Simulations for experiments on exotic hypernuclei

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HIC for FAIR Physics Day
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Outline

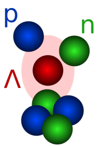
Outline

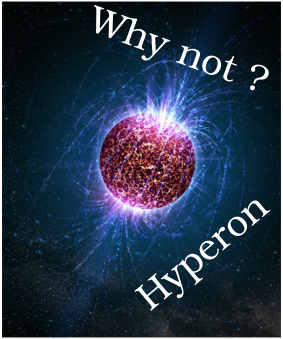
What and Why Hypernucleus ?

Classic example in Nuclear Physics:

Neutron Star

- Core of neutron star → strangeness ?
- EoS of hyper-matter : Potential of hyperons





But, what is an hypernucleus ?

- Bound state of p,n and hyperon (Λ, Ξ, Σ) : ${}^{A}_{Y}Z$

And why ?

- No direct study of hyperon-nucleon interaction

How to study Hypernucleus ?

Two distinct way

Missing mass spectroscopy

With secondary meson beams

- 50' to 70' : Emulsions ...
- Since the 70' : Counter experiments with fixed target.
- Since 2000 : also with e-beam on fixed target.

Invariant mass spectroscopy

With heavy ion :

- On fixed target : 1988 Dubna, 2009-2010 GSI
- Collider experiments : 2009 STAR, 2011 ALICE

How to study Hypernucleus ?

Missing mass spectroscopy

Advantage :

- very precise spectroscopy of hypernuclei.

Disadvantage :

- Only from stable target nuclei (production from elementary process)

Invariant mass spectroscopy

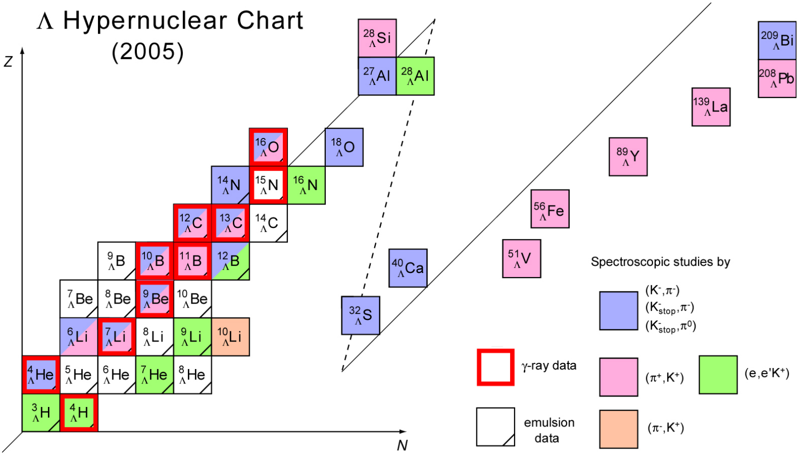
Advantage :

- Lifetime measurements
- Production of exotic hypernuclei

Disadvantage :

- Difficult experiments
- Lack of precise mass resolution

Current hypernuclear chart



[O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. **57** (2006) 564]

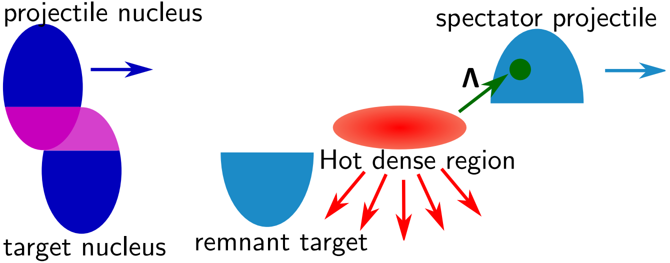
Outline

Aims of the HypHI project started in 2006

To Use heavy ion and RI beam to study:

- Hypernuclei toward the proton and neutron drip-lines:
  - High isospin effects in YN interaction,
- Magnetic moments of hypernuclei.
- Several other medium effects:
  - $\Lambda - \Sigma$ coupling in the nuclear matter.
- Exotic hypernuclei:
  - Decay of exotic hypernuclei,
  - Measurements of their lifetime & binding energy.
- Multistrangeness hypernuclei

Properties of the production mechanism

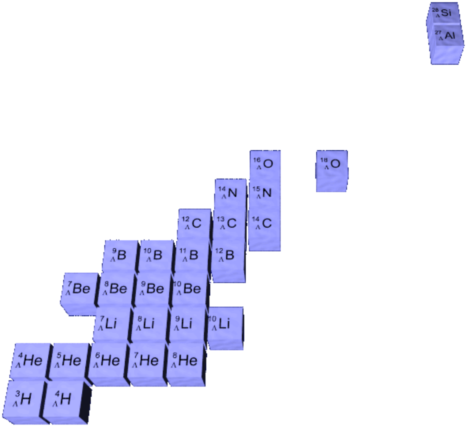


- $NN \to \Lambda K N$ Energy threshold $\sim$ 1.6 GeV.
- Beam energy $>$ E_{th}: available at GSI (2 A GeV)
- Coalescence of Λ or (π^+, K^+) reaction in spectator fragment.
  $\Rightarrow$ same velocity than projectile: Lorentz Boosted
- Effective lifetime longer:
  - 200 ps $\to$ 600 ps ($\gamma \sim 3$) at GSI: $c\tau \sim$ 15 to 20 cm.

$\Longrightarrow$ study Hypernuclei in flight
  - Lifetime measurement via decay vertex reconstruction.

Several phases

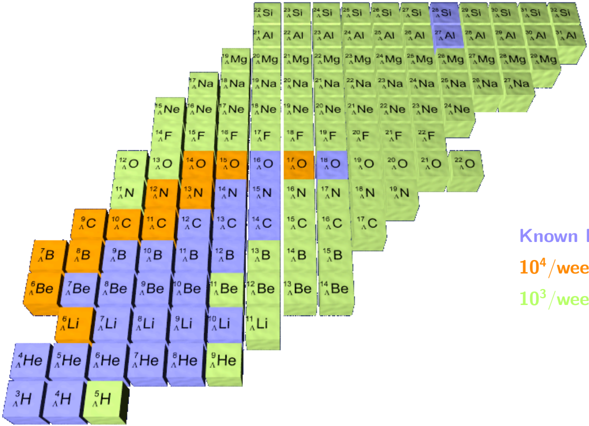
Current knowledge:



Known Hypernuclei

Several phases

Ideal outcome of the HypHI project :



Known Hypernuclei

10^4/week

10^3/week

Setup of Phase 0 experiment (October 2009)

$^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{3}\mathrm{He}$

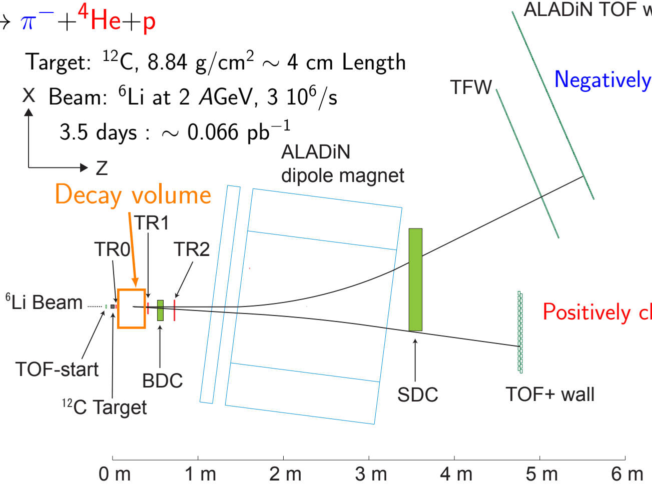
$^{4}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{4}\mathrm{He}$

$^{5}_{\Lambda}\mathrm{He} \rightarrow \pi^{-} + {}^{4}\mathrm{He} + p$

Target: ^{12}C, 8.84 g/cm^2 $\sim$ 4 cm Length

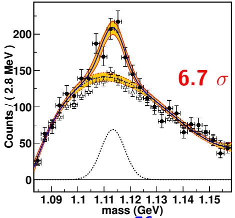
Beam: ^{6}Li at 2 AGeV, 3 10^6/s

3.5 days : $\sim$ 0.066 pb^{-1}



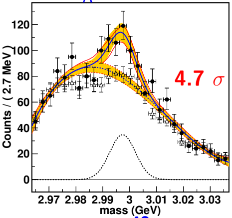
Hypernuclear spectroscopy from ^{6}Li+^{12}C @ 2 *A* GeV

$\Lambda \rightarrow$ **p**+π^-



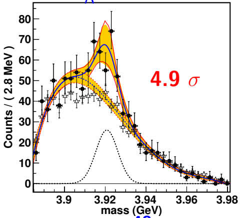
$\tau = 262^{+56}_{-43} \pm 45$ps

$^{3}_{\Lambda}$**H** $\rightarrow$ ^{3}**He**+π^-



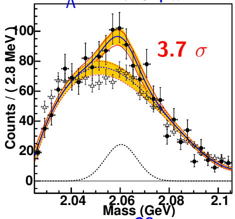
$\tau = 183^{+42}_{-32} \pm 37$ps

$^{4}_{\Lambda}$**H** $\rightarrow$ ^{4}**He**+π^-



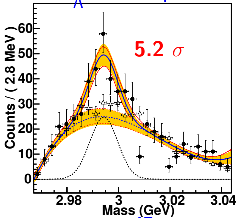
$\tau = 140^{+48}_{-33} \pm 35$ps

$^{3}_{\Lambda}$**n?** $\rightarrow$ **d**+π^-



$\tau = 181^{+30}_{-24} \pm 25$ps

$^{3}_{\Lambda}$**n?** $\rightarrow$ **t**+π^-



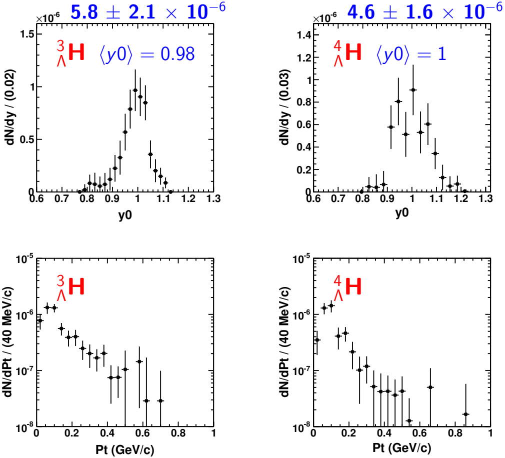
$\tau = 190^{+47}_{-35} \pm 36$ps

[C. Rappold *et al.*, Nucl. Phys. A. **913**, 170 (2013)]
[C. Rappold *et al.*, Phys. Rev. C (Rapid Comm.) **88**, 041001 (2013)]

Reaction mechanism study

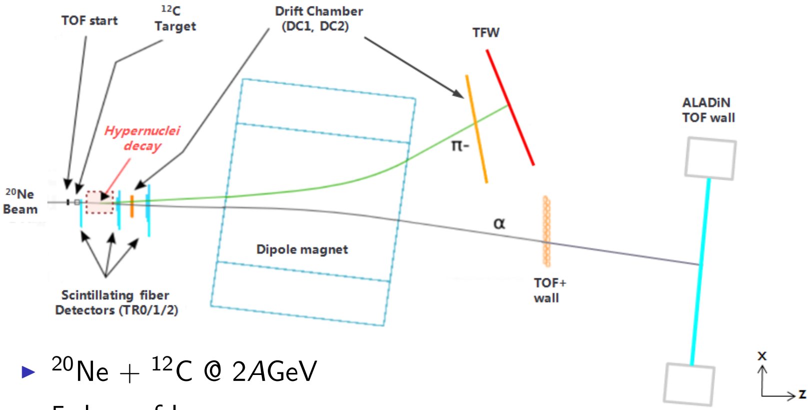
Production cross section & multiplicity :

	CS
Λ	1.7 ± 0.8 mb
$^{3}_{\Lambda}H$	3.9 ± 1.4 µb
$^{4}_{\Lambda}H$	3.1 ± 1.0 µb
$^{3}_{\Lambda}H/^{4}_{\Lambda}H$	1.4 ± 0.8
$^{3}_{\Lambda}H/\Lambda$	$2.6 \pm 1.4 \times 10^{-3}$
$^{4}_{\Lambda}H/\Lambda$	$2.1 \pm 1.1 \times 10^{-3}$



[C. Rappold *et al.*, Under review PLB]

Meanwhile the second experiment : Phase 0.5



- ^{20}Ne + ^{12}C @ 2AGeV
- 5 days of beam.
- Analysis on-going !
- good signals for Λ and $^{3}_{\Lambda}$H

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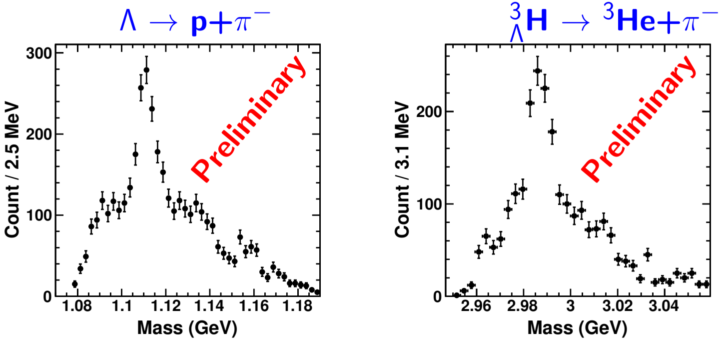

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- 5 days of beam.
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Outline

Prospects in Hypernuclear Physics for FRS/SuperFRS

Future of HypHI project : Exotic hypernuclei / strangeness cluster

Use heavy ion and RI beam to study @ FRS & SuperFRS :

- Hypernuclei toward the proton and neutron drip-lines with Exotic beam ⇒ **SuperFRS**
- $\Lambda - \Sigma$ coupling in the nuclear matter ⇒ **SuperFRS**
- Lifetime of exotic hypernuclei. ⇒ **FRS / SuperFRS**
- Most urgent : Confirmation of ${}^{3}_{\Lambda}$n ⇒ **FRS**

Prospects in Hypernuclear Physics for FRS/SuperFRS

Why at FRS / Super FRS ?

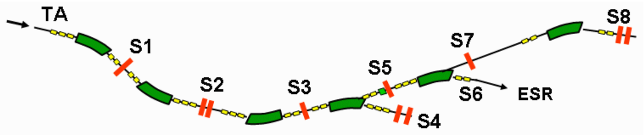
- high momentum resolution for forward fragments : $10^{-4}\delta p/p$ optimal
  - to be compared with previous experimental apparatus : $\sim 10^{-2}\delta p/p$
- Exotic hypernuclei : Need RI beam
  - With high energy ~ 2 AGeV (min 1.6AGeV)
  - With high intensity : small cross section ($\sim \mu$b)
- Optimizing each experiment to one decay / species

$\Rightarrow$ **Only possible at GSI/FAIR and FRS / SuperFRS**

Outline

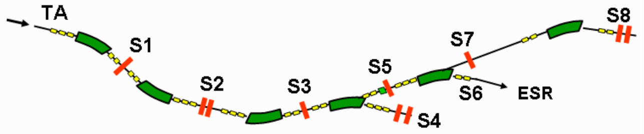
FRS setup: Physics case

- The most urgent : Confirmation of nnΛ
  - Repeat the experiment ^{6}Li + ^{12}C (at 1.8 AGeV → 2 AGeV)
  - Looking for : nnΛ → d+π^-
  - at the same time (Benchmark) : $^{4}_{\Lambda}$H → ^{4}He + π^-
  - (same regidity d / ^{4}He / ^{6}Li)
- Can be the test case to demonstrate that hypernuclear study can be performed within FRS, set as a fragment spectrometer.
- S2 as the location for the detector apparatus.



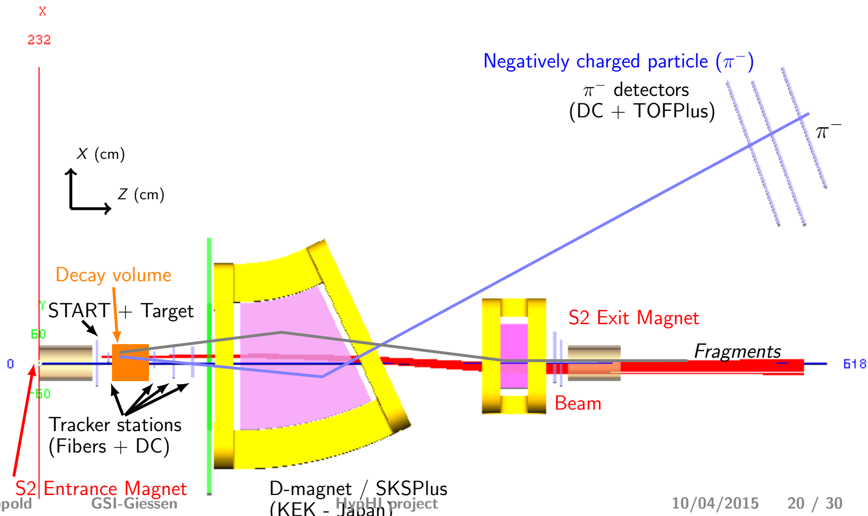
FRS setup: Physics case

- TA $\rightarrow$ S2 : primary beam transport
  - beam tuning such as: small angle to the hypernuclear production target at S2
- S2 $\rightarrow$ S4 : fragment spectrometer for momentum measurement for d and ^{4}He
- Two options : two dipole magnets OR one solenoid magnet.

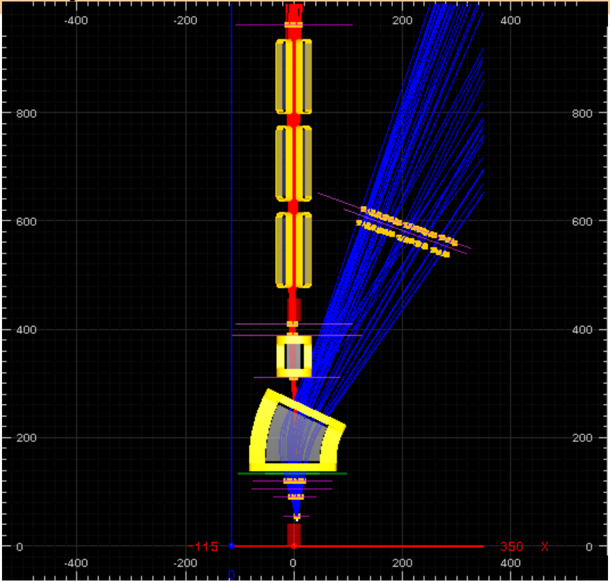


FRS setup : Two dipole magnet scenario

Possible setup at S2 of FRS with ^{6}Li+^{12}C @ 1.8 *A*GeV



More Geometry



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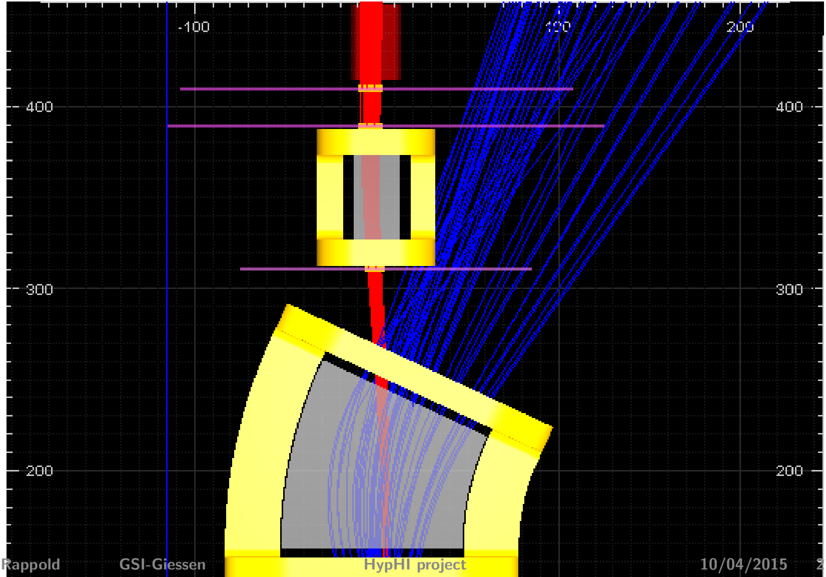
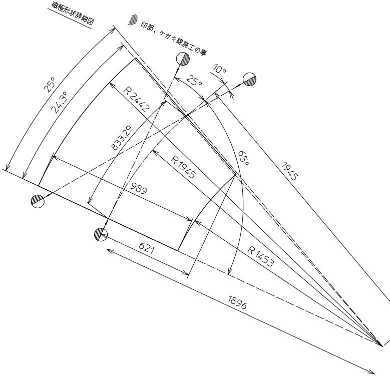


Characteristics

- Characteristic of the Sks magnet :
  - Gap (transversal) : 99 cm × 20 cm
  - L_{eff}=1.075 m
  - Field : 1.034 T
  - Angle : 25 degree / Rho : 1.945 m
  - Weigth : 29 t
- Characteristic of the second magnet :
  - Gap Width : 25 cm
  - Gap Height : 20 cm
  - Gap Length : 75 cm
  - Field : 1.5 T
- Calculation on the realistic magnetic field done in KEK by magnet expert.



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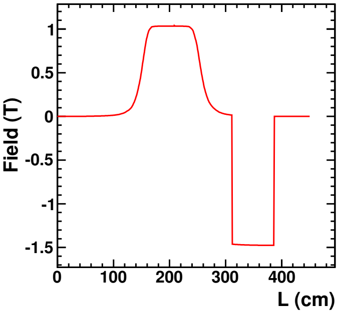
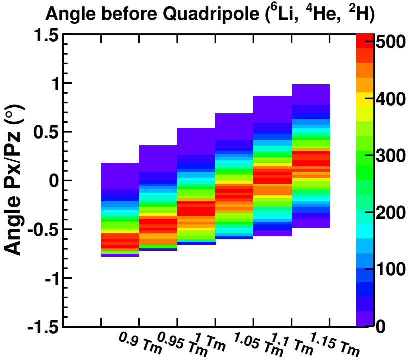
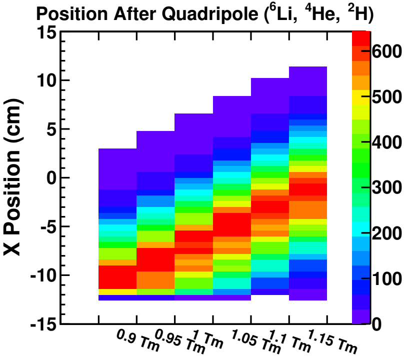


Results of the systematic study

From MC simulations of fragments (^{6}Li, ^{4}He, ^{2}H) :

How are the fragments with different field for the second dipole magnet ?

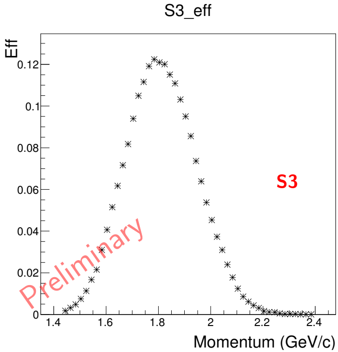


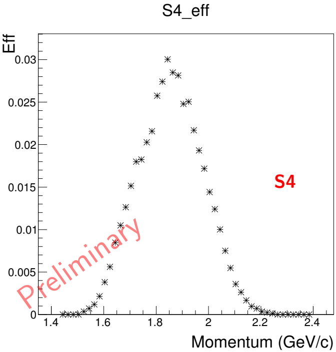


Results of the systematic study

Combining Monte Carlo simulation of the setup & Mocadi

- ROOT Tree from the MC simulation → input to Mocadi.
- The 4-vector of all deuteron at the entrance of the quandripole.
- propagation end of S2 → S4 done by Mocadi.





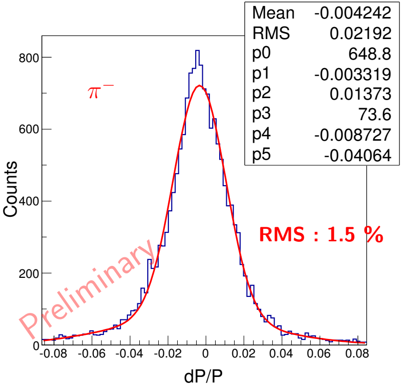
Results of the systematic study

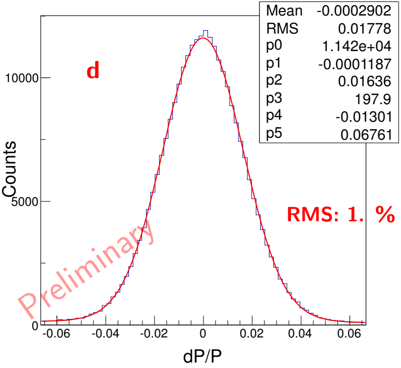
Rate estimation for d+π^- in comparison with Phase 0 :

- Cross section at 1.8 AGeV instead of 2.0AGeV
  - 0.5 times less than in Phase 0
- Geometrical acceptance :
  - 0.6 times less than in Phase 0
- Data acquisition efficiency without the secondary vertex trigger :
  - 10 times more than in Phase 0
- Total :
  - 3.0 times more yield than in Phase 0

Results of the systematic study

Preliminary event reconstruction from MC simulations :
From the fully detected tracks of d and π^-



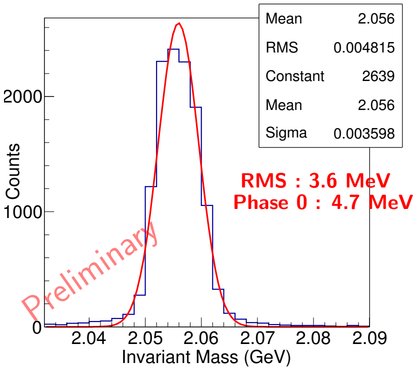


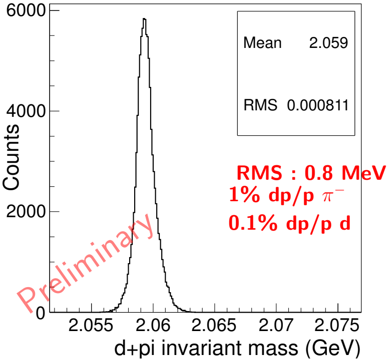
Results of the systematic study

Monte Carlo simulation with $^{3}_{\Lambda}n$ of $^{6}Li+^{12}C$ @ 1.8 AGeV

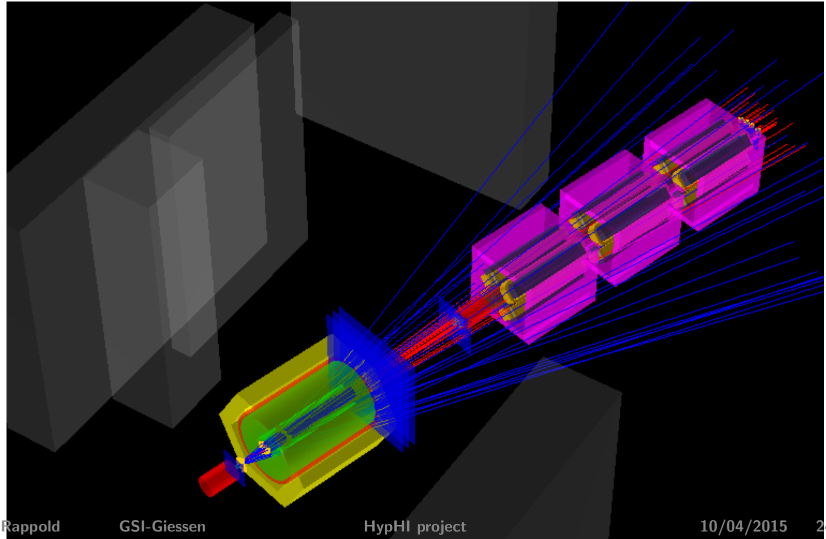
Preliminary event reconstruction from the MC simulation :
$\rightarrow$ From the fully detected tracks of d and π^-

[C. Rappold, GSI Scientific Report 2014]



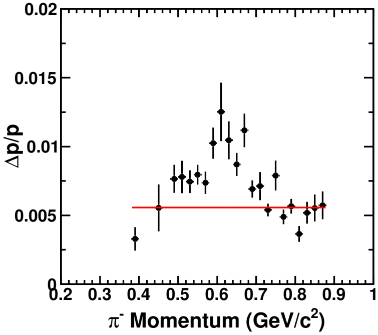


FRS setup: Solenoid magnet scenario



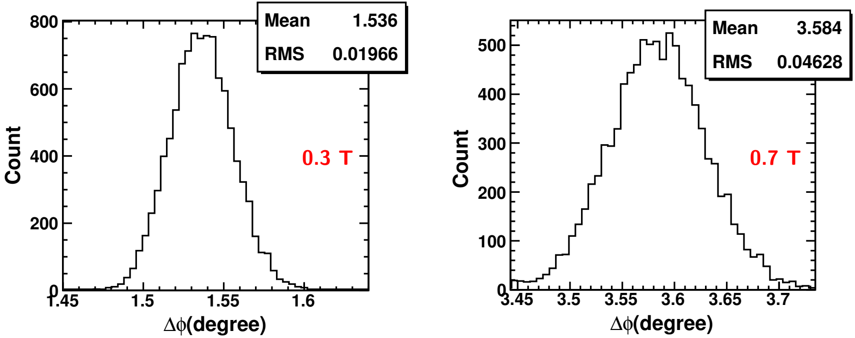
Results of solenoid simulation

- π^- momentum resolution within the solenoid+endcap.



Results of solenoid simulation

- Transversal angle $\Delta\Phi$ of the ^{6}Li beam for 0.3 T and 0.7 T.



Outline

Opportunity with the SuperFRS : Hypernuclei @ SuperFRS

Feasibility study : proton-rich hypernuclei

- Experimental setup not yet fixed :
  Like with FRS or more dedicated setup.
- Study of the Rare Isotope beam production (Epax+Mocadi)
- Study of the hypernuclei production cross section

Primary beam + Production Target →
Secondary beam + 2nd Target → **Exotic Hypernuclei + X**

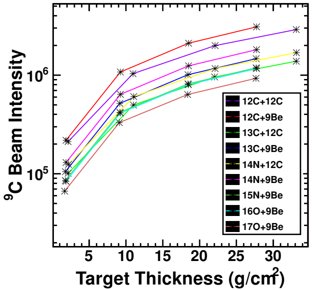
SuperFRS : Physics case

Use of Rare Isotope beam for proton rich hypernuclei

Mocadi simulation for ^9C beam :

- Production of secondary beam → 10^{10} / s primary beam
- Transport over the SuperFRS beamline

[C. Rappold, GSI Scientific Report 2013 p.176]



SuperFRS : Physics case

Use of Rare isotope Beam for proton rich hypernuclei

Theoretical cross section for the possible produced hypernuclei in the collision ^{9}C+^{12}C at 2*A*GeV (DCM model)
[A. Botvina *et al.* Phys. Rev. C. **86** (2012) 011601]

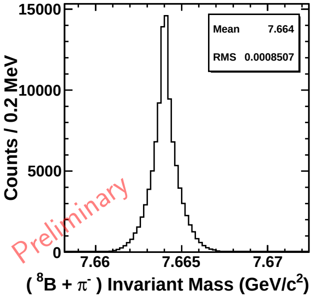
[C. Rappold, GSI Scientific Report 2013 p.176]

$^{3}_{\Lambda}$H 2 μb	$^{4}_{\Lambda}$H 1.2 μb	$^{3}_{\Lambda}$He 1.2 μb	$^{4}_{\Lambda}$He 3.4 μb	$^{5}_{\Lambda}$He 2.6 μb	$^{6}_{\Lambda}$He 1.4 μb
$^{4}_{\Lambda}$Li 1.4 μb	$^{5}_{\Lambda}$Li 1.2 μb	$^{5}_{\Lambda}$Be 0.4 μb	$^{6}_{\Lambda}$Be 1.6 μb	$^{7}_{\Lambda}$Be 0.6 μb	$^{8}_{\Lambda}$Be 0.8 μb
$^{6}_{\Lambda}$B 0.4 μb	$^{7}_{\Lambda}$B 0.2 μb	$^{8}_{\Lambda}$B 0.6 μb	$^{8}_{\Lambda}$C 0.2 μb		

SuperFRS : Physics case

Monte Carlo Simulation :

- Expected invariant mass of ${}^{8}_{\Lambda}$Be $\rightarrow$ ^{8}B $+ \pi^-$, $\Gamma(\pi^-) \sim 0.15$
  - $\rightarrow$ MWD still possible for medium size hypernucleus : ([T. Motoba *et al.* NPA **489** (1988) 683])



- Mass resolution 0.850 MeV (FWHM 0.79 MeV)
  - with 1% dp/p for π^- and 0.1% dp/p for ^{8}B

Outline

Summary

- The Phase 0 of the project was completed in October 2009 and March 2010
  - Demonstrated the feasibility of HypHI by observing the MWD of Λ, ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ & Evidence of ${}^{3}_{\Lambda}n$ existence
  - Open geometry experiment feasible : inclusive measurements.
  - Can study hypernuclear structure.
  - Can use hypernuclei as probe for nuclear reaction study.
- hypernuclear study @ FRS and SuperFRS
  - More precise hypernuclear spectroscopy.
  - FRS / SuperFRS as a dedicated fragment spectrometer.
  - Exclusive measurements : hypernuclear structure only.

Summary

- FRS and SuperFRS as high resolution forward spectrometer for hypernuclear study
  - in near future at FRS :
    $\Rightarrow$ Possibility to confirm the existence of ${}^{3}_{\Lambda}$n via d+π^- :
    ^{6}Li+^{12}C @ 1.8 $\sim$ 2 AGeV
  - in future at SuperFRS : First simulation for studying proton-rich hypernuclei
    $\Rightarrow$ Example of hypernuclei ${}^{8}_{\Lambda}$Be with a cross section of 0.8 μb
  - Unique opportunity with SuperFRS for exotic hypernuclei & MEMO (Metastable exotic multi-hypernuclear object)