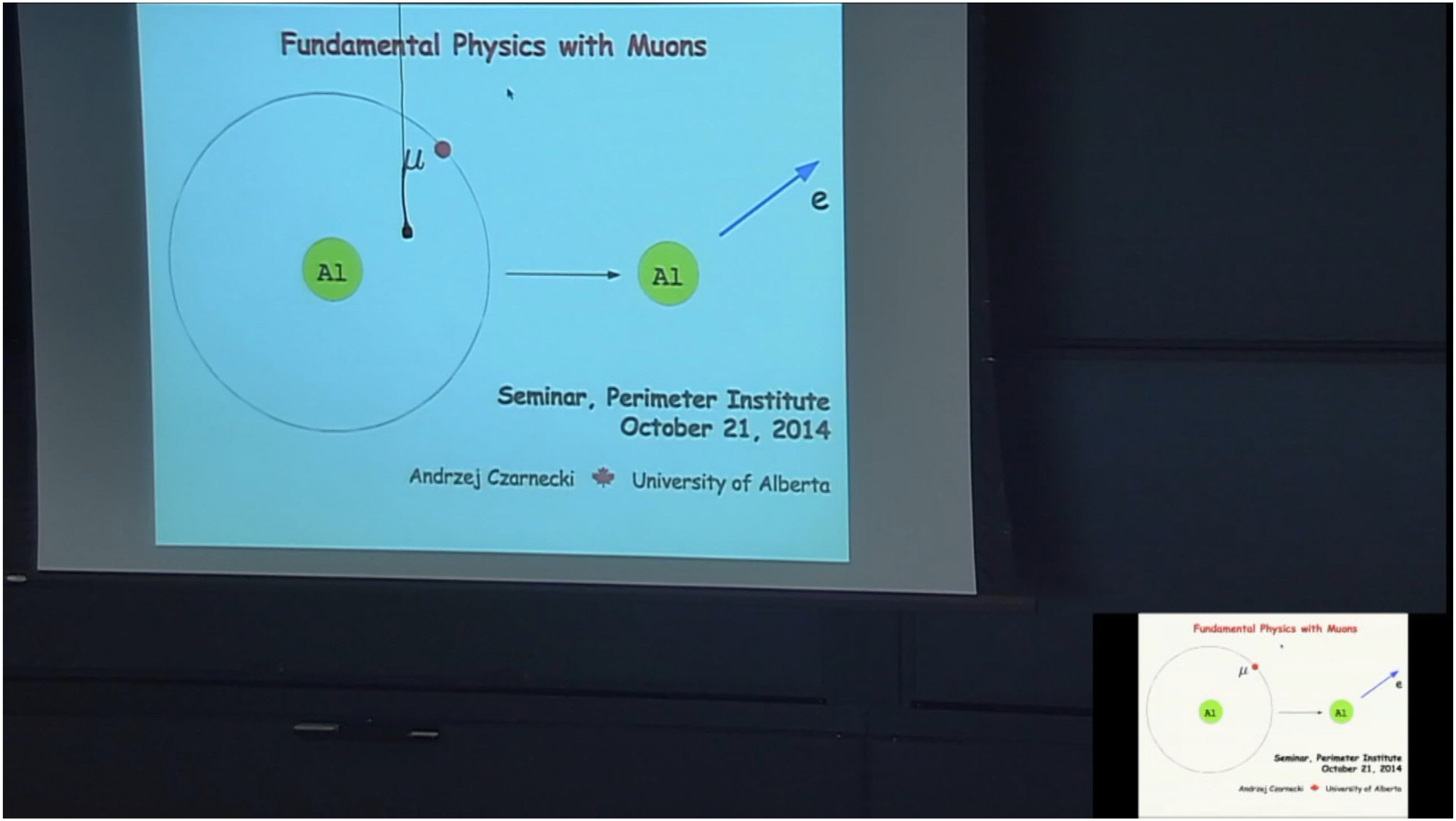
Title: Fundamental physics with muons

Date: Oct 21, 2014 01:00 PM

URL: http://pirsa.org/14100115

Abstract: I will review applications of the muon as a probe for new phenomena. Topics to be discussed include the free muon decay and the determination of the Fermi constant; the anomalous magnetic moment of the muon; and searches for lepton flavor violation such as mu->e+gamma, mu->3e, and the muon-electron conversion, with special emphasis on the modification of the muon decay by the atomic binding.


Fundamental Physics with Muons
μ
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Al
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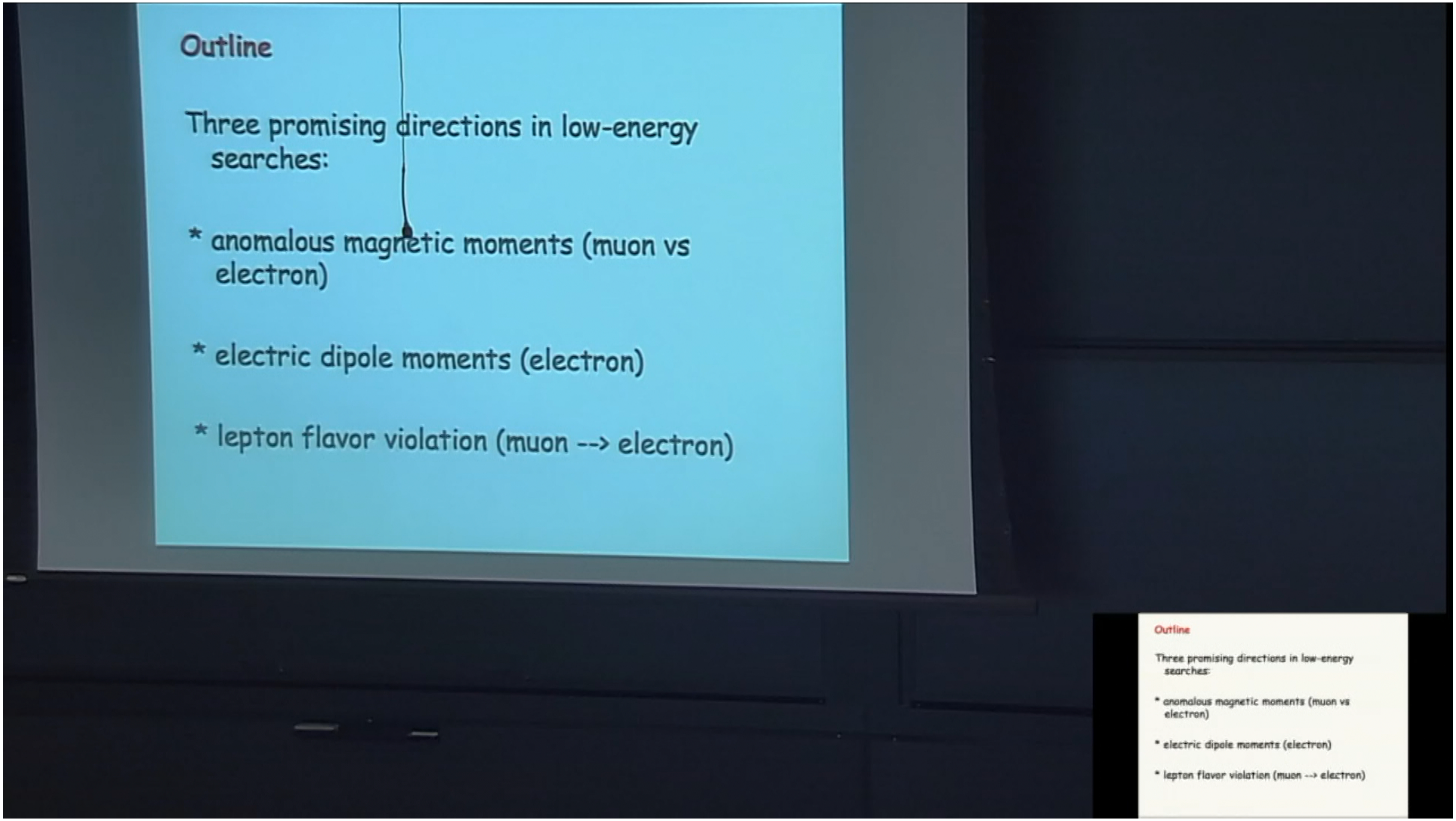
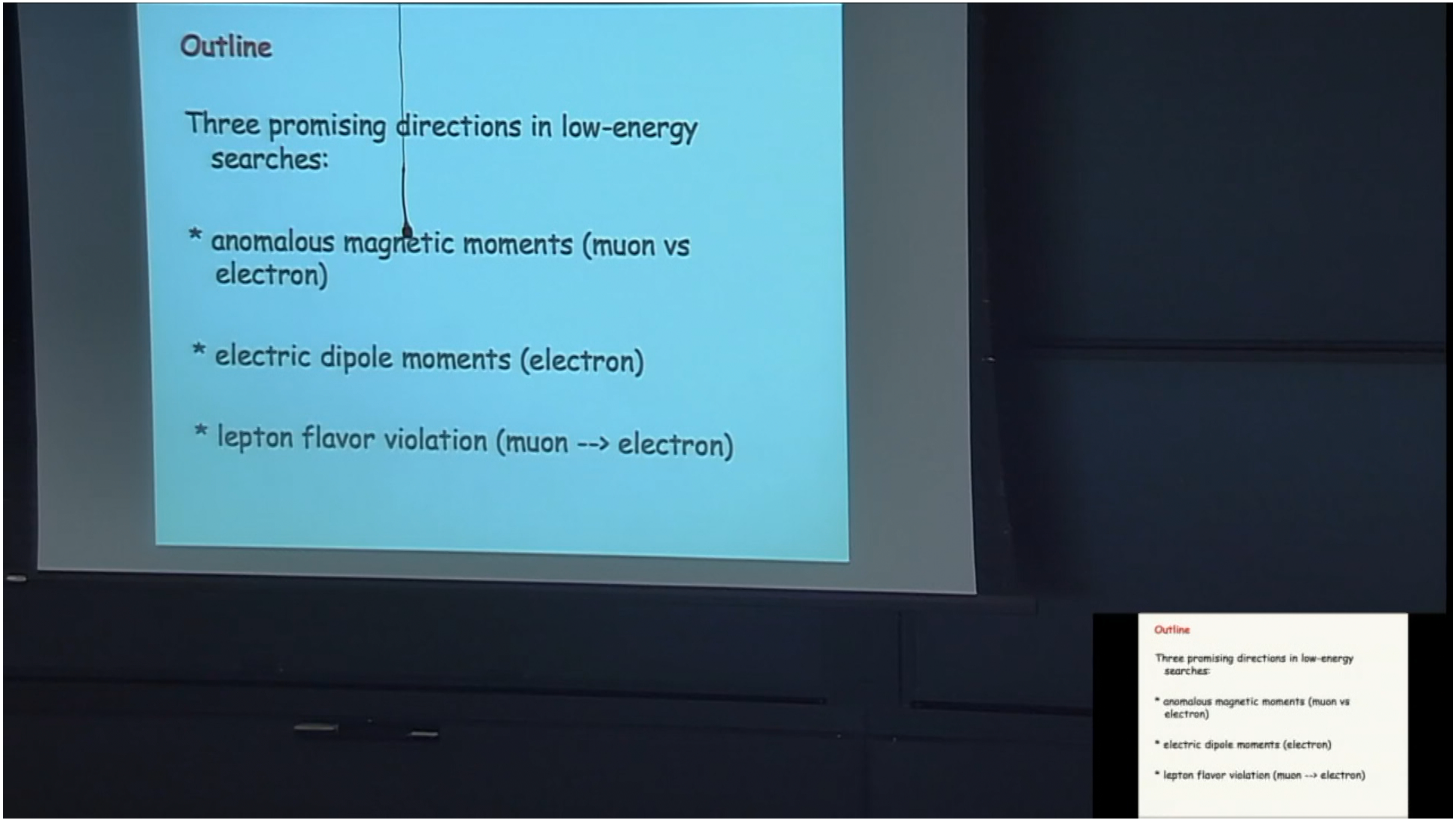
Seminar, Perimeter Institute
October 21, 2014
Andrzej Czarnecki
University of Alberta


Outline
Three promising directions in low-energy searches:
* anomalous magnetic moments (muon vs electron)
* electric dipole moments (electron)
* lepton flavor violation (muon --> electron)



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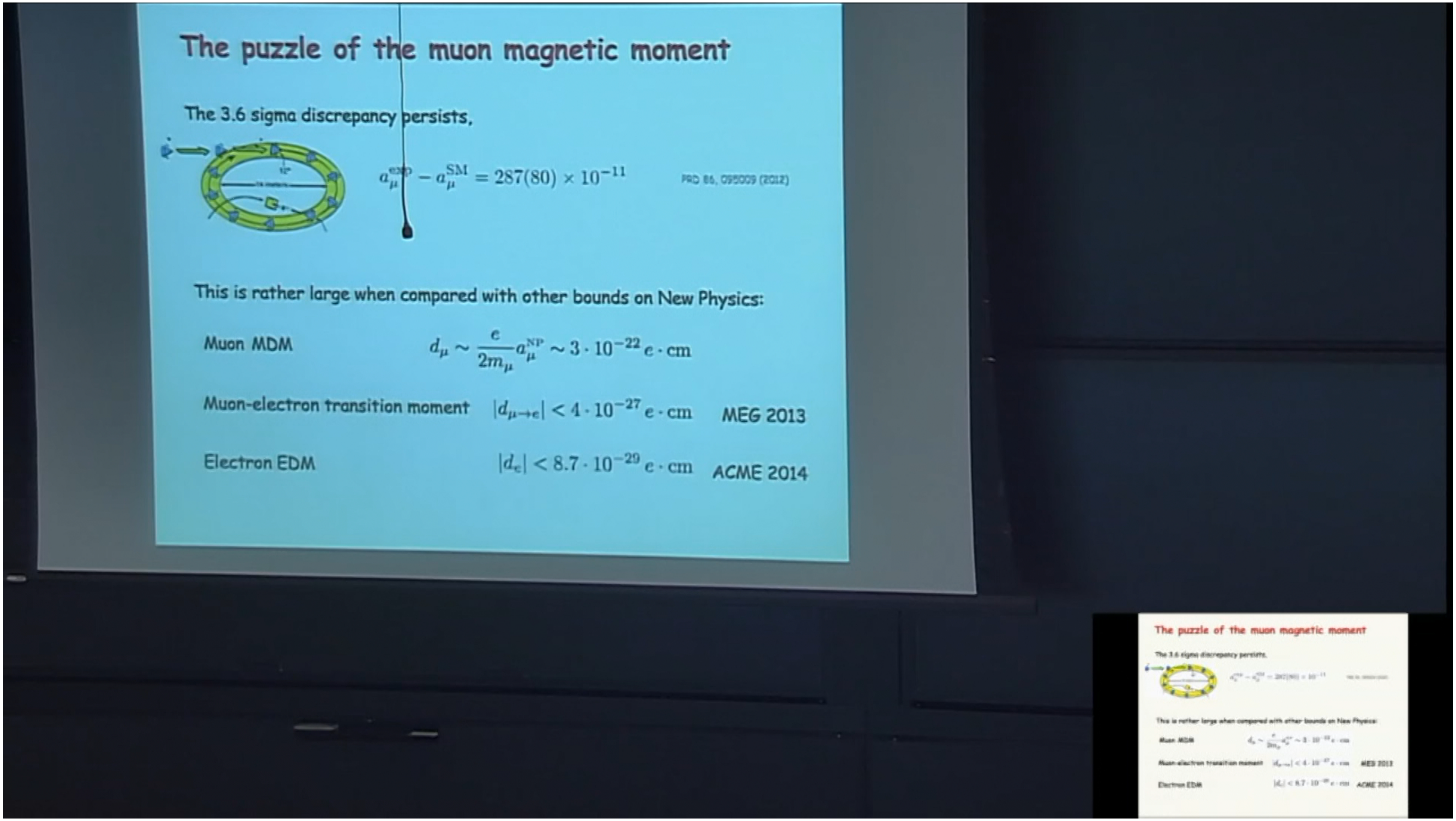
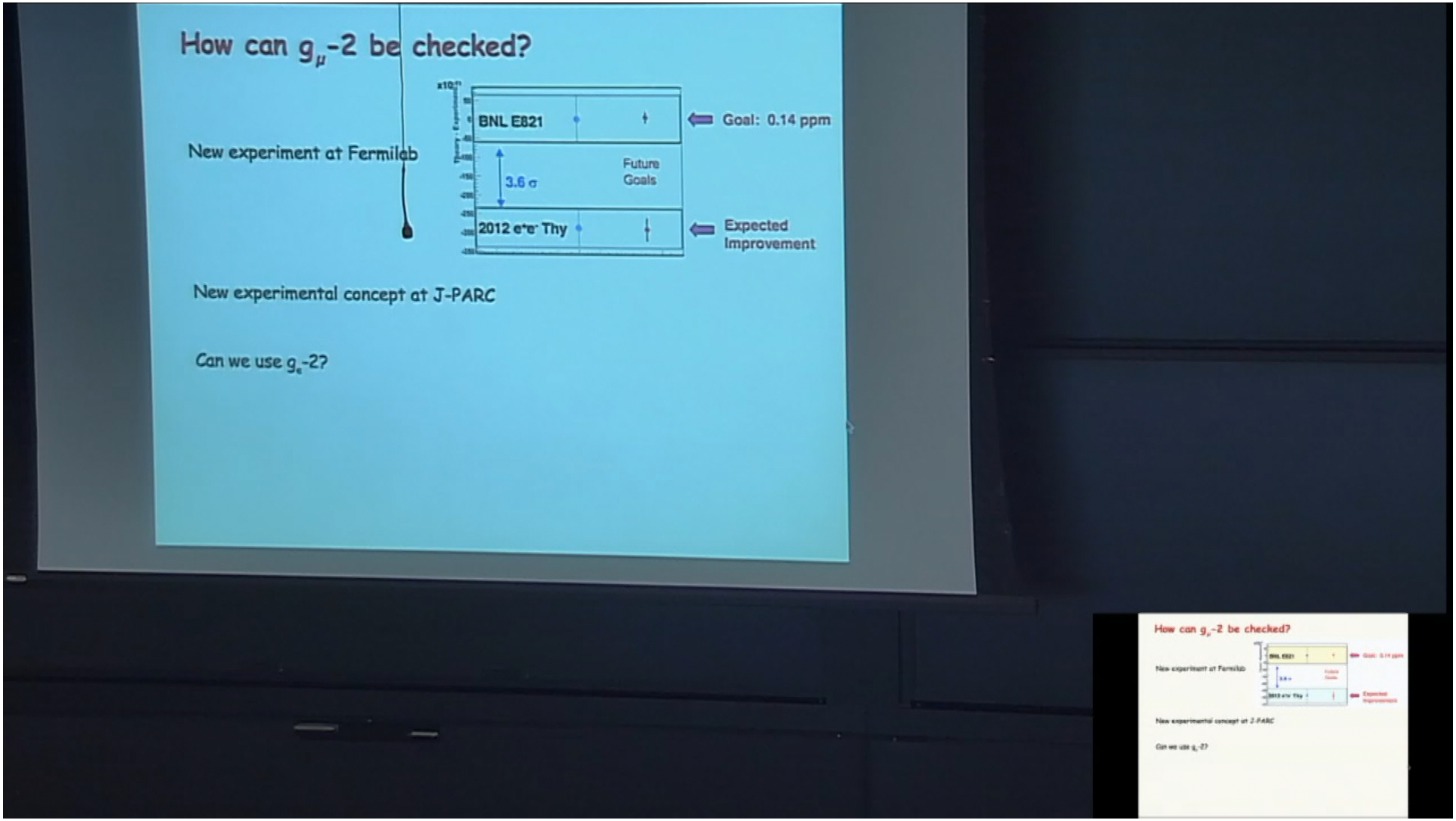
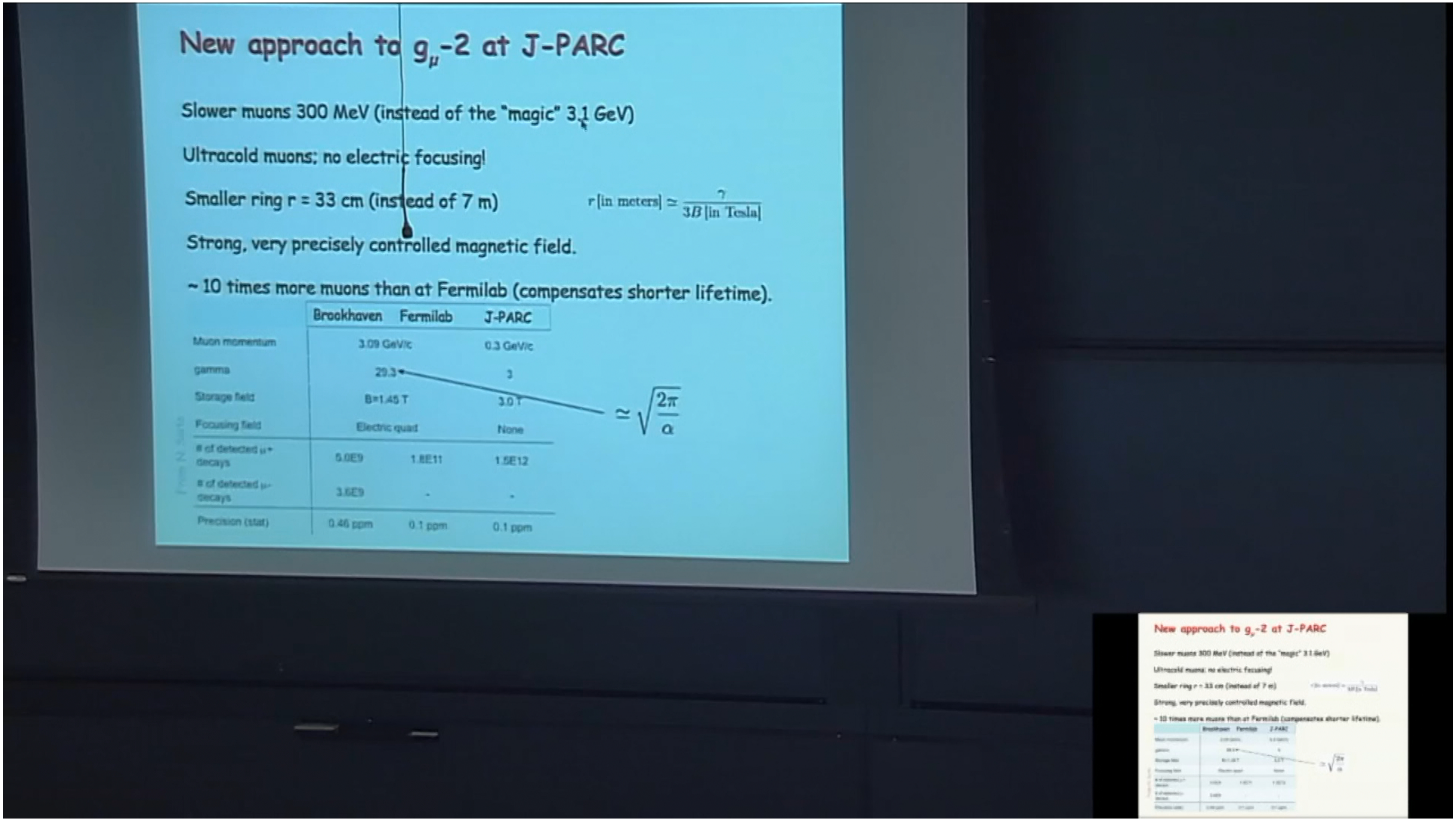
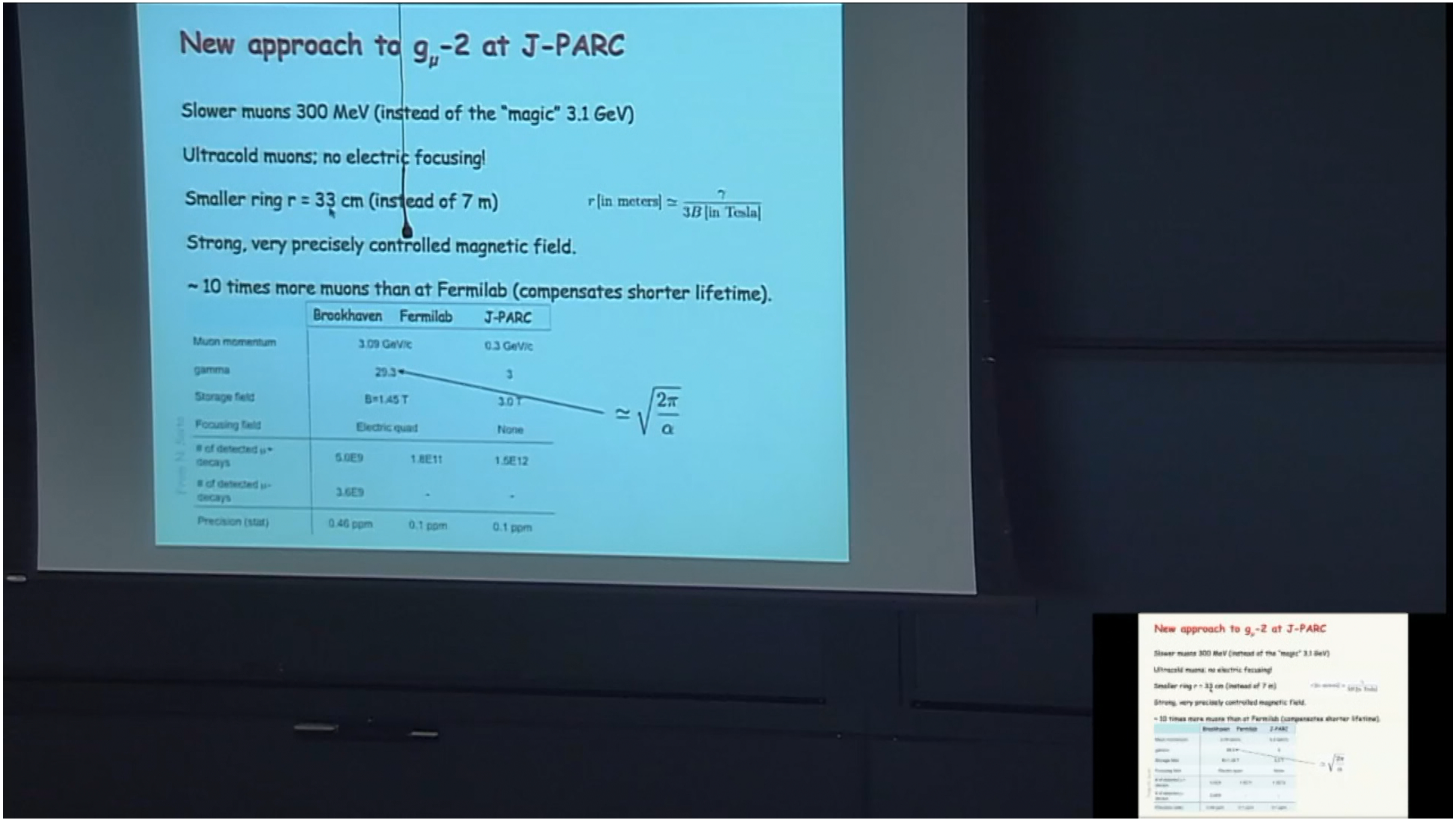

The puzzle of the muon magnetic moment
The 3.6 sigma discrepancy persists,
$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287(80) \times 10^{-11}$
PRD 86, 095009 (2012)
This is rather large when compared with other bounds on New Physics:
Muon MDM
$d_\mu \sim \frac{e}{2m_\mu} a_\mu^{\rm NP} \sim 3 \cdot 10^{-22}\, e \cdot {\rm cm}$
Muon-electron transition moment
$|d_{\mu\to e}| < 4 \cdot 10^{-27}\, e \cdot {\rm cm}$
MEG 2013
Electron EDM
$|d_e| < 8.7 \cdot 10^{-29}\, e \cdot {\rm cm}$
ACME 2014


How can g_μ-2 be checked?
New experiment at Fermilab
BNL E821
Goal: 0.14 ppm
3.6 σ
Future Goals
2012 e+e- Thy
Expected Improvement
New experimental concept at J-PARC
Can we use g_e-2?


New approach to g_μ-2 at J-PARC
Slower muons 300 MeV (instead of the "magic" 3.1 GeV)
Ultracold muons; no electric focusing!
Smaller ring r = 33 cm (instead of 7 m)
r [in meters] ≃ 7 / 3B [in Tesla]
Strong, very precisely controlled magnetic field.
~ 10 times more muons than at Fermilab (compensates shorter lifetime).
Brookhaven Fermilab J-PARC
Muon momentum 3.09 GeV/c 0.3 GeV/c
gamma 29.3 3
Storage field B=1.45 T 3.0 T
Focusing field Electric quad None
# of detected μ+ decays 5.0E9 1.8E11 1.5E12
# of detected μ- decays 3.6E9 - -
Precision (stat) 0.46 ppm 0.1 ppm 0.1 ppm
≃ √(2π/α)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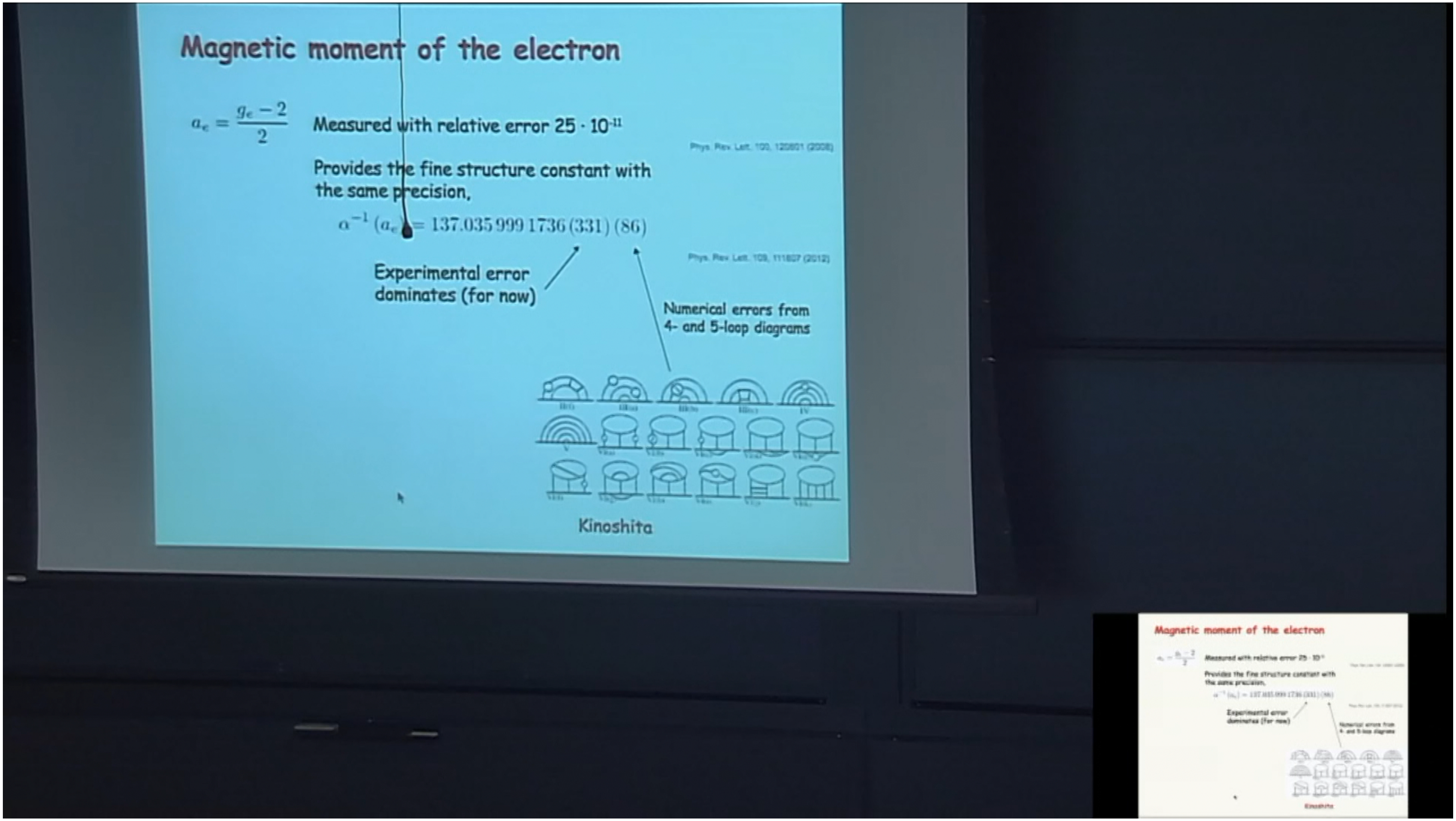
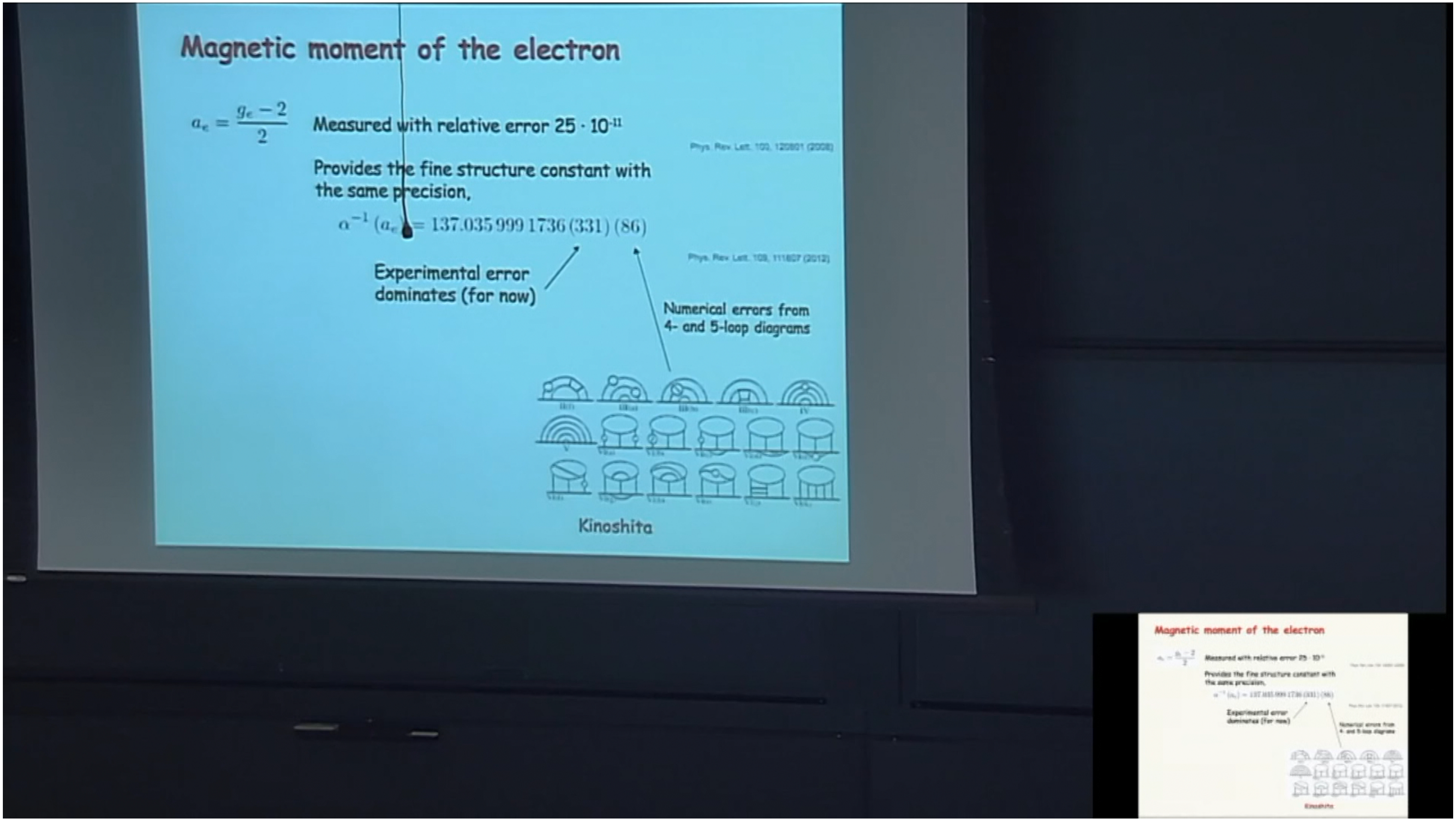
Precision (stat) 0.46 ppm 0.1 ppm 0.1 ppm
$\simeq \sqrt{\frac{2\pi}{\alpha}}$


(Futuristic?) approach to g_μ-2
USM2013
Gabrielse
Measure Muon Magnetic Moment in a Trap
trapped muons
muons ionized from slow muonium
positron detector
positron detector
channel plate to detect muons
Advantages: Use muons to measure the magnetic field in situ
Less expensive
Different systematics
Challenge: 2.2 microsecond muon lifetime
Thanks to A. Mills for helpful conversations


Magnetic moment of the electron
$a_e = \frac{g_e - 2}{2}$
Measured with relative error $25 \cdot 10^{-11}$
Phys. Rev. Lett. 100, 120801 (2008)
Provides the fine structure constant with the same precision,
$\alpha^{-1}(a_e) = 137.035\,999\,1736\,(331)\,(86)$
Phys. Rev. Lett. 109, 111807 (2012)
Experimental error dominates (for now)
Numerical errors from 4- and 5-loop diagrams
Kinoshita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How to use g_e-2 to check g_μ-2?

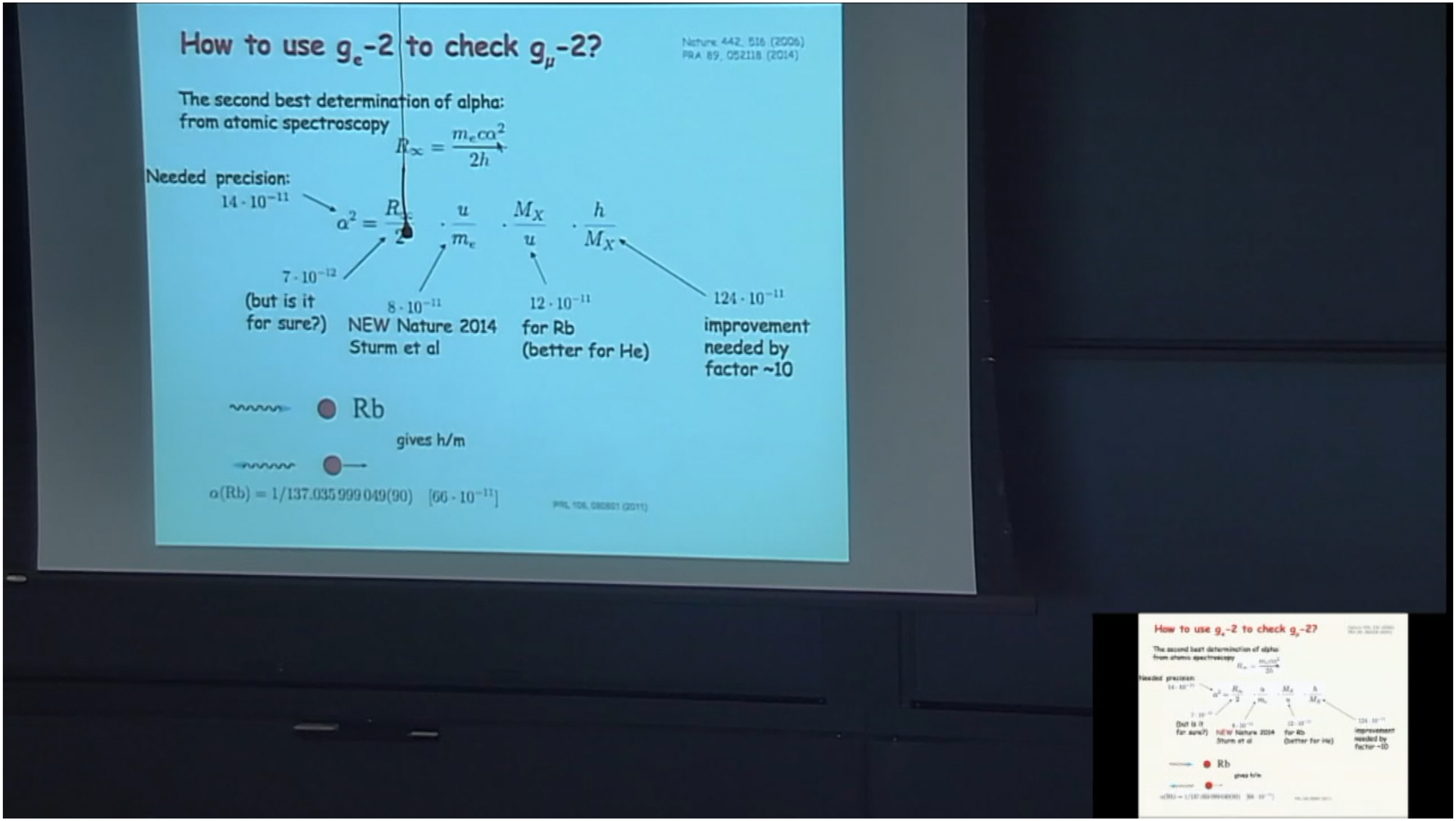
If the muon anomaly is due to New Physics, the expected effect for the electron is likely smaller by $\frac{m_e^2}{m_\mu^2} \sim \frac{1}{43000}$

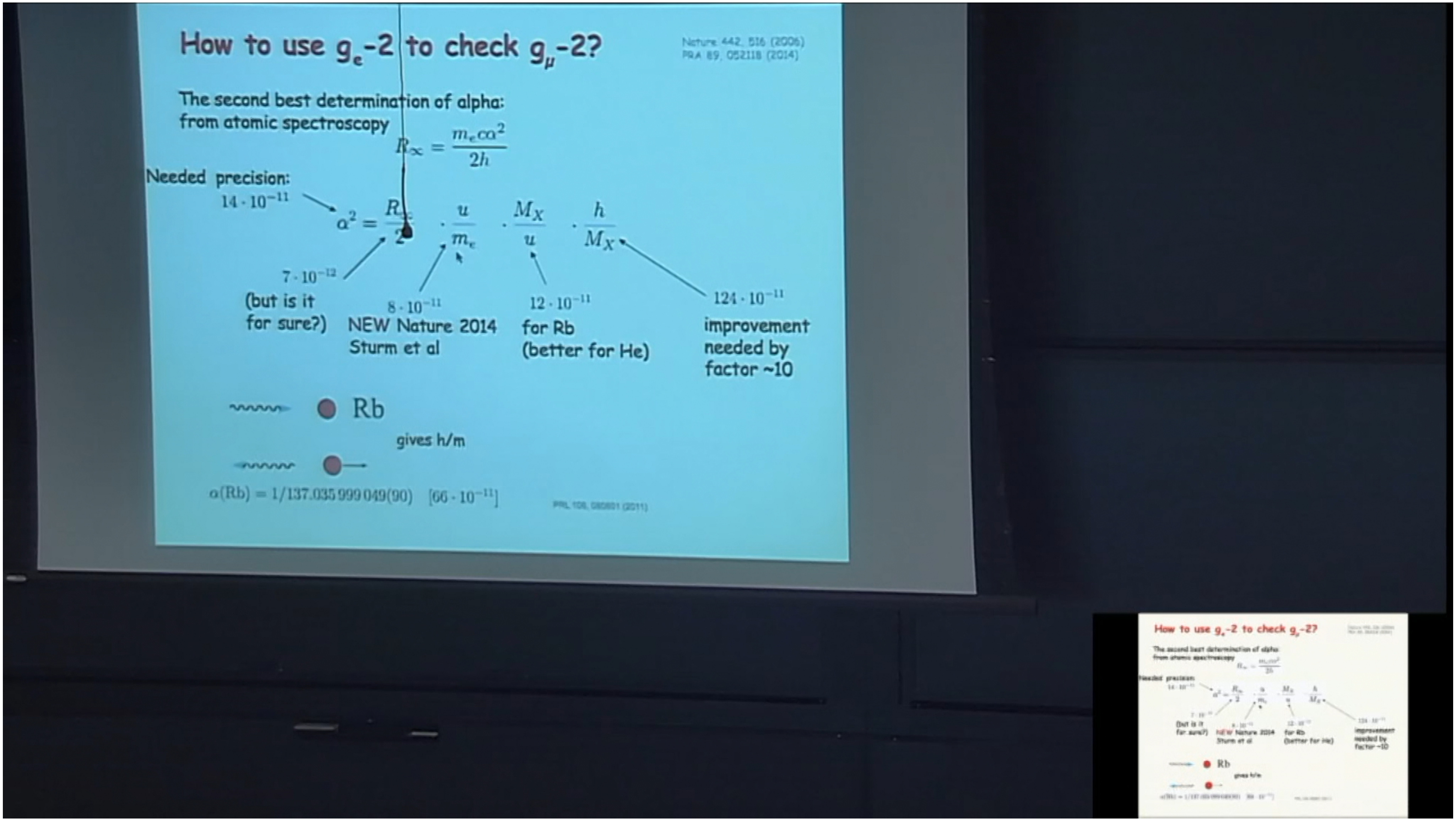
$$\Delta a_\mu \sim 287 \cdot 10^{-11} \rightarrow \Delta a_e \sim 7 \cdot 10^{-14}$$

This means relative uncertainty $\frac{\Delta a_e}{a_e} \sim 7 \cdot 10^{-11}$

and requires a factor of 4 improvement of the latest measurement.

In addition, an independent determination of the fine structure constant is needed, with matching precision.


How to use g_e-2 to check g_μ-2?
Nature 442, 516 (2006)
PRA 89, 052118 (2014)
The second best determination of alpha:
from atomic spectroscopy
$R_\infty = \frac{m_e c \alpha^2}{2h}$
Needed precision:
$14 \cdot 10^{-11}$
$\alpha^2 = \frac{R_\infty}{2} \cdot \frac{u}{m_e} \cdot \frac{M_X}{u} \cdot \frac{h}{M_X}$
$7 \cdot 10^{-12}$
(but is it
for sure?)
$8 \cdot 10^{-11}$
NEW Nature 2014
Sturm et al
$12 \cdot 10^{-11}$
for Rb
(better for He)
$124 \cdot 10^{-11}$
improvement
needed by
factor ~10
Rb
gives h/m
$\alpha(\text{Rb}) = 1/137.035\,999\,049(90) \quad [66 \cdot 10^{-11}]$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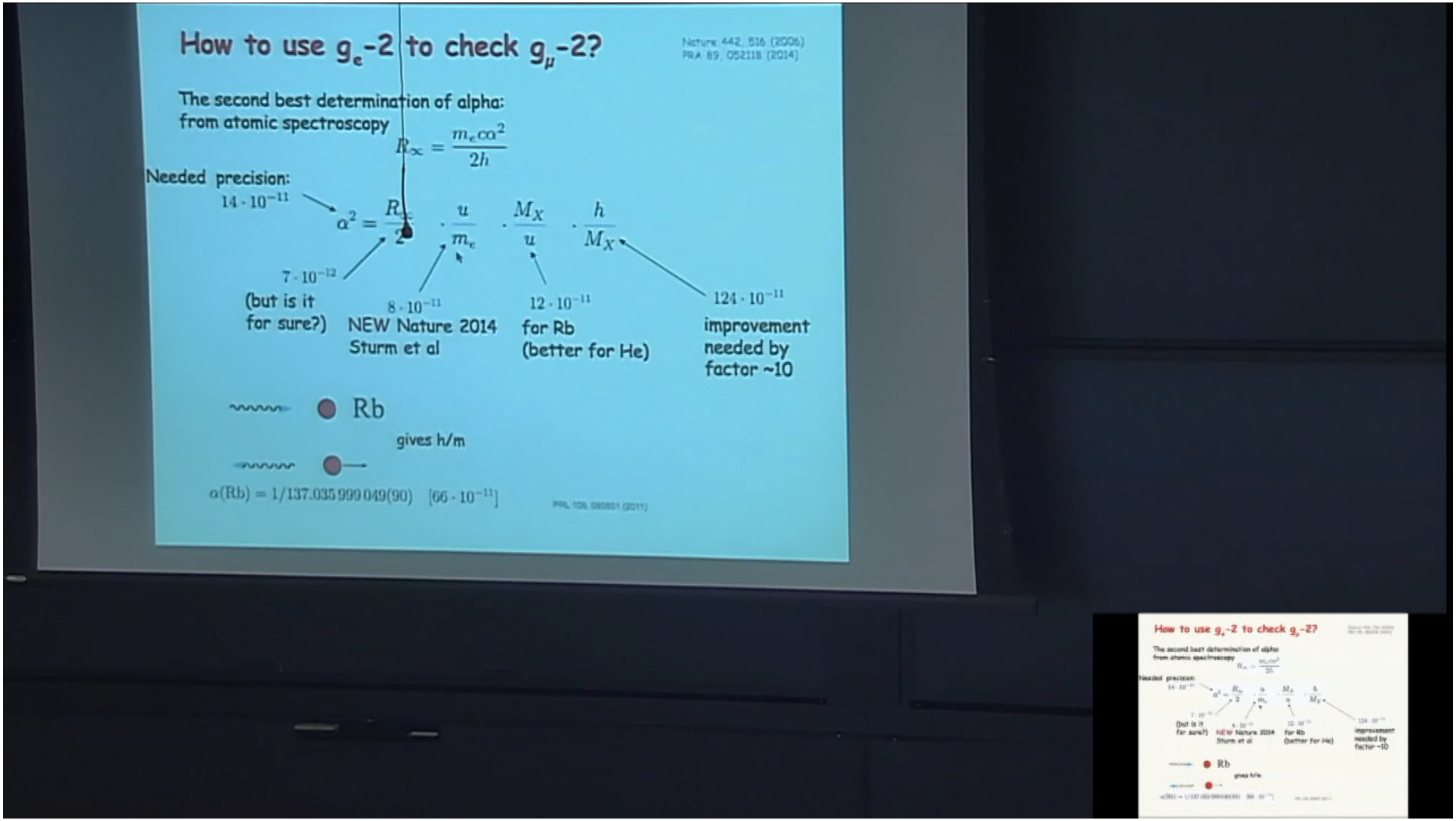
PRL 106, 080801 (2011)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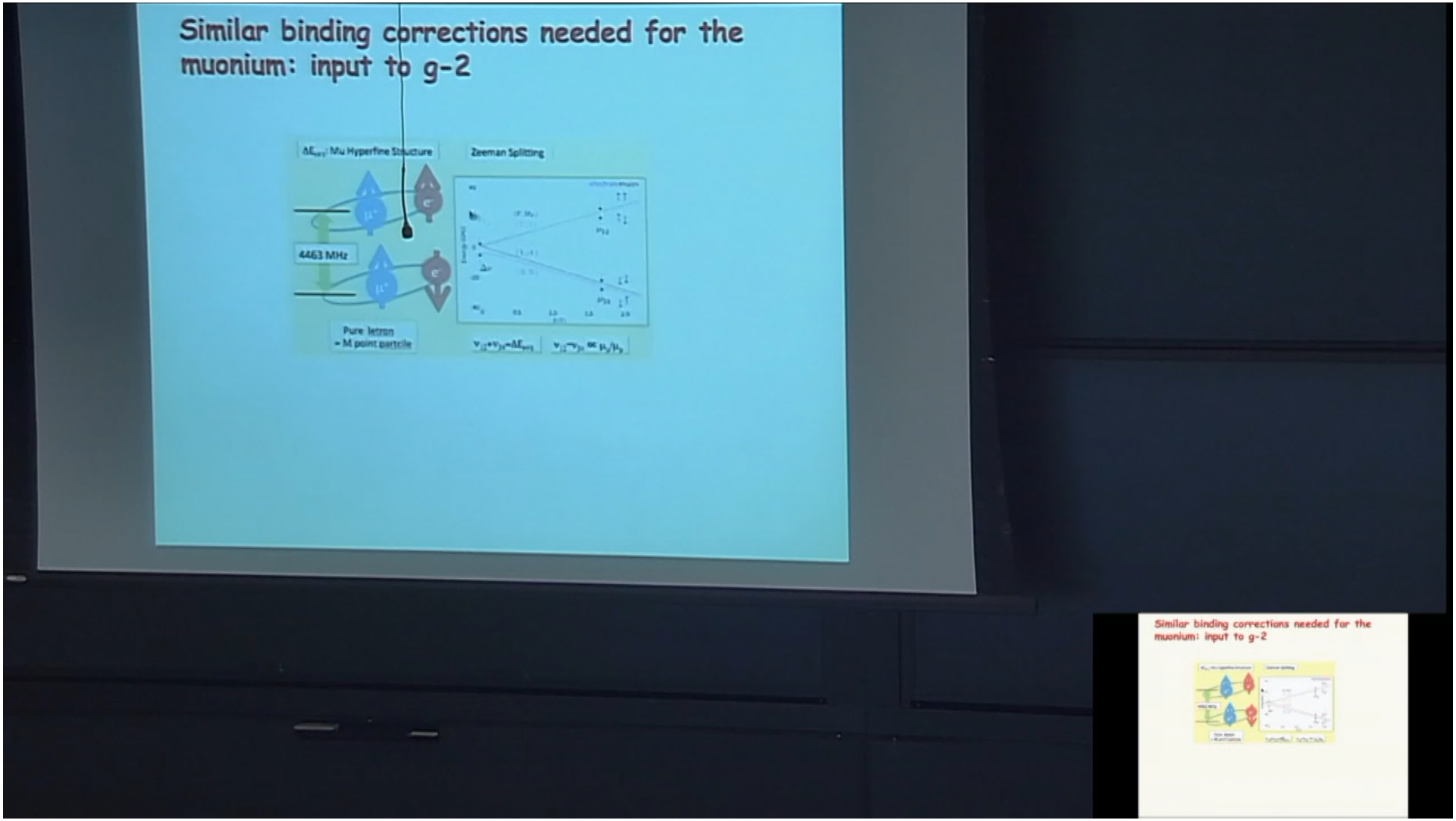
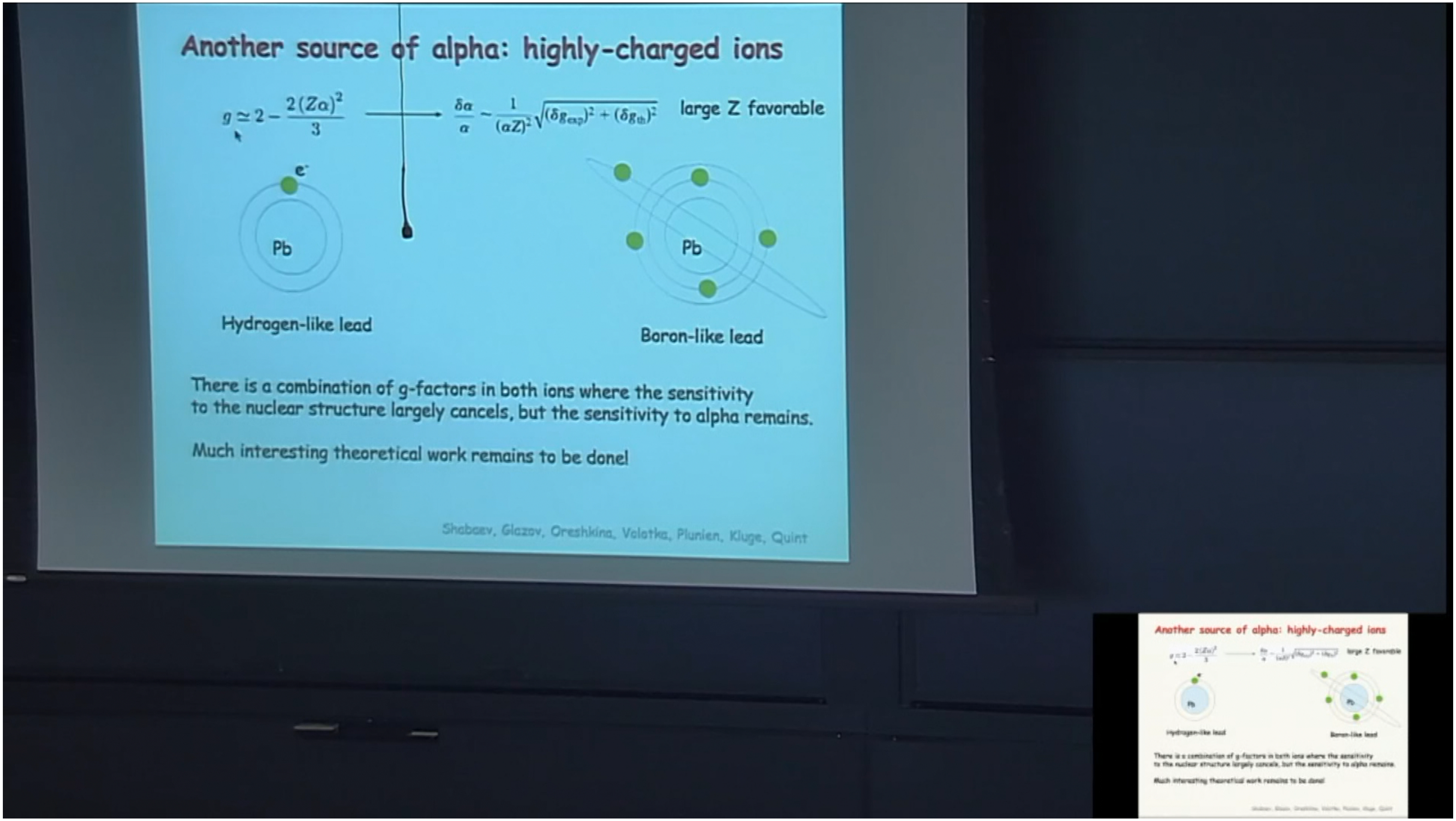
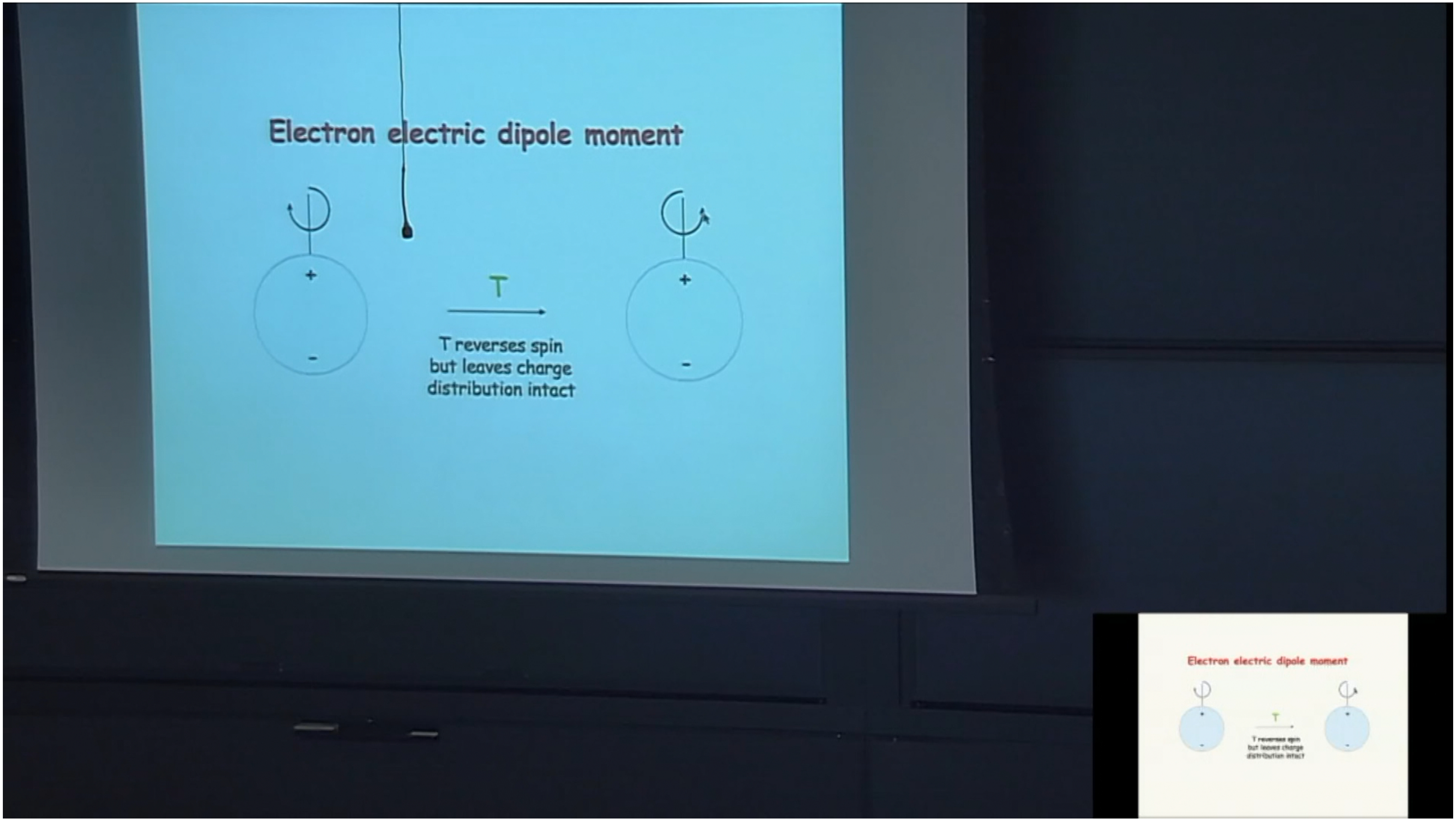
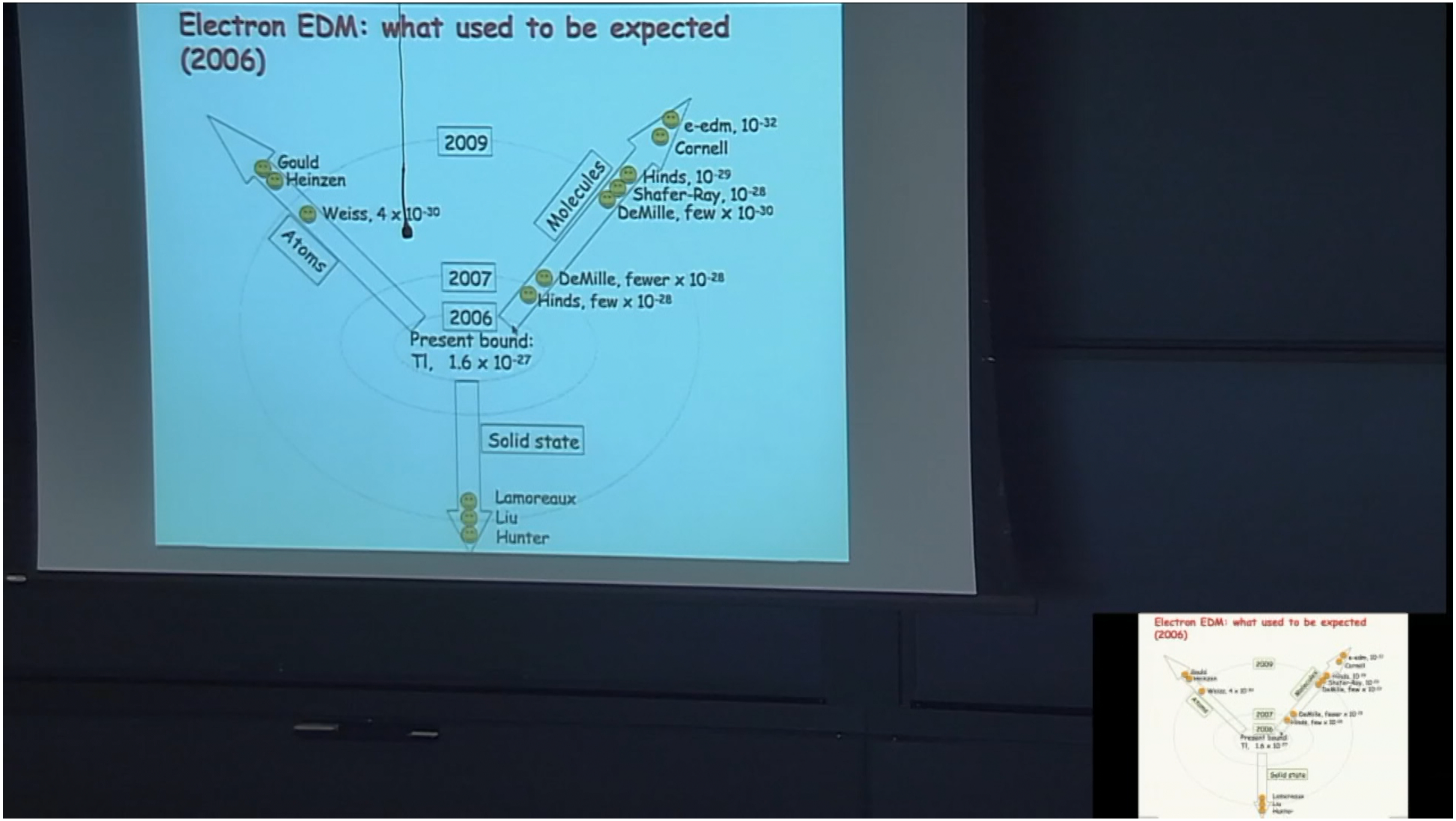
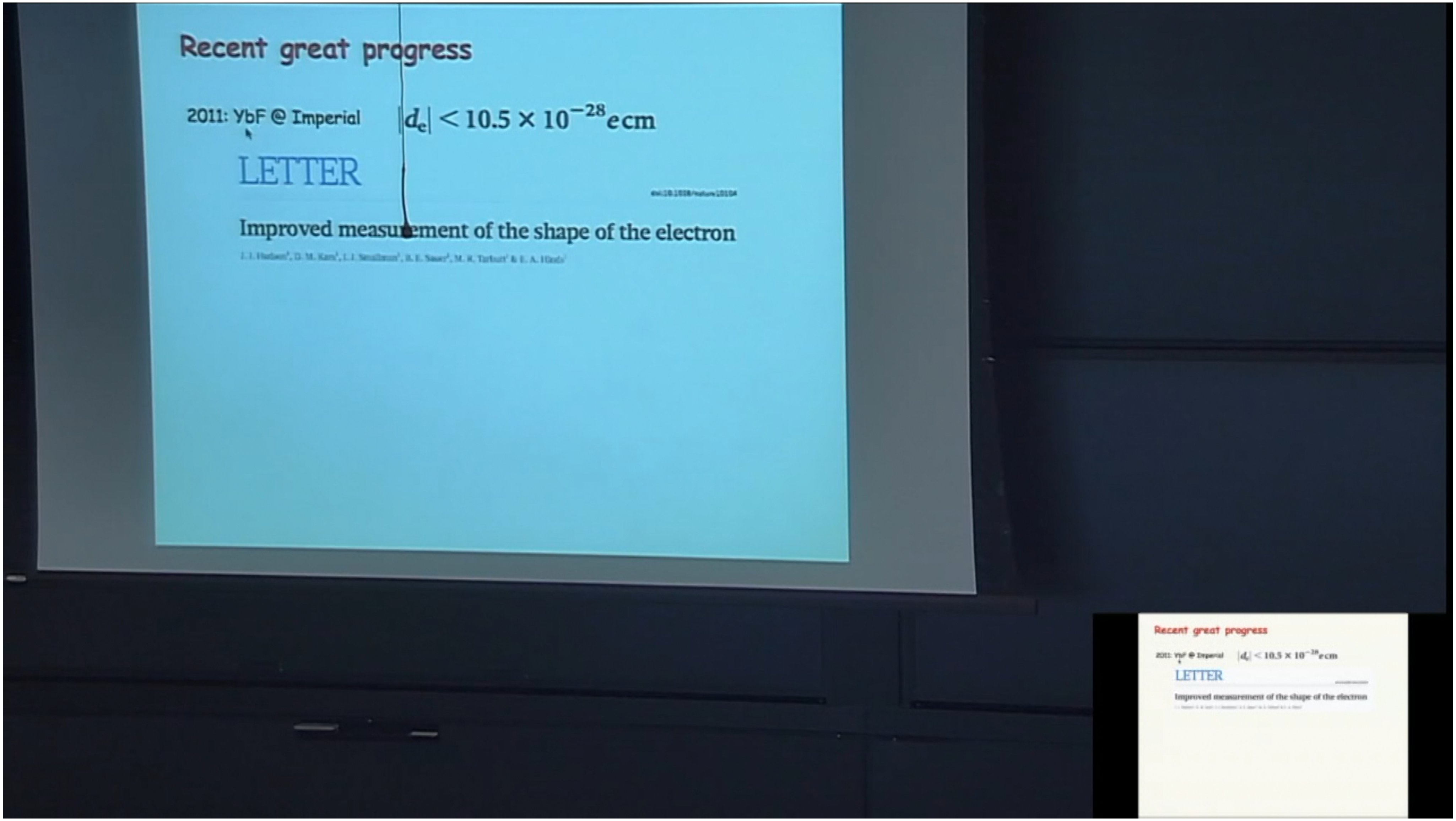

Similar binding corrections needed for the muonium: input to g-2
Mu Hyperfine Structure
Zeeman Splitting
4463 MHz
Pure letron
= M point partcile

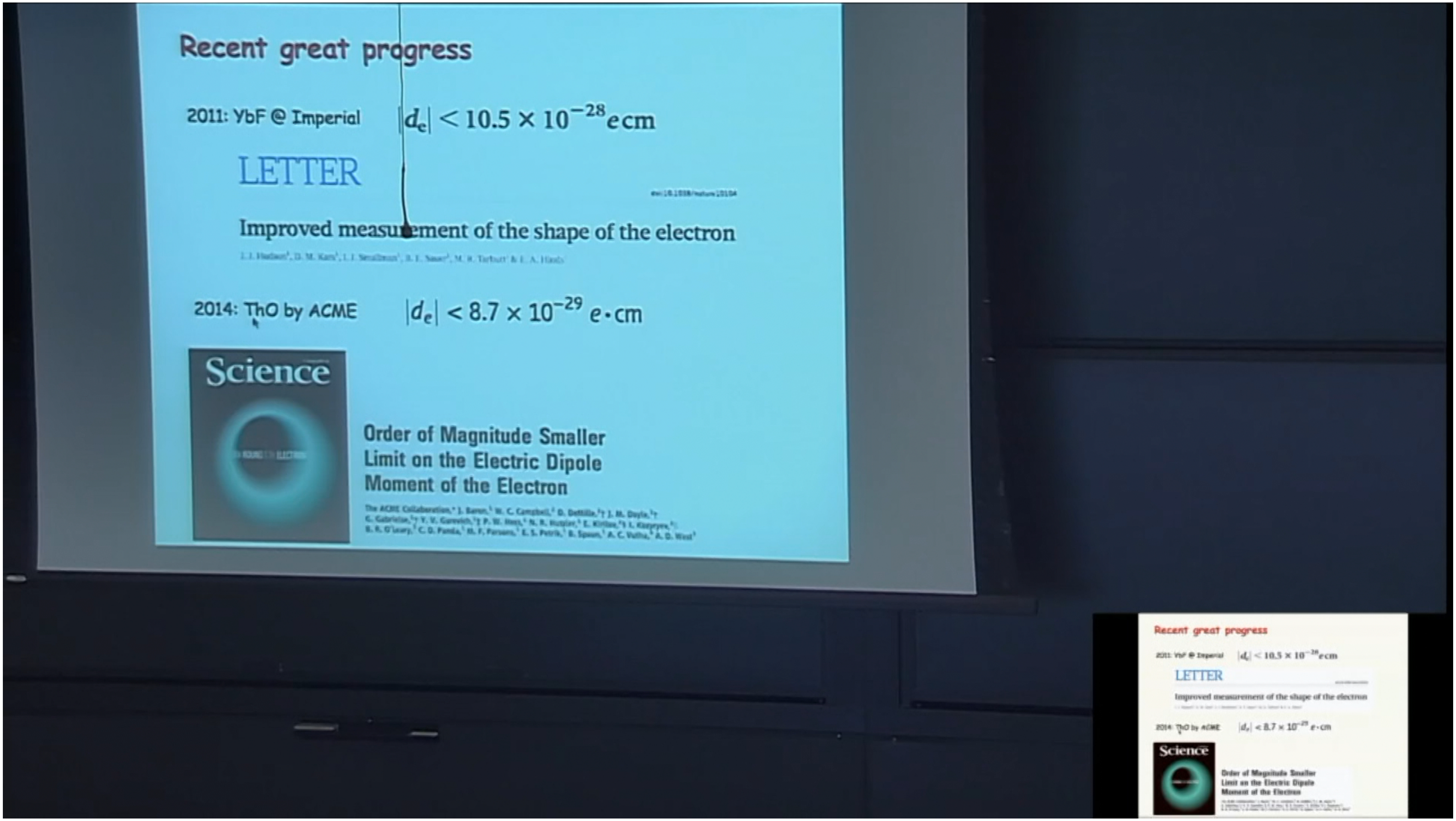

Another source of alpha: highly-charged ions
$g \simeq 2 - \frac{2(Z\alpha)^2}{3}$ → $\frac{\delta\alpha}{\alpha} \sim \frac{1}{(\alpha Z)^2}\sqrt{(\delta g_{\rm exp})^2 + (\delta g_{\rm th})^2}$
large Z favorable
e-
Pb
Pb
Hydrogen-like lead
Boron-like lead
There is a combination of g-factors in both ions where the sensitivity to the nuclear structure largely cancels, but the sensitivity to alpha remains.
Much interesting theoretical work remains to be done!
Shabaev, Glazov, Oreshkina, Volotka, Plunien, Kluge, Quint

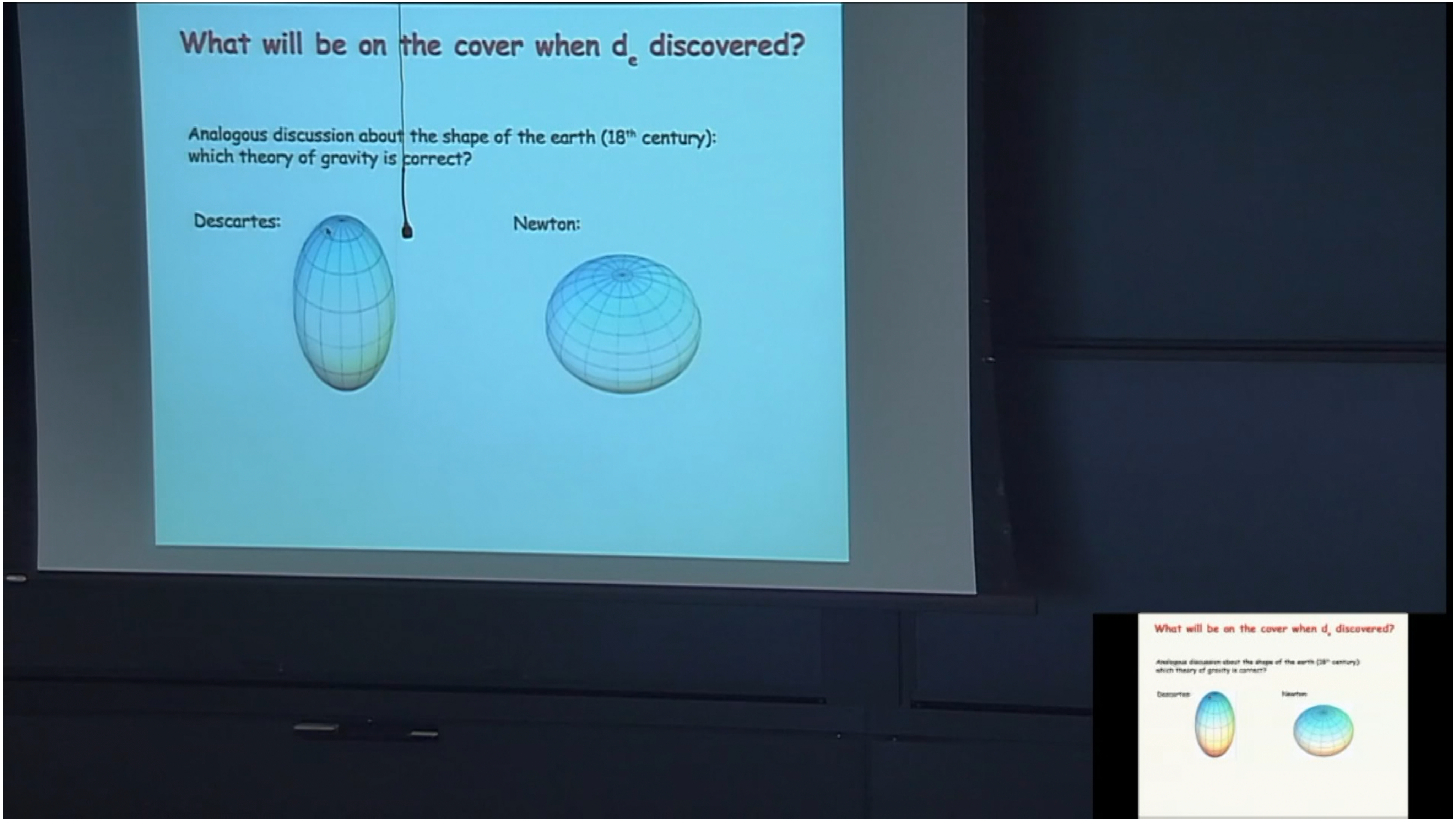

Electron electric dipole moment
+
-
T
T reverses spin
but leaves charge
distribution intact
+
-

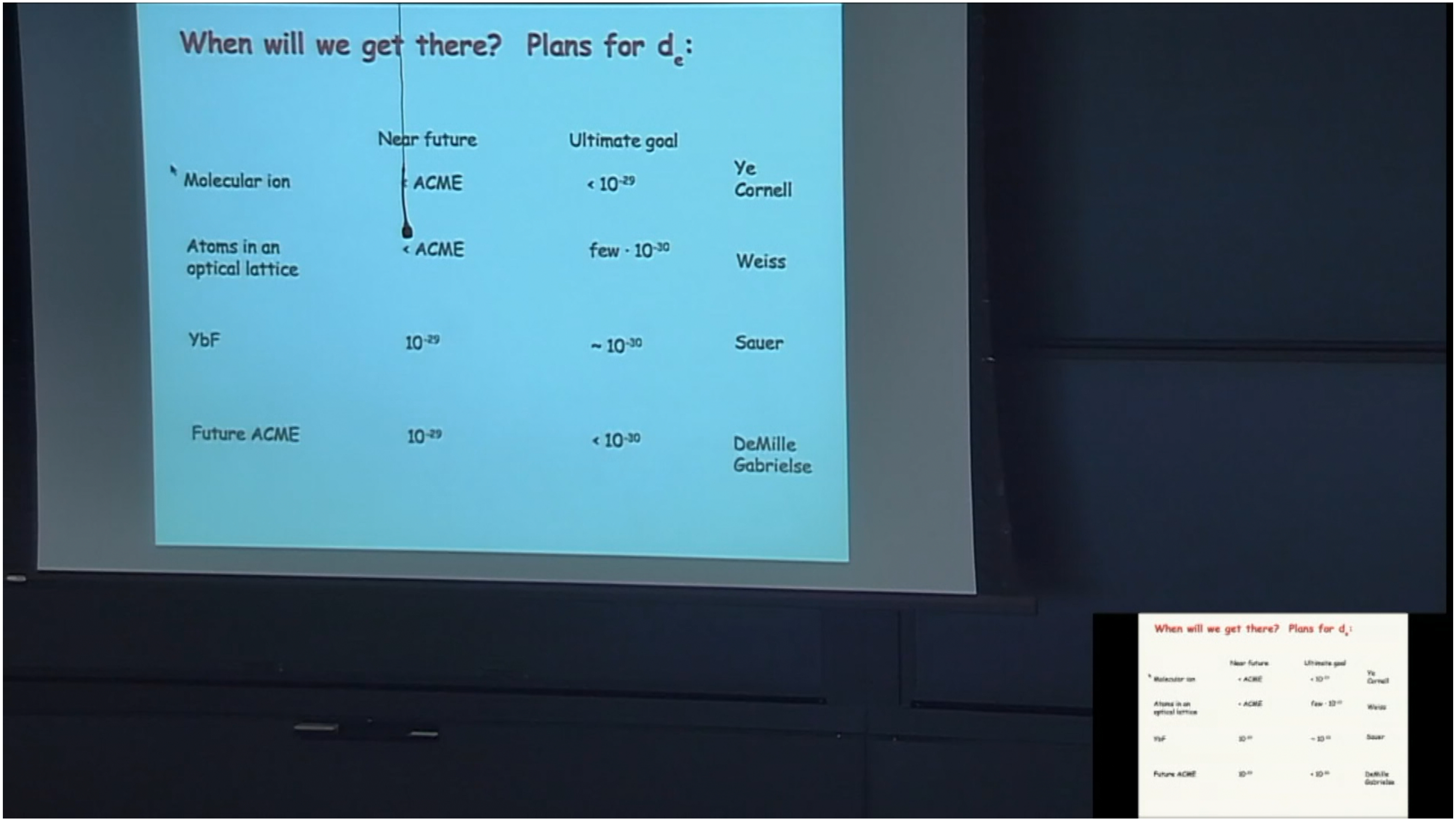

Electron EDM: what used to be expected (2006)
2009
2007
2006
Present bound:
Tl, 1.6 x 10-27
Atoms
Gould
Heinzen
Weiss, 4 x 10-30
Molecules
e-edm, 10-32
Cornell
Hinds, 10-29
Shafer-Ray, 10-28
DeMille, few x 10-30
DeMille, fewer x 10-28
Hinds, few x 10-28
Solid state
Lamoreaux
Liu
Hunter

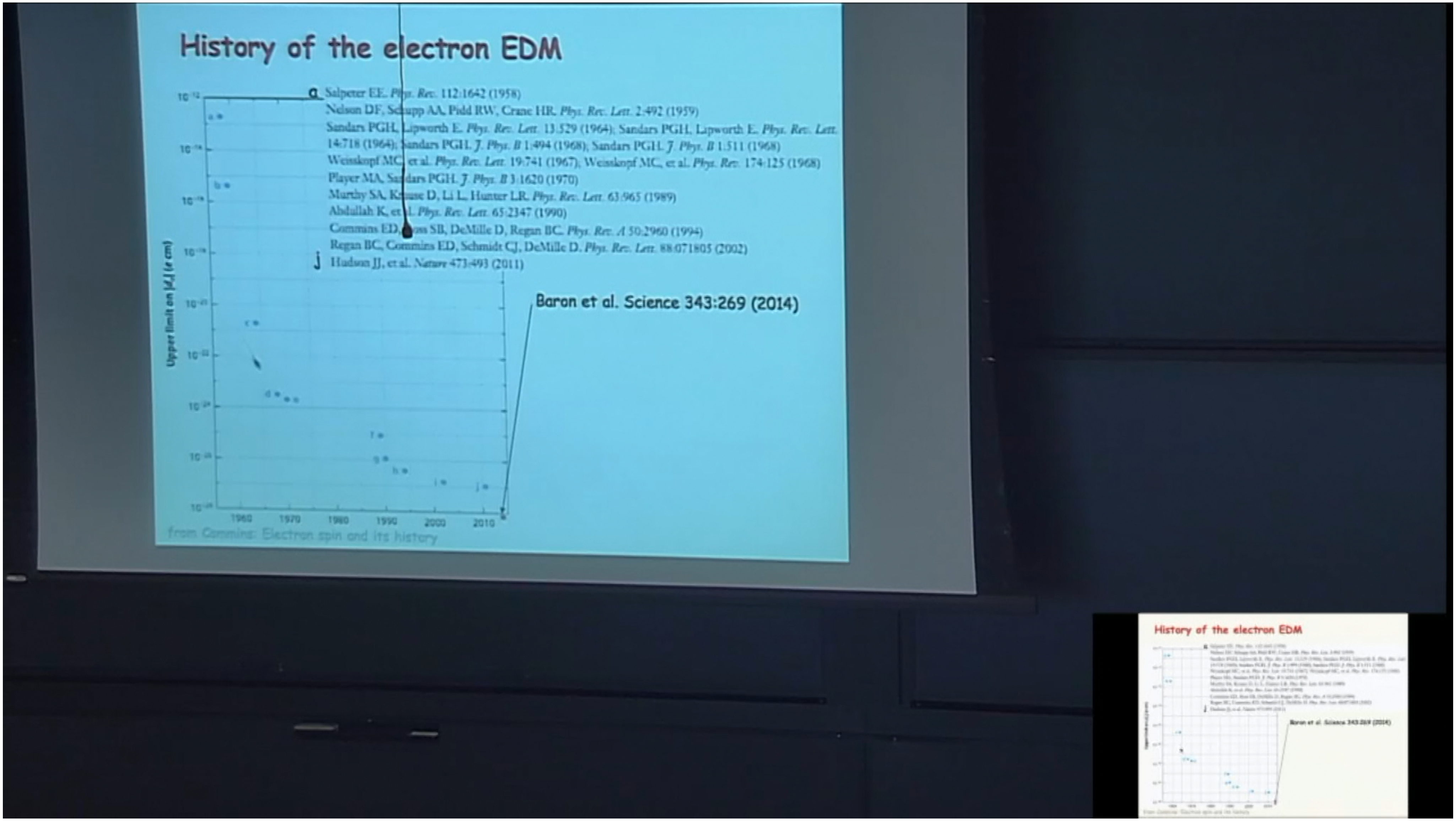

In 2010, Maxim Pospelov was suspicious:
Are they hiding new results?


Recent great progress
2011: YbF @ Imperial
$|d_e| < 10.5 \times 10^{-28} e\,\mathrm{cm}$
LETTER
Improved measurement of the shape of the electron


Recent great progress
2011: YbF @ Imperial $|d_e| < 10.5 \times 10^{-28} e\,\text{cm}$
LETTER
Improved measurement of the shape of the electron
2014: ThO by ACME $|d_e| < 8.7 \times 10^{-29}\, e \cdot \text{cm}$
Science
Order of Magnitude Smaller
Limit on the Electric Dipole
Moment of the Electron


What will be on the cover when d_e discovered?
Analogous discussion about the shape of the earth (18th century):
which theory of gravity is correct?
Descartes:
Newton:


When will we get there? Plans for d$_e$:
Near future
Ultimate goal
Molecular ion
< ACME
< 10^{-29}
Ye
Cornell
Atoms in an optical lattice
< ACME
few · 10^{-30}
Weiss
YbF
10^{-29}
~ 10^{-30}
Sauer
Future ACME
10^{-29}
< 10^{-30}
DeMille
Gabrielse


History of the electron EDM
a Salpeter EE. Phys. Rev. 112:1642 (1958)
Nelson DF, Schupp AA, Pidd RW, Crane HR. Phys. Rev. Lett. 2:492 (1959)
Sandars PGH, Lipworth E. Phys. Rev. Lett. 13:529 (1964); Sandars PGH, Lipworth E. Phys. Rev. Lett.
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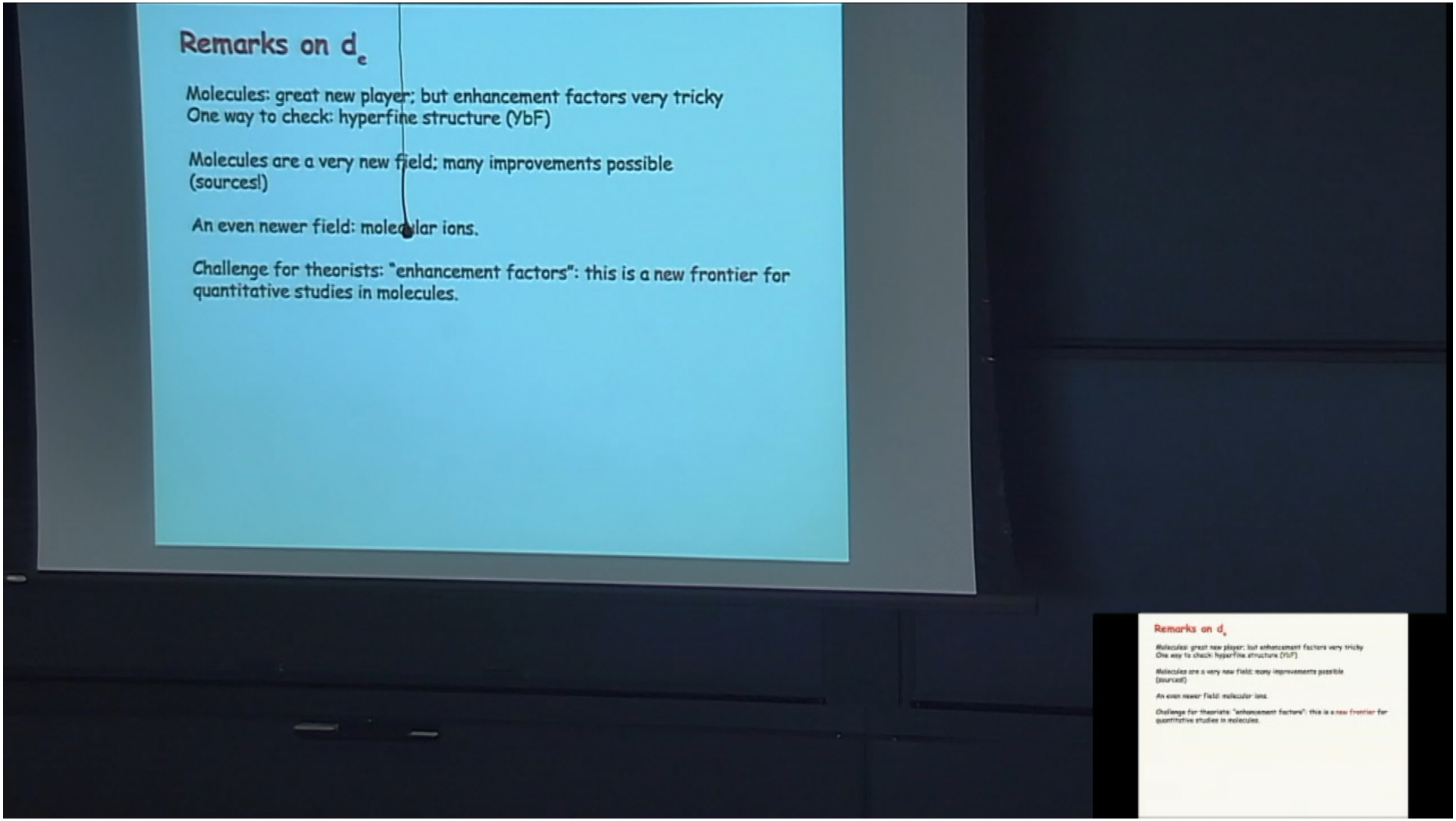
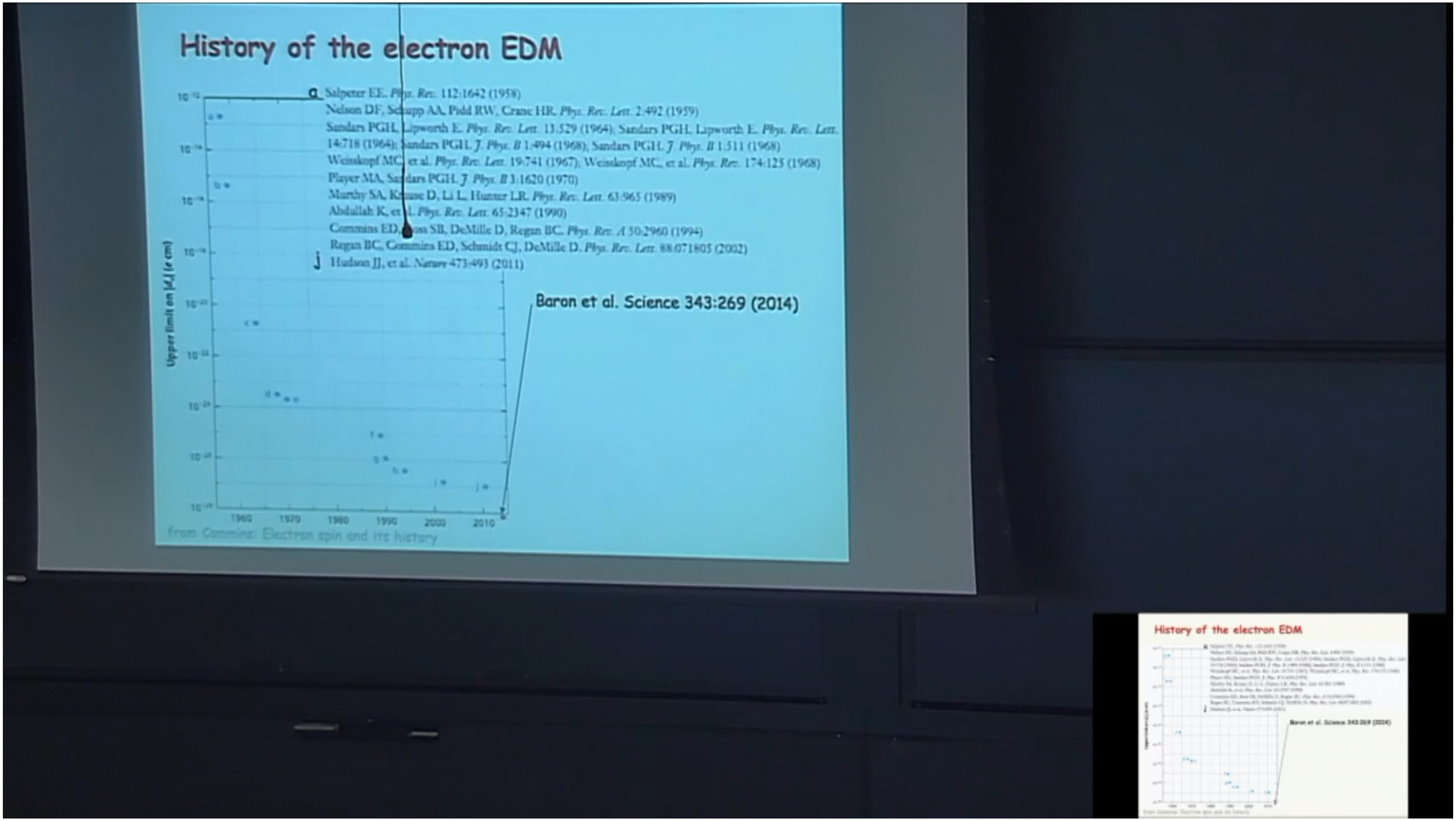
Regan BC, Commins ED, Schmidt CJ, DeMille D. Phys. Rev. Lett. 88:071805 (2002)
j Hudson JJ, et al. Nature 473:493 (2011)
Baron et al. Science 343:269 (2014)
Upper limit on |de| (e cm)
1960
1970
1980
1990
2000
2010
from Commins: Electron spin and its history


Remarks on d_e
Molecules: great new player; but enhancement factors very tricky
One way to check: hyperfine structure (YbF)
Molecules are a very new field; many improvements possible (sources!)
An even newer field: molecular ions.
Challenge for theorists: "enhancement factors": this is a new frontier for quantitative studies in molecules.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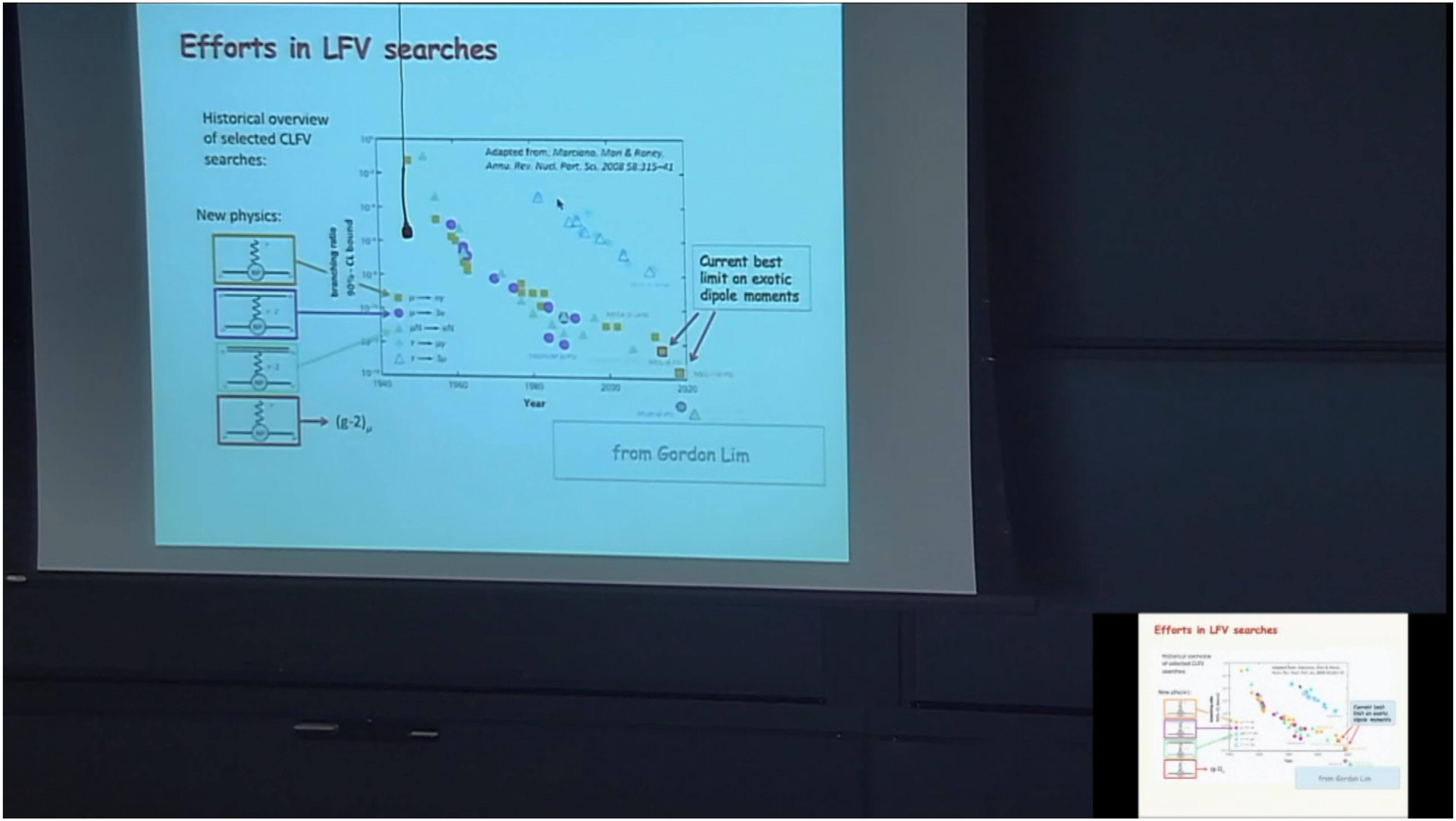
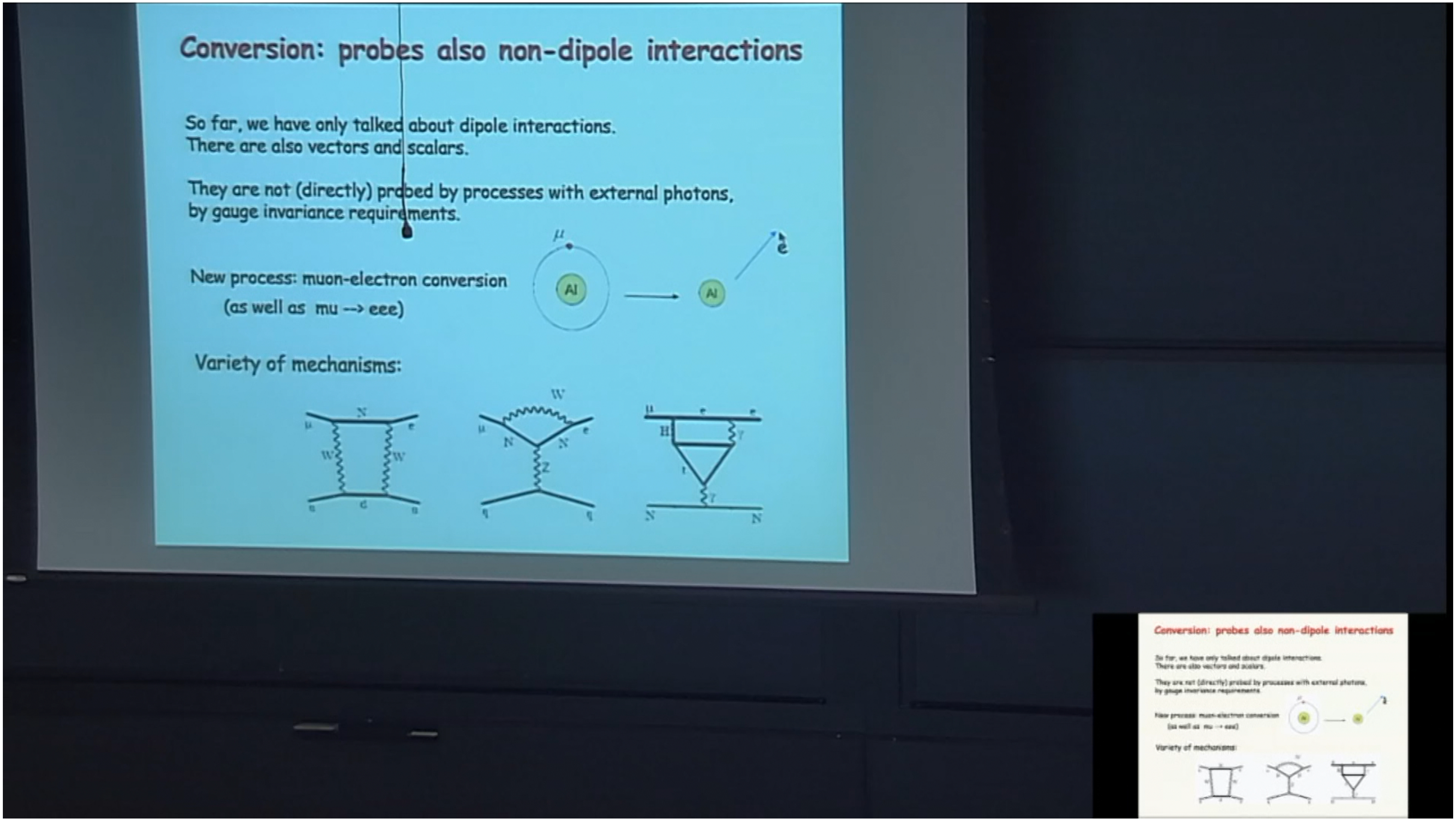
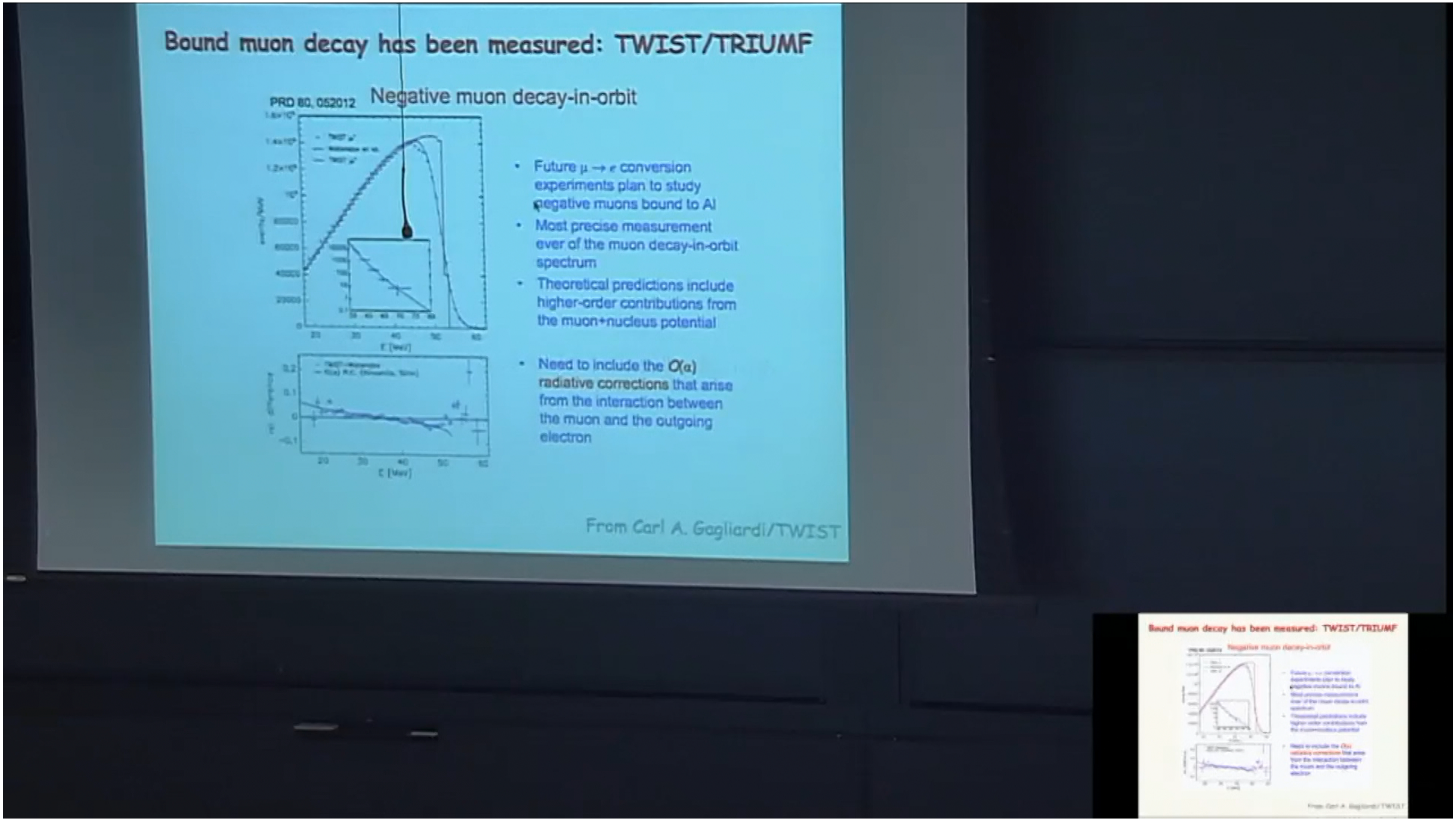
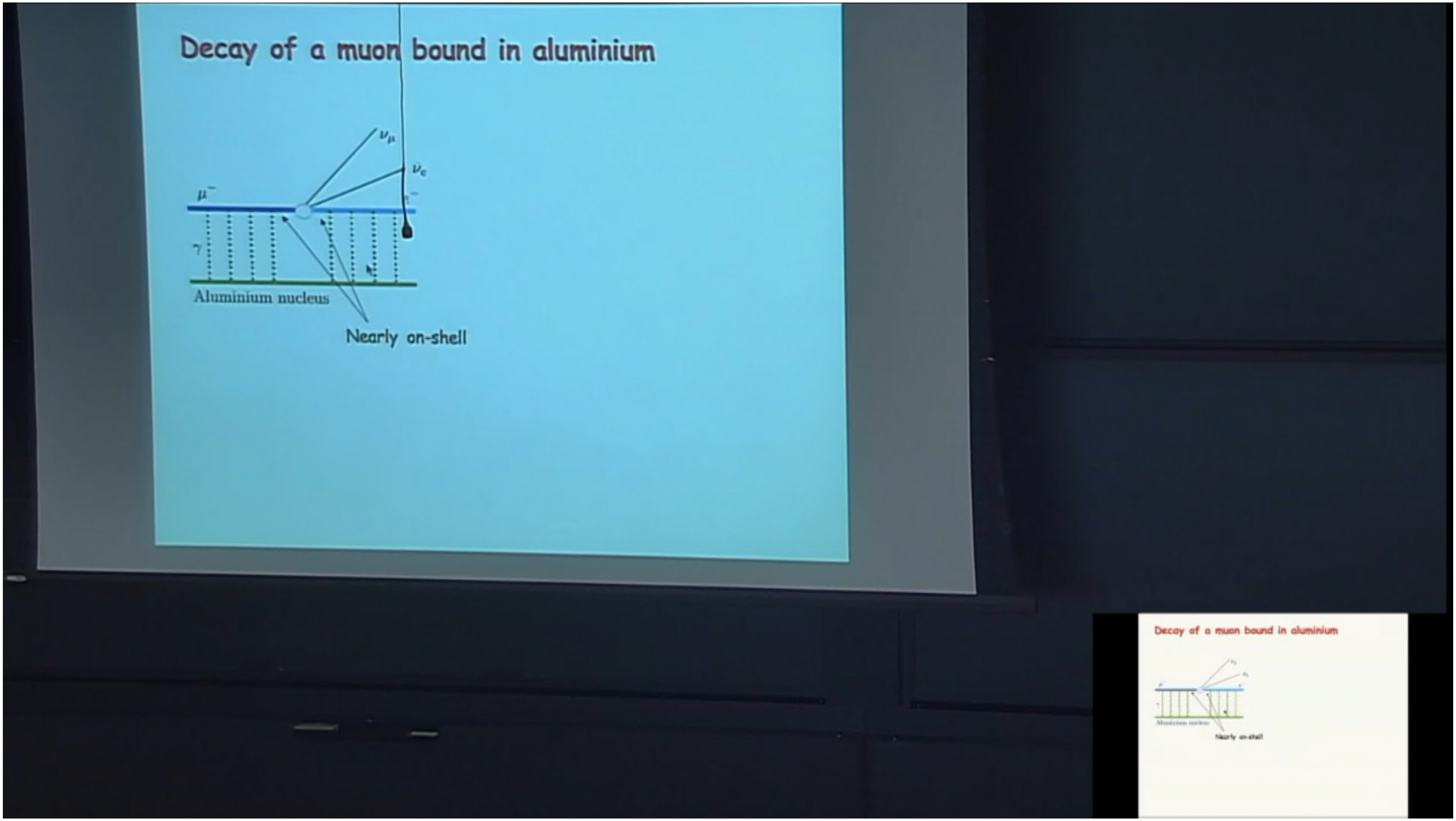
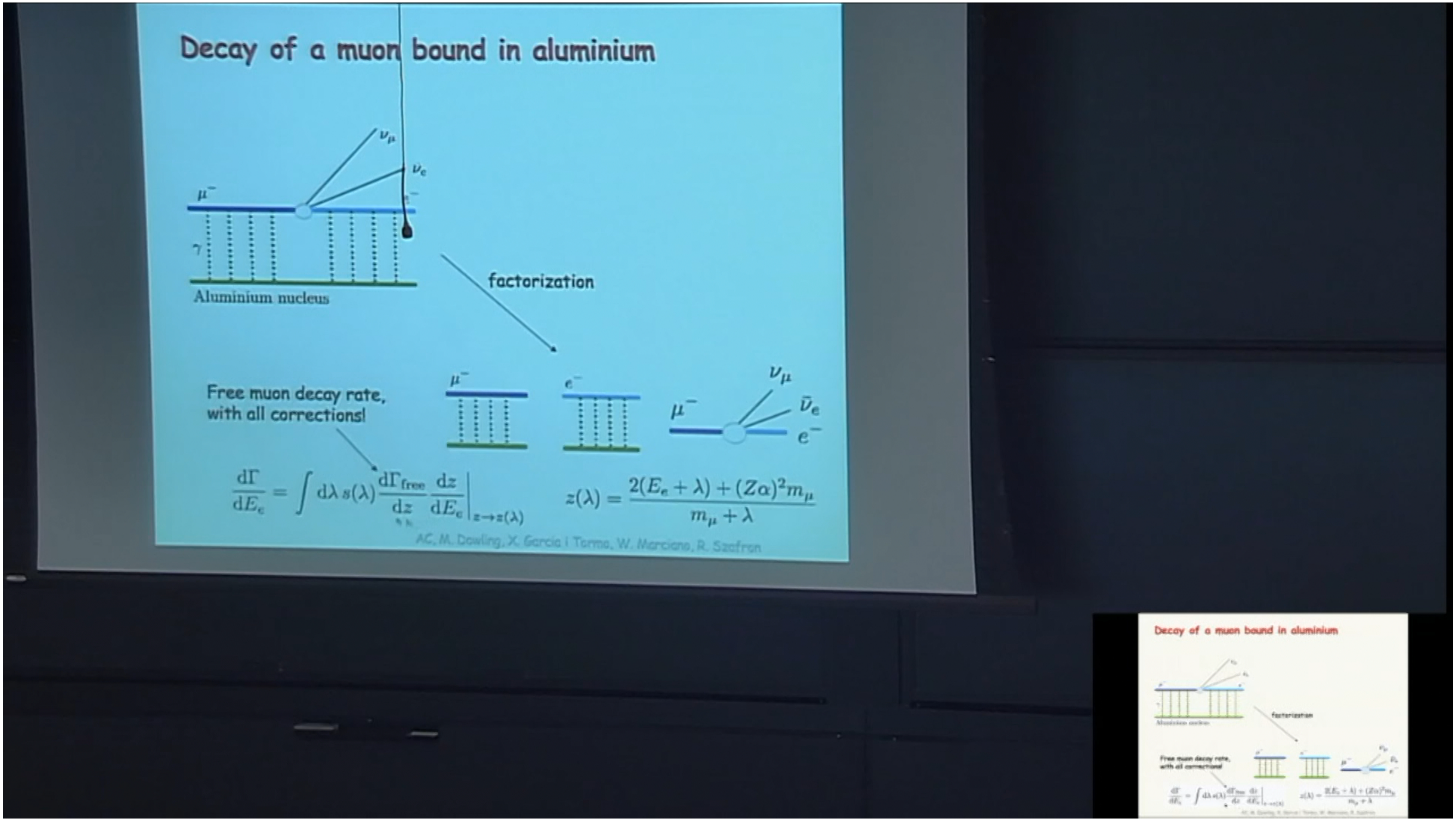
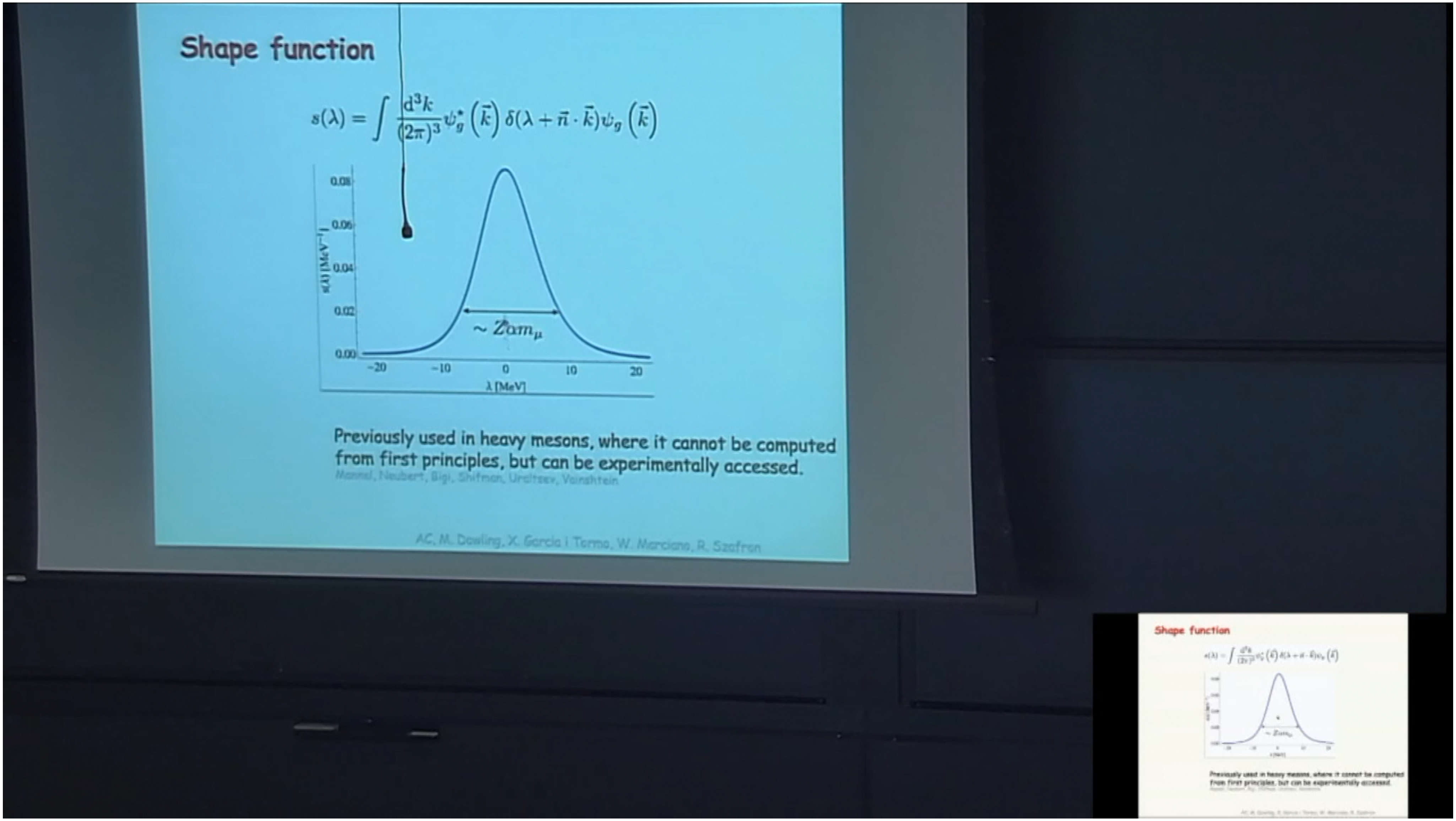

Efforts in LFV searches
Historical overview of selected CLFV searches:
New physics:
(g-2)μ
Adapted from: Marciano, Mori & Roney, Annu. Rev. Nucl. Part. Sci. 2008 58:315–41
branching ratio
90% - CL bound
Year
Current best limit on exotic dipole moments
from Gordon Lim
Efforts in LFV searches

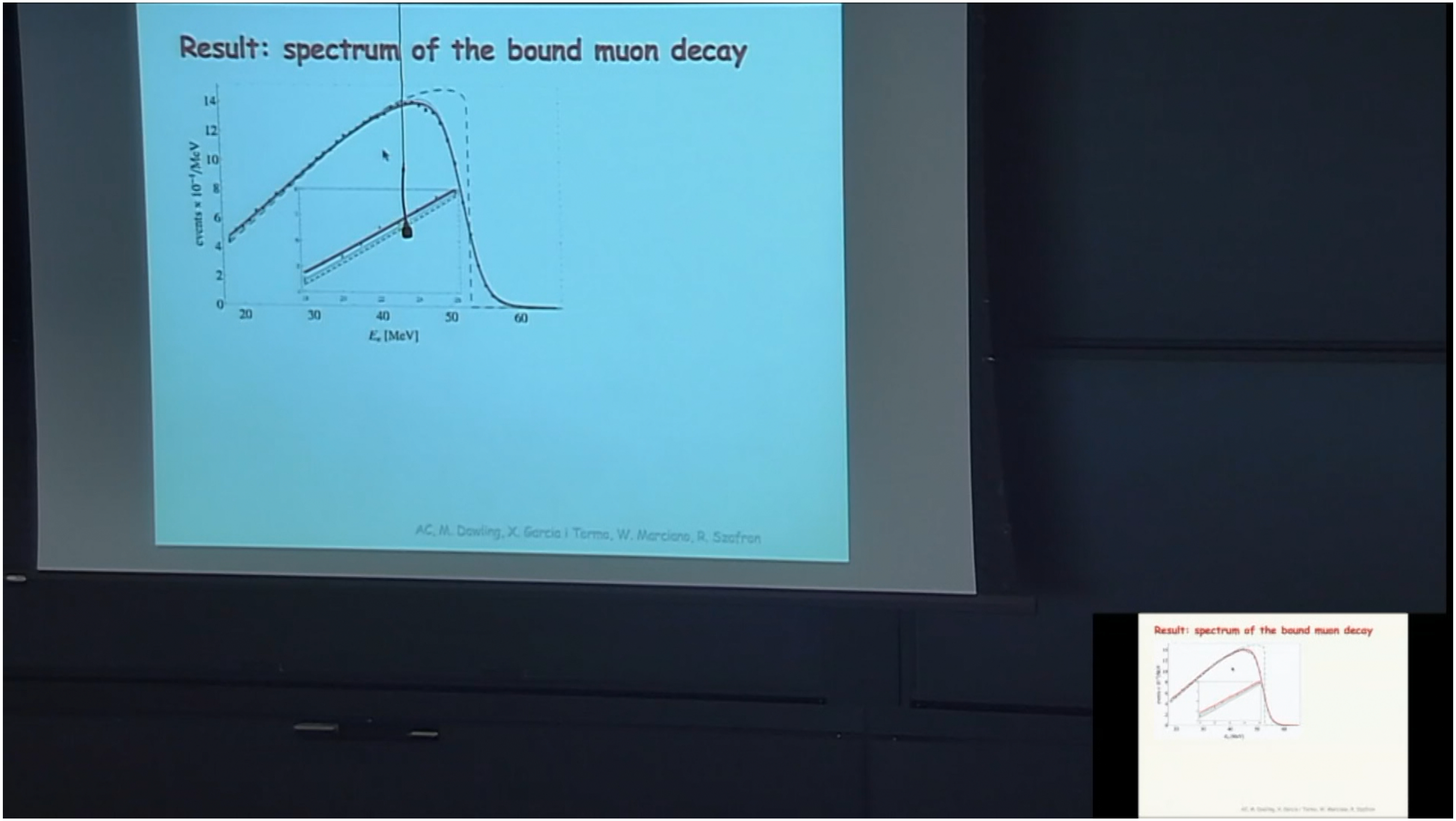

Conversion: probes also non-dipole interactions
So far, we have only talked about dipole interactions.
There are also vectors and scalars.
They are not (directly) probed by processes with external photons,
by gauge invariance requirements.
New process: muon-electron conversion
(as well as mu --> eee)
Al
Al
e
Variety of mechanisms:

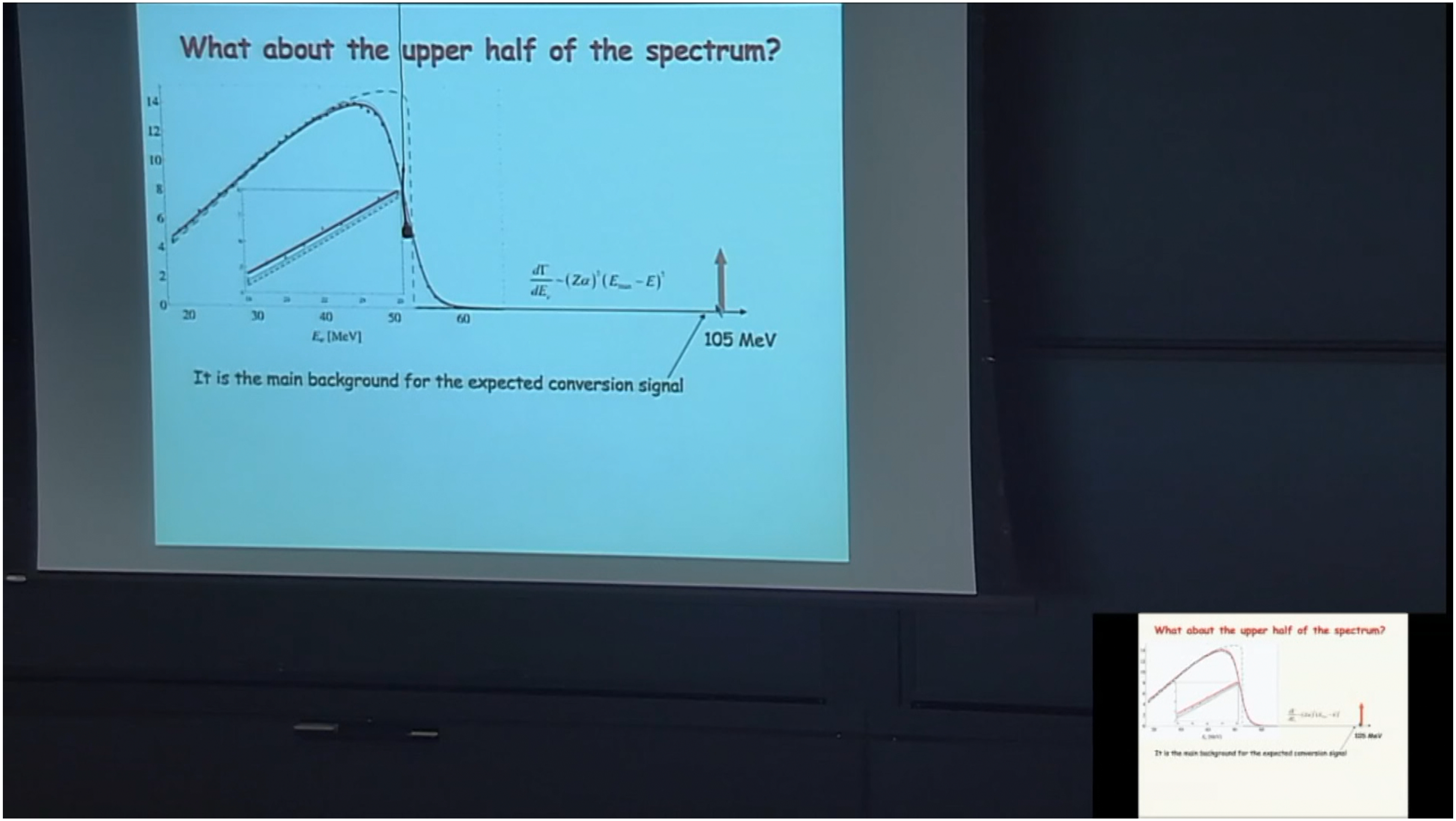

Bound muon decay has been measured: TWIST/TRIUMF
PRD 80, 052012
Negative muon decay-in-orbit
E [MeV]
Future μ → e conversion experiments plan to study negative muons bound to Al
Most precise measurement ever of the muon decay-in-orbit spectrum
Theoretical predictions include higher-order contributions from the muon+nucleus potential
Need to include the O(α) radiative corrections that arise from the interaction between the muon and the outgoing electron
From Carl A. Gagliardi/TWIST

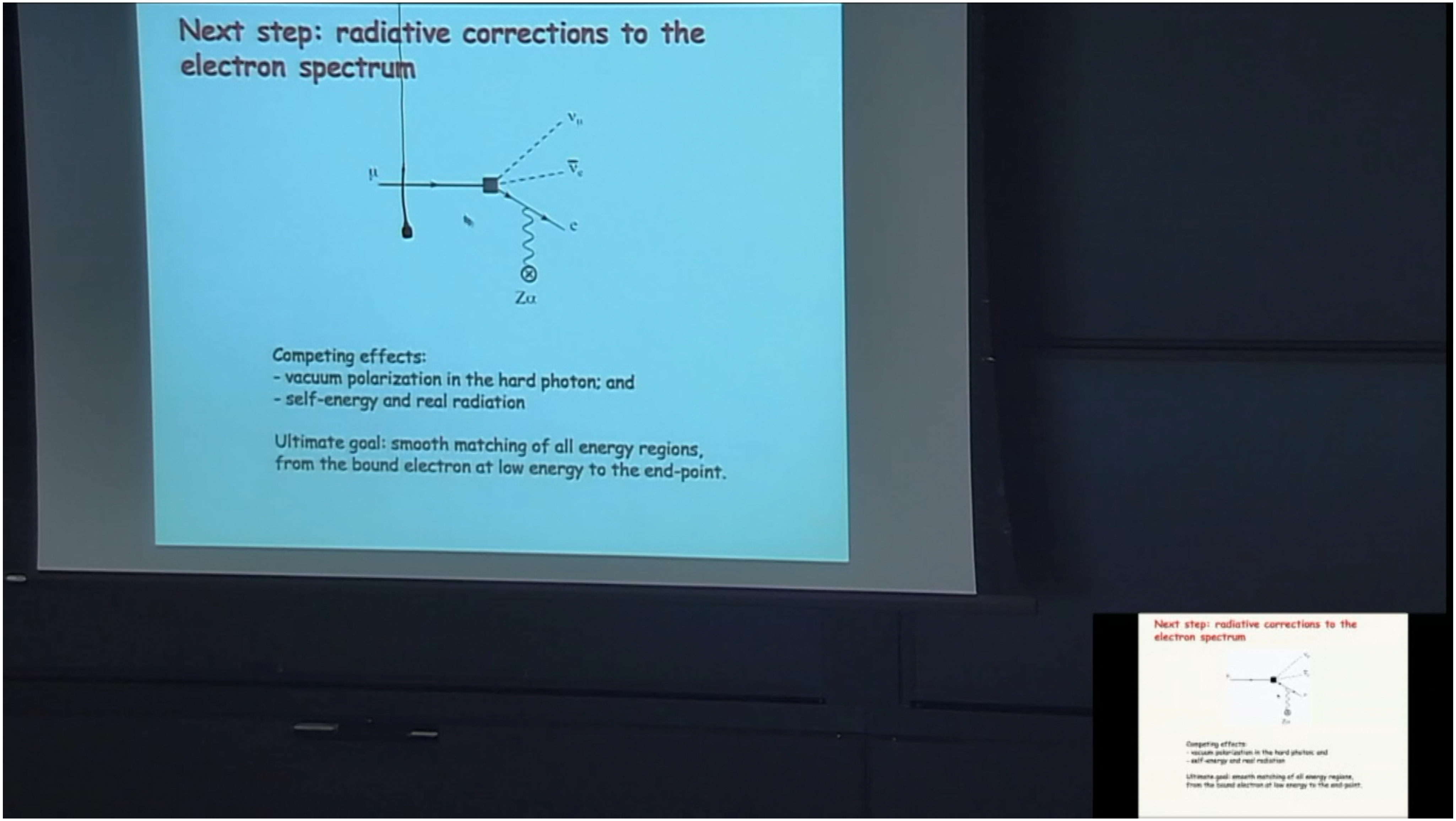

Decay of a muon bound in aluminium
ν_μ
$\bar{\nu}_e$
μ^-
γ
Aluminium nucleus
Nearly on-shell

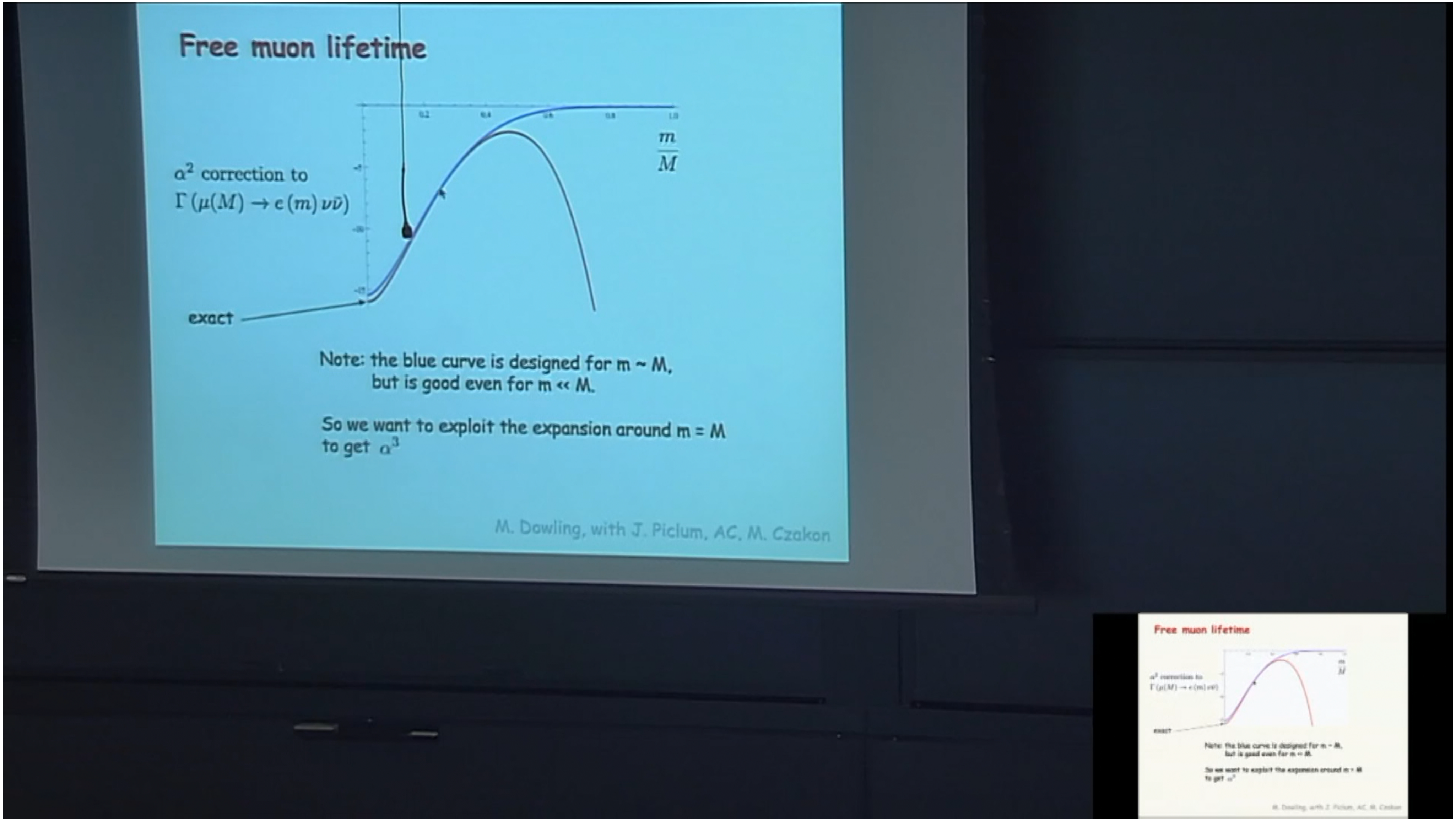

Decay of a muon bound in aluminium
ν_μ
ν_e
μ^-
γ
Aluminium nucleus
factorization
Free muon decay rate, with all corrections!
μ^-
e^-
μ^-
ν_μ
$\bar{\nu}_e$
e^-
$\frac{d\Gamma}{dE_e} = \int d\lambda\, s(\lambda) \frac{d\Gamma_{free}}{dz} \frac{dz}{dE_e}\Big|_{z \to z(\lambda)}$
$z(\lambda) = \frac{2(E_e + \lambda) + (Z\alpha)^2 m_\mu}{m_\mu + \lambda}$
AC, M. Dowling, X. Garcia i Tormo, W. Marciano, R. Szafron

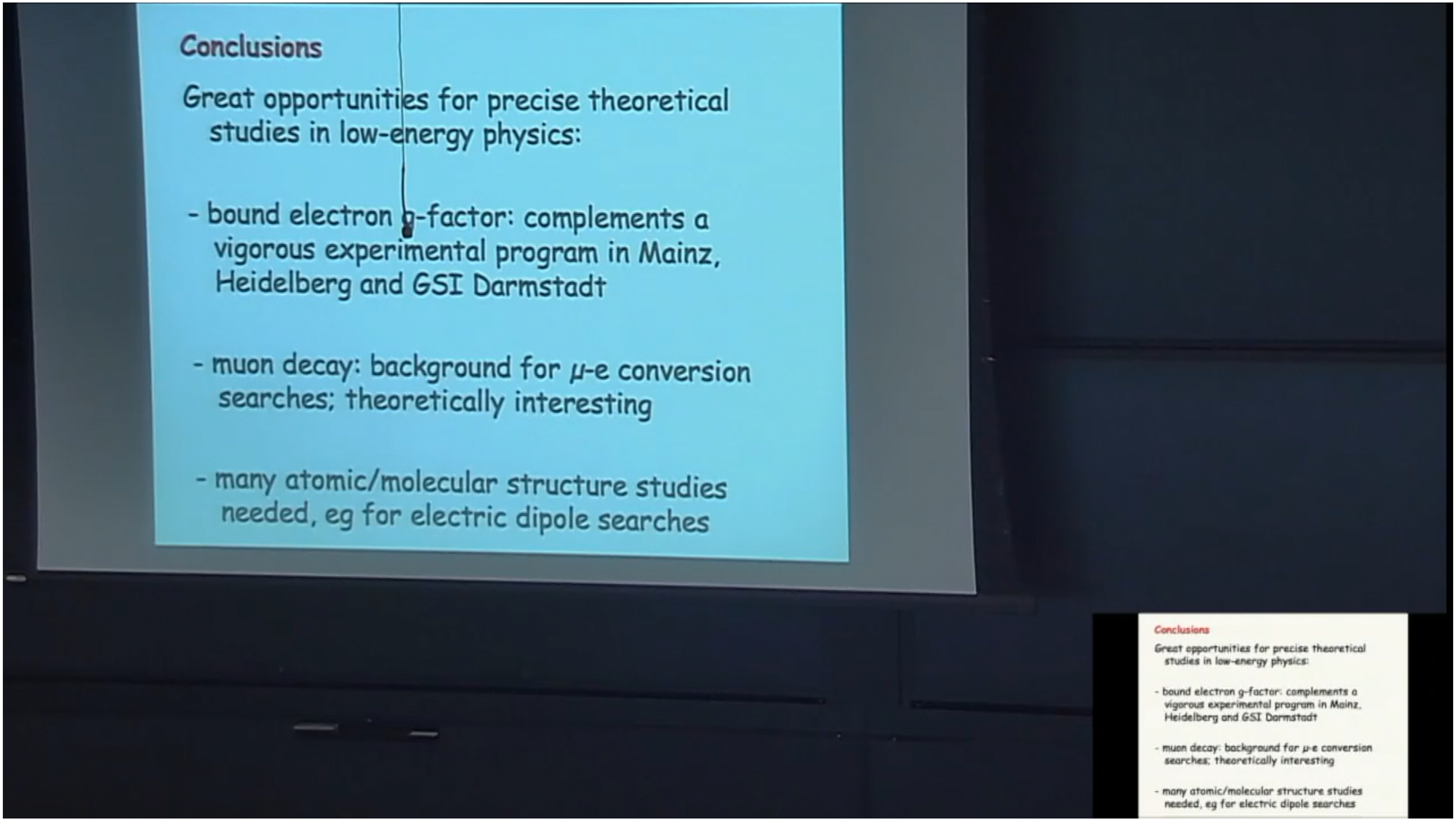

Shape function
$s(\lambda) = \int \frac{d^3k}{(2\pi)^3} \psi_g^*(\vec{k}) \delta(\lambda + \vec{n}\cdot\vec{k}) \psi_g(\vec{k})$
0.08
0.06
0.04
0.02
0.00
s(λ) [MeV⁻¹]
−20
−10
0
10
20
λ [MeV]
$\sim Z\alpha m_\mu$
Previously used in heavy mesons, where it cannot be computed from first principles, but can be experimentally accessed.
Mannel, Neubert, Bigi, Shifman, Uraltsev, Vainshtein
AC, M. Dowling, X. Garcia i Tormo, W. Marciano, R. Szafron


Result: spectrum of the bound muon decay
14
12
10
8
6
4
2
0
20
30
40
50
60
[MeV]
AC, M. Dowling, X. Garcia i Tormo, W. Marciano, R. Szafron


What about the upper half of the spectrum?
105 MeV
It is the main background for the expected conversion signal
E_e [MeV]


Next step: radiative corrections to the electron spectrum
μ
ν_μ
$\overline{\nu}_e$
e
Zα
Competing effects:
- vacuum polarization in the hard photon; and
- self-energy and real radiation
Ultimate goal: smooth matching of all energy regions, from the bound electron at low energy to the end-point.


Free muon lifetime
α^2 correction to
$\Gamma(\mu(M) \to e(m)\,\nu\bar{\nu})$
$\frac{m}{M}$
exact
Note: the blue curve is designed for m ~ M,
but is good even for m << M.
So we want to exploit the expansion around m = M
to get α^3
M. Dowling, with J. Piclum, AC, M. Czakon


Conclusions
Great opportunities for precise theoretical studies in low-energy physics:
- bound electron g-factor: complements a vigorous experimental program in Mainz, Heidelberg and GSI Darmstadt
- muon decay: background for μ-e conversion searches; theoretically interesting
- many atomic/molecular structure studies needed, eg for electric dipole searches