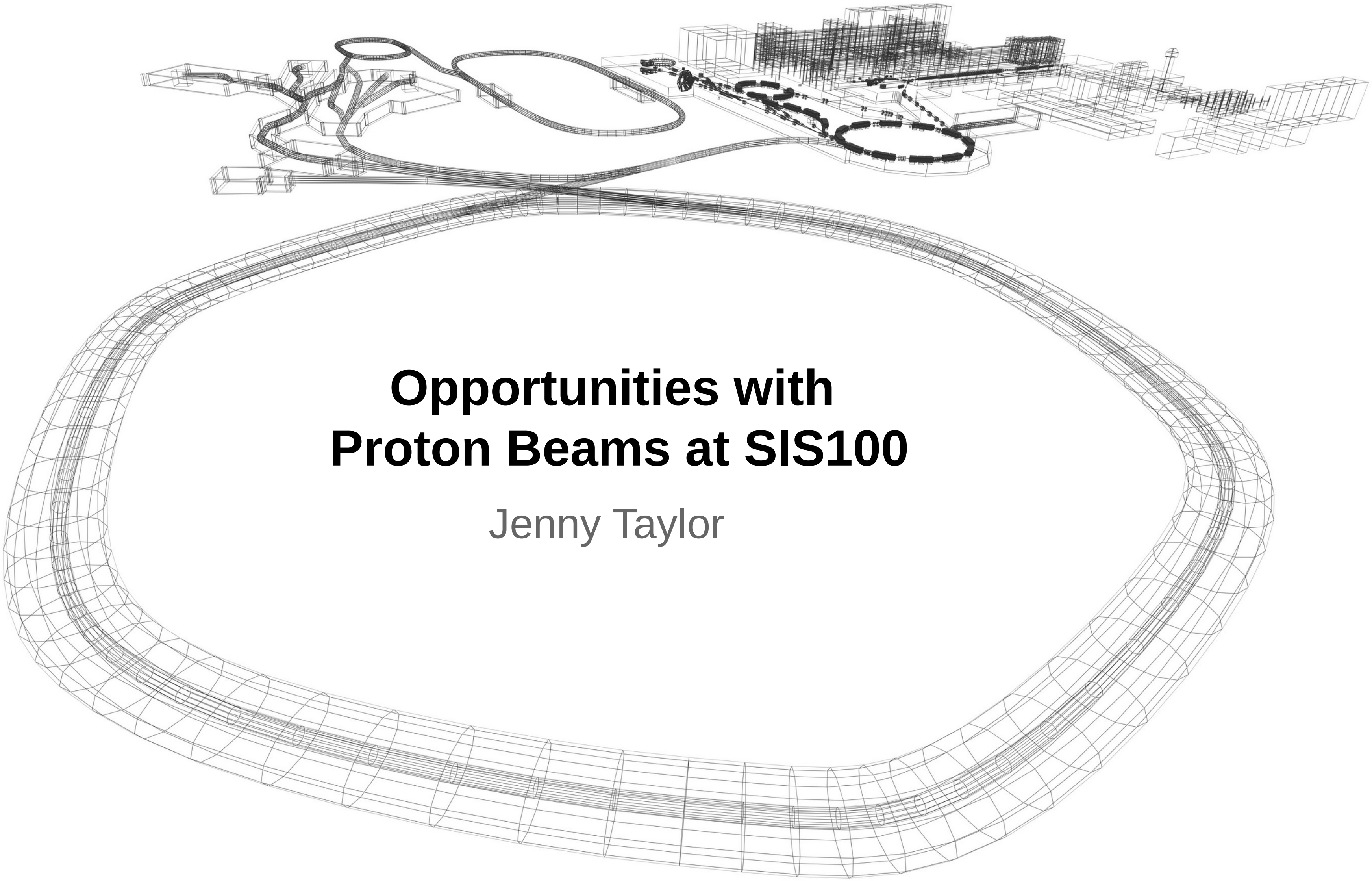


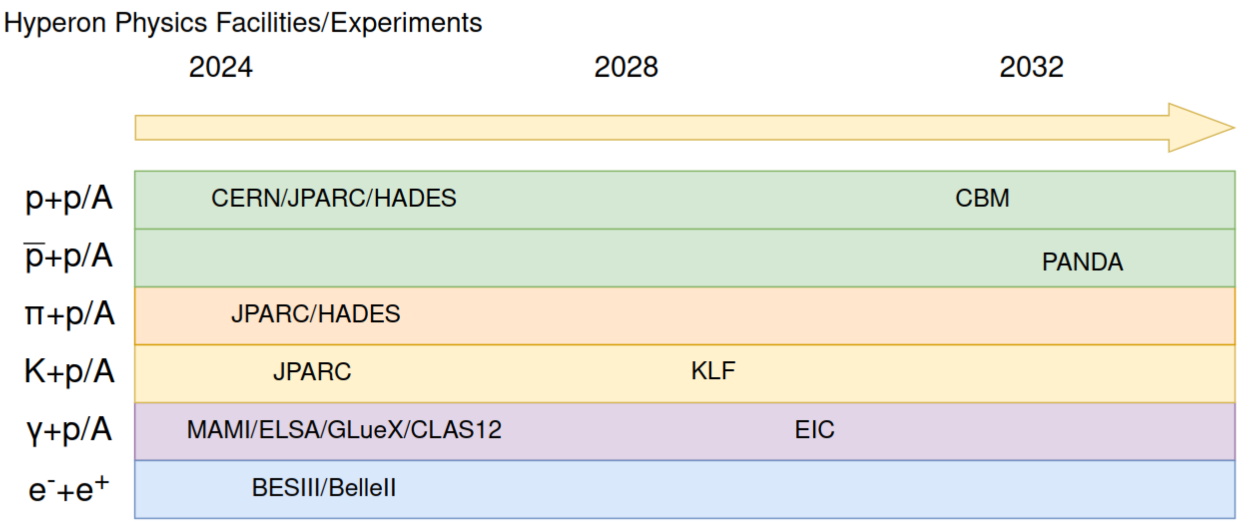
Opportunities with Proton Beams at SIS100

Jenny Taylor

Outline

- Why pp at SIS100?
- CBM setup
- Interaction Studies
- Baryon Spectrum (Line Shapes, PWA ..)
- Baryon Electromagnetic Structure

Why pp at SIS100?



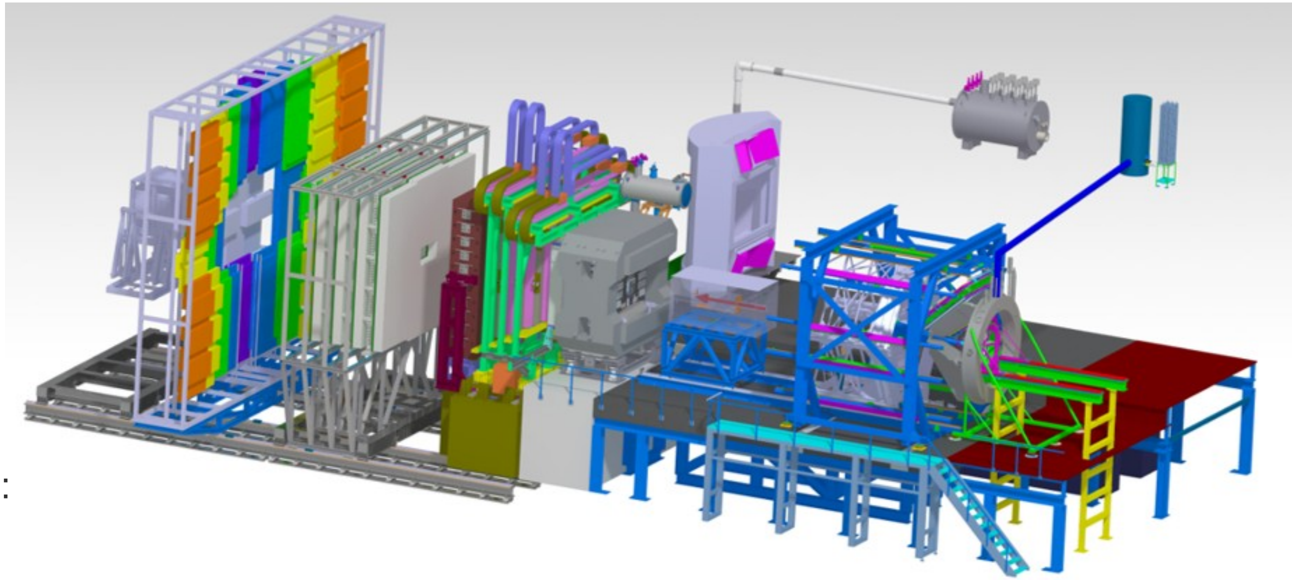
- Abundant usage of photoproduction (and kaon induced reactions) in existing and future experiments
- Few facilities uses protons as main probe
- CERN and FAIR protons in different **energy domains**
- p+p reactions very important for understanding effects in heavy ion reactions
  - Need to put resources on the future p+p experiments
  - Experiments at SIS100 can operate with a proton and heavy ion beam at the same detector setups – **State of the art!**
    - Difficult with secondary beams or electromagnetic probes

Setup and Simulation Details

CBM

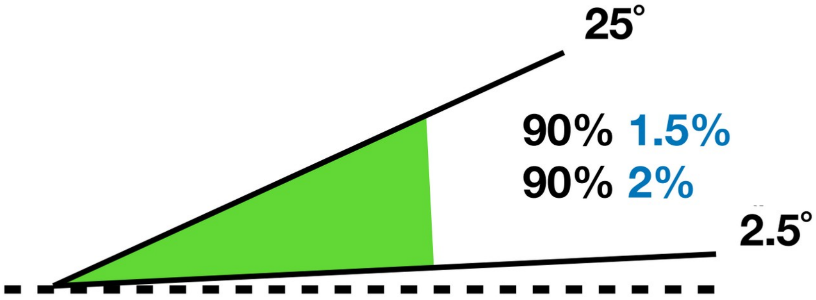
- 5 cm LH2 Target at entrance of Dipole
- Dipole
- STS (MVD…)
- RICH
- TRD
- TOF
- FSD

- Luminosity:
- $10^{11} – 10^{12}$ p/spill
- Interaction rates: 1-10 MHz
- 10 s/spill
- Duty cycle: 50%



FastSim*

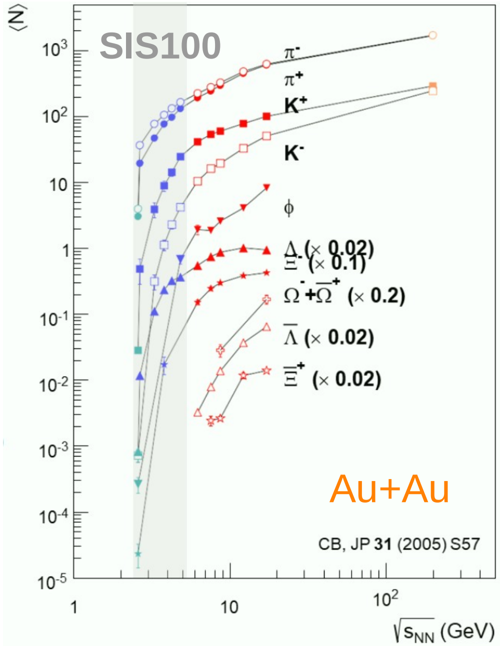
- Polar angle, θ, acceptance: 2.5° - 25°
- Momentum resolution:
  1.5% (p > 2.0 GeV/c) – 2.0% (p < 2.0 GeV/c)
- θ and Φ resolution: 0.002 rad
- Track efficiency: 90%



[*] Developed by Klaus Götzen, now HepFastSim to be published

Possibilities with Strangeness and Charm

- Hyperon Production
- Baryon Spectrum
  - Line shape
- Structure *i.e.* via eTFFs or FSI
- Polarization
- ….

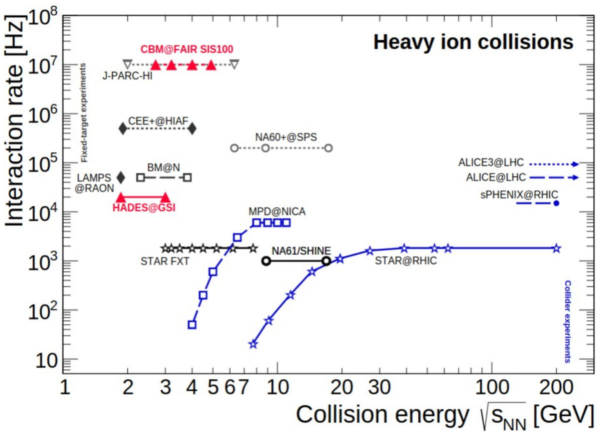


SIS18

SIS100

reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
$pp \rightarrow K^+\Lambda p$	2.548	1.6
$pp \rightarrow K^+K^-pp$	2.864	2.5
$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7
$pp \rightarrow K^+K^+K^+\Omega^-n$	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
$pp \rightarrow J/\Psi\, pp$	4.973	12.2

Picture credit: N. Herrmann, FAIR seminar, Krakow



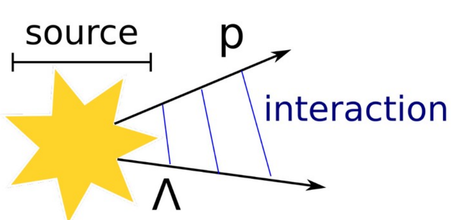
T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities

- Currently available channels at SIS18 up to T_{lab} = 4.5 GeV
- SIS100 up to T_{lab} = 29 GeV
- Many interesting hyperon channels (S = -1,-2,-3 and C = 1) opens up at larger T_{lab}
- **Anti hyperons**
- pp interactions important for understanding effects in heavy ion data

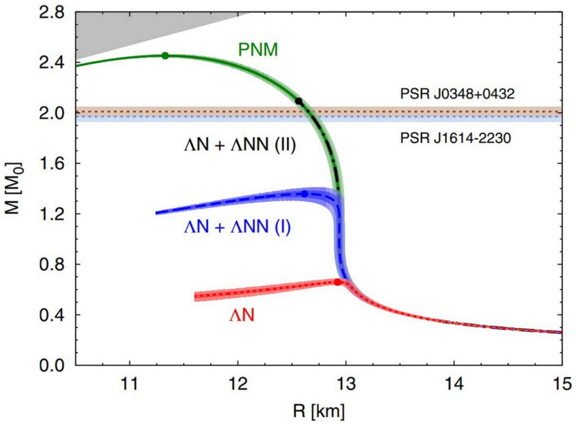
Interaction Studies

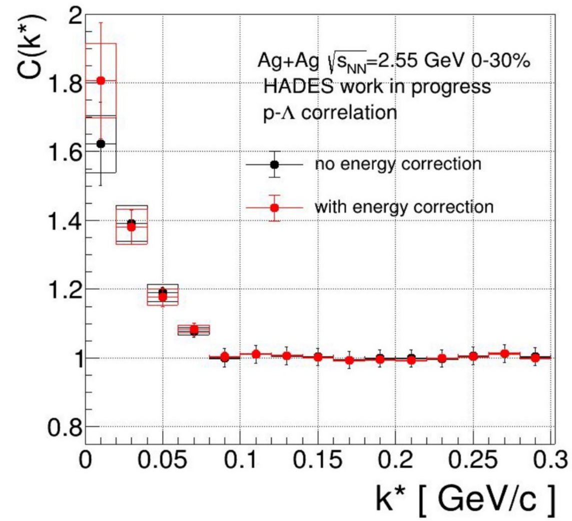
- Neutron stars – currently a very hot and interesting topic
- Hyperons energetically favorable to be created in neutron star cores
  - Reduction of Fermi pressure
  - Softer EOS
    - Lower allowed masses than those observed!
- Could solve the puzzle:
  - Three-body hyperon interactions
  - Strong repulsive YY, YN, YNN interactions
- **Femtoscopy to infer correlations and scattering length**
- Need pp measurements to separate the source contribution from elementary effects

Further measurements of the interactions required to constrain the EOS



PRL114, 092301 (2015)



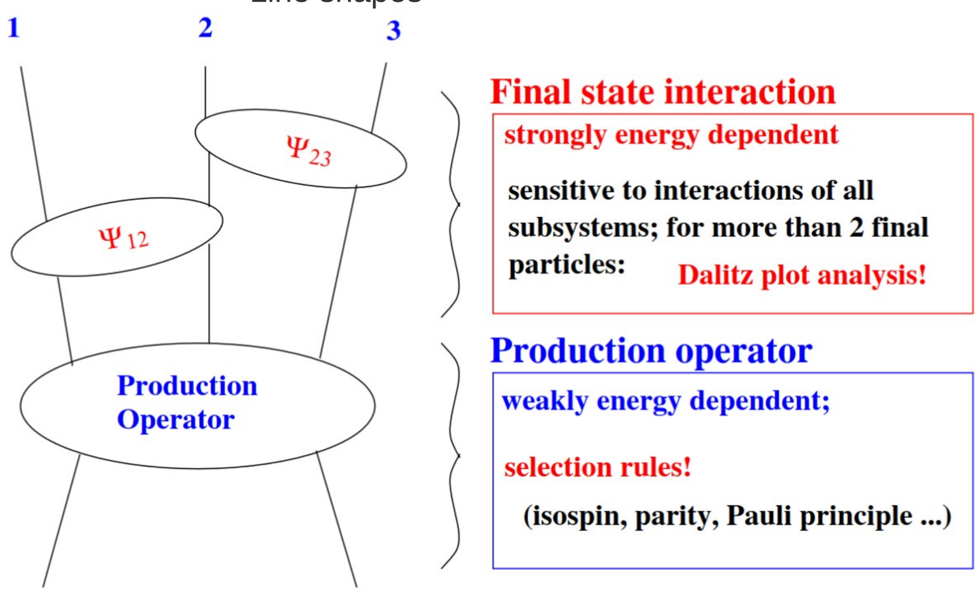


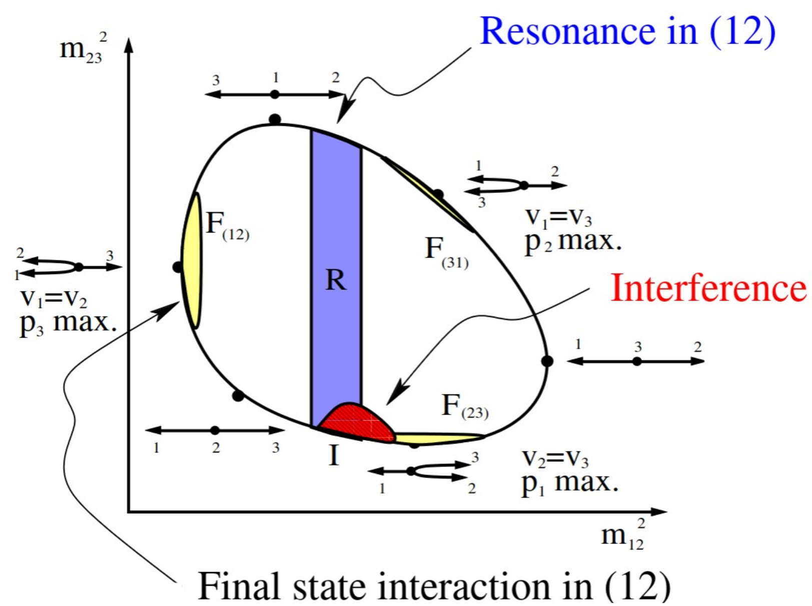
N. Rathod (Warsaw University of Technology

Dalitz Plot Analysis - Conceptually

Can do more with exclusive reactions!

- Dalitz plot analysis gives access to information about
  - 3-body final states
  - Final State Interactions (*e.g.* scattering lengths, get more dynamics from the data)
  - Resonances
  - Line shapes





Picture Credit: Christoph Hanhart

$\rightarrow d\sigma \propto |fM|^2$, where $M \simeq const.$ and $f = f[\Psi_{ij}]$.

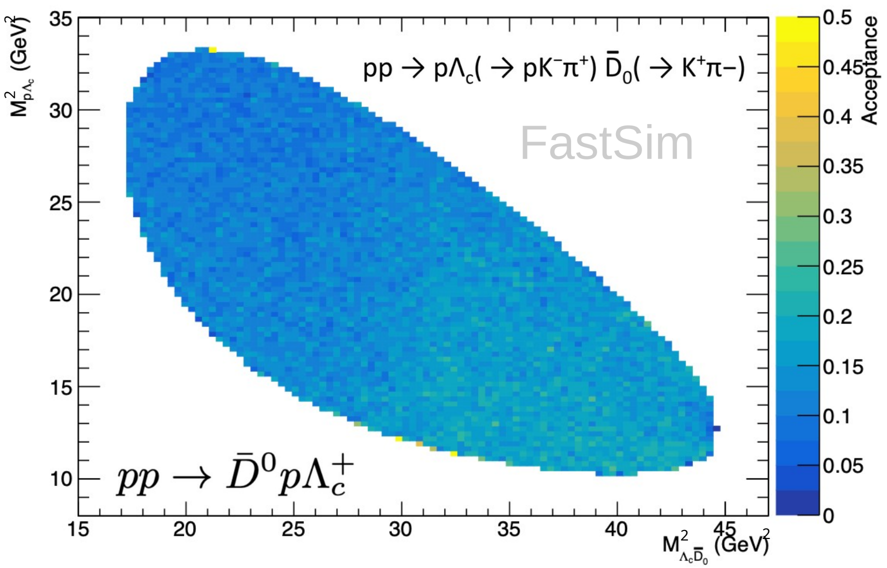
Λ_c-p and $\bar{D}^0$-p Interaction Studies

- SIS100 energies allow for charm production channels
- SU(4) estimates for exclusive charm hyperon production up to 1 μb @ SIS100
- All final state particles reconstructed
- Good phase space acceptance of the primary particles
- Detailed studies D-p and Λ_c-pInteractions possible with femtoscopy

Expected reconstructed exclusive events / Day @ 30 GeV/*c*, σ = 1 μb	
1 MHz	$2.7\cdot10^4$
10 MHz ?	$2.7\cdot10^5$

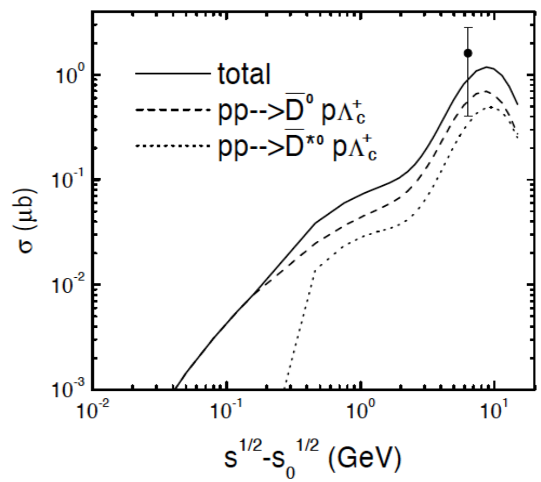
Ab-initio calculations at low energies and perturbation calculations at high energies

Calculations describing interactions needed at intermediate energies!



Johan Messchendorp

Nucl. Phys. A728 (2003) 457-470



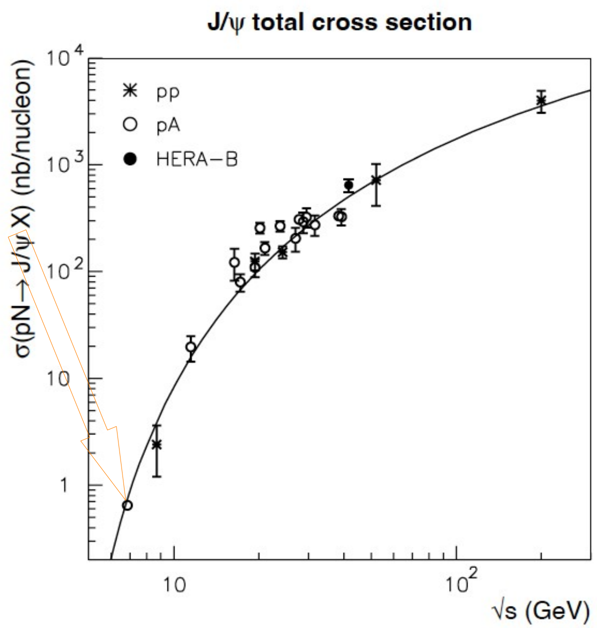
J/ψ-p Interaction Studies

- Influence of internal charm on cross section close to threshold?
- J/ψ-N interaction with multiple gluon exchange with proton
- Gives information about proton mass radius (trace anomaly)
- J/ψ-N interaction related to pentaquark searches
- Important to measure in pp-reactions to explain effects in NN-reactions

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

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

Scattering amplitude, ***F***, related to
r_0: Bohr radius of charmonium
M_N: nucleon mass
b: trace anomaly contribution (sensitive to r_0)
d_2: Wilson coefficient



J/ψ-p Simulation Results

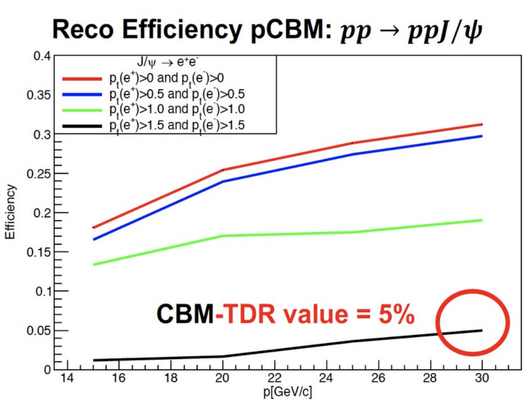
- Low cross sections at SIS100 energies but high reconstruction efficiencies
- Good phase space acceptance
- High expected count rates

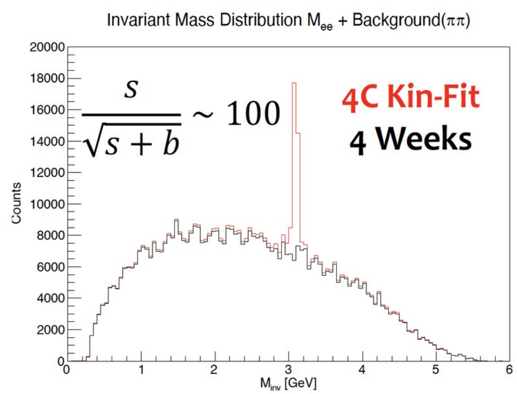
Expected reconstructed exclusive events / Day @ 30 GeV/*c*, σ = 10^{-3} μb	
1 MHz	$1.6\cdot10^{3}$
10 MHz	$1.6\cdot10^{4}$

Simulations by Ömer Penek
using FastSim

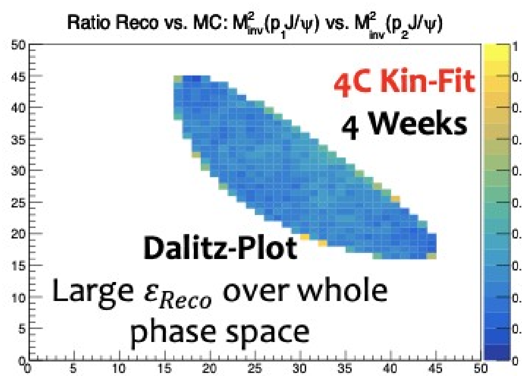
Signal	Cross Section [μb]
$pp \rightarrow ppJ/\psi(\rightarrow ee)$	10^{-3} (×0.06 BR)

Background	Cross Section [μb]
$pp \rightarrow pp\pi^+\pi^-$ ($\pi^+\pi^-$mis-ID as e^+e^-)	1000 (×10^{-6}, suppression factor)



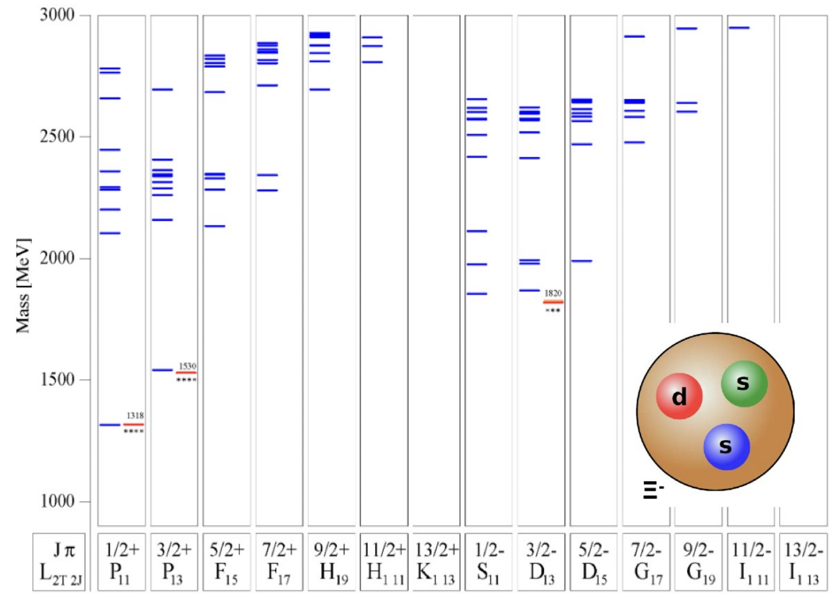


- Max ~30% Reco eff.
- 4C Kin-Fit very powerful

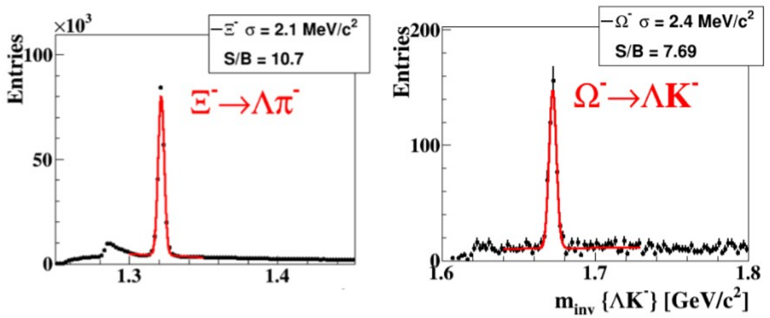


Excited Baryon Spectrum

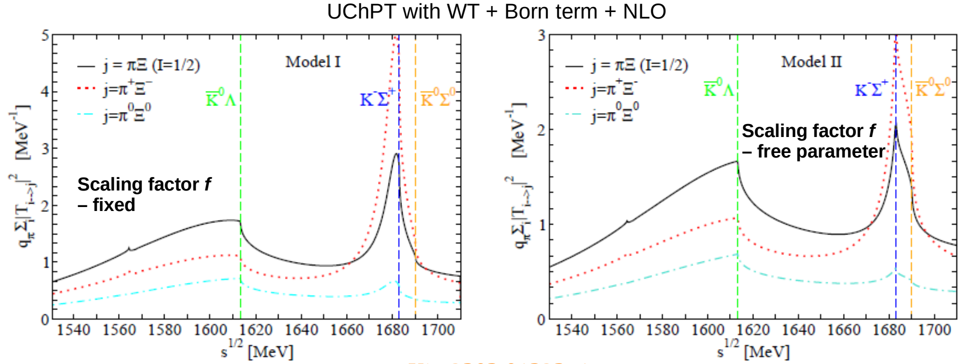
- Learn about the internal structure of baryons
  - Line shape measurements of resonances(Possible at SIS100 with resolution better than width)
    - Molecular states, pentaquarks ...
- Need more multi-strange excited baryon data for spin and parity assignments
  - PWA
- Focus on excited Ξ* and Ω* states
- **cm energy = 7.5 GeV enough to populate higher lying resonances**
- Mass resolution CBM, from MC ~2 MeV/c^2
- One can resolve the shapes!



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



UChPT with WT + Born term + NLO



Picture credit: N. Herrmann, FAIR seminar, Krakow

arXiv:2303.01323v1

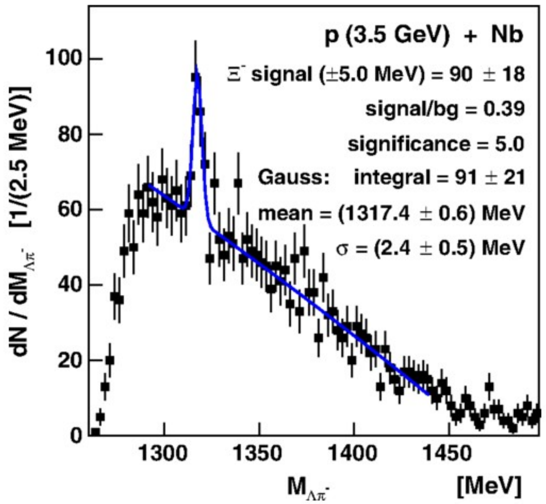
S=-2 at SIS18

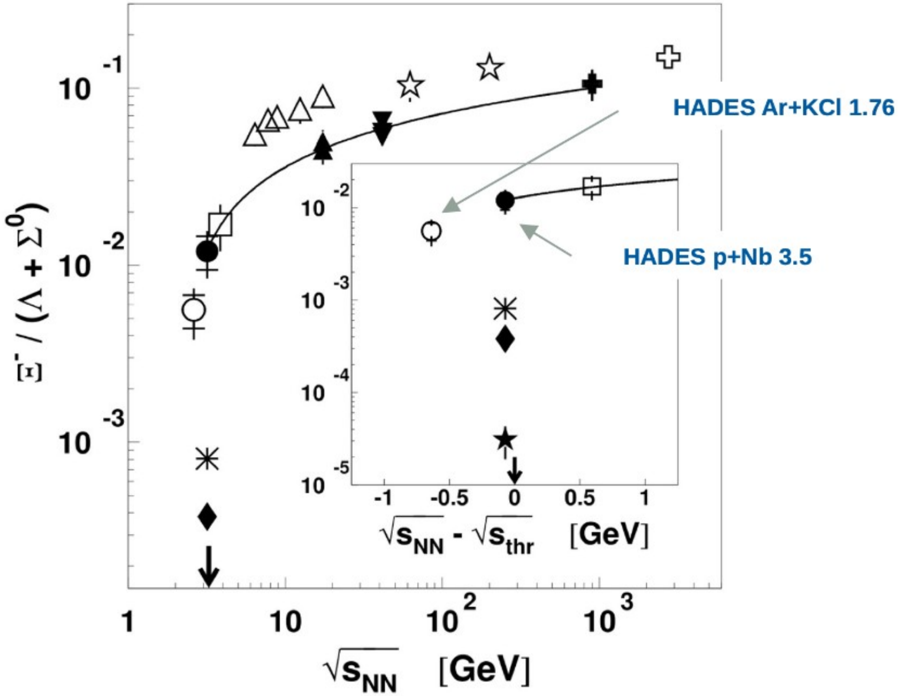
- Excess of sub-threshold Ξ⁻ production measured at HADES in Ar+KCl Reactions at 1.76AGeV [*] and p(3.5 GeV)+Nb collisions [**]
- Could be explained by resonances with significant branching fractions into the Ξ− channel [***]
- Need experimental observation of N*→ Ξ⁻K⁺K⁺ in p+p reactions

[*] PRL 103, 132301 (2009)

[**] Phys. Rev. Lett. 114, 212301 (2015)

[***] *J. Steinheimer et al.,* J.Phys. G43 (2016) 015104

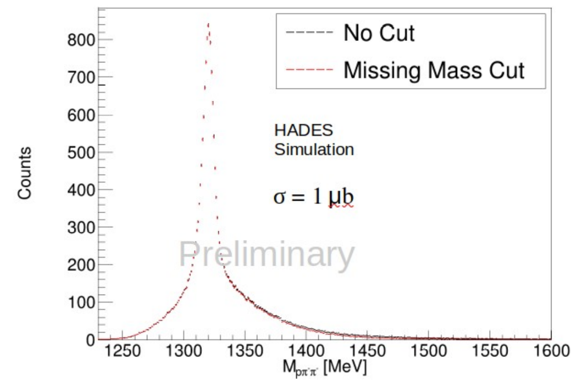


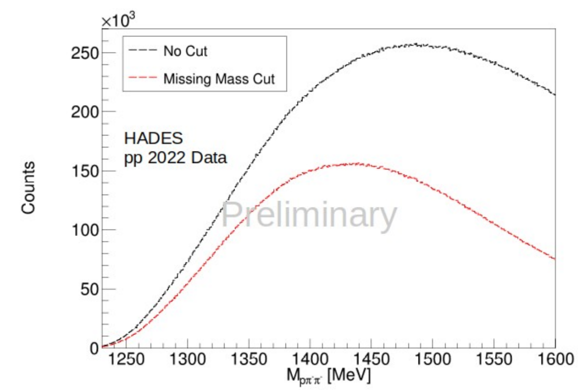


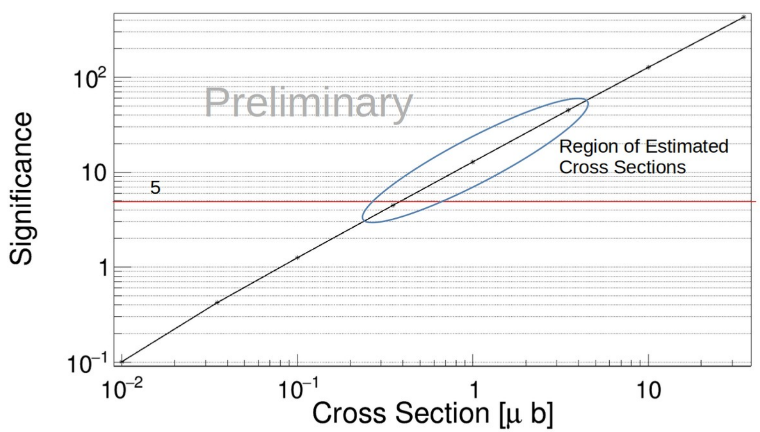
S=-2 at SIS18

- Cross section estimates: 0.35 µb - 3.6 µb [*]
- Main backgrounds
  - $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ with σ = 227 µb
  - Various Λ and K^0_S production channels
- Goal of Analysis
  - Total and differential cross section determination
- Preliminary results
  - > 0.4 µb can be excluded with 5 sigma

- **Signal entries** = entries in scaled simulation within Ξ^- range
- **Background entries** = entries in data within Ξ^- range







[*] Eur. Phys. J. A (2021) 57:138

At SIS100:

Ξ^- → excited Ξ , Ω and antihyperons

Near threshold Ξ production extended to near threshold production of excited Ξ and Ω!

S=-2 Prospects at SIS100

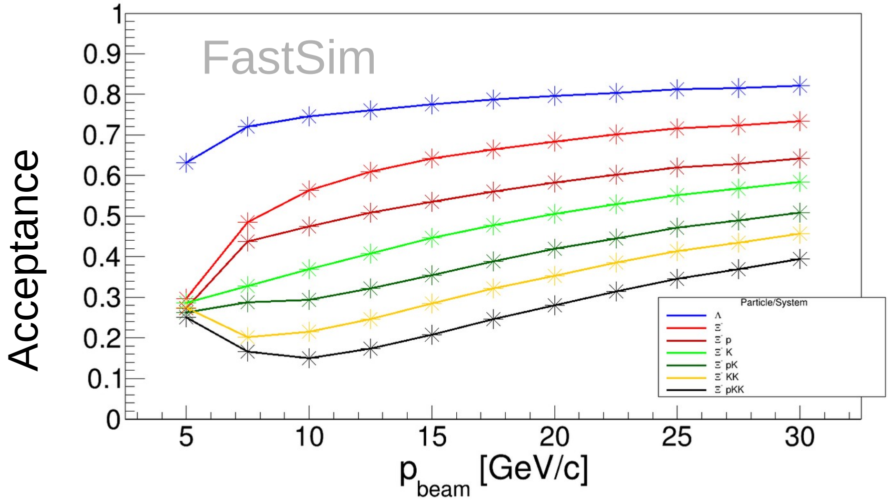
- Polarization (hyperons+antihyperons)
- Ξ^- yield is an important indicator of chiral symmetry restoration in dense matter (heavy ion reactions)
- Measurements in pp important for understanding the fundamental production at similar energies as heavy ion reactions
- High inclusive acceptance and expected count rates for Ξ^-
  - Promising for line shape studies

$pp \rightarrow pK^+K^+\Xi^-$

$\Xi^- \rightarrow \Lambda\pi^-$ (BR ~ 100%)

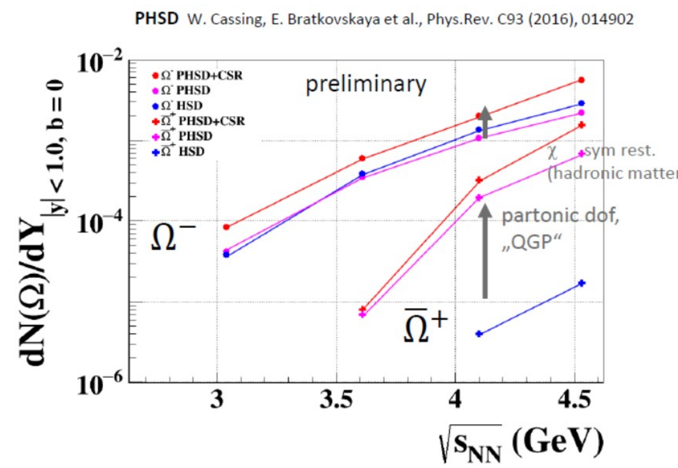
$\Lambda \rightarrow p\pi^-$ (BR = 64%)

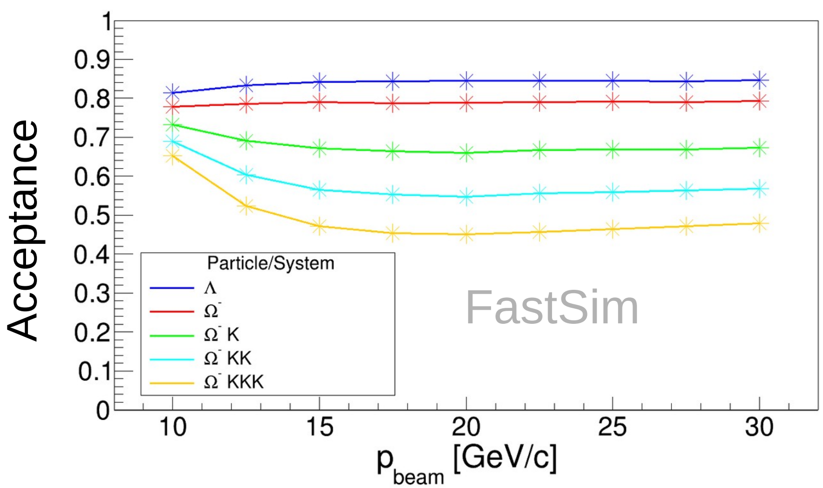
Expected reconstructed inclusive / Day @ 30 GeV/*c*, σ = 40 μb	
1 MHz	$1.2 \cdot 10^{9}$
10 MHz	$1.2 \cdot 10^{10}$



S=-3 Prospects at SIS100

- Information about in-medium properties of hadrons
- Multi-step production provides information about the EOS
- Distinguish partonic degrees of freedom vs. multi step production
- Transport model predictions of **near threshold** production shows sensitivity to multistep production
- Production in pp-collisions important for understanding effects in heavy ion collisions
- Preliminary simulations show high acceptance and count rates

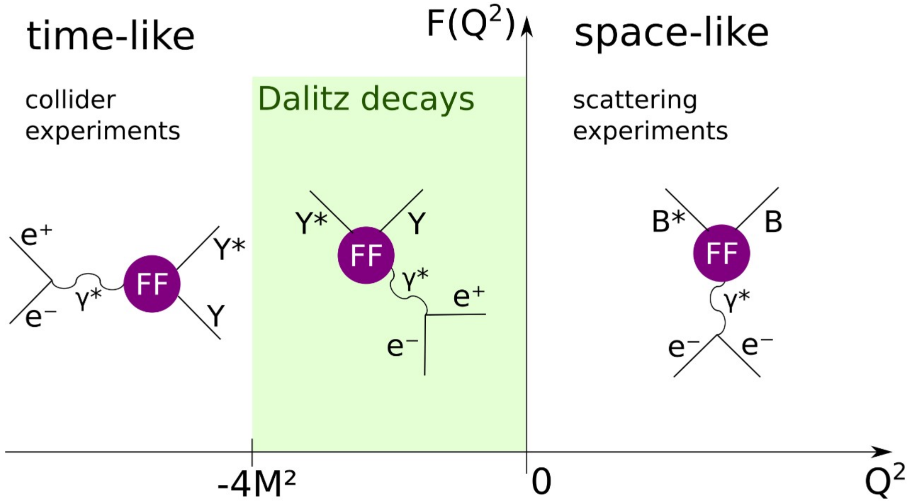




$$pp \rightarrow nK^+K^+K^+\Omega^-$$
$$\Omega^- \rightarrow \Lambda K^- \text{ (BR = 68\%)}$$
$$\Lambda \rightarrow p\pi^- \text{ (BR = 64\%)}$$

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

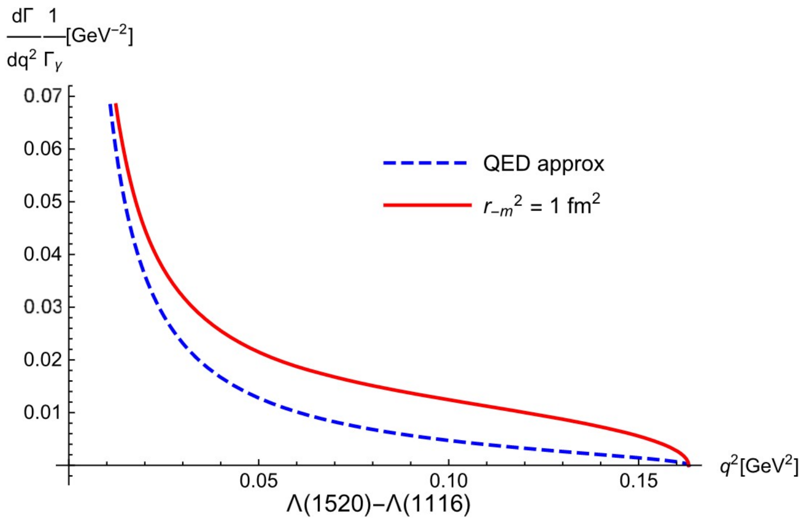
Hyperon Electromagnetic Structure



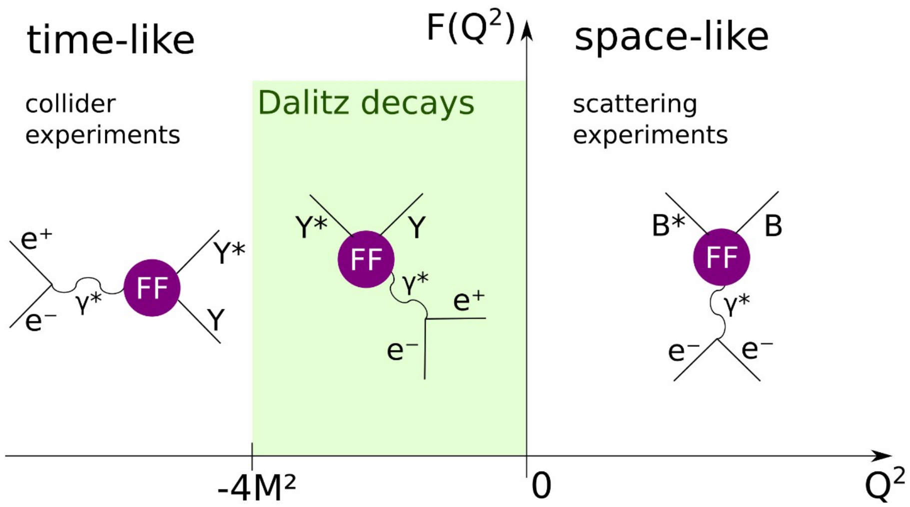
- Time like FF possible to measure for hyperon decays
- Electromagnetic structure of strange resonances, such as $\Sigma^0 \rightarrow \Lambda\gamma^* \rightarrow \Lambda e^+e^-$
- Structure described in terms of electric and magnetic transition form factors
- Dalitz decay rates sensitive to structure

S. Leupold *et al.* Eur. Phys. J. A (2021) 57 :183

- Dalitz decays of $\Sigma^0 \rightarrow \Lambda\gamma^* \rightarrow \Lambda e^+e^-$ not yet observed
- Low predicted brancing fraction < $5.0\cdot10^{-3}$
  - Need to separate Dalitz decay contribution from conversion electron contribution at HADES
  - High luminosities and larger cross sections needed
  - SIS100 excellent for the measurements



Hyperon Electromagnetic Structure



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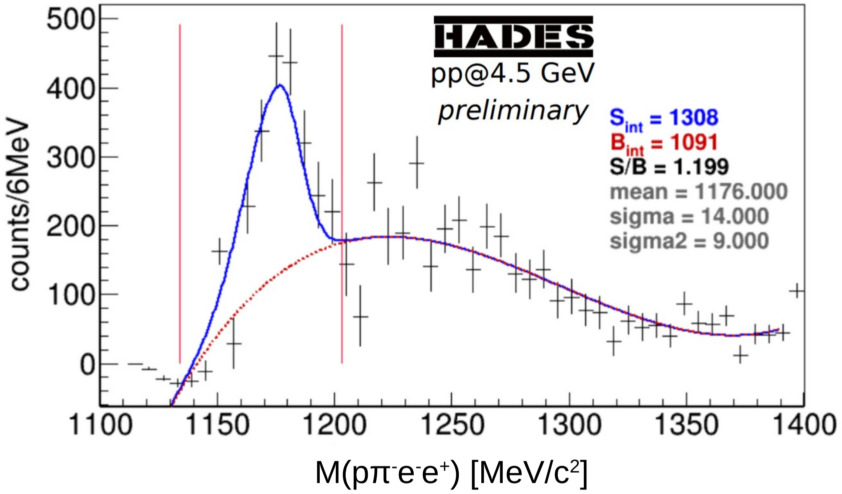
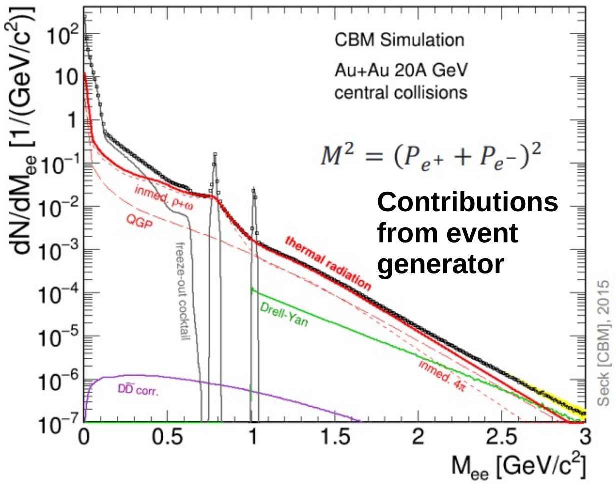
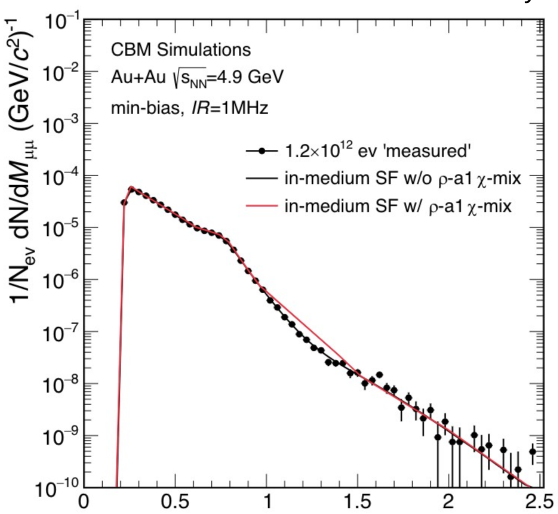


Di-lepton Measurements at CBM



TU Darmstadt / Université Paris Saclay



Picture credit: T. Galatyuk

Di-Lepton Spectra important to measure for understanding properties of the medium in heavy ion reactions, contains a lot of useful information

- Contains information about
  - Chiral symmetry restoration
  - Transport properties of the medium
  - Fireball acceleration, polarization, lifetime …
- Different contributions to the dilepton spectra
  - Freeze-out contributions (*e.g.* ρ, ω and ϕ)
  - Thermal radiation (from thermally excited hadrons from the fireball)
  - Drell-Yan processes
- Sign of chiral symmetry restoration:

  ρ - a_1 mixing / broadening into a continuum

pp-collisions needed to understand the source of di-lepton production in heavy ion collisions!

Summary

- Proton-proton interaction studies at SIS100 are crucial
  - Provides high luminosity of up to 10^{12} protons/spill
  - Opens up many reaction channels compared to SIS18 energies
  - Explaining heavy ion reaction results
- Physics possibilities includes
  - Interaction Studies
  - Investigation of Baryon Spectrum
    - Spectroscopy via PWA
    - Line shape studies
  - Baryon Electromagnetic Structure

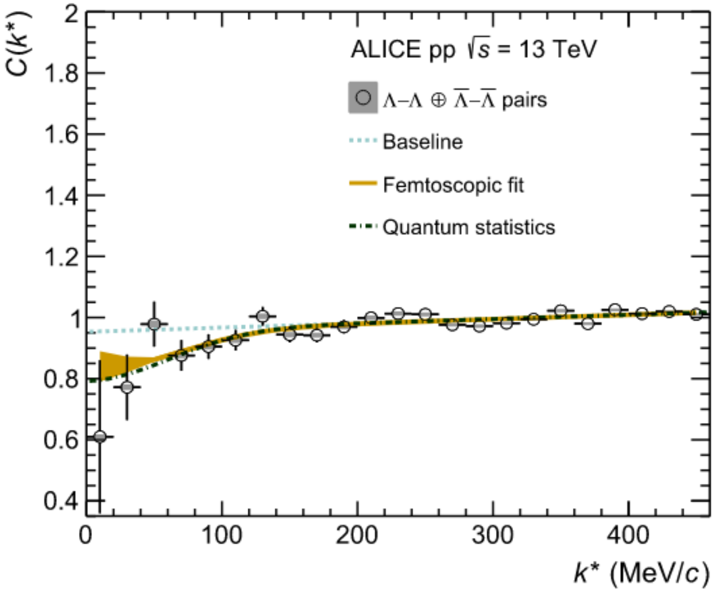
Expected reconstructed counts / Day @ 30 GeV/*c* for 1 MHz		
Ξ^-	~ 40 μb	**$1.2 \cdot 10^9$**
Ω^-	~ 0.6 μb	**$1.4 \cdot 10^7$**
p $\Lambda_C D^0$	~ 0.1 μb	**$2.7 \cdot 10^4$**
pp J/ψ	~ 1 nb	**$1.6 \cdot 10^3$**

- Preliminary simulation studies show high acceptance and yields for Ξ^-, Ω^-, $\Lambda_C D^0$ and J/ψ

Thank You! Questions?

Λ-Λ Interaction Studies

- Currently analyzed at HADES
  - 4.5 GeV kinetic beam energy
  - Complex final state, statistics of importance
    - **Higher rates beneficial**
  - Femtoscopy
    - ALICE and STAR has provided proof that correlations can be used to infer information about the strong interaction [*]
- ALICE [**] constrains the interaction
- Futher measurements in pp collisions needed
- Synergies with CBM physics program



[*] Annu. Rev. Nucl. Part. Sci. 2021. 71:377–402

Fig. From: [**] Phys. Lett. B 797:134822 (2019)

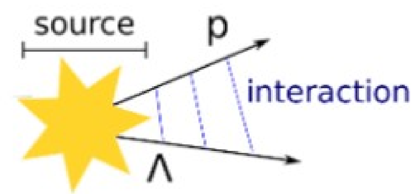
Hyperon Correlations

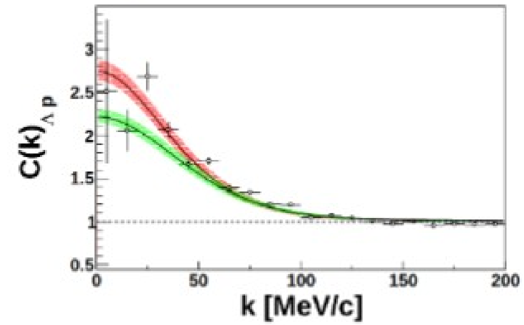
Important for understanding the strangeness content of neutron stars

Femtoscopy studies via correlation function

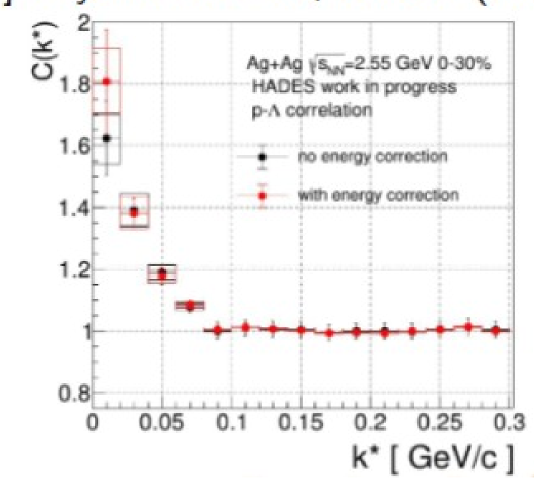
$$C(p_1, p_2) \equiv \frac{P(p_1, p_2)}{P(p_1) \cdot P(p_2)}$$

- Λp potential inferred from correlation function at HADES in p+Nb @ $\sqrt{S_{NN}} = 3.18$ GeV [*] (right upper plot)
- Need further studies in p+p and p+Ag reactions with HADES
- HADES operates at energy range close to production threshold which is beneficial for interaction studies
- Current work by N. Rathod (Warsaw University of Technology) to extract p-Λ correlations at HADES (lower plot)





[*] Phys. Rev. C 94, 025201 (2016)



J. Taylor from the Annual Winter Nuclear Physics Meeting in Bormio, 22-26 Jan, 2024