# Probing New Physics through Lepton Flavour Violation


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**Outline:**

1) Introduction
2) Searches for the $\mu$–e conversion (COMET, Mu2e)
3) Searches for LFV in muon decays (MEG, Mu3e)
4) Searches for LFV in kaon decays (NA62)
5) Summary

UNIVERSITY OF BIRMINGHAM

*HEPP & APP Annual Meeting*

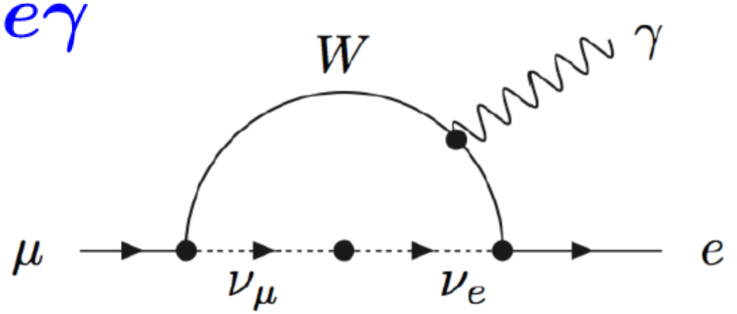
*Royal Holloway, University of London • 8 April 2014*

EXCELLENCE IN SCIENCE

# Charged Lepton Flavour Violation

- ❖ Neutrino oscillations: generalization of the Standard Model.
- ❖ Within **$\nu$SM**, CLFV is induced by neutrino oscillation in loops.
- ❖ Unlike FCNC involving quarks, CLFV rates are negligible.

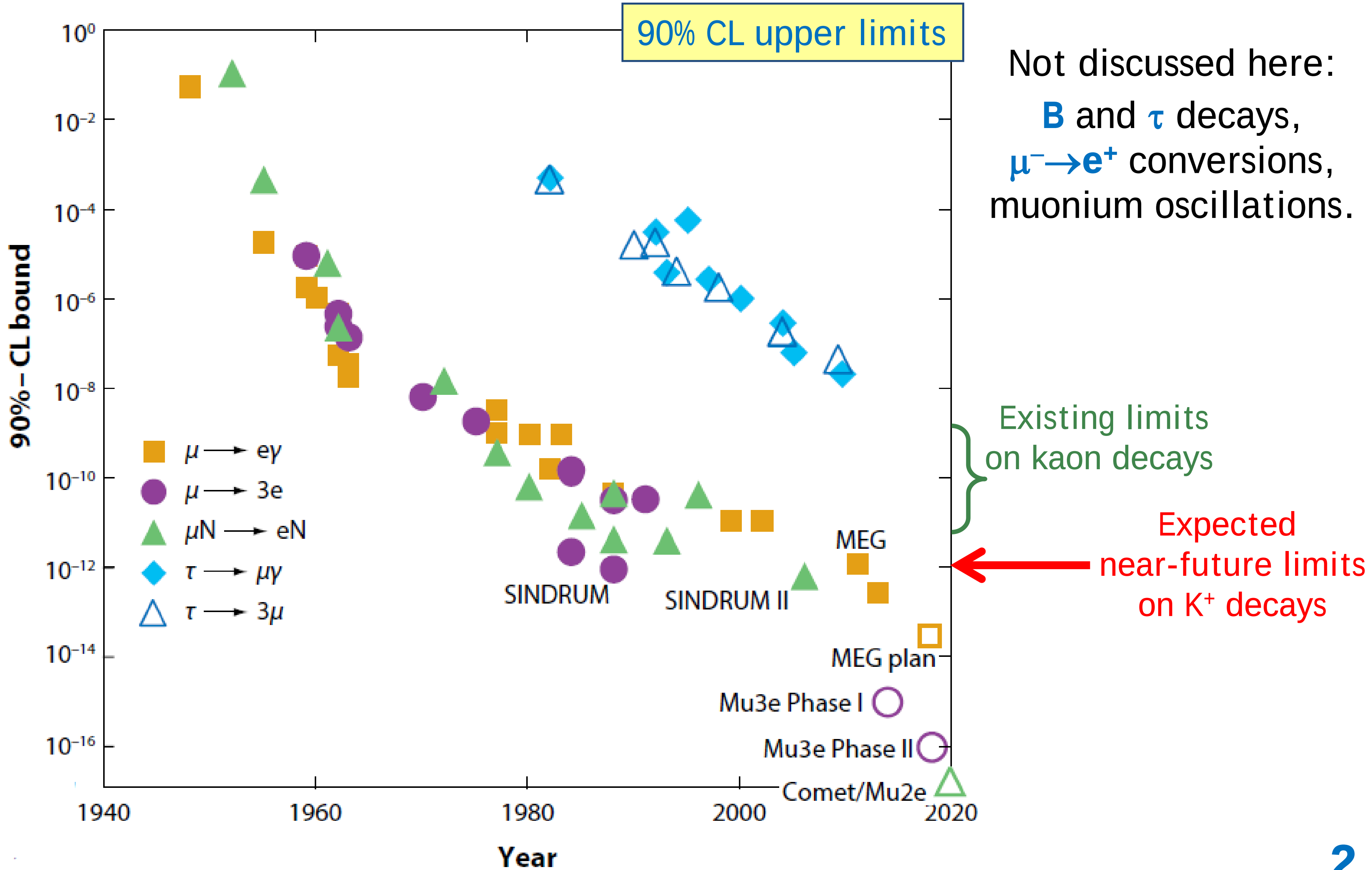
Example: $\mu \to e\gamma$




$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 \sim 10^{-54}$$

- ❖ This suppression is accidental due to smallness of $\Delta m^2_{ij}$.
- ❖ Can be enhanced beyond the SM (e.g. massive sleptons).

# Experiments: history & prospects




Not discussed here:

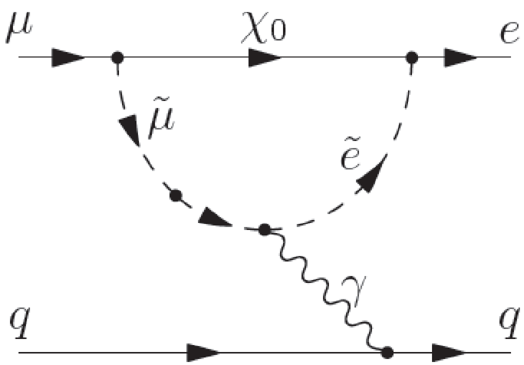
**B** and τ decays,

$\mu^- \to e^+$ conversions,

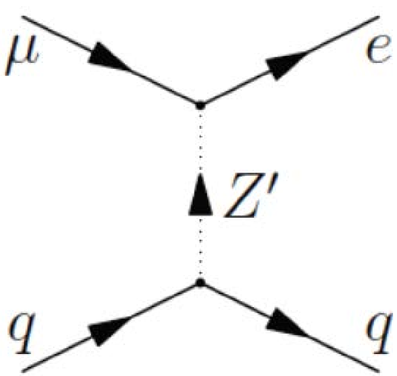
muonium oscillations.

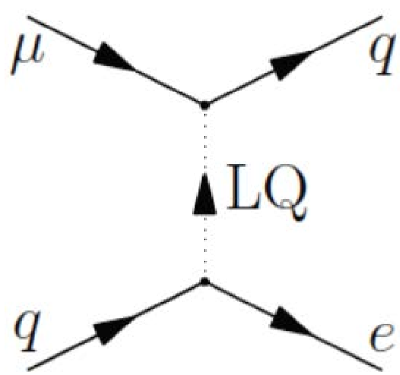
# New physics contributions: $\mu \to e$

## Loop terms (i.e. SUSY):



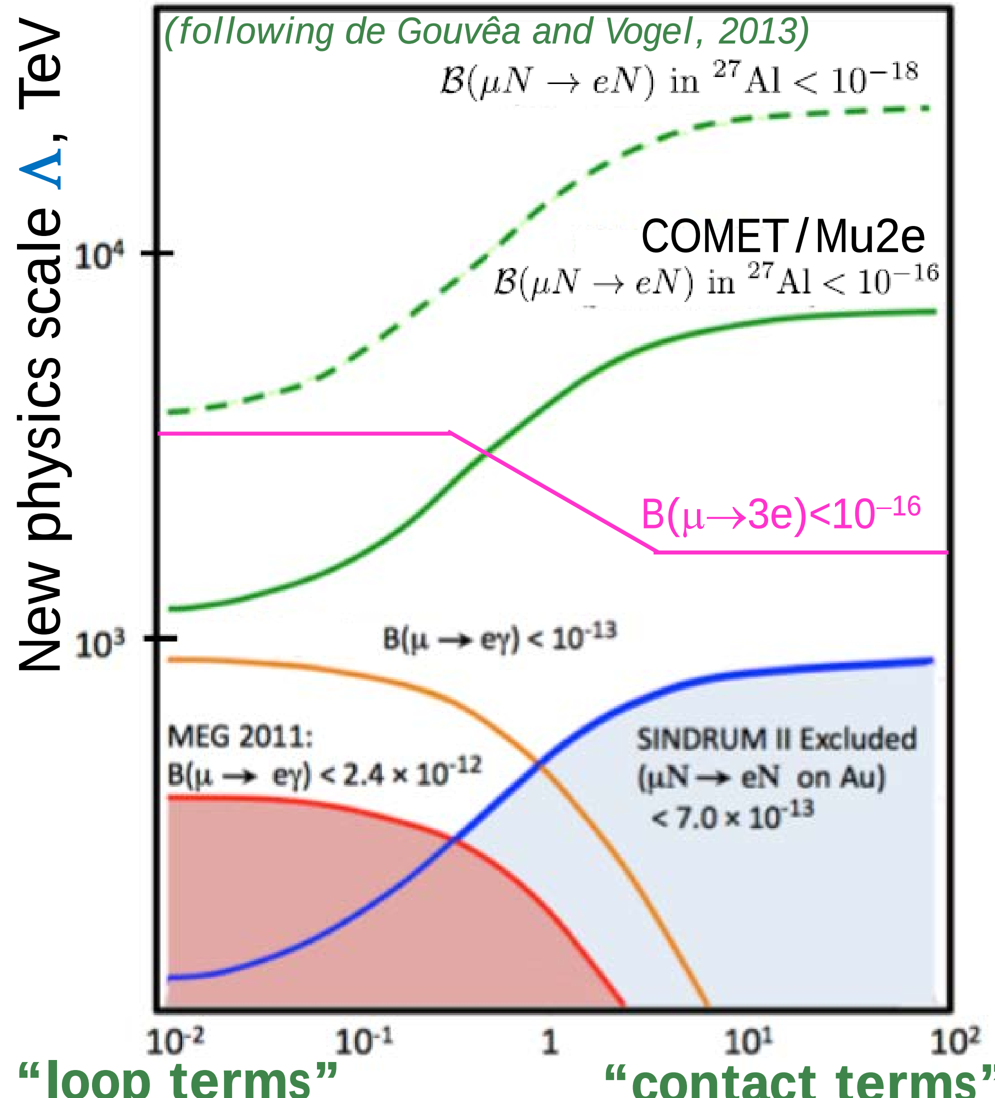

## Contact terms (particle exchange):




**~100 TeV** mass scales already excluded.
Near-future experiments aim
at **~$10^3$ TeV** scale.

Sensitivity of $\mu \to e$ experiments



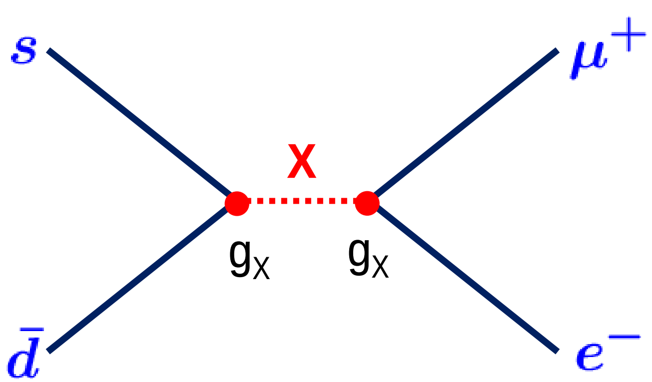
# LFV in K decays

Kaons decays:

- ❖ Copious production: high statistics.
- ❖ Simple decay topologies: clean experimental signatures.
- ❖ Source of tagged $\pi^0$ via $K^+\to\pi^+\pi^0$, $K_L\to 3\pi^0$, ... :
  best limits for LFV $\pi^0$ decays.

Sensitivity to the 4-fermion contact terms:

Example: $K_L \to \mu^+ e^-$




Dimensional argument:

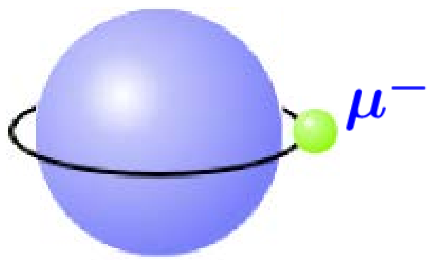
$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W}\cdot\frac{M_W}{M_X}\right)^4$$

For $g_X \approx g_W$ and $\mathcal{B} \sim 10^{-12}$,

$$M_X \sim 100\ \mathrm{TeV}$$

# Muon conversion

# Muonic atoms




Muonic atom formation:

- ❖ Stopped μ⁻ falls into the **1s** ground state.
- ❖ Emission of characteristic X-rays: can count stopped muons.

(a) Muon decay-in-orbit (DIO):

$$\mu^-(A,Z) \to e^-\bar{\nu}_e\nu_\mu(A,Z)$$

✓ rate weakly decreases with $Z$

(b) Muon capture by nucleus:

$$\mu^-(A,Z) \to \nu_\mu(A,Z-1)^*$$

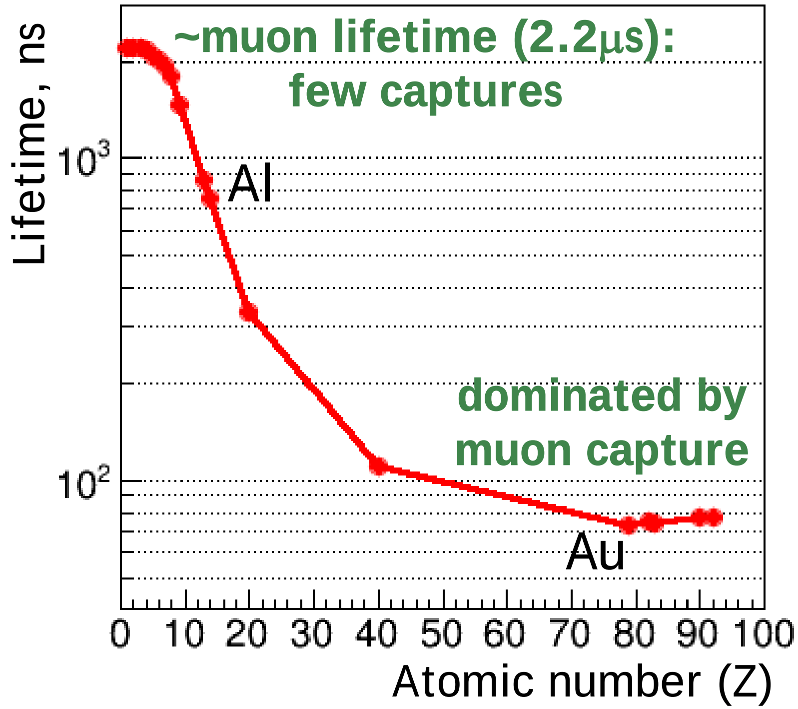
✓ rate $\sim Z^4$ ;

✓ unstable daughter nucleus (**n**, **p**, γ emission)

(c) New Physics: coherent **muon conversion**

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

Muonic atom lifetimes



# Muon conversion: $\mu^- N \to e^- N$

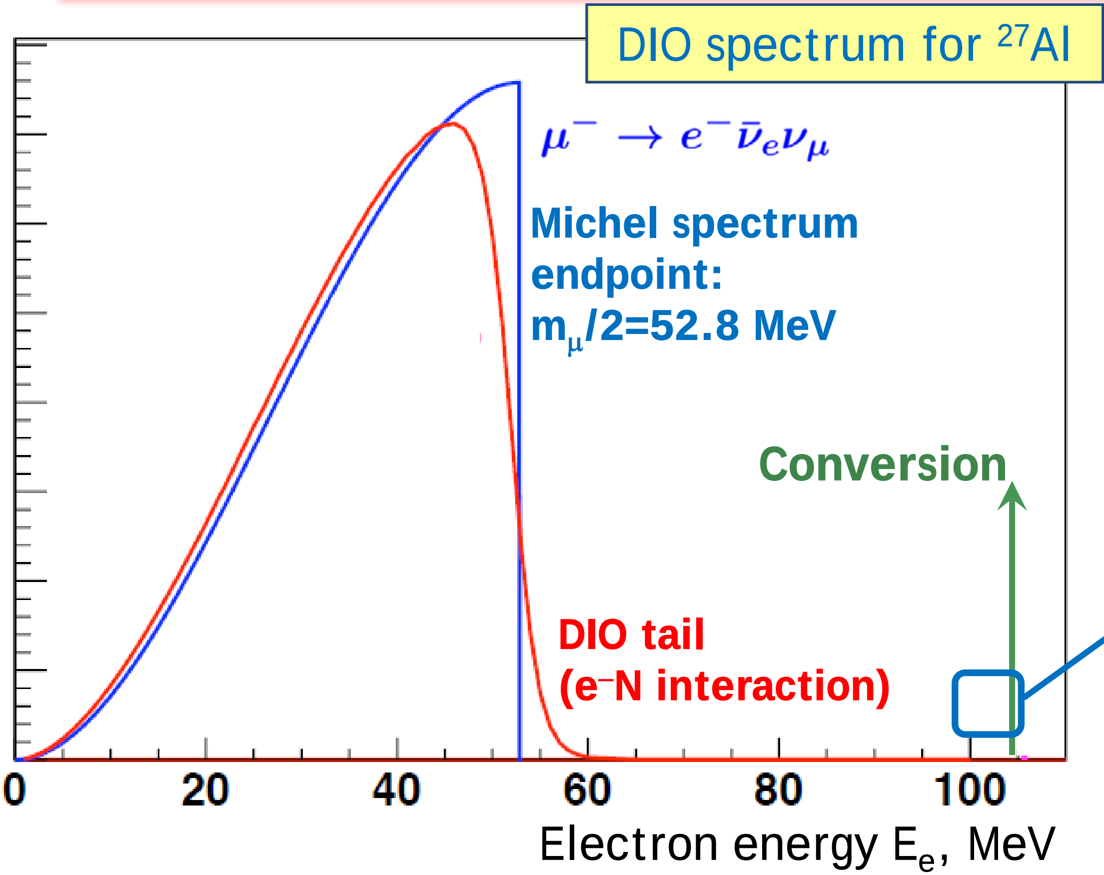
- Monochromatic electrons ($E_e \approx m_\mu$=106 MeV)
  **well above Michel endpoint** for free muon decay ($E_e \approx m_\mu/2$ =53 MeV).
- Background is *beam-related* rather than *detector-related*.
- Very high rate experiments are in principle possible.

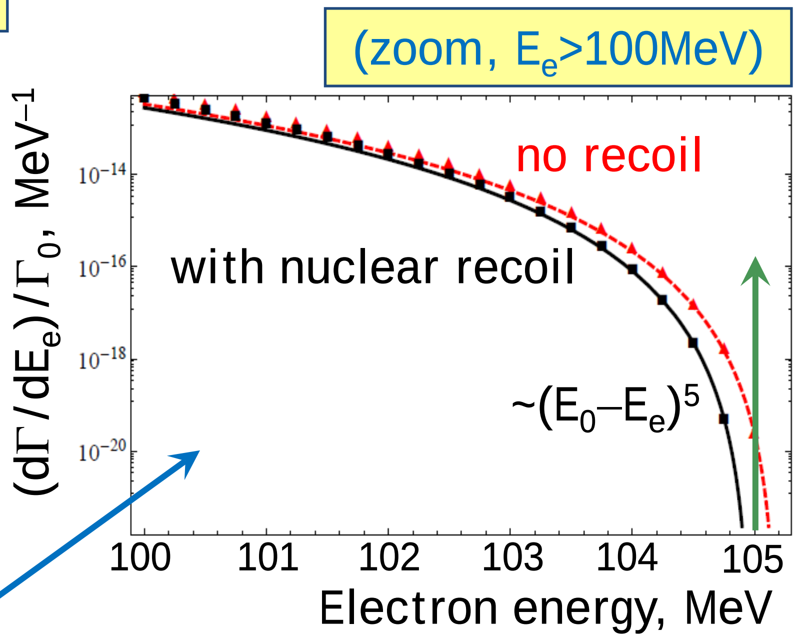
For muonic **Al**,

$$E_e = m_\mu - \underbrace{\frac{Z^2\alpha^2 m_\mu}{2}}_{\text{Binding energy} = 0.5\ \text{MeV}} - \underbrace{E_{\text{recoil}}}_{\text{Nuclear recoil } (\sim 1/A) = 0.2\ \text{MeV}} = 105.0\ \text{MeV}$$

- The measured quantity: $R_{\mu e} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')}$

# Decay-in-orbit (DIO)



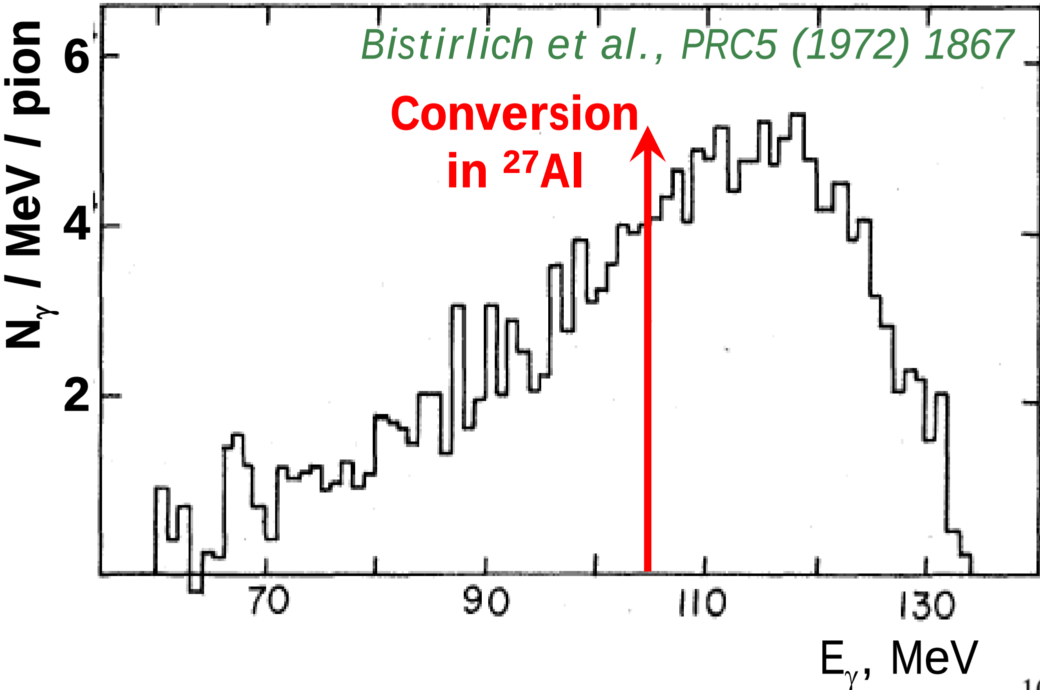




*(Czarnecki, Garcia i Torno, Marciano, PRD84 (2011) 013006)*

- Key issues: good **energy resolution** and **minimal energy loss**.
- Fraction of DIO within **1 MeV** from endpoint: **$\sim 10^{-17}$**.
- Energy resolution of near-future experiments: **$\delta E_e \sim 100$ keV**.
- DIO is not a limiting factor at **$R_{\mu e} \sim 10^{-17}$** precision.

# Radiative pion capture (RPC)

**Photon spectrum from RPC in $^{24}Mg$**



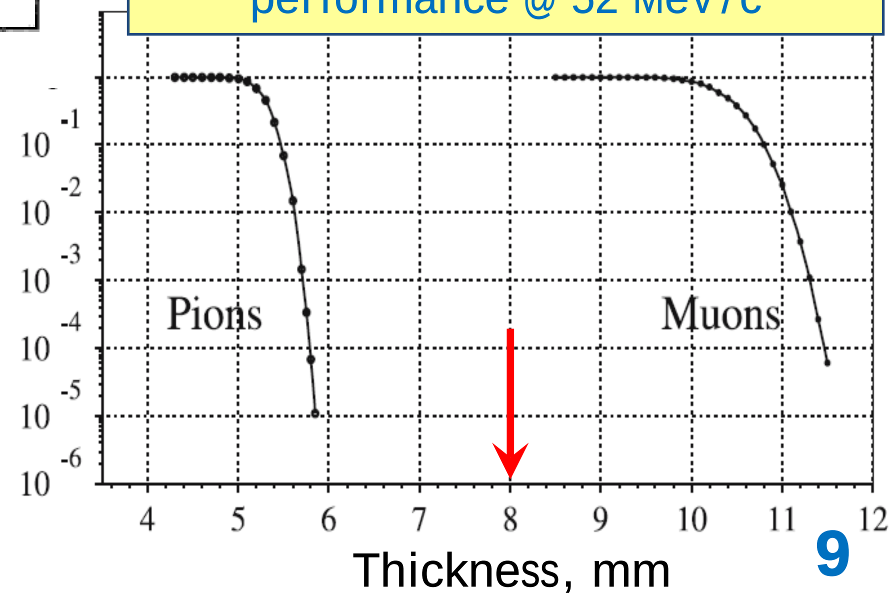

Residual $\pi^-$ in $\mu^-$ beam:

$$\pi^- N \to N'\gamma^{(*)}, \quad \gamma \to e^+e^-$$

→ Compatible to $\mu$–e conversion.

Anti-proton annihilation is similarly a background (production threshold: **$E=7m_p=6.6$ GeV**)

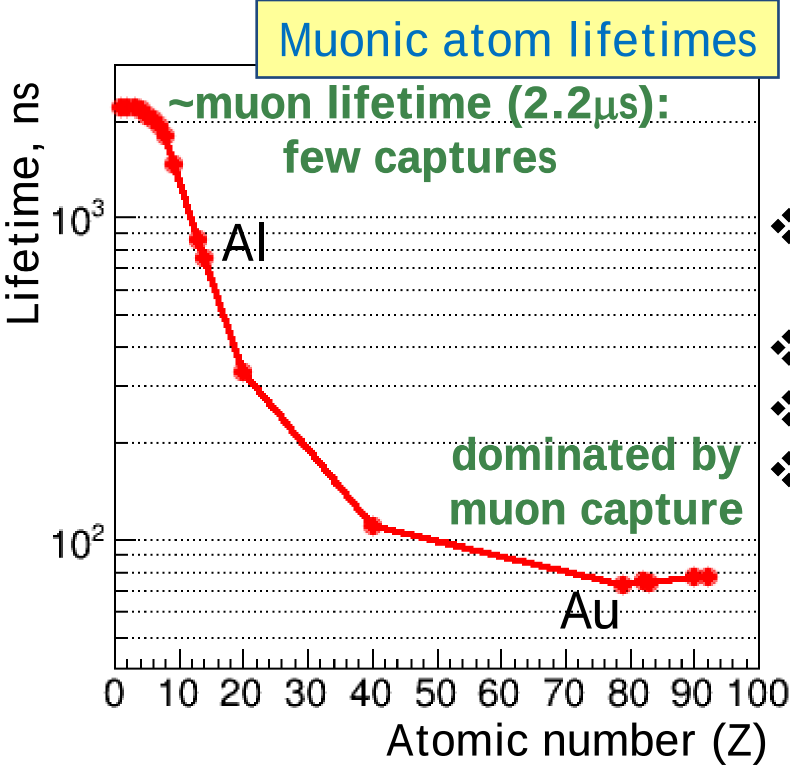
**SINDRUM II carbene ($CH_2$) degrader performance @ 52 MeV/c**




Beamline design for RPC suppression:

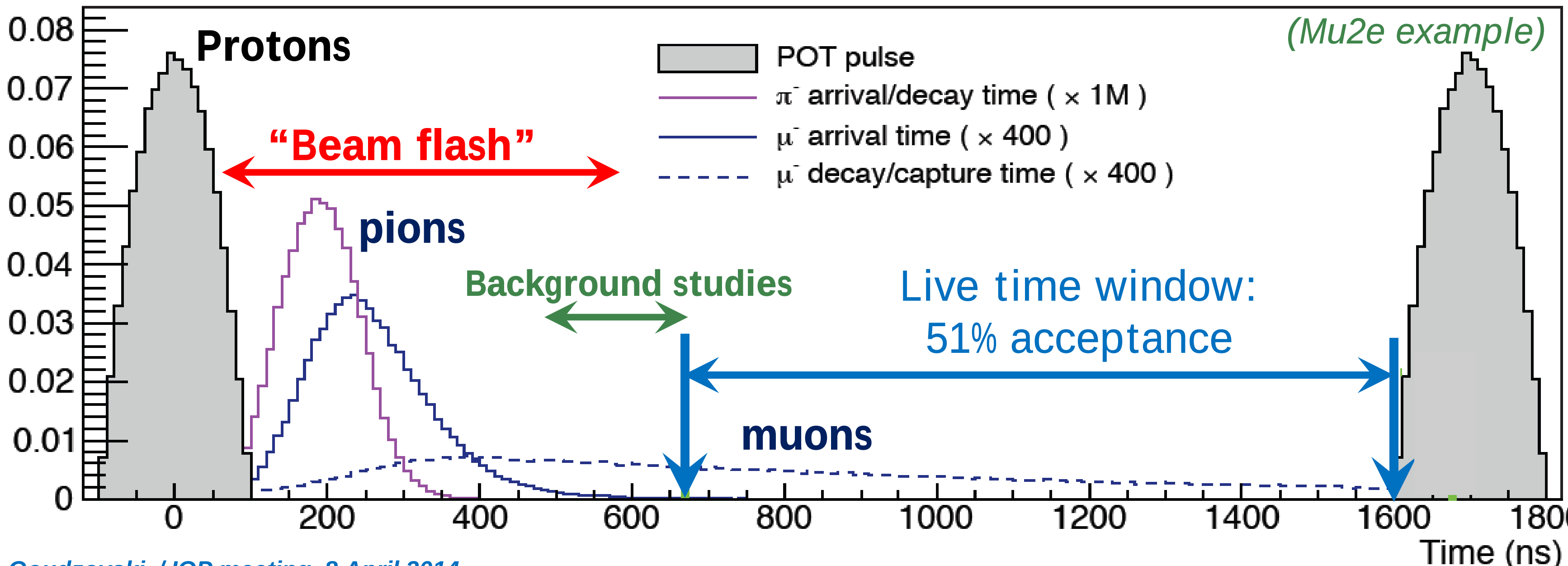
- using a degrader;
- if muonic atom lifetime ≫ $\pi^-$ lifetime (**=26 ns**), with timing conditions.

# RPC: timing

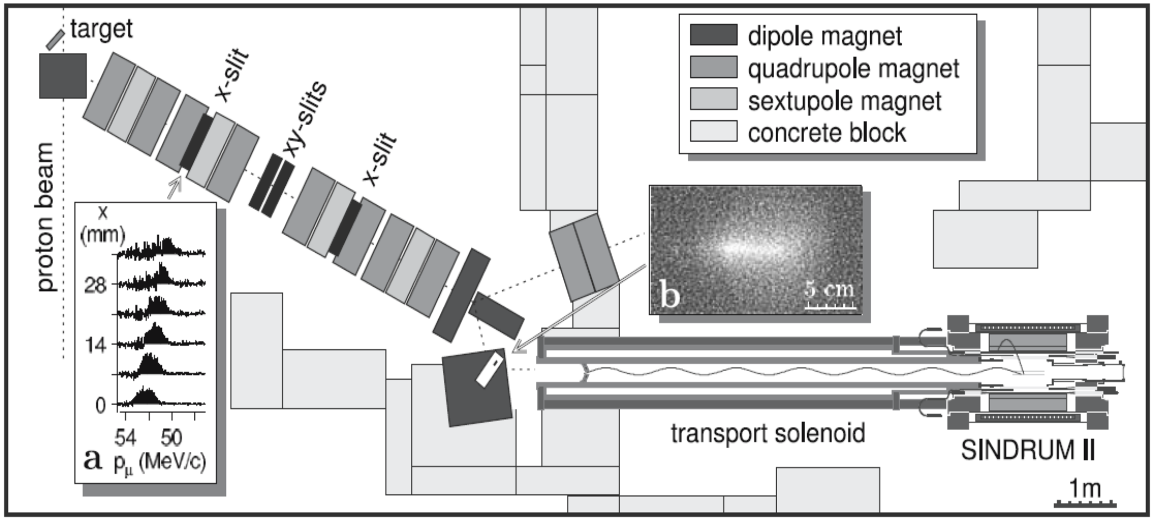



- Near-future experiments COMET, Mu2e: bunched proton beams (**~100 ns** / **~1 μs**).
- Low-**Z** (**Al**) target: RPC is **prompt background**.
- Proton extinction factor **$<10^{-9}$** required.
- High-**Z** measurements would elucidate underlying physics of a potential signal.

*[Muonic atom lifetime data: D.F.Measday, Phys.Rept.354 (2001) 243]*



# SINDRUM-II at PSI

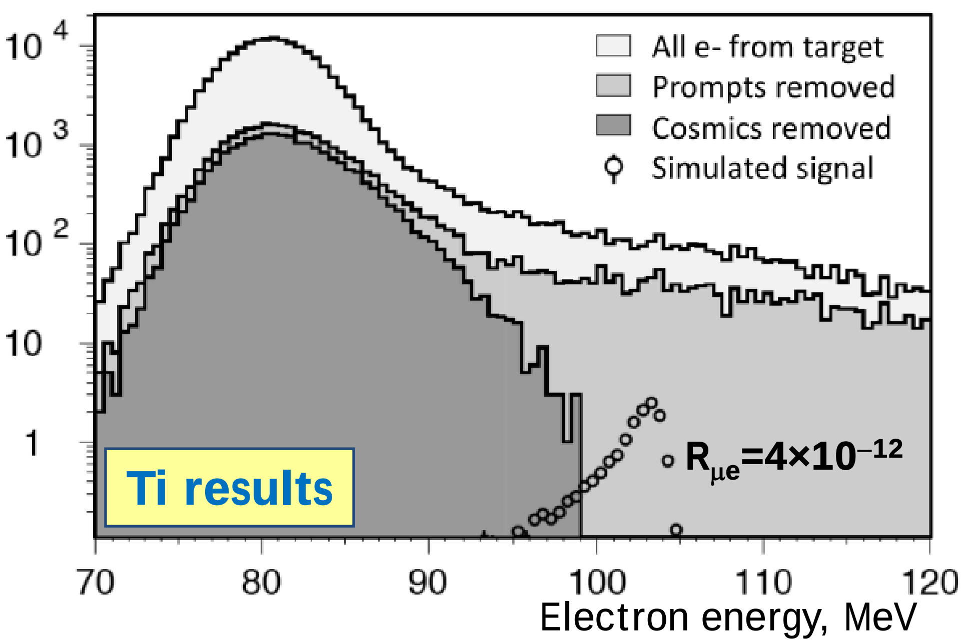


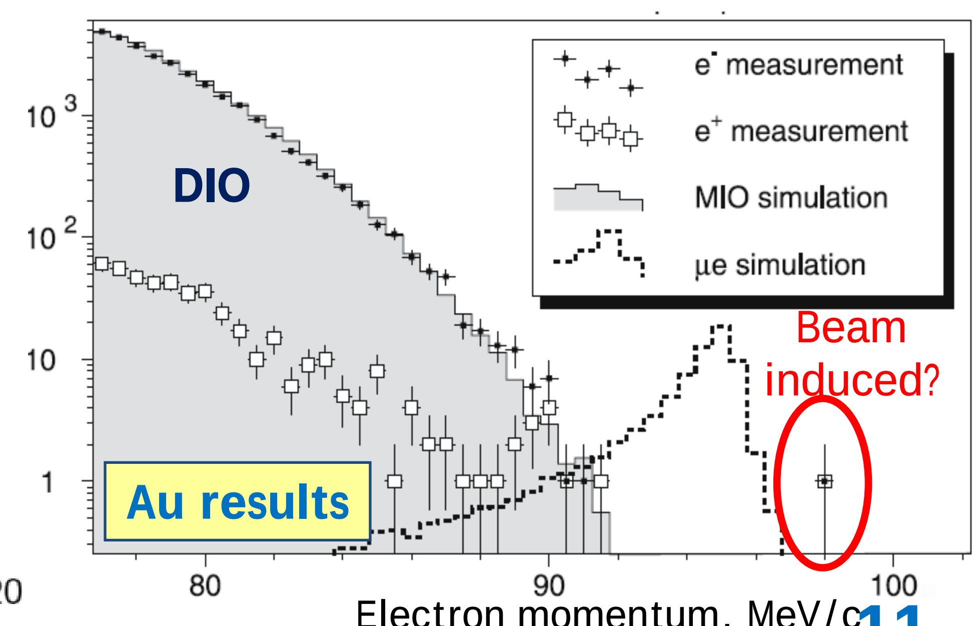

- Proton beam: **590 MeV/c**, **0.3/19.75 ns**.
- RPC suppression: **$CH_2$** degrader.
- **Ti**, **Pb**, **Au** targets.

Limit for muonic gold:

$$R_{\mu e}^{\mathrm{Au}} < 7 \times 10^{-13} \ (90\% \ \mathrm{CL})$$

*[Bertl et al., EPJ C47 (2006) 337]*



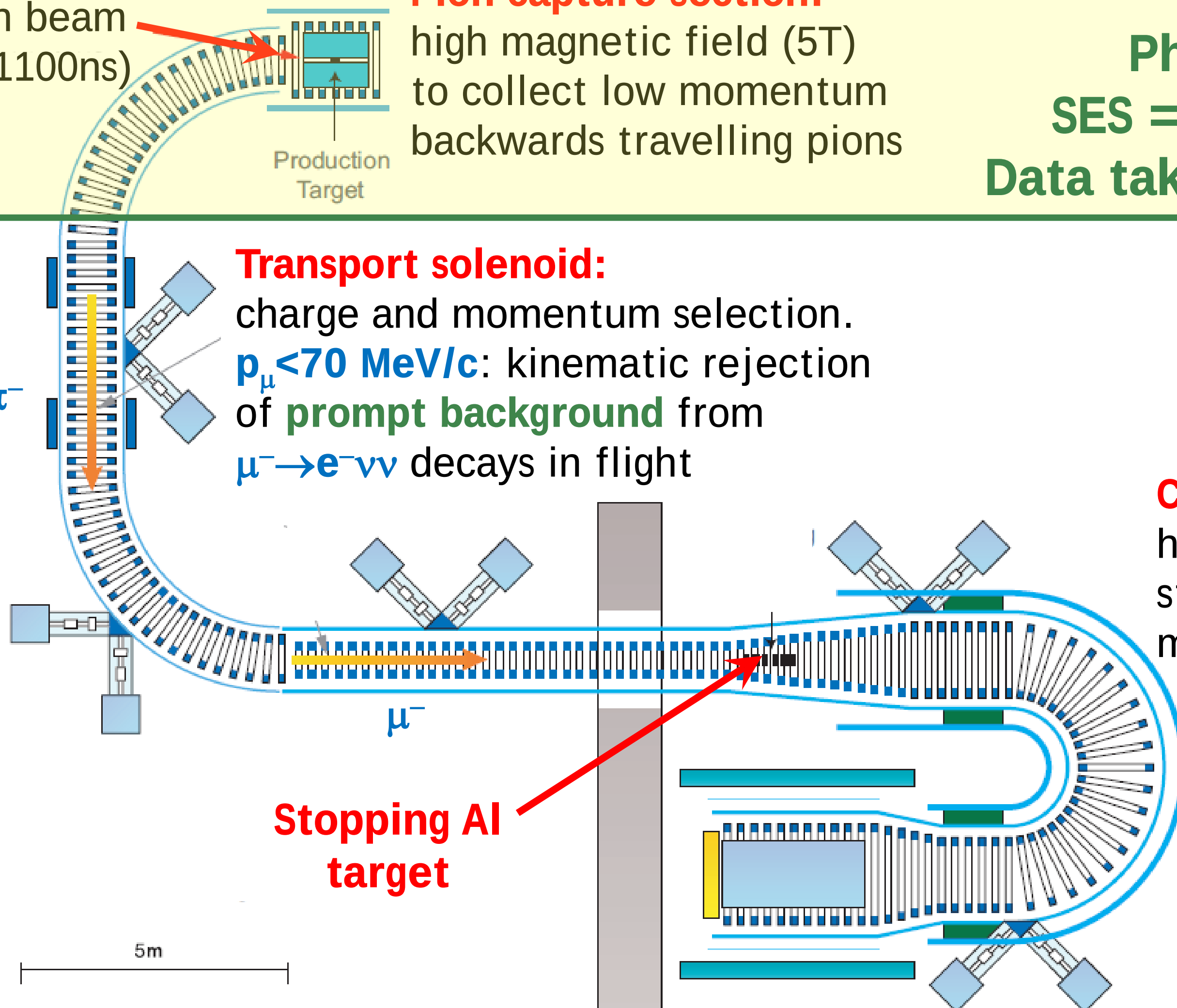



# COMET at J-PARC

Pulsed 8 GeV proton beam (100/1100ns)

**Pion capture section:**
high magnetic field (5T) to collect low momentum backwards travelling pions

**Phase I**
**SES = $3\times10^{-15}$**
**Data taking: 2016+**




**Transport solenoid:**
charge and momentum selection.
**$p_\mu$<70 MeV/c**: kinematic rejection of **prompt background** from $\mu^- \to e^- \nu\nu$ decays in flight

**Curved solenoid:**
high-momentum **e⁻** selection, stops most DIO and muon capture products

**Stopping Al target**

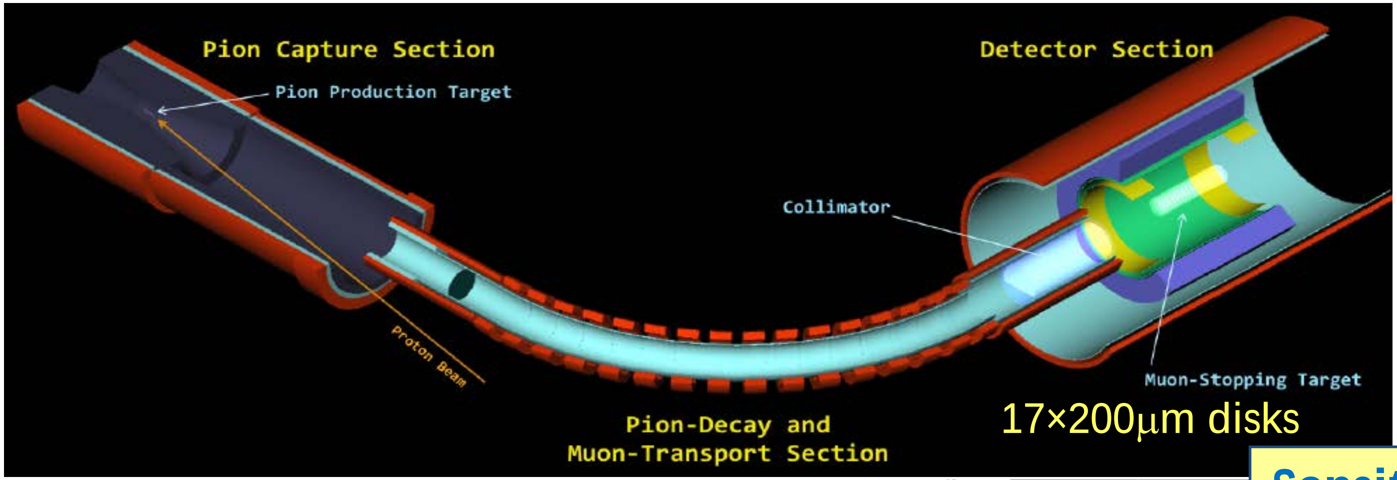
**Phase II (full setup)**
**SES = $3\times10^{-17}$**
**Data taking: 2020+**

**Forward detector:**
straw tracker followed by EM calorimeter.
**Rate < 1MHz.**

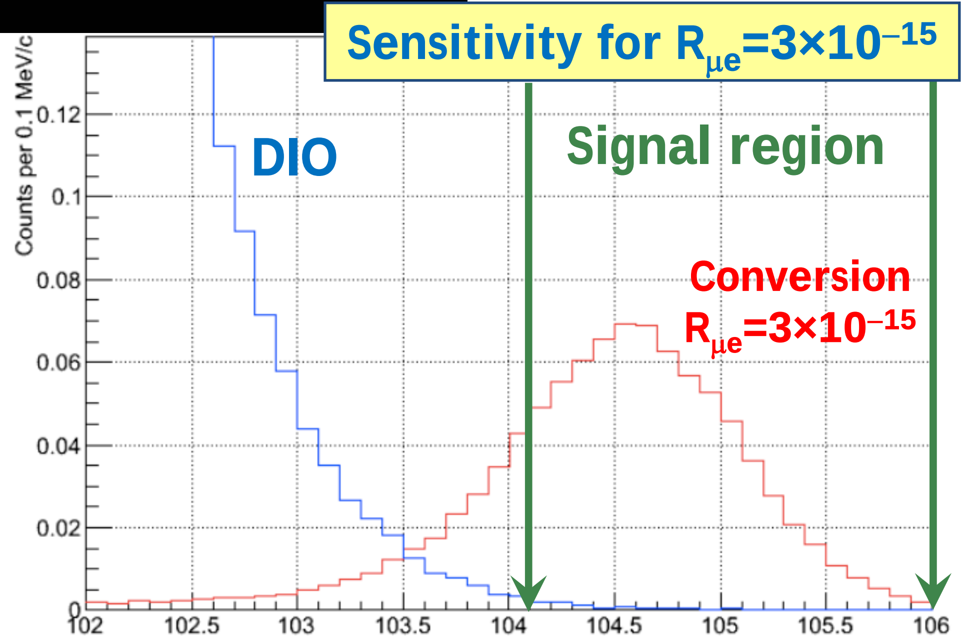
# COMET phase I (2016+)

A dedicated detector: cylindrical drift chamber in **1T** solenoidal field.

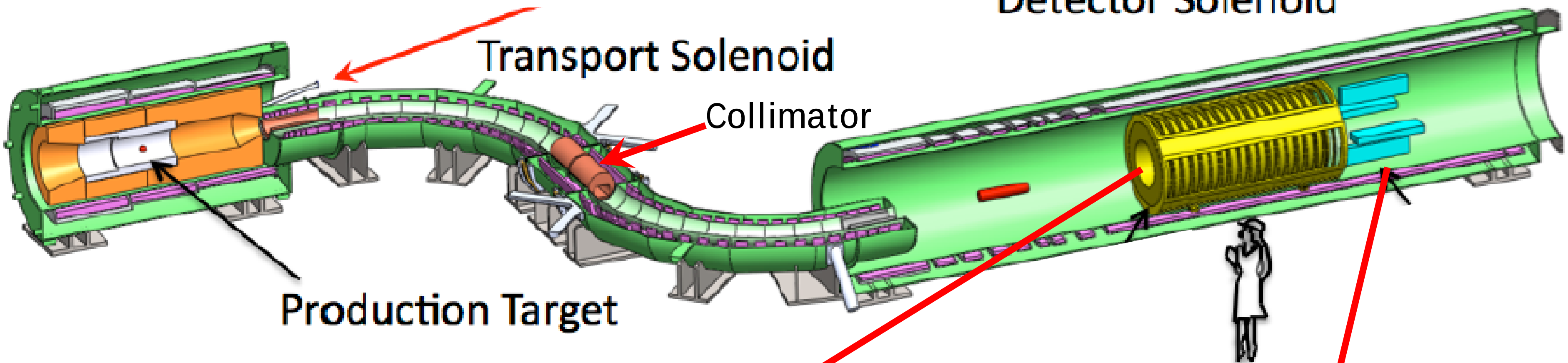
- Higher acceptance but worse resolution ($\delta p_e \approx$ **0.5 MeV/c**) wrt Phase II.
- No charge selection: can search for LNV process $\mu^- N \to e^+ N'$.




- Protons on target: **$4\times10^{18}$**.
- Signal acceptance: **~6%**.
  (timing: **39%**, geometrical: **24%**, momentum cut: **74%**, trigger: **90%**).
- Expected background: **0.03** events
  (DIO: **0.01** [determines the $p_e$ cut], RPC: **0.01**, anti-protons: **0.01**).
- Expected SES: **$3\times10^{-15}$**.



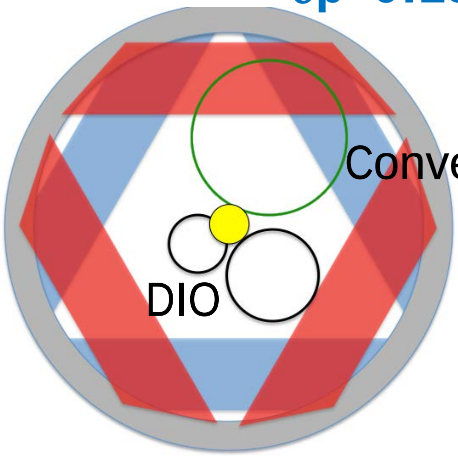
# Mu2e at FNAL

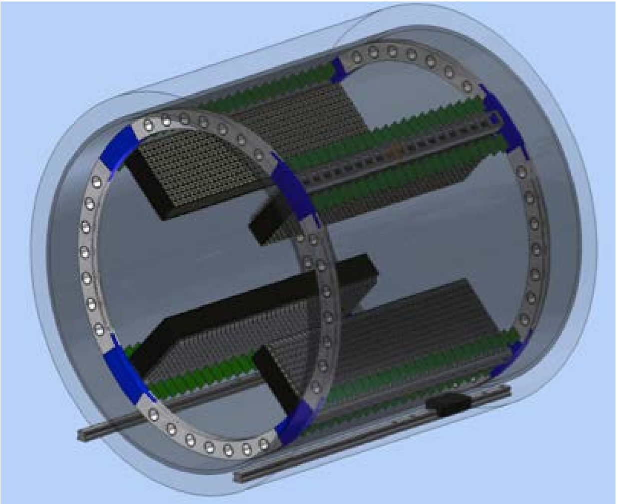



Protons: **1.7μs** structure,
**8 kW**, **$E_{kin}$=8 GeV**

Straw tracker in **1T** magnetic field.
**~22k** Mylar straws tubes (**D=5mm**).
**dE/dx** capability for proton suppression;
**δp<0.18 MeV/c**.

EM calorimeter
4×11×44 LYSO crystals
arranged in 4 vanes.



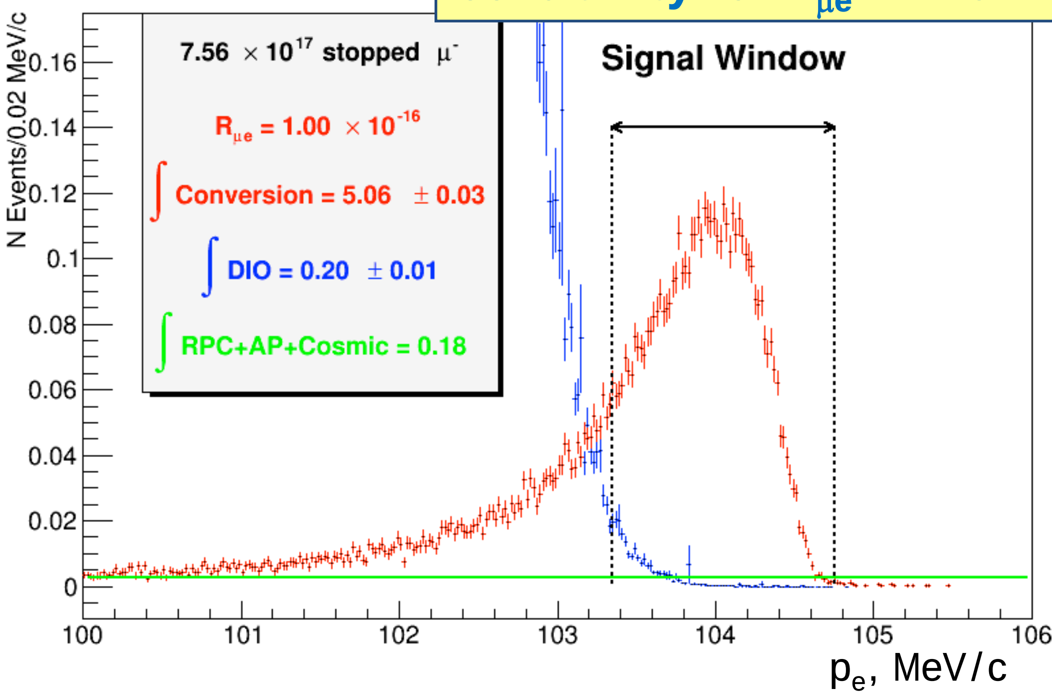



Resolutions:
- energy: **4.5%** at **105 MeV**;
- position: **4 mm**;
- timing: **~1ns**.

# Mu2e sensitivity

- Protons on target: **3.6×10$^{20}$**.
- $\mu^-$ stops per proton on target: **0.16%**.
- Signal acceptance: **5.25%** (timing: **51%**, selection & trigger: **10%**).
- Expected total background: **0.41** events
  (DIO: **0.22**, cosmic: **0.05**, RPC: **0.03**, anti-protons: **0.10**).
- Goal SES: **2.4×10$^{-17}$**.

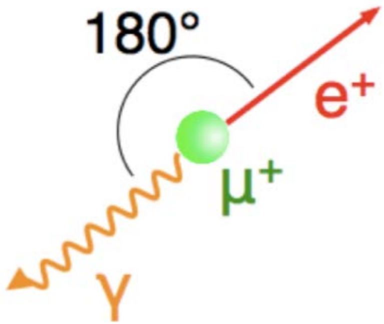
**Sensitivity for $R_{\mu e}=1\times10^{-16}$**



# LFV muon decays

# $\mu^+ \to e^+\gamma$: backgrounds

**Signal:**
two-body decay

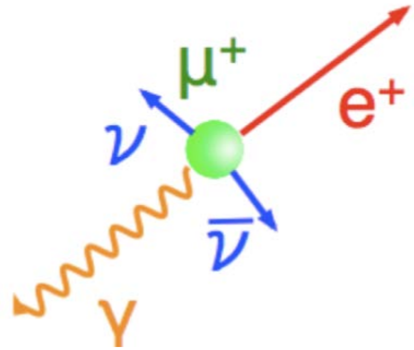



$$E_e = E_\gamma = \frac{m_\mu}{2} = 52.8\ \mathrm{MeV}$$

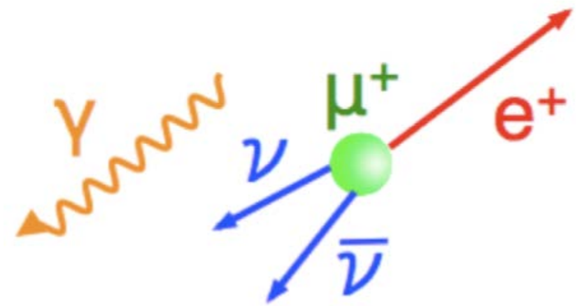
$$\theta_{e\gamma} = 180^\circ, \quad t_{e\gamma} = 0$$

**Backgrounds:**

Radiative Michel decay (RMD)




Accidental




Michel decay and photon from RMD, **$e^+e^- \to \gamma\gamma$**, **$eN \to eN\gamma$**

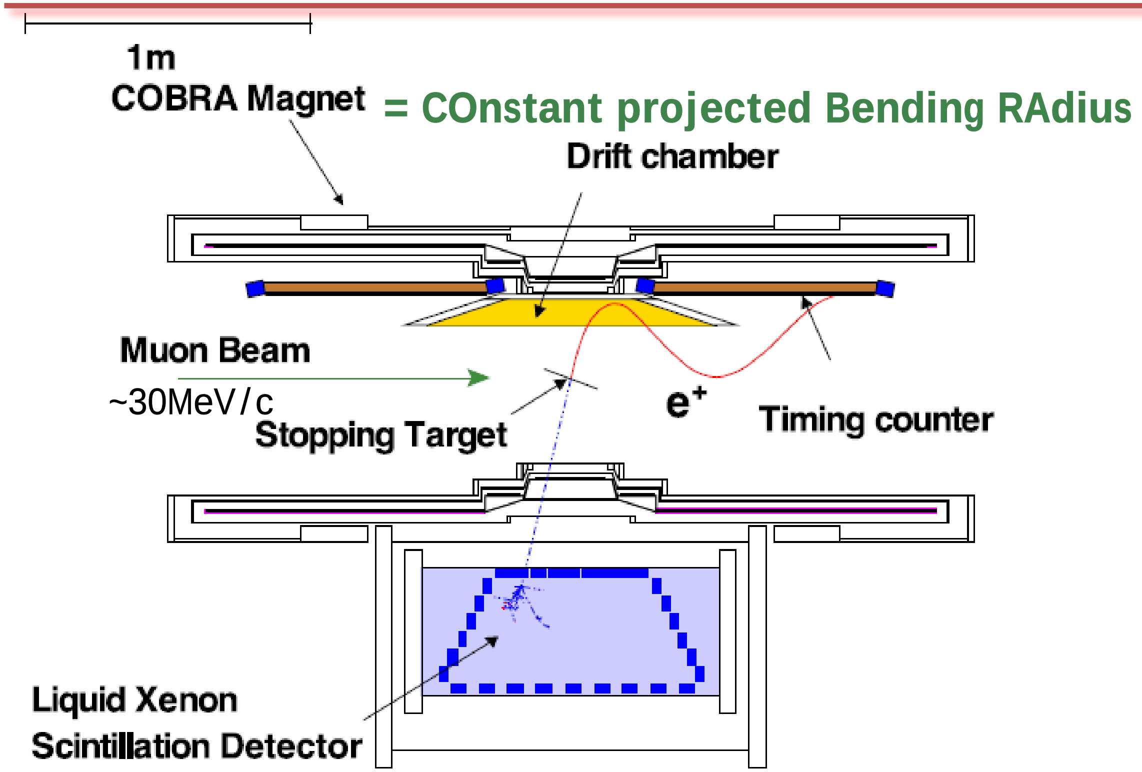
Accidental background dominates (**>90%**):

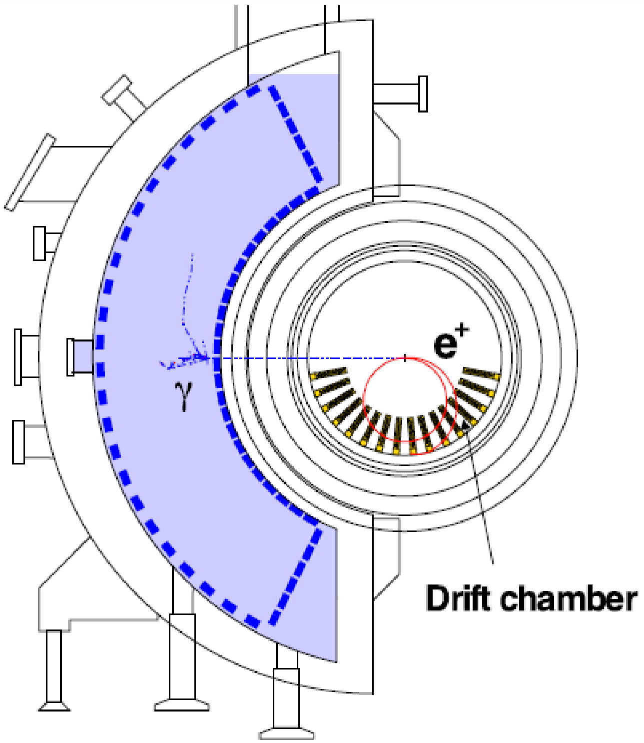
- ❖ contamination (**$N_{acc}/N_{sig}$**) scales linearly with **instantaneous muon rate**;
- ❖ therefore **continuous** rather than pulsed beam (**~$3\times10^7$ $\mu^+$/s**);
- ❖ background level is determined by the **detector resolution**.

$$\frac{N_{\rm acc}}{N_{\rm sig}} \sim R_\mu \cdot \underbrace{\delta E_e}_{0.5\,\mathrm{MeV}} \cdot \underbrace{(\delta E_\gamma)^2}_{1.0\,\mathrm{MeV}} \cdot \underbrace{\delta t_{e\gamma}}_{130\,\mathrm{ps}} \cdot \underbrace{(\delta\theta_{e\gamma})^2}_{\sim 0.015}$$

**Approximate MEG values:** 0.5MeV 1.0MeV 130ps ~0.015

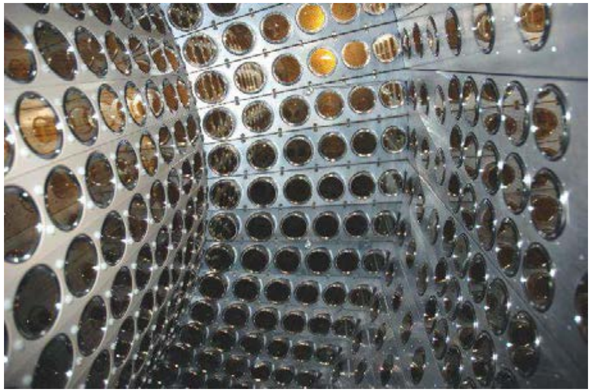
# MEG at PSI (2008–2013)




**Gradient magnetic field:** bending radius **~p**, not **~$p_T$**.

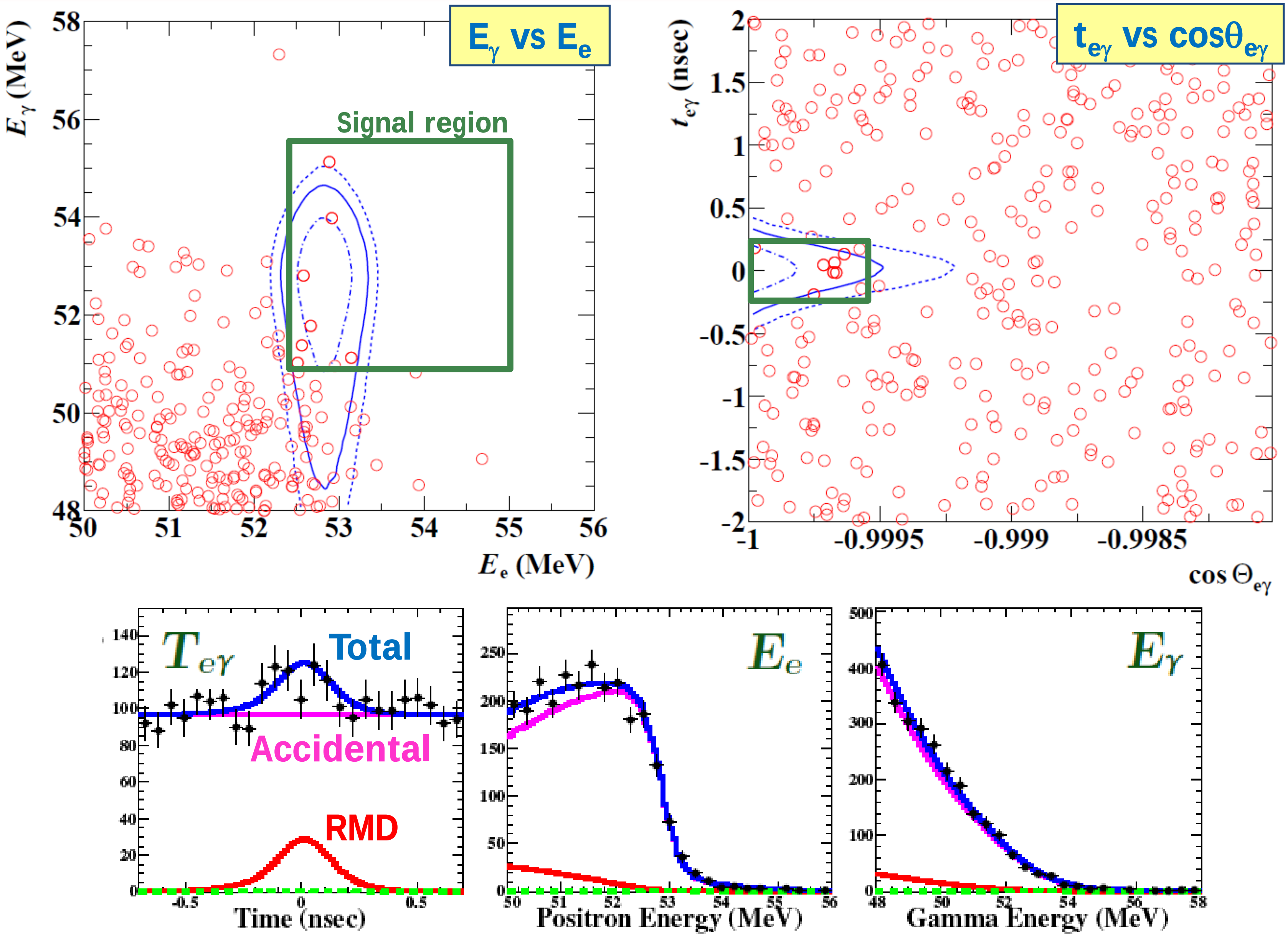
- ❖ only **$e^+$** near Michel endpoint reach the tracker;
- ❖ small number of curls for **$e^+$** emitted at **$\theta \approx 90°$**;
- ❖ therefore excellent spectrometer rate capability.



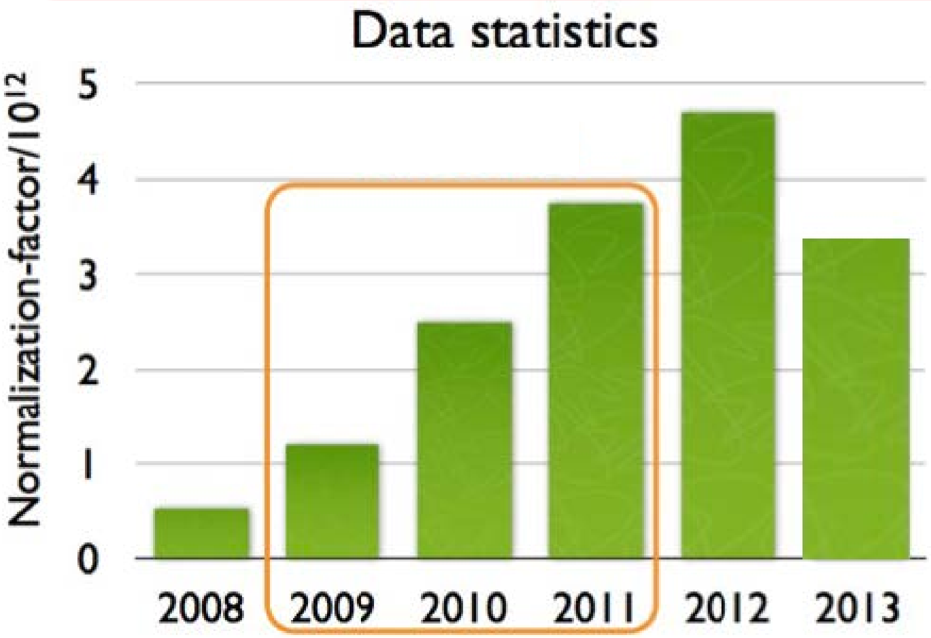
**EM calorimeter:** 846 PMTs immersed in 900 litres of **LXe**.

- ❖ prompt response: low pile-up.

# MEG 2009–2011 data



# MEG result




Final result with 2009–2011 sample ($3.6\times10^{14}$ stopped $\mu^+$):

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13} \quad (90\%\mathrm{CL})$$

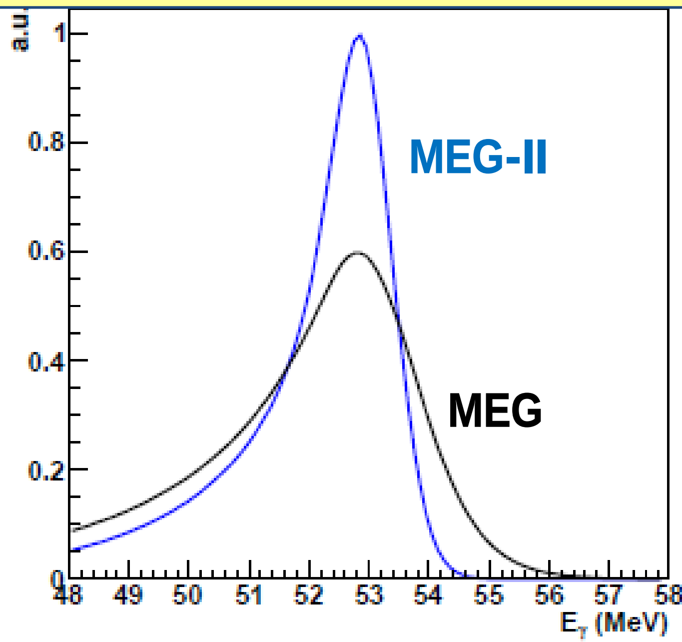
*PRL 110 (2013) 201801*

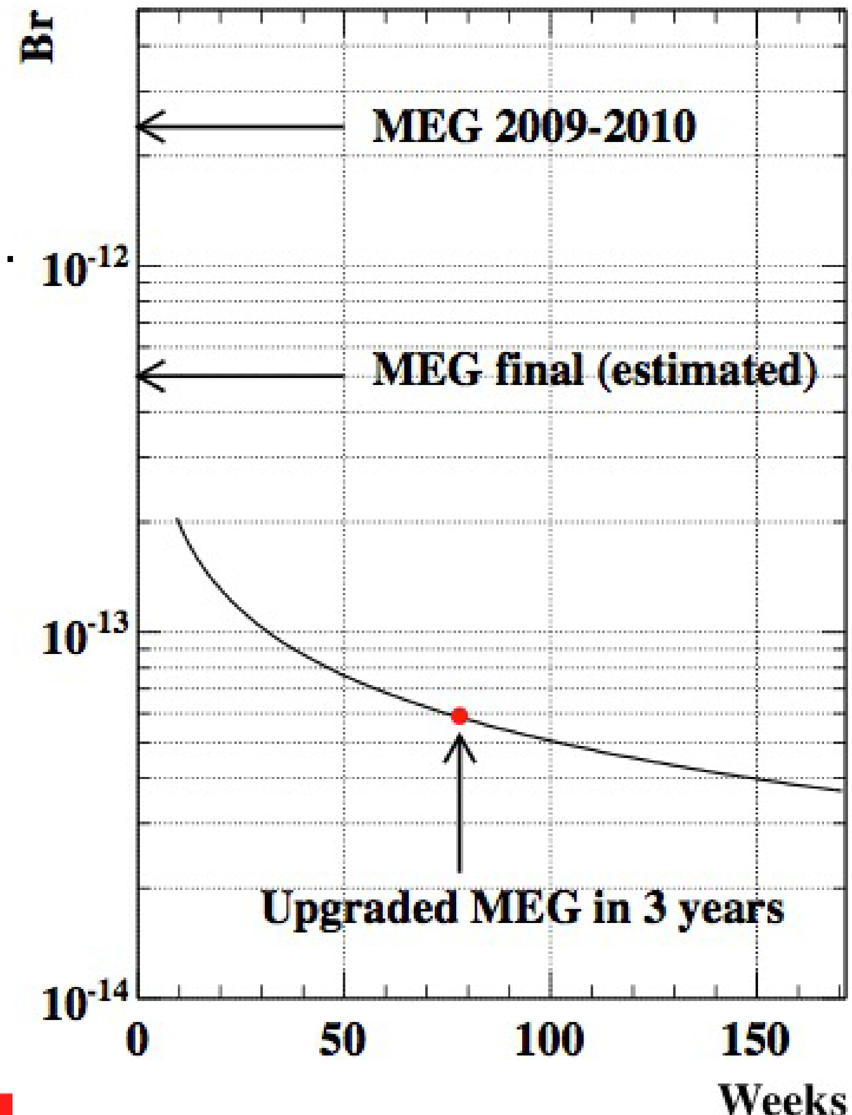
- MEG data taking completed in 2013.
- Sensitivity is limited by the accidental background.
- Improved detector resolution required to go beyond the **$\sim10^{-13}$** sensitivity.

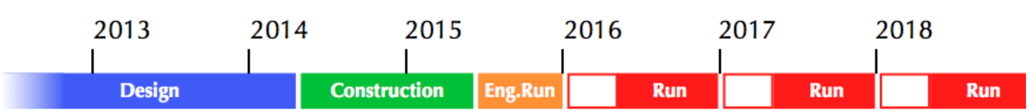
# MEG upgrade

- Higher beam rate (**~10⁸ μ⁺/s**).
- Thinner stopping target (**e⁺** direction).
- Higher tracker granularity (**$\delta E_e$**).
- New pixelated timing counter (**$\delta t_e$**).
- EM calorimeter: more PMTs (**$\delta E_\gamma$**; pileup).

Example: photon energy measurement



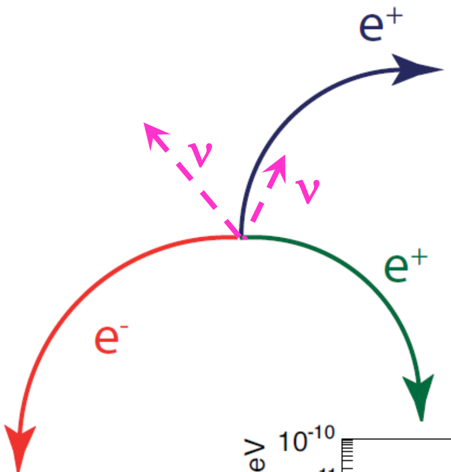
# Mu3e at PSI: $\mu^+ \to e^+e^+e^-$

For loop NP contributions, $\mathcal{B}(\mu^+ \to e^+e^+e^-)/\mathcal{B}(\mu^+ \to e^+\gamma) \sim \alpha$

Mu3e goal: $\mathcal{B}(\mu^+ \to e^+e^+e^-) \sim 10^{-16}$ (4 orders below SINDRUM, 1988)

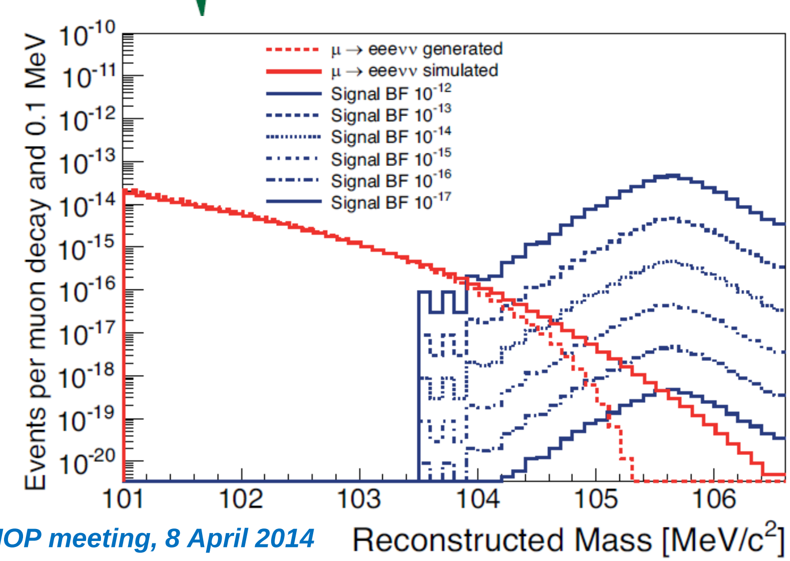
Note: $\mu^+ \to e^+e^+e^-$ is sensitive to contact interactions.

**Dominant irreducible background: radiative Michel decay + conversion**

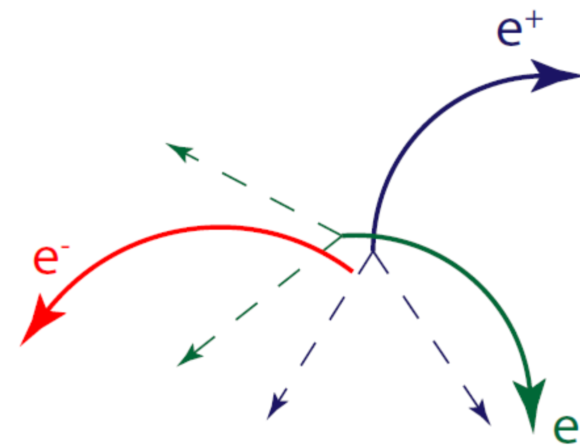



$$\mu^+ \to e^+\nu\bar{\nu}\gamma^*$$
$$\to e^+e^+e^-\nu\bar{\nu}$$

**Excellent momentum resolution required (<1MeV/c); determines the sensitivity**




**Accidentals**




Electrons ($e^-$) from:

- ❖ photon conversions;
- ❖ Bhabha scattering

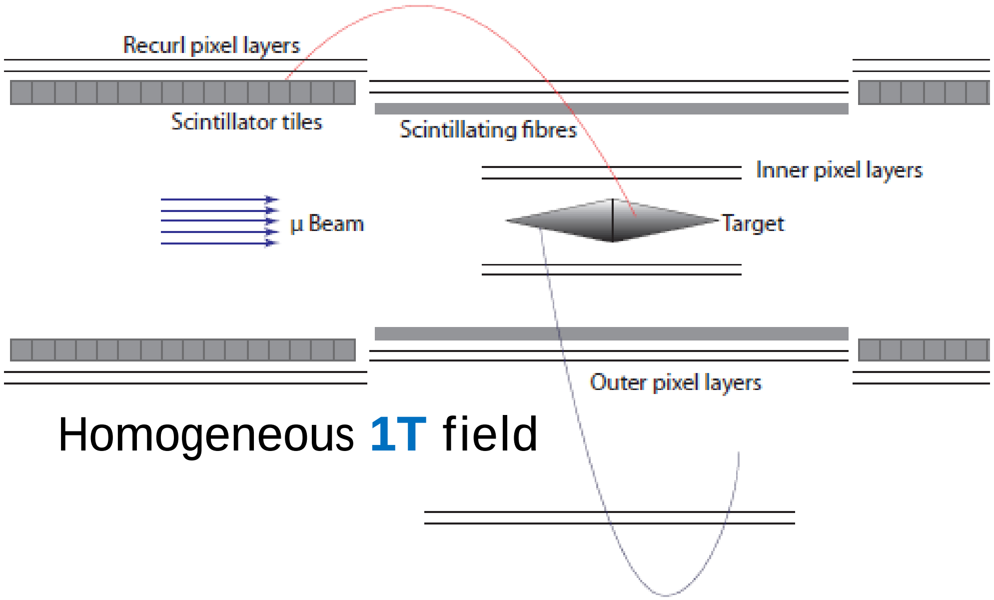
($e^+e^-$ vertex, missing energy);

- ❖ mis-reconstruction.

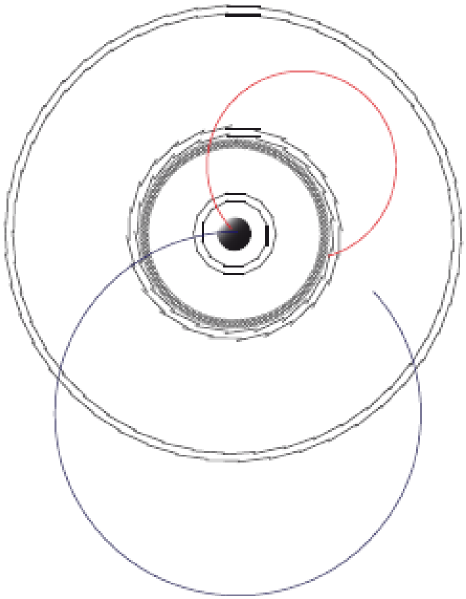
**Excellent vertex and time resolution required**

# Mu3e detector

- Acceptance over a wide momentum range: MEG tracker cannot be adapted.
- Beamline upgrade (**~$10^9$ $\mu^+$/s**) required to reach **~$10^{-16}$** sensitivity.
- SINDRUM sensitivity was limited by radiative background (**~$10^{-14}$**) though upper limit (**B<$10^{-12}$**) is determined by the number of muon stops.




Homogeneous **1T** field

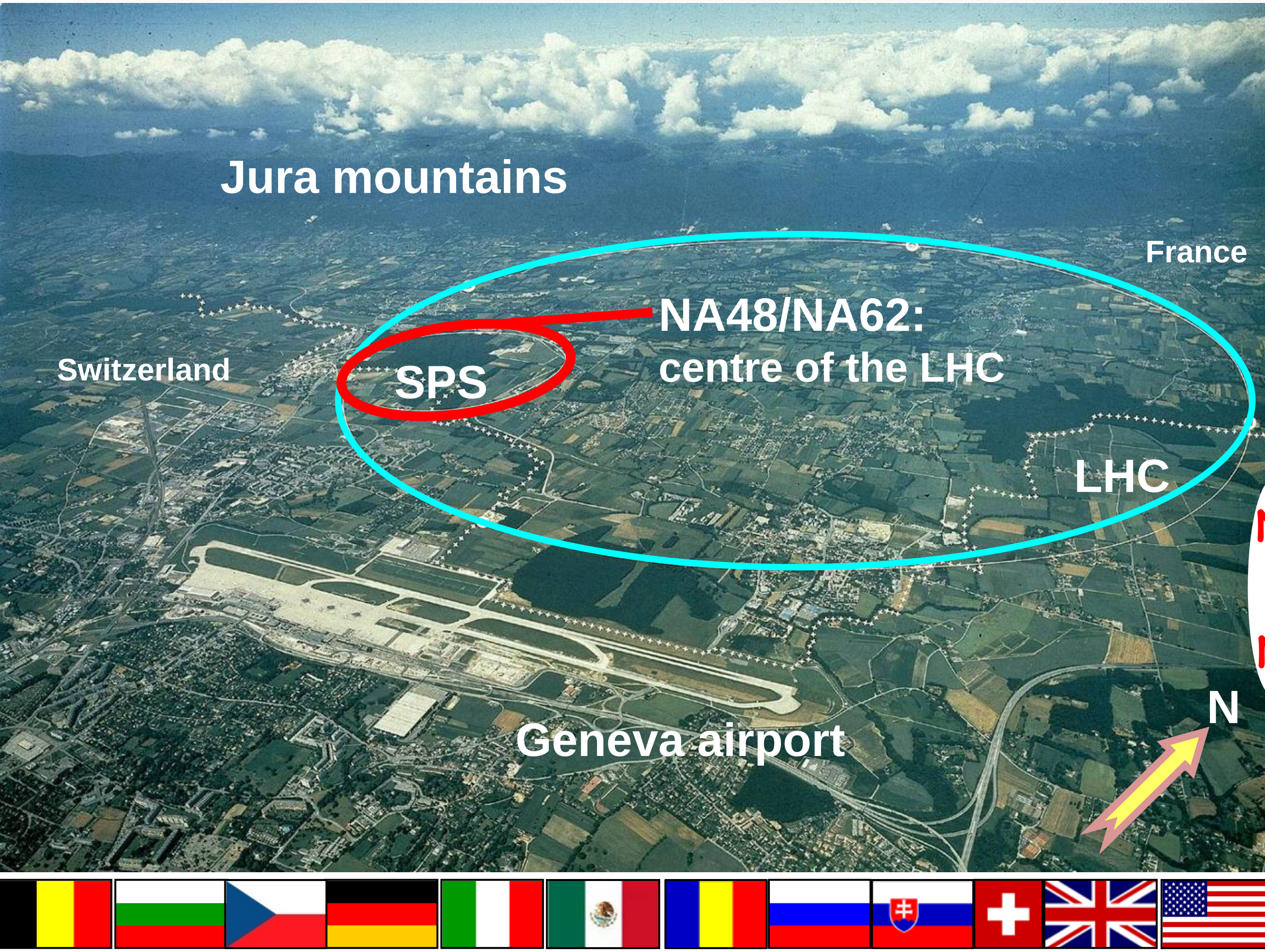


**Precision tracking:** **~$10^8$** Monolithic Active Pixel Sensors (HV-MAPS). High granularity, minimal material budget (pixel size: **~80 μm**, thickness: **~50 μm**).

**Precision timing:** scintillator fibre/tile hodoscope, **~100ps** resolution.

# Charged kaon decays

# NA62 at CERN



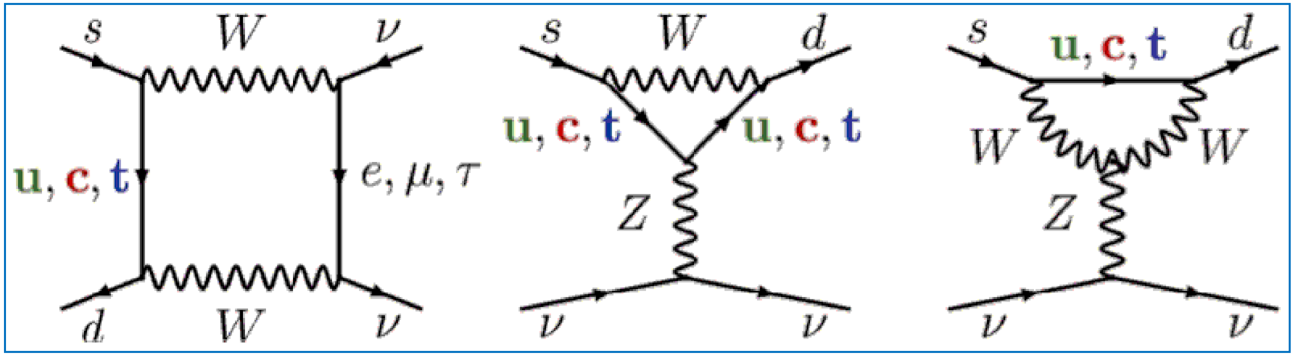

Earlier: NA31

| | | | |
|---|---|---|---|
| NA48 discovery of direct CPV | 1997 | $\varepsilon'/\varepsilon$: $K_L$+$K_S$ | |
| | 1998 | $K_L$+$K_S$ | |
| | 1999 | $K_L$+$K_S$ | $K_S$ HI |
| | 2000 | $K_L$ only | $K_S$ HI |
| | 2001 | $K_L$+$K_S$ | $K_S$ HI |
| NA48/1 | 2002 | $K_S$/hyperons | |
| NA48/2 | 2003 | $K^+/K^-$ | |
| | 2004 | $K^+/K^-$ | |
| NA62 $R_K$ phase | 2007 | $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests |
| | 2008 | $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests |
| NA62 | 2012 | technical run | |
| | *2014* | 1st $K^+\to\pi^+\nu\bar{\nu}$ run | |

Kaon decay in flight experiments.
NA62: currently **~180** participants,
**29** institutions, **12** countries

# The challenge: $K\to\pi\nu\bar{\nu}$

**SM: box and penguin diagrams**




Ultra-rare decays with the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$$

- Hadronic matrix element related to a measured quantity ($K^+\to\pi^0 e^+\nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–B mixing or $B^0\to\rho\gamma$.
- Optimal probe for non-MFV *(Gino Isidori, ESPP open symposium 2012)*

SM branching ratios

*Brod et al., PRD 83 (2011) 034030*

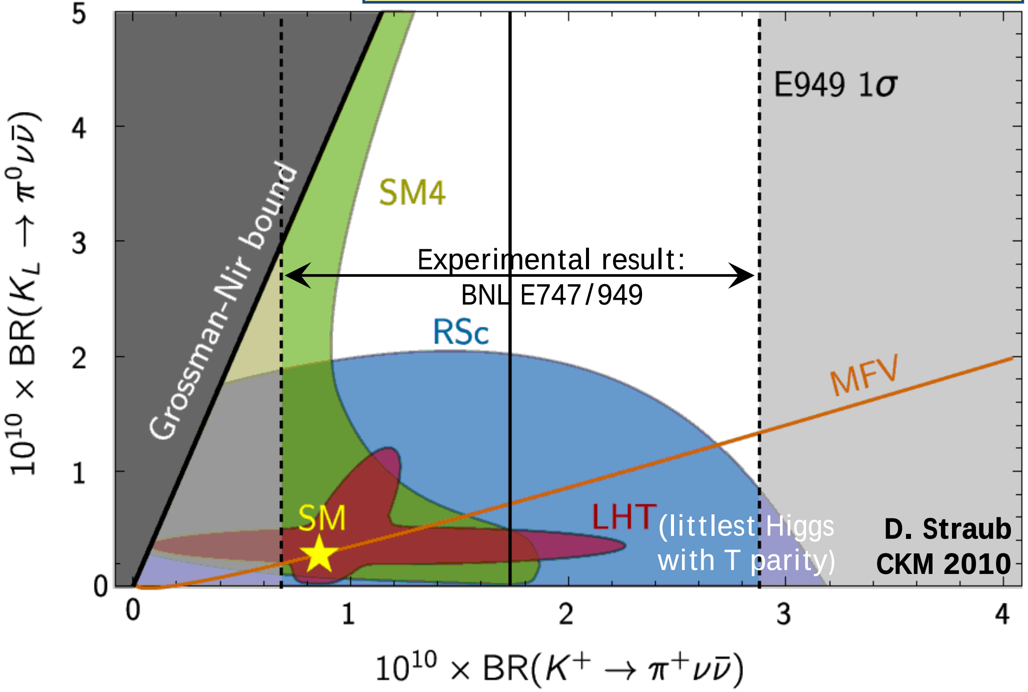
| Mode | $BR_{SM}\times10^{11}$ |
|---|---|
| $K^+\to\pi^+\nu\bar{\nu}(\gamma)$ | 7.81±0.75±0.29 |
| $K_L\to\pi^0\nu\bar{\nu}$ | 2.43±0.39±0.06 |

CKM parametric — Intrinsic

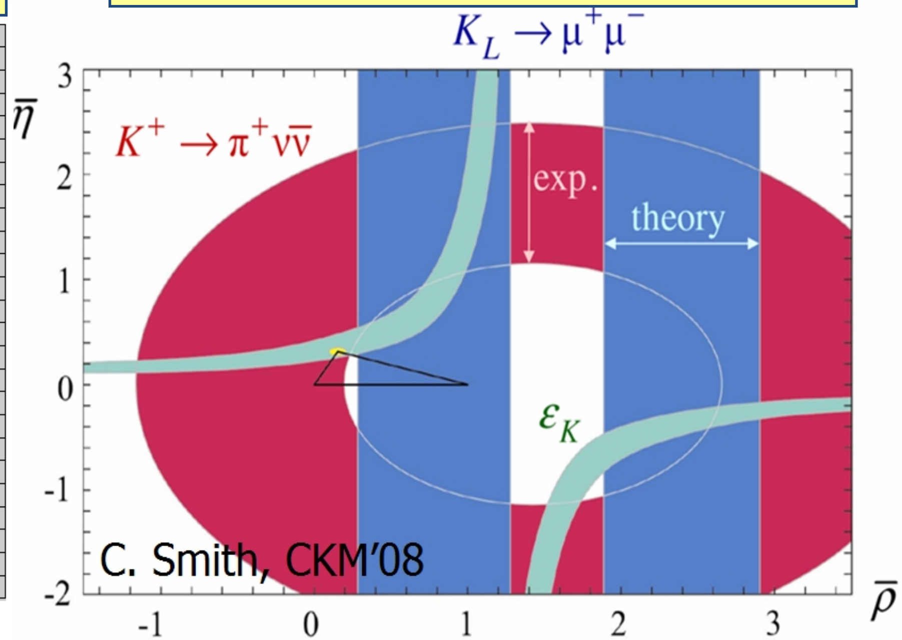
Theoretically clean, sensitive to new physics, almost unexplored

# $K \to \pi\nu\bar{\nu}$: experiment vs theory

$BR(K_L \to \pi^0\nu\bar{\nu})$ vs $BR(K^+ \to \pi^+\nu\bar{\nu})$




CKM unitarity triangle with kaons




NA62 aim: collect ~100 SM $K^+ \to \pi^+\nu\bar{\nu}$ decays with <20% background in 2 years of data taking using a novel decay-in-flight technique.

**Decay signature:** high momentum $K^+$ (75GeV/c) → low momentum $\pi^+$ (15–35 GeV/c).

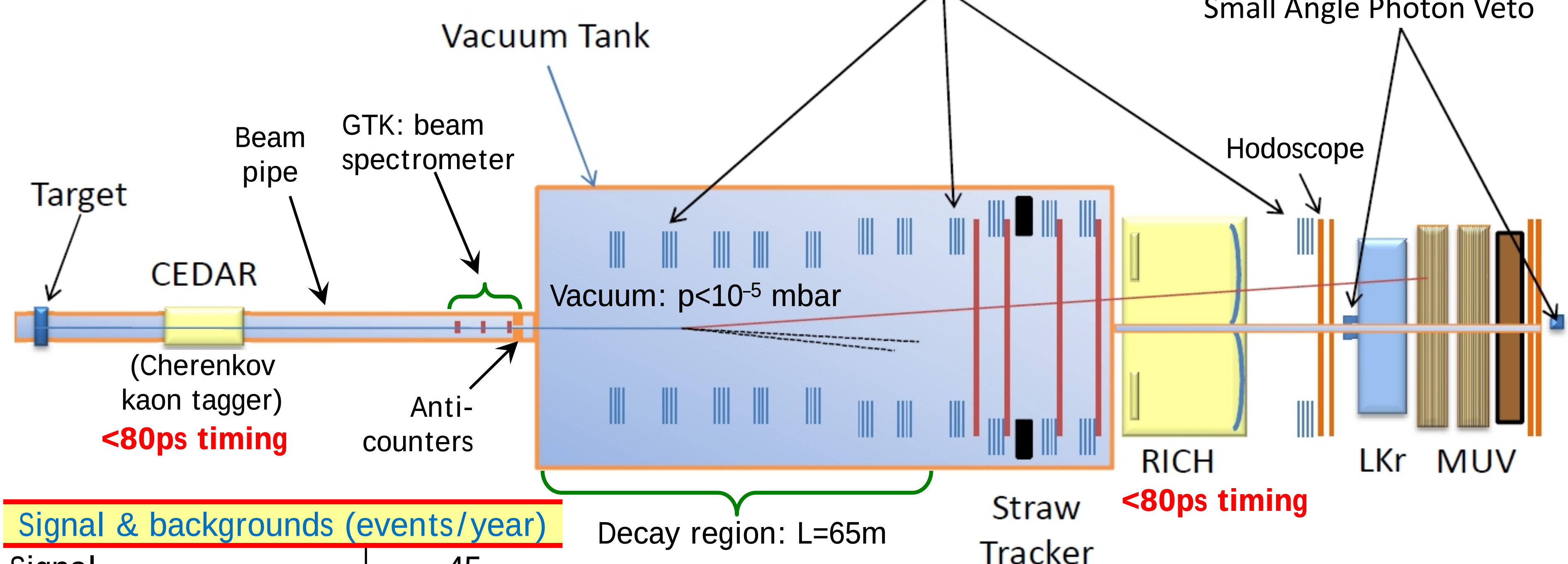
**Advantages:** max detected $K^+$ decays/proton ($p_K/p_0 \approx 0.2$); efficient photon veto (>40 GeV missing energy); good $\pi^+$ vs $\mu^+$ identification with RICH.

Un-separated beam (6% kaons) → higher rates, additional backgrounds.

# NA62 detector

Un-separated hadron ($\pi^+$/p/$K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
750MHz beam; 45MHz kaons; 10MHz L0 rate

Total length: ~270m

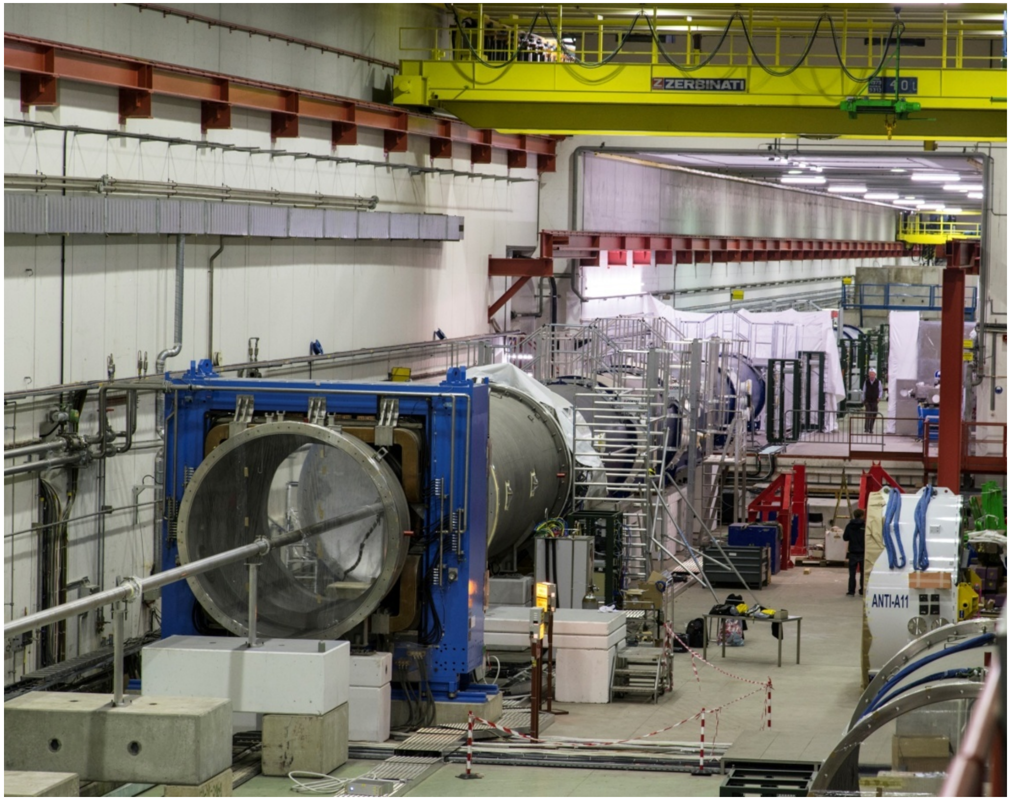



| Signal & backgrounds (events/year) | |
|---|---|
| Signal | 45 |
| $K^+\to\pi^+\pi^0$ | 5 |
| $K^+\to\mu^+\nu$ | 1 |
| $K^+\to\pi^+\pi^+\pi^-$ | <1 |
| Other 3-track decays | <1 |
| $K^+\to\pi^+\pi^0\gamma$ (IB) | 1.5 |
| $K^+\to\mu^+\nu\gamma$ (IB) | 0.5 |
| **Total background** | **<10** |

- Kinematic rejection factors (limited by beam pileup and tails of MCS): **$5\times10^3$** for **$K^+\to\pi^+\pi^0$**, **$1.5\times10^4$** for **$K\to\mu^+\nu$**.
- Photon veto: **$\sim10^8$** suppression of **$\pi^0\to\gamma\gamma$**.
- Particle ID: **$\sim10^7$** muon suppression.

# NA62 installation

Vacuum tank view in 2012




Photon veto (LAV) installation

Cherenkov kaon tagger (CEDAR+KTAG)

# LFV in $K^{\pm}$ and $\pi^0$ decays

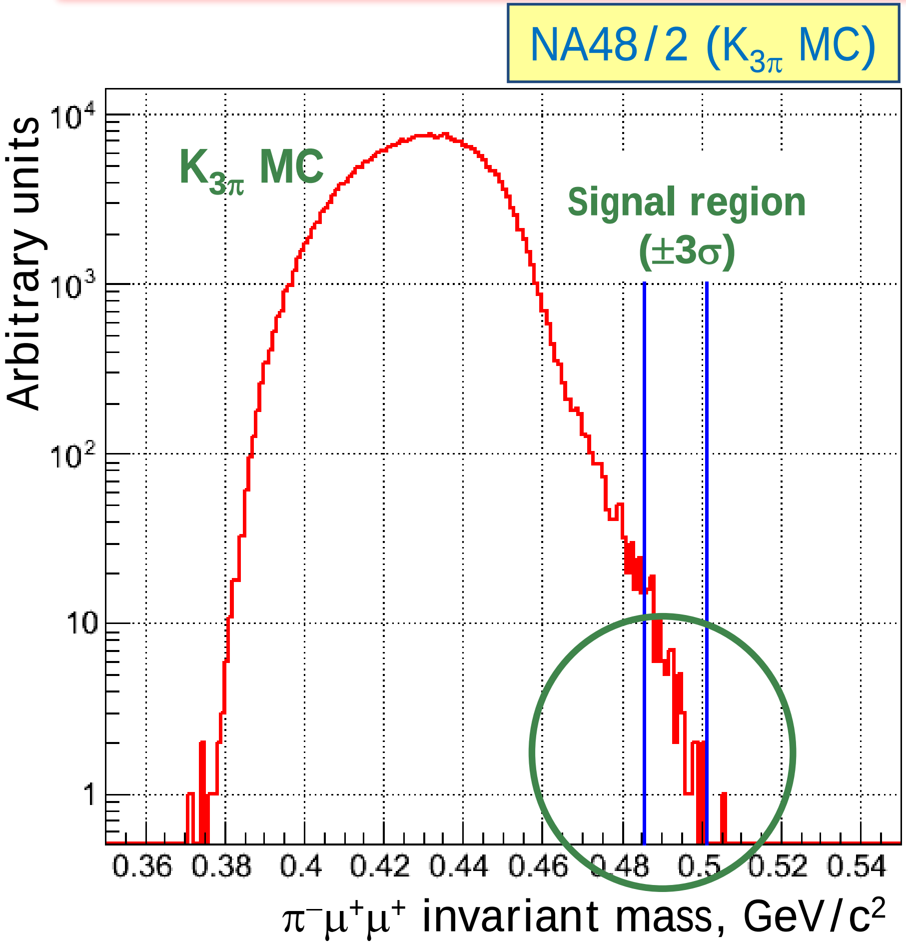
| Mode | UL at 90% CL | Experiment | Reference |
|---|---|---|---|
| $K^+ \to \pi^+ \mu^+ e^-$ | $1.3 \times 10^{-11}$ | BNL E777/E865 | PRD 72 (2005) 012005 |
| $K^+ \to \pi^+ \mu^- e^+$ | $5.2 \times 10^{-10}$ | BNL E865* | PRL 85 (2000) 2877 |
| $K^+ \to \pi^- \mu^+ e^+$ | $5.0 \times 10^{-10}$ | BNL E865* | PRL 85 (2000) 2877 |
| $K^+ \to \pi^- e^+ e^+$ | $6.4 \times 10^{-10}$ | BNL E865* | PRL 85 (2000) 2877 |
| $K^{\pm} \to \pi^{\mp} \mu^{\pm} \mu^{\pm}$ | $1.1 \times 10^{-9}$ | CERN NA48/2 | PLB 697 (2011) 107 |
| $K^+ \to \mu^- \nu e^+ e^+$ | $2.0 \times 10^{-8}$ | Geneva-Saclay | PL 62B (1976) 485 |
| $K^+ \to e^- \nu \mu^+ \mu^+$ | no data | | |
| $\pi^0 \to \mu^+ e^-$ | $3.6 \times 10^{-10}$ | FNAL KTeV | PRL 100 (2008) 131803 |
| $\pi^0 \to \mu^- e^+$ | $3.6 \times 10^{-10}$ | | |

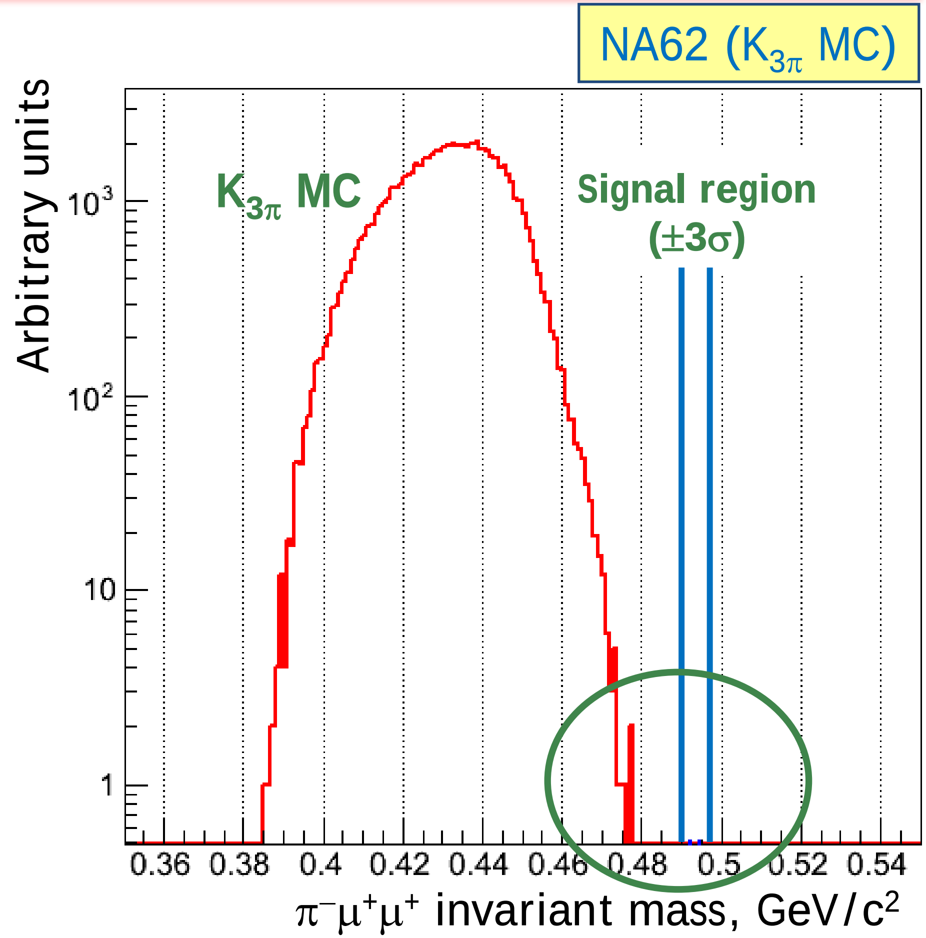
* CERN NA48/2 sensitivities for these 3 modes are similar to those of BNL E865

NA62: nominally **$1.2\times10^{13}$** $K^+$ decays in fiducial volume.
Expected SES: **$\sim10^{-12}$** for $K^+$ decays, **$<10^{-11}$** for $\pi^0$ decays.

*NA62 is expected to improve on all these decay modes*

# Example: $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$ at NA62




**NA48/2:** $K_{3\pi}$ background to $K_{\pi\mu\mu}$ due to $\pi^{\pm}\to\mu^{\pm}\nu$ decays in the spectrometer

**NA62:** no $K_{3\pi}$ background due to higher spectrometer $P_T$ kick (**270** vs **120 MeV/c**) and improved $\pi\mu\mu$ mass resolution (**1.1** vs **2.6 MeV/c²**)

# Summary

- Muons will play a central role in LFV searches.
  Upcoming specialized experiments: **COMET**, **Mu2e**, **MEG-II**, **Mu3e**.

- Near-future muon conversion and decay experiments aim at sensitivities from **$\sim 10^{-13}$** to **$\sim 10^{-17}$**.

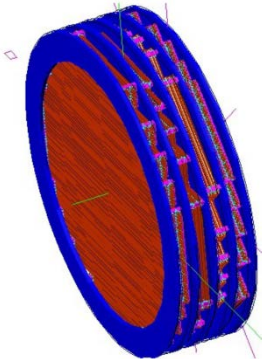
- In other sectors, significant progress can be achieved at marginal cost by building on existing experiments.

- **NA62** is expected operate as a multi-purpose **$K^+$** decay experiment with **$\sim 10^{-12}$** sensitivity to LFV **$K^+$** and $\pi^0$ decays.

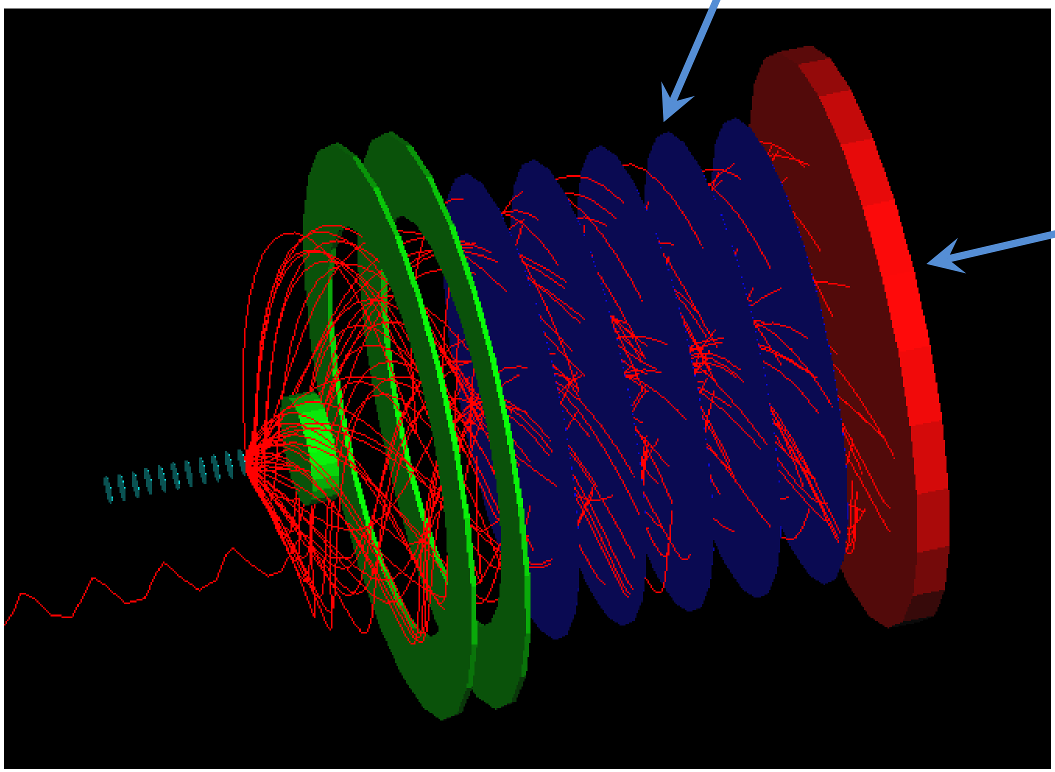
# SPARES

# COMET phase II detector prototype

(to be tested during Phase I)



**"Transverse tracker"**:
Straw tube tracker (5 multi-layer modules).
NA62-type straws produced at JINR (Dubna).
Momentum resolution: **$\delta p_e$ = few × 100 keV/c**.



EM calorimeter:
GSO or LYSO crystals.

Resolutions:
- ❖ Energy: **<5%** at **105 MeV**.
- ❖ Position: **<1.5 cm**.

✓ Redundant momentum measurement, avoiding tracker pattern recognition errors.

✓ Provides the trigger.

# Recent $K^{\pm}$ experiments at CERN

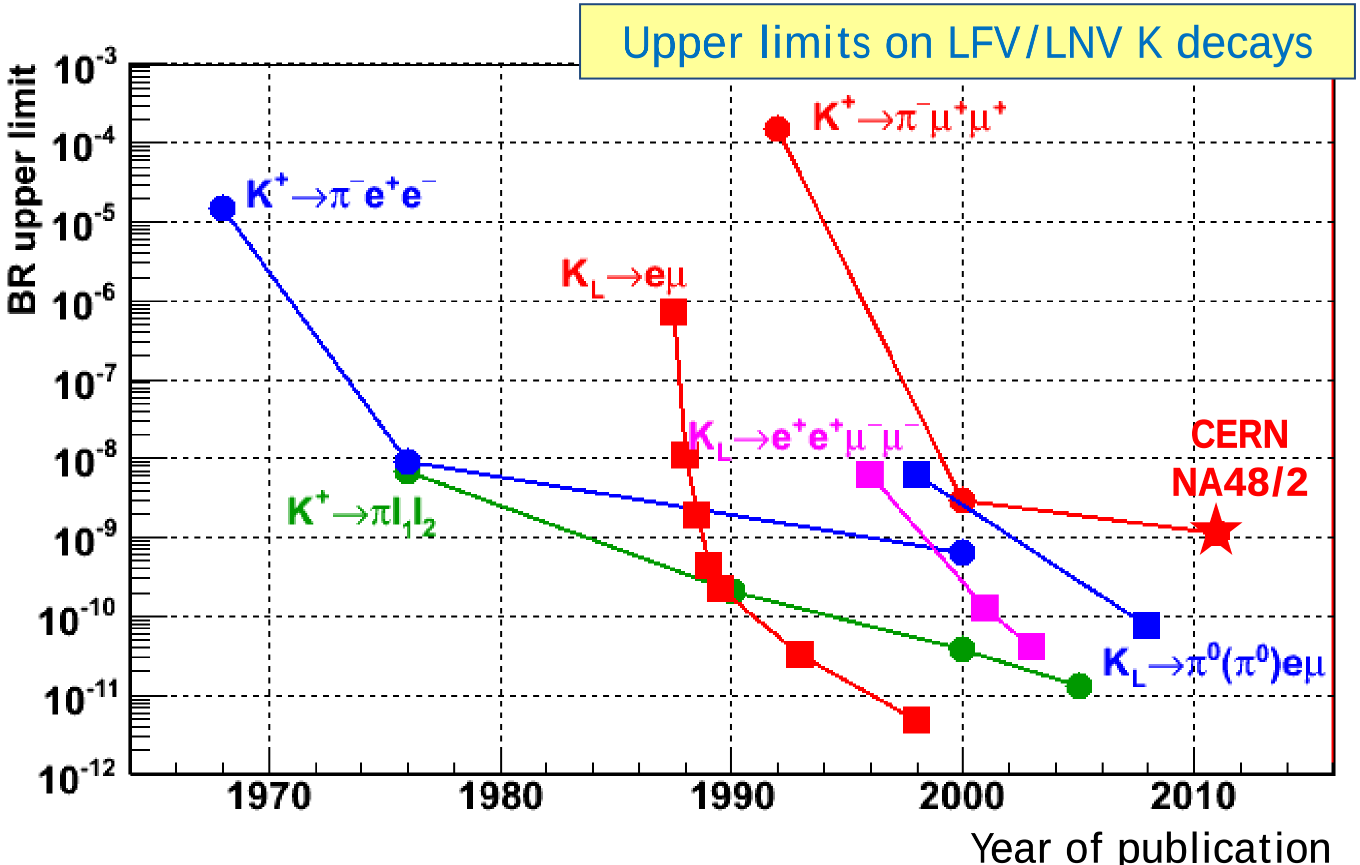
| Experiment | NA48/2 ($K^{\pm}$) | NA62-$R_K$ ($K^{\pm}$) | *NA62* *($K^+$; planned)* |
|---|---|---|---|
| Data taking period | **2003–2004** | **2007–2008** | **2014–2017** |
| Beam momentum, GeV/c | **60** | **74** | **75** |
| RMS momentum bite, GeV/c | **2.2** | **1.4** | **0.8** |
| Spectrometer thickness, $X_0$ | **2.8%** | **2.8%** | **1.8%** |
| Spectrometer $P_T$ kick, MeV/c | **120** | **265** | **270** |
| $M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/$c^2$ | **1.7** | **1.2** | **0.8** |
| K decays in fiducial volume | **$1.9\times10^{11}$** | **$2.5\times10^{10}$** | **$1.2\times10^{13}$** |
| Main trigger | Three-track; **$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$** | **$e^{\pm}$** | **$K_{\pi\nu\nu}$ + ...** |

Same detector (NA48) [NA48/2 and NA62-$R_K$]

**The new NA62 detector:**

- beam spectrometer and kaon tagger;
- improved mass reconstruction and particle identification;
- hermetic photon veto.

# NA48/2 $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ upper limit




$$\mathcal{B}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9}$$

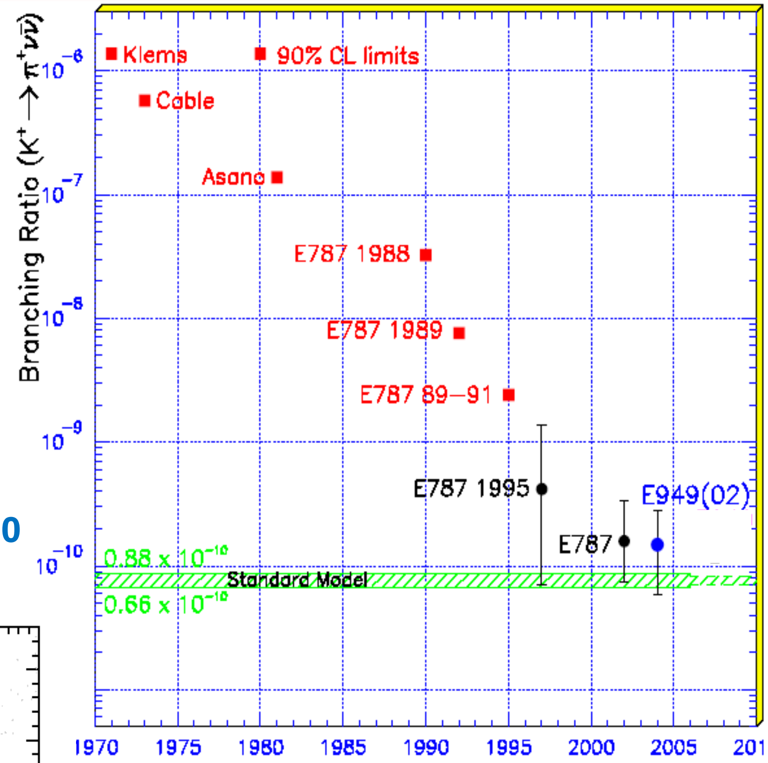
- ❖ Previous BNL E865 limit improved by a factor **~3**.
- ❖ By-product of the $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ analysis: non-optimized procedure.
- ❖ A dedicated re-analysis has a potential sensitivity of **$\sim 10^{-10}$**.

# $K^+ \to \pi^+ \nu \bar{\nu}$ at BNL E747/E949

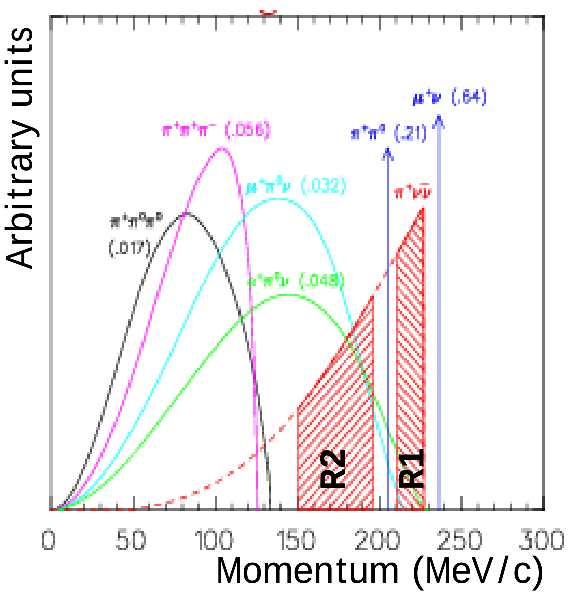
## Technique: $K^+$ decay at rest

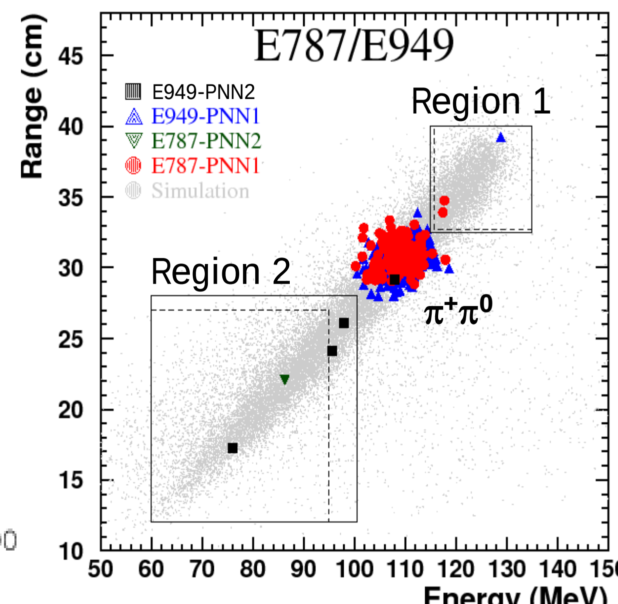
Data taking: E787 (1995–98), E949 (2002).
Separated $K^+$ beam (**710 MeV/c**, **1.6MHz**).
PID: range (entire $\pi^+ \to \mu^+ \to e^+$ decay chain).
Hermetic photon veto system.

Observed candidates: **7**
Expected background: **2.6**
Final result: **BR = $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$**




→ Significant background from the $K_{2\pi}$ decay (**~30%**) due to $\pi^+$ scattering in the target.

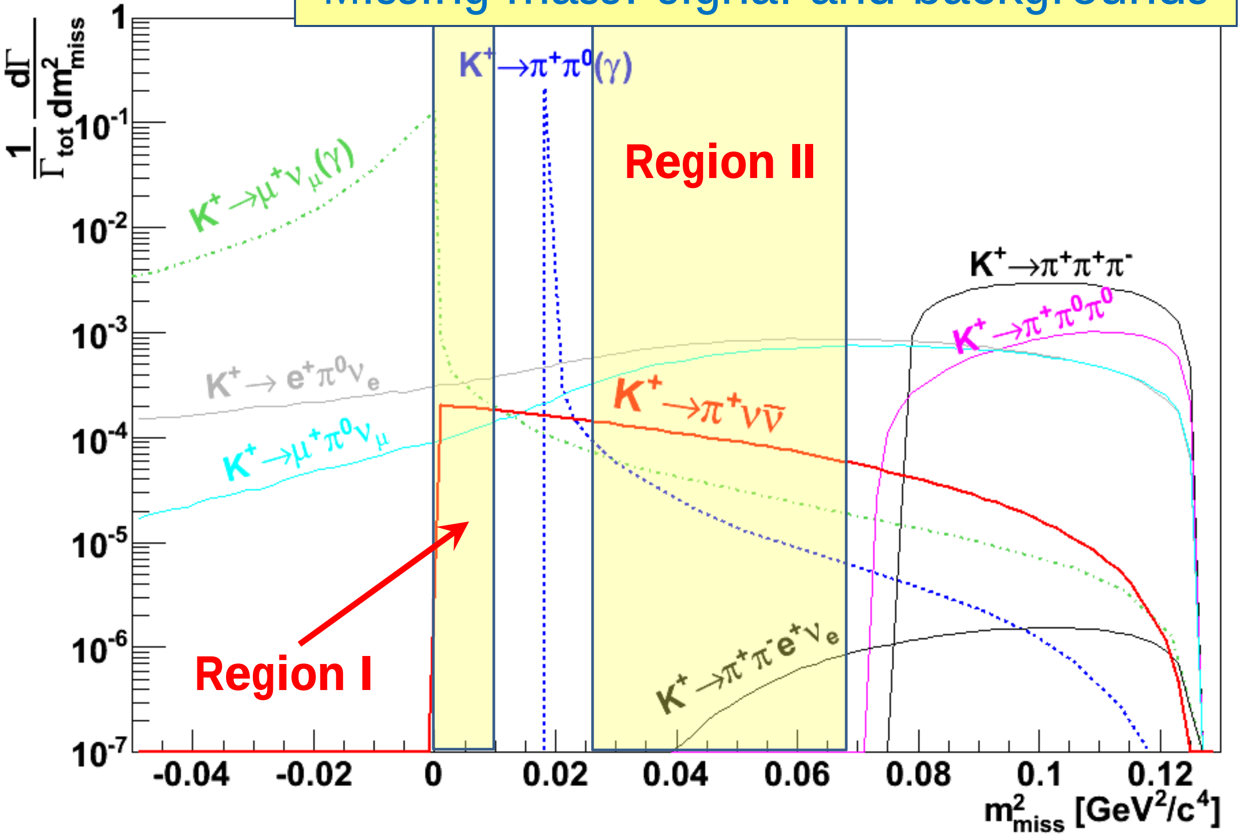



*PRL 101 (2008) 191802; PRD 79 (2009) 092004*

# NA62: $K_{\pi\nu\nu}$ signal region

Missing mass: signal and backgrounds




**92%** of total background ($K_{\mu2}$, $K_{2\pi}$, $K_{3\pi}$)

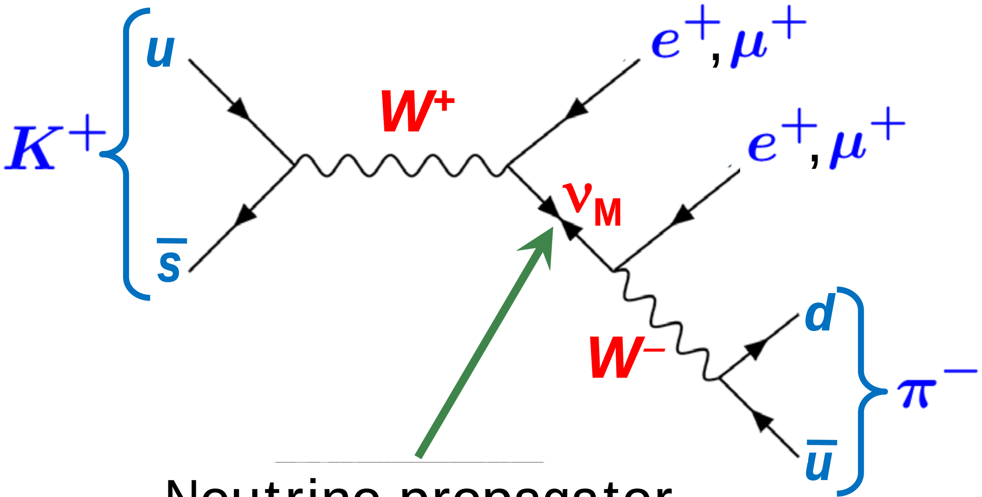
- Outside the signal kinematic region.
- Signal region is split into **Region I** and **Region II** by the $K^+ \to \pi^+\pi^0$ peak.

**8%** of total background

- Span across the signal region
- Not rejected by kinematic criteria
- Rejection relies on vetoes/PID

# LNV in K decays

$K^+ \to \pi^- \ell_1^+ \ell_2^+, \quad \ell = e, \mu$




Neutrino propagator

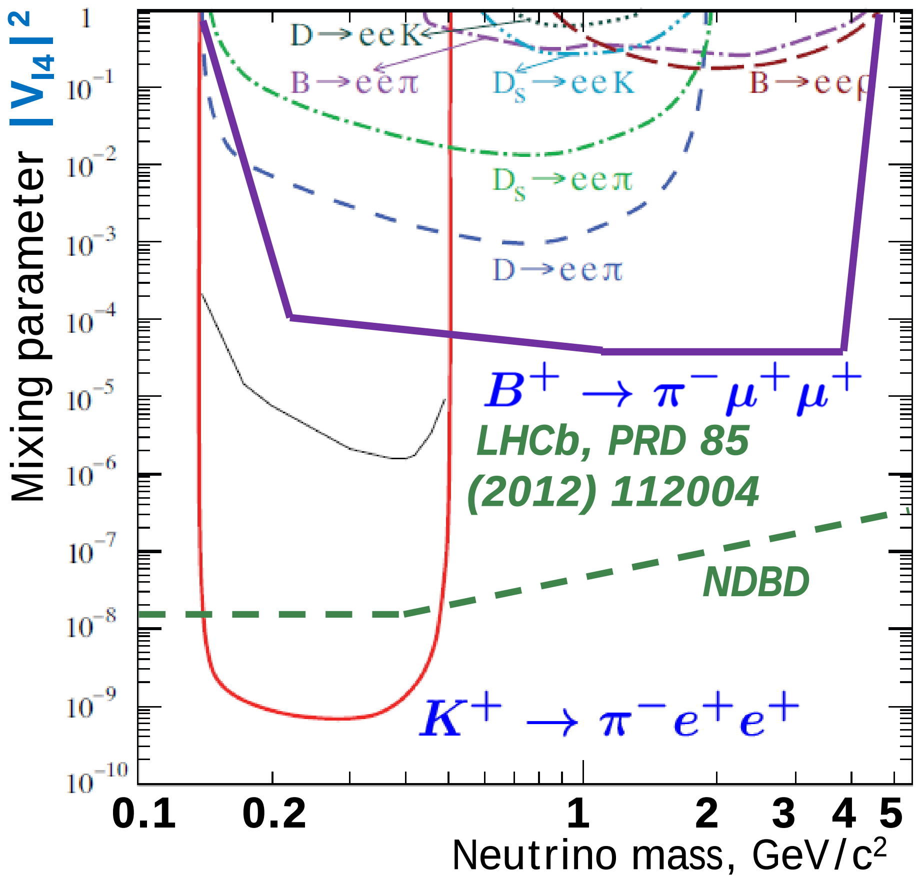
$$\frac{1}{q^2 - m_\nu^2}$$

→ resonant enhancement for

$$m_\pi \lesssim m_\nu \lesssim m_K$$

*Littenberg and Shrock, PLB491 (2000) 285*

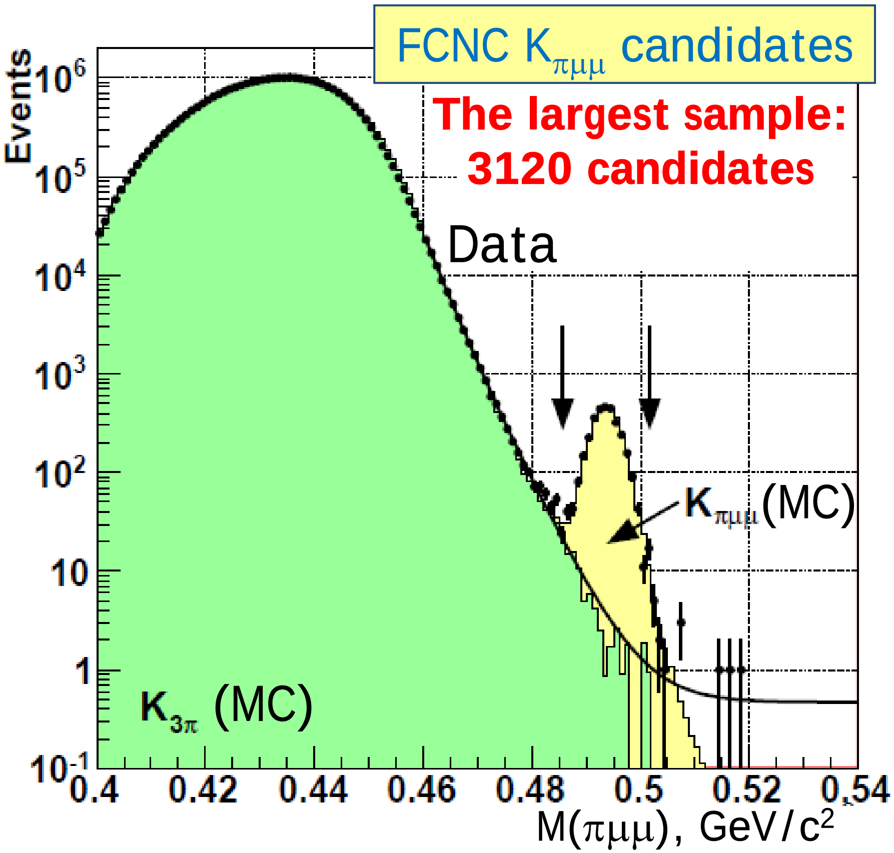
Majorana neutrino exclusion regions

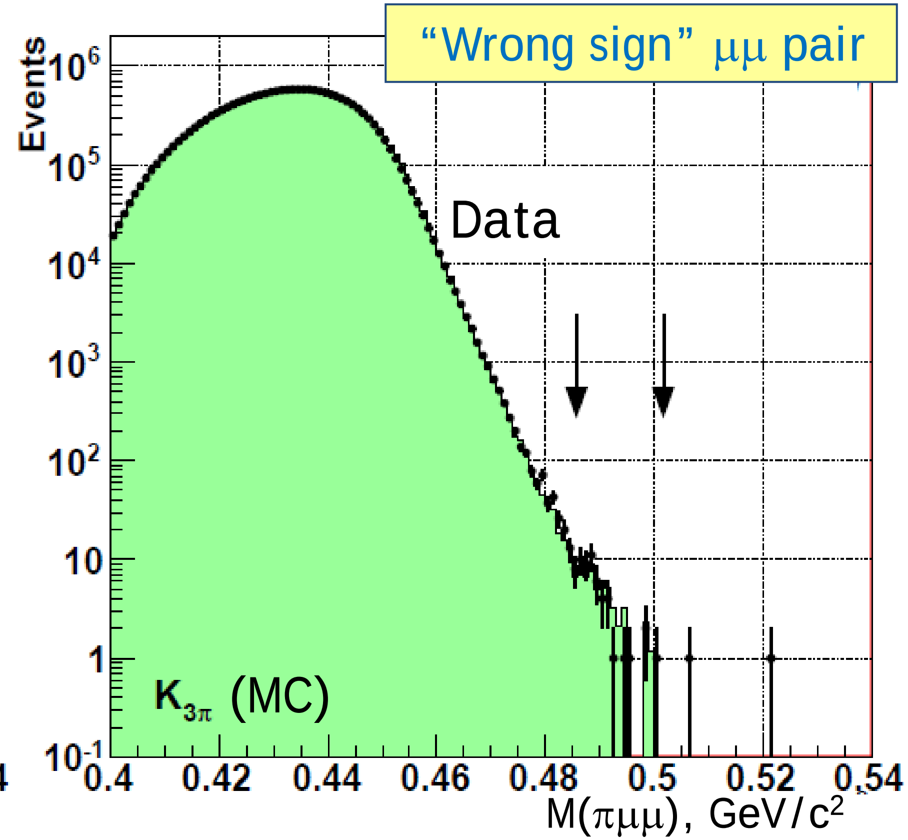



*Plot from Atre et al., JHEP 0905 (2009) 030*

# Proof of principle: NA48/2

*PLB 697 (2011) 107*



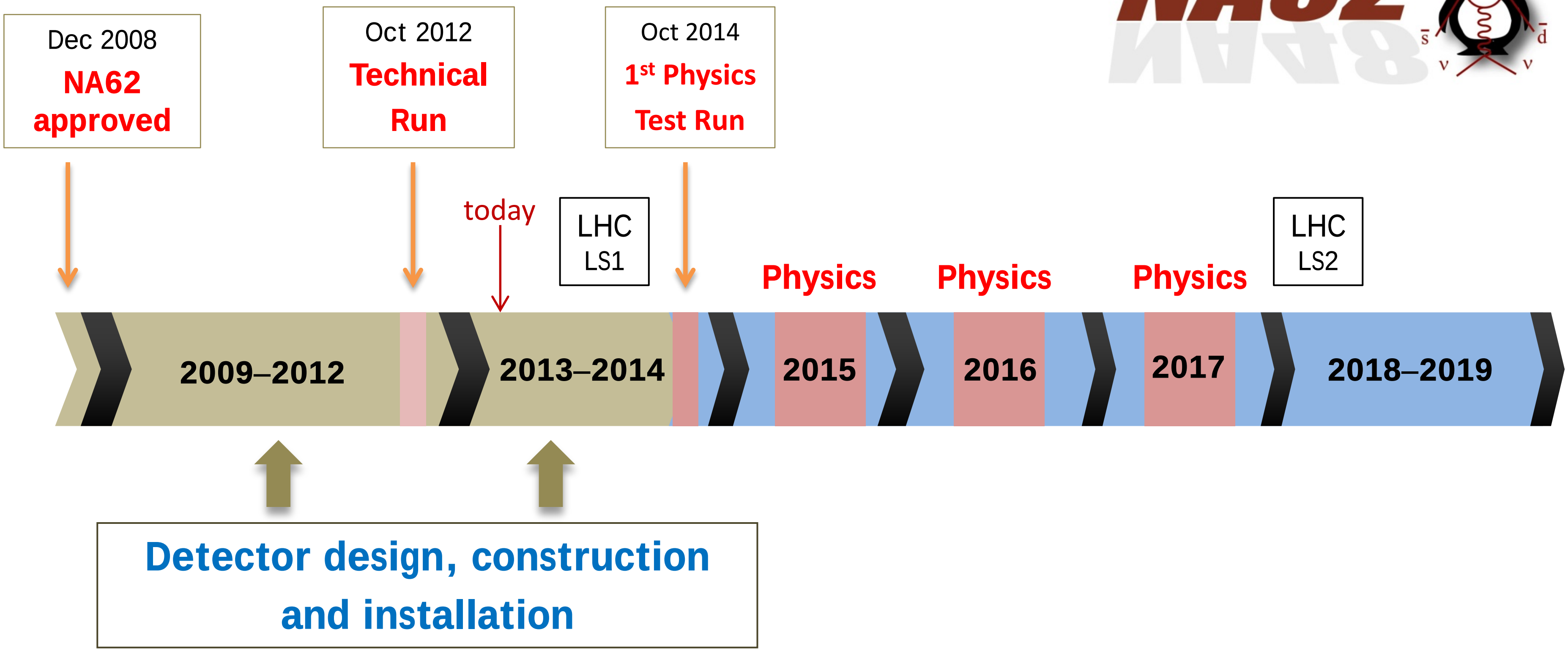




**$N_{data}$ = 52**
**$N_{bkg}$ = 52.6±19.8$_{syst.}$**

$\Rightarrow$ $\mathcal{B}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9}$ **@90% CL**

- Precision limited by background from $\pi^\pm \to \mu^\pm \nu$, despite **SES ≈ $3\times10^{-11}$**.
- A dedicated re-analysis (in progress) has a sensitivity of **~$10^{-10}$**.

# NA62 timeline

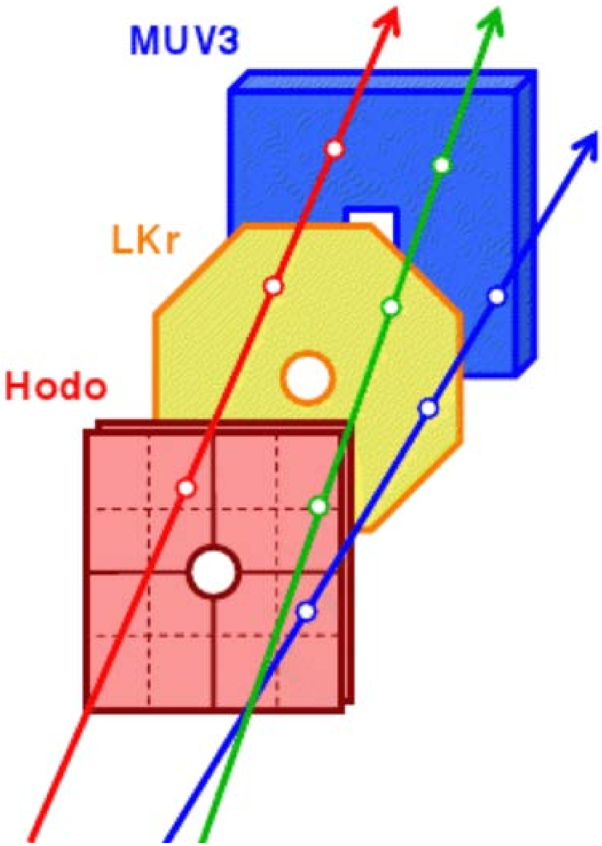



- 5 years of construction interleaved with a Technical Run in **October 2012**
- First Run with full detector in **2014**
- Plan 3 physics data taking runs before LHC Long Shutdown 2 (LS2)

# Triggering on lepton pairs

NA62 three-track decay rate upstream CHOD: **$F_{3track}$ = 640 kHz**

→ **Too high** to collect all three-track decays




Available L0 trigger primitives:

- **$Q_N$**: at least N hodoscope quadrants;
- **$LKR_N(x)$**: at least N LKr clusters with energy E>x GeV;
- **$MUV_N$**: hits in at least N MUV3 pads.

Possible L0 triggers for LFV searches:

| | |
|---|---|
| ee pair: | $Q_2 \times LKR_2(15)$ |
| μe pair: | $Q_2 \times LKR_1(15) \times MUV_1$ |
| μμ pair: | $Q_2 \times MUV_2$ |

Total expected lepton pair L0 rate: **~100 kHz**

→ *Charge-blind lepton pair collection is feasible*