PSI Colloquium   Villigen, 26th October 2017

g-2 of the muon: the next round

Thomas Teubner

- Introduction
- a_μ^{SM} : overview and update on hadronic contributions
- Status of the new experiments
- BSM?

Introduction & motivation:

SM `too' successful, but incomplete:

- ν masses (small) and mixing point towards some high-scale (GUT) physics
- Need to explain dark matter & dark energy
- Not enough CP violation in the SM for matter-antimatter asymmetry
- And: $a_\mu^{EXP} - a_\mu^{SM}$ at ~ 3-4 σ plus other deviations e.g. in the flavour sector

Is there a common New Physics (NP) explanation for all these puzzles?

- Uncoloured leptons are particularly clean probes to establish and constrain/distinguish NP, complementary to high energy searches at the LHC

- No direct signals for NP from LHC so far:
  - some models like CMSSM are in trouble already when trying to accommodate LHC exclusion limits and to solve muon g-2
  - is there any TeV scale NP out there? Or unexpected new low scale physics?

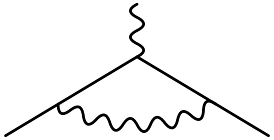
The key may be provided by low energy observables incl. precision QED, EDMs, LFV.

Introduction

- Dirac equation (1928): g is 2 for fundamental fermions $\vec{\mu} = g\frac{Qe}{2m}\vec{s}$
- 1947: small deviations from predictions in hydrogen and deuterium hyperfine structure; Kusch & Foley propose explanation with g_s= 2.00229 ± 0.00008
- 1948: Schwinger calculates the famous radiative correction:

  that g = 2 (1+a), with

  a = (g-2)/2 = α/(2π) = 0.001161



This explained the discrepancy and was a crucial step in the development of perturbative QFT and QED

`` If you can't join 'em, beat 'em "

- The anomaly a (Anomalous Magnetic Moment) is from the Pauli term:

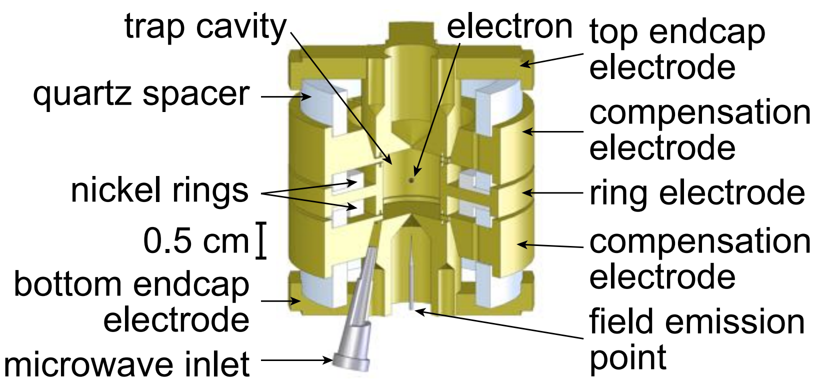
$$\delta\mathcal{L}_{\rm eff}^{\rm AMM} = -\frac{Qe}{4m}a\bar{\psi}(x)\sigma^{\mu\nu}\psi(x)F_{\mu\nu}(x)$$

This is a dimension 5 operator, non-renormalisable and hence not part of the fundamental (QED) Lagrangian. But it occurs through radiative corrections and is calculable in perturbation theory.

Magnetic Moments: a_e vs. a_μ

a_e = 1 159 652 180.73 (0.28) 10^{-12} [0.24ppb]
Hanneke, Fogwell, Gabrielse, PRL 100(2008)120801

a_μ = 116 592 089(63) 10^{-11} [0.54ppm]
Bennet et al., PRD 73(2006)072003



one electron quantum cyclotron

- a_e^{EXP} more than 2000 times more precise than a_μ^{EXP}, but for e^- loop contributions come from very small photon virtualities, whereas muon `tests' higher scales
- dimensional analysis: sensitivity to NP (at high scale Λ_{NP}): $a_\ell^{NP} \sim \mathcal{C}\, m_\ell^2/\Lambda_{NP}^2$

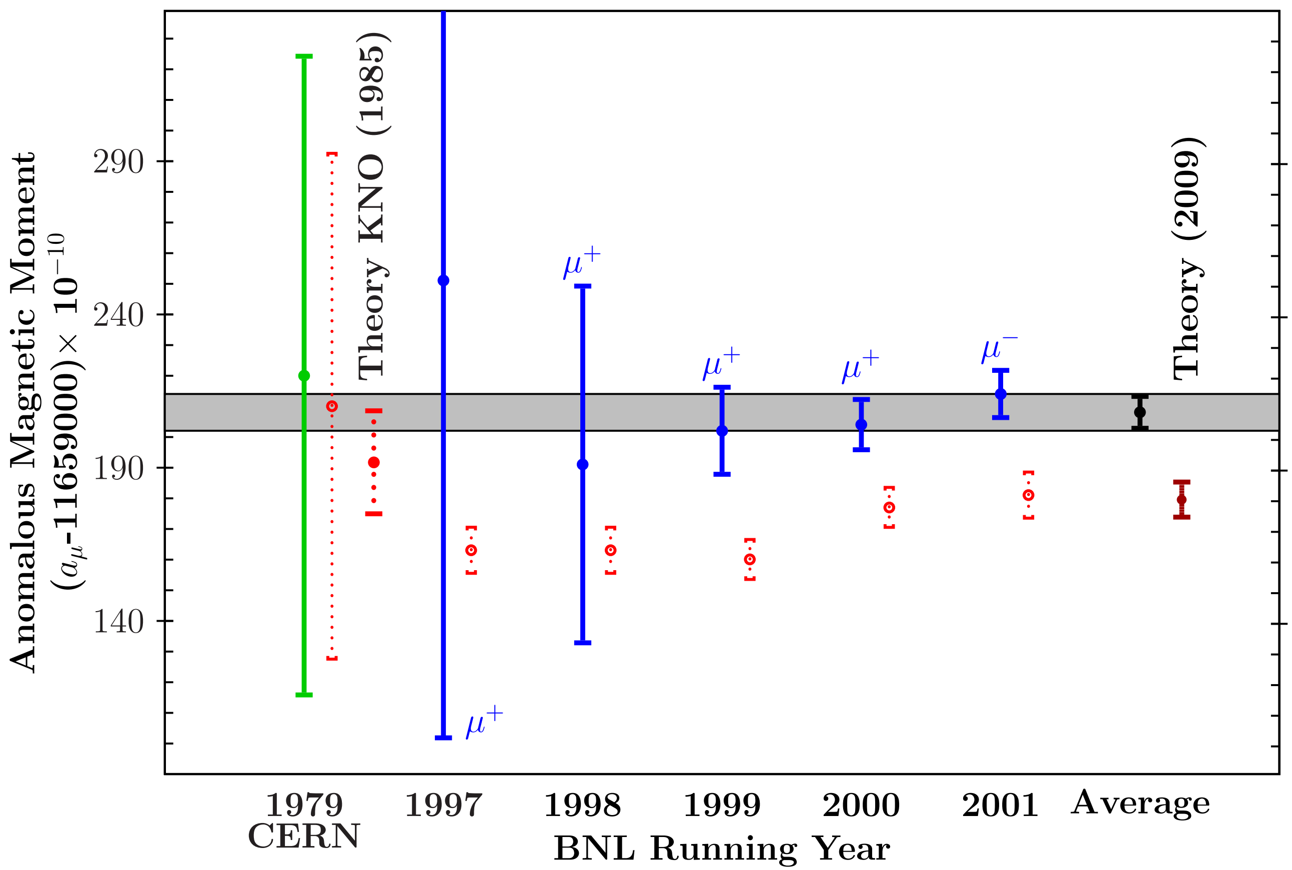
→ μ wins by $m_\mu^2/m_e^2 \sim 43000$ for NP, but a_e provides best determination of α

a_μ: back to the future

- CERN started it nearly 40 years ago
- Brookhaven delivered 0.5ppm precision
- E989 at FNAL and J-PARC's g-2/EDM experiments are happening and should give us certainty

g-2 history plot and book motto from Fred Jegerlehner:

`The closer you look the more there is to see'



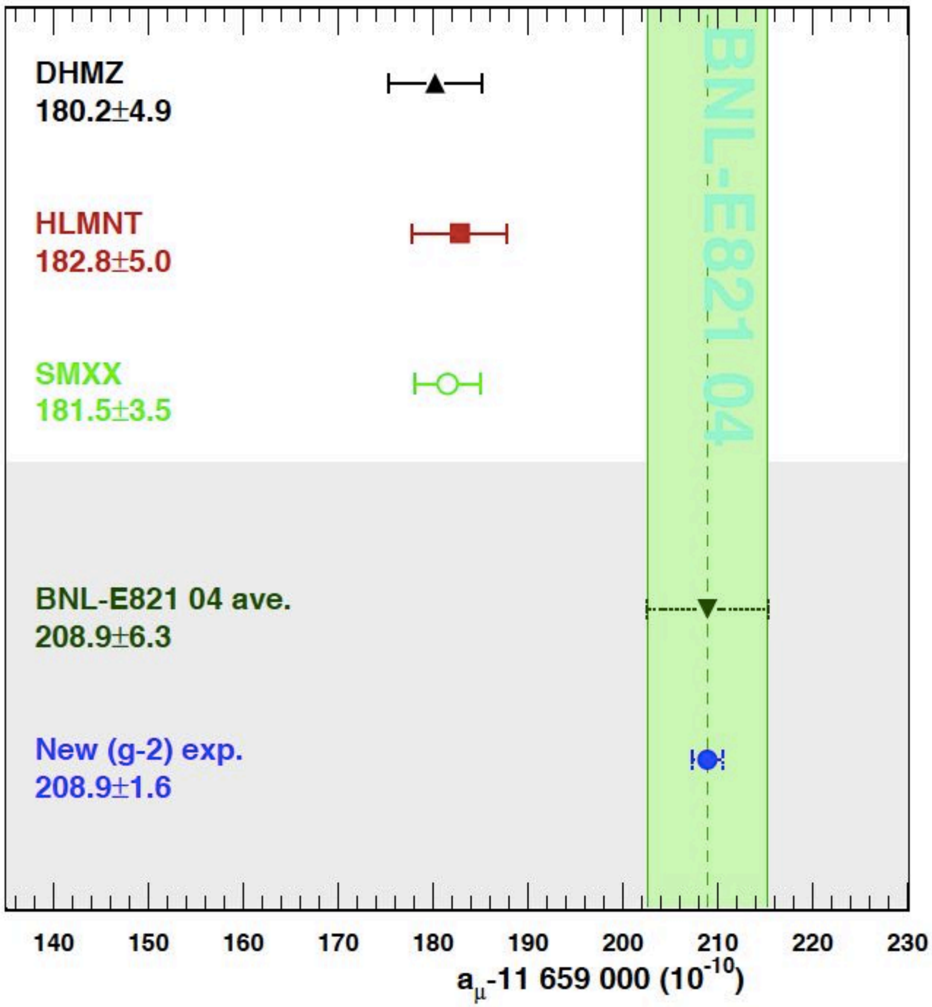
a_μ: Status and future projection → charge for SM TH

$$a_\mu = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm hadronic} + a_\mu^{\rm NP?}$$

- if mean values stay and with no a_μ^{SM} improvement: 5σ discrepancy

- if also EXP+TH can improve a_μ^{SM} \`as expected' (consolidation of L-by-L on level of Glasgow consensus, about factor 2 for HVP): NP at 7-8σ

- or, if mean values get closer, very strong exclusion limits on many NP models (extra dims, new dark sector, xxxSSSM)...

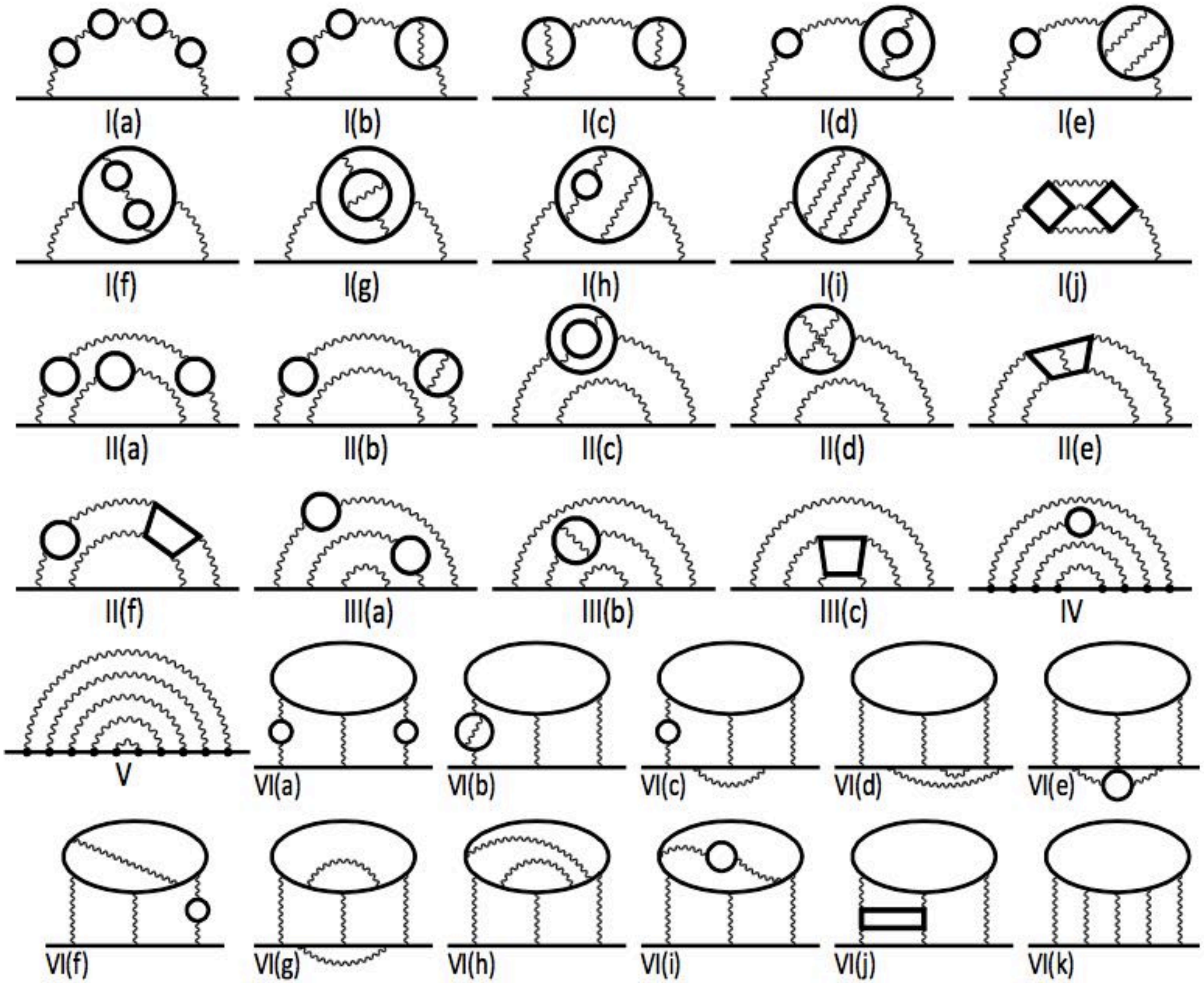


a_μ^{QED} Kinoshita et al.: g-2 at 1, 2, 3, 4 & 5-loop order

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRLs, 2012)

A triumph for perturbative QFT and computing!

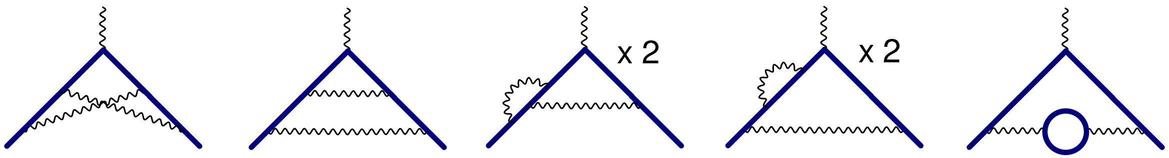
10th
12672
diagrams



- code-generating code, including
- renormalisation
- multi-dim. numerical integrations

a_μ^{QED}

- Schwinger 1948: 1-loop a = (g-2)/2 = $\alpha/(2\pi)$ = 116 140 970 × 10^{-11}
- 2-loop graphs:



- 72 3-loop and 891 4-loop diagrams …
- Kinoshita et al. 2012: 5-loop completed numerically (12672 diagrams):

  a_μ^{QED} = 116 584 718.951 (0.009) (0.019) (0.007) (0.077) × 10^{-11}

  errors from: lepton masses, 4-loop,   5-loop,   α from ^{87}Rb

- QED extremely accurate, and the series is stable: $a_\mu^{\rm QED} = C_\mu^{2n} \sum_n \left(\frac{\alpha}{\pi}\right)^n$

$$C_\mu^{2,4,6,8,10} = 0.5,\ 0.765857425(17),\ 24.05050996(32),\ 130.8796(63),\ 753.29(1.04)$$

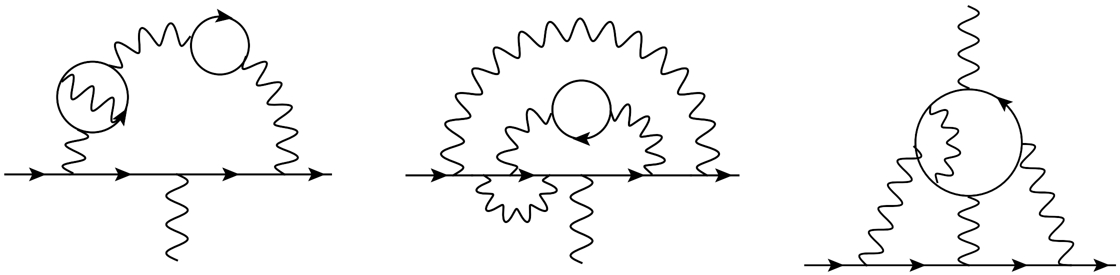
- Could a_μ^{QED} still be wrong?
  Some classes of graphs known analytically (Laporta; Aguilar, Greynat, deRafael),

a_μ^{QED}

- … but 4-loop and 5-loop rely heavily on numerical integrations

- Recently several independent checks of 4-loop and 5-loop diagrams:
  Baikov, Maier, Marquard [NPB 877 (2013) 647], Kurz, Liu, Marquard, Smirnov AV+VA, Steinhauser [NPB 879 (2014) 1, PRD 92 (2015) 073019, 93 (2016) 053017]:

- all 4-loop graphs with internal lepton loops now calculated independently, e.g.



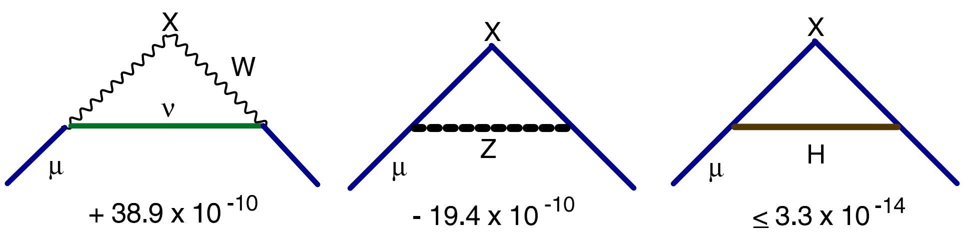
(from Steinhauser et al., PRD 93 (2016) 053017)

- 4-loop universal (massless) term calculated semi-analytically to 1100 digits (!) by Laporta, arXiv:1704.06996, also new numerical results by Volkov, 1705.05800

- all agree with Kinoshita et al.'s results, so QED is on safe ground ✓

a_μ Electro-Weak

- Electro-Weak 1-loop diagrams:



$a_\mu^{EW(1)} = 195{\times}10^{-11}$

- known to 2-loop (1650 diagrams, the first full EW 2-loop calculation):
  Czarnecki, Krause, Marciano, Vainshtein; Knecht, Peris, Perrottet, de Rafael

- agreement, a_μ^{EW} relatively small, 2-loop relevant: $a_\mu^{EW(1+2\ loop)} = (154{\pm}2){\times}10^{-11}$

- Higgs mass now known, update by Gnendiger, Stoeckinger, S-Kim,
  PRD 88 (2013) 053005

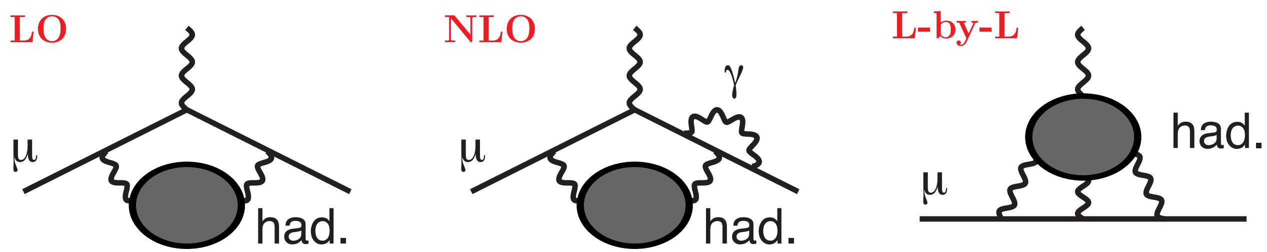
$$a_\mu^{EW(1+2\ loop)} = (153.6{\pm}1.0){\times}10^{-11}$$ ✓

compared with $a_\mu^{QED} = 116\,584\,718.951\ (80)\ {\times}10^{-11}$

a_μ^{hadronic}

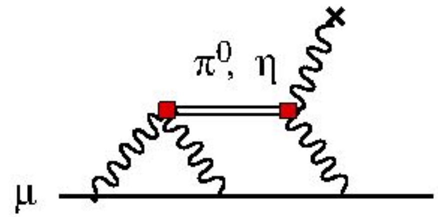
- Hadronic: non-perturbative, the limiting factor of the SM prediction ✗ ➠ ✓

$$a_\mu^{\rm had} = a_\mu^{\rm had,VP\ LO} + a_\mu^{\rm had,VP\ NLO} + a_\mu^{\rm had,Light-by-Light}$$



$a_\mu^{\text{had, L-by-L}}$: Light-by-Light

- L-by-L: $\gamma \to hadrons \to \gamma^*\gamma^*\gamma^*$ non-perturbative, impossible to fully measure ✗
- so far use of model calculations, based on large N_c limit, Chiral Perturbation Theory, plus short distance constraints from OPE and pQCD
- meson exchanges and loops modified by form factor suppression, but with limited experimental information:



- in principle off-shell form-factors (π^0, η, η′, 2π → $\gamma^* \gamma^*$) needed
- at most possible, directly experimentally: π^0, η, η′, 2π → $\gamma\gamma^*$
- additional quark loop, pQCD matching; theory not fully satisfying conceptually ☹
- several independent evaluations, different in details, but good agreement for the leading N_c (π^0 exchange) contribution, differences in sub-leading bits
- mostly used recently:
  - \`Glasgow consensus’ by Prades+deRafael+Vainshtein:

    $$a_\mu^{\text{had,L-by-L}} = (105 \pm 26) \times 10^{-11}$$

  - compatible with Nyffeler’s $a_\mu^{\text{had,L-by-L}} = (116 \pm 39) \times 10^{-11}$

$a_\mu^{\text{had, L-by-L}}$: Overview from A Nyffeler @ Frascati 2016

HLbL scattering: Summary of selected results for $a_\mu^{\mathrm{HLbL}} \times 10^{11}$

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN
π^0, η, η'	85±13	82.7±6.4	83±12	114±10	–	114±13	99 ± 16
axial vectors	2.5±1.0	1.7±1.7	–	22±5	–	15±10	22±5
scalars	−6.8±2.0	–	–	–	–	−7±7	−7±2
π, K loops	−19±13	−4.5±8.1	–	–	–	−19±19	−19±13
π,K loops +subl. N_C	–	–	–	0±10	–	–	–
quark loops	21±3	9.7±11.1	–	–	–	2.3 (c-quark)	21±3
Total	83±32	89.6±15.4	80±40	136±25	110±40	105 ± 26	116 ± 39

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, AN '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = AN '09, JN = Jegerlehner, AN '09

- Pseudoscalar-exchanges dominate numerically. Other contributions not negligible. Cancellation between π, K-loops and quark loops !
- Note that recent reevaluations of axial vector contribution lead to much smaller estimates than in MV: $a_\mu^{\mathrm{HLbL;axial}} = (8 \pm 3) \times 10^{-11}$ (Pauk, Vanderhaeghen '14; Jegerlehner '14, '15). This would shift central values of compilations downwards:
  ➔ $a_\mu^{\mathrm{HLbL}} = (98 \pm 26) \times 10^{-11}$ (PdRV) and $a_\mu^{\mathrm{HLbL}} = (102 \pm 39) \times 10^{-11}$ (N, JN).
- PdRV: Analyzed results obtained by different groups with various models and suggested new estimates for some contributions (shifted central values, enlarged errors). Do not consider dressed light quark loops as separate contribution. Added all errors in quadrature !
- N, JN: New evaluation of pseudoscalar exchange contribution imposing new short-distance constraint on off-shell form factors. Took over most values from BPP, except axial vectors from MV. Added all errors linearly.

$a_\mu^{\text{had, L-by-L}}$: Light-by-Light Prospects

- Transition FFs can be measured by KLOE-2 and BESIII using small angle taggers:

  $e^+e^- \to e^+e^-\gamma\gamma^* \to \pi^0, \eta, \eta', 2\pi$ expected to constrain leading pole contributions from π, η, η′ to ~ 15% Nyffeler, arXiv:1602.03398

- or calculate on the lattice: $\pi^0 \to \gamma^* \gamma^*$ Gerardin, Meyer, Nyffeler, arXiv:1607.08174

- Breakthrough with new dispersive approaches

  Pauk, Vanderhaeghen, PRD 90 (2014) 113012

  Colangelo, Hoferichter, Procura, Stoffer, JHEP 1704 (2017) 161

  - dispersion relations formulated for the general HLbL tensor or for a_μ directly
  - allowing to constrain/calculate the HLbL contributions from data
  - e.g. Colangelo et al. have first results for the π-box contribution from data for $F_V^\pi(q^2)$

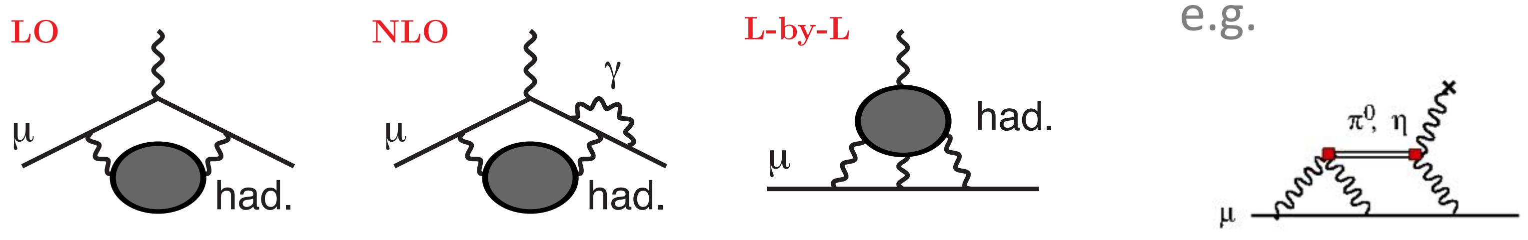
- Ultimately: `First principles' full prediction from lattice QCD+QED
  - several groups: USQCD, UKQCD, ETMC, … much increased effort and resources
  - within ~ 3 years a 10% estimate may be possible, 30% would already be useful
  - first results encouraging, proof of principle already exists

- We are already able to defend/confirm the error estimate of the Glasgow consensus, and probably bring it down significantly ✓

a_μ^{hadronic} : L-by-L one-page summary

- Hadronic: non-perturbative, the limiting factor of the SM prediction ✗ ➠ ✓

$$a_\mu^{\rm had} = a_\mu^{\rm had,VP\ LO} + a_\mu^{\rm had,VP\ NLO} + a_\mu^{\rm had,Light-by-Light}$$



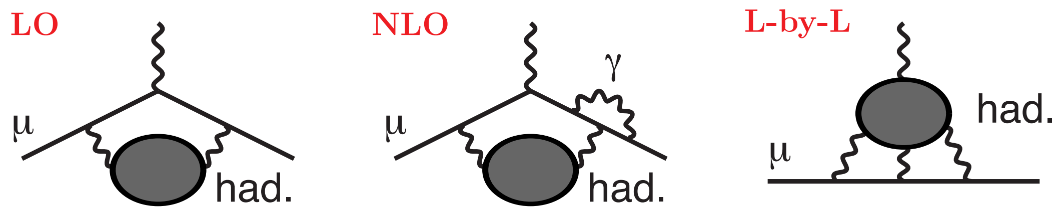
- L-by-L: - so far use of model calculations (+ form-factor data and pQCD constraints),
  - also good news from lattice QCD, and
  - new dispersive approaches

- Below I will use the `updated Glasgow consensus':
  (original by Prades+deRafael+Vainshtein) $a_\mu^{\text{had,L-by-L}} = (98 \pm 26) \times 10^{-11}$

- so far no indication for a big surprise
- expect that L-by-L prediction can be improved further
- with new results & progress, tell politicians/sceptics: L-by-L _can_ be predicted!

$a_\mu^{\text{had, VP}}$: Hadronic Vacuum Polarisation

$$a_\mu^{\rm had} = a_\mu^{\rm had,VP\ \ LO} + a_\mu^{\rm had,VP\ \ NLO} + a_\mu^{\rm had,Light-by-Light}$$

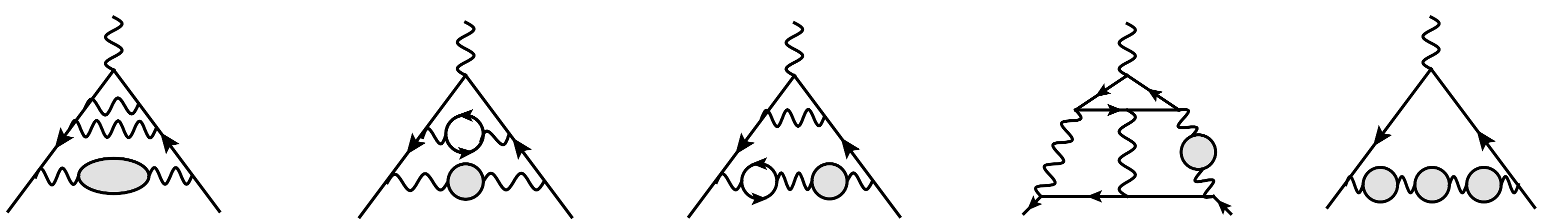


HVP: - most precise prediction by using e^+e^- hadronic cross section (+ tau) data and well known dispersion integrals

- done at LO and NLO (see graphs)

- and recently at NNLO [Steinhauser et al., PLB 734 (2014) 144, also F. Jegerlehner]

$a_\mu^{\text{HVP, NNLO}} = + 1.24 \times 10^{-10}$ not so small, from e.g.:

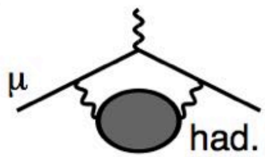


- Alternative: lattice QCD, but need QED and iso-spin breaking corrections

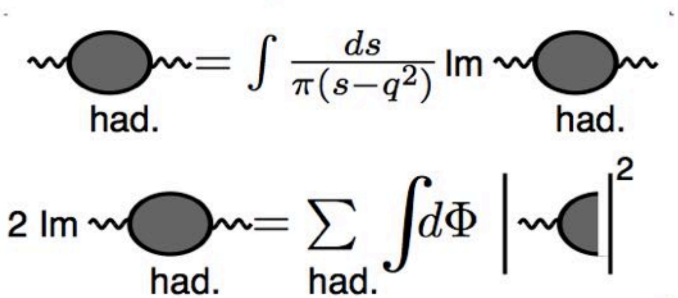
Lots of activity by several groups, errors coming down, QCD+QED started

Hadronic Vacuum Polarisation, essentials:

Use of data compilation for HVP:



pQCD not useful. Use the dispersion relation and the optical theorem.



$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds \, \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)$$

- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$

$\Longrightarrow$ Lower energies more important

$\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\mathrm{had,LO}}$

How to get the most precise σ^0_{had}? e^+e^- data:

- Low energies: sum ~30 exclusive channels, 2π, 3π, 4π, 5π, 6π, KK, KKπ, KKππ, ηπ, ..., use iso-spin relations for missing channels

- Above ~1.8 GeV: can start to use pQCD (away from flavour thresholds), supplemented by narrow resonances (J/Ψ, Υ)

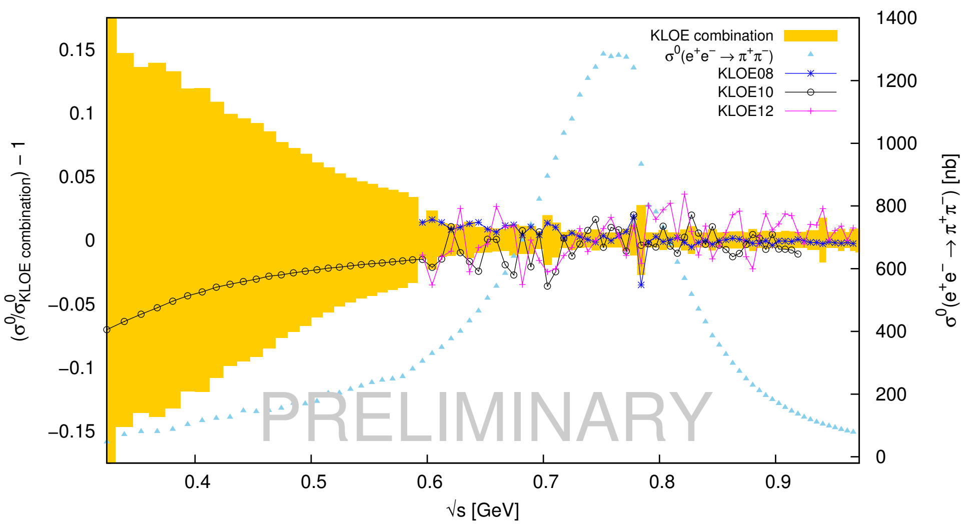
- Challenge of data combination (locally in √s): many experiments, different energy bins, stat+sys errors from different sources, correlations; must avoid inconsistencies/bias

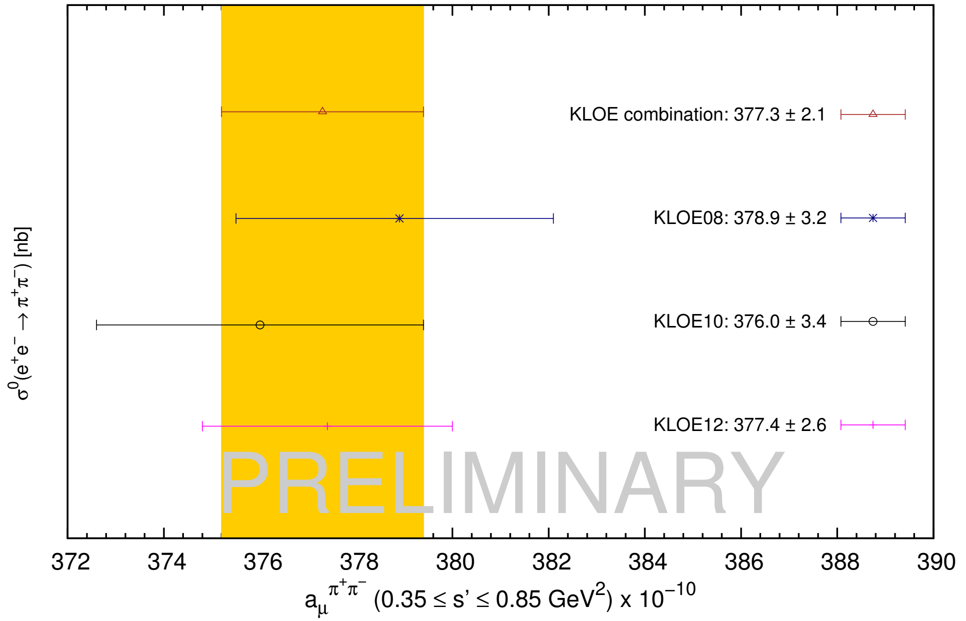
- traditional `direct scan' (tunable $e^+e^-$ beams) vs. `Radiative Return' [+ τ spectral functions]

- σ^0_{had} means `bare' σ, but WITH FSR: RadCorrs [HLMNT '11: $\delta a_\mu^{\mathrm{had,\,RadCor\ VP+FSR}} = 2 \times 10^{-10}$!]

HVP: KLOE 2π combination [on arXiv in next days]

⇒ Combination of KLOE08, KLOE10 and KLOE12 gives 85 distinct bins between $0.1 \leq s \leq 0.95$ GeV^2





→ Covariance matrix now correctly constructed

⇒ a positive semi-definite matrix

→ Non-trivial influence of correlated uncertainties on resulting mean value

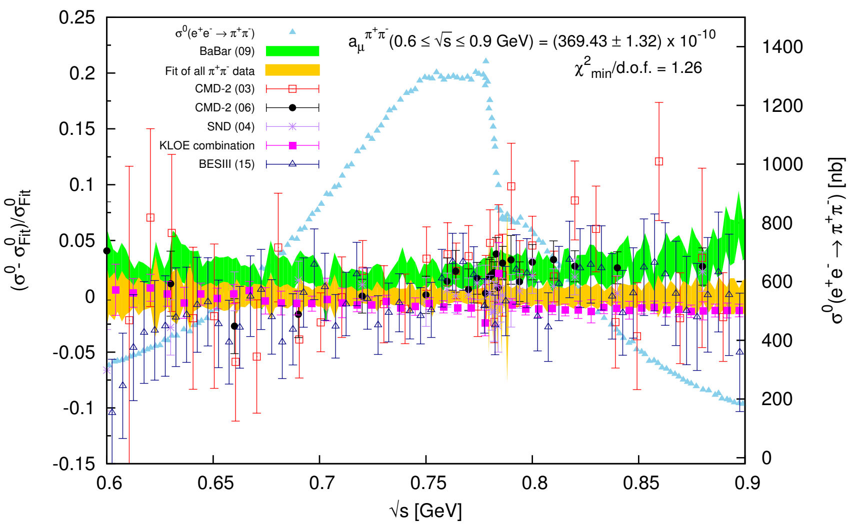
$$a_\mu^{\pi^+\pi^-}(0.1 \leq s' \leq 0.95\ \text{GeV}^2) = (489.9 \pm 2.0_{\text{stat}} \pm 4.3_{\text{sys}}) \times 10^{-10}$$

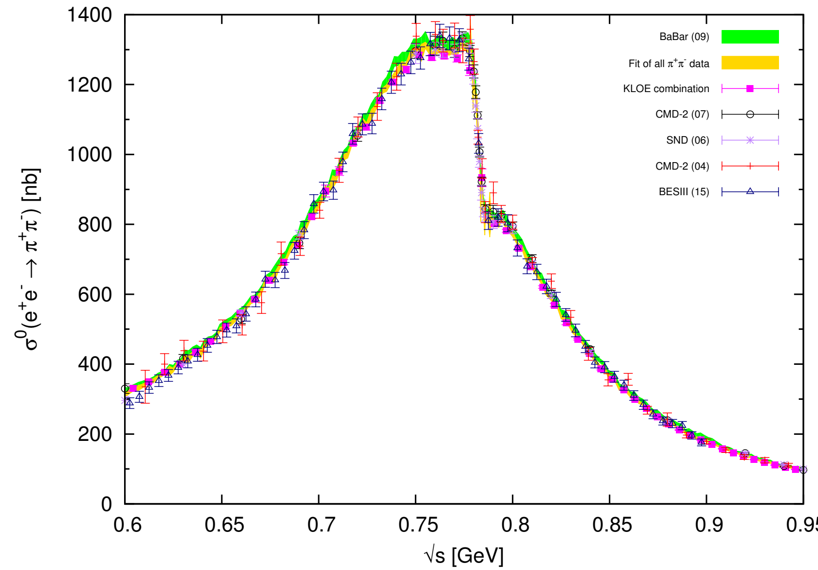
Publication by KLOE-2, Grazinao Venanzoni, Alex Keshavarzi, Stefan Mueller, TT: review finished

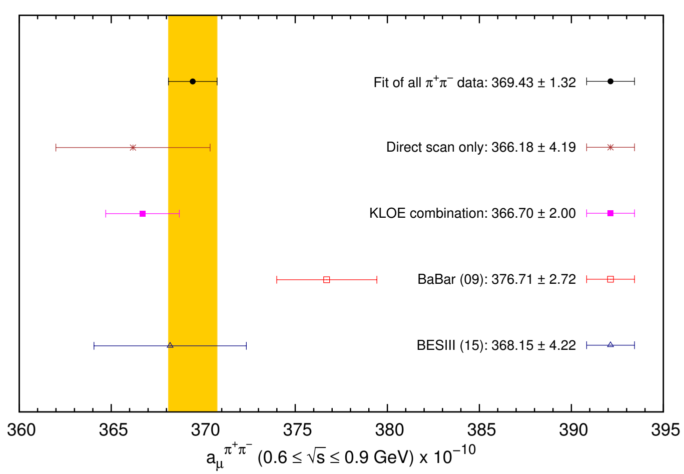
HVP: complete 2π combination by Keshavarzi+Nomura+T

⇒ Large improvement for 2π estimate

→ BESIII [Phys.Lett. B753 (2016) 629-638] and KLOE combination provide downward influence to mean value







⇒ Correlated & experimentally corrected $\sigma^0_{\pi\pi(\gamma)}$ data now entirely dominant

$$a_\mu^{\pi^+\pi^-}(0.305 \le \sqrt{s} \le 2.00 \text{ GeV}):$$

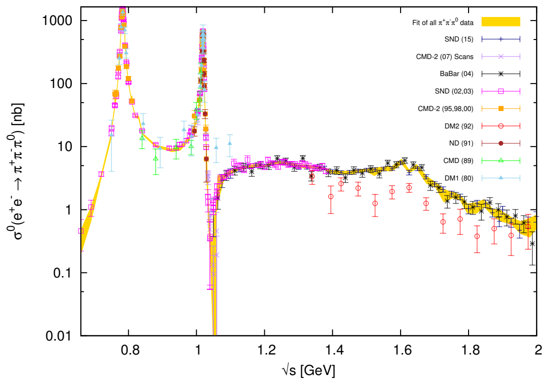
$$\text{HLMNT11: } 505.77 \pm 3.09$$

$$\text{KNT17: } 502.85 \pm 1.93 \text{ (!!)}$$

(no radiative correction uncertainties)

HVP: other notable exclusive channels [status June 2017]

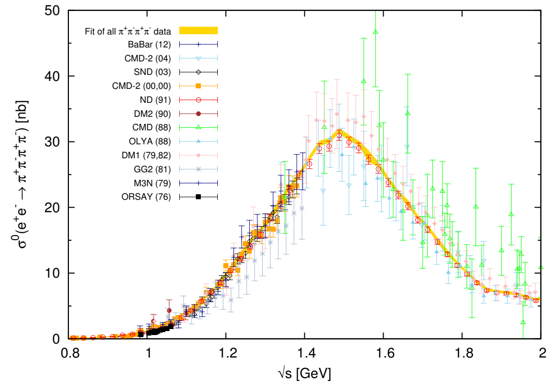
$\pi^+\pi^-\pi^0$



HLMNT11: 47.51 ± 0.99

KNT17: 47.68 ± 0.70

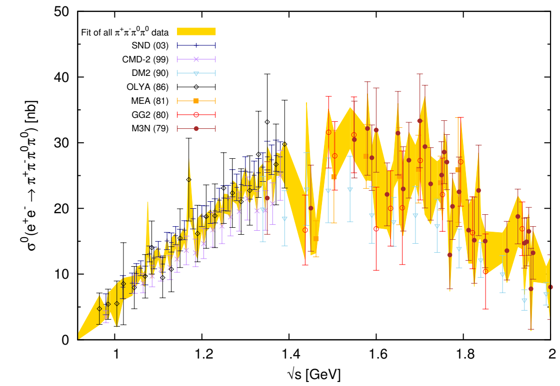
$\pi^+\pi^-\pi^+\pi^-$



HLMNT11: 14.65 ± 0.47

KNT17: 15.18 ± 0.14

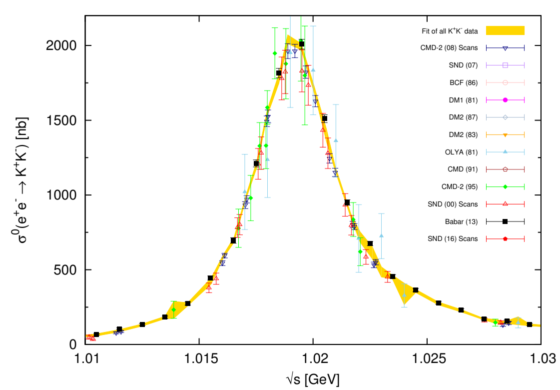
$\pi^+\pi^-\pi^0\pi^0$



HLMNT11: 20.37 ± 1.26

KNT17: 20.07 ± 1.19

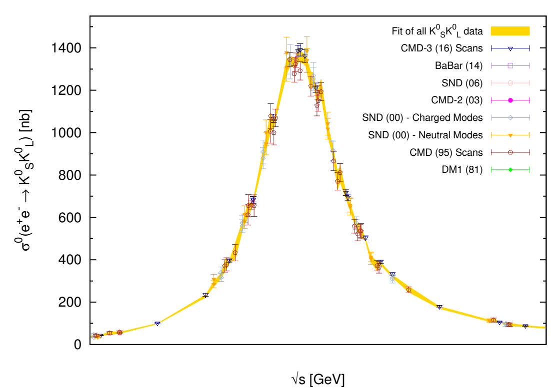
K^+K^-



HLMNT11: 22.15 ± 0.46

KNT17: 22.76 ± 0.22

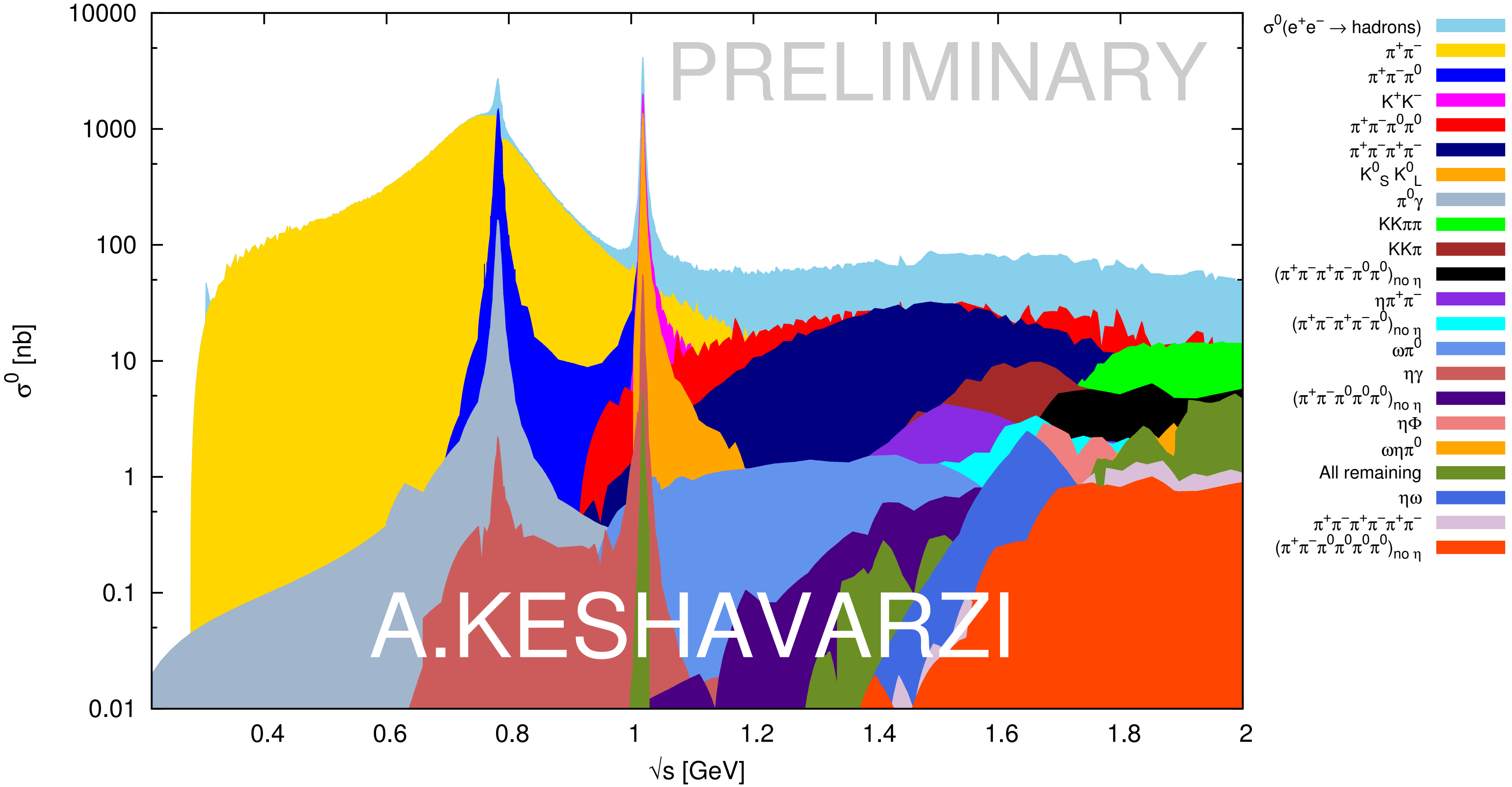
$K^0_S K^0_L$



HLMNT11: 13.33 ± 0.16

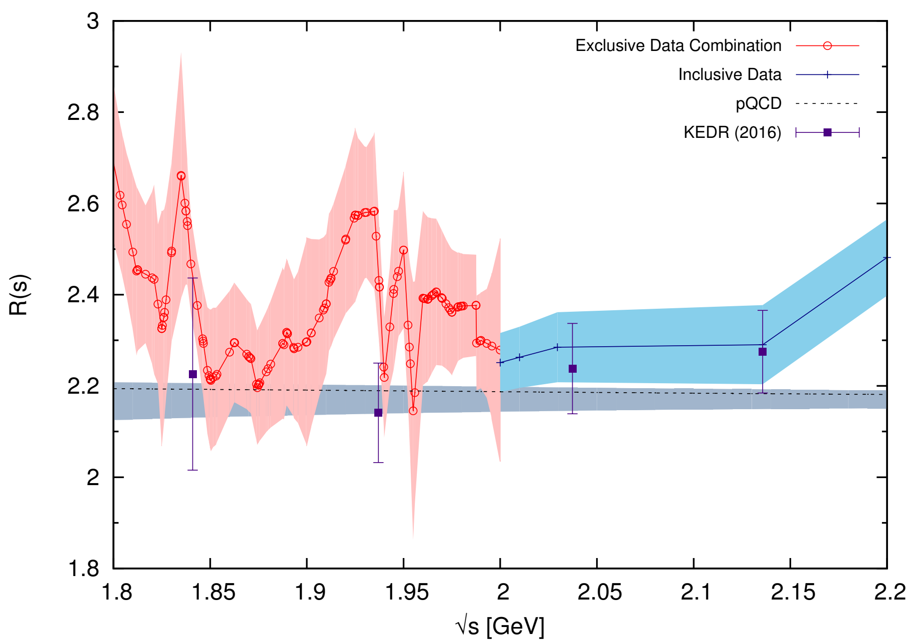
KNT17: 13.09 ± 0.12

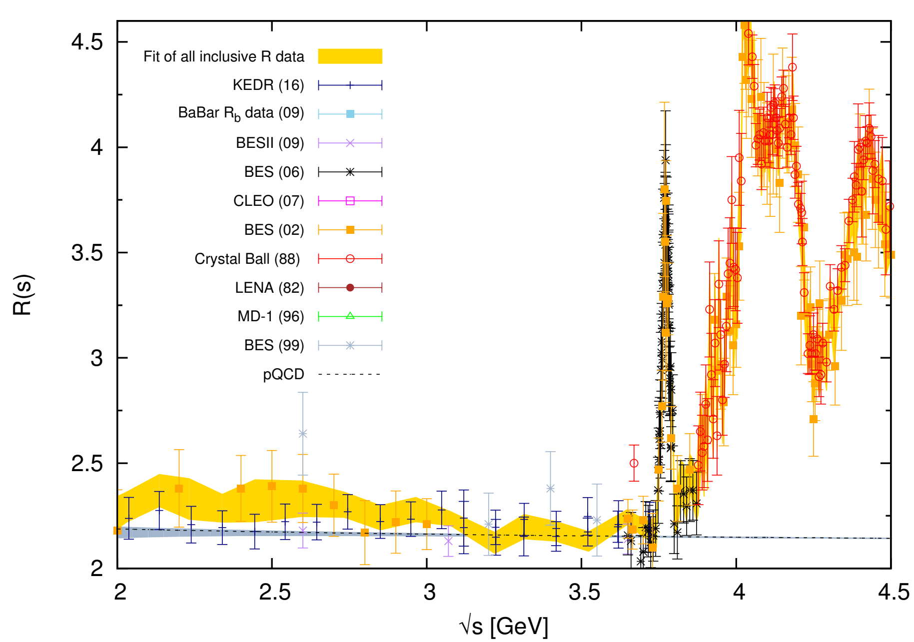
HVP: the channel landscape (by Alex Keshavarzi)



HVP: region of inclusive data/pQCD

$\Rightarrow$ New KEDR inclusive R data ranging $1.84 \leq \sqrt{s} \leq 3.05$ GeV [Phys.Lett. B770 (2017) 174-181] and $3.12 \leq \sqrt{s} \leq 3.72$ GeV [Phys.Lett. B753 (2016) 533-541]





$a_\mu^{\text{had, LOVP}}(1.84 \leq \sqrt{s} \leq 2.00 \text{ GeV})$:

pQCD : 6.42 ± 0.03

Data : 6.88 ± 0.25

$a_\mu^{\text{had, LOVP}}(2.60 \leq \sqrt{s} \leq 3.73 \text{ GeV})$:

pQCD (inflated errors) : 10.82 ± 0.38

Data : 11.20 ± 0.14

$\Longrightarrow$ **Choose to adopt entirely data driven estimate from threshold to 11.2 GeV**

a_μ^{SM}: update HLMNT11 → KNT17 (prel.) as presented @ TGM2

*to be discussed

	2011		2017	
QED	11658471.81 (0.02)	⟶	11658471.90 (0.01)	[Phys. Rev. Lett. 109 (2012) 111808]
EW	15.40 (0.20)	⟶	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	⟶	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]*
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]*
	HLMNT11		**KNT17**	
LO HVP	694.91 (4.27)	⟶	692.23 **(2.54)**	this work*
NLO HVP	-9.84 (0.07)	⟶	-9.83 (0.04)	this work*
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144] *
Theory total	11659182.80 (4.94)	⟶	11659181.00 (3.62)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	⟶	28.1 (7.3)	this work
Δa_μ	3.3σ	⟶	3.9σ	this work

$a_\mu^{\text{LO HVP}}$: comparison of the most recent results

KNT17 vs. DHMZ17 vs. FJ17 [preliminary]

⇒ Different data treatment/methods produce **very** different results

Channel $\sqrt{s} \leq 1.8$ GeV	KNT17	DHMZ17	FJ17
$\pi^+\pi^-$	502.73 ± 1.94	507.14 ± 2.58	
$\pi^+\pi^-2\pi^0$	17.82 ± 0.99	18.03 ± 0.54	
$2\pi^+2\pi^-$	14.00 ± 0.20	13.68 ± 0.31	
K^+K^-	22.75 ± 0.26	22.81 ± 0.41	
$K_S^0K_L^0$	13.03 ± 0.20	12.82 ± 0.24	
Total HVP $\sqrt{s} < \infty$ GeV	692.23 ± 2.54	693.1 ± 3.4	689.43 ± 3.25

⇒ Between $1.8 \leq \sqrt{s} \leq 2$ GeV, KNT use data, DHMZ use pQCD

BUT, pQCD $= 8.30 \pm 0.09$, KNT data $= 8.42 \pm 0.29$, DHMZ data $= 7.71 \pm 0.32$

⇒ DHMZ17 use correlated systematics differently in determination of the mean value

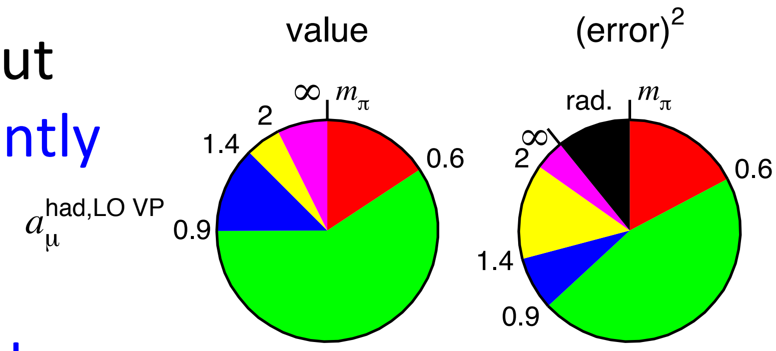
→ Determining $\pi^+\pi^-$ using only local weighted average gives 508.91 ± 2.84

⟶ Much better agreement when neglecting the effect of correlated uncertainties on the mean value

SM prediction: Summary

- All sectors of the Standard Model prediction of g-2 have been scrutinised a lot in recent years

- The basic picture has not changed, but recent data, many from ISR, significantly improve the prediction for a_μ^{HVP}

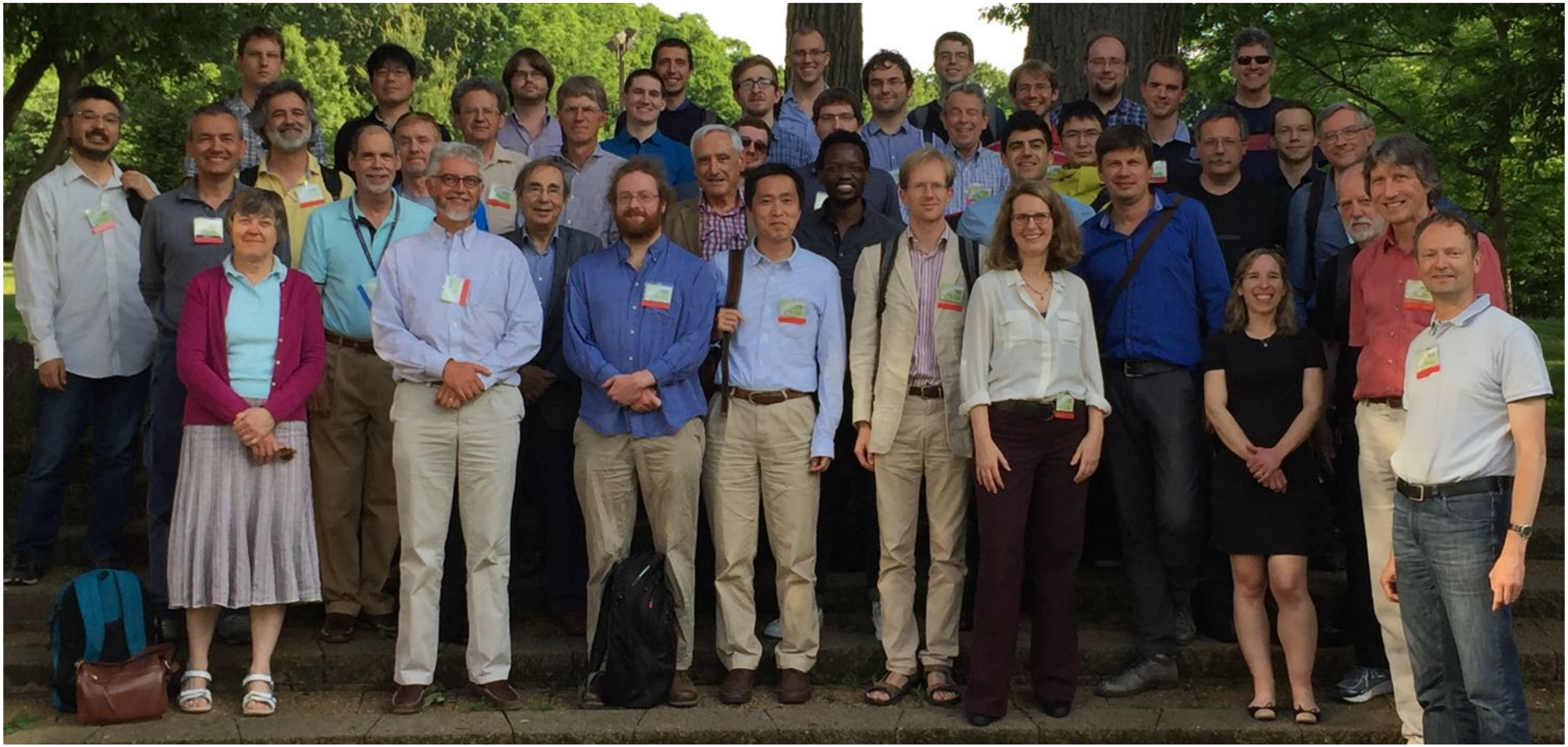


- Discrepancy ~ 3 -> 4 σ is consolidated

- With further hadronic data in the pipeline, also on FFs for HLbL, and efforts from lattice, the goal of squeezing Δa_μ^{SM} by a factor of two is in reach

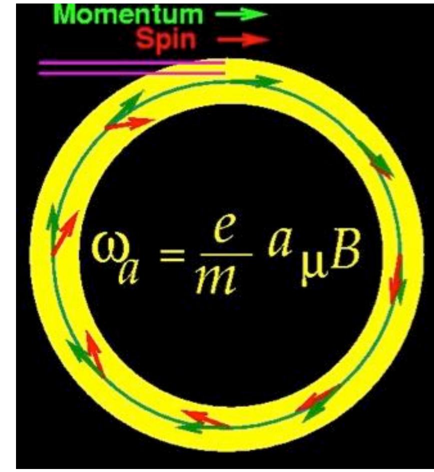
- Push for the community to compare and challenge results:

"Muon g-2 theory initiative" formed in June 2017



"map out strategies for obtaining the **best theoretical predictions for these hadronic corrections** in advance of the experimental results"

g-2 experiments slides thanks to Tsutomu Mibe and Lee Roberts



In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0

general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

FNAL E989

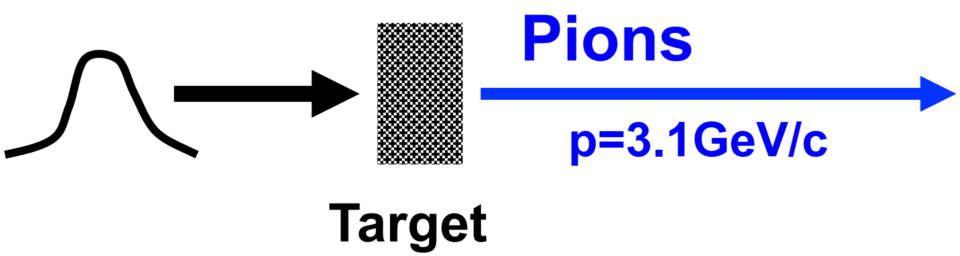
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

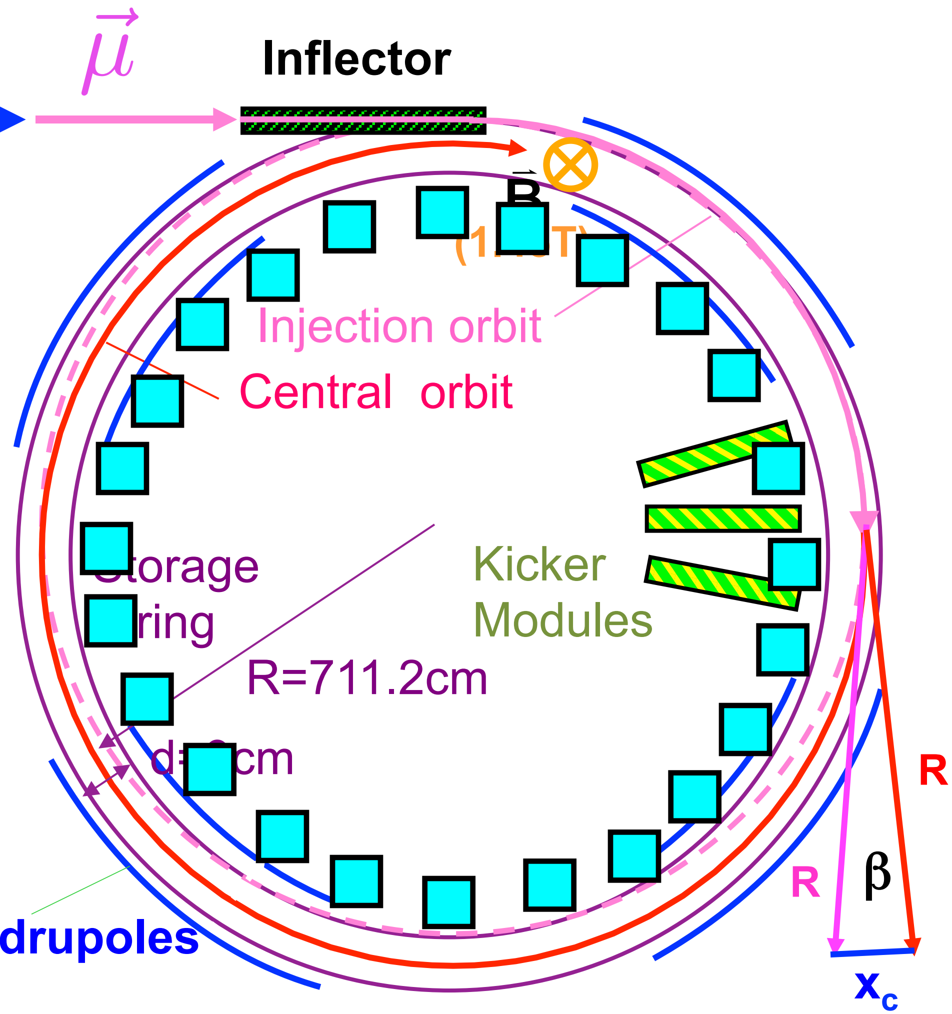
J-PARC E34

BNL&FNAL: Experimental Technique

narrow time bunch of protons

$x_c \approx 77$ mm
$\beta \approx 10$ mrad
$B\cdot dl \approx 0.1$ Tm



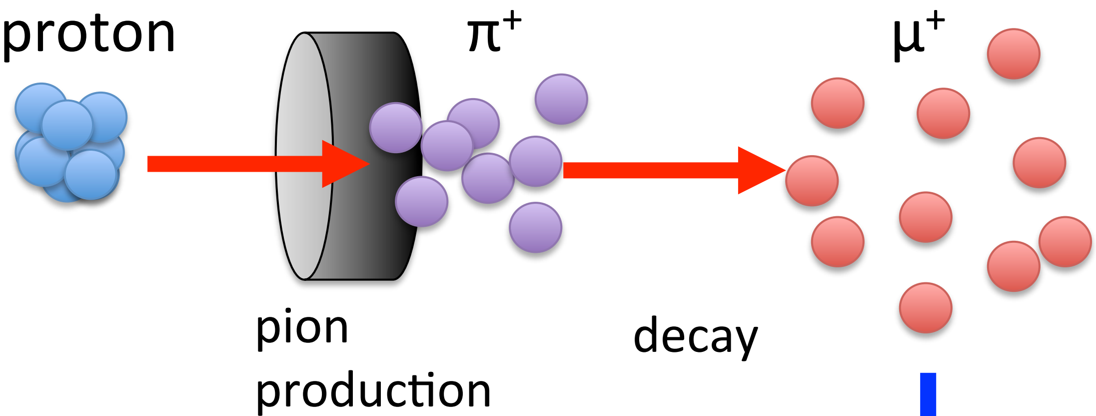


- Muon storage ring – weak focusing betatron
- Muon polarization
- Injection & kicking
- Focus with electric quads
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{Qe}{m} a_\mu \vec{B}$$

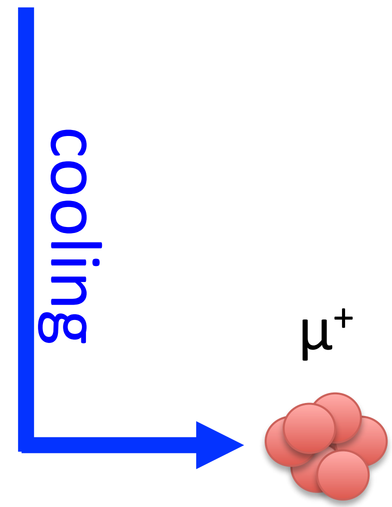
Muon beam

Conventional muon beam



emittance
~1000π mm･mrad

Strong focusing
Muon loss
BG π contamination



emittance
1π mm･mrad

Free from any of these

Ultra-cold muon beam

Ultra-cold Muon

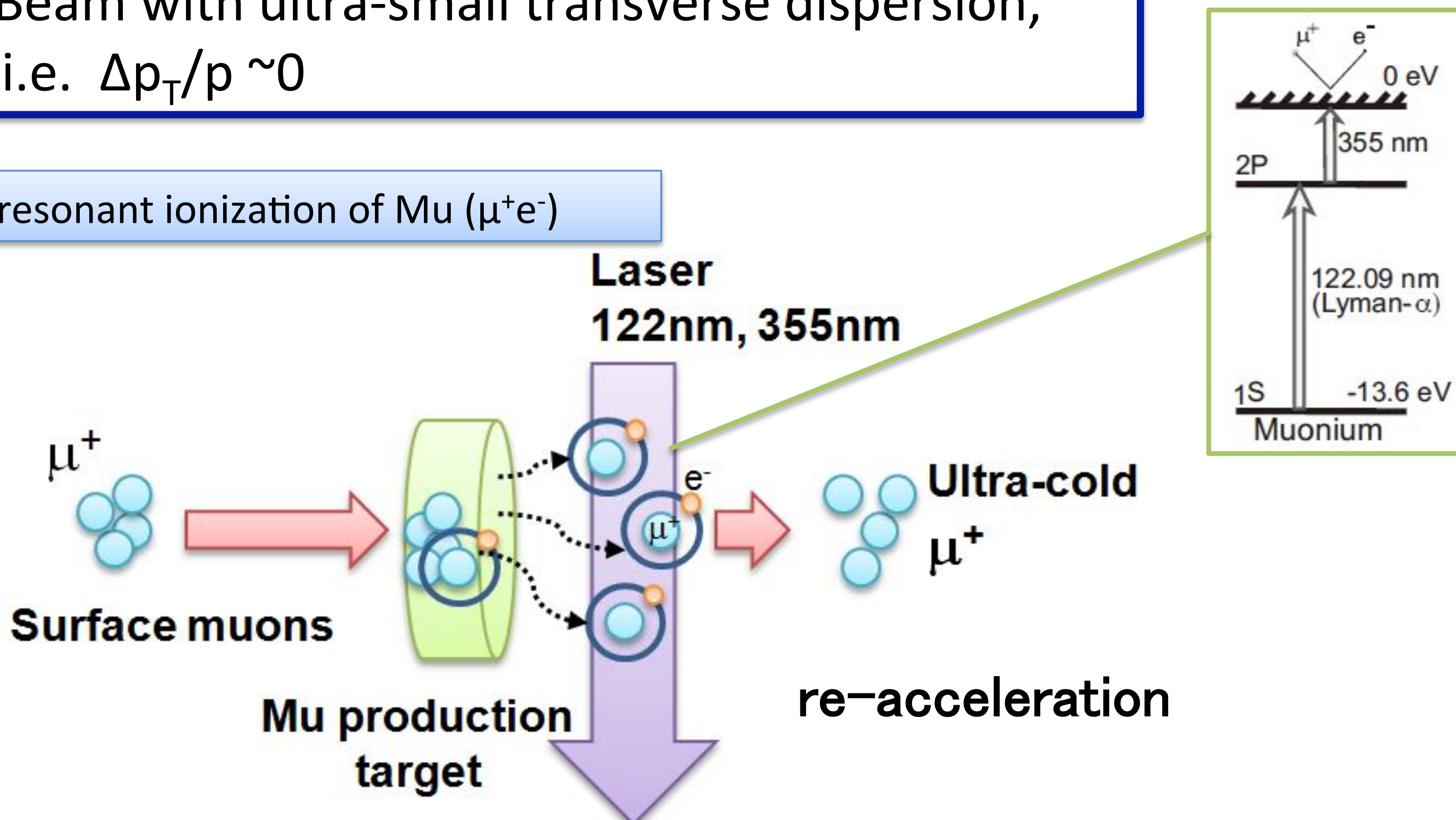
<u>Requirement for zero E-field:</u>

Muons should be kept stored without E-focusing

→ Beam with ultra-small transverse dispersion,

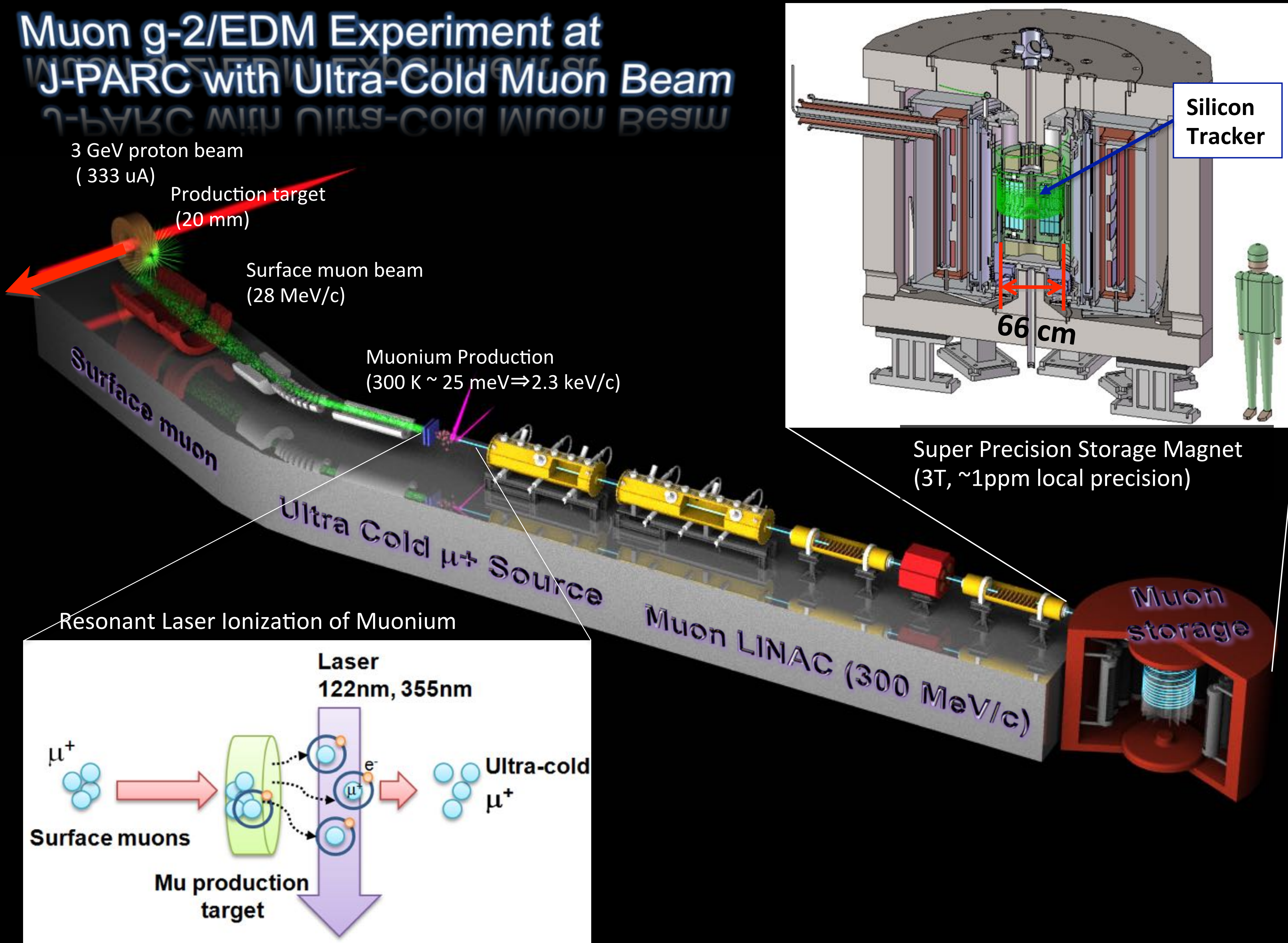
i.e. $\Delta p_T/p \sim 0$

Laser resonant ionization of Mu (μ^+e^-)

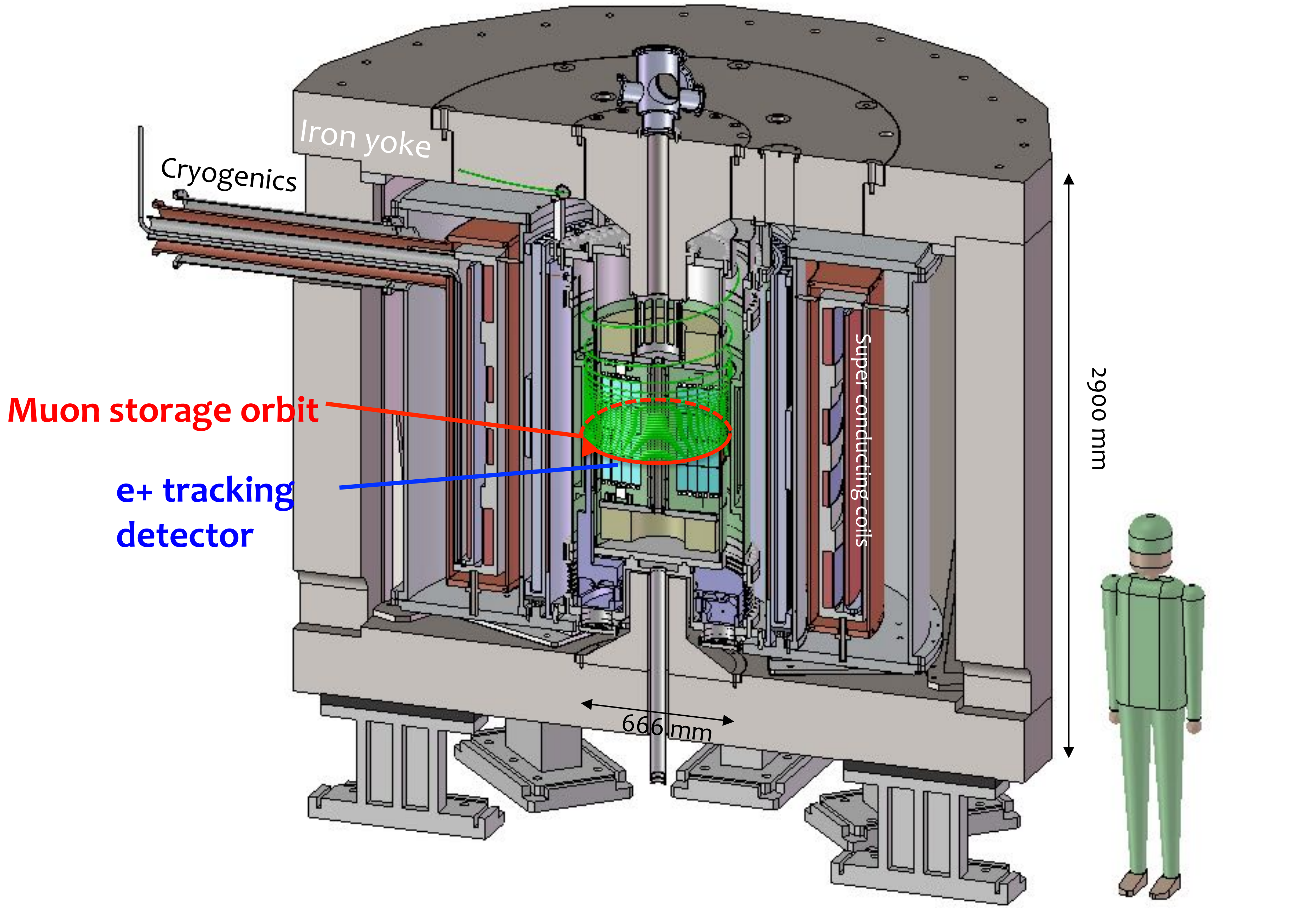


p = 28MeV/c 3 keV/c 300 MeV/c

$\Delta p_T/p$ ~3 keV / 300 MeV =1E-5


Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam
3 GeV proton beam
(333 uA)
Production target
(20 mm)
Surface muon beam
(28 MeV/c)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Silicon
Tracker
66 cm
Super Precision Storage Magnet
(3T, ~1ppm local precision)
Resonant Laser Ionization of Muonium
Laser
122nm, 355nm
μ+
e-
Surface muons
Mu production
target
Ultra-cold
μ+

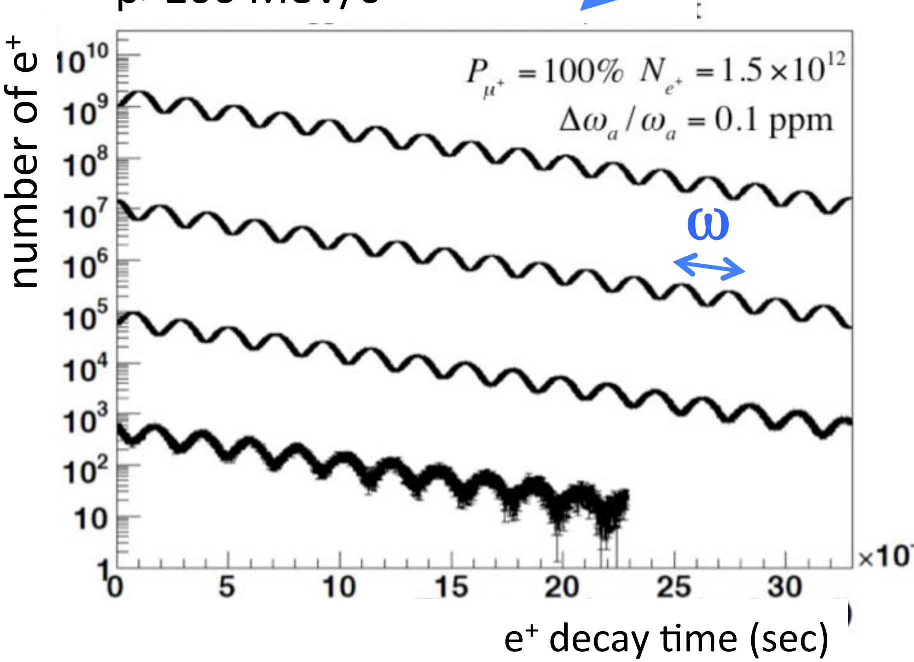
Muon storage magnet and detector

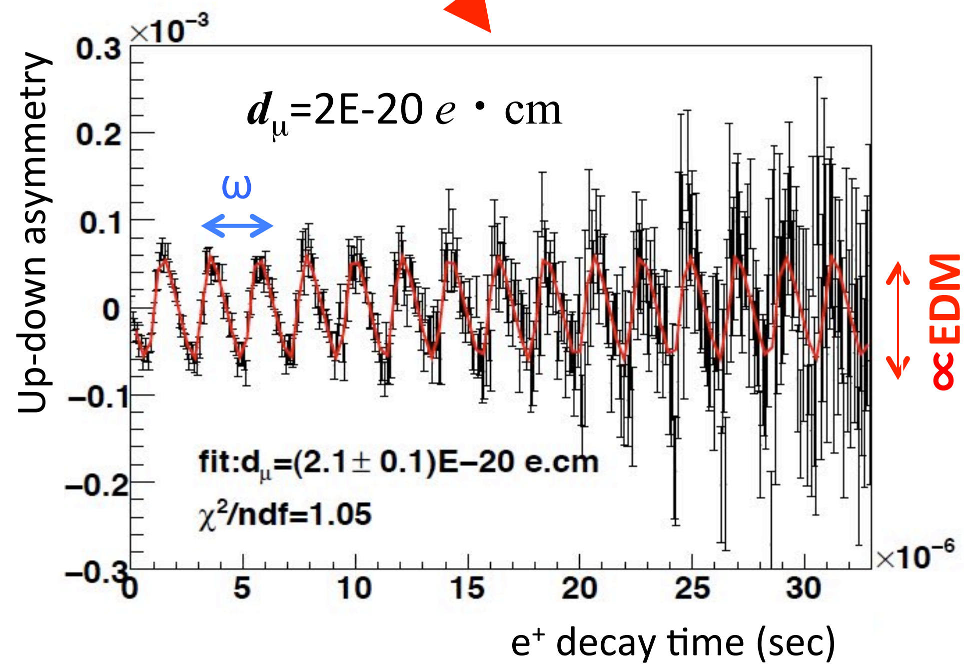


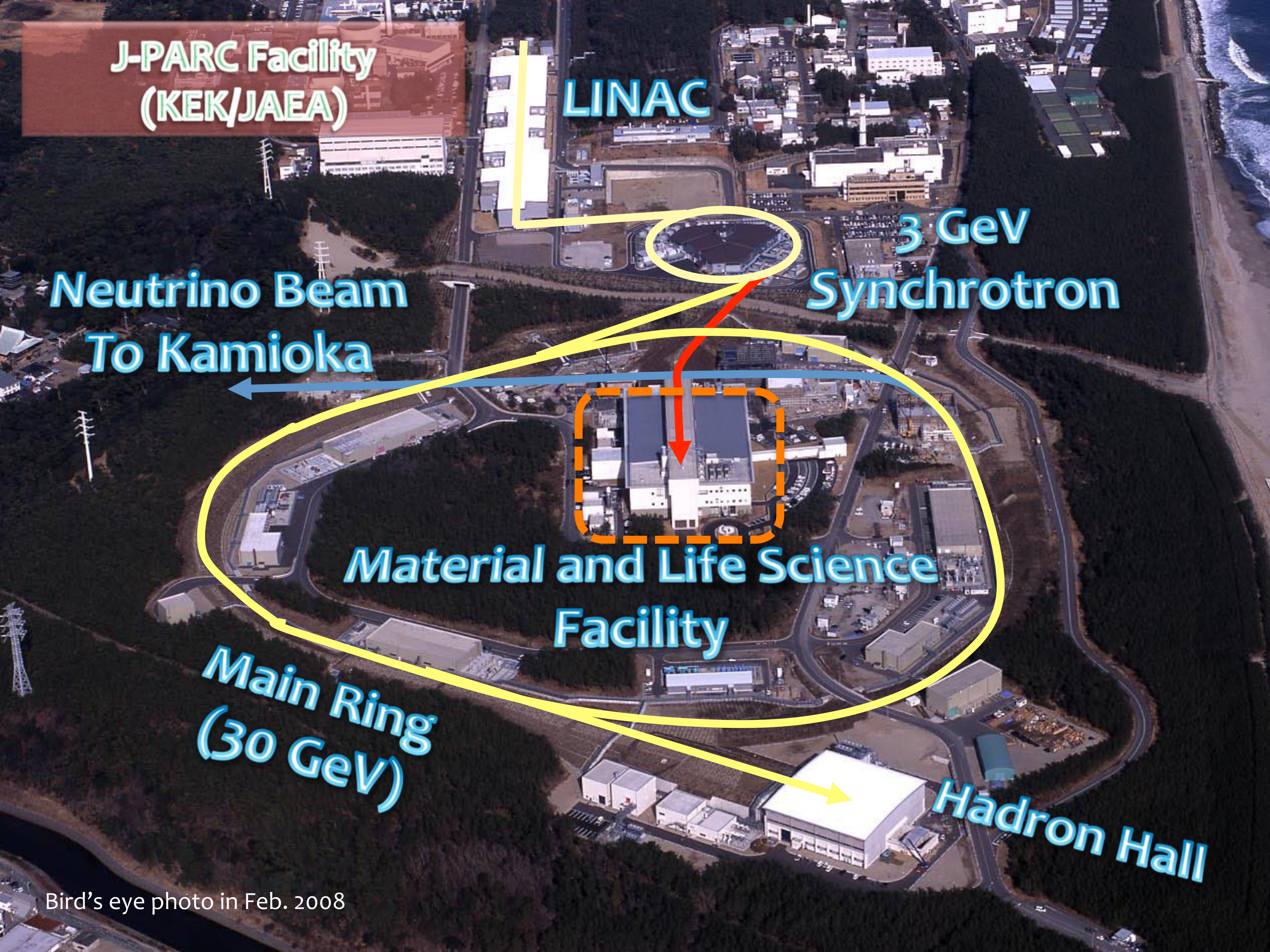
Expected time spectrum of e+ in μ→e+νν decay

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$

p>200 MeV/c







Bird's eye photo in Feb. 2008


2016.8.17
Muon S

Summary J-PARC

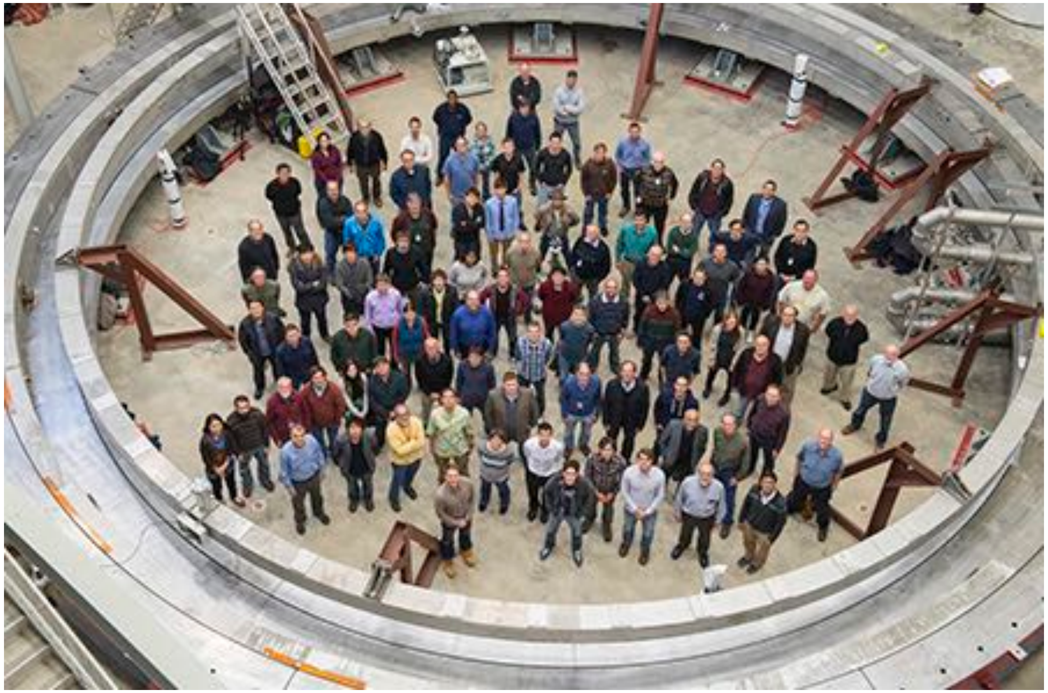
- New g-2/EDM experiment at J-PARC
  - Ultra-cold muon beam
  - Compact storage ring
- R&D phase is ending.
  - The TDR was reviewed by the focused review committee in Nov, 2016.
- Construction phase is starting.
  - Surface muon beamline under construction.
  - ~3-3.5 years to start data taking when full funding is provided.

Comparison of experiments

	BNL E821	J-PARC E34
muon momentum	3.09 GeV/c	0.3 GeV/c
storage ring radius	7 m	0.33 m
storage field	1.5 T	3.0 T
focusing field (n-index)	0.14 (electric)	1.5 E-4 (magnetic)
average field uniformity	≈1 ppm	<< 1ppm
(local uniformity)	≈50 ppm	≈1ppm
Injection	inflector + kick	spiral + kick
Injection efficiency	3-5%	80%
muon spin reversal	--	pulse-to-pulse
positron measurement	calorimeters	tracking
positron acceptance*	65%	≈100%
muon polarization	≈100%	≈50%
events to 0.46 ppm	9×10^{9}	5×10^{11}

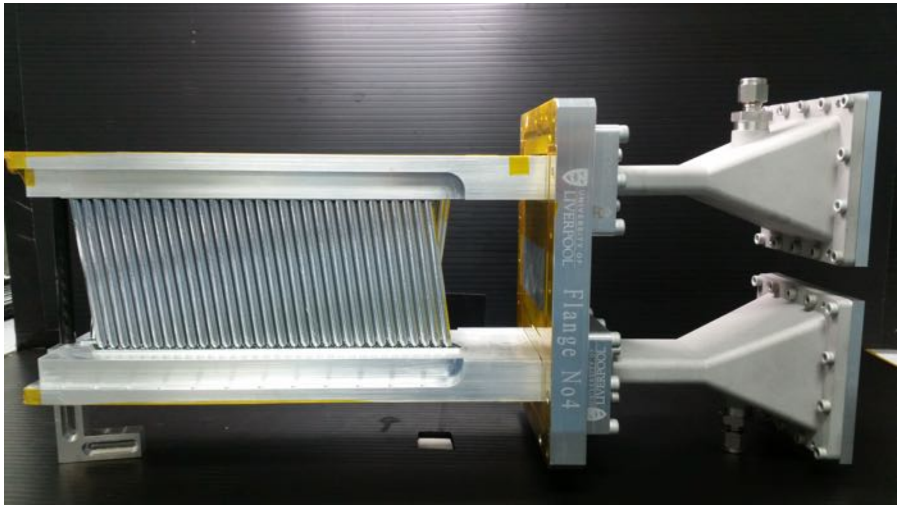
* in the energy region of interest

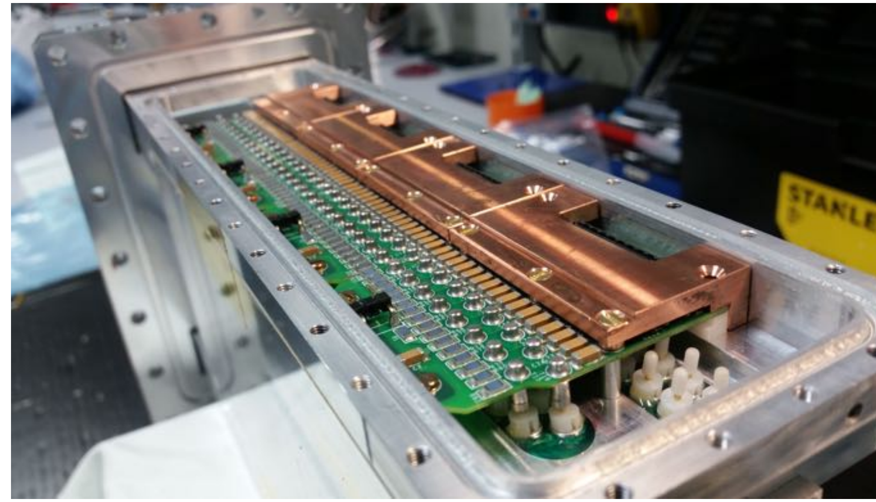
E989: Ring arrived after a long journey in one piece

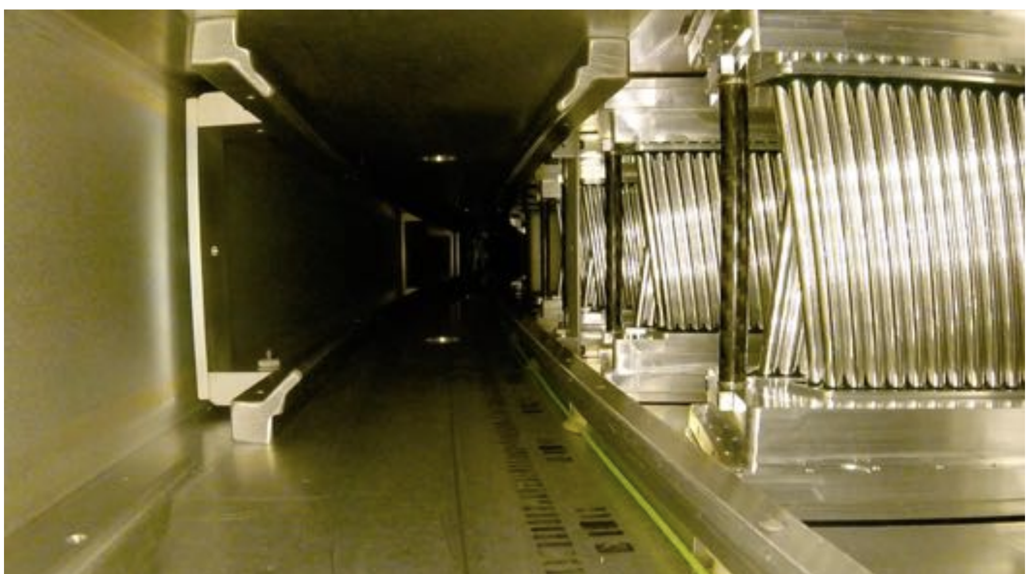


and the collaboration has been growing further since then (2014 ->)

E989 Liverpool: design and building of trackers



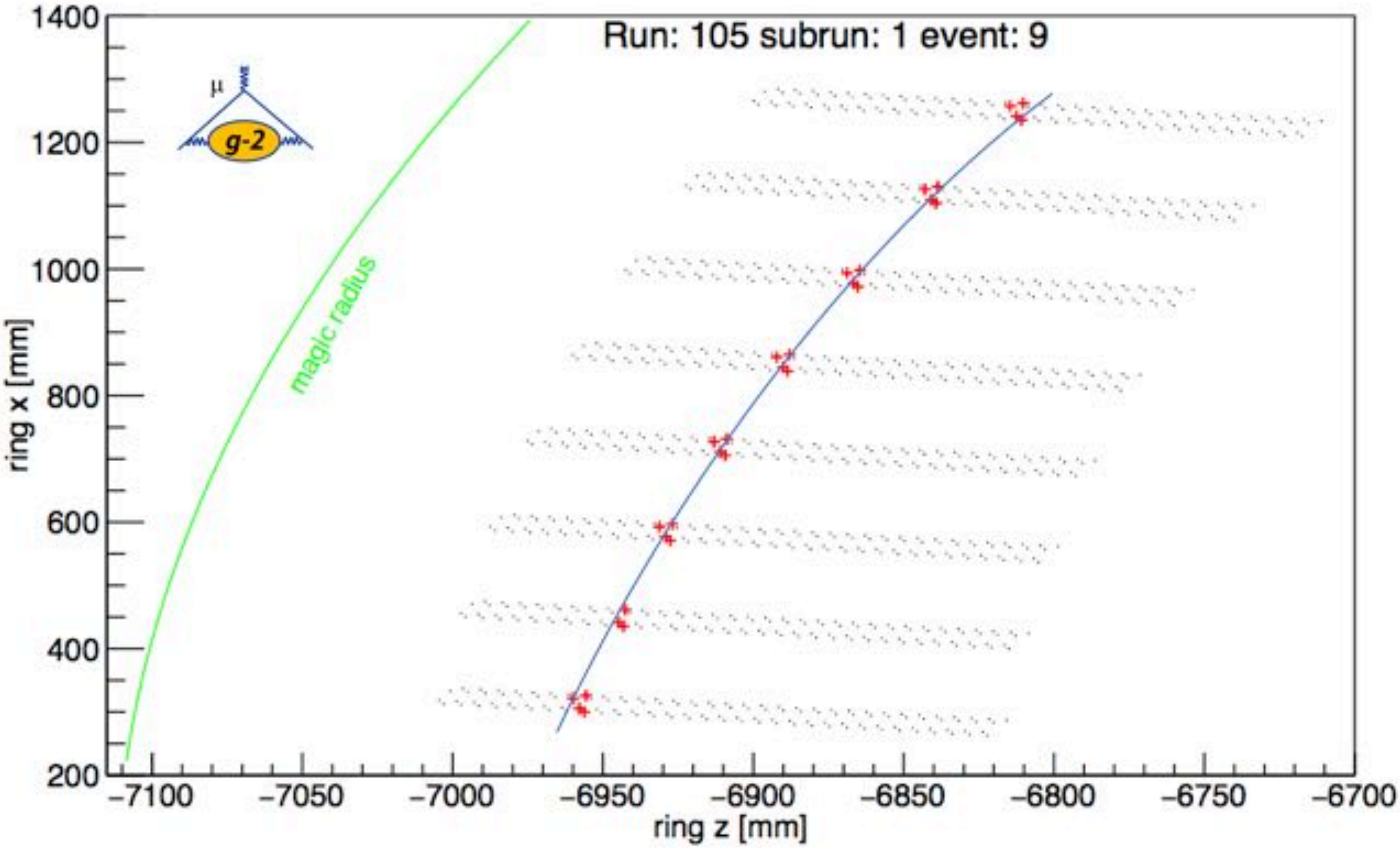




- 3 stations in ring, each 8 modules with straw trackers
- tool for monitoring beam dynamics
- very important for systematics and EDM measurement

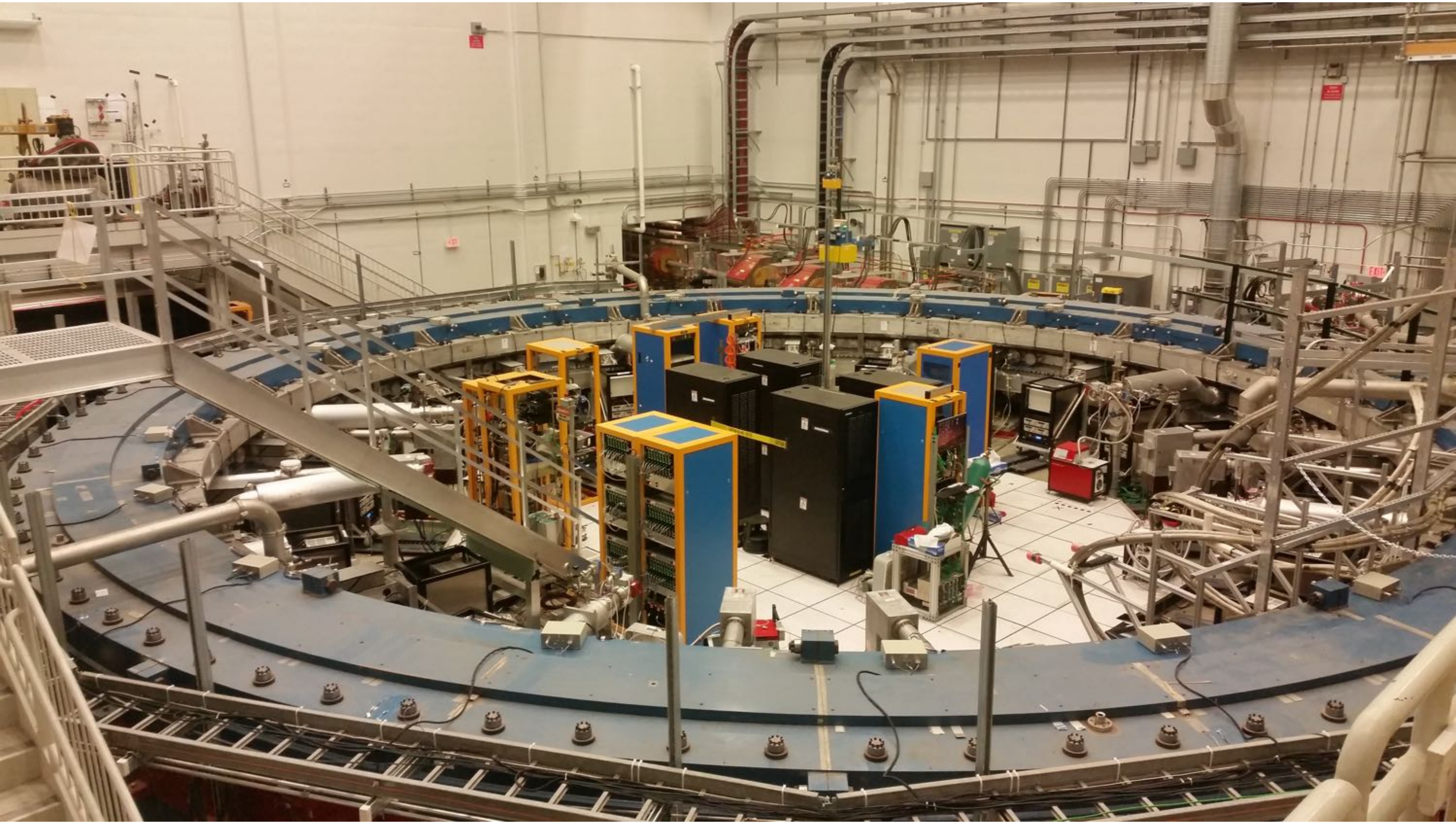
← photo taken in ring from trolley for NMR probes for B-mapping

E989 Liverpool: design and building of trackers

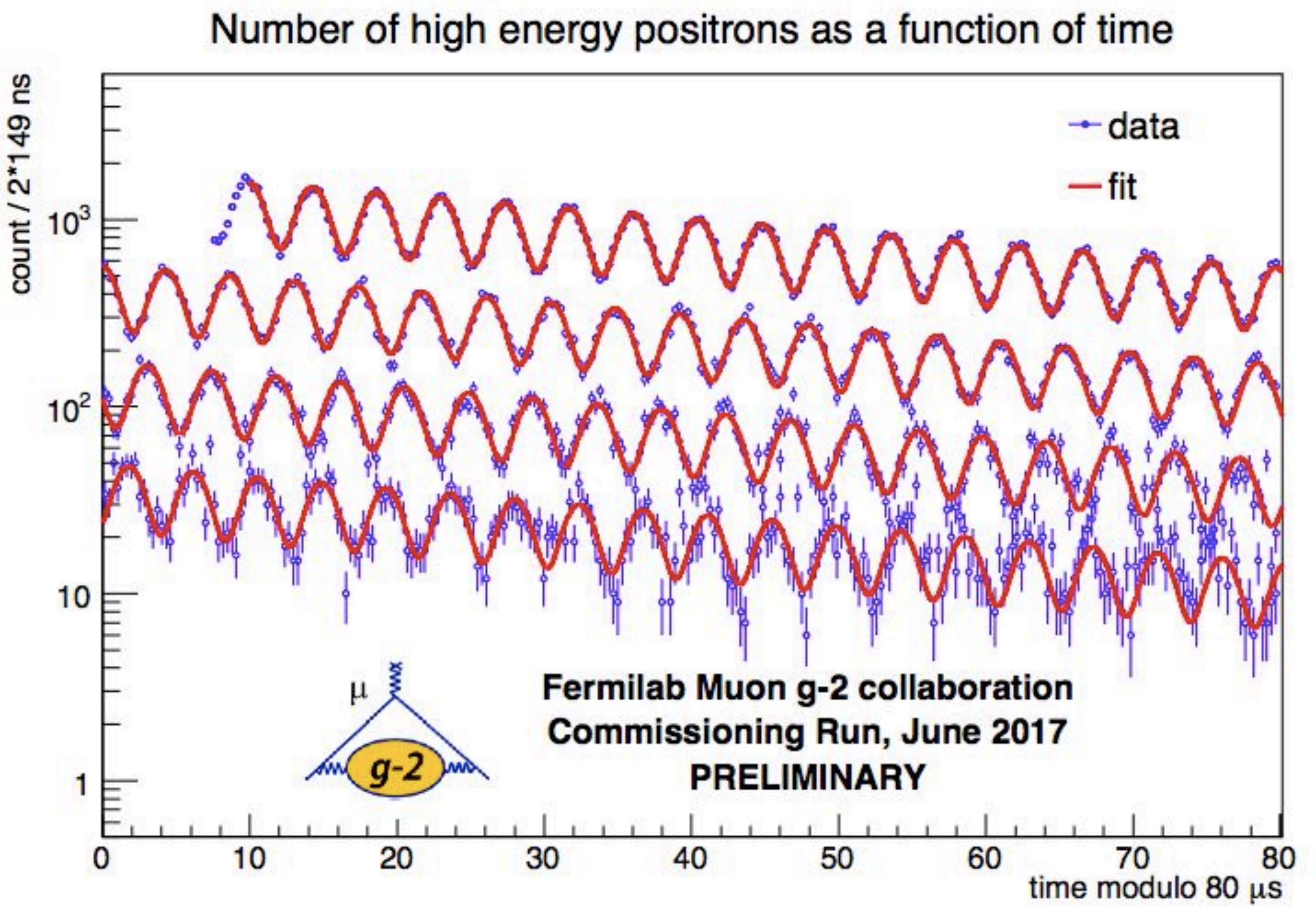


One of the first tracks recorded by the tracker showing the hits from a single charged particle (likely a proton) through the straw trackers and the (wire)-track fit and the magic radius

E989: ring ready for action soon [data taking starts Nov. 2017]



E989: the first new wiggle plot. More soon



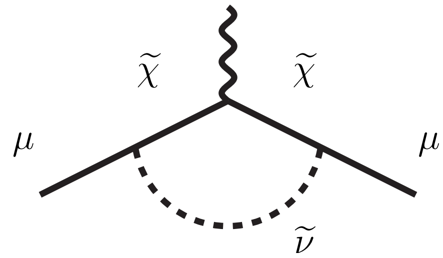
- Data accumulated during two weeks in June 2017, approximately 700k positrons
- The number of wiggles is somewhere between that achieved by CERN-II and CERN-III

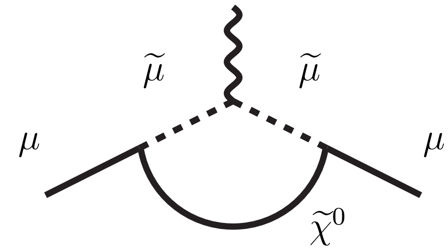
a_μ: New Physics?

- Many BSM studies use g-2 as constraint or even motivation

- SUSY could easily explain g-2

  - Main 1-loop contributions:





  - Simplest case:

$$a_\mu^{\rm SUSY} \simeq sgn(\mu)\, 130 \times 10^{-11}\, \tan\beta \left(\frac{100\,\mathrm{GeV}}{\Lambda_{\rm SUSY}}\right)^2$$

  - Needs $\mu > 0$, \`light' SUSY-scale Λ and/or large tan β to explain 281×10^{-11}

  - This is already excluded by LHC searches in the simplest SUSY scenarios (like CMSSM); causes large χ^2 in simultaneous SUSY-fits with LHC data and g-2

  - However:
    * SUSY does not have to be minimal (w.r.t. Higgs),
    * could have large mass splittings (with lighter sleptons),
    * be hadrophobic/leptophilic,
    * or not be there at all, but don't write it off yet…

New Physics? just a few of many recent studies

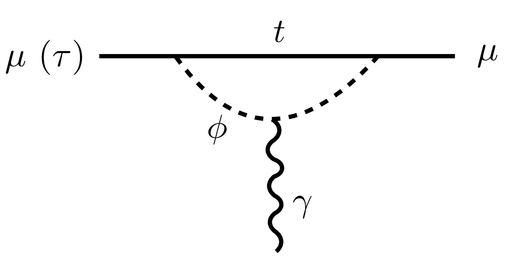
- Don't have to have full MSSM (like coded in GM2Calc [by Athron, ..., Stockinger et al., EPJC 76 (2016) 62], which includes all latest two-loop contributions), and

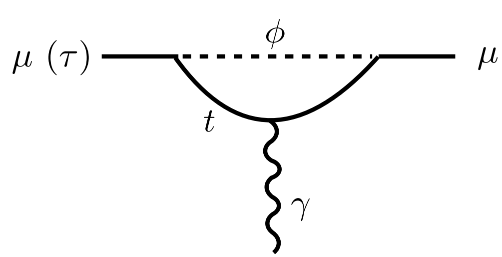
- extended Higgs sector could do, see, e.g. Stockinger et al., JHEP 1701 (2017) 007, `The muon magnetic moment in the 2HDM: complete two-loop result'

➔ lesson: 2-loop contributions can be highly relevant in both cases; one-loop analyses can be misleading

- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016) 141802

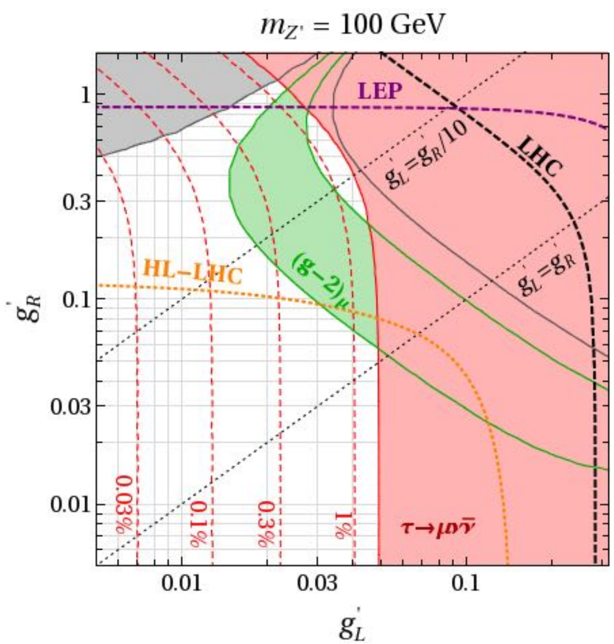
one new scalar could explain several anomalies seen by BaBar, Belle and LHC in the flavour sector (e.g. violation of lepton universality in B -> Kll, enhanced B -> Dτν) and solve g-2, while satisfying all bounds from LEP and LHC

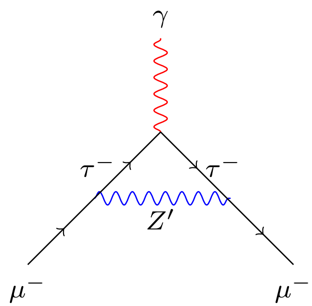


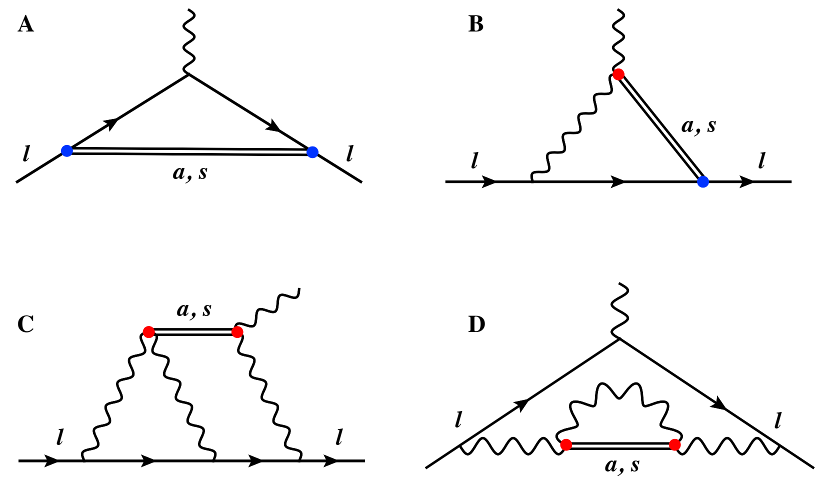


New Physics? just a few of many recent examples

- light Z’ can evade many searches involving electrons by non-standard couplings preferring heavy leptons (but see BaBar’s direct search limits in a wide mass range, PRD 94 (2016) 011102), or invoke flavour off-diagonal Z’ to evade constraints [Altmannshofer et al., PLB 762 (2016) 389]







- axion-like particle (ALP), contributing like π^0 in HLbL [Marciano et al., PRD 94 (2016) 115033]

- `dark photon’ - like fifth force particle [Feng et al., PRL 117 (2016) 071803]

Conclusions/Outlook:

- The still unresolved g-2 discrepancy, consolidated at about 3 -> 4 σ, has triggered two new experiments and a lot of theory activities

- The uncertainty of the hadronic contributions will be further squeezed, with L-by-L becoming the bottleneck, but a lot of progress (lattice + new data driven approaches) is expected within the next few years
- TH will be ready for the next round

- Fermilab's g-2 experiment is starting very soon,
  J-PARC will take a few years longer,
  both aiming at bringing the current exp uncertainty down by a factor of 4
- with two completely different exp's, hope to get closure

- Also expect vastly improved EDM bounds; complementarity with LFV

- Many approaches to explain the discrepancy with NP, linking g-2 with other precision observables, the flavour sector, dark matter and direct searches, but so far NP is only (con)strained.

Thank you.