Report from the 55th International Meeting on Nuclear Physics

Bormio, 23-27 January 2017

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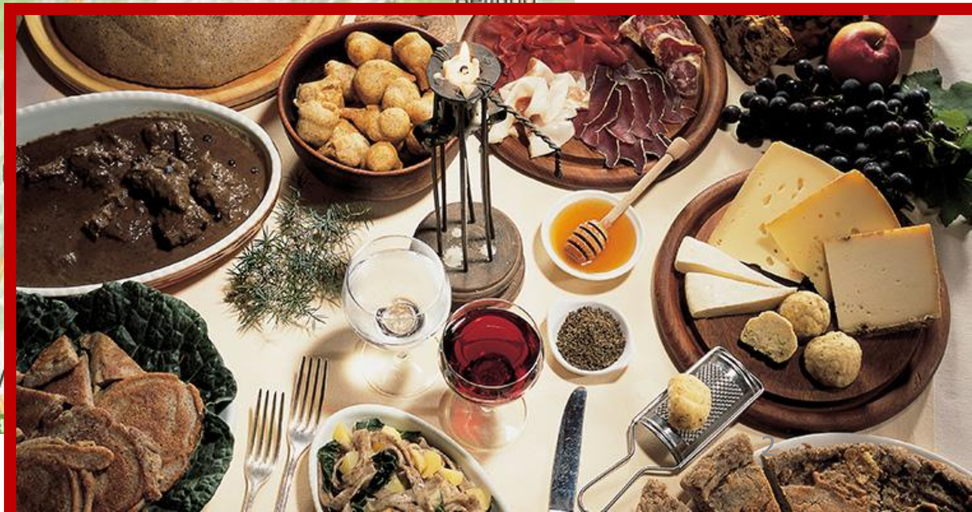
STFC RAL

Science & Technology Facilities Council
Rutherford Appleton Laboratory

PPd

Bormio

Schaffhausen
Konstanz
Friedrichshafen
Lindau
Winterthur
St Gallen
Zürich
Oberstdorf
E532
Lucerne
Serfaus
E43
Chur
Davos
Parc Ela
St Moritz
Livigno
Parco Nazionale dello Stelvio
Merano Meran
Bressanone Brixen
Brunico Bruneck
Ortisei Sankt Ulrich
Bolzano Bozen
Misurina
Cortina d'Ampezzo
Sondrio
Tirano
Parco Naturale Adamello Brenta
A22
Parco delle Orobie Bergamasche
Lecco
Varese
Como
Riva del Garda
Limone Sul Garda
Bergamo
A9
E62
Monza
A4
Brescia
Sirmione
Novara
E64
Milan
A35
A50
A58



55^{th} International Meeting on Nuclear Physics

"***Long-standing*** conference
bringing together ***researcher and students***
from various fields of **subatomic physics**"

Schedule

1-day preconference school
5 days of meetings (with ski break)

nowifi CONFERENCES HUMANS INSIDE

Interdisciplinary topics

- Hadron physics
- Heavy Ion Physics
- Nuclear Astrophysics
- Particle Physics
- Detectors and new facilities
- Applications

Bormio's conference
Pointer

http://www.bormiomeeting.com/

Typical Day Schedule

Mon 23/01 | Tue 24/01 | Wed 25/01 | **Thu 26/01** | Fri 27/01 | All days

Print | PDF | Full screen | Detailed view | Filter

Session legend

Thursday Afternoon | Thursday Morning

Morning

09:00	**Inferences on the specific heat and neutrino emissivity of dense matter from accreting neutron stars**	*Prof. Edward BROWN*	*Bormio, Italy*	09:00 - 09:45
10:00	**Optical Lattice Clocks: Reading the 18th decimal place of frequency**	*Prof. Hidetoshi KATORI*	*Bormio, Italy*	09:45 - 10:30
	Coffee Break		*Bormio, Italy*	10:30 - 11:00
11:00	**Recent developments in nuclear structure theory**	*Dr. Sonia BACCA*	*Bormio, Italy*	11:00 - 11:30
	LHCb Results on Flavour Physics	*Dr. Stefania RICCIARDI*	*Bormio, Italy*	11:30 - 12:00
12:00	**Theoretical Prediction of the Be8 anomaly**	*Dr. Tim TAIT*	*Bormio, Italy*	12:00 - 12:25
13:00				

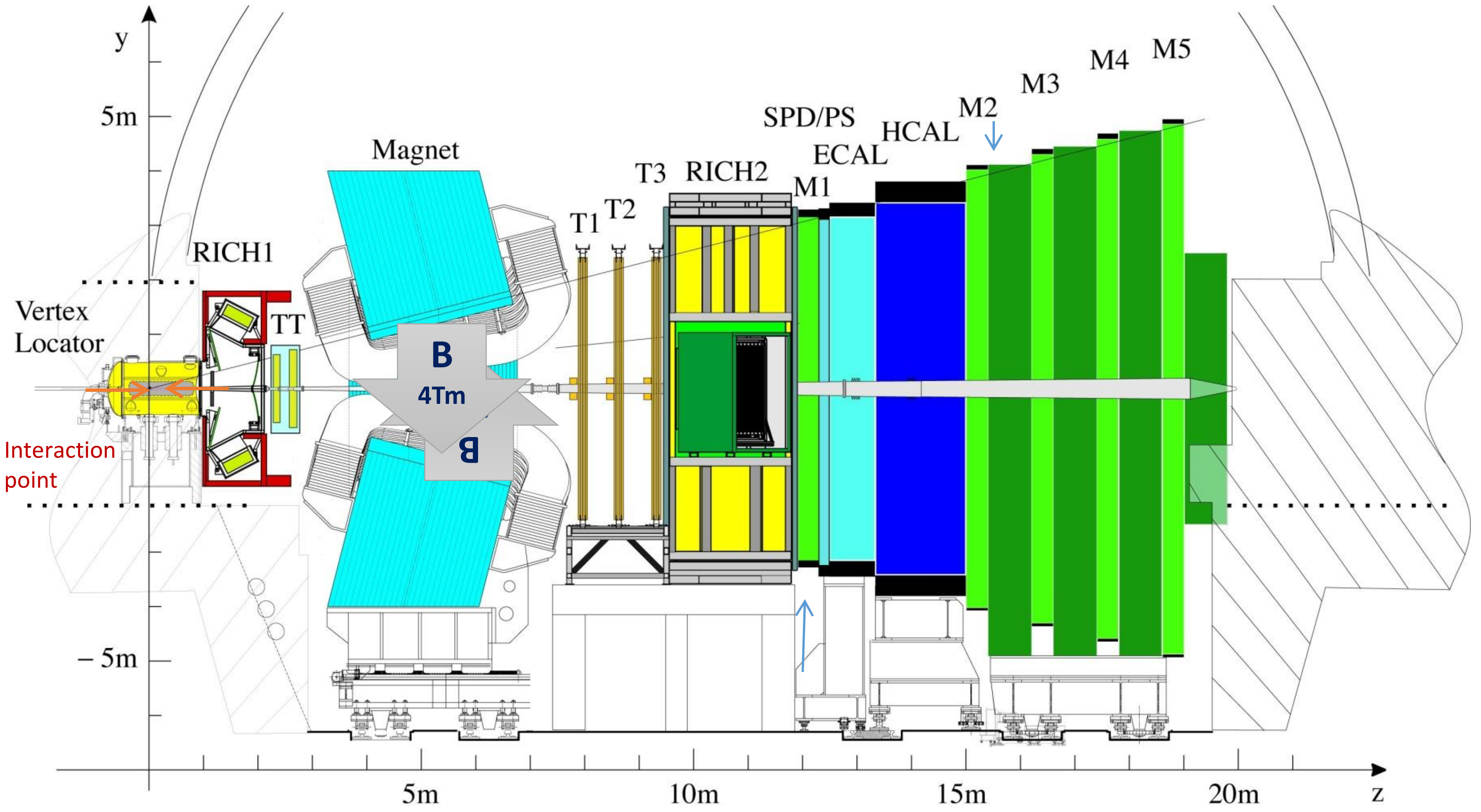
Afternoon

17:00	**Nuclear Reactions for Neutrinoless Double Beta Decay**	*Dr. Manuela CAVALLARO*	*Bormio, Italy*	17:00 - 17:25
	Calculations of kaonic nuclei based on chiral meson-baryon coupled channel interaction models	*Mrs. Jaroslava HRTANKOVA*		
	Recent results from the ATLAS heavy ion program	*Dr. Radim SLOVAK*	*Bormio, Italy*	17:45 - 18:05
18:00	**Constraining the symmetry energy at high density with the first SnRIT experiments**	*Dr. Giordano CERIZZA*		
	Two-neutron removal from ^{11}Li in a (p,t) reaction at low incident energy	*Prof. Anthony COWLEY*		
19:00	**Selected CMS Results in Higgs Physics**	*Dr. Milos DORDEVIC*	*Bormio, Italy*	18:45 - 19:05

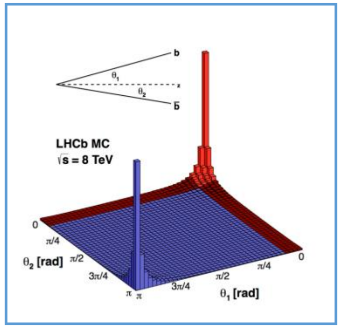
Selected highlights

- LHCb flavour anomalies
- Sterile Neutrinos
- Nuclear astrophysics
- Berillium-8 anomaly
- Proton radius puzzle

Hunting for anomalies on the Alps…

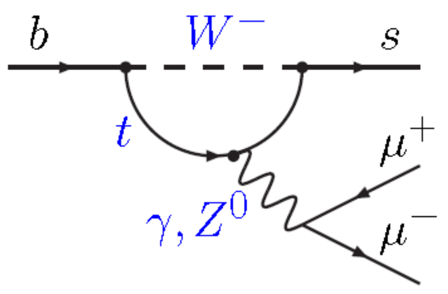


LHCb flavour results

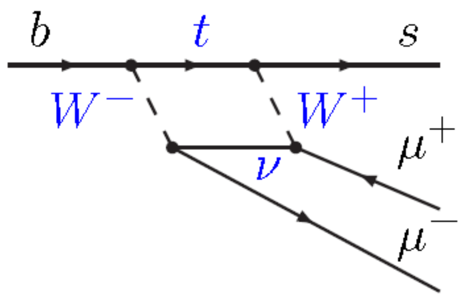


FCNC b→sμμ decays

b→s (and b →d) transitions
only occur at loop level in SM

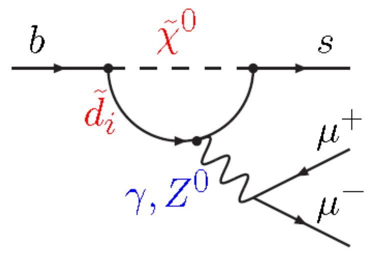


Penguin diagram

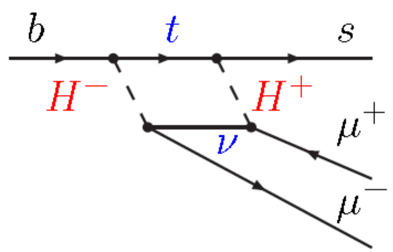


Box diagram

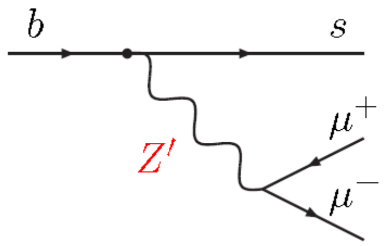
b→s (and b →d) transitions
at loop or tree level via NP. E.g.,



Penguin diagram



Box diagram



Tree diagram

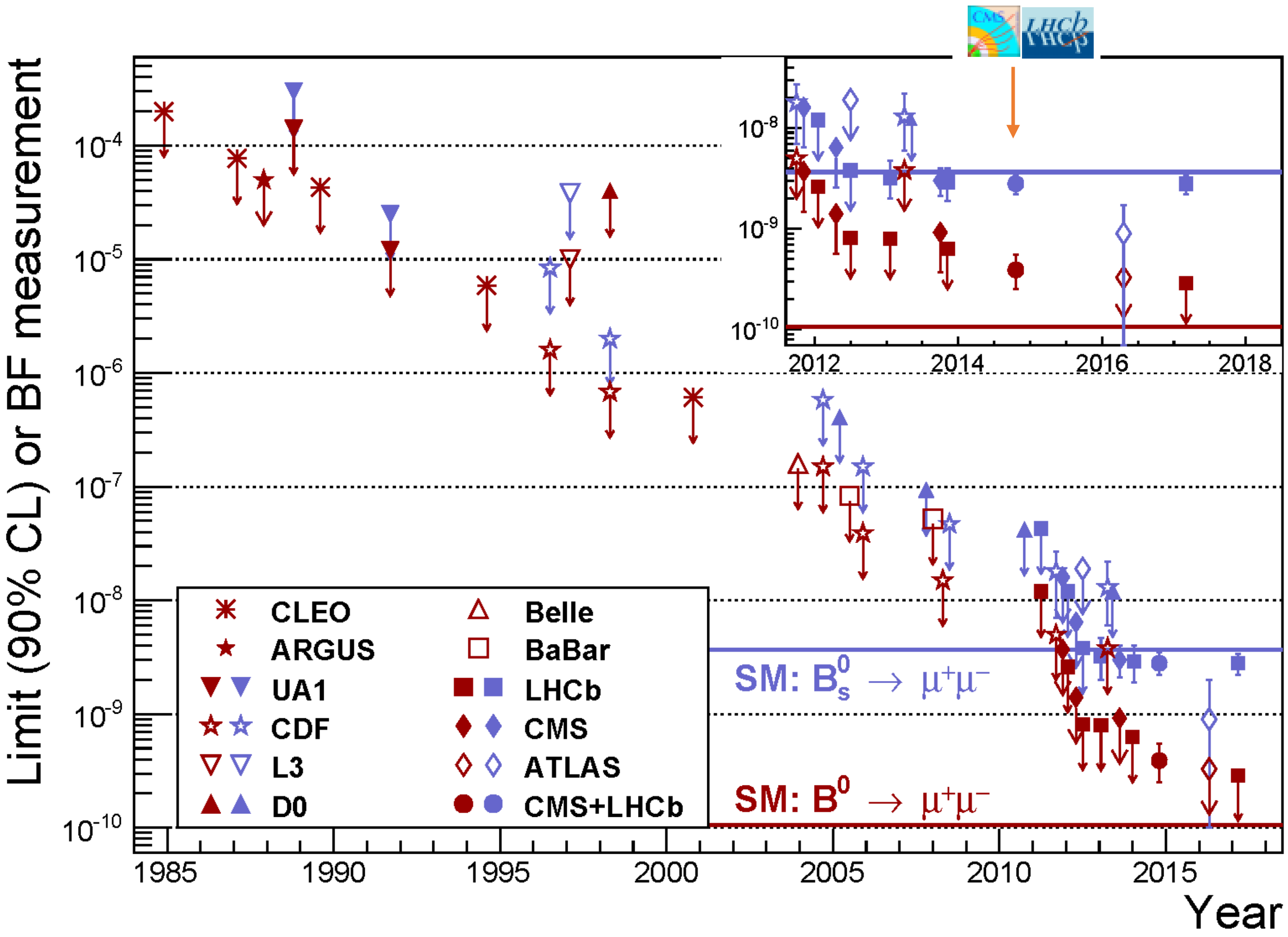
Indirect searches of NP

New particles can be virtually produced ⇒ sensitivity limited by precision, not by collision energy. Sensitivity to new particles up to ~100 TeV can be reached

[A. Buras et al. JHEP1411(2014)121]

Several observables: decay rates, CP asymmetries, angular distributions

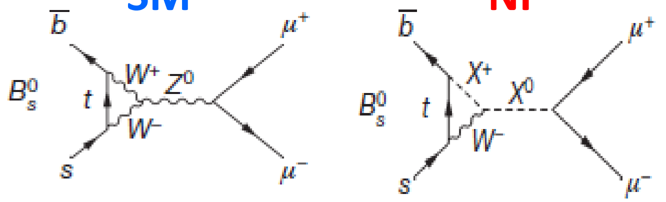
30 years-long search for $B_s \to \mu^+\mu^-$



First observation of $B_s \to \mu^+\mu^-$

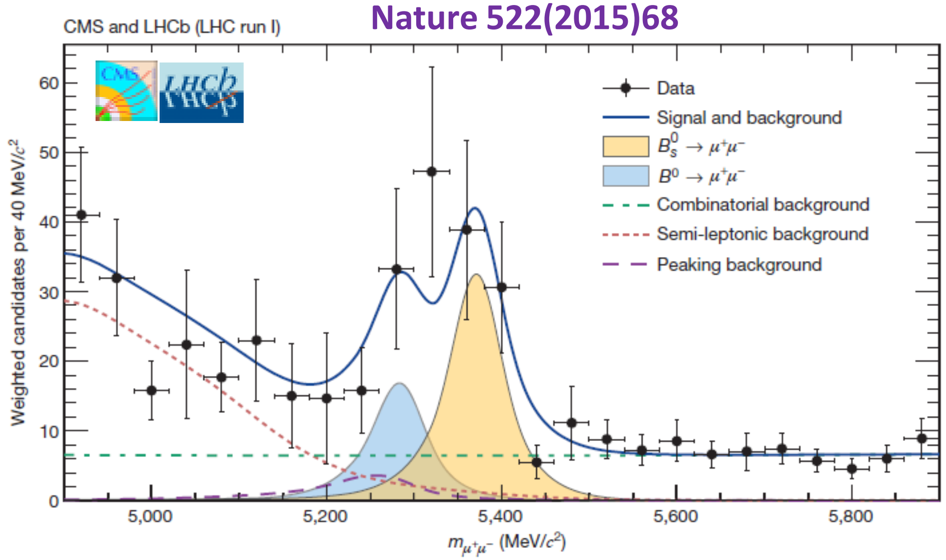
FCNC decay, very rare in SM

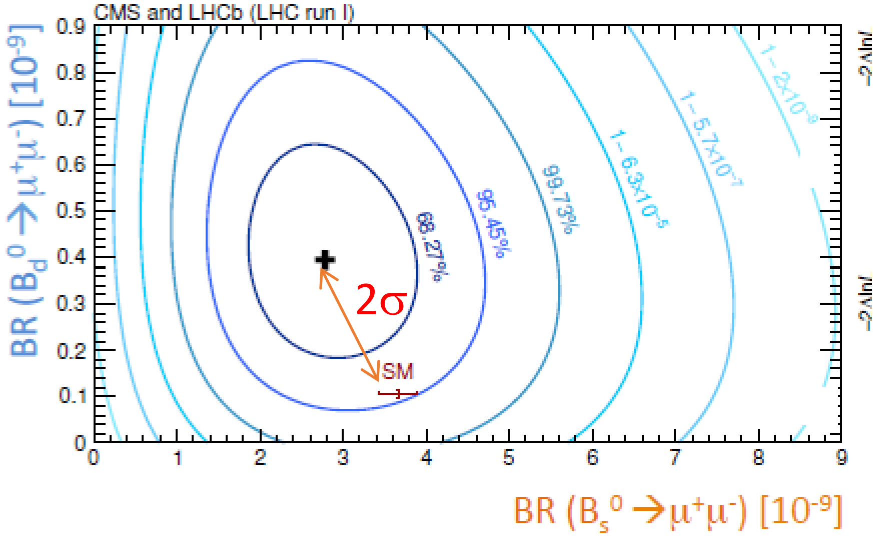
SM **NP**



BF can be significantly altered in many BSM models

Nature 522(2015)68





First observation (6.2 σ) of $B_s \to \mu^+\mu^-$

- BR = $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$

compatible with SM at 1.2σ

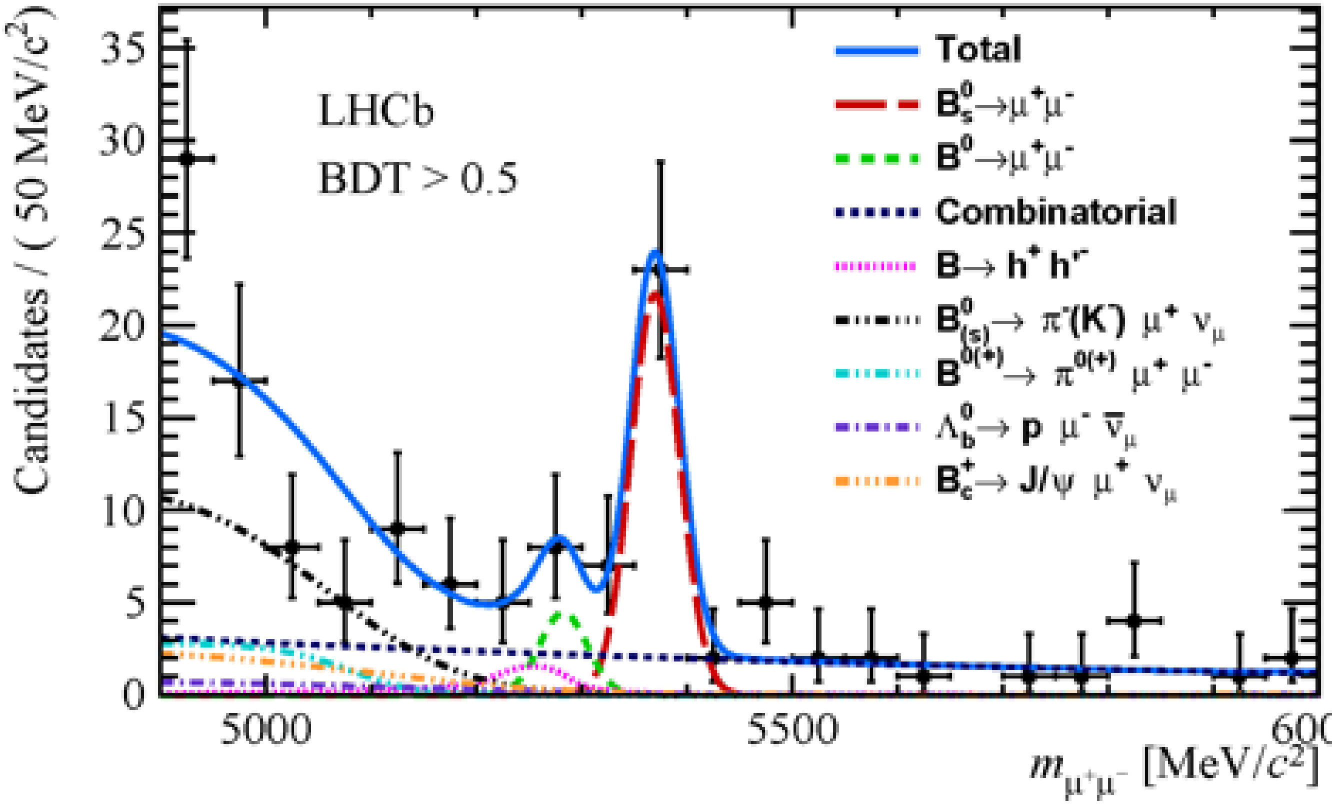
First evidence (3σ) of $B^0 \to \mu^+\mu^-$

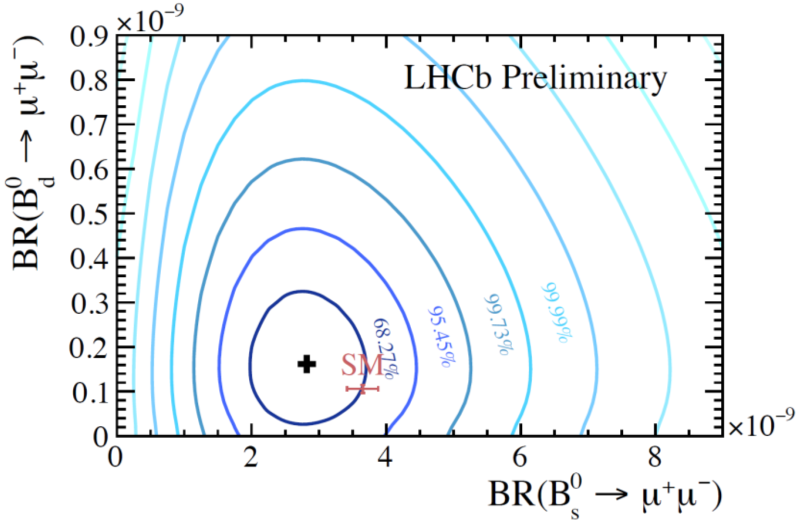
- BR = $(3.9^{+1.6}_{-1.4}) \times 10^{-10}$

compatible with SM at 2.2σ

New $B_s \to \mu^+\mu^-$ results (LHCb CERN Seminar, 14/4/2017)

LHCb-PAPER-2017-001



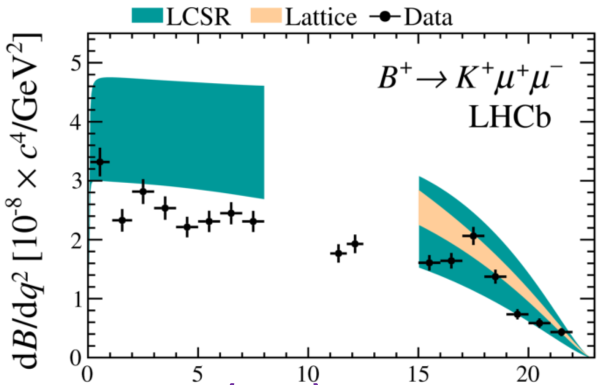


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.6) \times 10^{-9}$$ **7.8σ**

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.6^{+1.1}_{-0.9}) \times 10^{-10}$$ **1.9σ**

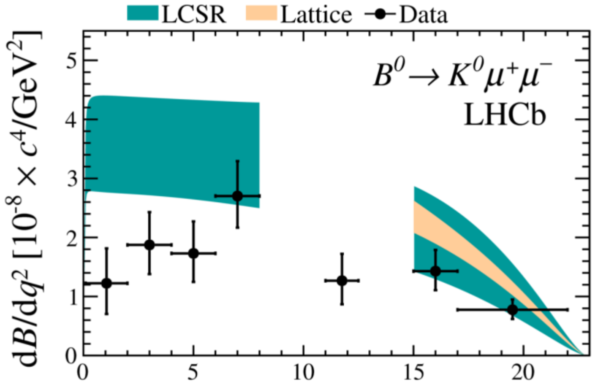
Exclusive $b \to s\mu^+\mu^-$ decay rates

$B^+ \to K^+\mu^+\mu^-$



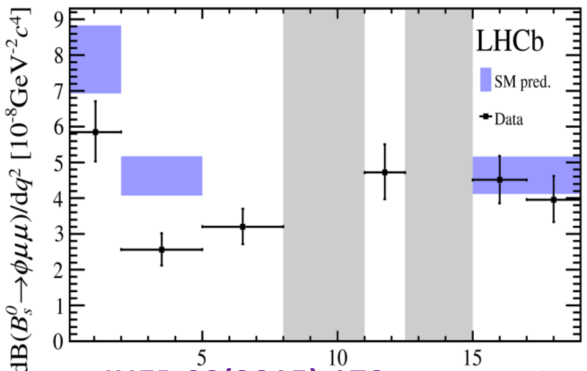
JHEP 06 (2014) 133

$B^0_s \to K^0\mu^+\mu^-$



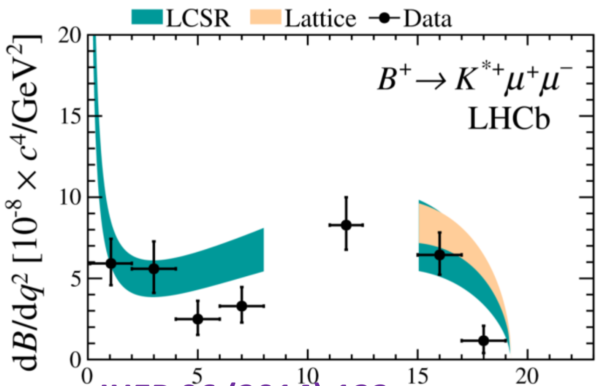
JHEP 06 (2014) 133

$B^0_s \to \phi\mu^+\mu^-$



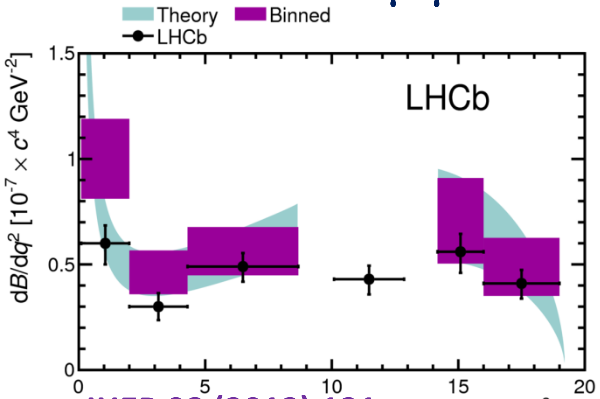
JHEP 09(2015) 179

$B^+ \to K^{*+}\mu^+\mu^-$



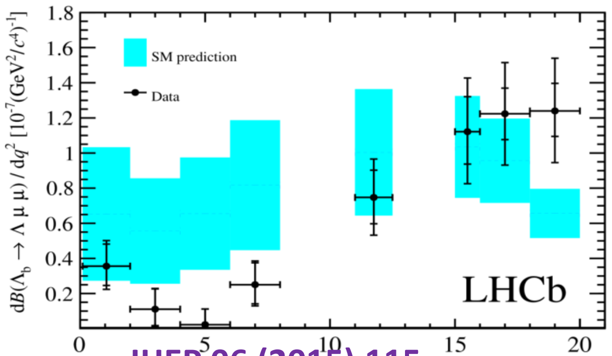
JHEP 06 (2014) 133

$B^0 \to K^{*0}\mu^+\mu^-$



JHEP 08 (2013) 131

$\Lambda_b \to \Lambda\mu^+\mu^-$



JHEP 06 (2015) 115

All lower than predicted!

But large uncertainties in the SM prediction from hadronic form factors

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

3fb^{-1} update in 2016

- Four-body final states
- System described by dimuon invariant mass q^2 and $\Omega=(\theta_l, \theta_K,\phi)$
  - Angular distributions sensitive to New Physics

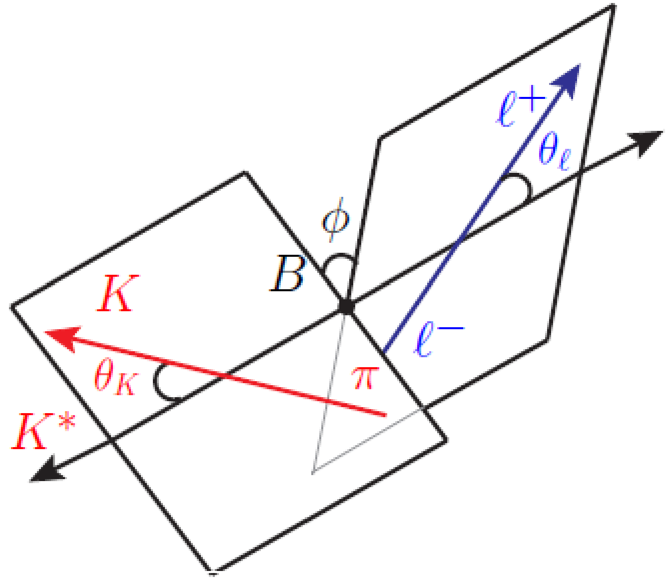
$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$I_i \to \overline{I^i}$ for B^0

Observables:

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$



The observables depend on Wilson coefficients (short-distance physics, evaluated perturbatively, universal) and on hadronic form factors for B→K* transition (long-distance physics, evaluated through lattice QCD or LCSR)

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

JHEP 02(2016) 104

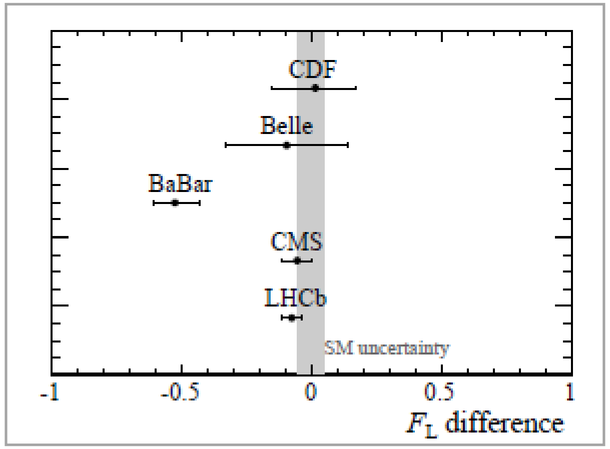
The CP-averaged angular distribution can be explicitely written as

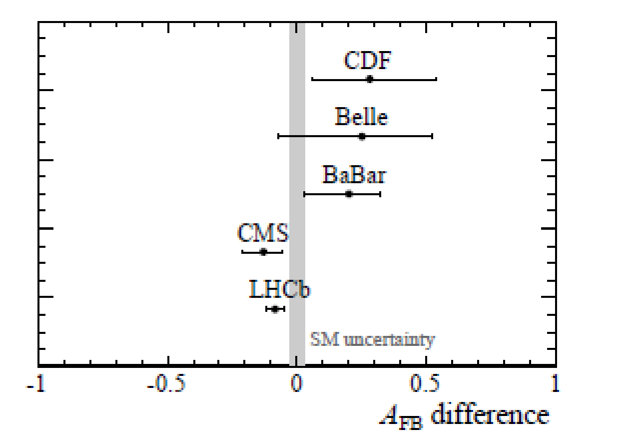
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\rm L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\rm FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

F_L = Fraction of longitudinal polarisation of the K^{*0}

A_{FB} = Forward-backward asymmetry of dimuon system

LHCb F_L and A_{FB} in good agreement with SM





Blake, Lanfranchi, Straub Prog.Part.Nucl.Phys. 92 (2017) 50-91

$B^0 \to K^{*0}\mu^+\mu^-$, P_5' observable

3fb^{-1} update in 2016

JHEP 02(2016) 104

Set of observables with reduced hadronic uncertainties can be defined using ratios

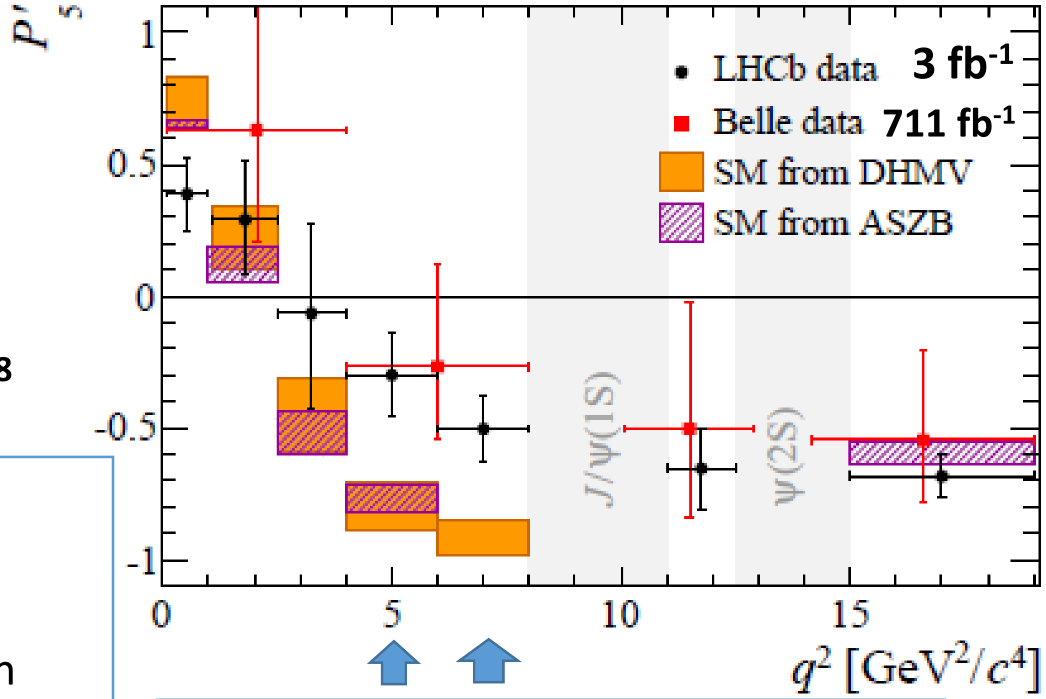
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

Independent of form-factors at leading order

S.Descotes-Genon et al., JHEP01(2013)048

LHCb has performed the first full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

Global analysis of LHCb results on CP-averaged observables at **3.4σ from SM**



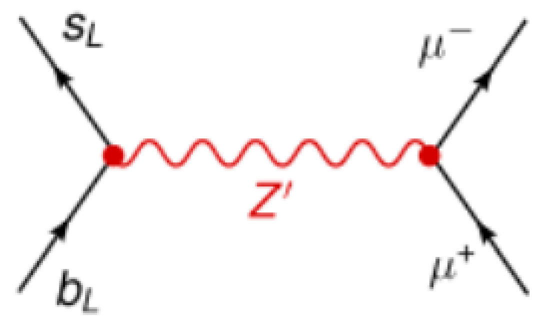
LHCb local tension with SM prediction

Belle data consistent with LHCb

2.1σ from SM, arXiV:1604.04042

Interpretation of b→s anomalies

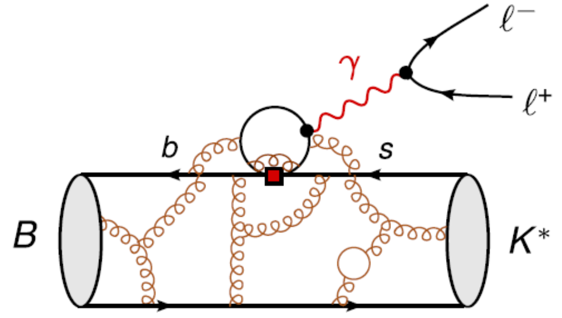
NP



Vector-like contribution could come from a Z' with a mass of a few TeV

OR?

SM



Vector-like contribution could be mimicked by poorly understood charm-loop contributions that may produce a di-muon pair via a virtual photon

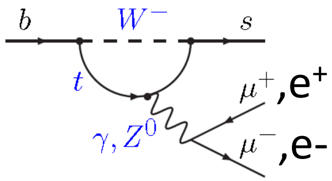
Lyon and Zwicky, arXiv:1406.0566
Altmannshofer, W. & Straub, D.M. Eur. Phys. J. C (2015)
Ciuchini et al., JHEP 06(2016)116

More effort on-going to clarify picture: e.g., measure $C_9(q^2)$ dependence (different from charm loops and NP contribution) –
Current statistics not sufficient to draw conclusions

Lepton Universality Test: e/μ

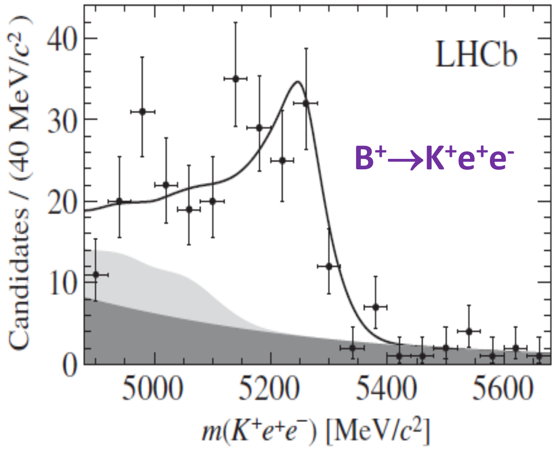
SM b→sll flavour universality

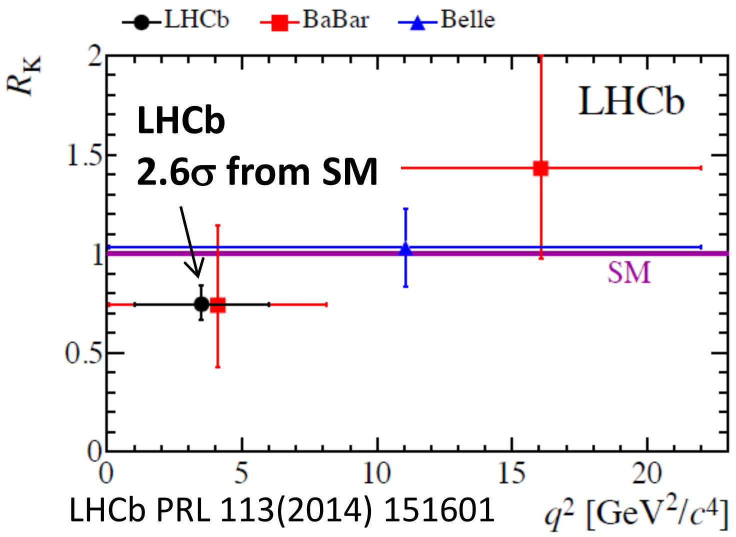
⇒ Expect:



$$R_K = \frac{BF(B^+ \to K^+\mu^-\mu^+)}{BF(B^+ \to K^+e^-e^+)} = 1 \pm O(10^{-3})$$

- Theoretically clean: hadronic uncertainties cancel in the ratio
- Experimentally challenging: electron-reconstruction (Bremsstrahlung tail)





LHCb PRL 113(2014) 151601

BaBar PRD 86(2012)032012

Belle PRL 103 (2009) 171801

LHCb Run-1 (3 fb^{-1}) for $1<q^2<6$ GeV^2:

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

R_K=0.8 consistent with angular anomalies in b→sμμ in some class of NP models

E.g [Altmannshofer et al, PRD 89 (2014) 095033]

Lepton Universality Test: μ/τ

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\upsilon)}{\Gamma(B \to D^{(*)}\mu\upsilon)}$$

≠1 due to phase-space

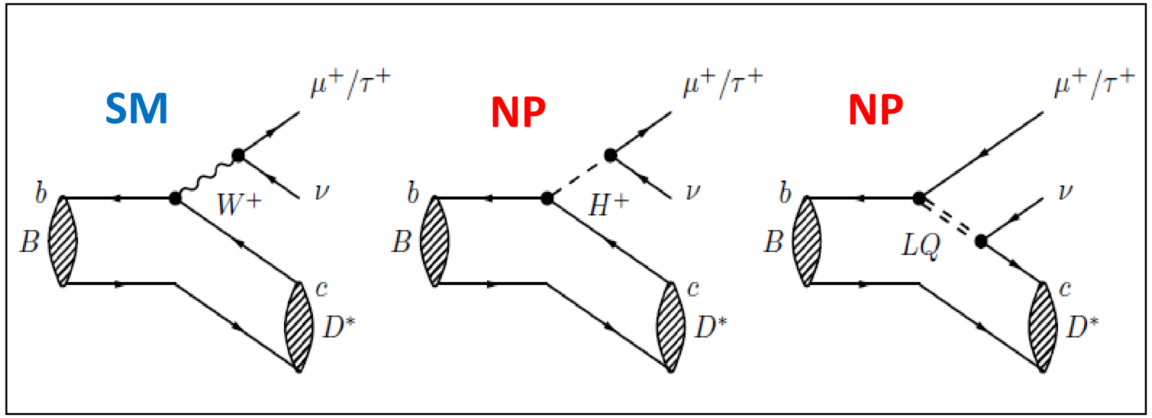
SM prediction theoretically very clean
Sensitive to NP: e.g. charged Higgs, leptoquark

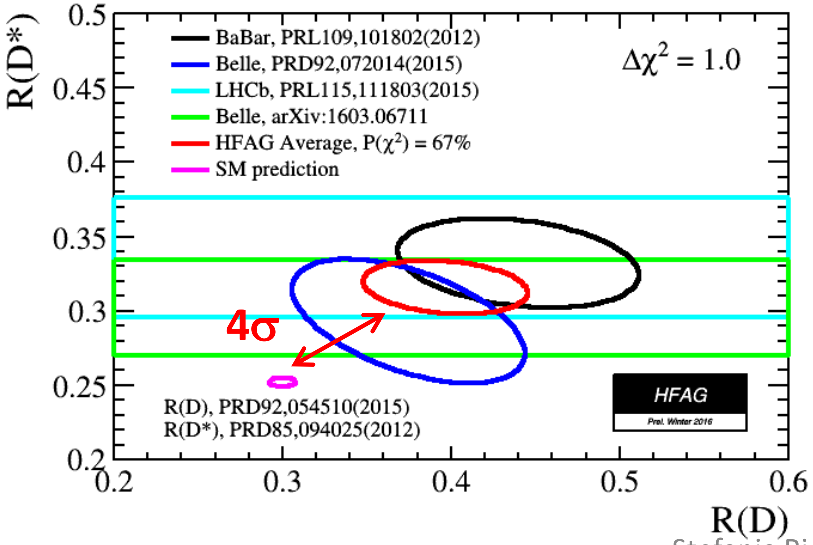
LHCb measured R(D*) with $\tau \to \mu\nu\nu$
Experimental challenge: missing neutrinos

LHCb result at 2.1σ from SM

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

LHCb, PRL115,111803(2015)





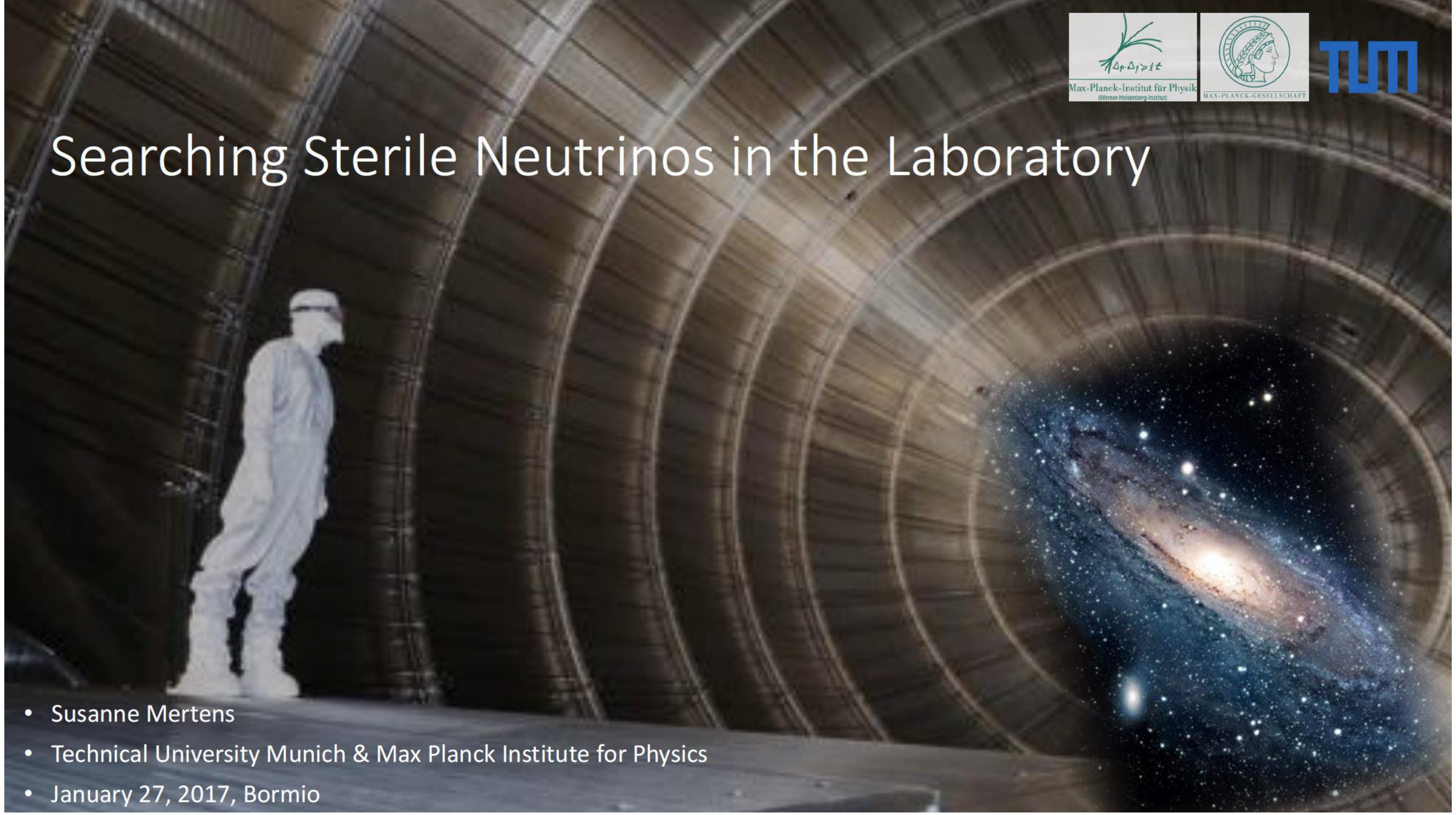
HFAG average of all R(D) and R(D*), including Belle, Babar, LHCb
4σ from expectations

More measurements of other $b \to c\tau\nu$ processes under way at LHCb.
Also using B_s, B_c, Λ_b decays

LHCb Flavour Summary

- Many new LHCb results published this year (>50 papers!)– Only a few, selected ones, presented here
- Increasing experimental precision and good agreement with SM for most of the flavour observables
- Some measurements showing interesting tensions with SM:
  - Some exclusive $b \to s\mu^+\mu^-$ branching fractions
  - $B^0 \to K^{*0}\mu^+\mu^-$ angular distributions (2016 first full angular analsys)
  - Hints of lepton non universality in $B \to Kll$ and $B \to Dl\nu$ decays

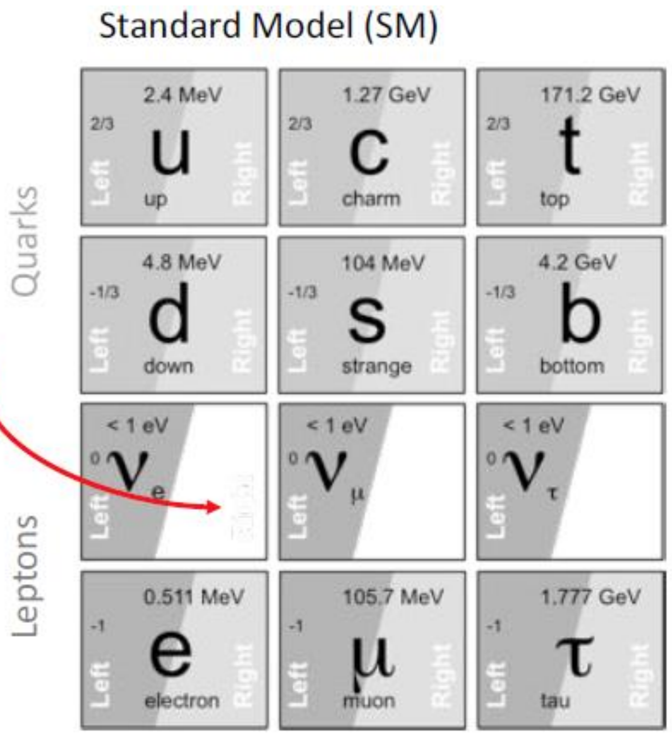
  New Physics or unaccounted uncertainties or statistical fluctuations?
- Most results using LHC Run-1, $3fb^{-1}$; b and c-quark data-samples from Run-2 on tape is already more than twice larger (accounting for larger cross-sections)
- Plans to collect $50fb^{-1}$ by end of LHC Run-4 (2030) with upgraded detector



Sterile neutrinos

Sterile neutrinos

Something is missing



Well-motivated theoretically and experimentally

Heavy sterile neutrinos (~ GeV)

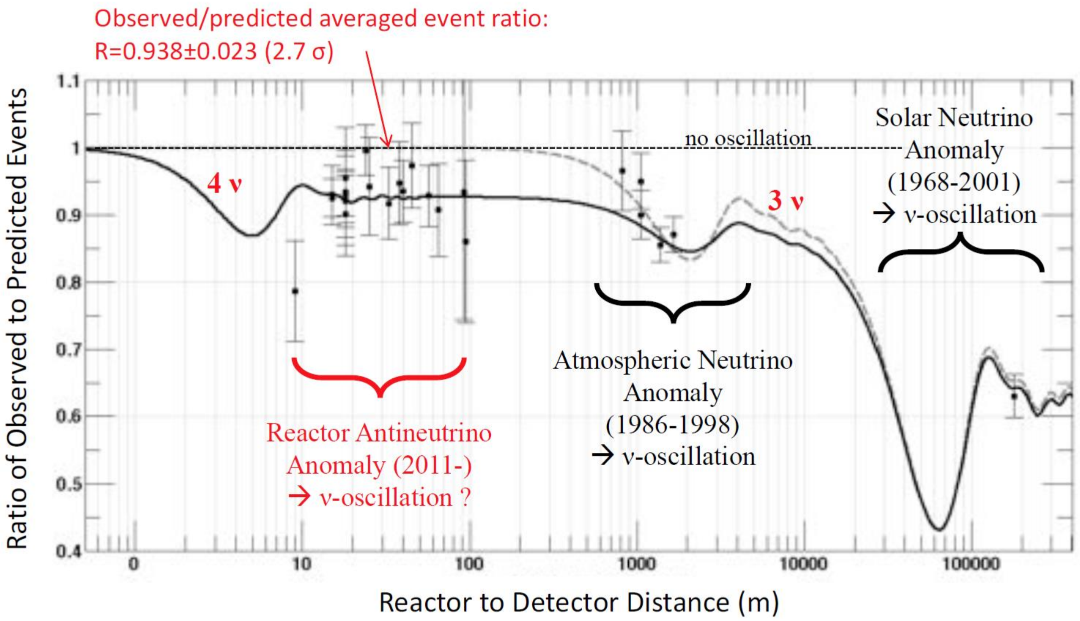
- Lightness of neutrinos via See-saw mechanism

Light sterile neutrinos (~1 eV)

- Reactor anomaly, Gallium anomaly, Short baseline accelerator results

KeV-scale sterile neutrinos (~ 1 - 50 keV)

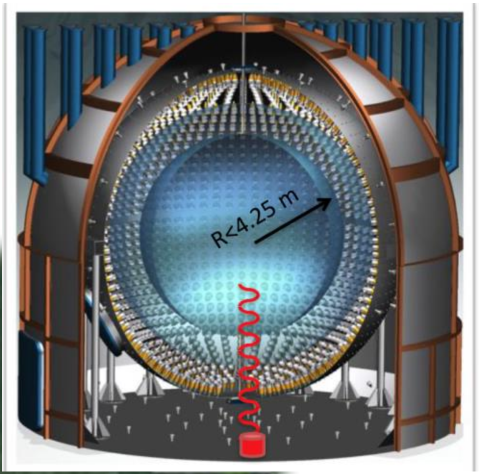
- Warm and cold dark matter candidates



World-wide Hunt for Steriles

Challenging Journeys...

CeSoX (2018)

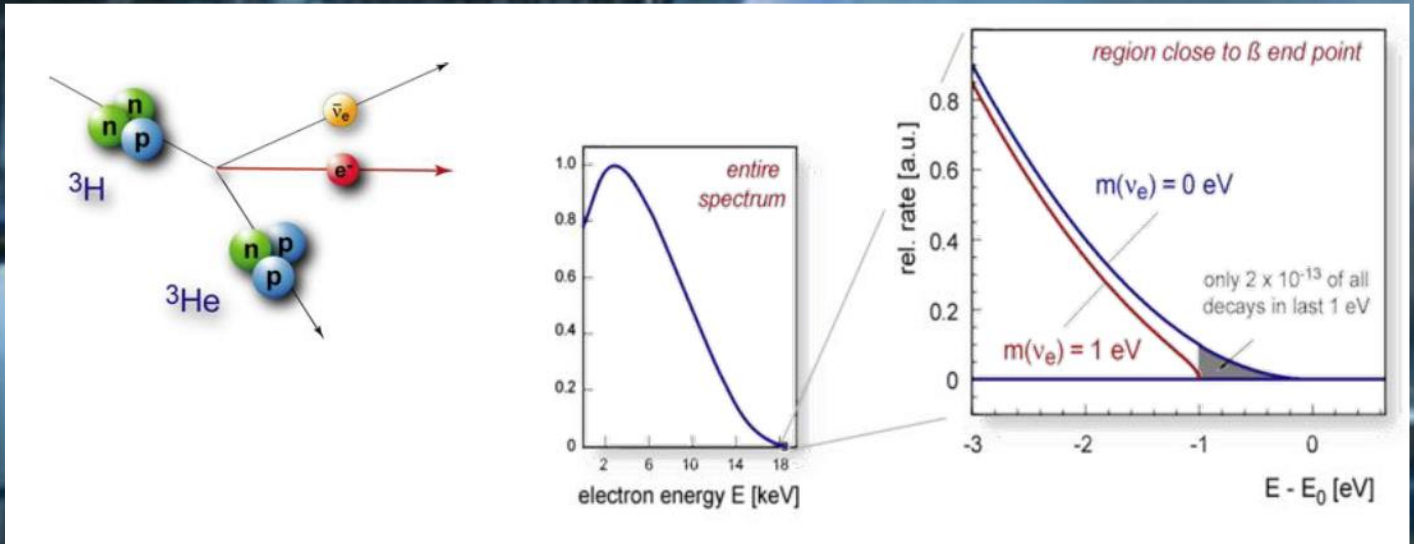


Katrin (2006)

The KATRIN Experiment

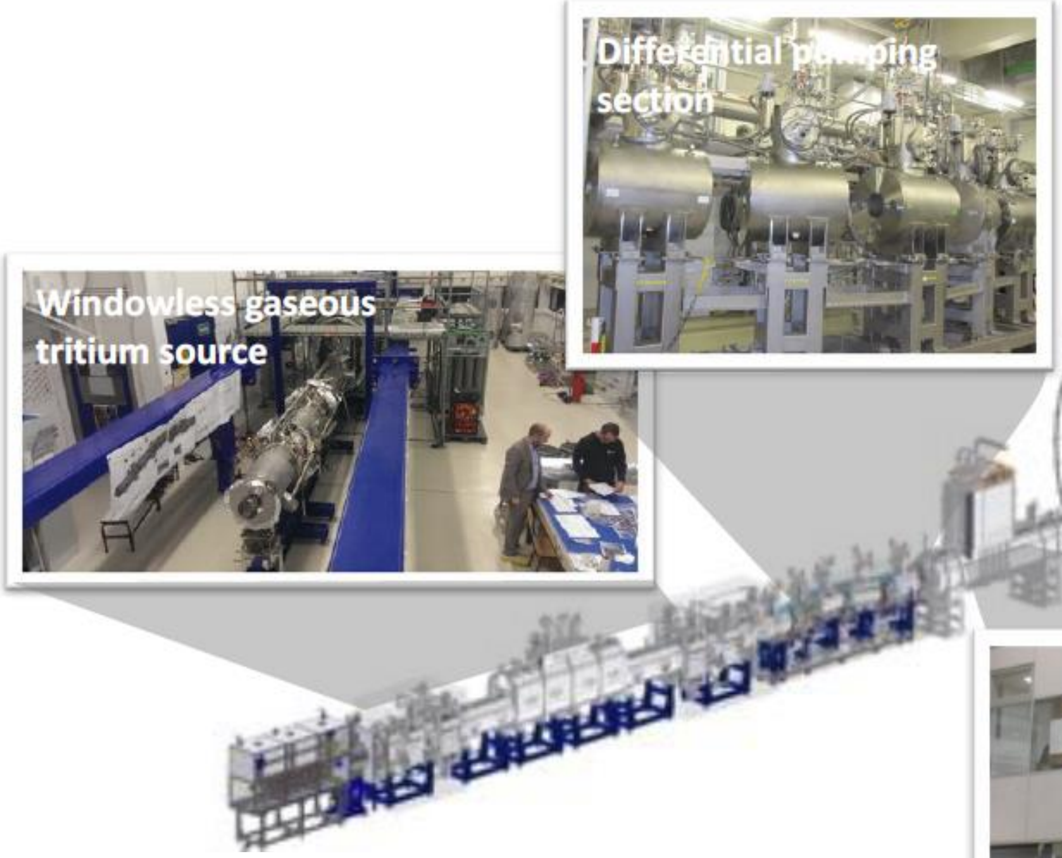
Goal:
Probing the effective electron anti-neutrino mass

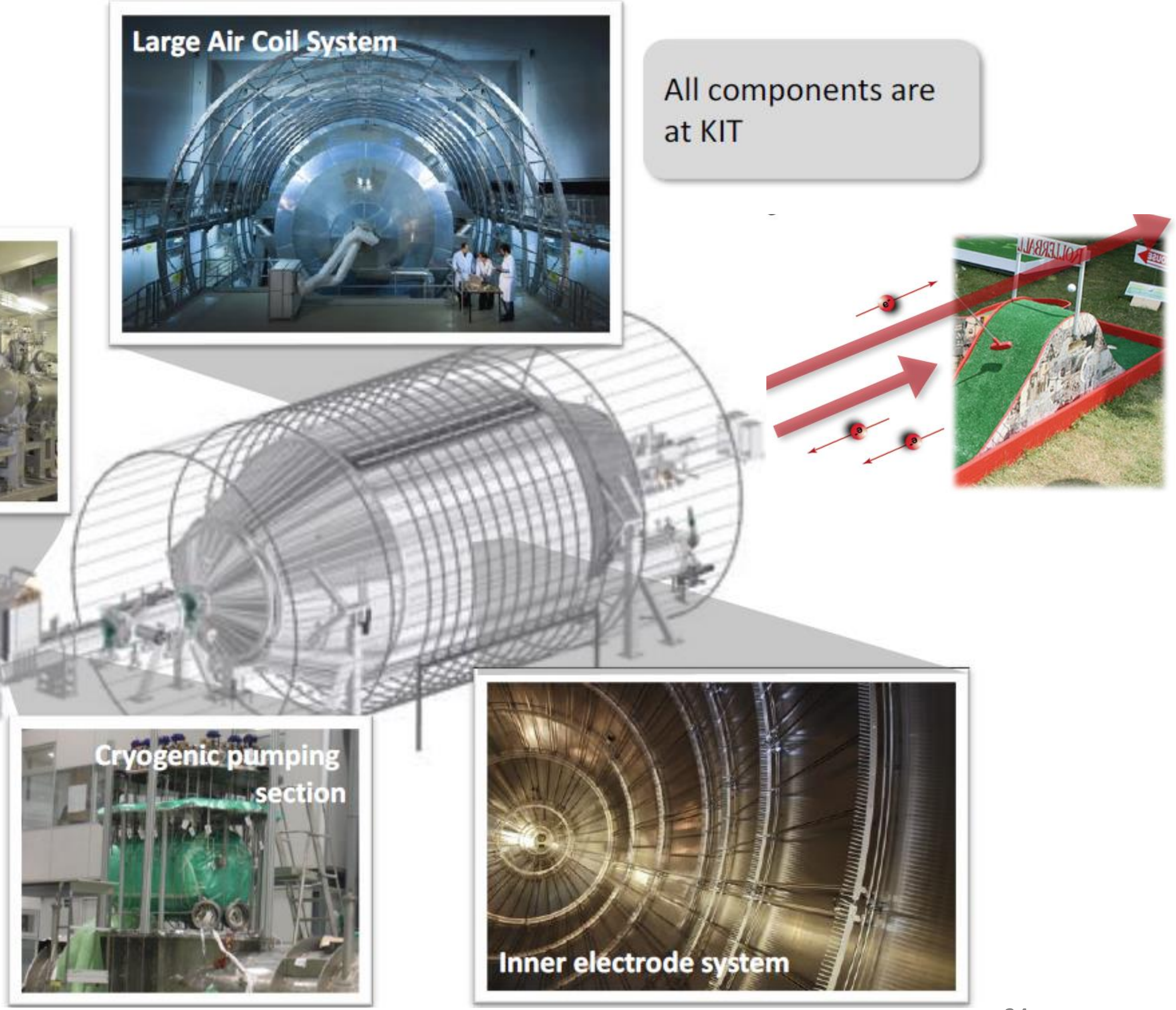
200 meV sensitivity @90%CL (3 years)



KATRIN Status

All components are at KIT

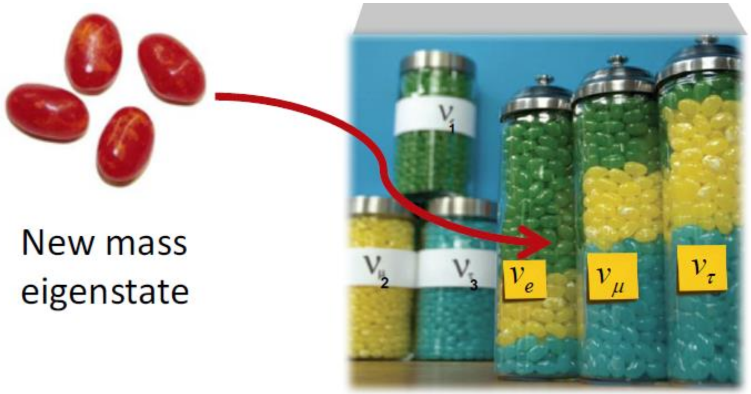




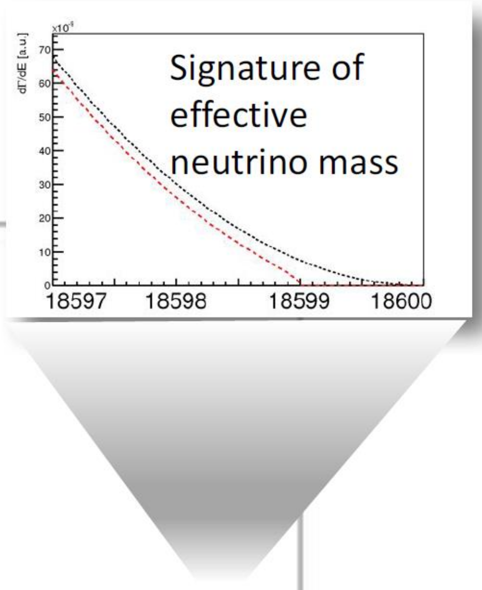
KATRIN's first light: October 14, 2016

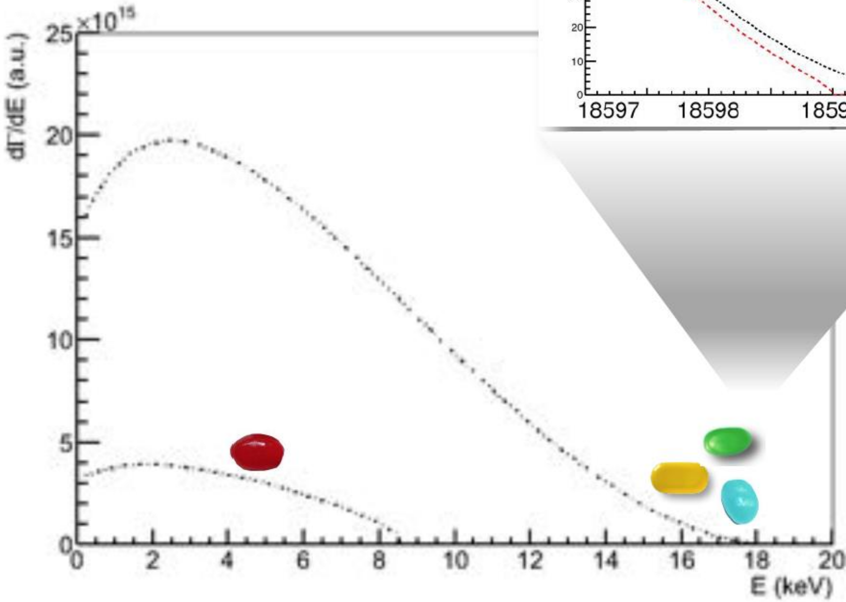
- The first electrons found their way through the 70-m long setup
- First tritium measurements planned for this year

β-spectrum

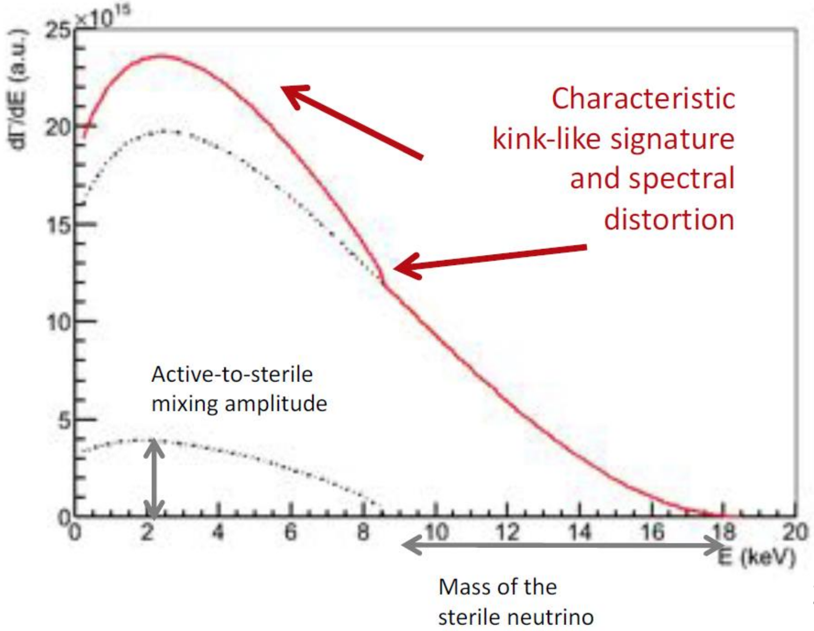


$$m_\beta^2 = \sum_i \left|U_{ei}\right|^2 m_{\nu i}^2$$



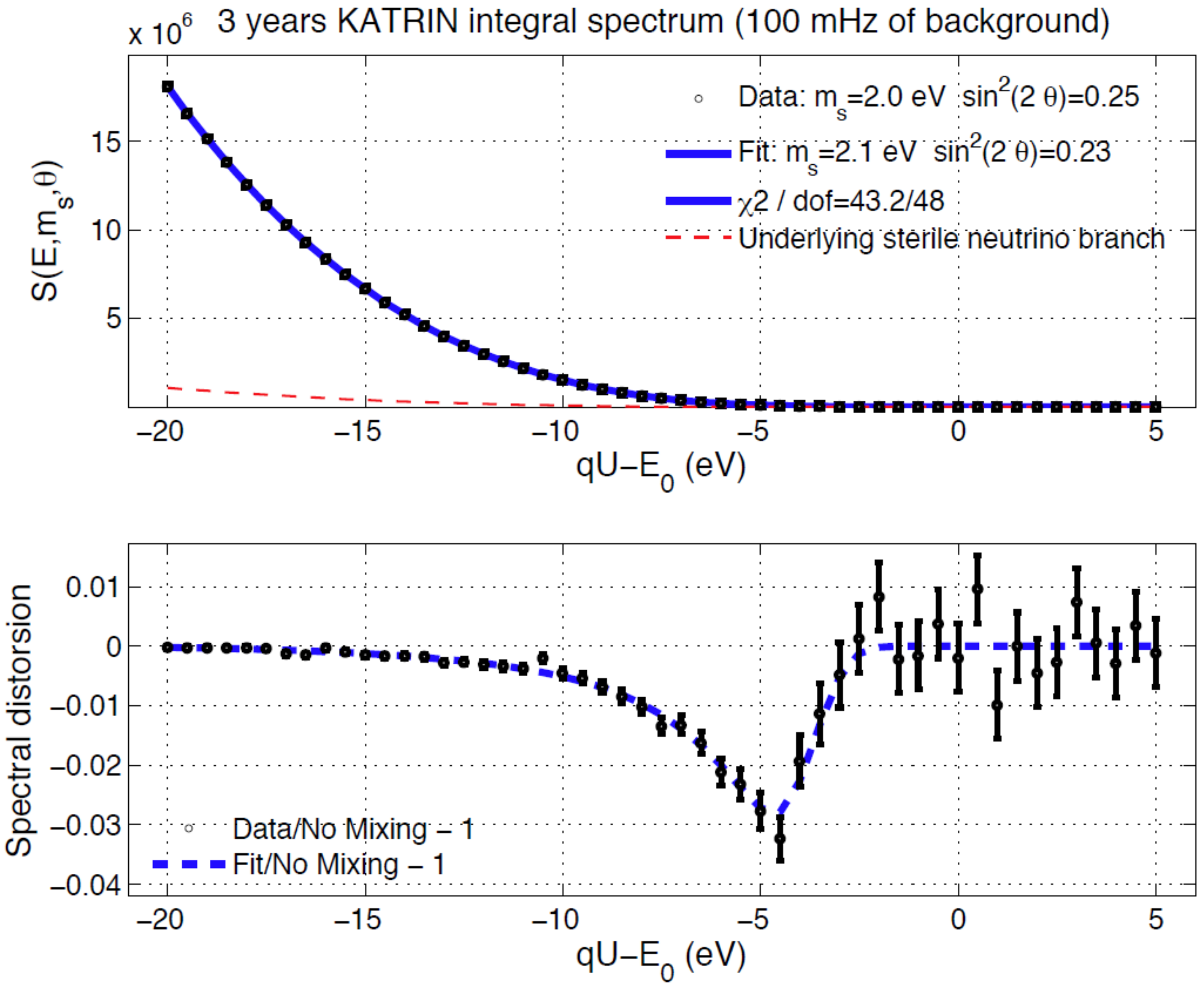


$$\frac{d\Gamma}{dE} = \cos^2\theta \, \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \, \frac{d\Gamma}{dE}(m_s)$$

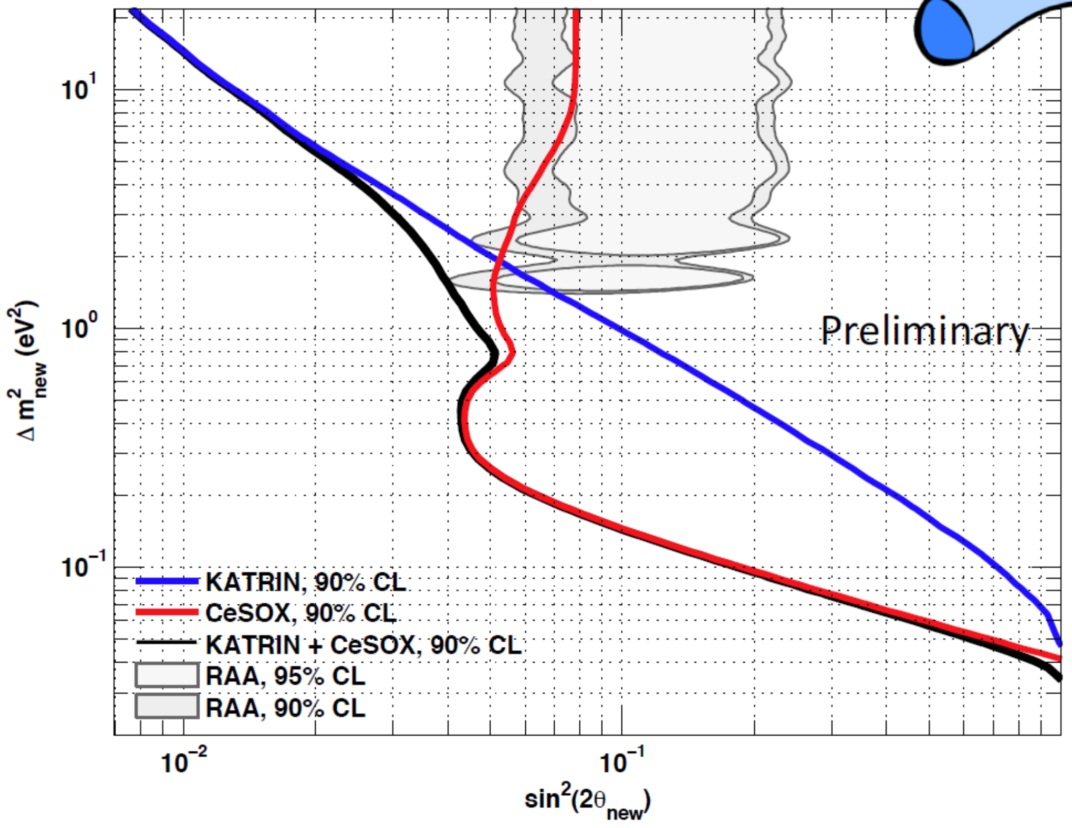


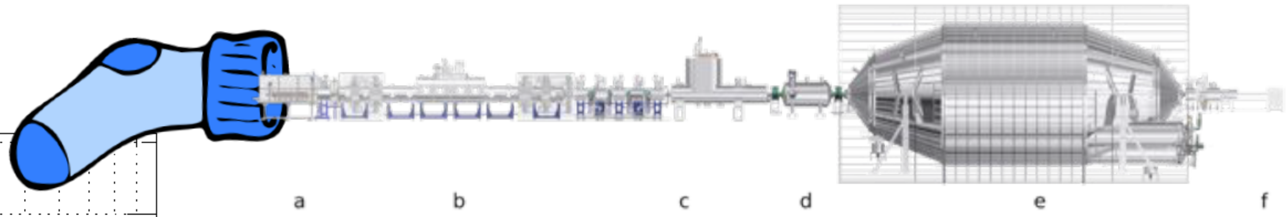
The signature eV sterile ν's in KATRIN

Kink-like signature close to the endpoint, where KATRIN is measuring anyway



KATRIN + SOX combined sensitivity

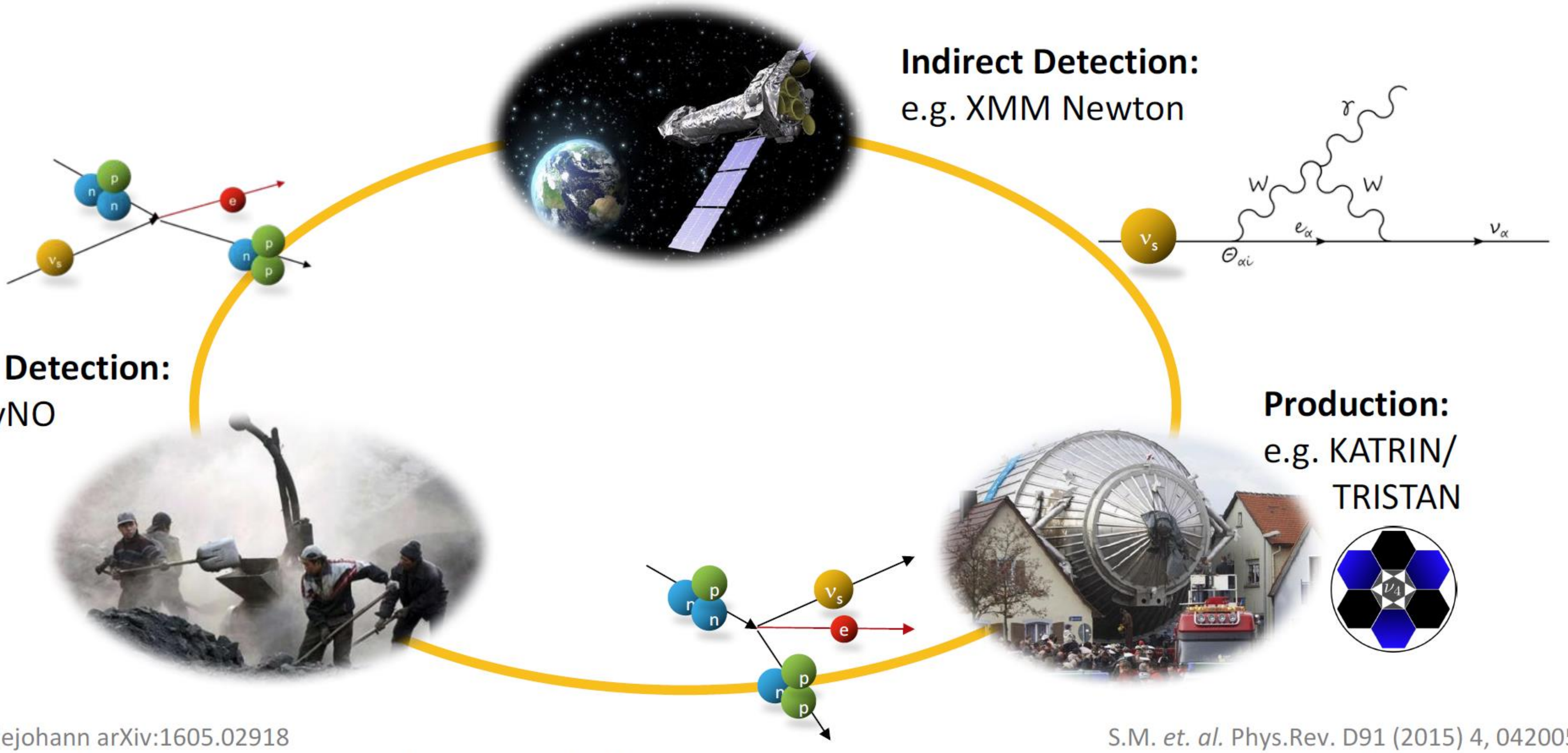




KATRIN "as is" probes the interesting parameter space and provides complementary information

Experimental searches ...keV-scale sterile ν

Strong constraint:
Mixing to active neutrinos
$\sin^2\theta < 10^{-6}$



Indirect Detection:
e.g. XMM Newton

Direct Detection:
e.g. DyNO

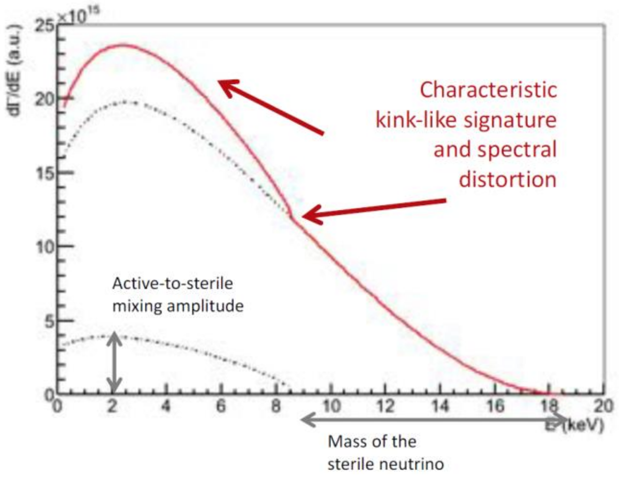
Production:
e.g. KATRIN/
TRISTAN

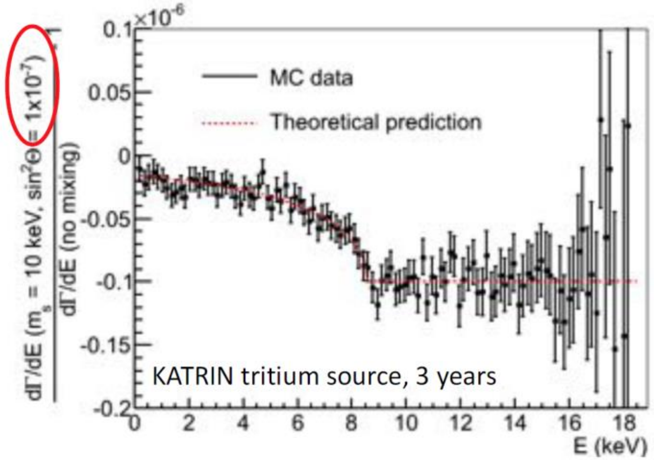
M. D. Campos, W. Rodejohann arXiv:1605.02918
T. Lasserre, K. Altenmueller, M. Cribier, A. Merle, S. M., M. Vivier arXiv:1609.04671

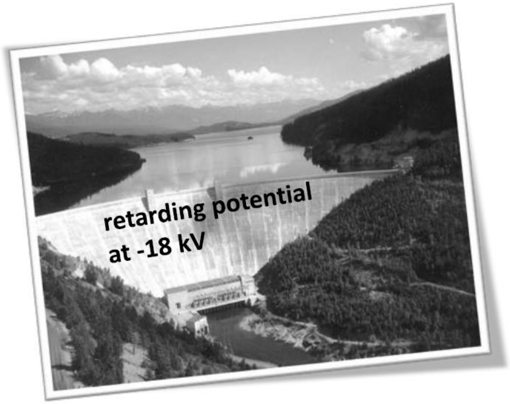
S.M. *et. al.* Phys.Rev. D91 (2015) 4, 042005
S.M. *et al.* JCAP 1502 (2015) 02, 020

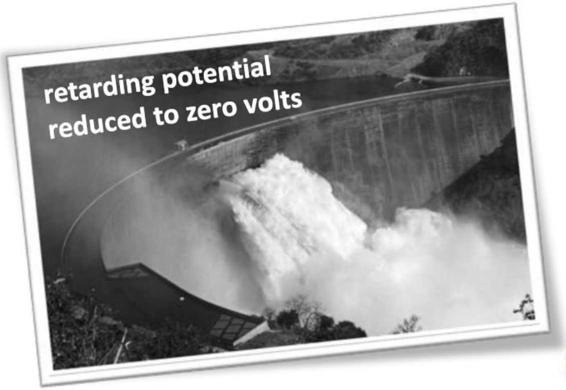
New Project: TRISTAN

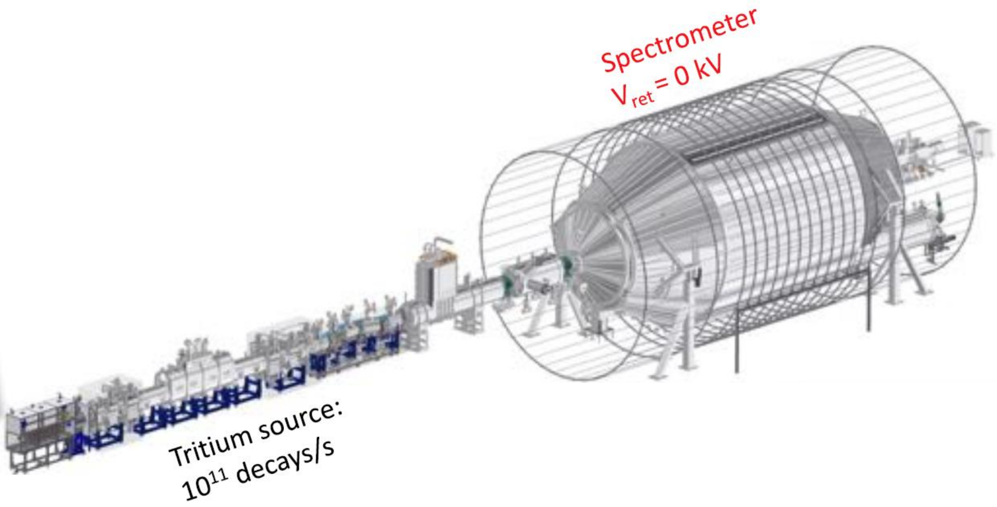
$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \frac{d\Gamma}{dE}(m_s)$$







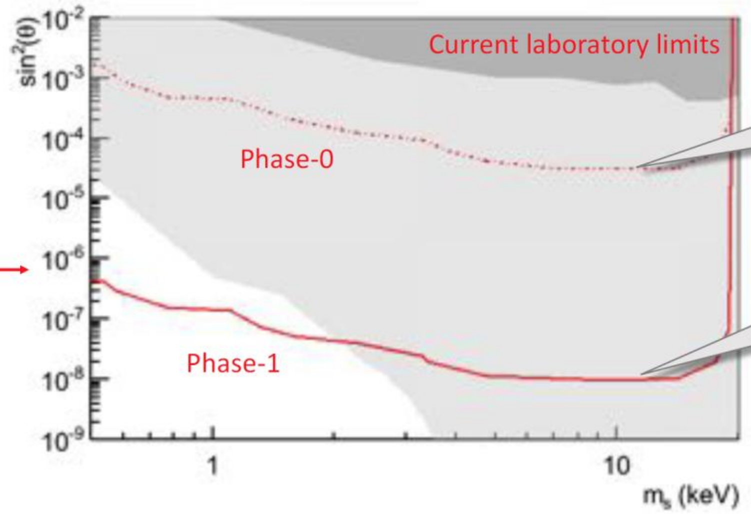




- ➢ Reduce the count rate (Phase – 0)
- ➢ Develop a new detector (Phase – 1)

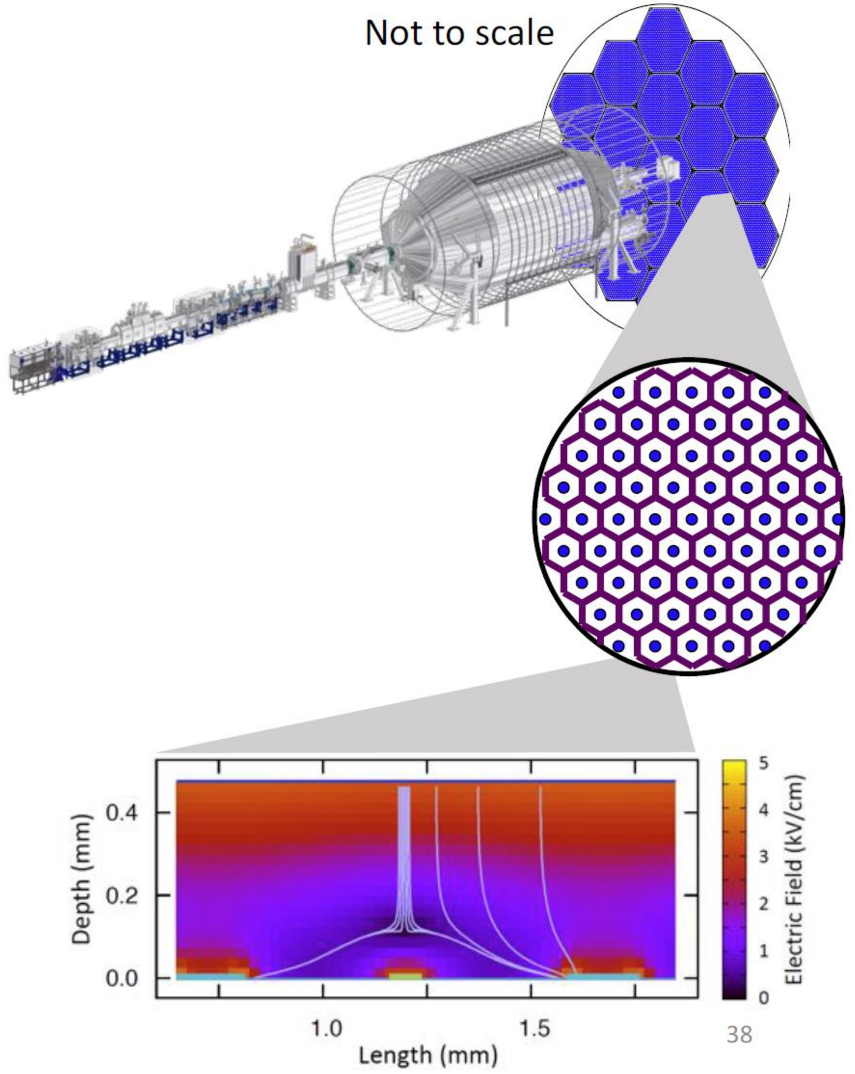
TRISTAN

Sensitivity to keV sterile neutrinos

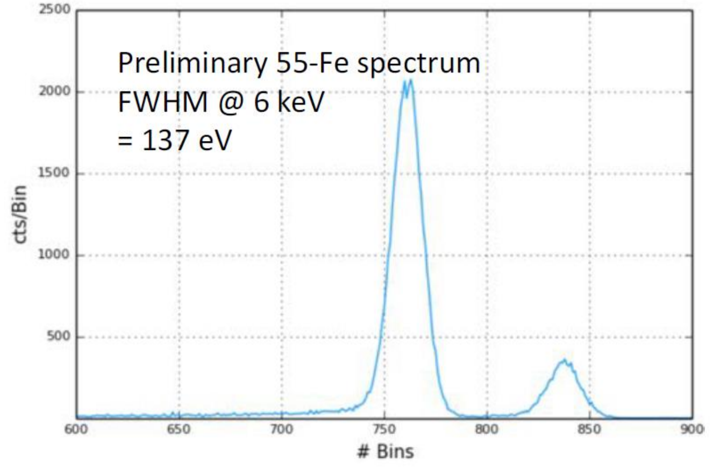


10^{11} electrons:
Reduced source strength and
7 days of measurement time
With KATRIN "as is"

10^{18} electrons:
Full source strength and
3 years of measurement time
With TRISTAN



TRISTAN prototype



TRISTAN Design requirements

- Capability of handling high rates (10^8 cps)
  - ➢ O(10 000) pixel
- Excellent energy resolution (300eV@20keV)
  Low energy threshold (1 keV)
  - ➢ Thin deadlayer (~10 nm)
- Large pixels (low noise at high rate)
  (cell size ~ 2mm)
  - ➢ Silicon Drift Detector design, capacity < 0.05 pF

Summary

Sterile neutrinos are a natural extension of the SM

- **eV-scale sterile neutrinos:**
  - 3 σ anomalies call for clarification
  - World-wide effort is ongoing
  - KATRIN and SOX will be among the first (~2 years) to provide results

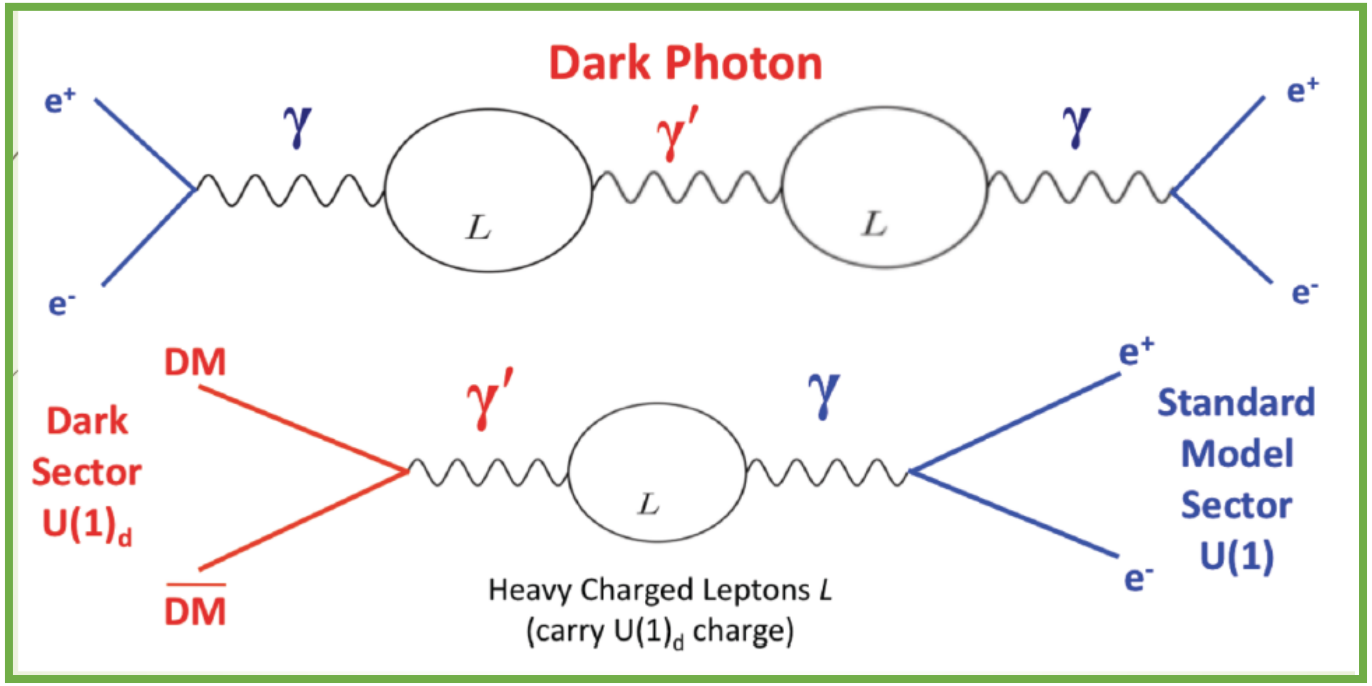
- **keV-scale sterile neutrinos:**
  - Alternative dark matter candidate
  - Strong indirect limits from X-ray observation
  - New ideas are being explored to catch up with laboratory searches TRISTAN + DyNO

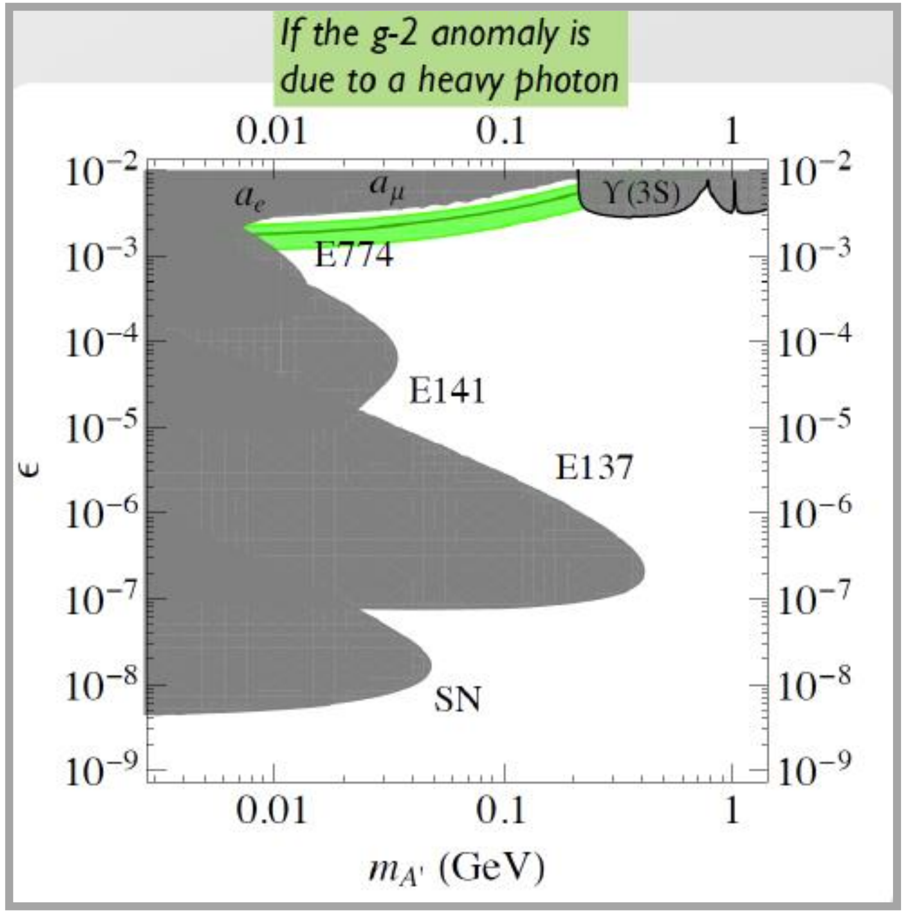
Nuclear Astrophysics

Be-8 Anomaly

The atomic nucleus is a femto-laboratory including probably all of the interactions in Nature. A real discovery machine like LHC, but at low energy.

Dark photon





γ' = New massive U(1) gauge boson, portal to dark sector, in several extensions of the SM.
Interaction of dark photon with SM particles by kinematic mixing with strength ε
It can experimental phenomena such as positron excess (PAMELA, FERMI, AMS-02)
It can also explain anomalous (g-2)μ via loop contributions of dark photons with masses between 10 and 200 MeV.

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
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T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

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(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+, T = 1$) state → ground state ($J^\pi = 0^+, T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+, T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{syst})\ \mathrm{MeV}/c^2$ and $J^\pi = 1^+$ was created.

Evidence for a Protophobic Fifth Force from ^{8}Be Nuclear Transitions

Jonathan L. Feng,[1] Bartosz Fornal,[1] Iftah Galon,[1] Susan Gardner,[1,2] Jordan Smolinsky,[1] Tim M. P. Tait,[1] and Philip Tanedo[1]
[1] *Department of Physics and Astronomy, University of California, Irvine, California 92697-4575 USA*
[2] *Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055 USA*

Phys. Rev. Lett. 117, 071803

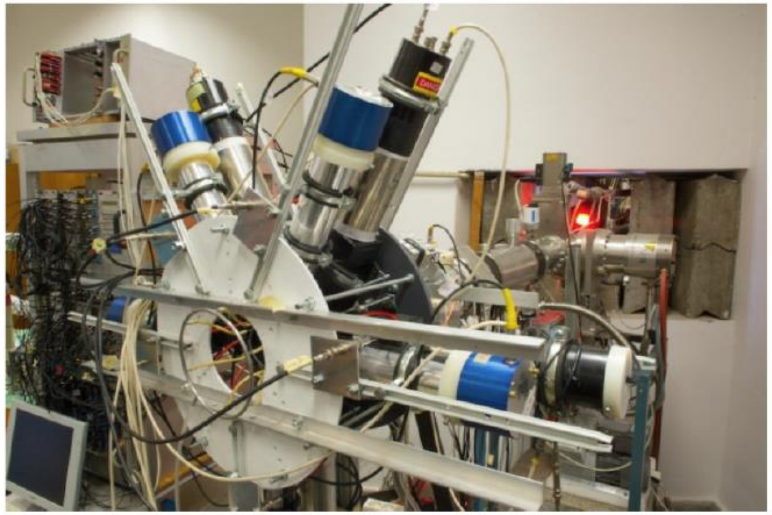
NATURE | NEWS

Has a Hungarian physics lab found a fifth force of nature?

Radioactive decay anomaly could imply a new fundamental force, theorists say.

Edwin Cartlidge

25 May 2016

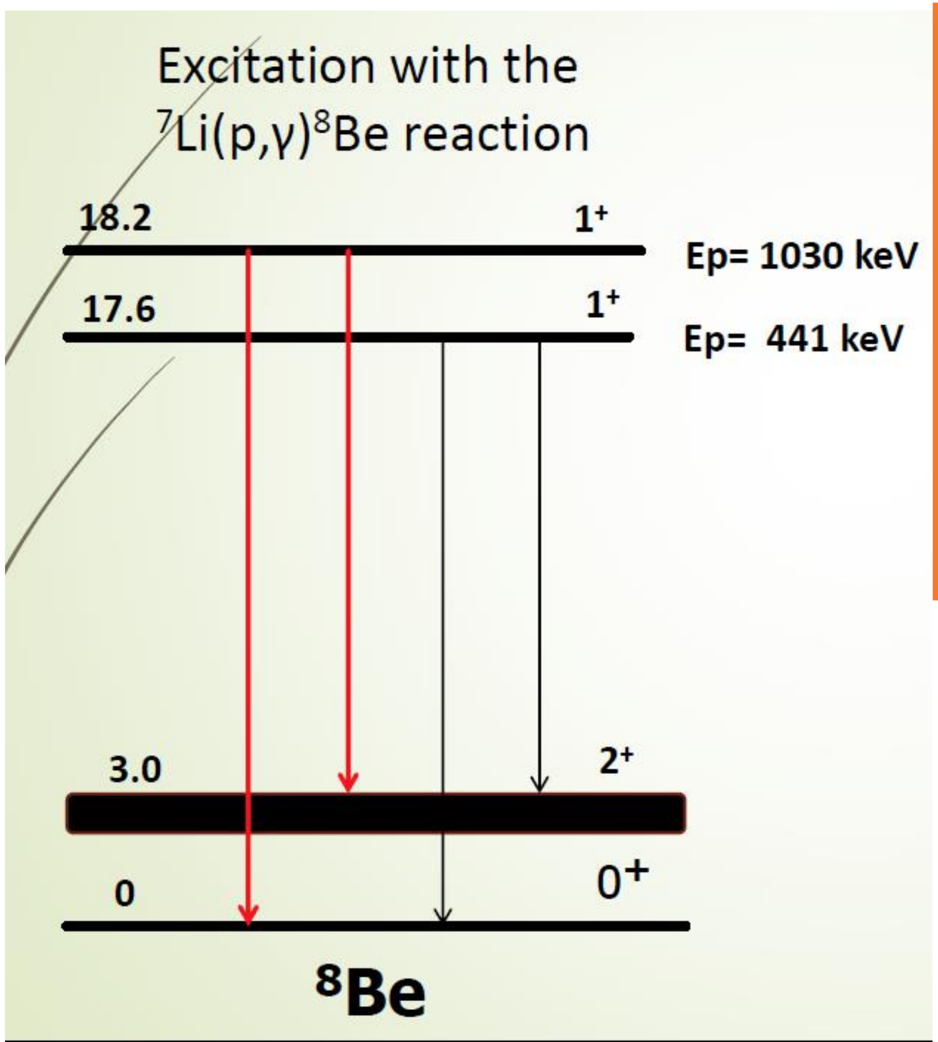


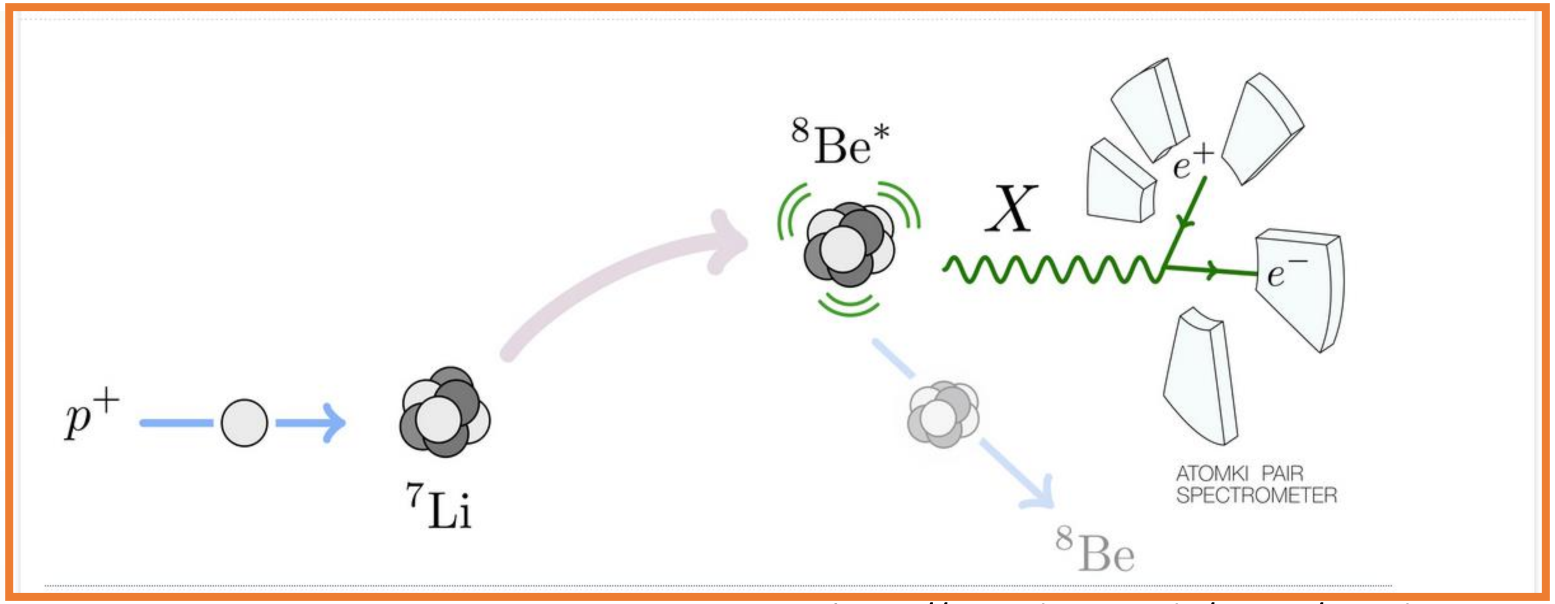
MTA-Atomki

Physicists at the Institute for Nuclear Research in Debrecen, Hungary, say this apparatus — an electron-positron spectrometer — has found evidence for a new particle.

Print

Schematic of the experiment





https://ucrtoday.ucr.edu/39192/tanedoipc

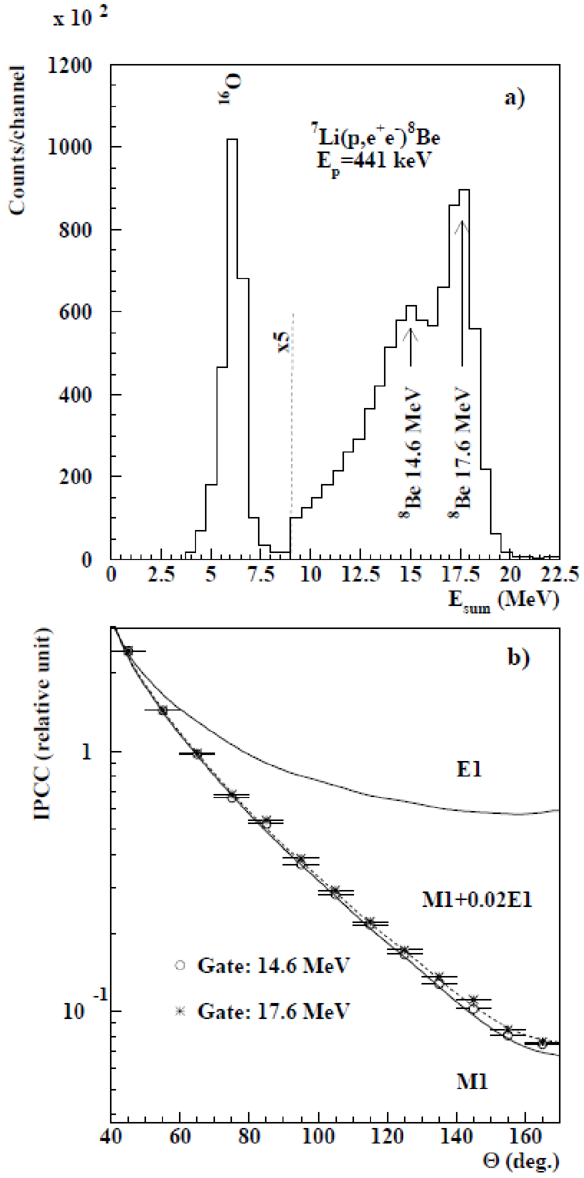


FIG. 1. *Measured total energy spectrum (a) and angular correlation (b) of the* e^+e^- *pairs originated from the decay of the 17.6 MeV resonance compared with the simulated angular correlations [37] assuming M1 (full curve) and M1+2%E1 mixed transitions (dashed line).*

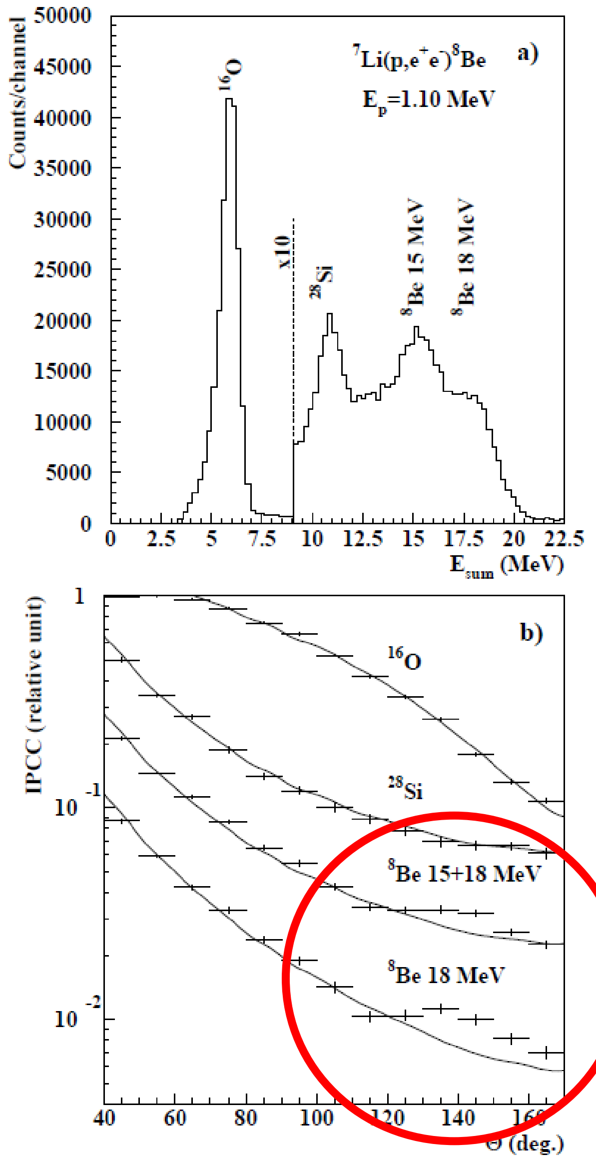
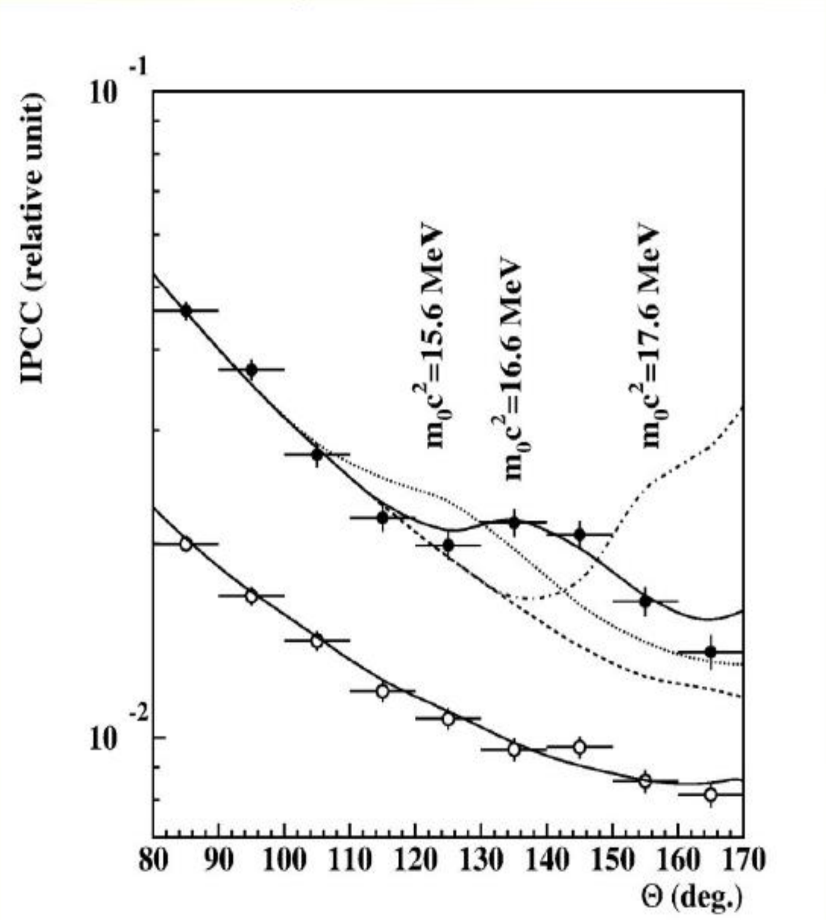
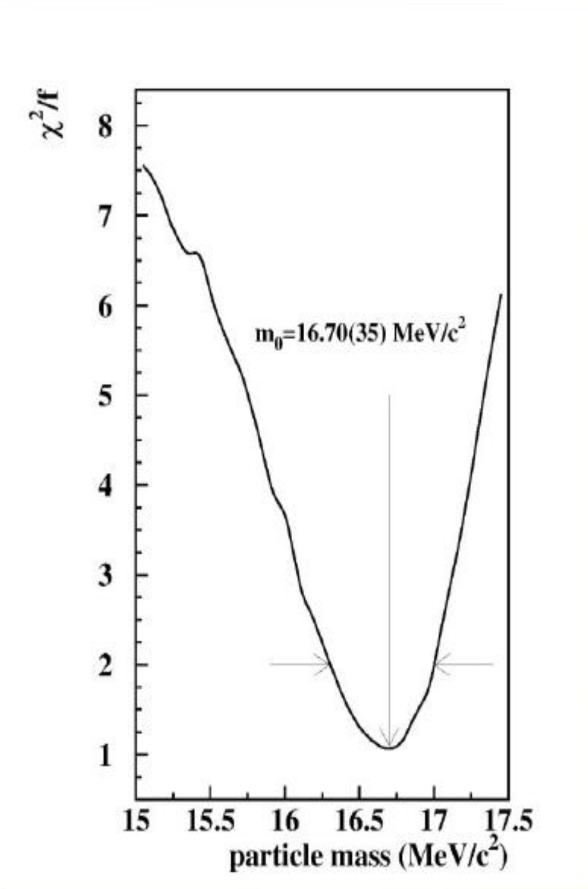
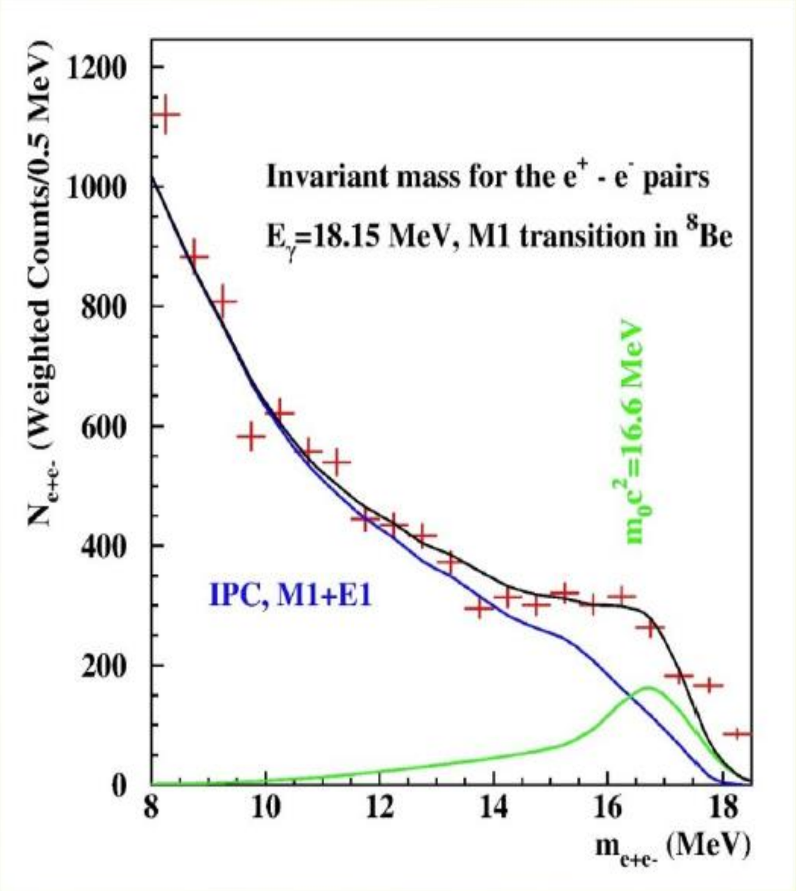


FIG. 2. *Measured total energy spectrum (a) and angular correlations (b) of the* e^+e^- *pairs created in the different transitions labelled in the figure, compared with the simulated angular correlations assuming E0 (from the* ^{16}O *peak) and M1+E1 mixed transitions from the other peaks.*

How can we understand the peak like deviation? Fitting the angular correlations







6.8 σ significance

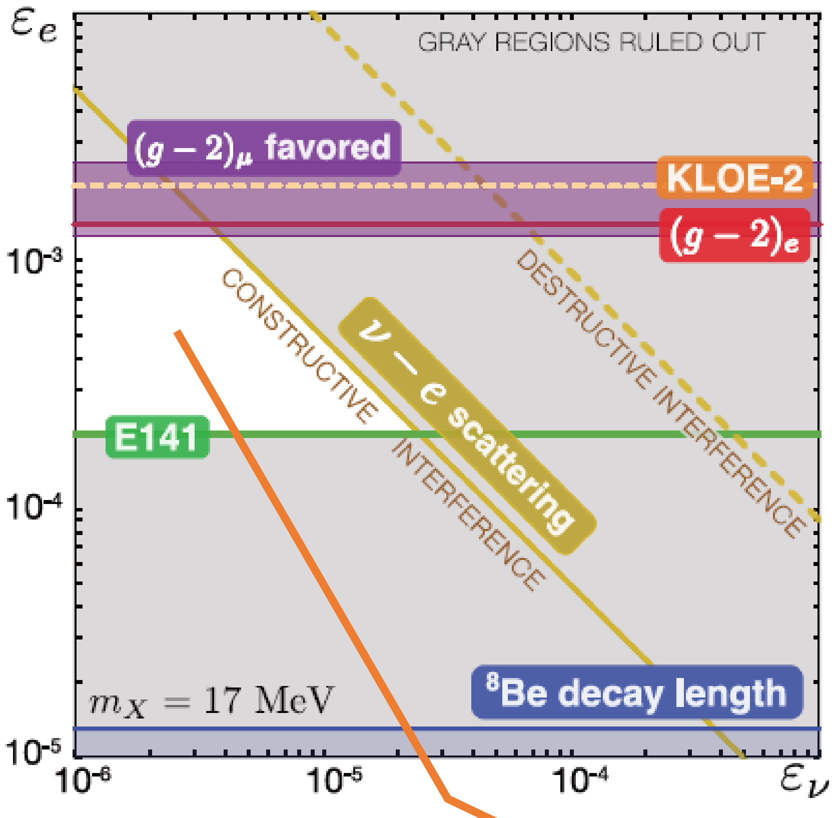
Interpretation [Feng et al.]

- Dark photon? NO! Bounds from NA48 from π^0 decay
- Scalar and pseudo-scalar interpretations also disfavoured
- Angular momentum and parity conservation => Protophobic J=1 gauge boson

$$
\begin{aligned}
|\varepsilon_n| &= (2-10)\times 10^{-3} \\
|\varepsilon_p| &\lesssim 1.2\times 10^{-3} \\
|\varepsilon_e| &= (0.2-1.4)\times 10^{-3} \\
\sqrt{|\varepsilon_e \varepsilon_\nu|} &\lesssim 3\times 10^{-4}\ .
\end{aligned}
$$

Prediction: a (smaller) bump should be seen also in the 17.6 MeV transition

arXiv:1608.03591

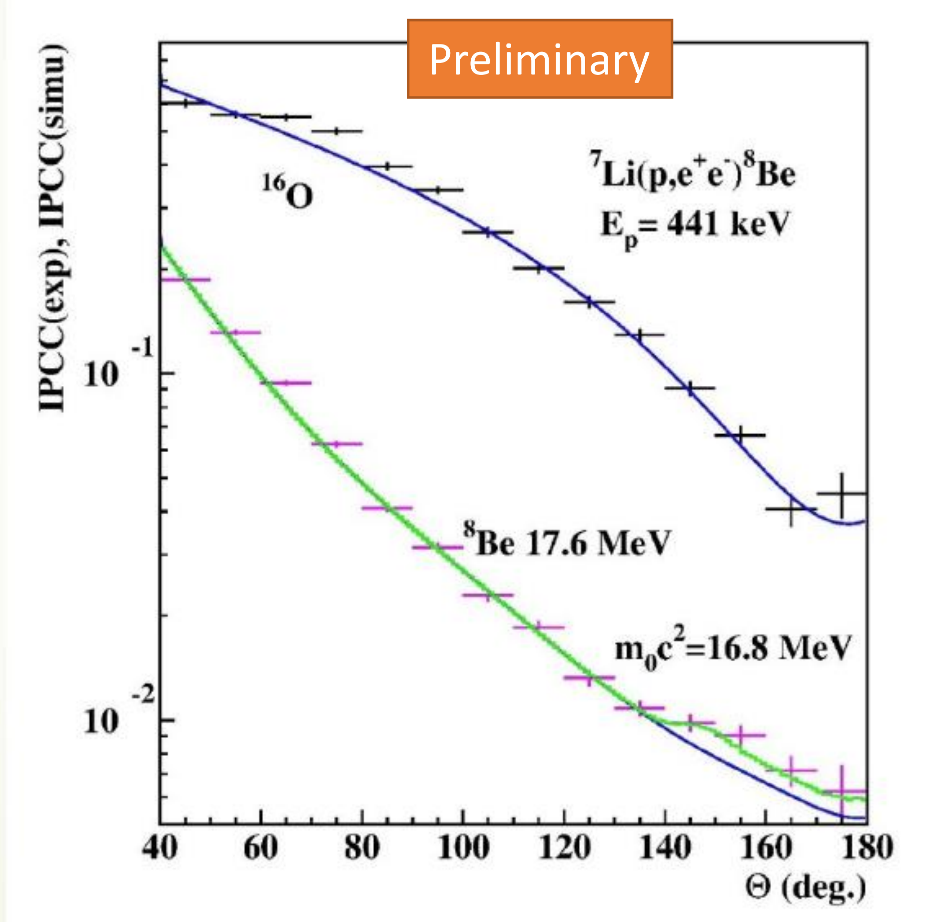


Allowed lepton-coupling Region

News from Atomki

- Upgraded accelerator-detector system

  - Beam current capability at 2 MV: 200 μA proton, 40 μA He



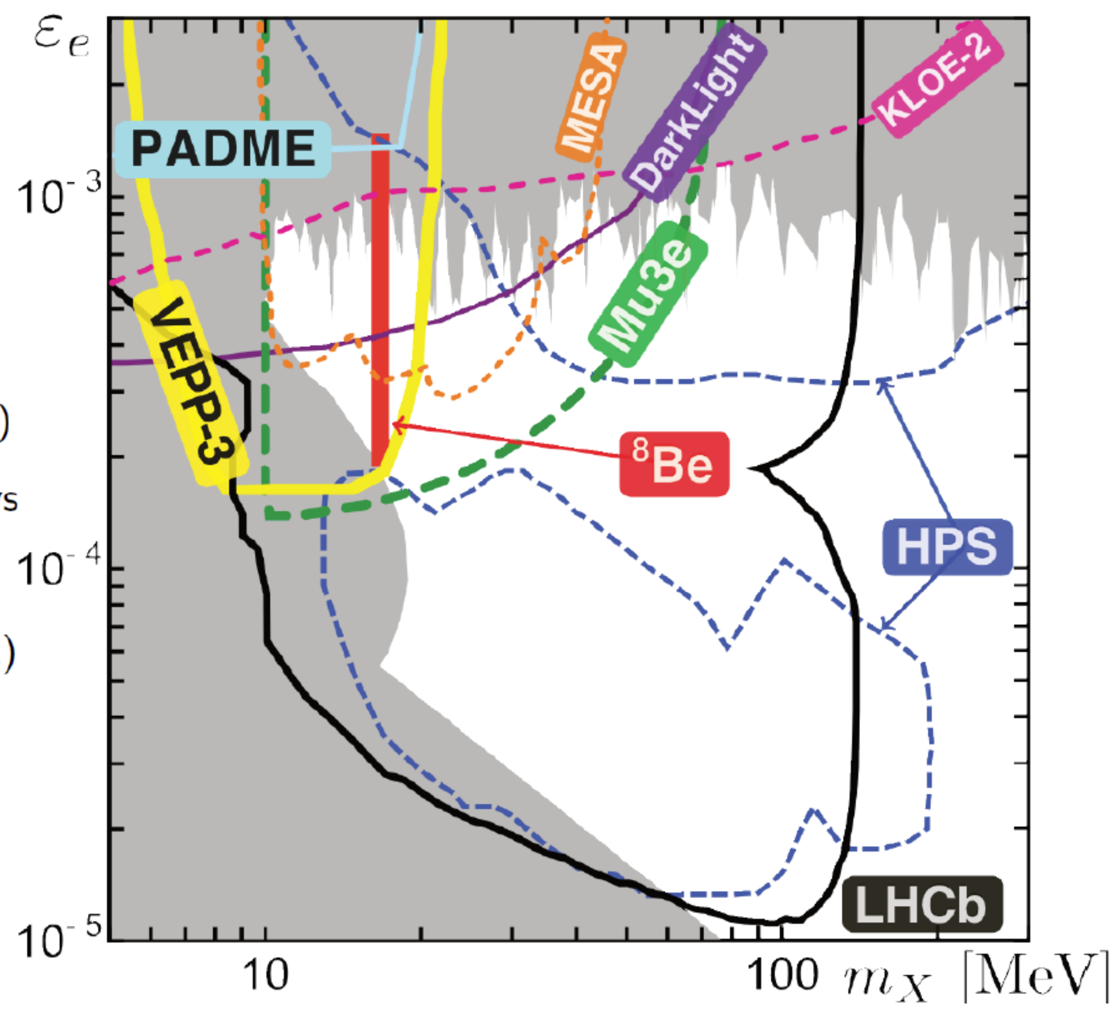
Outlook

IPC:

- verify ^{8}Be
- ^{10}B : 19.3 MeV
- ^{10}Be : 17.79 MeV

More Exp:

- TUNL (HIGS facility $_{\gamma\ Nuc}$)
- TREK@JPARC: K^+ Decays
- SHIP
- SeaQuest (Gardner & Holt)
- VdG UK
- BESIII (arXiv:1607.03970)



$$D^{*0} \to D^0 A', \quad A' \to e^+ e^-, \qquad (2)$$

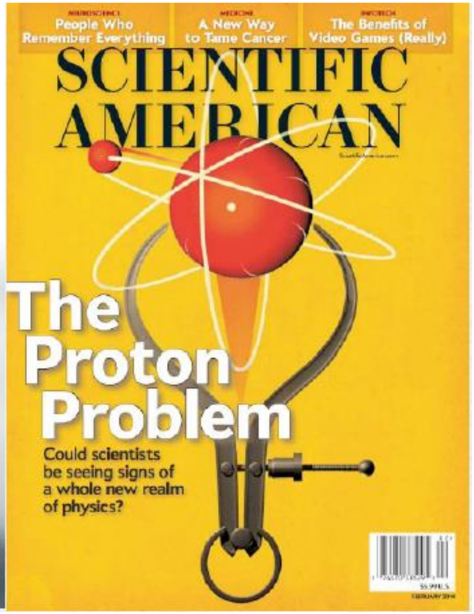
at the LHCb experiment during Run 3 of the LHC (scheduled for 2021–23).[3] The goal of this search is to explore the region between the prompt-A' and beam-dump limits for the range $m_{A'} \in [10, 100]$ MeV, which roughly includes $\epsilon^2 \in [10^{-10}, 10^{-6}]$. Reaching such small values of ϵ^2 is only possible for decays where the yield of the corresponding SM process (i.e. replacing A' with γ) is at least $\mathcal{O}(10^{10})$. Within the LHCb acceptance, over five trillion $D^{*0} \to D^0\gamma$ decays will be produced in proton-proton (pp) collisions at 14 TeV during Run 3, making this decay channel a suitable choice.

arXiv:1509.06765

Dark photons from charm mesons at LHCb

Philip Ilten,[1,*] Jesse Thaler,[2,†] Mike Williams,[1,‡] and Wei Xue[2,§]

[1] *Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*



Proton radius puzzle

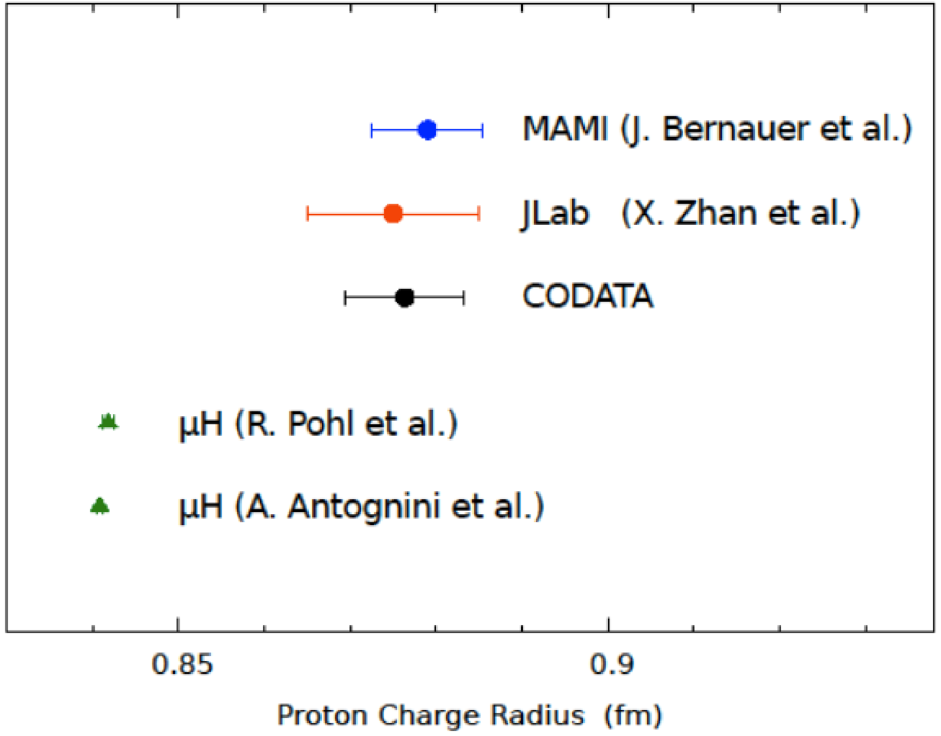
Marco Vanderhaeghen

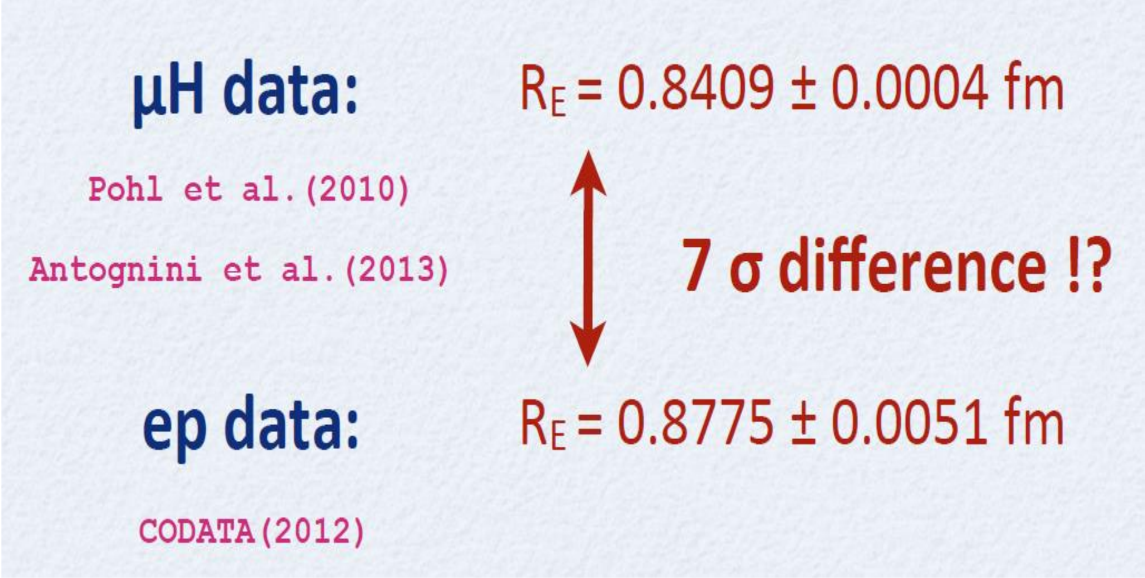
PRISMA

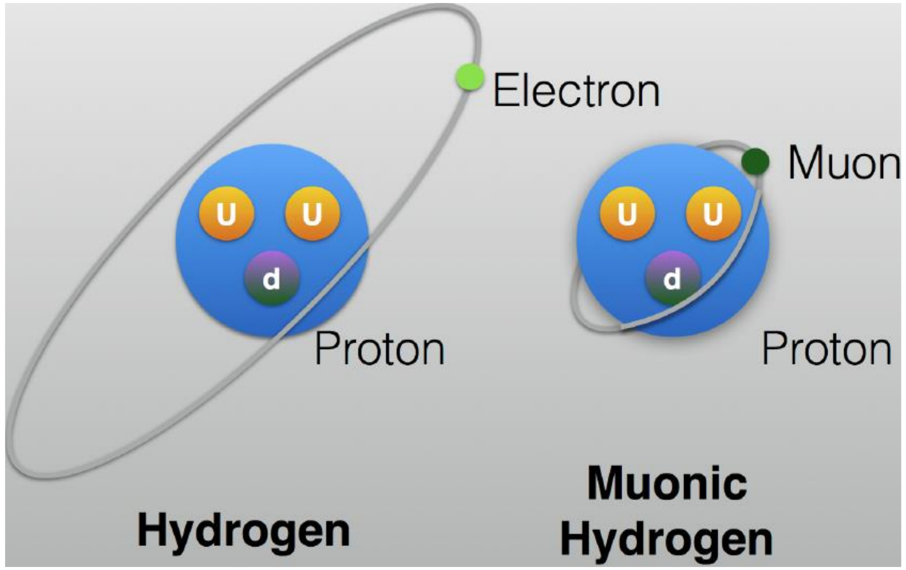
SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

The puzzle







The atomic Bohr radius is about 200 times smaller in μp than in H. Effects of the finite size of the proton on the muonic hydrogen energy levels are thus enhanced.

- Measurements with electron probes (atomic spectroscopy & ep scattering) 1% accuracy in good agreement among themselves despite different methods
- Measurements with muonic probes (muonic hydrogen spectroscopy) 0.1% accuracy

Proton radius from Hydrogen spectroscopy

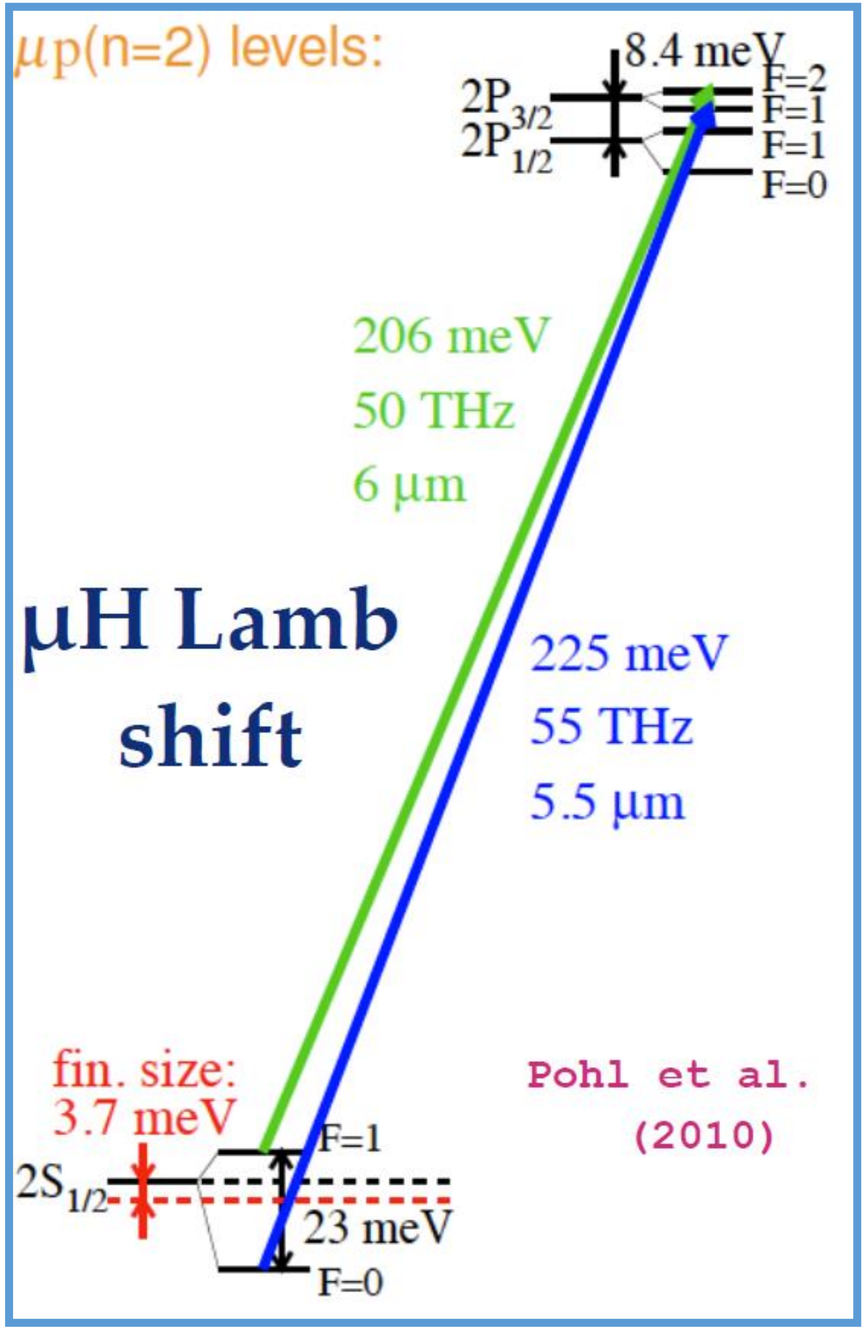
- S-states are shifted due to finite size of proton because the muon's wavefunction at the location of the proton is non-zero. P states are not significantly shifted.
- Fine (FS) [spin-orbit] and hyper-fine(HFS) [spin-spin]splitting of P-state can be accurately calculated
- Lamb-Shift (LS) , $2S_{1/2}$-$2P_{1/2}$ sensitive to proton charge radius R_E
- Two transitions are measured, among those allowed, that give largest signal. One can extract contemporarily ΔE_{LS} and ΔE_{HFS} of S-state

$$\Delta E_{LS} = 209.9779\ (49) - 5.2262\ R_E^{\,2} + 0.00913\ R^3_{(2)}\ \text{meV}$$

$R_E^{\,2}$ term ↓ 3.70 meV

$R^3_{(2)}$ term ↓ 0.026 meV

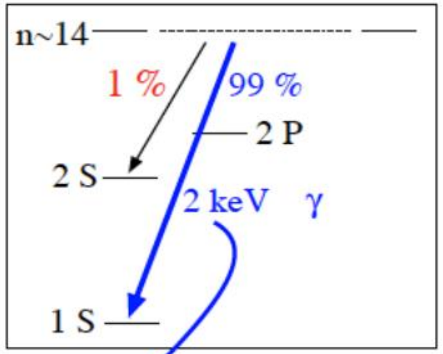
$O(\alpha^5)$ correction



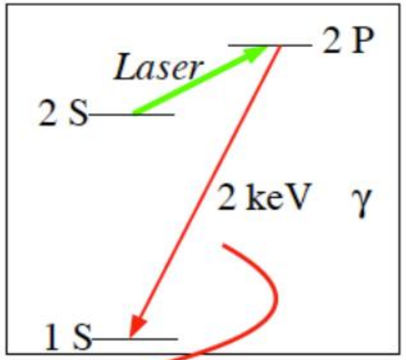
Principle of μH Lamb shift experiment

PSI experiment

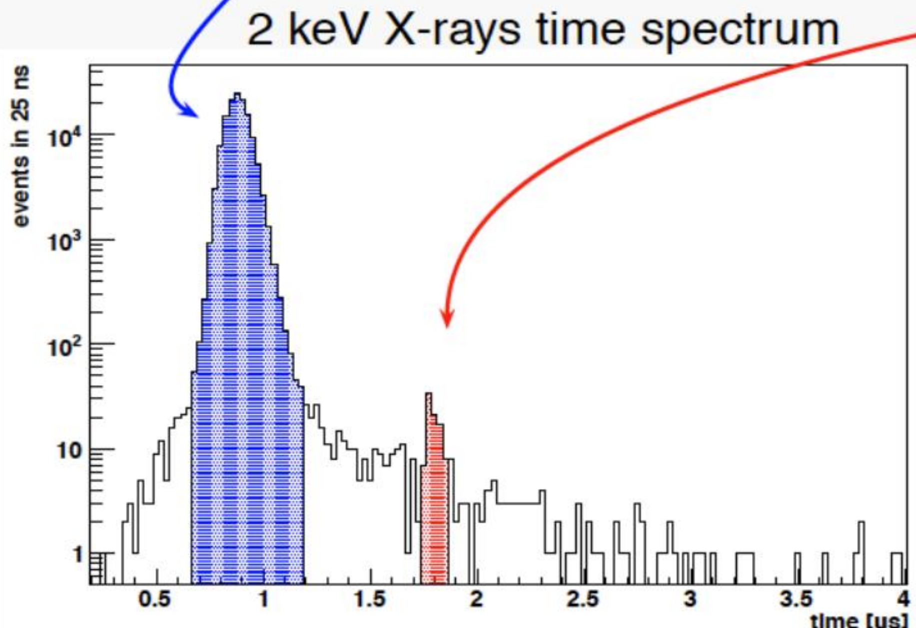
Pohl et al. (2010) Antognini et al. (2013)

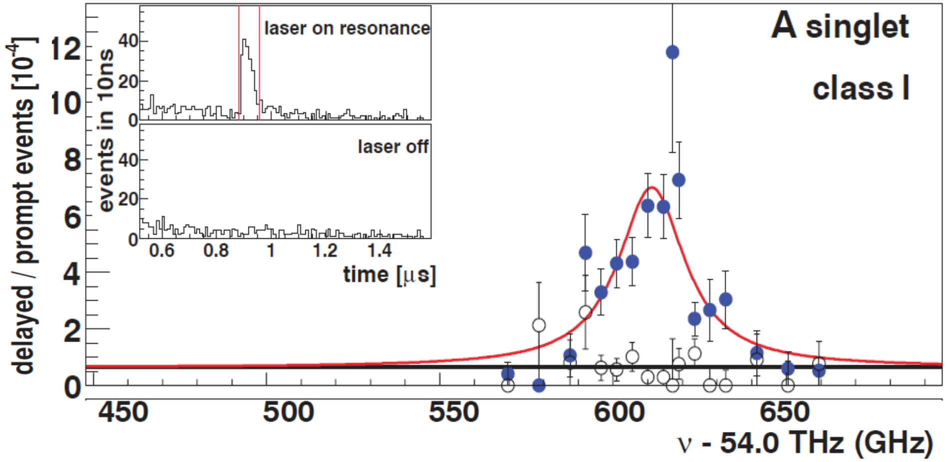


Muons are stopped in H_2 gas
Highly excited μp atoms (n ≈ 14) formed
~99% de-excite quickly to 1S
~1% populate the 2S state (τ~1 μs)



A laser pulse with a wavelength tunable illuminates the target, about 0.9 μs after the muon stop.
On-resonance light induces 2S → 2P transitions, which are immediately followed by 2P → 1S deexcitation via 1.9-keVx-ray emission





A resonance curve is obtained by measuring the number of 1.9-keV x-rays in time coincidence with the laser pulse (i.e., within a time window of 0.900 to 0.975 μs after the muon entry into the target)as a function of the laser wavelength.

Proton radius puzzle: what could it mean ?

$$\Delta E_{LS} = 209.9779\ (49) - 5.2262\ R_E^2 + 0.00913\ R^3_{(2)}\ \text{meV}$$

different radii

Lamb shift difference of ≈ 330 μeV

μH expt. wrong ?

eH theory wrong ?

μH theory wrong ?

- QED bound state corrections
- hadronic corrections
- check with different targets

eH expt. wrong ? -> R_∞ wrong

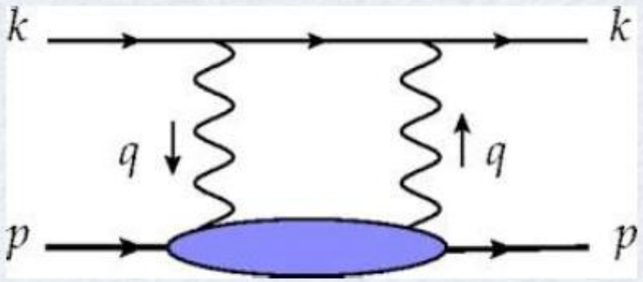
+ **ep** scattering wrong ?

- radiative corrections
- 2γ corrections
- low Q^2 extrapolation

new physics ?

Lamb-shift corrections

- QED corrections calculated up to level of 0.005 meV or smaller << 0.3 meV
- Hadronic correction from TPE (two photon exchange)



largest theoretical uncertainty

total hadronic correction on Lamb shift

$\Delta E_{(2P-2S)} = (33 \pm 2)\ \mu eV$

...or about 10% of needed correction

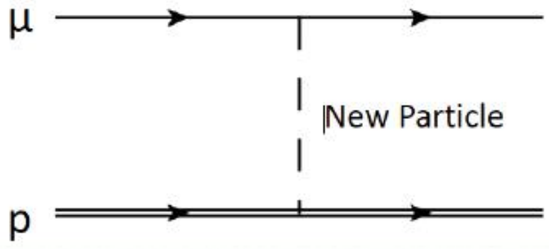
(μeV)	Pachucki [9]	Martynenko [10]	Nevado and Pineda [11]	Carlson and Vanderhaeghen [12]	Birse and McGovern [13]	Gorchtein et al. [14]	LO-BχPT [this work]
$\Delta E_{2S}^{(subt)}$	1.8	2.3	–	5.3 (1.9)	4.2 (1.0)	−2.3 (4.6)[a]	−3.0
$\Delta E_{2S}^{(inel)}$	−13.9	−13.8	–	−12.7 (5)	−12.7 (5)[b]	−13.0 (6)	−5.2
$\Delta E_{2S}^{(pol)}$	−12 (2)	−11.5	−18.5	−7.4 (2.4)	−8.5 (1.1)	−15.3 (5.6)	$-8.2(^{+1.2}_{-2.5})$

[a] Adjusted value; the original value of Ref. [14], +3.3, is based on a different decomposition into the 'elastic' and 'polarizability' contributions
[b] Taken from Ref. [12]

[9] K. Pachucki, Phys. Rev. A **60**, 3593 (1999).
[10] A. P. Martynenko, Phys. Atom. Nucl. **69**, 1309 (2006).
[11] D. Nevado and A. Pineda, Phys. Rev. C **77**, 035202 (2008).
[12] C. E. Carlson and M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).
[13] M. C. Birse and J. A. McGovern, Eur. Phys. J. A **48**, 120 (2012).
[14] M. Gorchtein, F. J. Llanes-Estrada and A. P. Szczepaniak, Phys. Rev. A 87, **052501** (2013).

[LO-BχPT] Alarcon, Lensky, Pascalutsa, EPJC (2014) 74:2852

New physics?



invoking exchange of

hypothetical light boson

➡ new **muonic forces** ?

lepton universality-violating models

challenge: new physics must also

respect $(g\text{-}2)_\mu$ discrepancy

Tucker-Smith Yavin (2010)

Barger,Chiang, Keung, Marfiata (2011)

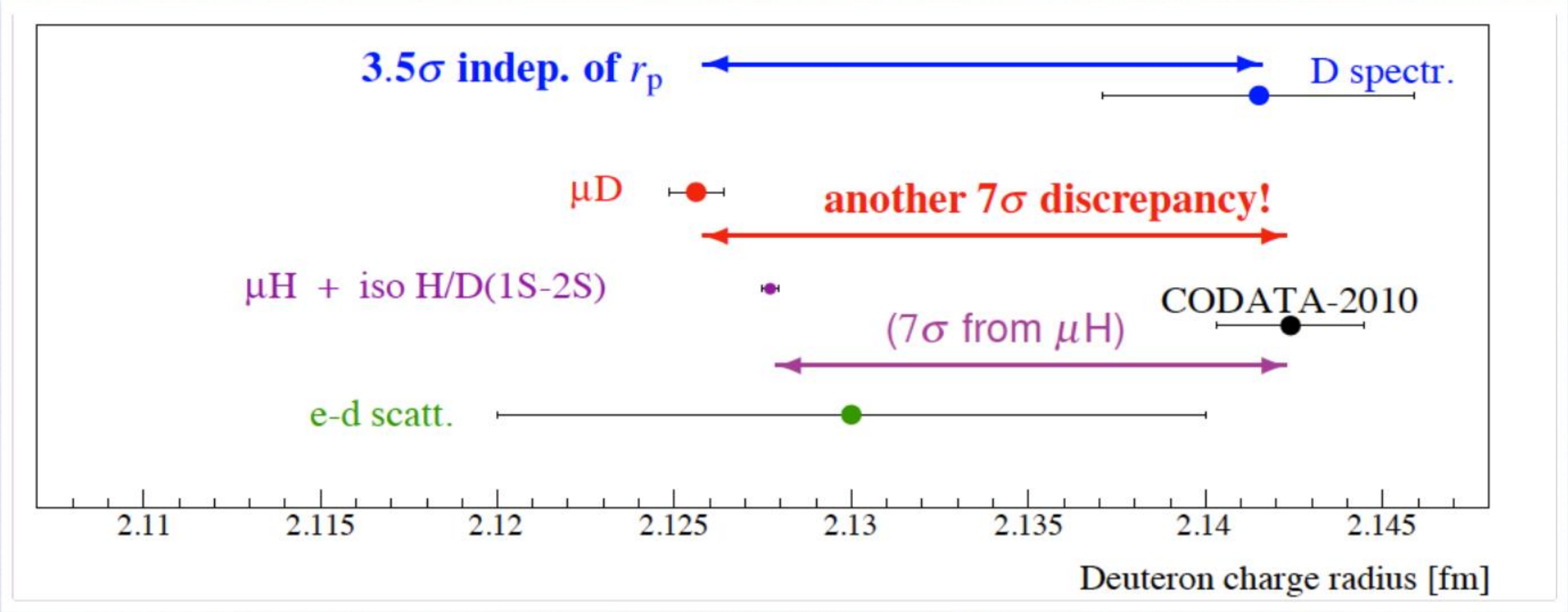
μD Lamb shift experiment

- H/D isotope shift (1S - 2S): $r_d{}^2 - r_p{}^2 =$ 3.82007 (65) fm^2 Parthey et al. (2010)

- CODATA 2010: r_d = 2.14240 (210) fm

- r_p from μH + isotope shift : r_d = 2.12771 (22) fm

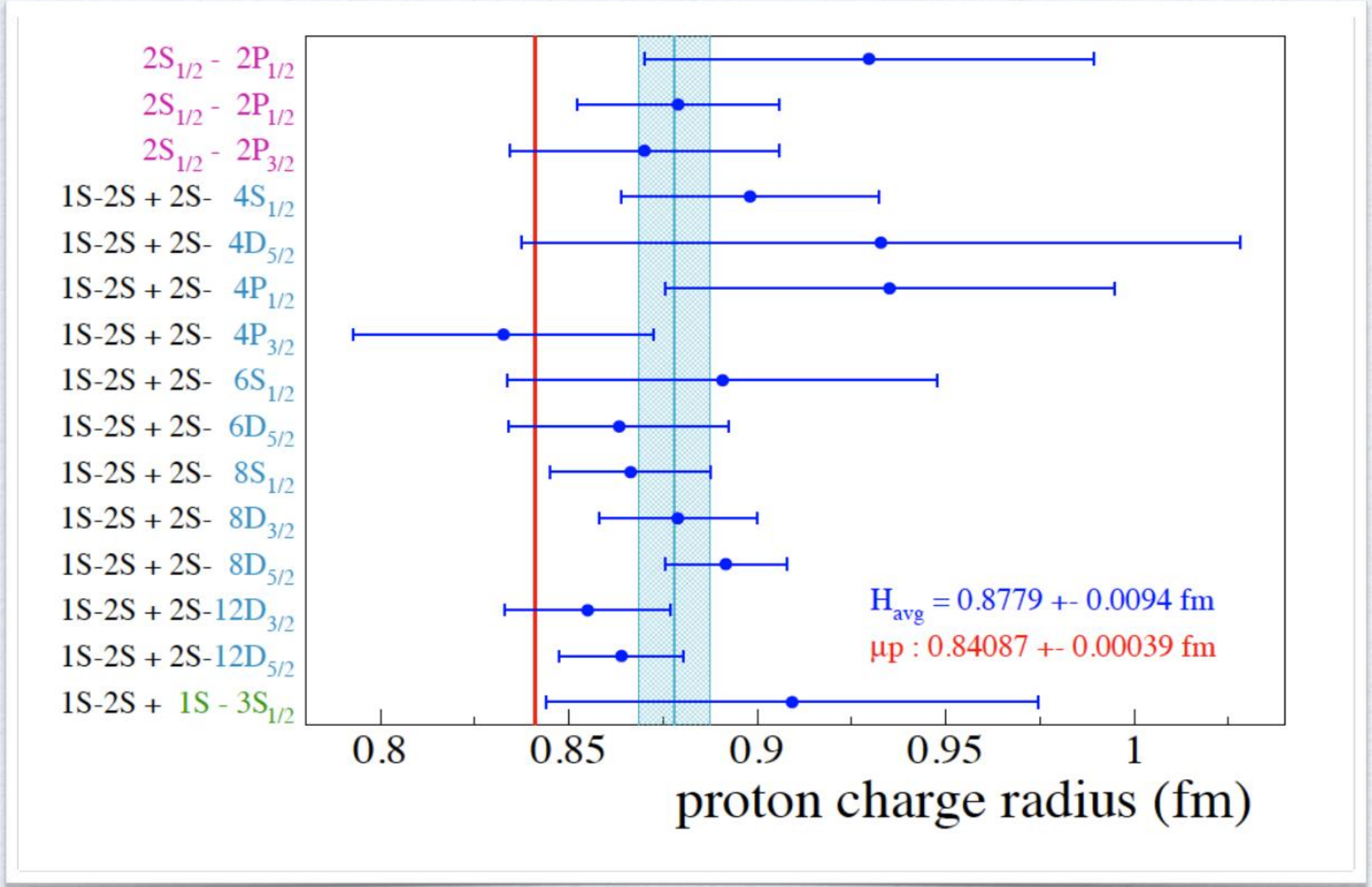
- new μD Lamb shift @ PSI: r_d = 2.12562 (13)$_{theo}$ (77)$_{theo}$ fm Pohl et al., Science 353,417 (2016)



- electronic D (r_p indep.): r_d = 2.14150 (450) fm ← 3.5 σ Pohl et al. (2016)

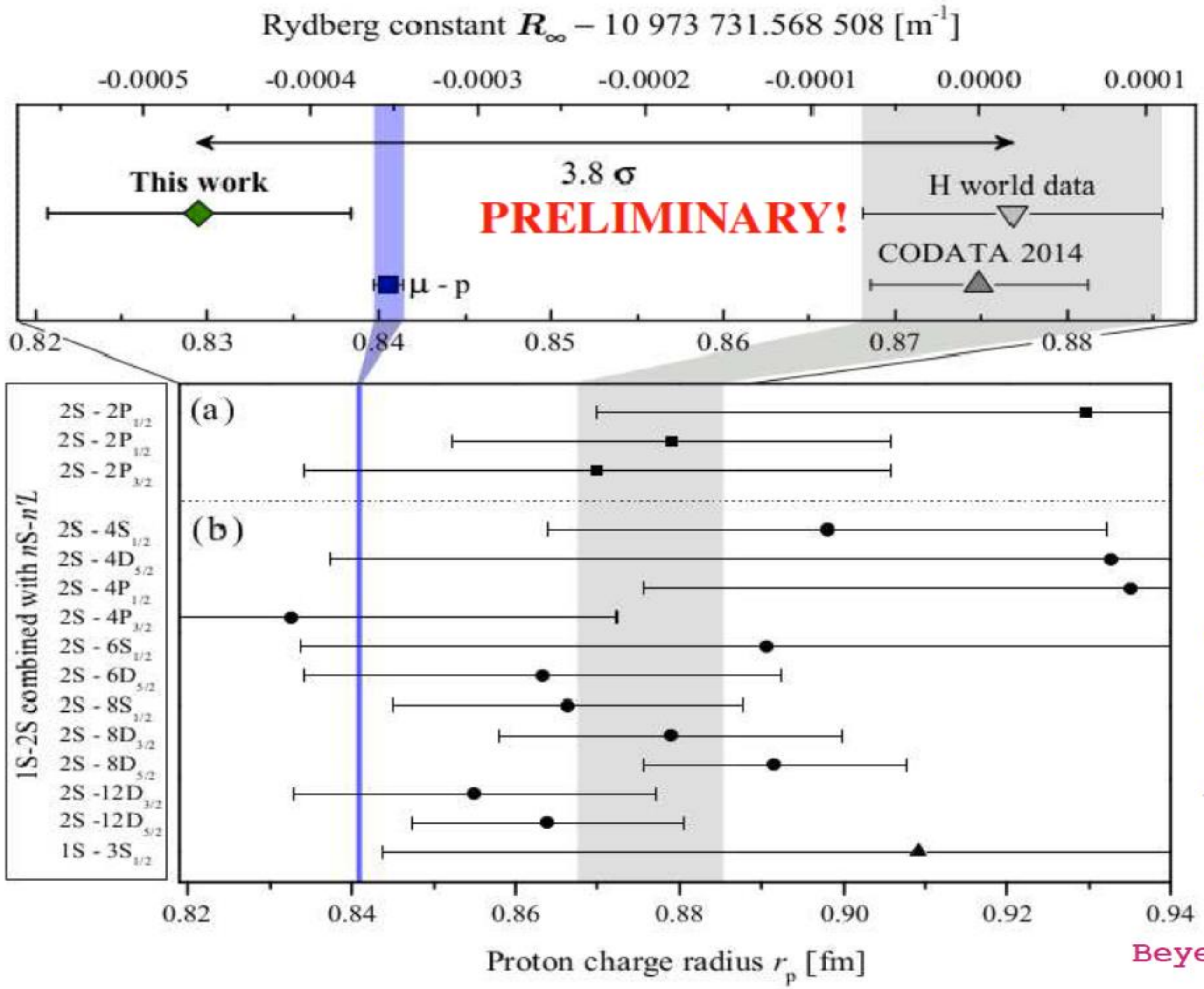
- improved radius measurement from e-d scattering was performed @ MAMI (2014)

Proton radius from electronic H spectroscopy



- < 1% uncertainty comes from average of 15 measurements
- large advances in instrumentation allow for new measurements with individual error better than the present average

new Hydrogen 2S - 4P experiment



slide from R. Pohl

Garching H group:

Beyer, Maisenbacher, Matveev, Yost, Kolachevsky, RP, Udem, *et al.*

$2S \rightarrow 4P_{1/2}$ and $4P_{3/2}$

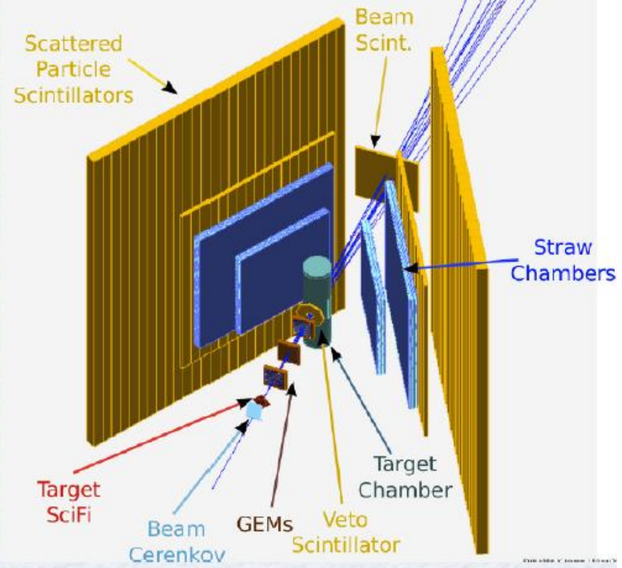
cold H(2S) beam optically excited ($1S \rightarrow 2S$)

$\Delta\nu \sim 2\,\mathrm{kHz} \quad \equiv \Gamma/10'000$

Beyer, Pohl et al. (submitted)

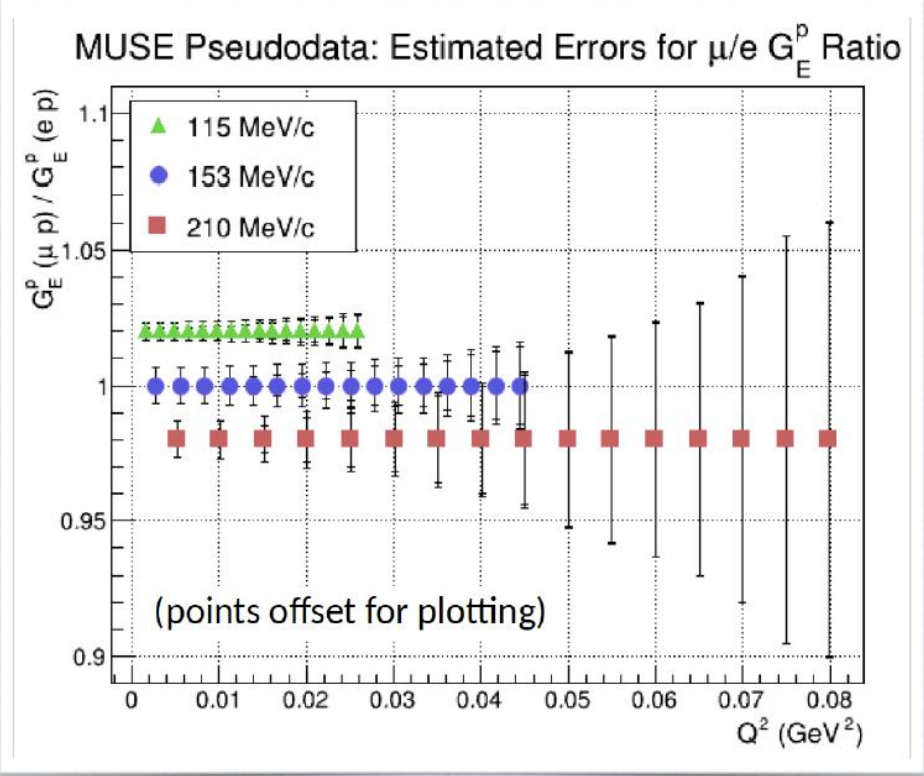
➡ new 2S-2P Lamb shift measurement presently under analysis Hessels

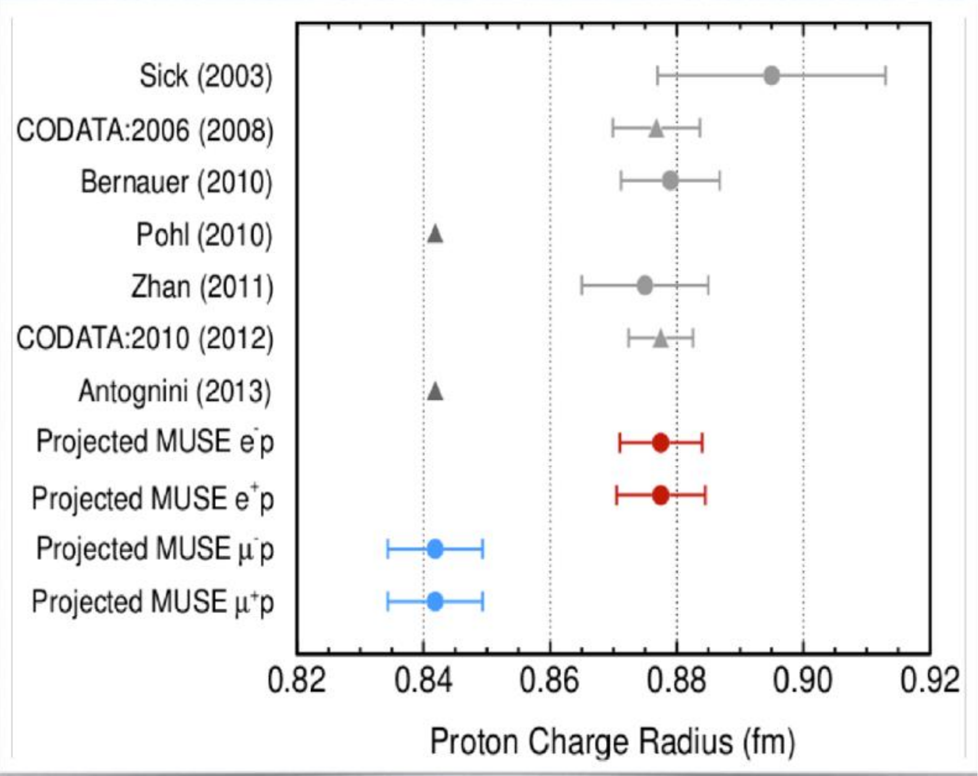
MUSE@PSI experiment



simultaneous measurement of ***e*** and **μ**

elastic scattering absolute cross sections





production run planned 2018 - 2019

Outlook: proton radius puzzle

- precision muonic atom spectroscopy has shifted precision frontier

- generated a large exp/theo activity
  - to scrutinize result
  - to improve on accuracy of hadronic corrections

- what can be expected ?

  $\mu\,^3He^+$, $\mu\,^4He^+$ (under analysis)

  eH Lamb shift (under analysis)

  new e^- scattering (in progress)

  μ^- scattering (~ 1-2 years)

stay tuned