Working Group 4 Summary
"Muon physics"

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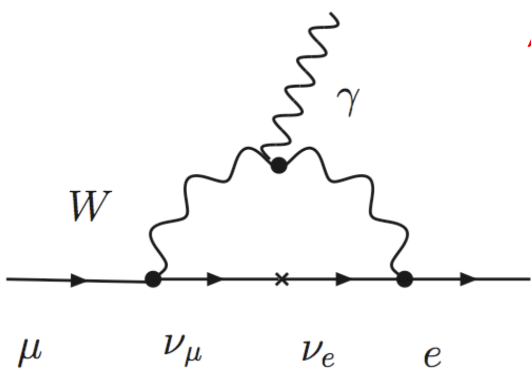
Introduction

Why Should Anyone Here Care About CLFV?

- Technology is linked:
  - When you make muon neutrinos, you make muons. Neutrino factories/nuSTORM, for example, make muon beams we can use for muon CLFV.
- Physics is linked: (Ana's talk! much deeper than this)
  - oscillations are neutral lepton flavor violation
  - explanations for neutral lepton mixing make predictions for charged lepton mixing; I'll show you examples.
  - *g-2:* can think of it as probing diagonal elements of a matrix; CLFV studies the off-diagonal

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

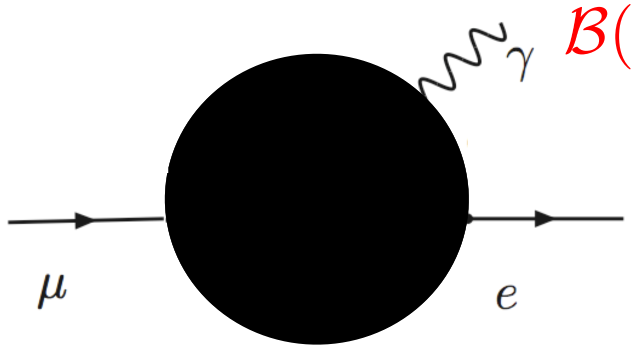


$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$

ν oscillations

too small to access experimentally

SM extensions

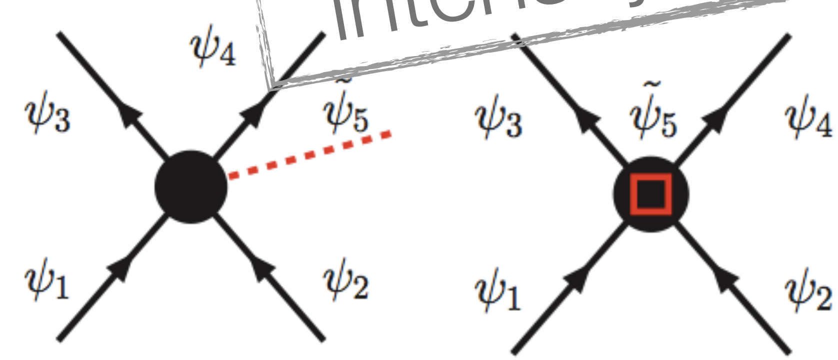


$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$

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

to unveil behind SM physics
via virtual particles

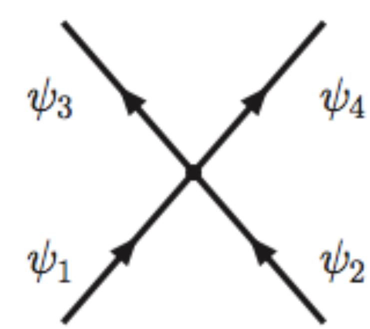
intensity frontier



to probe otherwise unreachable and
unexploited new physics energy scale

high energy probe

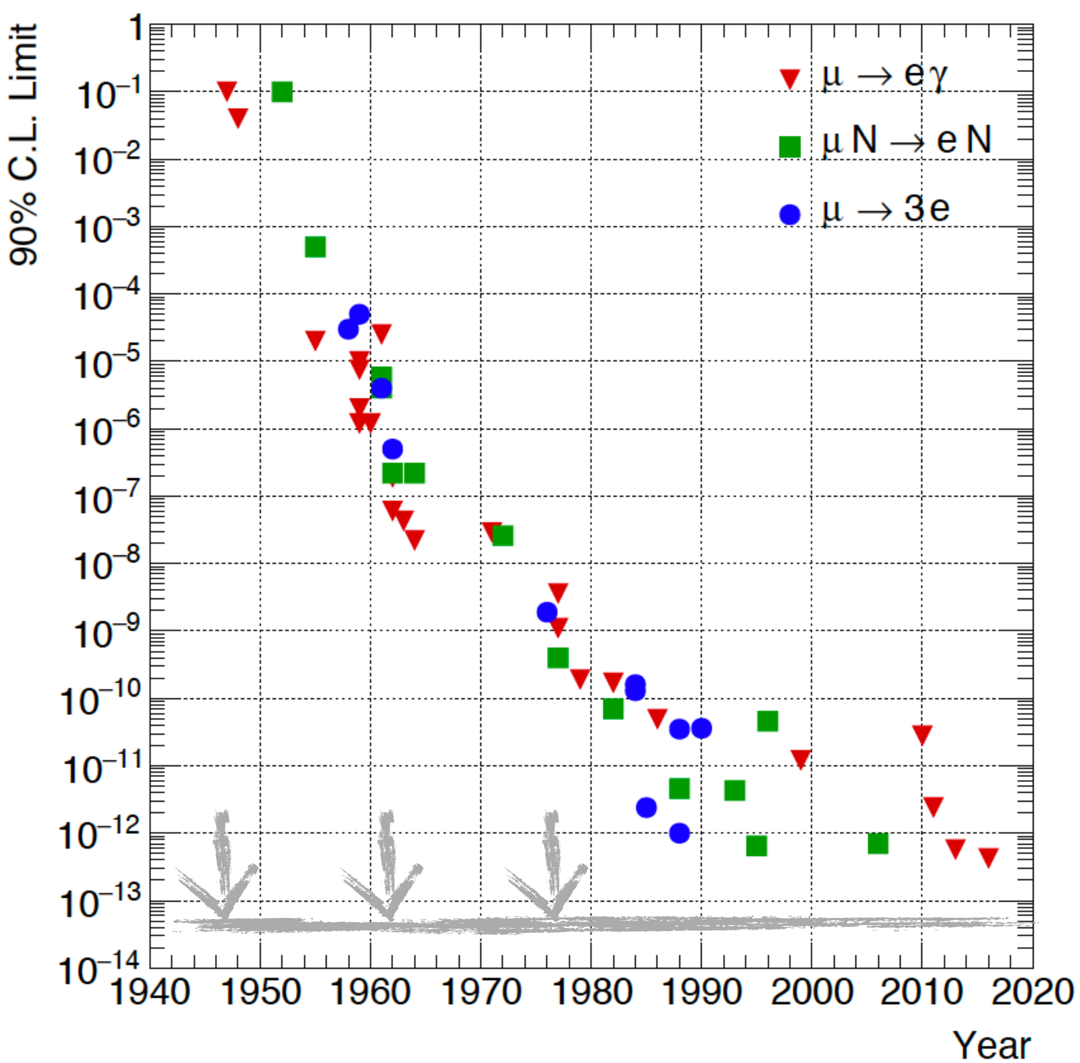
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



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

cLFV searches with muons: Status and prospects

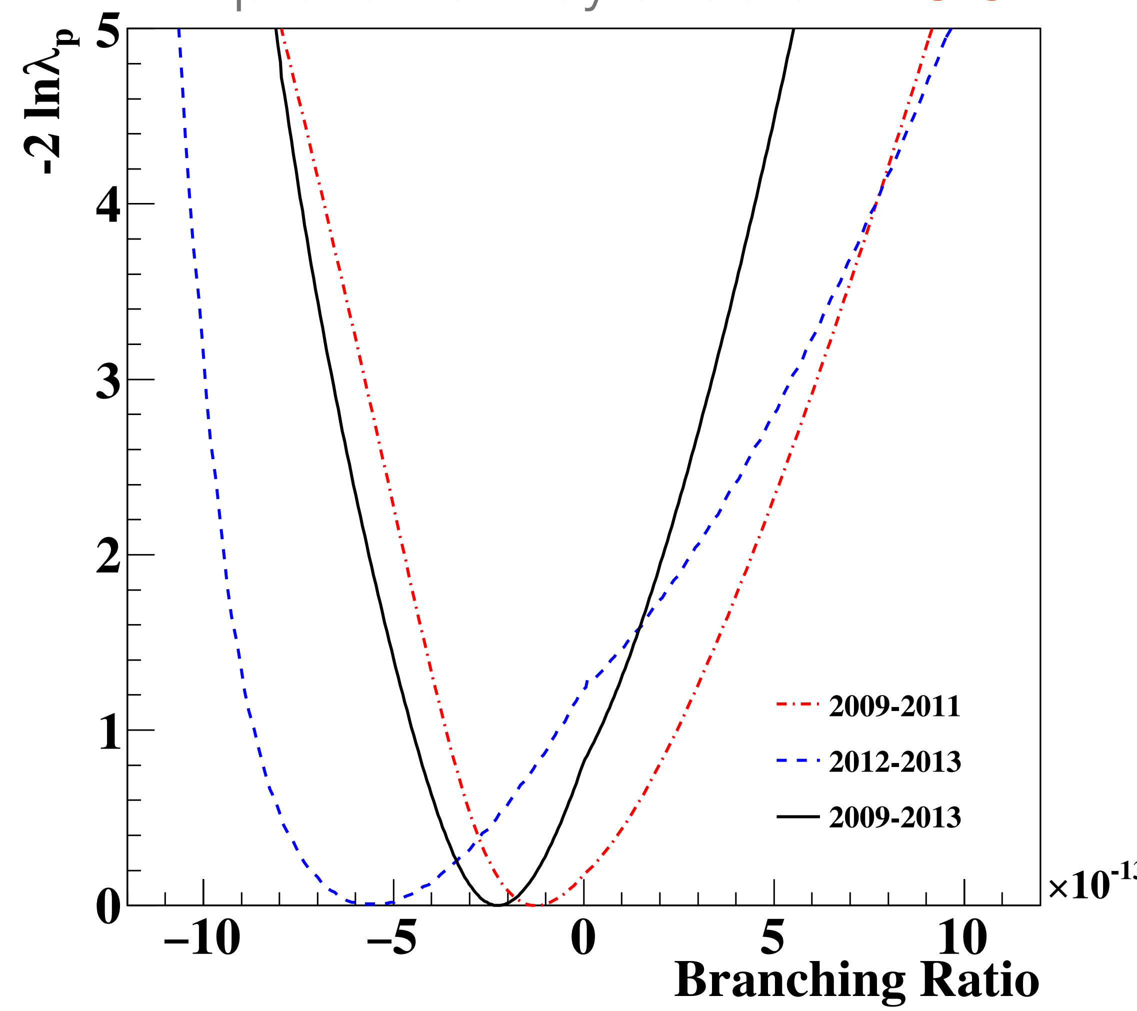
- In the near future impressive sensitivities: BR($\mu \to e\gamma$) < 4 10^{-14} ; BR($\mu \to eee$) < 1 10^{-16}; CR($\mu N \to eN'$) < 10^{-17}
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV



MEG Final result:

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

improvement by a factor ~ 30



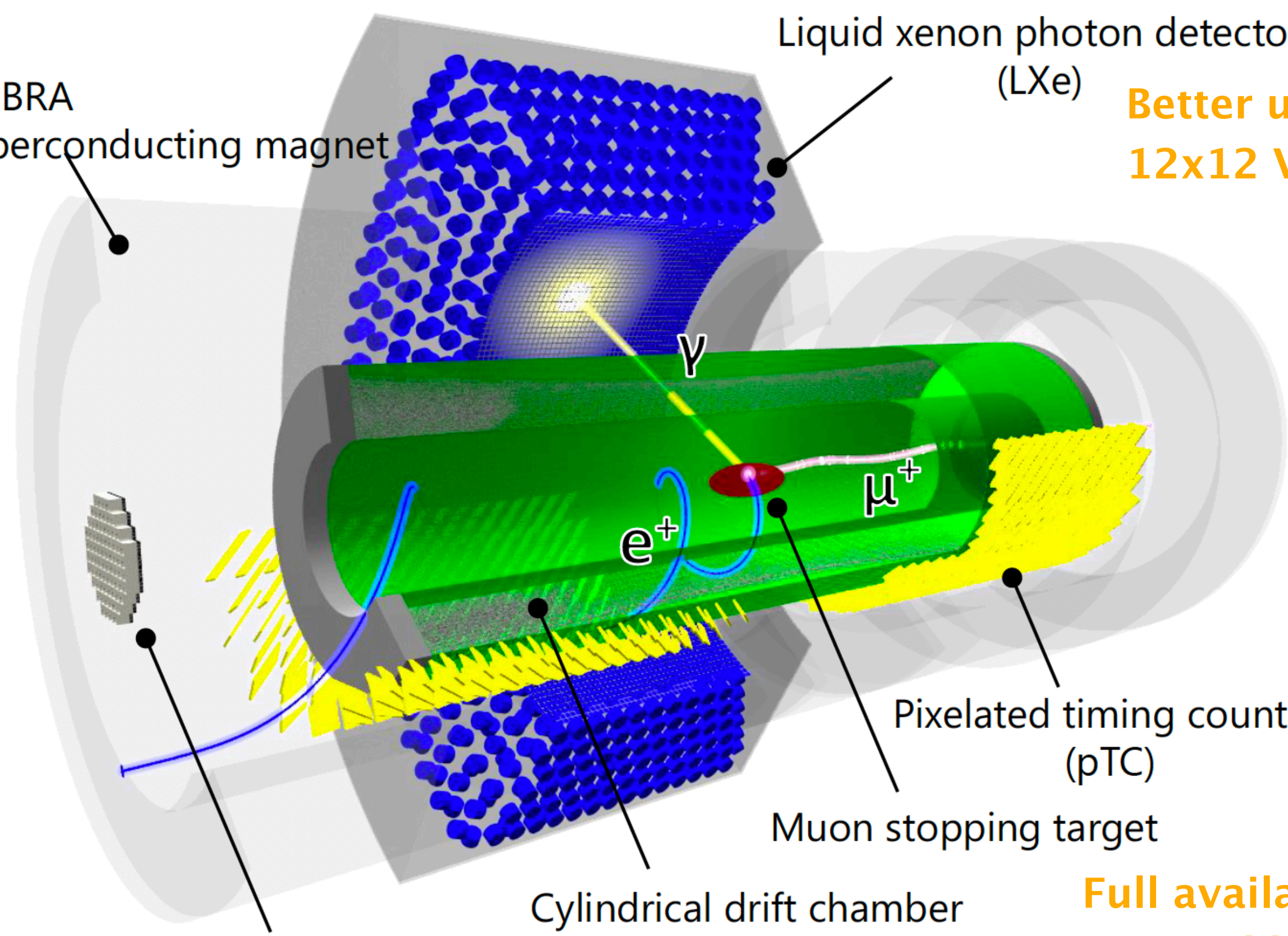
The MEGII experiment

- A real "upgrade": kept the skeletron of the experiment/key ideas and refurbished beam line and all sub-detectors

New electronics:
Wavedream
~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration
Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

35 ps resolution w/ multiple hits

Background rejection

Single volume $He:iC_4H_{10}$

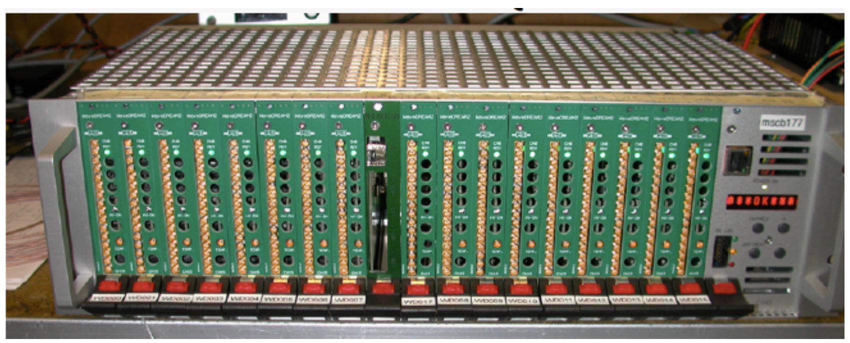
Full available stopped beam intensity
7×10^7

MEGII Status

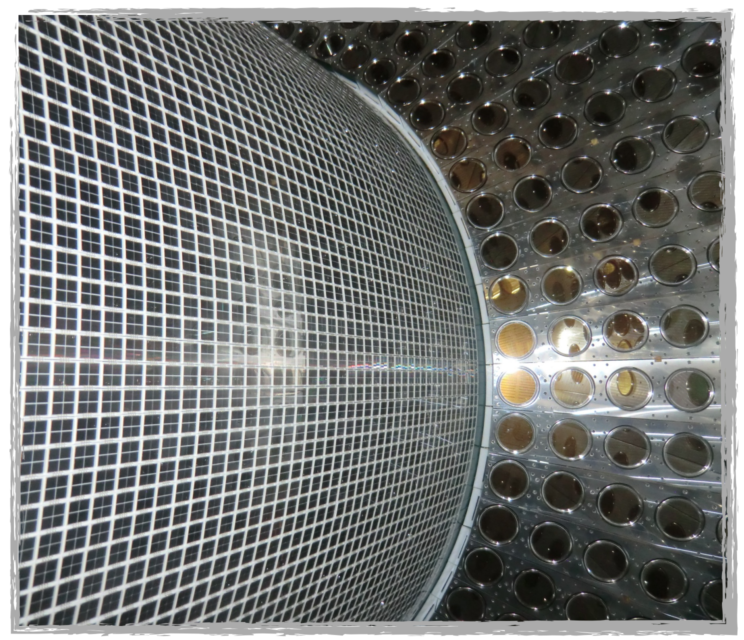
- Pre-engineering runs ongoing. Full engineering run [**2018**] followed by data acquisition

Optimum beam and calibrations: Ready

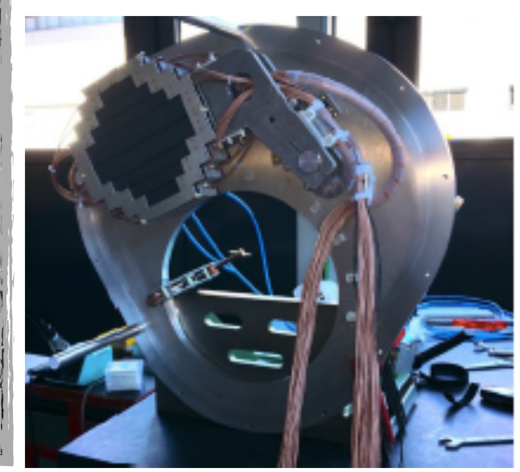
new DAQ + TRG (**5 Gsample/s**): Mass production Jan 2018



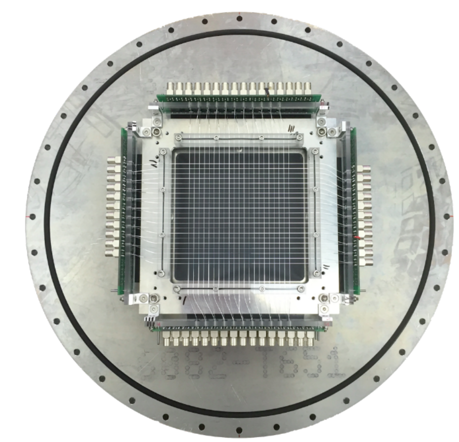
new MPPC in the **VUV:** Ready



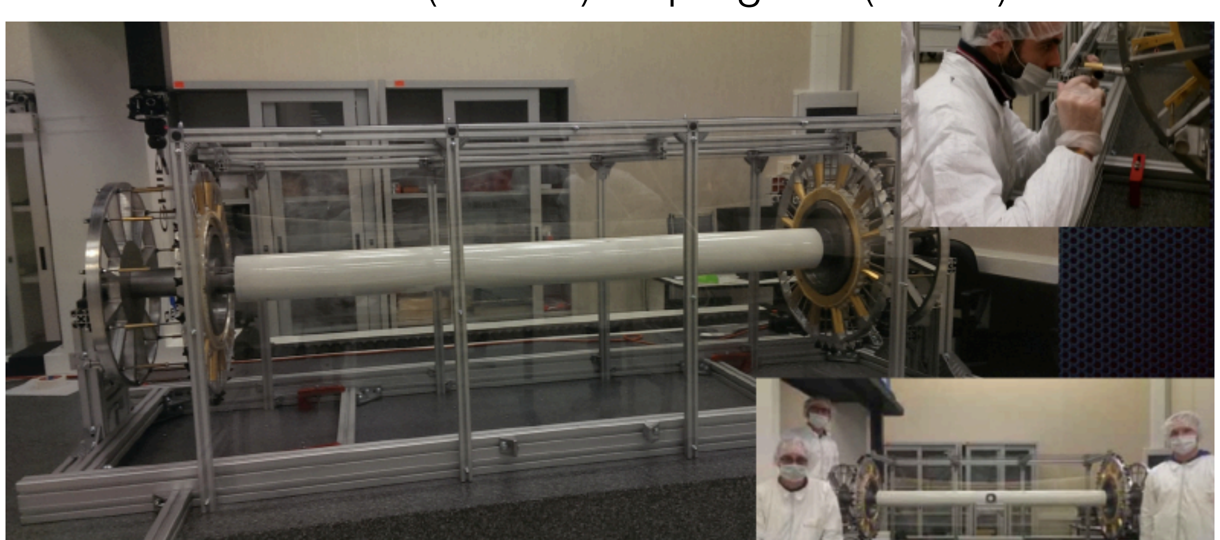
new AUX detector (**<< BKG**): Ready

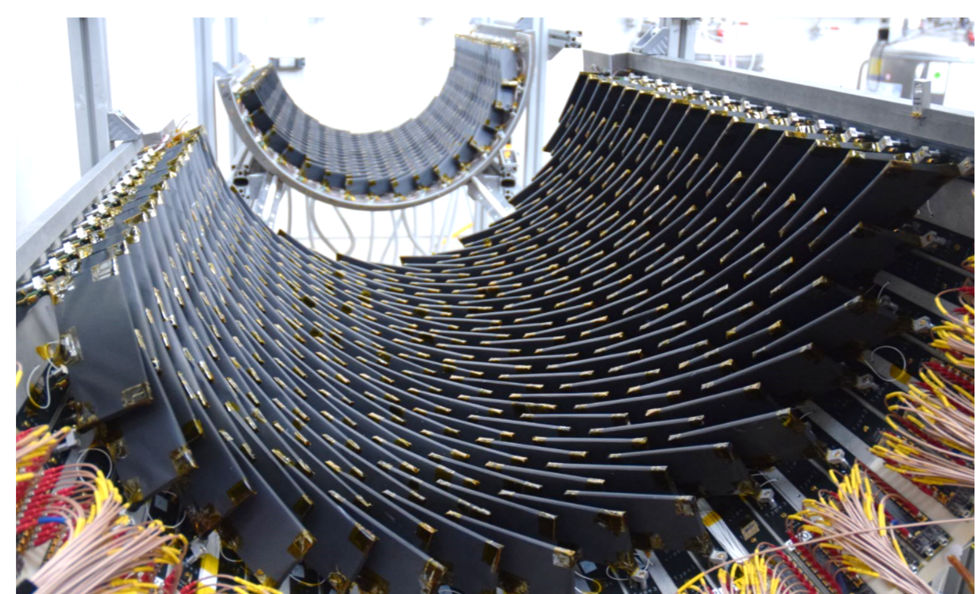


new Beam detector (**Online profile and rate**): Ready



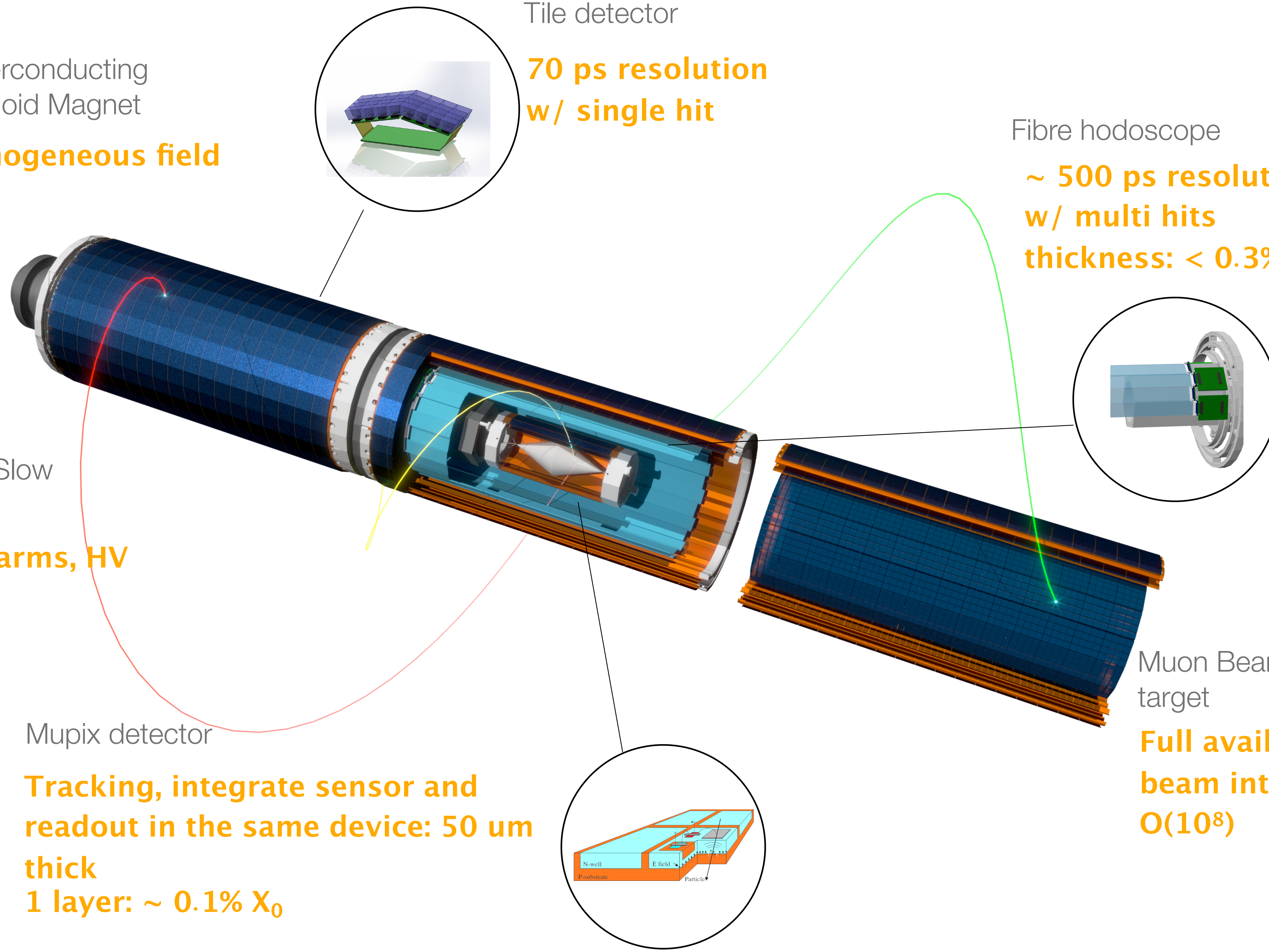
new DCH (**stereo**): in progress (~70%)





new TC (**multi-hits**): Ready

The Mu3e experiment



Tile detector

70 ps resolution w/ single hit

Superconducting solenoid Magnet

Homogeneous field 1T

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 $O(10^8)$

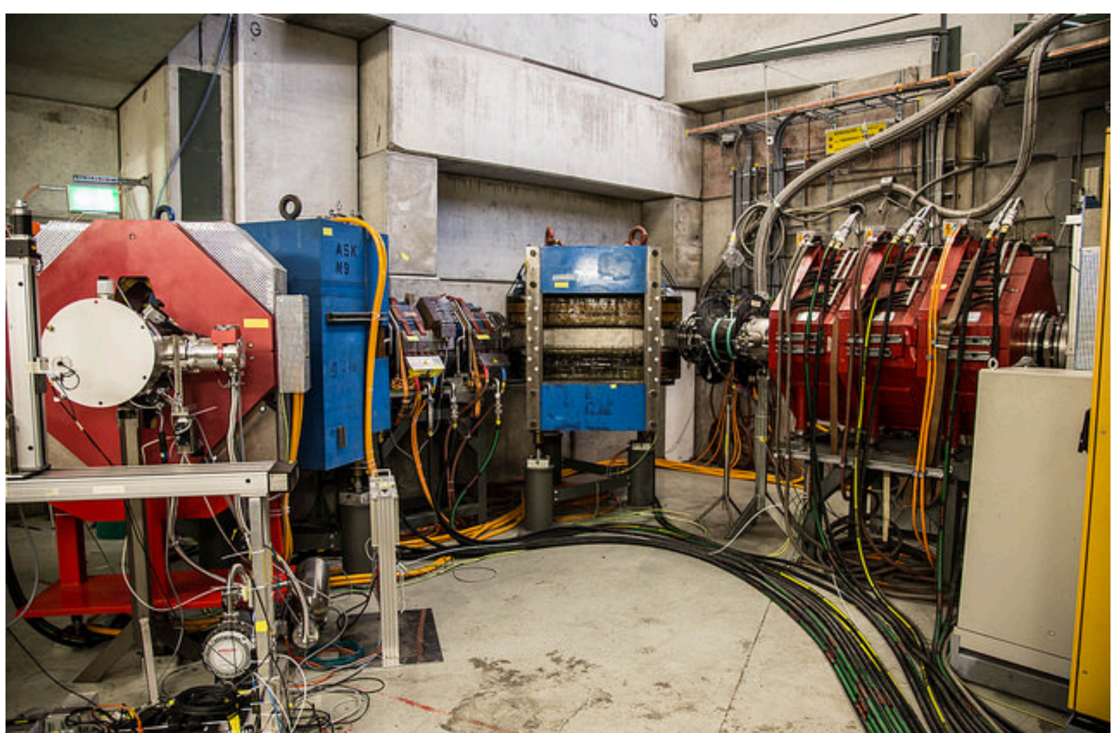
Mupix detector

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

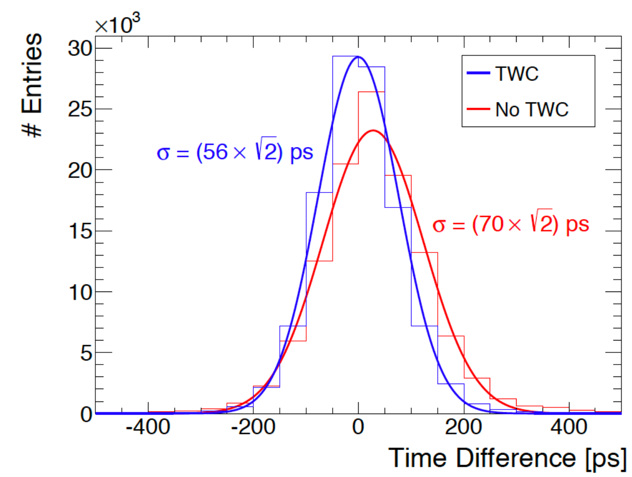
The Mu3e experiment: Status

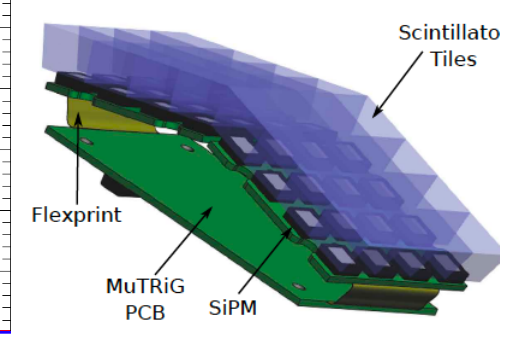
- The Mu3e experiment is completely based on new detector technologies and strongly connected with new beam line projects (HiMB at PSI aiming at 10^9 muon/s)
- The R&D phase for all sub-detectors and beam line has been concluded proving that the expected detector performances can be achieved
- Construction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

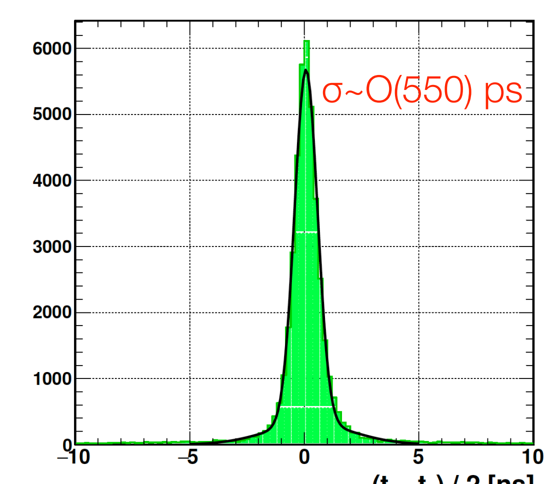
Compact Muon beam line: O(10^8 muon/s)

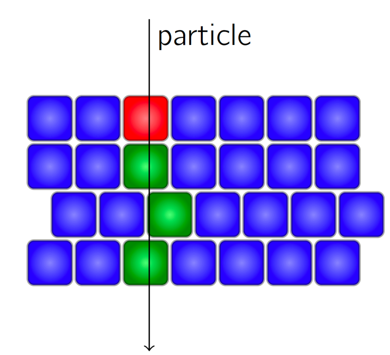


Large MuPix sensor: 2 x 1 cm^2





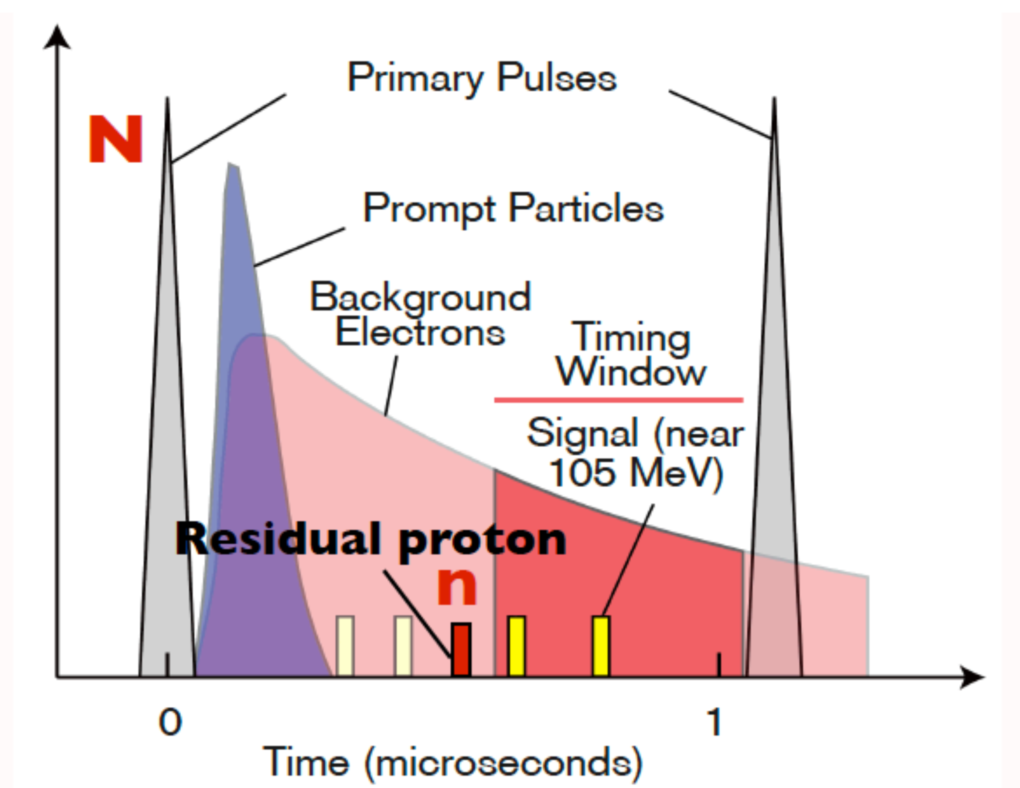


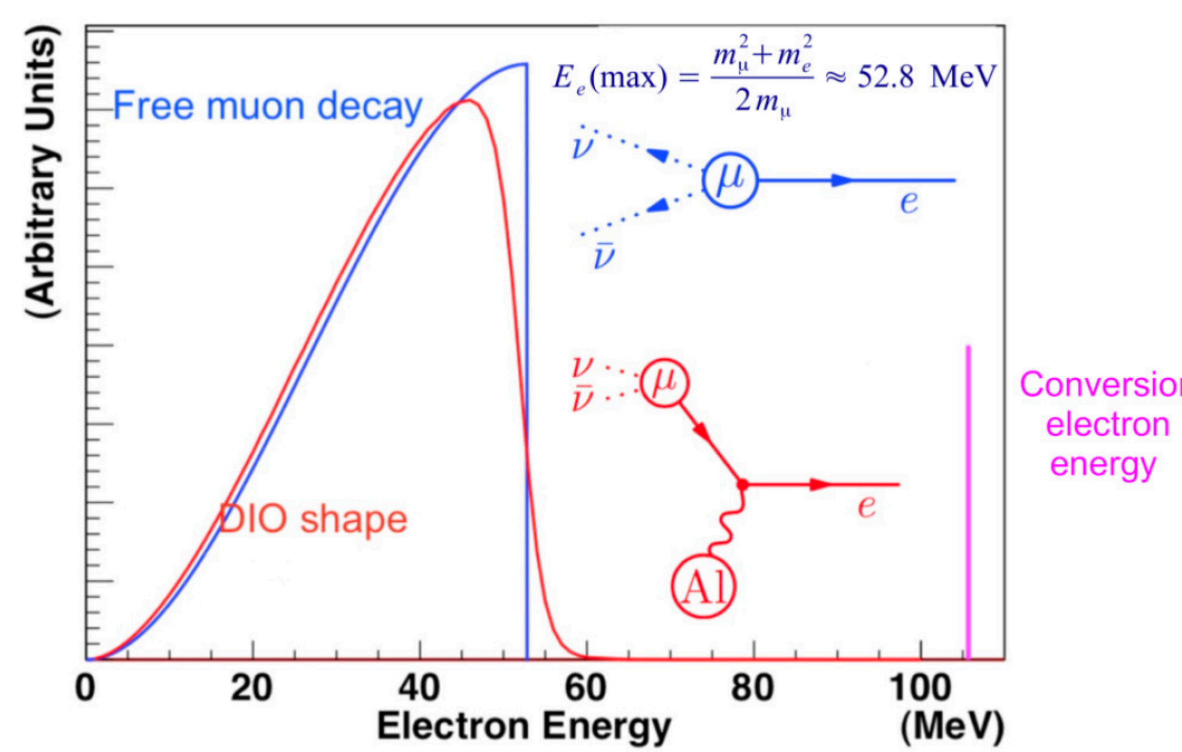


μ^- N → e^- N experiments

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

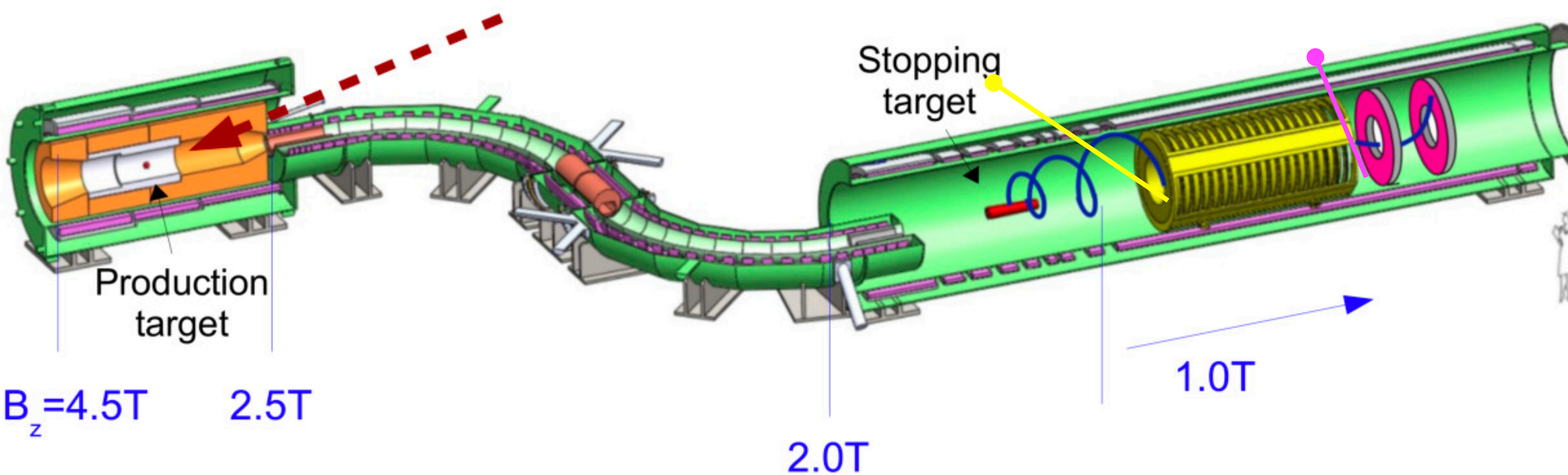
- Signal of mu-e conversion is single mono-energetic electron
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Stop a lot of muons! O(10^{18})
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays





The Mu2e experiment

- 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
- Scintillators for the Veto



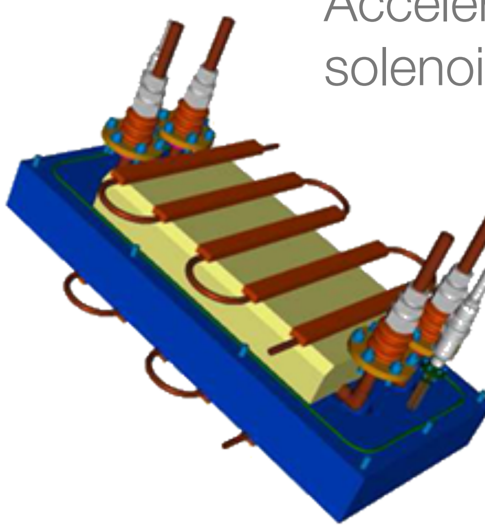
Mu2e status

- 2021: Detector and Beamline commissioning; 2022-2024: Data taking

Building: Completed

Beamline and Solenoids:

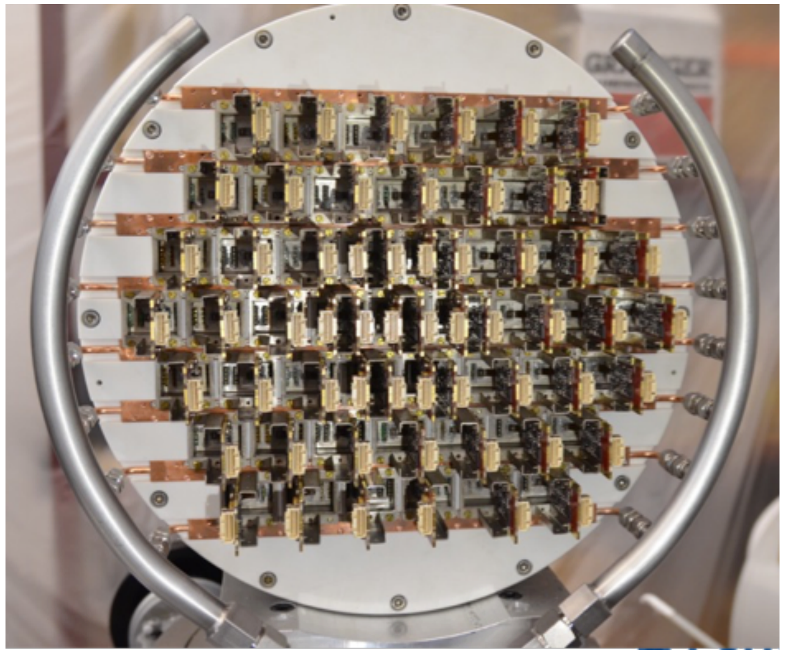
Accelerator work ~50% complete; solenoid work ~60% complete



Straw Tube Tracker

Cosmic Ray Veto module

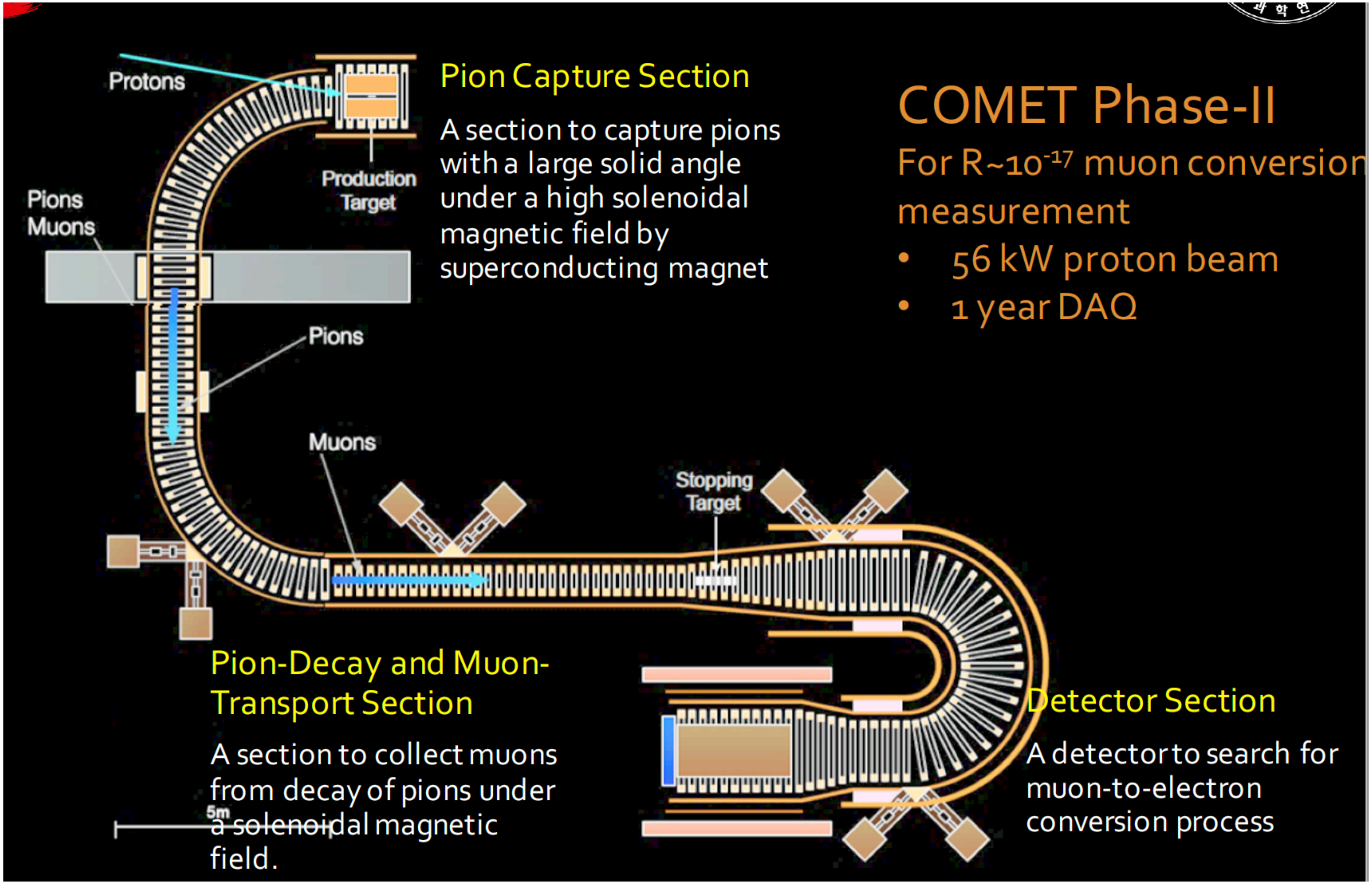
Calorimeter Crystal Test



Detectors:
Pre-production versions have been fabricated and successfully tested

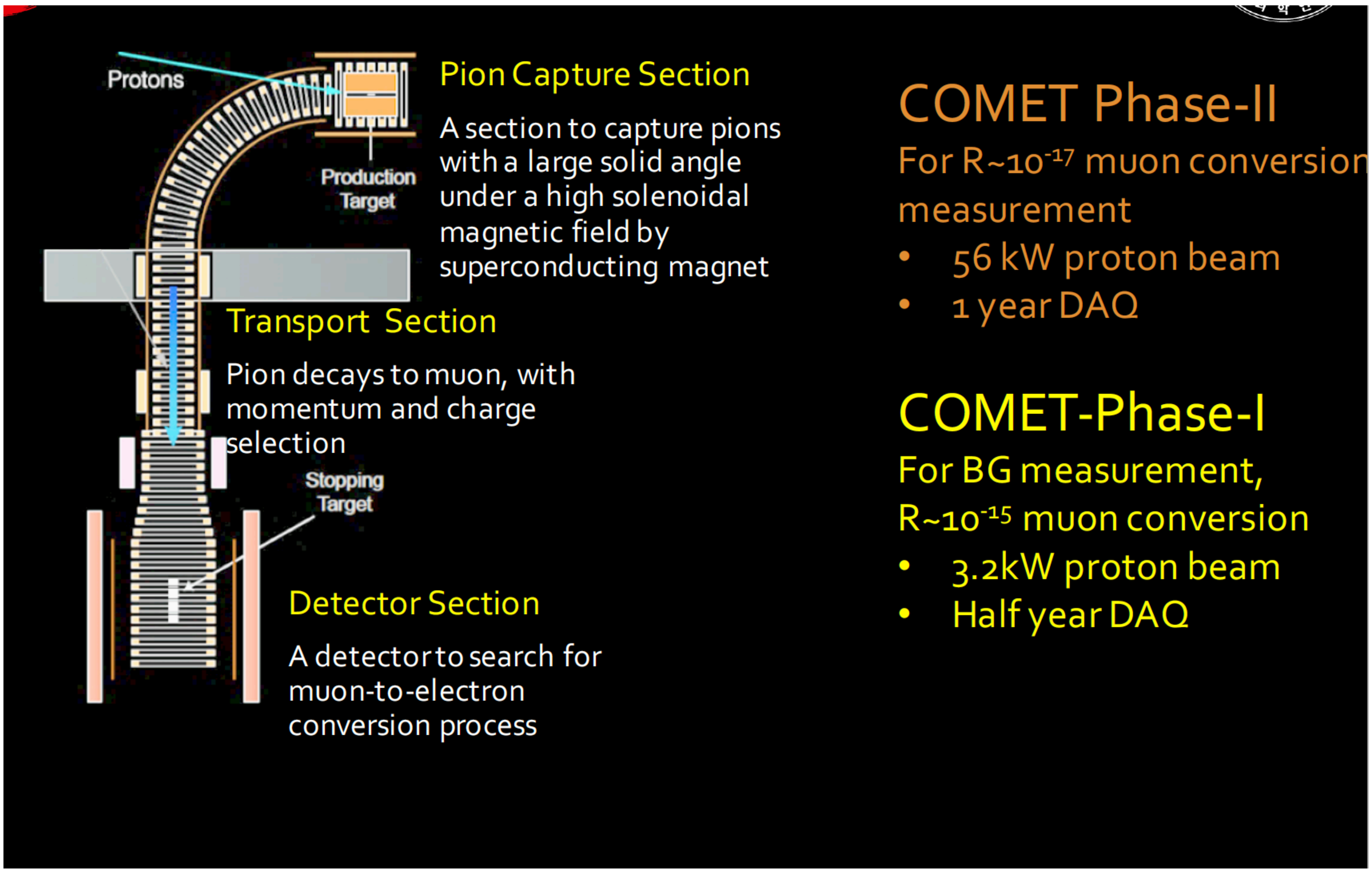
The COMET experiment

- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]



The COMET experiment

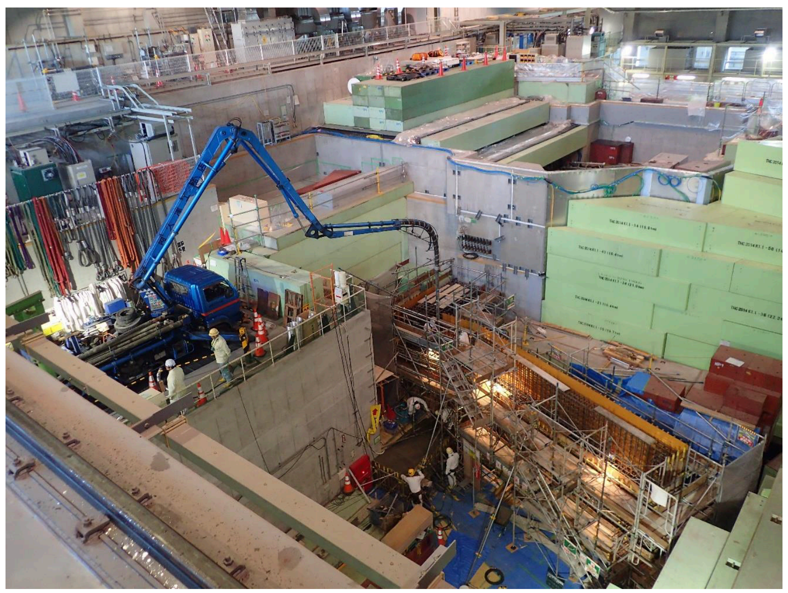
- Stage phase approach: phase I



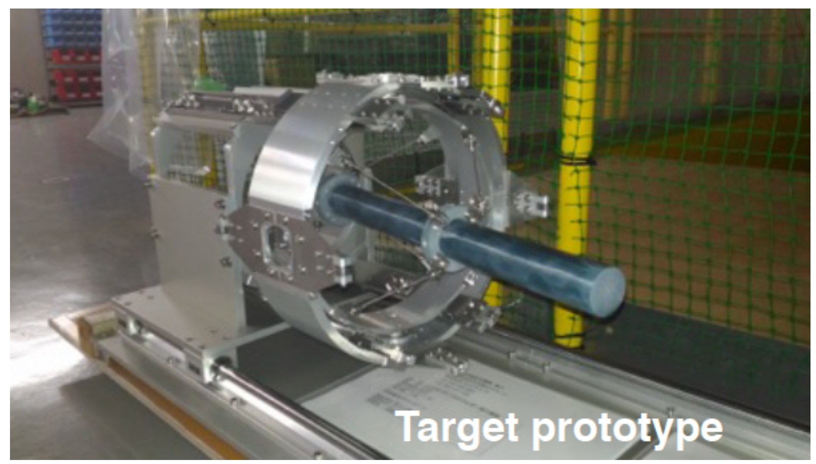
COMET Status

- Stage phase approach: phase I. CR data **STARTED** [August 2017]. Data taking from **2019**!

Proton beam line: under construction

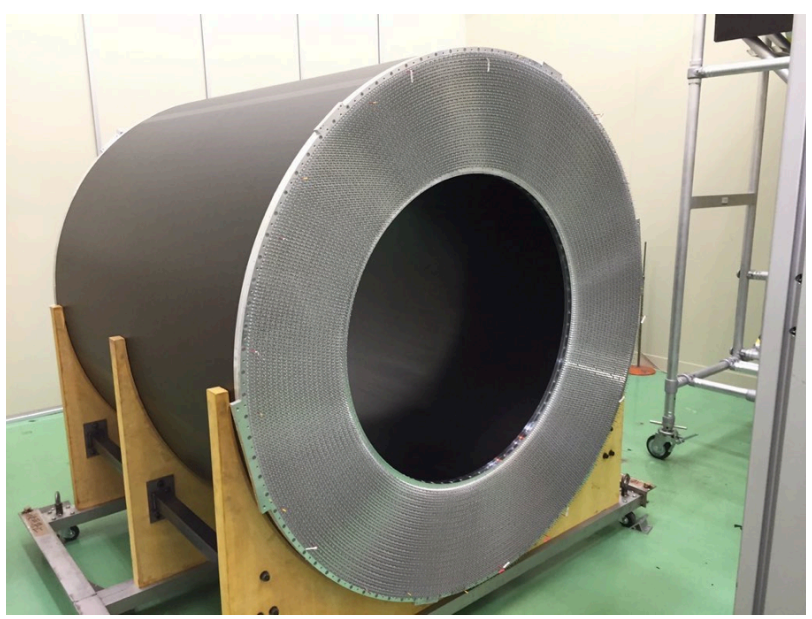


Pion capture Solenoid: DS ready, US under construction

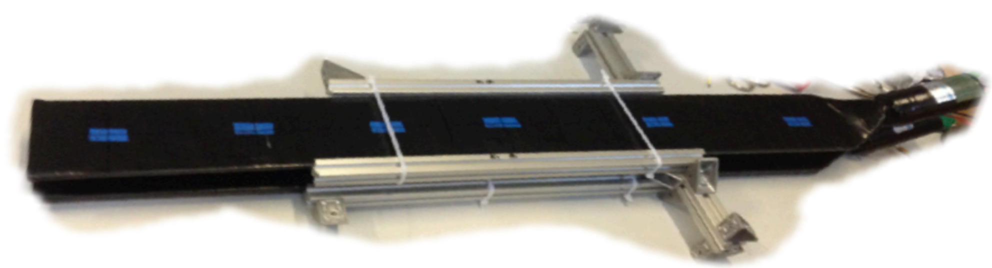


Transport Solenoid: Ready

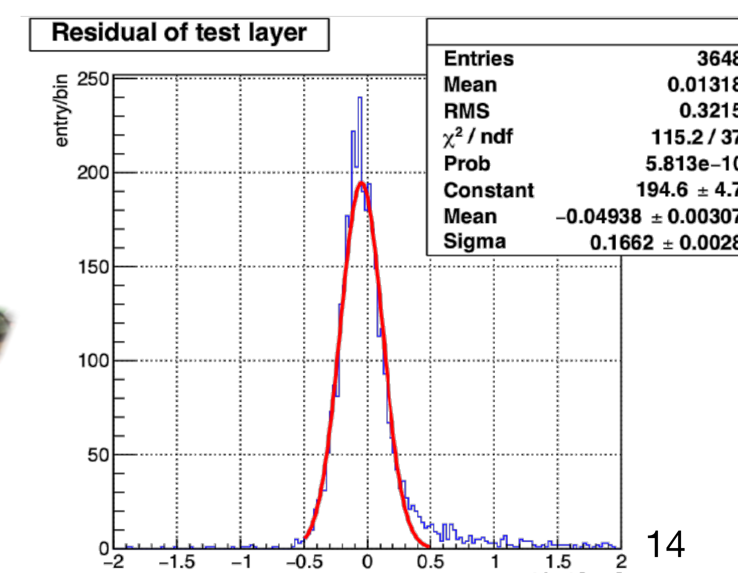
Cylindrical Drift Chamber: Ready



Trigger scintillators + Cerenkov detector: Ready

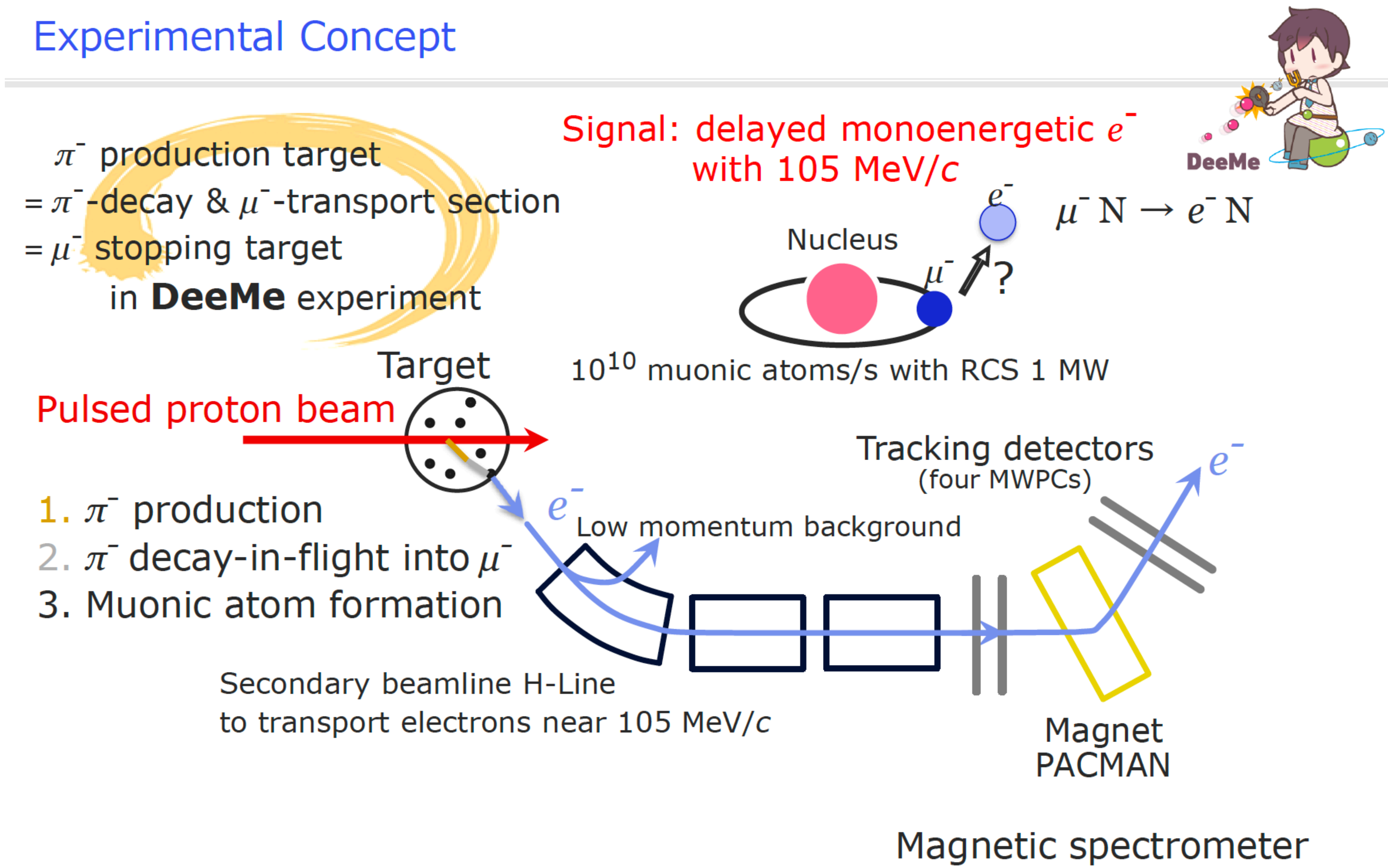


Trigger/DAQ/Analysis: in very good shape

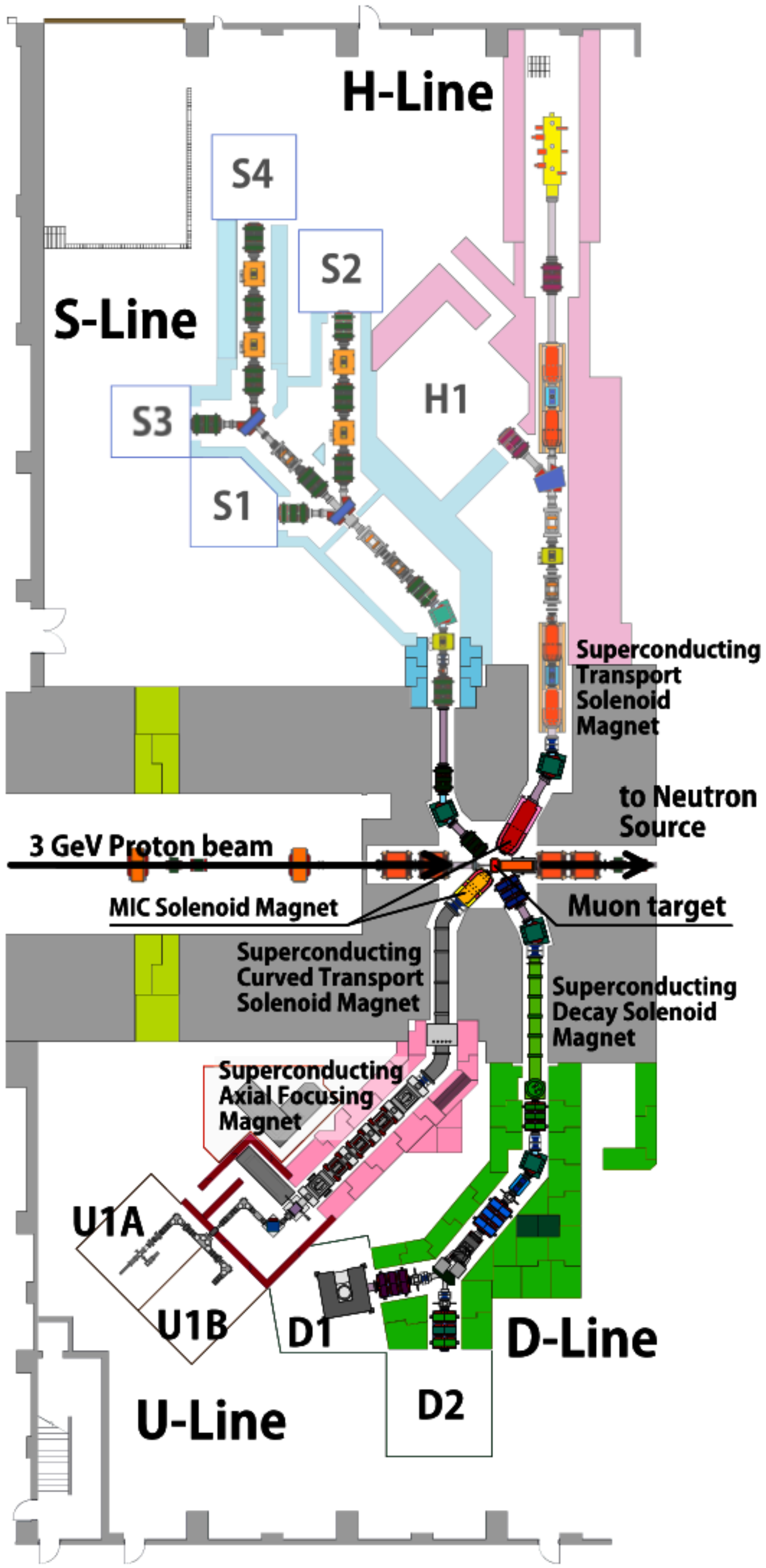


The DeeMe experiment

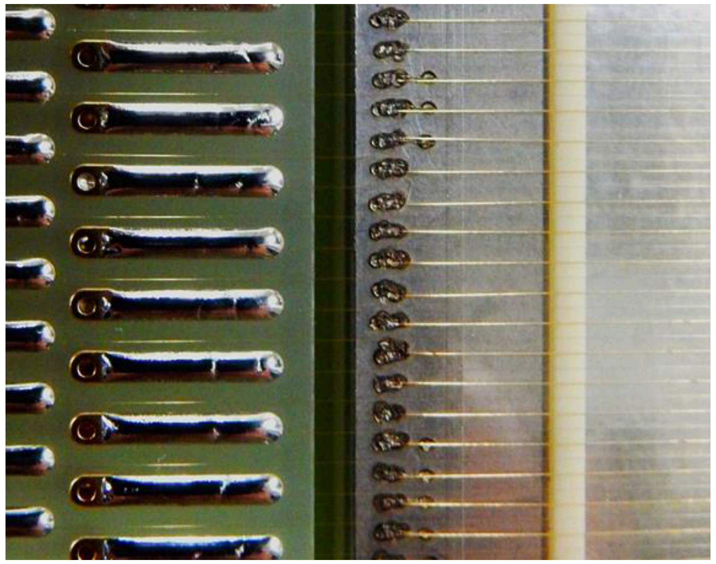
- Aiming at using different targets: SES < 10^{-13} with C, SES < 2 10^{-14} with SiC target
- Data taking in the near future



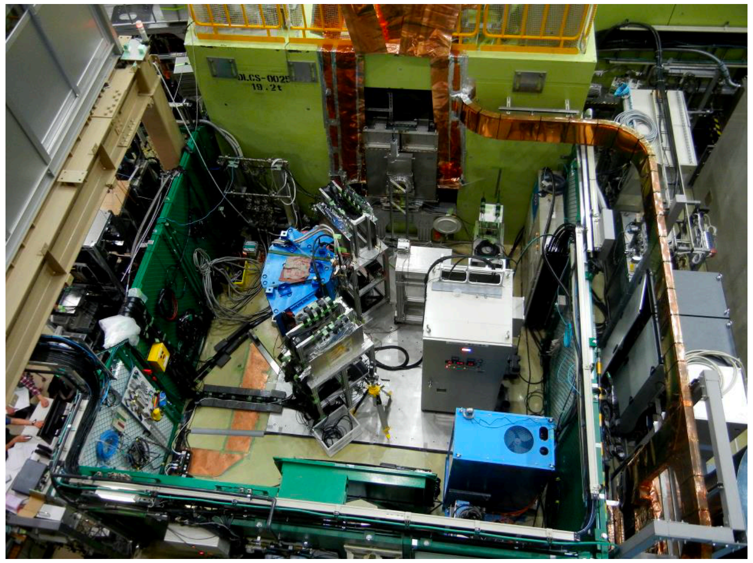
The DeeMe experiment and Status



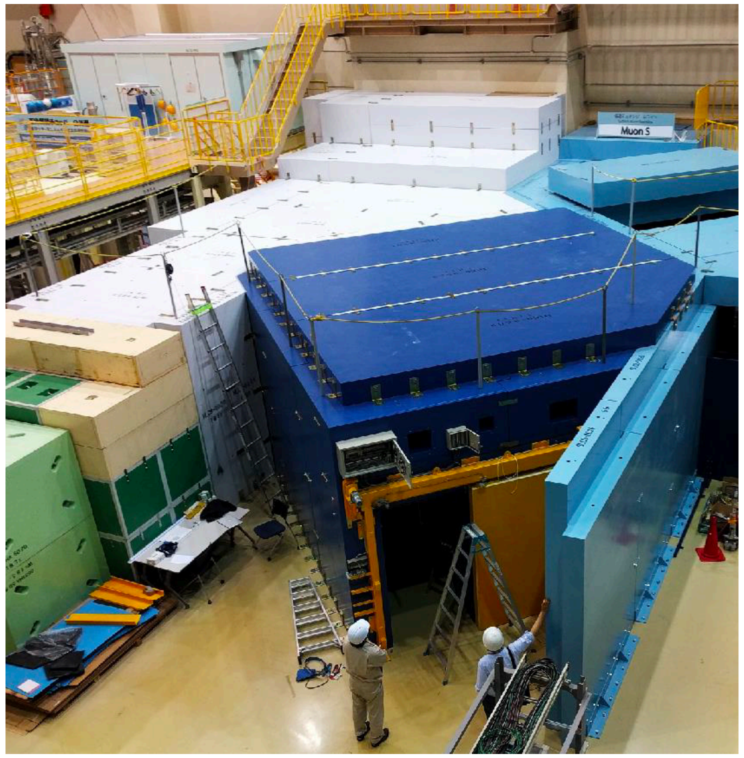
5 MWPC manufactured



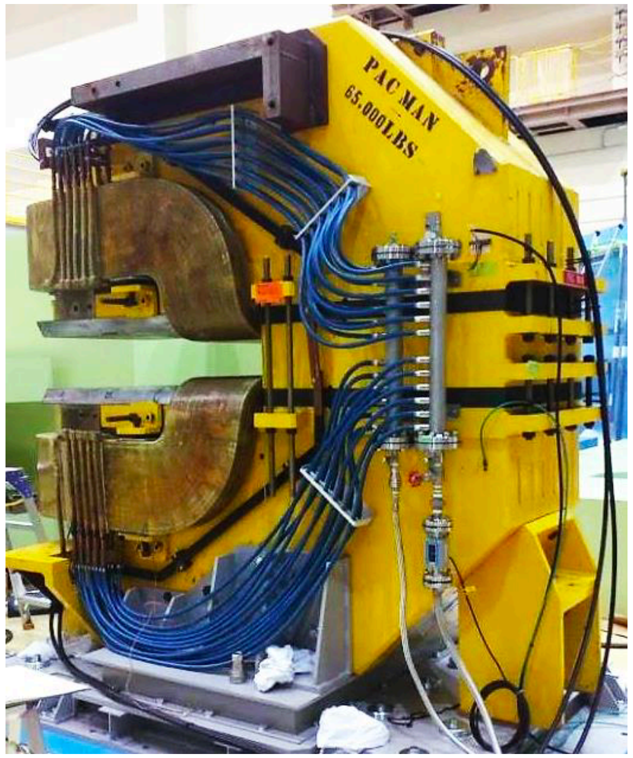
DIO spectrum measured at 55MeV/c (D line)



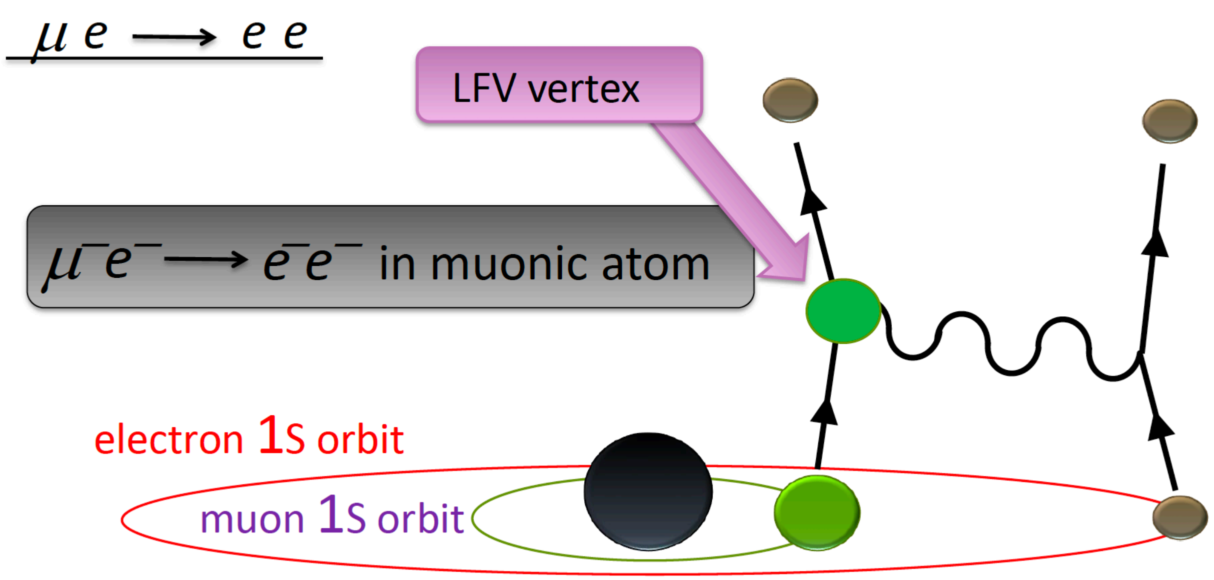
H experimental area: under construction



Spectrometer magnet (from TRIUMF): Installed and tested



New proposal: $\mu^- e^- \to e^- e^-$ in muonic atom

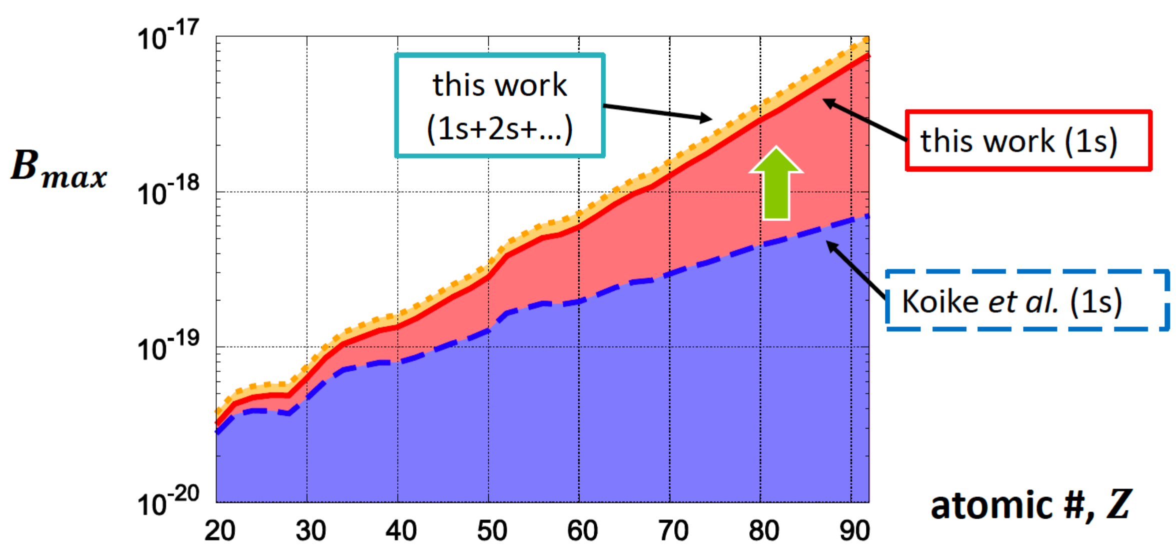


- Signature: two mono energetic electrons
- Discrimination among interaction via Z target, energy spectrum, position dependence

Interaction rate

$$\Gamma(\mu^- e^- \to e^- e^-; Z) = 2\sigma v_{\mathrm{rel}} \left|\psi_{1S}^{(e)}(0; Z-1)\right|^2$$

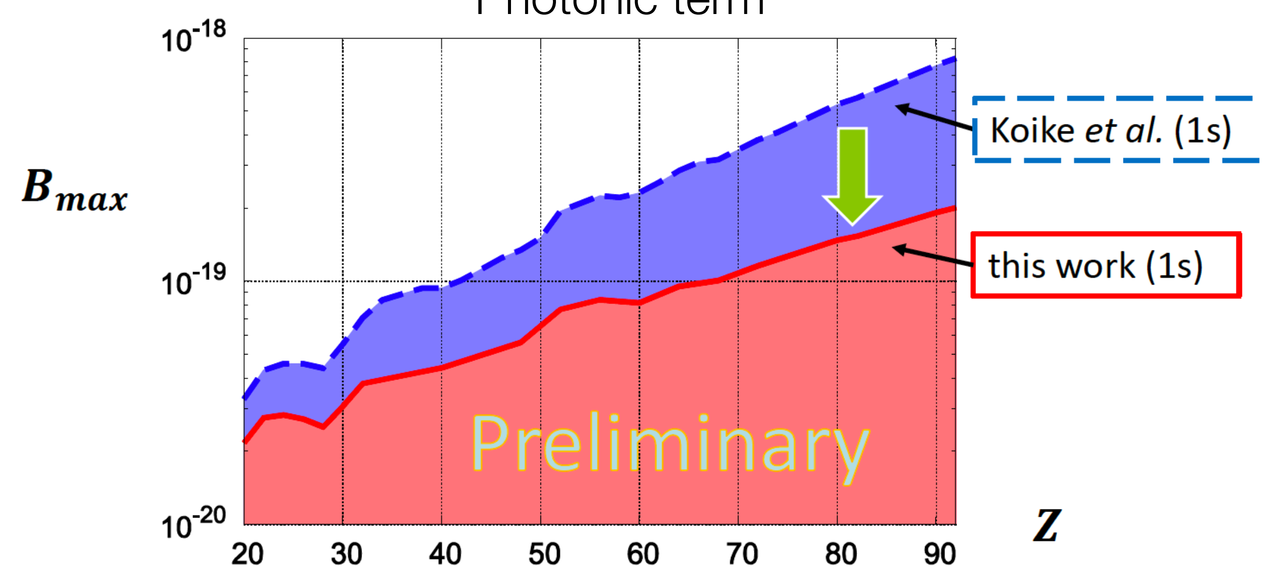
Contact term



needed # of muonic atoms ($Z = 82$)

2.1×10^{18} → 3.0×10^{17}

Photonic term



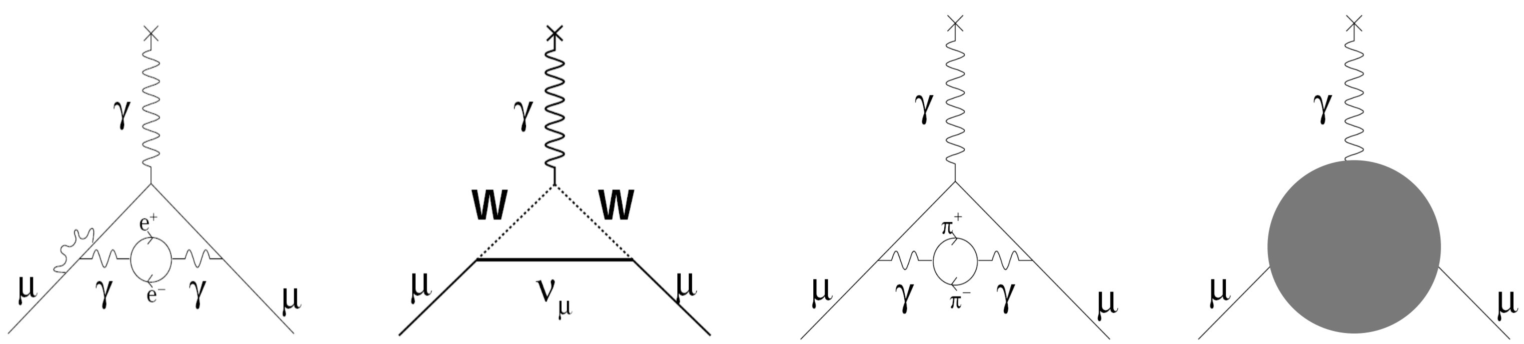
needed # of muonic atoms ($Z = 82$)

1.8×10^{18} → 6.6×10^{18}

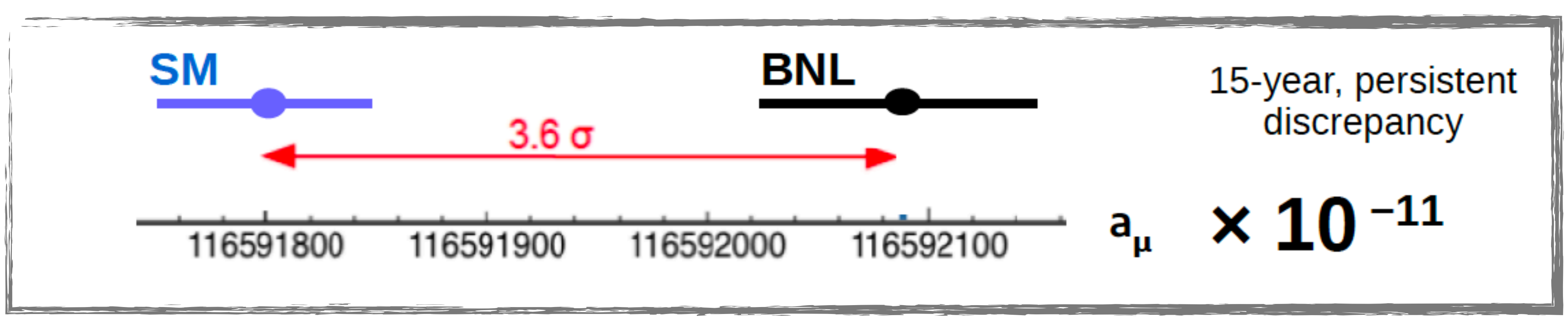
g_μ-2 Motivation

- 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) + **a (NP)**
- 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 UNKNOWN



g_μ-2 in numbers and experimental approaches

Anomalous magnetic moment (g-2)

a_μ = (g-2)/2 = 11 659 208.9 (6.3) x 10^{-10} (BNL E821 exp) **0.5 ppm**

11 659 182.8 (4.9) x 10^{-10} (standard model)

Δa_μ = Exp - SM = 26.1 (8.0) x 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)

J-PARC approach
E = 0 at any γ

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

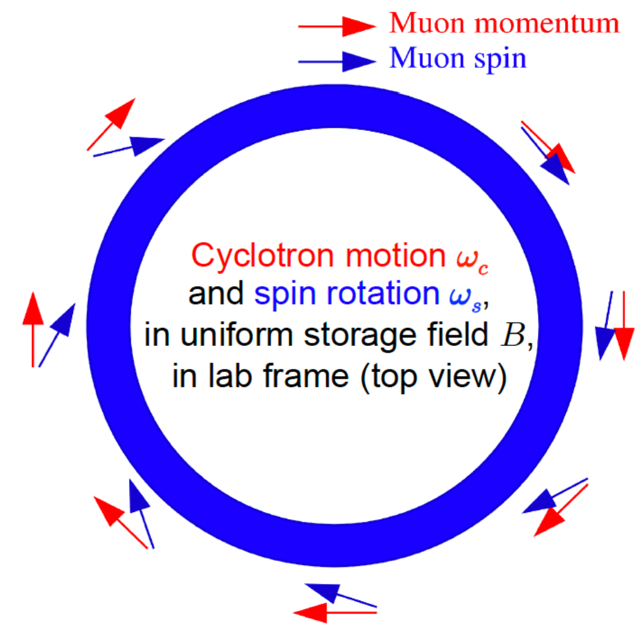
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

Continuation at **FNAL** with **0.1ppm** precision

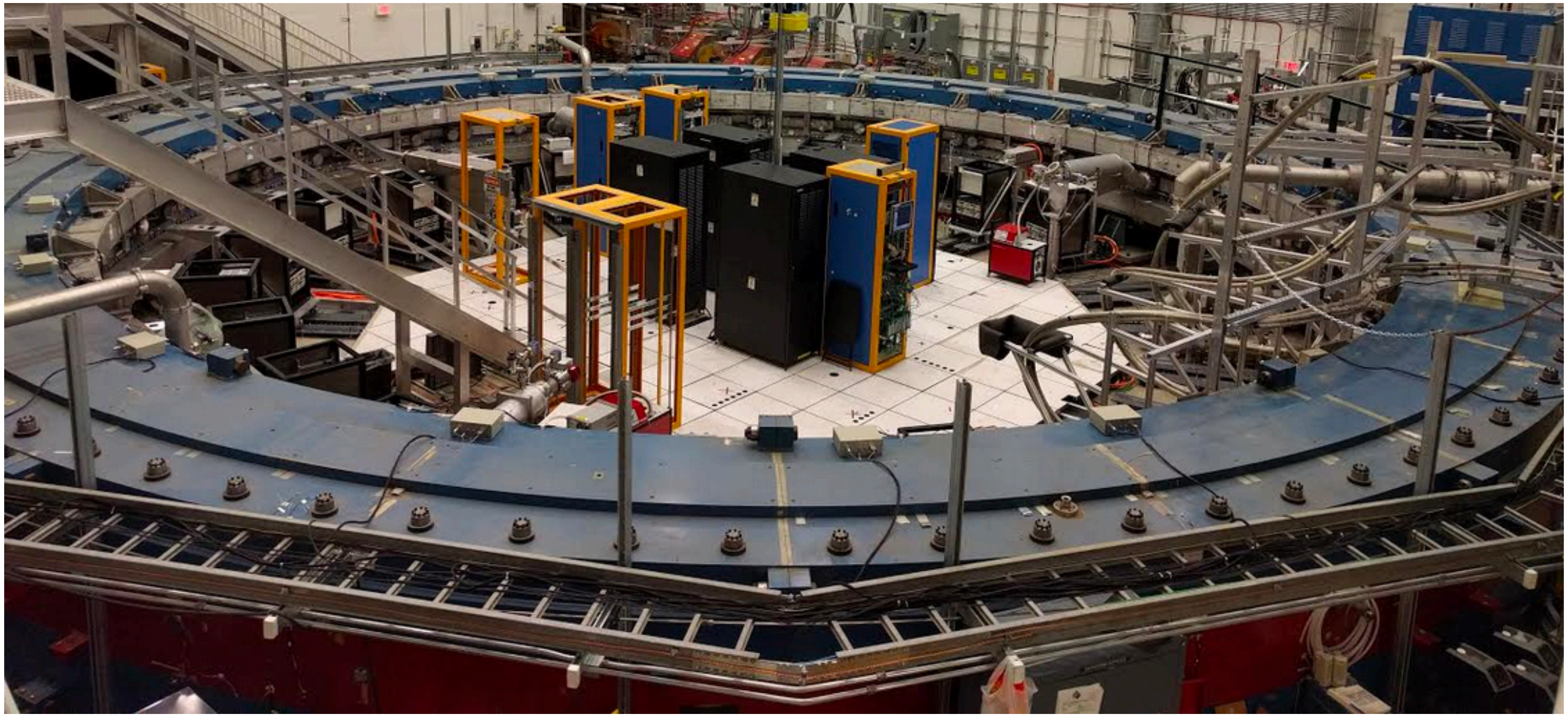
Proposed at **J-PARC** with **0.1ppm** precision

g_μ-2 at FNAL: Experimental setup **READY**

- ω_p is the proton Larmor frequency measured in a field B
- ω_a is the precession frequency measured with decay positrons
- μ_μ/μ_p magnetic moment ratio from muonium hyperfine measurement

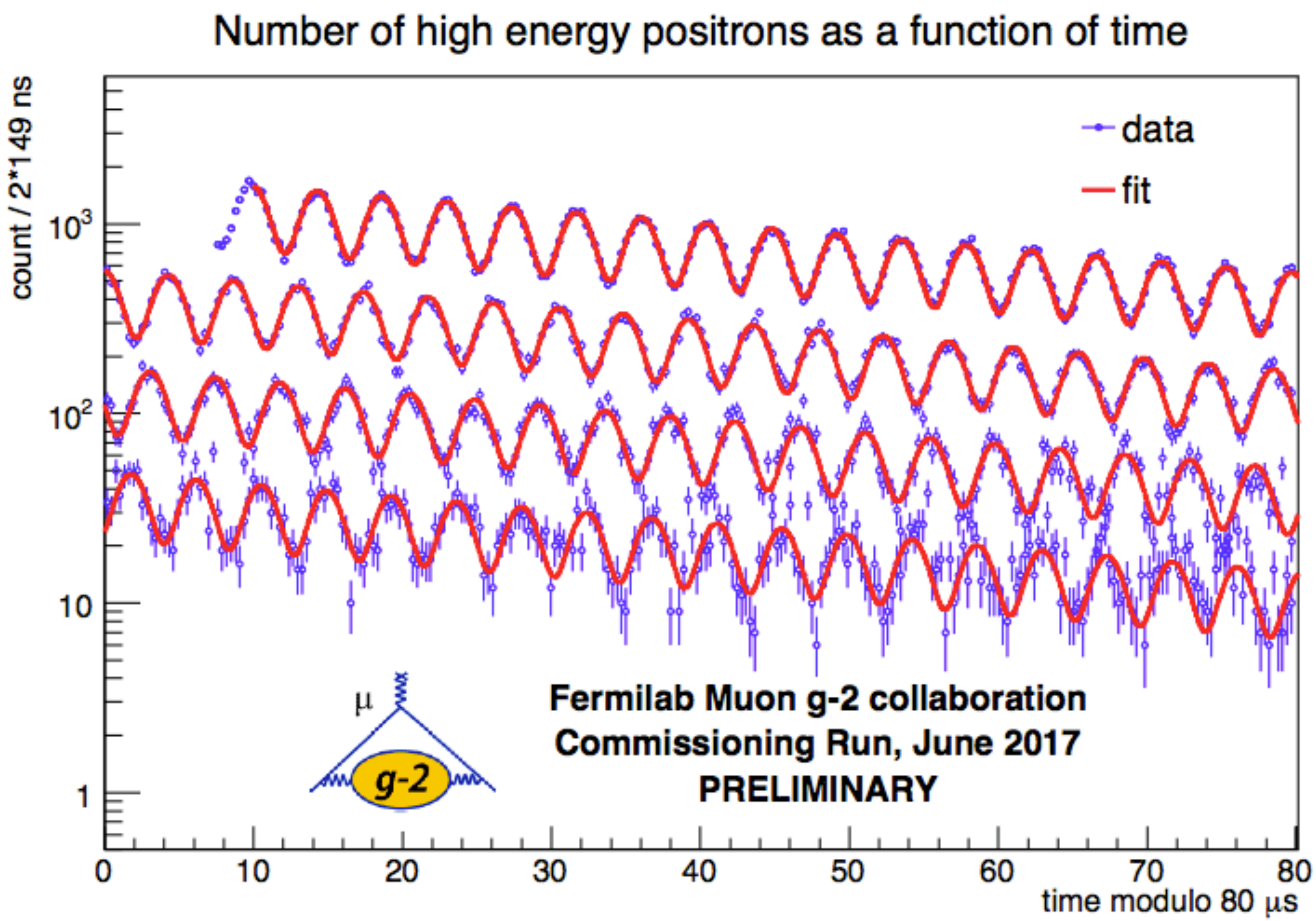


$$\boxed{a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}}$$



g_μ-2 at FNAL: Engineering Run phase

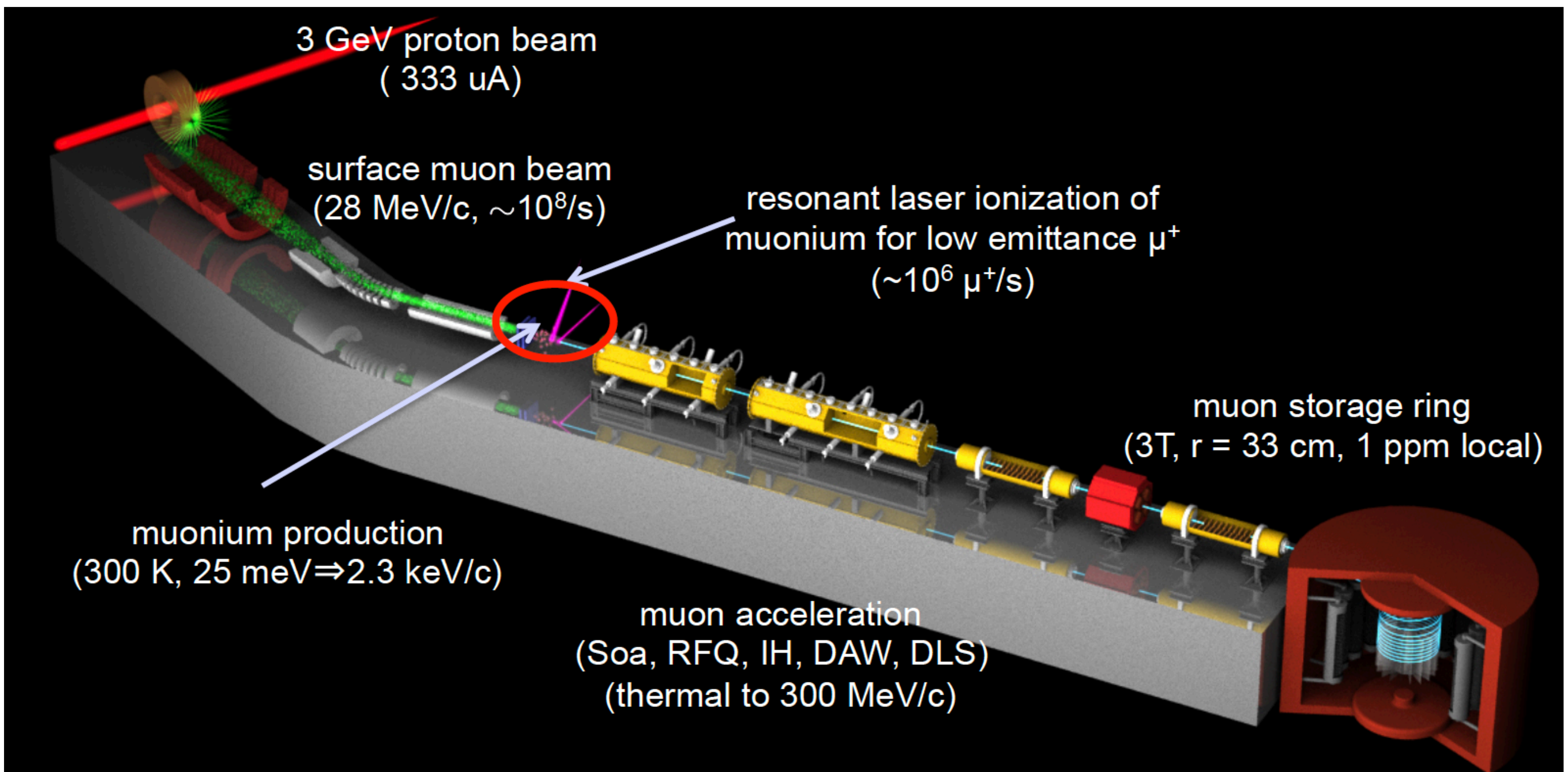
- First evidence of precessing muons
- Physics Run: **THIS WINTER**; First Results: 2018 [1-2 x BNL statistics], 2019 [5-10 x BNL statistics], 2020 [5-10 x BNL statistics]



g_μ-2/EDM at J-PARC

- Put E = 0;
- Weak B field focusing: Need low emittance cold muon
- Uniform tracker detector throughtout stored orbit

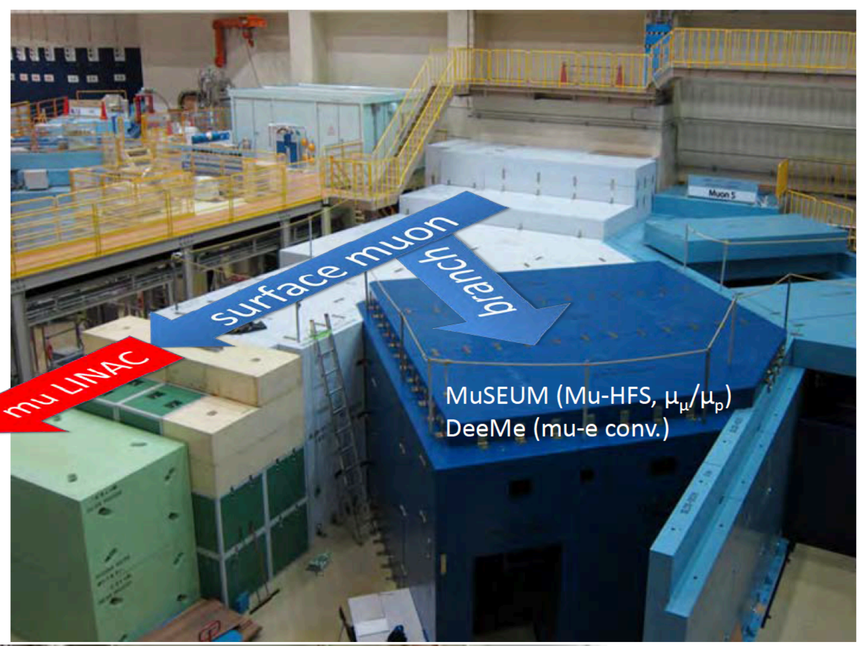
$$-\frac{q}{m_\mu}\left[a_\mu\vec{B}-\left(a_\mu-\frac{1}{\gamma^2-1}\right)\cancel{\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$



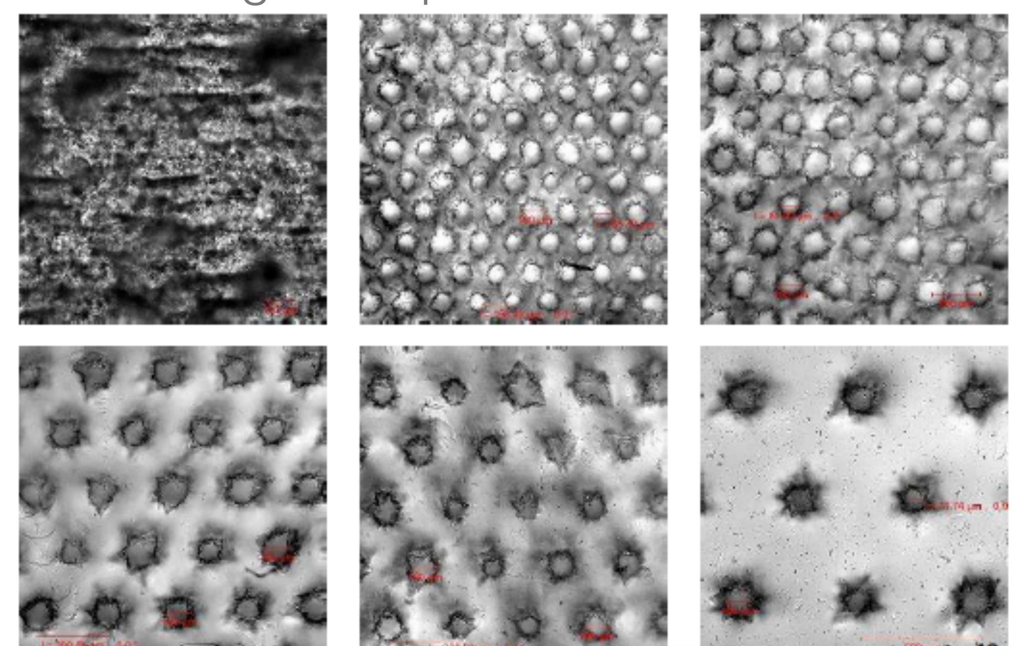
g_μ-2/EDM at J-PARC: Status

- Progress in all aspects. From phase I to phase 2
- New experimental methods and source-limited schedule requires fours years prior data taking

H line > 10^8 surface muon/s



Several silica-aerogel samples test at TRIUMF this summer




Laser available


Muon RFQ acceleration test in October


Spiral injection with mini-solenoid progress

The MuSEUM experiment

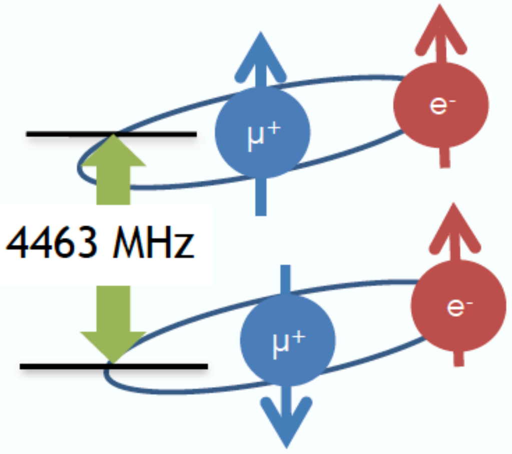
- **High precision measurement of muonium hyperfine structure (MuHFS) in Zero field & High field**
- Stringent test of bound state QED by comparing to the theoretical calculation

$$\Delta\nu_{\mathrm{HFS}}(theo) = 4\ 463\ 302\ 891(272)\mathrm{Hz}\ \ (63\mathrm{ppb})$$

D. Nomura and T. Teubner, Nucl. Phys. B **867**, 236 (2013).

$$\Delta\nu_{\mathrm{HFS}}(exp) = 4\ 463\ 302\ 765(53)\mathrm{Hz}\ \ (12\mathrm{ppb})$$

W. Liu *et al.*, Phys. Rev. Lett. **82,** 711 (1999).



- Relative uncertainty of 1.7 T measurement at LAMPF
  MuHFS : 12ppb, μ_μ/μ_p and m_μ/m_e :120ppb

W. Liu *et al.*, Phys. Rev. Lett. **82,** 711 (1999).

- MuSEUM's goal : improve the precision by a factor of 10
  MuHFS : ~1ppb, μ_μ/μ_p and m_μ/m_e :10ppb

The MuSEUM experiment and muon g-2

- ~3σ discrepancy between theory and experiment

$$a_\mu(exp) - a_\mu(th) = 250(89) \times 10^{-11}$$ (from CODATA 2014)

- μ_μ / μ_p : essential parameter for muon g-2 experiment

$$a_\mu(exp) = \frac{(g-2)_\mu}{2} = \frac{R}{\lambda - R}$$

$R = \omega_\mu / \omega_p$ (540ppb)

G.W. Bennett et al., Phys. Rev. D **73** 072003 (2006).

$\lambda = \mu_\mu / \mu_p$ (30ppb)

W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).
D. E. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).

- R : Planning 140ppb measurement at J-PARC and Fermilab

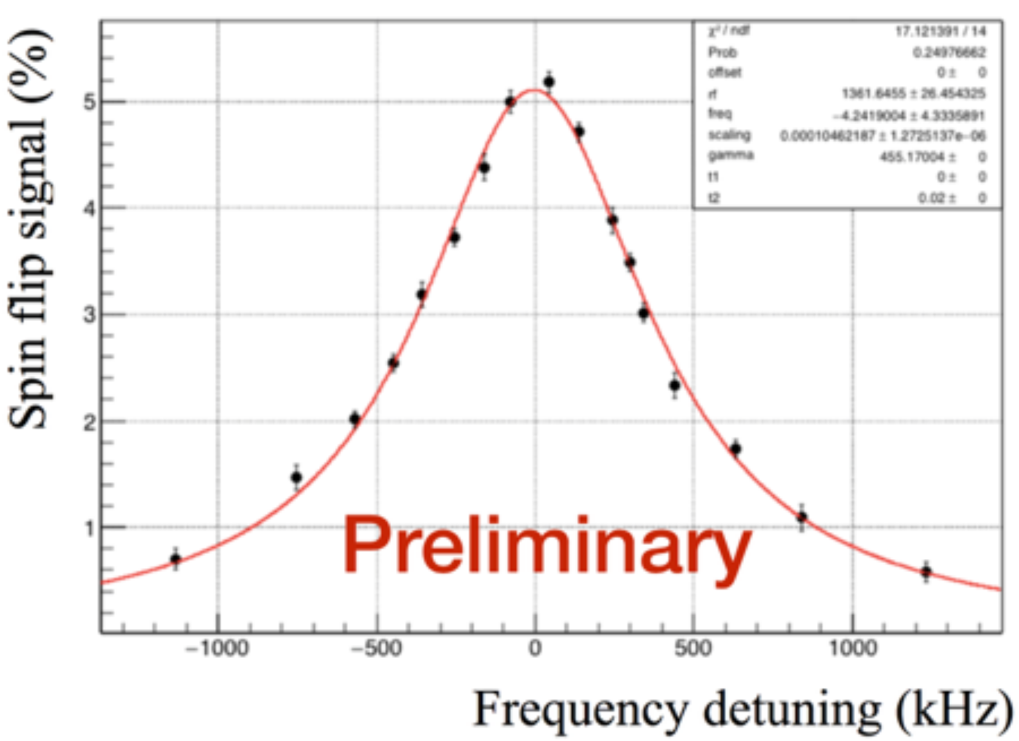
M. Otani, JPS Conf. Proc. **8**, 025008 (2015).
J. Grange Fermilab g-2 experiment technical design report (2015).

- λ : 30ppb (indirect) -> **direct** 10ppb measurement

The MuSEUM experiment: Status

- Extensive measurement campaign with **ZERO** magnetic field at JPARC
  - 1st Beam time [June 2016]: proof-of-principle **CONFIRMED, first muonium HF resonance observed**
  - 2nd Beam time [February 2017]: **IMPROVED** setup (reduced statistical uncertainty)
  - 3rd Beam time [June 2017]: **Larger cavity**
  - **Next measurement in 2018. Aim: to improve the current best measurement**

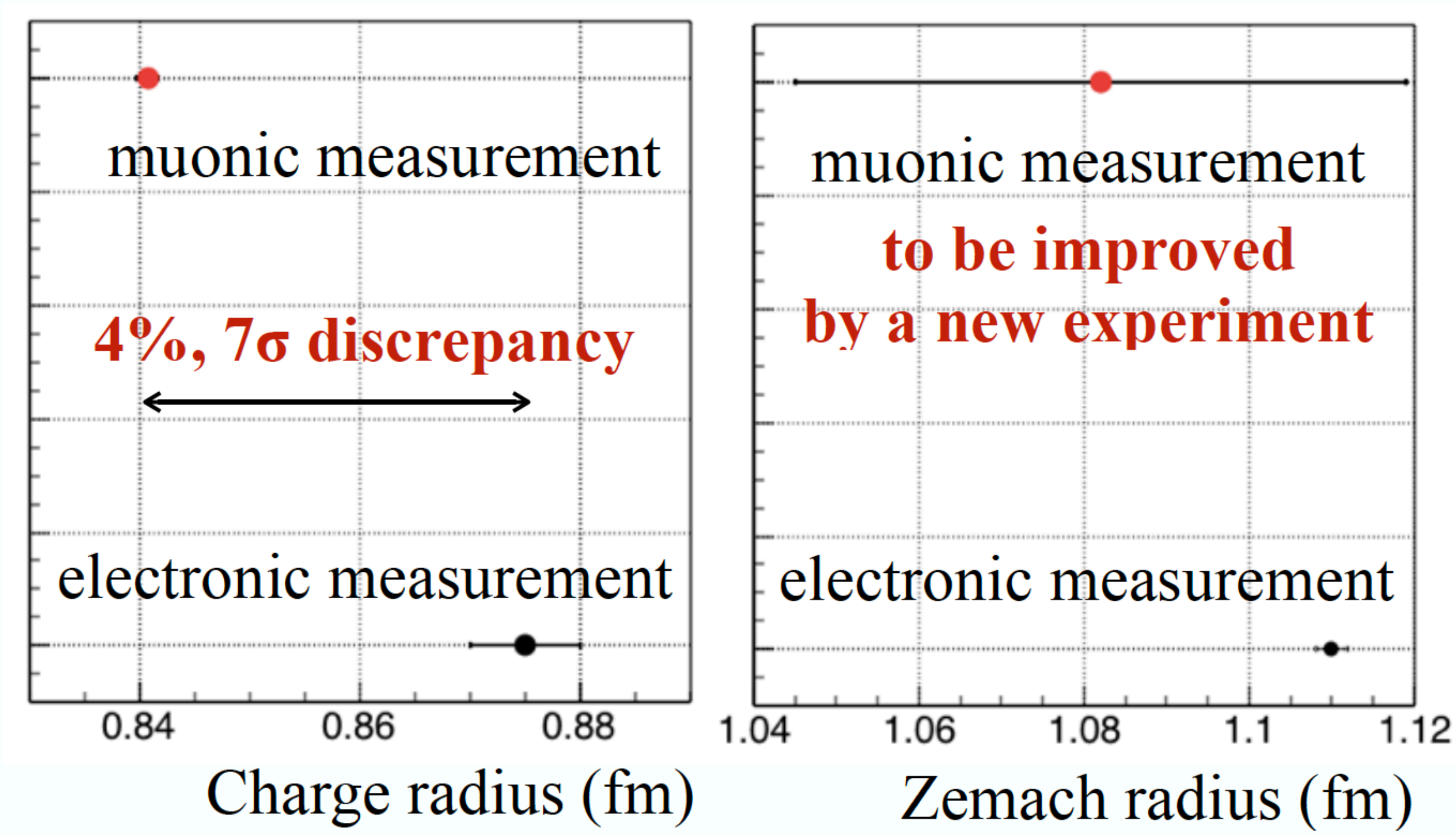
- Measurement with magnetic field in preparation:
  - Magnet available, high precision NMR probe R&D in progress



Muonic hydrogen

Proton Radius Puzzle

3

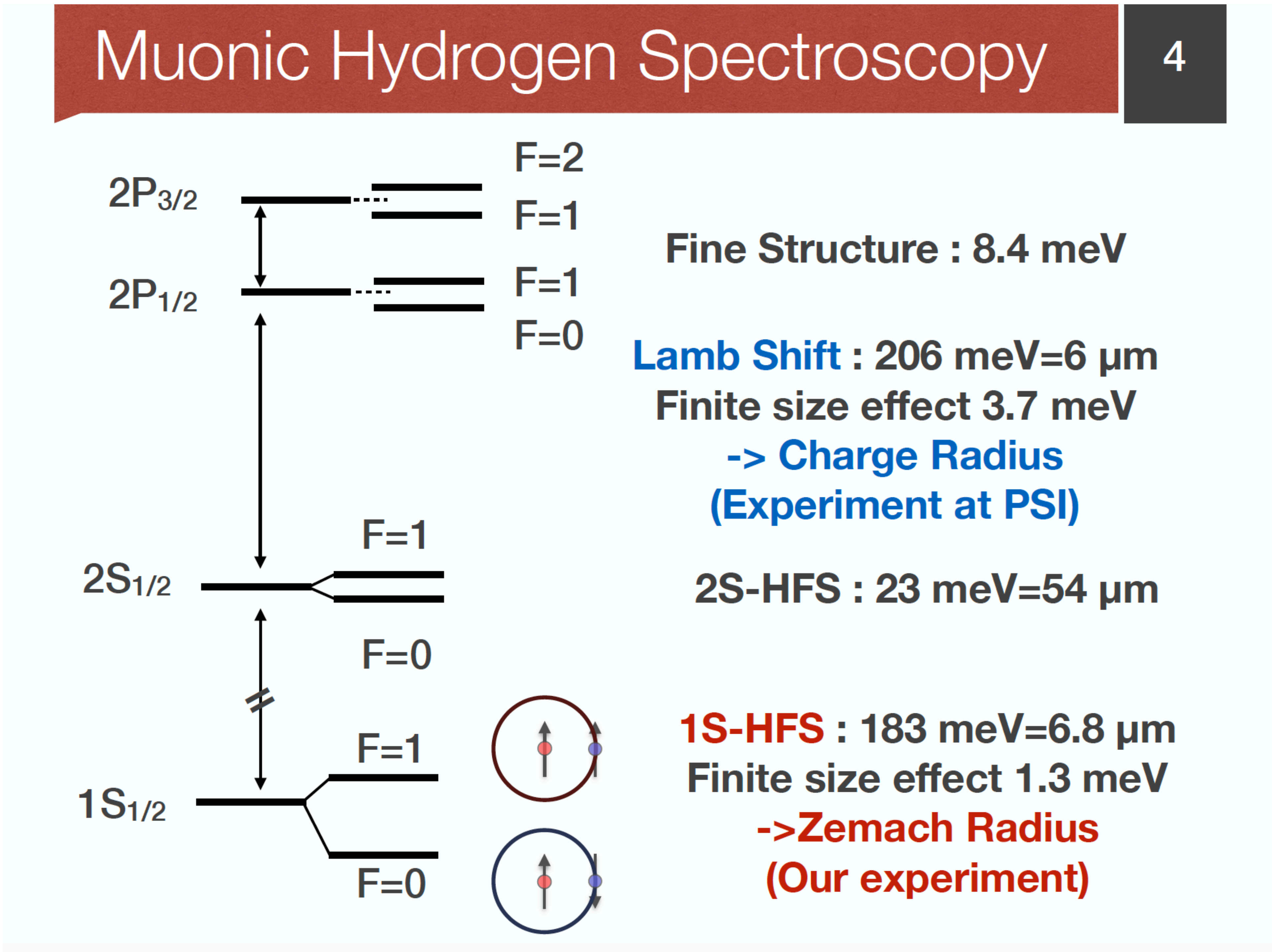


There is no definitive interpretation of the puzzle and new, independent experiment is needed.

Our goal is a factor of three improvement; 1% precision.

R. Pohl *et al*., Nature 466, 213 (2010). A. Antognini *et al*., Science 339, 417 (2013).
J. C. Bernauer *et al*., PRL. 105 (2010).

Muonic hydrogen

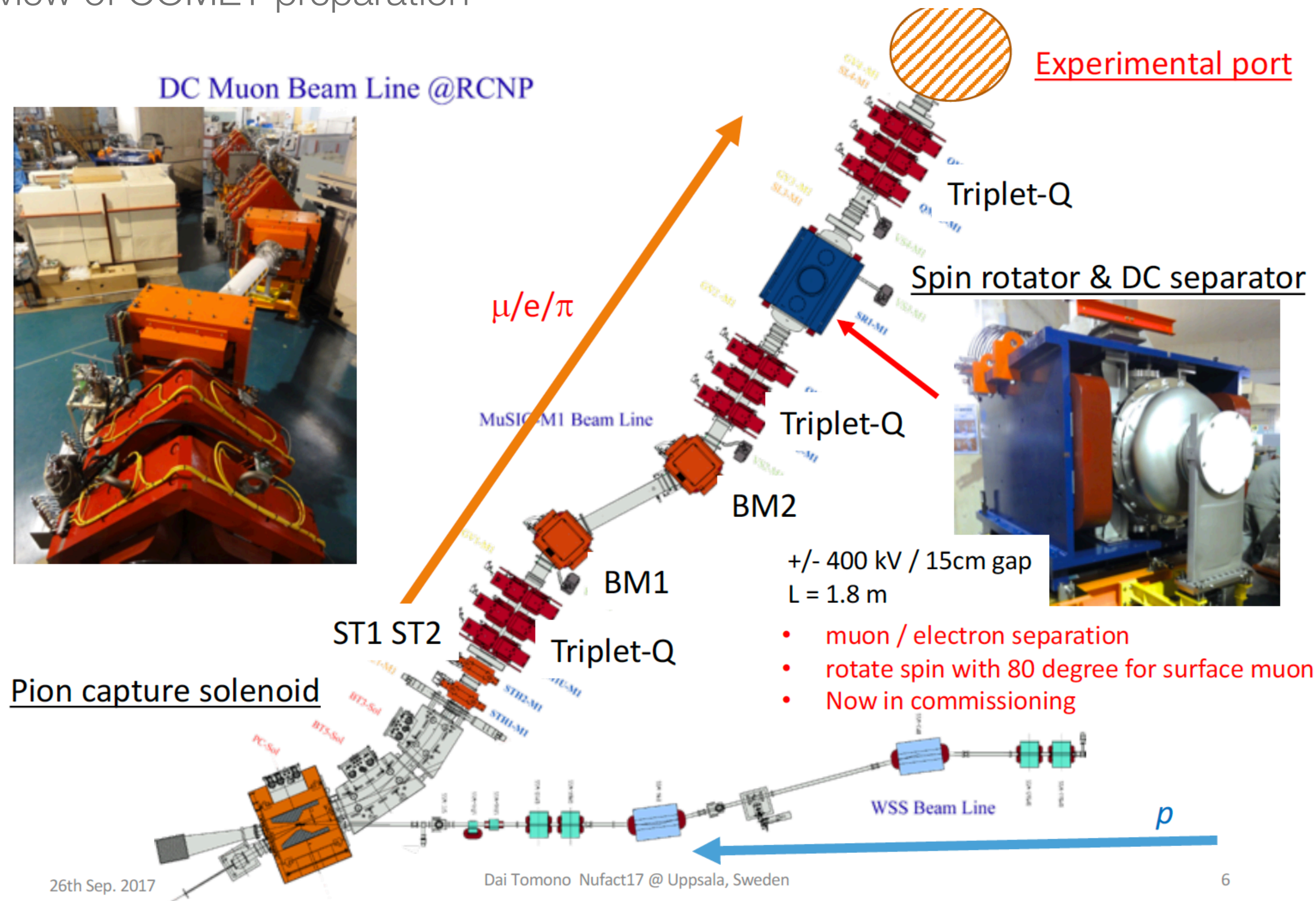


New muon facilities

- Next generation of muon cLFV searches, g-2/EDM, muonium etc.

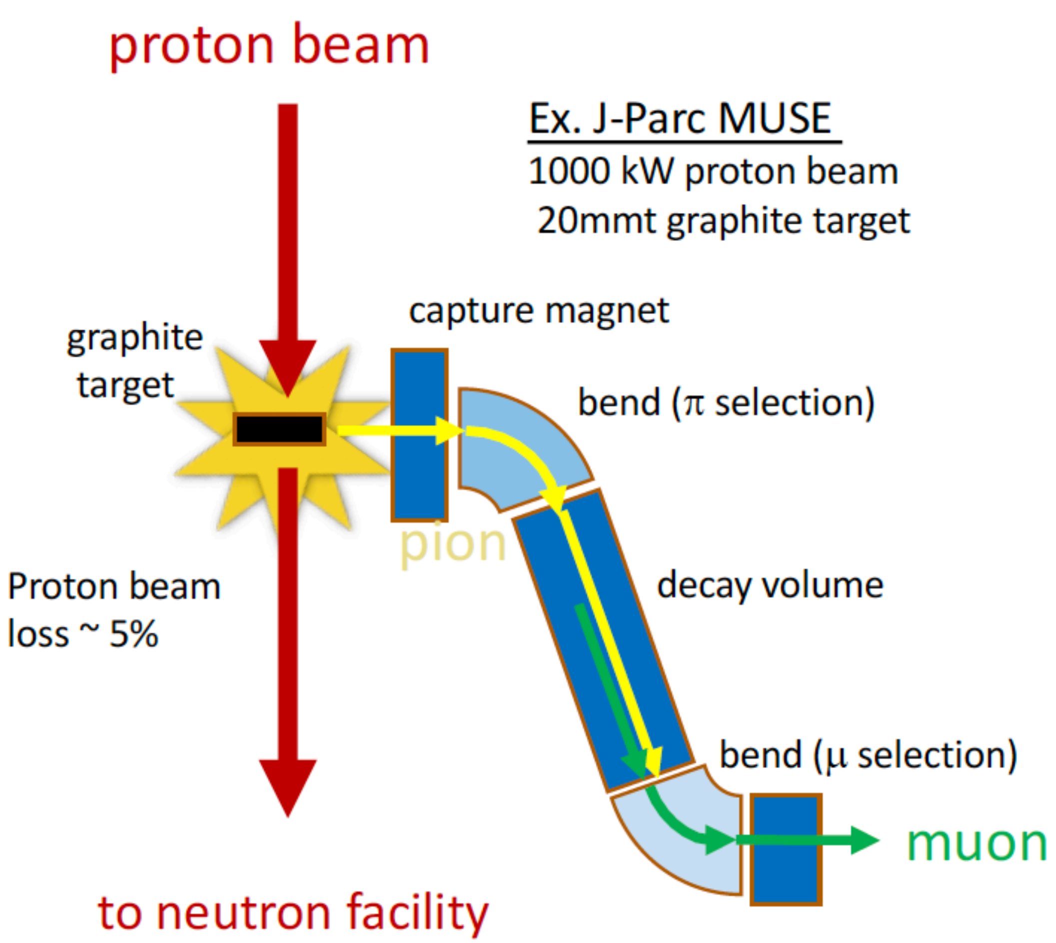
Music at RCNP

- In view of COMET preparation



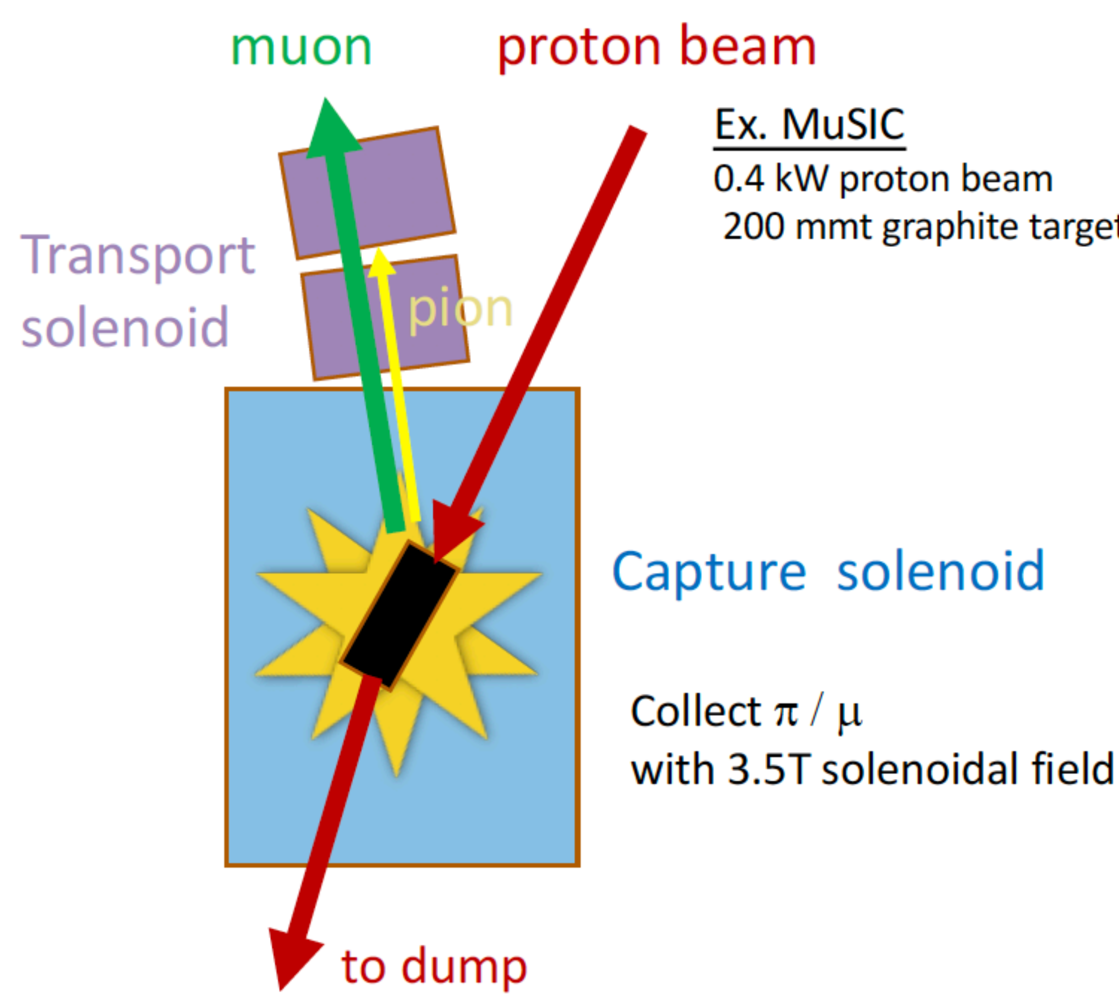
Music at RCNP

Conventional muon beamline



- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

MuSIC beamline

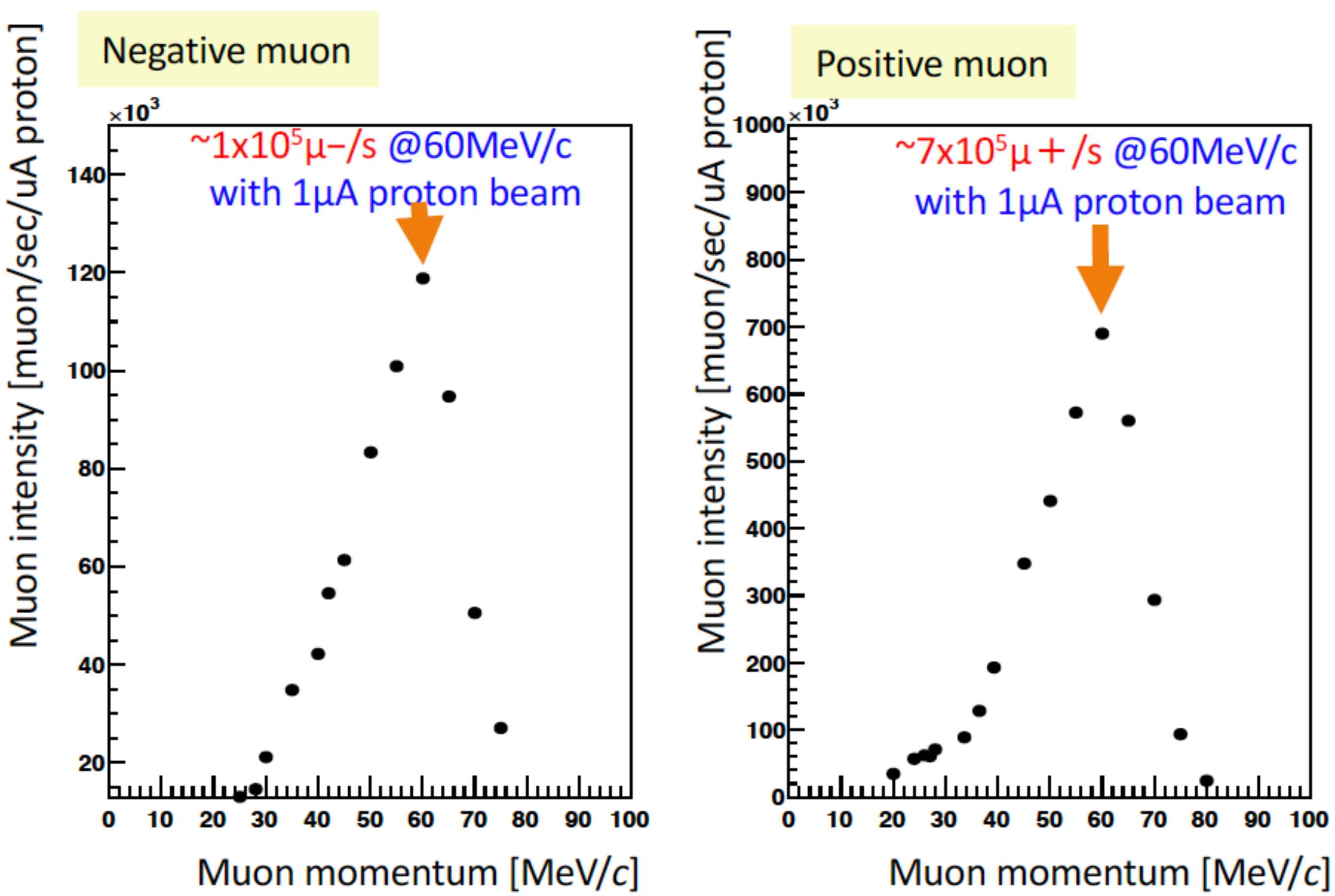


- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

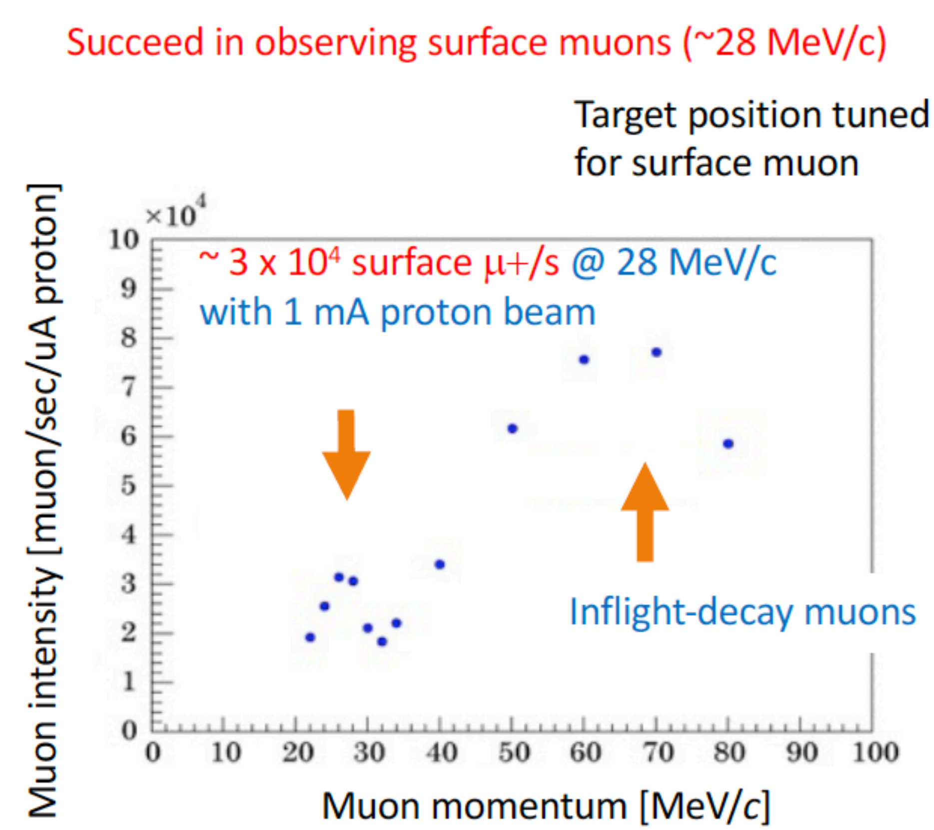
Music at RCNP

- Ready for muon physics at RCNP

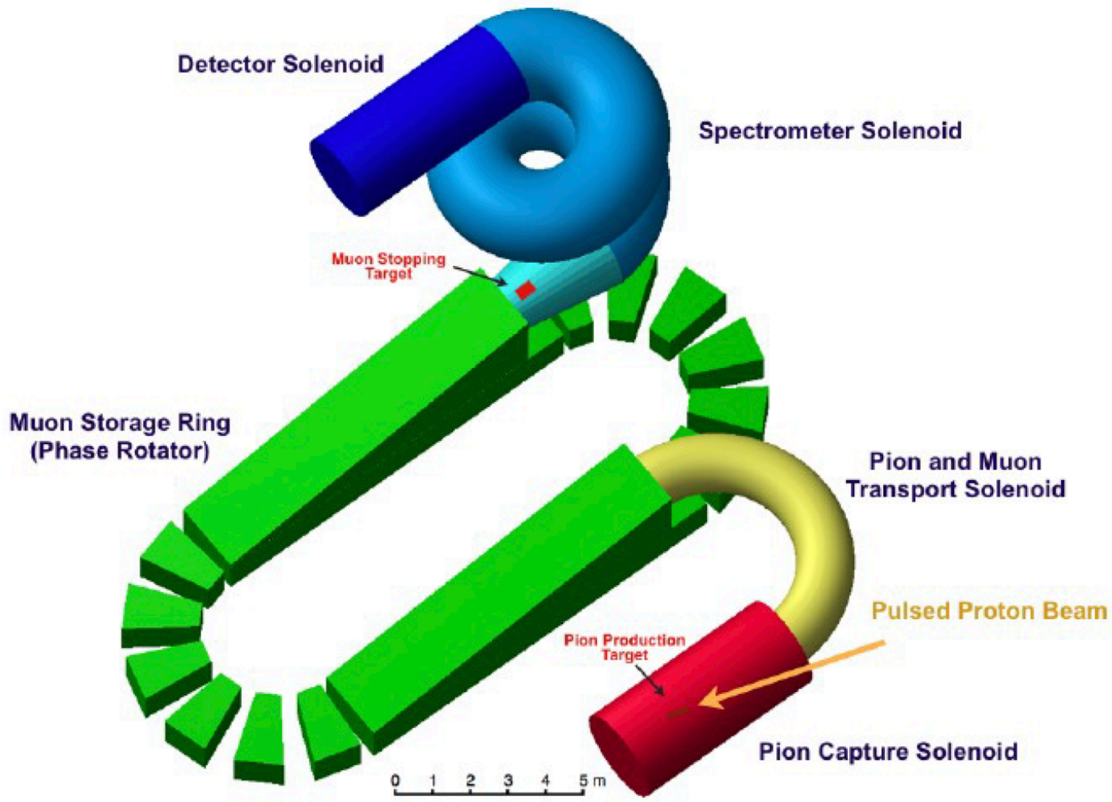
Inflight-decay muons ($\mu^{\pm}$)



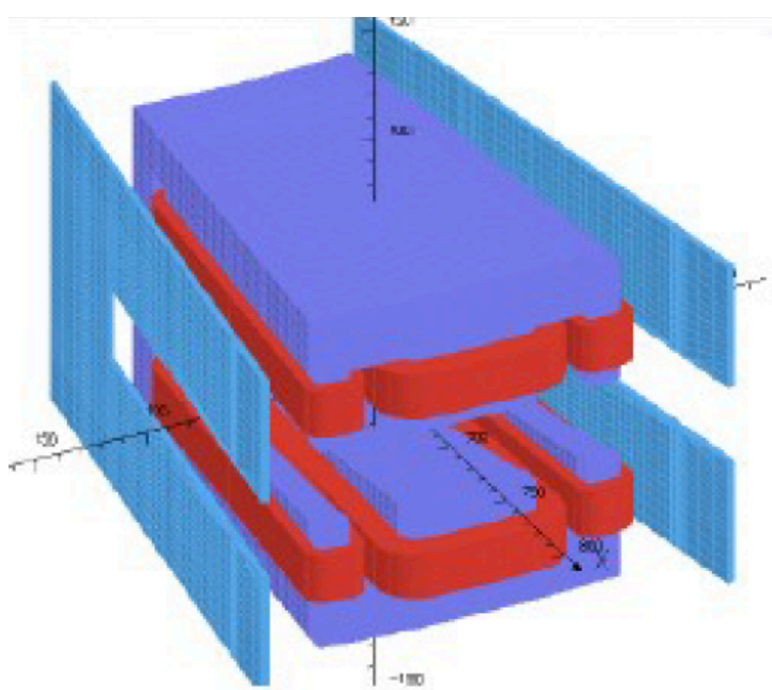
Surface muon (μ^{+})

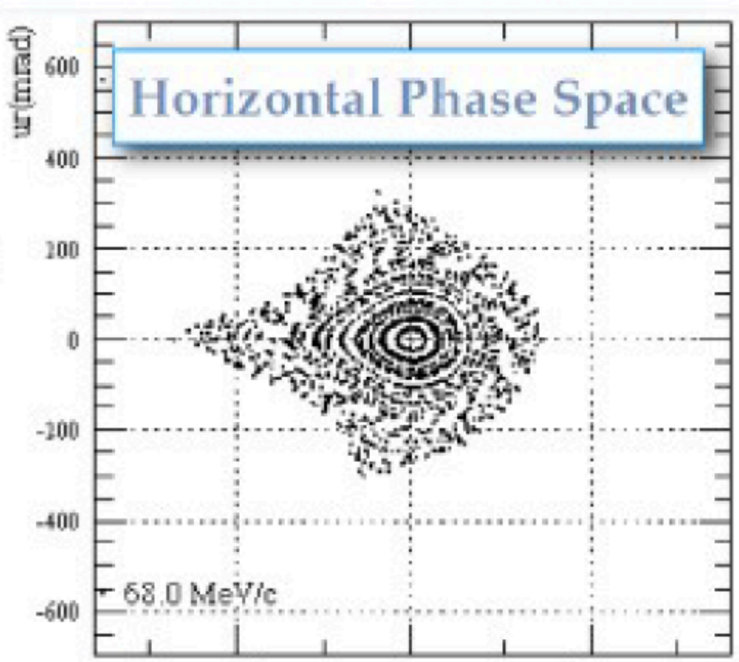


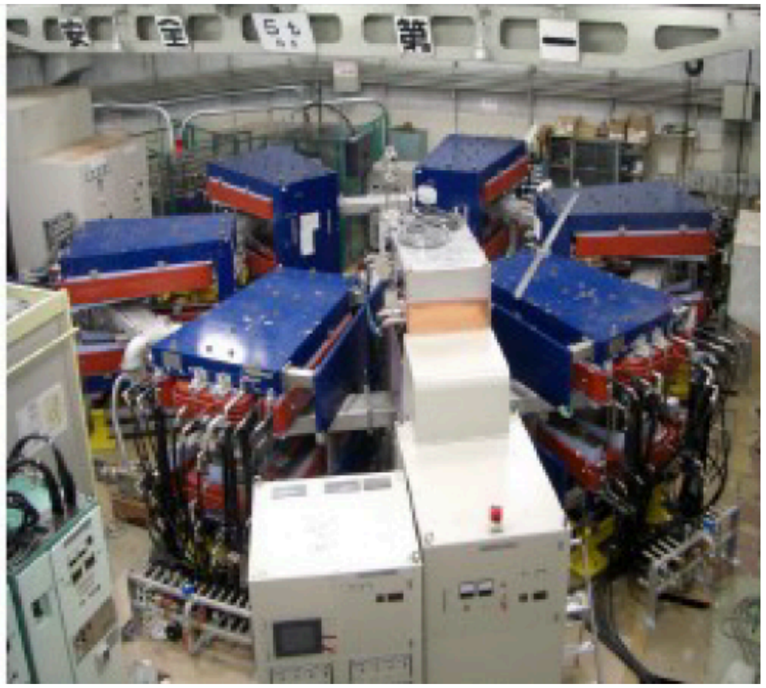
The PRISM project



- FFAG ring designed at RCNP, Osaka Uni.
- FFAG magnet designed, manufactured and tested
- Phase rotation principle demonstrated with alpha particles
- Problems if injection/extraction
    - A possible new solution under investigation: it looks promising (concept of inflector effectively switching off one of the magnets followed by vertical kicker)

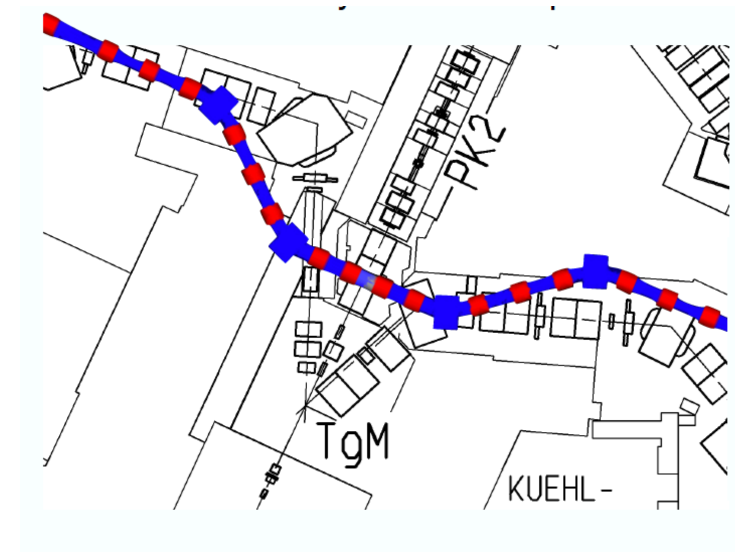


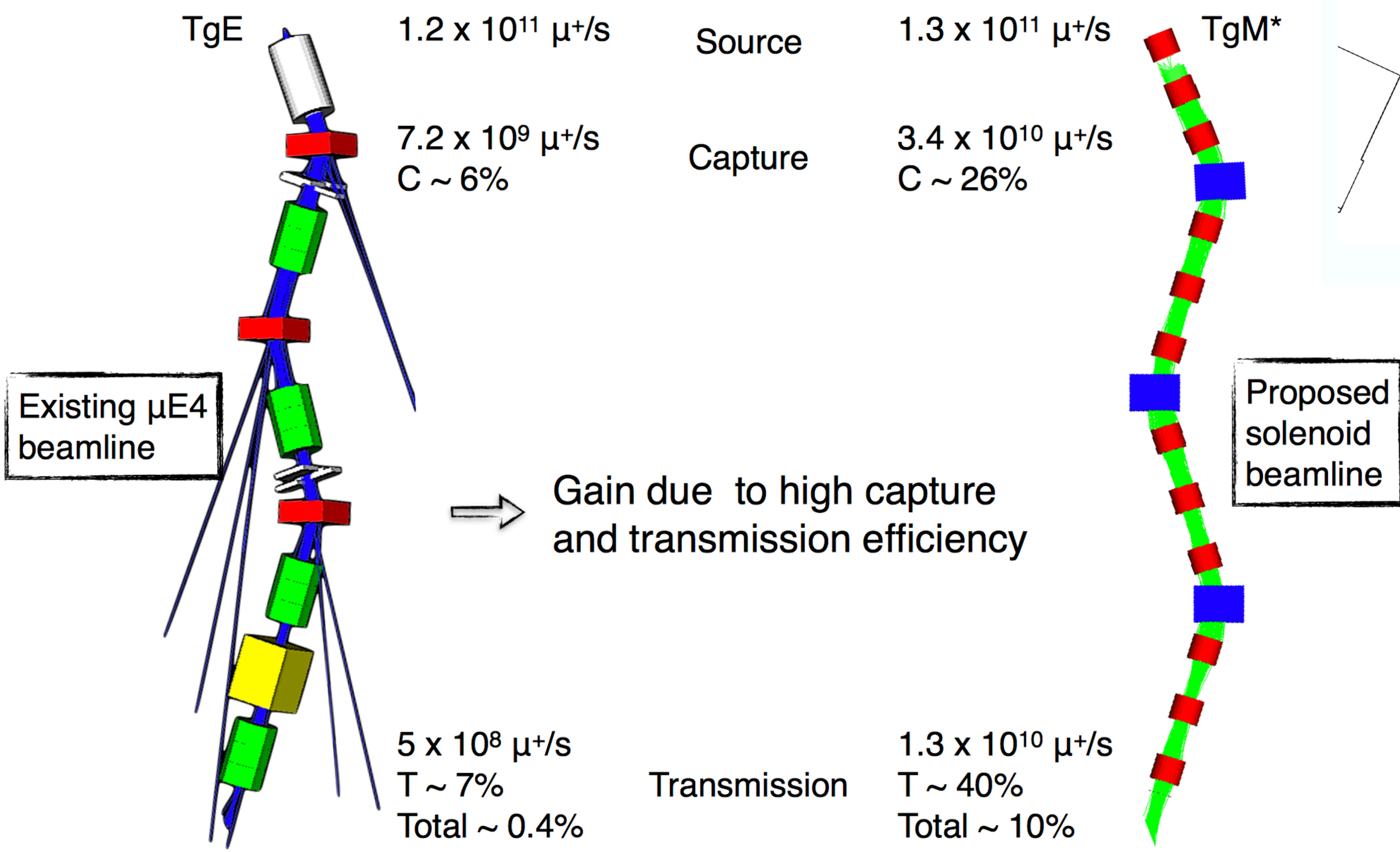




The HiMB project at PSI

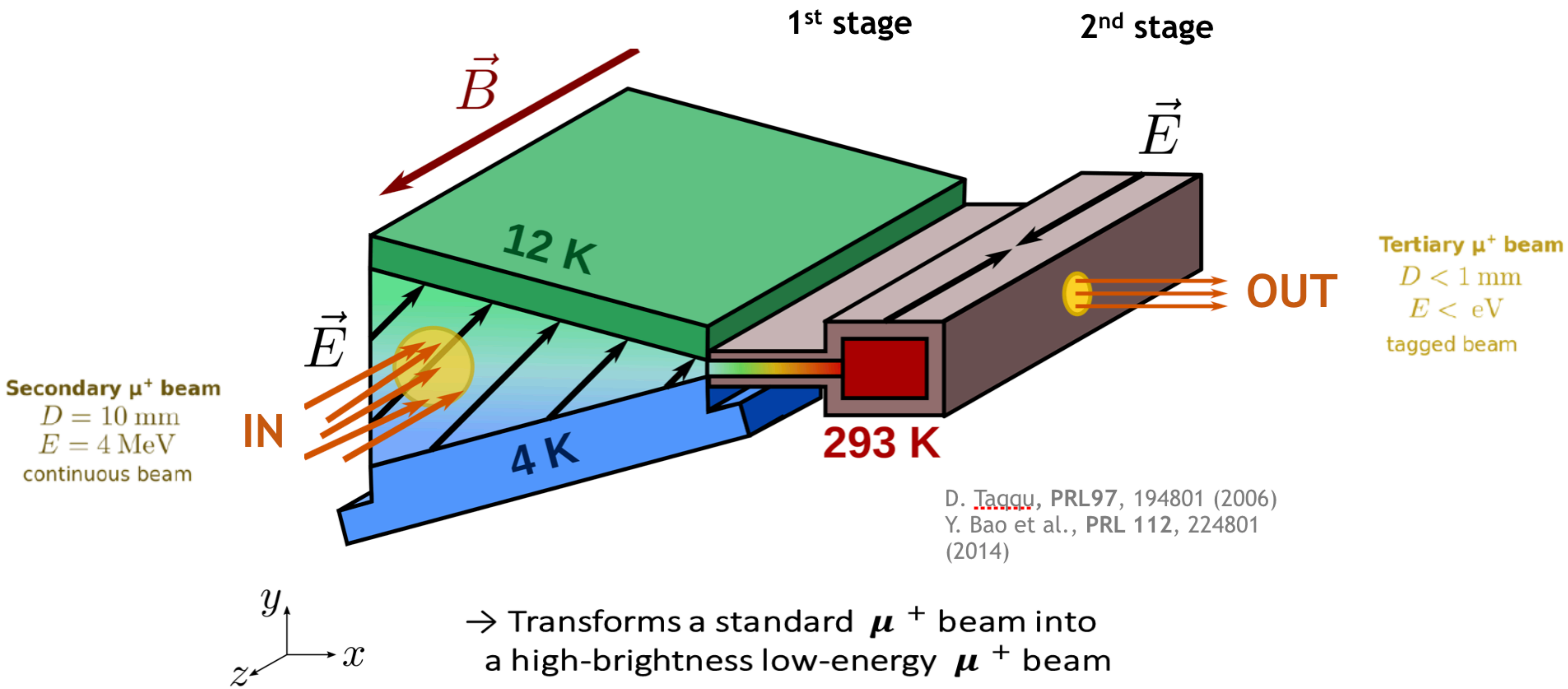
- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Slanted E target test (“towards the new M-target”): planned for **next year**
- Time schedule: **O(2025)**





The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^7** (taking into account an efficiency of **10^{-3}**)



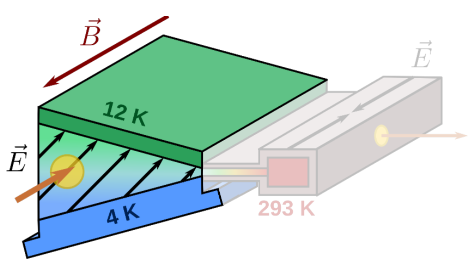
D. Taqqu, **PRL97**, 194801 (2006)
Y. Bao et al., **PRL 112**, 224801 (2014)

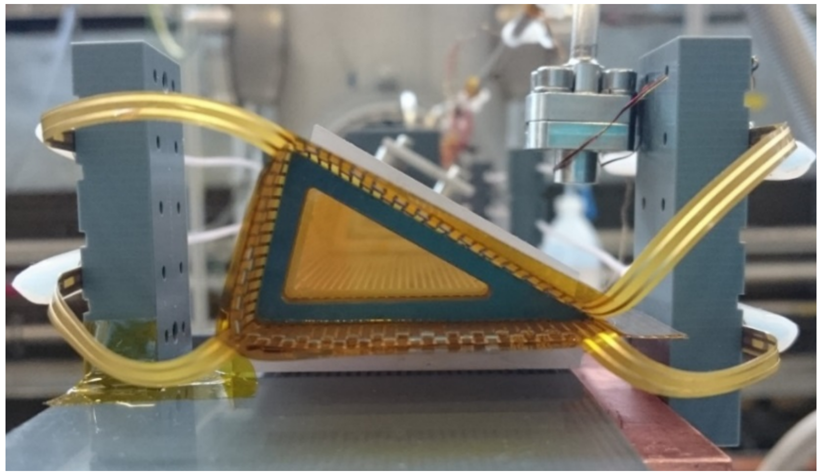
→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

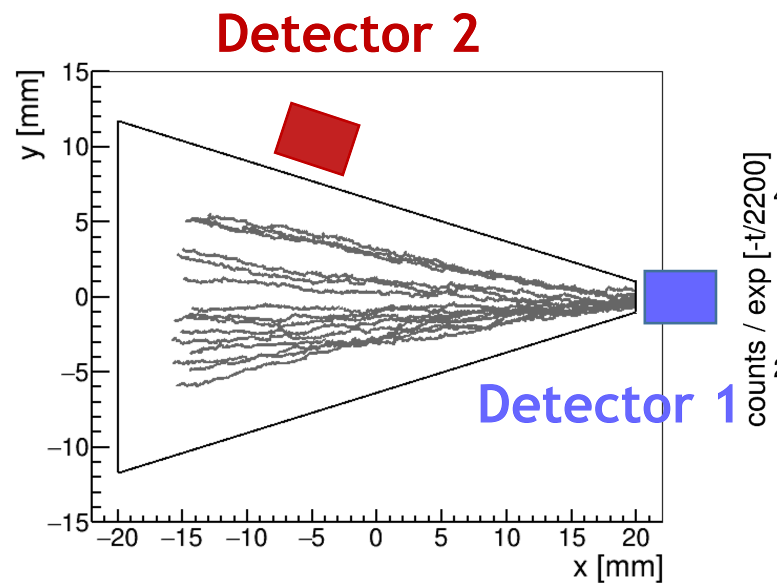
The muCool project at PSI: Status

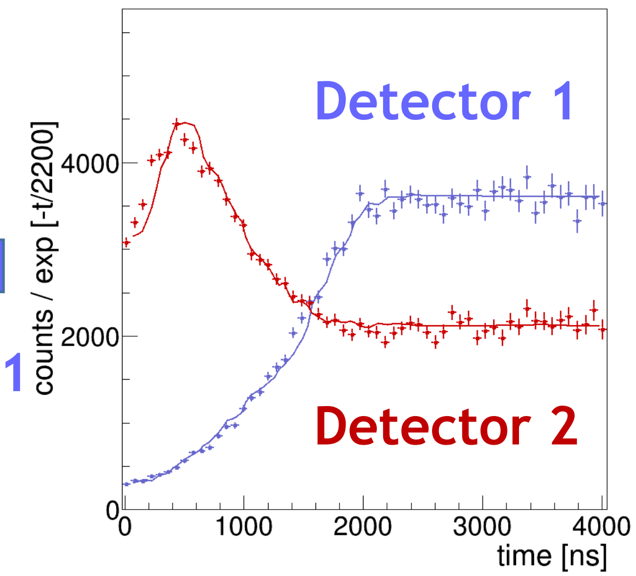
- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**

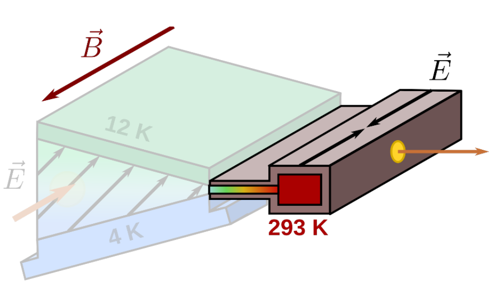
+ + data
— — simulation

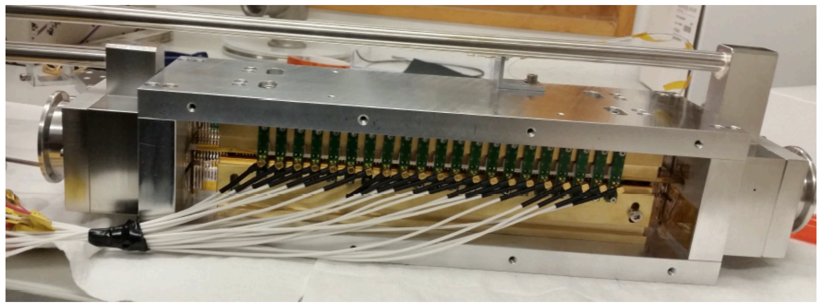


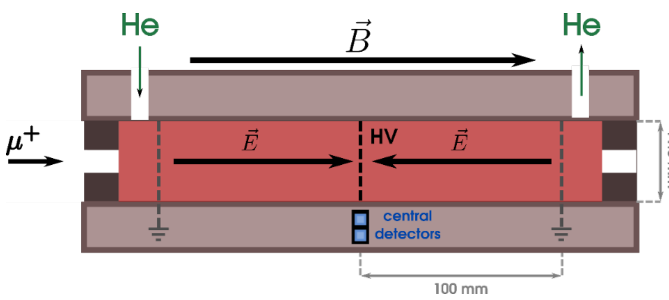


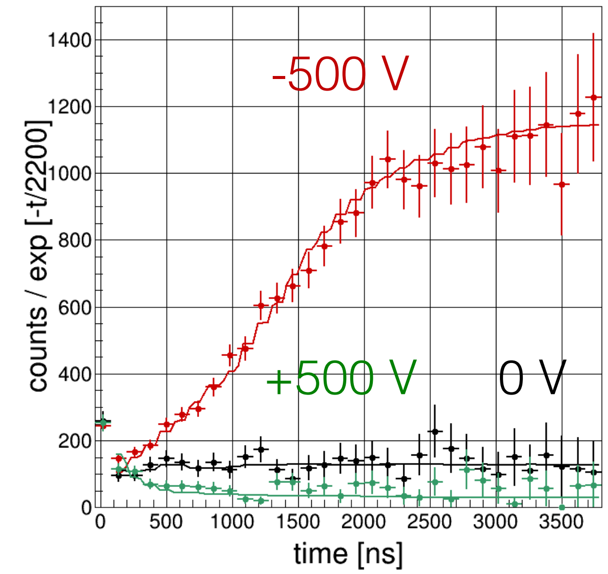






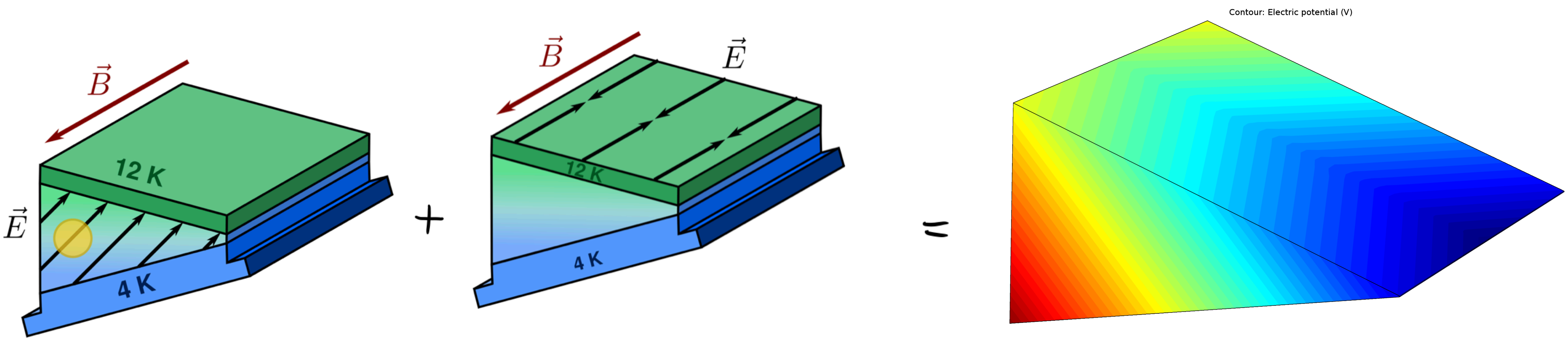


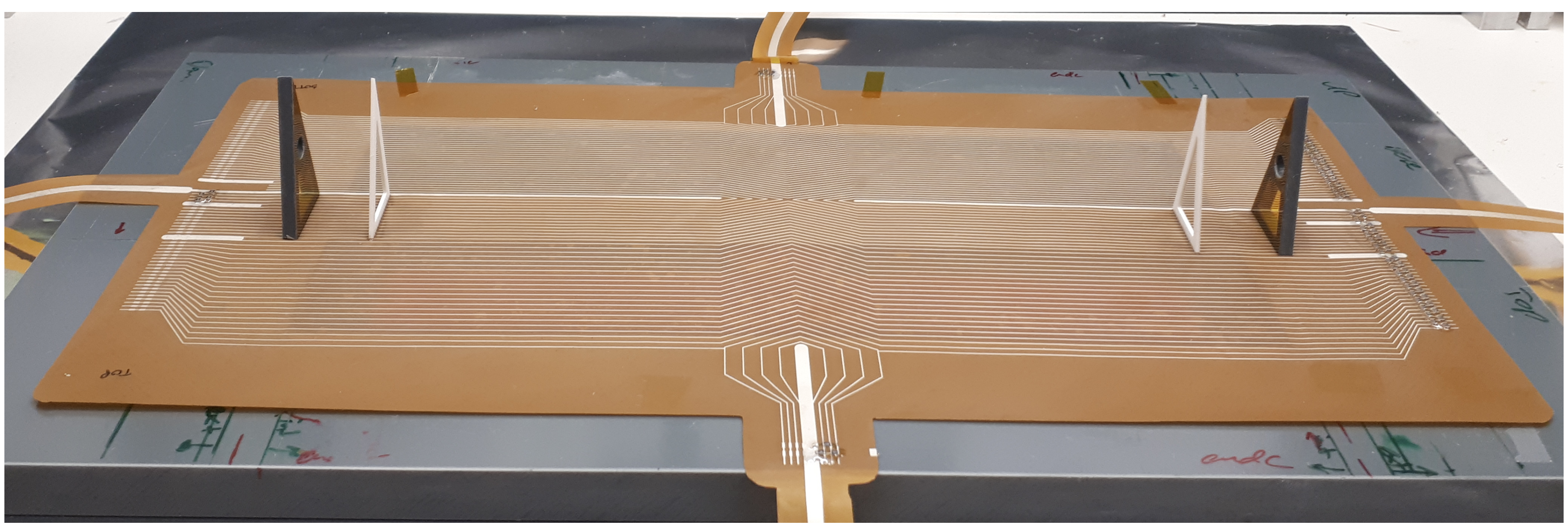




The muCool project at PSI: Status

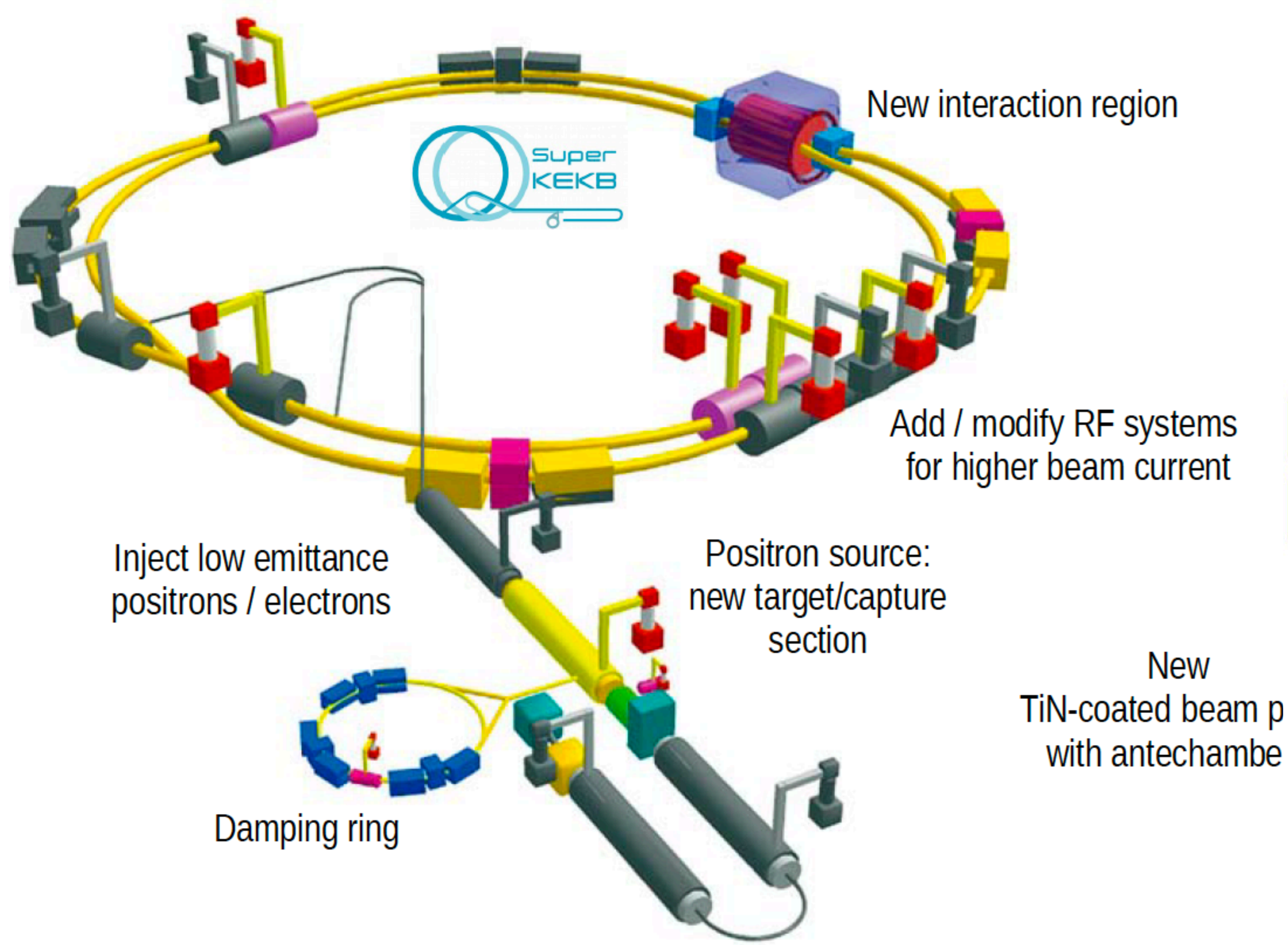
- Next step: 1st stage + 2nd stage
- Test beam scheduled by the end of **THIS YEAR**

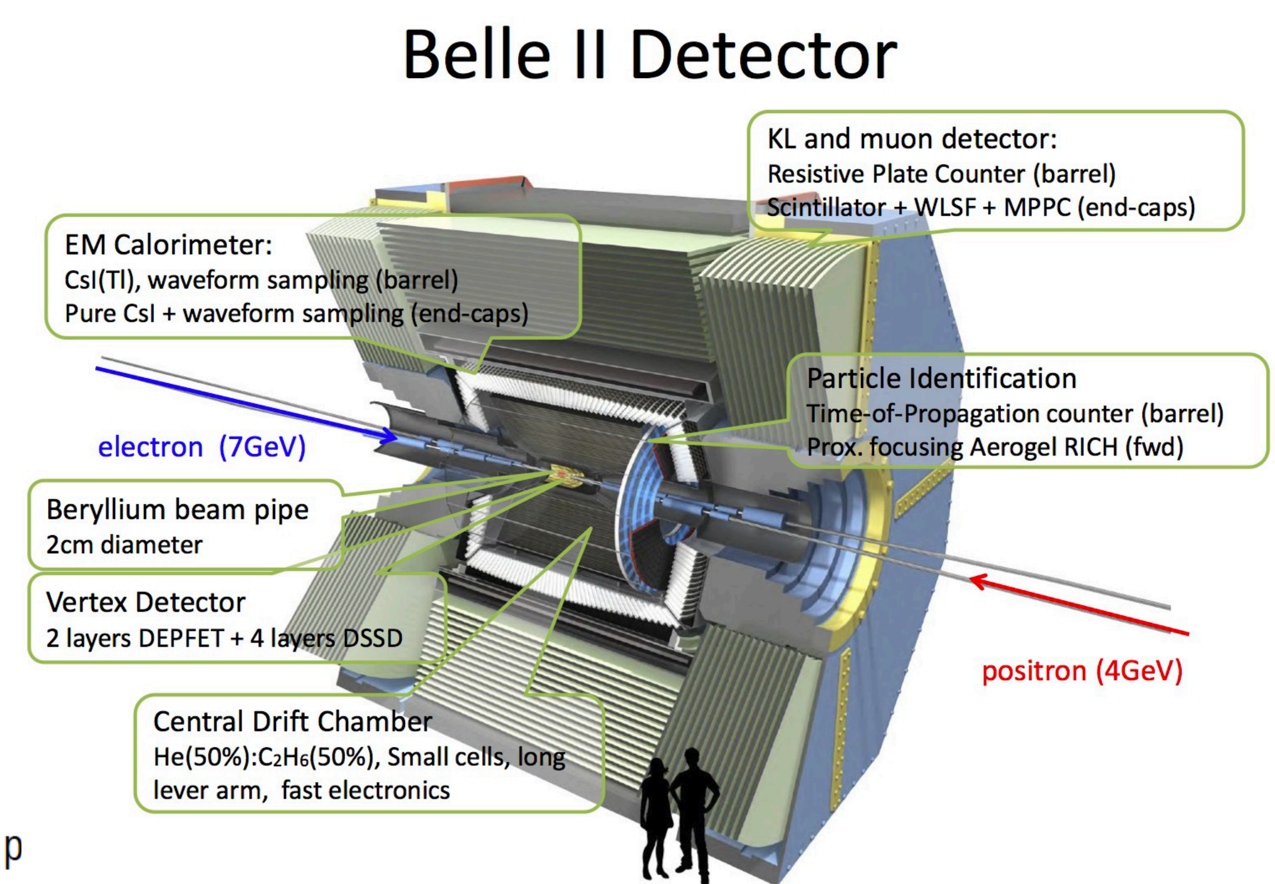




SuperKEKB accelerator and the BELLE II experiment

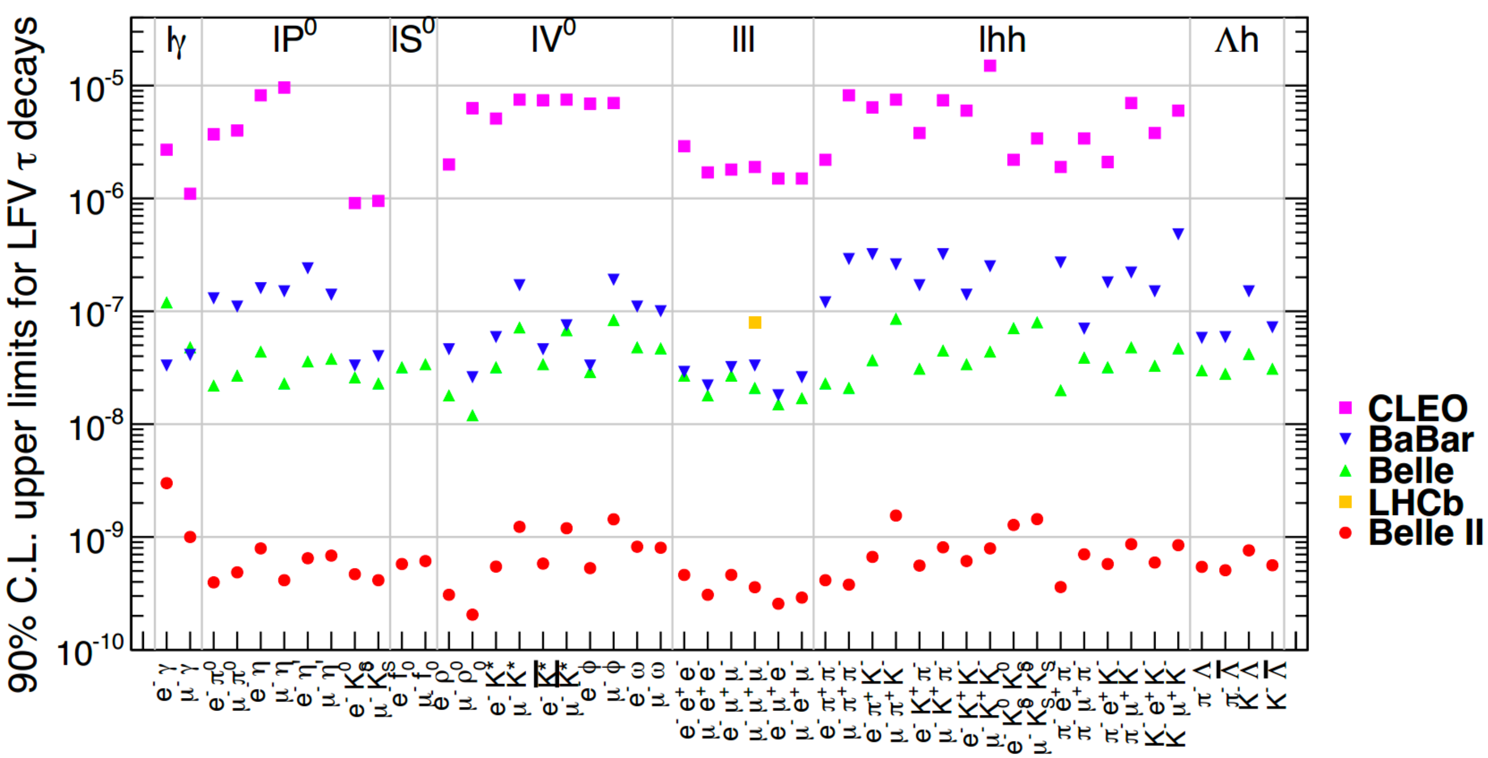
- Located in KEK, Tsukuba, Japan
- Increased luminosity: **40x** ; Beam energy changed to reduce beam background
- Belle II is built on basis of Belle: Main structure, magnet, ECL and KLM reused; vertex detector, DC, PID, upgraded; All electronics replaced.

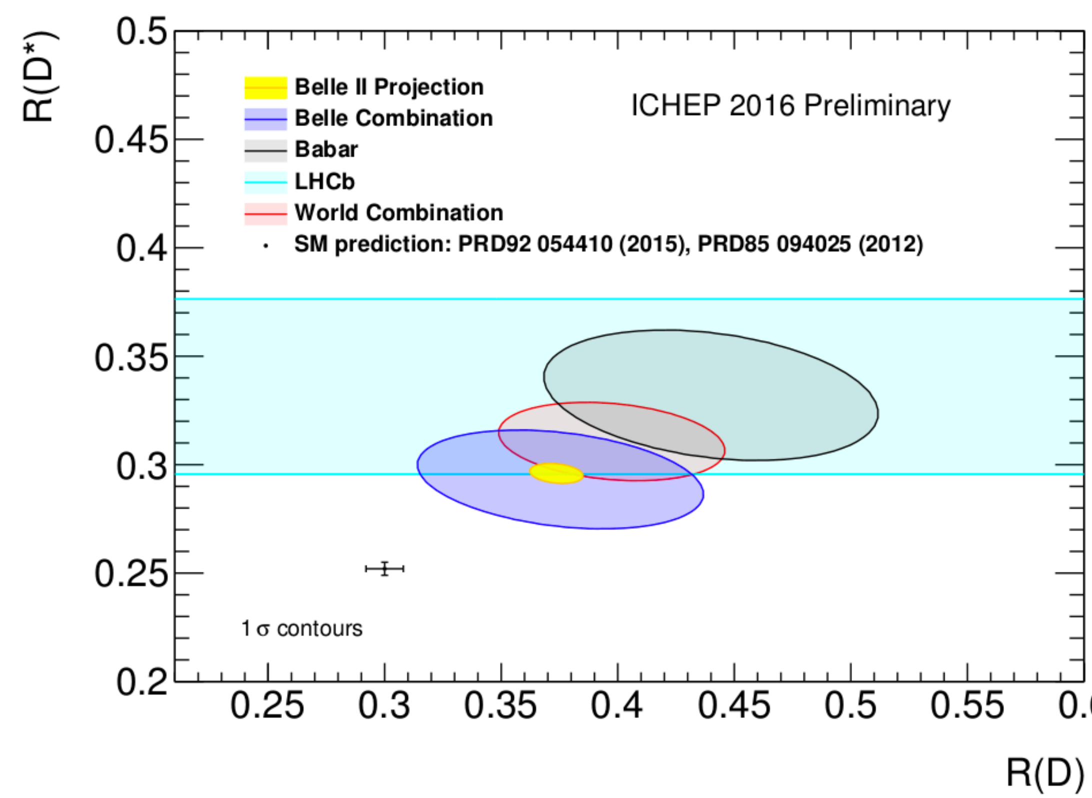




BELLE II: Prospects

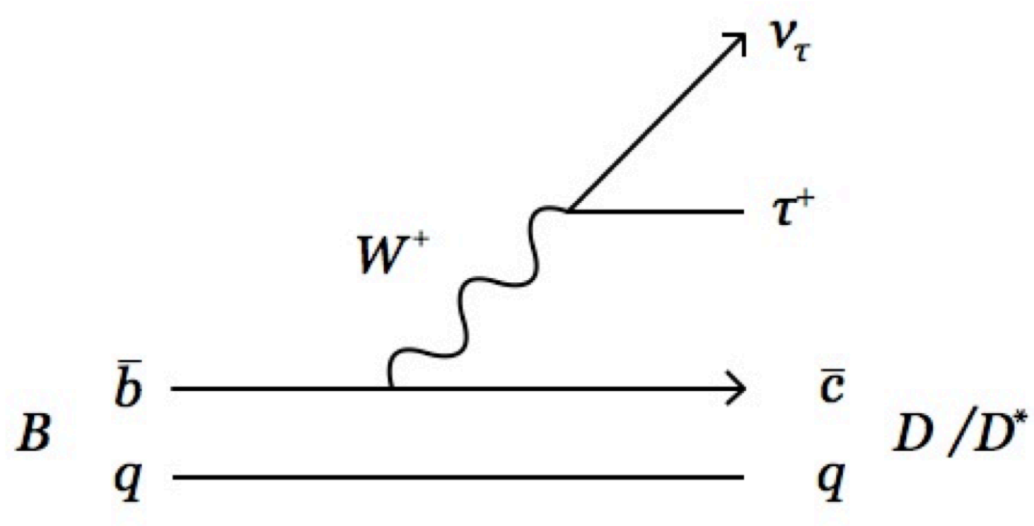
- Belle, being an e+ e– B-factory experiment, is a τ-factory experiment at the same time
- With nearly 1 billion τ+ τ– sample, Belle has obtained most stringent upper limits in most of the τ LFV, LNV and BNV decays, with 90% UL of O(10^{-8})
- For very clean modes (e.g. τ+ → ℓ+ℓ−ℓ+), cLFV upper limits are expected to improve linearly with luminosity
- 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]

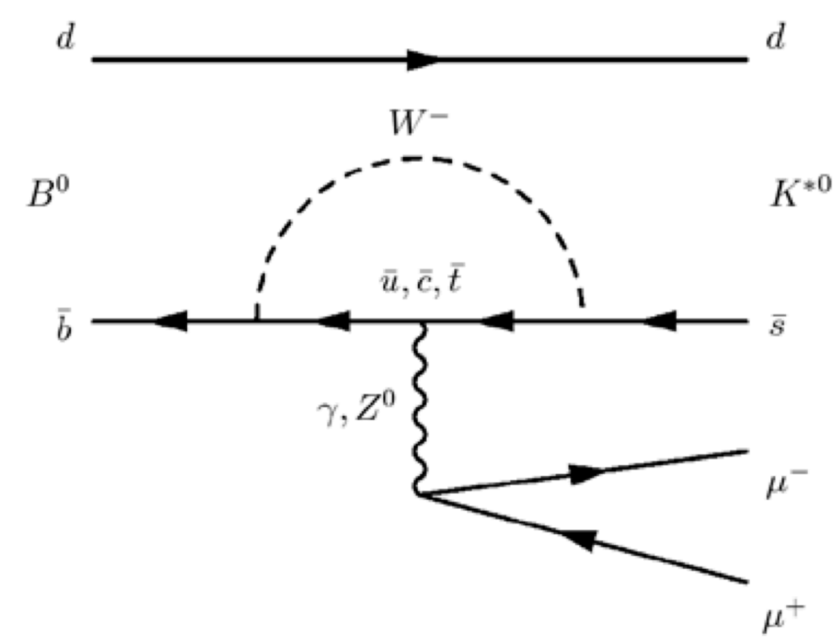




LHCb: Lepton universality

- In the SM couplings of leptons to gauge bosons are independent of the lepton flavor
- Violation of LFU: clear sign of NP
- Semi-leptonic decays:
    - Decay rate can be factored (weak and strong); theoretically simplified
    - Study ratio of BR to cancel theoretical hadronic uncertainties
- At LHCb measurement performed for both tree-level and loop-level processes





LHCb: Lepton universality

HFLAV R(D*) and R(D) combination

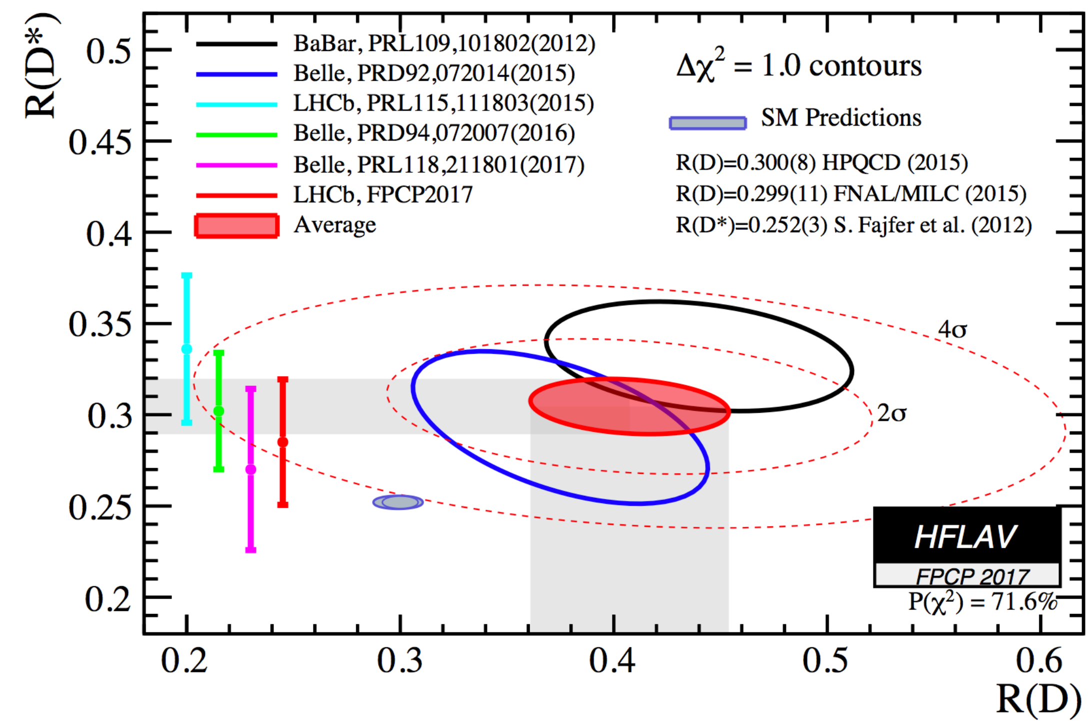
0.304 ± 0.015 (**4.1σ** from SM)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

(Precise) SM prediction = 0.252 ± 0.003 (PRD 85 (2012) 094025)

$$\boxed{\mathcal{R}(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})}$$

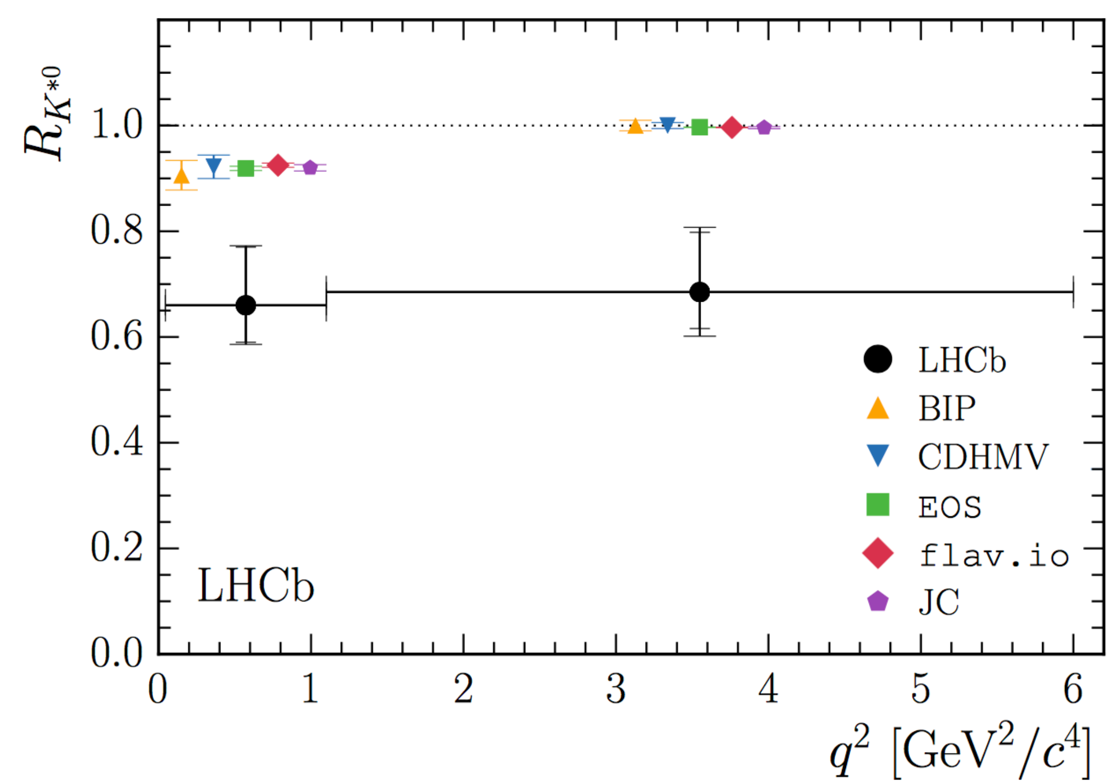
2.1σ away from SM prediction



$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

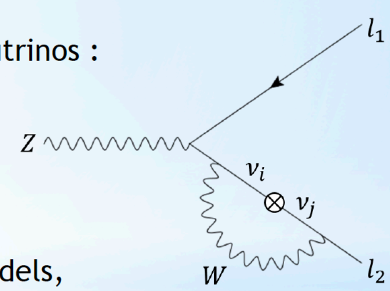
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2c^4 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2c^4 \end{cases}$$

- Compatible with the SM at 2.1σ - 2.3σ (2.4σ - 2.5σ) in the low (central) q^2 bin
- Measurement is statistically dominated



CMS - LVF in Z decay: Z -> eμ

- From one-loop decay with flavor-oscillating neutrinos : Predicts LFV in Z decay, $Br(Z \to e\mu) < 10^{-60}$

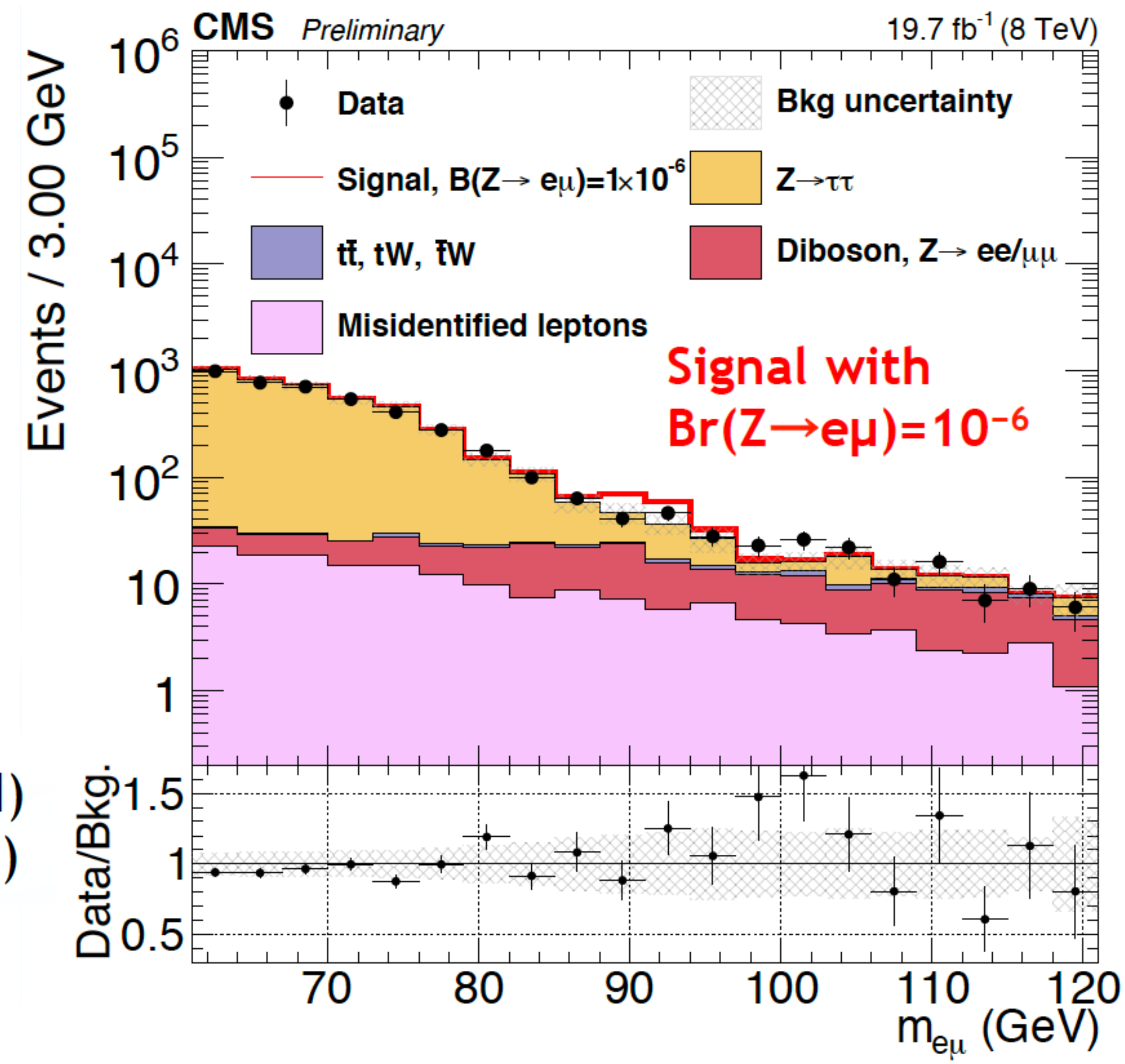


- In BSM scenarios : $Br(Z \to e\mu)$ can be enhanced to 10^{-8} or 10^{-9}
  ex : Models with massive Dirac
  or Majorana neutrinos, extended gauge models,
  or RPV SUSY arXiv:hep-ph/0010193

- Indirect constraint from low energy experiment : $\mu \to 3e$: $Br(Z \to e\mu) < 5 \times 10^{-13}$
  worth to check if this hold at high energy

- Limit from LEP : $Br(Z \to e\mu) < 1.7 \times 10^{-6}$ @95% CL

Limits @95% CL : $Br(Z \to e\mu) <$ $7.3\ 10^{-7}$ (Observed)
$6.7\ 10^{-7}$ (Expected)

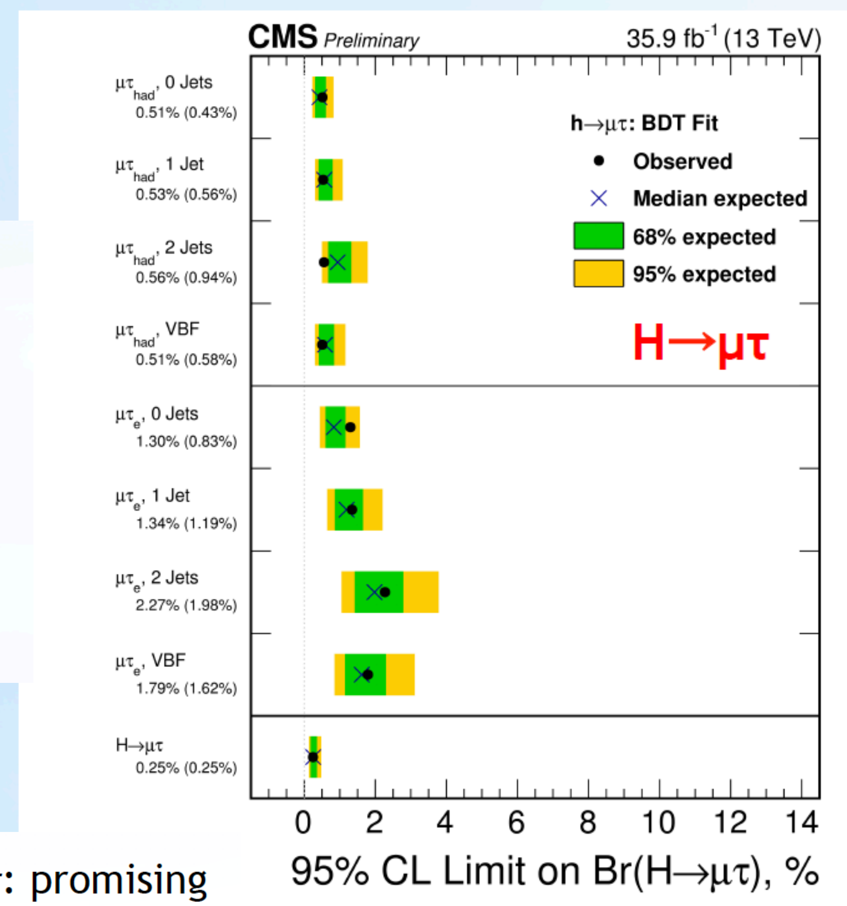


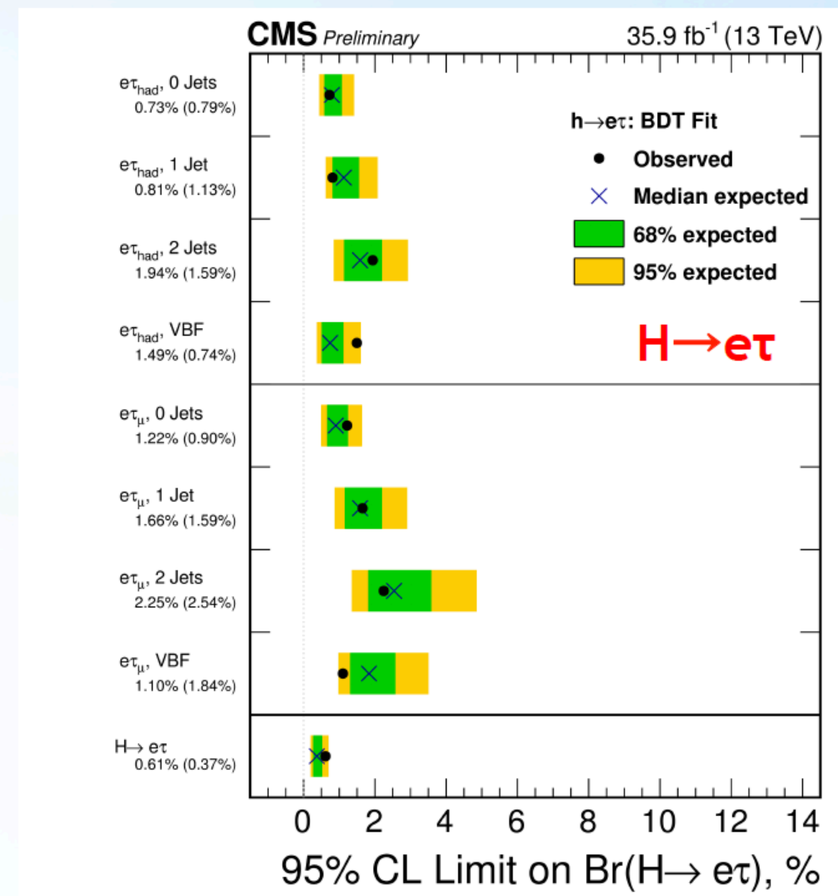
CMS - LVF in H decays

Results : H→μτ & H→eτ

NEW

BDT-fit analysis results for the 8 categories :





Upper limits @95% CL :

Br(H→μτ) <0.25% (0.25% exp.)   Br(H→eτ) <0.61% (0.37% exp.)

→ Clear improvements compared to results from 2012 and 2015 data analyses
The 2.4 sigmas excess (Run1) is now excluded by the 2016 data analyses

Strong constraint:
from searches for μ→eγ
Br(H→eμ) < O(10^{-8}) @ 95% CL

Weaker limits on
Br(H→e/μτ) < O(10%) @ 95% CL
from searches for τ→e/μγ and
μ/e g-2 measurements

→ direct search for H→eτ and H→μτ: promising

CMS - Heavy neutrinos

Results Reported on: (highlights on updates using the 2016 dataset)

- **Search for LFV in the decays :**
  $Z \to e\mu$, $X \to e\mu$, and $H \to e\tau$ and $H \to \mu\tau$
  $Br(H \to \mu\tau) < 0.25\%$ (0.25% exp.)
  $Br(H \to e\tau) < 0.61\%$ (0.37% exp.)

	M_{col}-fit	BDT-fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 2.05 \times 10^{-3}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.45 \times 10^{-3}$	$< 2.26 \times 10^{-3}$

- **Search for a heavy neutrinos:**
  - LRSM scenario right-handed N_l and a heavy W_R
  For the μμjj channels : $M(W_R) > 3.5$ TeV
  For the eejj channels : $M(W_R) > 3.3$ TeV
  - Heavy composite Majorana neutrino (HCMN): M>4.5 TeV
  - Type III seewsaw mechanism
  Multilepton final state : $M(\Sigma) > 840$ GeV (Be=Bμ=Bτ)

- **Prospects:**
  - Some of the analysis of the 2016 dataset: to be released soon
  - more data to come to perform precision measurements
    Run2 (2015-2018) and Run3 (2021-2023): about 120 and 300 fb^{-1} expected
    HL-LHC (2026-2036): about 3000 fb^{-1} expected
    Challenge : higher pileup (tracking, isolation, ...)

ATLAS - LVF in Z decay: Z -> eμ

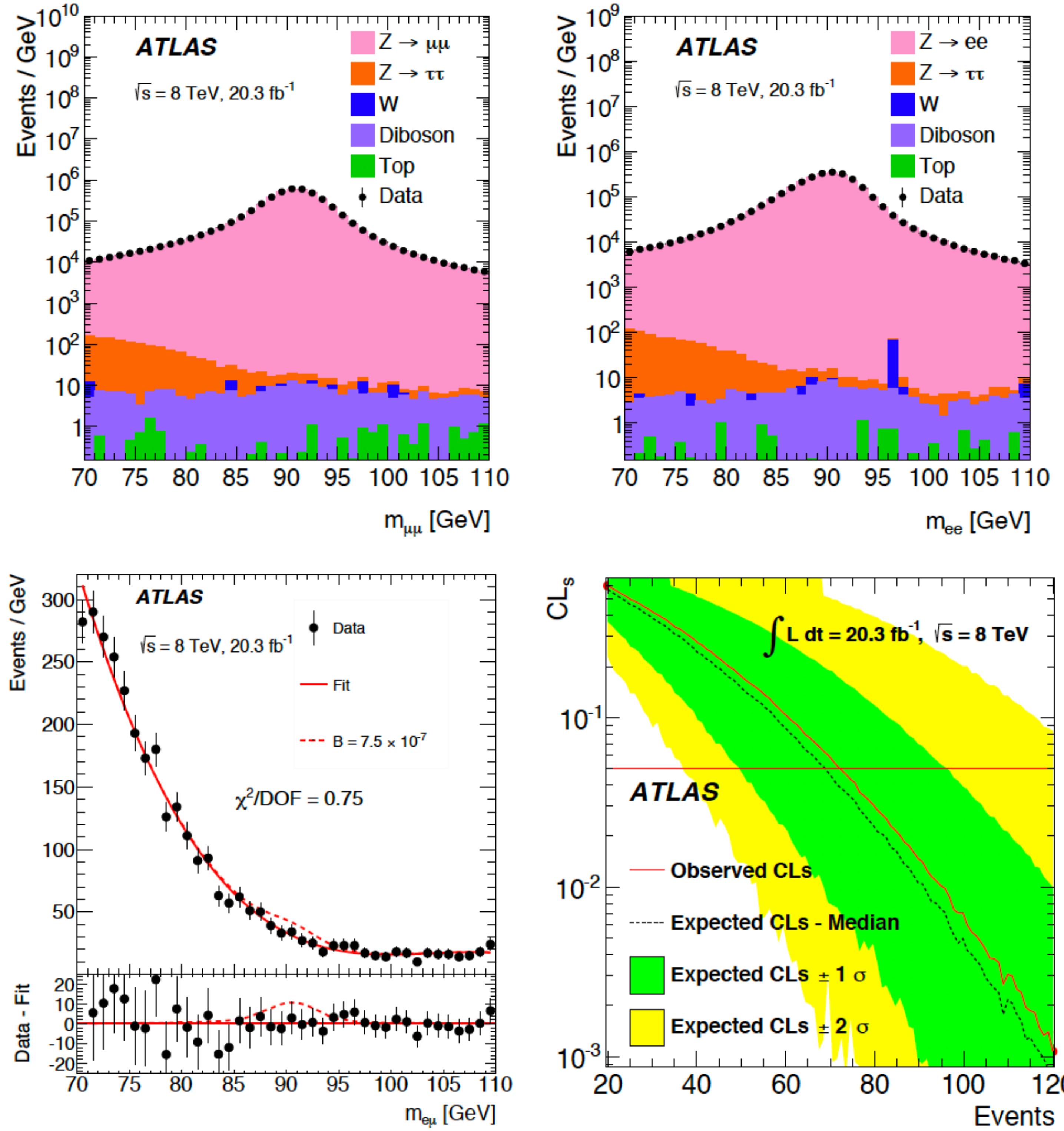
- Branching ratio estimate as ratio of 95% limit on Z → eμ events and total Z production:

$$\mathrm{BR}(Z \to e\mu) < \frac{N_{95\%}}{\epsilon_{e\mu} N_Z}$$

- N_Z estimated as weighted average from dilepton decays
- Relative ratios Z → ee and Z → μμ from events in window between 70 and 110 GeV

- Resulting limit:

$$\mathrm{BR}(Z \to e\mu) < 7.5 \times 10^{-7}$$



ATLAS - Taus decays

arXiv:1601.03567

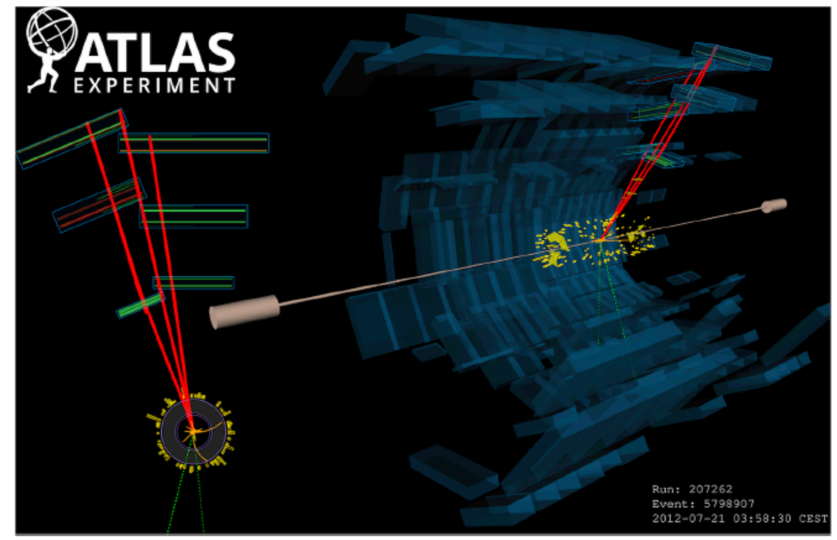
Neutrinoless $\tau \to 3\mu$ decays

- **Use decays $W \to \tau\nu \to 3\mu\nu$**
- Tau lepton produced with a transverse momentum, typically 25 to 50 GeV

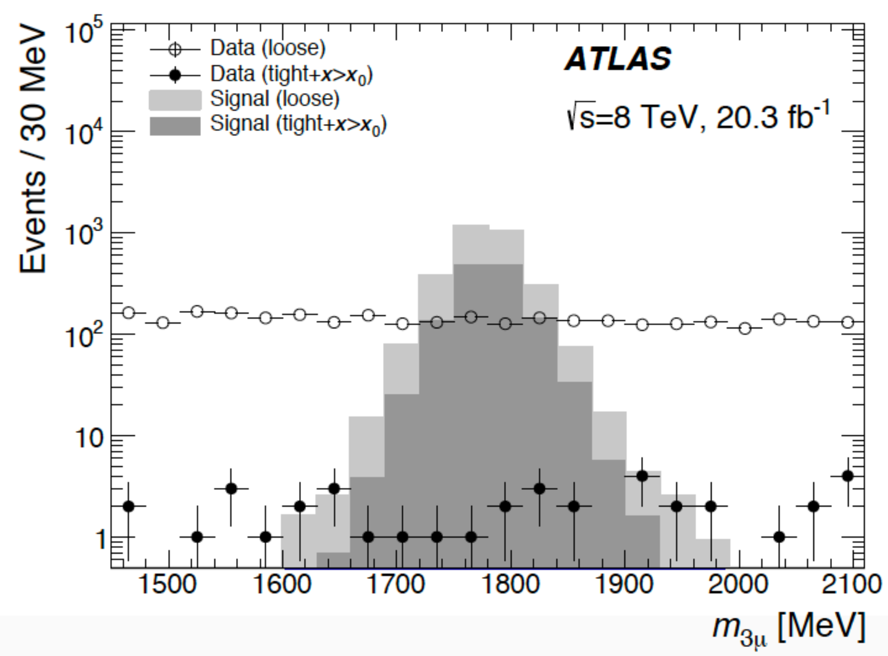
- Muons from tau decay close in space
- Neutrino carries away missing transverse energy

- **Basic selection: 3 muons from same vertex with $|m(3\mu) - m(\tau)| < 1$ GeV**
- Require $m(3\mu) < 2.5$ GeV; $pT(\mu) > 2.5$ GeV
- Rely on several multi-muon triggers

- **Events then categorised according to $m(3\mu)$**
- Loose selection to train BDT
- Study rejection in sidebands; tighter selection defined through optimisation on limit

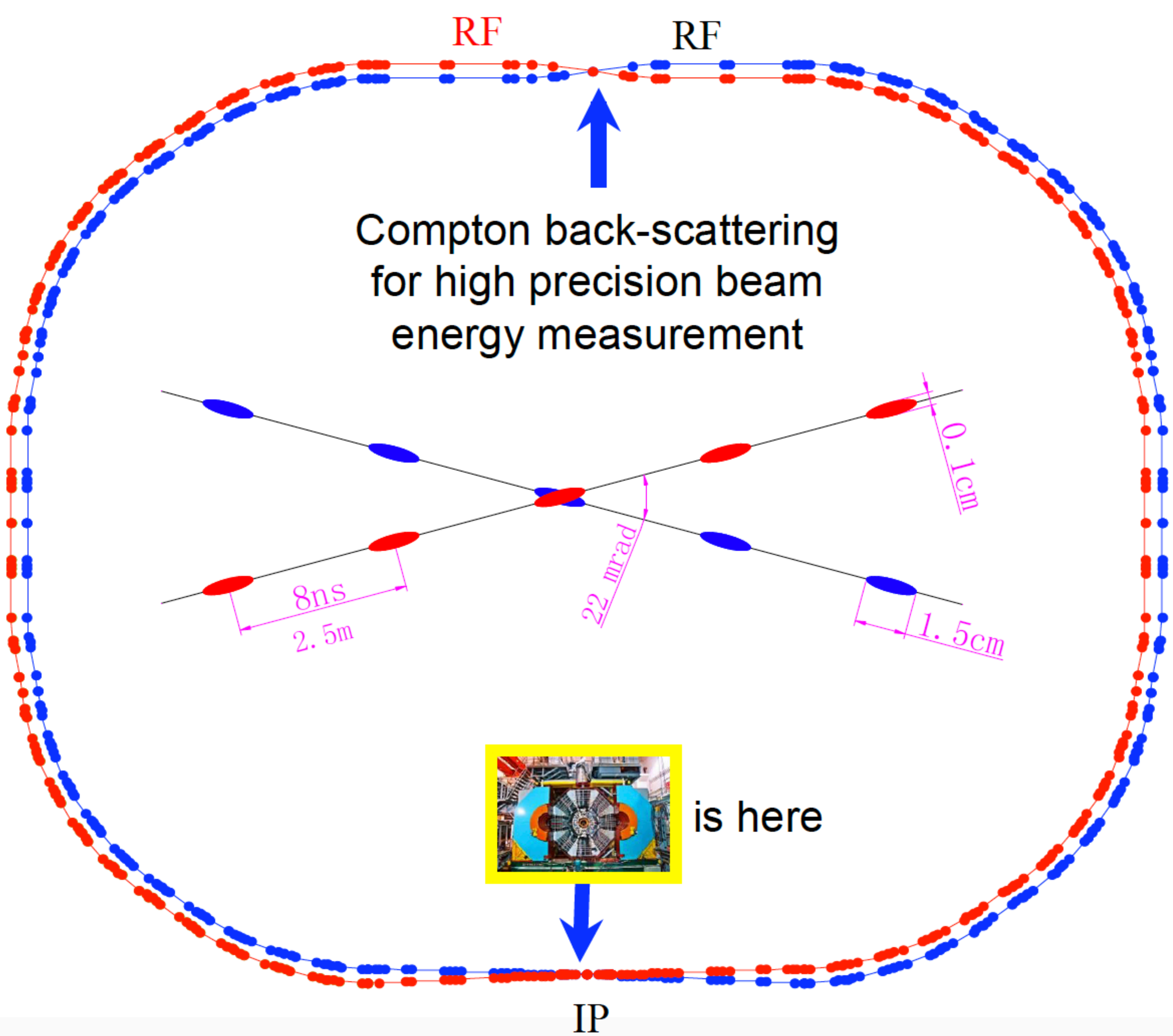


Region	Range in $m_{3\mu}$ [MeV]
Signal region	[1713, 1841]
Blinded region	[1690, 1870]
Sideband region	[1450, 1690] and [1870, 2110]
Training region	[750, 1450] and [2110, 2500]



The BESIII experiment

- 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/ψ → eμ,eτ,μτ at BESIII: Status

- 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/ψ → eμ decay
- Better sensitivities on J/ψ → eτ and J/ψ → μτ based on 1300 million J/ψ events are coming soon [**beginning of 2018**]
- J/ψ radiative decays will be studied as well J/ψ → γeτ, γμτ

Decay mode	BESII upper limit	BESIII upper limit	BESIII prospects
J/ψ → eμ	1.1×10^{-6} (58M)	1.6×10^{-7} (225M)	
J/ψ → eτ	8.3×10^{-6} (58M)	-	**6.3×10^{-8} (1300 M)**
J/ψ → μτ	2.0×10^{-6} (58M)	-	**7.3×10^{-8} (1300 M)**

Heavy neutrino search with the NA62 experiment

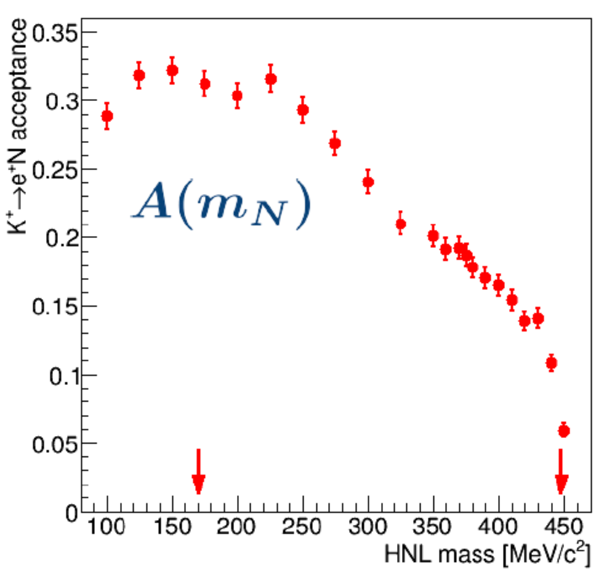
- If $m_N < m_{K^+}$, heavy neutrinos observable via production in:

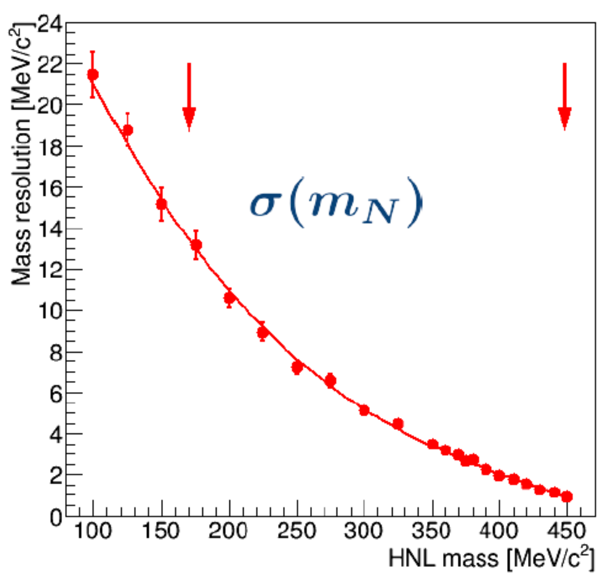
  $$\Gamma(K^+ \to l^+ N) = \Gamma(K^+ \to l^+ \nu_l)\ \rho_l(m_N)\ |U_{l4}|^2$$

- This talk: search for peaks in $m_{miss}(K_{l2}) = \sqrt{(P_K - P_l)^2}$
  - NA62 2007 data sample: $l = \mu$
  - NA62 2015 data sample: $l = e$
- Other searches look for decays of heavy neutrinos (HN), e.g.

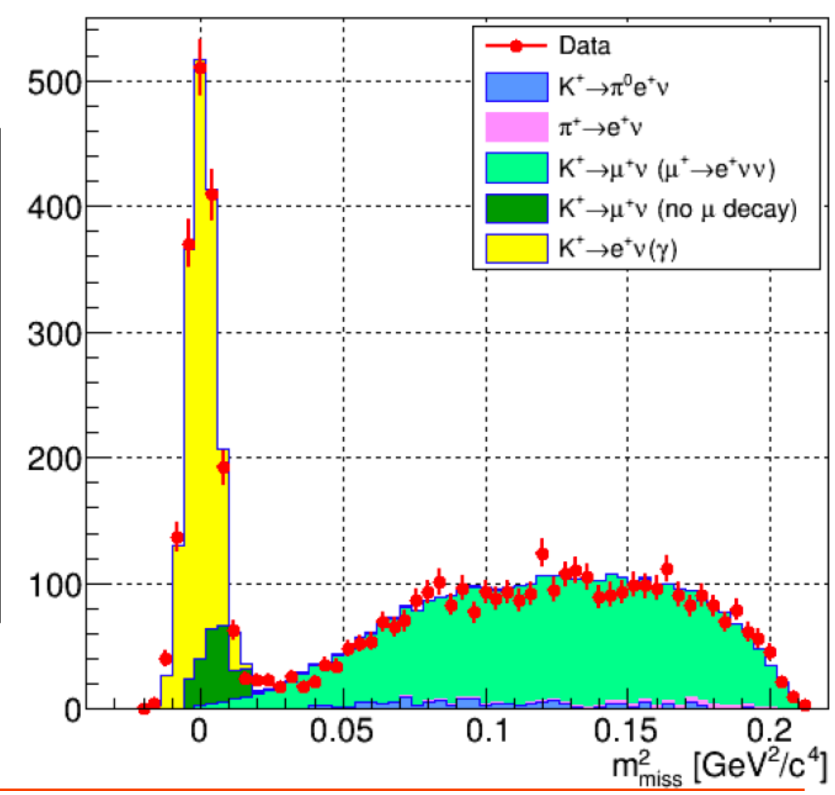
  $$N \to \pi^{\pm} l^{\mp}\ ,\ N \to \pi^0 \nu, \ldots$$

- Kaon decays in fiducial volume: $N_K = (3.01 \pm 0.11) \times 10^8$
- Heavy neutrino (HN) MC simulation
  - ➢Acceptance vs. HN mass: $A(m_N)$
  - ➢Missing mass resolution vs. HN mass: $\sigma(m_N)$





Squared missing mass: $m^2_{miss} = (P_K - P_e)^2$



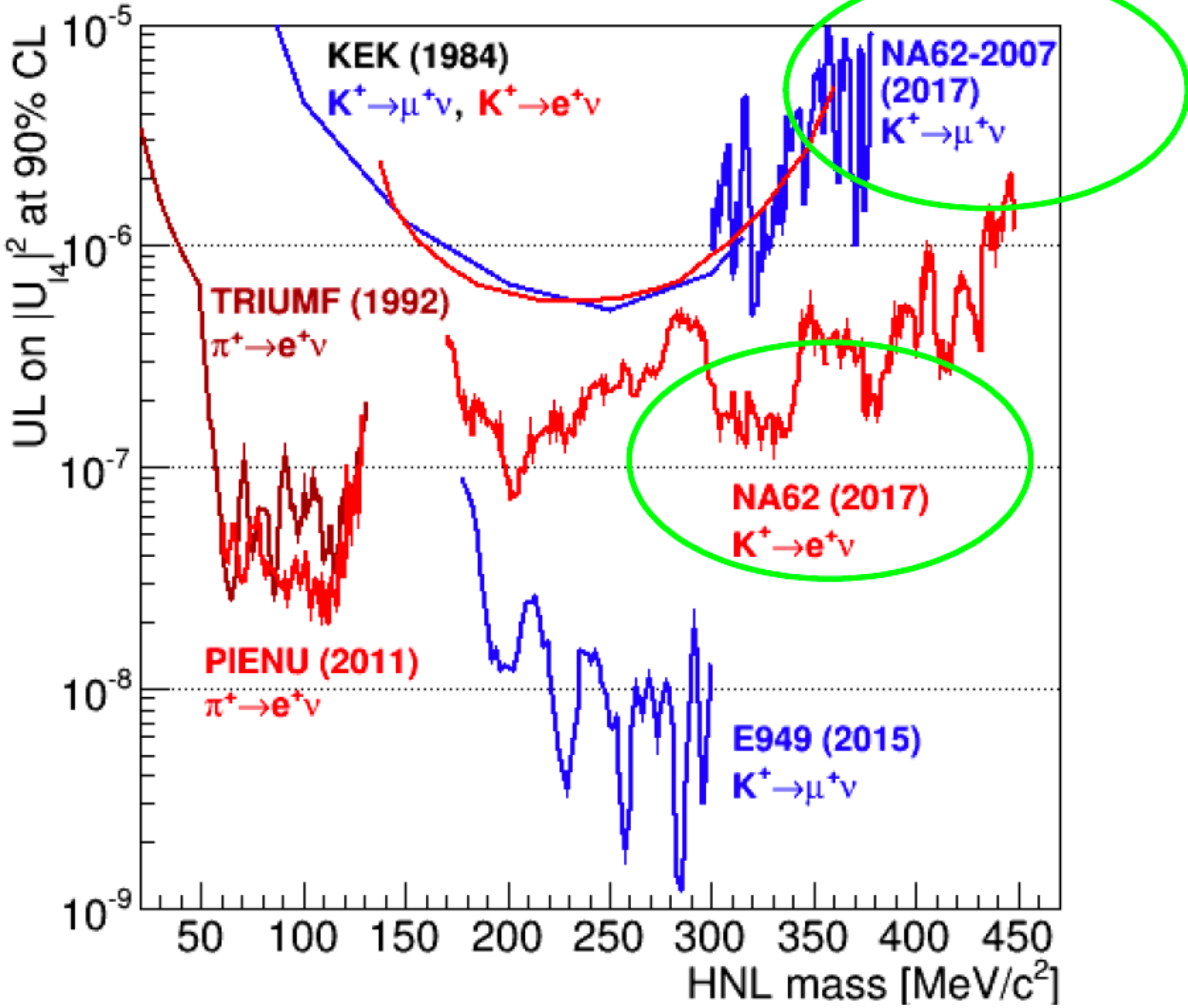
Signal region: $m_{miss} \in (170, 448)\ \mathrm{MeV}/c^2$

Heavy neutrino search with the NA62 experiment

Upper Limits on $|U_{l4}|^2$

$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \to l^+ N)}{\mathcal{B}(K^+ \to l^+ \nu_l)\ \rho_l(m_N)}$$

- NA62 2007 data analysis:
  - Extends the mass range for upper limits on $|U_{\mu 4}|^2$
  - Most stringent limit in $m_N \in (300, 375)\ \mathrm{MeV}/c^2$
- NA62 2015 data analysis:
  - Reaches $10^{-6} - 10^{-7}$ limits on $|U_{e4}|^2$ in the range $m_N \in (170, 448)\ \mathrm{MeV}/c^2$



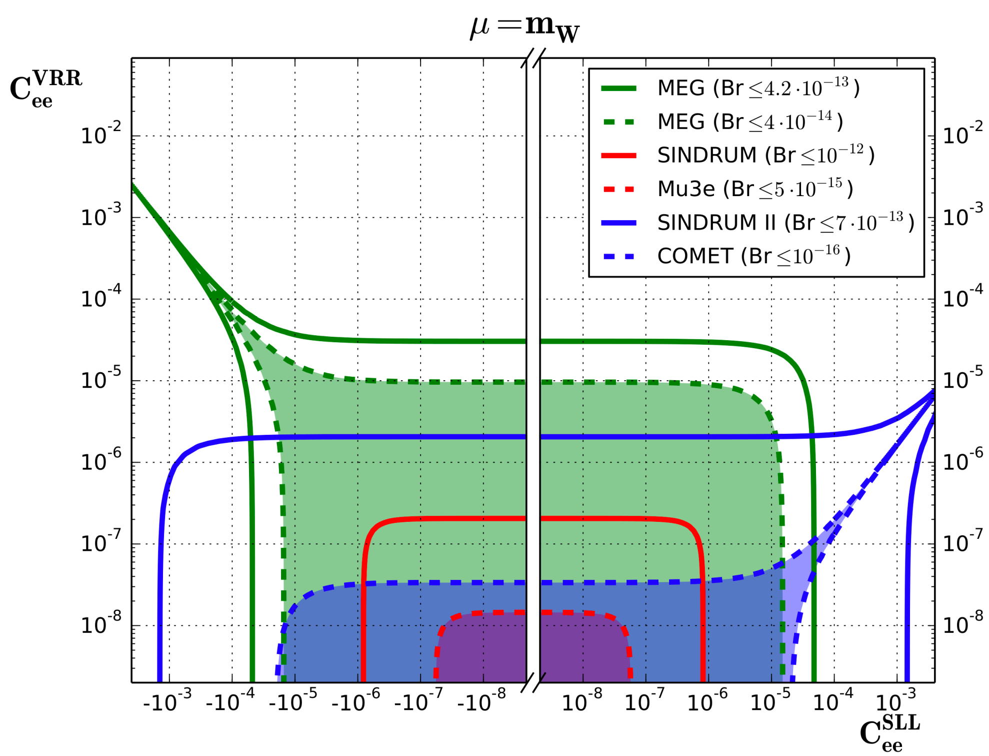
Th: SM Effective Field Theory

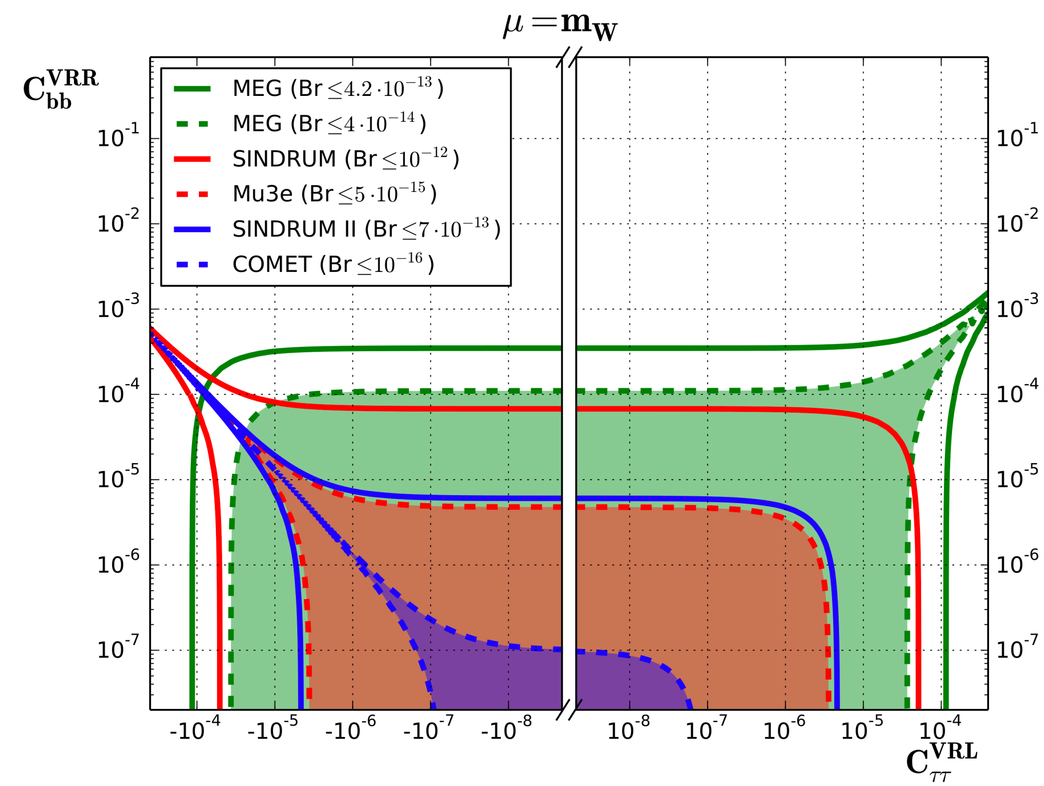
- Typical interpretive approaches
  - Top-down, UV-complete extensions of the SM (see Plenary Talk: Ana Teixeira)
  - **Bottom-up,** effective field theoretical formulation
- SM effective theory valid up to some scale Lambda. It can be extended to a field theory which reduces to SM via decoupling of New Physics

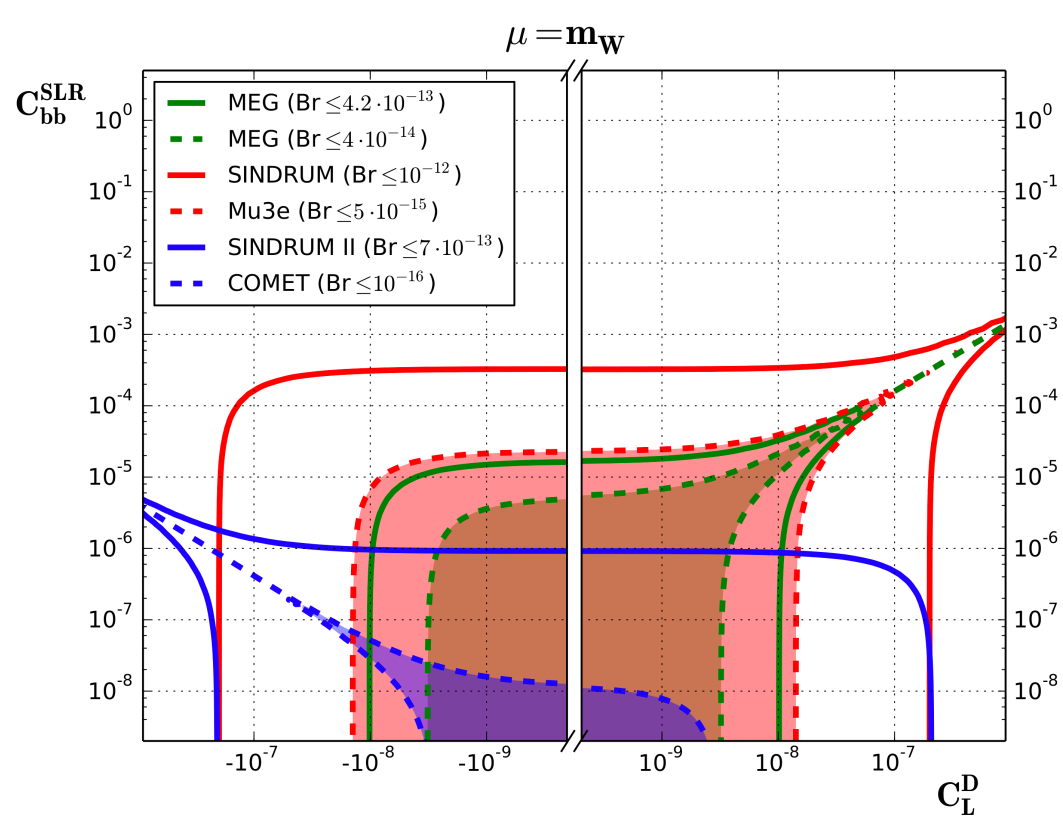
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

$$C_T^{(1)} = -\frac{v}{\sqrt{2}}\left(C_{e\gamma}\left(1 + e^2 c_{e\gamma}^{(1)}\right) + \sum_{i\neq e\gamma} e^2 c_i^{(1)}\, C_i\right)$$

Interplay of cLFV processes at EWSB

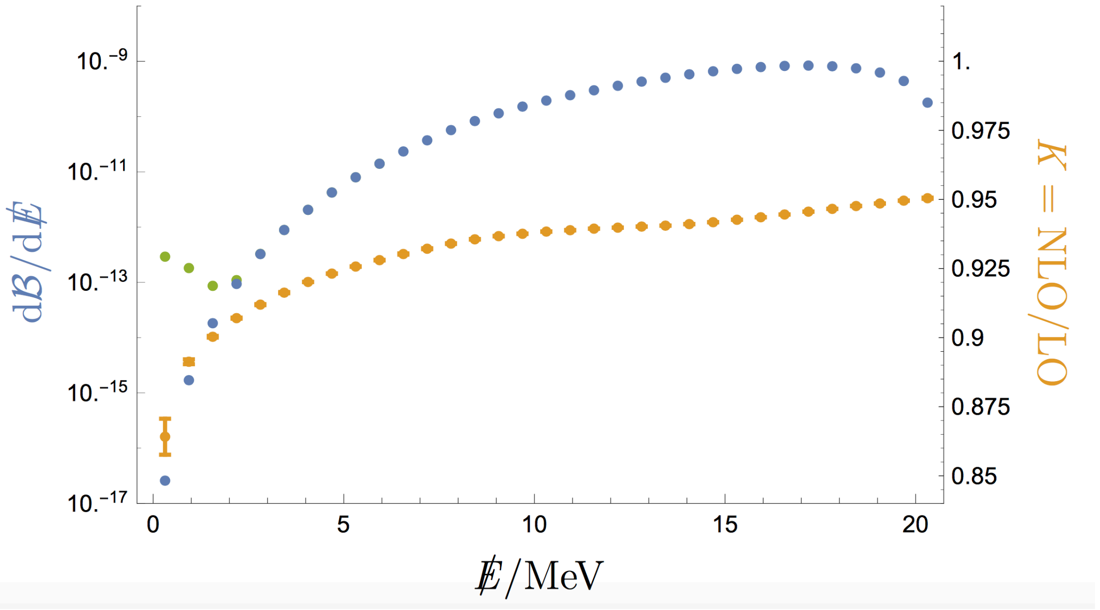






Th: Rare and radiative lepton decay at NLO

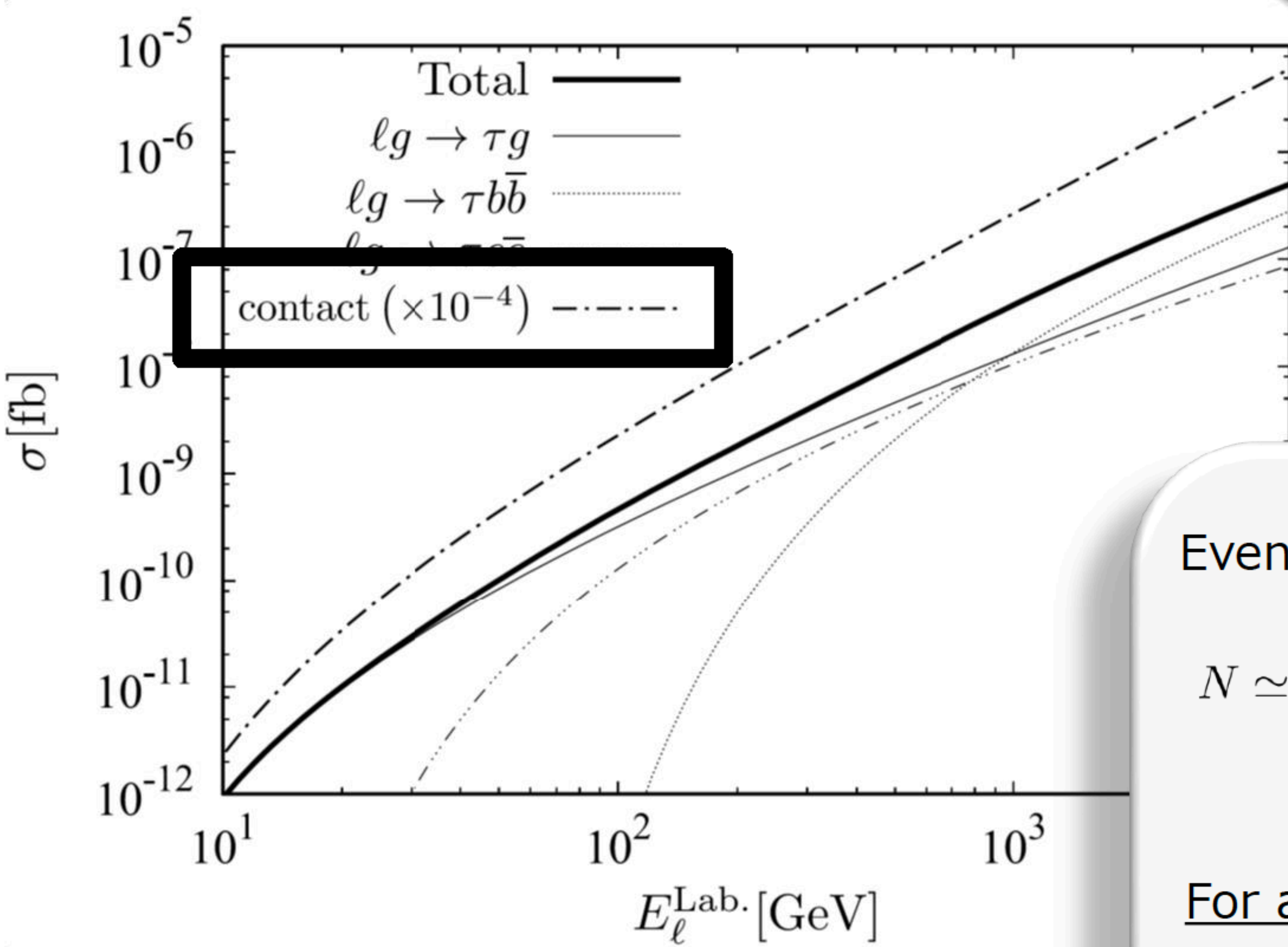
- Fully differential NLO prediction are available for both $\ell \to l\nu\bar{\nu} + \gamma$ and $\ell \to l\nu\bar{\nu} + l^+ l^-$
- Arbitrary cuts and arbitrary distributions are possible
- Radiative corrections can be extremely important when unfolding fiducial acceptance to 'PDG values' (cf. 3.5σ deviation in $\tau \to e\nu\bar{\nu} + \gamma$ @ BaBar)
- MEG & Mu3e: Corrections are negative, normally small (percent level) but can get larger $\mathcal{O}(10\%)$



Higgs mediated CLFV processes

New studies: $\mu N(eN) \to \tau X$ via gluon operators

Cross section vs beam energy for fixed target exp.



Event rate/year (T_m: target mass)

$$N \simeq 6 \times 10^{-16} N_{\ell_i} \left(\frac{\sigma_{\ell_i N \to \tau X}}{1\,\mathrm{fb}}\right)\left(\frac{T_m}{1\,\mathrm{g\,cm^{-2}}}\right)$$

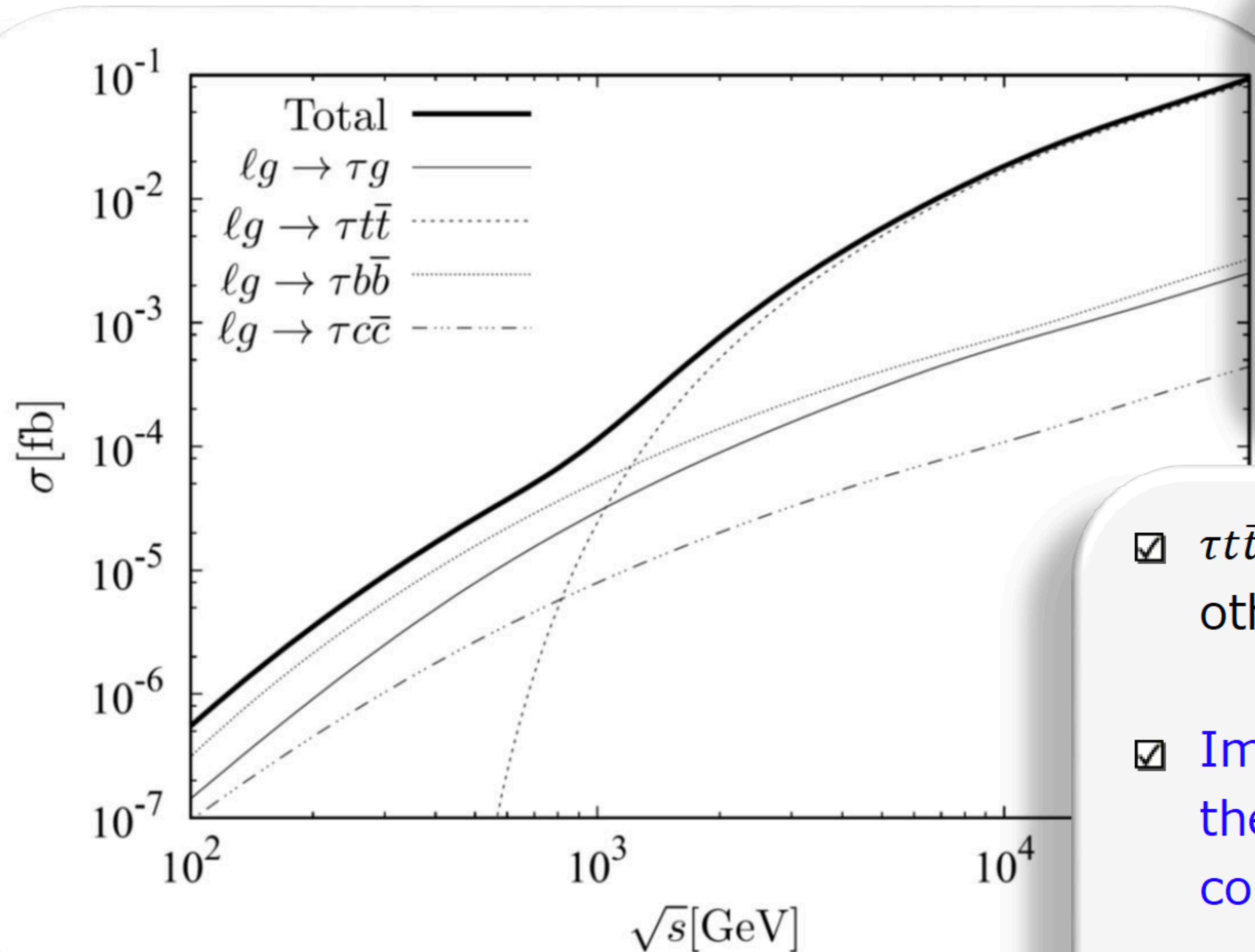
<u>For a mediator interacting with gluon</u>

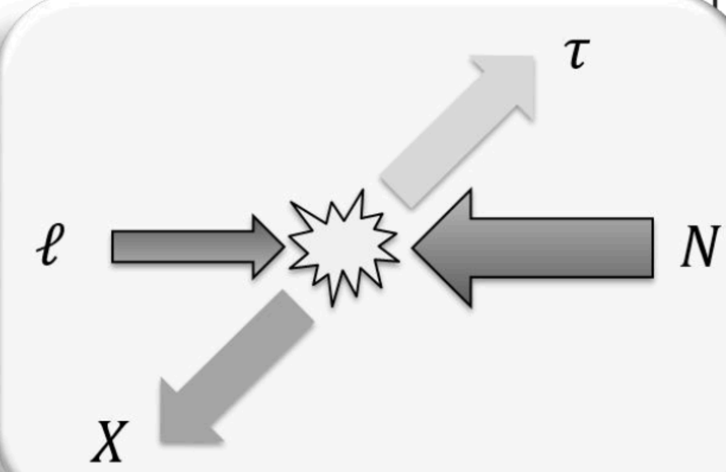
$O(10^5)$ event@ILC ($N_e \simeq 10^{22}$/year)

$O(10^4)$ event@ν factory ($N_\mu \simeq 10^{20}$/year)

New studies: Higgs mediated CLFV processes $\mu N(eN) \to \tau X$ via gluon operators

Cross section vs collision energy for collider exp.





- ☑ $\tau t\bar{t}$ channel dominates over others for $\sqrt{s} \gtrsim 1\ \mathrm{TeV}$
- ☑ Important to correctly calculate the cross section with q-number conservation
- ☑ Assuming $O(1000)\ \mathrm{fb}^{-1}/\mathrm{year}$, $O(10)$ event/year@VLHeC

Credits/WG4 speakers

- Ana M. Teixeira
- Robert Bernstein
- Toshiyuki Iwamoto
- Cecilia Voena
- Ann-Kathrin Perrevoort
- MyeongJae Lee
- E. Craig Dukes
- Natsuki Teshima
- Jaroslaw Pasternak
- Dai Tomono
- Antonino Sergi
- Masato Yamanaka
- Barbara Clerbaux
- Geert Jan Besjes
- Preema Renee Pais
- Jenny Holzbauer
- Katsuhiko Ishida
- Dmitri Liventsev
- Xiaoshen Kang
- Shun Seo
- Toya Tanaka
- Sohtaro Kanda
- Paride Paradisi
- Yannick Ulrich
- Marco Pruna
- Joe Sato
- Andreas Knecht
- Ivana Belosevic