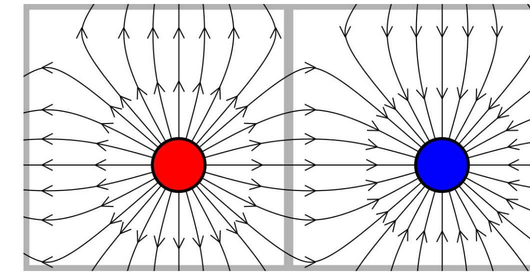


Unravelling the mysteries of strong interaction with supercomputers

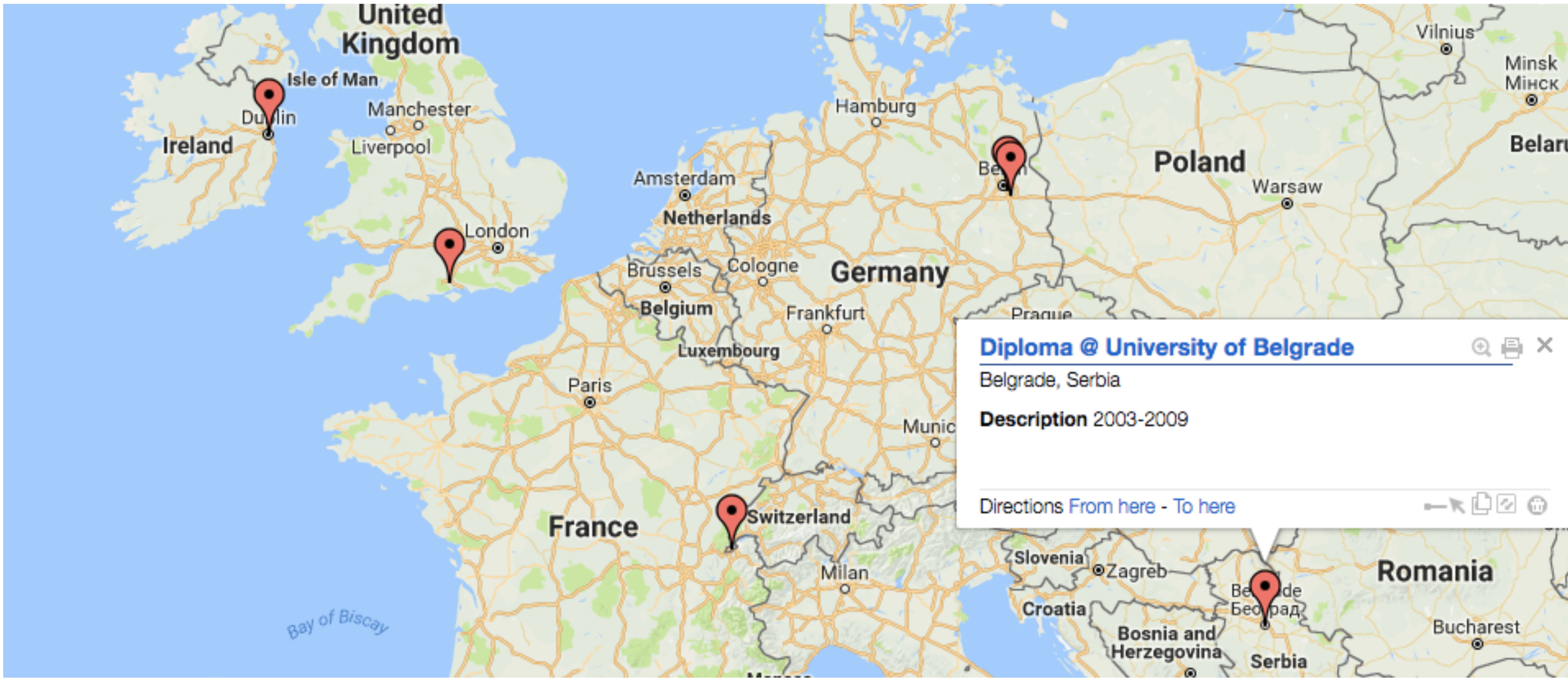
Marina Krstić Marinković

Abschlusskolloquium des GRK 1504

2018, March 9th

My scientific trajectory

My scientific trajectory



- 2006 - Summer Student Program @ DESY, Zeuthen

My scientific trajectory

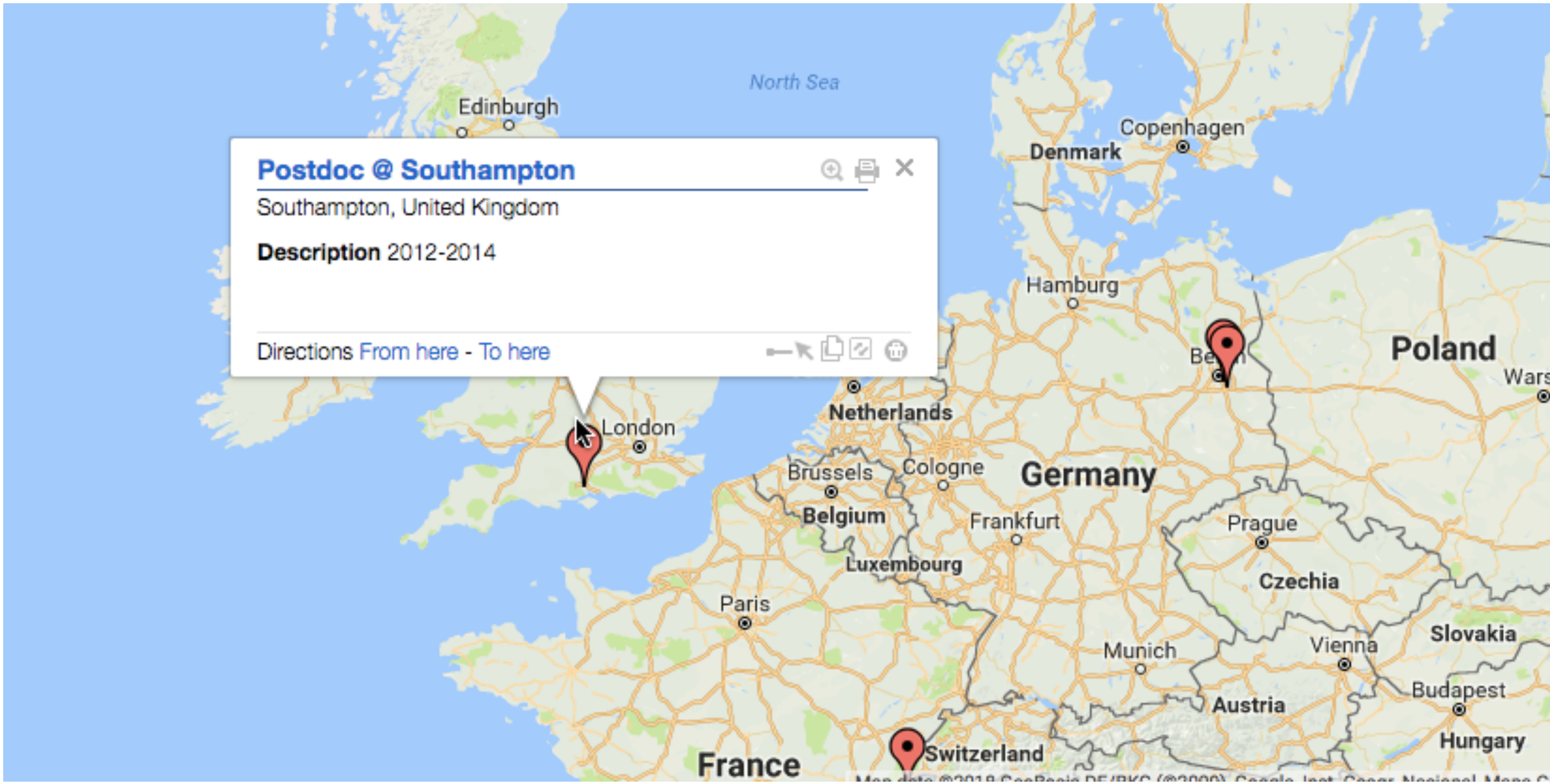
- **2008 - 2009**

My scientific trajectory

- **2009 - 2012**

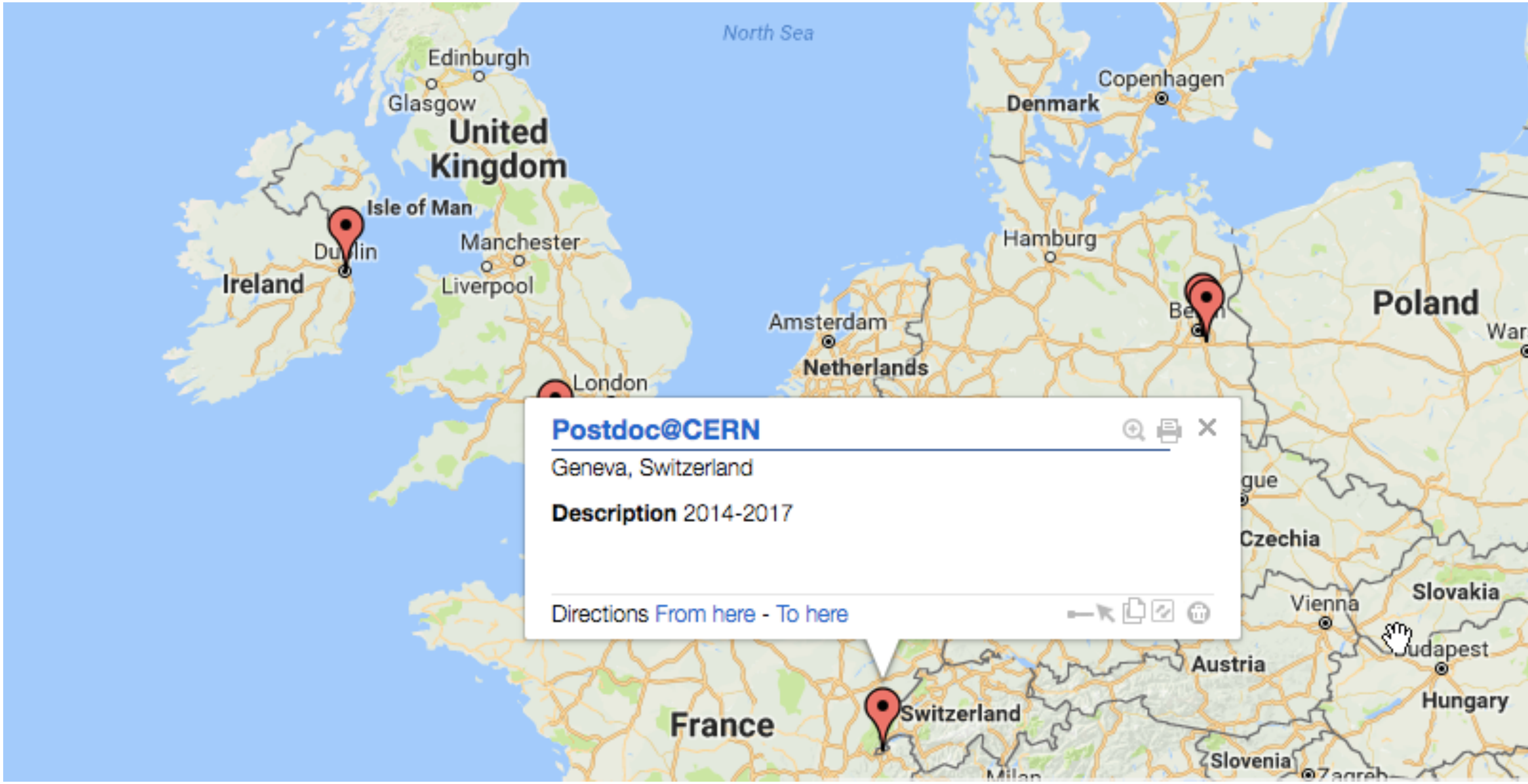
2009 – 2018
GRADUIERTEN KOLLEG
Masse-Spektrum-Symmetrie

My scientific trajectory



- 2012 - 2014

My scientific trajectory



- **2014 - 2017**

My scientific trajectory

- **2016 -**

Standard model of particle physics

- **Interactions (not) present in SM:**
  - ➡ Electromagnetic
  - ➡ Weak
  - ➡ Strong
  - ➡ Yukawa
  - ➡ Gravity
- **Is there some new physics beyond standard model (SM) ?**
  - ➡ dark matter
  - ➡ dark energy
  - ➡ hierarchy problem
  - ➡ strong CP-problem
  - ➡ matter/anti-matter asymmetry…

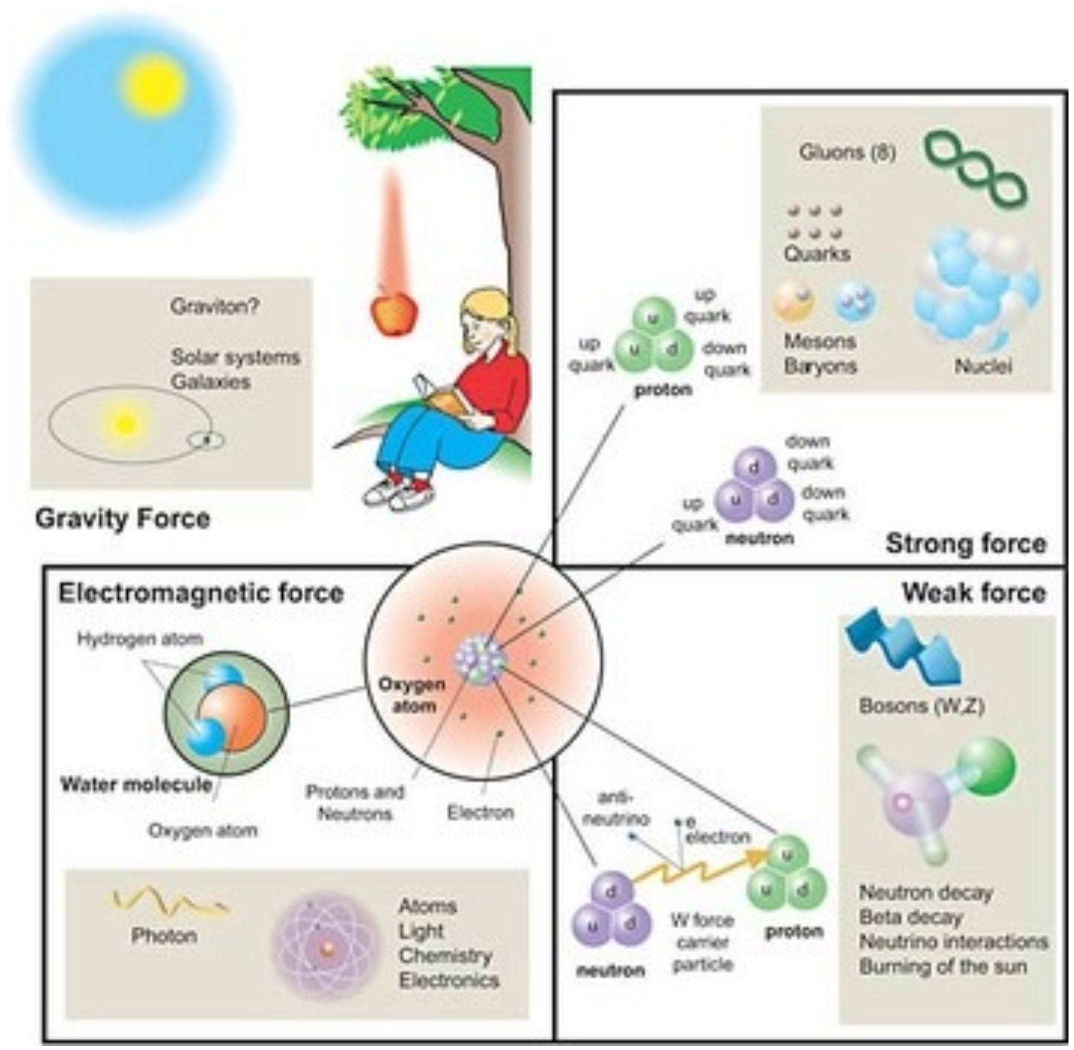


Illustration:[http://cdn2-b.examiner.com]

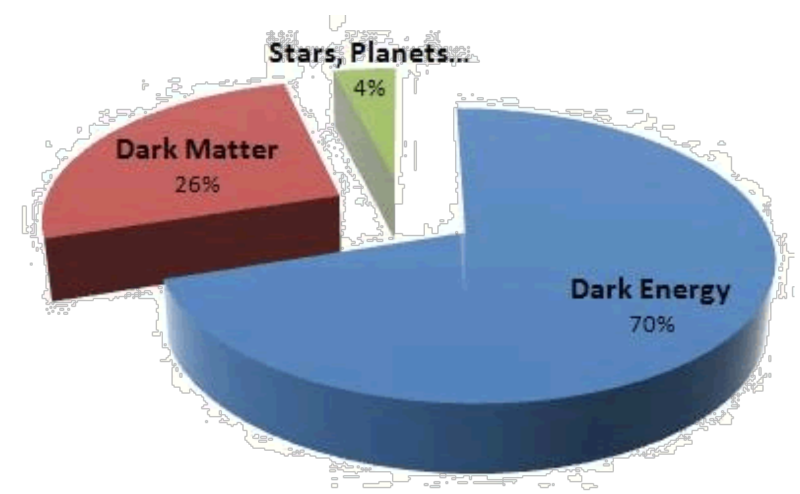


Illustration:[http://www.speed-light.info]

Standard model of particle physics

- **Interactions (not) present in SM**
  - ➡ Electromagnetic
  - ➡ Weak
  - ➡ Strong
  - ➡ Yukawa
  - ➡ Gravity

- **Is there some new physics beyond standard model (SM) ?**
  - ➡ dark matter
  - ➡ dark energy
  - ➡ hierarchy problem
  - ➡ strong CP-problem
  - ➡ matter/anti-matter asymmetry…

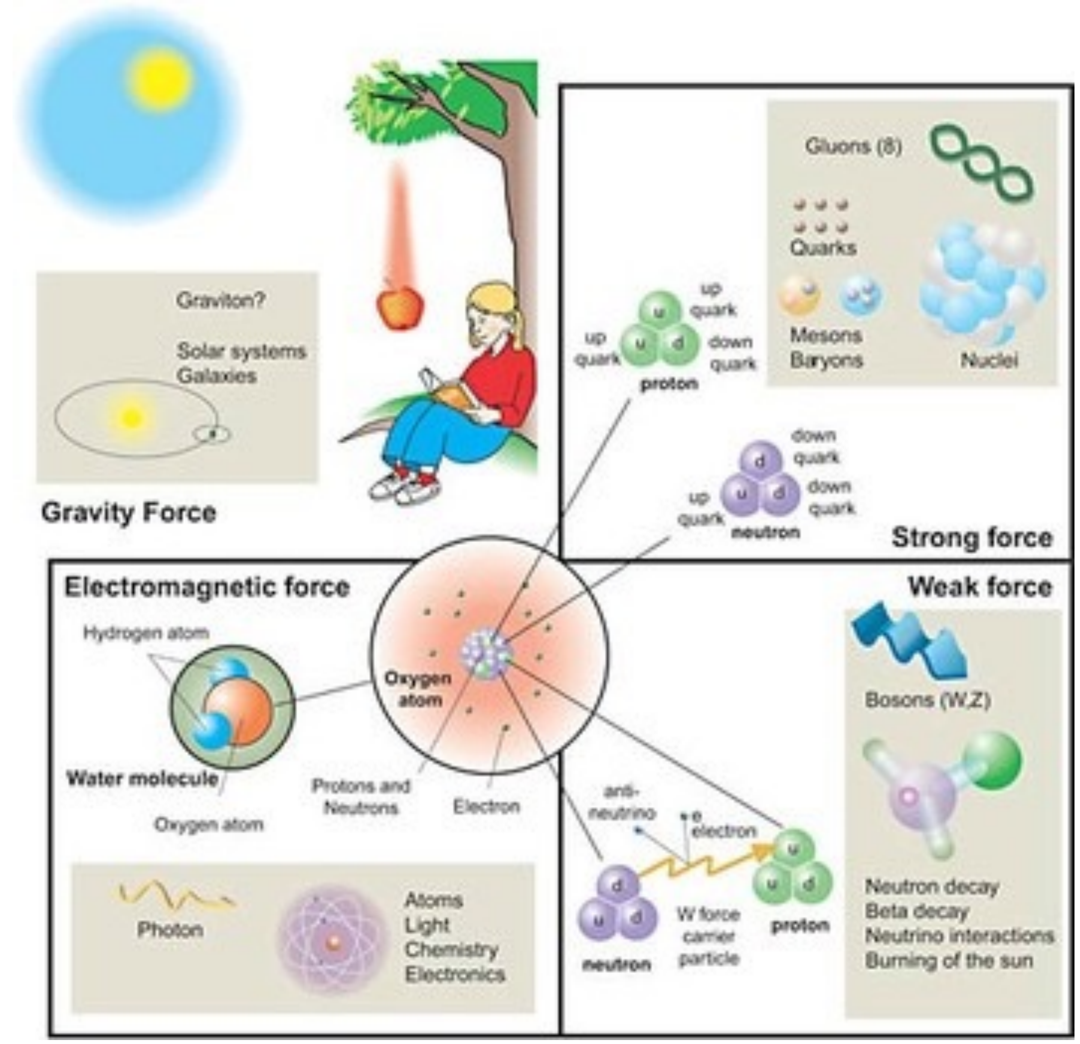


Illustration:[http://cdn2-b.examiner.com]

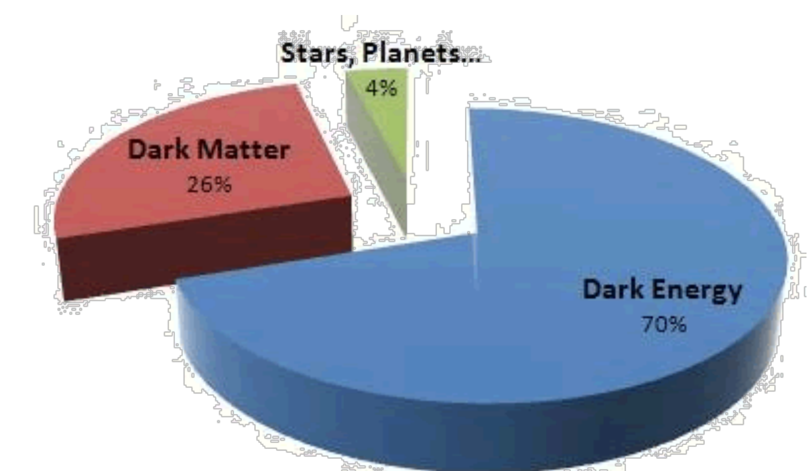
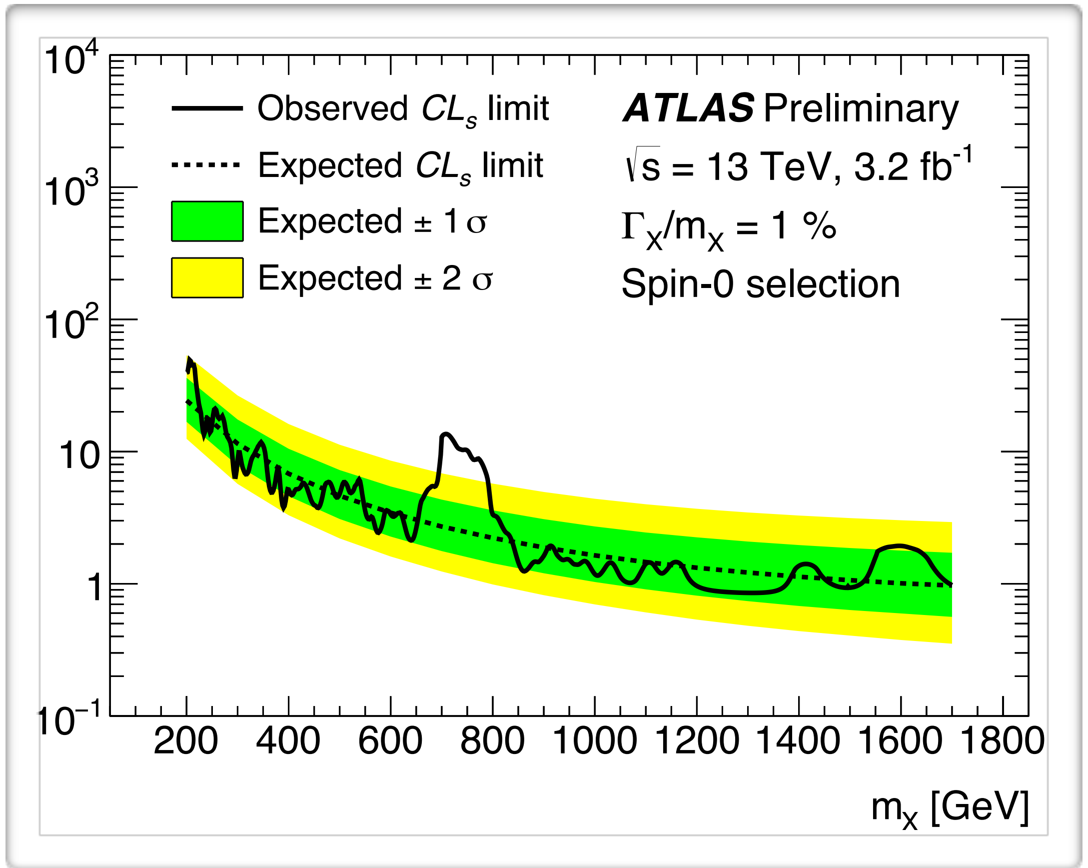


Illustration:[http://www.speed-light.info]

Looking for *new physics* beyond SM

- ➡ Direct searches
- ➡ Indirect searches

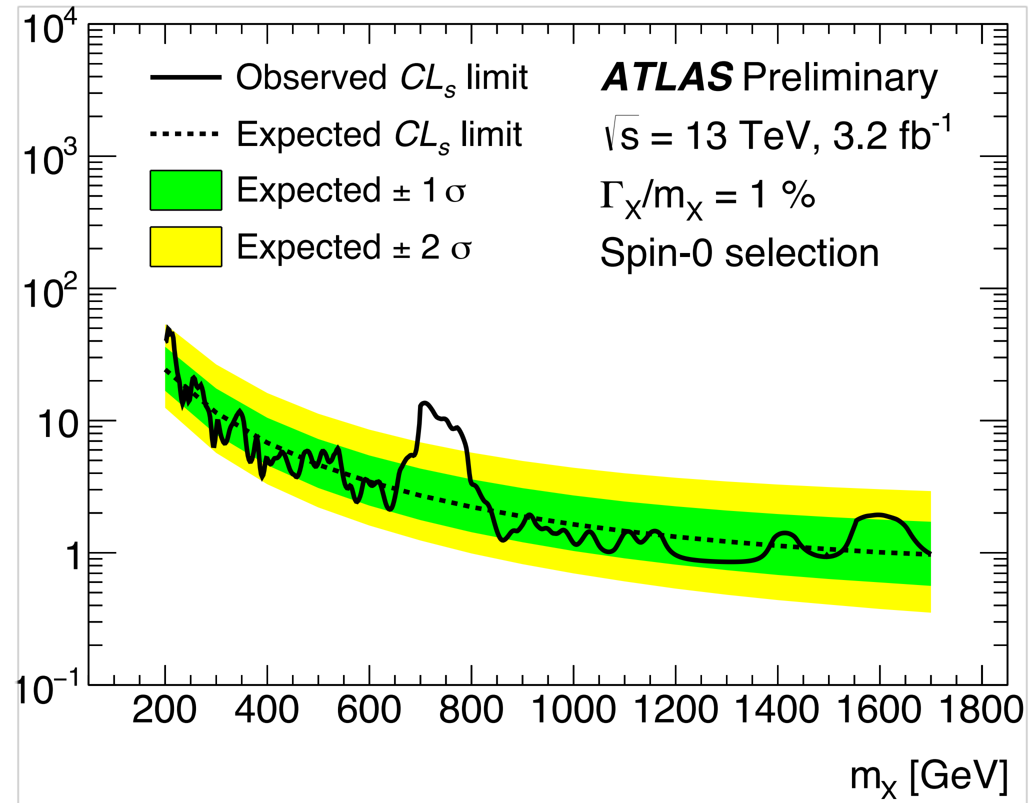


use experimental results and theory predictions to constrain the SM and figure out if there is a discrepancy indicating ***new physics (NP)***

- ➡ Theorist's job:
  - ➡ predicting the relevant input for the indirect searches of NP
  - ➡ creating a model that accommodates the potential discoveries of NP

Looking for *new physics* beyond SM

- ➡ Direct searches
- ➡ Indirect searches

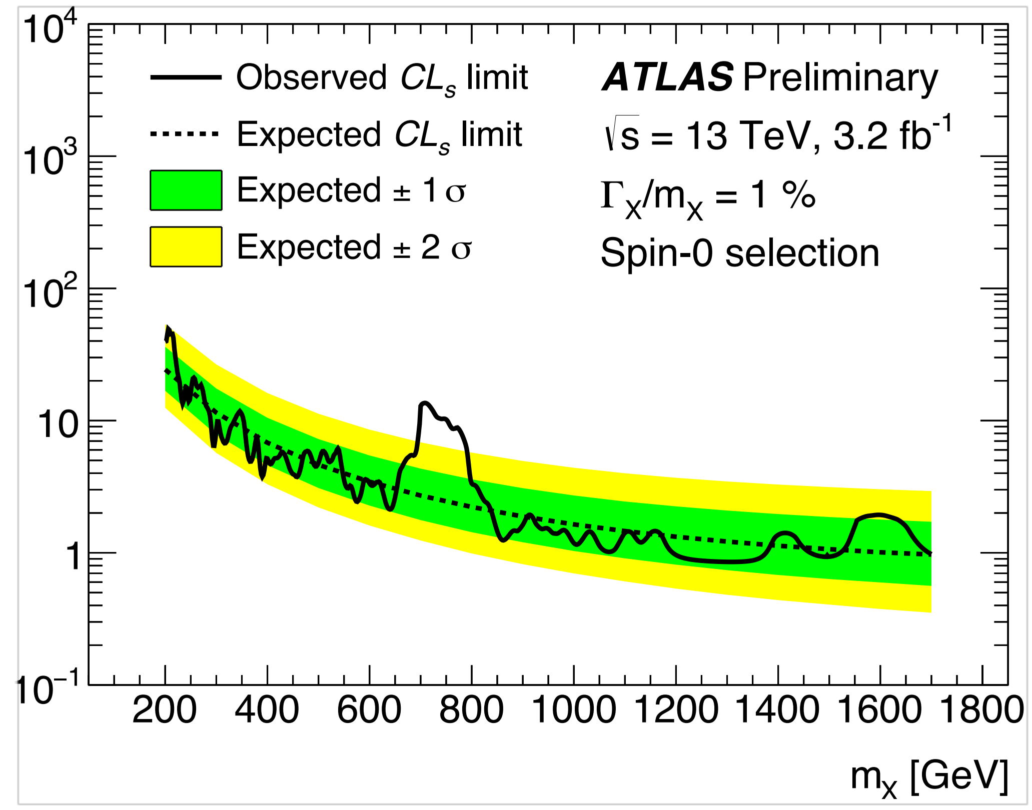


use experimental results and <u>theory predictions</u> to constrain the SM and figure out if there is a discrepancy indicating ***new physics (NP)***

- ➡ <u>Theorist's job:</u>
  - ➡ predicting the relevant input for the indirect searches of NP
  - ➡ creating a model that accommodates the potential discoveries of NP

Looking for *new physics* beyond SM

Dominating uncertainties:
Quantum Chromodynamics
(theory of strong interaction)

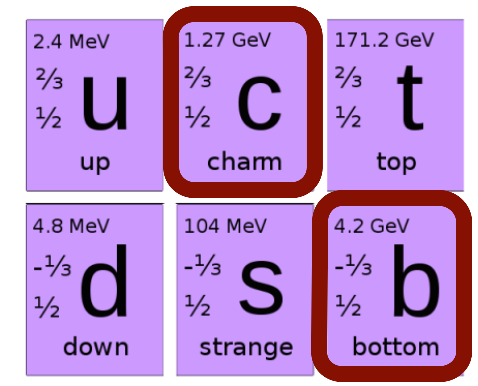


use experimental results and theory predictions to constrain the SM and figure out if there is a discrepancy indicating ***new physics (NP)***

- ➡ Theorist's job:
  - ➡ predicting the relevant input for the indirect searches of NP
  - ➡ creating a model that accommodates the potential discoveries of NP

The quest for New Physics beyond SM

- **Searches for rare processes and for tiny deviations from Standard model expectations**



- **Heavy flavour physics**

➡ Experimental values (**BaBar, Belle, LHCb)**

$$R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to Dl\overline{\nu}_l)} = 0.44 \pm 0.07$$

$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*l\overline{\nu}_l)} = 0.33 \pm 0.03$$

➡ SM prediction:

$$R(D)_{SM} = 0.297 \pm 0.017$$

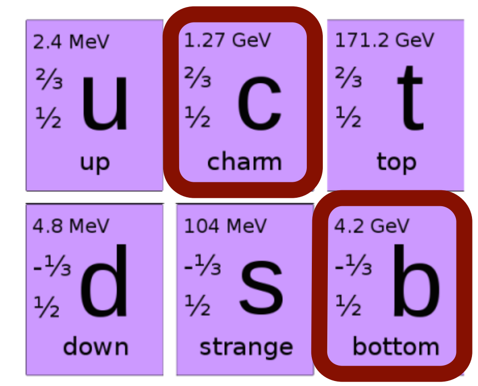
$$R(D^*)_{SM} = 0.252 \pm 0.003$$

➡ New intensity frontier experiments planned to crosscheck these measurements (e.g. **Belle II**)

The quest for New Physics beyond SM

- **Searches for rare processes and for tiny deviations from Standard model expectations**

- **Heavy flavour physics**



➡ Experimental values (**BaBar, Belle, LHCb)**

$$R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to Dl\overline{\nu}_l)} = 0.44 \pm 0.07$$

$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*l\overline{\nu}_l)} = 0.33 \pm 0.03$$

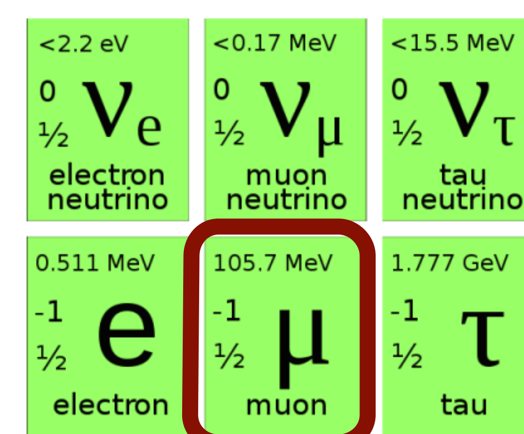
➡ SM prediction:

$$R(D)_{SM} = 0.297 \pm 0.017$$

$$R(D^*)_{SM} = 0.252 \pm 0.003$$

➡ New intensity frontier experiments planned to crosscheck these measurements (e.g. **Belle II**)

- **Muon anomalous magnetic moment**

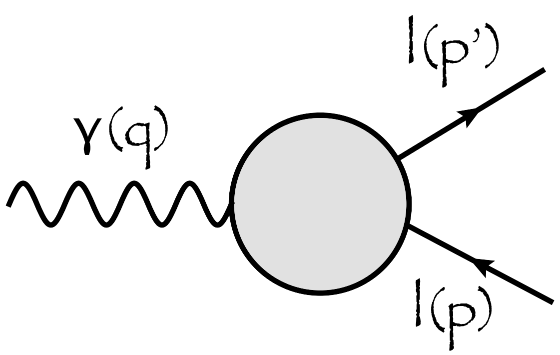


The magnetic moment of the lepton: a_l

- Intrinsic magnetic moment of any spinning particle

$$\vec{\mu} = g_l \frac{e\hbar}{2m_l c}\vec{S}$$

- For leptons, $s = \frac{1}{2}$, the giromagnetic factor from Dirac theory: $g_l = 2$



$$= (-ie)\bar{u}(p')\left[\gamma^\mu F_E(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_l}F_M(q^2)\right]u(p)$$

$$q = p' - p; \quad q^2 = 0: \quad F_E(0) = 1, F_M(0) = \boxed{a_l = \frac{g_l - 2}{2}}, l = e, \mu, \tau$$

➡ At what energies does the Standard Model stop to describe nature?

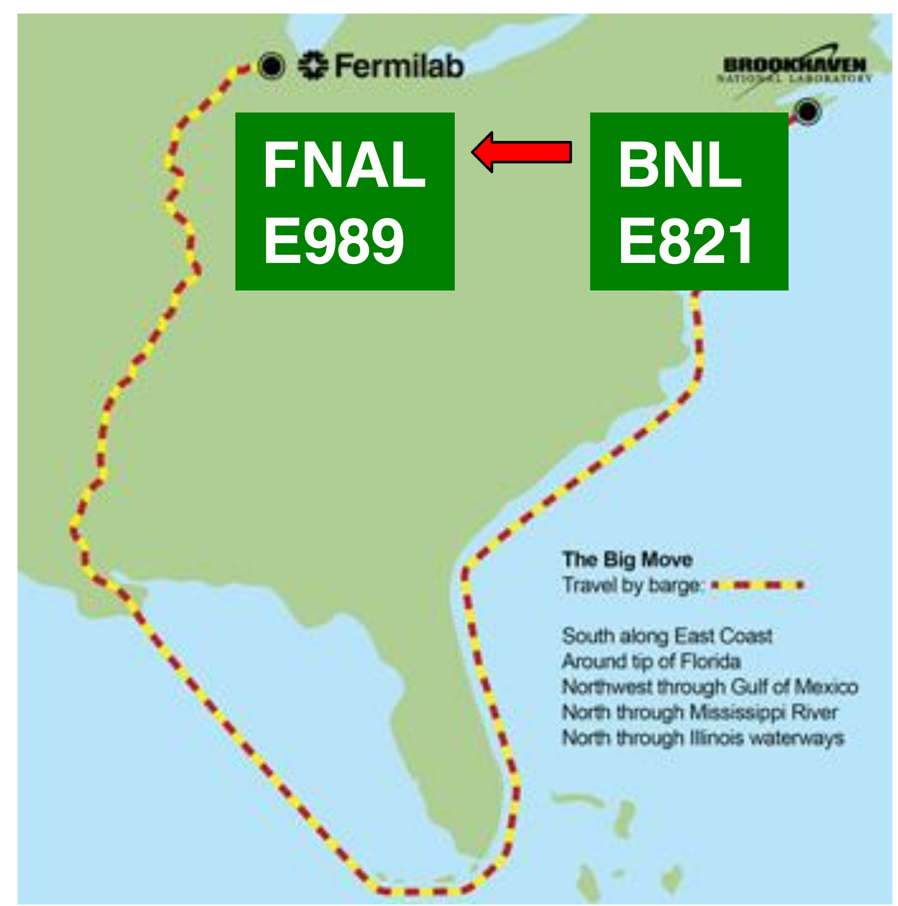
EXPERIMENT: a_μ^{exp} = 11659208.0(6.3) × 10 $^{-10}$ (0.54ppm) [**BNL E821, 2006-2008**]

THEORY: a_μ^{th} = 11659185.5(5.9) × 10 $^{-10}$ (0.51ppm) [**Benayoun et. al, arxiv:1507.02943**]

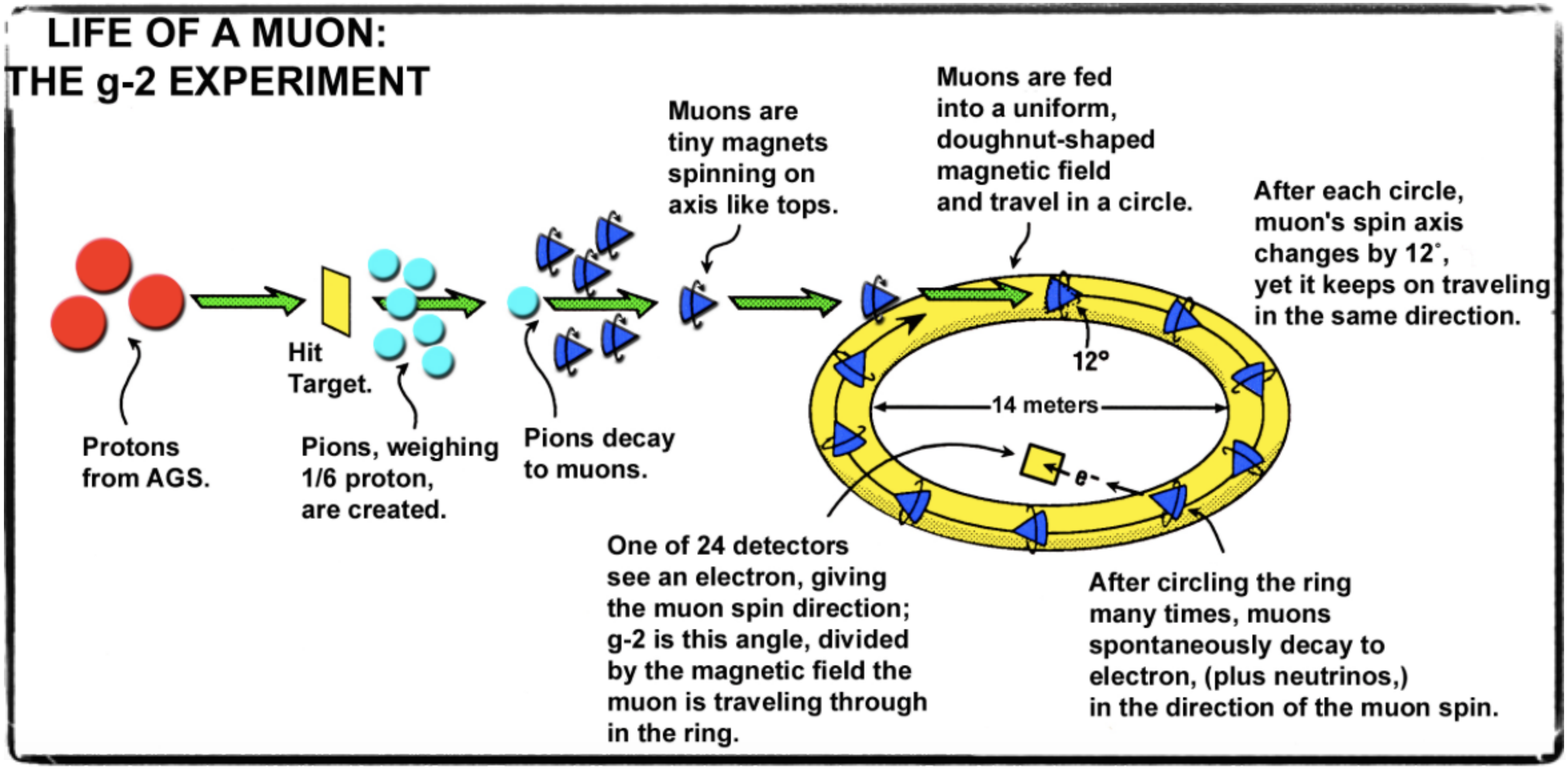
TENSION: **2.9- 4.5** σ

a_μ from the experiment: FNAL E989

- a_μ^{exp} = 11659208.0(6.3) × 10 $^{-10}$(0.54ppm) [**BNL, 2006-2008**]
- New experiments (J-PARC, FNAL E989) expected to perform 4× more precise measurement
- Improved precision of the theoretical estimates with dominating uncertainty required



a_μ from the experiment [BNL -> FNAL] [http://www.g-2.bnl.gov]

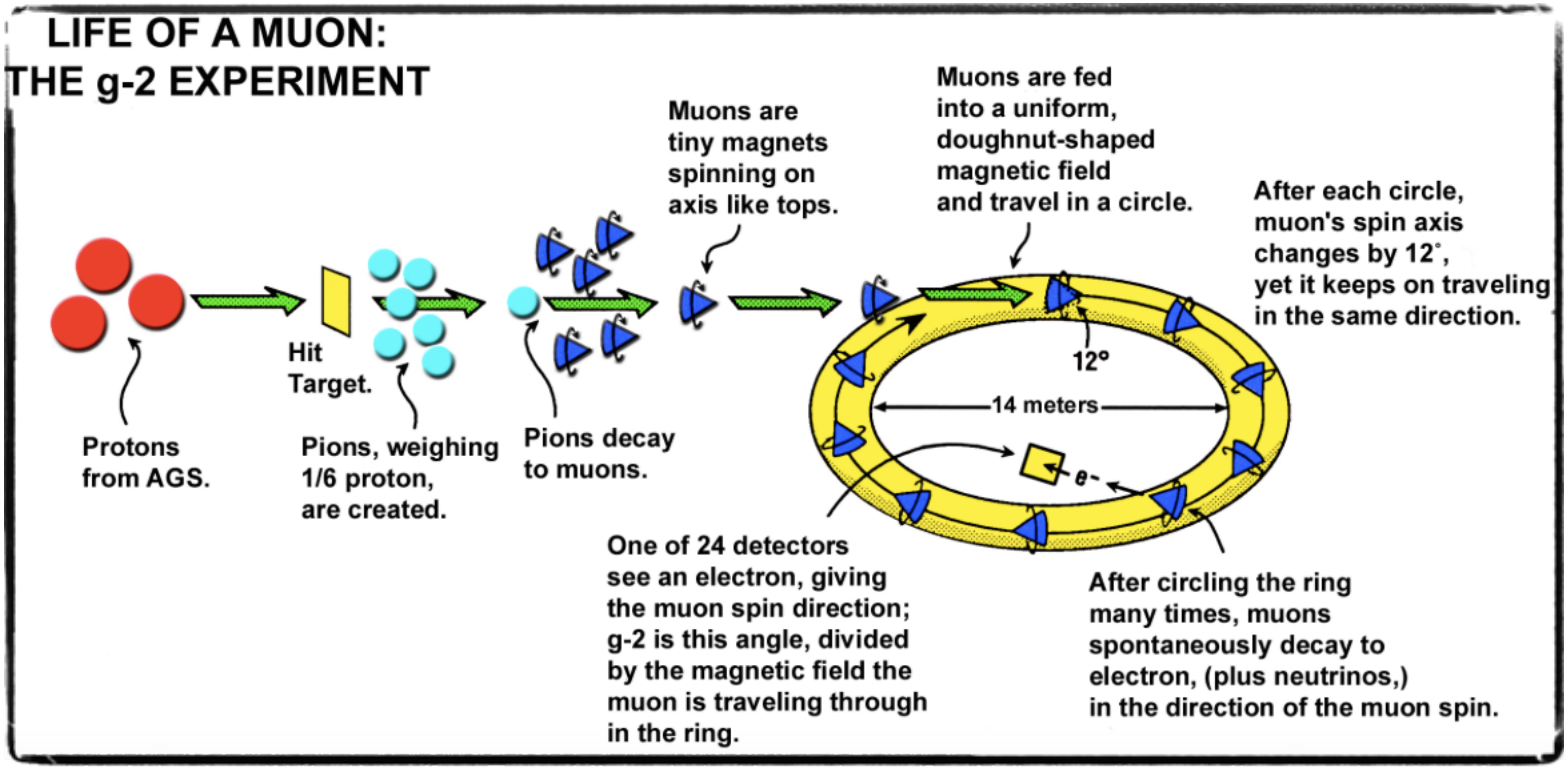


- Measured using polarised muons circulating in E and B fields

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

- At a momentum where $\beta \times E$ terms cancel (‘magic momentum’, $\gamma \approx 29.3$), the difference between spin and cyclotron frequencies:

a_μ from the experiment [BNL -> FNAL] [http://www.g-2.bnl.gov]



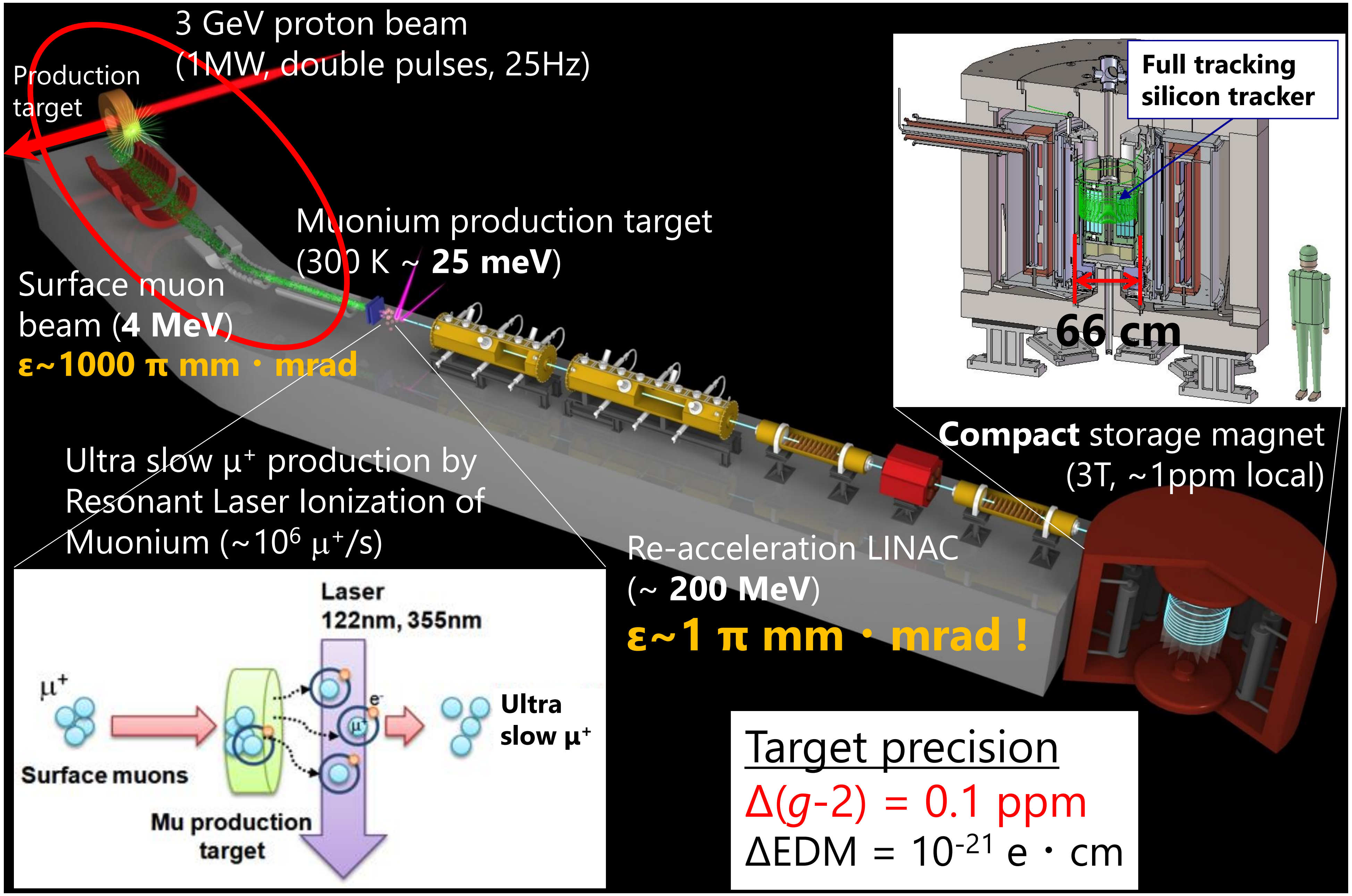
- Measured using polarised muons circulating in E and B fields

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

- At a momentum where $\beta \times E$ terms cancel ('magic momentum', $\gamma \approx 29.3$), the difference between spin and cyclotron frequencies:

$$\omega_a = -\frac{e}{m} \boxed{a_\mu} B$$

a_μ from the experiment: J-PARC E34



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

Ultra slow muon beam:
E-term cancels again

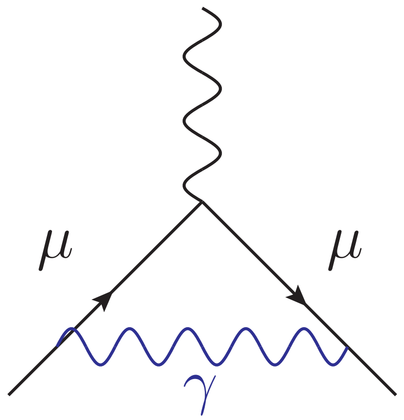
T.Yamazaki (@KEK 2018 g-2 WS): muon RF acceleration for the first time last month!

a_μ from the theory (SM + other experiments)

- BNL E982 experiment result and different th. contributions:

	a_μ $[10^{-11}]$	Δa_μ $[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.95	0.04
electroweak, total	153.6	1.0
HVP (LO) [Hagiwara et al. 11]	6 949.	43.
HVP (NLO) [Hagiwara et al. 11]	−98.	1.
HLbL [Jegerlehner-Nyffeler 09]	116.	40.
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.	2.
theory	116 591 855.	59.

$$\boxed{a_\mu^{exp} - a_\mu^{th,SM} \approx 3\sigma}$$



Schwinger 1948

$$a_\mu^{QED(1)} = \left(\frac{\alpha}{2\pi}\right)$$

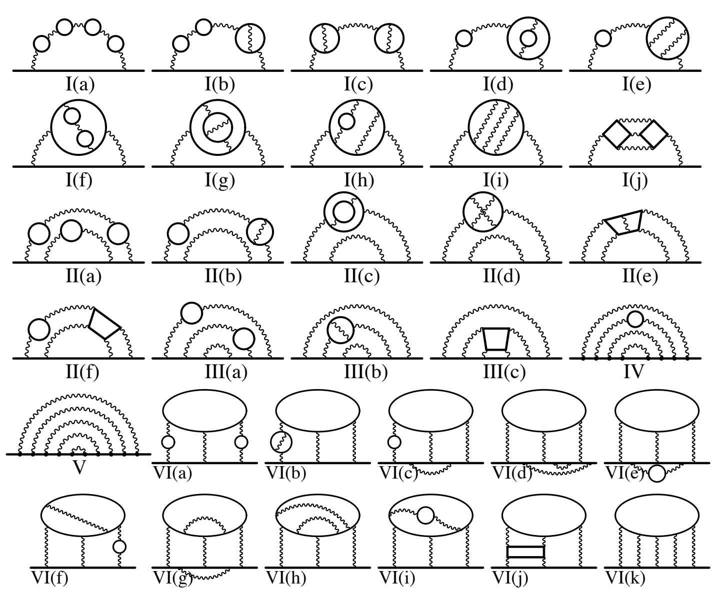
- Schwinger's result : g_e=2.00232
- Foley's experimental result: g_e=2.00238(10)
- First great success of QFT!

a_μ from the theory (SM + other experiments)

- BNL E982 experiment result and different th. contributions:

	$a_\mu\,[10^{-11}]$	$\Delta a_\mu\,[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.95	0.04
electroweak, total	153.6	1.0
HVP (LO) [Hagiwara et al. 11]	6 949.	43.
HVP (NLO) [Hagiwara et al. 11]	−98.	1.
HLbL [Jegerlehner-Nyffeler 09]	116.	40.
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.	2.
theory	116 591 855.	59.

$$a_\mu^{exp} - a_\mu^{th,SM} \approx 3\sigma$$



Kinoshita et al. 2012

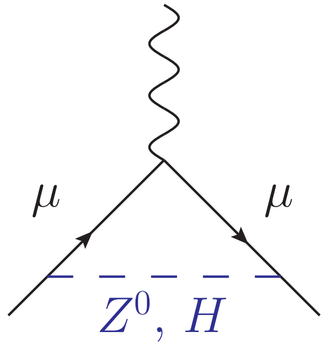
Universal part: checked by S. Laporta
[arXiv:1704.06996]
(computed up to 1100! digits)

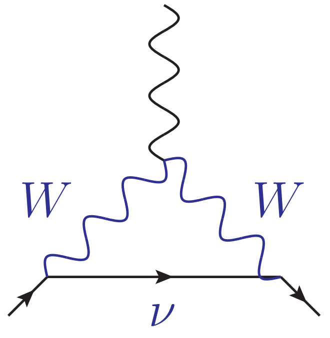
a_μ from the theory (SM + other experiments)

- BNL E982 experiment result and different th. contributions:

	$a_\mu\,[10^{-11}]$	$\Delta a_\mu\,[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.95	0.04
electroweak, total	153.6	1.0
HVP (LO) [Hagiwara et al. 11]	6 949.	43.
HVP (NLO) [Hagiwara et al. 11]	−98.	1.
HLbL [Jegerlehner-Nyffeler 09]	116.	40.
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.	2.
theory	116 591 855.	59.

$$a_\mu^{exp} - a_\mu^{th,SM} \approx 3\sigma$$





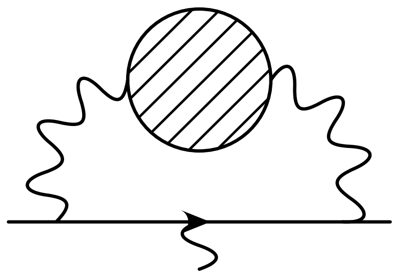
Czarnecki, Marciano, Vainshtein 2003
Heinemeyer, Stoeckinger, Weiglein 2004
Gribouk, Czarnecki 2005

a_μ from the theory (SM + other experiments)

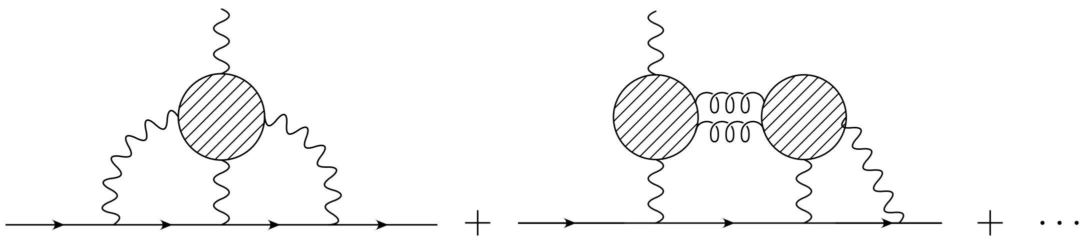
- BNL E982 experiment result and different th. contributions:

	$a_\mu\,[10^{-11}]$	$\Delta a_\mu\,[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.95	0.04
electroweak, total	153.6	1.0
HVP (LO) [Hagiwara et al. 11]	6 949.	43.
HVP (NLO) [Hagiwara et al. 11]	−98.	1.
HLbL [Jegerlehner-Nyffeler 09]	116.	40.
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.	2.
theory	116 591 855.	59.

$$a_\mu^{exp} - a_\mu^{th,SM} \approx 3\sigma$$



Hadronic Vacuum Polarisation



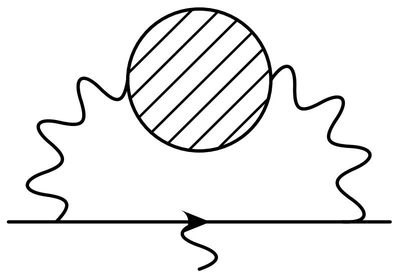
Hadronic Light by Light contribution

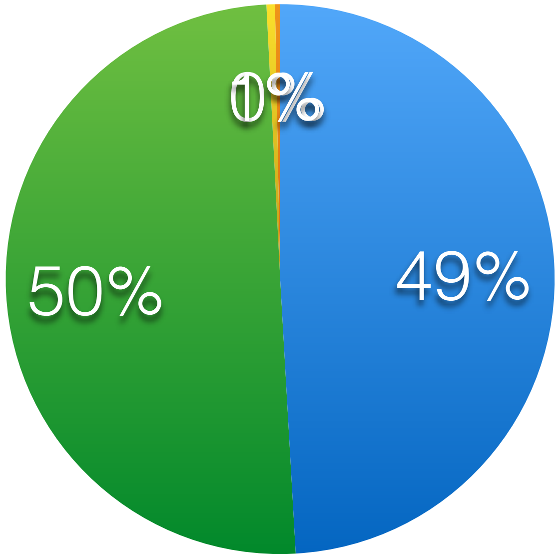
a_μ from the theory (SM + other experiments)

- BNL E982 experiment result and different th. contributions:

	$a_\mu\,[10^{-11}]$	$\Delta a_\mu\,[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.95	0.04
electroweak, total	153.6	1.0
HVP (LO) [Hagiwara et al. 11]	6 949.	43.
HVP (NLO) [Hagiwara et al. 11]	−98.	1.
HLbL [Jegerlehner-Nyffeler 09]	116.	40.
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.	2.
theory	116 591 855.	59.

$$a_\mu^{exp} - a_\mu^{th,SM} \approx 3\sigma$$



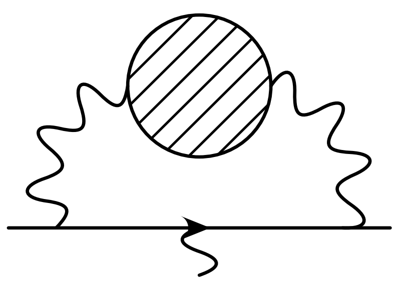


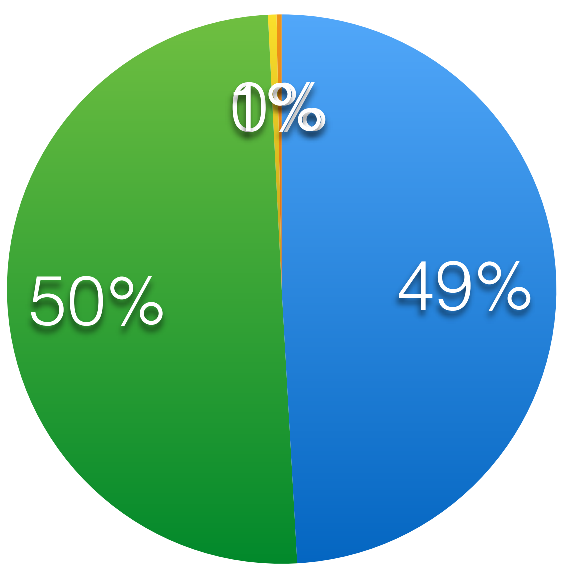
a_μ from the theory (SM + other experiments)

- BNL E982 experiment result and different th. contributions:

	$a_\mu\,[10^{-11}]$	$\Delta a_\mu\,[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.95	0.04
electroweak, total	153.6	1.0
HVP (LO) [Hagiwara et al. 11]	6 949.	43.
HVP (NLO) [Hagiwara et al. 11]	−98.	1.
HLbL [Jegerlehner-Nyffeler 09]	116.	40.
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.	2.
theory	116 591 855.	59.

$$a_\mu^{exp} - a_\mu^{th,SM} \approx 3\sigma$$





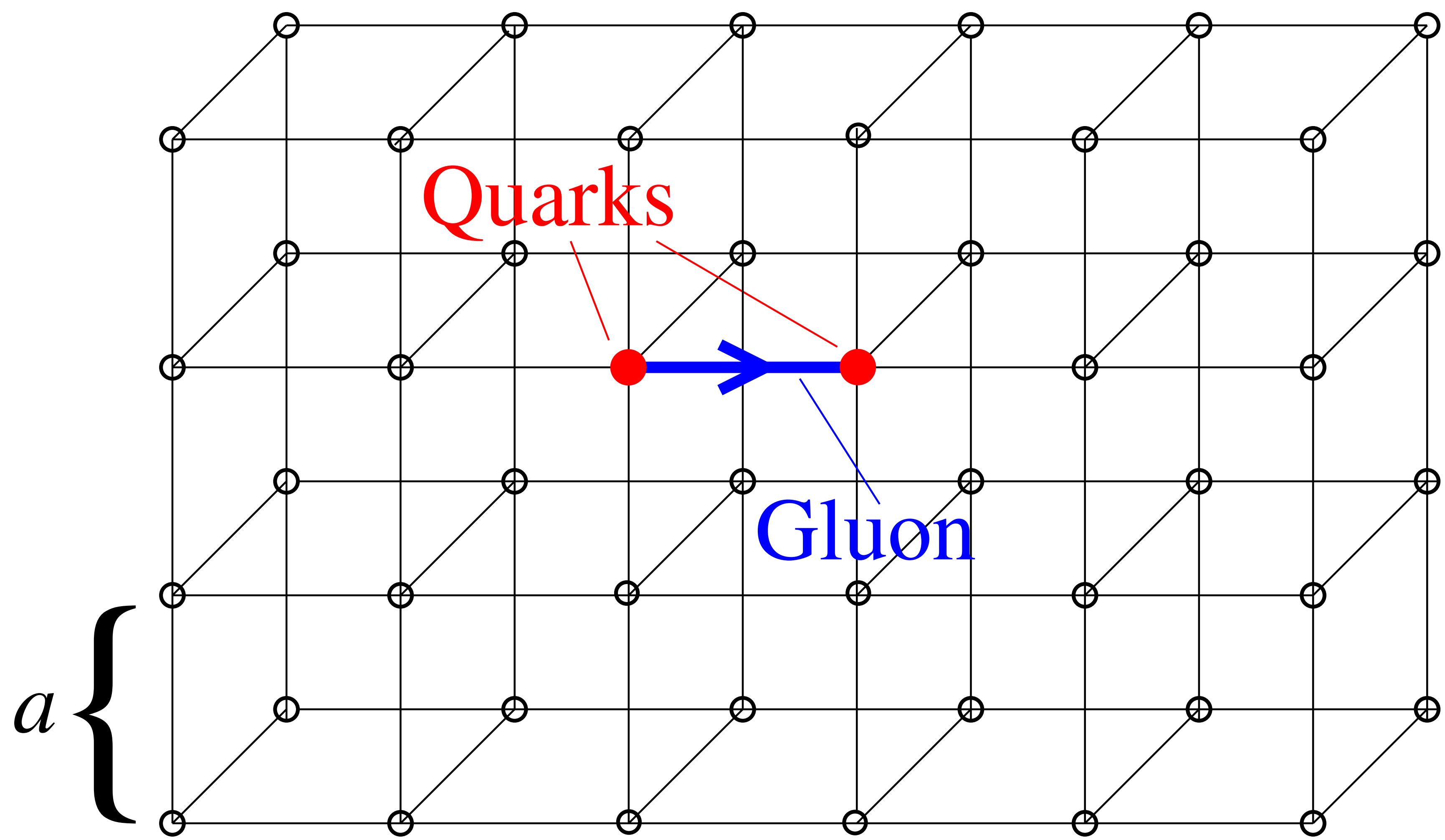
Lattice QCD (+QED) provide a way to compute these contributions in a model-independent way

From continuum to lattice QCD

$$
\begin{aligned}
S_{QCD}[\psi, \bar{\psi}, A] &= S_G + S_F \\
&= \frac{1}{2g} F_{\mu\nu} F_{\mu\nu} + \int d^4x \; \bar{\psi}(x) \; [\gamma_\mu \; (\partial_\mu + iA_\mu(x)) + m] \; \psi(x)
\end{aligned}
$$

$$
\begin{aligned}
x &\longrightarrow n = (n_1, n_2, n_3, n_4) \;\; n_1 = 0, \ldots, N-1 \\
\psi(x), \bar{\psi}(x) &\longrightarrow \psi(n), \bar{\psi}(n) \\
\int d^4x \ldots &\longrightarrow a^4 \sum_n \ldots \\
\partial_\mu \; \psi(x) &\longrightarrow \frac{\psi(n+\hat{\mu}) - \psi(n-\hat{\mu})}{2a} + \mathcal{O}(a^2)
\end{aligned}
$$

Non-perturbative QCD

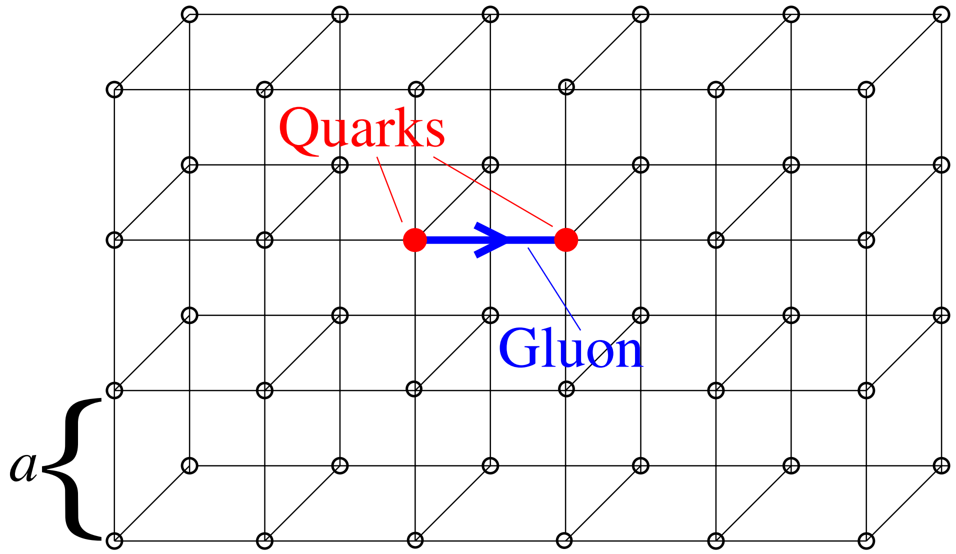


"Lattice QCD"

Quarks $\sim \overline{\psi}(x), \psi(x)$

Gluons $\sim U_\mu(x) = e^{iagA_\mu}$

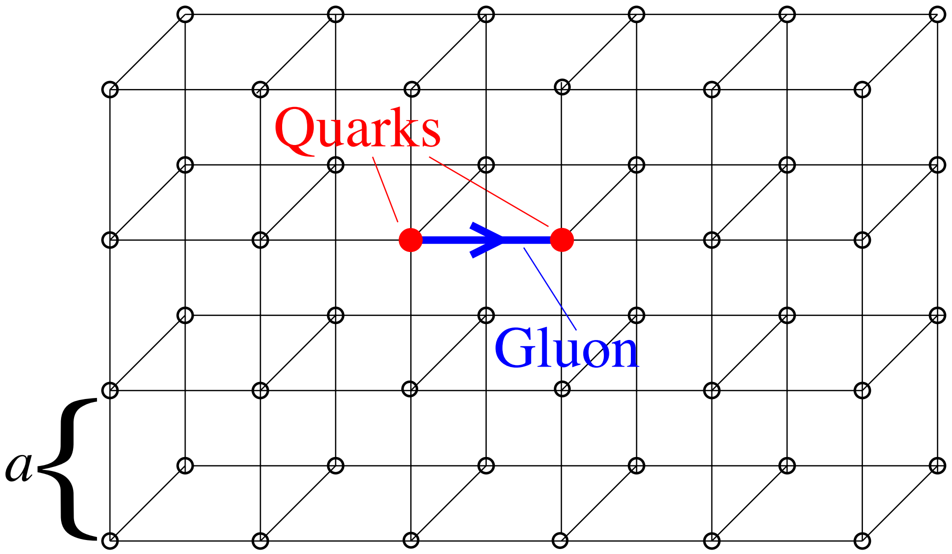
Non - perturbative computation of a_μ

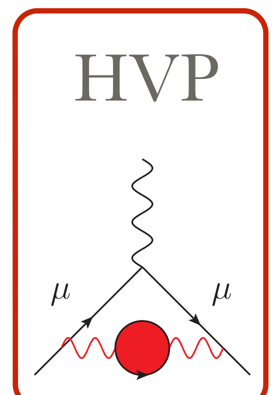


Recipe for lattice QCD computation :

1. Generate ensembles of field configurations using **Monte Carlo**
2. Average over a set of configurations:
   - ➡ Compute correlation function of fields, extract Euclidean matrix elements or amplitude
   - ➡ Computational cost dominated by quarks: inverses of large, sparse matrix
3. Extrapolate to continuum, infinite volume, physical quark masses (now directly accessible)

Non - perturbative computation of a_μ

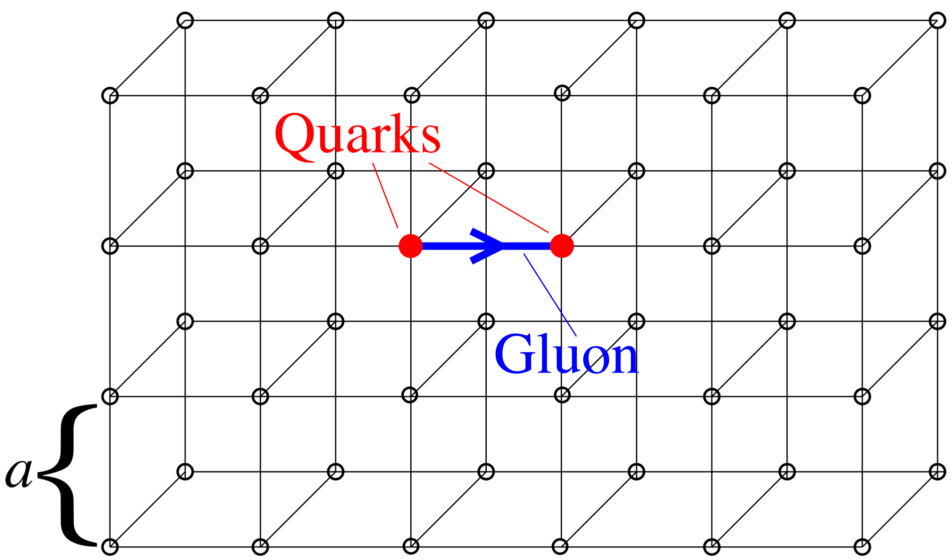




Recipe for lattice QCD computation :

1. Generate ensembles of field configurations using *Monte Carlo*
2. Average over a set of configurations:
   - ➡ Compute correlation function of fields, extract Euclidean matrix elements or amplitude
   - ➡ Computational cost dominated by quarks: inverses of large, sparse matrix
3. Extrapolate to continuum, infinite volume, physical quark masses (now directly accessible)

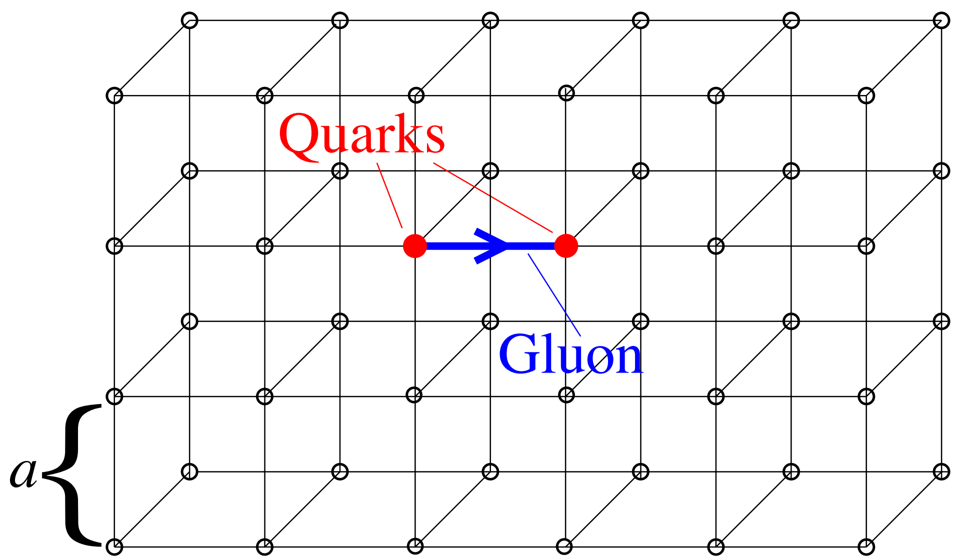
Lattice QCD computation



Typical lattice QCD computation :

- physical lattice size: **~3fm**, spacing **~0.5fm**
- **32^3 x 64** lattice —> **2 x 10^6** points
- propagation in time: multiple inversions of **10^6 x 10^6** matrices
- advanced algorithms
- large computer resources: **several TFlop years!**

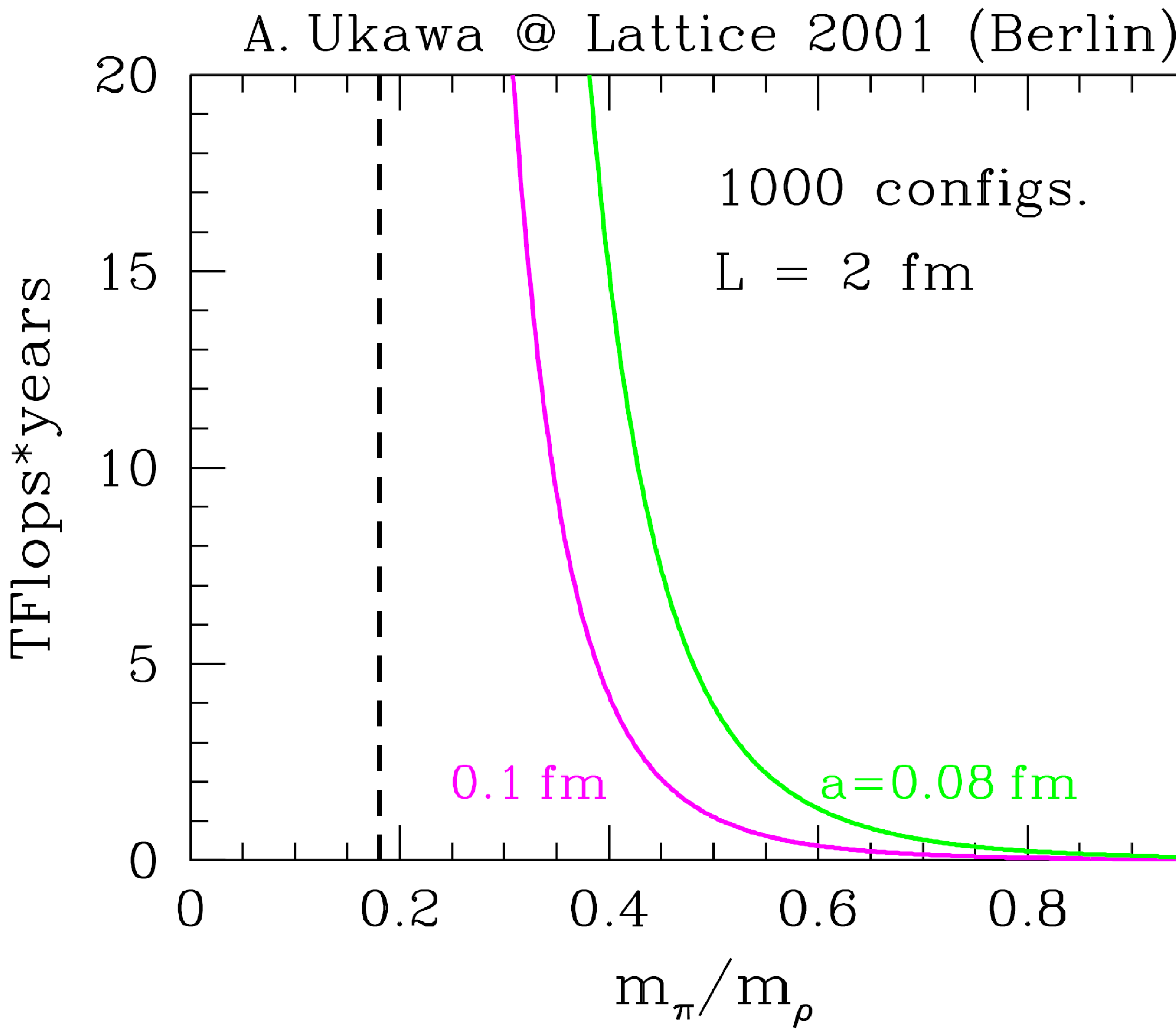
Non - perturbative computation of a_μ



Recipe for lattice QCD computation :

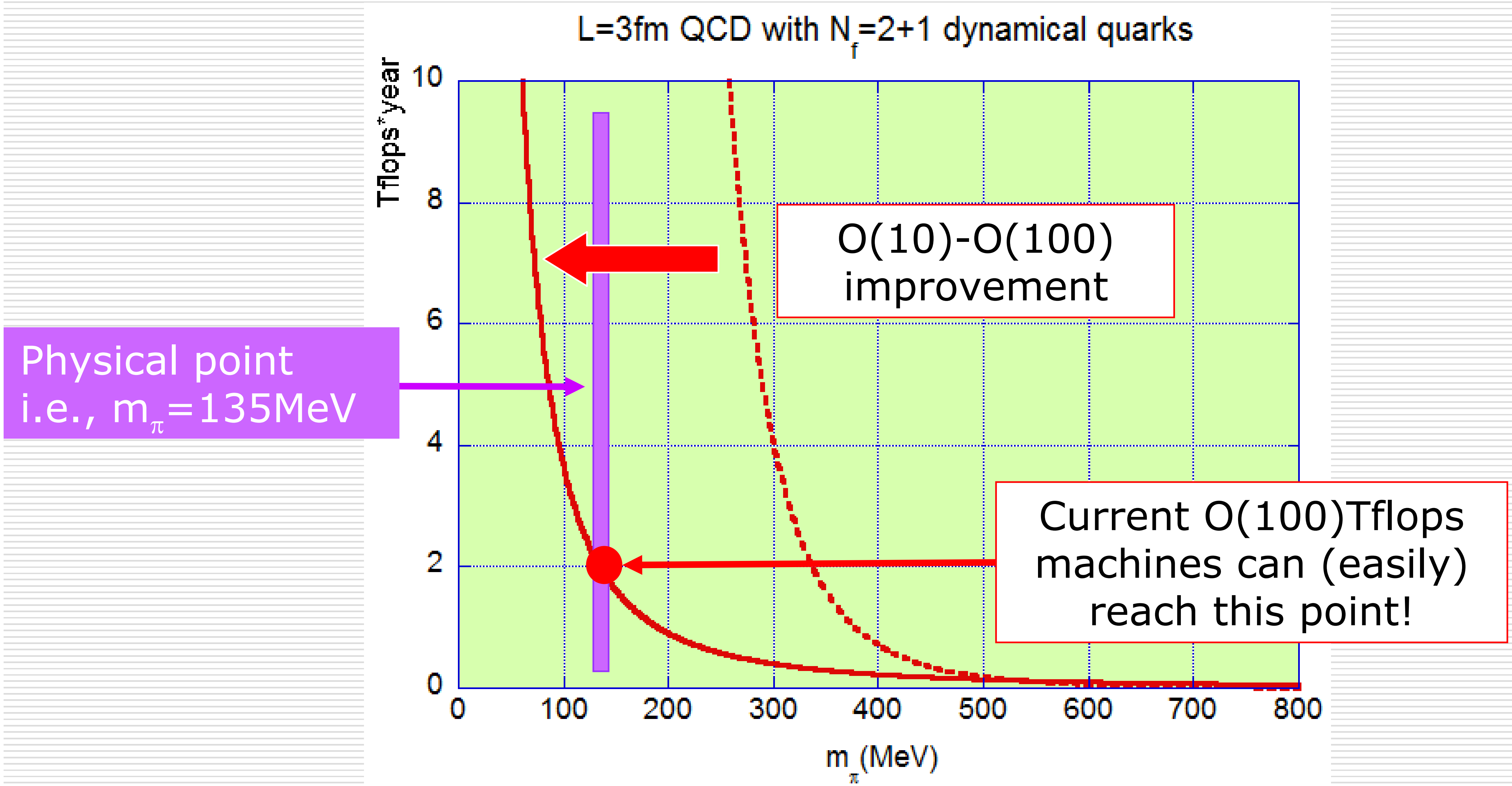
1. Generate ensembles of field configurations using *Monte Carlo*
2. Average over a set of configurations:
   - ➡ Compute correlation function of fields, extract Euclidean matrix elements or amplitude
   - ➡ Computational cost dominated by quarks: inverses of large, sparse matrix
3. Extrapolate to continuum, infinite volume, **physical quark masses** (now directly accessible)

Berlin Wall


A. Ukawa @ Lattice 2001 (Berlin)
1000 configs.
L = 2 fm
0.1 fm
a=0.08 fm
TFlops*years
m_π/m_ρ
0
5
10
15
20
0
0.2
0.4
0.6
0.8
1

[~start of my PhD]

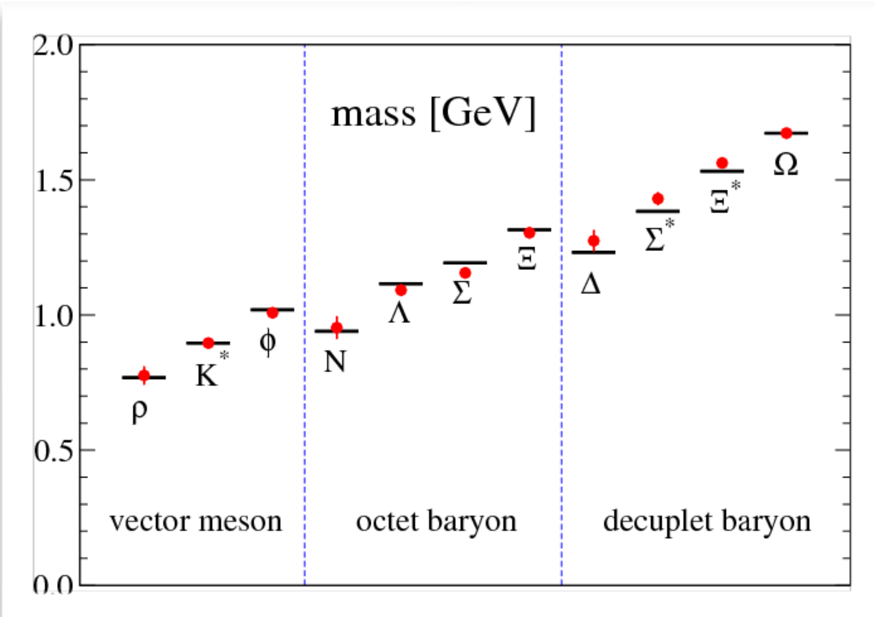
Berlin Wall update



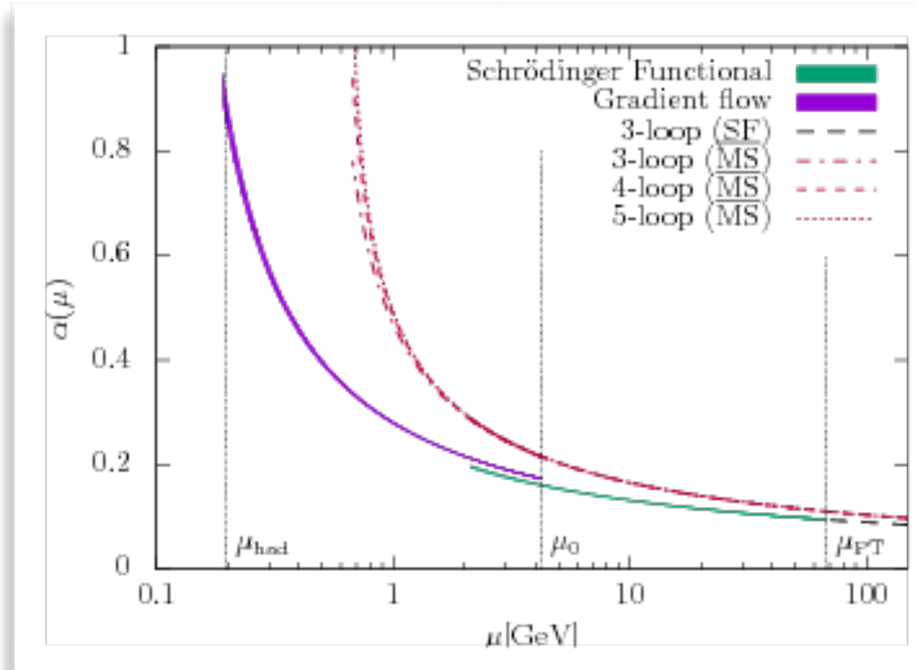
Physical Point Simulation has become reality

[Talk by A. Ukawa @CERN 2010]

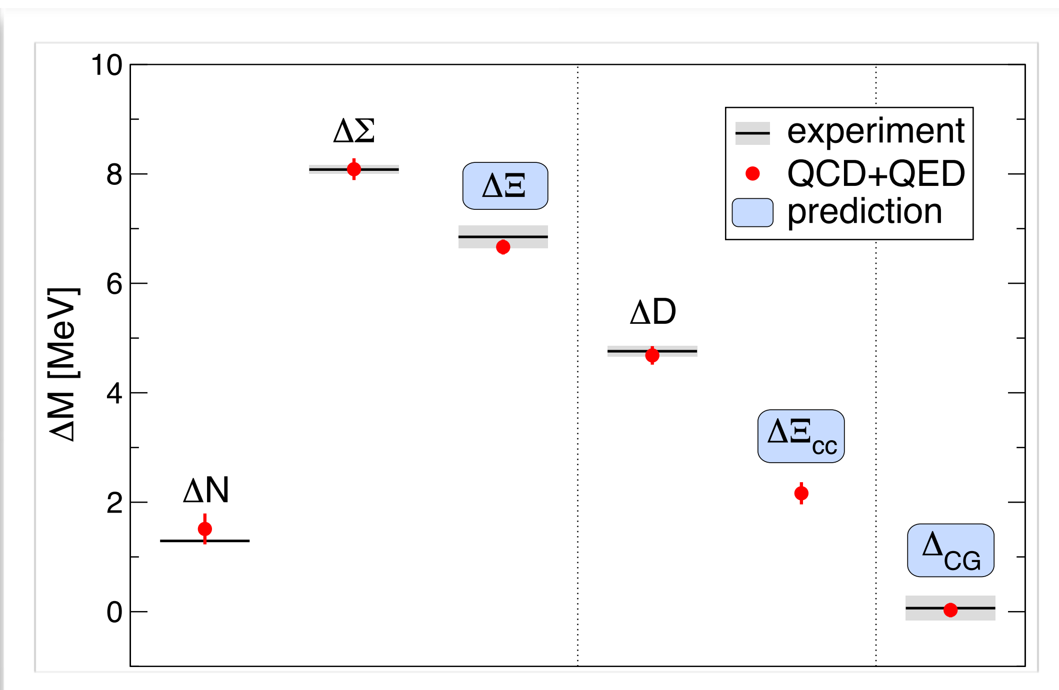
Highlights of modern lattice QCD computations



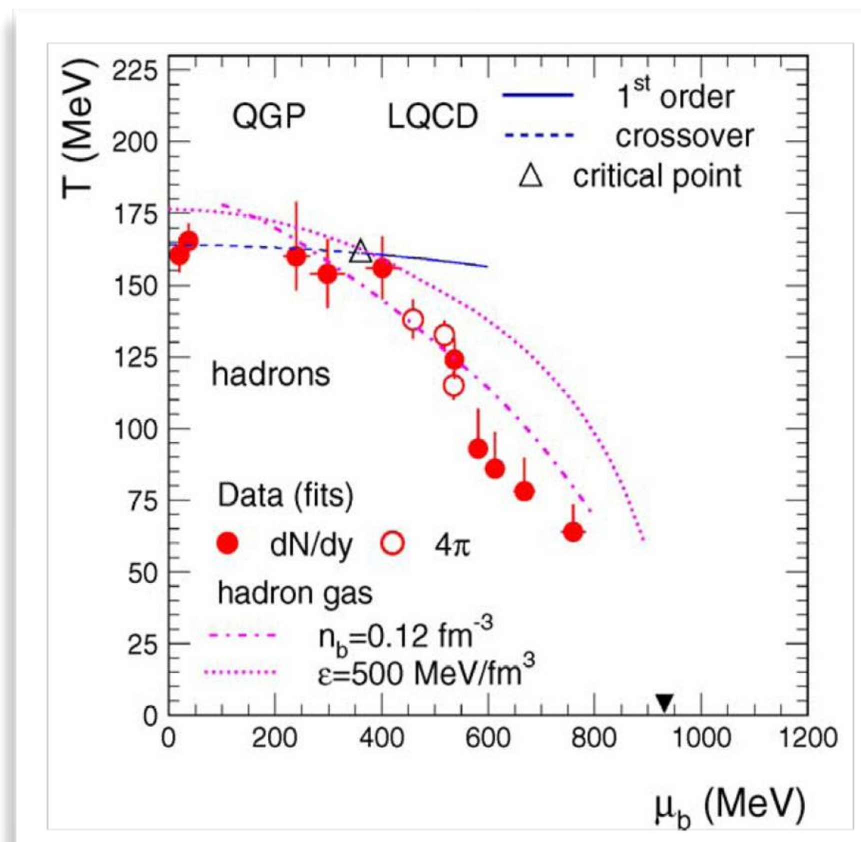
[Aoki et. al 2008]



[Bruno et. al 2017]

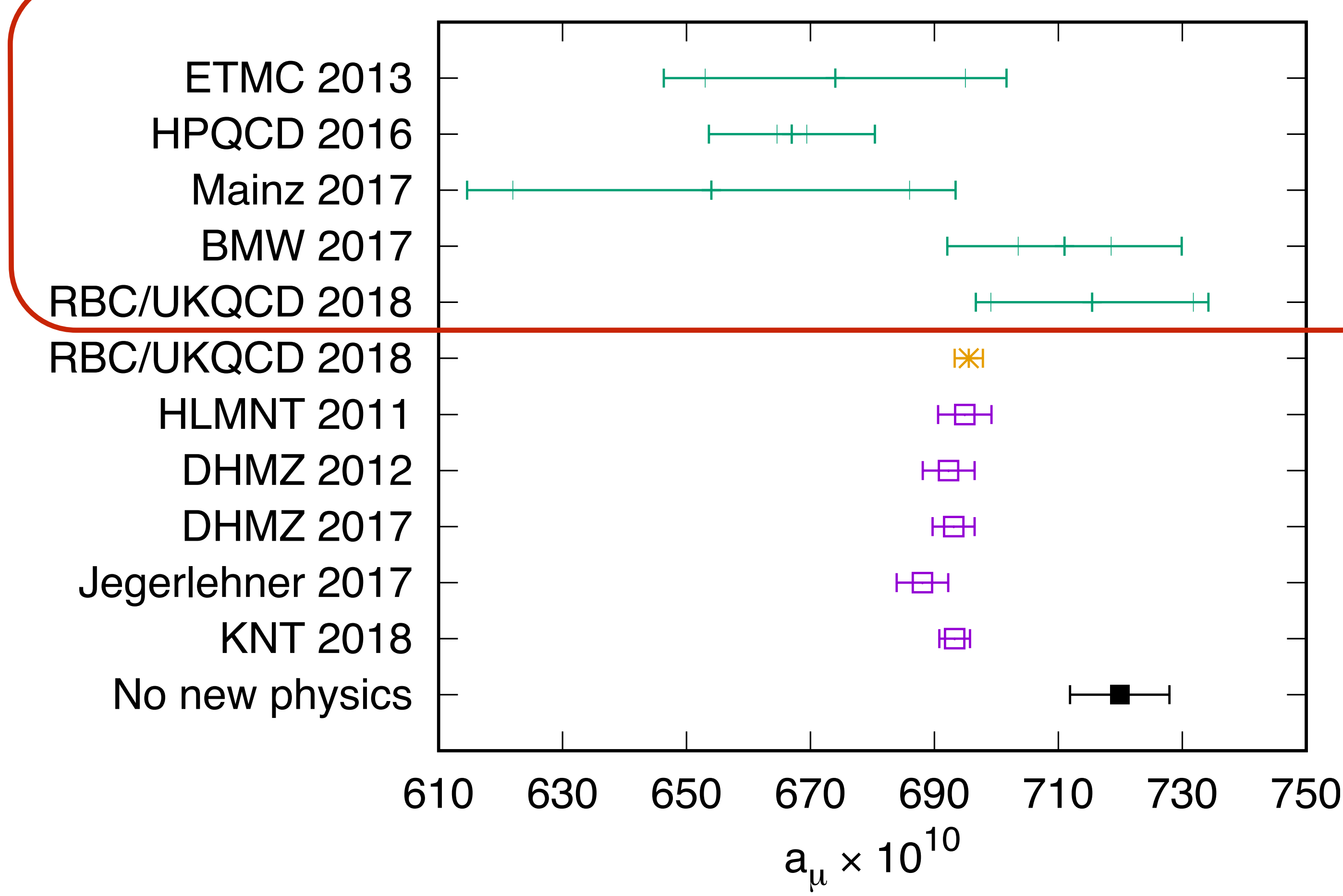


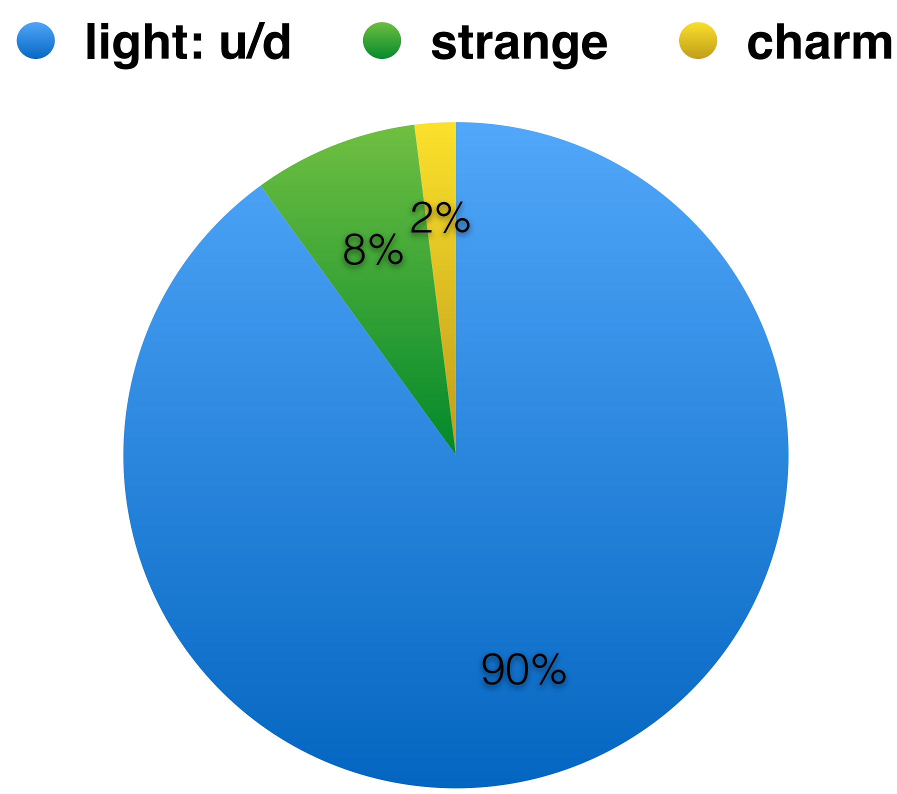
[Borsanyi et. al 2014]



[Hohne et. al 2009]

Summary: HVP from the lattice/R-ratios





Plot by C. Lehner @ KEK g-2 WS 2018

[**HPQCD: arXiv:1601.03071, Mainz: arXiv:1705.01775, BMW: arXiv:1711.04980, RBC/UKQCD: arXiv:1801.07224**]

1. Generate ensembles of field configurations using *Monte Carlo*
2. Average over a set of configurations:
   - ➡ Compute correlation function of fields, extract Euclidean matrix elements or amplitude
   - ➡ Computational cost dominated by quarks: inverses of large, sparse matrix
3. Extrapolate to continuum, infinite volume, physical quark masses, isospin breaking corrections

so far: m_u=m_d and α_{em}=0

Summary & Outlook

- Obtain predictions for new experiments and help verify/falsify extensions of the Standard Model
- **Muon anomalous magnetic moment** - good quantity for constraining new physics
- **Experimental** precision 0.54 p.p.m. —> **improvement 4x** expected (Fermilab, J-PARC, CERN?)
- **Lattice QCD** - needed to tackle the non-perturbative regime of QCD
- **Lattice FT** gives an independent theory prediction of **hadronic contributions**
- Large computing power and advanced algorithms needed

Thanks! Questions??

Next steps & new approaches:

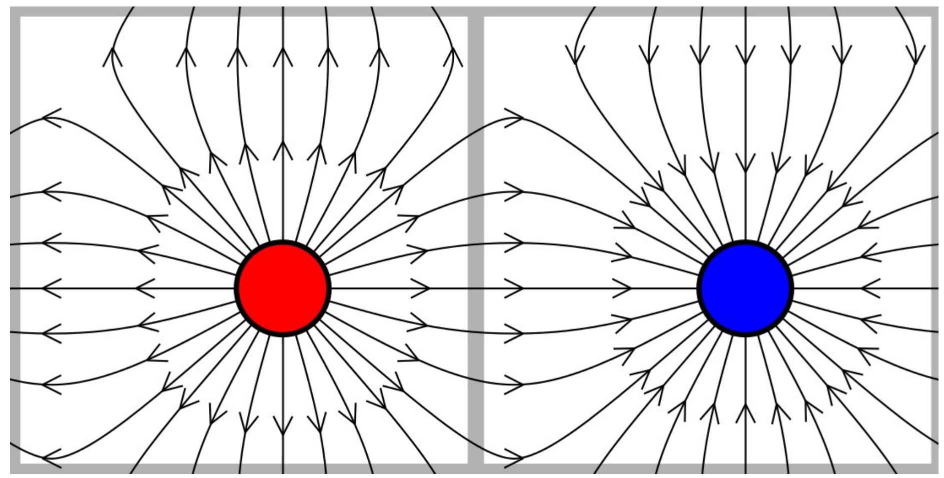
➡ Including electromagnetic interaction: **Lattice QCD+QED**

➡ Predictions for coming experiments: LHC(b), NA62, Fermilab g-2 (E981), RHIC, FAIR, …

➡ New experiments: **MUonE @ CERN**

➡ New algorithmic advances and new supercomputers for more extensive calculations

RC* Collaboration http://rcstar.web.cern.ch/



Rome II - University of Rome Tor Vergata

- N. Tantalo
- G.M. de Divitiis

CSIC, Santander

- Isabel Campos

CP3 - University of Southern Denmark

- Martin Hansen

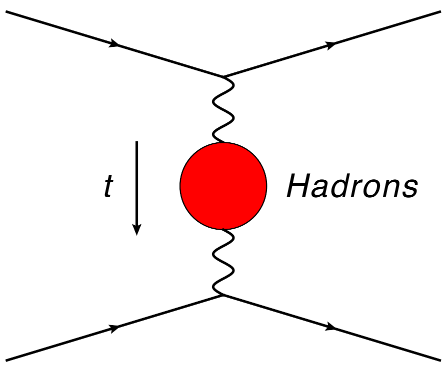
CERN

- Patrick Fritzsch
- Agostino Patella

Trinity College Dublin

- Alberto Ramos
- Marina Krstic Marinkovic

Space-like measurement of HVP @ CERN?



$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

- ➡ New proposals for the **space-like** experimental measurements of HVP
  - ➡ [Phys.Lett. B746 (2015) 325-329 by Carloni, Passera, Trentadue, Venanzoni] @KLOE2
  - ➡ [Eur.Phys.J. C77 (2017) no.3, 139 by Abbiendi et al.] MUonE **Physics beyond colliders@CERN**

G. Abbiendi, M. Alacevich, M. Bonomi, A. Broggio, C. Carloni Calame, E. Conti, E. Del Nobile, M. Fael, A. Ferroglia, D. Galli, F.V. Ignatov, M. Incagli, U. Marconi, M.K. Marinković, P. Mastrolia, C. Matteuzzi, G. Montagna, O. Nicrosini, G. Ossola, L. Pagani, P. Paradisi, M. Passera, C. Patrignani, F. Piccinini, F. Pisani, M. Prest, A. Primo, A. Principe, M. Pruna, M. Rocco, U. Schubert, F. Simonetto, L. Tancredi, R. Tenchini, L. Trentadue, E. Vallazza, G. Venanzoni, A. Vicini…

JOIN US!