Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

PIONIC HYDROGEN and DEUTERIUM

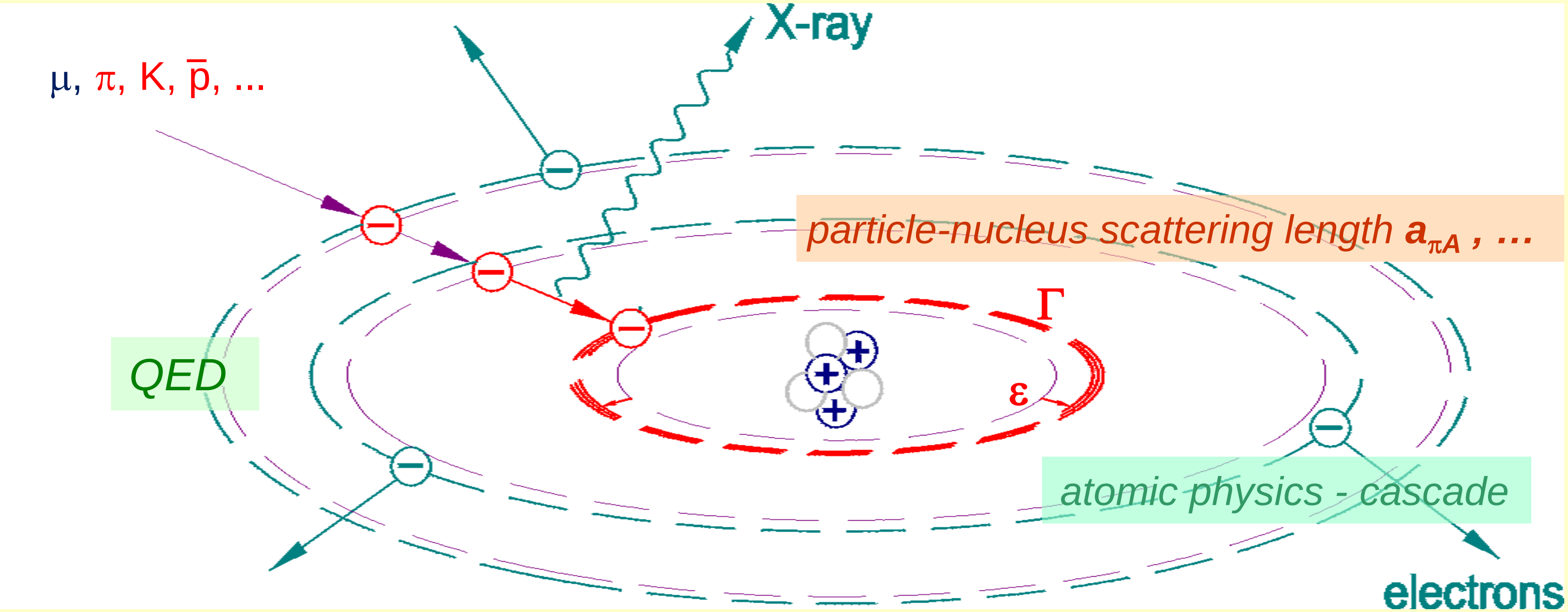
Detlev Gotta

Institut für Kernphysik, Forschungszentrum Jülich

for the PIONIC HYDROGEN collaboration

EXA 2011, Vienna, September 5-9, 2011

EXOTIC ATOM



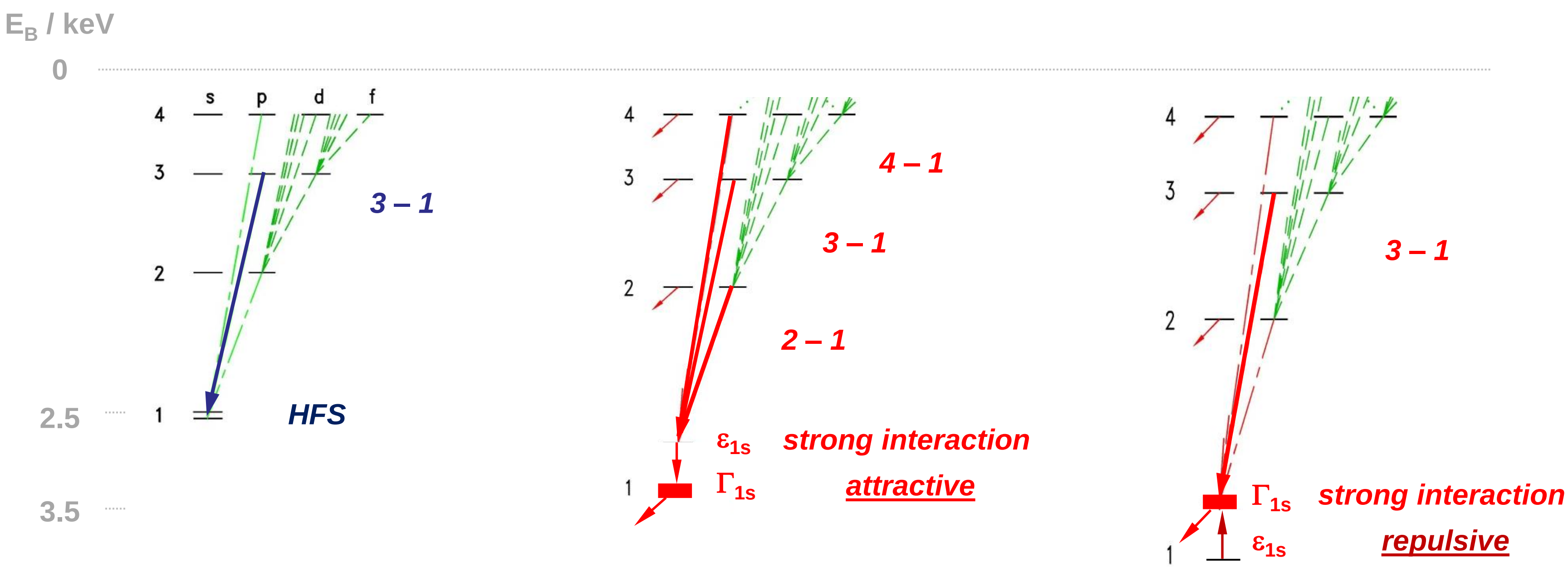
X-ray experiments measure

- *energy*
- *line width*
- *line yield*

strong interaction $\varepsilon - i\,\Gamma/2 \;\propto\; \boldsymbol{a_{\pi A}} + \ldots$

MEASUREMENTS

μH | **πH** | **πD**



„dangerous" cascade effects

Coulomb de-excitation

molecular formation

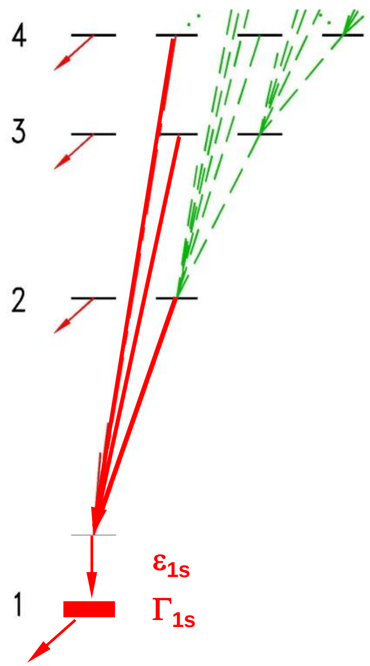
10 bar	***3, 10, 28 bar and LH_2***	***3, 10 and 17 bar***

STRONG INTERACTION

- ***PION-NUCLEON SCATTERING LENGTHS***
- ***PION PRODUCTION AND ABSORPTION***

PIONIC HYDROGEN - πN scattering at „rest“

which scattering length where?



shift ε *few eV*

broadening Γ $\approx$ *1eV*

$\pi H \quad \varepsilon_{1s} \propto a_{\pi^- p \to \pi^- p} \propto a^+ + a^- + \ldots$

$\pi H \quad \Gamma_{1s} \propto (a_{\pi^- p \to \pi^0 n})^2 \propto (a^-)^2 + \ldots$

$\pi D \quad \varepsilon_{1s} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} \propto 2 \cdot a^+ + \ldots$

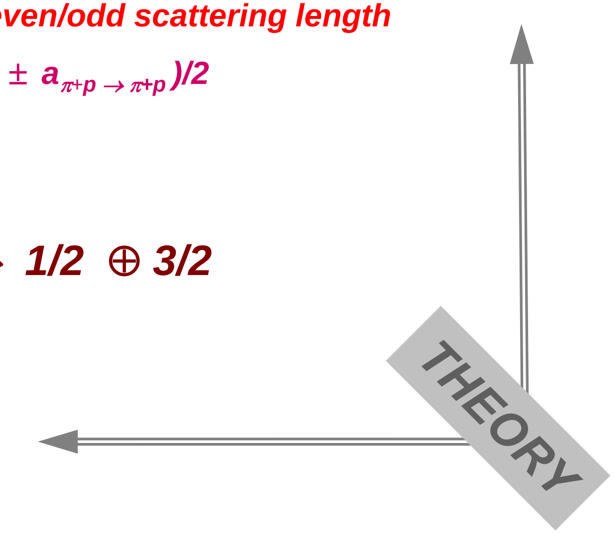
a^- *appears in multiple scattering term*

$a^{\pm}$ = *isospin even/odd scattering length*

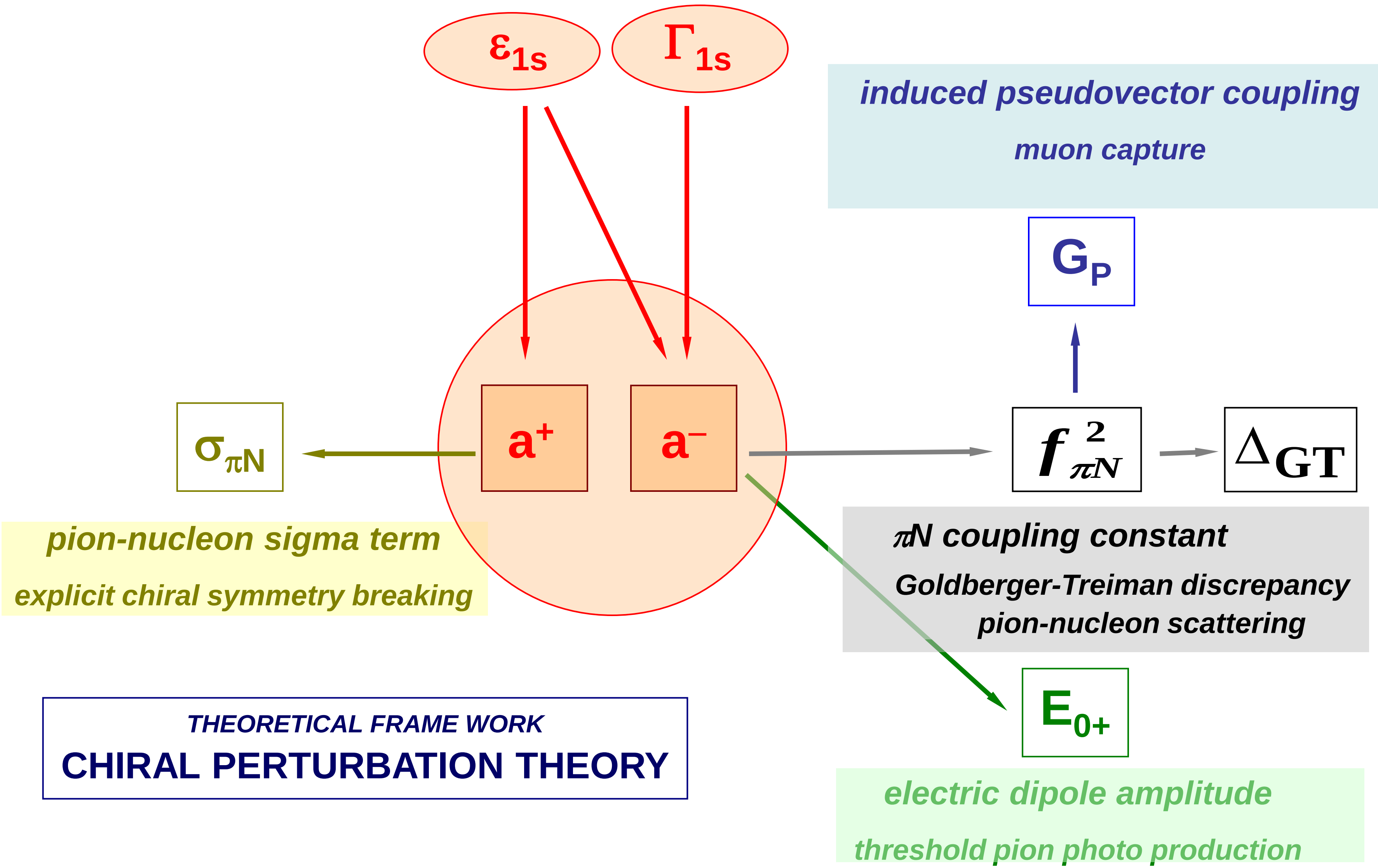
$= (a_{\pi^- p \to \pi^- p} \pm a_{\pi^+ p \to \pi^+ p})/2$

πN isospin $1 \otimes 1/2 \Rightarrow 1/2 \oplus 3/2$

isospin breaking corrections
few-body effects etc,
under control !!!



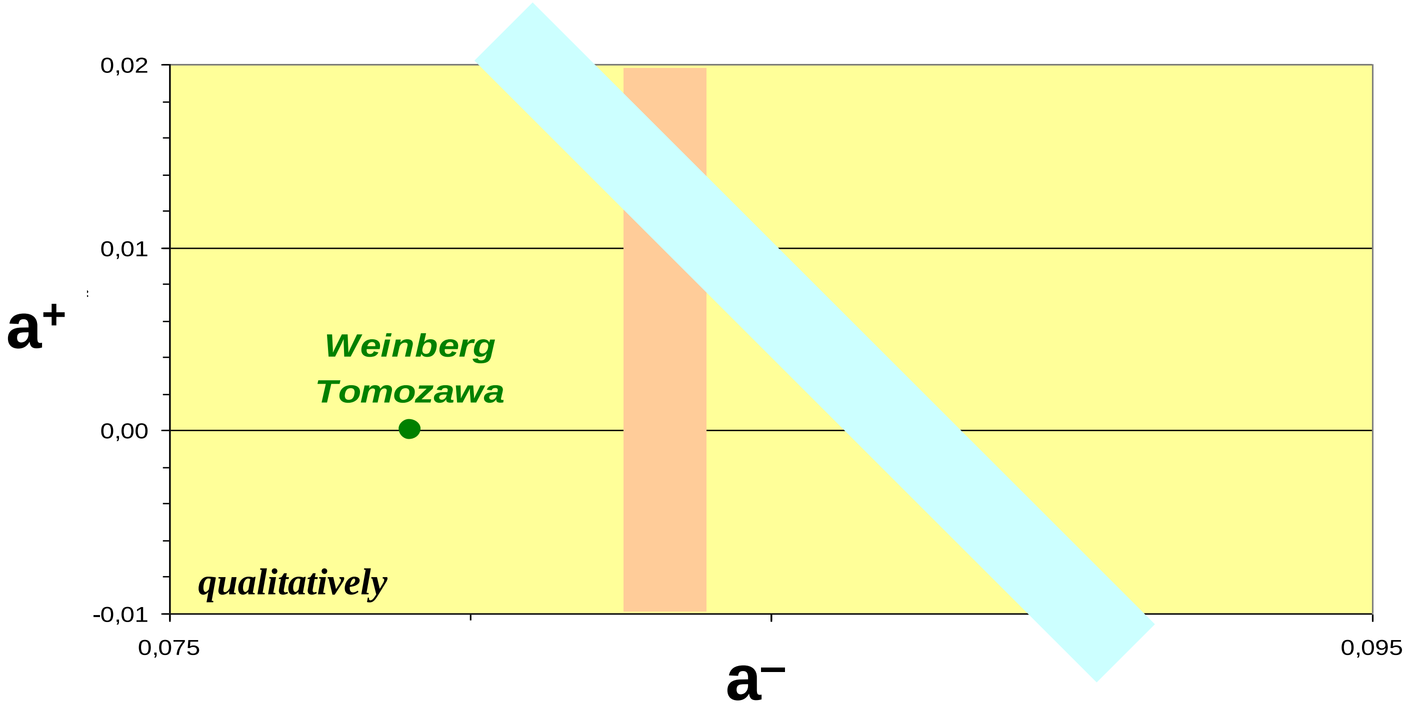
PION-NUCLEON SCATTERING LENGTHS *related quantities*



CONSTRAINTS for $a^{\pm}$ from πH

$\pi H \quad \varepsilon_{1s} \quad \propto \quad f\,(\,a^{+} + a^{-},\ LEC(c_1, f_1, f_2)\,)$

$\pi H \quad \Gamma_{1s} \quad \propto \quad [\,f\,(\,a^{-},\ LEC(c_1, f_2)\,)\,]^{2}$

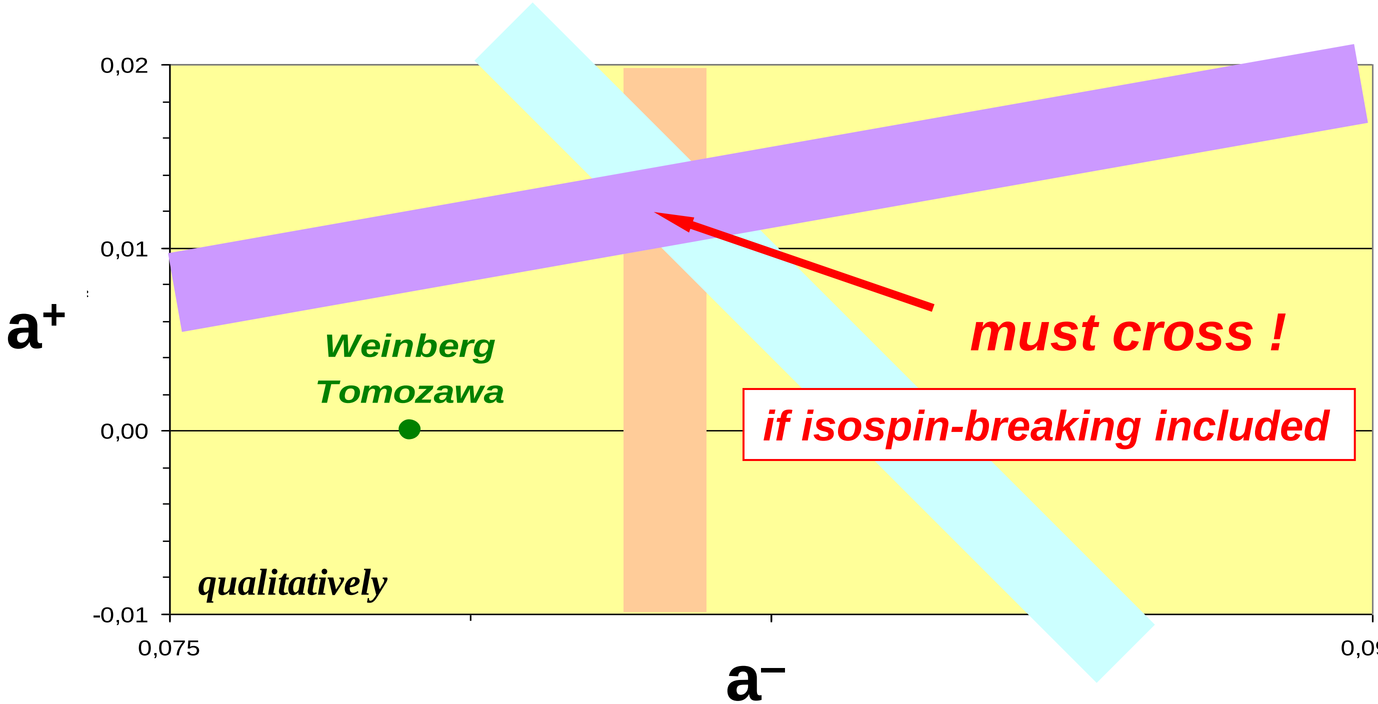


CONSTRAINTS for $a^{\pm}$ from πH and πD

$\pi H \quad \varepsilon_{1s} \propto f\,(a^{+} + a^{-},\ LEC(c_1, f_1, f_2))$

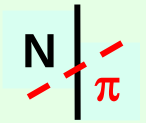
$\pi H \quad \Gamma_{1s} \propto [\,f\,(a^{-},\ LEC(c_1, f_2))\,]^2$

$\pi D \quad \varepsilon_{1s} \propto f\,(a^{+},\ LEC(c_1, f_1, f_2),\ h.o.(a^{+}, a^{-}))$



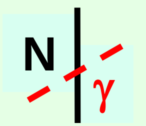
ORIGIN of Γ_{1s}

CEX scattering



πH *scattering* $\pi^- p \rightarrow \pi^0 n + n\gamma$

radiative capture



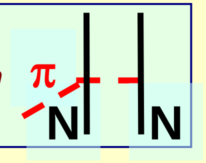
BR are well known from experiment

πD *absorption* $\pi^- d \rightarrow nn + nn\gamma$

NN ⇔ NNπ

s-wave pion production / absorption

„true" absorption



!!! $\Gamma_{1s} \propto \Im\, a_{\pi - d \rightarrow nn+nn\gamma}$

$NN \Leftrightarrow \pi NN$ threshold parameter α

charge symmetry *detailed balance*

$a_{\pi^- n \to \pi^- n} = a_{\pi^+ p \to \pi^+ p}$

$$\sigma_{\pi^- d \to nn} \leftrightarrow \sigma_{\pi^+ d \to pp} \leftrightarrow \sigma_{pp \to \pi^+ d}$$

$NN \quad {}^3S_1(I=0) \to {}^3P_1(I=1)$

πD atom

$$\Im\, a_{\pi D} \propto \Gamma_{\pi^- d \to nn} + \Gamma_{\pi^- d \to nn\gamma} \propto \alpha$$

directly from Γ

π production experiments

$$\sigma_{pp \to \pi^+ d} \to \alpha\, C_0^2\, \eta + \beta\, C_1^2\, \eta^3$$

extrapolation to threshold

$$\eta = k_\pi / m_\pi$$

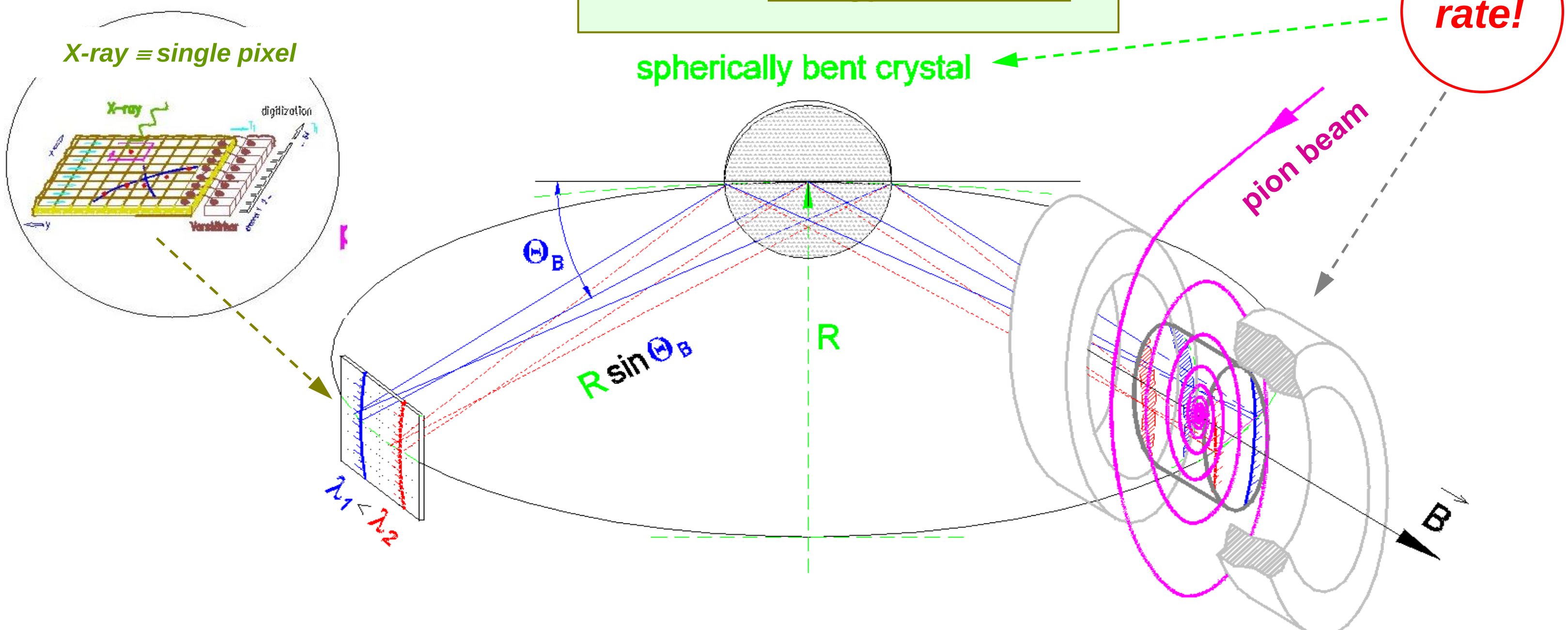
advantage – *no normalisation*
– *no extrapolation to threshold*
– *no Coulomb correction factors C_0, C_1*

EXPERIMENT

- *Suitable X-ray source*
- ***Crystal spectrometer performance***
- ***Background minimisation***

JOHANN-TYPE SET-UP

ultimate <u>energy resolution</u>



position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

<u>position & energy resolution</u>

⇒ **background reduction I**
by analysis of hit pattern

high <u>stop density</u>

⇒ **high X - ray line yields**
⇒ **bright X - ray source**

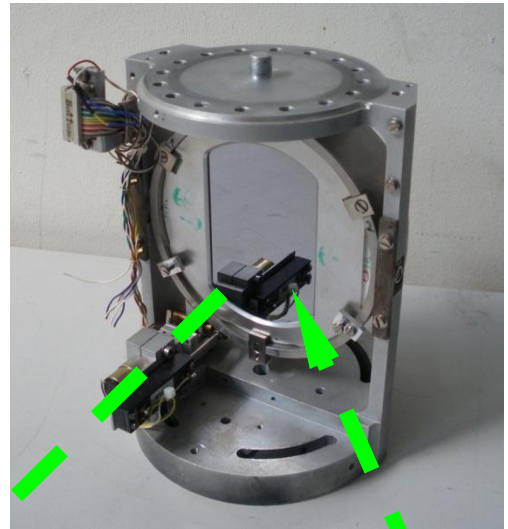
L. Simons, Physica Scripta 90 (1988), Hyperfine Int. 81 (1993) 253

BRAGG CRYSTAL

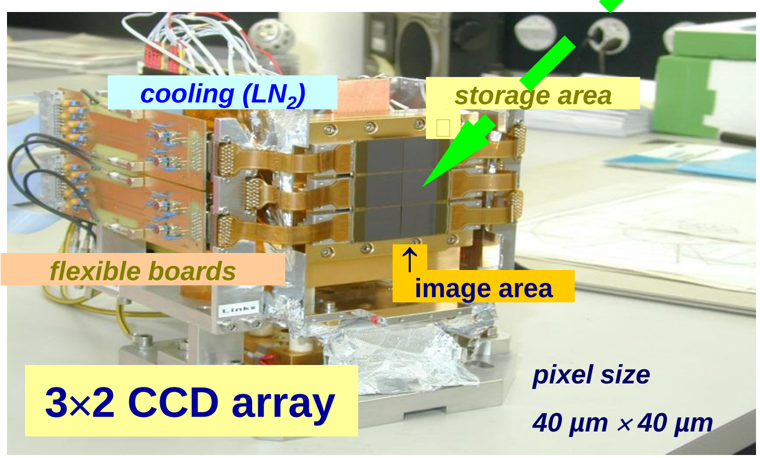
Si 111

spherically curved

R = 3 m
Φ = 10 cm



Large - Area Focal Plane Detector

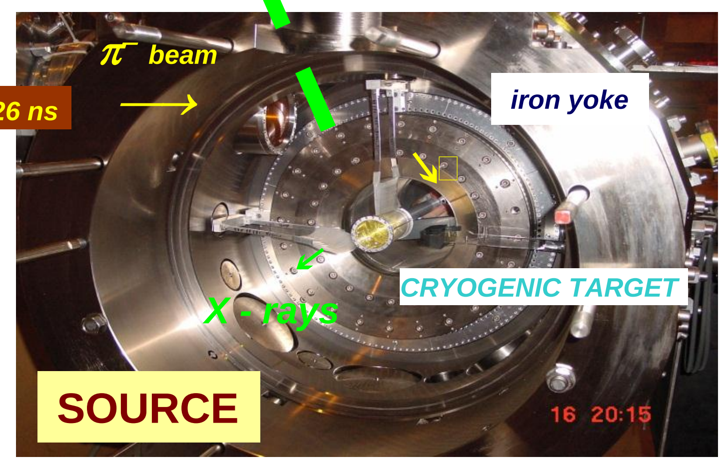


CYCLOTRON TRAP

one coil removed

10^9 π/s

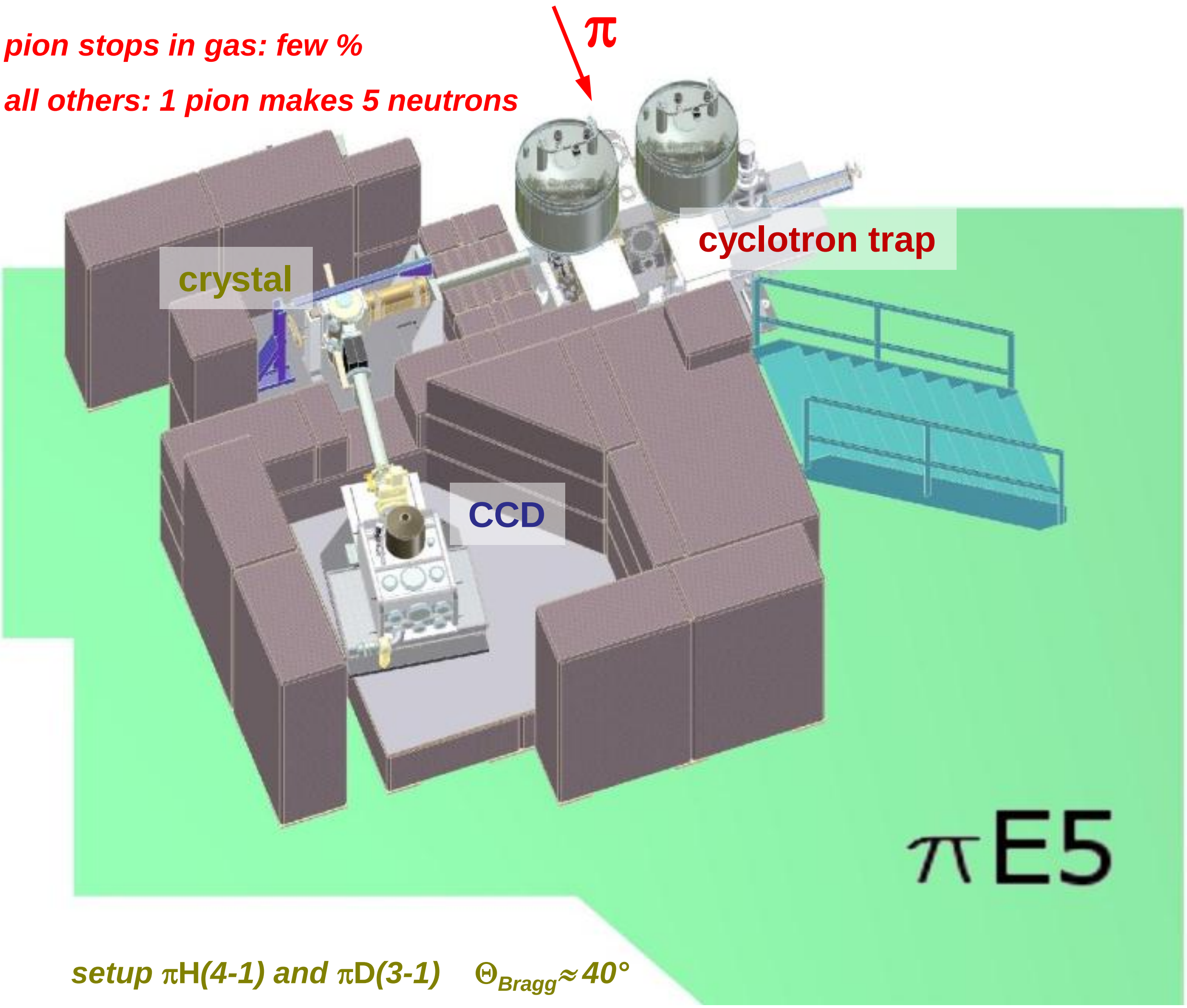
$\tau_{\pi\pm}$ = 26 ns



TYPICAL SET-UP at PSI

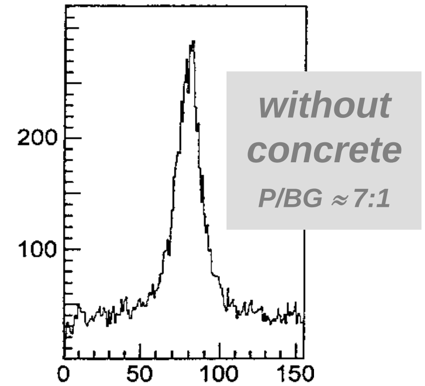
pion stops in gas: few %

all others: 1 pion makes 5 neutrons

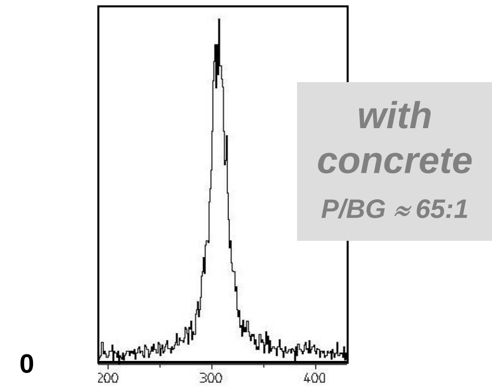


setup πH(4-1) and πD(3-1) $\Theta_{Bragg} \approx 40°$

pionic hydrogen



peak/background x 10



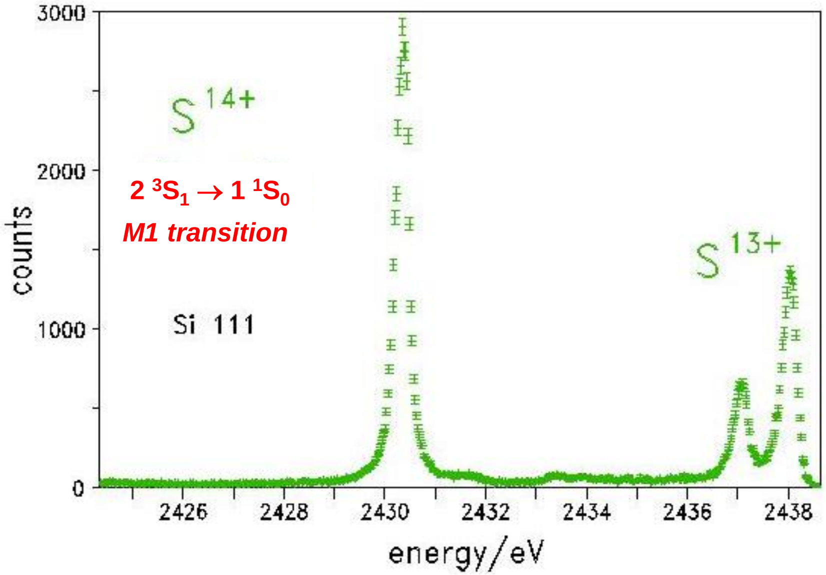
background reduction II

SPECTROMETER RESPONSE from FEW-ELECTRON ATOMS

X-rays produced in ECRIT

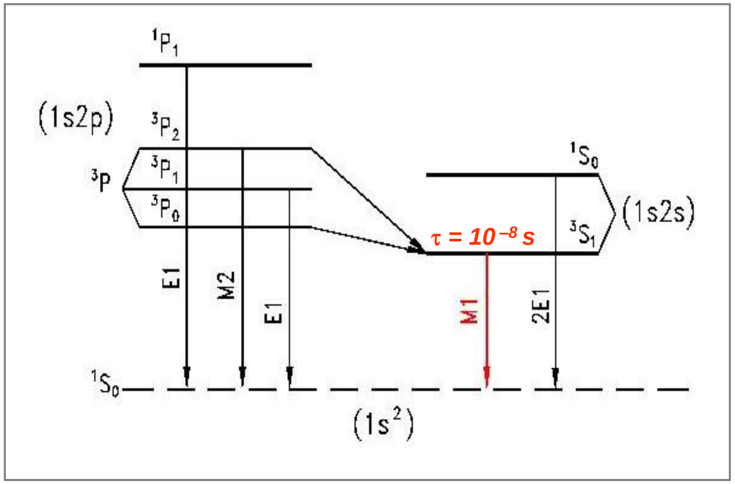
(= Electron Cyclotron Resonance Ion Trap)

„cold“ ions



M1 transitions in He - like

S	⇔	**πH(2p-1s)**
Cl	⇔	**πH(3p-1s)**
Ar	⇔	**πH(4p-1s) / πD(3p-1s)**



30000 events in line (3 h) ⇔ tails can be fixed with sufficient accuracy

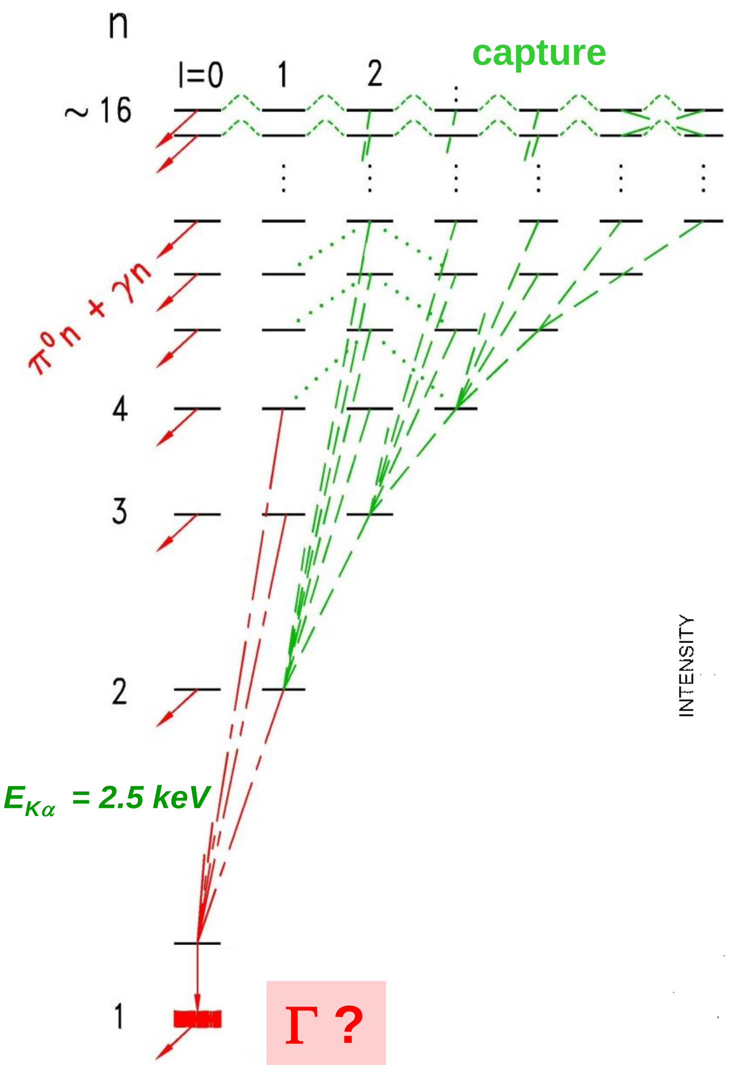
to be compared with Monte-Carlo ray tracing folded with plane crystal response

D.F.Anagnostopoulos et al., Nucl. Instr. Meth. B 205 (2003) 9
D.F.Anagnostopoulos et al., Nucl. Instr. Meth. A 545 (2005) 217

ATOMIC CASCADE

- *Coulomb de-excitation*
- *Molecular formation*

πH - ATOMIC CASCADE I



density dependent

Coulomb de-excitation

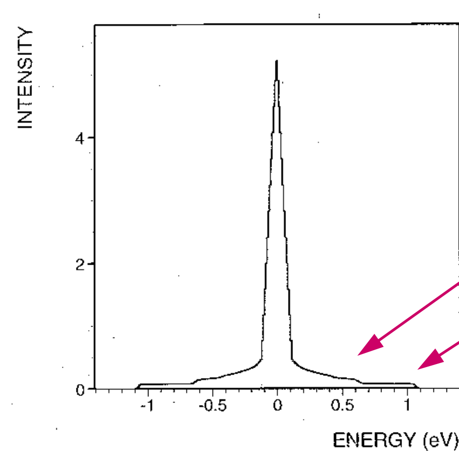
$\pi^- p_{nl}$ + H=H $\rightarrow$ $\pi^- p_{n'l'}$ + H+H + *kinetic energy*

>>> Doppler broadening ! <<<

identified first from n TOF

J.B. Czirr *et al.*, Phys. Rev. **130**, 341 (1963)

A. Badertscher et al., Eur. Phys. Lett. 54 (2001) 313 (status)



µH(3p-1s) ***MC simulation***

tails from Doppler broadening

5-4

4-3

remove Γ_{1s}

LINE SHAPE = R ⊗ ~~L~~ ⊗ Σ D

crystal response | ~~Lorentzian Γ_{1s}~~ | Doppler broadening *Coulomb de-excitation*

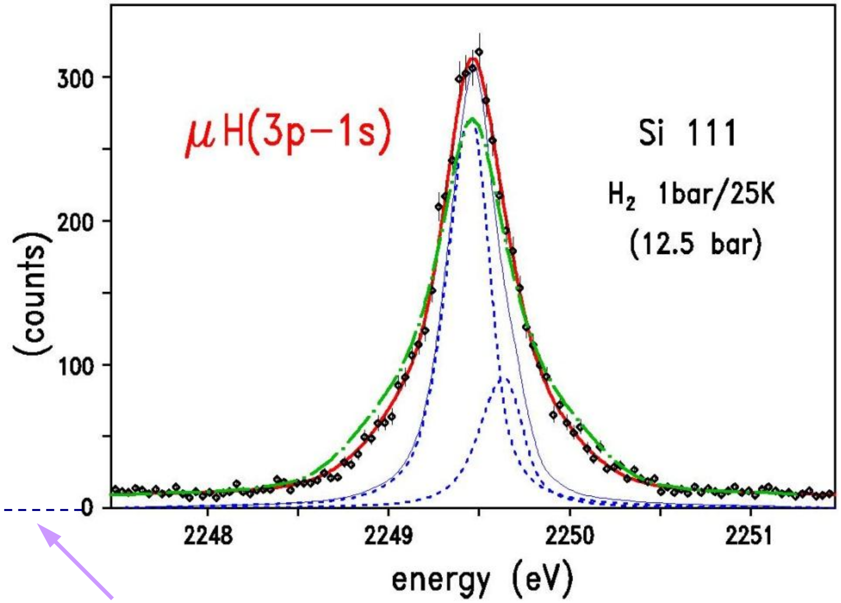
depends on initial state

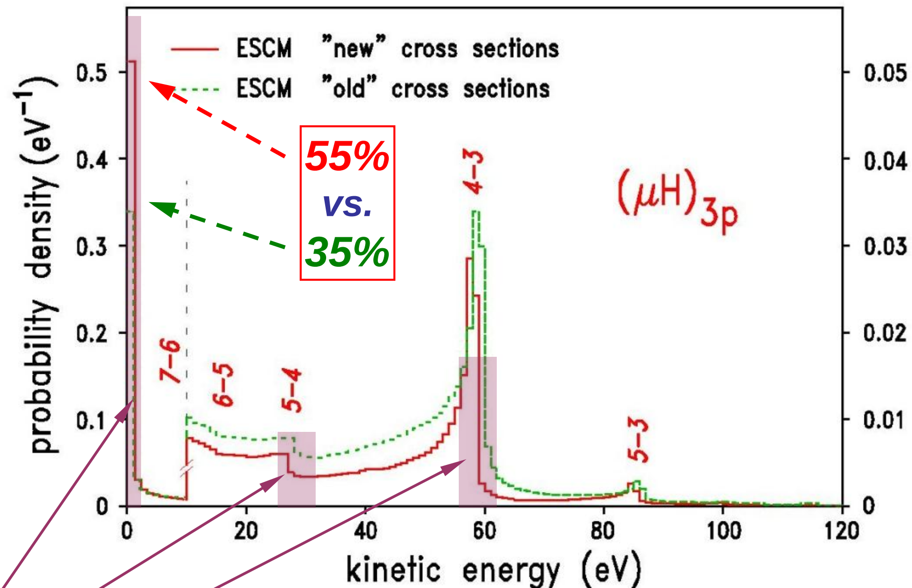
ECRIT

MUONIC HYDROGEN

CONSTRAINT from CASCADE CALCULATION ?

MUONIC HYDROGEN





no satellites from molecular formation identified

low-Tkin:	61 ± 2 %
medium-Tkin	25 ± 3 %
high-Tkin	14 ± 4 %

„box" fits = model free fit

re-calculation of cross sections

triplet / singlet = 3.0 ± 0.3

ΔE= 183 meV (theory)

PhD thesis: D. Covita, Coimbra 2008
D.S. Covita et al., Phys. Rev. Lett. 102 (2009) 023401

ESCM: extended standard cascade calculation and cross sections
T.S.Jensen and V.E.Markushin, Eur. Phys. J. D 19,165 (2002); ibid.D 21,261 (2002); ibid.D 21,271 (2002)
cross sections
G.Ya. Koreman, V.N. Pomerantsev and V.P. Popov, JETP. Lett. 81, 543 (2005)
V.N. Pomerantsev and V.P. Popov, Phys. Rev 130, 341 (2006)
V.P. Popov and V.N. Pomerantsev, arXiv:0712.3111v1[nucl-th] (2007)
Poster V. Pomerantsev, Talk V. Popov Friday 14:40

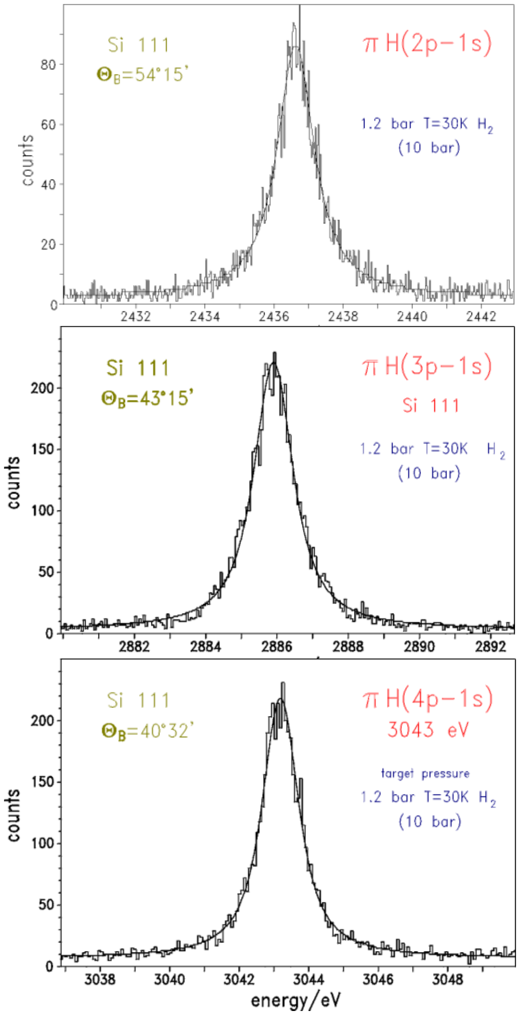
Γ_{1s}

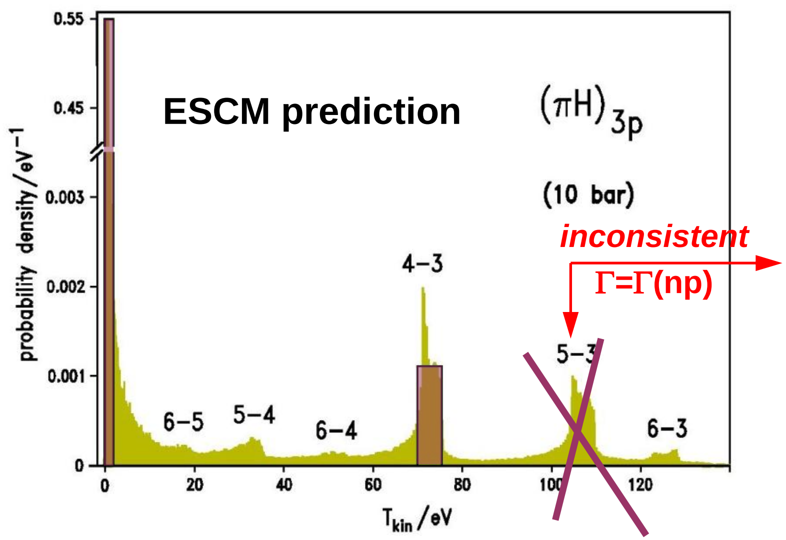
LINE SHAPE **=** **R** $\otimes$ **L** $\otimes$ Σ **D**

crystal	**Lorentzian**	**Doppler broadening**
response	Γ_{1s}	***Coulomb de-excitation***
	↑	***depends on initial state***

model free approach

"BOX" FITS πH





Coulomb transition

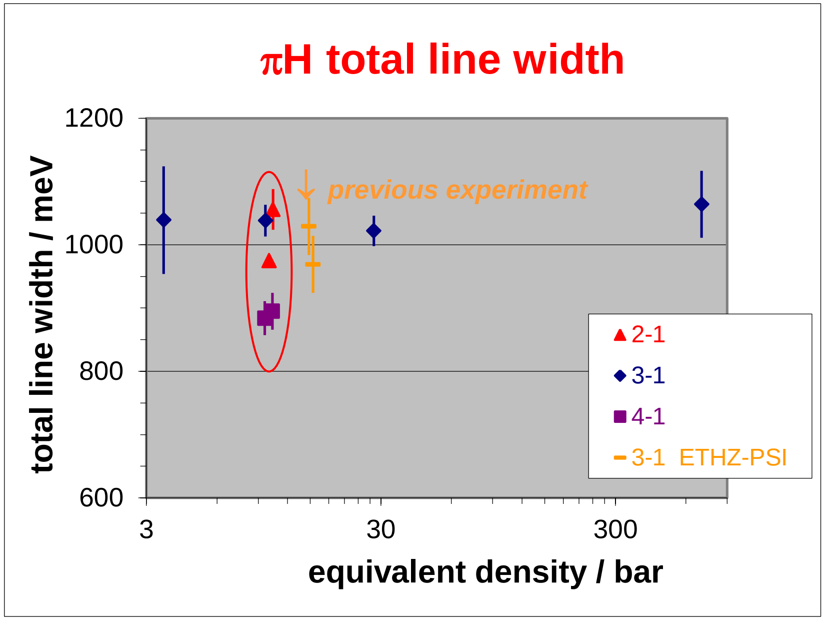
low-energy	***≈ 50%***
5-4	***---***
6-4	***---***
4-3	***≈ 50%***
3-2	***?***

low-energy	***≈ 55%***
5-4	***---***
6-4	***---***
4-3	***≈ 45%***
5-3	***---***

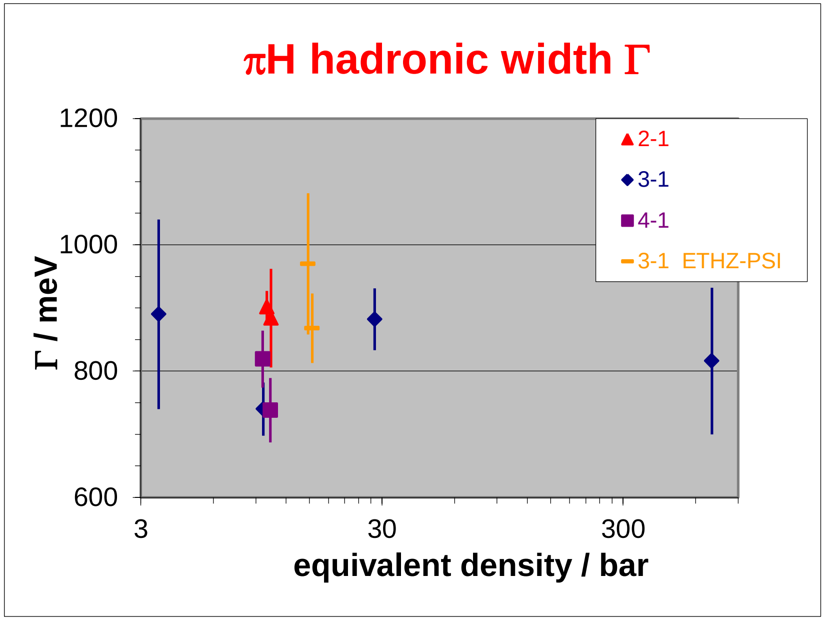
low-energy	***≈ 50%***
6-5	***---***
5-4	***≈ 50%***
6-4	***---***

PIONIC HYDROGEN - LINE WIDTH and INITIAL STATE

not corrected for Coulomb de-excitation



„box" fits



„upper" limit	$\Gamma_{1s} \approx 880 \pm 25$ meV	*from 4p-1s no Coul. de-exc.*
4p-1s	$\Gamma_{1s} \approx 790 \pm 40$ meV	
3p-1s	$\Gamma_{1s} \approx 800 \pm 60$ meV	→ *limit without cascade theory* ←
2p-1s	$\Gamma_{1s} \approx 900 \pm 30$ meV	

all $\Gamma_{1s} \approx 850 \pm 40$ meV

next steps for Γ πH

limit without input from cascade theory

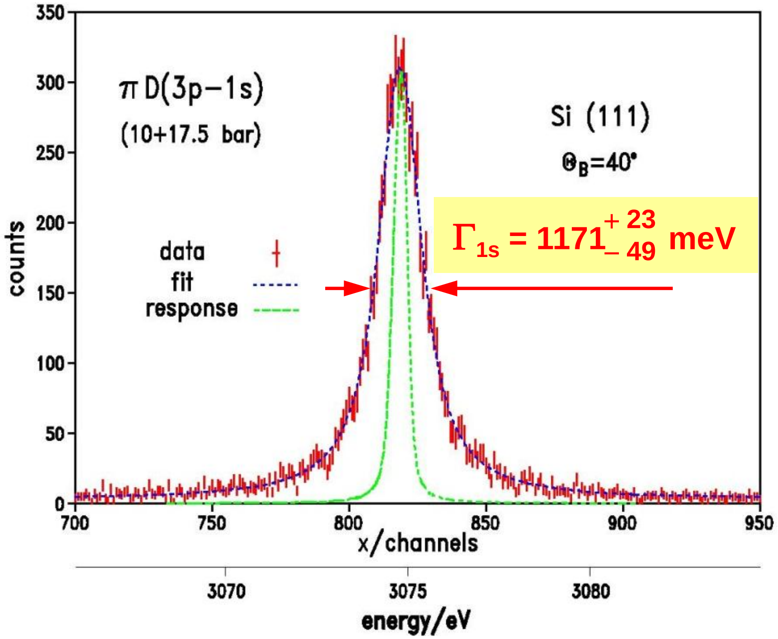
in progress

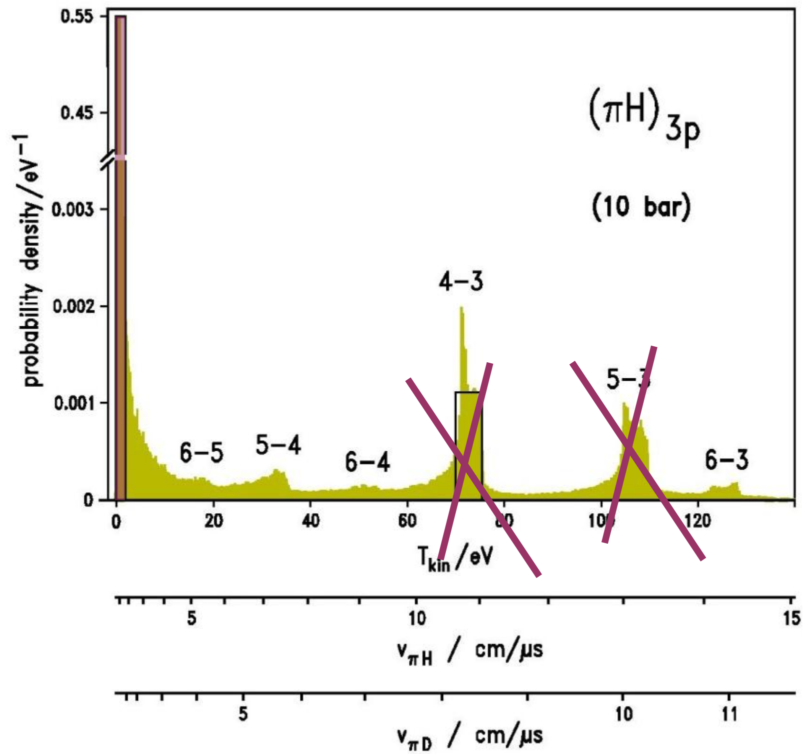
analysis in Bayesian approach $\rightarrow$ unbiased estimate

$\rightarrow$ error estimate

$\rightarrow$ final accuracy $\approx$ 3 - 4%

"BOX" FITS πD





< 10%

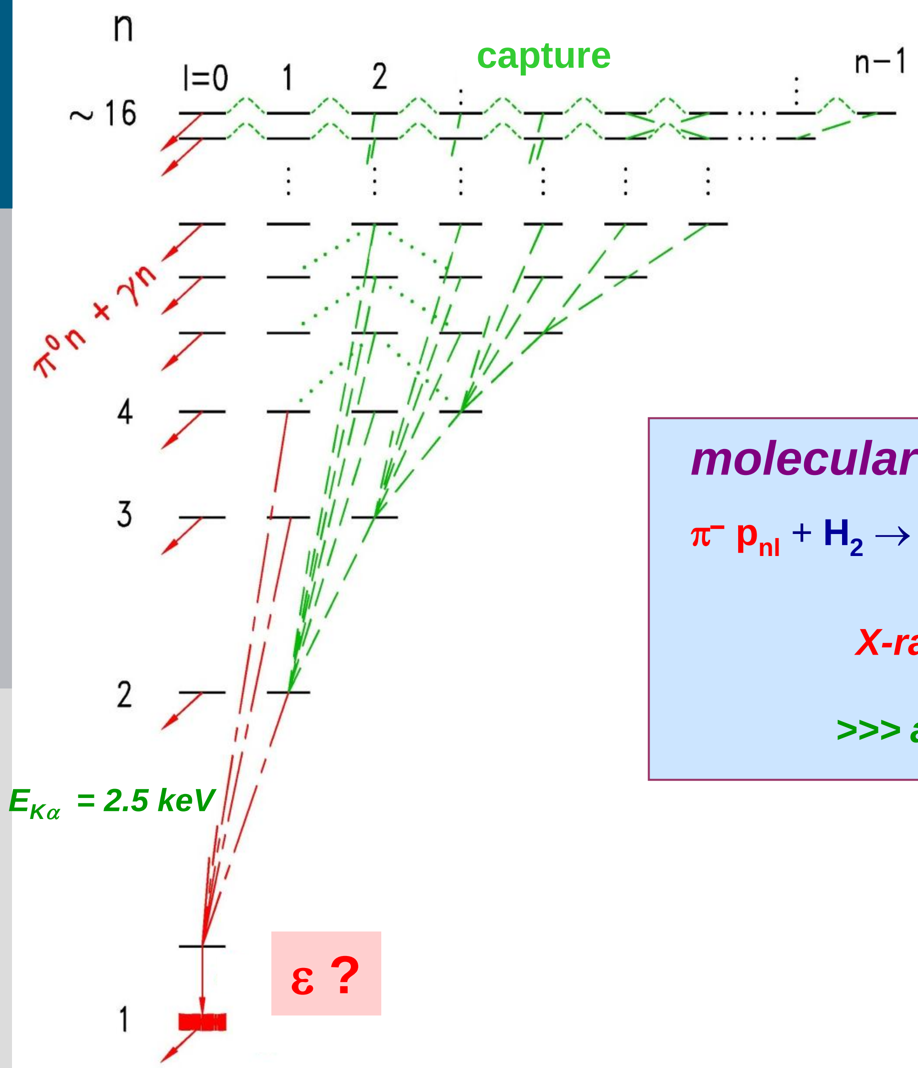
PhD thesis: Th. Strauch, Cologne 2009

Th. Strauch et al.,
Phys. Rev. Lett.104 (2010)142503;
Eur. Phys. J A 47 (2011)88

no (small) high-energy components **?**

unexplained

πH - ATOMIC CASCADE II



density dependent

molecular formation

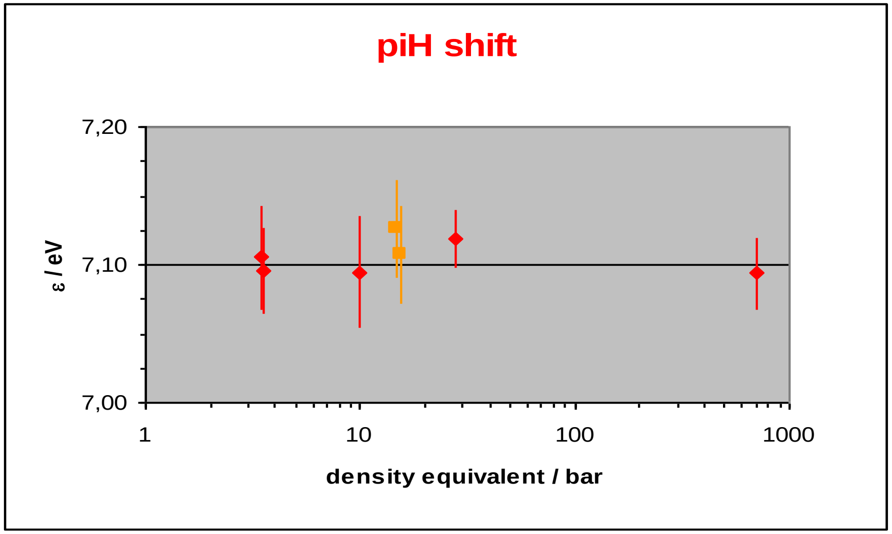
$\pi^- p_{nl} + H_2 \rightarrow [(\pi^- pp)_{nj\nu} \cdot p]\ ee_{k\nu}$ ***decay usually by Auger process***

X-rays from molecular states ?

>>> additional energy shift ? <<<

$\pi H(3p\text{-}1s)$ energy density dependence - result

***no* density dependence identified ⇒ "no" X-ray transitions from molecular states**



previous experiment – Ar Kα

ETHZ-PSI H.-Ch.Schröder et al. Eur.Phys.J.C 1(2001)473

R-98.01

$\varepsilon_{1s} = +\,7.120 \pm 0.008 \pm 0.009$ eV

PhD thesis: Maik Hennebach, Cologne 2003

↓

mainly pion mass $\Delta E_{QED} = \pm\, 0.006$ eV !

new calculation πH ⇒ $\Delta E_{QED} = \pm\, 0.001$ eV !

P. Indelicato, priv. comm.

there is new QED value available since 2011!

not yet used here

S. Schlesser et al. Phys. Rev. C 84 (2011) 015211

$\varepsilon_{1s} = +\,7.120 \pm 0.008 \pm 0.006$ eV ($\pm$ 0.2%) *preliminary*

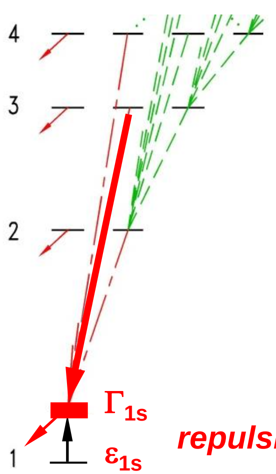
↑

will change by a few per mille

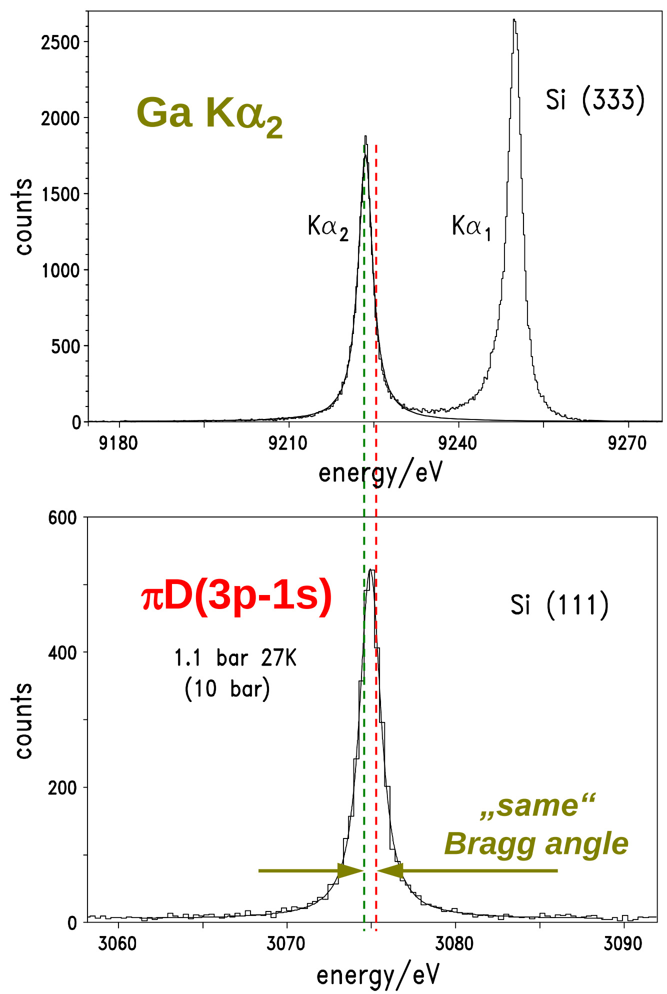
PIONIC DEUTERIUM

energy calibration

strong interaction



repulsive



PhD thesis: Th. Strauch, Cologne 2009
Th. Strauch et al., Phys.Rev.Lett.104 (2010)142503; Eur. Phys.J A 47 (2011)88

target material: GaAs

by chance: tabulated energy
also from GaAs
⇒ no chemical shift

3 bar
10 bar
22 bar
} *no molecule formation seen*

$$\varepsilon_{1s} = -2.356 \pm 0.031 \quad (\pm 1.3\%)$$

uncertainties

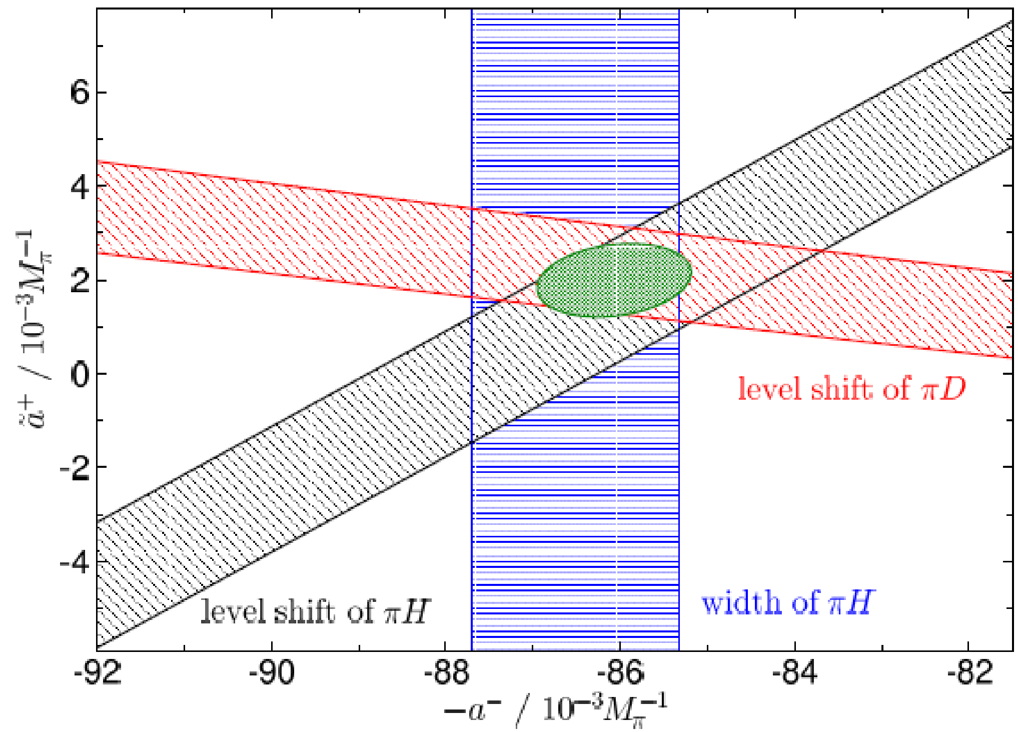
±	27 meV	Ga Kα_2
±	10 meV	statistics
±	8 meV	pion mass
±	5 meV	systematics
±	2 meV	QED

SUMMARY OF RESULTS

- ***PION-NUCLEON SCATTERING LENGTHS***
- ***PION PRODUCTION AND ABSORPTION***

πN scattering lengths a^+ and a^-

Δ exp ≈ 2 × Δ theory - no f_1



Δ exp <<Δ theory - LEC f_1

Δ exp << Δ theory - LEC f_1

experimental input

πH	ε_{1s}, Γ_{1s}
πD	ε_{1s}

FIG. 2: Combined constraints in the $\tilde{a}^+$–a^- plane from data on the width and energy shift of πH, as well as the πD energy shift.

χPT: V. Baru, C. Hanhart, M. Hoferichter, B. Kubis, A. Nogga, and D. R. Phillips, Phys.Lett.B 694(2011)473
data: R-98.01 (preliminary) and R-06.03 (final)

NN ⇔ πNN threshold parameter α

exotic-atom results

χPT

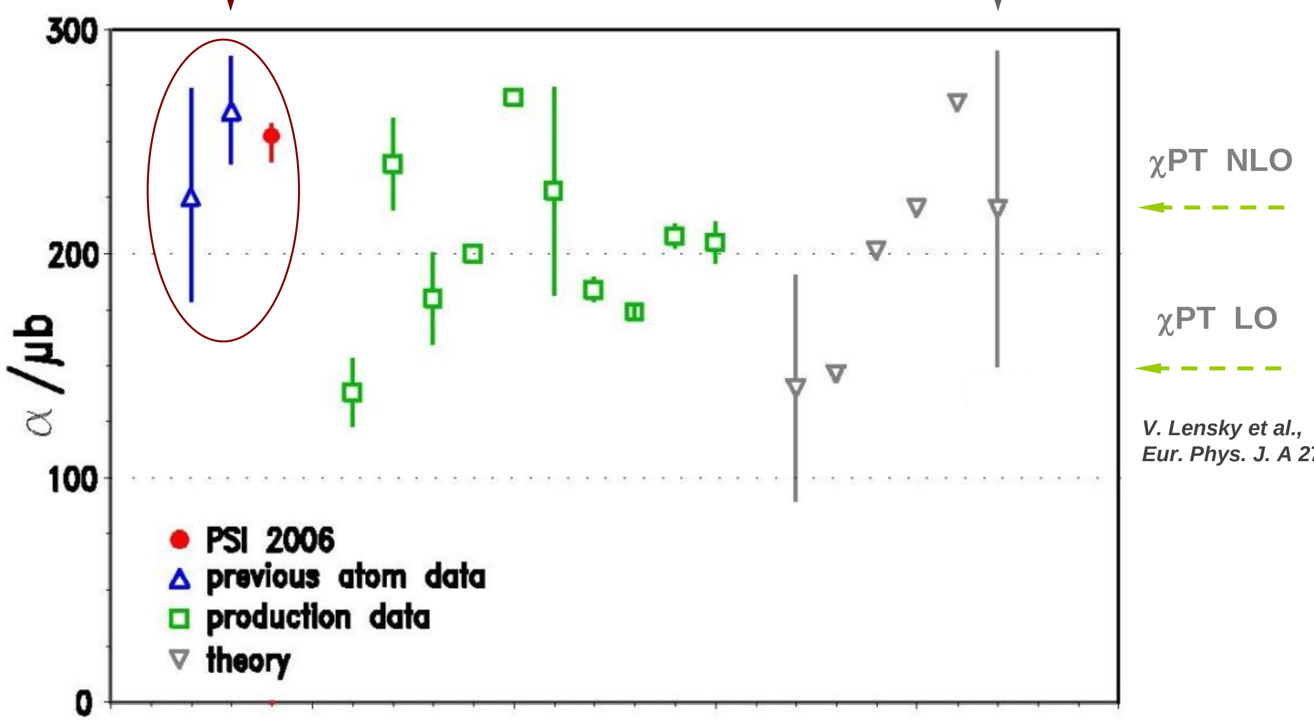
at present *expected*

$\Delta\alpha/\alpha \approx 30\% \rightarrow$ few %

D. Chatellard et al.
Phys. Rev. Lett. 74 (1995) 4157;
Nucl. Phys. A 625 (1997) 855

P. Hauser et al.
Phys. Rev. C 58 (1998) R1869

Th. Strauch et al.,
Phys.Rev.Lett.104 (2010) 142503;
Eur. Phys.J A 47 (2011) 88



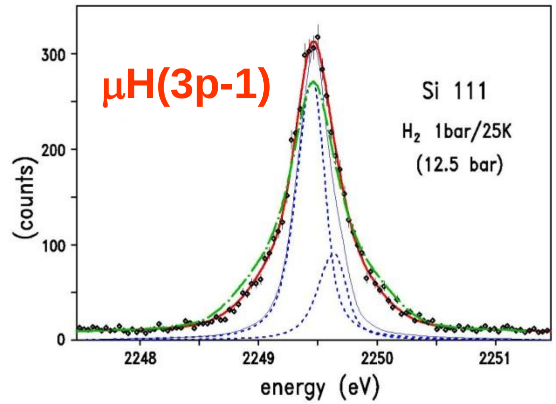
chronological order each

V. Lensky et al.,
Eur. Phys. J. A 27 (2006) 37

OPEN QUESTIONS

CASCADE or IS SOMETHING MISSING ?

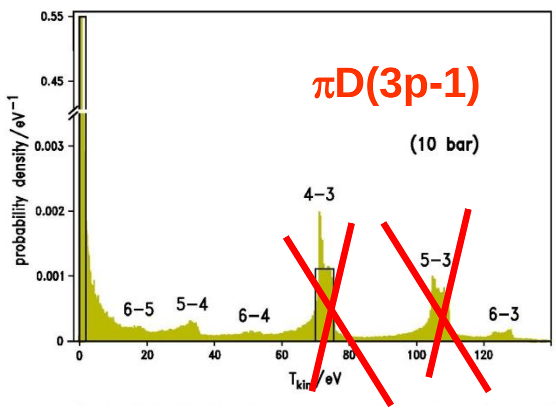
? *X-ray satellites from molecular formation*



0-2 eV	*61 ± 2 %*
5-4	*25 ± 3 %*
4-3	*14 ± 4 %*

μD

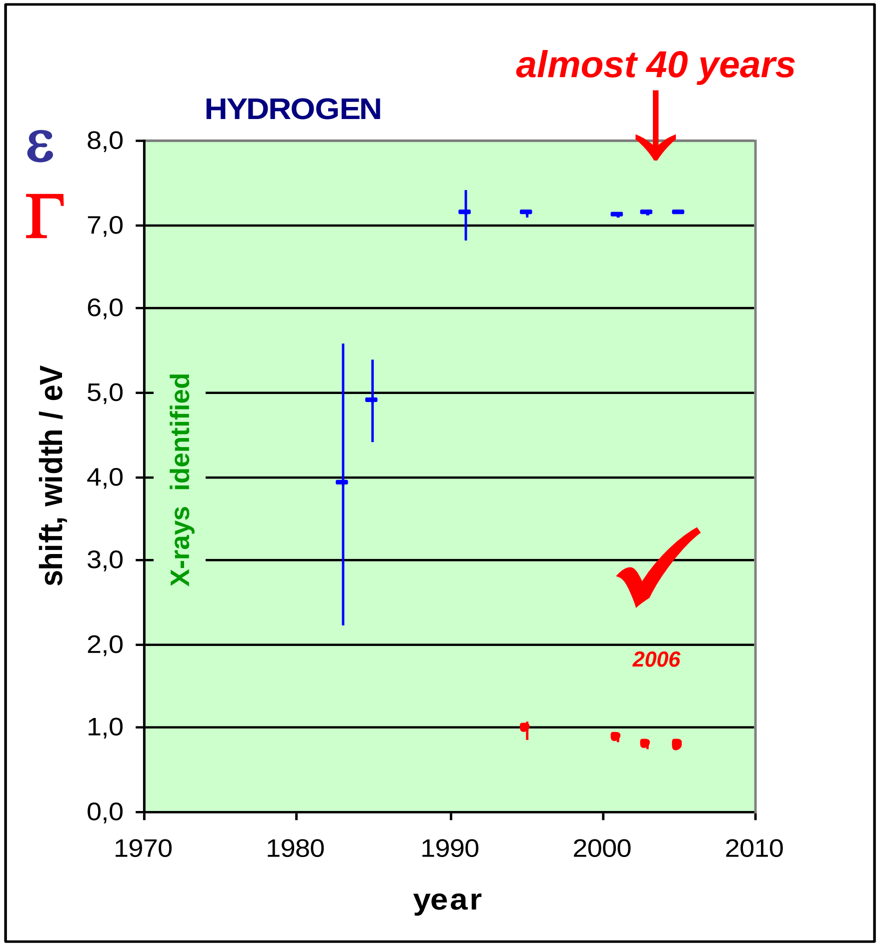
? *high-energy components*

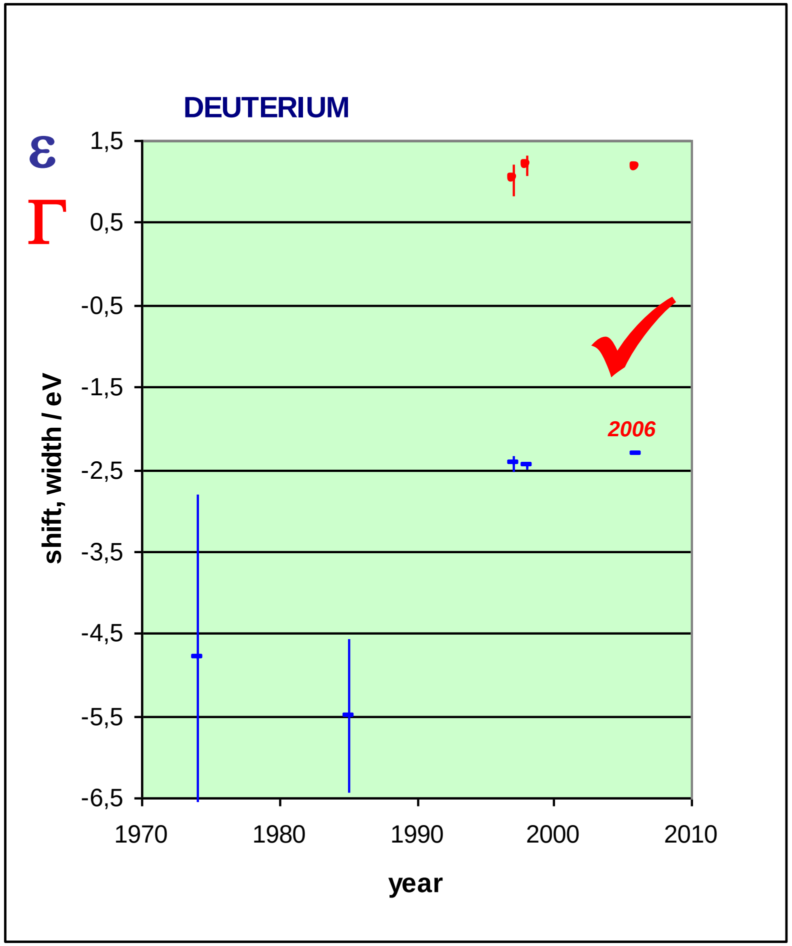


? *does cascade theory improve for πH as for μH - if yes: ΔΓ → ΔΓ /2*

cross sections

PIONIC HYDROGEN STORY





THANK YOU

PIONIC HYDROGEN collaboration

PSI experiments R-98.01 and R-06.03

Debrecen , Inst. of Nucl. Research

S. Biri

Coimbra, Dept. of Physics

F. D. Amaro, D. S. Covita, J. M. F. dos Santos, J. F. C. A. Veloso,

Ioannina, Dept. of Material Science

D. F. Anagnostopoulos

Forschungszentrum Jülich, IKP, JCHP, ZEL

A. Blechmann, H. Gorke, D.Gotta, M. Hennebach, M. Nekipelov, Th. Strauch

Paris, Lab. Kastler-Brossel UPMC ENS CNRS

E.-O. Le Bigot, P. Indelicato, S. Schlesser, M. Trassinelli

PSI, Lab. for Part. Physics

A. Schmelzbach, L. M. Simons

Vienna, SMI

P. Bühler, H. Fuhrmann, A. Gruber, A. Hirtl, T. Ishiwatari, J. Marton, Ph. Schmid, J. Zmeskal

Cascade theory

V. E. Markushin (PSI), Th. Jensen (ETHZ,PSI,LKB,FZJ,SMI), V. Pomerantsev, V. Popov (MSU)

→ ***Diploma and PhD thesis*** ←