Pionic hydrogen and friends

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for the PIONIC HYDROGEN COLLABORATION

EXA 2014

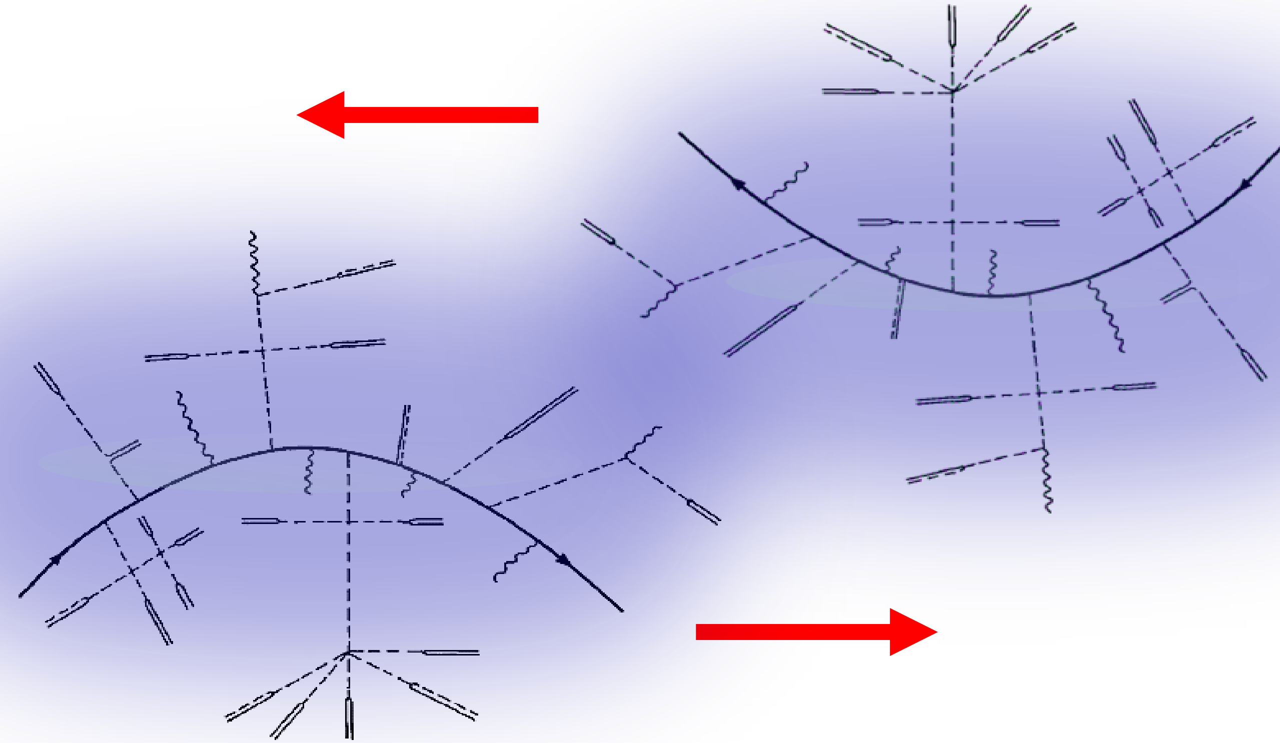
Vienna, September 17, 2014

- **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

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.

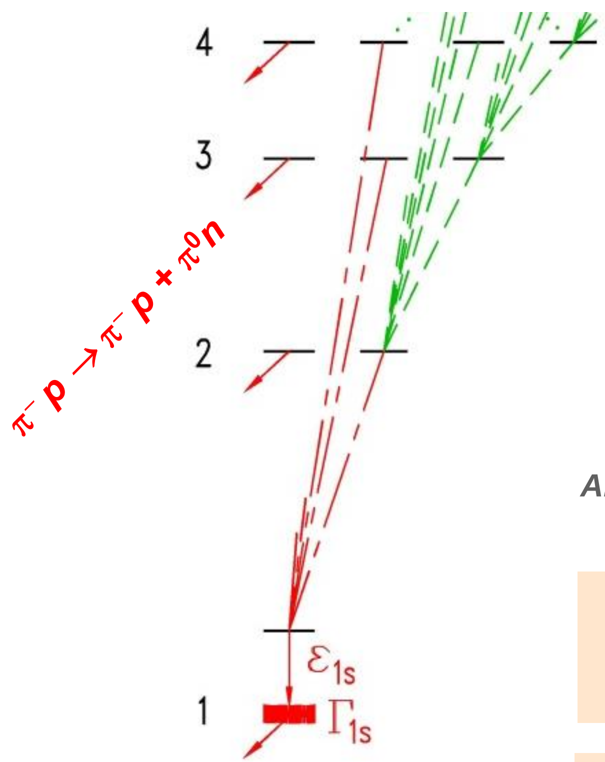
CHIRAL PERTURBATION THEORY (χPT), …

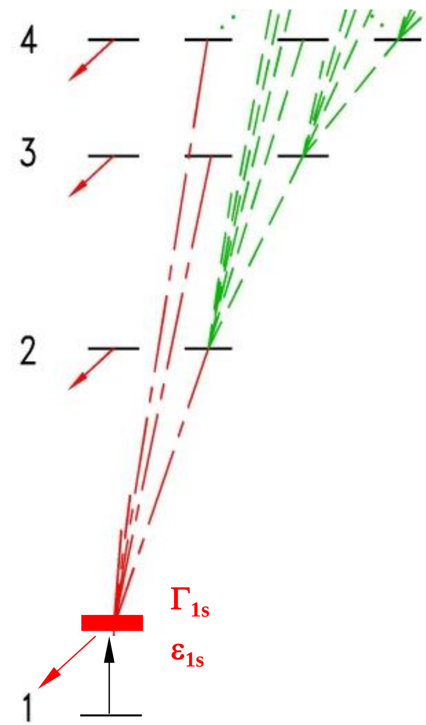
Strong - interaction effects in *X-ray transitions*

πH

„another friend“ **μH**

πD





ADAPT EXPERIMENTAL PRECISION

ALONG THEORETICAL ACHIEVEMENTS

shift ε_{1s}

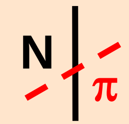
broadening Γ_{1s}

strong interaction
attractive

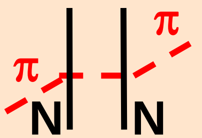
strong interaction
repulsive

πH & πD - *origin of* ε_{1s}

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



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

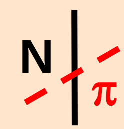


πH & πD - *origin of* Γ_{1s}

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

CEX = charge exchange

CEX scattering

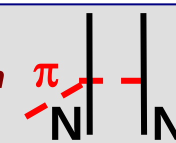


radiative capture

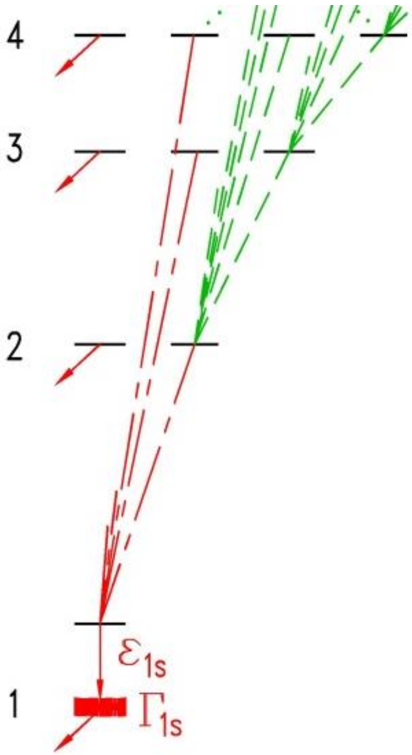
BR well known from experiment

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

„true“ absorption



SCATTERING LENGTHS *and* PION-PRODUCTION STRENGTH



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

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

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

$$\propto 2 \cdot a^+ + \ldots$$

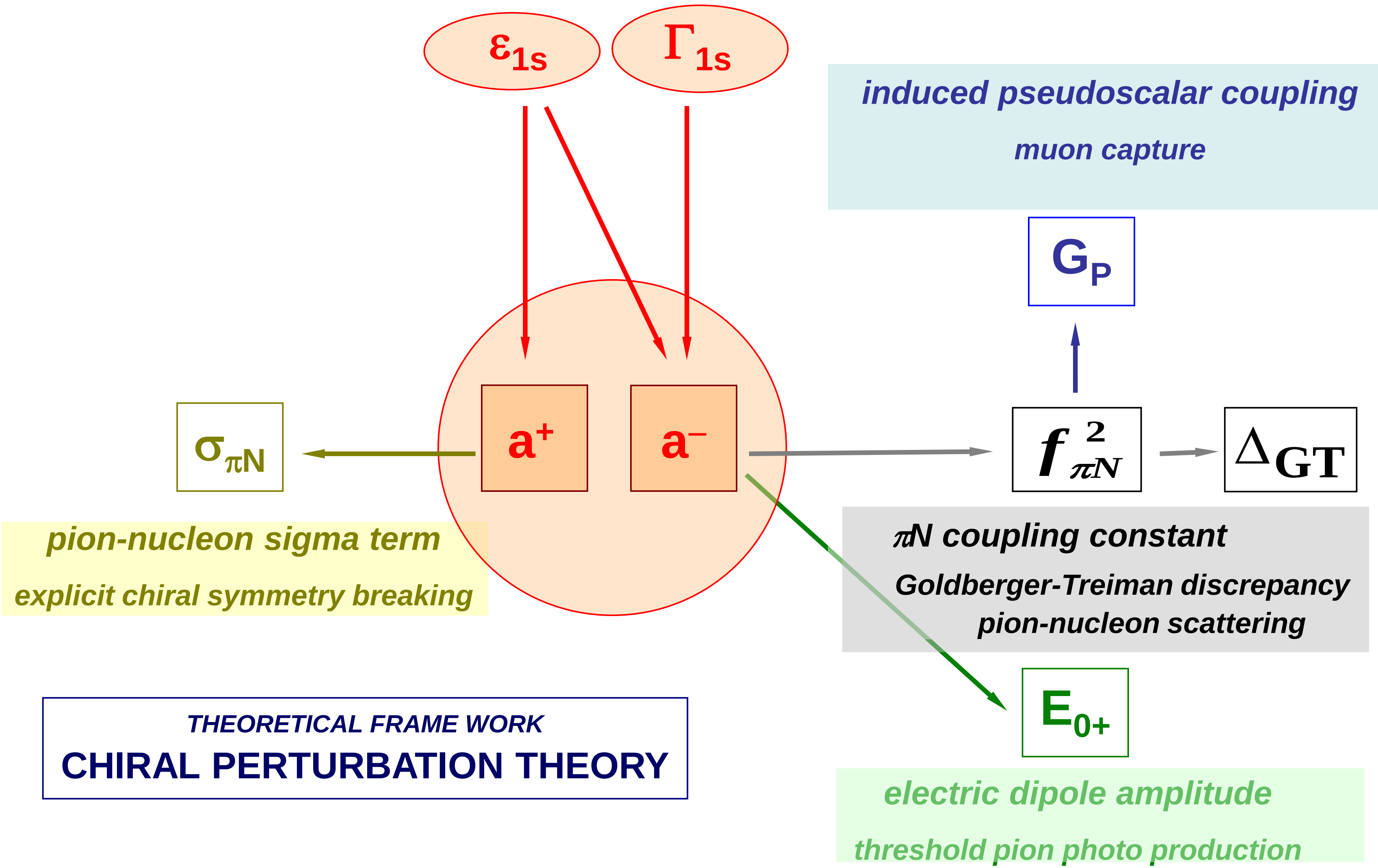
charge symmetry $a_{\pi^- n \to \pi^- n} = a_{\pi^+ p \to \pi^+ p}$

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

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

} *detailed balance*
charge symmetry

PION-NUCLEON SCATTERING LENGTHS *related quantities*



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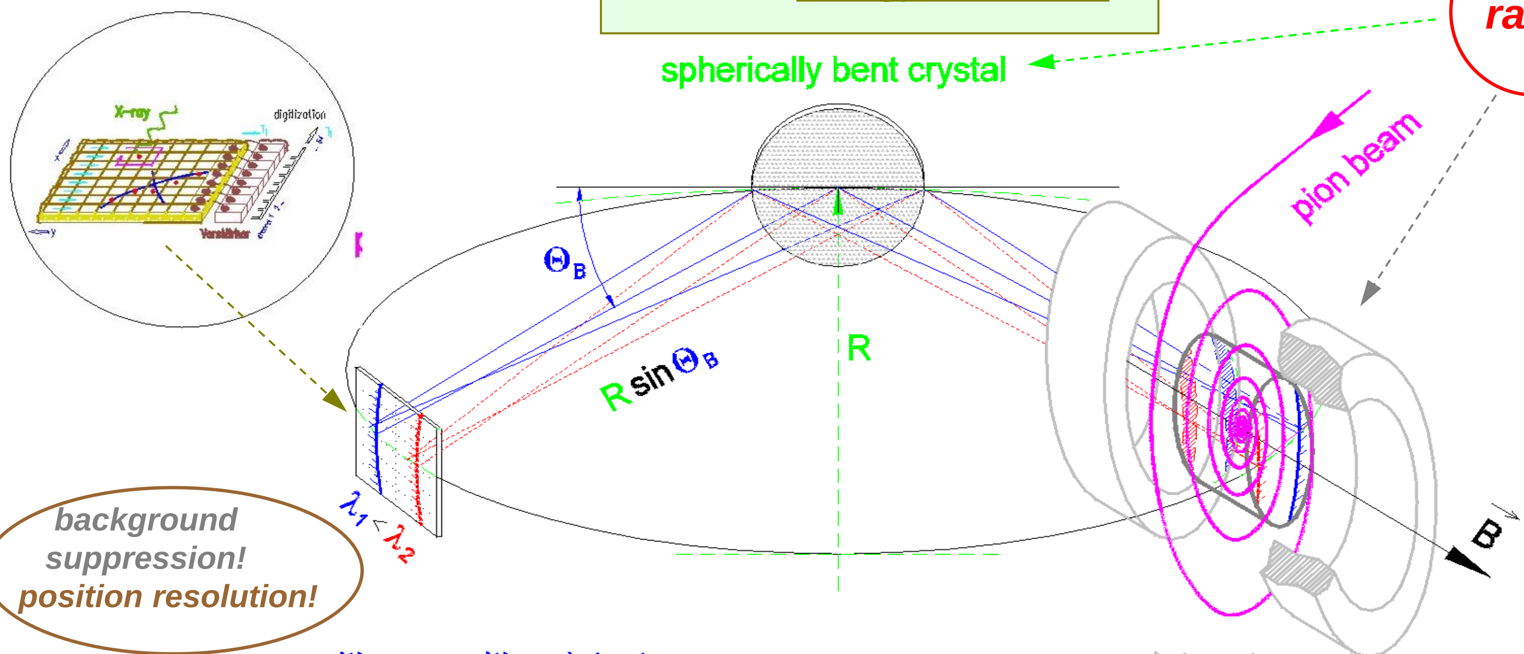
- CONCLUSIONS

Johann-type SET-UP

ultimate energy resolution

rate!



background suppression!
position resolution!

position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

position & energy resolution

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

high stop density

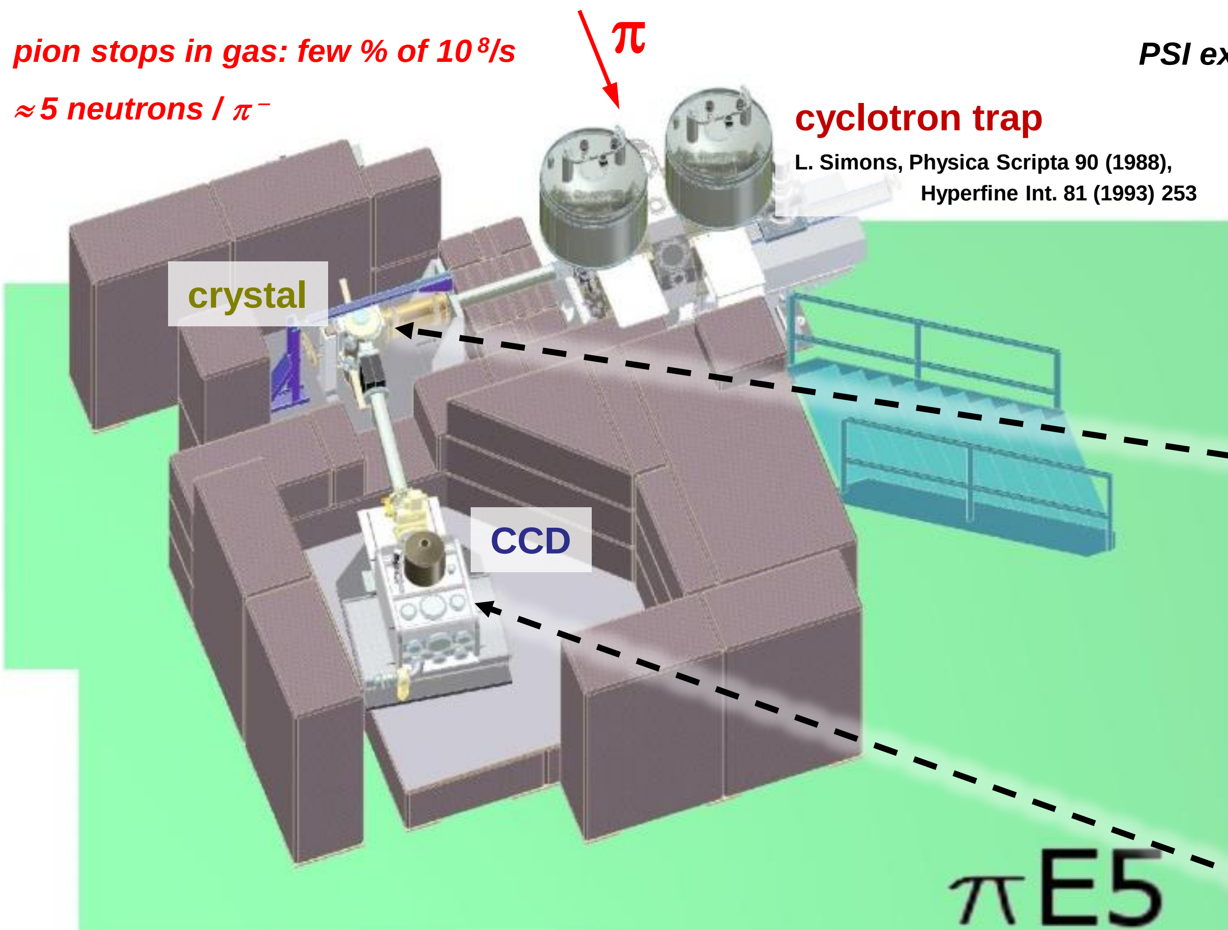
⇒ **high X - ray line yields**
⇒ **bright X - ray source**

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) $\Theta_{Bragg} \approx 40°$

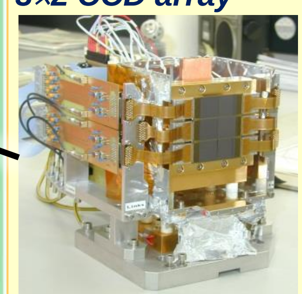
BRAGG CRYSTAL *Si, quartz*

spherically bent

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

FOCAL PLANE DETECTOR

3×2 CCD array



pixel size

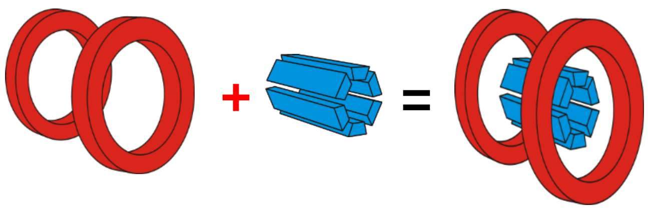
40 µm × 40 µm

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

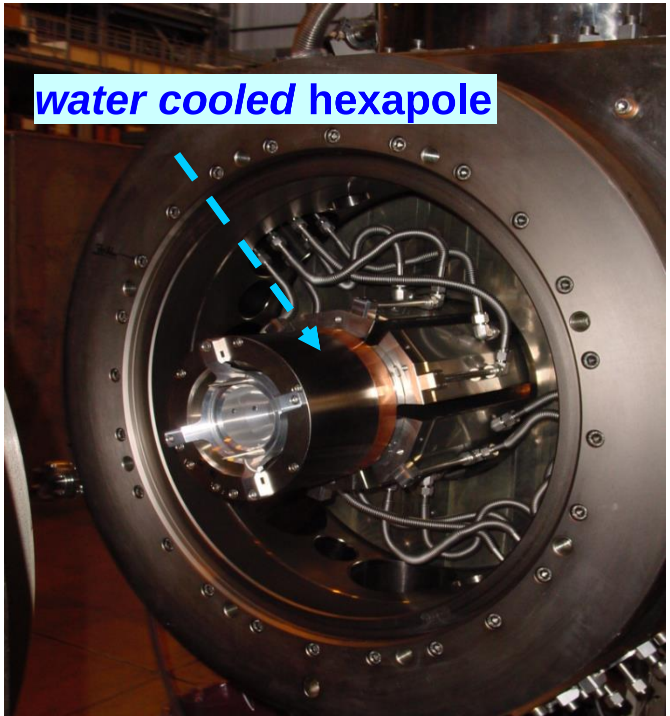
SPECTROMETER RESPONSE

new approach

Electron Cyclotron Resonance Ion Trap



cyclotron trap + **permanent hexapole** = *ECRIT*



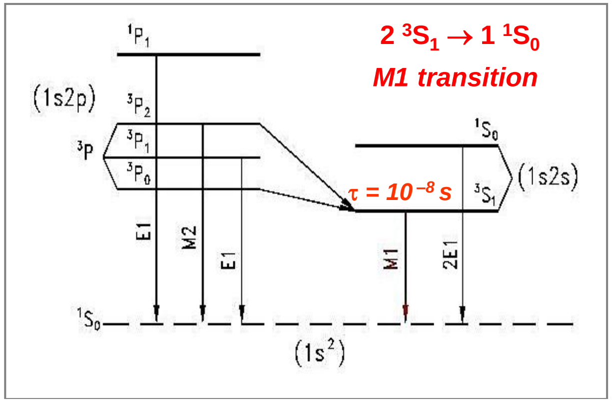
S. Biri, L. Simons, D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116
K. Stiebing, Frankfurt – design assistance

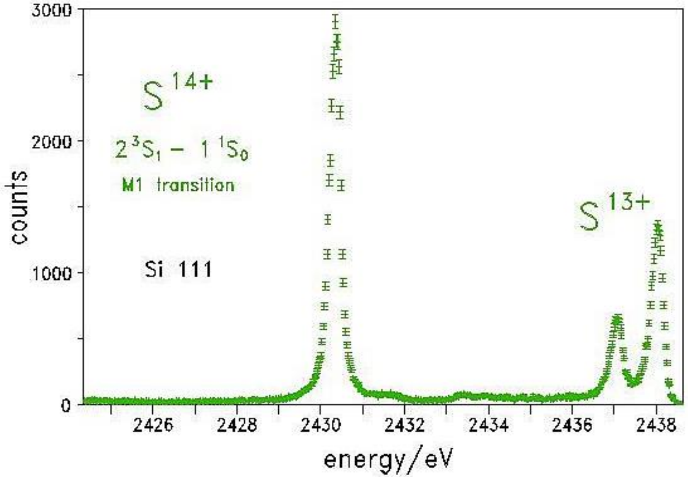
He - like

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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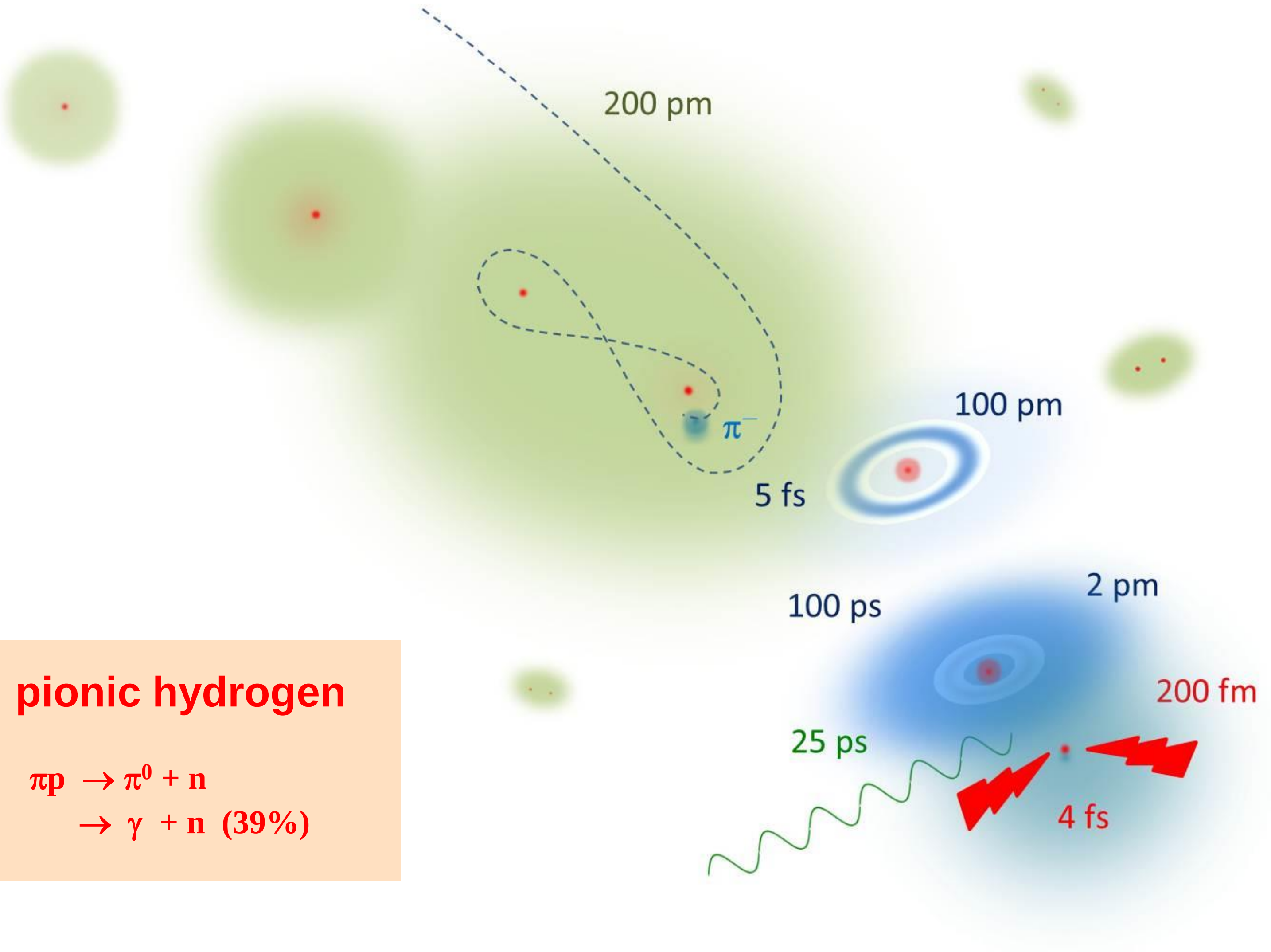
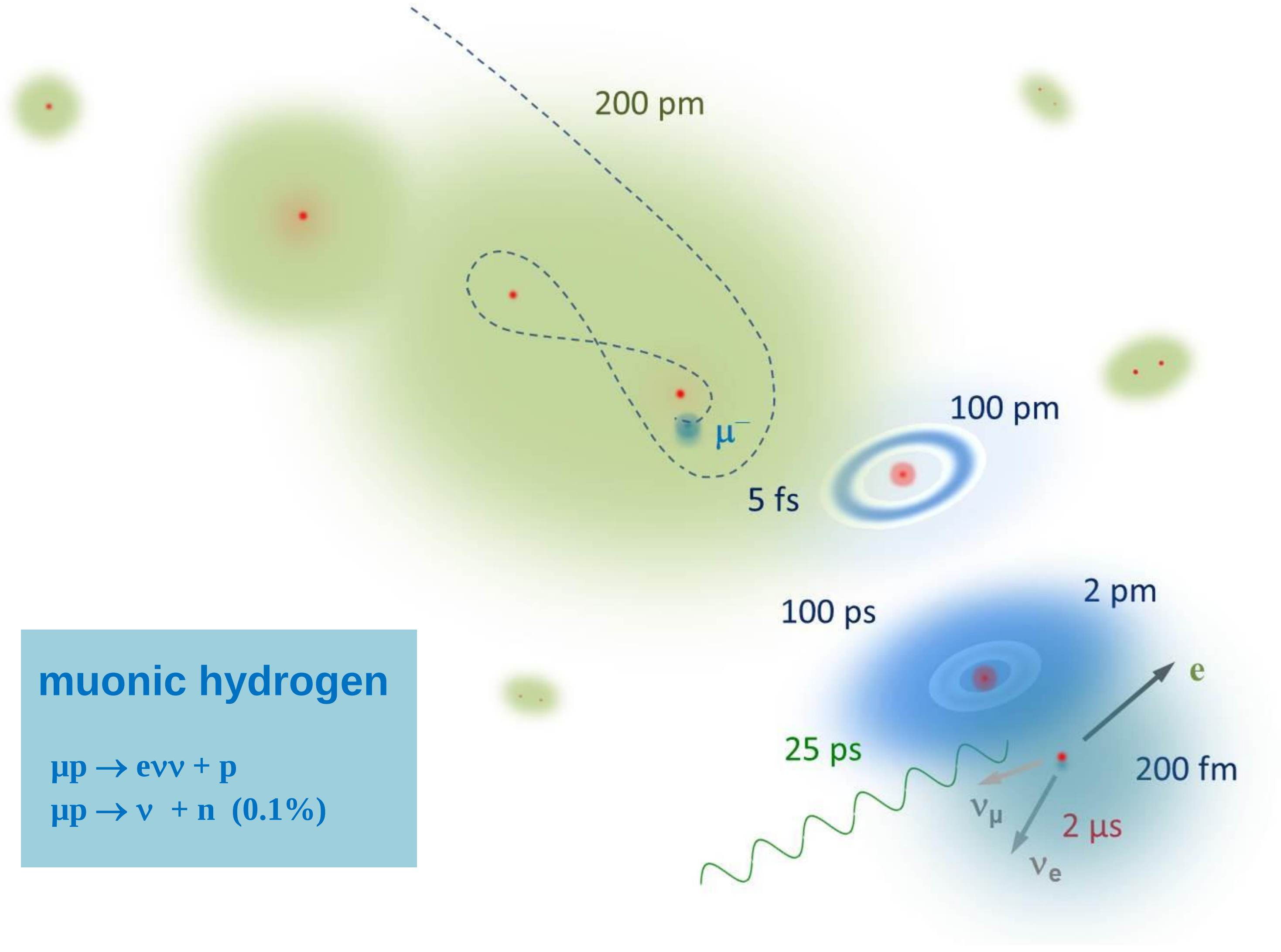


pionic hydrogen

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

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



muonic hydrogen

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

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

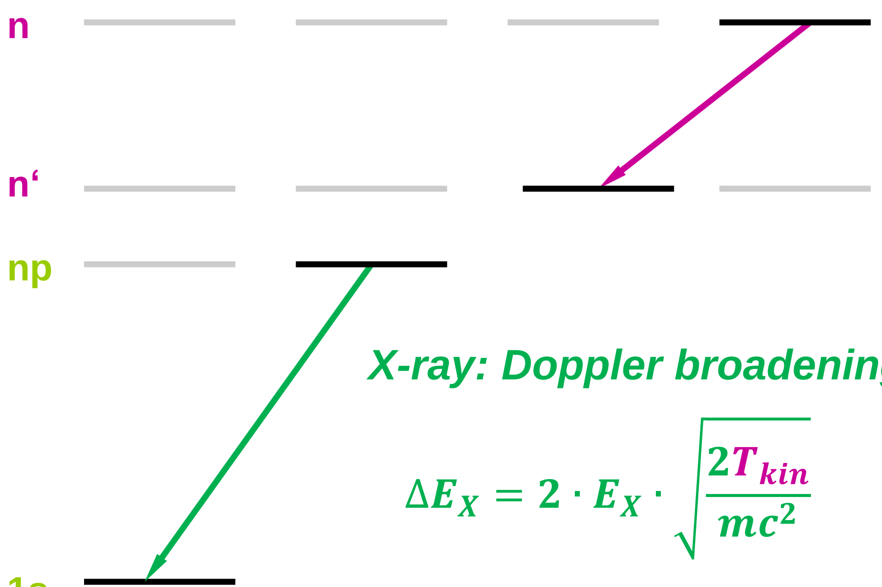
COULOMB DE-EXCITATION

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)

target densit > 0: πH or μH ARE NOT ISOLATED SYSTEMS !

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

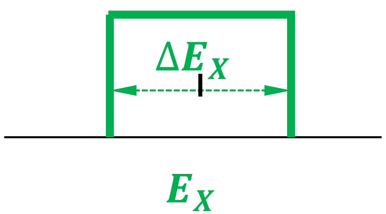


radiationless Coulomb transition

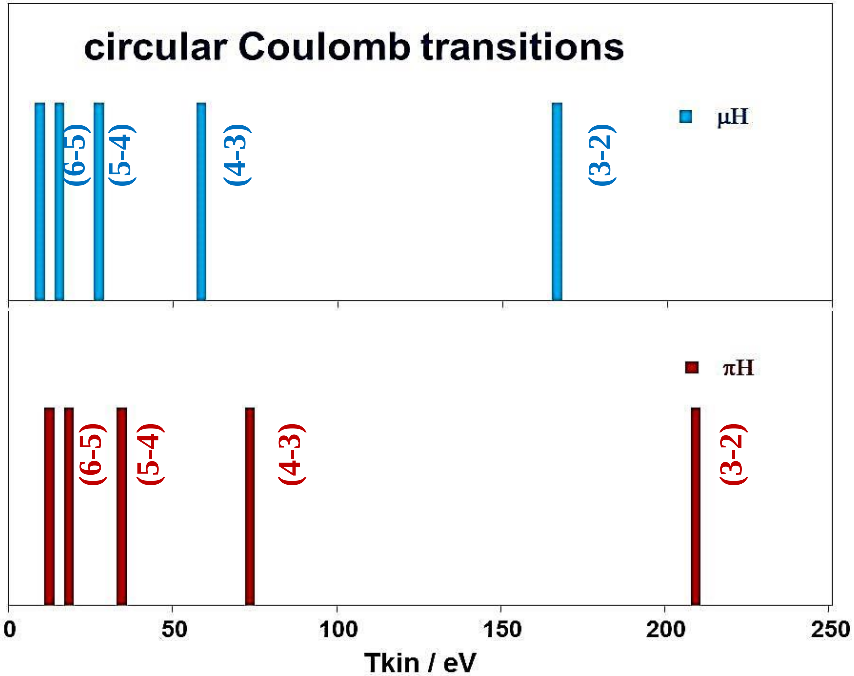
$\Delta E_{nn'} \rightarrow$ *kinetic energy* $T_{kin} \approx \Delta E_{nn'} / 2$

X-ray: Doppler broadening

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



STRATEGY I - model independent approach



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

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

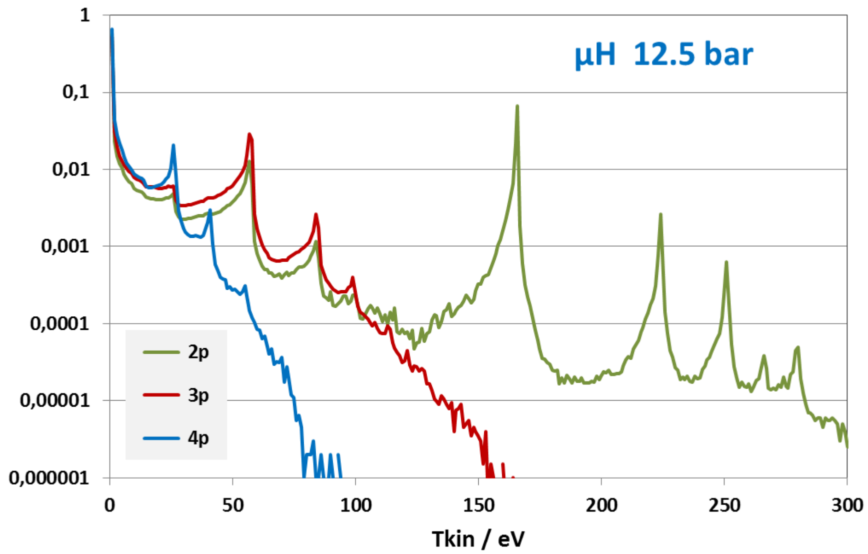
$\Delta E_{X,max} = 2,1\ eV \quad \pi H(3p-1s)$

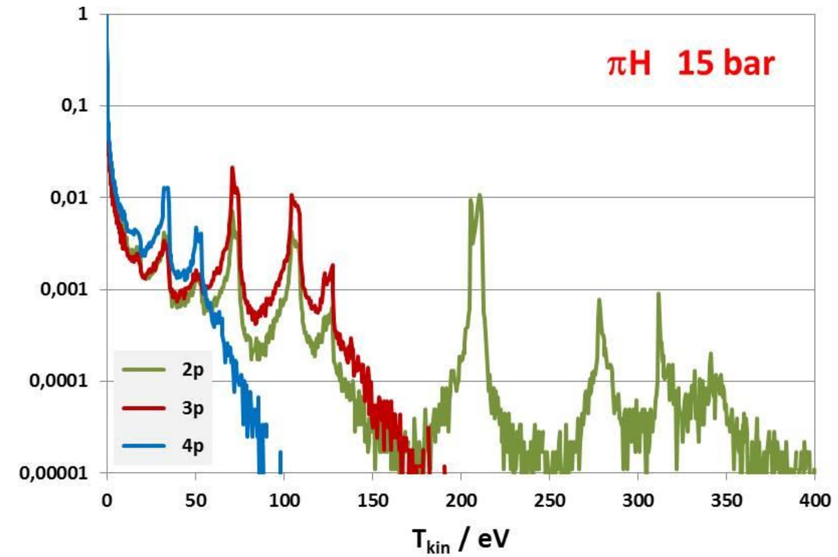
$\Delta E_{X,max} = 1,5\ eV \quad \pi H(3p-1s)$

neglected here: possible Δn=2 Coulomb transitions

STRATEGY II - input from cascade theory

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

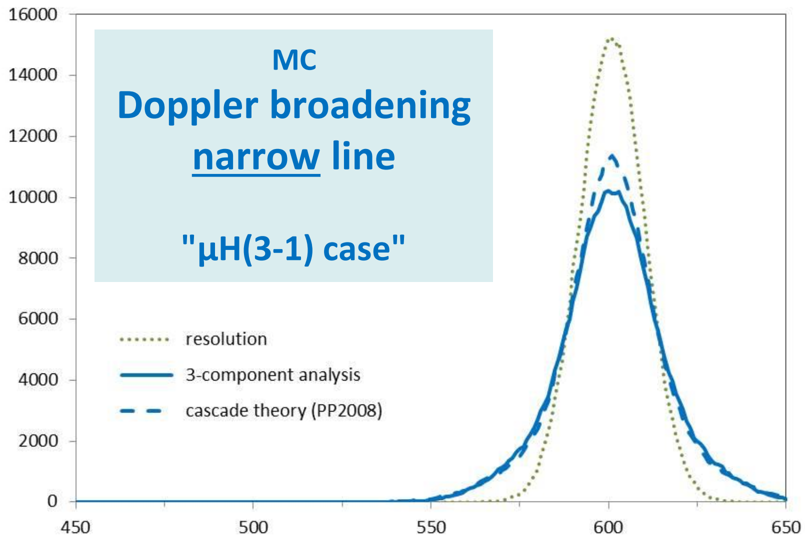


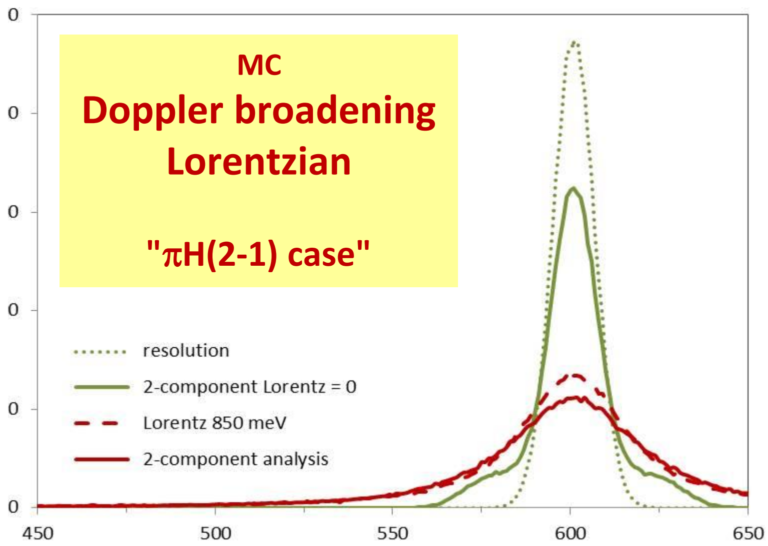


T.Jensen and V.Markushin — ***introduction of ESCM***

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

EXEMPLIFICATION

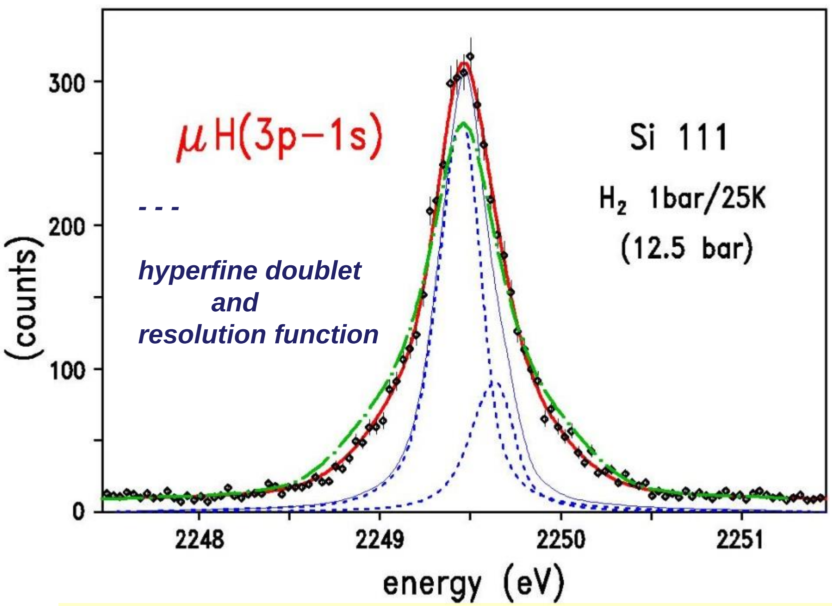


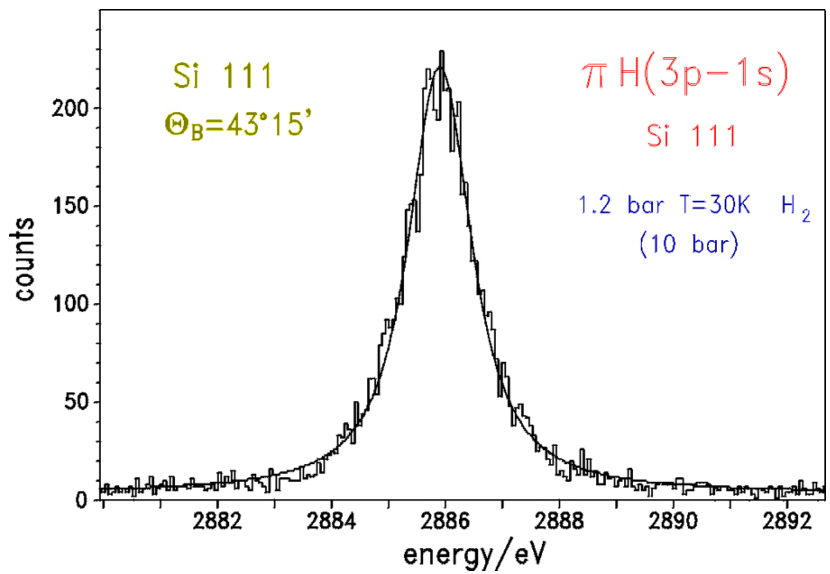


typical resolution (FWHM)

272 meV ***390 meV***

TYPICAL SPECTRA - parameter space





position
intensity
background
(response)

T/S ratio (HFS)

Γ_{hadronic}

kinetic energy distribution

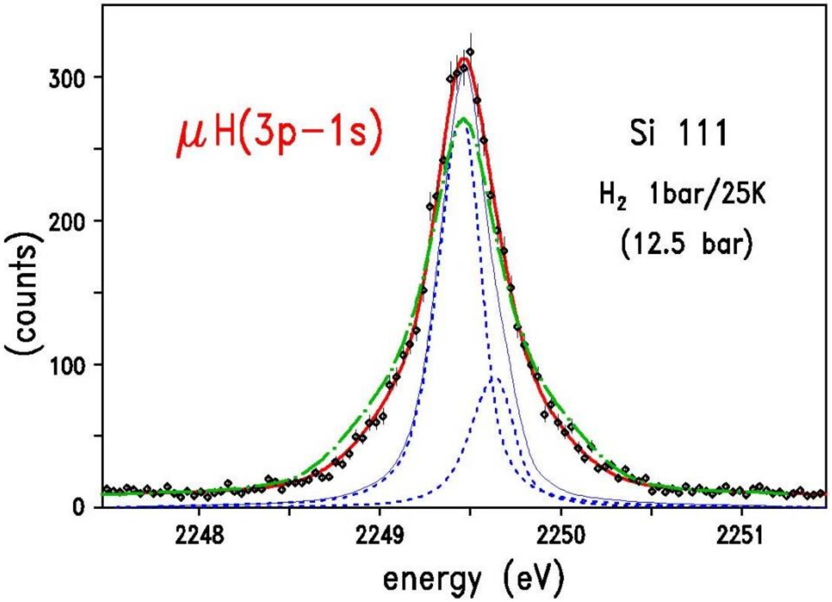
ANALYSIS METHODS

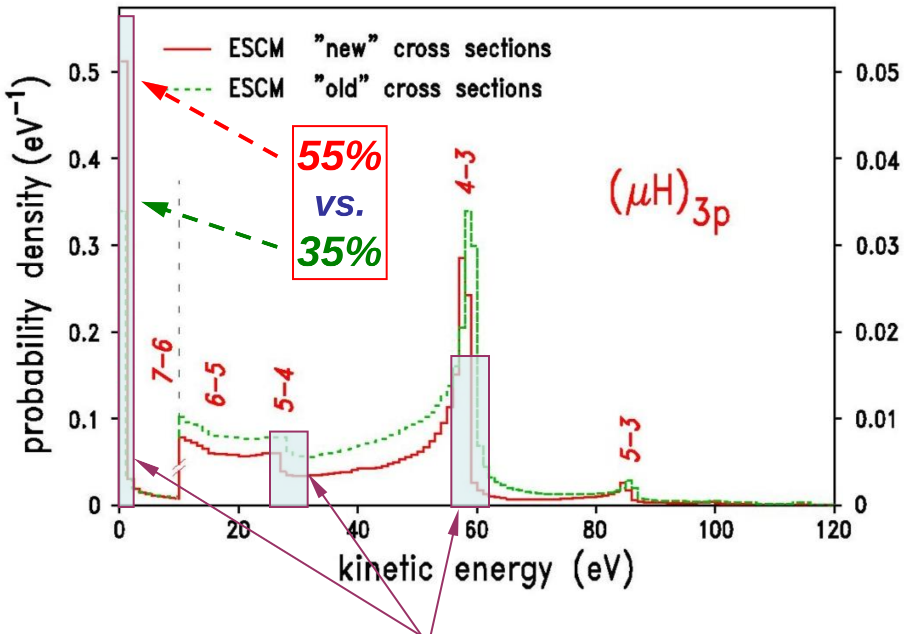
I **MAXIMUM LIKELIHOOD „FIT“**

„MINUIT“ χ^2 analysis

II **BAYESIAN APPROACH**

ANALYSIS METHOD I - µH(3p-1s) results





re-calculation of cross sections

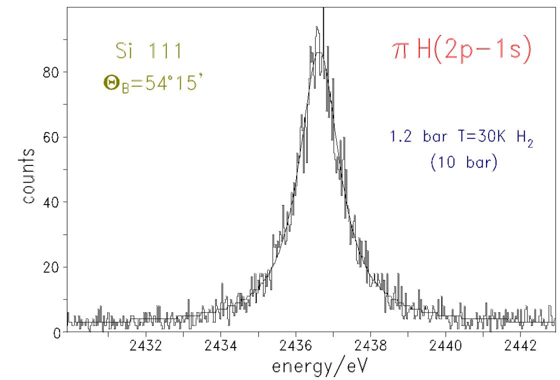
„box“ fits = model free fit

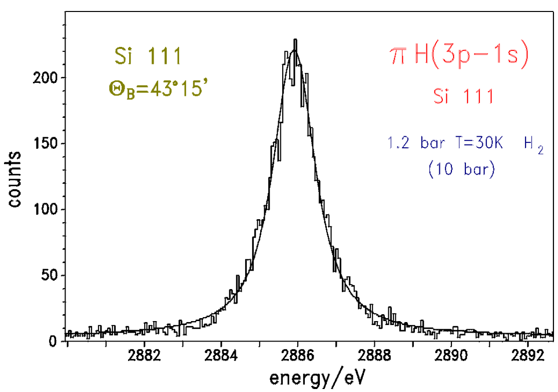
low-Tkin:	61 ± 2 %
medium-Tkin	25 ± 3 %
high-Tkin	14 ± 4 %

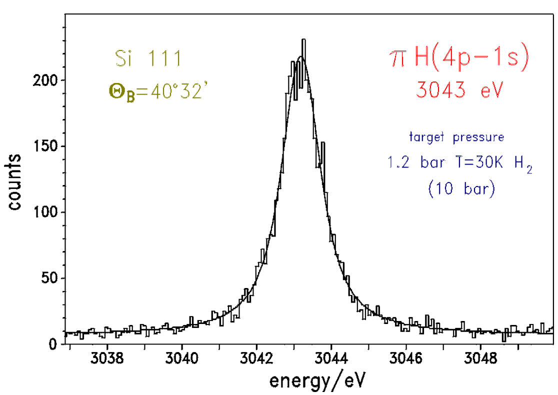
ESCM: extended standard cascade calculation and cross sections
T.S.Jensen and V.E.Markushin, Eur. Phys. J. D 19,165 (2002); ibid.D 21,261 (2002); ibid.D 21,271 (2002)

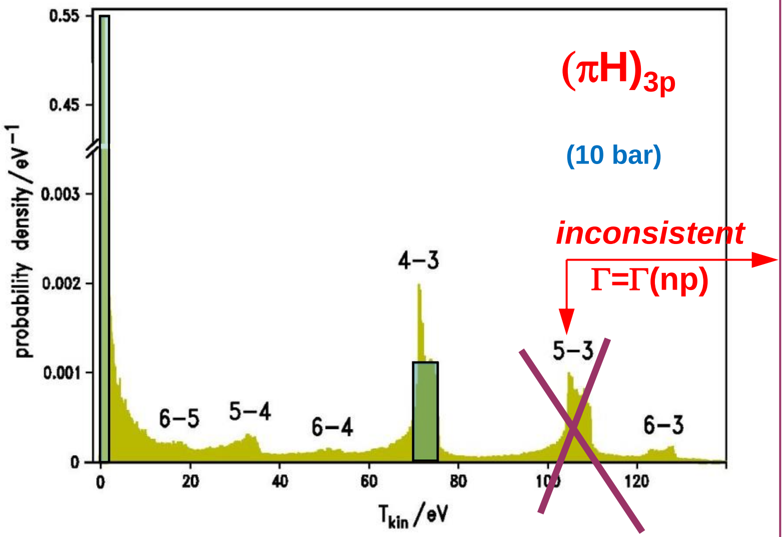
new cross sections G.Ya. Koreman, V.N. Pomerantsev and V.P. Popov, JETP. Lett. 81, 543 (2005)
V.N. Pomerantsev and V.P. Popov, Phys. Rev A 73, 040501 (2006)
V.P. Popov and V.N. Pomerantsev, arXiv:0712.3111v1[nucl-th] (2007)
V.P. Popov and V.N. Pomerantsev, Phys. Rev A 86, 052520 (2012)

ANALYSIS METHOD I - πH(np-1s) results









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	---

RE – ANALYSIS - BAYESIAN APPROACH

ASSESSMENT - of various MODELS ≈ kinetic energy distribution

?

- **discard MODELS**
- **average MODELS**
- **of error bars**

„FITS“	**BAYESIAN APPROACH**
How well fit	
data to the model?	***models to the data?***
↓	↓
numbers (bias!)	***probability distributions***

BAYES THEOREM

$$P(H \mid d, I) = \frac{L(d \mid H, I)\, P(H, I)}{P(d \mid I)}$$

H (the hypothesis)
d (the observed data)
I (any background information)

P(H | d,I) : posterior — state of knowledge about H after seeing the data
L(d | H,I) : likelihood — probability of obtaining data if hypothesis H is true
P(H,I) : prior — what we know (random choice)
P(d|I) : evidence — normalization constant (Model comparison!)

Given the data D, which is the probability for the the parameters?

Bayes' theorem describes a method to update knowledge

method for multi-parameter space: nested sampling John Skilling 2004

„walk up“ the hill until top

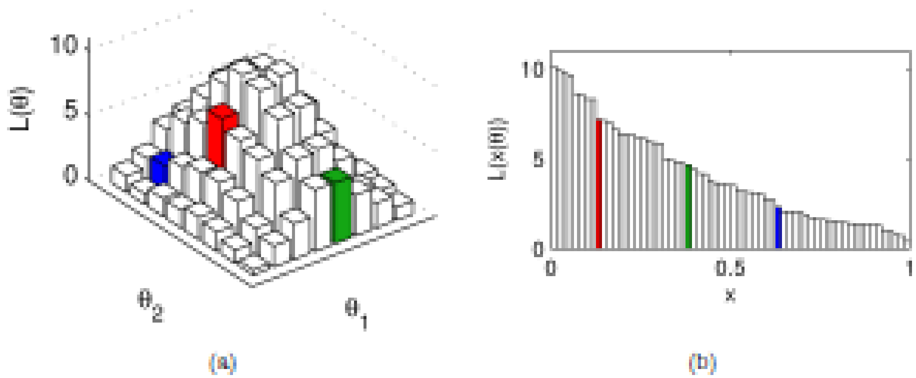
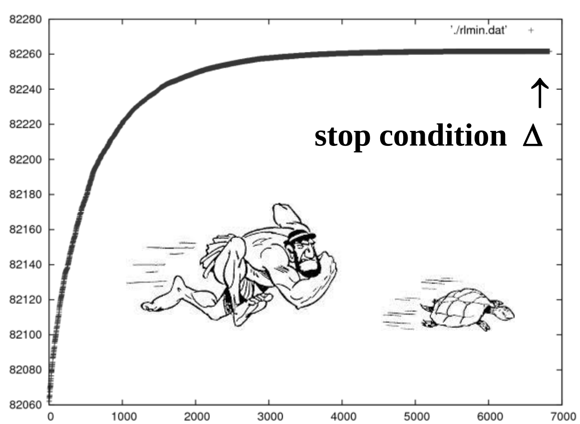
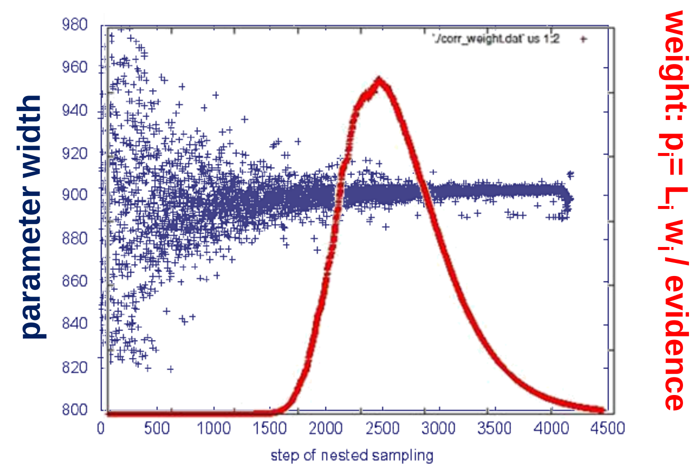


figure from: Iain Murray, Thesis, University of London, 2007

example for 2-dim parameter space

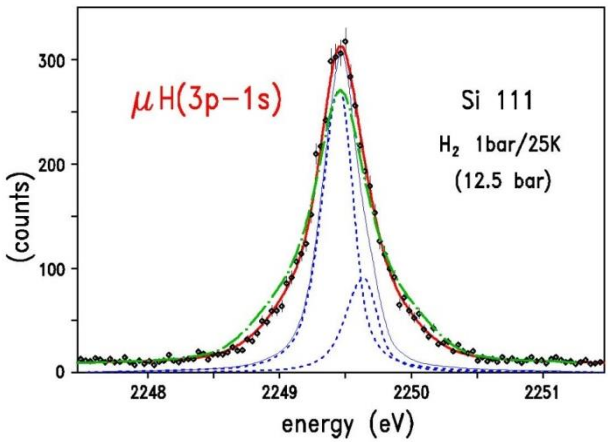
log(L_i)



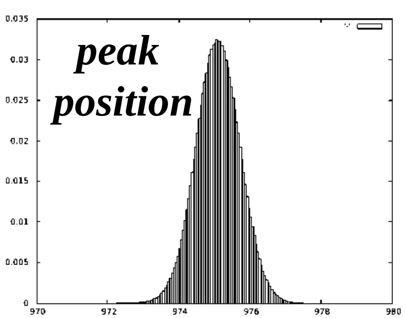


prior Γ: 600 – 1200 meV

ANALYSIS METHOD II - µH(3p-1s) results

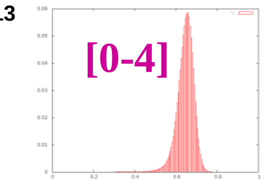


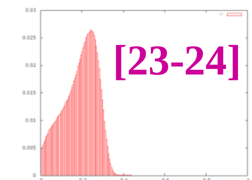
„obvious" parameters look like Gaussian

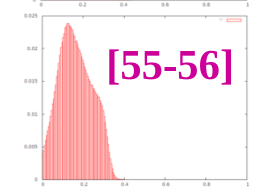


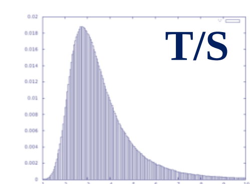
comparison: 3-component model

χ^2 analysis		Bayesian approach (M.Theisen, Diploma thesis FZJ 2013)	
[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		$2.5^{+1.1}_{-0.5}$









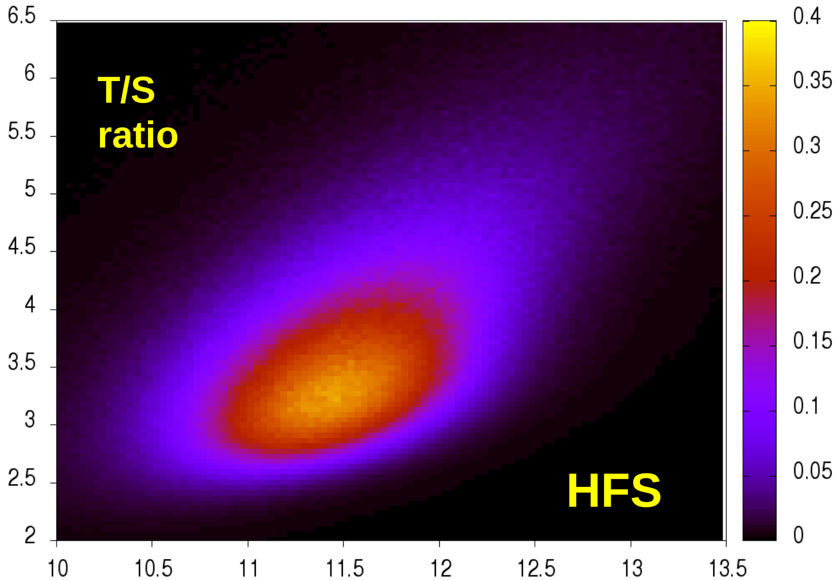
ANALYSIS METHOD II - μH(3p-1s) results

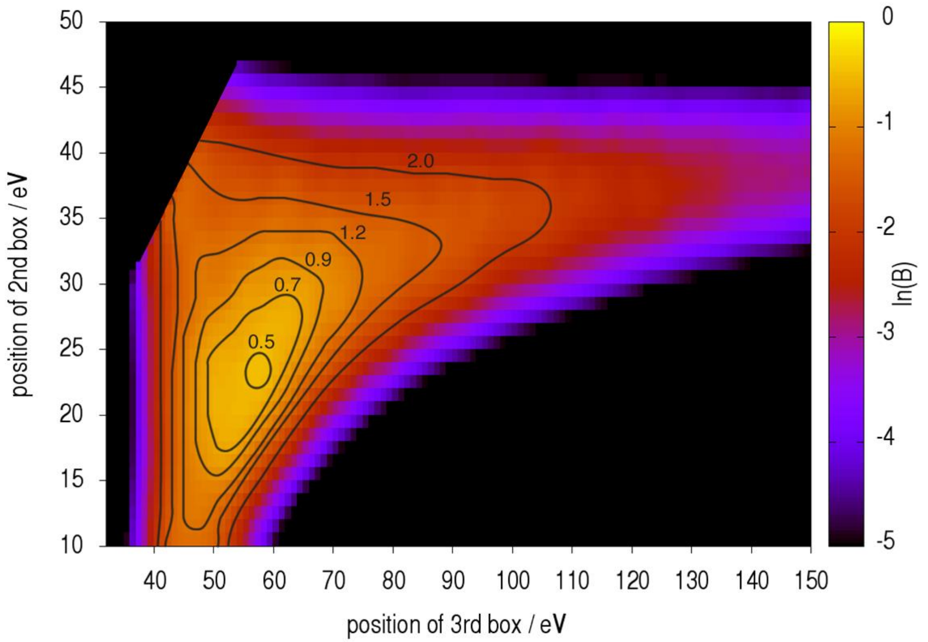
two-dimensional posterior probability

HFS free 212^{+23}_{-21}

T/S $3.2^{+1.6}_{-0.7}$

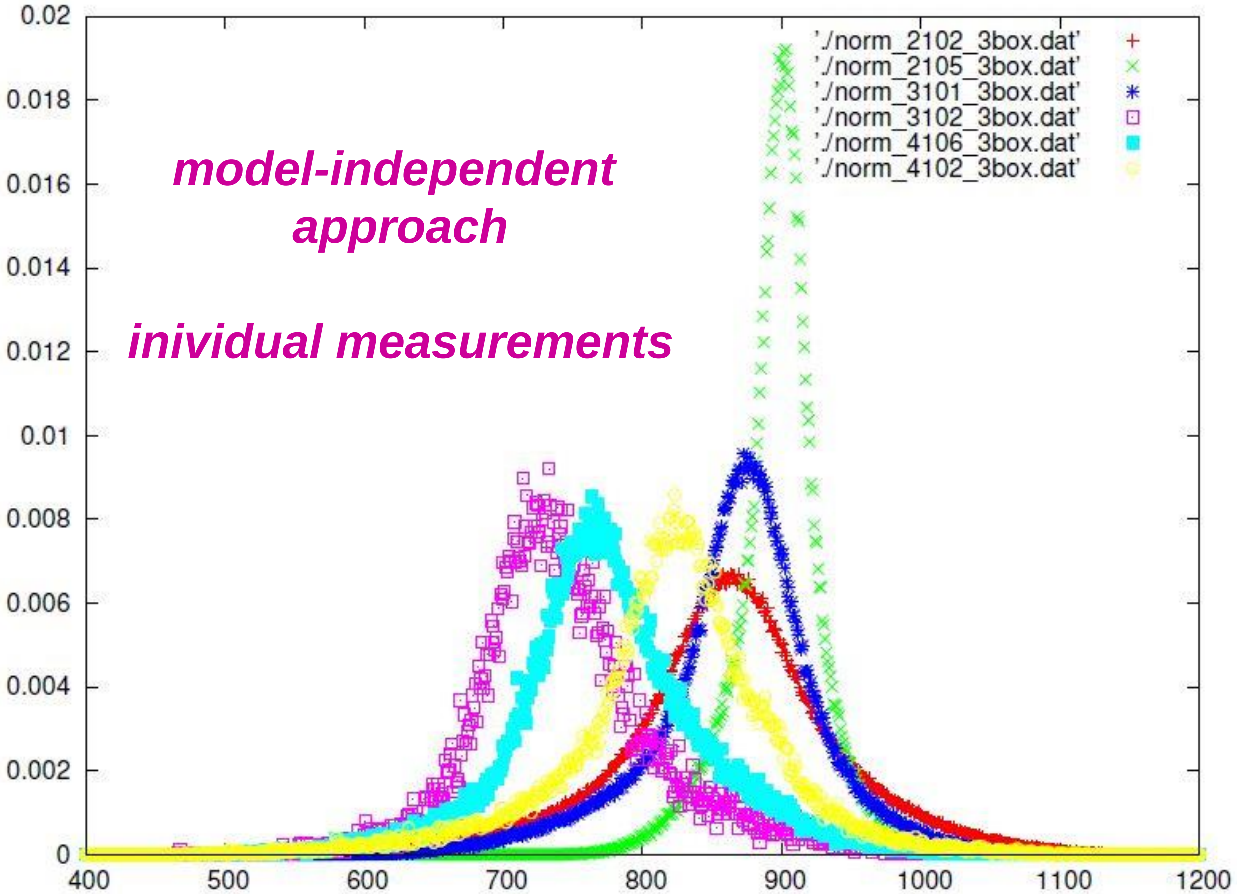
High-energy components





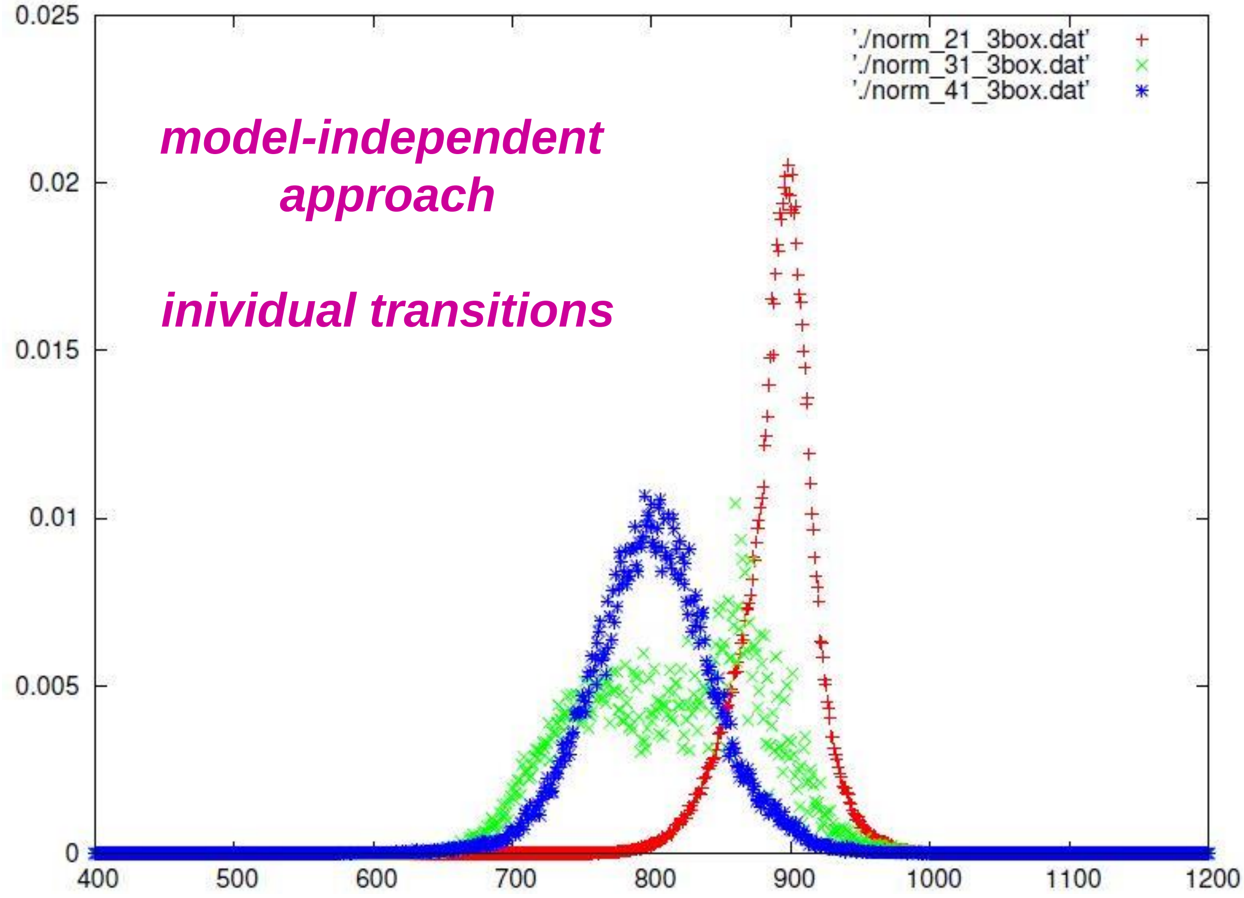
M.Theisen, Diploma thesis FZJ 2013

ANALYSIS METHOD II - πH(np-1s) Γ results



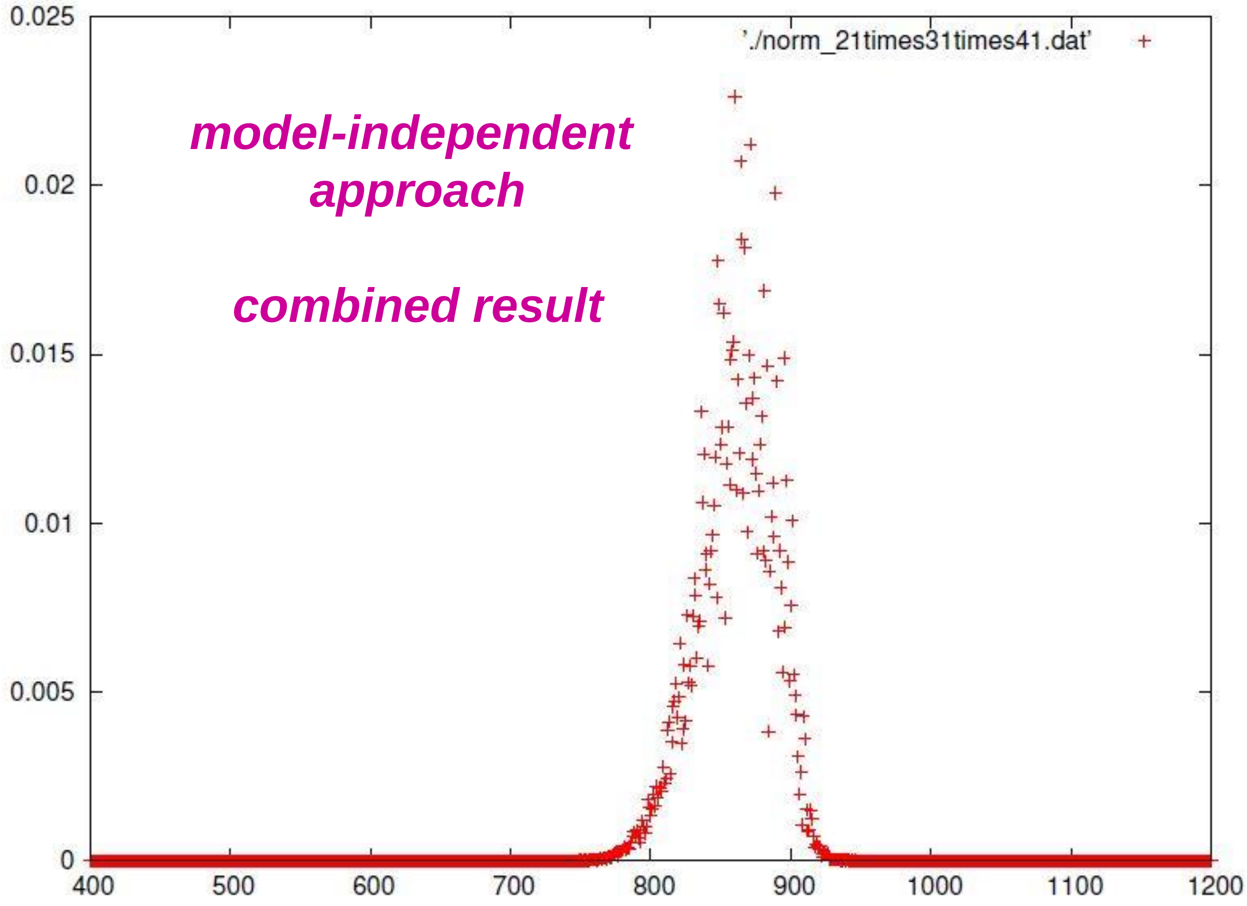
3-component model

ANALYSIS METHOD II - πH(np-1s) Γ results



3-component model

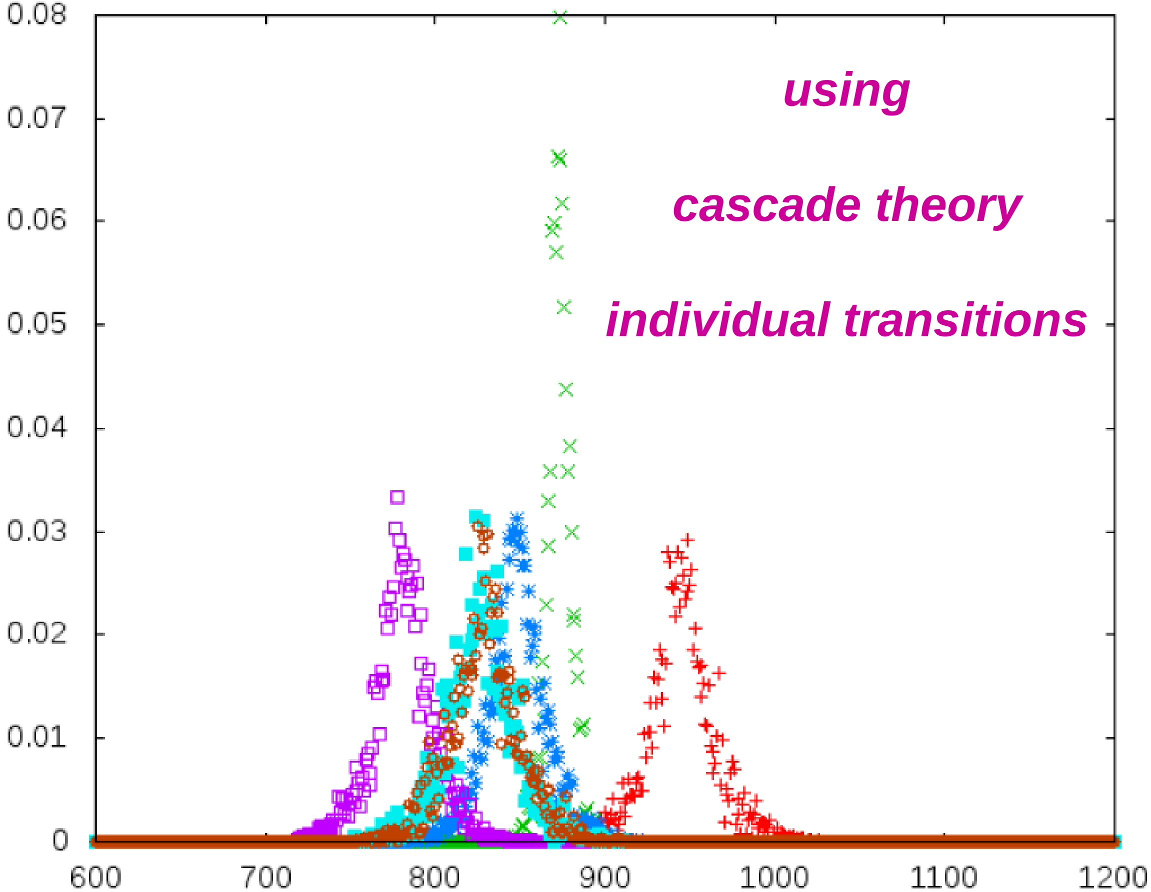
ANALYSIS METHOD II - πH(np-1s) Γ results



3-component model

$$\Gamma = 850 {}^{+40}_{-50} \text{ meV}$$

ANALYSIS METHOD II - πH(np-1s) Γ results



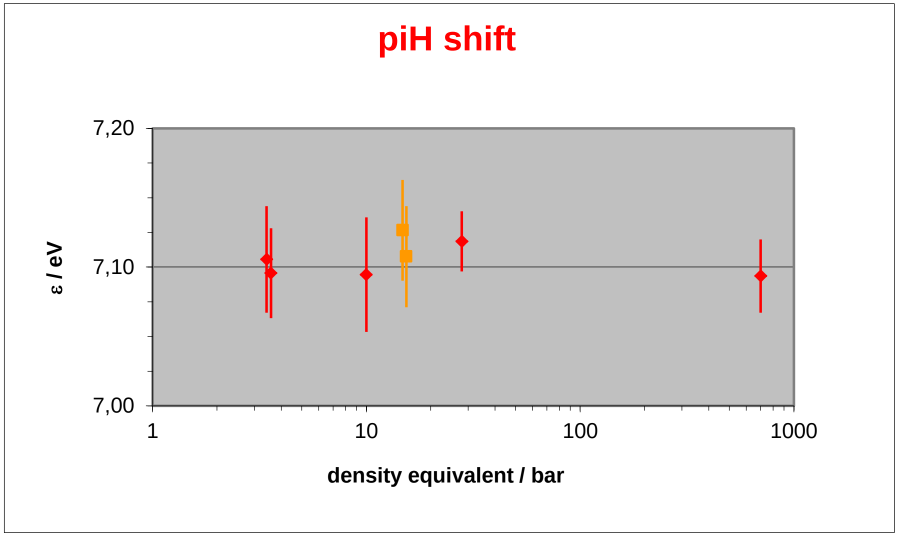
cascade calculation

V.N. Pomerantsev and V.P. Popov

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

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

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



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

P. Indelicato, priv. comm.

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

cancels mainly using πO *calibration*

new QED value available since 2011: - 22 meV!

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

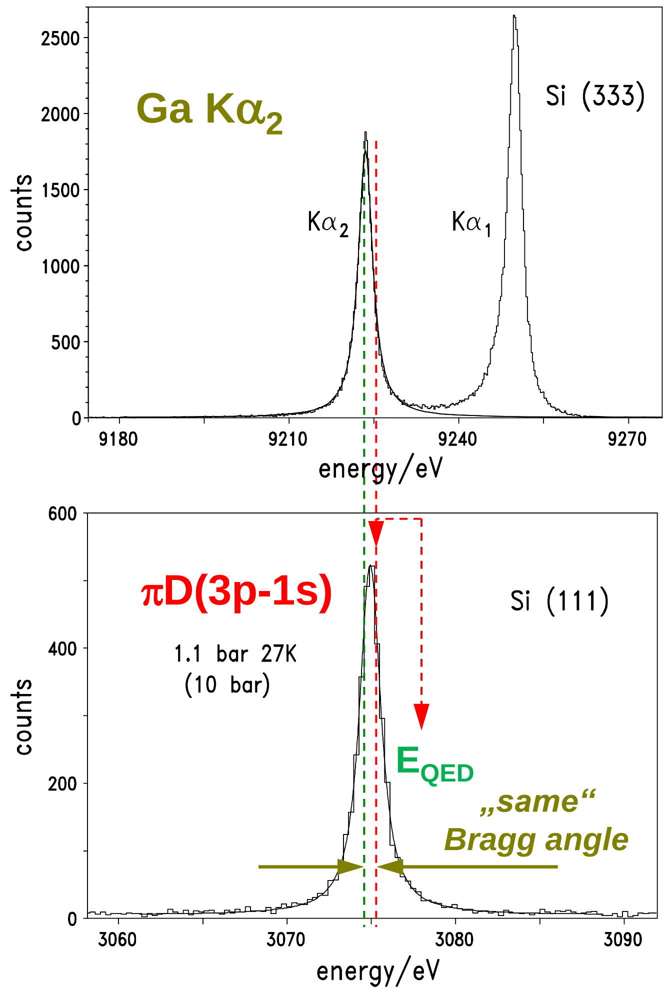
previous experiment – Ar Kα

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

$$\varepsilon_{1s} = +\ 7.0869 \pm 0.0071 \pm 0.0064\ \text{eV}\ \ (\pm\ 0.13\%)\ \text{final}$$

$\pi D(3p\text{-}1s)$ *density dependence of transition energy*

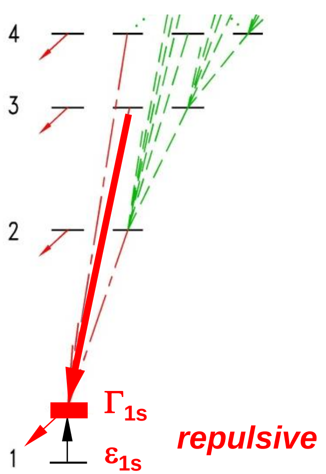
energy calibration



target material: GaAs

by chance: tabulated energy
<u>also</u> from GaAs
⇒ no chemical shift

strong interaction



3 bar
10 bar
22 bar
} no molecule formation seen

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

error budget

± 27 meV	Ga Kα$_2$
± 10 meV	statistics
± 8 meV	pion mass
± 5 meV	systematics
± 2 meV	QED

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^-

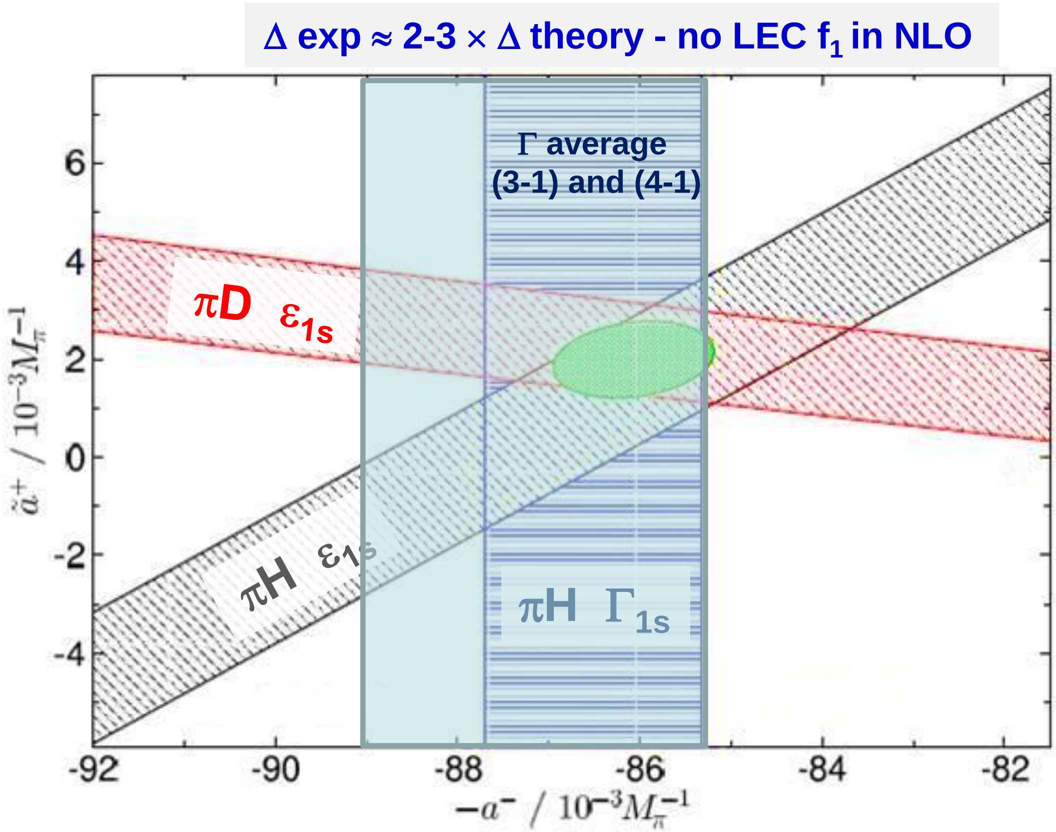


FIG. 2: Combined constraints in the $\tilde{a}^+ - a^-$ plane from data on the width and energy shift of πH, as well as the πD energy shift.

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 (208) 165 (preliminary)
πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88 (final)

NN ⇔ πNN threshold parameter α

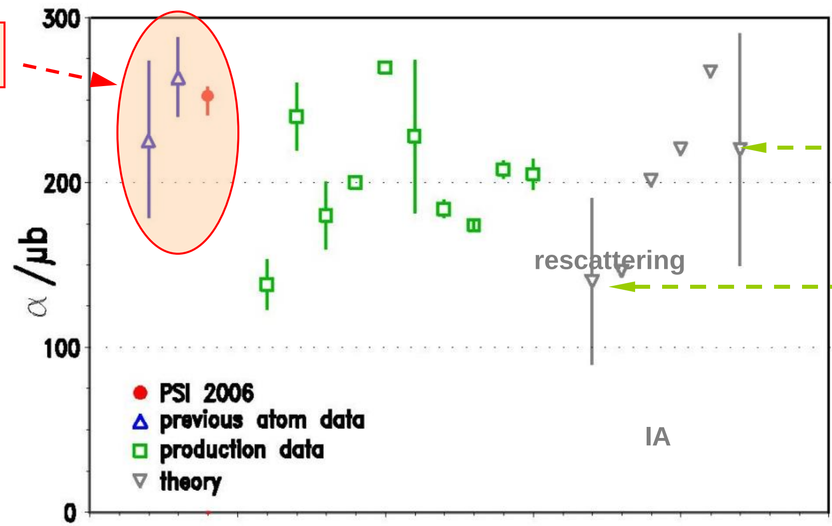
$\pi D \quad \Gamma_{1s} \propto \alpha$

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 NLO

χPT LO

χPT

at present

Δα/α ≈ 30%

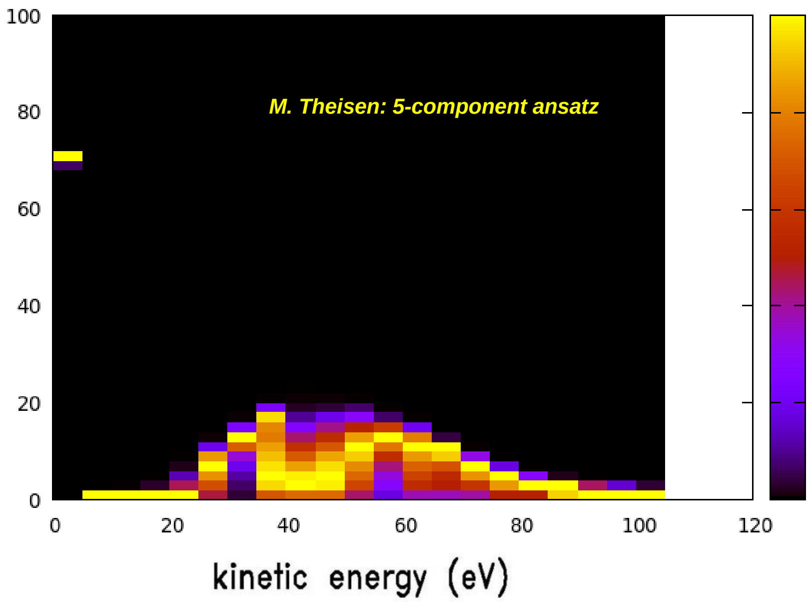
→ few % !?

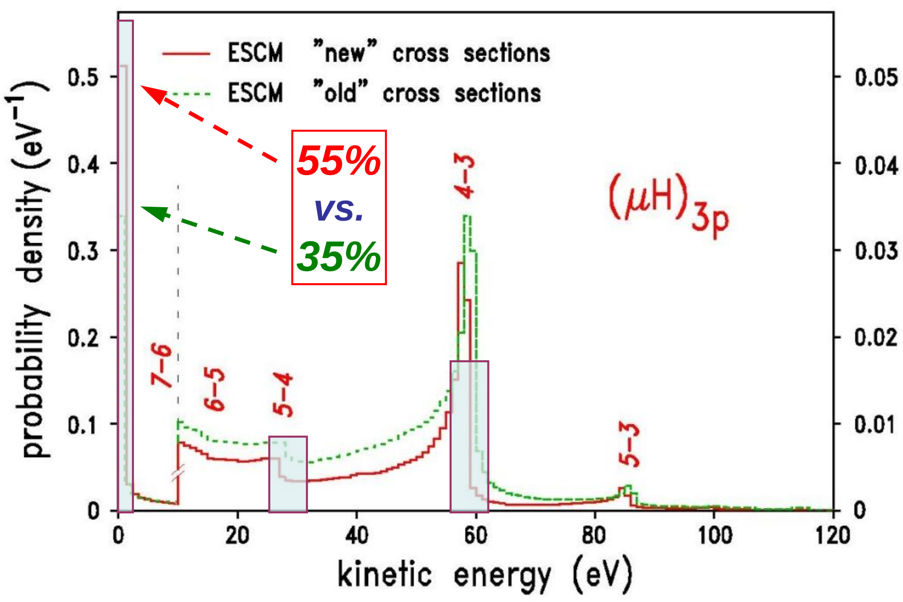
V. Lensky et al., Eur. Phys. J. A 27 (2006) 37

MUONIC HYDROGEN – *NEW UNFOLDING METHOD ?*

Can we infer a kinetic energy distribution by the Bayesian approach?

L.Simons, priv. comm.





Is this a reasonable description of line the shape?

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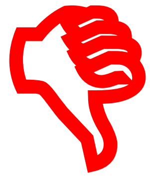
- πN scattering length: bands cross
- s - wave π - production strength
- μH – singlet / triplet
  - ΔE_{HFS}
  - cascade theory explains line shape



- π**H – spreading of Γ_{1s} unsatisfactory**

origin unknown ***- cascade ?***

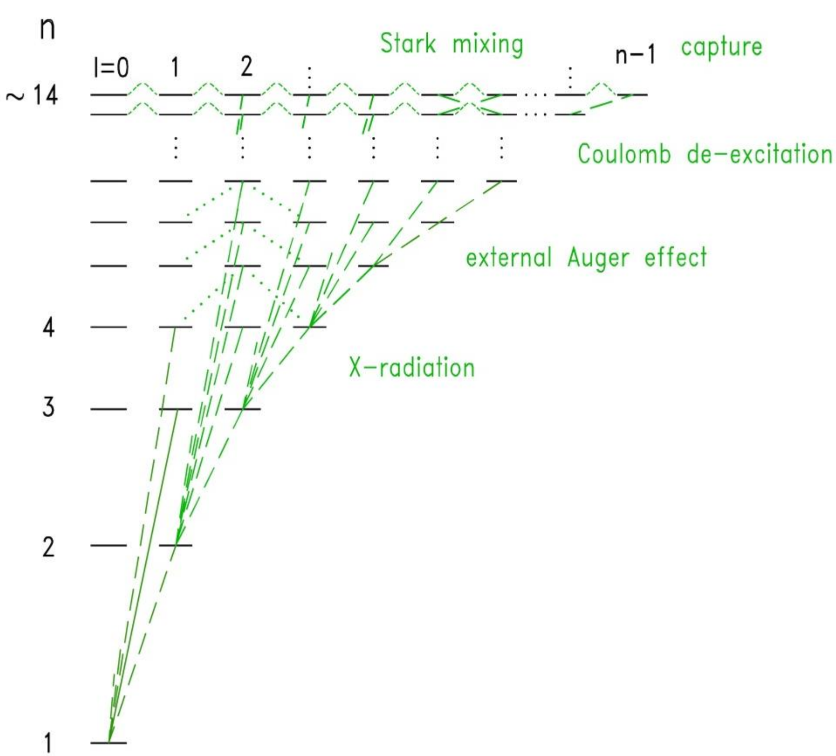
- analysis ?

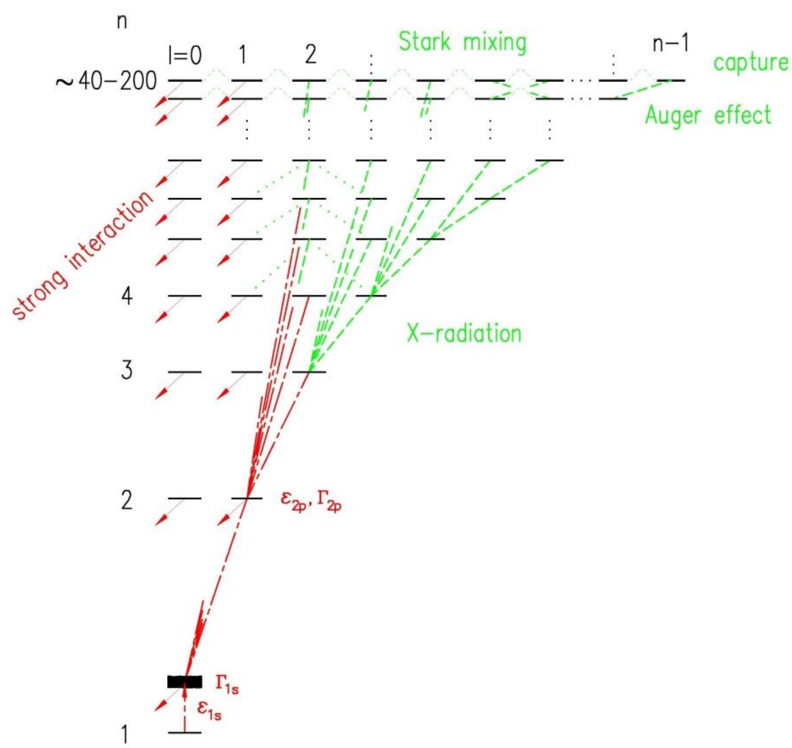
- experiment ?

- π**D – Coulomb de-excitation ?**

WHERE DO THEY GO ?

μH	πH
X-rays from p-states fed from ***everywhere***	*X-rays from p-states fed from* ***l > 1***

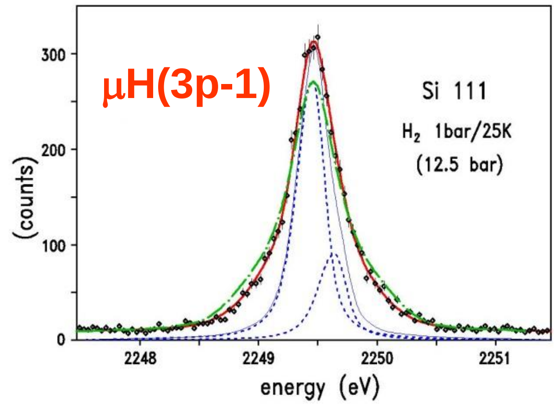




IS SOMETHING MISSING ?

? *X-ray satellites from molecular formation*

- none seen in πD -



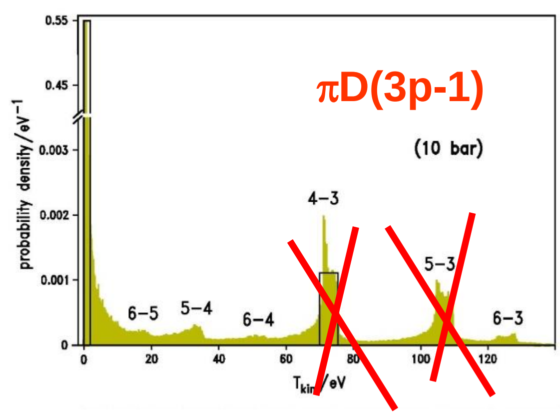
0-2 eV	*61 ± 2 %*
5-4	*25 ± 3 %*
4-3	*14 ± 4 %*

≈ πH

μD

? *high-energy components*

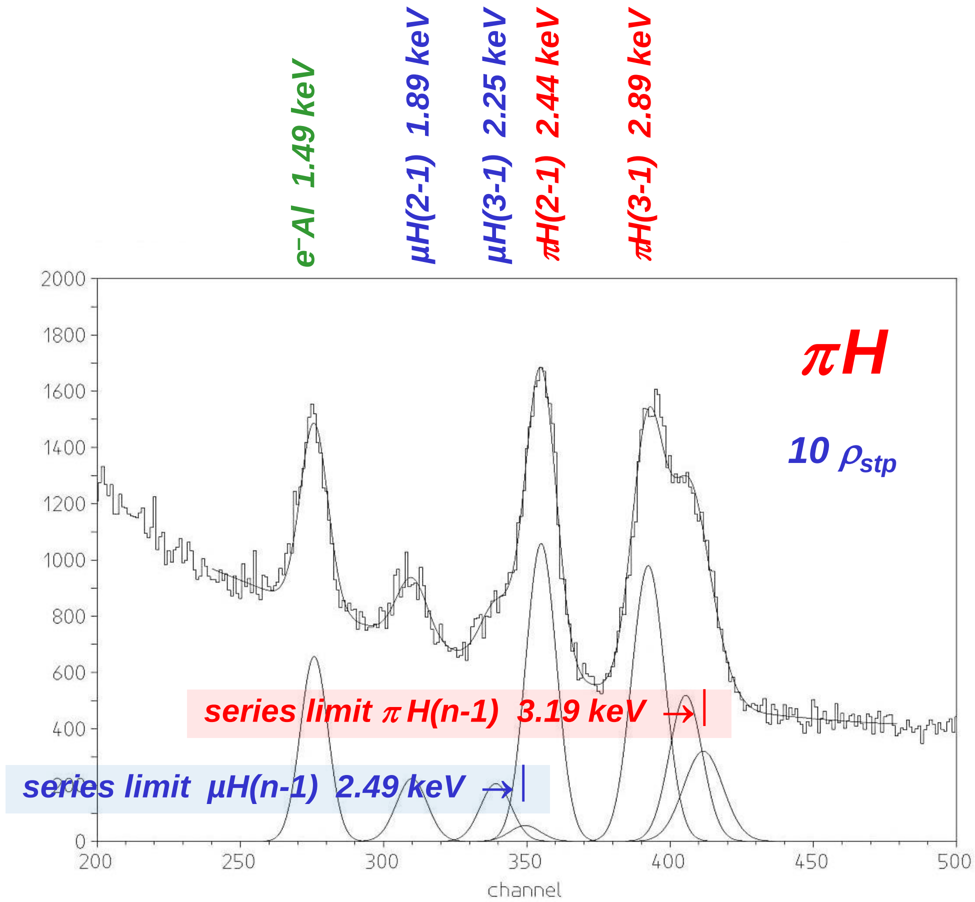
- no cascade calculation yet -



? *does cascade theory improve for πH as for μH - if yes: $\Delta\Gamma \rightarrow \Delta\Gamma /2$*

cross sections

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

PIONIC HYDROGEN collaboration

PSI experiments R-98.01 and R-06.03

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Vienna, SMI
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Cascade theory

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

→ Diploma and PhD thesis ←

THANK YOU