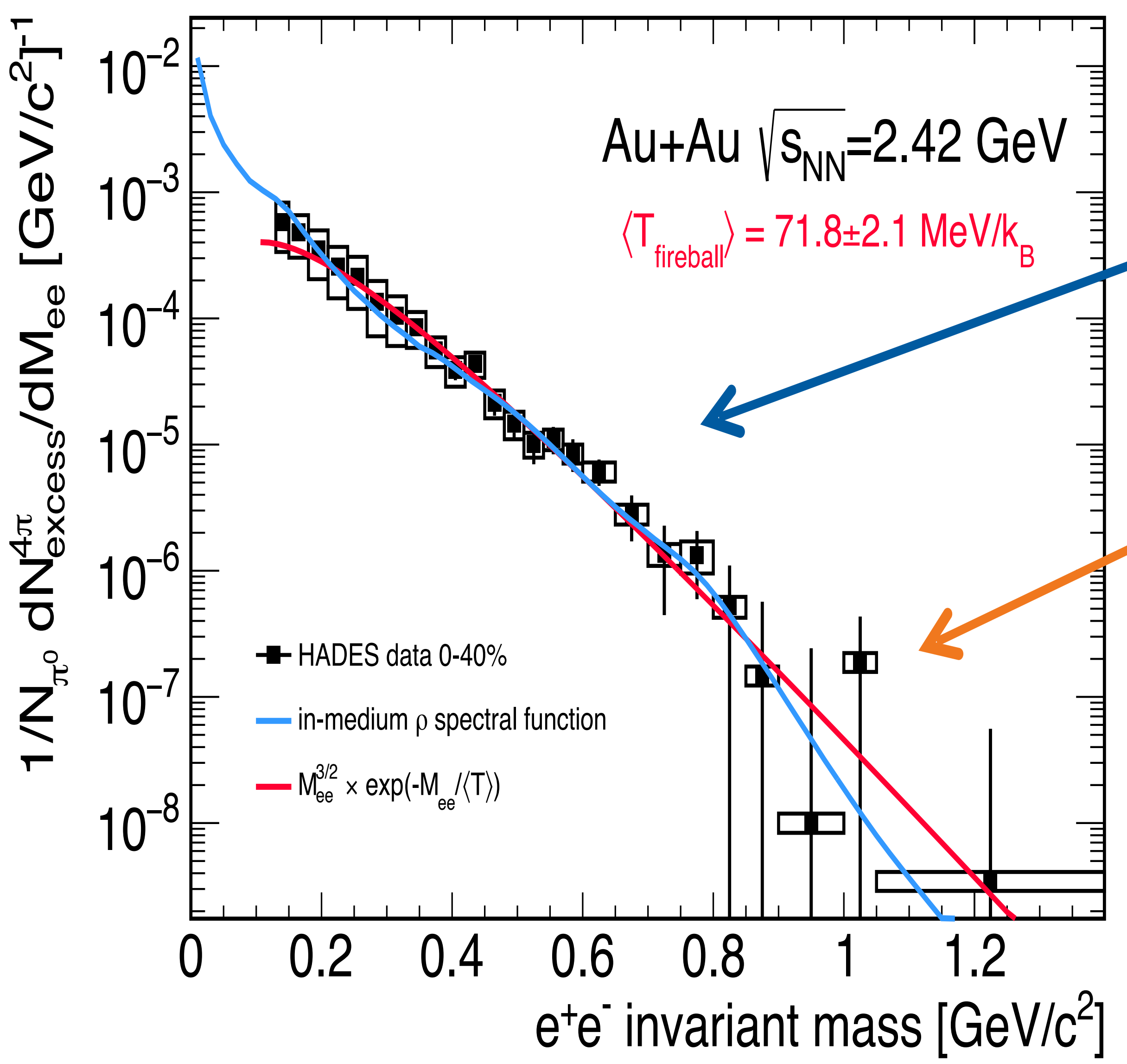


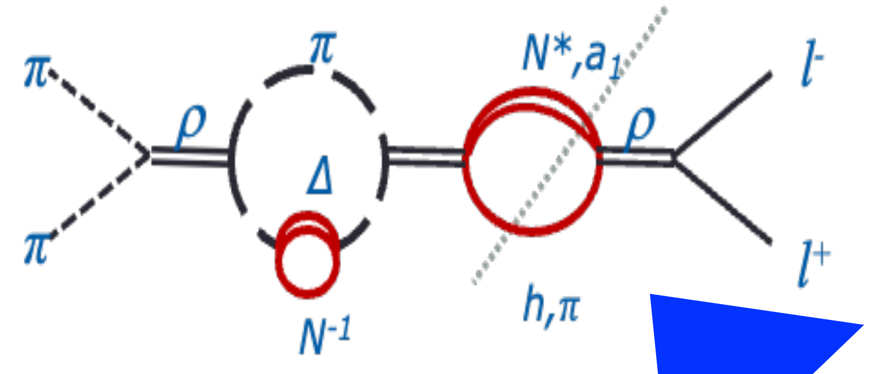


0.3 < M < 0.7 GeV:
- In-medium spect. funct.
- fireball life time
- fireball temperature[1]

M > 1 GeV/c²:
- ρ – a1 chiral mixing
- dominated by contribution from the hottest and densest region

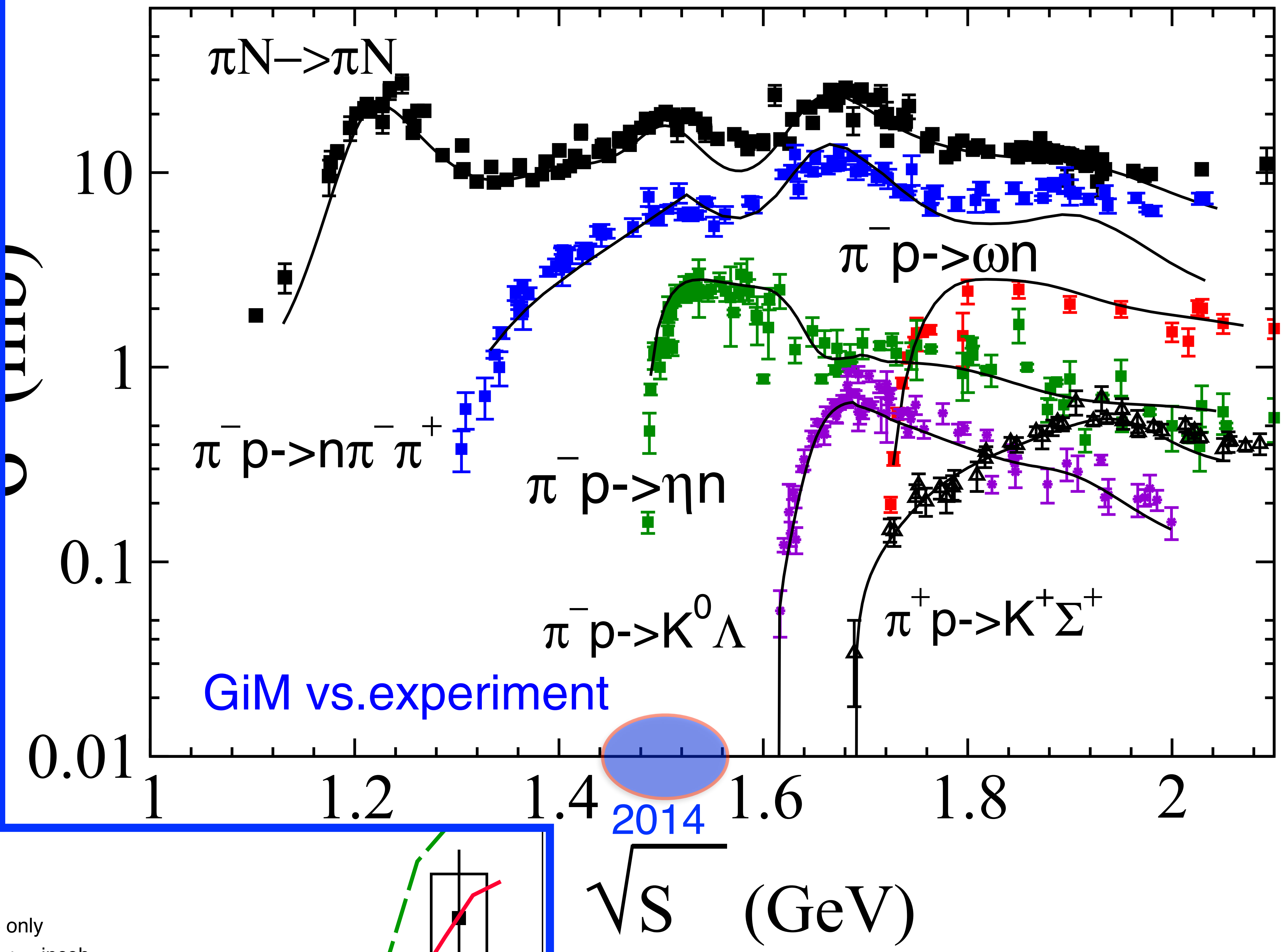
Coarse-grained UrQMD & thermal emissivity with in-medium propagator

Rapp, van Hees; arXiv:1411.4612v
CG GSI-TAMU; Galatyuk, Seck, et al.; arXiv:1512.08688



HADES; Nature Phys. 15 (2019) 10, 1040-1045

klyar, Lenske, Mosel, PR



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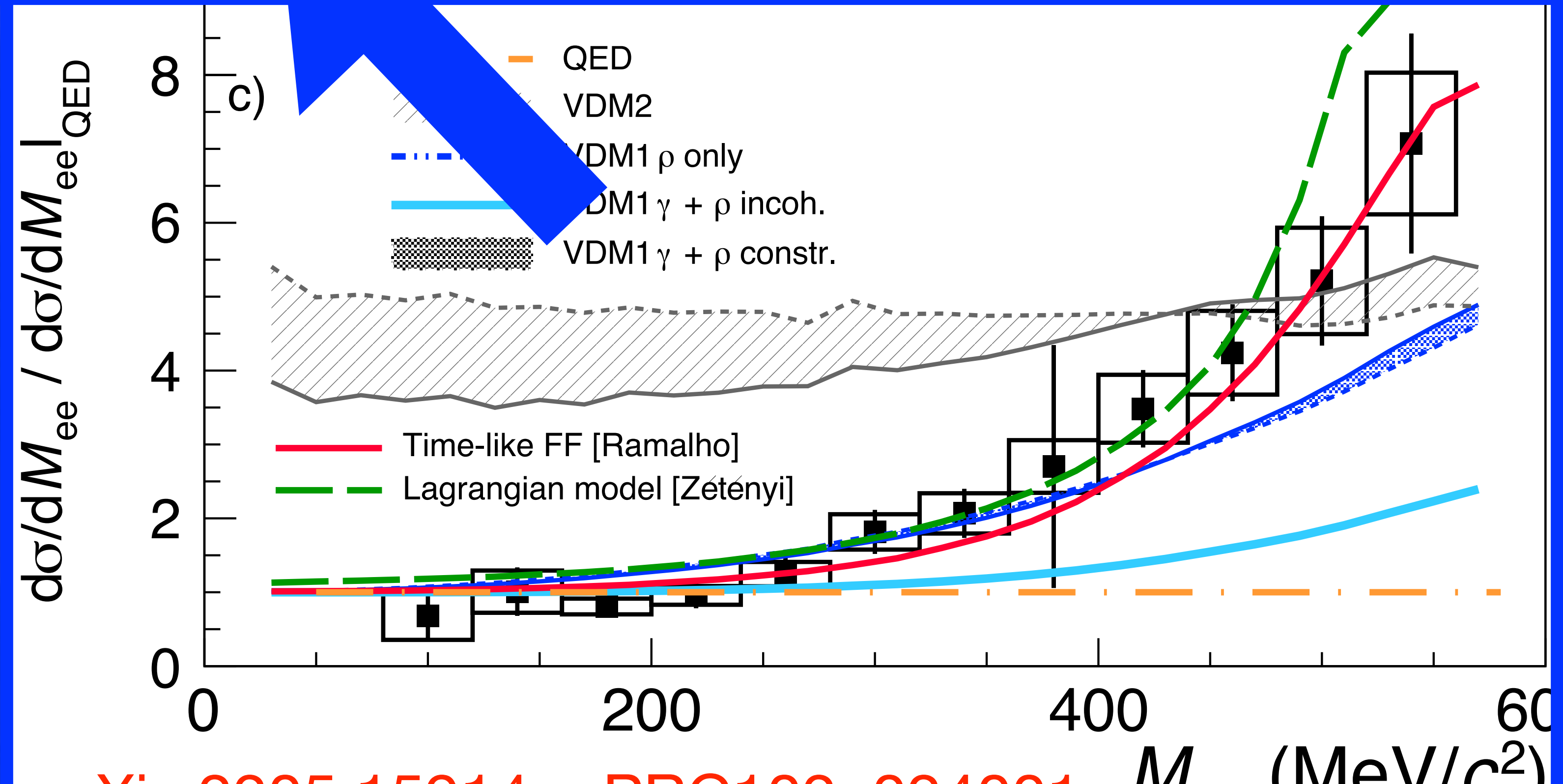

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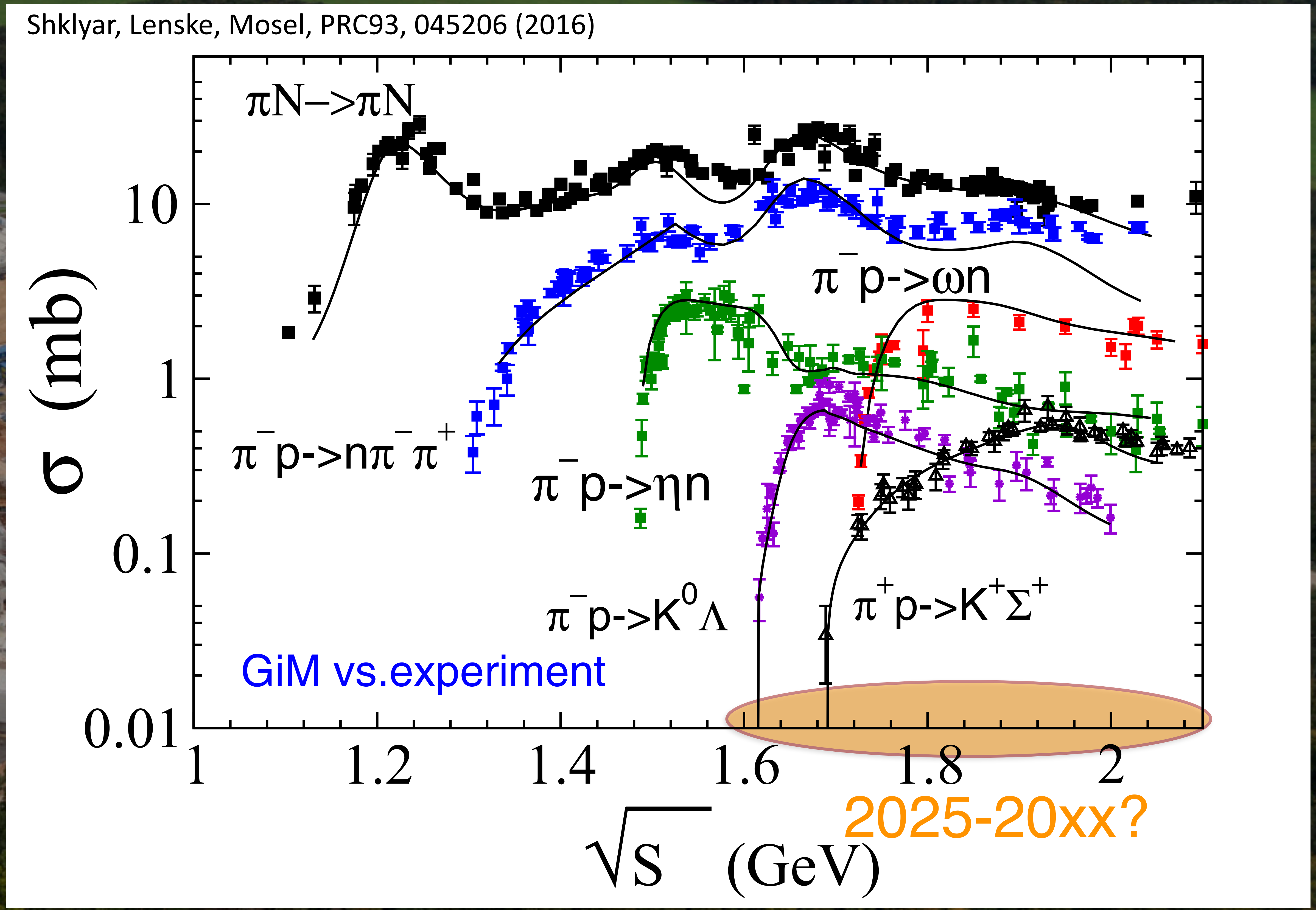

October 2023

A comprehensive QCD program!

QCD dynamics within hadrons

Hadron structure

Hadron spectroscopy

QCD@GSI/FAIR

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

Reference measurements for p+A,A+A

Production *mechanisms* of hadrons

Few-body interactions

Hadron production

Heavy-ion dynamics

Microscopic study of hadron-hadron interactions

A comprehensive QCD program!

QCD dynamics within hadrons

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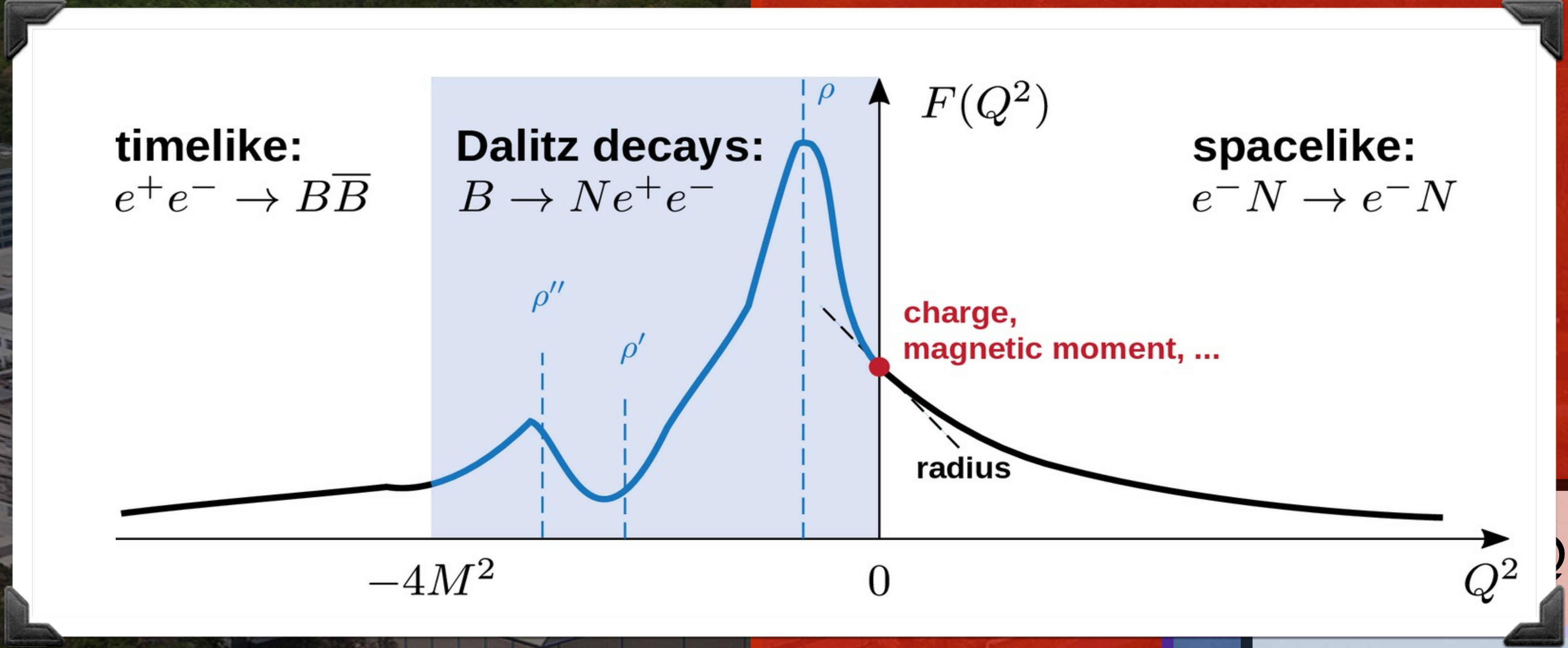

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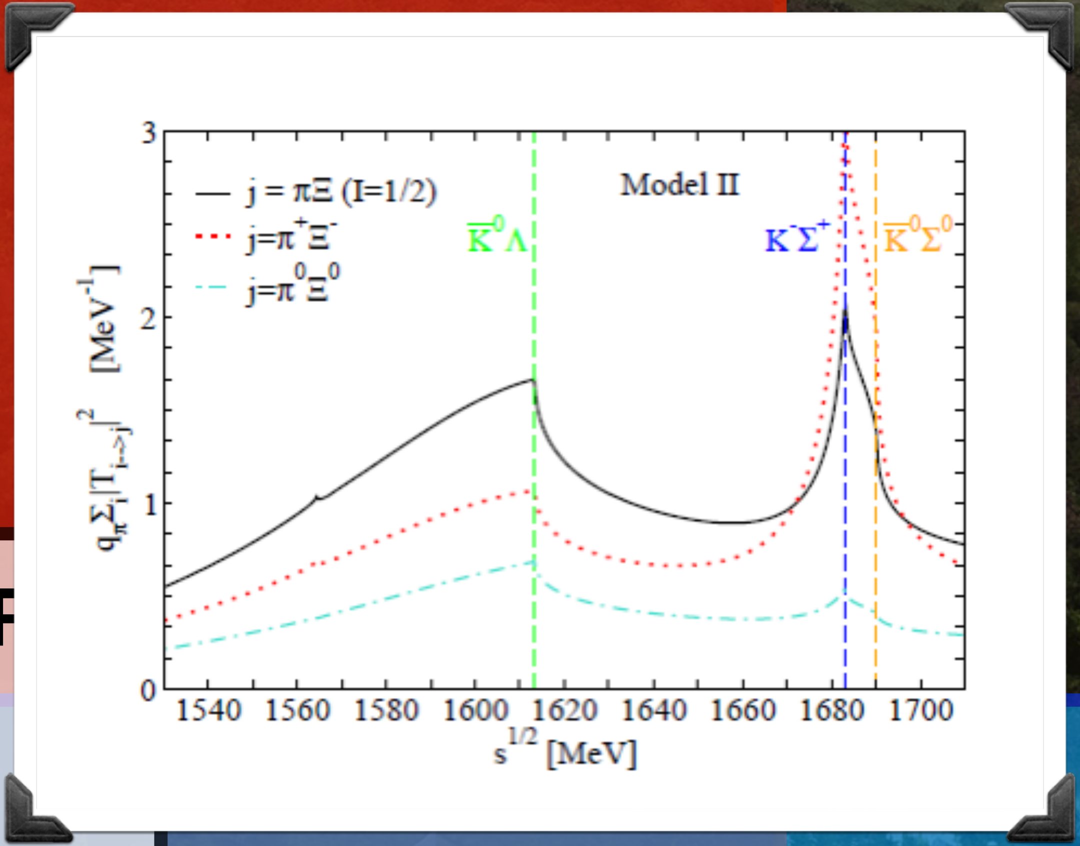

GSI/FAIR

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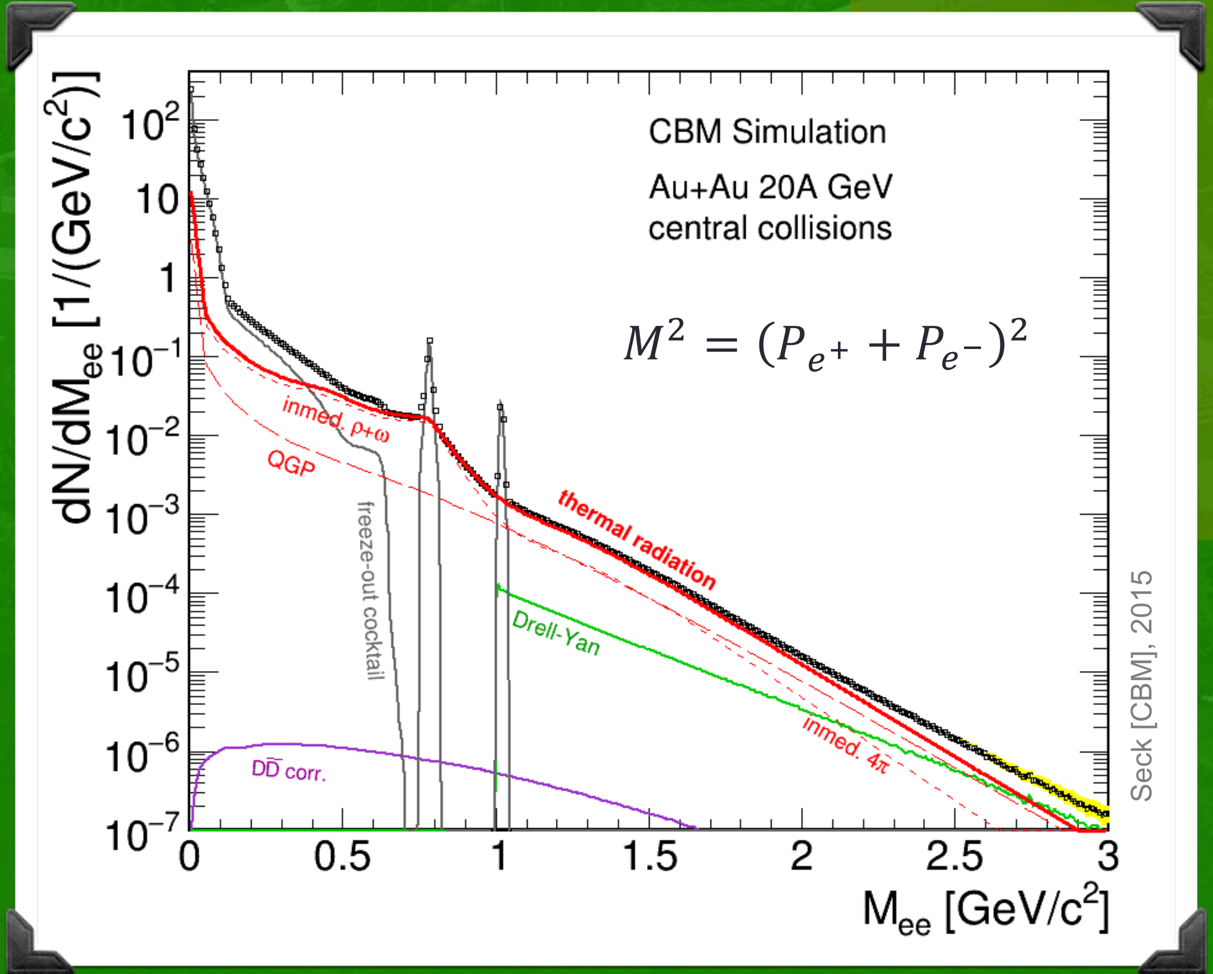
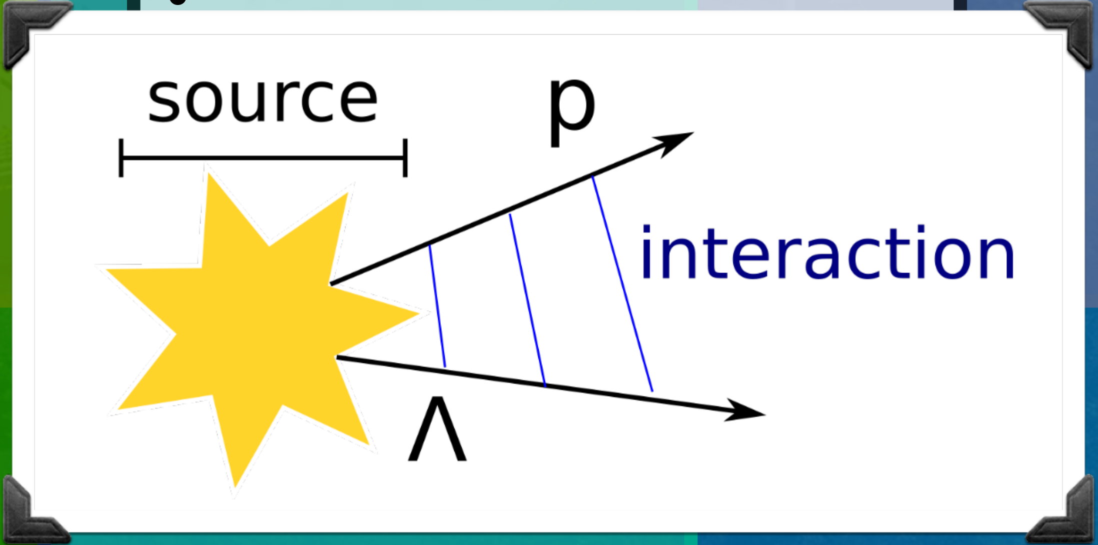
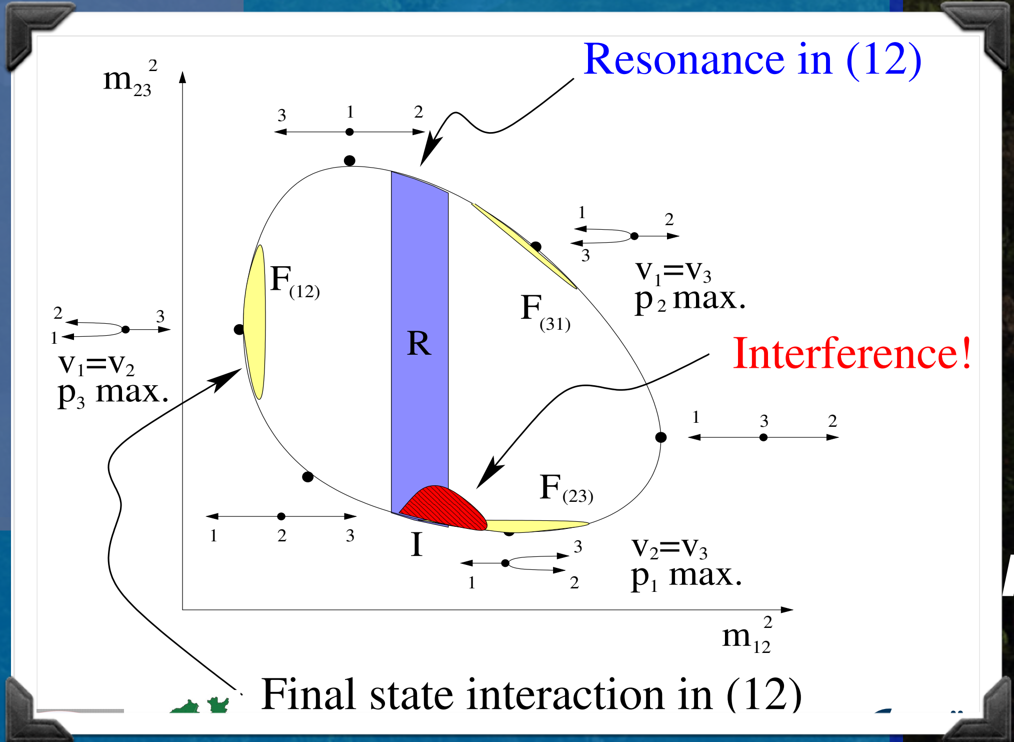




Few-body interactions



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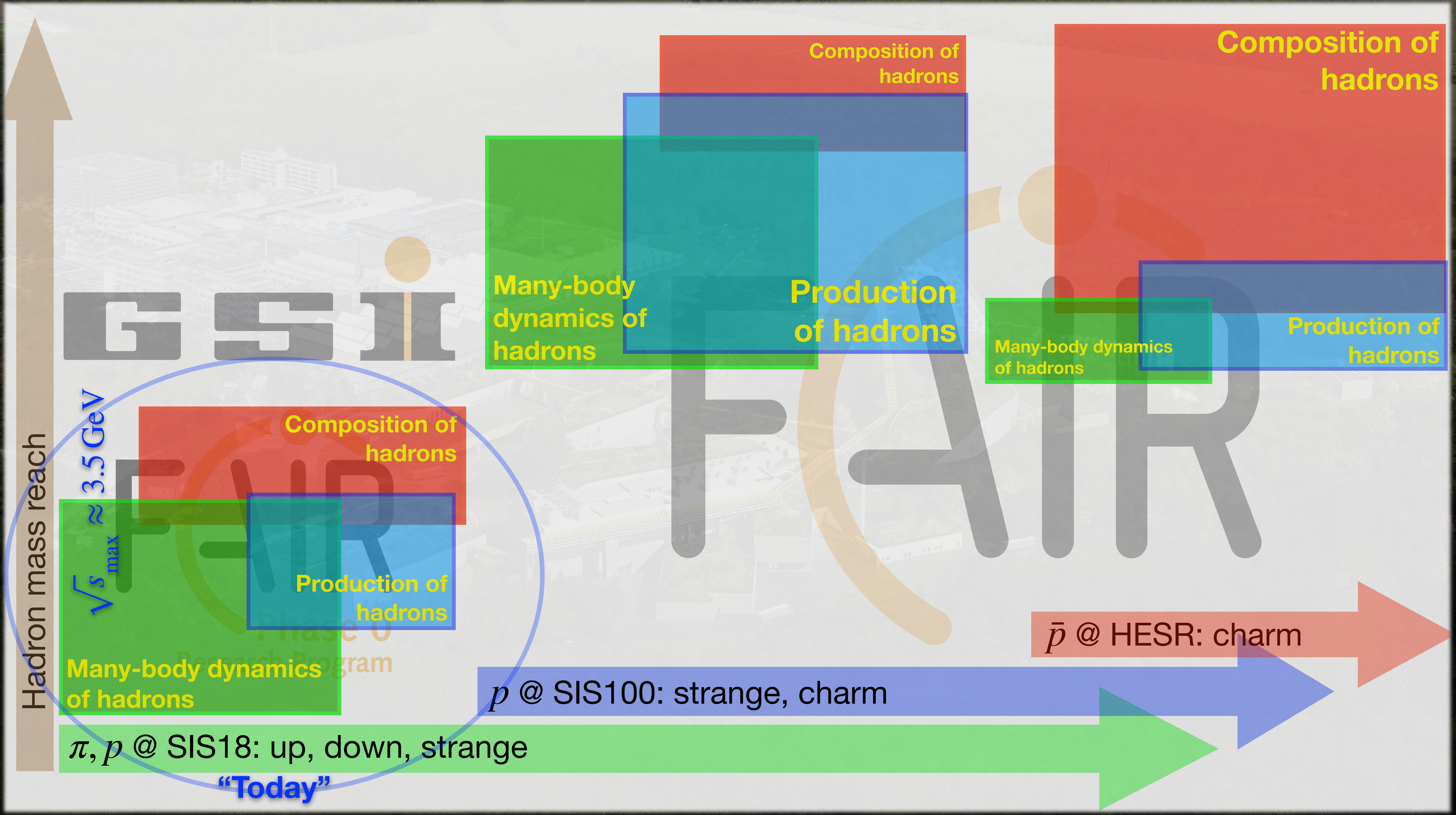
Roadmap



Hadron mass reach
$\sqrt{s}_{max} \approx 3.5$ GeV
Composition of hadrons
Production of hadrons
Many-body dynamics of hadrons
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Production of hadrons
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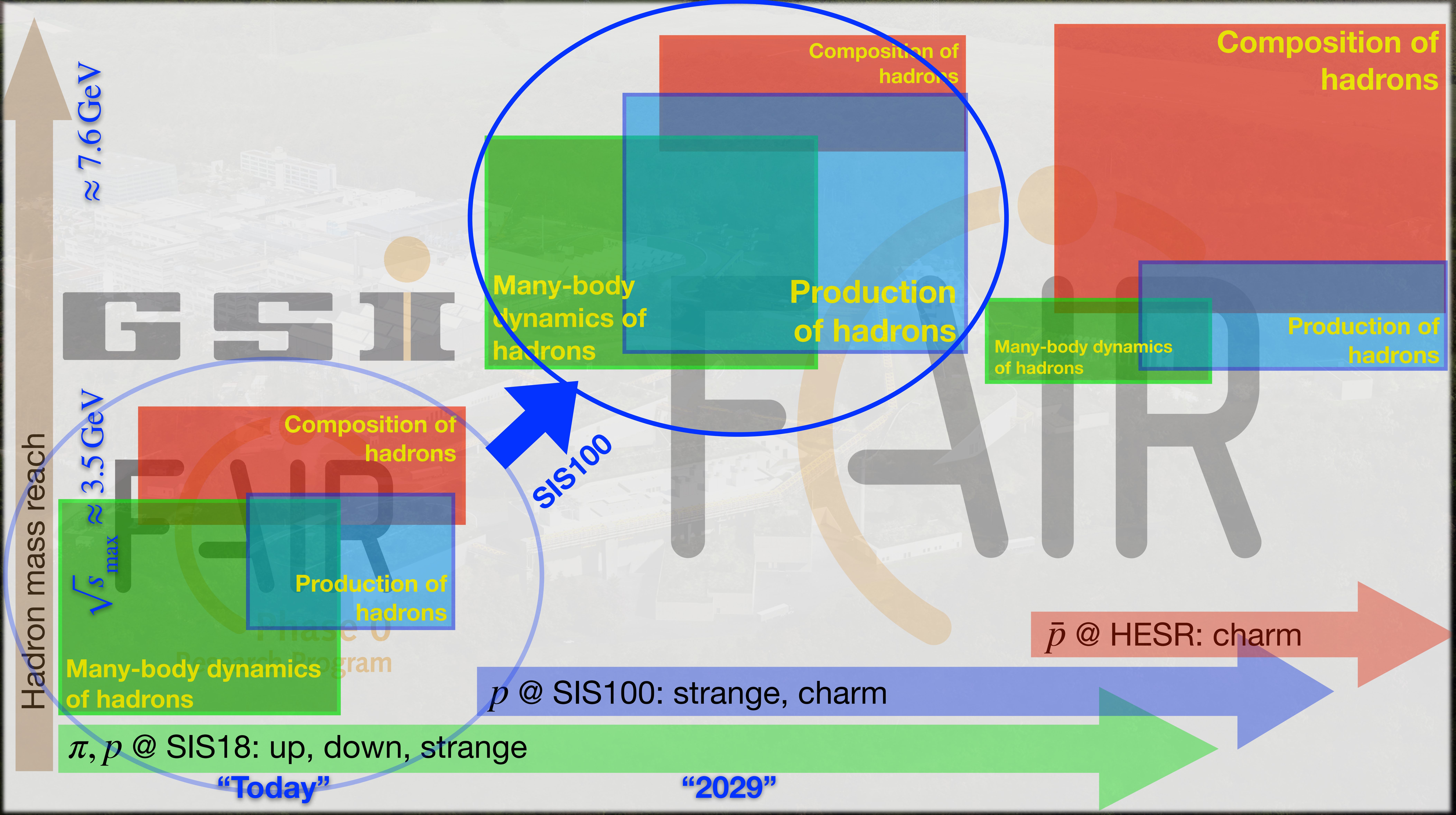
Many-body dynamics of hadrons
$\bar{p}$ @ HESR: charm
p @ SIS100: strange, charm
π, p @ SIS18: up, down, strange
"Today"

Roadmap



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SIS100
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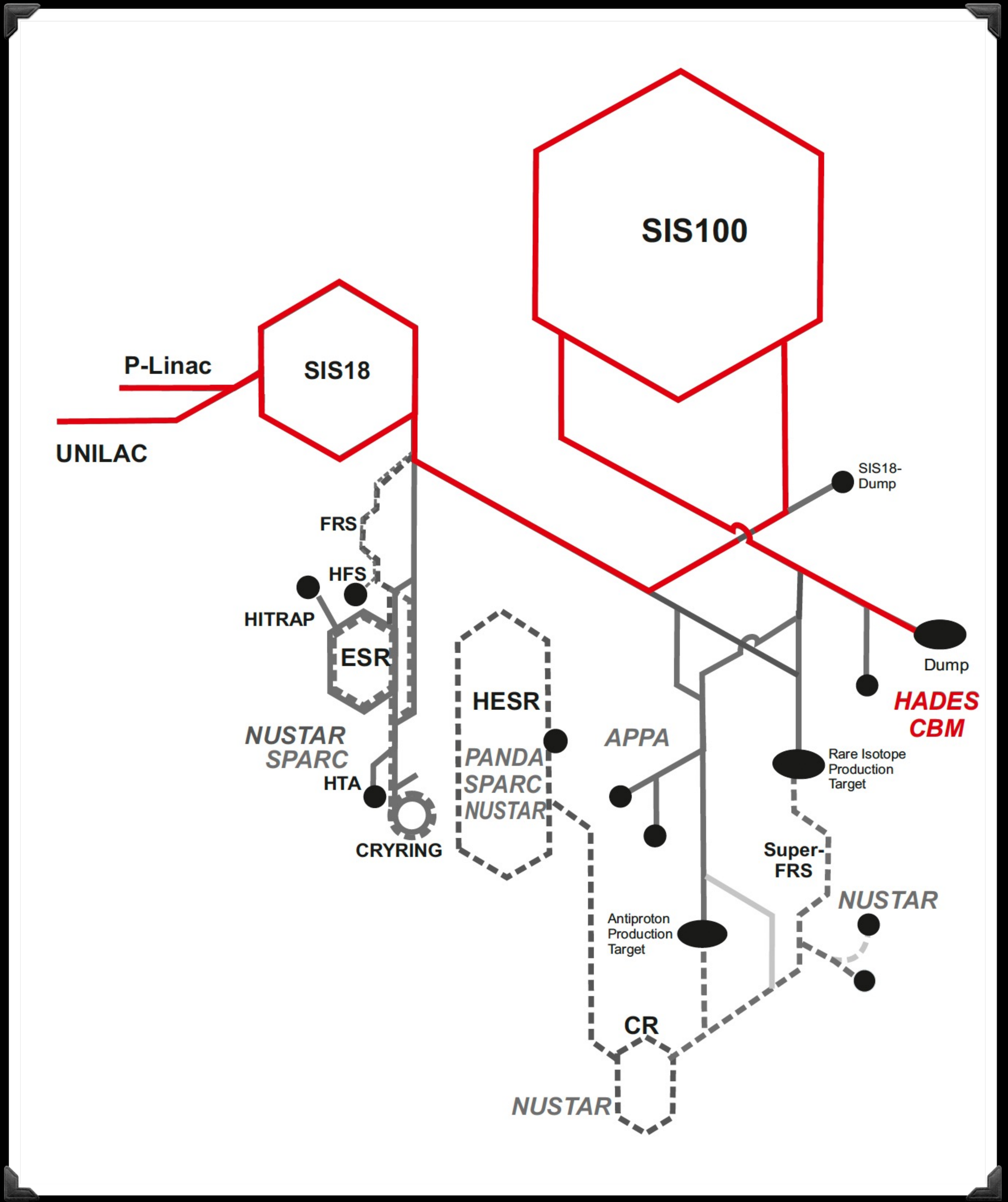
"Today"
"2029"

From SIS18 to SIS100

…what could that add in hadron physics?



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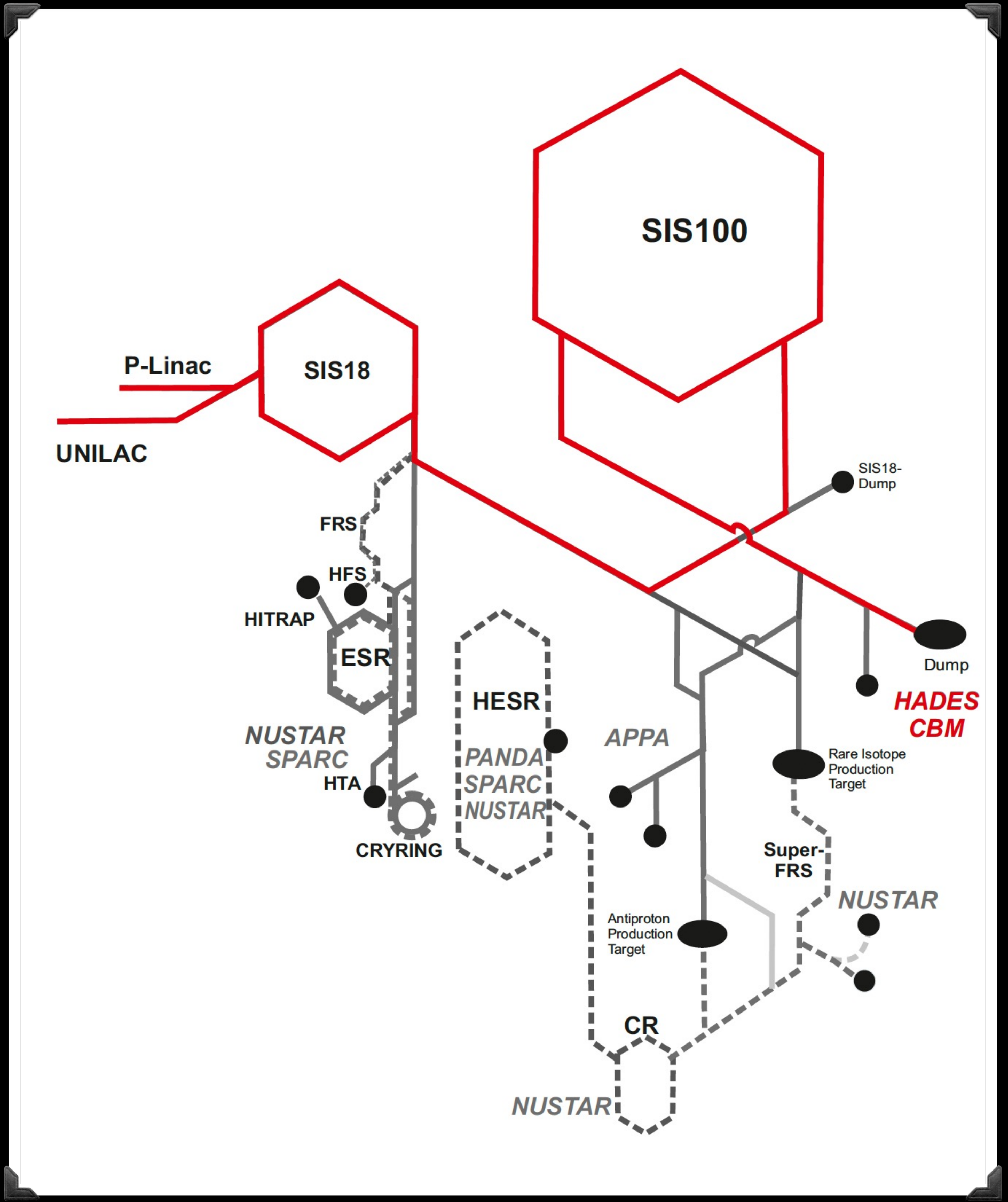
…what could that add in hadron physics?

- **Energy upgrade:**
  - From max 4.7 GeV (SIS18) to 29 GeV (SIS100) proton energy
  - Opening new realm: double+triple strangeness and even charm baryons and mesons!
  - Significant increase in production yield of hyperons



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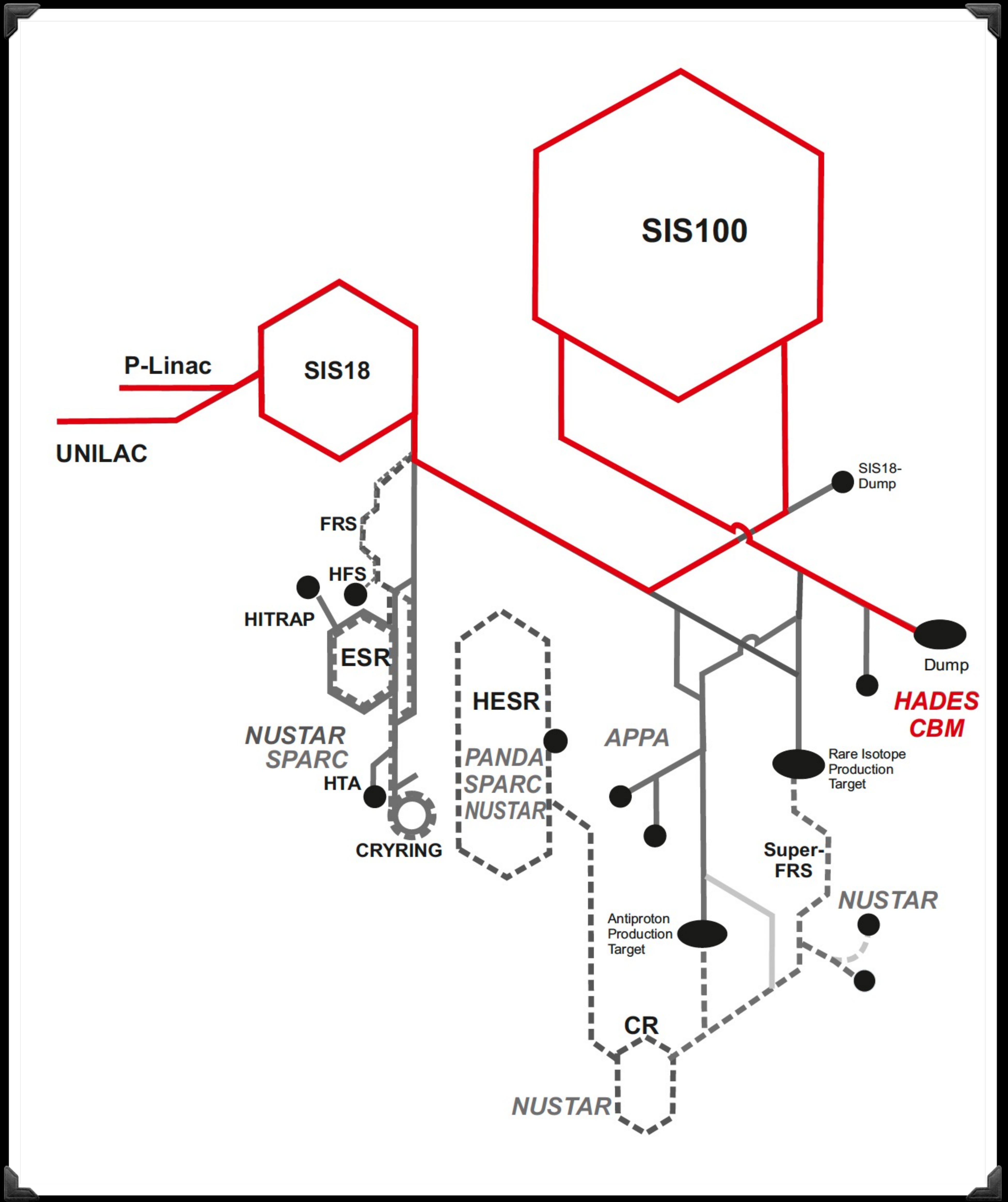

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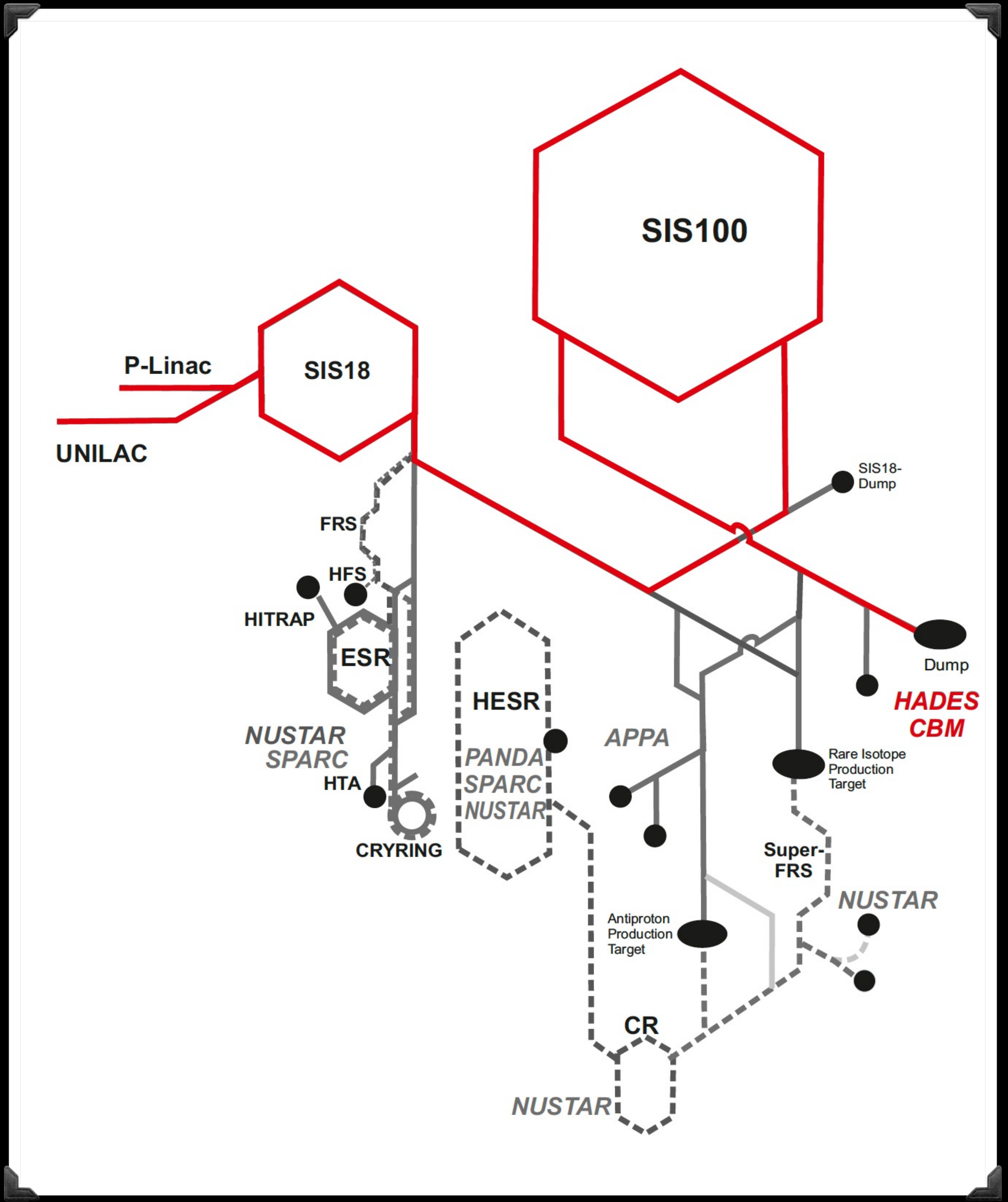

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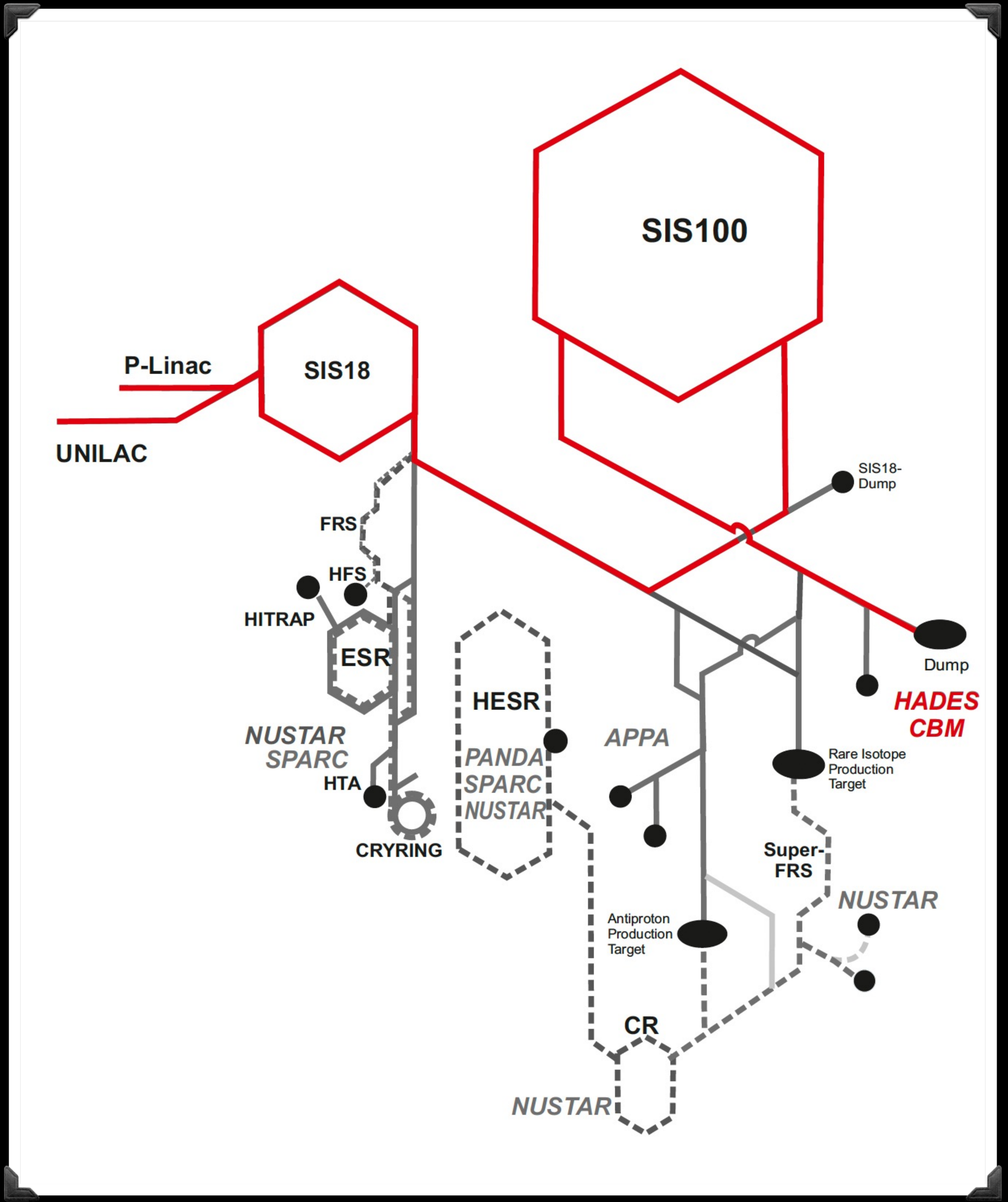
- **Theory enrichment:**
  - Terra incognita: intellectual challenges in this energy regime!



Physics opportunities with proton beams at SIS100

6-9 February 2024
Wuppertal University
Europe/Berlin timezone

Physics opportunities with proton beams at SIS100

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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 proton-driven physics program
- Evaluate its complementarity with programs at other facilities
- Prepare towards a white-paper

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Physics perspectives with hadron beams at GSI and FAIR

...

April 2024

Eds: Frank Nerling & J.M.

Executive summary

1 Introduction

Convenors: *J. Messchendorp, F. Nerling, C. Roberts*

2 Exploiting hadronic beams

Convenors: *T. Galatyuk, J. Messchendorp, F. Nerling*

3 Hadron-hadron interactions

Convenors: *C. Blume, C. Hanhart*

4 Composition of hadrons

Convenors: *C. Fischer, P. Salabura*

5 Exotic hadrons

Convenors: *N. Brambilla, S. Dobbs*

6 Hadrons as probes to study dense matter

Convenors: *J. Aichelin & E. Bratkovskaya, M. Lorenz*

7 Connections & input to astrophysics

Convenors: *K. Kampert, T. Saito*

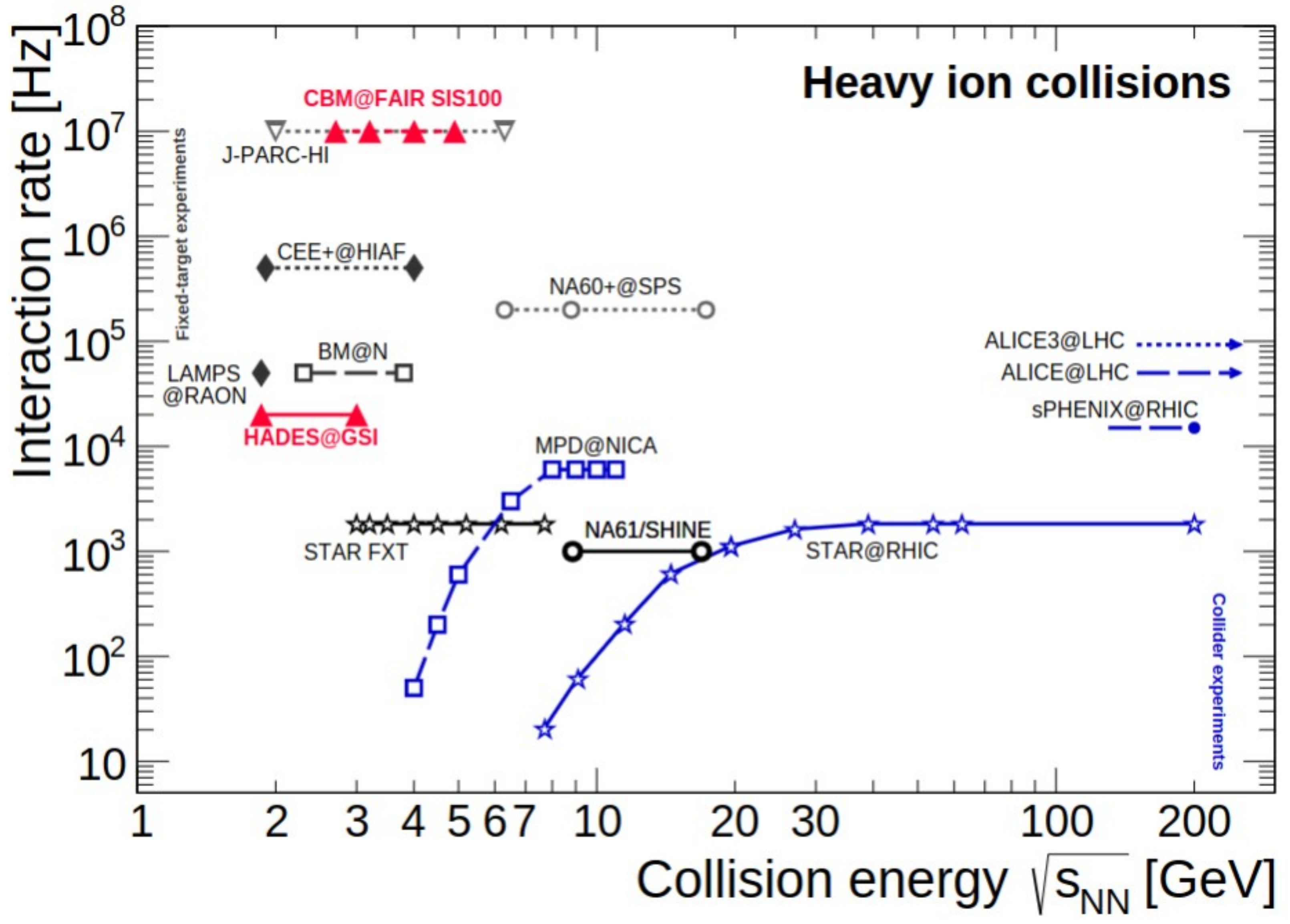
8 Experimental infrastructure

Convenors: *J. Ritman, C. Sturm*

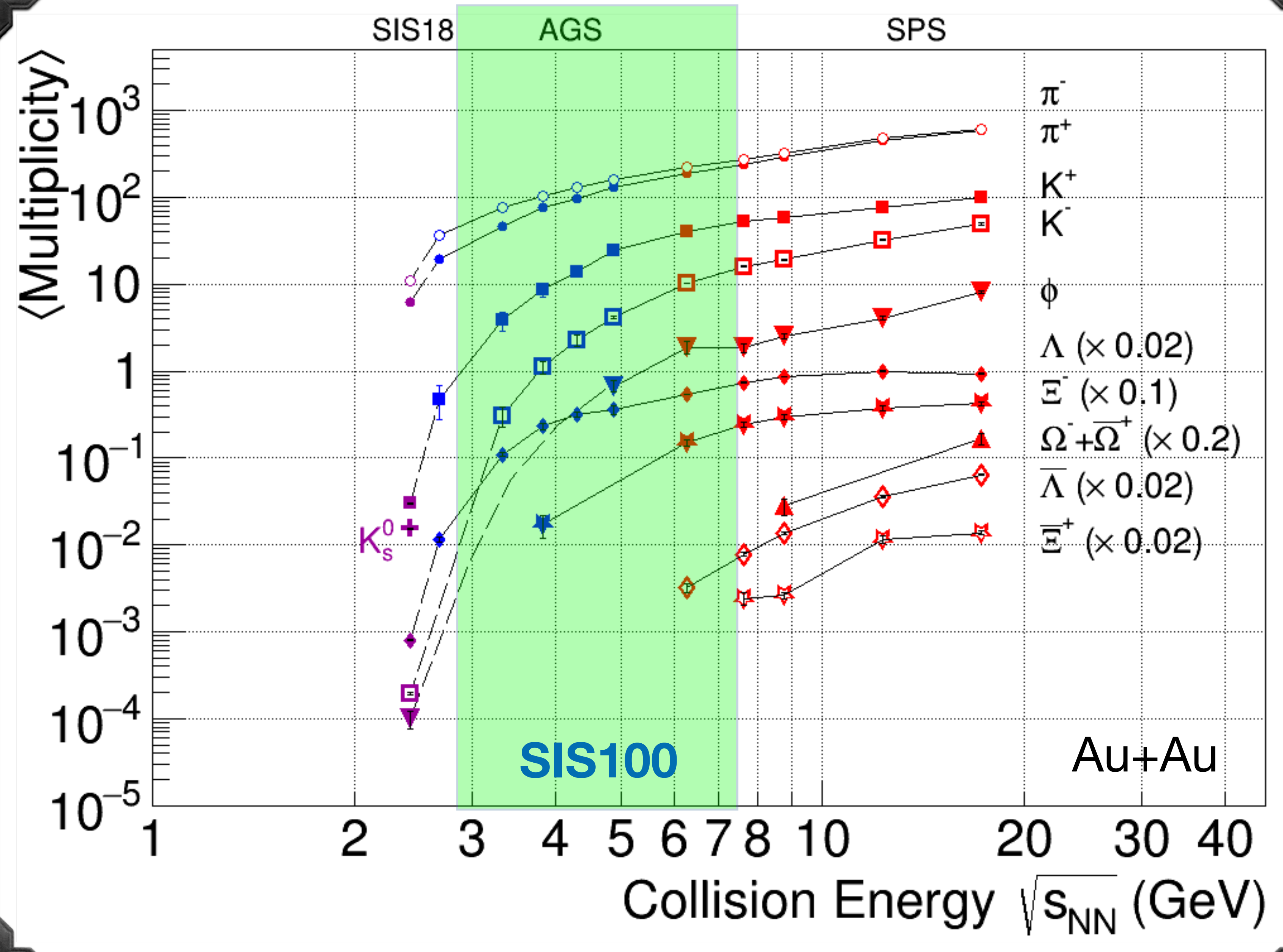
Hyperon factory with CBM@SIS100

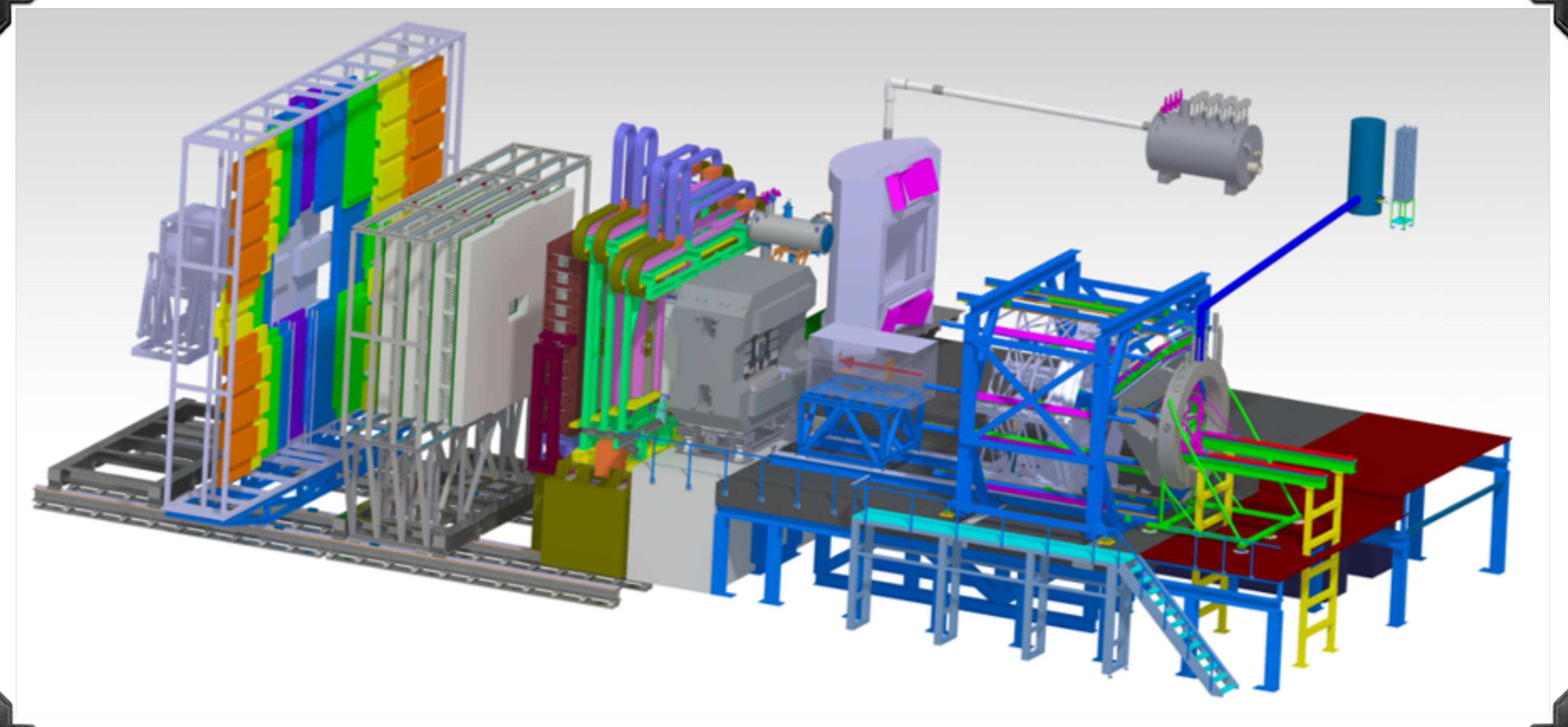
…providing a basis for interaction, spectroscopy, and structure studies

- **CBM** designed for:
  - p+p, p+A, A+A studies
  - Identification of variety of hadrons, particularly with strangeness+charm
  - High-rate capabilities



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





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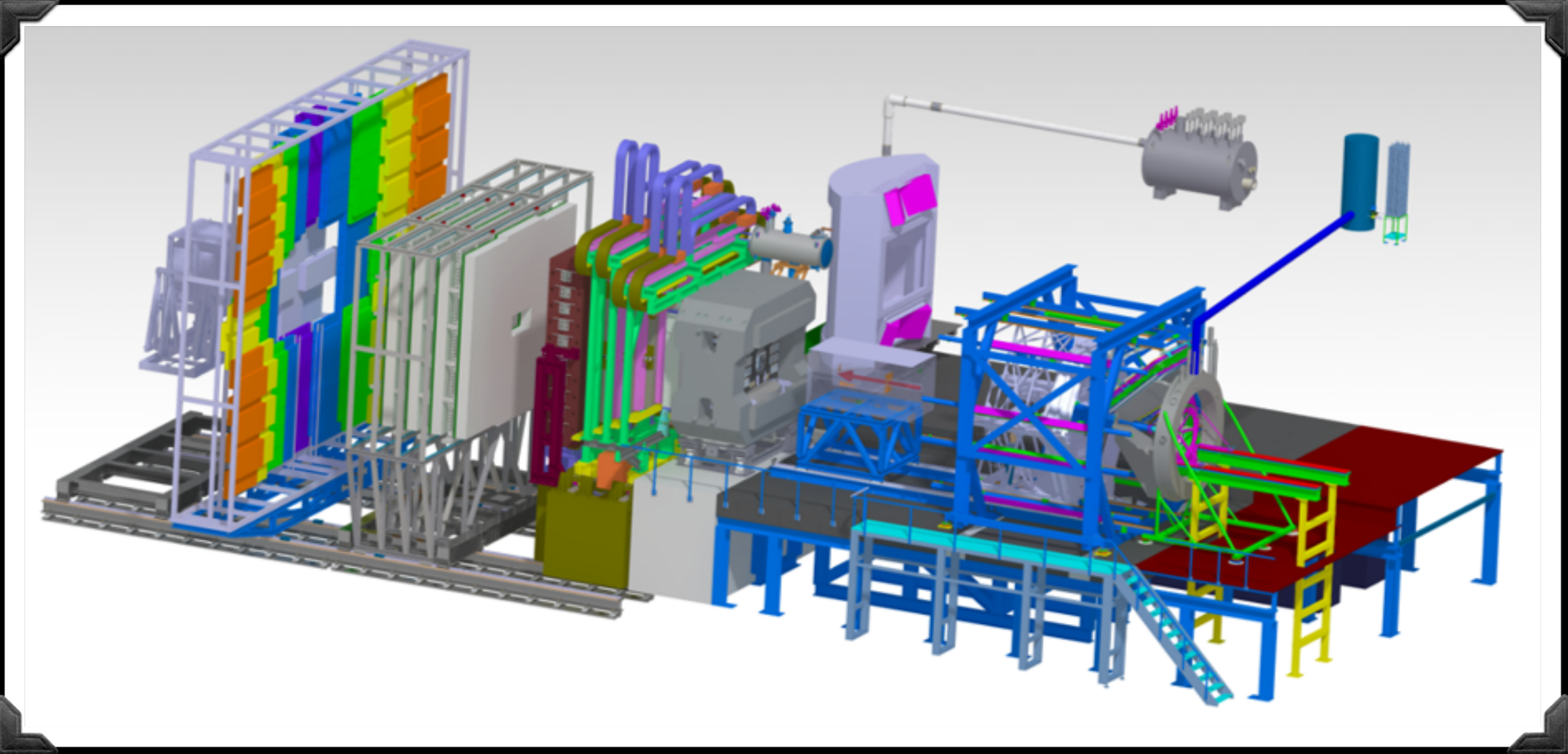
	reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
SIS18	$pp \to K^+ \Lambda p$	2.548	1.6
	$pp \to K^+ K^- pp$	2.864	2.5
	$pp \to K^+ K^+ \Xi^- p$	3.247	3.7
SIS100	$pp \to K^+ K^+ K^+ \Omega^- n$	4.092	7.0
	$pp \to \Lambda \bar{\Lambda} pp$	4.108	7.1
	$pp \to \Xi^- \bar{\Xi}^+ pp$	4.520	9.0
	$pp \to \Omega^- \bar{\Omega}^+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

Picture credit: N. Herrmann, FAIR seminar, Krakow

- Potential for exclusive processes:
  - 5 cm LH_2 target,Dipole,STS,RICH, TRD,TOF,FSD(+NCAL)
  - Luminosity: 10^{11} - 10^{12} p/spill (10 s)
  - Interaction rates 1-10 MHz
  - Angular coverage ~2.5-25^{o}
  - Angular resolution ~2 mrad
  - Momentum resolution 1.5-2.0%
  - Tracking efficiencies 90%



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	$pp \to \Lambda\bar{\Lambda} pp$	4.108	7.1
	$pp \to \Xi^-\bar{\Xi}^+ pp$	4.520	9.0
	$pp \to \Omega^-\bar{\Omega}^+ pp$	5.222	12.7
	$pp \to J/\Psi\, pp$	4.973	12.2

Picture credit: N. Herrmann, FAIR seminar, Krakow

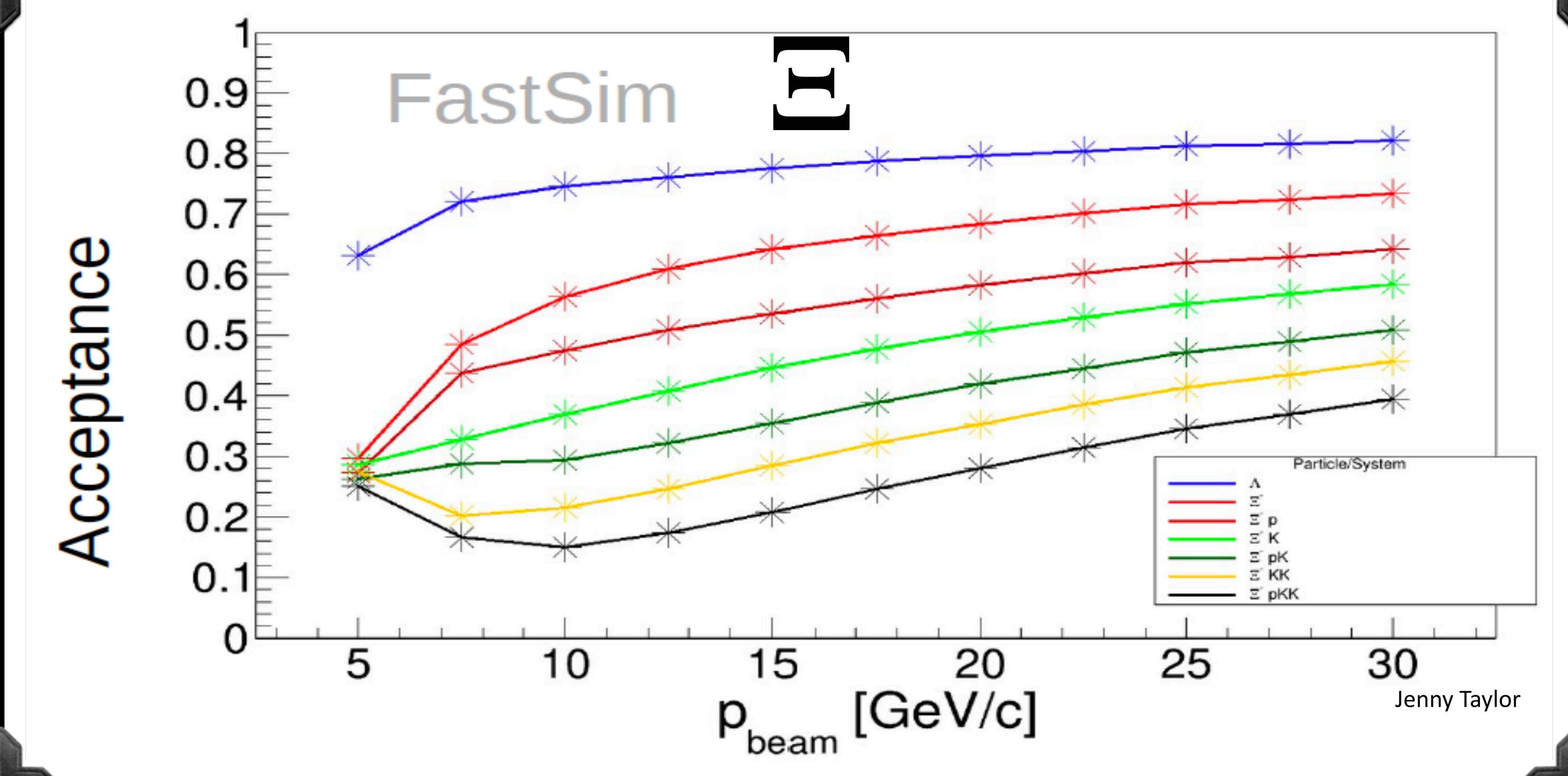
Jenny Taylor, FastSim studies

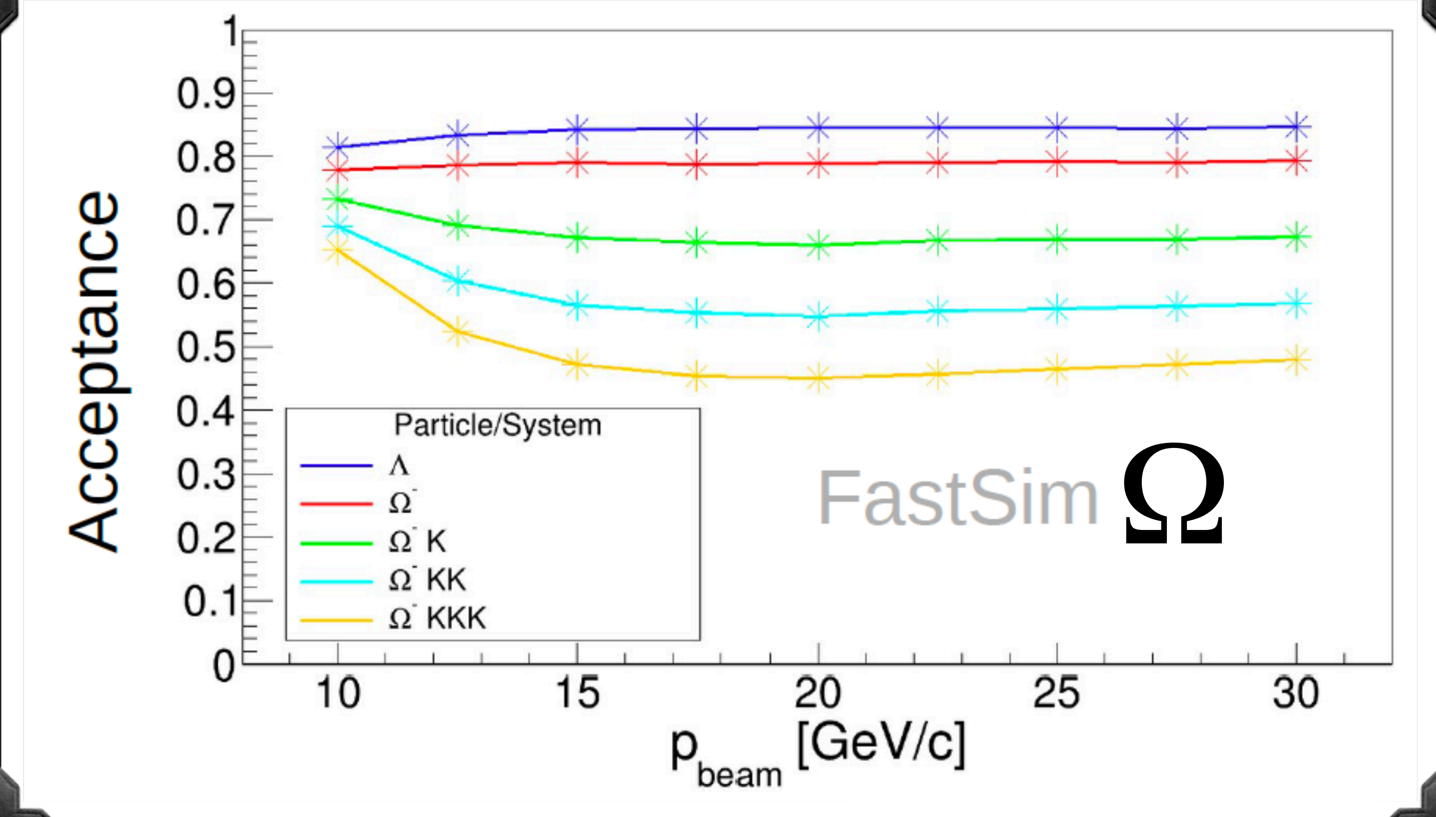
Expected reconstructed inclusive / Day @ 30 GeV/c, σ = 40 μb	
1 MHz	$1.2\cdot10^9$
10 MHz	$1.2\cdot10^{10}$

$pp \to pK^+K^+\Xi^-$
$\Xi^- \to \Lambda\pi^-$ (BR ~ 100%)
$\Lambda \to p\pi^-$ (BR = 64%)

Expected reconstructed inclusive events / day @ 30 GeV/c, σ = 0.6 μb	
1 MHz	$1.4\cdot10^7$
10 MHz	$1.4\cdot10^8$

$pp \to nK^+K^+K^+\Omega^-$
$\Omega^- \to \Lambda K^-$ (BR = 68%)
$\Lambda \to p\pi^-$ (BR = 64%)





Topics in the strange sector

…and complementary to JLAB (KL), JPARC, …

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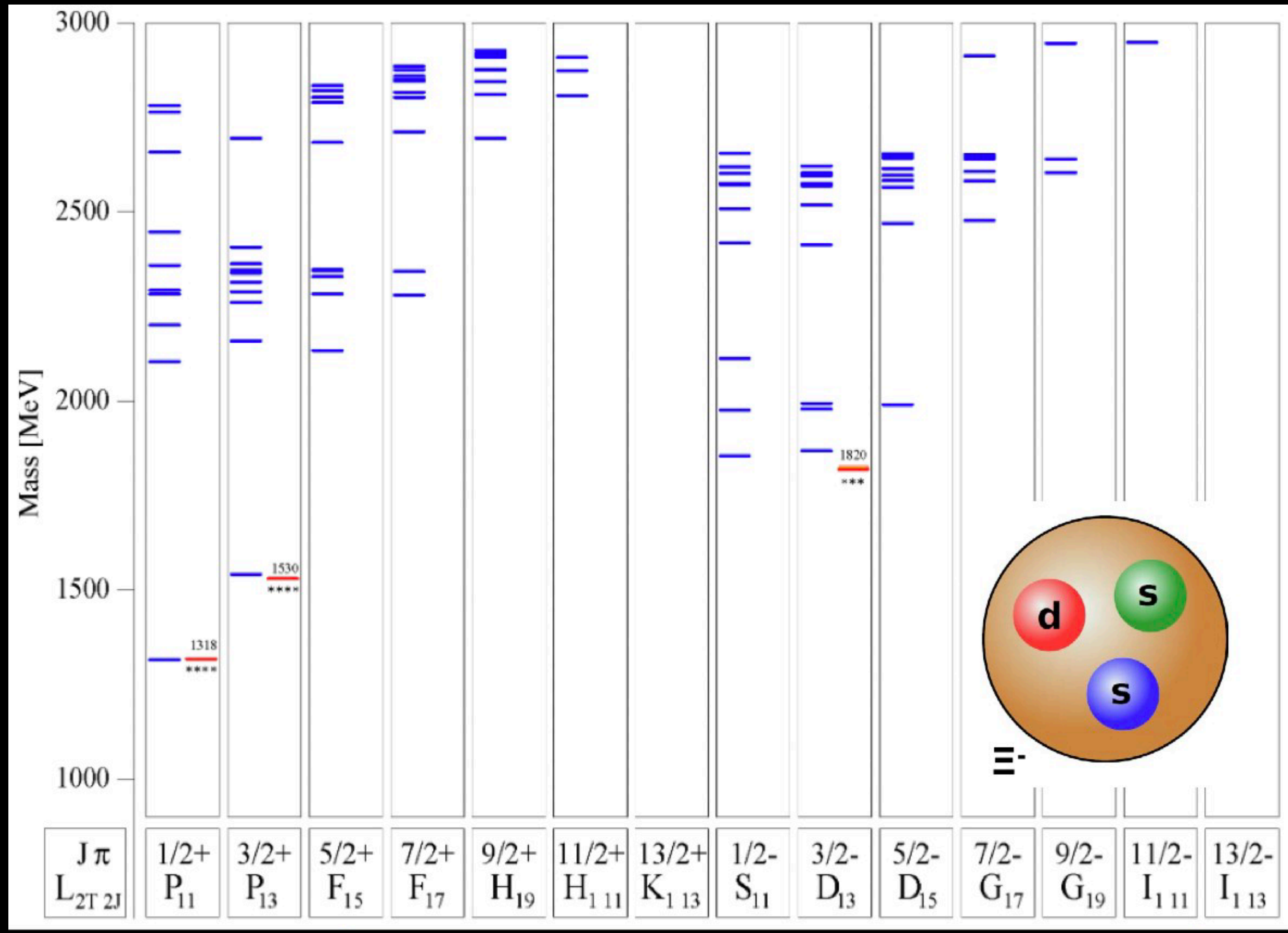
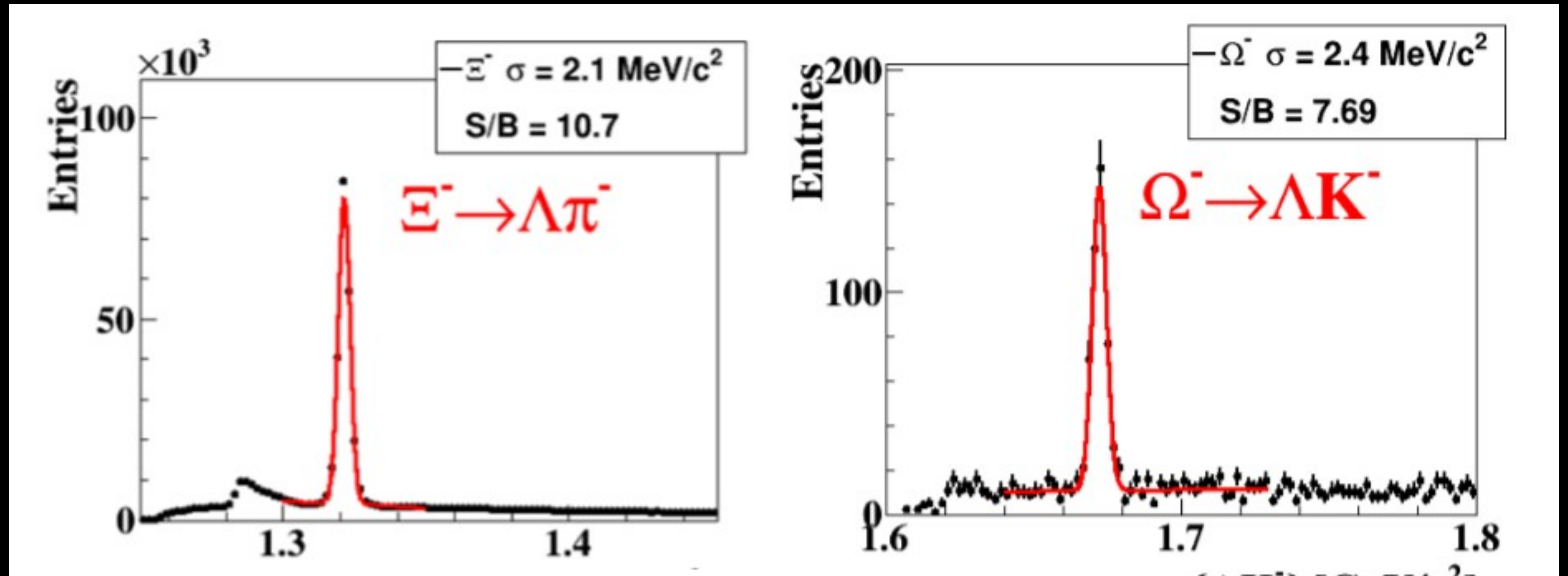
…and complementary to JLAB (KL), JPARC, …

- **Y* composition: spectroscopy & structure**
  - Excited Ξ^*, Ω^* spectroscopy
  - Line-shape measurements (~2 MeV resolution)
  - Electromagnetic (& weak) transition form factors

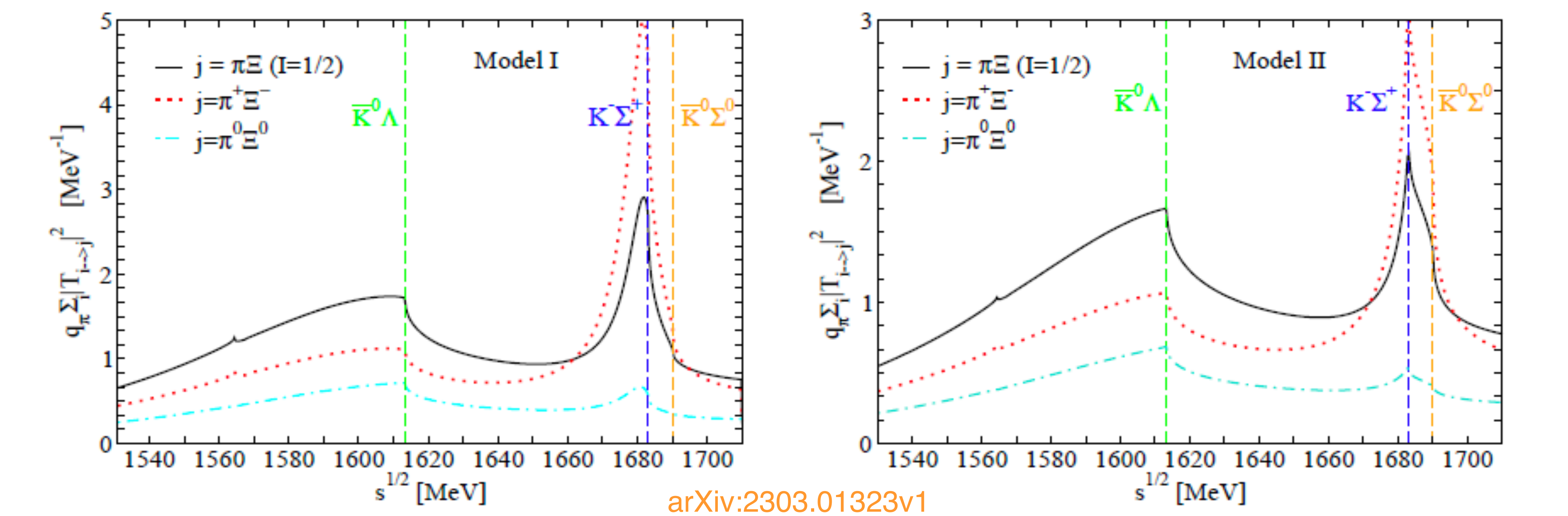


Quark models: U. Löring *et al.*, EPJA 10 (2001) 447



Picture credit: N. Herrmann, FAIR seminar, Krakow

Feijoo, Valcarce, Magas UChPT with WT + Born term + NLO



arXiv:2303.01323v1

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

Topics in the strange sector

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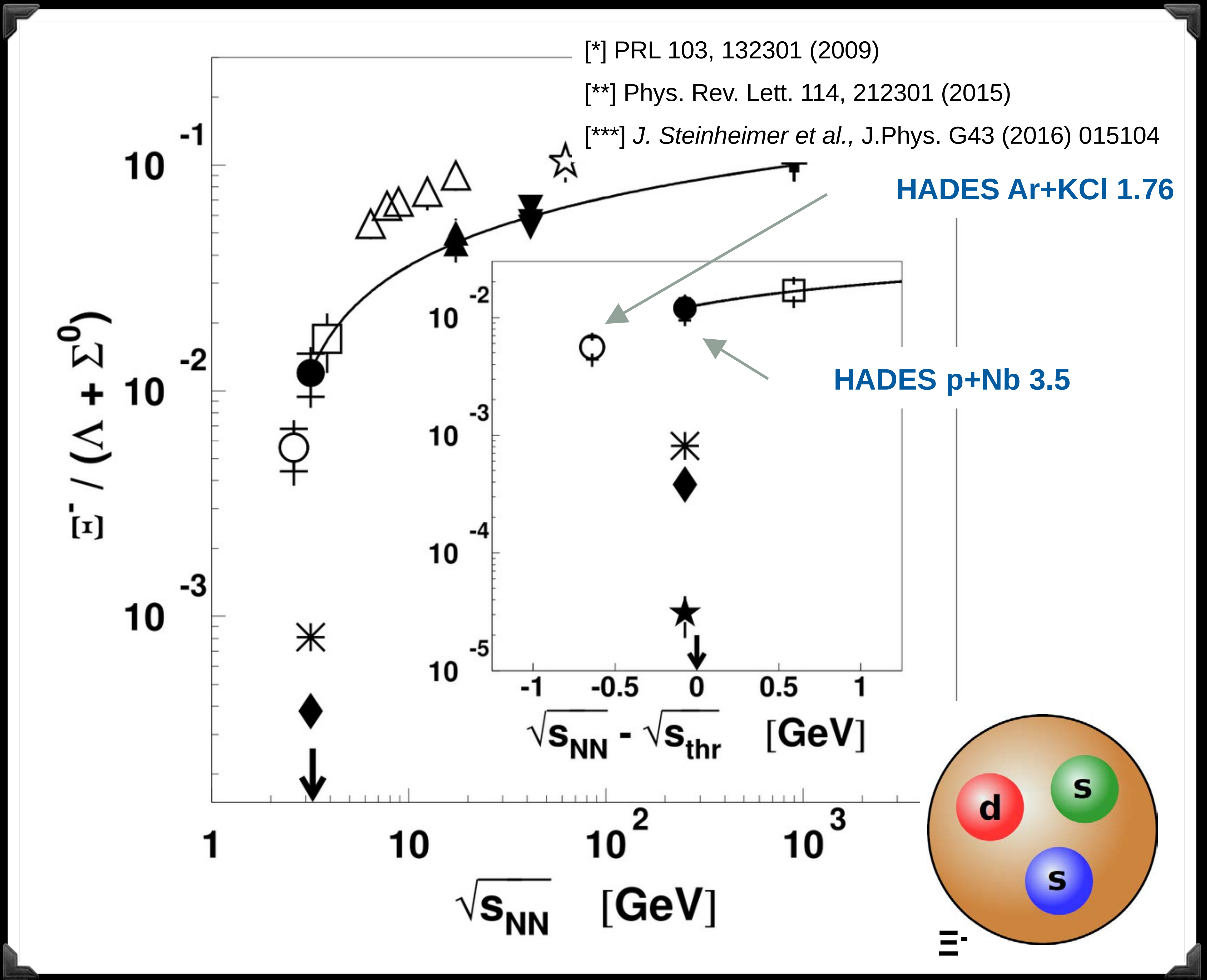

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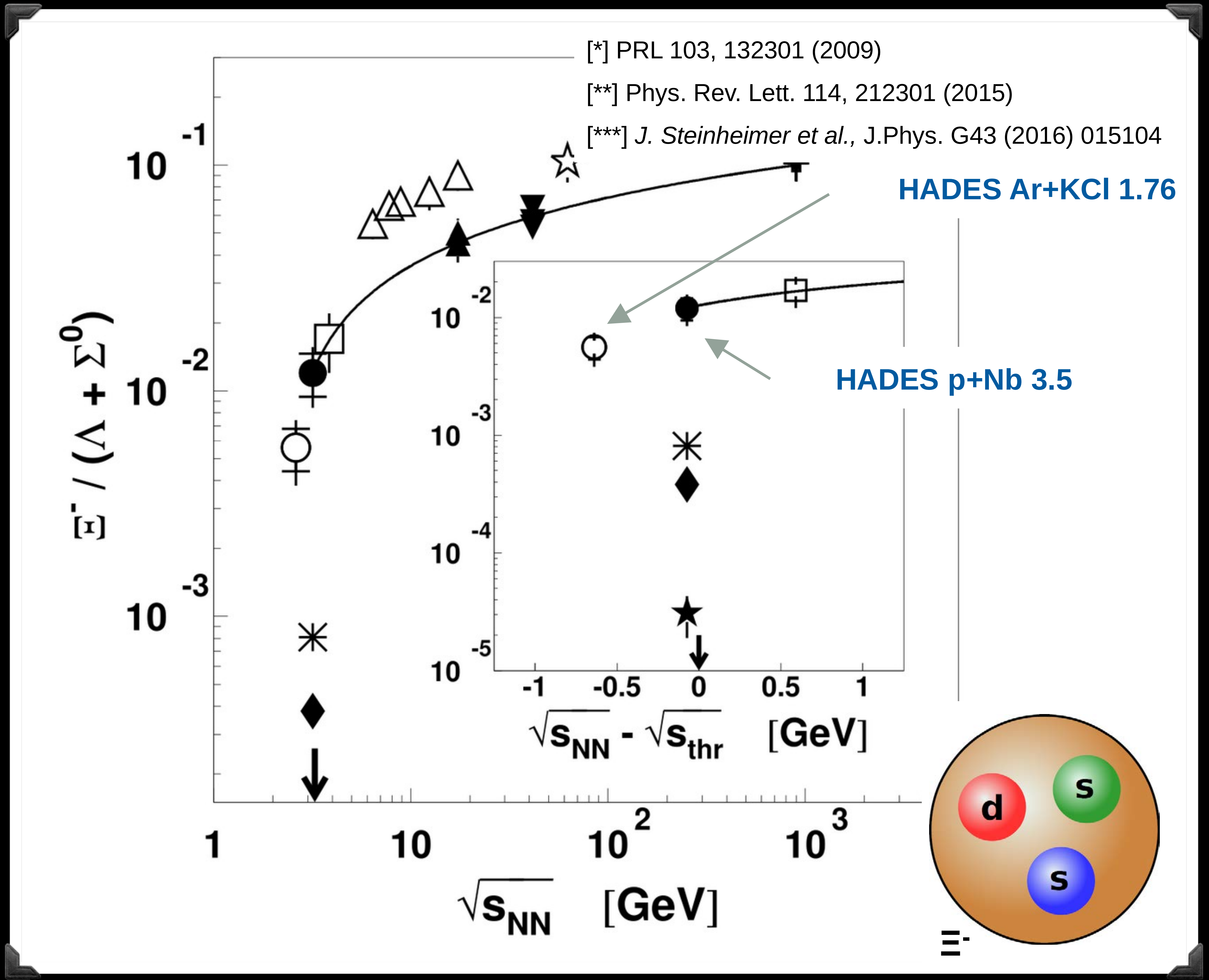
- **Strangeness propagation in cold matter**
  - Reference spectra for p+A, A+A
  - ➡ Nuclear modification factors R_{AA}



Interaction studies in strange and charm sectors

YN & YY *interaction* studies, *complementary* approaches

Interaction studies in strange and charm sectors

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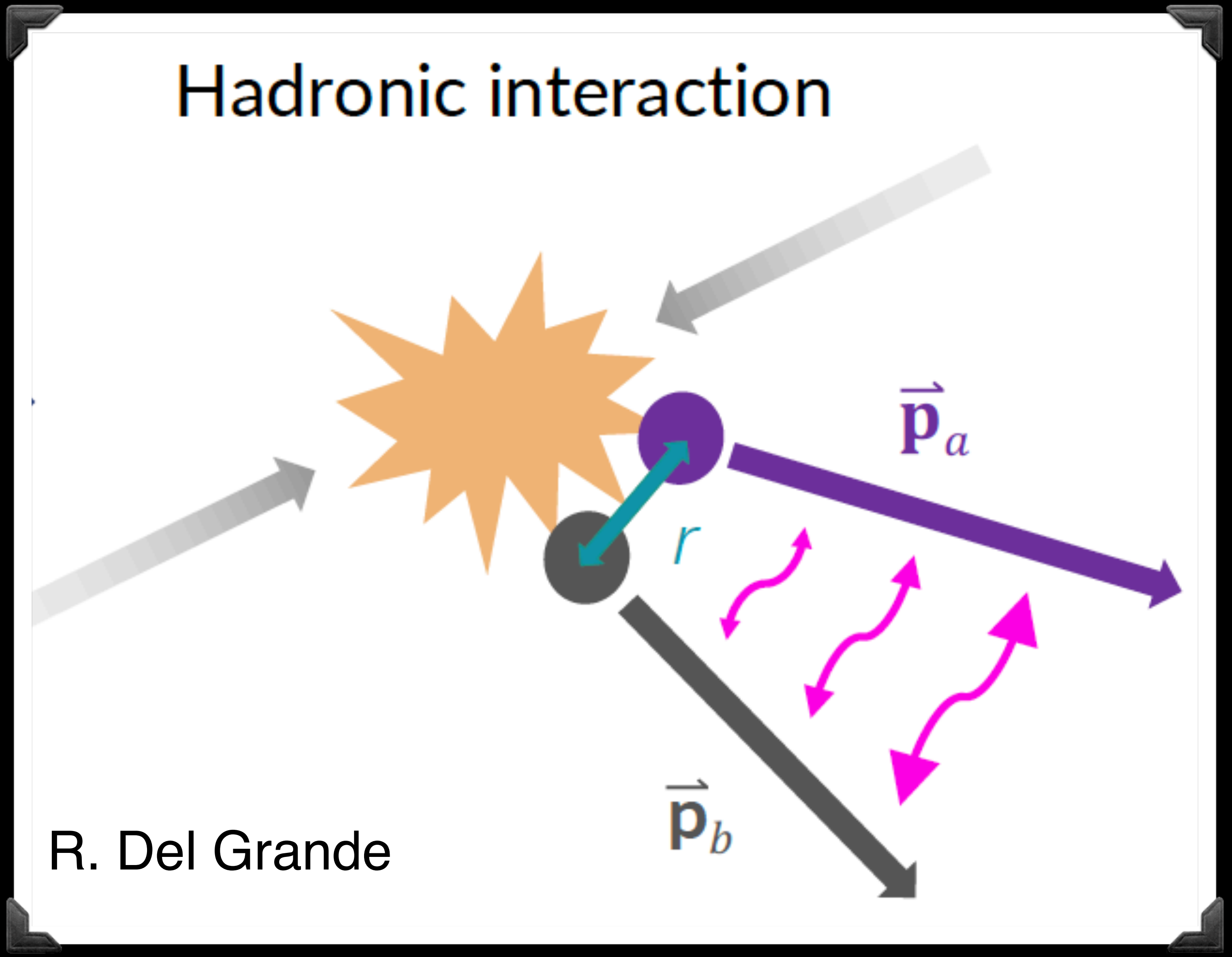

- **Femtoscopy**
  - Measure two-particle correlation function towards small relative momenta
  - Source distribution known —> info about interaction
  - Disadvantages: source size, feed-down contributions
  - Advantages: @SIS100 less feed-down than @LHC, weak dependence on production

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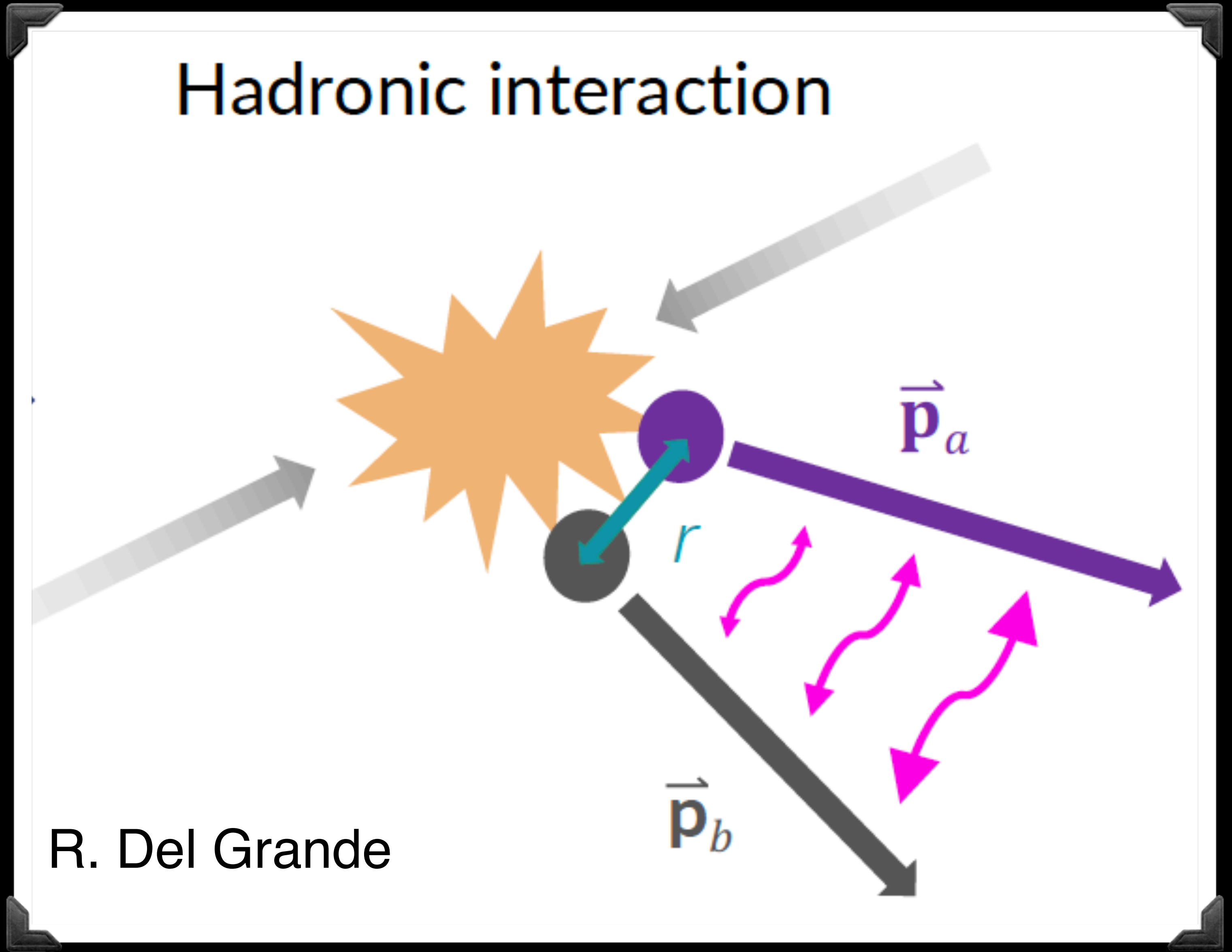

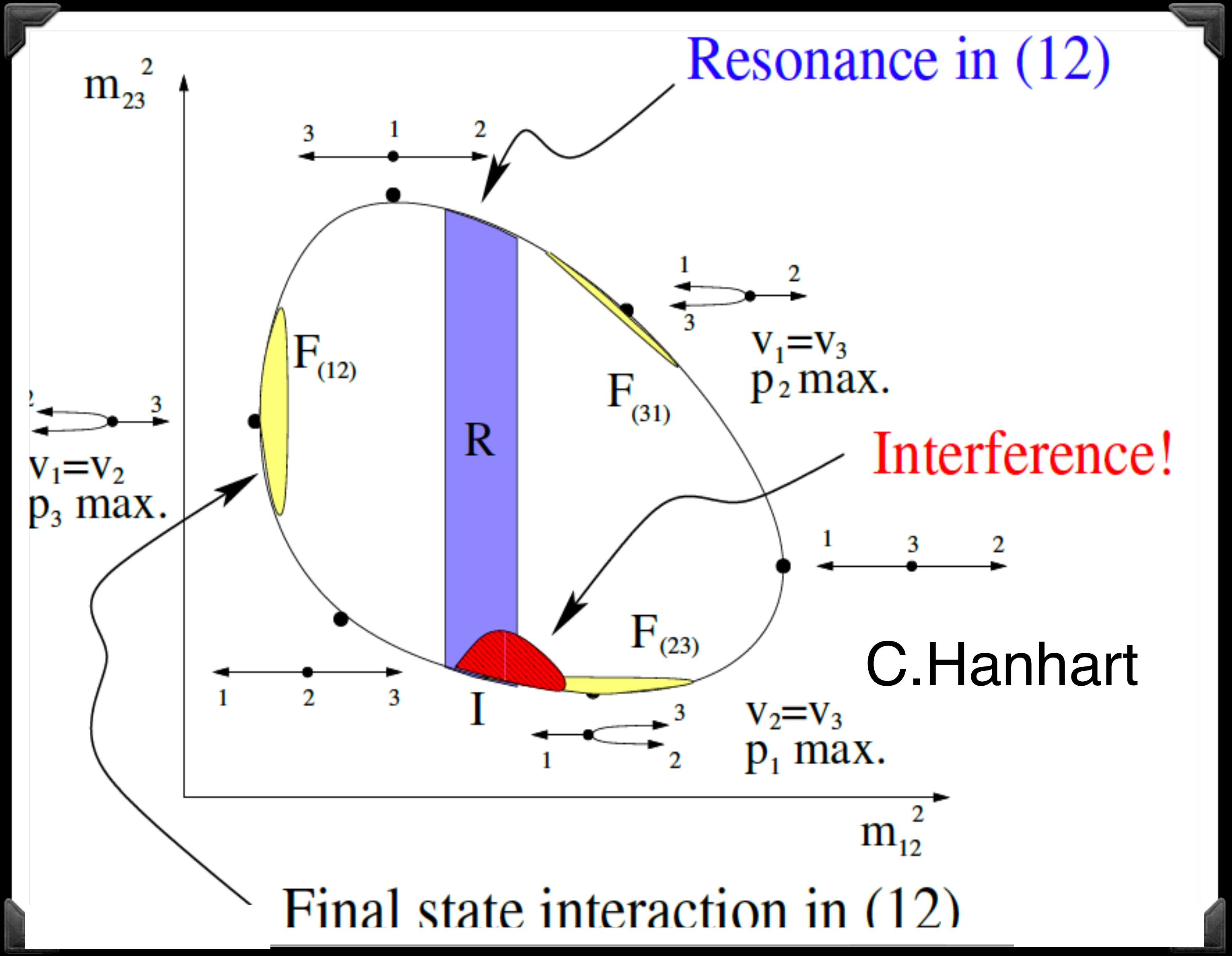

Interaction studies in strange and charm sectors

YN & YY *interaction* studies, *complementary* approaches

C. Hanhart

- $pp \to ppJ/\psi$ and the pJ/ψ interaction $\sqrt{s} > 5$ GeV
  $\Longrightarrow$ discovery channel of $\bar{c}c$ pentaquarks & role of $\Lambda_c D^{(*)}$ channels
- $pp \to p\Sigma_c^{(*)}\bar{D}^{(*)}$ and the $\Sigma_c^{(*)}\bar{D}^{(*)}$ interaction $\sqrt{s} > 5.6$ GeV
  $\Longrightarrow$ formation of $\bar{c}c$ pentaquarks
- $pp \to \bar{K}^0\bar{K}^0\Sigma^+\Sigma^+$ and the $\Sigma^+\Sigma^+$ interaction (S=0 only!) $\sqrt{s} > 3.4$ GeV
  $\Longrightarrow$ closely SU(3) related to pp scattering
- .... certainly many more $\sqrt{s_{\mathrm{max}}} = 7.5$ GeV

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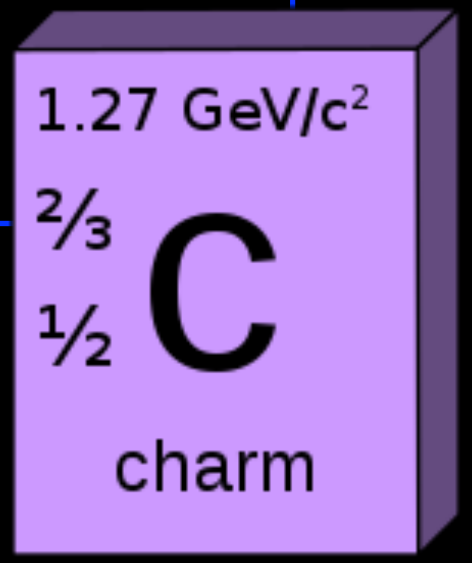
Charm-nucleon interactions

$pp \rightarrow ppJ/\Psi$ **final state**

Charm *valuable* probe in QCD:

- Mass scale ~1.5 GeV > Λ_{QCD}~0.2 GeV
- Short formation times ~0.1 fm/c
- Narrow states, “QCD beacons”
- …



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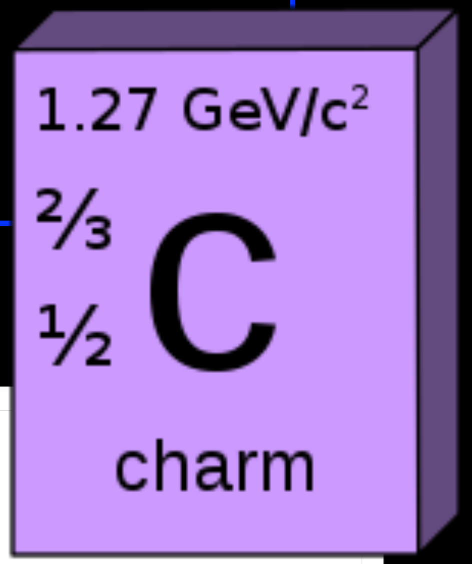

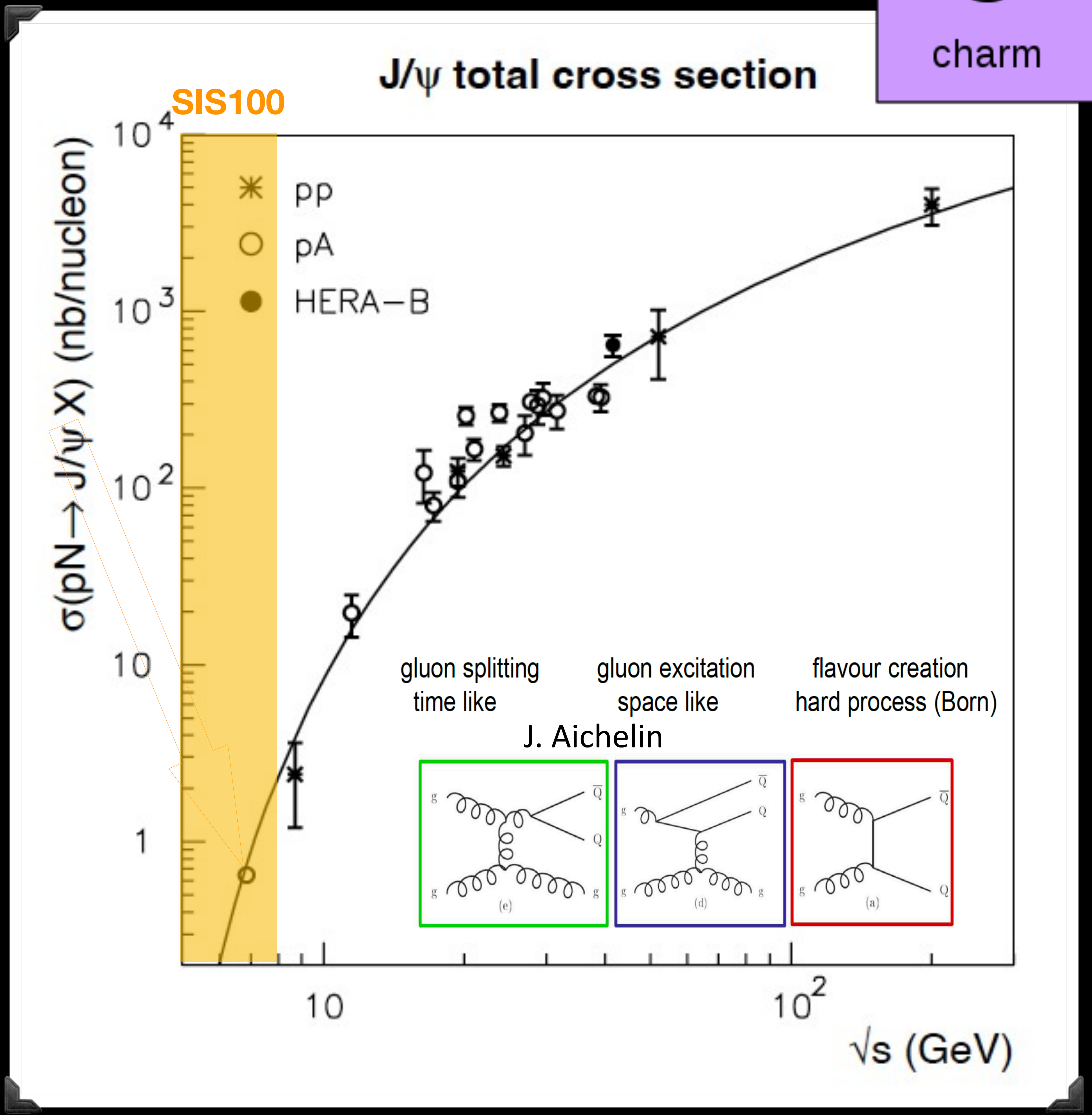

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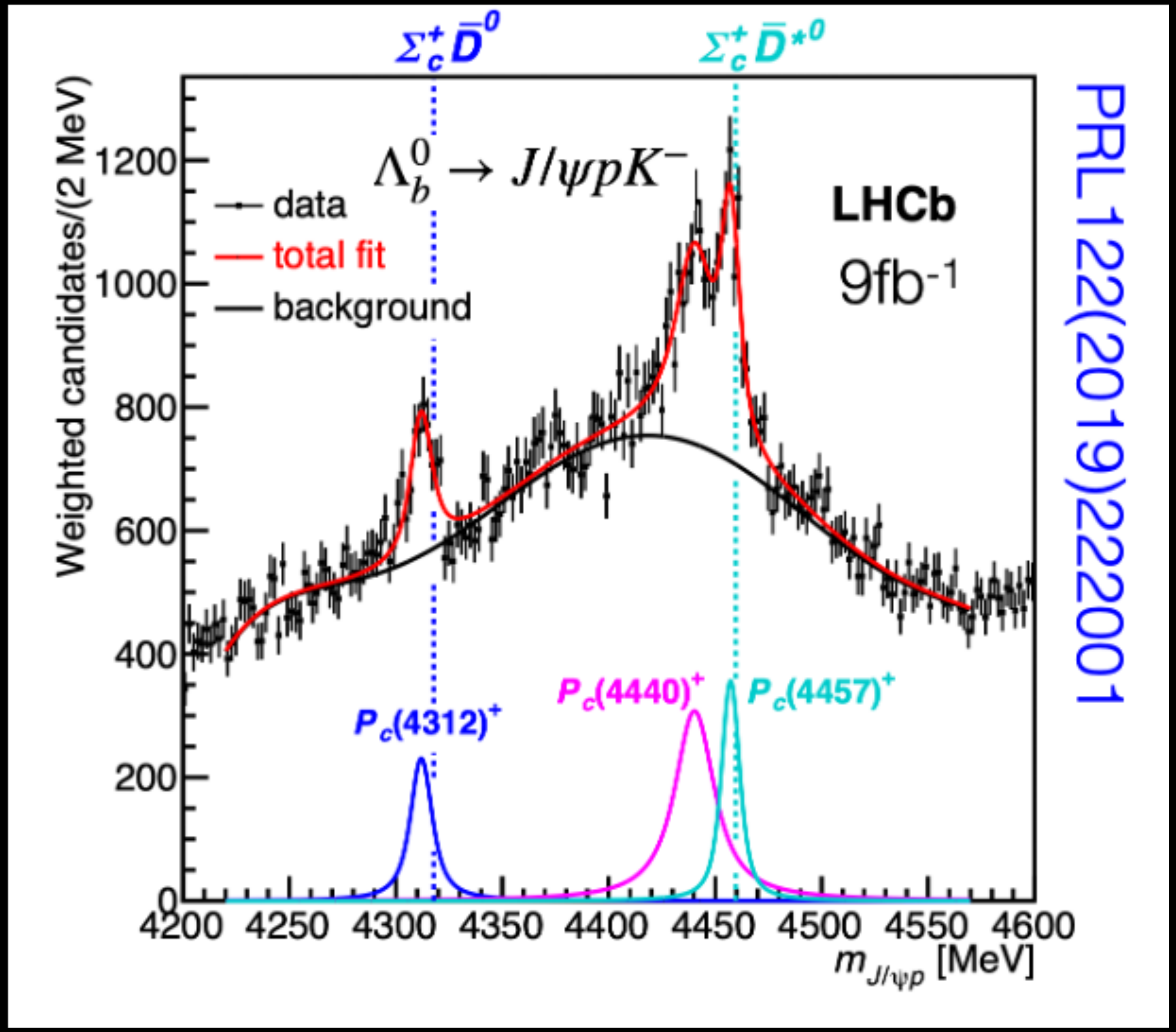
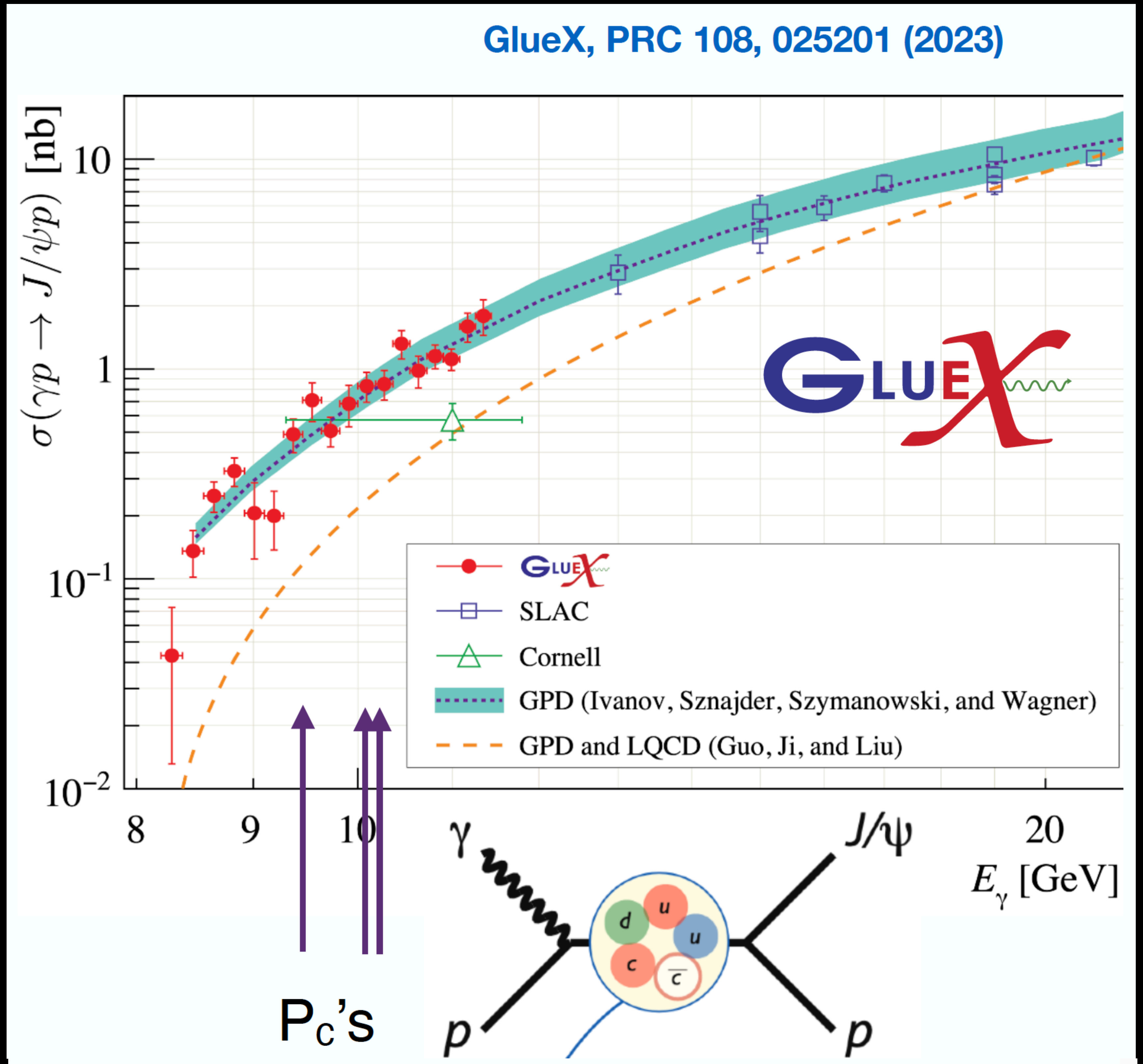
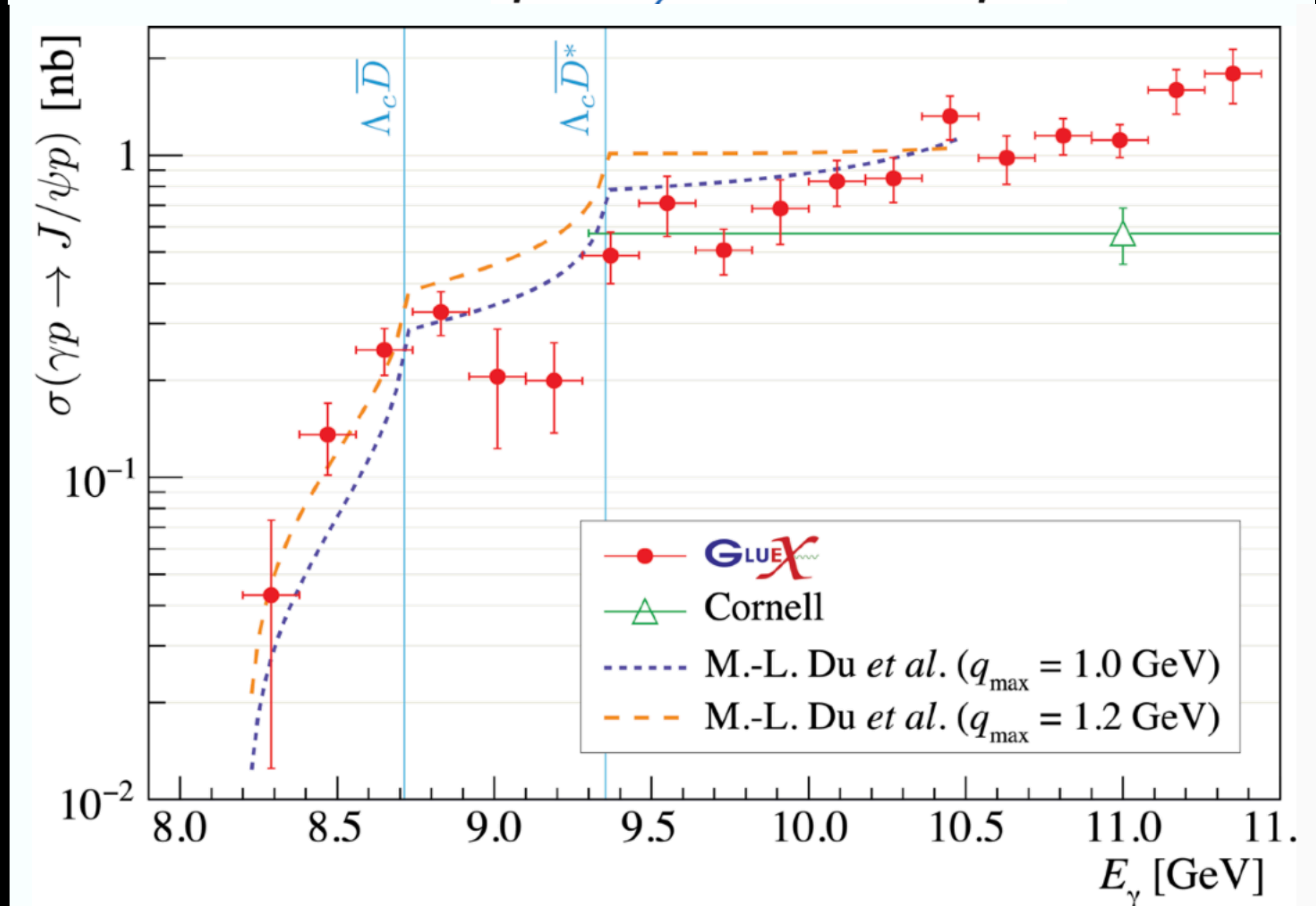
- Search for "LHCb" pentaquarks



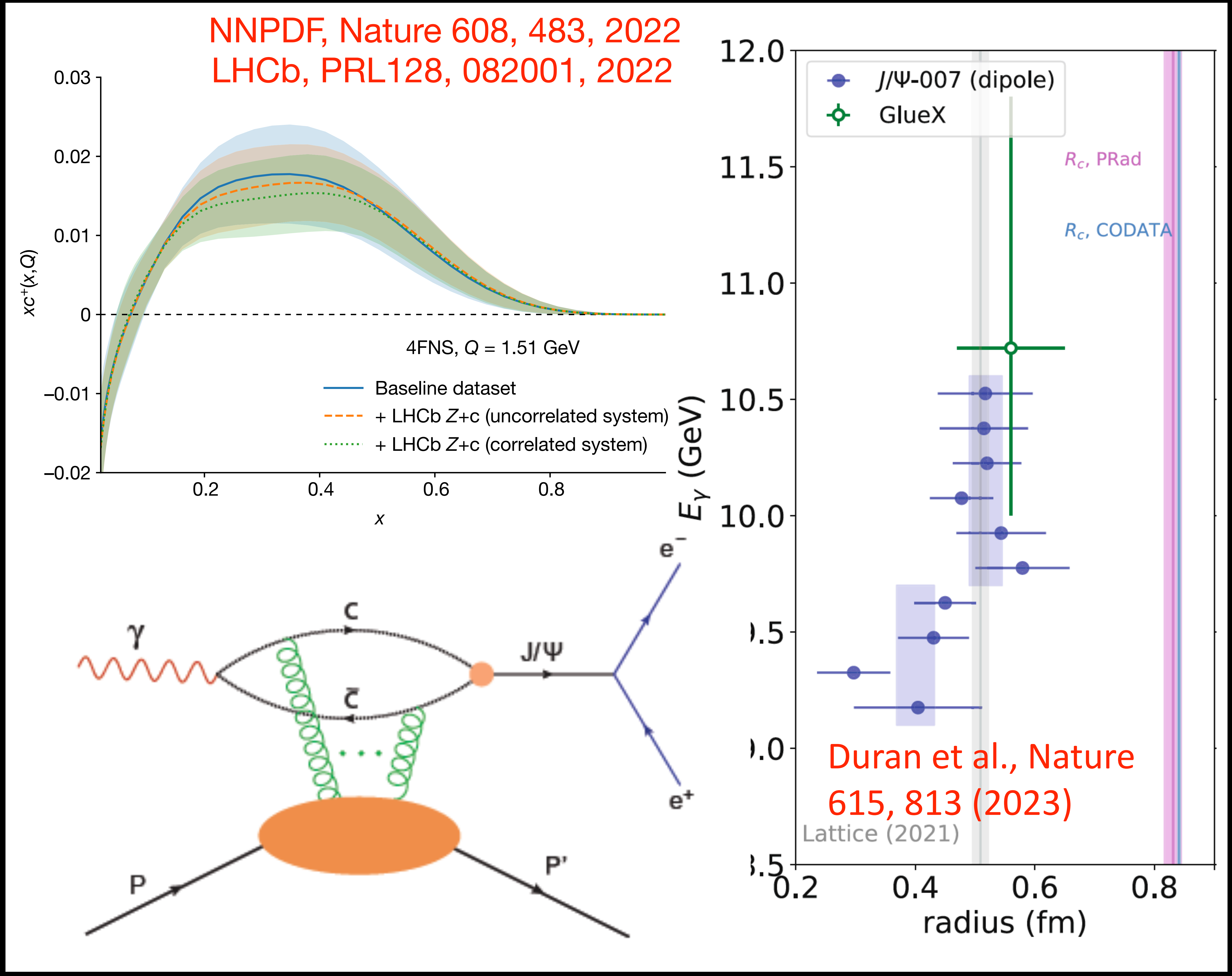




Charm-nucleon interactions

$pp \rightarrow ppJ/\Psi$ final state

- (Near-threshold) charm production in NN scattering contains rich info: PDFs, multi-gluon dynamics, …
- Search for “LHCb” pentaquarks
- Input to nucleon-structure studies (“controversial”):
  - Role of intrinsic charm of nucleon? (claim LHCb, NNPDF)
  - Trace anomaly contribution to mass of nucleon?
  - Mass radius of the nucleon, “gravitational form factor”?



Validity of VMD and two-gluon exchange questionable (dominance of open-charm $\Lambda_c\bar{D}^{(*)}$ / Pomeron exchange?)

Charm-nucleon interactions

Simulations by Ömer Penek
using FastSim

$pp \rightarrow ppJ/\Psi$ final state

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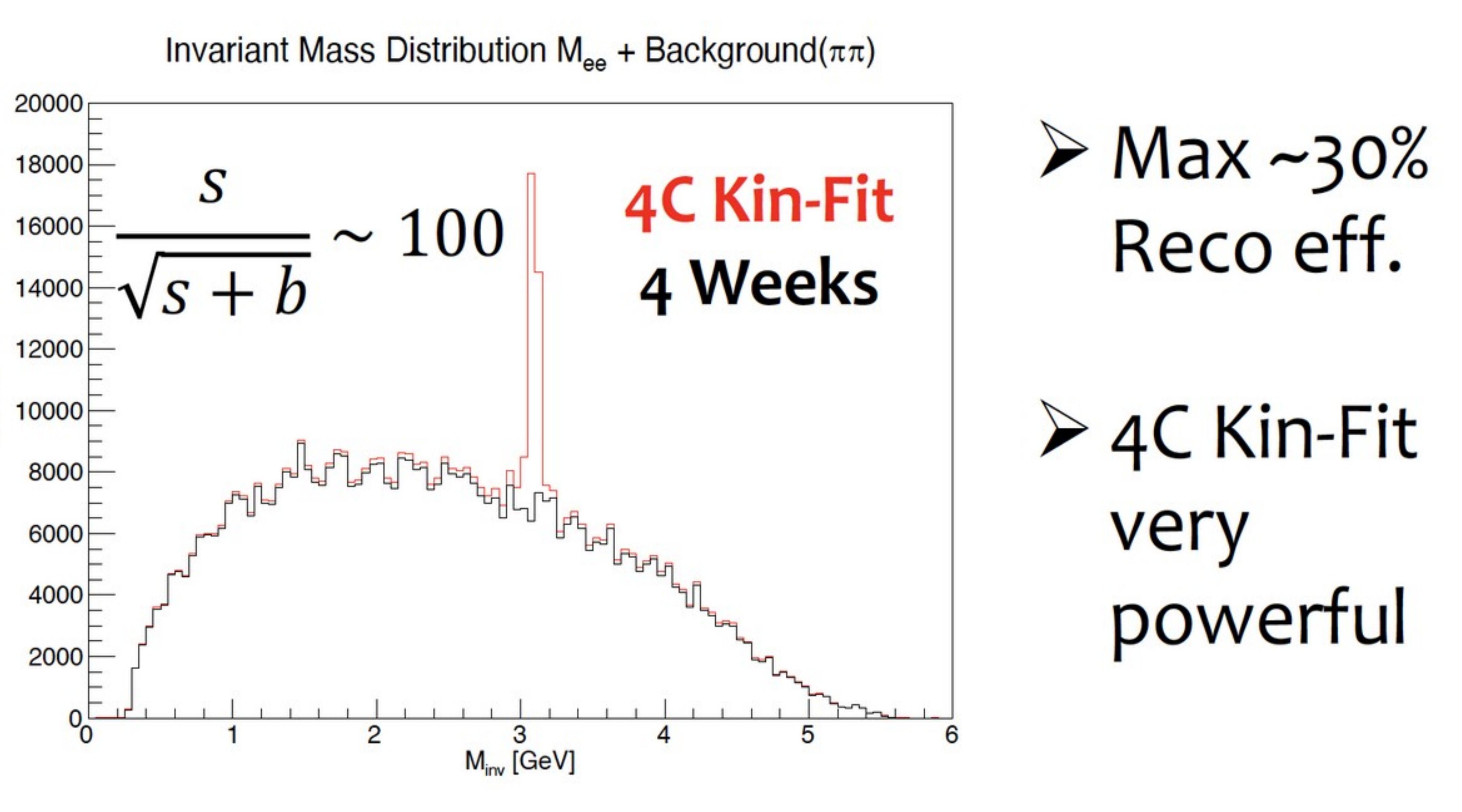

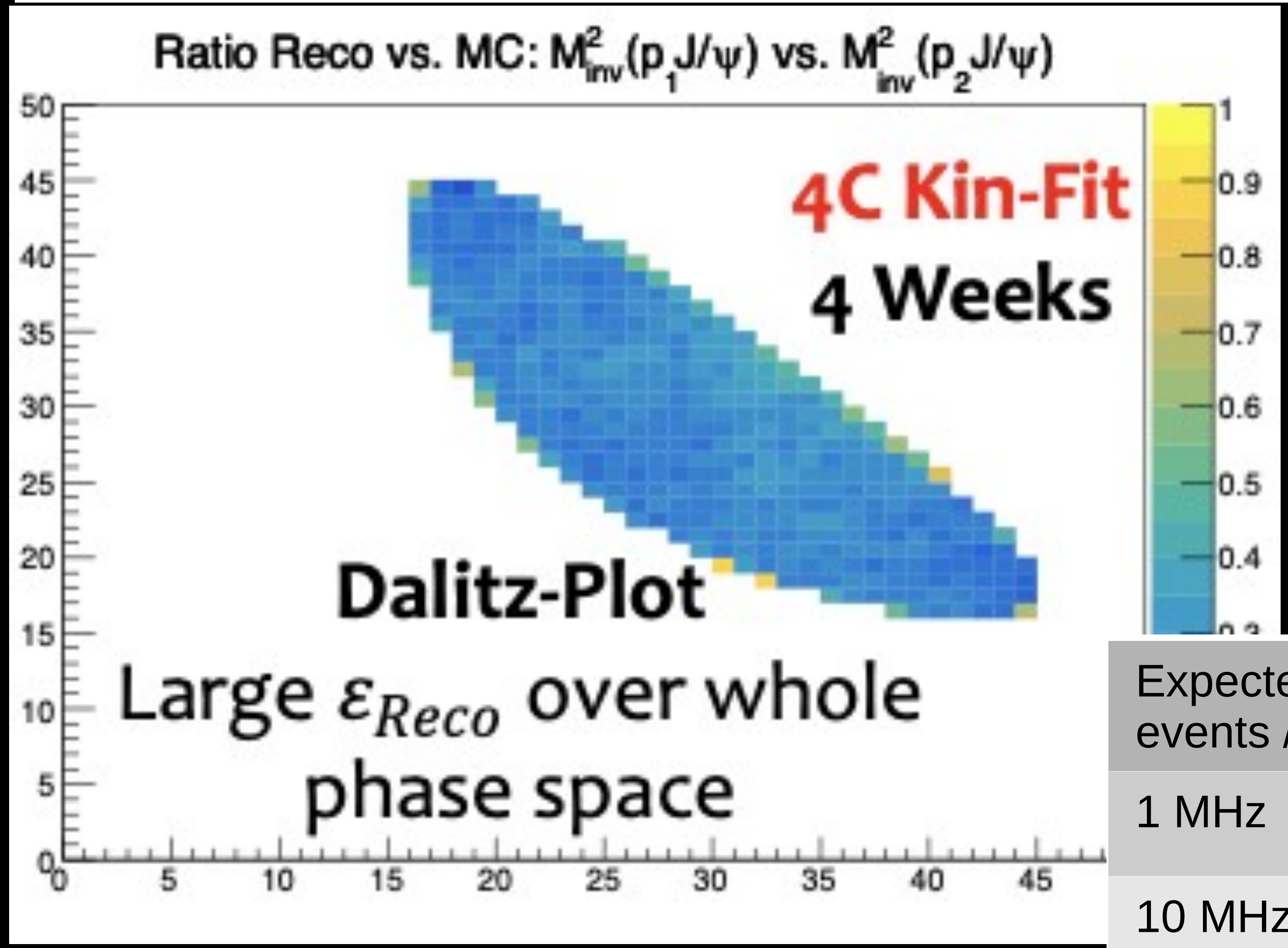

Expected reconstructed exclusive events / Day @ 30 GeV/c, $\sigma = 10^{-3}$ μb	
1 MHz	$1.6 \cdot 10^3$
10 MHz	$1.6 \cdot 10^4$

Charm-nucleon interactions

$pp \to ppJ/\Psi$ **final state** **+** $pp \to p\bar{D}\Lambda_c, \ldots$ **to *complete* the picture**

- (Near-threshold) charm production in NN scattering contains rich info: PDFs, multi-gluon dynamics, …
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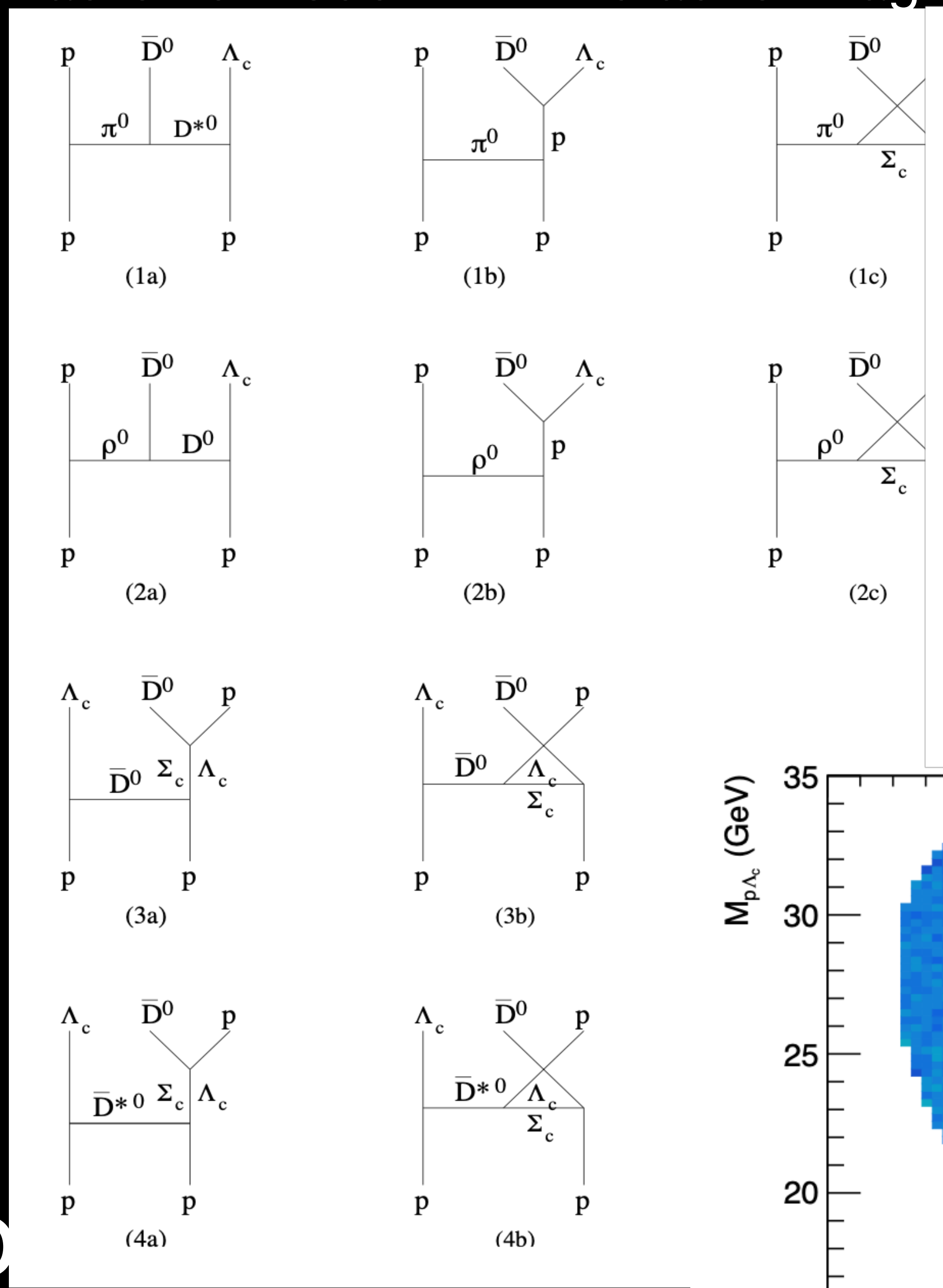
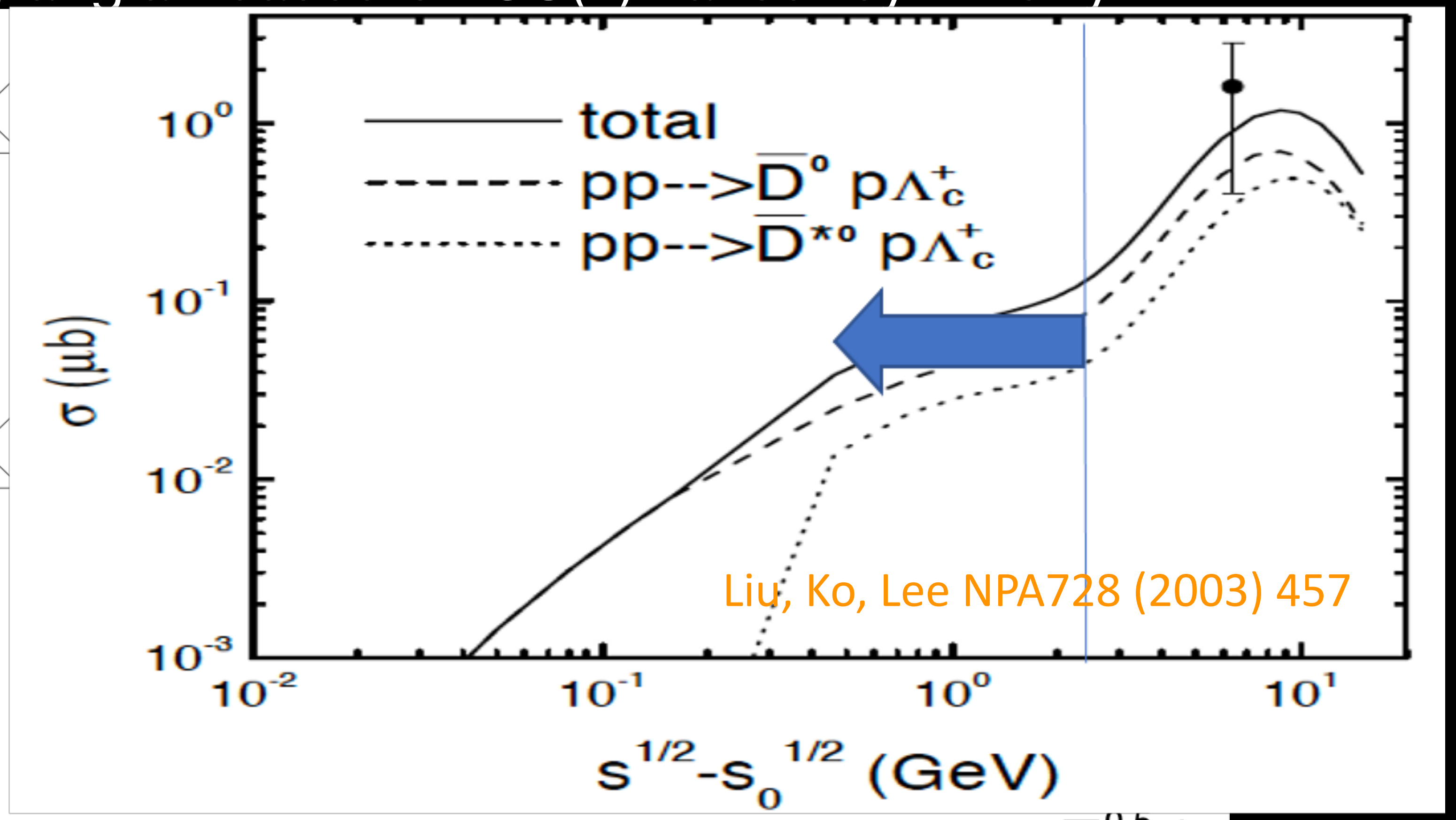
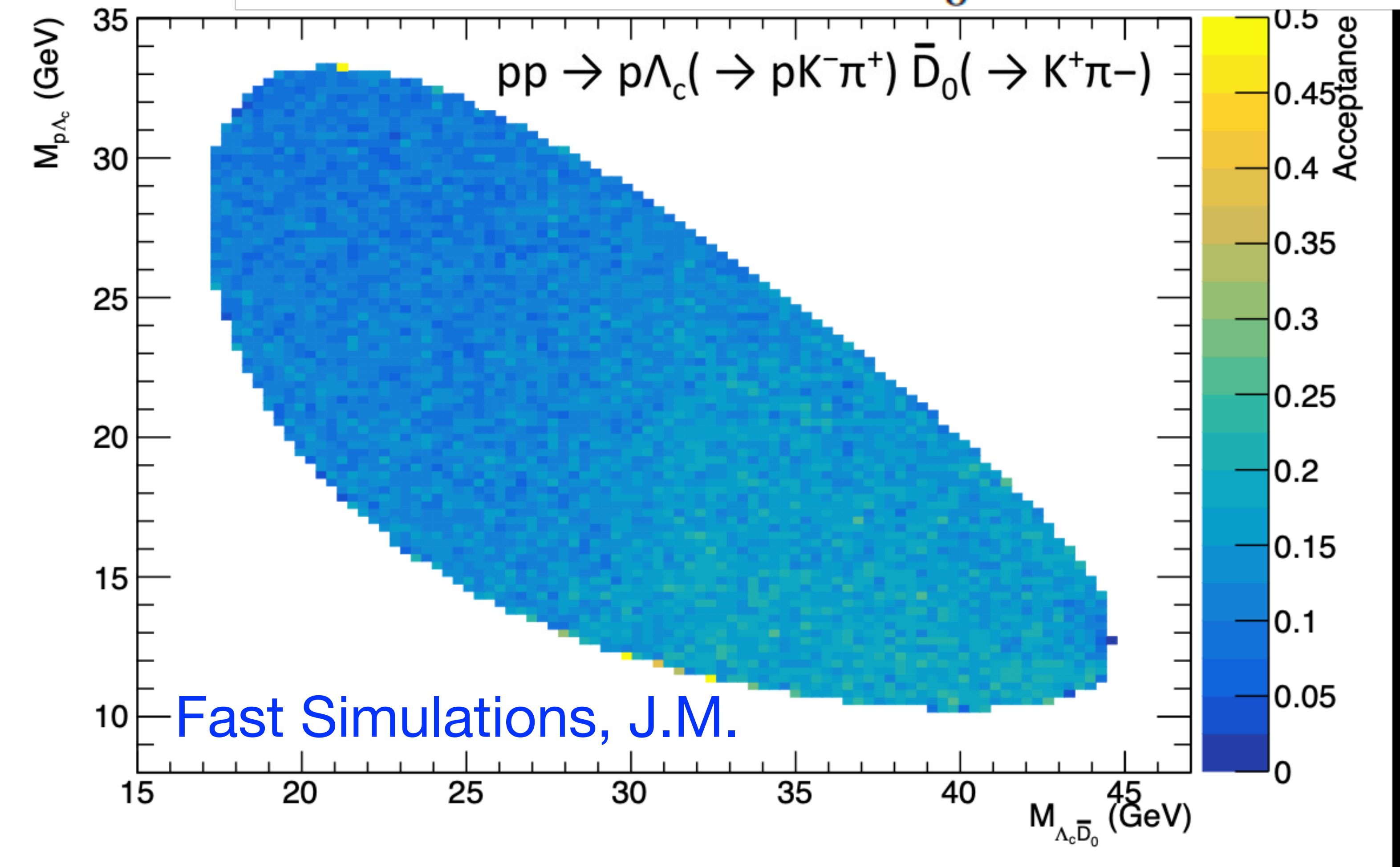
Hadronic model with interaction Lagrangian based on SU(4) flavour symmetry

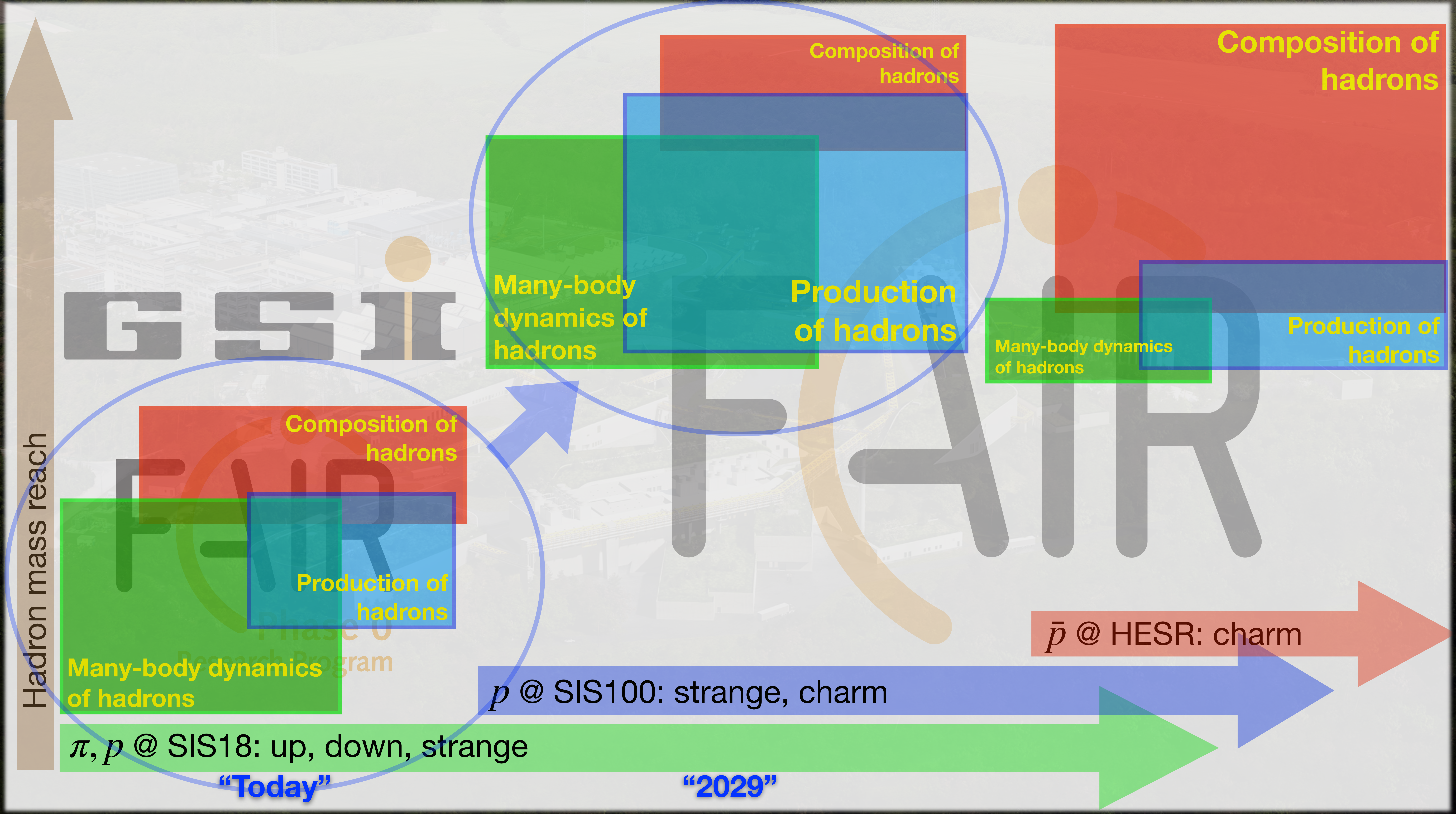






Good acceptance, low branching fractions and requires vertex detector

Roadmap


Hadron mass reach
Composition of hadrons
Production of hadrons
Many-body dynamics of hadrons
Composition of hadrons
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Composition of hadrons
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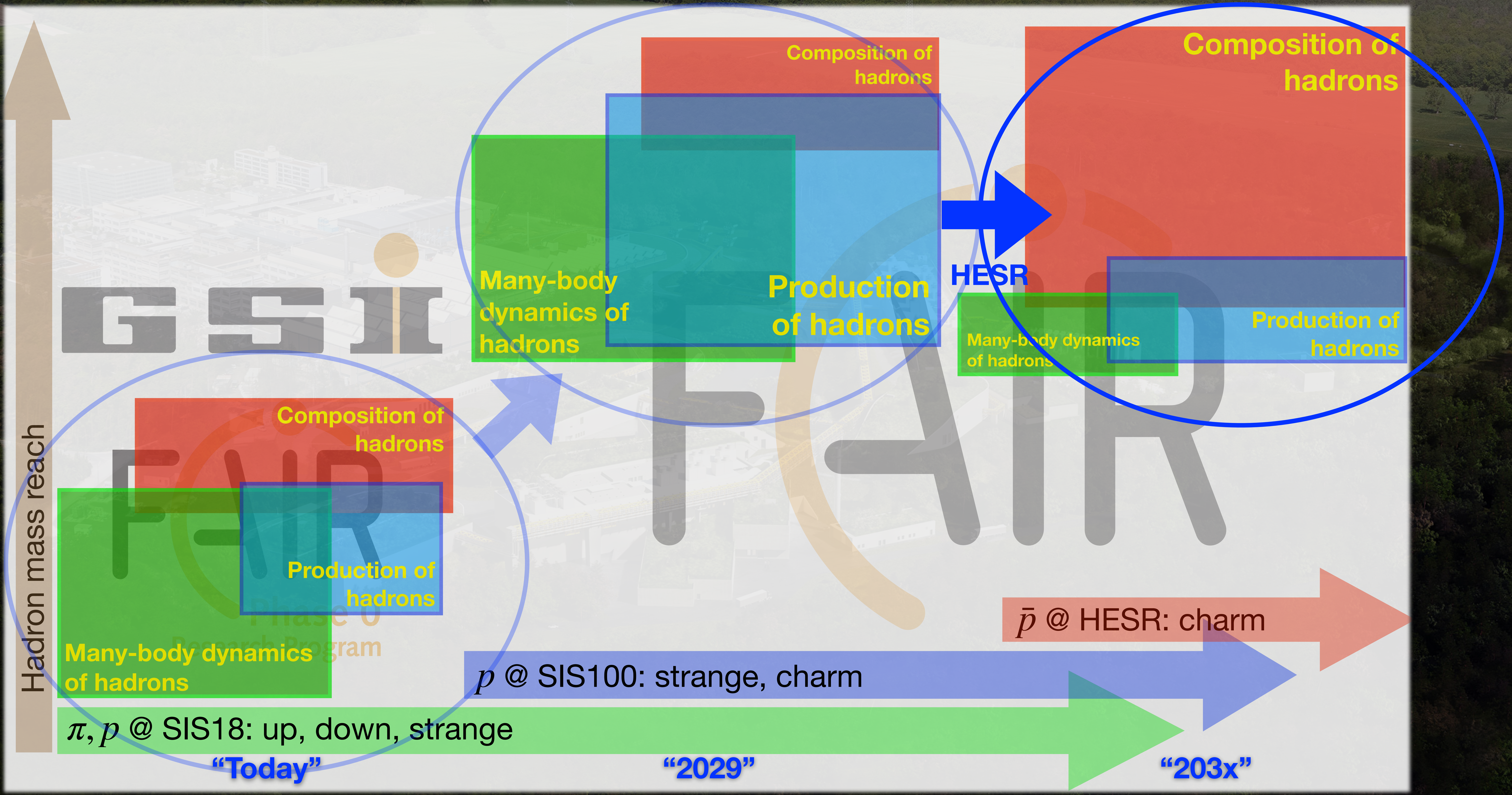
$\bar{p}$ @ HESR: charm
p @ SIS100: strange, charm
π, p @ SIS18: up, down, strange
"Today"
"2029"

Roadmap



Hadron mass reach
Composition of hadrons
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Composition of hadrons
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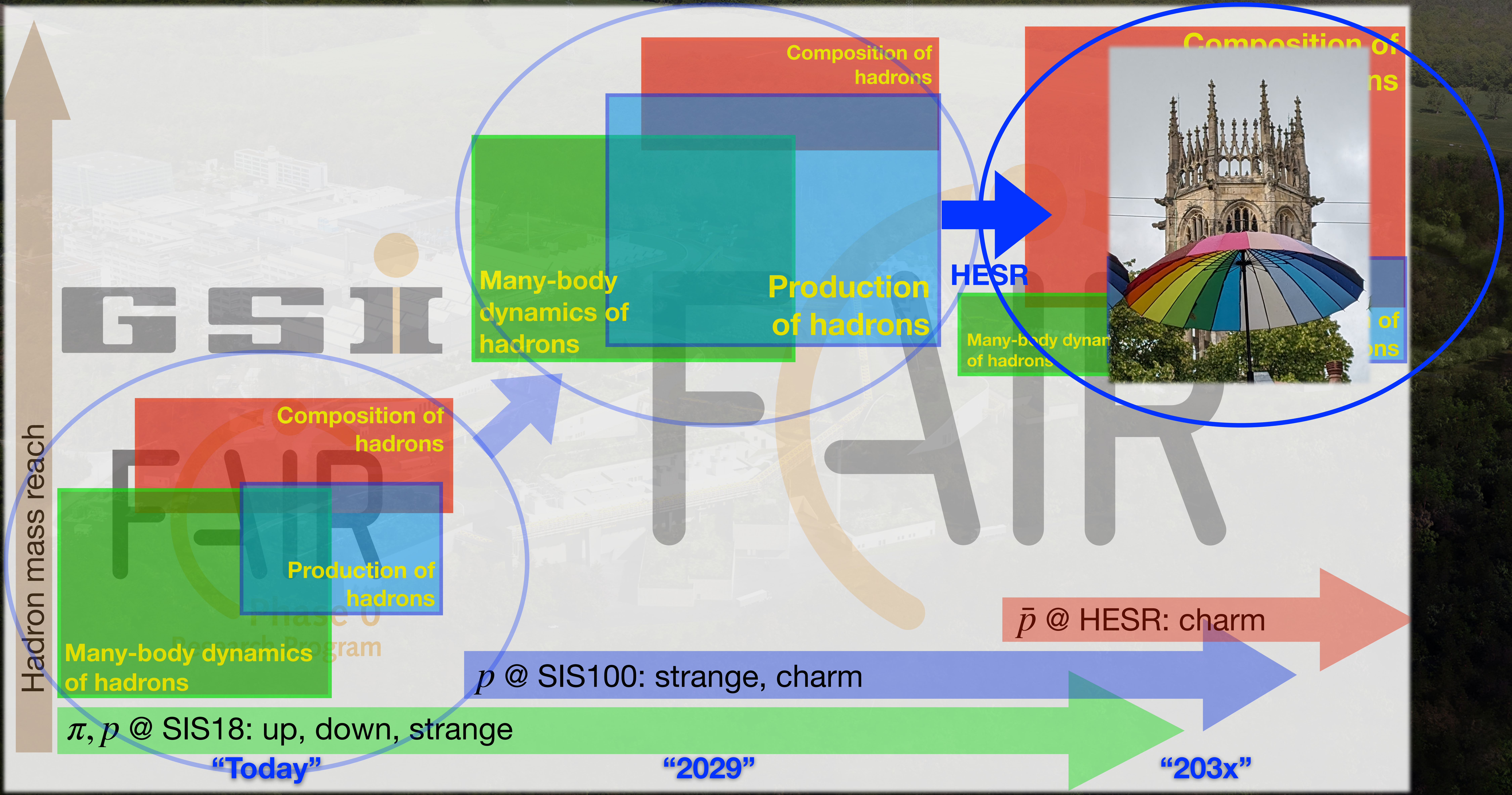
"203x"

Roadmap



Hadron mass reach
Composition of hadrons
Production of hadrons
Many-body dynamics of hadrons
Phase 0 Research Program
Composition of hadrons
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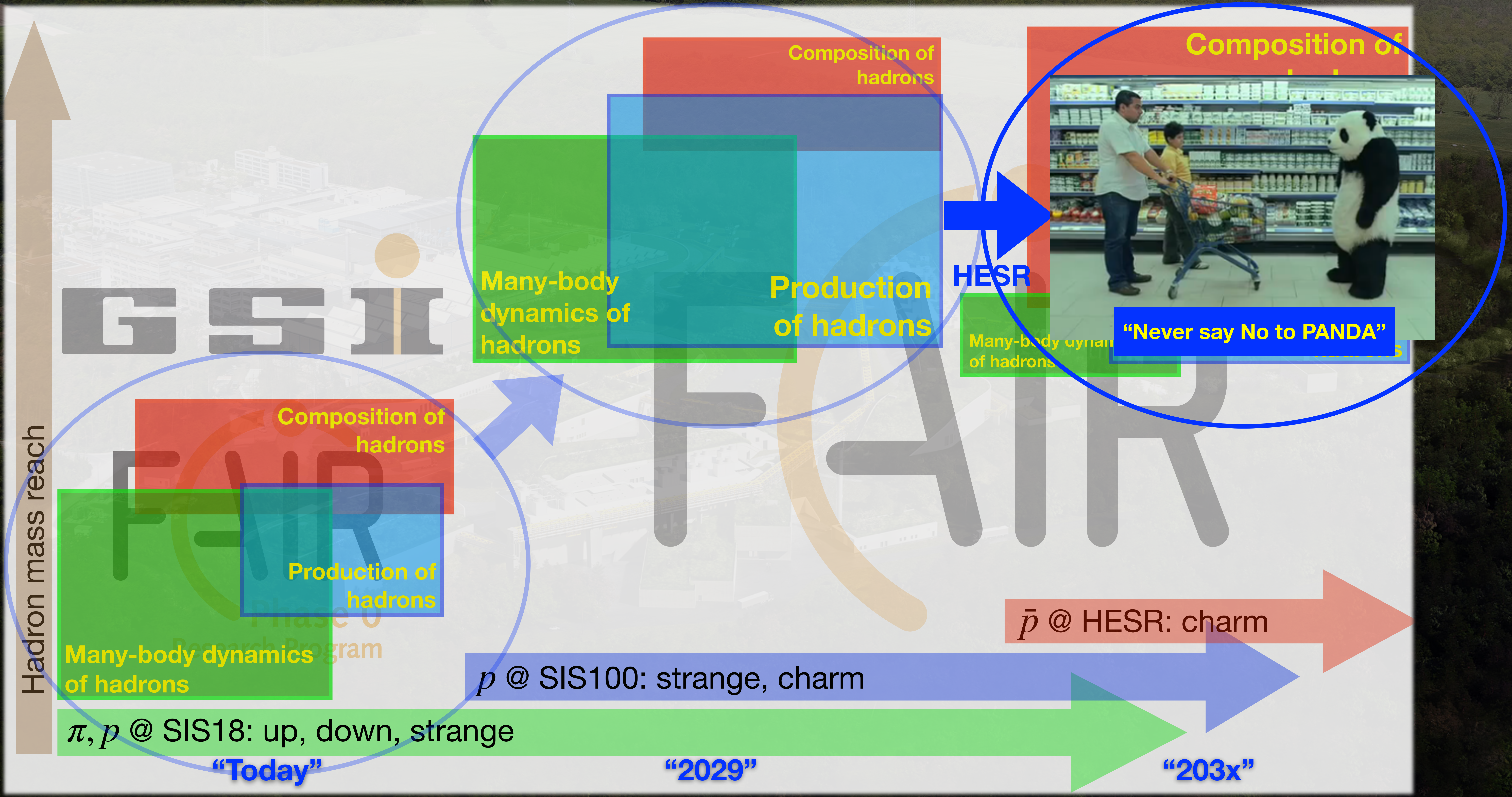
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Composition of
HESR
Many-body dynam
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"Never say No to PANDA"
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"Today"
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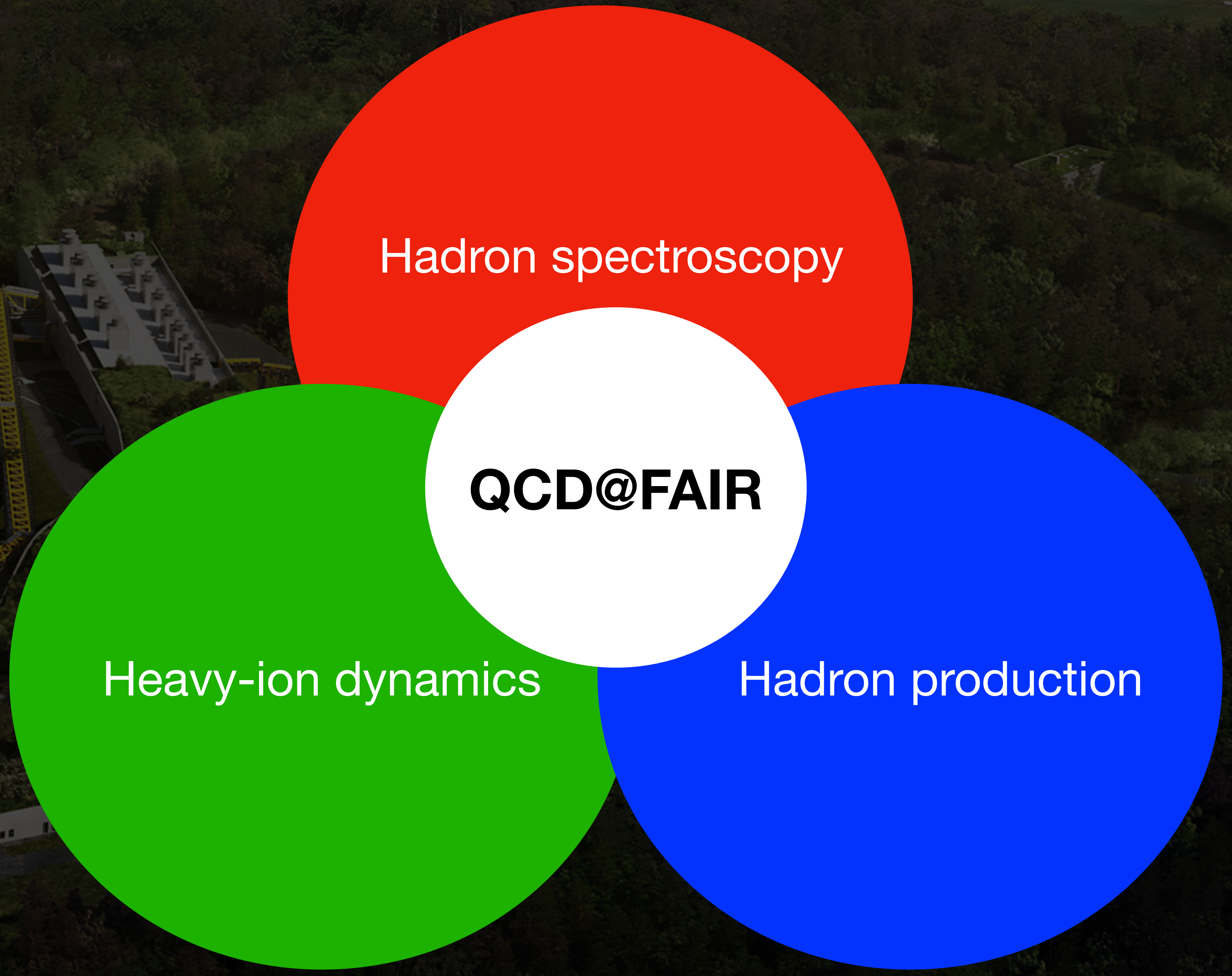
Pion- and (anti)proton-induced QCD studies at GSI/FAIR

...from SIS18 to SIS100

- Ambition: realise a long-term prosperous QCD-driven program @GSI/FAIR
- Exploit hadronic beams in the strong, “baryon-rich”, QCD regime
- Address questions in QCD connecting the interest and expertise of hadron, nuclear and heavy-ion communities
- White paper in preparation: you are welcome to join and contribute!



j.messchendorp@gsi.de

Backup material

Adapted from talk by J. Ritman

Some of the topics

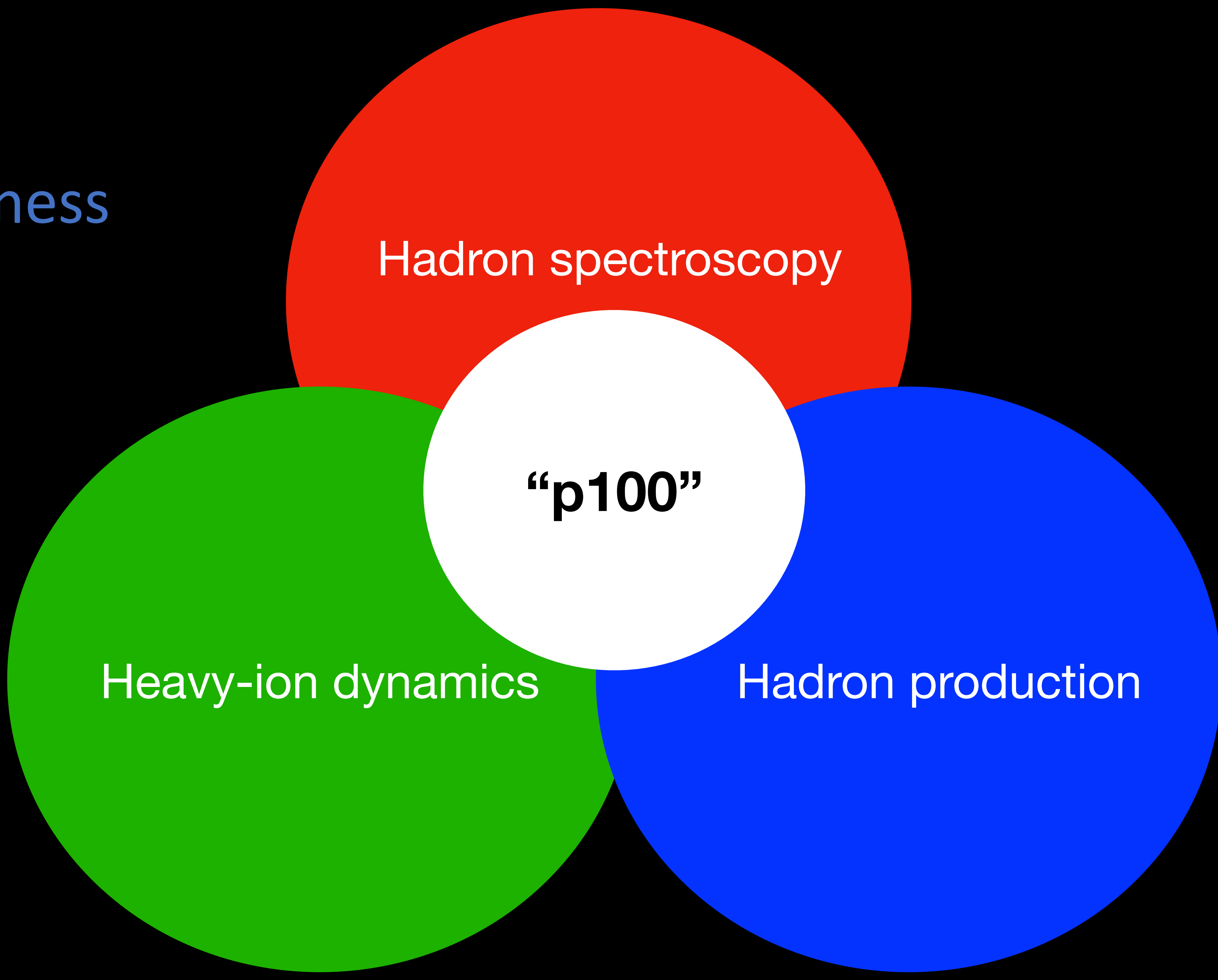
…from light, to strange up to charm!
…from quark & gluonic to hadronic up to cold matter studies!

- |S| = 2, 3 Hyperon Spectroscopy & Production
- Ξ Hyperon Production: From pp to pA & AA
- ϕ Production and K^- Rescattering
- Hyperon Interaction Studies
- Hyperon EM&Weak-Structure
- PP J/ψ Final State, Open Charm
- Exotics
- Hard Hadronic Processes: Transition GPDs
- Forward Spectators and Neutrons
- Input for pA and AA Physics, polarization

Strangeness

Charm

"Nuclei"



A comprehensive QCD program!

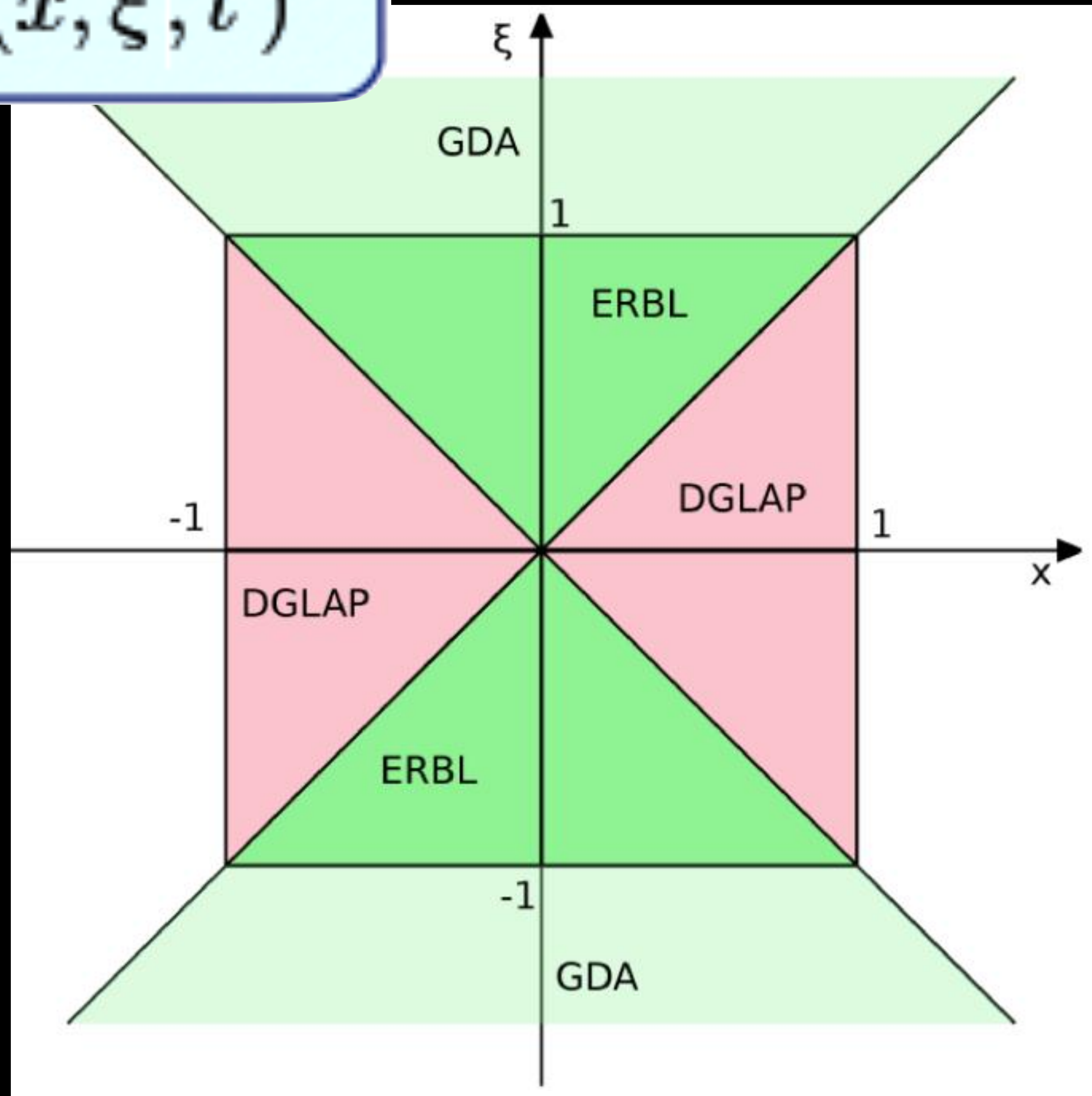
Transition GPDs

$$p + p \rightarrow p + \pi + B(n, \Delta^0, \Delta^{++})$$

- GPDs provide 3D image in the transverse coordinate and longitudinal momentum space
- At the forward scattering limit ($\xi = 0, t = 0$), GPDs become the usual PDFs; first moments of GPDs provide elastic form factor limit
- $2 \rightarrow 3$ hadronic reactions access ERBL
- Meson-nucleon scattering at large angles good probe of short-distance effects (Color Transparency -> heavy-ion studies!)

$H(x, \xi, t)$

Stefan Diehl, seminar GSI



C. Mezrag, Particles 2023, 6(1), 262-296

$|x| \geq |\xi|$ Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) region

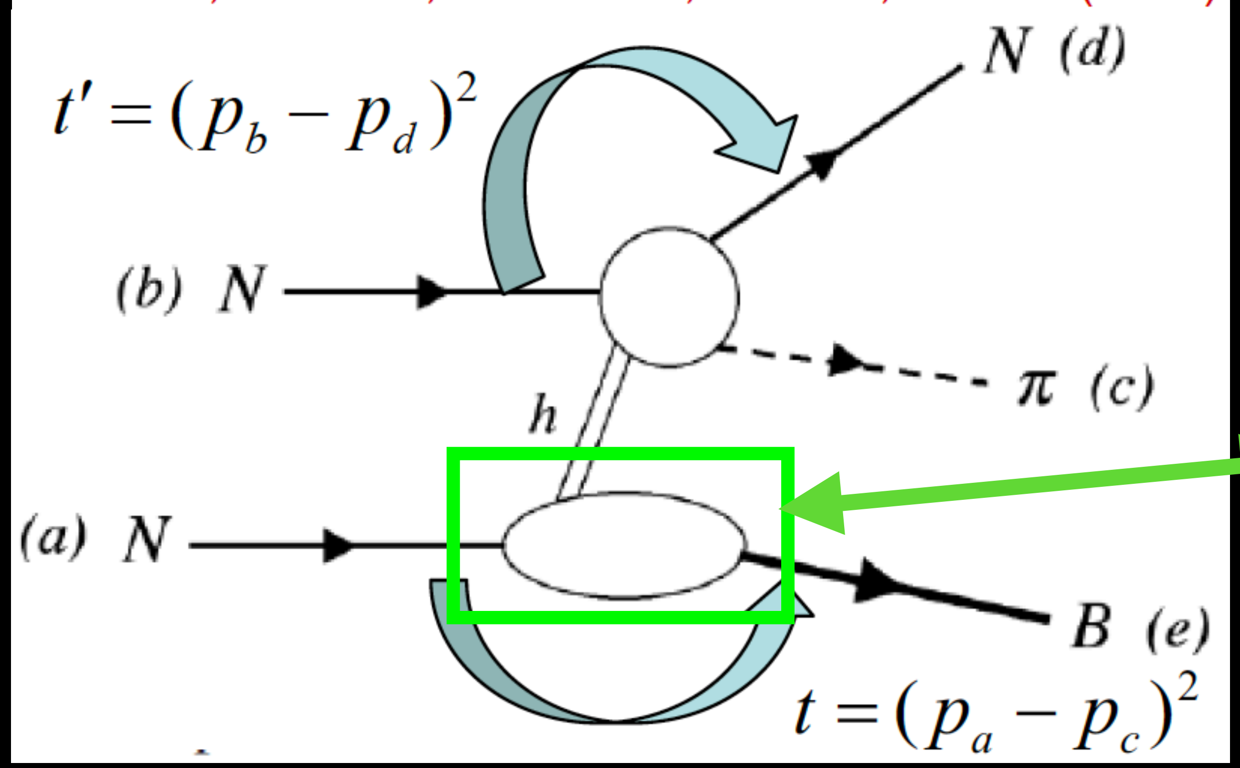
$|\xi| \geq |x|$ Efremov–Radyushkin–Brodsky–Lepage (ERBL) region

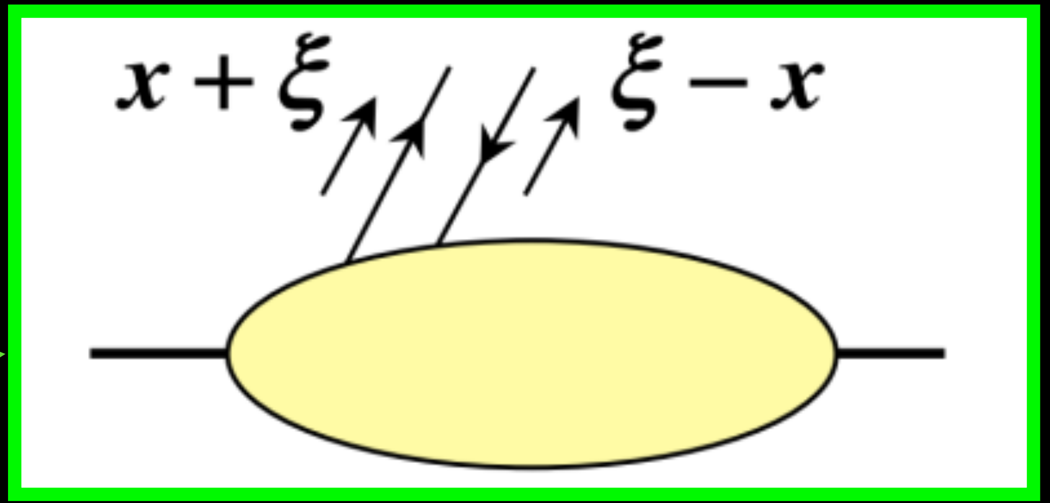
➔ **Accessibel with hadronic reactions**

$|\xi| \geq 1$ Time linke region

➔ **Annihilation reactions**

Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)





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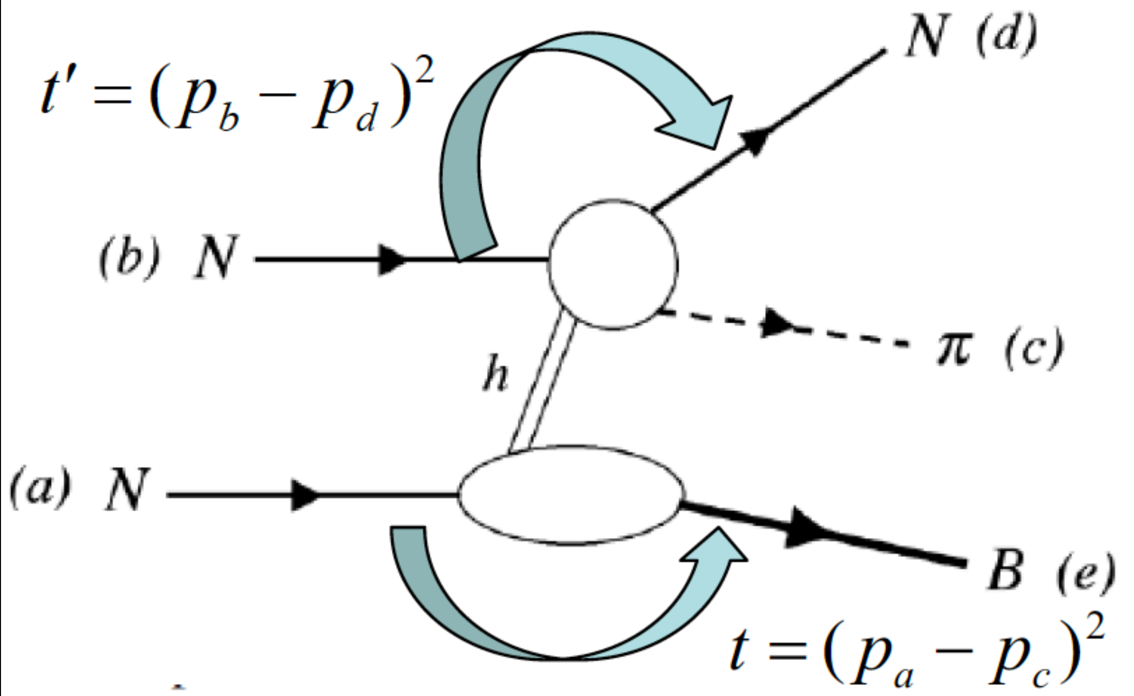
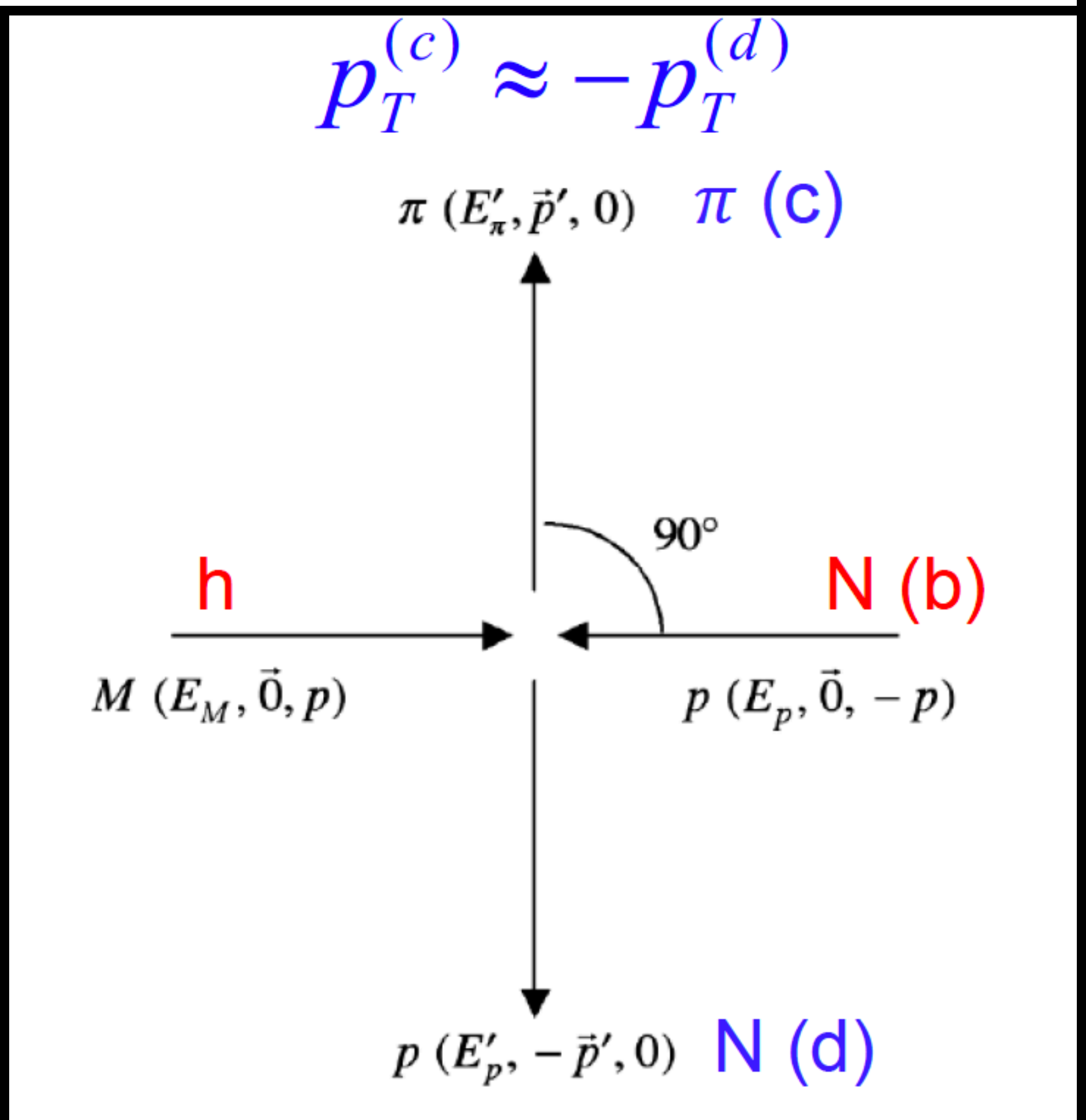
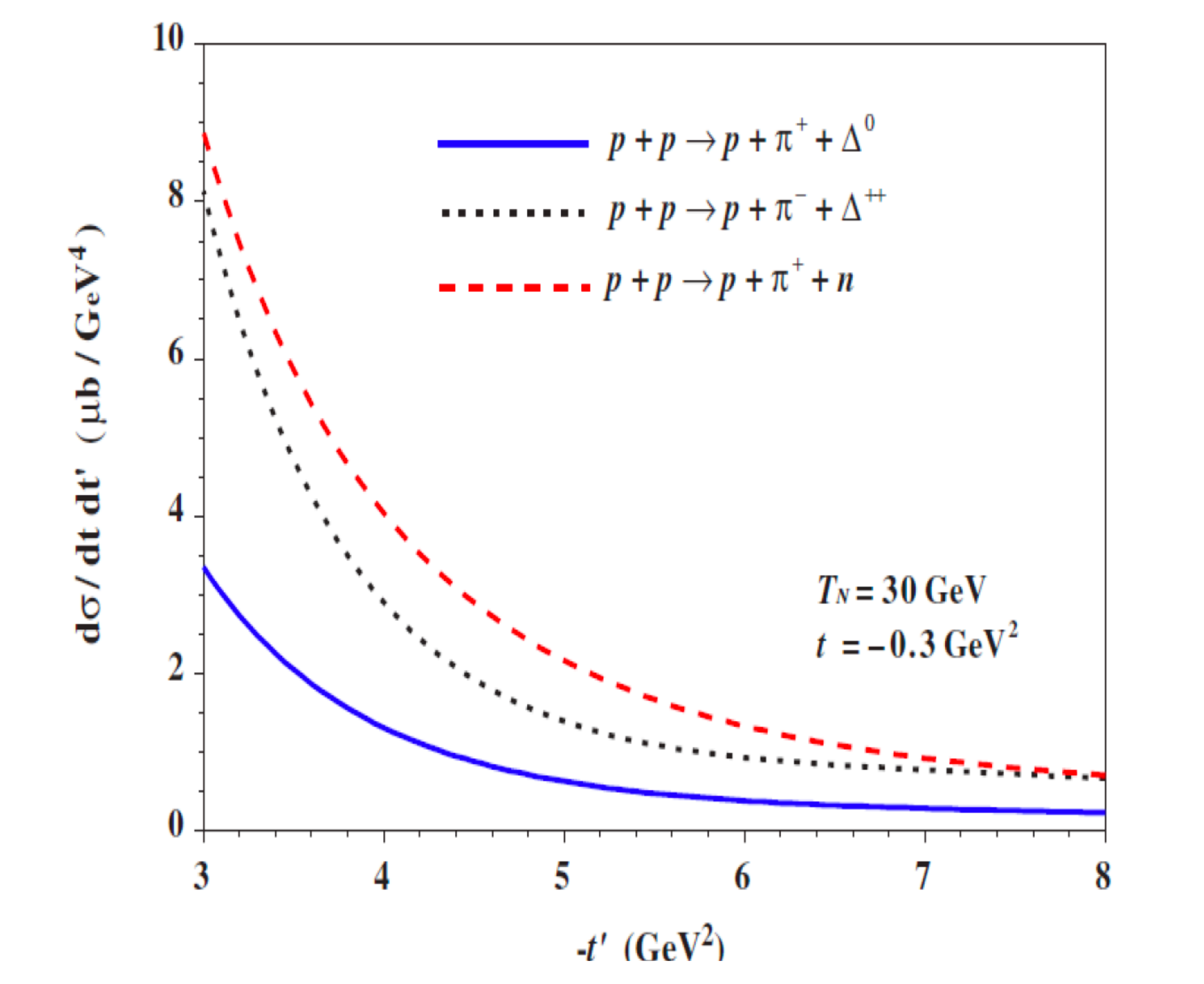
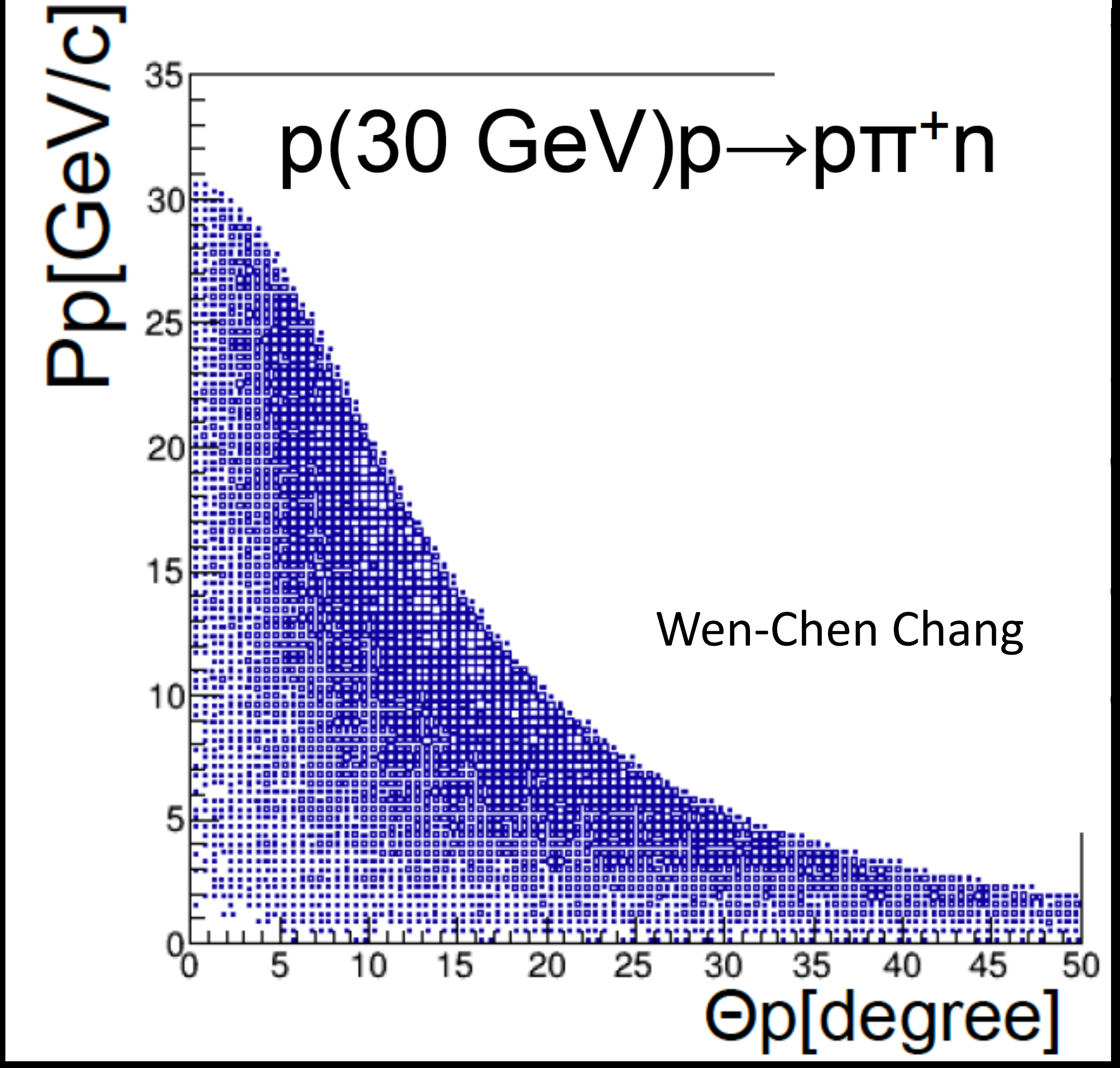
- $2 \to 3$ hadronic reactions access ERBL
- Meson-nucleon scattering at large angles good probe of short-distance effects (Color Transparency -> heavy-ion studies)
- Factorisation $p \to B$ (GPD) with $h + p \to \pi + p$ may appear at $\theta_{\pi p}$~ 90°
- High cross sections (μb) expected (meson-pole model)
- Complementary kinematics covered at CBM ($\theta_{\pi,p} < 25°$) and JPARC E16 ($\theta_{\pi,p} > 15°$)

Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)





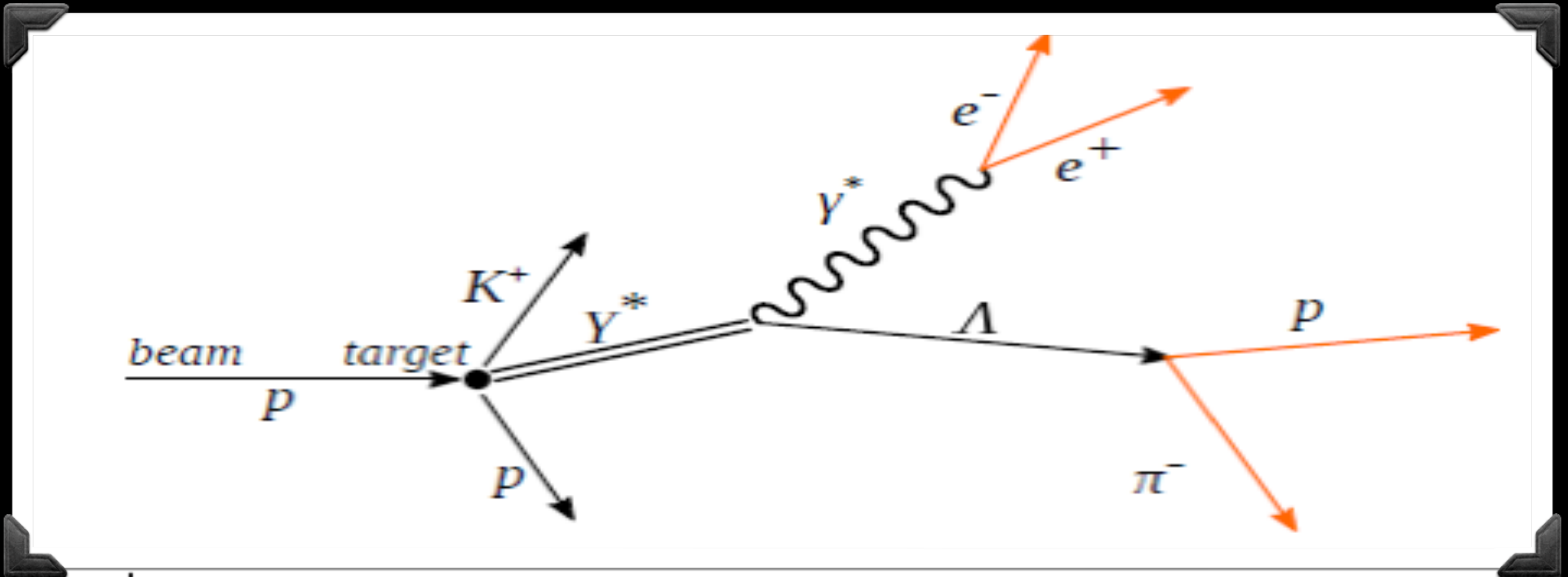


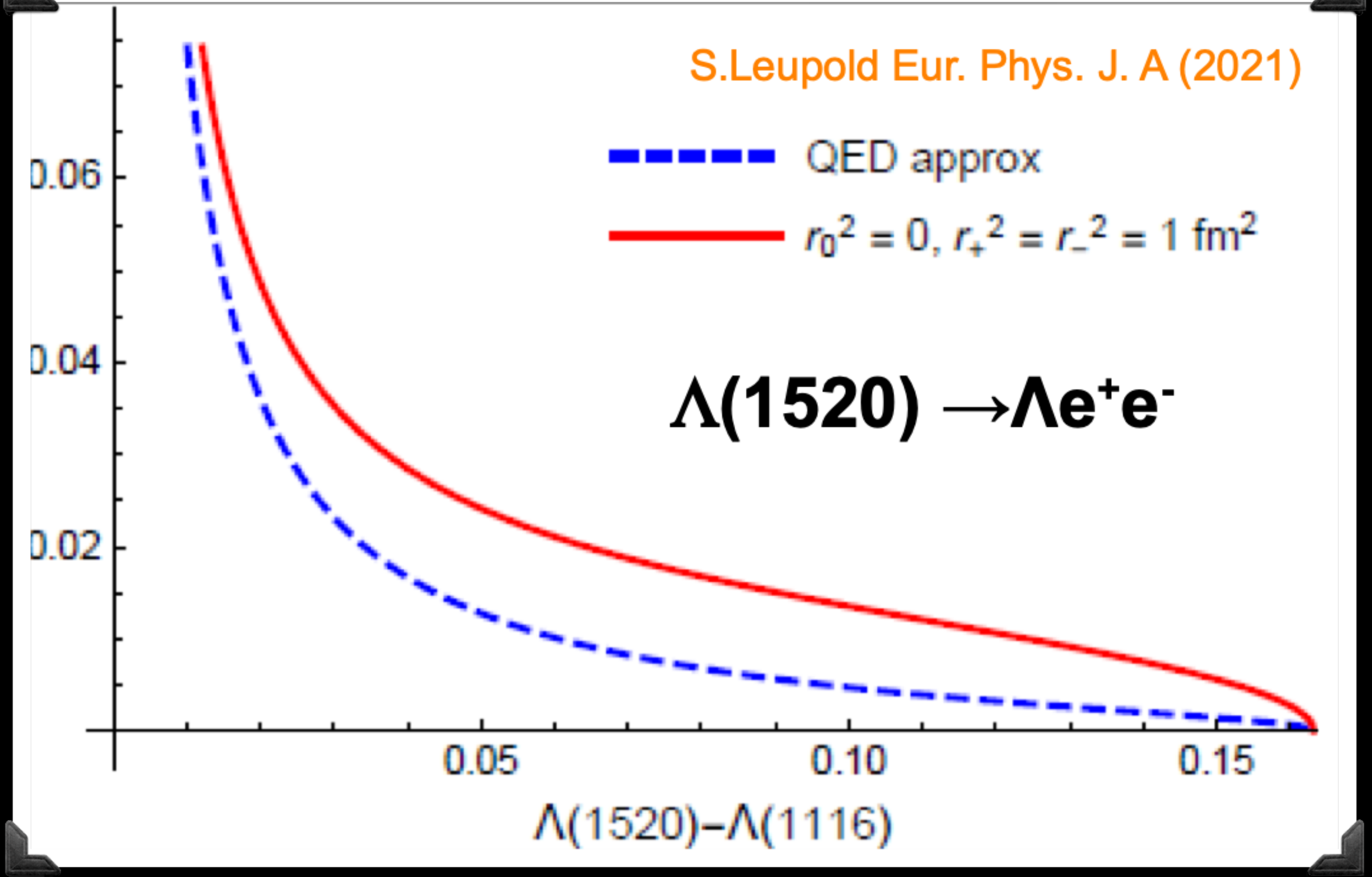


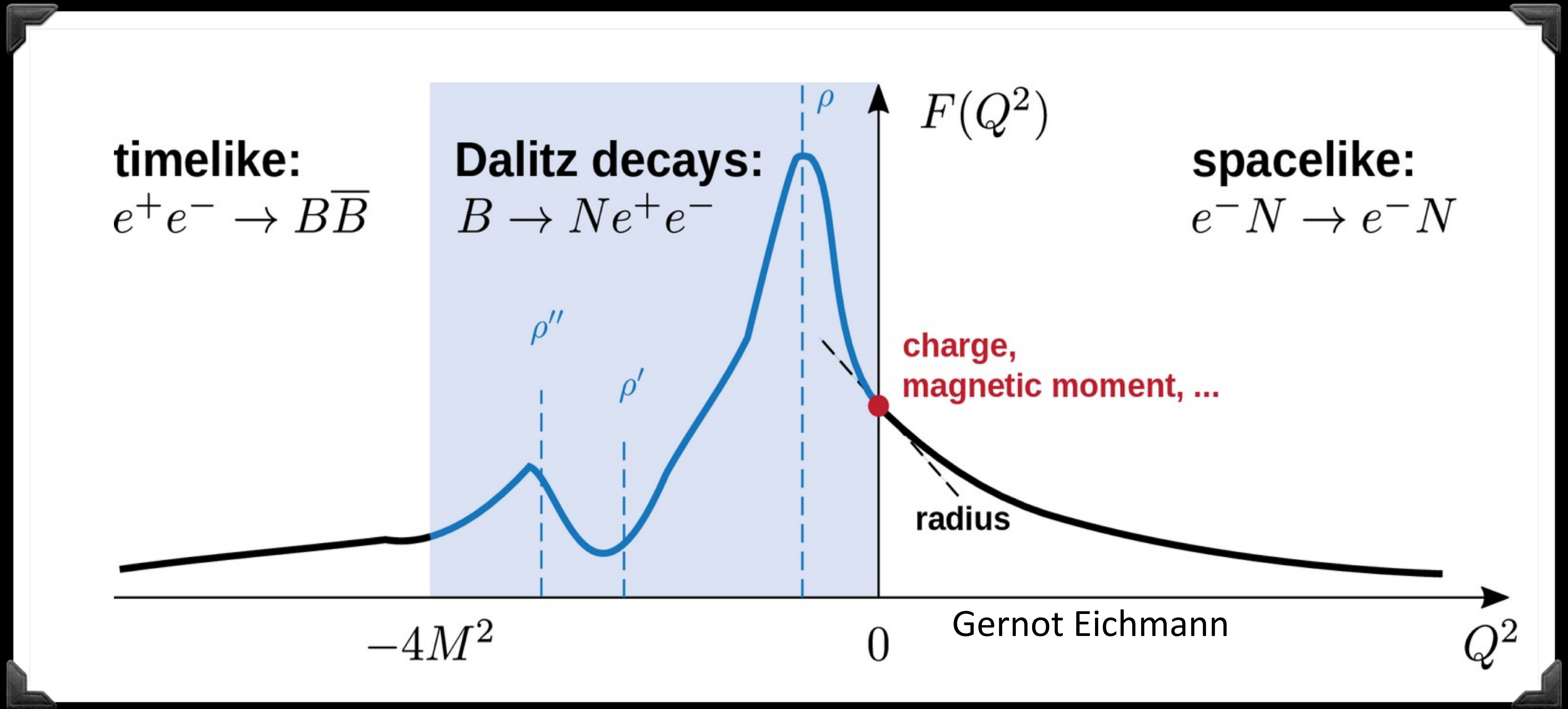
Example topics in the strange sector

Hyperon *structure* studies

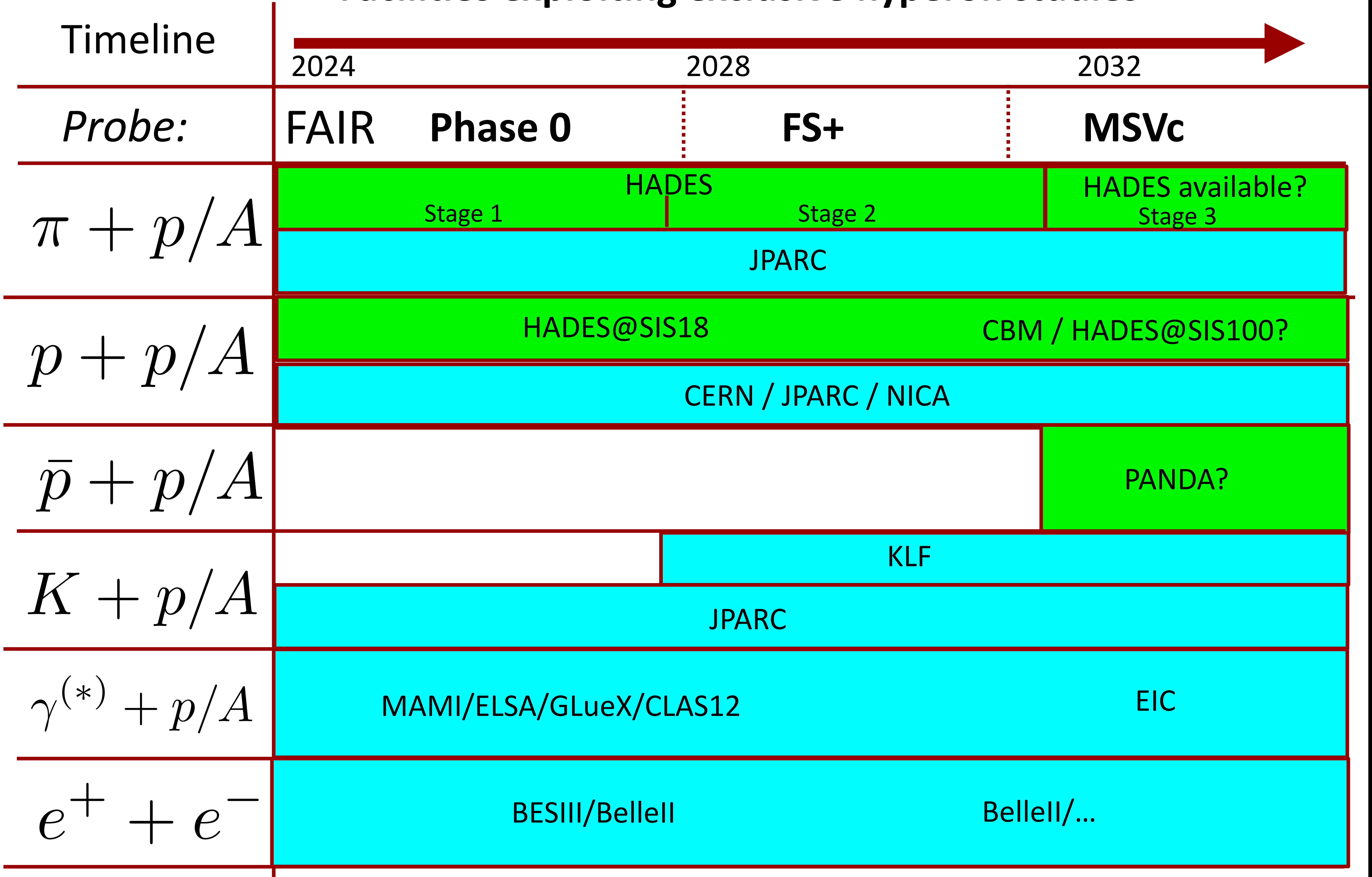
- **Electromagnetic properties of hyperons**
  - Study $Y^* \to Y\gamma^* \to Ye^+e^-$
  - Determine electric and magnetic time-like form factors
  - Decay rates sensitive to structure, q^2 dependence
  - Low branching fractions accessible at SIS100 energies with CBM
  - Study of *weak* transition form factors ($\Omega \to \Xi^* \bar{\nu}_\ell \ell^-$)
  - Many theoretical activities: Eichmann, Fischer, Leupold, Pena, …



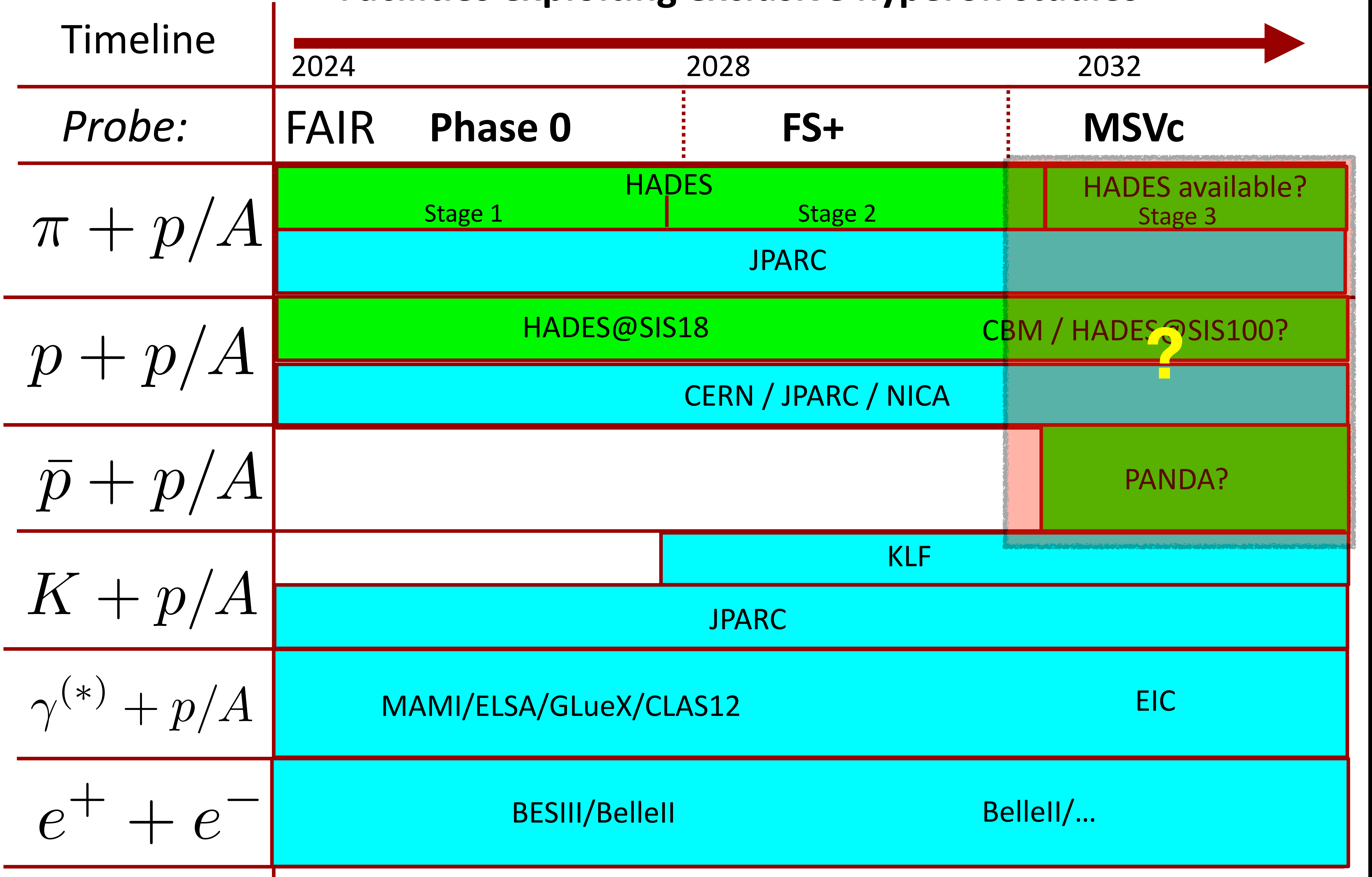




"Facilities exploiting exclusive hyperon studies"



“Facilities exploiting exclusive hyperon studies”



Conceptual long-term pion program

Conceptual long-term pion program

Years

Stage 1: "N/Δ* spectroscopy, dynamics and structure"

- *Scan* various c.m. energies at *moderate luminosities (~10^5 - $10^6 \pi$/spill)*
- Physics: precision data in S=0, e.g. $\pi N \rightarrow \pi\pi N/\eta N/\omega N/KY$; eTFF with N^*/Δ; Cold matter studies
- Energies range $\sqrt{s} = 1.4 - 2.0\,\mathrm{GeV}$ (including 2014 & 2025 runs)

Stage 2: "Y(|S|=1) spectroscopy and dynamics"

- *Selected* c.m. energies at *high luminosities (~10^6 - 10^7 π/spill)*
- Physics: precision data in |S|=1 sector with hadronic final states; radiative transition studies (γ/e^+e^-) of (excited) hyperons
- Energies points selected within $\sqrt{s} = 1.8 - 2.0\,\mathrm{GeV}$

Stage 3: "Y(|S|=1) structure"

- Precision di-lepton spectroscopy with high q^2 sensitivity in Y* e.m. decays