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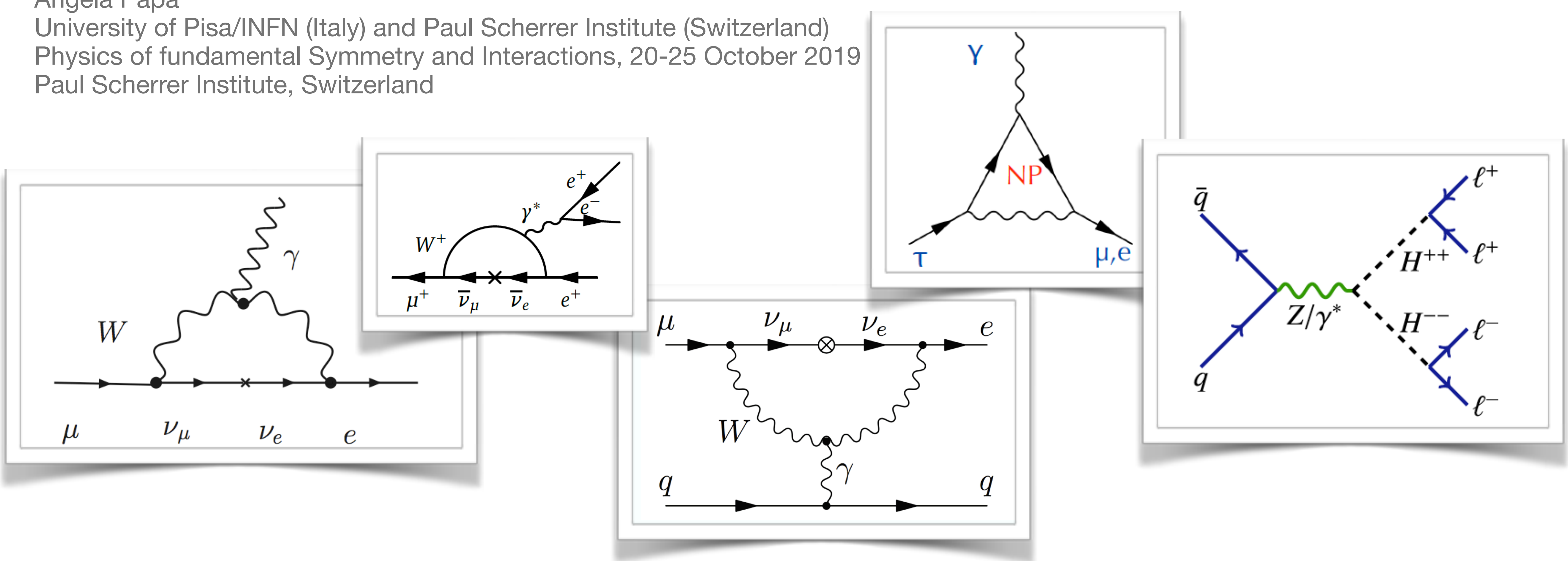
Overview of worldwide efforts in the search for charged lepton flavour violation (with special emphasis on muon based searches)

Angela Papa
University of Pisa/INFN (Italy) and Paul Scherrer Institute (Switzerland)
Physics of fundamental Symmetry and Interactions, 20-25 October 2019
Paul Scherrer Institute, Switzerland

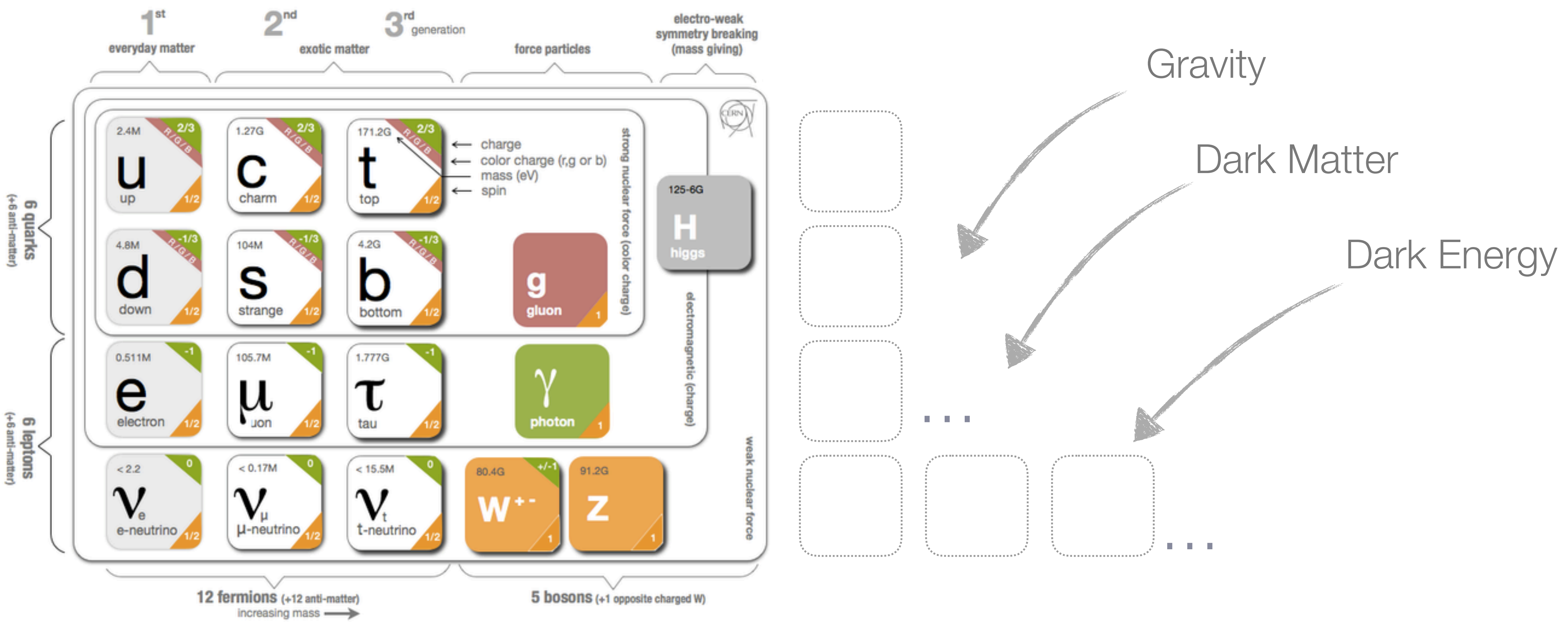


Content

- Introduction:
  - Charged Lepton flavour motivation
  - The role of low energy physics, precision measurements and its complementary counter part at high energy colliders
- Overview of current experimental activities based muon-beams, B-Factories, hadron productions and LHC experiments
  - MEGII @PSI, Mu3e @PSI, Mu2e @Fermilab, COMET @JPARC
  - BelleII@SuperKEKB (ref. CLEO, BABAR and BELLE)
  - BESIII@BEPCII
  - LHCb, ATLAS, CMS and NA62 @ CERN

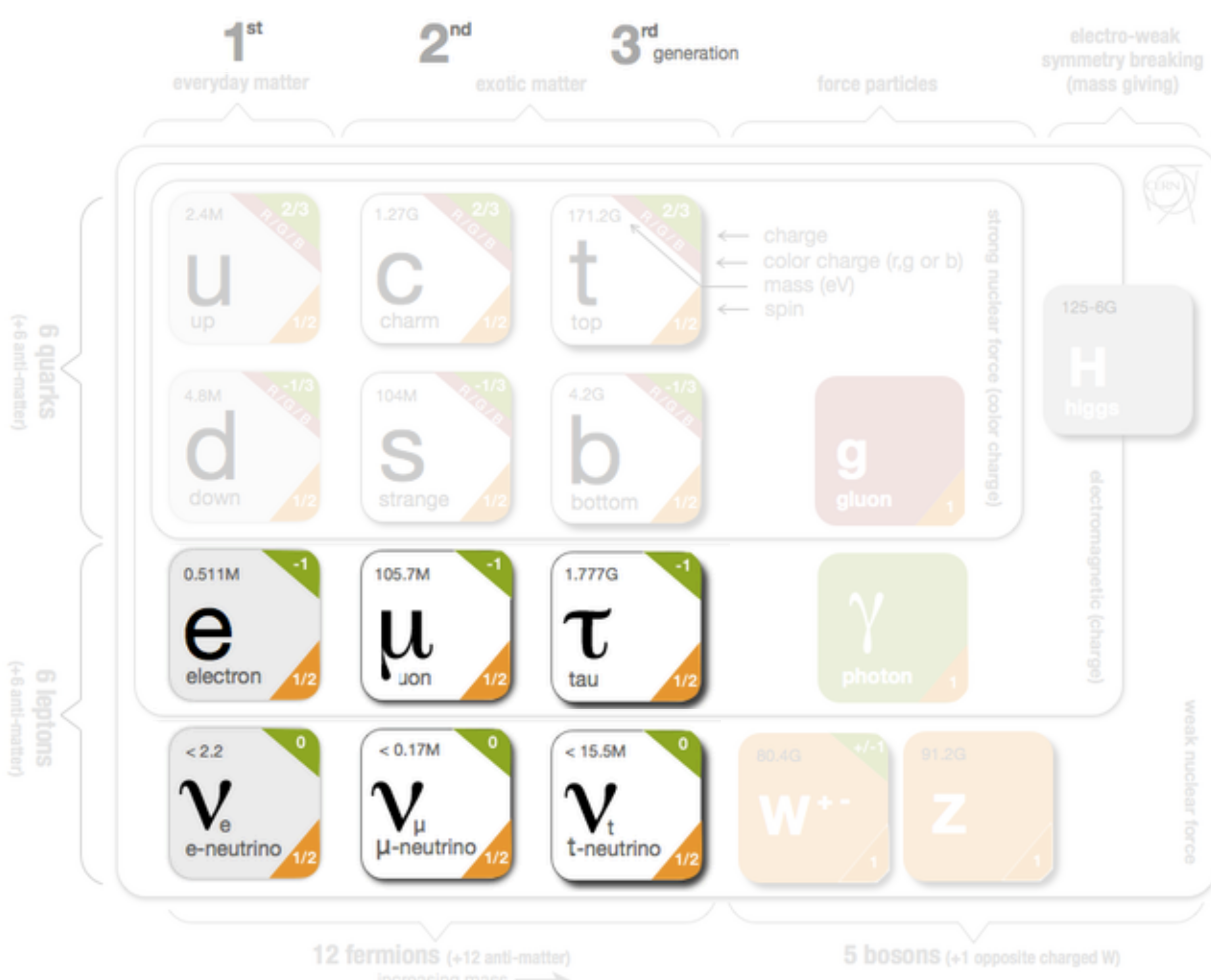
The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



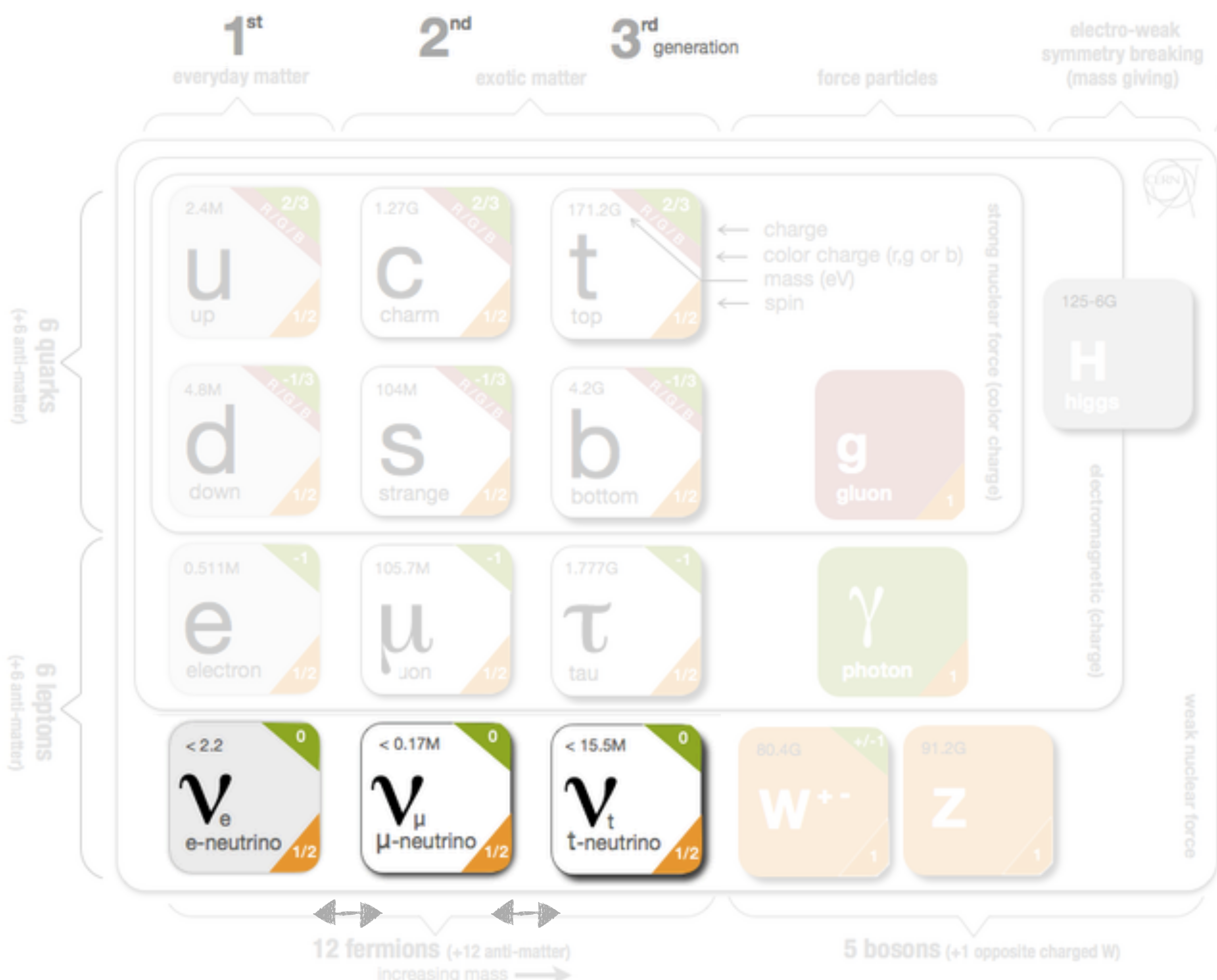
- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

Charged lepton flavour violation



Charged lepton flavour violation

- Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)
  Neutral lepton flavour violation



$\Delta N_i \neq 0$ with i = 1,2,3

Charged lepton flavour violation

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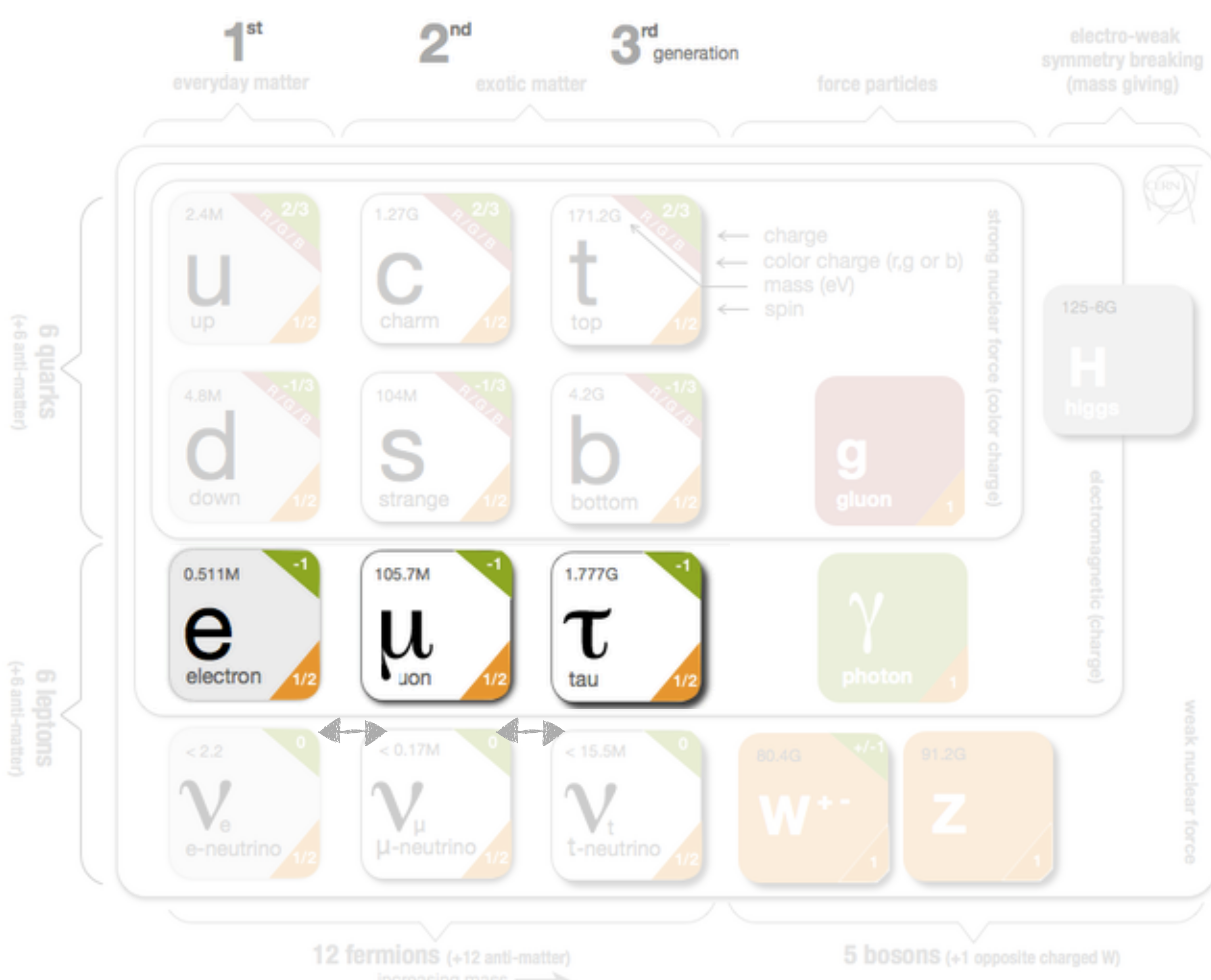
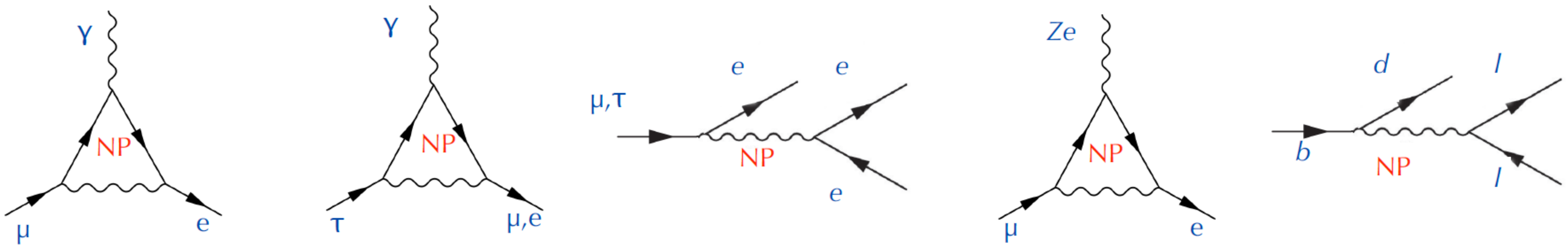


$\Delta N_i \neq 0$ with i = 1,2,3

- Charged lepton flavour violation: NOT yet observed

cLFV searches: Many channels



- A wide field of research
    - LVF decays of leptons
    - Muon-to-electron conversion
    - LVF in meson decays

cLFV search landscape

Rough estimate of numbers of researchers, in total ~ 850 (with some overlap)

Muons ~ 250

- MEG, PSI
- MEGII, PSI
- Mu3e, PSI
- DeeMee, J-PARC
- MuSiC, Osaka
- Mu2e, FNAL
- COMET, J-PARC
- PROJECT X, FNAL
- PRIME, J-PARC

Kaons ~ 100

- NA48,CERN
- NA62,CERN
- KOTO, J-PARC

Taus ~ 250

- BABAR, PEPII
- BELLE/BELLE II, KEKB/SuperKEKB

cLFV @ LHC ~ 250

- ATLAS,CERN
- CMS,CERN
- LHCb, CERN

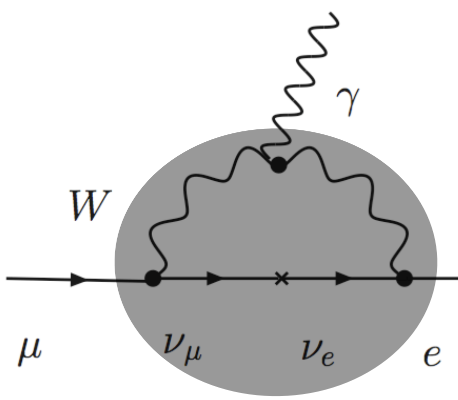
J/ψ @ BEPCII ~ 100

- BESIII, Beijing

Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

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

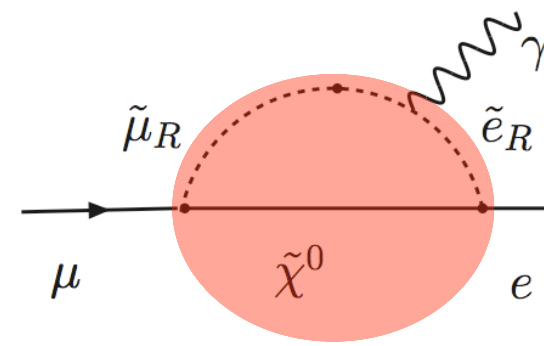


ν oscillations

too small to access experimentally

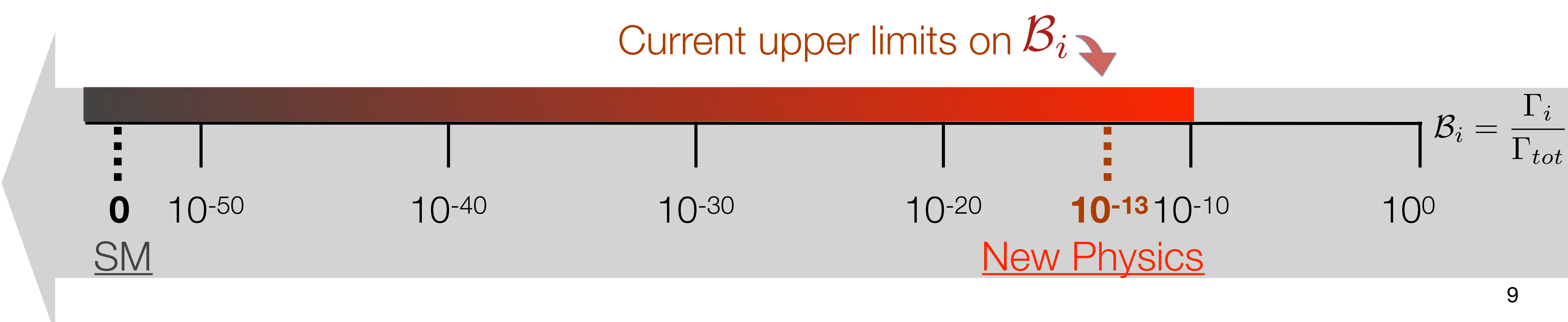
BSM

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

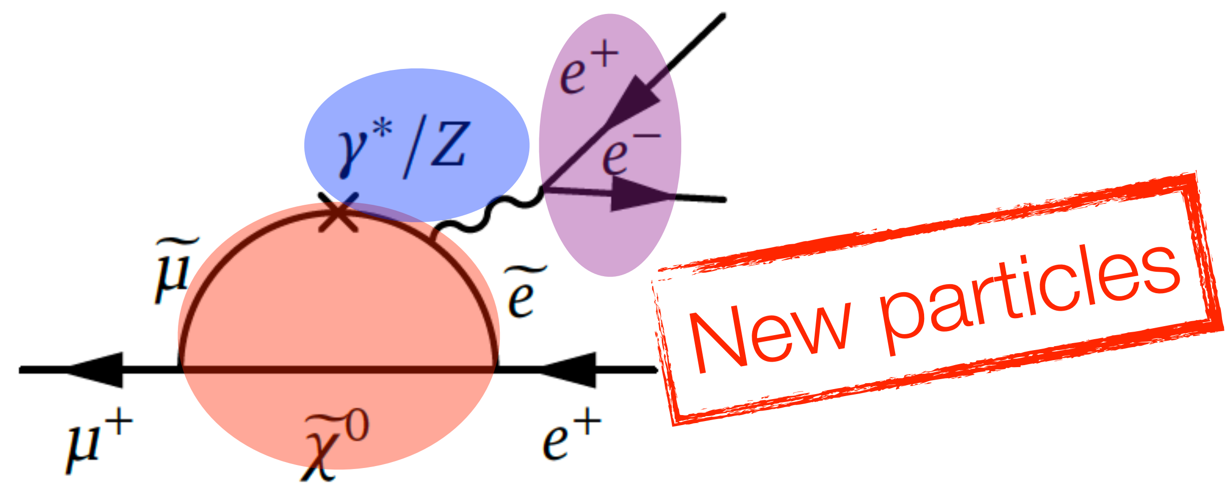


New particles

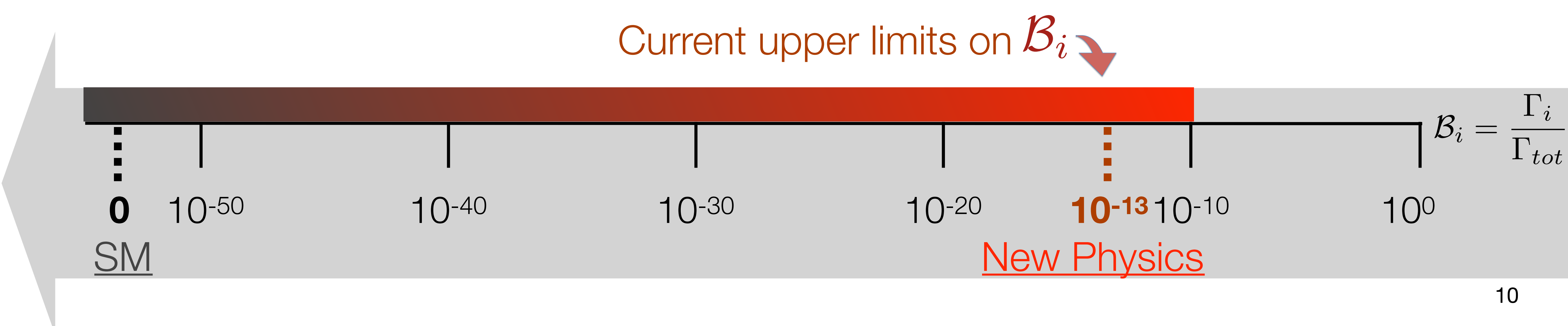
an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)



Charged lepton flavour violation search: Motivation



$$\mu^+ \rightarrow e^+e^+e^-$$



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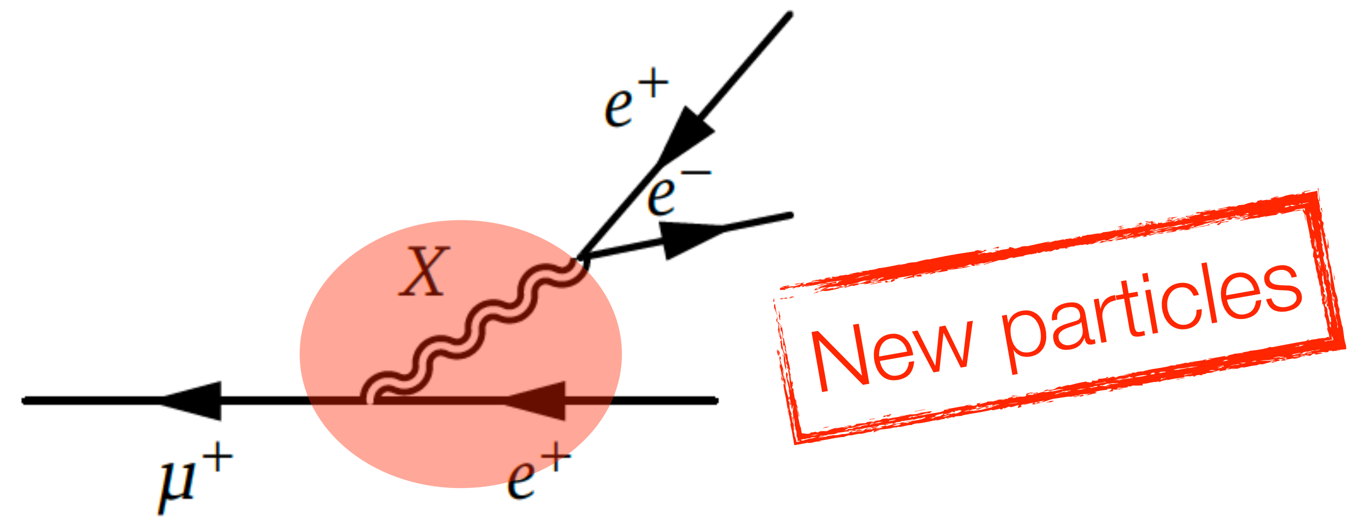

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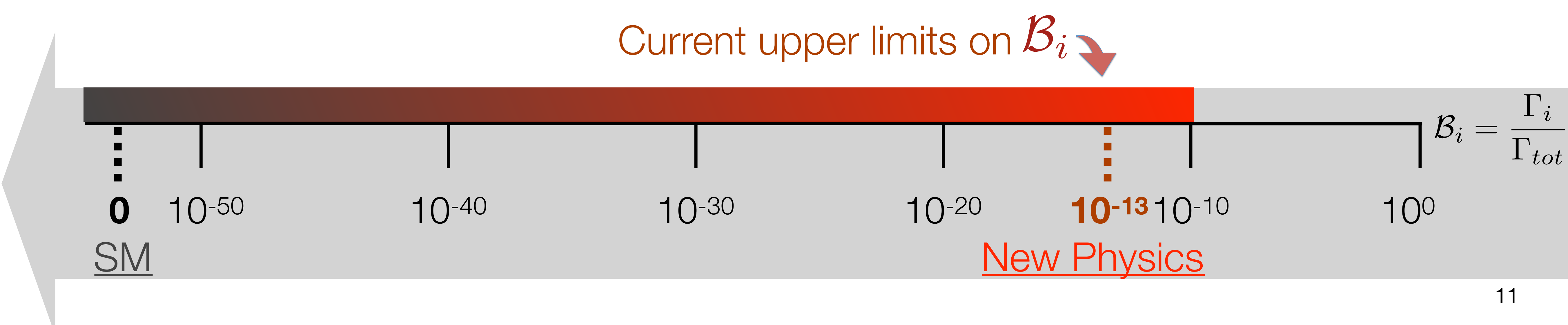
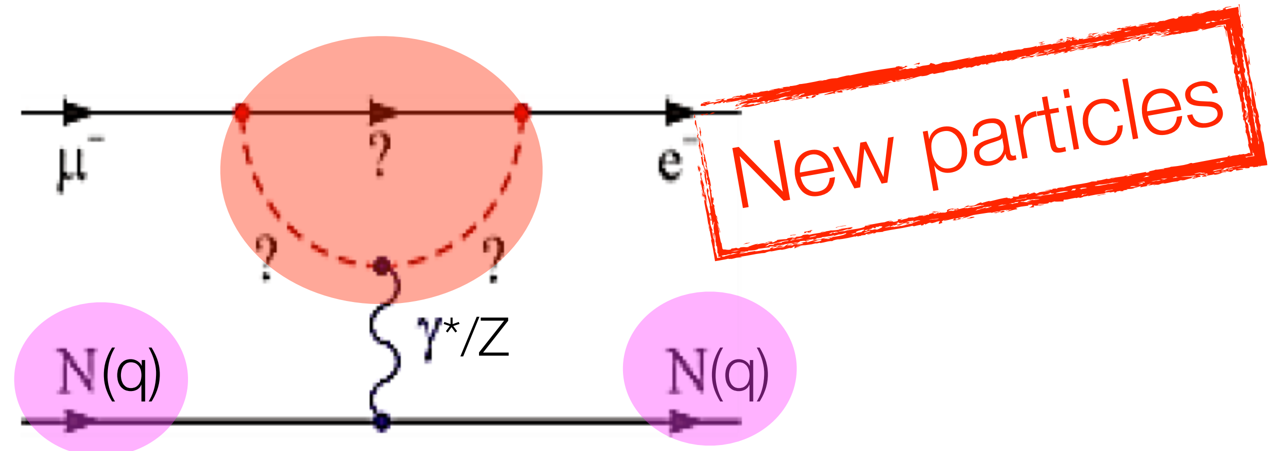
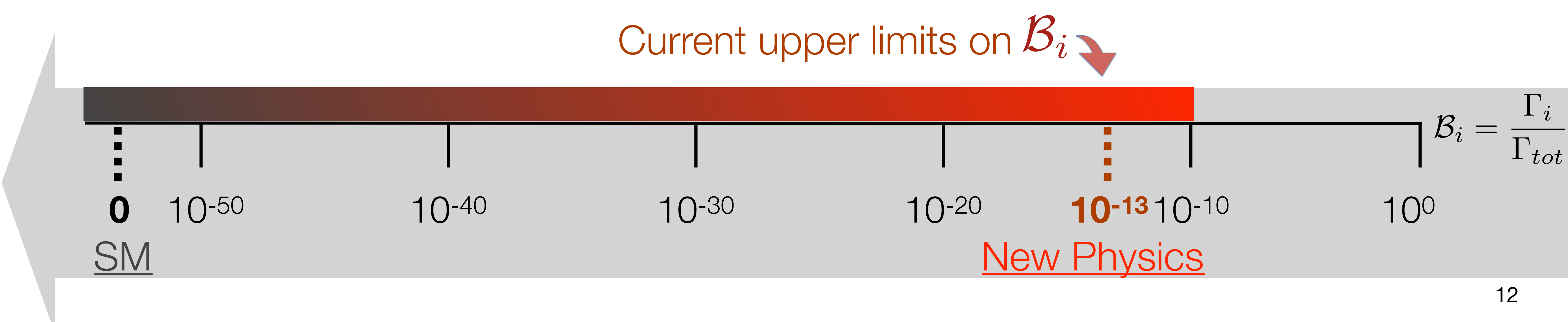


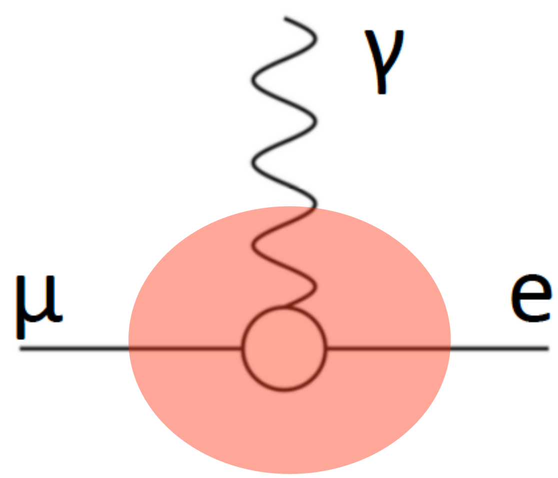
Charged lepton flavour violation search: Motivation

$$\mu^- N \to e^- N$$

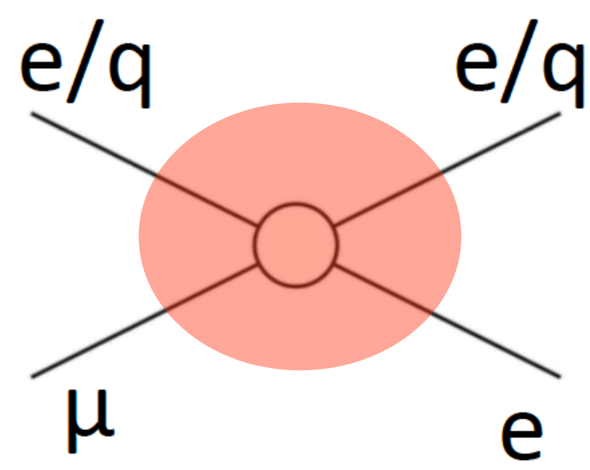




Charged lepton flavour violation search: Motivation

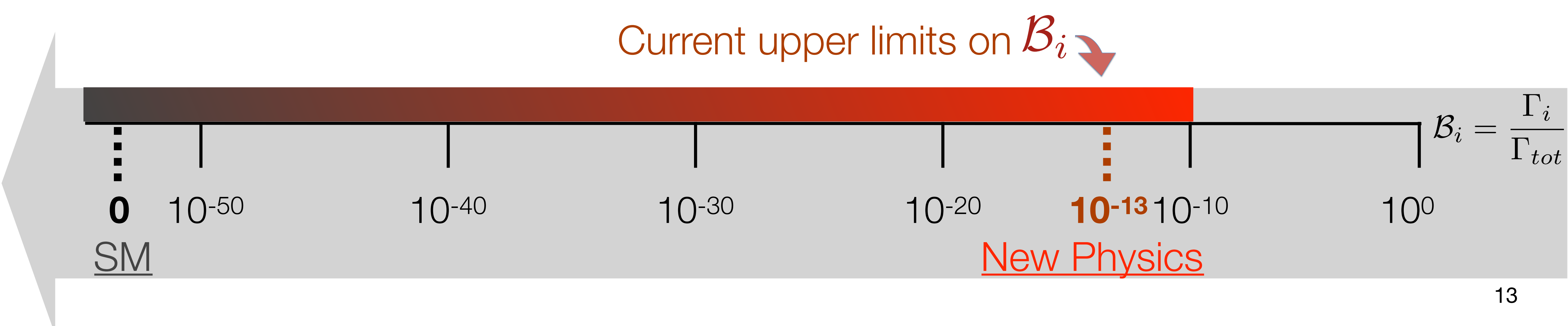


dipole term

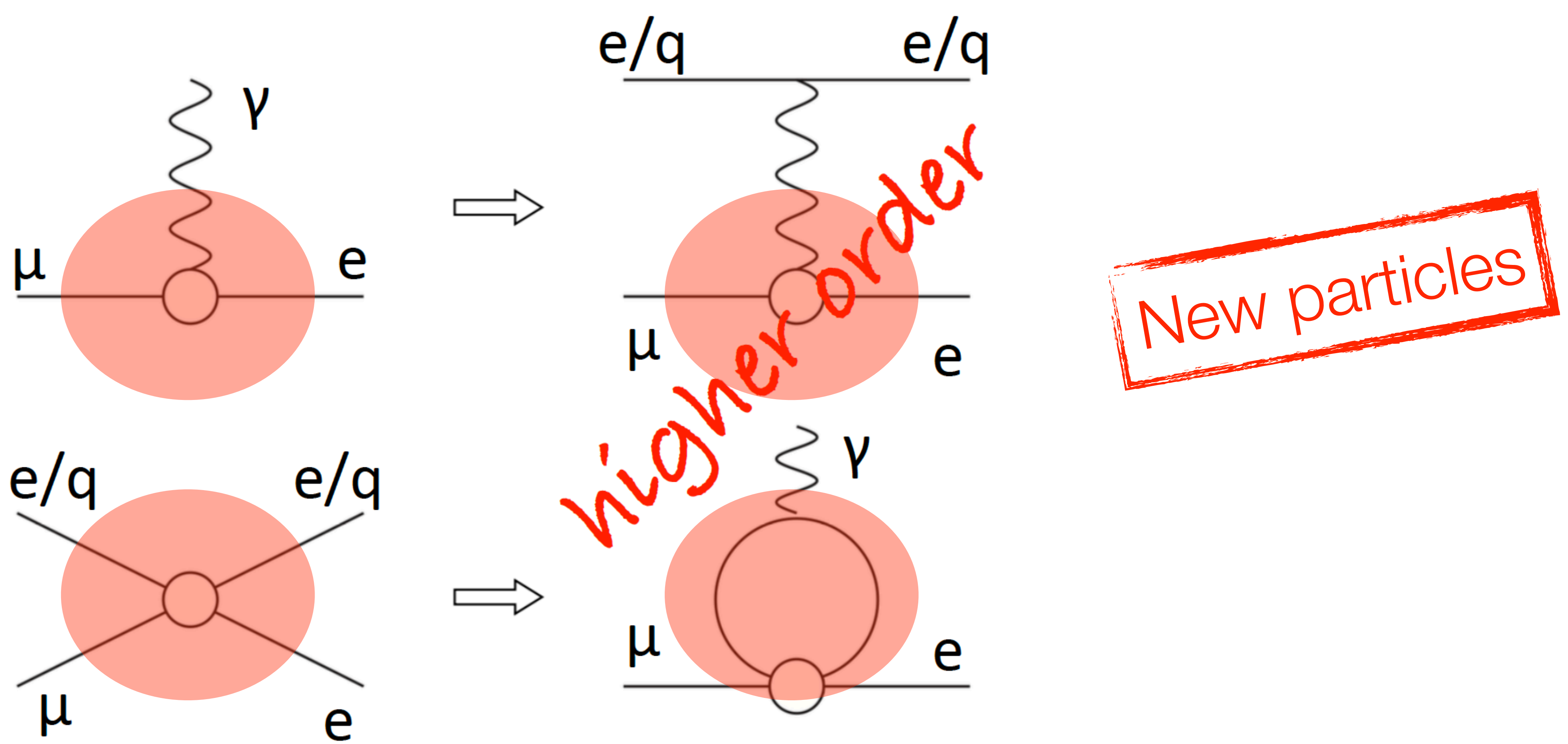


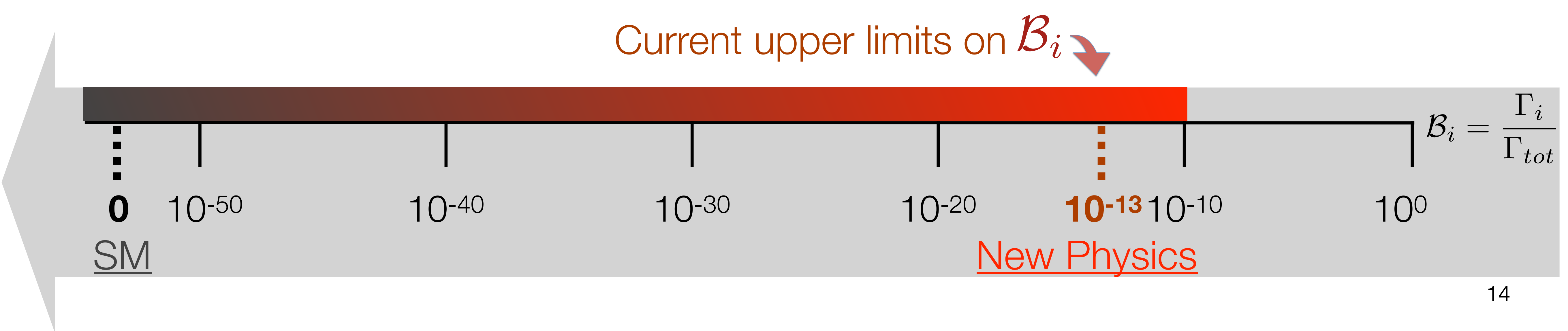
contact term

New particles



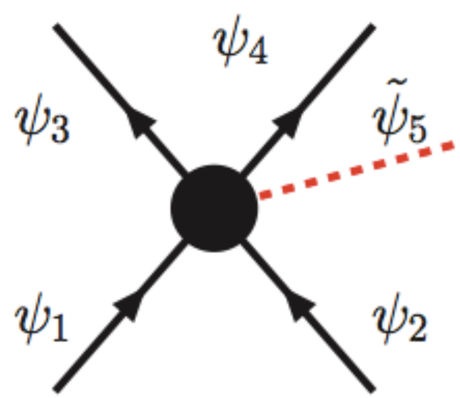
Charged lepton flavour violation search: Motivation





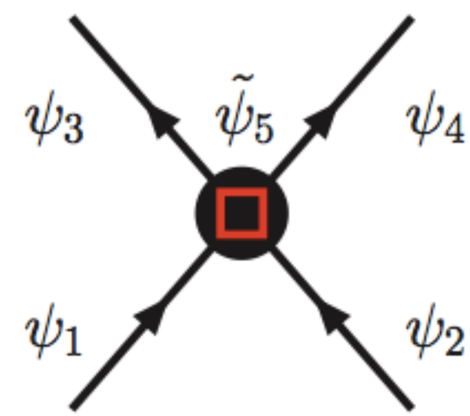
Complementary to “Energy Frontier”

Energy frontier



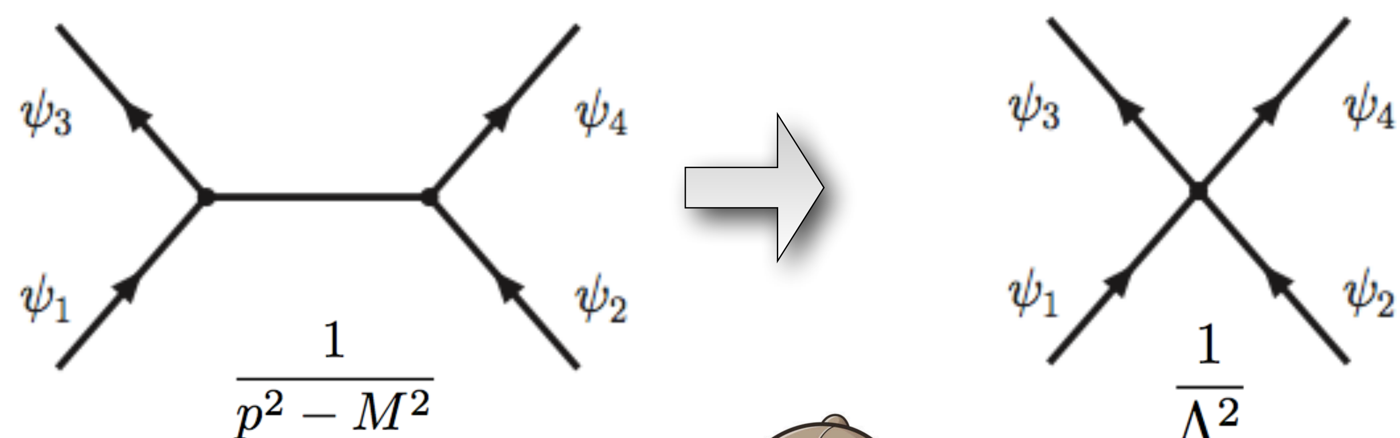
Real BSM particles

Precision and intensity frontier

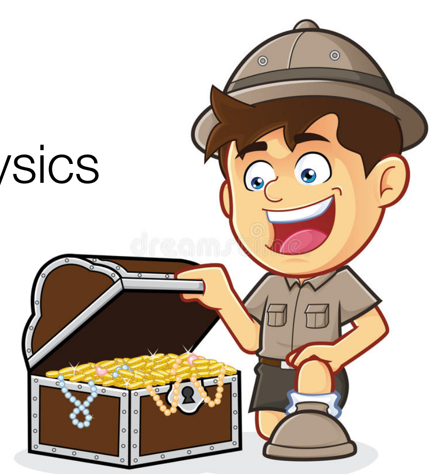


Virtual BSM particles

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



Unveil new physics

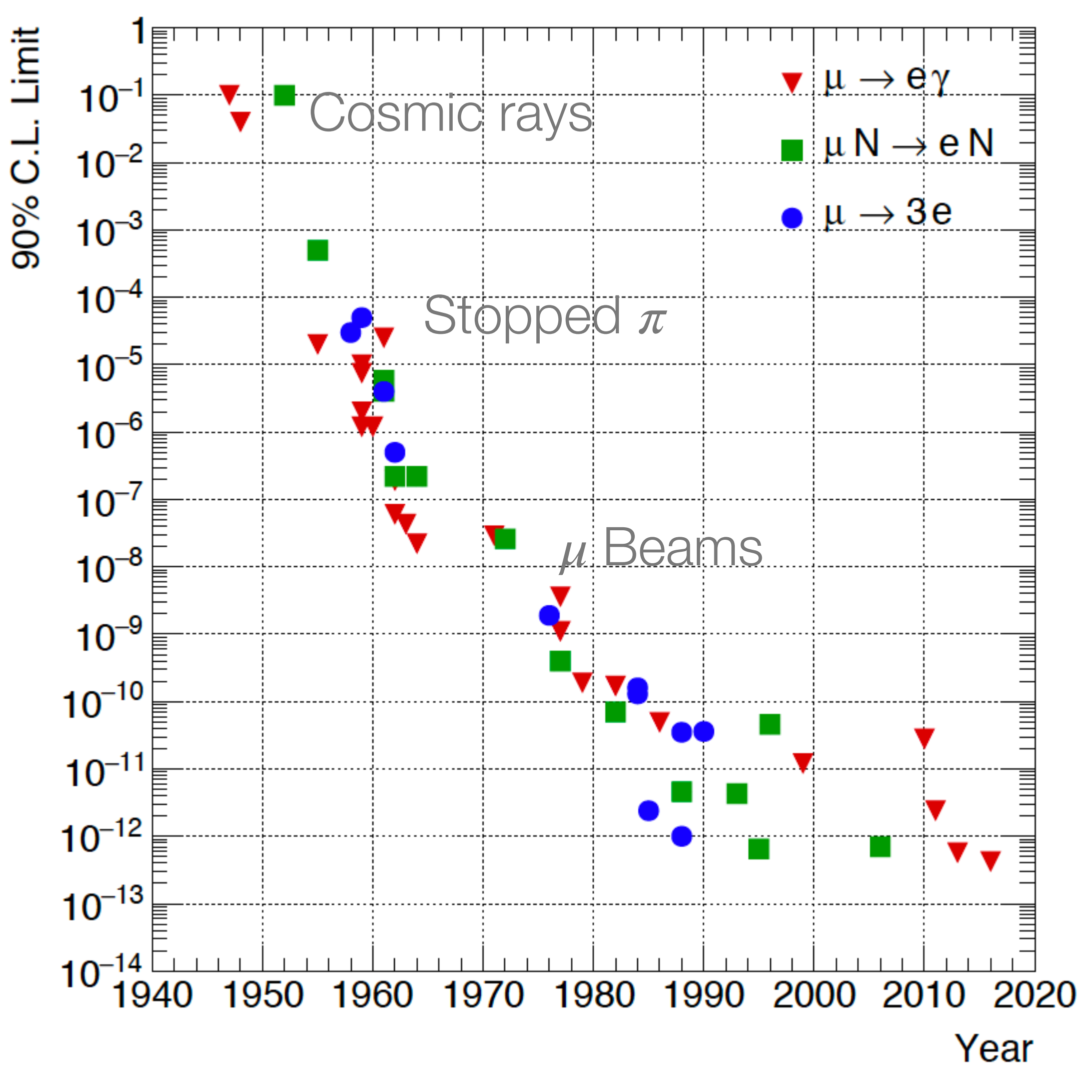


Probe energy scale otherwise unreachable

E > 1000 TeV

cLFV searches with muons: Status and prospects

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	$\sim 4 \times 10^{-14}$
$\mu \to eee$	1.0×10^{-12}	$\sim 1.0 \times 10^{-16}$
$\mu N \to eN'$	7.0×10^{-13}	few $\times 10^{-17}$



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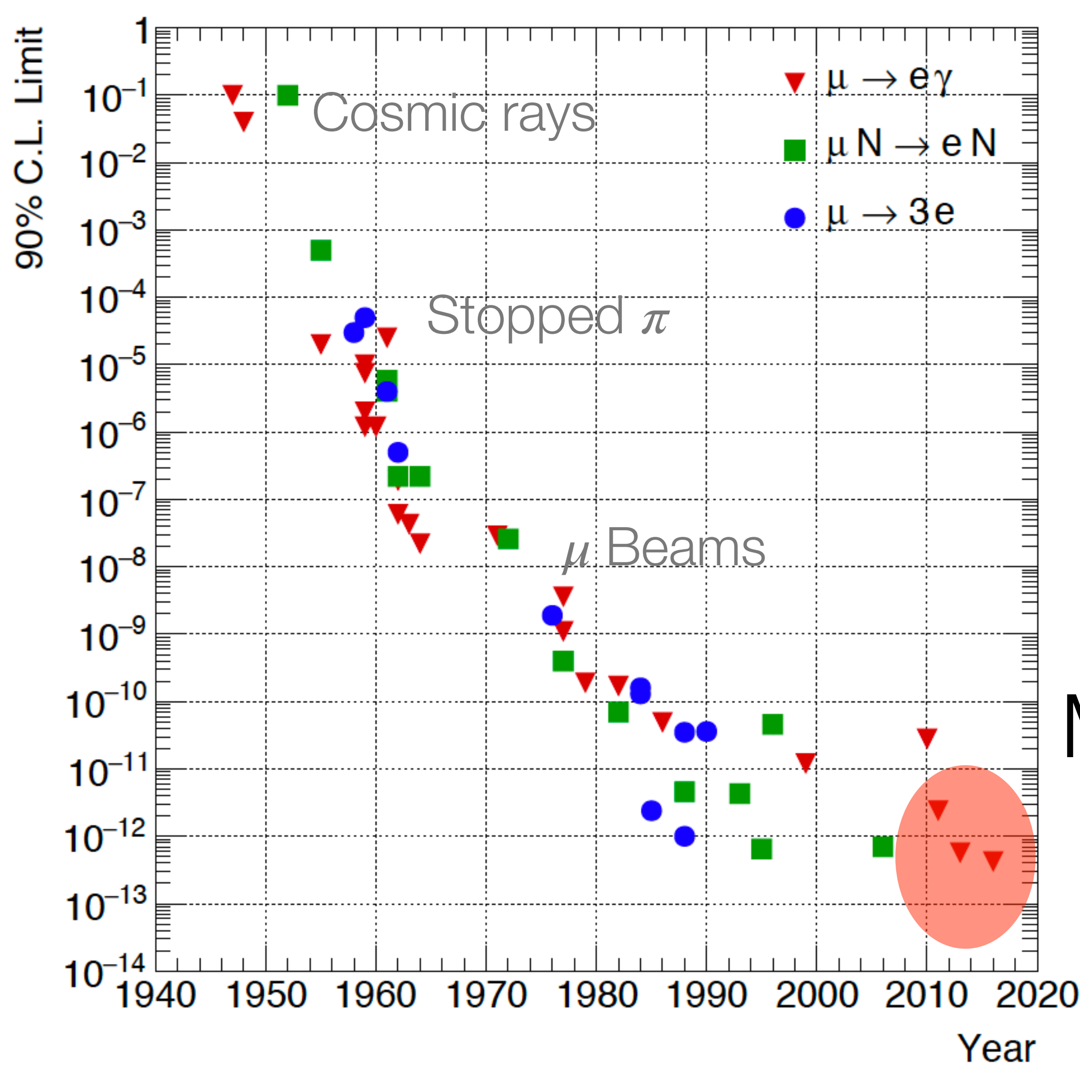

MEG exp

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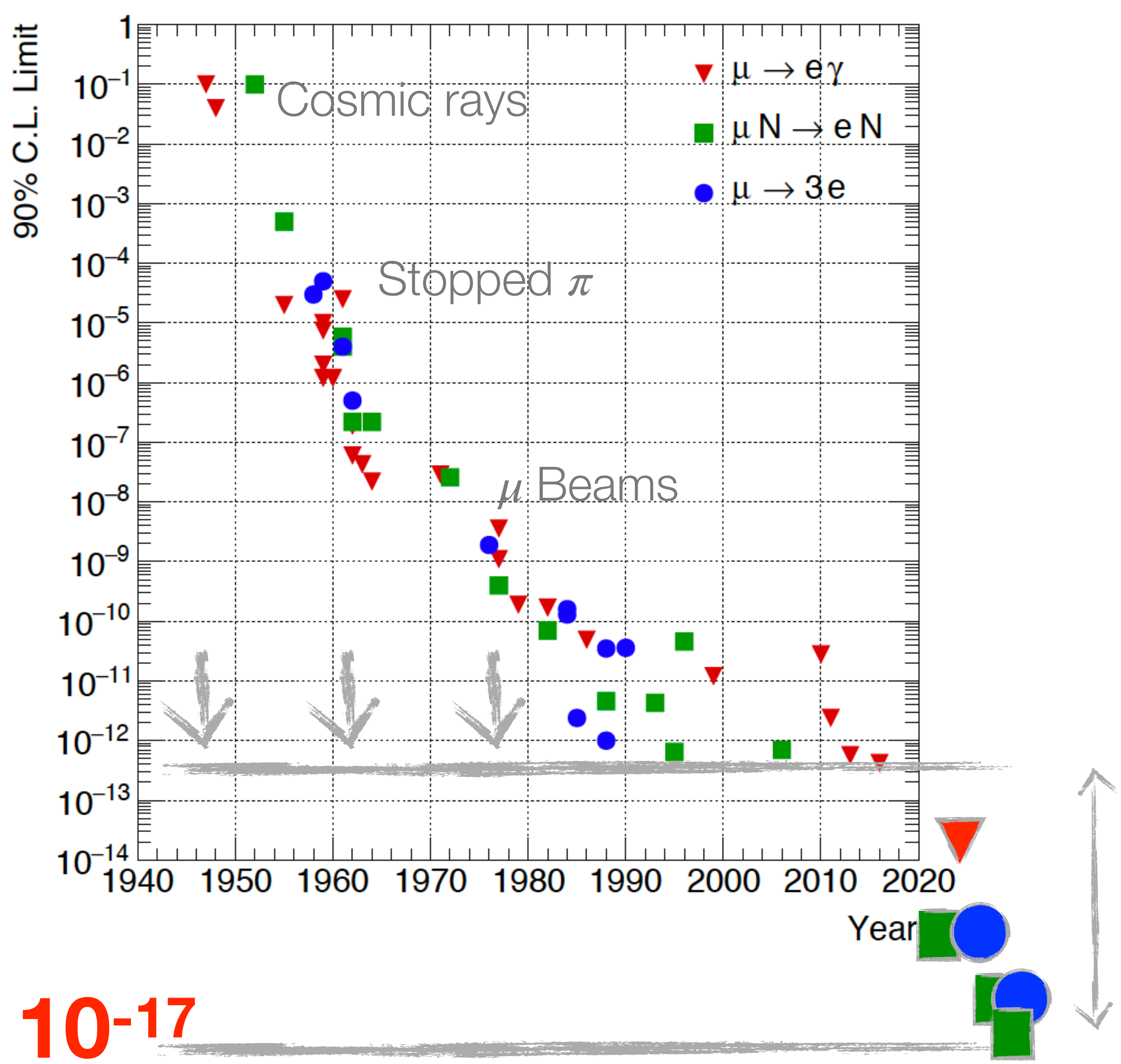

In the near future O(5-10) years: Impressive sensitivity

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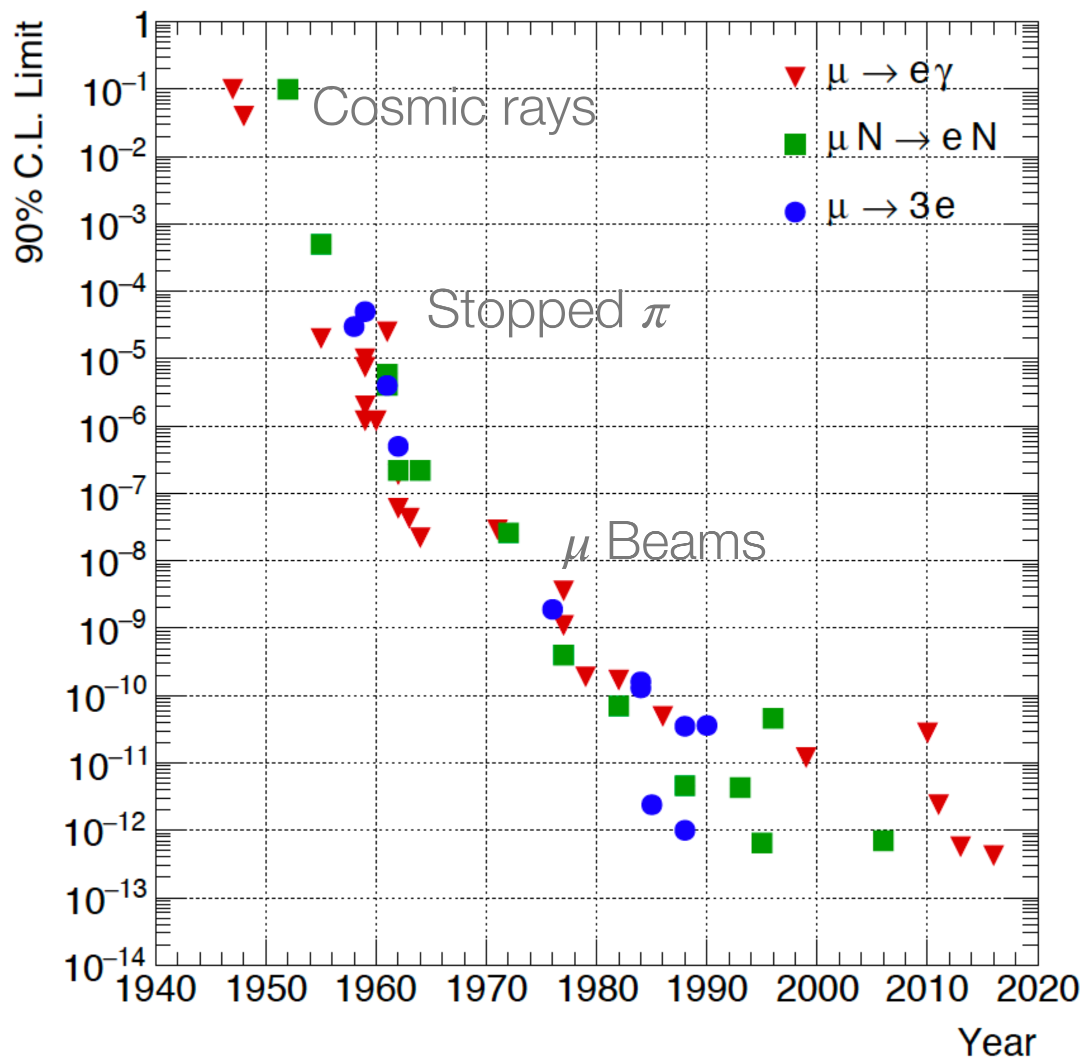
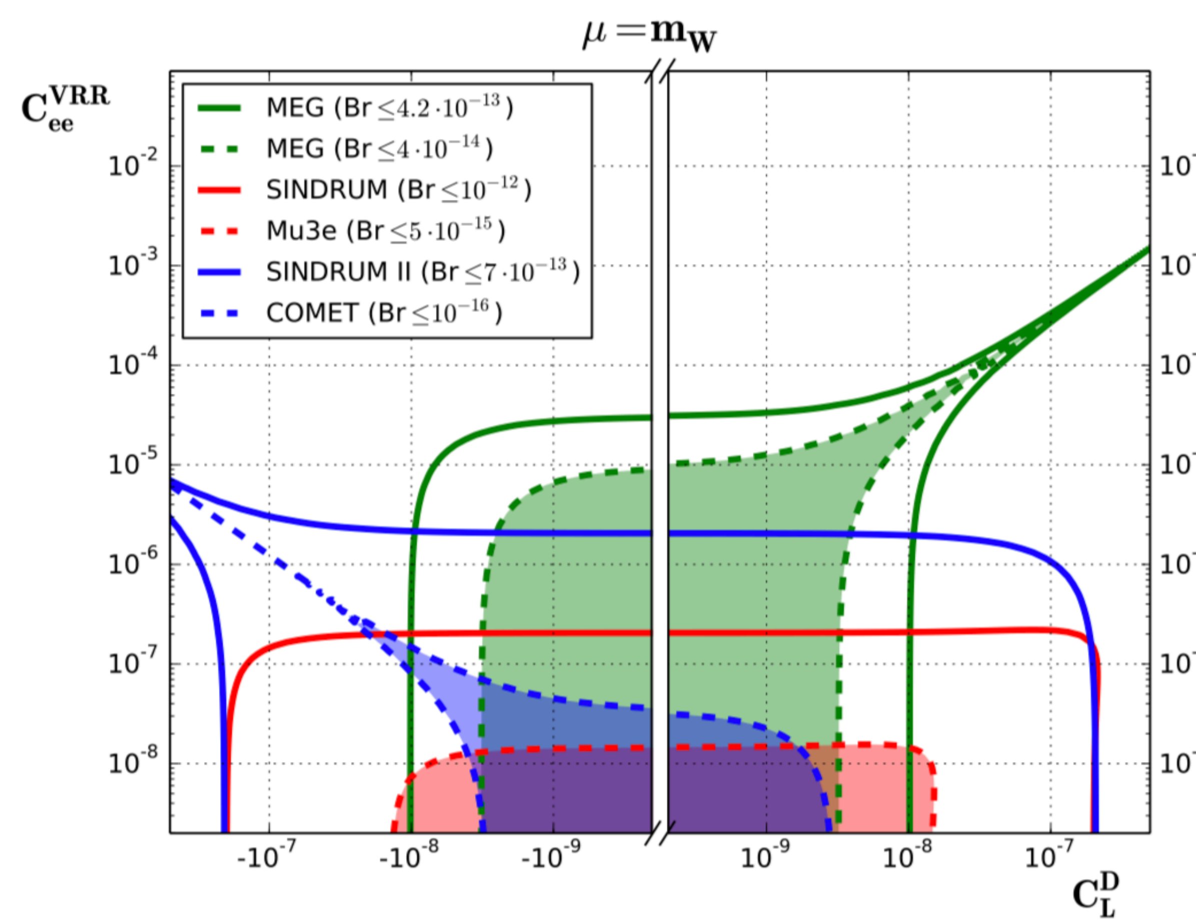


doi:10.1007/JHEP05(2017)117

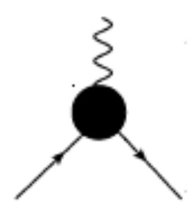
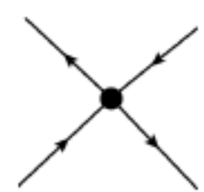


- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV

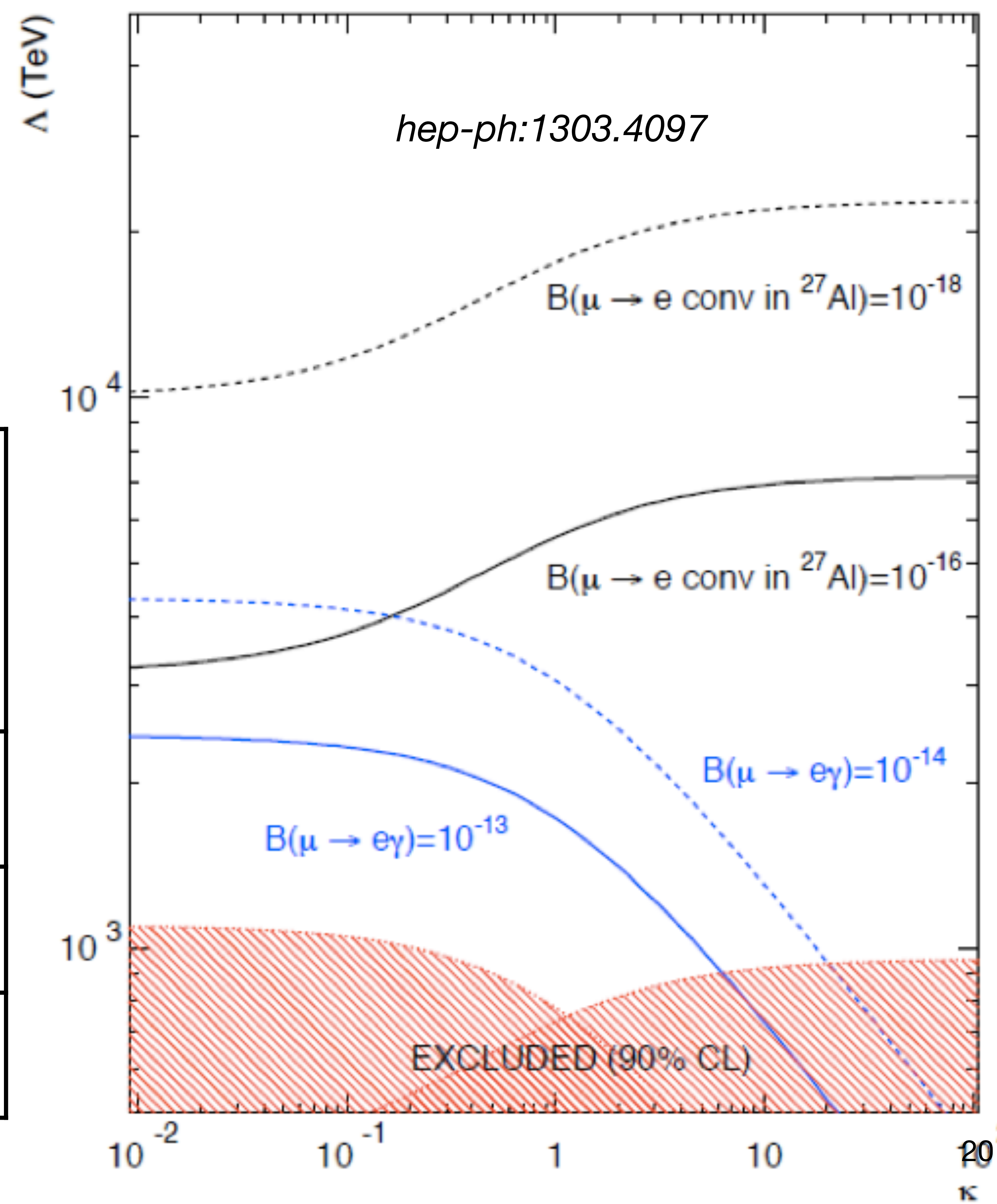
cLFV: “Effective” lagrangian with the k-parameter

- Due to the **extremely-low** accessible **branching ratios**, muon cLFV can strongly **constrain** new physics models and scales

Model independent lagrangian

$$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$$  $$+ \quad \frac{\kappa}{(\kappa+1)\Lambda^2} \times$$ 

dipole term	contact term
$\mu \rightarrow e\gamma$	
$\mu \rightarrow eee$	
$\mu N \rightarrow eN$	



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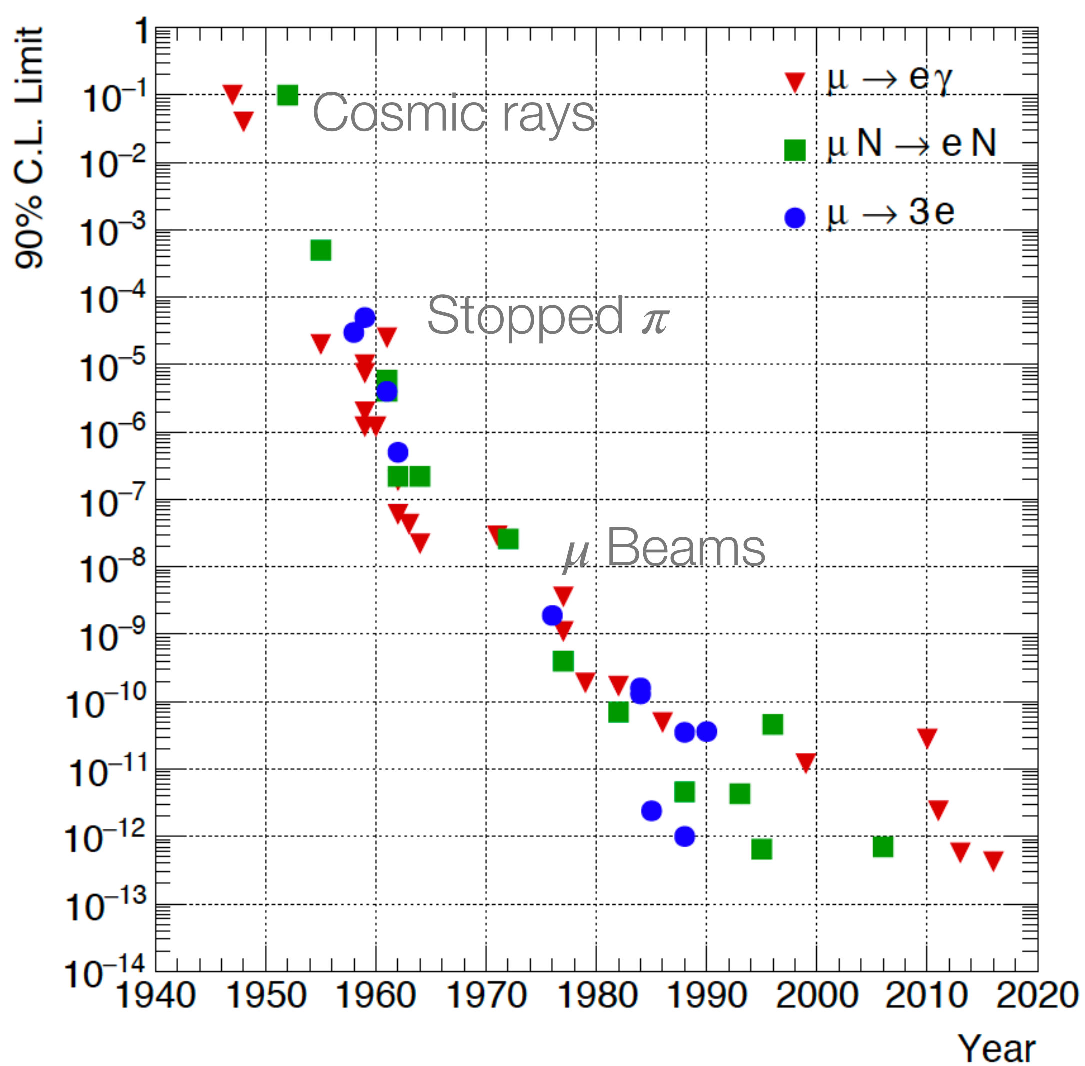

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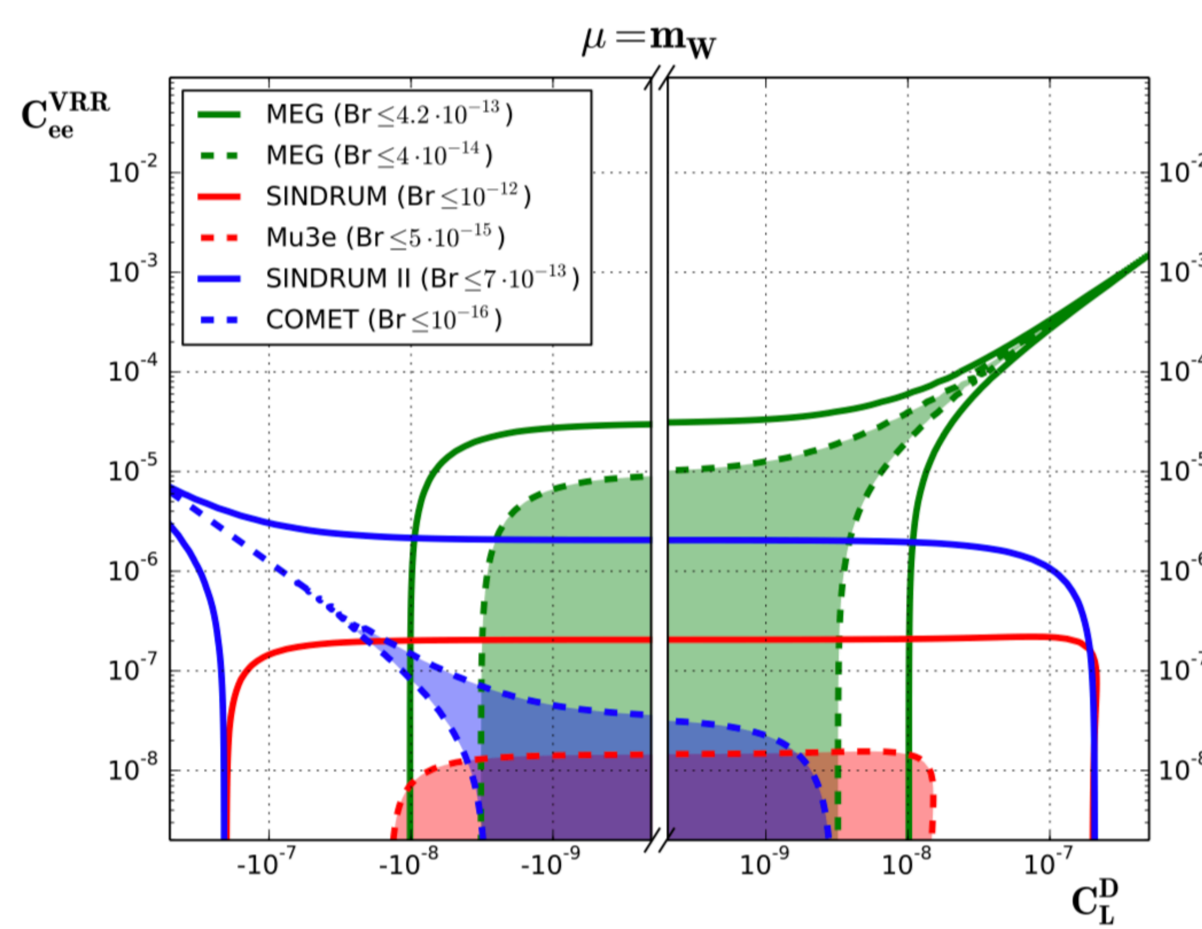


- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV

Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

DC or Pulsed?

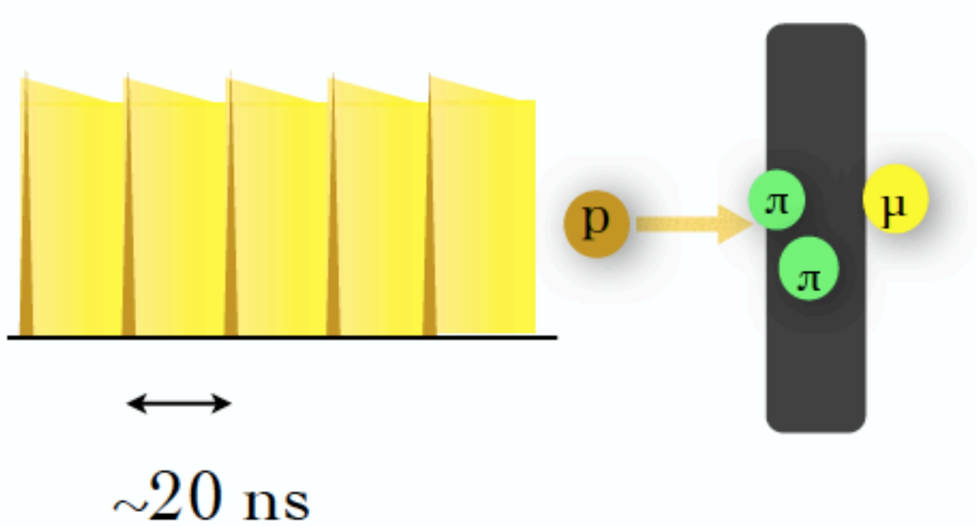
$I_{beam} \sim 10^{8} - 10^{10}\ \mu/s$

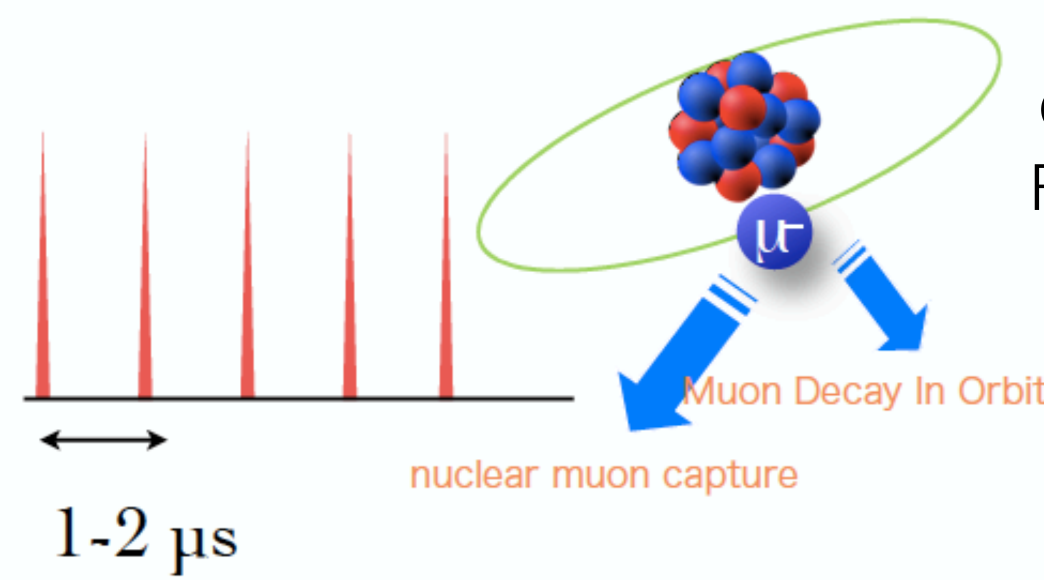
- DC beam for coincidence experiments
  - $\mu \to e\gamma$, $\mu \to e e e$

$I_{beam} \sim 10^{11}\ \mu/s$

- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI





@ JPARC, FERMILAB

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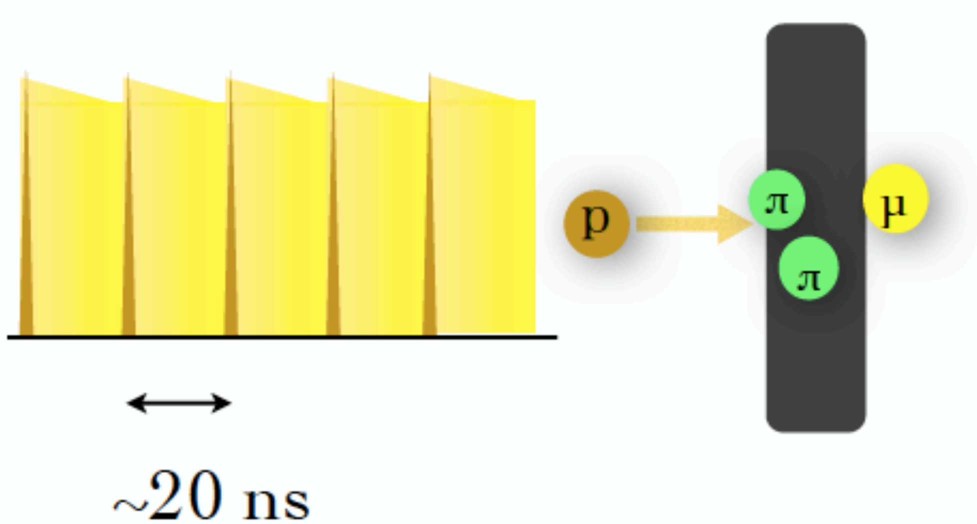
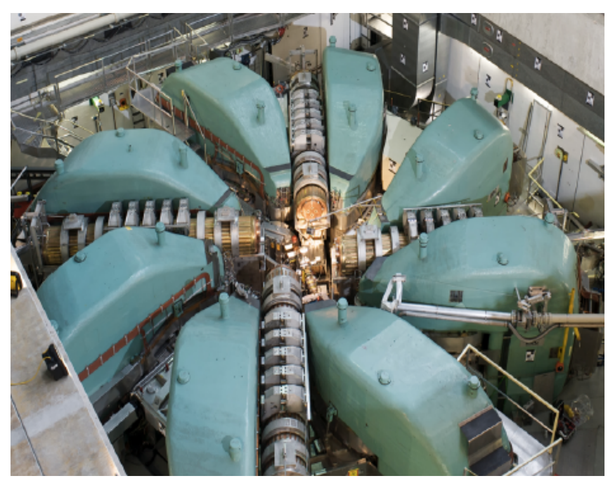


@ JPARC, FERMILAB

The world's most intense continuous muon beam

- τ ideal probe for NP w. r. t. μ
  - Smaller GIM suppression
  - Stronger coupling
  - Many decays
- μ most sensitive probe
  - Huge statistics

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
- MEG/MEG II/Mu3e beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 29 MeV/c
  - Small straggling and good identification of the decay



590 MeV proton
ring cyclotron
1.4 MW

PSI landscape

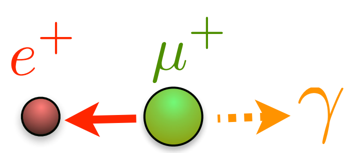
MEG: Signature, experimental setup and result

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

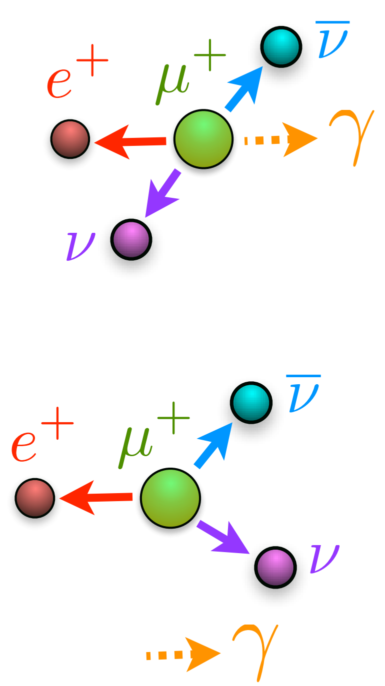
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

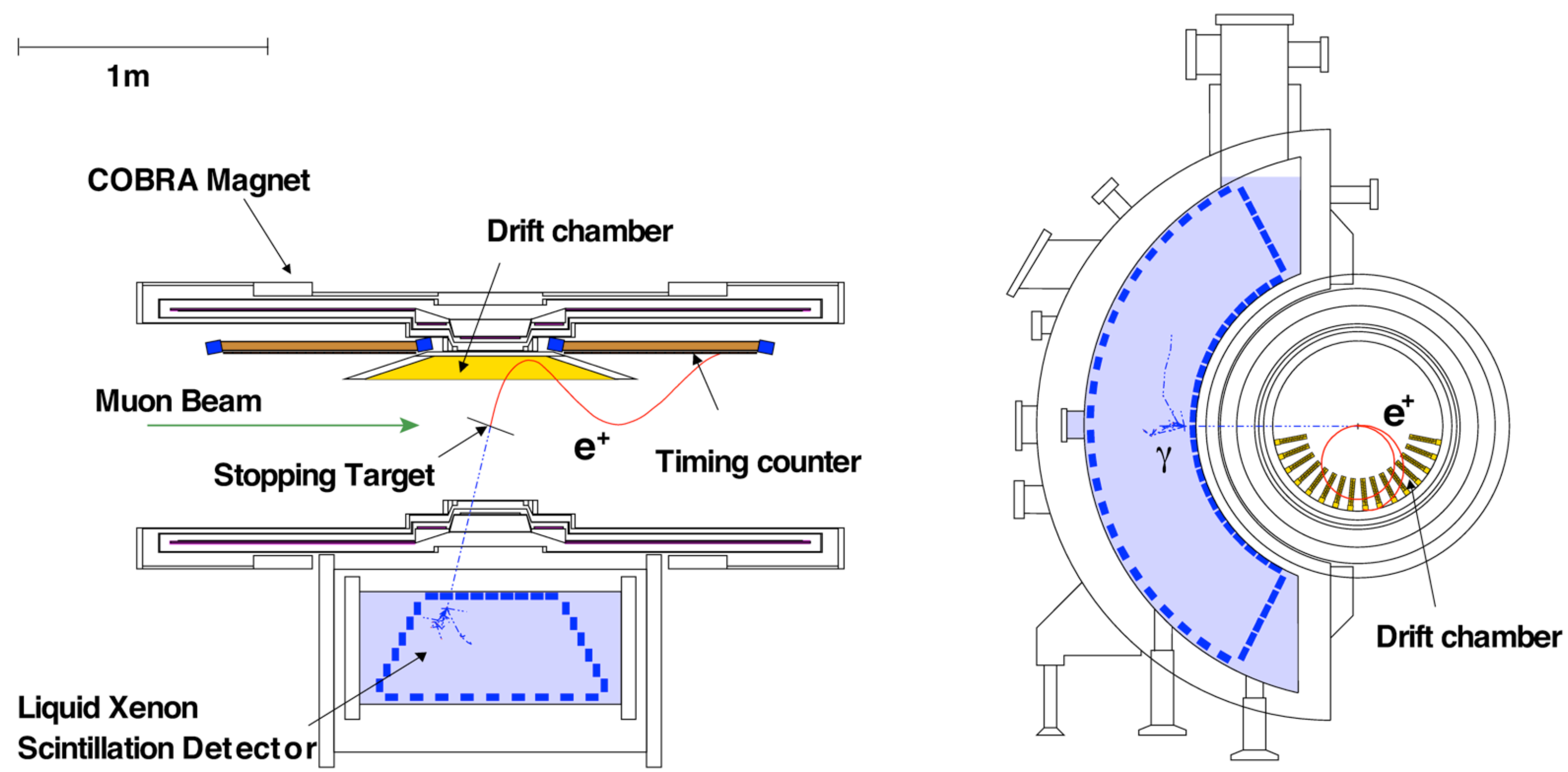
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events

Signature



Backgrounds





Full data sample: 2009-2013

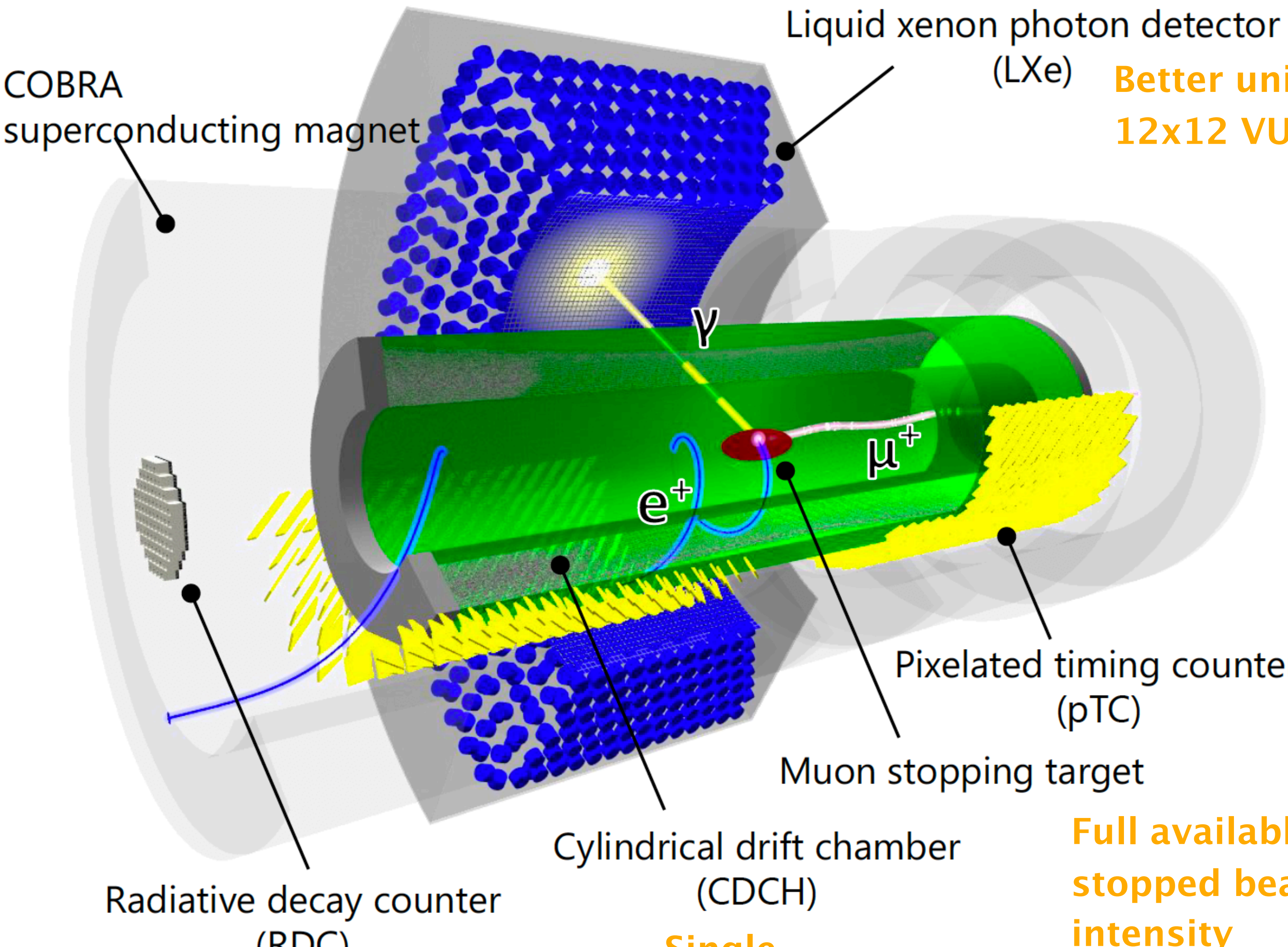
Best fitted branching ratio at 90% C.L.:

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

The MEGII experiment

New electronics:
Wavedream

~9000 channels at 5GSPS



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

x2 Resolution everywhere

35 ps resolution w/ multiple hits

Updated and new Calibration methods

Quasi mono-chromatic positron beam

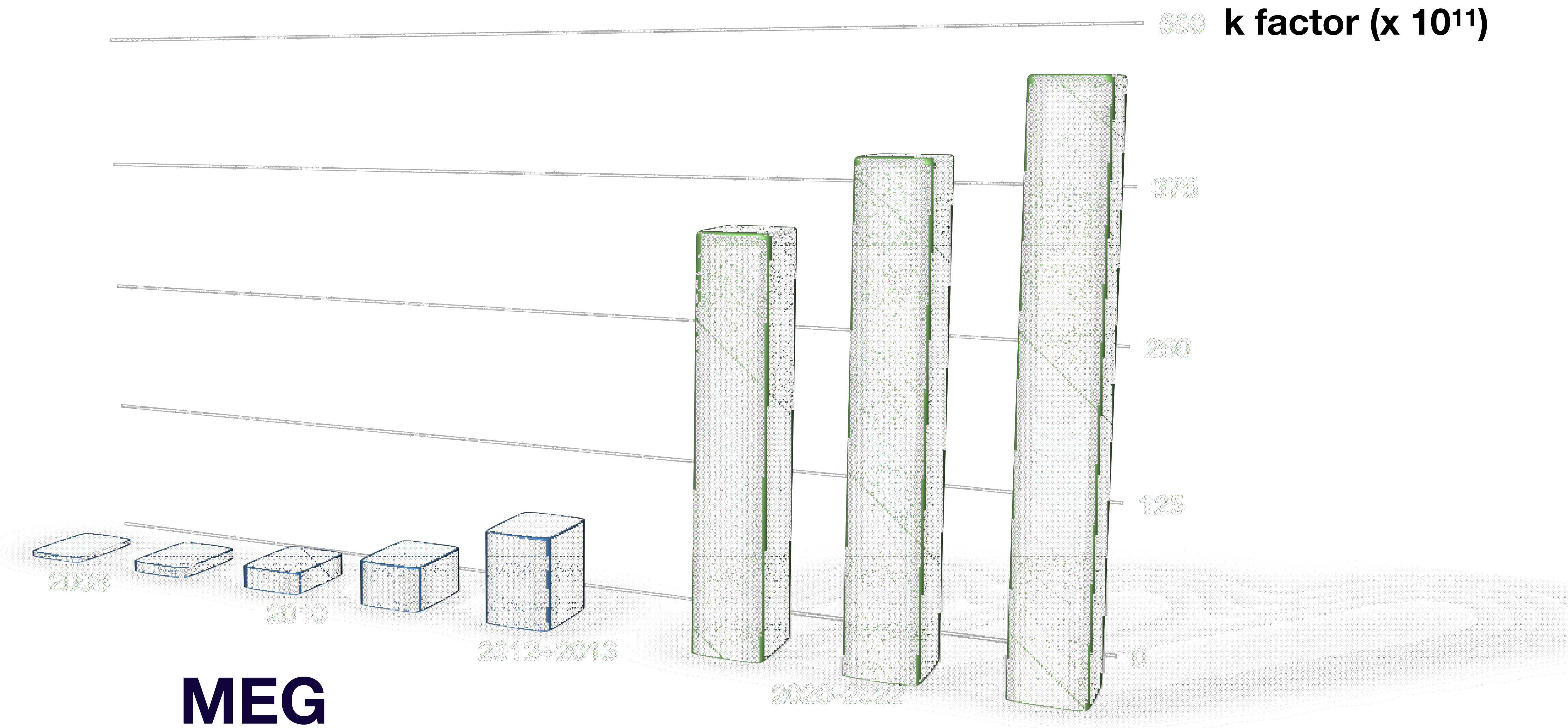
Background rejection

Single volume $He{:}iC_4H_{10}$

Full available stopped beam intensity
7×10^7

Where we will be

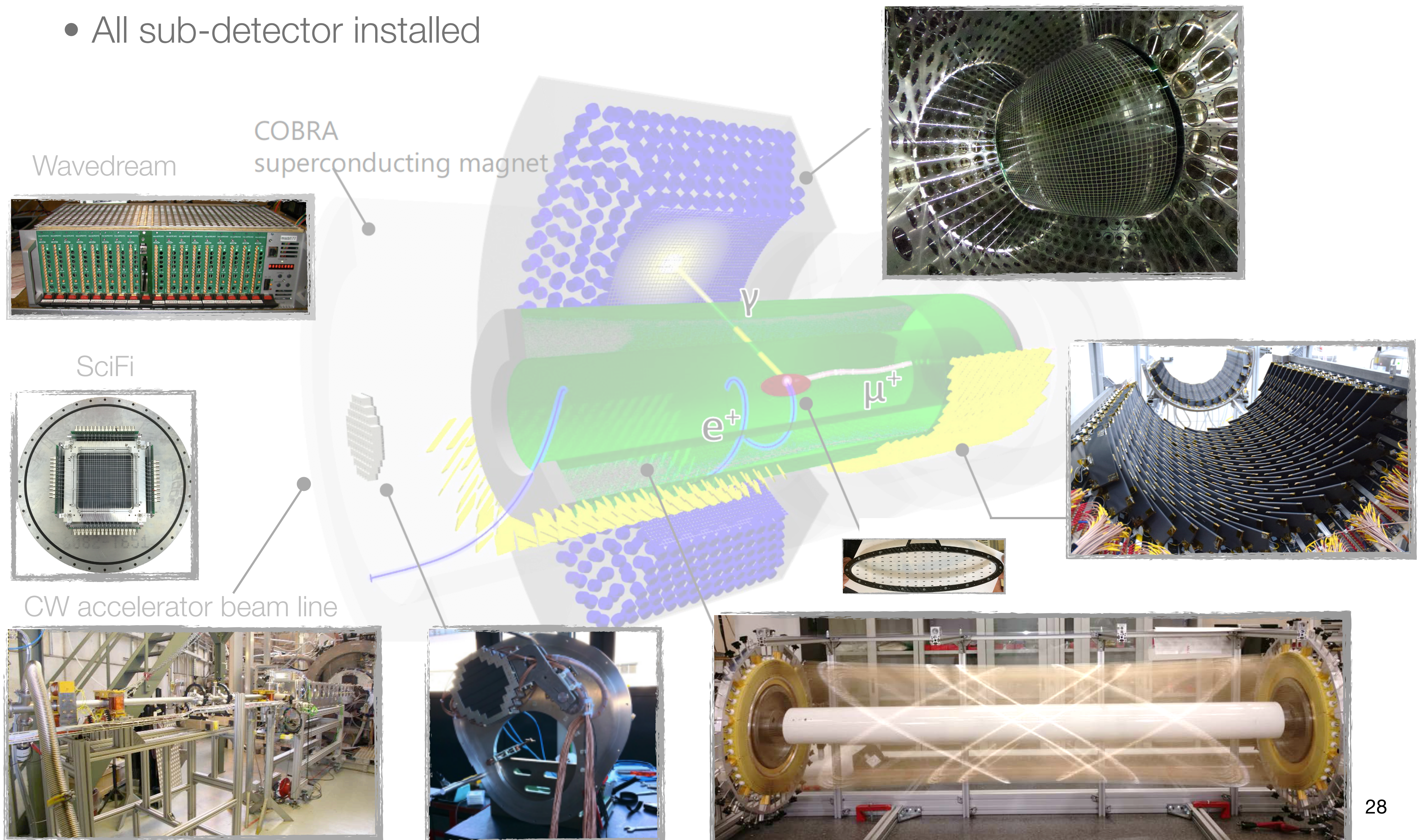
~ 6 x 10^{-14}



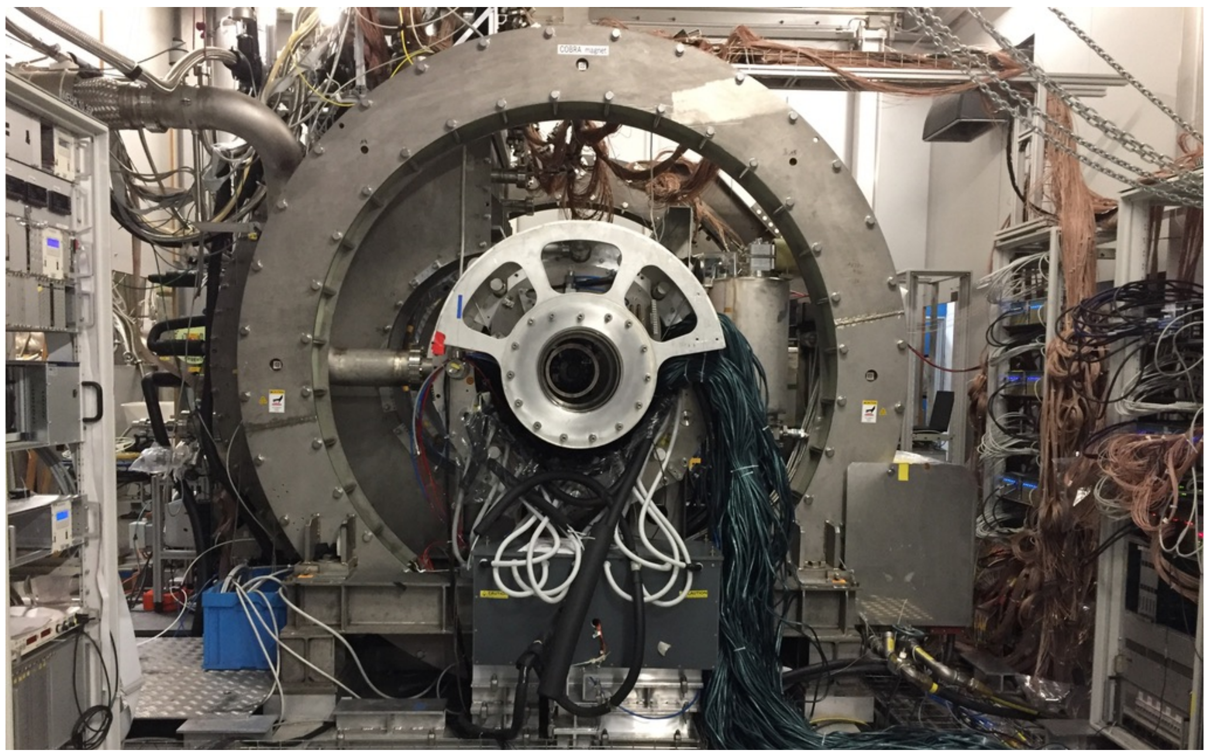
MEGII

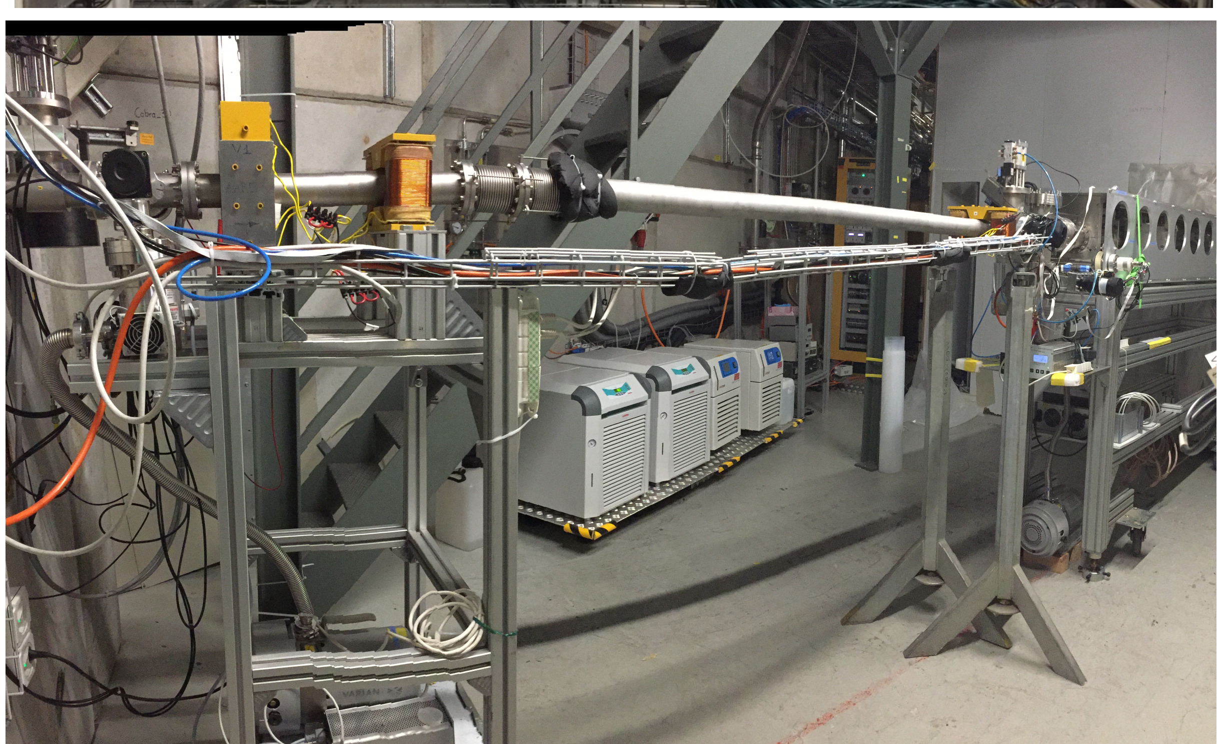
Where we are: Pre-engineering run ongoing

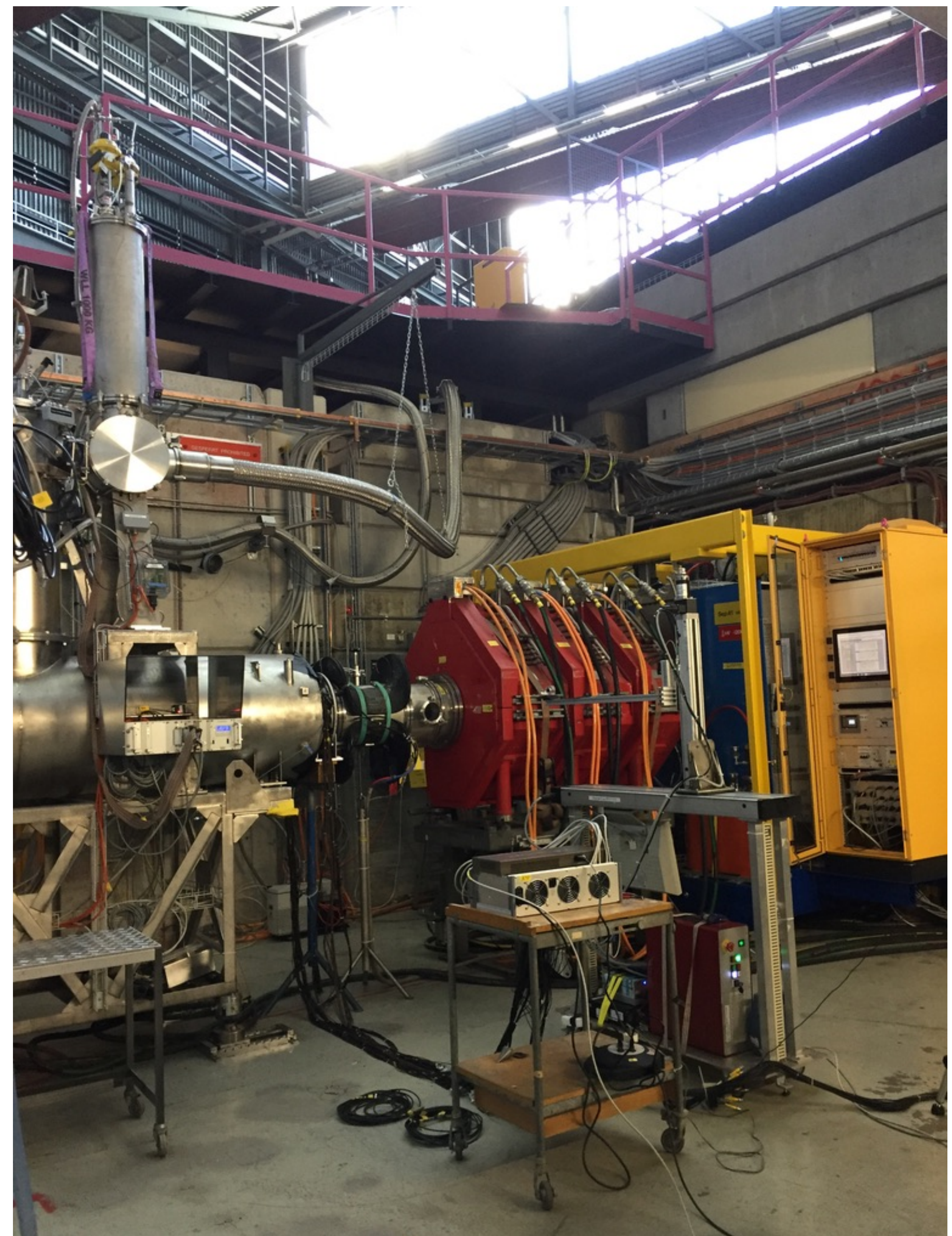
- All sub-detector installed



Where we are: Pre-engineering run ongoing



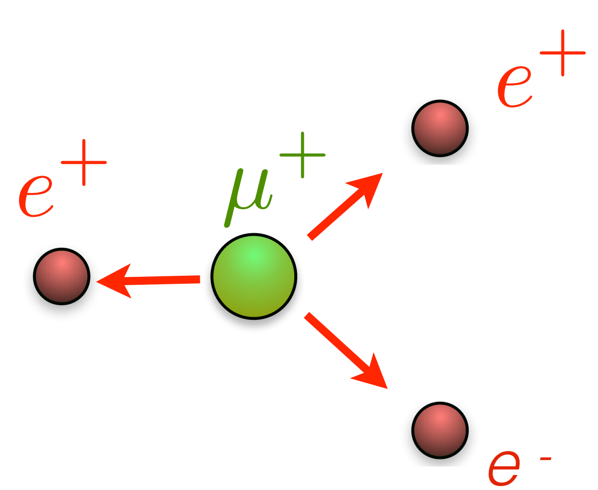




Mu3e: The $\mu^+ \rightarrow e^+ e^+ e^-$ search

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \rightarrow eee$ events

Signature

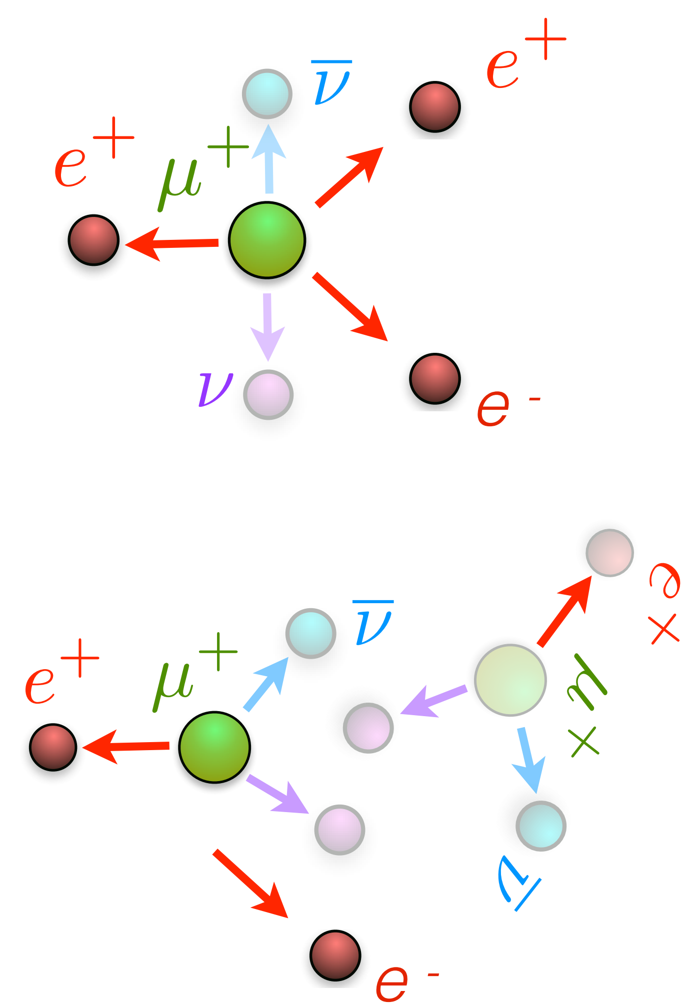


$$\Delta t_{eee} = 0$$

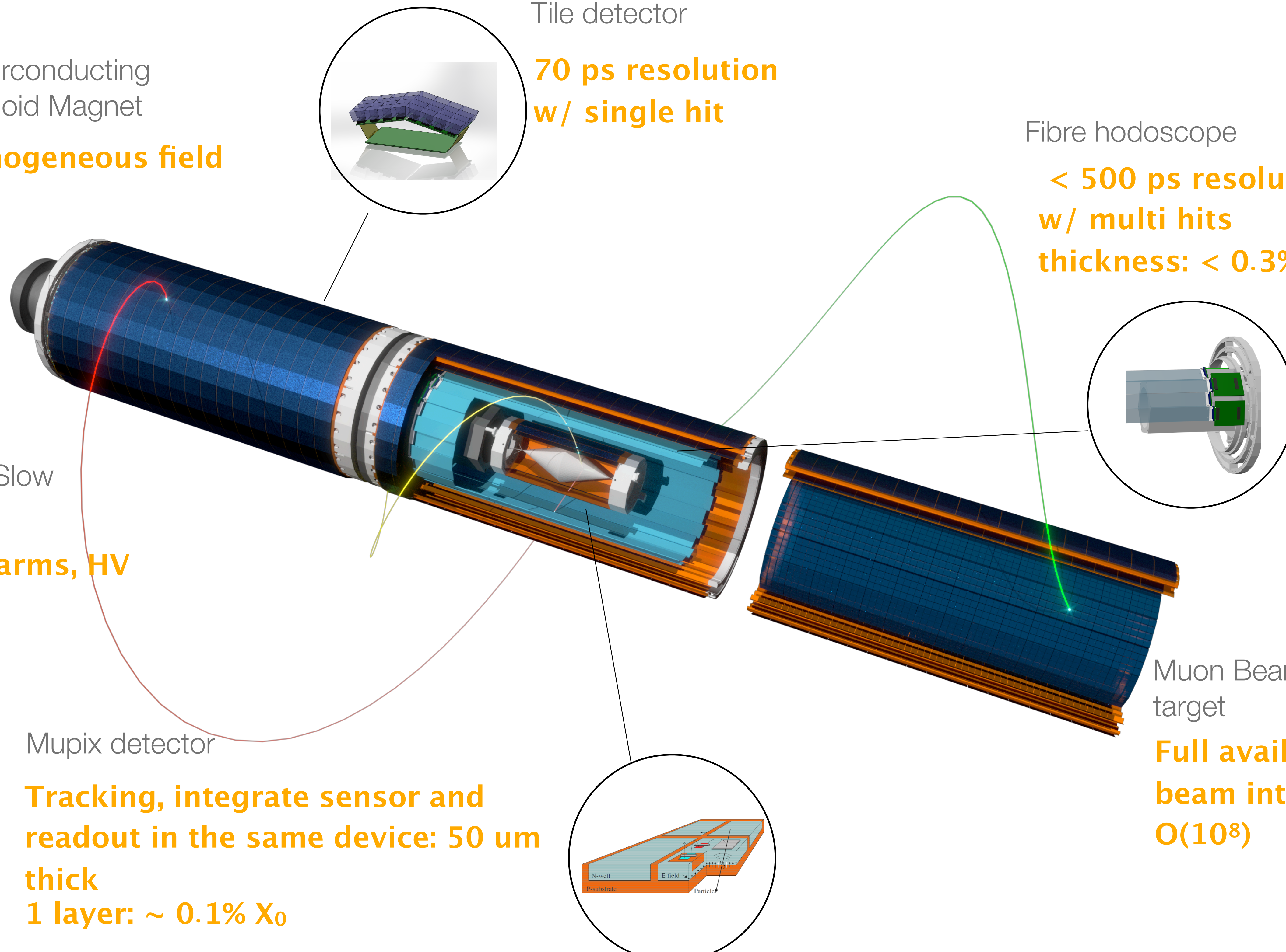
$$\Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

Background



The Mu3e experiment: Schematic 3D



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)

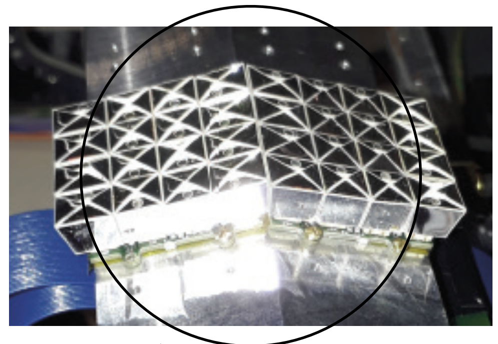
Mupix detector

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

The Mu3e experiment: R&D completed. Prototyping phase

Superconducting solenoid Magnet

Homogeneous field 1T

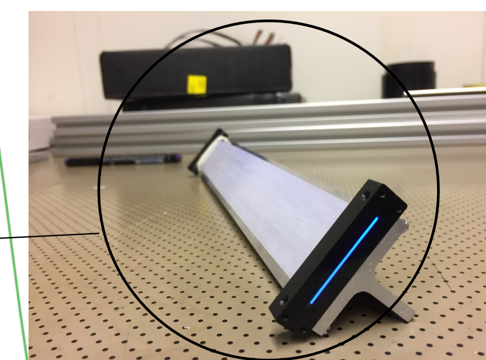


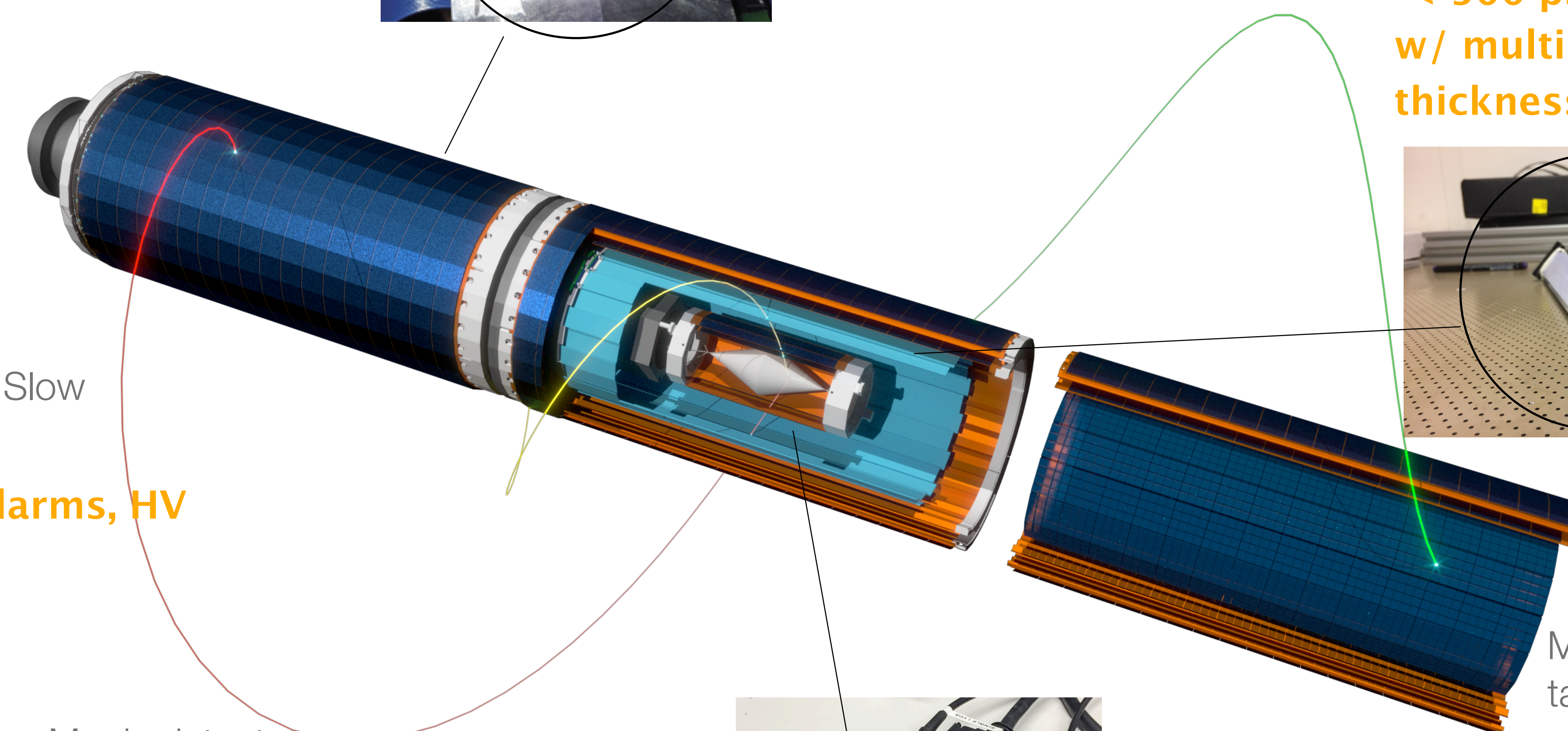
Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

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



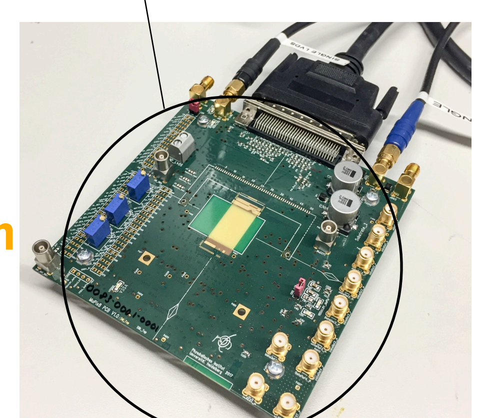


MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Mupix detector

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



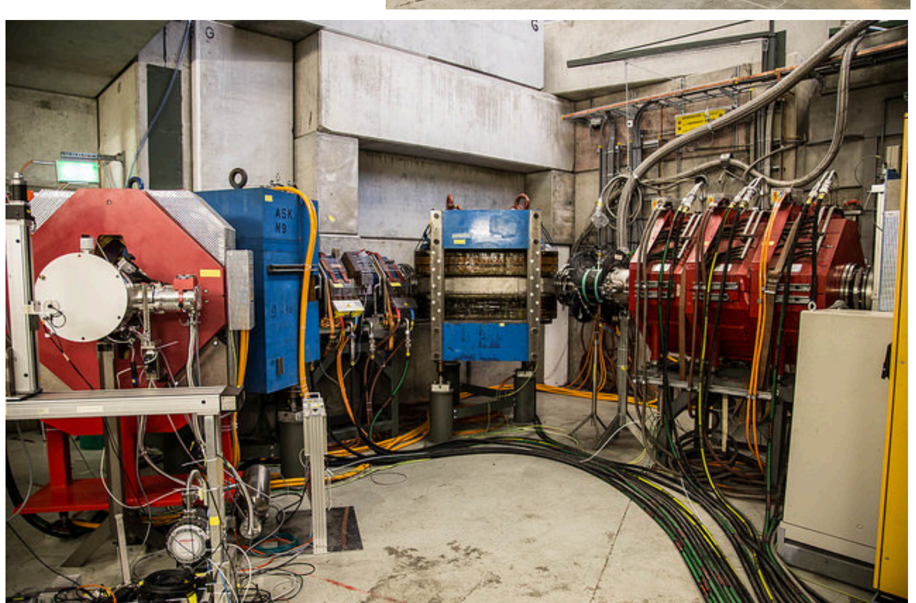
Muon Beam and target

Full available beam intensity $O(10^8)$

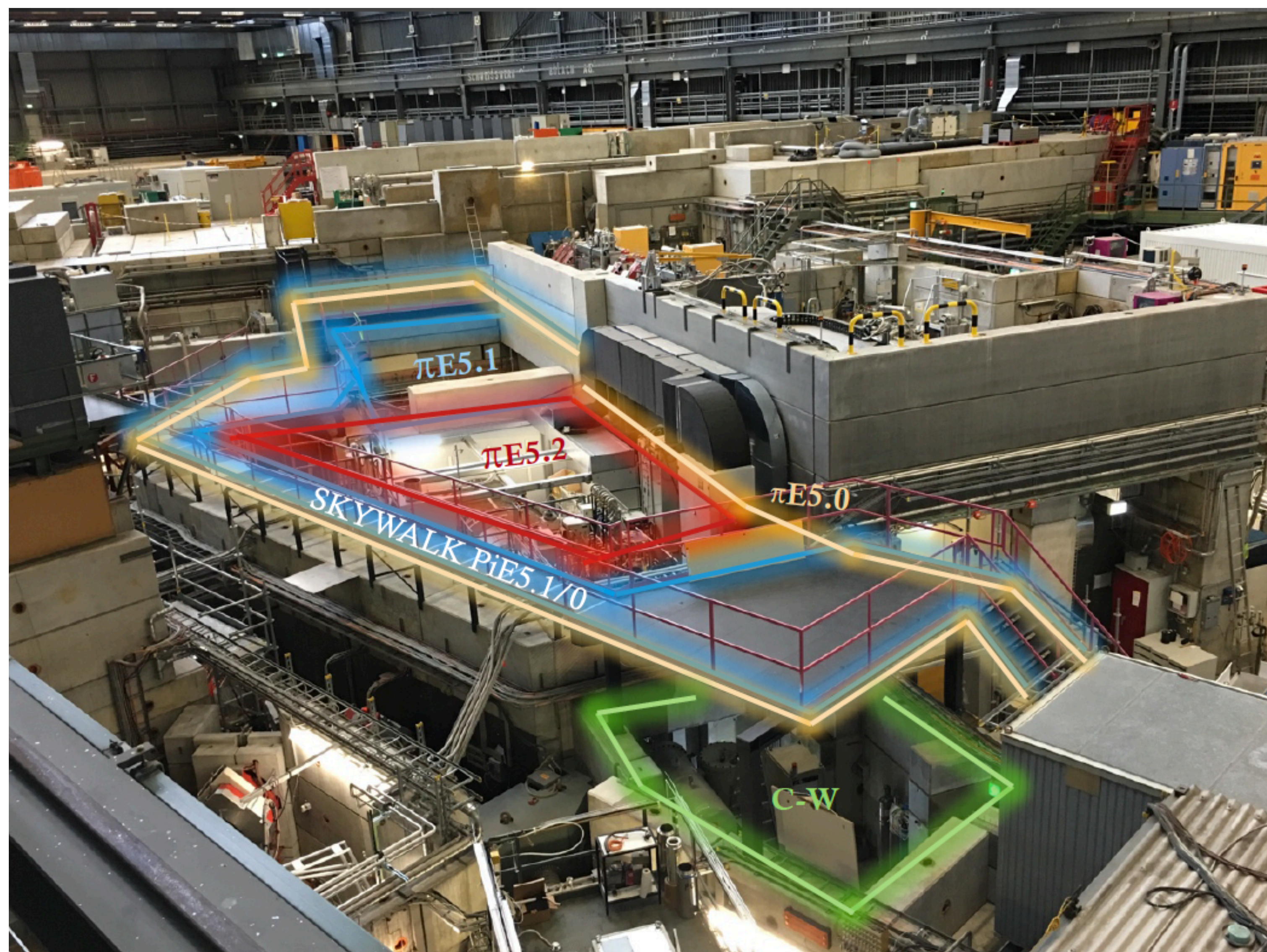
The MEGII and Mu3e experimental area: Pictures

- Beam: Delivered 8 x 10^7 muon/s via the CMBL
- Infrastructure ready

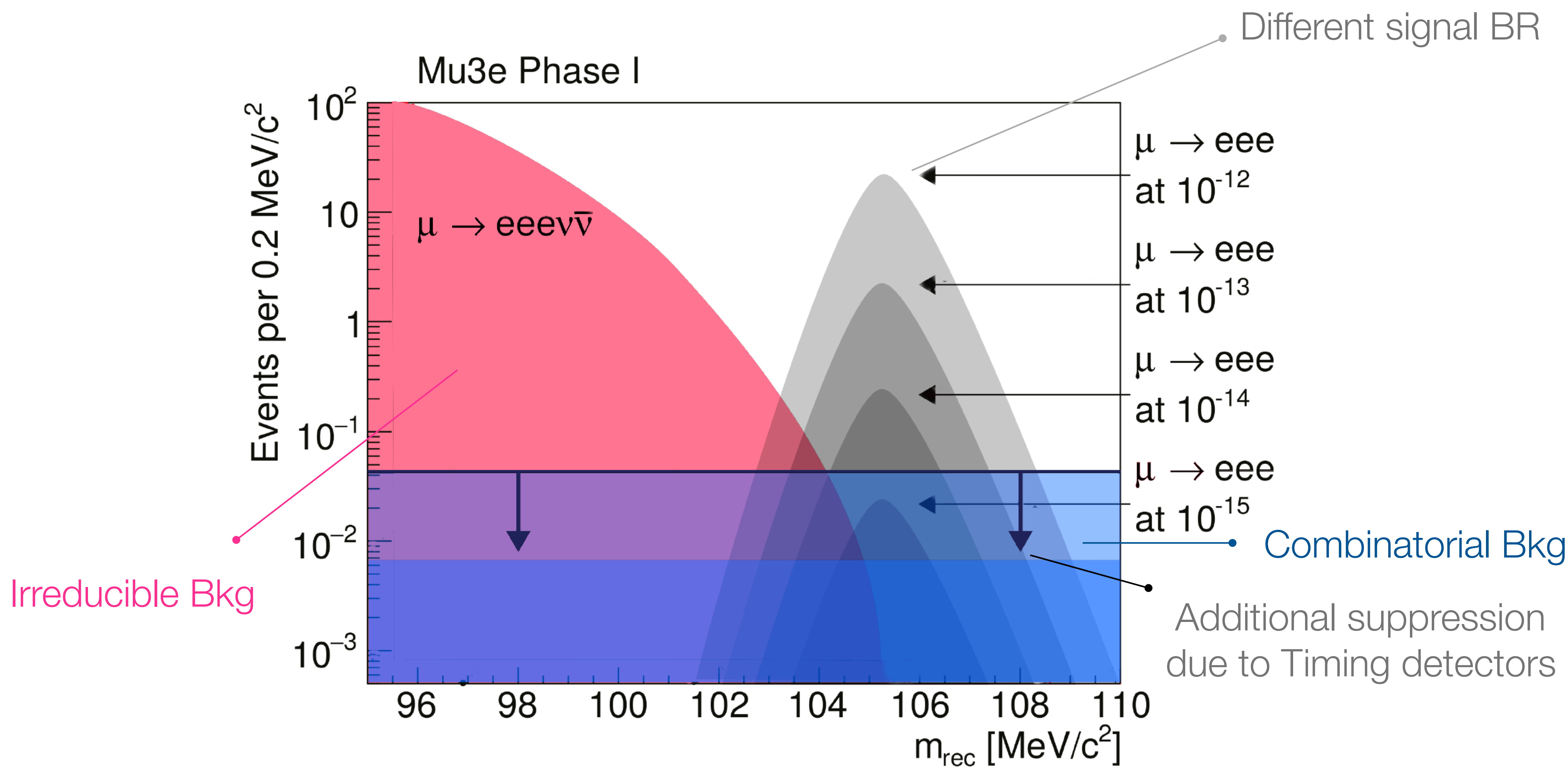
Mu3e control room



Overview piE5 area



Mu3e Phase I sensitivity



Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

I_{beam} ~ 10^8 - 10^{10} μ/s

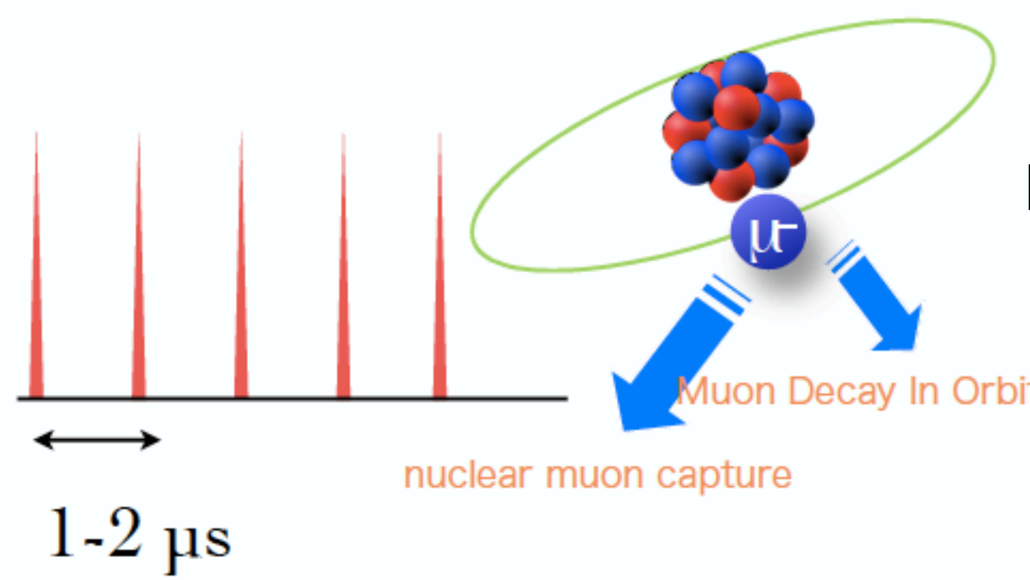
DC or Pulsed?

I_{beam} ~ 10^{11} μ/s

- DC beam for coincidence experiments
    - $\mu \to e \gamma$, $\mu \to e\ e\ e$

- Pulse beam for non-coincidence experiments
    - μ-e conversion

@ PSI



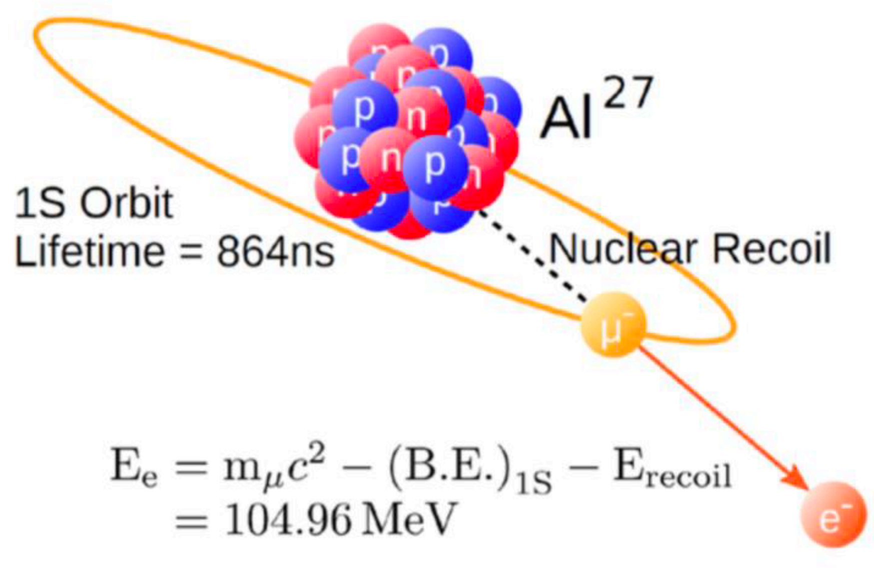
@ JPARC, FERMILAB

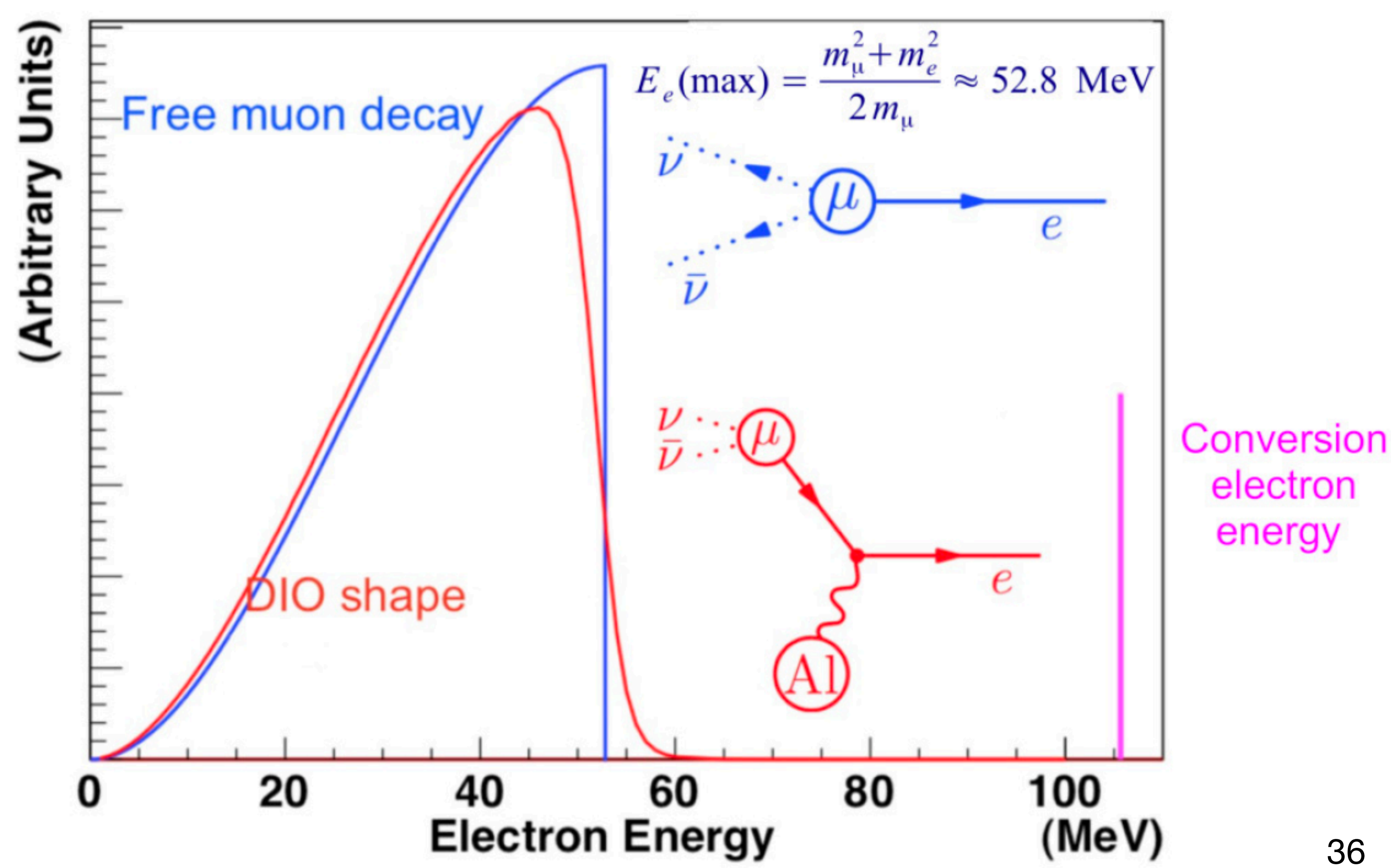
μ⁻ N → e⁻ N experiments

- Signal of mu-e conversion is single mono-energetic electron

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

- Background: Any event at the endpoint energy can mimic the signal



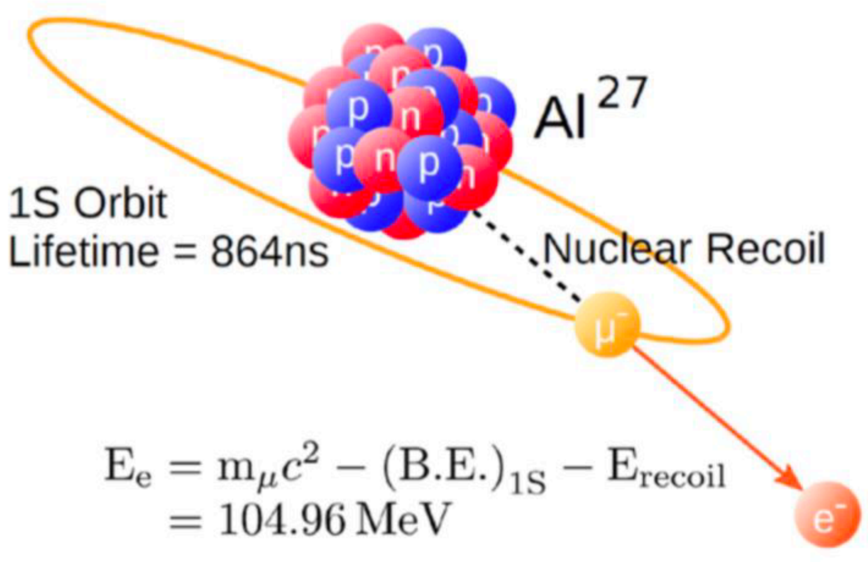


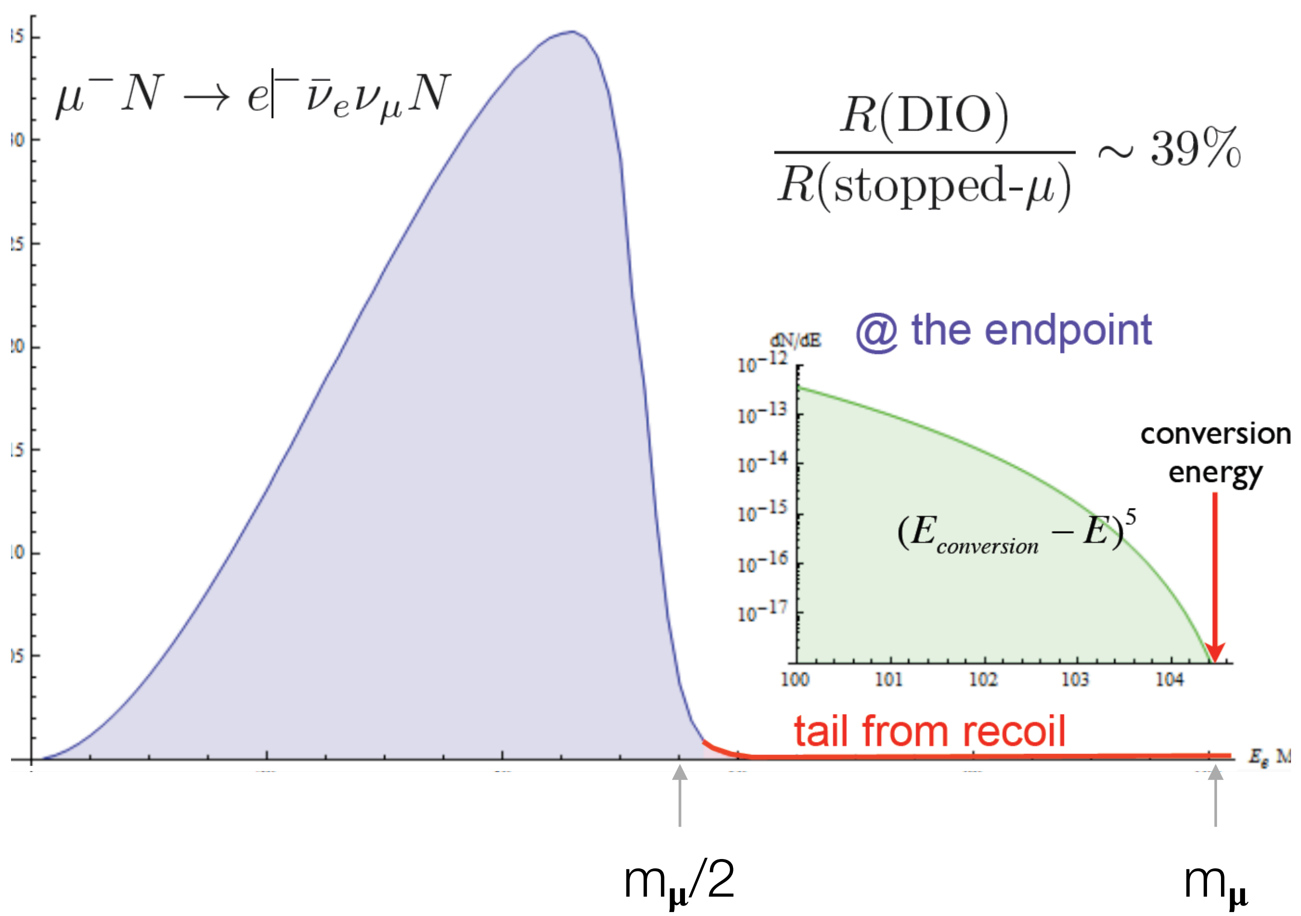
μ^- N → e^- N experiments

- Signal of mu-e conversion is single mono-energetic electron

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

- Background: Any event at the endpoint energy can mimic the signal

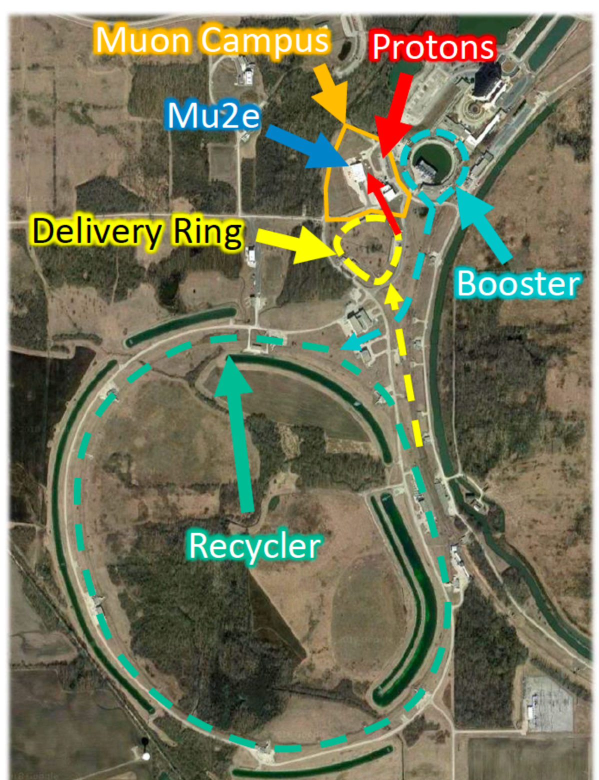




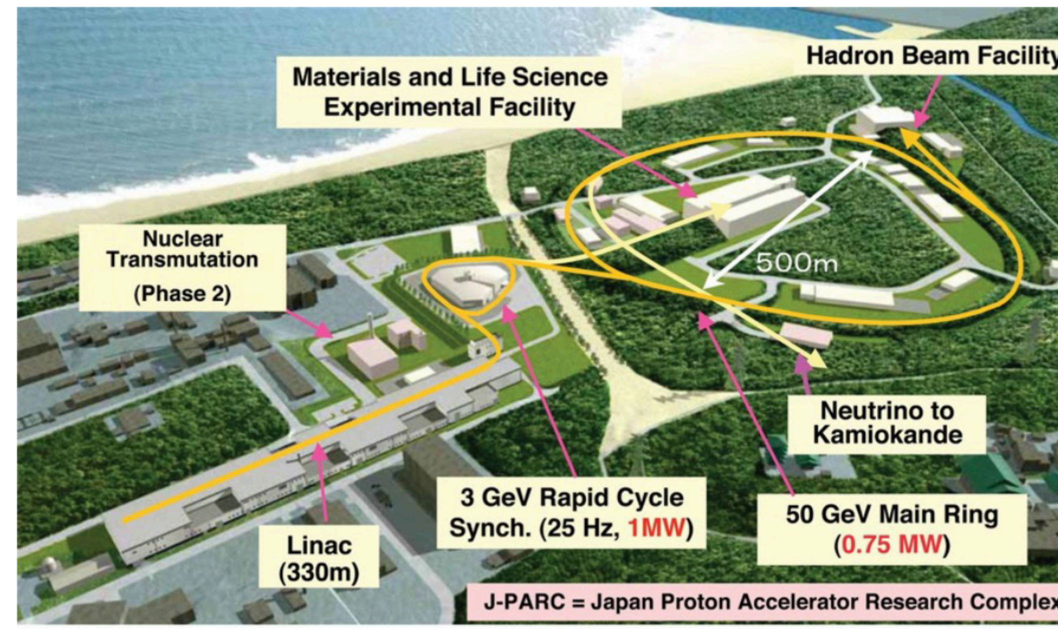
The two giants campus delivering astonishing intese pulsed muon beams

Fermilab

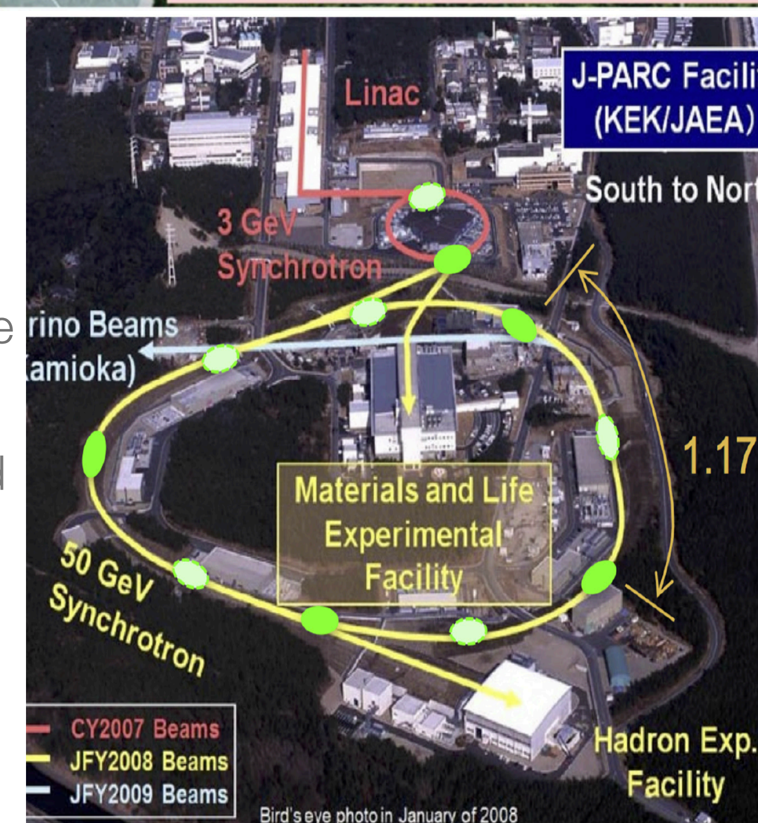
- **Booster** provides 8 GeV protons to the **Recycler**
- **Recycler** stacks protons into 4 bunches
- **Delivery Ring** takes 1 out of every 4 bunches from the **Recycler**
- **Mu2e** slow extracts **protons** every 1695 ns



JPARC

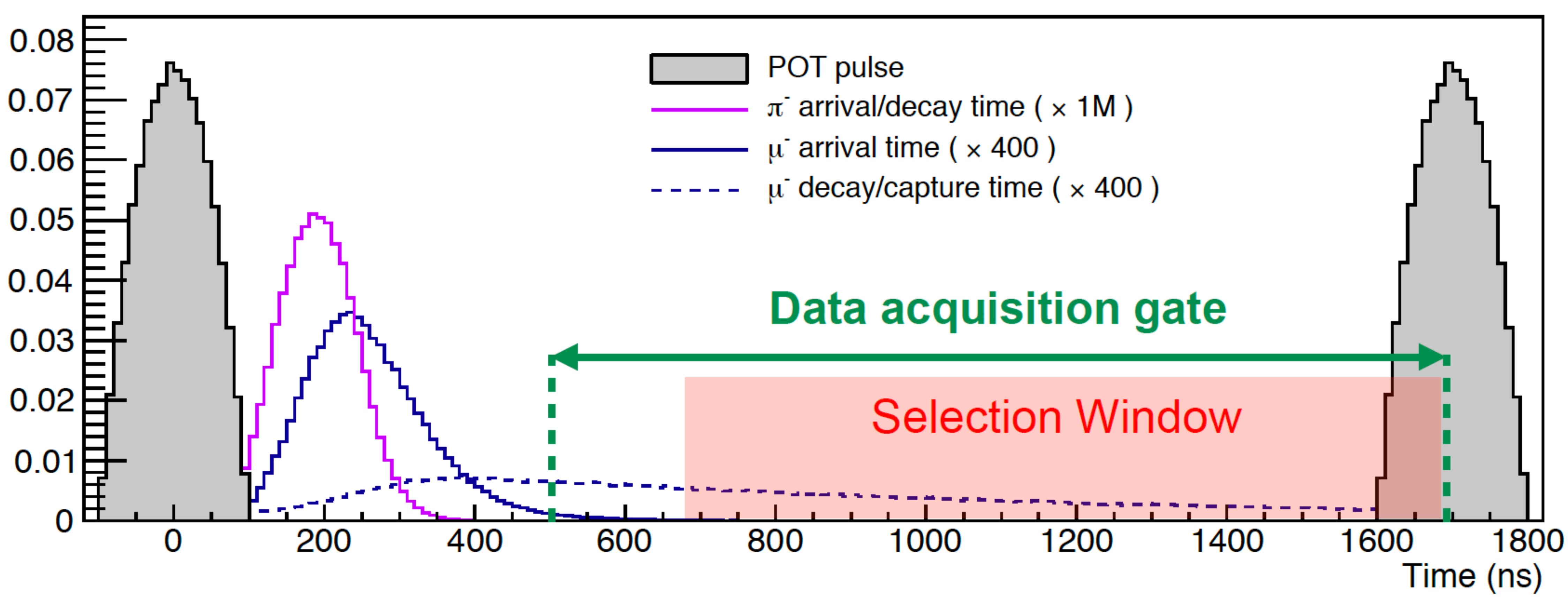


- **Bunched** 8 GeV protons extracted from the Main Ring and delivered to the pion target production inside a capture solenoid
- **Muons** are charge and momentum selected using curved superconducting solenoids



$\mu^- N \rightarrow e^- N$ experiments

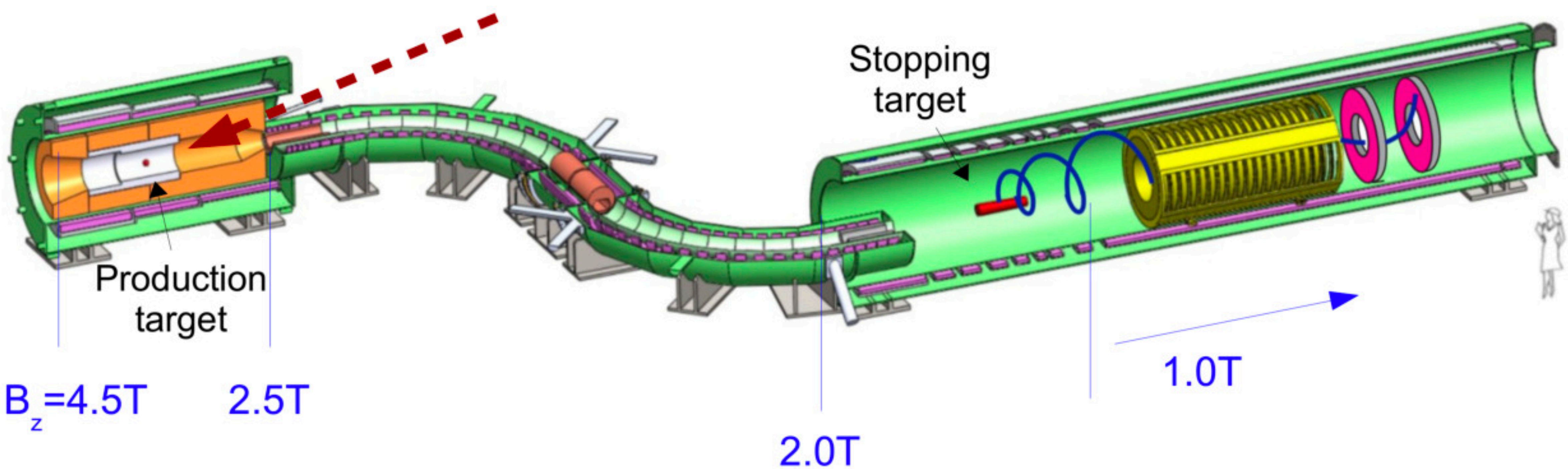
- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! $O(10^{18})$
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 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

Talk: S. Di Falco

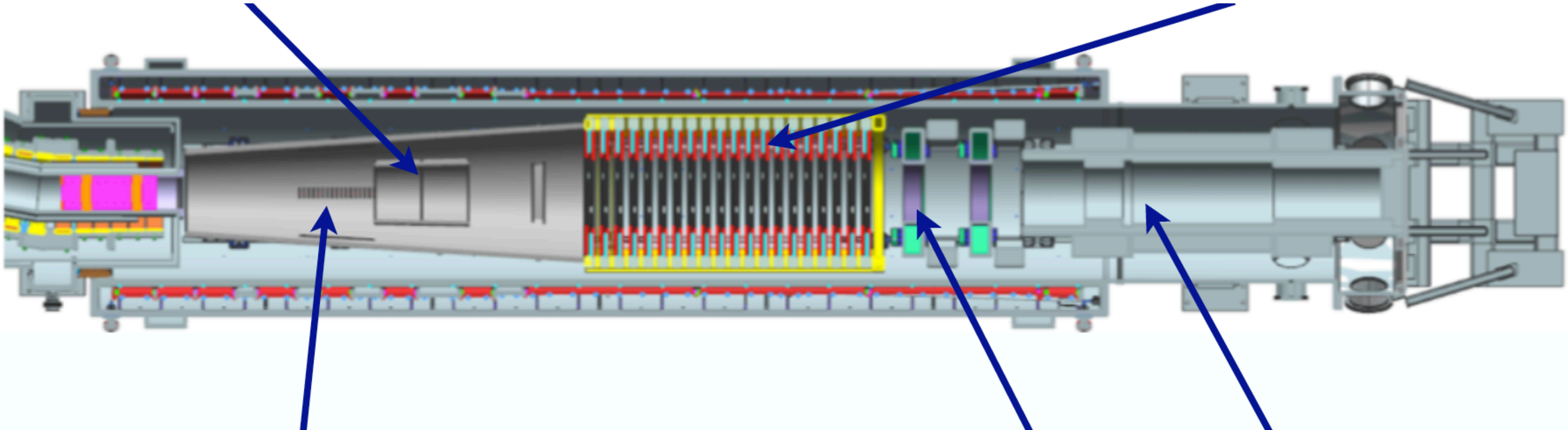
- Three superconducting solenoids: Production, Transport and Detector solenoids
- Muons stop in thin aluminum foils
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID
- Scintillators for the Veto



The Mu2e experiment

• *Proton absorber:*
❖ made of high-density polyethylene
❖ designed in order to reduce proton flux on the tracker and minimize energy loss

• *Tracker:*
❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
❖ Expected momentum resolution < 200 keV/c



• *Targets:*
❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

• *Calorimeter:*
❖ 2 disks composed of undoped CsI crystals

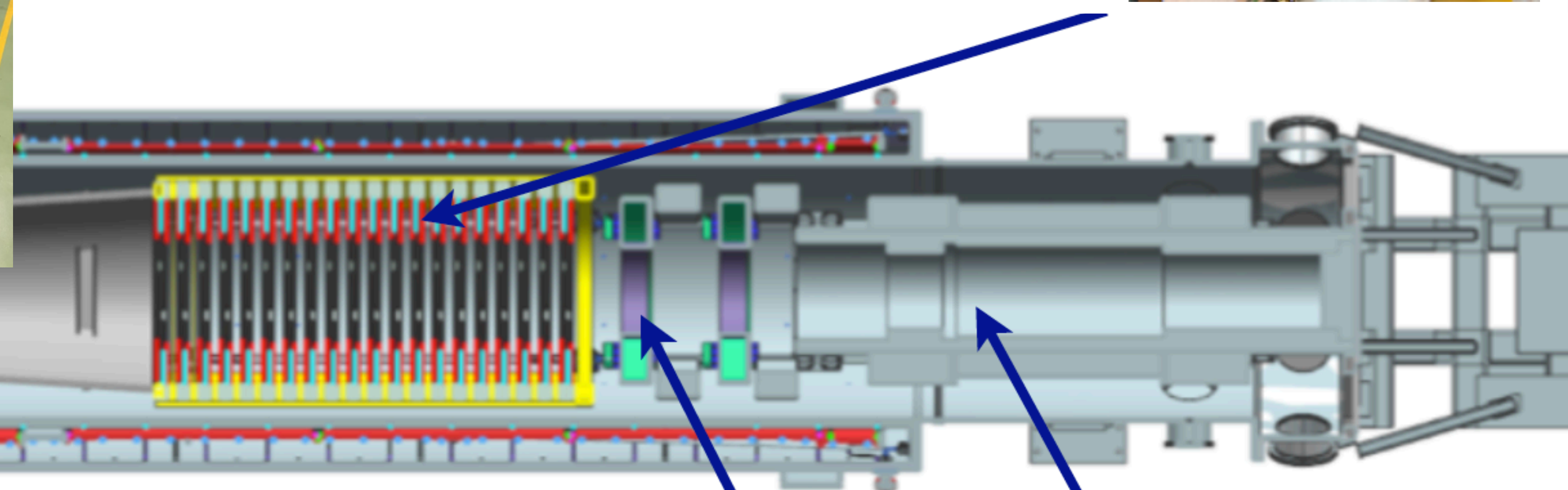
• *Muon beam stop:*
❖ made of several cylinders of different materials: stainless steel and polyethylene

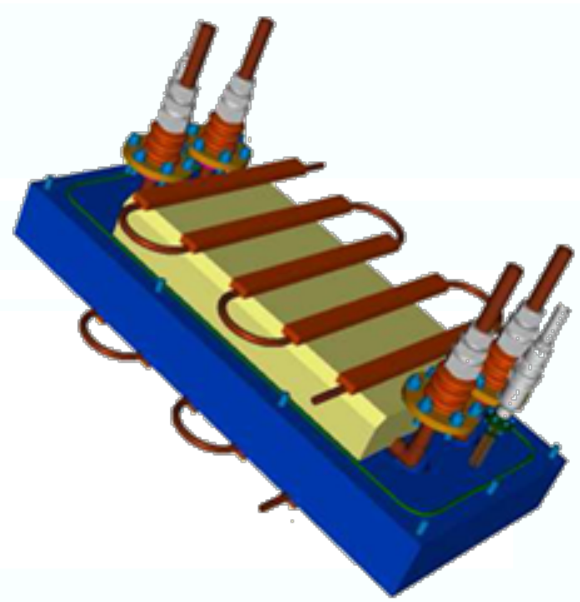
The Mu2e experiment: Status

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

- *Tracker:*

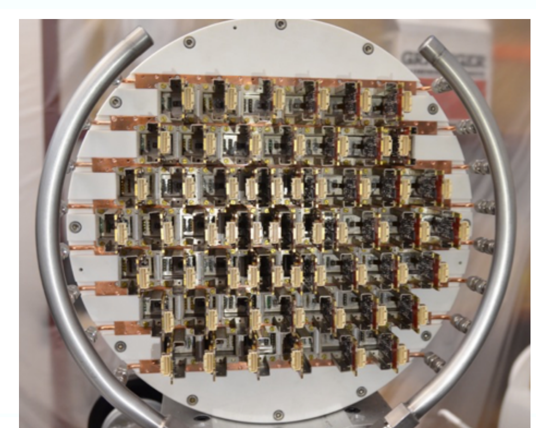
- *Beamline and solenoids*



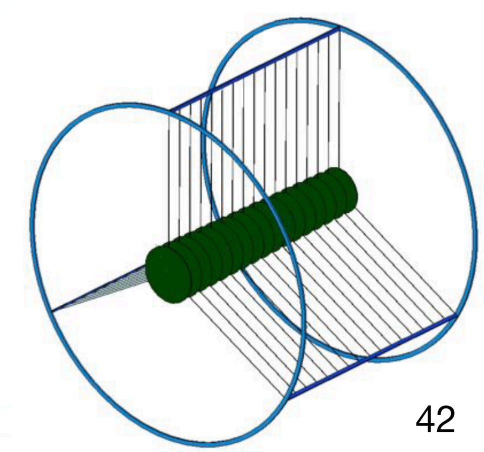


- *Cosmic Ray Veto*

- *Calorimeter:*



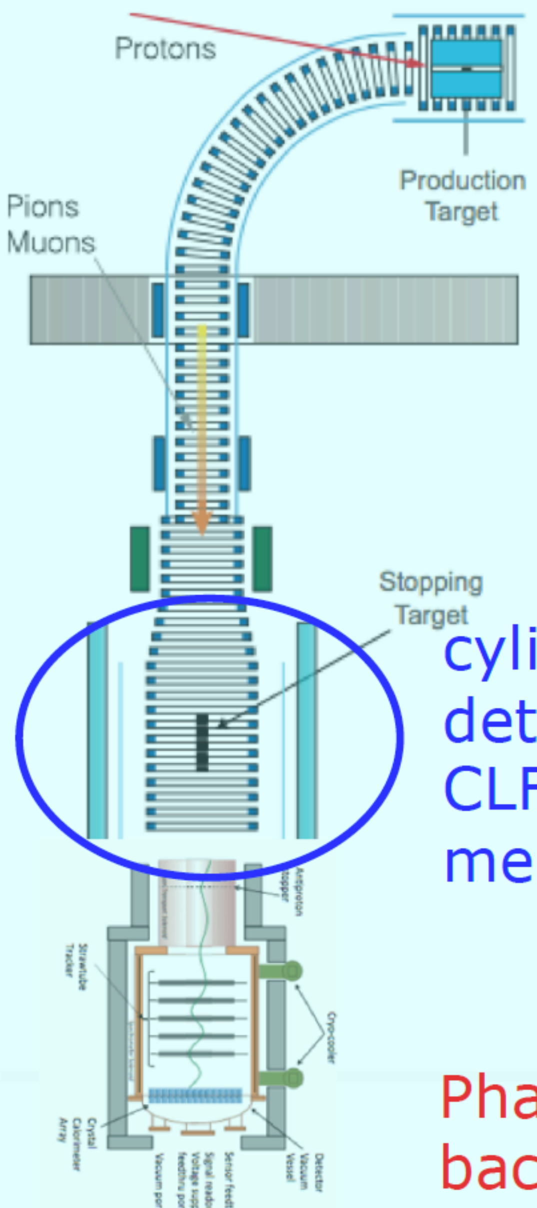
- *Muon beam stop:*



The COMET experiment

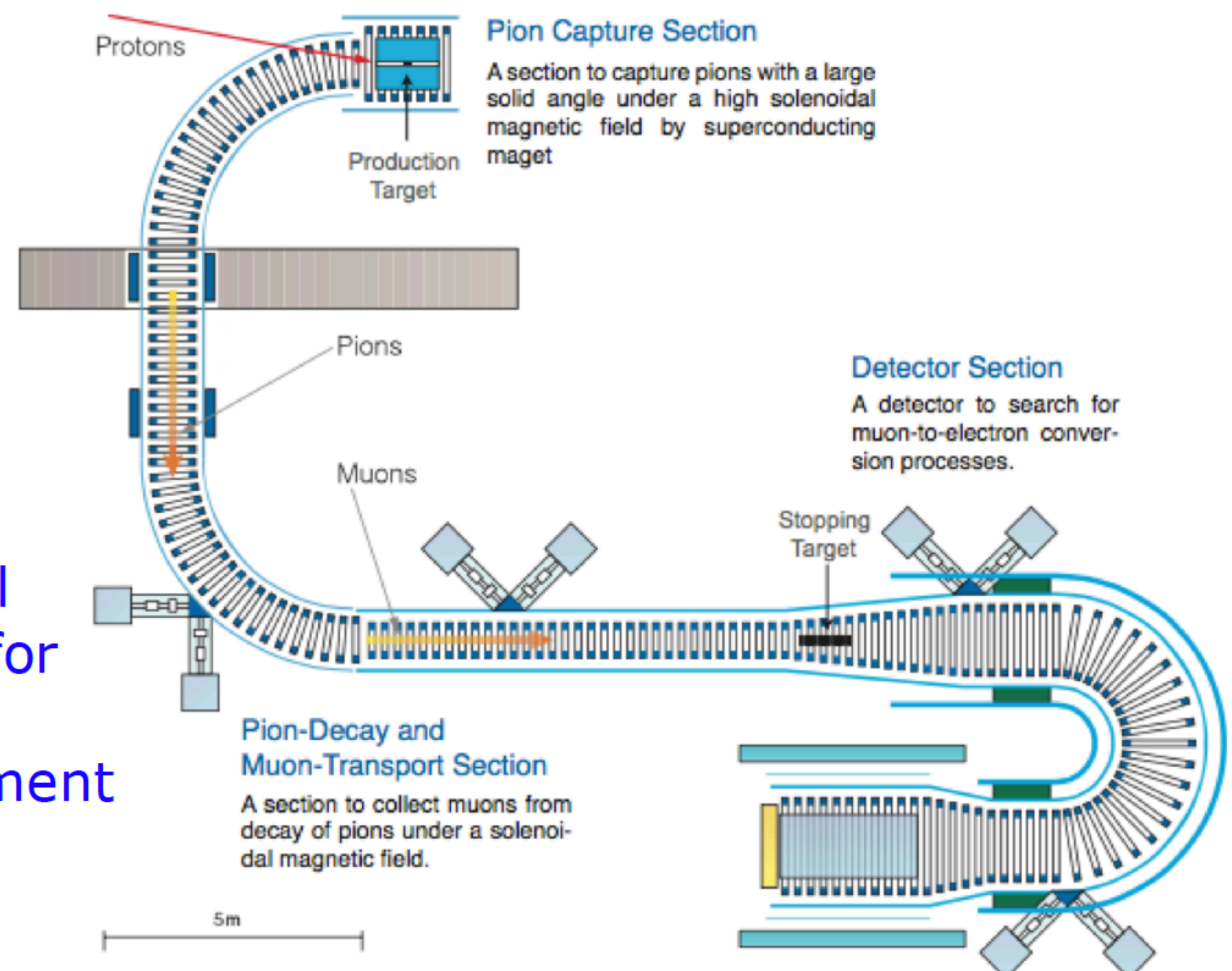
- Stage phase approach: Phase I and Phase II

COMET phase I



cylindrical detector for CLFV measurement

COMET phase II

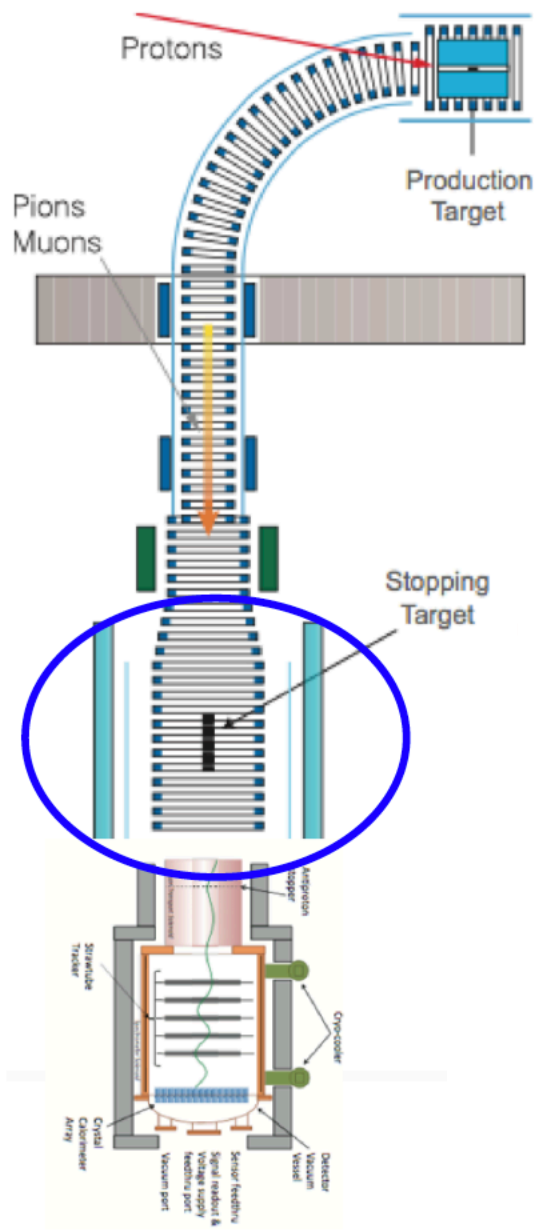


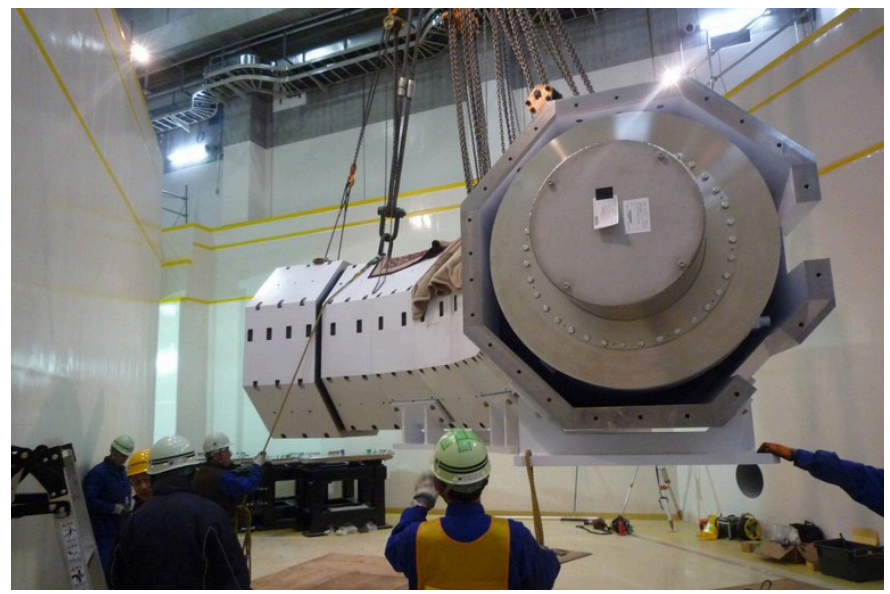
Phase-II prototype for background characterisation

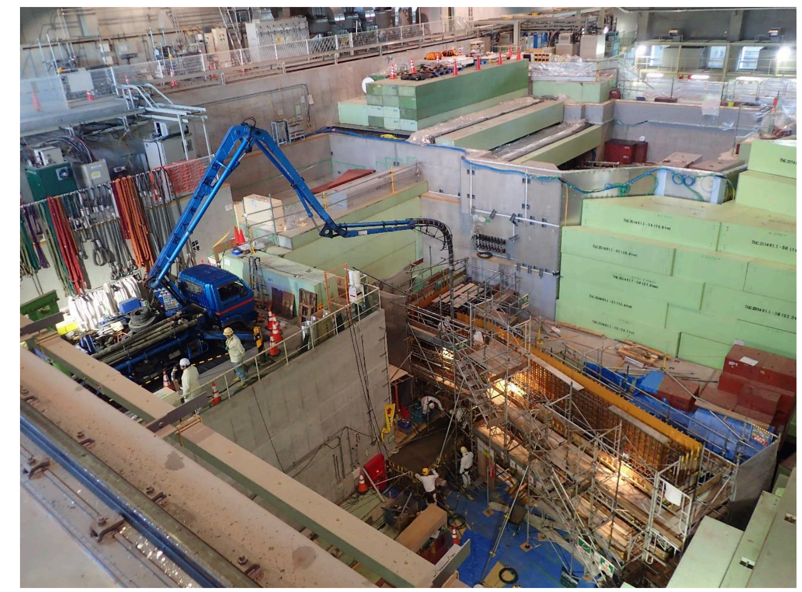
The COMET experiment: Status

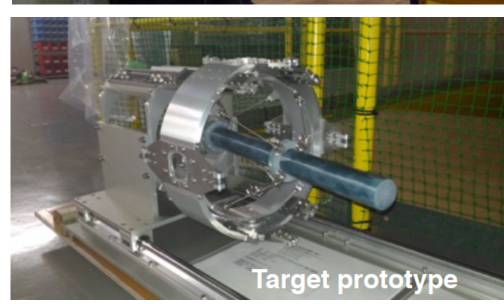
- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]

COMET phase I

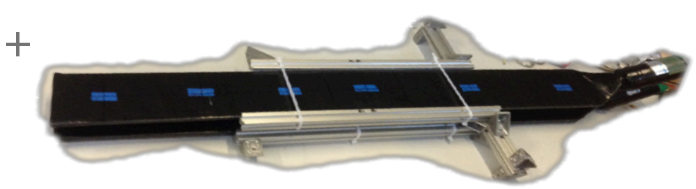




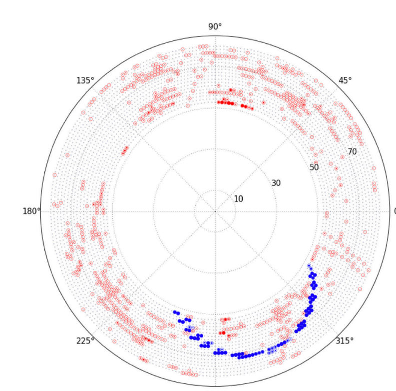


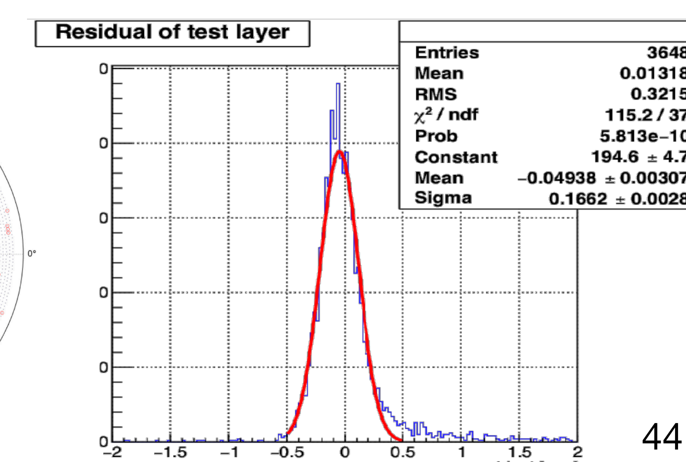


Trigger scintillators + Cerenkov detector



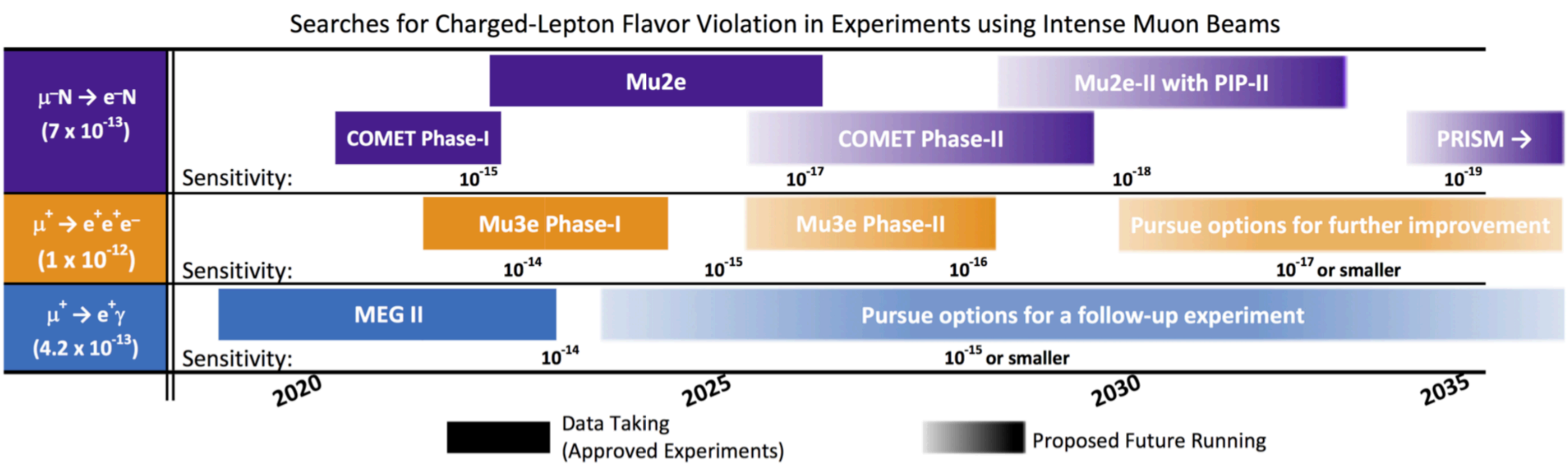
Trigger/DAQ/Analysis: in very good shape





Muon cLFV searches: Present and Future

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- Submitted inputs to the European Strategy Committee



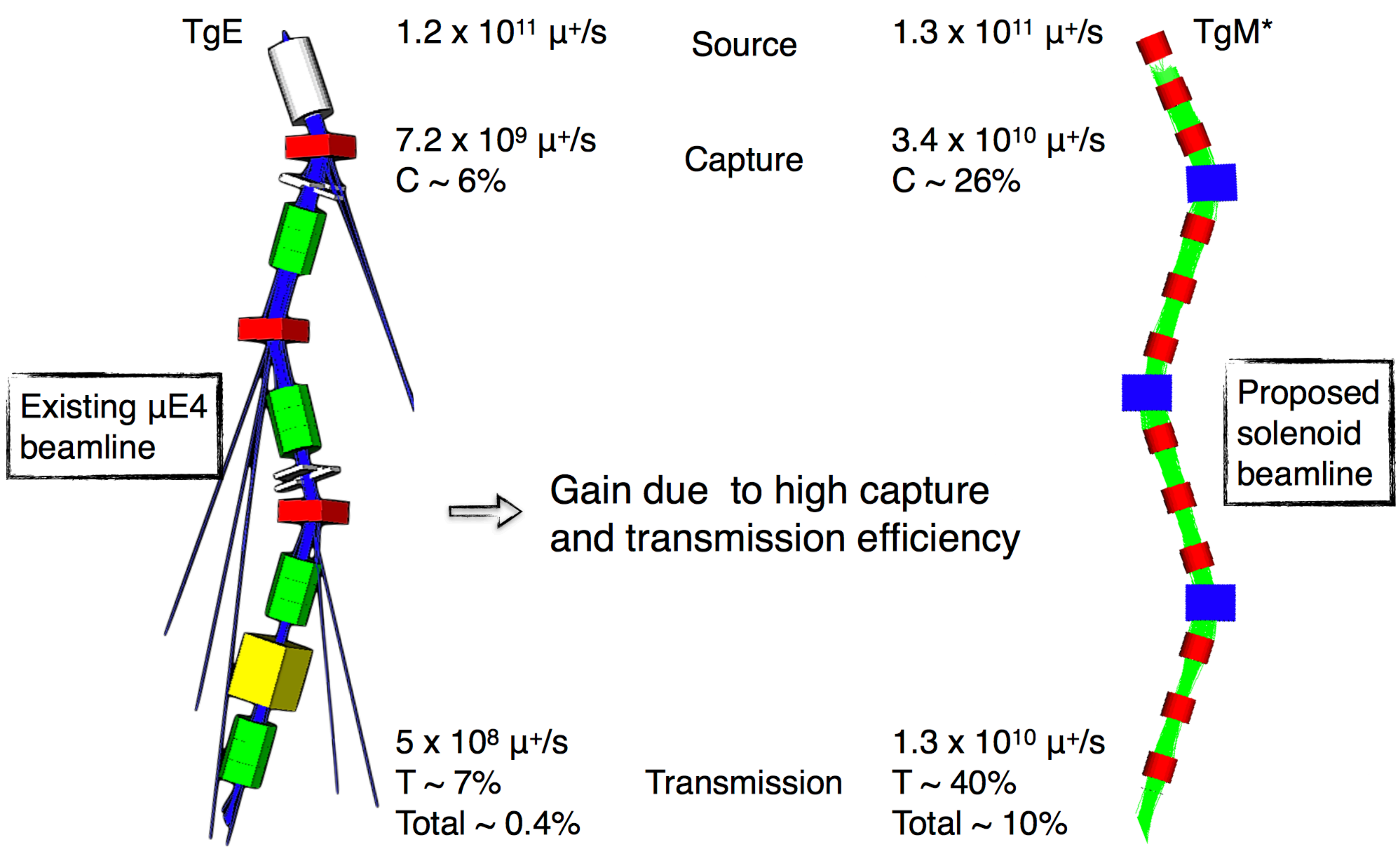
L. Calibbi and G. Signorelli, il Nuovo Cimento **41** (2018) 71

DC and Pulsed muon beams - present and future

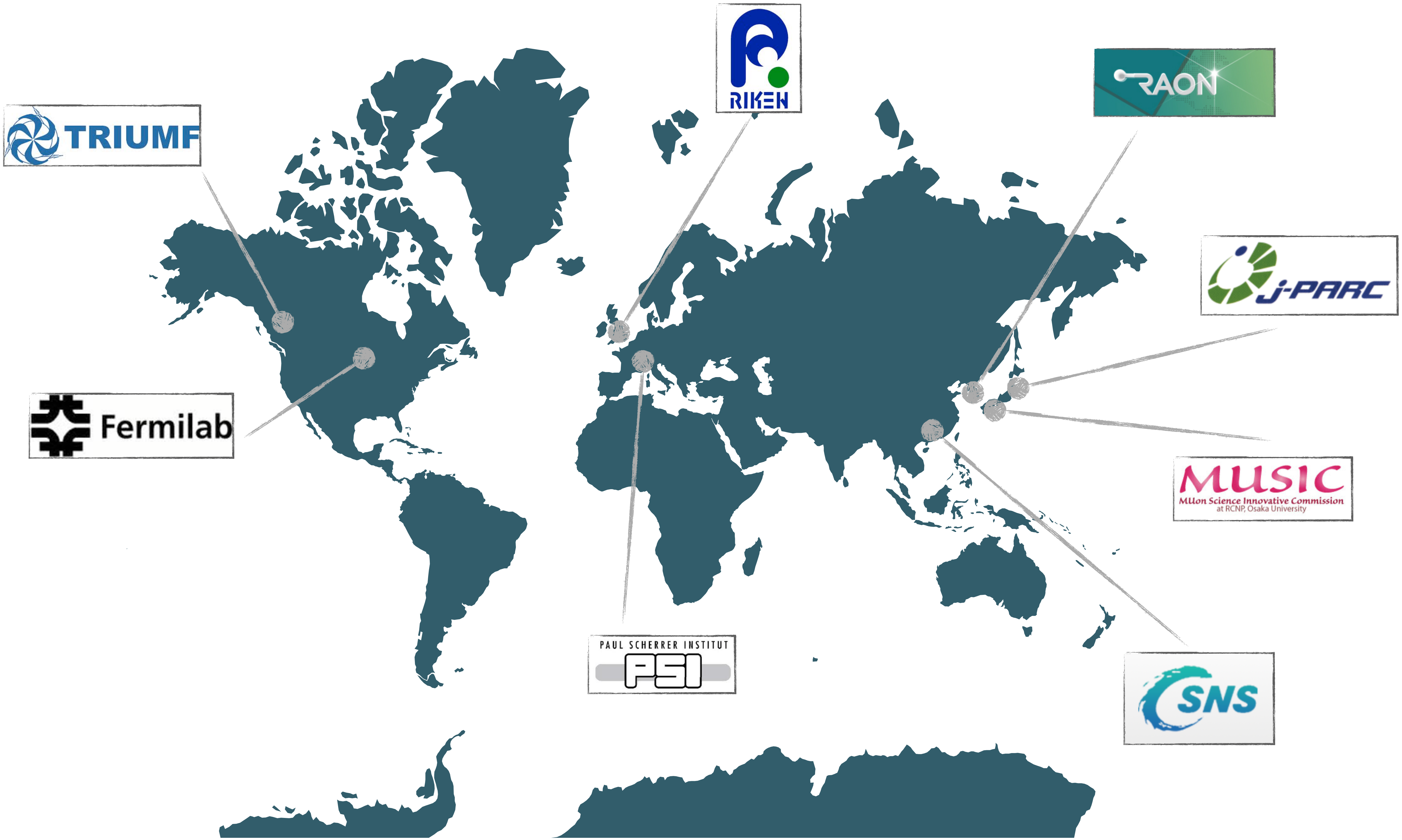
Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7 (\mu^+)$ $6.4 \times 10^7 (\mu^+)$ $1 \times 10^{11} (\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10} (\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6 (\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4 (\mu^-)$ $6 \times 10^5 (\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5 (\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4 (\mu^-) \div 10^5 (\mu^+)$ $10^7 (\mu^-) \div 10^8 (\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5 (\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8 (\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8 (\mu^+)$(>2020)	

The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2025)**
- Put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**



DC and Pulsed muon beams - present and future



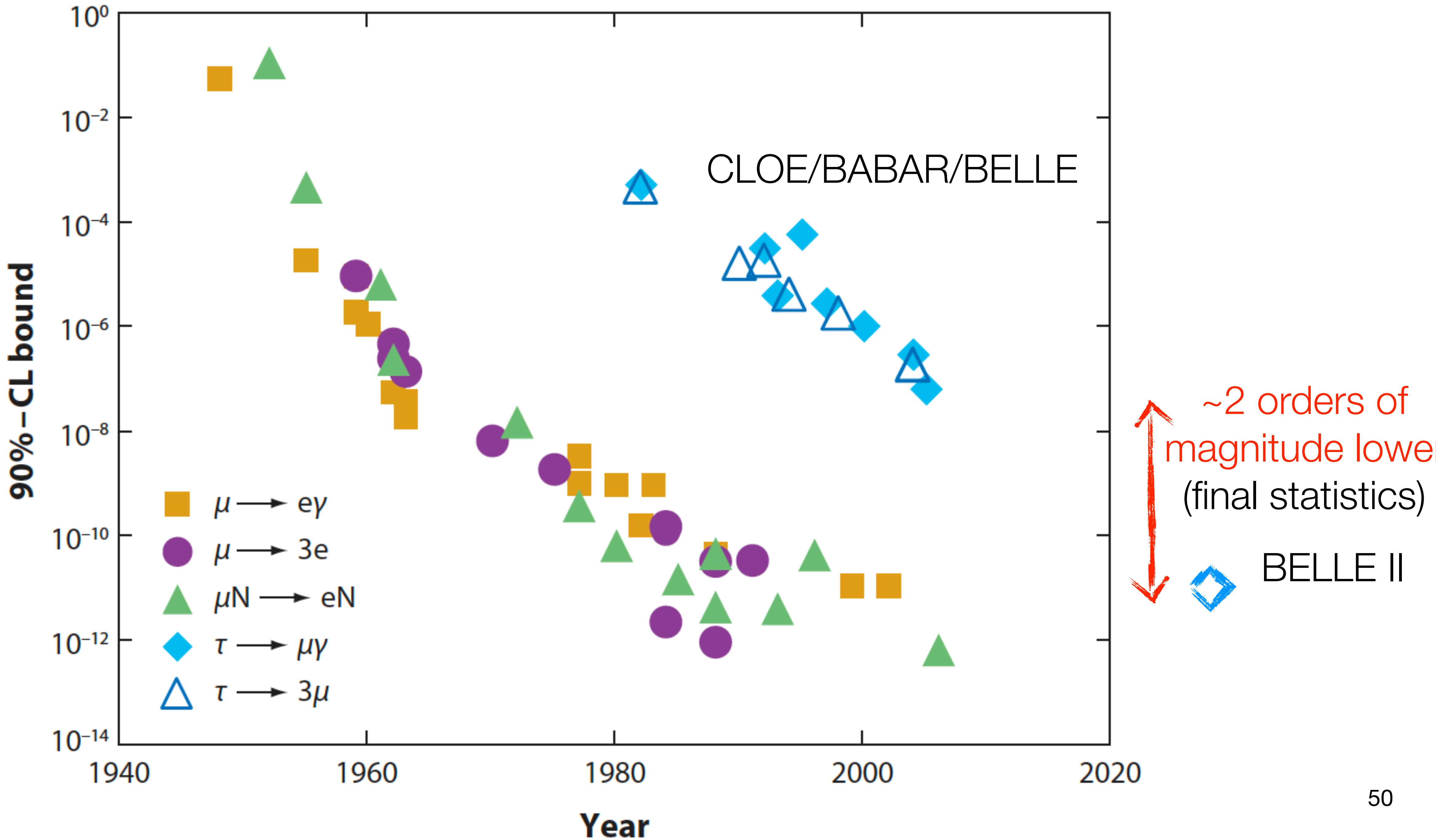
cLFV searches at B-factories

- B-factory are τ-factory at the same time
  - A lot of studies can be done:
    - tau physics: tau decays from tau pair production
    - b => lls: LFV in B decays

tau-based cLFV searches

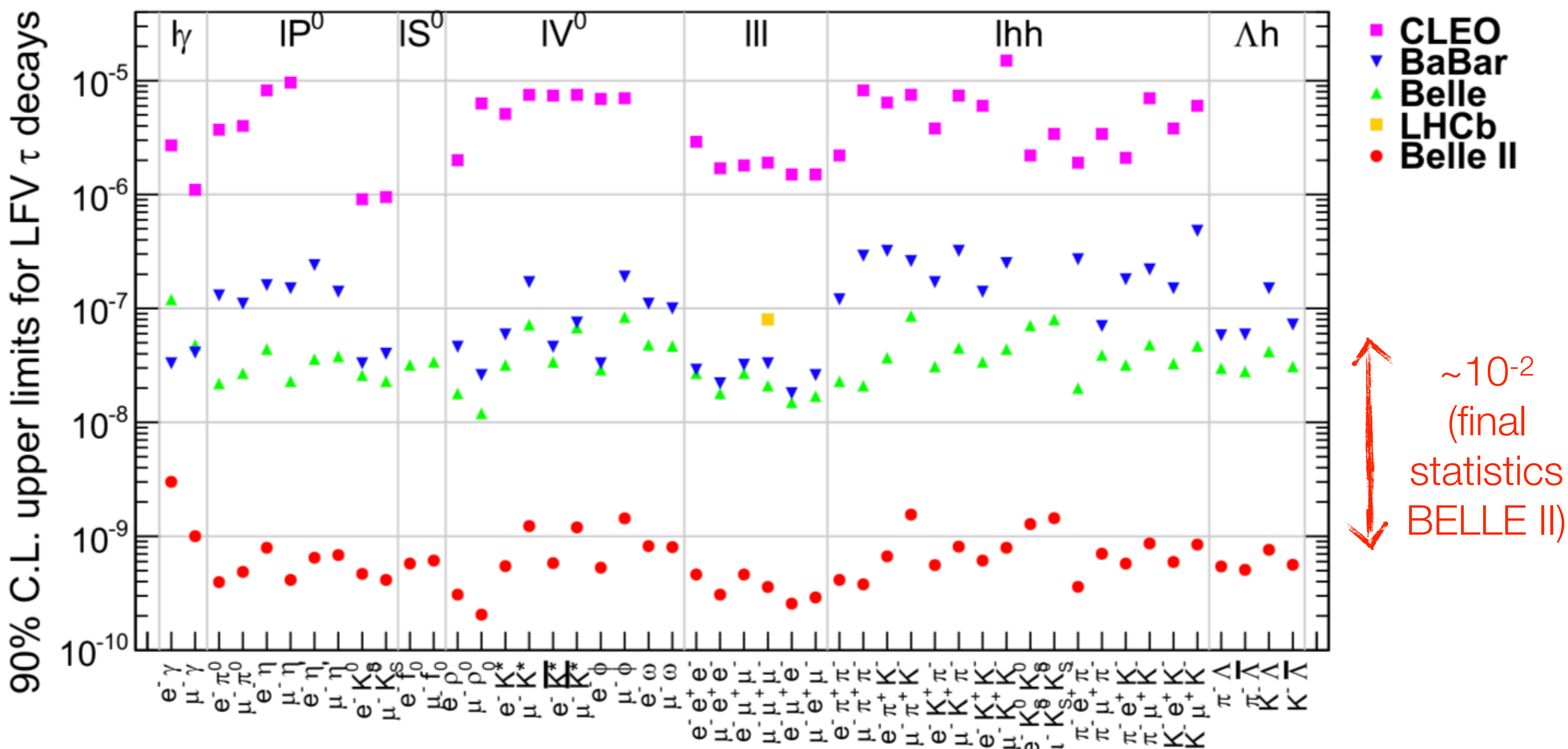
- B-factory are τ-factory at the same time
- Present and future prospects

Annu. Rev. Nucl. Part. Sci. 2008.58:315-341



tau-based cLFV searches

- B-factory are τ-factory at the same time
- Present and future prospects



The Belle II Physics Book arXiv:1808.10567

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 $\tau^+ \tau^-$ sample, Belle has obtained the most stringent upper limits in most of the τ LFV, LNV and BNV decays, with 90% UL of $O(10^{-8})$

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{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

The incoming future: Belle II

- With ~50 billion $\tau^+ \tau^-$ 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. $\tau^+ \to \ell^+\ell^-\ell^+$), CLFV upper limits are expected to improve linearly with luminosity: They will be very powerful probes for new physics beyond the SM
- First τ LFV sensitivity study:

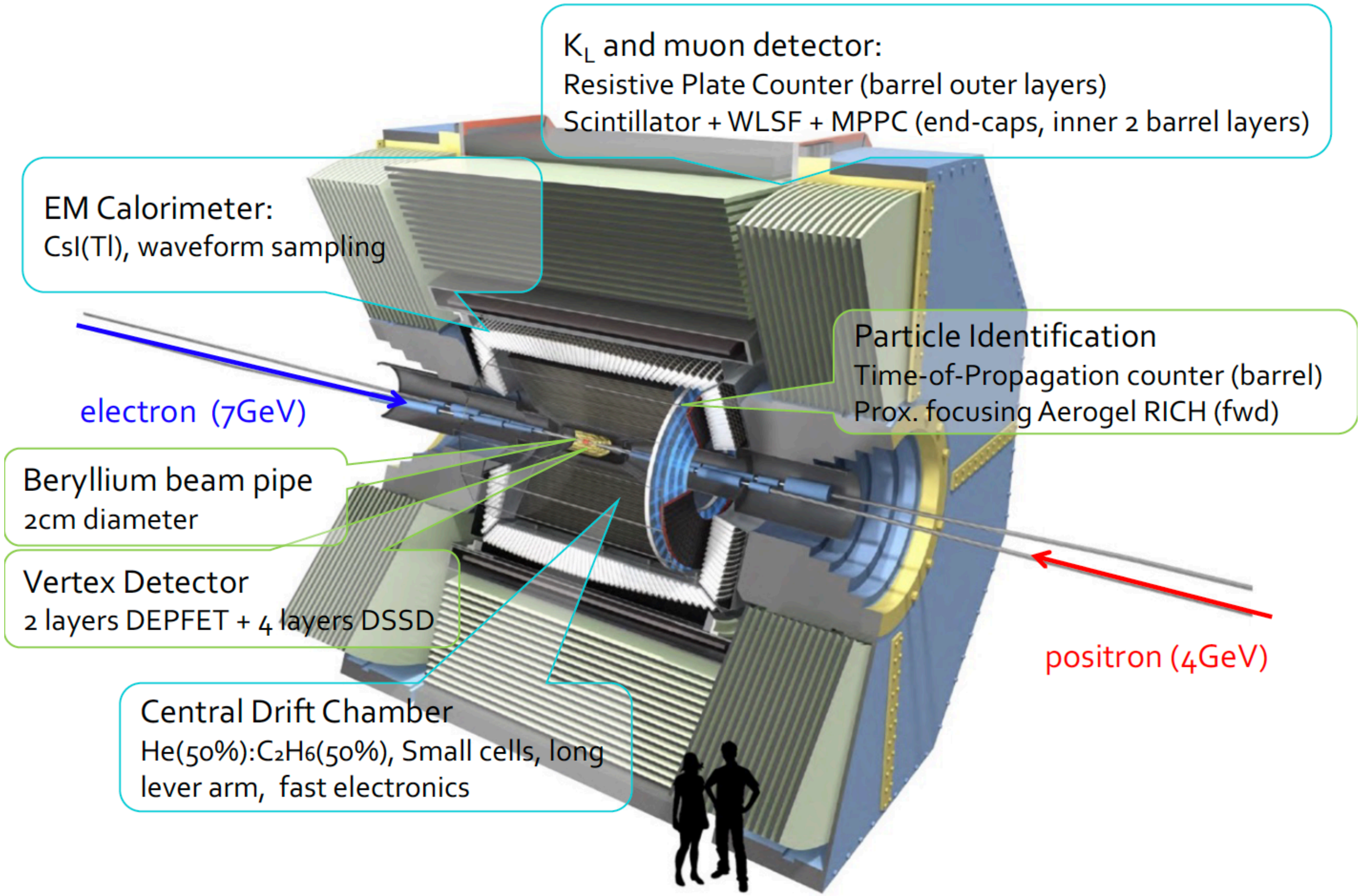
	Belle (535 fb^{-1})	**Belle II (1 ab^{-1})**
$\mathcal{L}$ (cm^2/s)	2.11×10^{34}	80×10^{34}
ε_{signal}	5.09%	4.59%
n_{BG}	10	-
$B_{90}(\tau \to \mu\gamma)$	**4.5×10^{-8}**	**2.7×10^{-8}**

→

Belle II (50 ab^{-1})
5.5×10^{-10}

a naive extrapolation by luminosity

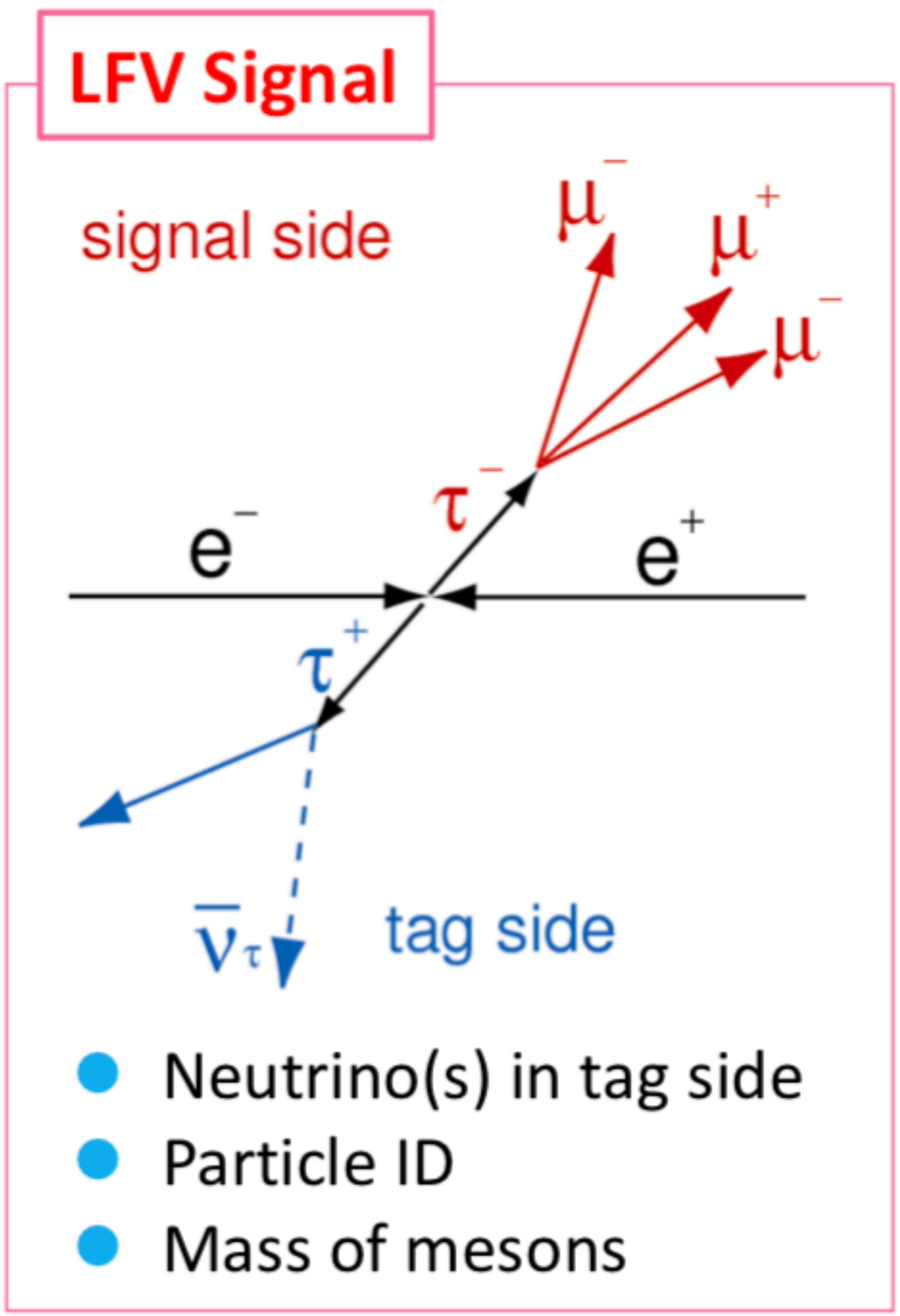
Belle II

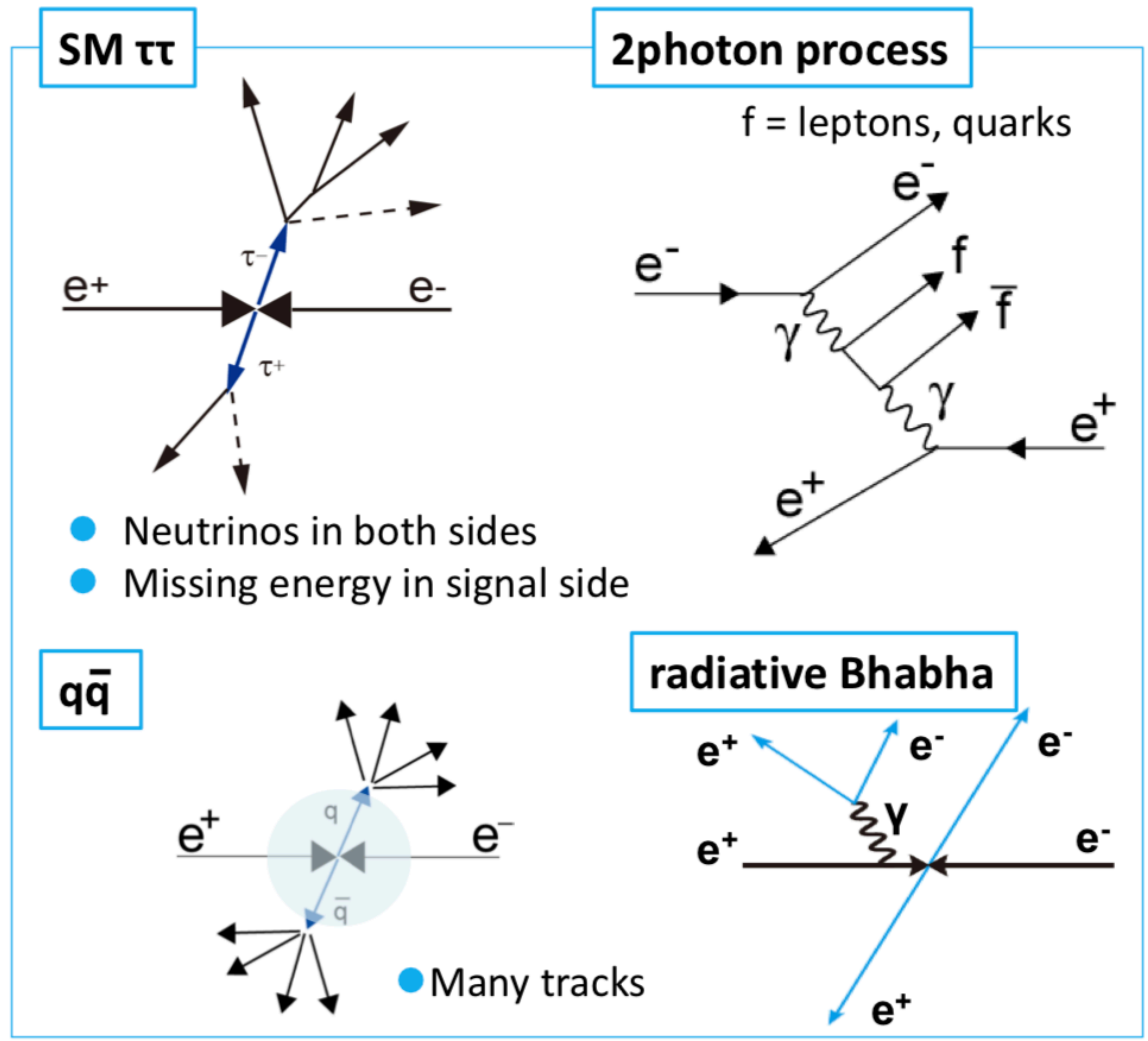


K$_L$ and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
EM Calorimeter:
CsI(Tl), waveform sampling
electron (7GeV)
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)
Beryllium beam pipe
2cm diameter
Vertex Detector
2 layers DEPFET + 4 layers DSSD
positron (4GeV)
Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long
lever arm, fast electronics

Signal and backgrounds

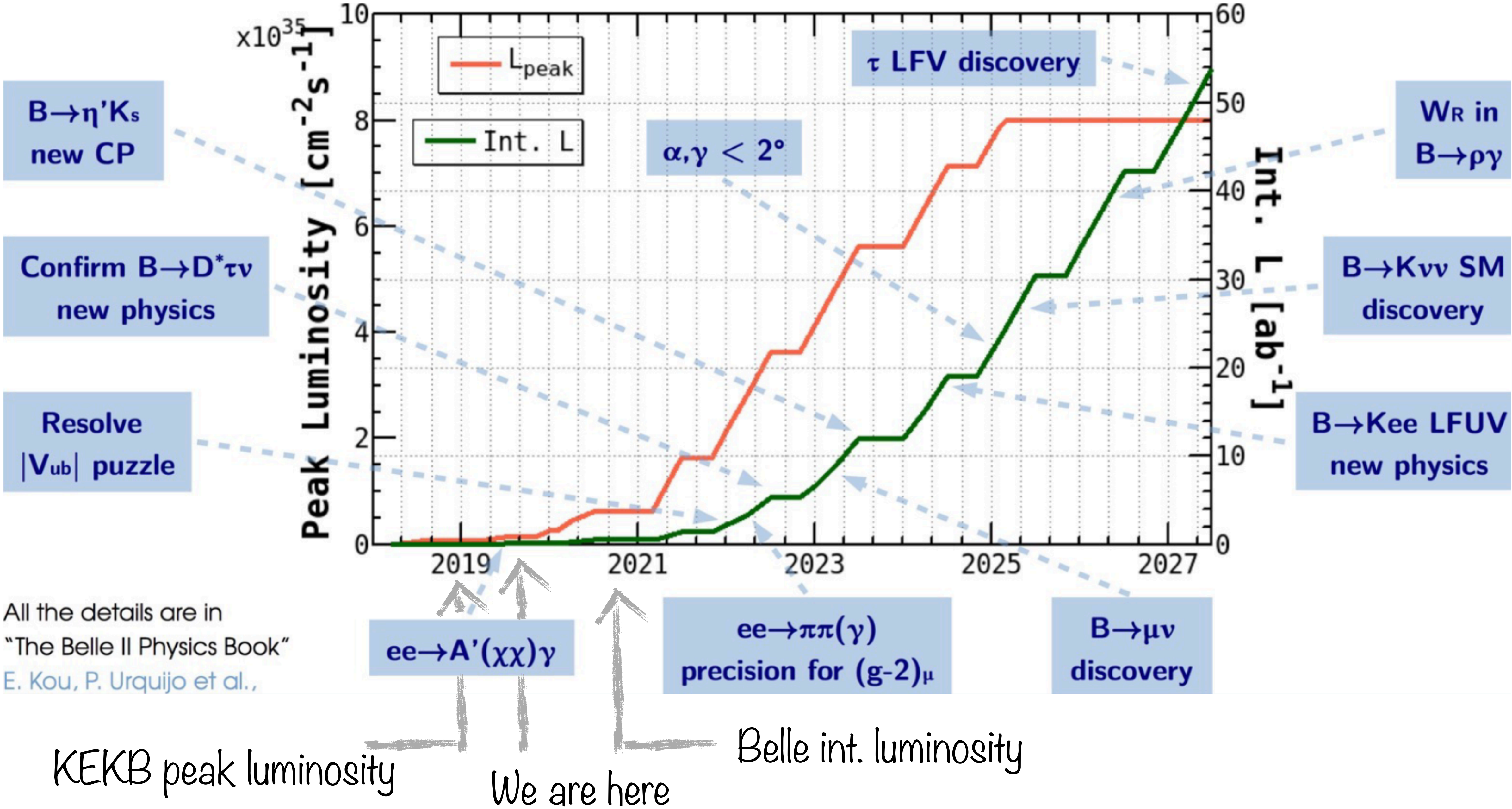
- Major backgrounds differ among LFV channels





BELLE II: Status

- Very reach physics potentiality (**arXiv 1808.10567**)
- FInal goal: 40x KEKB Luminosity

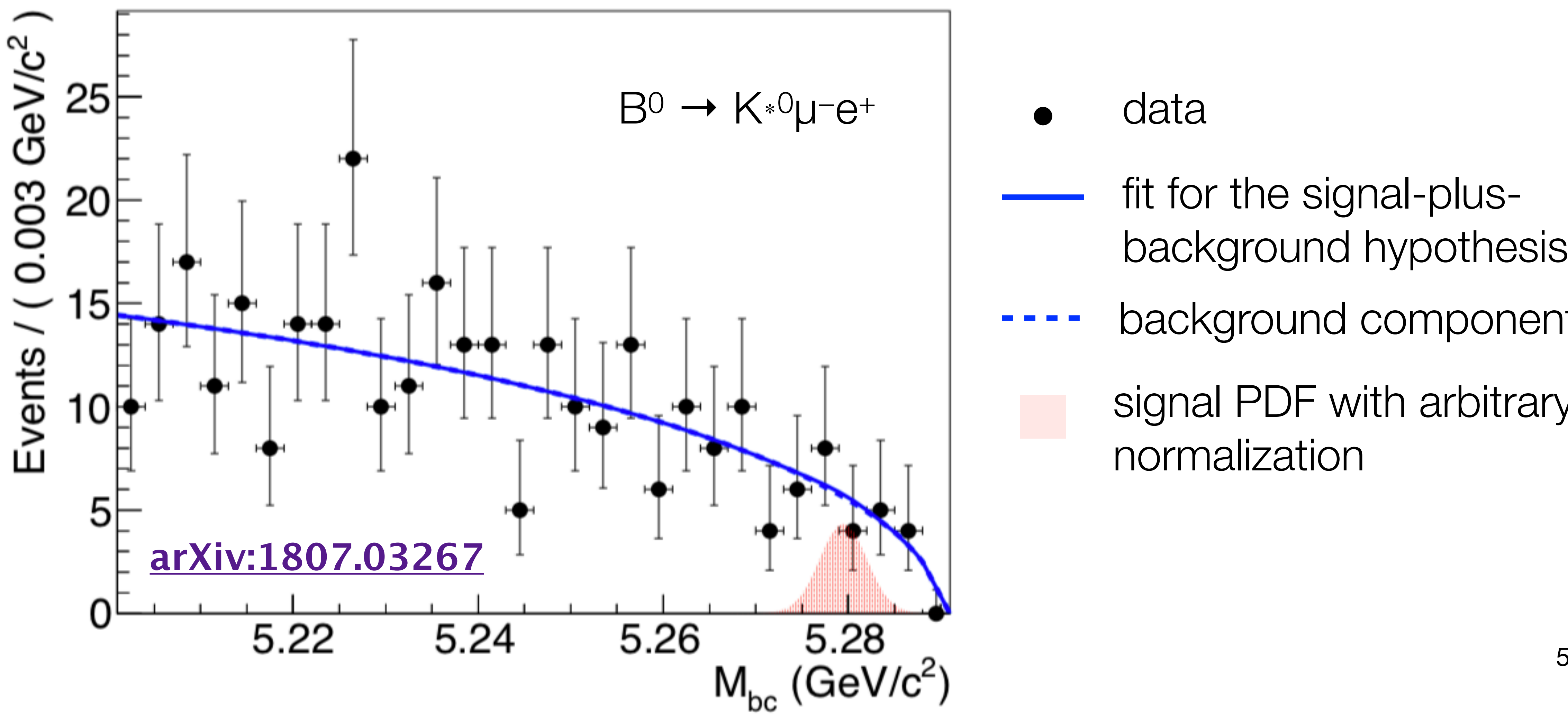


All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

LVF K* l+ l- decays: Belle updated results

- Belle opened world best constraints of the LVF k* ll modes @ 90% C.L.
- Belle II will aim at an improved sensitivity of O(10^{-8})

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 1.2 \times 10^{-7}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 1.6 \times 10^{-7}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$$



Violations in D0-> hh’ll’: Babar updated results

- Updated analysis from the Babar experiment: **arXiv 1905.00608v1**
- Lepton flavour violating (LFV) and lepton number violating (LNV) processes
- No signal but improvements wrt the previous limits

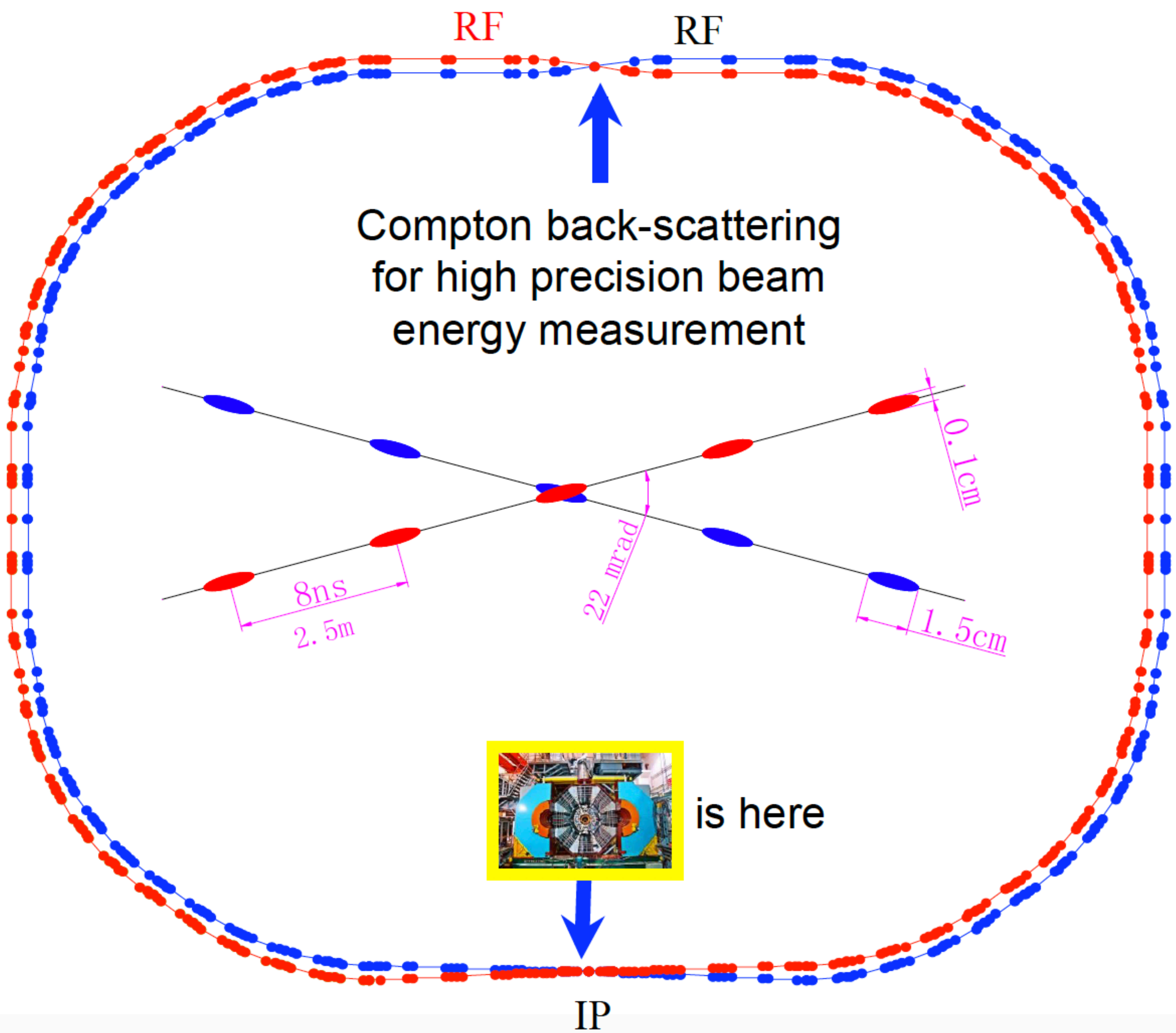
Lepton flavour violating (LFV)

$\pi^-\pi^+e^{+-}\mu^{-+}$ $\quad$ $K^-\pi^+e^{+-}\mu^{-+}$ $\quad$ $K^-K^+e^{+-}\mu^{-+}$

Decay mode $D^0 \to$	$N_{\rm sig}$ (candidates)	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$)	Previous best limit ($\times 10^{-7}$)
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38	$0.27 \pm 3.90 \pm 0.67$	9.1	1120
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	4.91	$7.40 \pm 5.40 \pm 0.91$	15.2	290
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	4.38	$15.4 \pm 6.59 \pm 1.85$	30.6	790
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	4.79	$1.55 \pm 6.97 \pm 1.45$	17.1	150
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	3.19	$-0.38 \pm 1.60 \pm 2.11$	5.0	2060
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	3.30	$-0.05 \pm 3.34 \pm 0.64$	5.3	3900
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	3.48	$5.84 \pm 5.97 \pm 3.56$	21.0	2180
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	3.65	$3.62 \pm 6.61 \pm 1.95$	19.0	5530
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	3.25	$0.43 \pm 1.54 \pm 0.58$	3.4	1520
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	6.21	$-0.81 \pm 0.96 \pm 0.32$	1.0	950
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	4.63	$1.93 \pm 1.93 \pm 0.84$	5.8	570
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83	$3.93 \pm 2.89 \pm 1.45$	10.0	1800

BESIII

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



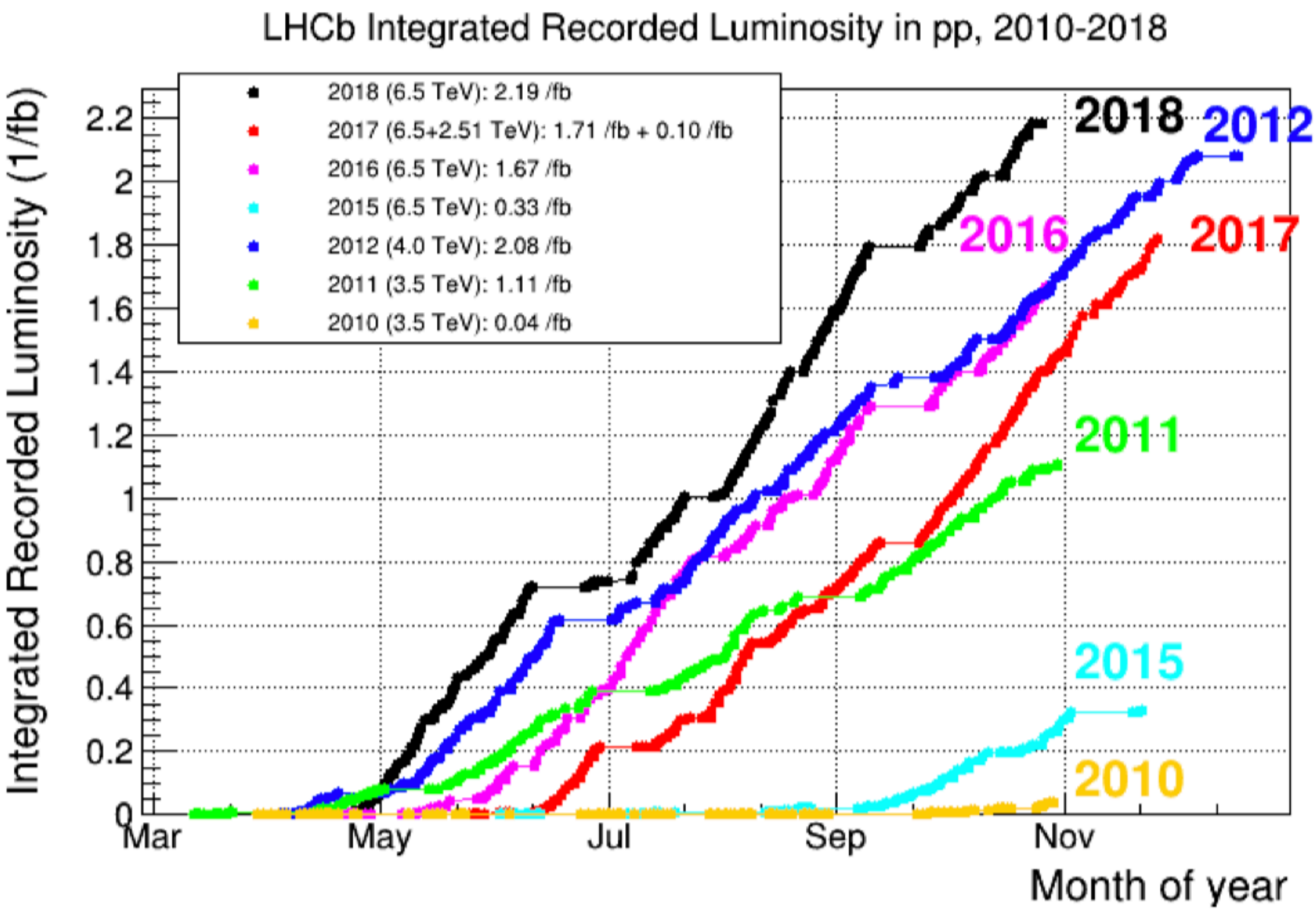
Beam energy:
1-2.3 GeV
Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A @ 2.5 GeV

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)	-	-

cLFV most recent results with LHCb



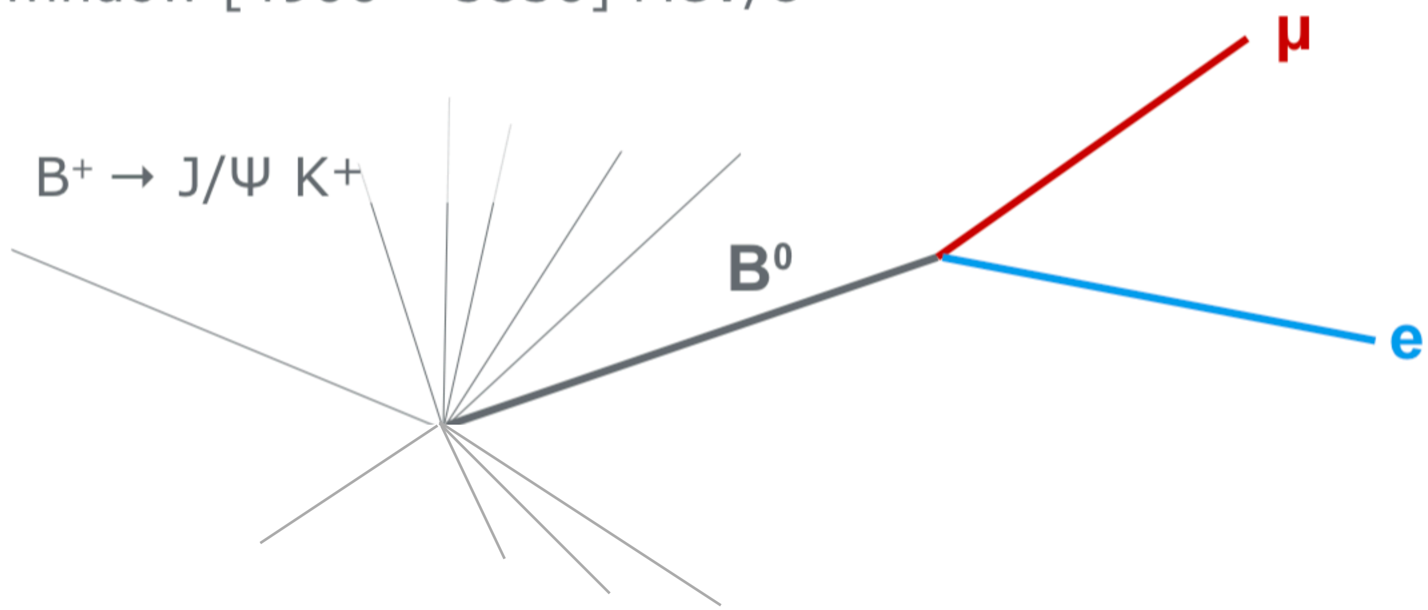
cLFV most recent results with LHCb

- **$B^0_{(s)} \to e\mu$** JHEP 03 (2018) 043
- **$B^0_{(s)} \to \tau\mu$** arXiv:1905.06614 (PRL)
- **$h^0 \to \tau\mu$** EPJ C78 (2018) 1008

Pair of tracks with
good secondary vertex
clearly separated from primary vertex (15x uncertainty)

B-candidate
transverse momentum > 0.5 GeV/c
originating from primary vertex
invariant mass window [4900 – 5850] MeV/c^2

Normalization
$B^0 \to K^+\pi^-$ and $B^+ \to J/\Psi\, K^+$



cLFV most recent results with LHCb

$B(B^0 \rightarrow e\mu) < 1.0(1.3) \times 10^{-9}$

$B(B_s^0 \rightarrow e\mu) < 5.4(6.3) \times 10^{-9}$*

@ 90%(95%) C.L.

2–3x improvement over previous result

$B(B^0 \rightarrow \tau\mu) < 1.2(1.4) \times 10^{-5}$

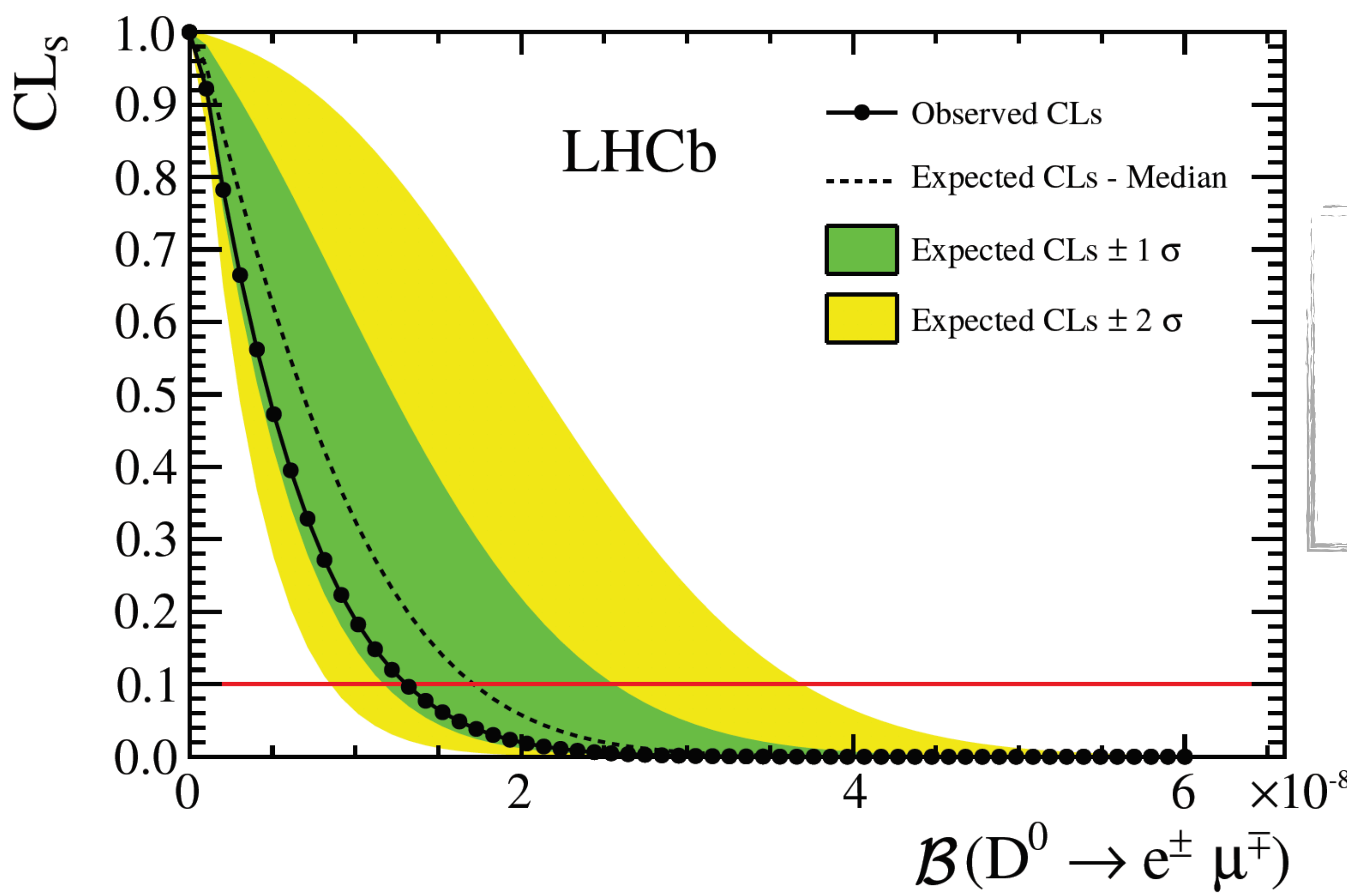
$B(B_s^0 \rightarrow \tau\mu) < 3.4(4.2) \times 10^{-5}$

@ 90%(95%) C.L.

B^0 : 2x improvement over previous result
B_s^0 : first measurement

LHCb: cLFV in charm

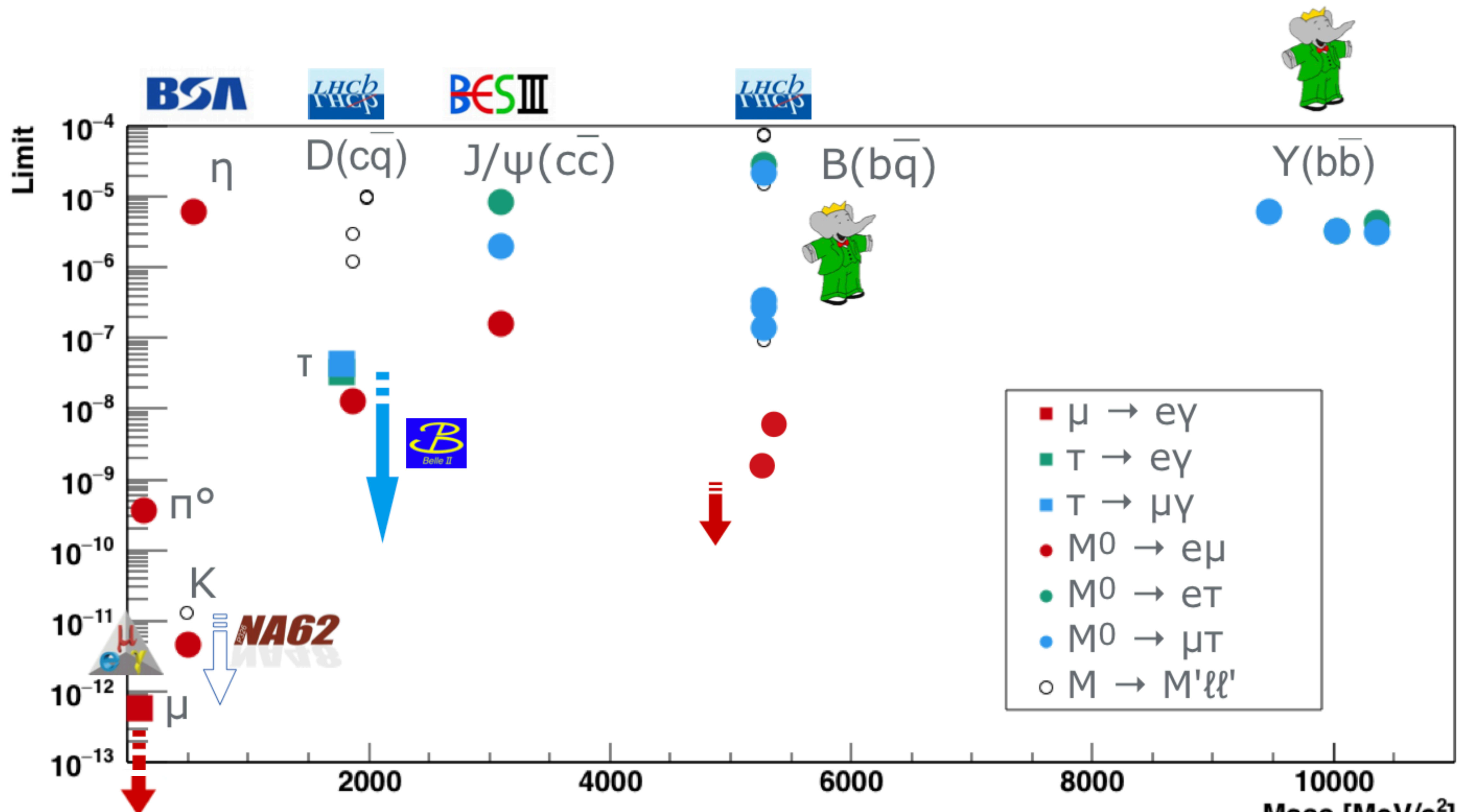
- CLFV searches in D^0 -> e^+ μ^-
- If only upper limits are set: Strong constraints on RPV SUSY models for improved $O(10^{-7})$ and parameter space in some lepton-quarks models for $O(10^{-8})$
- New upper limit set (previous upper limit from Belle: BR (D^0 -> e^+ μ^-) < 2.6 10^{-7} @ 90% C.L.



$$BR(D^0 \to e^+\mu^-) < 1.3\ 10^{-8}$$
at 90% C.L.

credits: G.Onderwater

LFV prospects with hadrons



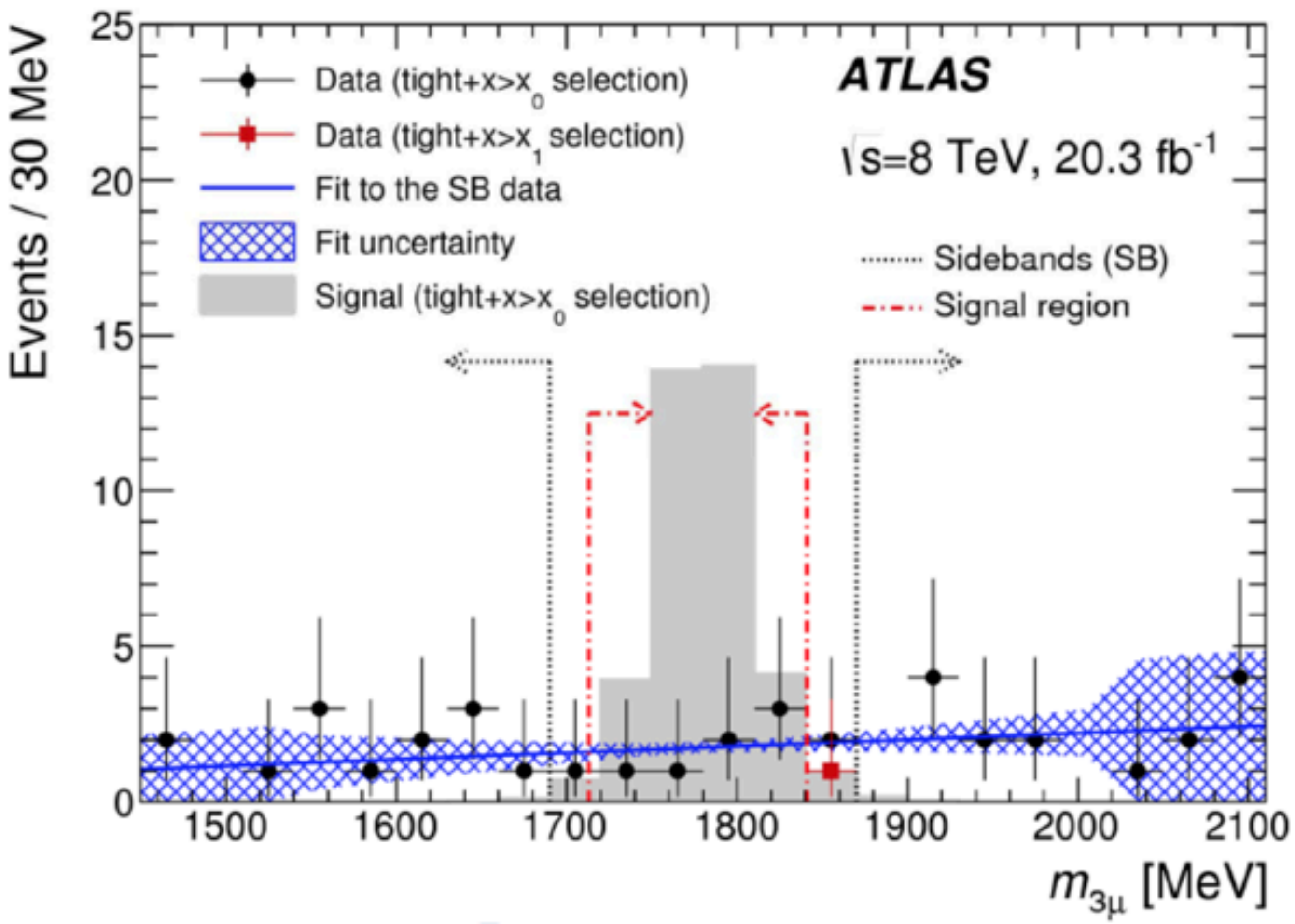
Take away message

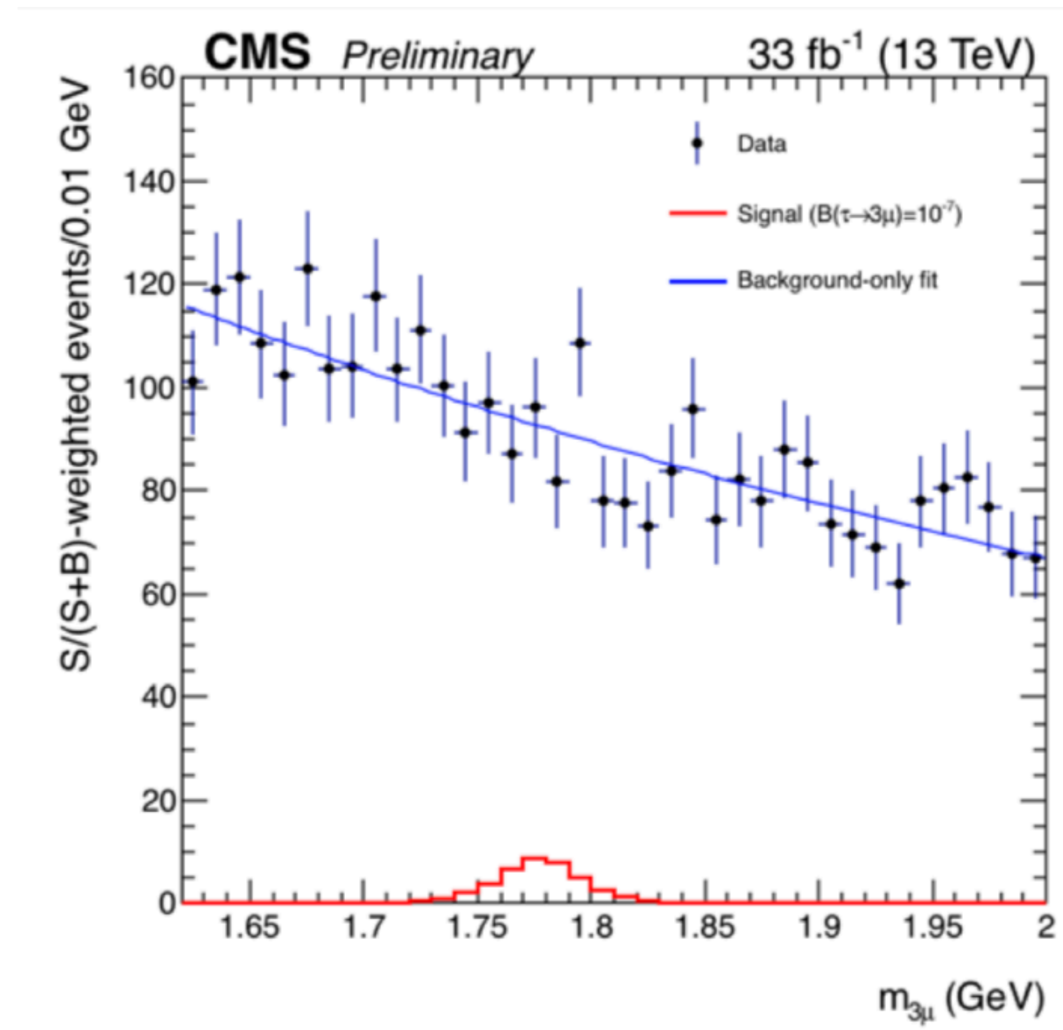
- **LHCb**: study flavour physics with all three lepton generations
- With LHC Run-I data LHCb sharpened limits for many LFV (LNV, BNV) channels
- No significant deviations from **SM** seen
- Demonstrated sensitive **BSM** searches @ hadron collider
- Many additional channels available
- Lots of additional data to be analyzed from Run-II (just completed) & expected from Run-III

Eur. Phys. J. C (2016) 76:232
CMS-PAS-BPH-17-004

ATLAS&CMS

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





ATLAS: BR(τ→μμμ)< 3.8 10^{-7} @ 95% CL
CMS: BR(τ→μμμ)< 8.8 10^{-8} @ 90% CL

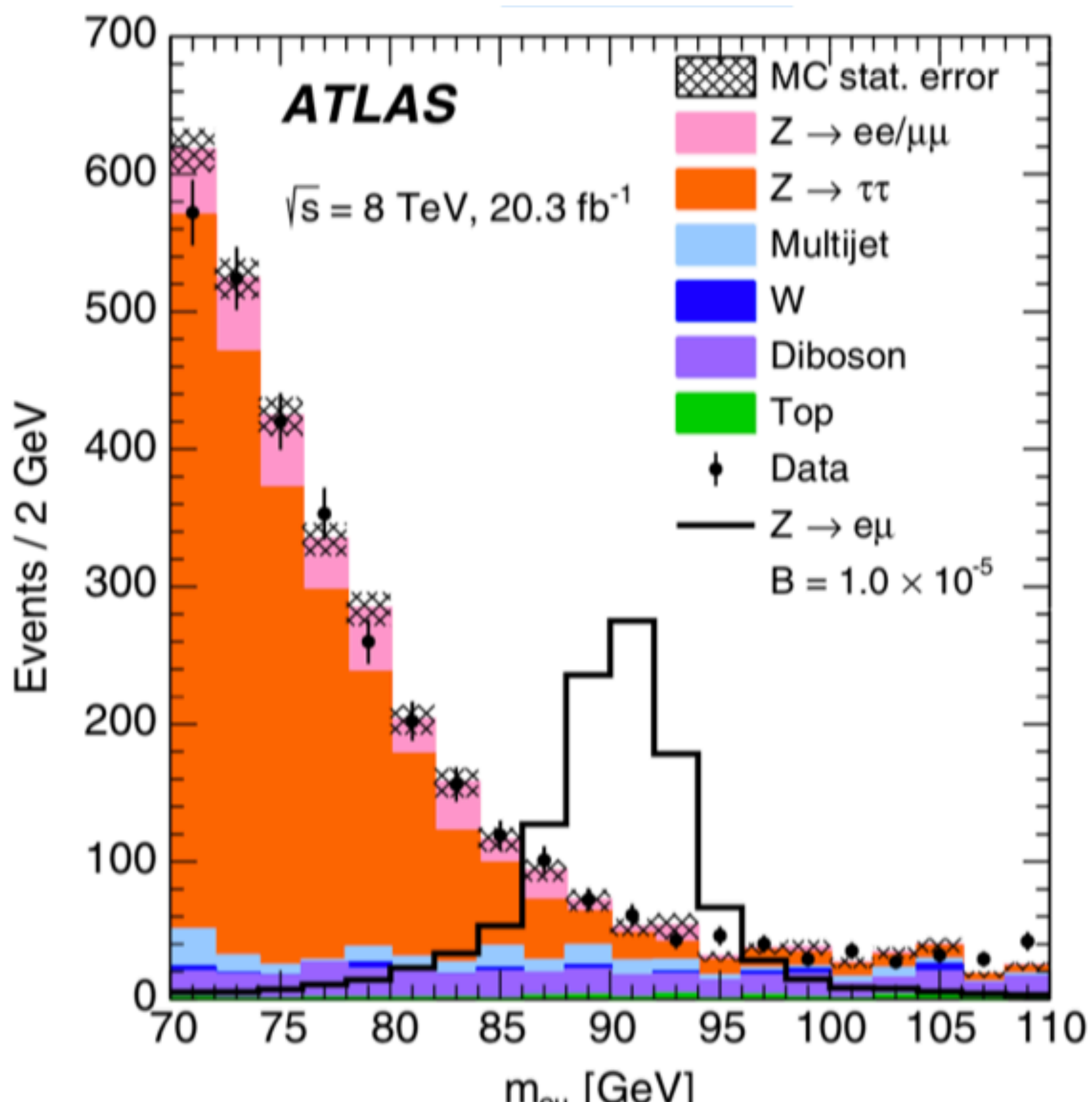
PDG : BR(τ→μμμ) < 2.1 10^{-8} @ 95% CL. (BELLE)
< 3.3 10^{-8} @ 95% CL. (BABAR)
< 4.6 10^{-8} @ 95% CL. (LHCb)

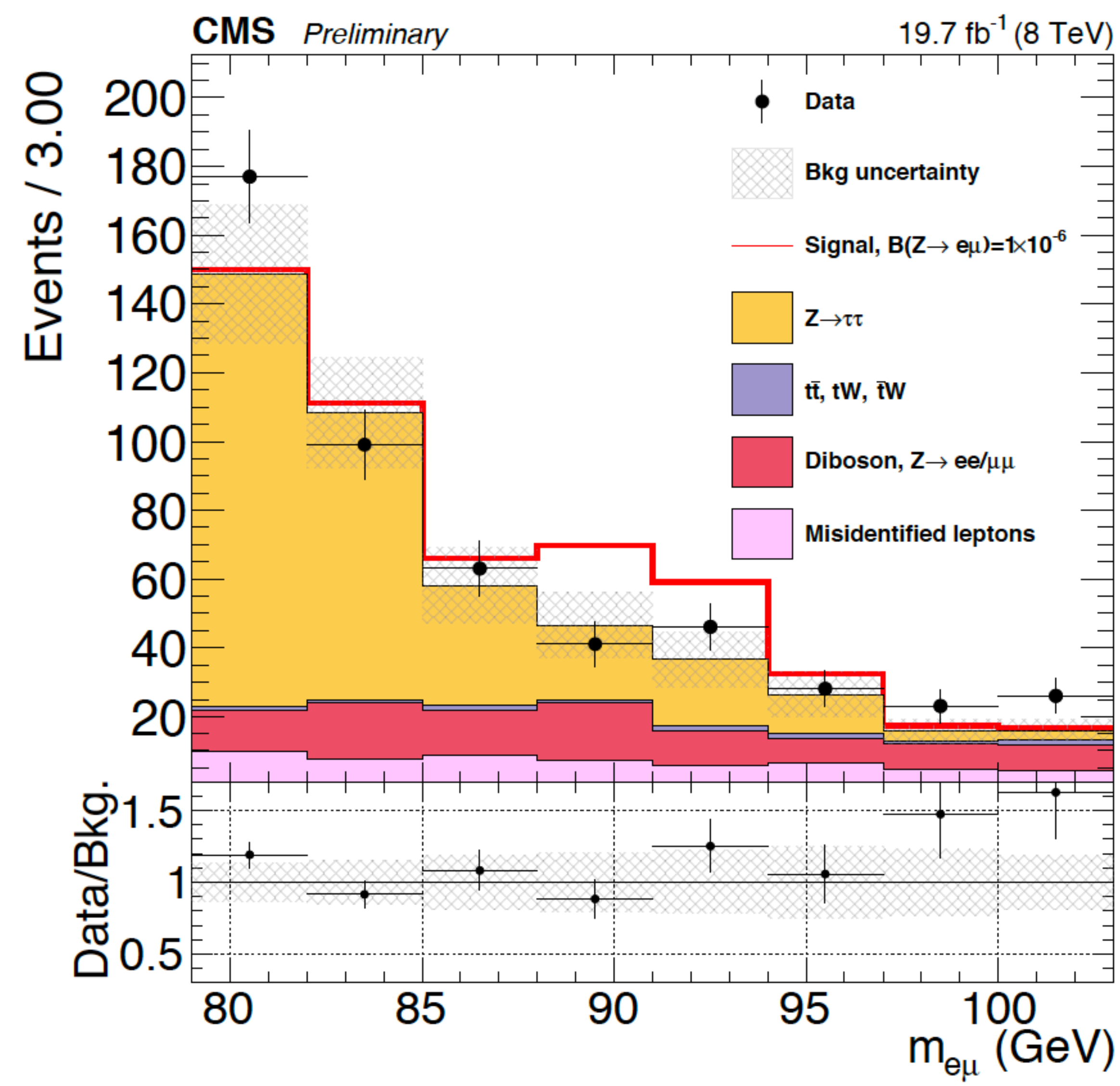
Phys. Rev D90,072101

CMS PAS EXO-13-005

ATLAS&CMS

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

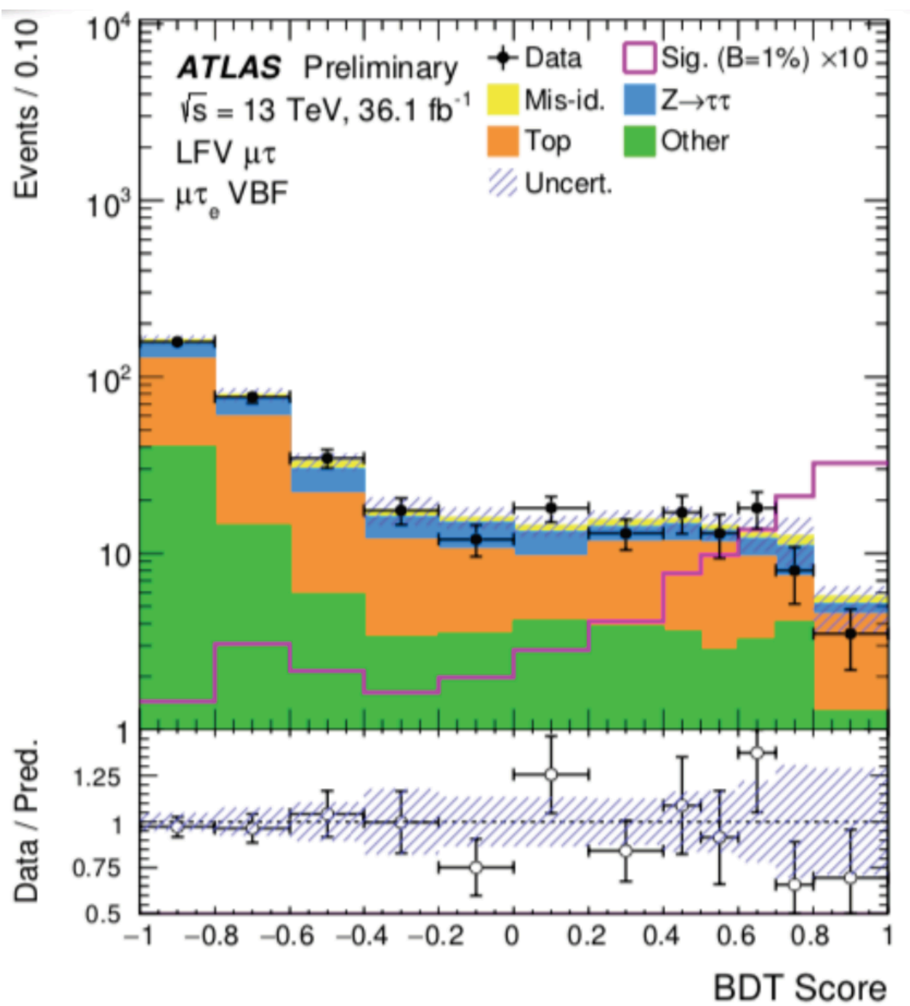


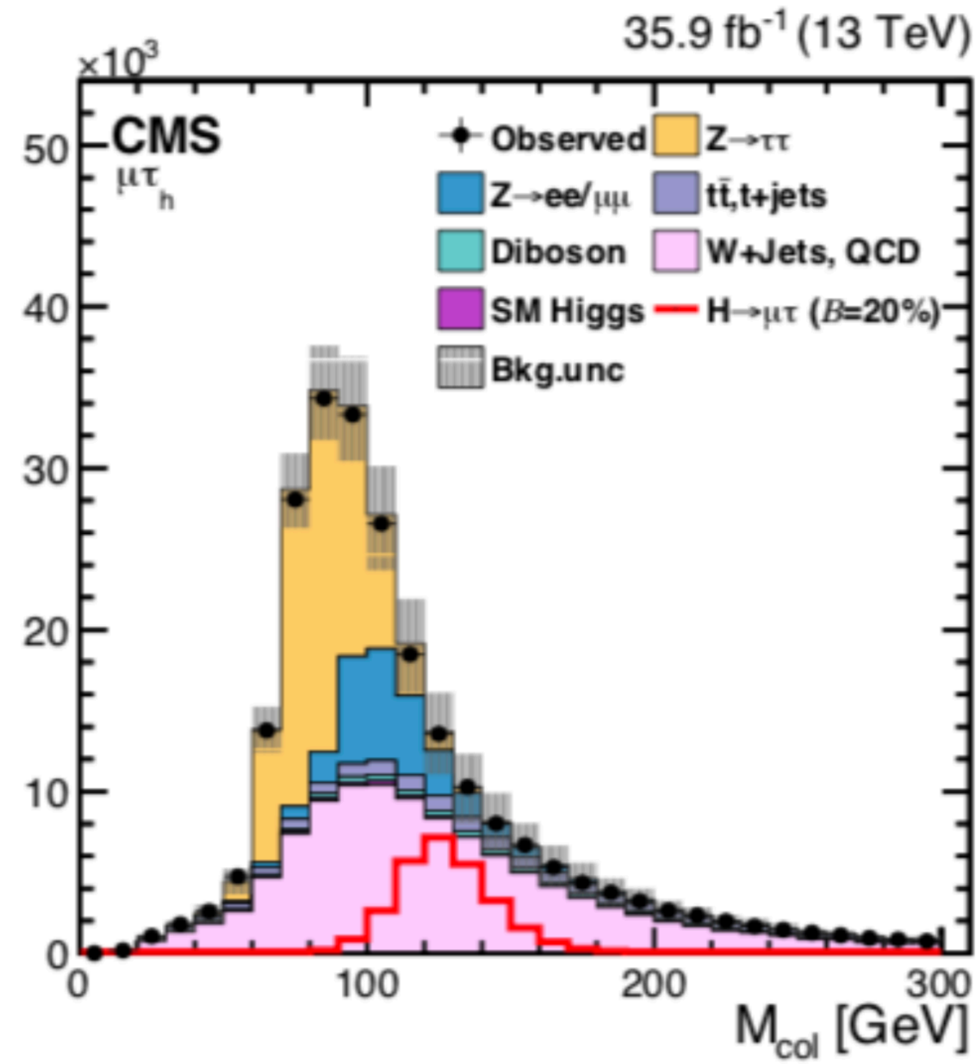


ATLAS: BR (Z -> e μ) < 7.5 10^{-7} CMS: BR (Z -> e μ) < 7.3 10^{-7}

ATLAS&CMS

- H -> μ τ/e τ searches
- Main backgrounds are the Z-> τ τ, W=jets, ttbar and QCD production





Observed (expected) limits at 95% CL

ATLAS: BR (H -> μτ) < 0.28 (0.37+0.14-0.10) %
BR(H -> eτ) < 0.47 (0.34+-.13-0.10) %

CMS: BR (H -> μτ) < 0.25(0.25) %
BR(H -> eτ) < 0.61 (0.37) %

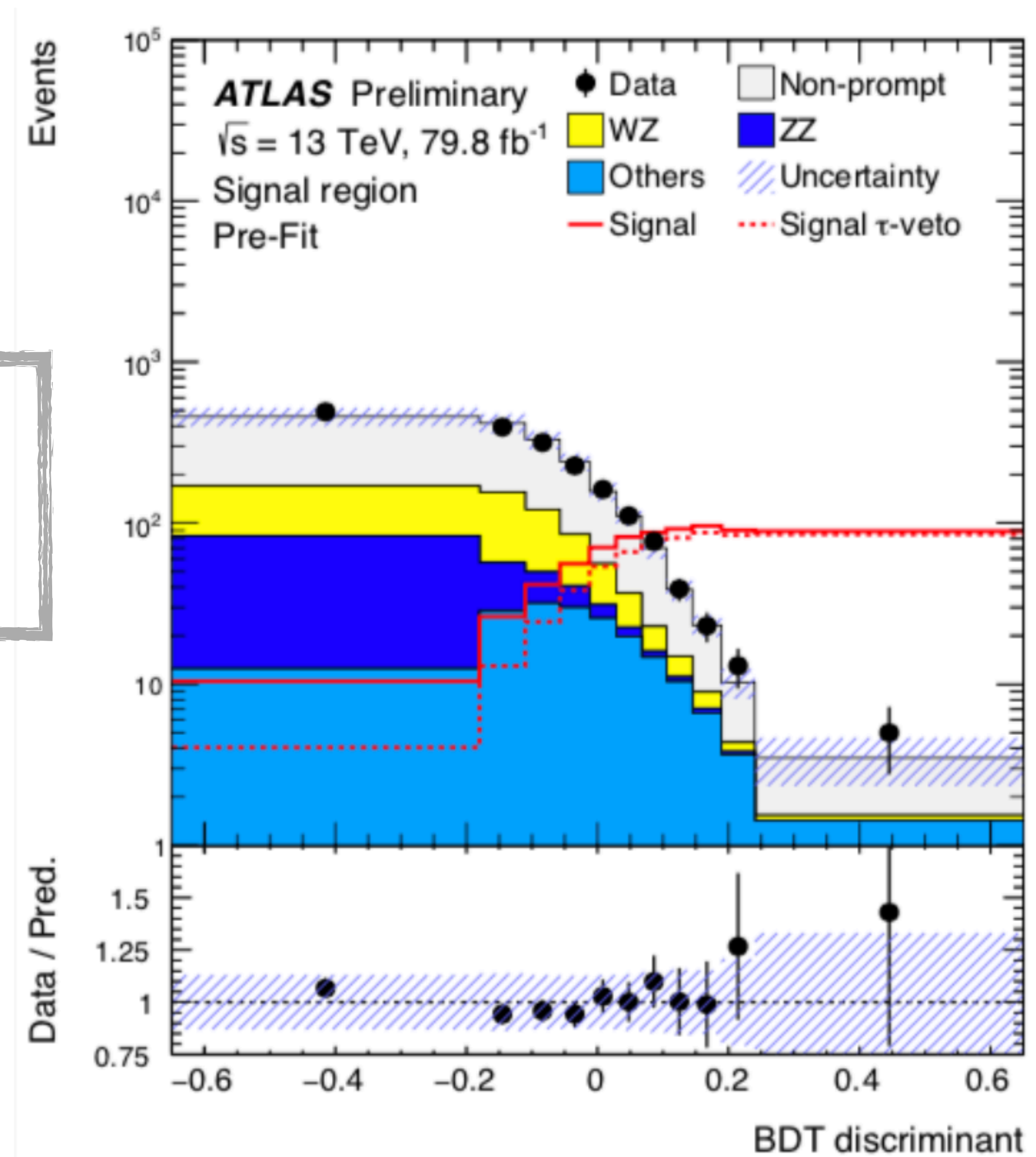
Eur Phys J C 2015; 75(9): 450

ATLAS

- LVF top decays: First direct search
- Couplings with cLFV top quark less unconstrained: within the sensitivity of the LHC

BR(t -> ll'q) < 1.86 10^{-5} at 95% CL

BR(t -> eμq) < 6.6 10^{-6} at 95% CL

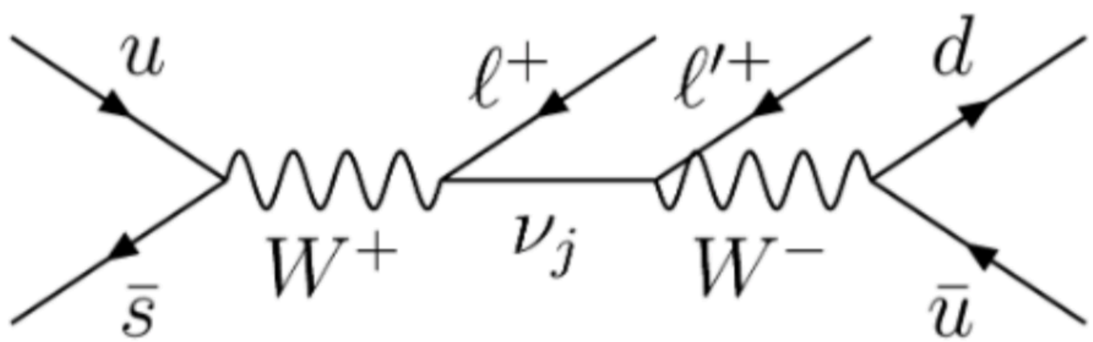


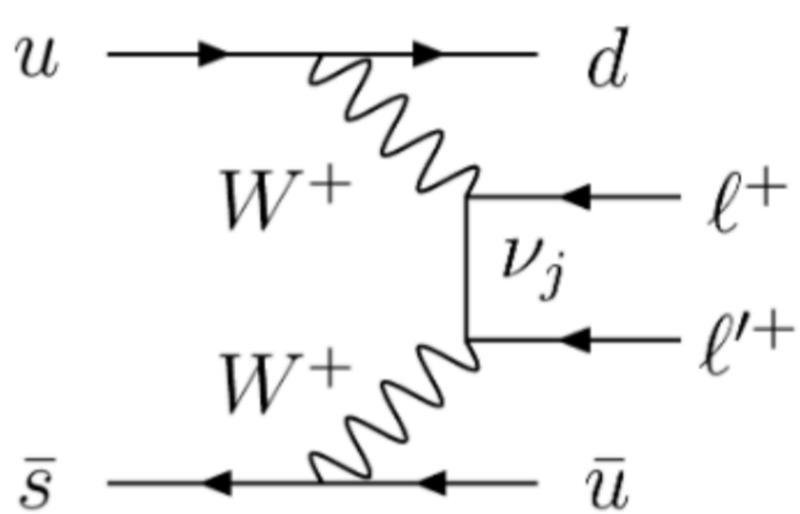
Take away message

- **ATLAS & CMS** have diverse and expanding program of direct and indirect cLFV searches
- Intriguing hints of new physics in B meson decays have renewed interest
- No evidence or discovery of LFV processes so far **but there is still room with the full run2 (2016+ 2017+ 2018) datasets**

NA62: LFV/LNV $K^+ \to \pi^- l^+ l^+$

- $K^+ \to \pi^- l^+ l^+$: $\Delta L = 2$ and $\Delta L_\mu = 2$ or $\Delta L_e = 2$ ($l = \mu/e$) via Majorana neutrinos U [PL B491 (2000) 285-290, JHEP 0905 (2009) 030]





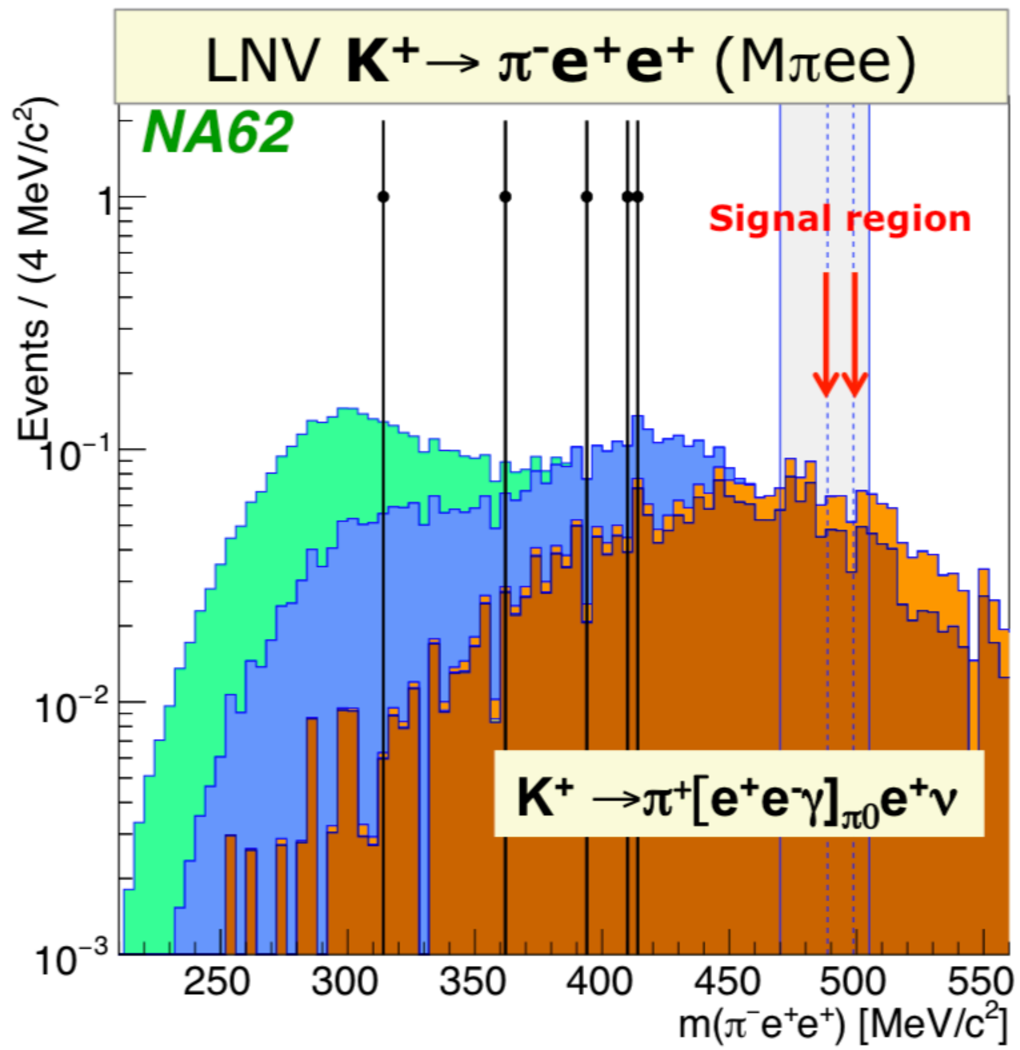
- **Experimental status**
- **BR($K^+ \to \pi^- e^+ e^+$): 6.4×10^{-10}** at 90% CL [BNL E865, PRL 85 (2000) 2877]
- **BR($K^+ \to \pi^- \mu^+ \mu^+$) < 8.6×10^{-11}** at 90% CL [NA48, PL B769 (2017) 67]

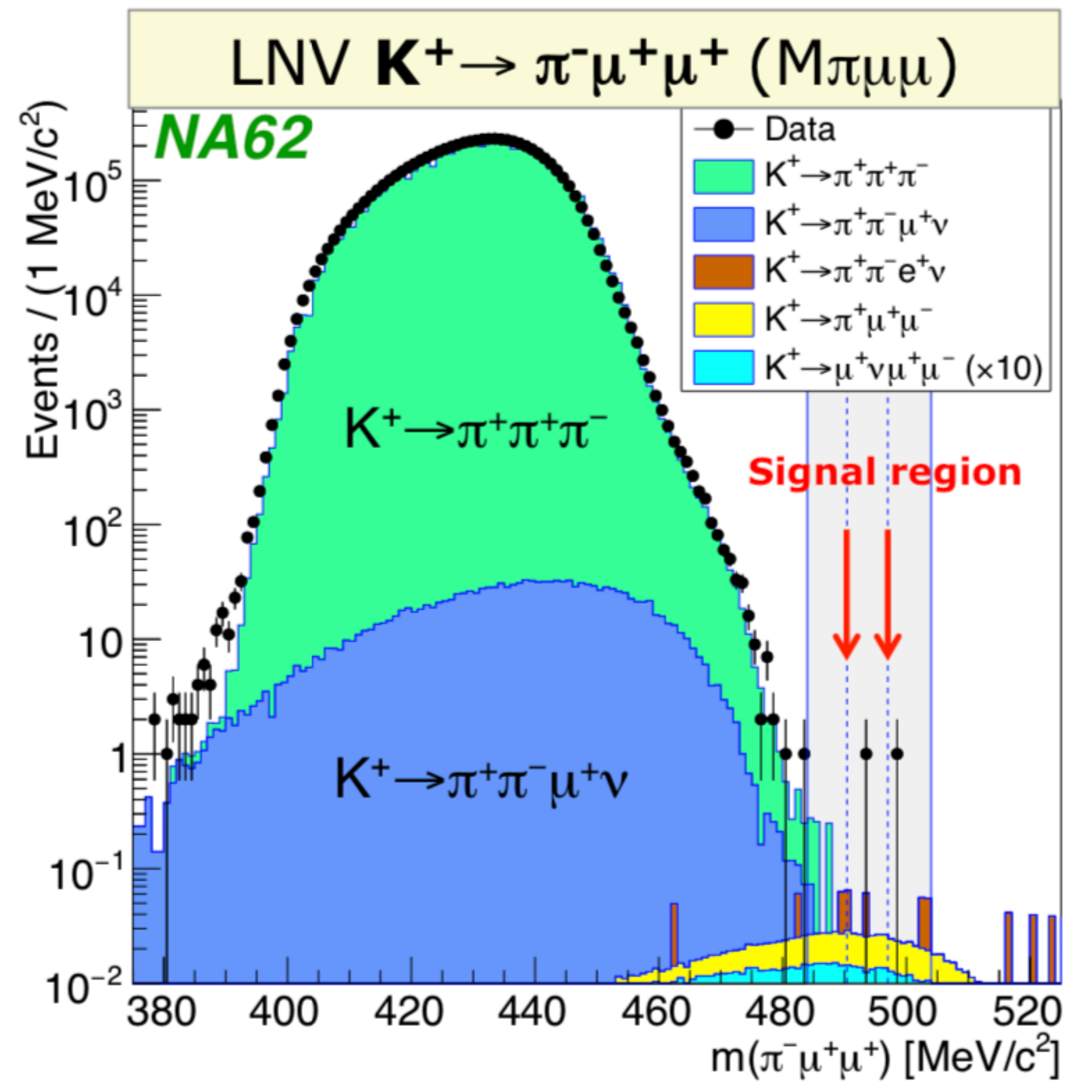
$K^+ \to \pi^- e^+ e^+ / \pi^- \mu^+ \mu^+$

Talk: C. Lazzeroni

- Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

arXiv:1905.07770





$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ at 90% CL $BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ at 90% CL arXiv:1905.07770

Future prospects

Upper Limits set with 80% of the 2017 NA62 data set:

- **BR($K^+ \rightarrow \pi^- e^+ e^+$) < 2.2 x 10^{-10}** at 90% CL
- **BR($K^+ \rightarrow \pi^- \mu^+ \mu^+$) < 4.2 x 10^{-11}** at 90% CL

Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

Competitive SES achieved with 2017 data for:

- $K^+ \rightarrow \pi^- \mu^+ e^+$ [LNV] & $K^+ \rightarrow \pi^+ \mu^- e^+$ [LFV]
  SES ~5 x 10^{-11} (factor ~5 improvement on BNL-E865)

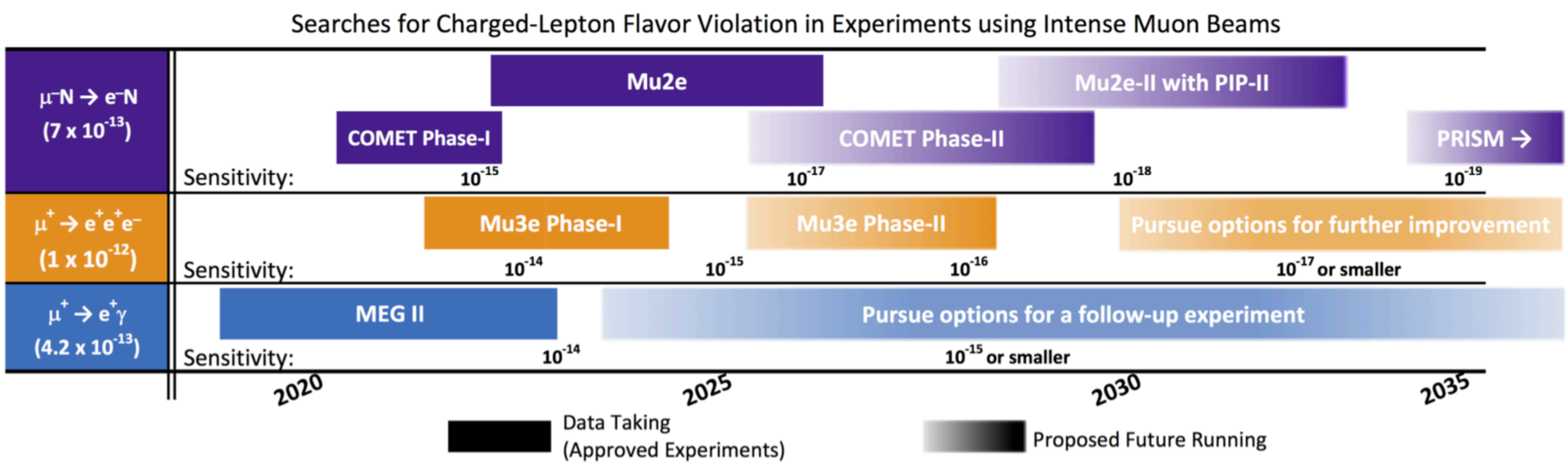
- $K^+ \rightarrow e^- \nu \mu^+ \mu^+$ [LFV]
  SES ~5 x 10^{-11} (first search for this mode)

- $K^+ \rightarrow \mu^- \nu e^+ e^+$ [LFV]
  SES ~1 x 10^{-10} (factor 100 improvement on PDG)

Analysis in progress

Final remarks: Low energy prospects

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- **muon-cLFV remains one of the most exciting place where to search for new physics**
- **Strong support from the European Strategy Committee**



Final remarks: Precision measurements at B-factories

- Flavour physics provide an extremely rich landscape of measurements opening windows on New Physics
- High luminosity e+e- colliders offer a pristine and well defined environment
- Existing data sets (Babar and Belle) are still providing new results
- BESIII is providing more measurements at the tau/charm energy
- BelleII just started looking forward to more luminosity

Final remarks: LHC & low energy

7 Conclusions

From the comprehensive case study in this work, we see that precision measurements and the LHC study are indeed complementary. Which experiment gives the best reach depends on both the quark flavour and the lepton pair in the operator. For light quarks u, d and s, precision measurements clearly outperform the LHC irrespective of the charged lepton flavour. However, the LHC becomes competitive for heavier quarks, c and b, and there is an interesting interplay between the two approaches to obtain limits on LFV operators with two quarks and two leptons. Operators with $e\mu$ are still highly constrained by precision measurements, particularly μ-e conversion in nuclei, but the LHC competes for LFV operators with right-handed τ leptons and can set limits independent of the phase of the Wilson coefficient. We set a lower limit of 600–800 GeV on the cutoff scale of all these operators.

"A Case Study of the Sensitivity to LFV Operators with Precision Measurements and the LHC", Cai & Schmidt, JHEP02(2016)176

cLFV best upper limits

Process	Upper limit	Reference	Comment
$\mu^+ \to e^+ \gamma$	4.2×10^{-13}	Eur. Phy. J. c 76 (2016) 434	MEG
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	Nucl. Phy. B299 (1988) 1	SINDRUM
$\mu^- N \to e^- N$	7.0×10^{-13}	Eur. Phy. J. c 47 (2006) 337	SINDRUM II
$\tau \to e \gamma$	3.3×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau \to \mu \gamma$	4.4×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau^- \to e^- e^+ e^-$	2.7×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^- \mu^+ \mu^-$	2.1×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$B0 \to e \mu$	1.0×10^{-9}	JHEP 03 (2018) 043	LHCb
$B0 \to \tau \mu$	1.2×10^{-5}	arXiV:1905.06614 (PRL)	LHCb
$Z \to \mu e$	7.5×10^{-7}	Phy. Rev. D 90 (2014) 072010	Atlas
$Z \to \mu e$	7.3×10^{-7}	CMS PAS EXO-13-005	CMS
$H \to \tau \mu$	0.25×10^{-2}	JHEP 06 (2018) 001	CMS (*)
$H \to \tau e$	0.47×10^{-2}	ATLAS-CONF-2019-013	ATLAS (*)
$K_L \to \mu e$	4.7×10^{-12}	PRL 81 (1998) 5734	BNL

* $B(H \to \mu e) < O(10^{-8})$ from $\mu \to e \gamma$

Conclusions

- Thanks a lot for your attention
- Credits: all cLFV community

Back-up

The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Strategy:
  - Target optimization
  - Beam line optimization
- Time schedule: **O(2025)**

The High intensity Muon Beam (HiMB) project at PSI

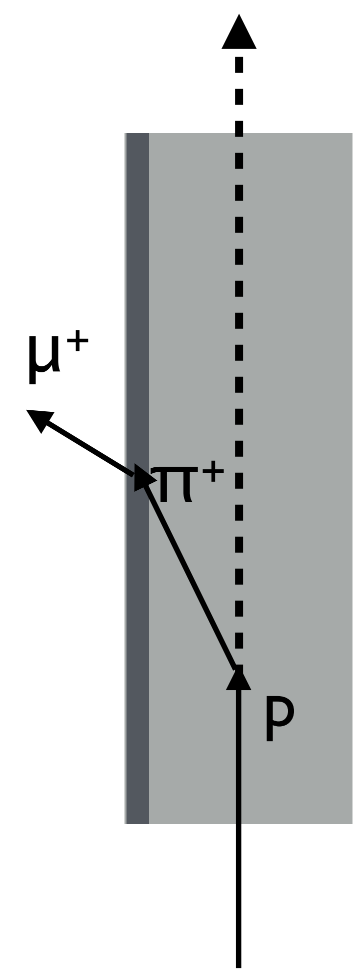
- Back to standard target to exploit possible improvements towards high intensity beams:
  - **Target geometry and alternate materials**
    - Search for high pion yield materials -> higher muon yield

$$relative\ \mu^+ yield \propto \pi^+ stop\ density \cdot \mu^+ Range \cdot length$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_X (Z/A)_X}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

$$\propto \frac{1}{Z^{2/3}}$$



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- Back to standard target to exploit possible improvements towards high intensity beams:
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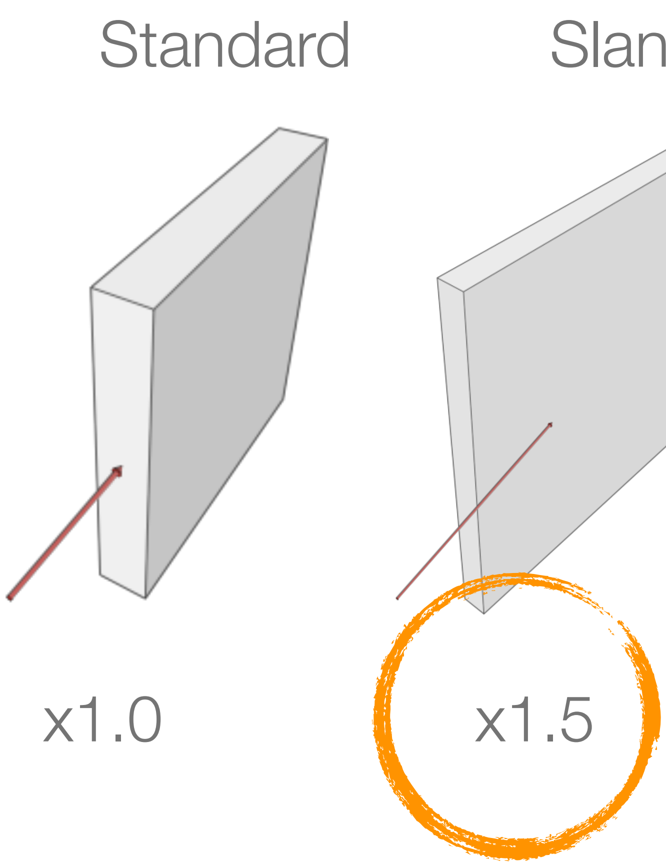
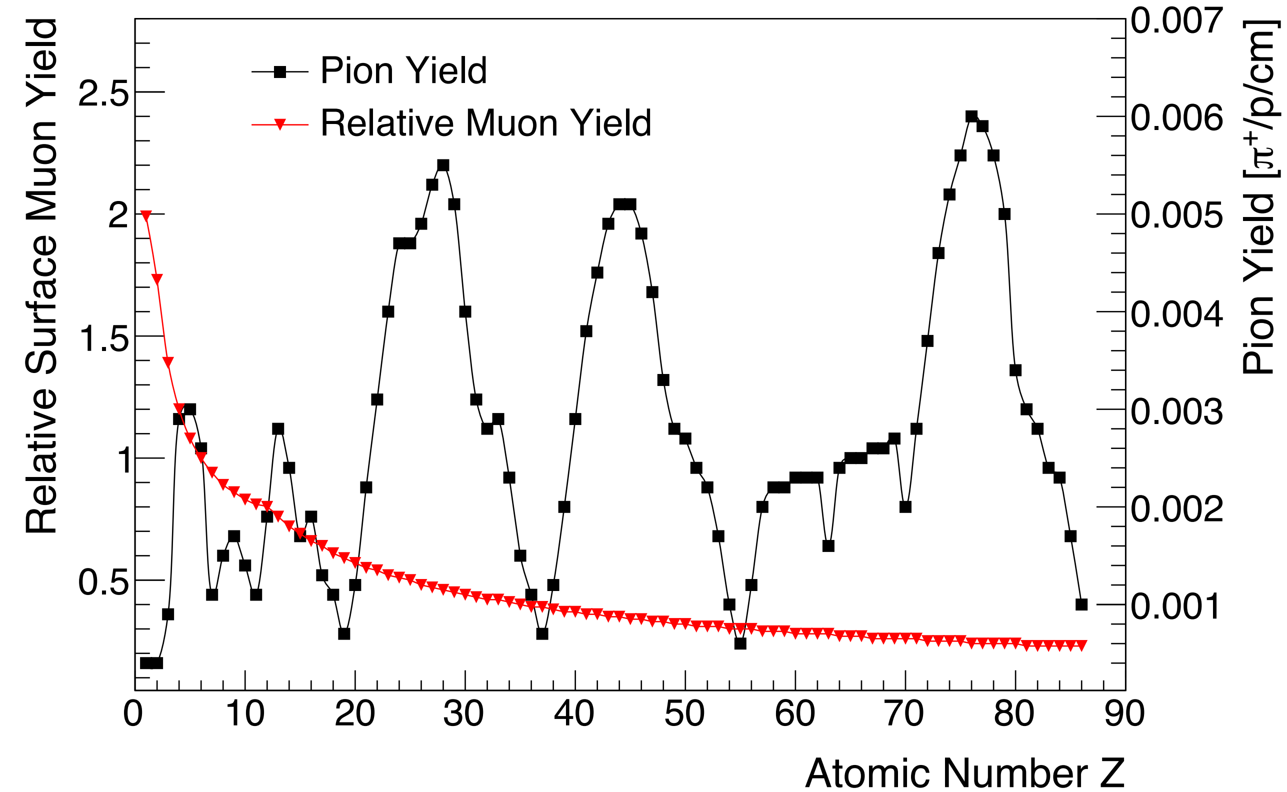
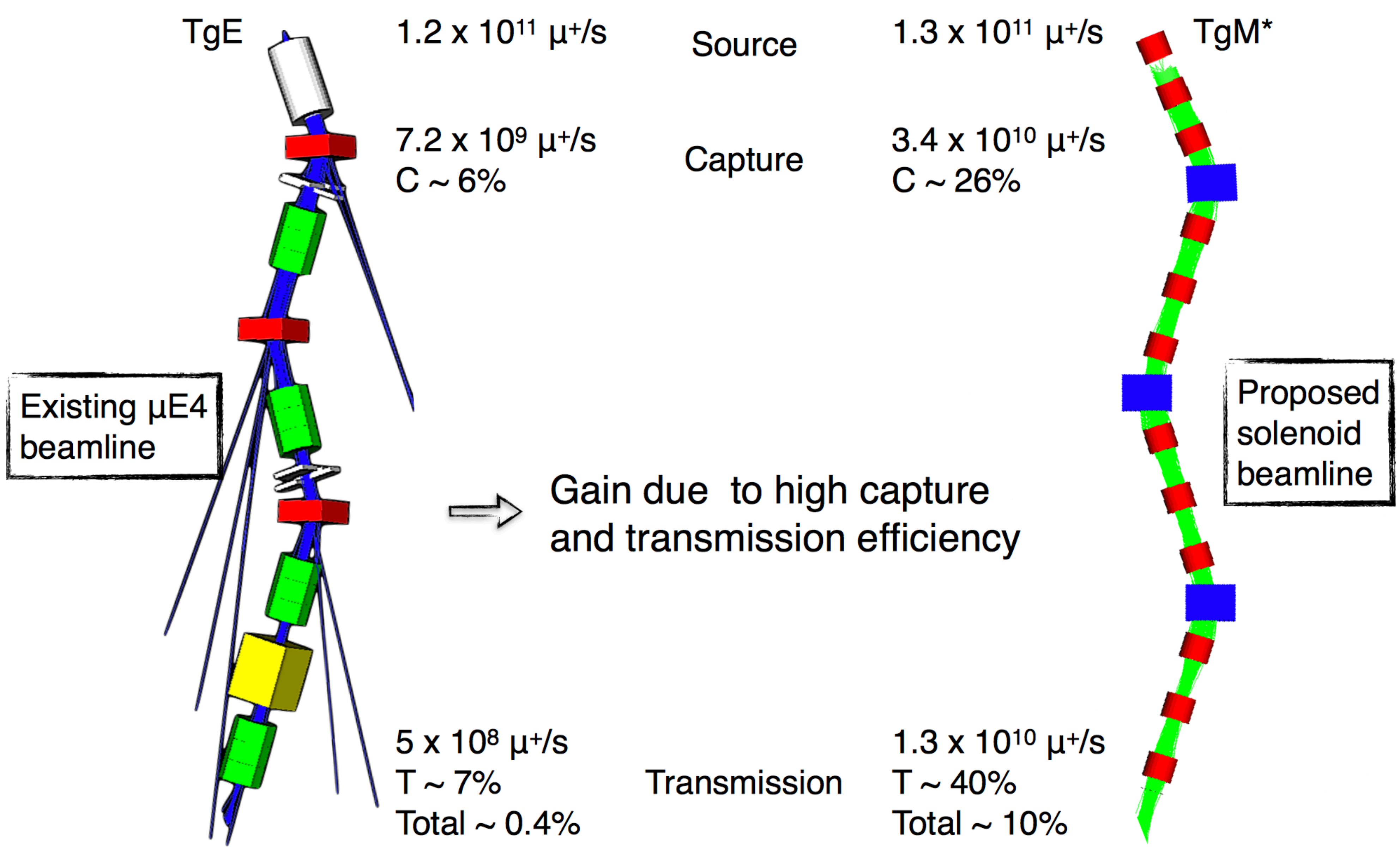




- **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW** without the additional complications such ad increased energy and radiation deposition into the target and its surroundings

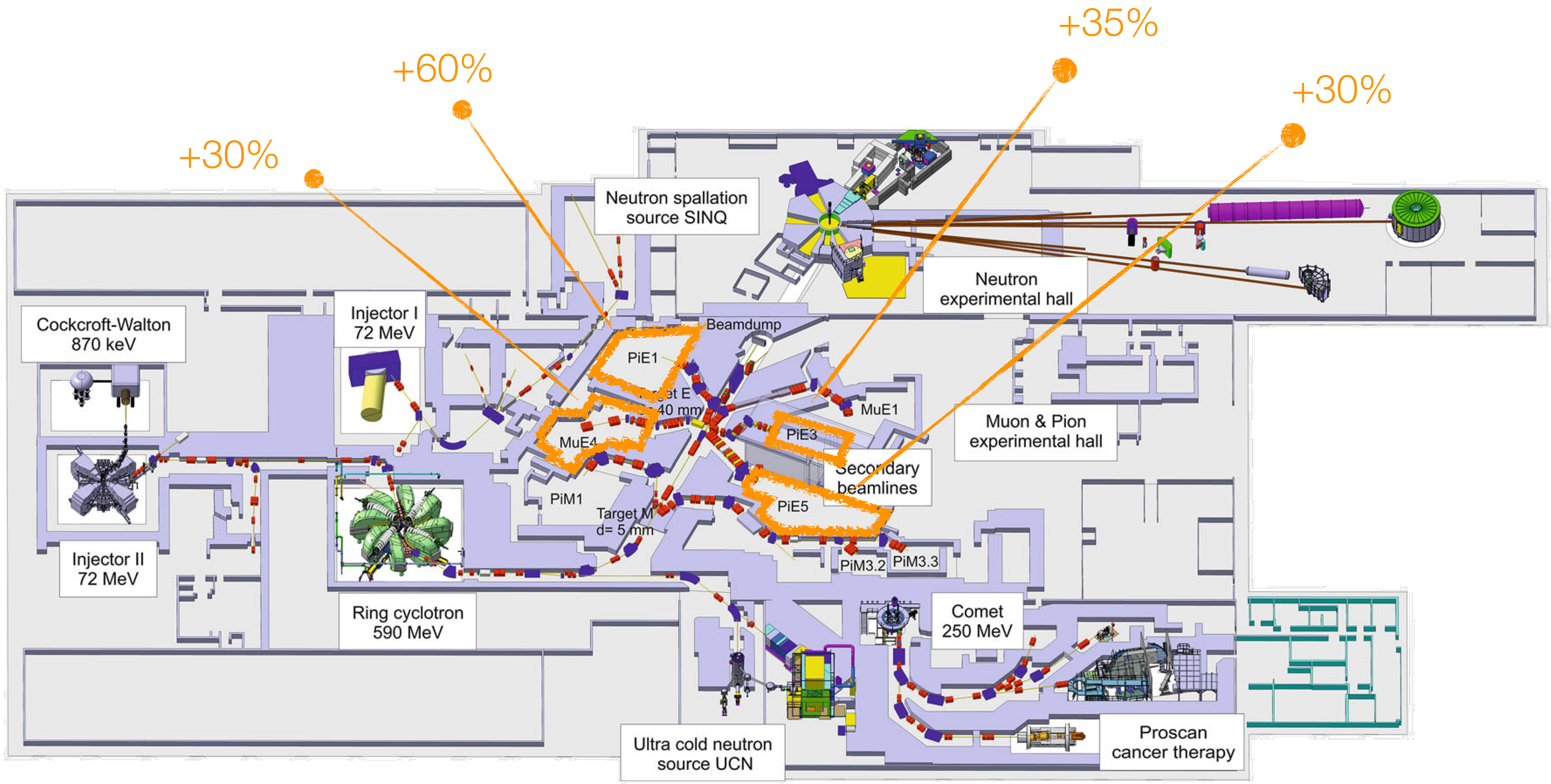
The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2025)**
- Put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**



Slanted target: Prototype test this year

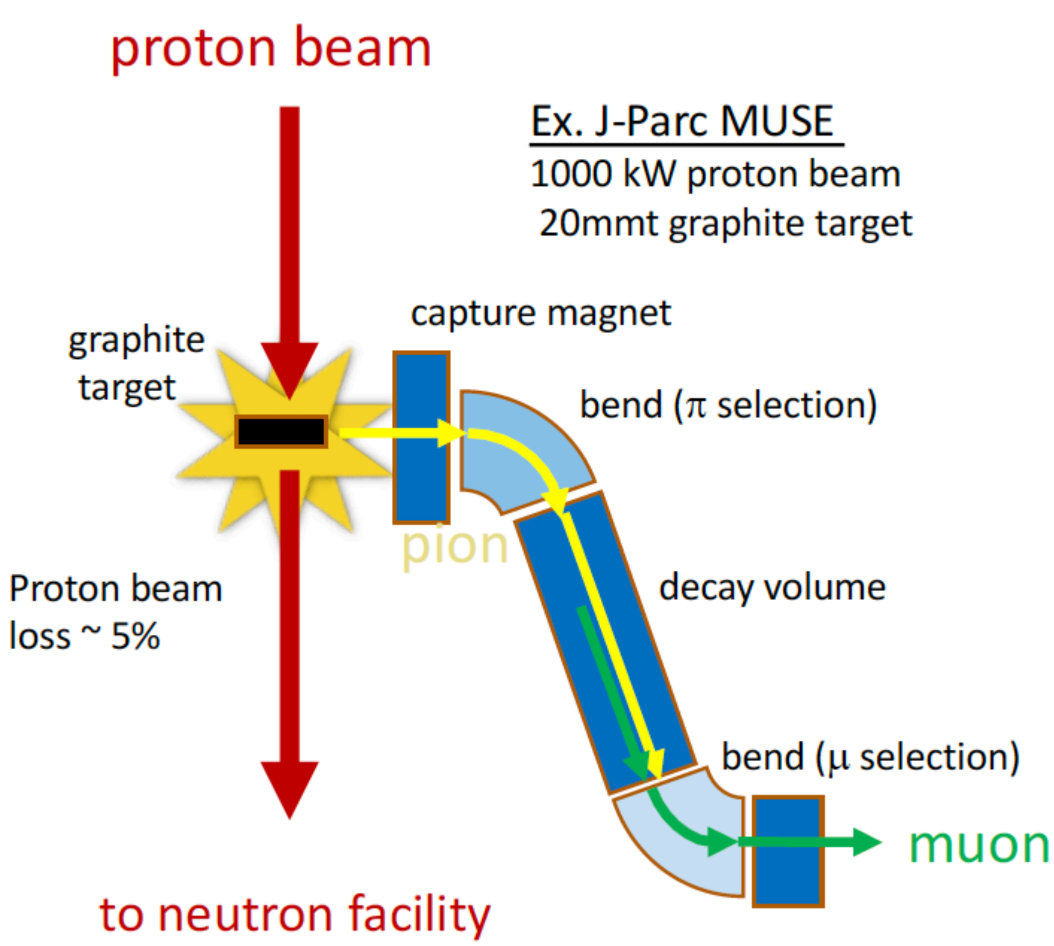
- Expect 30-60 % enhancement
- Measurements foreseen in three directions in 2019



MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Aim: O(**10^8** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam

Conventional muon beamline

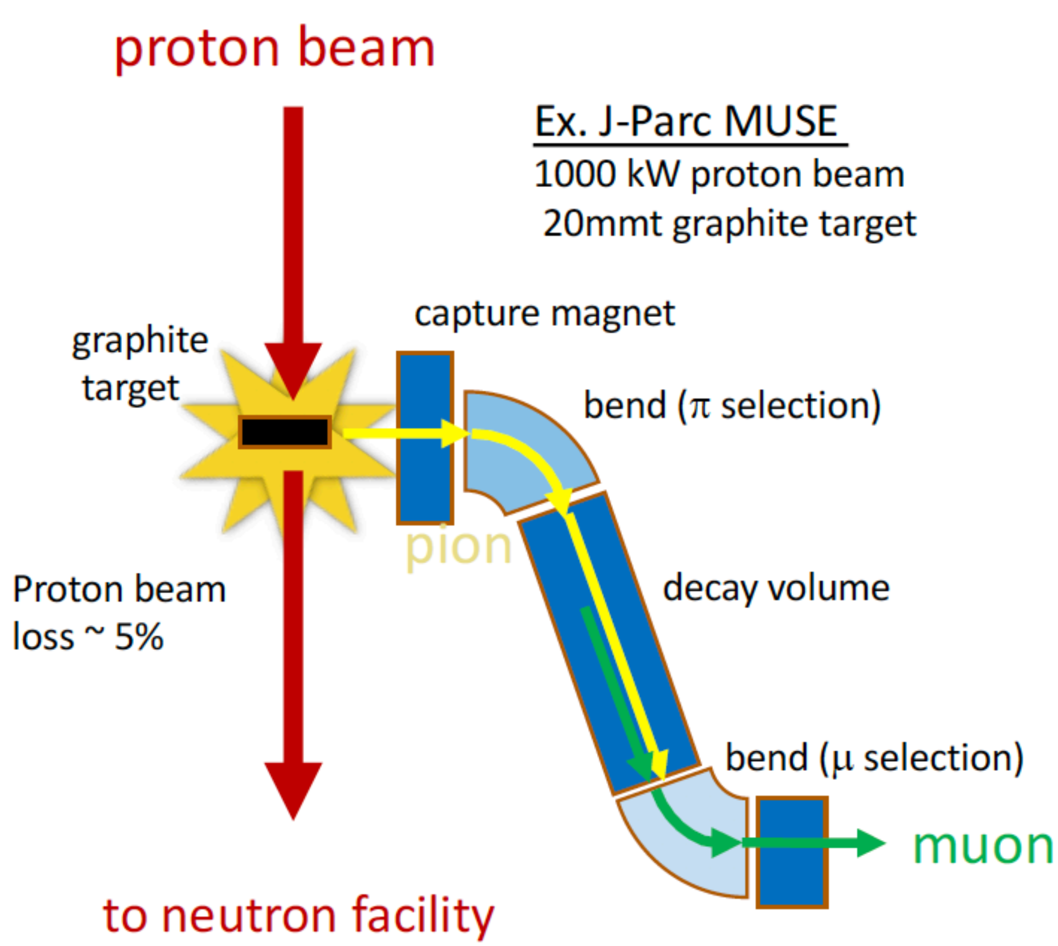


- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

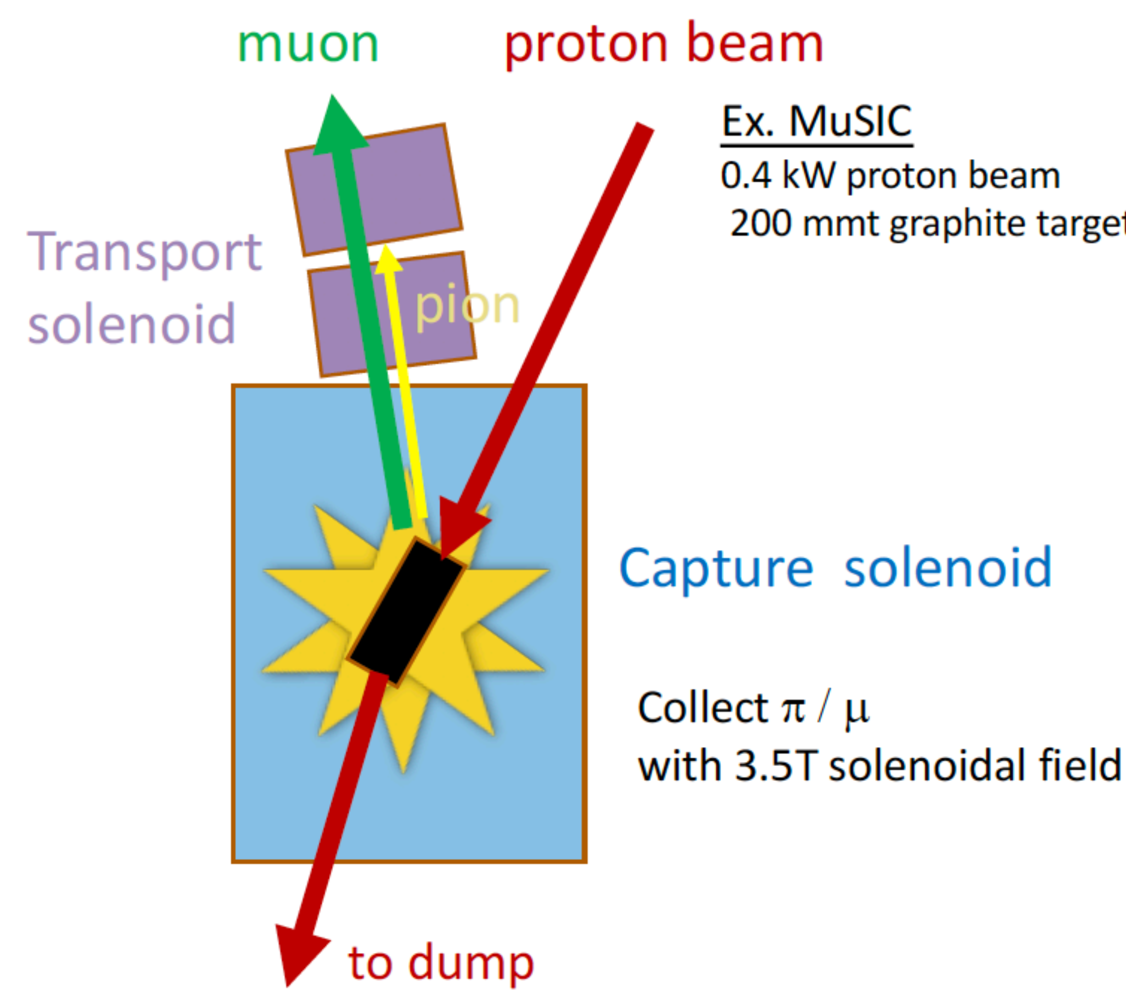
- Aim: O($\mathbf{10^8}$ muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam

Conventional muon beamline



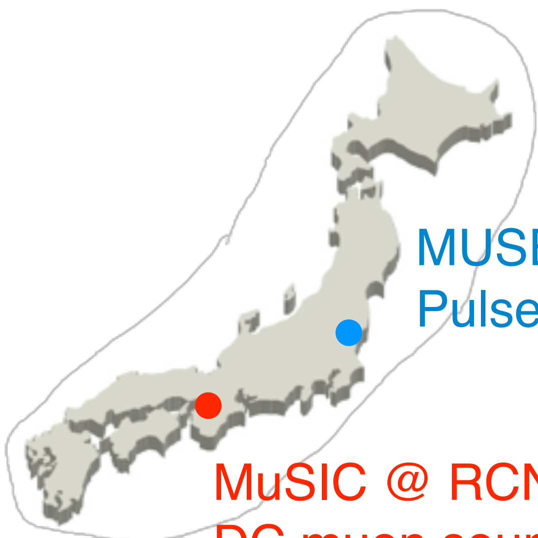
- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

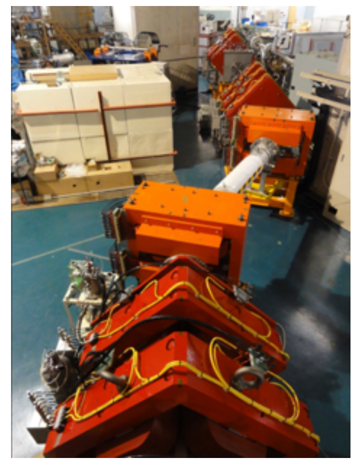
MuSIC beamline



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

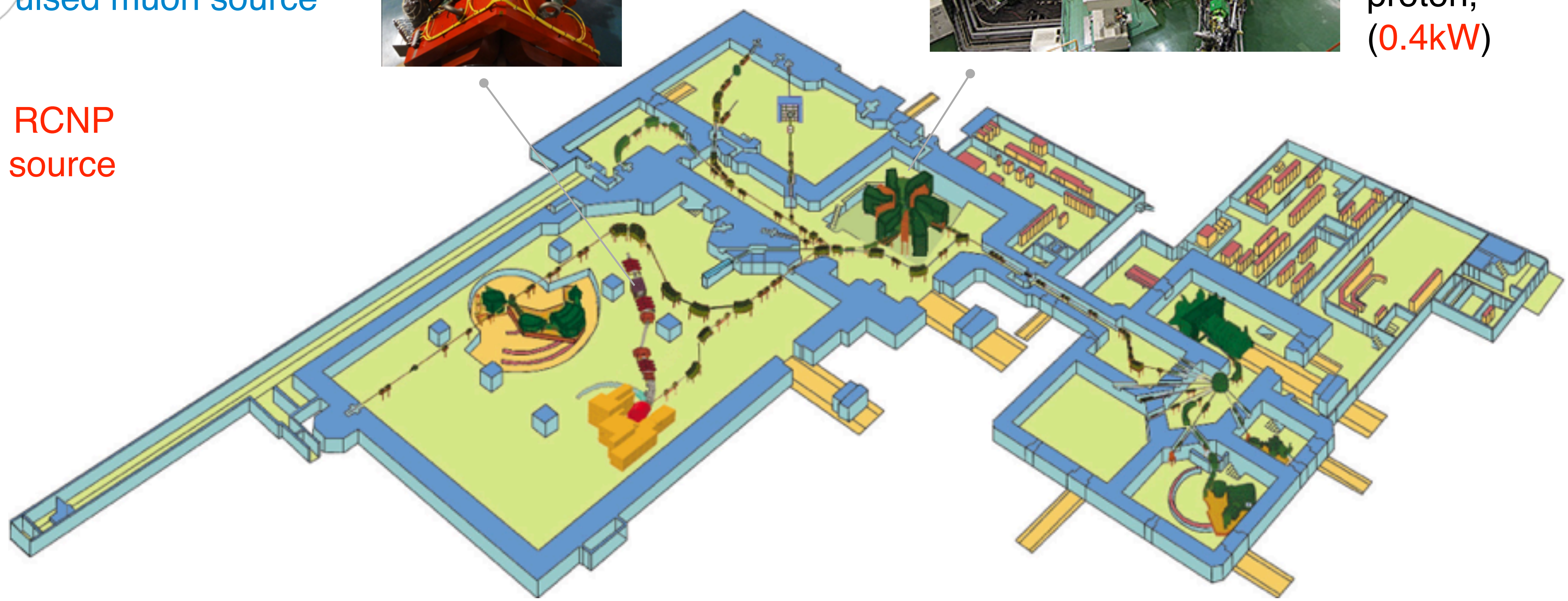
MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University





MuSIC
M1 Beam line

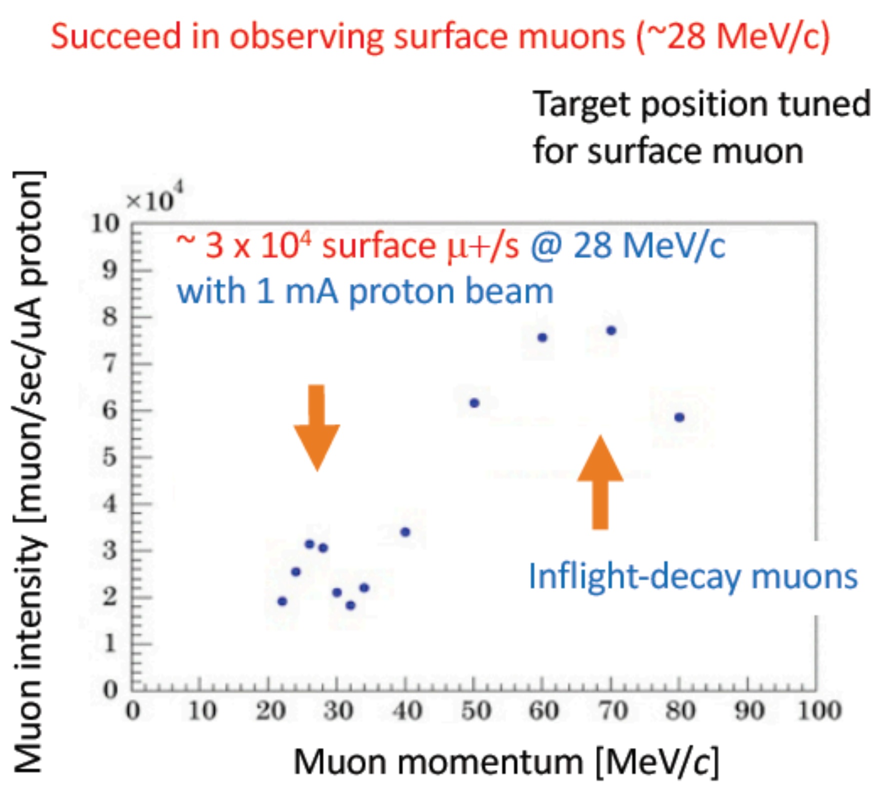
Ring
Cyclotron
~392MeV
(variable)
1.1uA
proton,
(0.4kW)

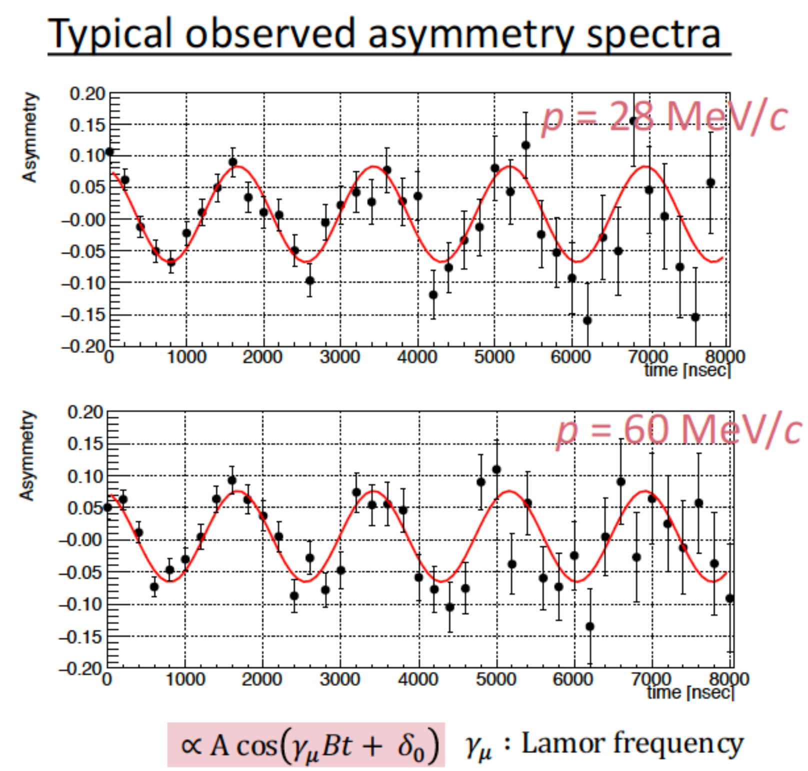


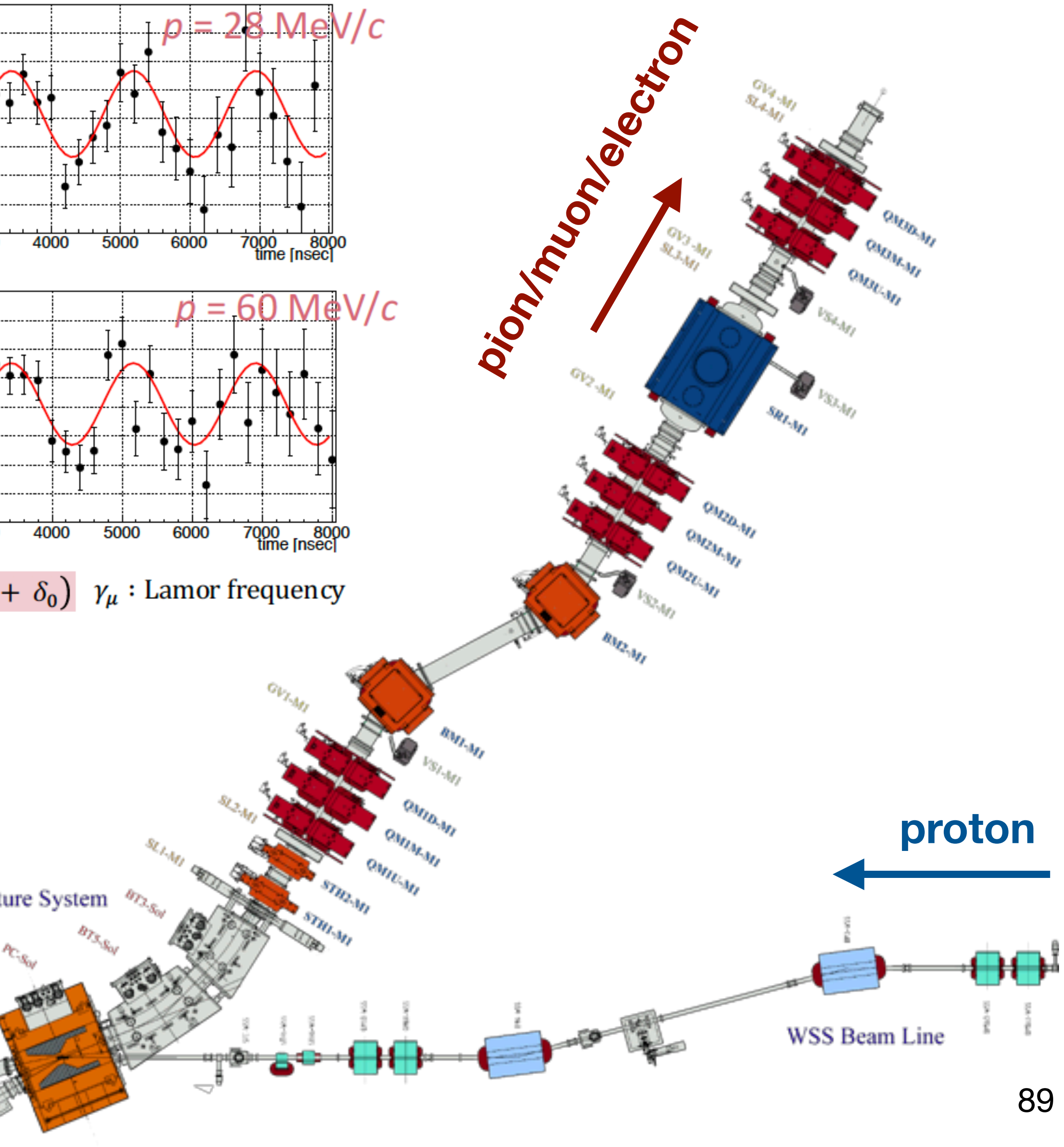
- proton beam energy is only 100 MeV above pion production threshold (～$2m_{\pi}$)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)

MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Multi-purpose facility. Beam line commissioning



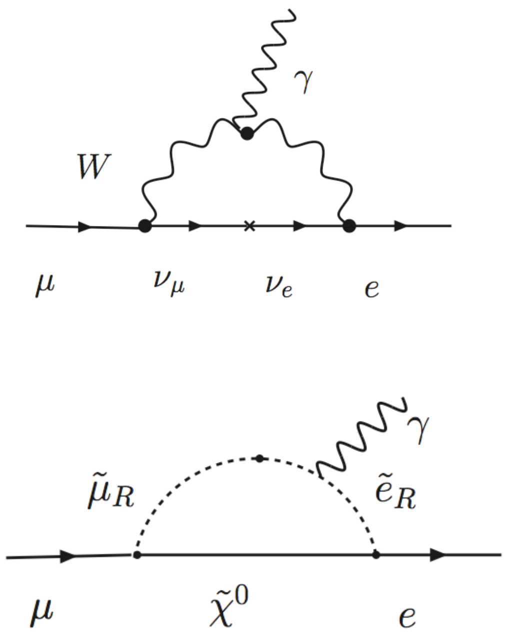


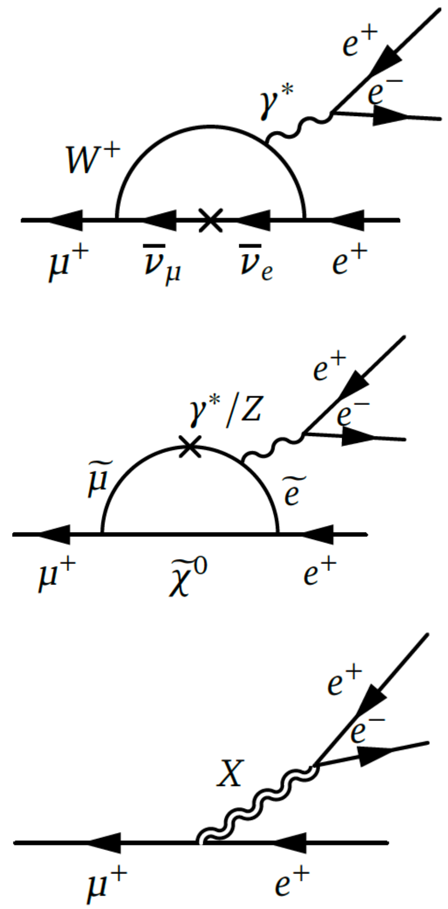


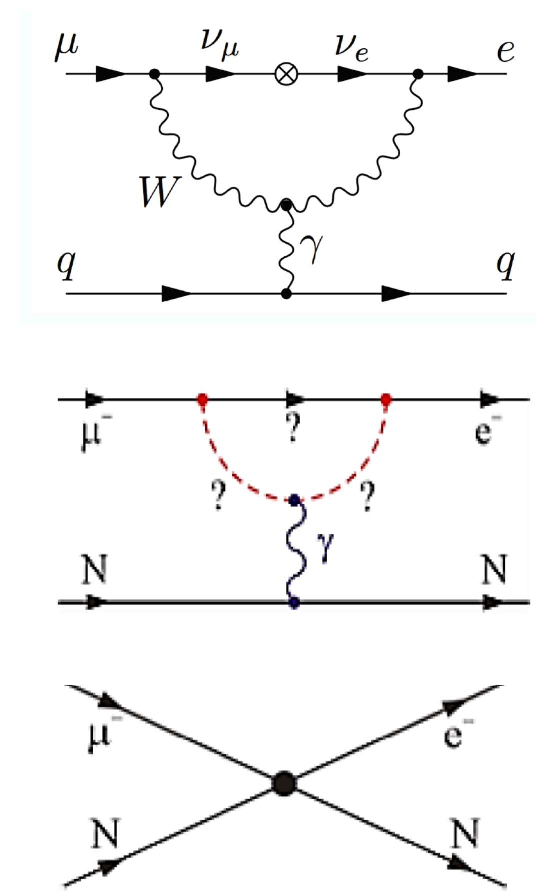
Status:

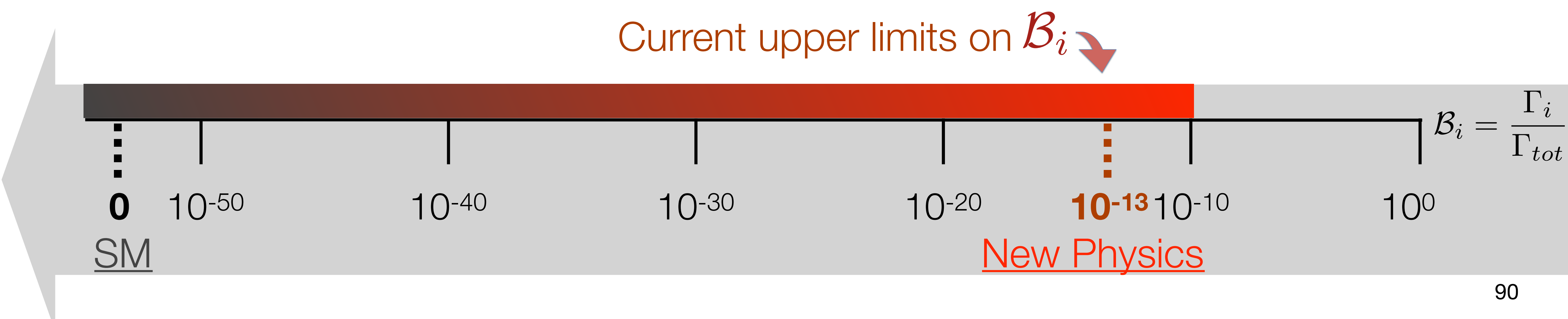
- Start experiments with negative and positive muons
- Muon capture and X-ray elemental analysis are in progress
- DC μSR study (still in commissioning for user experiments)

Muon golden channels with the Feyman's eyes







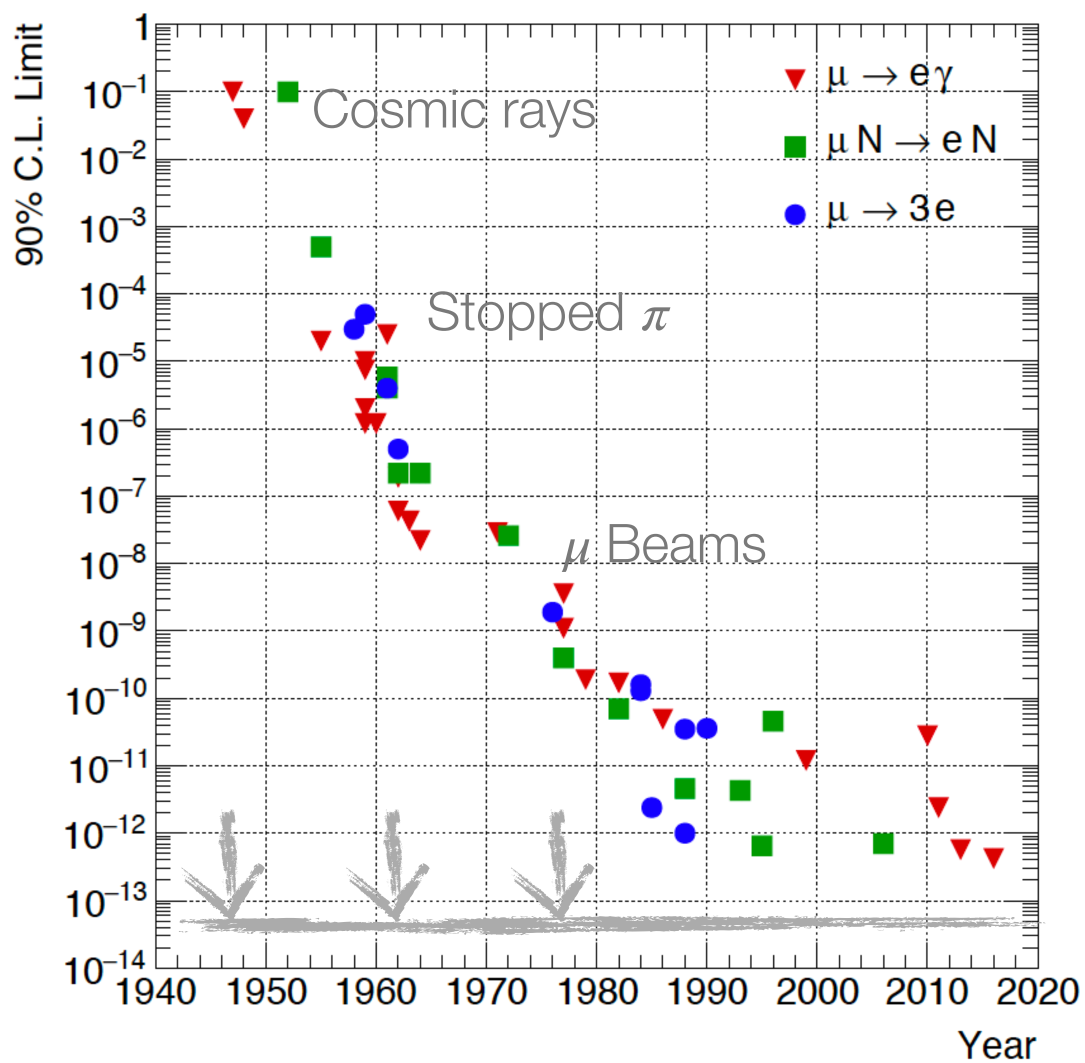


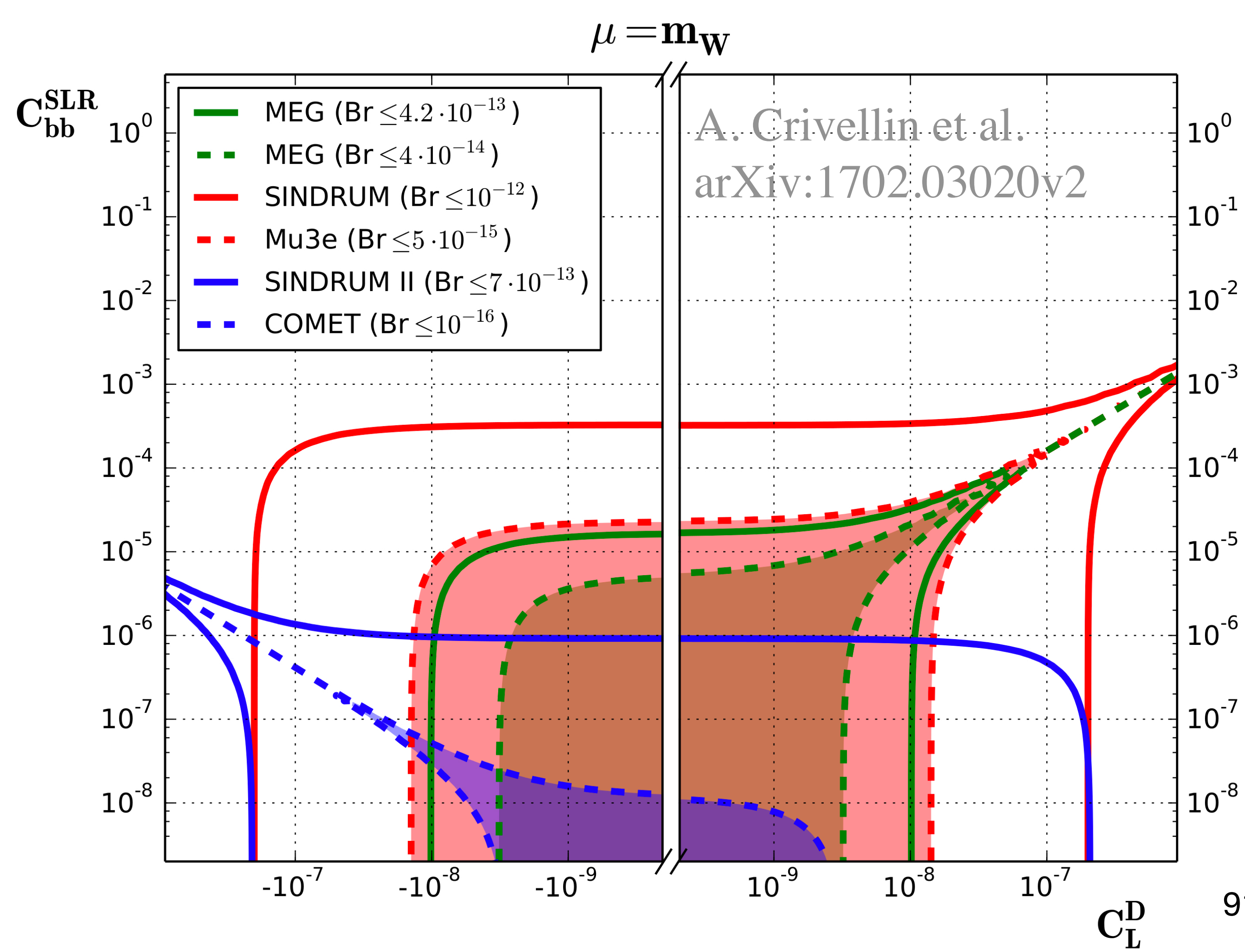
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 4 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	< 10^{-16}

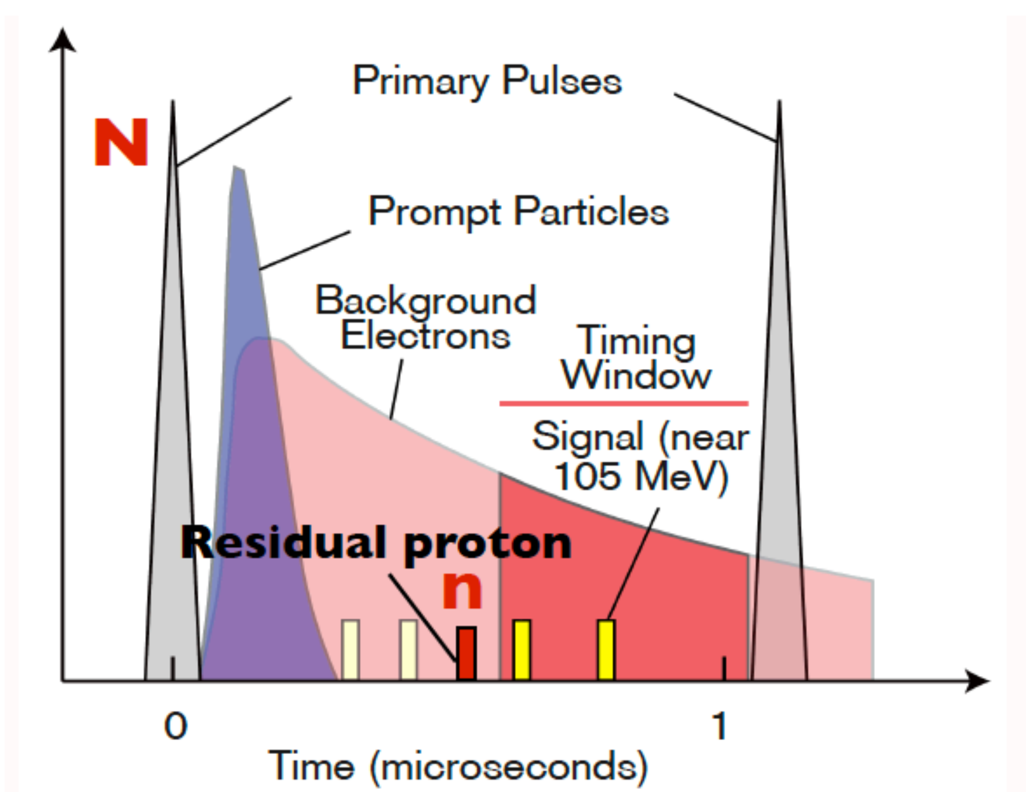
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV

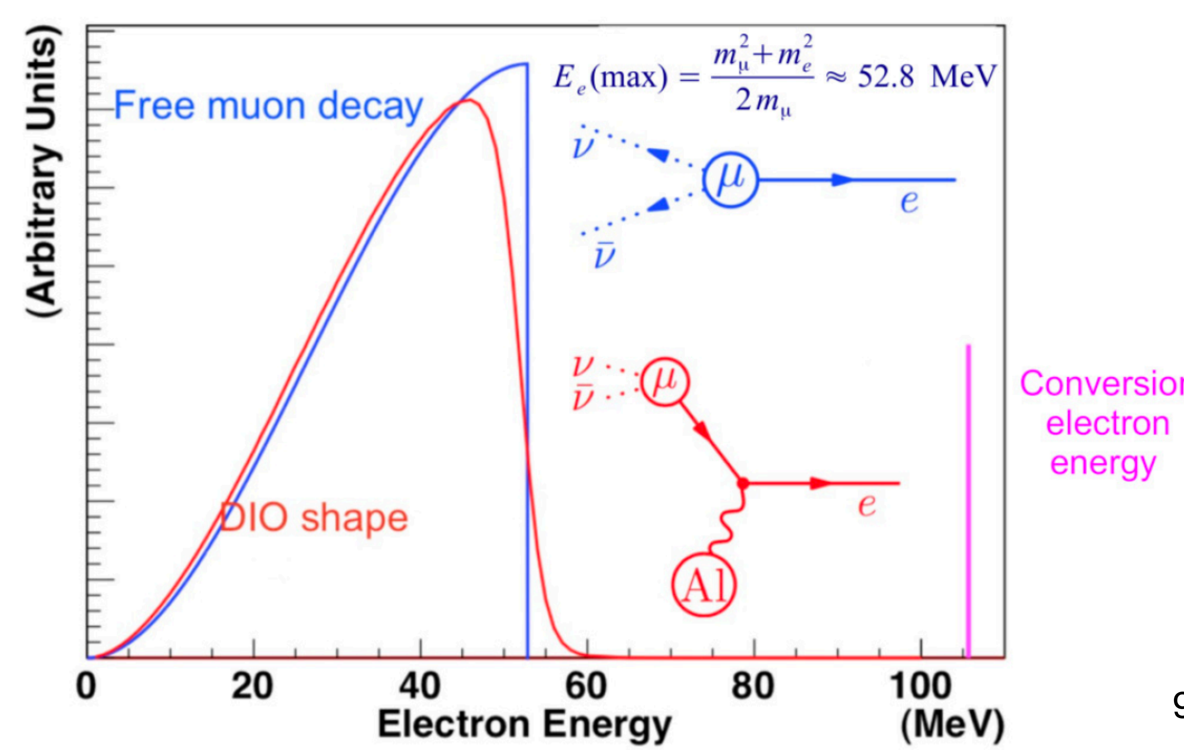




$\mu^- N \rightarrow e^- N$ experiments

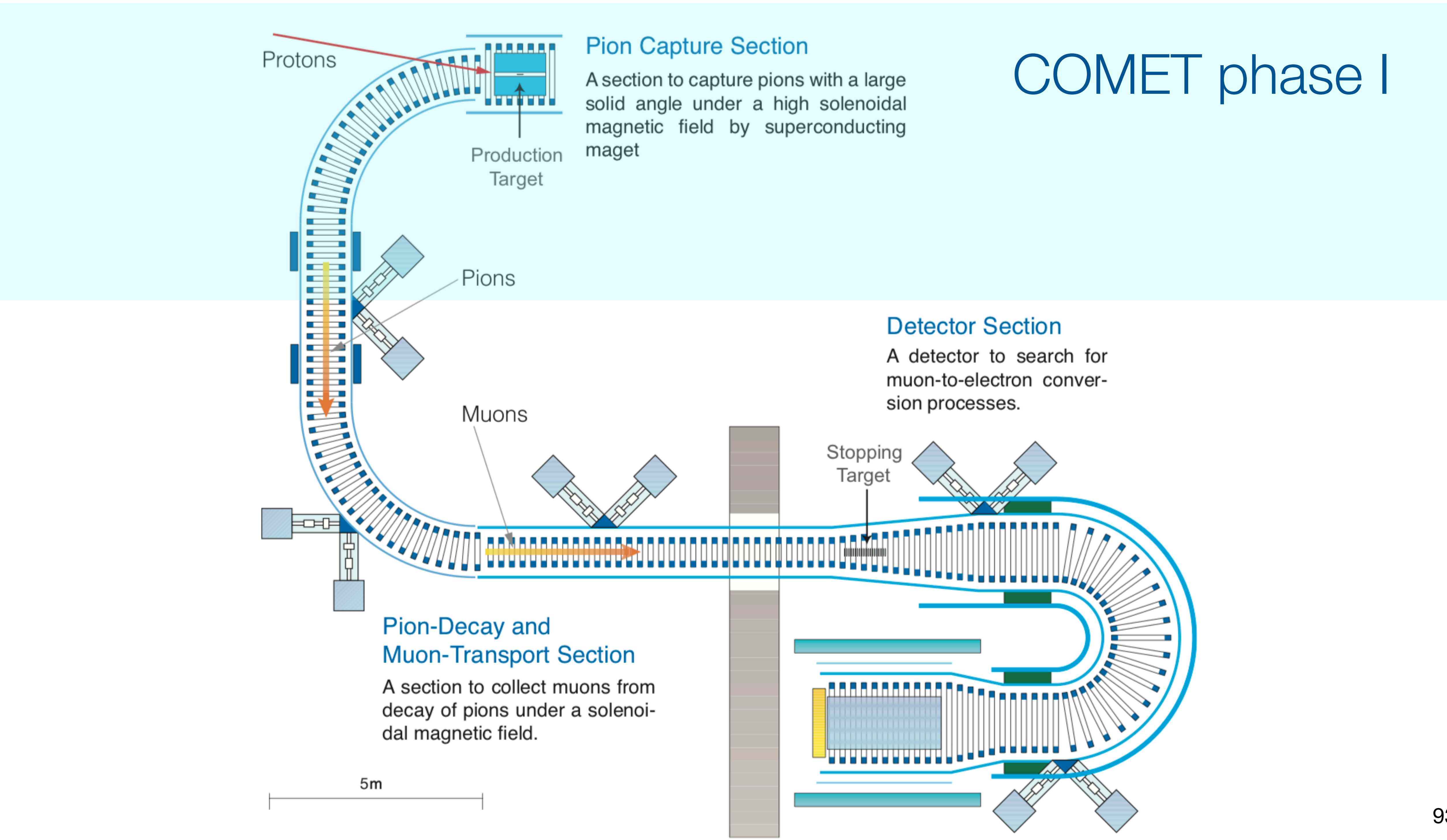
- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! $O(10^{18})$
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 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 COMET experiment

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



The COMET experiment: Status

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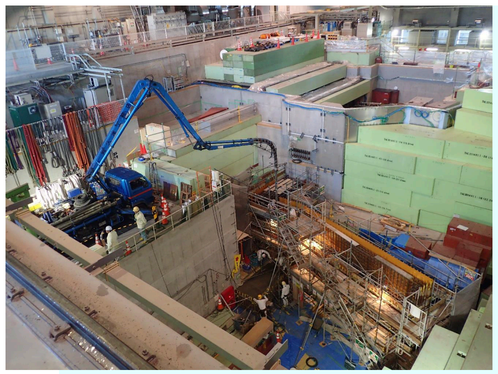
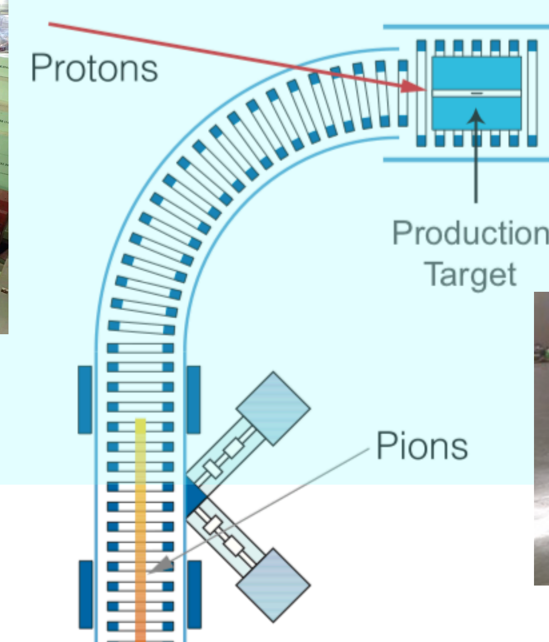
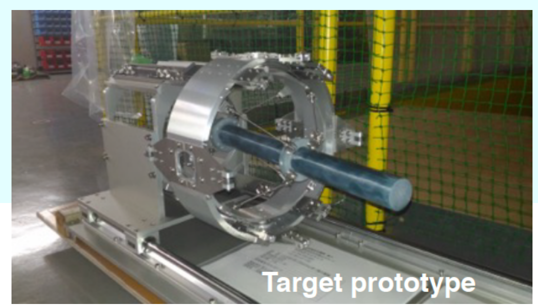




Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

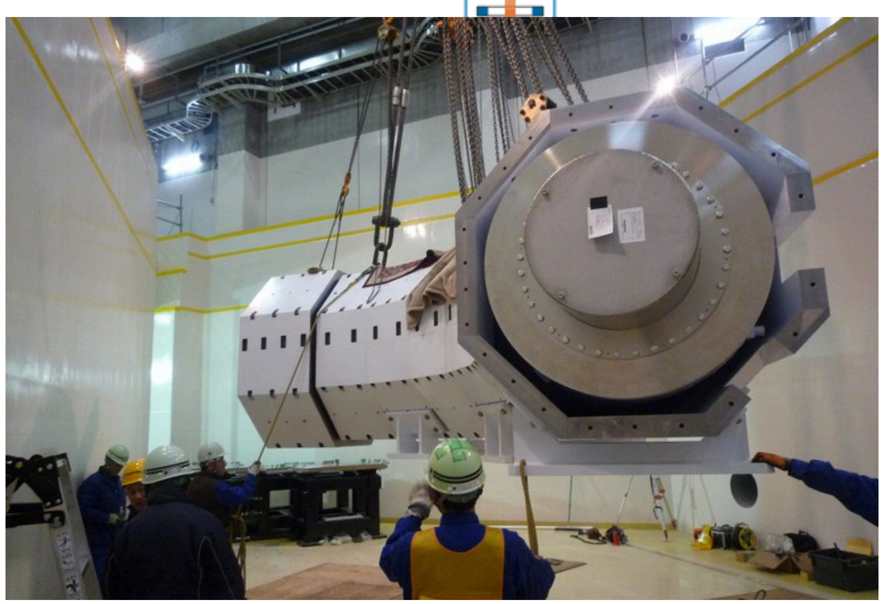
COMET phase I

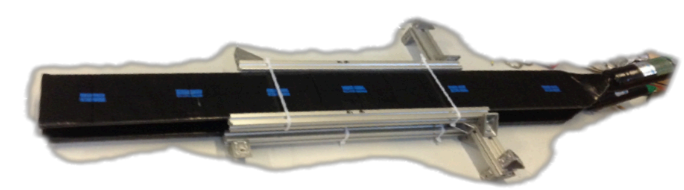


Detector Section

A detector to search for muon-to-electron conversion processes.

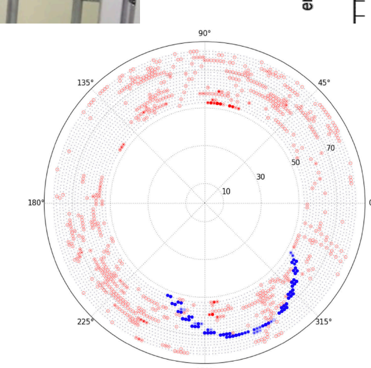
Trigger scintillators + Cerenkov detector: Ready

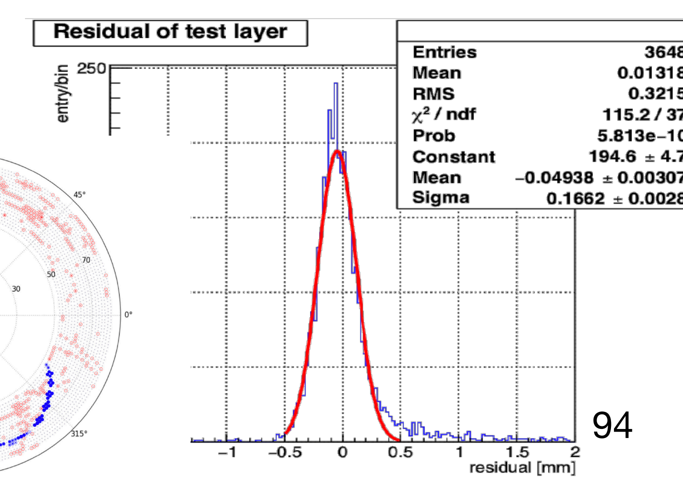




Cylindrical Drift Chamber: Ready

Trigger/DAQ/Analysis: in very good shape





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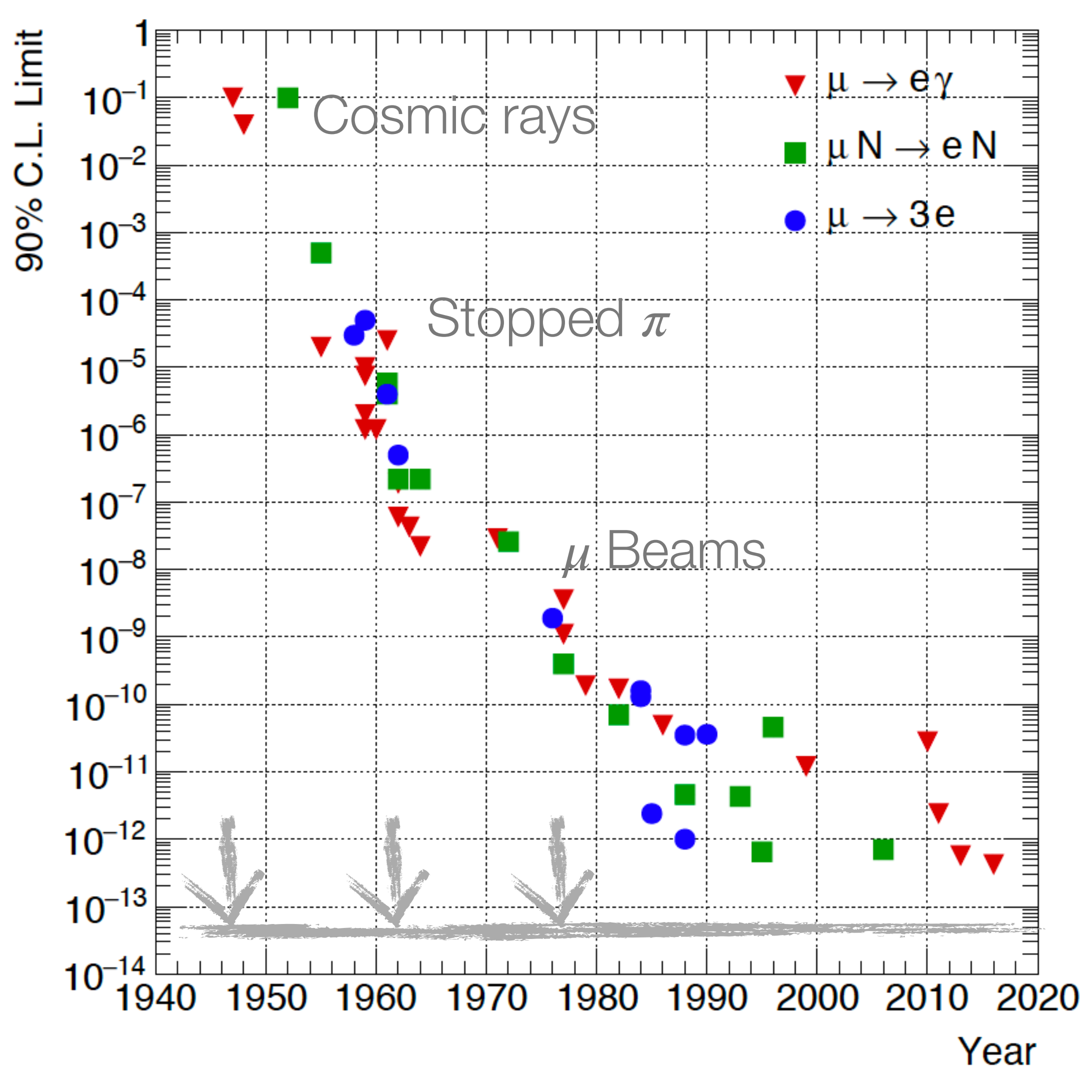
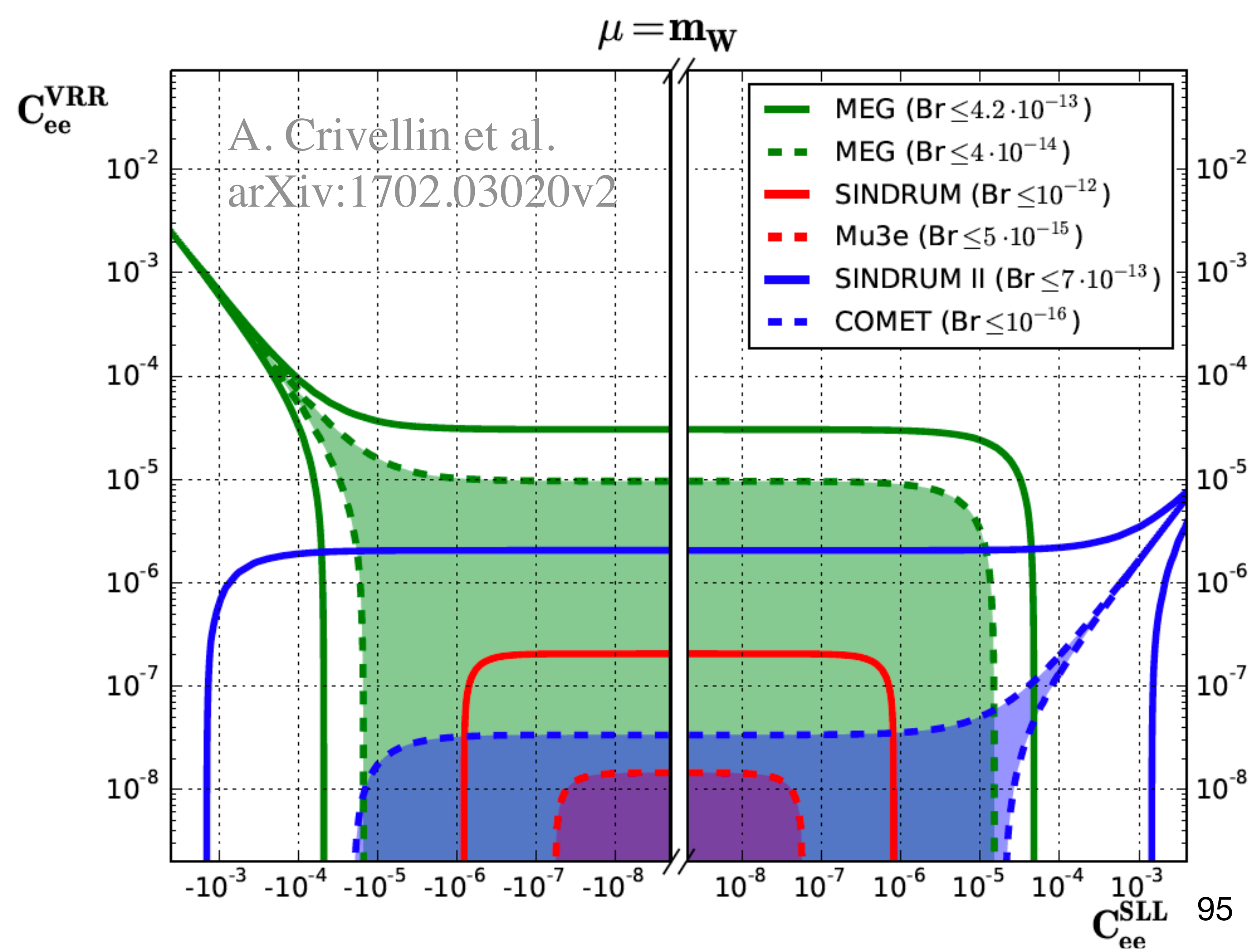
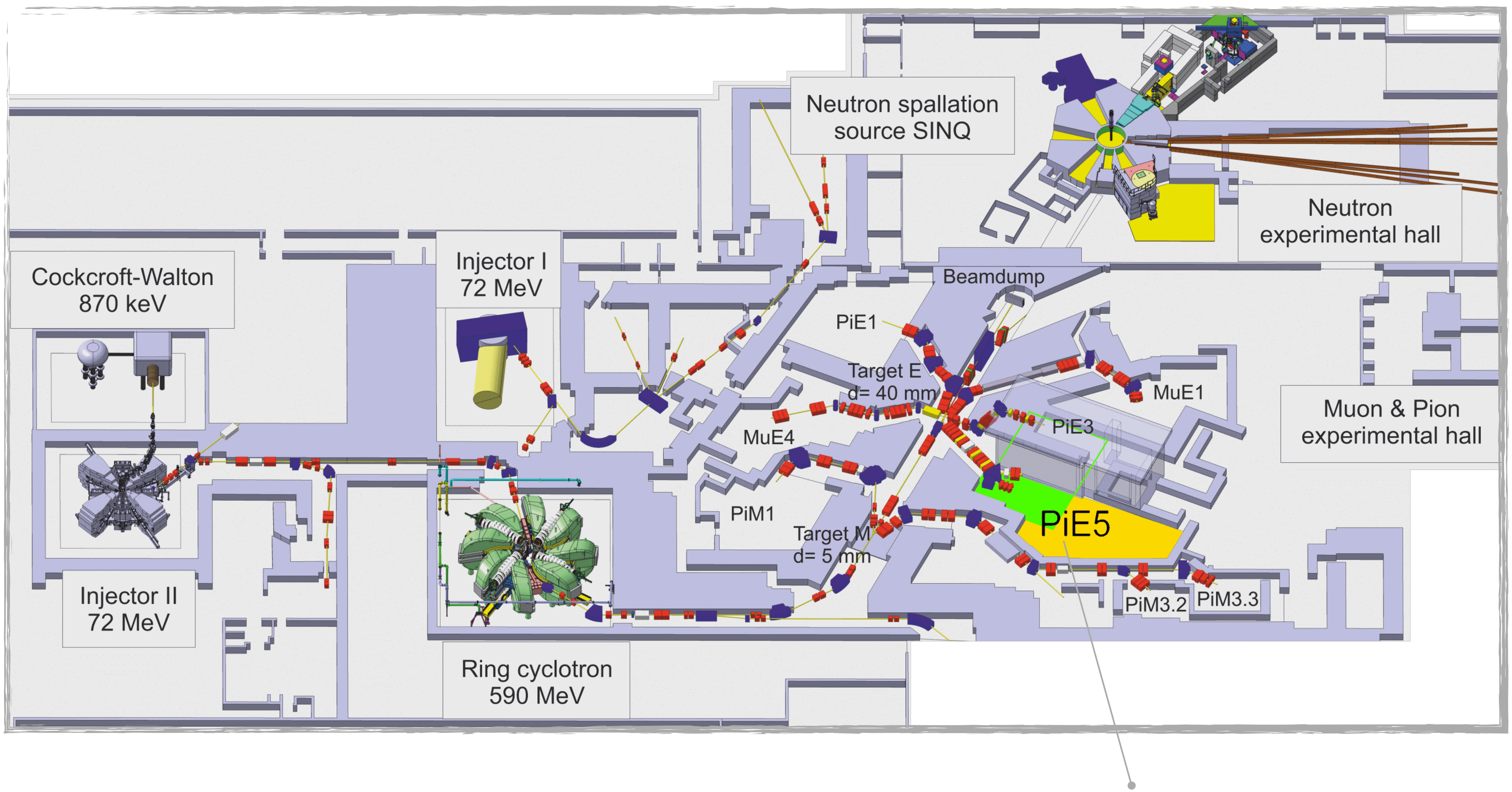




The world's most intense continuous muon beam

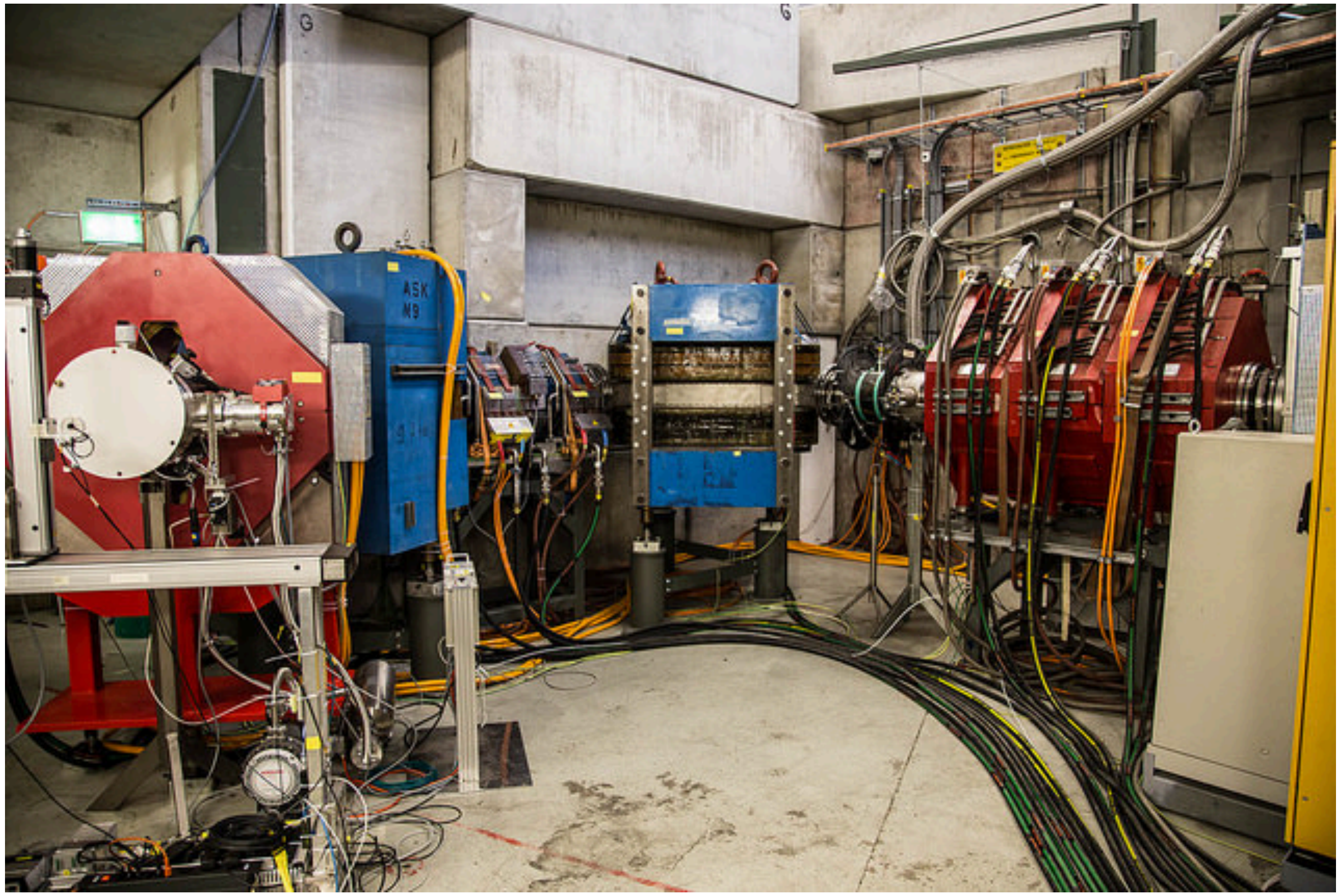
- PSI High Intensity Proton Accelerator experimental areas



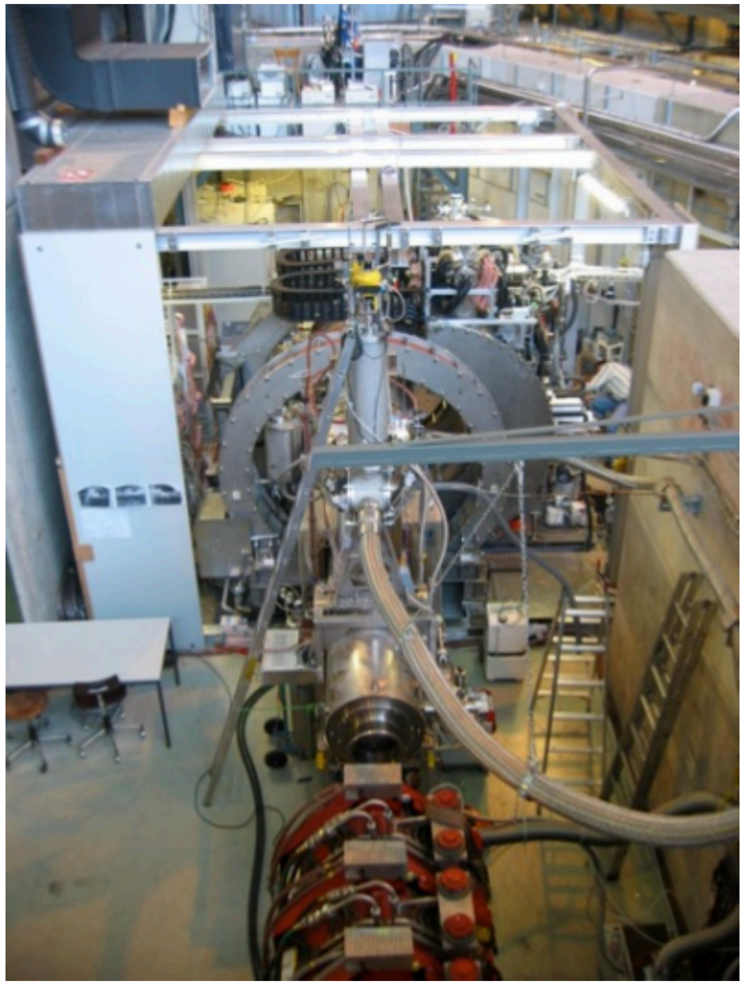
The MEGII (and Mu3e) beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8 x 10^7 muon/s during 2016 test beam

The Mu3e CMBL

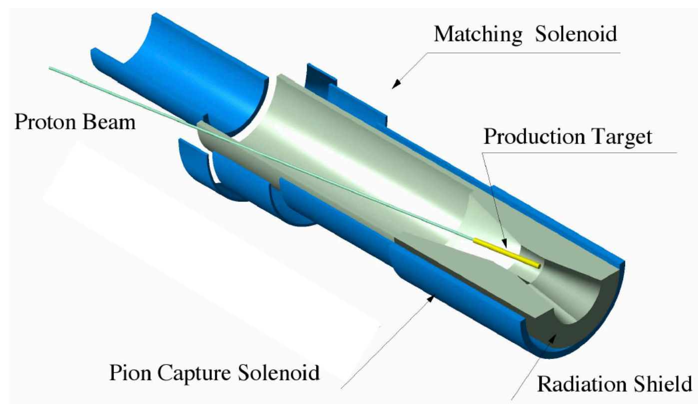


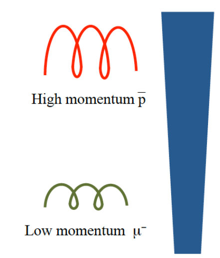
The MEGII BL



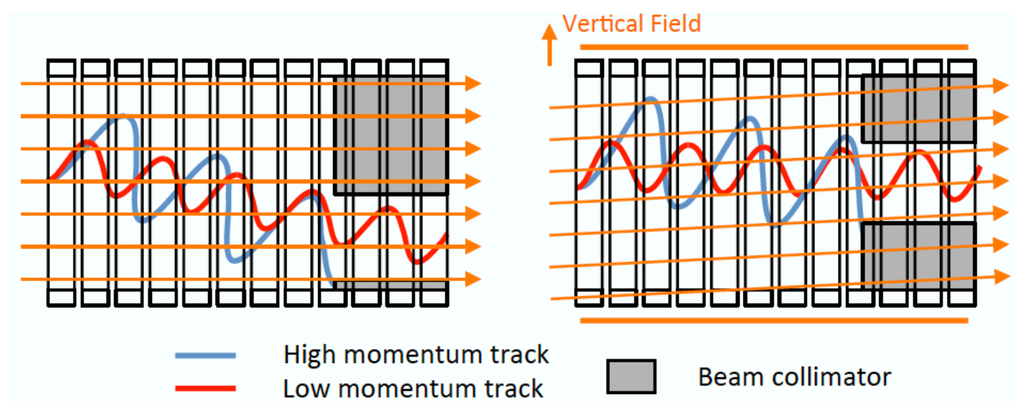
More and selected pulsed muons in three steps

- 1. Pion production in magnetic field

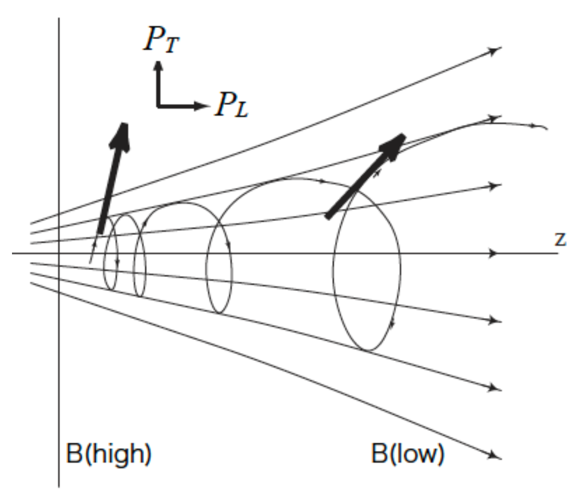


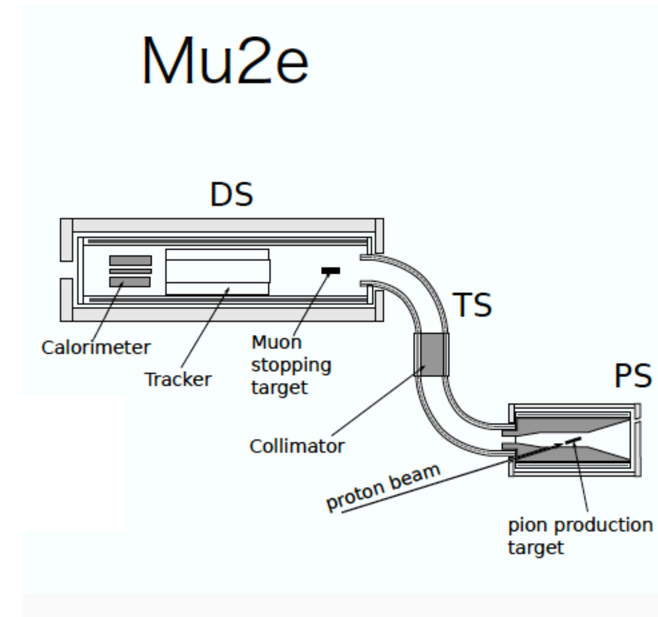


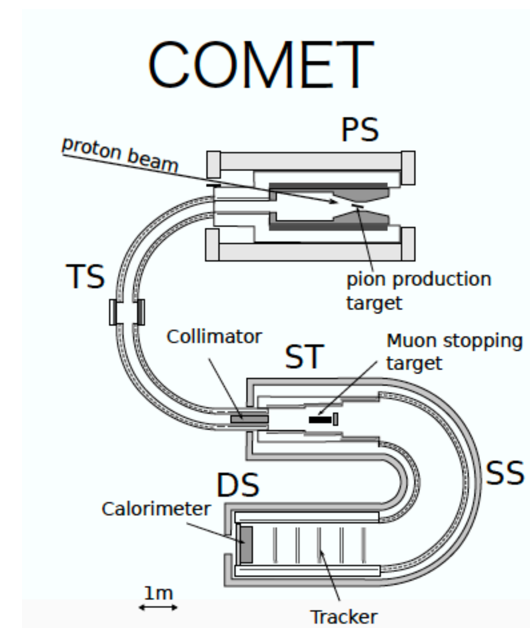
- 2. Pion/muon collection using gradient magnetic filed



- 3. Beam transport with curved solenoid magnets







More and selected pulsed muons in three steps

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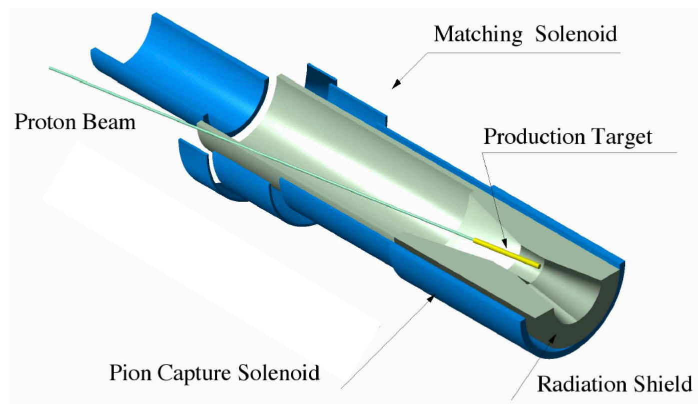

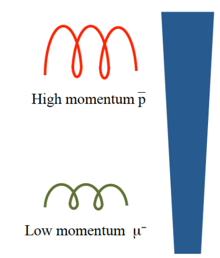

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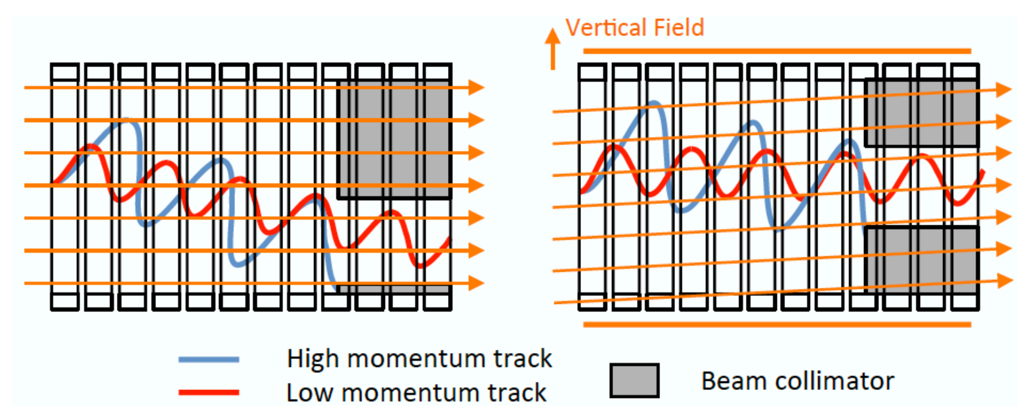

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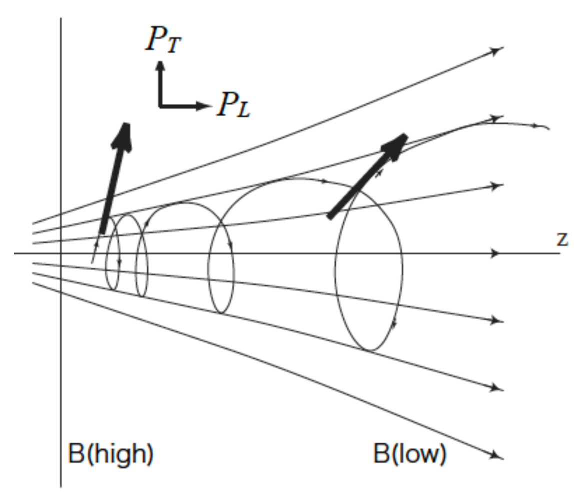
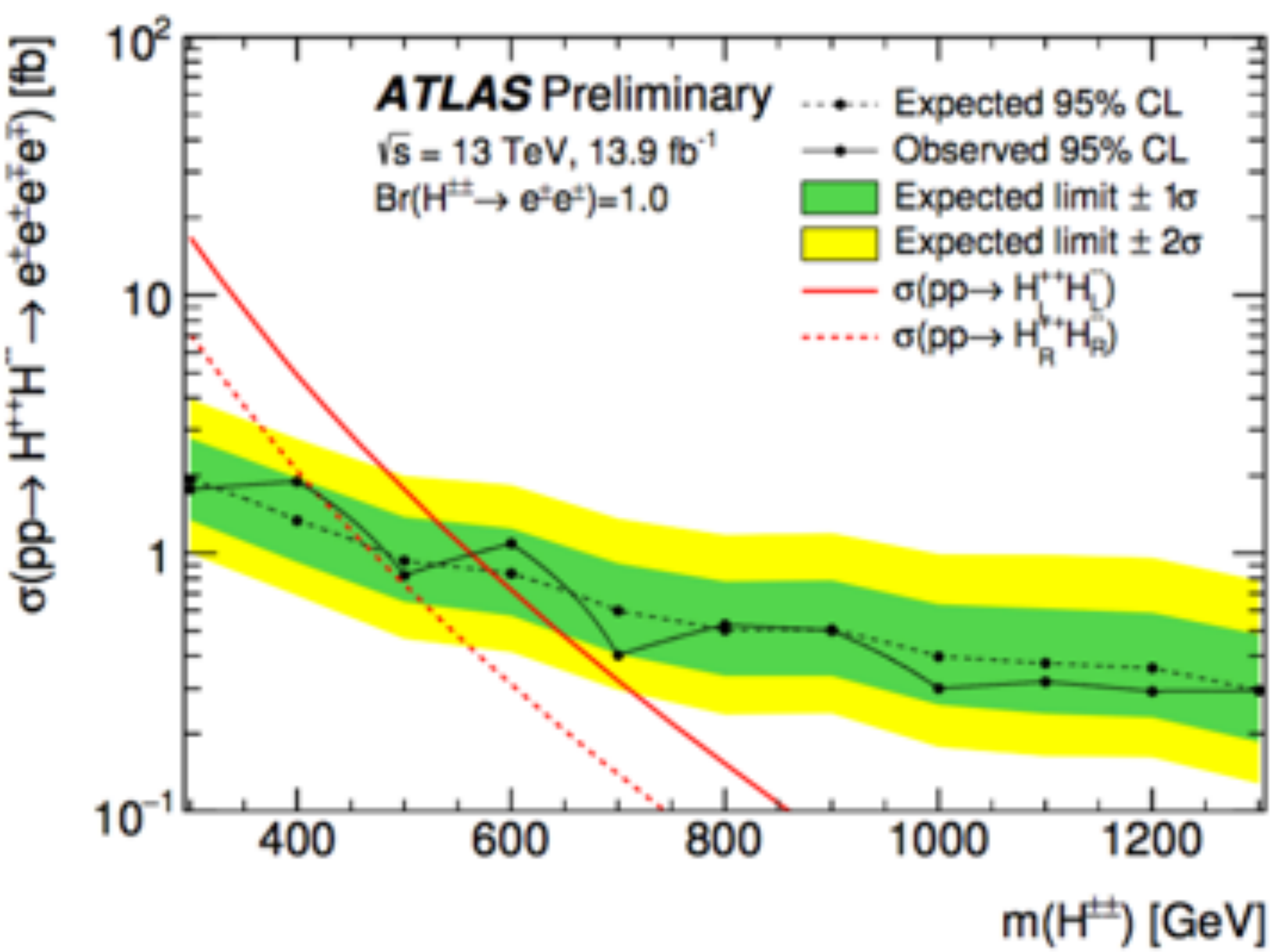
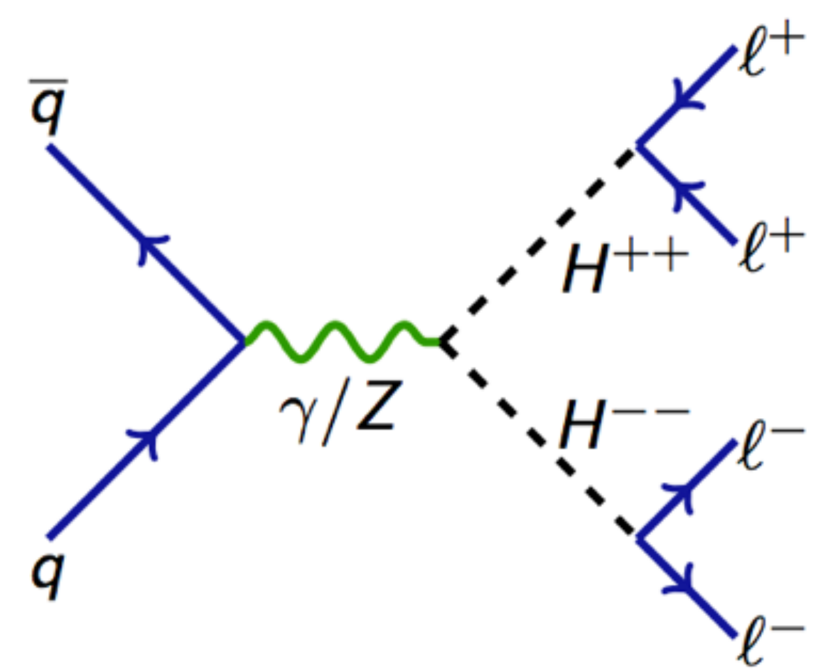


ATLAS

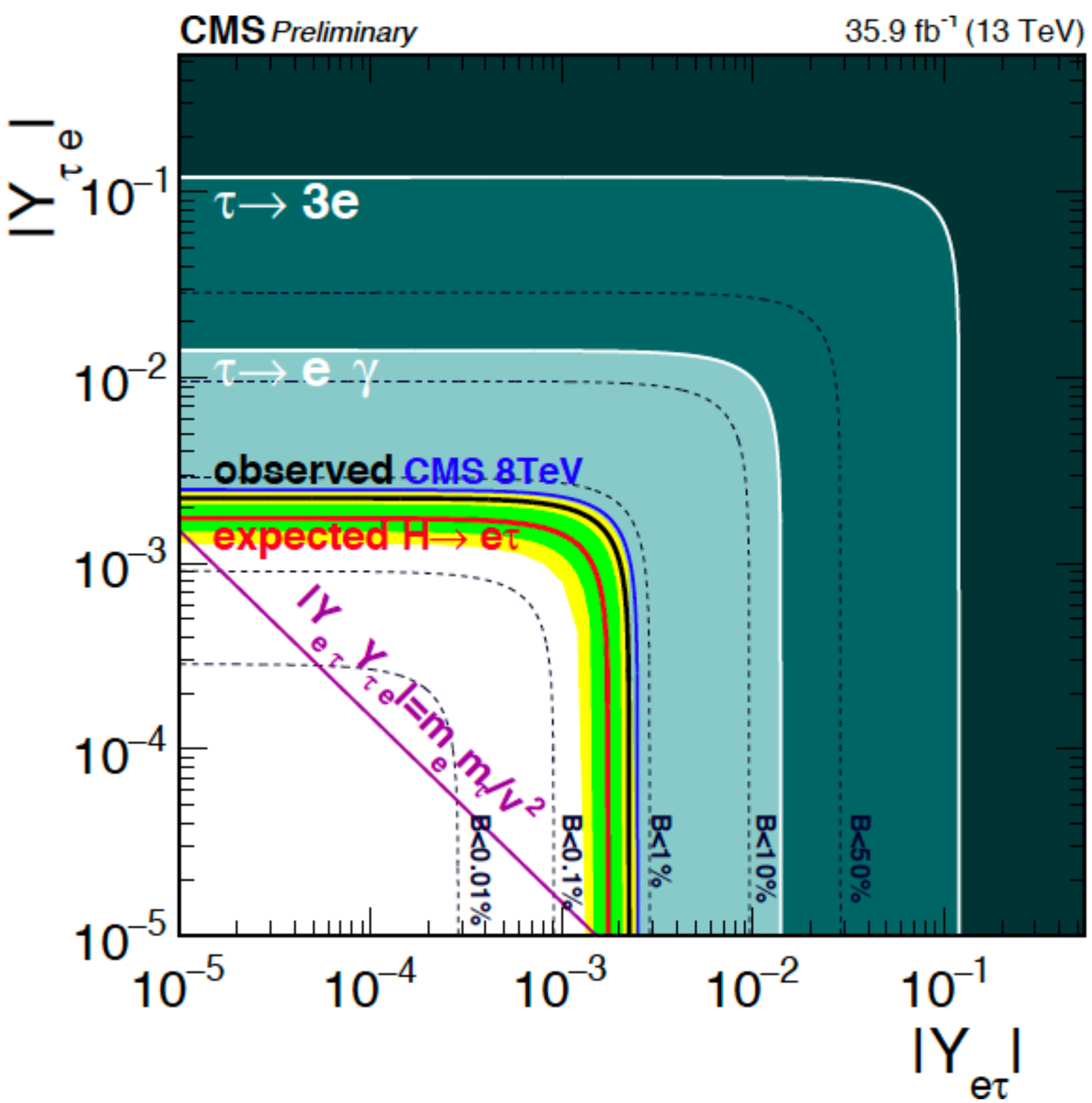
- CLFV double charged Higgs decays (H++/H - -); possible also LNV
- 3.2 fb-1 [2015] + 10.7 fb-1 [2016] data set





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 √s = 13 TeV

Boosted decision tree and cut based analysis

$$BR(H \to e\tau) < 0.61\%$$
at 95 % C.L.
$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26\ 10^{-3}$$

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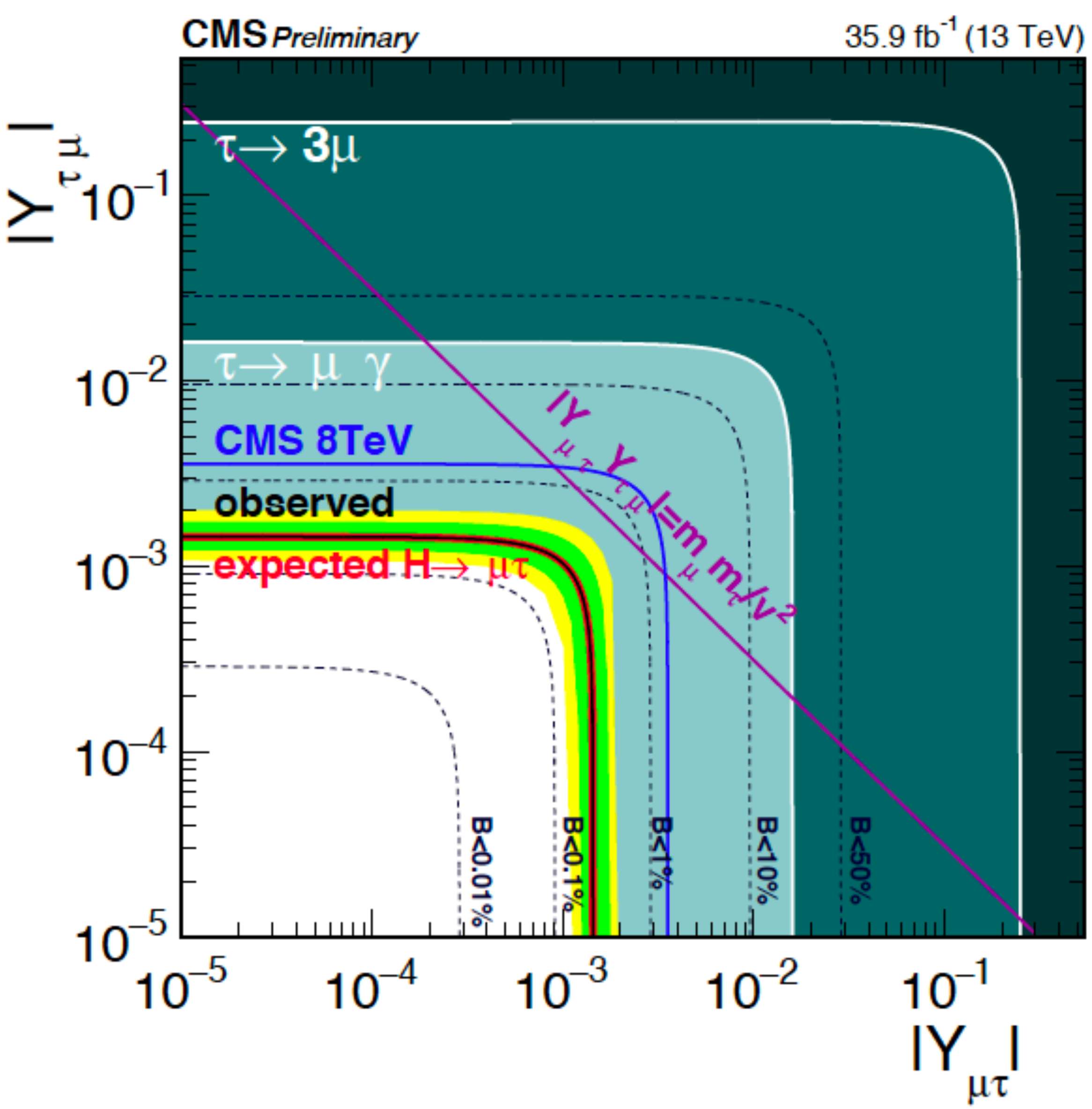
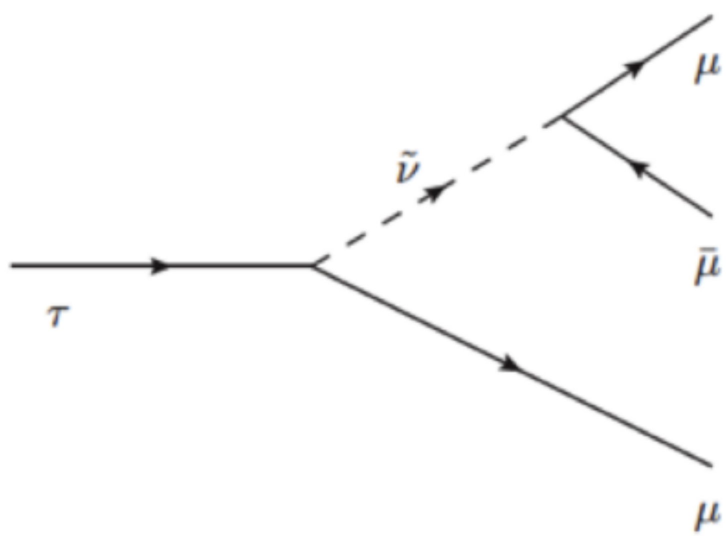


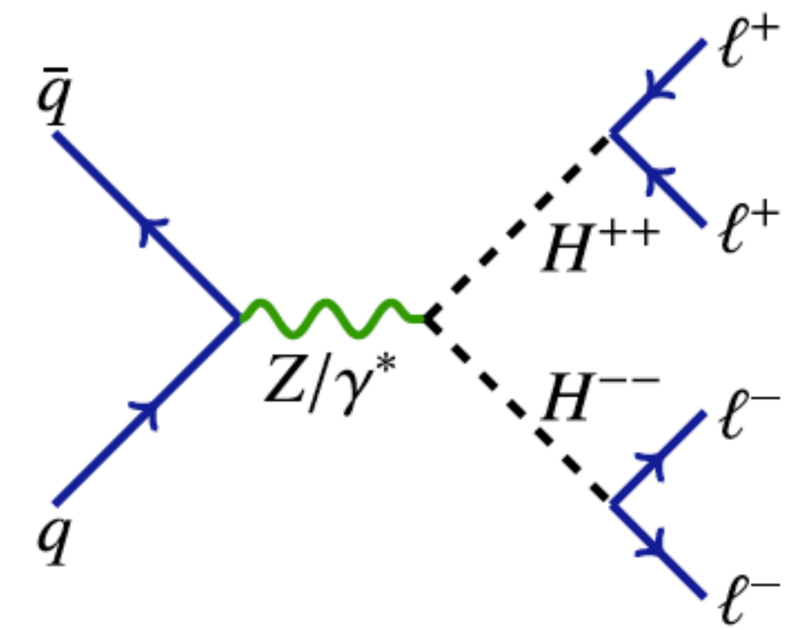
2016 data set up to 35.9 fb-1 at √s = 13 TeV

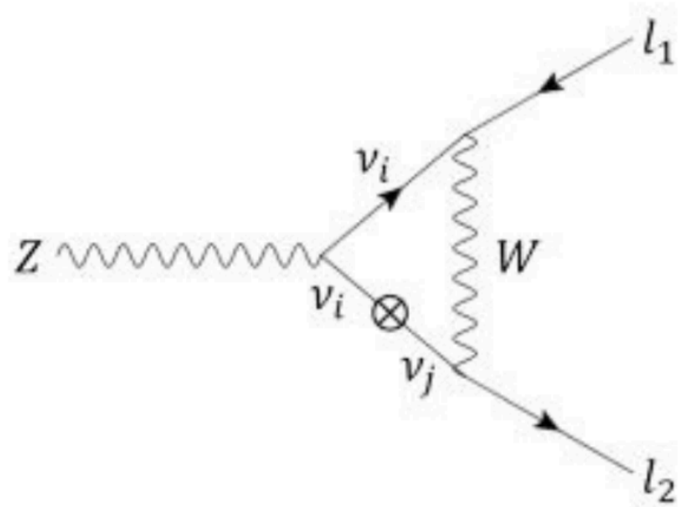
Boosted decision tree and cut based analysis

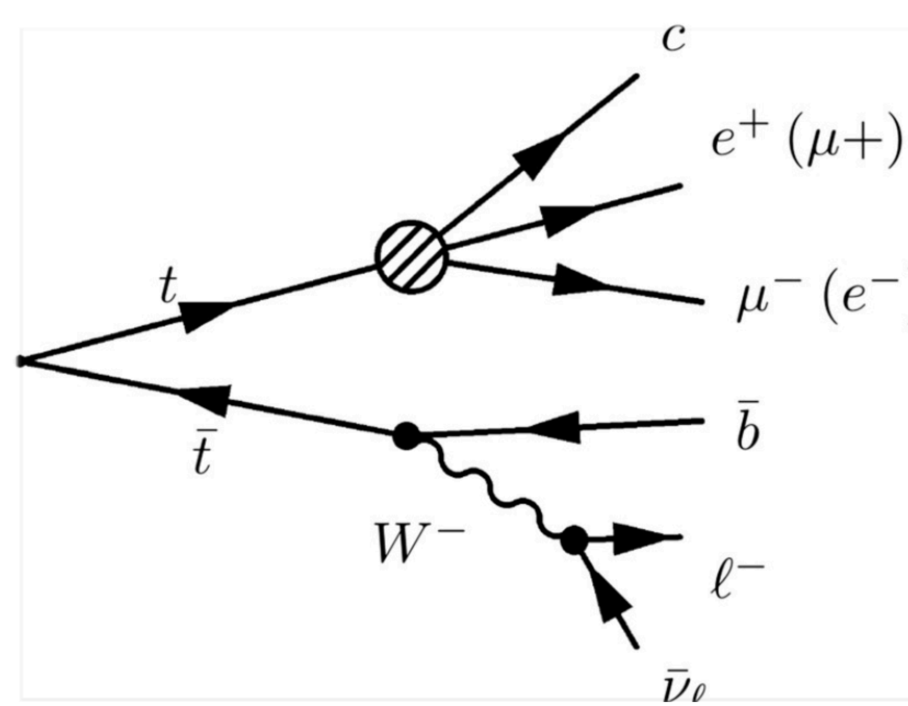
$$\mathrm{BR}(\mathrm{H} \to \mu\tau) < 0.25\%$$
$$\text{at 95 \% C.L.}$$
$$\sqrt{|\mathrm{Y}_{\mu\tau}|^2 + |\mathrm{Y}_{\tau\mu}|^2} < 1.43\ 10^{-3}$$

Feyman diagrams

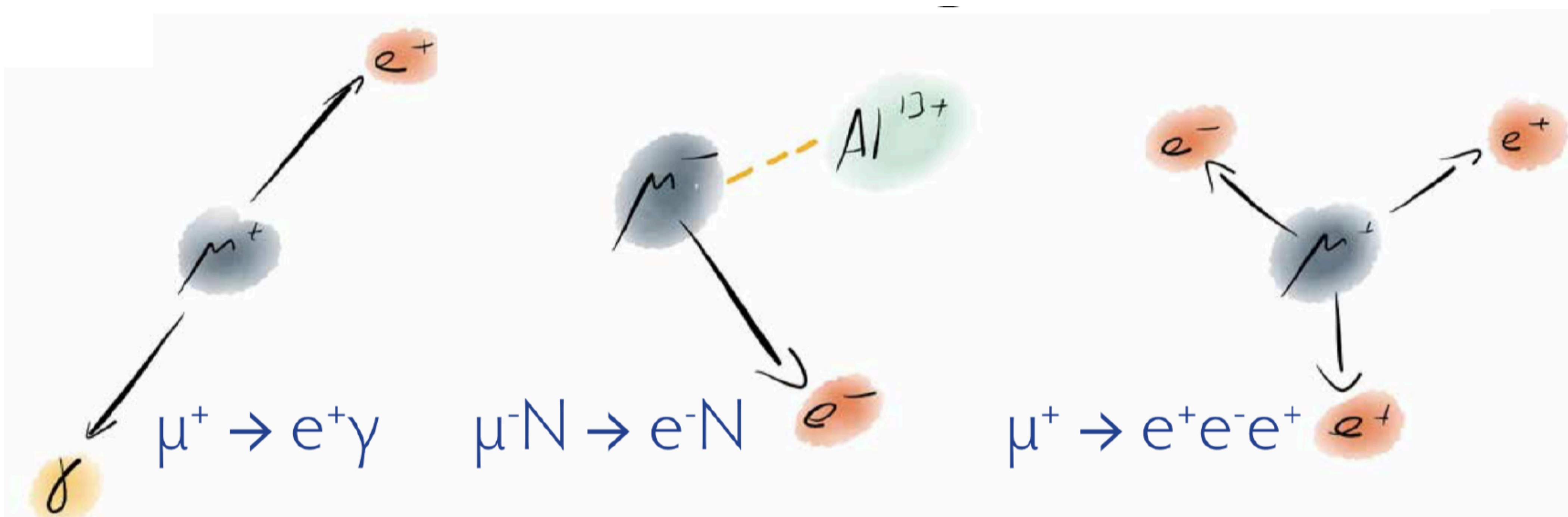








Signature and background vs beam characteristics



Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions

Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

Background

- Radiative decay
- Accidental background