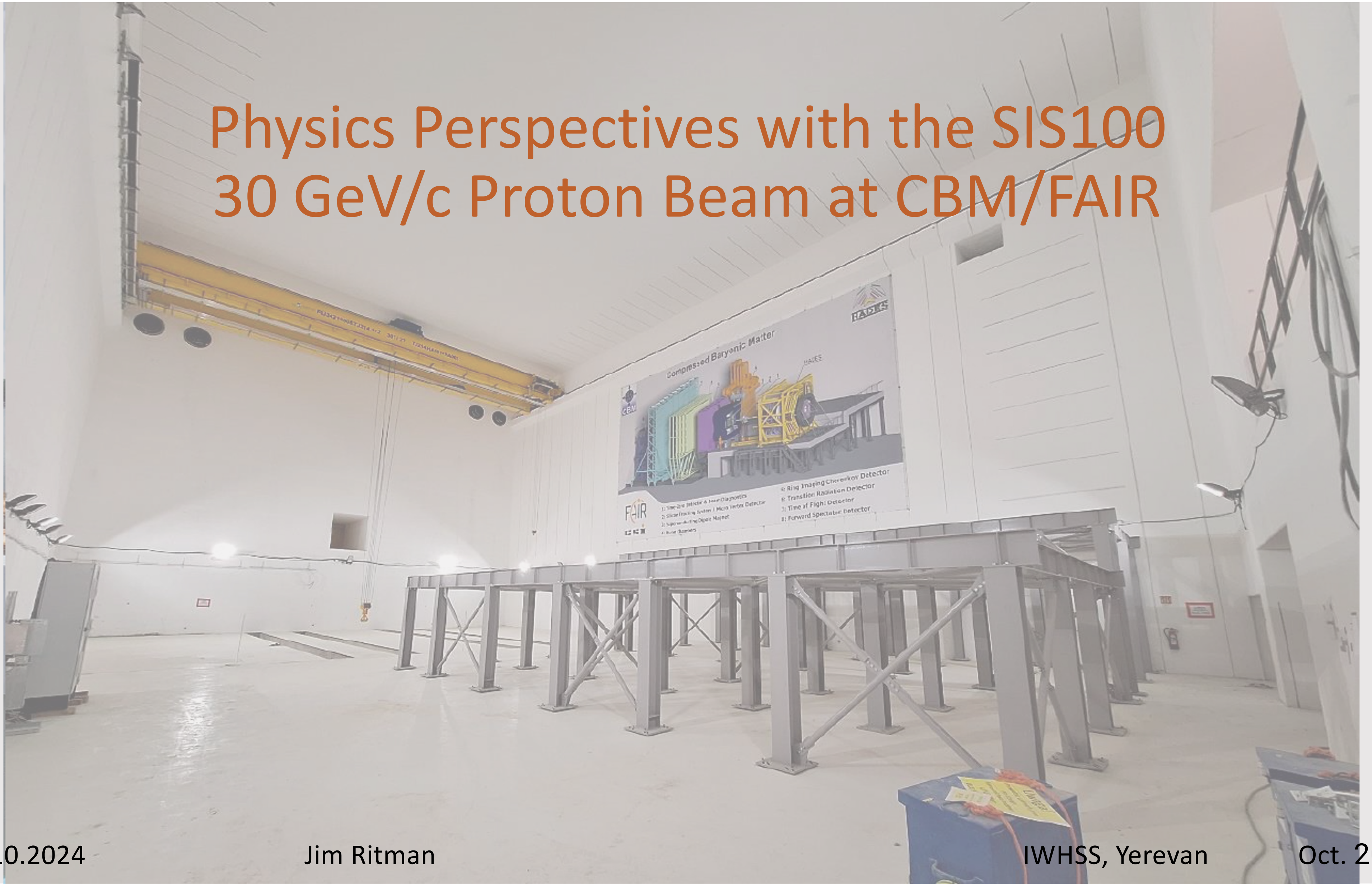
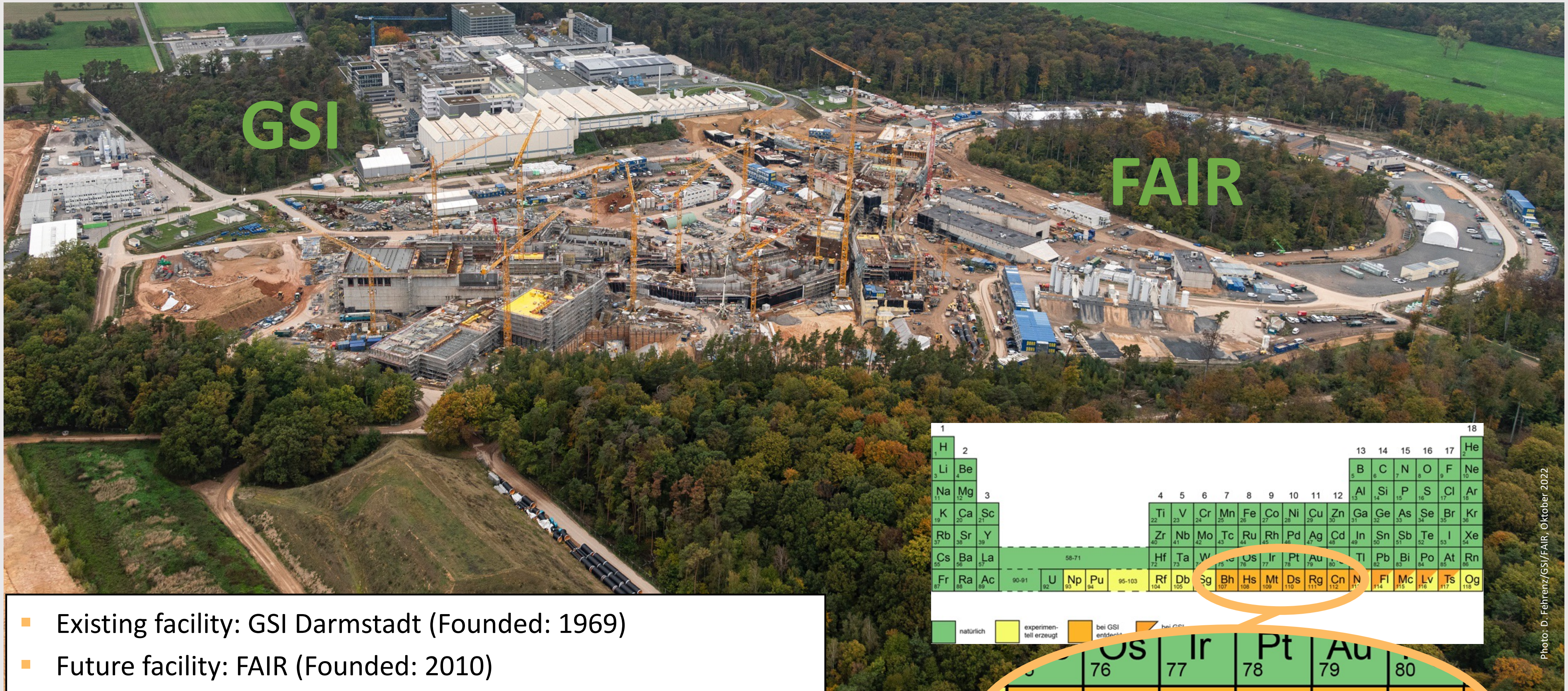
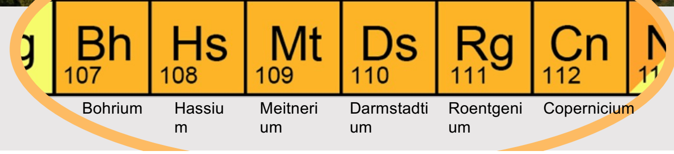
# Physics Perspectives with the SIS100 30 GeV/c Proton Beam at CBM/FAIR



# Accelerator Laboratories GSI and FAIR



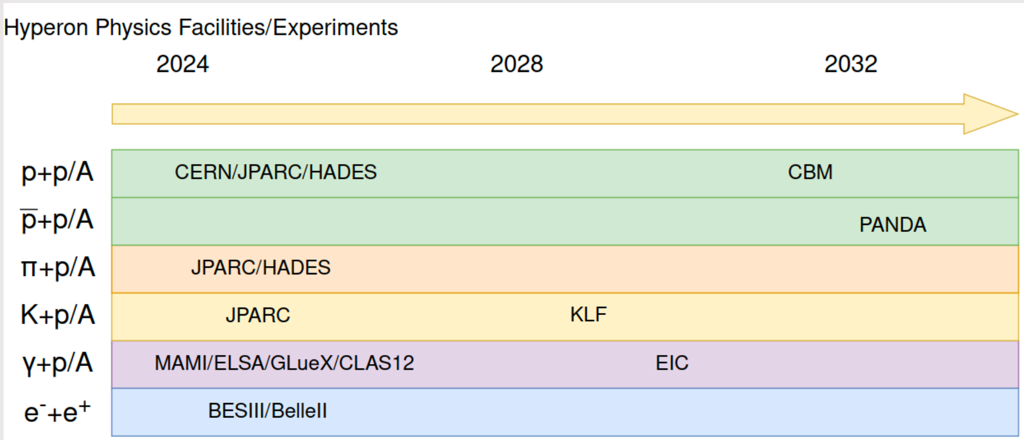




- Existing facility: GSI Darmstadt (Founded: 1969)
- Future facility: FAIR (Founded: 2010)
- Landmark in the European research roadmap (ESFRI)
- Employees on location: approx.1580

# Why Proton-Induced Reactions at SIS100?

- Currently, in this energy regime only poor data on pp and very little data on np multiplicities, spectra, correlations
- Theoretically complicated region to describe, transition from resonance to string production
- Good understanding mandatory for HIC

- Numerous $\gamma$, $\pi$, K facilites now and upcoming
- CERN primarily serves higher energy domain,
  → different production mechanism
- JPARC uses dedicated experiments,
  → complementary to CBM
- CBM can measure p- and A-induced reactions
  → backgrounds, systematics *etc.*




Jenny Taylor

# Overview

- |S| = 2, 3 Hyperon Spectroscopy & Production
- Ξ Hyperon Production: From pp to pA & AA
- ϕ Production and $K^-$ Rescattering
- Hyperon Interaction Studies
- Hyperon EM-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

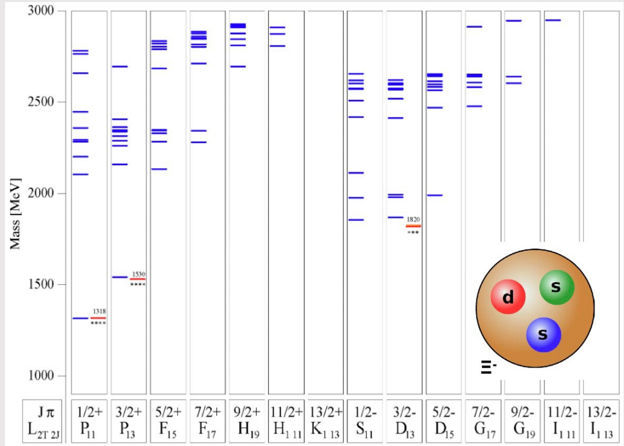
Strangeness

Charm

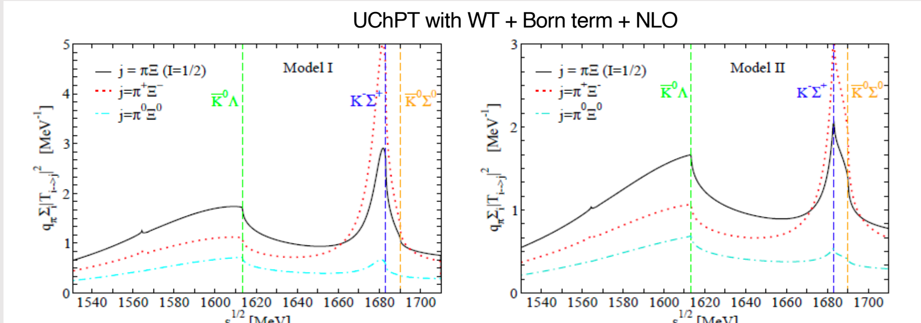
"Nuclei"

# |S| = 2, 3 Hyperon Spectroscopy

- Very little data exist for $\Xi^*$, $\Omega^*$
- More complete spectra needed for thermal & transport model calculations
- Learn about structure and nature, molecules, pentaquarks…
- Focus on excited $\Xi^*$ and $\Omega^*$ states at CBM
  - Sufficient c.m. energy for higher Y* plus associated particles
  - Resolve line shapes with ≈2 MeV resolution (*e.g.* Flatte)
  - PWA for Spin-Parity assignment
- Access to production mechanism via $N^* \rightarrow \Xi^*$ KK in exclusive pp reactions ?



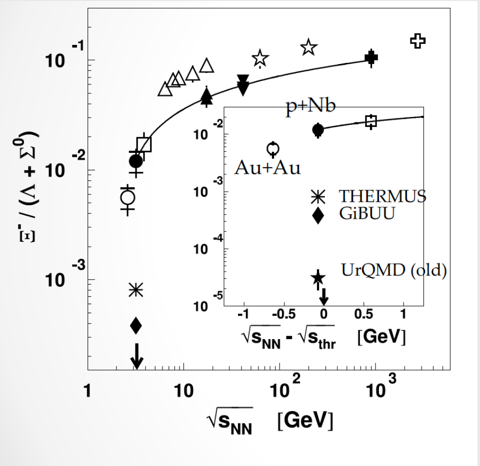

Quark models: U. Löring *et al.*, EPJA 10 (2001) 447




arXiv:2303.01323v1

# Ξ Hyperon Production: From pp to pA & AA

- Strong enhancement of near(sub) threshold Ξ cross section observed in AA (PRL 103, 132301 (2009))
- Confirmed in pA PRL114, 212301 (2015)
  → not Y-Y→ΞN exchange
- Could be explained by assuming significant
  N* → Ξ* KK populated by multistep processes
  J. Steinheimer *et al.*, J. Phys. G43 (2016) 015104




G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **80**, 025209 (2009)

# $\Xi$ Hyperon Production: From pp to pA & AA

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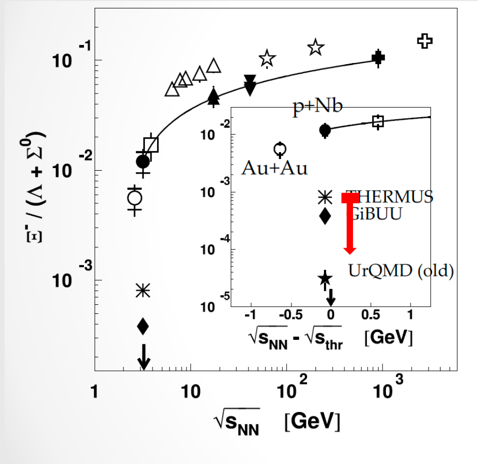
- Could be explained by assuming significant
  N* → Ξ* KK populated by multistep processes
  J. Steinheimer *et al.*, J. Phys. G43 (2016) 015104
- $\Xi$ not seen in pp 4.5 GeV at SIS18 (prelim HADES)
  upper limit: $\Xi/(\Lambda+\Sigma^0) < 0.5\ \mu b / 0.5\ mb = 10^{-3}$
- Does pp approach pA & AA at higher √s ?
  →SIS100 proton energy range

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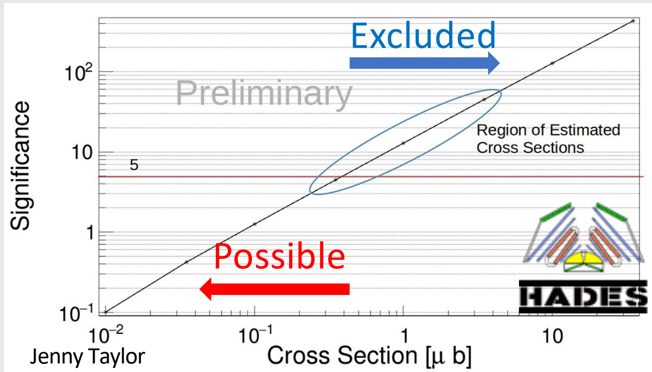
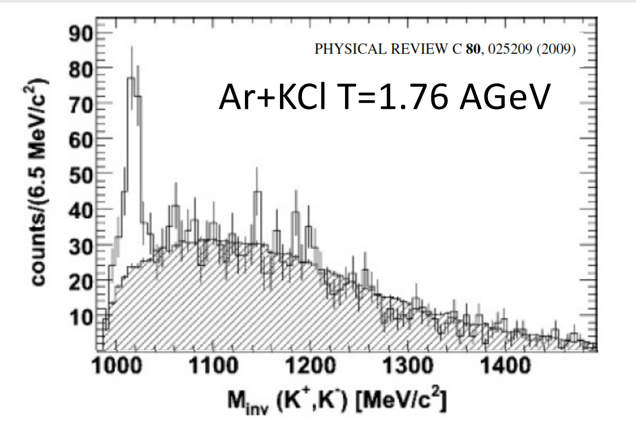
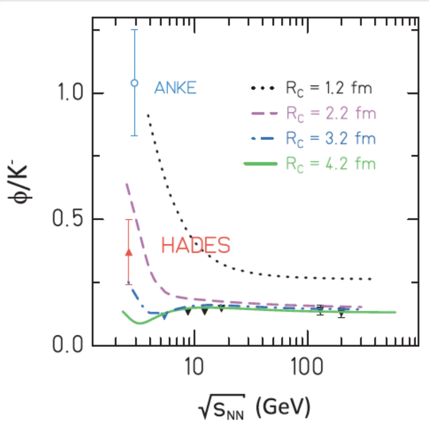
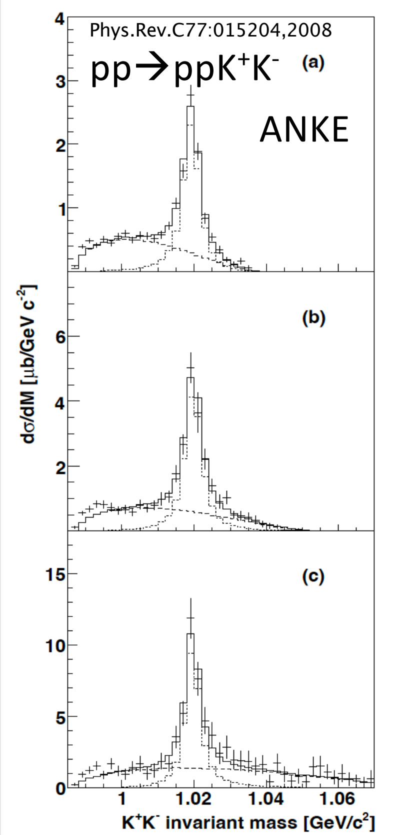


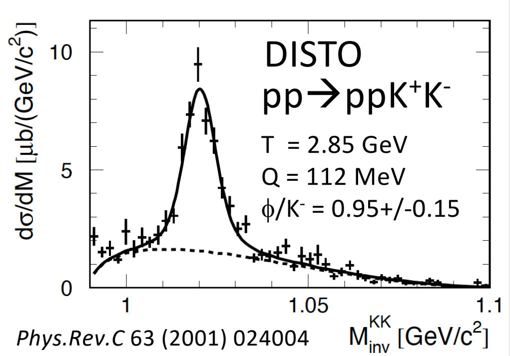
# $\phi$ Production and $K^-$ Rescattering

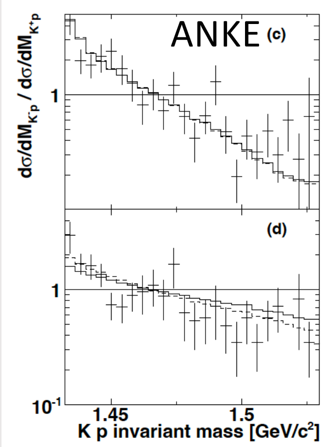
- $\phi/K^-$ ratio much lower in AA than pp
  Ratio rises close to thresh. (FOPI&HADES)
- Sensitive to interaction radius
- $K^-p/K^+p$ ratio vs $M_{inv}$ sensitive to Kp scat. length
- Subthreshold competition between multi-step production and $K^-N$ rescattering



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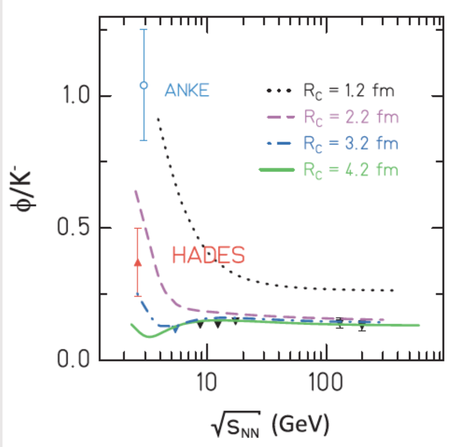
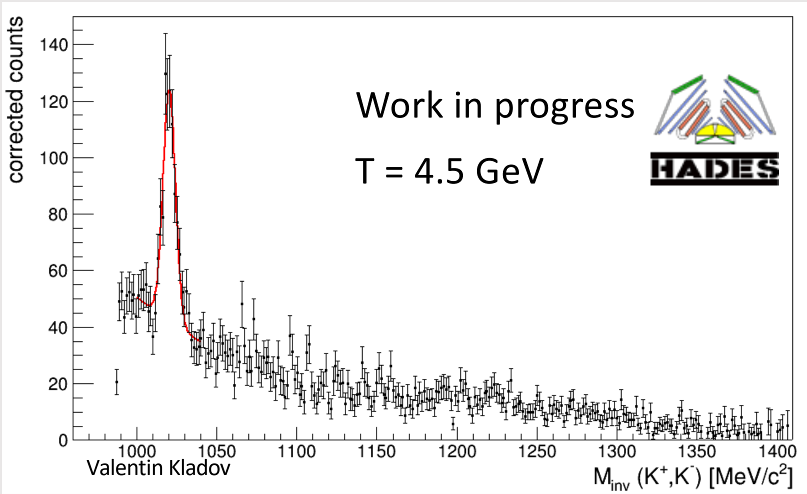
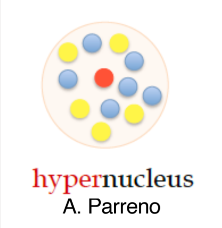
  Ratio rises close to thresh. (FOPI&HADES)
- Sensitive to interaction radius
- $K^-p/K^+p$ ratio vs $M_{inv}$ sensitive to Kp scat. length
- Subthreshold competition between multi-step production and $K^-N$ rescattering
- Big drop of $\phi$/K- ratio with increasing Q seen in HADES pp 4.5 GeV data (1.0→0.1)

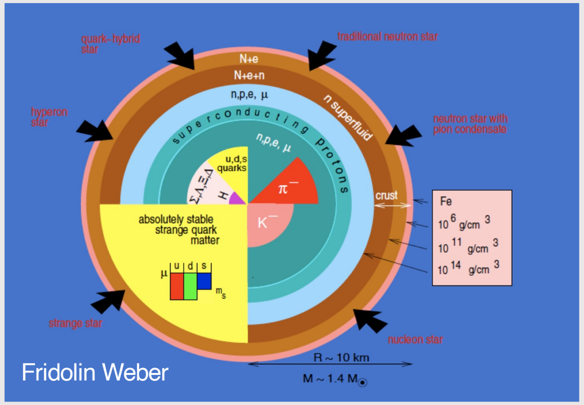


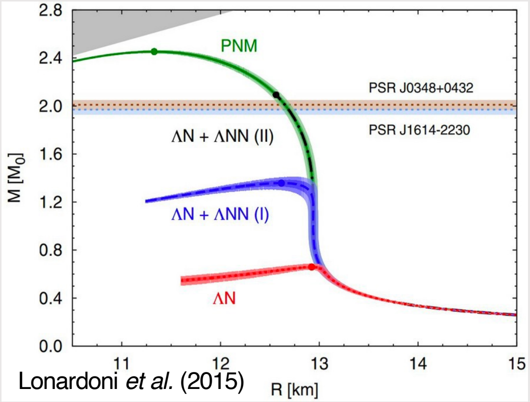



# Hyperon Interaction Studies: Hypernuclei

- $\Lambda$ as probe of nuclear structure
- Neutron stars: hyperon puzzle (*i.e.* $M_{allowed} < M_{observed}$)
  Y energetically favorable at 2-3 $\rho_0$, but soft EOS
- 3-Body interactions
  YN, YY, YNN
- Hypernuclei
  - -> 40 Λ - hypernuclei (ΛN attractive)
  - few Λ Λ - hypernuclei (weak attraction)
  - few Ξ - hypernuclei (ΞN attractive)

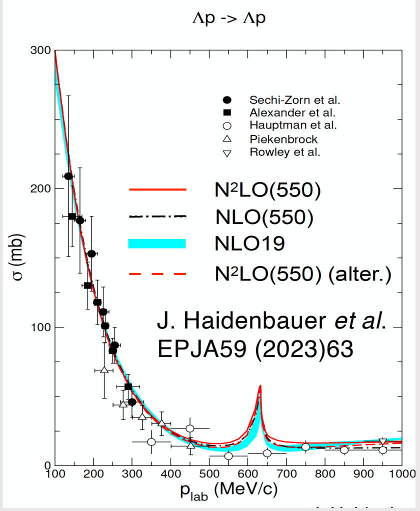


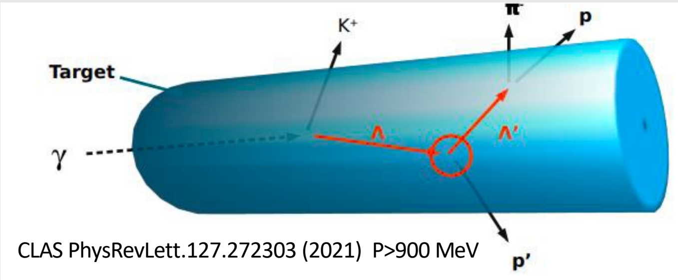



# Hyperon Interaction Studies: Λ-N Scattering

- Scattering data with hyperon beam
  - ΛN < 50 data points (poor beam quality, short lifetime, extrapolation down to low momenta)
  - NN > 5000 data points below 350 MeV

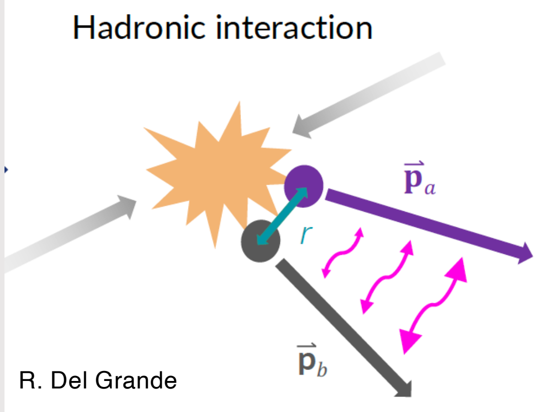


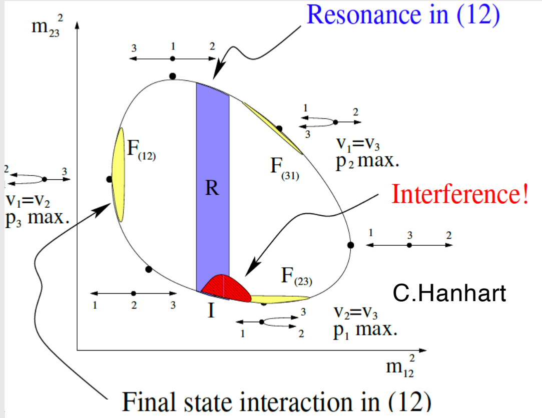



CLAS PhysRevLett.127.272303 (2021) P>900 MeV

# Hyperon Interaction Studies: Λ-N Scattering

- Scattering data with hyperon beam
  - ΛN < 50 data points (poor beam quality, short lifetime, extrapolation down to low momenta)
  - NN > 5000 data points below 350 MeV
- 2 methods to investigate Y-N (YNN) interaction using Final State Interactions (FSI):
  - Femtoscopy
  - Dalitz plot analysis of exclusive final states
  
  → more on both of these on next page

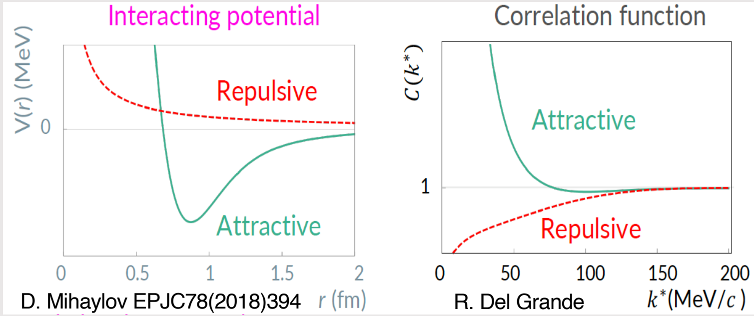


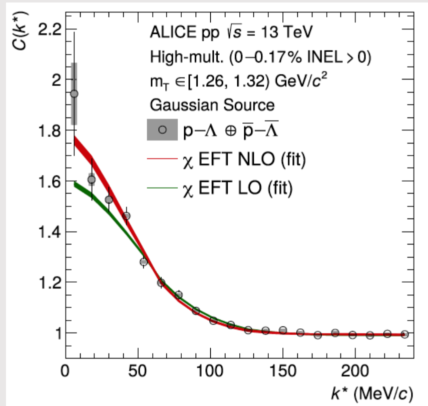



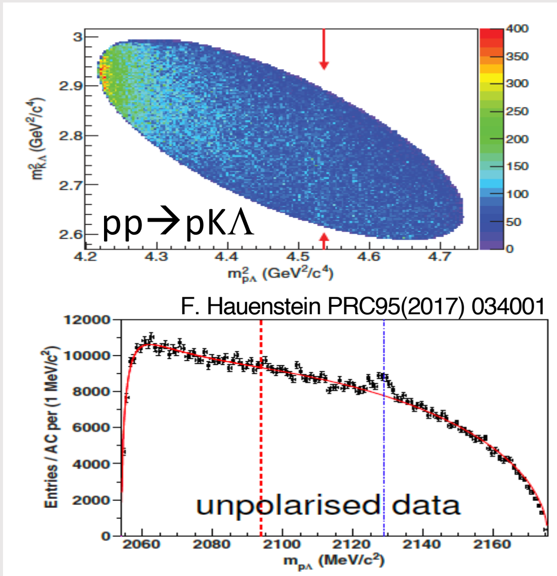
# Hyperon Interaction Studies: FSI

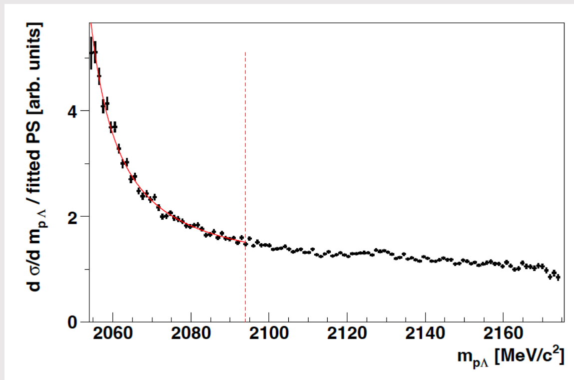
- Femtoscopy
  (measure C, fix S → interaction)
  - uncertainty hard to quantify
  - Source-size
  - Feed-down
  + Known spin weights
  → pSIS100: less feeddown than LHC
  → help separate S from elem. effects

- Dalitz plot analysis
  + controllable uncertainties
  + feed-down manageable
  - spin admixture unknown
    (polarized beam/target)
  → pSIS100: exlusive final states



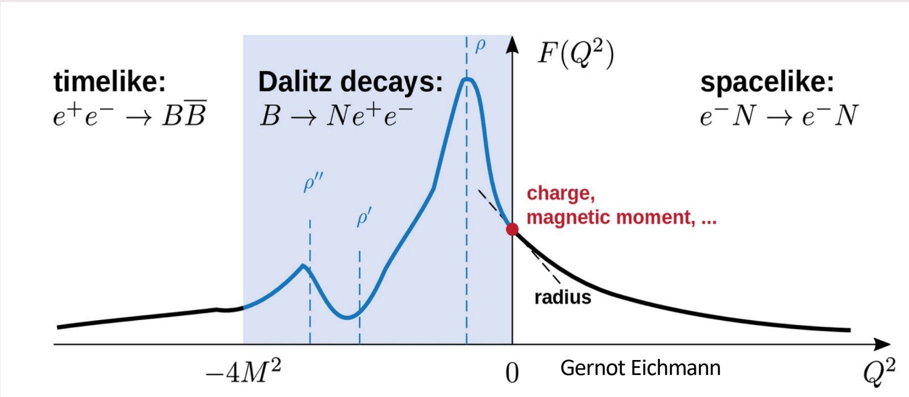



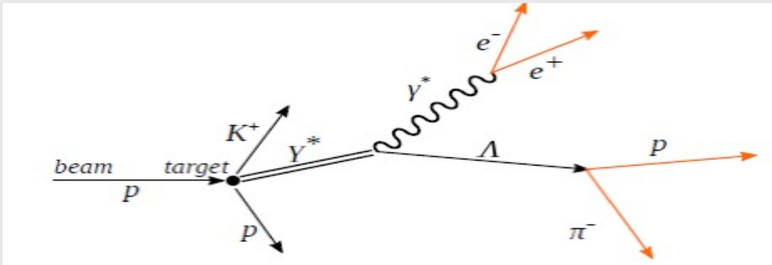



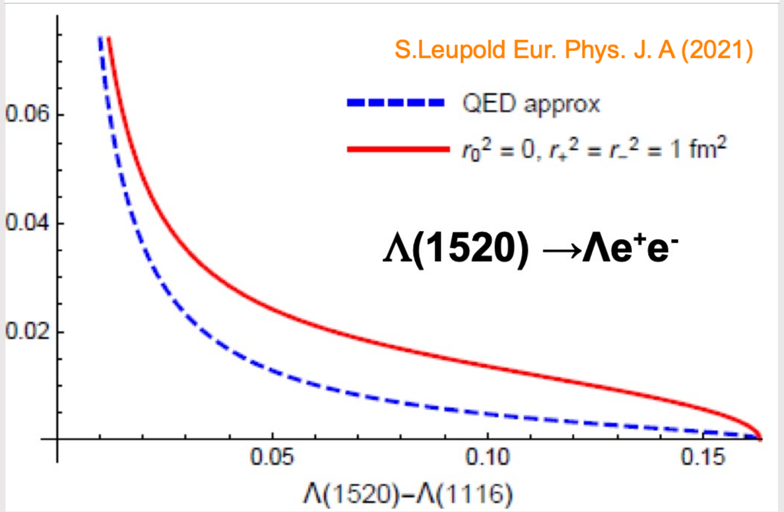



# Hyperon EM-Structure

- Measure Y*→Yγ*→Ye⁺e⁻
- Determine Electric and Magnetic TFFs
- Decay rates sensitive to structure
- Low BR → higher Lumi and σ at SIS100

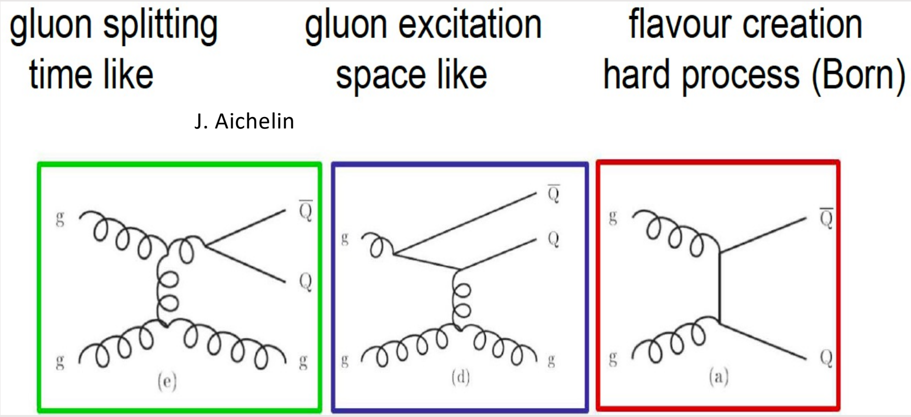


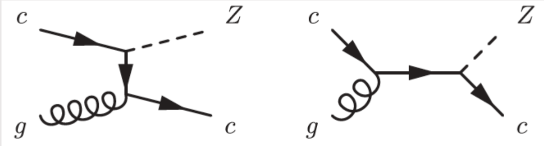
# PP J/ψ Final State

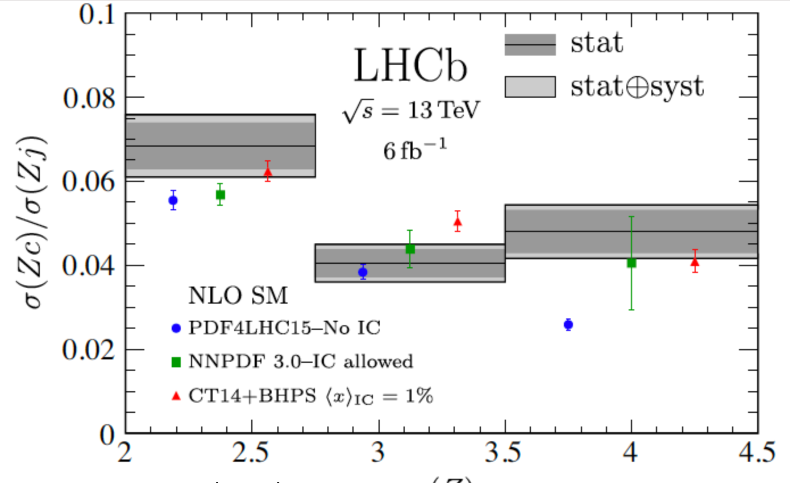
- Factorization questionable at 30 GeV/c,
  PDFs, Production via multiple gluon exchange ?



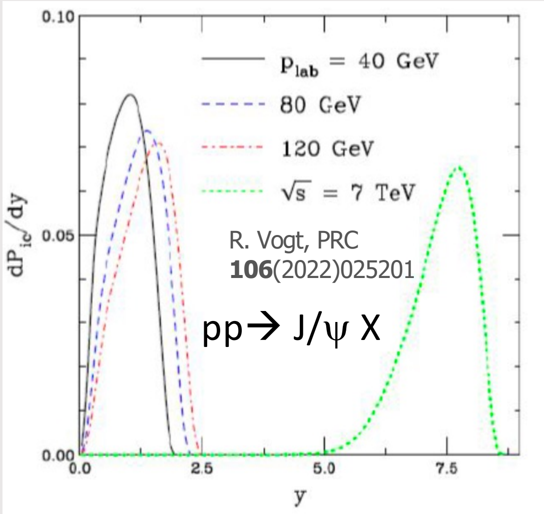
# PP J/ψ Final State

- Factorization questionable at 30 GeV/c:
- Intrinsic Charm
  LHCb measured Z+c-jets,
  enhancement at large $x_F$
  $|uudc\bar{c}>$ up to 1%
  lower $T_{beam}$ pp seems best
  need $p_t$ and Y distributions



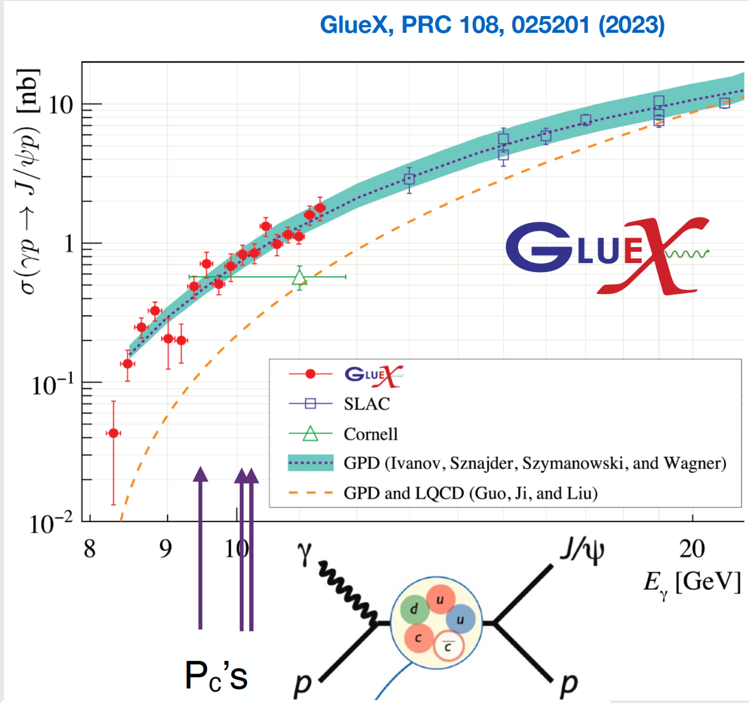


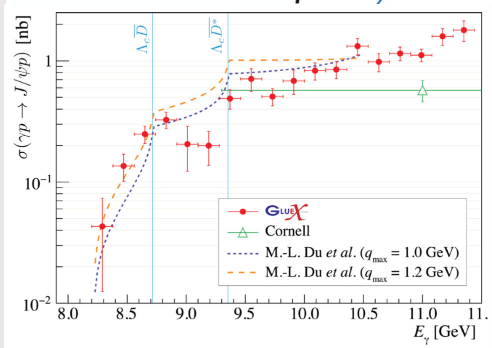
PRC128(2022)082001



# PP J/ψ Final State

- Factorization questionable at 30 GeV/c:
- Intrinsic Charm
- LHCb Pentaquarks not seen at GlueX
  - → Different production mechanism
  - → Structures near Open Charm thresholds (<3σ)?
  - → XYZ studies with pSIS100



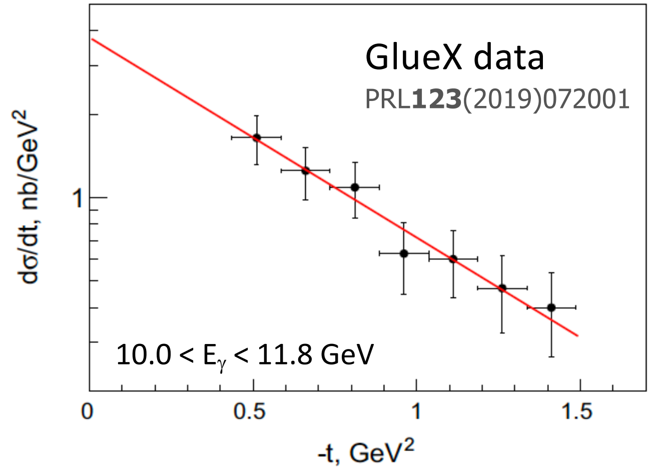
# PP J/ψ Final State

- Factorization questionable at 30 GeV/c:
- Intrinsic Charm
- LHCb Pentaquarks not seen at GlueX
- Forward (t=0) J/ψ dσ/dt related to J/ψ–N scattering amplitude, and nucleon mass via trace anomaly

$$F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 (1-b).$$

Eur. Phys. J. C (2020) 80:507

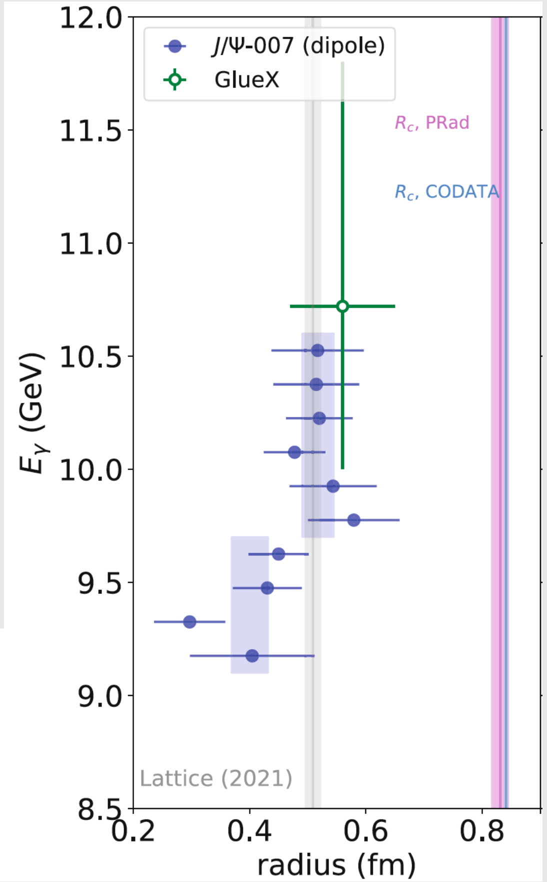
$$bM_N = \Sigma_{\pi N} + \Sigma_{sN}$$

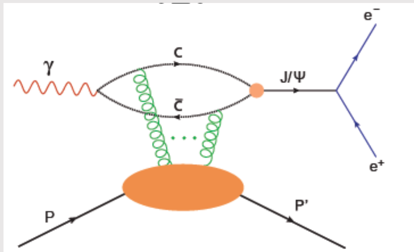


# PP J/ψ Final State

- Factorization questionable at 30 GeV/c:
- Intrinsic Charm
- LHCb Pentaquarks not seen at GlueX
- Forward (t=0) J/ψ dσ/dt related to J/ψ–N scattering amplitude, and nucleon mass via trace anomaly
- "Gravitational Form Factor"
  → fits to t-spectra at different $E_\gamma$
  → mass radius (most E carried by gluons)

Duran et al., Nature 615, 813 (2023),
*"Determining the gluon gravitational form factor of the proton"*



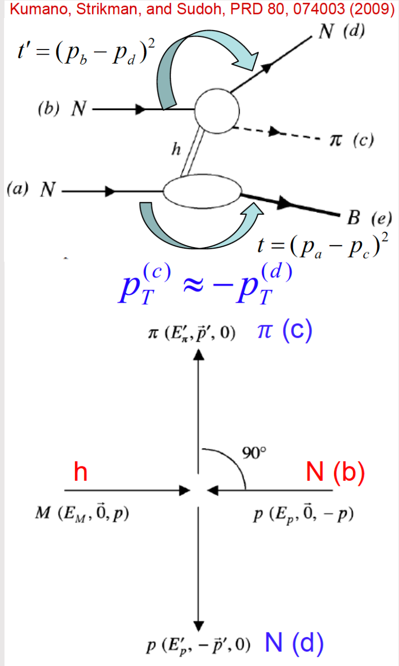



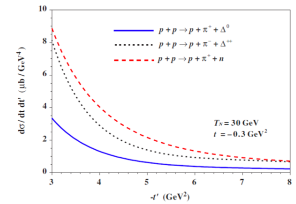
# Hard Hadronic Processes → Transition GPDs

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

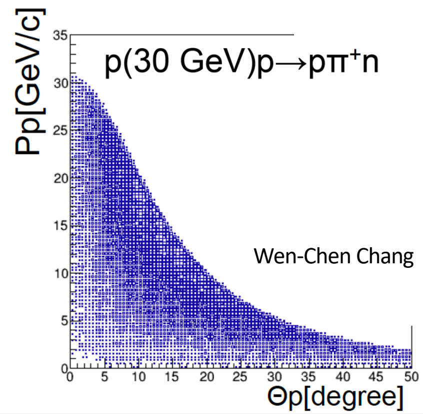
- a+b→c+d+e may access GPDs with proton beam
  Fourier transform of GPDs' dependence on $\sqrt{t}$ provides access to spatial distribution of quarks and gluons inside the hadron in slices of x
- Forward baryon B, and π N at ≈ 90°
- Limits to t' at JPARC E16 (30 GeV/c protons)
  $\Theta_{\pi,p} > 15°$, $\phi_{\pi\text{-}p} > 160°$
- CBM covers complimentary kinematics
  $\Theta_{\pi,p} < 25°$, all $\phi_{\pi\text{-}p}$ NCAL for forward neutron

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



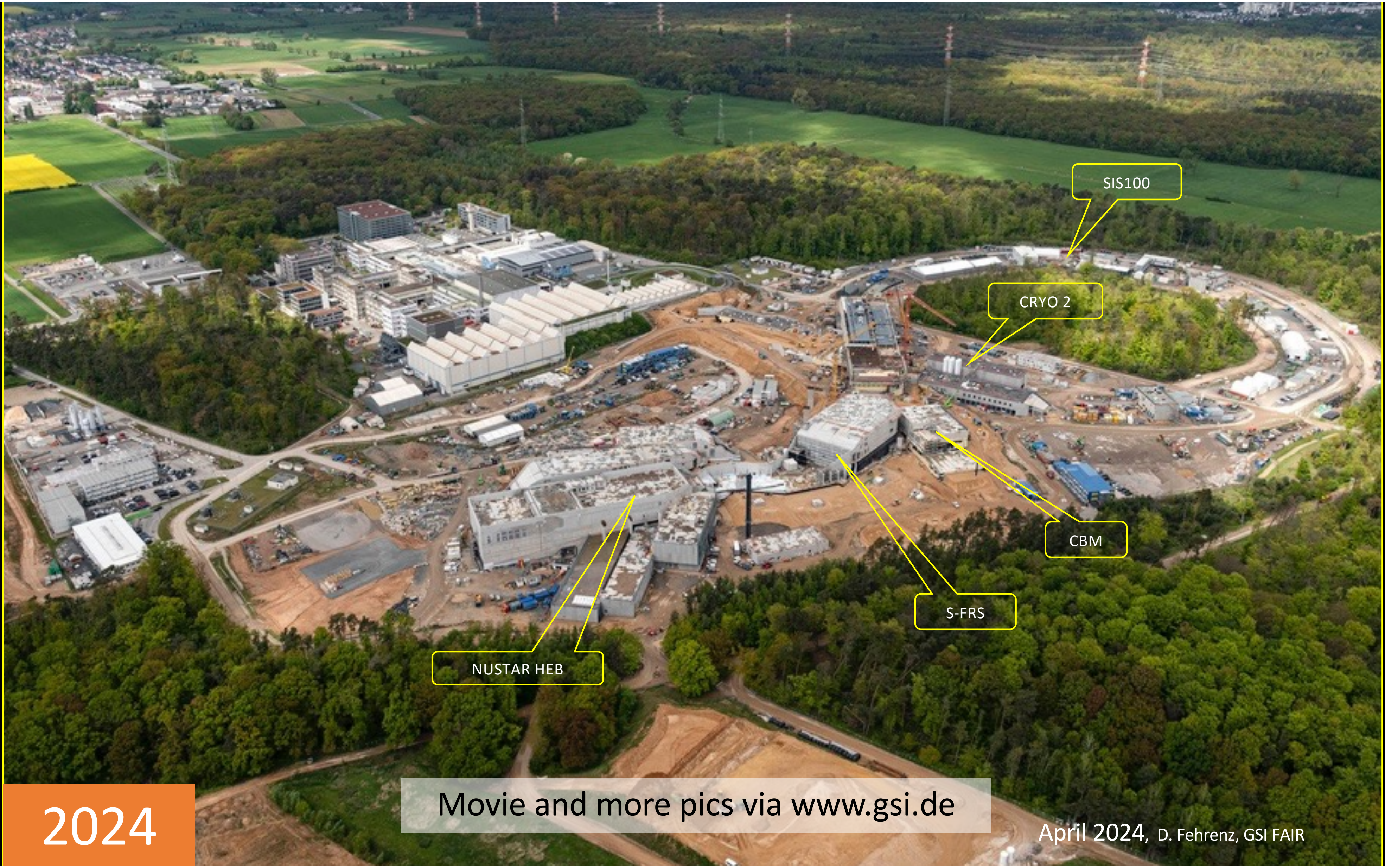

The measurement of –t' (~ qT of forward-moving N) dependence could be used to explore the x-dependence of GPDs.
Qiu & Yu, JHEP 08 (2022) 103, PRD 107 (2023) 014007, arXiv:2305.15397



# Proton-Beam as Input for AA Physics

- PP / PN Interactions
  - ’input’ (hadron production cross sections, momentum distributions) in theoretical models in order to obtain robust conclusions on in medium dynamics in heavy ion collisions
  - Reference for nuclear effects (*e.g.* R(AA/NN ), slope parameter etc.)
  - Polarization of dileptons
  - Isospin effects, *e.g.* $pp \rightarrow pp\phi$ vs $pn \rightarrow pn\phi \approx 0.25$ expected, sensitive to intrinsic strangeness
- PA Interactions
  - Isospin effects on had. prod. with light nuclei (Be, C): indep. constraint on p+n and n+n reactions and baryonic ($\Delta$, N*) resonance excitations
  - ’cold’ nuclear matter (at $\approx \rho_0$) with p + heavy nuclei (Au, Pb, U)
  - In medium effects up to $\rho_0$
    role of rescattering and baryon absorption mechanisms
    cumulative particle production with large momentum
    “subthreshold” particle production
    NN potential
    cluster production

Elena Bratkovskaya


SIS100
CRYO 2
CBM
S-FRS
NUSTAR HEB
2024
Movie and more pics via www.gsi.de
April 2024, D. Fehrenz, GSI FAIR

## FAIR Highlights – Integration
## Units are being installed in the tunnels
## Commissioning from 2025 onwards

April 2024


Compressed Baryonic Matter
HADES
CBM
FAIR
Ring Imaging Cherenkov Detector
Transition Radiation Detector
Time of Flight Detector
Forward Spectator Detector
2024


2028
© GSI/FAIR, Zeitrausch

# FAIR Commissioning is Starting

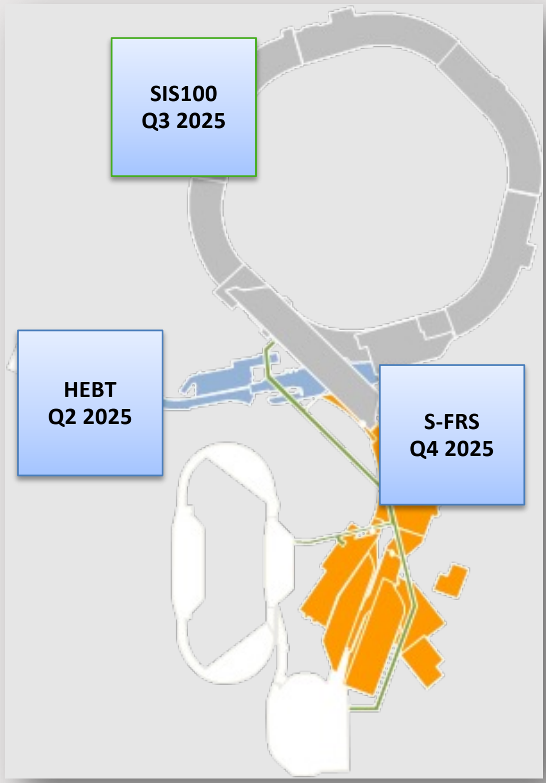
- First steps are being made in 2024
  - Helium is being bought
  - Fellow and Associate program will start

- In 2025 Commissioning to start for real

- Commissioning Phase to run until 2028

- Operation Phase from 2029 onwards

Start of ACC Commissioning



# Summary

- Tremendous physics potential with proton beam from SIS100, from heavy ion dynamics to hadron production and spectroscopy
- CBM seems well adapted to this pp program
- Competitive and complementary program to other facilites world-wide
- Preparations for a “white-paper” beginning

→

# “White Paper”

Explore physics potential at SIS100
Feasibility based on FASTSIM-CBM
In planning phase
Goal: → JSC

About 60 people contributing
→ More highly welcome

Afterwards: concrete proposal at CBM

0. **Executive summary**
1. **Introduction**
- key questions in strong QCD
- context, objectives, process of whitepaper
2. **Exploiting proton (and pion) beams in the field of QCD matter**
- general key features
- state-of-art in experiment and theory
3. **Hadron-hadron interactions**
- femtoscopy
- final-state interaction & partial-wave analysis
- meson-baryon interactions
- charm-nucleon dynamics SU(4)
- hypernuclei
4. **Hadron spectroscopy**
- baryon spectroscopy: double+triple strangeness
- charm spectroscopy
- spectral/line-shape studies
- exotics such as diquark correlations
5. **Structure of hadrons**
- e.m & weak transition form factors of hyperons
- Structure of the proton: intrinsic charm, EHM, GFF, GPDs
6. **Hadron production mechanism**s
- production mechanisms of light mesons, strangeness and charm
- near-threshold production studies of hadrons in p+p/A
- connection to LHC energies/neutrino physics
7. **Hadrons as probes to study dense matter**
- elementary p+p, p+n reactions
- hadron properties in dense matter
- connection to dilepton spectrum
- short-range correlations
8. **Experimental infrastructure**
- GSI/FAIR proton (& possibly pion-beam) facility
- experimental setups: hades, cbm
- modifications to enable elementary proton-driven studies
- international play-field
9. **Discussion & conclusions**
- summary
- roadmap

# SPARES

# Forward Spectators and Neutrons: FSD and NCAL

- Use deuteron beam
  →Forward $p_{sp}$ for p-n reactions
  →Forward $n_{sp}$, compare p-p ($LH_2$) to p-p+$n_{sp}$ (for systematics)
  →NB: $B\rho(p_{sp}) = 0.5\ B\rho(d)$ & $B\rho(n_{sp}) = \infty$
- Hard hadronic processes, pp→p$\pi^+$n (low t')
- Add NCAL behind FSD
  Improves centrality & EP for AA
- Beam pipe limits acceptance
- Need to include beam emmittence (1mrad)etc.