Experimental study of

hadron properties in the nuclear medium

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早野龍五

THE UNIVERSITY OF TOKYO

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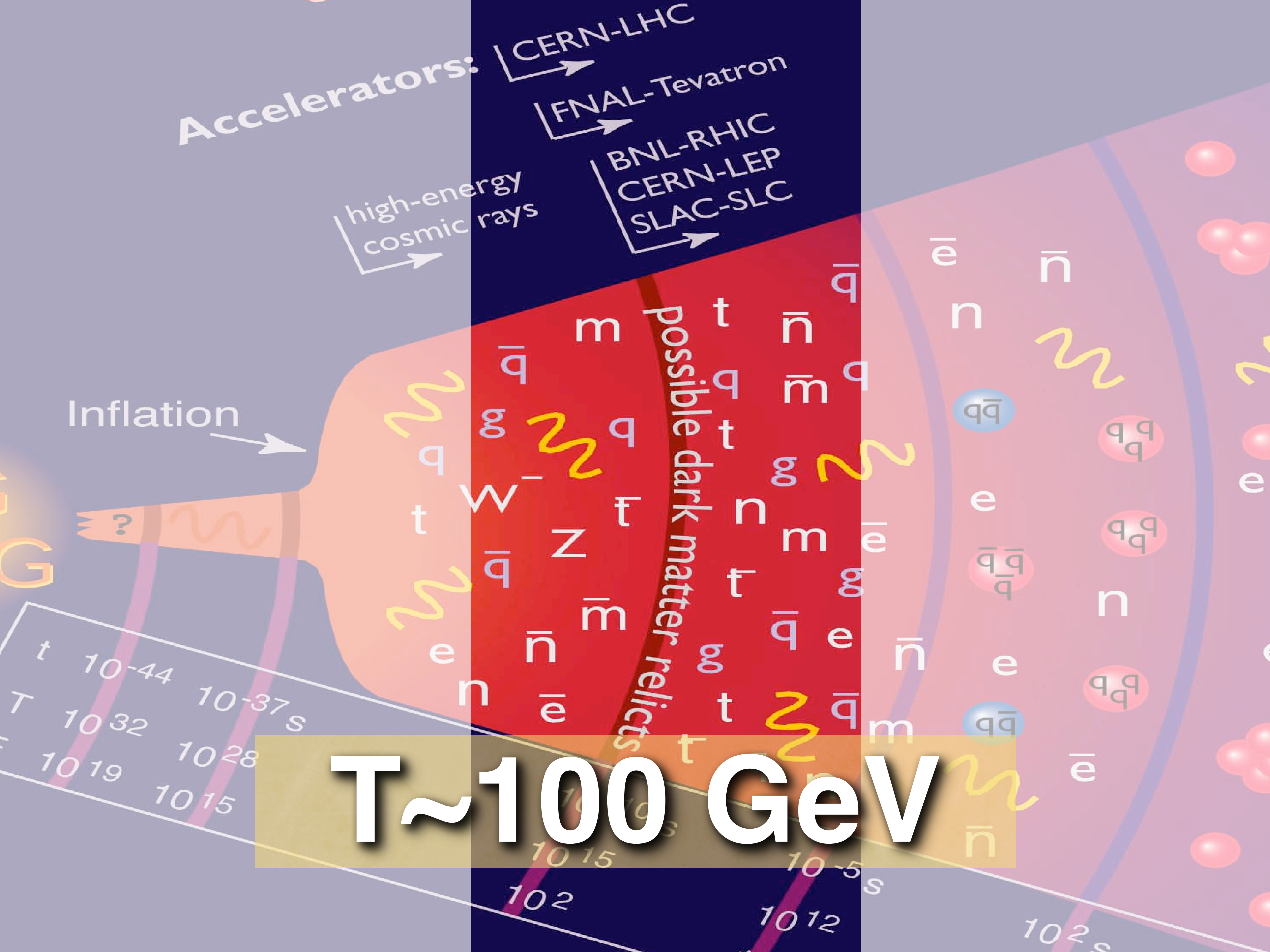
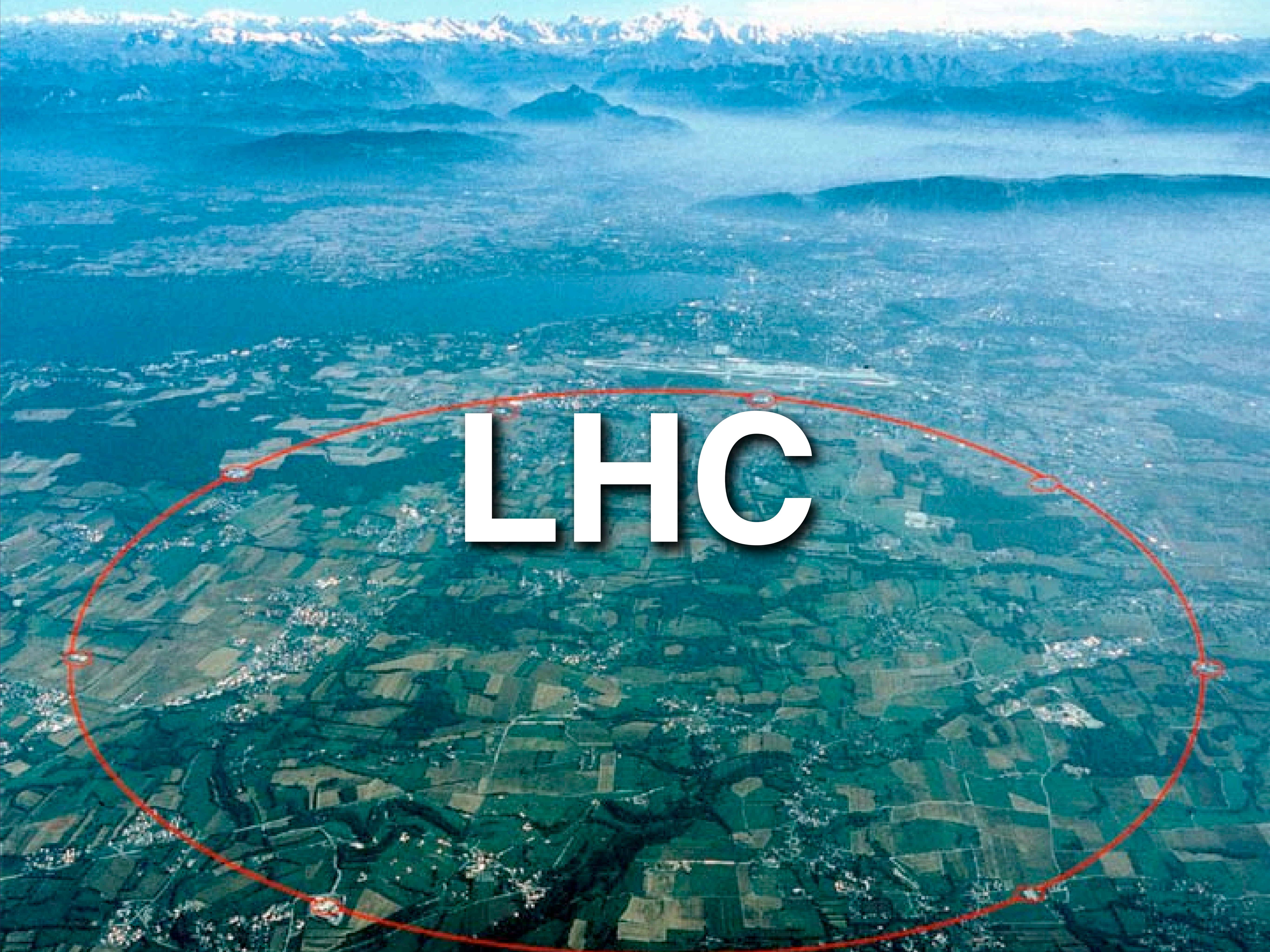
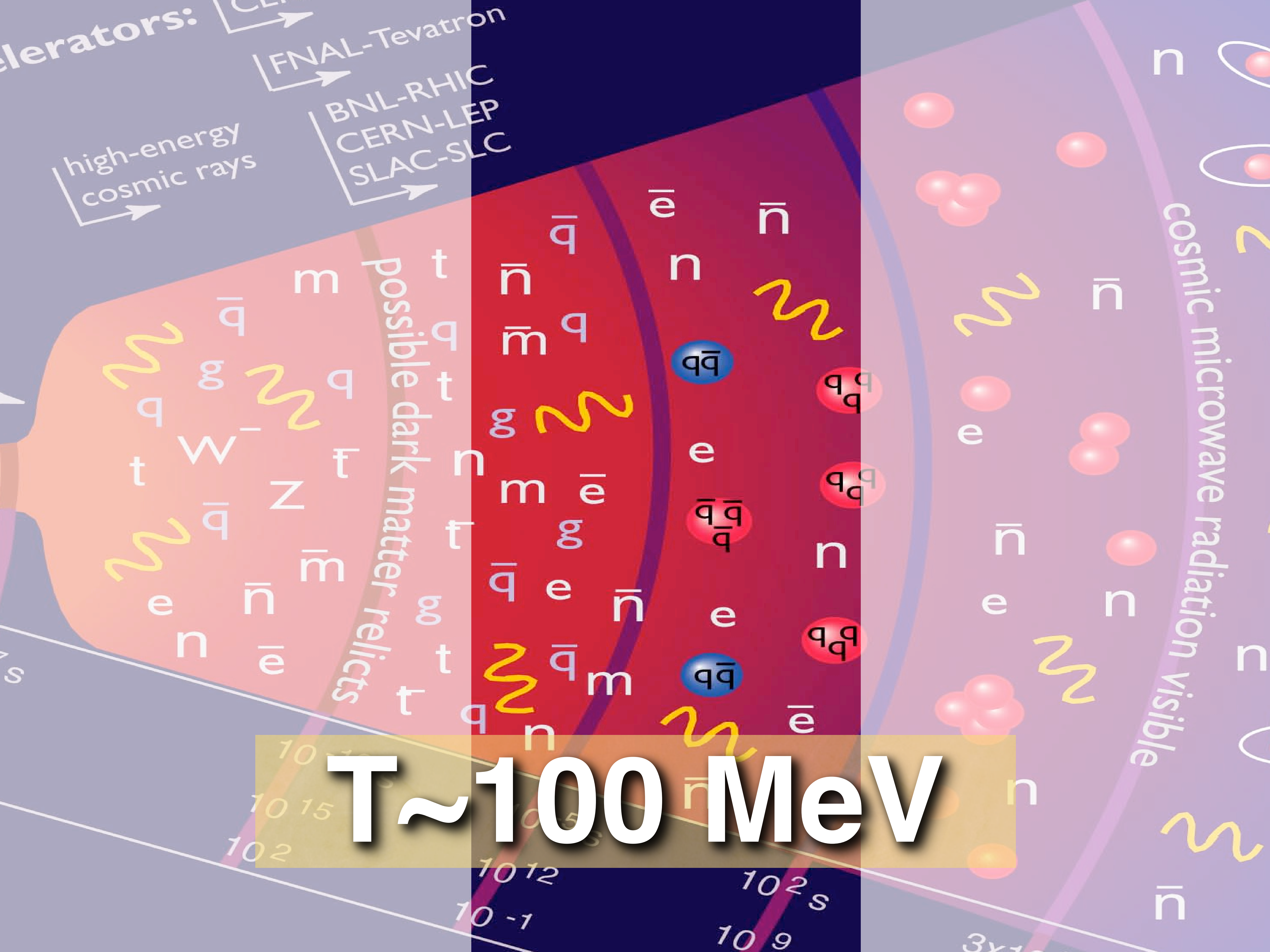
始

Beginning

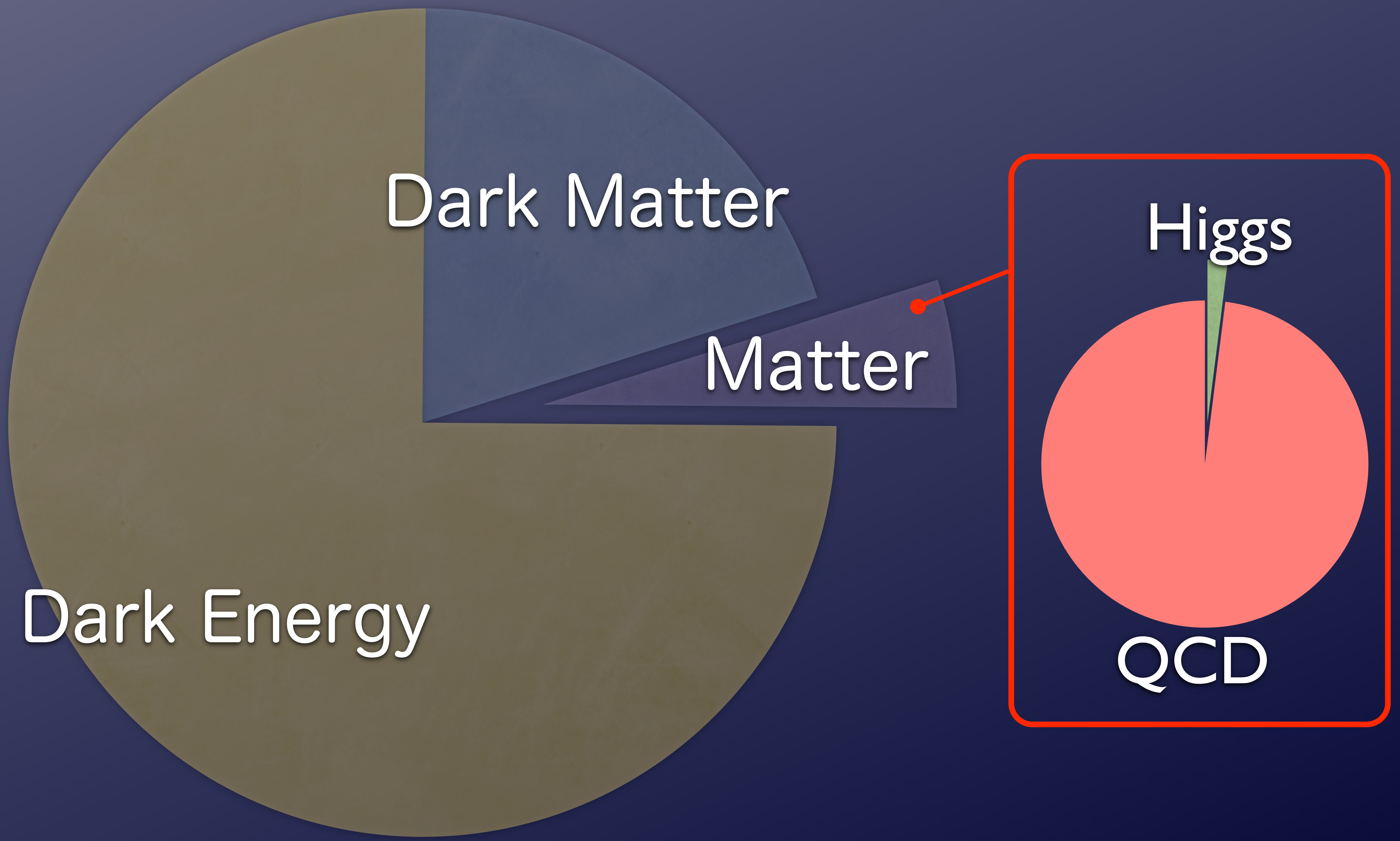

Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
possible dark matter relicts
T~100 GeV

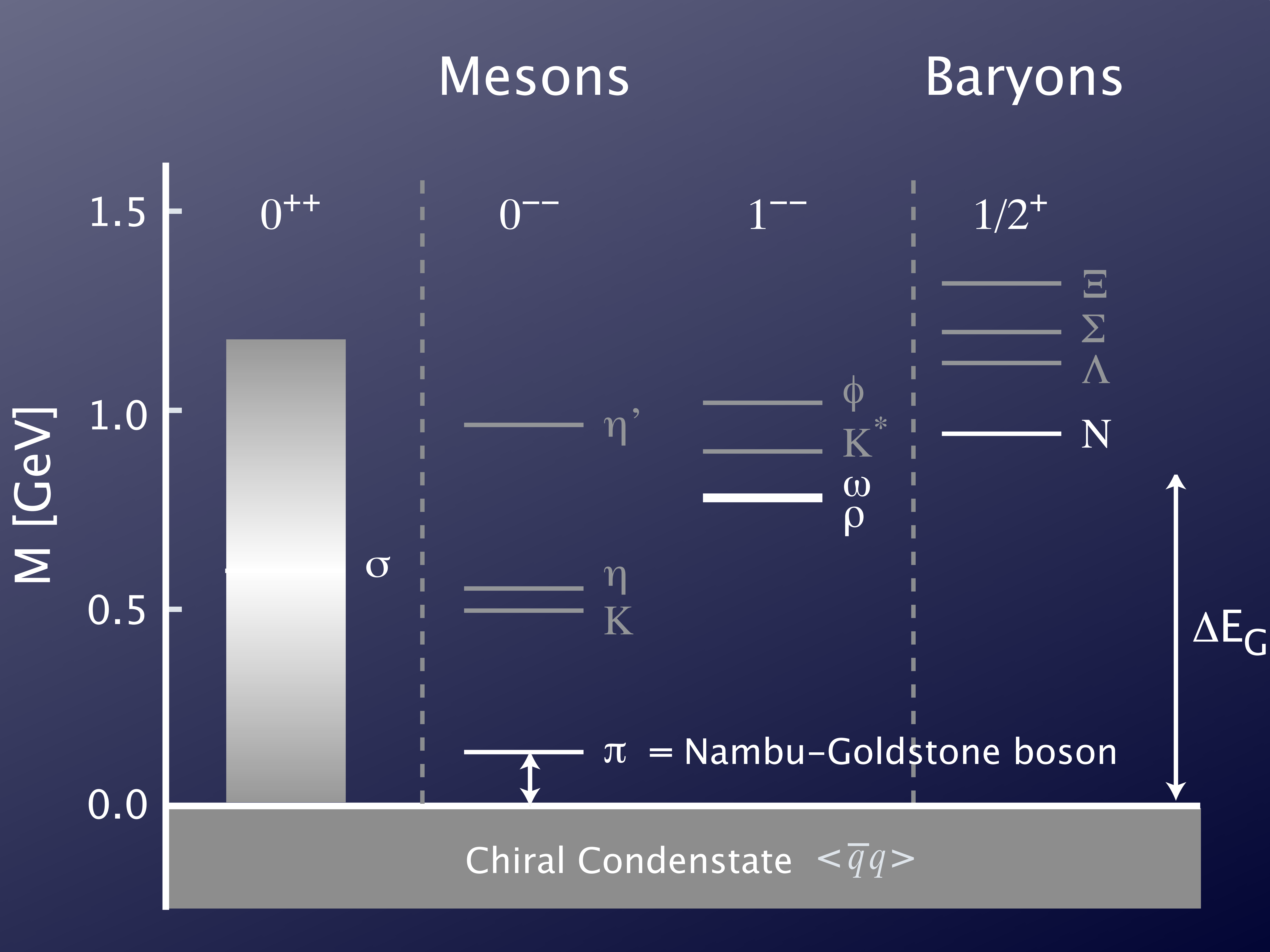

LHC


Higgs Search



FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
possible dark matter relicts
cosmic microwave radiation visible
T~100 MeV


Dark Matter
Matter
Dark Energy
Higgs
QCD


Mesons
Baryons
M [GeV]
1.5
1.0
0.5
0.0
0++
0--
1--
1/2+
σ
η'
η
K
φ
K*
ω
ρ
Ξ
Σ
Λ
N
π = Nambu–Goldstone boson
ΔE_G
Chiral Condensate <q̄q>

The Origin of the proton mass

why the proton is heavy
when its ingredients are essentially massless

回顧

retrospect

NUCLEAR PHYSICS A

Journal devoted to the experimental and theoretical study of the fundamental constituents of matter and their interactions

INPC'92, Wiesbaden

VOLUME A553

MARCH 1993

Welcome address

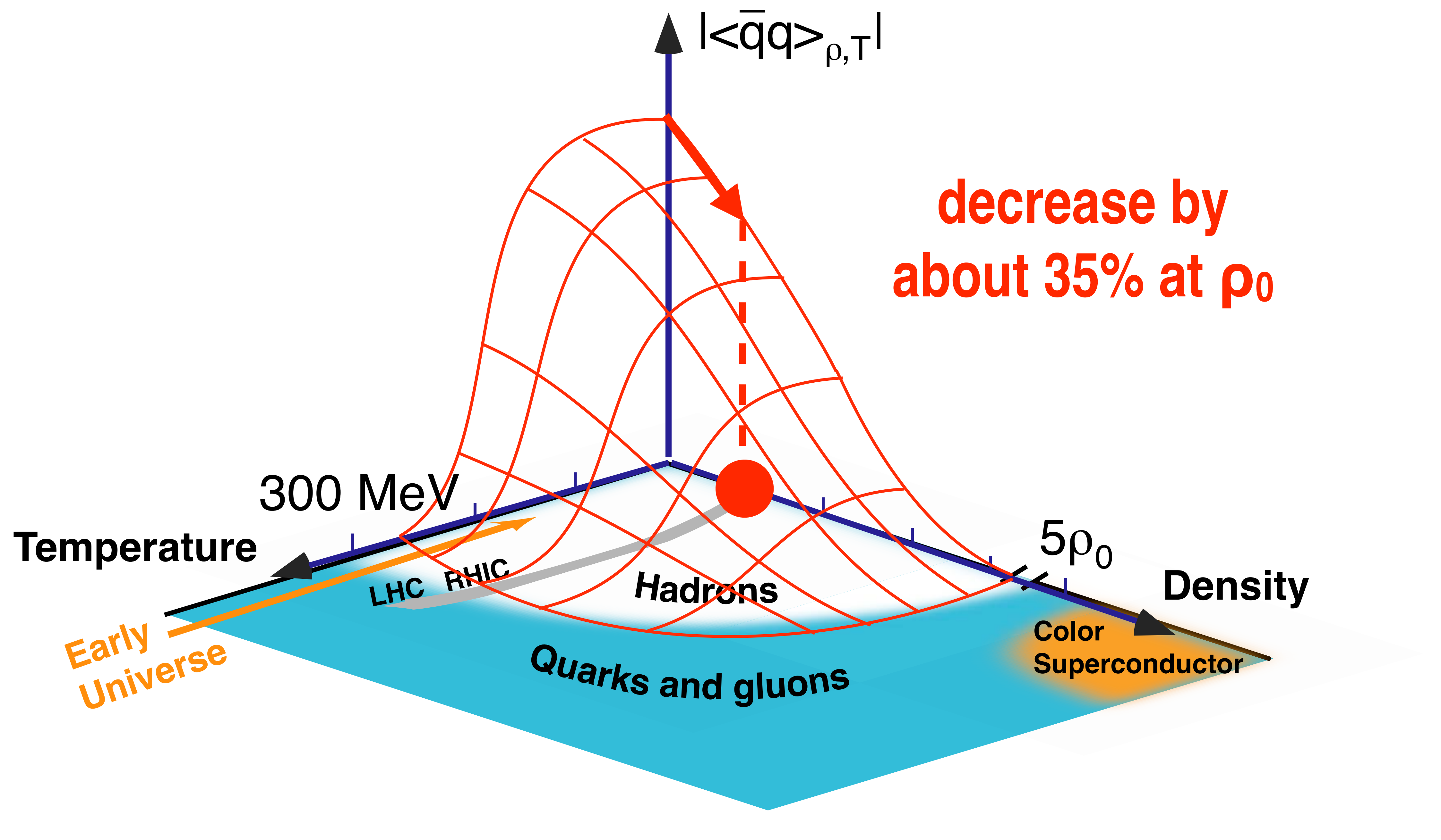
P. Kienle

Hochverehrte Frau Minister,
Sehr geehrte Frau Stadtkämmerin,
Sehr geehrter Herr Ministerialdirigent,
Dear colleagues,

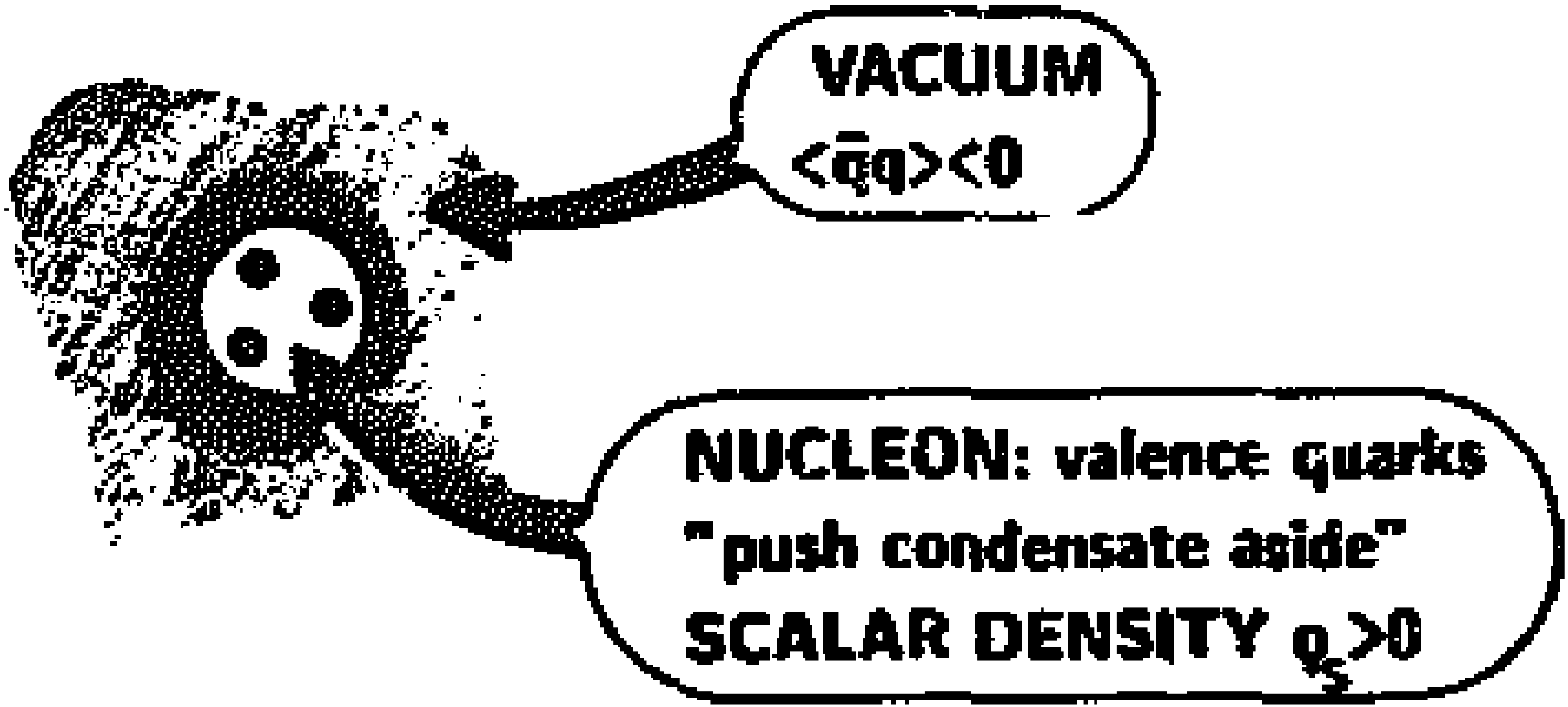
It is a great honour and pleasure for me to welcome you at the INPC'92 in charming Wiesbaden. I am very pleased that we can host this most prestigeous meeting of nuclear physicists a second time in Germany after the illustrious Munich Conference in 1973, with the noble state reception in the Antiquarium of the Residence, and the less noble battle of our participants for a Käfer buffet in Schloss Schleissheim. We cannot offer you anything like that, because this was the golden era of *our* science and science in general. Since then the reputation of science has declined in the hands of our opinion makers, but as science is made in laboratories and not in newspapers, it has survived all this. On the contrary, it became very virile in the public exile of the last decade.

Broken symmetries and the physical vacuum	T. D. Lee
Recent developments in neutrino physics	Rudolf L. Mößbauer
Ultra-relativistic heavy-ion collisions: Searching for the quark-gluon plasma	J. Schukraft
Lattice QCD and nuclear physics	John W. Negele
Nuclear aspects of chiral symmetry	**W. Weise**
The quark-gluon plasma	Jean-Paul Blaizot

Chiral condensate



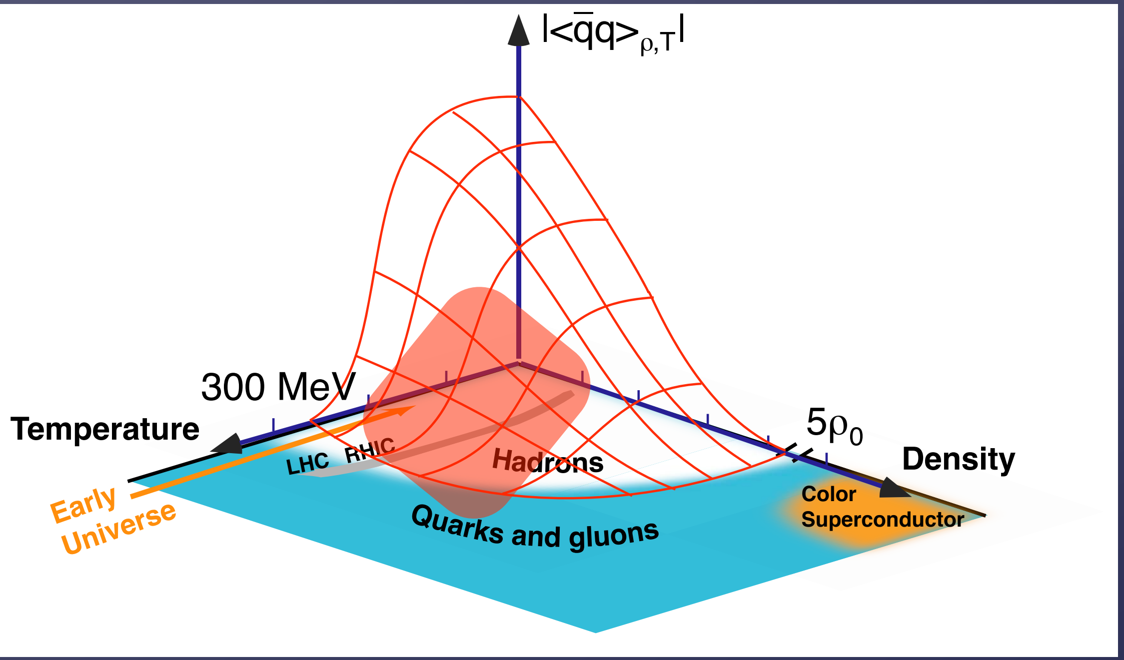
W. Weise, NPA 553 (1993) 59

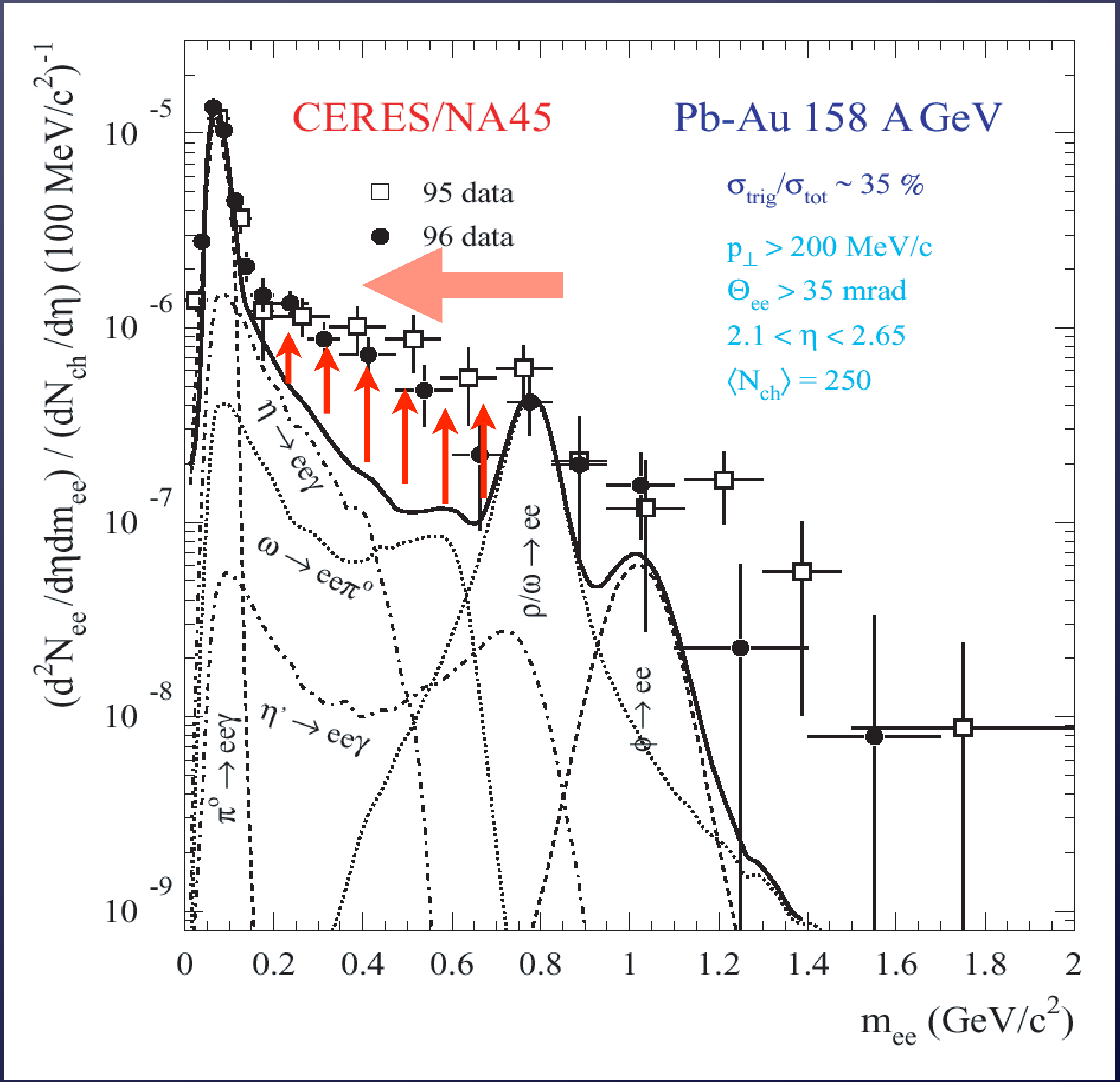


W. Weise, NPA 553 (1993) 59

15 years since Wiesbaden

High energy heavy ion collisions

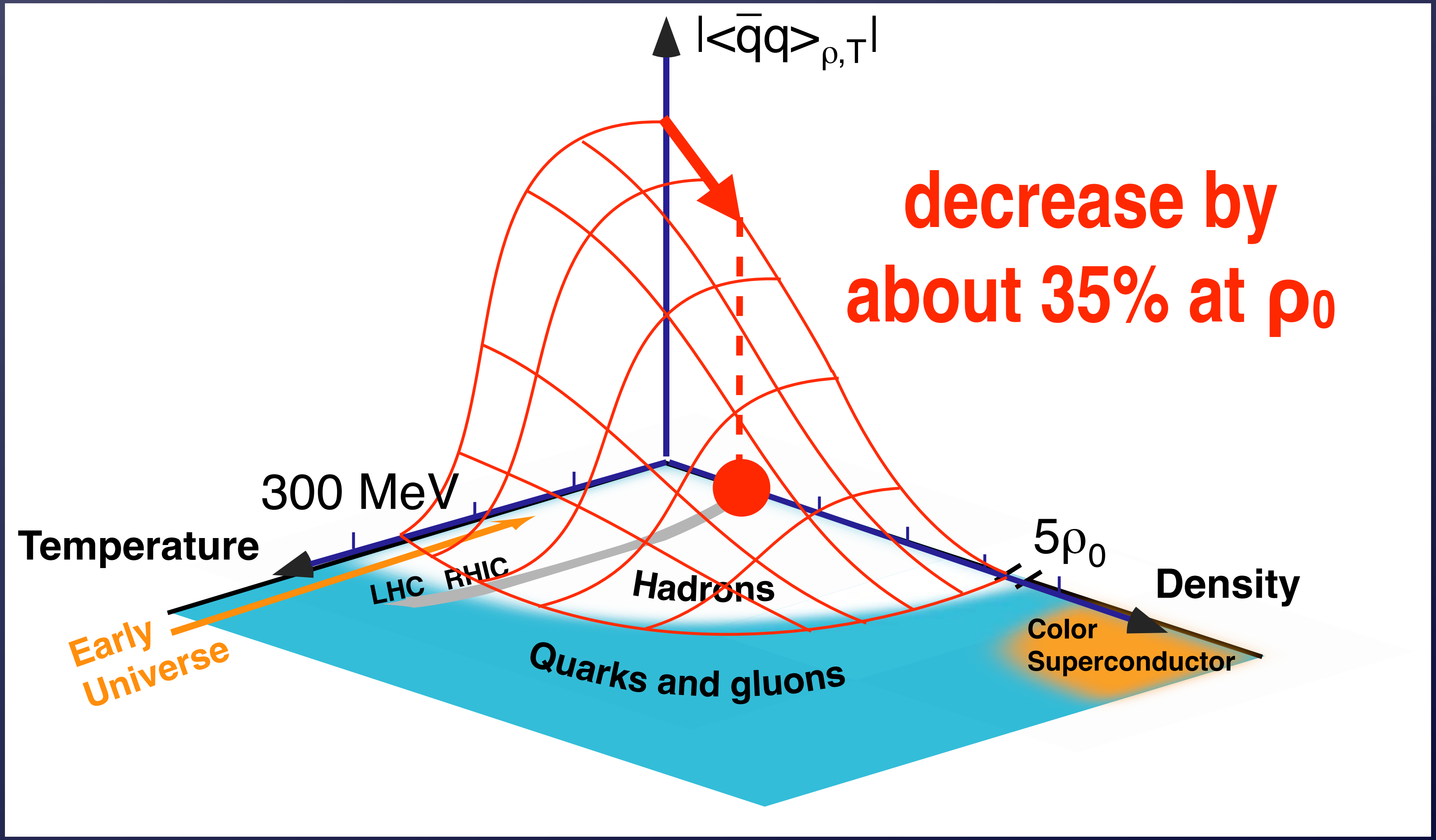




This talk

Status of experiments to look for

this ↓ effect



While m_H is an observable,

$\langle \bar{q}q \rangle$ is not.

Brown-Rho scaling

Brown and Rho, PRL 66 (1991) 2720

$$\frac{m_\sigma^*}{m_\sigma} \approx \frac{m_N^*}{m_N} \approx \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} \approx 0.8(\rho = \rho_0)$$

$$\frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} = \left(\frac{f_\pi^*}{f_\pi} \right)^3$$

Hatsuda-Lee

Hatsuda and Lee, PRC 46 (1992) R34

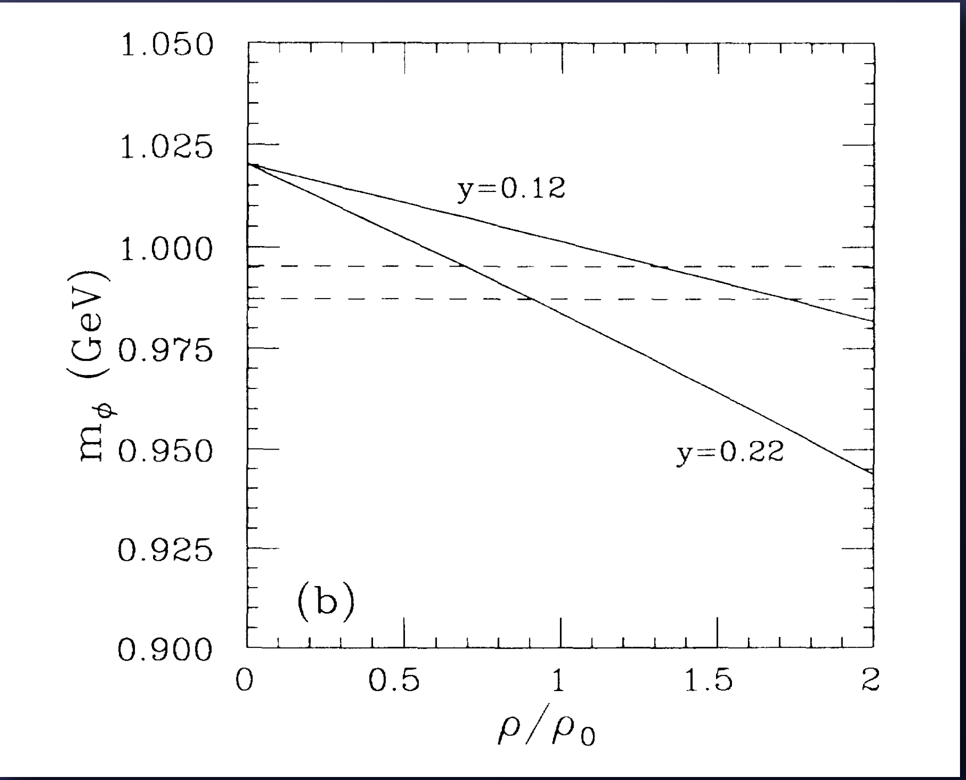
(QCD sum rules)

$$\frac{m_V^*}{m_V} = \left(1 - \alpha \frac{\rho}{\rho_0}\right),$$

$$\begin{aligned} \alpha &\approx 0.18(\pm 30\%) \text{ for } V = \rho, \omega, \\ &\approx 0.15y \text{ for } V = \phi \end{aligned}$$

y; nucleon strangeness content

ϕ meson



質量変化

in-medium mass shift,
how to detect?

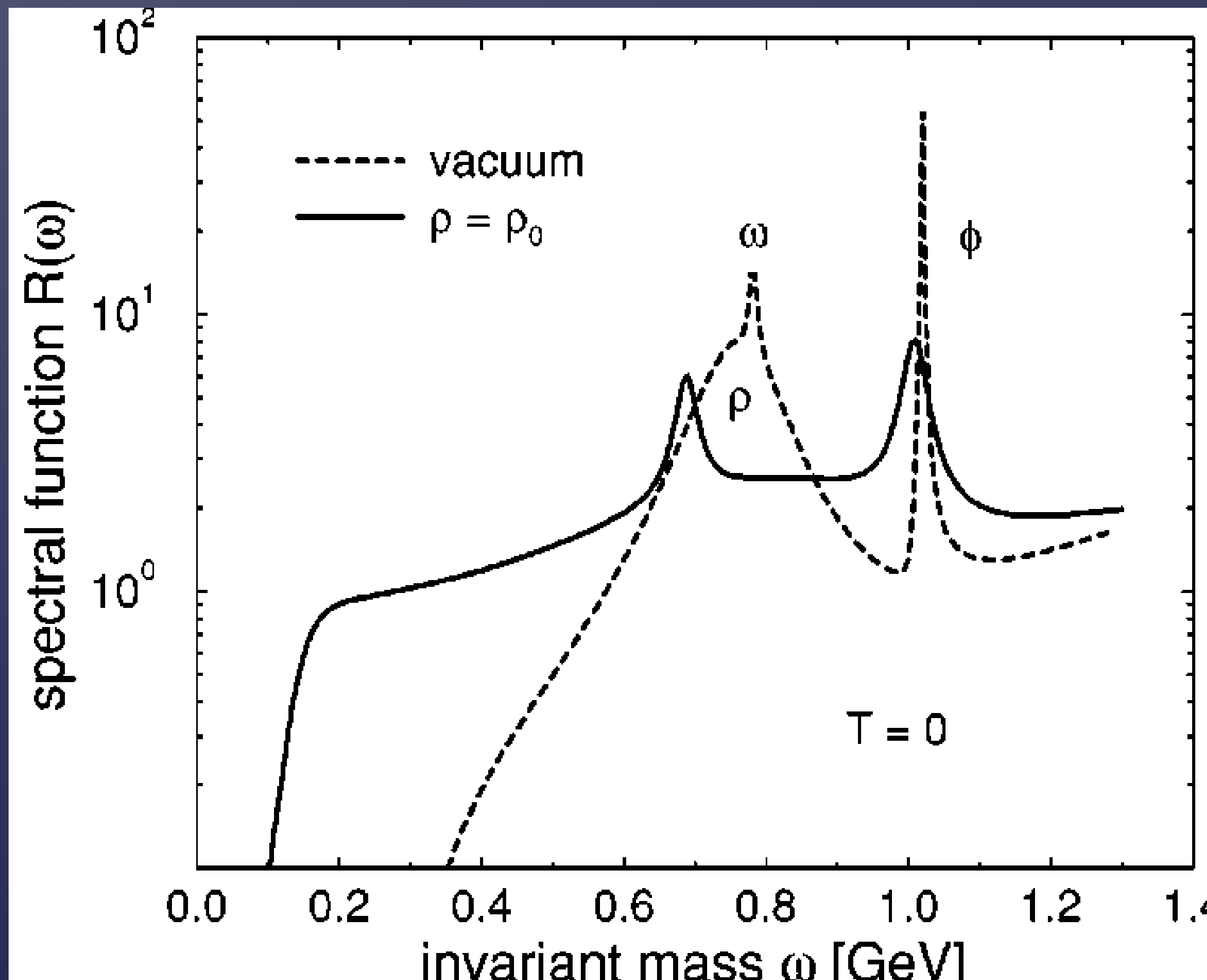
1. **decay** (m_{inv})

2. **production**

$d\sigma/dM_{e+e-} \propto$ BR (mass dependent) × “spectral function”

lowering & broadening at finite ρ

Im (current correlation)

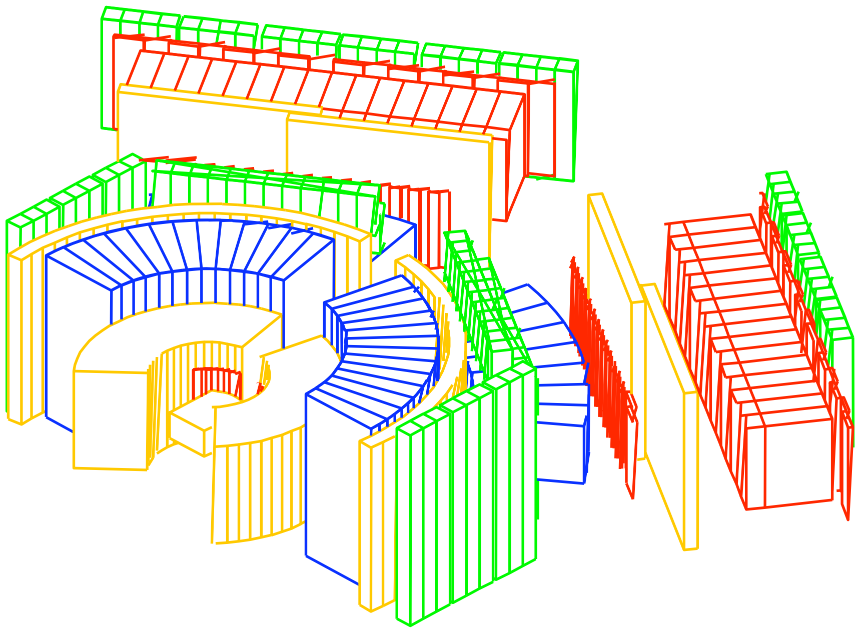


Renk, Schneider, Weise, PRC 66 (2002) 014902

also see Muehlich et al., NPA 773 (2006) 156

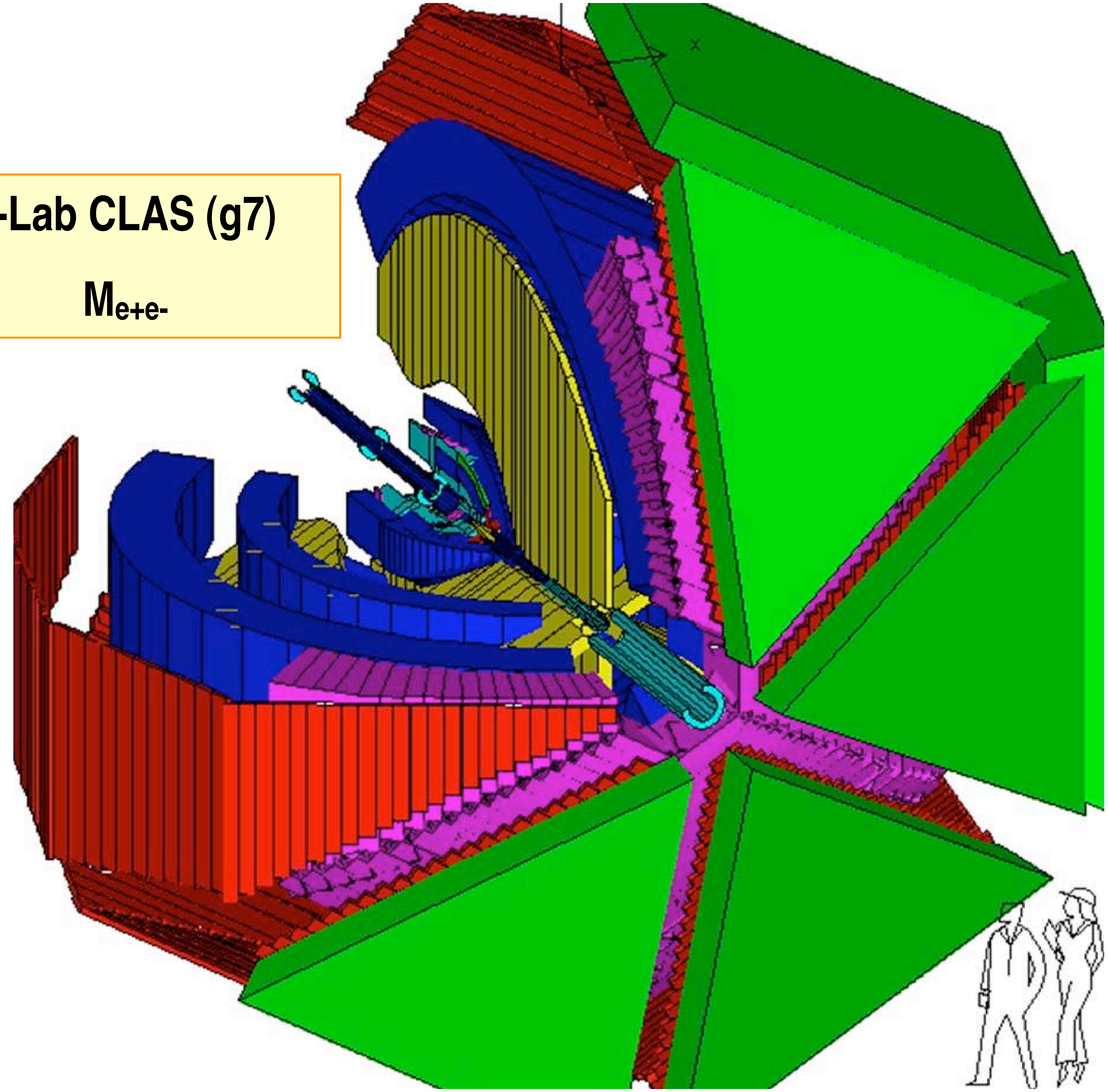
KEK-PS E325

M_{e+e-}



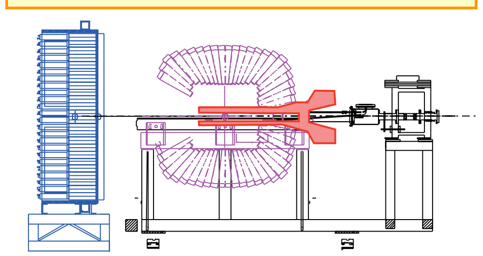
J-Lab CLAS (g7)

M_{e+e-}



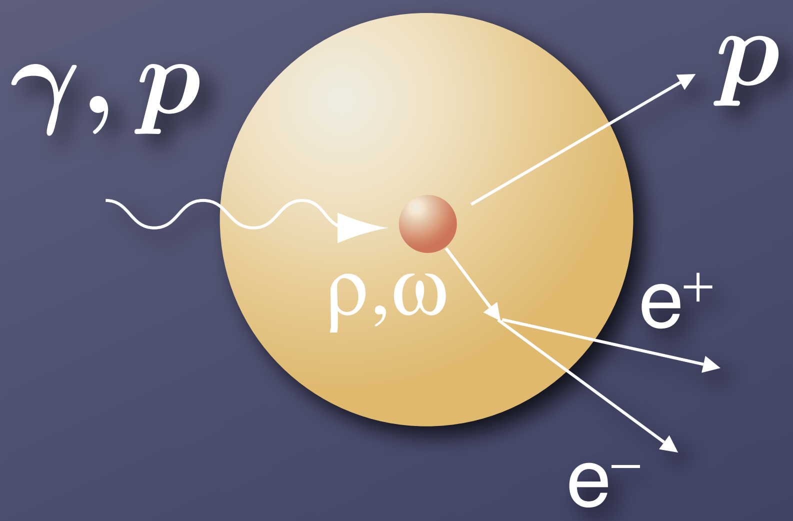
CBELSA / TAPS

$M_{\pi 0 \gamma}$



← 10 m →

M_{e+e-}



KEK E325 p+A → V + X

J-LAB g7 γ+A → V + X

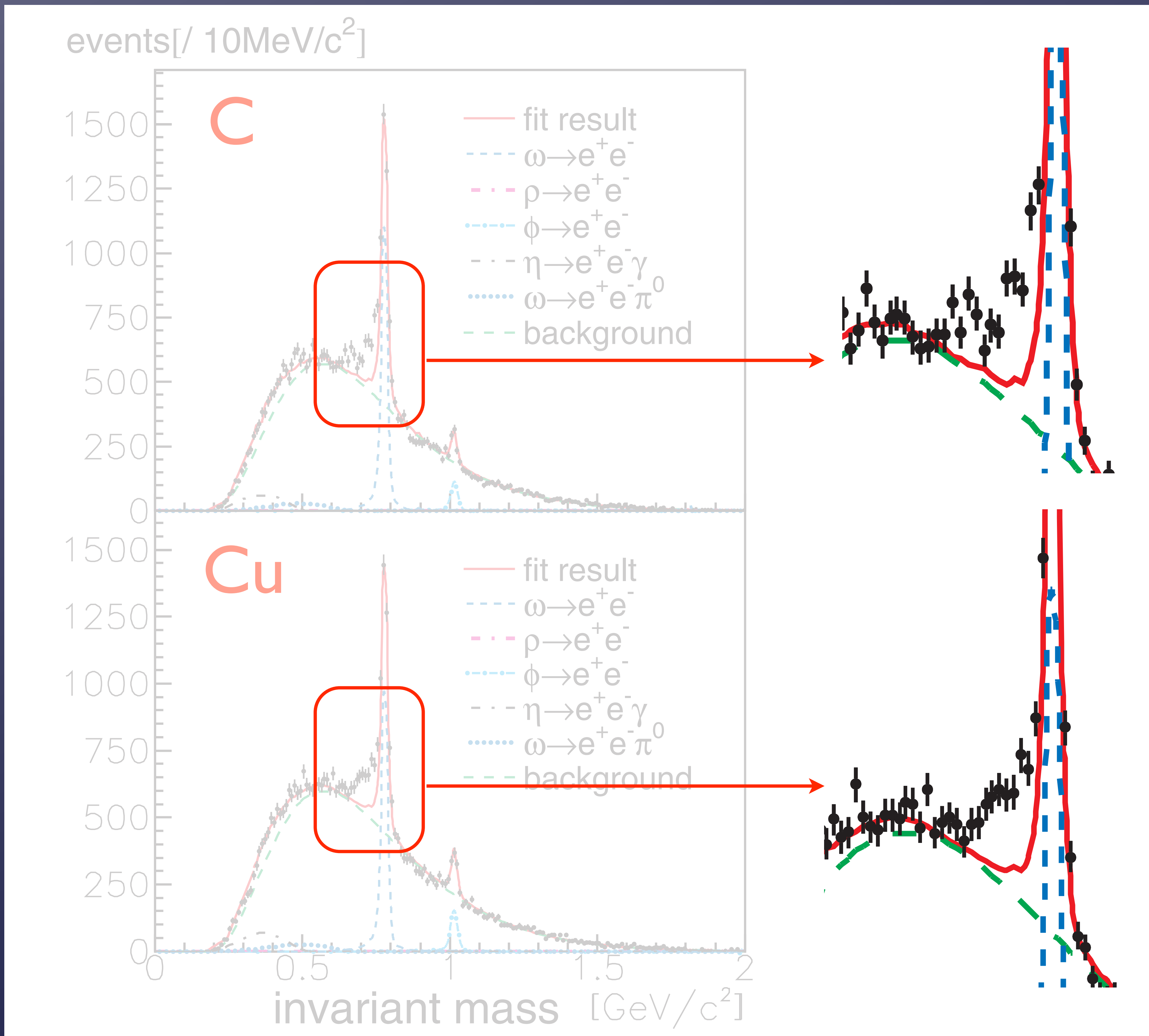
$$m_{\rho,\omega} = \sqrt{(p_{e+} + p_{e-})^2}$$

- small FSI
- rare decay
- fast ω, ϕ decay outside

	$BR(e^+e^-)$	$c\tau$
ρ (770)	4.7×10^{-5}	1.3 fm
ω (782)	7.2×10^{-5}	23 fm
ϕ (1020)	3×10^{-4}	44 fm

E325 e^+e^- invariant mass spectra

Naruki et al., PRL 96 (2006) 092301

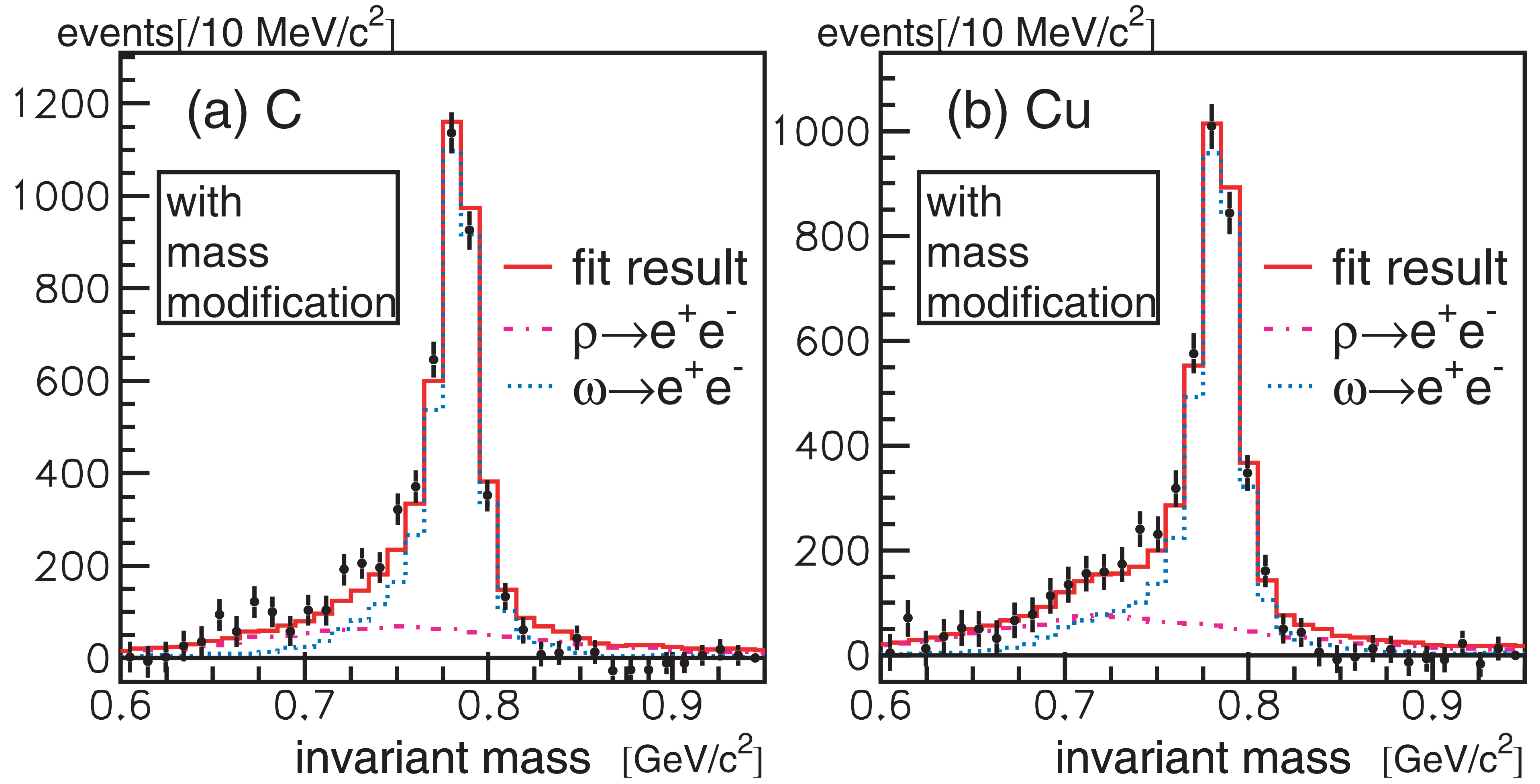


excess over the known hadronic sources

lowering of the ω mass?

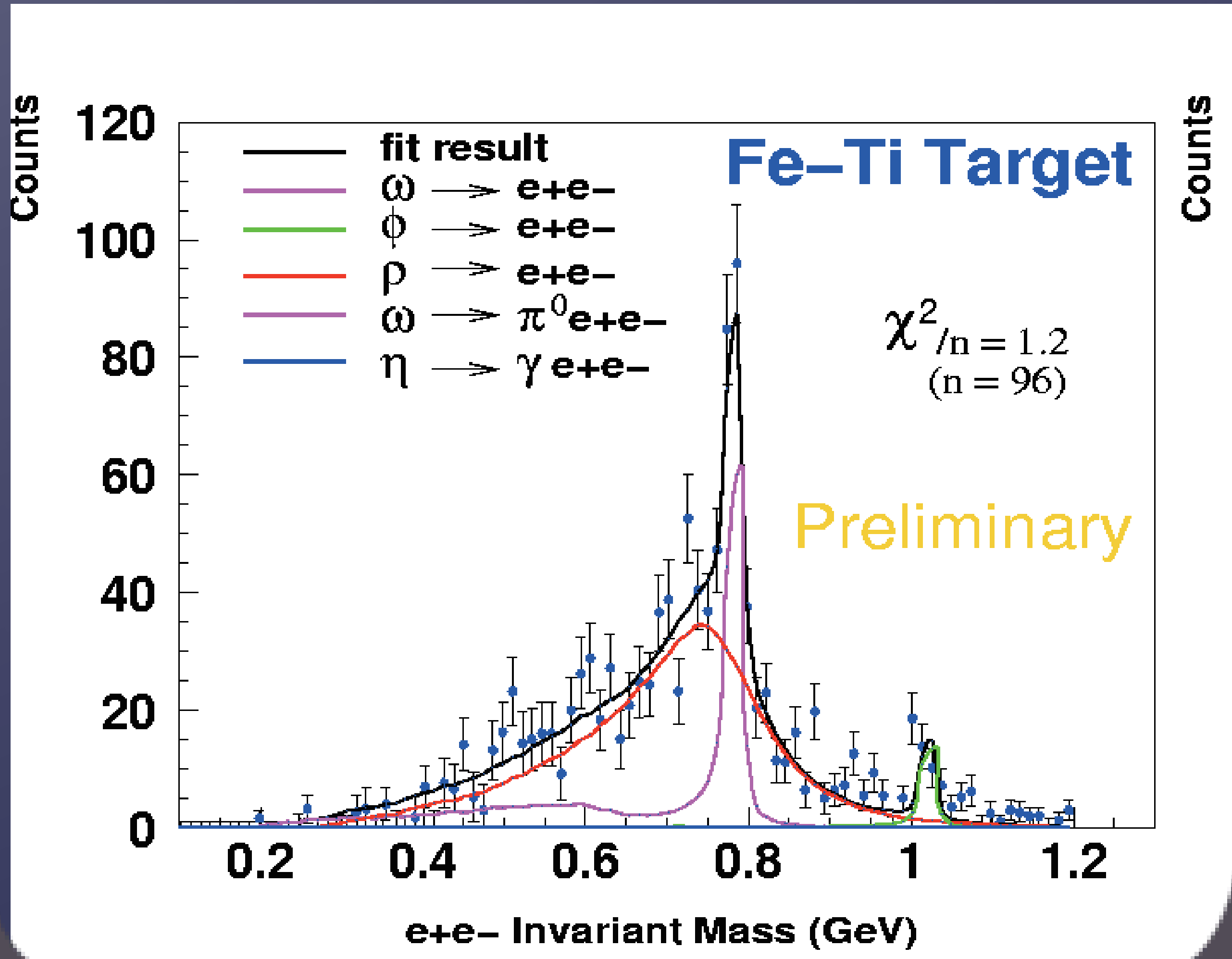
Naruki et al., PRL 96 (2006) 092301

E325: fit with $m_{\rho/\omega}=m_0(1-0.092\rho/\rho_0)$ works

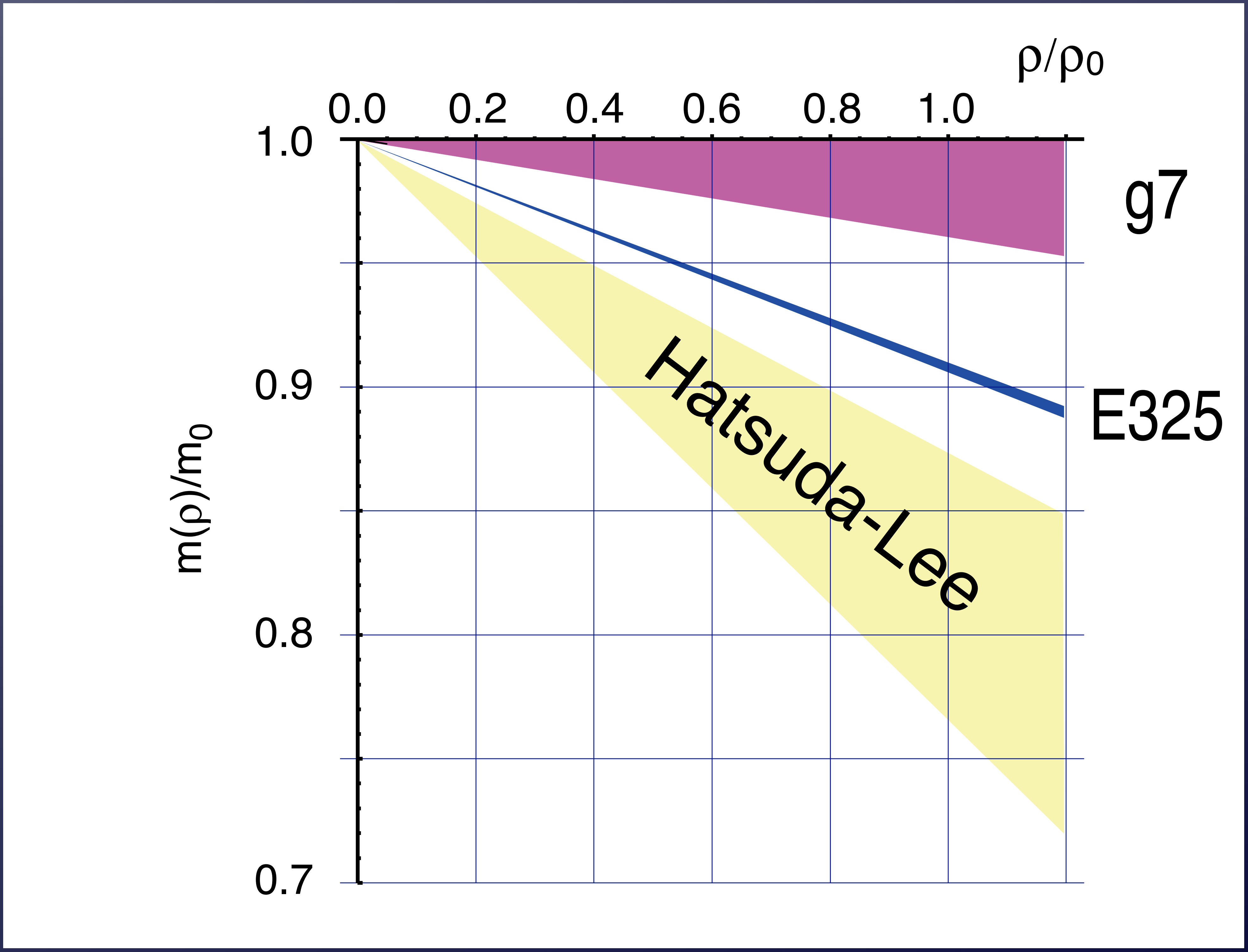


on the other hand

fit without mass shift



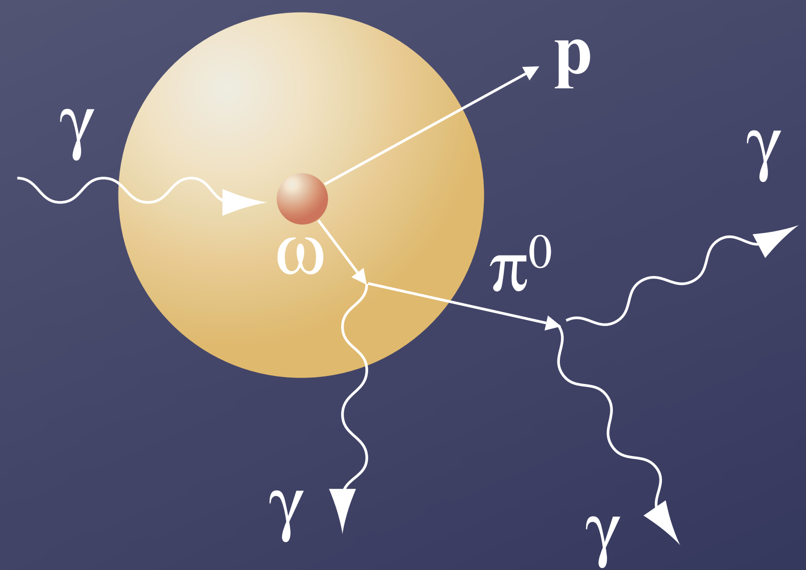
tantalizing, but more work needed



How to disentangle ρ / ω /background?

J.G.Messchendorp et al., Eur. Phys. J. A 11 (2001) 95

CBELSA / TAPS



$$\gamma A \longrightarrow \omega + X$$

$\hookrightarrow \pi^0\gamma$

$\hookrightarrow \gamma\gamma$

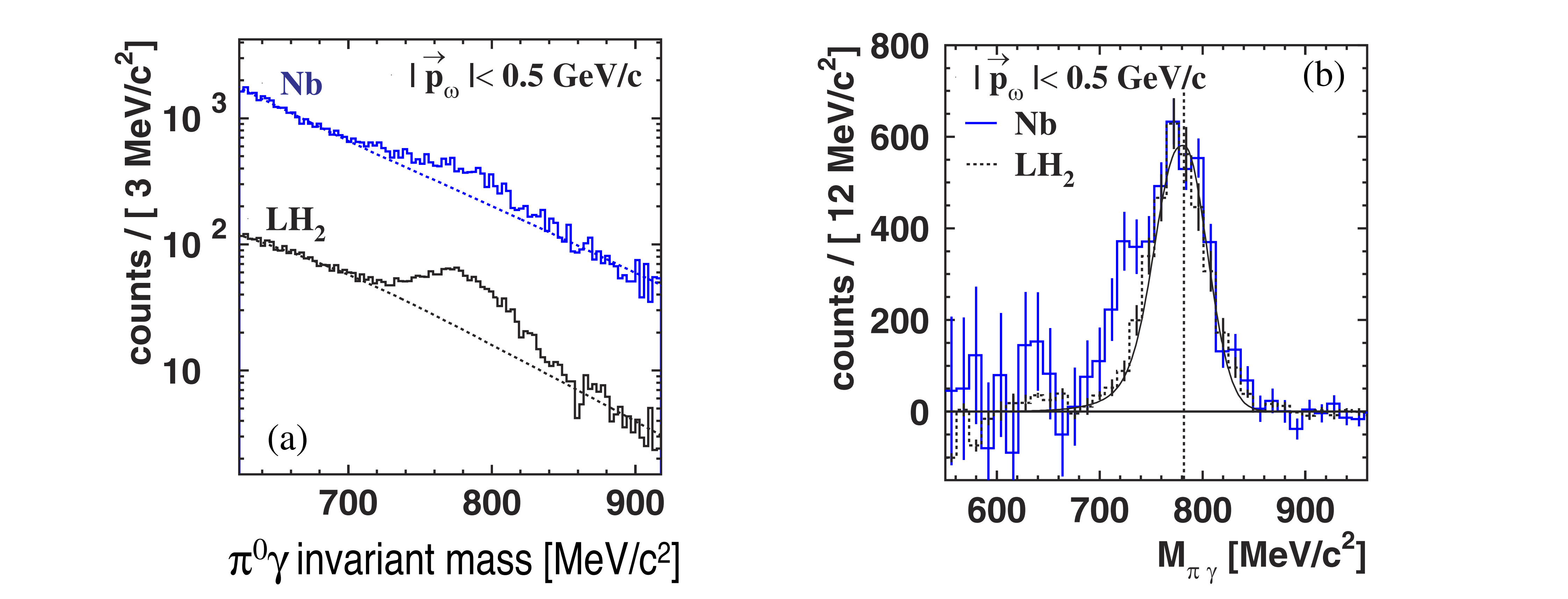
$$m_\omega = \sqrt{(p_\pi + p_\gamma)^2}$$

- No ρ contribution
- BR($\pi^0\gamma$: 8.9%)
- π^0 FSI

CBELSA / TAPS H, Nb comparison

$$\gamma A \to \omega + X$$
$$\quad\quad \hookrightarrow \pi^0\gamma$$

background subtraction →

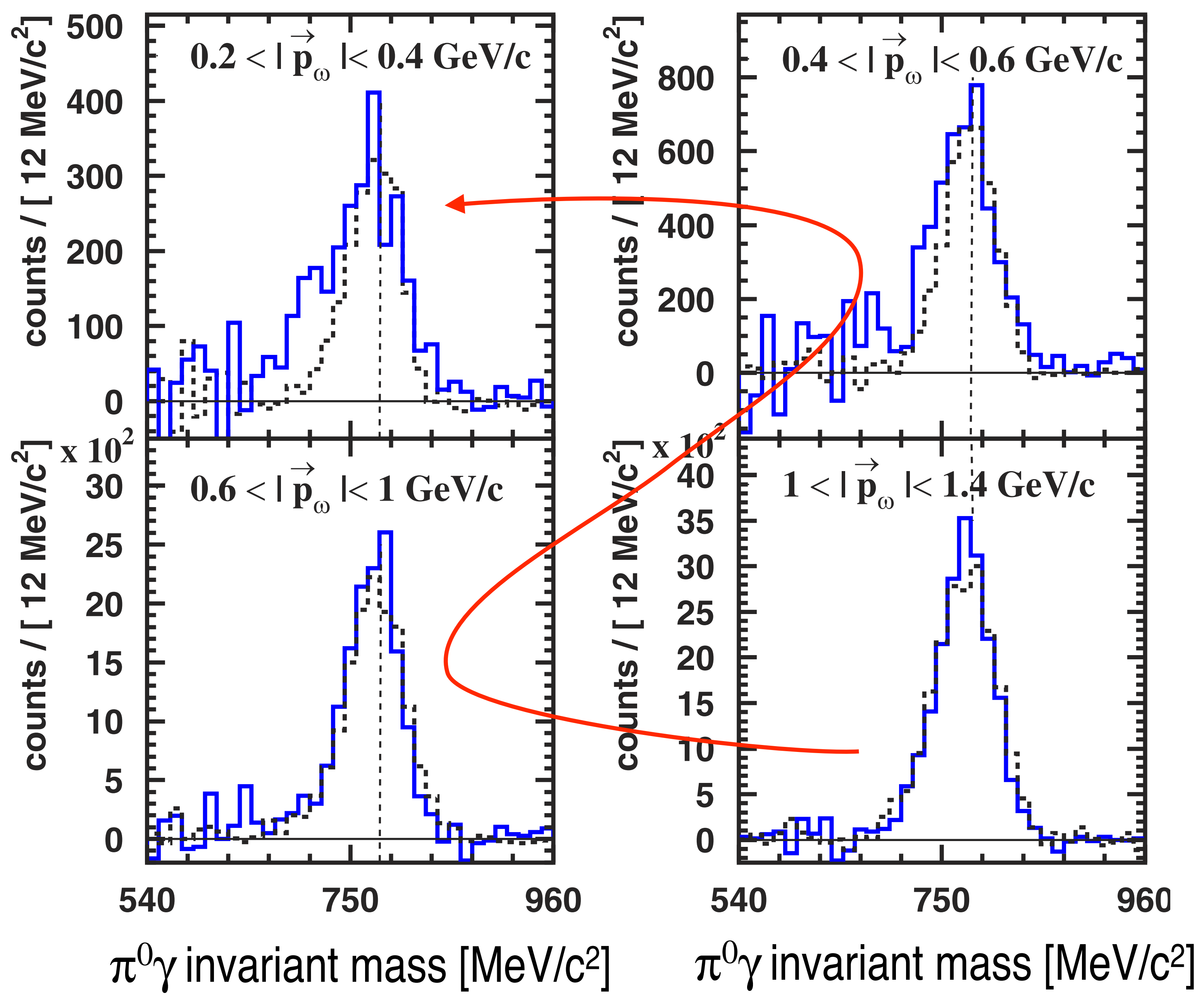


consistent with $m_\omega = m_0\,(1 - 0.13\ \rho/\rho_0)$

D. Trnka et al., PRL 94 (2005) 192203

Slower ω, larger effect

CBELSA / TAPS

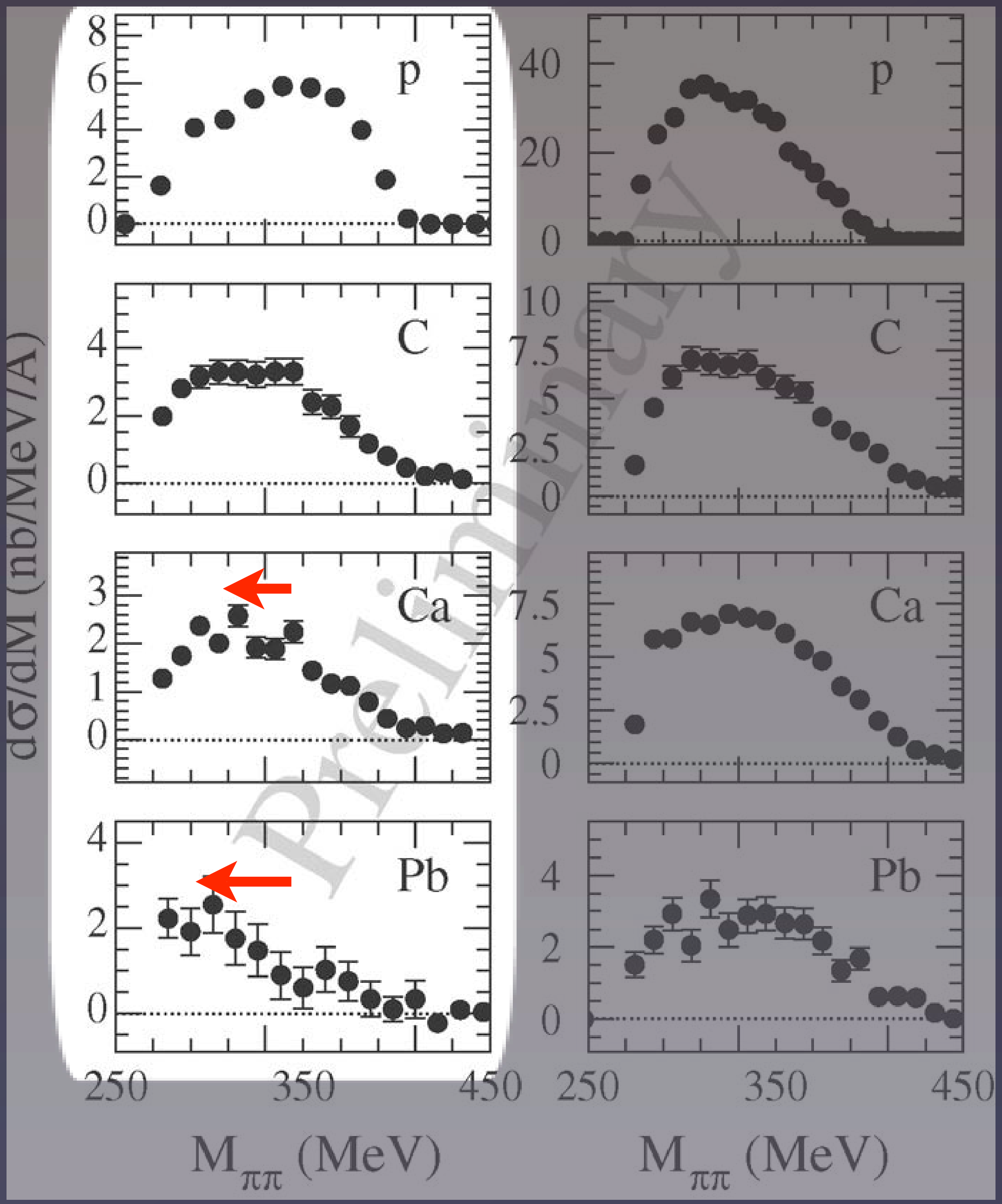


D. Trnka et al., PRL 94 (2005) 192203

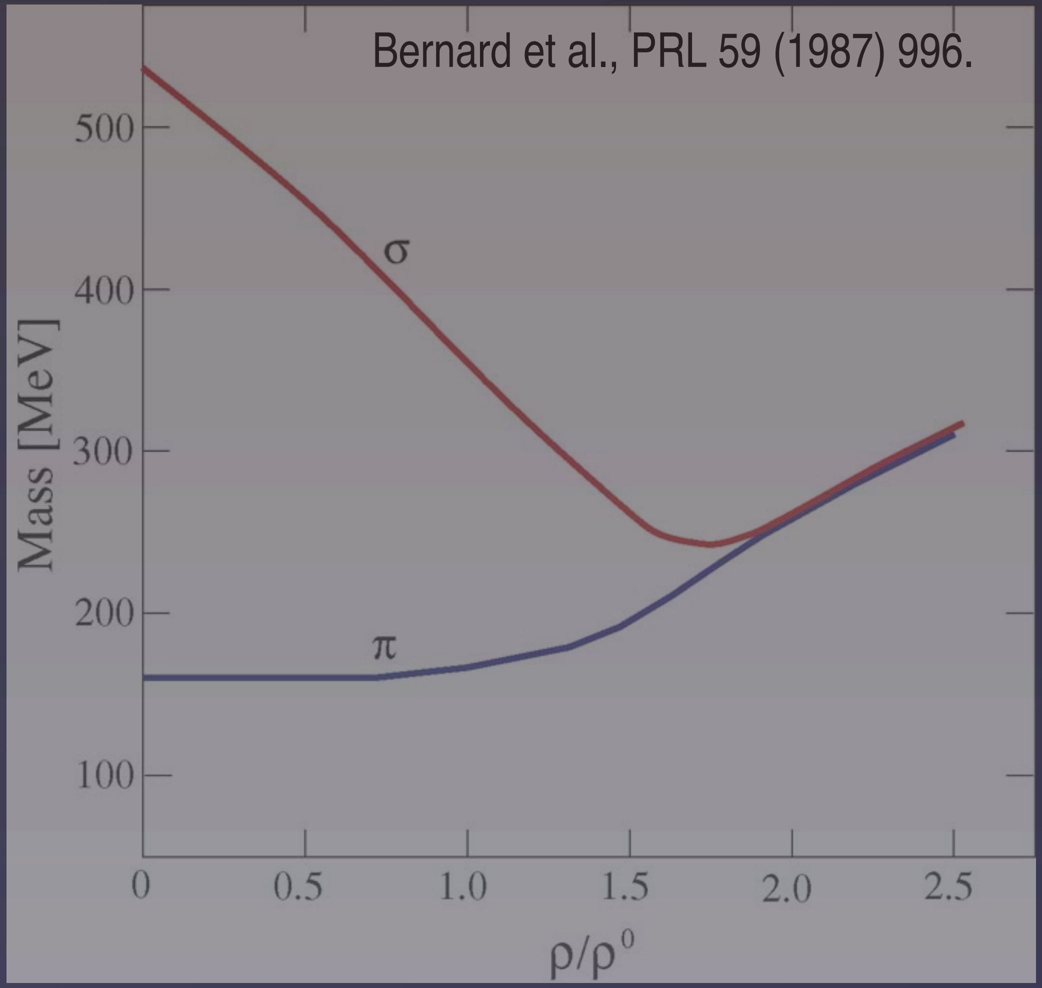
looks convincing,
but what about FSI?

TAPS “σ” mass shift

Metag, PPNP 55 (2005) 35



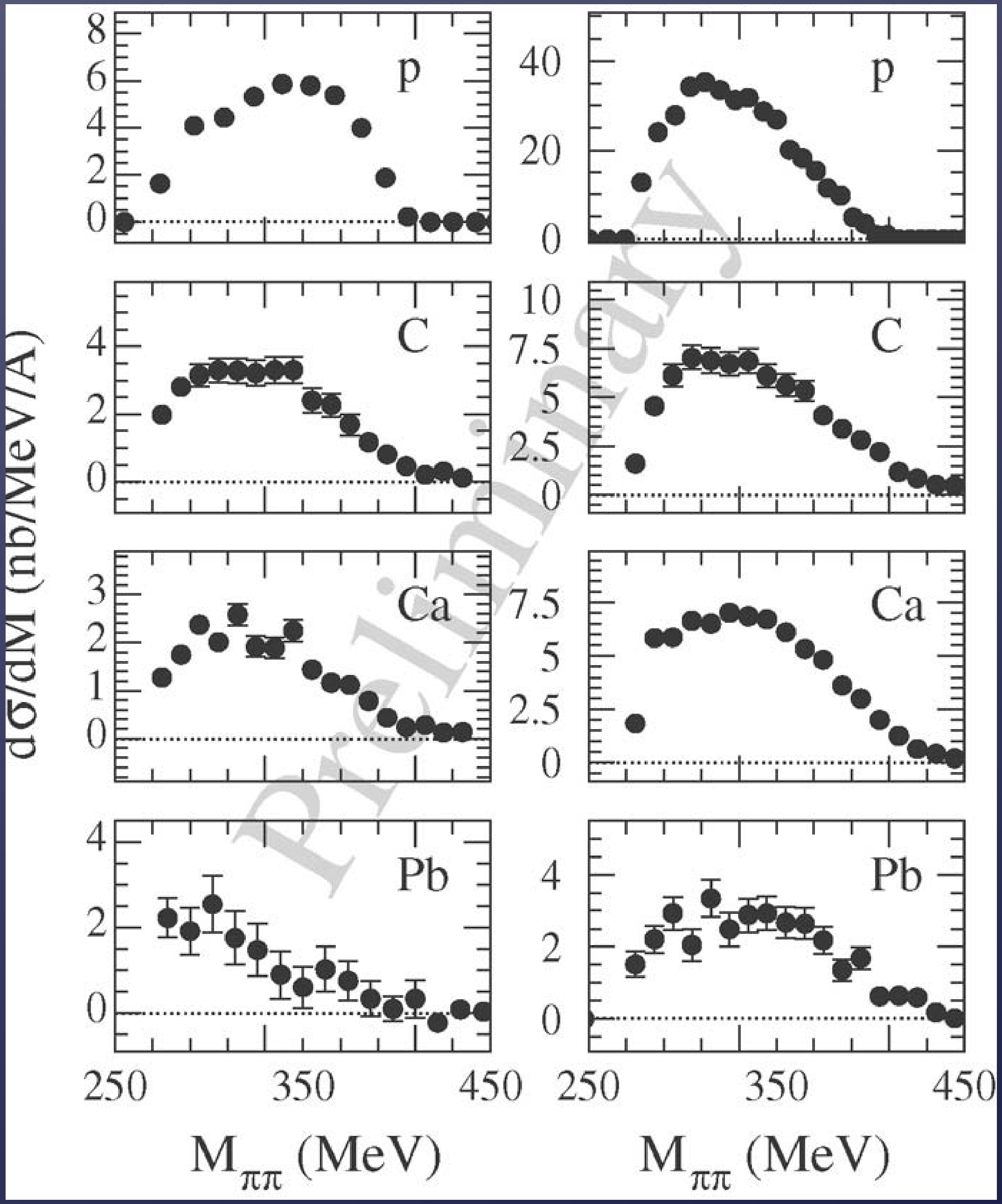
$\pi^0\pi^0$ $\pi^0\pi^\pm$



FSI can mimic mass shift

TAPS "σ" mass shift

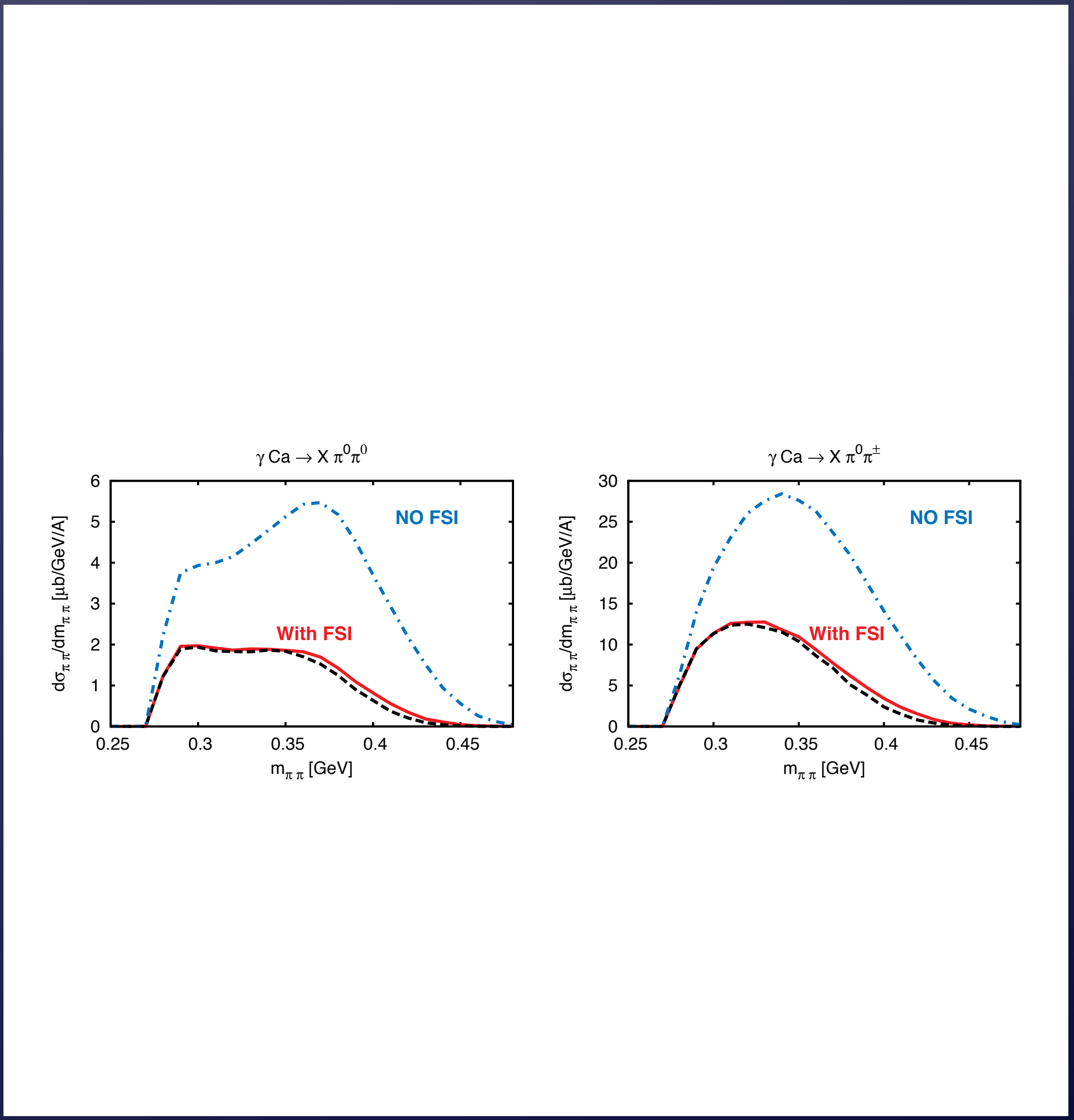
Metag, PPNP 55 (2005) 35



$\pi^0\pi^0$ $\pi^0\pi^\pm$

FSI on $\pi\pi$

Buss et al, EPJA 29 (2006) 189



Scoreboard

	Proton induced		γ induced ($E\gamma$ GeV)			
E_{inc}	12GeV		0.6-2.5	0.8-1.1	1.5-2.4	0.6-3.8
Exp	KEK		TAPS	TAGX	LEPS	CLAS
A	12, 64 0.2~0.07g/cm^2		1, 93 0.37-0.85 g/cm^2	2, 3, 12	7, 12, 27, 64 5.4,8.2,6.5,2.6g/cm^2	2,12,48,56,207. 1g/cm^2
ϕ	e^+e^-	K^+K^-			K^+K^-	e^+e^-
	Shift **3.4 ±0.6%**	Limits on Γ^*			In-media broadening ?	seen No report yet
ω	e^+e^-		$\pi^0\gamma$			e^+e^-
	Shift **9.2 ± 0.2%** **Not very sensitive for ω mod.**		***Shift*** 13%	⇐ ? ⇒		***No shift*** **2±2%(1σ)** **Not very sensitive for ω mod.**
ρ				$\pi^+\pi^-$		
				Shift **5~8%**		

Originally by Metag, updated by En'yo at YKIS2006

1. decay (m_{inv})
2. production

Klein-Gordon Eq.

$$[\vec{\nabla}^2 + \omega^2 - m_0^2 - \Pi(\omega, \vec{r})]\Phi(\vec{r}) = 0$$

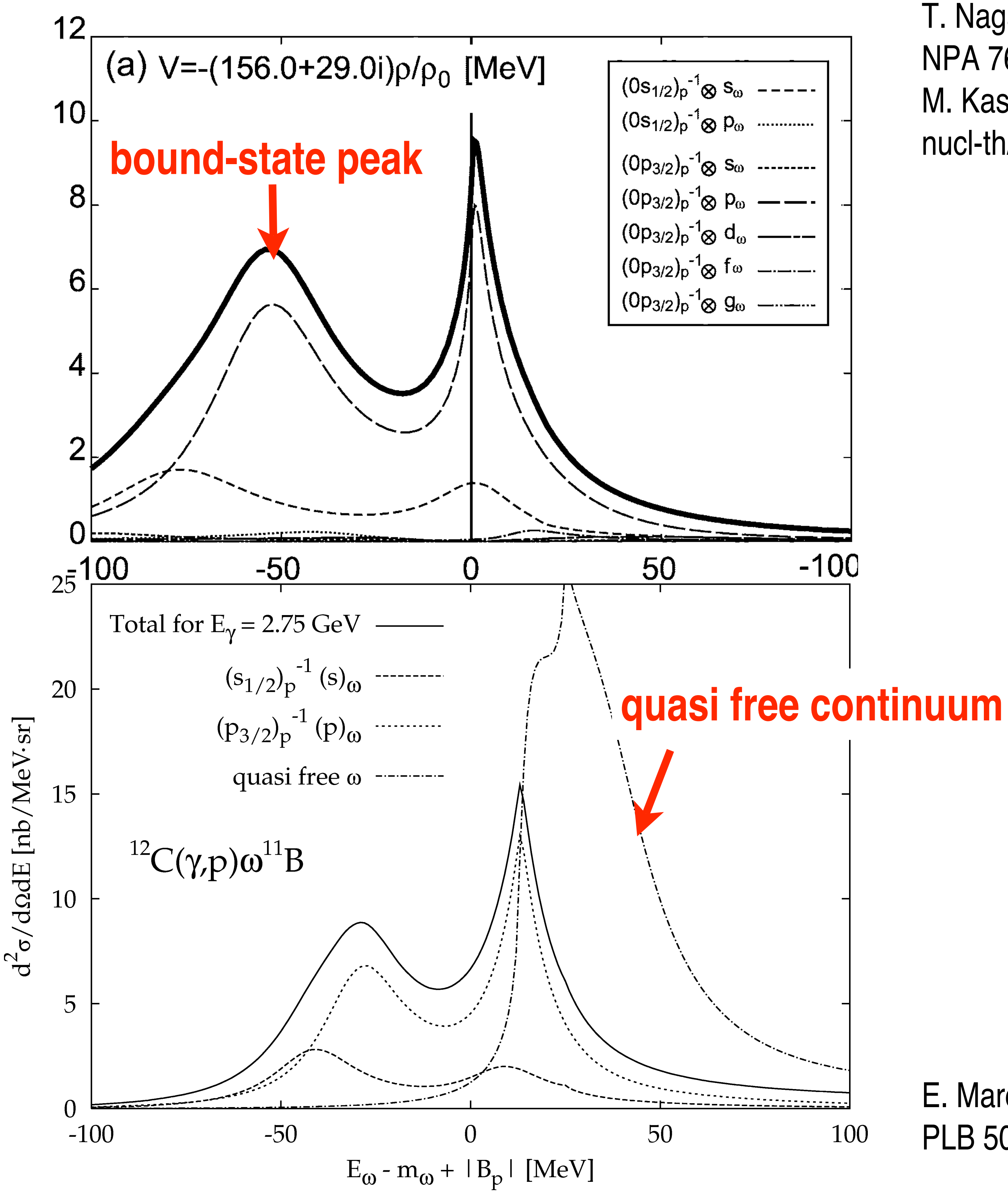
self energy

$$\Pi(\omega, \vec{r}) = 2\omega U(\omega, \vec{r})$$ **potential**

$$\Delta m = m_{\text{eff}} - m_0 \approx ReU^s$$

mass ↘ attraction → bound state?

$^{12}C(\gamma,p)\ \omega$ recoilless production



T. Nagahiro et al.
NPA 761 (2005) 92 &
M. Kaskulov et al,
nucl-th/0610085

E. Marco and W. Weise,
PLB 502 (2001) 59

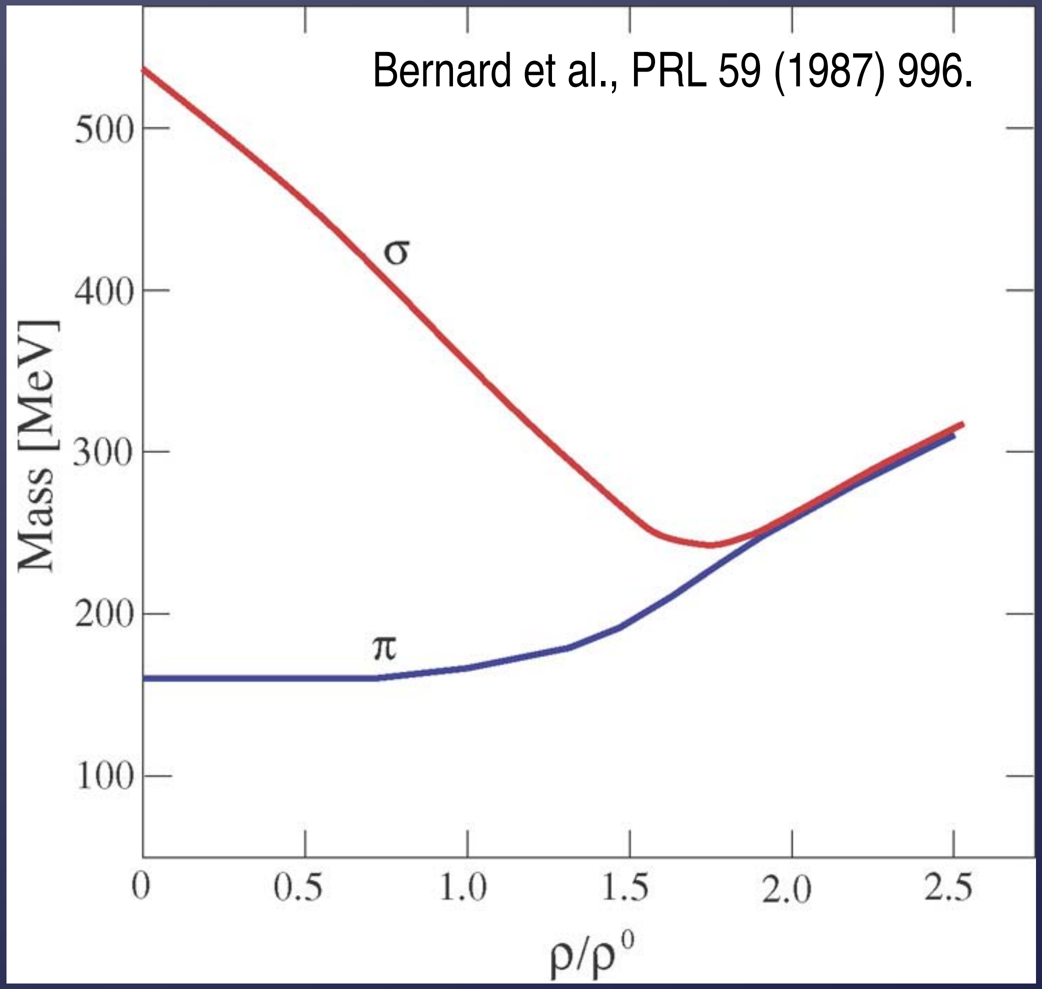
- **Bound state:**
  - **well-defined meson wavefunction**
  - **well-defined nuclear density**
- **This possibility not fully exploited yet**

some hint from CBELSA/TAPS?

湯川

Yukawa

Pion mass is not expected to depend on ρ



What do we measure, then?

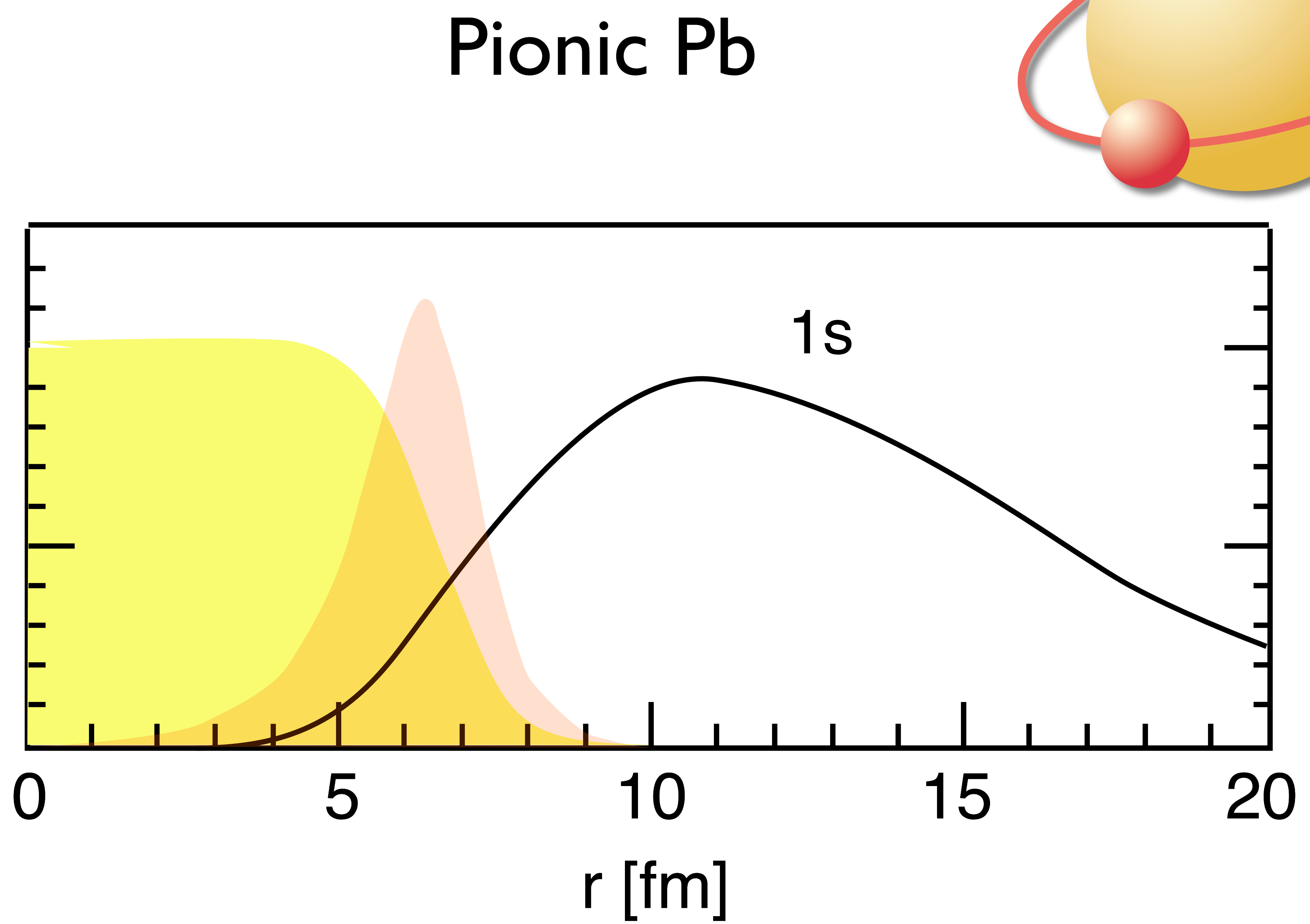
Remember, e.g., Brown-Rho scaling

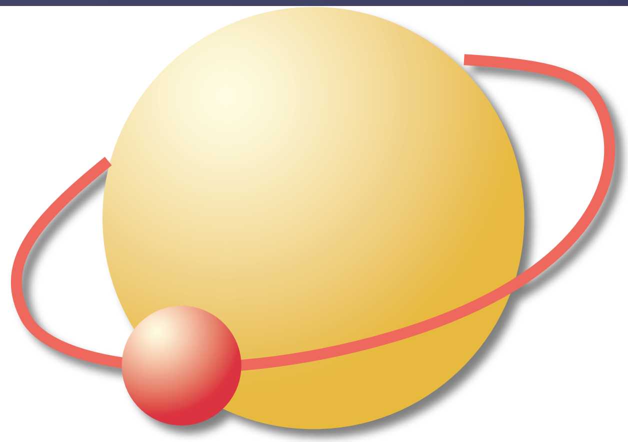
$$\approx \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} \approx 0.8(\rho = \rho_0)$$

Goal: in-medium modification of f_π

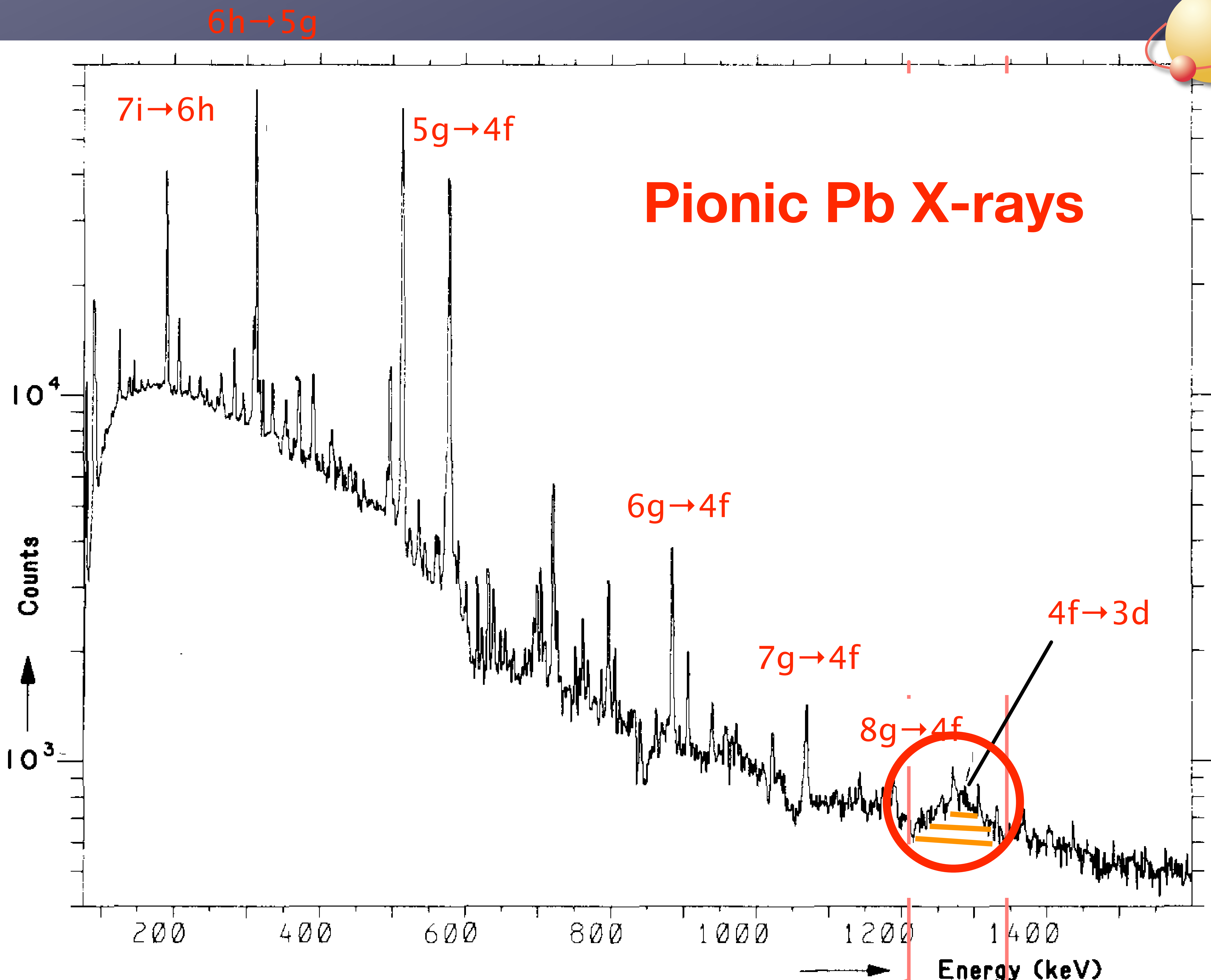
Tool: pionic atom 1s state

Pion in nuclei



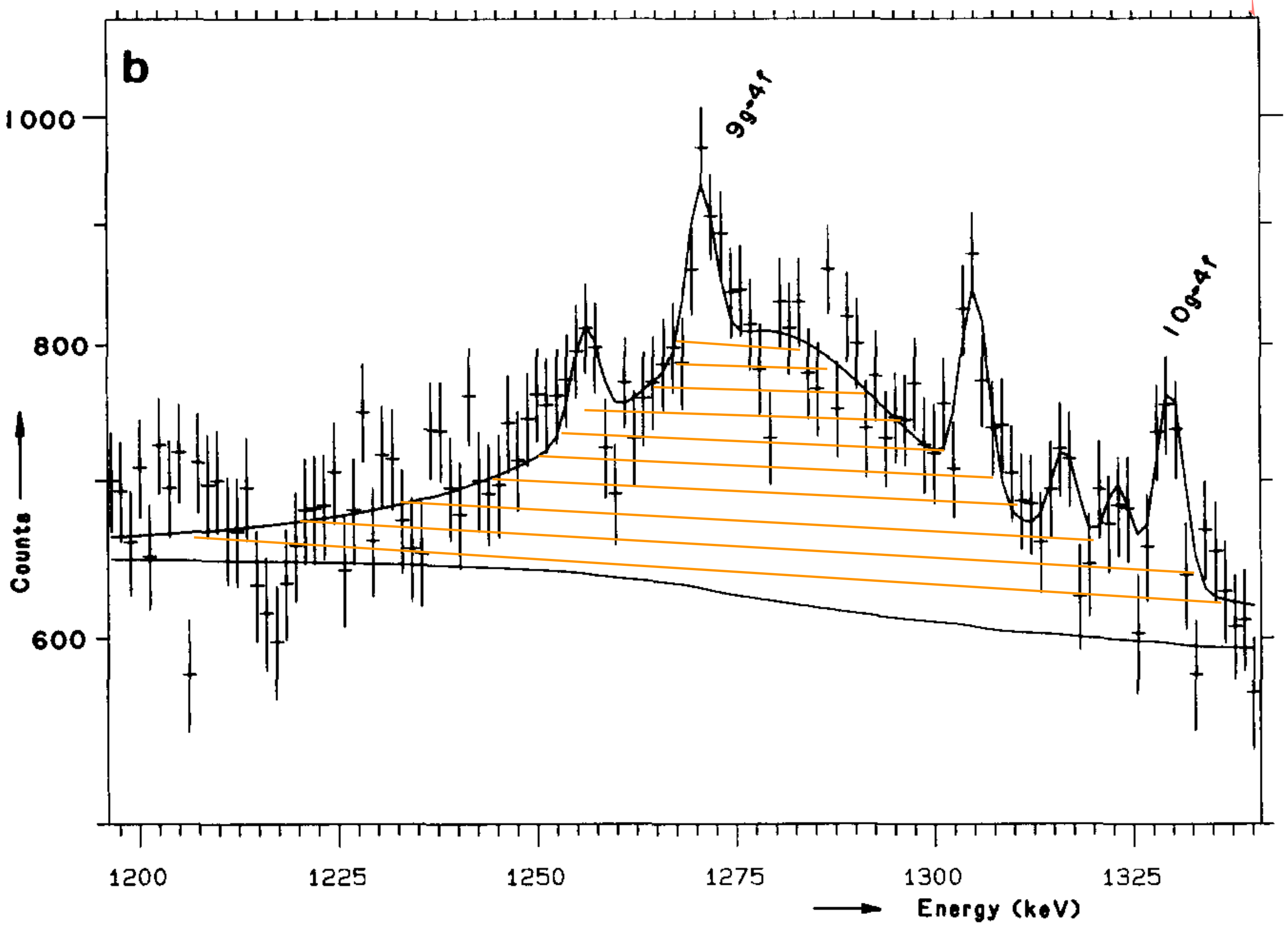


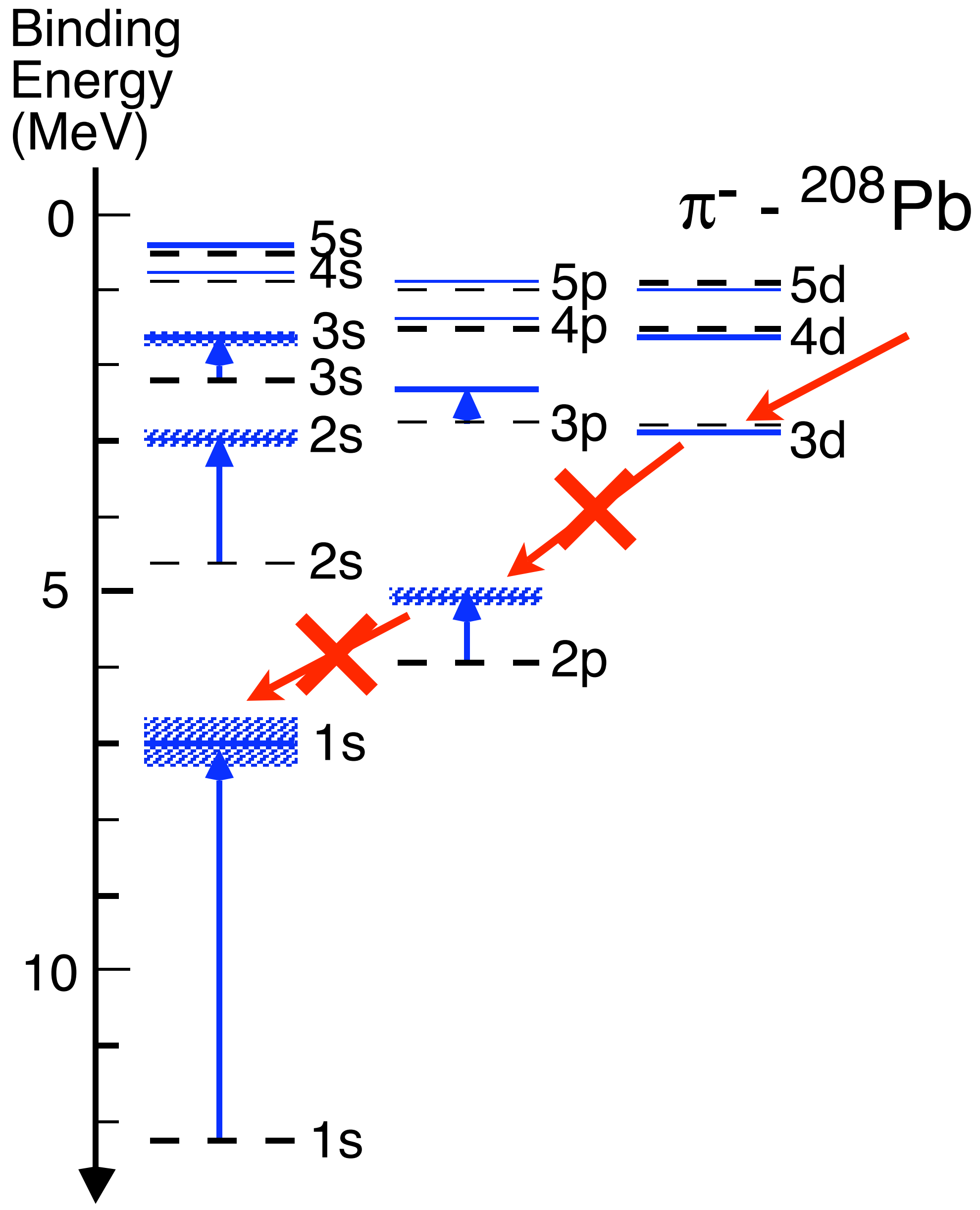
Pionic Pb X-rays



“last orbit”

Pionic Pb, 4f→3d (“last orbit”)

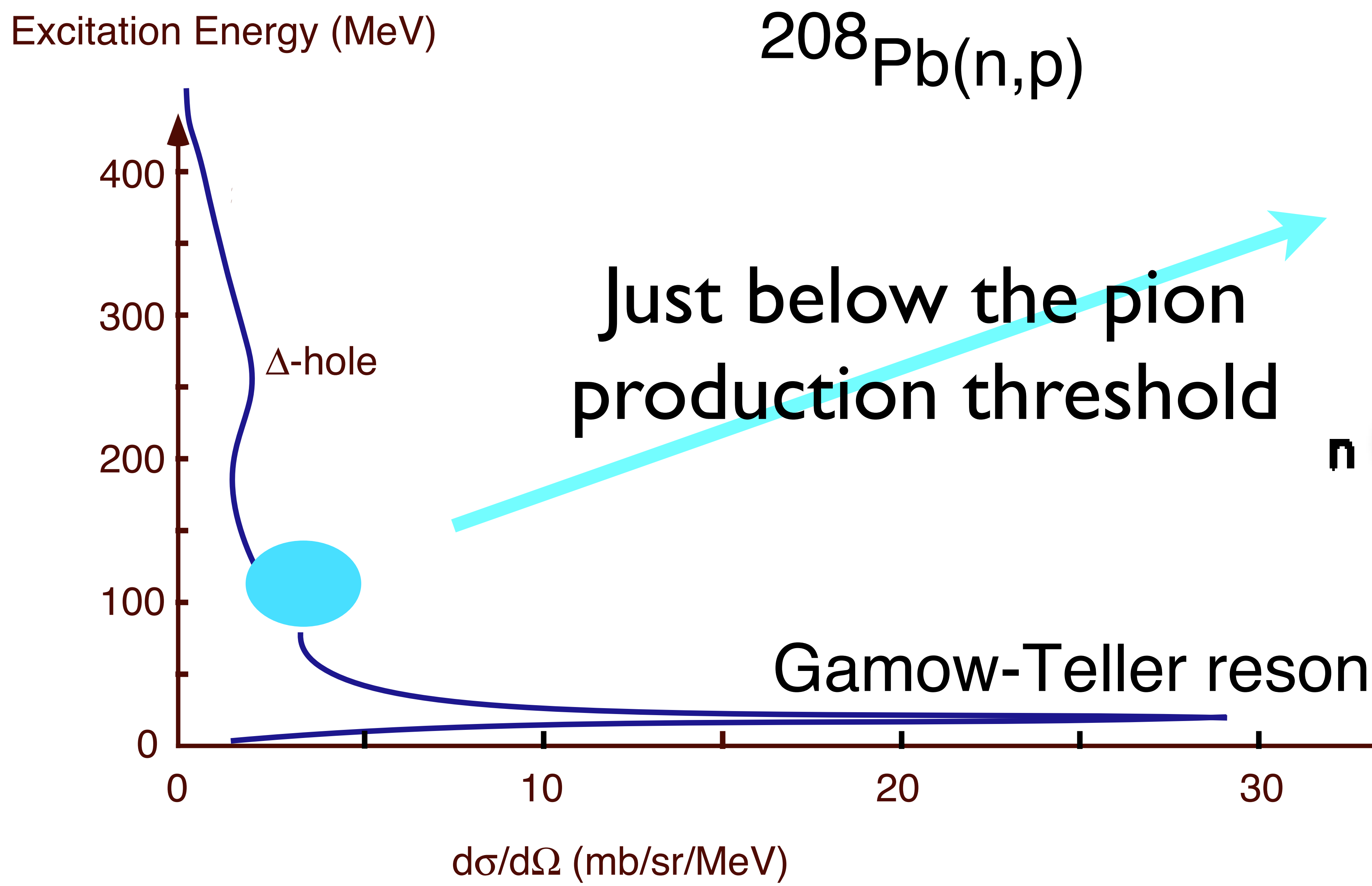




~~feeding from above~~

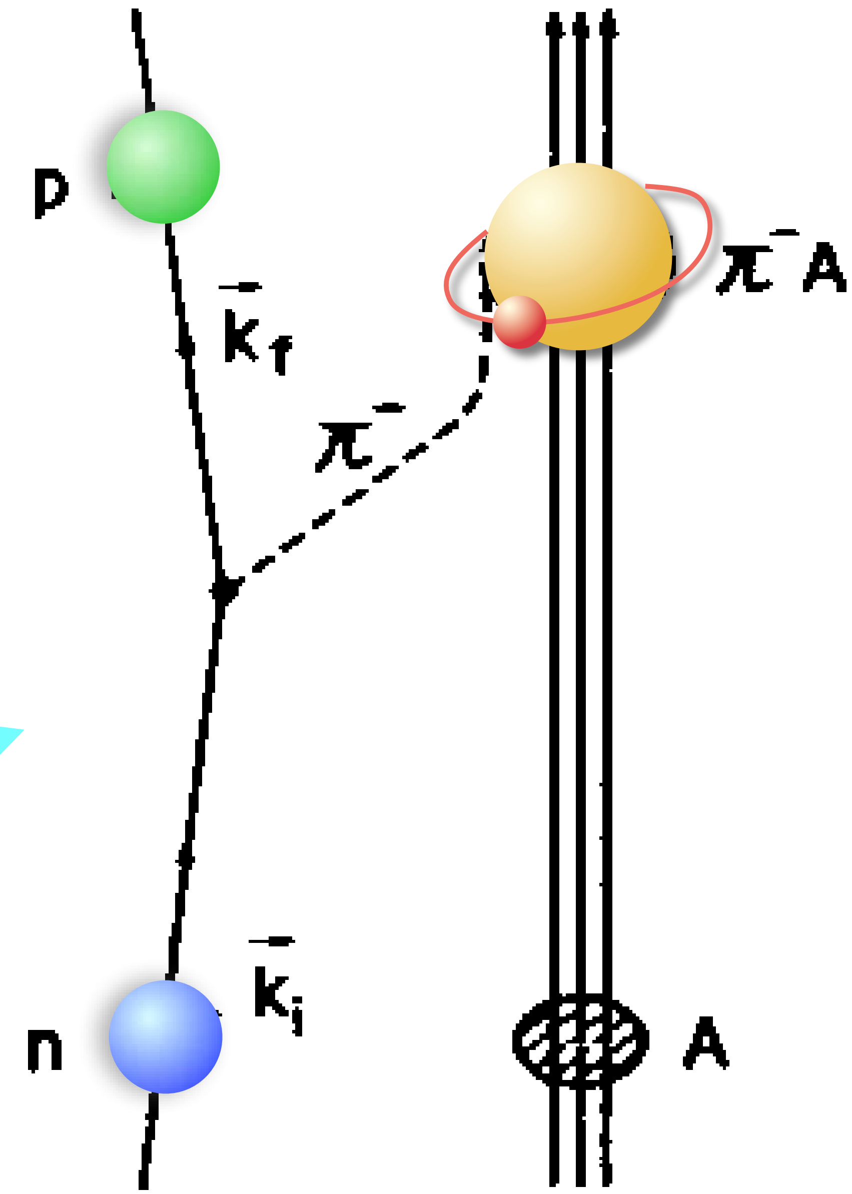
why not from below?

H. Toki and T. Yamazaki, Phys. Lett. B213 (1988) 129.
H. Toki, S. Hirenzaki, T. Yamazaki and R.S. Hayano, Nucl. Phys. A501 (1989) 653.



^{208}Pb(n,p)

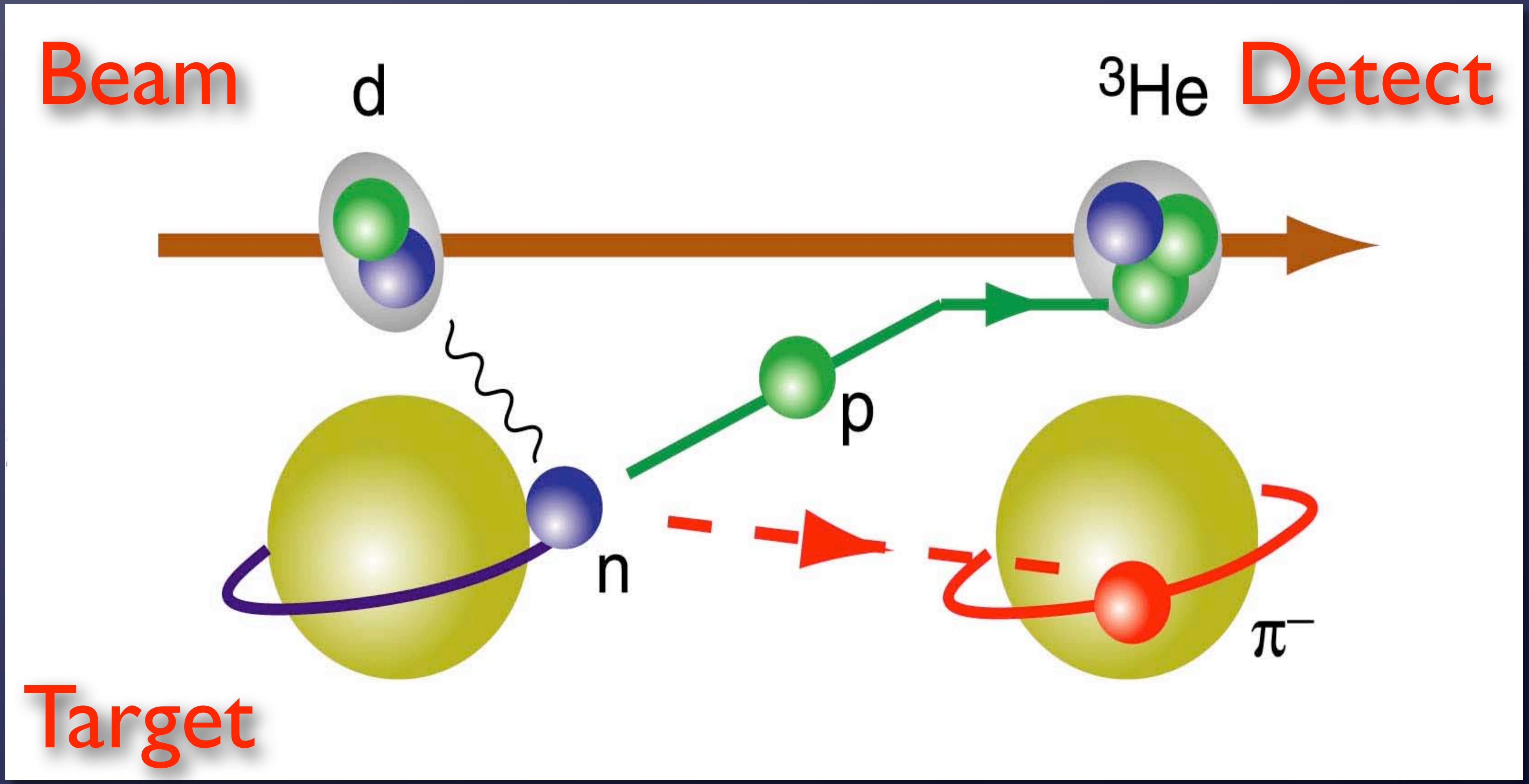
Just below the pion production threshold



The reaction

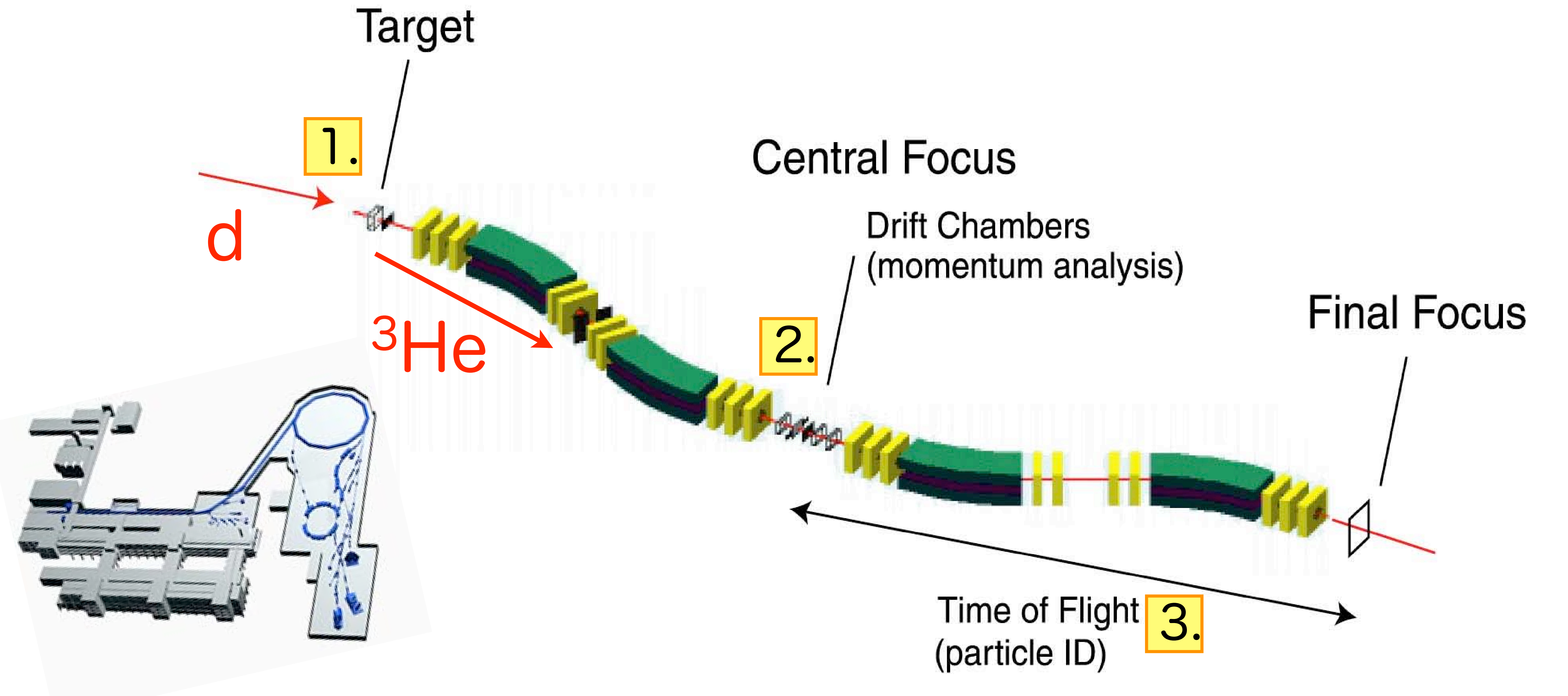
recoilless

500-600 MeV



substitutional reaction:
s-shell neutron hole pion in 1s

FRS @ GSI

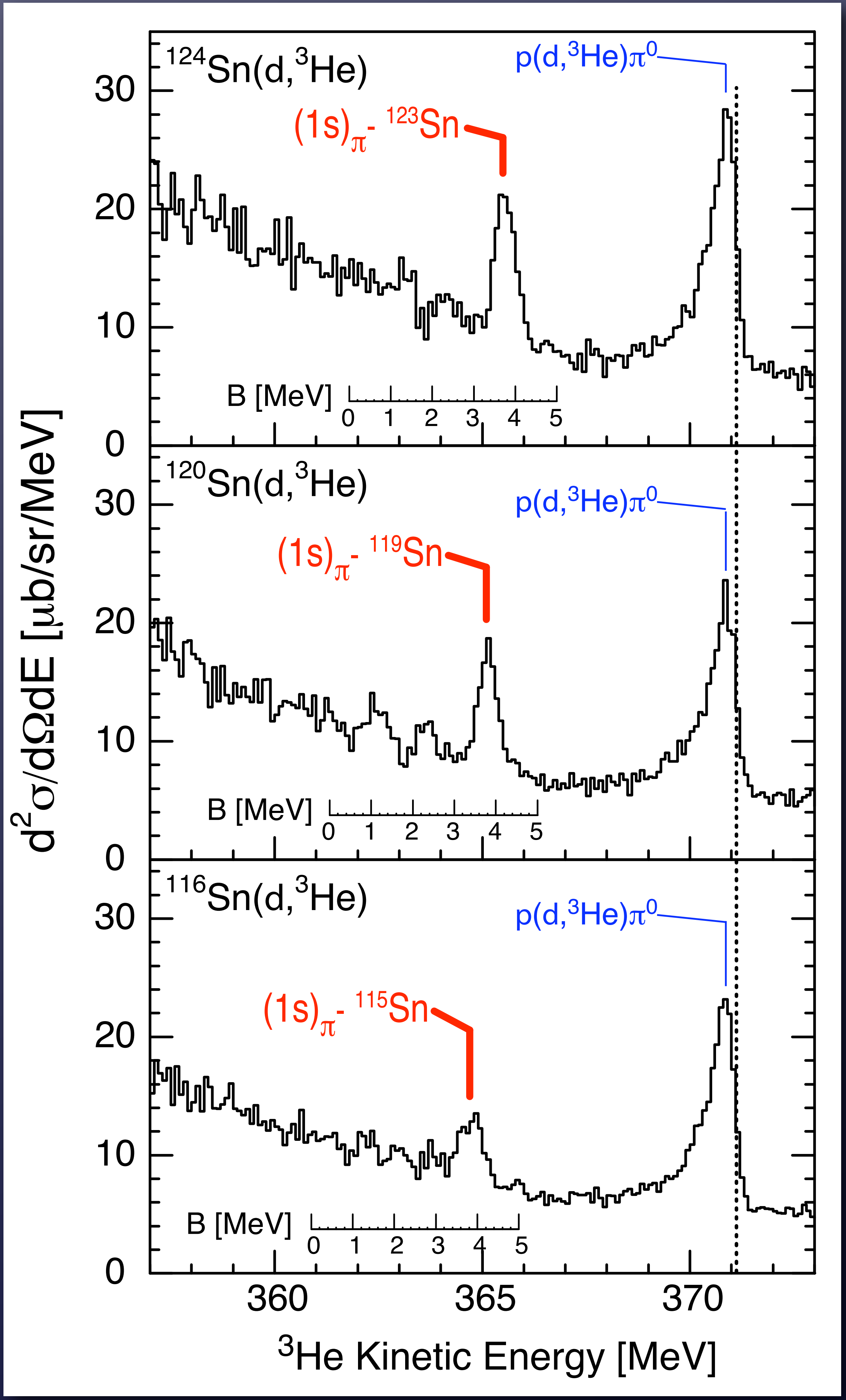


1. **250 MeV/u deuteron on target**
2. **Measure ^{3}He momenta at the central focal plane**
3. **Identify ^{3}He form time of flight in the 2nd half of FRS**

Pionic ^{123}Sn

Pionic ^{119}Sn

Pionic ^{115}Sn



resolution 400 keV FWHM

absolute binding energy uncertainty ~10 keV

Suzuki et al, PRL 92 (2004) 072302

pionic atom 1s energy Coulomb + strong

$$\pi - \text{nucl potential} \propto$$

$$b_0(\rho_n + \rho_p) + b_1(\rho_n - \rho_p)$$

isoscalar isovector

TW (Tomozawa-Weinberg)

$$b_0(\rho_n + \rho_p) + b_1(\rho_n - \rho_p)$$

isoscalar $b_0 \approx 0$

isovector $b_1 \propto \frac{m_\pi}{f_\pi^2}$

pion mass
&
pion "decay constant"

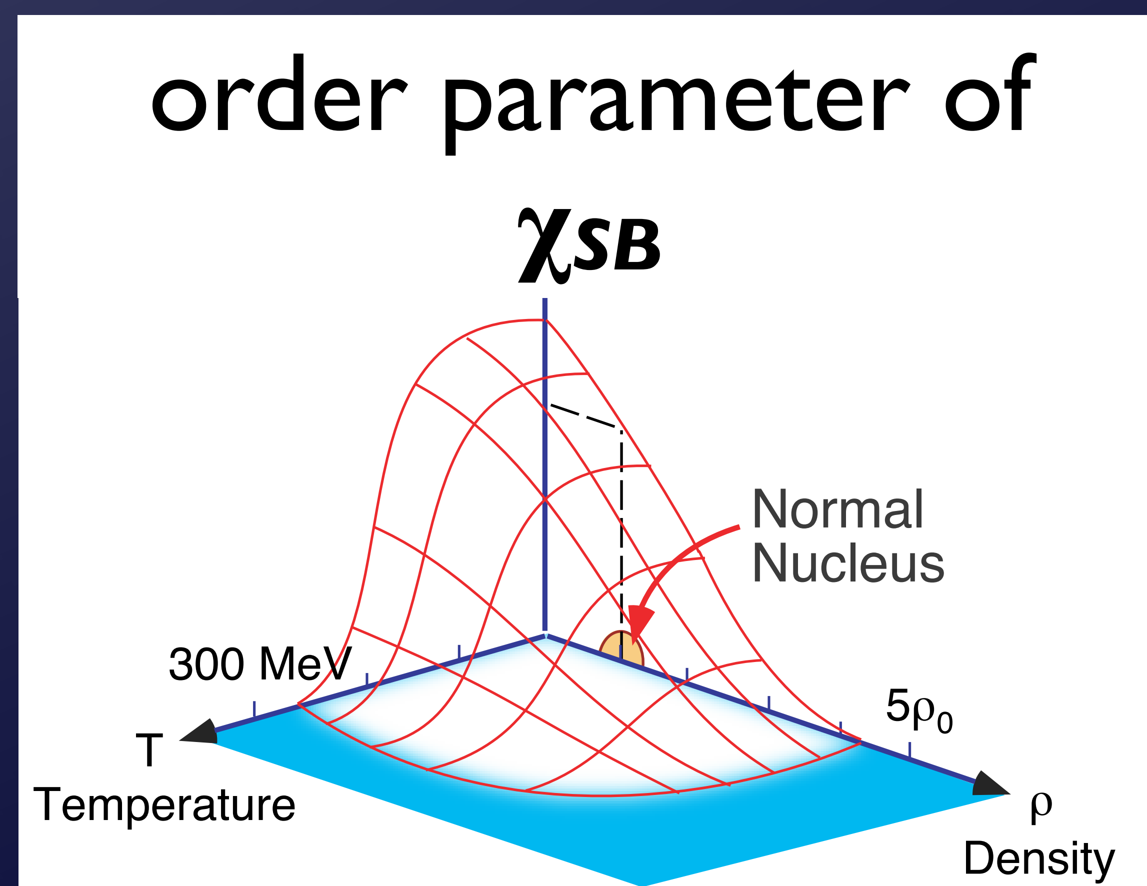
GOR (Gell-Mann - Oakes - Renner)

$$m_\pi^2 f_\pi^2 = -m_q < \bar{q}q >$$

$$F_t^* Z_\rho^{1/2} = -\langle \bar{q}q \rangle_\rho$$

$$Z_\rho = Z \left(1 - \left. \frac{\partial \Pi_\rho}{\partial \omega^2} \right|_{\omega=0} \right)^{-1}$$

Jido et al.



Putting these together...

pionic atom 1s energy

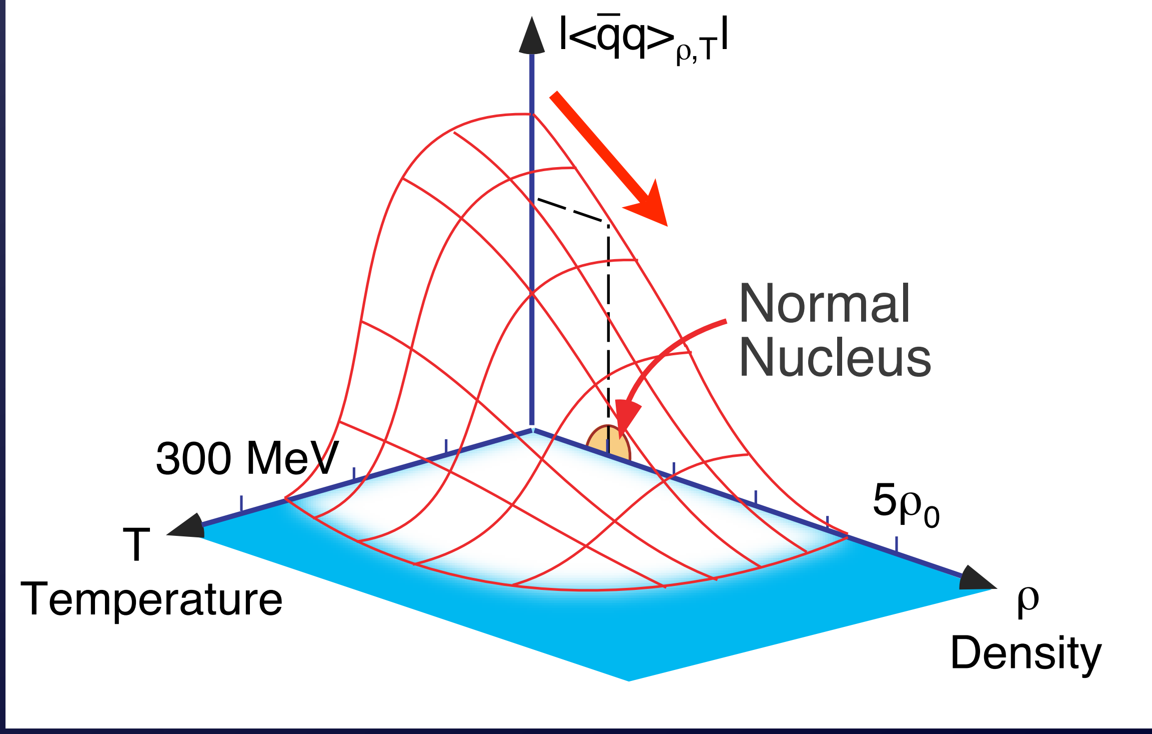
$$\not{b_0}(\rho_n + \rho_p) + b_1(\rho_n - \rho_p)$$

$$b_1 \propto \frac{m_\pi}{f_\pi^2(\rho)}$$

TW

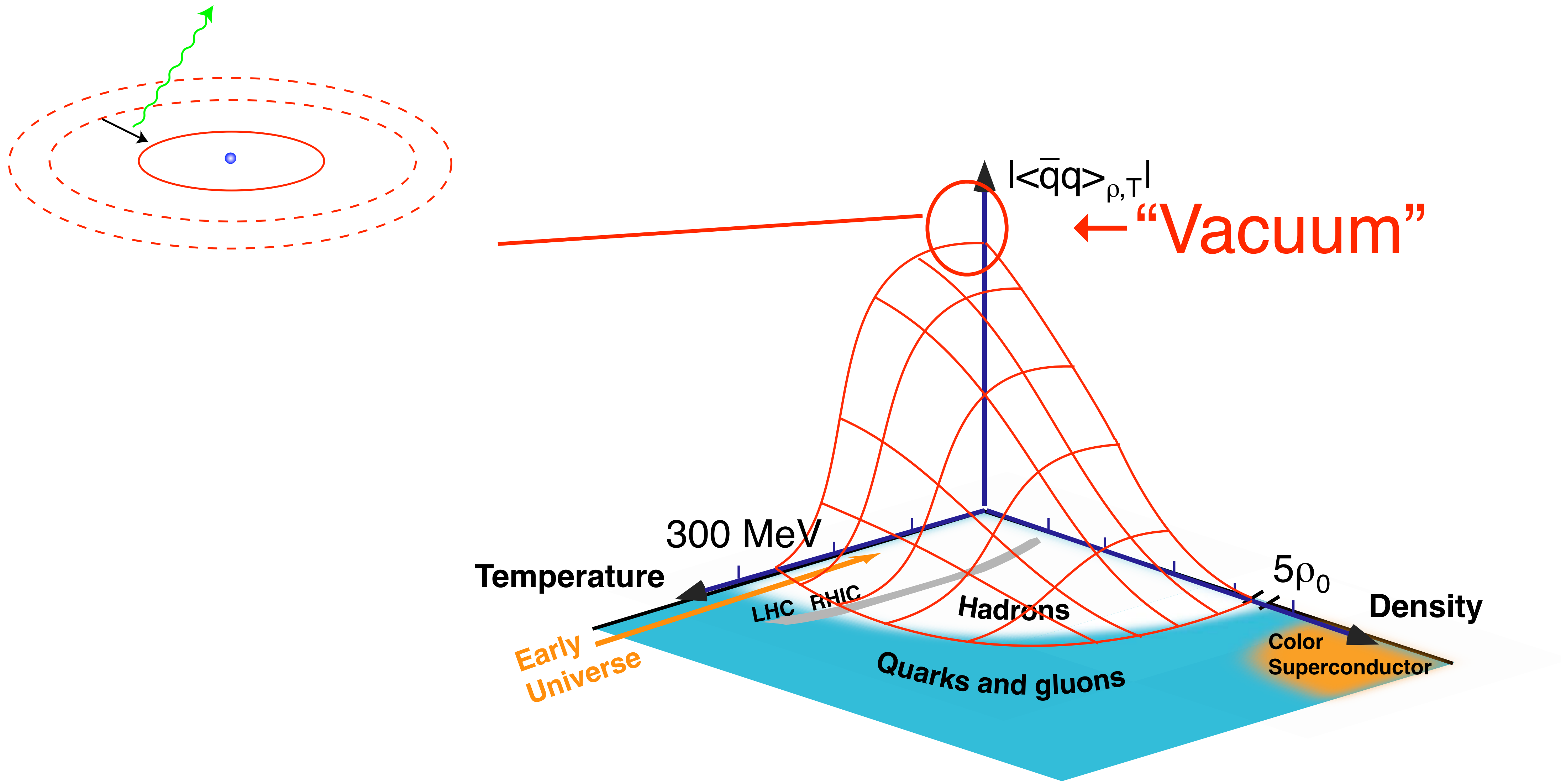
GOR

$$f_\pi^2(\rho) m_\pi^2 \approx -m_q < \bar{q}q >_\rho$$



By the way, we also need the "vacuum" b_1 value

pionic hydrogen x-ray spectroscopy

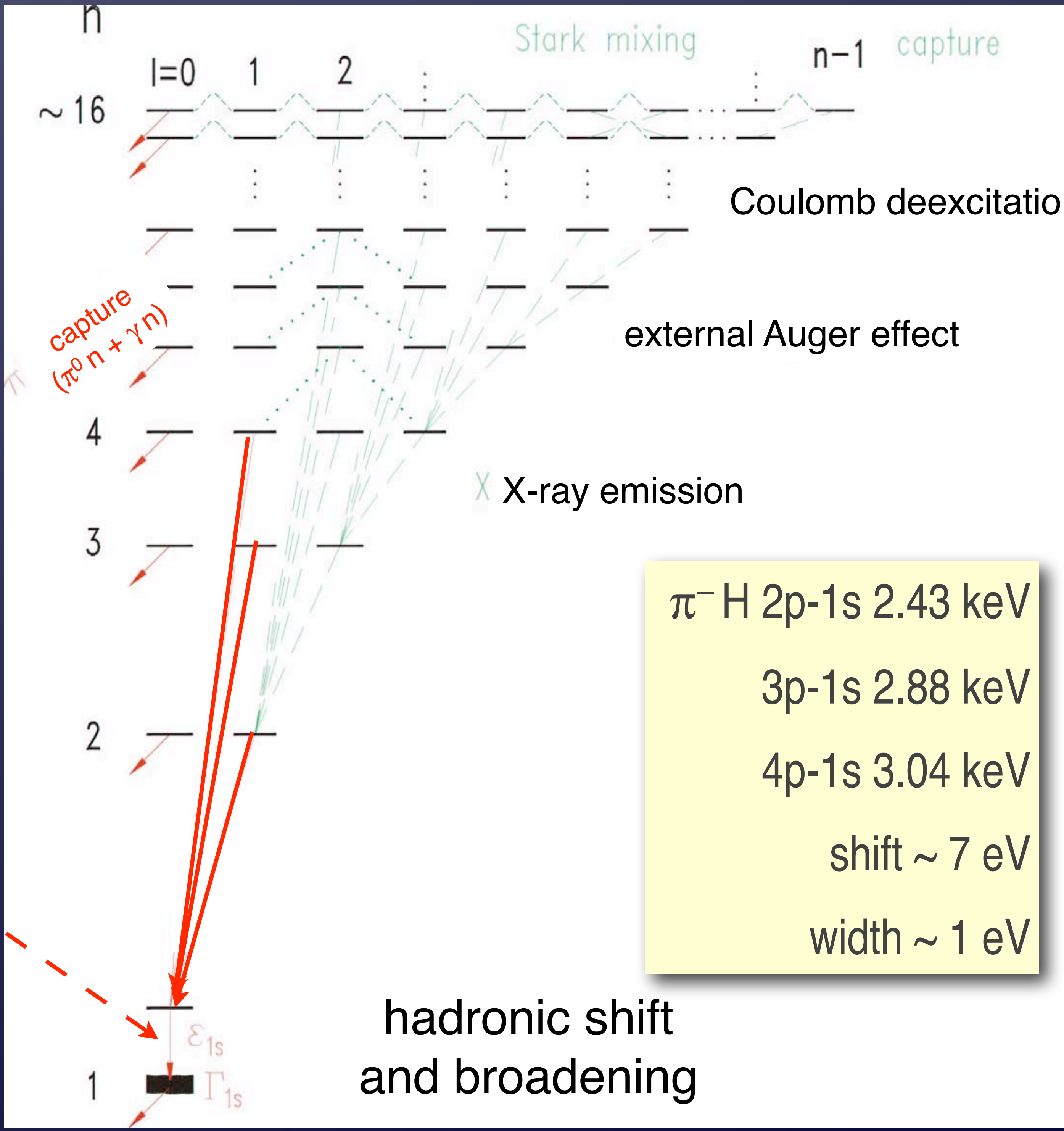


Pionic Hydrogen

b_0: isoscalar scattering length

b_1: isovector scattering length

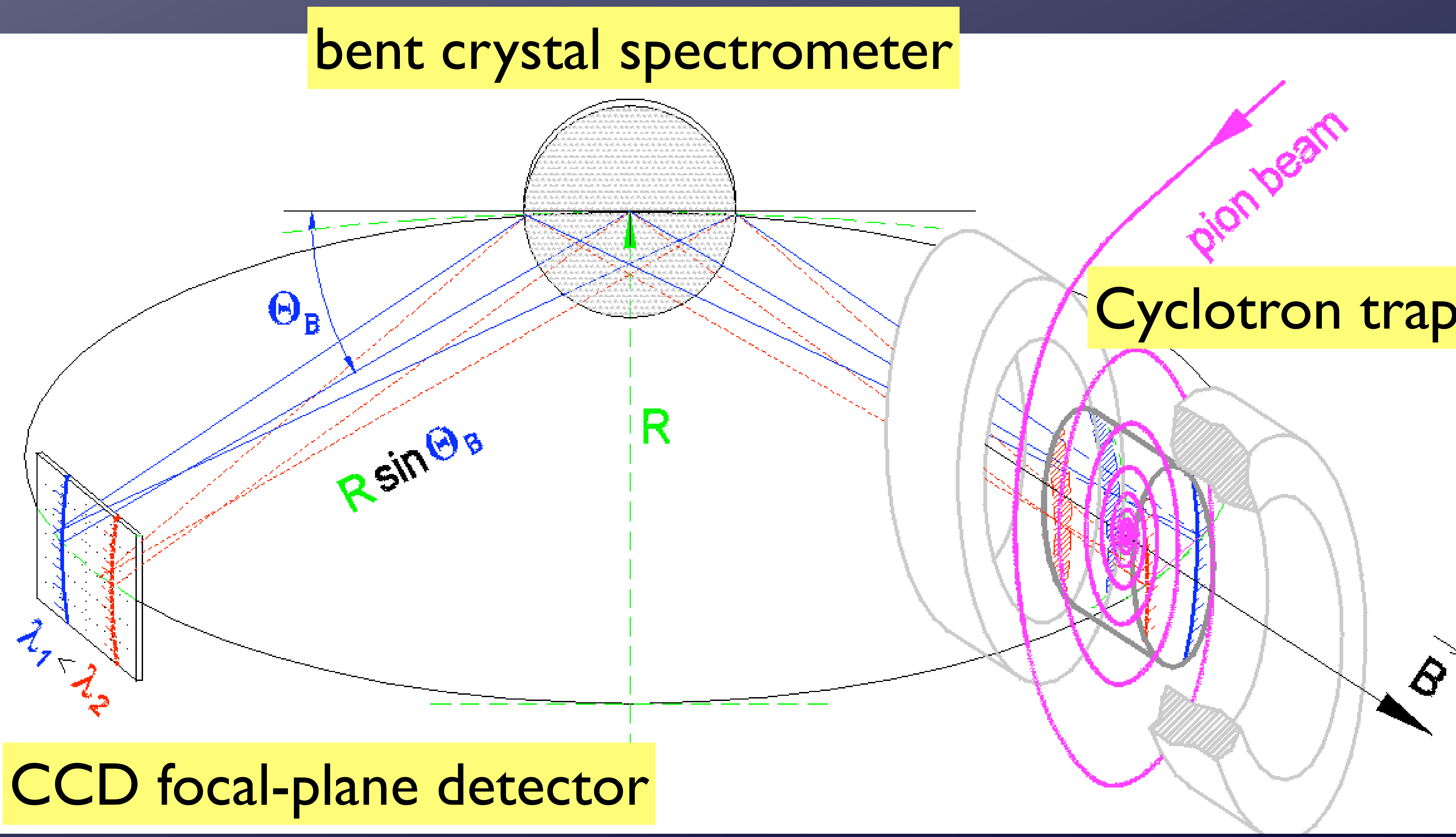
$$\epsilon_{1s} \propto a_{\pi^- p \to \pi^- p}$$
$$\propto b_0 + b_1$$
$$\Gamma_{1s} \propto (a_{\pi^- p \to \pi^0 n})^2$$
$$\propto b_1^2$$

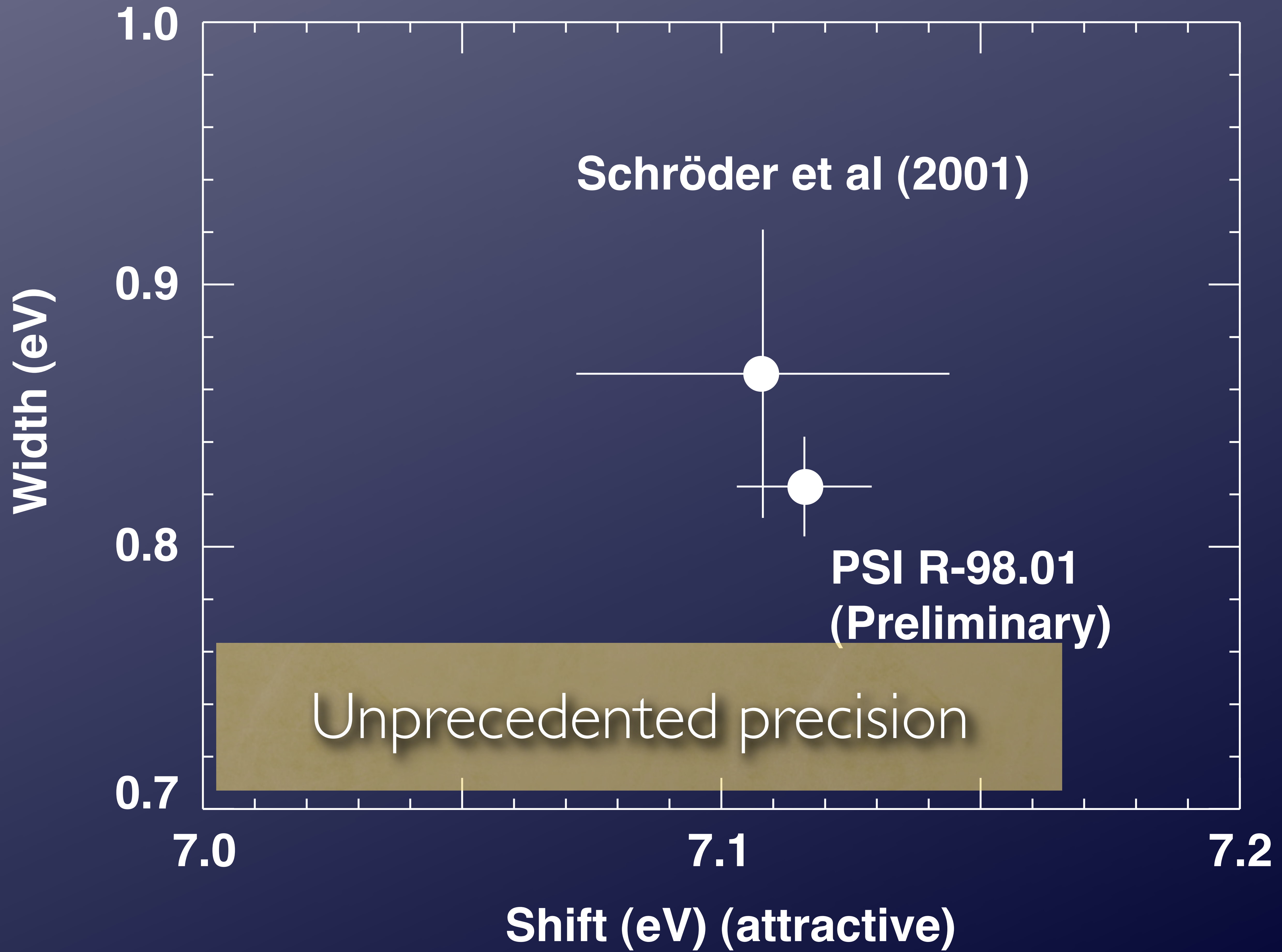


π^- H 2p-1s 2.43 keV
3p-1s 2.88 keV
4p-1s 3.04 keV
shift ~ 7 eV
width ~ 1 eV

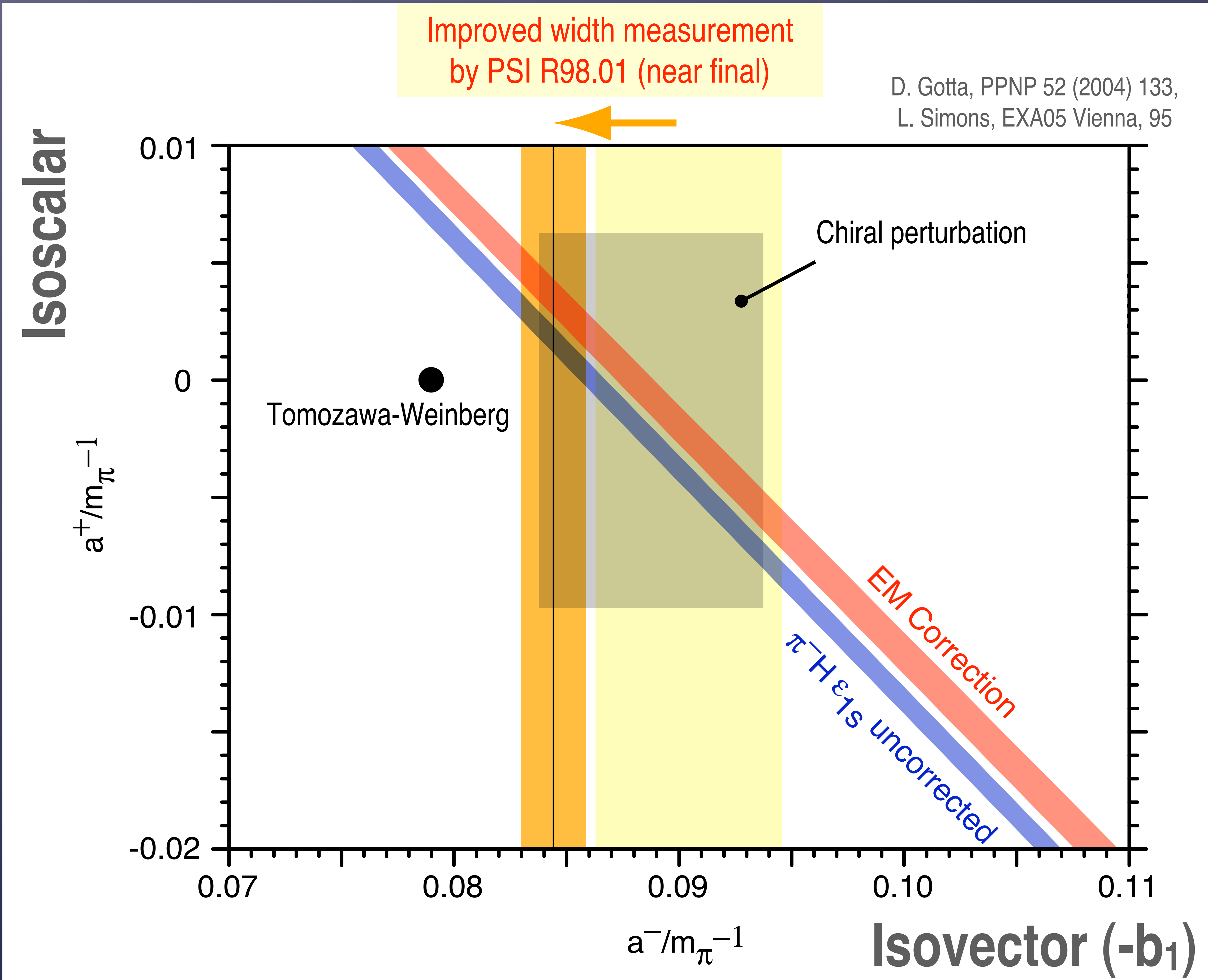
PSI experiment R-98.01

Debrecen – Ioannina – FZ Jülich – Paris – PSI – IMEP Vienna – ETH Zürich

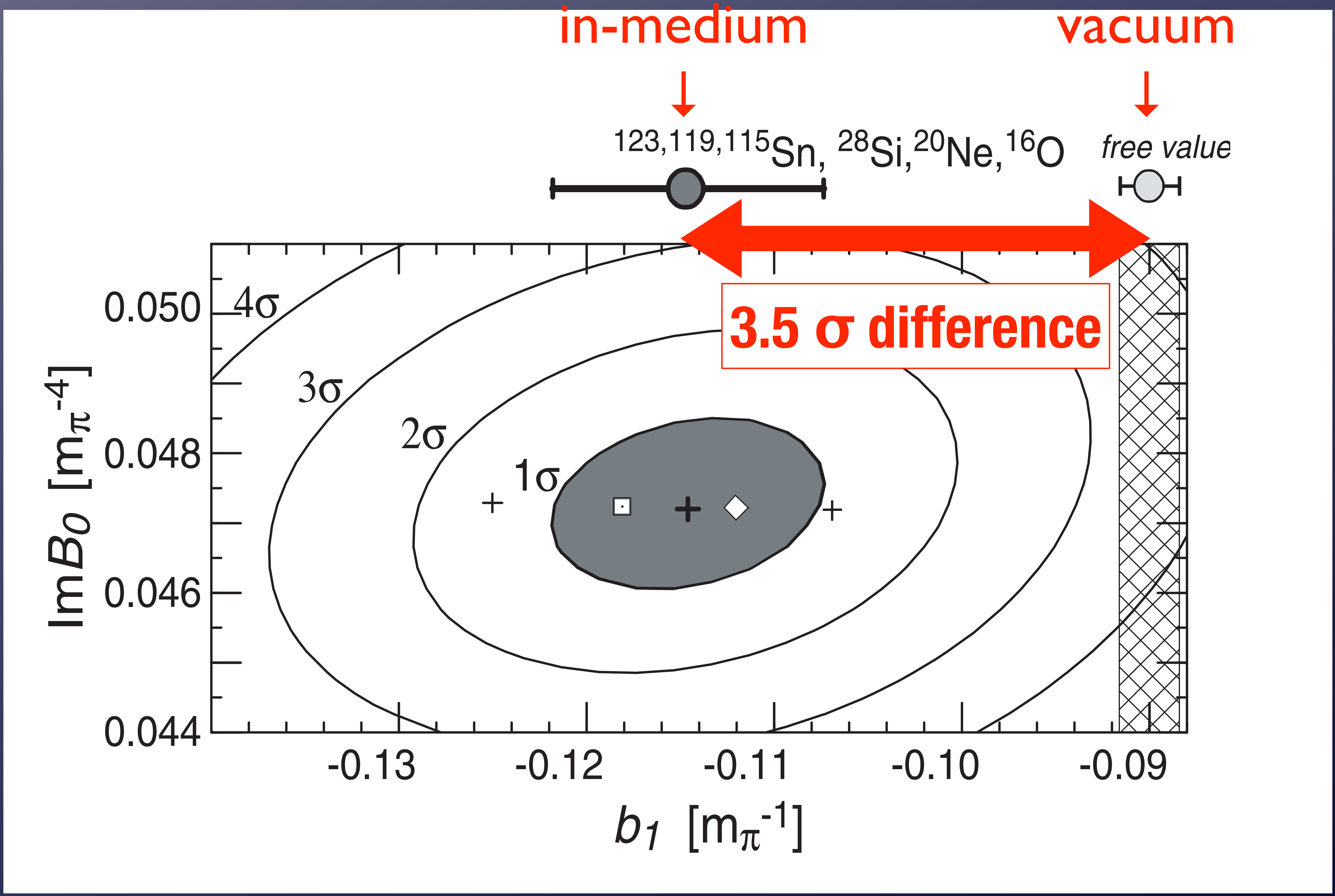




1.0
0.9
0.8
0.7
Width (eV)
7.0
7.1
7.2
Shift (eV) (attractive)
Schröder et al (2001)
PSI R-98.01
(Preliminary)
Unprecedented precision



Improved width measurement
by PSI R98.01 (near final)
D. Gotta, PPNP 52 (2004) 133,
L. Simons, EXA05 Vienna, 95
Isoscalar
a^{+}/m_{π}^{-1}
0.01
0
-0.01
-0.02
Chiral perturbation
Tomozawa-Weinberg
EM Correction
$\pi^{-}H\ \varepsilon_{1s}$ uncorrected
0.07
0.08
0.09
0.10
0.11
a^{-}/m_{π}^{-1}
Isovector ($-b_1$)



Suzuki et al, PRL 92 (2004) 072302

$$
\begin{aligned}
b_1^{\text{free}}/b_1 &= 0.78 \pm 0.05 \text{ at } \rho \sim 0.6\rho_0 \\
&\downarrow \\
\langle \bar{q}q \rangle_{\rho_0} / \langle \bar{q}q \rangle_0 &\sim 0.67
\end{aligned}
$$

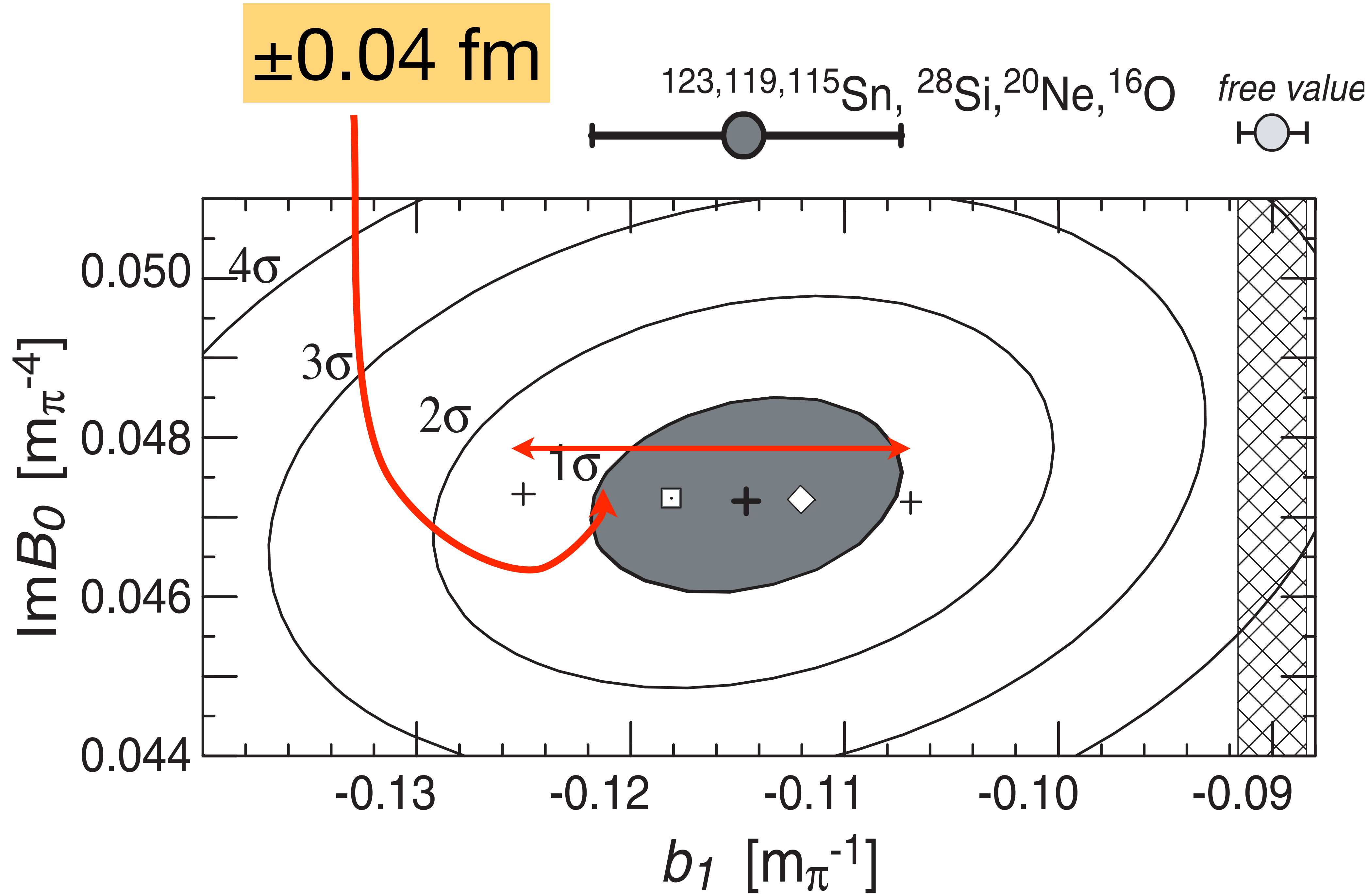
quantitative demonstration of the
“proton-mass” generation mechanism

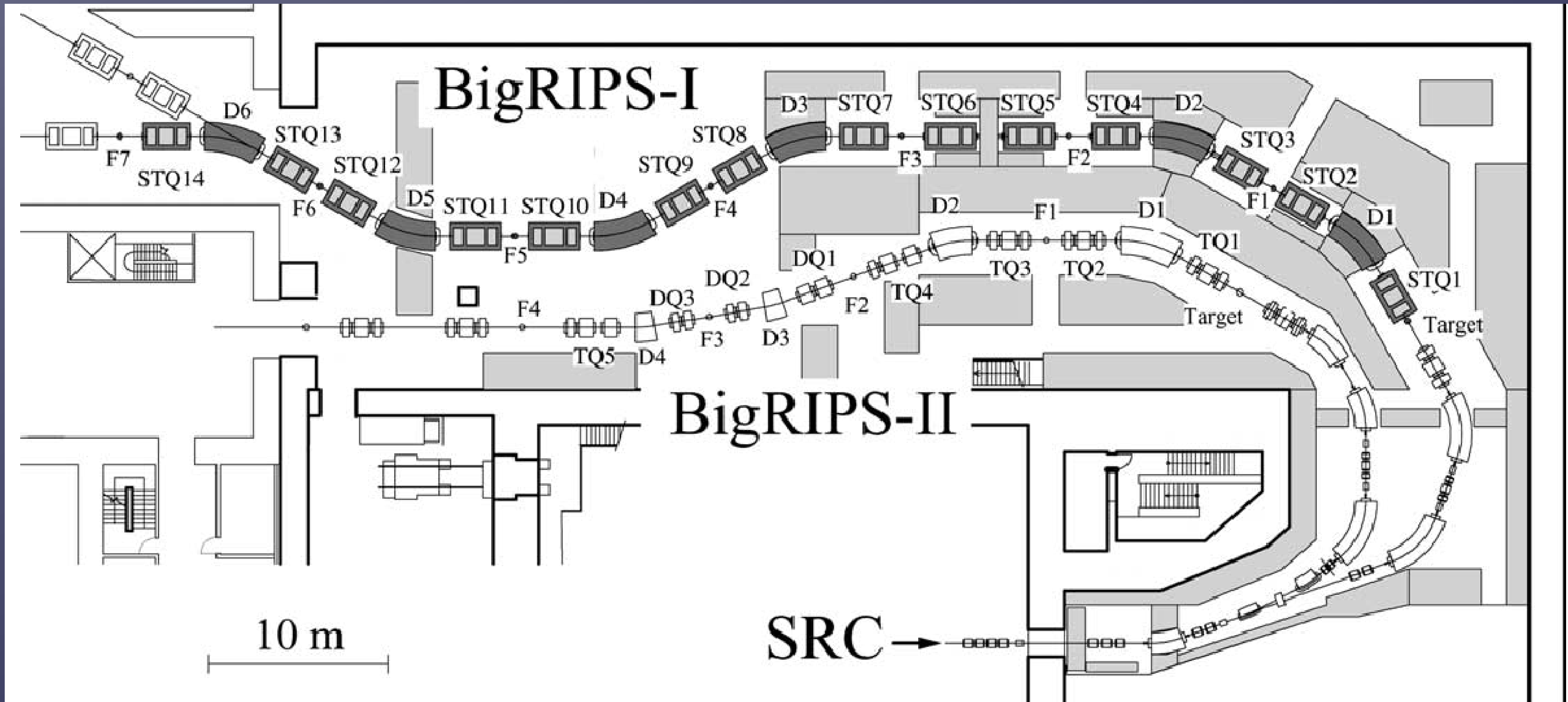
b_1 is coupled to $\rho(r)$

$$b_1(\underline{\rho_n - \rho_p})$$

how well are ρ_ns known ?

Uncertainty due to our insufficient knowledge of the neutron radii of Sn nuclei





- Systematic studies at RIKEN/BigRIPS
  - better energy resolution
  - absolute beam energy measurement
  - disentangle b_1 vs neutron radii

K. Itahashi et al.

結

Summary

- 15 years since Wiesbaden
- experiments on mass, f_π modification
- mass shift : tantalizing results, but more work needed
- f_π : must understand “conventional” nuclear physics
- study of meson-nucleus bound states important