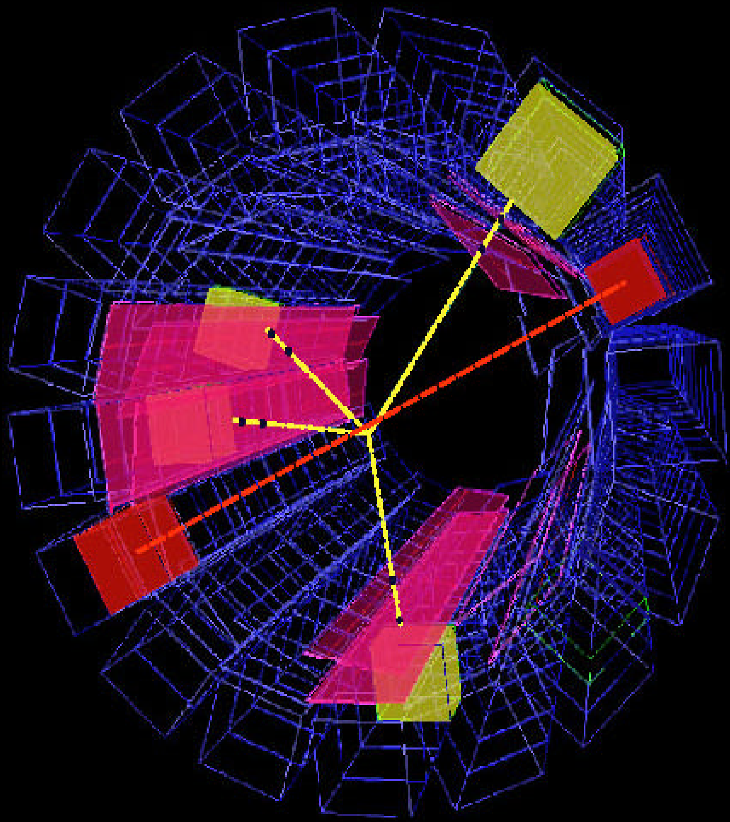
First Production and Detection of Cold Antihydrogen

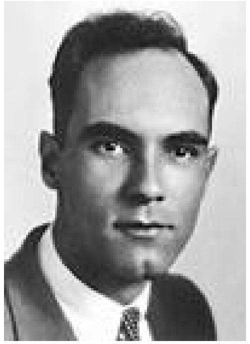


RIKEN ·CERN
藤原　真琴

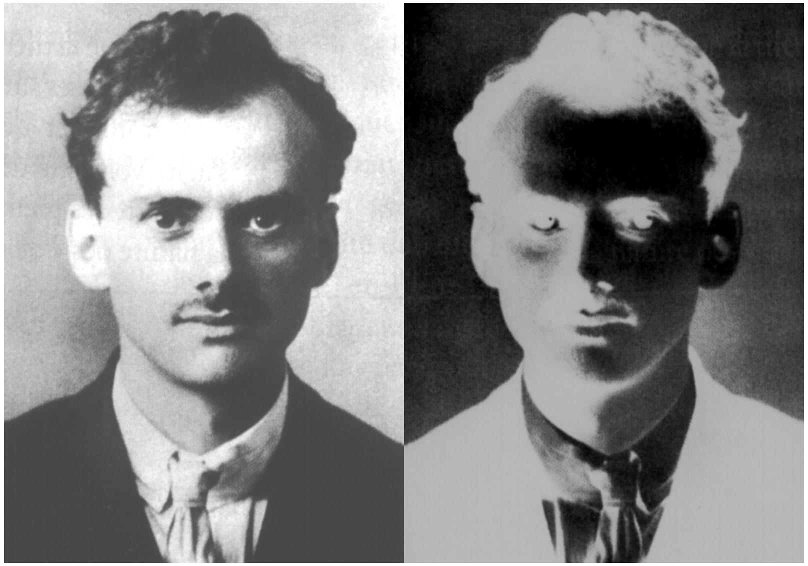
京都大学　May, 26 2003

反物質

1927 Dirac predicts the anti-electron
1931 Anderson registers positrons from cosmic rays
1955 Discovery of the Antiproton at the Bevatron



Anderson

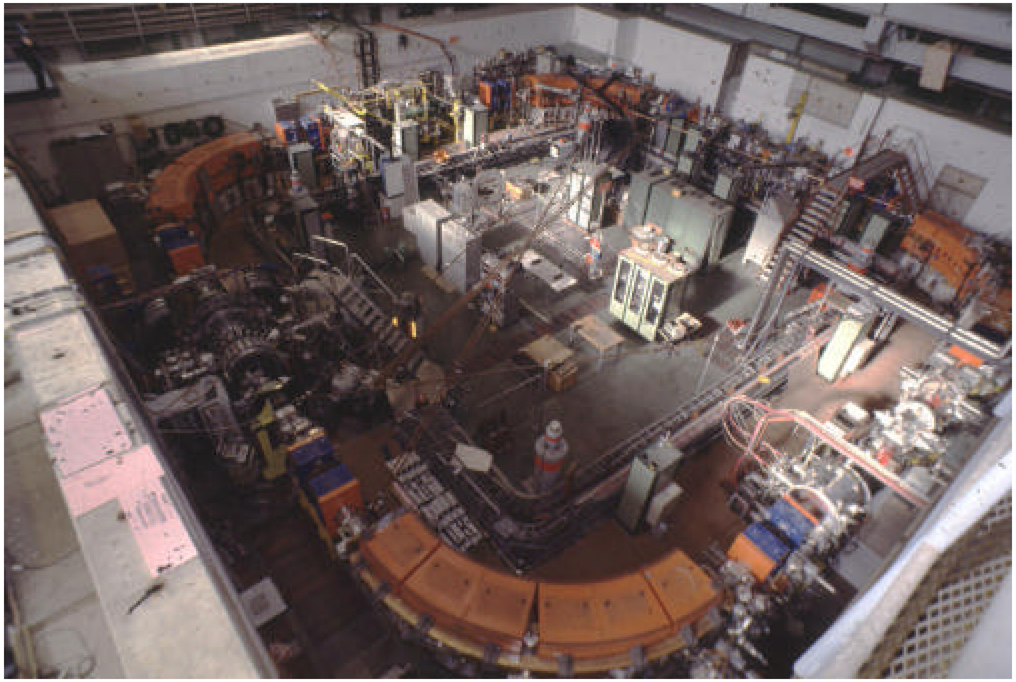


Paul Dirac

Emilio Segre, Clyde Wiegand, Edward Lofgren
Owen Chamberlain, Tom Ypsilantis

高速反水素の生成

- 1992 Munger et al. による提案: pbar + Z → Hbar
- 1996 LEARで~9 個の相対論的反水素生成が報告される



LEAR
1986-1996

詳しい測定はできなかった→低速反水素が必要

反水素研究の動機

CPT 対称性

重力

宇宙論

Cold Antihydrogen

原子物理

トラップ

プラズマ

素粒子

超高真空

低温

検出器

レーザー

CPT対称性の検証

- パリティとCPは破れている
- CPT定理
  - 物質と反物質（粒子と反粒子）では
    - 質量・寿命が等しい
    - 電荷・磁気モーメントの大きさが同じ、符号が逆
    - エネルギー準位が等しい
  - 定理の仮定

    局所場の理論、ローレンツ対称性, ユニタリティ等

    (議論がある e.g. Greenberg *PRL* ‘02 vs Barenboim et al. *PLB* ’02）
- プランク・スケールで成り立つか
  - 重力 (時空が曲がる) → ユニタリティ?
  - ひも理論 → 局所場の理論ではない
  - 高次元の理論・非可換幾何学→ ローレンツ対称性の破れ？
- 最近の~~CPT~~理論 (Kostelecky, Ellis, 村山・柳田 etc.)

最近のCPTおよびローレンツ対称性を破る理論

- **Robert Bluhm, V. Alan Kostelecký, Charles D. Lane, and Neil Russell**
  Clock-comparison tests of Lorentz and CPT symmetry in space, Phys. Rev. Lett. **88,** 90801 (2002)
- **V. Alan Kostelecký, Charles D. Lane, and Austin G.M. Pickering**
  One-loop renormalization of Lorentz-violating electrodynamics, Phys. Rev. D **65,** 56006 (2002)
- **Sean M. Carroll, Jeffrey A. Harvey, V. Alan Kostelecký, Charles D. Lane, and Takemi Okamoto**
  Noncommutative field theory and Lorentz violation, Phys. Rev. Lett. **87**, 141601 (2001)
- **V. Alan Kostelecký and Matthew Mewes**
  Cosmological constraints on Lorentz violation in electrodynamics, Phys. Rev. Lett. **87,** 251304 (2001)
- **V. Alan Kostelecký and Robertus Potting**
  Analytical construction of a nonperturbative vacuum for the open bosonic string, Phys. Rev. D **63,** 46007 (2001)
- **V. Alan Kostelecký and Ralf Lehnert** Stability, causality, and Lorentz and CPT violation, Phys. Rev. D **63,** 65008 (2001)
- **V. Alan Kostelecký and Ágnes Roberts** Analogue models for T and CPT violation in neutral-meson oscillations, Phys. Rev. D **63,** 96002 (2001)
- **V. Alan Kostelecký** CPT, T, and Lorentz violation in neutral-meson oscillations, Phys. Rev. D **64,** 76001 (2001)
- **V. Alan Kostelecký** Signals for CPT and Lorentz violation in neutral-meson oscillations, Phys. Rev. D **61,** 16002 (2000)
- **Robert Bluhm, V. Alan Kostelecký, and Charles D. Lane** CPT and Lorentz tests with muons, Phys. Rev. Lett. **84,** 1098 (2000)
- **Robert Bluhm and V. Alan Kostelecký** Lorentz and CPT tests with spin-polarized solids, Phys. Rev. Lett. **84,** 1381 (2000)
- **V. Alan Kostelecký and Charles D. Lane** Constraints on Lorentz violation from clock-comparison experiments, Phys. Rev. D **60,** 116010 (1999)
- **Robert Bluhm, V. Alan Kostelecký, and Neil Russell** CPT and Lorentz tests in hydrogen and antihydrogen, Phys. Rev. Lett. **82,** 2254 (1999)
- **R. Jackiw and V. Alan Kostelecký** Radiatively induced Lorentz and CPT violation in electrodynamics, Phys. Rev. Lett. **82,** 3572 (1999)
- **V. Alan Kostelecký** Sensitivity of CPT tests with neutral mesons, Phys. Rev. Lett. **80,** 1818 (1998)
- **Robert Bluhm, V. Alan Kostelecký, and Neil Russell** CPT and Lorentz tests in Penning traps, Phys. Rev. D **57,** 3932 (1998)
- **D. Colladay and V. Alan Kostelecký** Lorentz-violating extension of the standard model, Phys. Rev. D **58,** 116002 (1998)

最近のCPTおよびローレンツ対称性検証

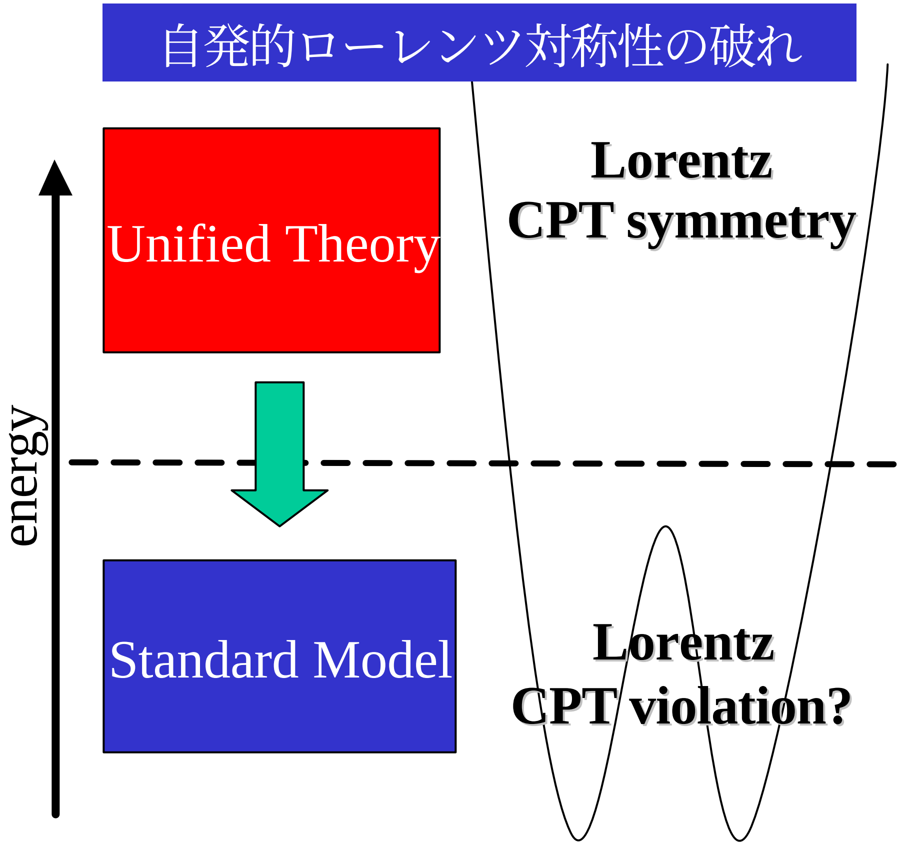
Other Theory

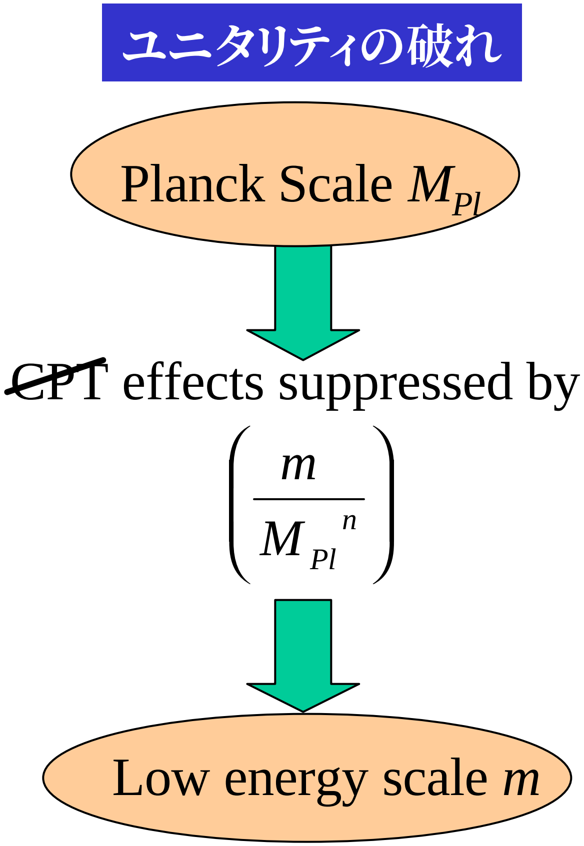
- **J. Bachall et al.** How accurately can one test CPT conservation with reactor and solar neutrino experiments**?** hep-ph/0201211 (2002)
- **H. Murayama and T. Yanagida** LSND, SN1987A, and CPT violation, Phys. Lett. **520B** 263 (2001)
- **N. Isger et al**. Background enhancement of CPT reach at an asymmetric phi factory, Phys. Lett. **515B** 333 (2001)
- **S. Coleman and S. Glashow** High energy tests of Lorentz invariance, Phys. Rev. D **59** 116008 (1999)
- **J. Ellis et al.** Phys. Lett. **293B** 142 (1992)
- **P. Huet and M. E. Peskin** Nucl. Phys. B **434** 3 (1995)
- **S. Hawking** Phys. Rev D **14** 2460 (1975)
- **I. Mocioiu et al.,** Breaking CPT by mixed non-commutability hep-ph/0108136

Experimental Tests

- **M. Hori et al.** ASACUSA: anti-protonic helium
- **V. Hughes et al.** Muonium hyperfine structure
- **H. Dehmelt et al.** electron and positron in penning trap
- **G. Gabrielse et al.** proton and antiproton in penning trap
- **CPLEAR** neutral kaon mass difference

CPTの破れでプランク・スケールの物理を探る





普通は $M_{Pl} \sim 10^{19}$ GeV

「大きな」隠れた次元があれば $M_{Pl}^* \sim 10^3$ GeV

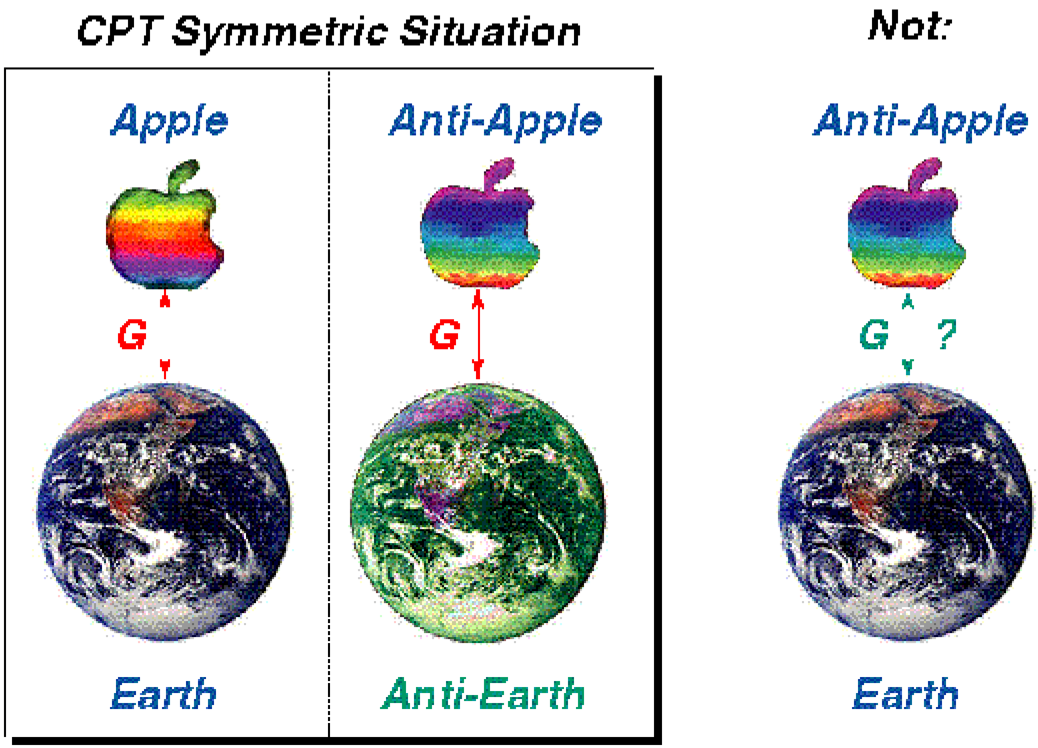
→ CPTの破れも起こるか？

反物質に働く重力

物質に働く重力と同じか？

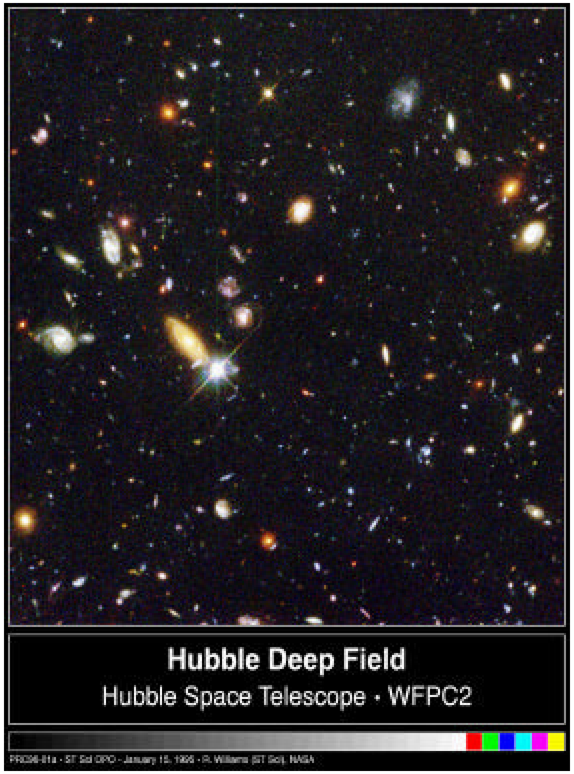
直接測定はない

CPT 定理とは独立



バリオン創生: 反物質はどこへ消えた？

- 宇宙の物質-反物質非対称
  物質はなぜ生き残ったのか
- 標準的なシナリオ:
  サハロフの 3条件
  - バリオン数の破れ
  - CとCPの破れ
  - 熱非平衡状態



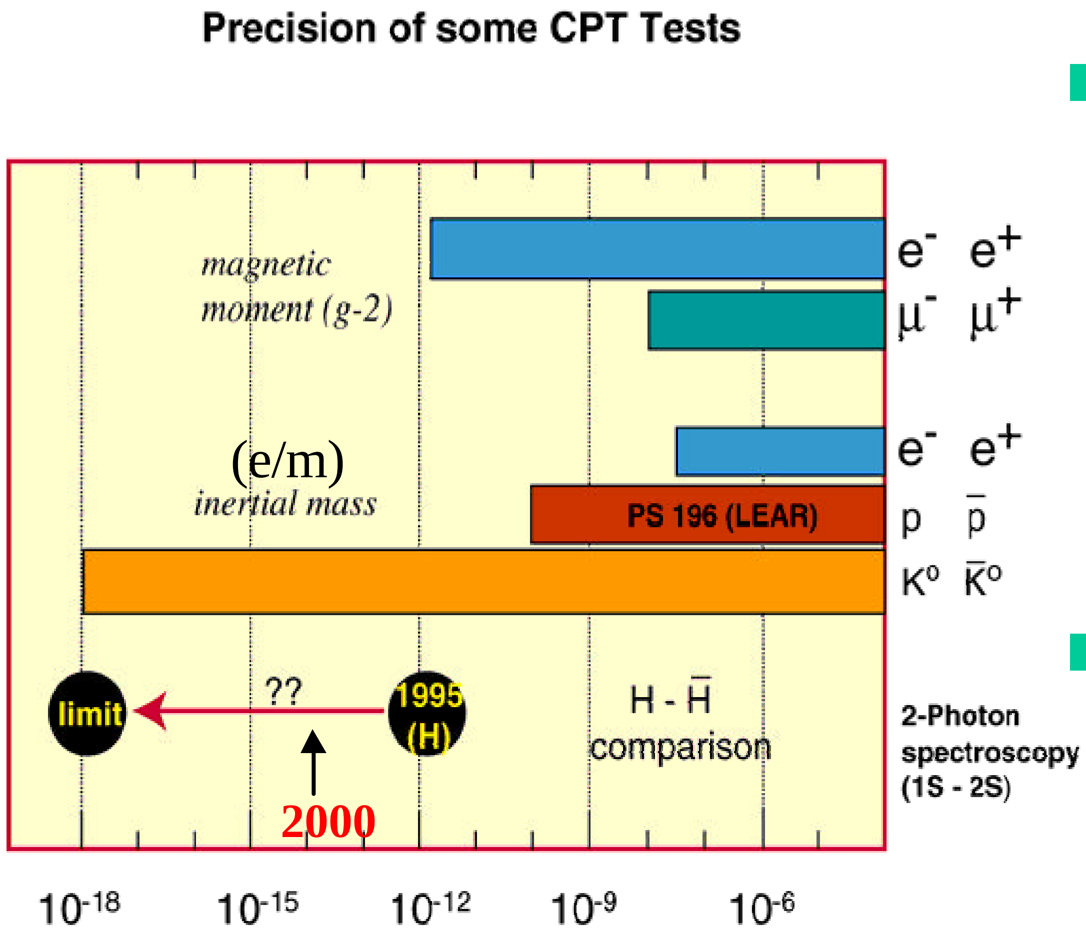
- 標準模型を超える物理が必要
  - CKM行列によるCPの破れは小さすぎる
  - MSSMも厳しい？
- 他のやり方があるか？
  →CPTの破れによって反物質を壊す

A.D. Dolgov, Ya.B. Zeldovich, Rev. Mod. Phys. 53, 1 (1981)
O. Bertolami et al., Phys. Lett. B 395, 178 (1997)

反物質研究の動機 (一般向け)

反物質で宇宙の起源・
異次元世界を探る」

これまでのCPT検証



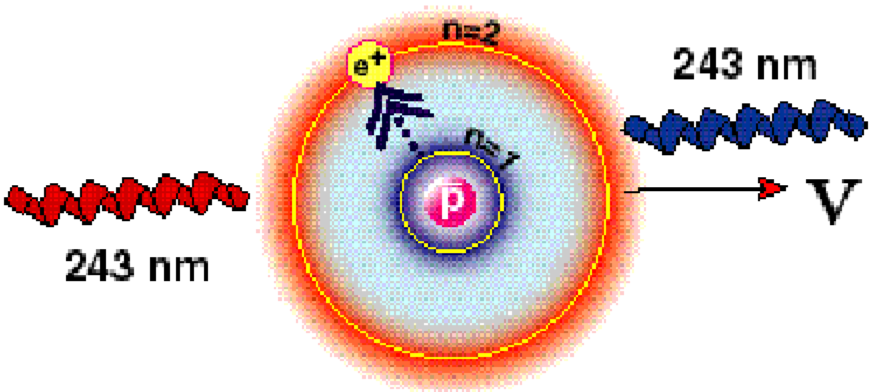
Relative Accuracy → **何で割るかが問題**

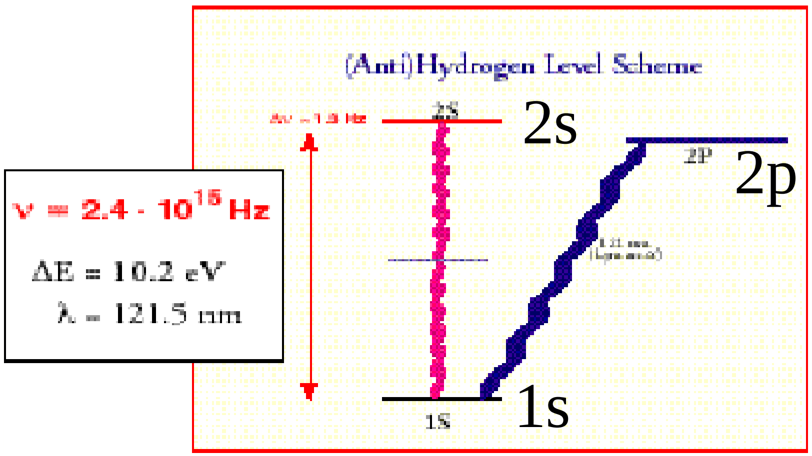
- 中性Kaon解析
  モデル依存
  - e.g. Bell-Steinberger relation
  - Possible CPTV suppressed M_{K_L}-M_{K_S} (10^{-15})
  - 10% test of CPTV interact. (小林 ·三田1992)
- CPTの破れのパターンは、全く分からない

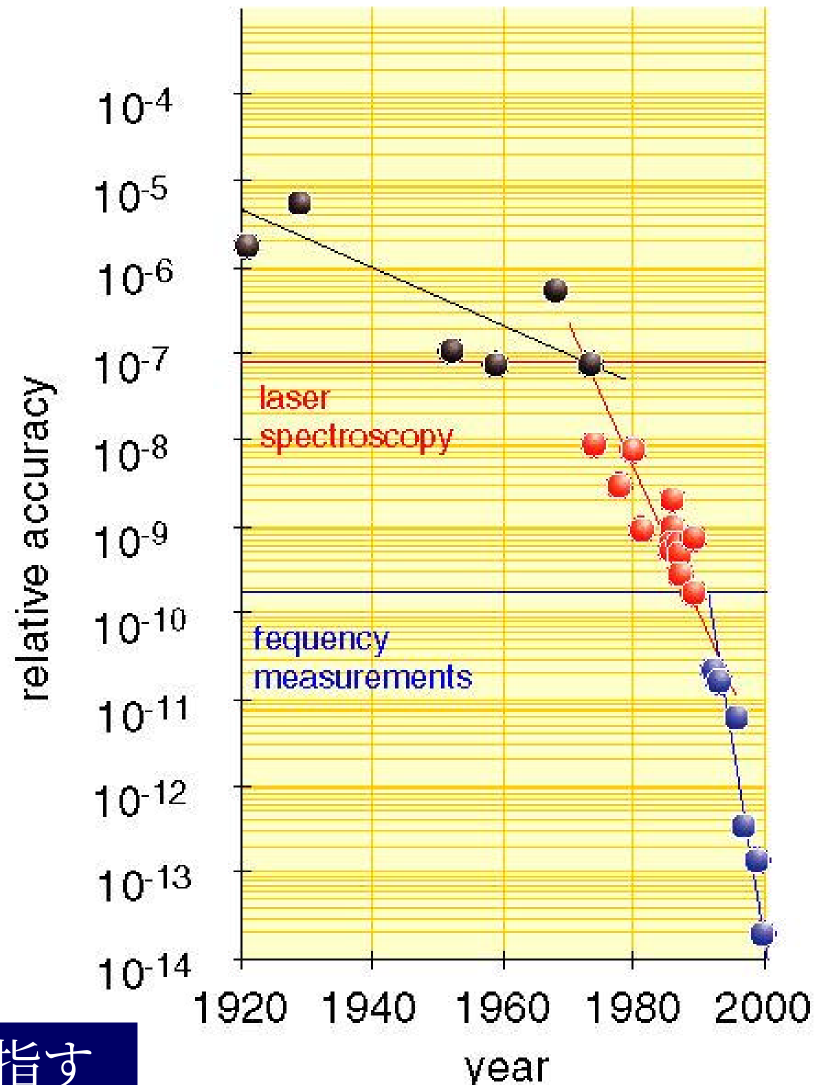
→ すべての粒子で精密検証すべき

長期目標 :反水素の精密分光

- 水素原子の2光子分光の進展







水素との比較によりCPT高精度検証を目指す

冷たい反水素原子をつくる（大量に、誰よりも先に）

10^{-12}

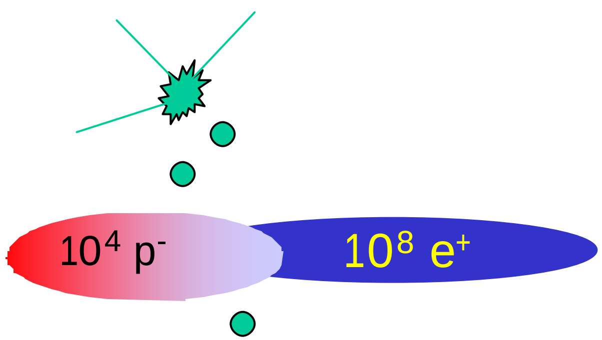
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



Plasma diagnosis/manipulation

p^- and e^+ in mixing trap

Antihydrogen formation

Detection of annihilation

10^{-9}

Na-22

e^+ Production (MeV)

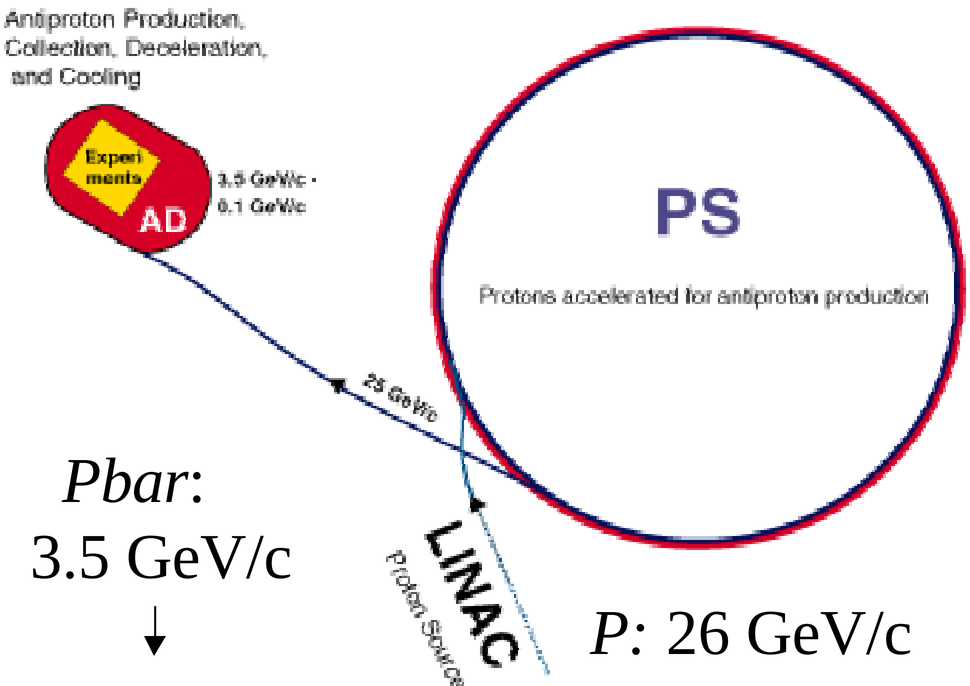
Moderation

Accumulation (eV)

Cooling (~ meV)

- 実験技術の組合せ
- 激しい競争

CERNの反陽子減速施設
AD:Antiproton Decelerator



Pbar:
3.5 GeV/c
↓
100 MeV/c

P: 26 GeV/c

- 唯一の低速反陽子施設
- 日本が建設に多大な貢献

- **Pulsed beam**:
  4×10^7 /pulse, every 100 sec
- **3 experiments at AD**:
  Asacusa --- pbar-He, collisions
  Athena --- antihydrogen
  Atrap --- antihydrogen

CERN-AD における 3実験

冷たい反水素の生成

「冷たい反物質をめぐる熱い闘い」

2000年までの状況 (反陽子国際会議LEAP00)

- **ATHENA**
  - 反陽子捕獲
  - 反陽子の電子冷却

- **ATRAP**
  - 反陽子捕獲
  - 反陽子の電子冷却
  - 反陽子積み重ね
  - 陽電子蓄積
  - 反陽子-陽電子相互作用
  - 反陽子の陽電子冷却

LEAP 2000以降の進展

June 2001
Pbar lifetime >10 hours

July 2001
Pbar transfer between traps

Sept 2001
Pbar Vertex Imaging

Dec 2001
25M positrons in 3T

July 2002
First indications

Detailed studies →

Aug 27
Hbar paper submitted

Sep 3
Hbar paper accepted

Sep 18 2002
Published in ***Nature*** on-line

Oct 31
ATRAP published

ATHENAの現状

- 131± 22 の "Golden Events "に基づいて反水素生成を報告
  →50000 個以上の冷たい反水素
- しかしこれは非常に控えめなLower Limitだった
- 新しい予備結果：
  - ~1 million 反水素の生成
  - 高い生成率 >100 Hz
  - その他、各種測定
- 将来への展望

ATHENA 国際共同実験

Particle Traps + Control

Genoa
Amoretti M. Carraro C. Lagomarsino V.
Macri M. Manuzio G. Testera G. Variola A.

CERN
Bonomi G. Bouchta A. Doser M. Holzscheiter M.
Landua R. Riedler P. Rouleau G.

TOKYO-RIKEN
早野龍五, 船越亮, 藤原真琴
山崎泰規,桧垣浩之, 山崎敏光

Precision lasers

Aarhus
Bowe P. Hangst J.S.

Rio de Janeiro (UFRJ)
Lenz Cesar C.

Positron Plasma

Swansea
Charlton M. Collier M. Jorgensen L.
Watson T. Van der Werf D.P.

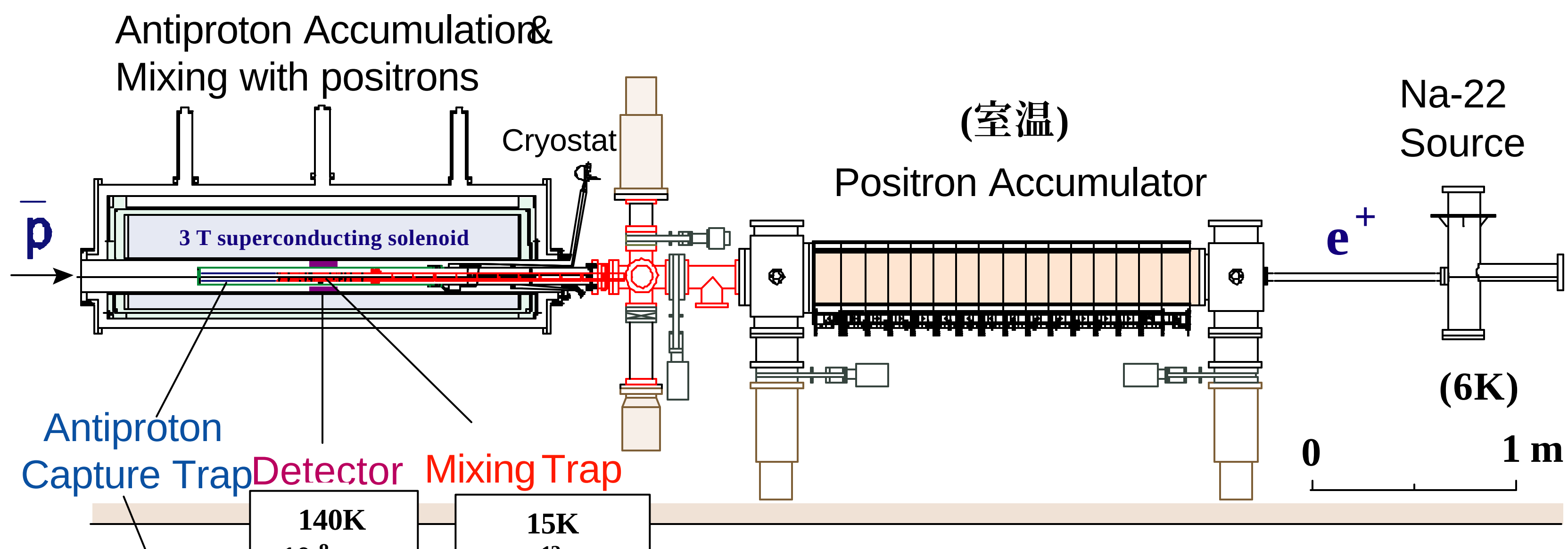
Detector + Analysis

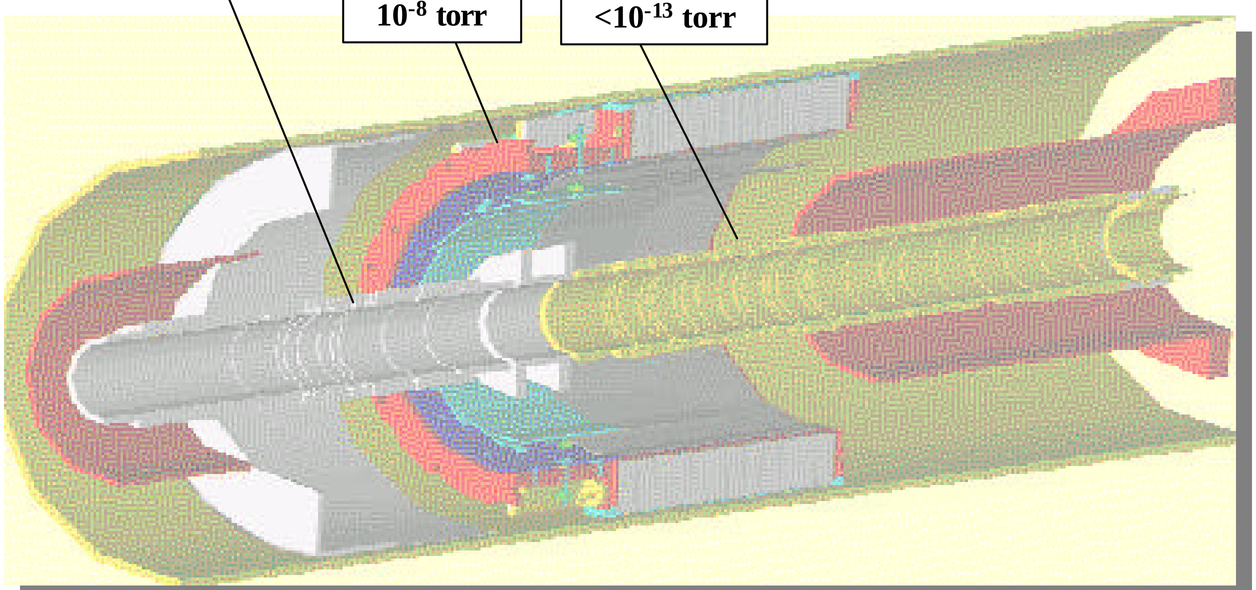
Zurich Univ.
Amsler C. Glauser A. Grögler D.
Lindelof D. Madsen N. Pruys H.
Regenfus C.

Pavia
Filippini V. Fontana A. Genova P.
Marchesotti M. Montagna P. Rotondi A.

Brescia
Lodi-Rizzini E. Venturelli L.

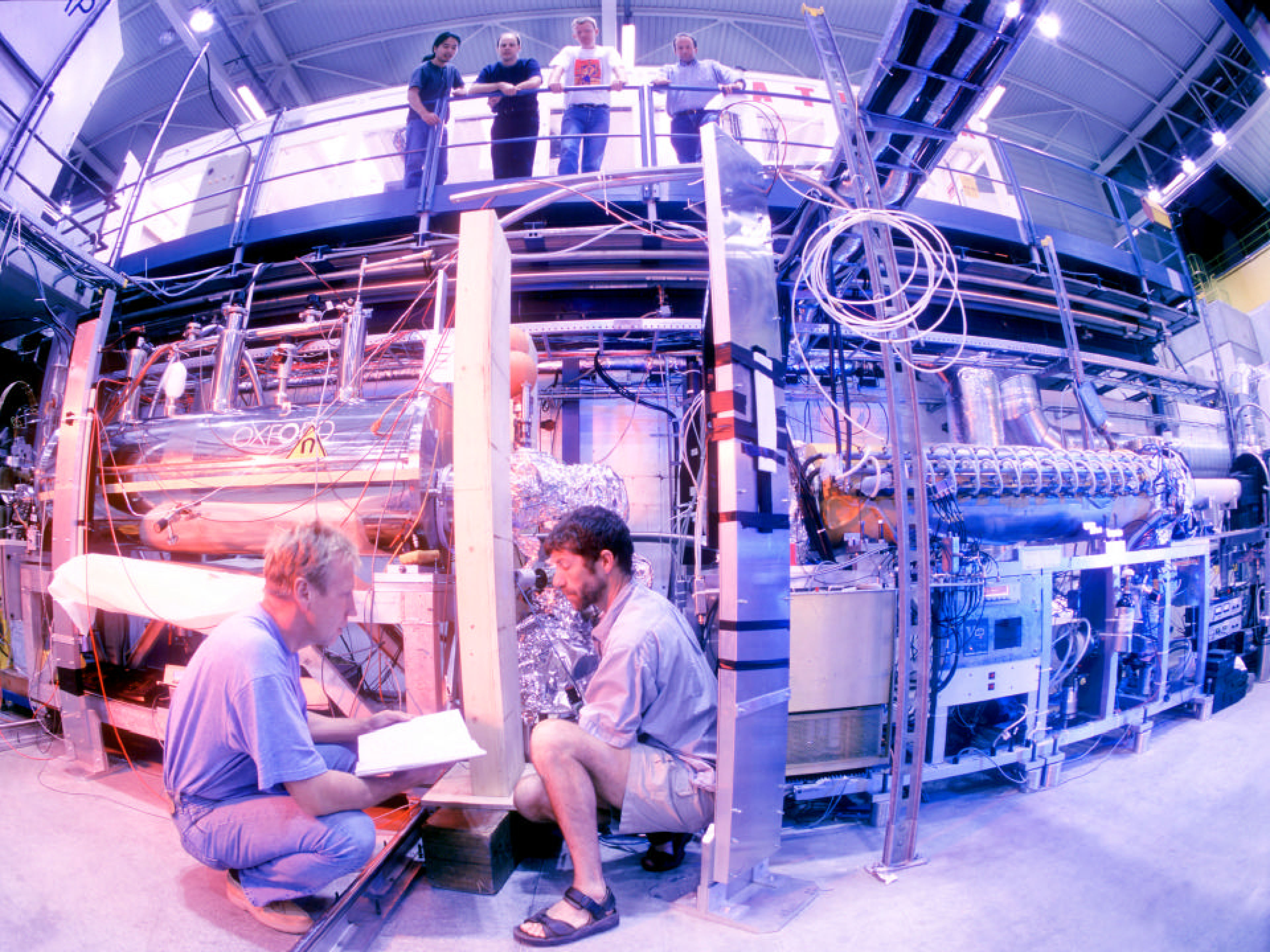
ATHENA 全体像



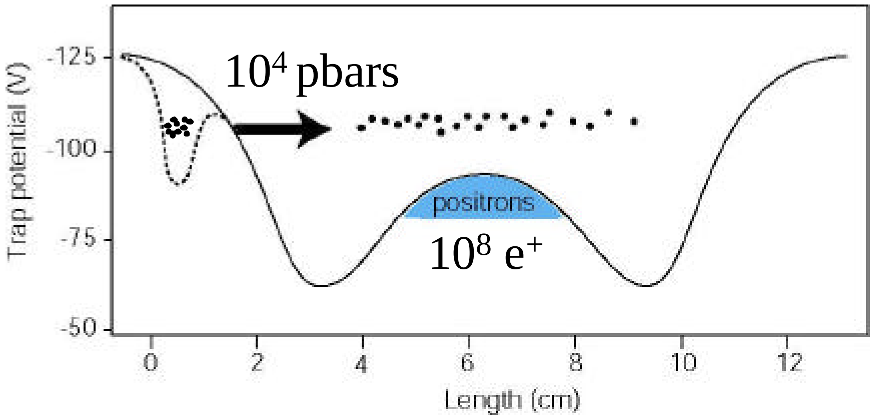


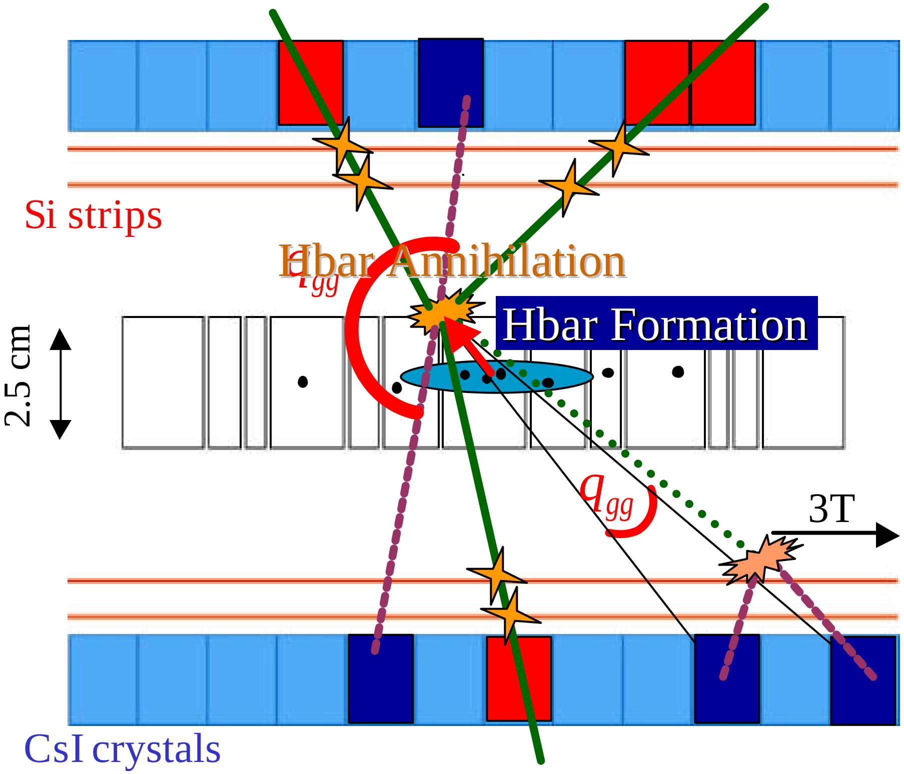
ATHENA Features

- 開放システム (室温部分を含む)
- 強力なe+源
- プラズマ制御
- 高度な検出器

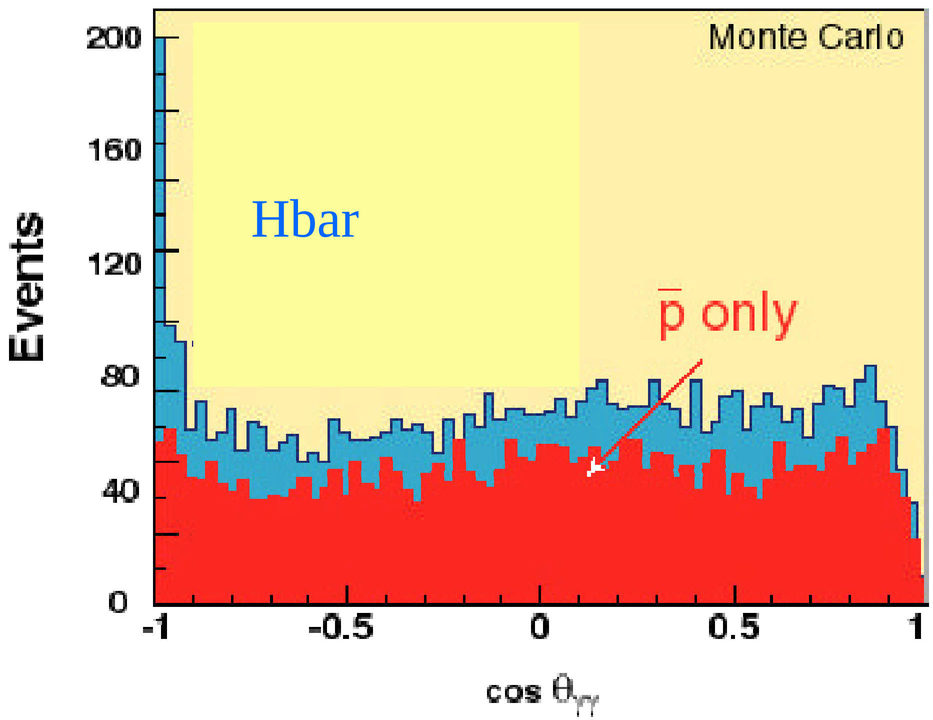

OXFORD

冷たい反水素原子の生成　August 2002 *ATHENA*

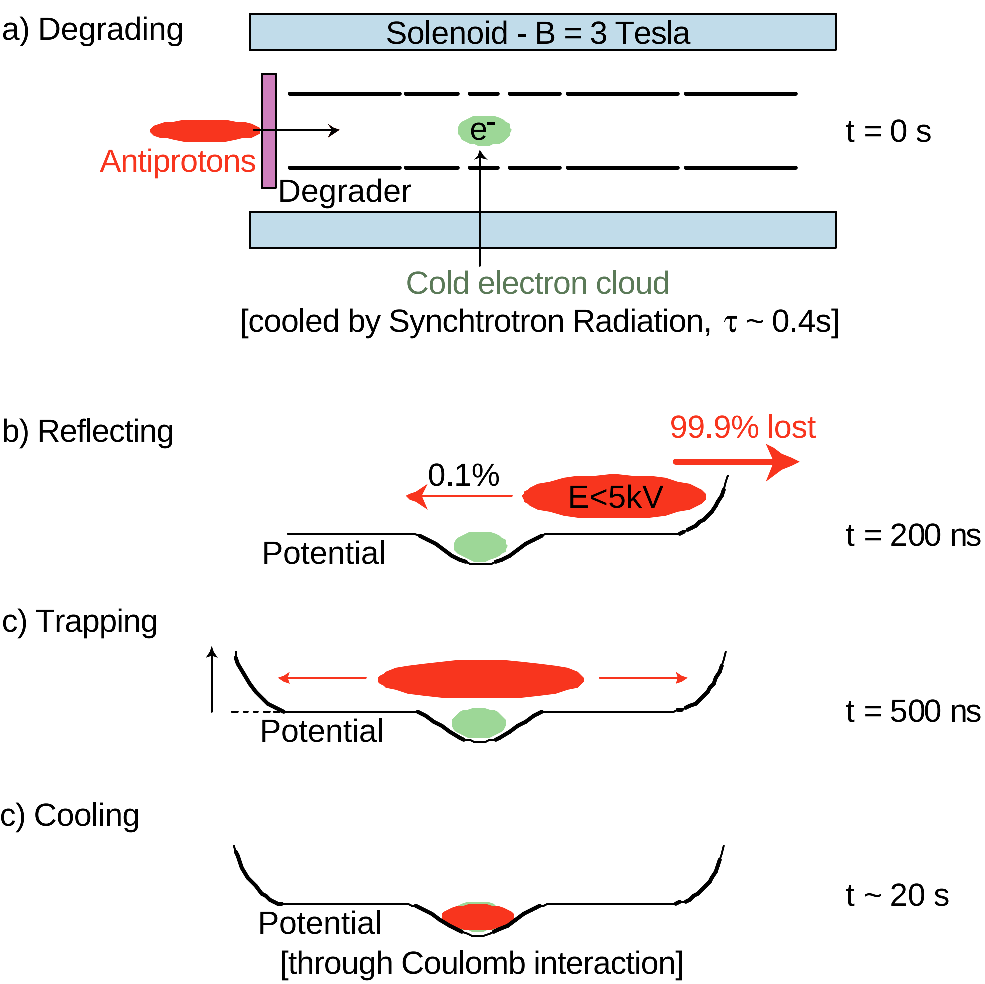


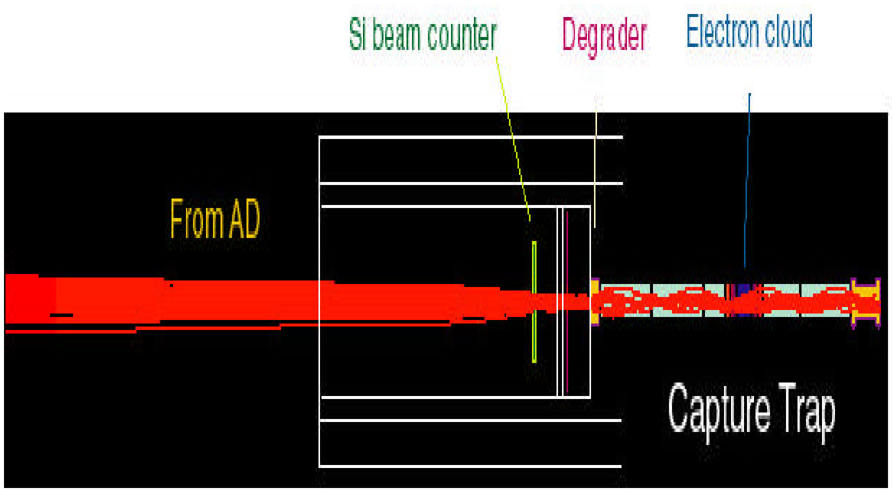


- 10^4 pbars と10^8 e^+ をトラップ中で混合
- 反水素生成、電極壁に衝突し消滅
- 反陽子が消滅、数個の荷電π中間子放出
- e^+が2つの back-to-back γに消滅
- バーテックスからみた2つの511keV γの開き角度、opening angle $\cos(\theta_{\gamma\gamma})$
- 角度相関のないγがバックグランド（中性π）

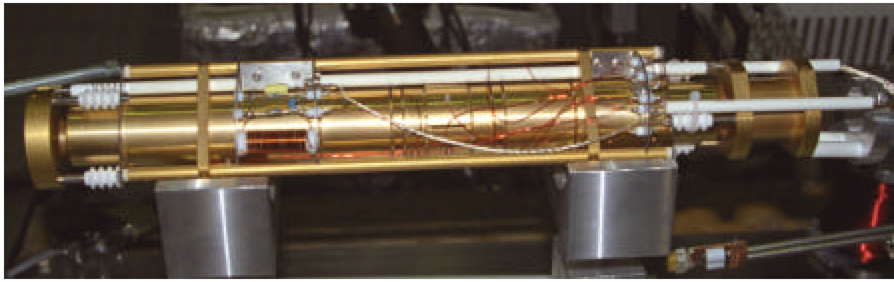


反陽子の捕獲と冷却





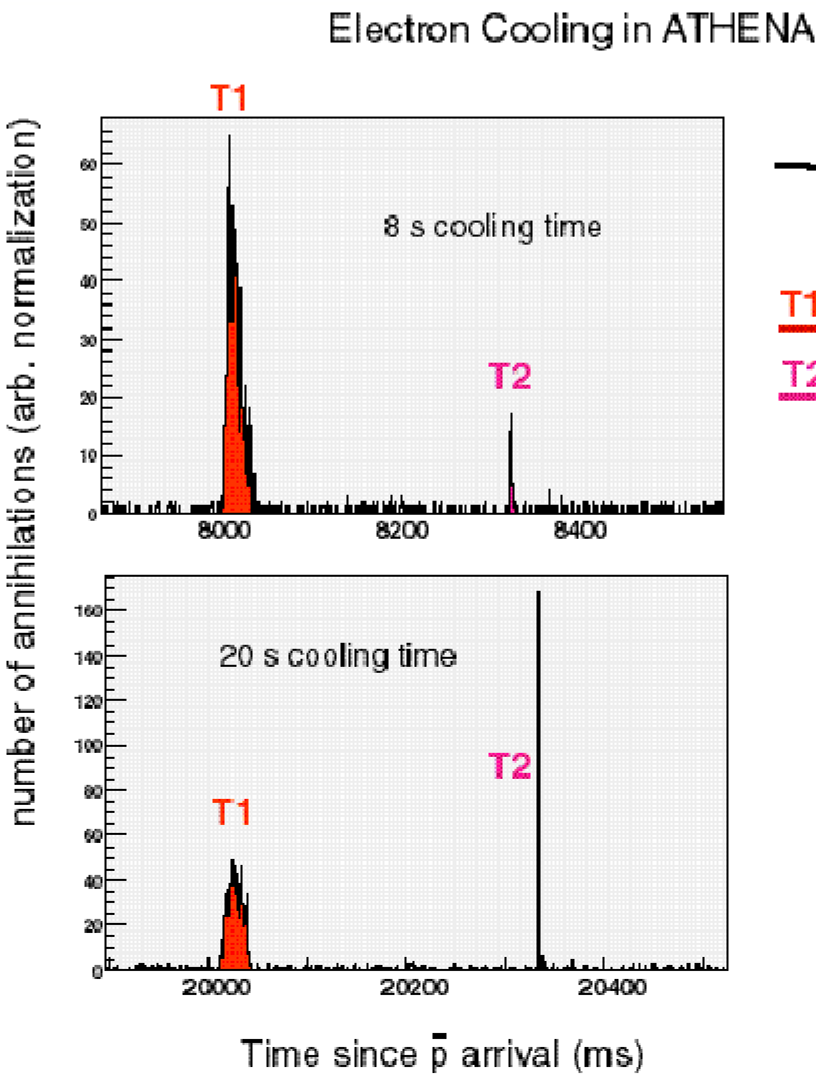
Segmented Si (67 μ) beam counter

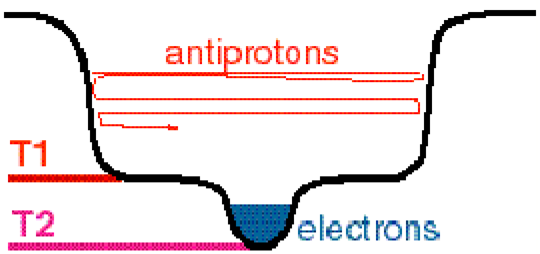


Antiproton Capture Trap

10^4 反陽子を捕獲 ·冷却後の混合トラップへ移動、電子除去

反陽子の電子冷却

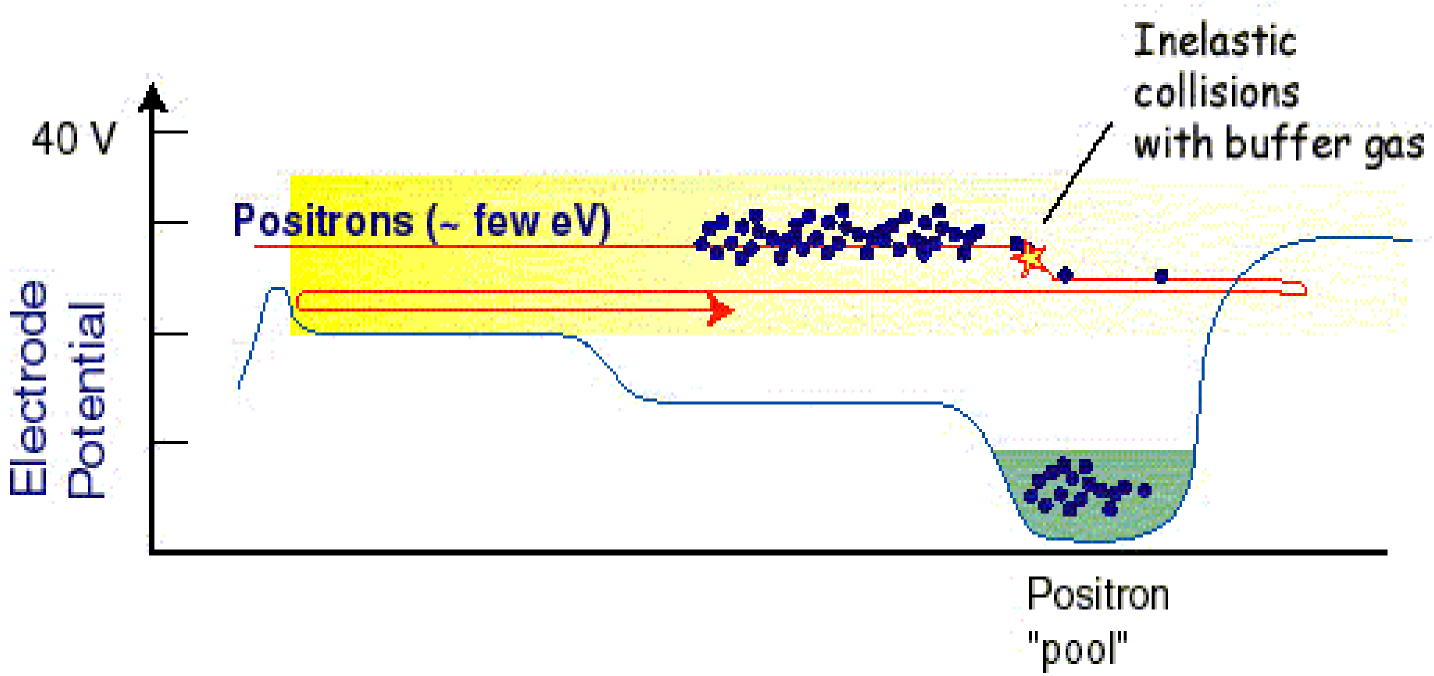




- 冷却時間 ～20-40 sec
- 冷却効率>80%
- 寿命 > 10 h
- 反陽子のトラップ間の移動
- 移動後、電子の除去

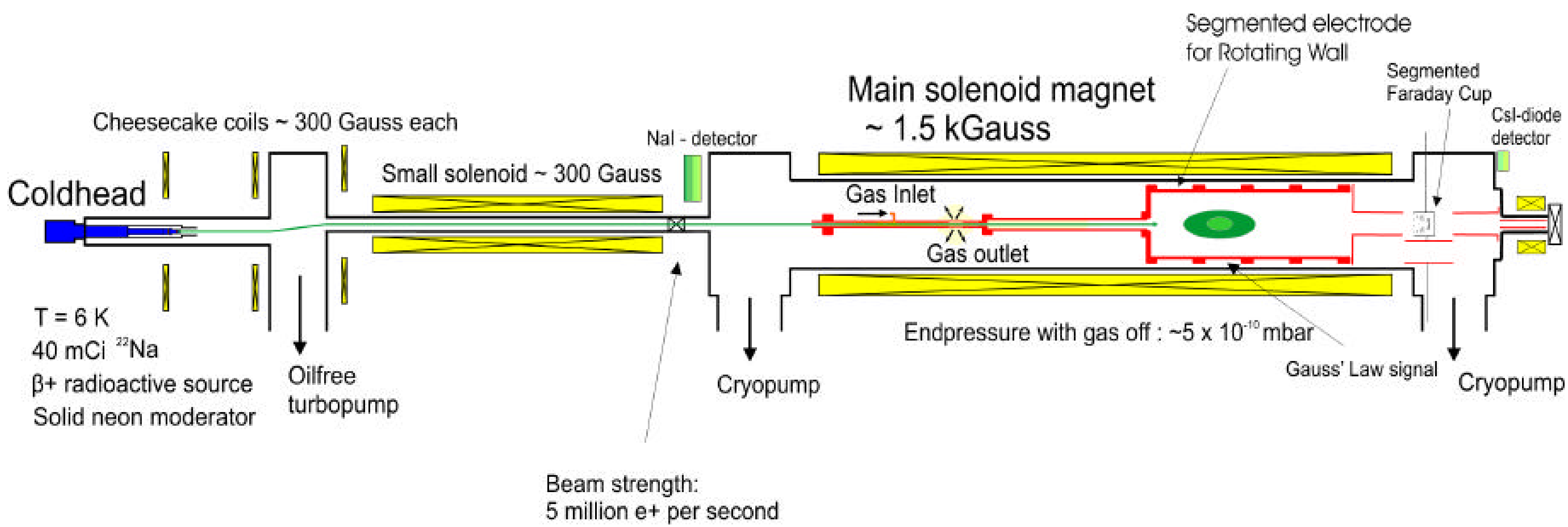
陽電子の蓄積

窒素バッファ•ガスのよる散逸を用いた陽電子蓄積



(concept by C. Surko et al., Non-neutral plasmas Vol. 3, 3-12; AIP 1999)

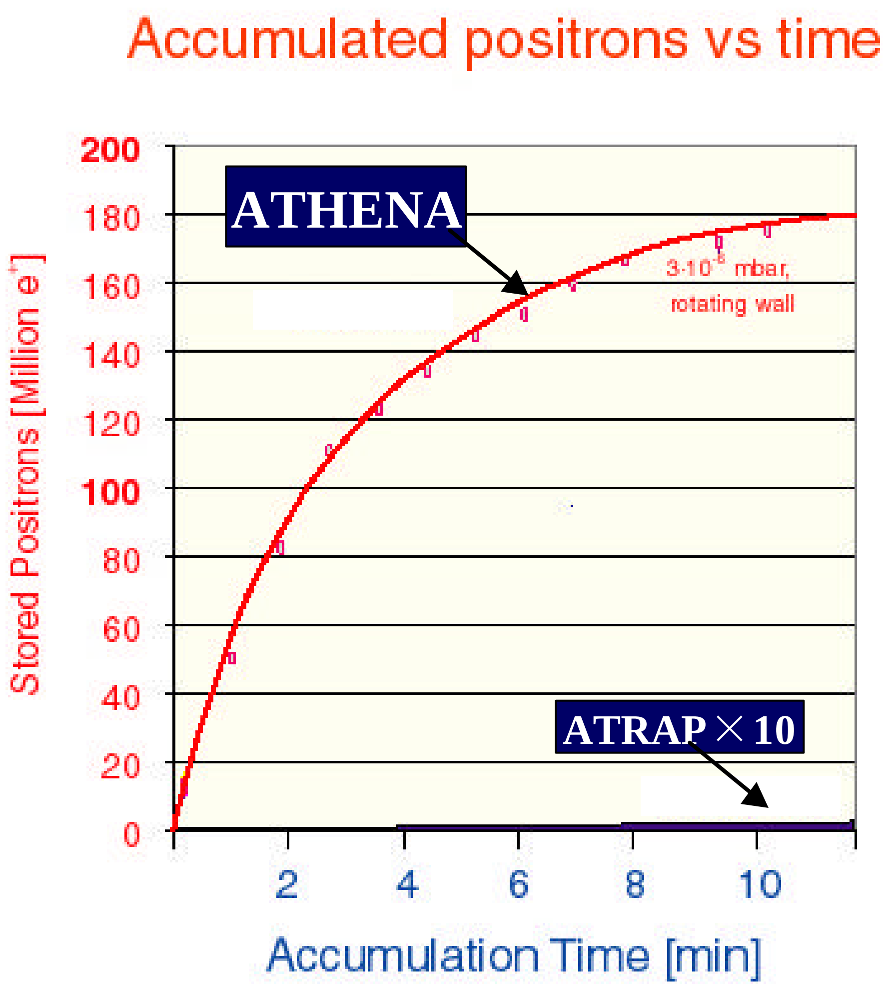
陽電子の蓄積



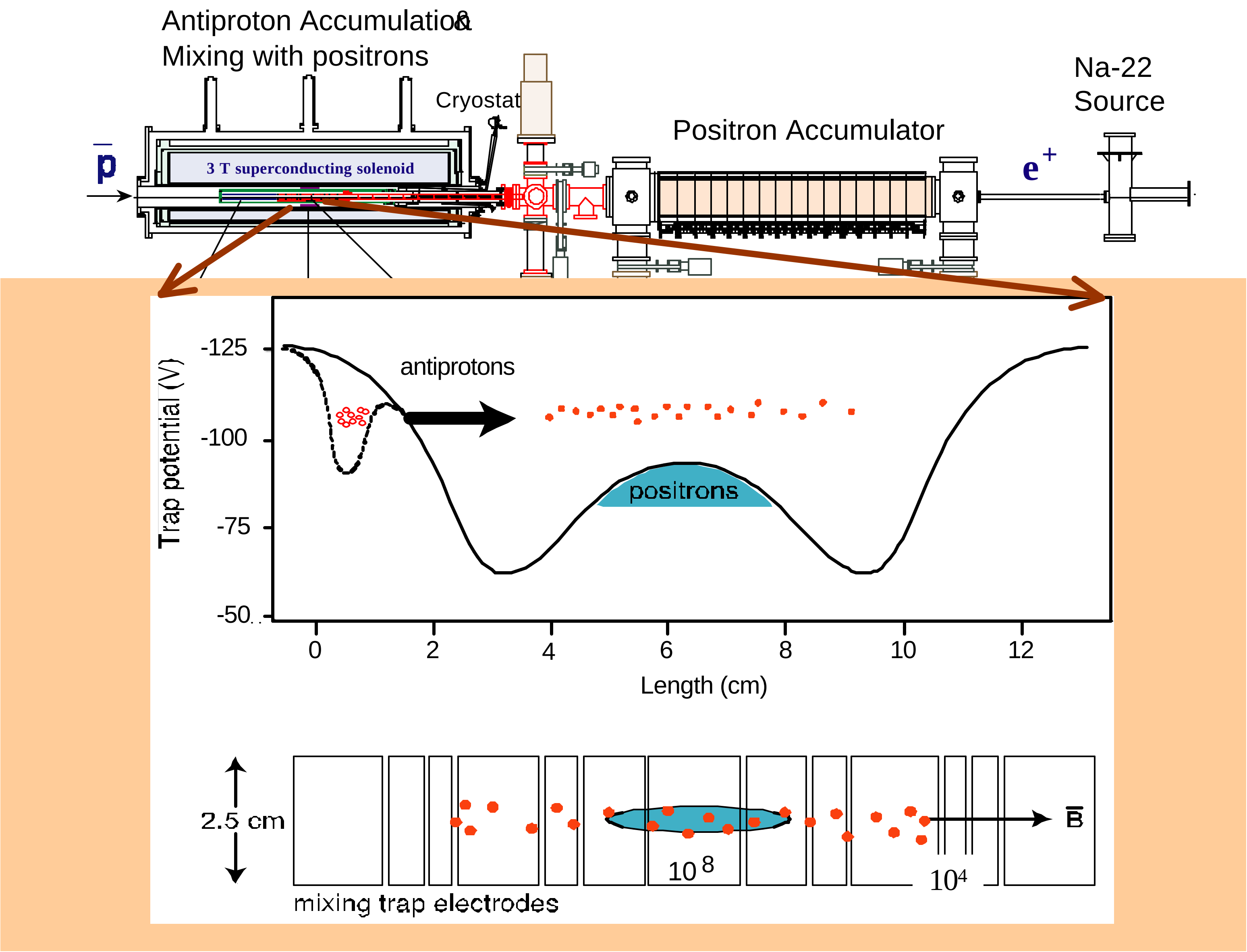
^{22}Na Source → Solid Ne Moderator → N_2 Buffer Gas Cooling → Plasma Compression → Transfer into 3T magnet

75 million 冷たい 陽電子 / 5 min

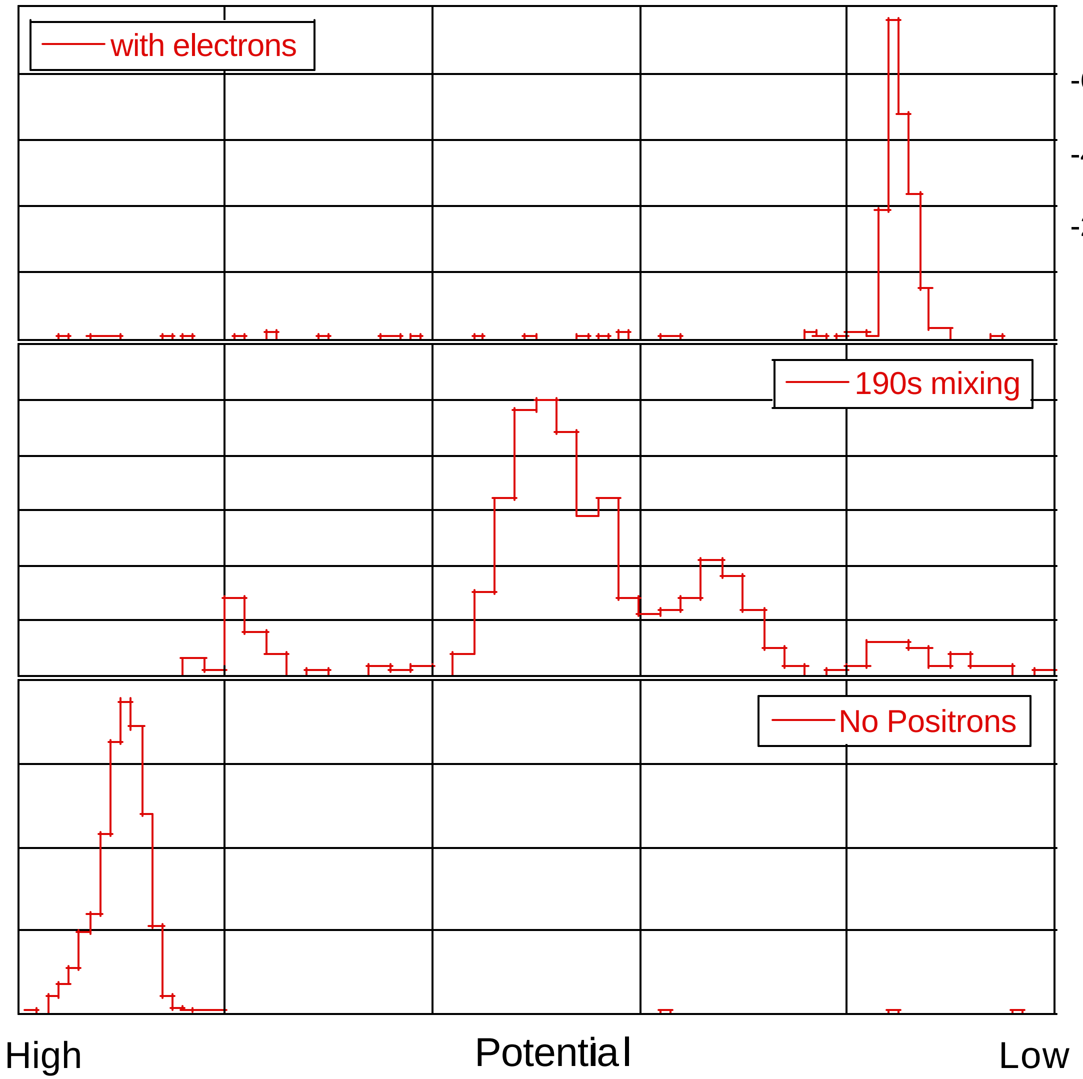
ATHENAの陽電子蓄積装置

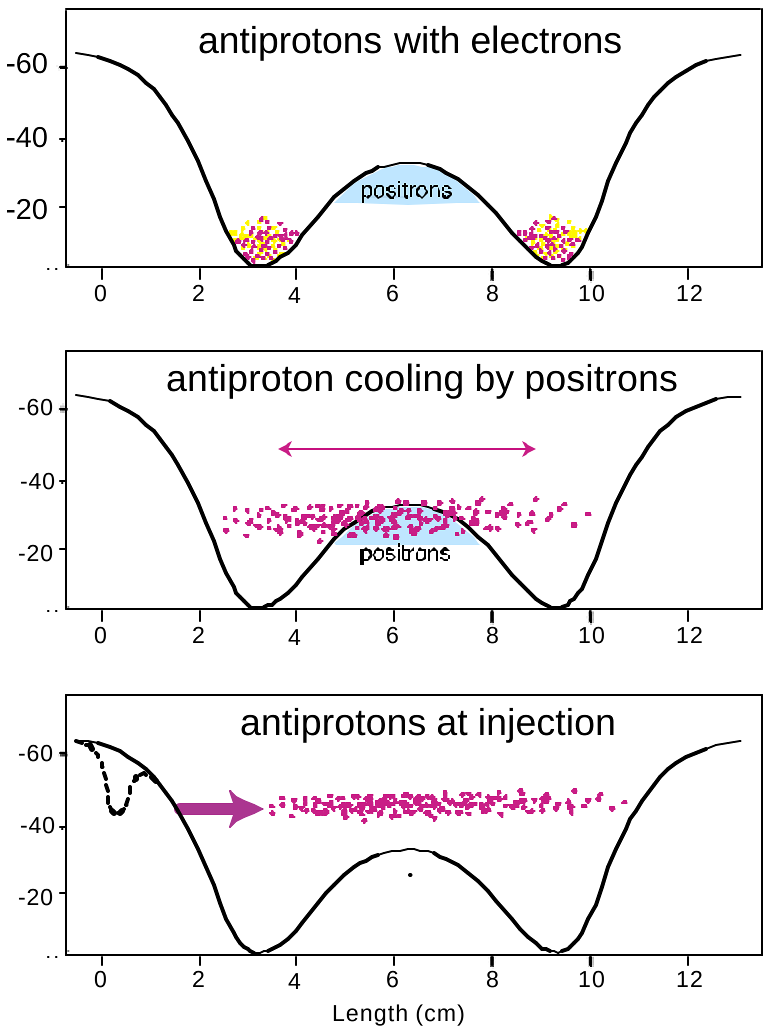


反陽子と陽電子の混ぜ合わせ



反陽子と陽電子の相互作用

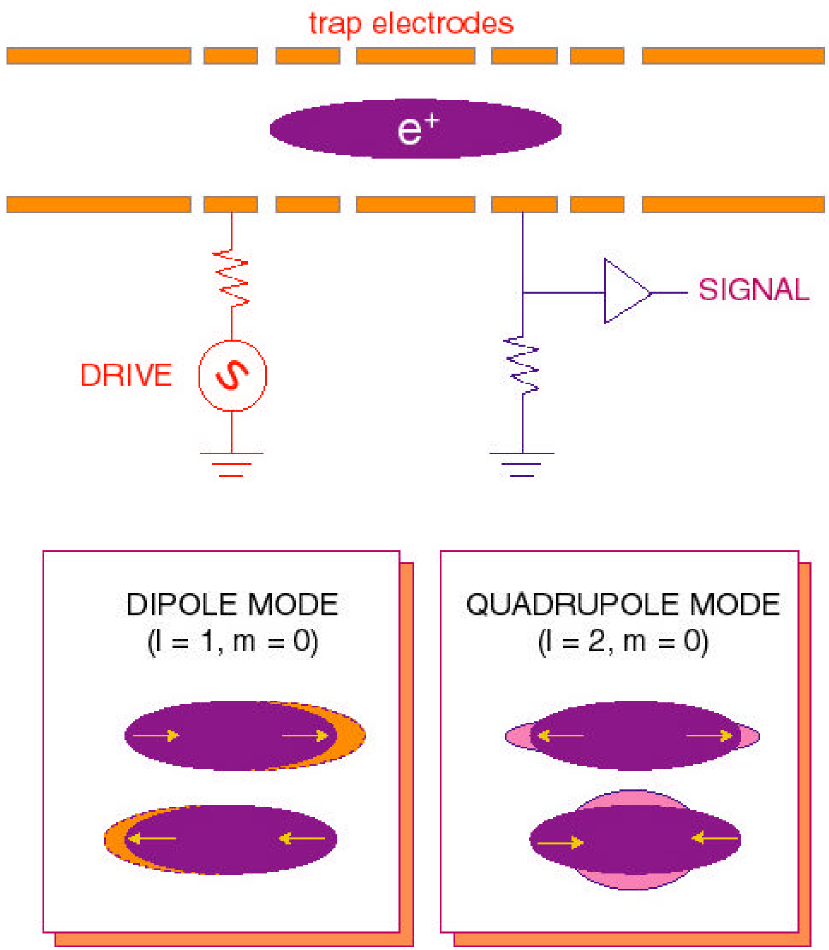




新しいプラズマ診断と操作の方法

PLASMA MODES DIAGNOSTICS

Submitted to *Phys. Rev. Lett.*



等価回路モデル

高周波プラズマ加熱

非破壊的
同時決定

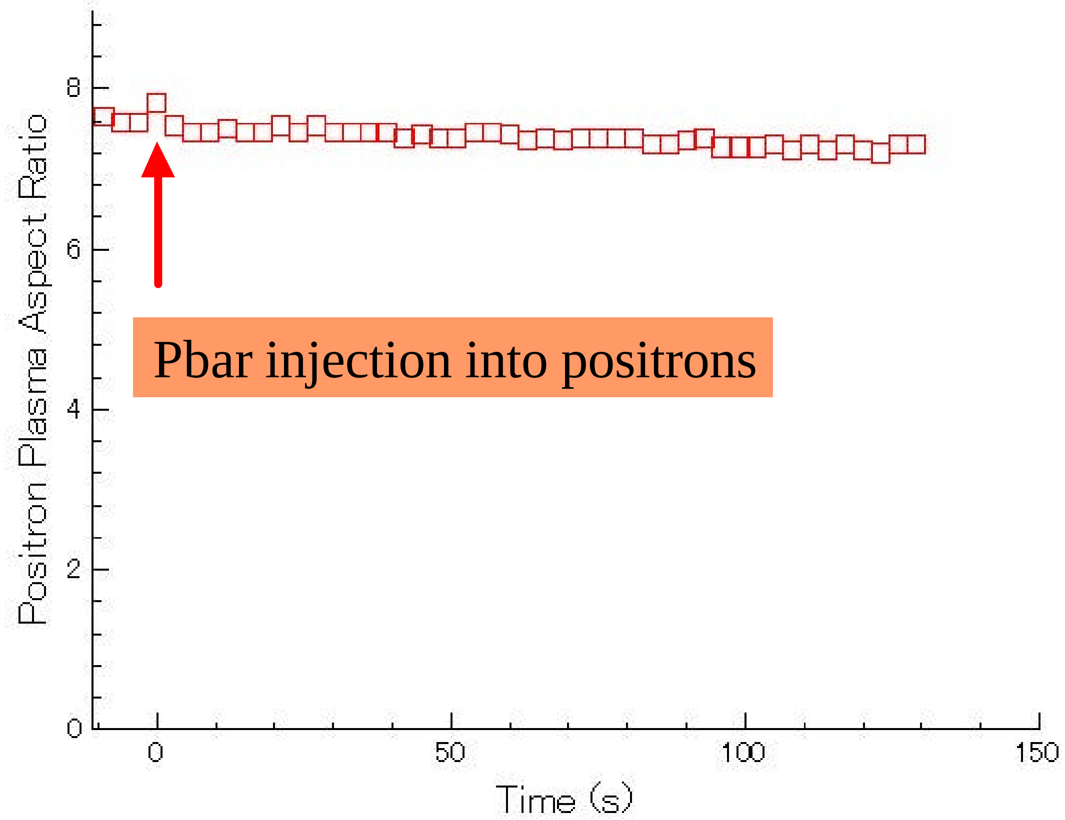
プラズマ形状, 密度,
粒子数,
プラズマ温度

反水素生成中のオンライン・プラズマ観察

プラズマ振動測定

Plasma Modes Measurement during Mixing

Higaki’s suggestion

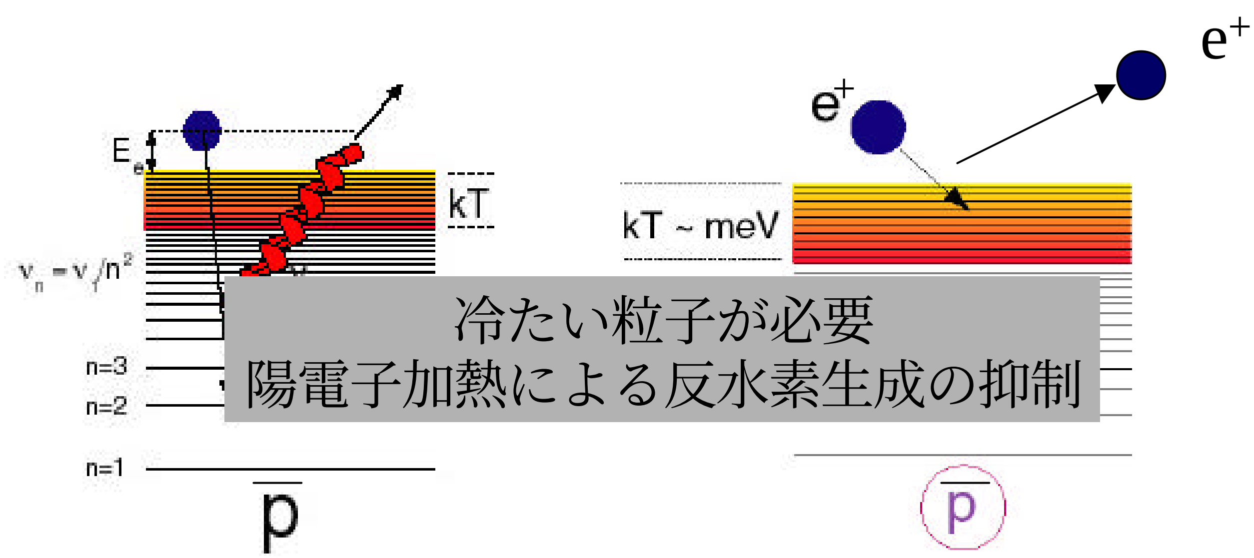


- No significant changes in e+ plasma shape due to pbar injection
- gamma detector rates consistent with hbars

⇩

- No evidence for anomalous plasma transport due to pbars

反水素生成過程

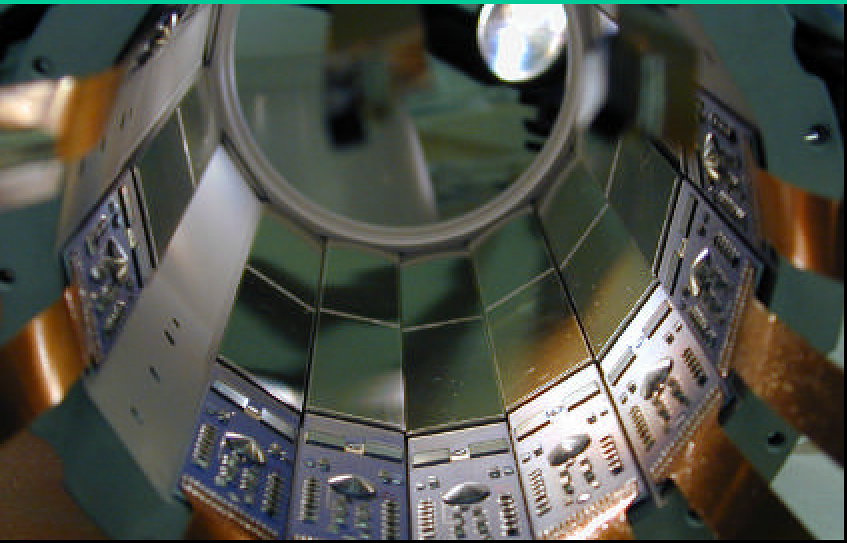


冷たい粒子が必要
陽電子加熱による反水素生成の抑制

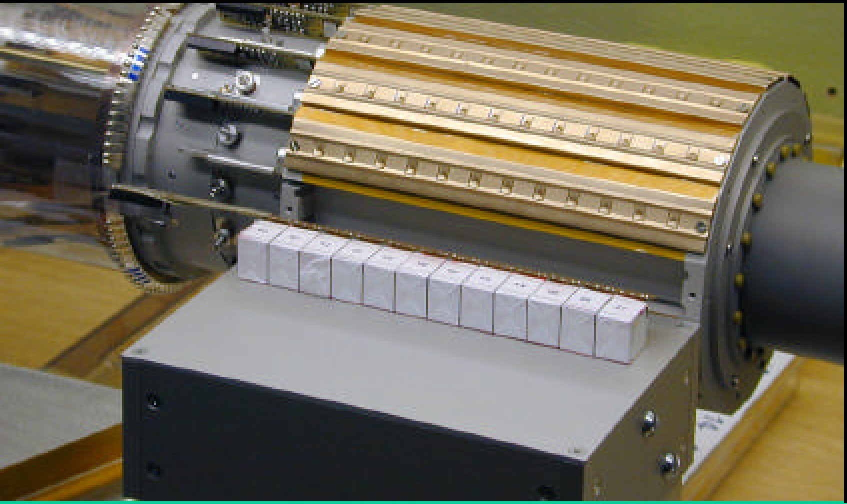
Energy-momentum conservation requires 3rd body

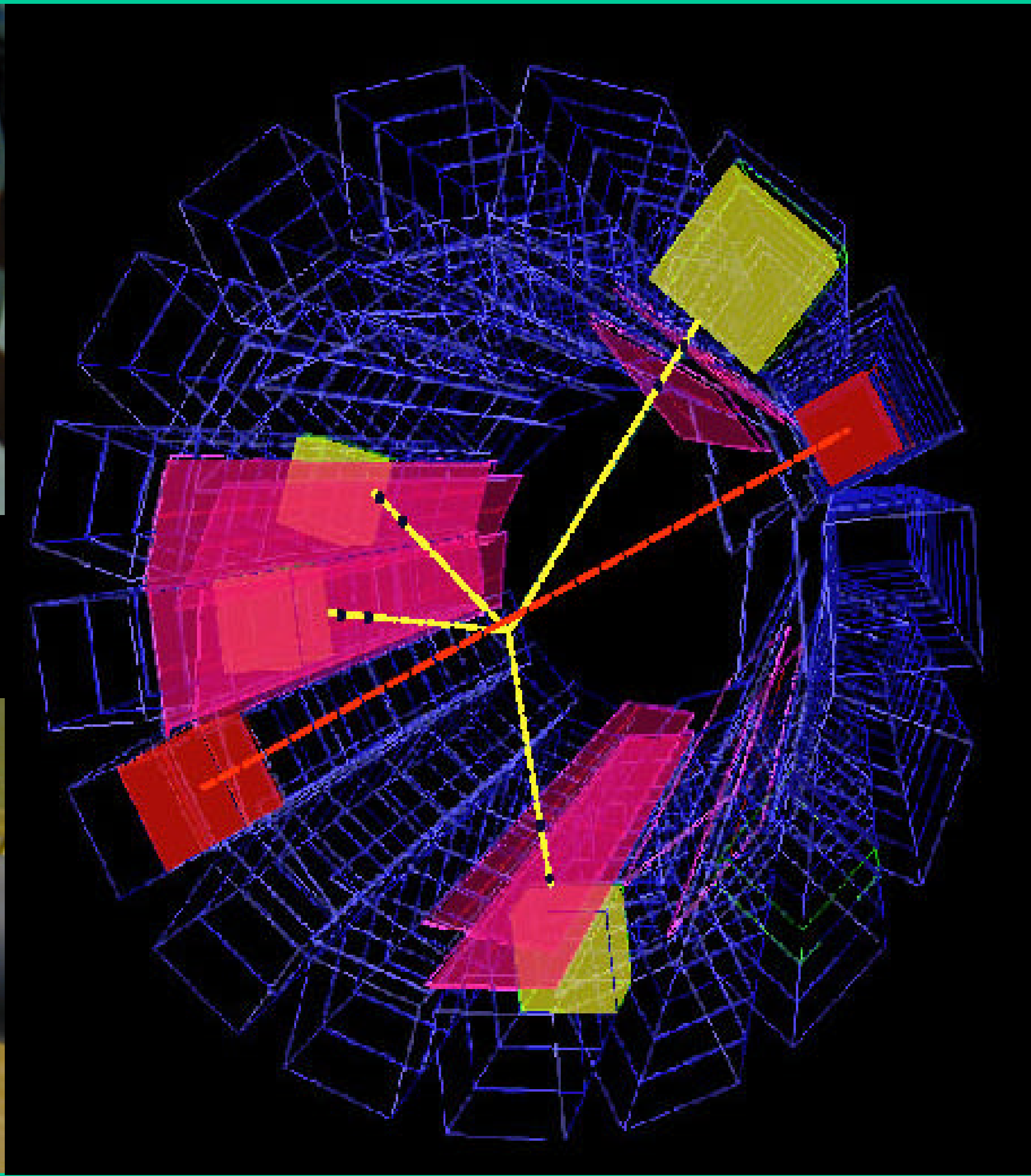
	Radiative	Three-body
Cross-section [cm^2]	10^{-16} (1 K)	10^{-7} (1 K)
Rate T dependence	**$T^{-0.5}$**	**$T^{-4.5}$ → stabilization**
Final quantum state	n < 10	n >> 10
Stability (re-ionization)	high	low
Expected rates	~10s Hz	???

ATHENA 反水素検出器

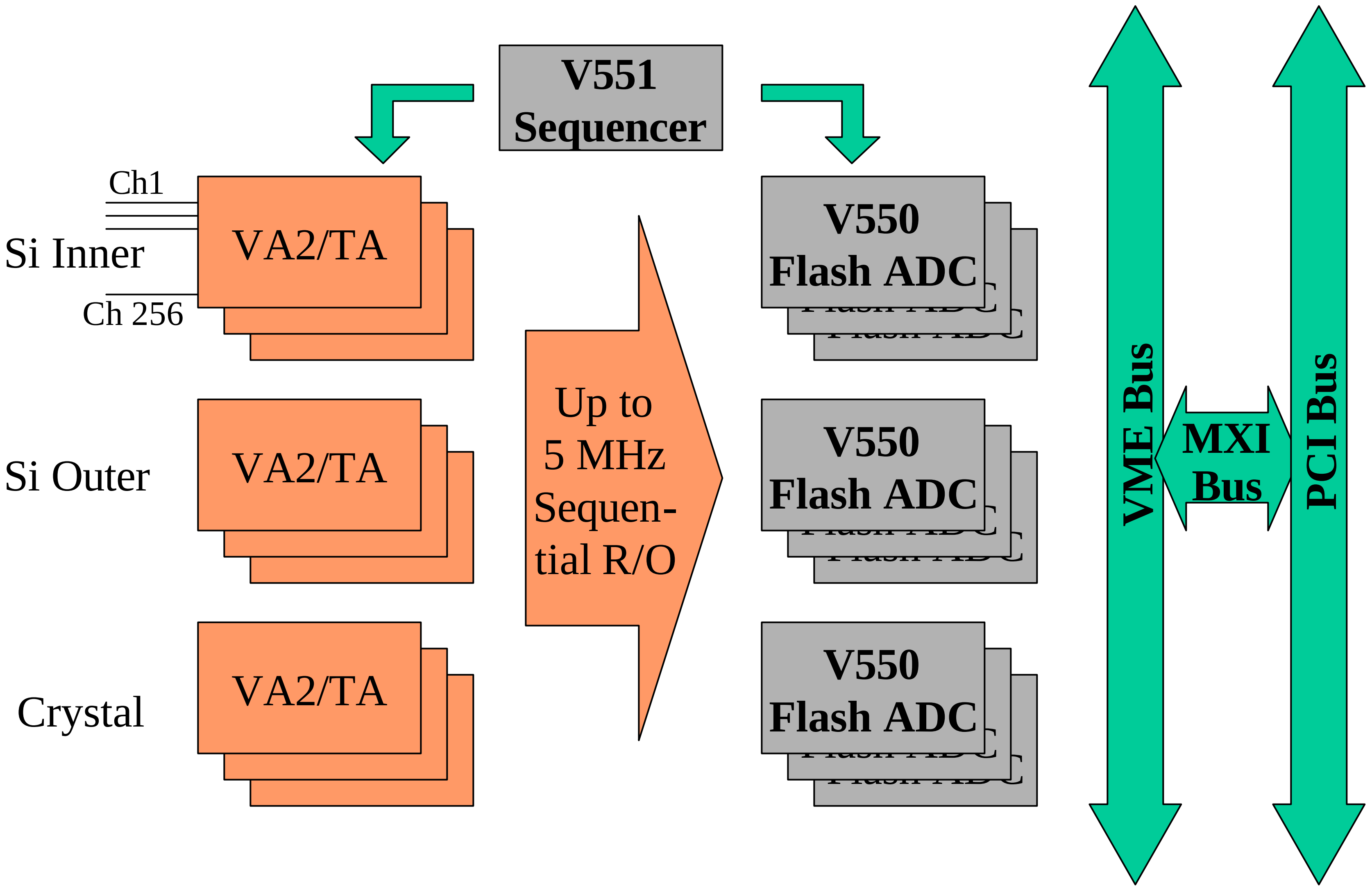


Operated at 140K, 3T, small space
- Si microstrips: 2 layers ~8000 ch
- CsI read out by APD: 192 ch

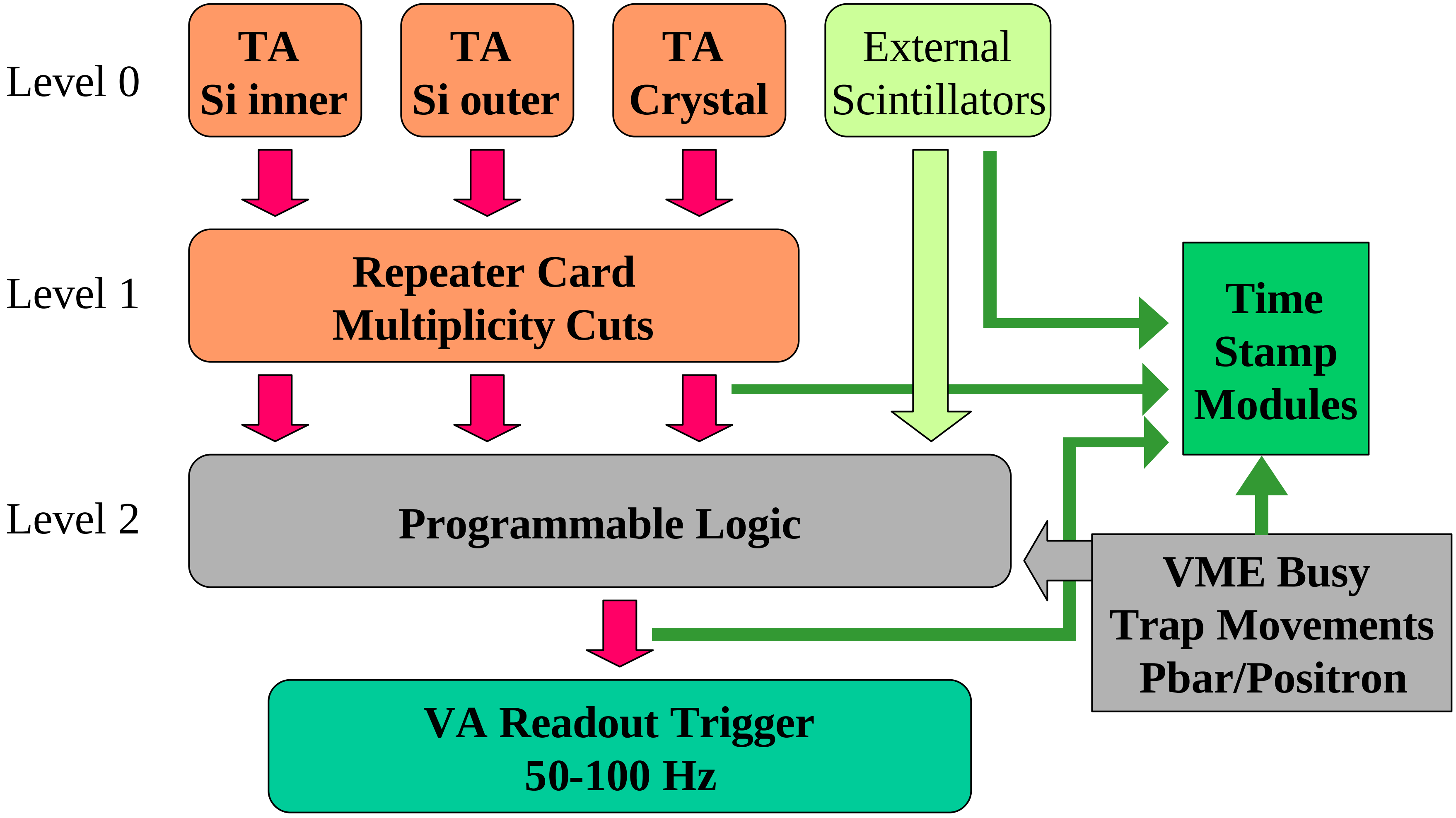




検出器読み出し概略


V551
Sequencer
Ch1
Si Inner
Ch 256
VA2/TA
Si Outer
VA2/TA
Crystal
VA2/TA
Up to
5 MHz
Sequen-
tial R/O
V550
Flash ADC
V550
Flash ADC
V550
Flash ADC
VME Bus
MXI
Bus
PCI Bus

トリガー概略

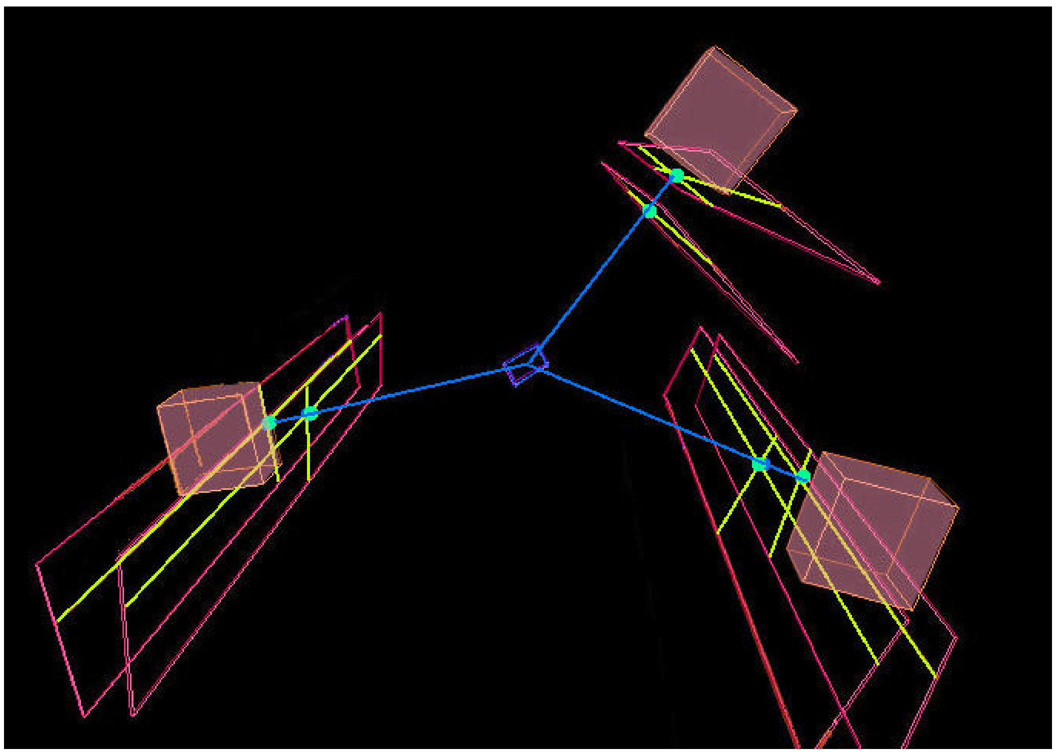


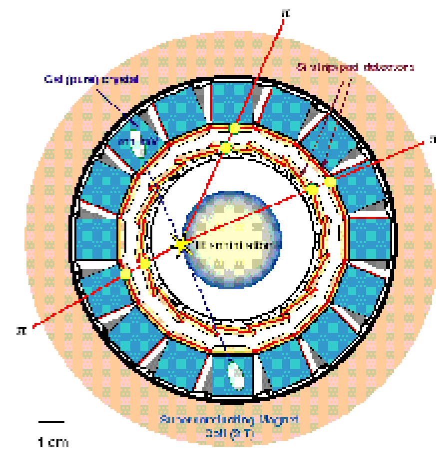
Level 0
TA
Si inner
TA
Si outer
TA
Crystal
External
Scintillators
Level 1
Repeater Card
Multiplicity Cuts
Time
Stamp
Modules
Level 2
Programmable Logic
VME Busy
Trap Movements
Pbar/Positron
VA Readout Trigger
50-100 Hz

反水素検出器 – 反陽子バーテックス

Antiproton Annihilation (example)

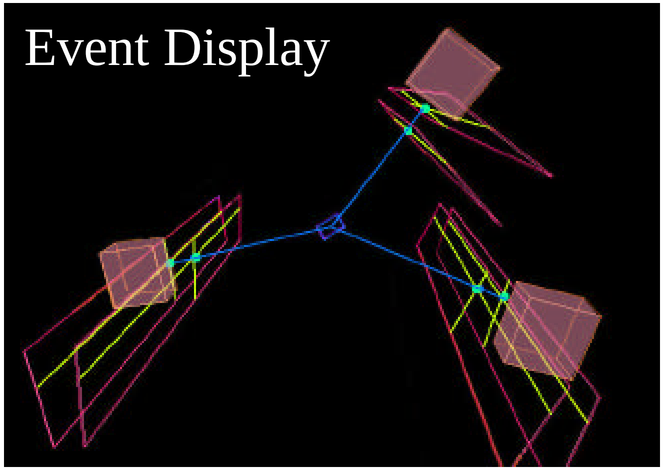
- into three charged particles
- hits on strips (r-phi) and pads (z) , inner/outer layer
- 3 crystals hit by tracks
- vertex reconstruction s ~ 3-4 mm (curvature @ 3 T)



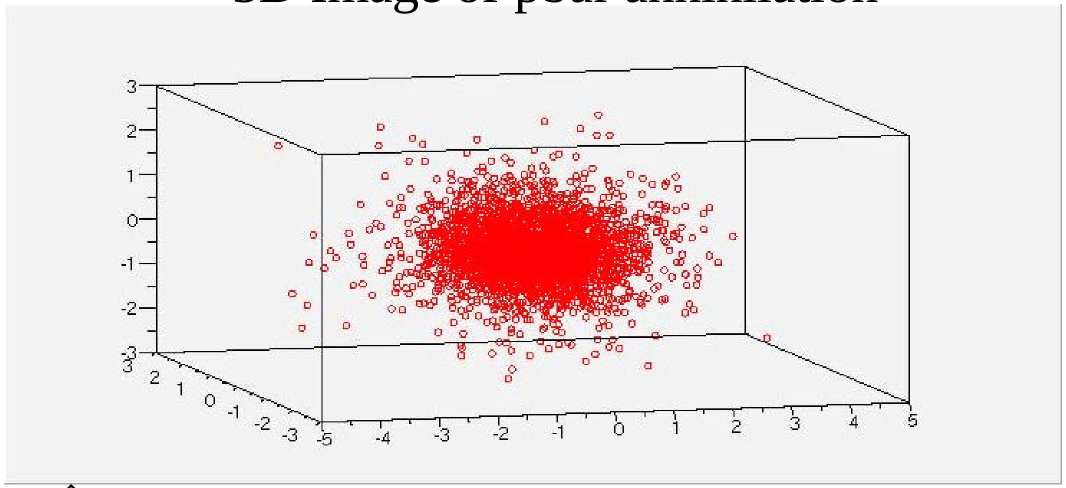


実時間反陽子イメージング

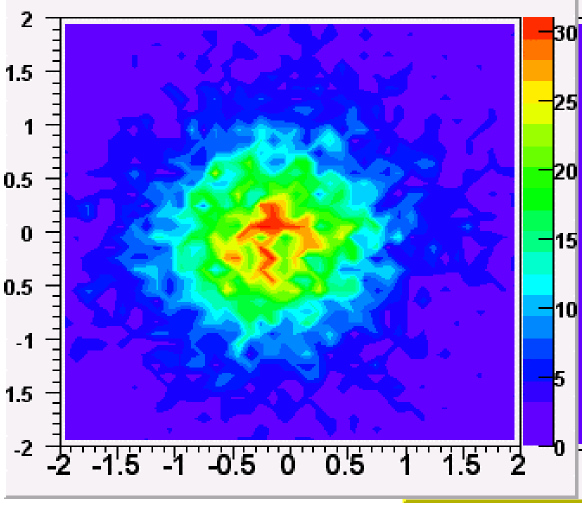
to be published



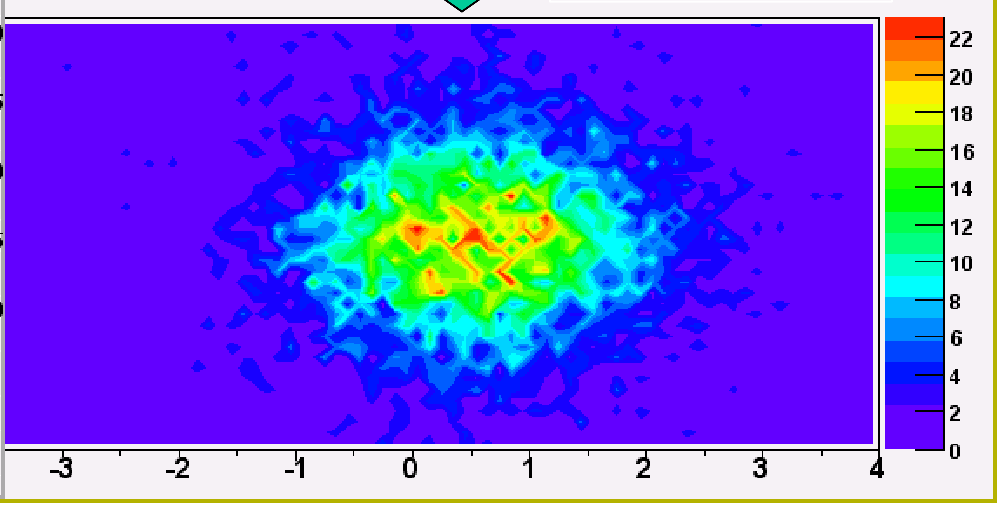
3D Image of pbar annihilation



XY projection



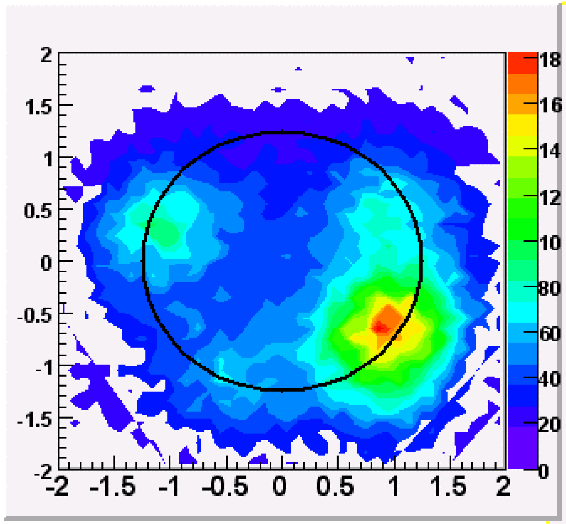
YZ projection



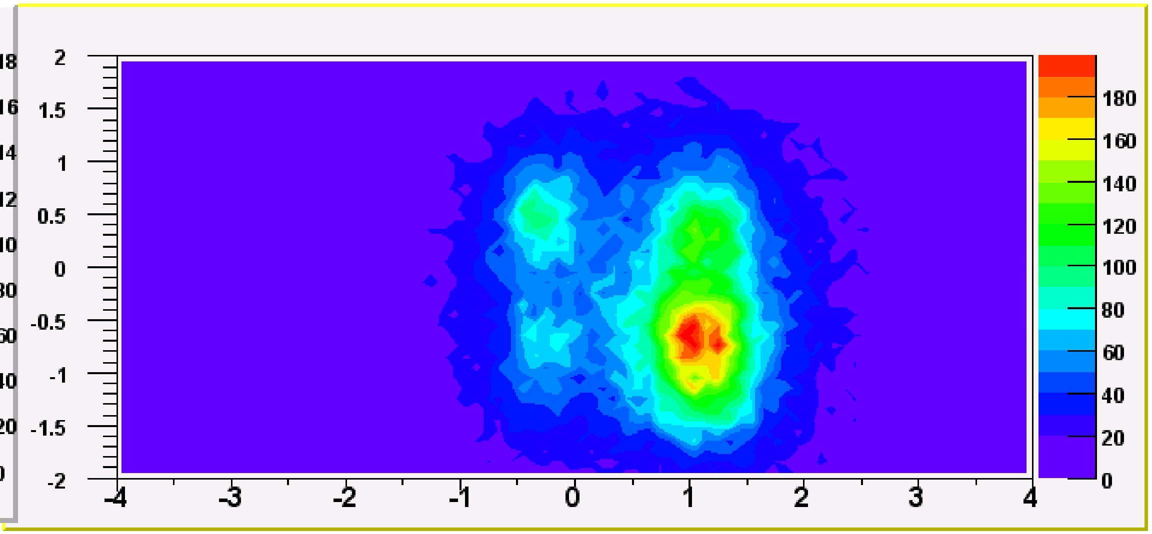
Pbar Imaging: Localized annihilations

to be submitted to Phys. Rev. Lett.

Pbar-only (with electrons)

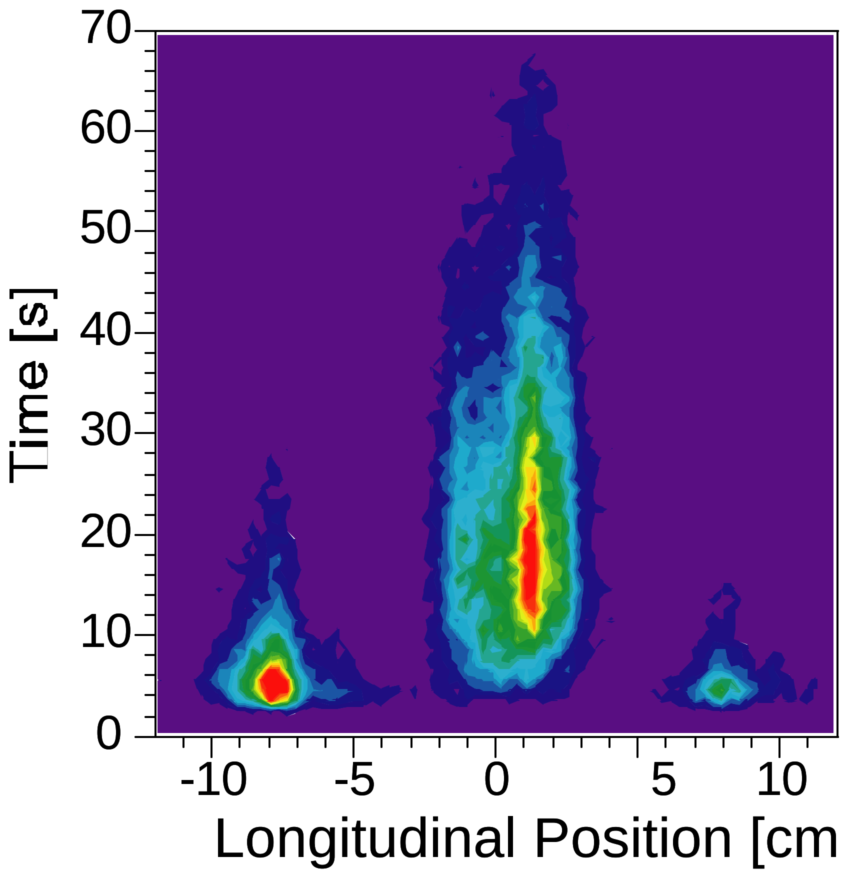


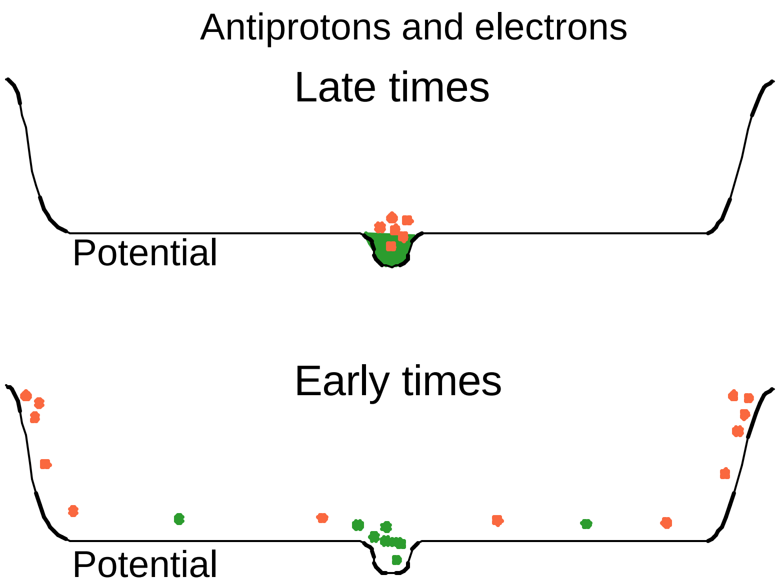
XY projection



YZ projection

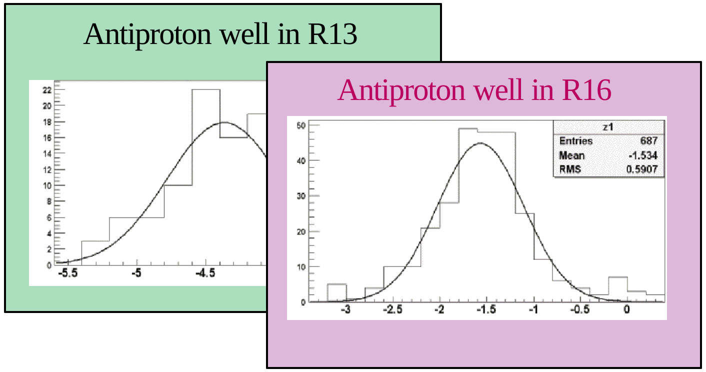
時間分解プラズマ視覚化

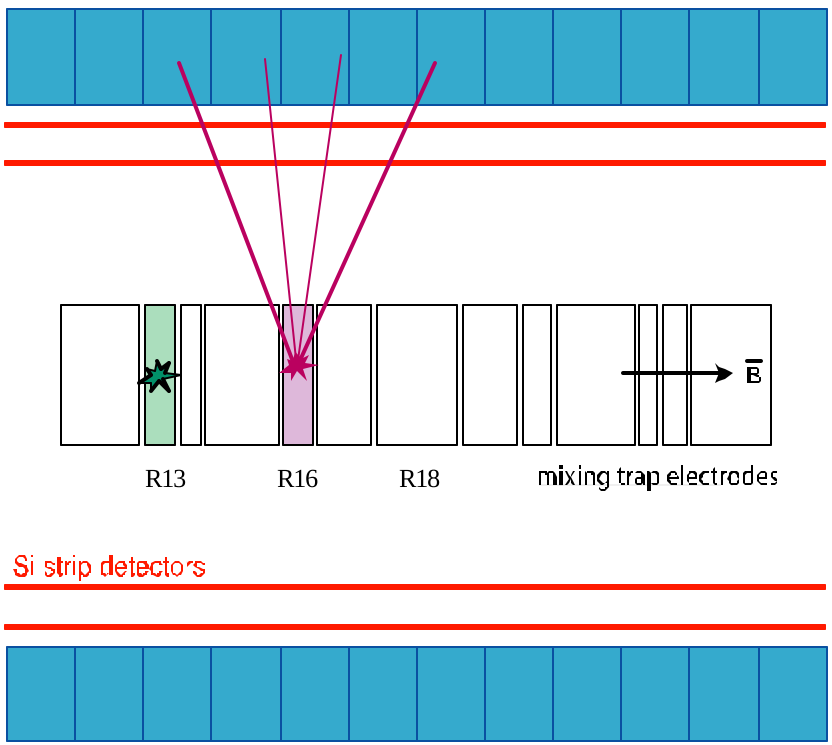


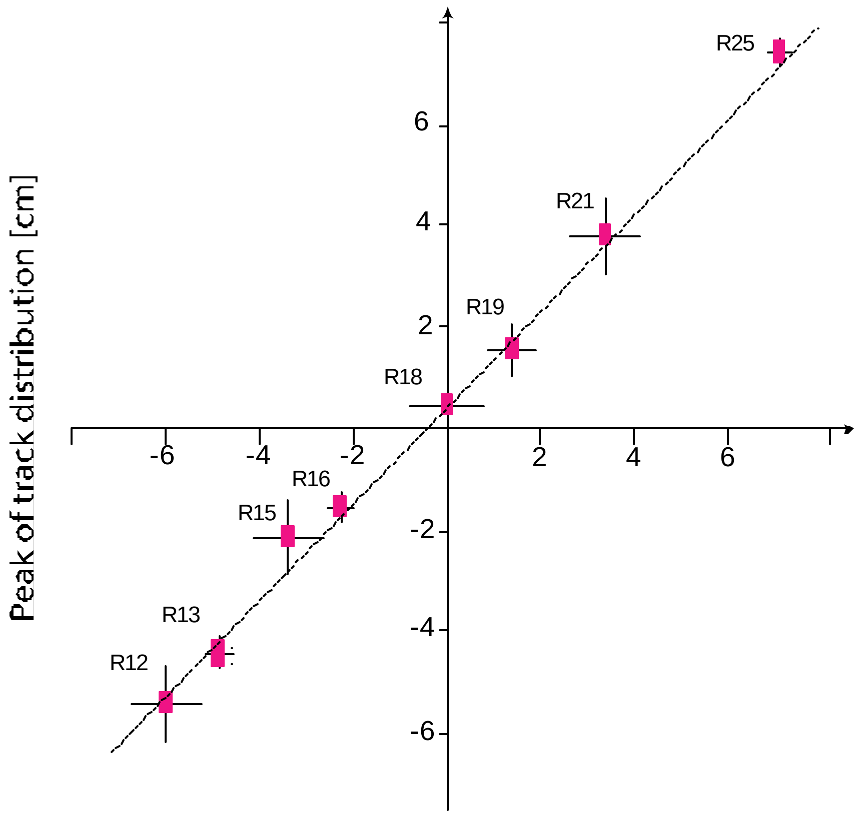


Powerful plasma and loss diagnostics !

反陽子消滅によるZ 位置較正

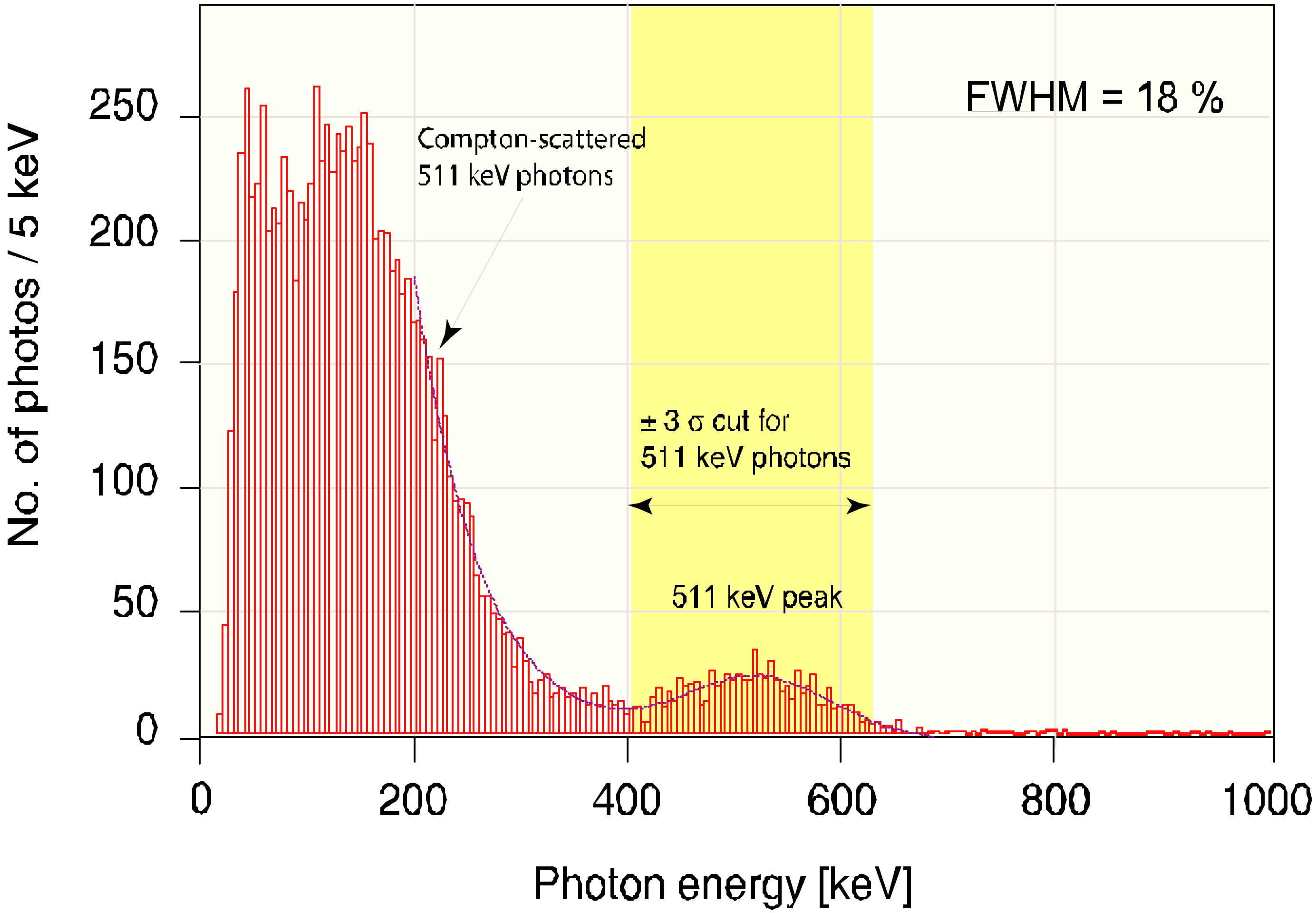






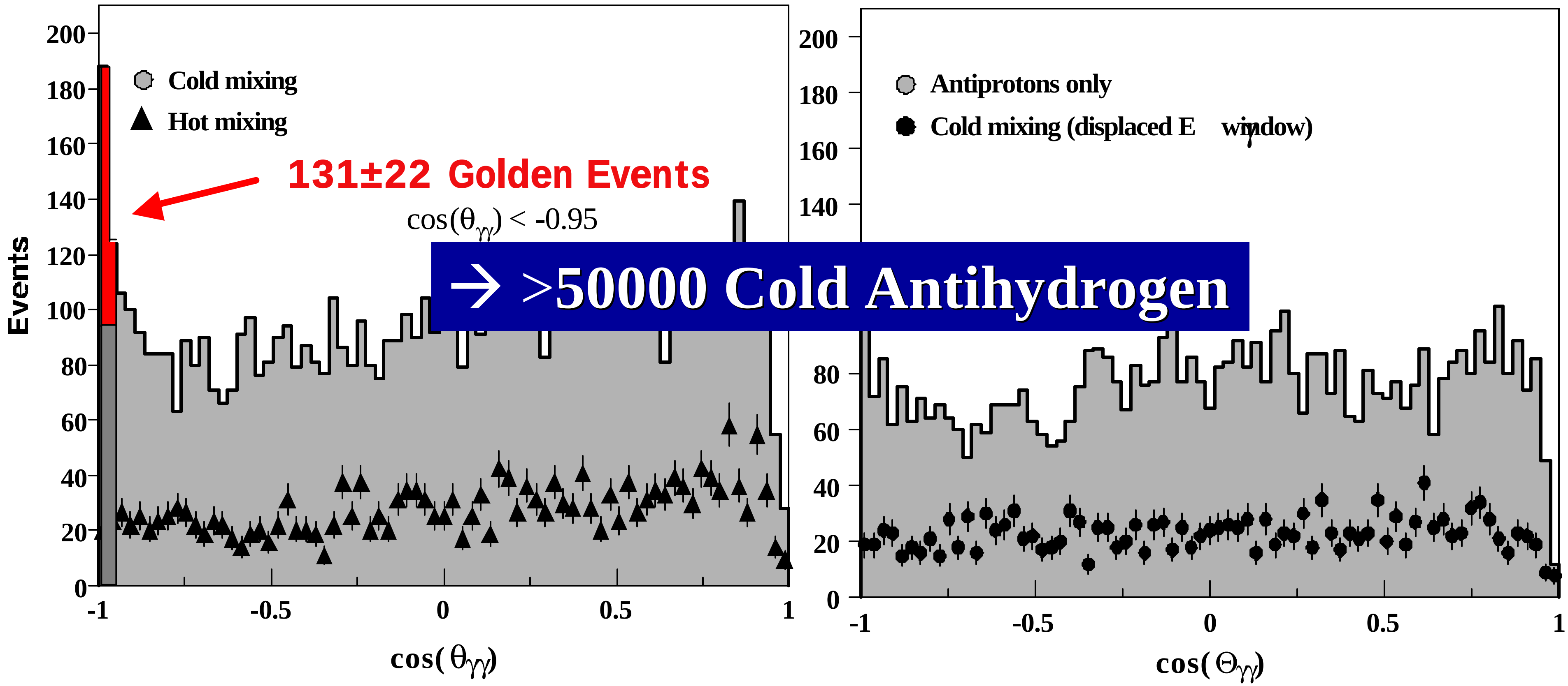
CsI スペクトラム（511 keV γ線）

192 Pure CsI read out via APD



冷たい反水素生成の信号 August 2002 *ATHENA*

Amoretti et al., ***Nature*** 419 (2002) 456



Background Measurements

1. Hot-Mix: mixing with RF heated e^+ (~3000K):
→turning off Hbar formation

2. Pbar-Only annihilation in interaction region
3. Displaced Eγ window
(NB: random coinc negligible)

ATHENAが勝った！

***Nature*, September 18, 2002**

advance online publication

letters to nature

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe||, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst||, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#**

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|| *Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*
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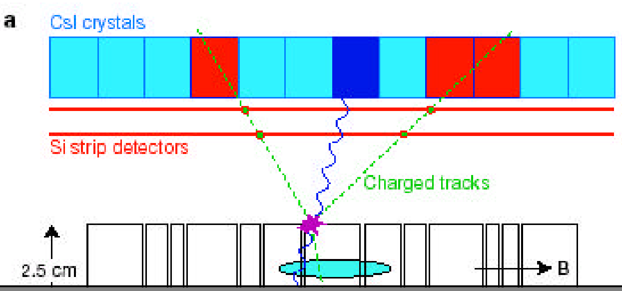
# *Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK*
☆ *Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, and ** Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy*
†† *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

A theoretical underpinning of the standard model of fundamental particles and interactions is CPT invariance, which requires that the laws of physics be invariant under the combined discrete operations of charge conjugation, parity and time reversal. Antimatter, the existence of which was predicted by Dirac, can be used to test the CPT theorem—experimental investigations involving comparisons of particles with antiparticles are numer-

drogen annihilation detector. All traps in the experiment are variations on the Penning trap[6], which uses an axial magnetic field to transversely confine the charged particles, and a series of hollow cylindrical electrodes to trap them axially (Fig. 1a). The catching and mixing traps are adjacent to each other, and coaxial with a 3 T magnetic field from a superconducting solenoid. The positron accumulator has its own magnetic system, also a solenoid, of 0.14 T. A separate cryogenic heat exchanger in the bore of the superconducting magnet cools the catching and mixing traps to about 15 K. The ATHENA apparatus[7] features an open, modular design that allows great experimental flexibility, particularly in introducing large numbers of positrons into the apparatus—an essential factor in the current work.

The catching trap[8] slows, traps, cools and accumulates antiprotons. To cool antiprotons, the catching trap is first loaded with 3×10^8 electrons, which cool by synchrotron radiation in the 3 T magnetic field. Typically, the AD delivers 2×10^7 antiprotons having kinetic energy 5.3 MeV and a pulse duration of 200 ns to the experiment at 100-s intervals. The antiprotons are slowed in a thin foil and trapped using a pulsed electric field. The antiprotons lose energy and equilibrate with the cold electrons by Coulomb interaction. The electrons are ejected before mixing the antiprotons with positrons. Each AD shot results in about 3×10^3 cold antiprotons for interaction experiments.

a



ATHENA in the News

September 19, 2002

- International Herald Tribune 一面
- Guardian 社説
- Financial Times
- USA Today
- Le Monde (France)
- Die Welt (Germany)
- Spiegel (Germany)
- Tribune de Geneve (Switzerland)
- El Mundo (Spain)
- Corriere della Sera (Italy)
- Ingeniøren (Denmark)
- Dagens Nyheter (Sweden)
- Helsigin Sanomat (Finland)
- Spits (Netherlands)
- Gazeta Wyborcza (Poland)
- The Times of India (India)
- etc…

2002年の重大科学ニュース

- 英物理学会*Physics World*：2002年のトップ1物理ニュース
- 米物理学会*Physics News Update*：同率トップ1ニュース(SNO)
- 一般科学雑誌ディスカバー：トップ4科学ニュース
- ネイチャー：2002年のハイライトの一つ
- サイエンス：来年（2003年）の注目株

…

- ネット·カルチャー雑誌 *Wired* Magazine：

  Annual Rave Awards Nomination

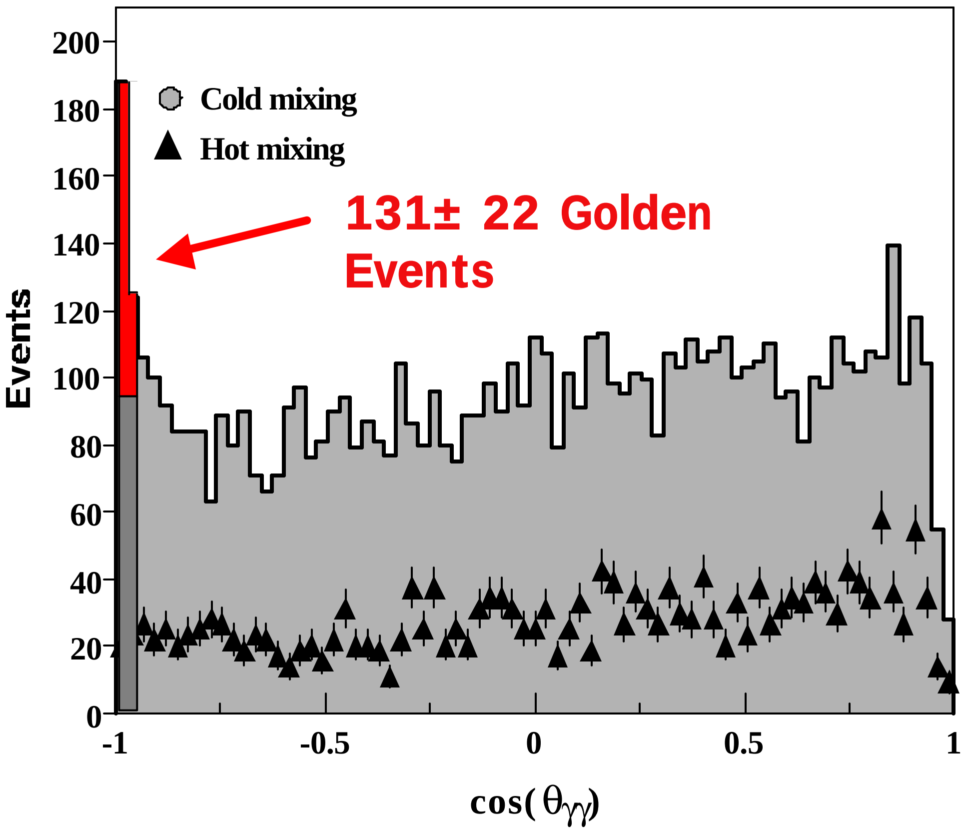
  「今年新しい文化を創った人々」

  (Eminem, スピルバーグ, 宮崎駿)

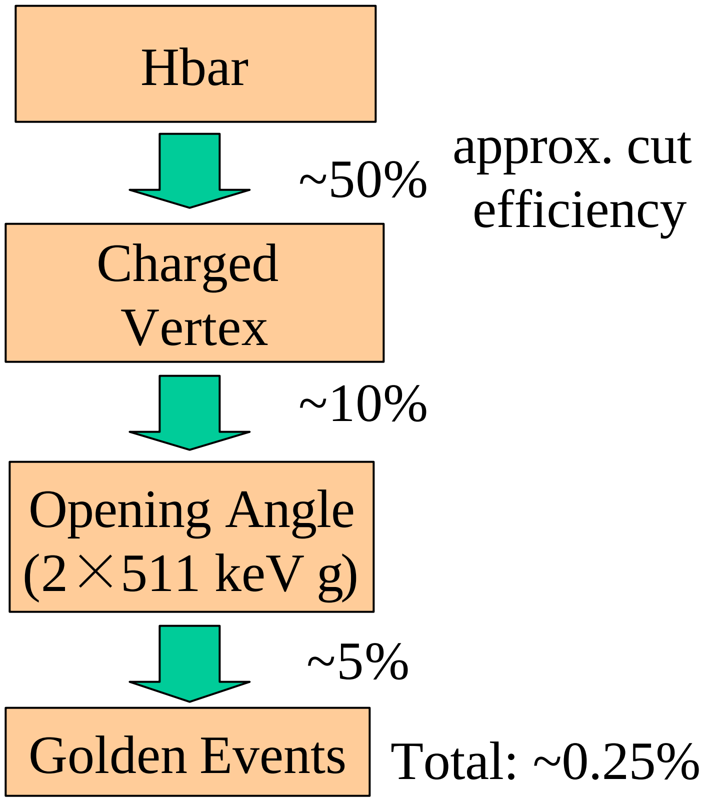
ATHENAその後の結果

PRELIMINARY

Golden Event を超えて

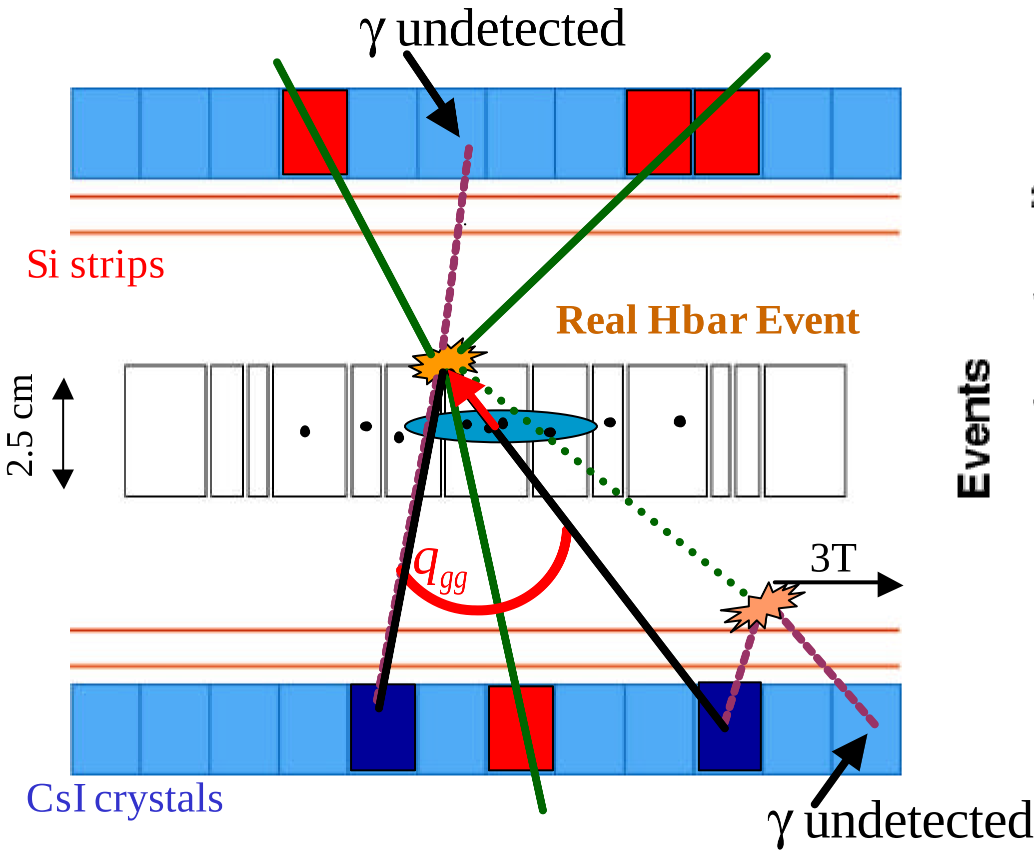


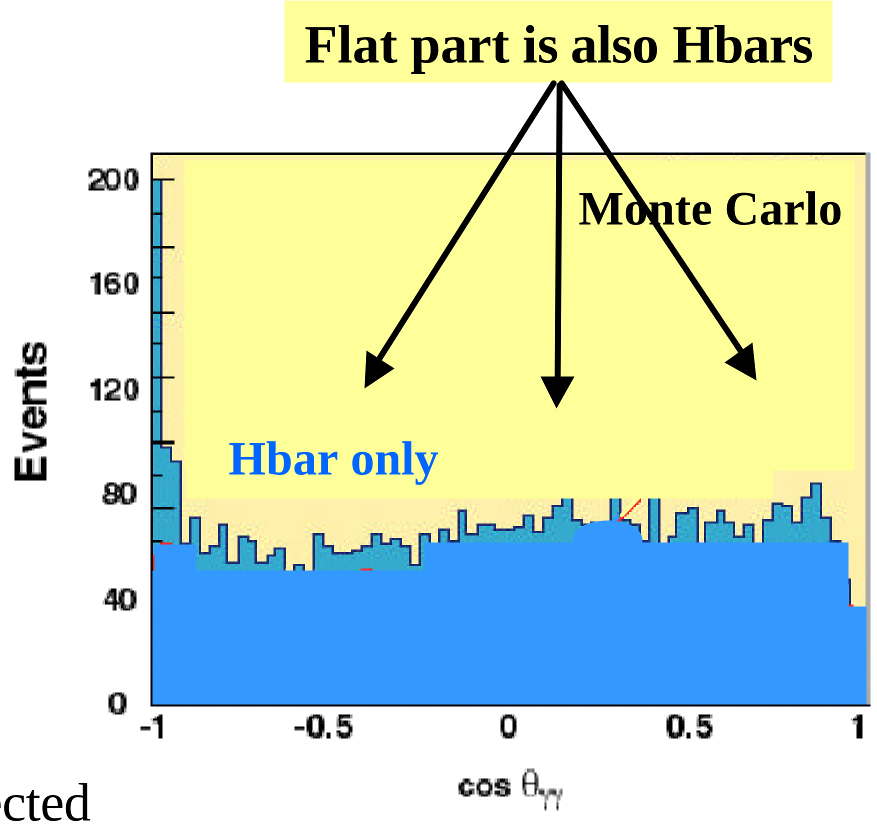
Golden Event Selection



- Very restrictive cuts: threw away >99.7% of events
- Can we make connection between Hbars and Vertices?

γ 角度分布の平らな部分





Hbar event can have >two 511keV γs, but not all are detected (eff. ~20%)

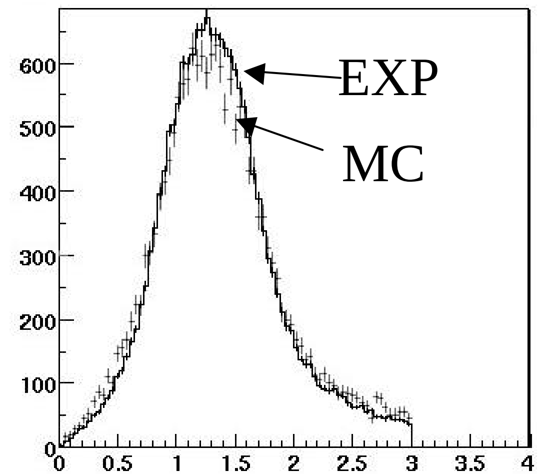
e.g. one γ from pbar→pion shower, another γ from e^+ in Hbar:

can give opening angles, $\cos(\theta_{\gamma\gamma}) \neq -1$

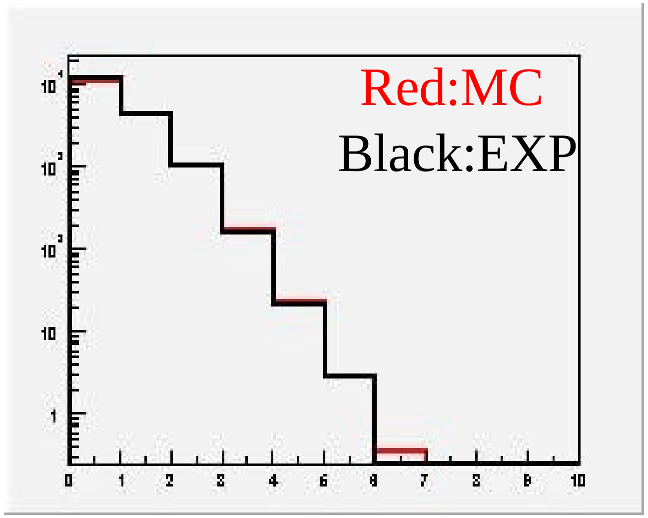
モンテカルロ ·シミュレーション

- •GEANTフル ·シミュレーション
- •検出器の位置はCADから
- •モジュールごとの検出効率を較正
- •シミュレーションと実験解析に同じソフト

Pbar-Only Data



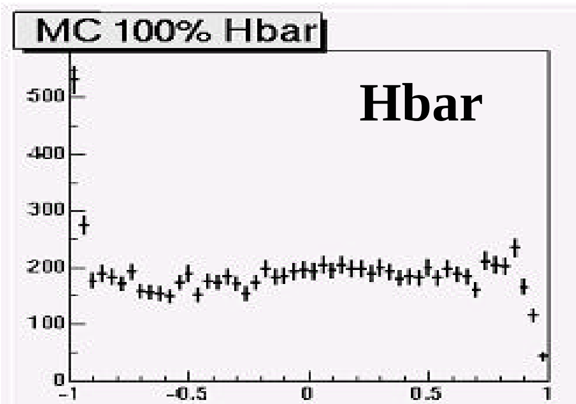
Vertex radial distribution (cm)

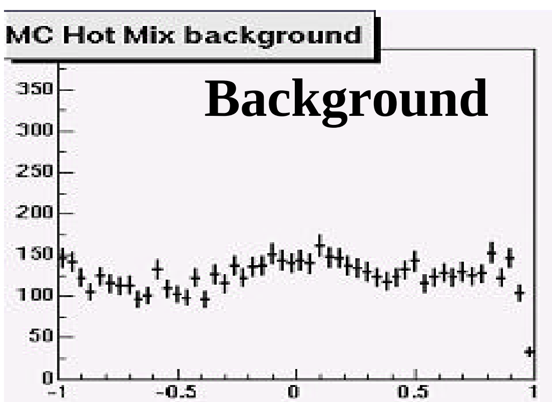


511 keV γ multiplicity

γ角度分布のフィット

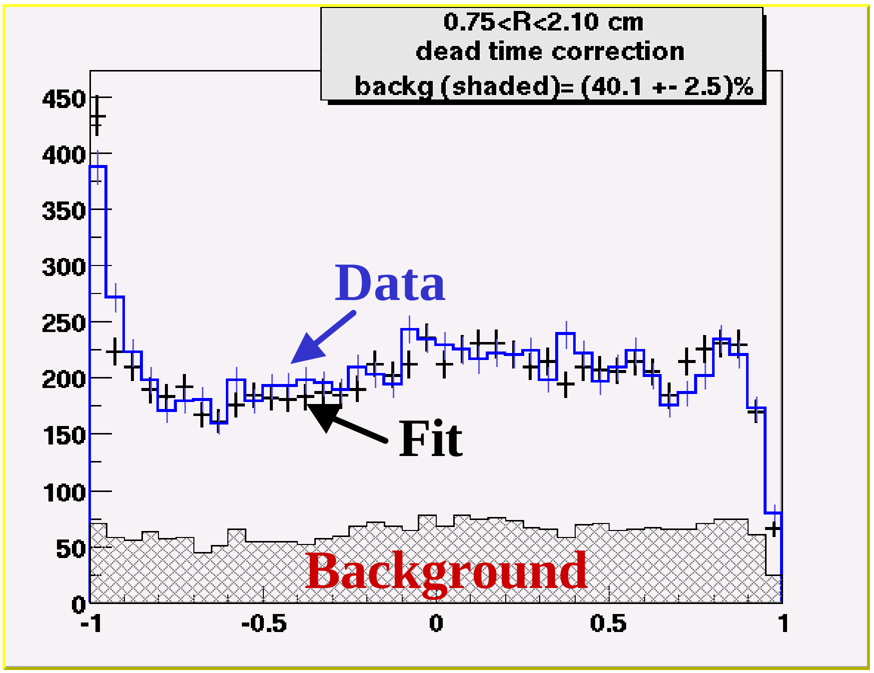
Fit Input MC





$\cos(\theta_{\gamma\gamma})$

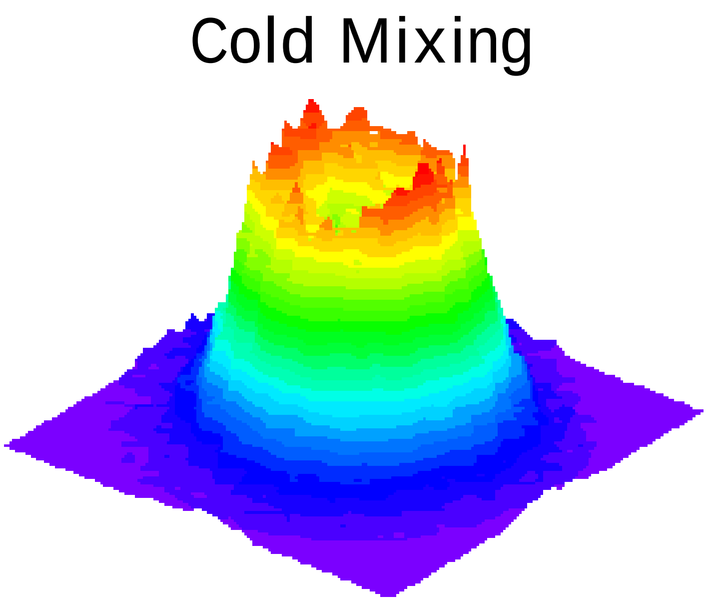
Fit Result



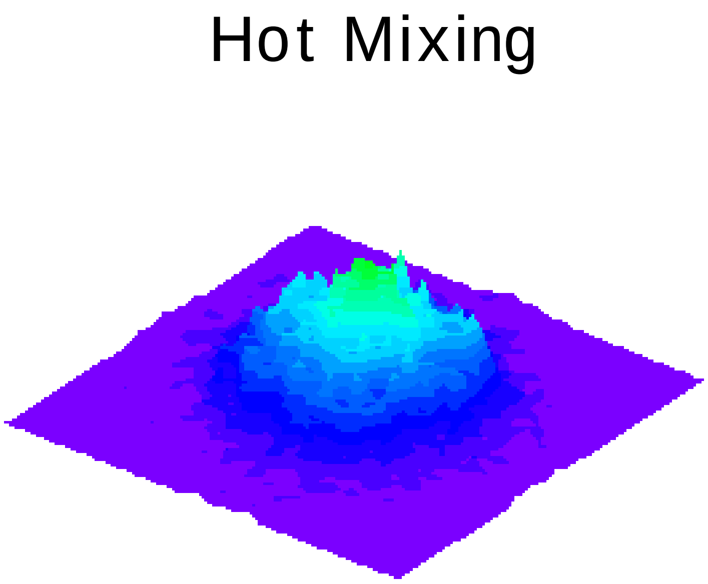
$\cos(\theta_{\gamma\gamma})$

- Good agreement between Data and MC fit
- Indicates 2/3 of the entries are Hbars (not only the peak)

反陽子消滅バーテックス (γカットなし)



主に反水素が壁に当たって消滅
(+残留気体バックグランド)



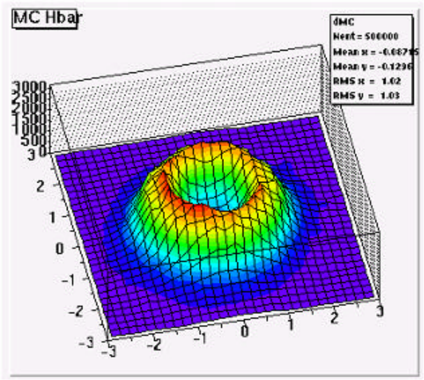
反陽子が残留気体・イオンと消滅

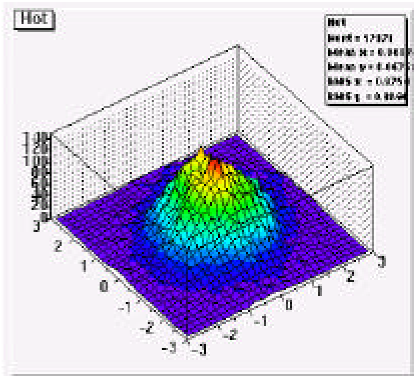
シミュレーションを使ってCold Mixingの分布を反水素成分とバックグランド成分に分解

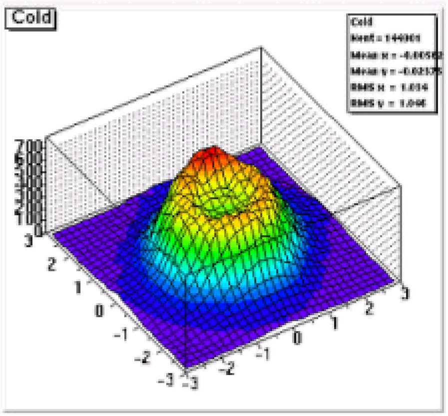
→Signal ~60%; background ~40%

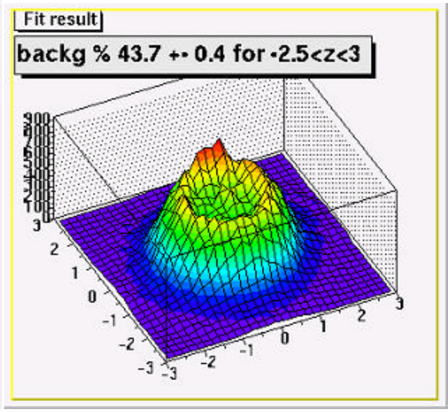
バーテックス空間分布のフィット

Hbar (MC) **BG (Hot Mix)** **Cold Mix Data** **Fit Result**



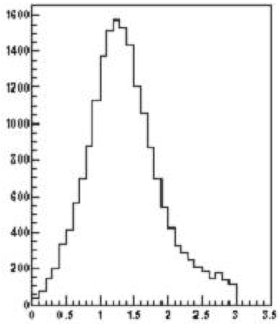


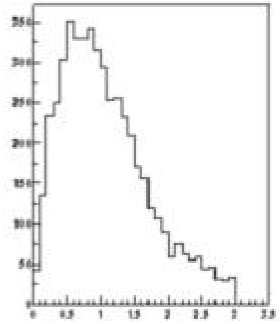


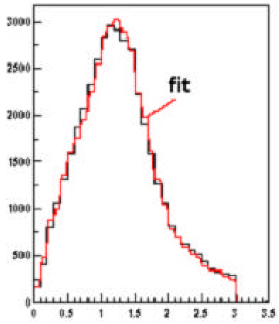


Pbar Vertex XY Projection (cm)

Fit Result







Pbar vertex R distribution (cm)

フィット結果 (Preliminary）

g g opening angle
Vertex XY distribution
Vertex R distribution
Two γ events yield
Charged trigger yield

→

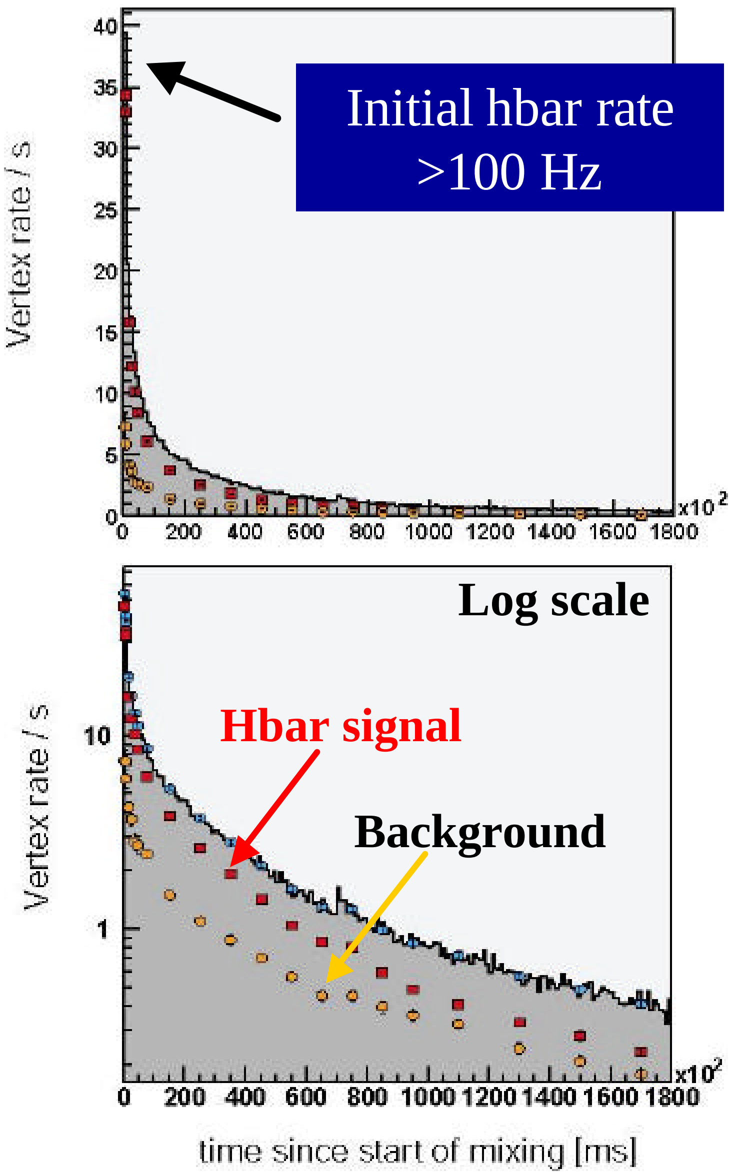
Hbar fraction in during mixing
(ave. over 180 sec)

~65 ±10 %

~700k reconstructed vertices → ~400k Hbars

In 2002, *ATHENA* produced
~ One Million Hbars!

反水素の高効率生成



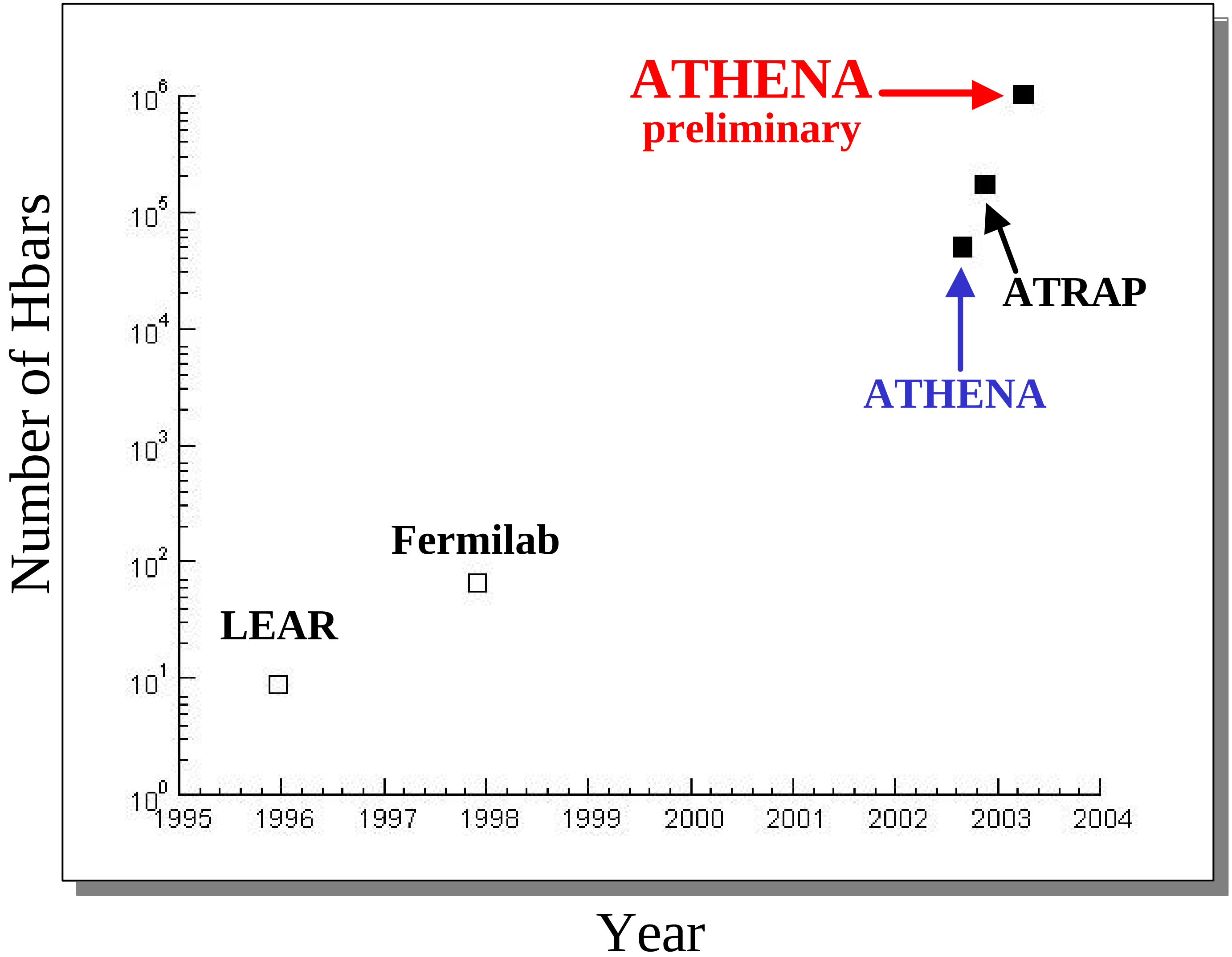
+

消滅位置分布のフィットにより、シグナルとバックグランドの時間的変化をとりだすことが可能

Antihydrogen produced with

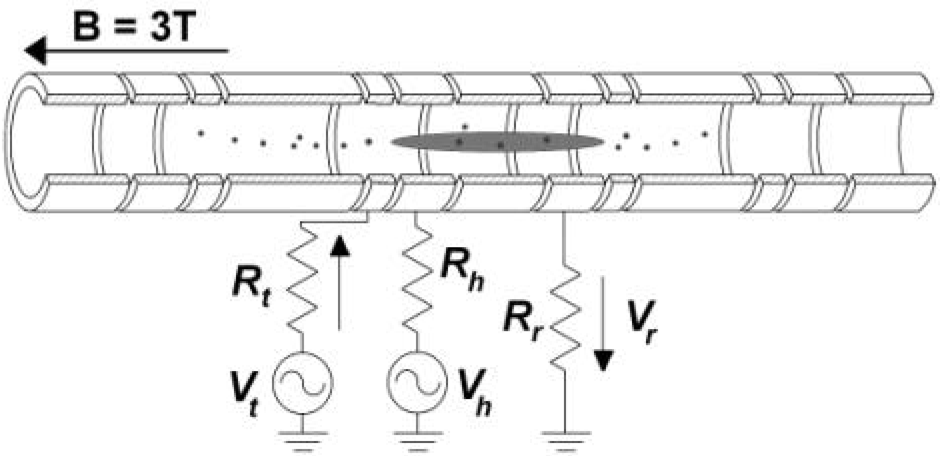
High Initial Rate (>100 Hz)

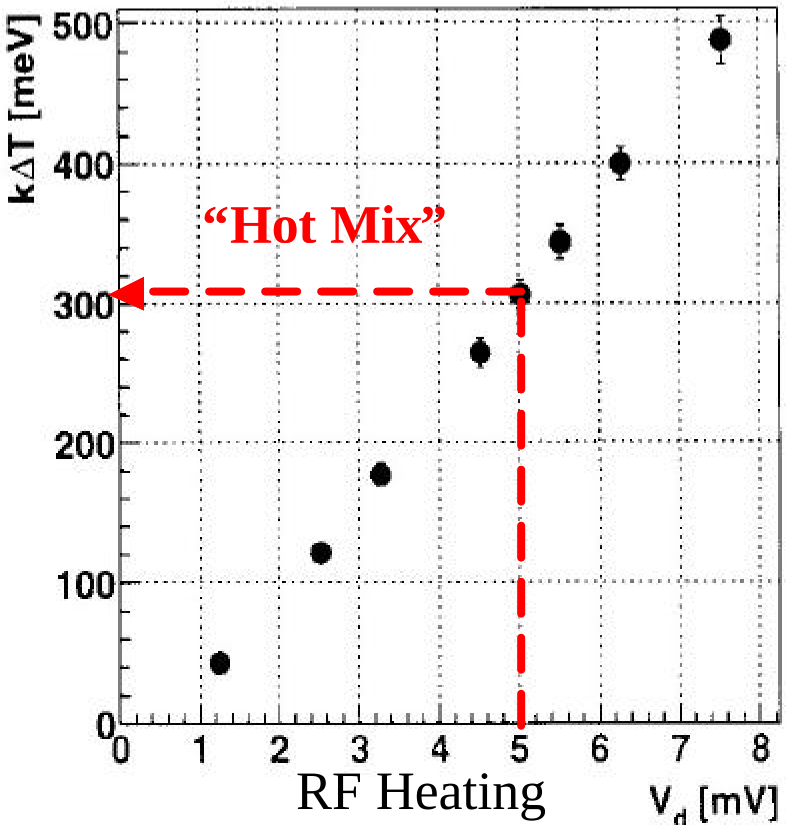
Produced Antihydrogen vs Year



反水素生成の温度依存性

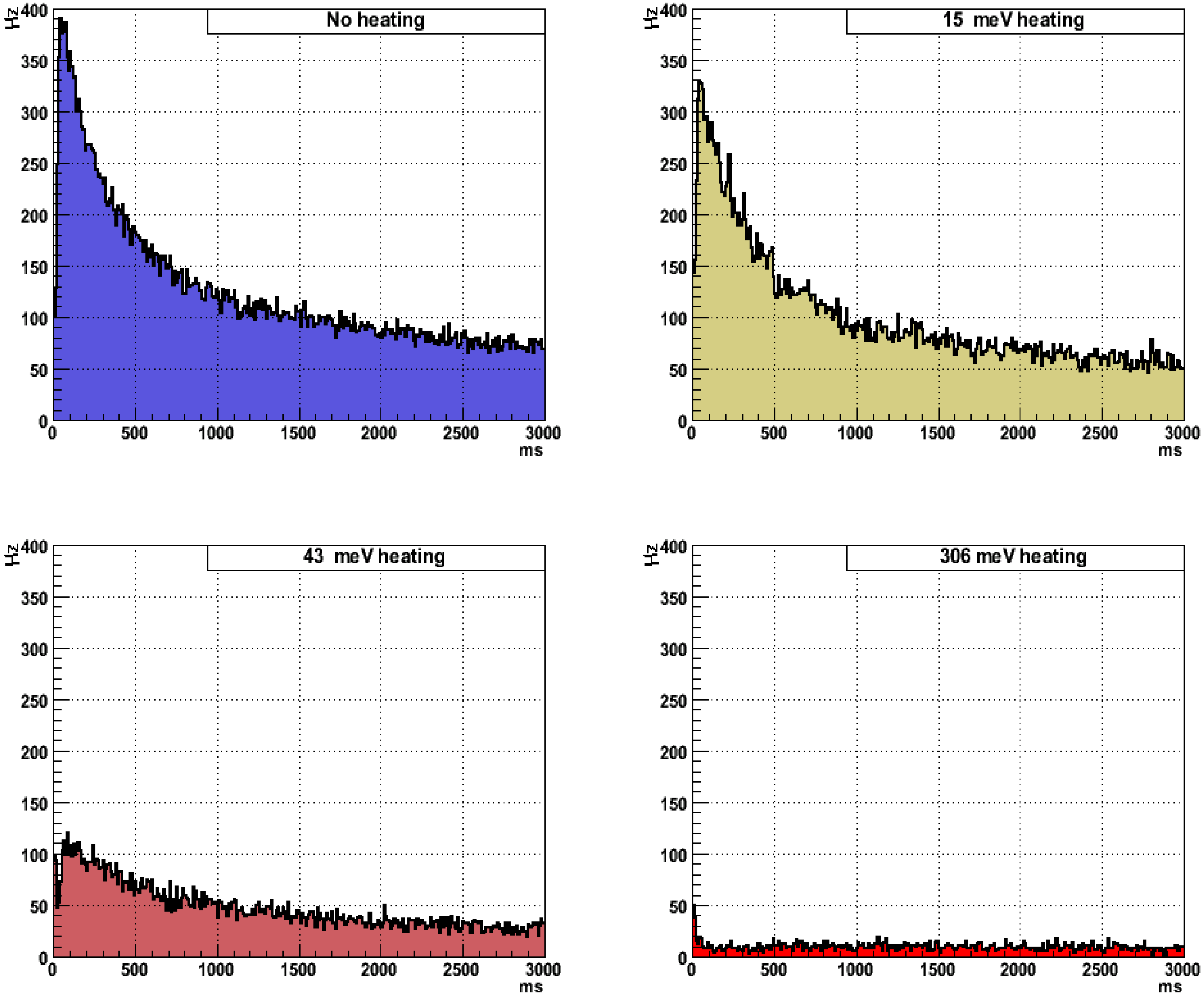
T dependence gives information of formation mechanism
e.g. radiative vs 3-body formation





- Positron plasma heating via RF
- Temperature calibrated by modes measurements

反水素生成の温度依存性 (生成過程による)



High statistics for:

1) no heating
"COLD MIXING"

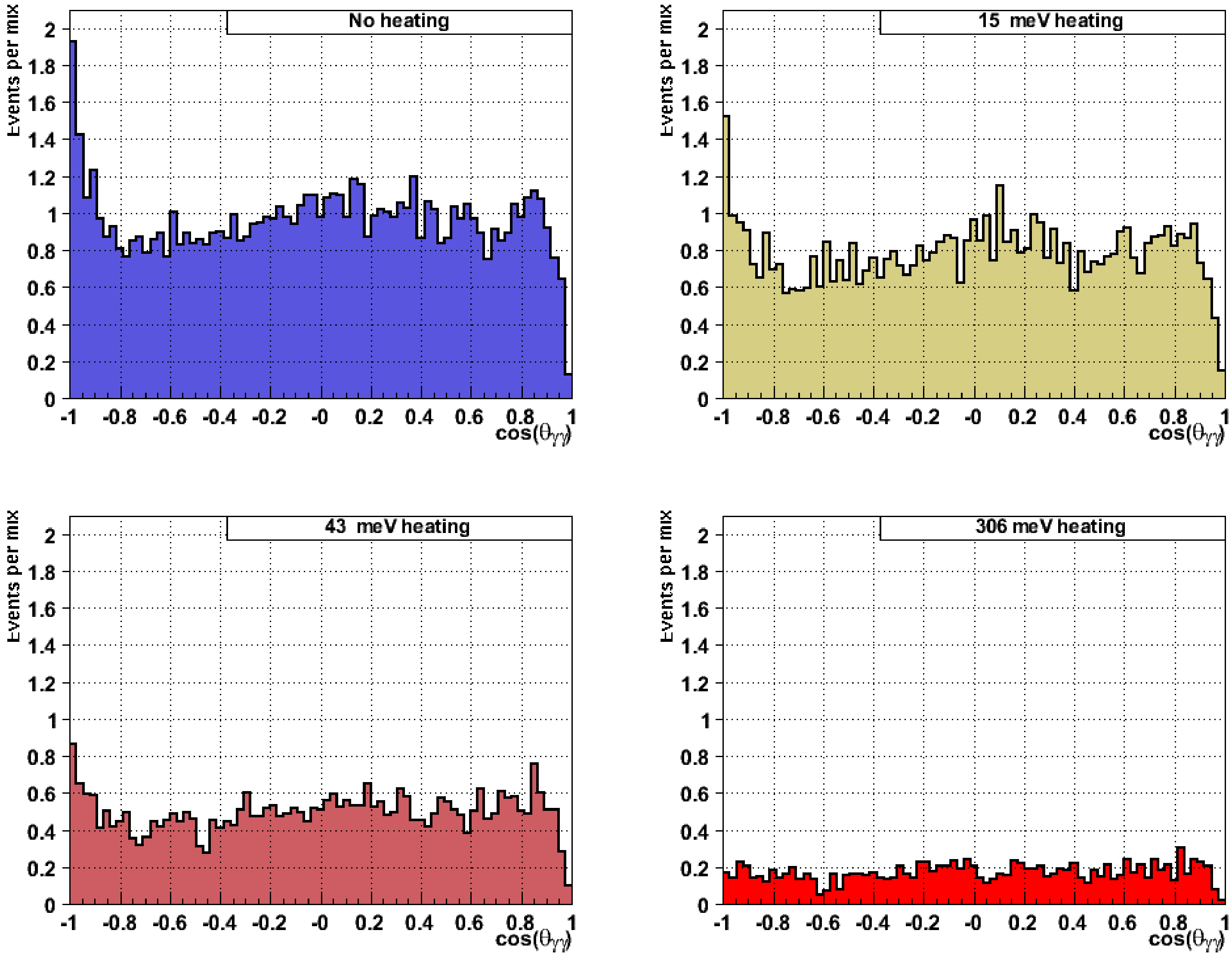
2) ΔT: 15 ± 15 meV
~175 K

3) ΔT: 43 ± 17 meV
~500 K

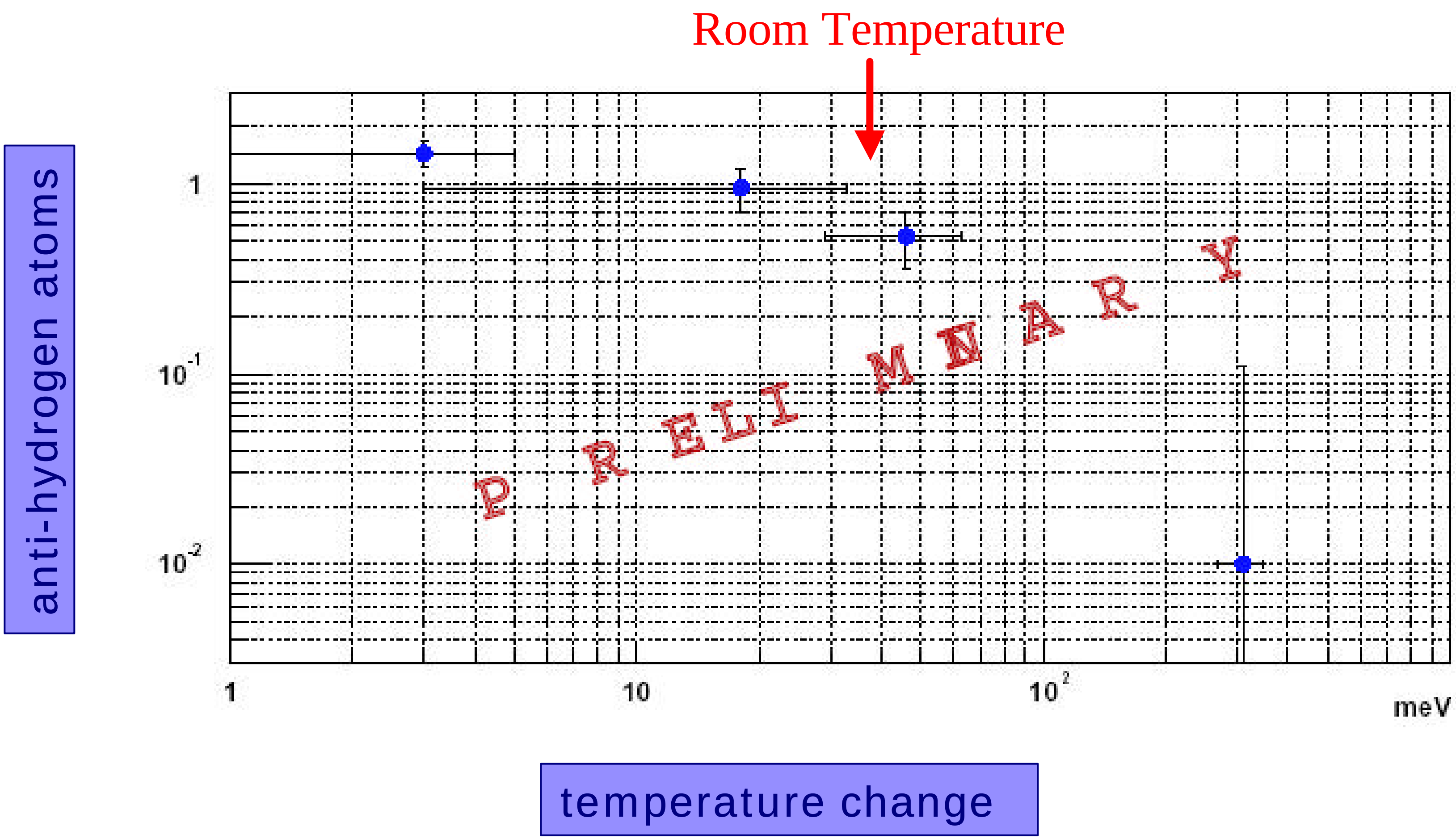
4) ΔT: 306 ± 30 meV
~3500 K
"HOT MIXING"

Very different trigger rate behavior

2γ 角度分布の温度依存性



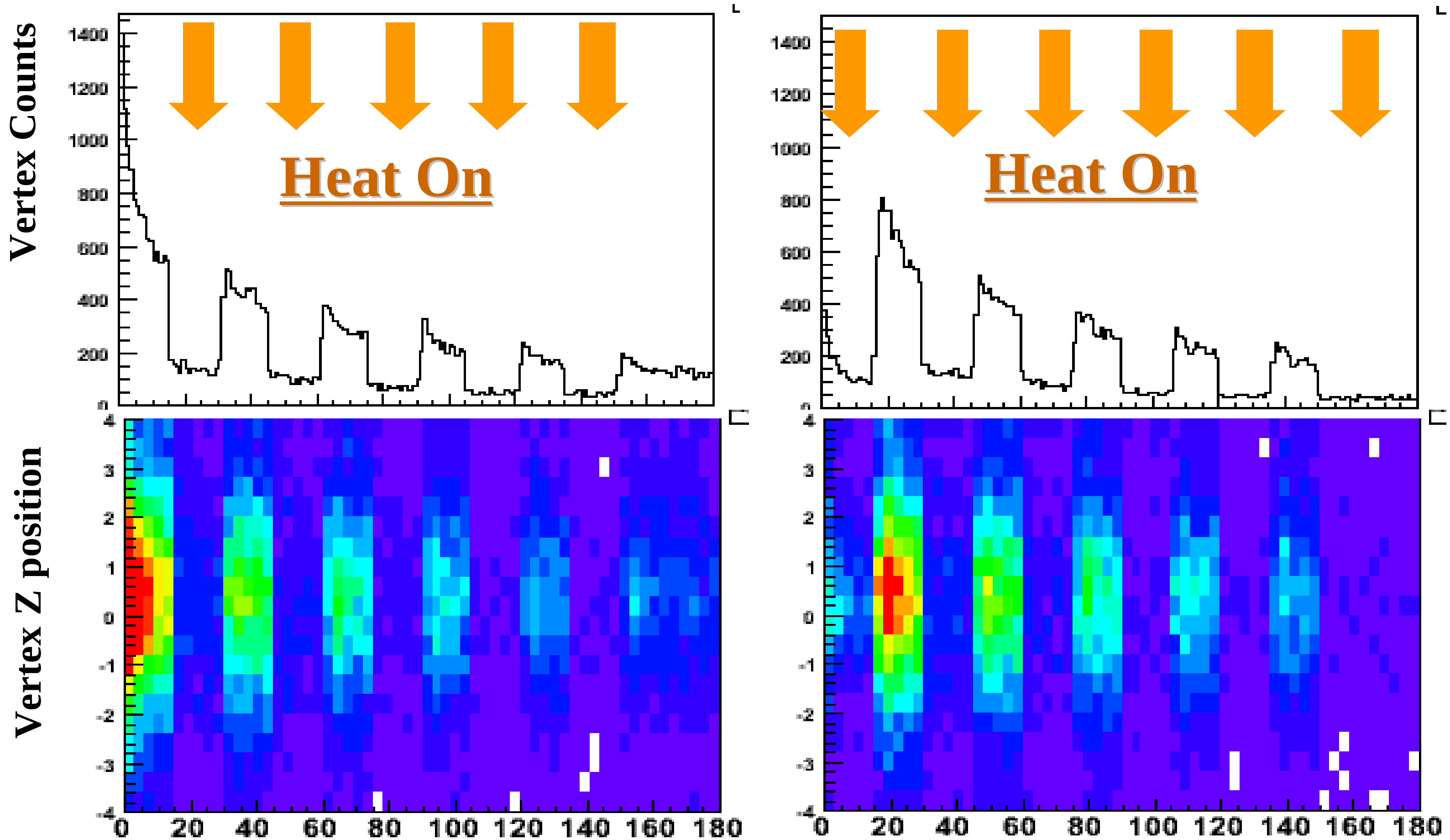
Hbar Temperature dependence



Preliminary: systematics being studied

反水素生成のパルス化

RF heating of e^+ to switch off formation

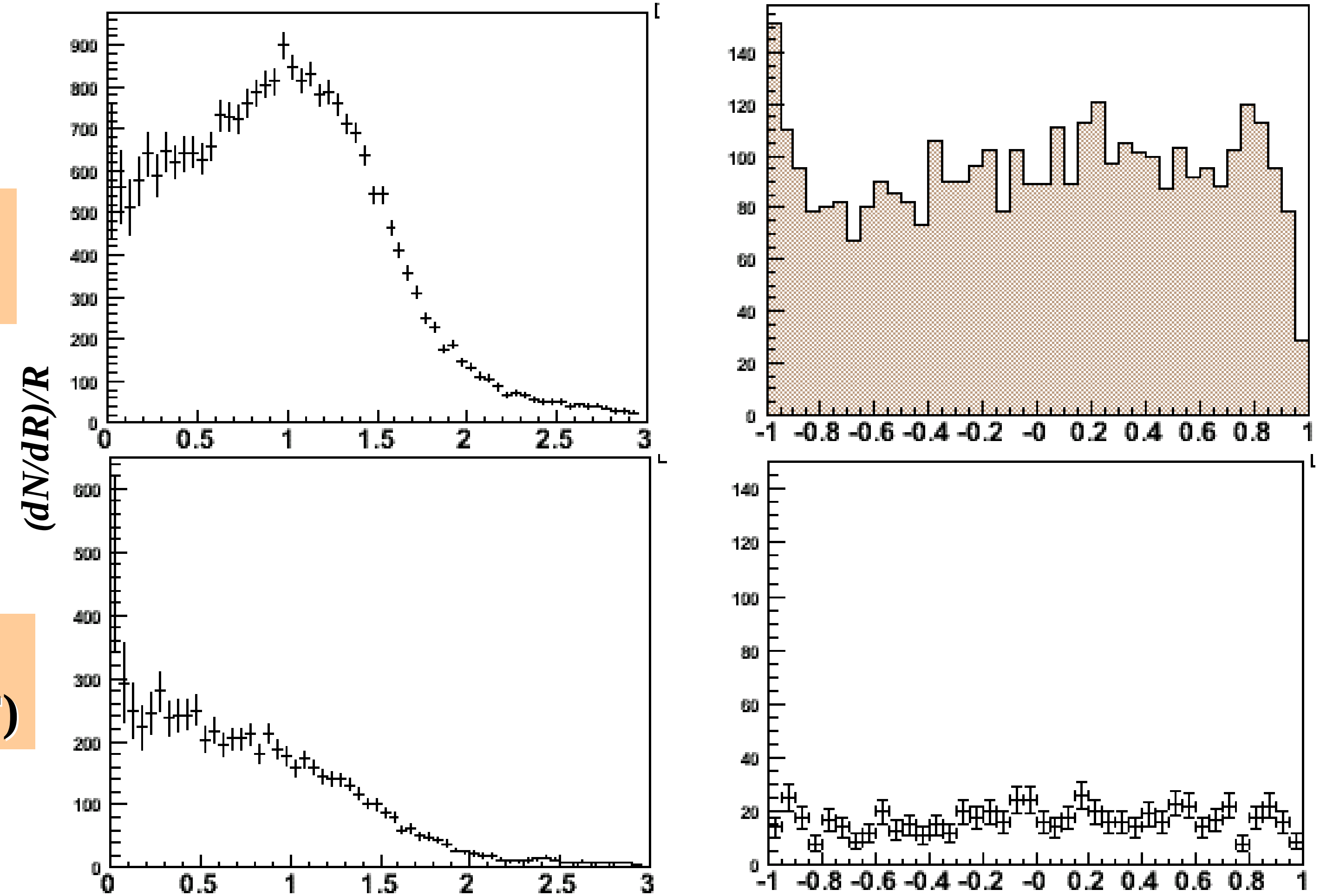


A Pulsed Source on Cold Antihydrogen !

反水素生成のパルス化

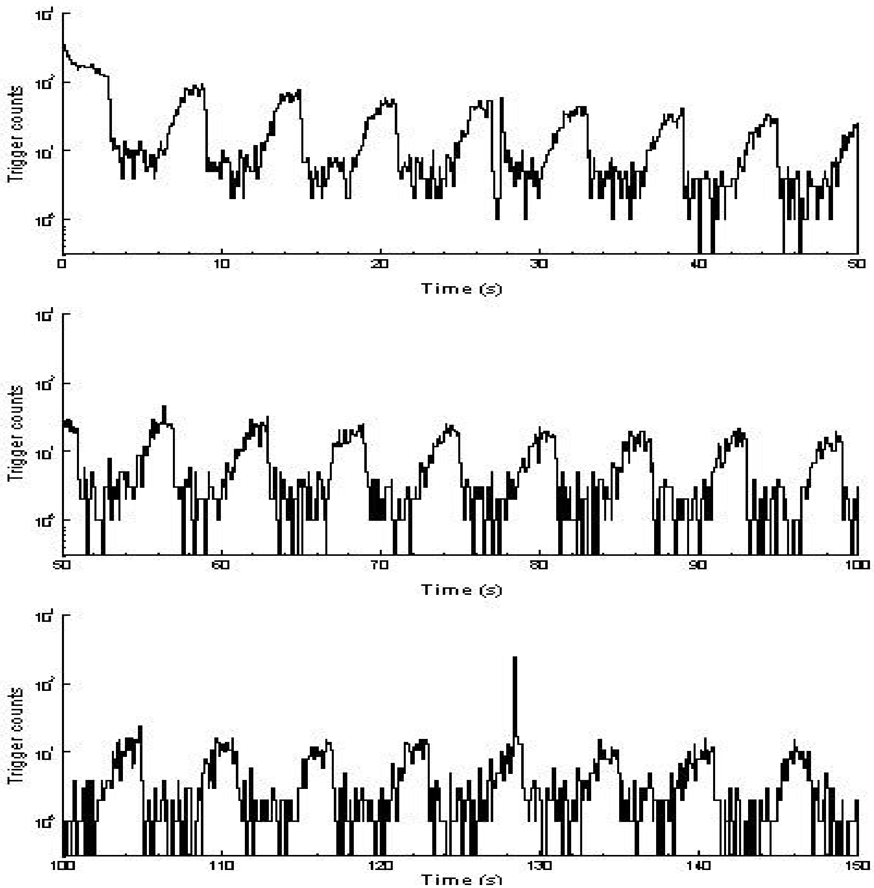
Heat OFF (Hbar ON)

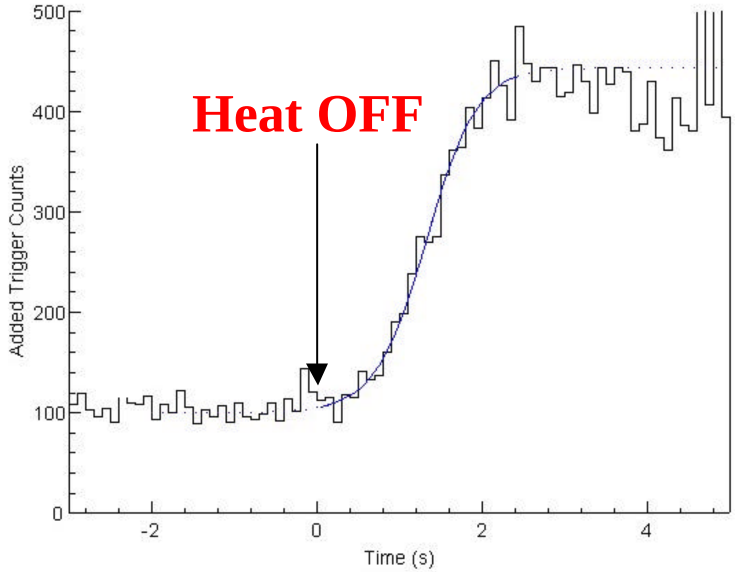
Heat ON (Hbar OFF)



Vertex radial distribution (cm) **Gamma opening angle cos(q_{gg})**

反水素生成のパルス化



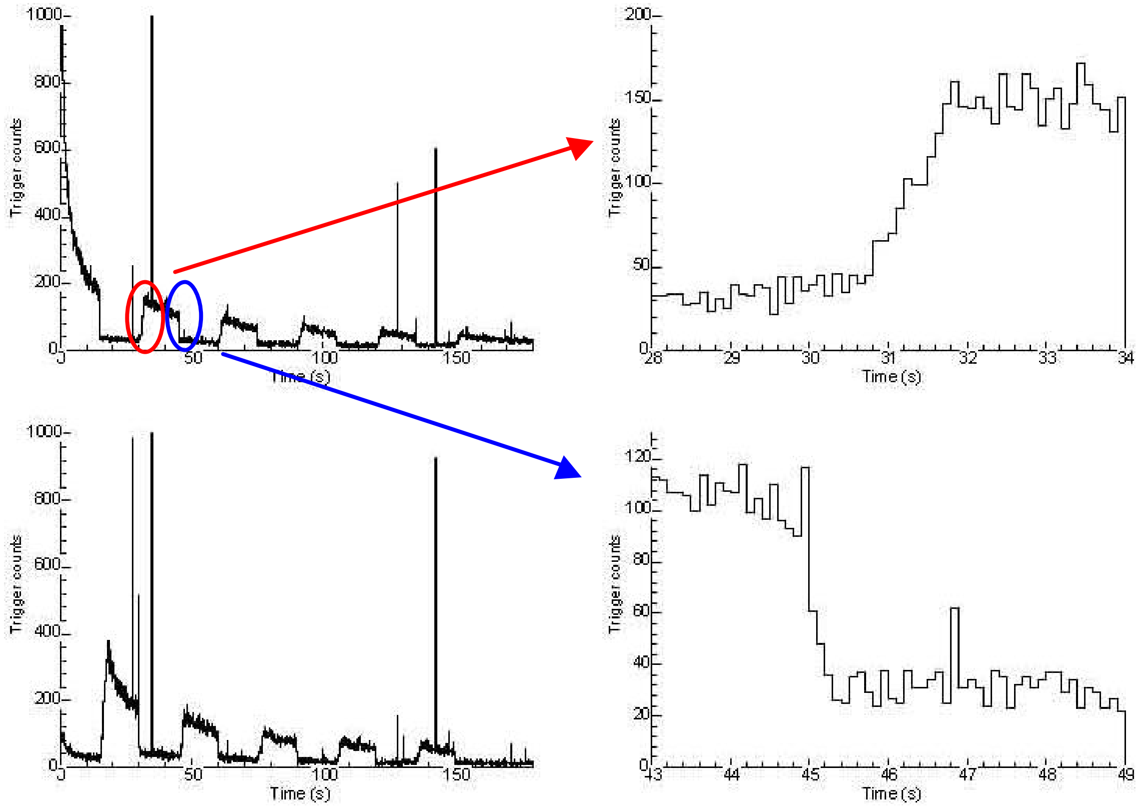


Heat On/Off every 3 sec

<u>Rise time contains Physics</u>

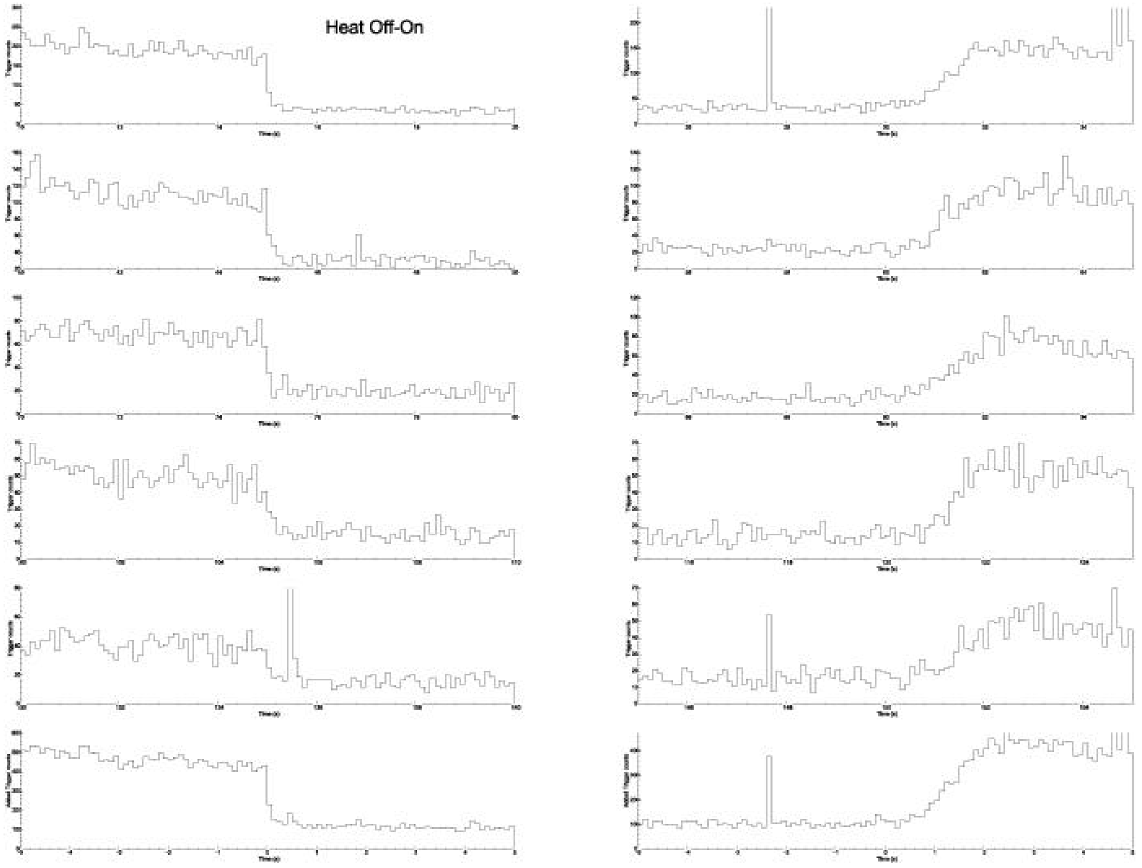
- Positron Plasma Cooling time
- Hbar formation temperature dependence

反水素生成のパルス化



Trigger counts
Time (s)
1000
800
600
400
200
0
50
100
150
200
150
100
50
28
29
30
31
32
33
34
120
100
80
60
40
20
43
44
45
46
47
48
49

反水素生成のパルス化



反水素生成のパルス化

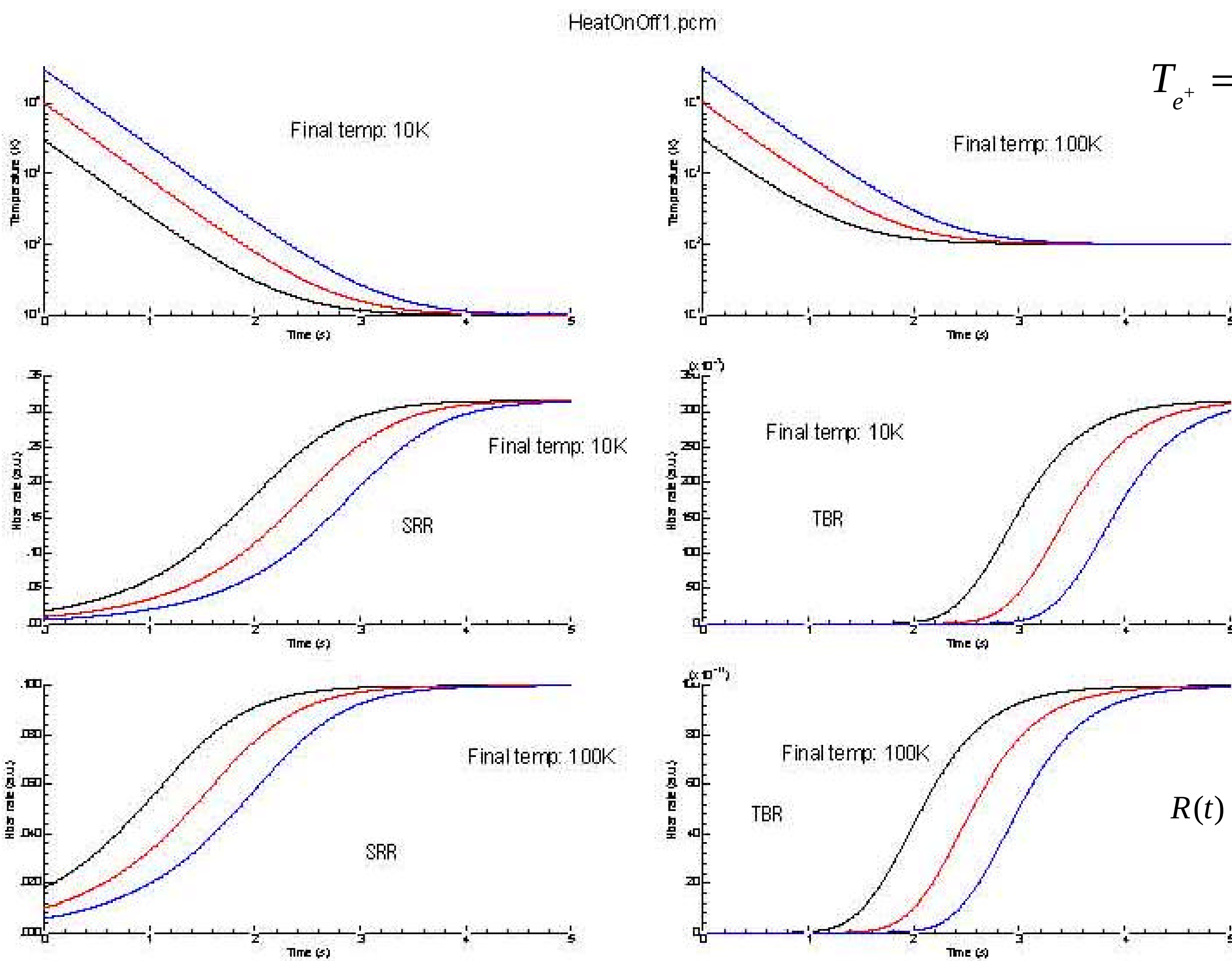
- Positron temperature evolution:

$$\frac{dT_{e^+}}{dt} = -\frac{1}{t_c}\left(T_{e^+} - T_{fin}\right)$$

$$T_{e^+} = T_{init}\exp\left(-\frac{t}{t_c}\right) + T_{fin}$$

- Hbar rate: fit with

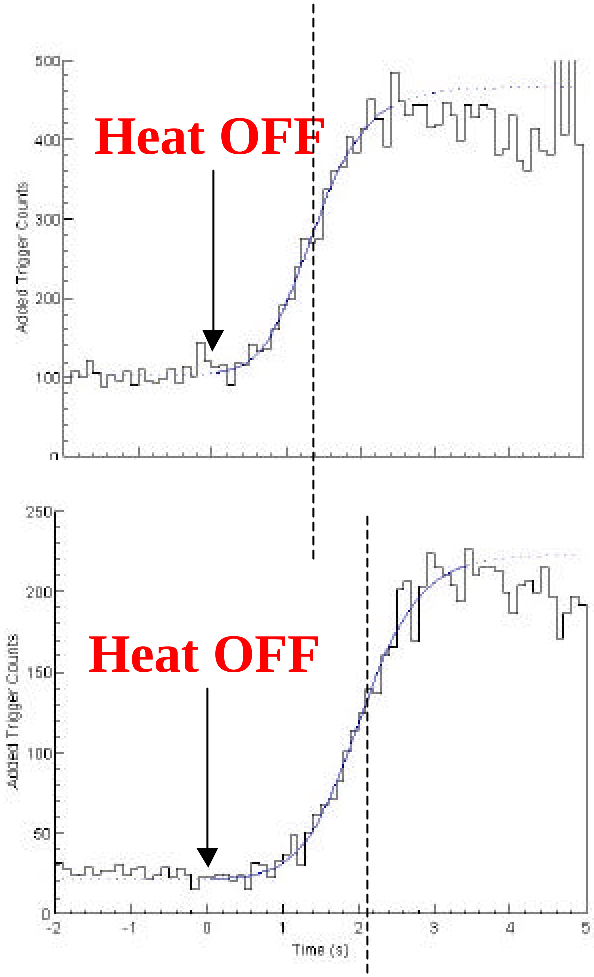
$$R(t) = bkgd + norm \times T_{init}\left(\exp\left(-\frac{t}{t_c}\right) + T_{fin}\right)^P$$



$$T_{e^+} = T_{init} \exp\left(-\frac{t}{t_c} \right) + T_{fin}$$

$$R(t) \sim T_{init} \left(\exp\left(-\frac{t}{t_c} \right) + T_{fin} \right)^P$$

Modulation of Hbar Production



T_{init}~ 3000K

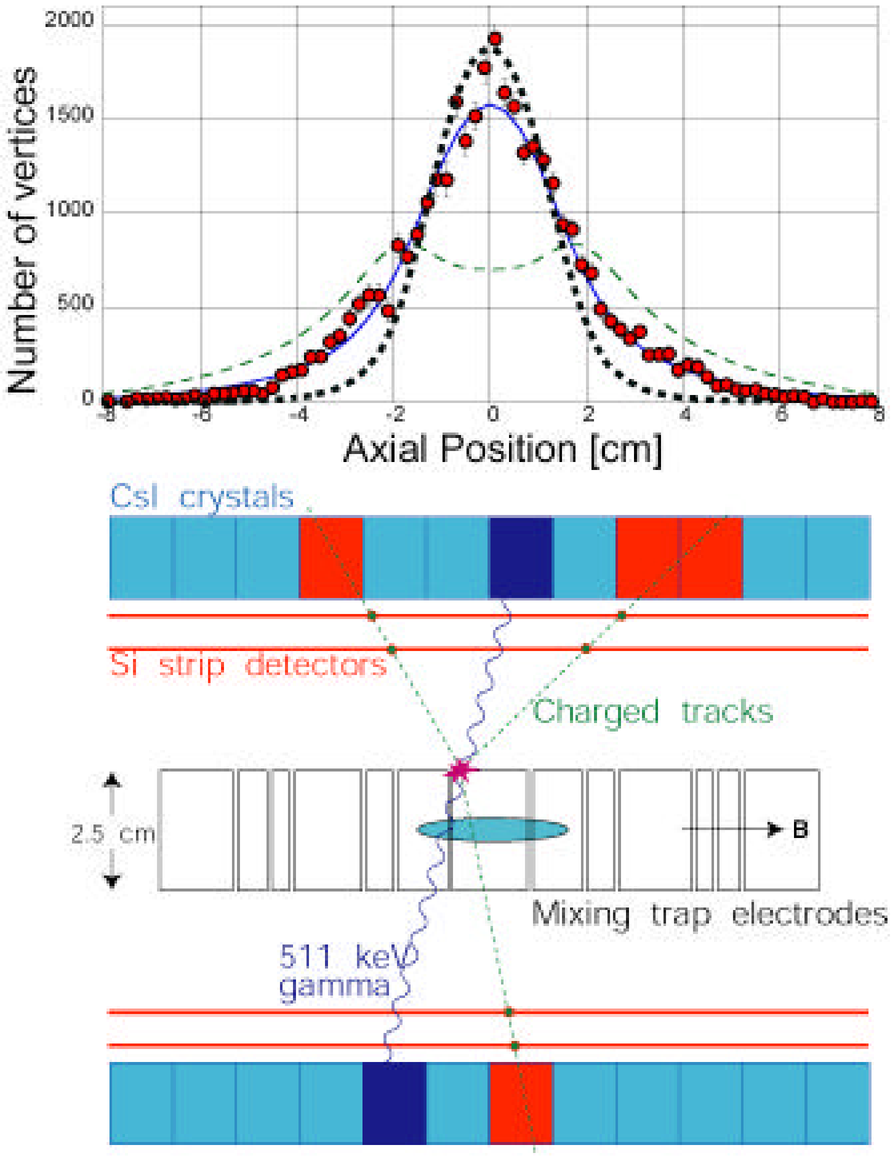
T_{init}~ 15000K

- Fits suggests ~T^(-1) scaling
- Synch. Cooling ~ 0.4 sec
- Final Temp ~ 100 k

- P.O. Fedichev
  Phys. Lett. A. 226 (1997) 289
  $T^{-0.8}$ for stabilized Hbar from 3-body recommbination

- B. Zygelman
  J. Phys. B 36 (2003) L31

反水素放出の角度分布



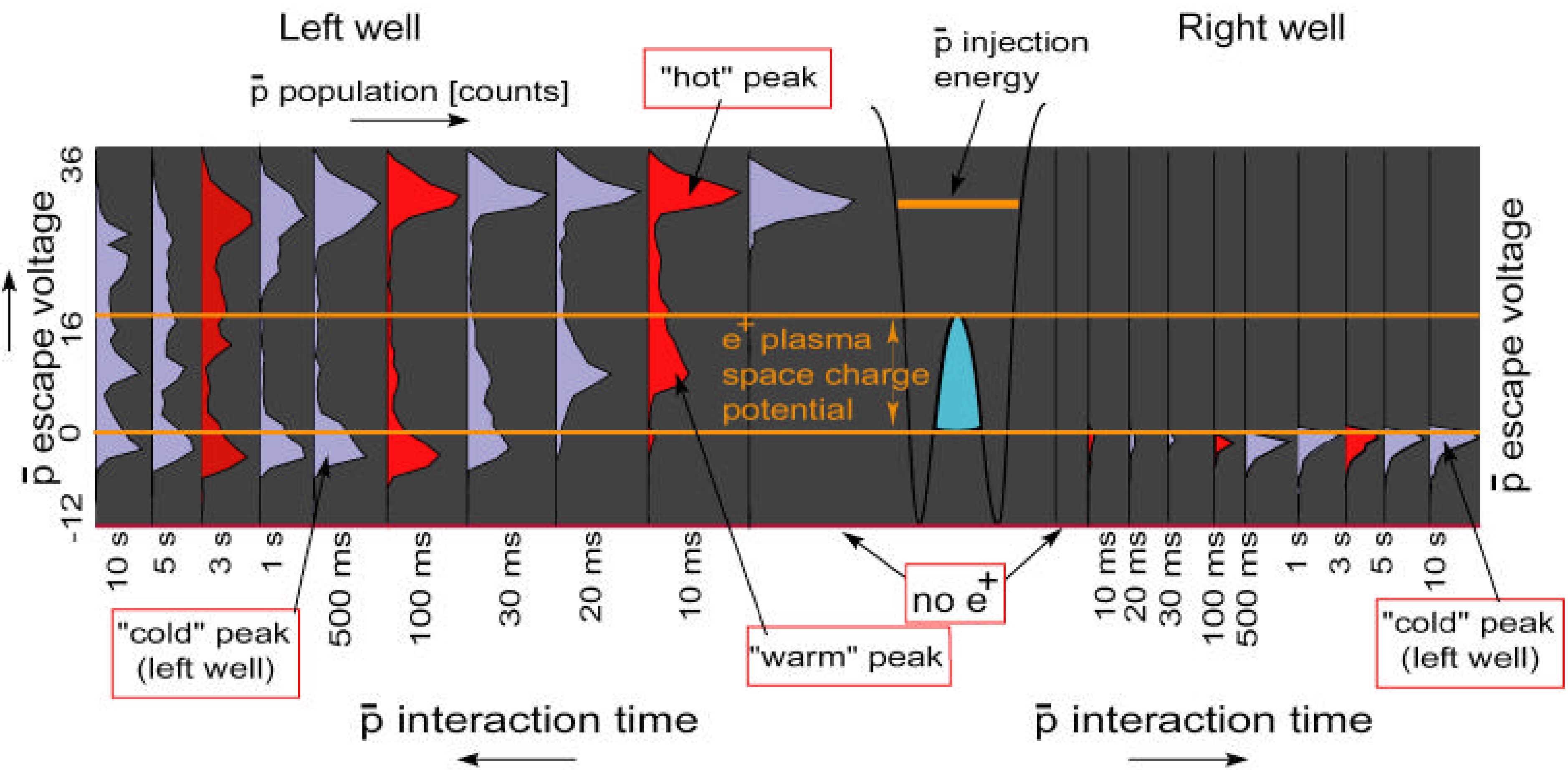
放出角度は実験上重要

Vertex Z Distribution

- ***Detected* Antihydrogen: ~isotropic**
- **Some radial component possible**
- **Focused "beam" excluded**

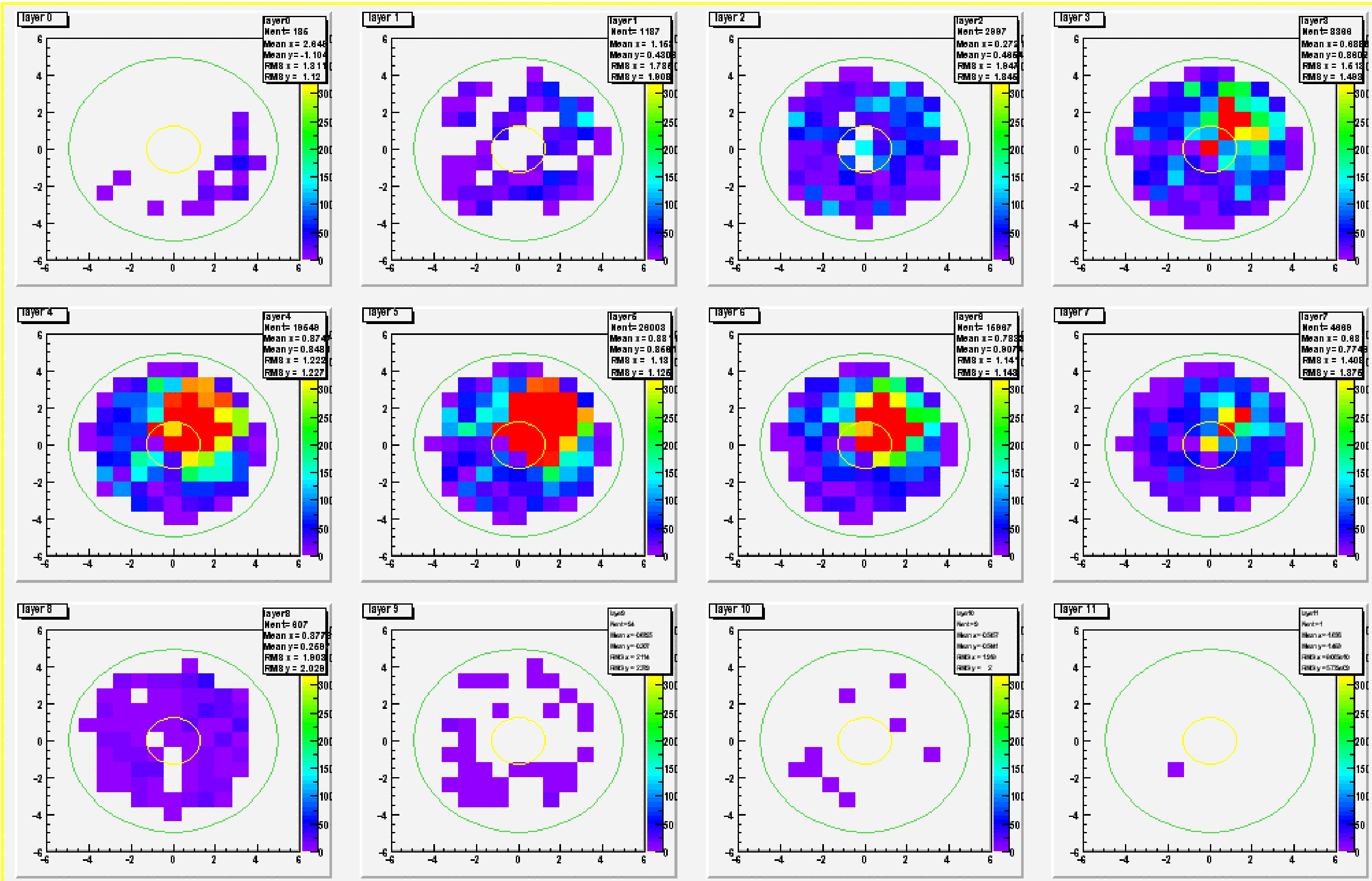
75 million 陽電子による反陽子冷却

To be submitted Phys. Rev. Lett.



PET Imaging of Positron Plasma

Simulations

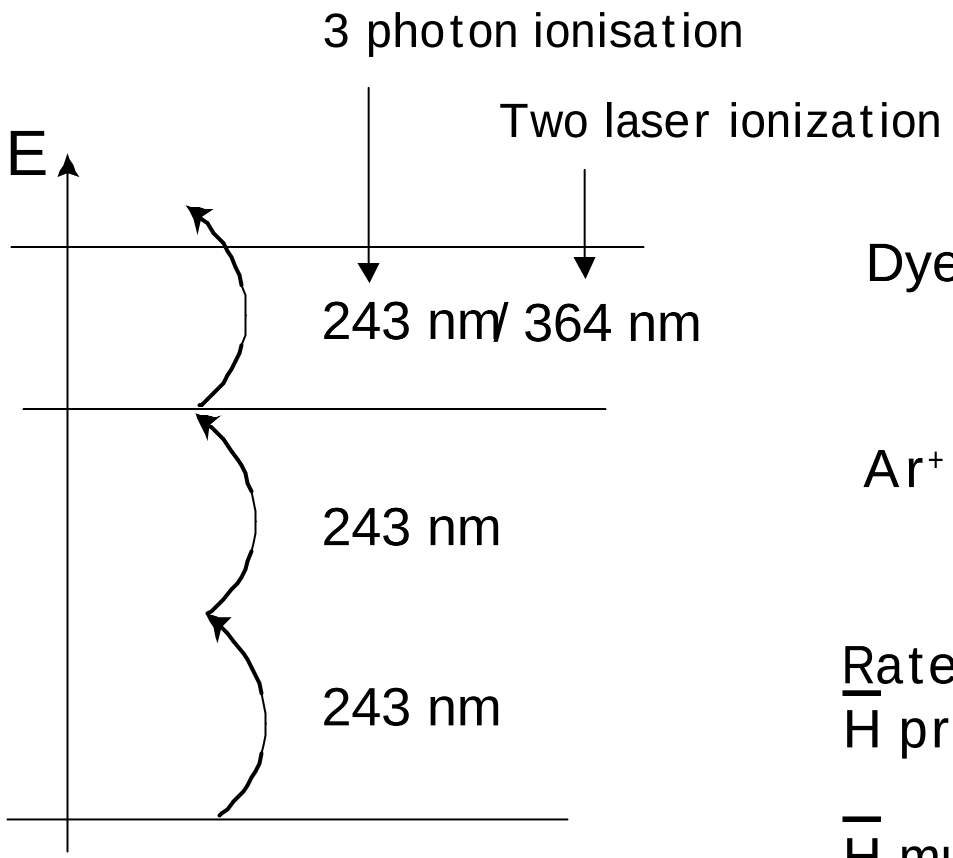


将来展望

将来展望

- **反水素生成過程の理解・最適化**
  - トラップ中のダイナミクス
  - 反水素の量子状態
  - 生成を最適化 (例えばRFQ減速器で×100)
- **レーザー分光へ向けて**
  - 反水素分光をまず“in-beam”でやる
  - いくつかの方法を検討中 (イオン化、誘導再結合)
  - ASACUSAは超微細構造測定を提案
  - 反物質は中性か？
- **もっと冷たい反水素 (長い道のり)**
  - 反水素トラップ
  - レーザー冷却、反物質波、反物質BEC
  - 反物質重力測定

レーザー分光: 光イオン化



Dye Laser (243 nm):
P = 40 mW (243nm)

Ar^+ Laser:
P(363.8+351nm) = 700 mW

Rates depend on interaction time, $\bar{H}$ production rate, but are small.

<u>$\bar{H}$ must be in 1S state!</u>

レーザー誘導による反水素生成

Stimulate hbar formation from continuum

2-step process (reduces required power)

	continuum→*nd* ; followed by *nd*→*2p*	
	3d: 820 nm	3d →2p: 656 nm
Pulse	4d: 1459 nm	4d →2p: 486 nm
	5d: 2279 nm	5d →2p: 434 nm
	...	...
CW	11d: 11.1 μm	11d→2p: 377 nm

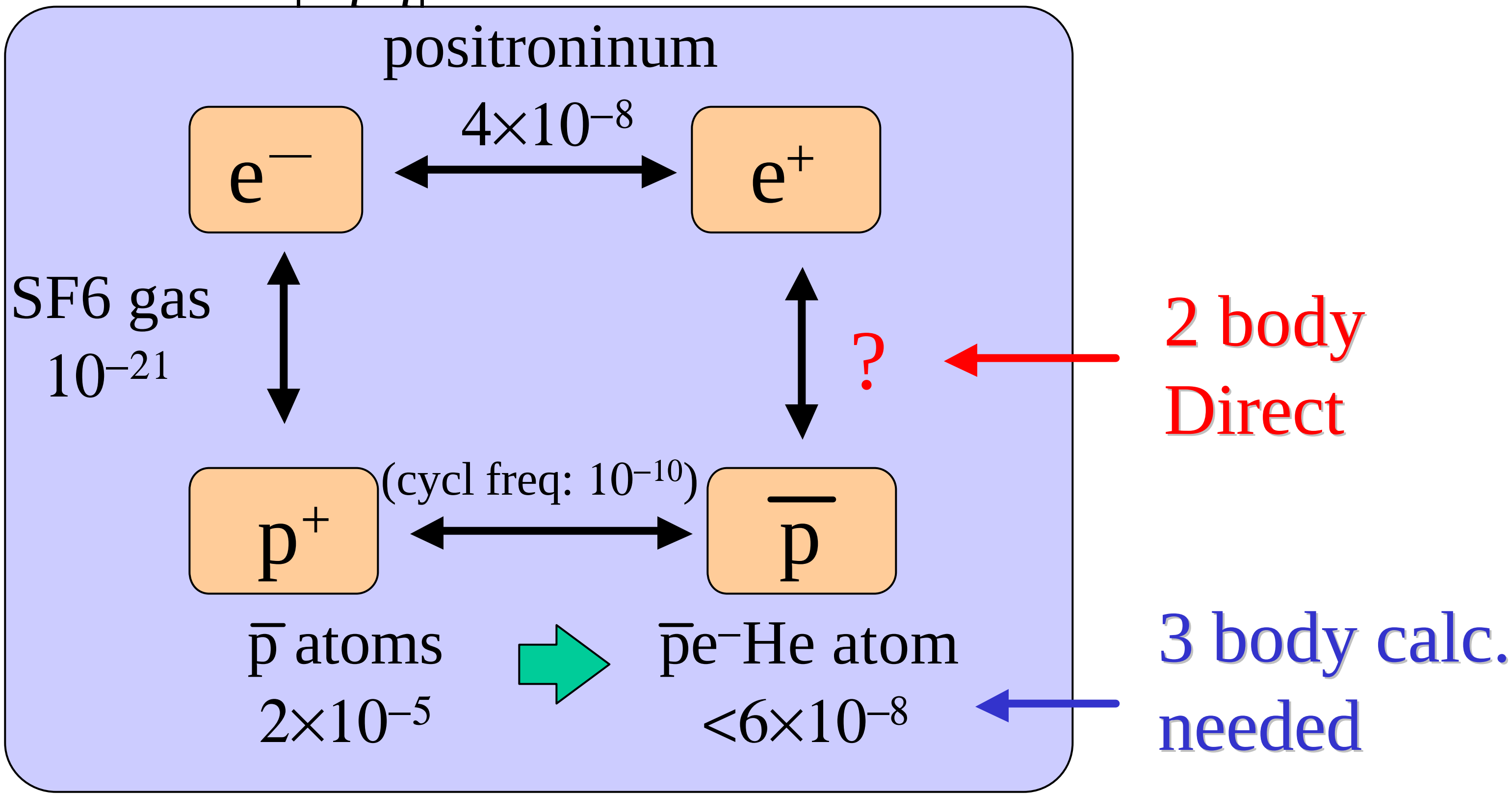
どの方法も極めてchallenging

反物質は中性か？

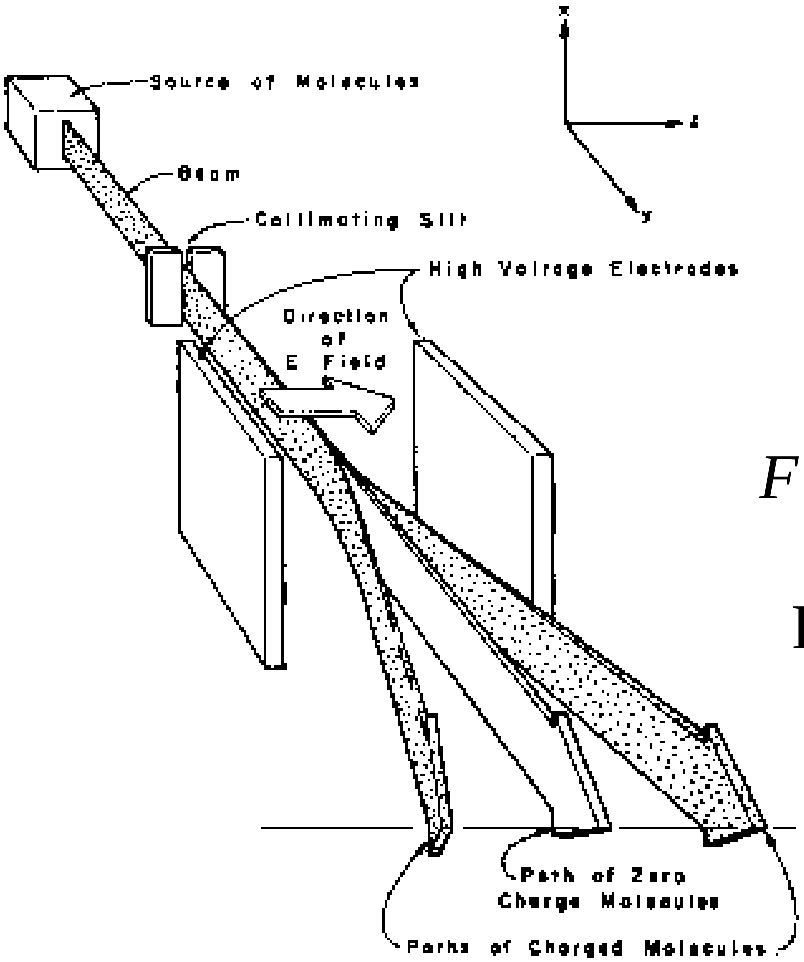
Charge quantization, (anti)matter neutrality

- Experimental fact (*cf*. anomaly cancellation)
- Put in “by hand” in the Standard Model

Limits on $|\delta q/q|$



反物質は中性か？



Based on H_2 molecular beam measurement by Zorn, Hughes et al.

Force F by the field E

$$F = qE + \nabla(d \cdot E) + 1/6\,\nabla(M_Q \cdot \nabla E) + \cdots$$

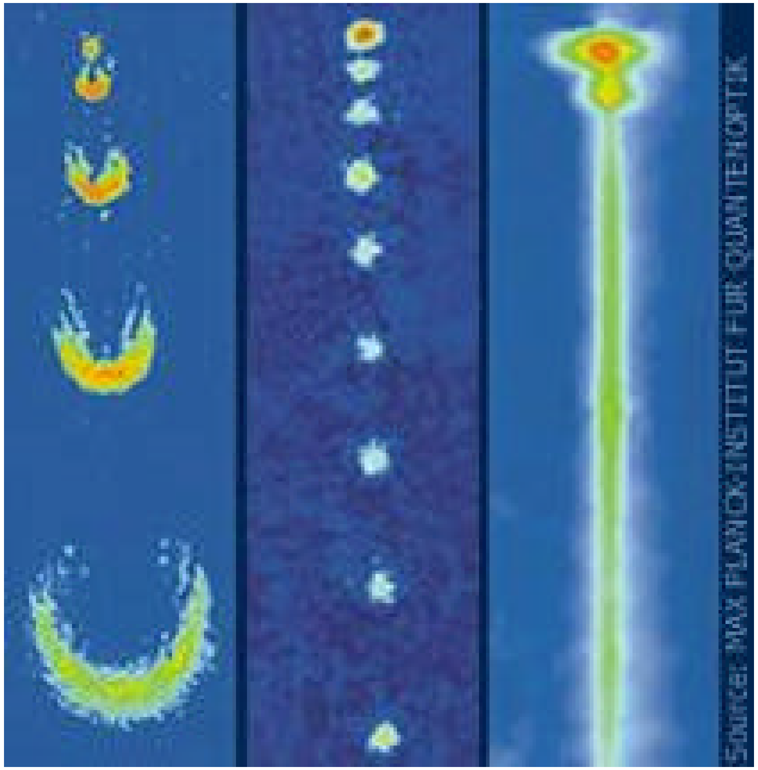
Reversing the field sign, 2nd term cancels. (3rd term small)

原理的には

$q < 10^{-15} \sim 10^{-16}$可能

反物質 ボーズ・アインシュタイン凝縮?

Atom laser with BEC at JILA, MIT



「過去数年の間に反水素の生成は"totally visionary"から"merely very difficult"に進歩した」

D. Kleppner, 1992年
反水素ワークショップのまとめ

まとめ

- **ATHENAは世界で初めて冷たい反水素原子を生成**
  - 決め手は、強力な陽電子源、高度な検出器、プラズマ操作
    体育会系的がんばり!
- **その後の結果(preliminary)**:
  - これまで既に~1 Million の反水素を生成
  - 高生成率 > 100 Hz
  - 反水素生成のパルス化
  - 温度依存性
  - その他多くの物理: プラズマ振動、粒子混合仮定、反水素放出角度
- **レーザー分光を準備中 難しい!)**
- **冷たい反水素の物理は始まったばかり**

請うご期待!