Experimental status and prospects of light pionic atoms

Detlev Gotta

Institut für Kernphysik & JCHP, Forschungszentrum Jülich

for the PIONIC HYDROGEN COLLABORATION

HC2NP 2016

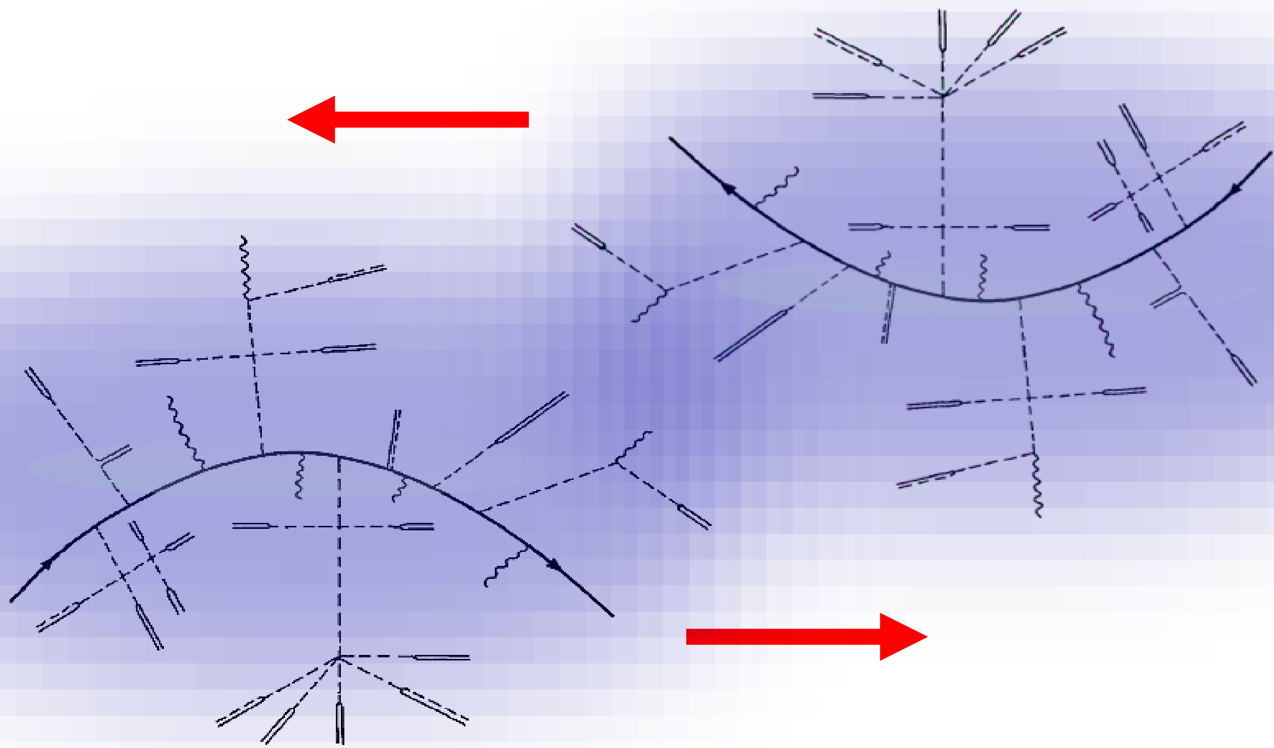
Puerto de la Cruz, September 26, 2016

- **WHY PIONIC HYDROGEN & … ?**
- **EXPERIMENTAL APPROACH**
- **ANALYSIS**
- **RESULTS**
- **CONCLUSIONS**

PIONS, NUCLEONS - INTERACTION in terms of QCD

N ⇔ N

πN ⇔ πN



J. Gasser et al., Nucleons with chiral loops, Nucl. Phys. B307, 779 (1988)

Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. ——▸—— nucleon; - - - pions; ~~~ vector current; ═══ axial vector current; --⊏ pseudoscalar density; ═══ scalar density.

CHIRAL PERTURBATION THEORY (χPT), …

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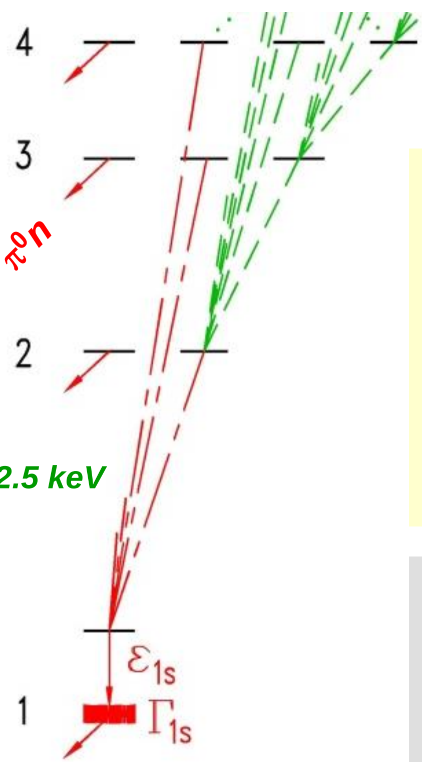
Strong - interaction effects in *X-ray transitions*

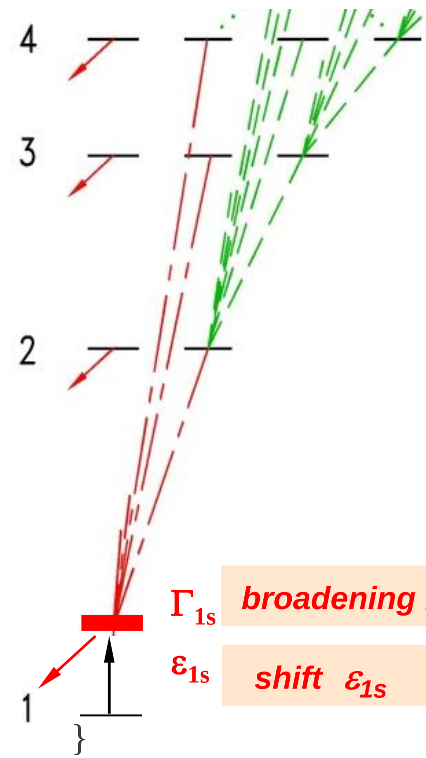
πH



strong interaction

<u>attractive</u>

πD



broadening Γ_{1s}

shift ε_{1s}

strong interaction

<u>repulsive</u>

πH: $\varepsilon_{1s} \propto a_{\pi^- p \to \pi^- p} + \ldots$

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

πD: $\varepsilon_{1s} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + \cdots$

πD: $\Gamma_{1s} \propto g_1(\pi^- d \to nn)$

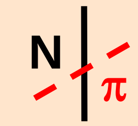
$$\propto \alpha(pp \to \pi^+ d)$$

detailed balance & charge symmetry

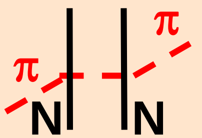
ε, Γ = few eV

πH & πD - *origin of* ε_{1s}

πH ***elastic scattering*** $\pi^- p \rightarrow \pi^- p$ …



πD ***coherent sum*** $\pi^- p \rightarrow \pi^- p + \pi^- n$ …

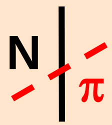


πH & πD - *origin of* Γ_{1s}

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

CEX = charge exchange

CEX scattering

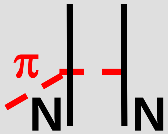


radiative capture

BR well known from experiment

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

„true“ absorption



general review experiment: D. Gotta, Prog. Part. Nucl. Phys. Rep. 52, 133 (2004)

PION-NUCLEON SCATTERING LENGTHS

$\pi \otimes N$ isospin $1 \otimes 1/2 = 1/2 \oplus 3/2$

$$a^{\pm} \equiv \frac{1}{2}\left(a_{\pi^- p} \pm a_{\pi^+ p}\right)$$

$$a_{\pi^- p} = \frac{1}{3}\left(2a_{1/2} + a_{3/2}\right) = a^+ + a^-$$

$$a_{\pi^- p \to \pi^0 n} = -\frac{\sqrt{2}}{3}\left(a_{1/2} - a_{3/2}\right) = -\sqrt{2}\, a^-$$

$$a_{\pi^+ p} = a_{\pi^- n} = a_{3/2} = a^+ - a^-$$

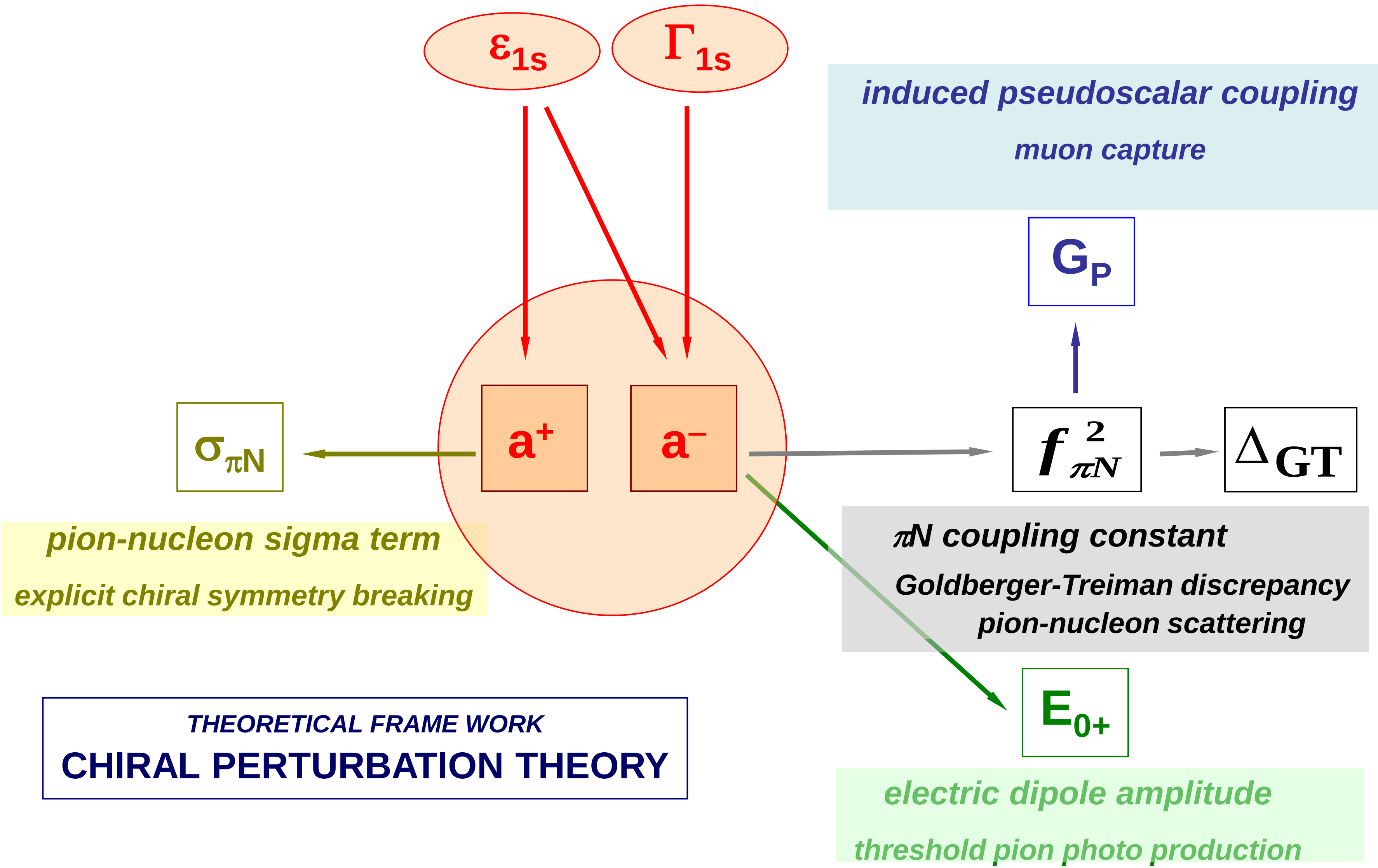
χPT

$$a^+ \to a^+ + \Delta a^+$$

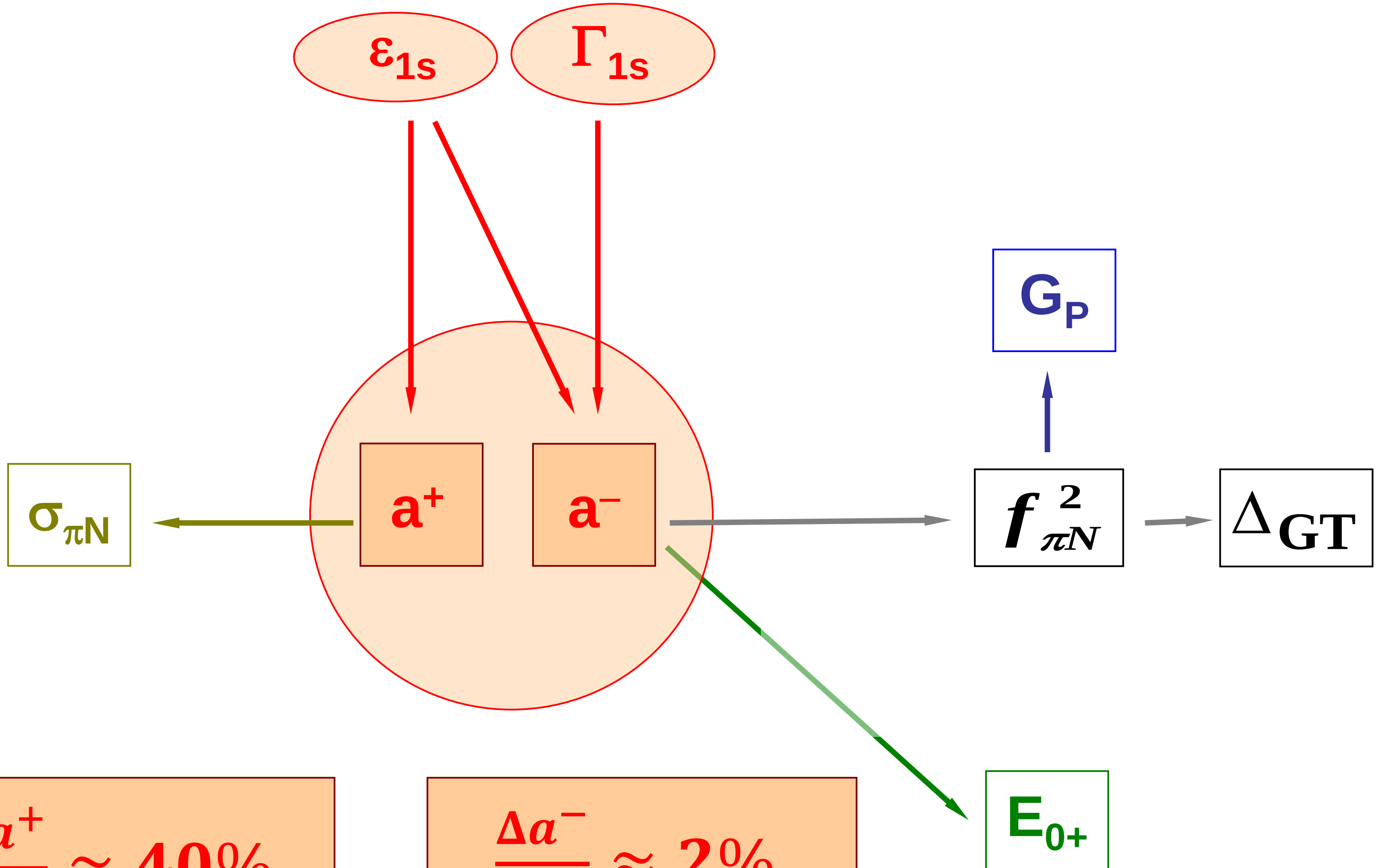
$$a^- \to a^- + \Delta a^-$$

review theory: J. Gasser, V.E. Lyubovitskij, A. Rusetsky, Phys. Rep. 456, 167 (2008)

PION-NUCLEON SCATTERING LENGTHS *related quantities*



PION-NUCLEON SCATTERING LENGTHS *present accuracy*



$$\frac{\Delta a^{+}}{a^{+}} \approx 40\%$$

$$\frac{\Delta a^{-}}{a^{-}} \approx 2\%$$

WHICH SCATTERING LENGTH ?

$$\epsilon_{1s} = -2\alpha^3 \mu_c^2 \mathcal{A}(1 - 2\alpha\mu_c(\ln\alpha - 1)\mathcal{A}) + \cdots$$

analogue Trueman expansion, 1961

analogue for Γ_{1s}

$$\mathcal{A} = a_{0+}^{+} + a_{0+}^{-} + \epsilon$$

purely hadronic $\pi^- p$ scattering length

$$= \frac{1}{8\pi(m_p + M_{\pi^+})F_\pi^2} \times \left\{ m_p M_{\pi^+} - \frac{g_A^2 m_p M_{\pi^+}^2}{m_n + m_p + M_{\pi^+}} + m_p\left(-8c_1 M_{\pi^0}^2 + 4(c_2 + c_3)M_{\pi^+}^2 - 4e^2 f_1 - e^2 f_2\right)\right\} + O(\delta^3) \ldots$$

LECs f_1, f_2, c_1 contribute to isospin breaking in $O(\delta^2)$

review: J. Gasser, V.E. Lyubovitskij, A. Rusetsky, Phys. Rep. 456 (2008) 167

RELATIONS *simplified*

scattering lengths

LO: current algebra

Weinberg,Tomozawa:

chiral limit $m_{quark} \to 0$

$$\left.\begin{aligned} a^+ &= 0 \\ a^- &= -0.079/m_\pi \\ f_{\pi N}^2 &= \frac{m_\pi^2}{4}\frac{g_A^2}{F_\pi^2} = 0.072 \end{aligned}\right\} + \text{higher orders } \chi PT$$

Goldberger-Treiman relation

πN coupling constant $f_{\pi N}^2$

Sigma term

explicit chiral symmetry breaking

$$\sigma_{\pi N} = \frac{m_u + m_d}{4M}\langle p|\bar{u}u + \bar{d}d|p\rangle \leftrightarrow \langle p|\bar{s}s|p\rangle \text{ contents}$$

πN sigma-term σ_N

$$(1+\frac{m_\pi}{M})a^+ = \frac{m_\pi^2}{4\pi f_\pi^2}\cdot\left(\frac{\sigma_{\pi N}}{m_\pi^2} + d - \frac{g_A^2}{4M_N}\right)$$

πN coupling constant $f_{\pi N}$

$$(1+\frac{m_\pi}{M})\frac{a^-}{m_\pi} = \frac{2f_{\pi N}^2}{m_\pi^2 - (m_\pi^2/2M)^2} + \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma_{\pi^- p}^{tot}(k_\pi) - \sigma_{\pi^+ p}^{tot}(k_\pi)}{2\omega(k_\pi)}dk_\pi$$

Goldberger- Miyazawa-Oehme
(GMO)
sum rule

$\Delta f_{\pi N} \approx 1\%$

$\sigma_{\pi N}$ ⇔ WIMP – nucleon scattering

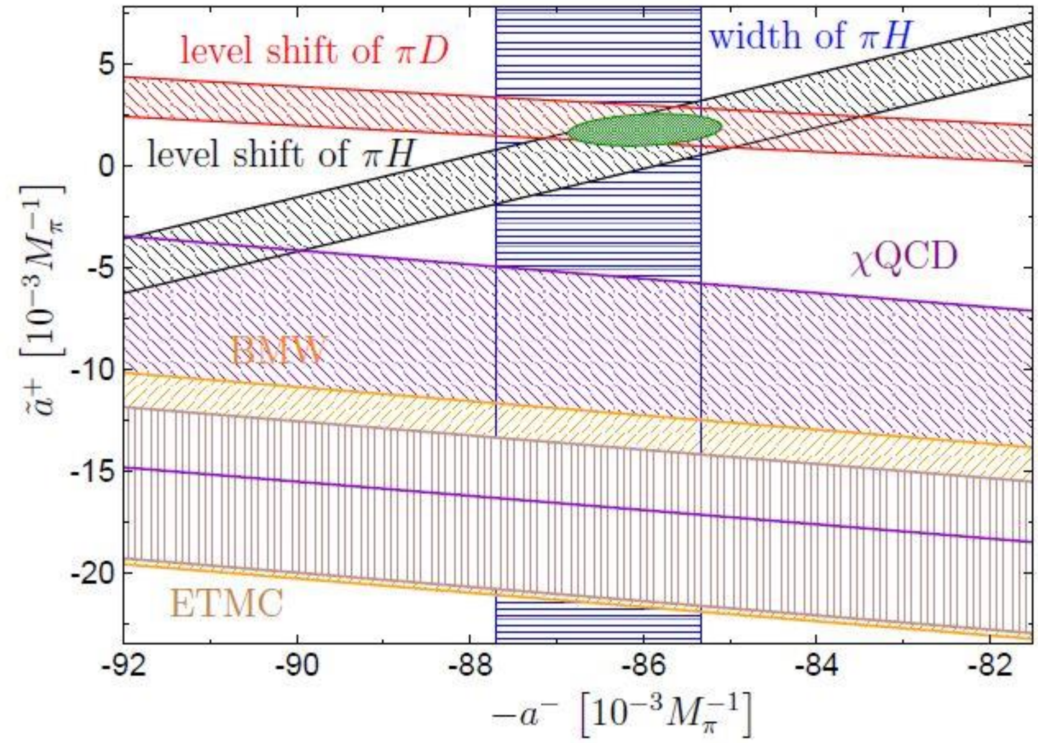
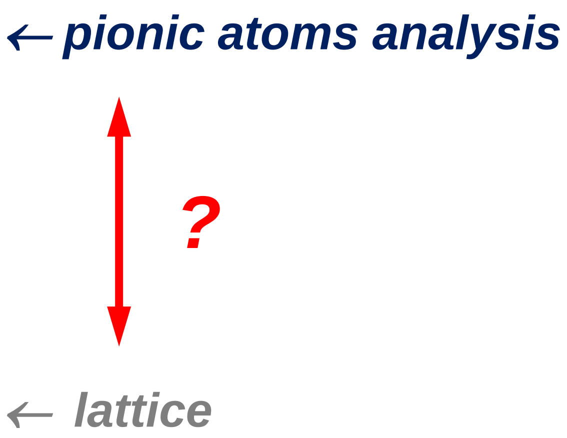


Figure 1: Constraints on the πN scattering lengths from pionic atoms (black: level shift in πH, blue: width of πH ground state, red: level shift in πD) and from lattice σ-terms (orange: BMW [20], violet: χQCD [21], brown: ETMC [22]).



Hoferichter et al. , arXiv: 1602.07688v2
Crivellin et al., Phys. Rev. D 89, 054021 (2014)
Ellis et al., Phys. Rev D,065026 (2008)
…

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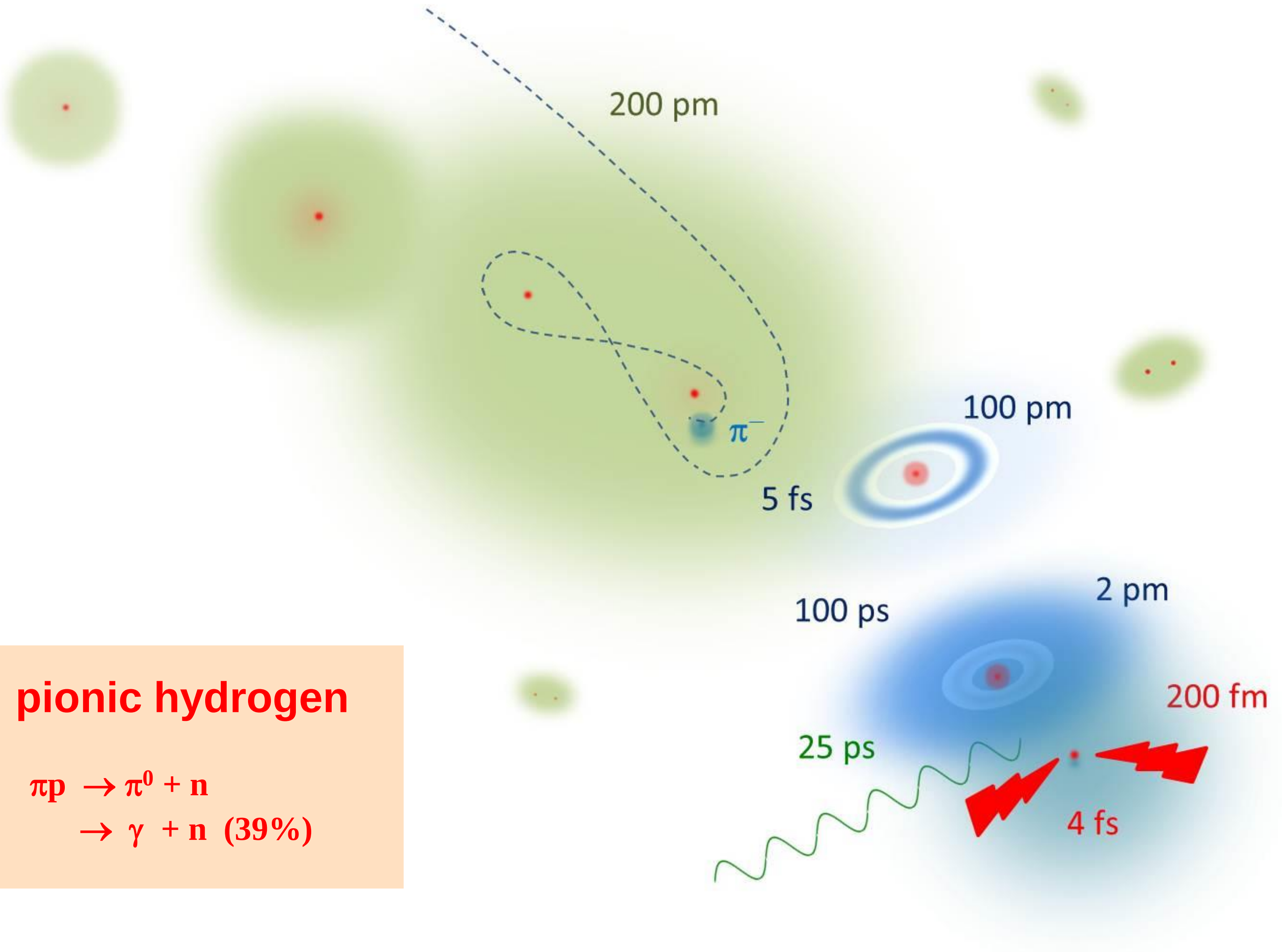
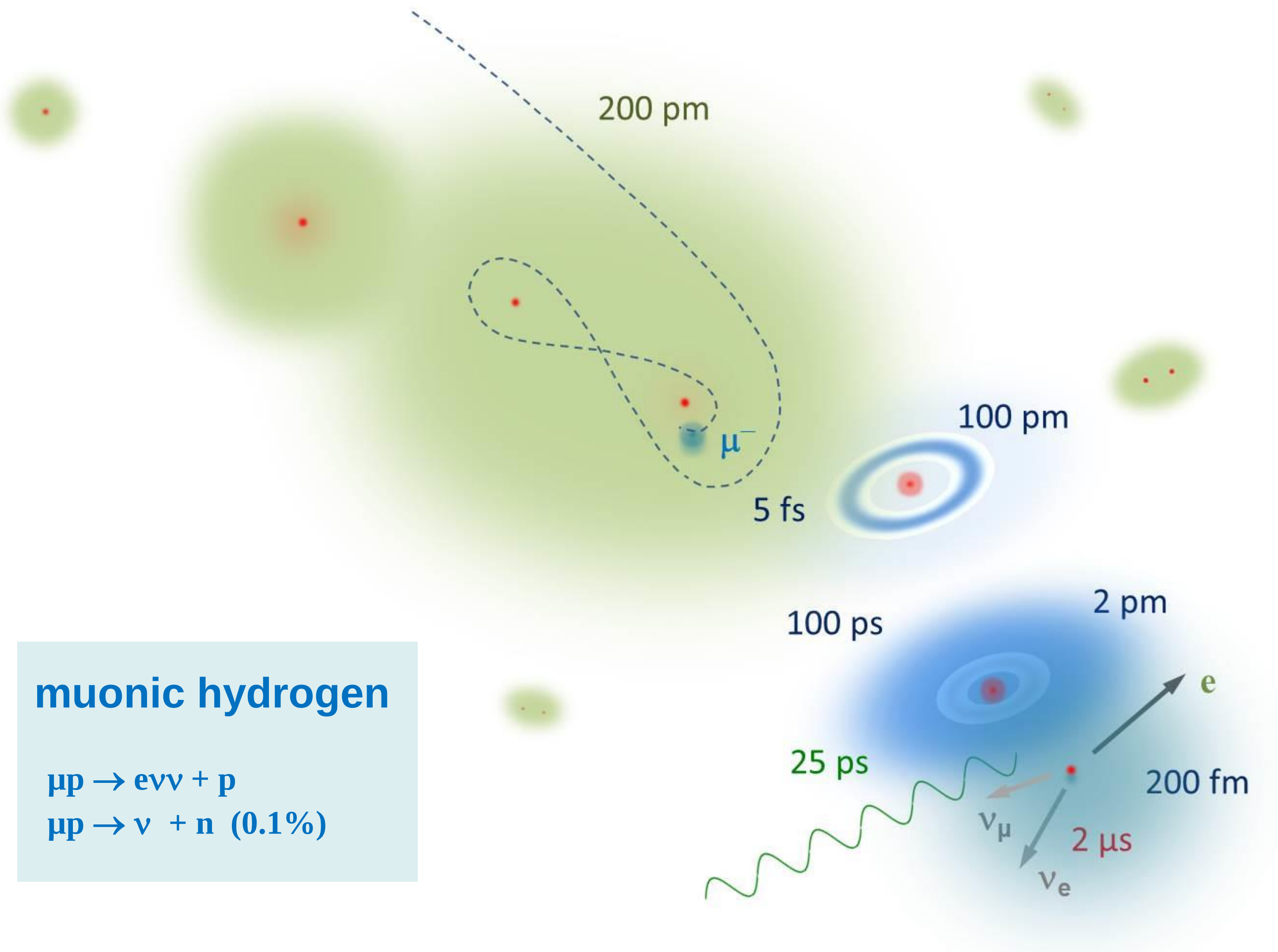


pionic hydrogen

$\pi p \rightarrow \pi^0 + n$

$\rightarrow \gamma + n$ (39%)



muonic hydrogen

$\mu p \rightarrow e\nu\nu + p$

$\mu p \rightarrow \nu \ + n \ \ (0.1\%)$

DE-EXCITATION CASCADE and COLLISIONAL EFFECTS

target density > 0

πH or μH are NOT ISOLATED SYSTEMS !

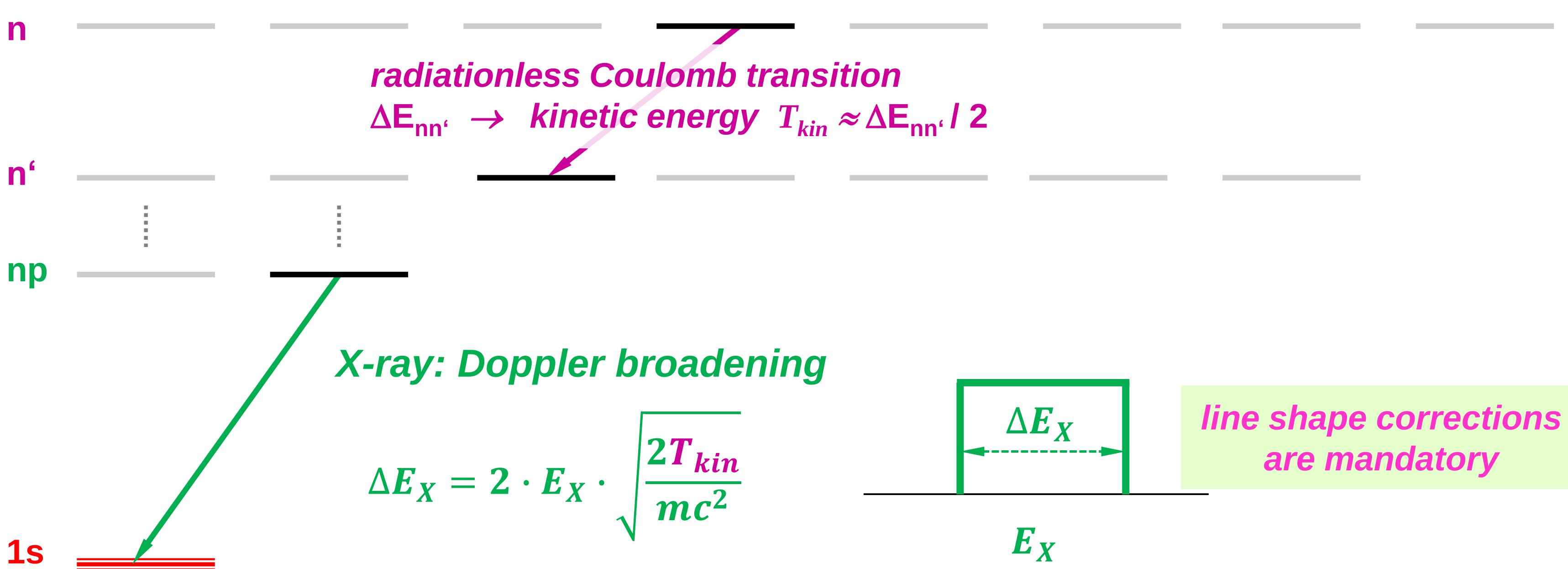
density dependent effects on line energy and/or width ?

COULOMB DE-EXCITATION

first observed from NEUTRON - TOF

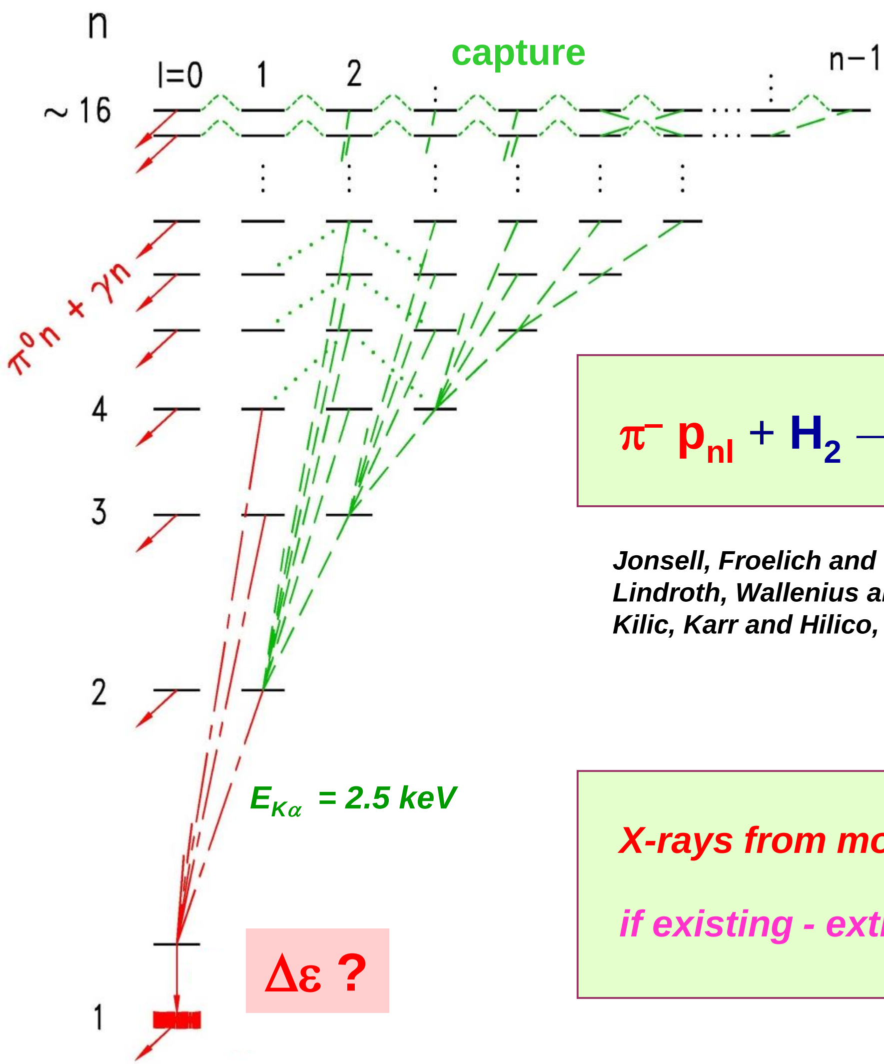
J.B. Czirr et al., Phys. Rev. 130, 341 (1963)
A. Badertscher et al., Eur. Phys. Lett. 54 (2001) 313 (status)

$$(\pi^- p)_{nl} + H{=}H \rightarrow (\pi^- p)_{n'l'} + H + H + \textit{kinetic energy}$$



$$\Delta E_X = 2 \cdot E_X \cdot \sqrt{\frac{2T_{kin}}{mc^2}}$$

MOLECULAR FORMATION



- *known to exist from muon-catalysed fusion*
- *μH experiment quenching of μp_{2s} via [(μpp)p]ee formation*

  R. Pohl et al., Phys. Rev. Lett. 97 (2006) 193402

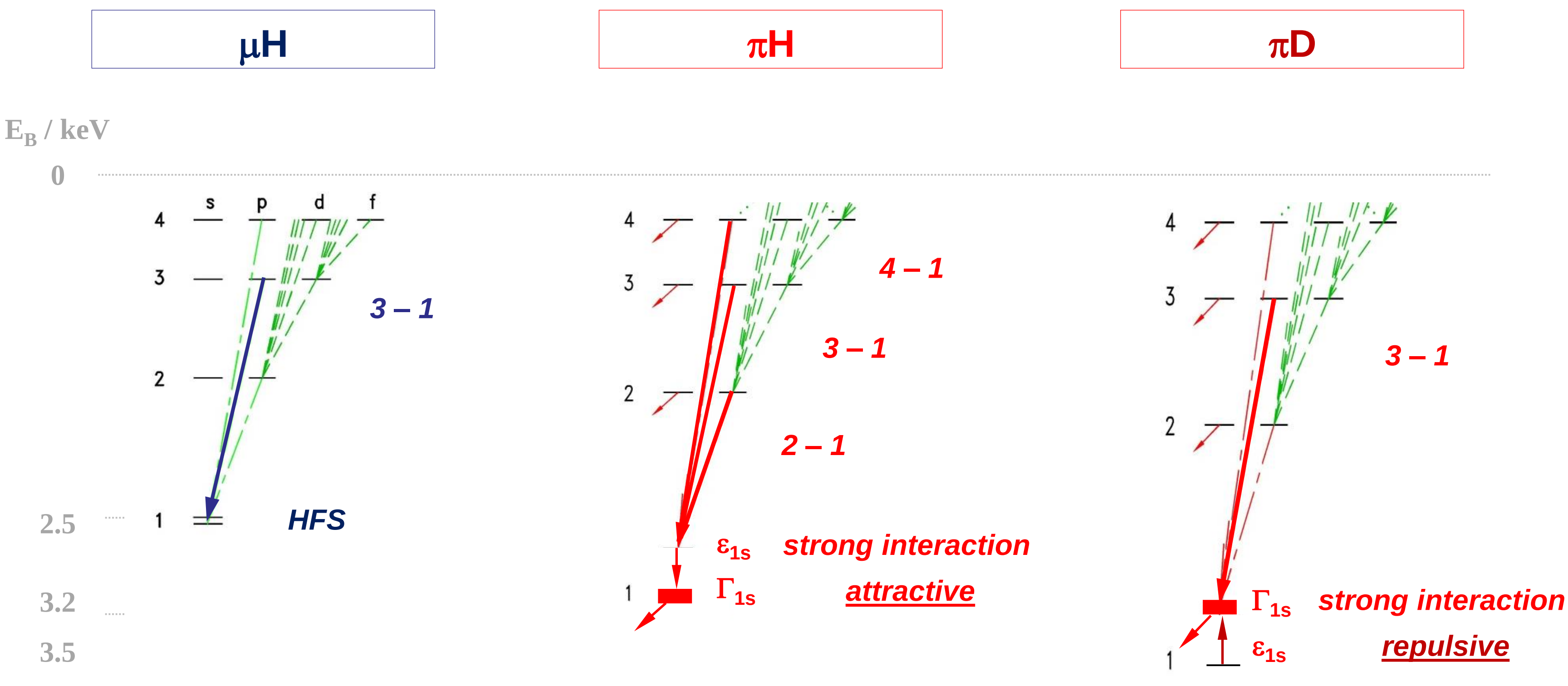
$\pi^- p_{nl} + H_2 \rightarrow [(\pi^- pp)_{nj\nu} \cdot p]\, ee_{\,k\nu}$ *decay usually by Auger process*

Jonsell, Froelich and Wallenius for n = 1,2,3, Phys. Rev A 59 (1999) 3440
Lindroth, Wallenius and Jonsell, Phys. Rev A 68 (2003) 032502
Kilic, Karr and Hilico, Phys. Rev. A70 (2004) 042506

X-rays from molecular states ? ⇒ energy shift of np levels

if existing - extrapolation to density zero necessary!

STRATEGY – VARY TRANSITION + VARY DENSITY



„dangerous" cascade effects

Coulomb de-excitation

molecular formation

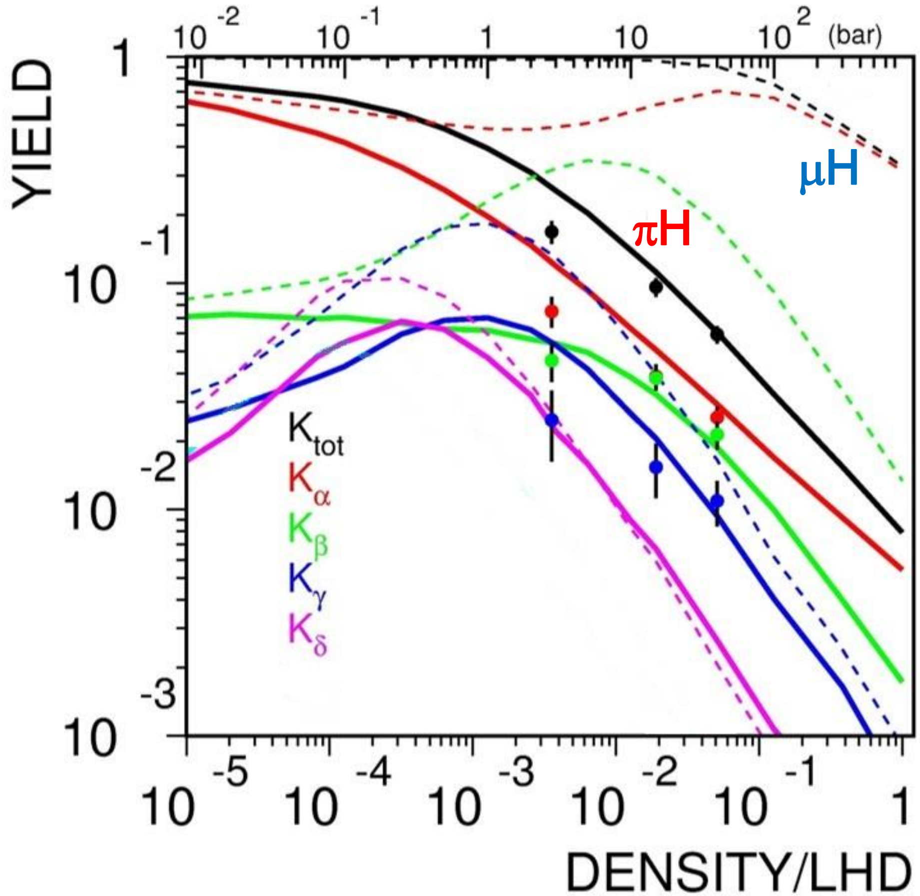
μH	πH	πD
10 bar	*3, 10, 28 bar and LH_2*	*3, 10 and 17 bar*

X-RAY YIELDS

πH

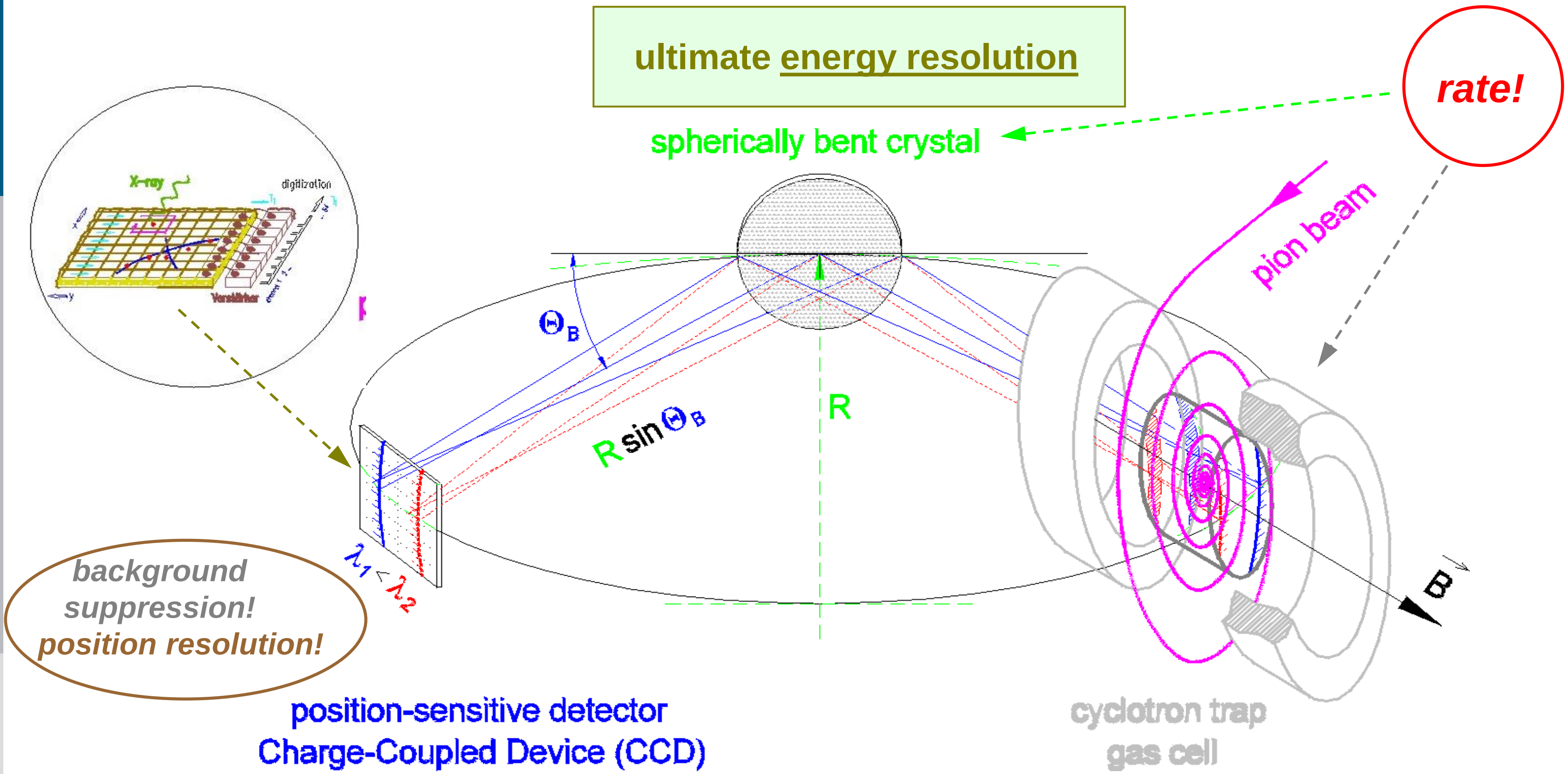
μH

Lyman series



cascade calculation: V. E. Markushin, PSI

Johann-type SET-UP



position & energy resolution

⇒ **background reduction**

by analysis of hit pattern

high stop density

⇒ **high X - ray line yields**

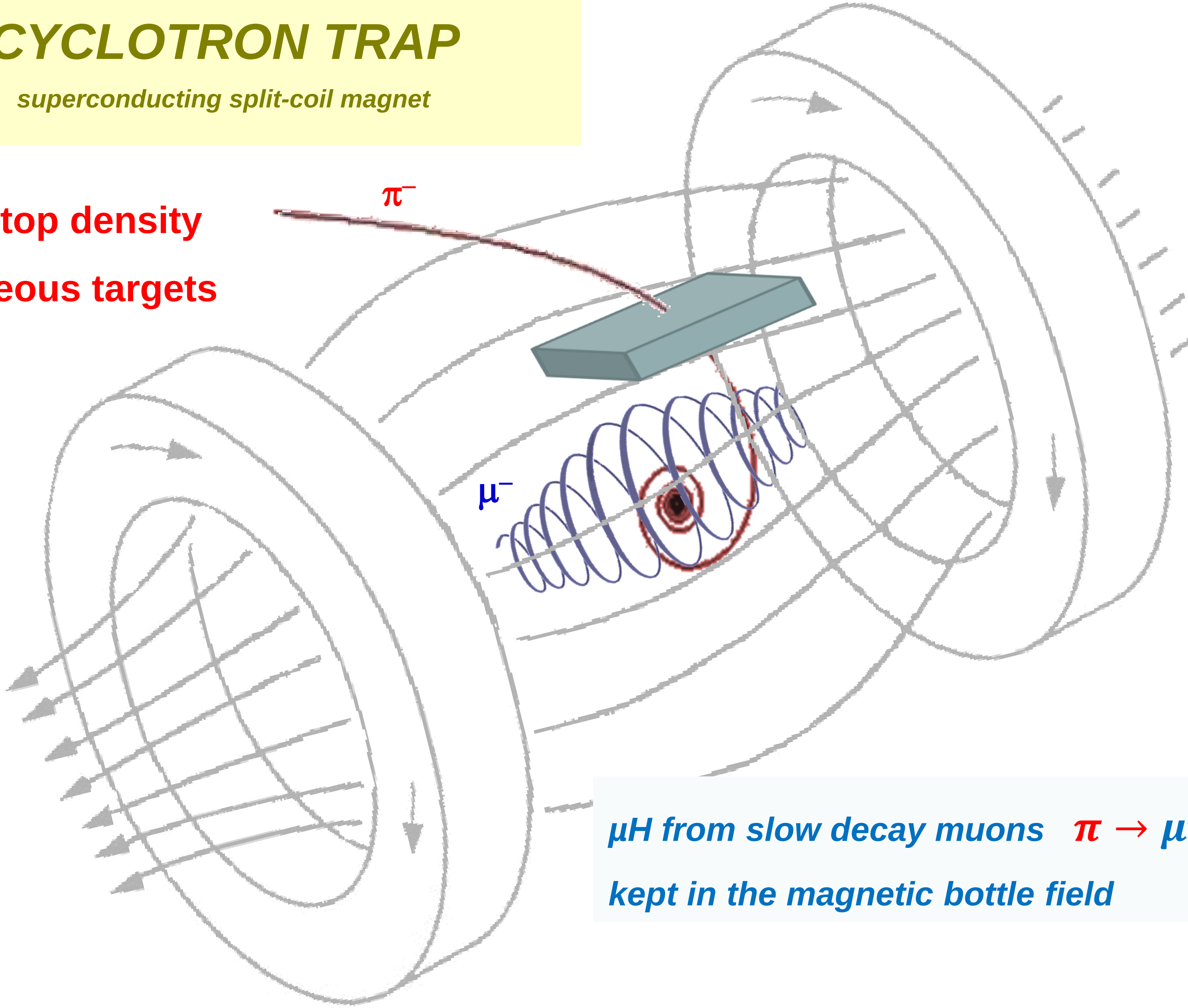
⇒ **bright X - ray source**

CYCLOTRON TRAP

superconducting split-coil magnet

high stop density

in gaseous targets



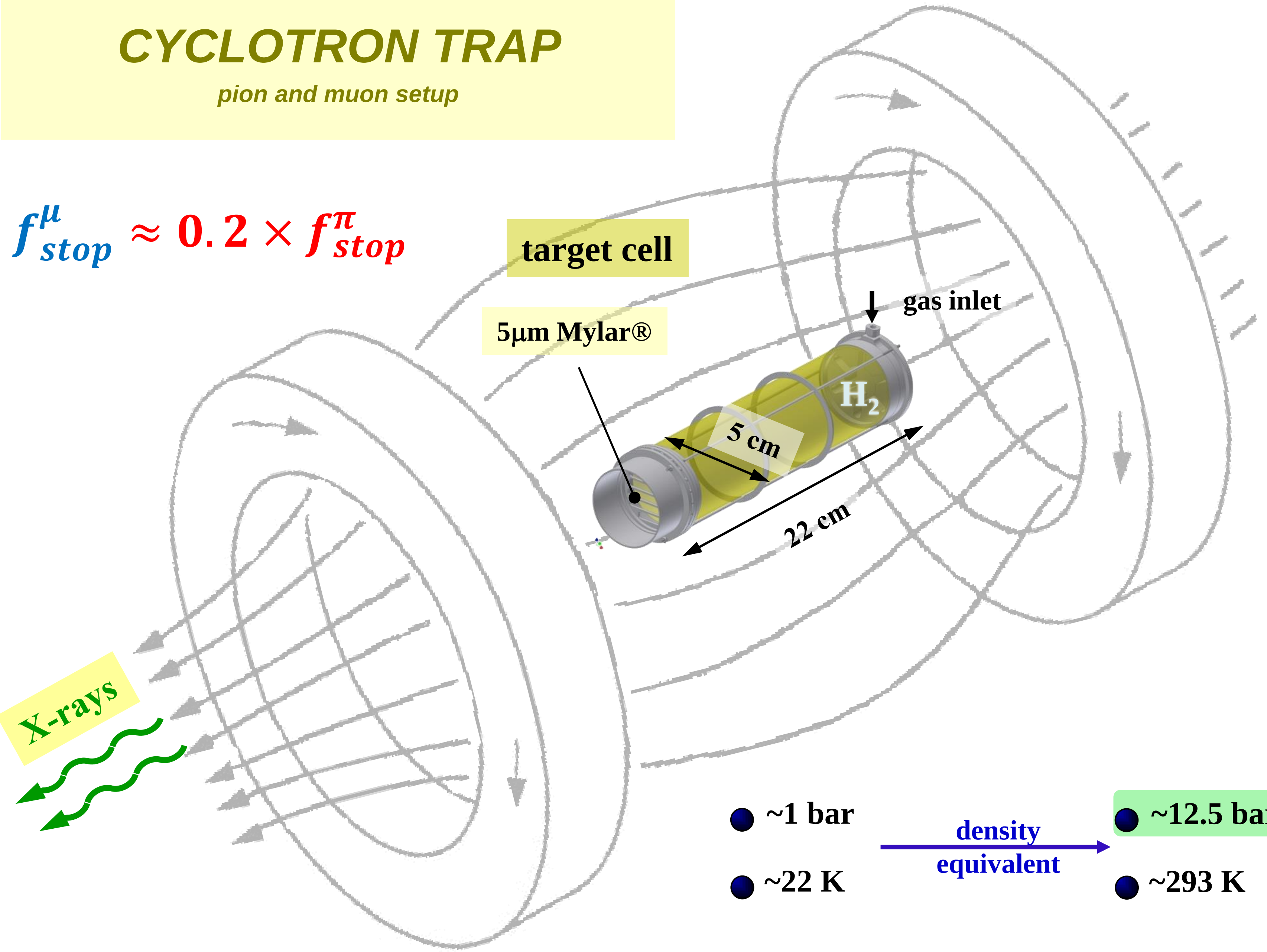
μH from slow decay muons $\pi \to \mu\nu$

kept in the magnetic bottle field

CYCLOTRON TRAP

pion and muon setup

$$f^{\mu}_{stop} \approx 0.2 \times f^{\pi}_{stop}$$



- ~1 bar
- ~22 K

density equivalent →

- ~12.5 bar
- ~293 K

TYPICAL **SET-UP at PSI**

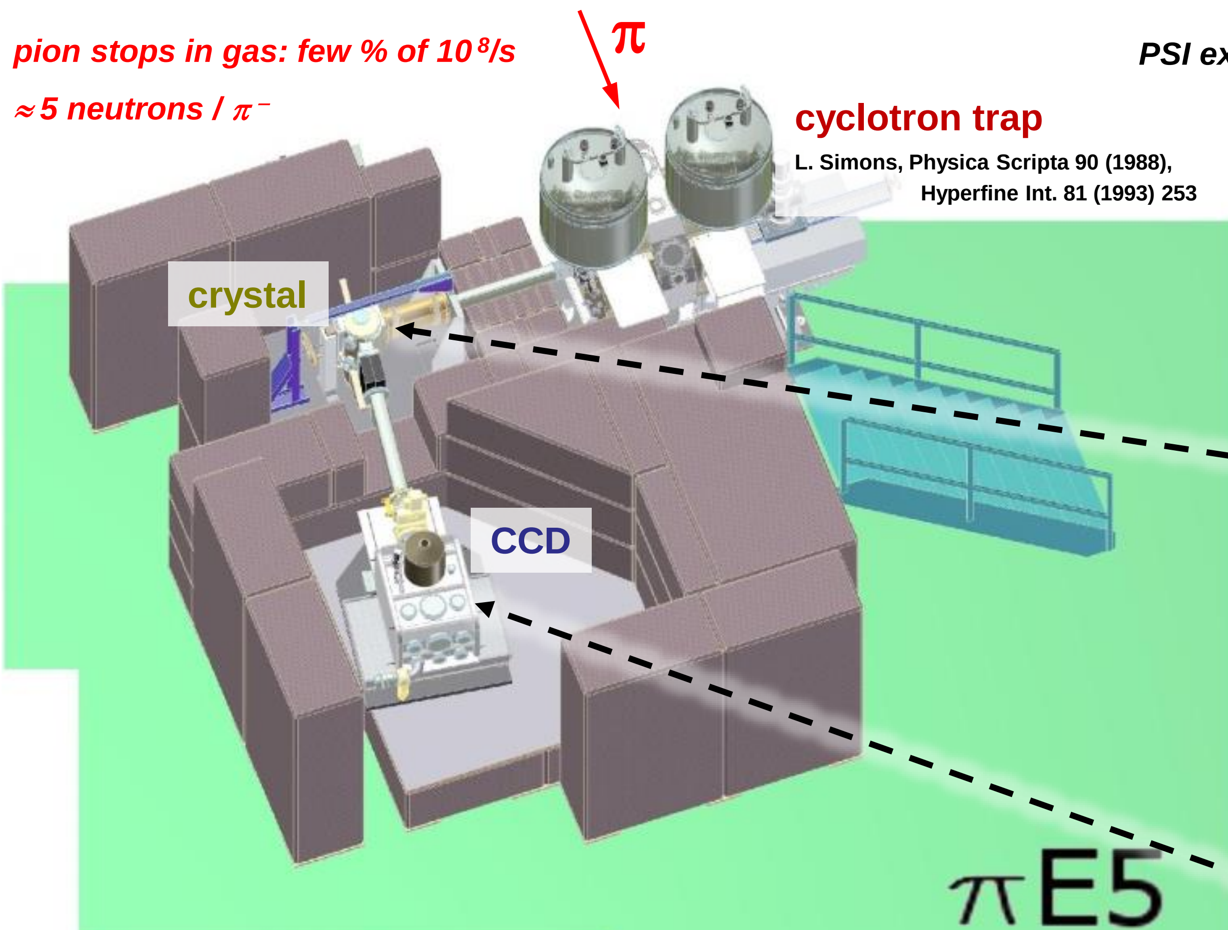
pion stops in gas: few % of 10^8/s

$\approx$ 5 neutrons / π^-

PSI experiments R-98.01 and R-06.03

cyclotron trap

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



crystal spectrometer setup

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

BRAGG CRYSTAL *Si, quartz*

spherically bent

$R = 3$ m
$\Phi = 10$ cm

FOCAL PLANE DETECTOR

3×2 CCD array

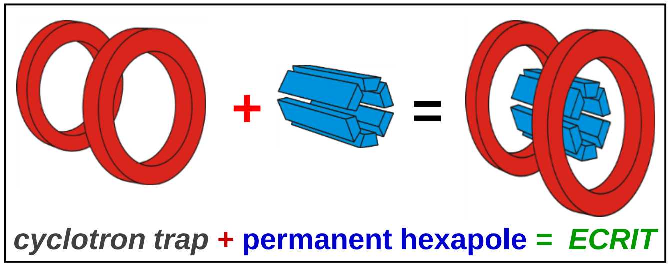
pixel size

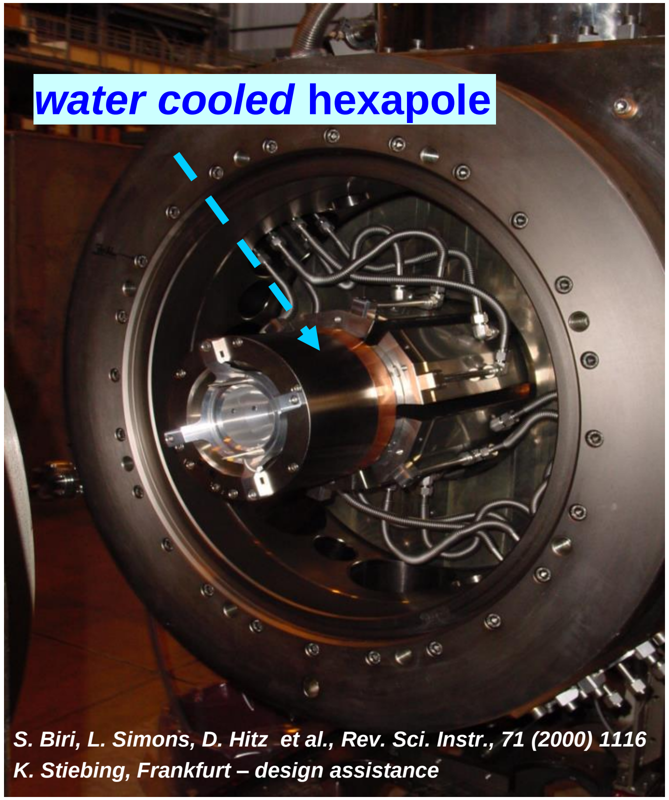
40 µm × 40 µm

N. Nelms et al.Nucl. Instr. Meth.A484 (2002)419

SPECTROMETER RESPONSE

new approach
Electron Cyclotron Resonance Ion Trap



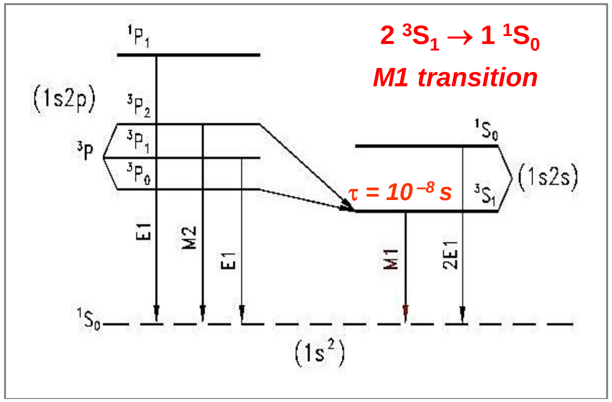


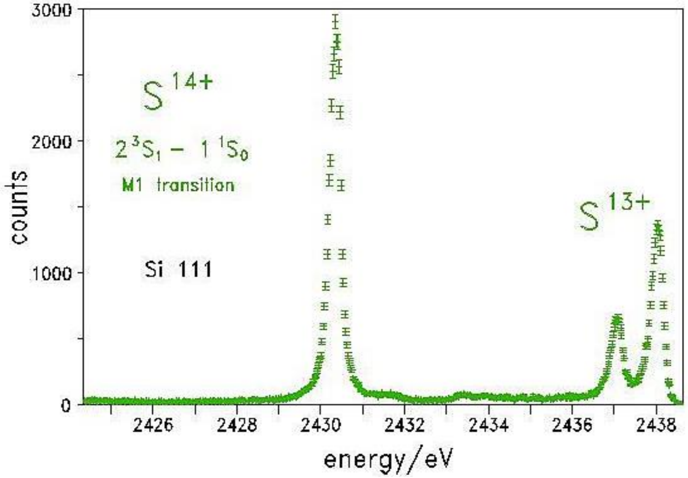
S. Biri, L. Simons, D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116
K. Stiebing, Frankfurt – design assistance

He - like

S ↔ πH(2p-1s)
Cl ↔ πH(3p-1s)
Ar ↔ πH(4p-1s)

30000 events
in M1 line (3 h)





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

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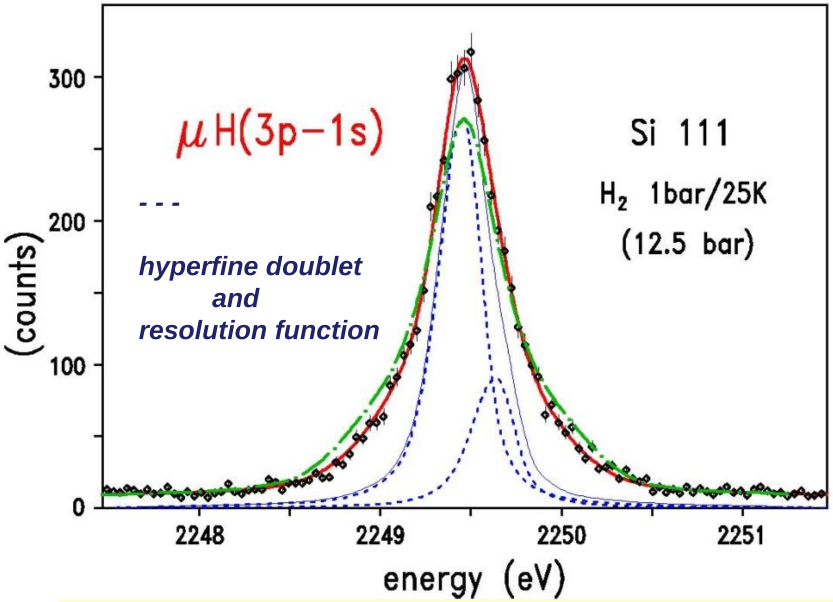
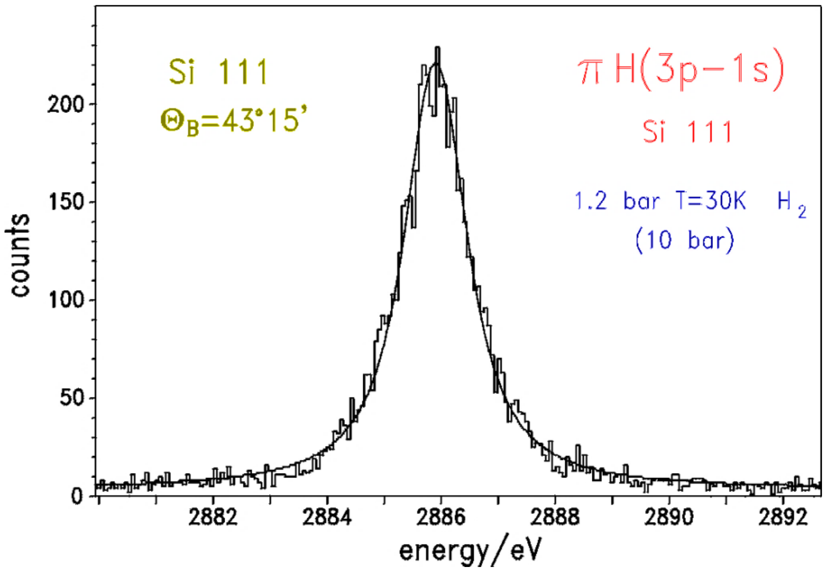
TYPICAL SPECTRA - parameter space





position

intensity

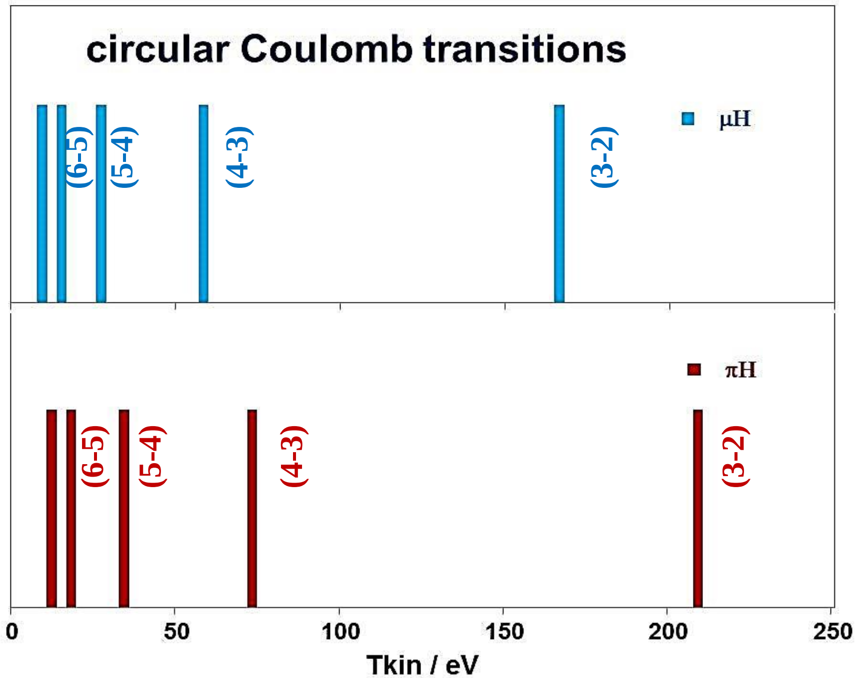
background
(response)

T/S ratio
(HFS)

Γ_{hadronic}

kinetic energy distribution

STRATEGY I - model independent approach



neglected here: possible Δn=2 Coulomb transitions

$\Delta E_{X,max} = 1,5\ eV \quad \mu H(3p-1s)$

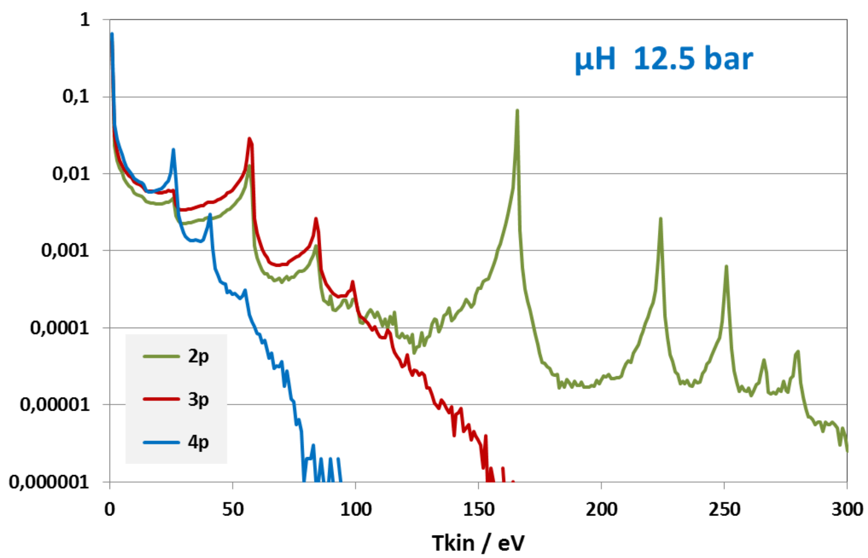
$\Delta E_{X,max} = 3,0\ eV \quad \pi H(2p-1s)$

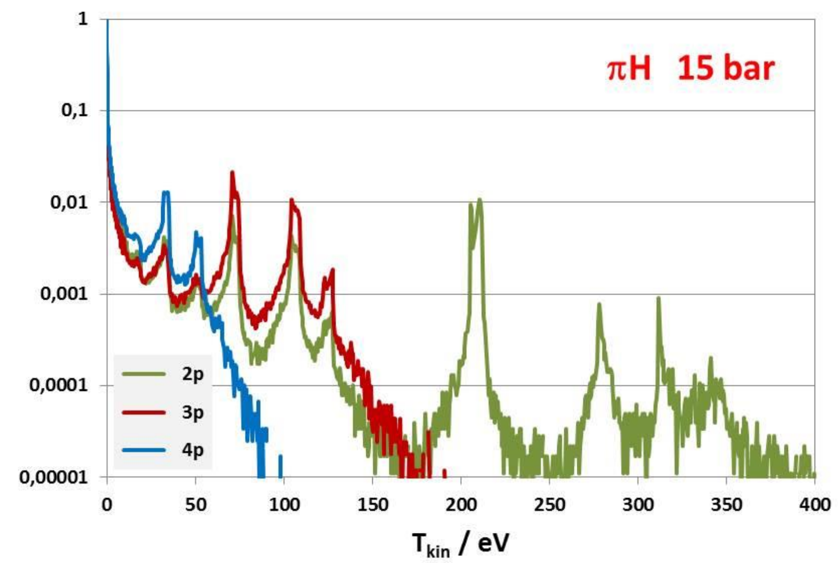
$\Delta E_{X,max} = 2,1\ eV \quad \pi H(3p-1s)$

$\Delta E_{X,max} = 1,5\ eV \quad \pi H(3p-1s)$

STRATEGY II - input from cascade theory

ESCM (extended standard cascade model) model follows development of kinetic energy

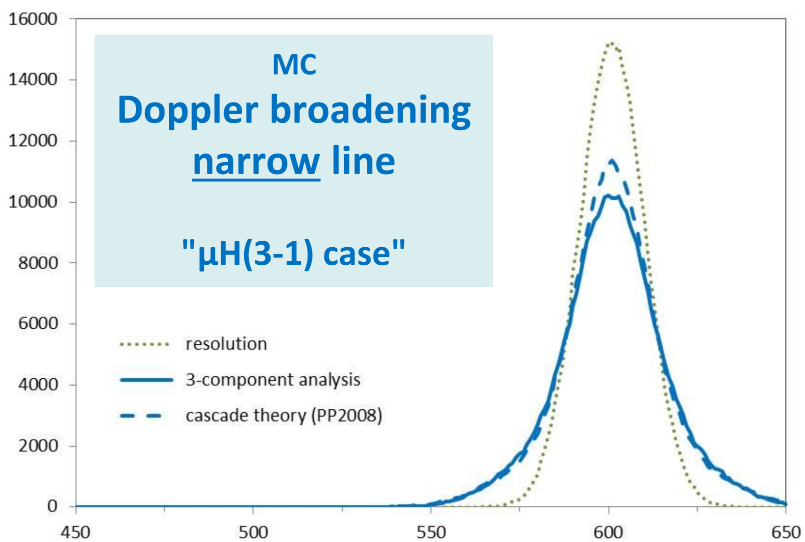


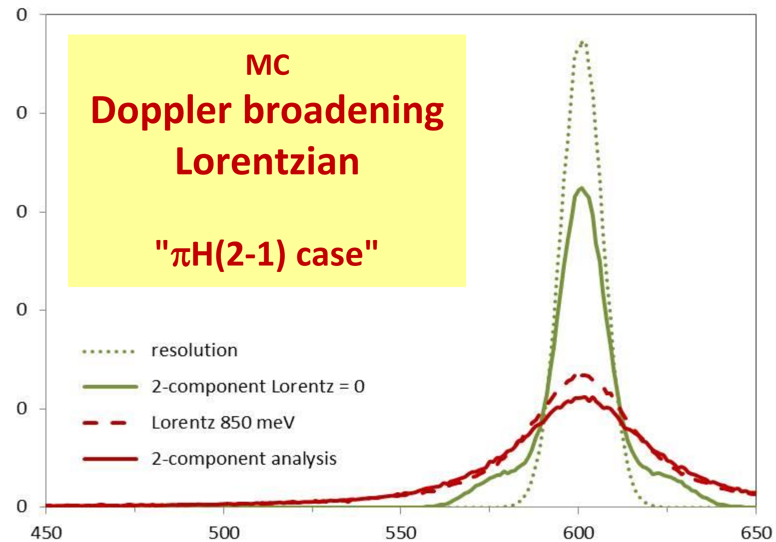


T.Jensen and V.Markushin — *introduction of ESCM*

V.N. Pomerantsev and V.P. Popov — *new collision cross sections*

EXEMPLIFICATION

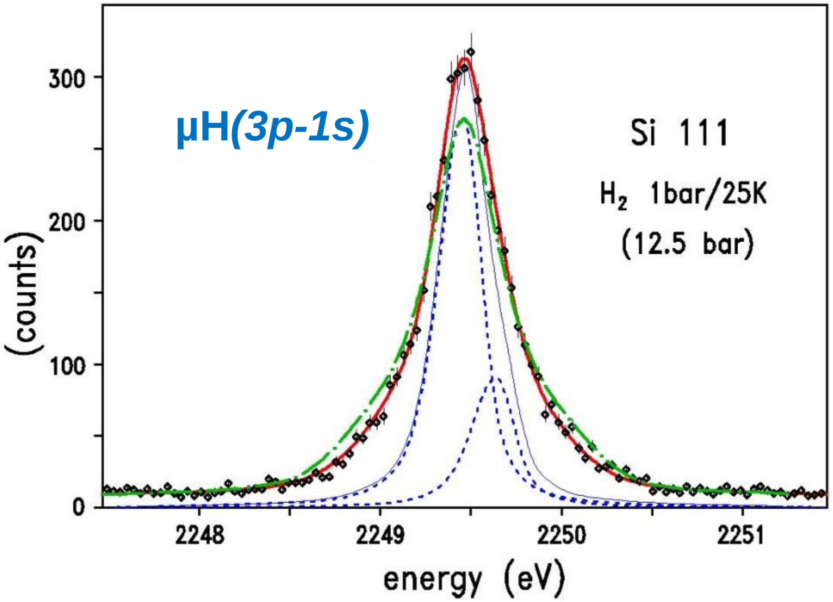


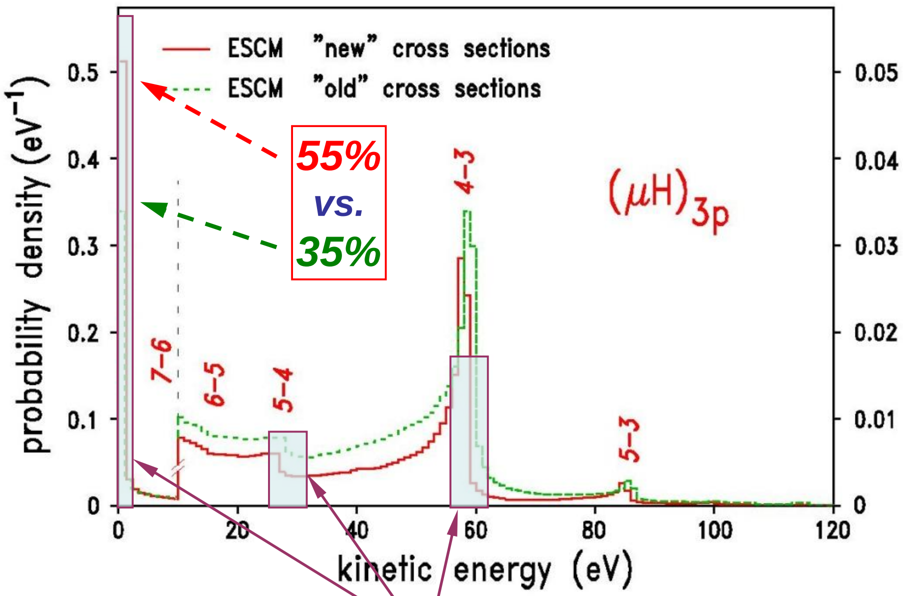


typical resolution (FWHM)

272 meV ***390 meV***

ANALYSIS - µH(3p - 1s) I





re-calculation of cross sections

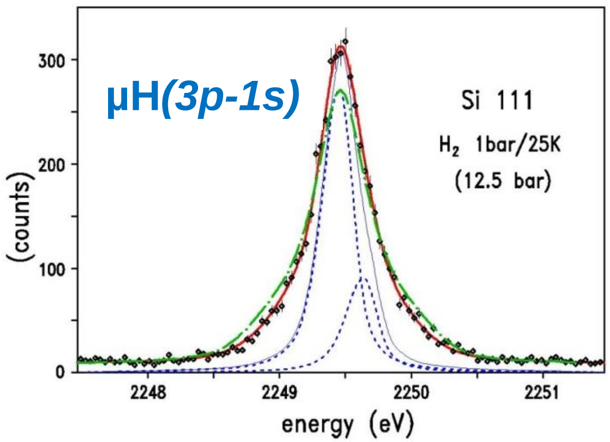
„box" fits = model free fit

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

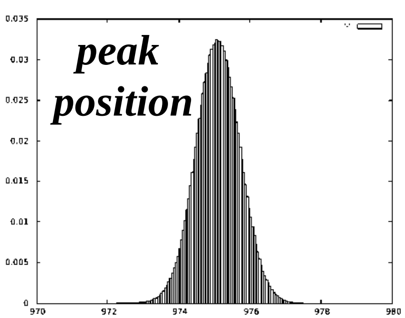
ESCM: extended standard cascade calculation and cross sections
T.S.Jensen and V.E.Markushin, Eur. Phys. J. D 19,165 (2002); ibid.D 21,261 (2002); ibid.D 21,271 (2002)

new 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 A 73, 040501 (2006)
V.P. Popov and V.N. Pomerantsev, arXiv:0712.3111v1[nucl-th] (2007)
V.P. Popov and V.N. Pomerantsev, Phys. Rev A 86, 052520 (2012)

ANALYSIS - μH*(3p - 1s) II*



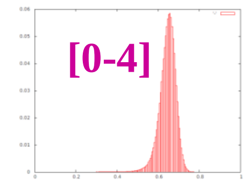
„obvious" parameters look like Gaussian

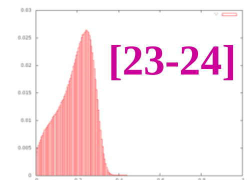


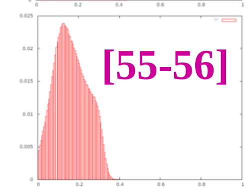
comparison: 3-component model

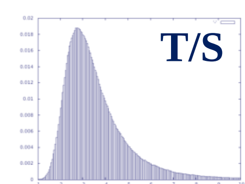
M.Theisen, Diploma thesis FZJ 2013

χ^2 analysis		Bayesian approach	
[0-2]	61±2	[0-4]	65^{+3}_{-4}
[24-27]	25±3	[23-24]	24^{+4}_{-10}
[57-58]	14±4	[55-56]	16^{+10}_{-4}
HFS free	211±19		212^{+23}_{-21}
T/S	3.6±0.6		$3.2^{+1.6}_{-0.7}$
HFS fixed			
T/S	2.9±0.2		$2.5^{+1.1}_{-0.5}$







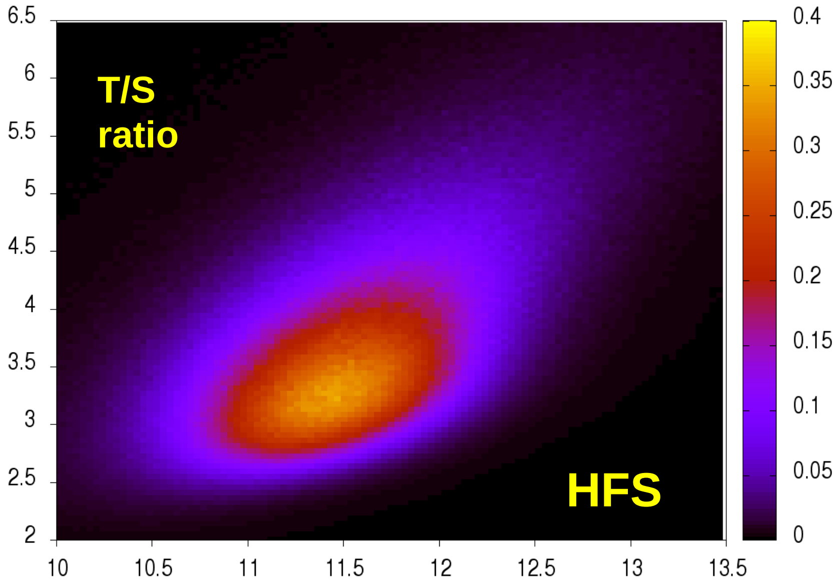


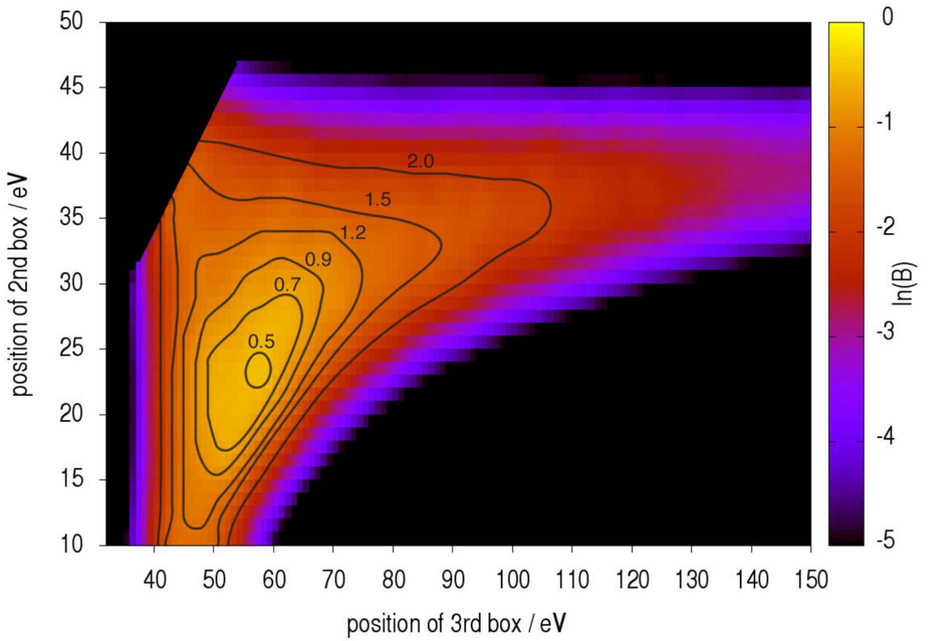
ANALYSIS - μH(3p - 1s) III

two-dimensional posterior probability

HFS free	**212**	**+23 / –21**
T/S	**3.2**	**+1.6 / –0.7**

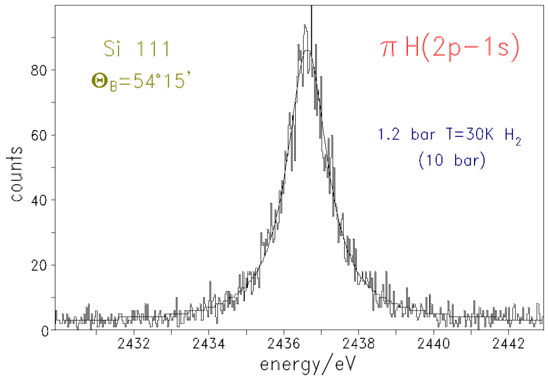
High-energy components

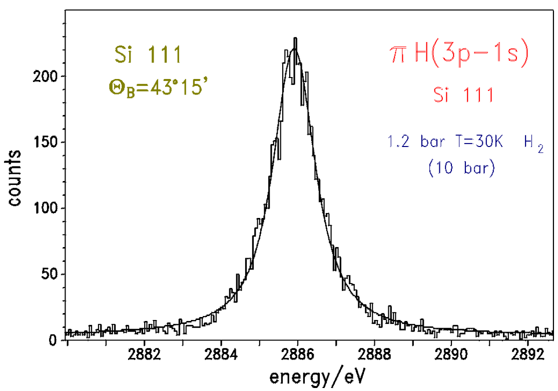


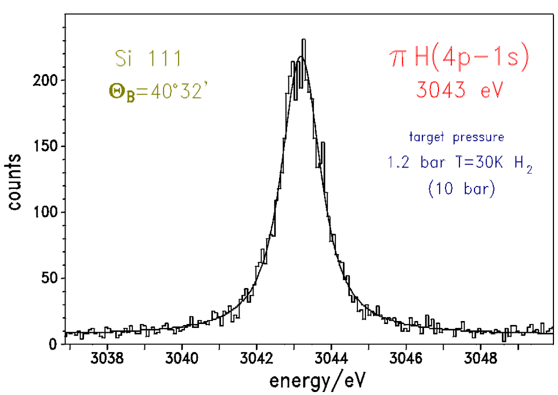


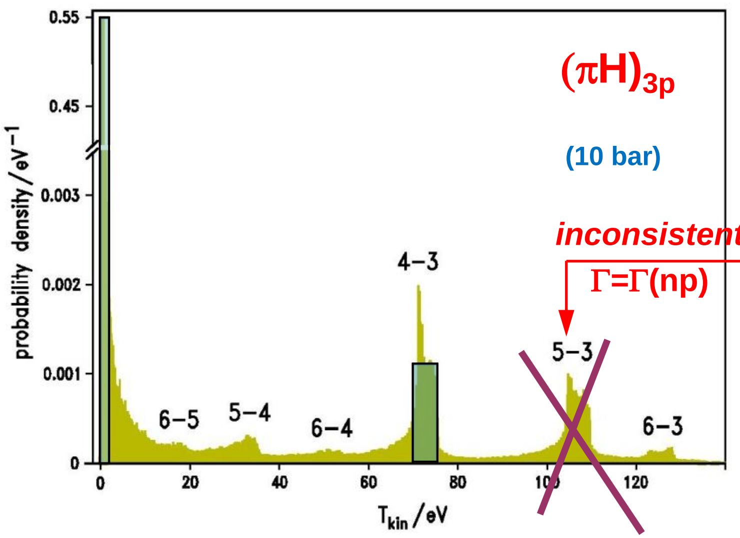
M.Theisen, Diploma thesis FZJ 2013

ANALYSIS - πH(np - 1s) I









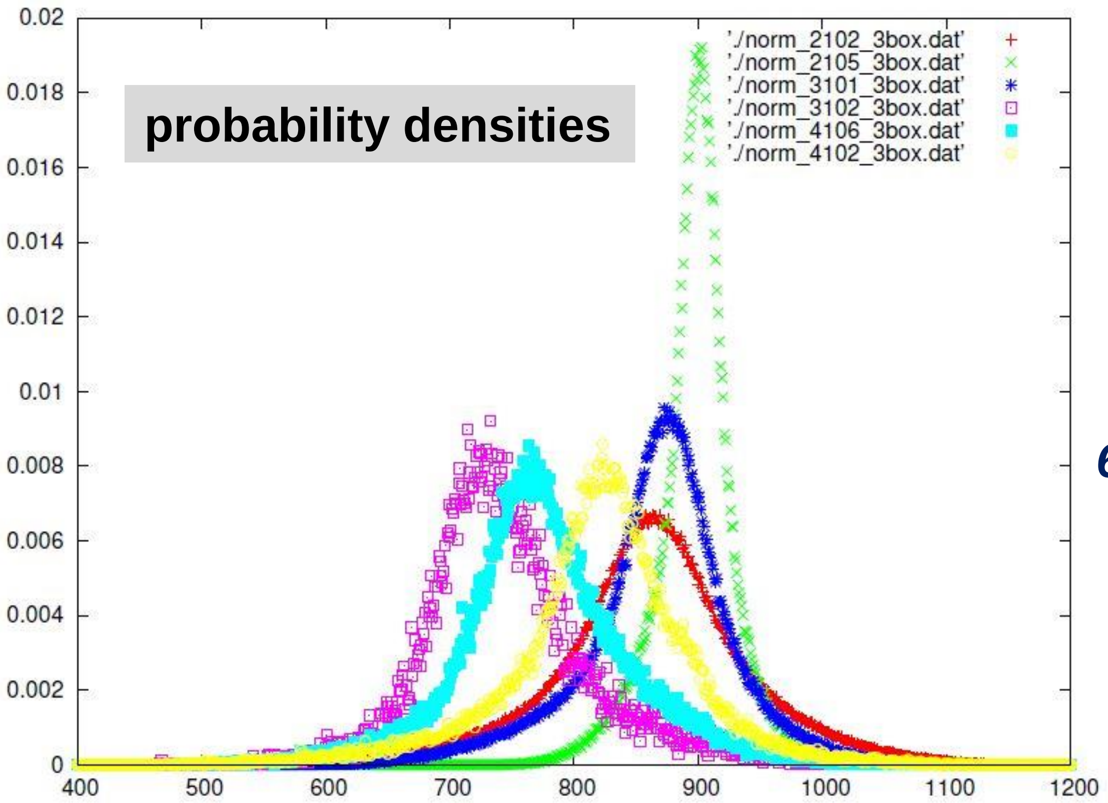
Coulomb transition

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	---

ANALYSIS - πH(*np - 1s*) Γ_{1s} *II*



model-independent

approach

3-component model

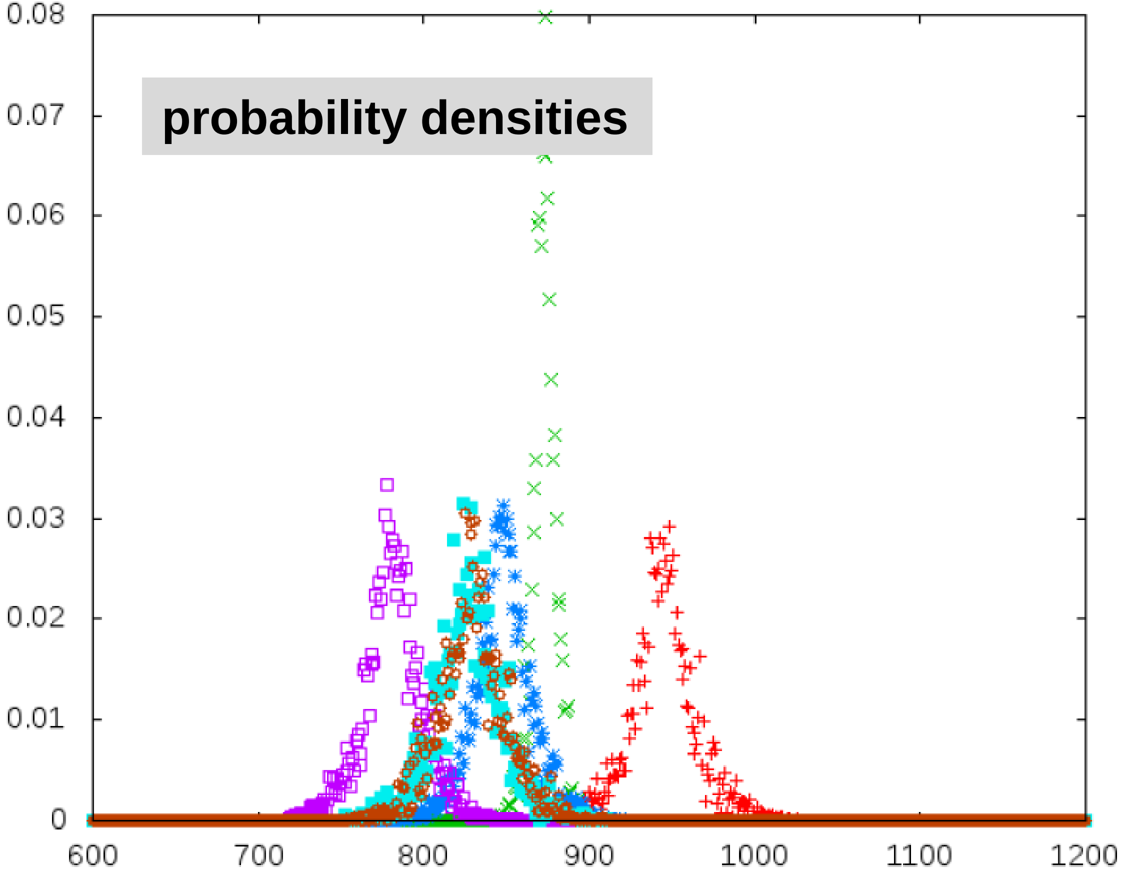
6 individual measurements

2 x πH(2p-1s)

2 x πH(3p-1s)

2 x πH(4p-1s)

ANALYSIS - πH(np - 1s) Γ_{1s} III



using

kinetic energy distribution

from cascade theory

6 individual measurements

2 x πH(2p-1s)

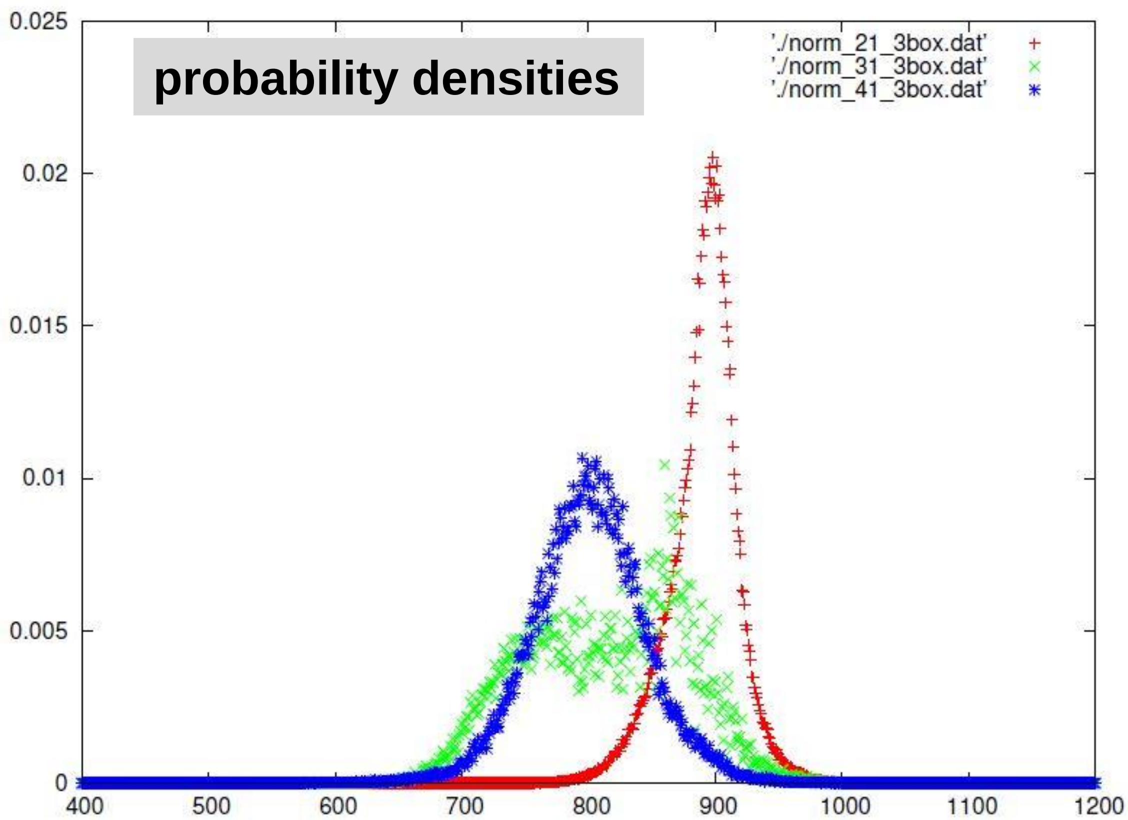
2 x πH(3p-1s)

2 x πH(4p-1s)

cascade calculation

V.N. Pomerantsev and V.P. Popov

ANALYSIS - πH(np - 1s) Γ_{1s} IV



model-independent

approach

3-component model

individual transitions

πH(2p-1s)

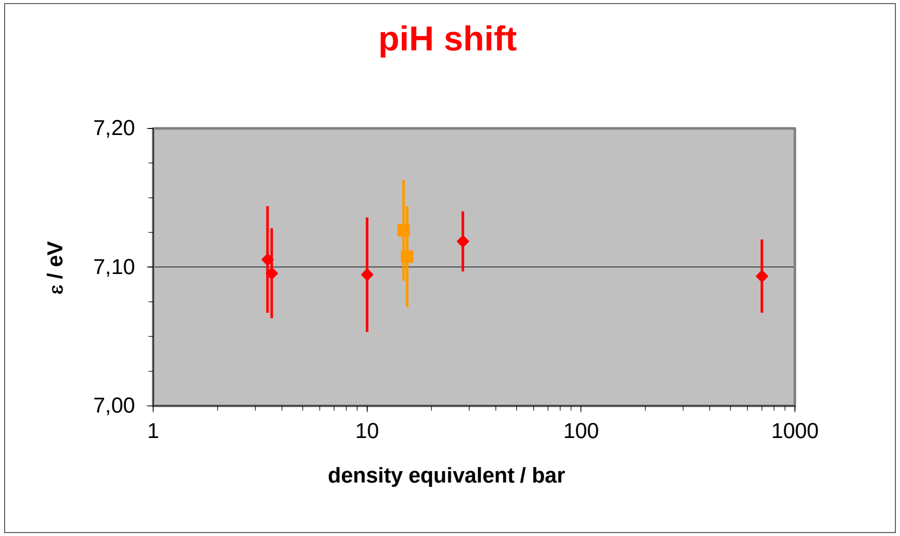
πH(3p-1s)

πH(4p-1s)

- WHY PIONIC HYDROGEN & … ?
- EXPERIMENTAL APPROACH
- ANALYSIS
- **RESULTS**
- CONCLUSIONS

πH(3p - 1s) ε_{1s} *final*

***no* density dependence identified $\Rightarrow$ "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

new calculation πH $\Rightarrow$ ΔE_{QED} = ± 0.001 eV !

P. Indelicato, priv. comm.

mainly pion mass ΔE_{QED} = ± 0.006 eV !

*cancels mainly using πO calibration** ↓

new QED value available since 2011: - 22 meV!

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

new mass measurement ± 1.3ppm

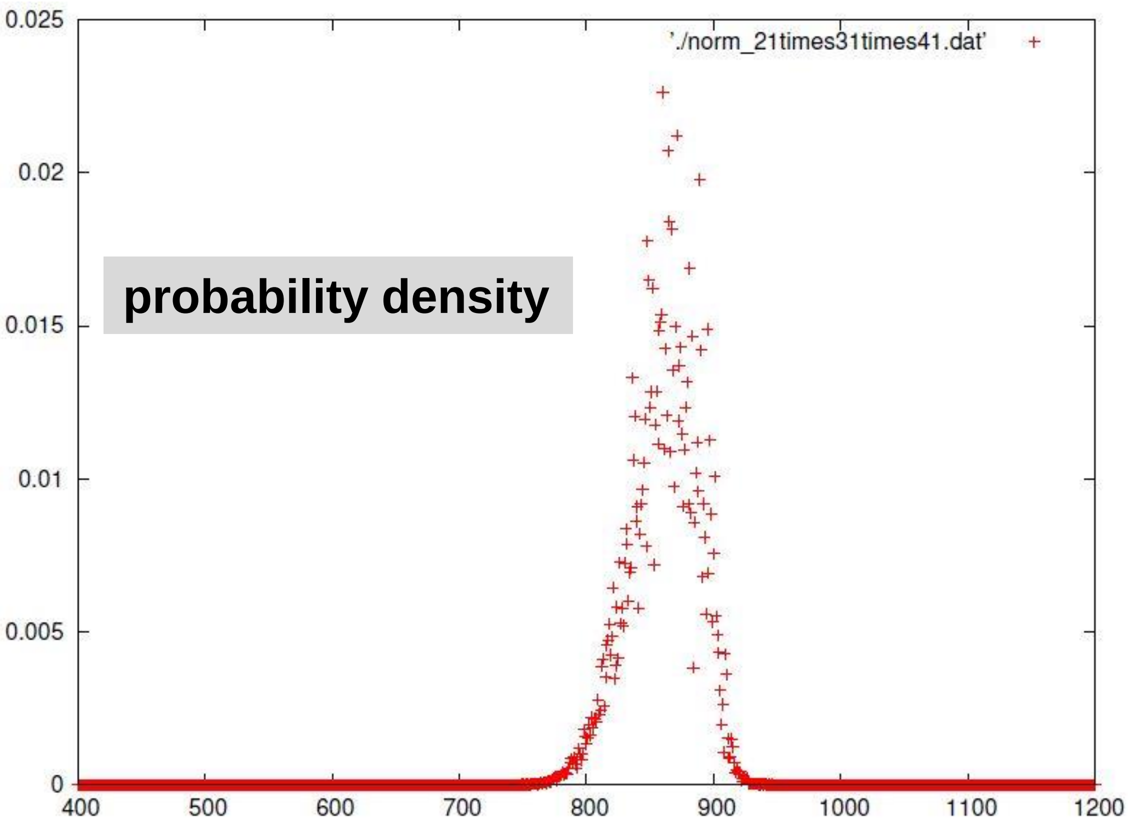
M. Trassinelli et al, Phys. Lett. B 759 (2016) 583

$$\varepsilon_{1s} = +\,7.087 \pm 0.009\ \text{eV}\ \ (\pm\,0.13\%)$$

$$a_{\pi^- p} = (85.26 \pm 0.12) \cdot 10^{-3}\, m_\pi^{-1}$$

M. Hennebach, PhD thesis, Cologne 2003
M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190

πH(*np* - *1s*) Γ_{1s} *preliminary*



model-independent

approach

3-component model

all measurements

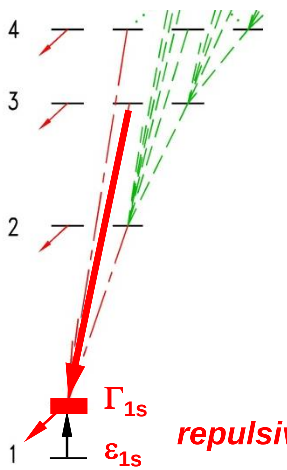
$$\Gamma_{1s} = \left(0.85\ ^{+0.04}_{-0.05}\right)\ \text{eV}$$

$$a_{\pi^- p \to \pi^0 n} = (124 \pm 3) \cdot 10^{-3}\ m_\pi^{-1}$$

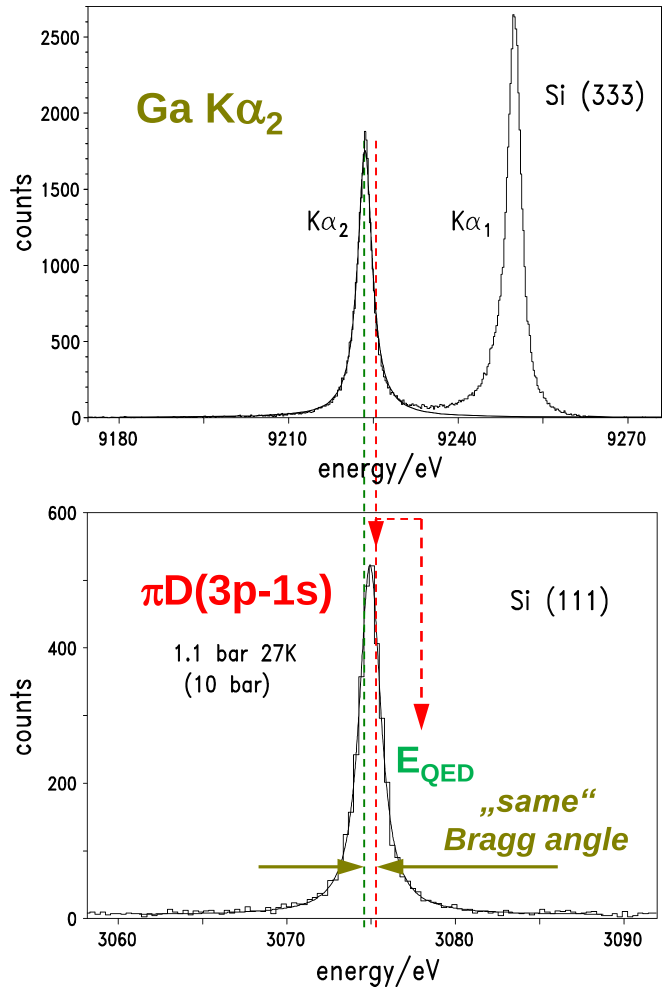
$\pi D(3p - 1s)$ ε_{1s} *final*

energy calibration

strong interaction



repulsive



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

error budget

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

ε_{1s} = (-2.356 ± 0.031) eV (± 1.3%)

$$\Re\, a_{\pi^- d} = (25.0 \pm 0.3) \cdot 10^{-3}\, m_\pi^{-1}$$

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

πN ISOSPIN SCATTERING LENGTHS a^+ and a^-

Δ exp ≈ 2 × Δ theory - no LEC f_1 in NLO

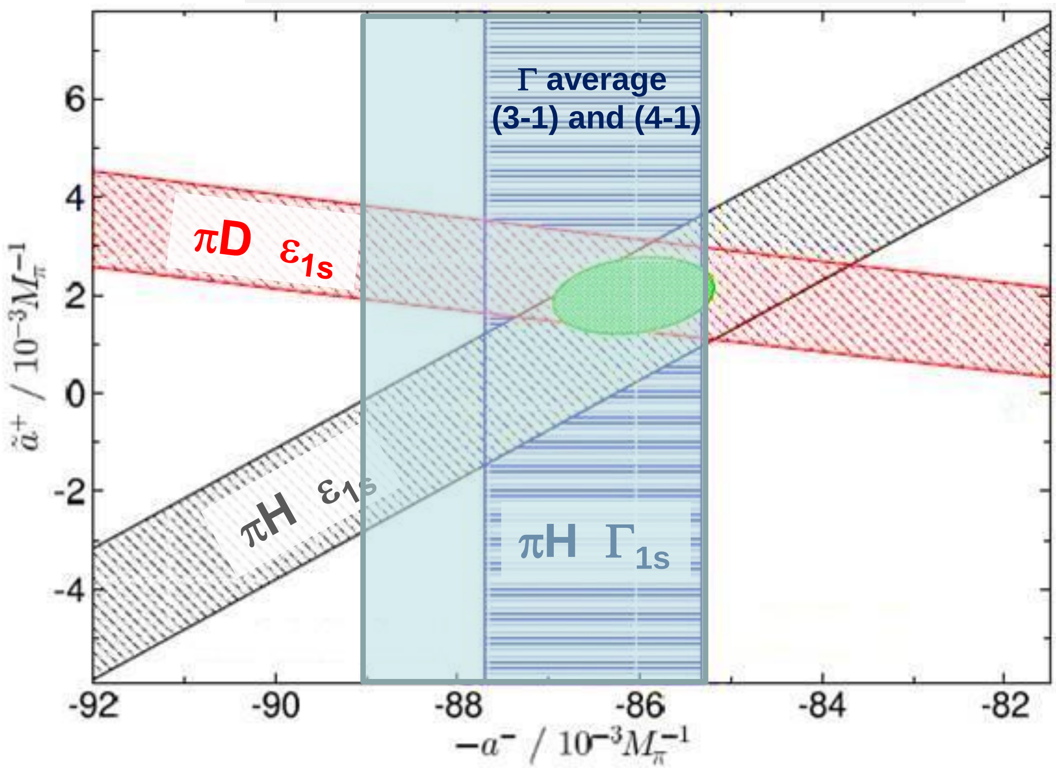


FIG. 2: Combined constraints in the $\tilde{a}^+ - a^-$ plane from data on the width and energy shift of πH, as well as the πD energy shift.

Δ exp << Δ theory - LEC f_1

Δ exp << Δ theory - LEC f_1

- constistency ✓
- πD decisive
- $a^+ > 0$!

χPT: J. Gasser et al., Phys. Rep. 456 (2008) 167
M. Hoferichter et al., Phys. Lett. B 678 (2009) 65
V. Baru, C. Hanhart, M. Hoferichter, B. Kubis, A. Nogga, and D. R. Phillips, Phys. Lett. B 694 (2011) 473
data: πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (2008) 165
M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190
πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88

NN ⇔ πNN threshold parameter α

$$\Gamma_{1s} = \left(1.171 \,{}^{+0.023}_{-0.049}\right)\ \text{eV} \ \left({}^{+2\%}_{-4\%}\right)$$ *final*

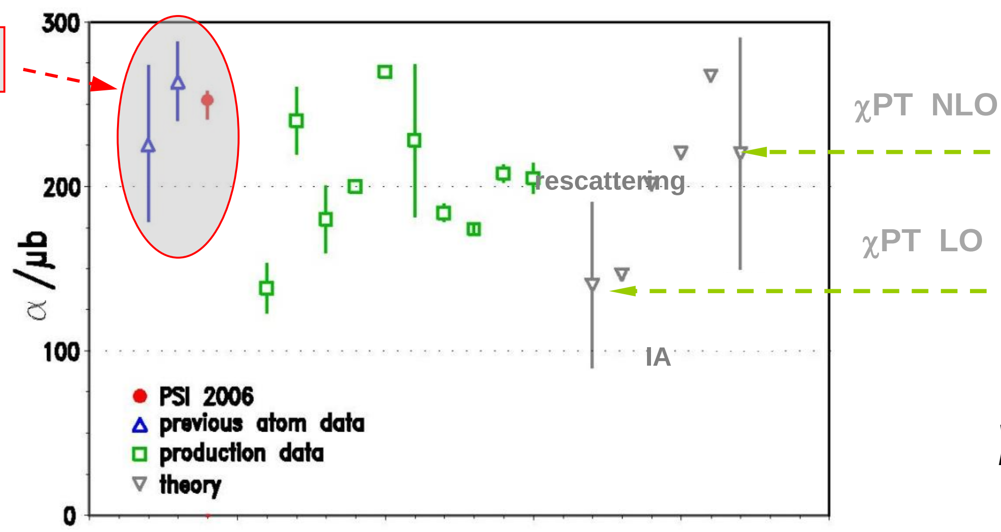
$$\Im\, a_{\pi^- d} \propto \alpha(pp \to \pi^+ d) = (251\ {}^{+5}_{-11})\ \mu b$$

exotic-atom results

Th. Strauch, PhD thesis, Cologne 2009

Th. Strauch et al., Phys.Rev.Lett.104 (2010)142503

Th. Strauch et al., Eur.J.Phys.47 (2011)88



χPT

at present
Δα /α ≈ 30%

→ few % !?

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

- WHY PIONIC HYDROGEN & … ?
- EXPERIMENTAL APPROACH
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- RESULTS
- **CONCLUSIONS**

πA *INTERACTION – ADDITIONAL ACCESS TO a$^{\pm}$?*

$$a_{\pi^- A} = \left(\frac{\mu_{\pi A}}{\mu_{\pi N}}\right) \cdot \left(A \cdot a^+ + T_3^A \cdot a^-\right) + IV + few - body$$

S. Baru et al., Eur. Phys. J. A 16 (2003) 437

S. Liebig et al., Eur. Phys. J. A 47 (2011) 69

$$a_{\pi^- p} \propto (a^+ + a^-) + (9\pm4)\%$$

$$a_{\pi^- n} \propto (a^+ - a^-) + (9\pm4)\%$$

$$\Re e\, a_{\pi^- D} \propto (2a^+ + 0) + \ldots + 80\%$$

$$\Re e\, a_{\pi^- T} \propto (3a^+ - a^-) + \ldots + 25\%$$

$$\Re e\, a_{\pi^- {}^3He} \propto (3a^+ + a^-) + \ldots + 40\,\%$$

$$\Re e\, a_{\pi^- {}^4He} \propto (4a^+ + 0) + \ldots + 80\%$$

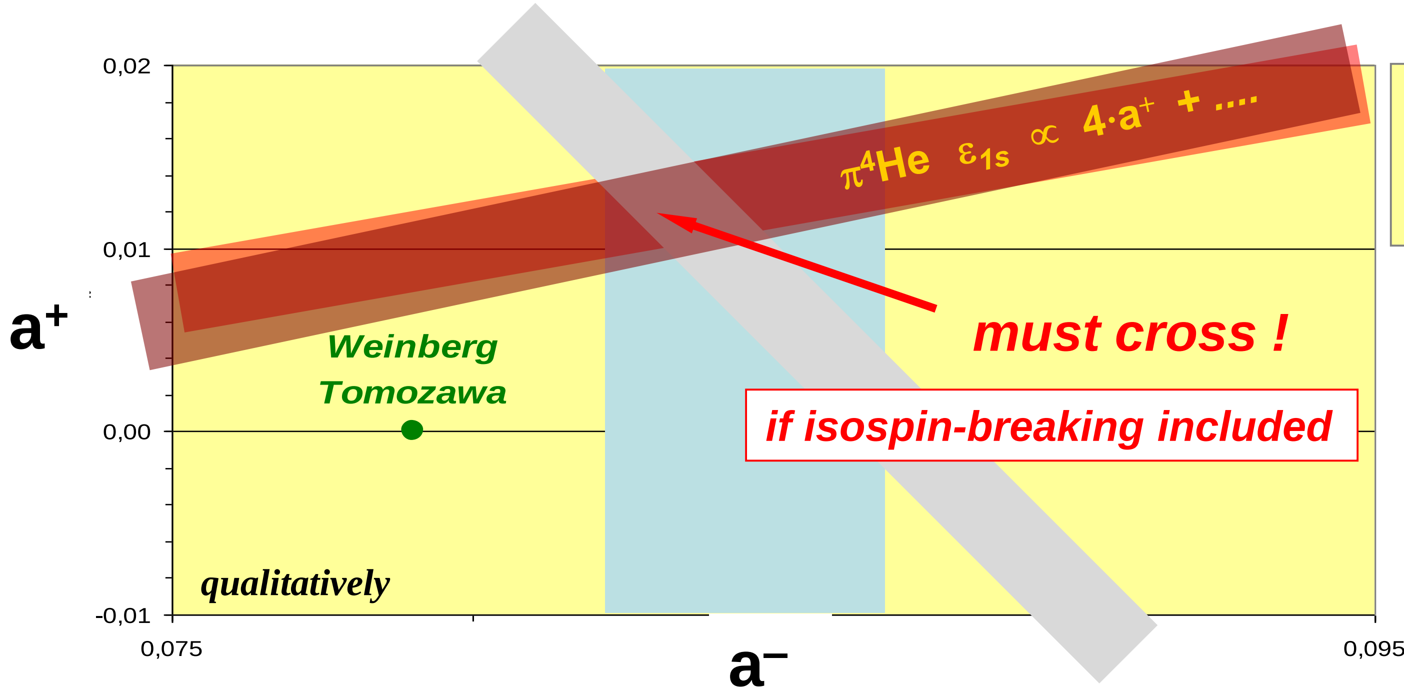
$\Re e\, a_{\pi^- A} \,/\, m_\pi^{-1}$

	experiment	theory
p	+ 0.0853 ± 0.0001	} $a^+ + a^-$ from e.g. χPT analysis
d	- 0.0250 ± 0.0003	↓
n	- 0.0907 ± 0.0016*	- 0.0902 ± 0.0021
T	unpopular	- 0.103 ± 0.008
^{3}He	+ 0.047 ± 0.009**	+ 0.062 ± 0.008
^{4}He	- 0.098 ± 0.003**	- 0.055 ± 0.005

* opt. potential

** new data to be analysed

a^+ *vs.* a^-



$\varepsilon_{1s} \propto A \cdot a^+ + \ldots$

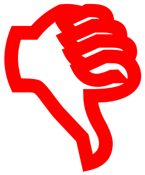
I = 0 nuclei

constraints for I = 1/2 nuclei ^{3}He / T ?

Theory — *C.Werntz and H. S.Valk, Phys. Rev. C 37, 724 (1988).* $\Gamma(\pi T)$ *predicted from radiative capture* $\pi T \rightarrow \gamma\, nnn$
Baru, Haidenbauer, Hanhart, Niskanen, Eur. Phys. J. A 16 (2003) 437, T/ ^{3}*He comparison:*
.... more coming

Experiment — ^{3}He/^{4}He *new data for* ε_{1s} *at* $\approx$ *3% level available - analysis still preliminary*

- **πN scattering length: bands cross**
- **s - wave π - production strength**
- **μH – singlet / triplet**
  - **ΔE_{HFS}**
  - **cascade theory ≈ line shape**



- **πH – spreading of Γ_{1s} unsatisfactory**

origin unknown - *cascade ?*

- *analysis ?*
- *experiment ?*

- **πD – Coulomb de-excitation ?**

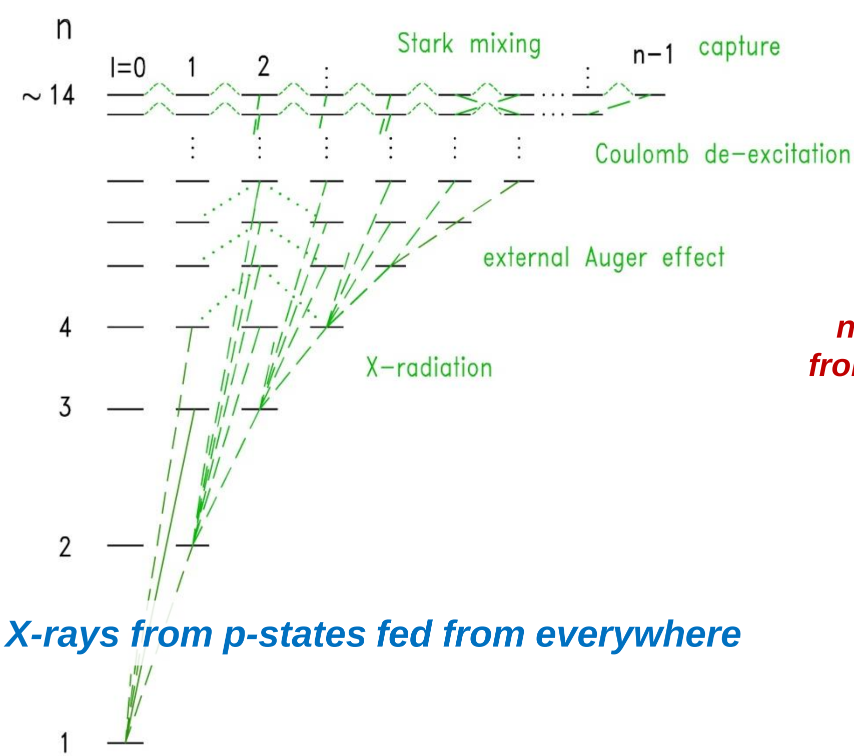
WHERE DO THEY GO ?

μH

πH

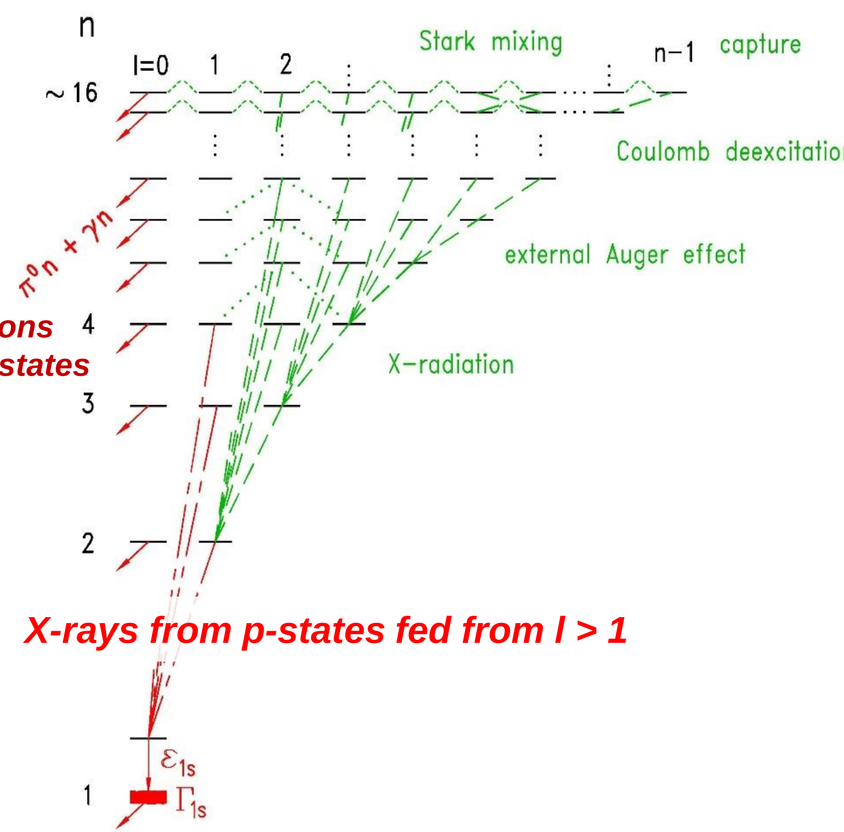
X-rays from p-states fed from ***<u>everywhere</u>***

X-rays from p-states fed from ***<u>l > 1</u>***



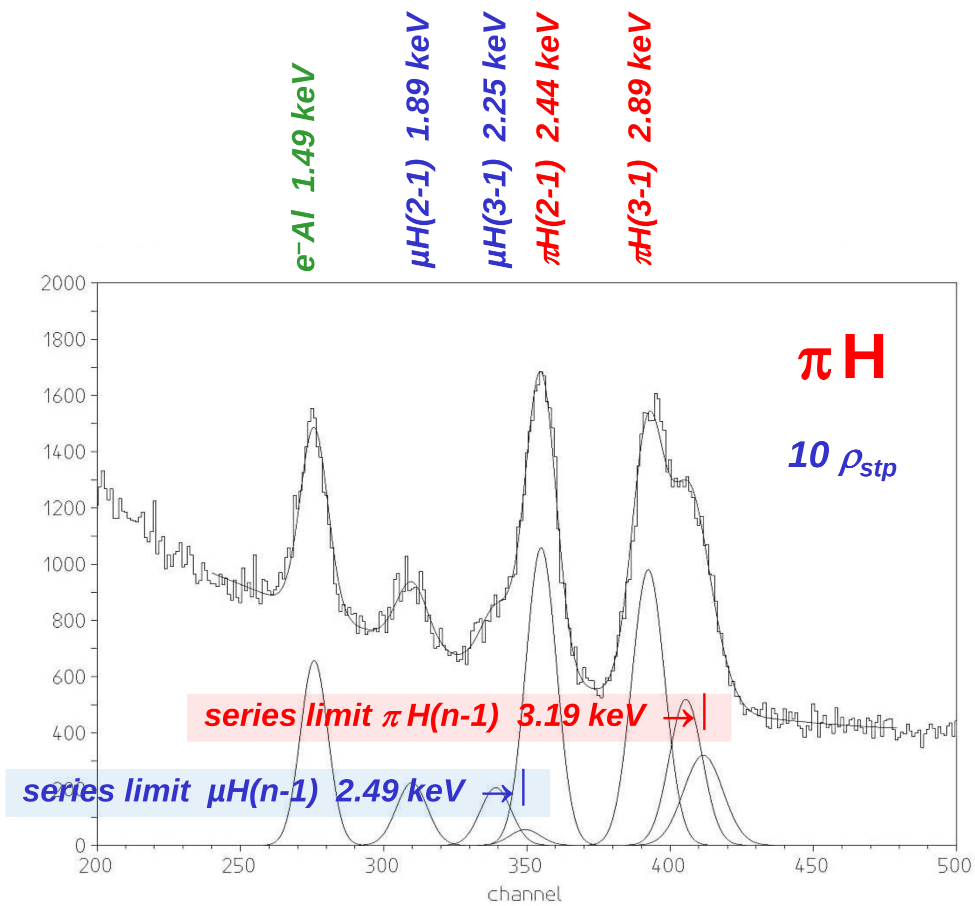
X-rays from p-states fed from everywhere

neutrons from s-states



X-rays from p-states fed from l > 1

CASCADE - MORE INSIGHT ?



crystal spectrometer

$$n_{max} \approx \sqrt[3]{2n_f^2 \Big/ \left(\Delta E / E_{\infty - n_f}\right)}$$

$n_{max} \approx 25$ for $\Delta E = 400$ meV

n_{max} : resolvable state

n_f : final state

ΔE : energy resolution

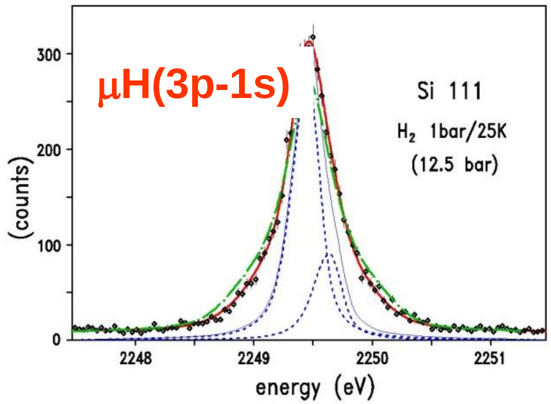
$E_{\infty-n_f}$: transition energy from series limit

IS SOMETHING MISSING ?

?

X-ray satellites from molecular formation

- none seen in πD -



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

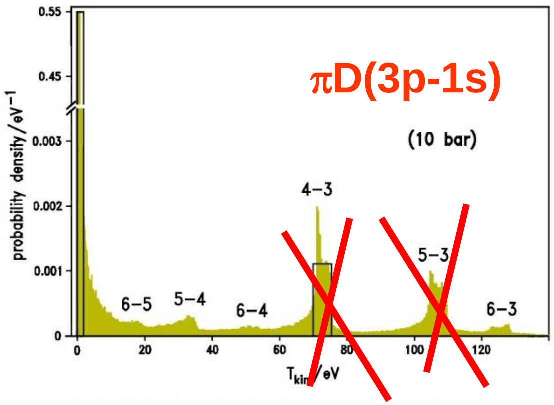
≈ πH

μD

?

high-energy components

- no cascade calculation yet -



?

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

cross sections

WHAT TO DO?

$\Gamma_{1s} \rightarrow 1\%$	**minimize Coulomb de-excitation**	**πH(4p-1s)** **πH(5p-1s) ?**
set-up	**increase resolution**	**quartz 10-2**
cascade	**understand better** **kinetic energy distribution**	**μH, μD**

exploit higher pion fluxes at PSI

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

Jülich, FZJ IKP, ZEL
A. Blechmann, H. Gorke, D.Gotta, M. Hennebach, M. Nekipelov, Th. Strauch, M. Theisen

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 ←

THANK YOU