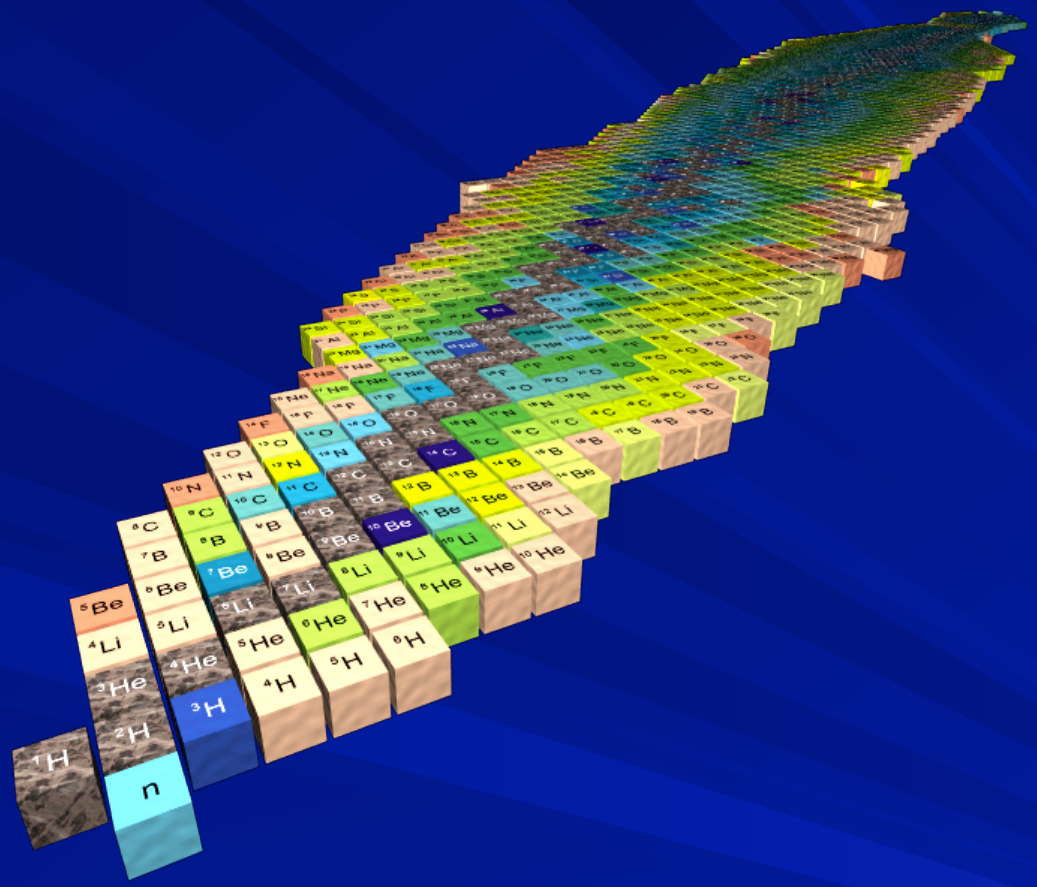
Recent results from the HypHI project at GSI

Take R. Saito for the HypHI collaboration
GSI-Darmstadt and Mainz University, Germany

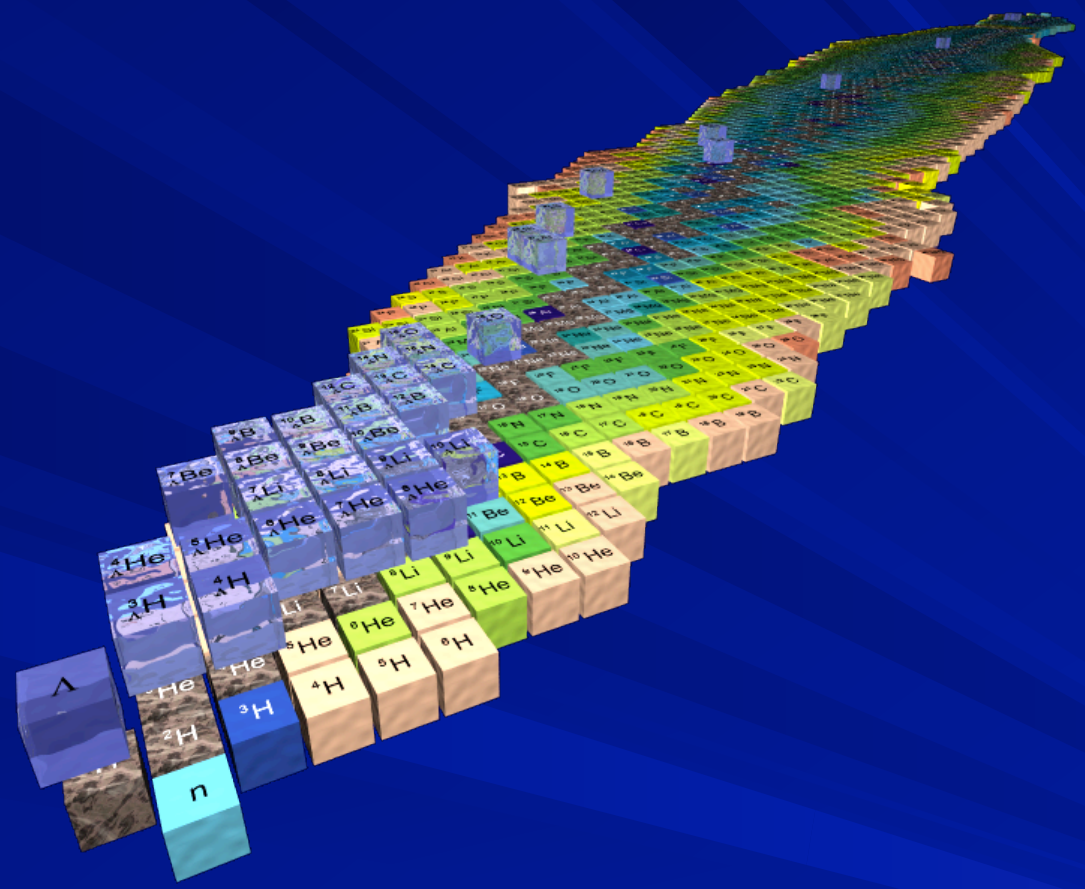
S=0 nuclear landscape and production



- With stable beams
- With rare isotope (RI) beams

  GSI/FAIR, GANIL, MSU, RIKEN ……

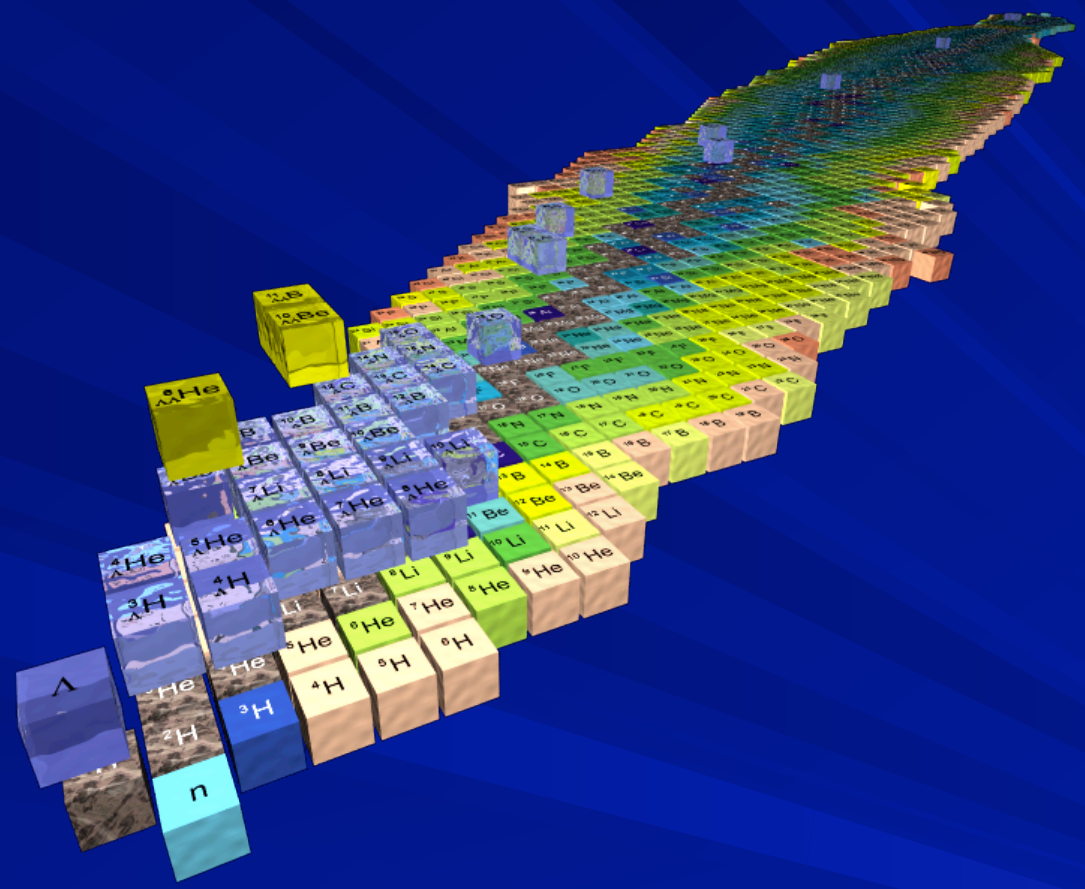
S=-1 nuclear landscape and production



- Single-Λ hypernuclei
- (π^+,K^+), (K^-,π^-), $(e,e'K^+)$
  CERN, BNL, KEK, CEBAF, DAΦNE, JPARC

} Conversion: $N \rightarrow \Lambda$

S=-2 nuclear landscape and production



- Double-Λ hypernuclei
- (K^-,K^+)
  BNL, KEK

} Conversion: $p \rightarrow \Xi^-$: $\Xi^- p \rightarrow \Lambda\Lambda$

S=-2 nuclear landscape and production

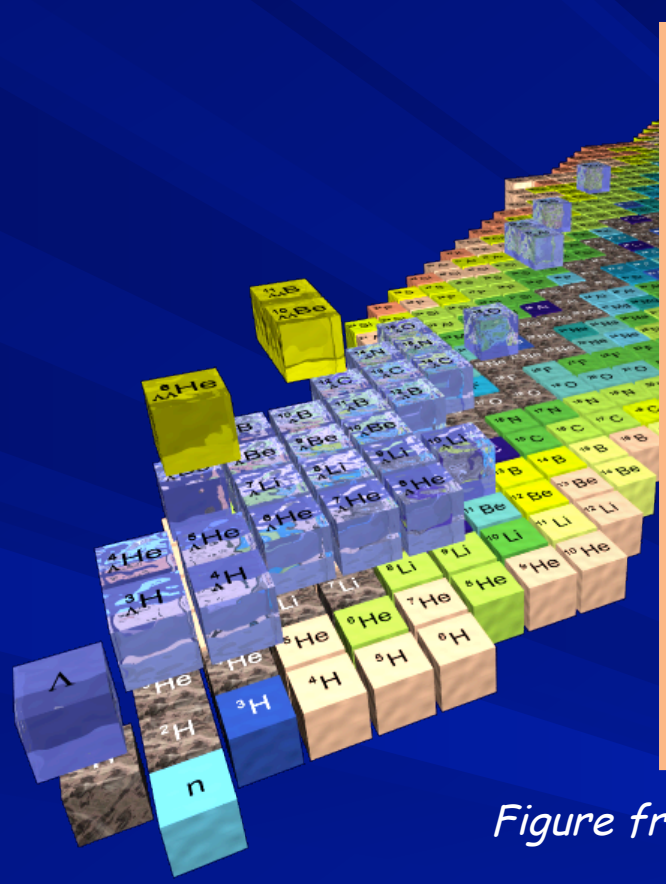


Figure from H. Merkel (Mainz Univ.) for HYP2006

Advantage

- Precise spectroscopy
  - Structure in detail
- Clean experiment

Disadvantage

- Limited isospin
- Small momentum transfer to separate hypernuclei
- Difficulties on decay studies
- Only up to double-strangeness

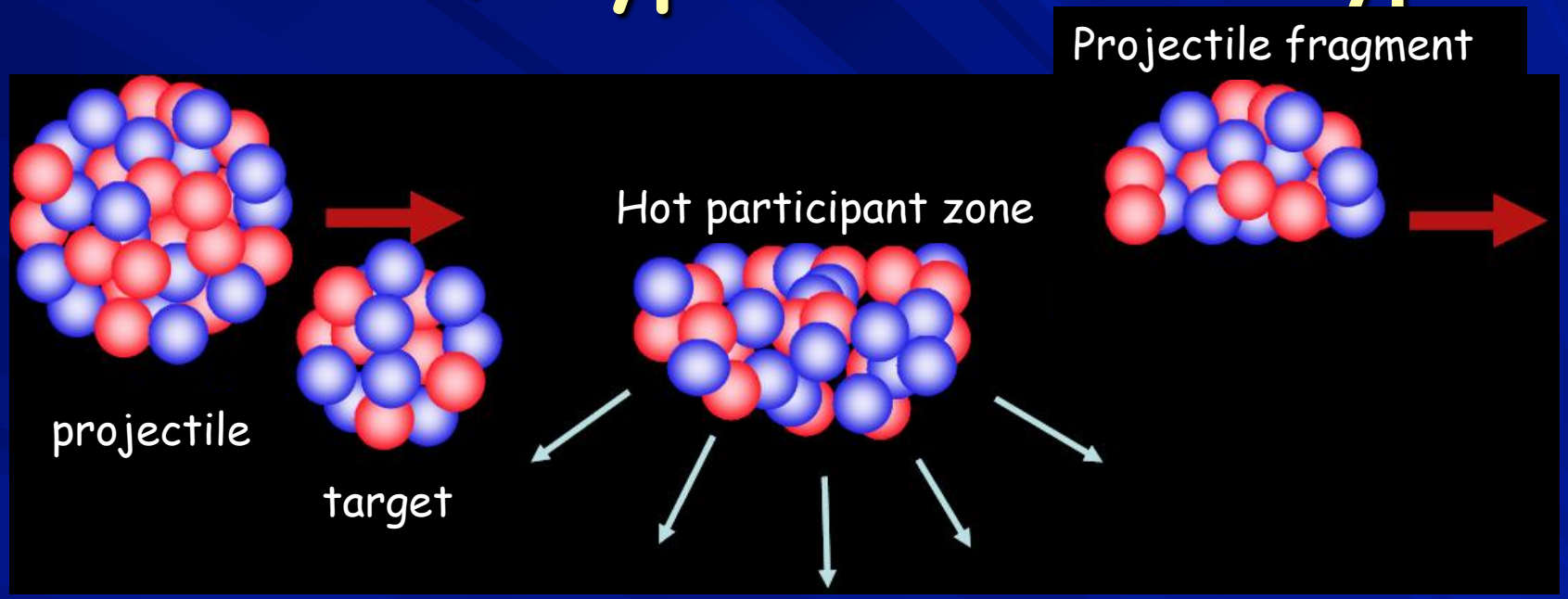
Hypernuclear spectroscopy with heavy ion beams

HypHI project

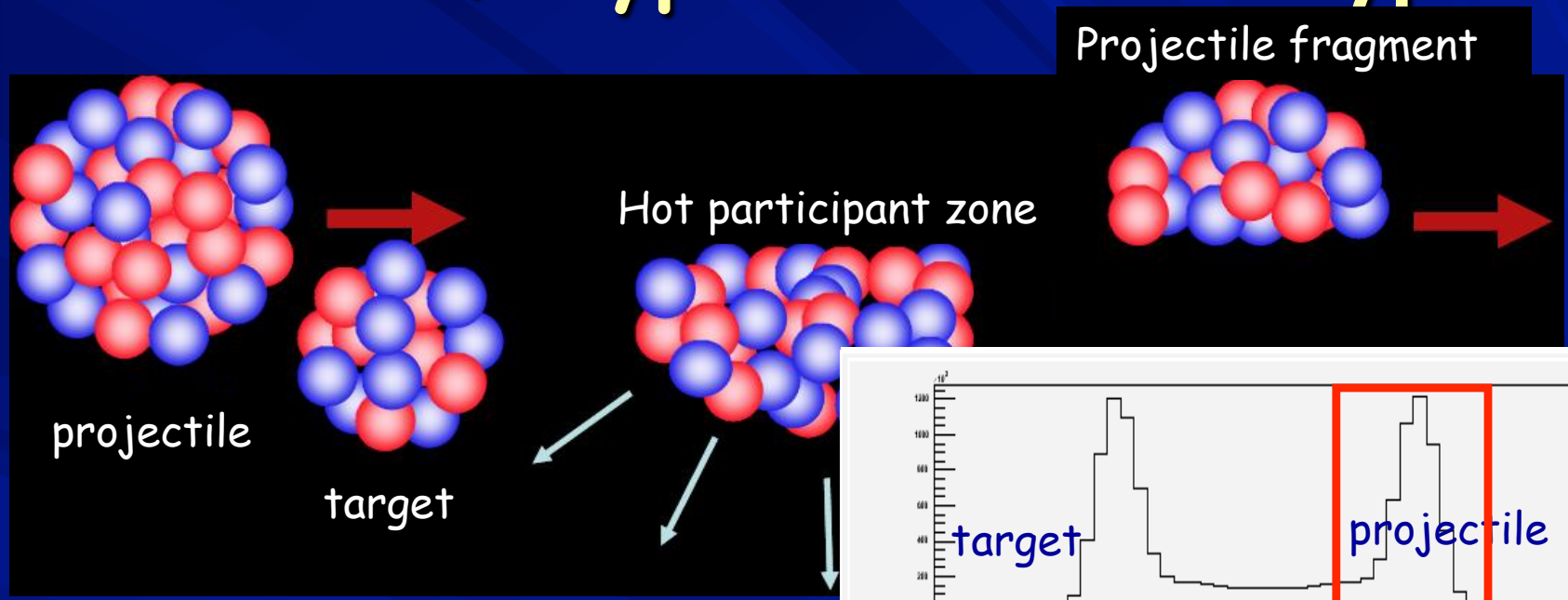
- **Double-Λ hypernuclei**
- **(K^-,K^+)**
  BNL, KEK

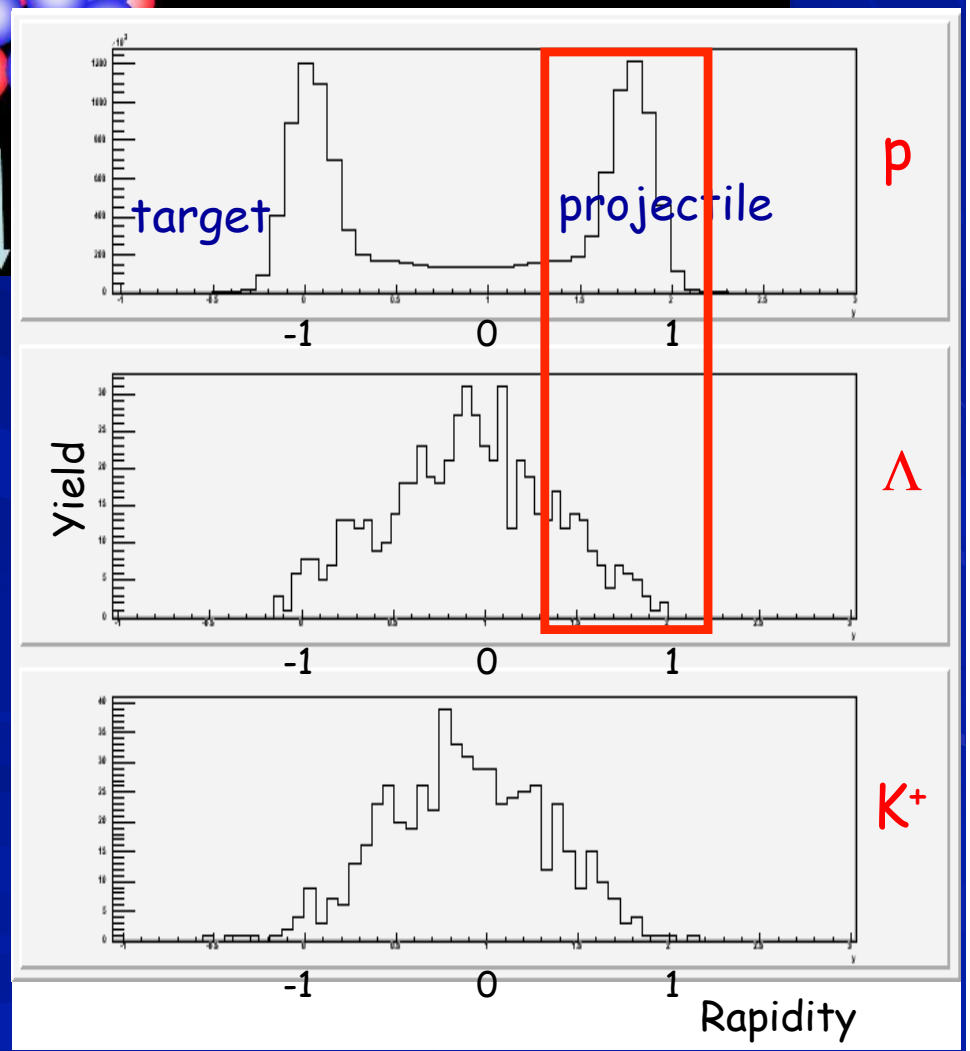
} Conversio

Production of Hypernuclei with HypHI

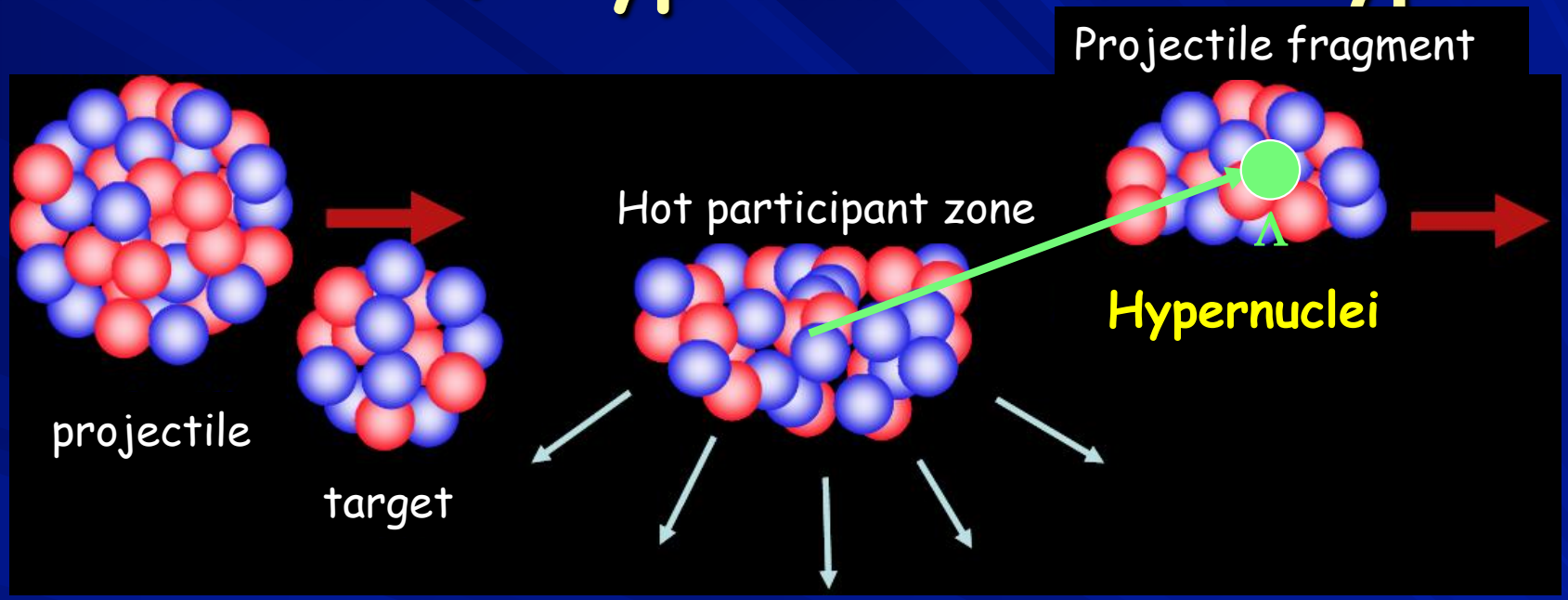


Production of Hypernuclei with HypHI



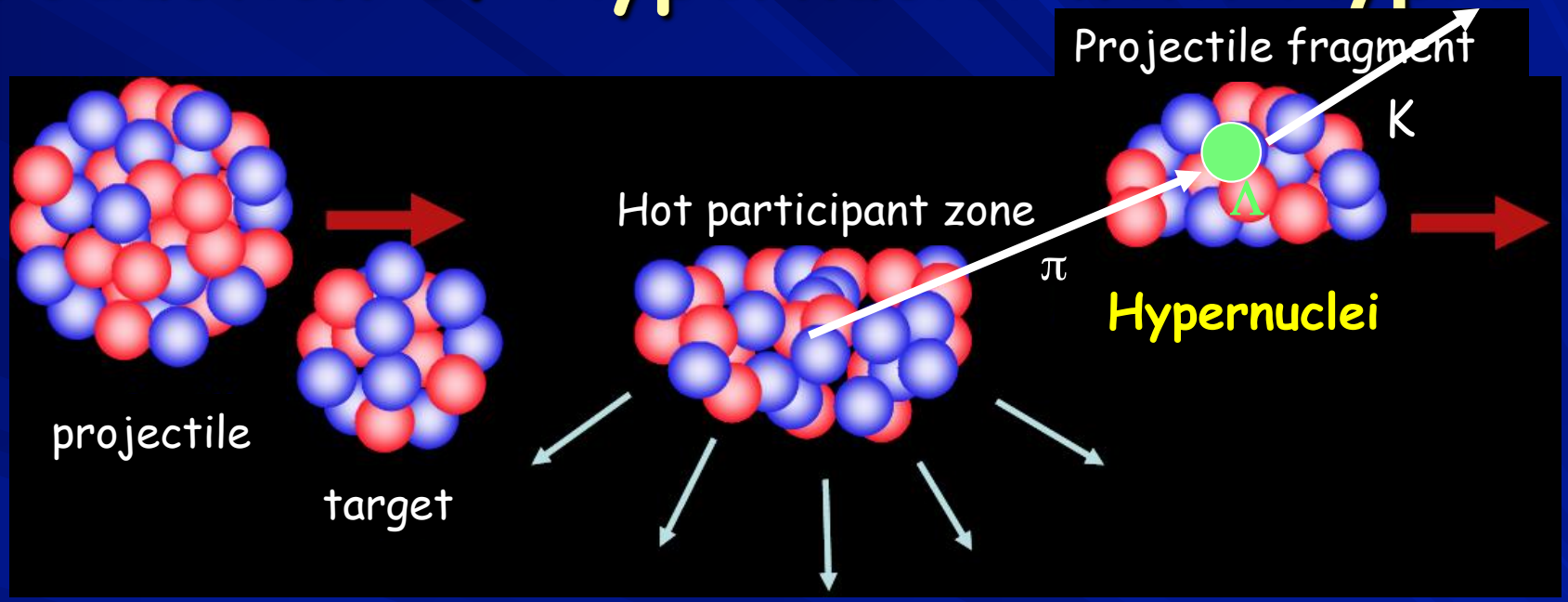


Production of Hypernuclei with HypHI



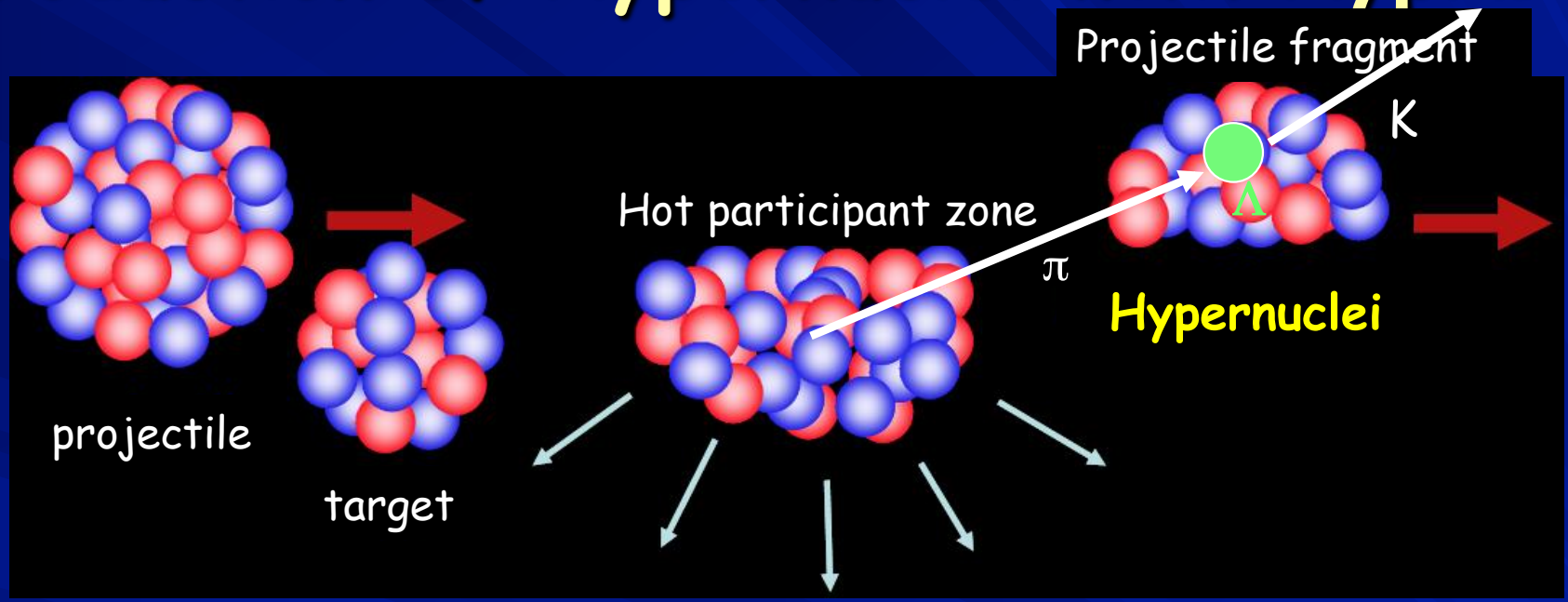
- Coalescence of Λ in projectile fragments

Production of Hypernuclei with HypHI



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

Production of Hypernuclei with HypHI



- **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**

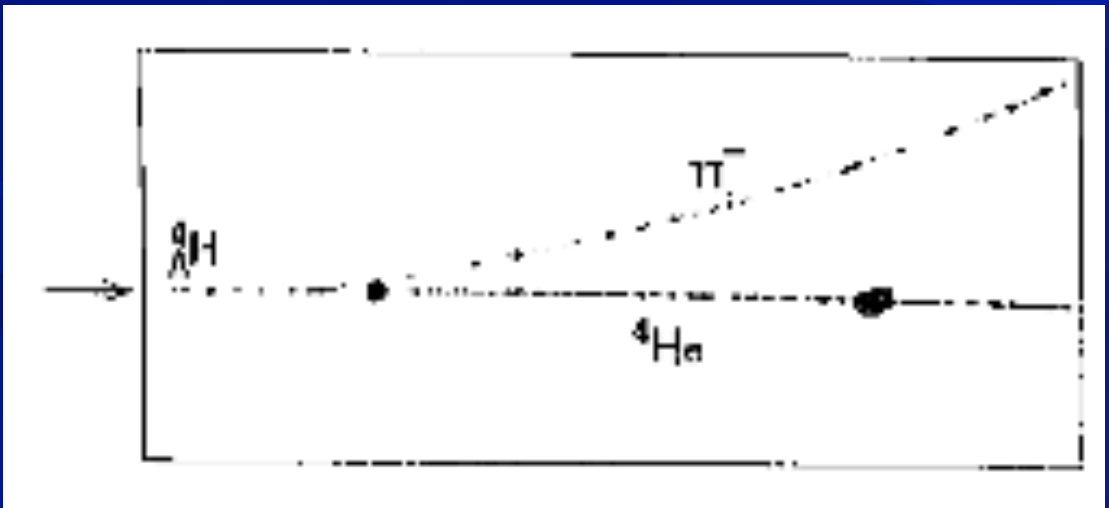
Accessible to neutron- and proton rich hypernuclei

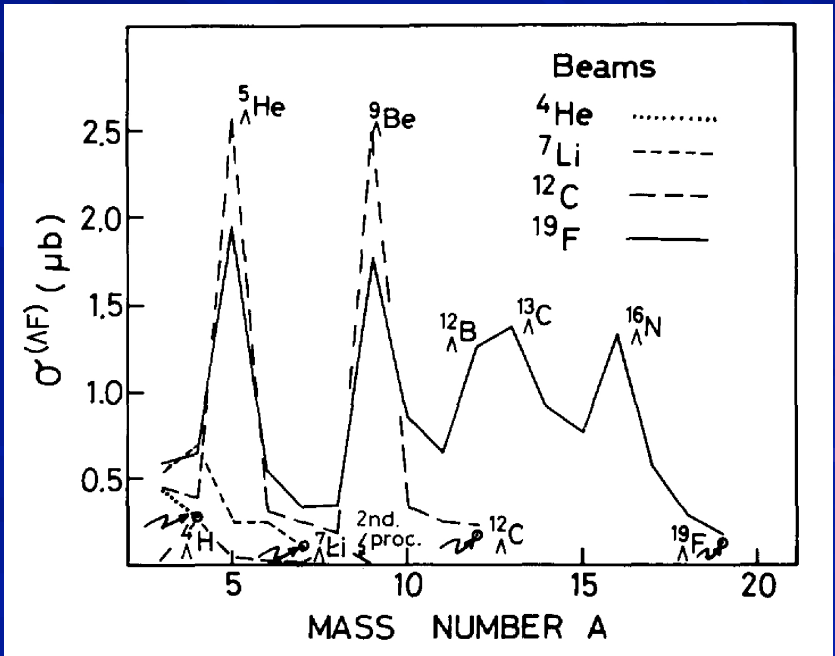
Heavy-ion induced hypernuclear production

- No RI-beam induced hypernuclear production so far

- Stable heavy-ion induced hypernuclear production at Dubna in 1989.
  - ^{4}He beam at 3.7 GeV/u on a polyethylene target
  - ^{7}Li beam at 3.0 GeV/u on a polyethylene target

  - Streamer chamber
  - Cross section: an order of 10^{-7} barn

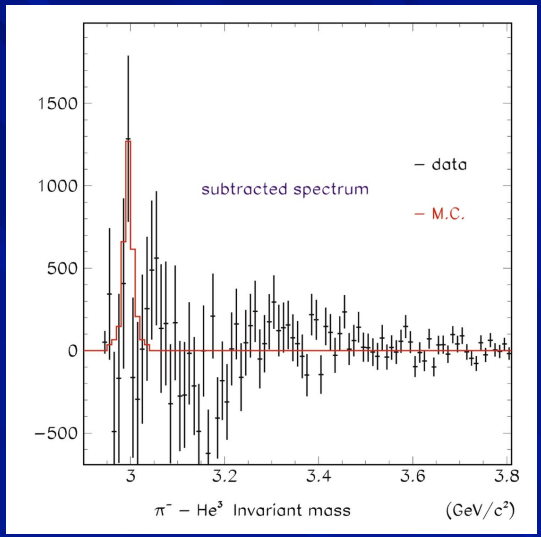




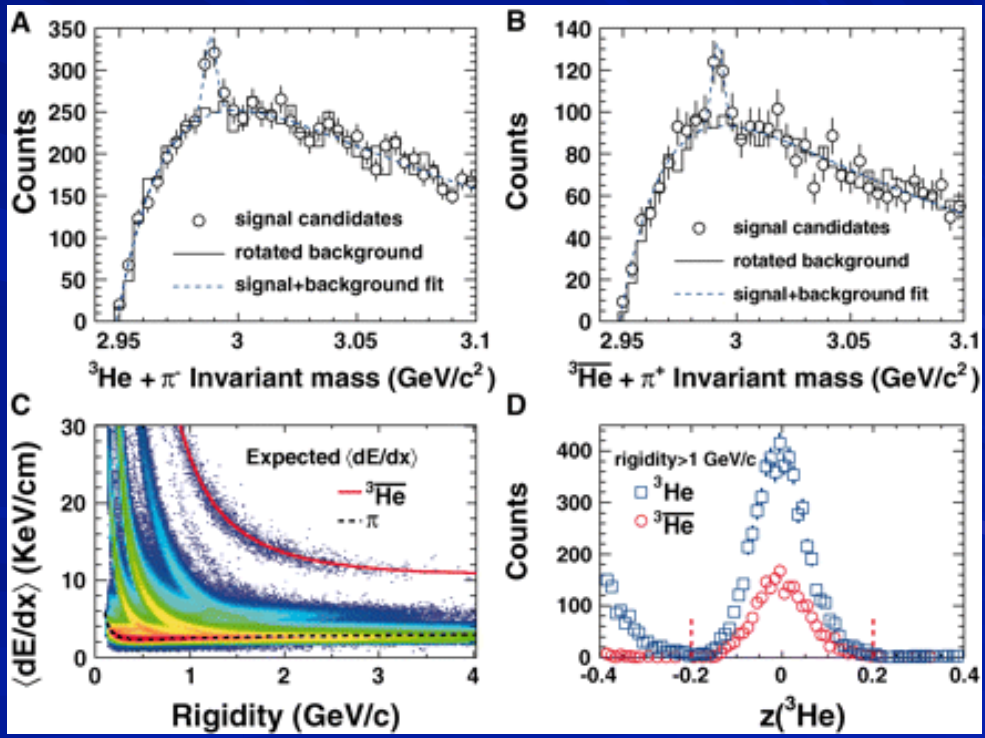
H. Bando et al., NPA 501 (1989) 900

AGS and STAR

- **AGS**
  - Au at 11.5 A GeV on Pt
  - Hypertriton
    PRC 70 (2004) 024902

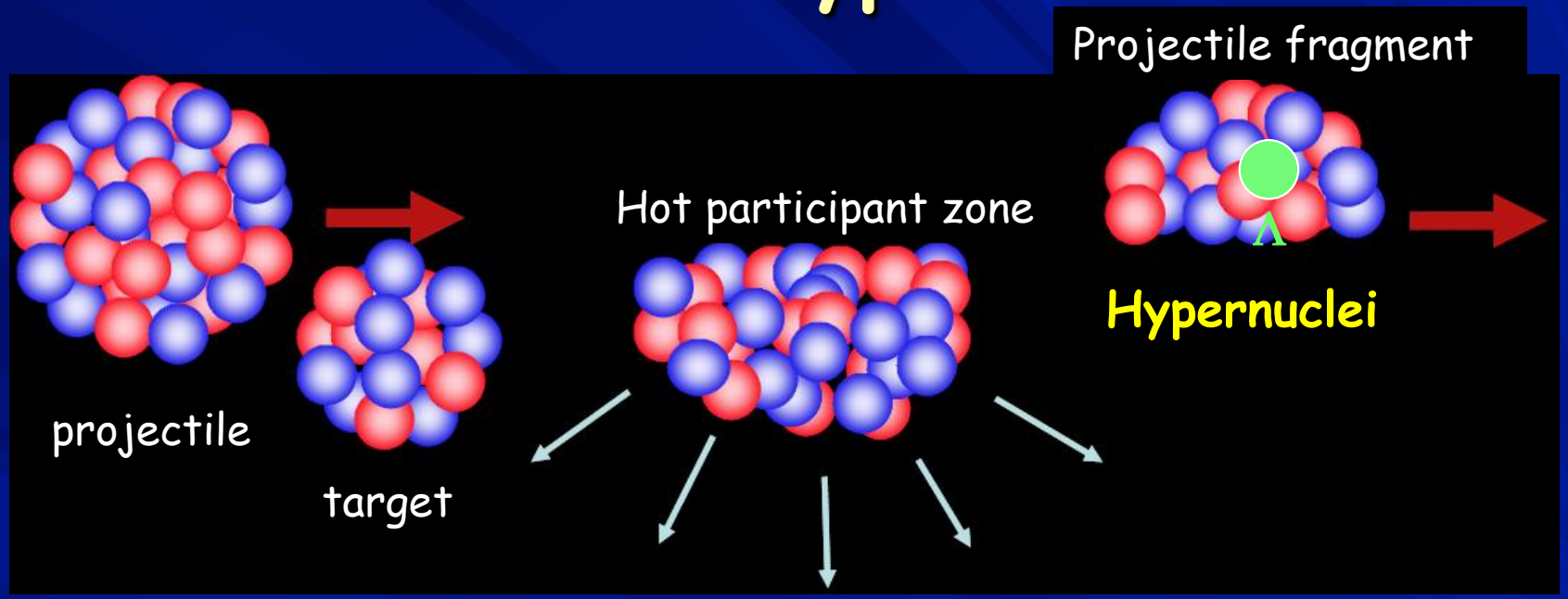


- **STAR**
  - Au+Au at 200 GeV per n-n collision
  - Hypertriton and Anti-hypertriton
    Science 328 (2010) 58



Difficult in yields for A>4

Relativistic hypernuclei

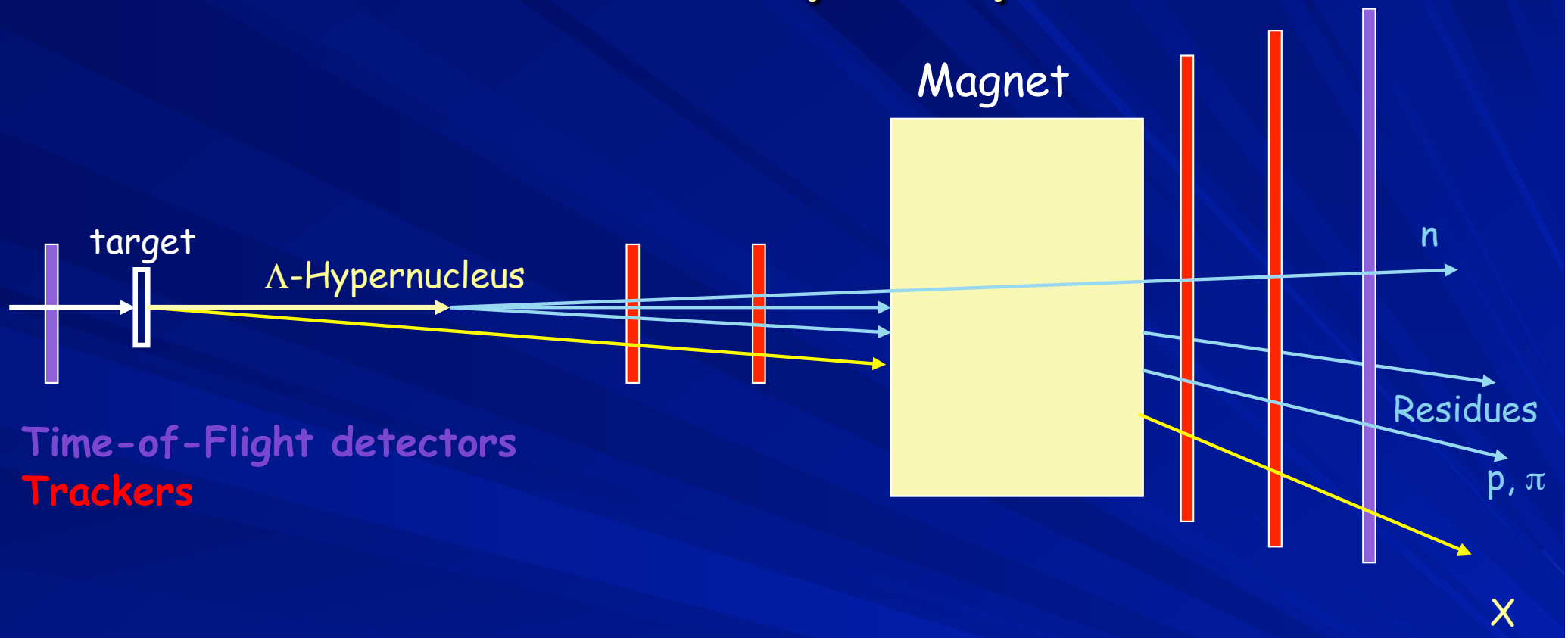


- **Large Lorentz factor** γ (>3)
  - Effective lifetime : Longer by the Lorentz factor
    200 ps -> 600 ps at GSI (ct ~ 20 cm)
    200 ps -> 4 ns at FAIR (ct ~ 120 cm)

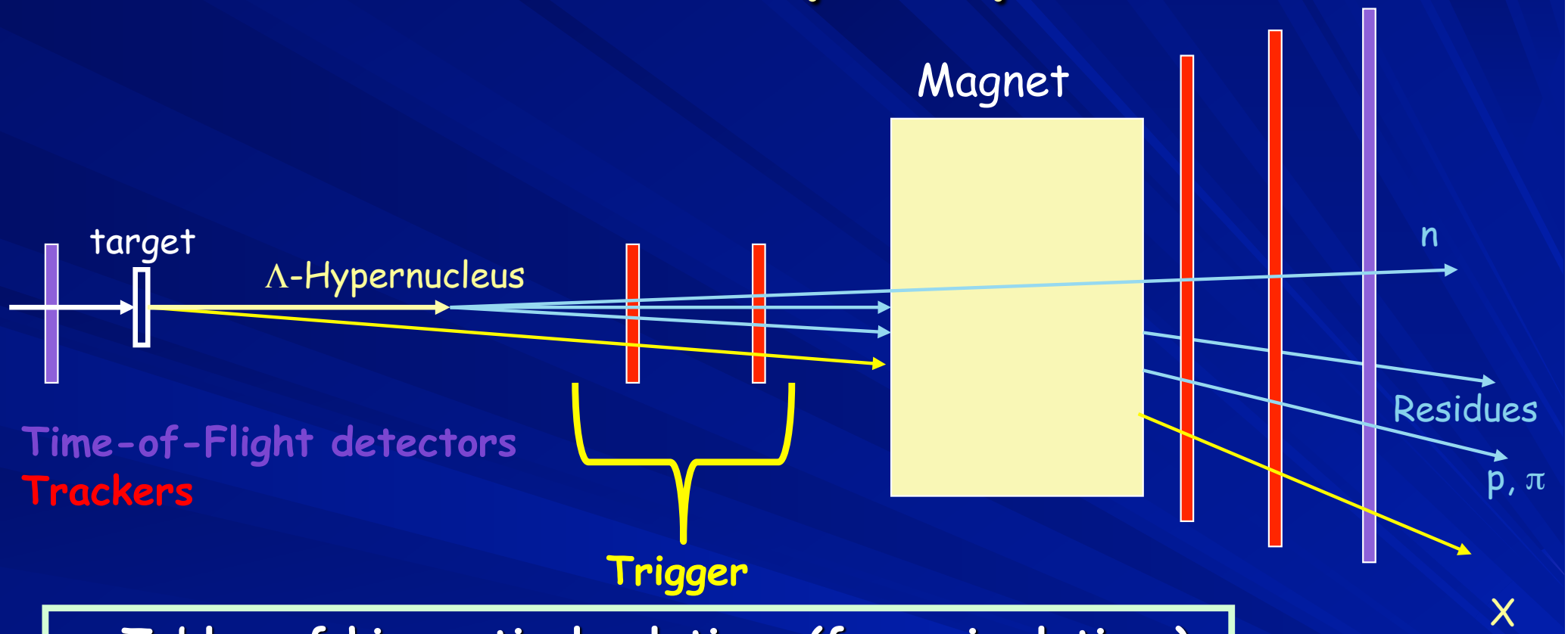
- **Hypernuclear separation and spin precession**
  - Can be feasible with 20 Tm at 20 A GeV
  - Large spin precession in magnetic fields
    - 225 degrees with free-Λ magnetic moment

Nuclear matter with multiple-strangeness

Detection principle



Detection principle

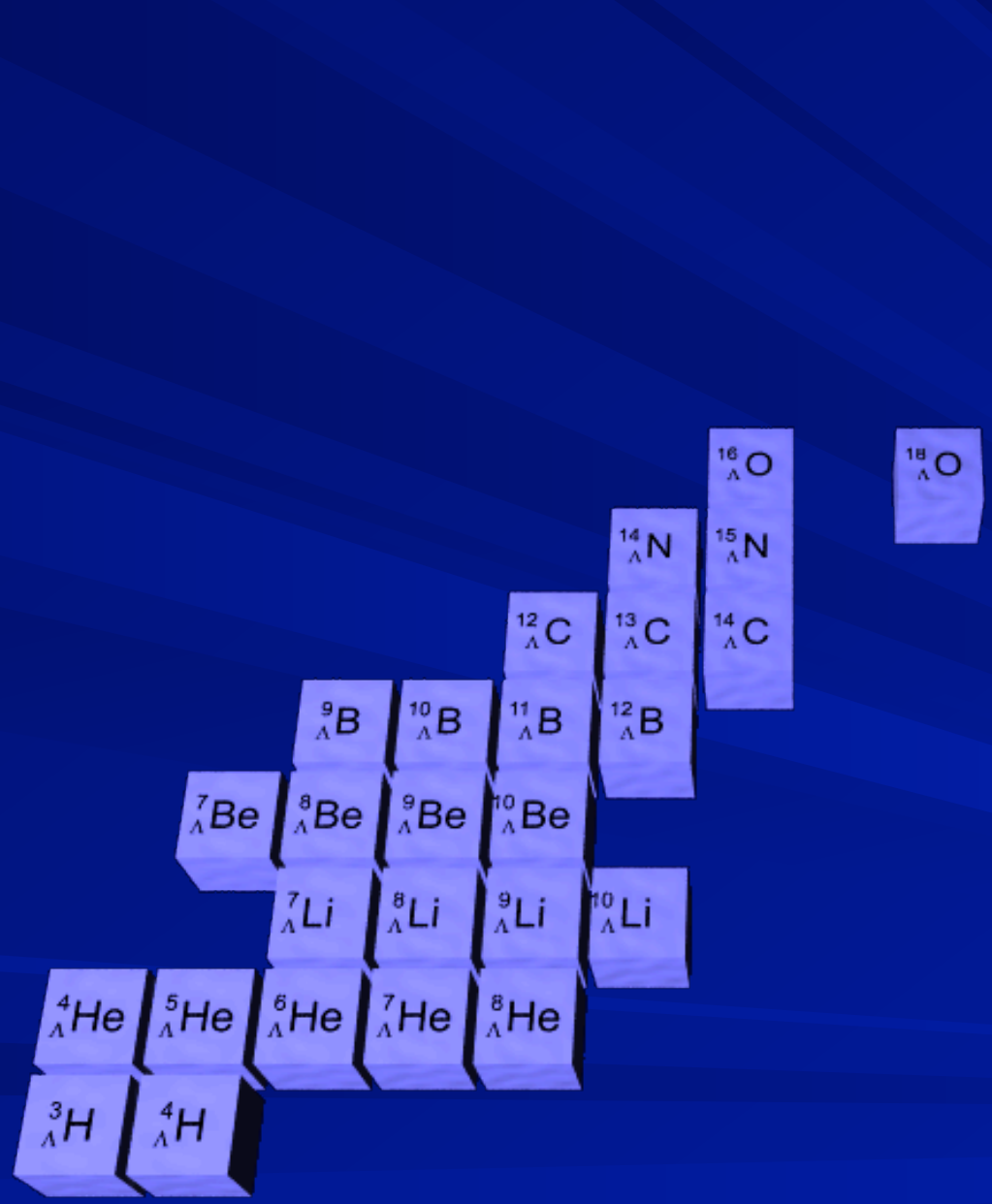


- Tables of kinematical relations (from simulations)
- Programmed in fast online hardware (FPGA)

→ Displaced vertex trigger

C. Rappold, PhD thesis

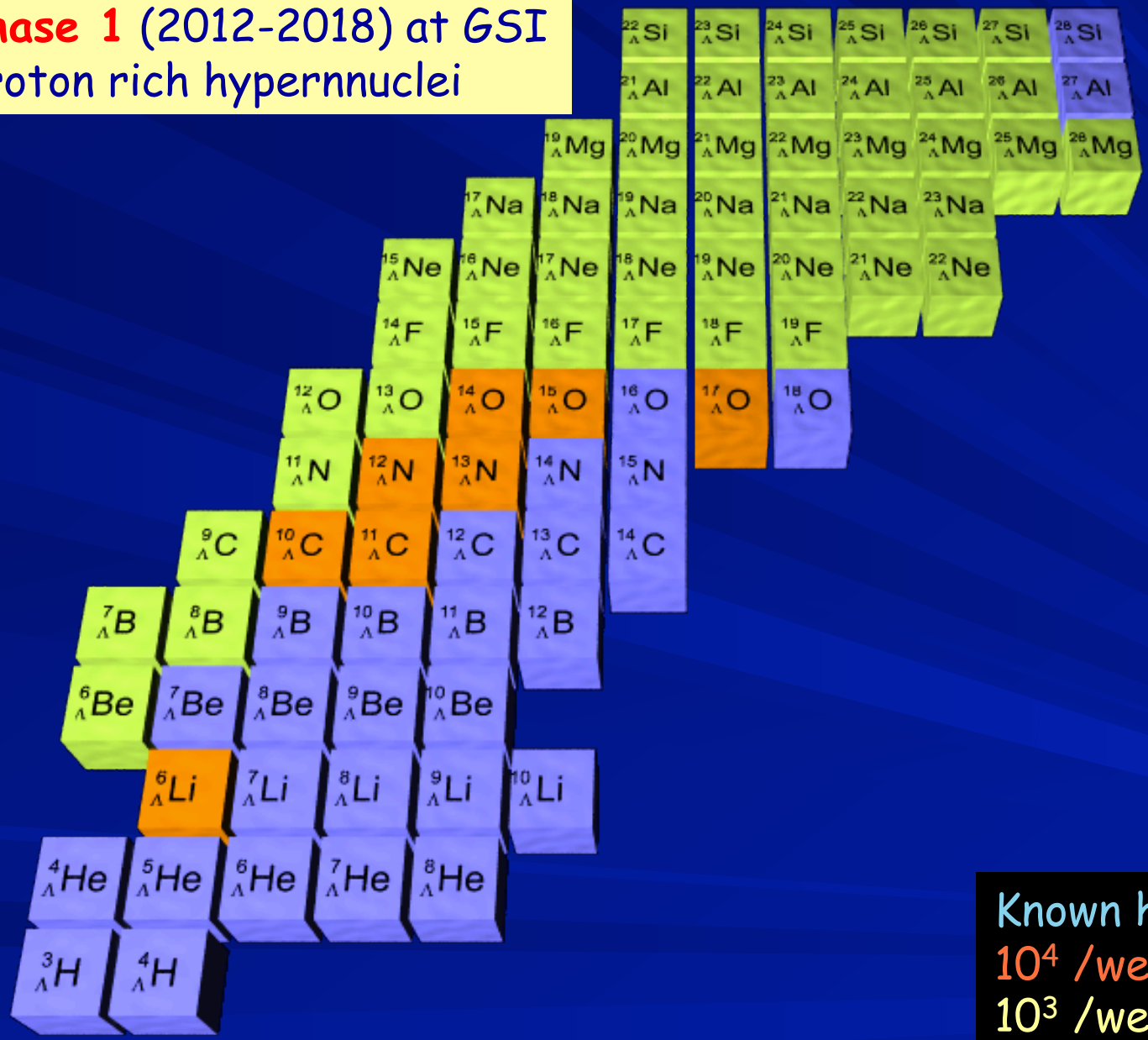
Present hypernuclear landscape



Known hypernuclei

Hypernuclear landscape with HypHI

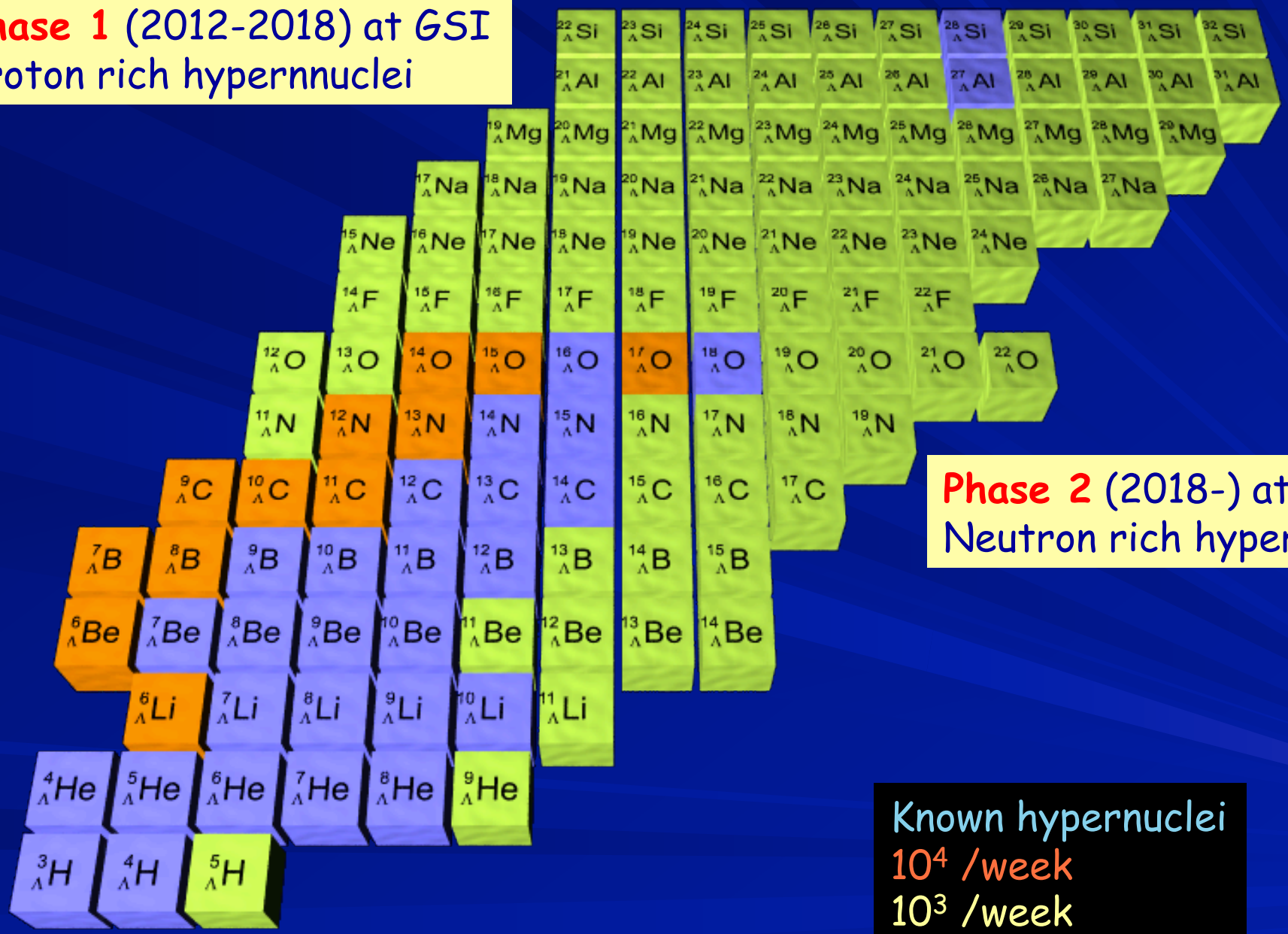
Phase 1 (2012-2018) at GSI
Proton rich hypernnuclei



Known hypernuclei
10^4 /week
10^3 /week

Hypernuclear landscape with HypHI

Phase 1 (2012-2018) at GSI
Proton rich hypernnuclei

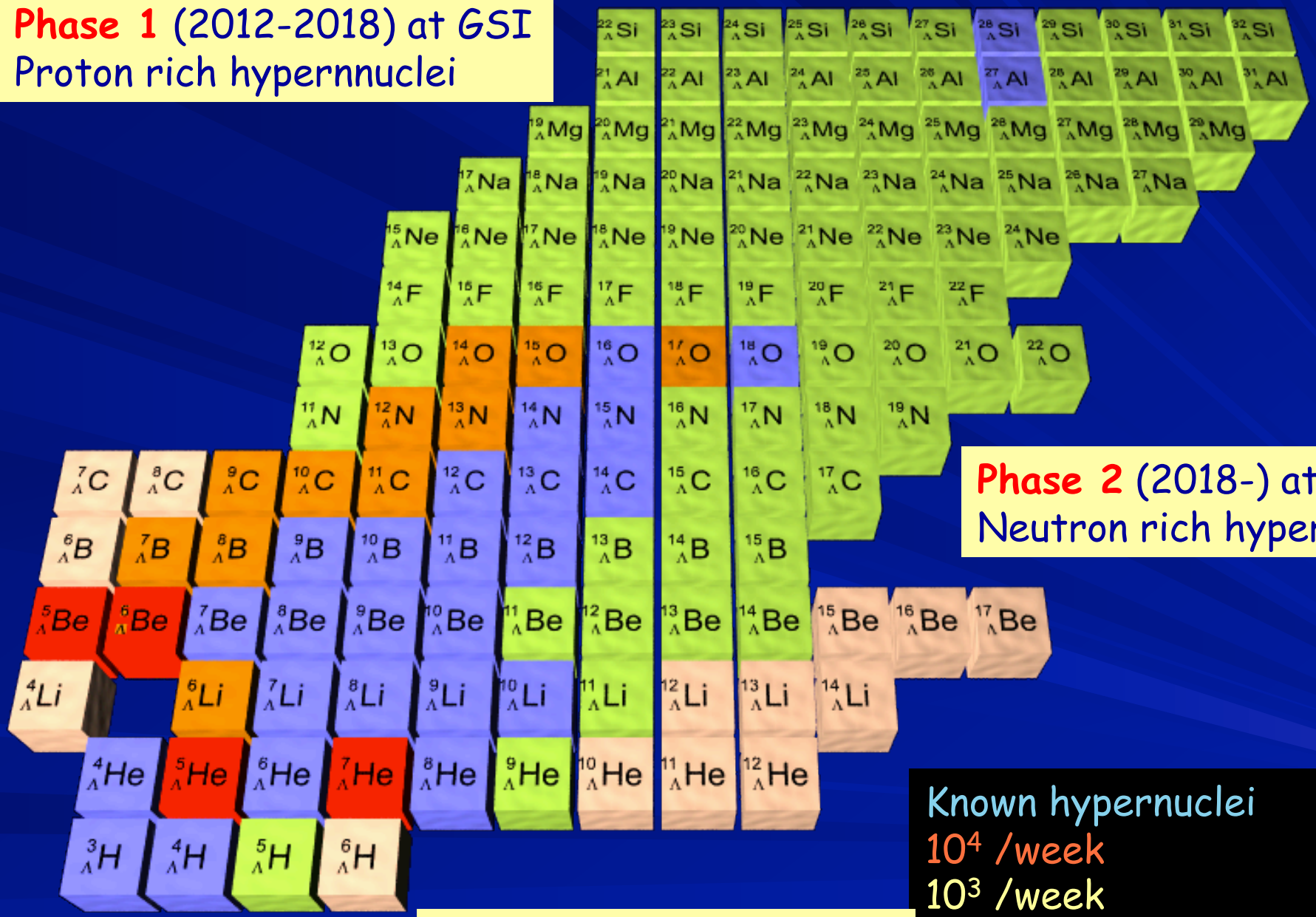


Phase 2 (2018-) at R3B/FAIR
Neutron rich hypernuclei

Known hypernuclei
10^4 /week
10^3 /week

Hypernuclear landscape with HypHI

Phase 1 (2012-2018) at GSI
Proton rich hypernnuclei



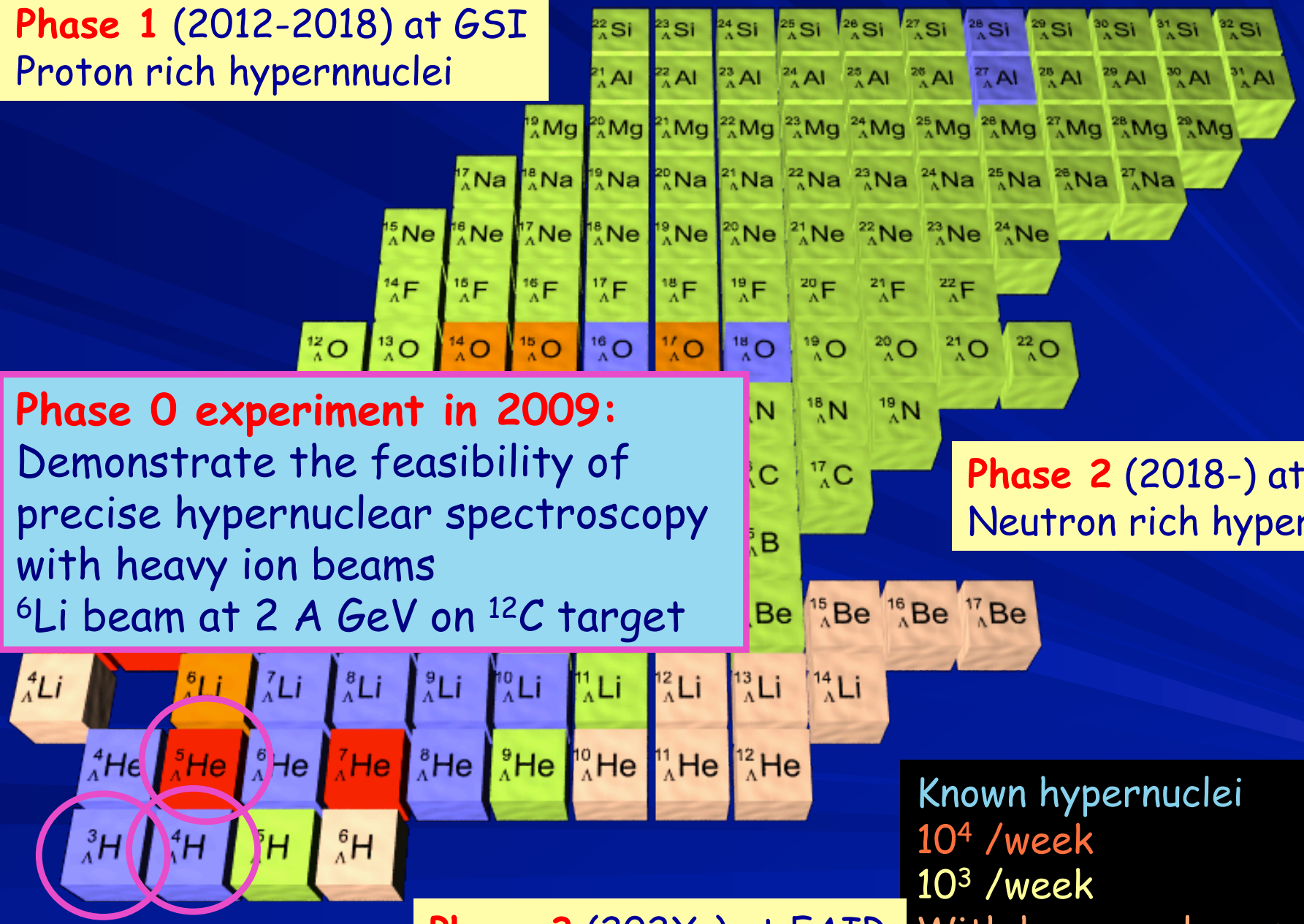
Phase 2 (2018-) at R3B/FAIR
Neutron rich hypernuclei

Phase 3 (202X-) at FAIR
Hypernuclear separator

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

Hypernuclear landscape with HypHI

Phase 1 (2012-2018) at GSI
Proton rich hypernnuclei



Phase 0 experiment in 2009:
Demonstrate the feasibility of precise hypernuclear spectroscopy with heavy ion beams
^{6}Li beam at 2 A GeV on ^{12}C target

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

HypHI Phase 0 in October 2009

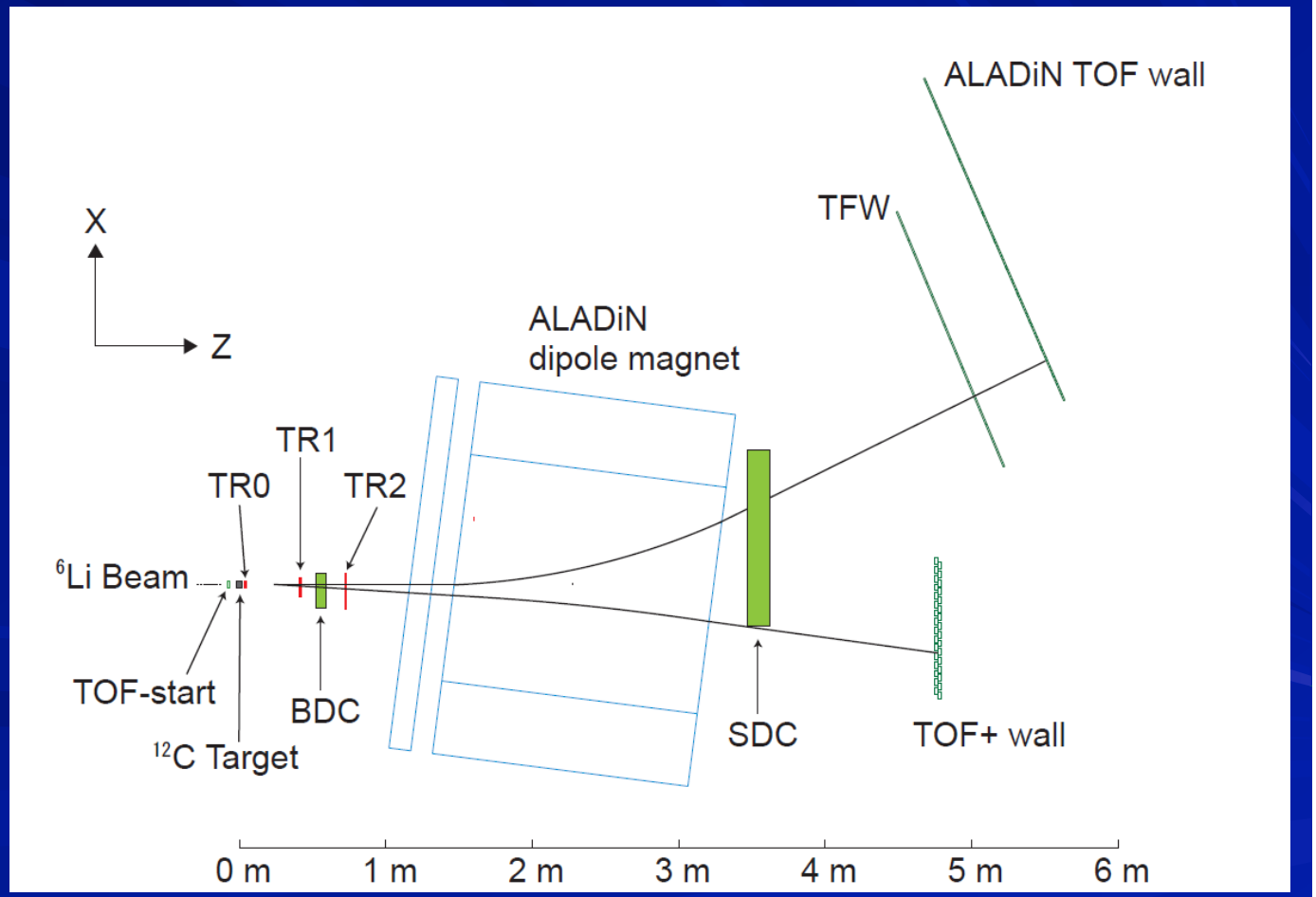
- The goal of the Phase 0 experiments
  - To demonstrate the feasibility of precise hypernuclear spectroscopy with ^{6}Li primary beams at 2 A GeV : Mesonic decay $\Lambda \rightarrow \pi^- + p$

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

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

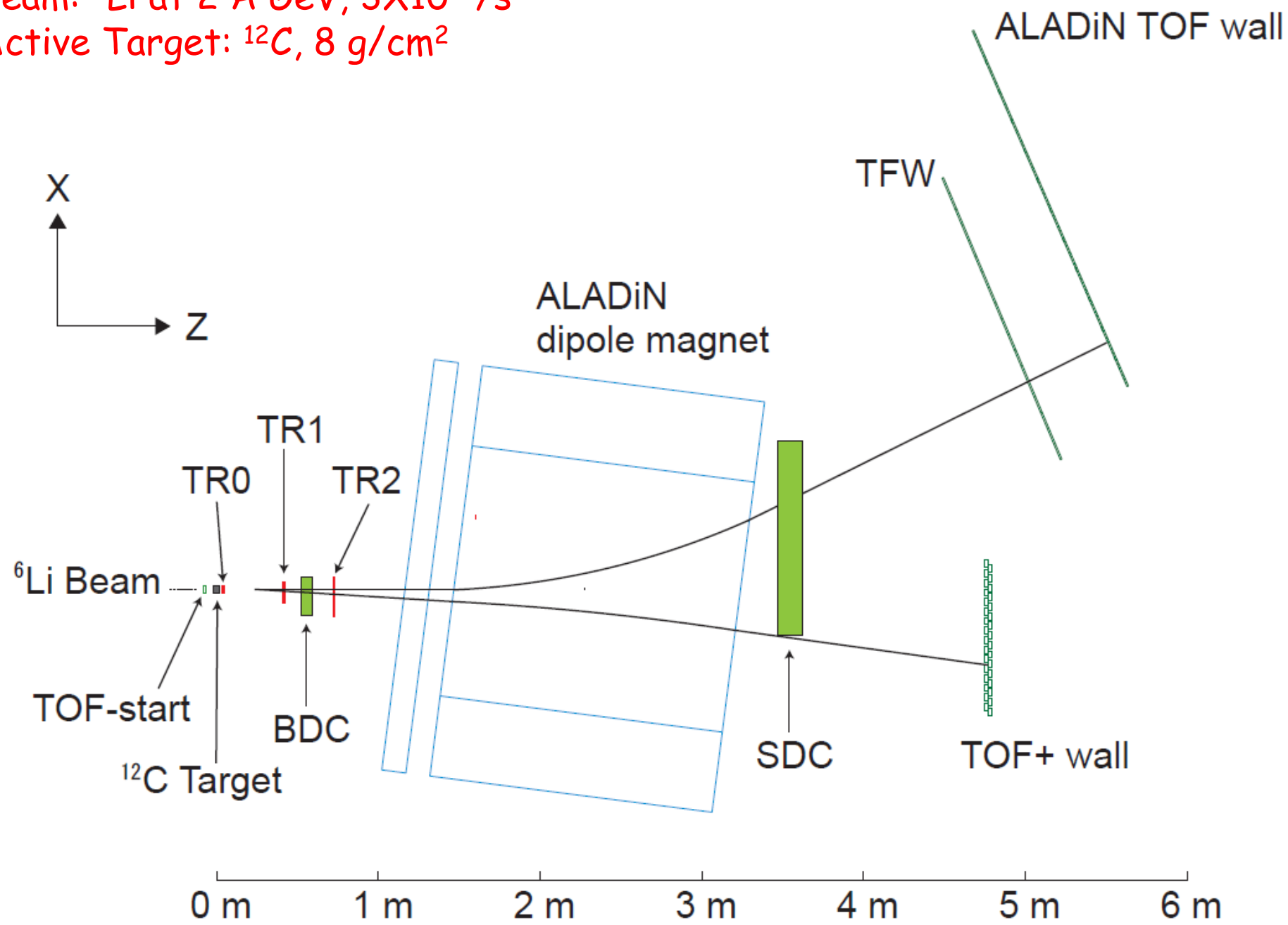
$^{5}_{\Lambda}He \rightarrow \pi^- + {}^{4}He + p$

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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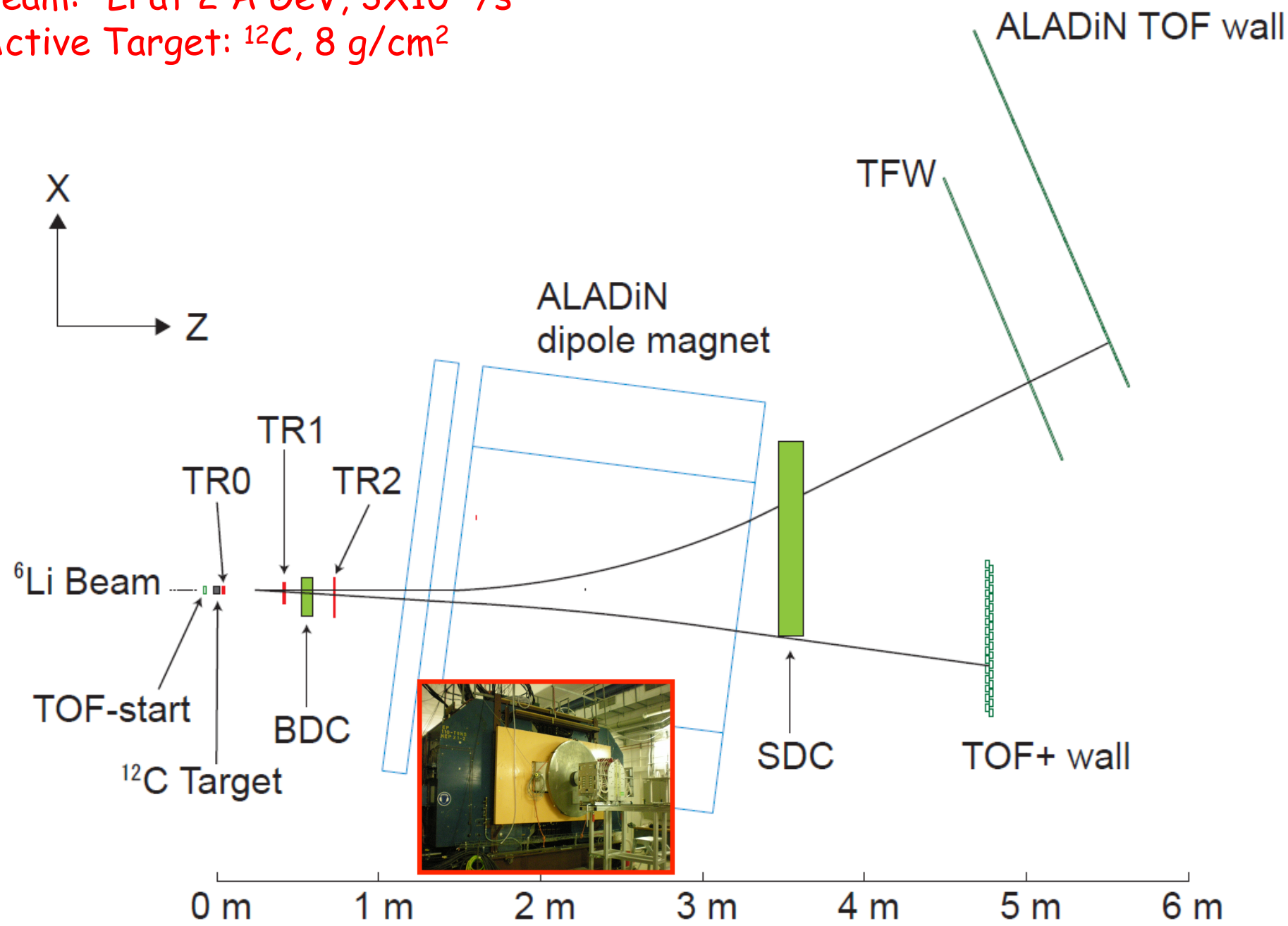

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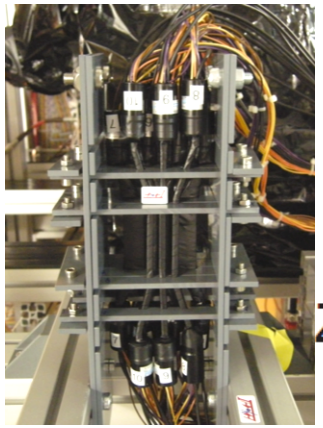

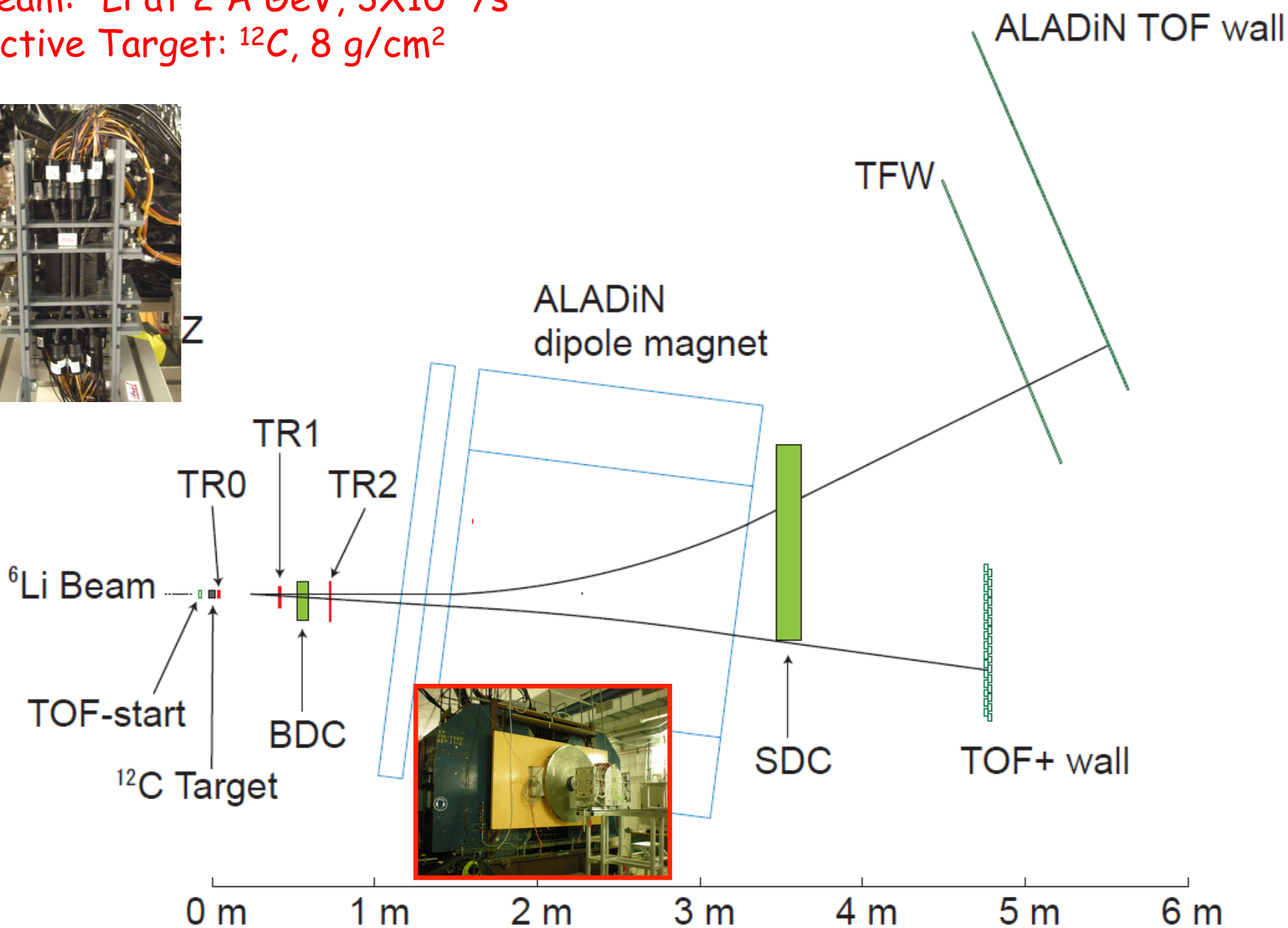

Phase 0 setup

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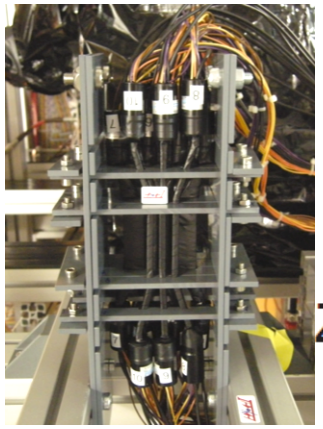

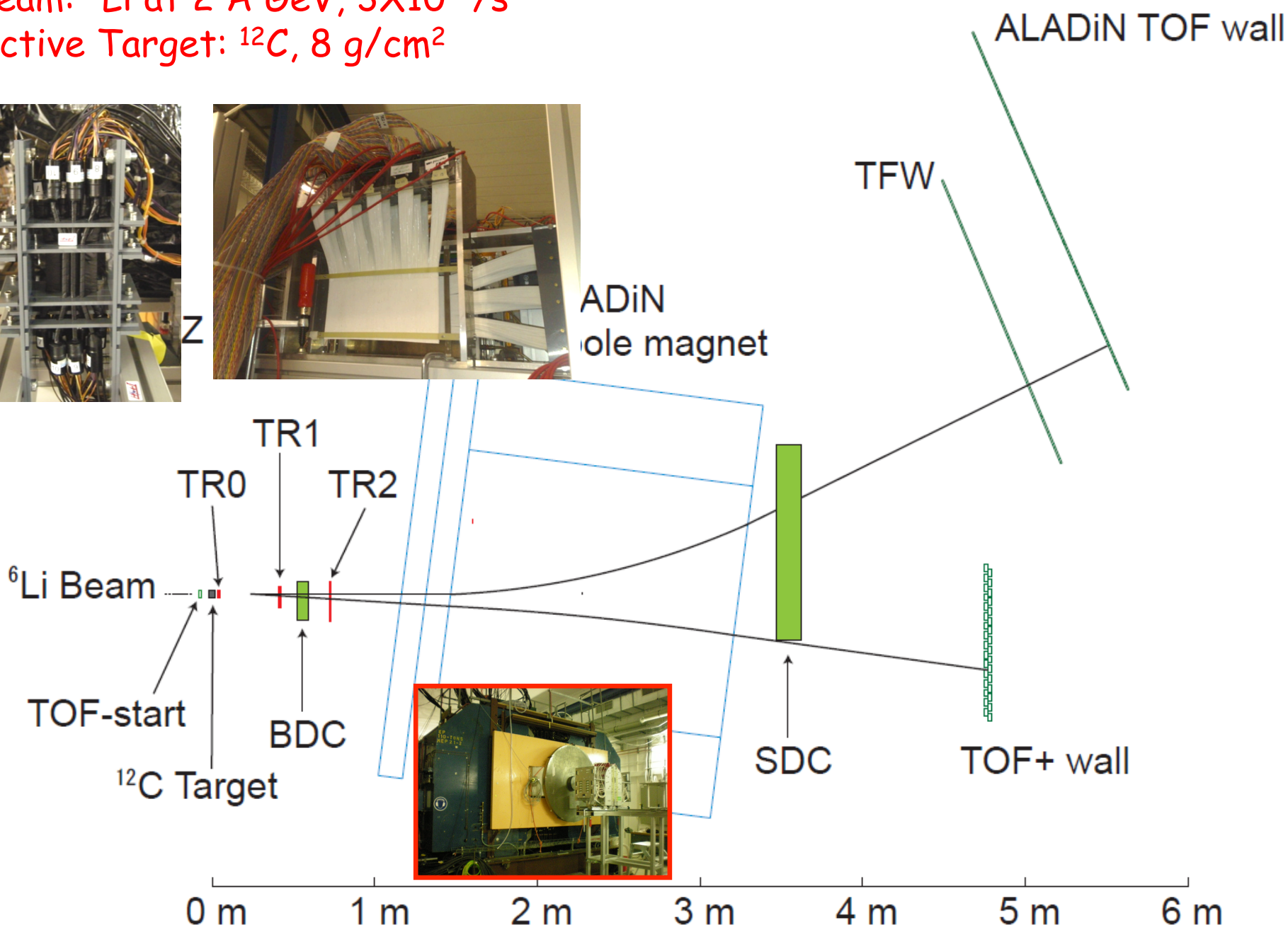

Phase 0 setup

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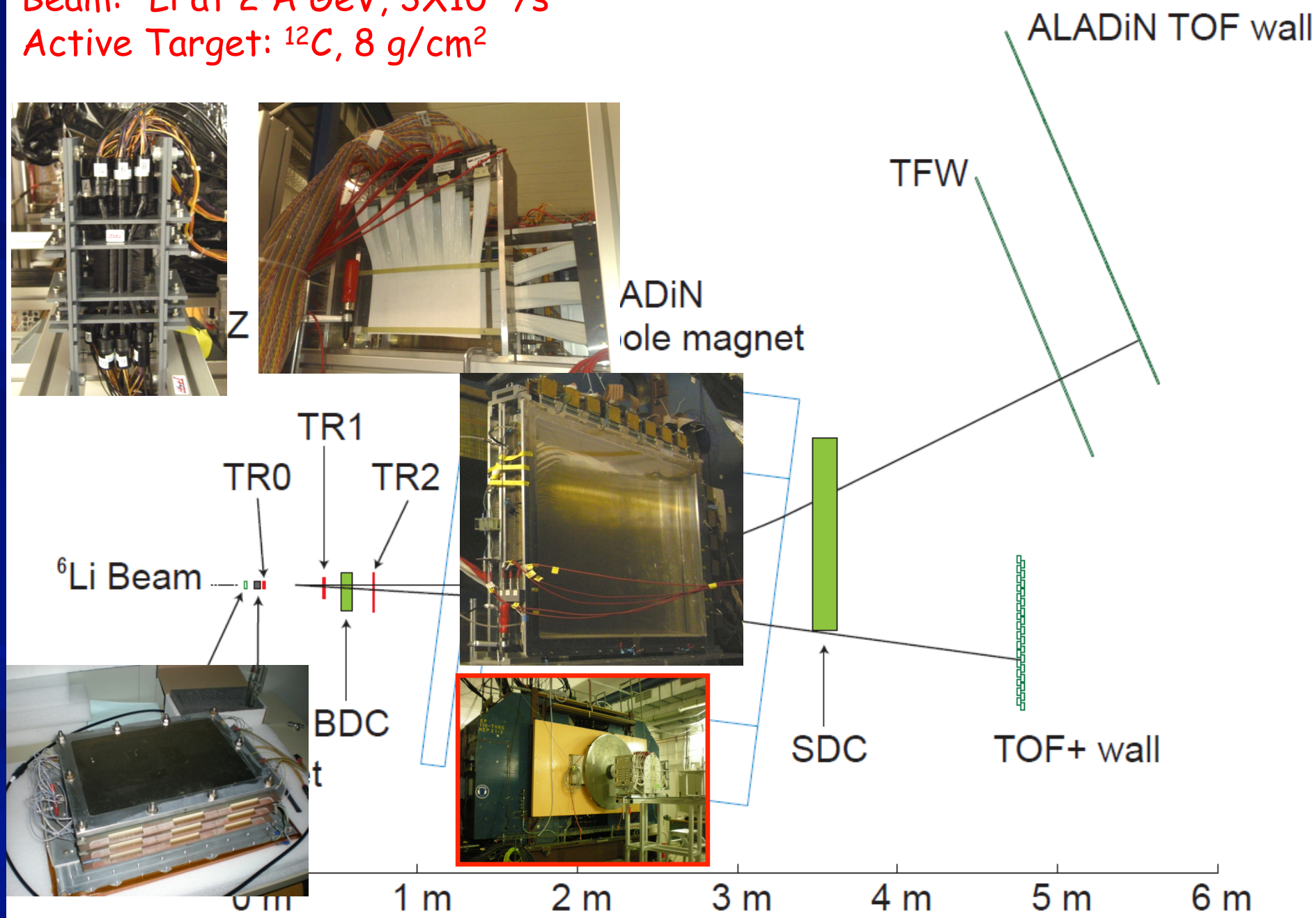

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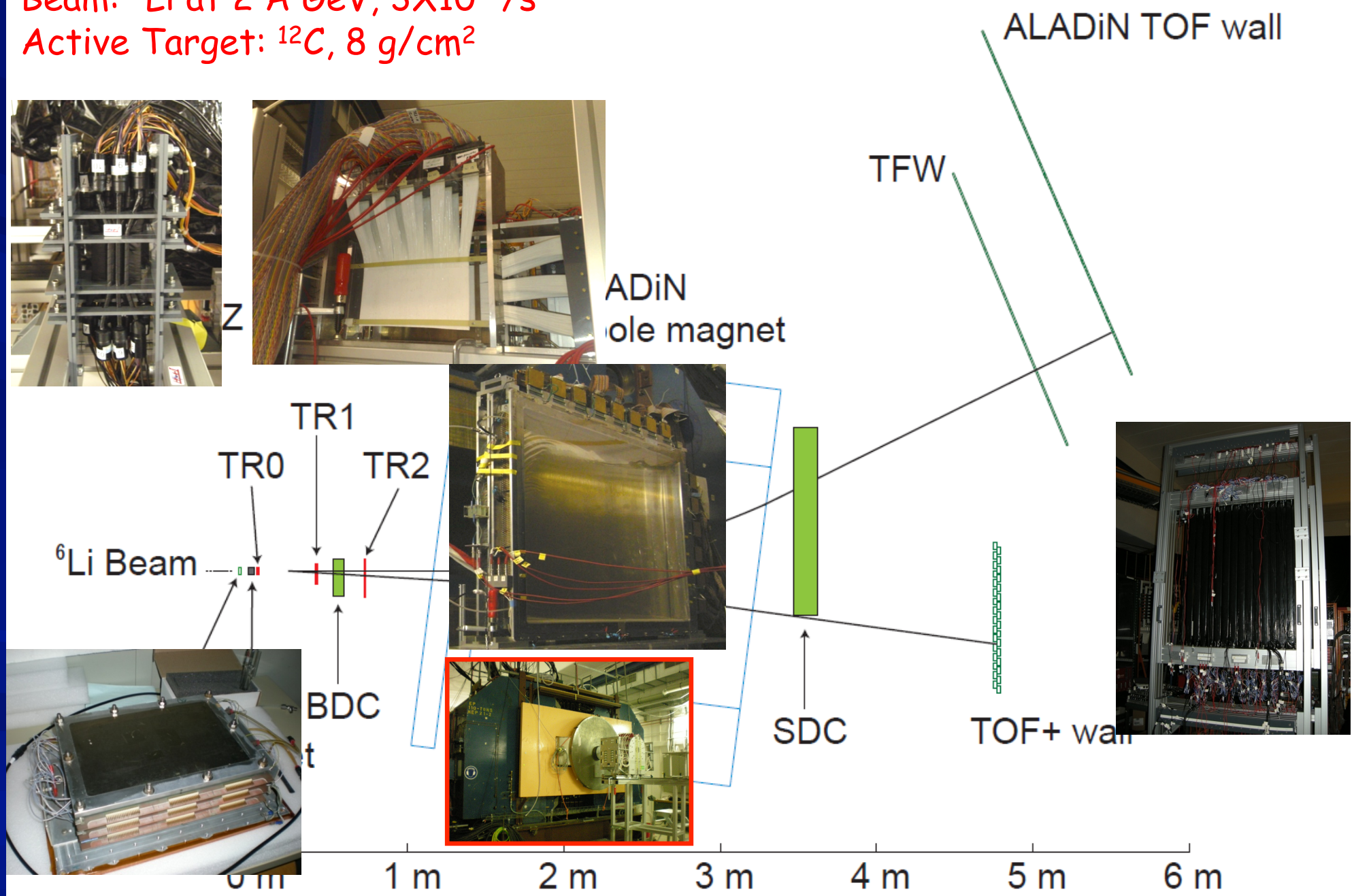

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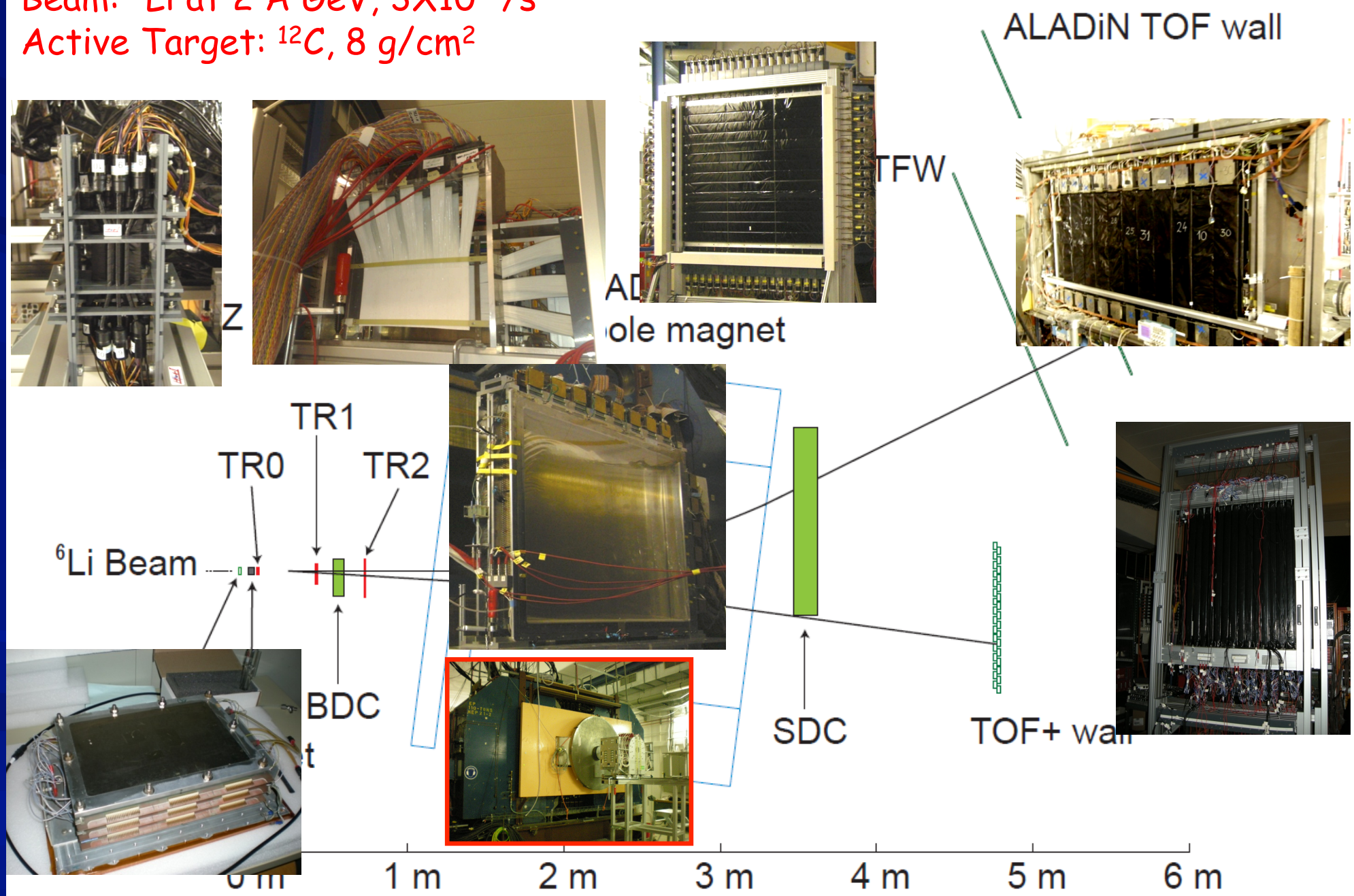
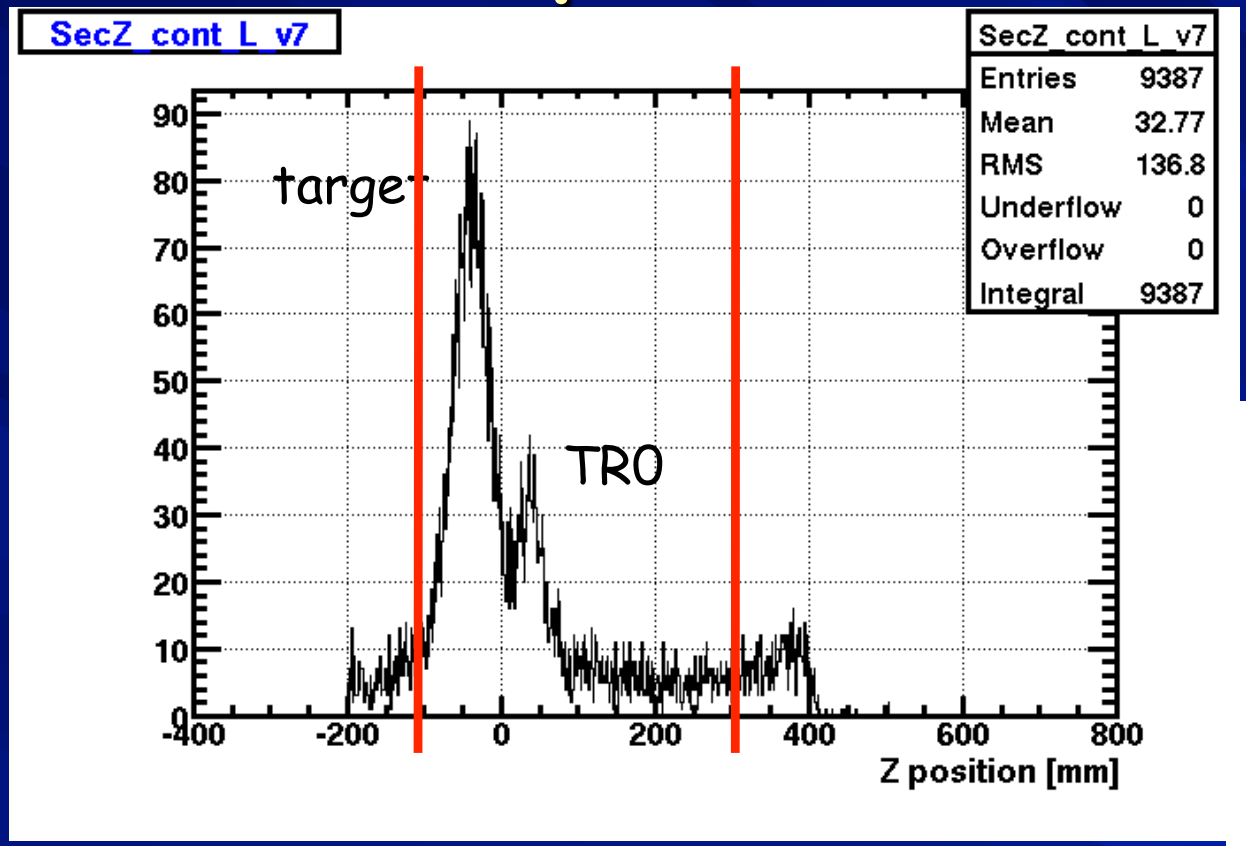
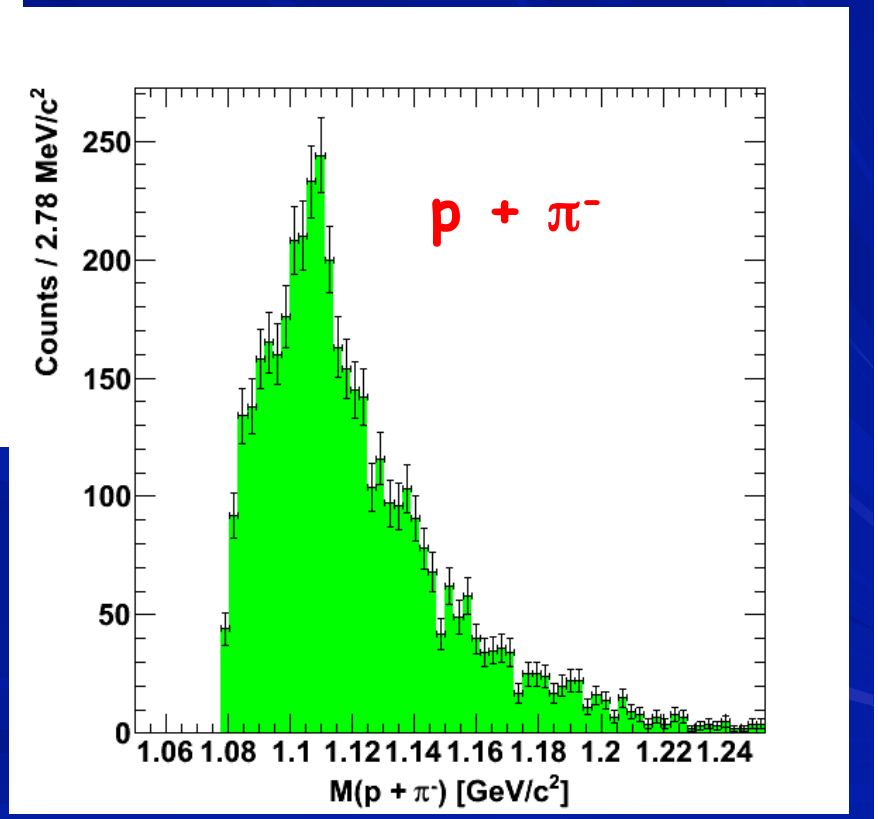


Displaced secondary vertex





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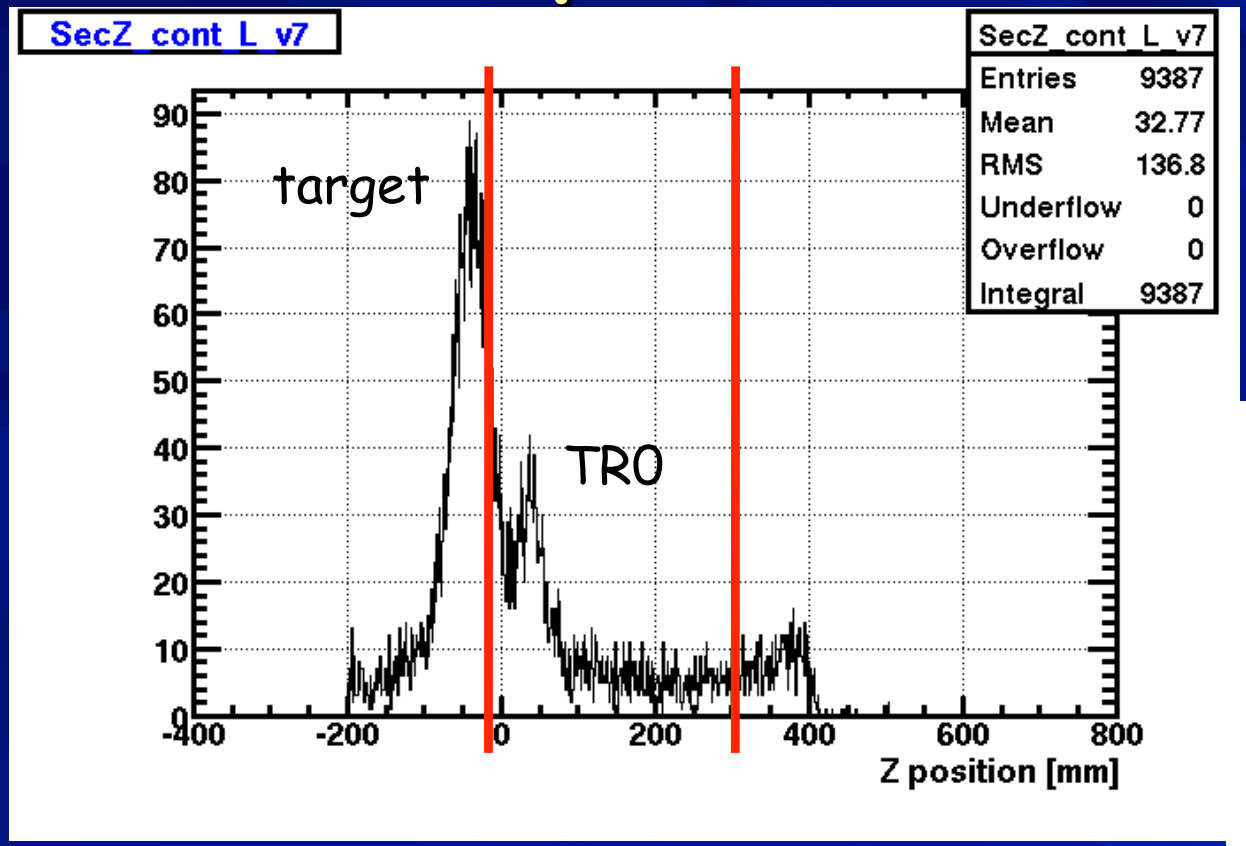

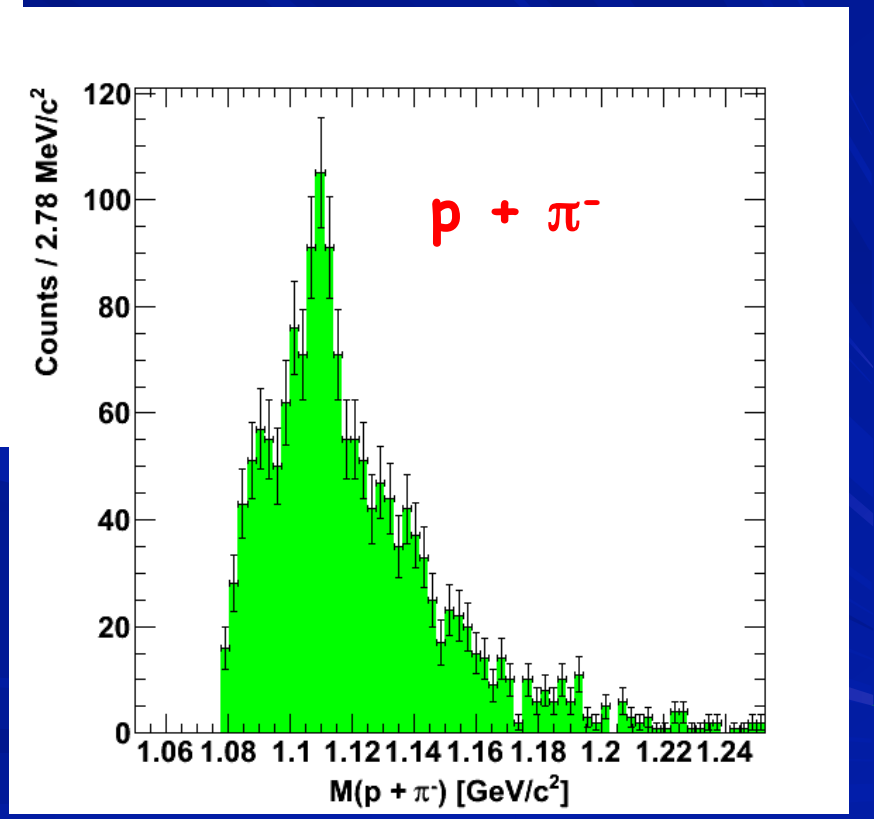

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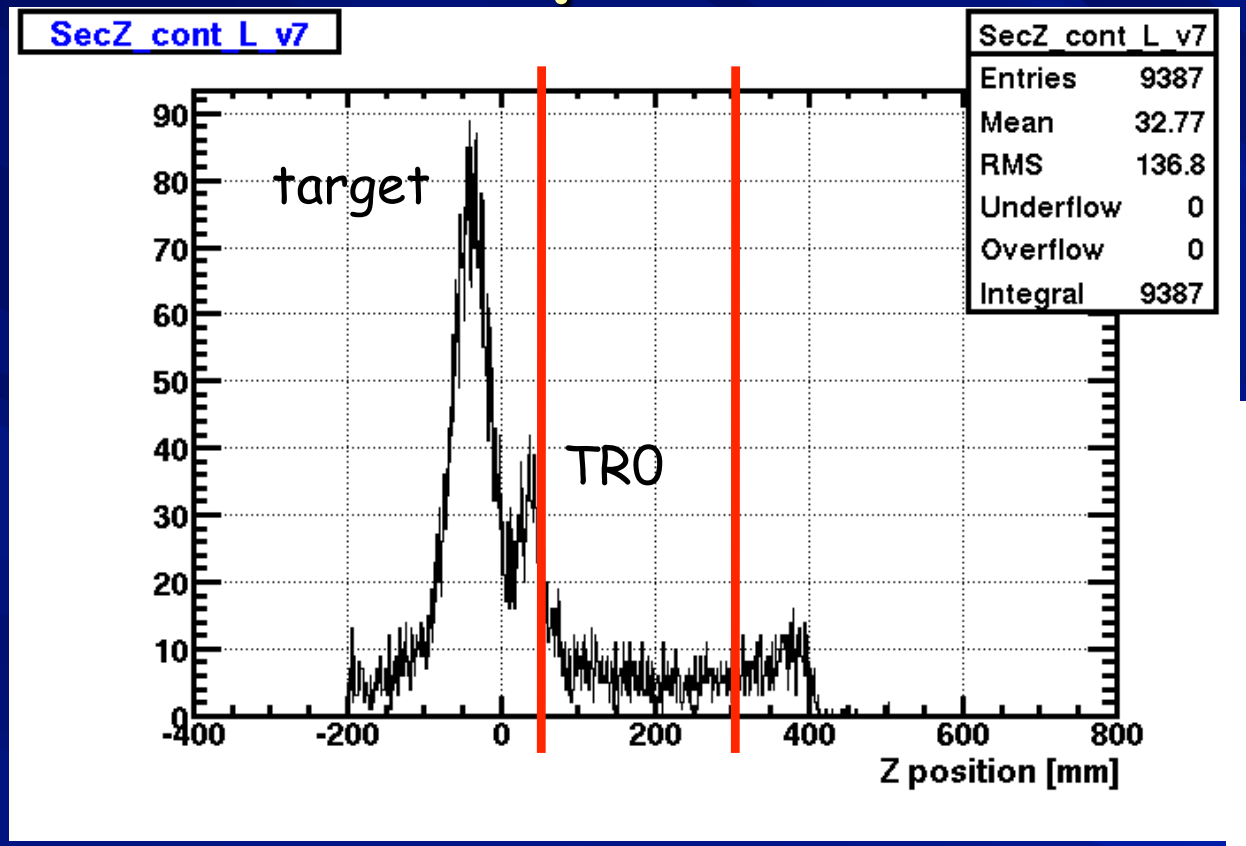
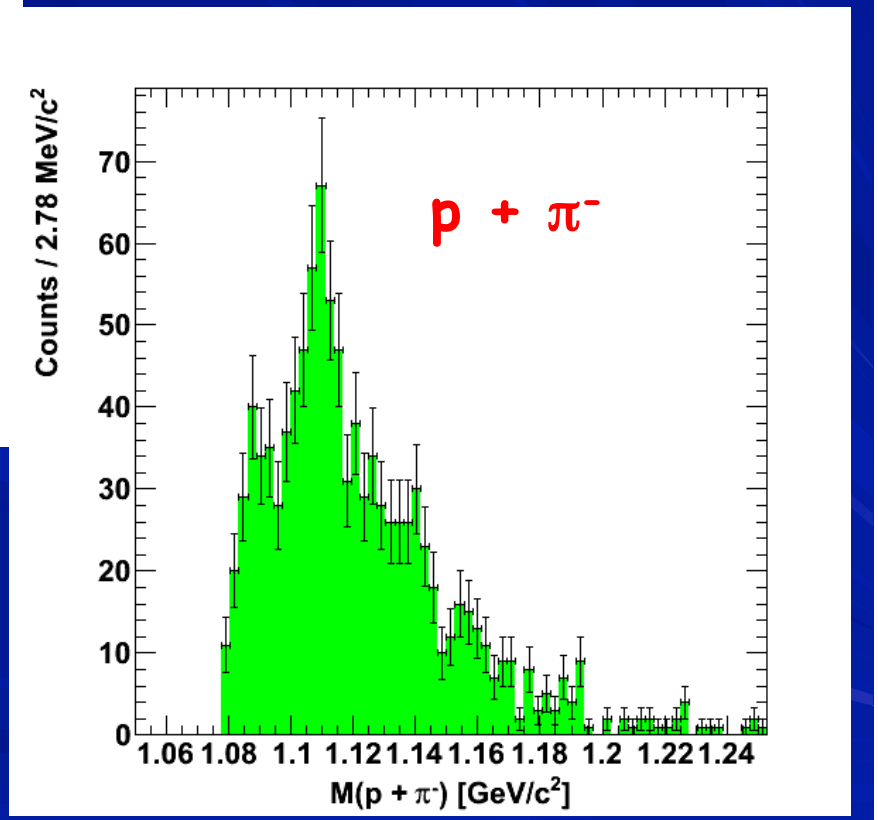
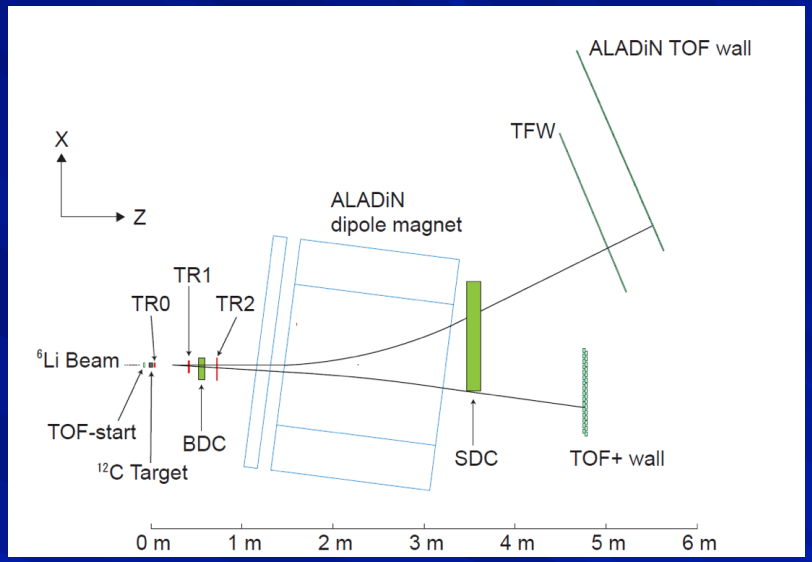




Analysis for Phase 0

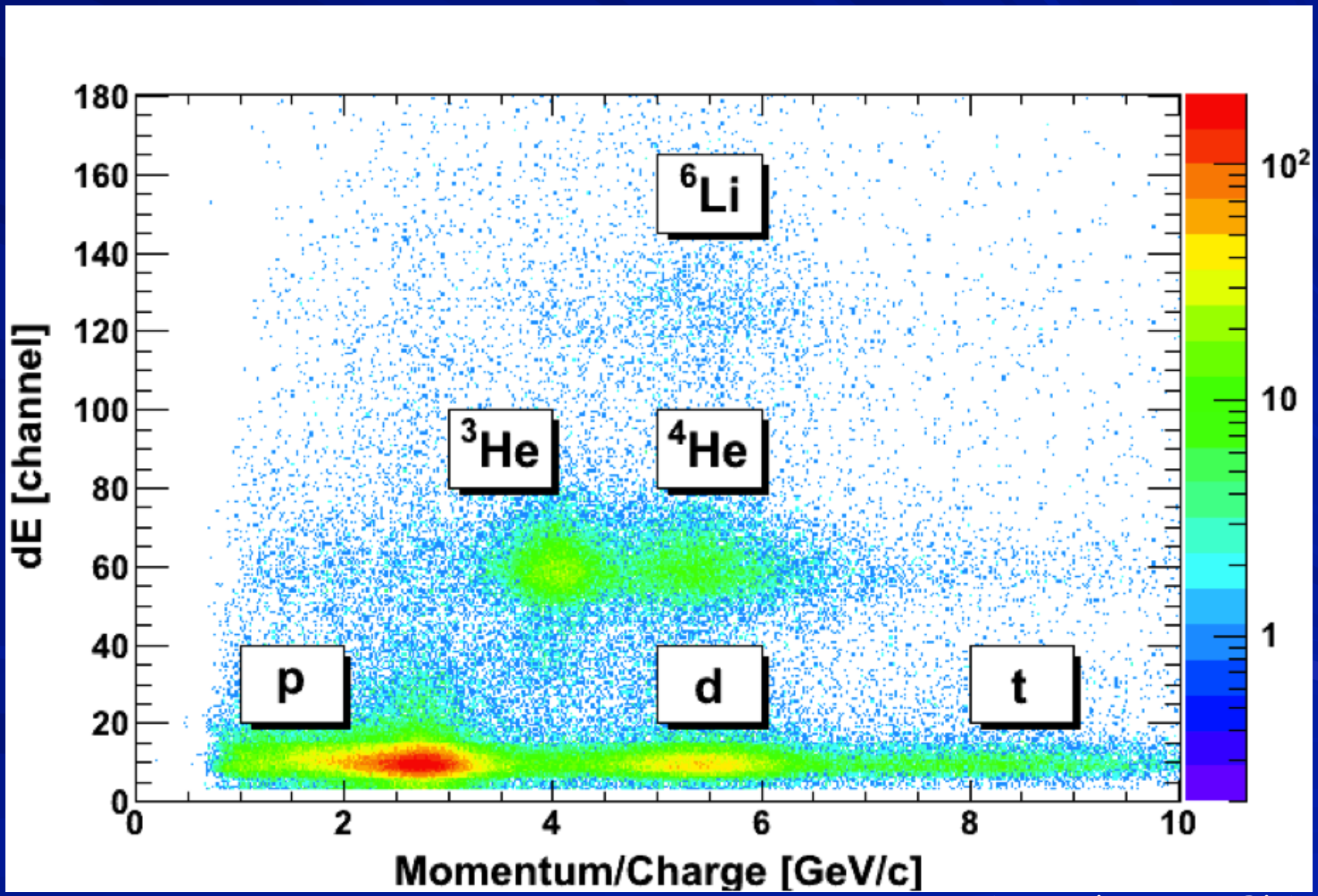
- Independent calibrations for each detector
- Track-candidate finding and calibrations
- Track fitting: Kalman filter
- Particle ID
  - dE/dx in TOF+
  - TOF with TOF+ and TFW
  - Momentum from tracking
- Decay vertex
  - Pairs of corresponding tracks
  - Minimum track distance: < 4 mm
  - Longitudinal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



O. Borodina, V. Bozkurt, E. Kim, D. Nakajima, C. Rappold, K. Yoshida , PhD thesis

PID: Z>0

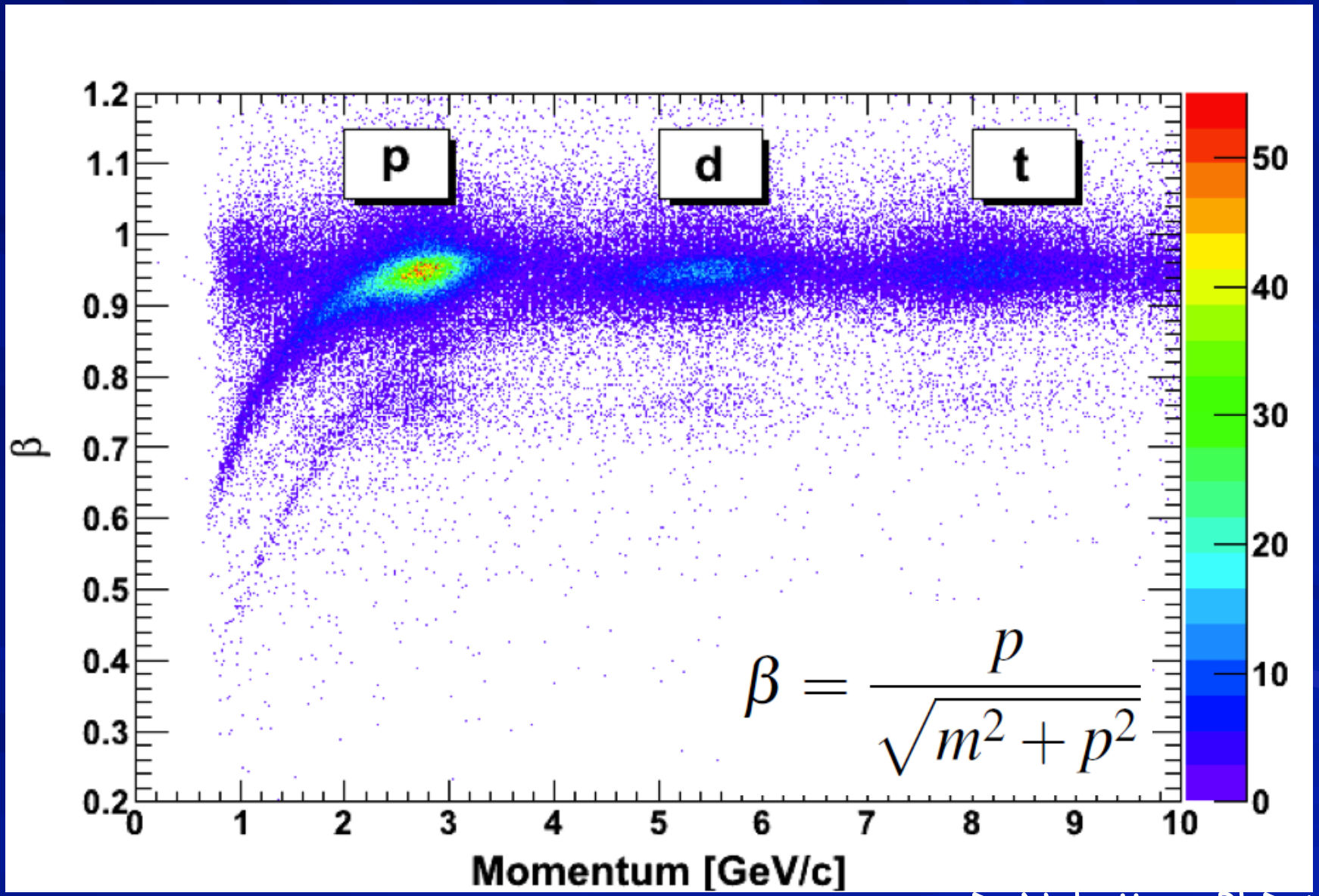
- dE (TOF+) versus momentum/Z (pre-tracking and tracking)



D. Nakajima, PhD thesis

PID: Z=1

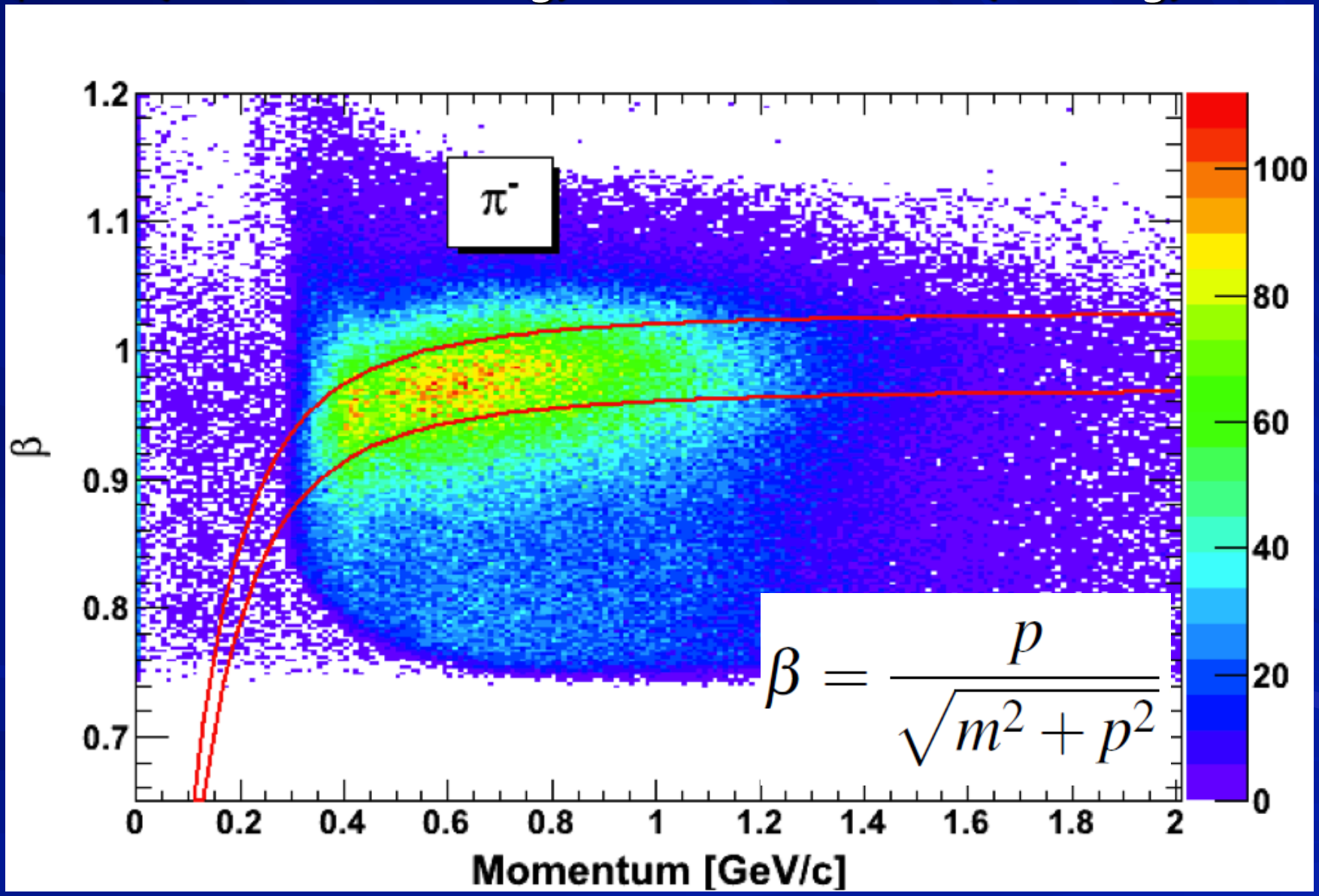
- β=v/c (TOF+ and tracking) versus momentum (tracking)



D. Nakajima, PhD thesis

PID: Z=-1 (π^-)

- β=v/c (TFW and tracking) versus momentum (tracking)

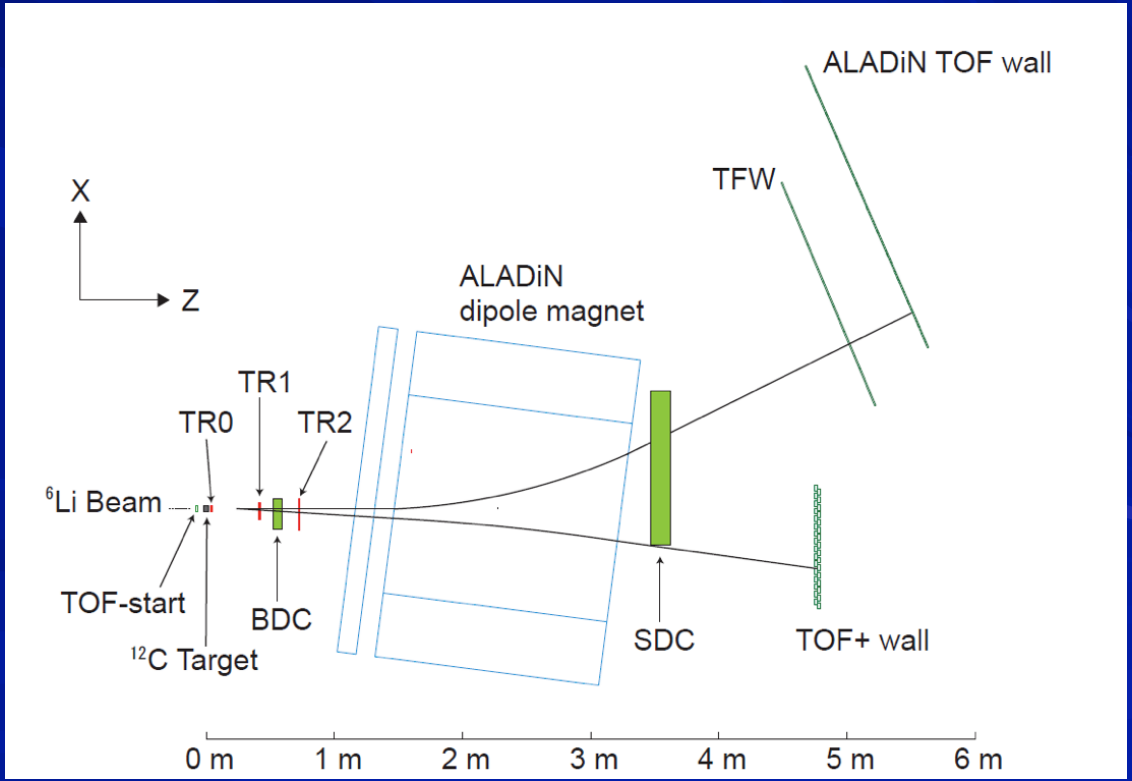


D. Nakajima, PhD thesis

Analysis without BDC

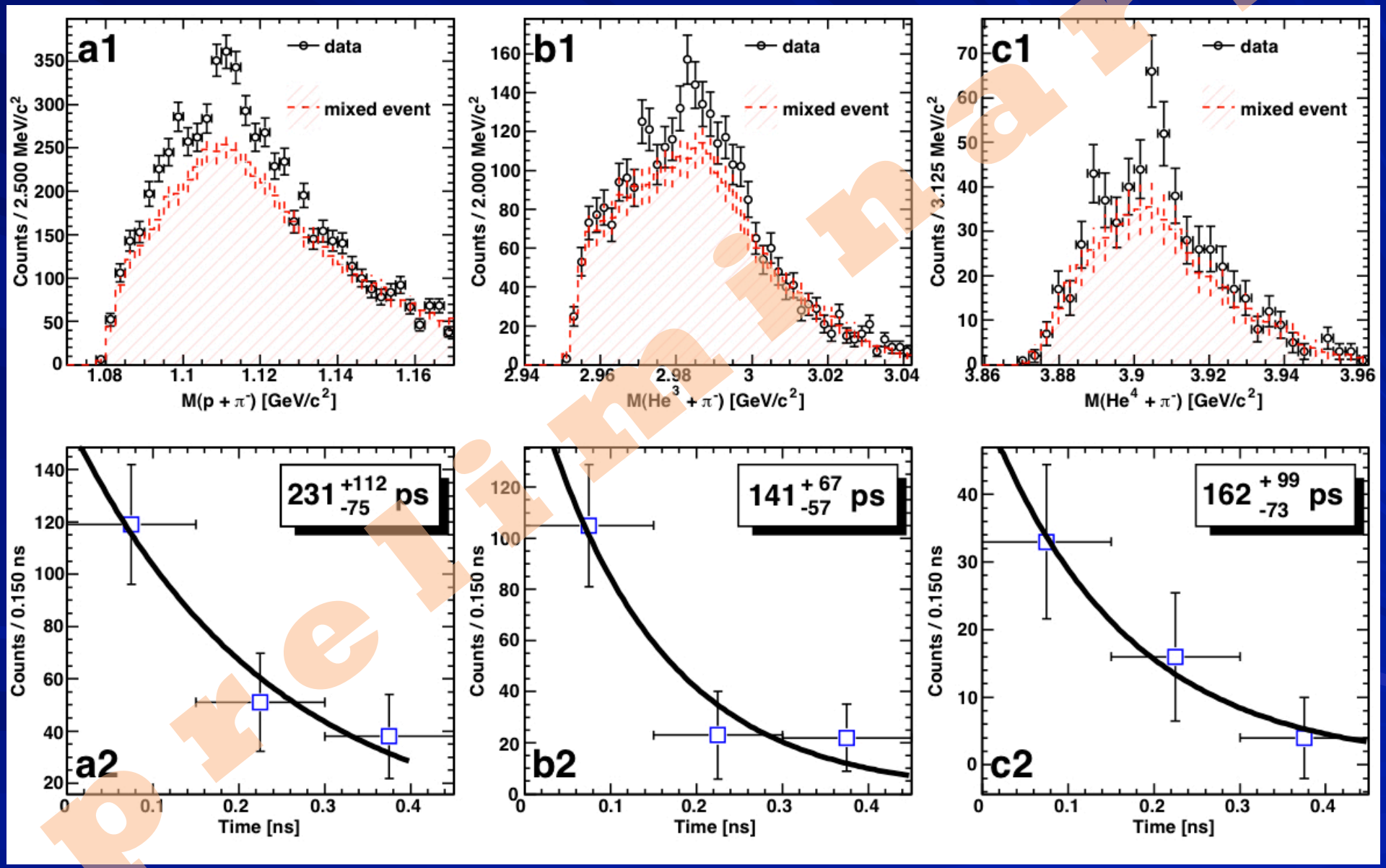
- **Tracking layers**
  - In front of the bending magnet:
    - Fiber detectors, TR1 and TR2
  - Behind the bending magnet
    - Drift chamber SDC and TOF walls

- **Poor redundancy**
- **Tight cut conditions**
- **Sufficient statistics**



Analysis without BDC

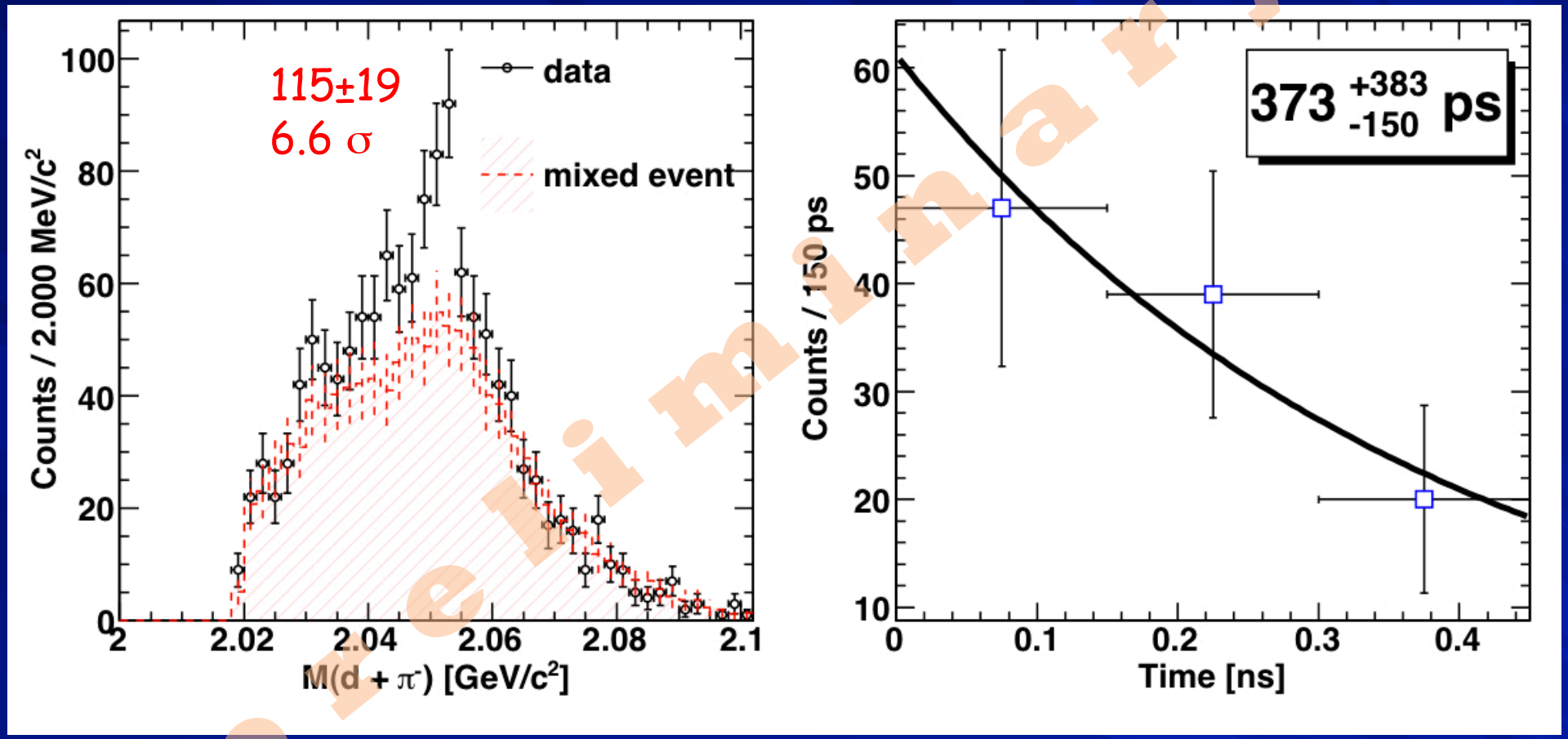
$p + \pi^-$ for Λ | $^3He + \pi^-$ for $^3_\Lambda H$ | $^4He + \pi^-$ for $^4_\Lambda H$



preliminary

D. Nakajima, PhD thesis, NPA in press

Analysis: without BDC: d + π^-



Preliminary

- Calibrated mass: 2.054 - 2.064 GeV/c^2 (n+Λ threshold = 2.055)

Summary of observed peaks

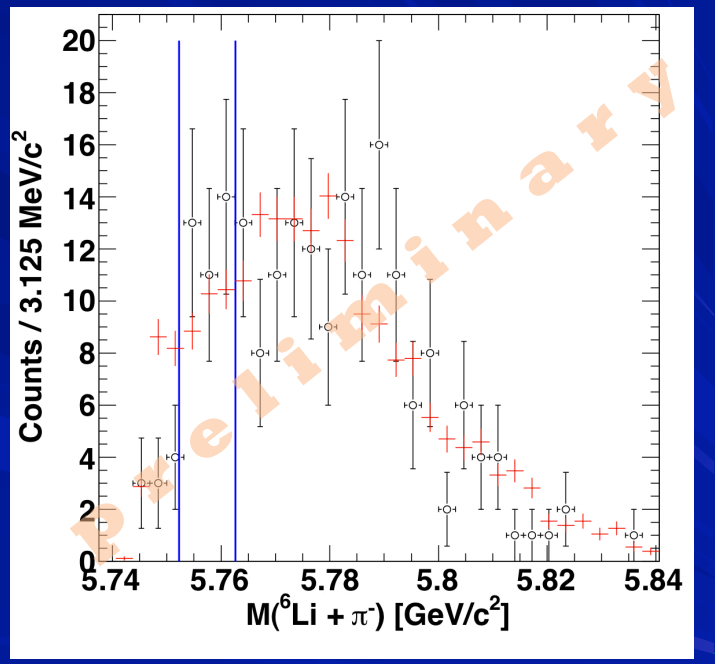
Final state	$p + \pi^-$	$^3He + \pi^-$	$^4He + \pi^-$	$d + \pi^-$
Initial state	Λ	$^3_\Lambda H$	$^4_\Lambda H$	
Uncalibrated mass	1111.3 ± 0.4	2984.6 ± 0.6	3905.6 ± 0.6	2051.3 ± 0.5
Width	7.3	8.6	5.2	4.8
Peak integral	403 ± 41	178 ± 31	66 ± 14	115 ± 19
Significance in σ	7.1	6.2	5.3	6.6
Known mass	1115.683 ± 0.006 [26]	2991.68 ± 0.05 [3]	3923.03 ± 0.06 [3]	
Measured lifetime	231^{+112}_{-75}	141^{+67}_{-57}	162^{+99}_{-73}	373^{+383}_{-150}
Known lifetime	263.2 ± 2.0 [26]	$246^{+62}_{-41} \pm 27$ [27]	194^{+24}_{-26} [28]	

$$\sum_{i=0}^{n_0-1} e^{-n_b} \frac{n_b^i}{i!} = \frac{1}{\sqrt{2\,\pi}} \int_{-\infty}^{S} \exp\left(\frac{-x^2}{2}\right) dx$$

Possible miss-reconstructions

- $^{3}_{\Lambda}H$ -> $^{3}He^{*}$ + π^{-}
  -> p + d
  - Mean mass position ~ 2.045 GeV
    - $^{3}_{\Lambda}H$ -> p- + ^{3}He : branch = 0.379*2/3 = 0.25
    - $^{3}_{\Lambda}H$ -> p- + p + d: branch = 0.619*2/3 = 0.412
    - Observed $^{3}_{\Lambda}H$ -> pi- + ^{3}He : 178
    - Estimated p-+d from $^{3}_{\Lambda}H$:
      153 * 0.412/0.25 * 0.61 * 0.98 * 0.03 = 5
- $^{6}_{\Lambda}He$ -> $^{6}Li^{*}$ + π^{-}
  -> ^{4}He + d
  - Mean mass position ~ 2.055 GeV
    - Upper limit: 8 counts
    - R(3-body)/R(2-body)=5 (from A. Gal)
    - Estimated p-+d from $^{6}_{\Lambda}He$:
      8 * 5 * 0.61 * 0.98 * 1.0 = 24

	Z=1	Z=2 and 3
Fiber eff.	0.61	1
Chamber eff.	0.98	1
TOF+ trigger sup	0.03	1

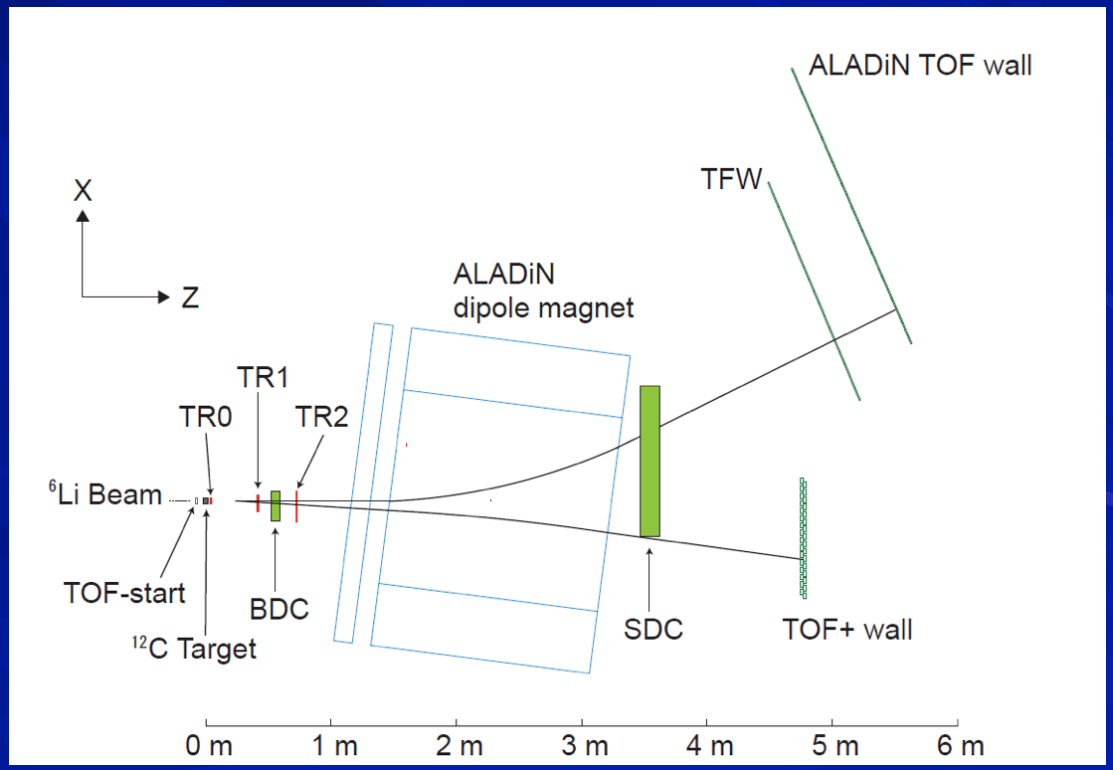


These values are small than the observed integral of 115

Analysis with BDC

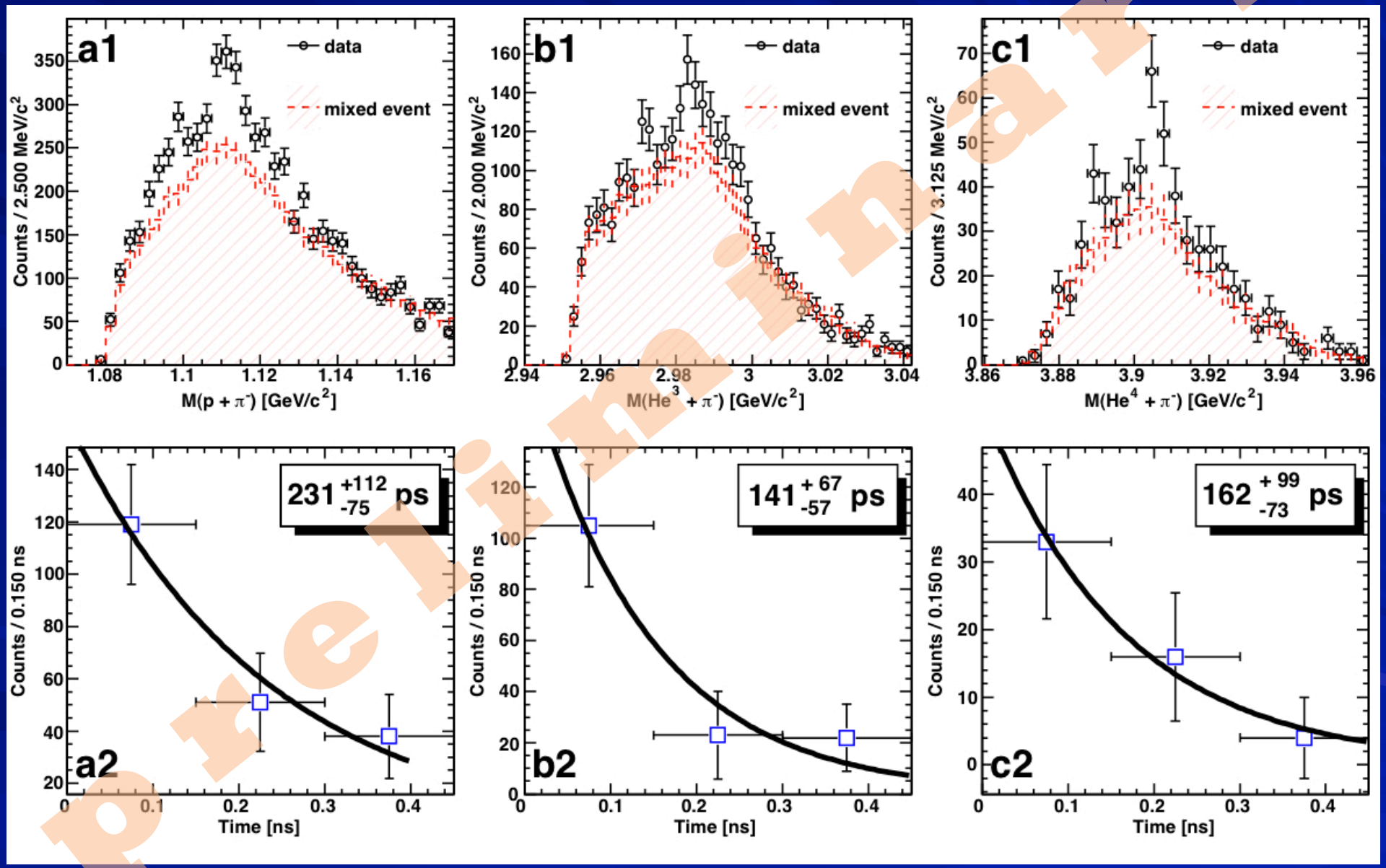
- Tracking layers
  - In front of the bending magnet:
    - Fiber detectors, TR1 and TR2, and drift chamber BDC
  - Behind the bending magnet
    - Drift chamber SDC and TOF walls

- More redundancy
- Better precision
- Small BDC efficiency
- Much looser cut conditions
- Less statistics



Analysis without BDC

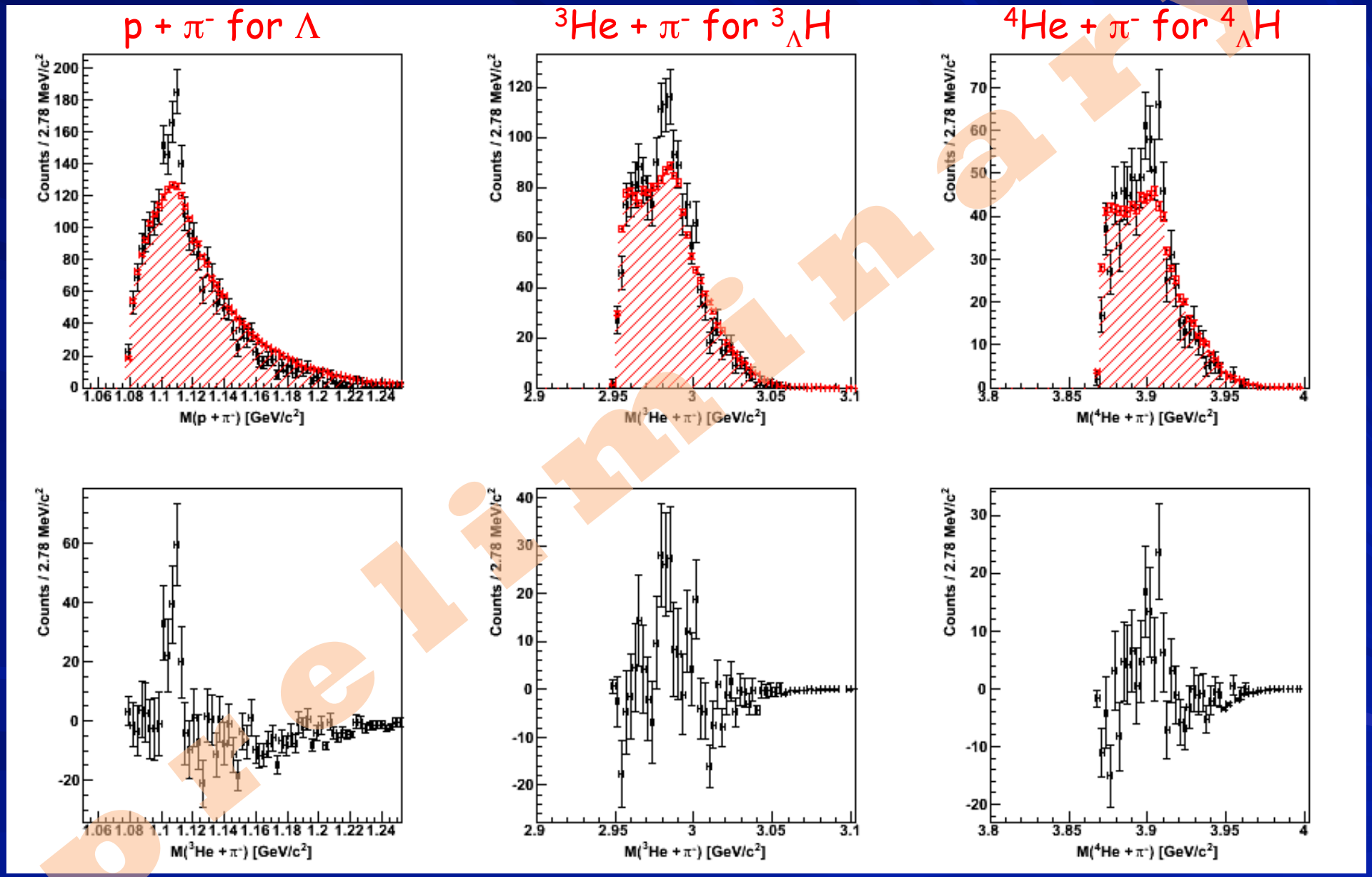
$p + \pi^-$ for Λ | $^3He + \pi^-$ for $^3_\Lambda H$ | $^4He + \pi^-$ for $^4_\Lambda H$



preliminary

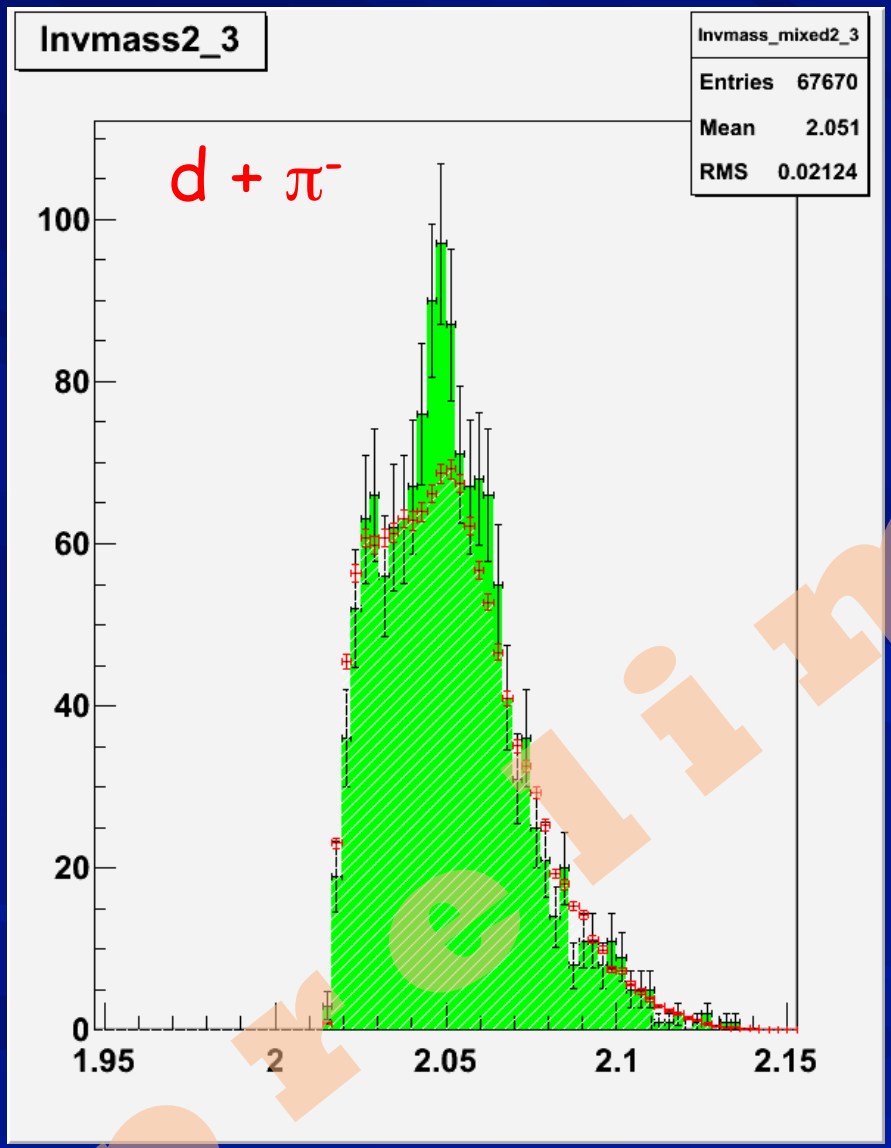
D. Nakajima, PhD thesis, NPA in press

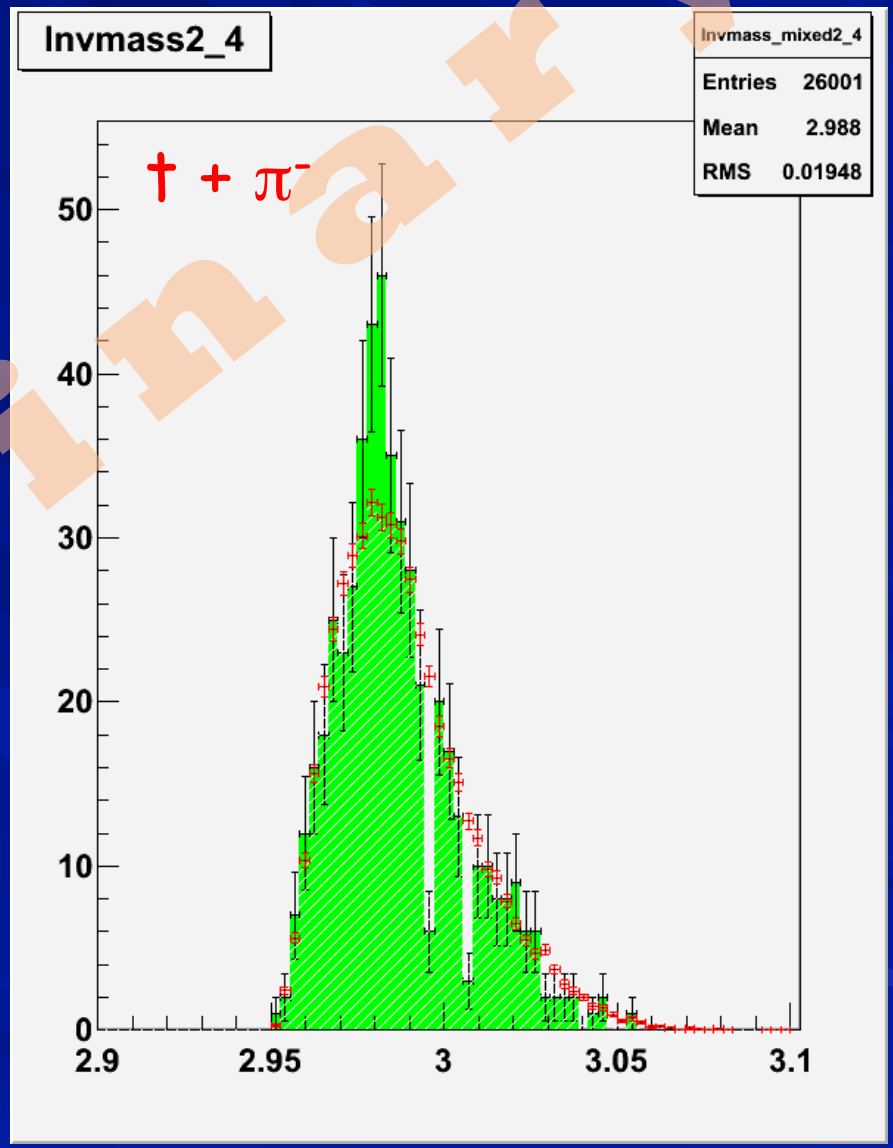
Analysis with BDC



E. Kim, PhD thesis, NPA in press

Analysis with BDC

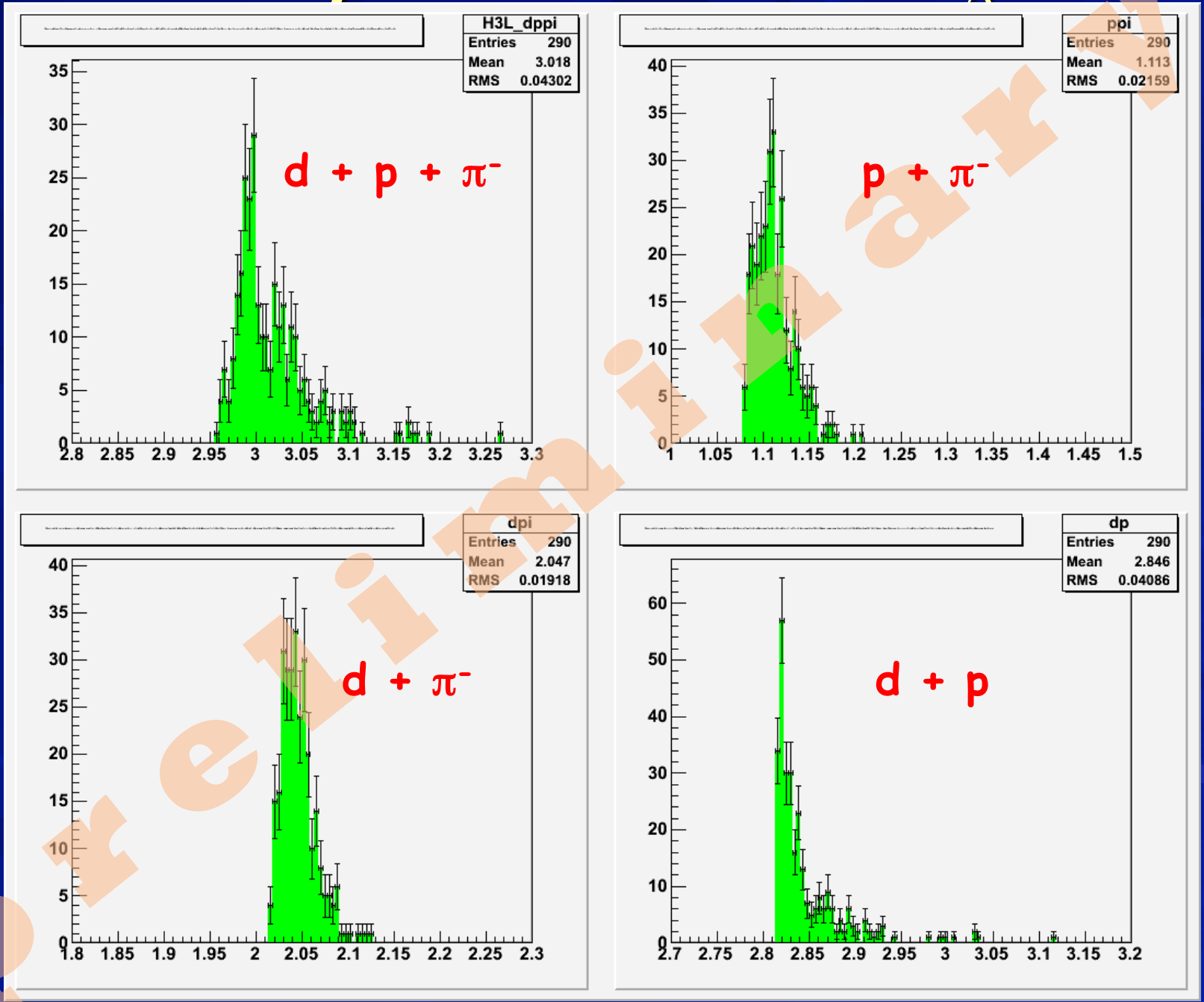




preliminary

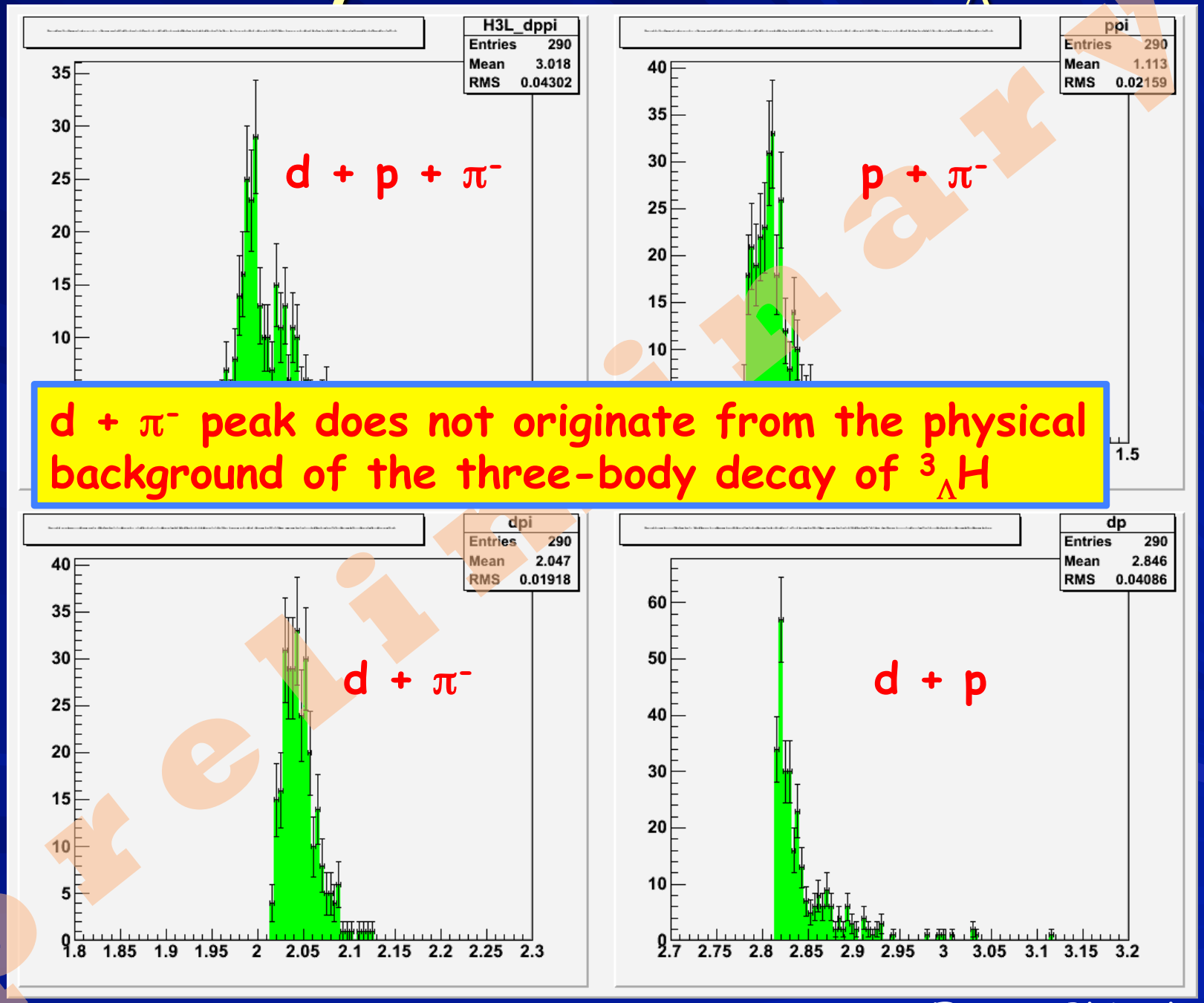
E. Kim, PhD thesis

3-body reconstruction: $^{3}_{\Lambda}H$



E. Kim, PhD thesis

3-body reconstruction: $^{3}_{\Lambda}H$

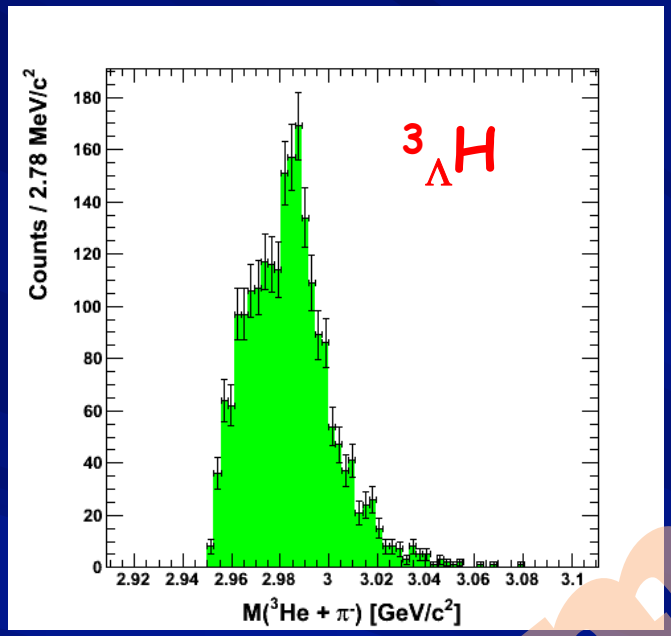


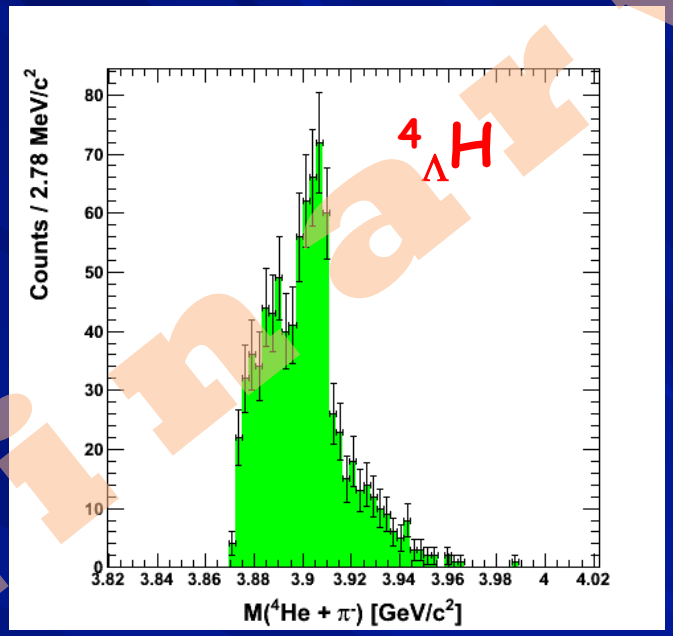
d + π^- peak does not originate from the physical background of the three-body decay of $^{3}_{\Lambda}H$

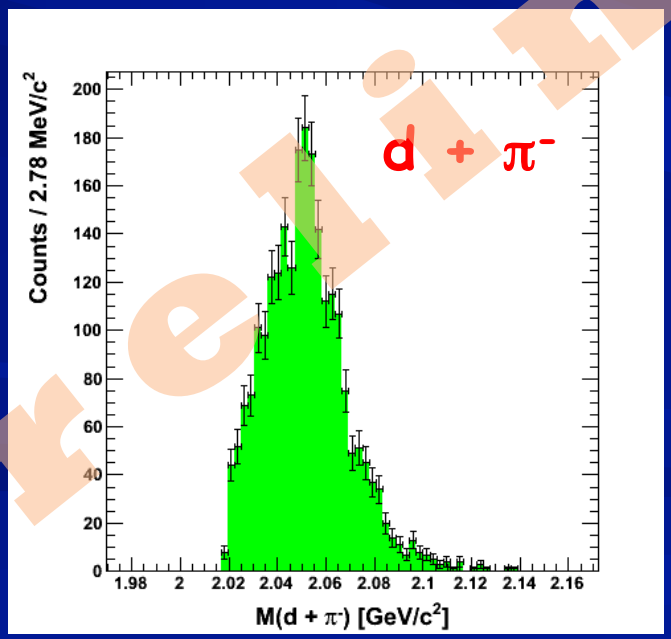
preliminary

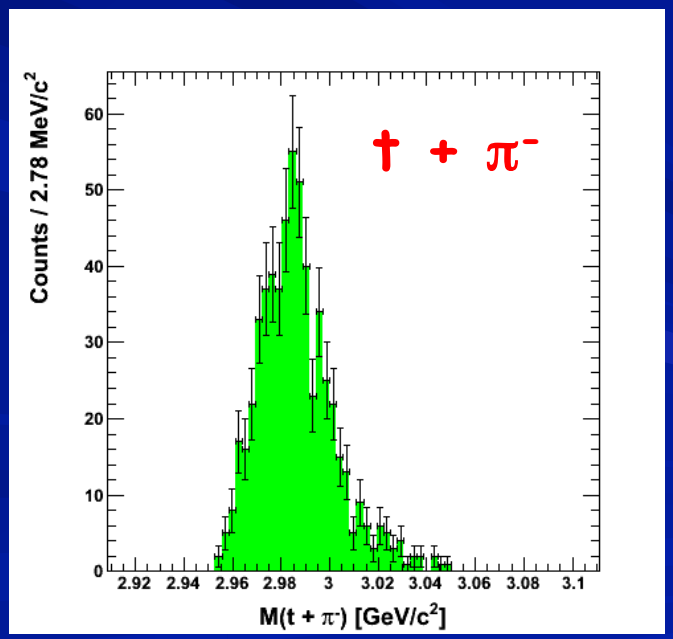
E. Kim, PhD thesis

Very recent results









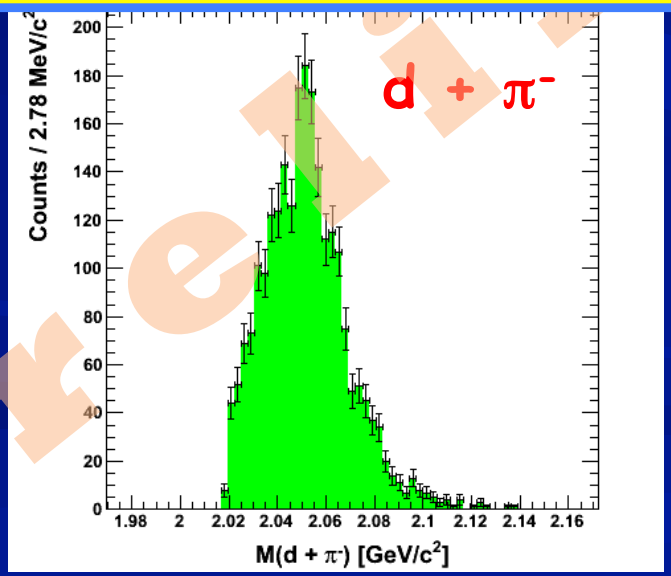
preliminary

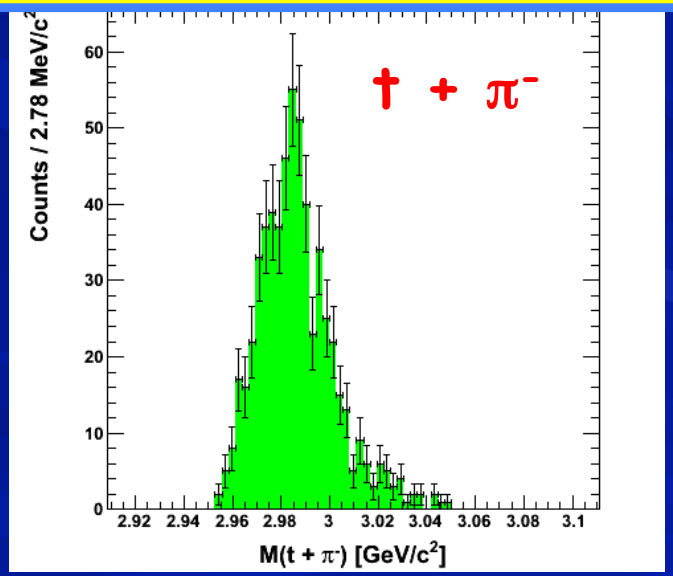
E. Kim, PhD thesis

Very recent results

Possible sources of d + π^- and t + π^- peaks

- d + π^-
  - nΛ bound state -> d + π^- ???
  - Conflicting to former studies with scattering length and structures of 3- and 4-body hypernuclei
  - nnΛ bound state -> t* + π^- -> d + n + π^- (n is missing in the measurements)
- t + π^-
  - nnΛ bound state -> t + π^- ???





E. Kim, PhD thesis

preliminary

Summary

- The HypHI project at GSI and towards FAIR
  - Hypernuclei at different isospin
  - Hypernuclear magnetic moments
- Accomplished Phase 0 and 0.5 experiments
- Demonstrated the feasibility of HypHI by observing Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$
  - Milestone of Phase 0
- Additional signal in the d + π^- and t + π^- reconstructions

- To complete analyses on Phase 0 very soon
- Analysis on Phase 0.5: ${}^{20}Ne$ + ${}^{12}C$
- Phase 1: 2014 ~

HypHI Phase 0 collaboration

- GSI Helmholtz-University Young Investigators Group VH-NG-239
  - S. Bianchin (GSI -> TRIUMF)
  - O. Borodina (Mainz Univ., GSI)
  - V. Bozkurt (Nigde Univ., GSI)
  - E. Kim (Seoul Univ., GSI)
  - D. Nakajima (Tokyo Univ., GSI)
  - B. Özel-Tashnov (GSI -> Areva)
  - C. Rappold (HIM)
  - K. Yoshida (Osaka Univ., GSI)
  - T.R. Saito (Spokes person)
- Mainz University
  - P. Achenbach, J. Pochodzalla
- GSI HP2 and Mainz University
  - D. Khaneft, Y. Ma, F. Maas
- GSI HP1
  - W. Trautmann
- GSI EE department
  - J. Hoffmann, K. Koch, N. Kurz, S. Minami, W. Ott, S. Voltz
- GSI Nuclear reaction
  - T. Aumann, C. Caeser, H. Simin
- GSI Detector Lab.
  - M. Träger, C. Schmidt
- KEK
  - T. Takahashi, Y. Sekimoto
- KVI
  - E. Guliev, M. Kavatsyuk, G.J. Tambave
- Kyoto University
  - Y. Hayashi, T. Hiraiwa, M. Moritsu, A. Okamura, T. Nagae, M. Sako, T. Sugimura
- Nigde University
  - B. Goekuezuem, Z.S. Ketenci, S. Erturk
- Osaka University
  - S. Ajimura, A. Sakaguchi
- Osaka Electro-Communication University
  - Y. Mizoi
- Seoul National University
  - H. Bhang, M. Kim, S. Kim, C.J. Yoon
- Tohoku University
  - T. Koike, H. Tamura

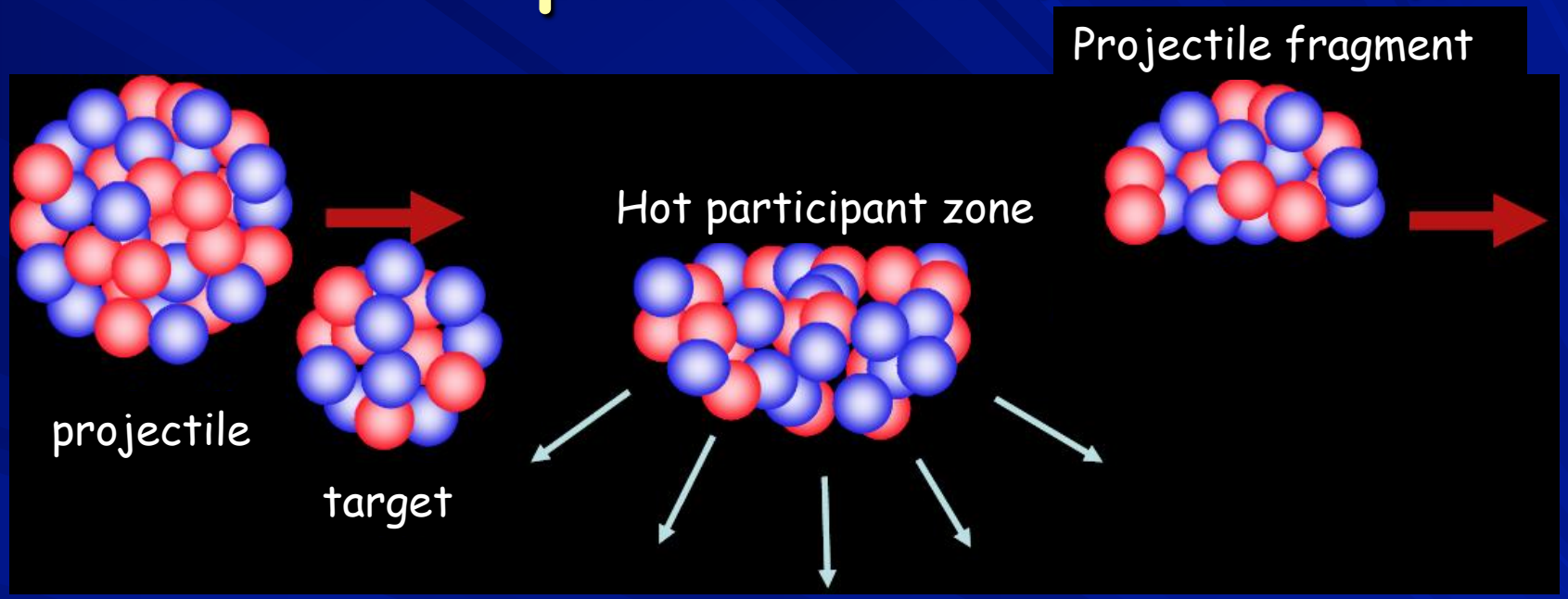
Student
Postdoc
Tenure track

Spares

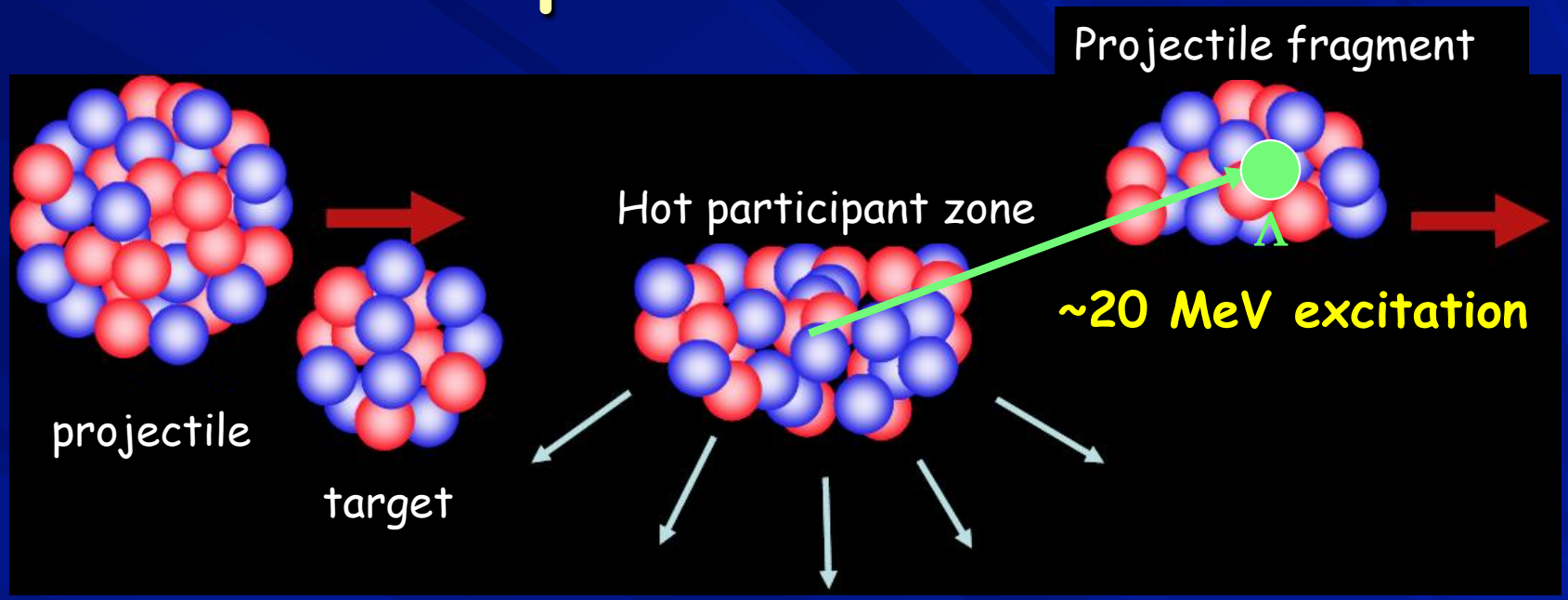
Fermi breakup of strange systems

- **A. Botvina and I. Mishustin**
- Established theory to explain results of the multi-fragmentation reactions (ALADiN experiments)
- For double-Λ hypernuclear production: PLB 696 (2011) 222

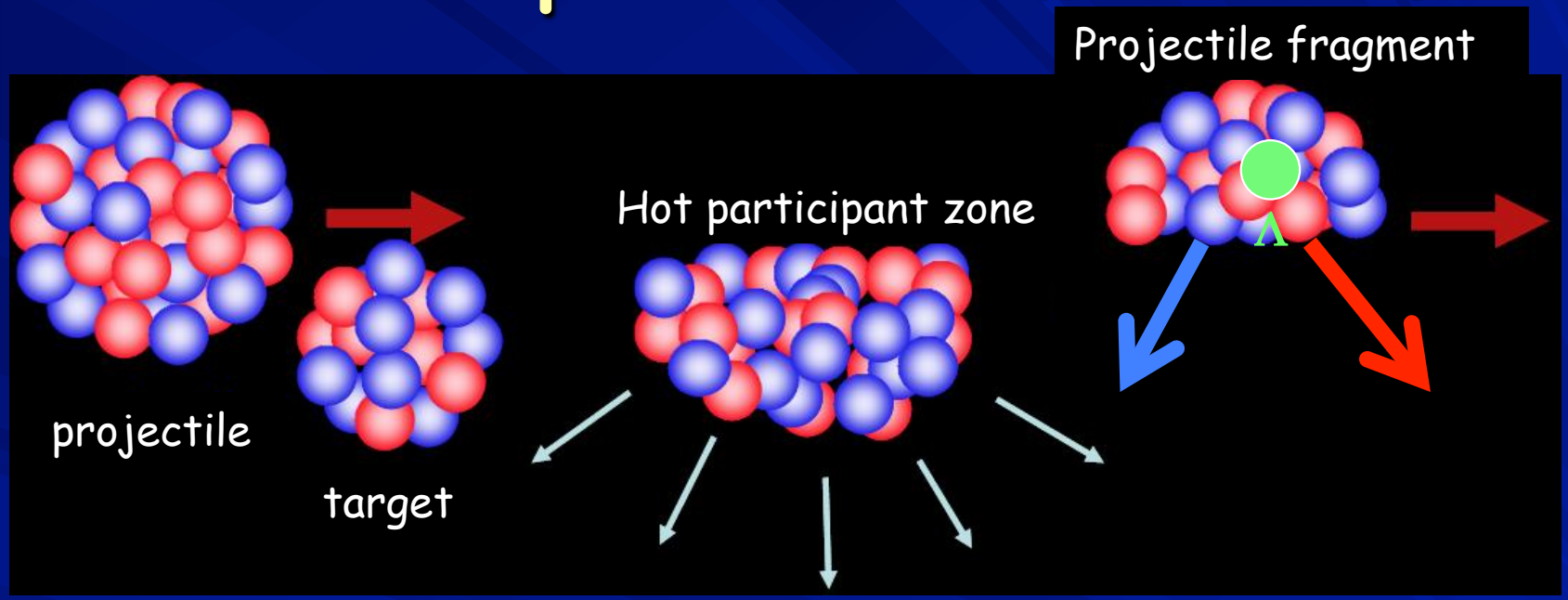
Considered production mechanism



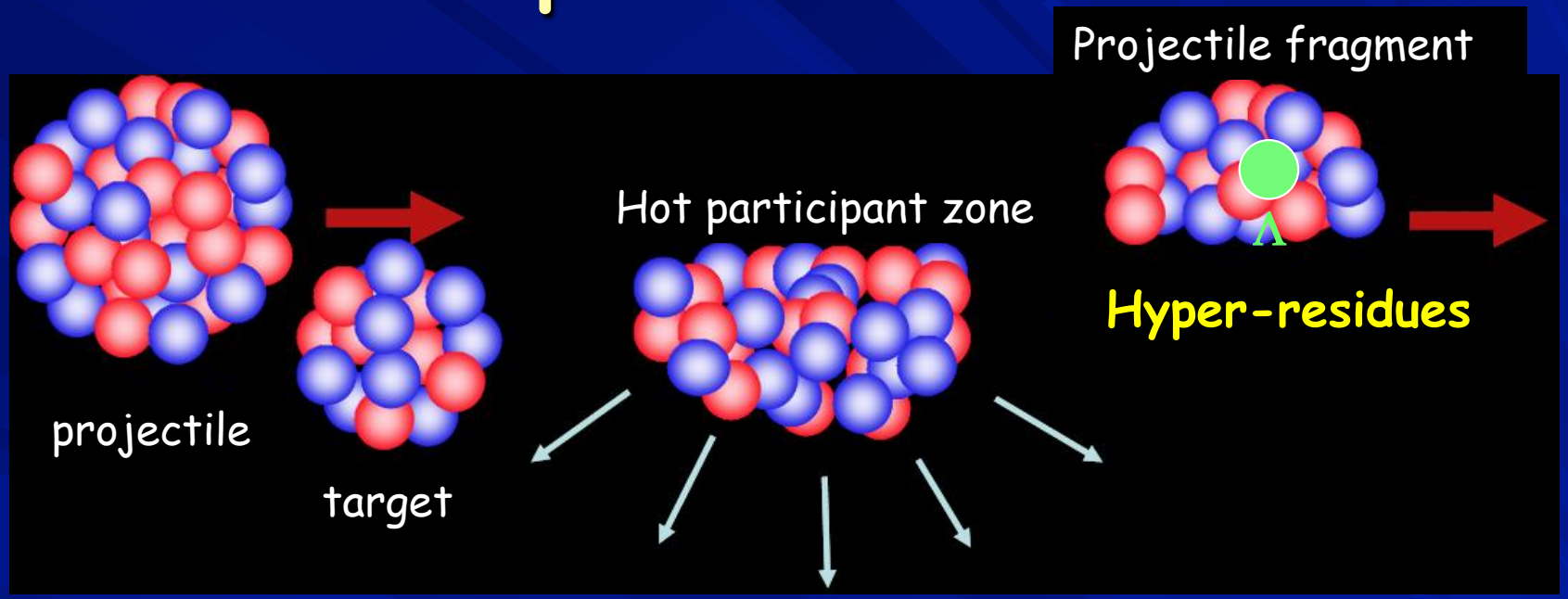
Considered production mechanism



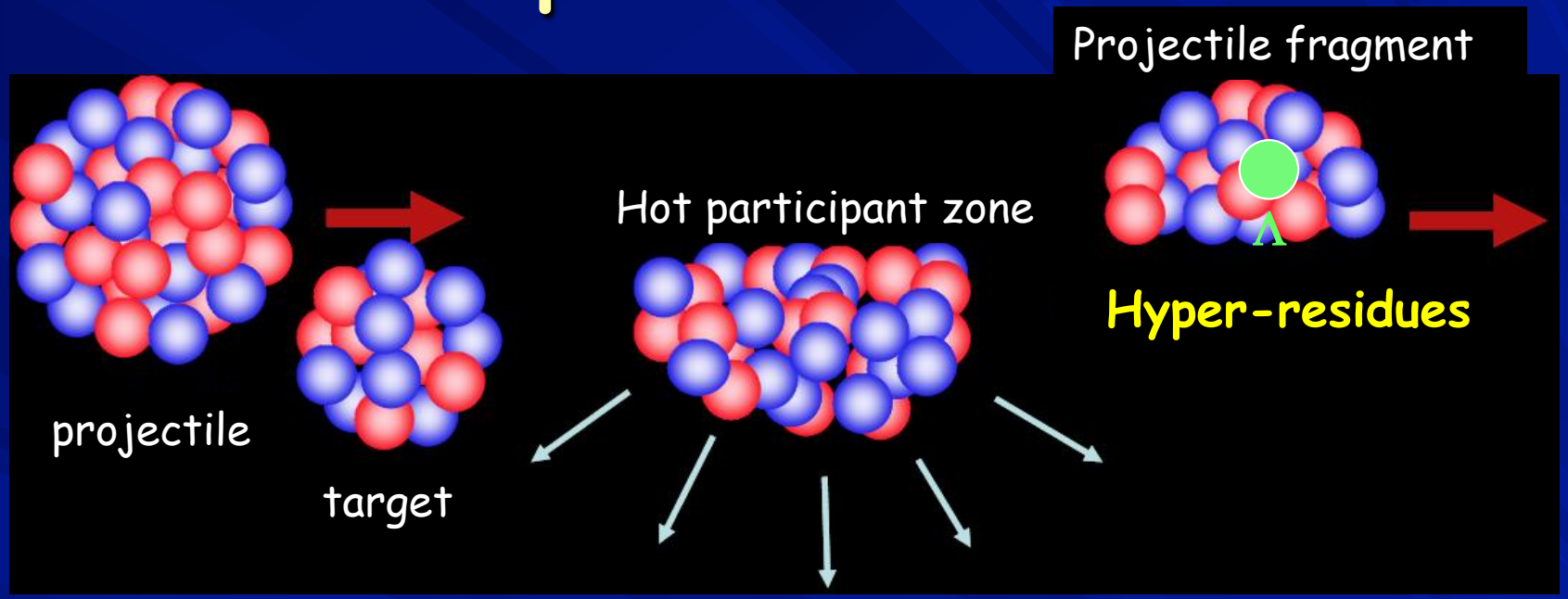
Considered production mechanism



Considered production mechanism



Considered production mechanism



Must be suppressed in the central collision

HypHI : projectile fragment
Other heavy ion experiments: central collision

Preliminary theoretical results by A. Botvina

Fermi break-up of excited light hyper-residues *5LHe, *4LH, *3LH
with production of L , Ln , Lp, Lnp, Lnnp bound nuclei

[Binding energy for Ln and Lp is 50 KeV, Spin=1]

(Eb in MeV - barrier energy for the first break-up channel)

PROBABILITIES of hypernuclei

Excit.	*5LHe (Eb=3.2)	*4LH (Eb=2.1)	*3LH (Eb=0.2)
4 MeV	L= 1.0	L= 1.0	L= 0.430
	Ln= 0.	Ln= 0.	Ln= 0.287
	Lp= 0.	Lp= 0.	Lp= 0.283
	Lnp= 0.	Lnp= 0.	Lnp= 0.
	Lnnp= 0.	Lnnp= 0.	Lnnp= 0.
8 MeV	L= 1.0	L= 1.0	L= 0.375
	Ln= 0.	Ln= 0.	Ln= 0.310
	Lp= 0.	Lp= 0.	Lp= 0.315
	Lnp= 0.	Lnp= 0.	Lnp=
	Lnnp= 0.	Lnnp= 0.	Lnnp=
12 MeV	L= 1.0	L= 0.273	L= 0.367
	Ln= 0.	Ln= 0.559	Ln= 0.320
	Lp= 0.	Lp= 0.002	Lp= 0.313
	Lnp= 0.	Lnp= 0.167	Lnp=
	Lnnp= 0.	Lnnp= 0.	Lnnp=
16 MeV	L= 1.0	L= 0.260	L= 0.377
	Ln= 0.	Ln= 0.568	Ln= 0.314
	Lp= 0.	Lp= 0.011	Lp= 0.309
	Lnp= 0.	Lnp= 0.160	Lnp=
	Lnnp= 0.	Lnnp= 0.	Lnnp=
20 MeV	L= 1.0	L= 0.259	L= 0.389
	Ln= 0.	Ln= 0.563	Ln= 0.308
	Lp= 0.	Lp= 0.026	Lp= 0.303
	Lnp= 0.	Lnp= 0.152	Lnp=
	Lnnp= 0.	Lnnp= 0.	Lnnp=
24 MeV	L= 0.201	L= 0.277	L= 0.396
	Ln= 0.131	Ln= 0.554	Ln= 0.302
	Lp= 0.206	Lp= 0.038	Lp= 0.302
	Lnp= 0.	Lnp= 0.131	Lnp=
	Lnnp= 0.236	Lnnp= 0.	Lnnp=
	Lnpp= 0.226		
28 MeV	L= 0.110	L= 0.291	L= 0.408
	Ln= 0.212	Ln= 0.539	Ln= 0.296
	Lp= 0.231	Lp= 0.052	Lp= 0.296
	Lnp= 0.087	Lnp= 0.119	Lnp=
	Lnnp= 0.176	Lnnp=	Lnnp=
	Lnpp= 0.183		
32 MeV	L= 0.128	L= 0.302	L= 0.424
	Ln= 0.201	Ln= 0.520	Ln= 0.288
	Lp= 0.207	Lp= 0.069	Lp= 0.288
	Lnp= 0.150	Lnp= 0.109	Lnp=
	Lnnp= 0.158	Lnnp= 0.	Lnnp=
	Lnpp= 0.155		
36 MeV	L= 0.158	L= 0.307	L= 0.438
	Ln= 0.210	Ln= 0.507	Ln= 0.280
	Lp= 0.209	Lp= 0.082	Lp= 0.282
	Lnp= 0.155	Lnp= 0.104	Lnp=
	Lnnp= 0.133	Lnnp= 0.	Lnnp=
	Lnpp= 0.136		
40 MeV	L= 0.186	L= 0.321	L= 0.458
	Ln= 0.210	Ln= 0.496	Ln= 0.268
	Lp= 0.221	Lp= 0.092	Lp= 0.274
	Lnp= 0.158	Lnp= 0.091	Lnp=
	Lnnp= 0.116	Lnnp= 0.	Lnnp=
	Lnpp= 0.109		

Similar results for B = 5 keV !!!!!

Calculations by Botvina

- Intermediating $^{4}_{\Lambda}H^{*}$ excited states at 20 MeV
- $B(n\Lambda)$ = 50 keV

	$^{3}_{\Lambda}H$ (d+Λ)	$^{4}_{\Lambda}H$ (t+Λ)	nΛ (n+Λ)
Normalized observed ratio	1.00	0.17	4.12
Fermi breakup	1.0	0.0	3.7

- Comparison to the relativistic heavy ion collision experiments
  - Direct coalescence of each single baryon
    - Contribution from Fermi breakup is very small
      - Production of nuclear clusters with A+1 is suppressed by 100-1000

-> Talk by A. Botvina

Trigger

1: Secondary vertex with fiber

- Vertex out of the target
  - Hypernuclear decay
  - Free-Λ decay
- **FPGA/DSP based trigger module**
- Efficiency to $^{4}_{\Lambda}H$ $\pi^{-}\alpha$ decay channel : ~ 14 %

2: π^{-} with TFW

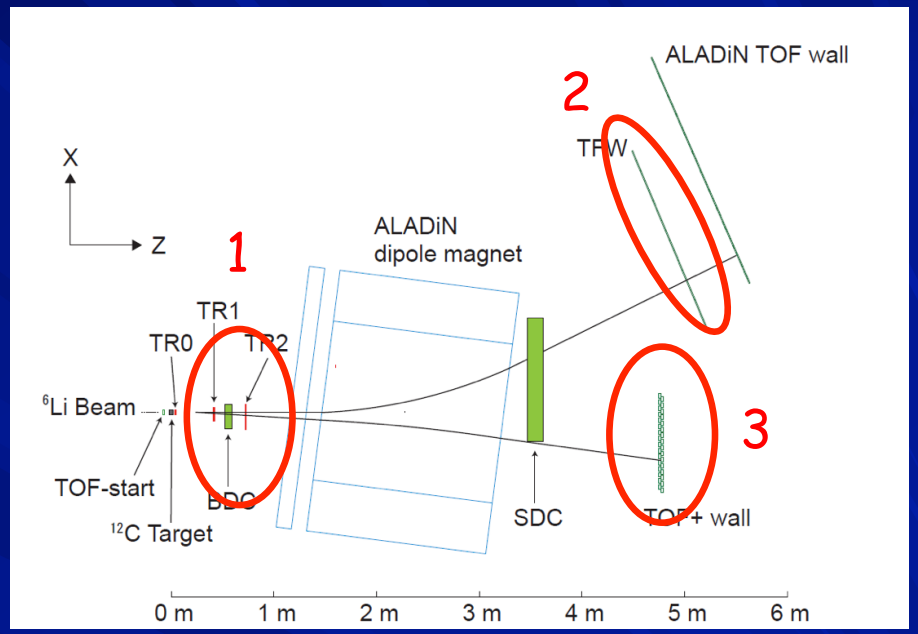
- π^{-} from hypernuclear decay
- 28 % for $^{4}_{\Lambda}H$ $\pi^{-}\alpha$ decay channel

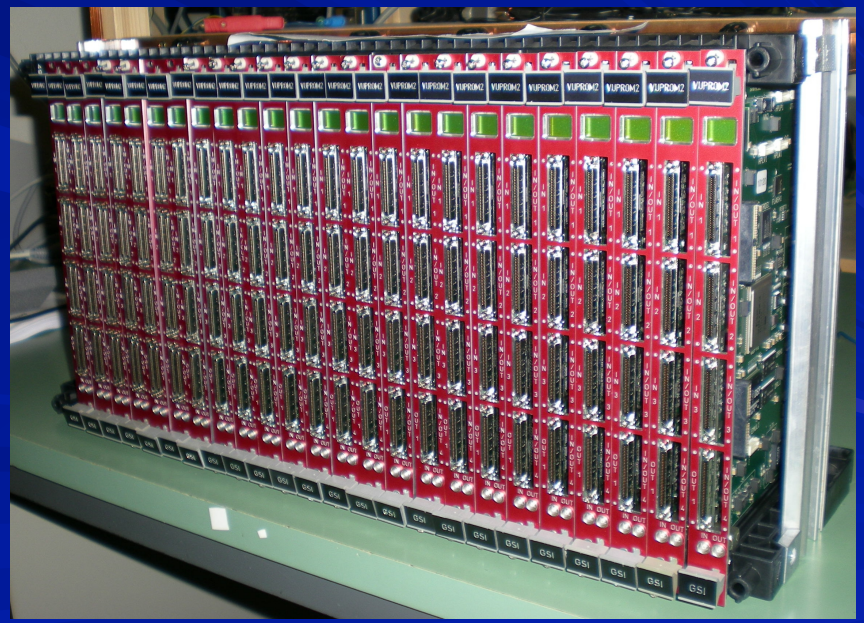
3: Fragments with TOF+

- $^{3}_{\Lambda}H$ -> **^{3}He** + π^{-}, $^{4}_{\Lambda}H$ -> **^{4}He** + π^{-}, $^{5}_{\Lambda}He$ -> **^{4}He + p** + π^{-}, $^{4}_{\Lambda}He$ -> **d + d**
- Efficiency to $^{4}_{\Lambda}H$ $\pi^{-}\alpha$ decay channel : ~ 94 %

1 & 2 & 3: Efficiency 7%

- Background reduction down to 0.017 %

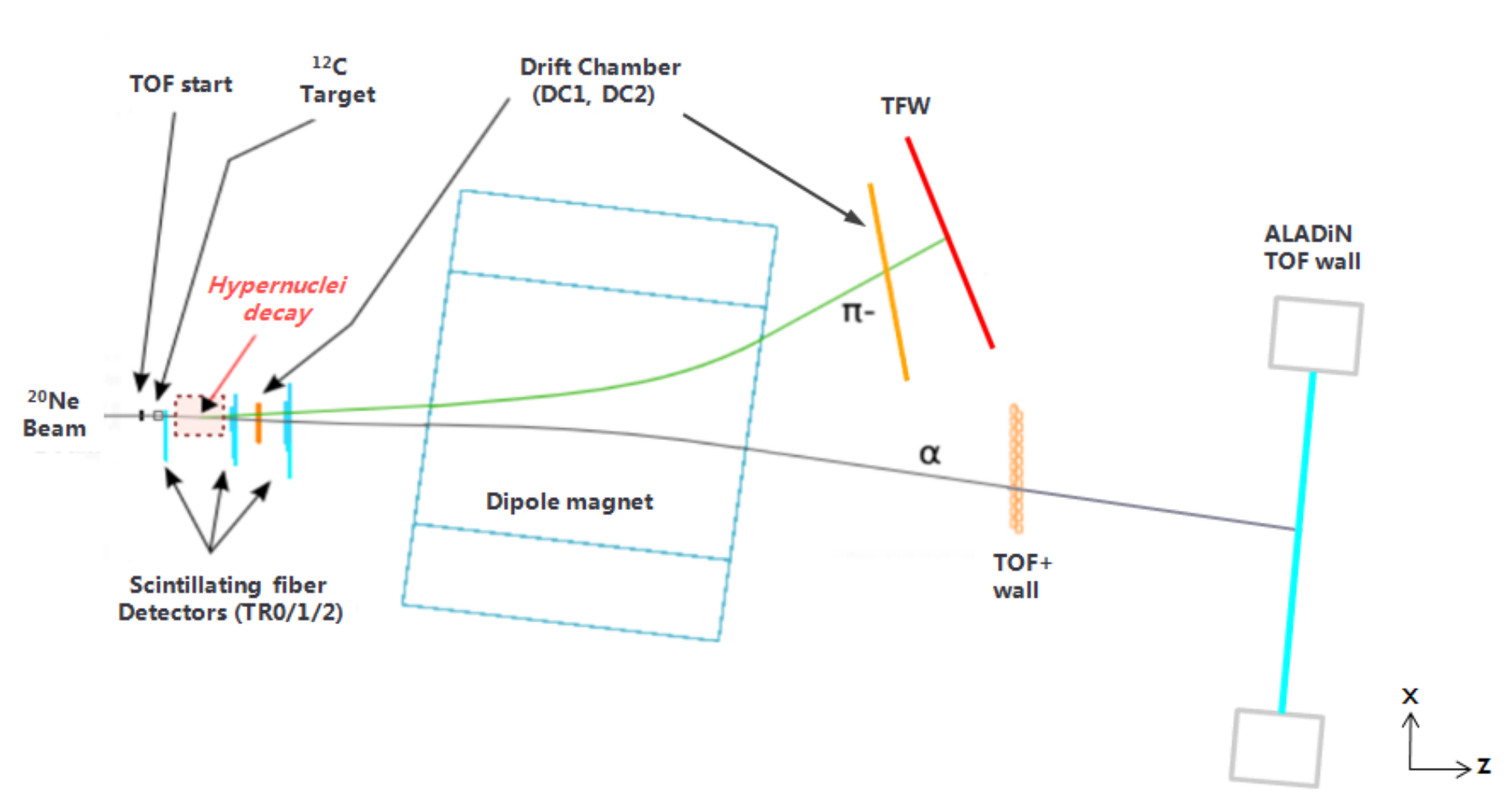




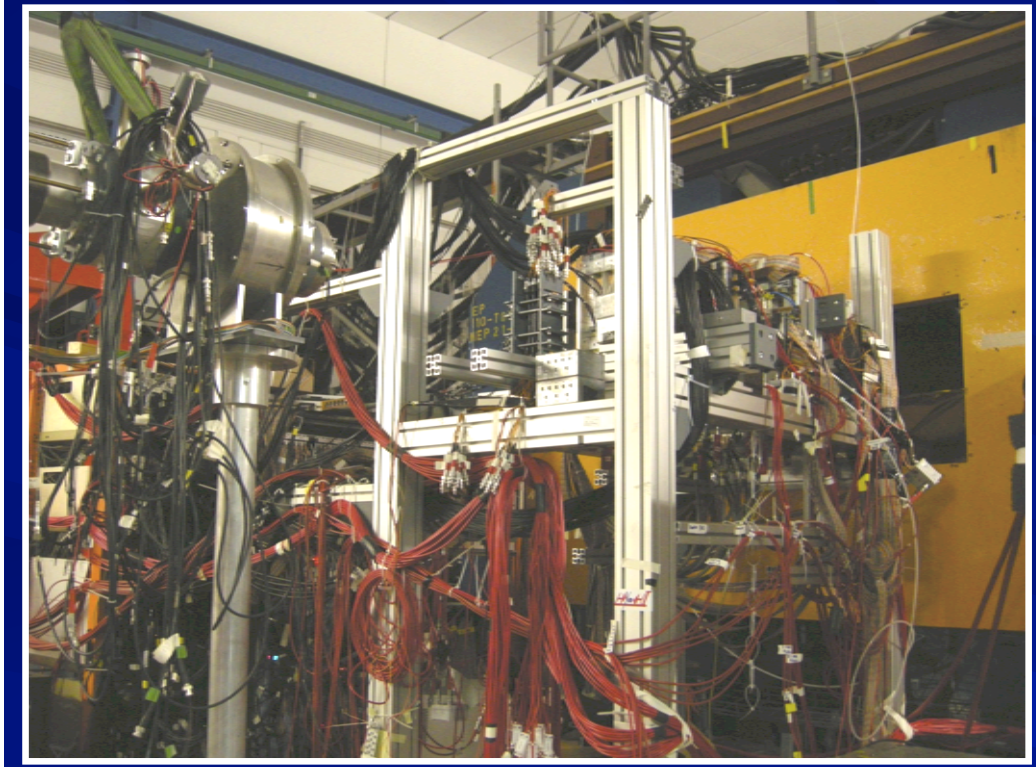
C. Rappold, PhD thesis

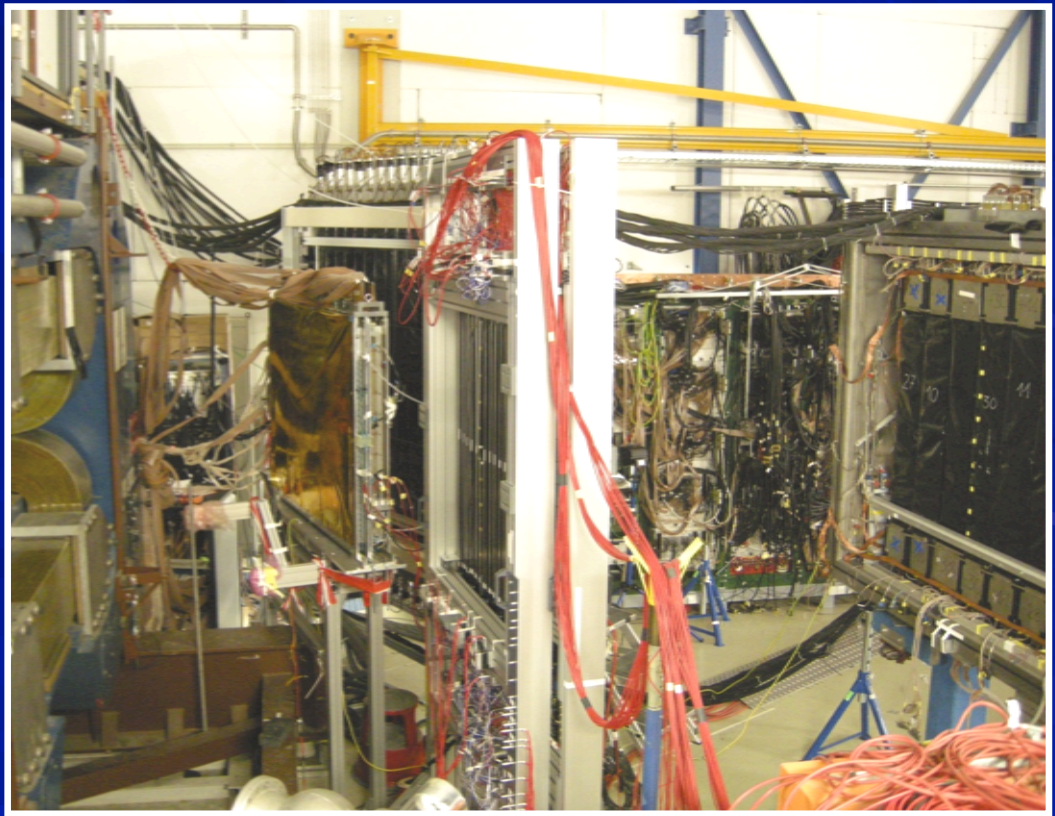
Phase 0.5 experiment in March 2010

- Hypernuclear spectroscopy with heavier projectiles: ^{20}Ne
- H and He hypernuclei
- Li, Be, B and C hypernuclei



Setup in March 2010





Physical background

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

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

  $\hookrightarrow {}^{3}He + p$

Physical background

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

- ${}^{4}_{\Lambda}He \rightarrow {}^{4}Li^{*} + \pi^{-}$ ${}^{3}_{\Lambda}H$

  ↳ ${}^{3}He + p$

Physical background

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

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

  $\hookrightarrow {}^{3}He + p$

  Λ