ASACUSA Status

Atomic Spectroscopy And Collisions Using Slow Antiprotons

124th Meeting of the SPSC
January 17, 2017

Ryugo S. Hayano, University of Tokyo
Spokesperson, ASACUSA

ASACUSA collaboration

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ASACUSA:
Atomic Spectroscopy And Collisions Using Slow Antiprotons

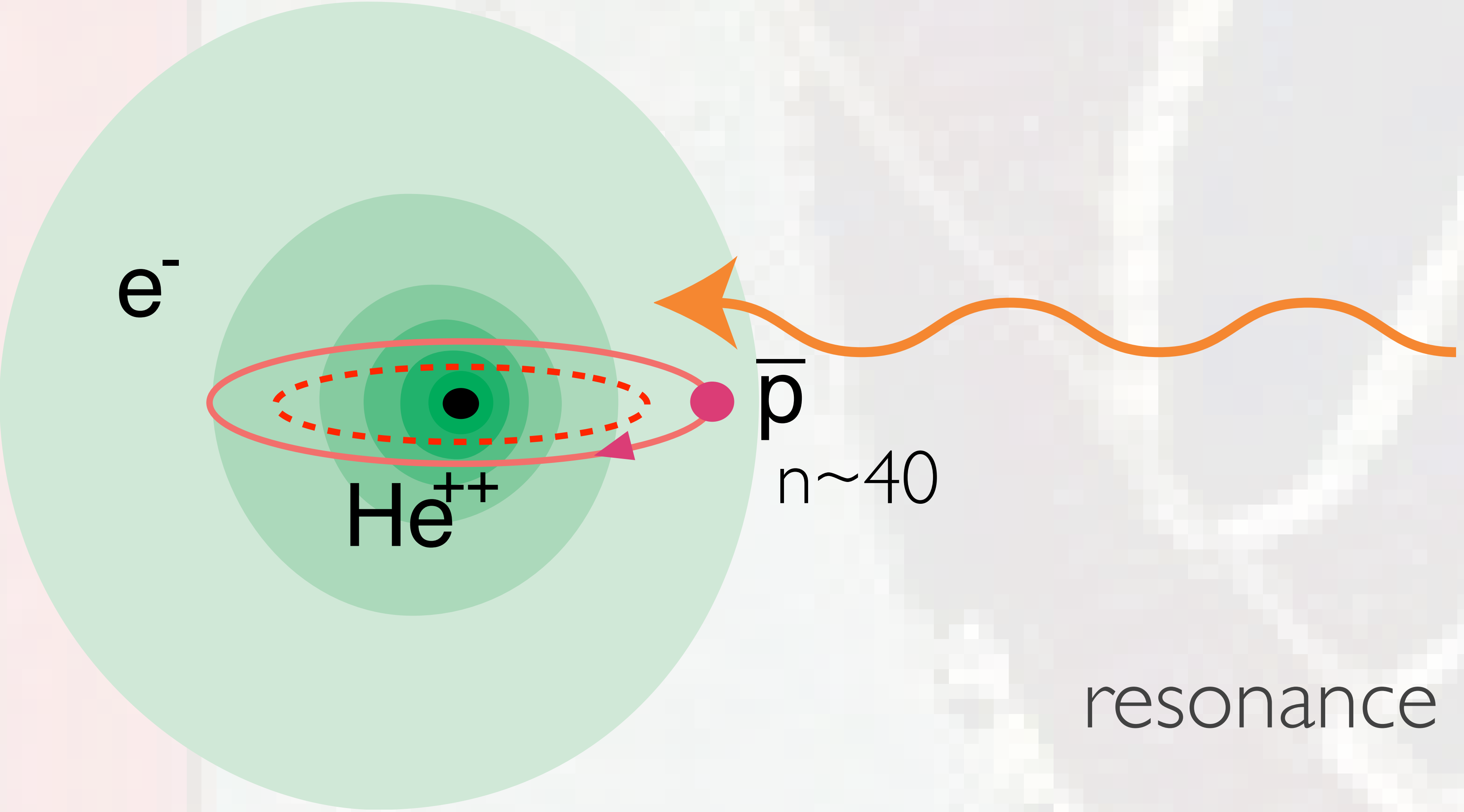
1. Antiprotonic helium ($\bar{p}$ - e^- - He) laser **spectroscopy** (CPT & fundamental const.)

2. Antihydrogen ground-state hyperfine splitting **spectroscopy** (CPT)

3. Hydrogen ground-state hyperfine splitting (closely related to 2.)

4. $\bar{p}$-nucleus **collision** (annihilation cross section σ_{ann}) (no beam used in 2016)

1. Antiproton-to-electron mass ratio



laser pulse changes the $\bar{p}$ orbit

resonance detection via $\bar{p}$ annihilation

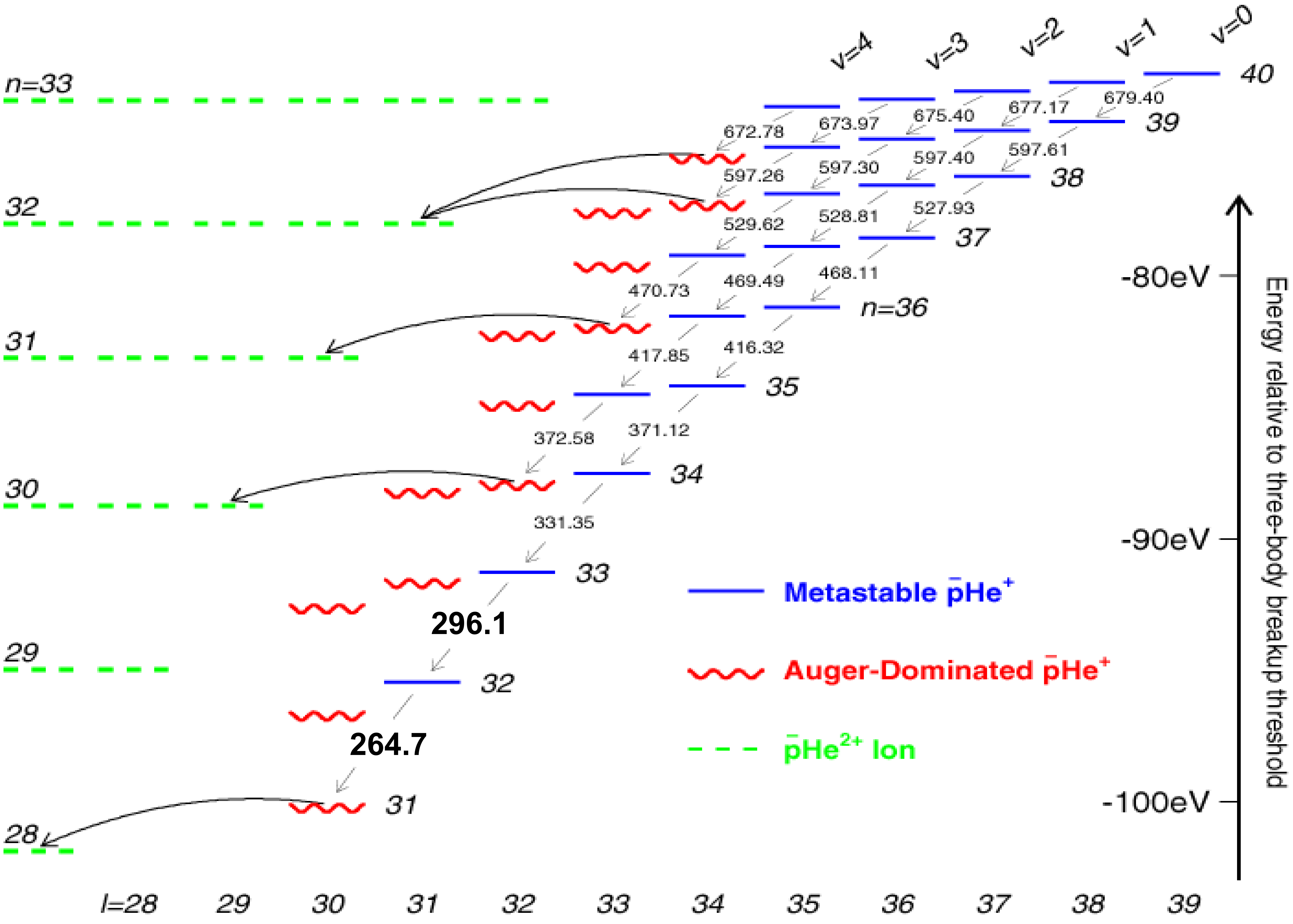
Frequency

$$\nu_{n,\ell\to n',\ell'} = Rc\frac{m^*_{\bar{p}}}{m_e} Z^2_{\mathrm{eff}}\left(\frac{1}{n'^2}-\frac{1}{n^2}\right)$$

+QED

$\bar{p}$ (p) - e mass ratio

Theory



v=4
v=3
v=2
v=1
v=0
n=33
32
31
30
29
28
40
39
38
37
n=36
35
34
33
32
31
679.40
677.17
675.40
673.97
672.78
597.61
597.40
597.30
597.26
527.93
528.81
529.62
468.11
469.49
470.73
416.32
417.85
371.12
372.58
331.35
296.1
264.7
-80eV
-90eV
-100eV
Energy relative to three-body breakup threshold
Metastable p̄He⁺
Auger-Dominated p̄He⁺
p̄He²⁺ Ion
l=28
29
30
31
32
33
34
35
36
37
38
39

Single-photon experiments

(Doppler width reduced by cooling the atoms to ~1.5K) antiprotonic helium

Science 04 Nov 2016:
Vol. 354, Issue 6312, pp. 610-614
DOI: 10.1126/science.aaf6702

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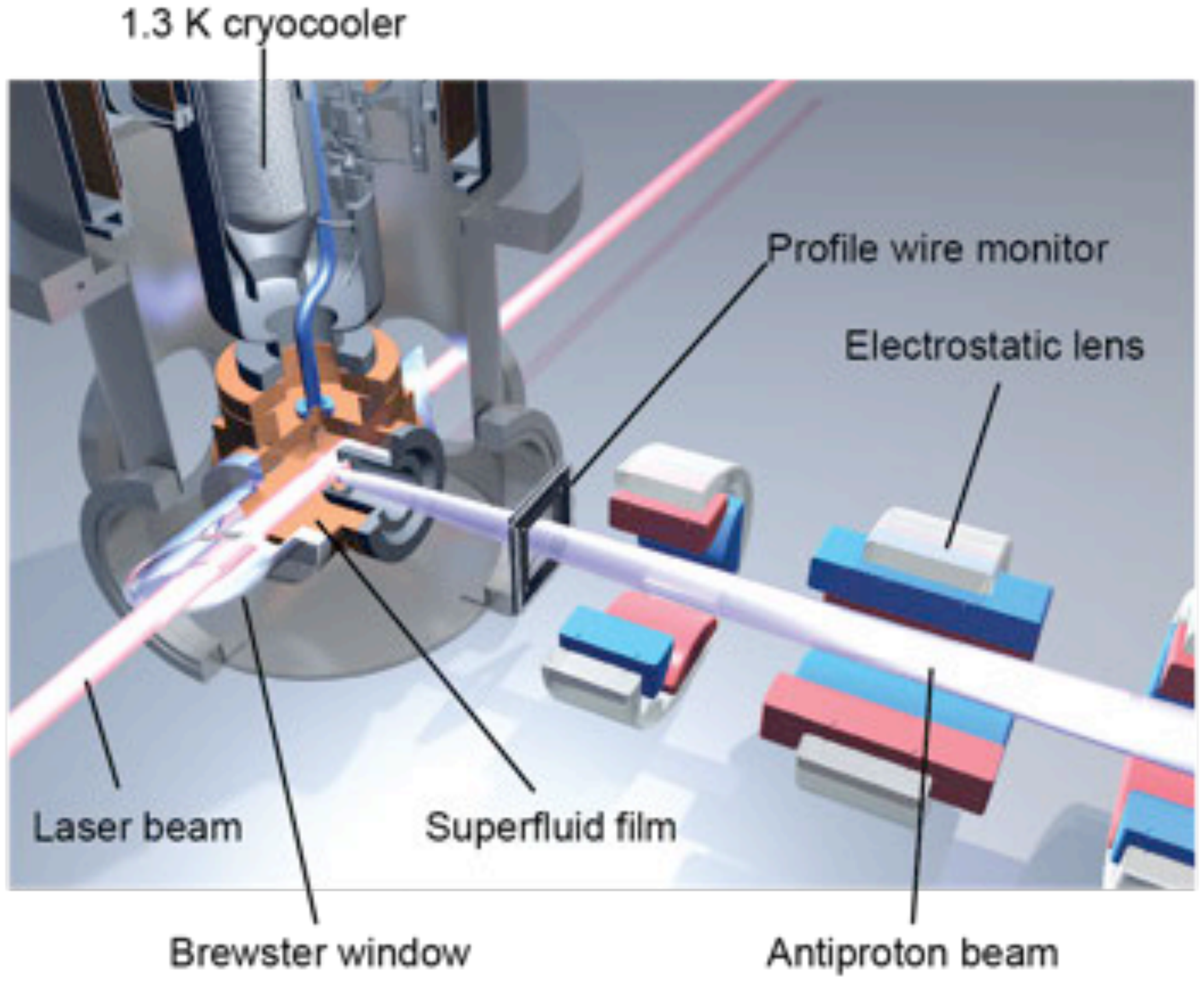
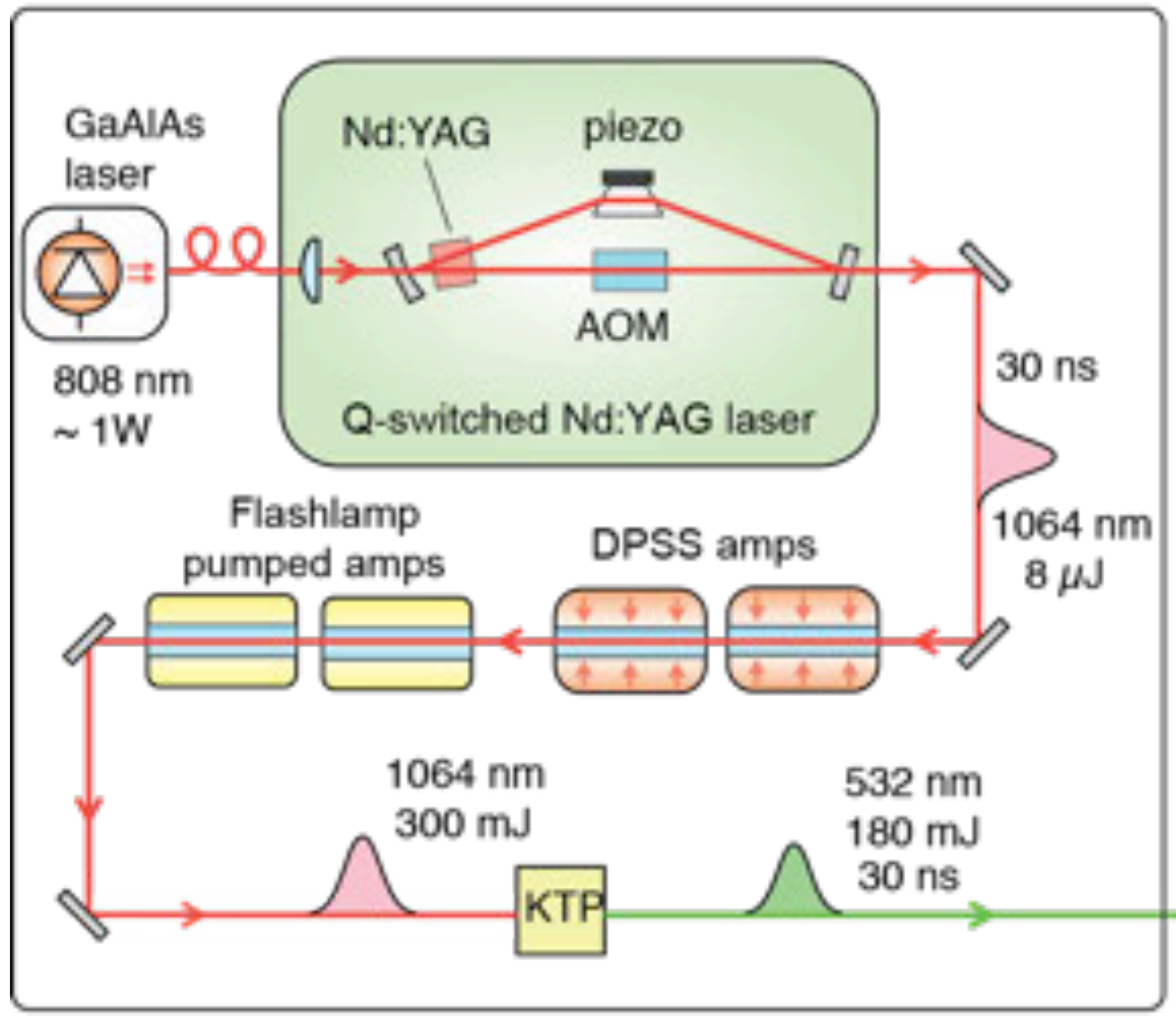
REPORT | PHYSICS

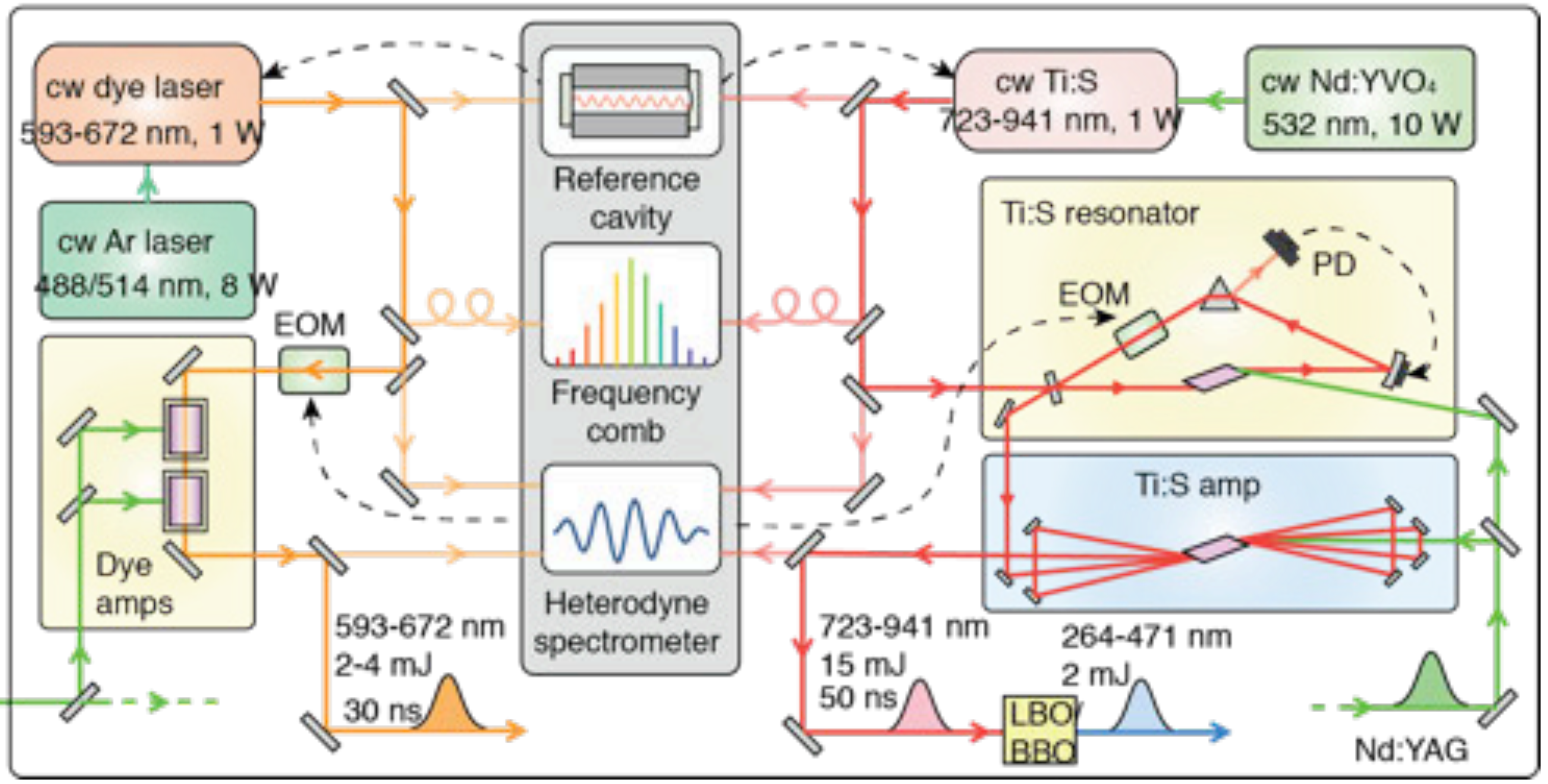
Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to–electron mass ratio

Masaki Hori[1,*], Hossein Aghai-Khozani[1], Anna Sótér[1], Daniel Barna[2], Andreas Dax[3,†], Ryugo Hayano[3], Takumi Kobayashi[3,‡], Yohei Murakami[3], Koichi Todoroki[3,§], Hiroyuki Yamada[3], Dezső Horváth[2,4], Luca Venturelli[5]

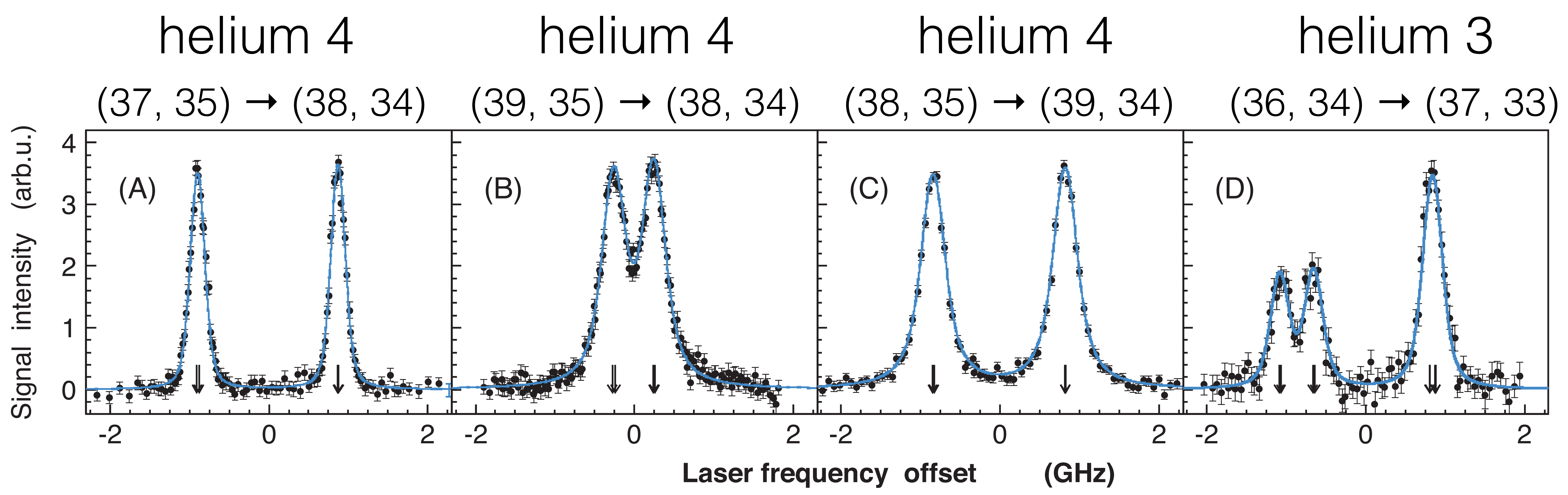
Experimental setup





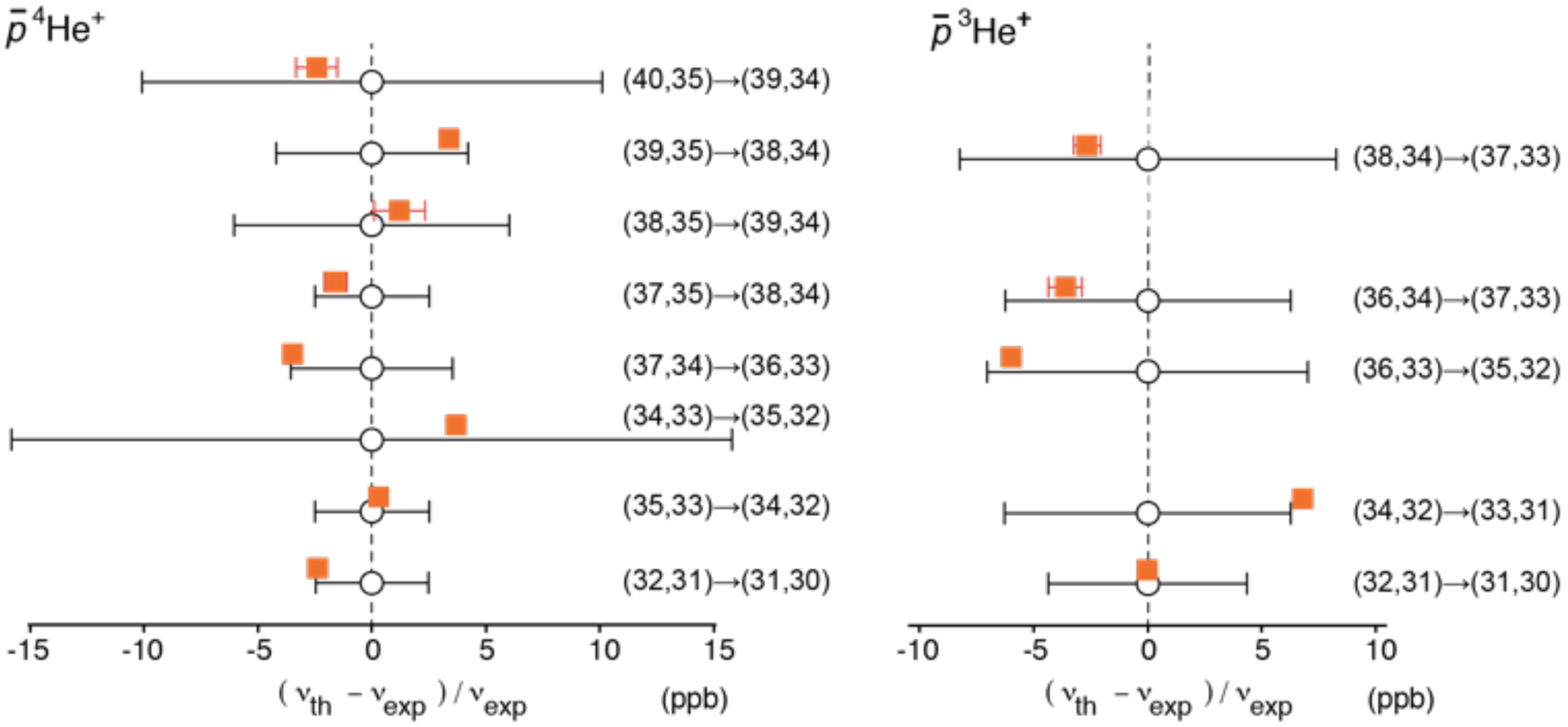


Single-photon resonances of cooled antiprotonic helium



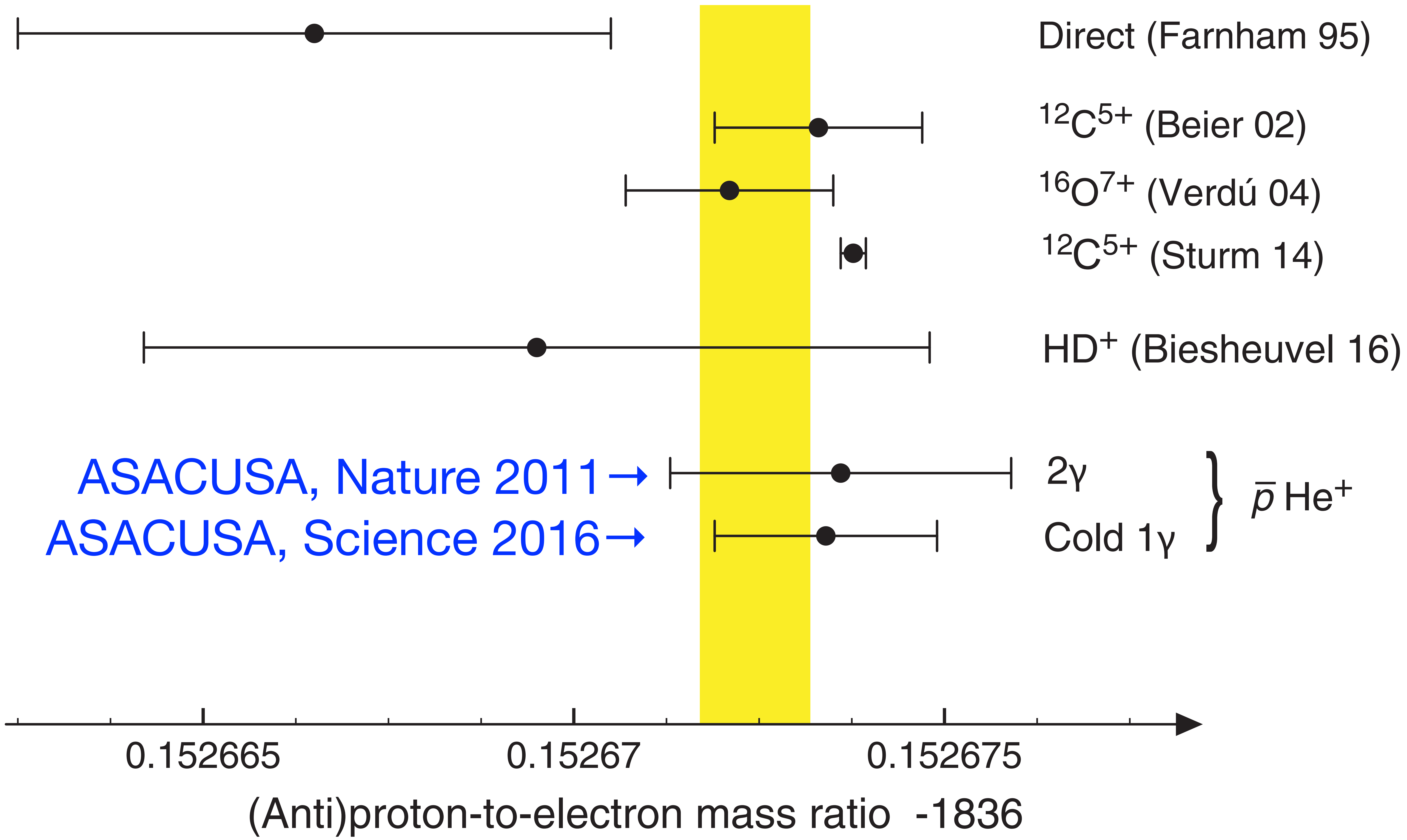
Resonance lines imply Doppler width consistent with atoms cooled to T=1.5-1.7 K…

Comparison between experimental and theoretical transition frequencies of 13 single-photon resonances



Science 354, 610 (2016)

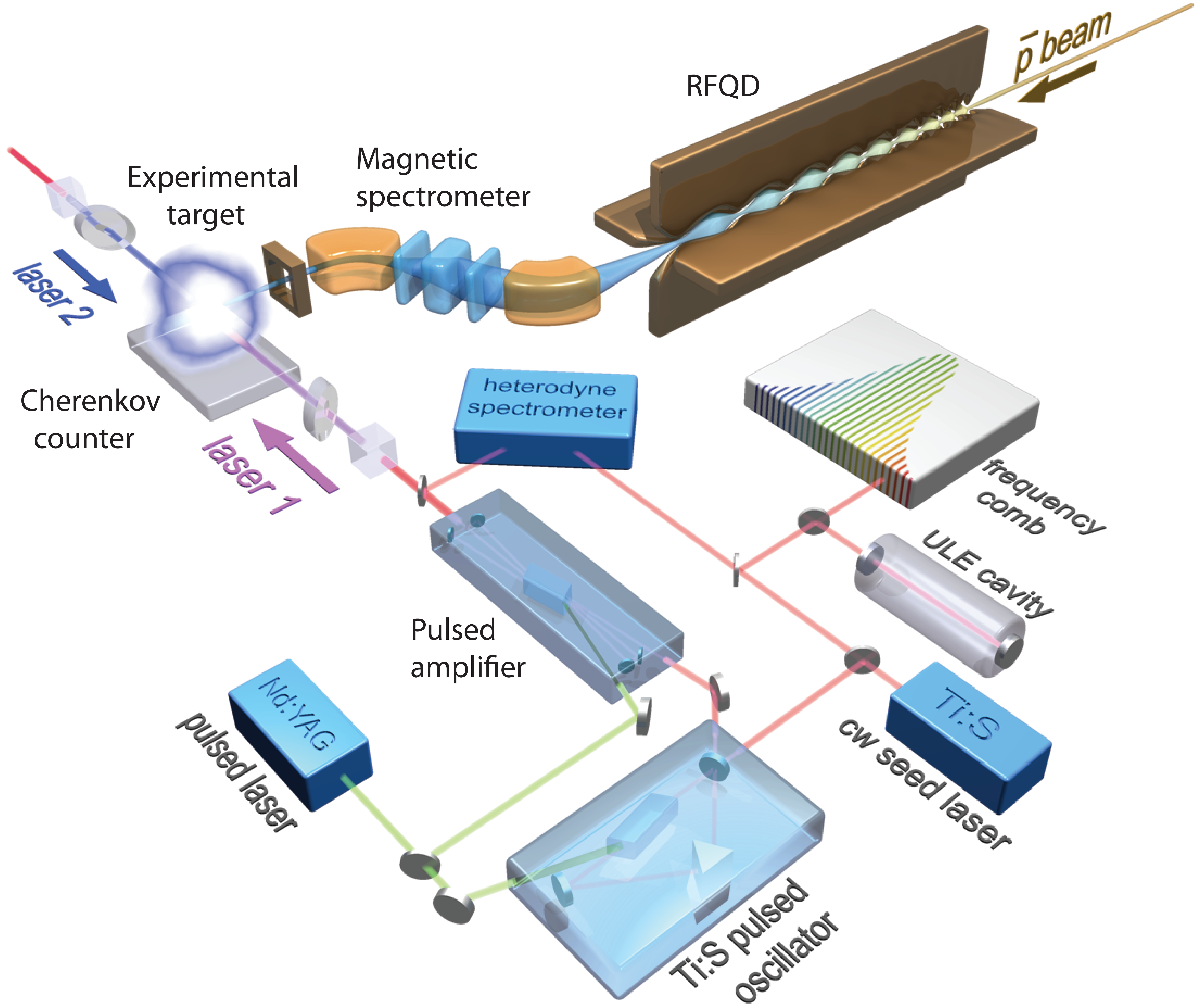
Single-photon resonance (Final result)



Antiproton-to-electron mass ratio 1836.1526734 (15)

two-photon experiments

(Doppler width further reduced by using counter-propagating beams)


p̄ beam
RFQD
Magnetic spectrometer
Experimental target
laser 2
Cherenkov counter
laser 1
heterodyne spectrometer
frequency comb
ULE cavity
Pulsed amplifier
Nd:YAG
pulsed laser
Ti:S
cw seed laser
Ti:S pulsed oscillator

Beam usage 2016

Weeks 1-2.5 (1.5 week): Continued switchover from CUSP, setup, cooldown
Beam tuning, RFQD energy tuning, laser optimization
Careful work to avoid accidents like 2015.

Weeks 2.5-4.5 (2 weeks):
Single-photon resonance, debugging.
Two-photon signal tuning (optimization of laser energy)
Old wavelength meter CCD failure, new wavelength meter
had calibration issue, took time to debug

Breakdown of Infinity Nd:YAG pump laser
Coherent doesn't support laser.
Guy in US still fixes the laser and had spare parts.
Flew to Texas to get new pump crystal.

Weeks 4.5 - 7 (3.5 weeks)
Accumulated **18 days** of publishable data
High voltage electrostatic lens cable issue.

Week 7 -7.5 (0.5 weeks) Discovered new resonance 3He
(39,35)->(40,34) 1168 nm

Improvements 2016

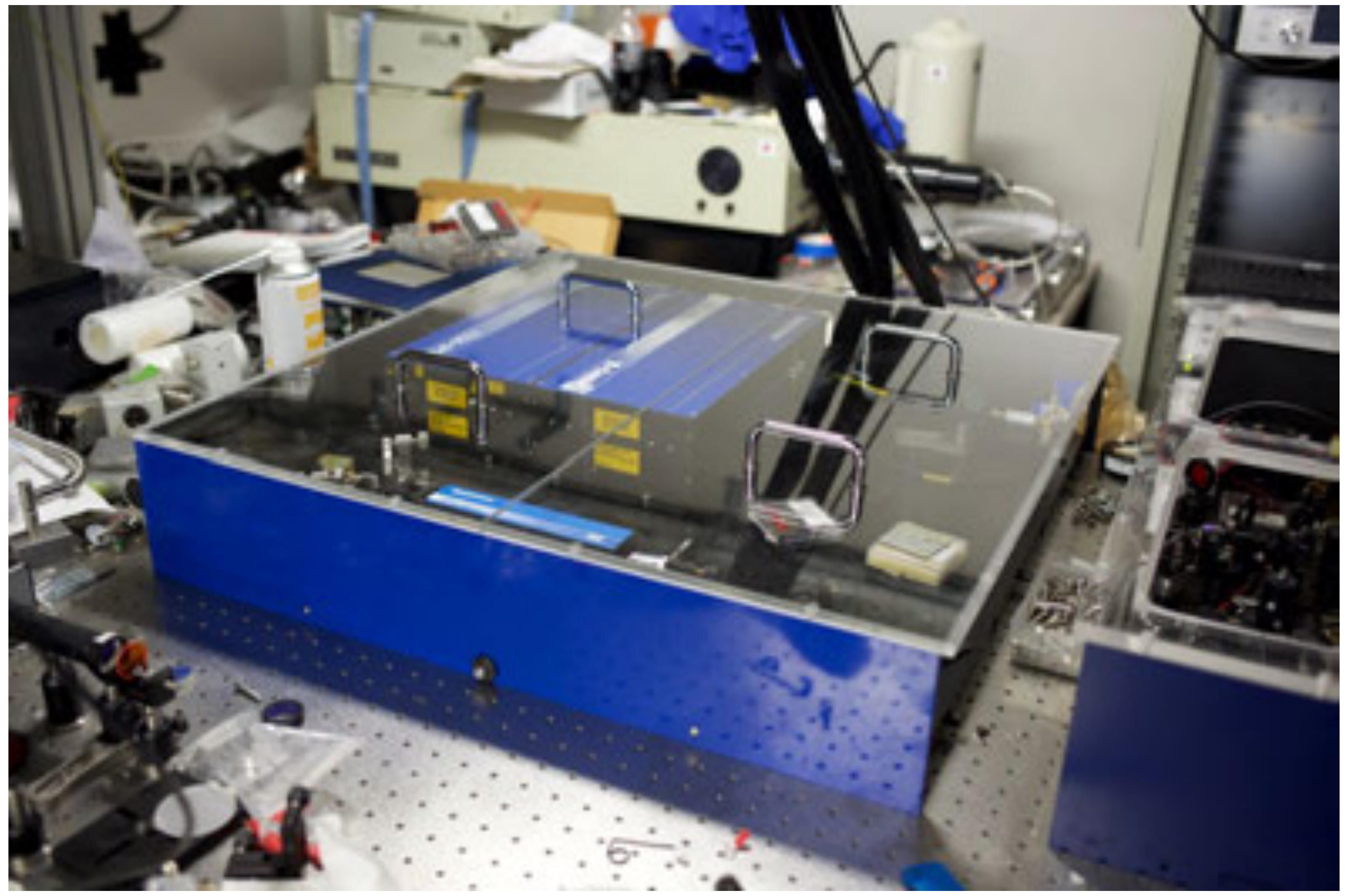


Figure-9 femtosecond resonator
90 mW visible output power

New Er fiber frequency comb

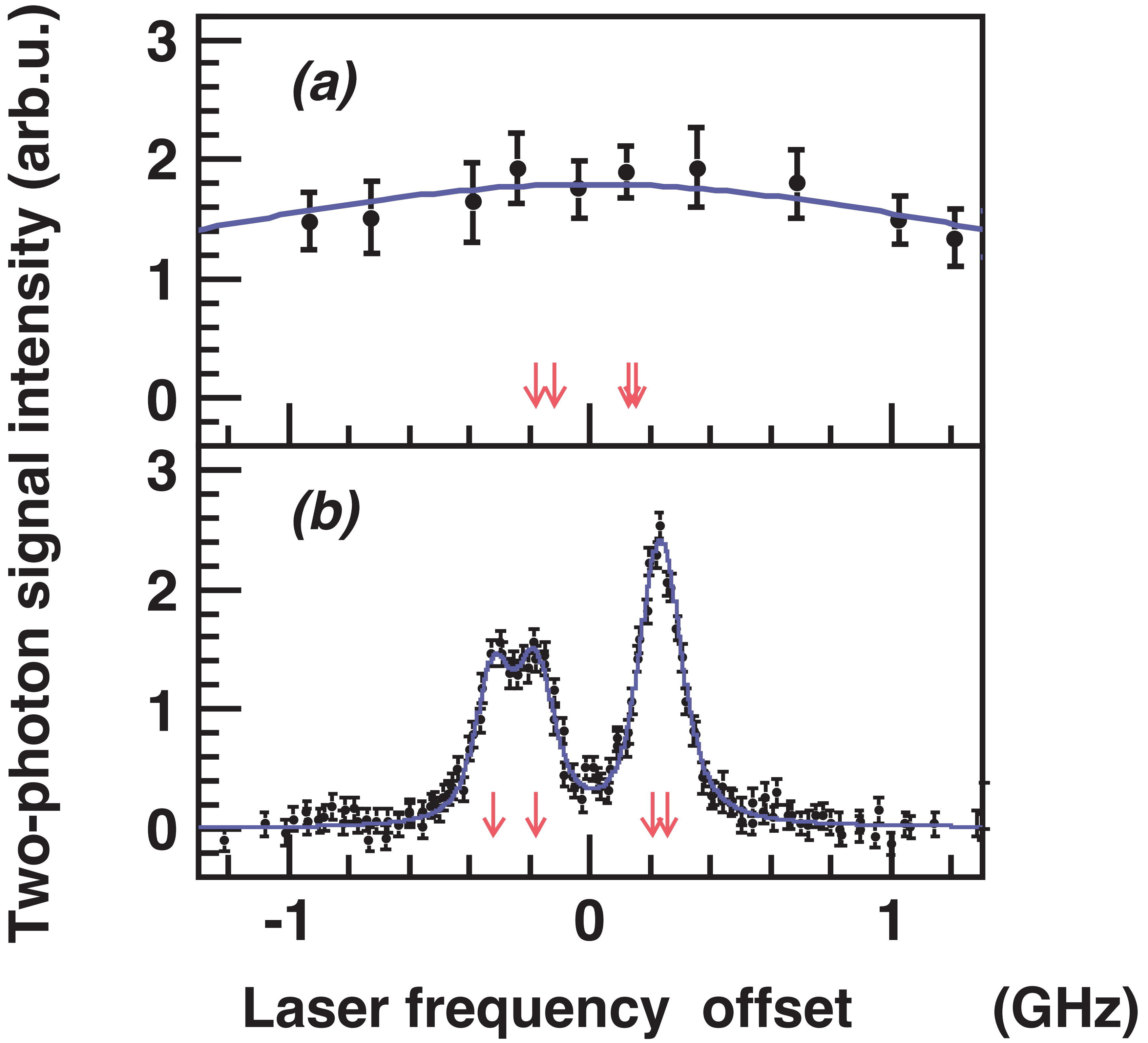
New large-memory capacity oscilloscope

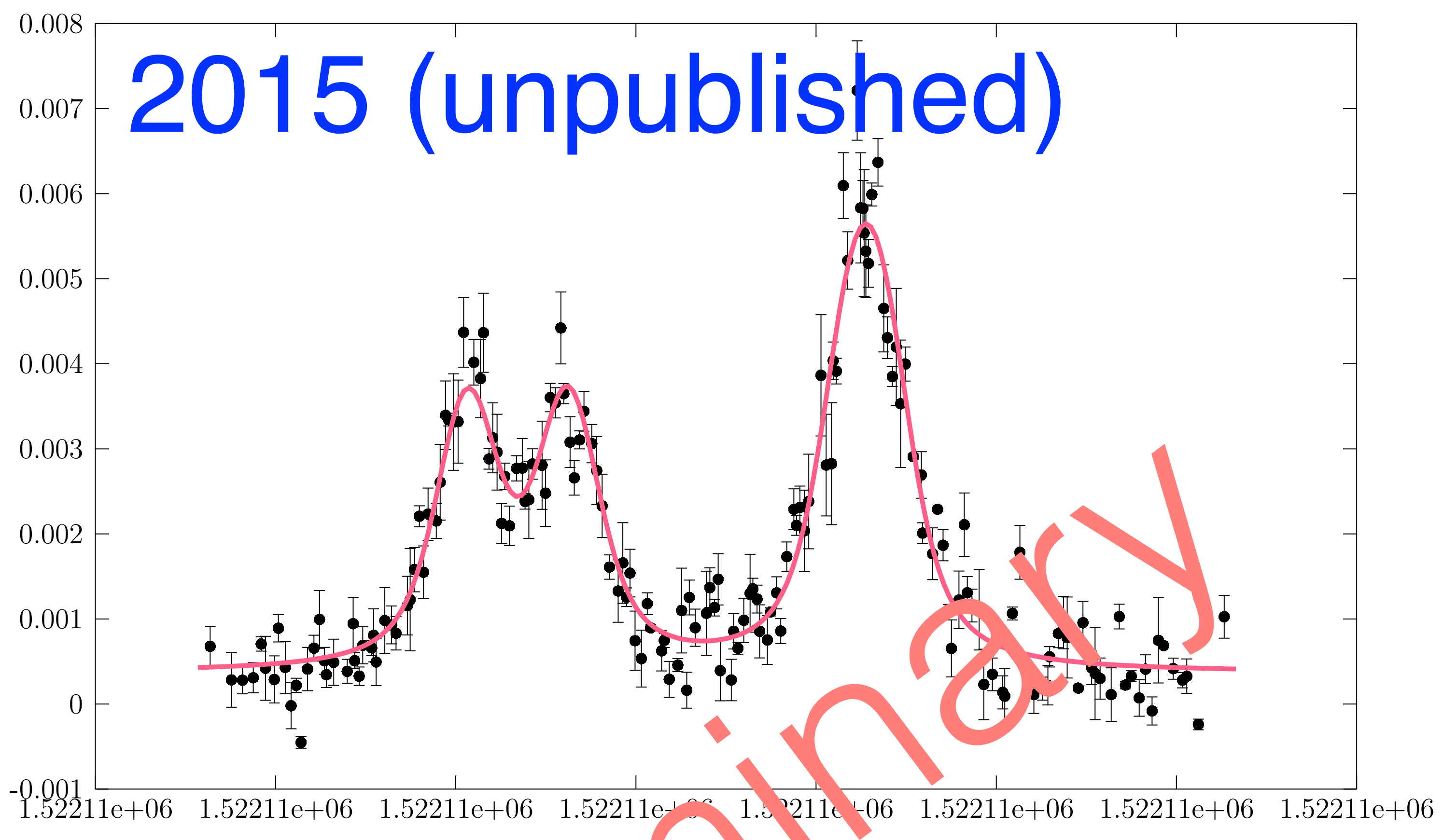
Improved pump laser (refurbished)

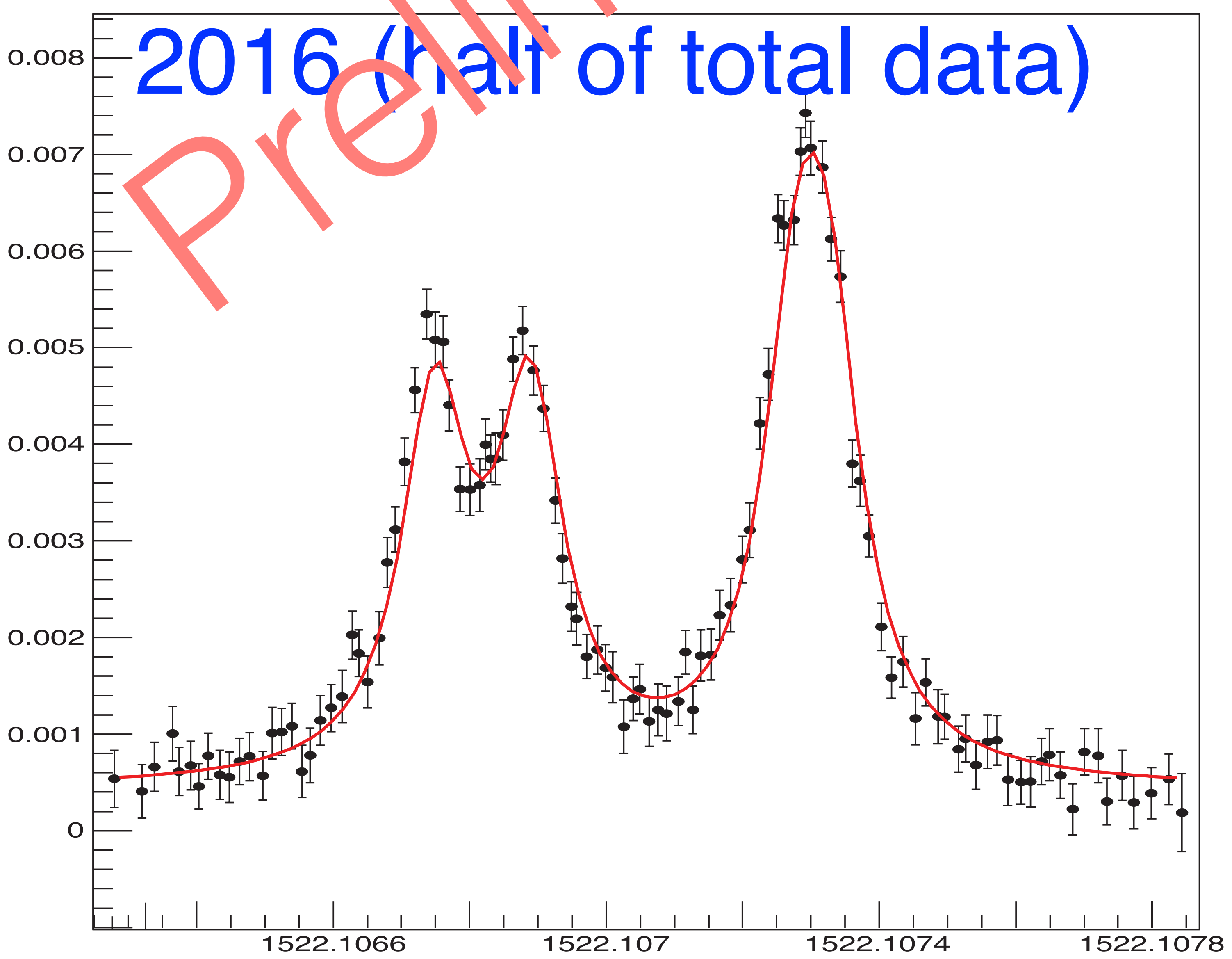
Fixed entrance window

New cryogenic brewster window

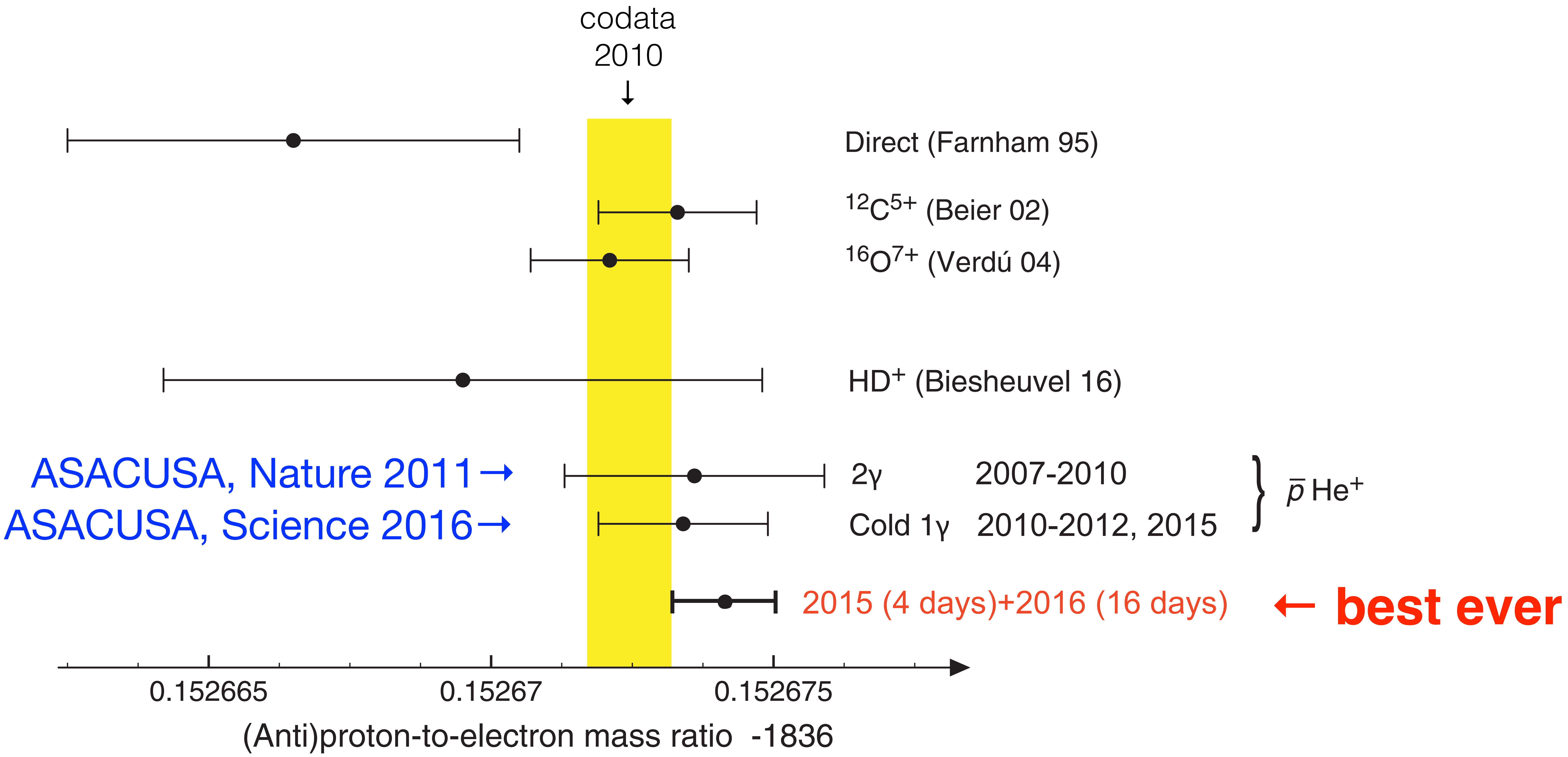
Two-photon resonance 4He (36,34)->(34,32)





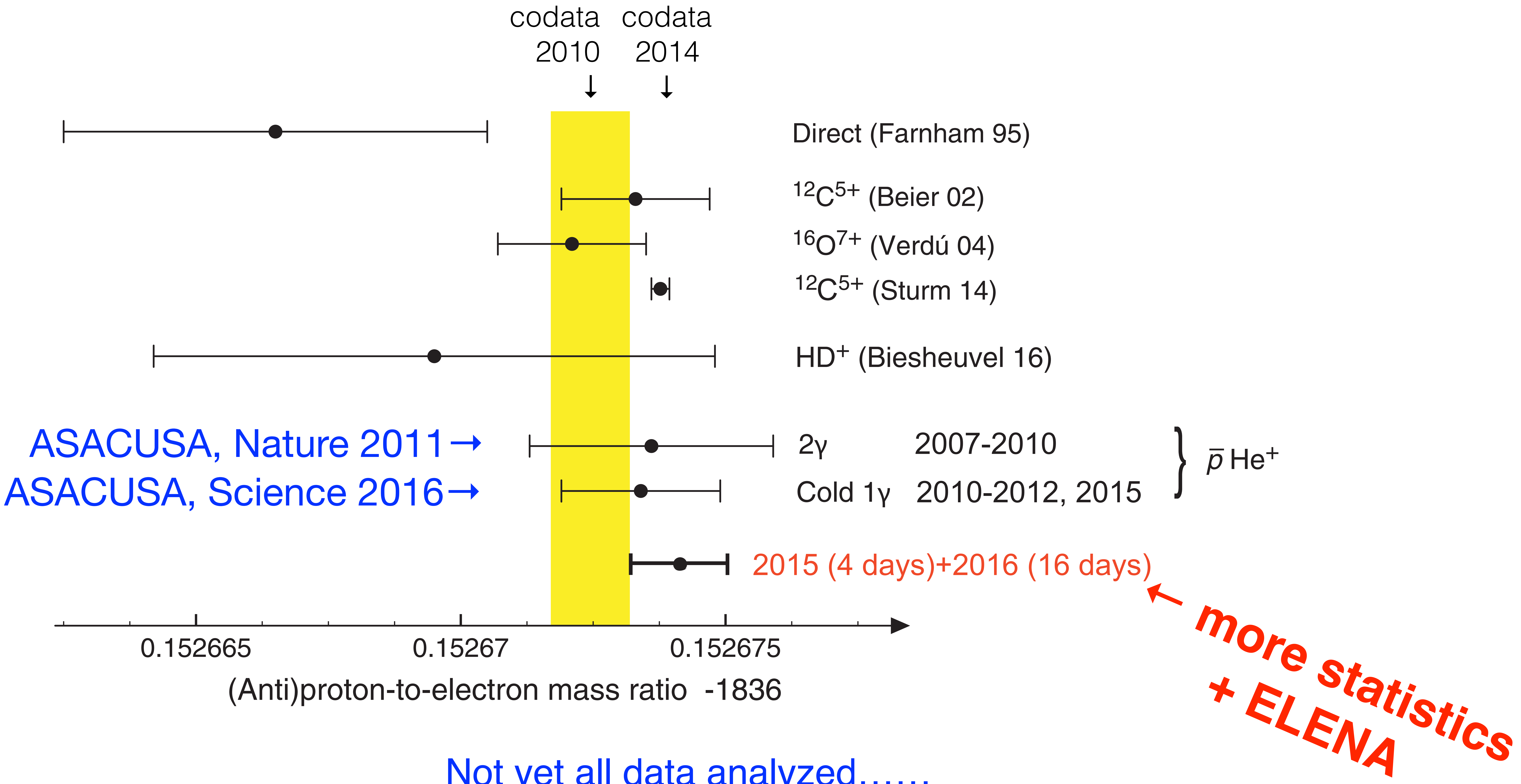


2015+2016 **VERY** preliminary result



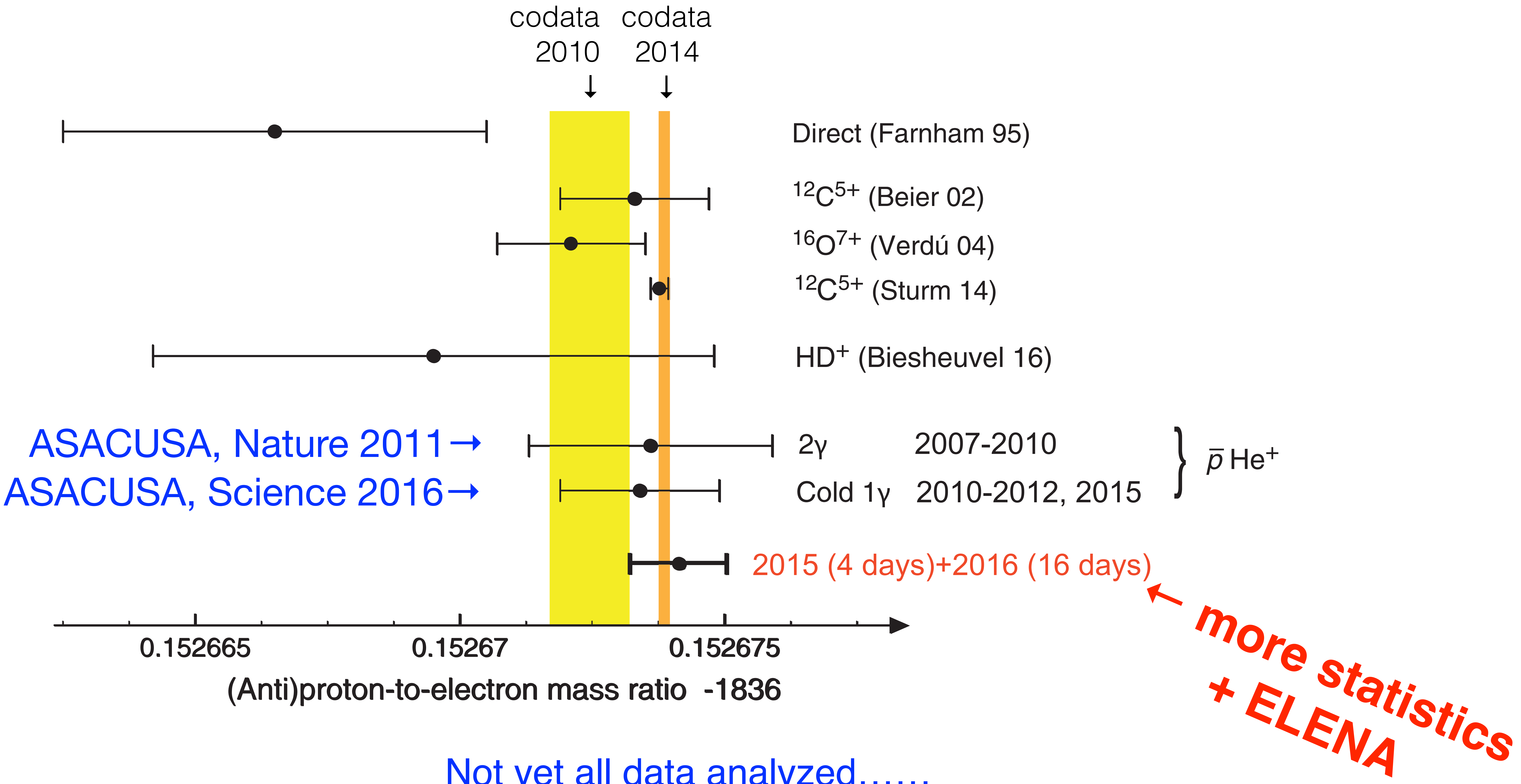
Not yet all data analyzed……

2015+2016 VERY preliminary result

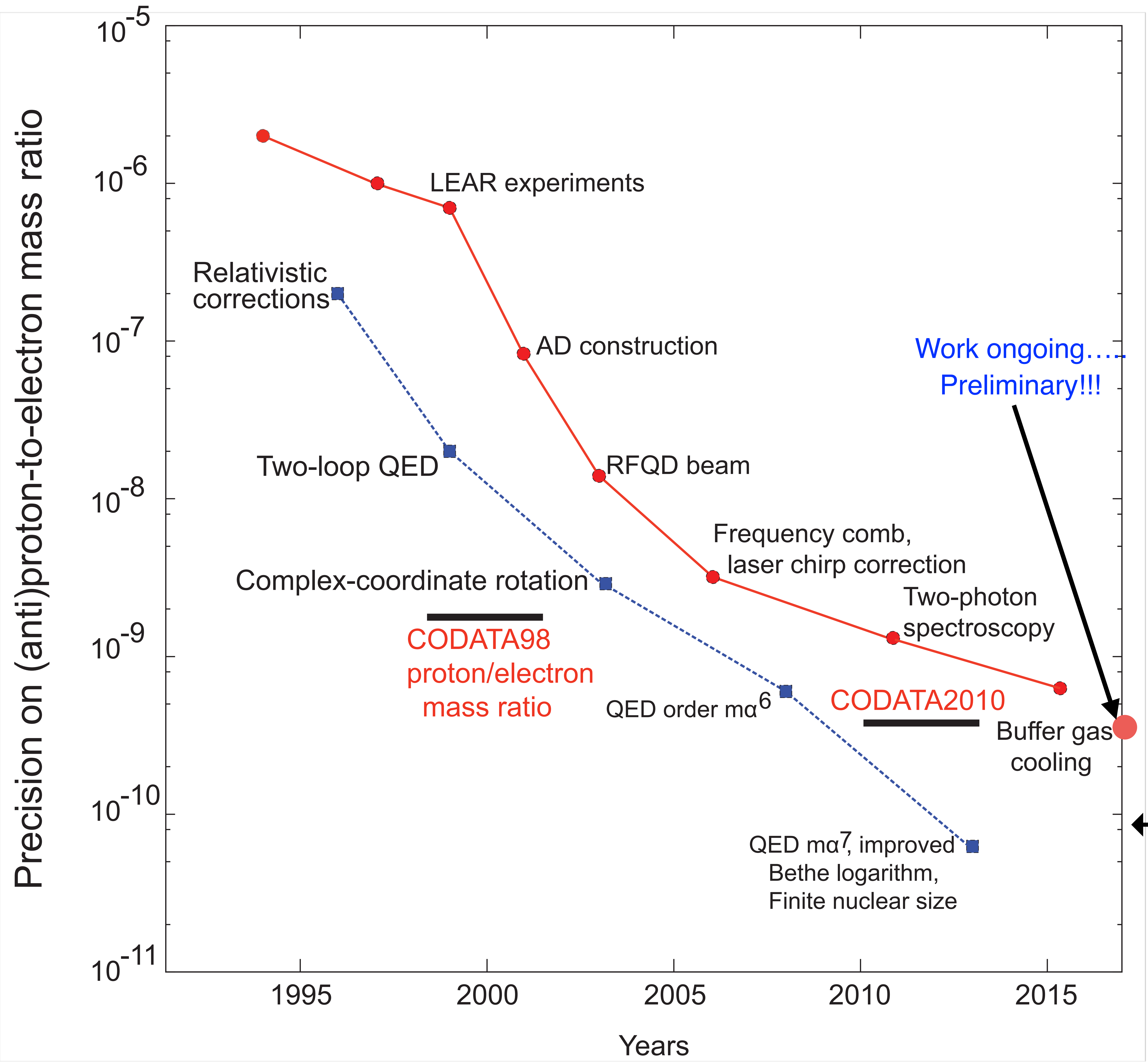


Not yet all data analyzed……

2015+2016 **VERY** preliminary result

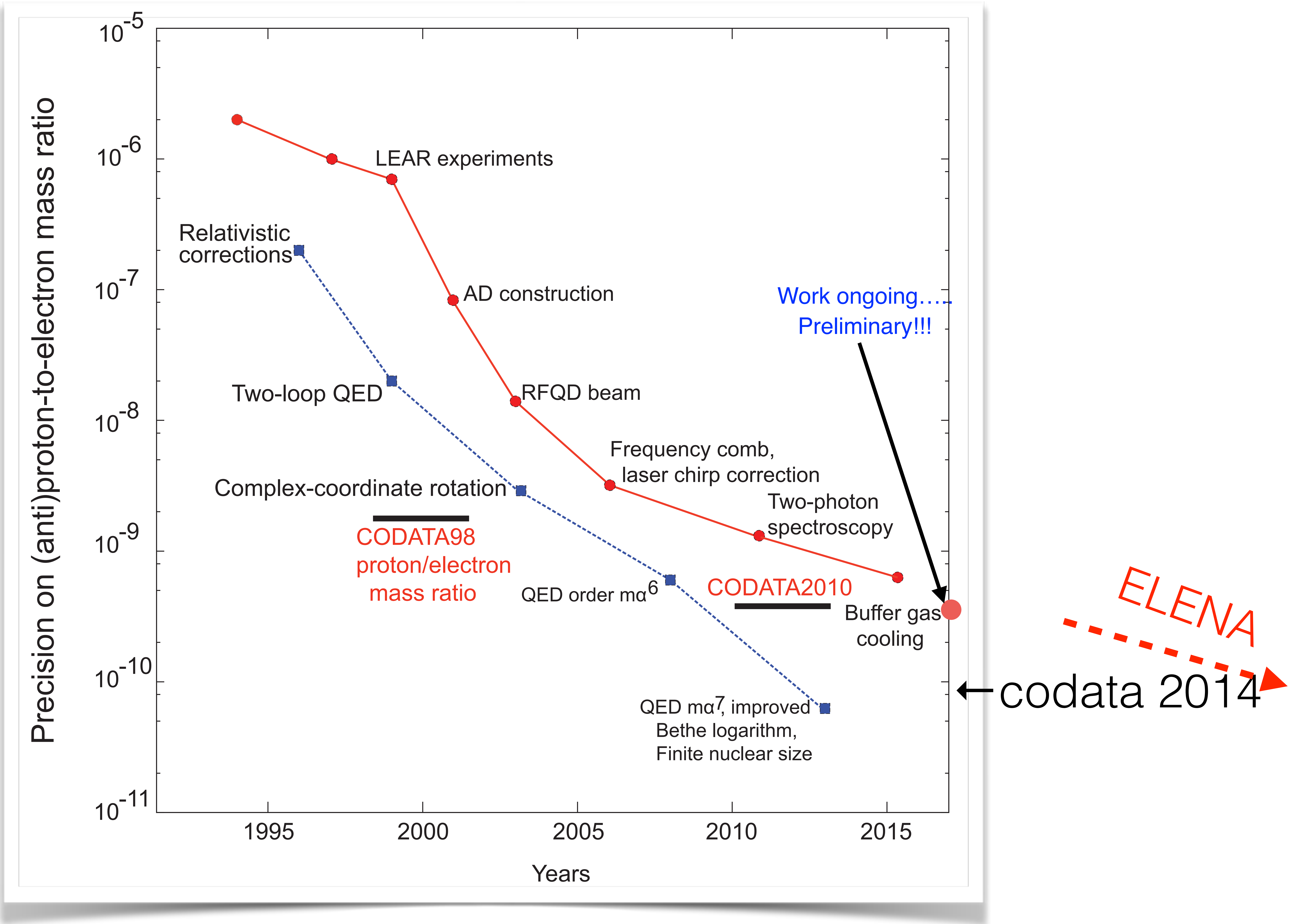


Not yet all data analyzed……



Precision on (anti)proton-to-electron mass ratio
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1995
2000
2005
2010
2015
Years
LEAR experiments
AD construction
RFQD beam
Frequency comb, laser chirp correction
Two-photon spectroscopy
Buffer gas cooling
Relativistic corrections
Two-loop QED
Complex-coordinate rotation
QED order mα6
QED mα7, improved Bethe logarithm, Finite nuclear size
CODATA98 proton/electron mass ratio
CODATA2010
Work ongoing….
Preliminary!!!

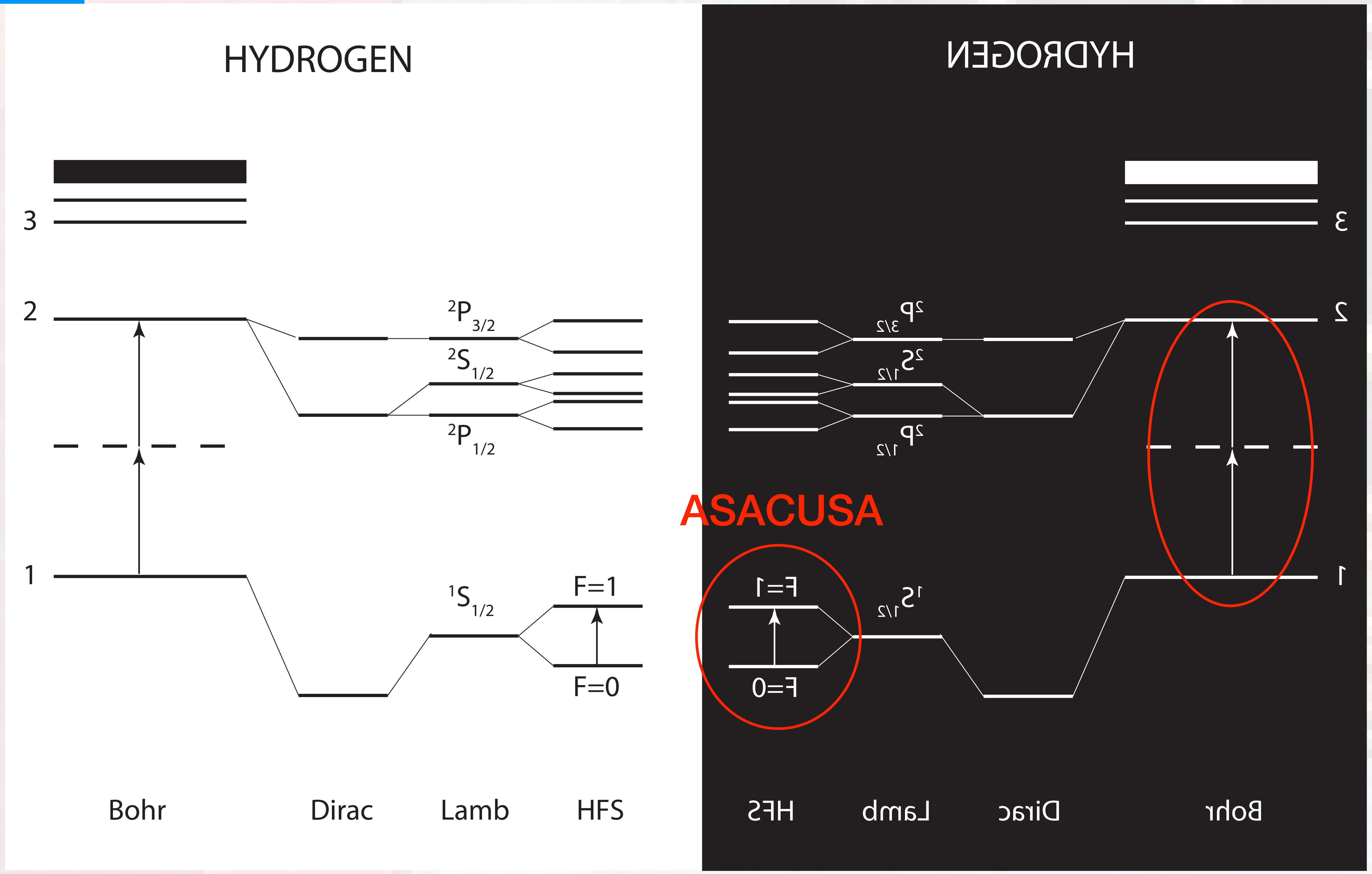
←codata 2014

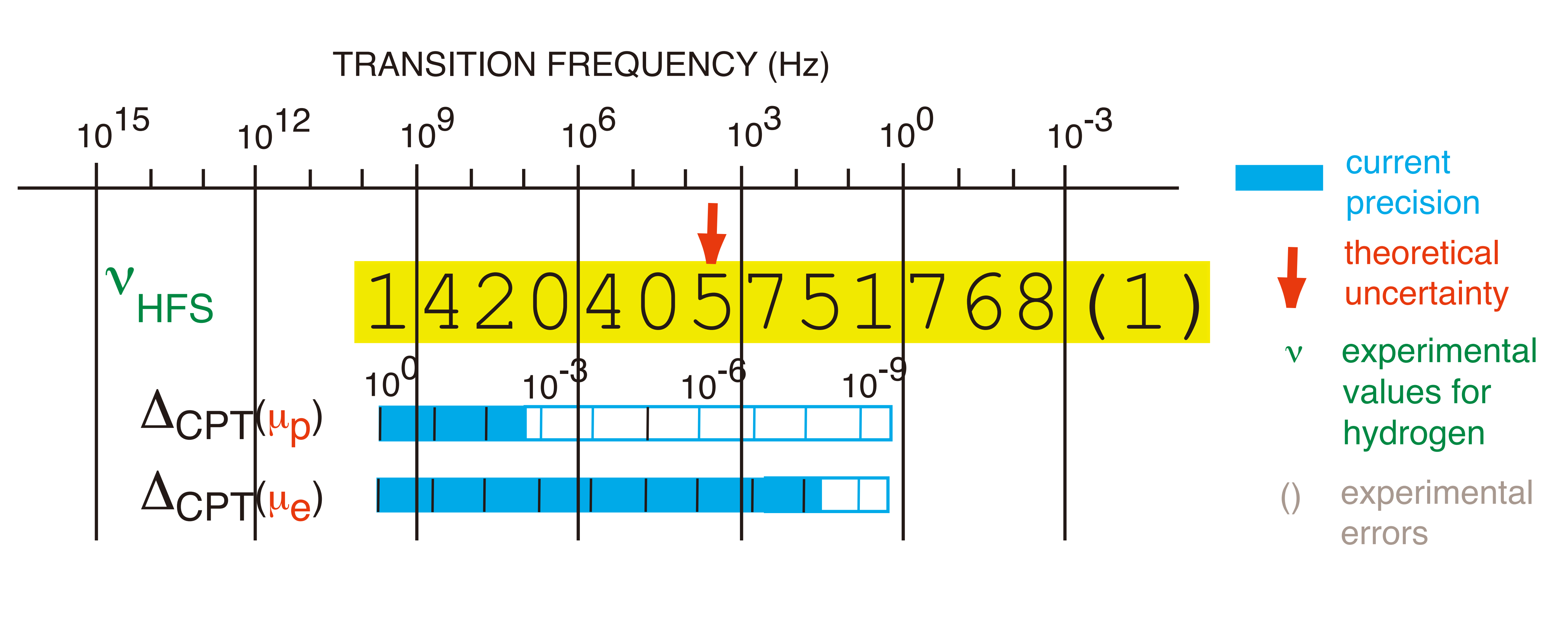


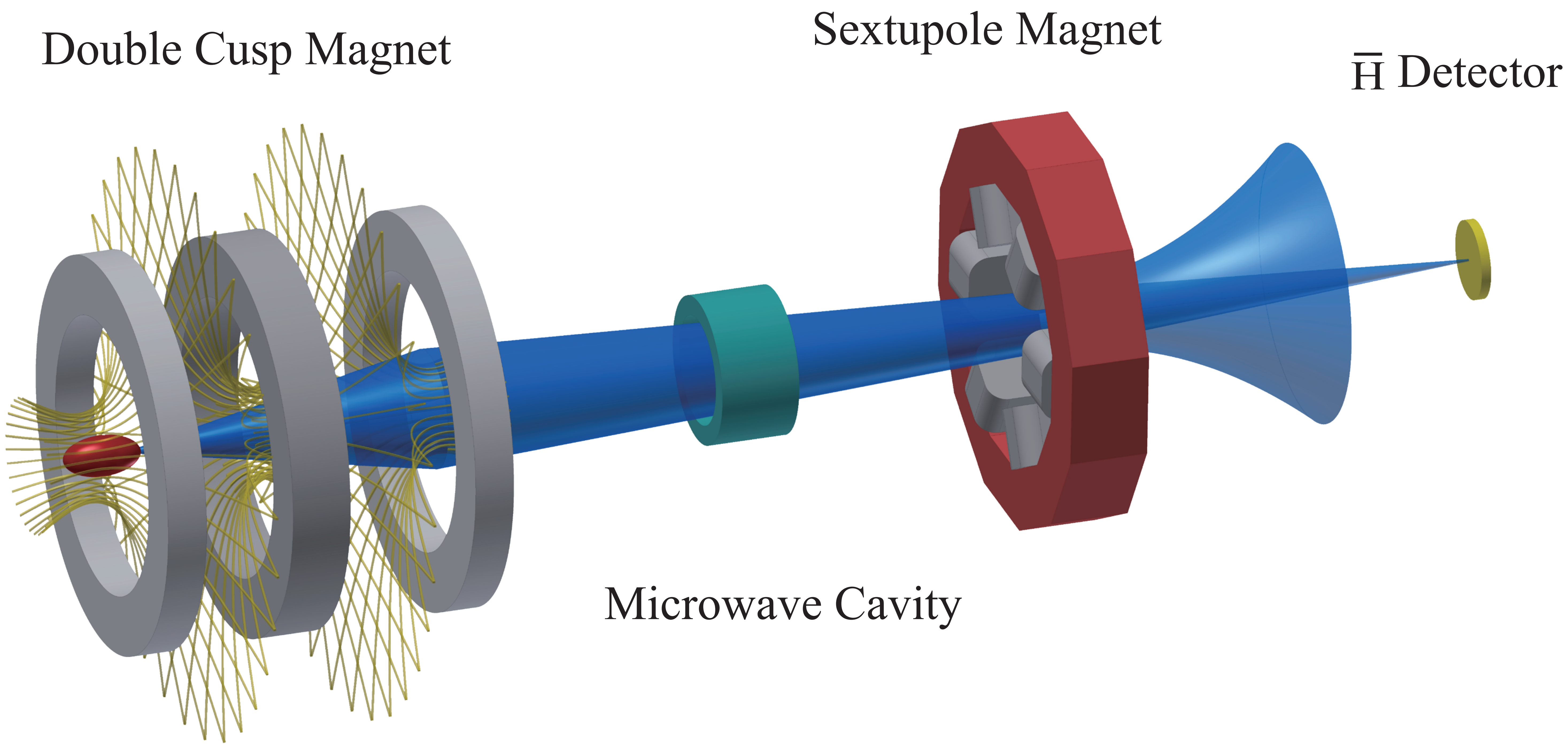
Precision on (anti)proton-to-electron mass ratio
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1995
2000
2005
2010
2015
Years
LEAR experiments
Relativistic corrections
AD construction
Two-loop QED
RFQD beam
Frequency comb, laser chirp correction
Complex-coordinate rotation
Two-photon spectroscopy
CODATA98 proton/electron mass ratio
QED order mα^6
CODATA2010
Buffer gas cooling
QED mα^7, improved Bethe logarithm, Finite nuclear size
Work ongoing….
Preliminary!!!
ELENA
←codata 2014

antihydrogen

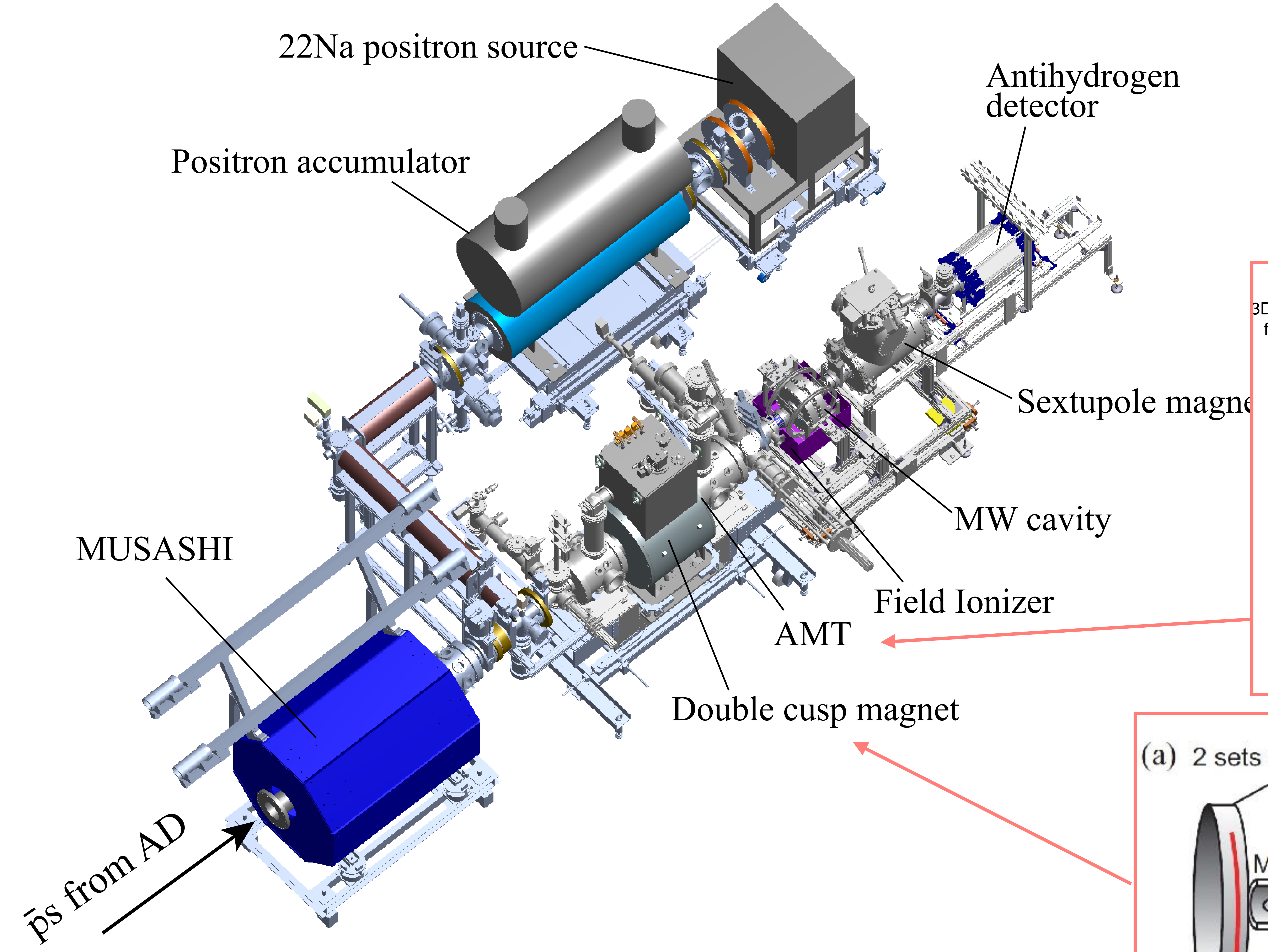
2. Toward $\bar{H}$ GSHFS Spectroscopy

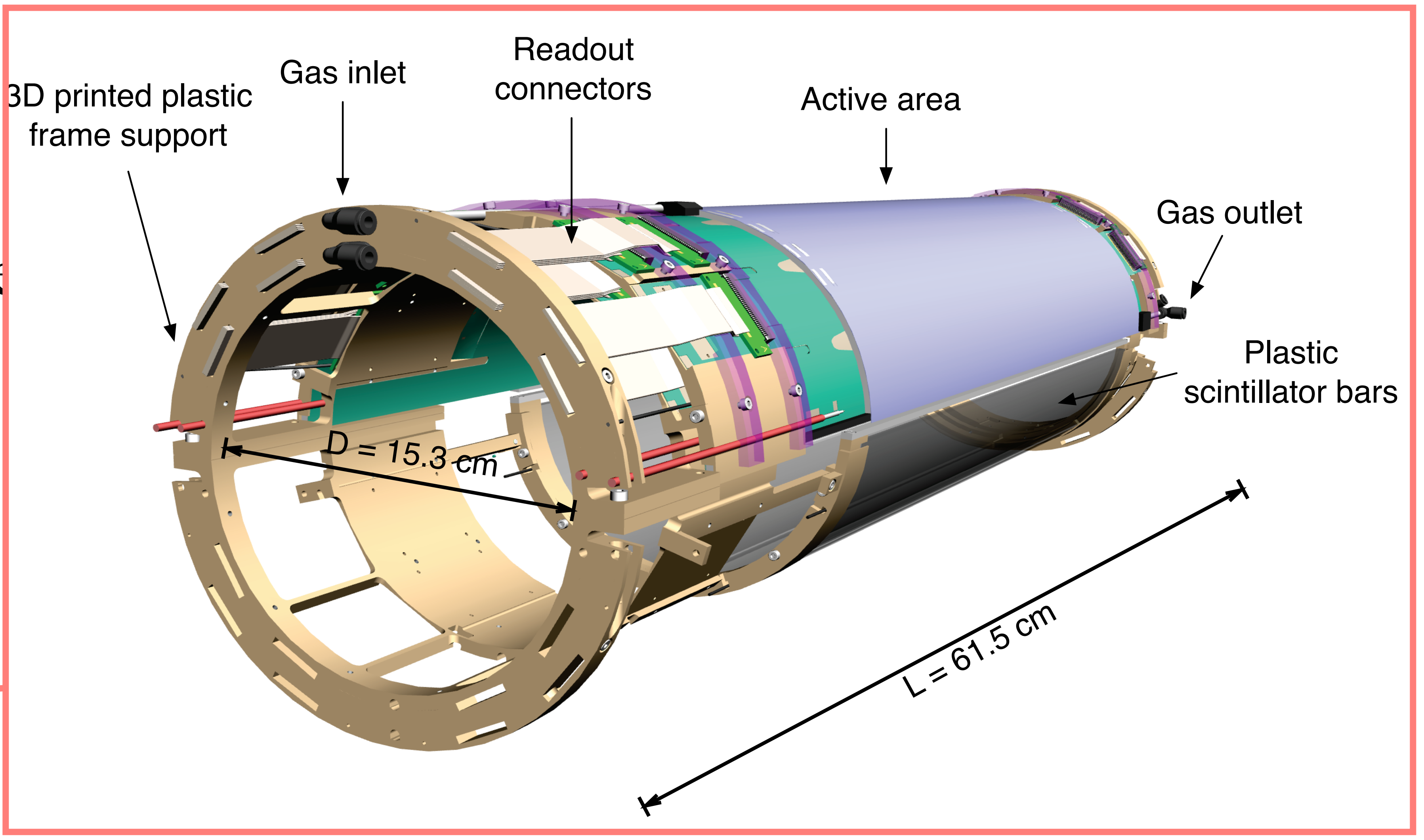


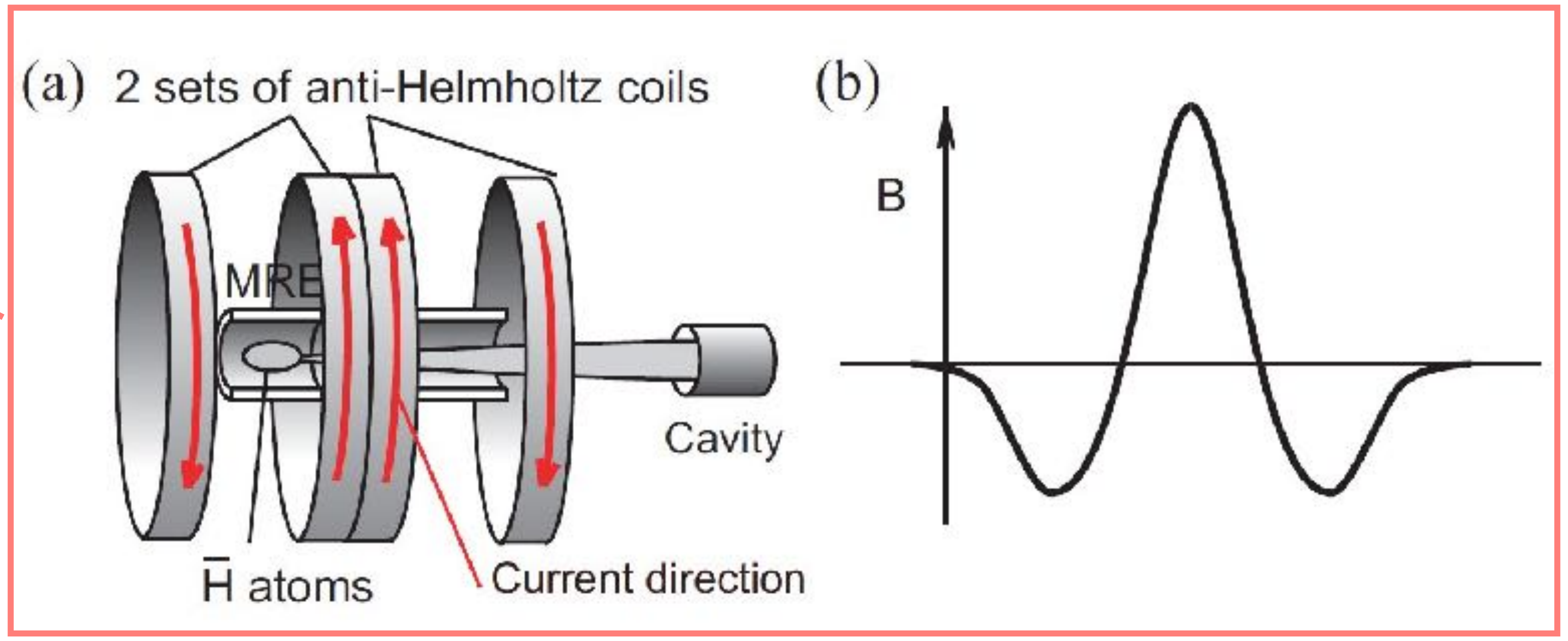



Double Cusp Magnet
Sextupole Magnet
$\bar{H}$ Detector
Microwave Cavity

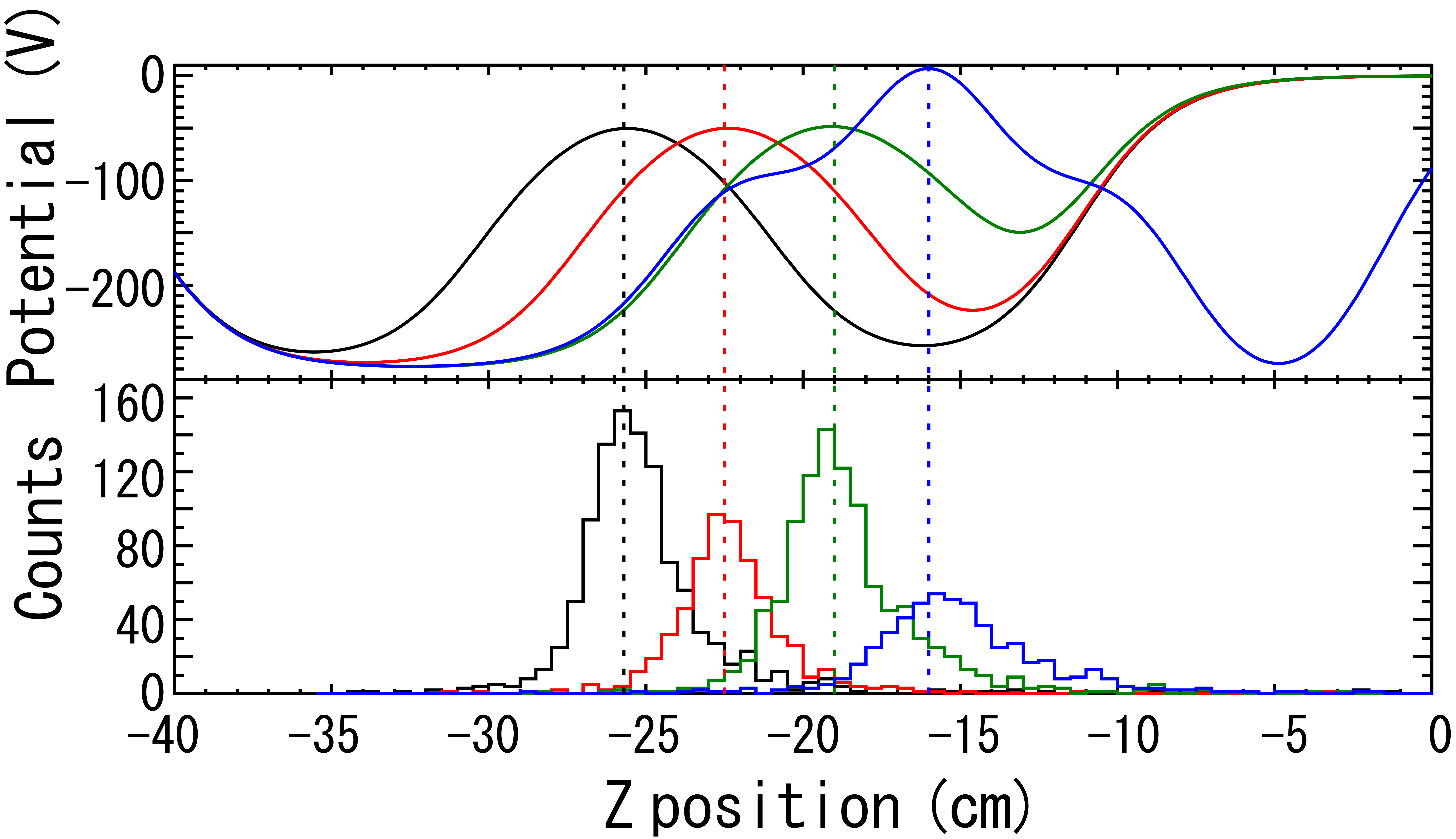
distance from the mixing position
Cavity: +1840mm
Sextupole: +2628mm
$\bar{H}$ detetor: +3739mm

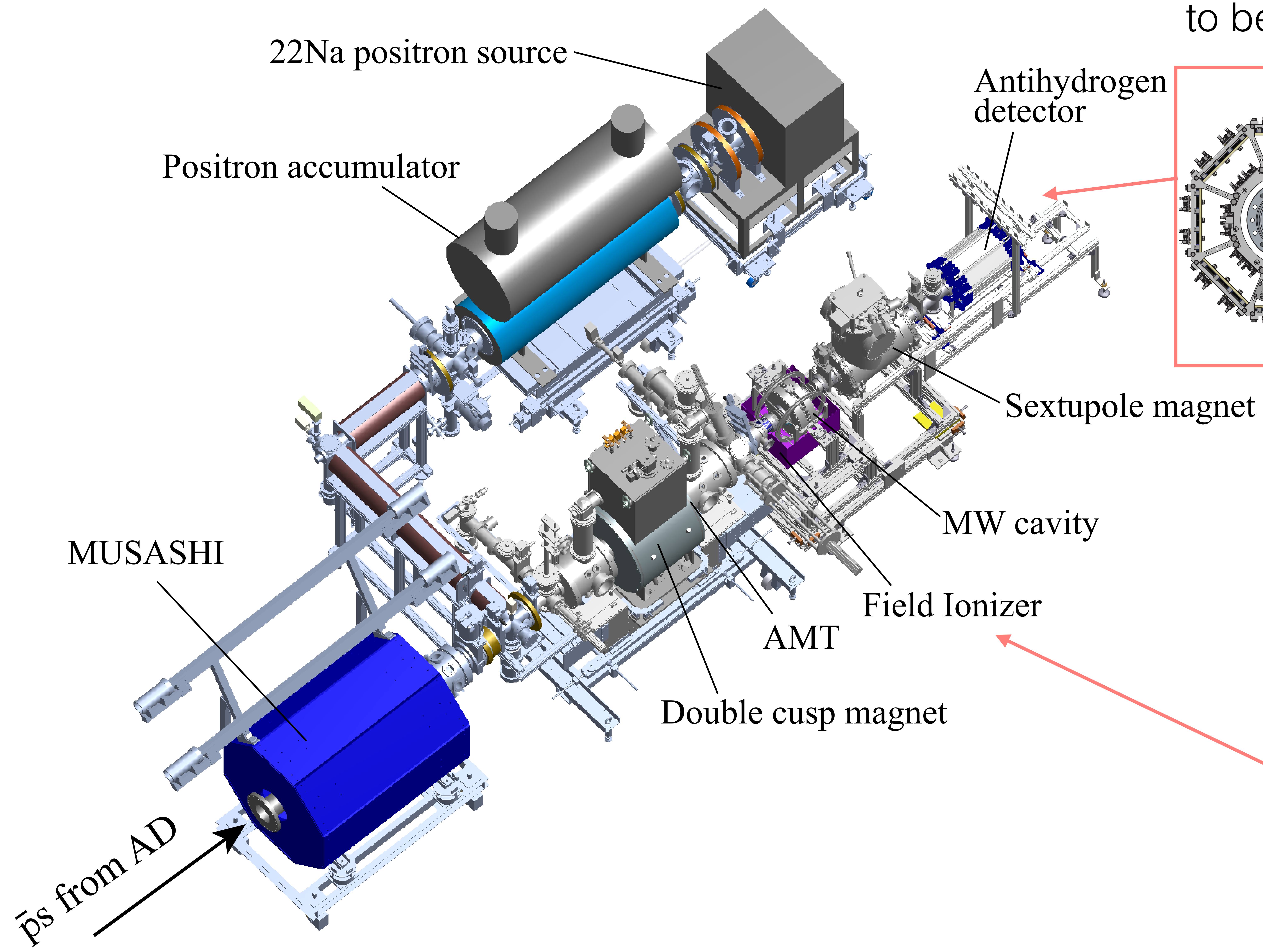




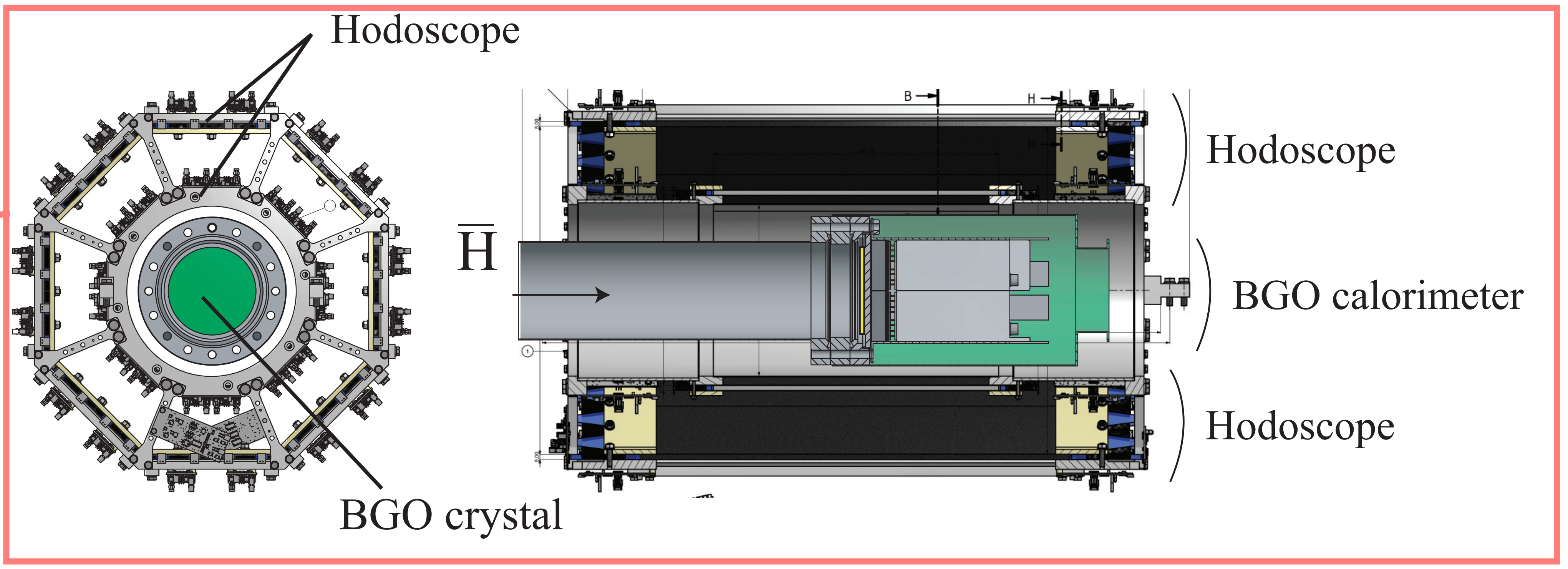


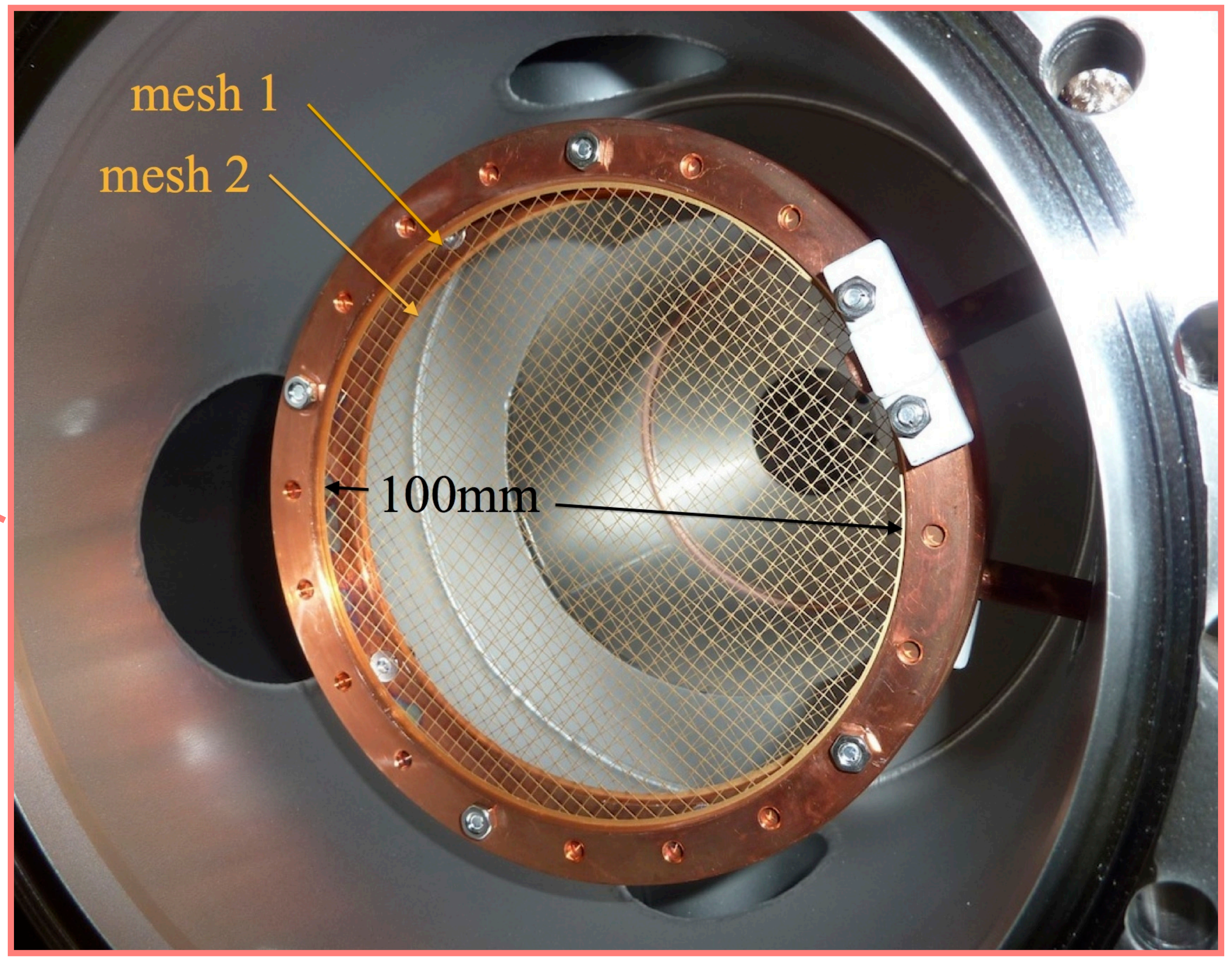
Z-axis calibration of the AMT





to be upgraded using fibers and the Timepix3





beamtime in 2016

- Start on week 17, and run until week 38.
- in May : (fire at PS MPS)

  test with 20 eV of transport energy

  MUSASHI potential manipulation to minimize ΔE of $\bar{\mathbf{p}}$
- in June :

  lowering transport energy (10, 5, 2.5, 1.5, and 1 eV)

  measurement of energy spread of $\bar{\mathbf{p}}$ beams

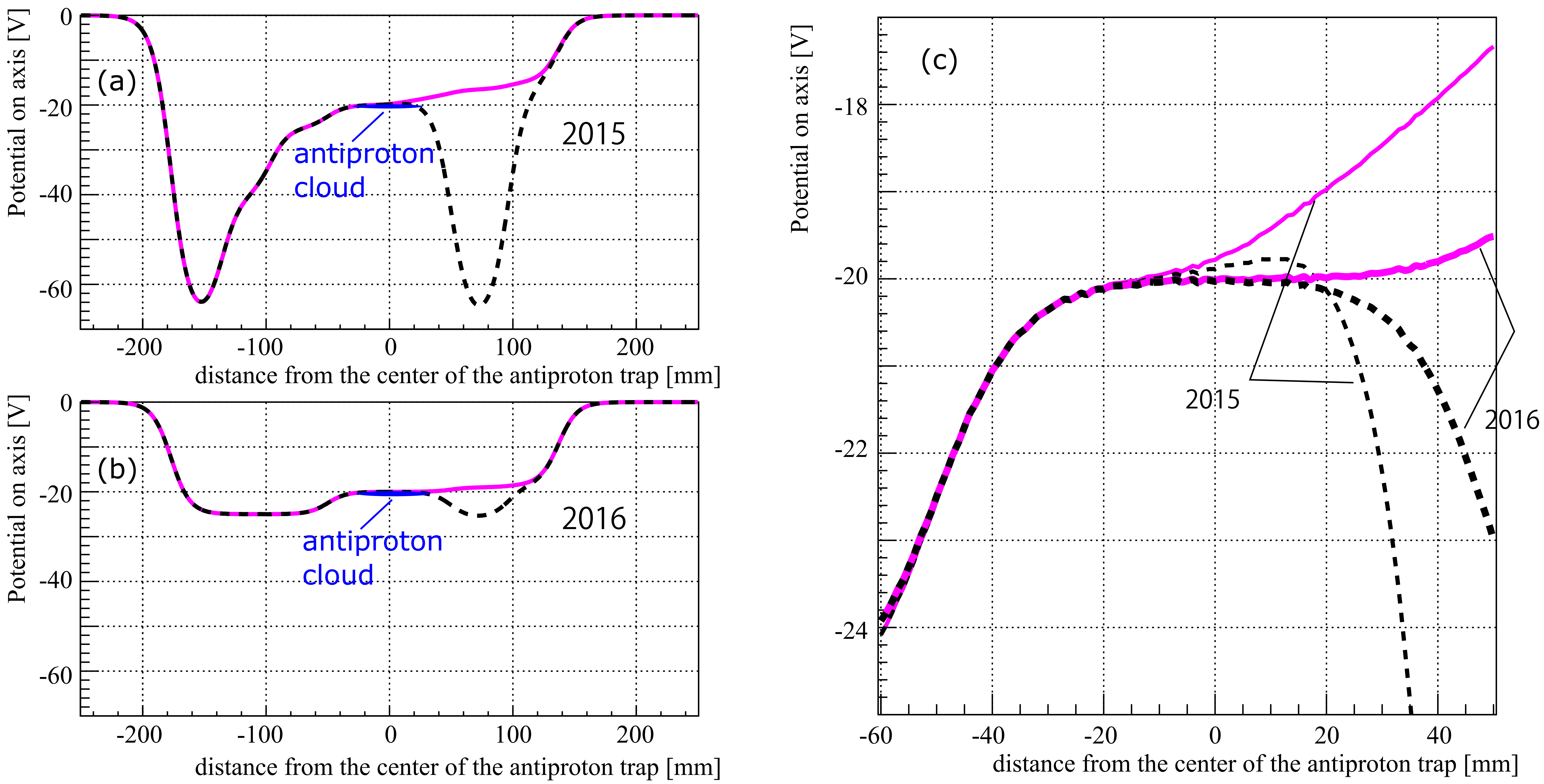
  $\bar{\mathbf{H}}$ production by adjusting energy diff. between $\bar{\mathbf{p}}$ and $\mathbf{e}^+$
- in July

  $\bar{\mathbf{H}}$ production with 1.5 eV beam

  optimization of catching pulse (height, timing) and potential configuration of the nested well (steep or shallow?)
- in August and September

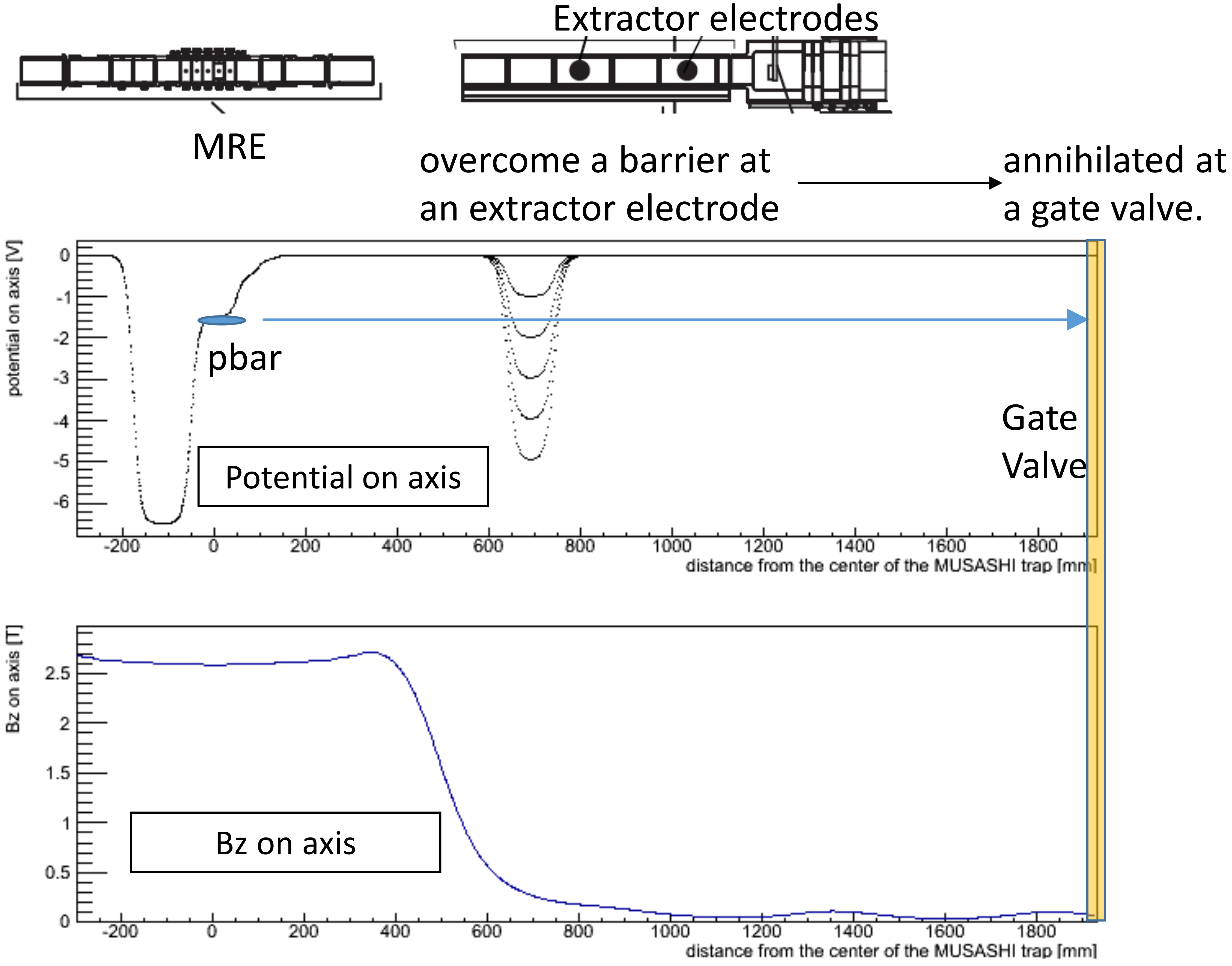
  optimization of $\bar{\mathbf{H}}$ production and measurement of n distribution of $\bar{\mathbf{H}}$

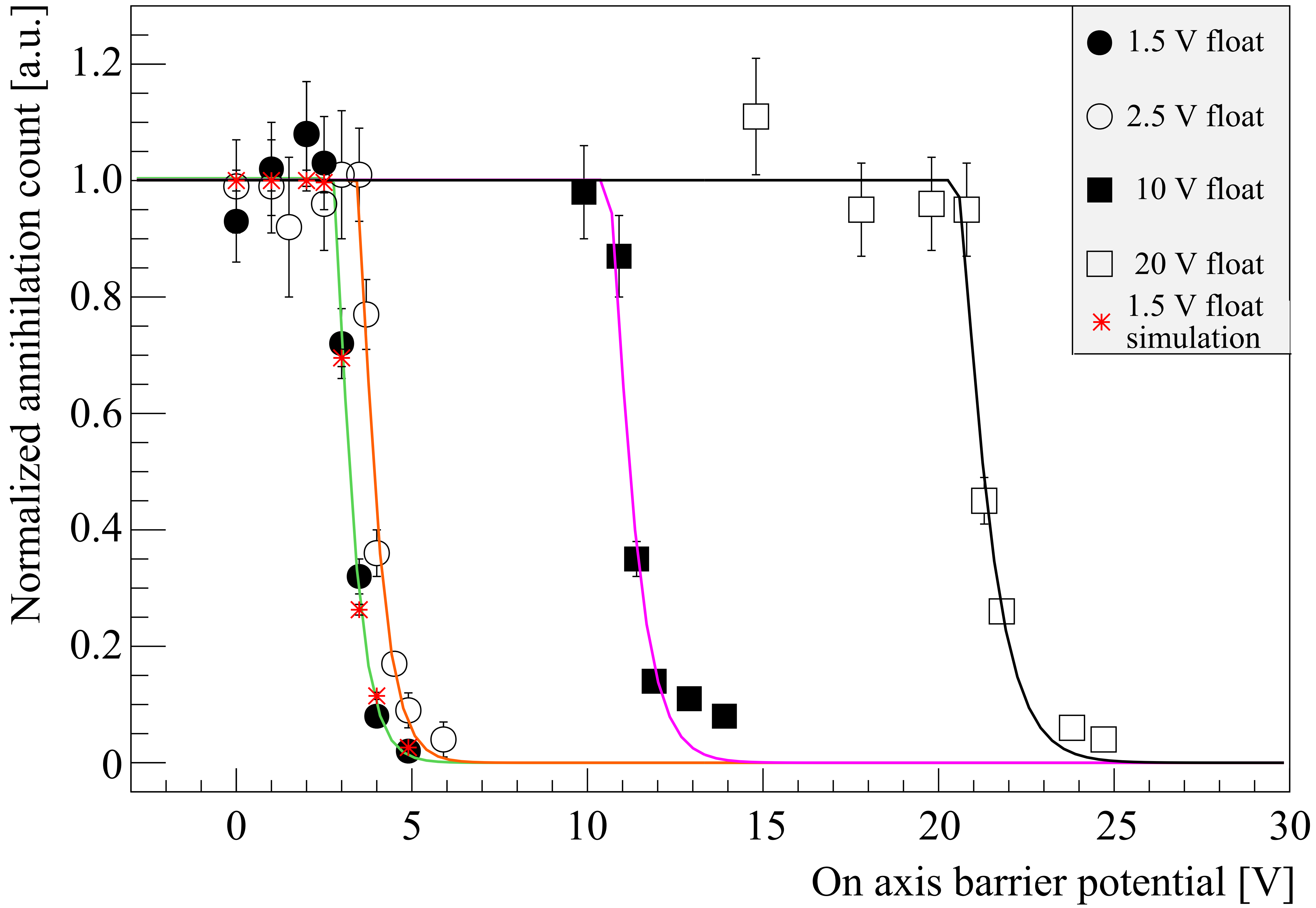
Optimization of extraction scheme for better initial $\overline{p}$ energy distribution
2015 - 20 eV beam, 2016 - 1.5 eV beam



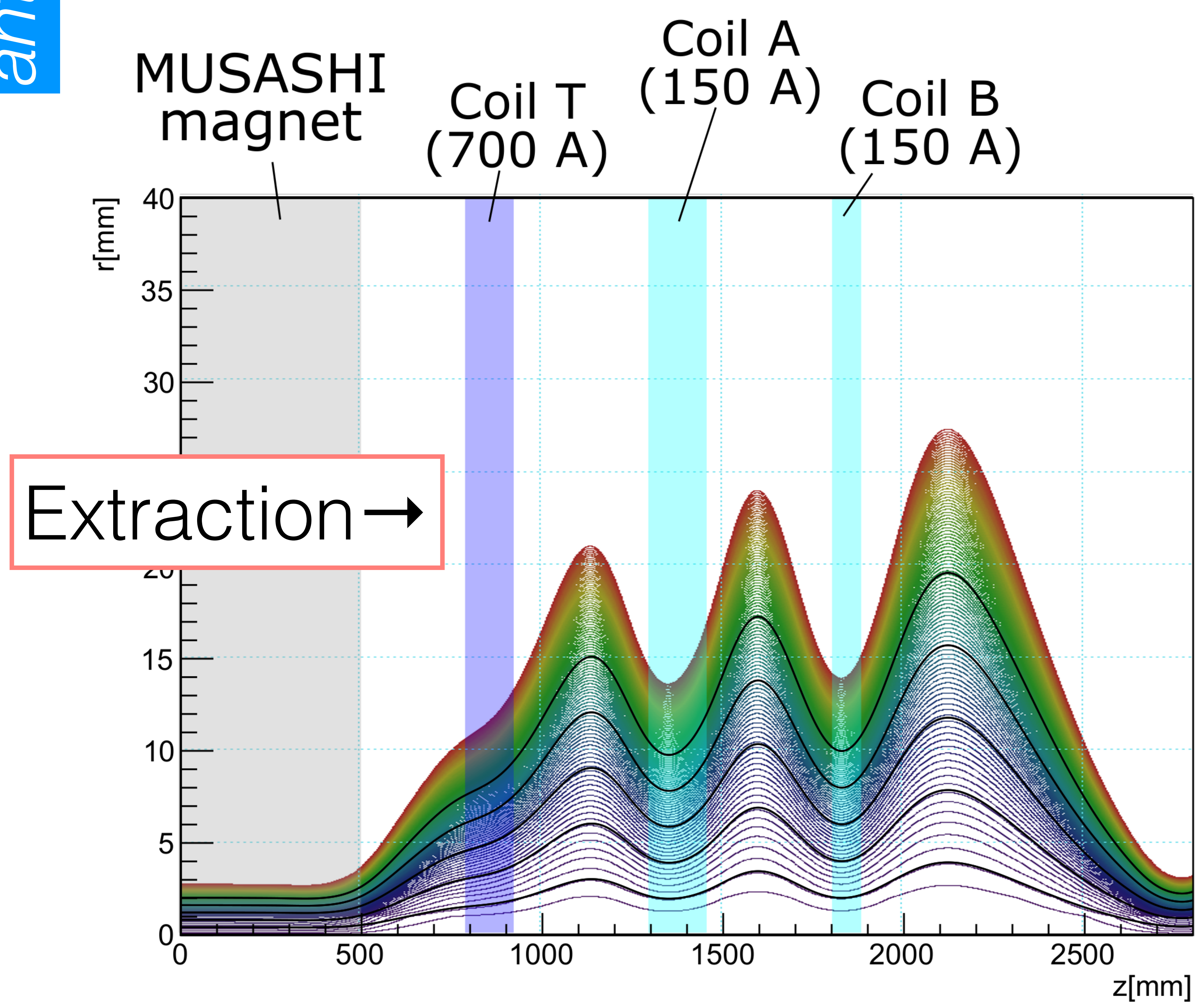
Axial p̄ energy distributions at ~700 mm downstream

$$\frac{3}{2}k_BT = 0.4^{+0.1}_{-0.1}eV$$

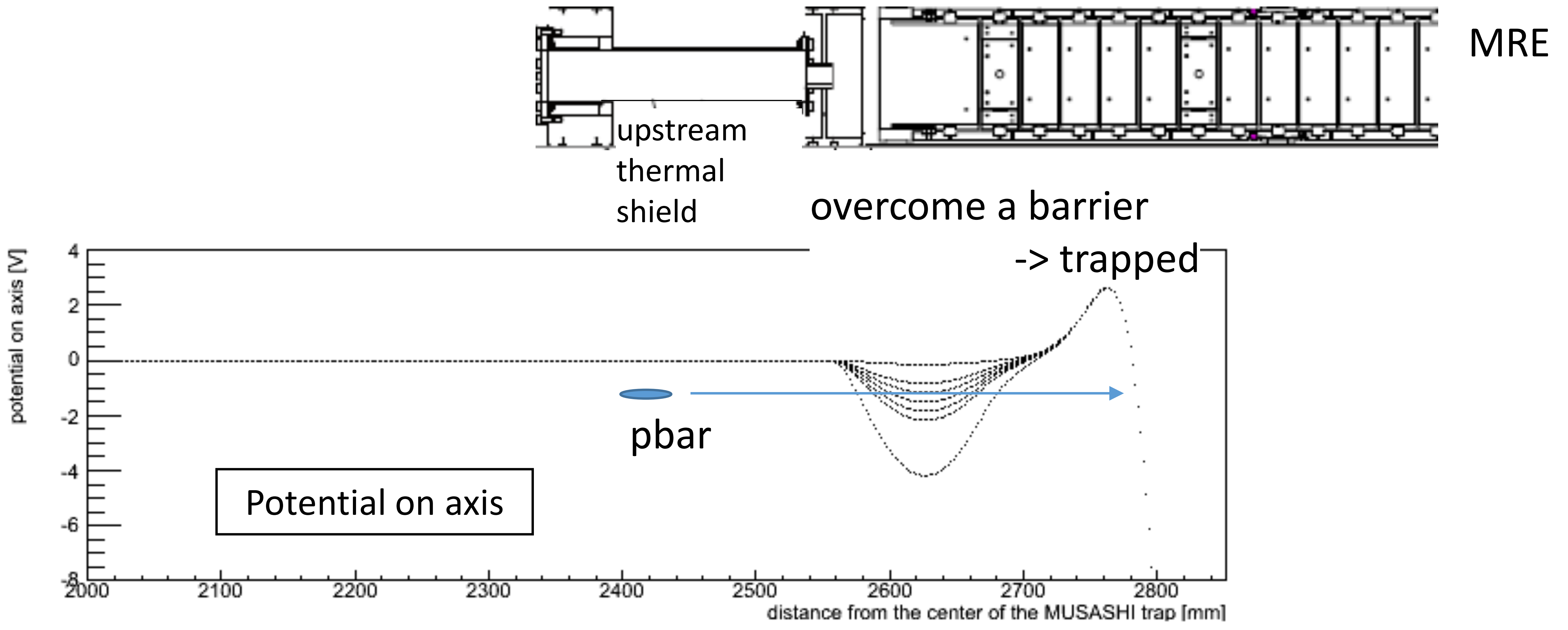


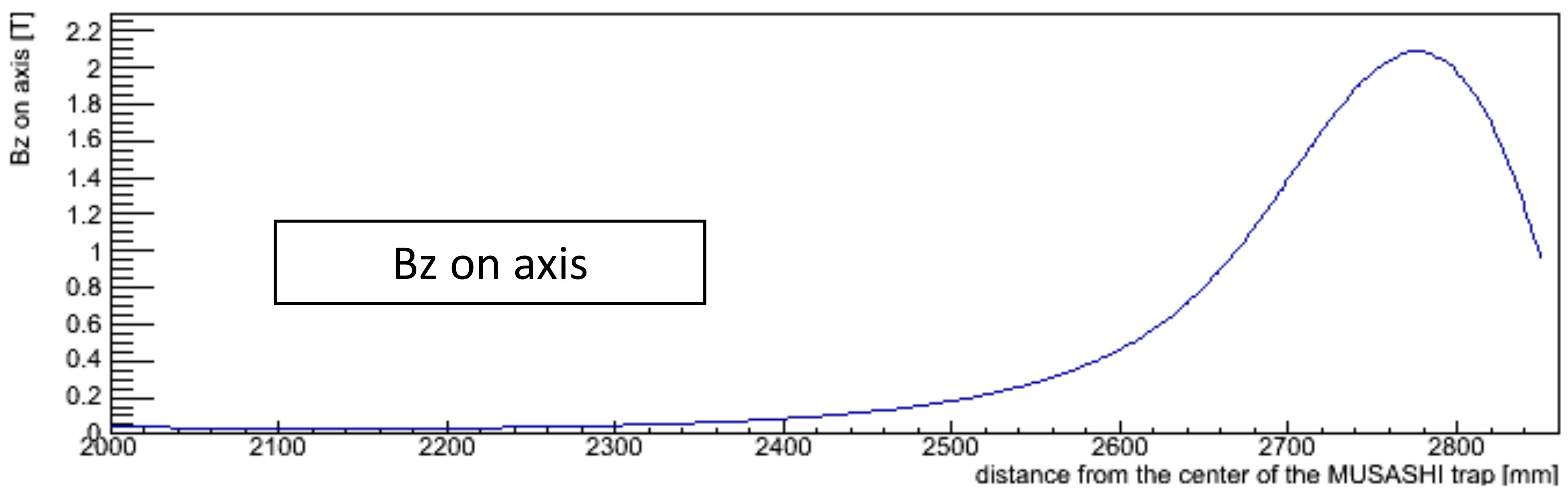


Guide $\bar{p}$s using pulsed coils



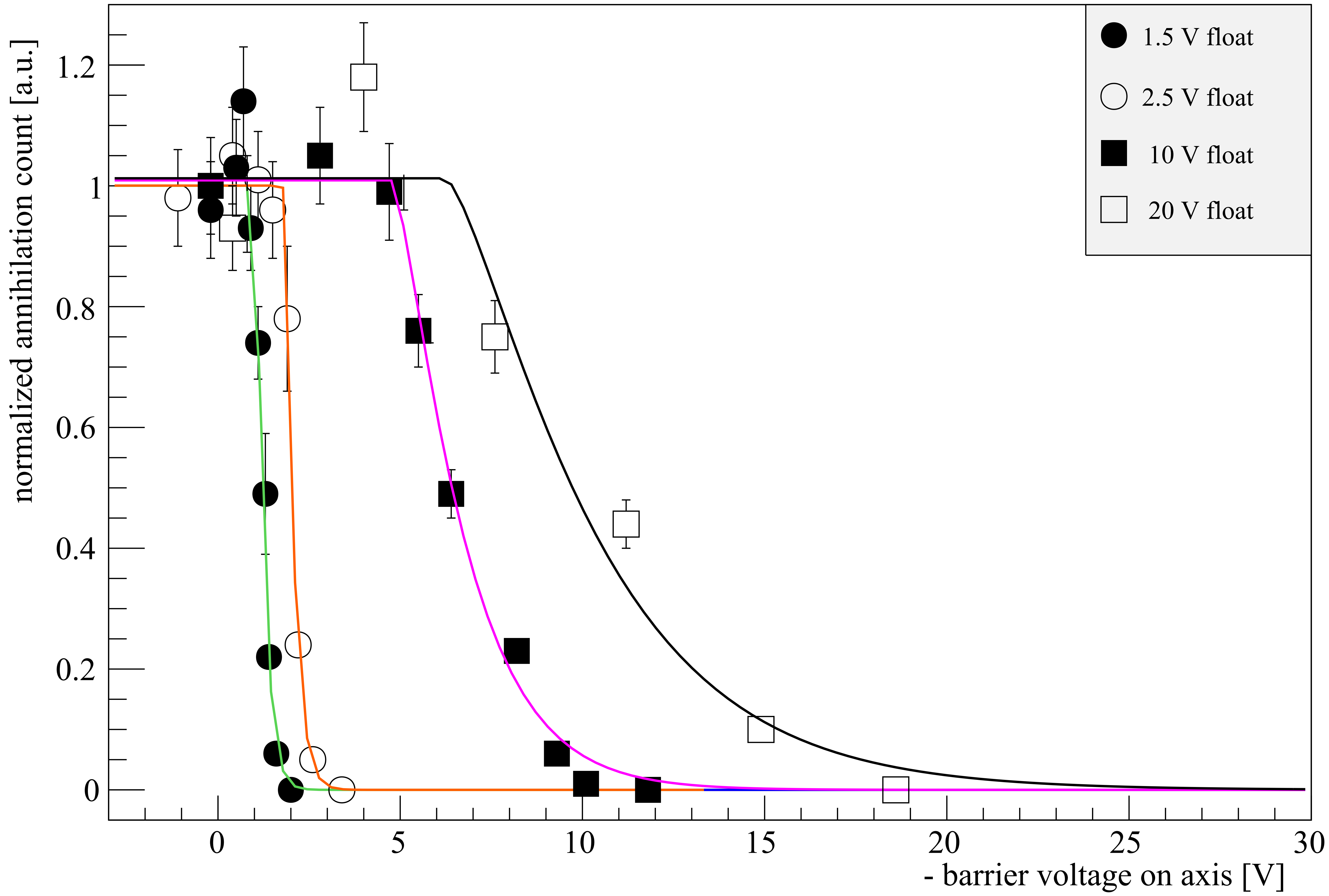
Measure $\bar{p}$ energy distribution in cusp

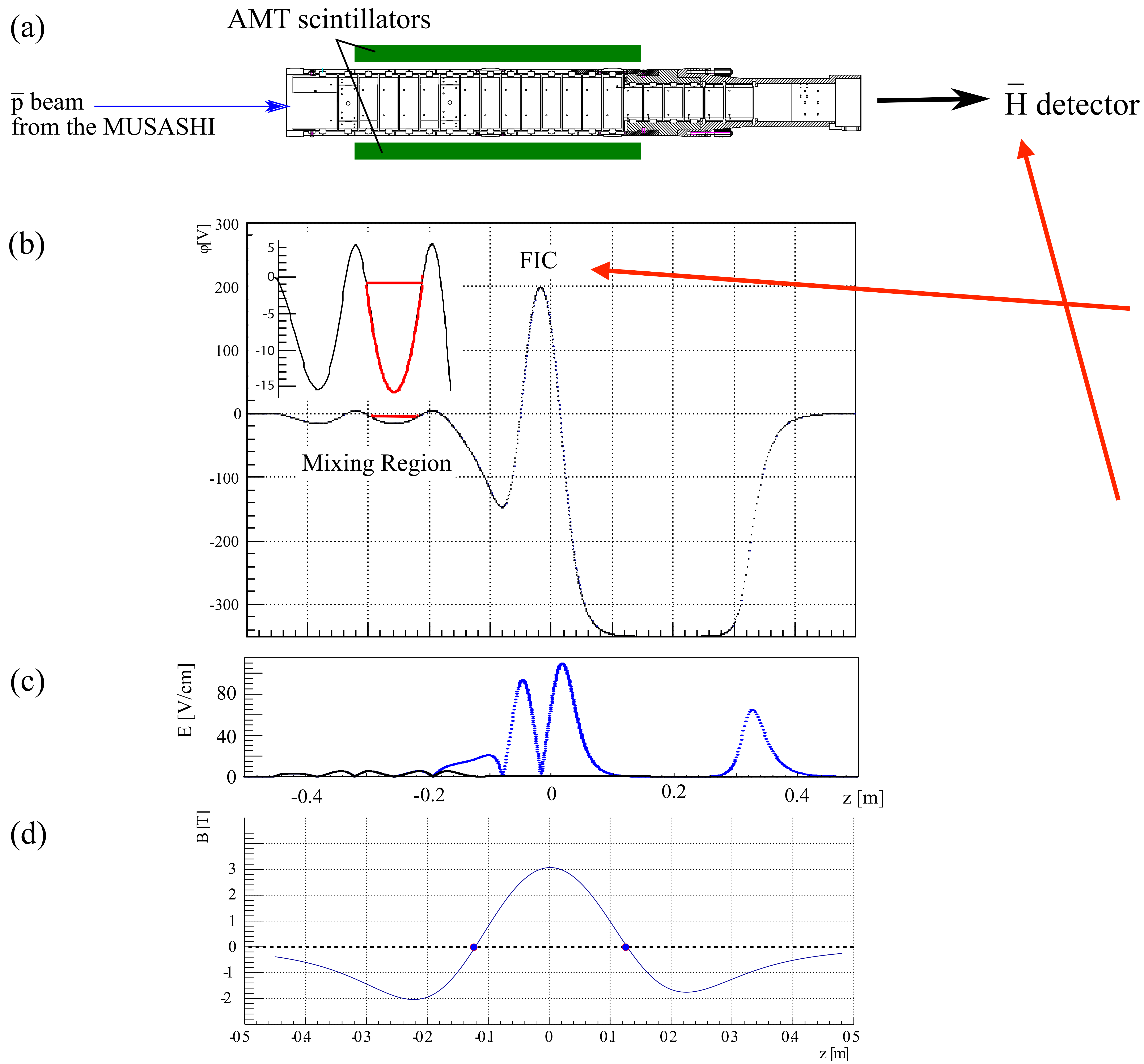




$\bar{p}$ energy distribution in the cusp trap $\frac{3}{2}k_BT = 0.3^{+0.1}_{-0.1}eV$

Transport efficiency ~20% at 1.5 eV (typically 600 k $\bar{p}$s)





Field ionization counting of H̄s

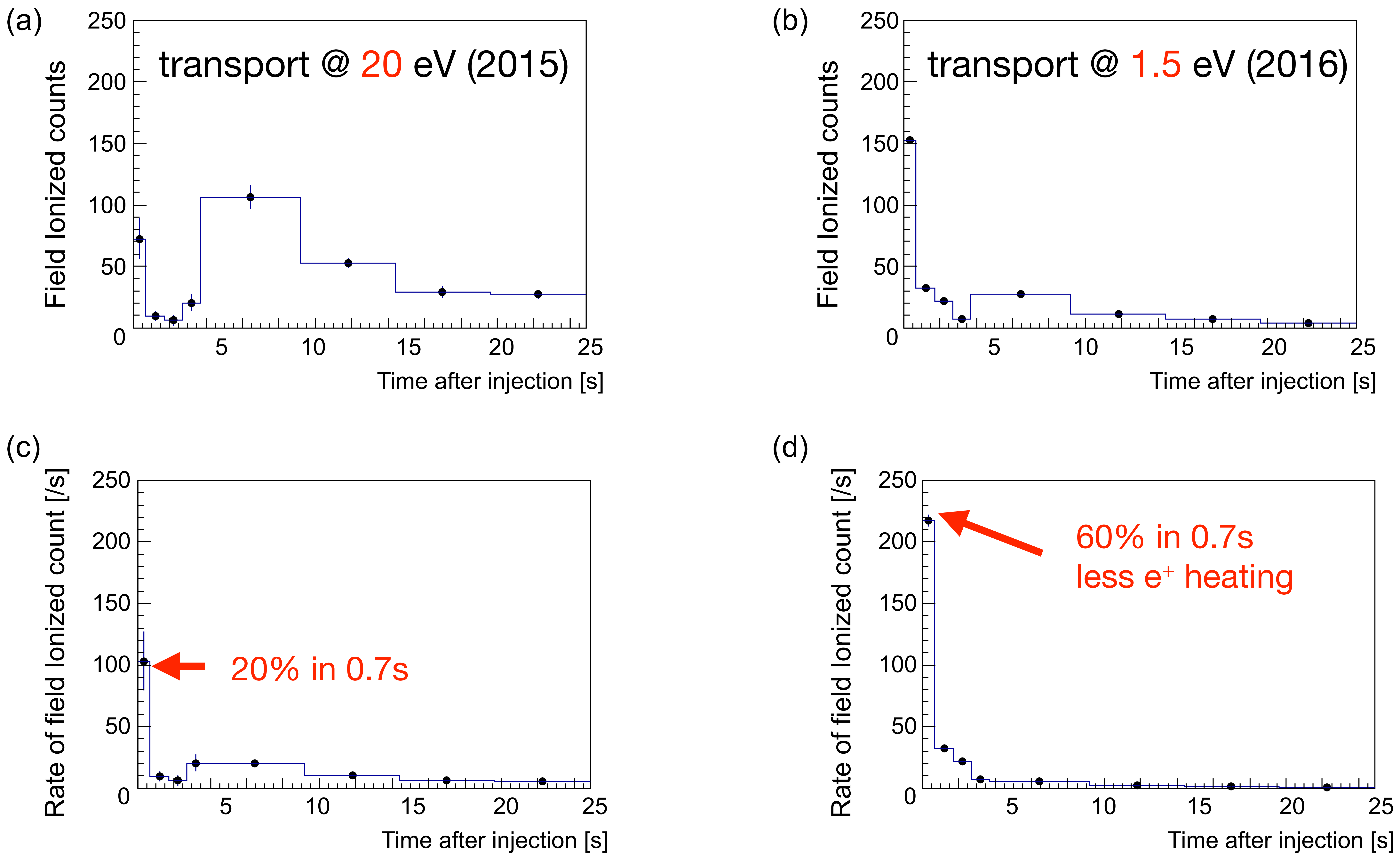
- 43 < n ≲ 54 can be observed
- $\Omega_{FI} \sim 0.0132/4\pi$

- 14 < n ≲ 54 can be observed
- $\Omega_{det} \sim 0.00018/4\pi$

mixing conditions

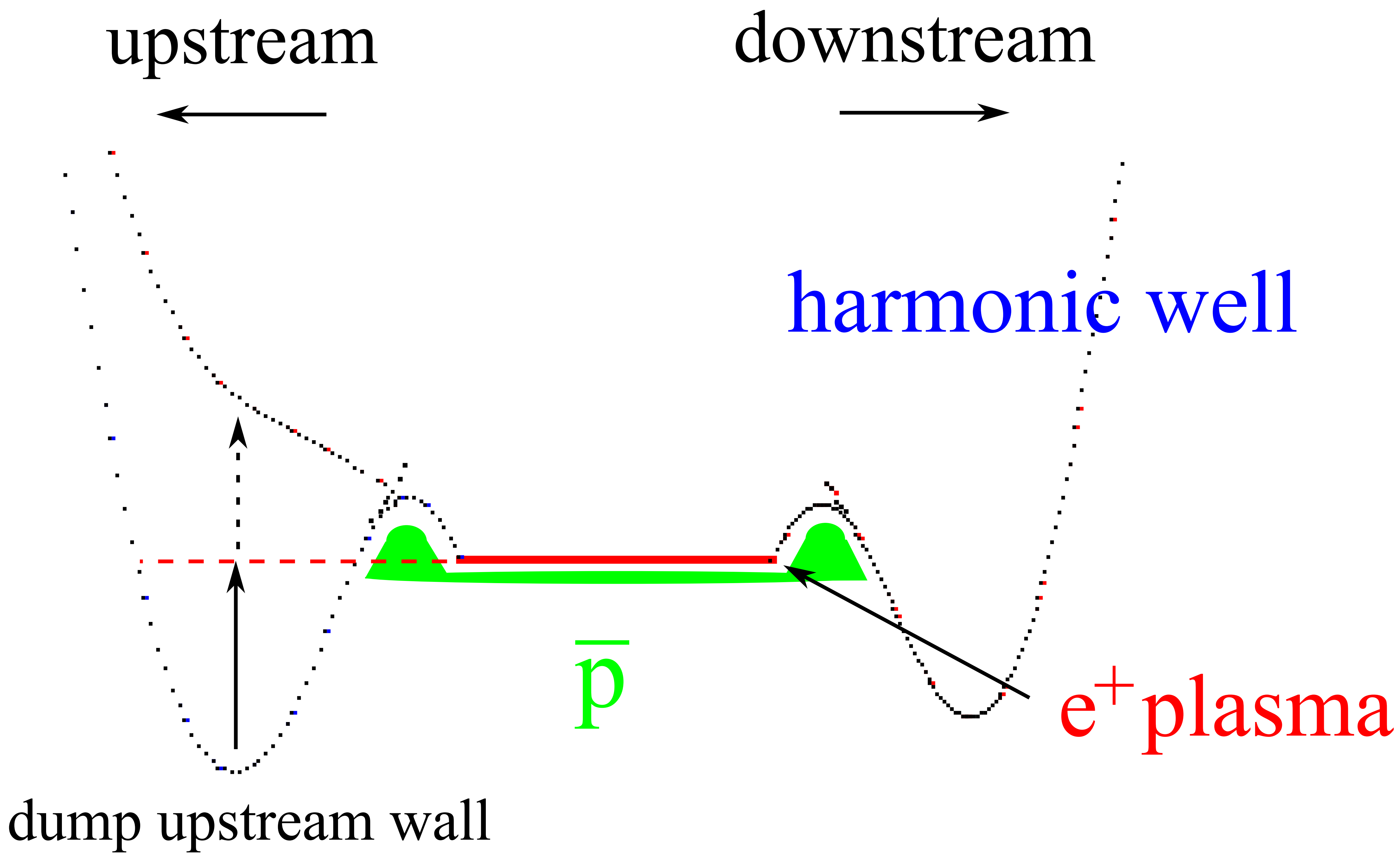
1. 0.6×10^8 e^+ (12 stacks), r~2.1mm, n~$1\times10^8/cm^3$ captured $\bar{p}$ = ca. 6–8 × 10^5
2. 1.2×10^8 e^+ (25 stacks), r~1.3mm, n~$1\times10^8/cm^3$ captured $\bar{p}$ = ca. 6–8 × 10^5
3. 1.2×10^8 e^+ (25 stacks), r~0.9mm, n~$6\times10^8/cm^3$ captured $\bar{p}$ = ca. 6 × 10^5
4. 1.9×10^8 e^+ (40 stacks), r~1.2mm, n~$8.3\times10^8/cm^3$ captured $\bar{p}$ = ca. 3 × 10^5

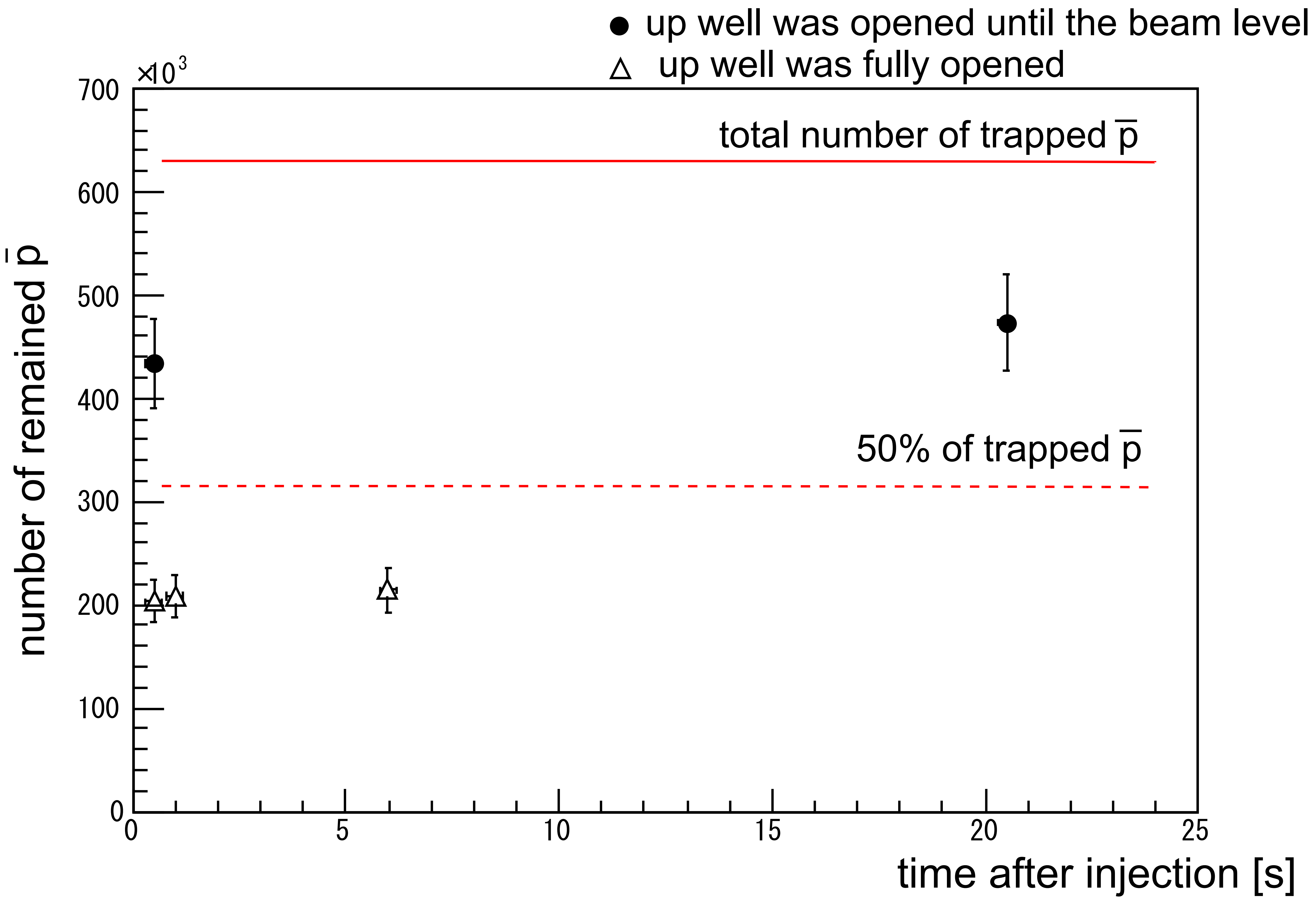
Time distribution of field-ionized (FI in cusp) counts & rates



quick separation of p̄s from e^+

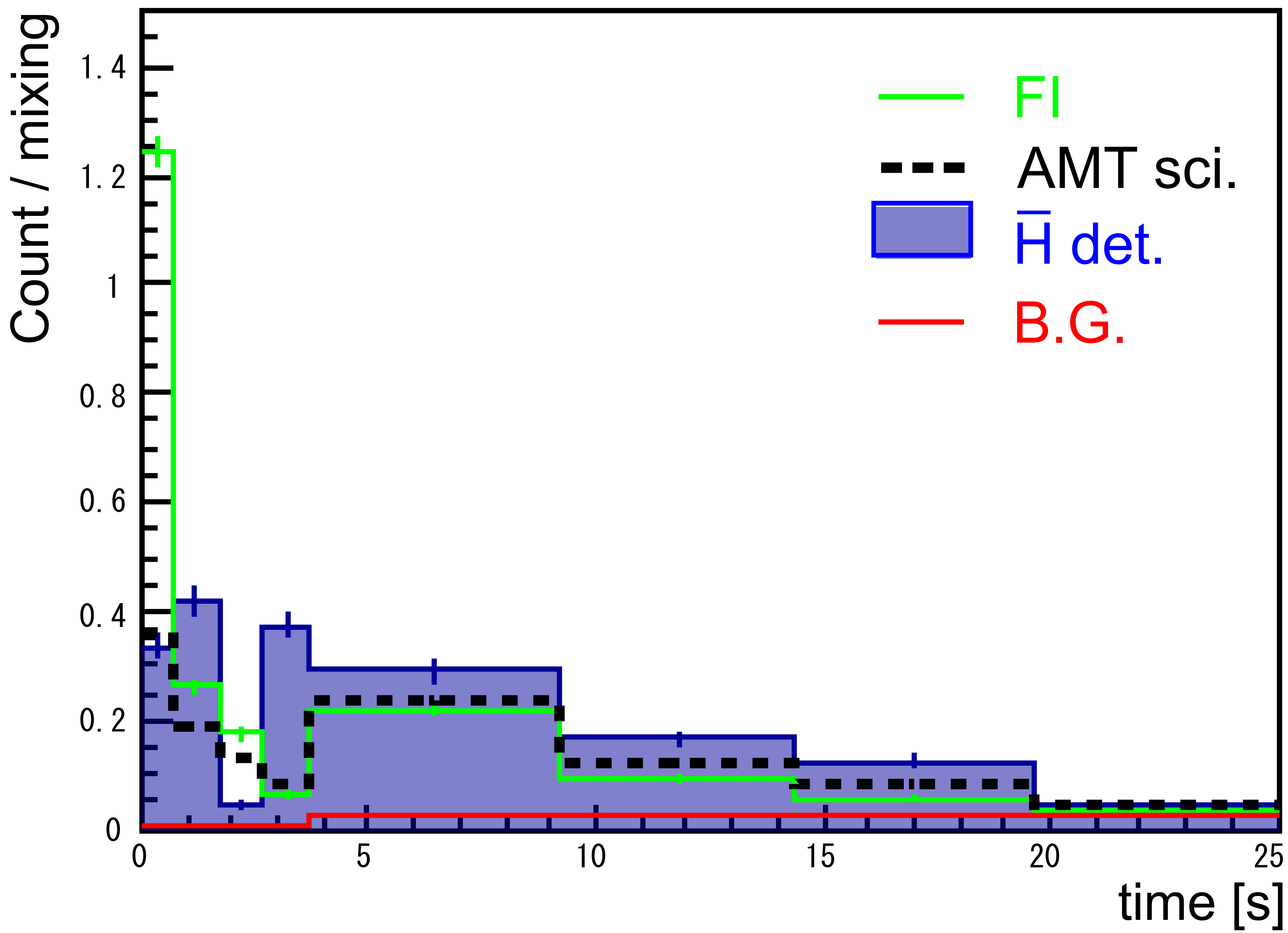
~80% of p̄s quickly separated within 1 s; the rest continue interacting





Annihilation time distribution (measured with the $\overline{H}$ detector)

t<0.7, the counts less than estimated from the FI result (more study needed)

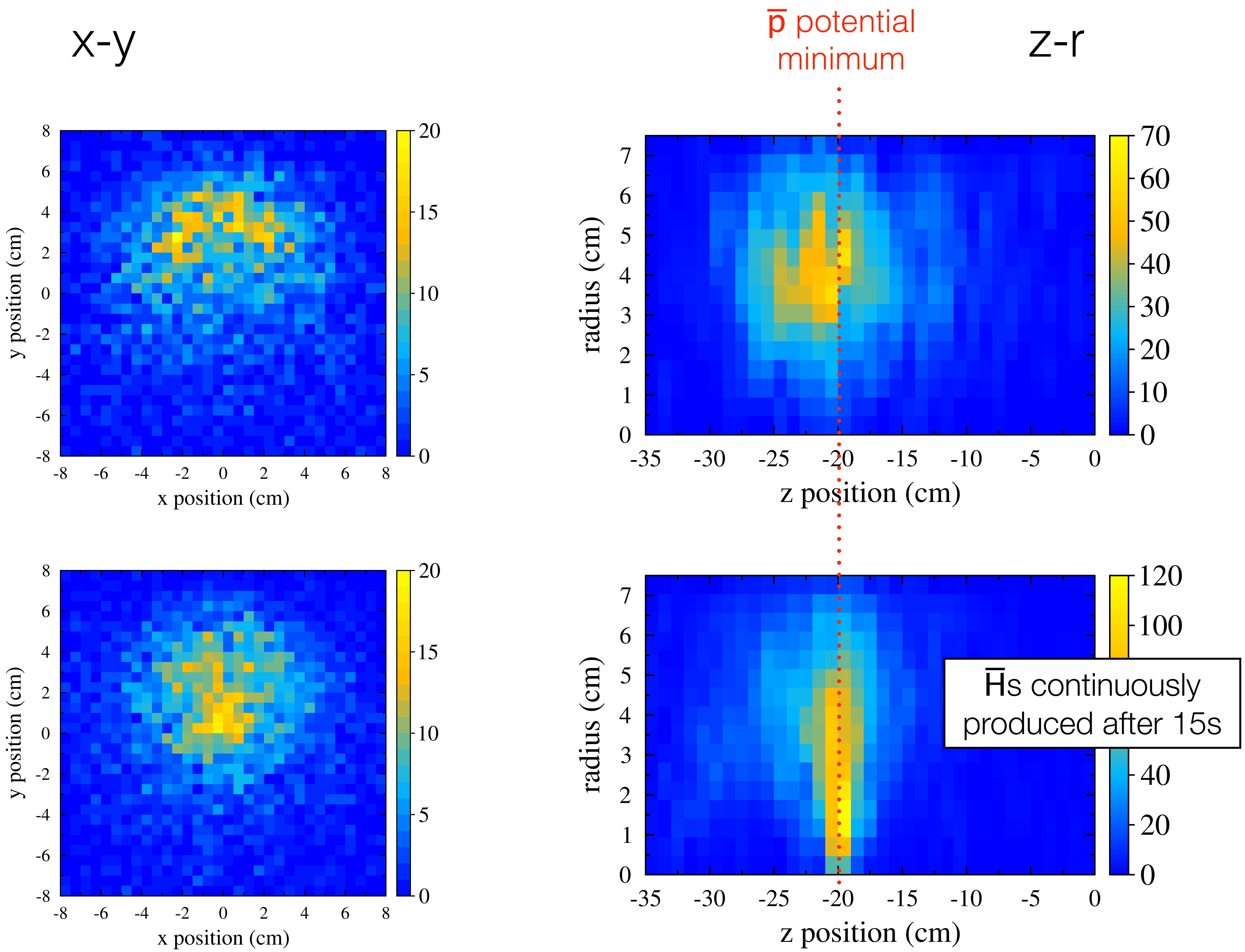


x-y

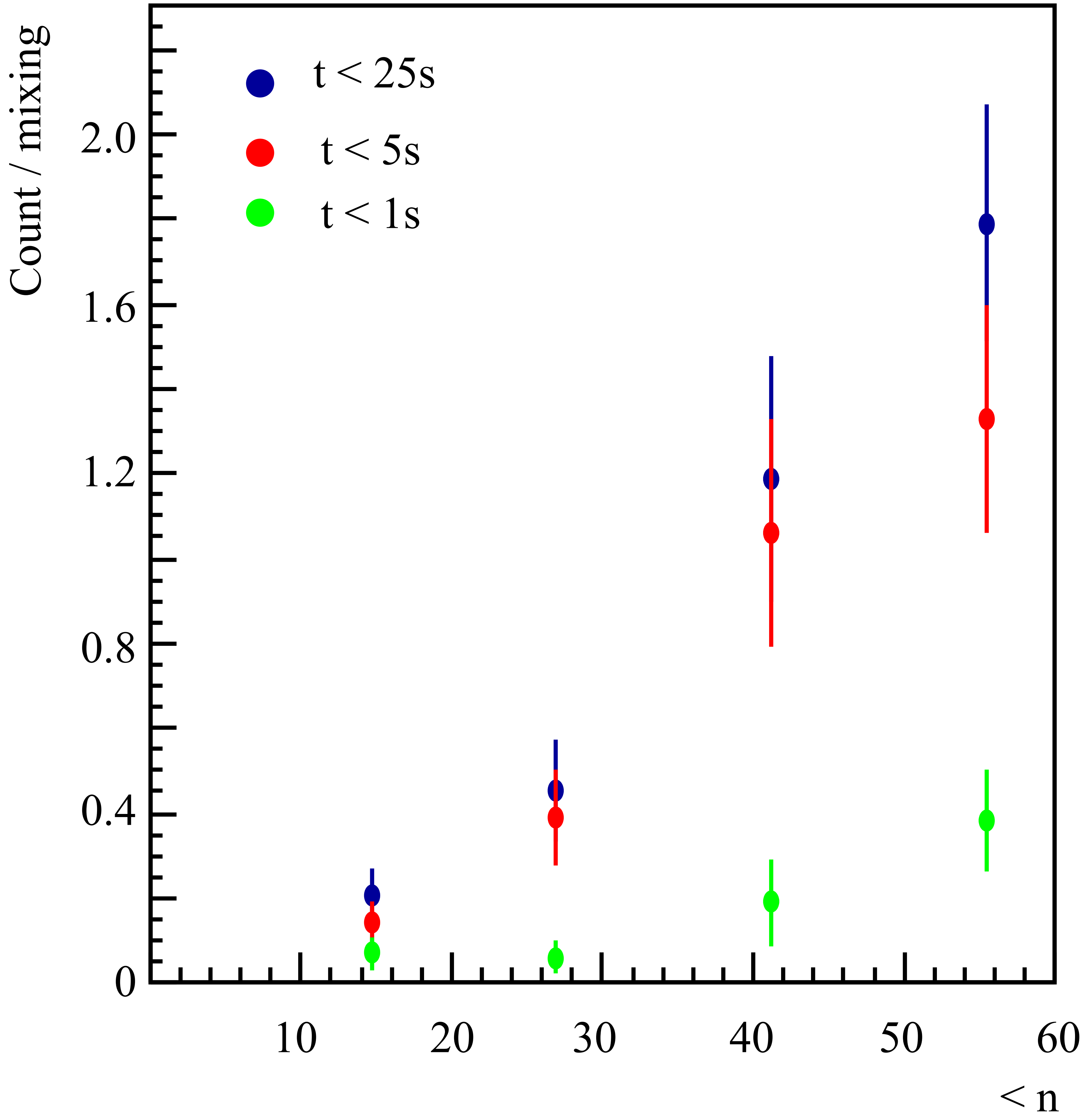
z-r

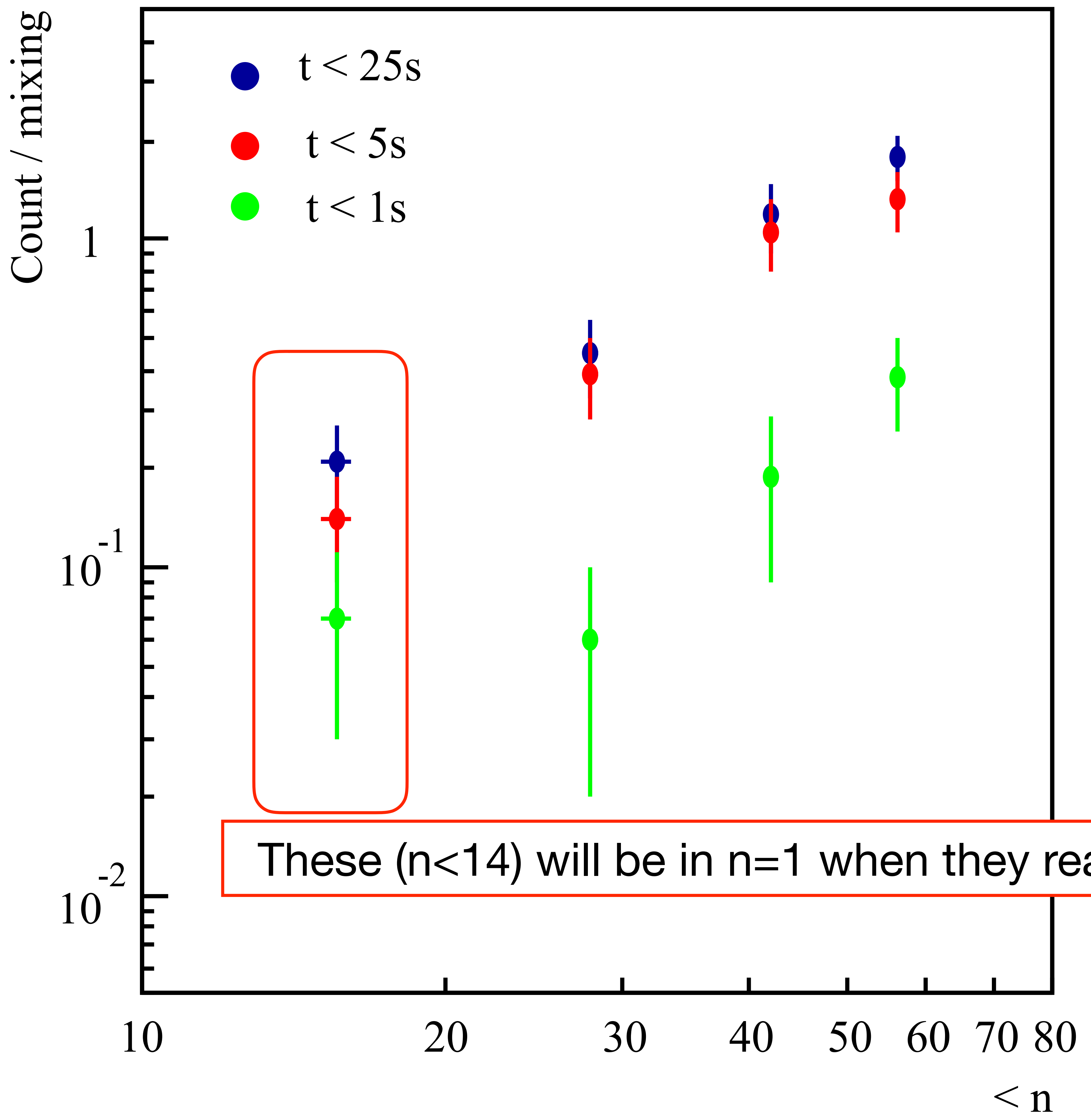
t=0-3s

t=15-30s



$\overline{H}$ principal quantum number study (using the FI in front of the $\overline{H}$ detector)





These (n<14) will be in n=1 when they reach the cavity

1. Successful transport of $\bar{p}$s at 1.5 eV (T~0.4 eV)

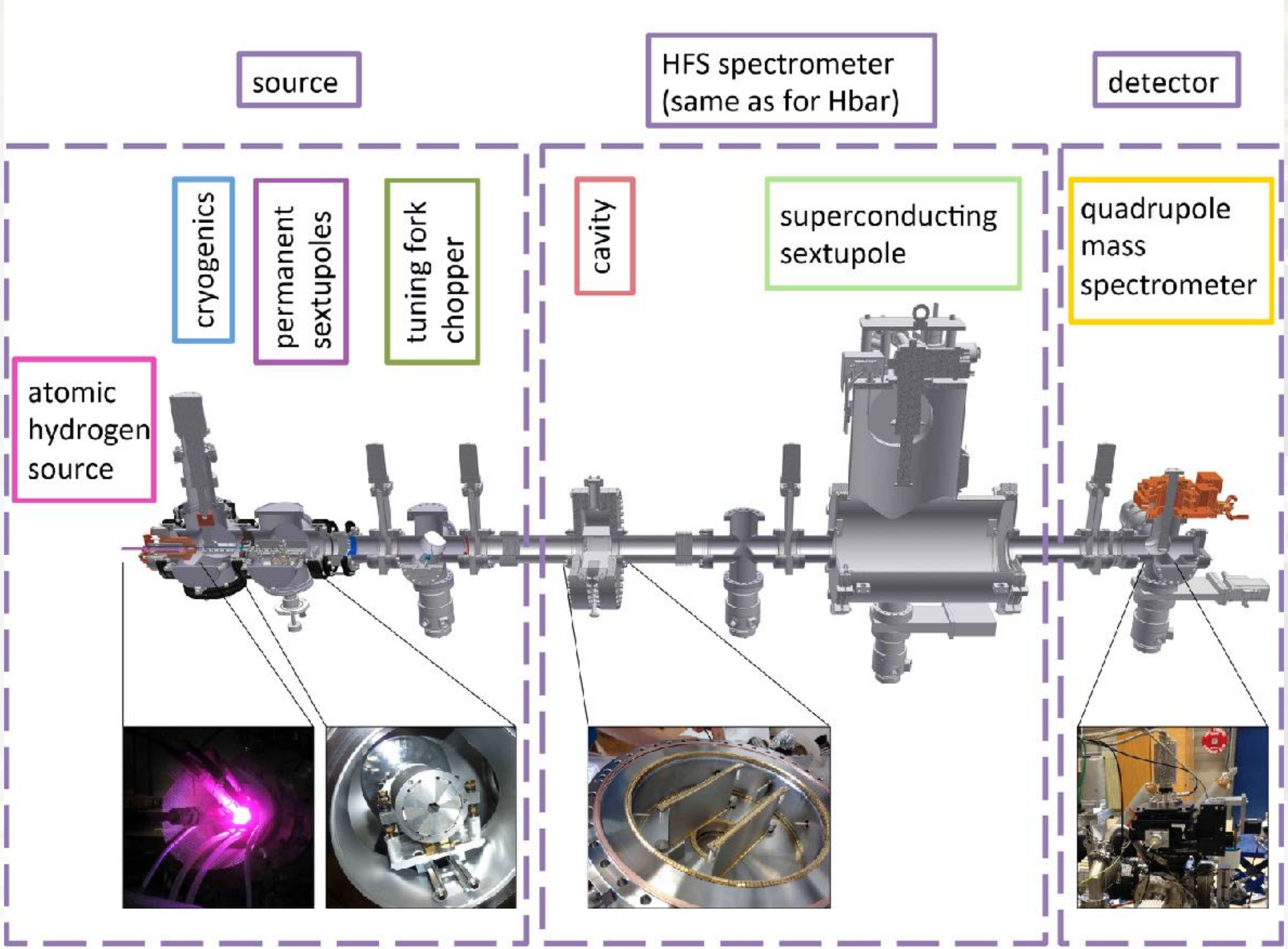
2. Around 60% of FIC events were localized within the first 0.7 s
(this is different from the $\bar{H}$-detector result - more study needed)

3. ~80% of $\bar{p}$s quickly separated from e+ while the rest continue to contribute to the $\bar{H}$ formation

4. $\bar{H}$ formation fraction is ~ 4%
n<14 $\bar{H}$ production confirmed

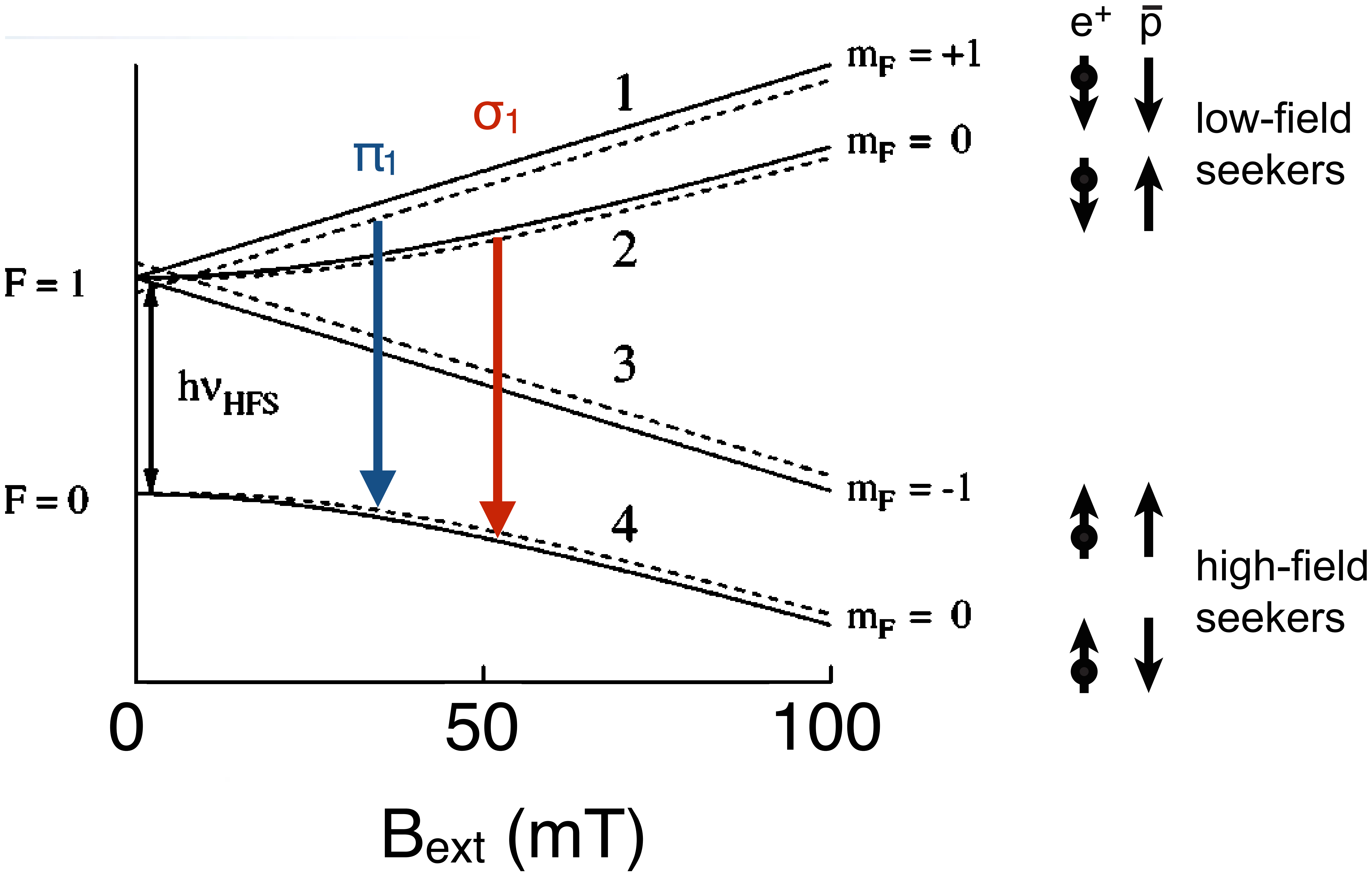
5. 10 $\bar{H}$gs / mixing needed for spectroscopy

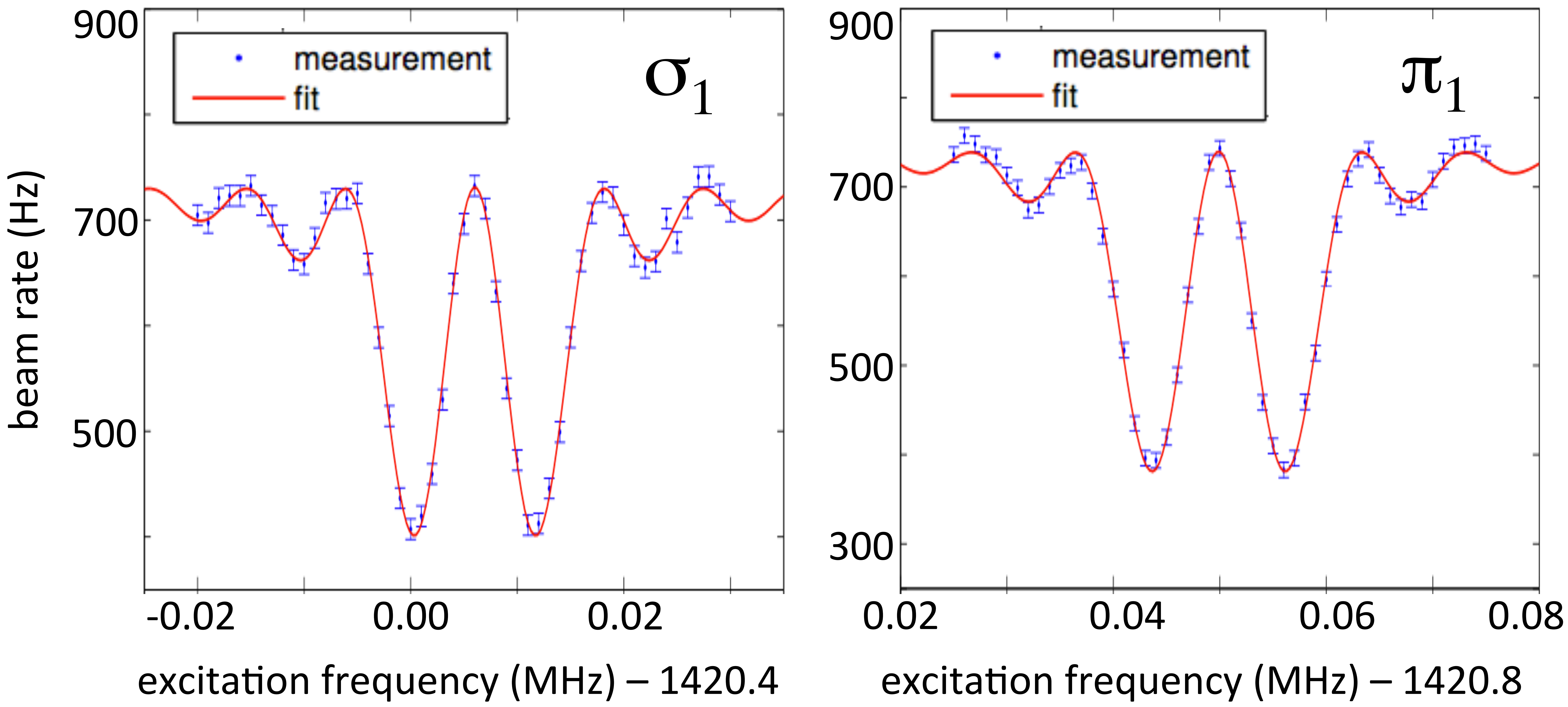
3. H GSHFS Spectroscopy



σ_1 - less sensitive to B_{ext}

π_1 - more sensitive to B_{ext}
& possible CPTV effects



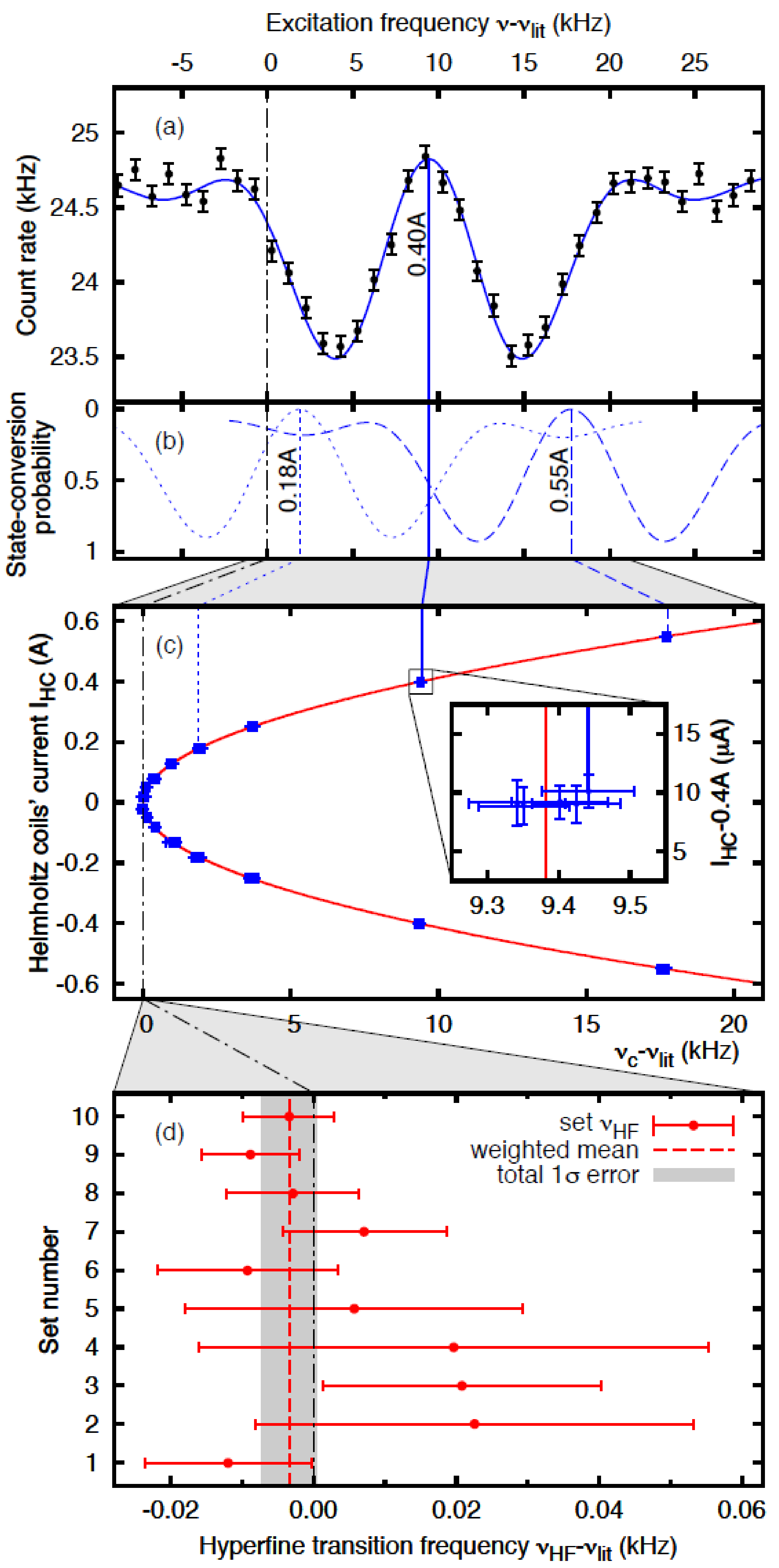

900
700
500
beam rate (Hz)
measurement
fit
σ1
-0.02
0.00
0.02
excitation frequency (MHz) – 1420.4
900
700
500
300
measurement
fit
π1
0.02
0.04
0.06
0.08
excitation frequency (MHz) – 1420.8

H-HFS σ_1

$\nu_{\rm HF} = 1\ 420\ 405\ 748.4(3.4)(1.6)\ \mathrm{Hz}$

Error **2.7 ppb**: 18x improvement over
Kush, Phys. Rev. 100, 1188 (1955)
Deviation from maser ($\Delta f/f \sim 10^{-12}$) :
3.4 Hz < 1σ error

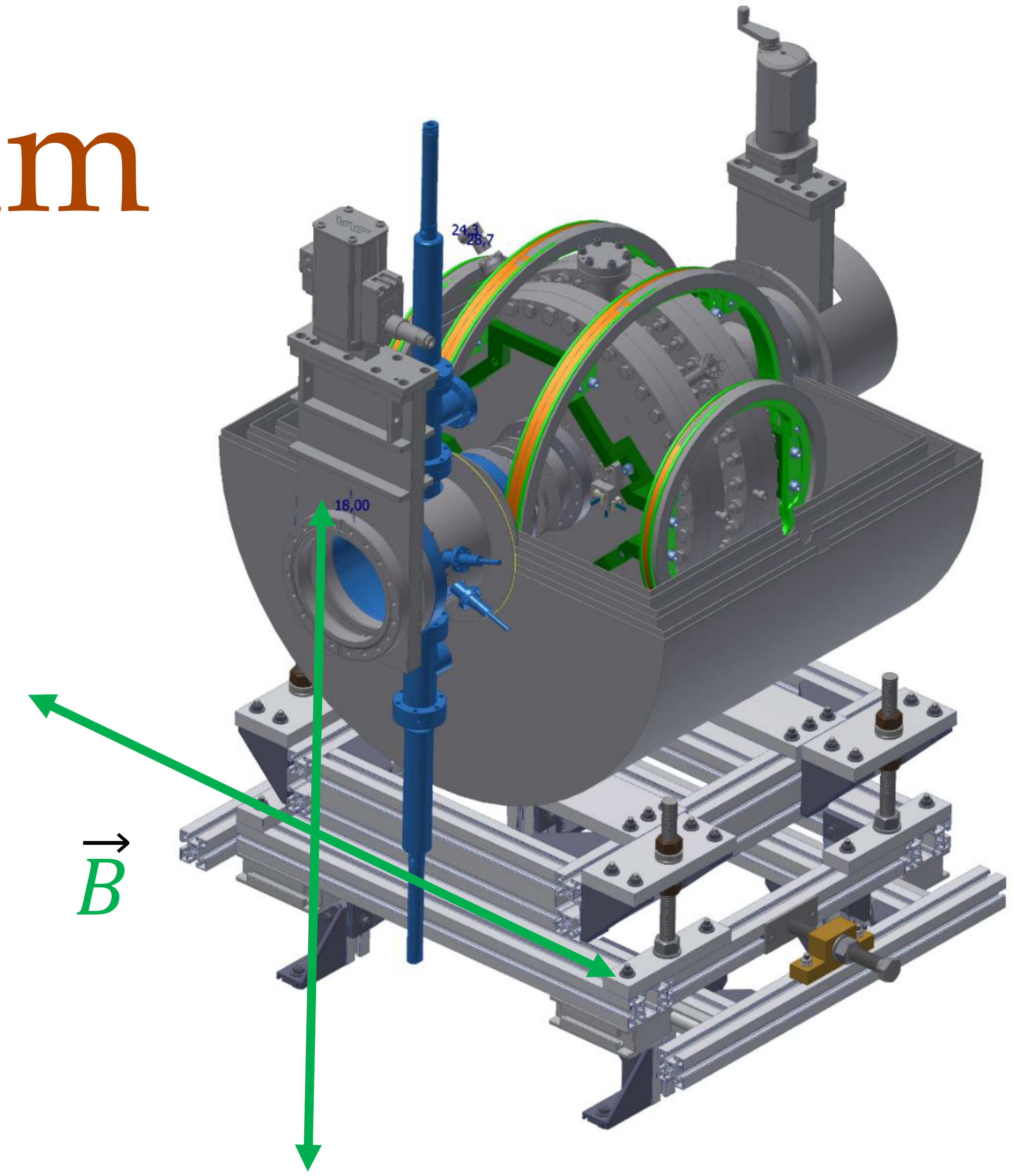
contribution	1σ st.dev. (Hz)
systematic error	
frequency standard	1.62
common fit parameters	
$\bar{v}_H$	0.05
σ_v	0.03
$B_{\rm osc}$	0.02
systematic error total	1.62
statistical error	3.43
total error	3.79

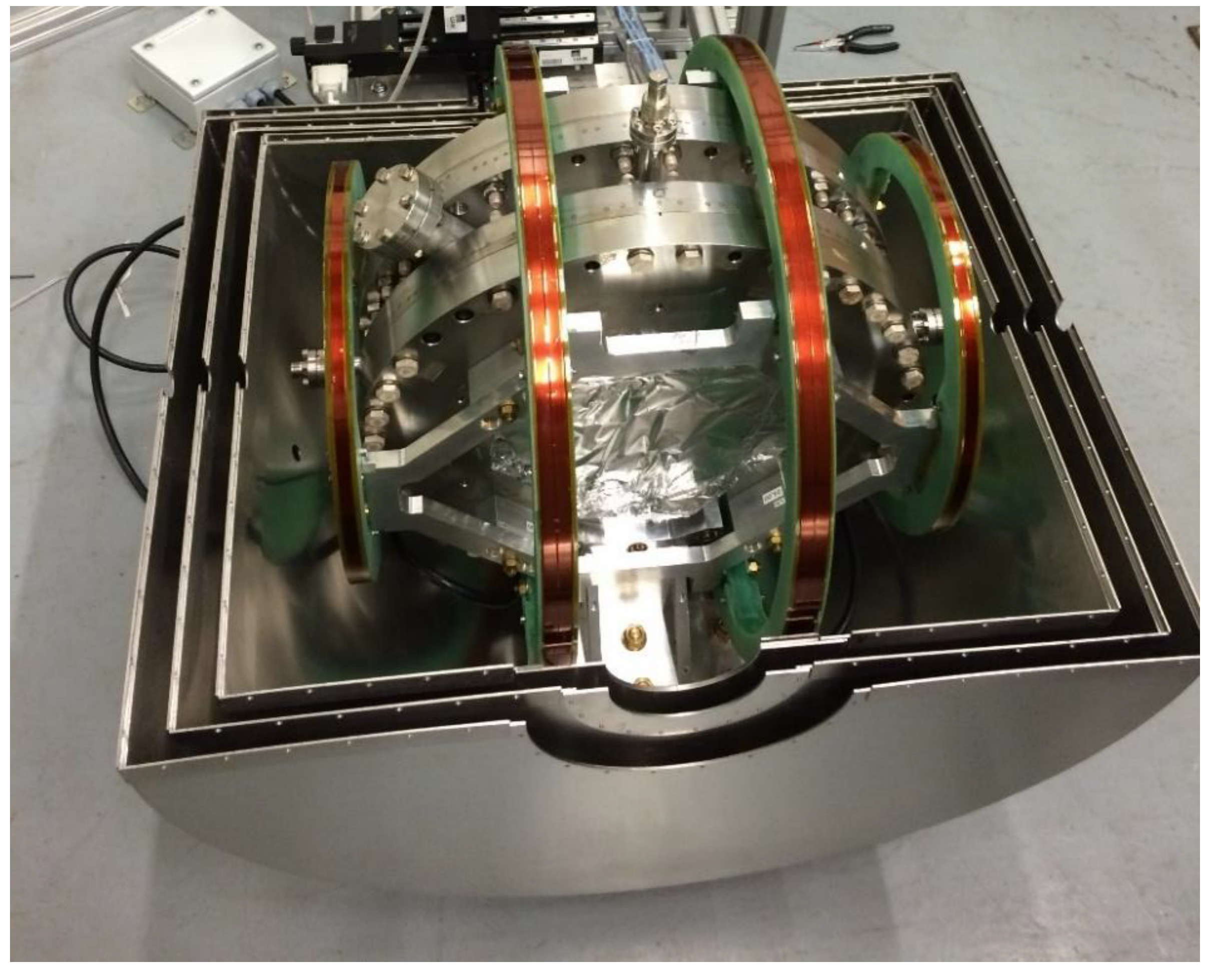


arXiv:1610.06392

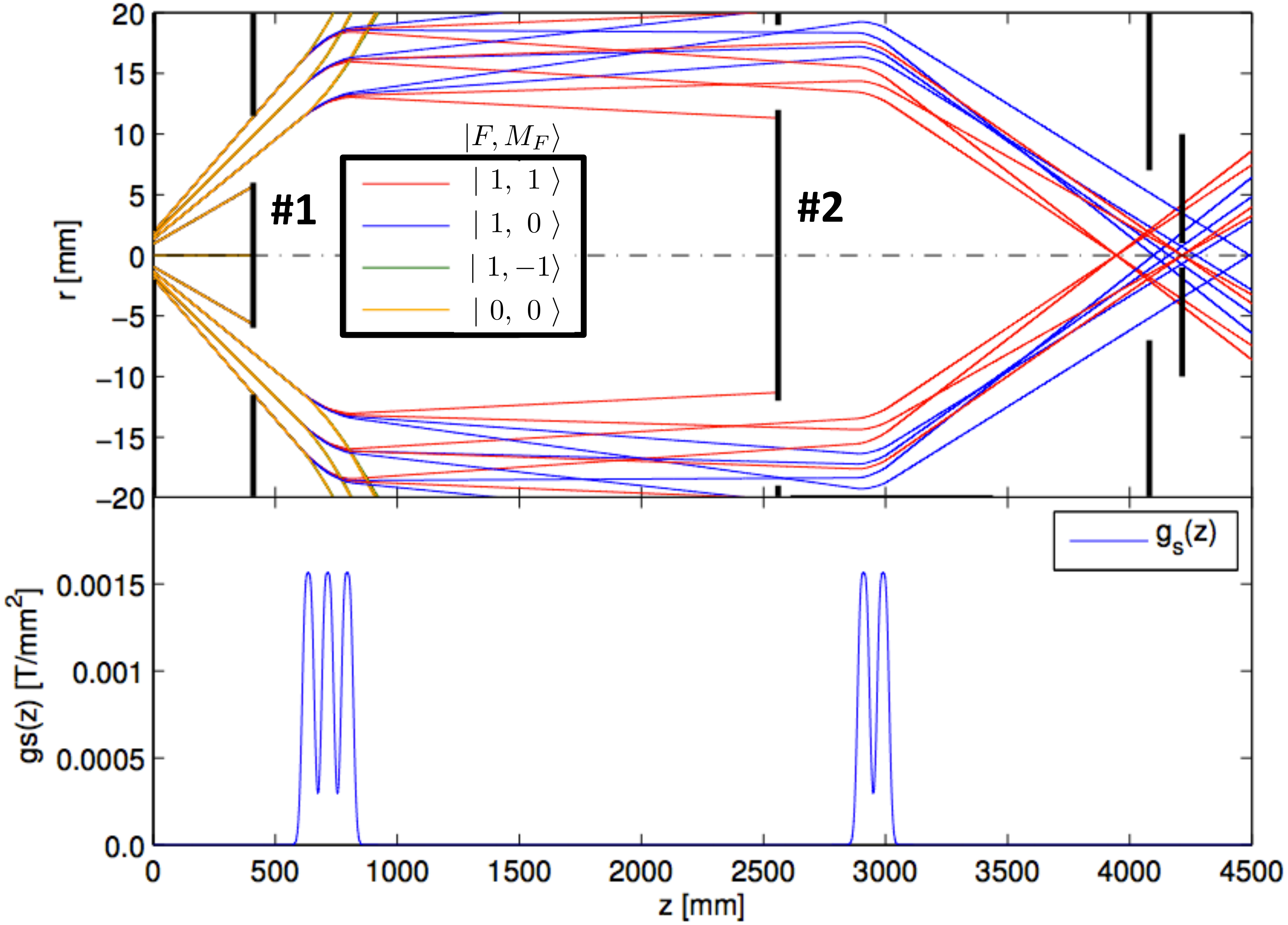
Next steps for H-beam

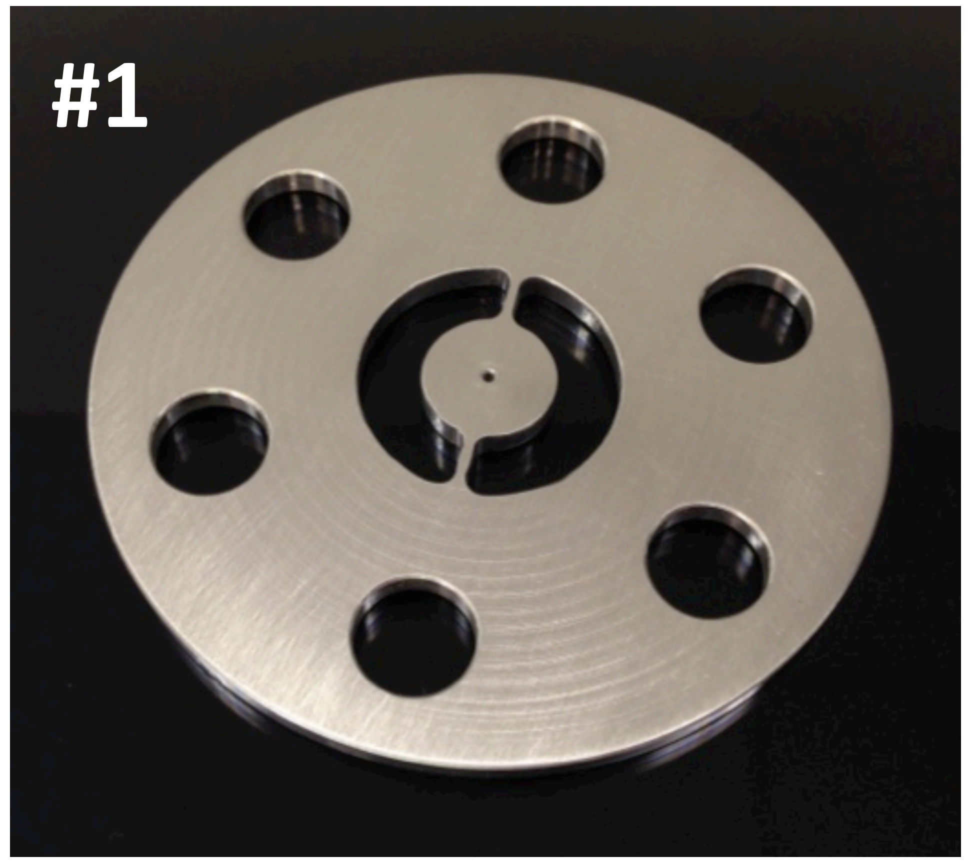
- π_1 transition
  - Better field homogeneity
    - Inproved coils, shielding
  - SME: effect only in π_1
  - Non-minimal SME: direction dependent coefficients accessible by beam
- Conditions
  - Invert direction of B-field
  - Rotate B-field
  - Measure also σ_1 (no CPTV) as reference

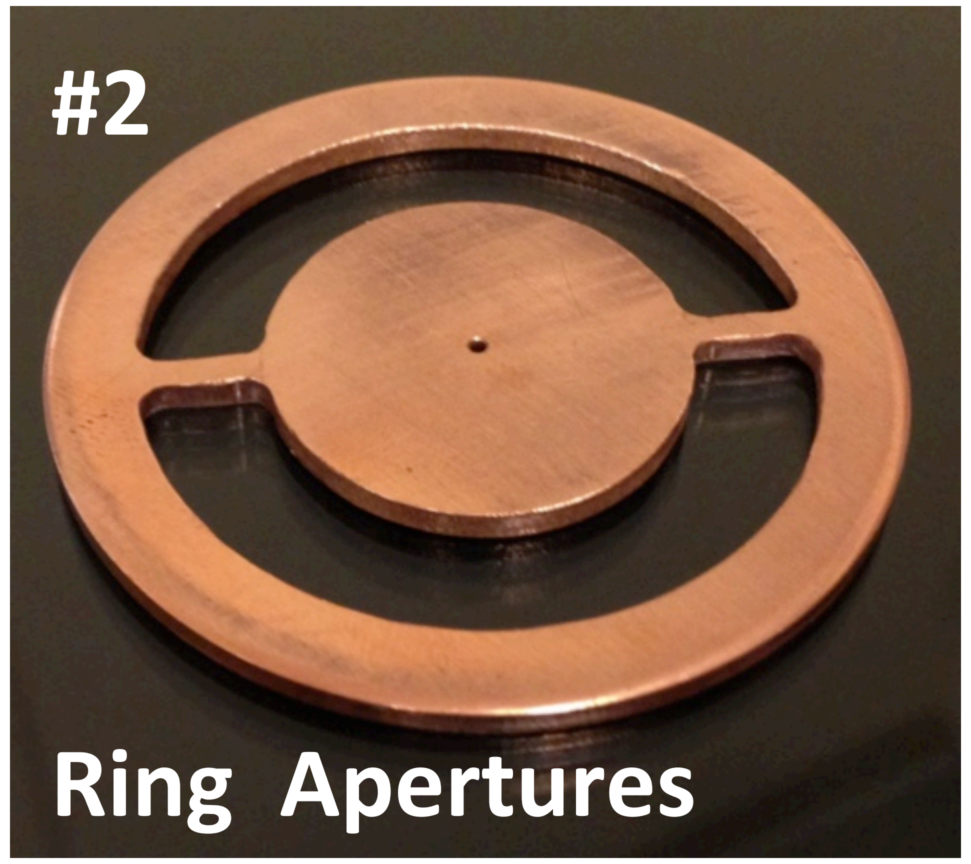




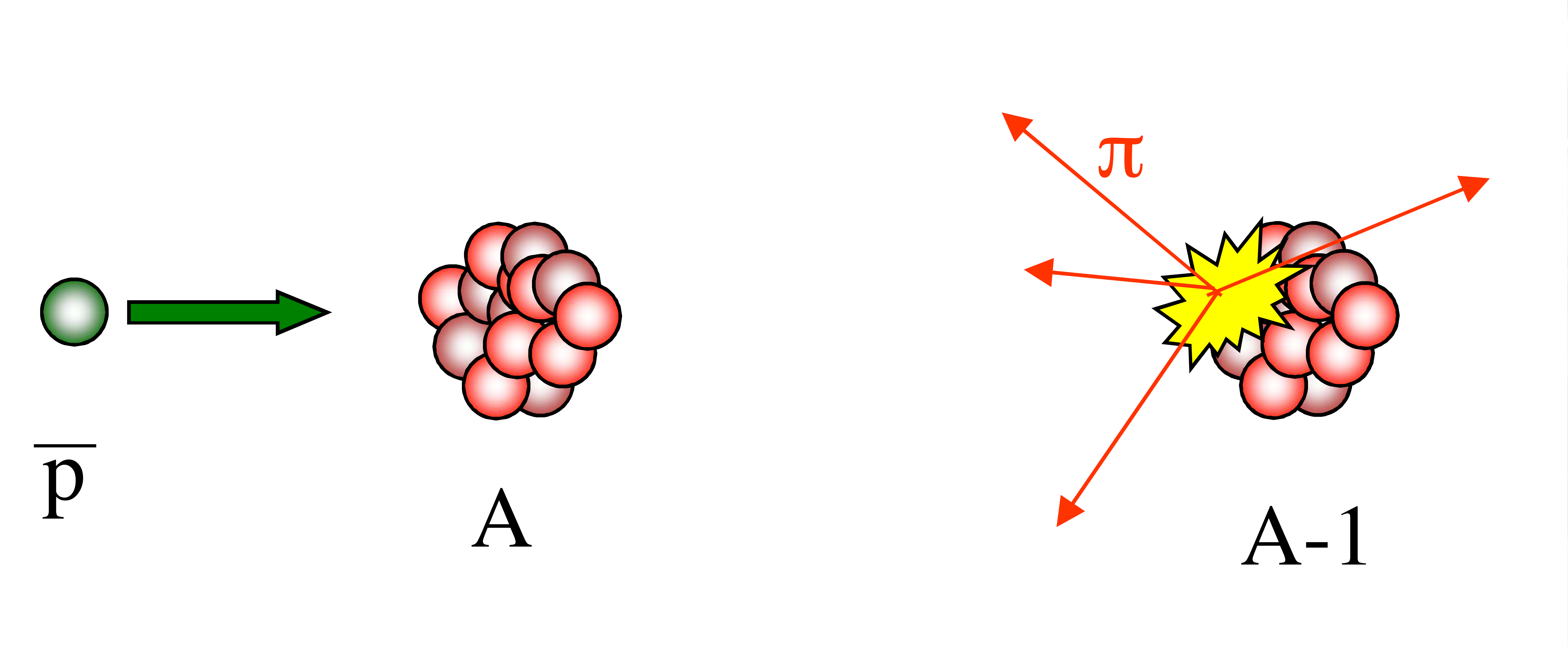
hollow hydrogen beam (simulation)



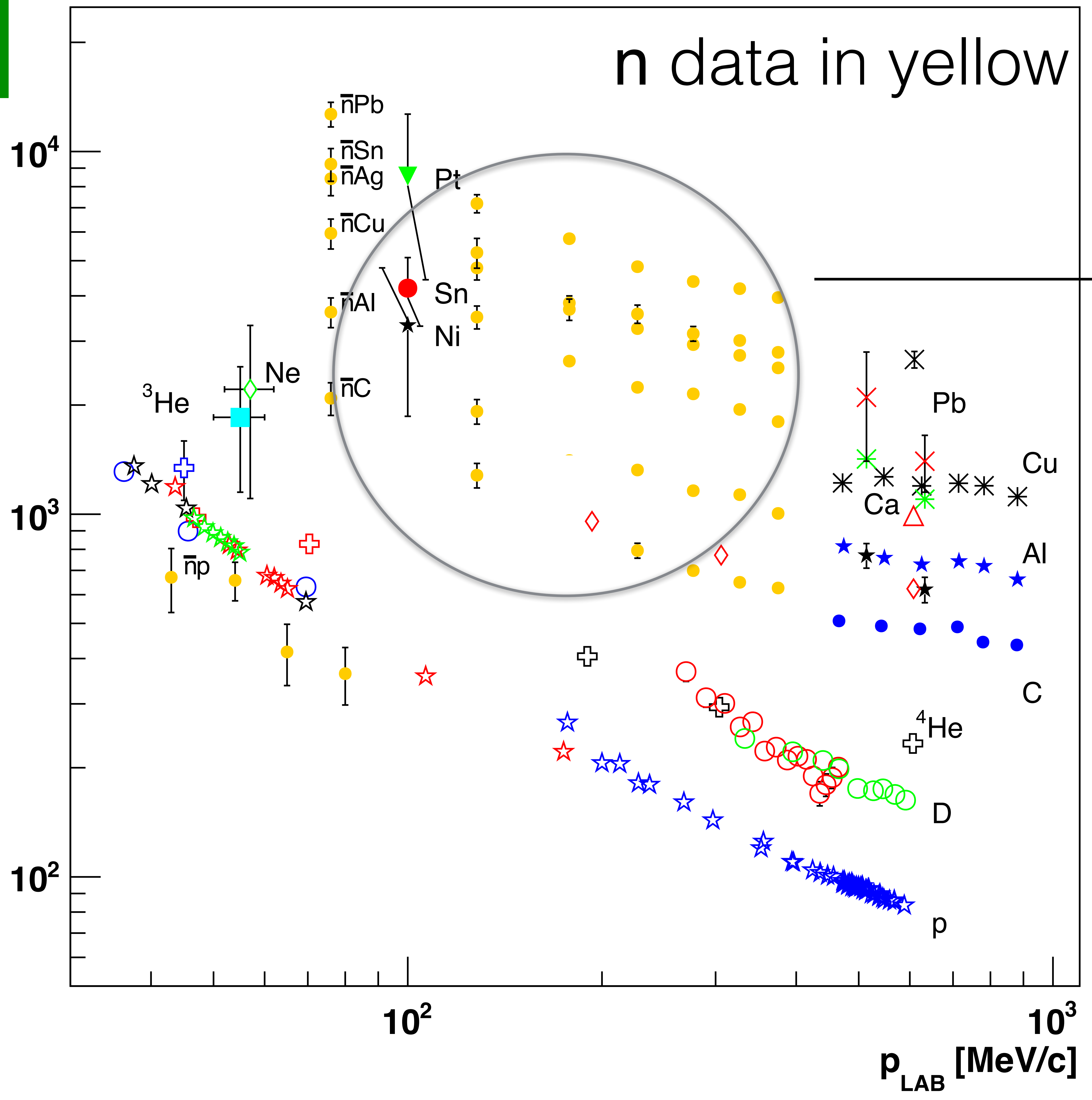


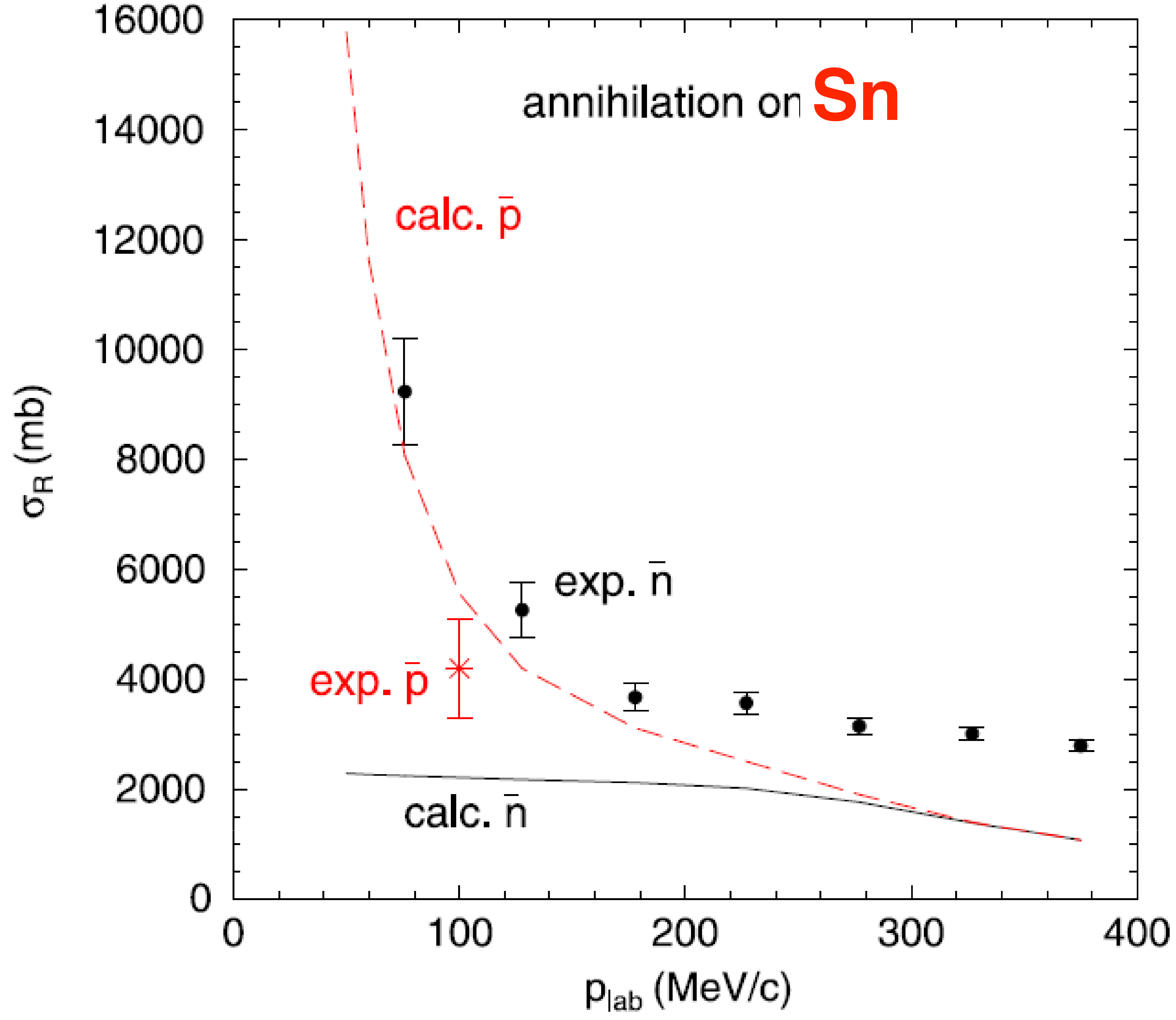


4. $\bar{p}$ annihilation σ at 5.3 MeV



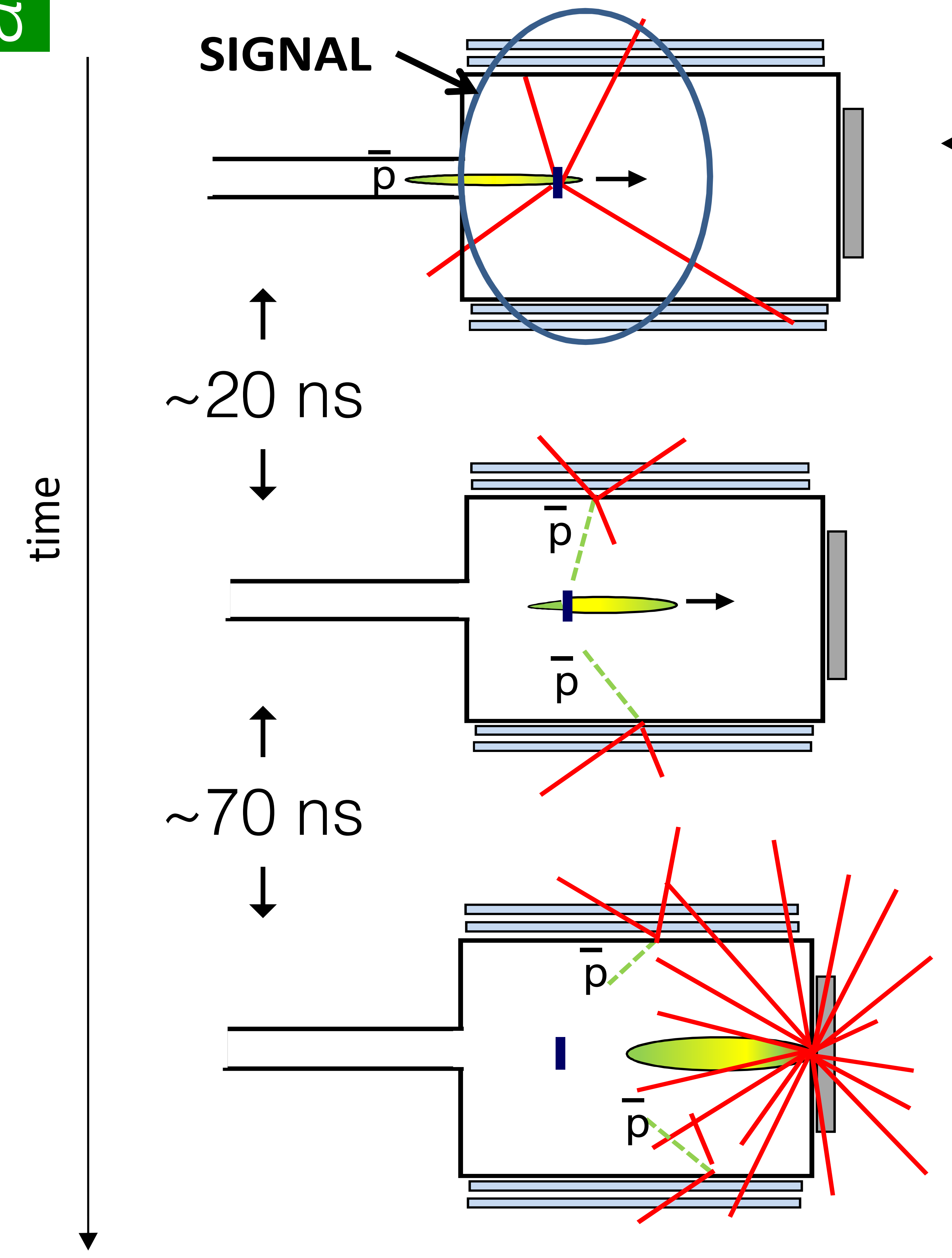
Existing data



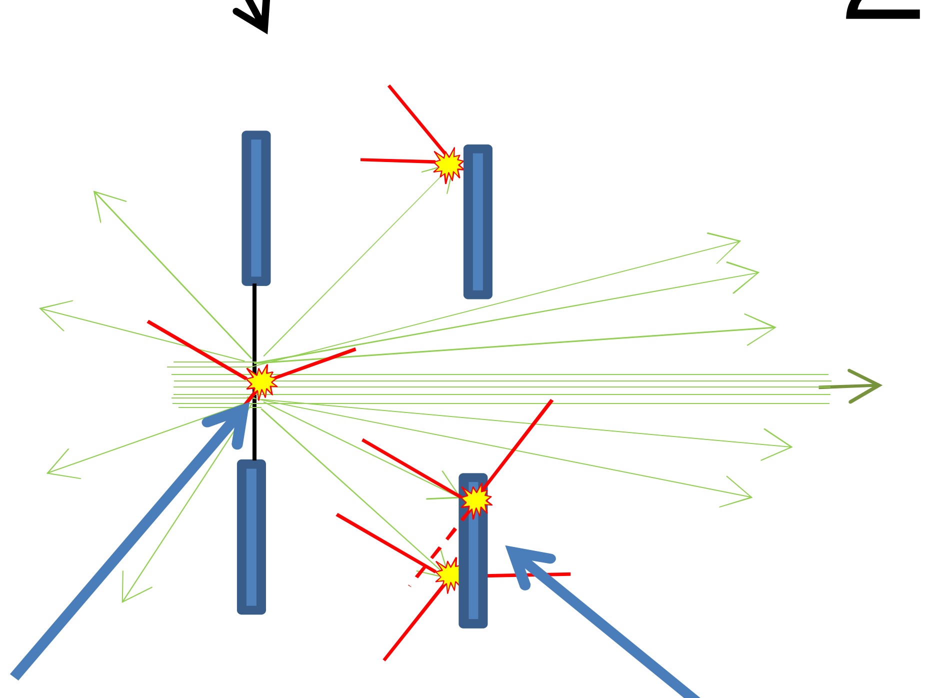


why $\bar{n}$ behaving like $\bar{p}$?
puzzling behavior at ~ 5 MeV

p̄ on C at 5.3 MeV, σ precision <10%

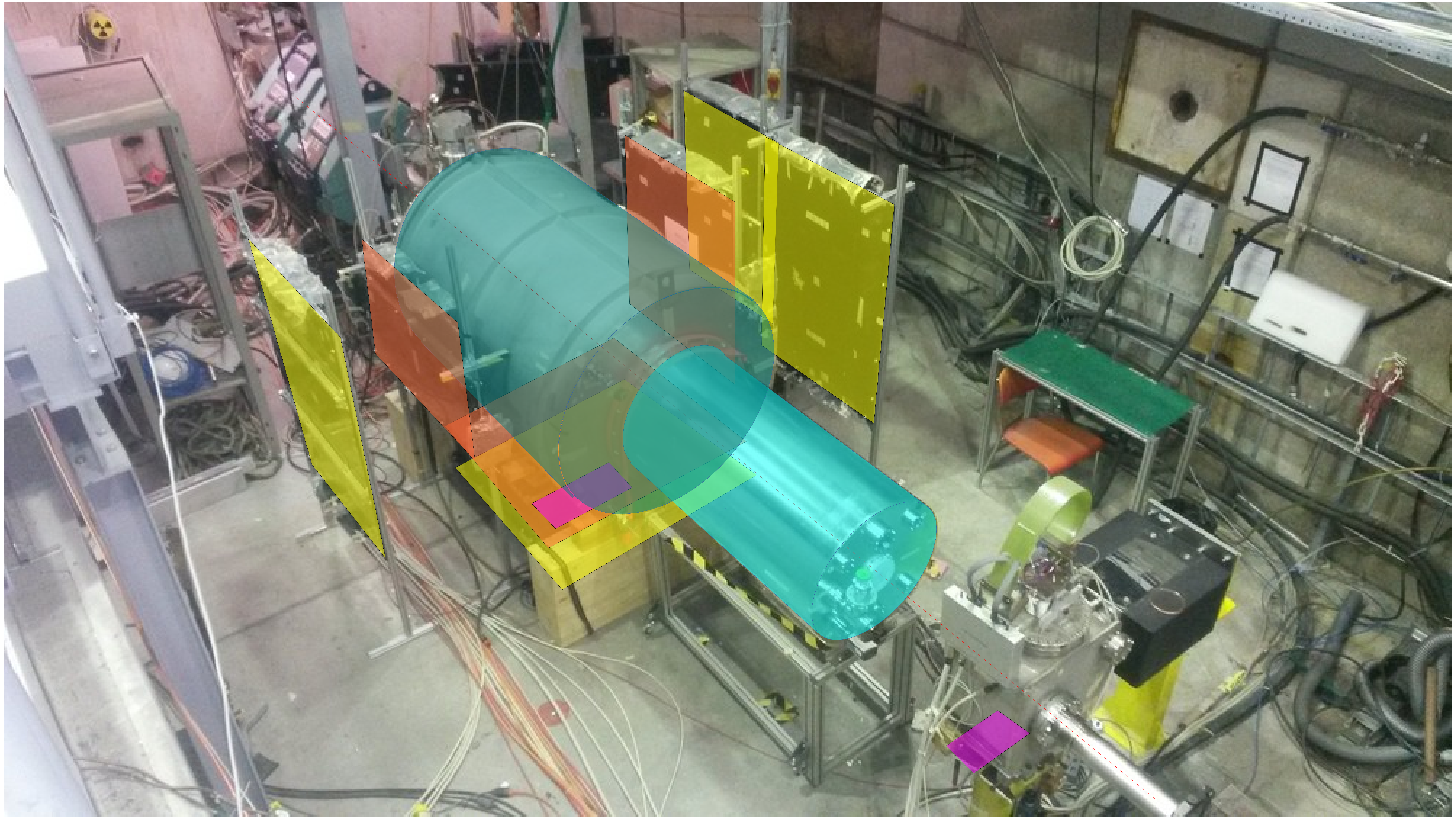


$$\sigma_{ann}(\bar{p}A) \propto \frac{N_{events}}{N_{beam}}$$

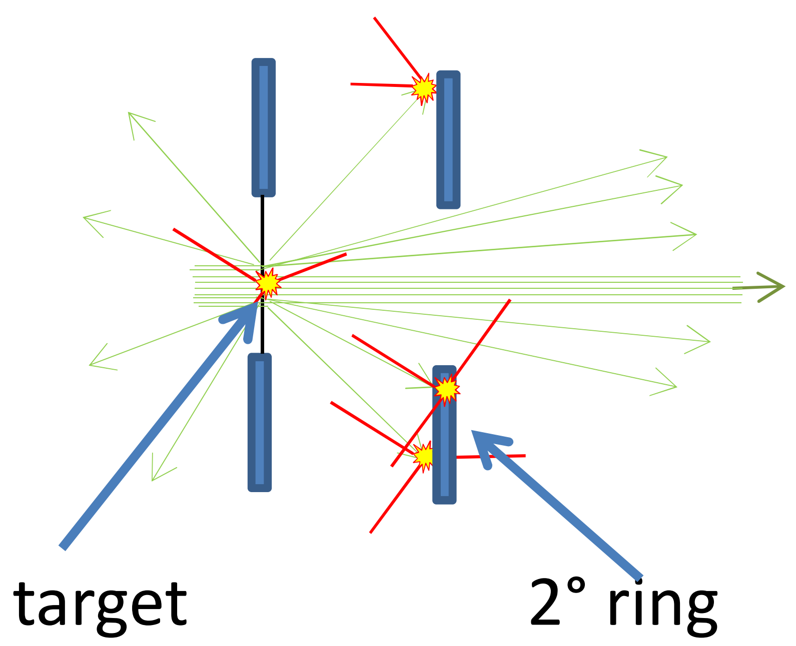


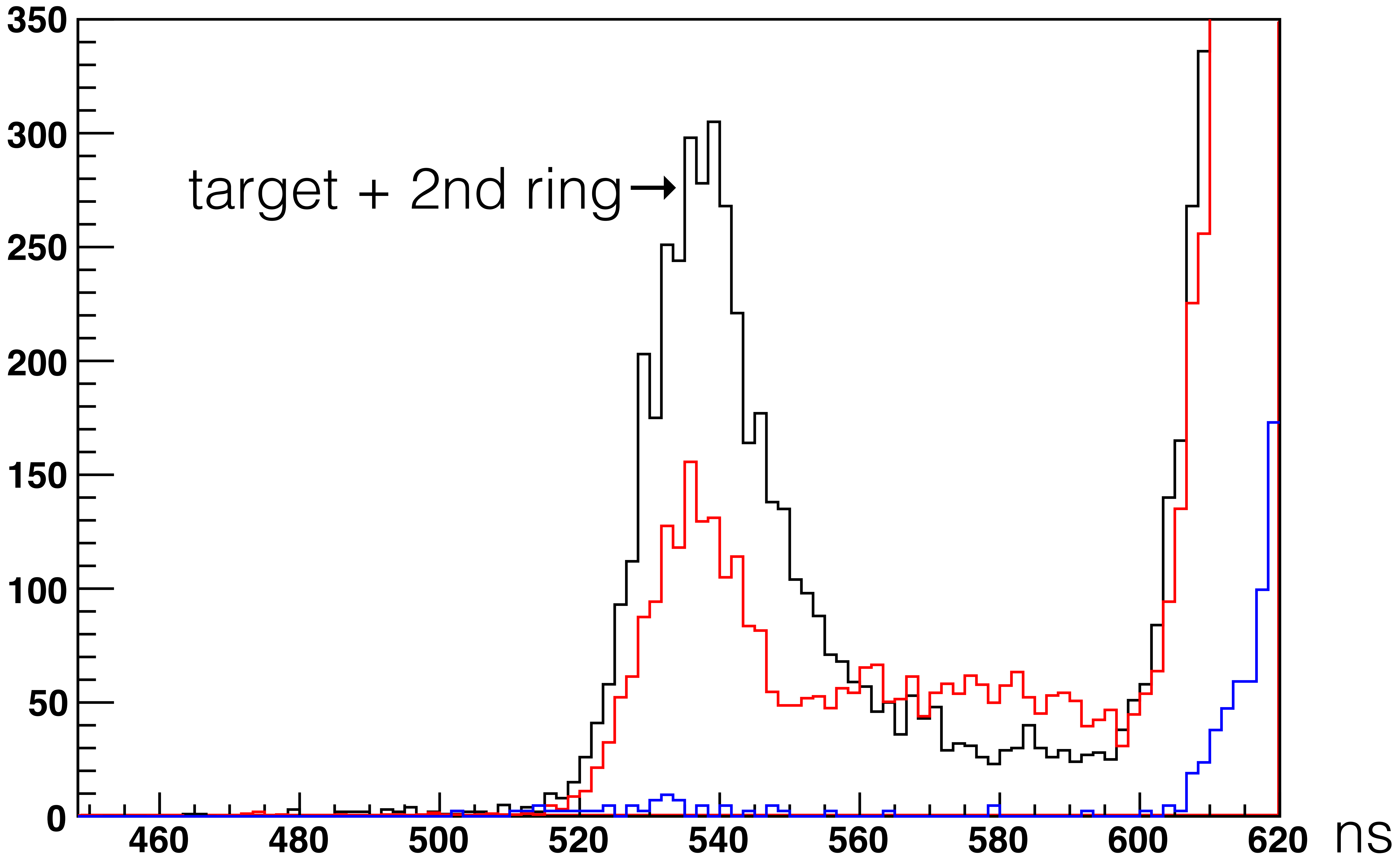
1. use timing to separate signal from background
2. use 2nd ring (Rutherford) to obtain absolute σ

σ_{ann} setup 2015 (5.3 MeV beam)



annihilation on the target clearly separated





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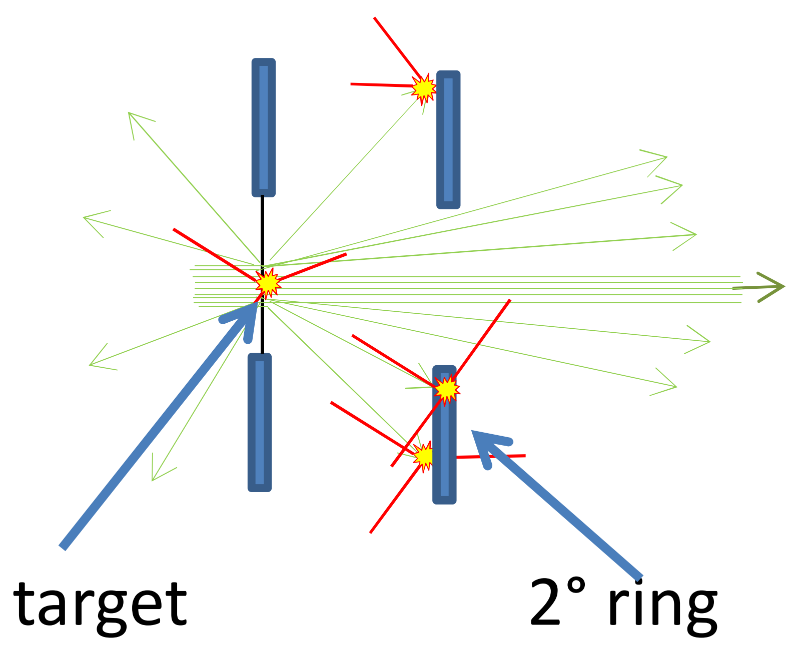

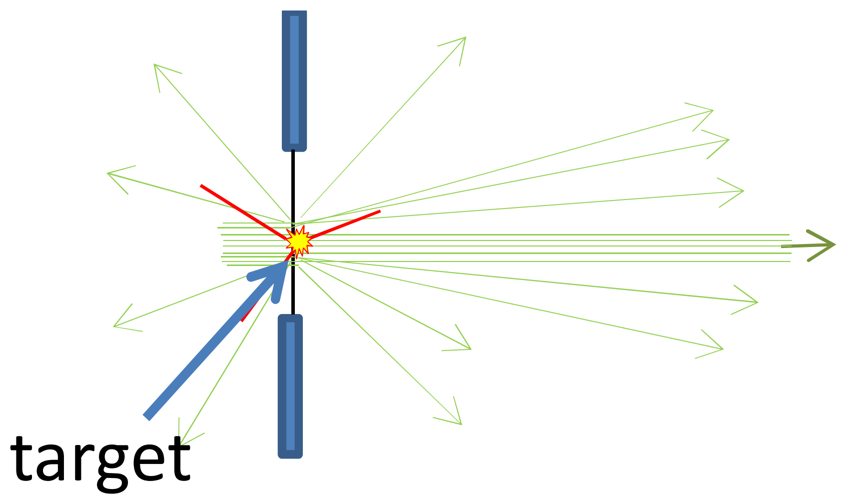

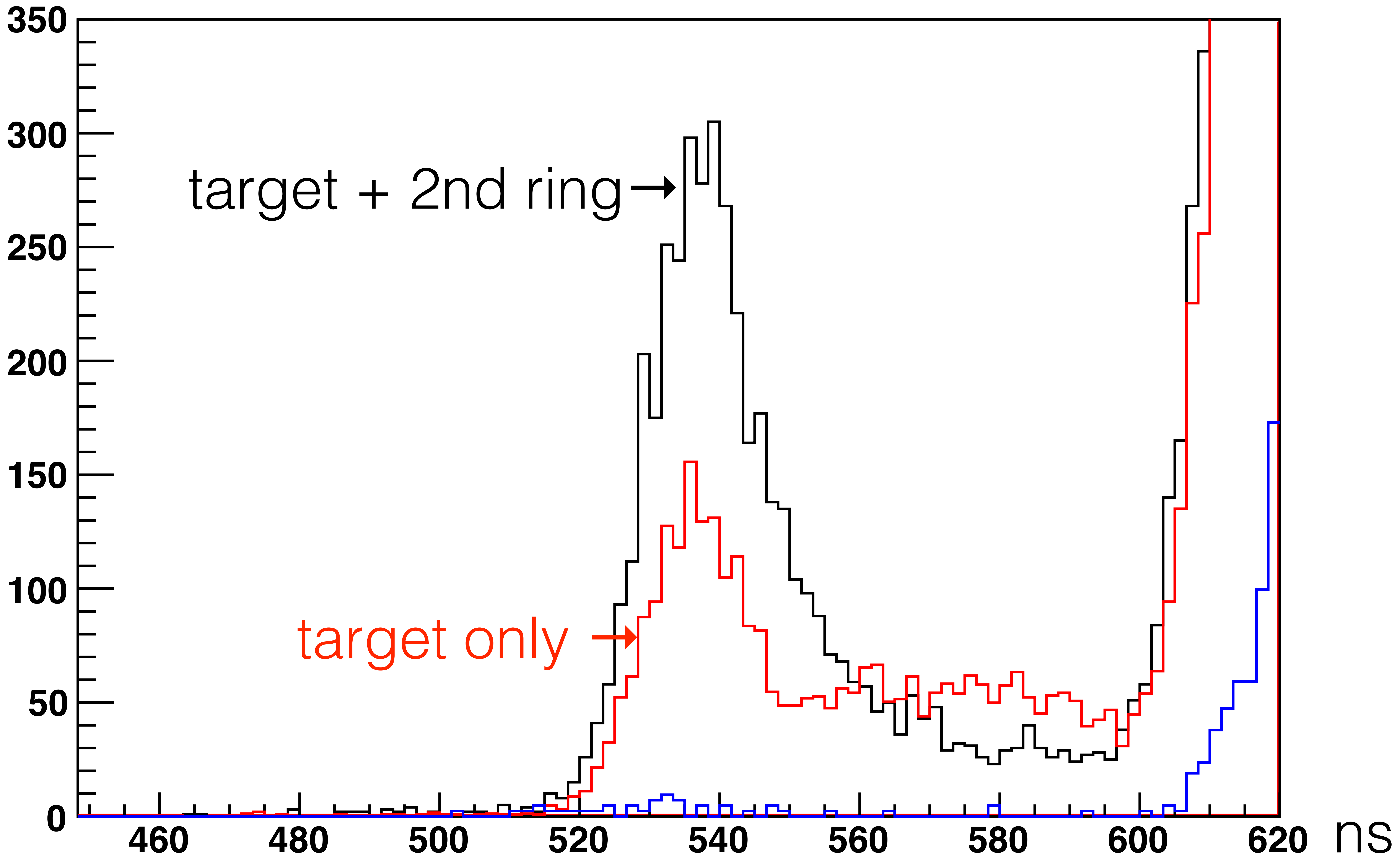

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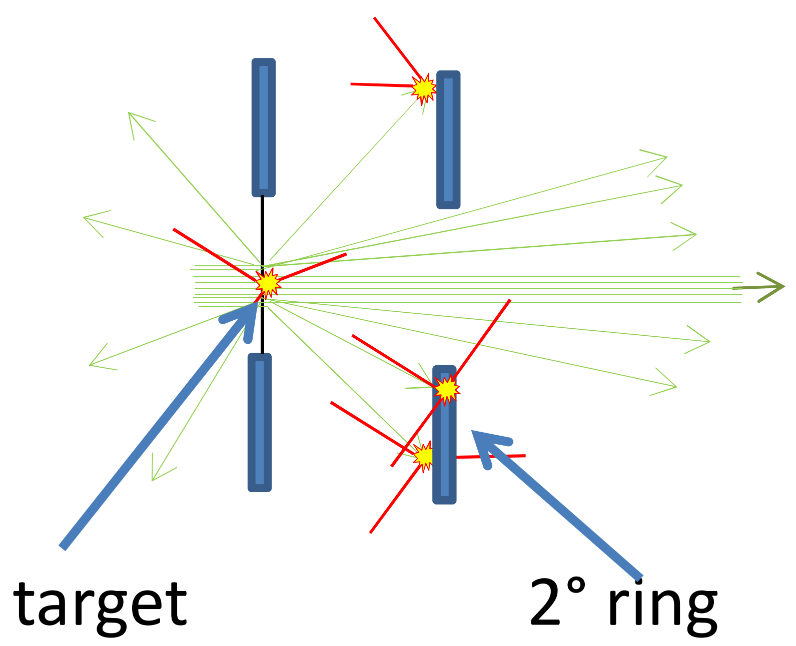

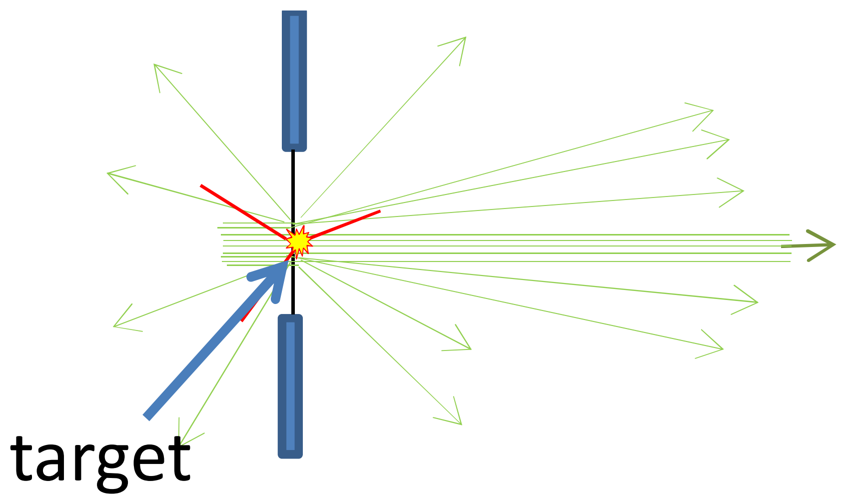

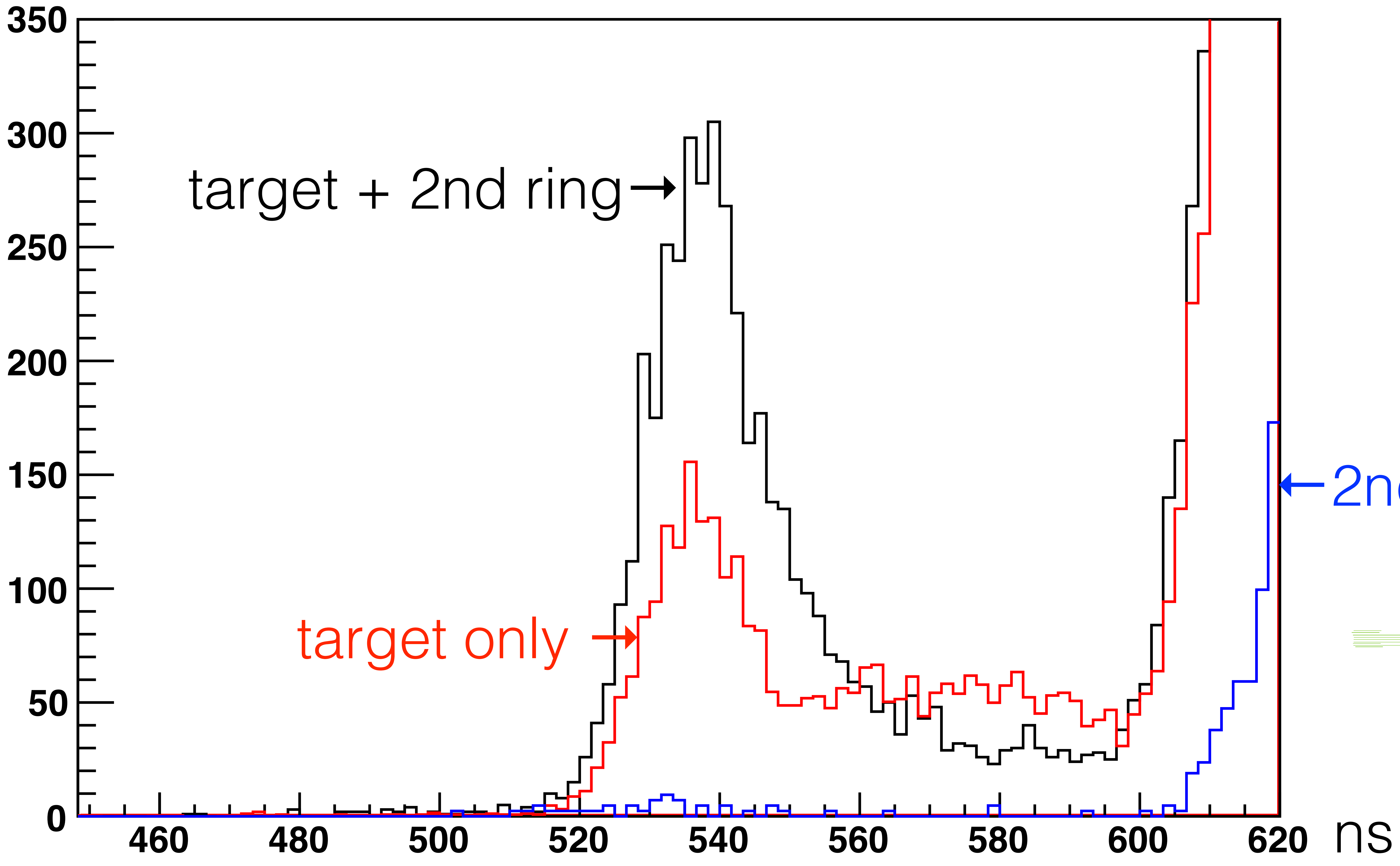

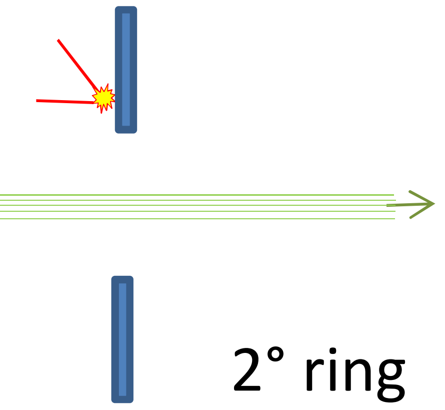

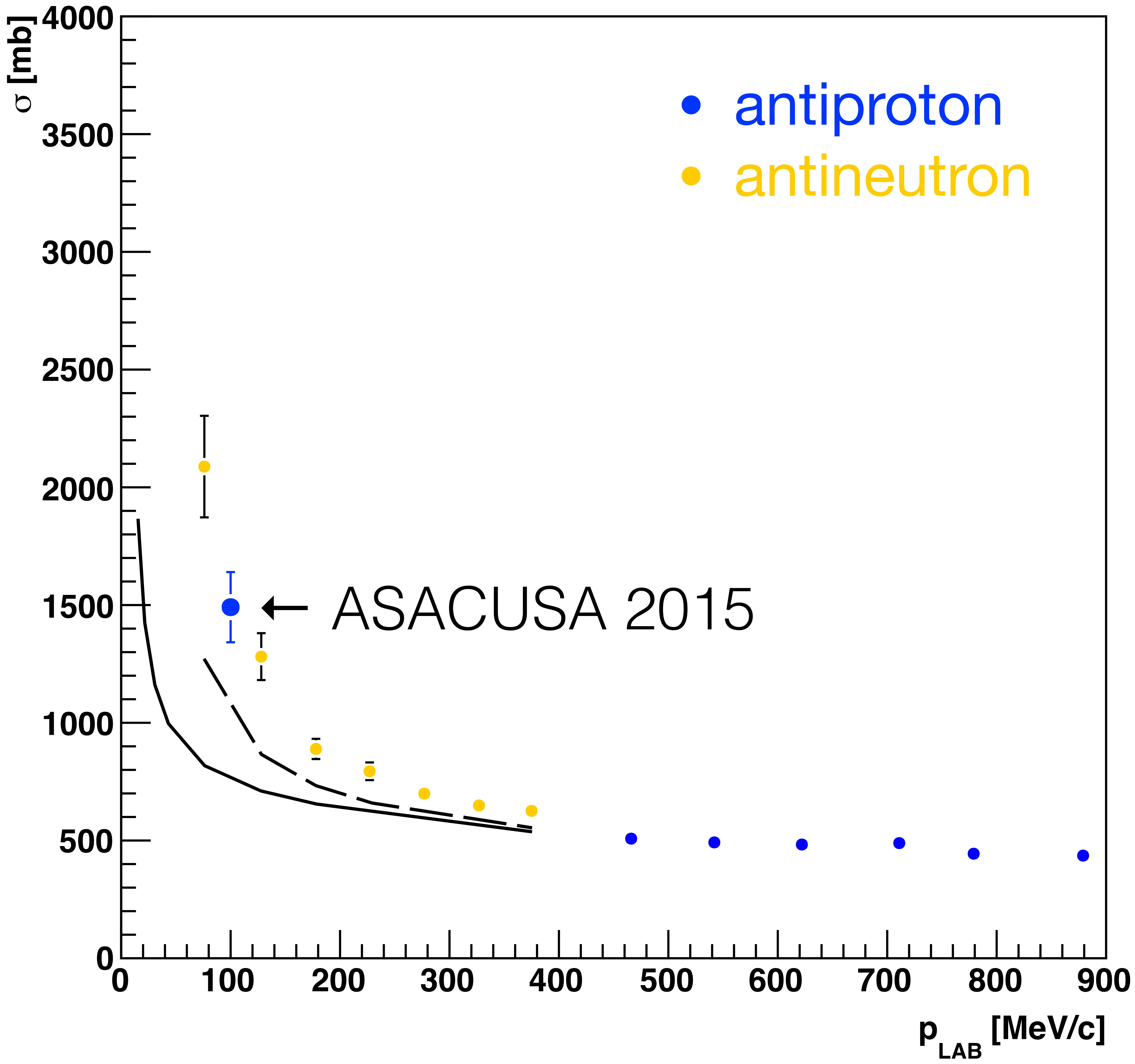

Why pbar and nbar σ_{ann} similar?
pbar σ_{ann} higher than theory?
no clear explanations yet…

Conclusions

- In 2016, ASACUSA achieved:

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  single-photon $\bar{p}$He at 1.5 K, published in Science

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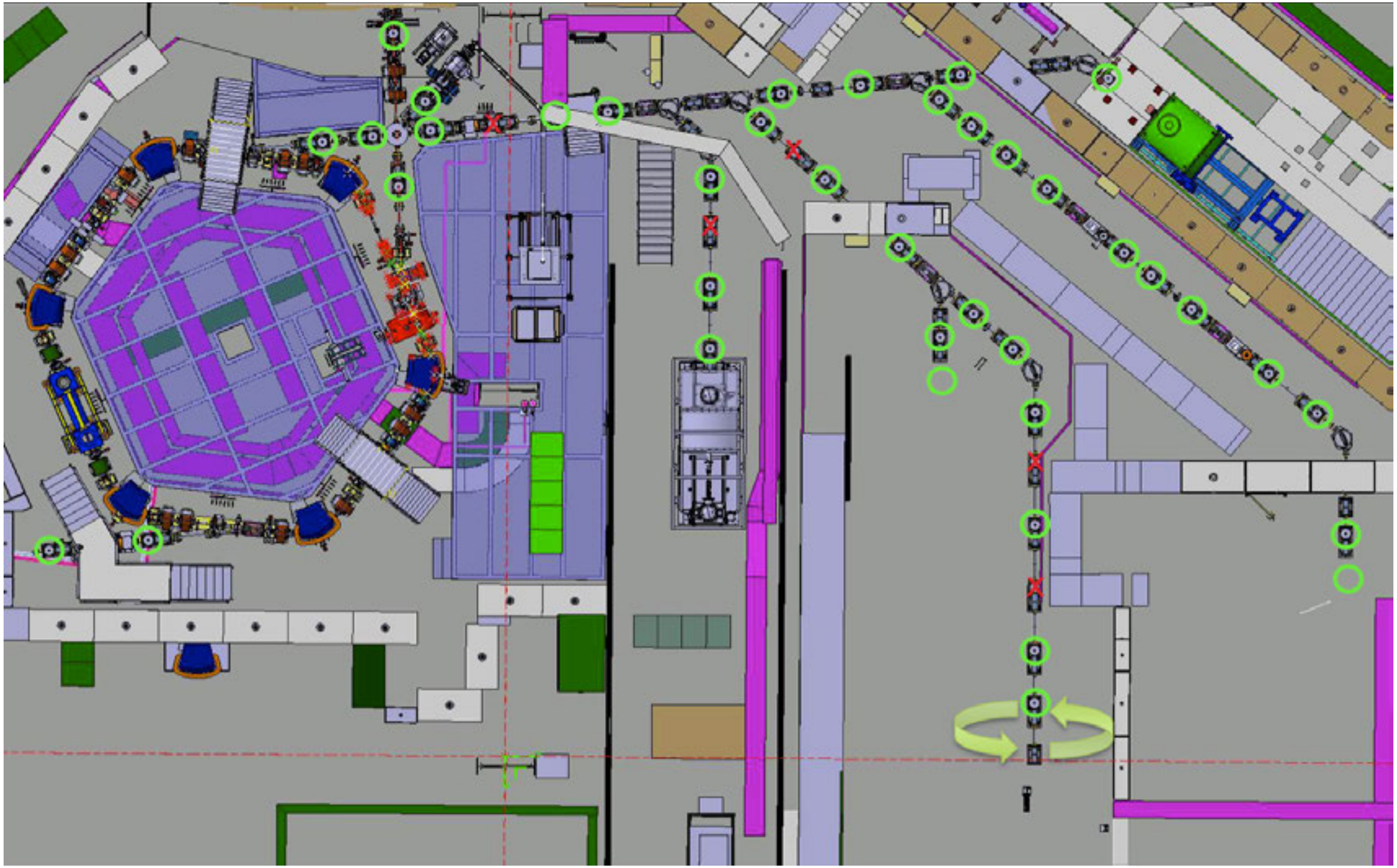
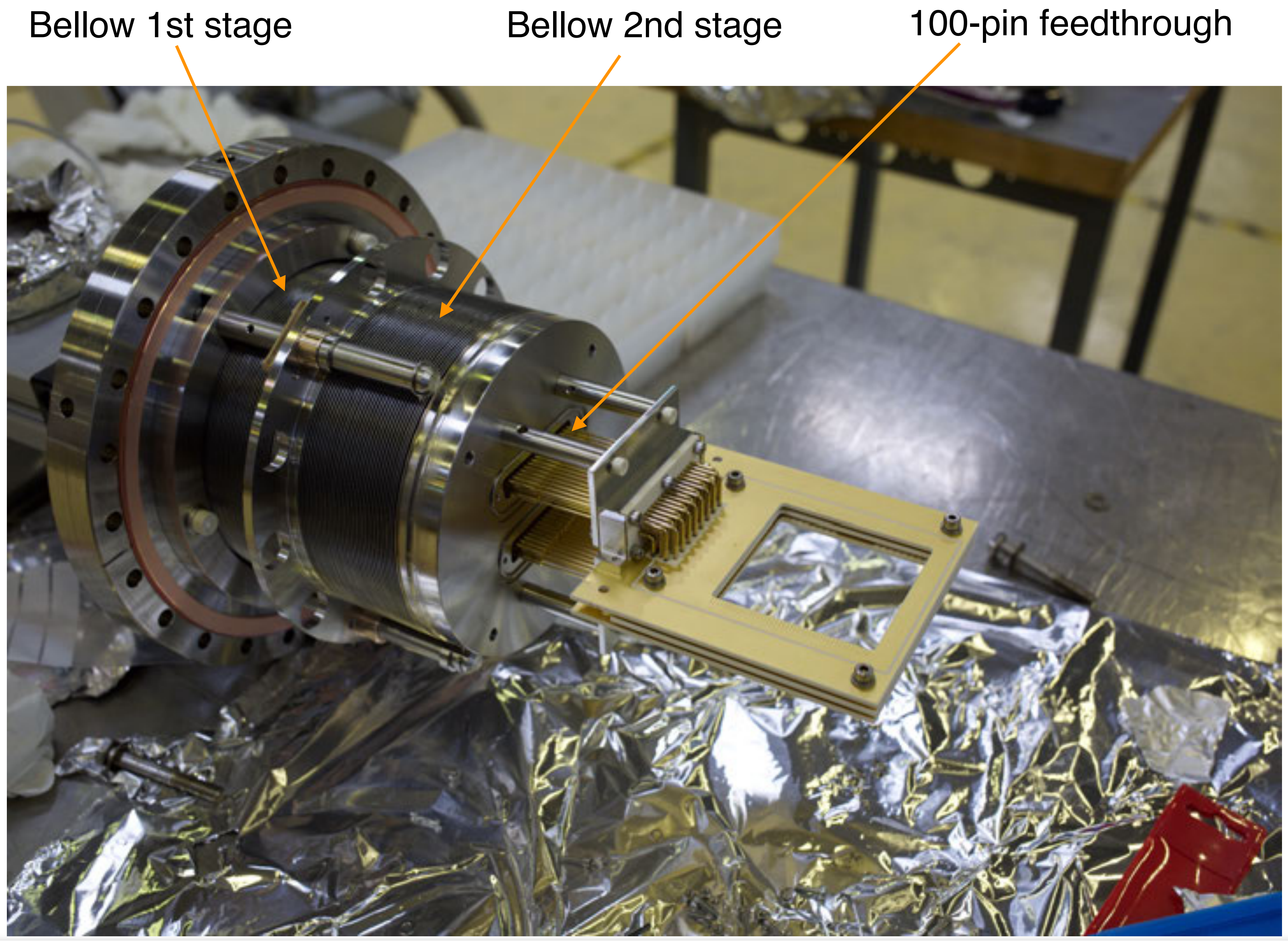
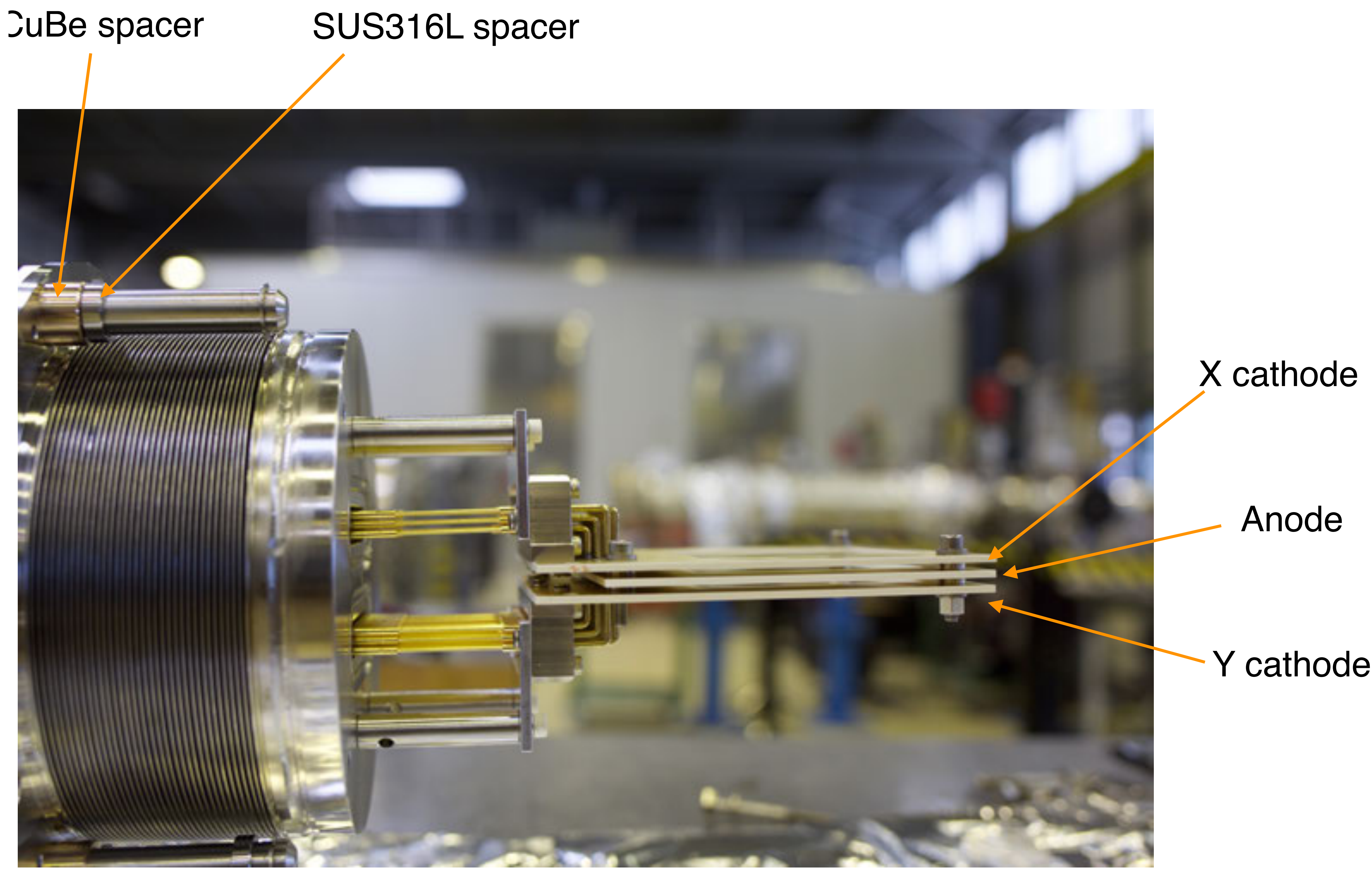
  measure hydrogen π_1 frequency

ASACUSA’s contribution to ELENA

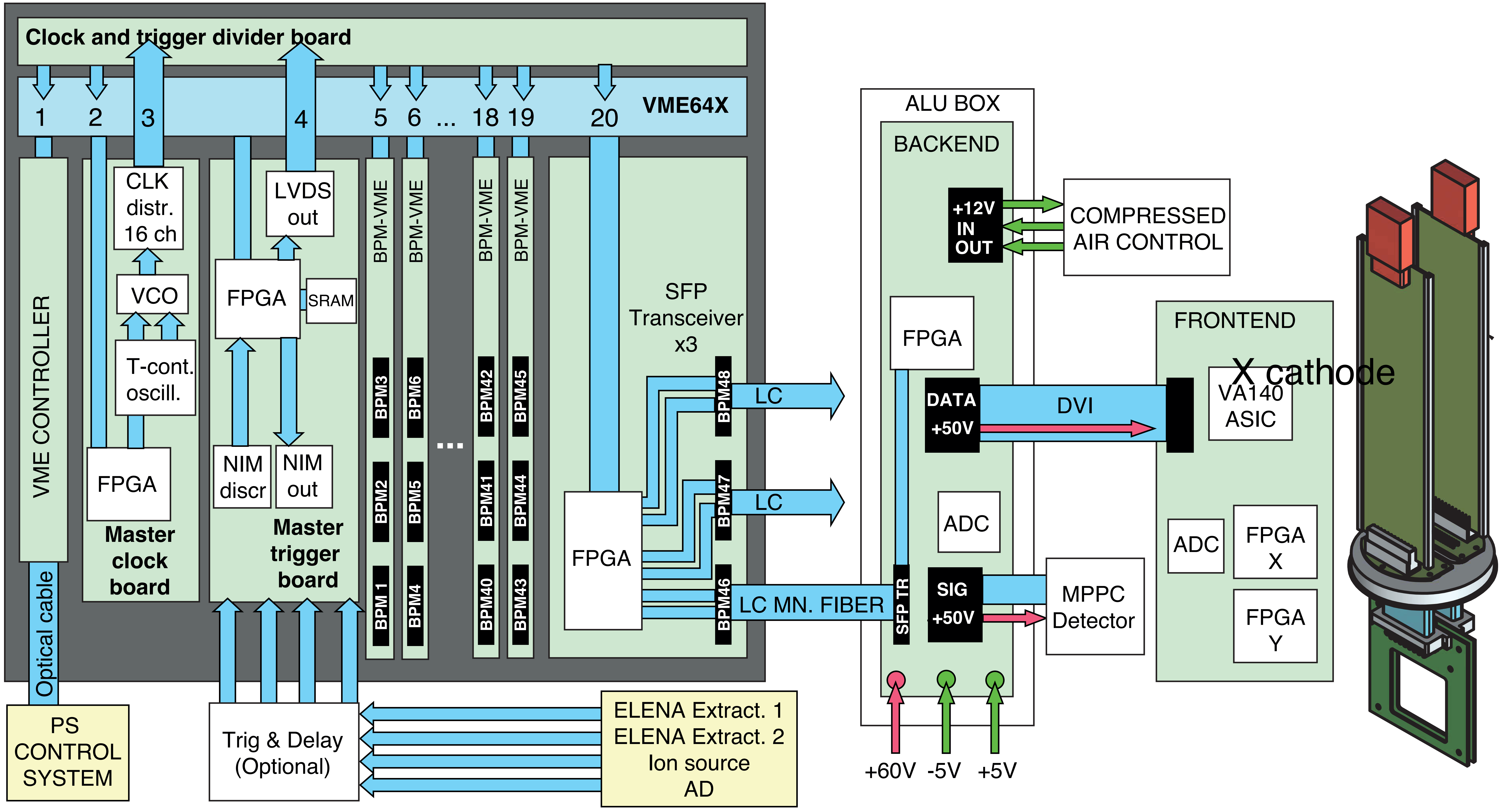
Beam profile monitors for ELENA







Financed by Tokyo, developed by Hori @ MPQ



4 types of triggers, controls 45 monitors