Hypernuclei: Spectroscopy with heavy ion beams

Take R. Saito

GSI Helmholtz Center for Heavy Ion Research,

Helmholtz Institute Mainz

and

Mainz University

Hypernuclei: Laboratory for baryon-baryon interaction with hyperon

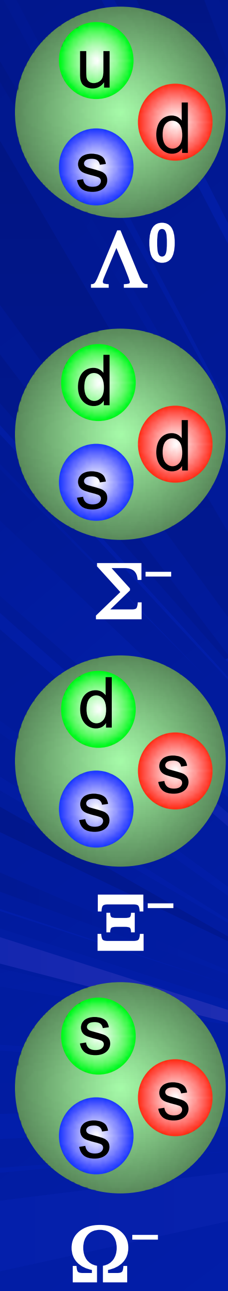
Baryon-baryon interaction with u-, d- and s-quarks

- Towards hyperon(Y)-nucleon(N) and Y-Y interaction
- Comprehensive understanding of nuclear force under $SU(3)_f$
- Input for theories describing the nature of neutron stars

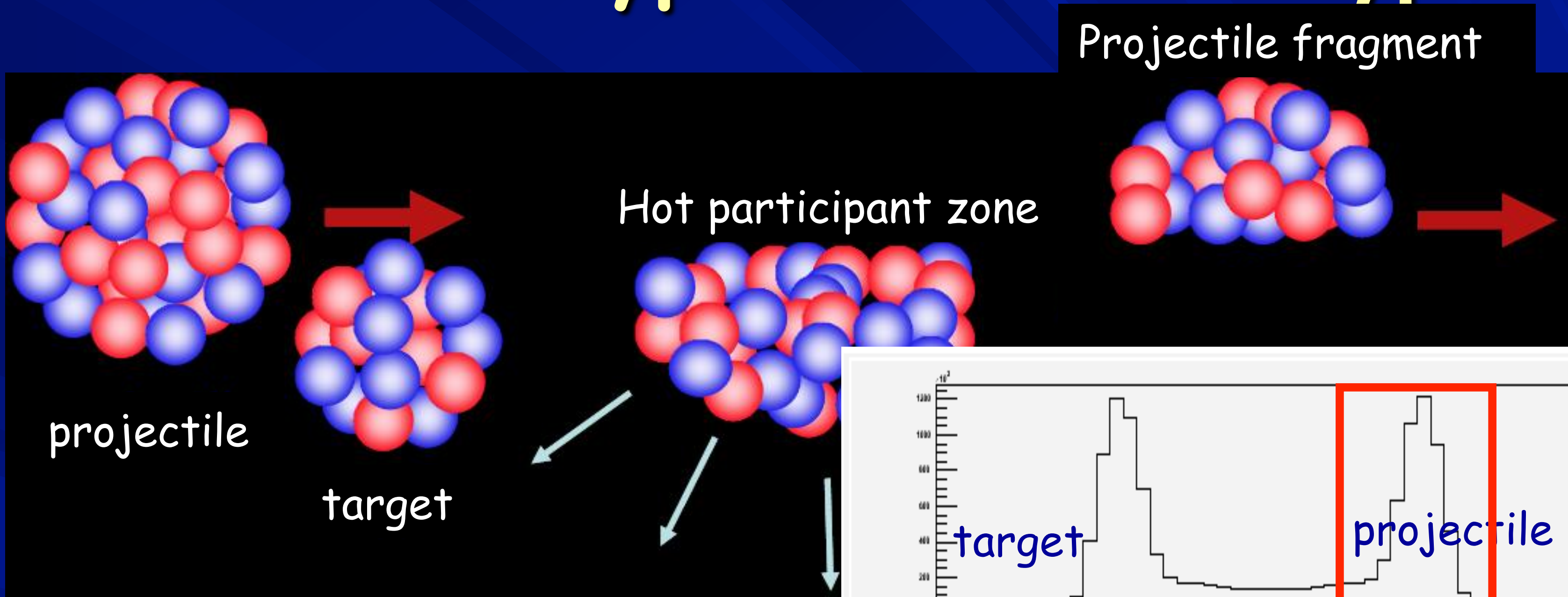
Are Y-N and Y-Y scattering experiments possible?

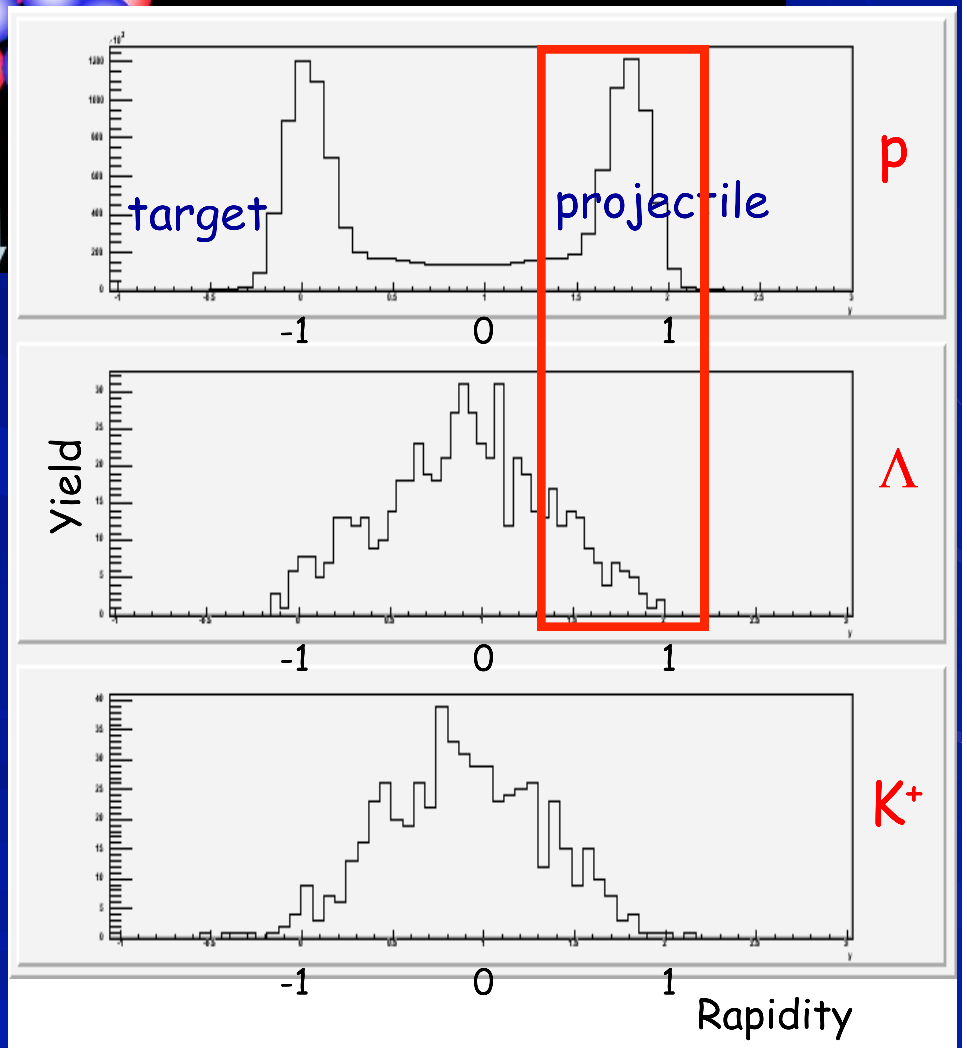
- No hyperon target available: $\tau_Y \sim 10^{-10}$ s
- Difficulty to study low energy interaction with
  - Very high energy hyperon beams: CERN WA89 and SELEX
  - Hyperon production experiments

> **Impossible to deduce precise YN interactions**
> **Not possible for YY interactions**
> ⬇
> **Using hypernuclei as a micro-laboratory**



Production of Hypernuclei with HypHI





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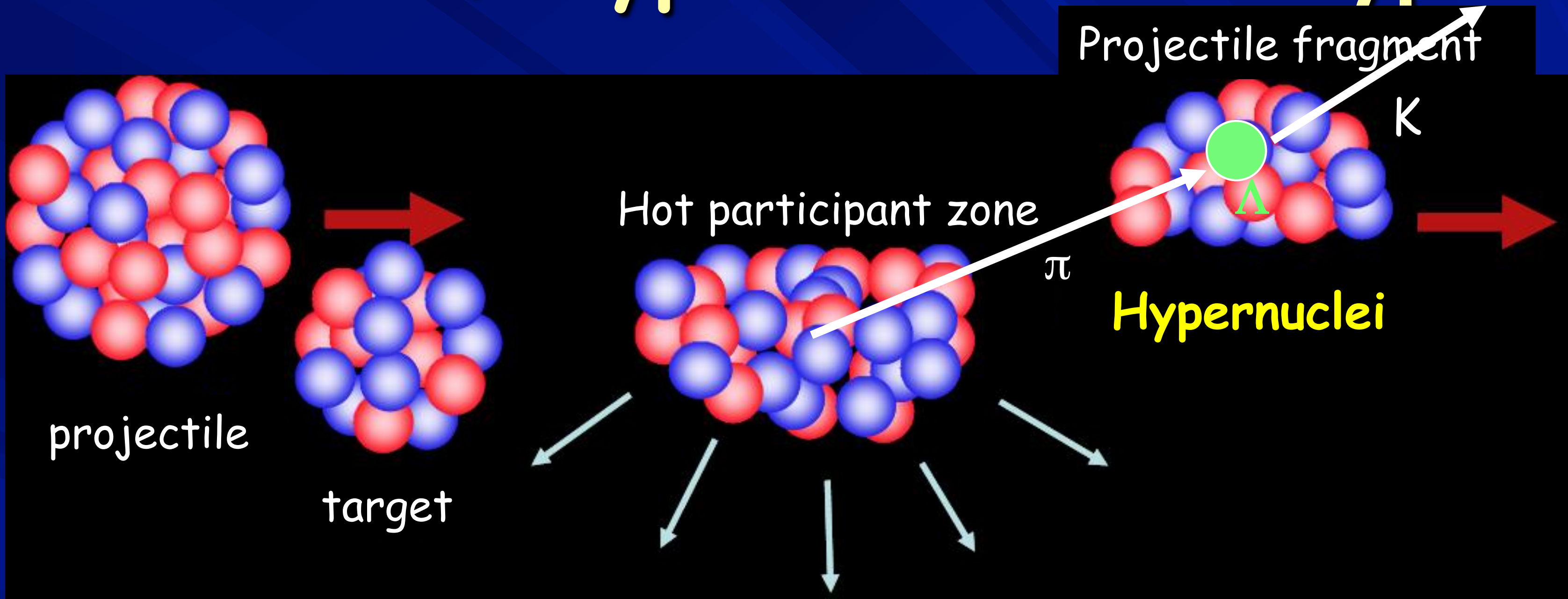


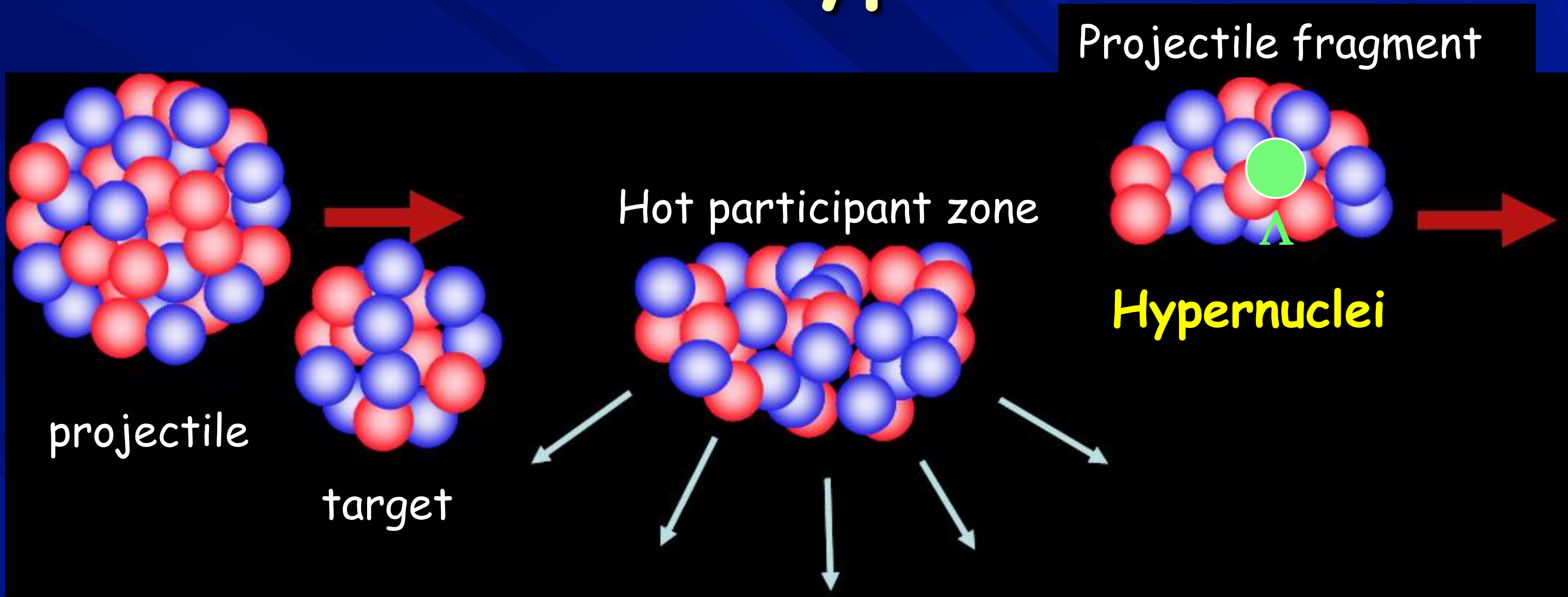
- **Coalescence of Λ in projectile fragments**
- **(π^+,K^+) reactions in projectile fragments**

- **NN -> ΛKN : Energy threshold ~ 1.6 GeV**
  - Heavy ion beams with E > 1.6 A GeV needed
    - Stable heavy ion beam at GSI
    - Stable heavy ion beam at FAIR
    - **RI-beam from FRS and super-FRS**

Accessible to neutron- and proton rich hypernuclei

Other exotic searches also possible

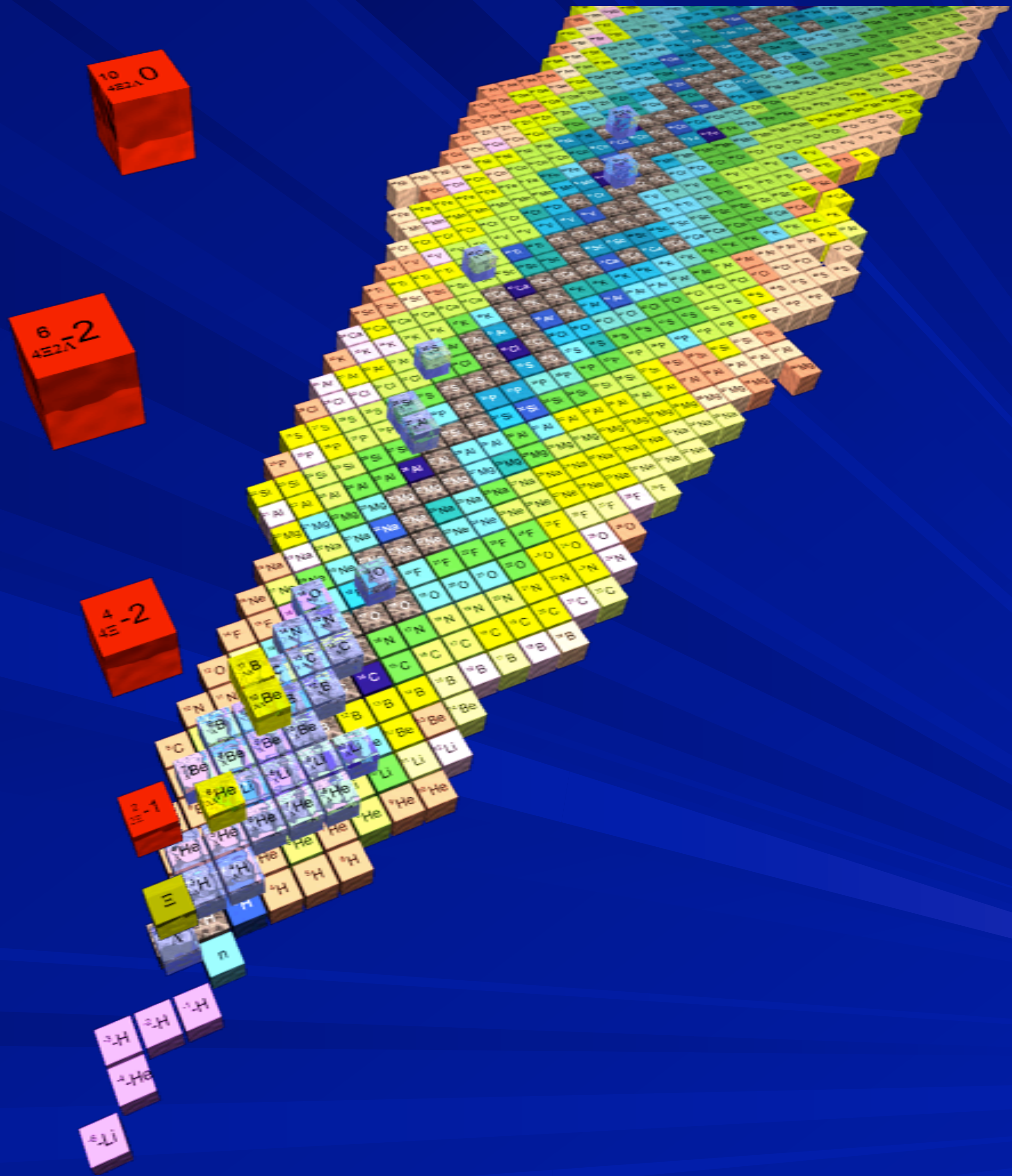
Relativistic hypernuclei



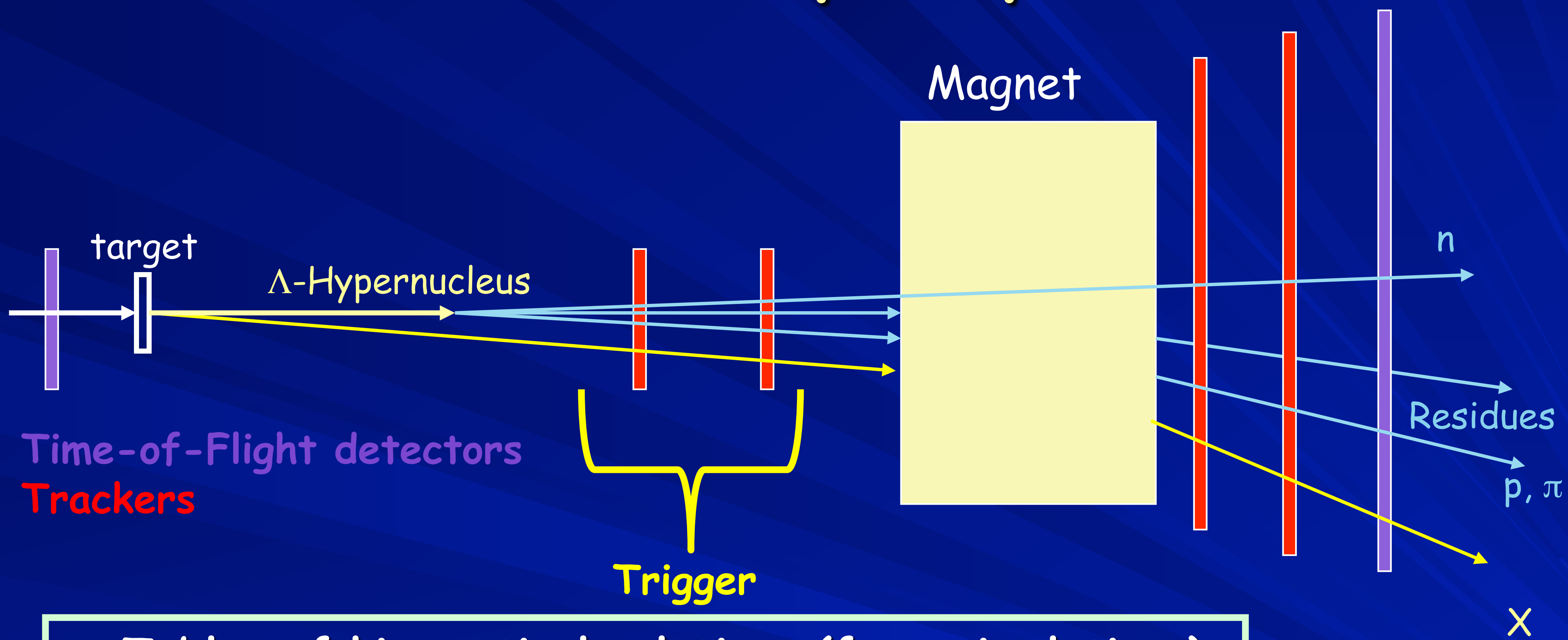
- **Large Lorentz factor** γ (>3)
  - Effective lifetime : Longer by the Lorentz factor
    200 ps -> 600 ps at GSI (ct ~ 20 cm)
    200 ps -> 4 ns at FAIR (ct ~ 120 cm)

- **Hypernuclear separation and spin precession**
  - Can be feasible with 20 Tm at 20 A GeV
  - Large spin precession in magnetic fields
    - 225 degrees with free-Λ magnetic moment

Nuclear matter with multiple-strangeness



Detection principle



- Tables of kinematical relations (from simulations)
- Programmed in fast online hardware (FPGA)

➡ **Displaced vertex trigger**

C. Rappold, PhD thesis

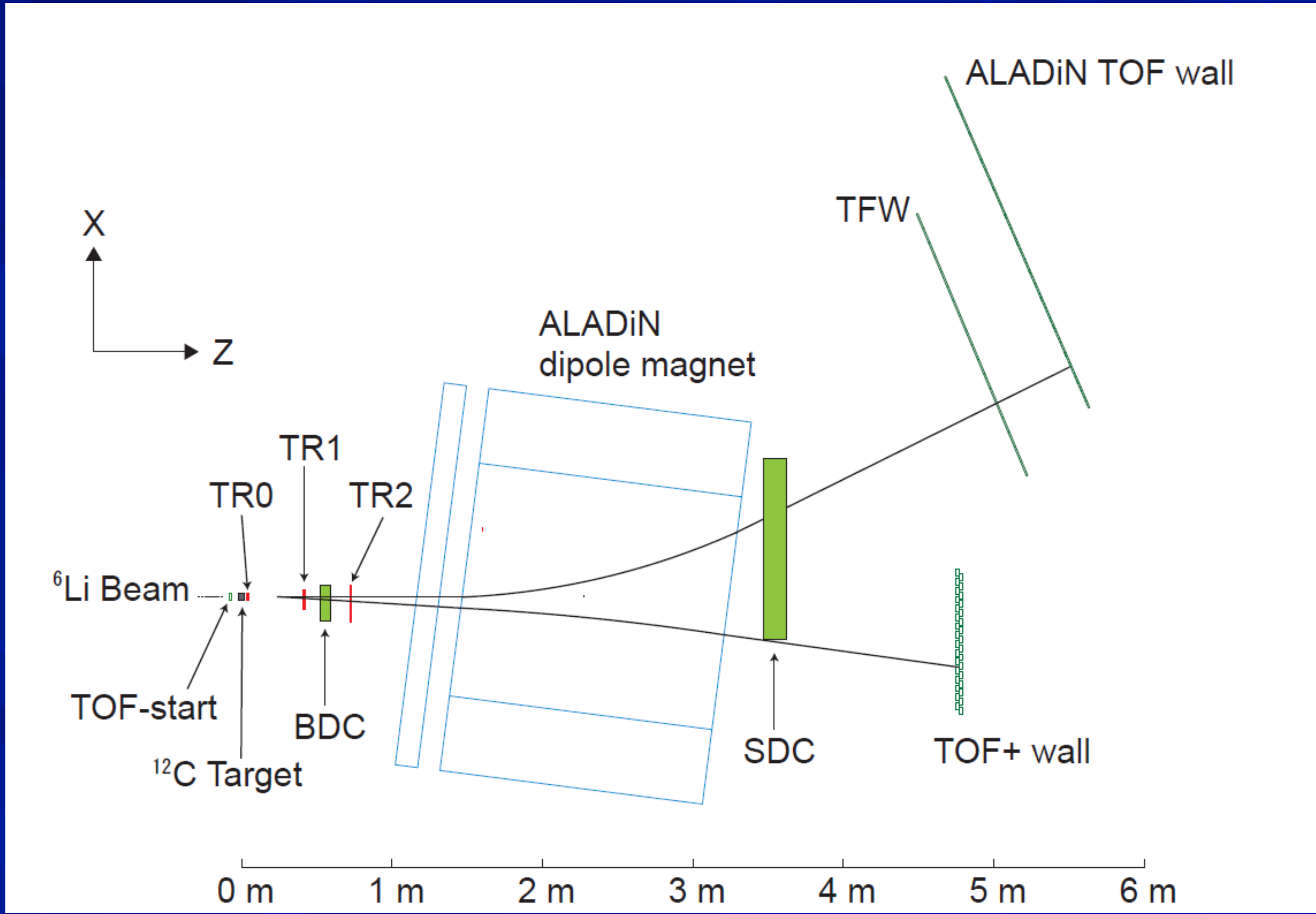
HypHI Phase 0 in October 2009

- The goal of the Phase 0 experiments
  - To demonstrate the feasibility of precise hypernuclear spectroscopy with ^{6}Li primary beams at 2 A GeV : Mesonic decay $\Lambda \rightarrow \pi^{-} + p$

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

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

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

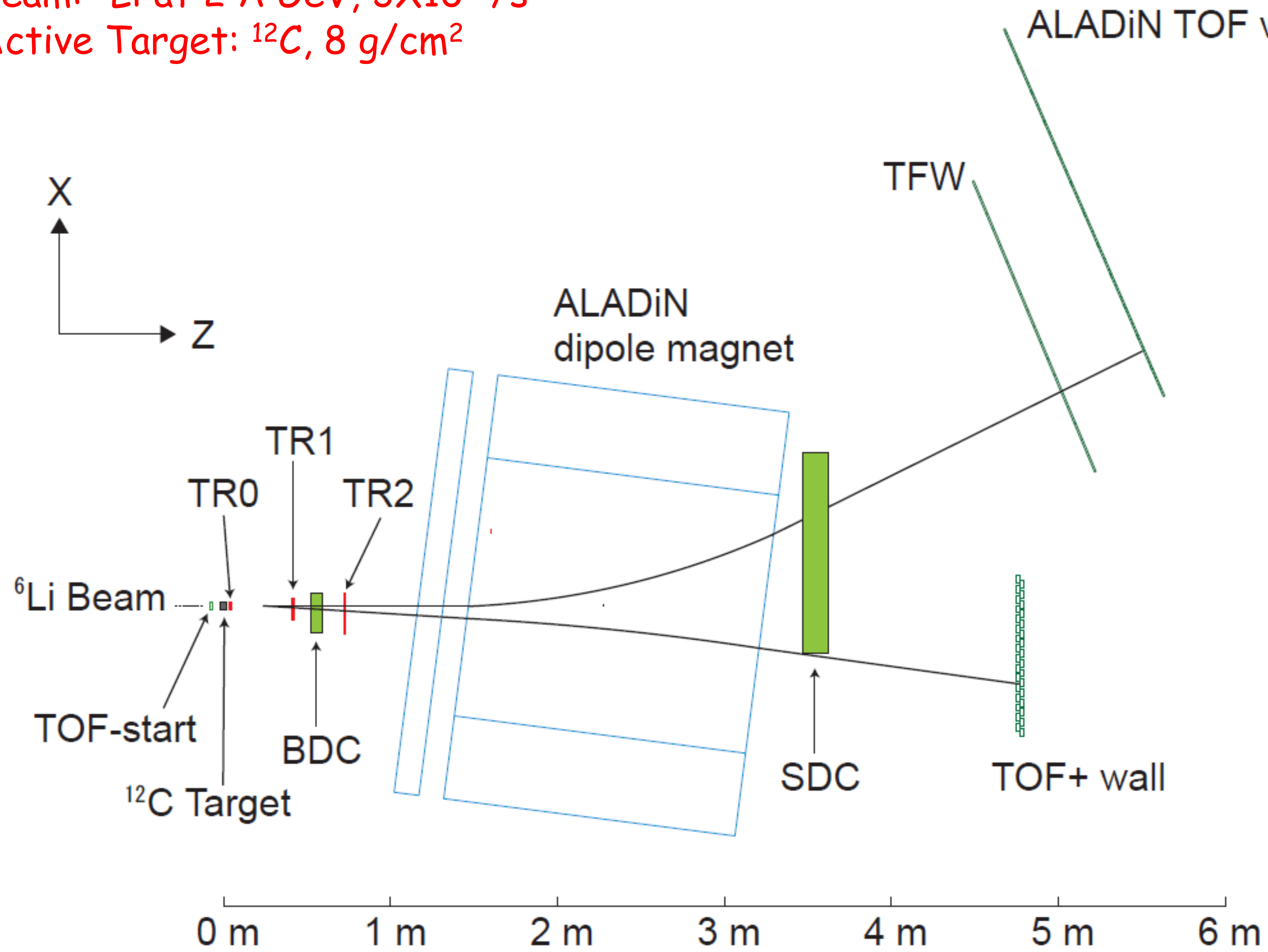


Funding

- Helmholtz-University Young Investigators Group VH-NG-239, 2006-2012
- DFG grant SA1696/1-1 2007-2009, TOF detectors

Phase 0 setup

Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s
Active Target: ^{12}C, 8 g/cm^{2}



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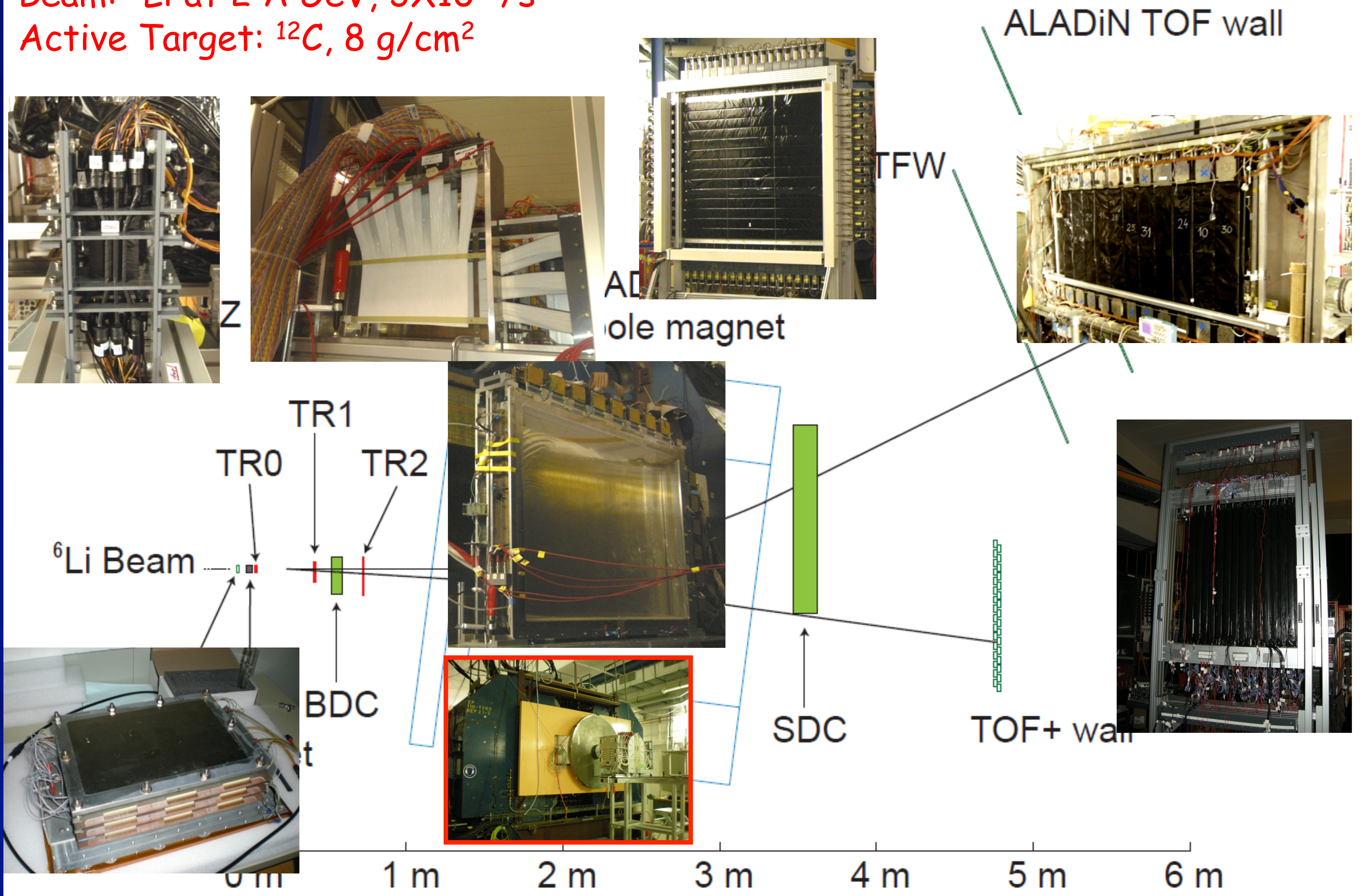
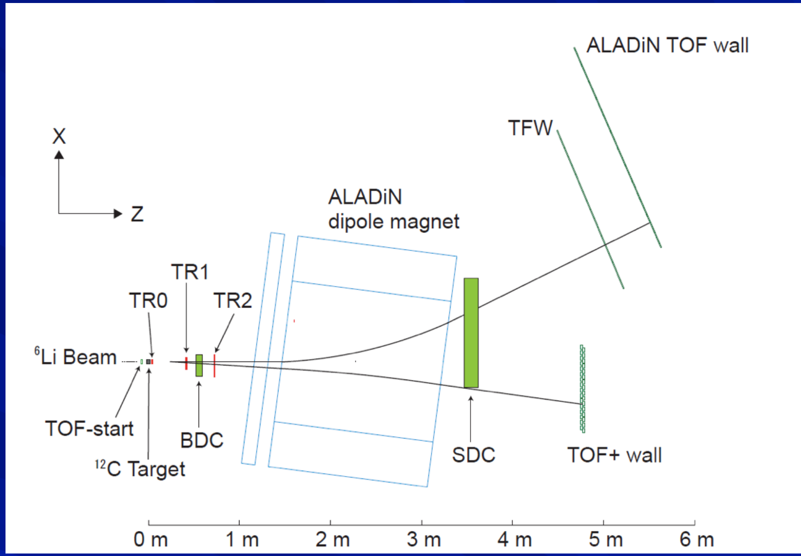


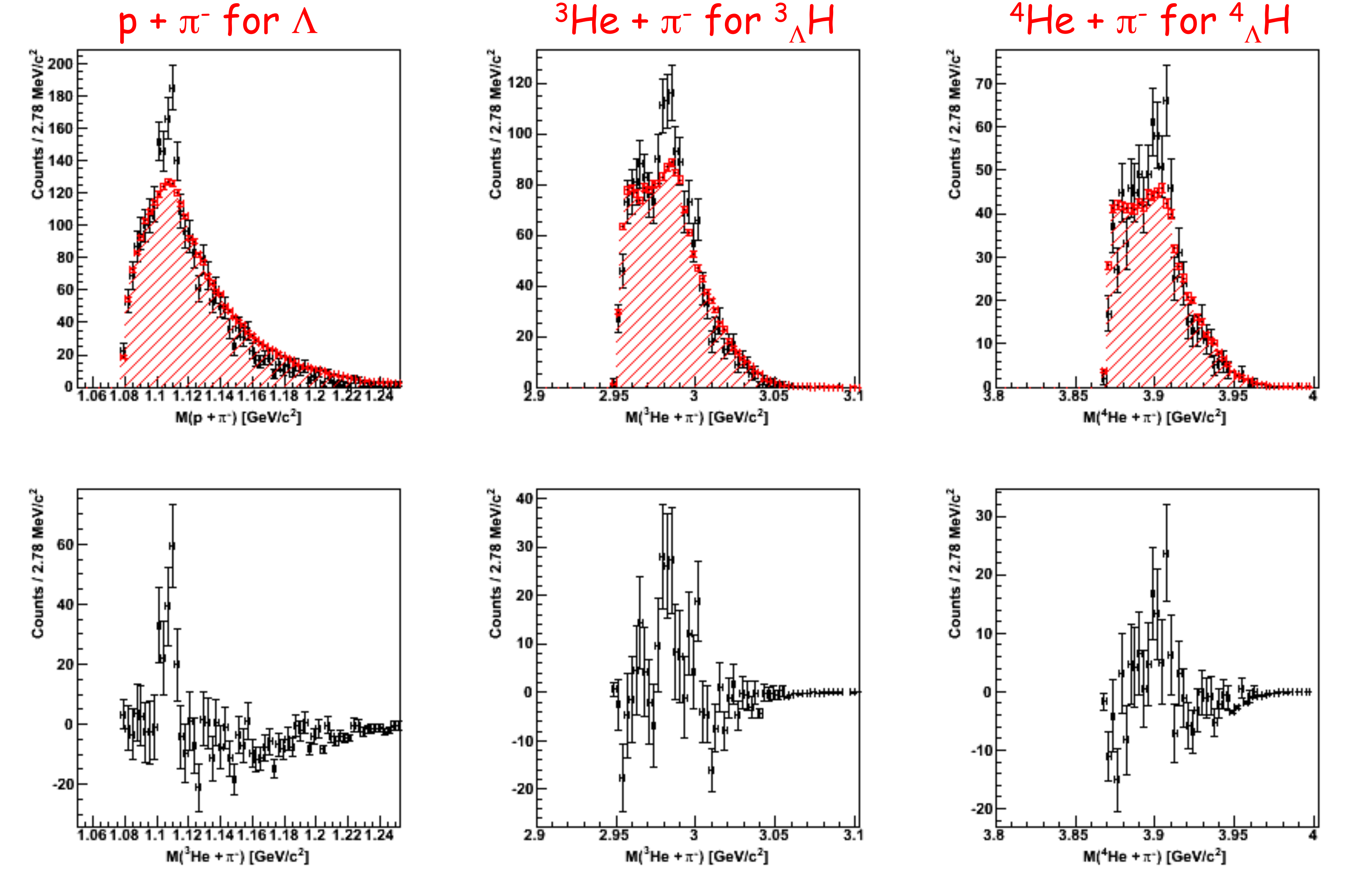
Analysis for Phase 0

- Independent calibrations for each detector
- Track-candidate finding and calibrations
- Track fitting: Kalman filter
- Particle ID
  - dE/dx in TOF+
  - TOF with TOF+ and TFW
  - Momentum from tracking
- Decay vertex
  - Pairs of corresponding tracks
  - Minimum track distance: < 4 mm
  - Longitudinal vertex position
- Directional cut
- Momentum cut for π^-: > 0.4 GeV/c
- Estimation of combinatorial background
  - Mix different events from data



C. Rappold, D. Nakajima, E. Kim, PhD thesis,
NPA 881 (2012) 218,
C. Rappold to be published

Analysis with BDC

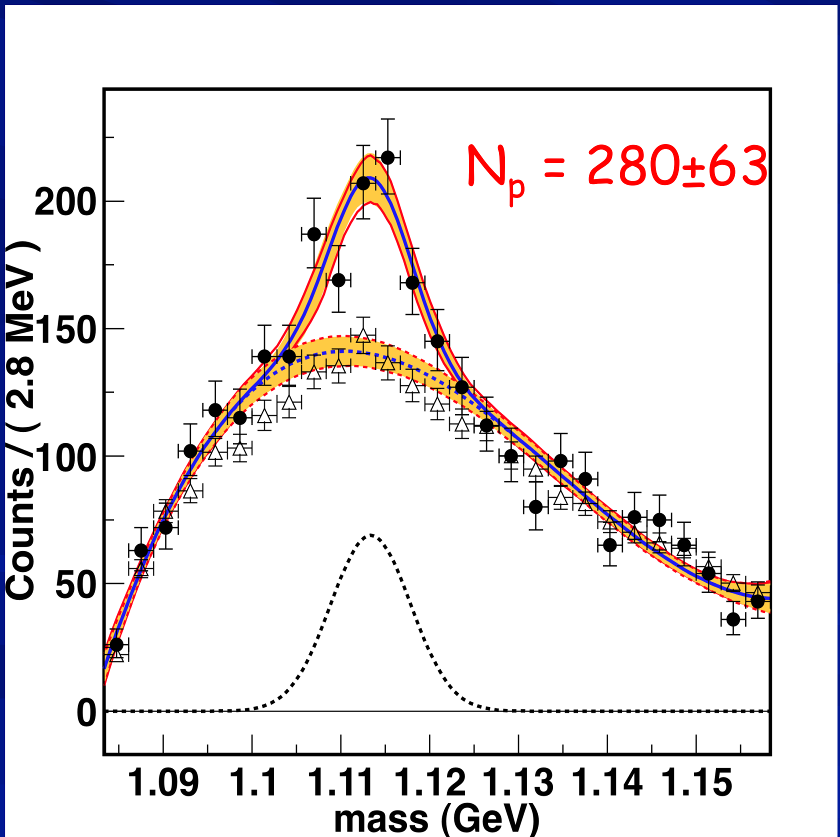


E. Kim, PhD thesis, NPA 881 (2012) 218

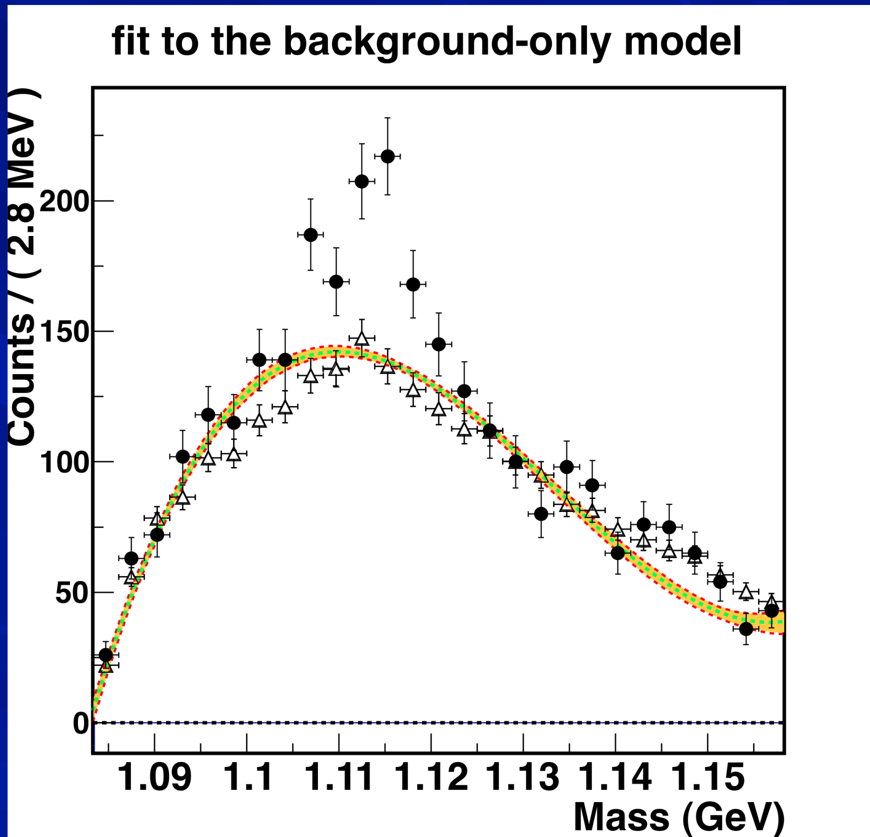
Latest Results: $\Lambda \rightarrow p + \pi^-$

- Statistical analysis of Λ invariant mass (-100 mm < Vertex Z < 300 mm) with RooStats and RooFit package
- Fitting model = n_s *(Gaus: sig_m, sig_s)* + n_b *(Chebychev: a0, a1, a2)*

Fit to the signal + background model♪



Fit to the background-only model♪



E. Kim, PhD thesis, C. Rappold to be published

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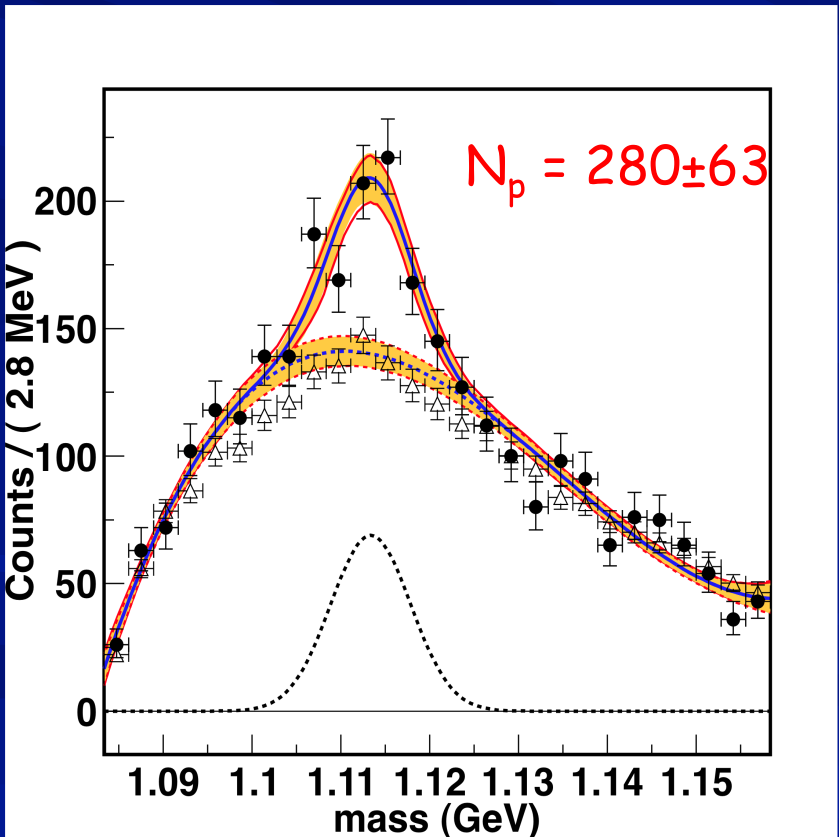
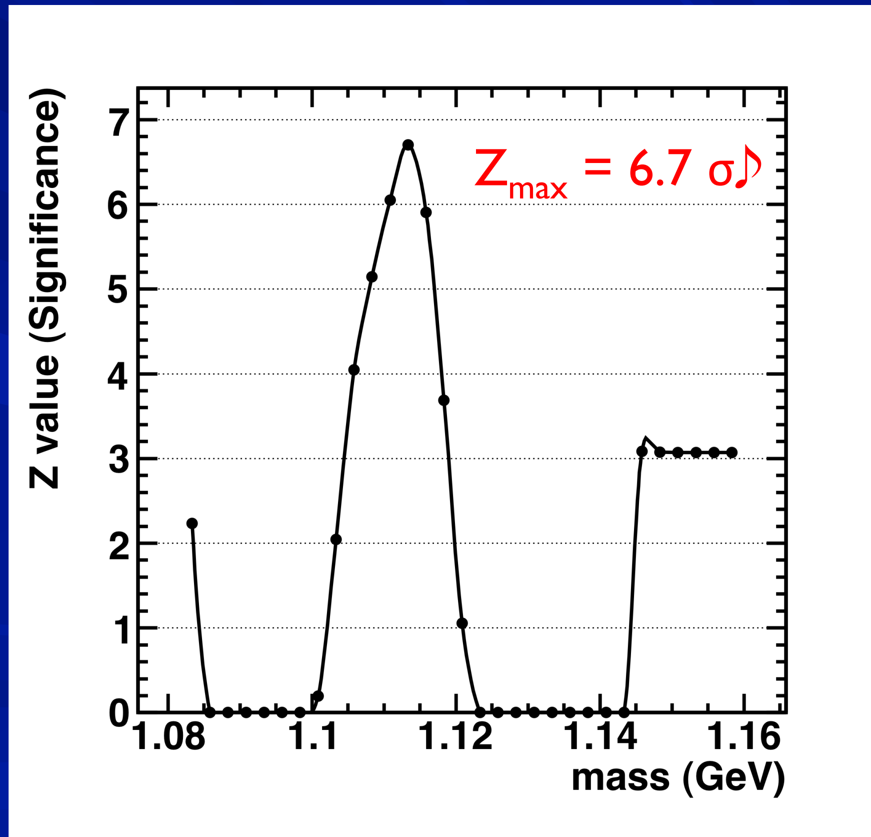
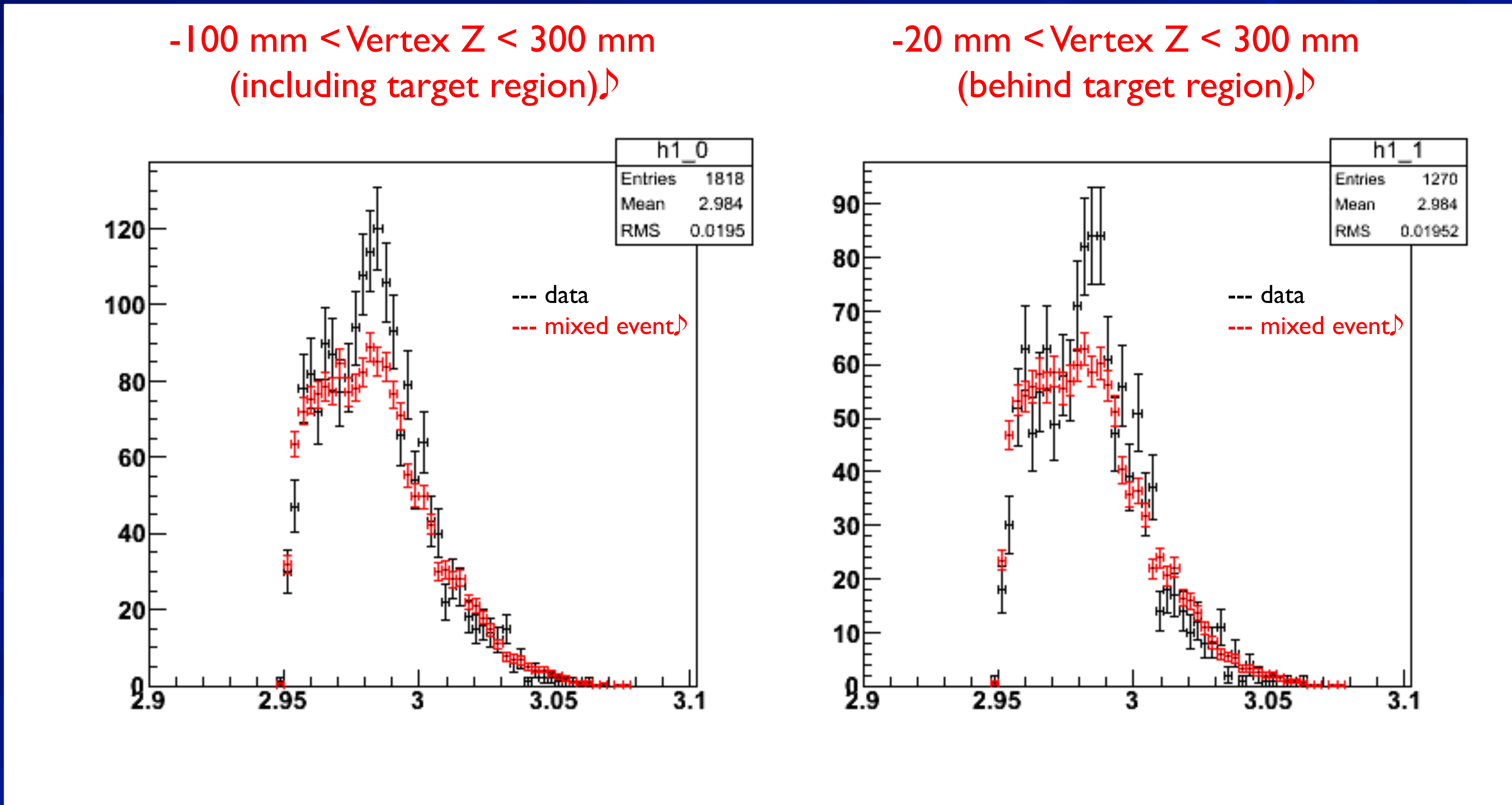


Significance♪



E. Kim, PhD thesis, C. Rappold to be published

Latest Results: $^{3}_{\Lambda}H$ -> $^{3}He + \pi^{-}$



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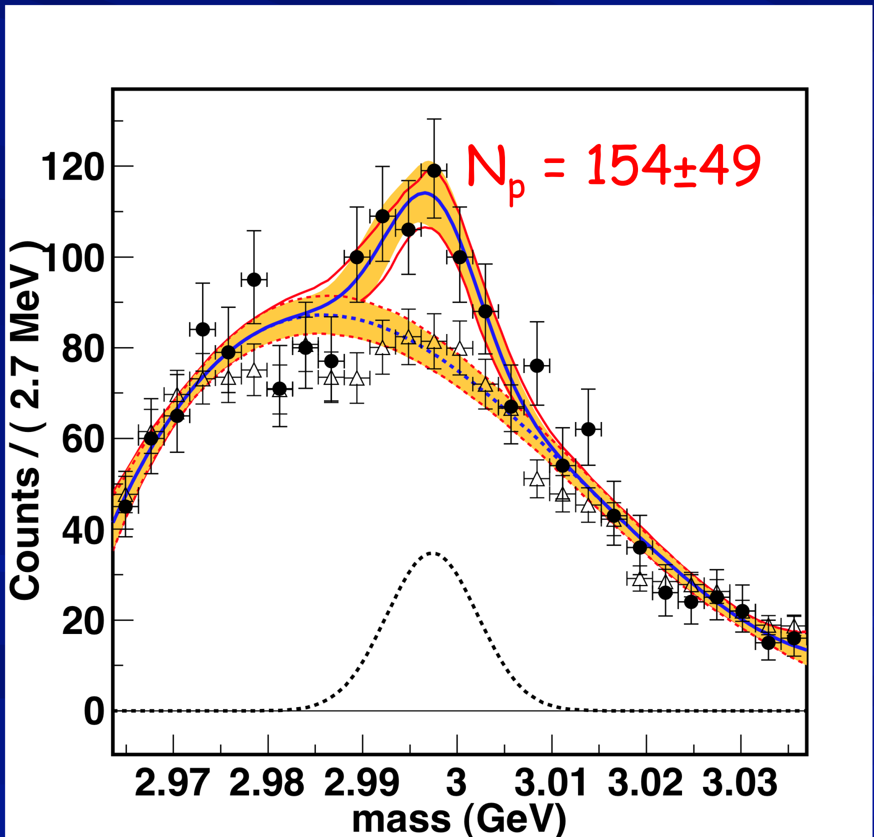

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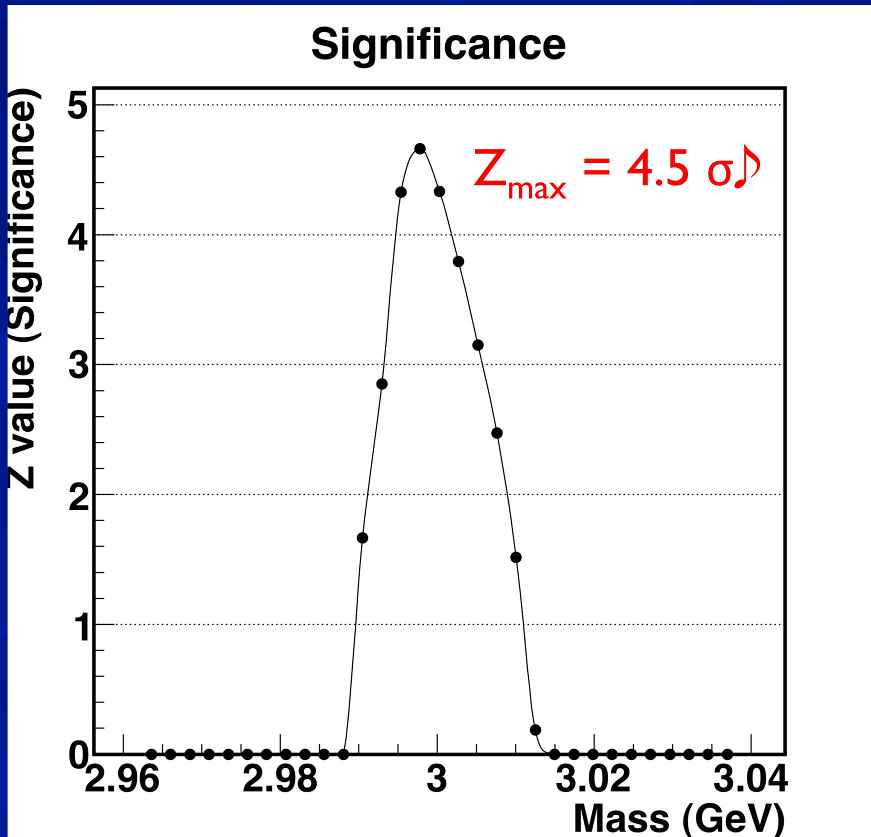
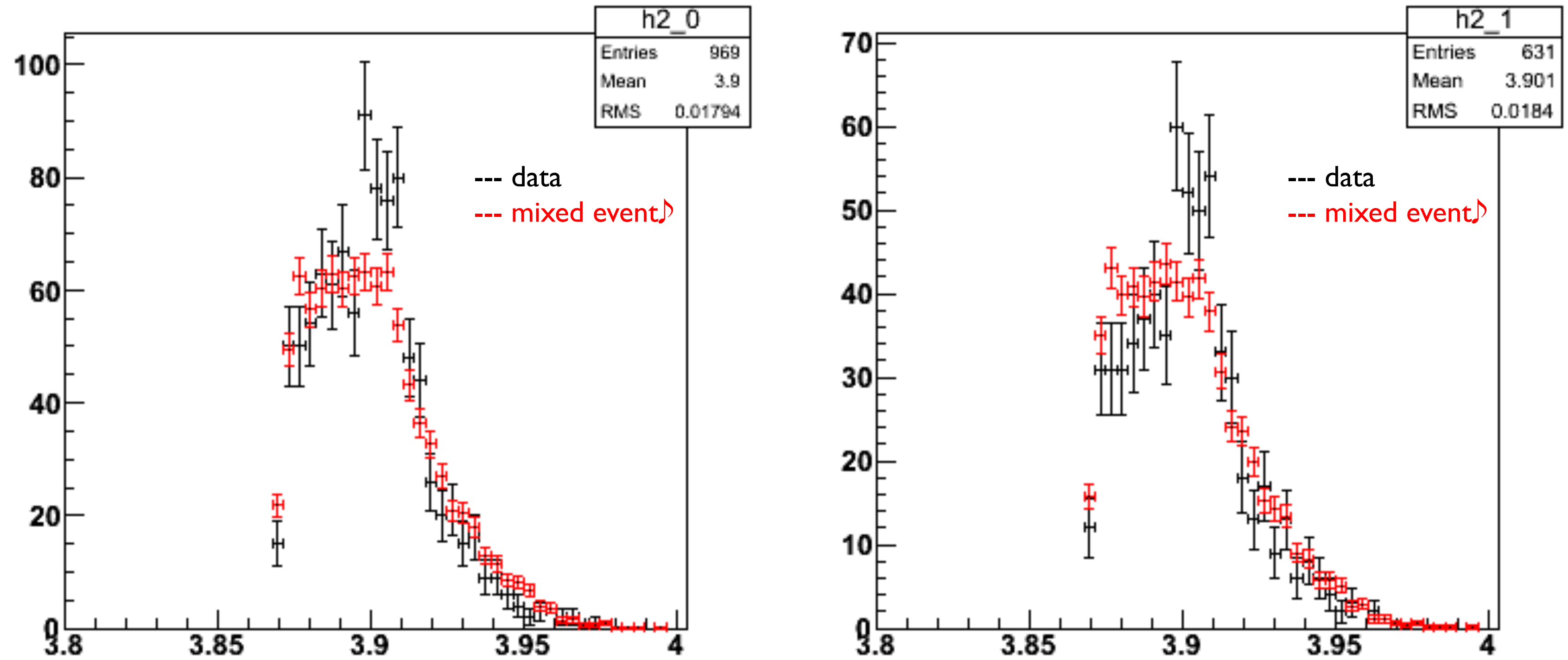


E. Kim, PhD thesis, C. Rappold to be published

Latest Results: ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$

-100 mm < Vertex Z < 300 mm
(including target region)

-20 mm < Vertex Z < 300 mm
(behind target region)



E. Kim, PhD thesis, C. Rappold to be published

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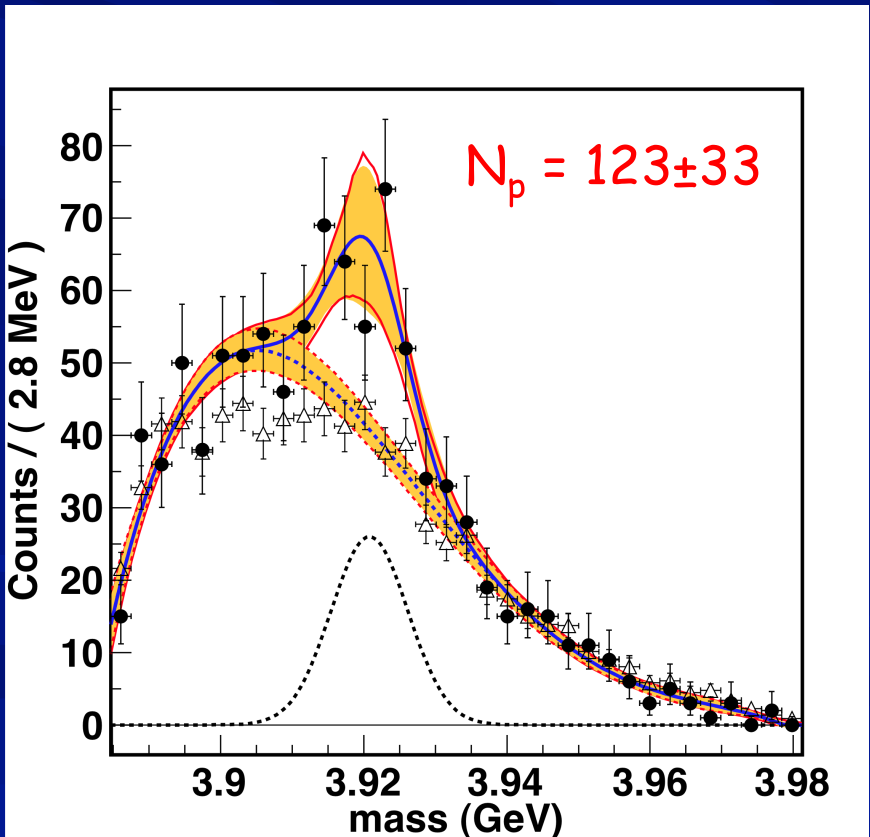

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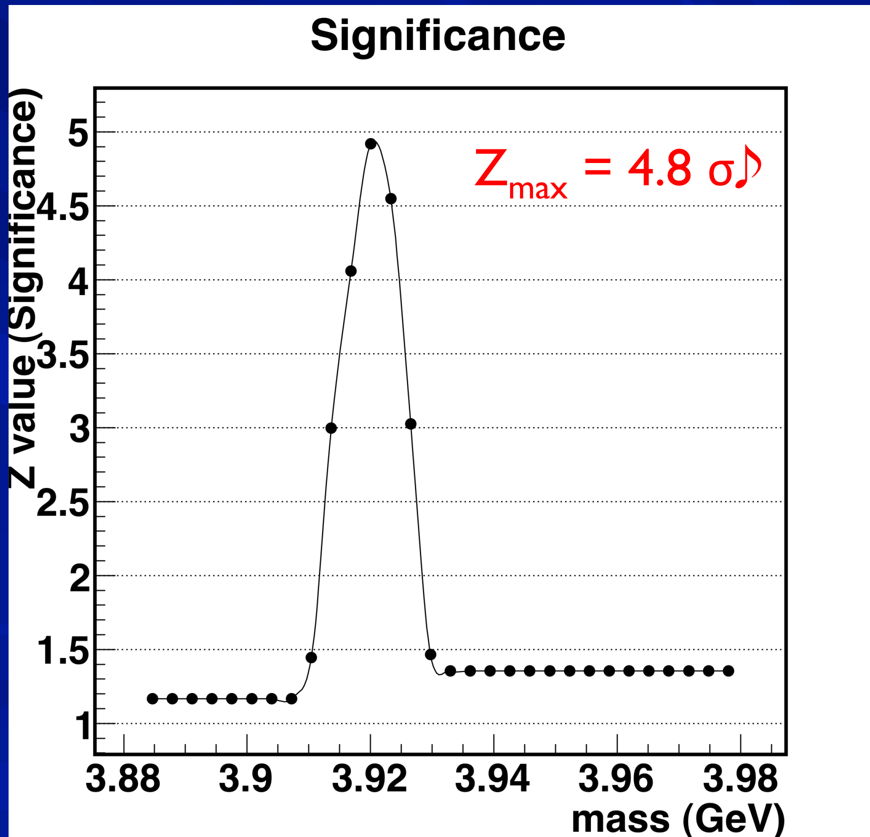

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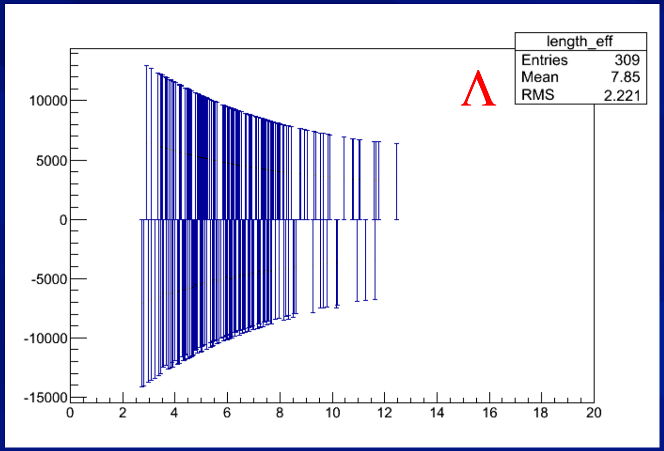
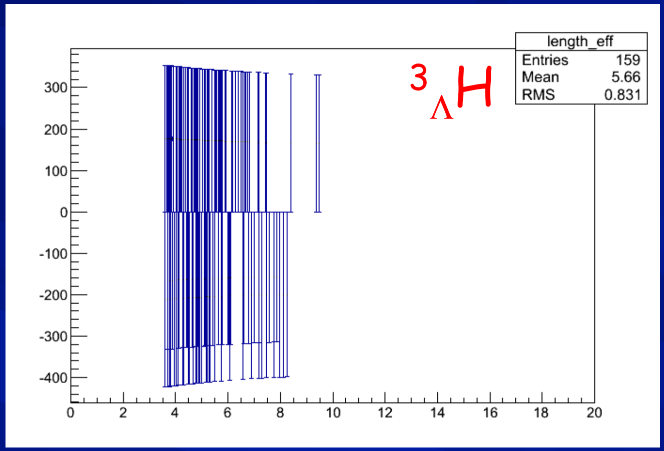
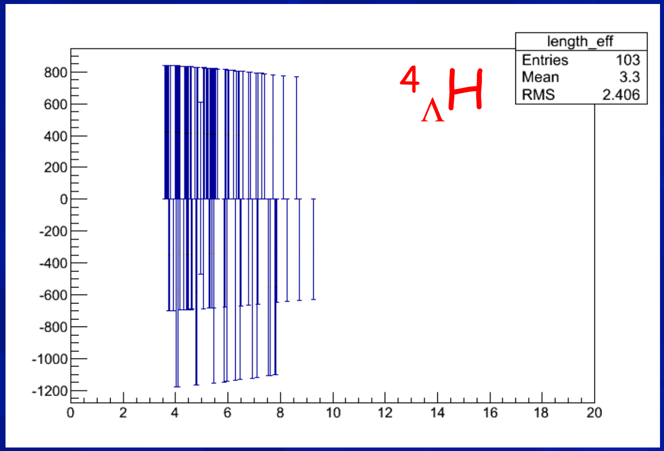
Lifetime

- Signal region: peak position ± 2σ
- Sideband subtraction: 2σ in both sides
- Acceptance from the full Monte Carlo simulations







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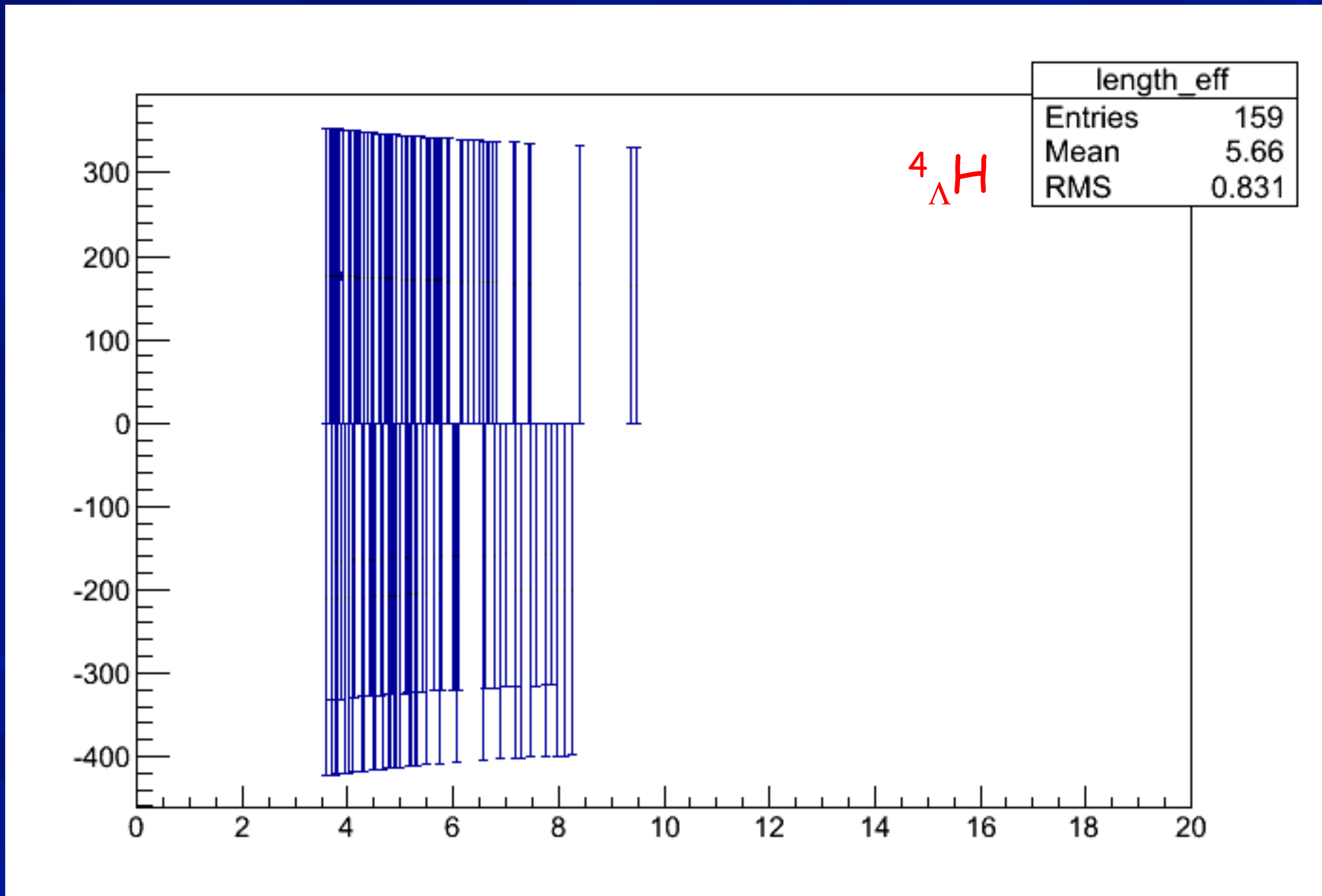

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Unbinned maximum likelihood fitting

- Probability Density Function PDF for the exponential decay

$$P(x) = \frac{1}{\tau} e^{-\frac{x}{\tau}}$$

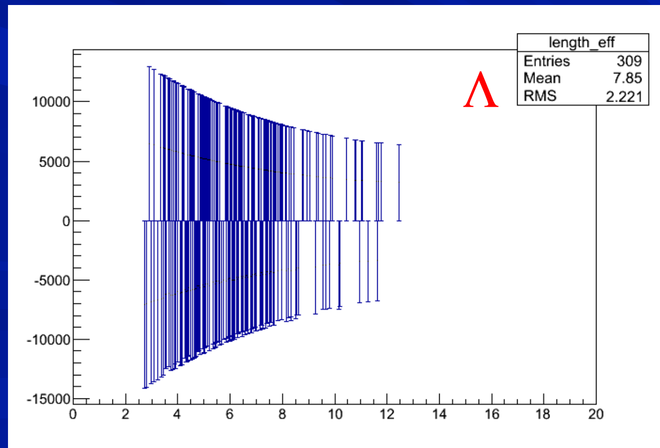
- If NOT normalized, the likelihood function is

$$L(x_i) = \frac{e^{-\mu}\mu^n}{n!} \prod_i \left(\frac{1}{\tau} e^{-\frac{x_i}{\tau}} \right)$$

- With scaling factors (acceptance and efficiency)

$$n = a \sum_i w_i$$

$$L(x_i) = \frac{e^{-\mu}\mu^{a\sum w_i}}{(a\sum w_i)!} \prod_i \left(\frac{1}{\tau} e^{-\frac{x_i}{\tau}} \right)^{aw_i}$$



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Unbinned maximum likelihood fitting

- Log of the likelihood

$$log(L(x_i)) = -\mu + log(\mu)a\sum w_i - log(\Gamma(a\sum w_i + 1) + log\left(\frac{1}{\tau}\right) - \frac{1}{\tau}\sum x_i w_i$$

- Partial differentiation of Log(L) on τ

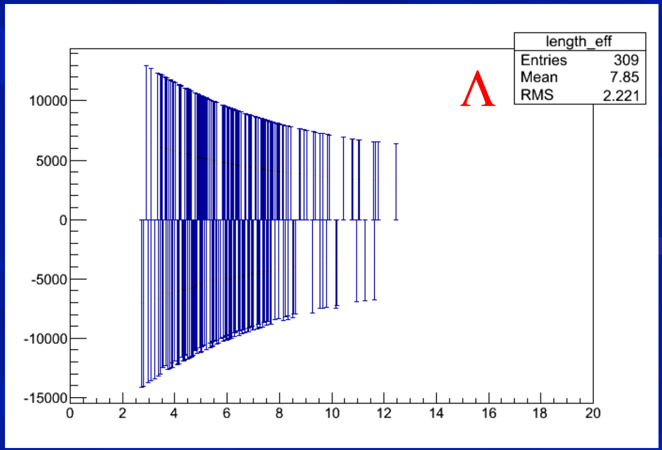
$$\frac{\partial log(L(x_i))}{\partial \tau} = -\frac{a}{\tau}\sum w_i + \frac{a}{\tau^2}\sum x_i w_i = 0$$

$$\tau = \frac{\sum x_i w_i}{\sum w_i}$$

- Partial differentiation of Log(L) on μ

$$\frac{\partial log(L(x_i))}{\partial \mu} = -1 + \frac{a}{\mu}\sum w_i = 0$$

$$\mu = a\sum w_i = n$$



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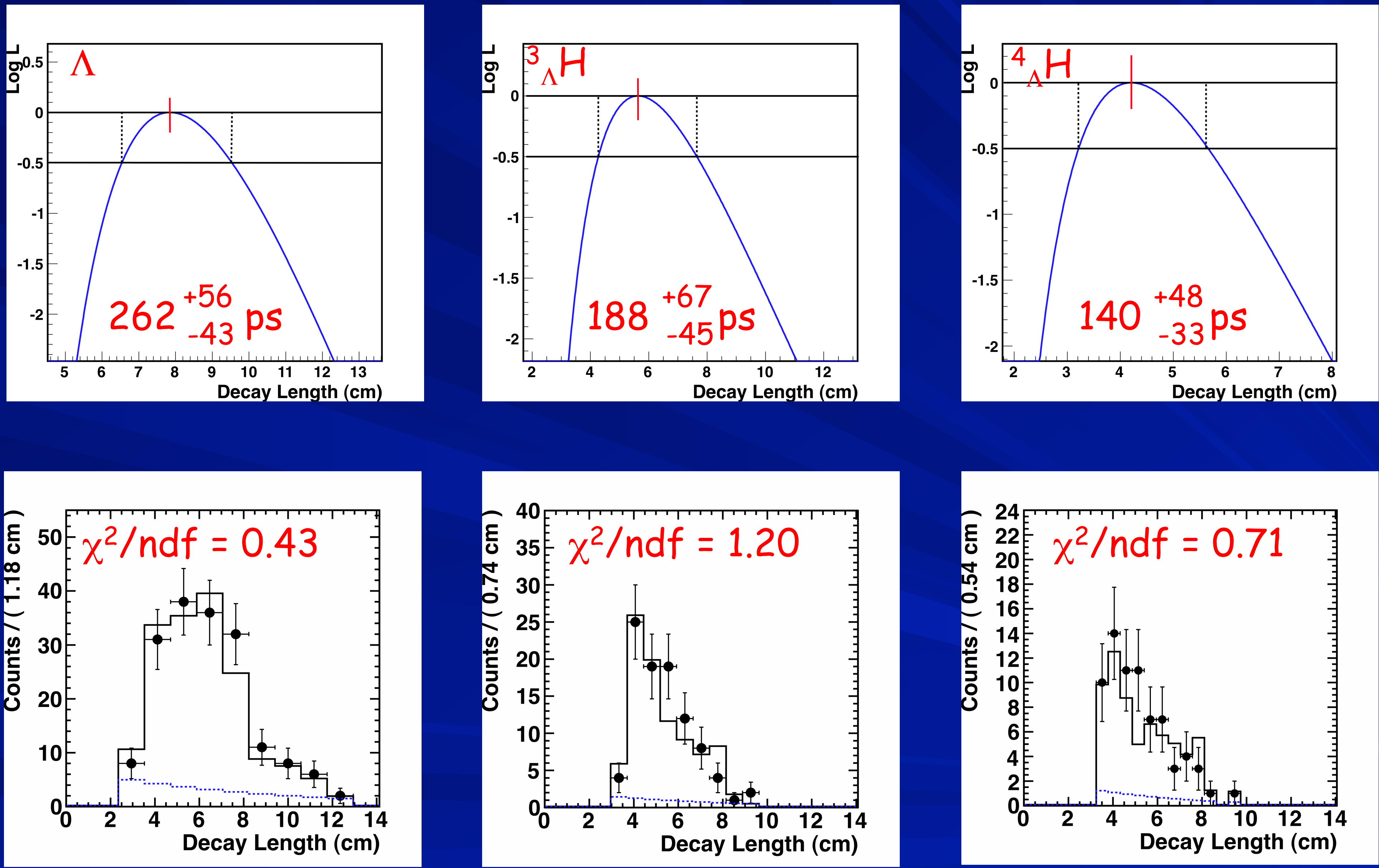

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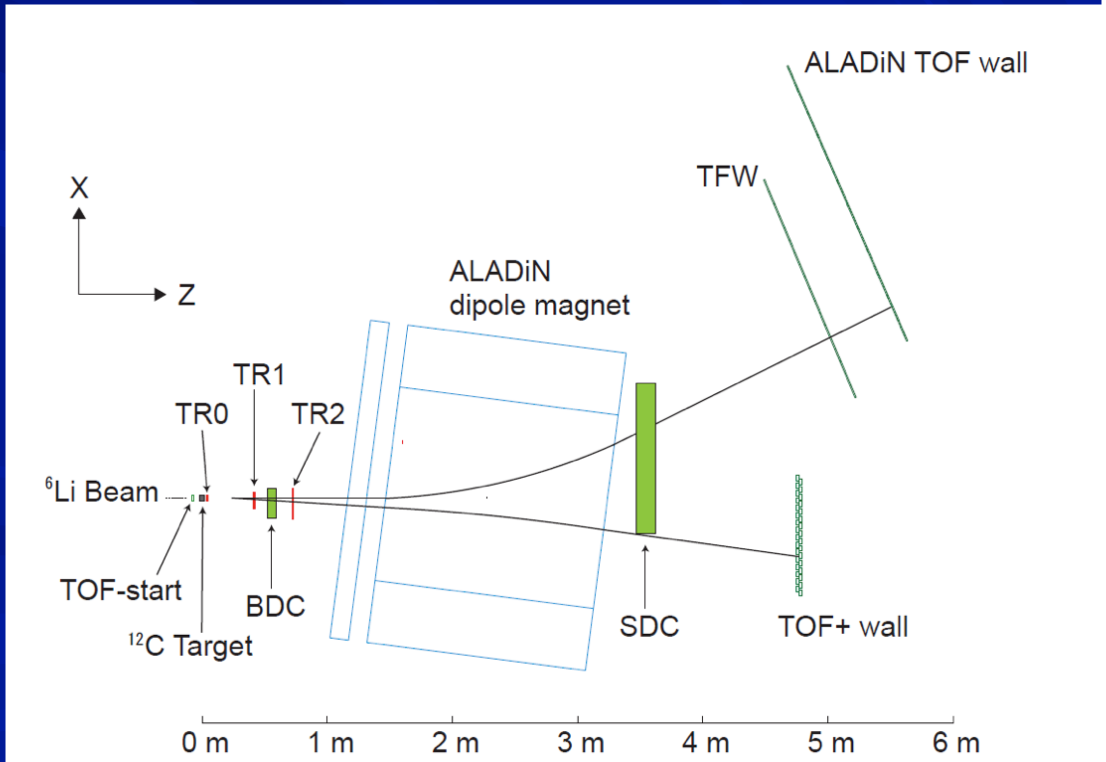
Analysis without BDC, but with vertex fitting

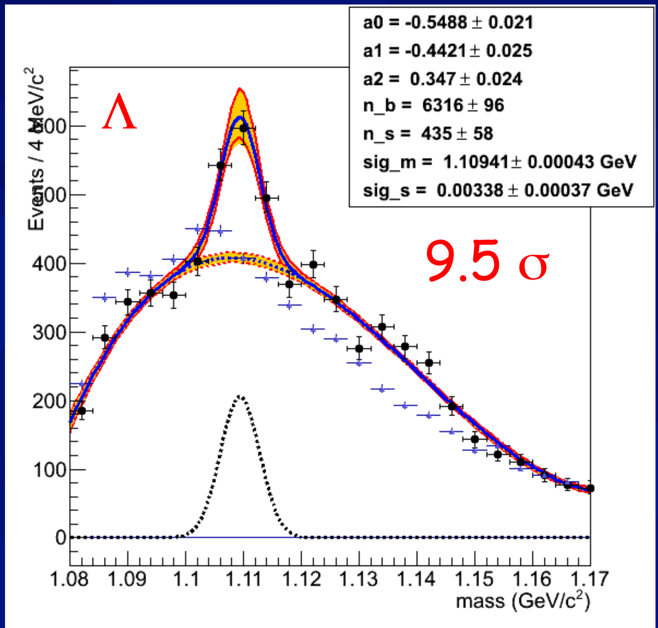
- Tracking layers
  - In front of the bending magnet:
    - Fiber detectors, TR1 and TR2
  - Behind the bending magnet
    - Drift chamber SDC and TOF walls

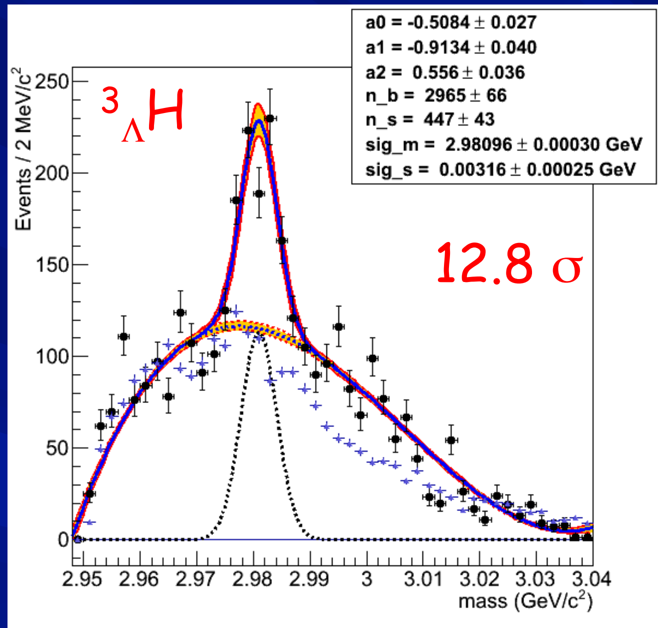
- **Vertex fitting**
  - **Better selectivity**

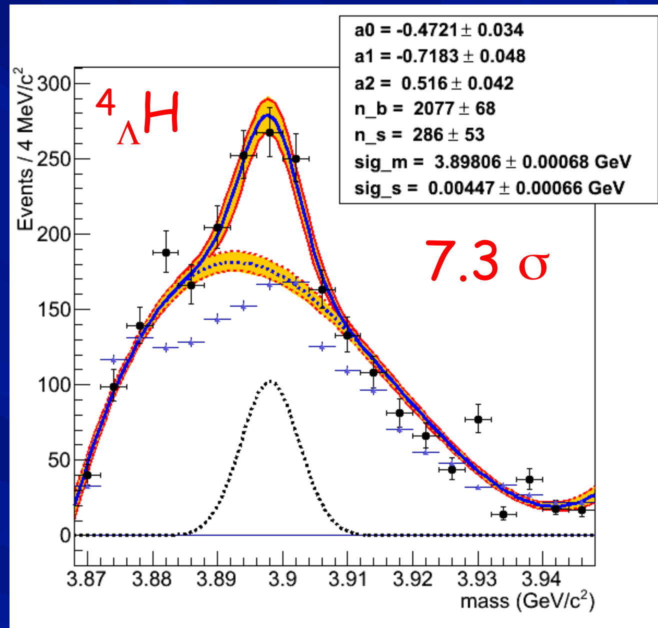


O. Bertini, Ph.D. thesis

Invariant mass distributions with vertex fitting





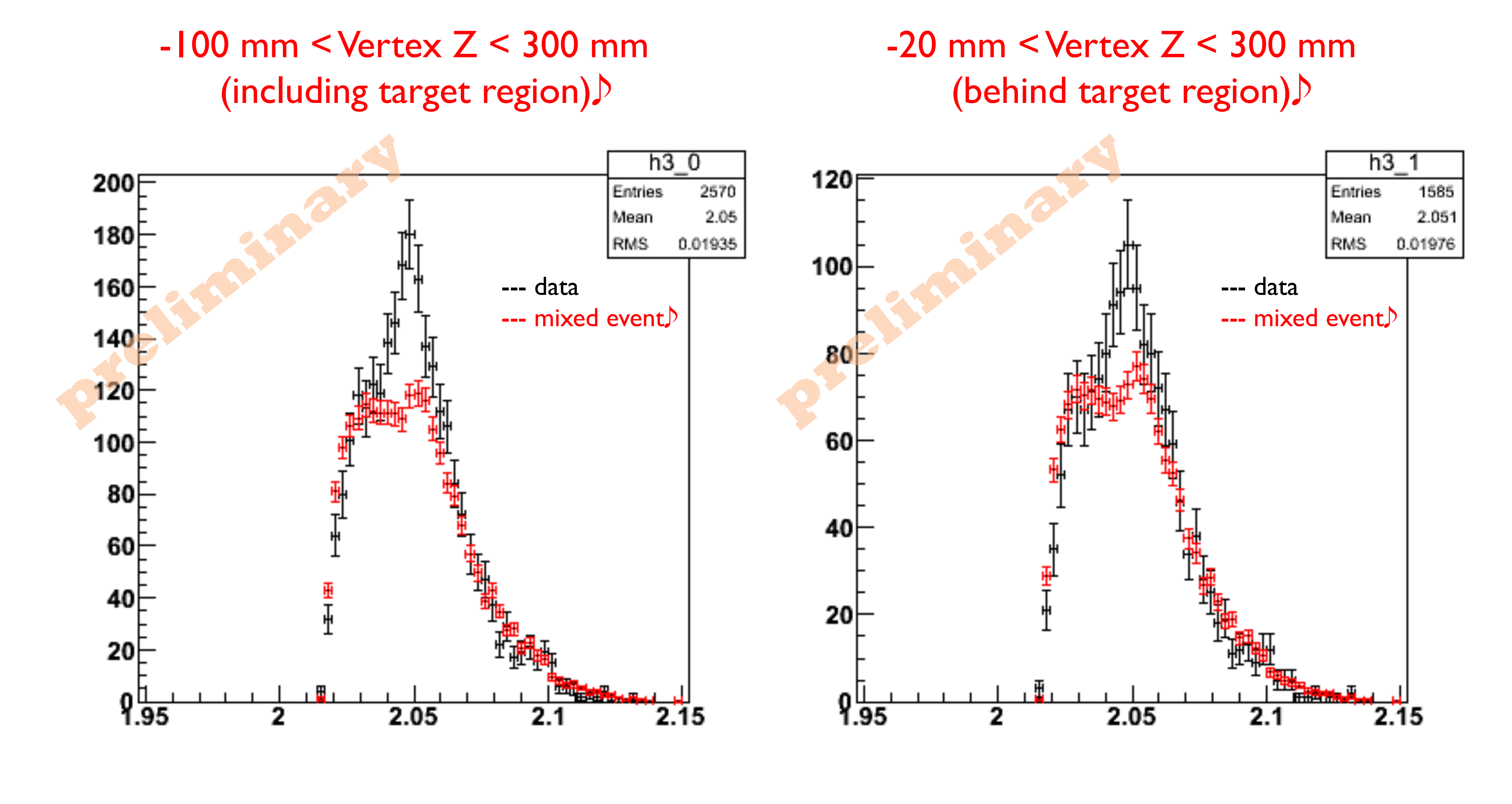


O. Bertini, Ph.D. thesis

Some final states:

NOT observed so far
in the other experiments

Latest Results: ??? -> d + π^-



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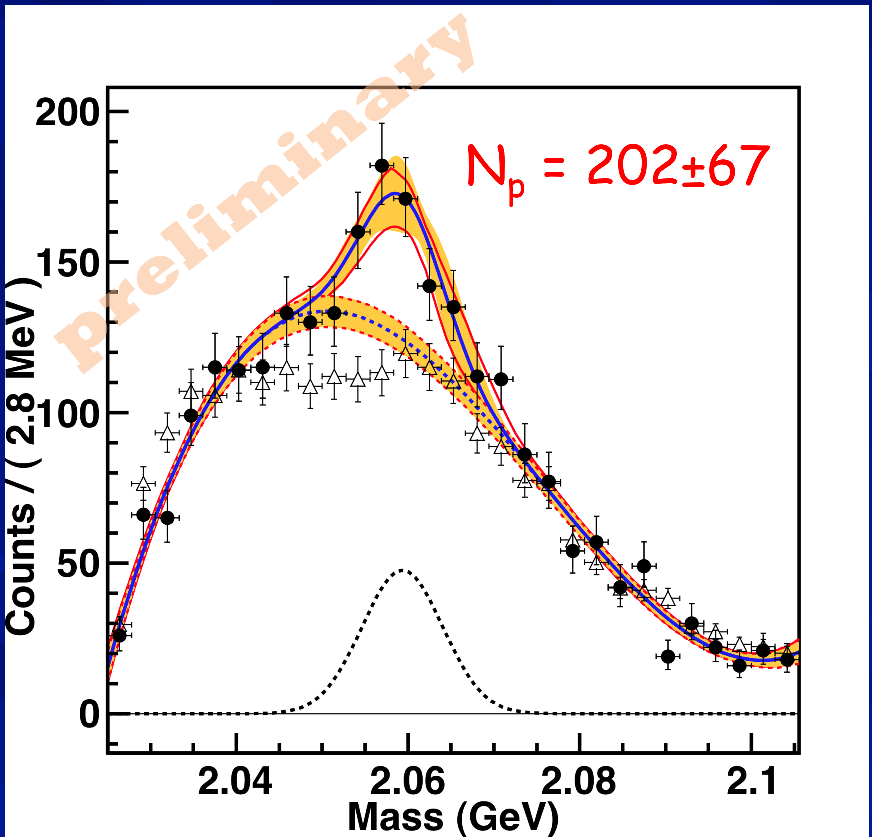
Fit to the signal + background model



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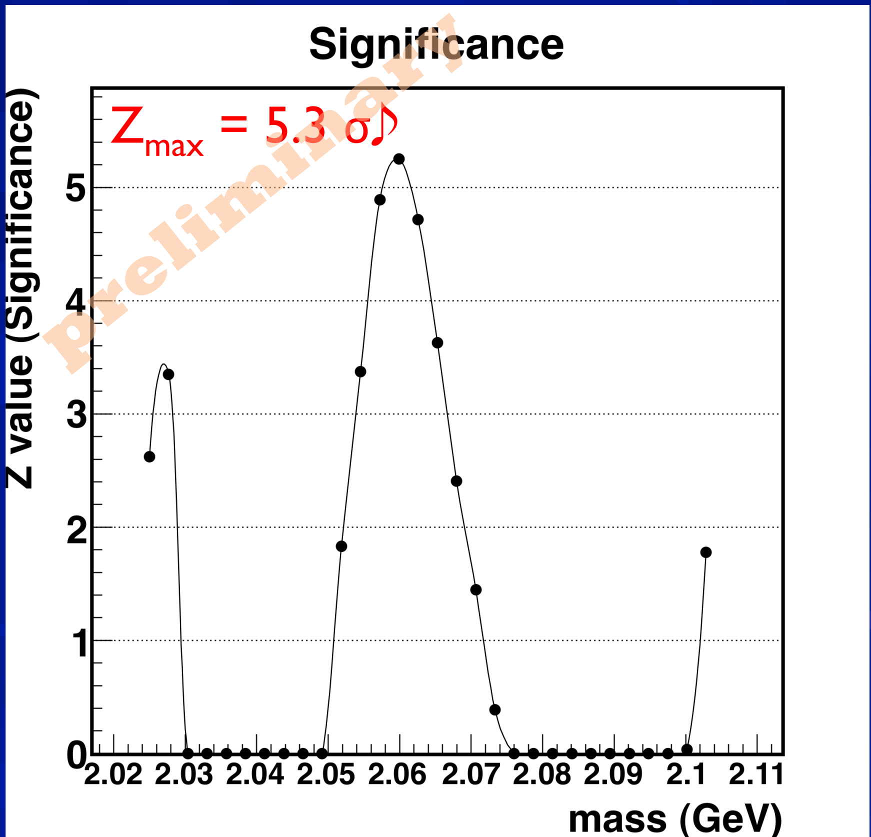

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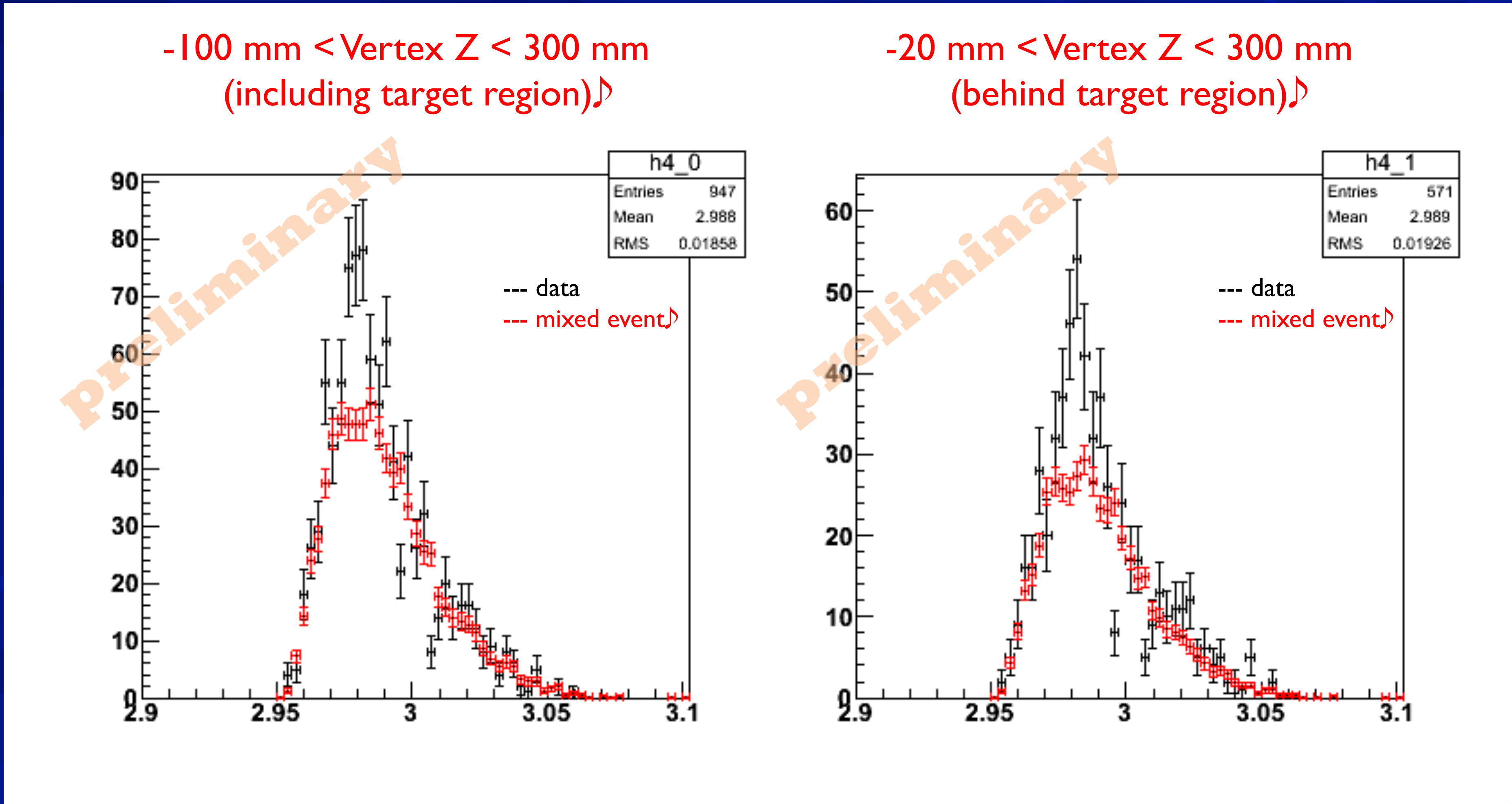
Latest Results: ??? -> t + π^-



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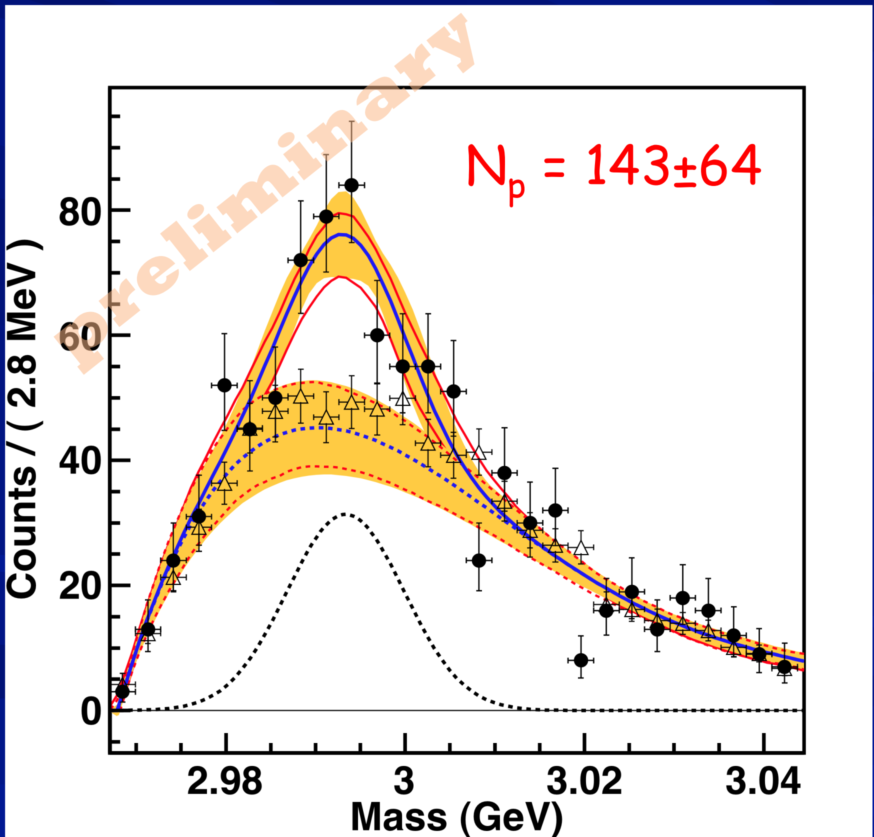

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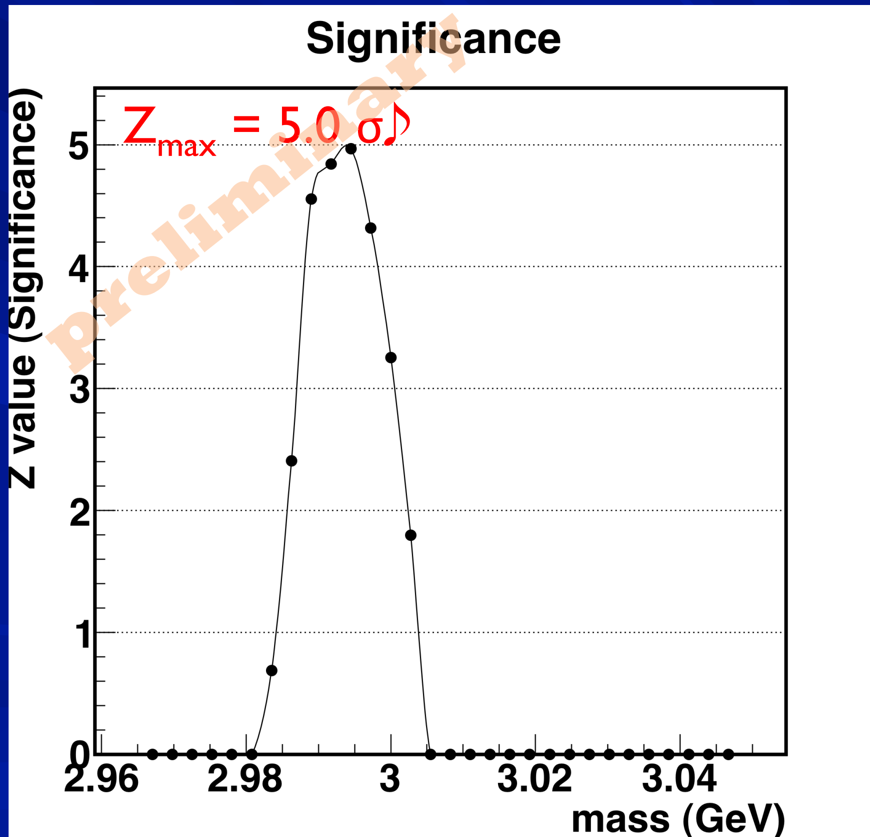

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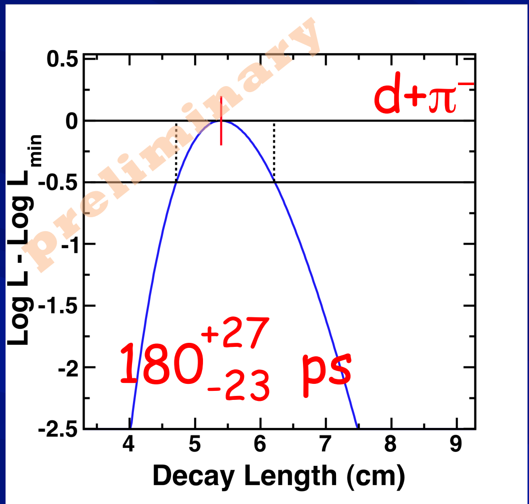

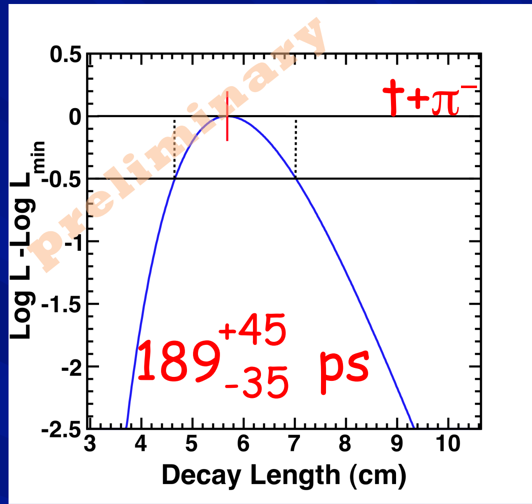

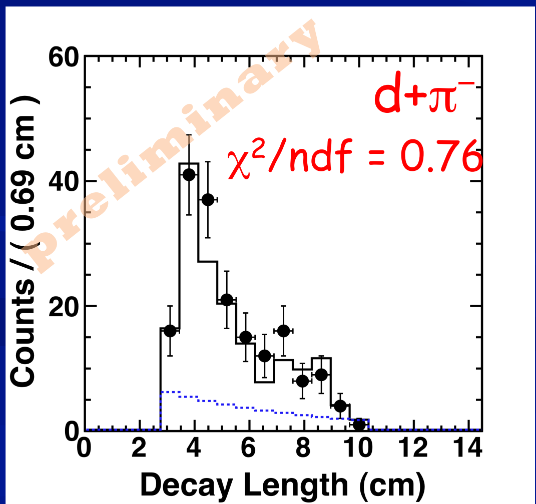

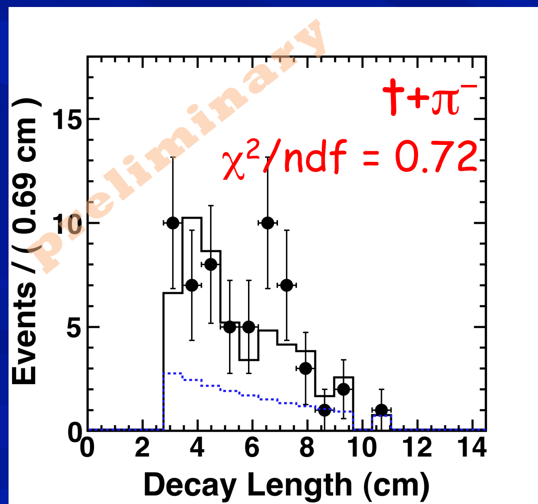

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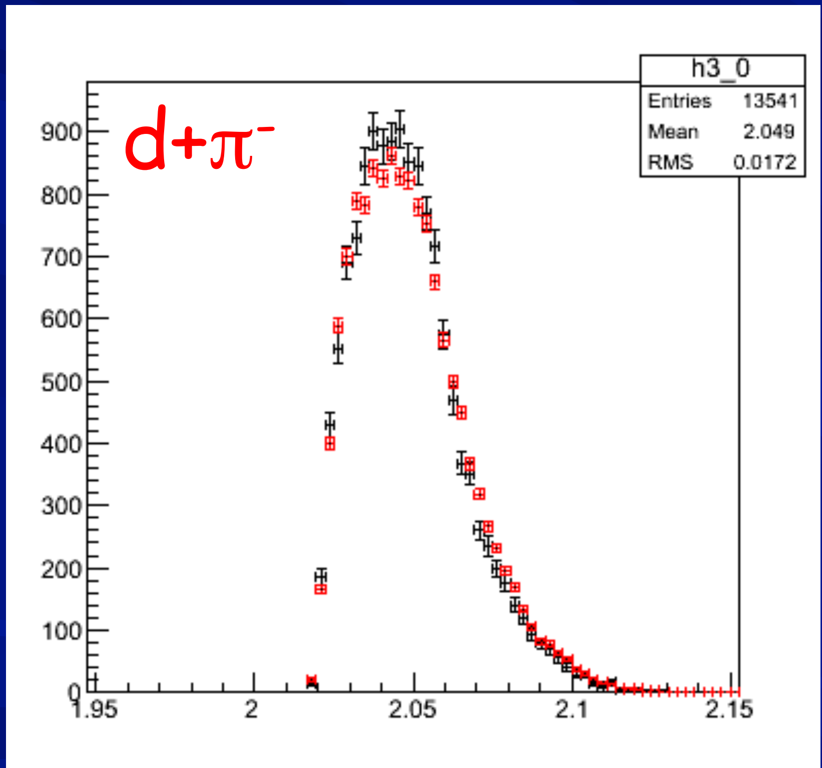
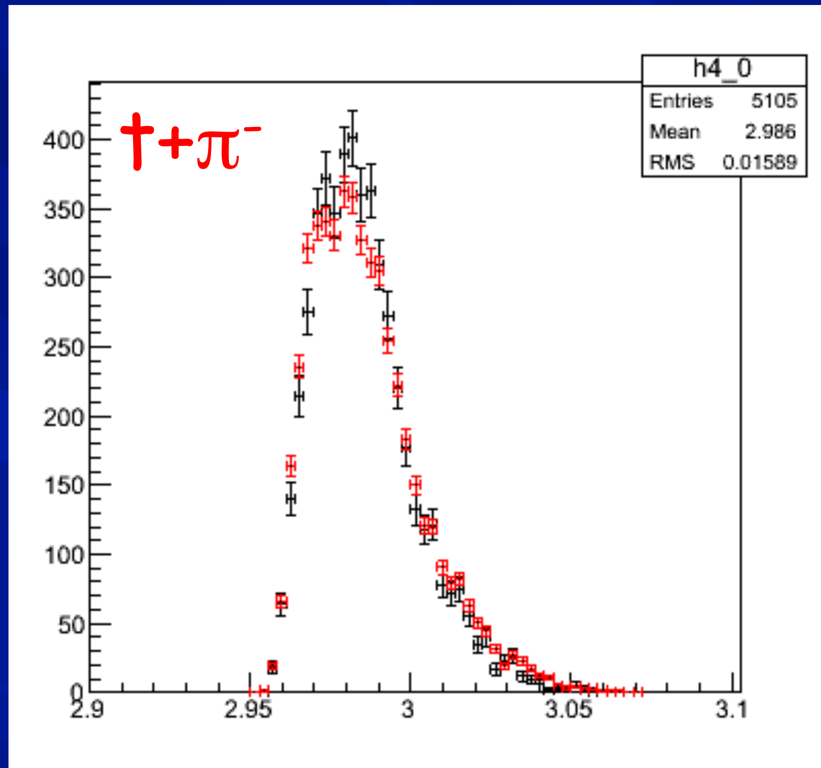
d+π⁻ and t+π⁻ from MC

- UrQMD + Full MC simulations
- No source for d+π⁻ and t+π⁻ peaks





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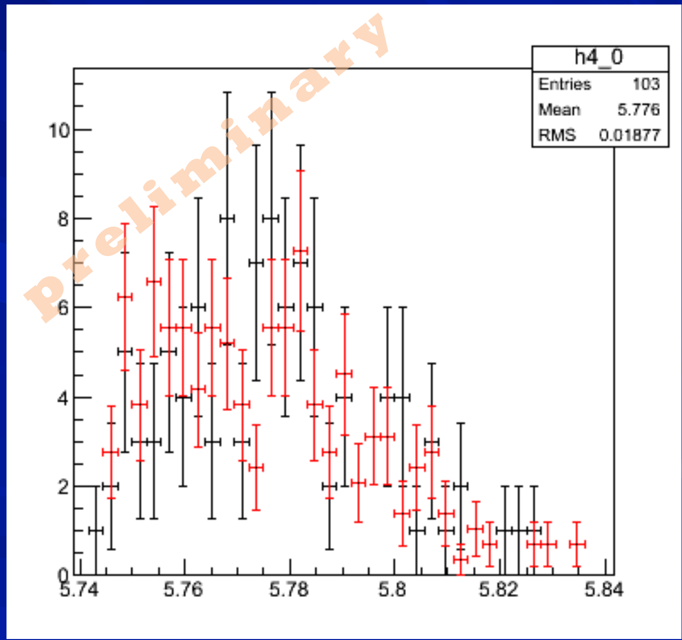
Possible miss-reconstructions

- ${}^{3}_{\Lambda}H$ -> ${}^{3}He^{*}$ + π^{-}
  - ->p + d
  - ${}^{3}_{\Lambda}H$ -> p- + ${}^{3}He$: branch = 0.379*2/3 = 0.25
  - ${}^{3}_{\Lambda}H$ -> p- + p + d: branch = 0.619*2/3 = 0.412
  - Observed ${}^{3}_{\Lambda}H$ -> π^{-} + ${}^{3}He$: 129
  - Estimated π^{-}+d from ${}^{3}_{\Lambda}H$: 7 counts
- ${}^{6}_{\Lambda}He$ -> ${}^{6}Li^{*}$ + π^{-}
  - ->${}^{4}He$ + d
  - Upper limit: 8 counts
  - R(3-body)/R(2-body)=5 (from A. Gal)
  - Estimated π^{-}+d from ${}^{6}_{\Lambda}He$: 3 counts
- ${}^{4}_{\Lambda}H$ -> ${}^{4}He^{*}$ + π^{-}
  - ->p + t
  - Observed ${}^{4}_{\Lambda}H$ -> π^{-} + ${}^{4}He$: 122
  - R(3-body)/R(2-body)=1 (Assumption)
  - Estimated π^{-}+t from ${}^{4}_{\Lambda}H$: 13 counts

Observed d+π^{-} : 212

Observed t+π^{-} : 172



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Is the $d+\pi^-$ signal from $n\Lambda$??

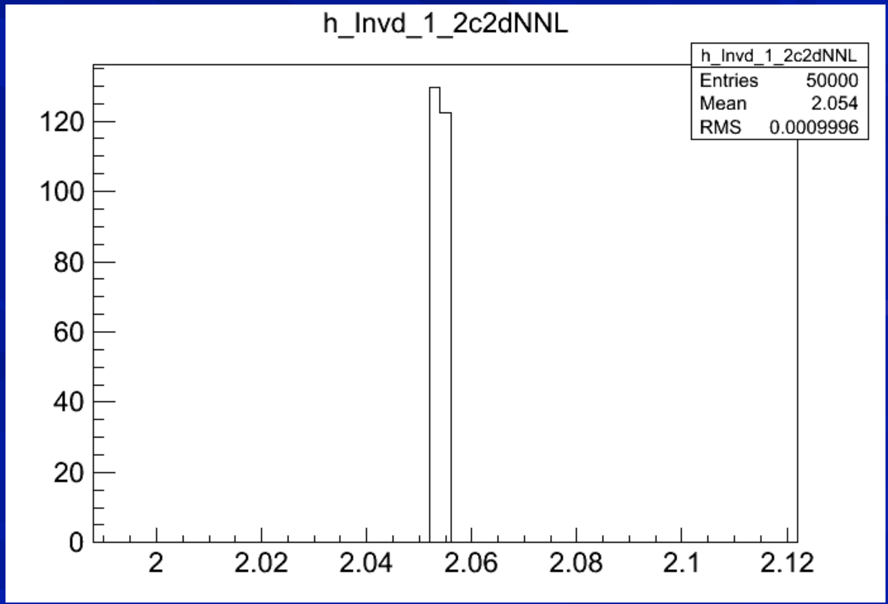
- Observed mass range: crossing the mass of $n+\Lambda$
- No $p\Lambda$ bound state observed with emulsion experiments
- Scattering length of $p\Lambda$ at COSY
- We also observe the $t+\pi^-$ signal

Possibilities (not excluded yet)

nnΛ ⟶ triton + π^-

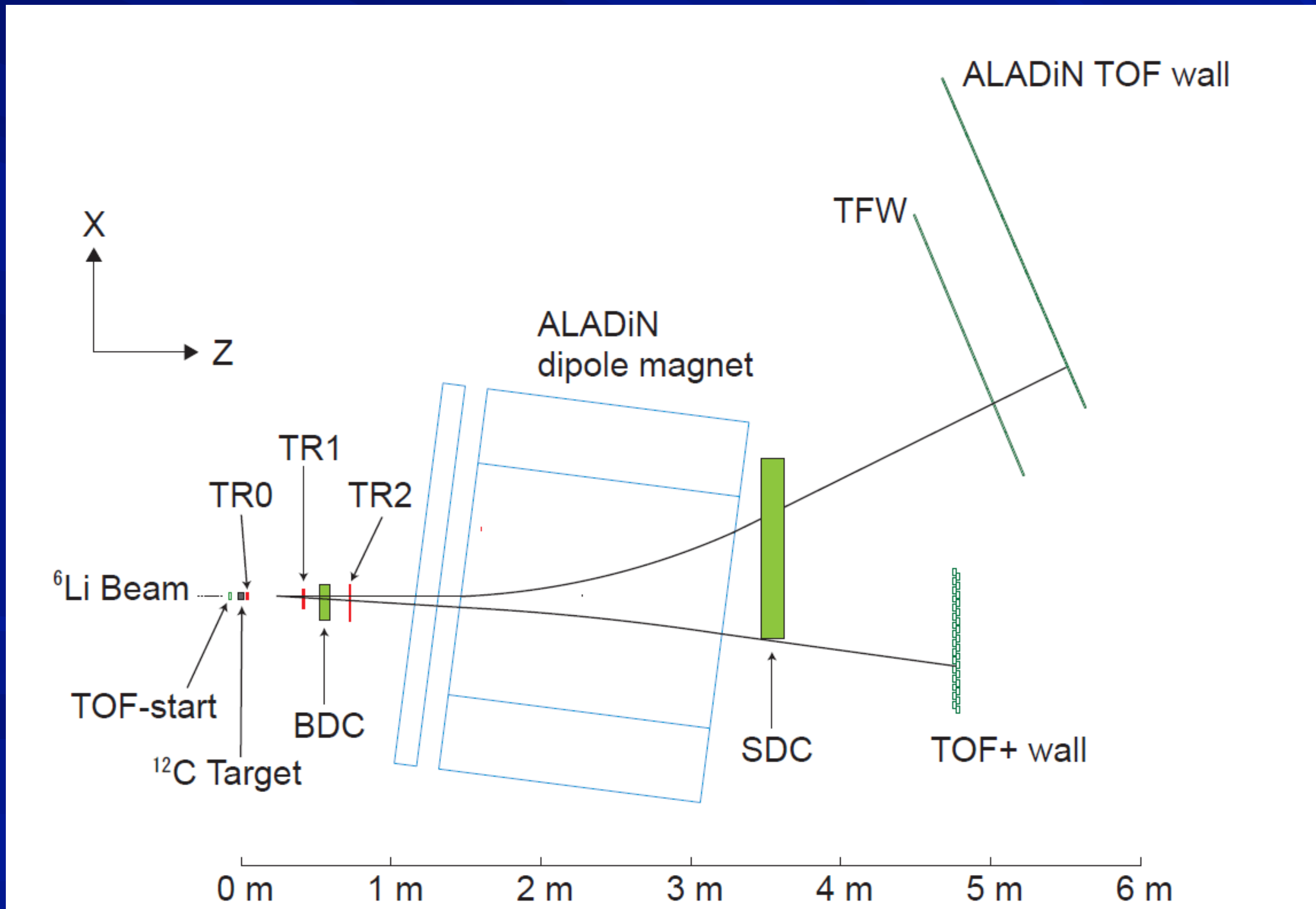
↳ deuteron + n

- Further experimental confirmation
- Analysis of Phase 0.5 (^{20}Ne on ^{12}C)

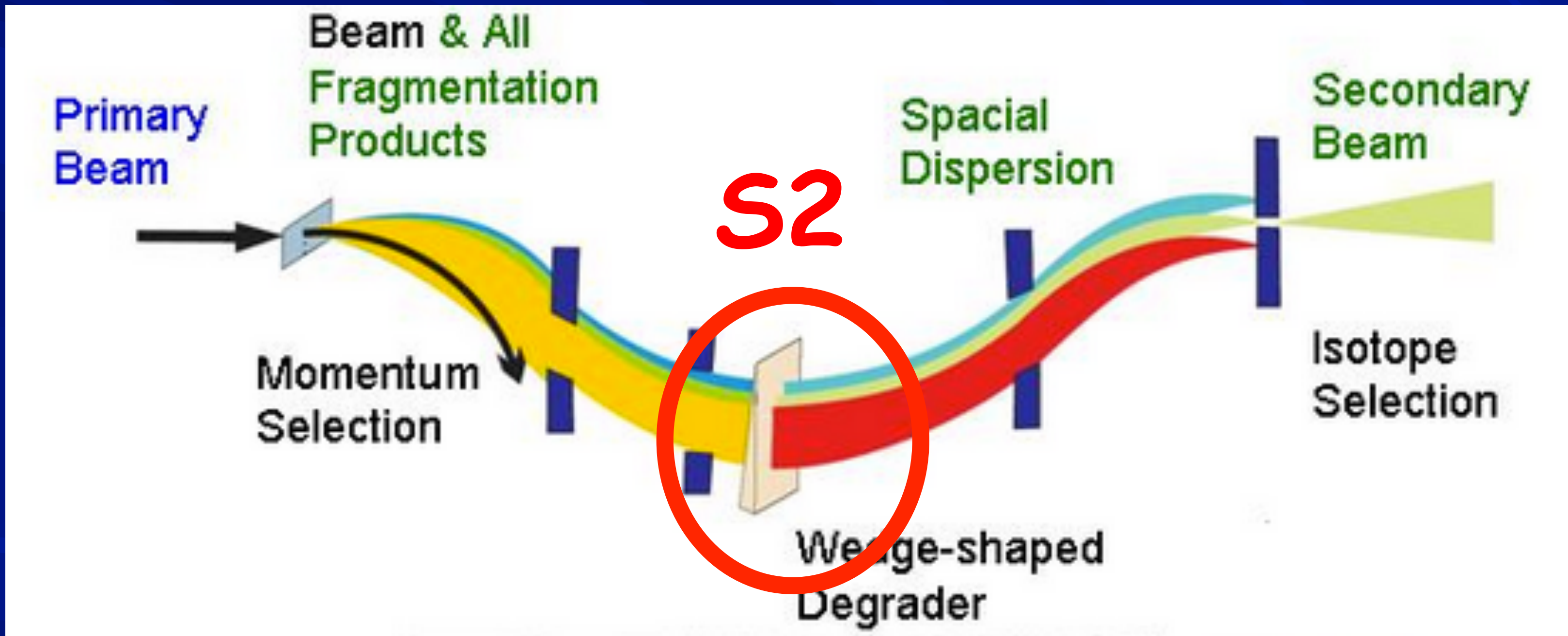


Future of HypHI????

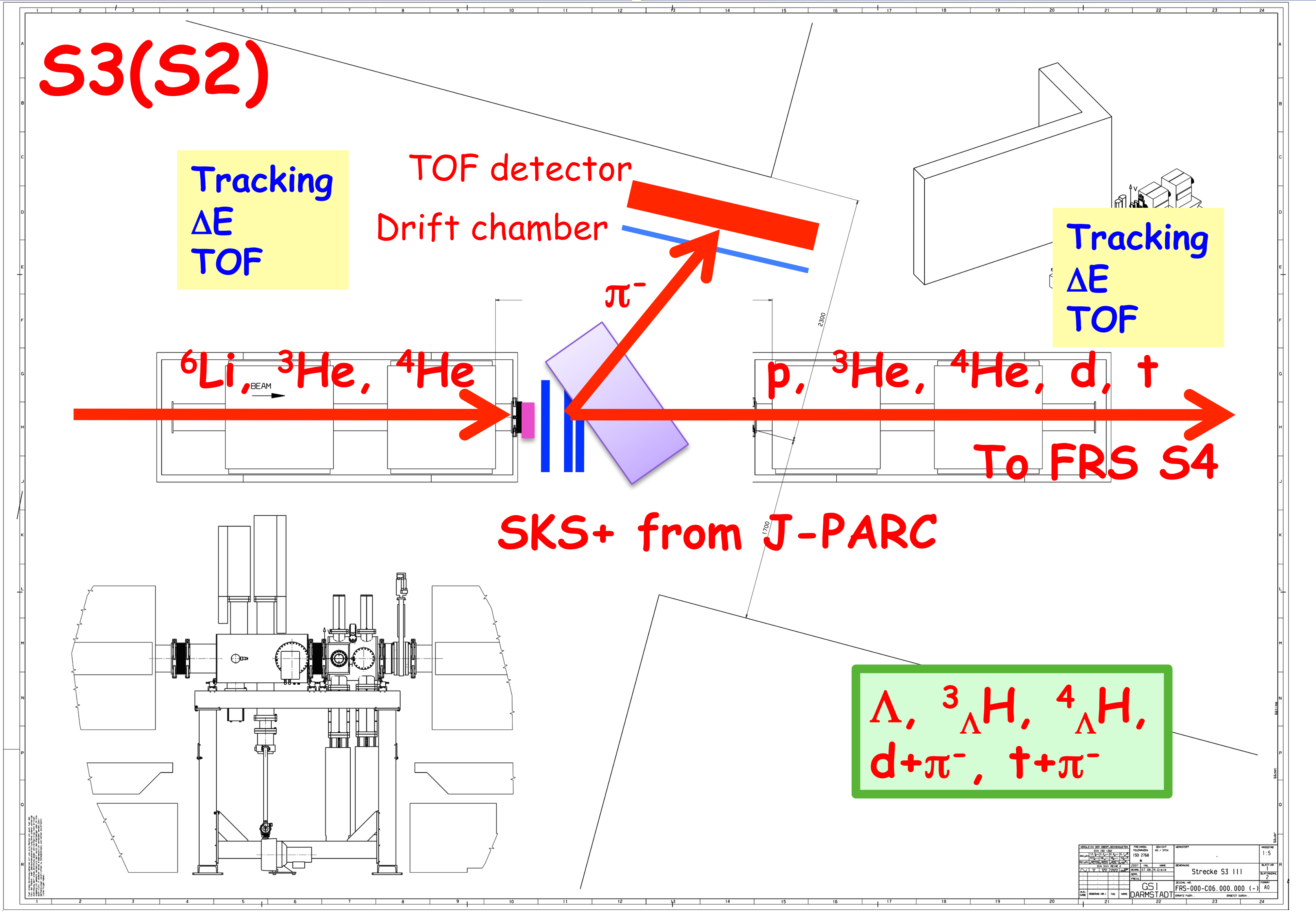
- We planed to continue HypHI with the ALADiN magnet in cave B
- Cave B and the ALADiN magnet will not be available
- With super-FRS, we can continue HypHI with R3B magnet



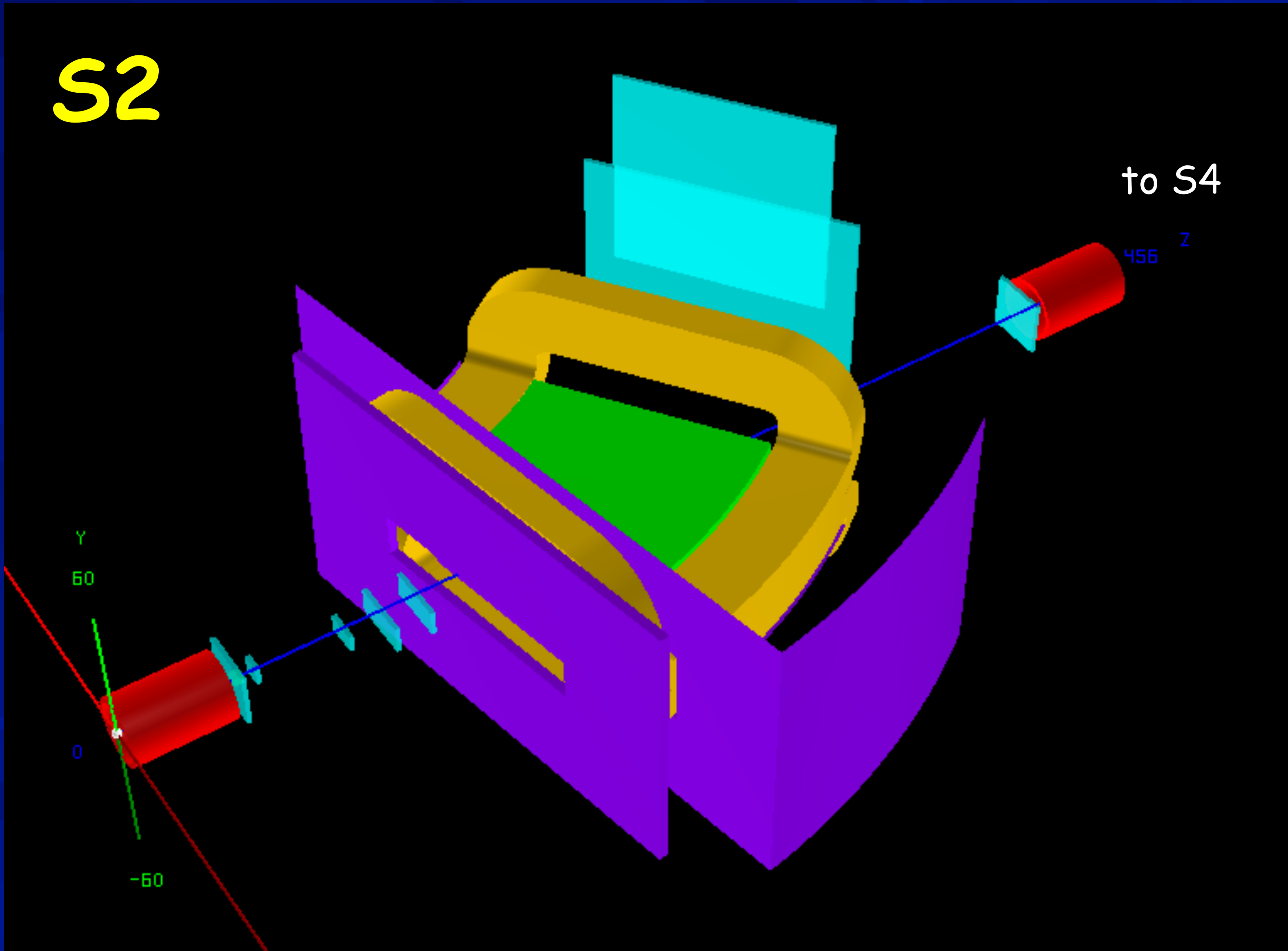
Possibility with FRS



Possibility with FRS



Setup with SKS-Plus magnet from KEK

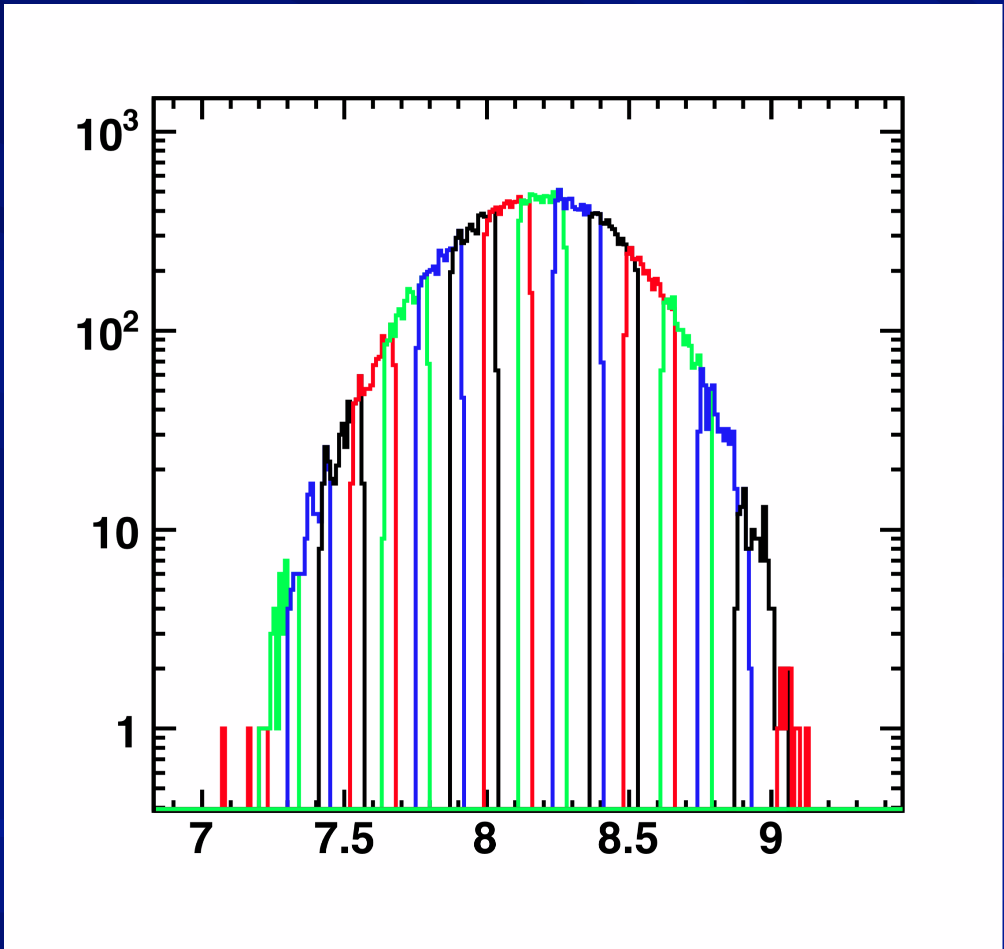


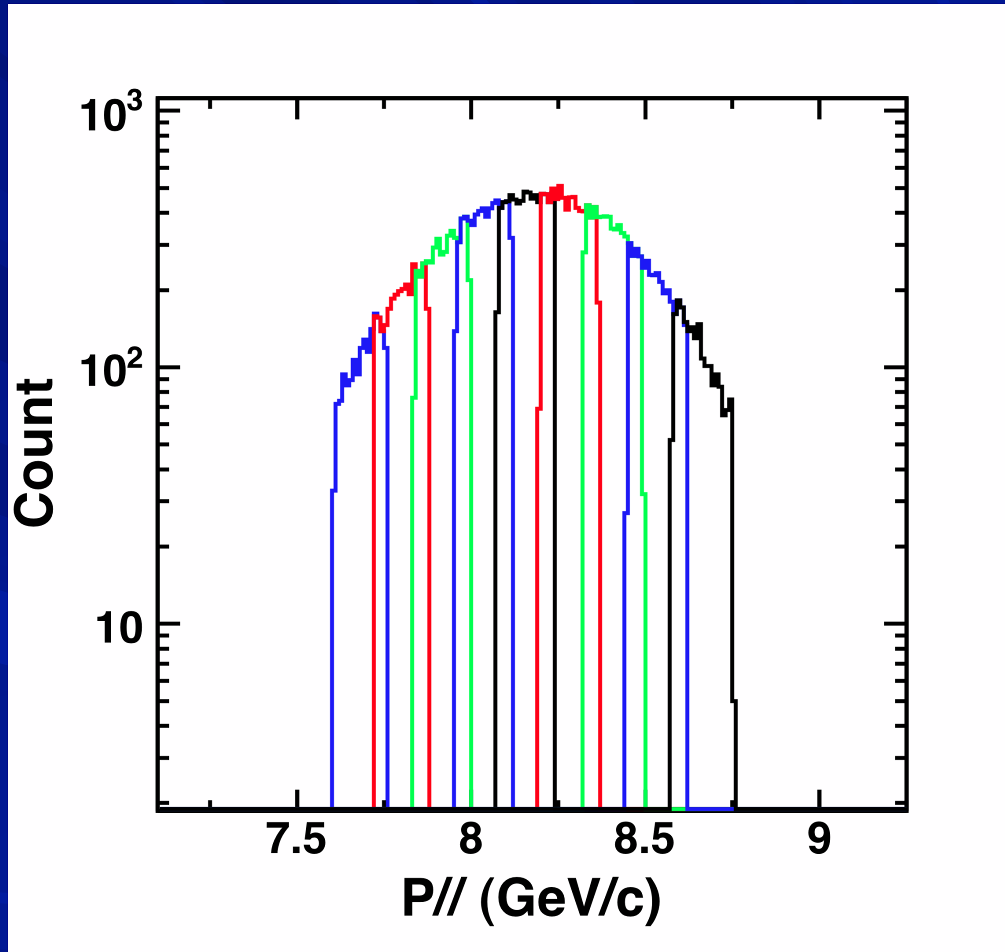
With FRS/super-FRS

- RI-beam production + spectrometer

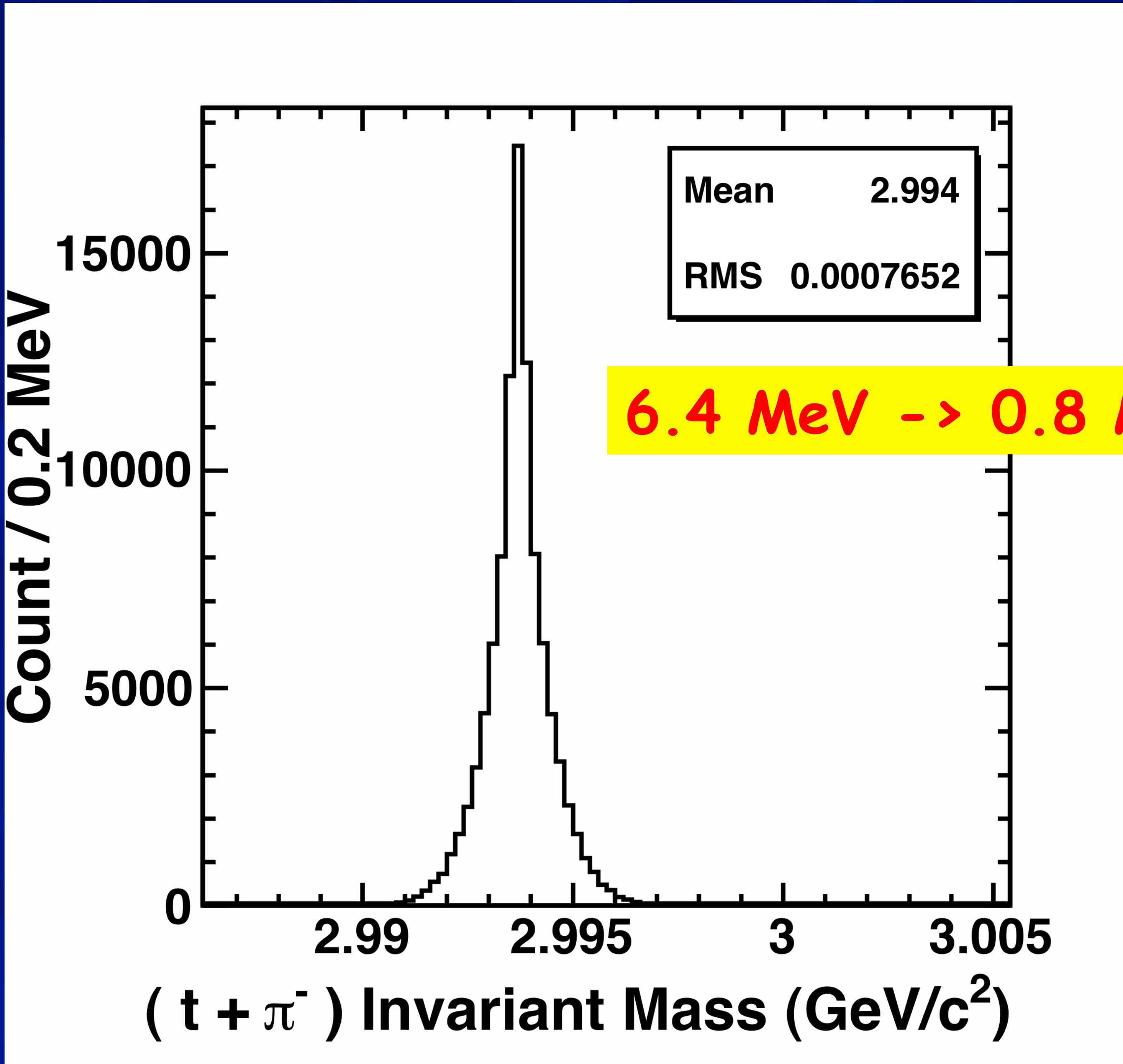
- Confirmation on the $t+\pi^-$ and $d+\pi^-$ invariant mass signals
  - Direct information on the hyperon driven three body force by the ΛN-ΣN coupling

Momentum scan for tritons





Expected $t+\pi^-$ invariant mass



6.4 MeV -> 0.8 MeV

With FRS/super-FRS

- RI-beam production + spectrometer

- Confirmation on the $t+\pi^-$ and $d+\pi^-$ invariant mass signals
  - Direct information on the hyperon driven three body force by the ΛN-ΣL coupling

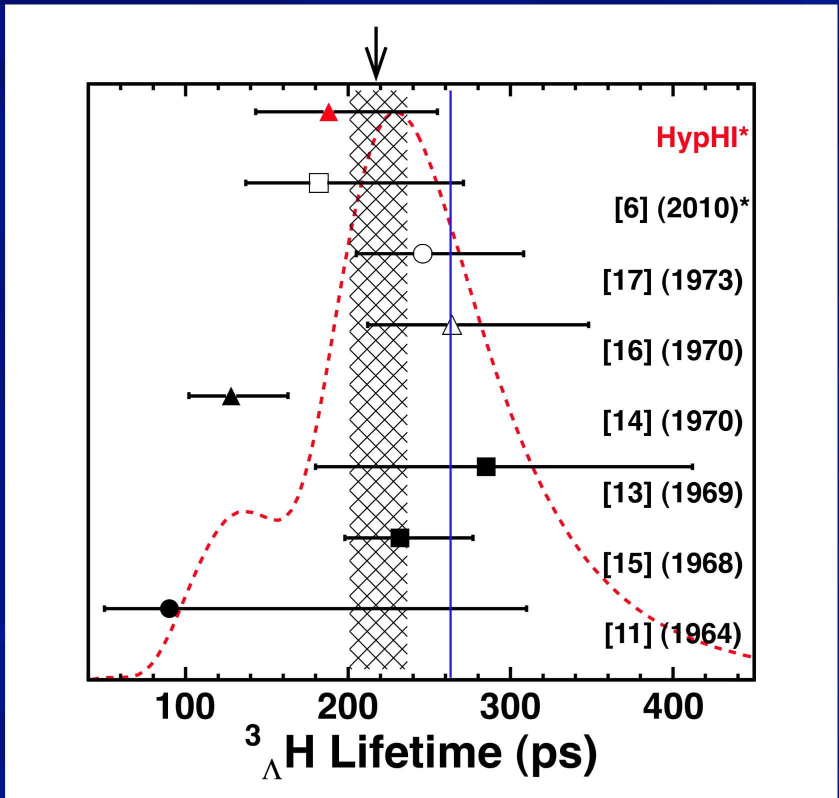
- Lifetime measurement
  - Independent to the time resolution of detector
  - ΛN-ΣL coupling on isospin and mass values

Present hypernuclear landscape

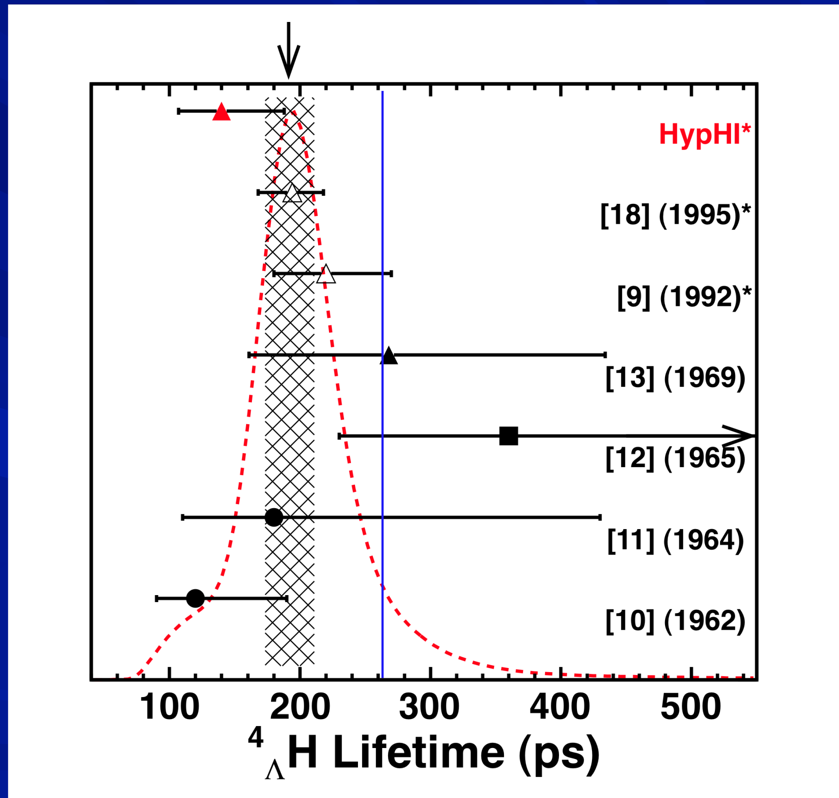
Known hypernuclei

${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$

- ${}^{3}_{\Lambda}H$
  - Weakly bound d+Λ : B_{Λ} ~ 150 keV
- ${}^{4}_{\Lambda}H$
  - Weakly bound t+Λ : B_{Λ} ~ 2 MeV



217^{+19}_{-16} ps

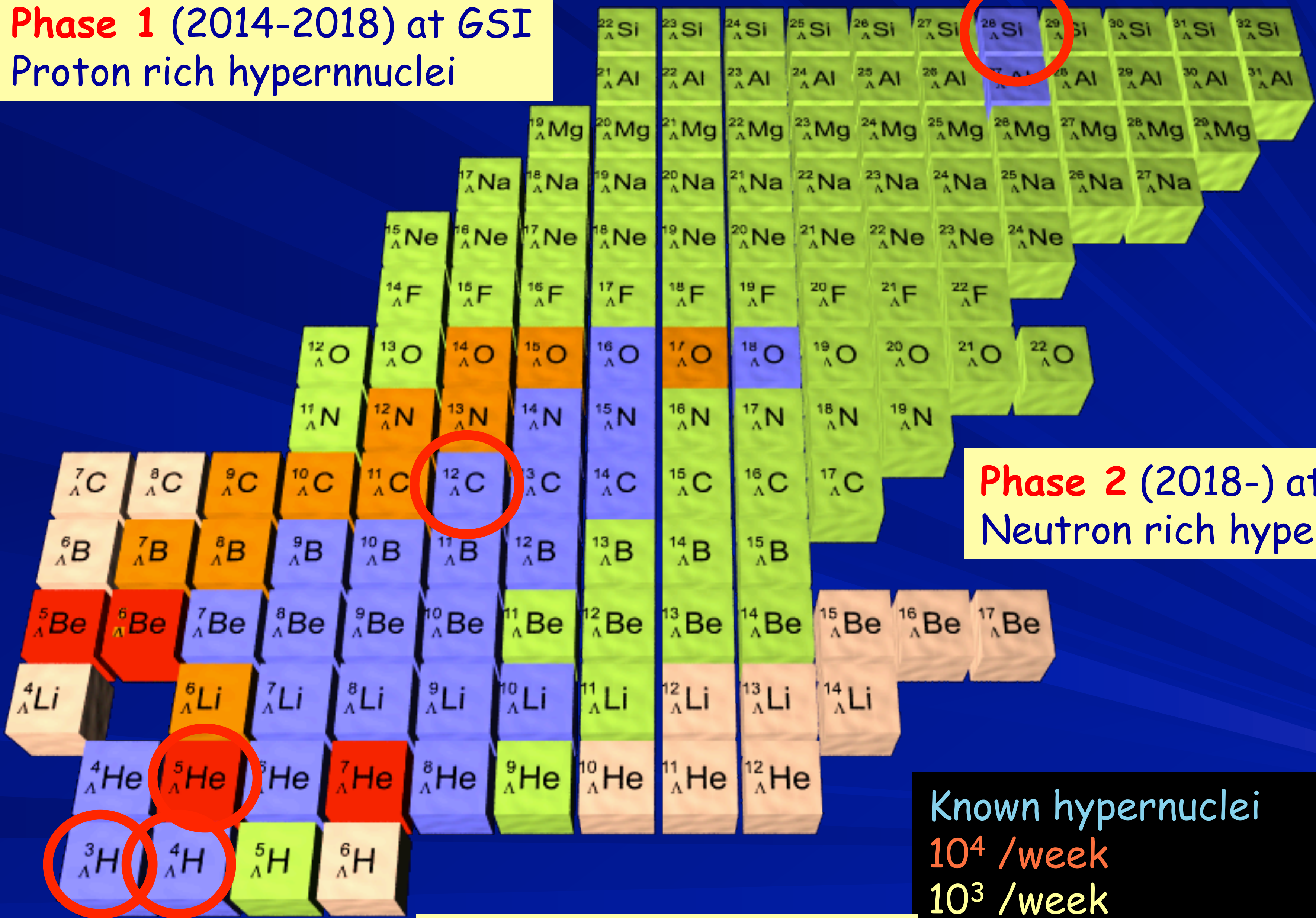


191^{+20}_{-18} ps

C. Rappold to be published

Hypernuclear landscape with HypHI

Phase 1 (2014-2018) at GSI
Proton rich hypernnuclei



Phase 2 (2018-) at R3B/FAIR
Neutron rich hypernuclei

Phase 3 (202X-) at FAIR
Hypernuclear separator

Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

With FRS/super-FRS

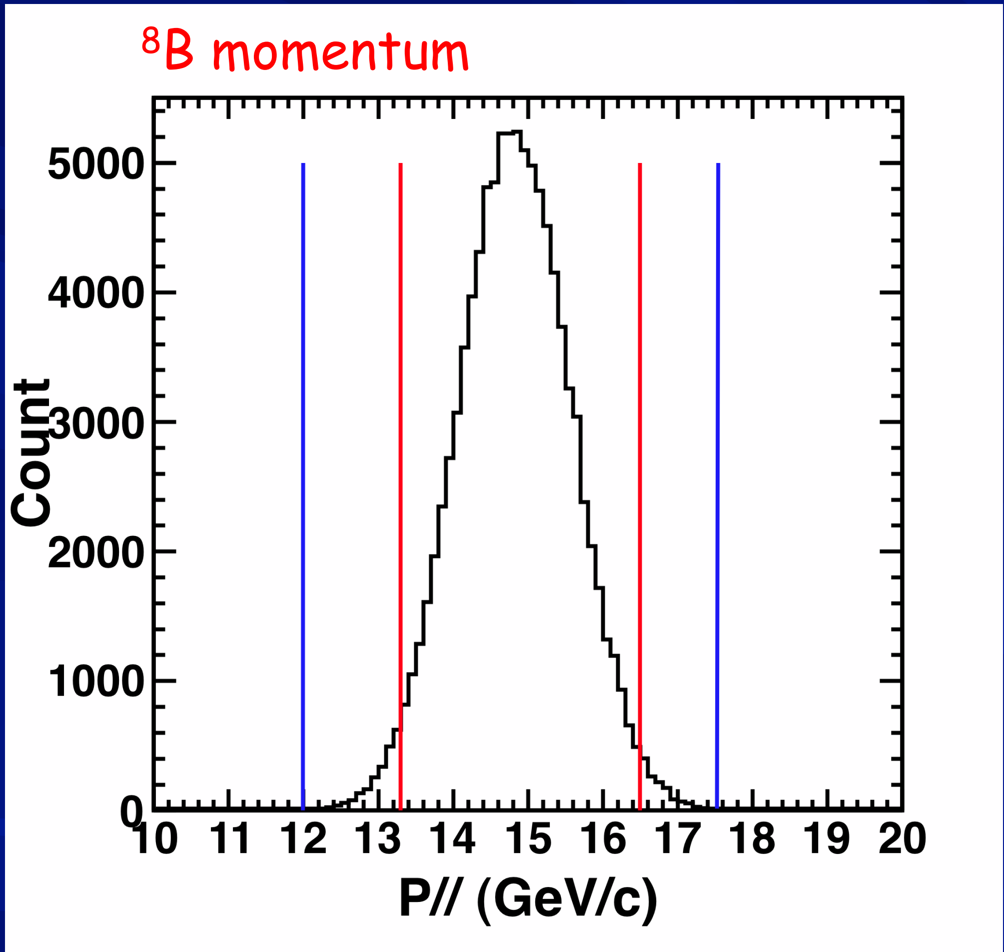
- **RI-beam production + spectrometer**

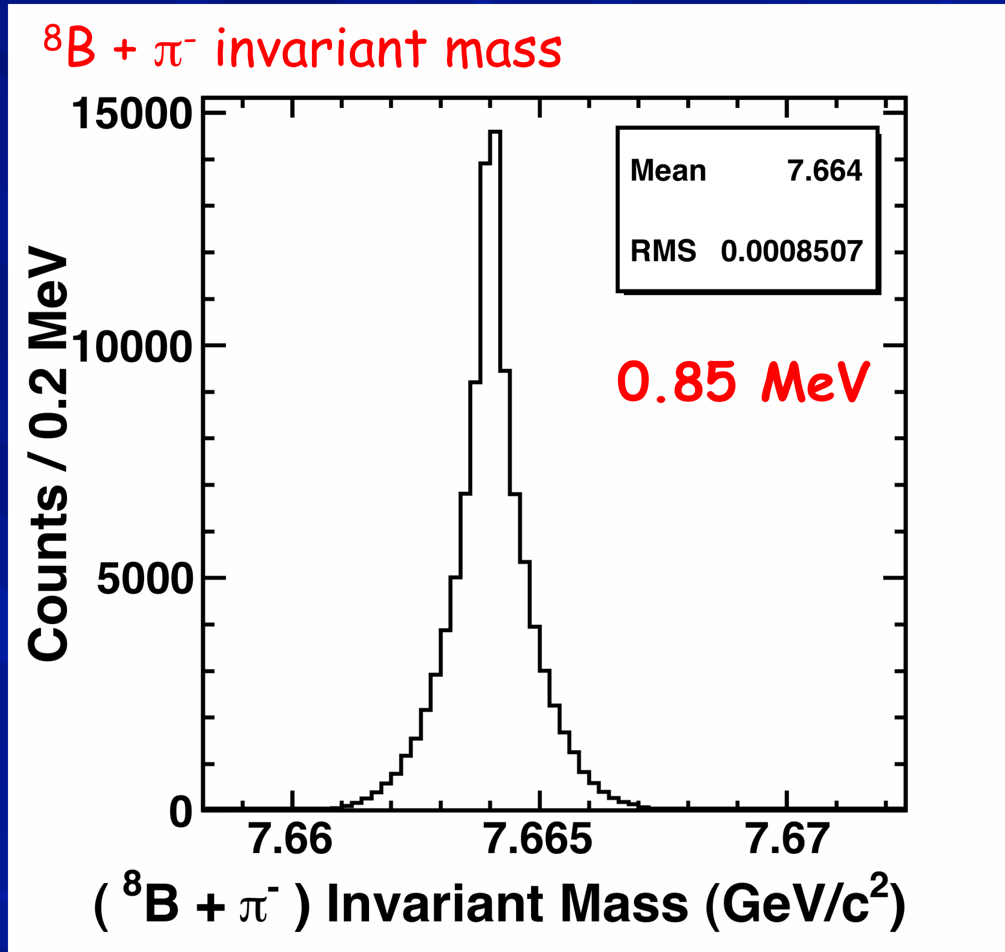
- **Confirmation on the t+π^- and d+π^- invariant mass signals**
  - Direct information on the hyperon driven three body force by the ΛN-ΣL coupling

- **Lifetime measurement**
  - Independent to the time resolution of detector
  - ΛN-ΣL coupling on isospin and mass values

- **Exotic hypernuclei**
  - **Modification of stability of nuclei by inducing strangeness**
  - **For example: $^{8}_{\Lambda}$Be -> ^{8}B + π^-**

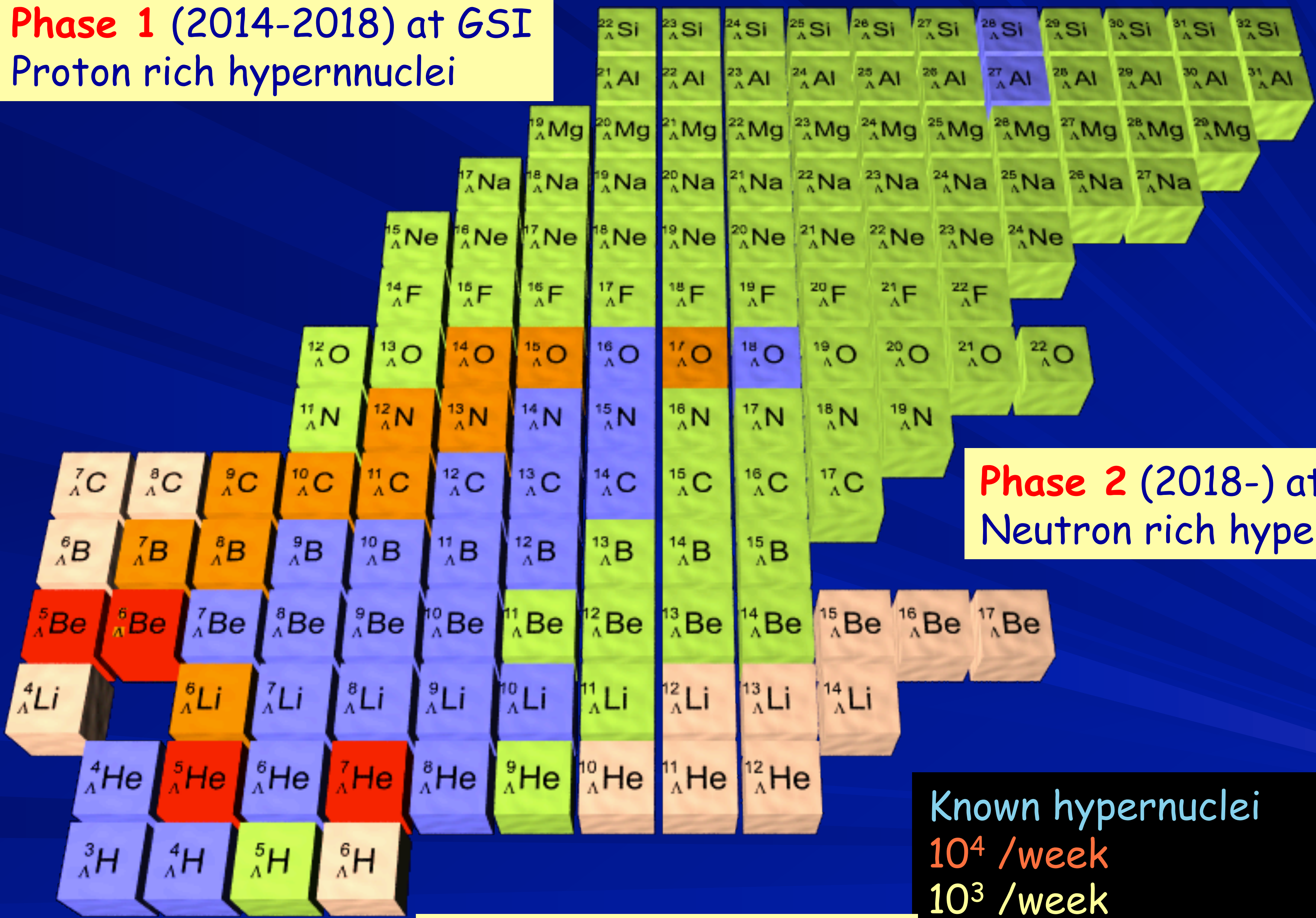
For $^{8}_{\Lambda}Be$





Hypernuclear landscape with HypHI

Phase 1 (2014-2018) at GSI
Proton rich hypernnuclei



Phase 2 (2018-) at R3B/FAIR
Neutron rich hypernuclei

Phase 3 (202X-) at FAIR
Hypernuclear separator

Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

Summary

- HypHI: with heavy ion beams
  - A new doorway to study hypernuclei
- Phase 0 experiment with ^{6}Li + ^{12}C
  - Successfully demonstrated the feasibility
  - Λ, $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$
  - Shorter lifetime of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$
  - Additional signals: $d+\pi^-$ and $t+\pi^-$
- New ideas with FRS/super-FRS