



# ExtreMe Matter Institute EMMI

EMMI Workshop

## Probing Dense Baryonic Matter with Hadrons II: FAIR Phase-0

February 19-21, 2024

SB1 Lecture Hall, GSI, Darmstadt, Germany

### *Perspectives for pion-induced physics at GSI/FAIR*

*...with a bias on exclusive measurements*



# HADES in a nutshell

... *versatile* experimental setup!

**Outstanding** in dilepton spectrometry

Excellent tracking & PID capabilities

**Modular** at forward angles

Additional **photon** detection

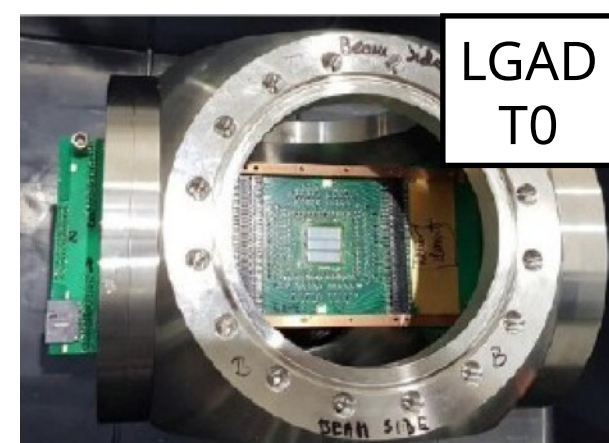
Good angular **coverage**

Designed for *various* SIS18 beams

...including **pions**!



CBM RICH

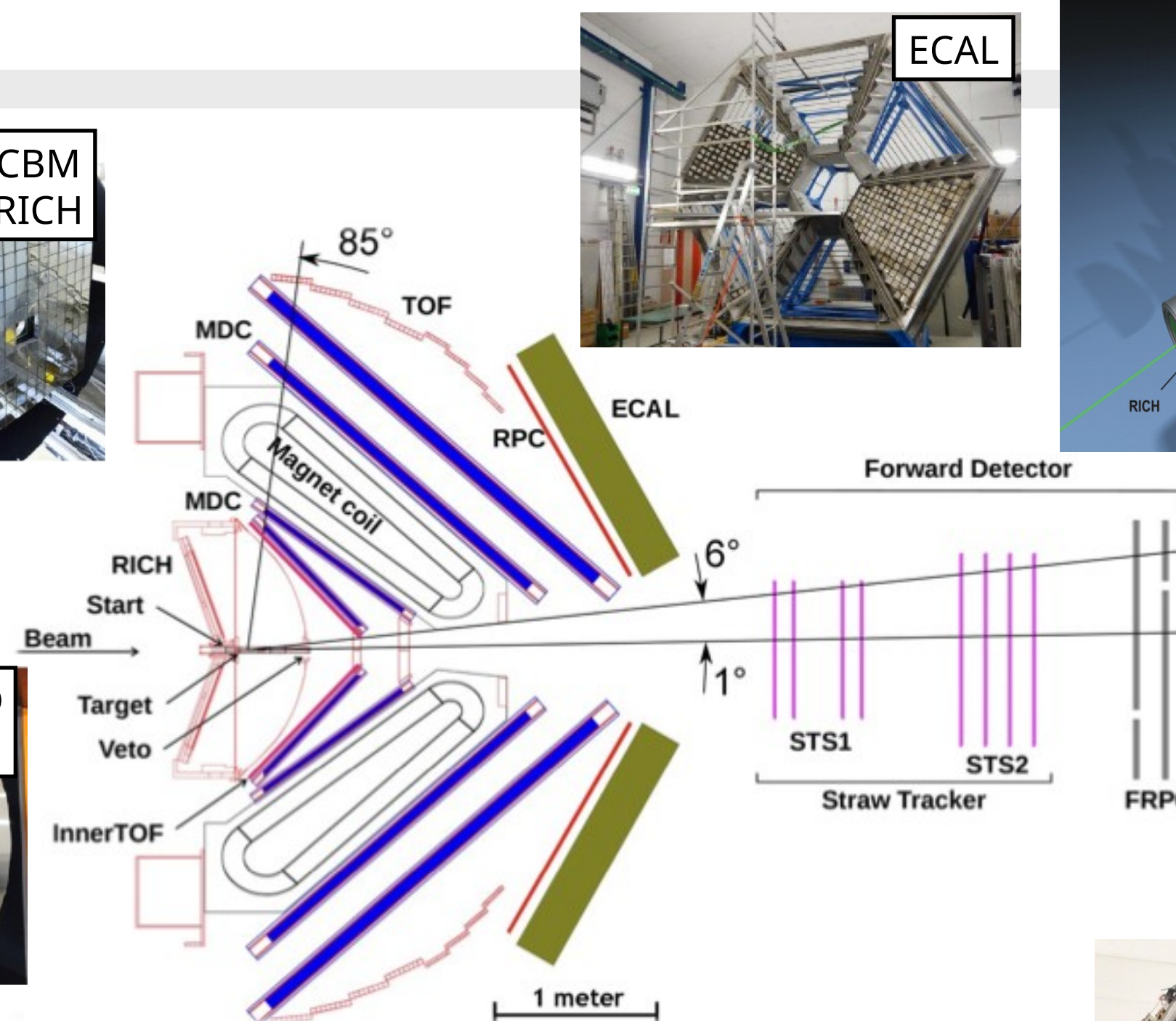


LGAD TO



SIPMs

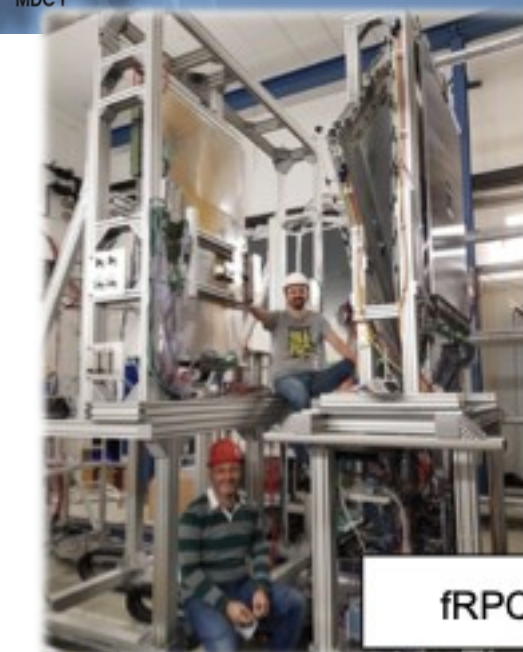
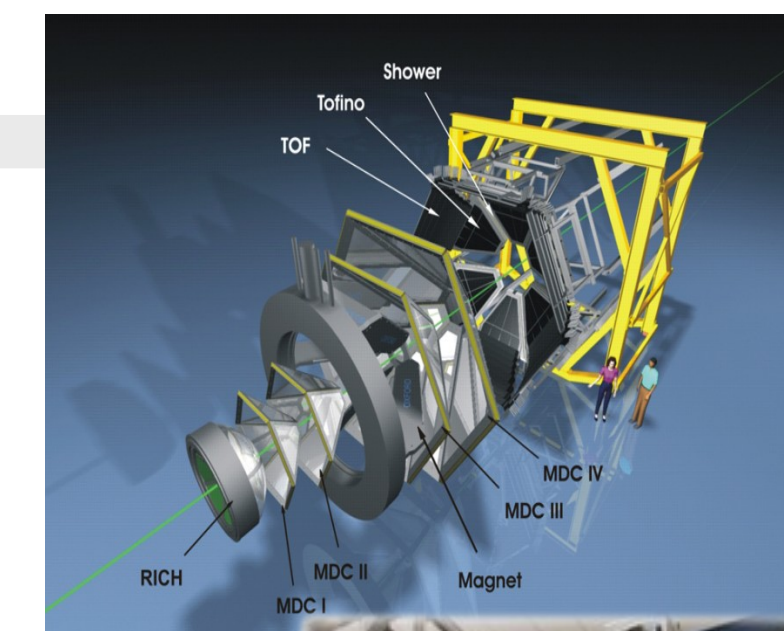
InnerTOF



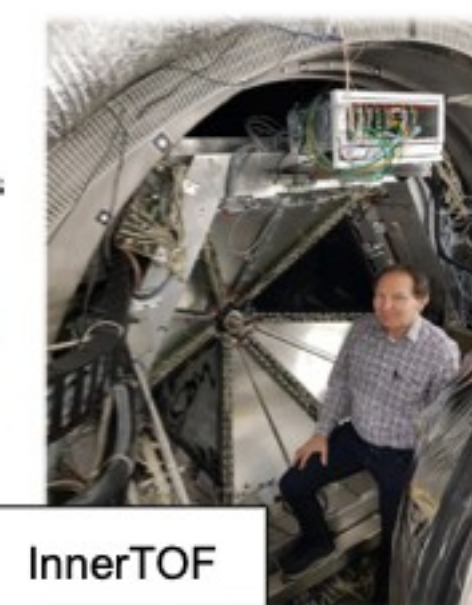
1 meter



ECAL



fRPC



STS1



STS2



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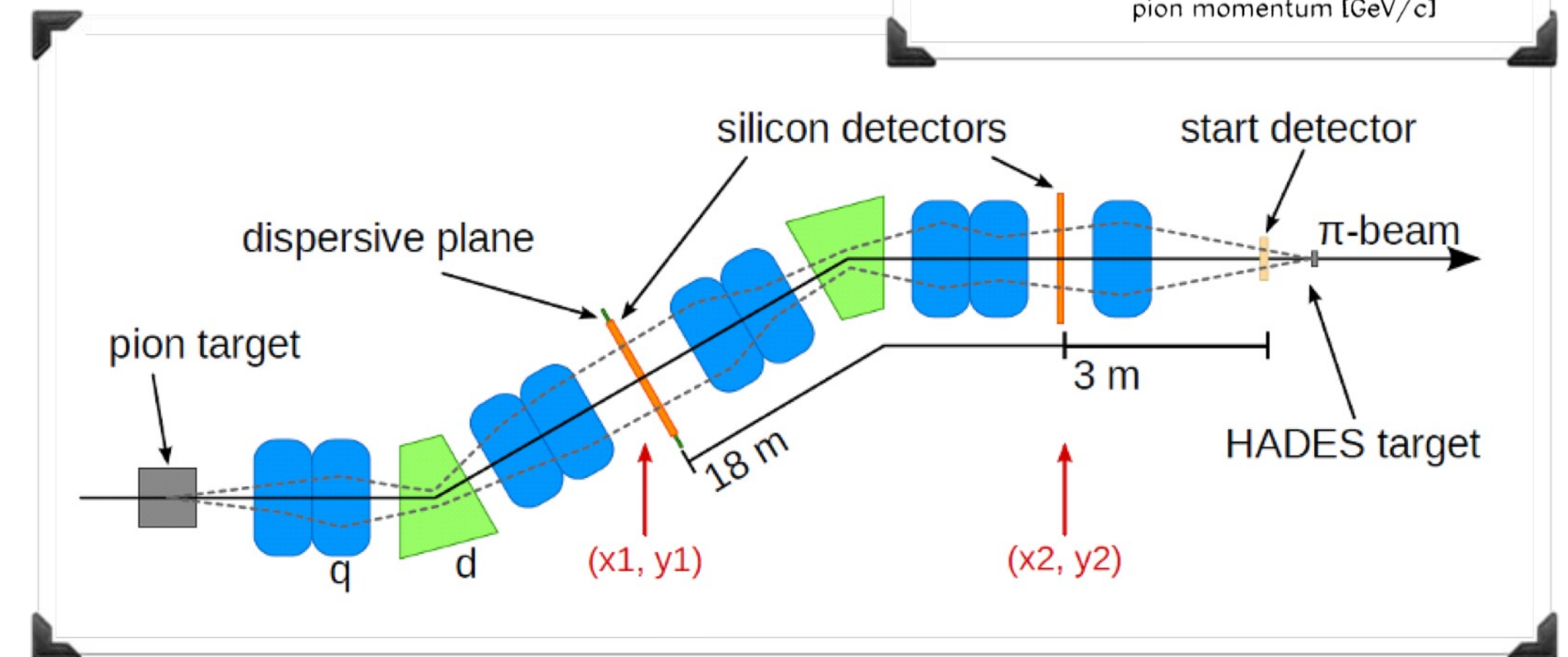
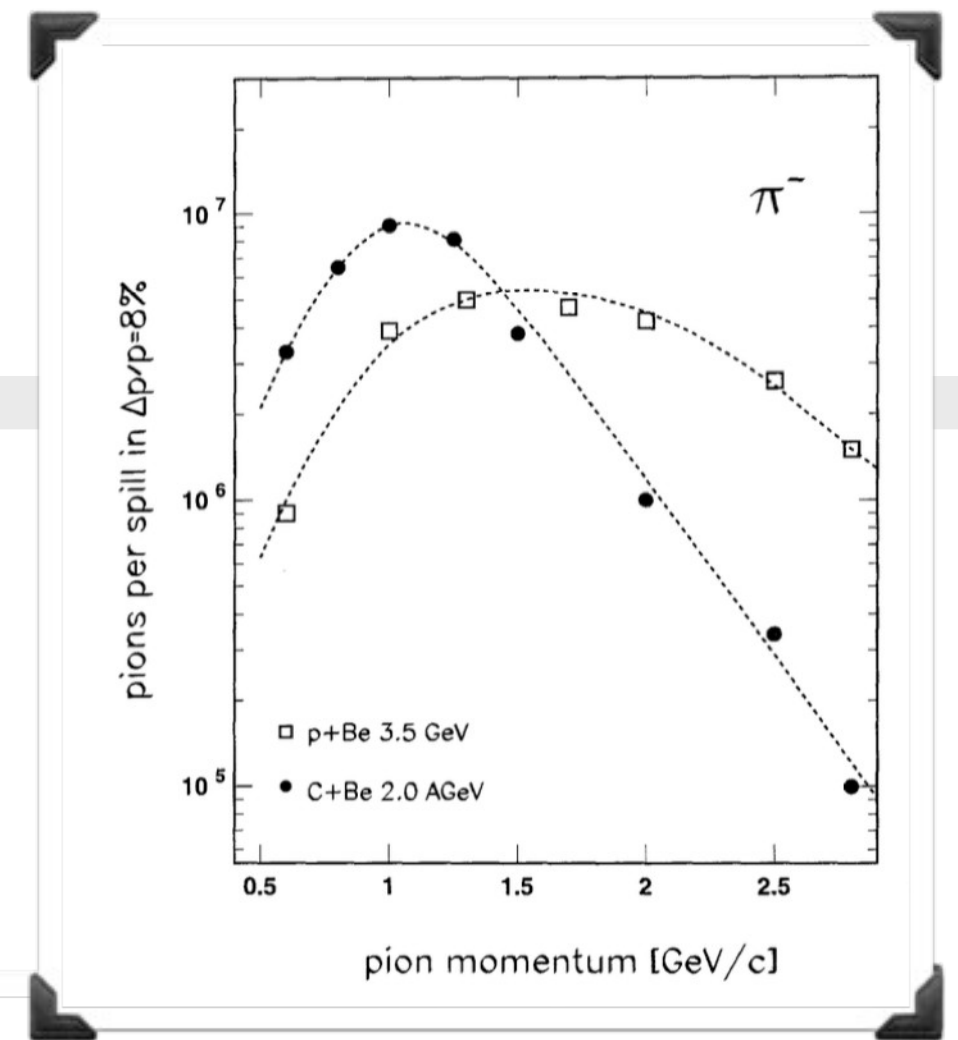
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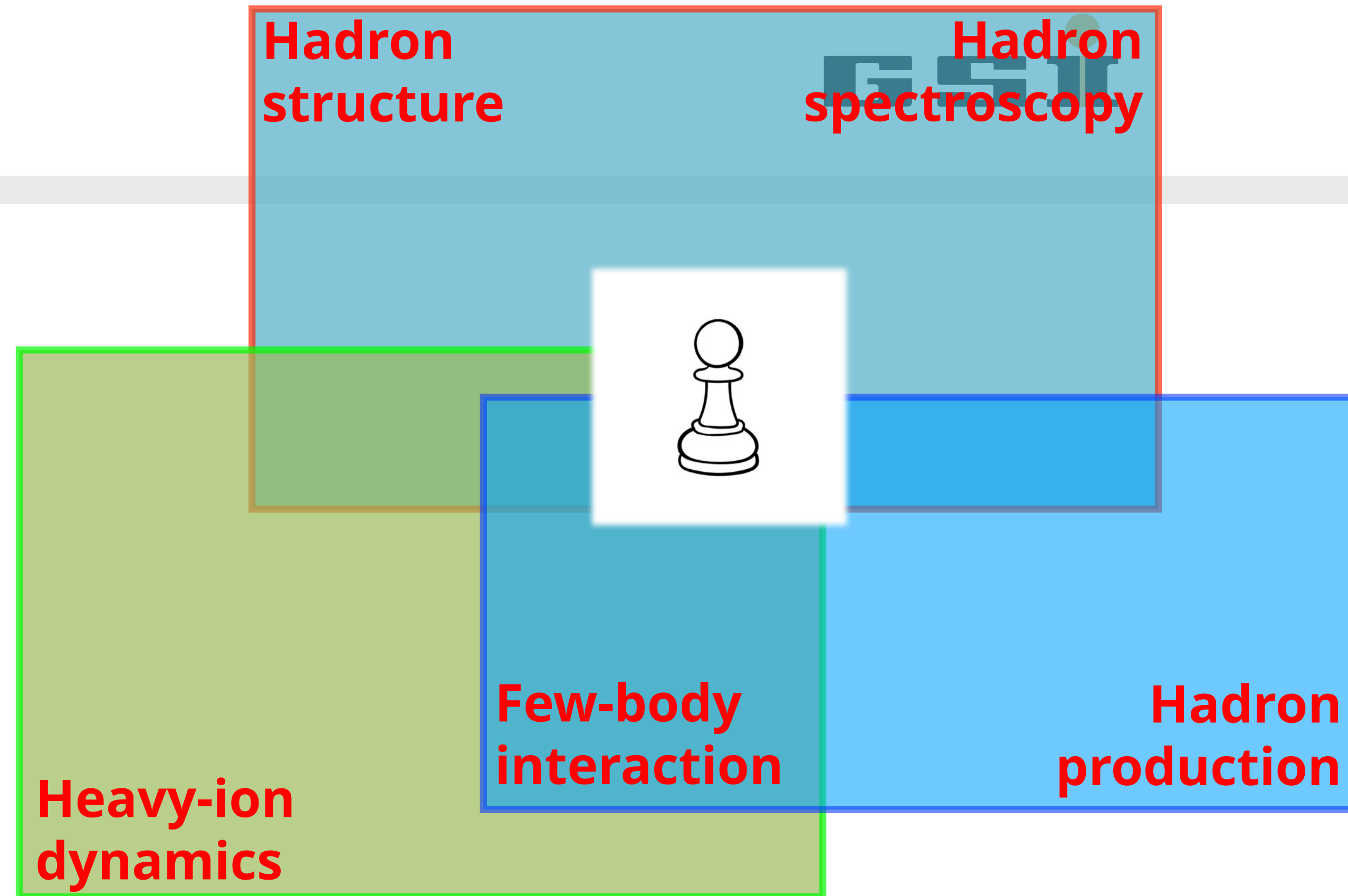
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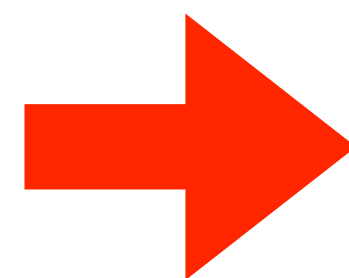
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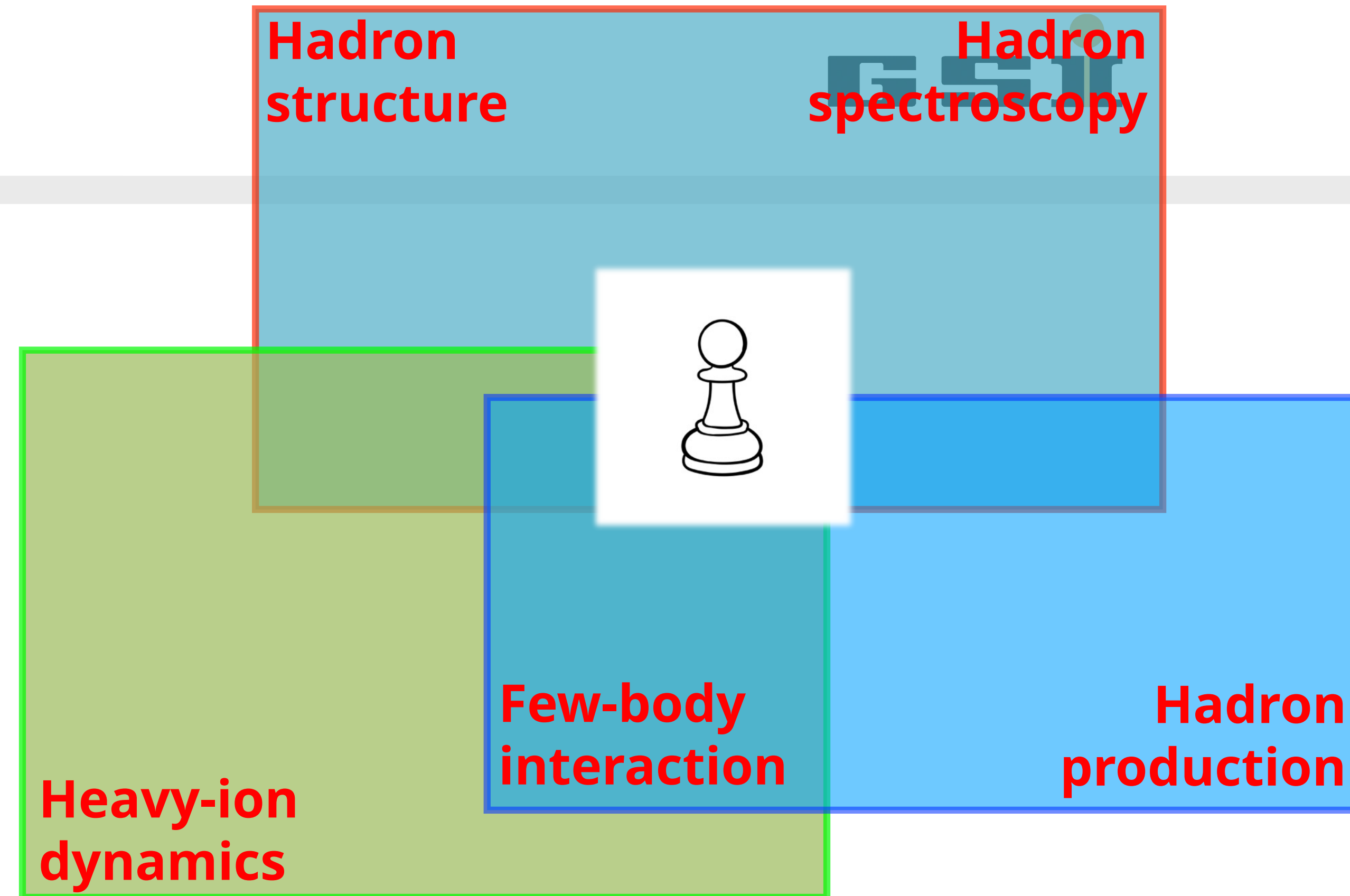
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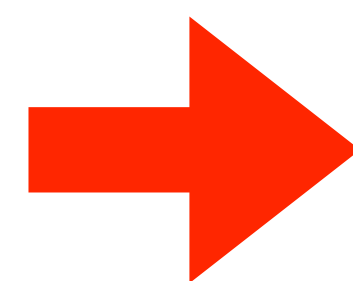
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Enabling a rich **QCD** program integrating heavy-ion, hadron (and nuclear) physics



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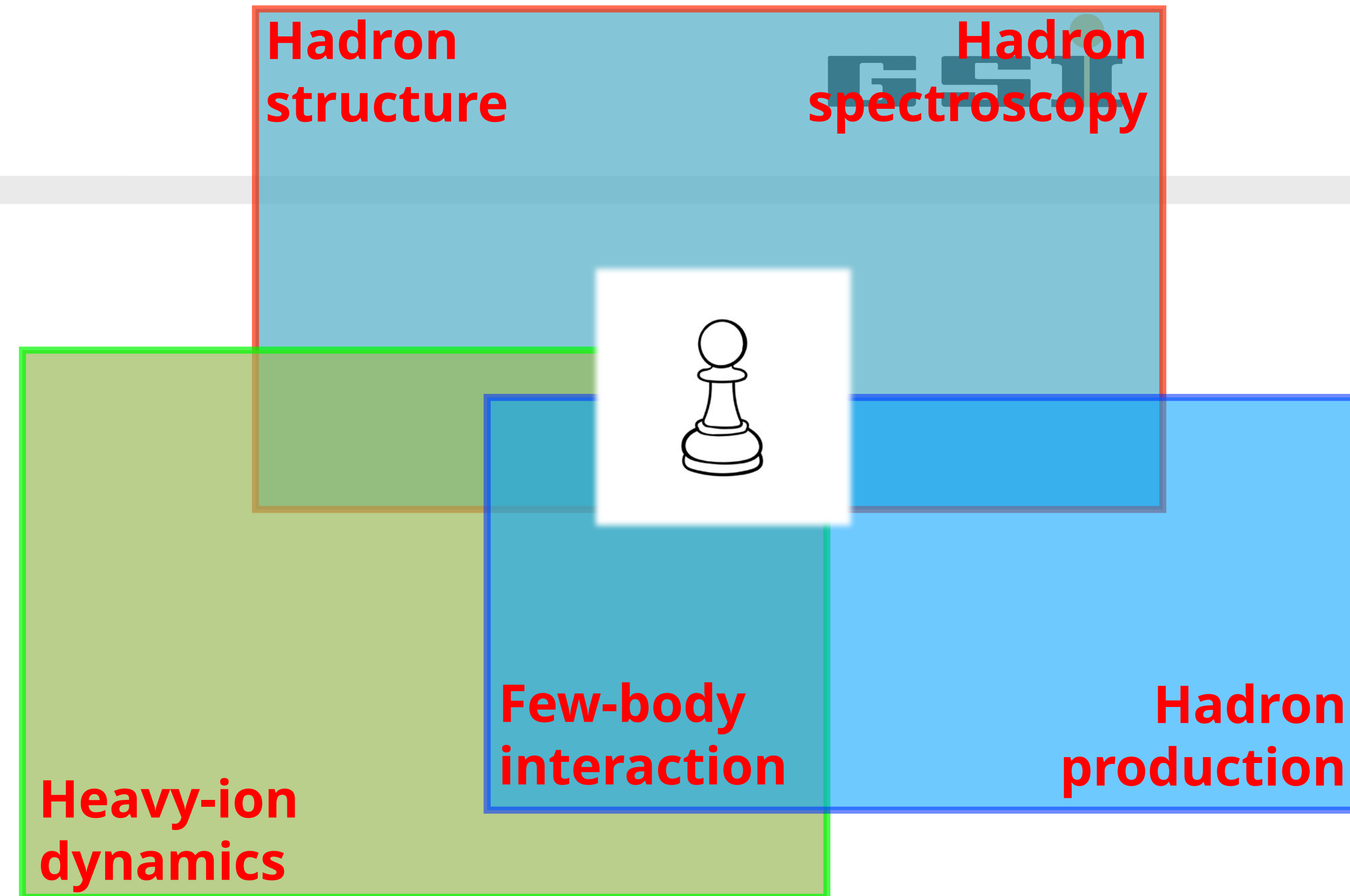
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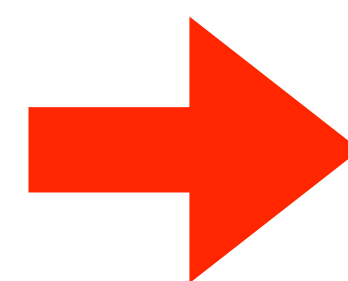
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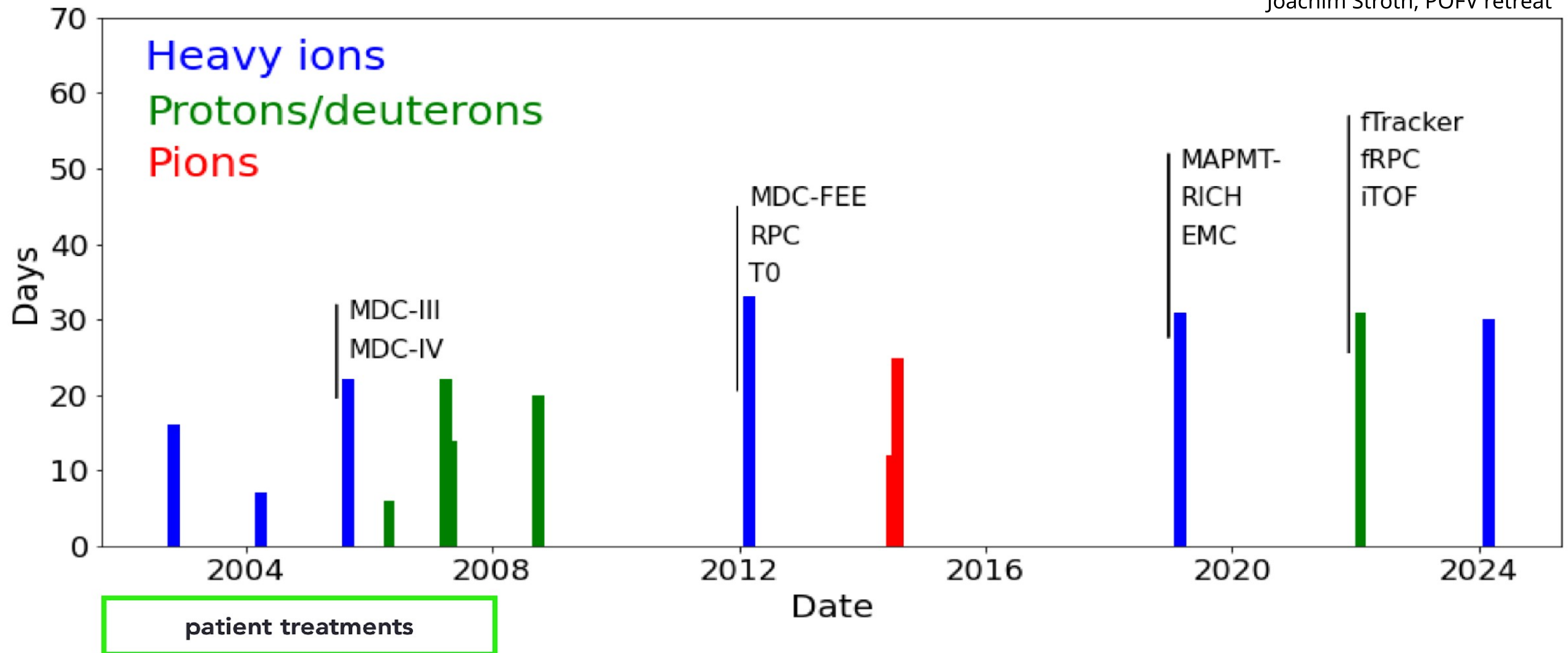
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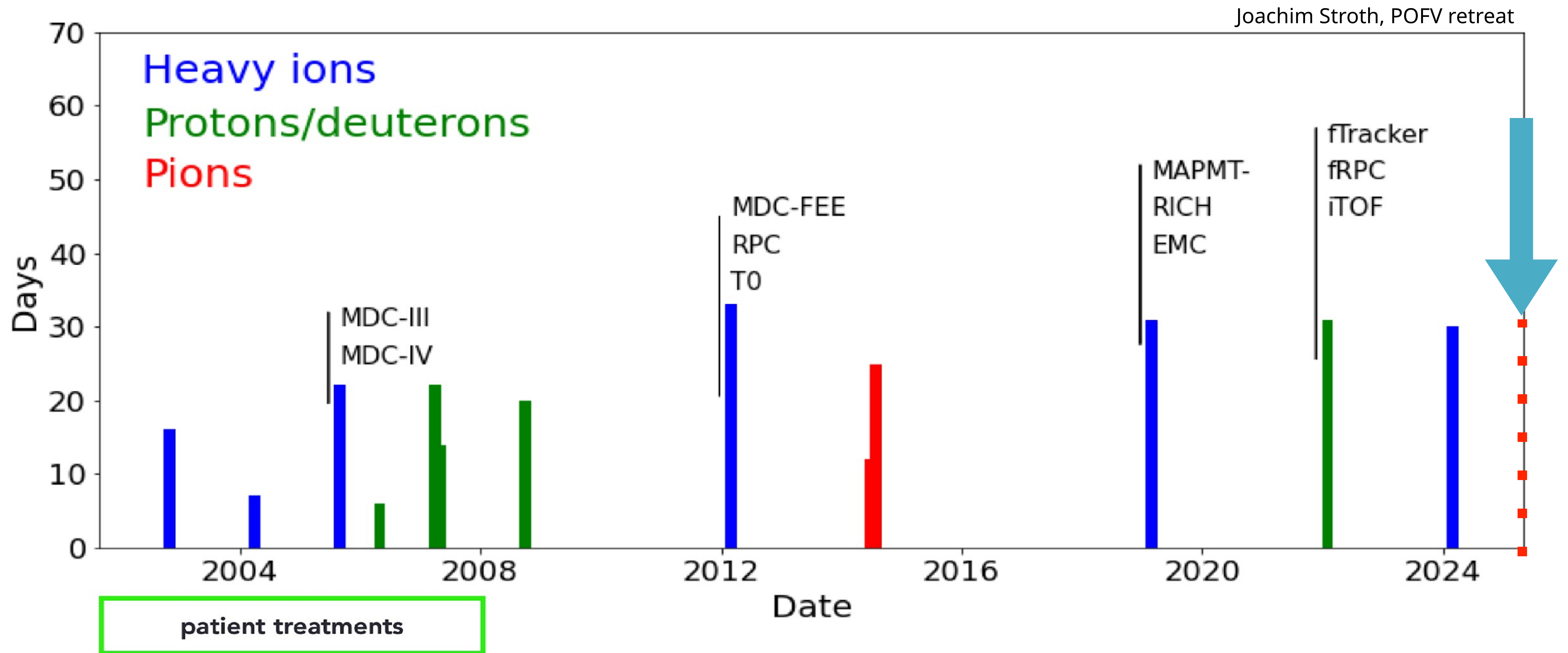
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# HADES beamtimes

Joachim Stroth, POFV retreat



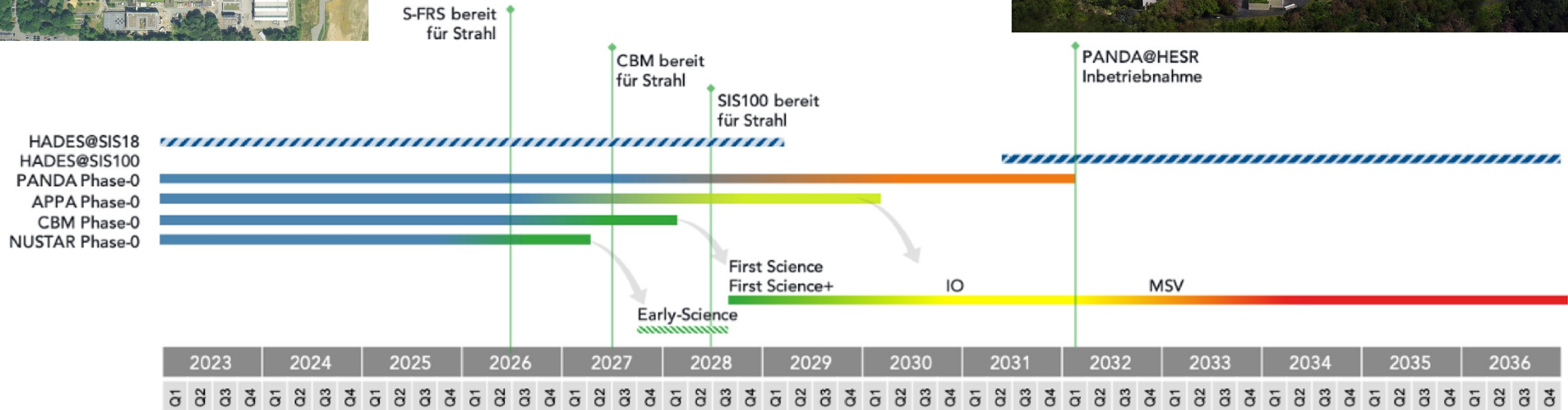
# HADES beamtimes





# Perspectives

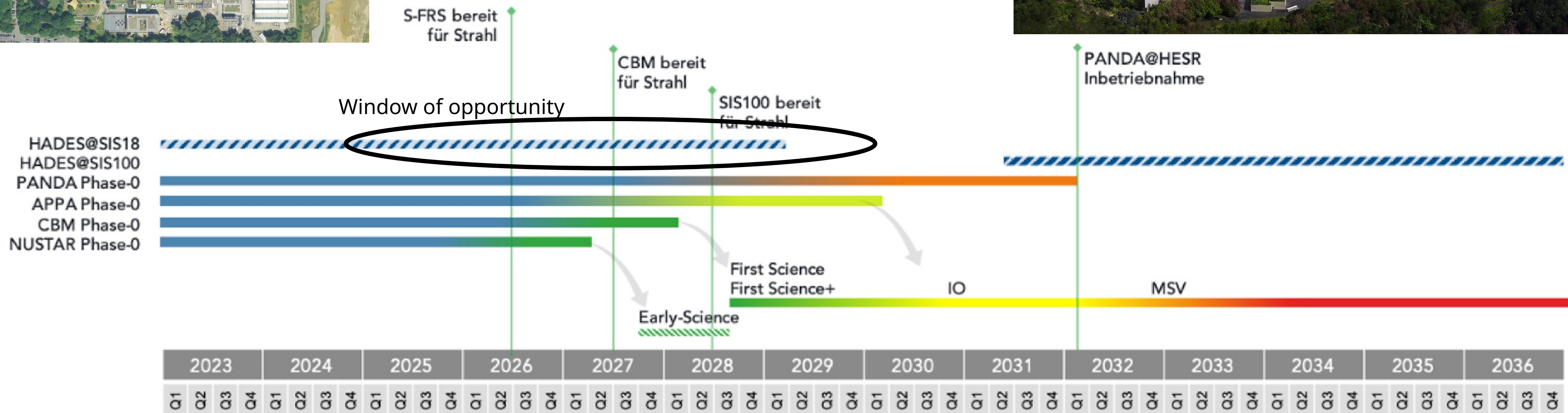
## ... from SIS18 towards SIS100





# Perspectives

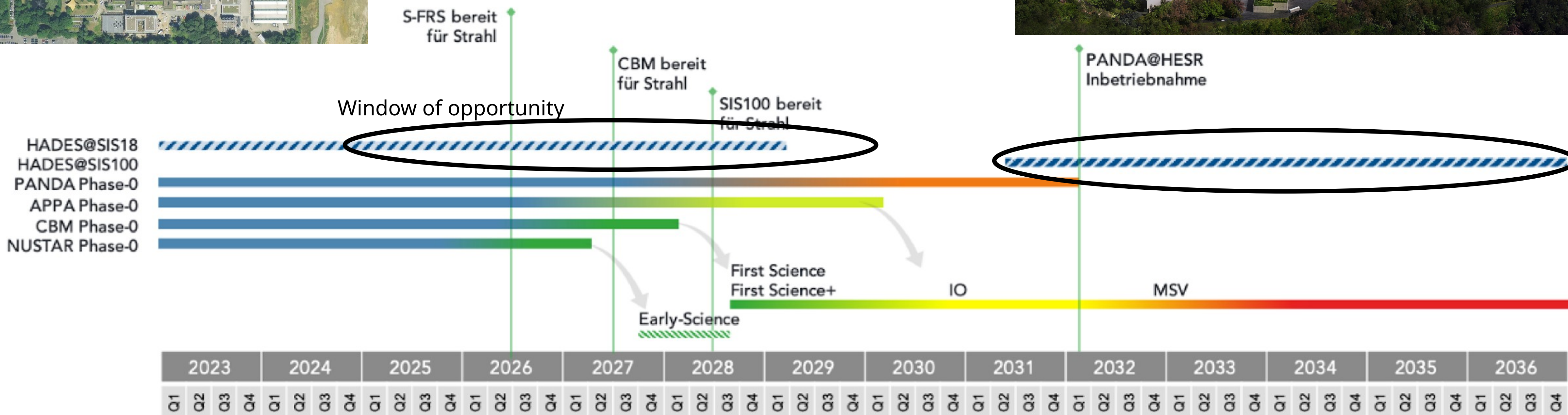
## ... from SIS18 towards SIS100





# Perspectives

... from SIS18 towards SIS100





# This talk...

Perspectives of physics with pion beams exploiting *exclusive* reactions

Emphasis on *cold matter* applications —> Beatrice Ramstein

Note: *synergetic* topics bringing lots of *cross fertilisation!*





# Case study: “exclusive reactions”

*... to stay close to my field of interest*

## Why “exclusive reactions”?

Provide “**elementary**” **input** for heavy-ion studies

Study the **couplings** of baryons with mesons

Study the **internal properties** of short and long-lived hadrons

Study hadron-hadron interactions using “**elementary femtoscopy**”

Overall philosophy: **stay close to QCD** and avoid phenomenology





# Case study: “exclusive reactions”

*... to stay close to my field of interest*

**A successful campaign depends on...**

- Choosing **controllable reactions** avoiding ambiguities in interpretation!
- At least **complementary** to other data/experiments
- Excellent  **$S/\sqrt{S+B}$**  preferably with high S/B
- Kinematically **complete** measurements
- Sufficient **phase space coverage** (partial wave analysis)
- **Versatile detector** with *“the right probe to do the right job”*

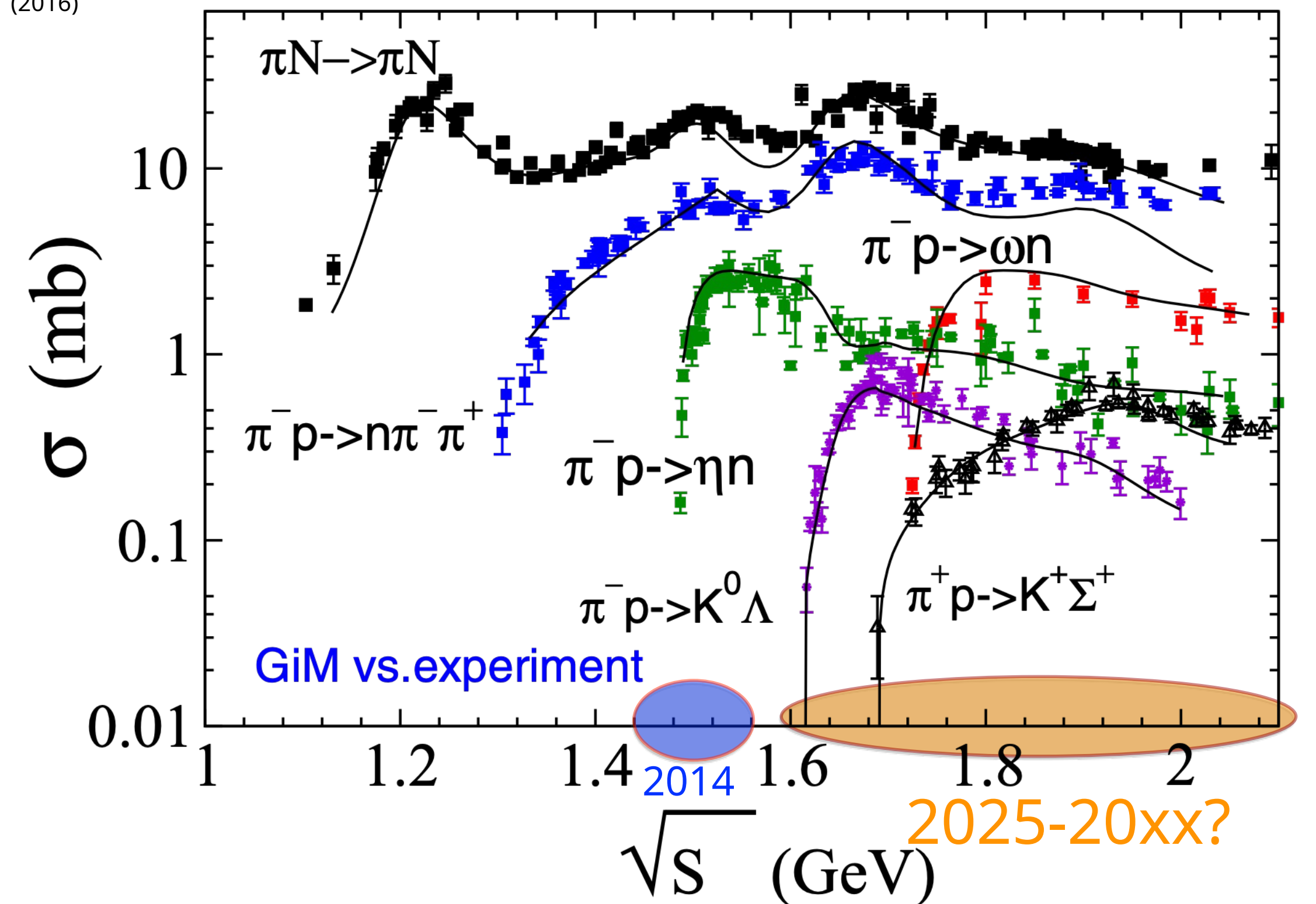




# Pion beam facility at SIS18

... *its conceptual features*

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



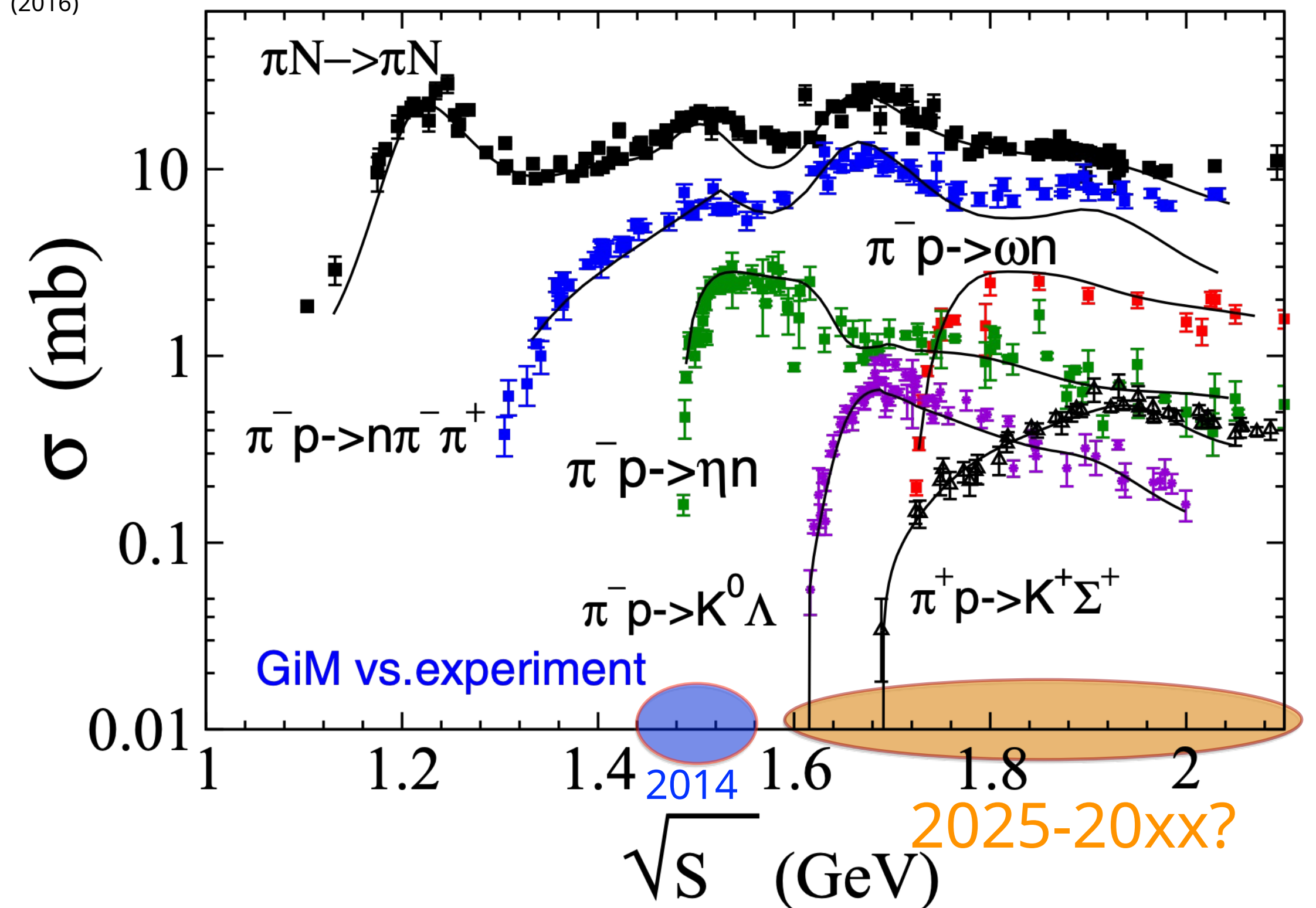


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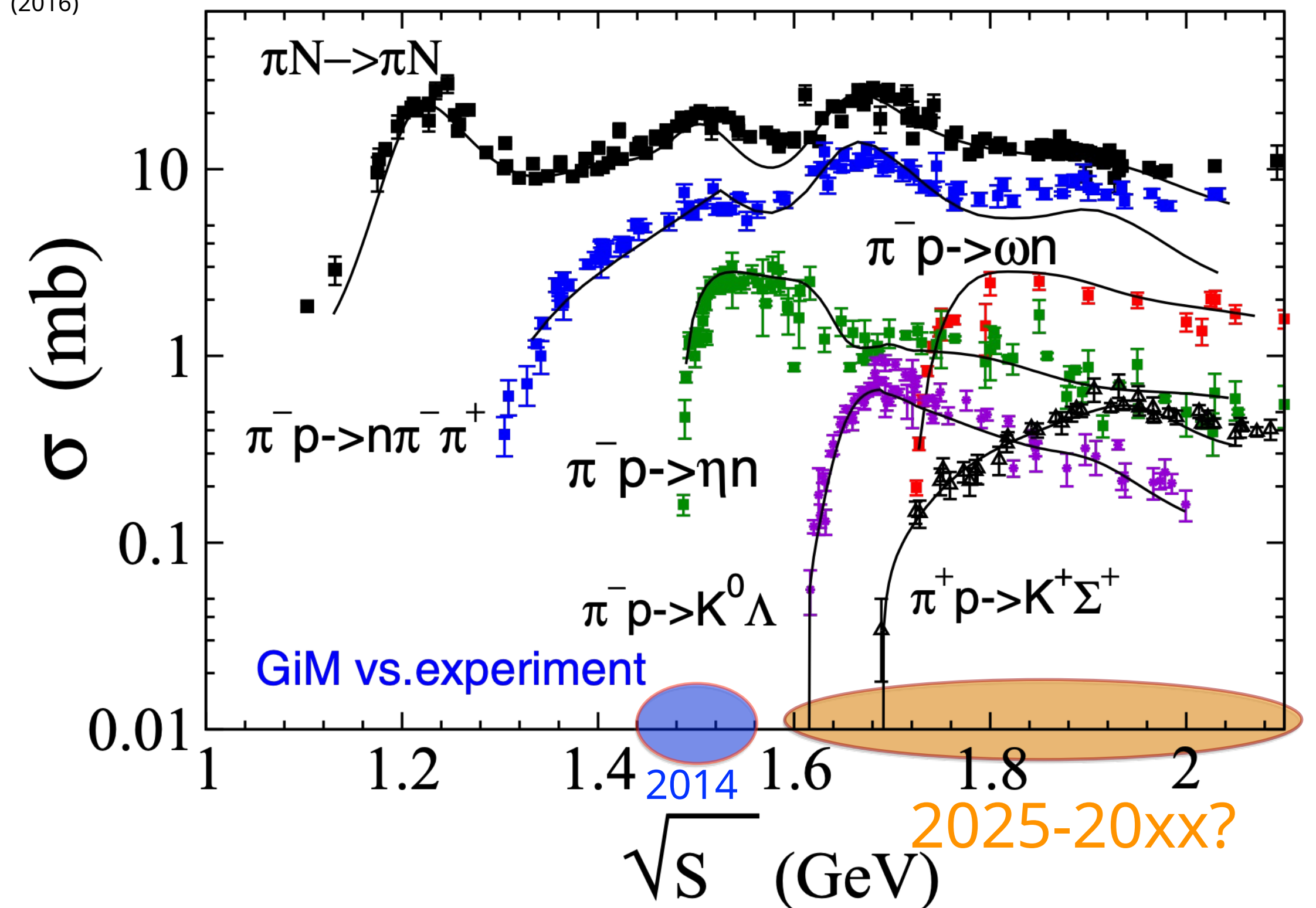


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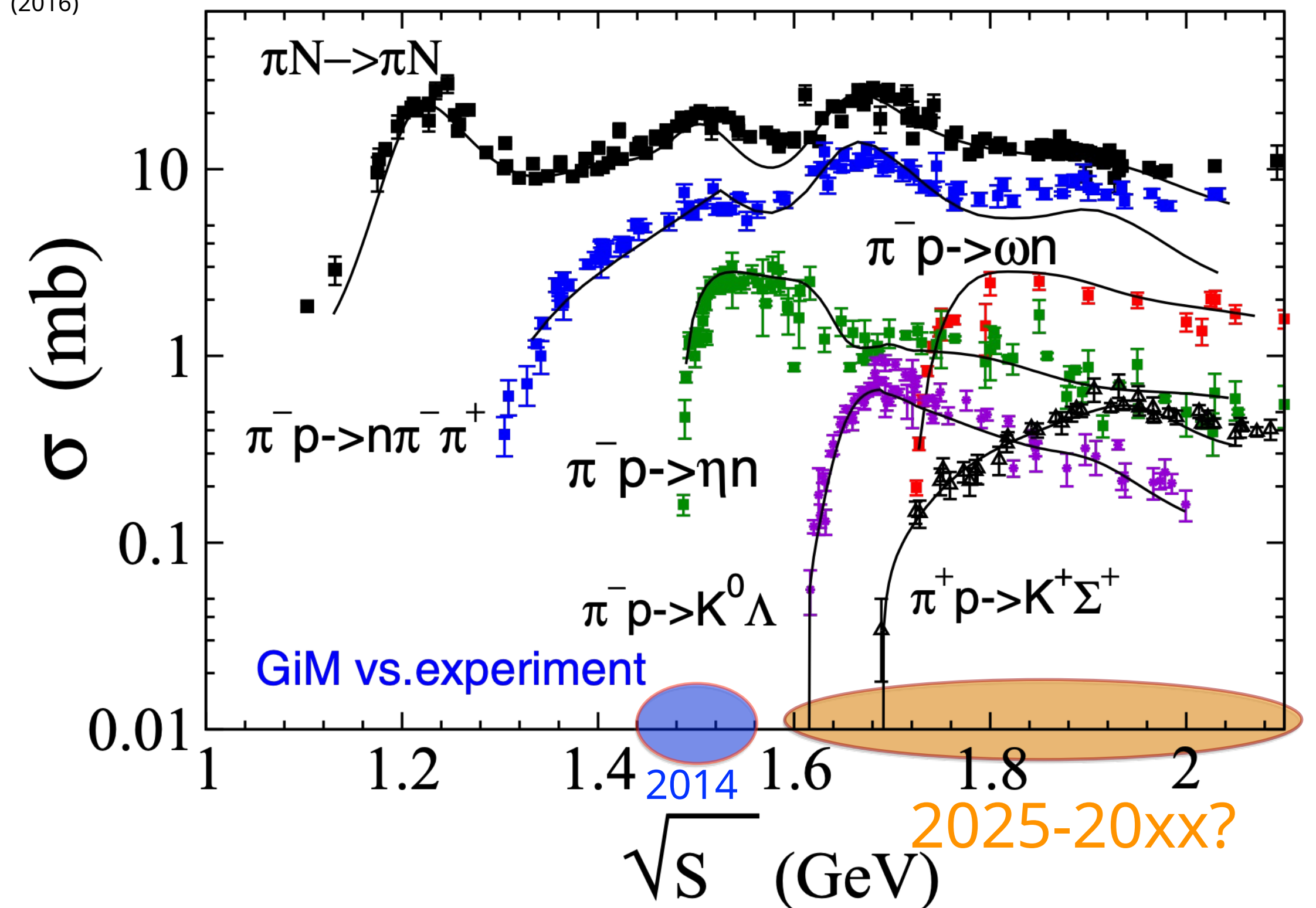


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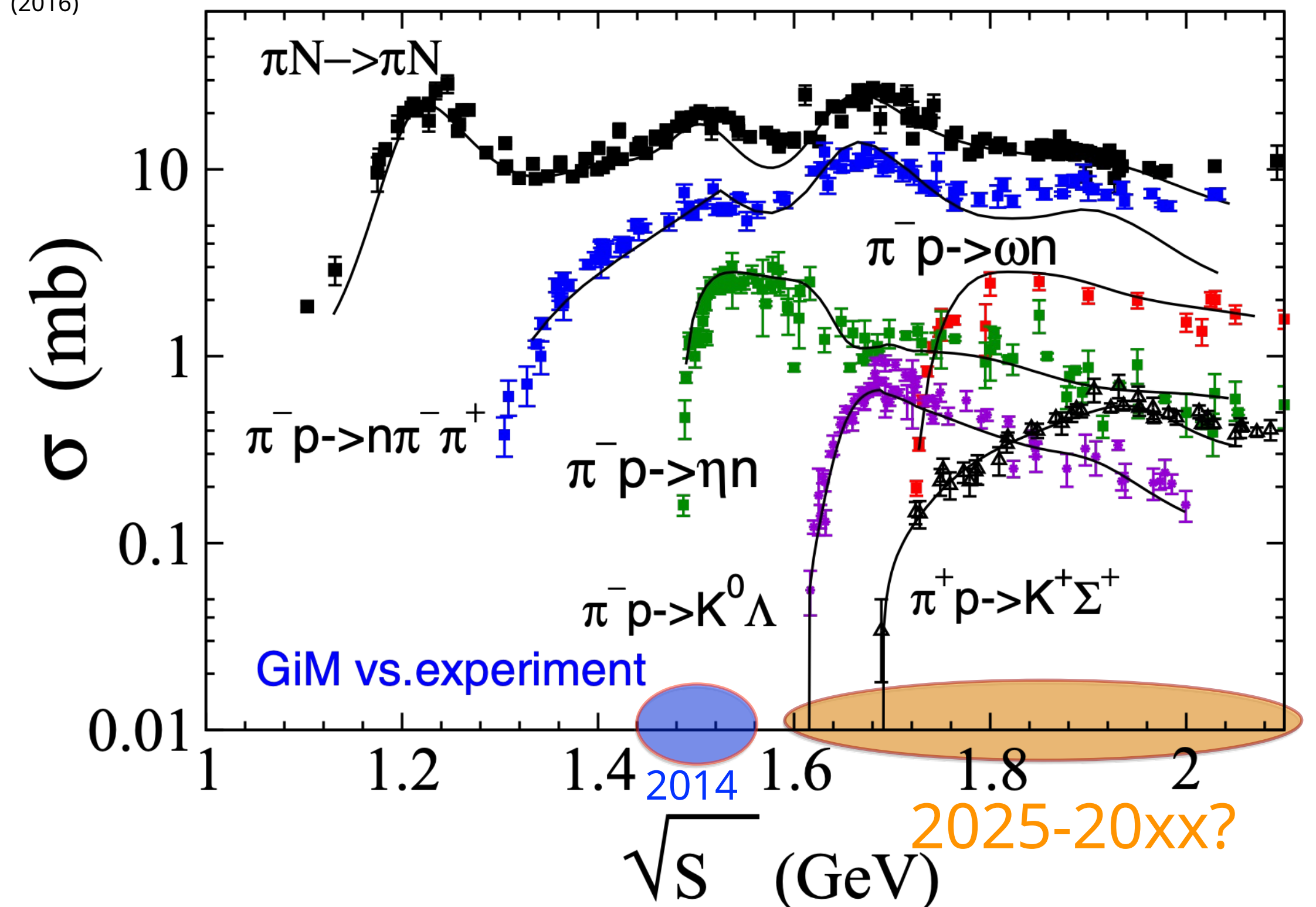


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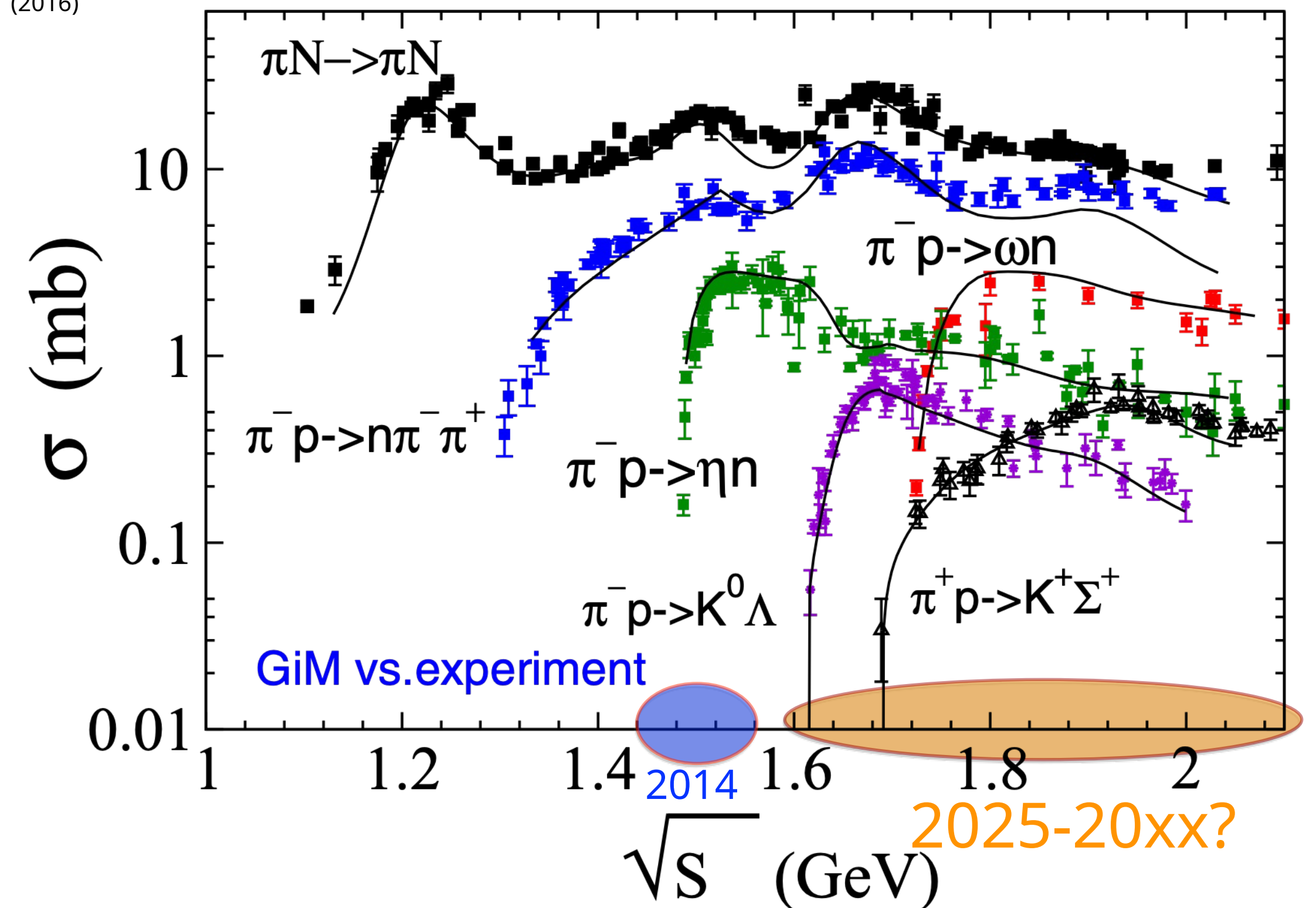


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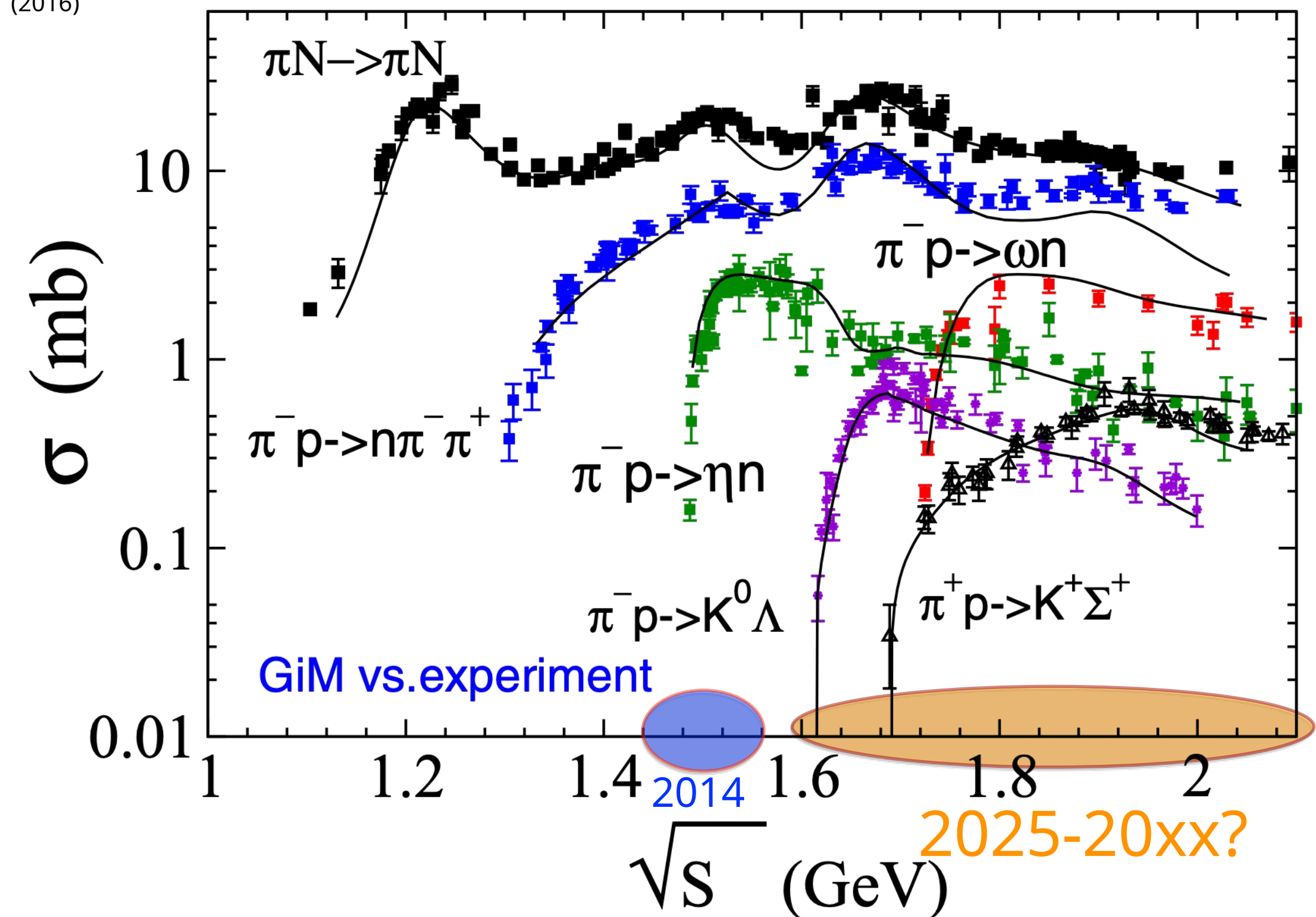


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- **'Simple' final states**, 2/3-bodies
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- Promising tool for *precision PWAs* & probing **(e.m.) decay properties** of various baryons/mesons/...

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

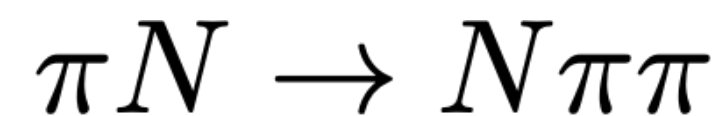




# The "2014" pion success story

... some key aspects

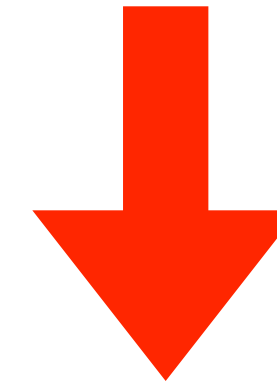
- *Selectivity* of baryon resonances in **s-channel formation**
- Focus on "**2nd resonance region**" ( $\sqrt{s} = 1.46 - 1.55$  GeV)
- Study **baryon-meson reaction dynamics** via 2-pion production



- **Time-like electromagnetic structure** of baryons via

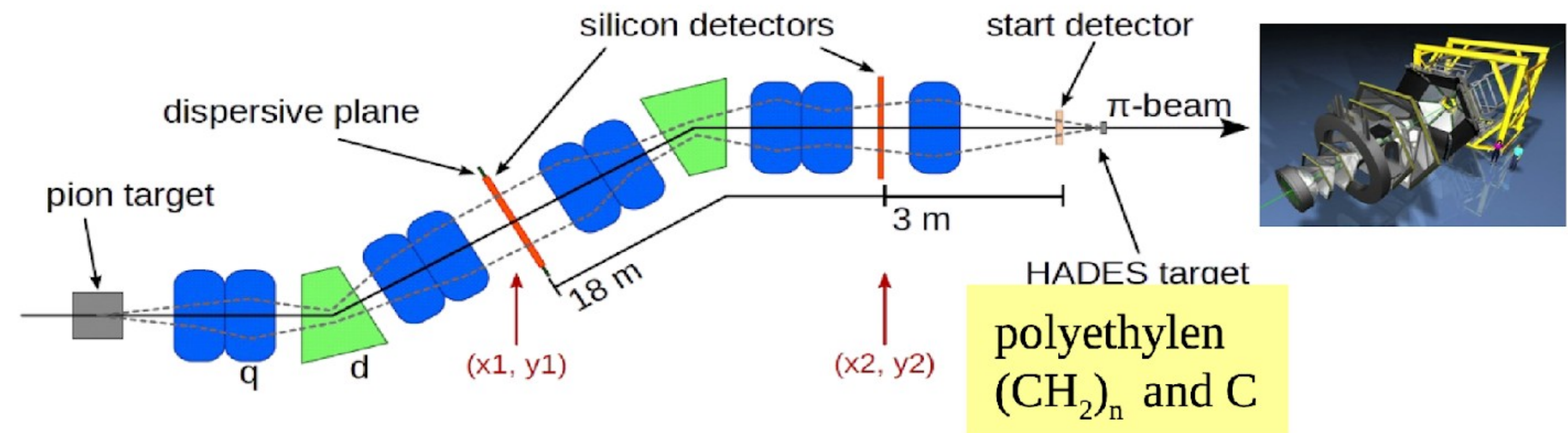
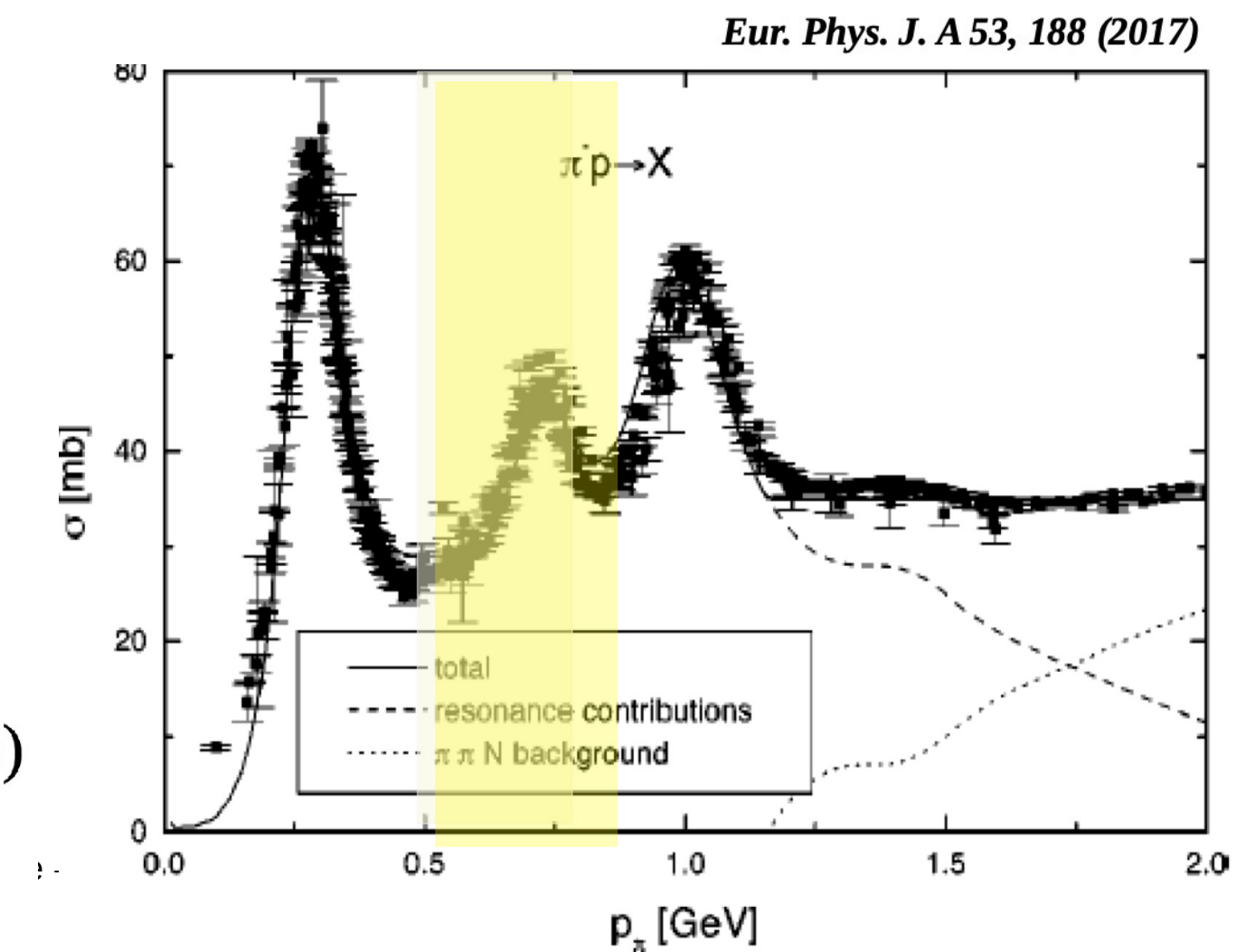


## 2<sup>nd</sup> resonance region



**N(1420, 1520, 1535)**

- reaction **N+Be**,  $8-10 \cdot 10^{10}$  N<sub>2</sub> ions/spill (4s)
- secondary  $\pi^-$  with  $I \sim 2-3 \cdot 10^5/s$
- $p = 650, \mathbf{685}, 733, 786$  (+/- 1) MeV/c
- **PE (CH<sub>2</sub>)<sub>n</sub>** and **C** targets

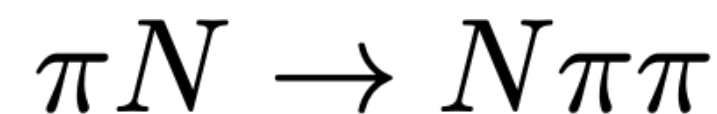




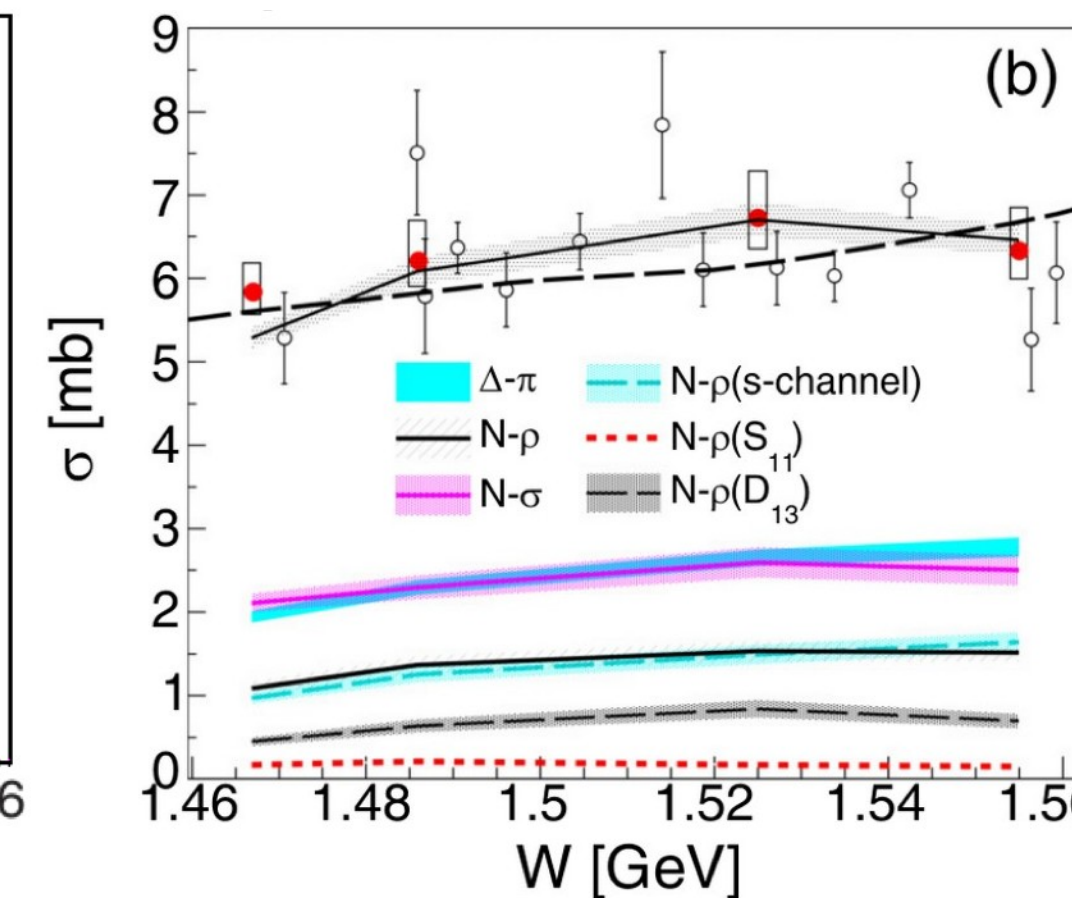
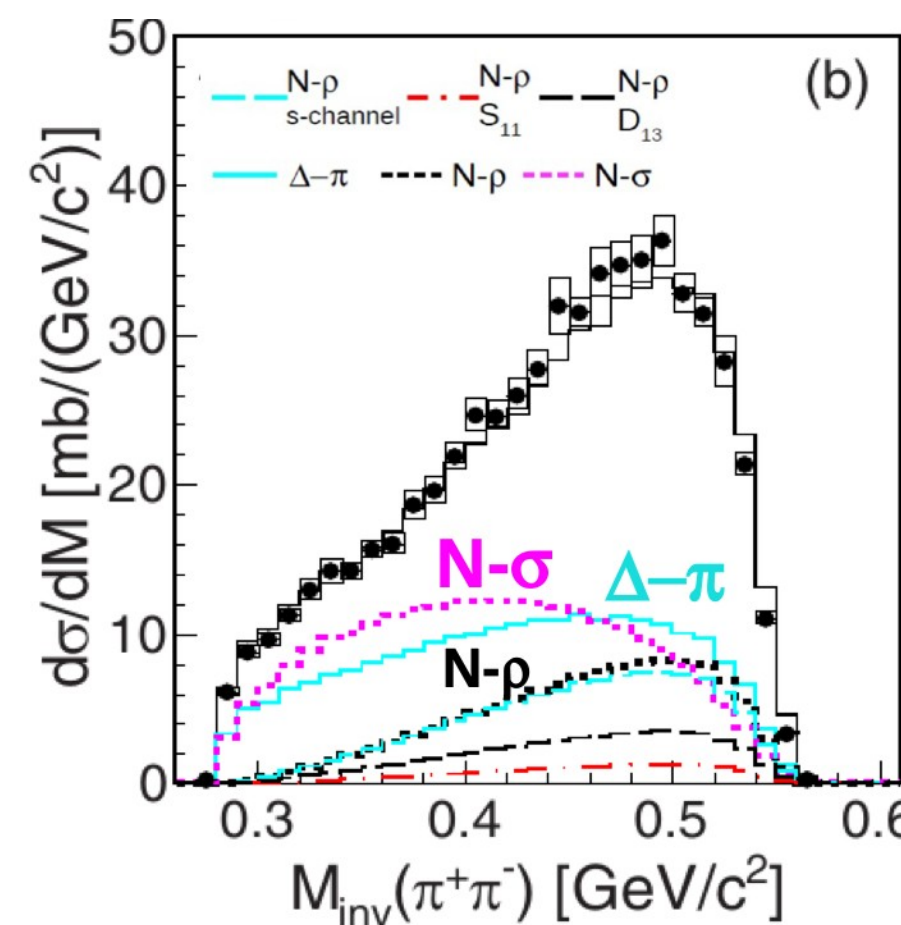
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- **Time-like electromagnetic structure** of baryons via



*Phys. Rev. C 102, 024001, (2020)*

Bn-Ga PWA: [pwa.hisp.uni-bonn.de](http://pwa.hisp.uni-bonn.de)

## 2π data included in the fit

Reaction	Observable	W (GeV)	Experiment
$\gamma p \rightarrow \pi^0 \pi^0 p$	DCS, Tot	1.2-1.9	MAMI
$\gamma p \rightarrow \pi^0 \pi^0 p$	E	1.2-1.9	MAMI
$\gamma p \rightarrow \pi^0 \pi^0 p$	DCS, Tot	1.4-2.38	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	$P, H$	1.45-1.65	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	$T, P_x, P_y$	1.45-2.28	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	$P_x, P_x^c, P_x^s$ (4D)	1.45-1.8	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	$P_y, P_y^c, P_y^s$ (4D)	1.45-1.8	CB-ELSA
$\gamma p \rightarrow \pi^+ \pi^- p$	DCS	1.7-2.3	CLAS
$\gamma p \rightarrow \pi^+ \pi^- p$	$I^c, I^s$	1.74-2.08	CLAS
$\pi^- p \rightarrow \pi^0 \pi^0 n$	DCS	1.29-1.55	Crystal Ball
$\pi^- p \rightarrow \pi^+ \pi^- n$	DCS	1.45-1.55	HADES
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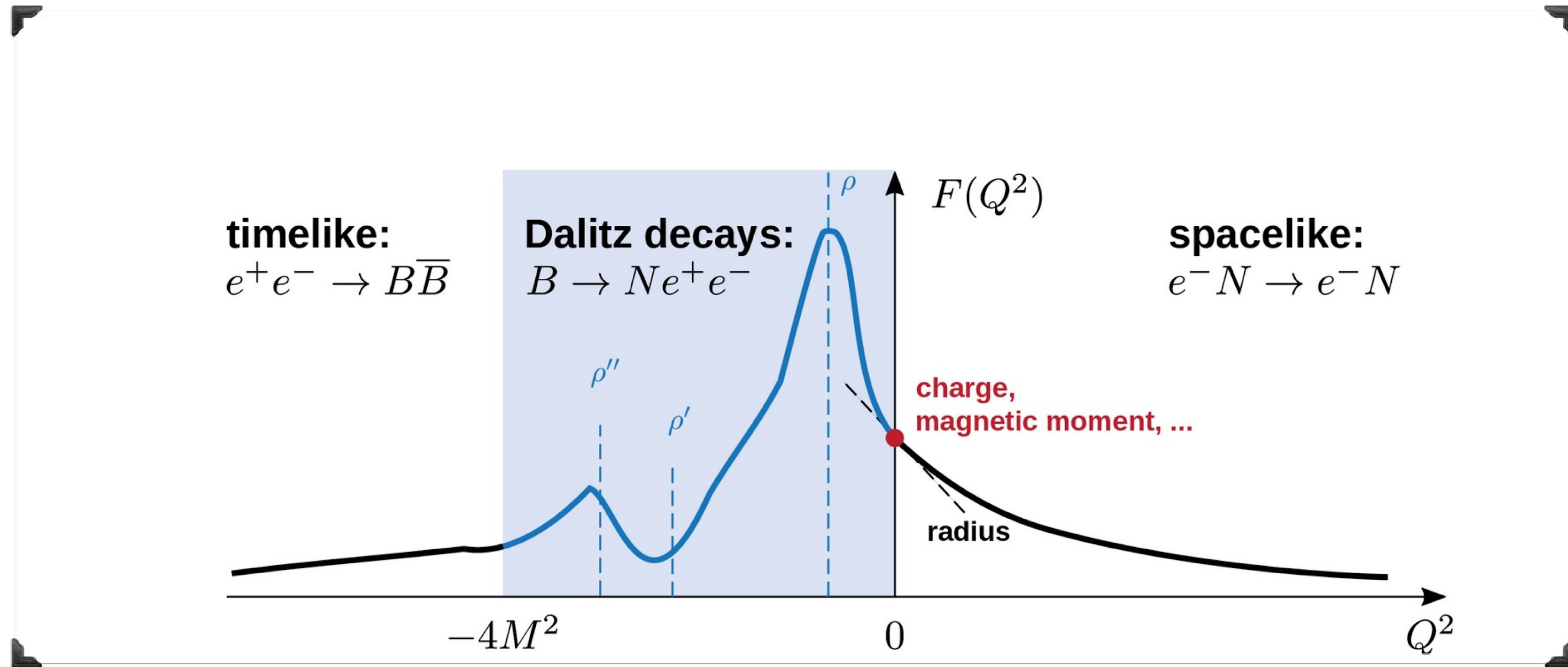
**unique data set**

## ρ meson production:

- **s-channel  $D_{13}$  (N(1520) 3/2<sup>-</sup>) dominant contribution**
- N(1520) → Nρ BR=12.2 +/- 2 %
- N(1535) → Nρ BR=3.2 +/- 0.6 %



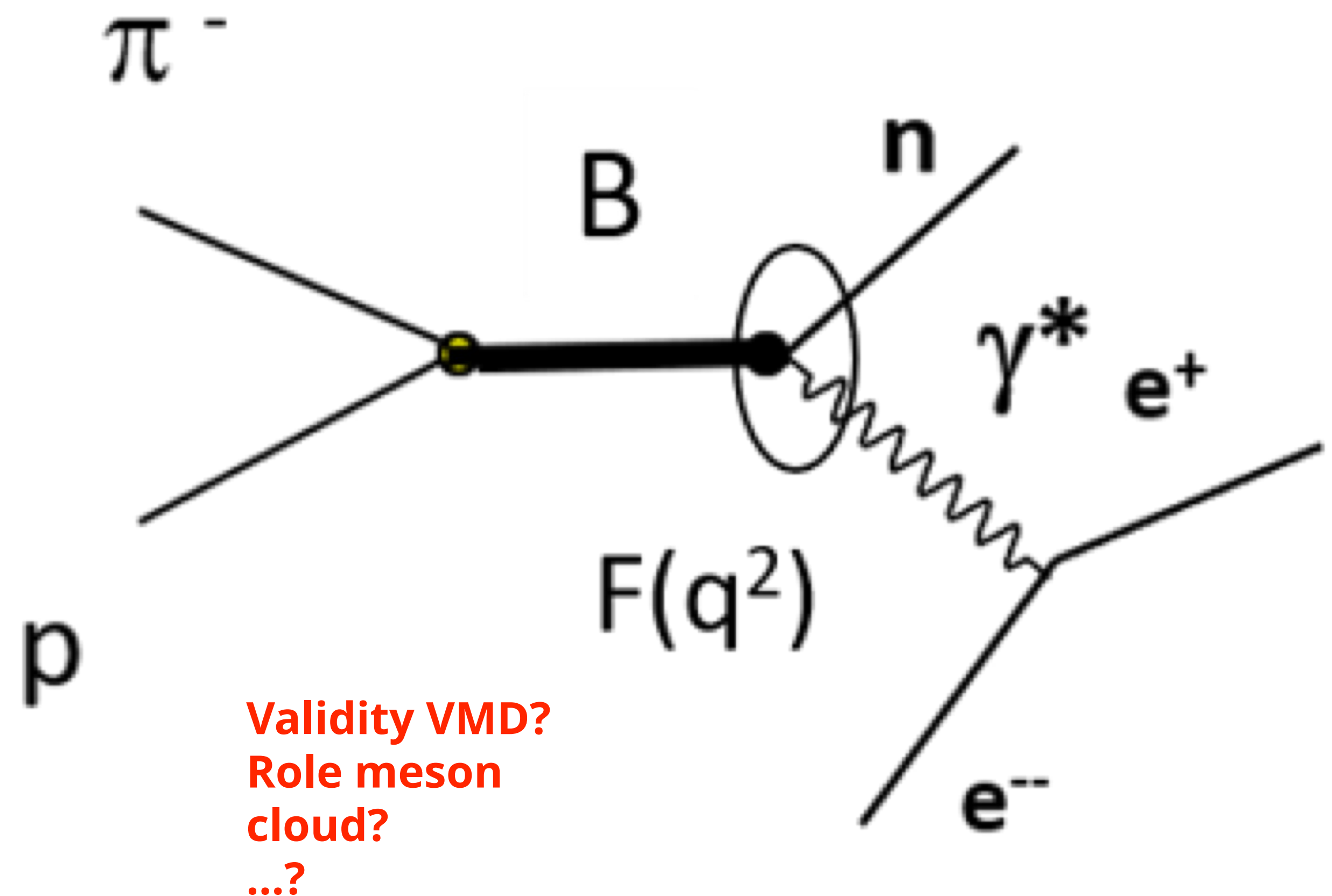
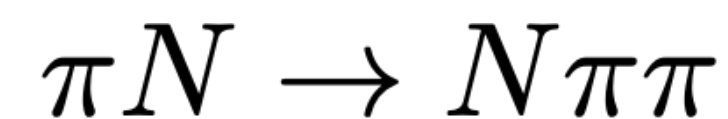
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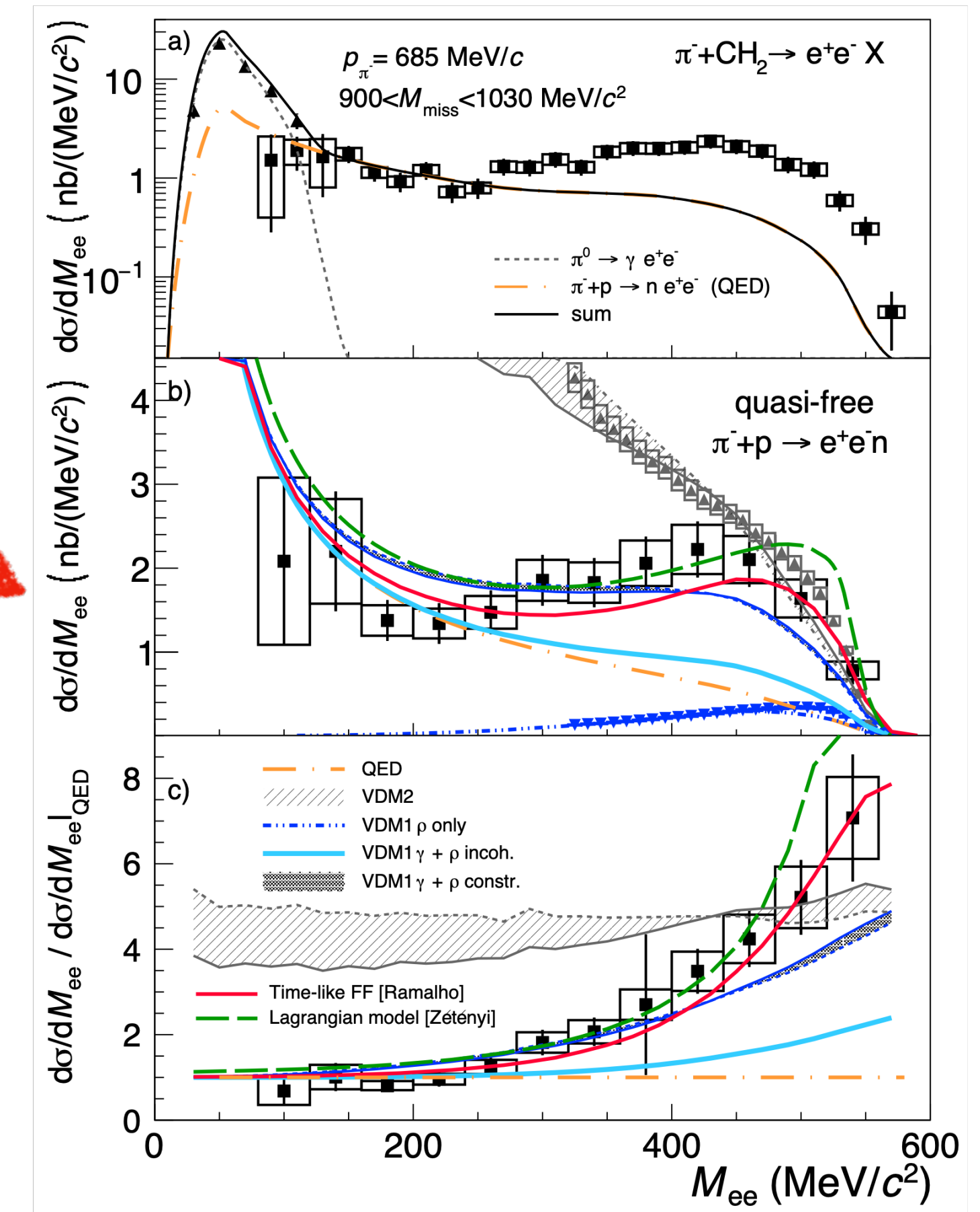
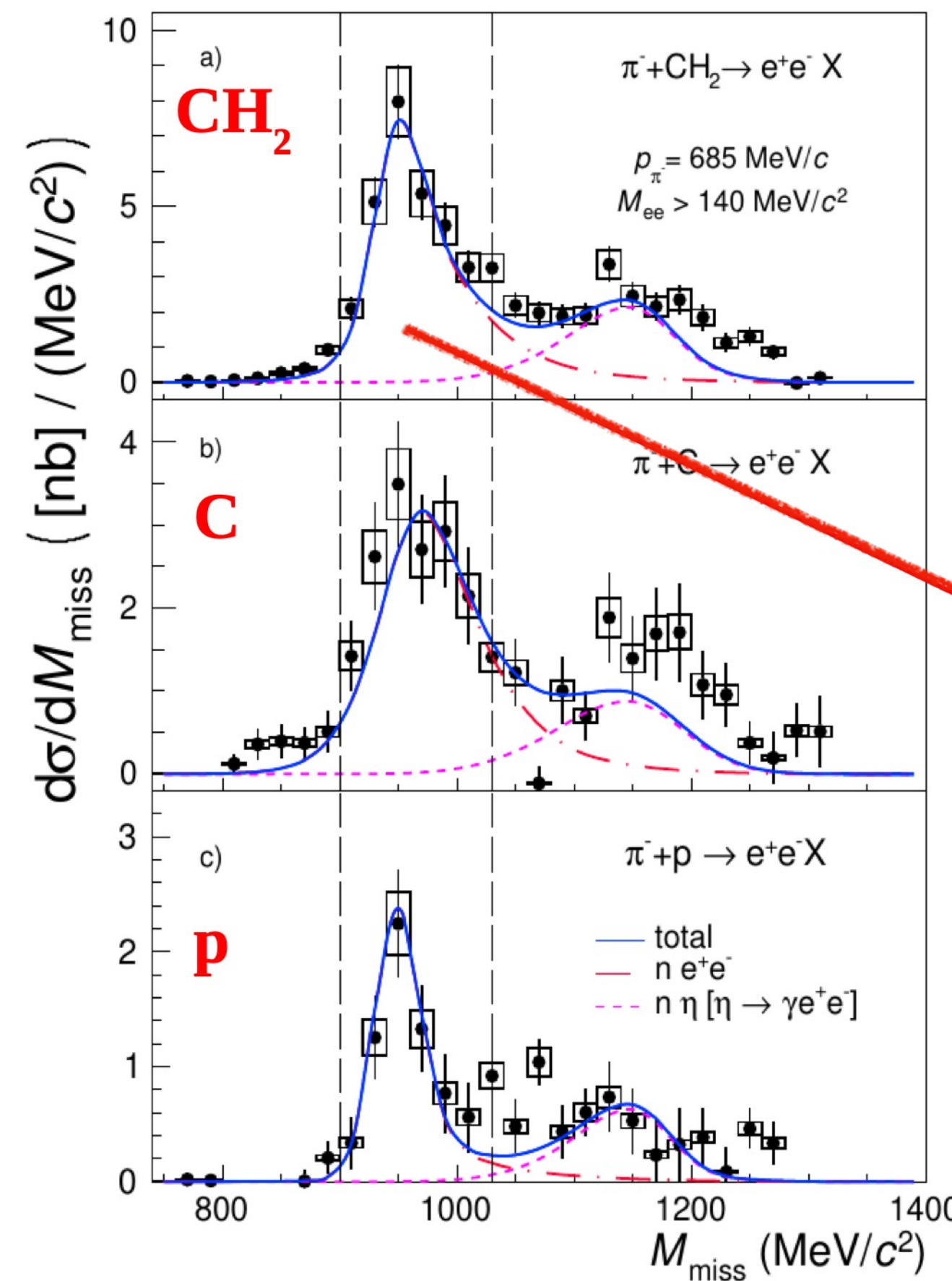
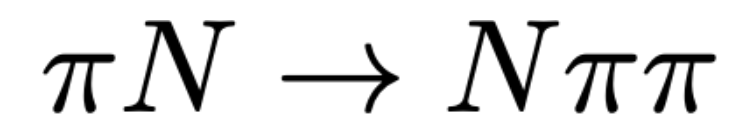
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- Powerful in **combination with the PWA** of hadronic decay mode





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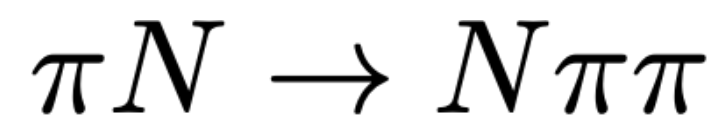
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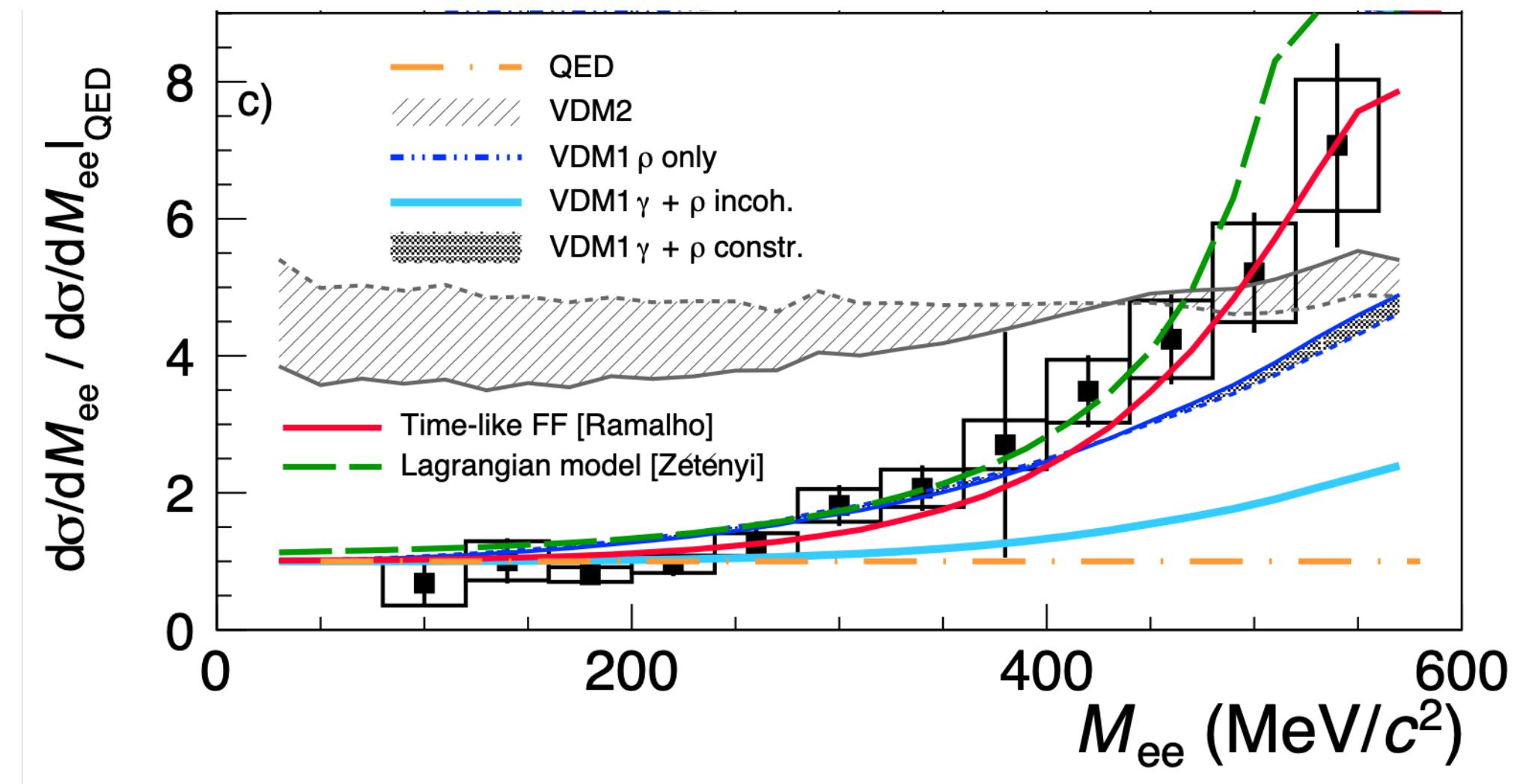


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- **Deep insight** into photon-baryon coupling

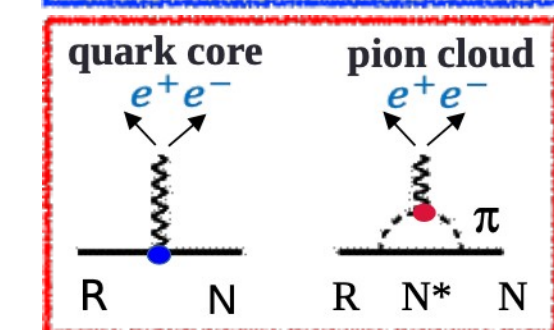
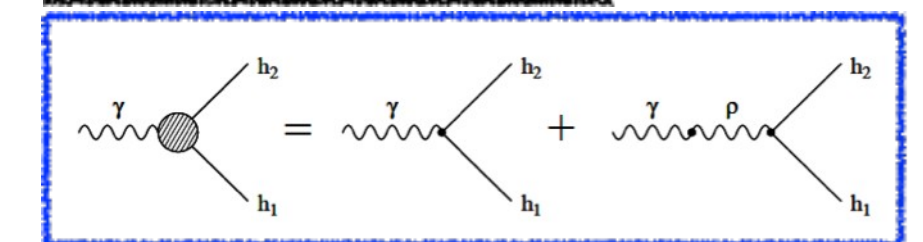
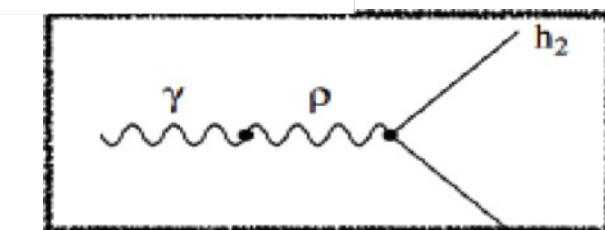
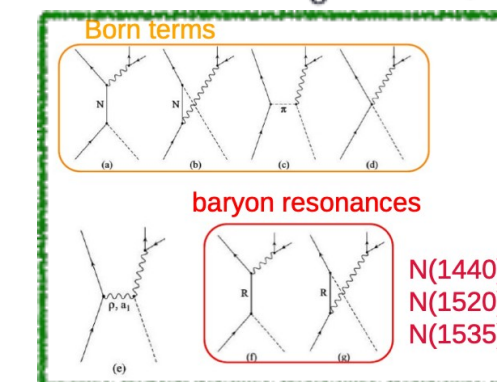


arXiv:2205.15914

- **VMD2** (*strict VMD*) overestimates data below 400 MeV (used in HI transport models)
- **2-component VMD (VMD1)** gives reasonable description
- **Lagrangian model** – very promising
- **Time-like FF** - dominant pion cloud contribution (pion emFF)

$$\Gamma_{\rho}^{VDM2} = \left(\frac{M_0}{M}\right)^3 \Gamma_{\rho}^0$$

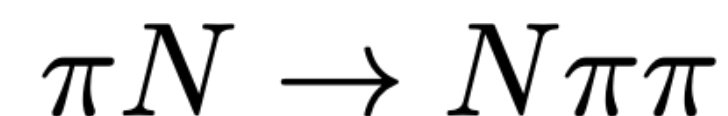
$$\Gamma_{\rho}^{VDM1} = \left(\frac{M}{M_0}\right) \Gamma_{\rho}^0$$





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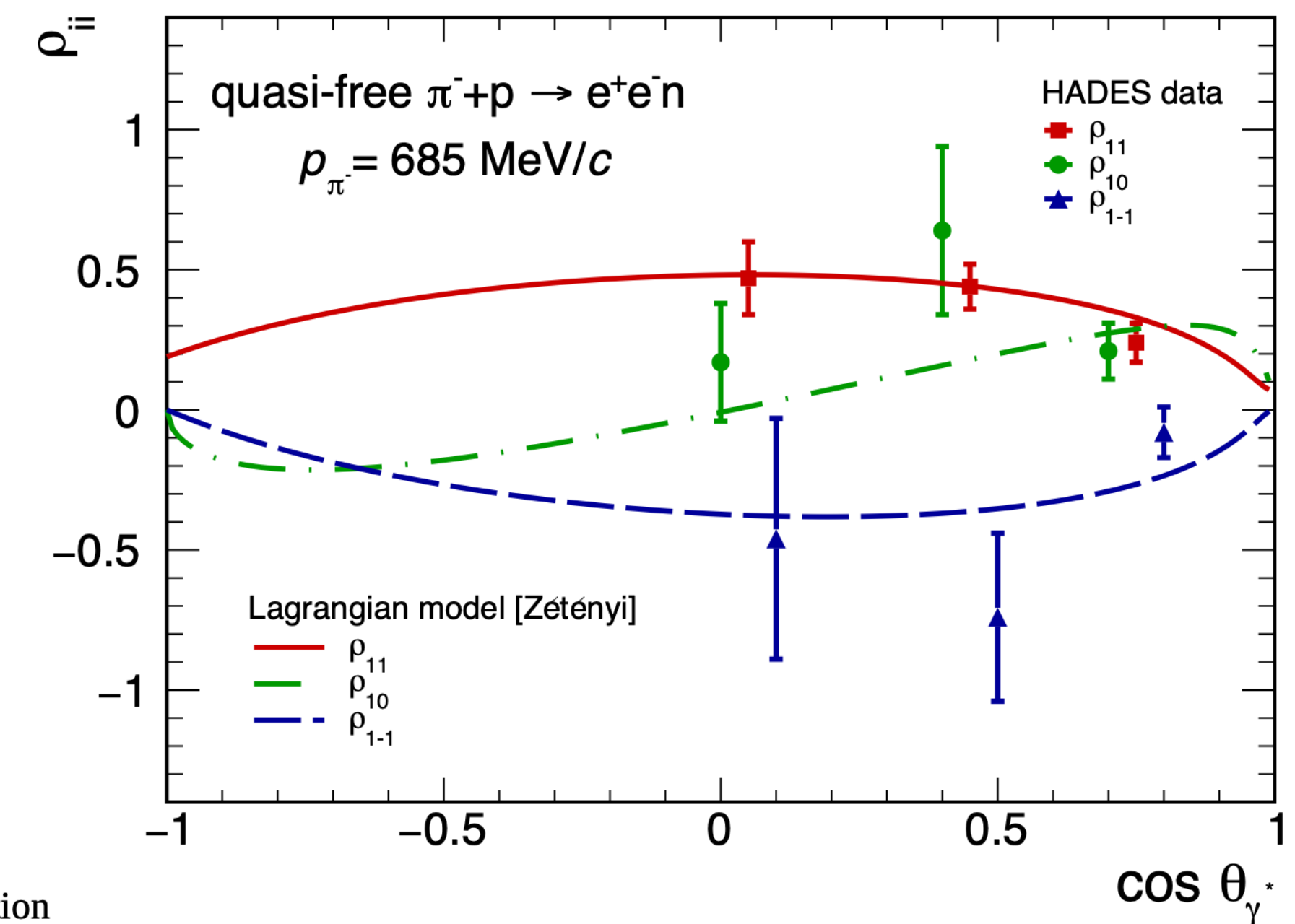
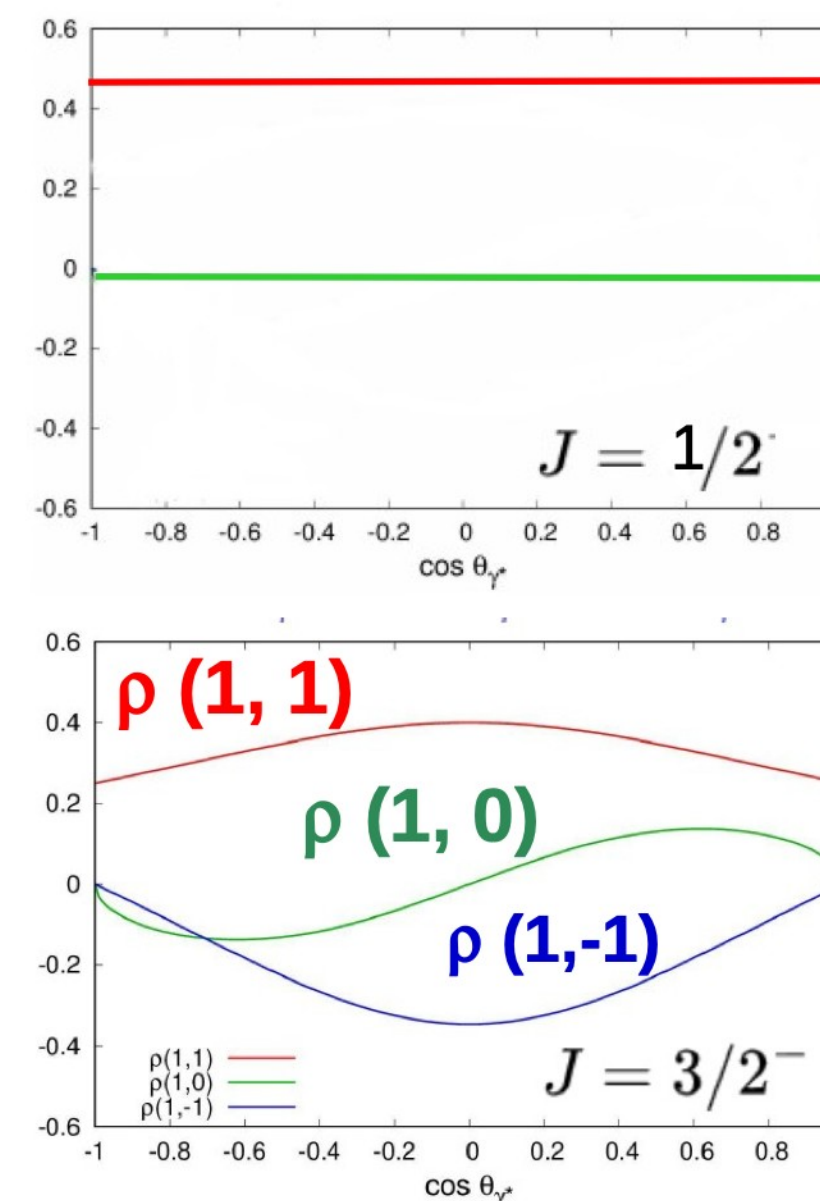
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- **Deep insight** into photon-baryon coupling

- Polarization analysis of the virtual photon -> extract **spin-density matrix elements**

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



$\rho_{11} = 0.5$ ,  $\rho_{10} = 0$  for transverse polarization (real photon) => contribution from virtual photon angular dependence  
 → contributions of spins larger than  $1/2$ :  
 N(1520) resonance  
**more precise data needed !**



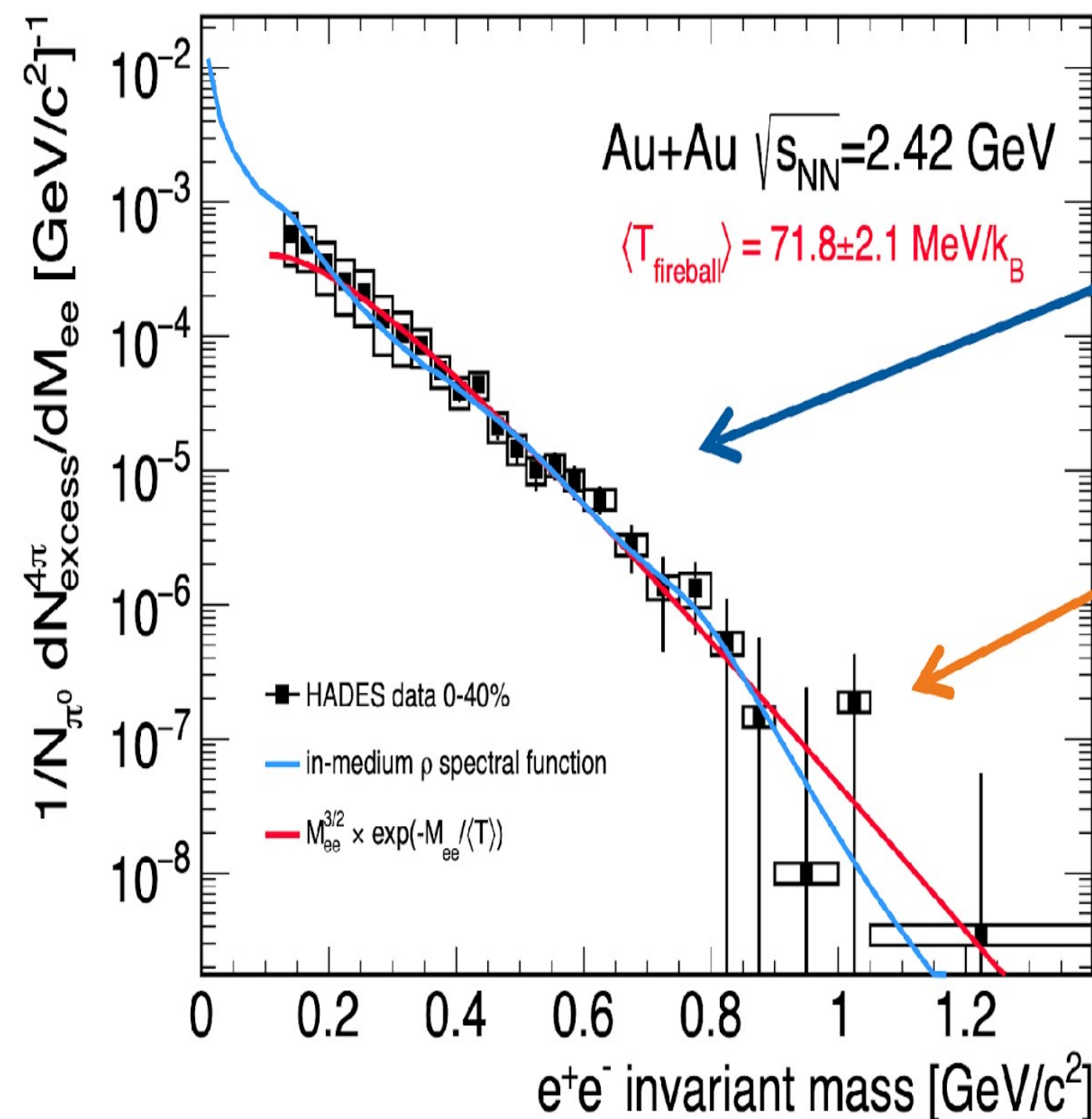
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$$\pi N \rightarrow N \pi \pi$$

- **Deep insight** into photon-baryon coupling
- Polarization analysis of the virtual photon -> extract **spin-density matrix elements**
- **Complementary** in study of emissivity of baryonic matter

Joachim Stroth, p@SIS100 workshop, Wuppertal



0.3 < M < 0.7 GeV:

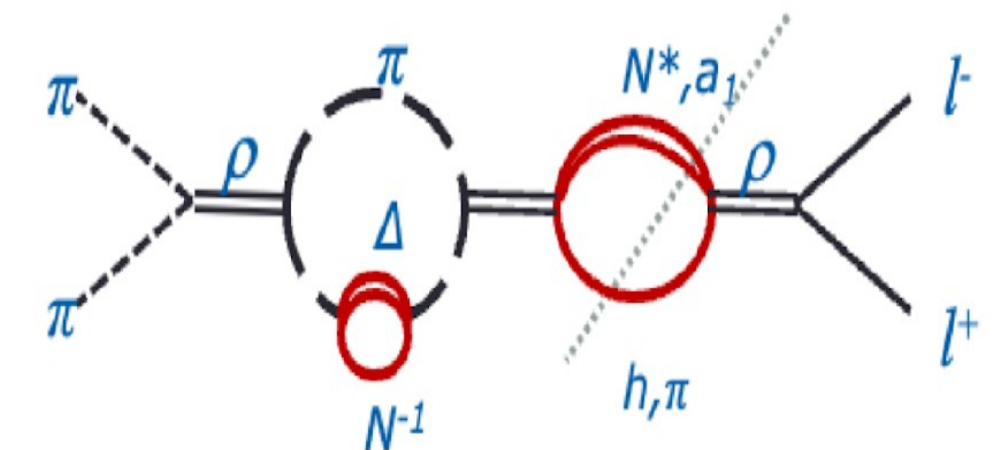
- In-medium spect. funct.
- fireball life time
- fireball temperature<sup>(1)</sup>

M > 1 GeV/c<sup>2</sup>:

- $\rho - a_1$  chiral mixing
- dominated by contribution from the hottest and densest region

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

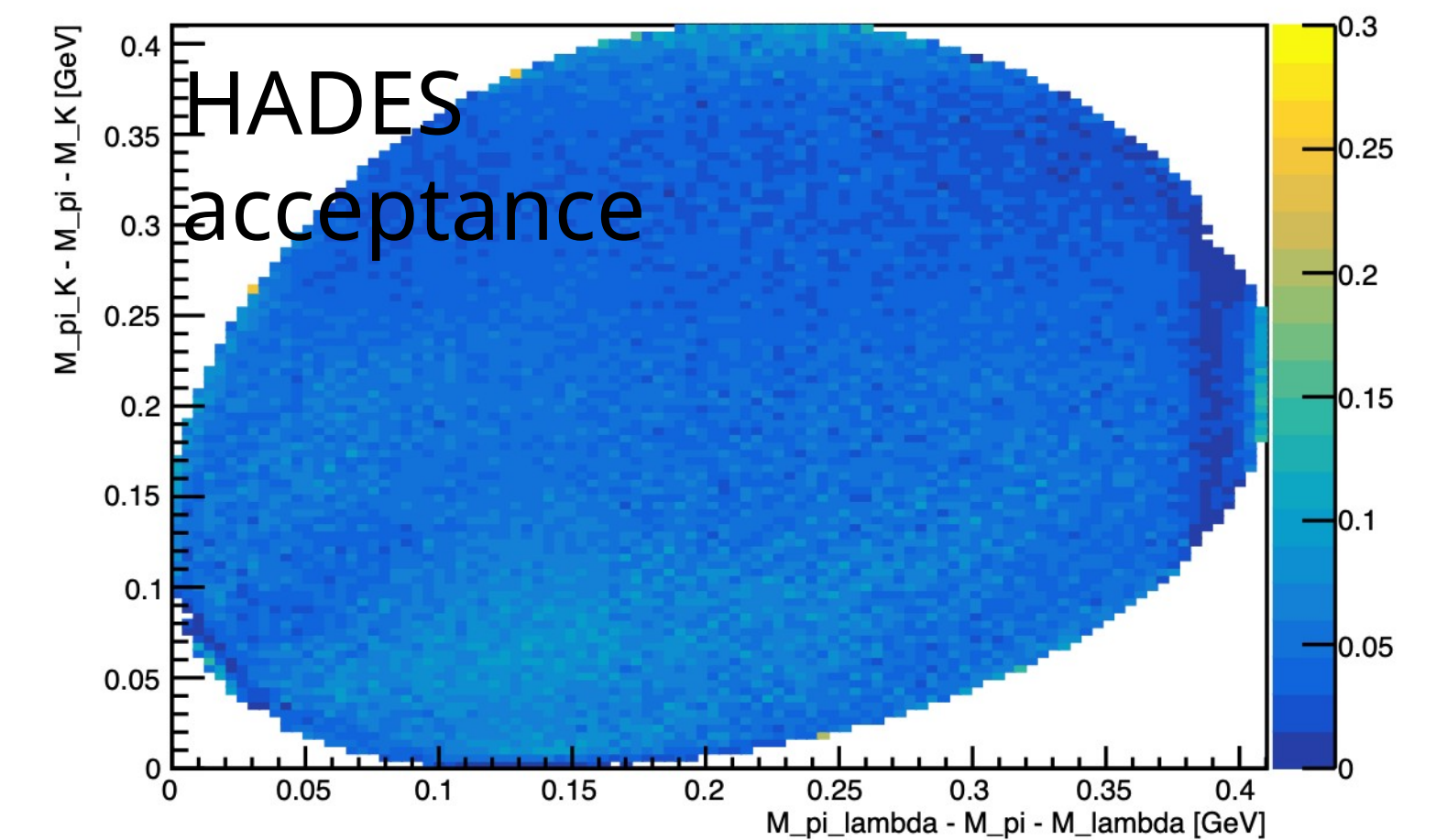
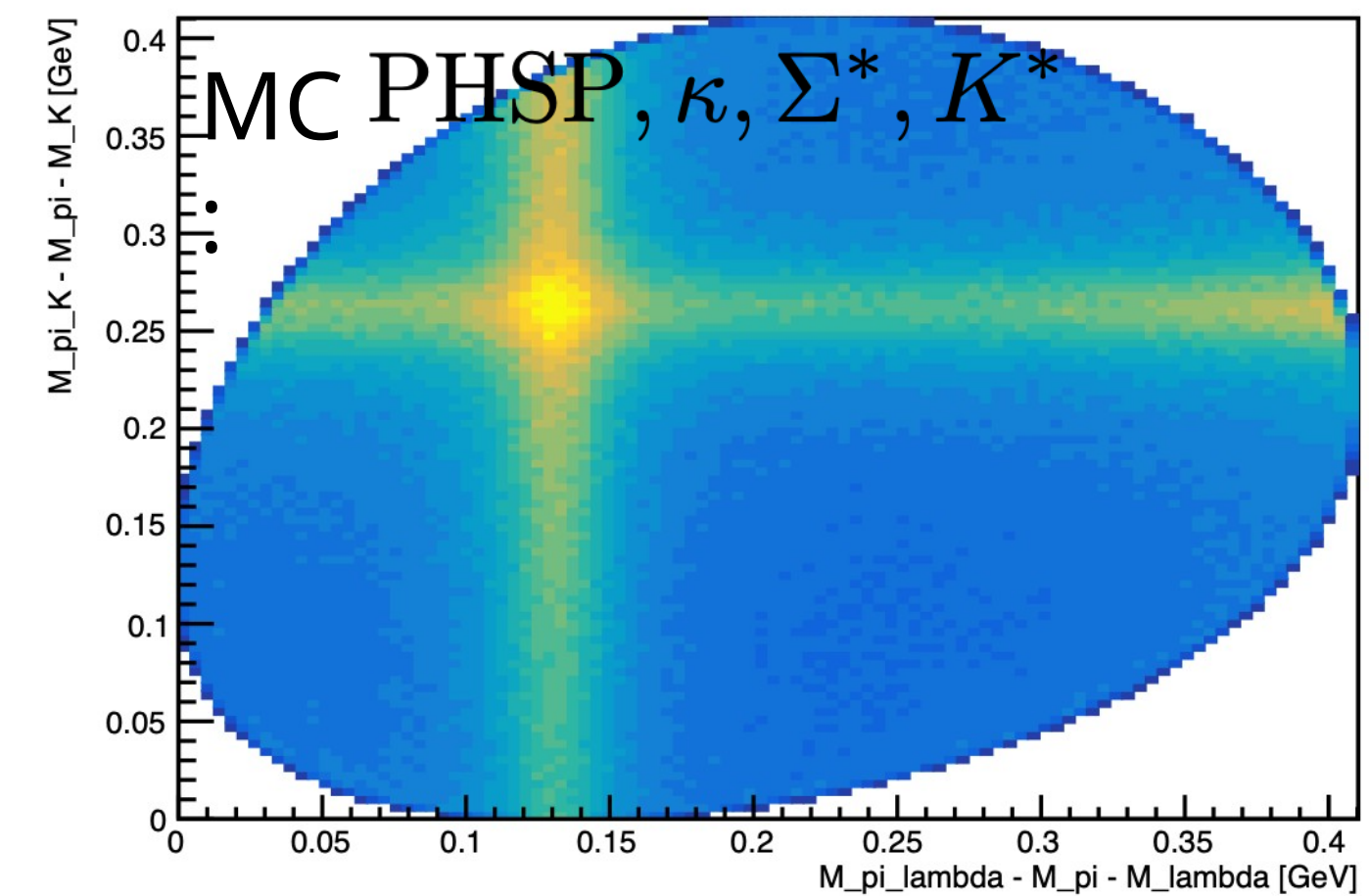
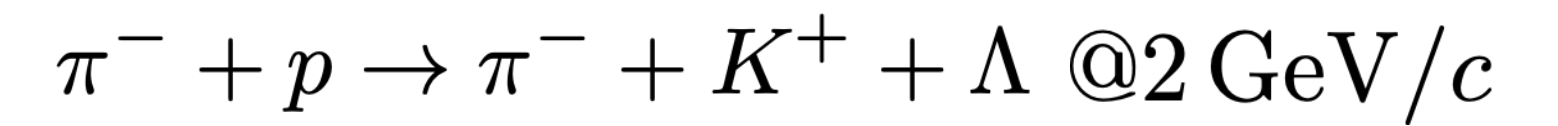
Rapp, van Hees; arXiv:1411.4612v  
CG GSI-TAMU; Galatyuk, Seck, et al.; arXiv:1512.08688



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

# Pion beam program

*... wide physics opportunities*

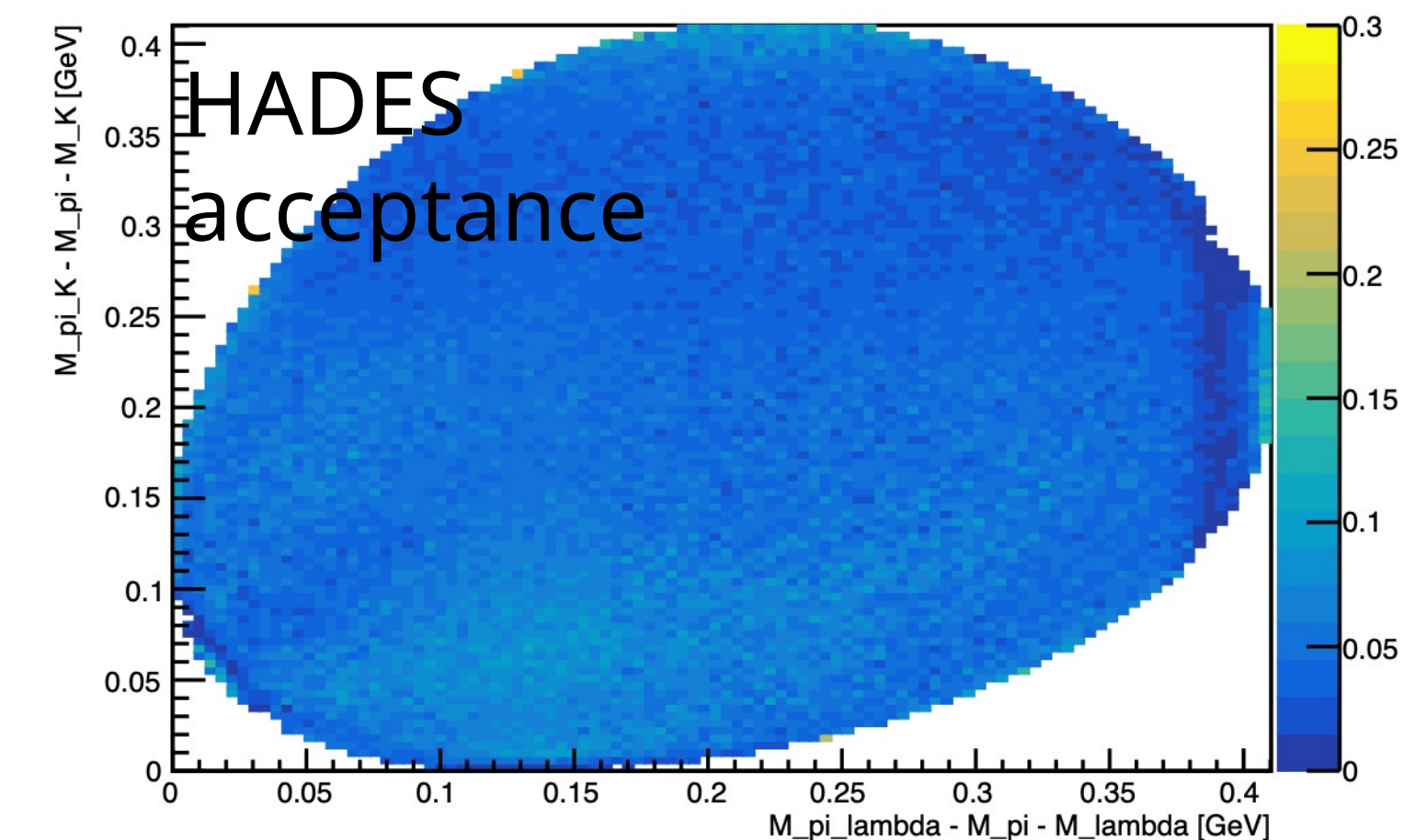
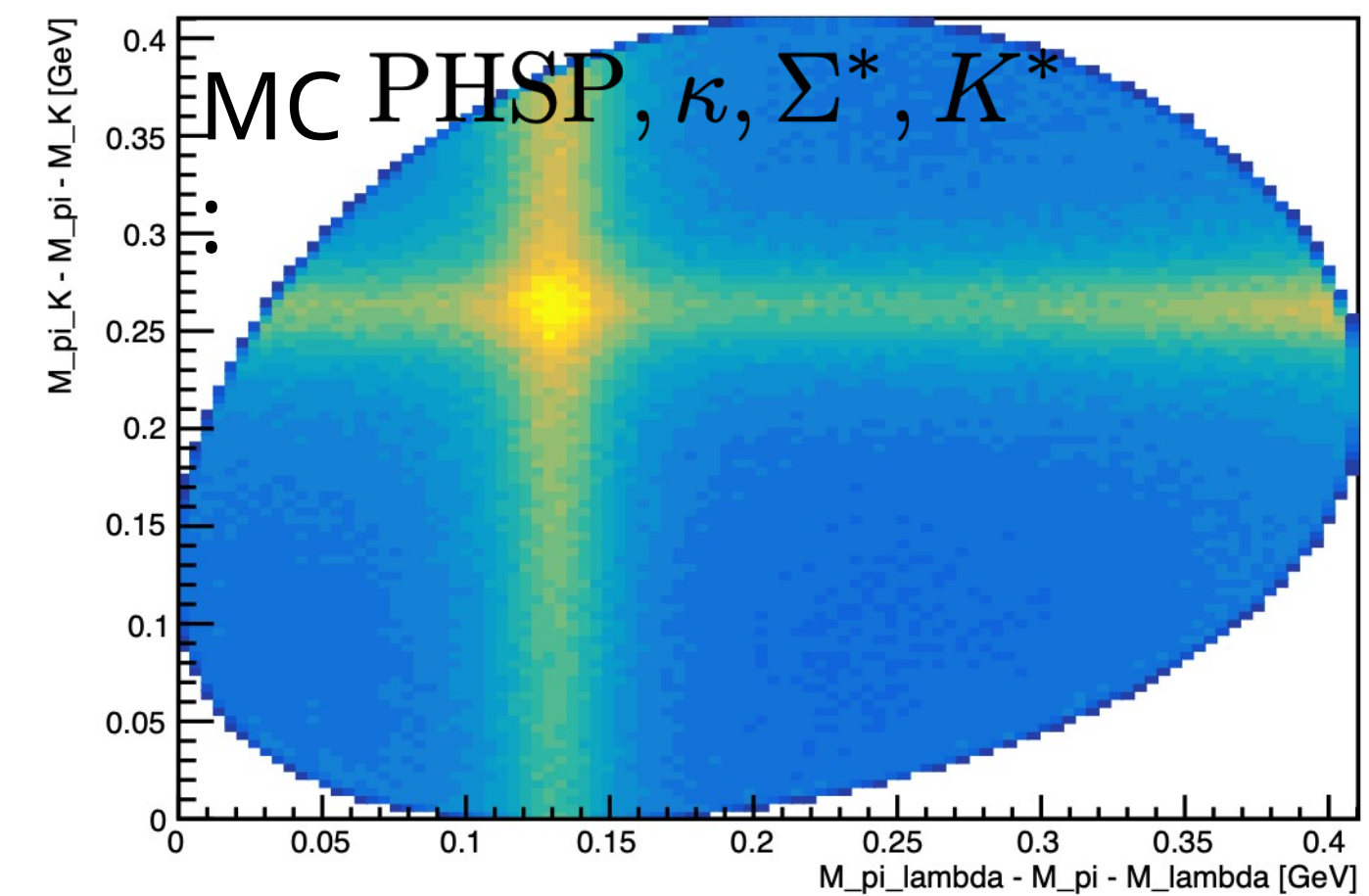
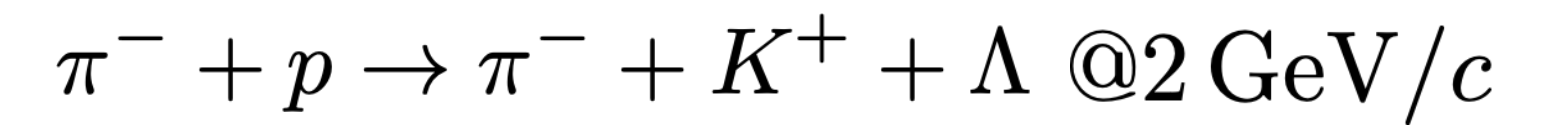




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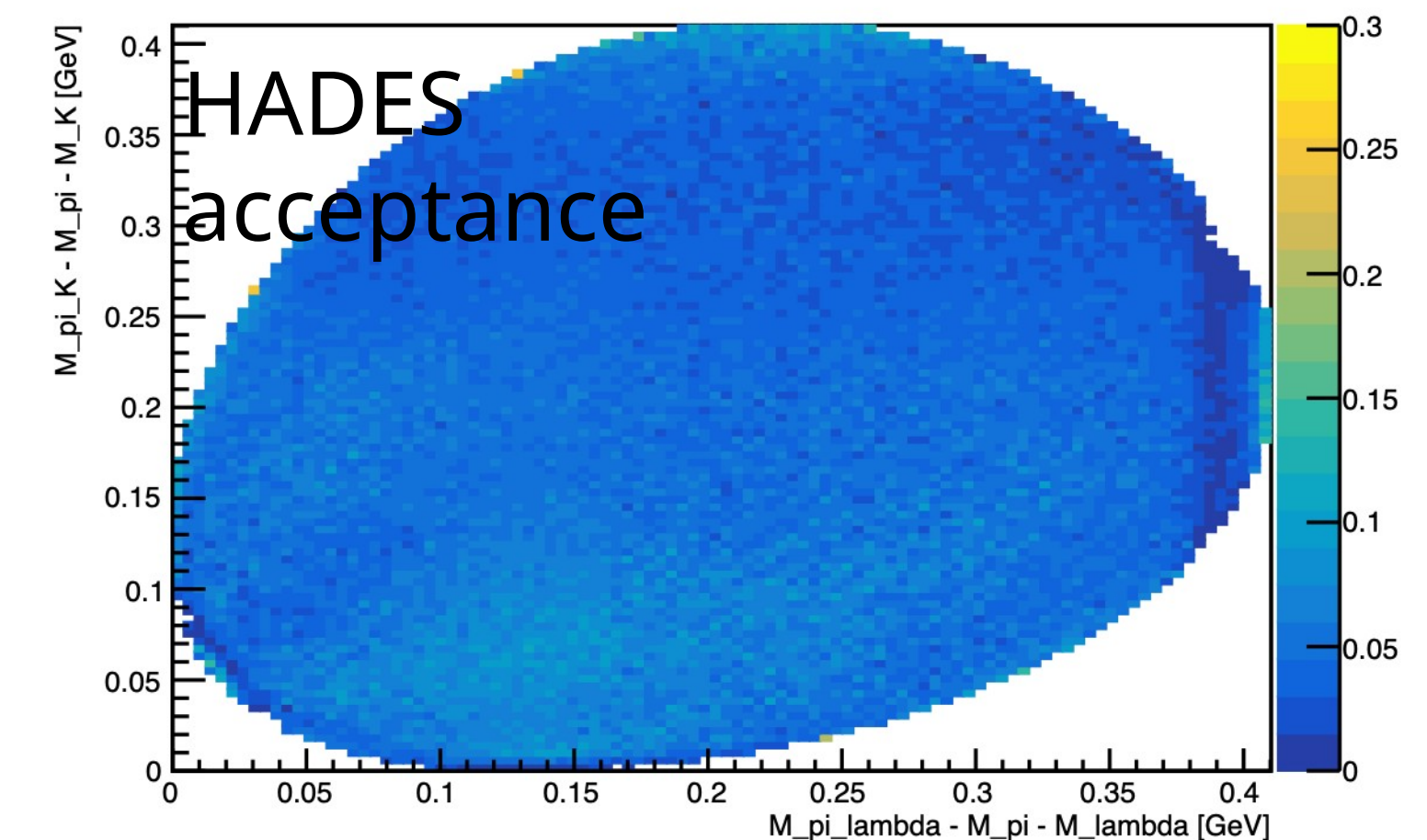
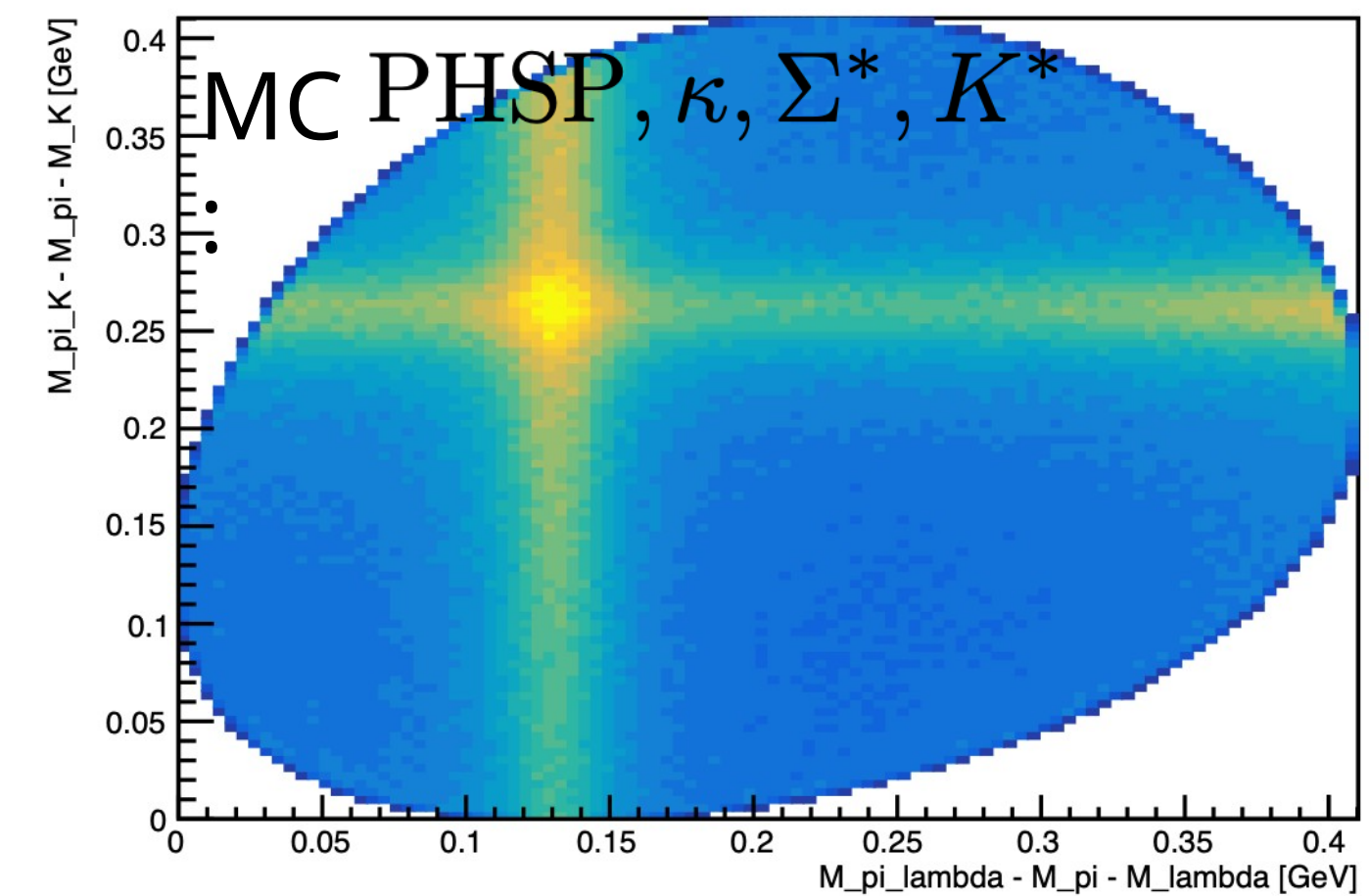
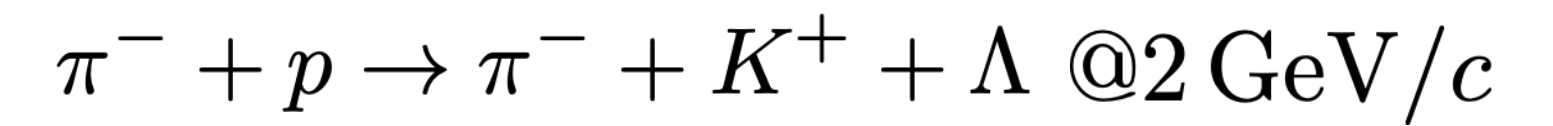
- **Baryon  $|S|=0,1$  spectroscopy** in formation and production, f.e.  $N(1720)/N'(1720)$



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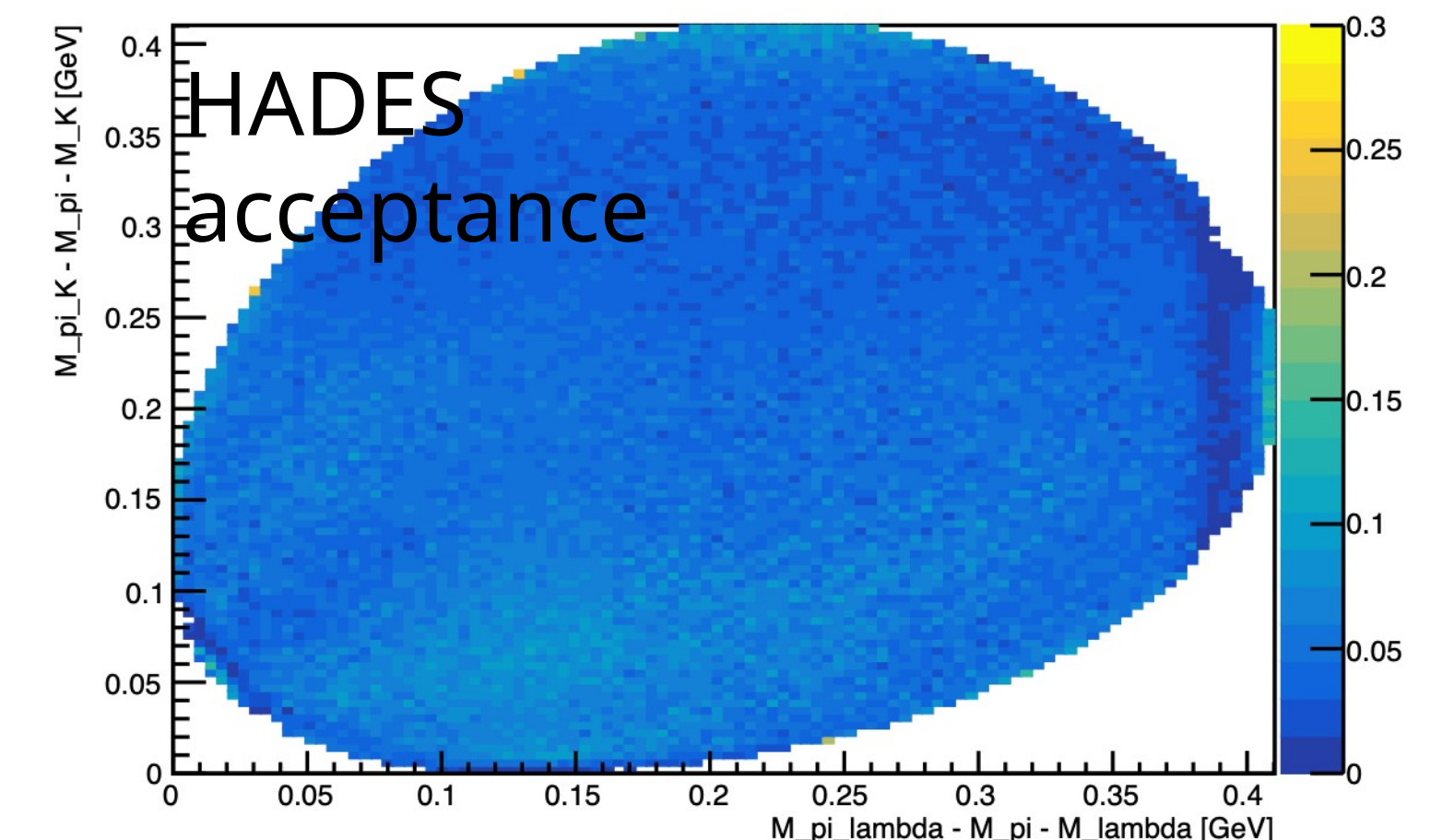
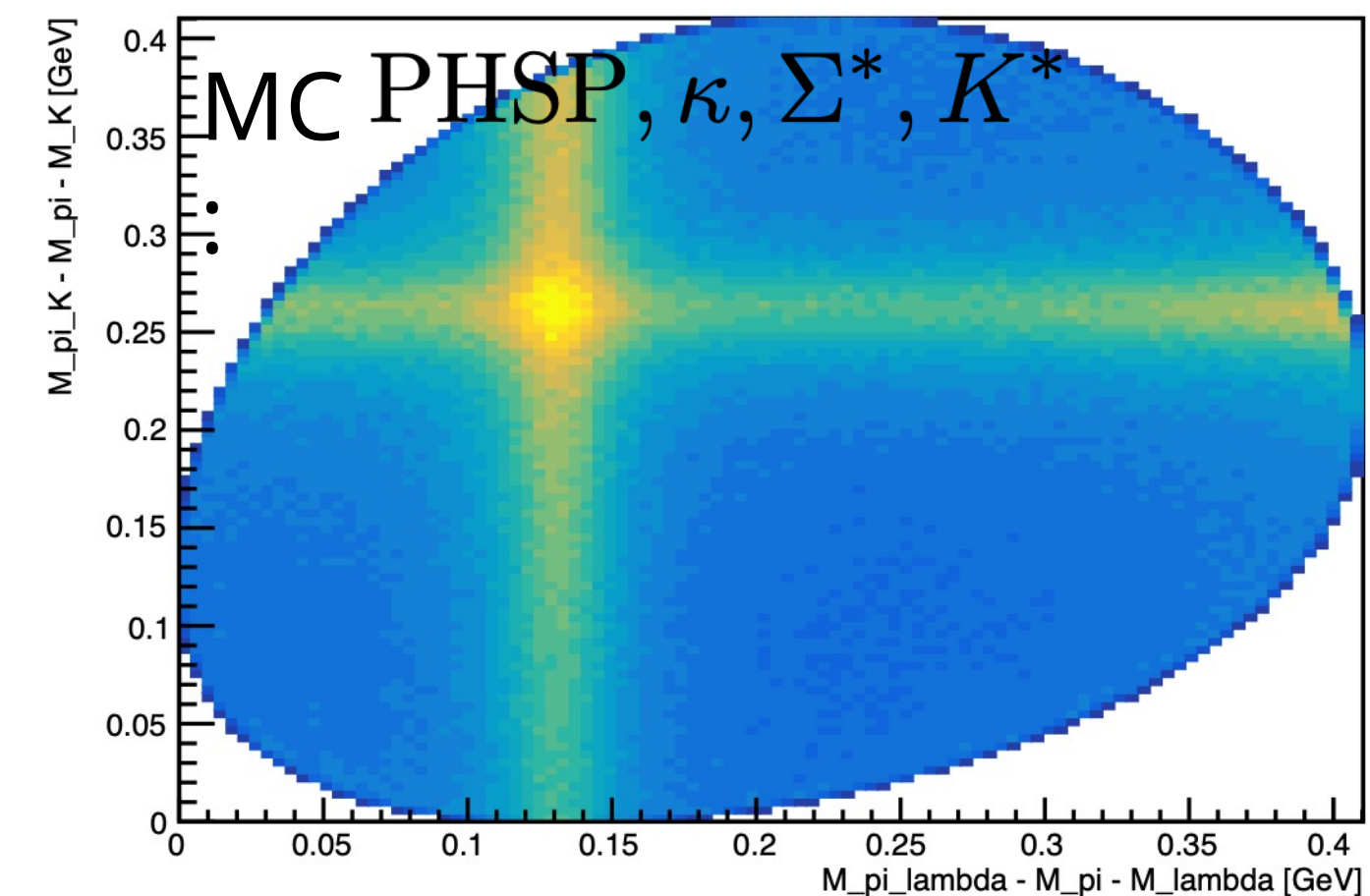


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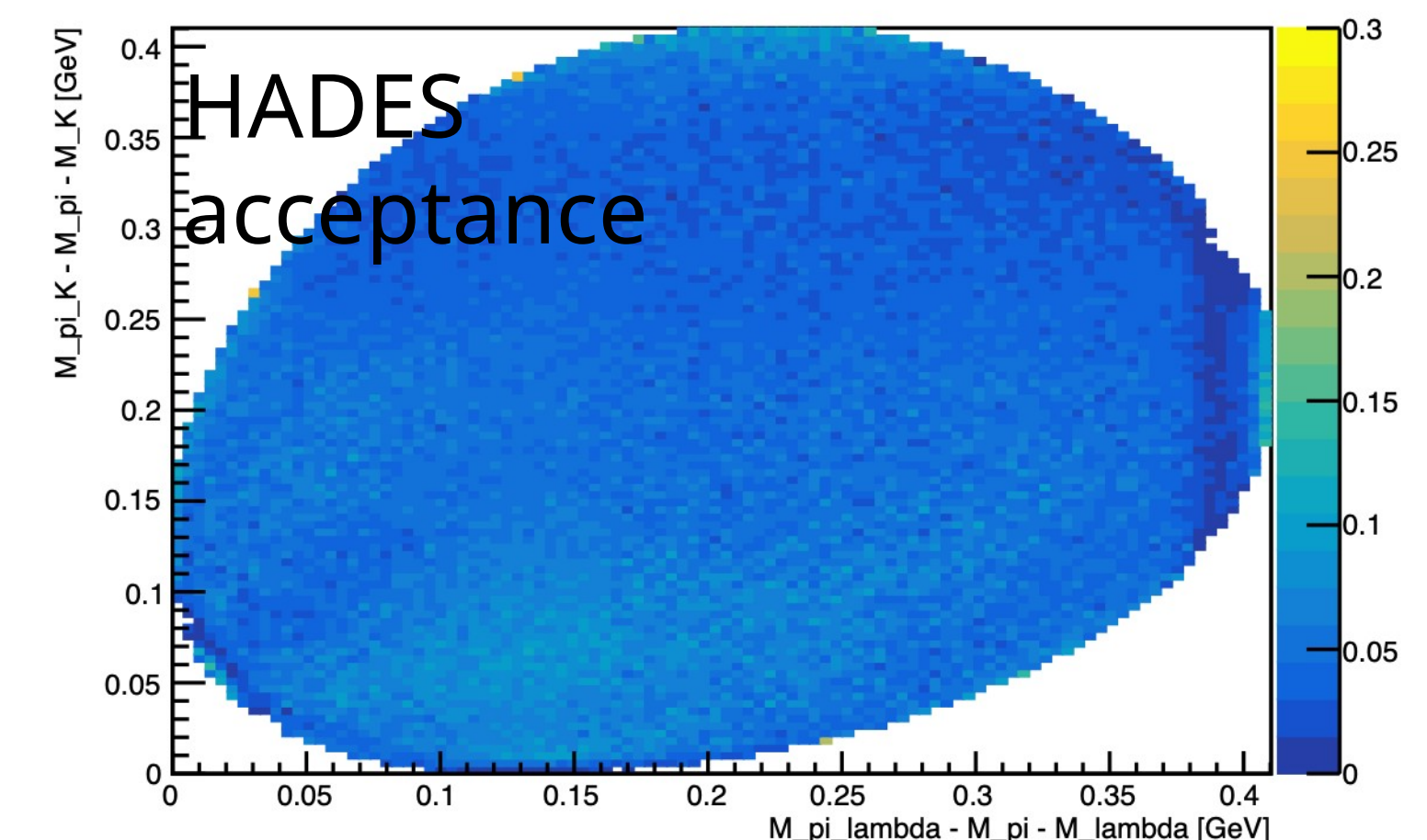
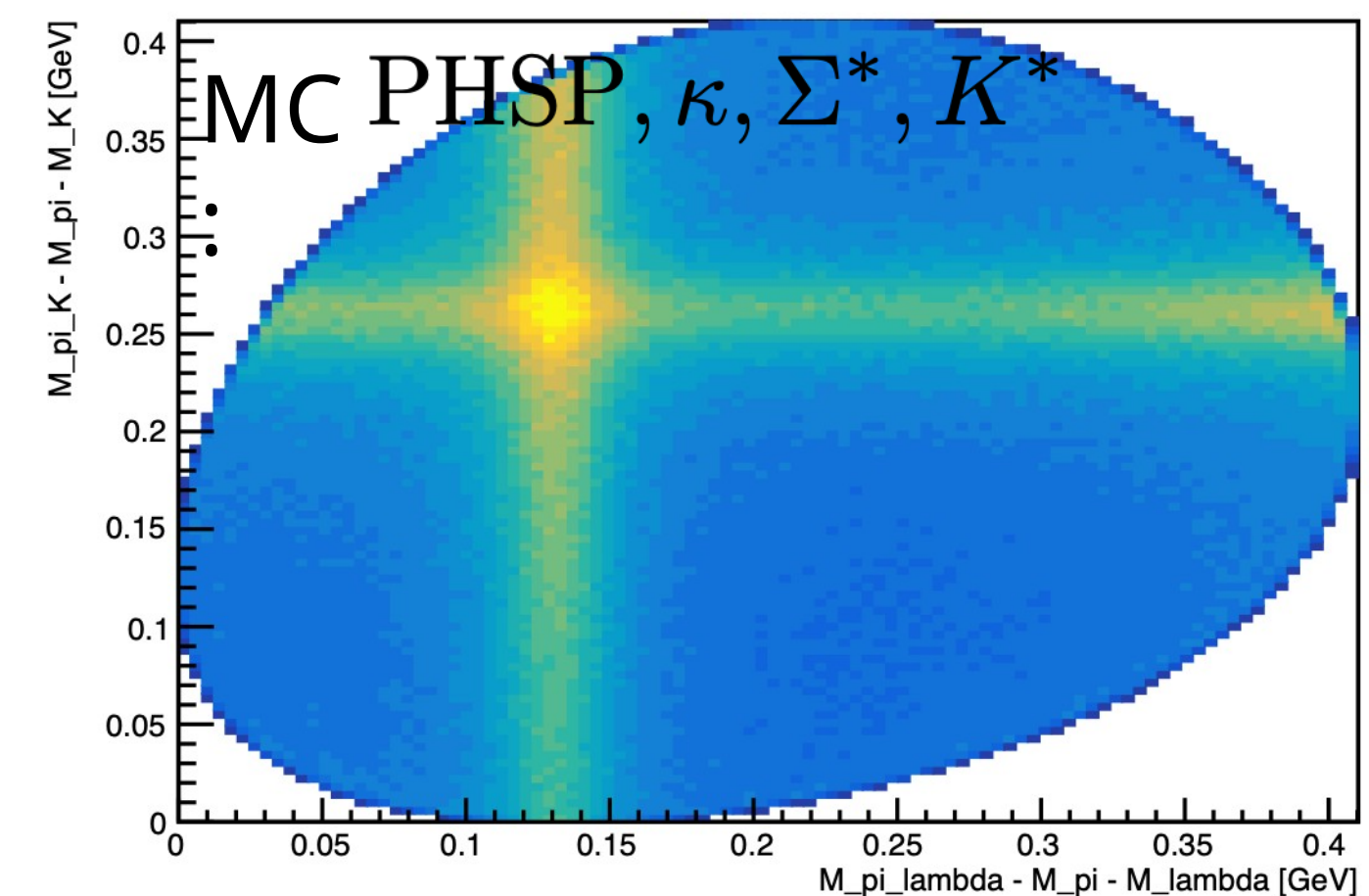


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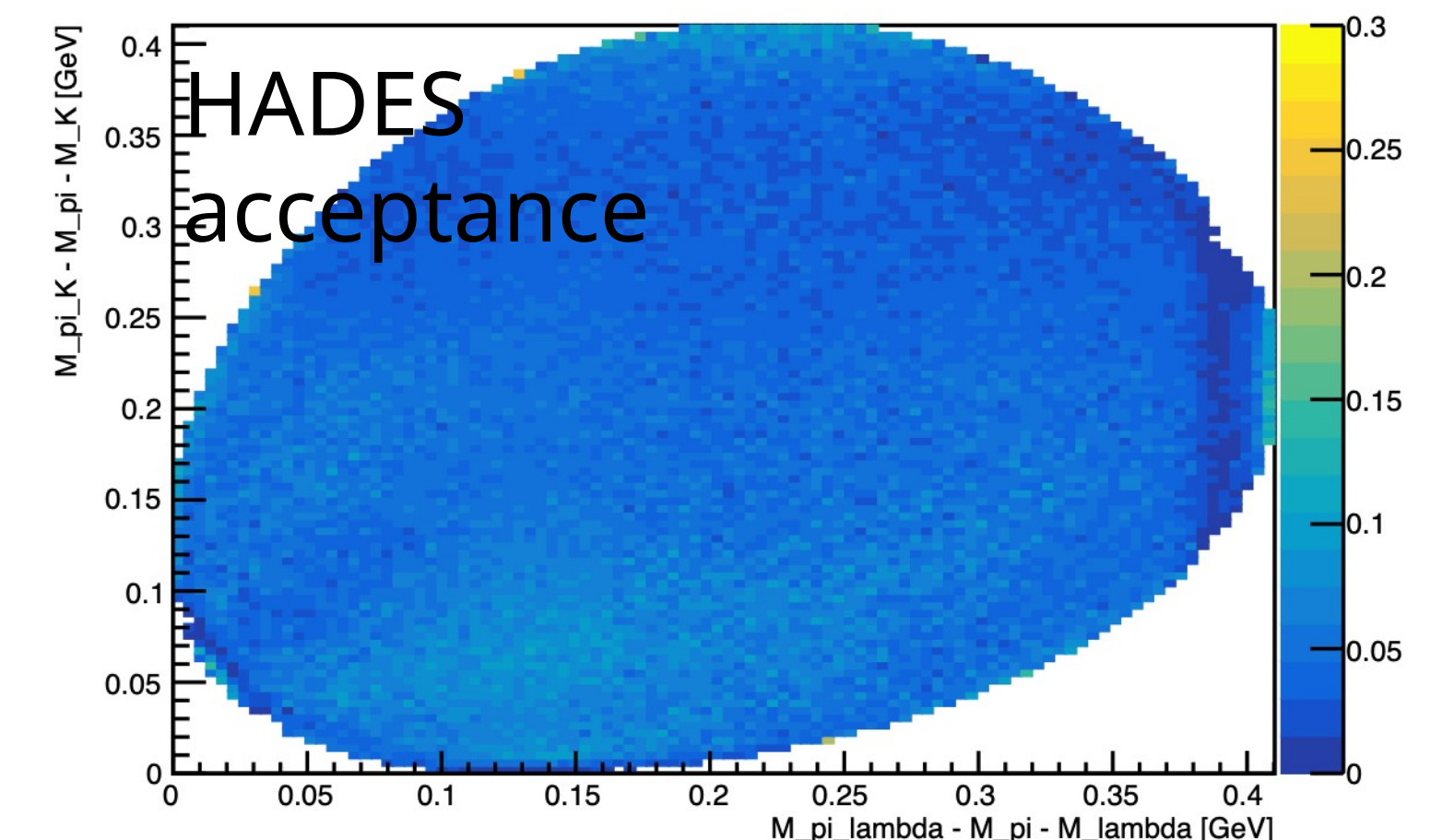
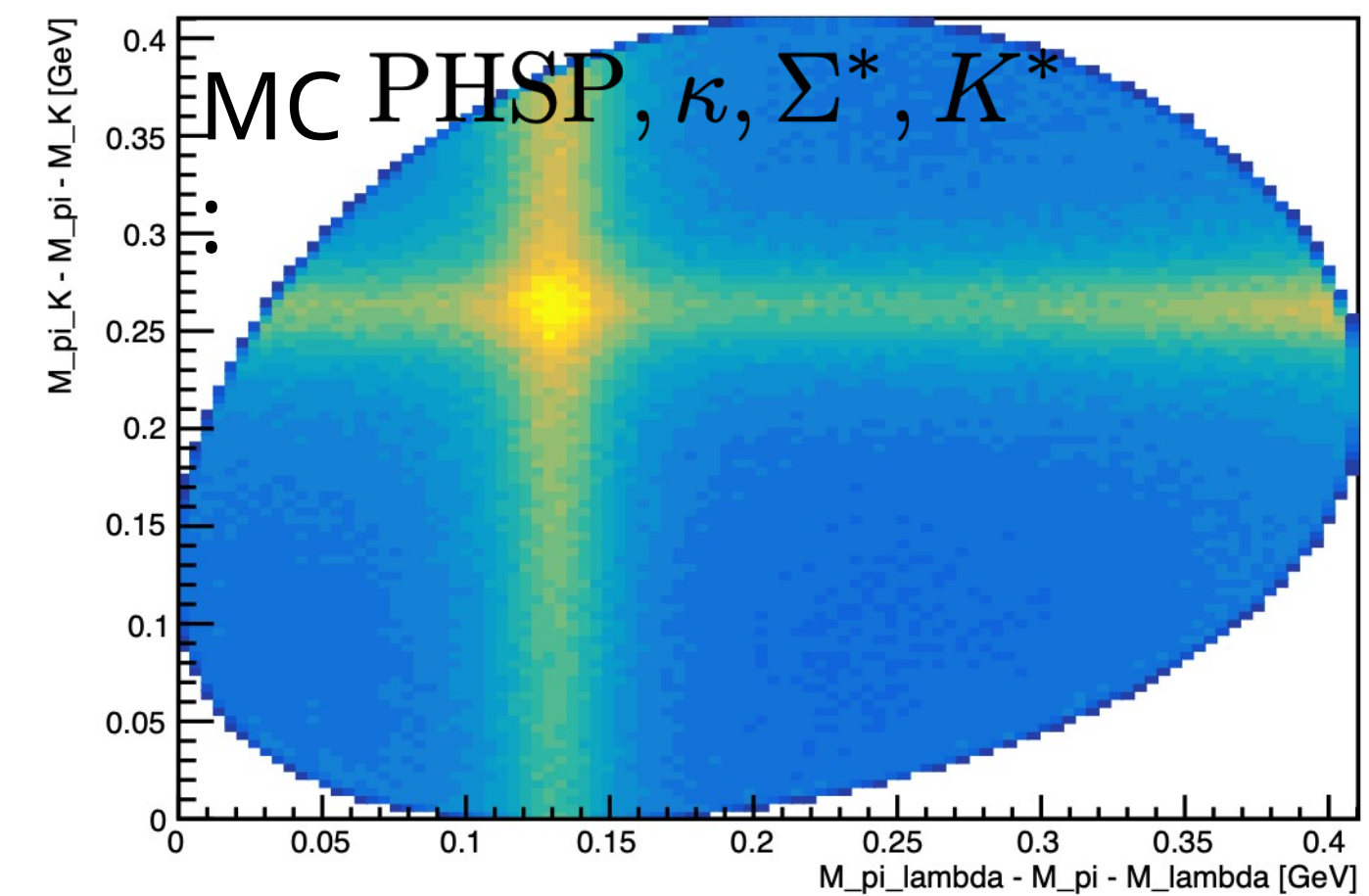


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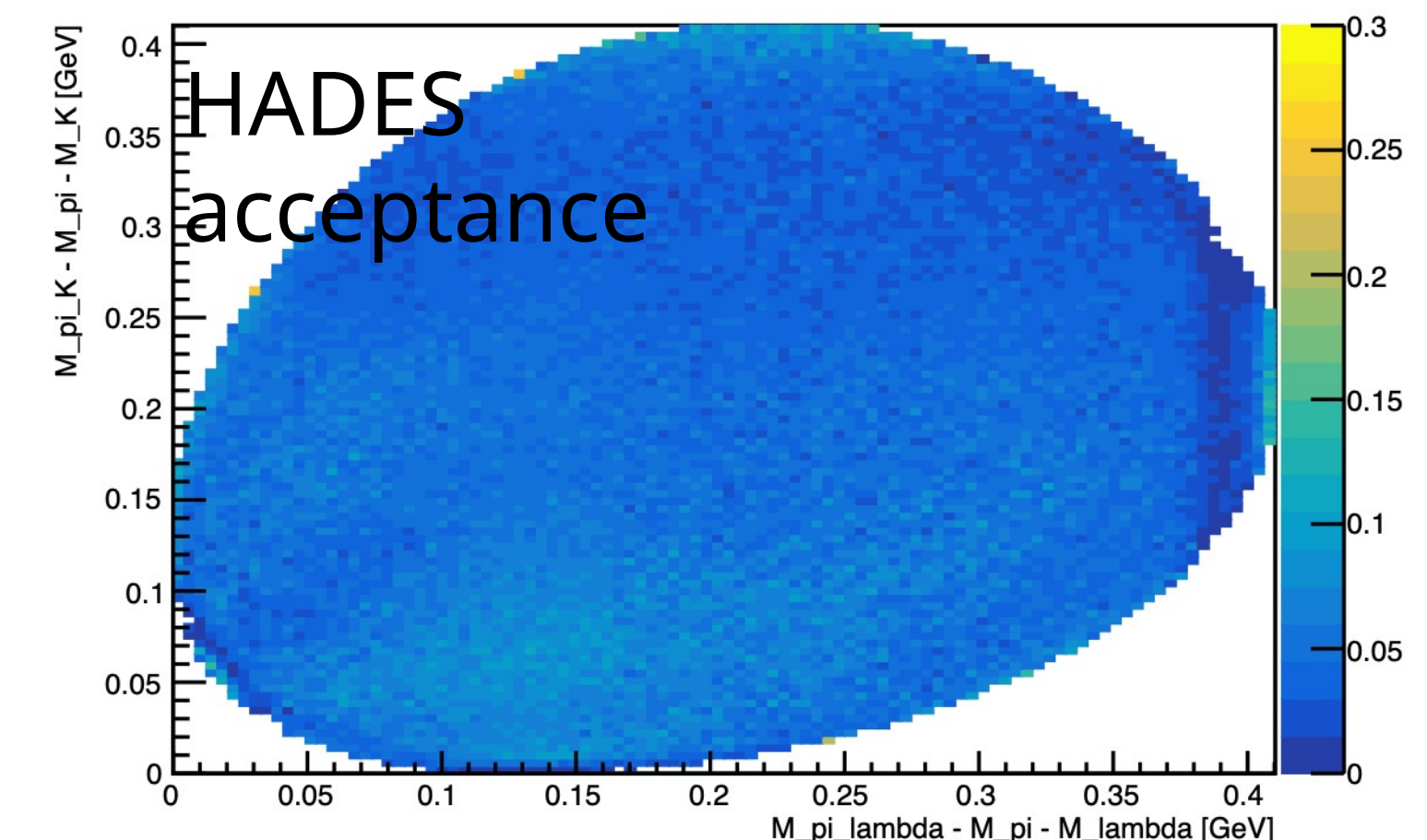
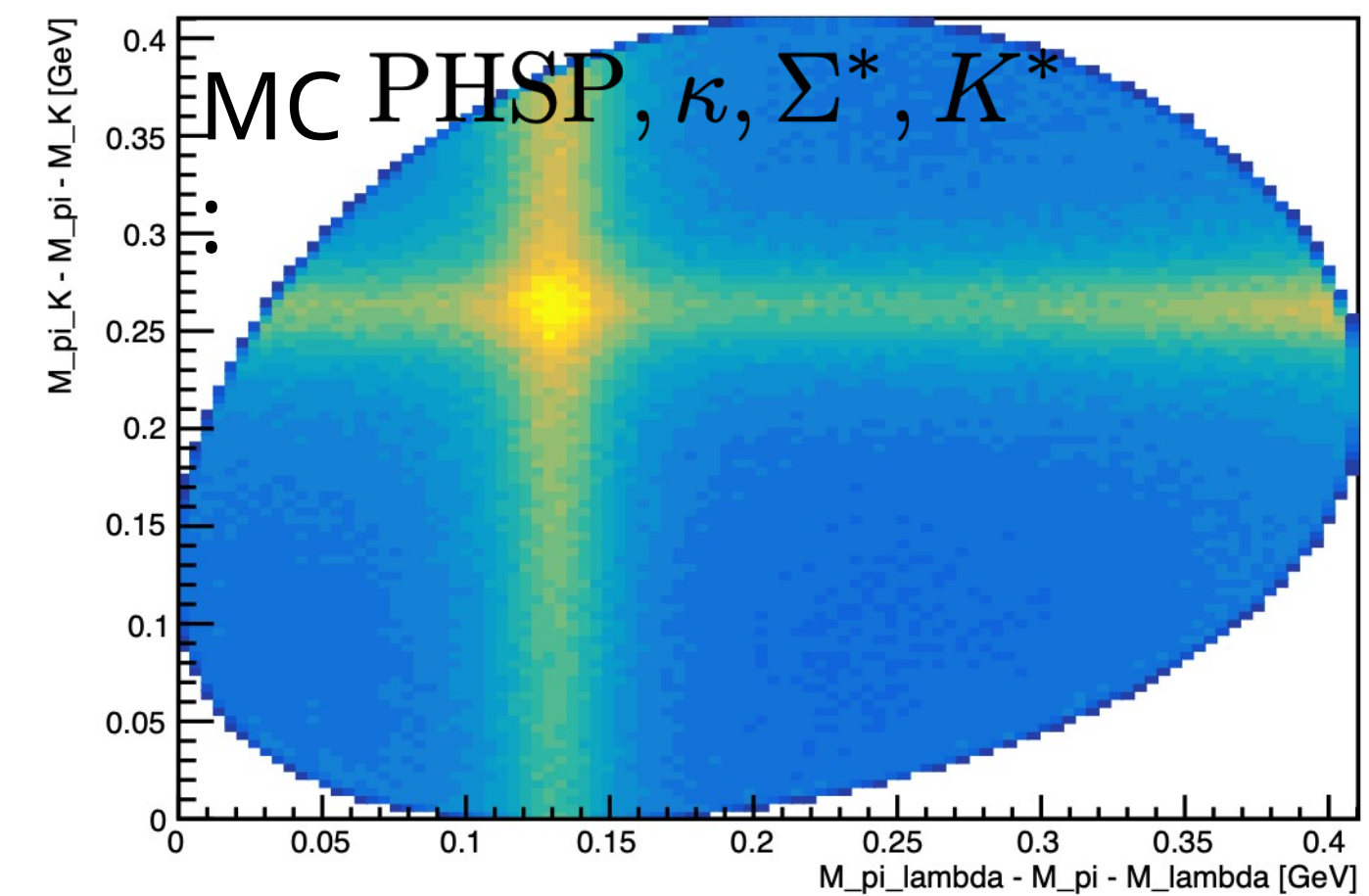


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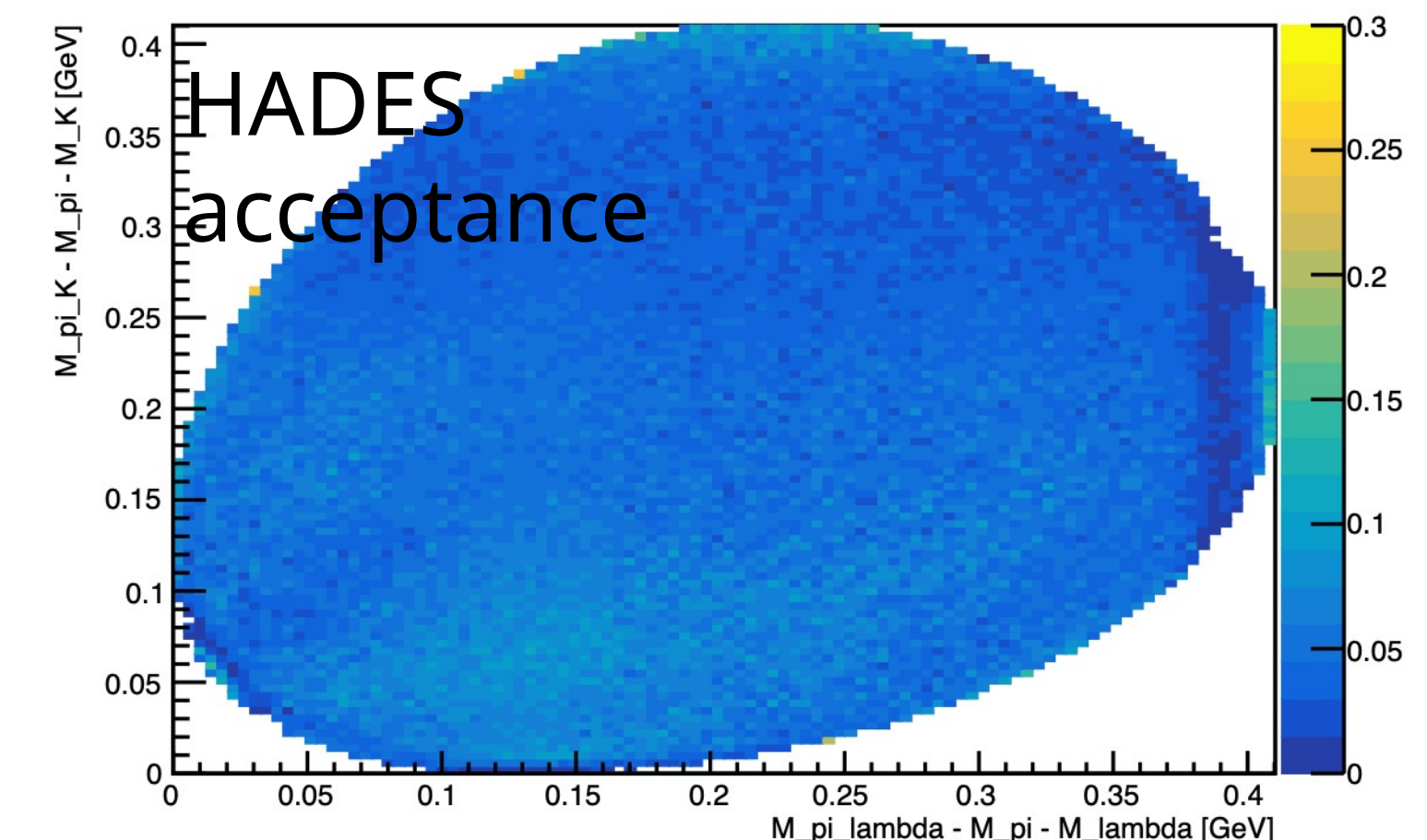
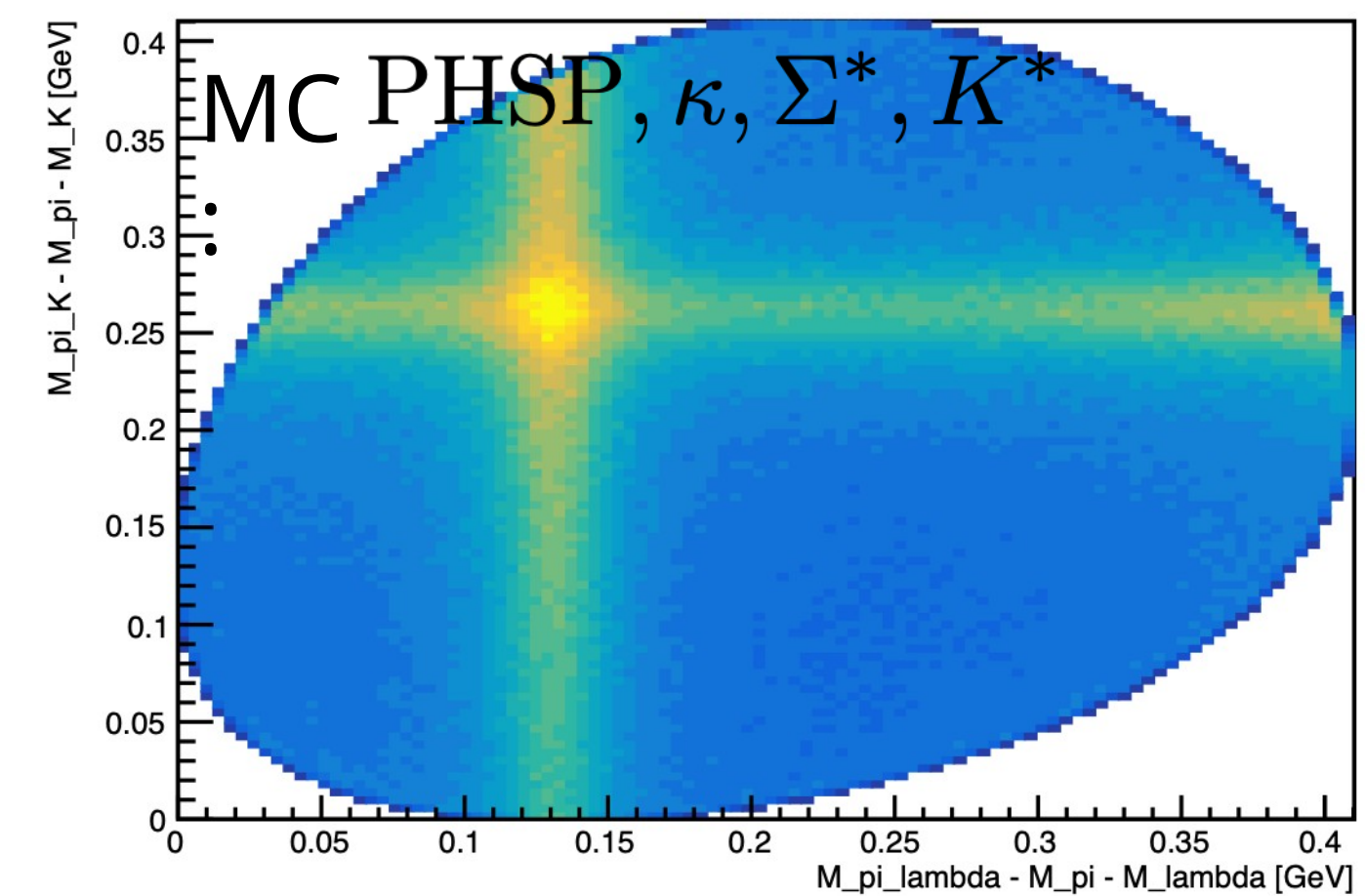


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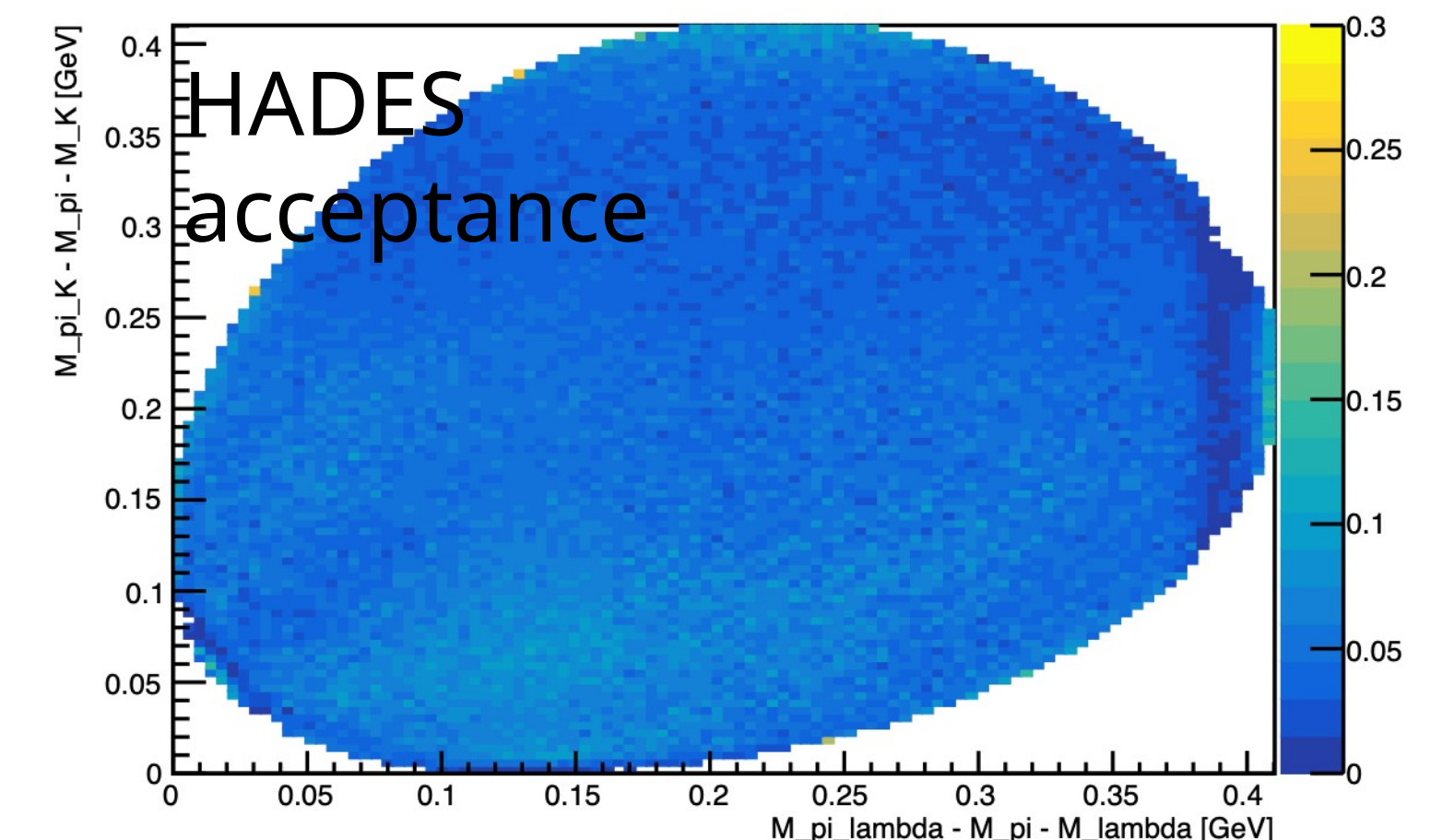
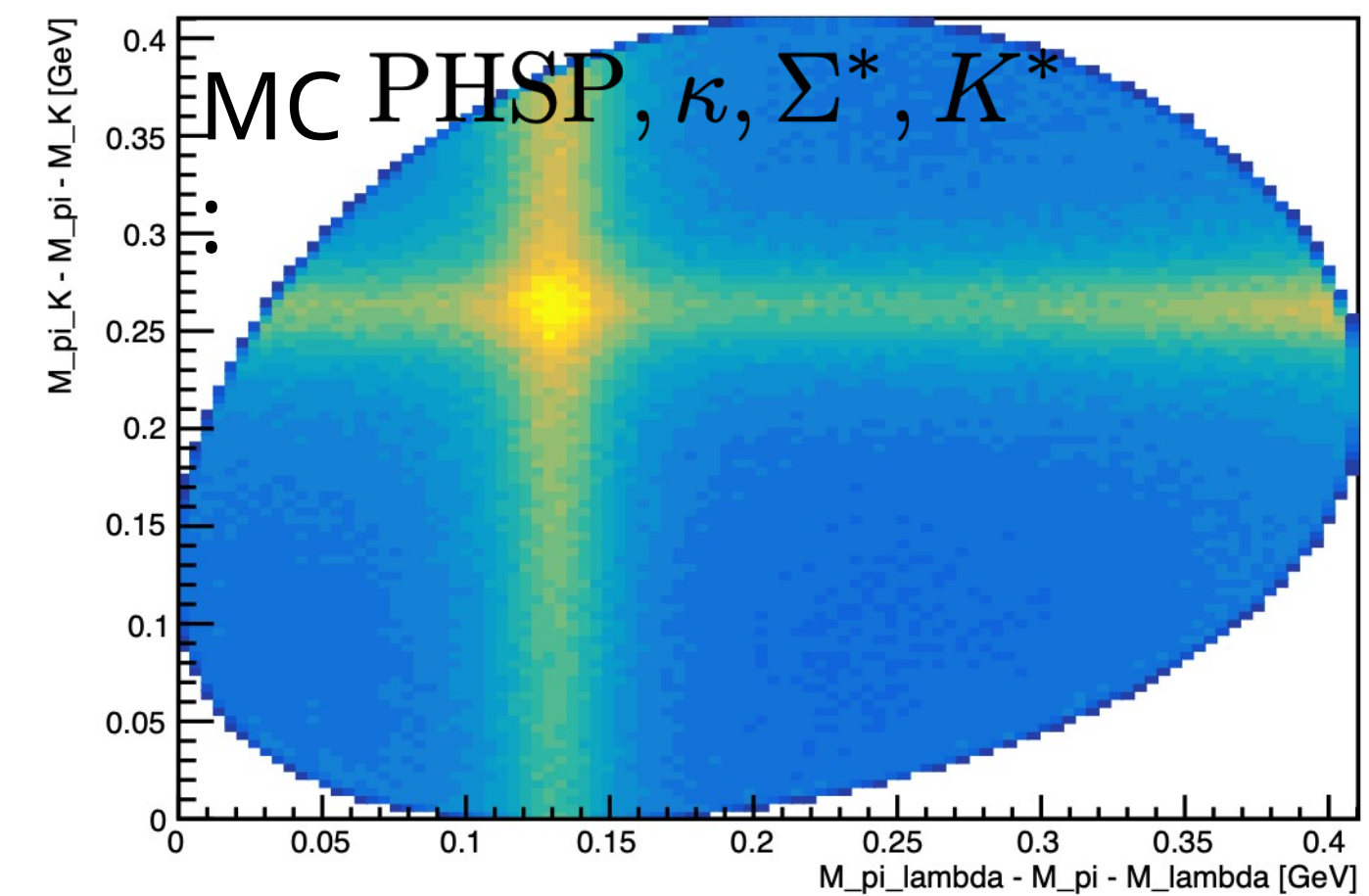


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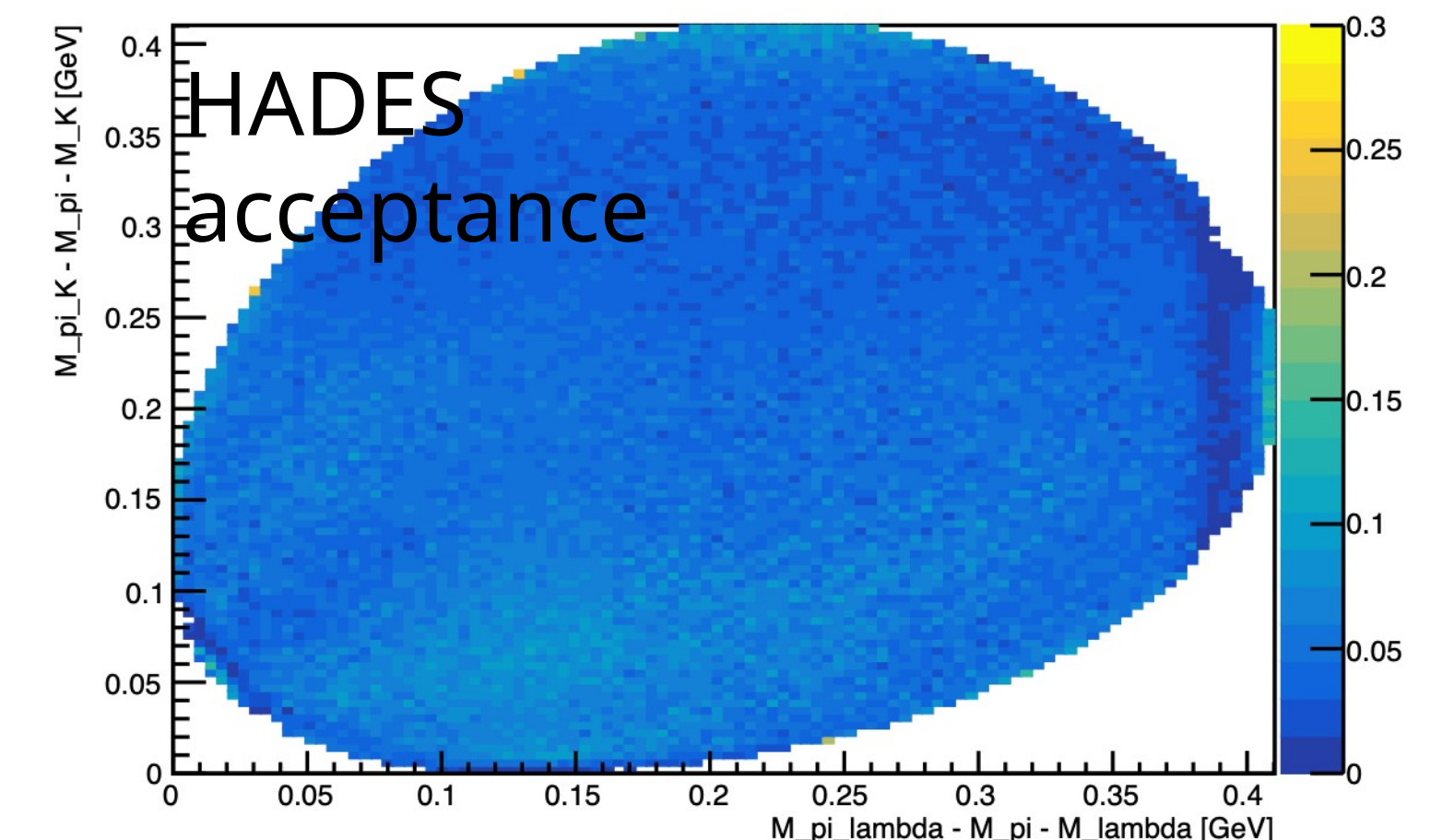
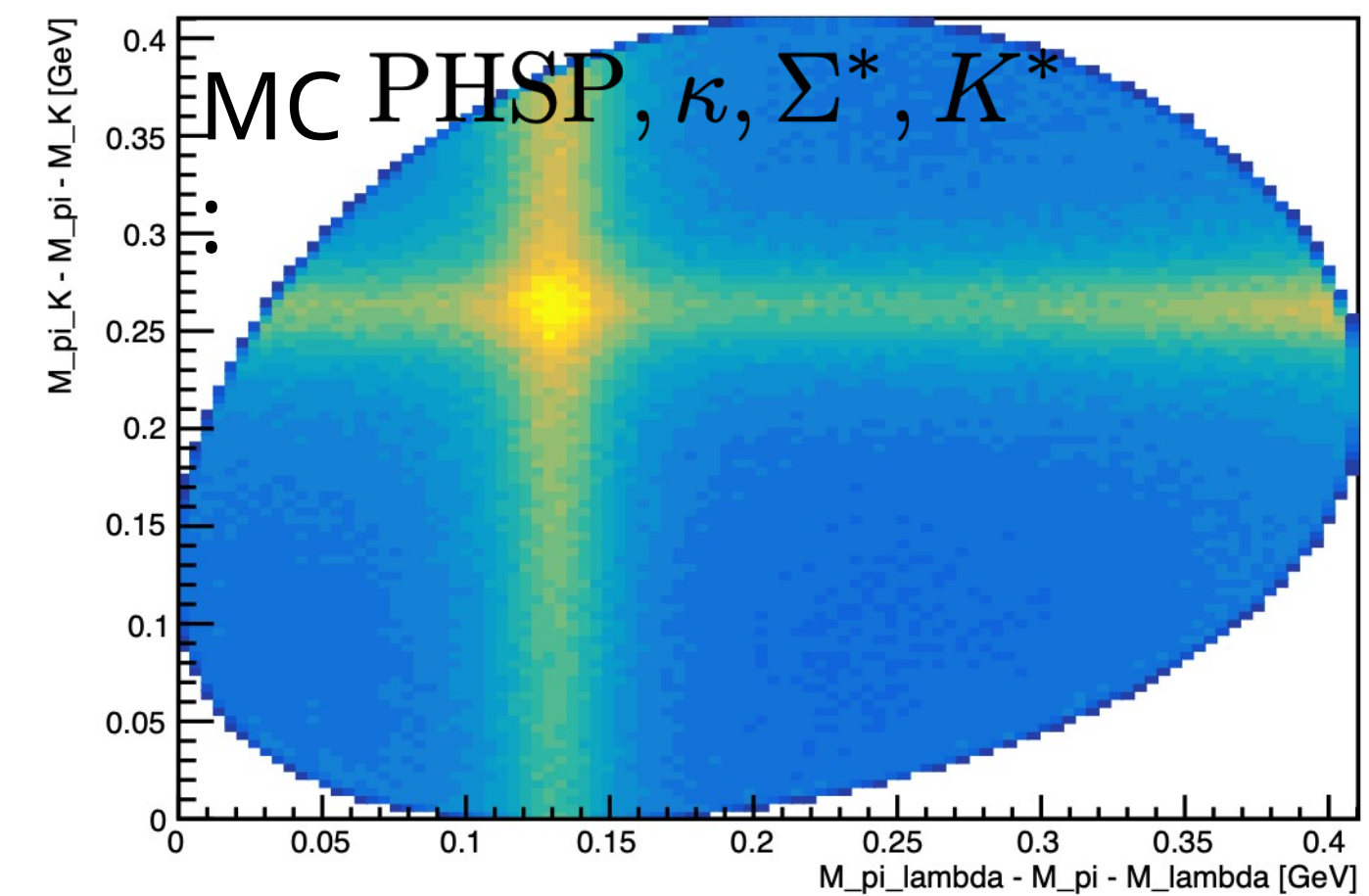


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# *Conceptual* long-term pion program





# Conceptual long-term pion program

## Stage 1: "N/\* $\Delta$ spectroscopy, dynamics and structure"

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



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

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

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

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

# “Facilities exploiting exclusive hyperon studies”



Timeline	2024			2028		2032	
Probe:	FAIR	Phase 0		FS+		MSVc	
$\pi + p/A$	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/...		



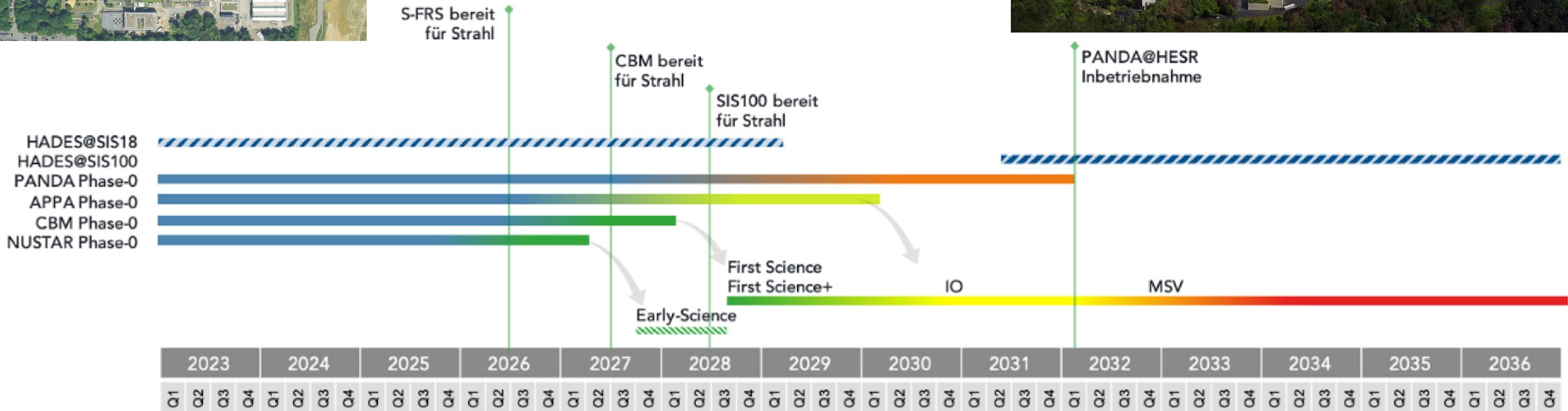
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Probe:	FAIR	Phase 0		FS+		MSVc	
$\pi + p/A$	Stage 1		HADES	Stage 2		HADES available? Stage 3	
	JPARC						
$p + p/A$	HADES@SIS18				CBM / HADES@SIS100?		
	CERN / JPARC / NICA						
$\bar{p} + p/A$							PANDA?
$K + p/A$				KLF			
	JPARC						
$\gamma^{(*)}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

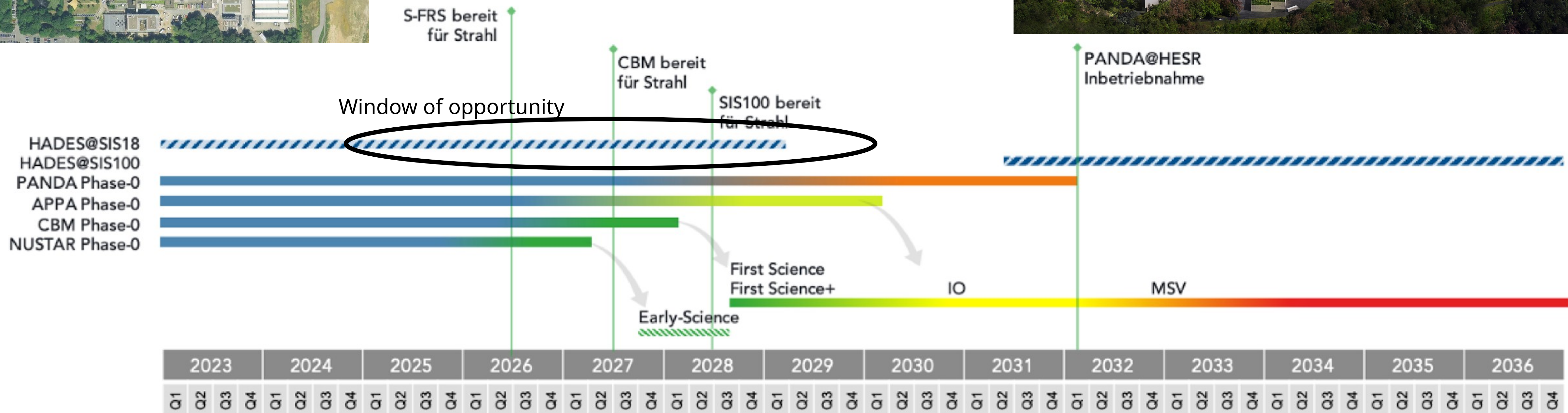


## ... from SIS18 towards SIS100





## ... from SIS18 towards SIS100





## ... from SIS18 towards SIS100

