A Reaction Microscope in ELENA ?

Helge Knudsen, Ulrik Uggerhøj
Department of Physics and Astronomy, Aarhus, Denmark
Daniel Fischer, Robert Moshammar
Max Planck Inst. für Kernphysik, Heidelberg, Germany
Yasunori Yamazaki
Riken, Tokyo, Japan
Michael Charlton
Department of Physics, Swansea, UK
Masaki Hori
Max Planck Institute of Quantum Optics, Garching, Germany

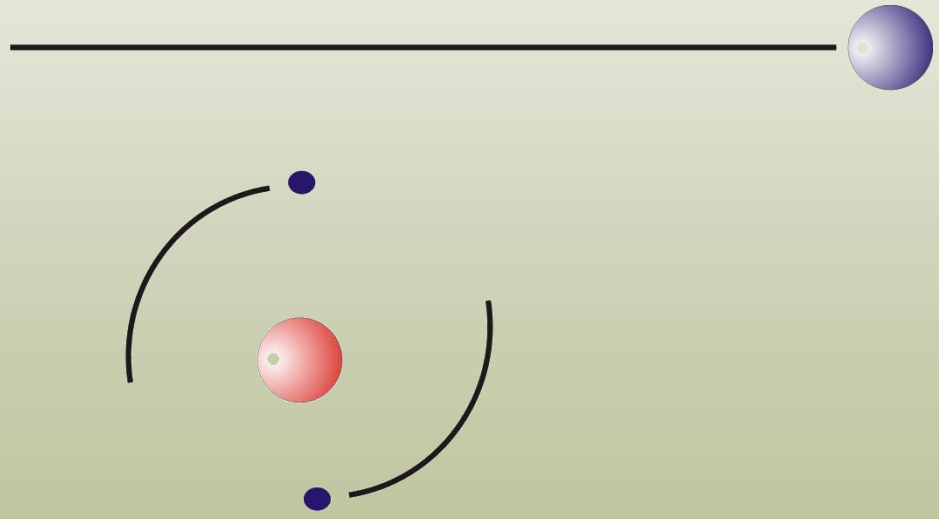
Physics motivation :

Create benchmark data for the improvement of atomic collision theory

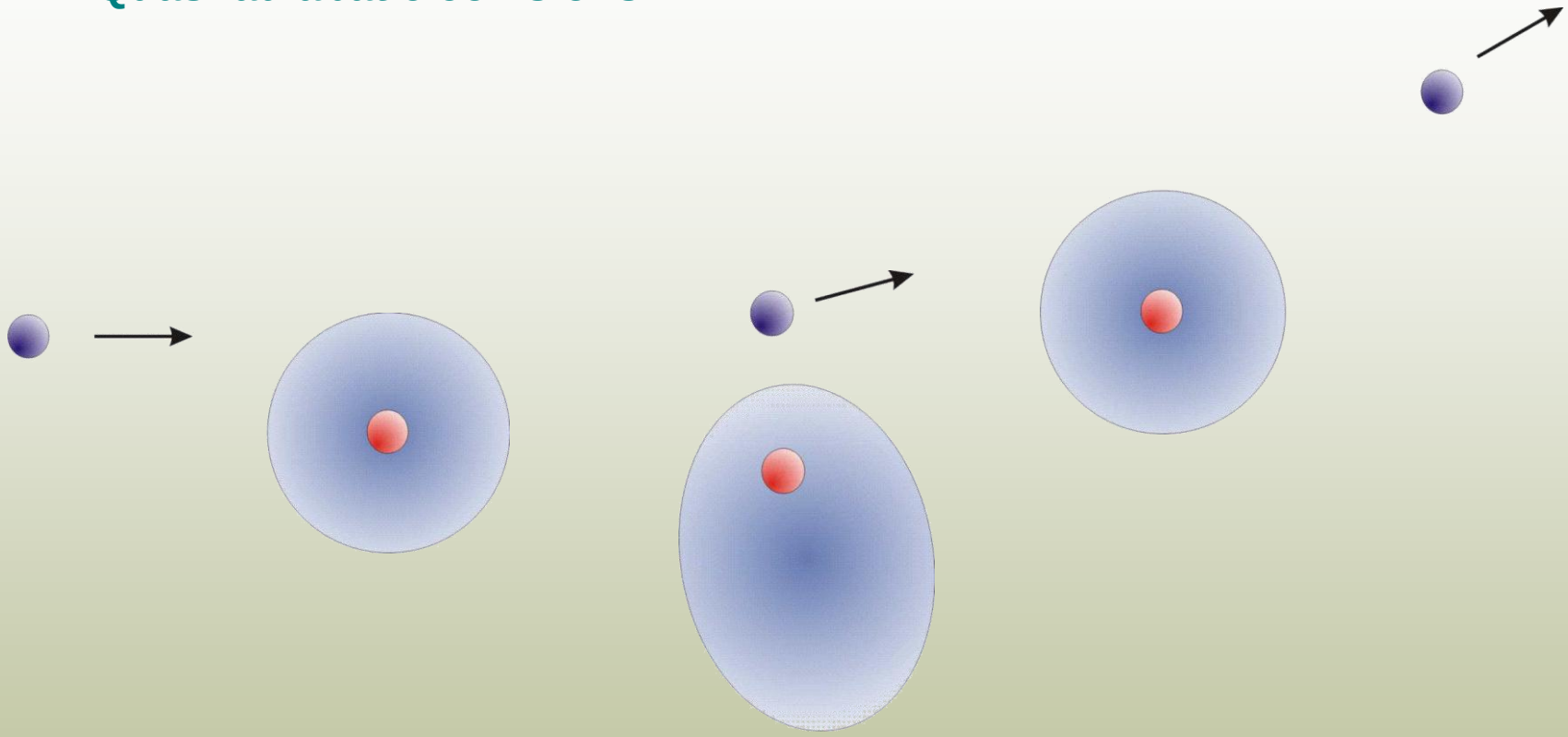
Means:

Use very slow antiproton projectiles

→ a stringent test of theory!



Quasi-adiabatic collisions



We are far from a perturbation picture:
Advanced models are needed

Quasi-adiabatic collisions

Simple, unsolved questions:

Scattering angle? - not adequate to use “mean potentials” like the TF or LJ

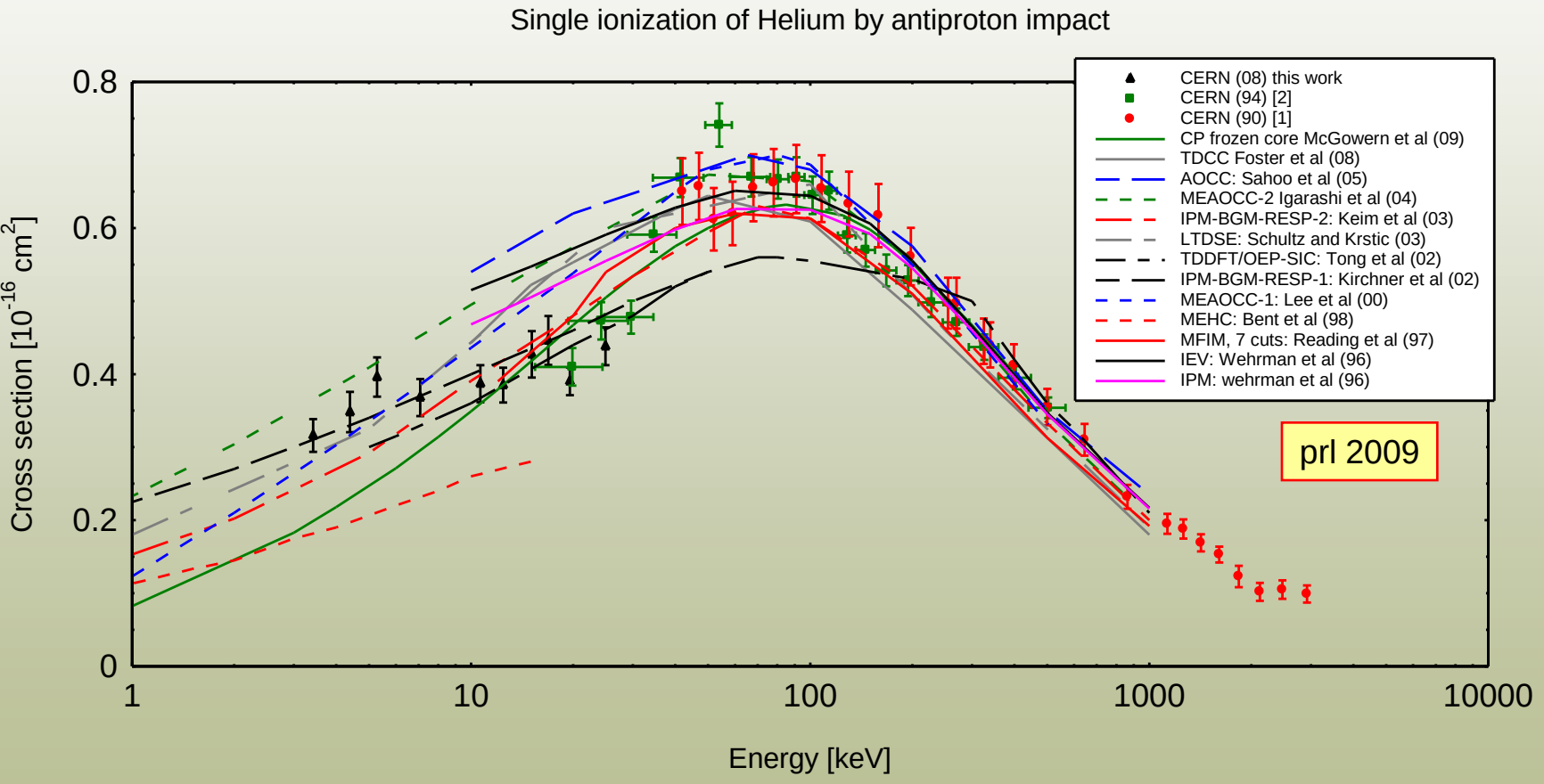
Target ionization?

Target fragmentation (molecules) ?

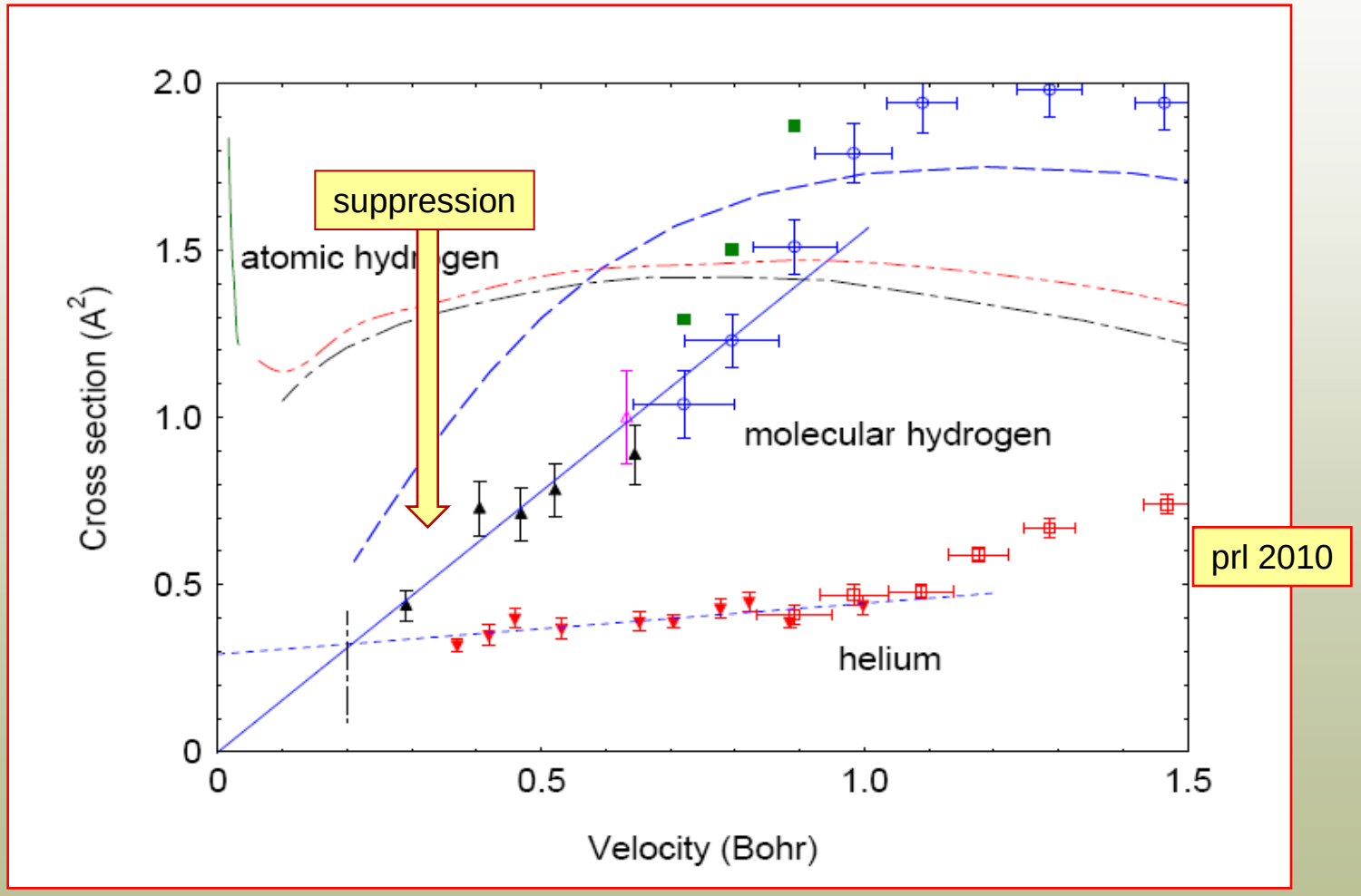
Positive projectiles (p+) very complicated due to electron transfer:

Use antiprotons

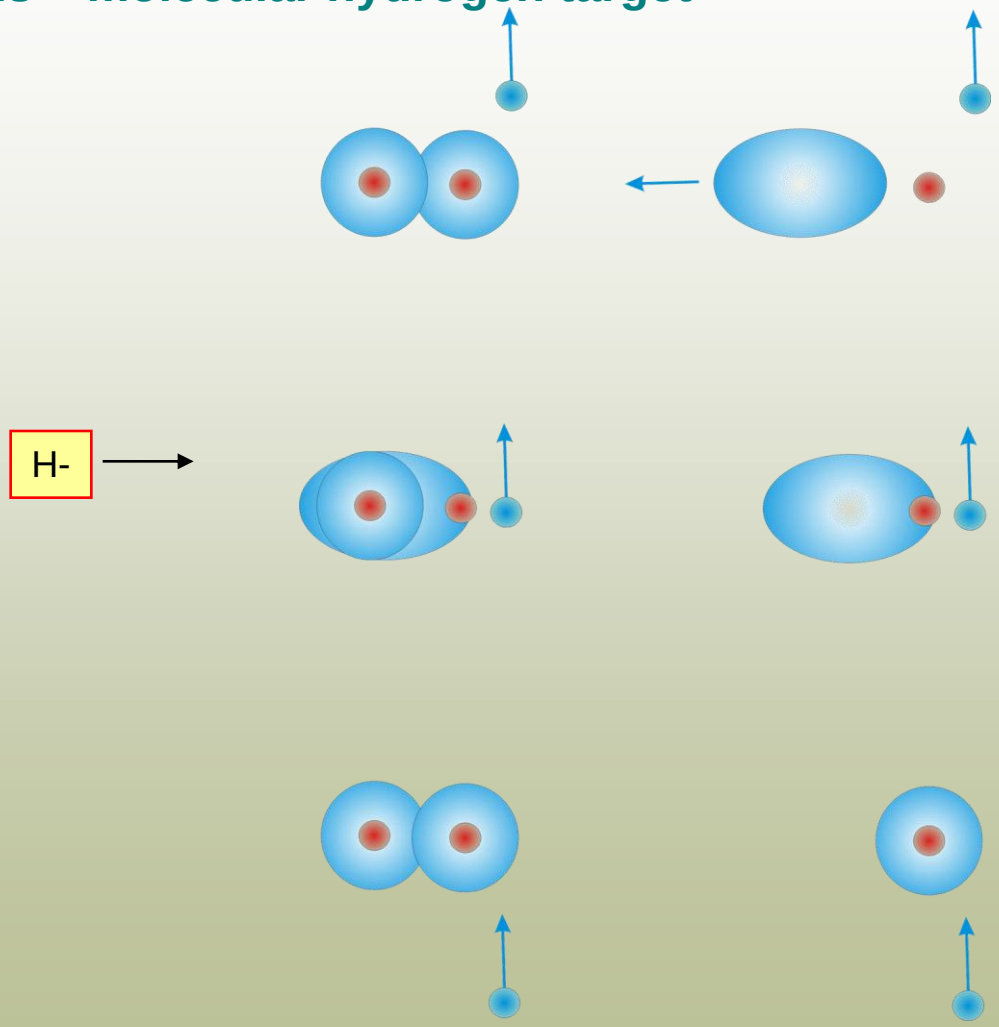
Recent low energy results: Helium total ionization cross sections



Recent low energy results: Molecular hydrogen total cross sections



Quasi-adiabatic collisions – molecular hydrogen target



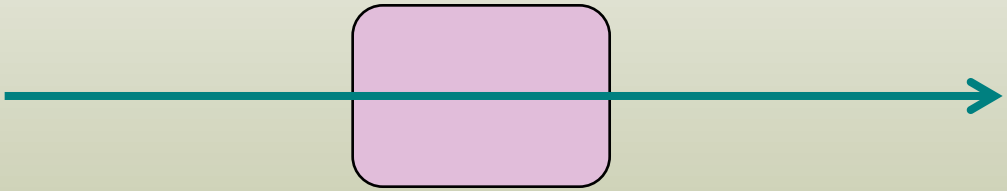
This mechanism has never been seen before !!

Quasi-adiabatic collisions – molecular hydrogen target

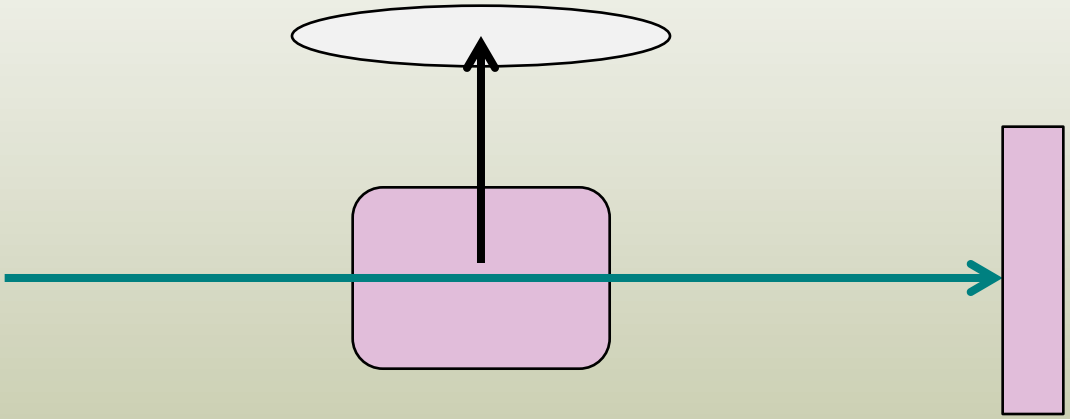
Is this a general suppression mechanism for molecular single ionization?

Is it compensated for by enhanced production of other reaction products?

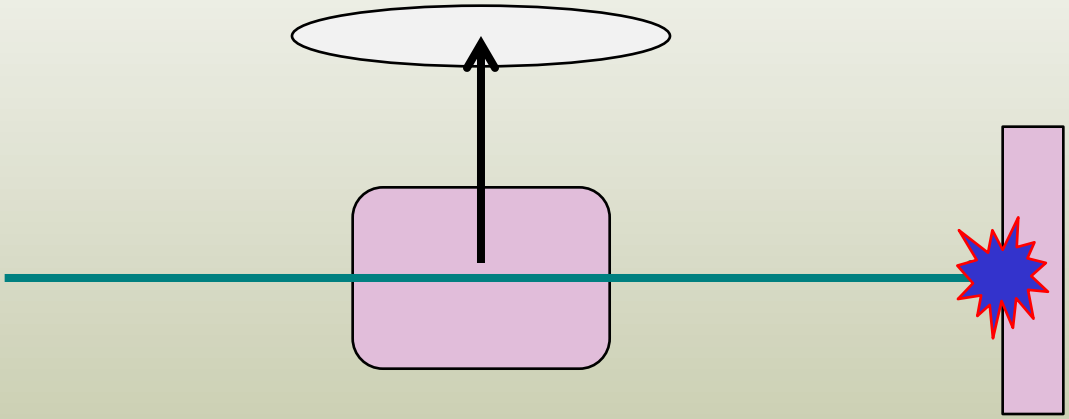
Until now: Single pass measurement → total cross sections



Until now: single pass measurement → total cross sections



Until now: single pass measurement → total cross sections

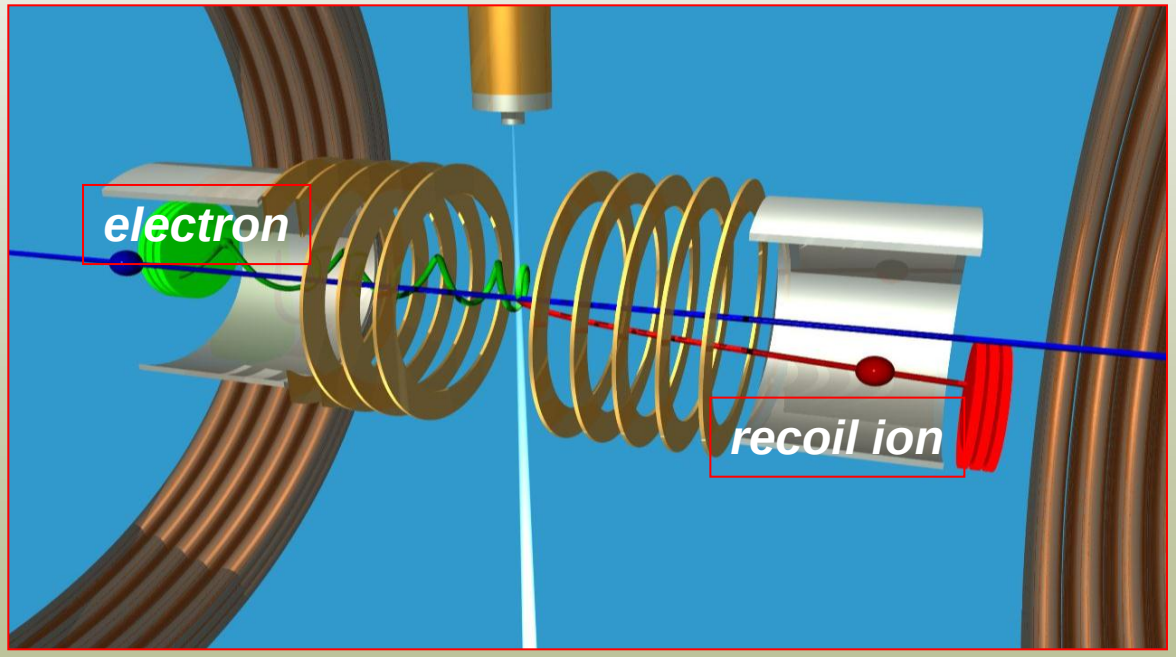


To advance to differential measurements we need much more projectiles:

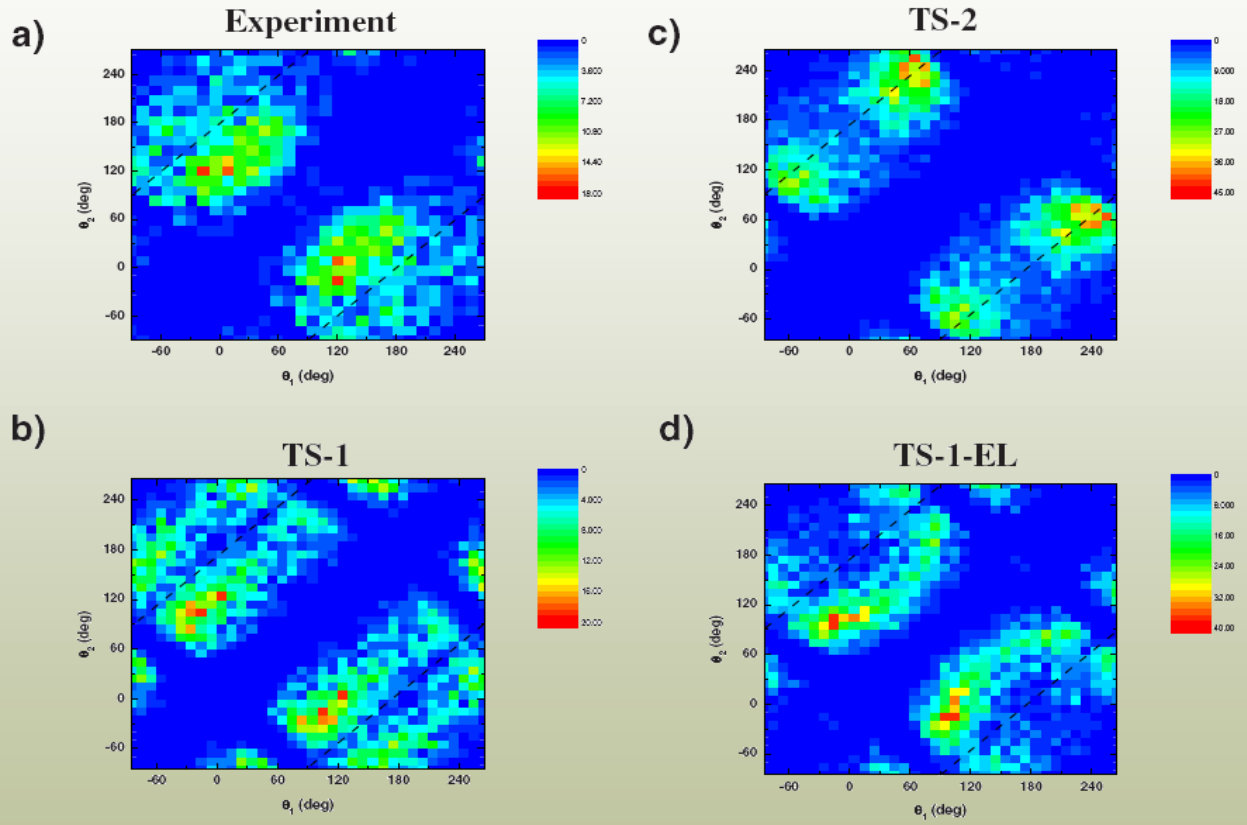
The future experiment:

Differential measurements

"Reaction microscope"



– A powerful method in fast projectile measurements:

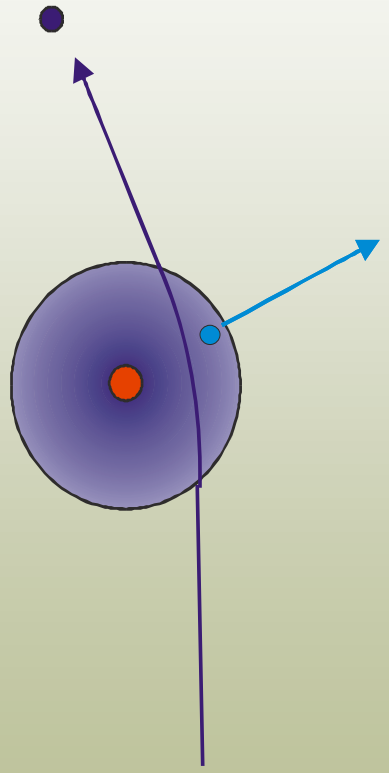


6 MeV on He, double ionization Schultz et al PRA 79 (**2009**)

Helge Knudsen

Quasi-adiabatic collisions THEORY – helium target

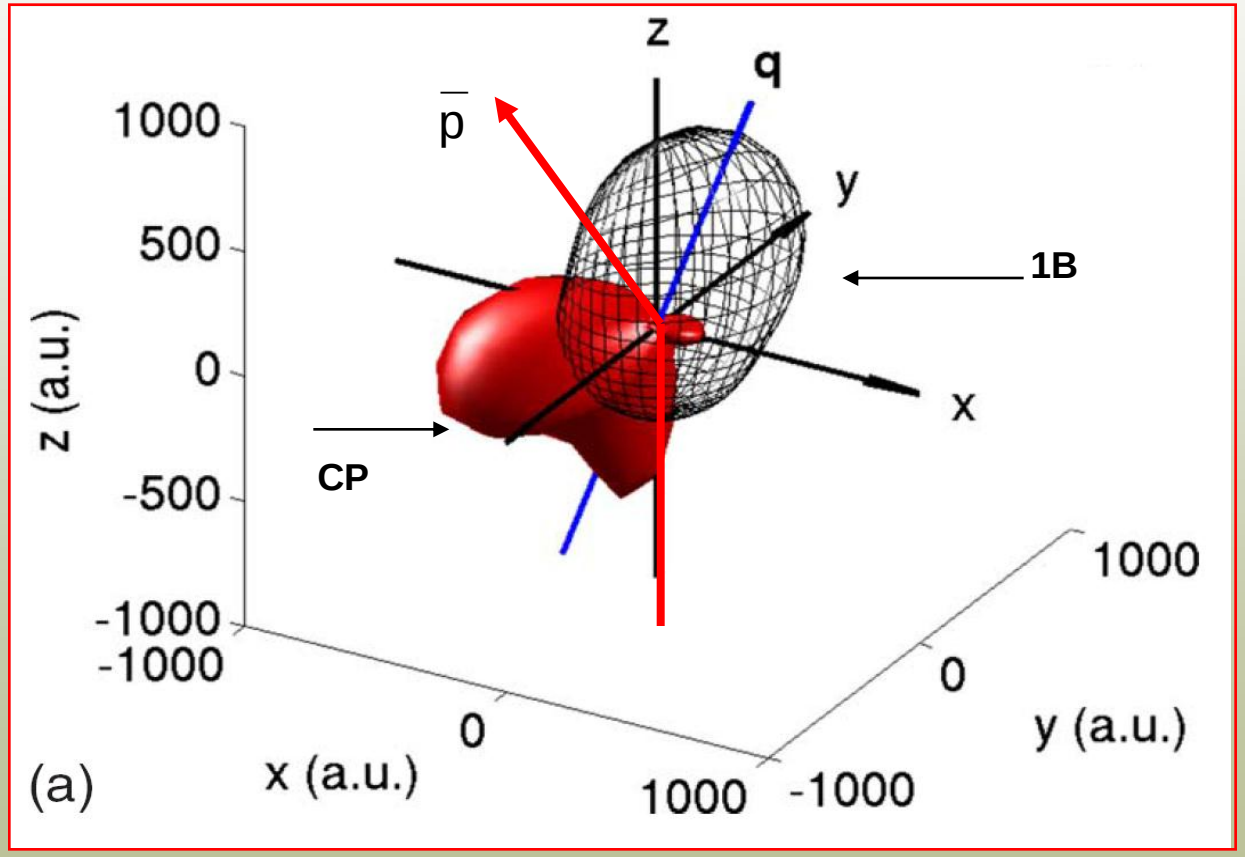
Quasi-adiabatic collisions THEORY – helium target - an example of what we may see:



generic ionization event

Quasi-adiabatic collisions THEORY – helium target - what we may see:

Triple Differential cross sections



3 keV pbar on helium
q = 3.25 au

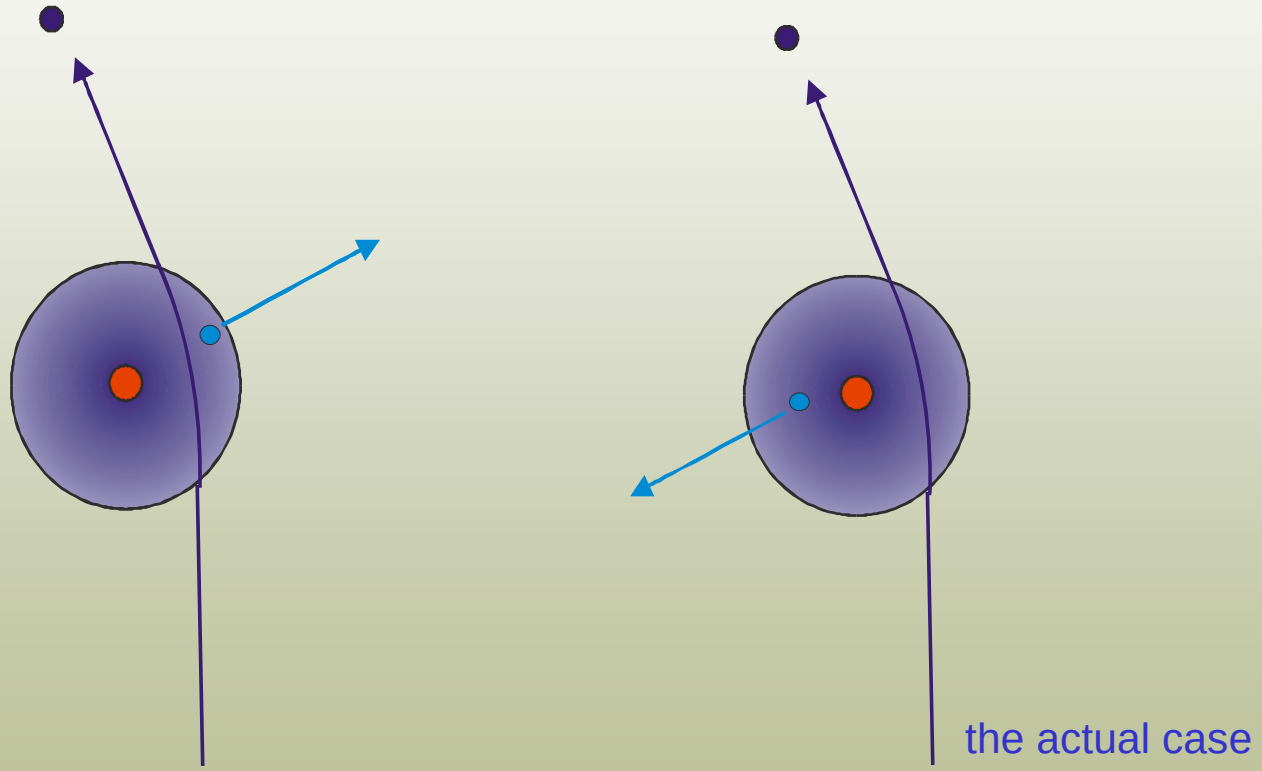
First Born calculation

McGovern et al 2009
Coupled Pseudostates
Frozen He+(1s) core

PCI
proj - nucl interaction

Notice:Almost equal total cross sections

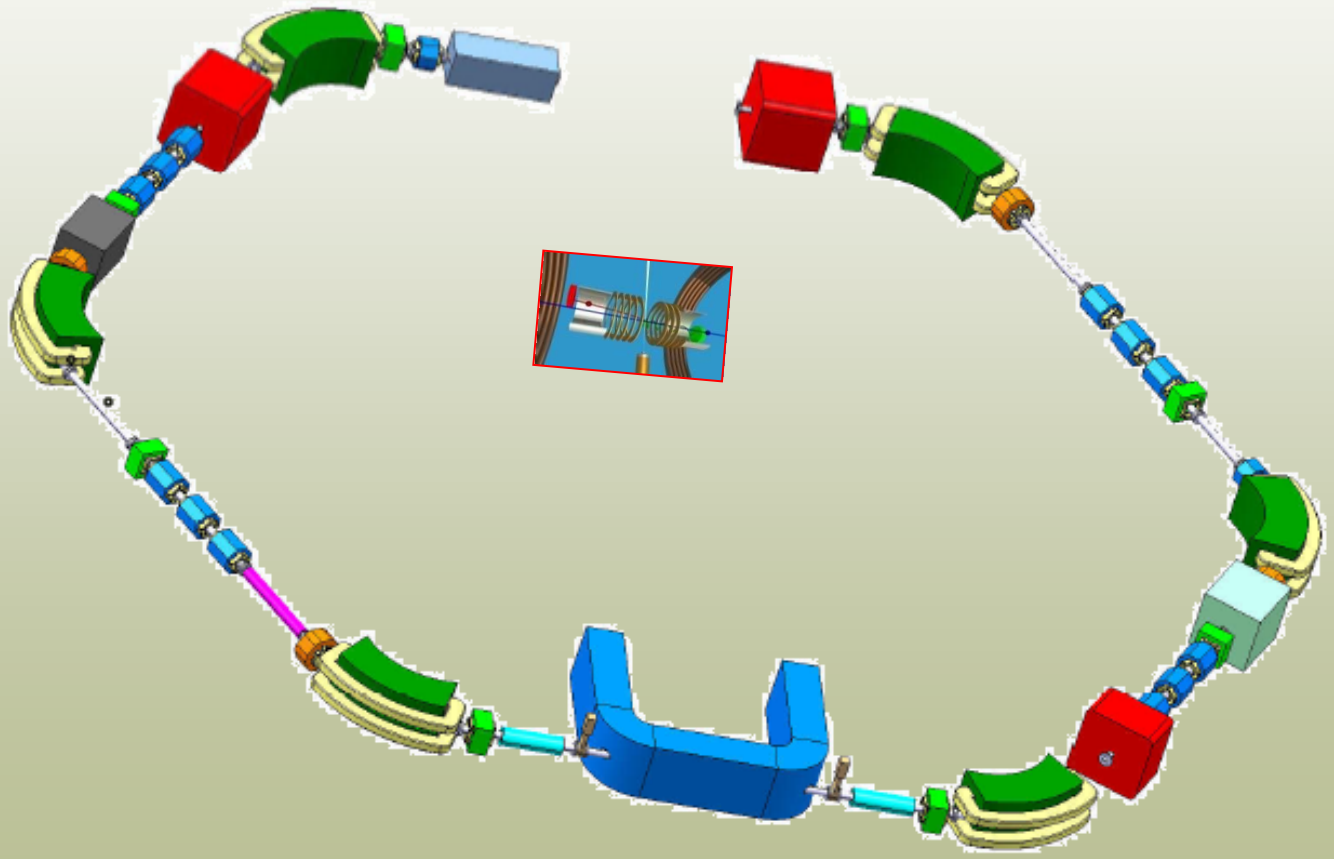
Quasi-adiabatic collisions THEORY – helium target - what we may see:



Technique…

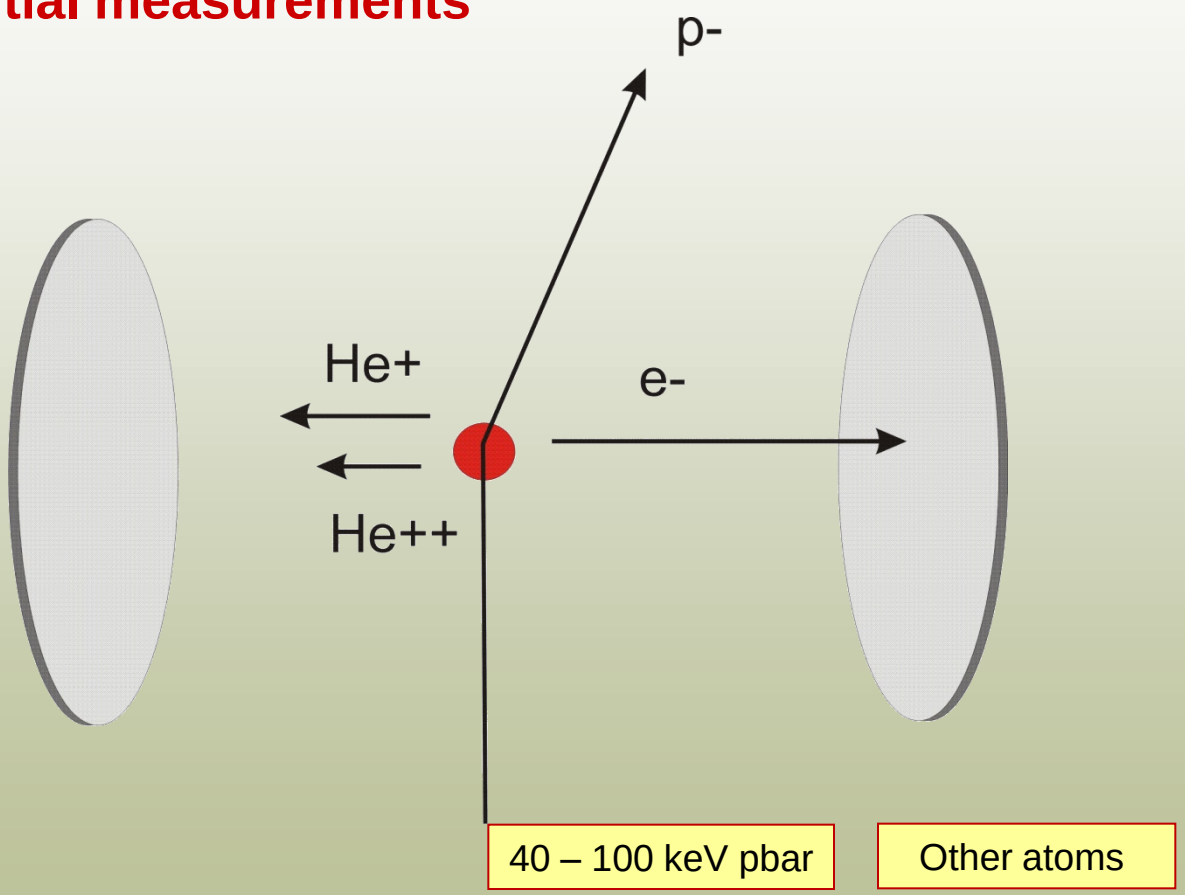
ReMi in ELENA

Suggested experiments:



Quasi-adiabatic collisions – atomic targets

Differential measurements



Quasi-adiabatic collisions – molecular hydrogen target

Differential measurements

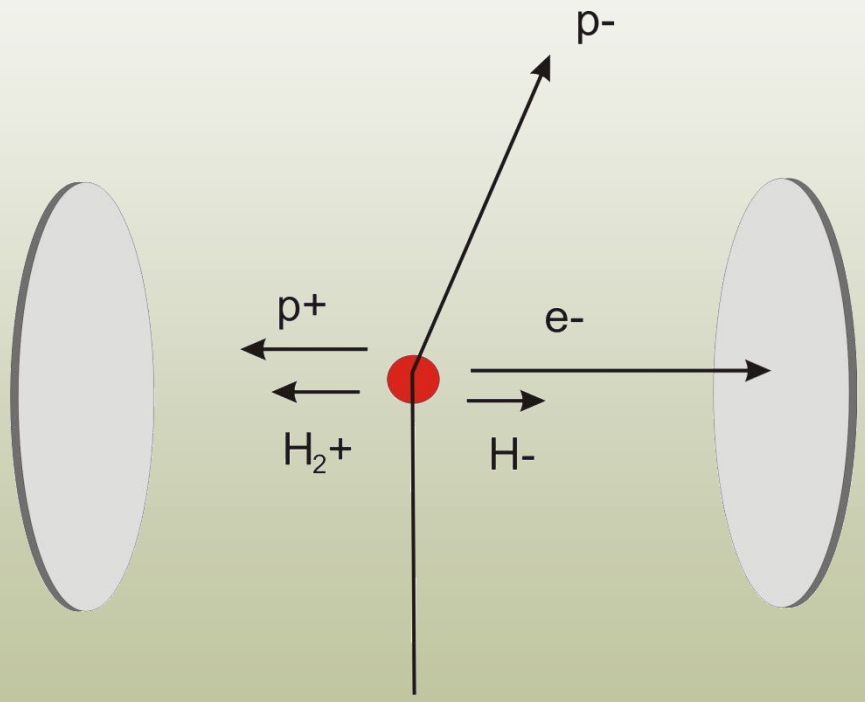
$p^- + H_2$

$\rightarrow$ $e^- + H_2^+$

$\rightarrow$ $e^- + H + p^+$

$\rightarrow$ $e^- + e^- + p^+ + p^+$
(Coulomb explosion)

$\rightarrow$ $p^+ + H^-$



40 – 100 keV pbar

Other molecules

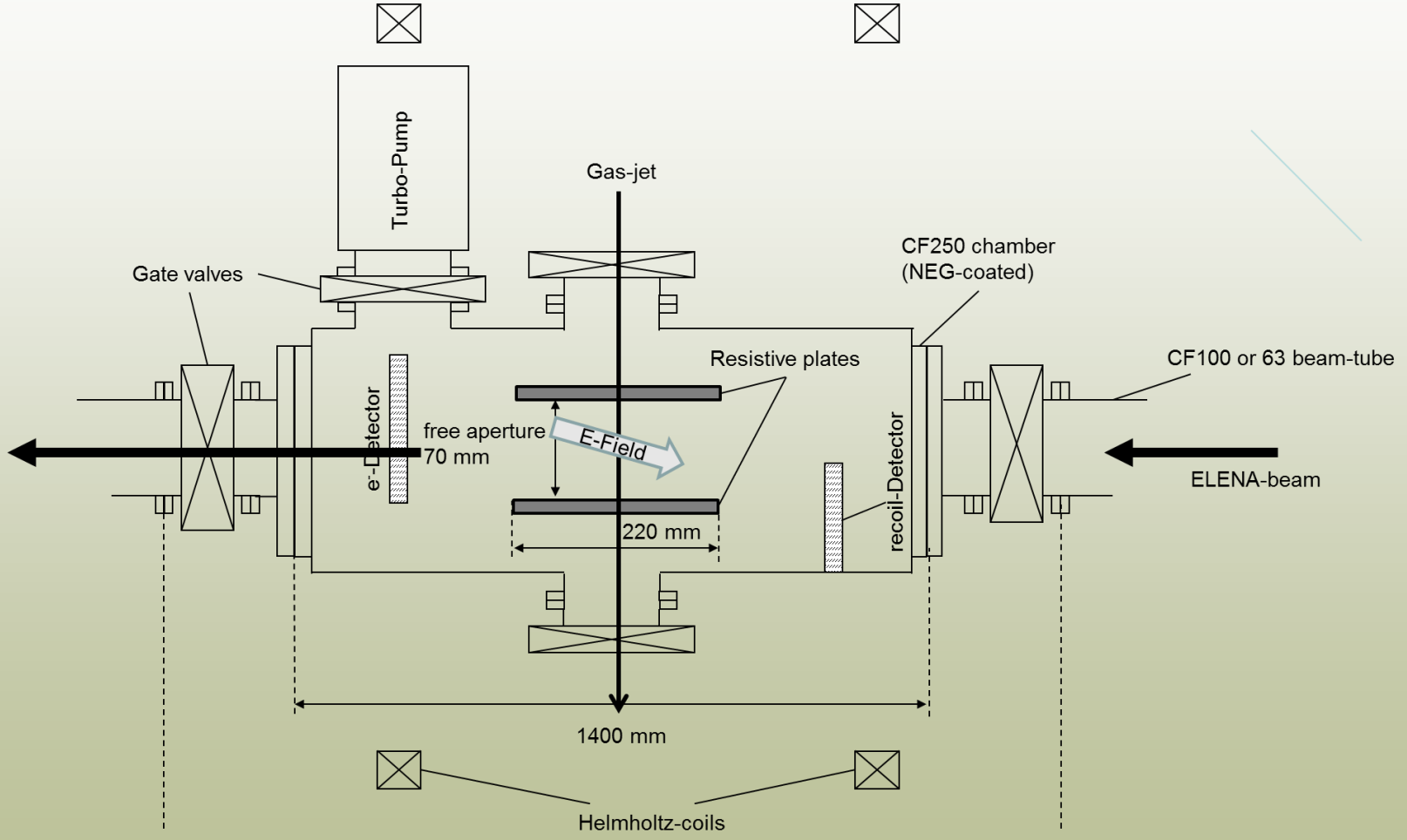
Helge Knudsen

Quasi-adiabatic collisions – molecular hydrogen target

100 kV injector to ELENA - either H- or H+

coluld be used to do comparative measurements with these ions, and to tune the ReMi.

ReMi at ELENA: Technical details



Helge Knudsen

ReMi at ELENA: Technical details

Helge Knudsen

ReMi at ELENA: Technical details

Requirements for the atomic collision experiments

Mandatory:

1. Sufficient space with low (inhomogeneous) magn. stray fields (about < 0.02 Gauss/cm)
2. Beam size and intensity at the target location: Beam diameter should not significantly larger than 1-2 mm
3. When indicated beam-orbit corrections (in the ring or at the ReMi)

(Highly) desirable:

4. ns-pulsing of the beam
5. deceleration to 50kev
6. Tuning and reference measurements with a H- beam in ELENA

Quasi-adiabatic collisions THEORY – helium target

Foster, Colgan and Pindzola prl **100** 033201 (2008)

10 keV – 1 MeV antiprotons on helium
Time dependent close coupling (TDCC)

Guan and Bartschat prl **103** 213201 (2009)

3 keV – 6 MeV antiprotons on helium
Grid-based ab-initio finite element discrete variable representation FE-DVR

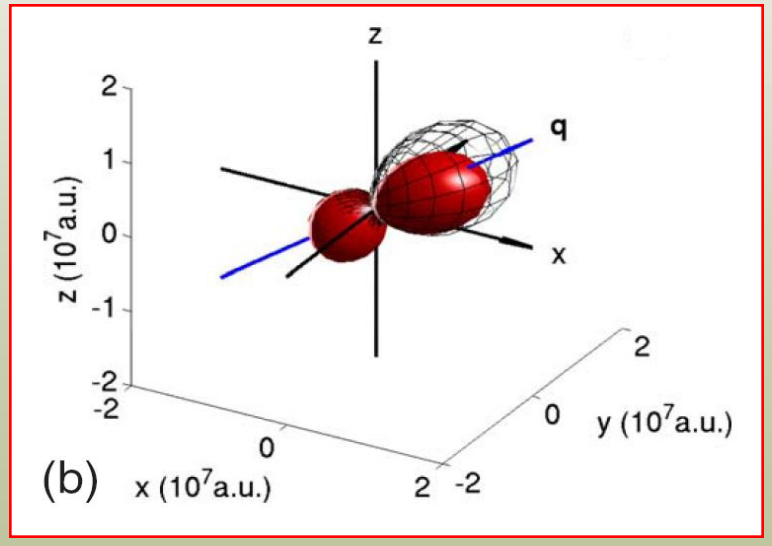
McGovern et al pra **81**, 032708 (2010)
pra **79**, 042707 (2009)

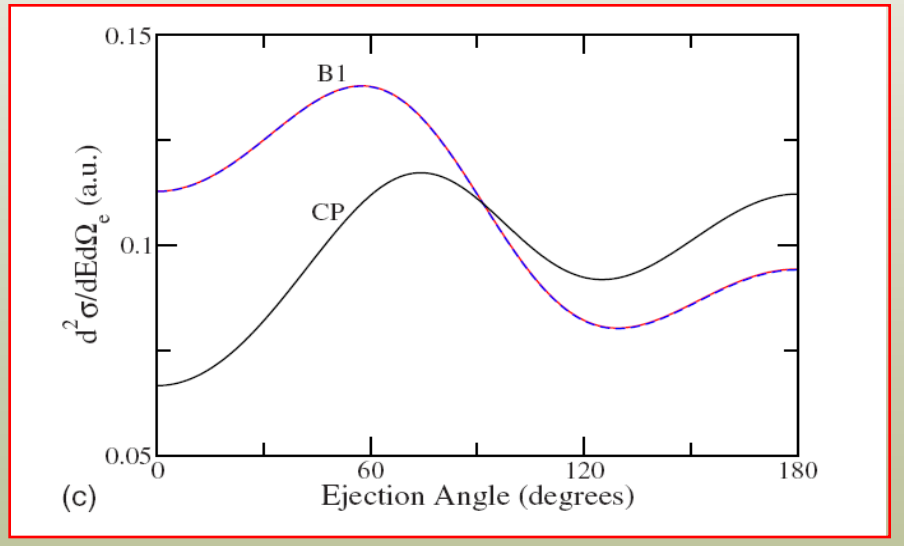
3 – 500 keV antiprotons on helium and atomic hydrogen
Coupled Pseudostates frozen He+(1s) core IPM with 165 states.
Atomic hydrogen and helium targets

Quasi-adiabatic collisions THEORY – helium target

500 keV
single ionization

McGovern et al pra **81**, 032708 (2010)
pra **79**, 042707 (2009)

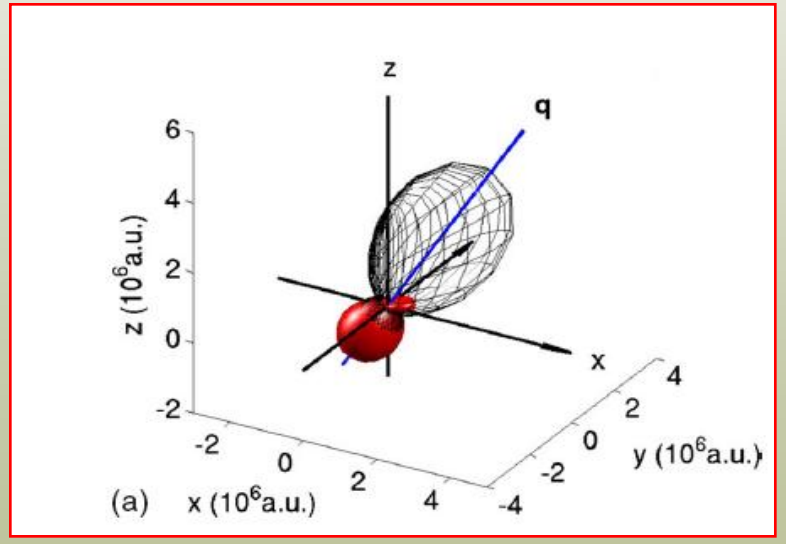


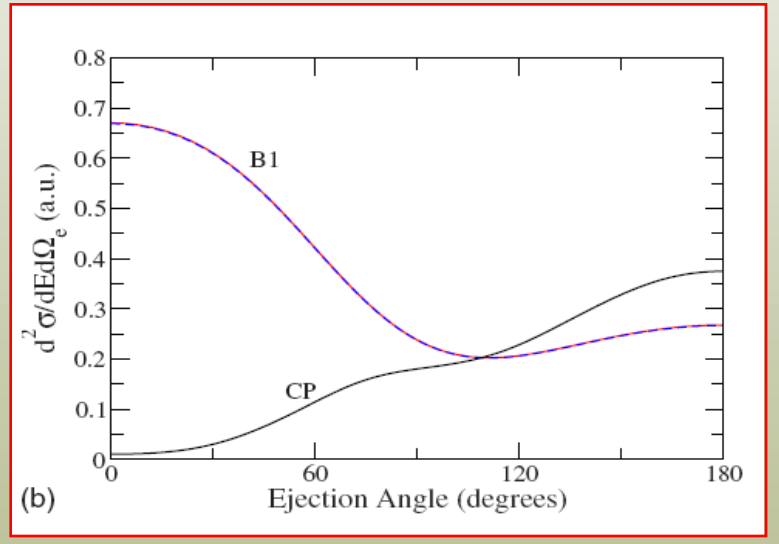


Quasi-adiabatic collisions THEORY – helium target

60 keV
single ionization

McGovern et al pra **81**, 032708 (2010)
pra **79**, 042707 (2009)

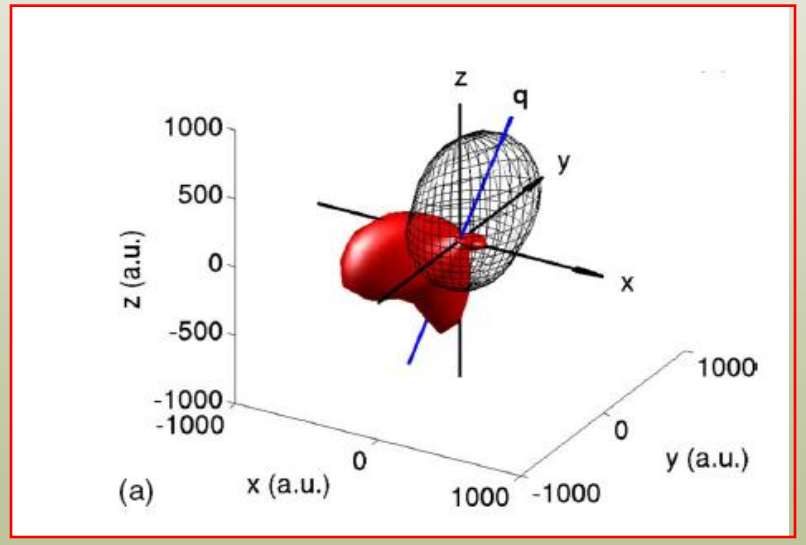


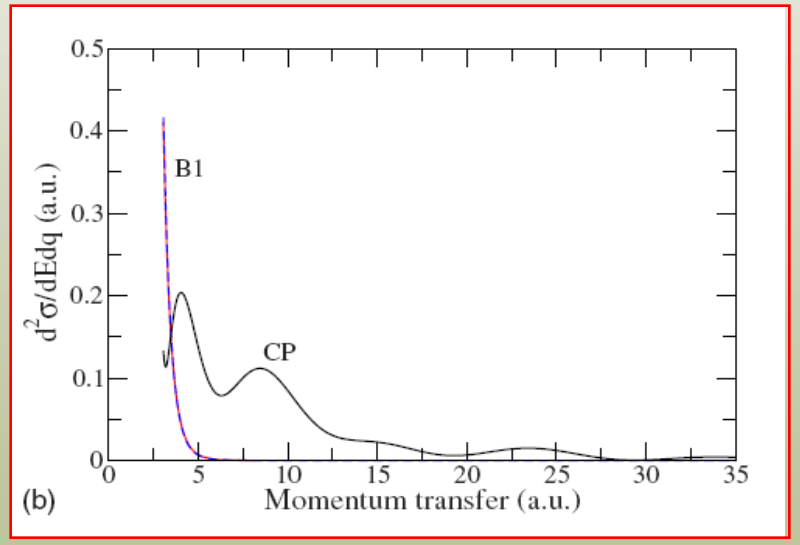


Quasi-adiabatic collisions THEORY – helium target

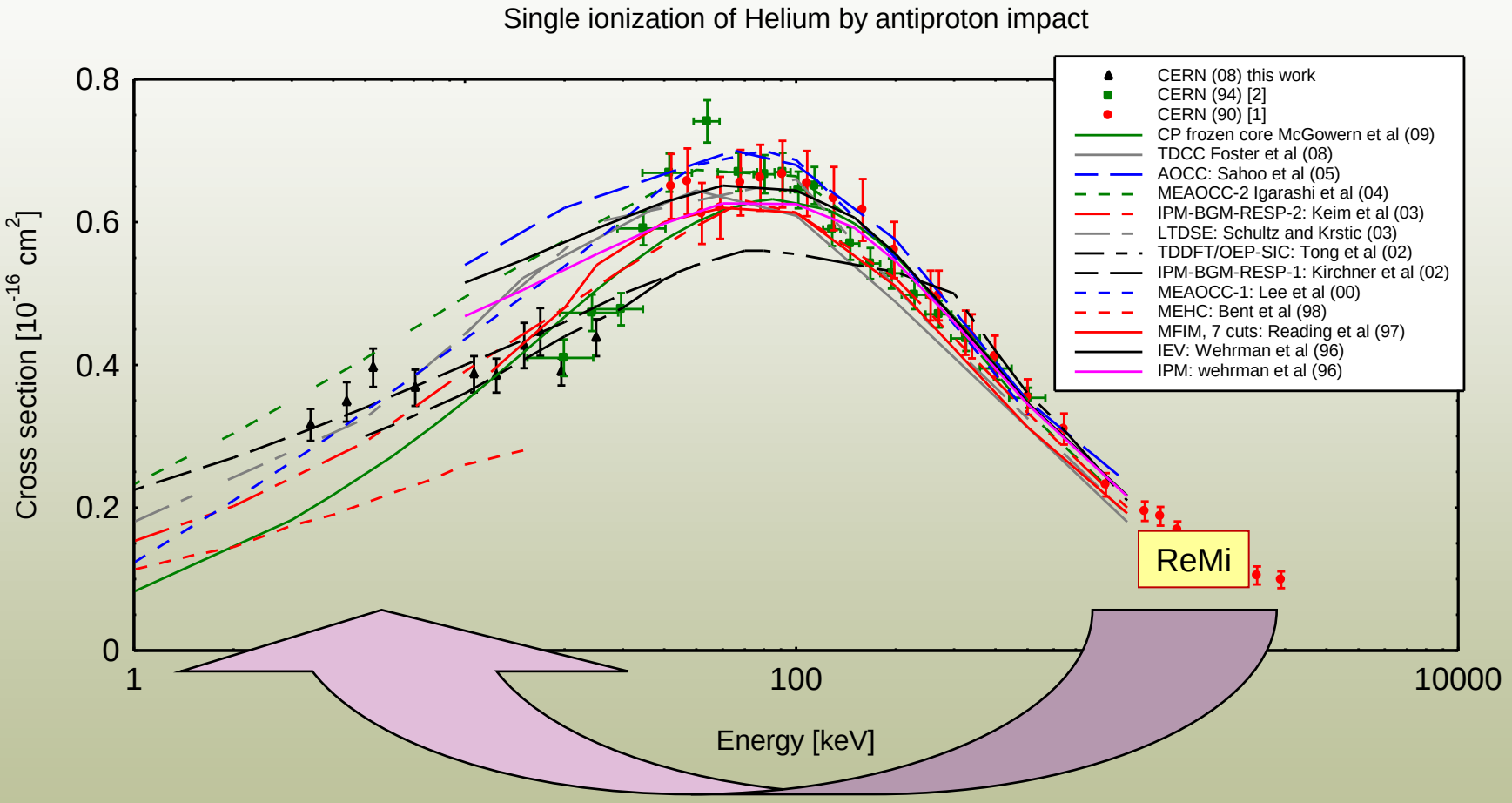
3 keV
single ionization

McGovern et al pra **81**, 032708 (2010)
pra **79**, 042707 (2009)





From fast to slow projectile measurements

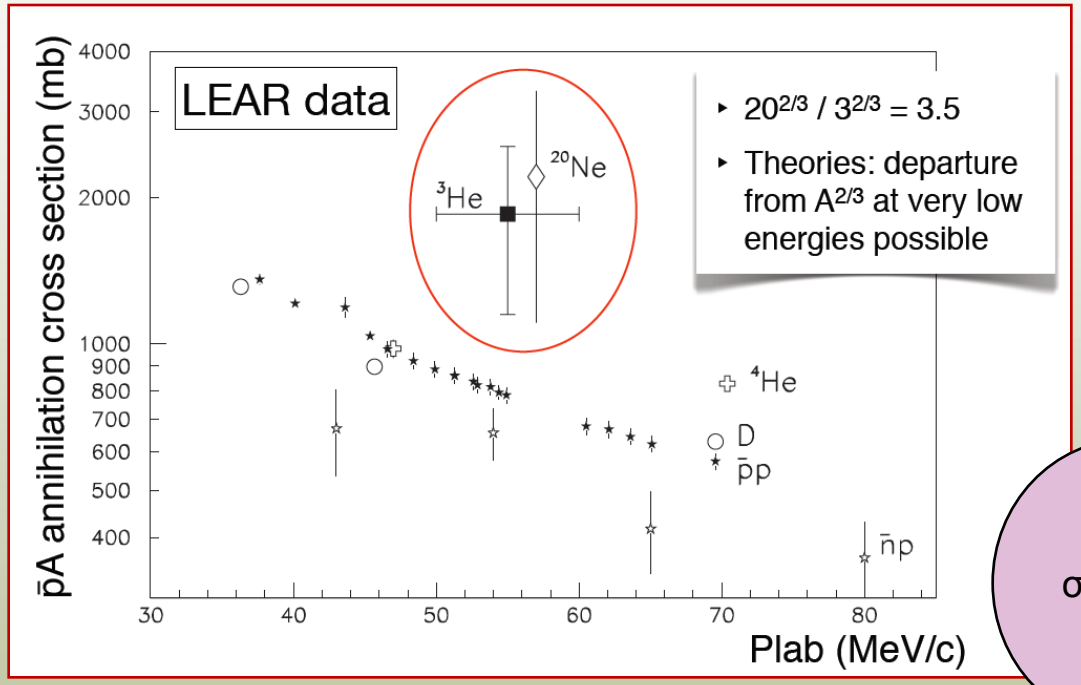


Physics motivations…

Annihilation cross sections

Physics motivations…

ASACUSA experiment (INFN group and others) :

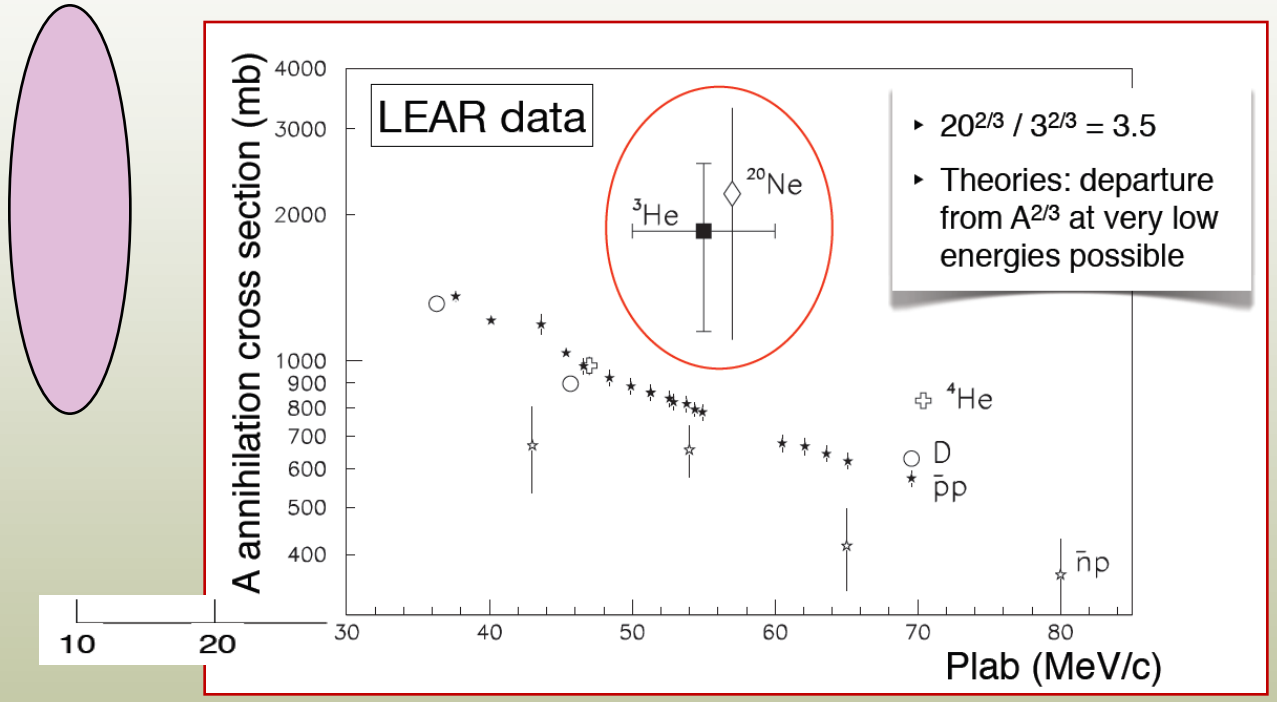


$\sigma \sim A^{2/3}$

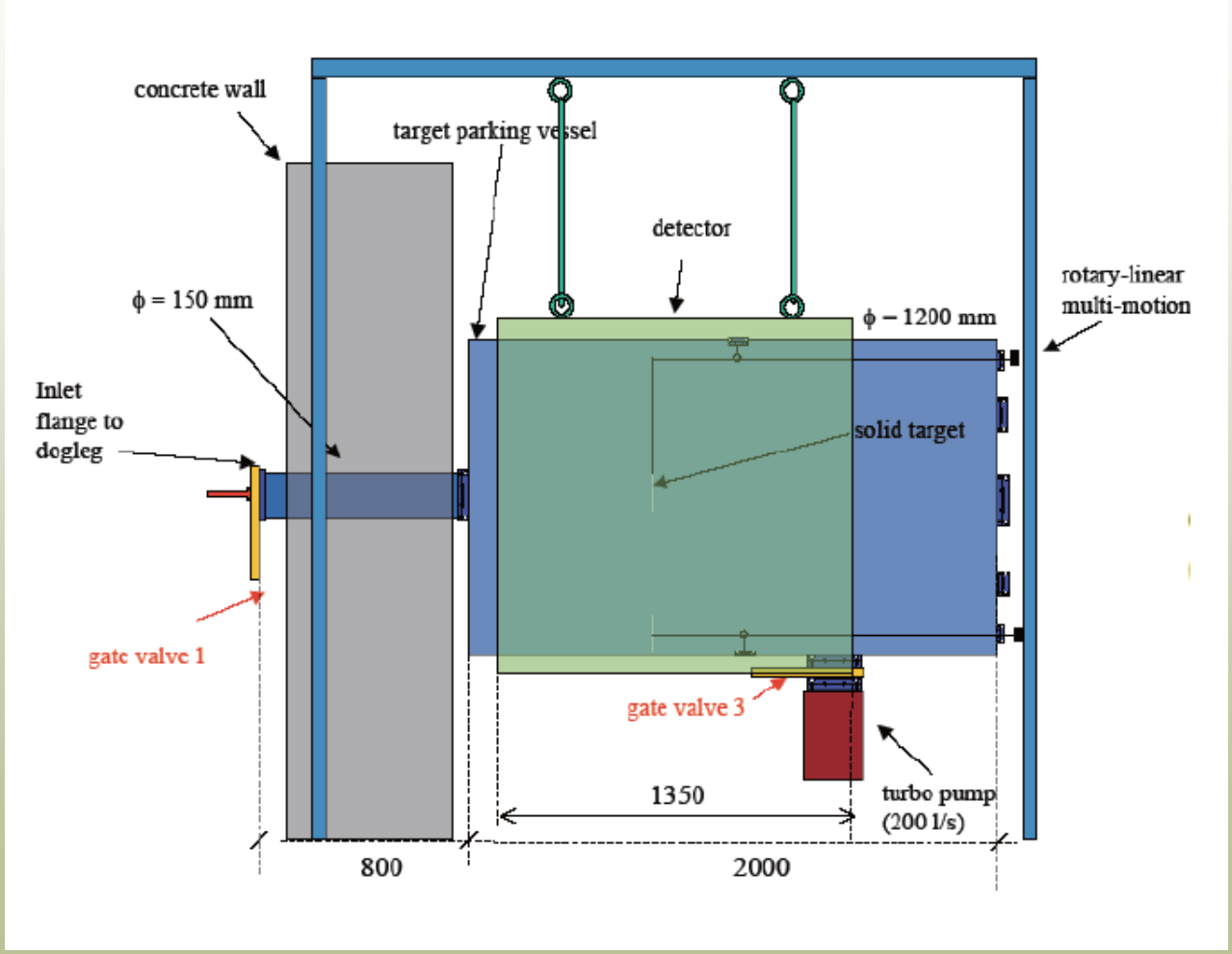
At low energies, s-wave components of the antiproton dominate.
As the wavelength of the antiproton becomes larger than the target nucleus, ”saturation ” sets in
Complication: Coulomb focussing.

Physics motivations…

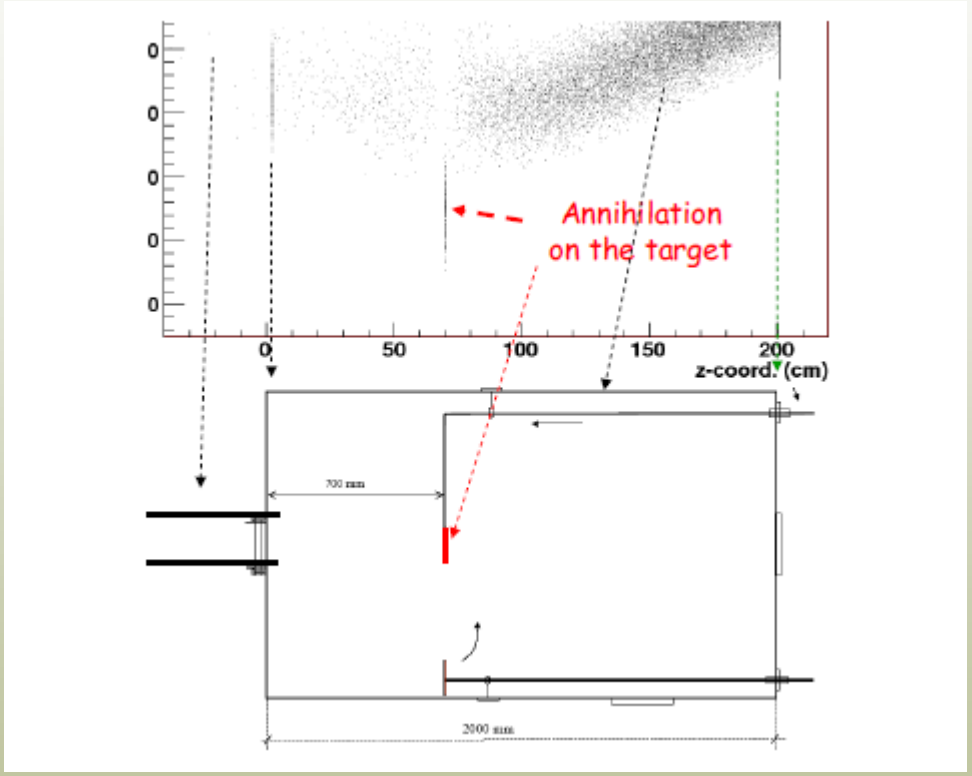
ASACUSA experiment (INFN group and others) :



Annihilation cross sections…



Annihilation cross sections…



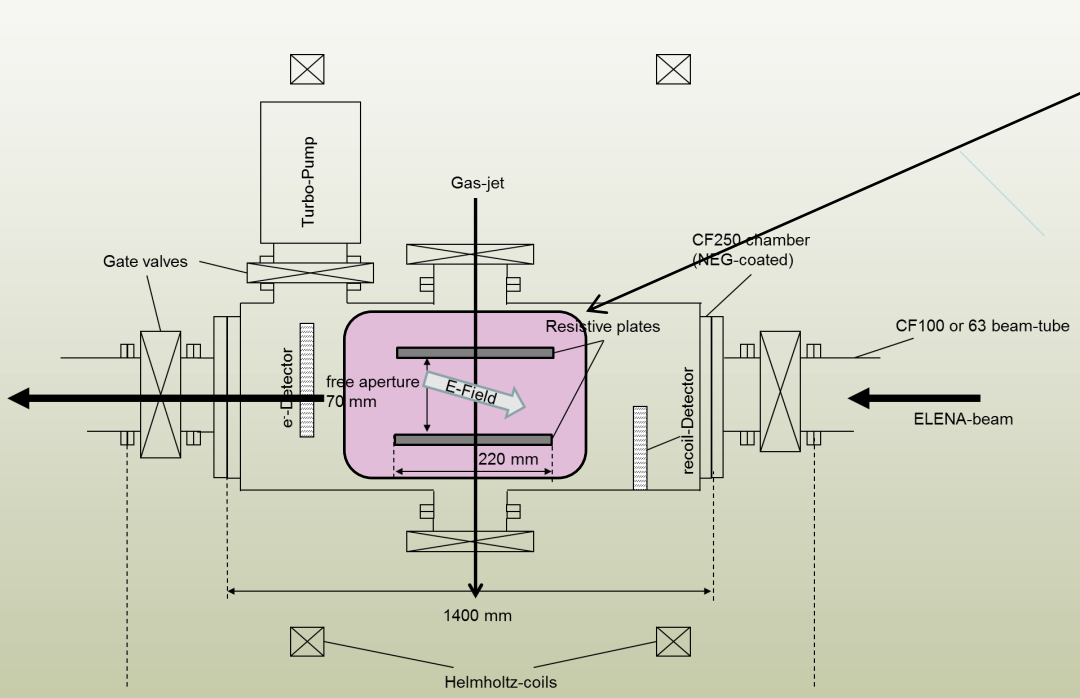
Target must be very thin to prevent dE degradation

7o nm but with 8 cm diameter

Very difficult to clean surface

Low signal rate 0.1 / sec

Annihilation in ELENA: Technical details



Annihilation cross sections…

Signal rate:

Detection of one pion:

σ ~ 10 Barn
Gas density ~ 10^12 cm^3
Beam: Number of antiprotons in ELENA 3x10^7 in four bunches, revolution frequency in 70 kHz
3 charged pions emerging, detected with > 95% efficiency
Detector solid angle 30-40%

Signal rate ~ 10 /sec

If reconstruction is needed, this would lower the rate.

Quasi-adiabatic collisions – THEORY - molecular hydrogen target

Luehr and Saenz PRA **81**, 010701 (2010)

1 keV – 6.5 MeV antiprotons on molecular hydrogen
Full two-electron calculations
Time dependent close coupling (TDCC)

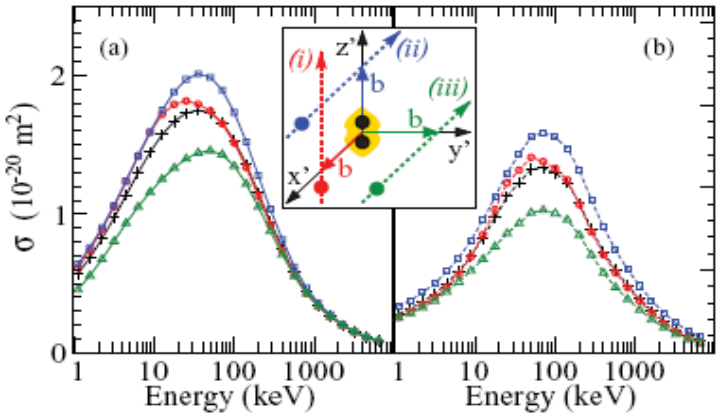
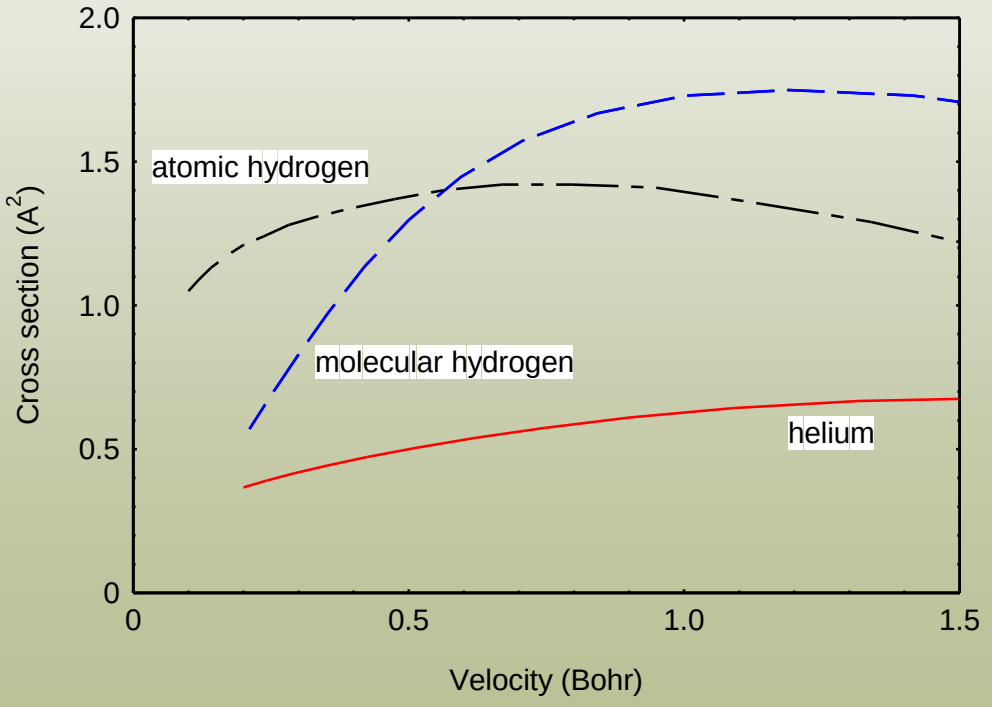


FIG. 3. (Color online) Cross sections for (a) single ionization and (b) excitation of molecular hydrogen by antiproton collisions for different molecular orientations. Black pluses, orientationally averaged; red circles, (i); blue squares, (ii); green triangles, (iii). The inset shows a sketch of the three orientations in the molecule-fixed frame.

Quasi-adiabatic collisions – THEORY - molecular hydrogen target

Luehr and Saenz PRA **81**, 010701 (2010)

1 keV – 6.5 MeV antiprotons on molecular hydrogen, atomic hydrogen, helium
Full two-electron calculations
Time dependent close coupling (TDCC)



ReMi at ELENA: Technical details