Flavour and Precision Physics

WG summary (experiment), Angela Papa - PSI; WIN2017

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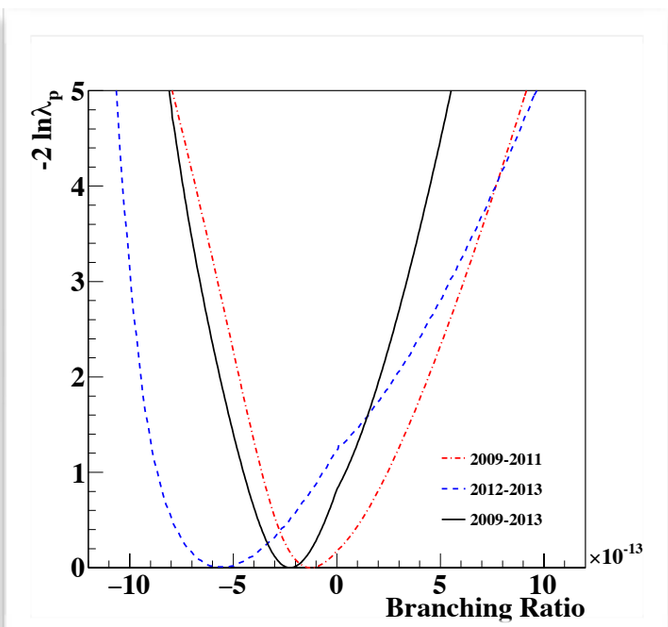
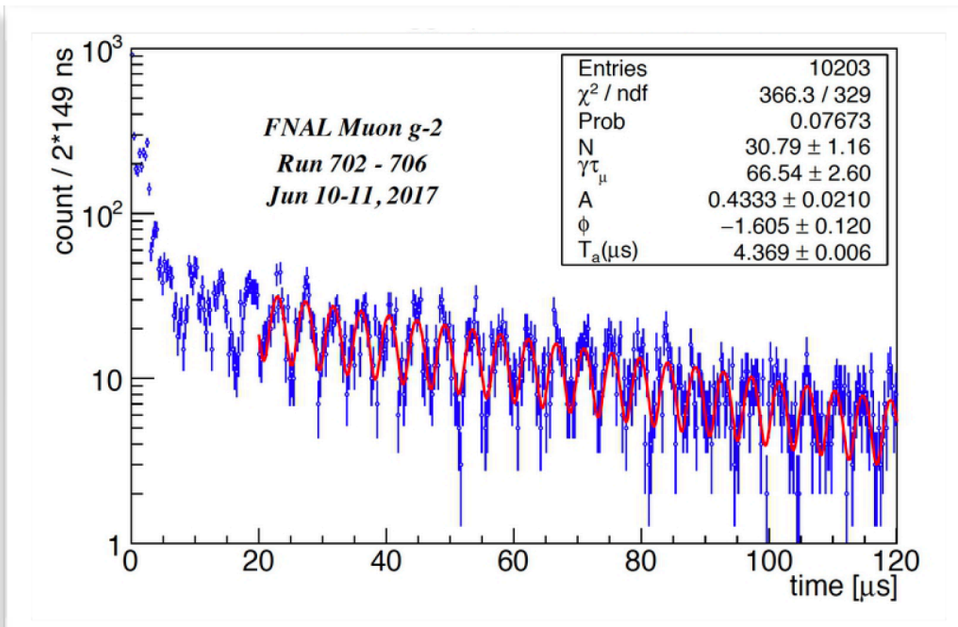
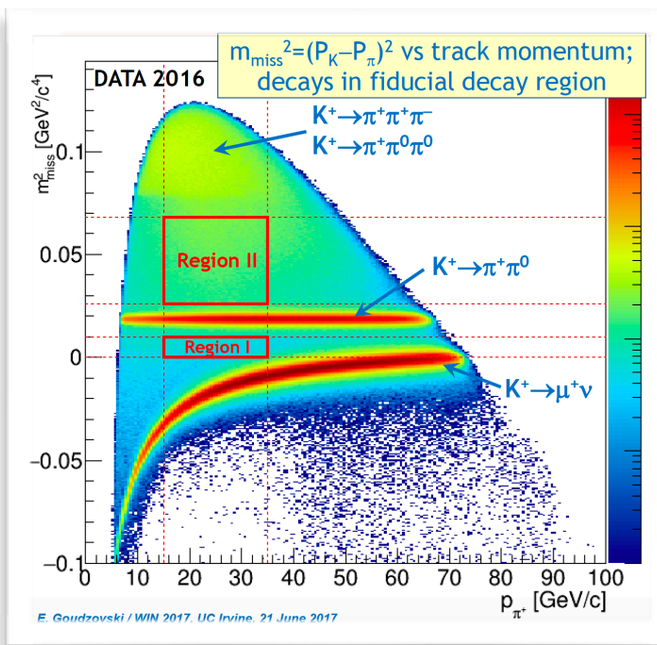
MEG Final result @ PSI



Muon g-2 commissioning @ FNAL



NA62 acquisition and data @ CERN



Flavour and Precision Physics

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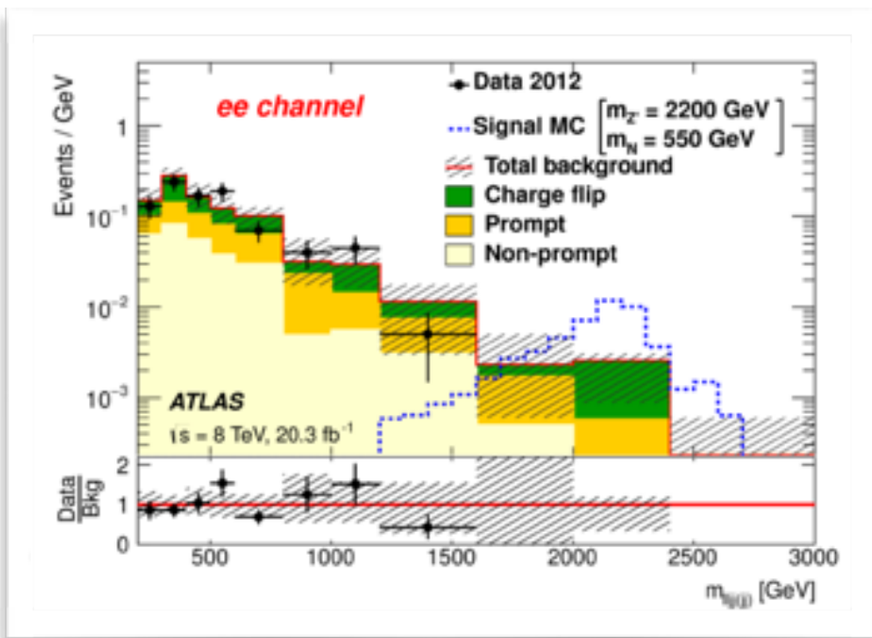
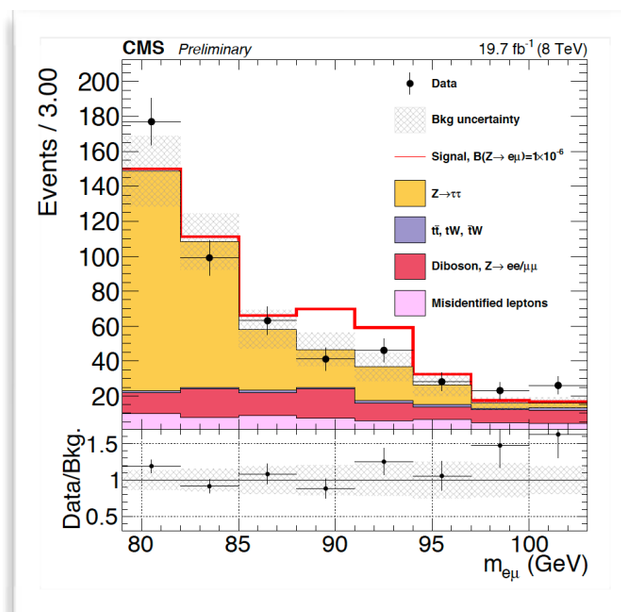
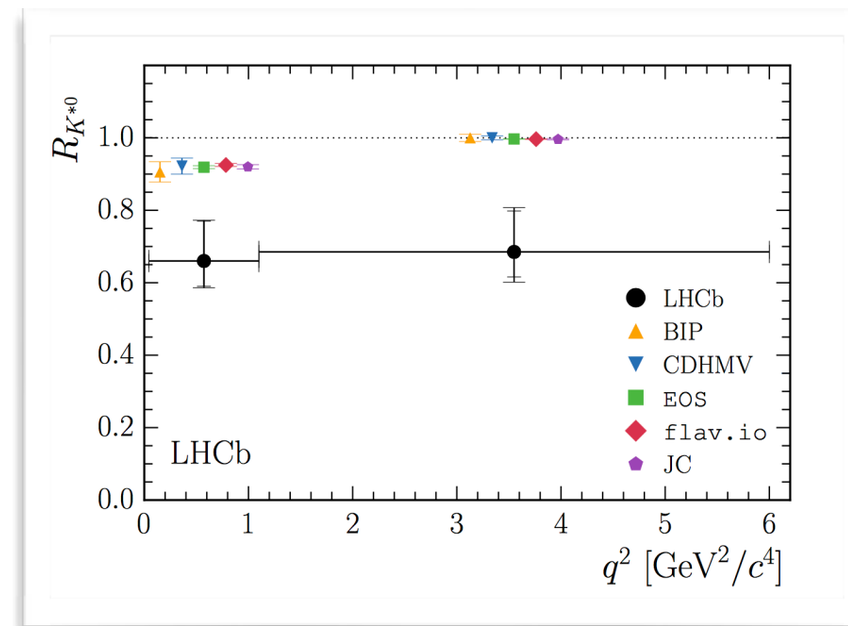
ATLAS @ CERN



CMS @ CERN



LHCb @ CERN



Flavour and Precision Physics

WG summary (experiment), Angela Papa - PSI; WIN2017

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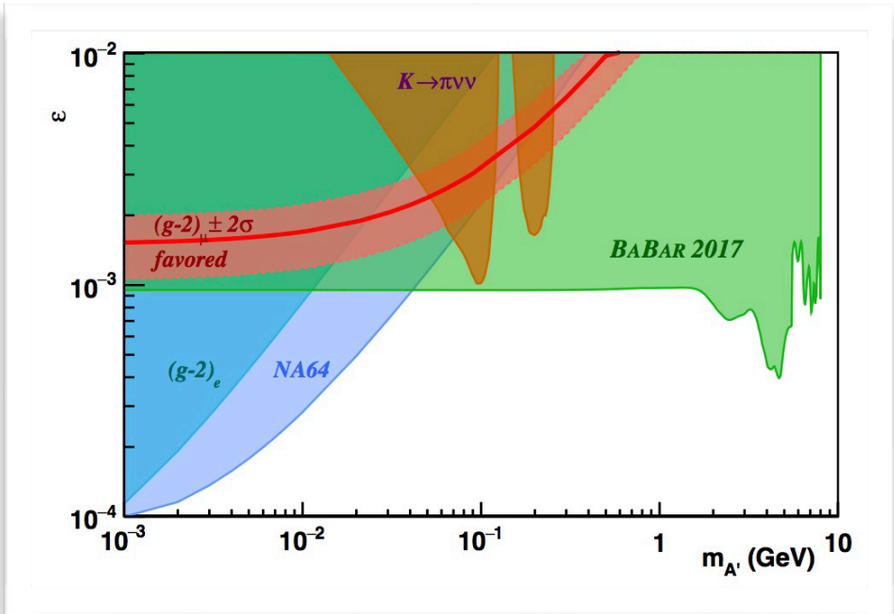
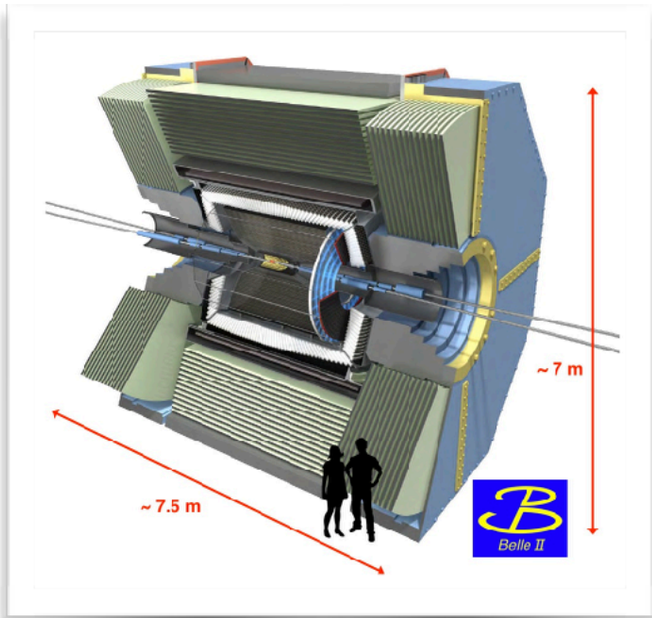
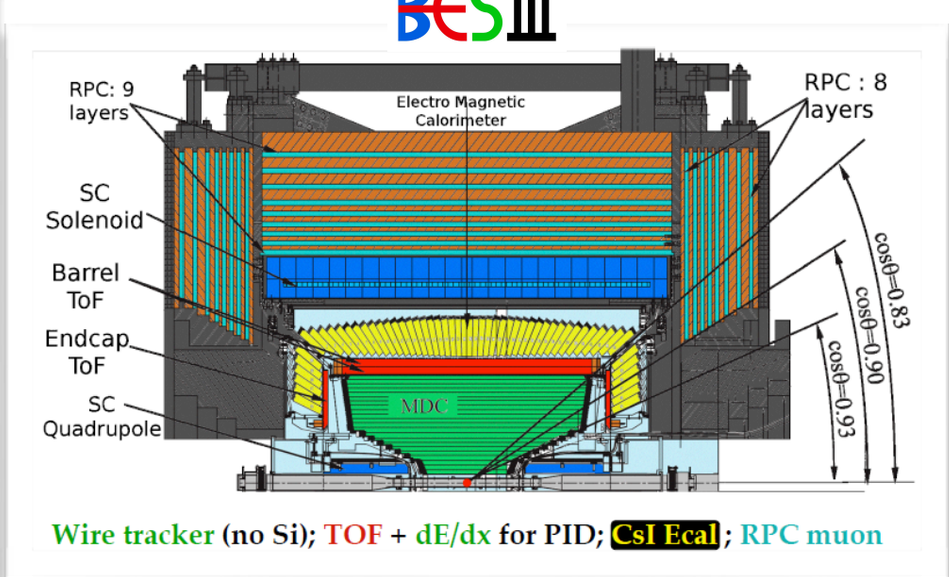
Babar @ SLAC



BELLE II @ SuperKEKB



BESIII @ BESIII



Flavour and Precision Physics

WG summary (experiment), Angela Papa - PSI; WIN2017

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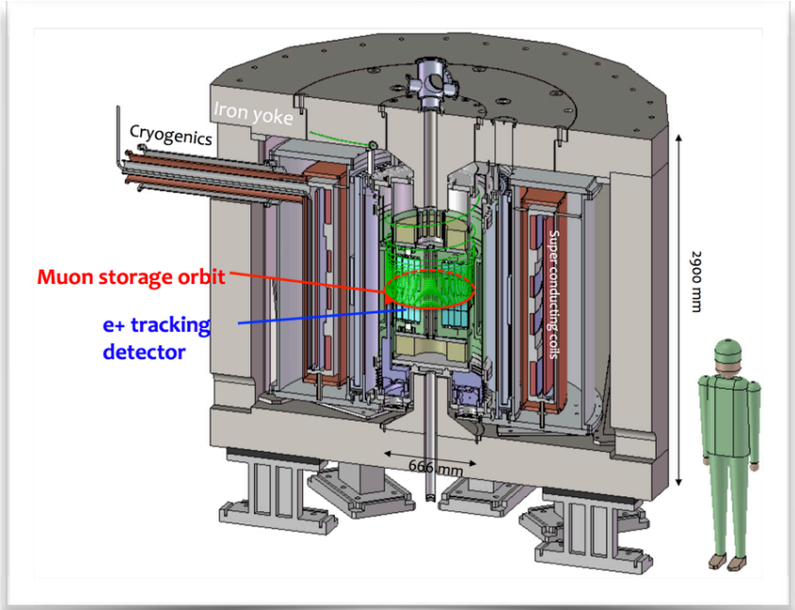
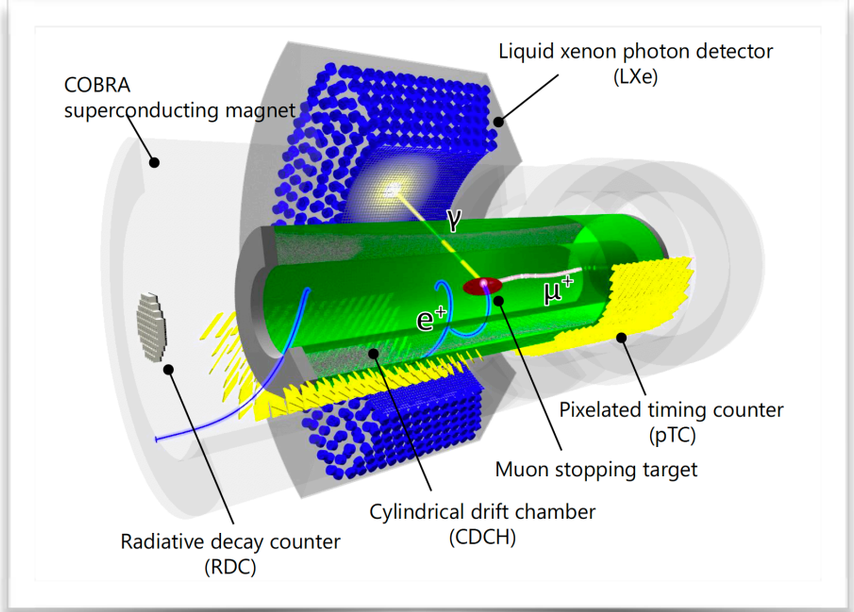
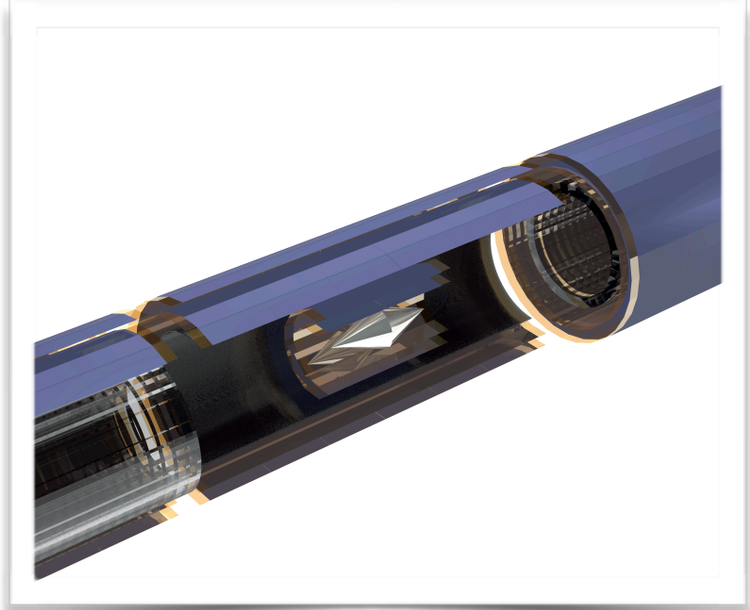
g-2/EDM @ JPARC



MEG II @ PSI



Mu3e @ PSI



Flavour and Precision Physics

WG summary (experiment), Angela Papa - PSI; WIN2017

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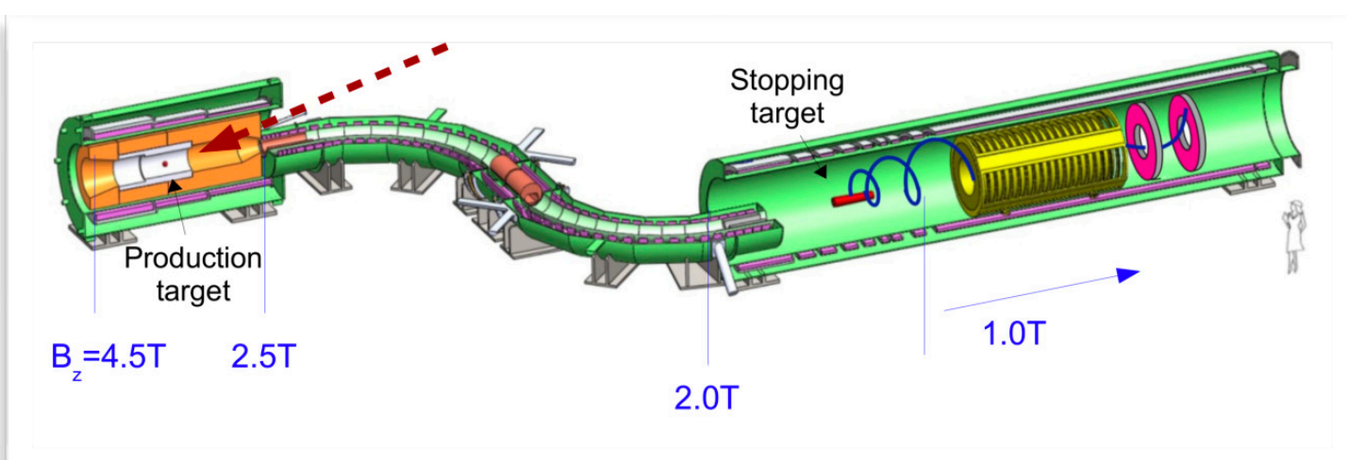
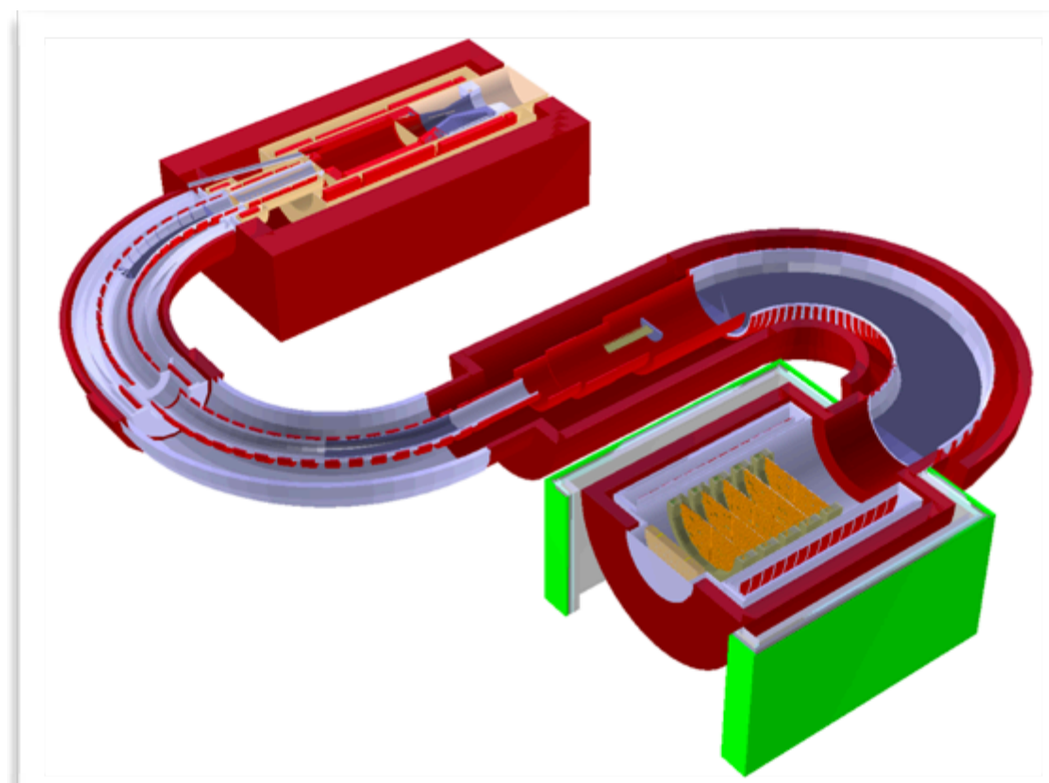
Mu2e @ FNAL



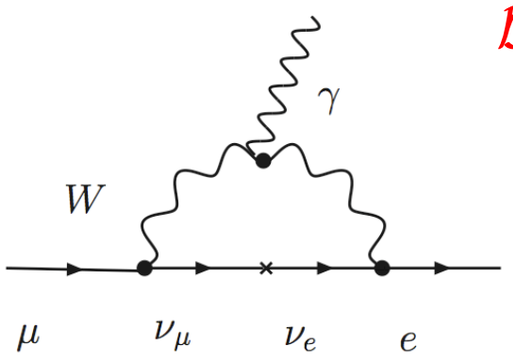
COMET @ JPARC



Content

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

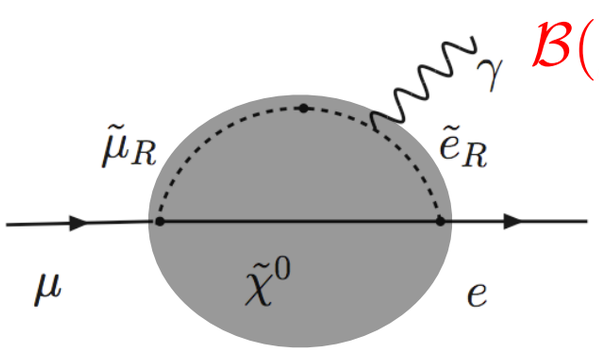


$$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$$

ν oscillations

too small to access experimentally

i.e. SU(5) SUSY-GUT or SO(10) SUSY-GUT

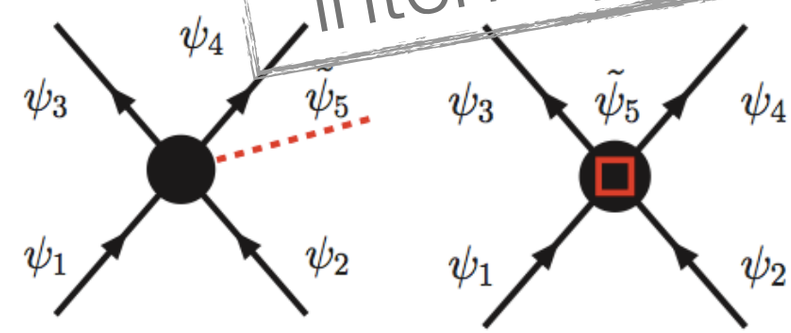


$$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$$

an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

to unveil behind SM physics
via virtual particles

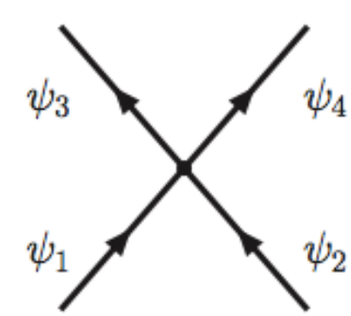
intensity frontier



to probe otherwise unreachable and
unexploited new physics energy scale

high energy probe

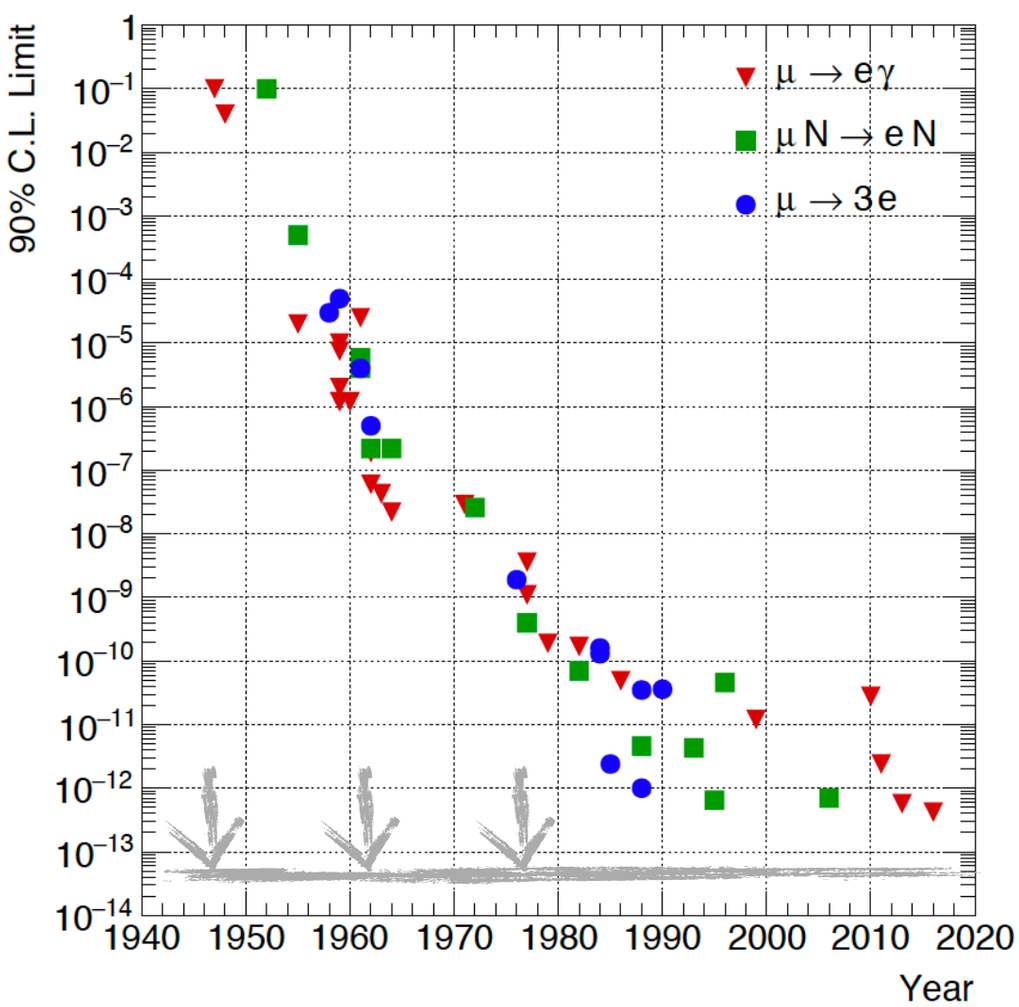
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



$$\frac{1}{\Lambda^2}$$

cLFV searches with muons: Status and prospects

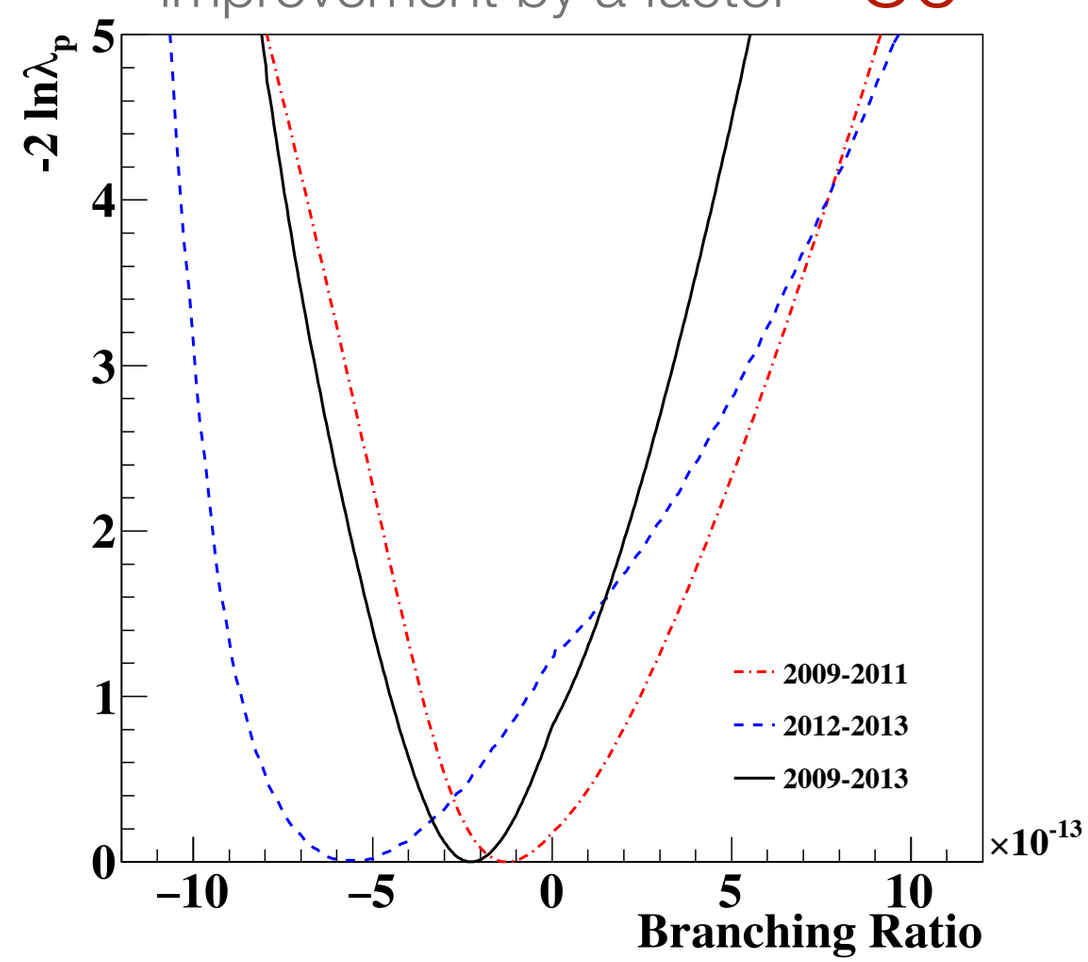
- In the near future impressive sensitivities: BR($\mu \to e\gamma$) < 4 10^{-14} ; BR($\mu \to eee$) < 1 10^{-16}; CR($\mu N \to eN'$) < 10^{-17}
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV



MEG Final result:

$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$

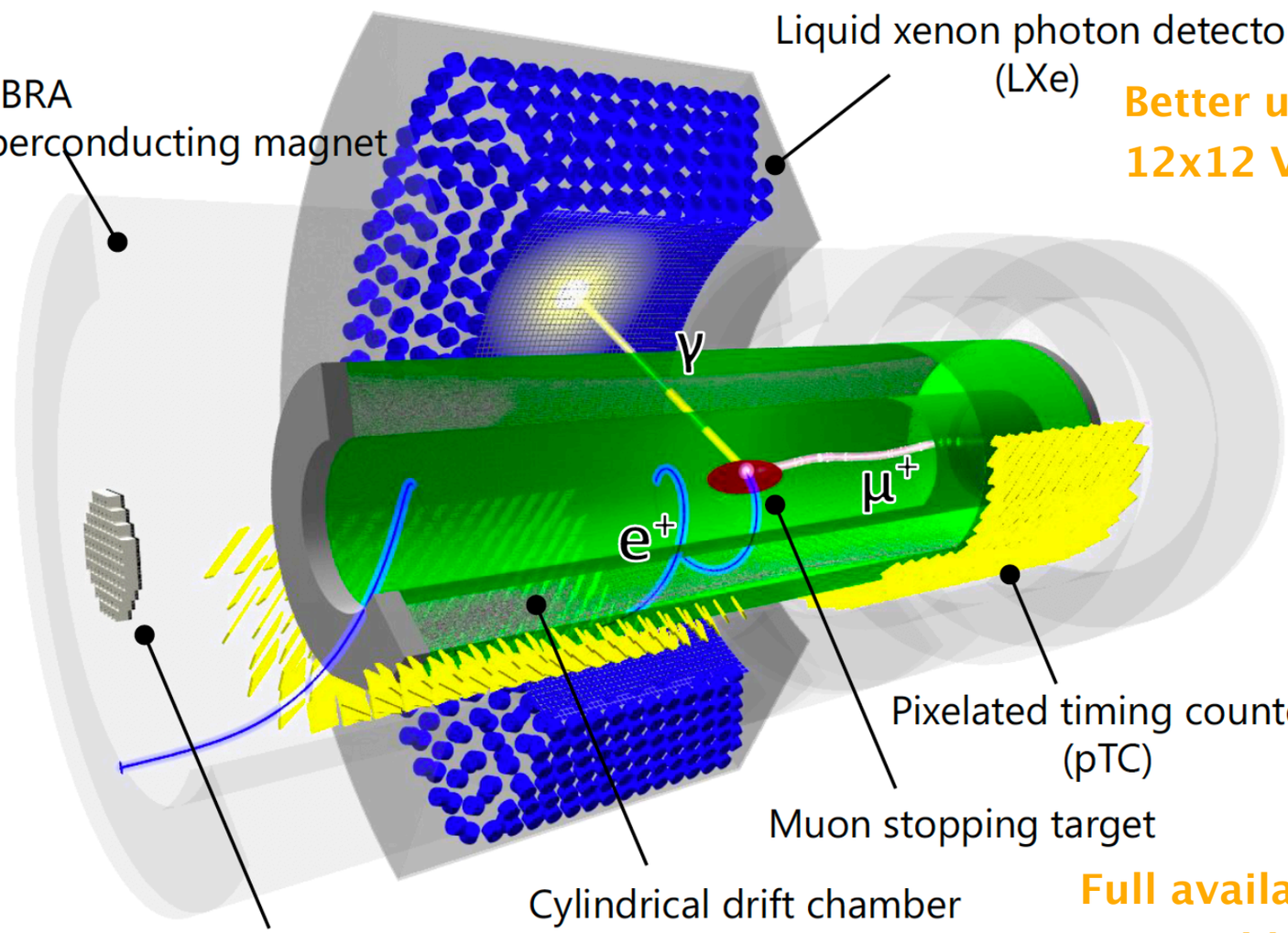
improvement by a factor ~ 30



The MEGII experiment

- Pre-engineering runs ongoing. Full engineering run [2018] followed by data acquisition

New electronics:
Wavedream
~9000 channels at 5GSPS



Better uniformity w/ 12x12 VUV SiPM

x2 Resolution everywhere

x2 Beam Intensity

35 ps resolution w/ multiple hits

Updated and new Calibration
Quasi mono-chromatic positron beam

Background rejection

Single volume He:iC_4H_{10}

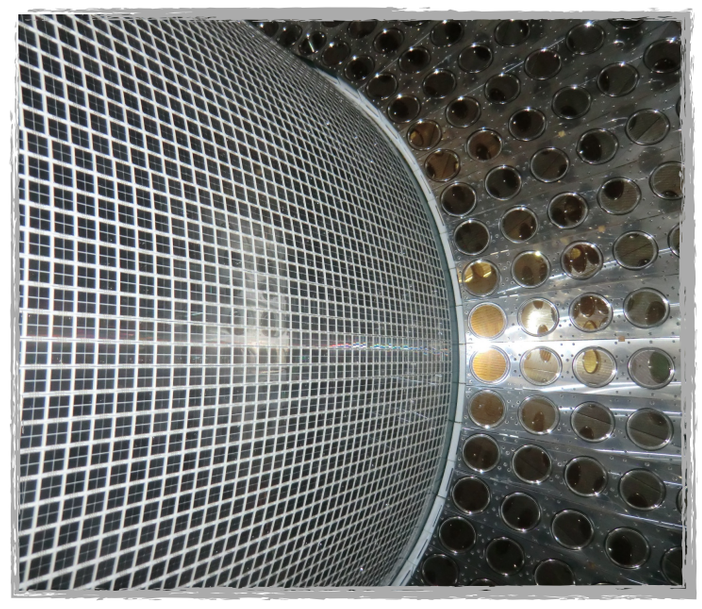
Full available stopped beam intensity 7×10^7

MEGII Status

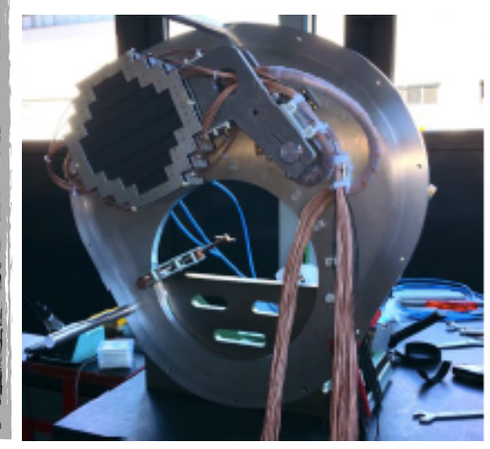
- a real “upgrade”: kept the skeletron of the experiment/key ideas and refurbished beam line and all sub-detectors. All sub-detectors completed or in construction

Optimum beam and calibrations

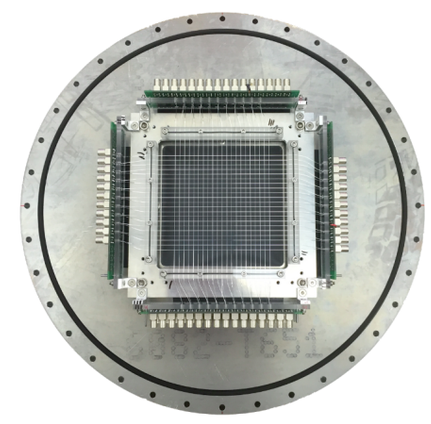
new MPPC in the **VUV**



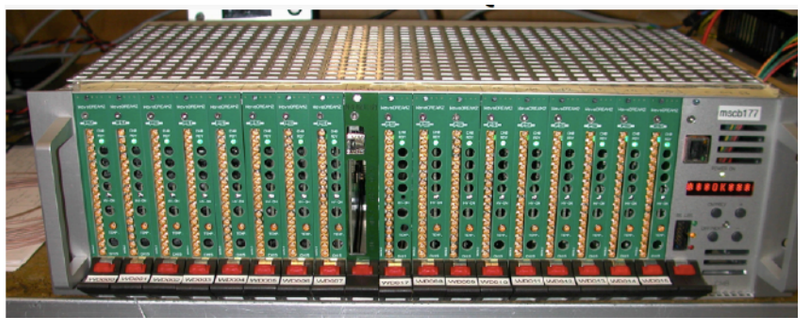
new AUX detector (**<< BKG**)



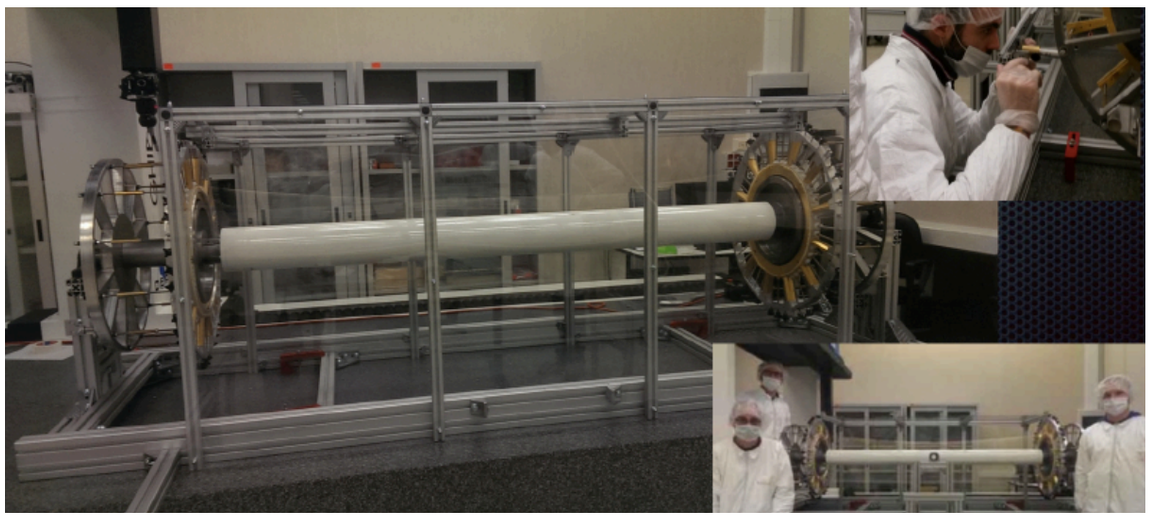
new Beam detector (**Online profile and rate**)



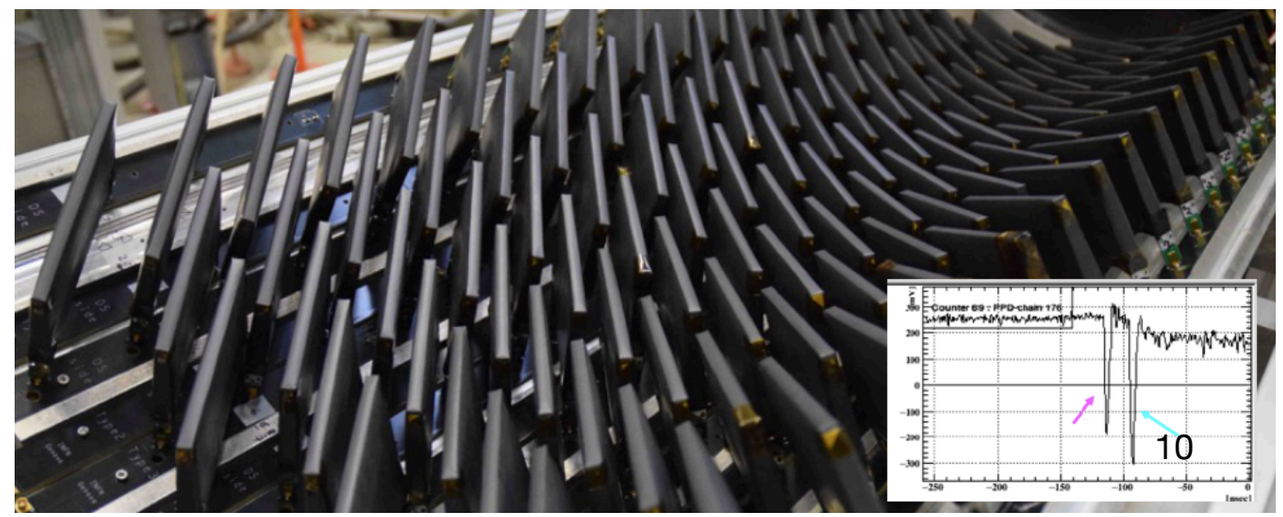
new DAQ + TRG (**5 Gsample/s**)



new DCH (**stereo**)



new TC (**multi-hits**)



The Mu3e experiment

Superconducting solenoid Magnet

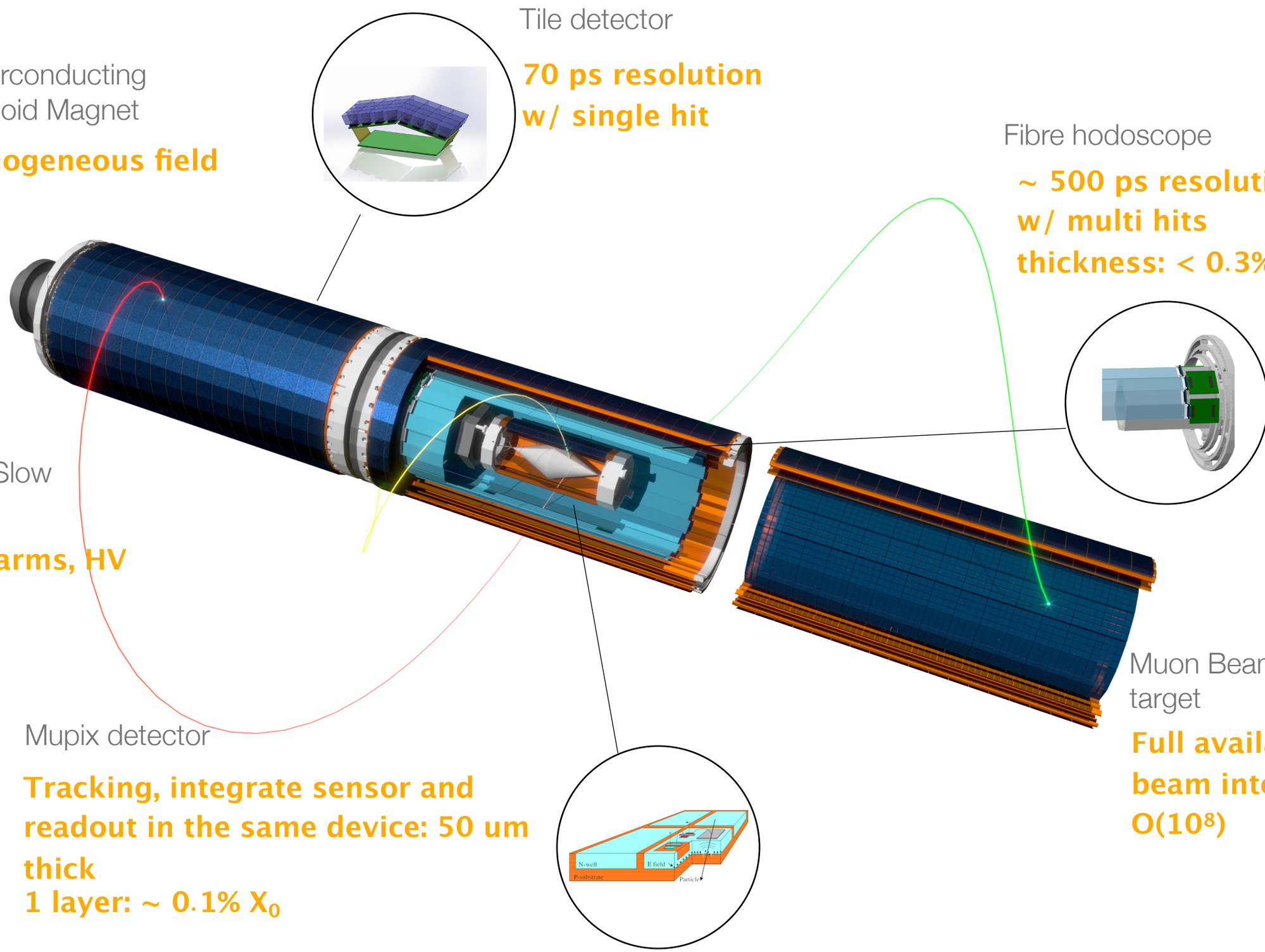
Homogeneous field 1T

Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

~ 500 ps resolution w/ multi hits thickness: < 0.3% X_0



MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Muon Beam and target

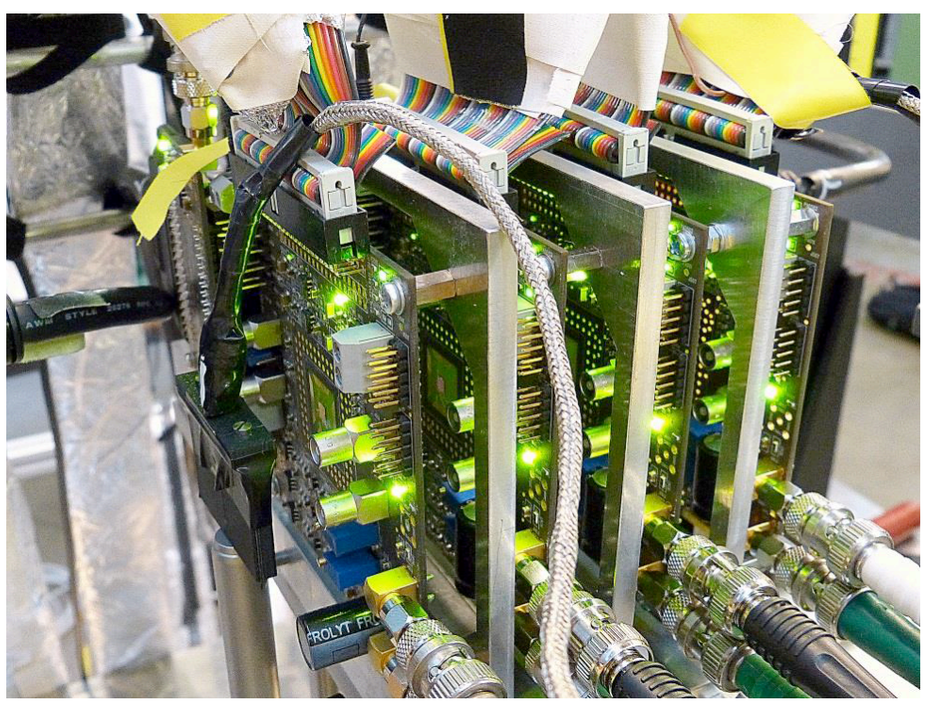
Full available beam intensity O(10^8)

Mupix detector

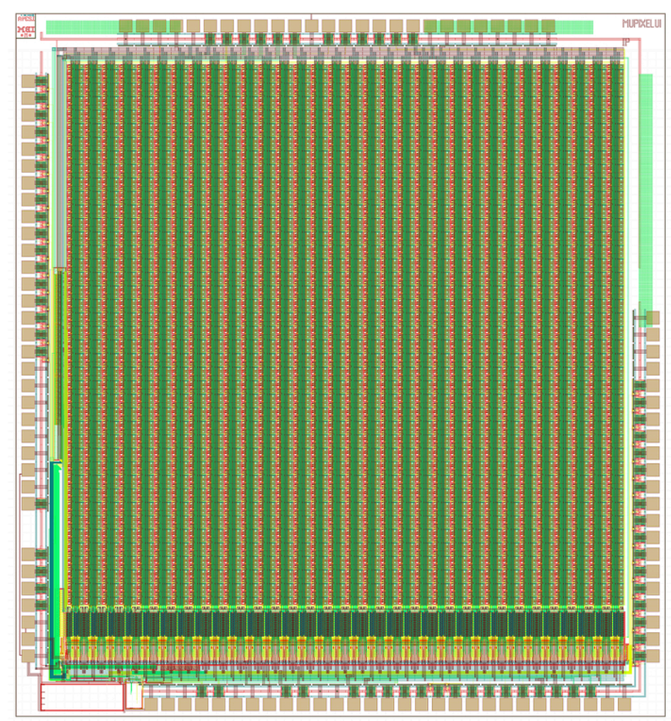
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0

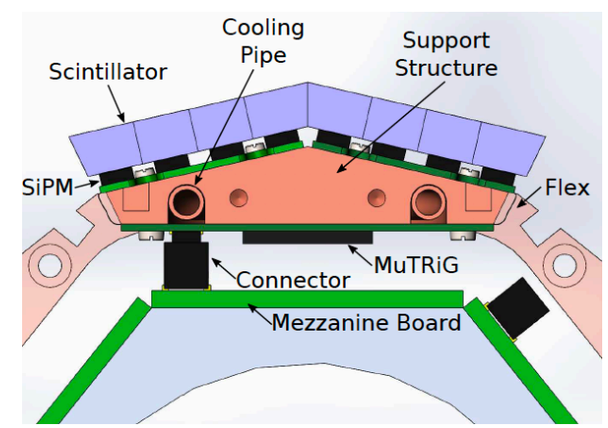
The Mu3e experiment: Status

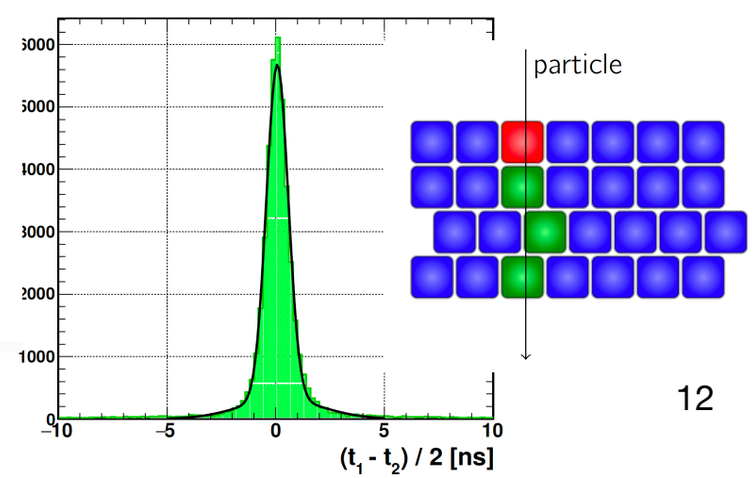
- The Mu3e experiment is completely based on new detector technologies and strongly connected with new beam line projects (HiMB at PSI aiming at 10^9 muon/s)
- The R&D phase for all sub-detectors and beam line has been concluded proving that the expected detector performances can be achieved
- Construction and characterisation of all sub-detector prototype are extensively ongoing
- A full engineering run is expected for 2019 followed by data acquisition



MuPix7



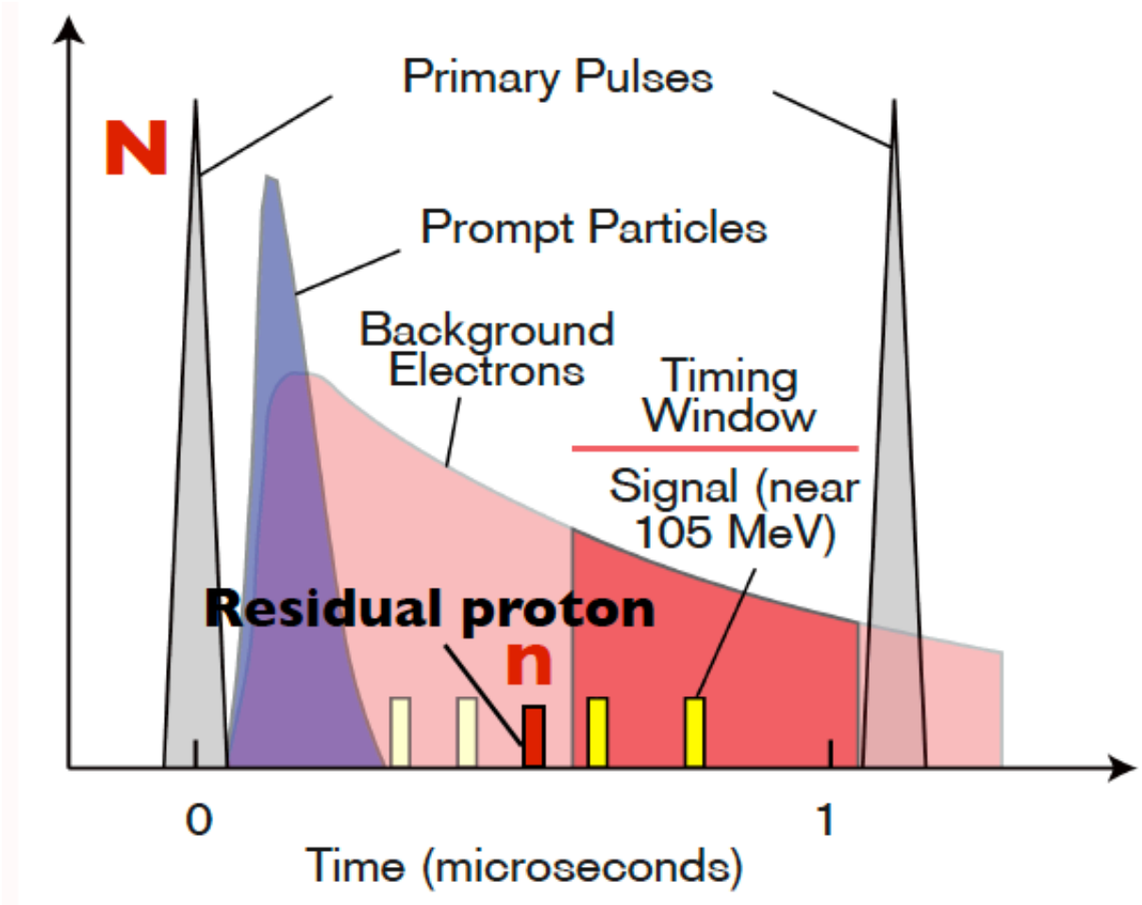


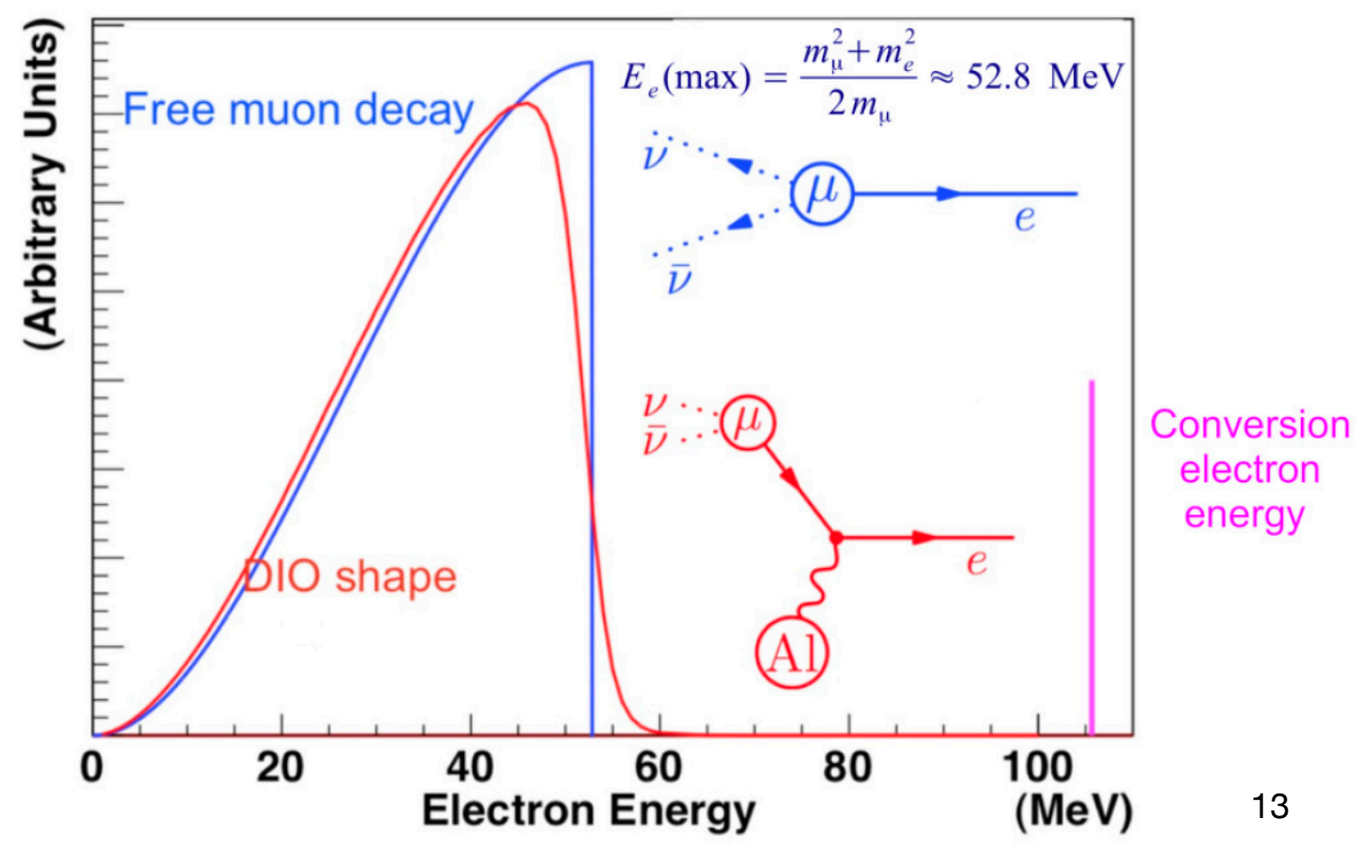


CLFV via μ^- N → e^- N

- Signal of CLFV conversion is single mono energetic electron
- Backgrounds:
  - Beam related, Cosmic rays, Muon Decay in orbit
- Stop a lot more muons! O(10^{18})
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime

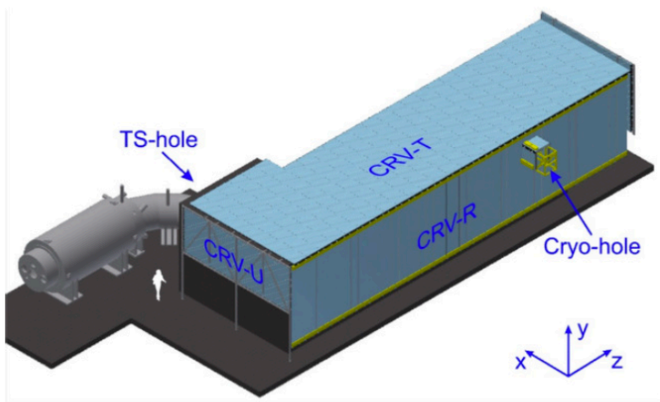
$$R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}$$

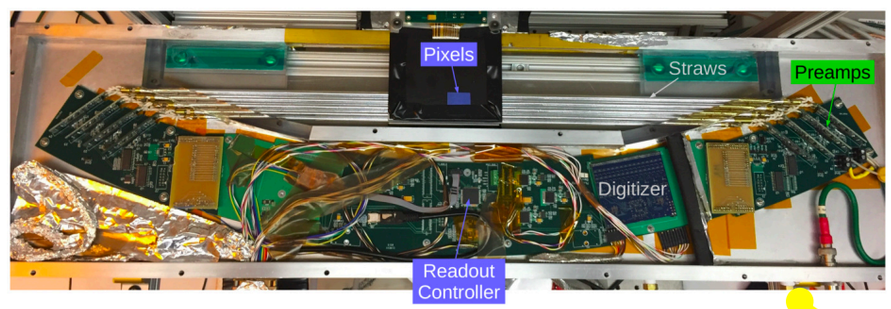


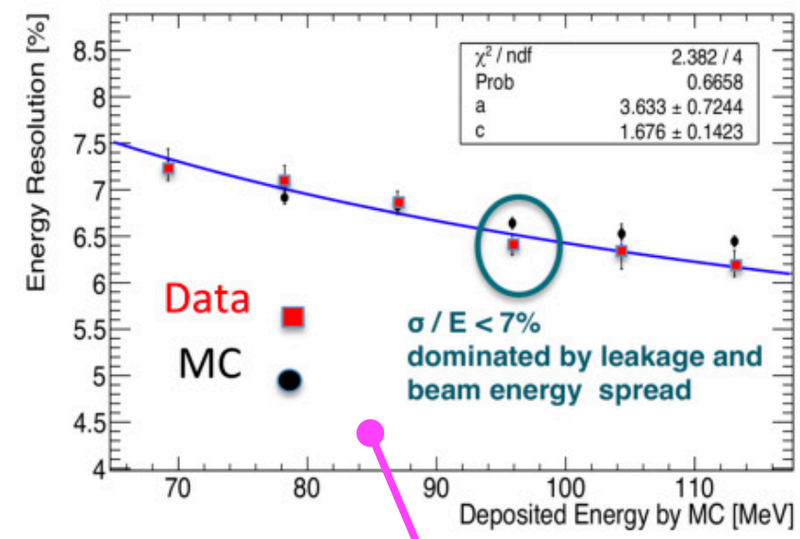


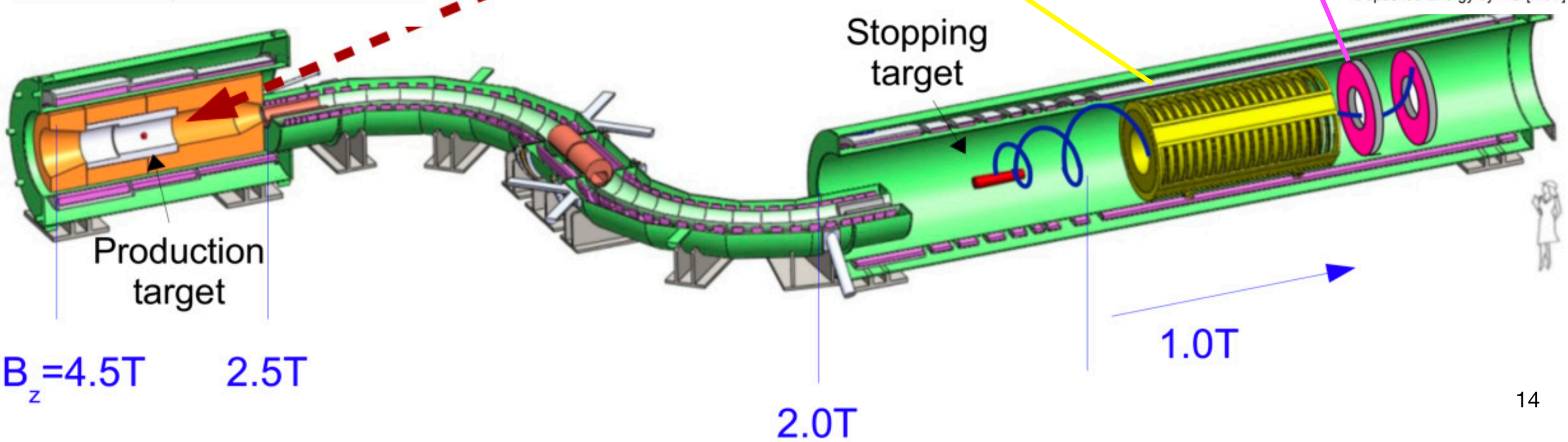
Mu2e status

- Three superconducting solenoids: Production, Transport and Detector solenoids
- Muons stop in thin aluminum foils
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID

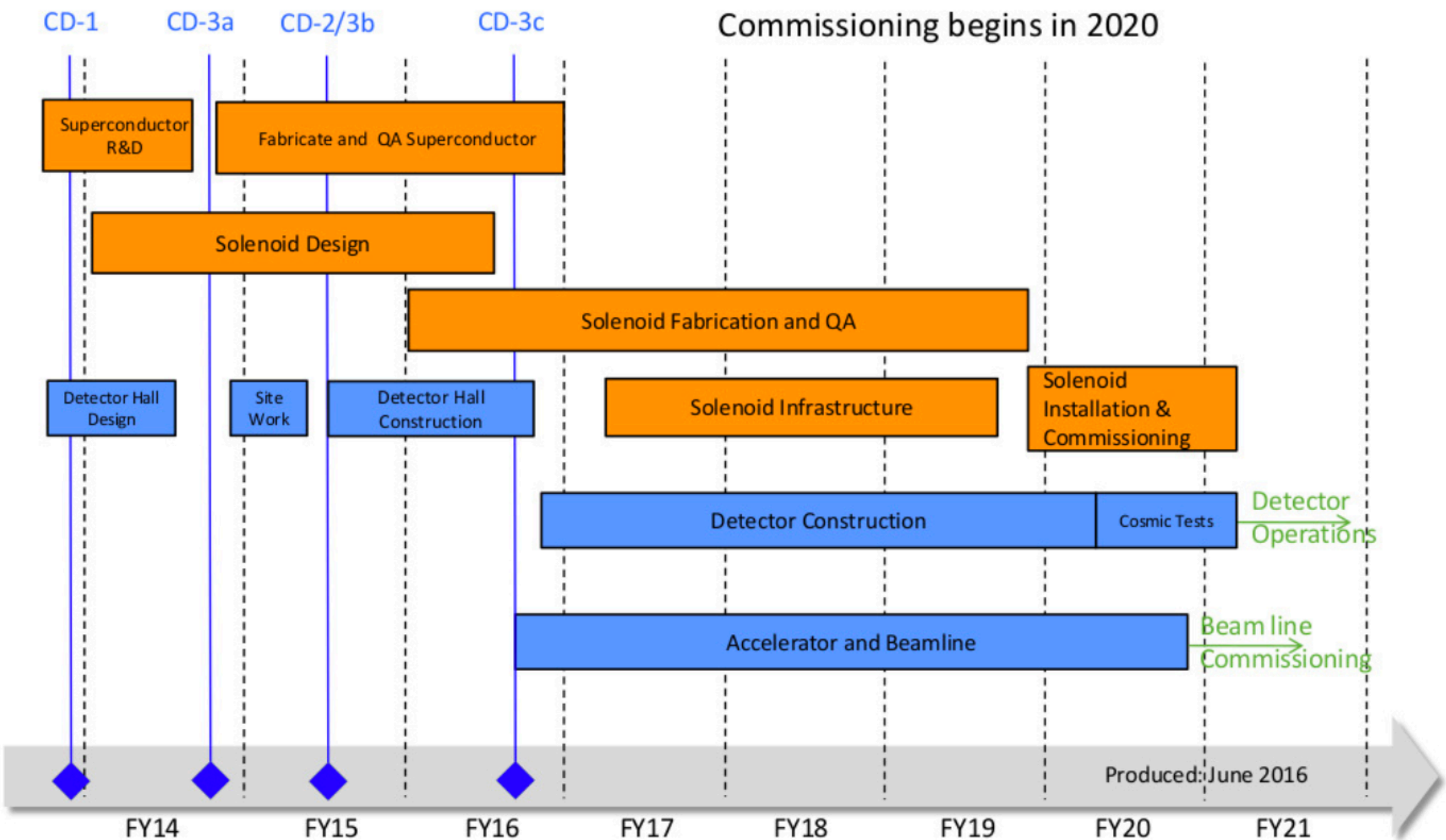




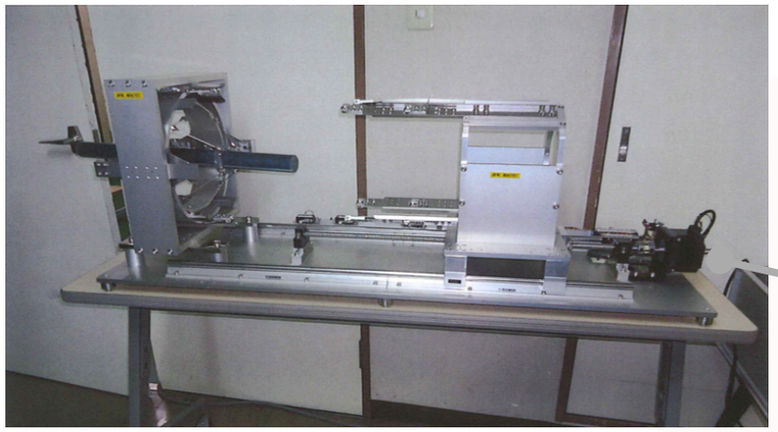


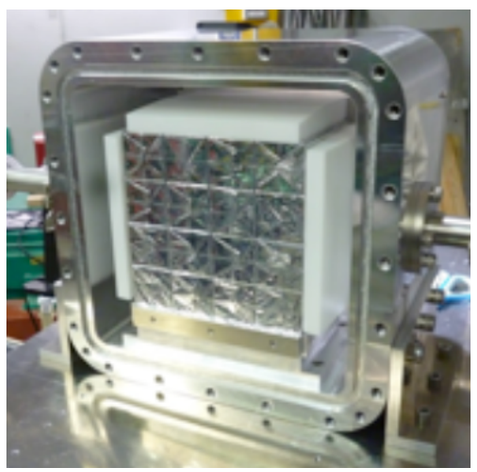


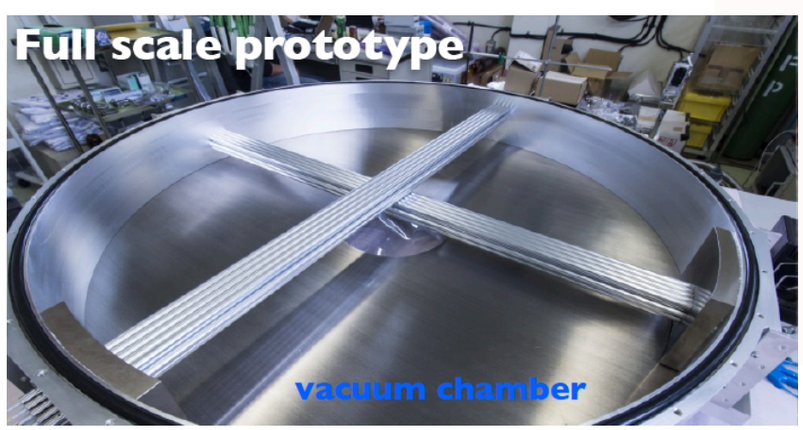
Mu2e Schedule

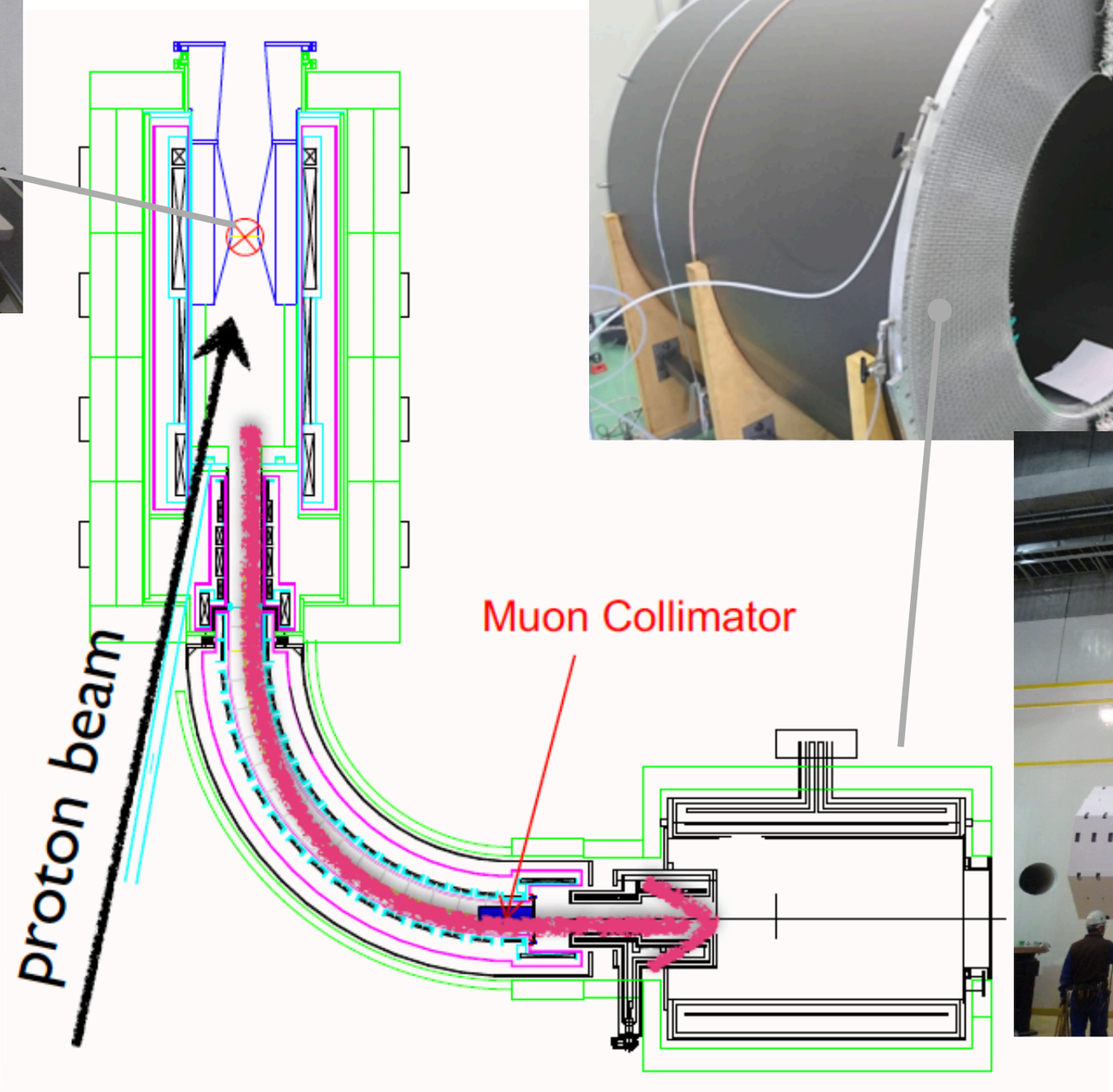


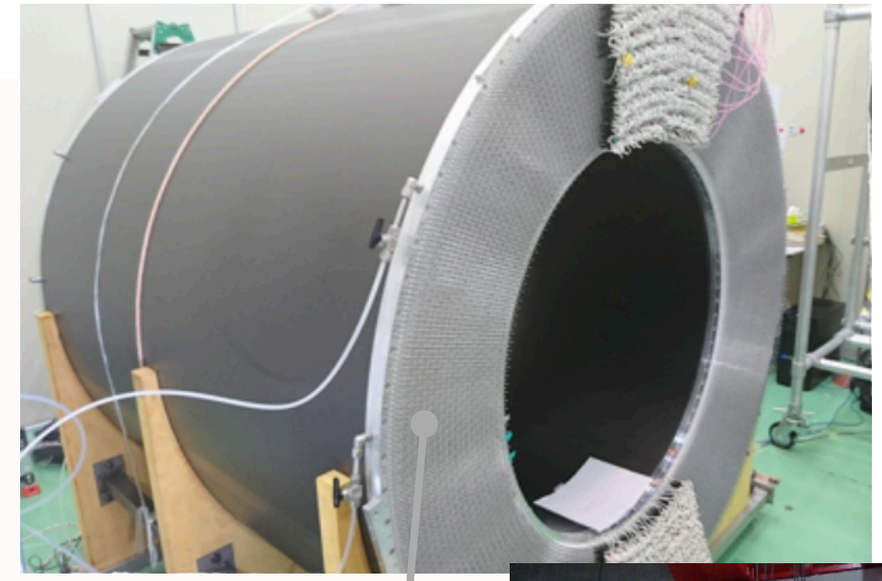
COMET status

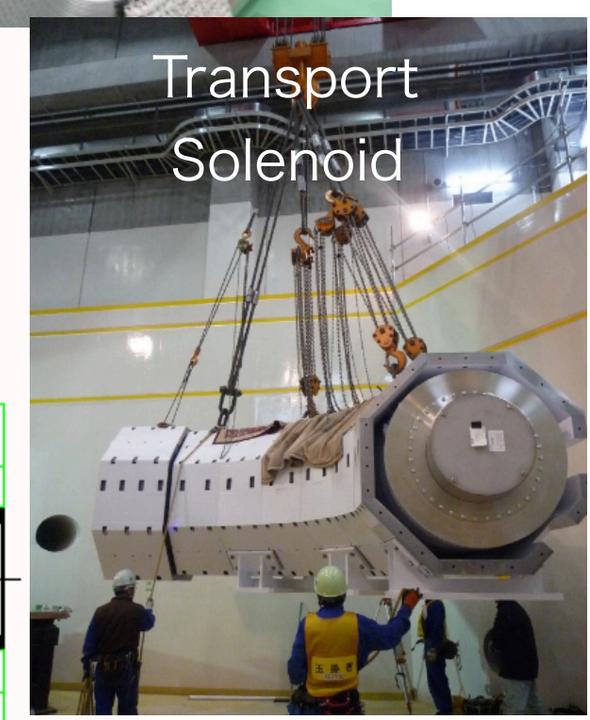






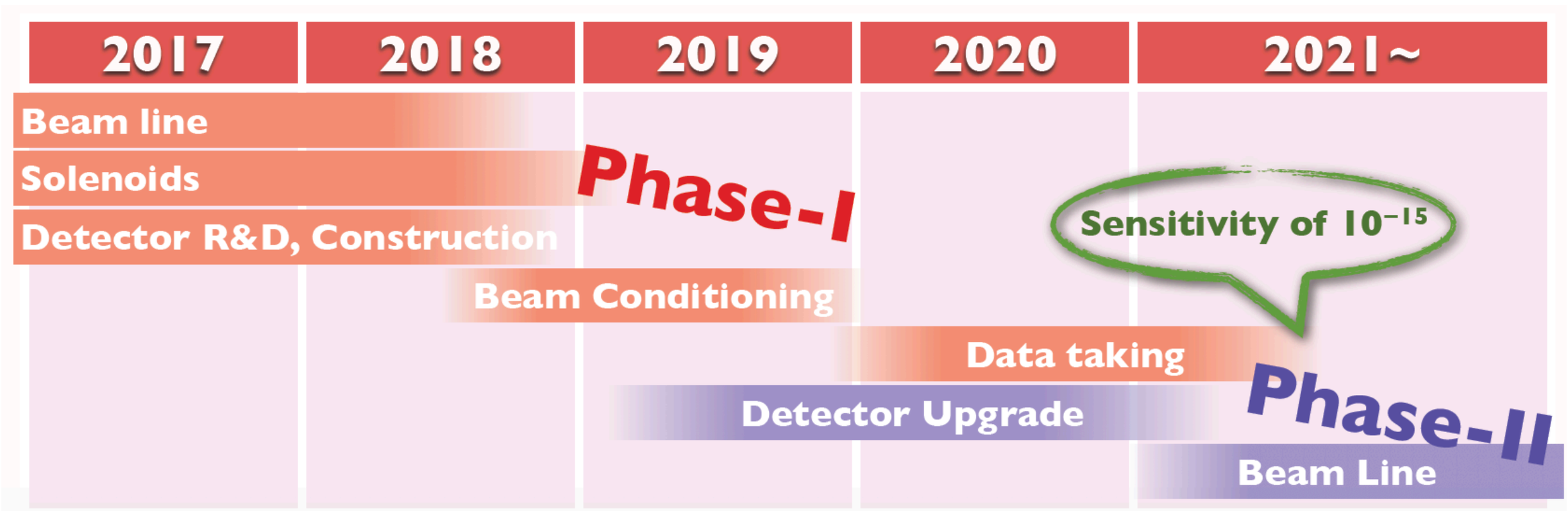






COMET schedule

- The facility is under construction.
- R&D of the detectors, CyDet & StrECAL, is progressing.
- Single event sensitivity: 3 10^{-15} (Phase-I) and 1.9 10^{-17} (Phase-II)

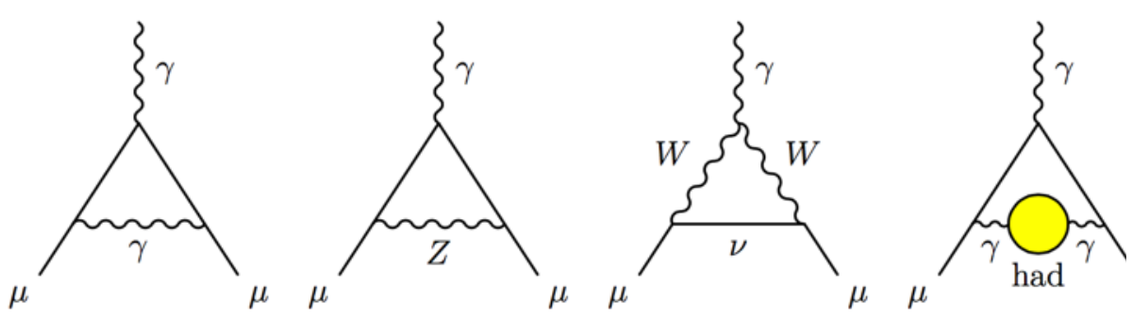


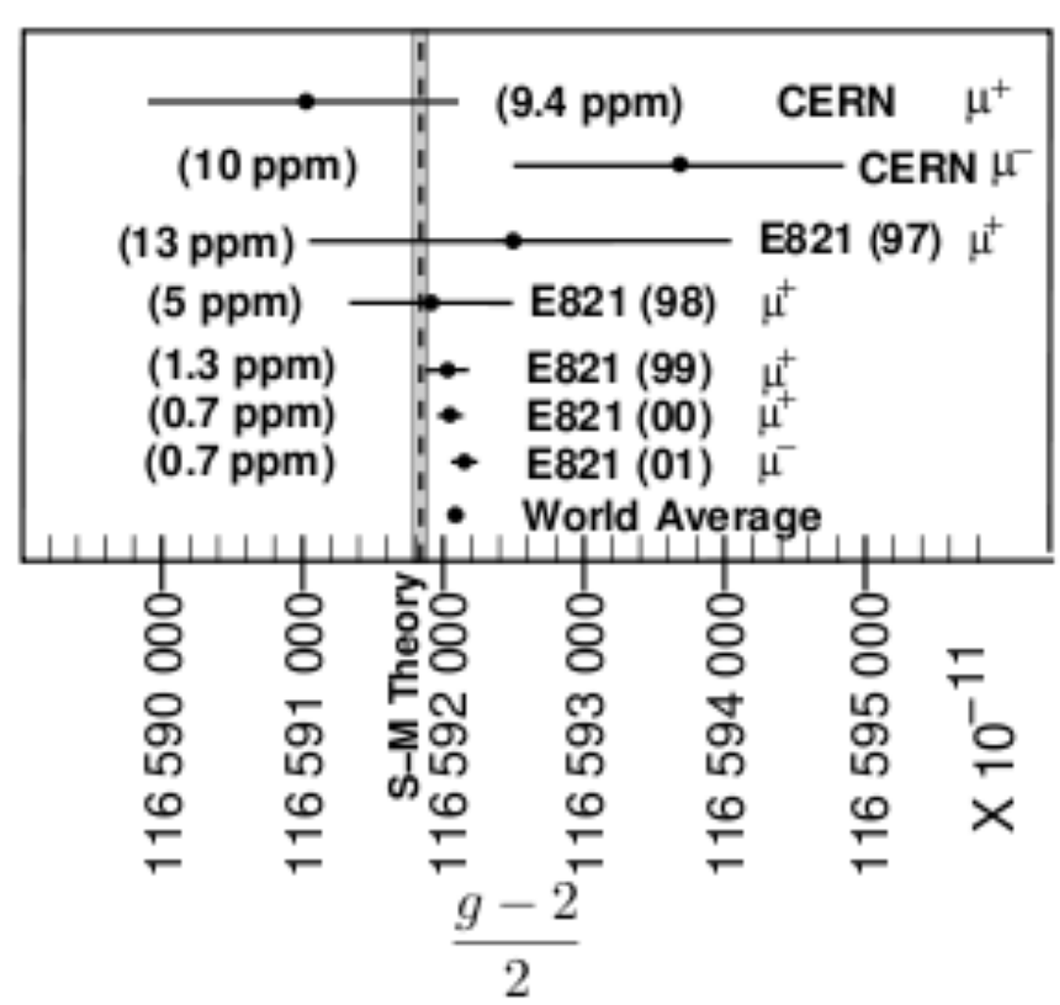
g_μ-2 at FNAL and JPARC

- Dirac's relativistic theory predicted muon magnetic moment “g” = 2
- Experiment suggested that g-factor differs from the expected value of 2
- Standard Model prediction: a(SM) = a(QED) + a(Had) + a (Weak)
- BNL E821 result: 3.3σ deviation from SM prediction

$$\mu = (1 + a_\mu)\frac{e\hbar}{2m} \qquad a_\mu = \frac{g_\mu - 2}{2}$$

QED EW QCD





g_μ-2 in numbers and experimental approaches

Anomalous magnetic moment (g-2)

$a_\mu = (g-2)/2 = 11\,659\,208.9\ (6.3) \times 10^{-10}$ (BNL E821 exp) **0.5 ppm**

$11\,659\,182.8\ (4.9) \times 10^{-10}$ (standard model)

$\Delta a_\mu = \text{Exp} - \text{SM} = 26.1\ (8.0) \times 10^{-10}$ **3σ anomaly**

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

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

BNL E821 approach
γ=30 (P=3 GeV/c)

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

Continuation at FNAL with 0.1ppm precision

J-PARC approach
E = 0 at any γ

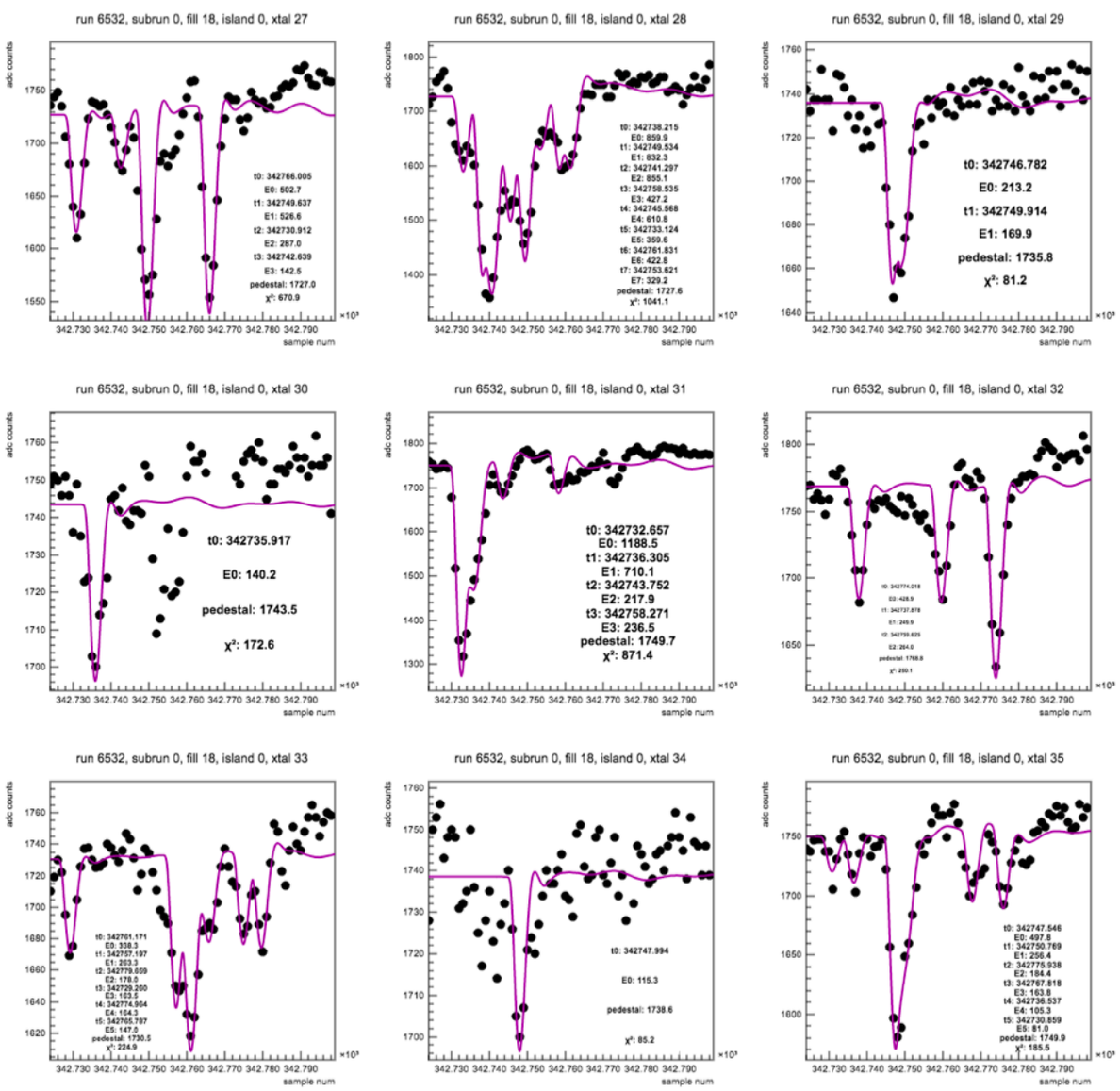
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$

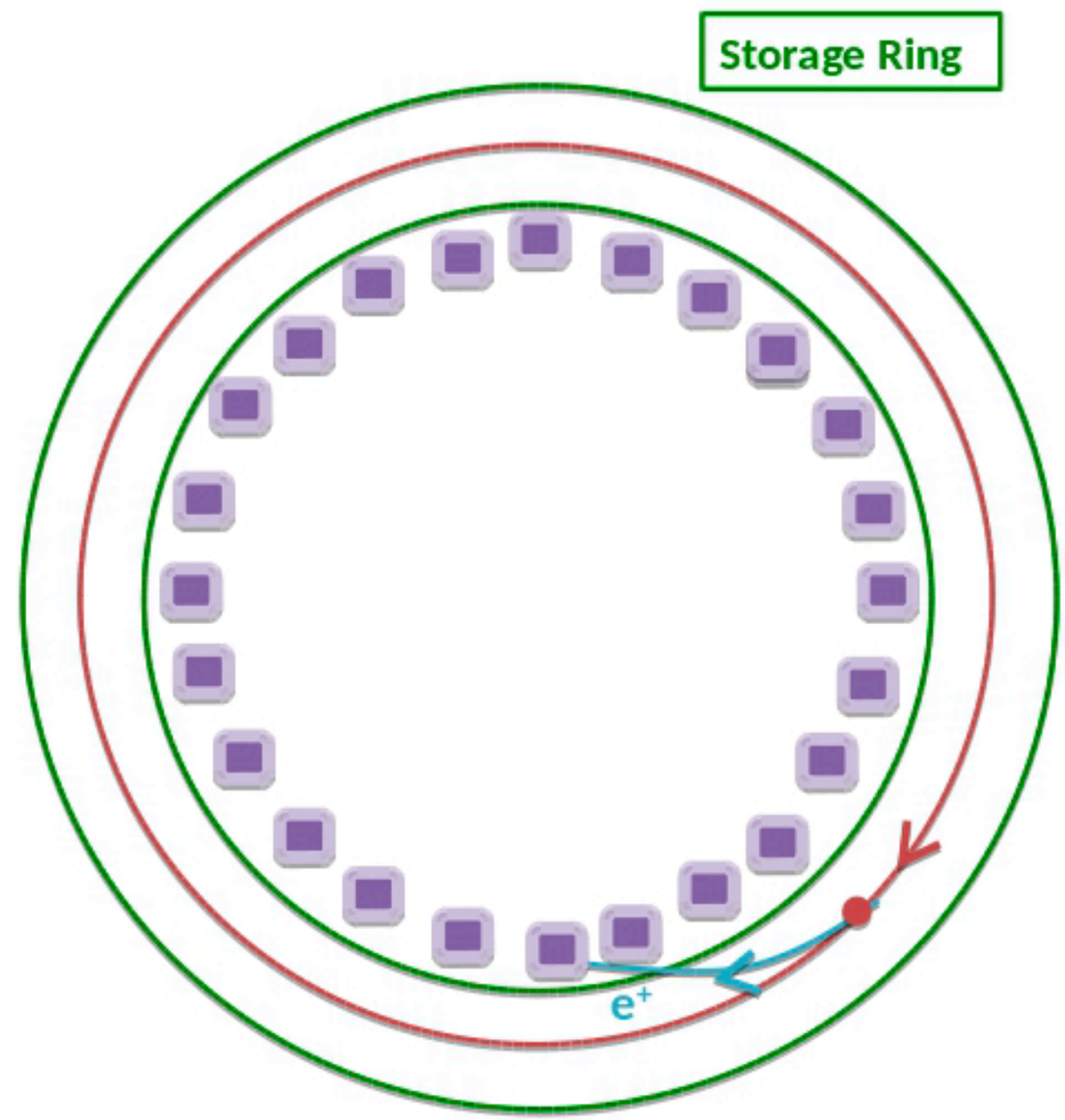
Proposed at J-PARC with 0.1ppm precision

g_μ-2 at FNAL: Commissioning phase

- Beam arrived on May 24th

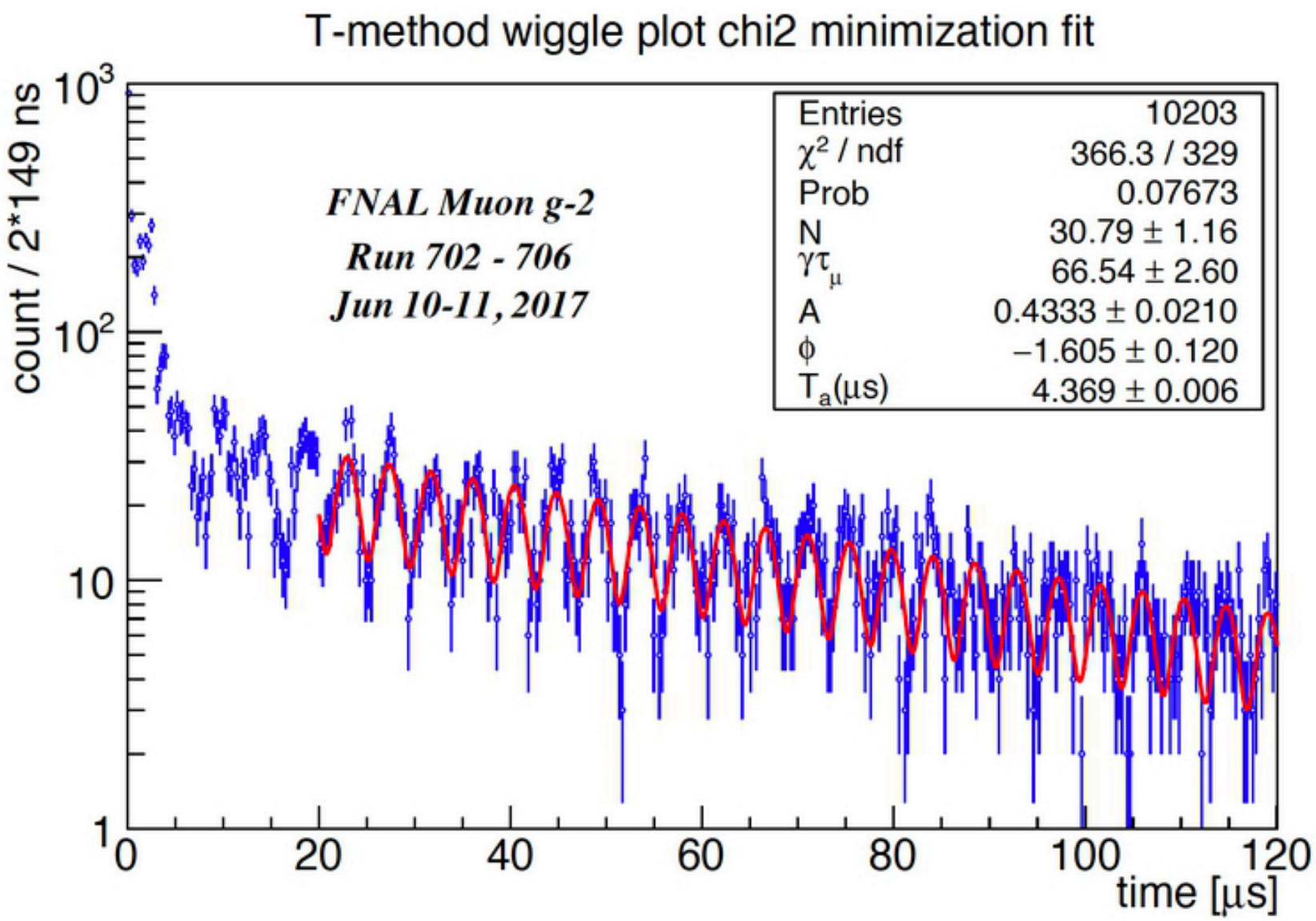
Splash of beam hitting calorimeter 24.





g_μ-2 at FNAL: Commissioning phase

- First evidence of precessing muons
- First Results: 2018 [1-2 x BNL statistics], 2019 [5-10 x BNL statistics], 2020 [5-10 x BNL statistics]

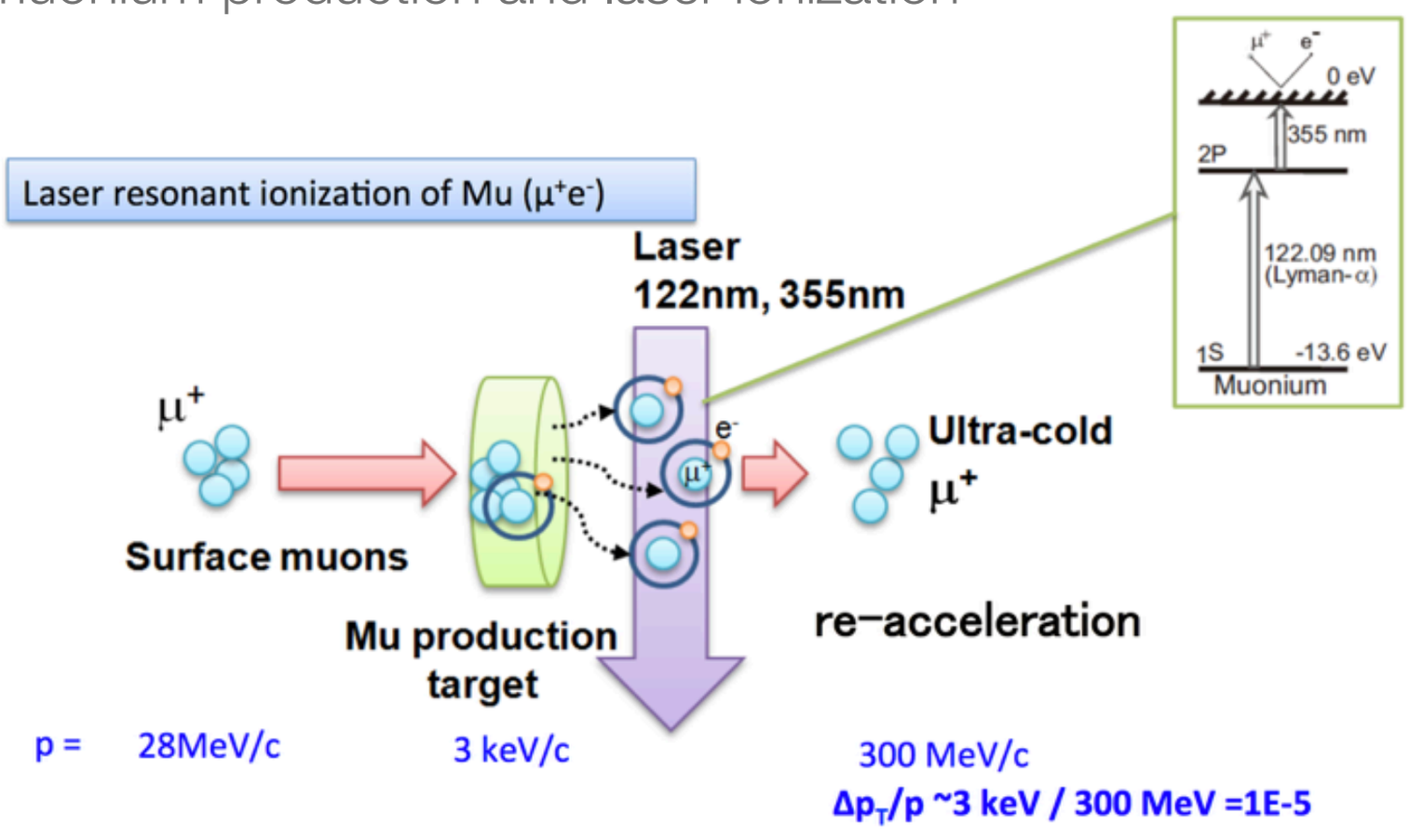


g_μ-2 AND EDM at JPARC

- Zero E-field: J-PARC E34
- Separation of a_μ and η_μ
  - A new technology is necessary
  - Muon beam w/o E-focusing

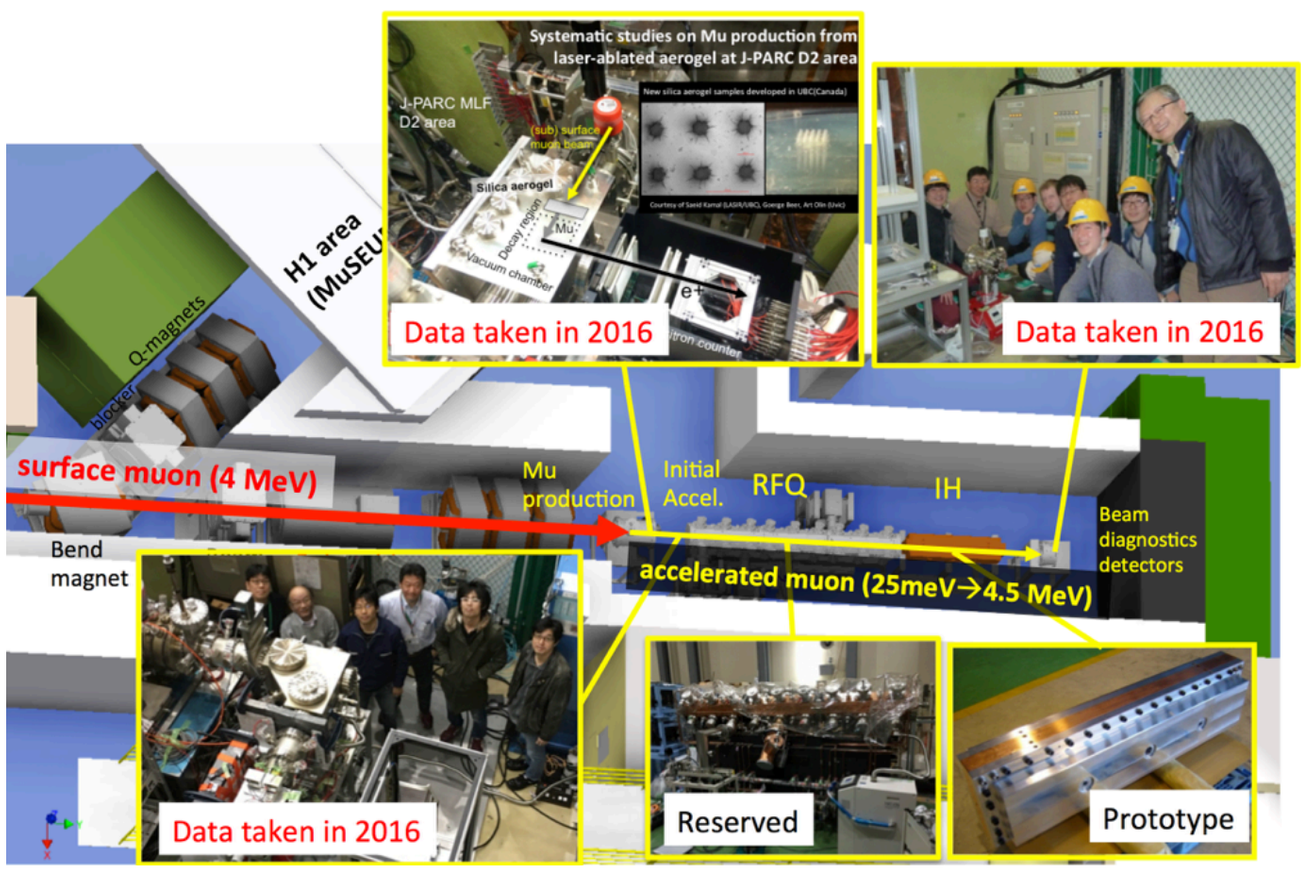
→ Ultra-cold muon beam

- Ultra-small transverse dispersion : $\Delta p_T/p_T < 10^{-5}$
- Cooling with muonium production and laser ionization

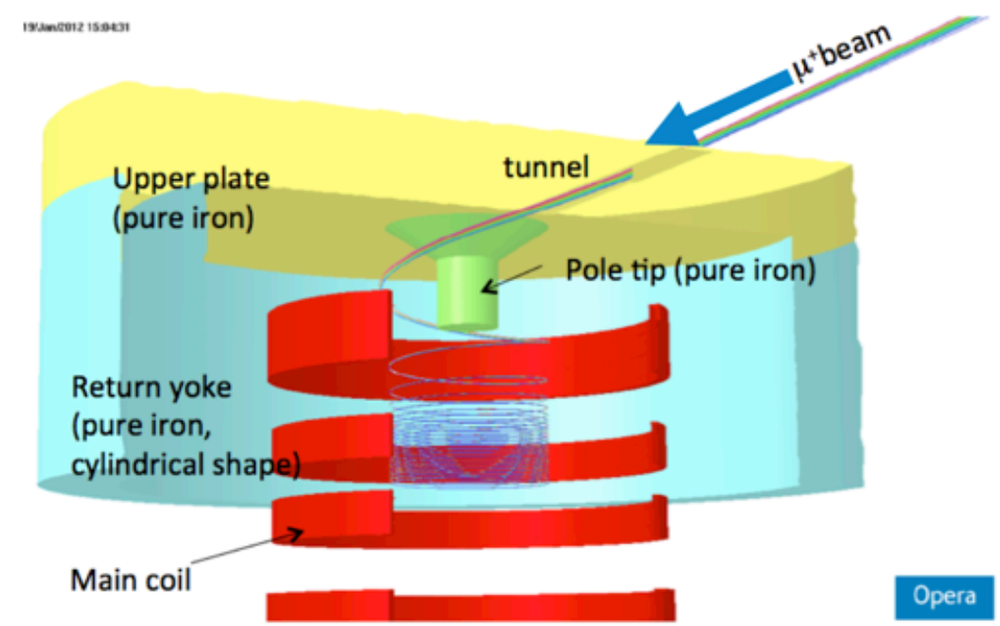


Muon acceleration, Beam injection and Storage

- The R&Ds in all the area are progressing very well towards the readiness for the construction



3D spiral injection + kicker (J-PARC E34)

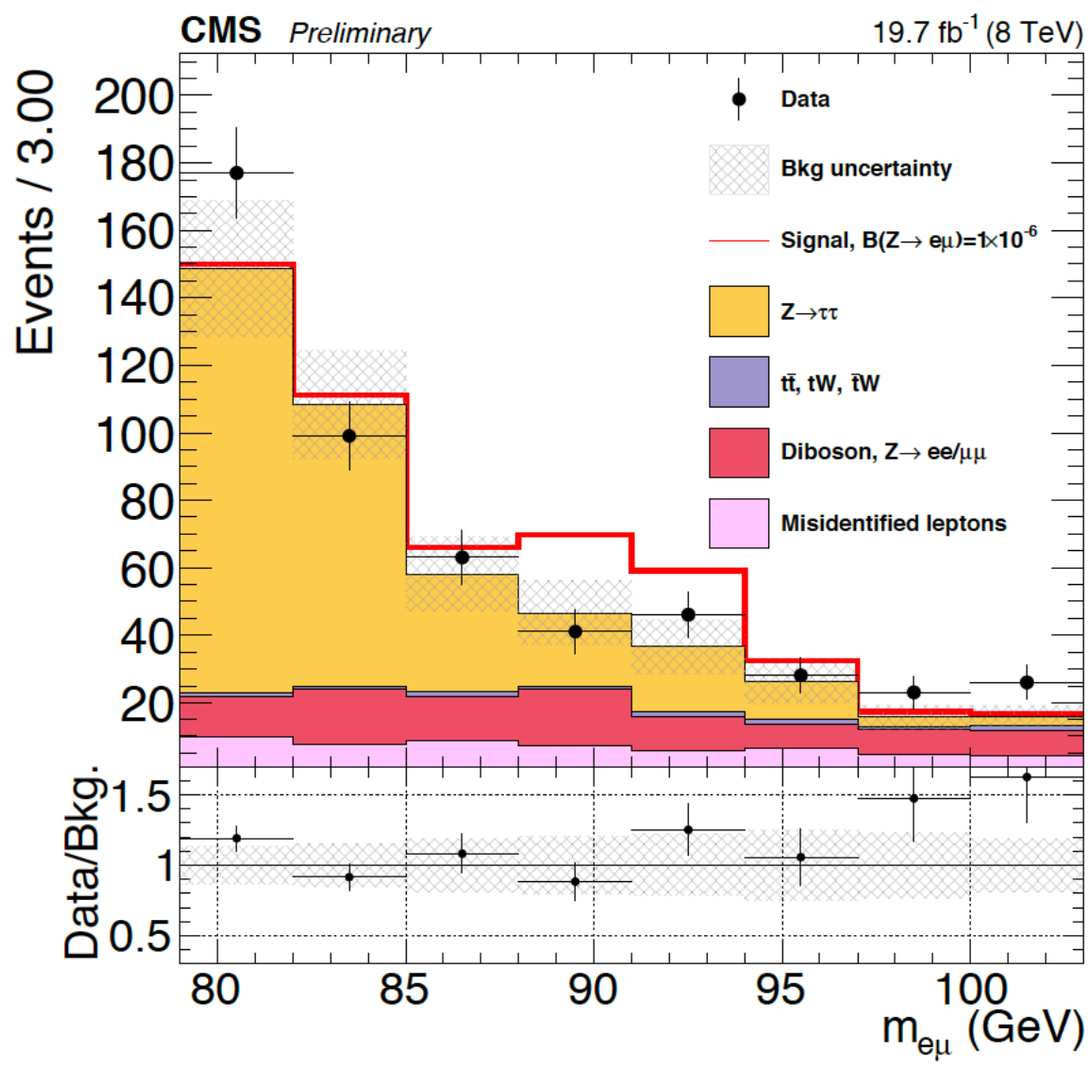


Injection efficiency : ~90%

NIM A 832, 51 (2016) by H. Iinuma et al.

CMS

- $Z \rightarrow e\,\mu$ suppressed in the SM (BR < 4 10^{-60})
- Clear signature for new physics ($e^+ \mu^-$ or $e^- \mu^+$)



2012 data set up to 19.7 fb-1 at $\sqrt{s}$ = 8 TeV

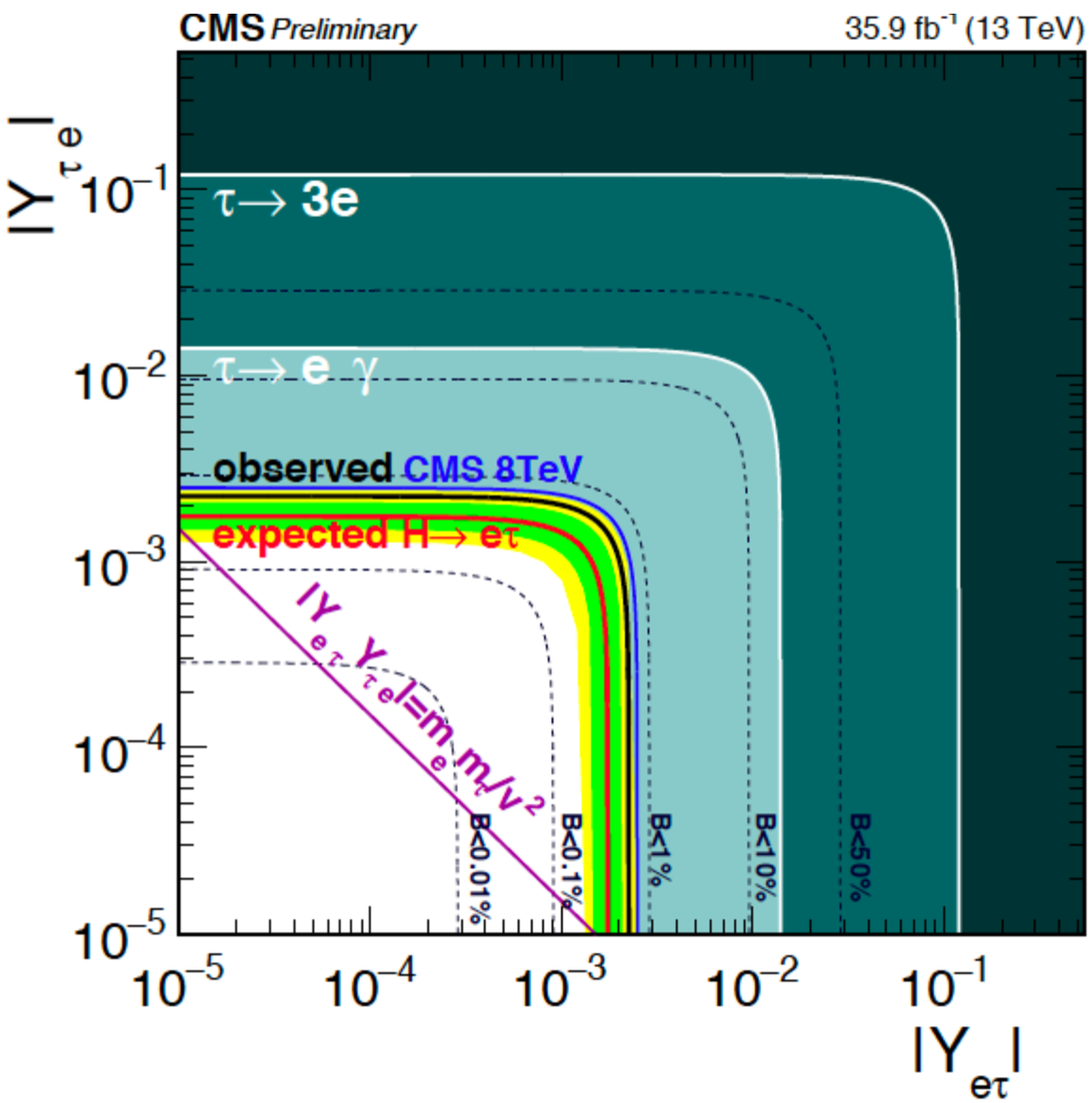
Search for Z mass resonance

No excess evidence (consistent with expected background: 87 (obs.), 83 +- 9 (SM exp) in the signal region [88 - 94] GeV

$$\mathrm{BR}(\mathrm{Z} \rightarrow \mathrm{e}\mu) < 7.3\ 10^{-7}$$

CMS

- Lepton flavour violating Higgs decays: H -> e τ and H -> μ τ. Four final states (e τ_e, e τ_h, μ τ_μ, μ τ_h)
- Derive limit on BR and Yukawa couplings



2016 data set up to 35.9 fb-1 at $\sqrt{s}$ = 13 TeV

Boosted decision tree and cut based analysis

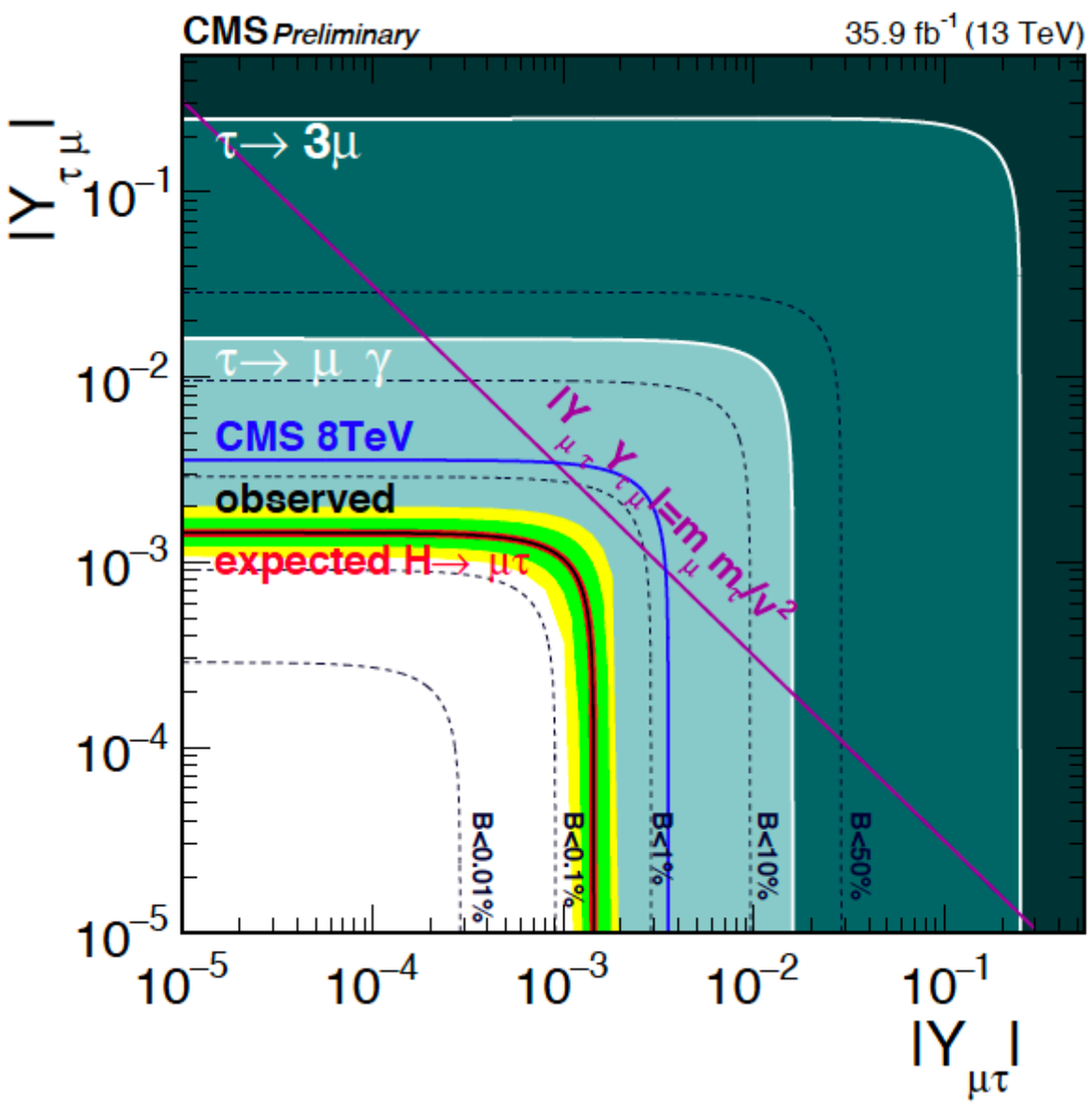
$$\mathrm{BR}(\mathrm{H} \to \mathrm{e}\tau) < 0.61\%$$

at 95 % C.L.

$$\sqrt{|\mathrm{Y}_{\mathrm{e}\tau}|^2 + |\mathrm{Y}_{\tau\mathrm{e}}|^2} < 2.26\ 10^{-3}$$

CMS

- Lepton flavour violating Higgs decays: H -> e τ and H -> μ τ. Four final states (e τ_e, e τ_h, μ τ_μ, μ τ_h)
- Derive limit on BR and Yukawa couplings



2016 data set up to 35.9 fb-1 at $\sqrt{s}$ = 13 TeV

Boosted decision tree and cut based analysis

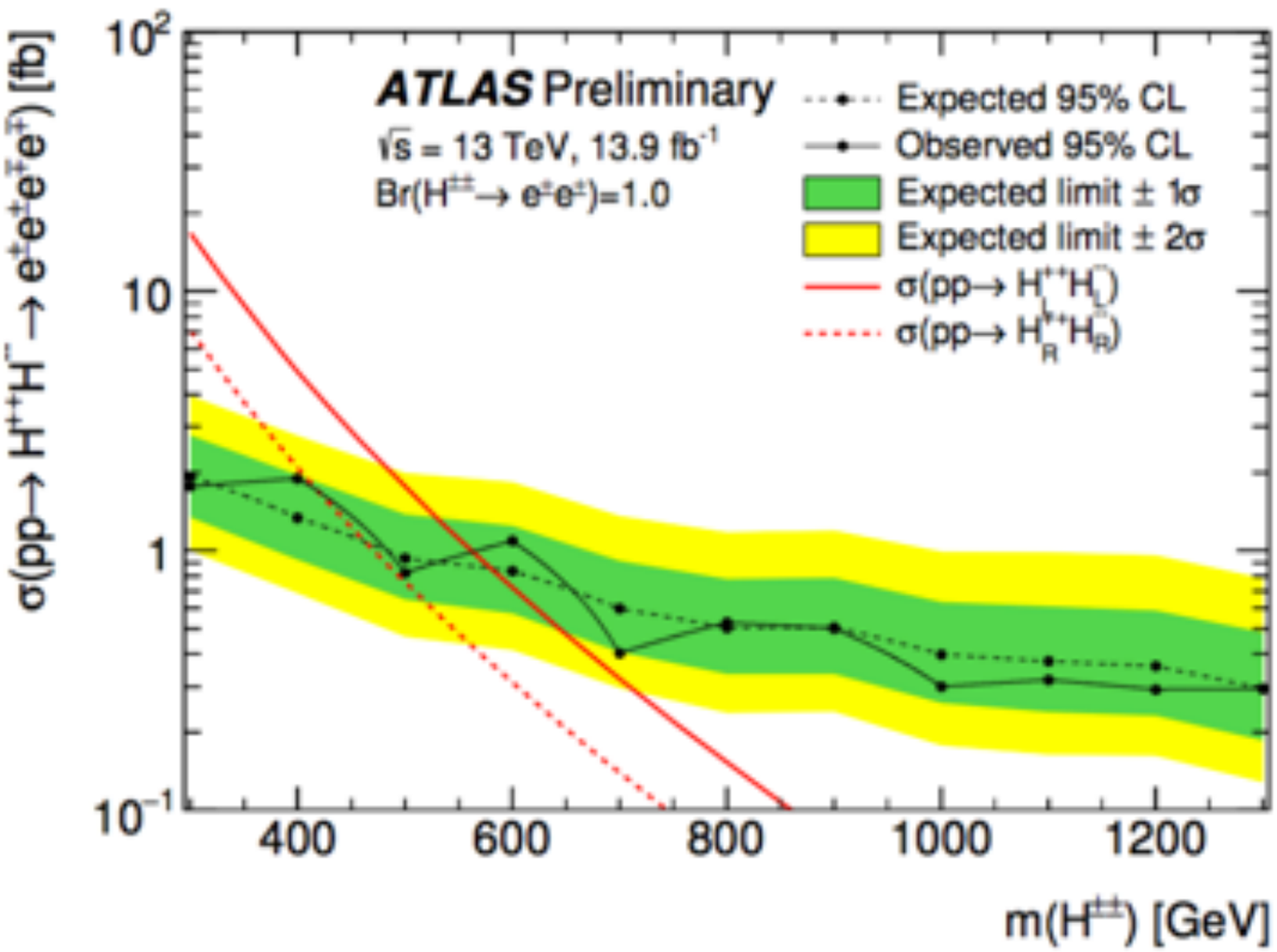
$$\mathrm{BR}(\mathrm{H} \to \mu\tau) < 0.25\%$$

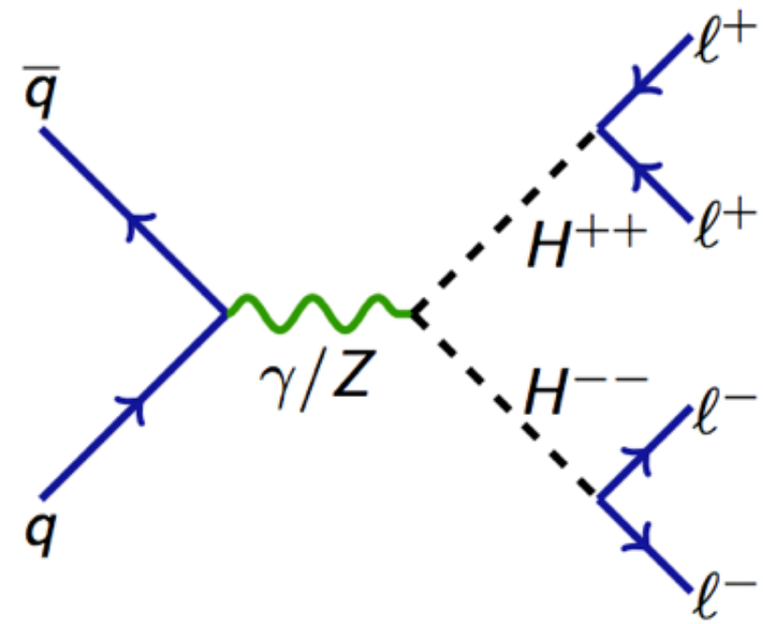
at 95 % C.L.

$$\sqrt{|\mathrm{Y}_{\mu\tau}|^2 + |\mathrm{Y}_{\tau\mu}|^2} < 1.43\ 10^{-3}$$

ATLAS

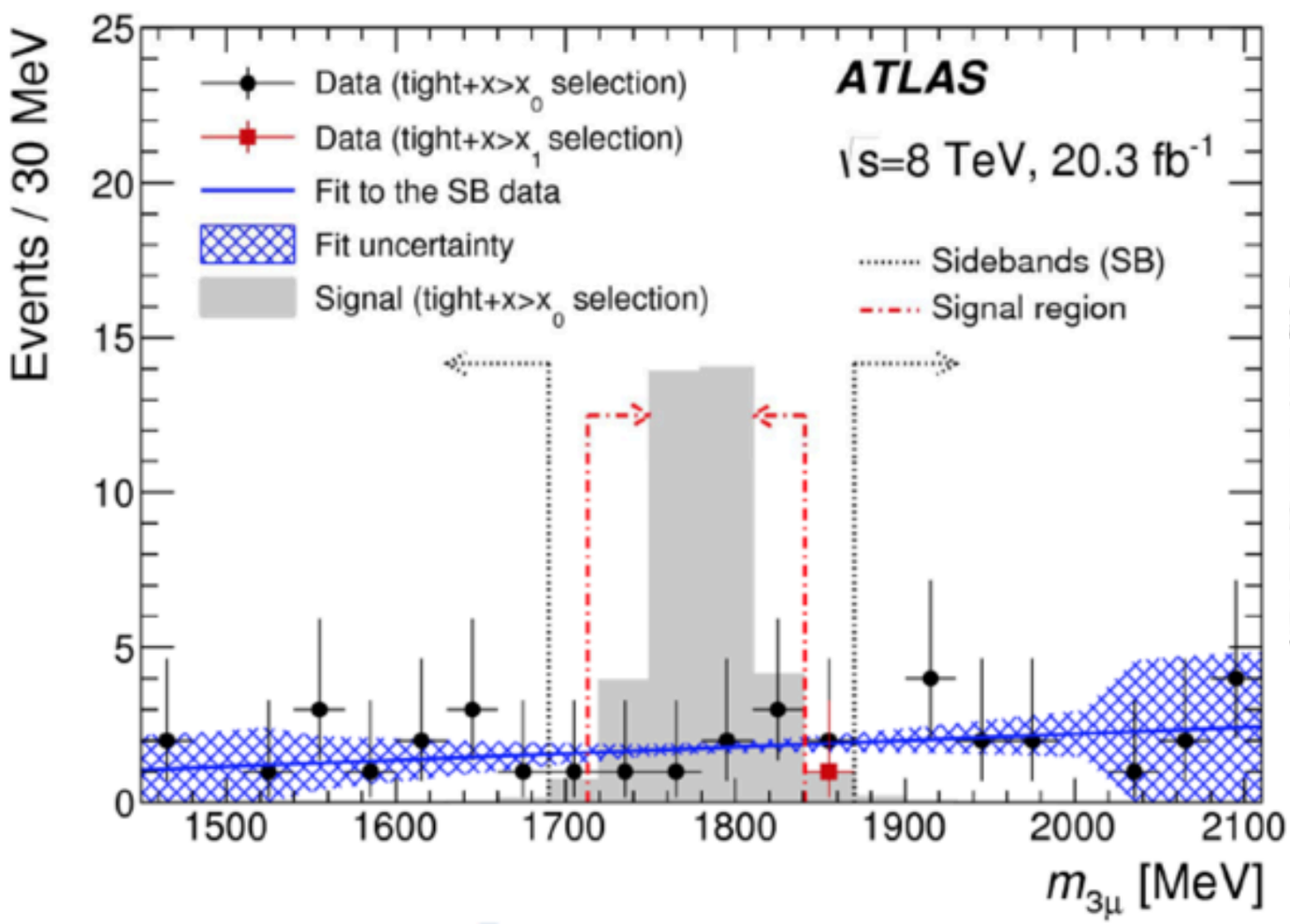
- CLFV double charged Higgs decays (H++/H - -); possible also LNV
- 3.2 fb-1 [2015] + 10.7 fb-1 [2016] data set





ATLAS

- CLFV in τ -> μμμ
- soon be competitive with limits set by LEP and other facilities such as Belle

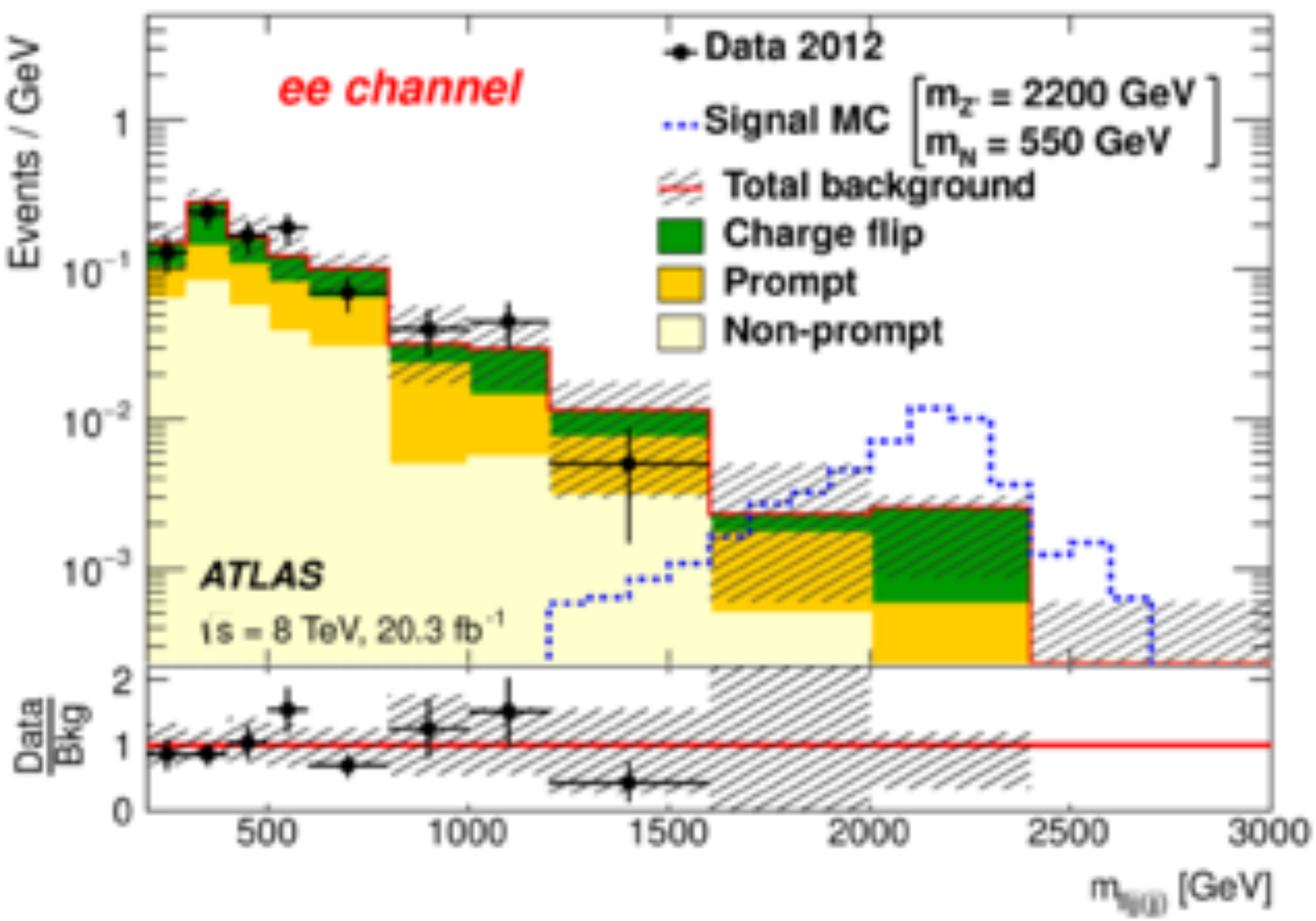


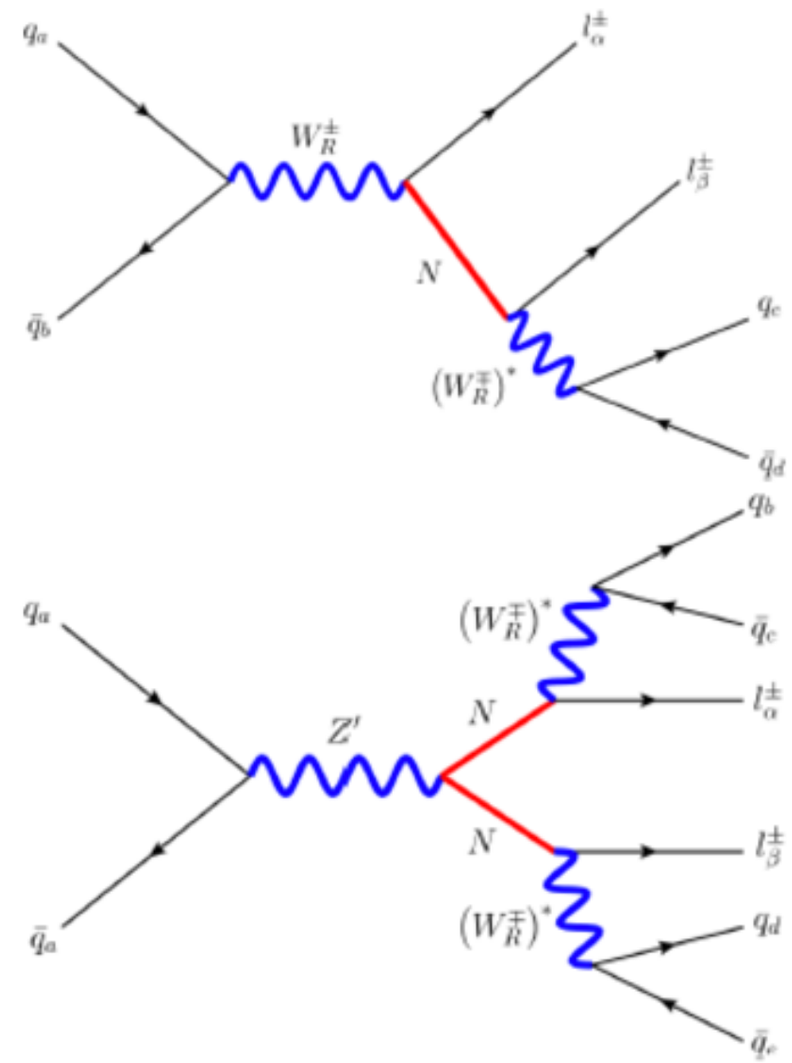
$BR(\tau \rightarrow \mu\mu\mu) < 3.8\ 10^{-7}$
@ 95% CL
PDG : $BR(\tau \rightarrow \mu\mu\mu) < 2.1\ 10^{-8}$
@ 95% CL

(see also LHCb)

ATLAS

- LNV, Majorana neutrinos
- Observable: $m_{llj(j)}$ for W_R and $m_{lljj(jj)}$ for Z_R

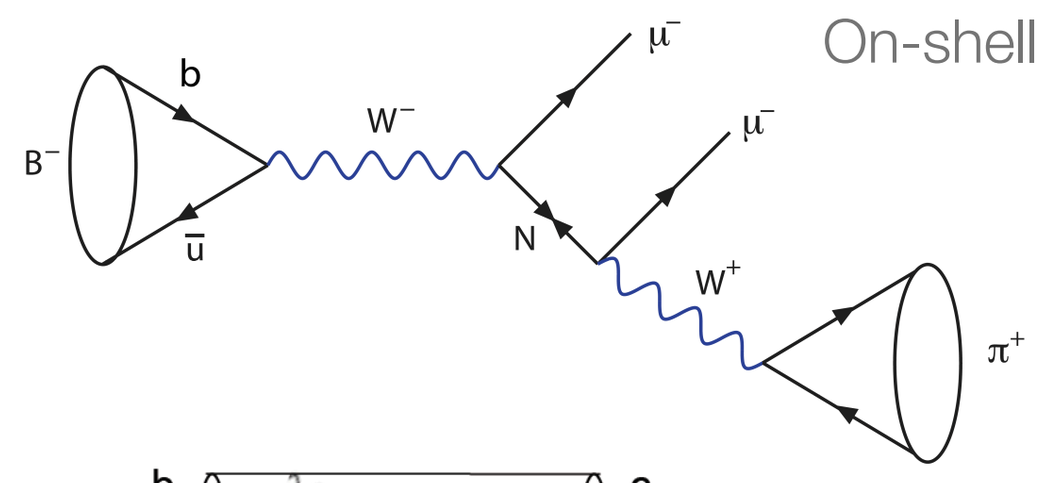


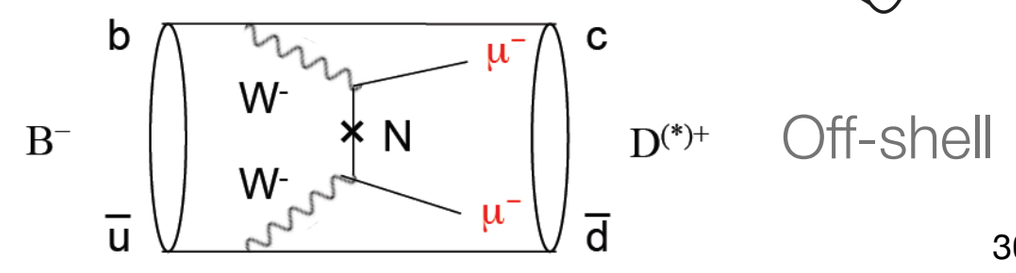


LHCb: Majorana neutrino in B- decays

- Very sensitive search for GeV-scale 4th generation sterile Majorana neutrinos; New mass versus mixing limits
- B -> μ N(μ^- π^+) [on Shell] and B -> μ^- μ^- D^{*+} for short-lived modes: The world's best limit to date in their mass range
- Updates to the full luminosity acquired by LHCb in Run1 will follow. Improvements scale as $\sqrt{\mathcal{L}}$
- Similar Majorana searches in the 250 < $m_{\pi\,\mu}$ < 2000 MeV from charm decays D_s^- -> π^+ μ^- μ^-

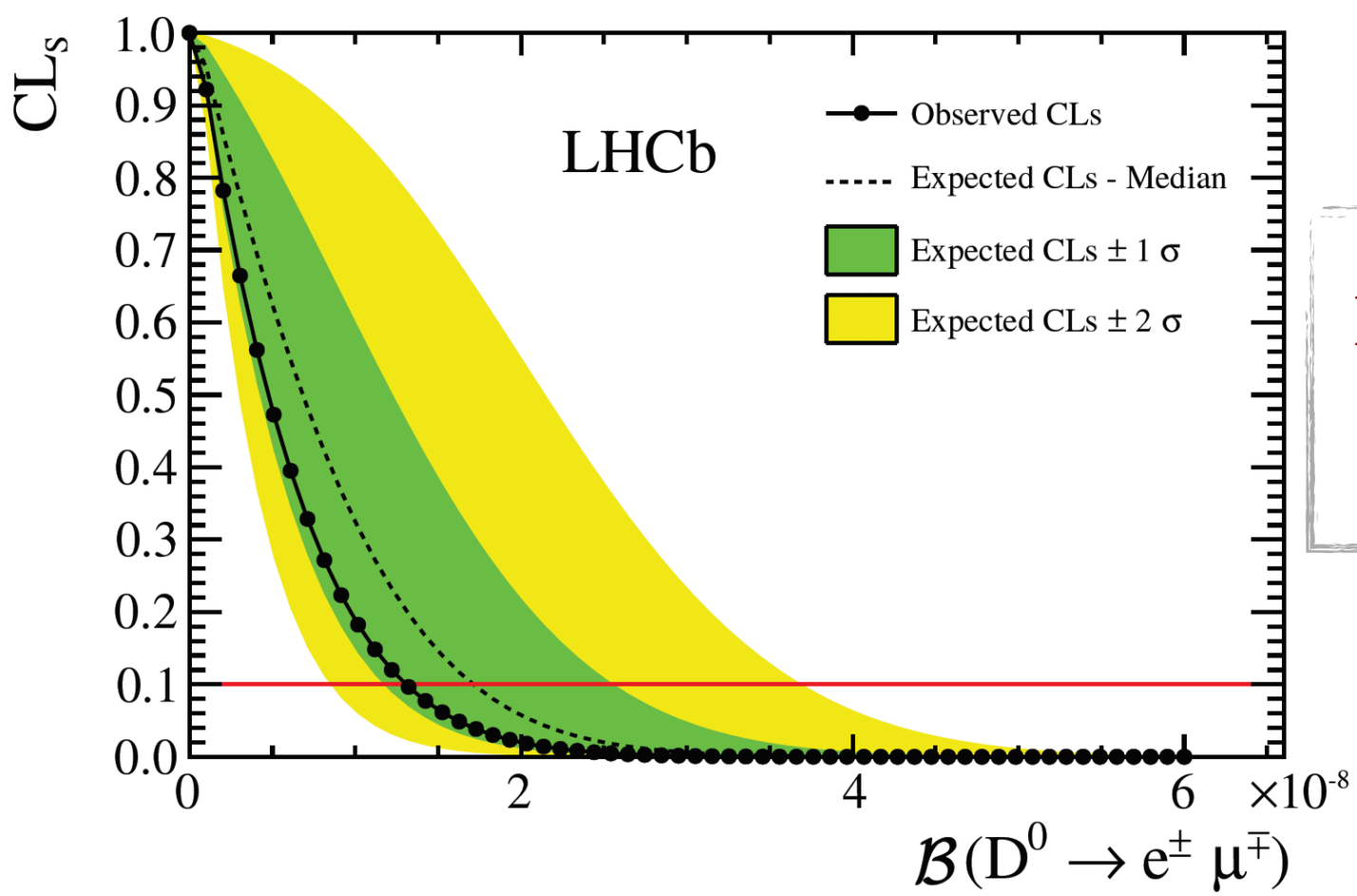
MODE	$\mathcal{B}_{\rm UL}$ 95 % CL
$B^\pm \to K^\mp\mu^\pm\mu^\pm$	5.4×10^{-8}
$B^\pm \to D^\mp\mu^\pm\mu^\pm$	6.9×10^{-7}
$B^\pm \to D^{*\mp}\mu^\pm\mu^\pm$	2.4×10^{-6}
$B^\pm \to \pi^\mp\mu^\pm\mu^\pm$	4.0×10^{-9}
$B^\pm \to D_s^\mp\mu^\pm\mu^\pm$	5.8×10^{-7}
$B^\pm \to D^0\pi^\mp\mu^\pm\mu^\pm$	1.5×10^{-6}





LHCb: CLFV in charm

- CLFV searches in $D^0 \to e^+ \mu^-$
- If only upper limits re set: Strong constraints on RPV SUSY models for improved O(10^-7) and parameter space in some lepton-quarks models for O(10^-8)
- New upper limit set (previous upper limit from Belle: BR ($D^0 \to e^+ \mu^-$) < 2.6 10^{-7} @ 90% C.L.

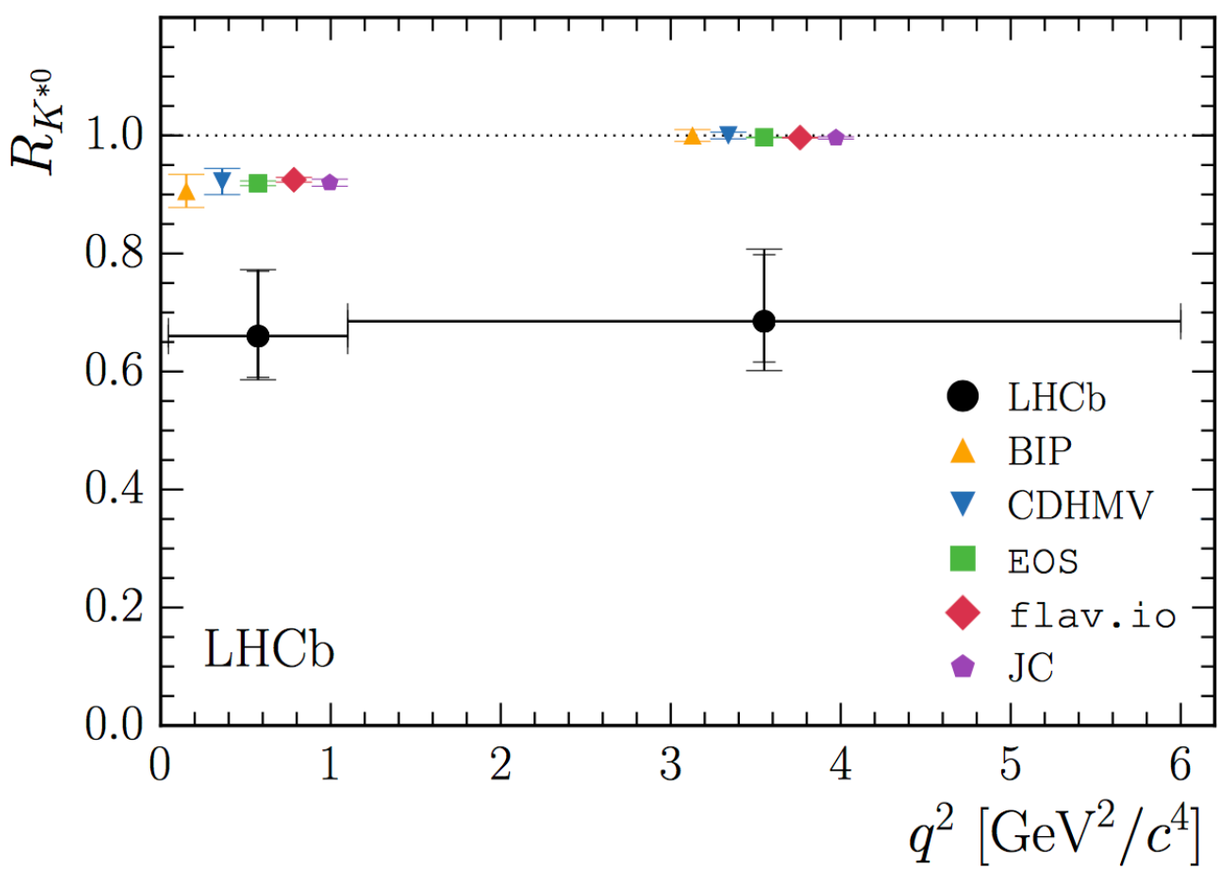


$$BR(D^0 \to e^+ \mu^-) < 1.3\ 10^{-8}$$

at 90% C.L.

LHCb: Lepton universality

- Recent results have been reported by the LHCb experiment on possible lepton flavour non universality (2.1-2.5 sigma deviation)
- Together with $B^0 \to K^{+0} \mu^+ \mu^-$ angular analysis distortion w.r.t. SM predictions (3.4 sigma deviation)
- Any departure from LU is necessarily associated with LF violation, and no known symmetry principle can protect one in the absence of the other



- Limits on the above LFV decays are close to the level of providing complementary cross-checks of the observed LNU in the weak anomalies, particularly in the channels:
- $B \to K\mu e$, $K\mu\tau$ and $B_s \to \mu e$, $\mu\tau$

BELLE: A τ-factory

- Belle, being an e+ e– B-factory experiment, is a τ-factory experiment at the same time
- With nearly 1 billion τ+ τ– sample, Belle has obtained most stringent upper limits in most of the τ LFV, LNV and BNV decays, with 90% UL of O(10^{-8})

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.7	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.6	1	4.01	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.7	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.19	5.5	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.19	6.1	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	6.2	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.7	0	2.29	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.5	0	2.39	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.28	6.2	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	6.4	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.7	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	6.2	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	6.1	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	6.2	0	2.03	3.2

BELLE II: Prospects

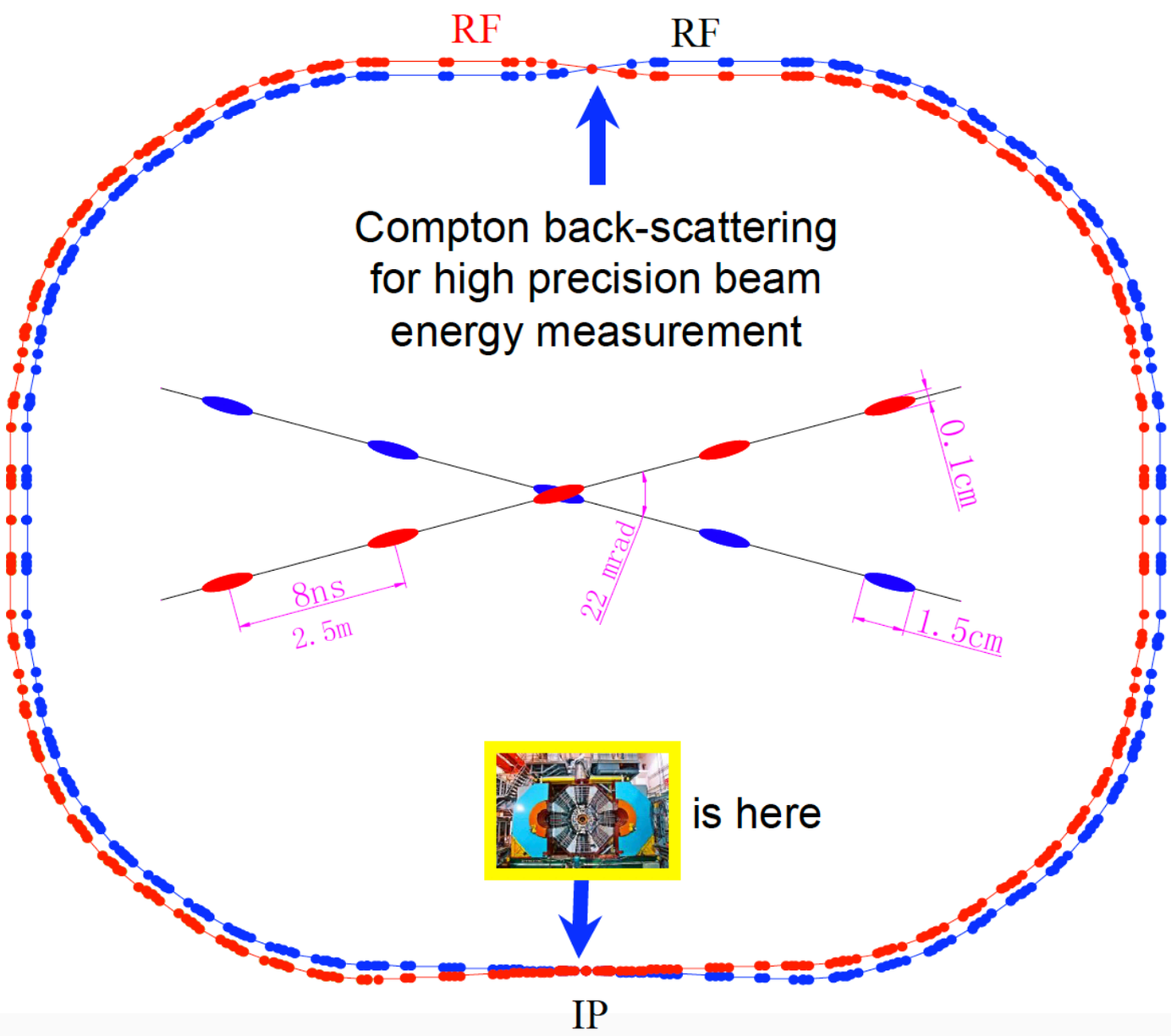
- With ~50 billion τ+ τ– events expected in the upgraded Belle II experiment, B-physics searches will be greatly improved: LFUV involving B decays to τ [R(D), R(D*)]; LFUV, LFV involving EW penguin B decays [R(K), R(K*) for LFUV, B → K(*) l τ, K(*) e mu etc. for LFV]
- For very clean modes (e.g. τ+ → ℓ+ℓ–ℓ+), CLFV upper limits are expected to improve linearly with luminosity: They will be very powerful probes for new physics beyond the SM
- Physics Run: Expected to start by the end of 2018
- First τ LFV sensitivity study:

	Belle (535 fb^{-1})	**Belle II (1 ab^{-1})**		**Belle II (50 ab^{-1})**
$\mathcal{L}$ (cm^2/s)	2.11 x 10^{34}	80 x 10^{34}		
ε_{signal}	5.09%	4.59%		
n_{BG}	10	-	→	
$B_{90}(\tau \to \mu\gamma)$	**4.5 x10^{-8}**	**2.7 x10^{-8}**		**5.5 x10^{-10}**

a naive extrapolation by luminosity

BESIII

- The BESIII experiment at BEPCII in Beijing is designed to provide a comprehensive world-class physics program in the charm threshold region



Beam energy:
1-2.3 GeV
Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A @ 2.5 GeV

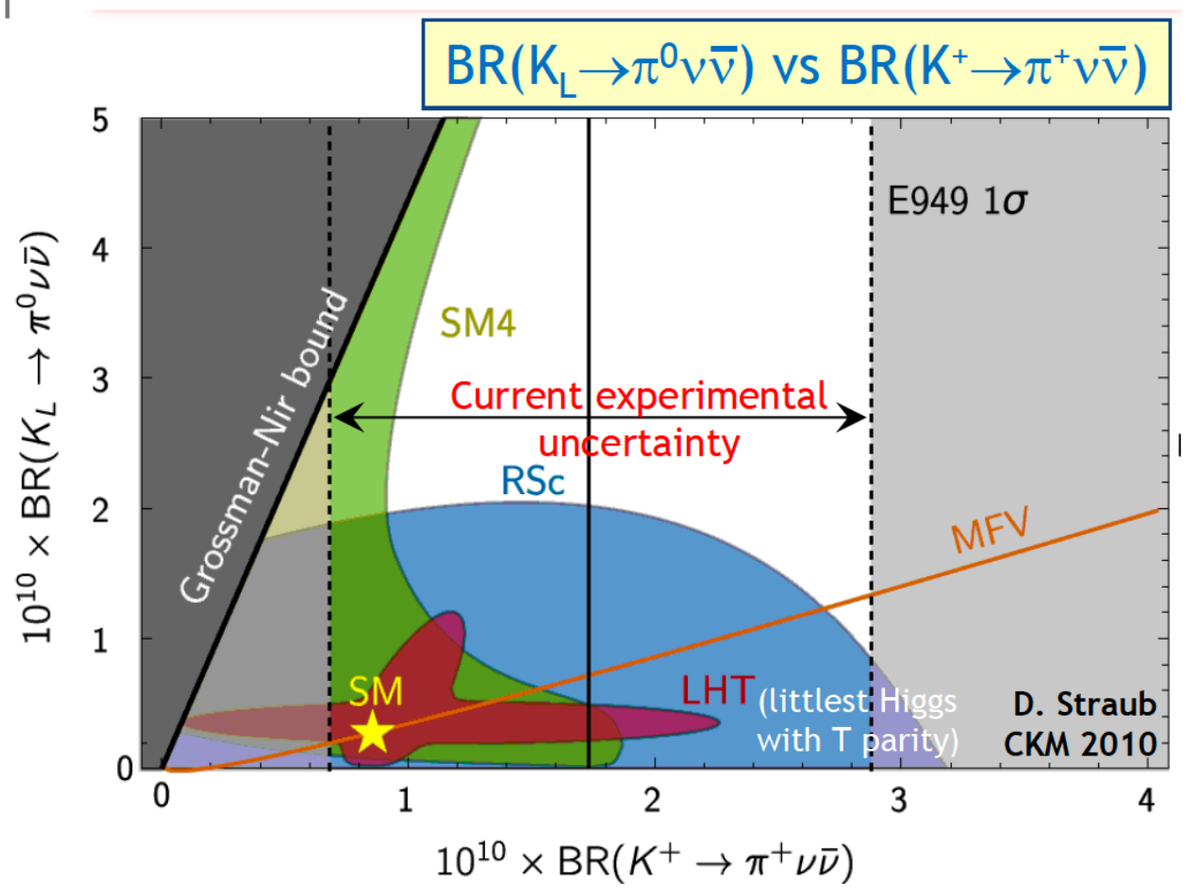
CLFV via $J/\psi \to e\mu$ at BESIII

- With the world largest e+ e- annihilation J/ψ data including more than 225 million J/ψ events, the BESIII collaboration got the leading upper limit on $J/\psi \to e\mu$ decay
- Event topology: two opposite, back-to-back, charged tracks, no obvious extra EMC showers. Most of the backgrounds are from $J/\psi \to e_+ e_-$, $J/\psi \to \mu_+ \mu_-$, $J/\psi \to \pi_+ \pi_-$, $J/\psi \to K_+ K_-$, $e_+ e_- \to e_+ e_- (\gamma)$ and $e_+ e_- \to \mu_+ \mu_- (\gamma)$
- Better sensitivities on $J/\psi \to e\tau$ and $J/\psi \to \mu\tau$ based on 1300 million J/ψ events are coming soon

Decay mode	BESII upper limit	BESIII upper limit	Other experiment
$J/\psi \to e\mu$	1.1×10^{-6} (58M)	1.6×10^{-7} (225M)	-
$J/\psi \to e\tau$	8.3×10^{-6} (58M)	-	-
$J/\psi \to \mu\tau$	2.0×10^{-6} (58M)	-	-

NA62

- Main goal: collect 100 SM $K^+ \to \pi^+ \nu\nu$ [2016-2018]; $BR_{SM} = (8.4 \pm 1.0)\ 10^{-11}$
  - Ultra-rare decays with the highest CKM suppression, SM precision surpasses any other FCNC process involving quarks, measurements of $|V_{td}|$ complementary to those from B-B mixing or $B^0 \to \rho\ \gamma$
  - Theoretical clean, almost unexplored, sensitive to new physics
- Current measurement (BNL-E949): $BR(1.73 + 1.15 - 1.05) \times 10^{-11}$ (based on 7 candidates with 2.6 expected background events)



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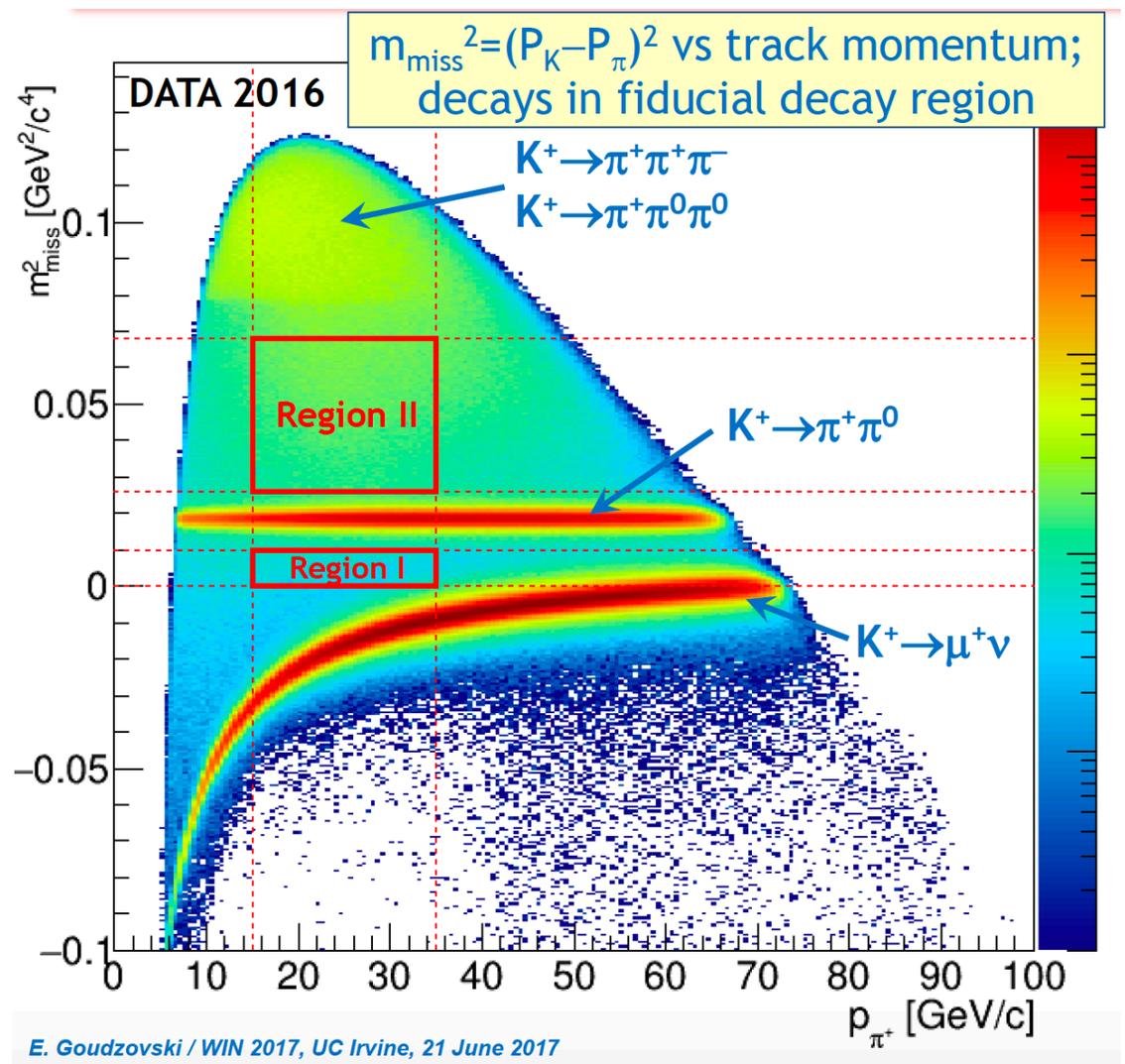
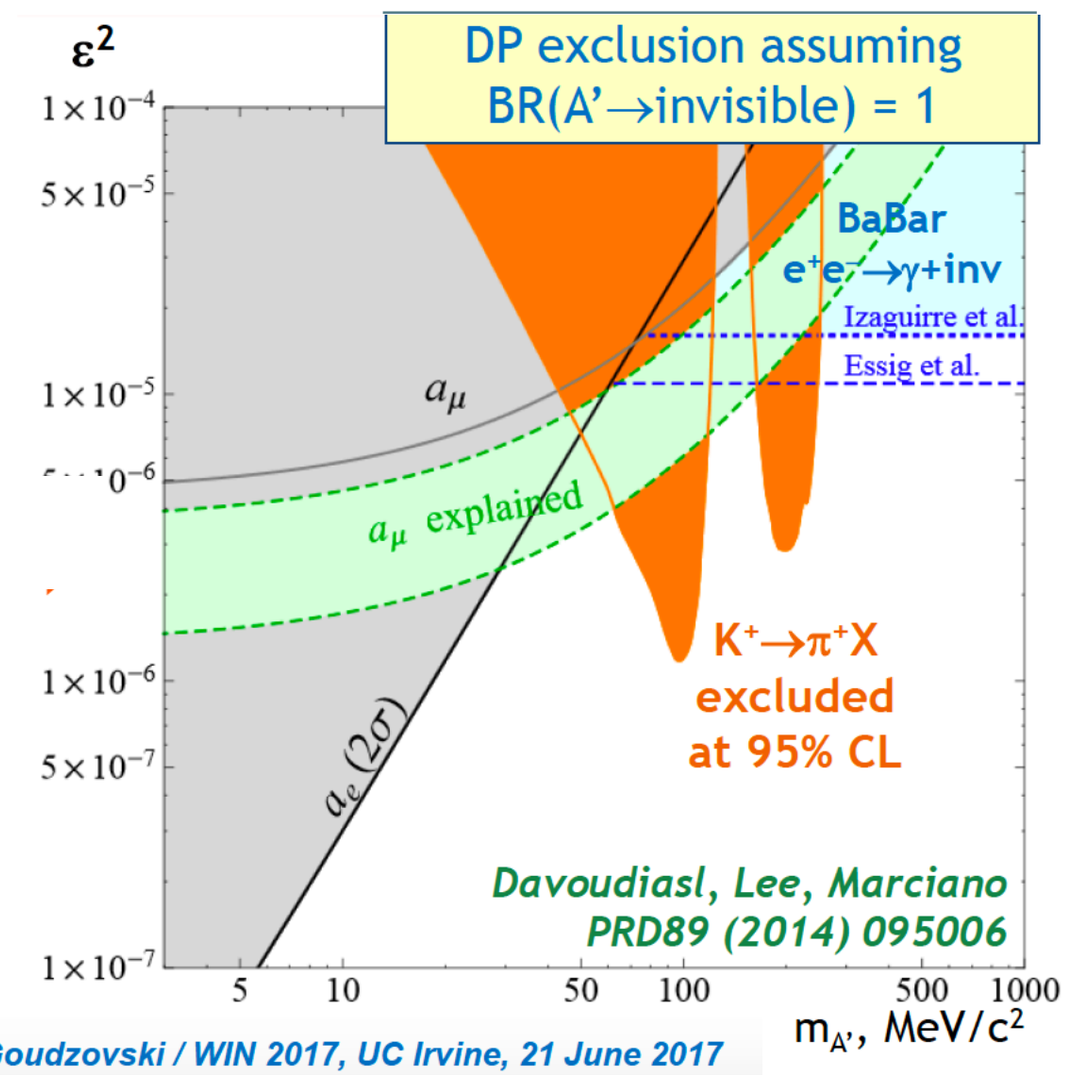
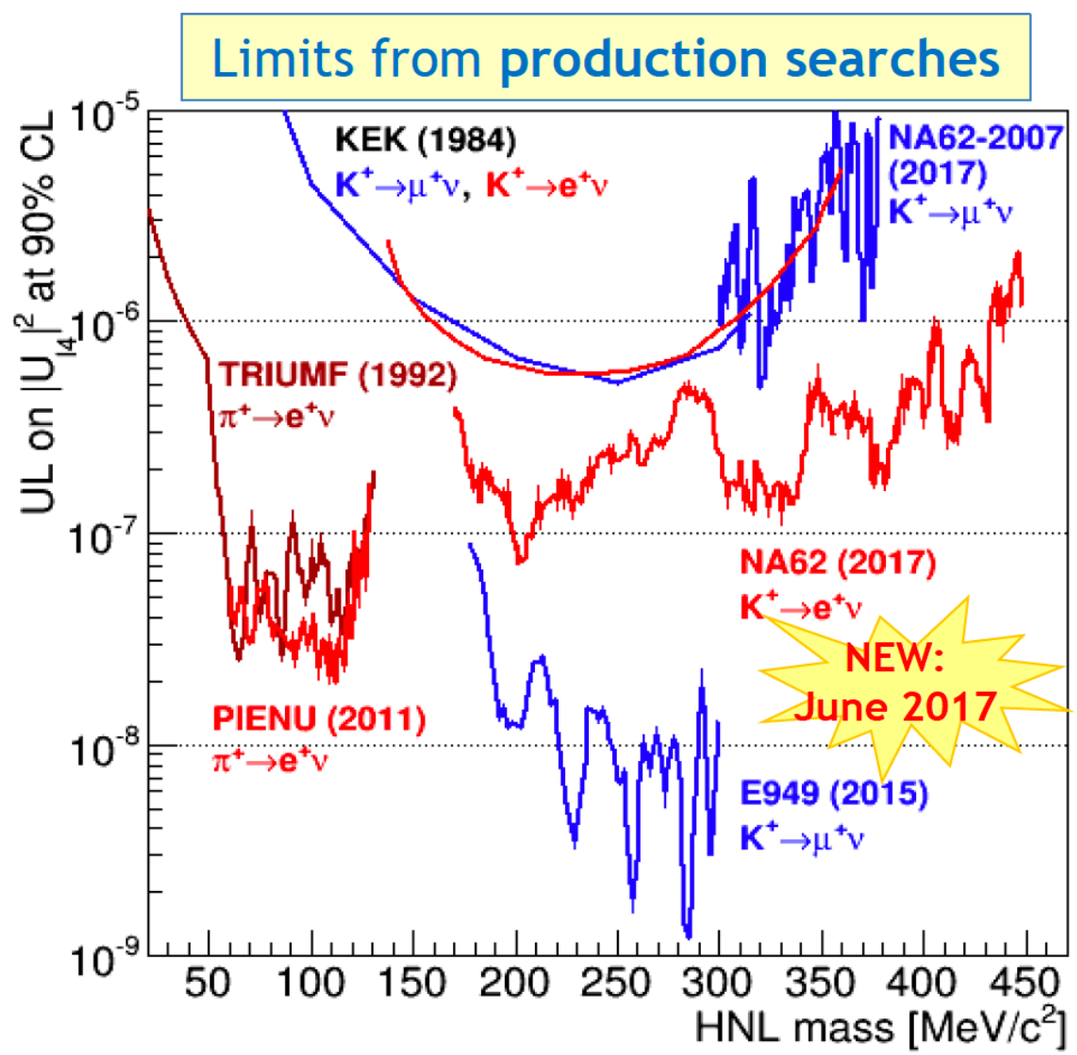


NA62

- Other measurements: $K^+ \to l^+ N$ (New Result!)
- $K^+ \to \pi^+ A'$, $A' \to$ invisible at nominal SES ~ 10^{-12} (O(10) improvement on ξ^2 current limit). Physics program 2021-2024 under discussion





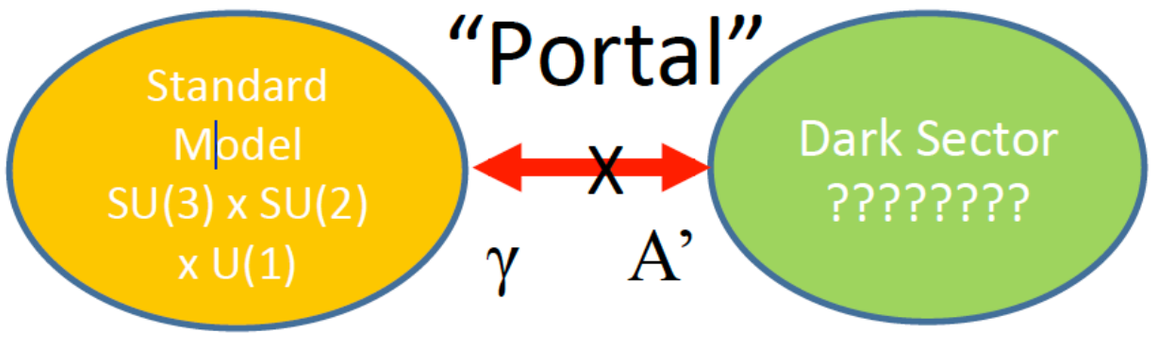
Babar: visible/invisible decay searches

- Dark sector particles couple weakly to the Standard Model
- Dark sector particles still interact gravitationally
- Can be in mass range MeV – GeV
- Dark photon A' could:

  Mix with SM photon, which in turn couples to SM final states: "Visible"

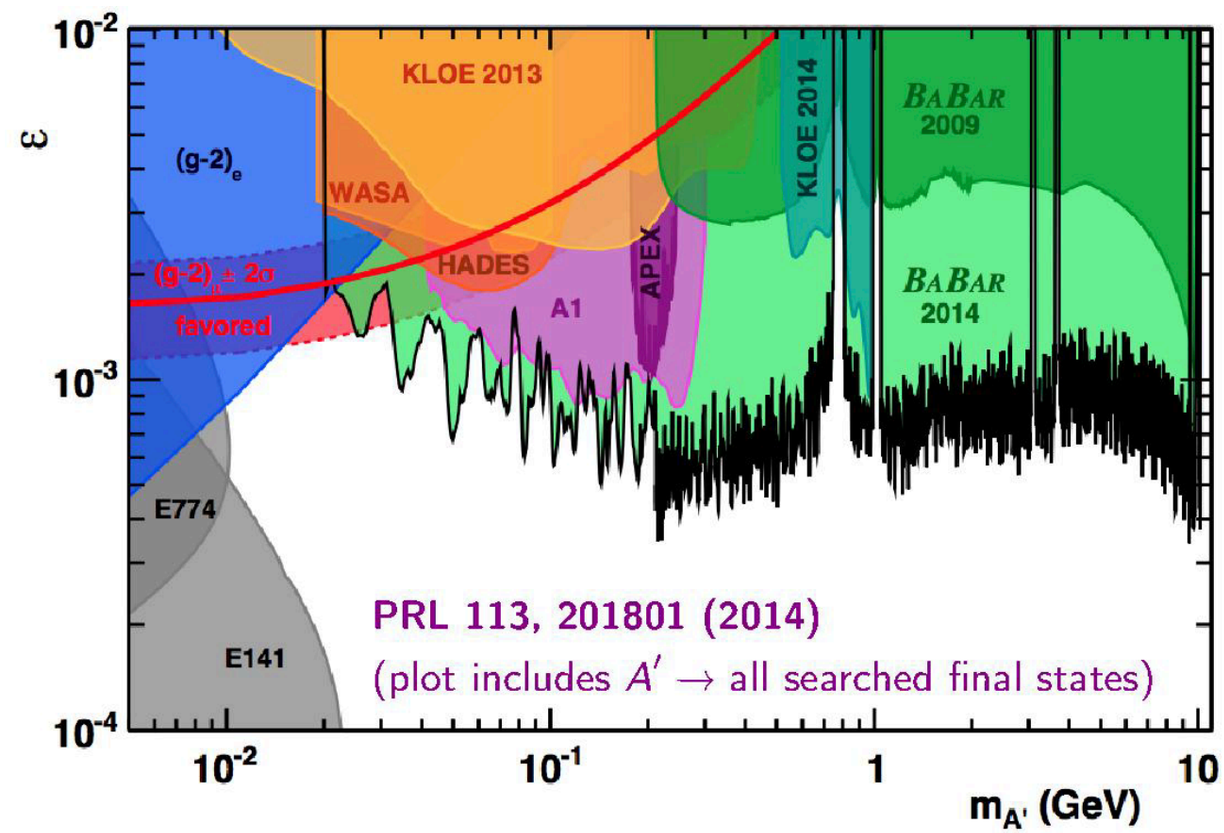
  Decay to lighter dark matter particles χ that escape detection: "Invisible"
- Could explain:

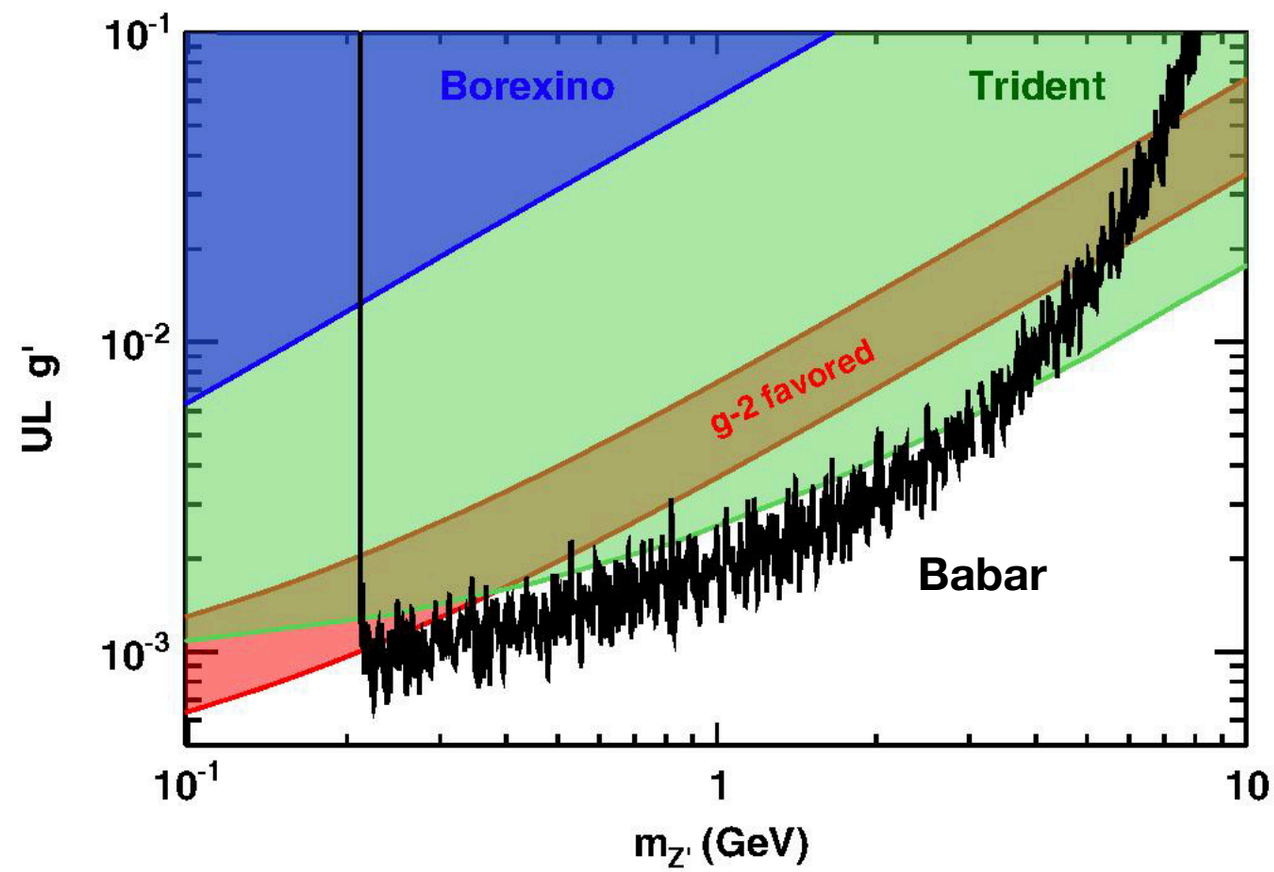
  Dark Matter, muon g-2 anomaly, proton charge radius, …



Babar: search for visible decays

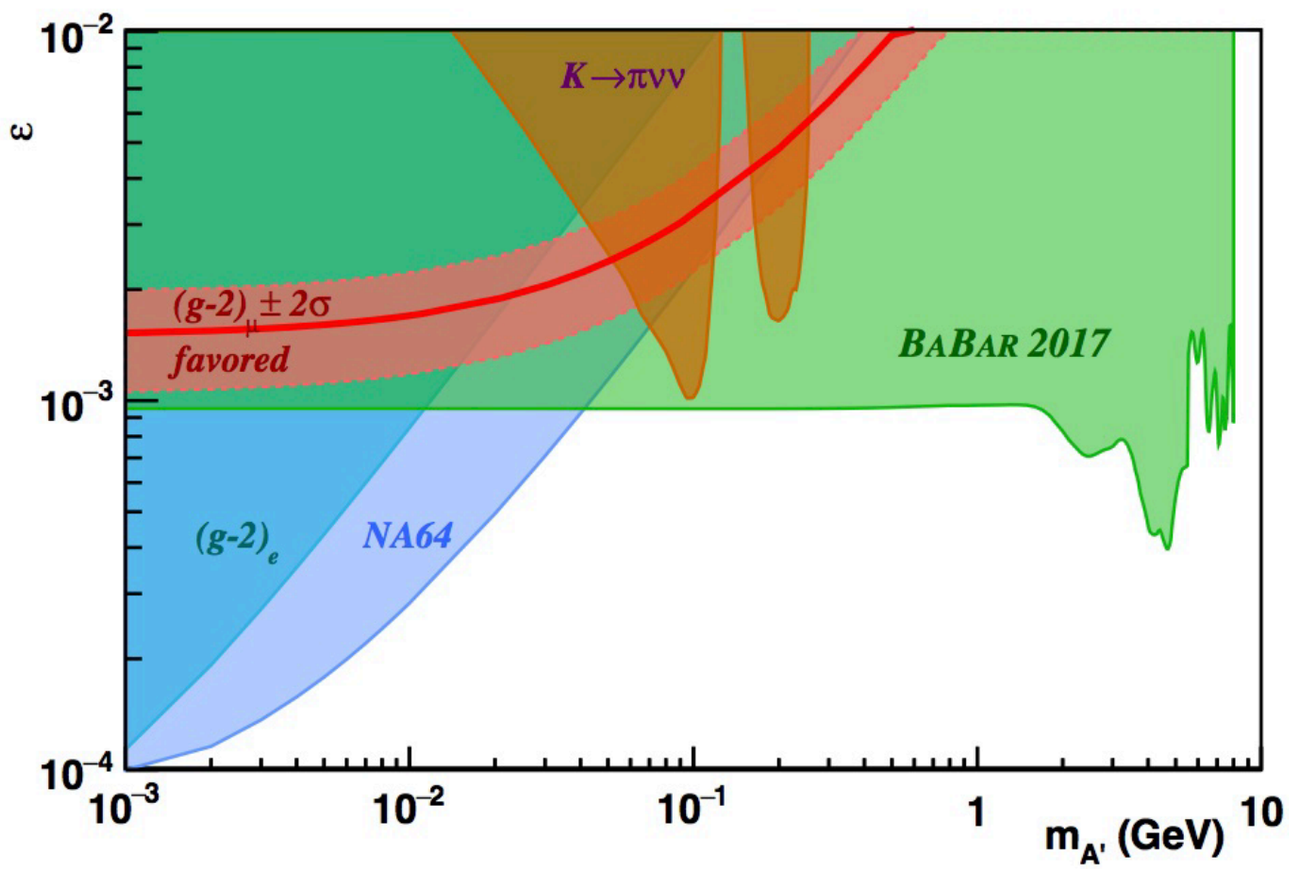
- Search for dark photon in $e^+ e^- \rightarrow \gamma A'$, $A' \rightarrow \mu^+\mu^-, e^+e^-$
- Search for muonic dark forces in $e^+ e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \mu^+\mu^-$
- Search for dark Higgs boson in $e^+ e^- \rightarrow h' A'$, $h' \rightarrow A' A'$, $A' \rightarrow f^+ f^-$
- Limits assume no decays to invisible final states





Babar: search for invisible decay of dark photon

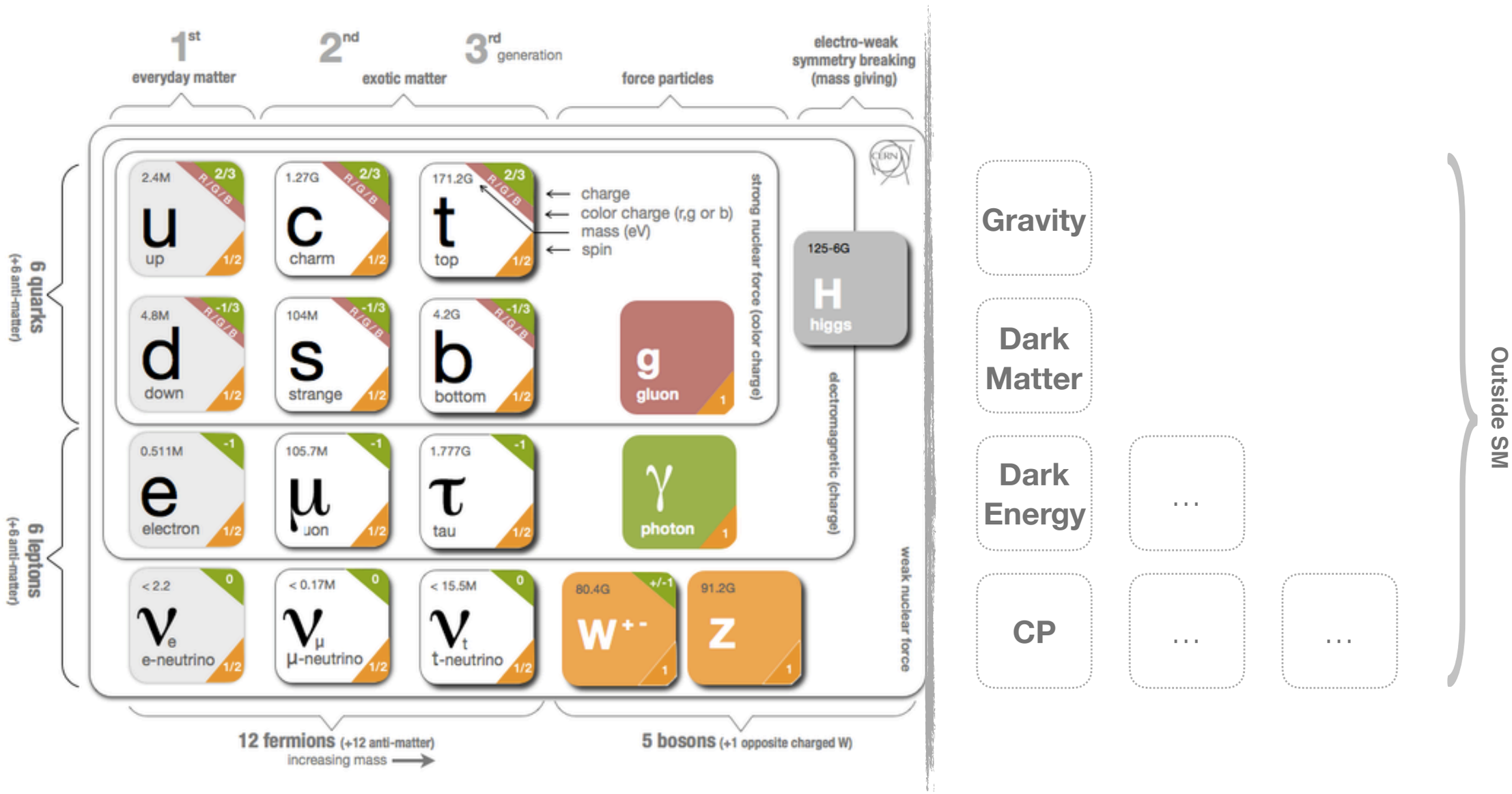
- Search for photon and missing energy/mass in range 0-8 GeV/c^2
- Reconstruct missing mass squared, M_X
- Scan through M_X distribution, looking for bumps above a smooth background
- Assume A' width less than experimental resolution
- Assume a single A' is present



Extends excluded range in both ε and $M_{A'}$

Region that would explain muon g-2 anomaly now excluded by both visible and invisible decay channels

The role of the flavour and precision physics



- Searches for rare/forbidden decays
- Symmetry tests
- Precision measurements

very sensitive tools for

- unveiling new physics
- probing high energy scale

Thank you

- S. Mihara
- K. Oishi
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- S. Xella
- M.G. Zhao
- Y. Kwon