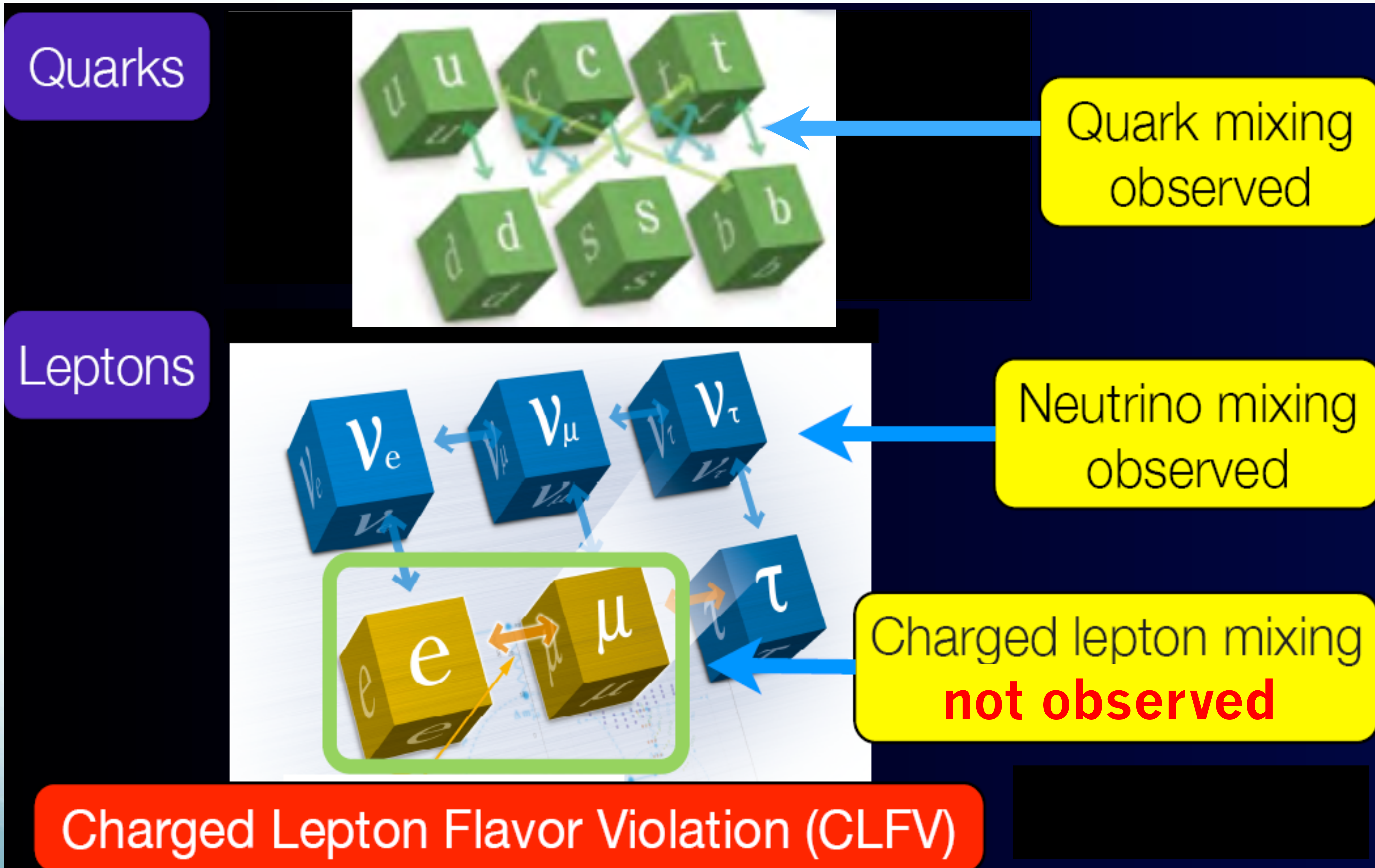
What shall we learn from the COMET ?

Phenomenology & Physics

G. Kozlov, JINR

Project COMET:
Experimental search for coherent neutrino-less μ - e conversion at J-PARC

Flavor violation



CLFV can be investigated in many different processes.
The instructive ones are *processes with muons*

In the SM the branching ratios of the CLFV muon decays are almost vanishingly small and would not be applied to an experiment

$\Delta L=1$

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+e^+e^-$
- $\mu^- + N(A,Z) \to e^- + N(A,Z)$
- $\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$

In theories BSM the branching ratios of the CLFV muon decays are not vanishingly small and would have an experimental approach

$\Delta L=2$

- $\mu^+e^- \to \mu^-e^+$
- $\mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$

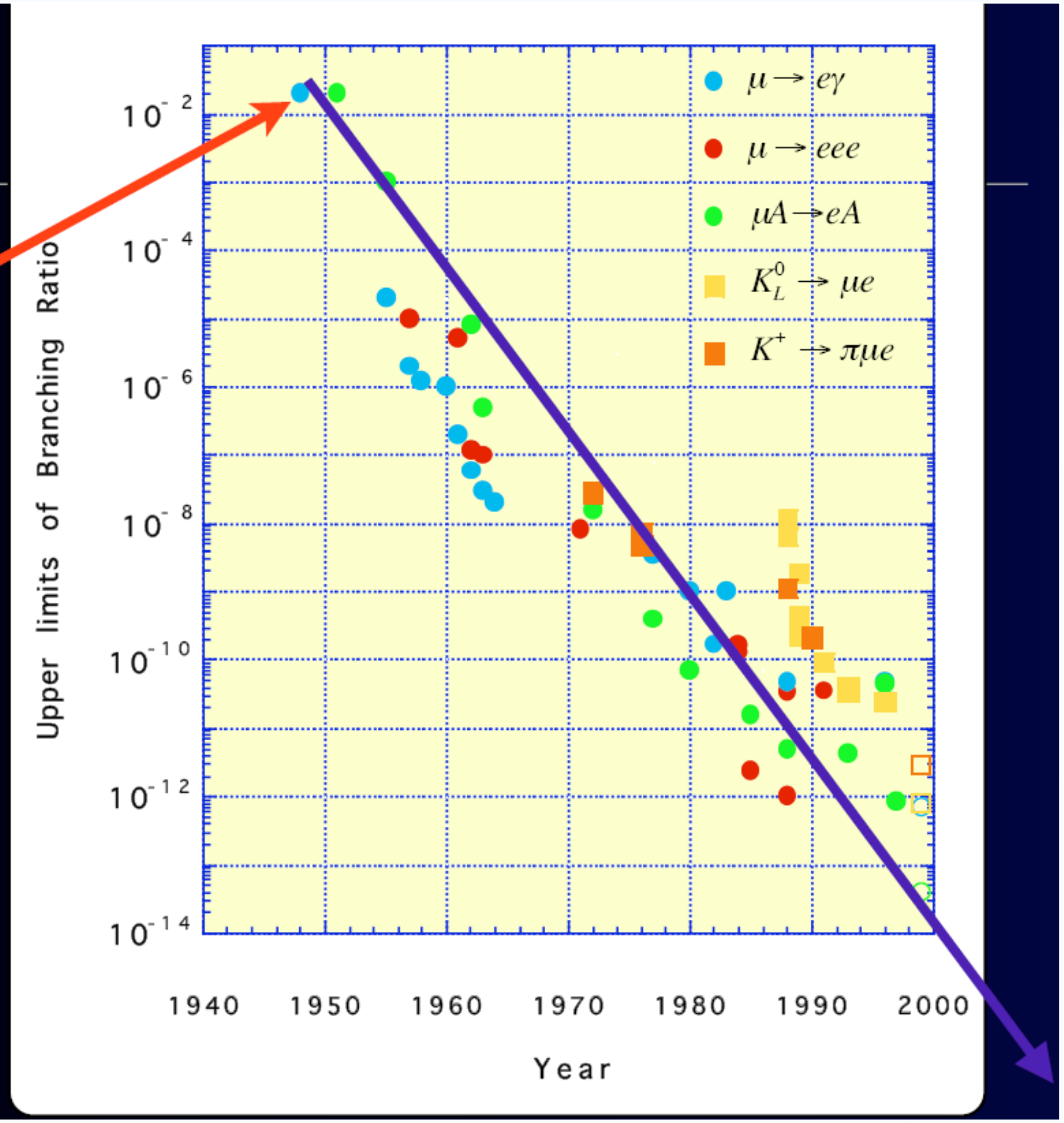
An observation of the conversion $\mu \to e$ would mean manifestation of **NP** beyond the Standard Model, and hence the results of the experiment could be of fundamental importance.

cLFV History

First cLFV search

Pontecorvo in 1947

In 1947, B.Pontecorvo and E.P.Hincks established first search for $\mu \rightarrow e\gamma$ by using cosmic rays: upper limit BR ~ 1%



The goal of COMET (as well as of Mu2e) **is to observe the pure μ-e conversion events.**

Four order improvement in uBR expected!

process	present limit (PSI)	future
$\mu\rightarrow e\gamma$	<5.7 x 10^{-13} (MEG, 2013)	<5.0 x 10^{-14} MEG at PSI
$\mu\rightarrow eee$	<1.0 x 10^{-12} (SINDRUM, 1988)	~10^{-16} as a new proposal at PSI approved
$\mu N\rightarrow eN$	<7.0 x 10^{-13} (in Au) (SINDRUM-II,2006)	➡ <$10^{-16\ -17}$ COMET / Mu2e J-PARC/FNAL

$e\mu\tau - u$

In the EW theory the dominant process is

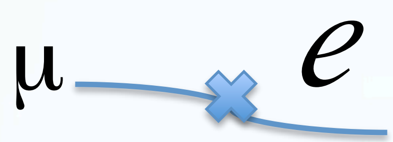
$t \to W\ b \to l\bar{\nu}_l\ b\ (l = e, \mu, \tau)$, where

$$\Gamma(W \to l\bar{\nu}_l) = \frac{G_F m_w^3}{6\sqrt{2}\pi}$$ that means

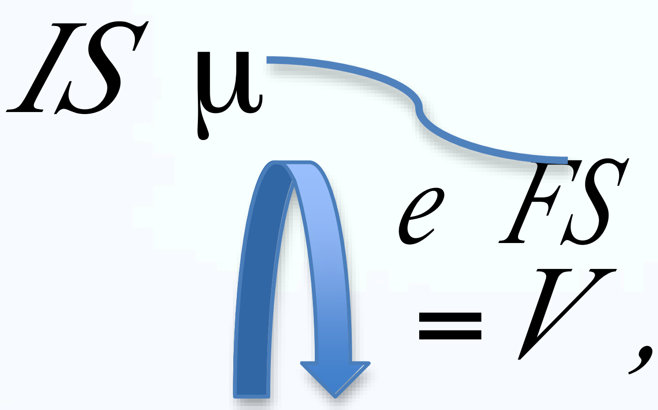
$e\mu\tau$- universality (for all leptons)

- ✓ Can one suppose this rate is violated for diff. l-flavors?
- Yes, UA (1) & UA(2) experiments @ CERN for e & μ
- ✓ What is the origin? No explanation in SM EW.

The transition μ to e



$$= SM + \not{SM}$$



$$= V\,, S\,, Ps$$

$$V : Z', U_{\nu}, \ldots (\gamma_{\mu})$$

$$S : Higgs, U_{s}, \ldots (1)$$

$$Ps : Higgs(2HDM), U_{Ps}, \ldots (\gamma_{5})$$

$$L_{eff} = L_{SM} + \Delta L_{e\mu}$$

$$\Delta L_{e\mu} = \sum_{\alpha,\beta} \frac{C^{j}_{\alpha\beta}}{\Lambda^{2}} \left(\bar{e}\Gamma\mu\right)\left(\bar{q}^{\alpha}\Gamma q^{\beta}\right) + h.c.$$

Eff. interaction parametrizes NP effects associated with $e-\mu$ flavor-violation below UV scale Λ.

Dim-6 operator is generated from the exchange of *new messengers*: gauge, S, Ps at Λ.

- Could we see something else – not in terms of SM?

In the absence of an explicit sector that breaks gauge invariance, the interactions of SM gauge bosons with fermions are approximately conformal down to QCD scale.

- Should one expect new stuff?

Great!

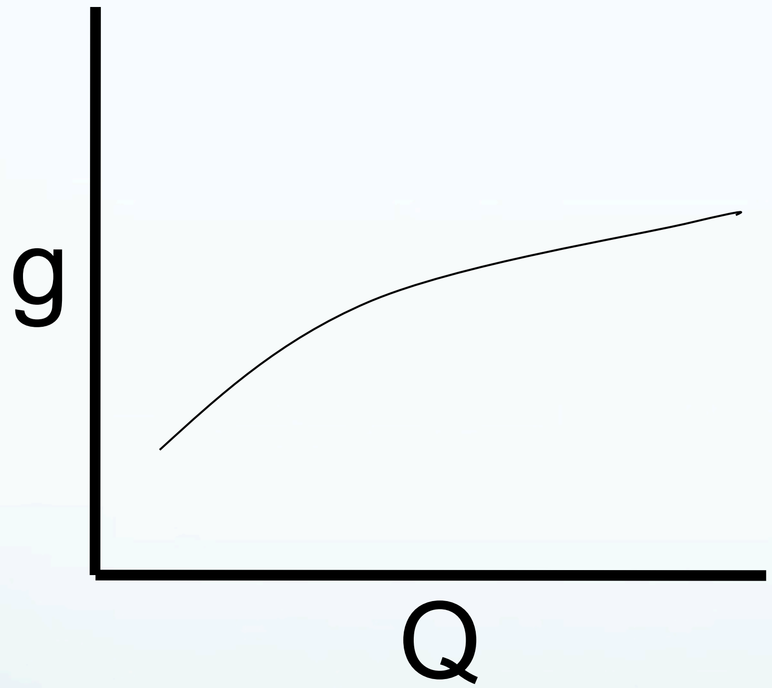
- **Scale invariant hidden world?**

The question of what triggers gauge symmetry breaking in the SM is tied to the dynamical breaking of scale invariance.

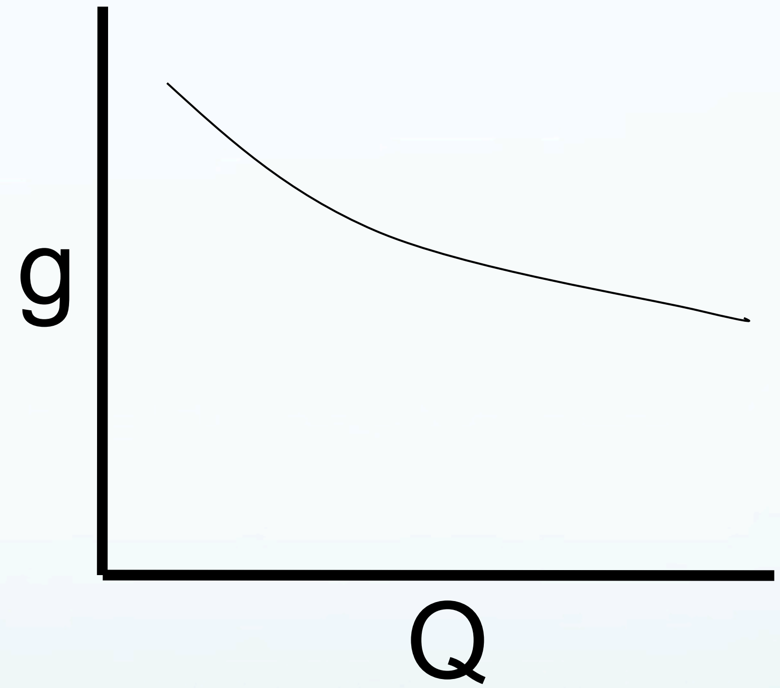
GK, ICHEP2014 Report

No CONFORMAL INVARIANCE

- At the quantum level, dimensionless couplings depend on scale: renormalization group evolution



QED



QCD

are not conformal theories

Couplings of hidden & SM sectors.

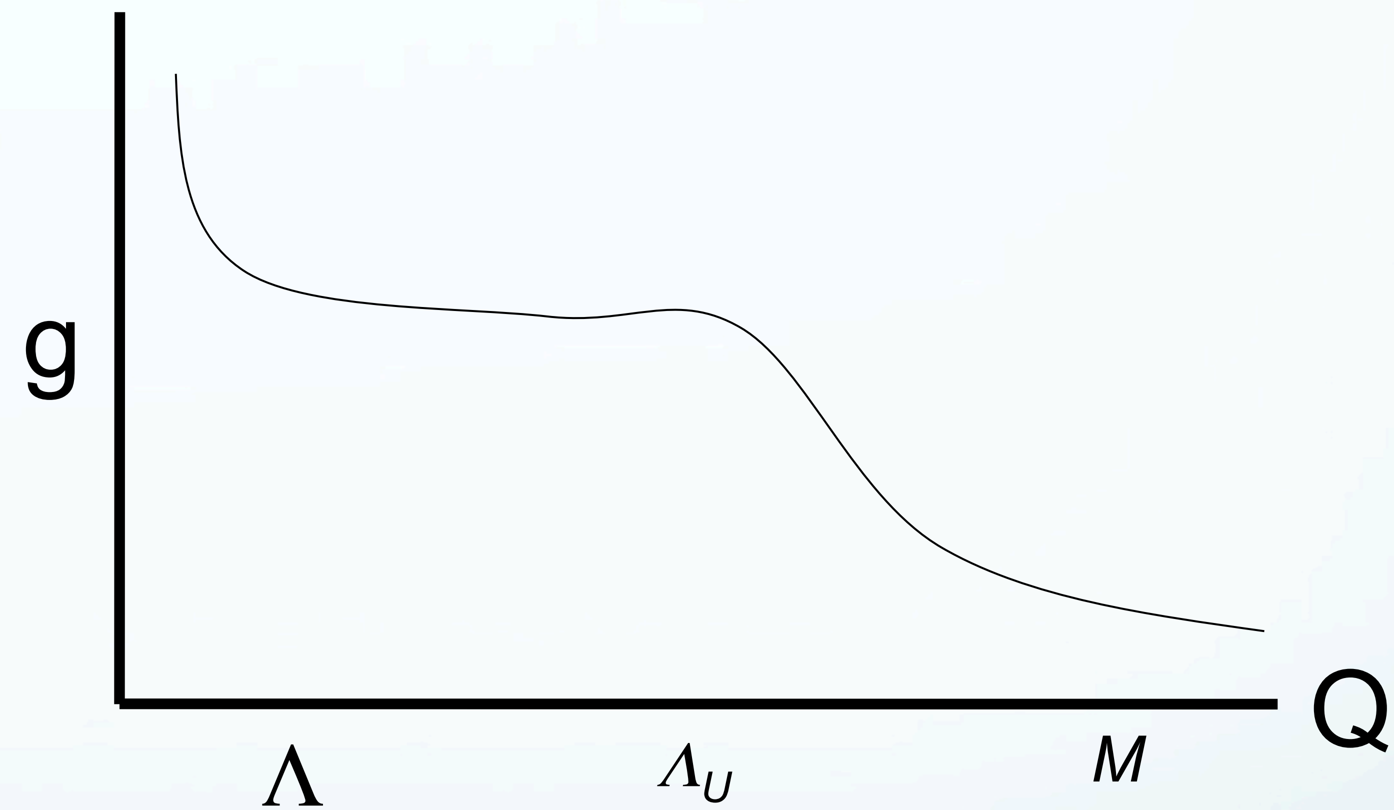
3 characteristic scales: M, Λ_U, Λ

-Hidden sector couples at M

- Conformal $\Lambda < \Lambda_U < M$

- EWSB $\Leftarrow$ CSB at $Q < \Lambda$

Conformal anomaly appears



- The hidden sector (the unparticle stuff) physics is only possible in the conformal valley
- Width of this valley depends on d, Λ, Λ_U, M

What does COMET measure?

$$R_{\mu e}^{exp} = \frac{\Gamma\left[\mu^- + \left(A,z\right) \to e^- + \left(A,z\right)\right]}{\Gamma\left[\mu^- + \left(A,z\right) \to \nu_\mu + \left(A,z-1\right)\right]} = excess\,?$$

Standard capture

Expected $R_{\mu e}^{exp} \sim 10^{-17}$ 2 years run? More?

✓ SM does explain nothing

$\mu \to e$ is sensitive to **NP** stuff $\sim O\left(TeV\right)$

Puzzle of $\mu \to e$. ***Hidden world***

At high enough energies $Q \sim O(M)$ (**UV**, Cosmology)

the nearly conformal (matter) sector couples in the UV to the HIDDEN world through the exchange of heavy state(s), the messenger(s)

Stage I

$$\begin{bmatrix} Nearly \\ conformal \end{bmatrix} \overset{heavy}{\underset{messenger(s)}{\leftrightarrow}} \begin{bmatrix} Hidden \\ world \end{bmatrix}$$

$$Below\ UV\ M : \frac{1}{M^{n-4}} O_{\chi} \frac{1}{M^{d_{UV}}} O_{UV}$$ Non-renormalizable coupling

Abundance of rare transitions, even the forbidden ones (in terms of SM).

$$E.g., \ \mu \to e.$$

U-stuff message.

The SM does not have properties of conformal (or at least scale) invariance.

There could be a sector of theory, yet unseen, that is exactly scale invariant and very weakly coupled to SM.

In D=4 SI sector there are no particles because there can be no particle states with $m \neq 0$.

SI stuff, if it exists, is made of ***unparticles***.

H. Georgi (2007)

Puzzle of $\mu \to e.$ **Unparticle stuff.** ***Hidden world***

Stage II **Dimensional transmutation scale**

$$\Lambda_U < M \quad Q_{UV} \to Q_{UV}^{d_{UV}-d} O, \quad d = [O], and \quad d$$ **Even non-integer**

H. Georgi (2007)

$$\downarrow$$

Un-particle operator, continuous spectrum at scale Λ_U

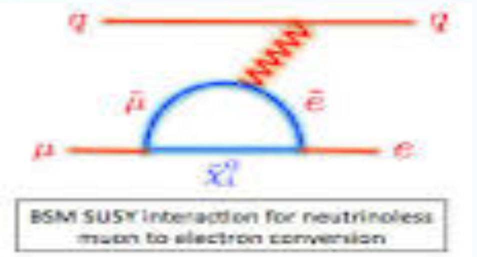
- ✓ **The U-sector may flow away from its conformal window where NP processes are expected**

$$[SM] \Leftarrow const \frac{1}{M^{n-4}} O_{SM} \frac{1}{\Lambda_U^d} O \left(\frac{\Lambda_U}{M}\right)^{d_{UV}} \Rightarrow \begin{bmatrix} Unparticle \\ stuff \end{bmatrix}$$

In the IR, the U-stuff can couple strongly enough to the SM sector (fields) to be seen

U-stuff

There will be a much more striking physics discoveries than the more talked about SUSY or extra D. *SUSY is more new particles.*



U-model postulates the existence of SI (conformal) sector, indicating NP that ***cannot be described in terms of particles***.

Non-integer number d of invisible particles.
SI sector is connected to the SM at Λ_U.

CMS lower bound @ 8 TeV: $\Lambda_U \geq 2\ TeV\ @\ d \approx 2$
(it means scalar unparticles), arXiv 1408.3583

In the IR any physical process is provided by

$$\left|\left\langle \mathcal{SP}_{out}\left|\omega \mathcal{O}_{SM}\mathcal{O}\right|\mathcal{SP}_{in}\right\rangle\right|^2 = \omega^2 \left|\left\langle \mathcal{SP}_{out}\left|\mathcal{O}_{SM}\right|\mathcal{SP}_{in}\right\rangle\left\langle \mathcal{U}\left|\mathcal{O}\right|0\right\rangle\right|^2$$

The physical result with the U-stuff influence would be seen at the level $\sim \mathcal{O}\left(\omega^2\right)$

- **U-scale factor**

$$\omega = \Lambda_U^{d_{UV}-d} / M^k, \quad k = n - 4 + d_{UV}$$

depends on the energy of a given experiment.

$\mathcal{U}$ - stuff dimension d for primary operators obeys the unitarity condition $d \geq j_1 + j_2 + 2 - \delta_{j_1 j_2, 0}$

Primary: not a derivative of another operator

At low energies $Q < \Lambda_U$ **any observable** ε

obeying the SM and the unparticle insertions

$$const \;\; \omega \;\; O_{SM} \;\; O$$

is proportional to ω

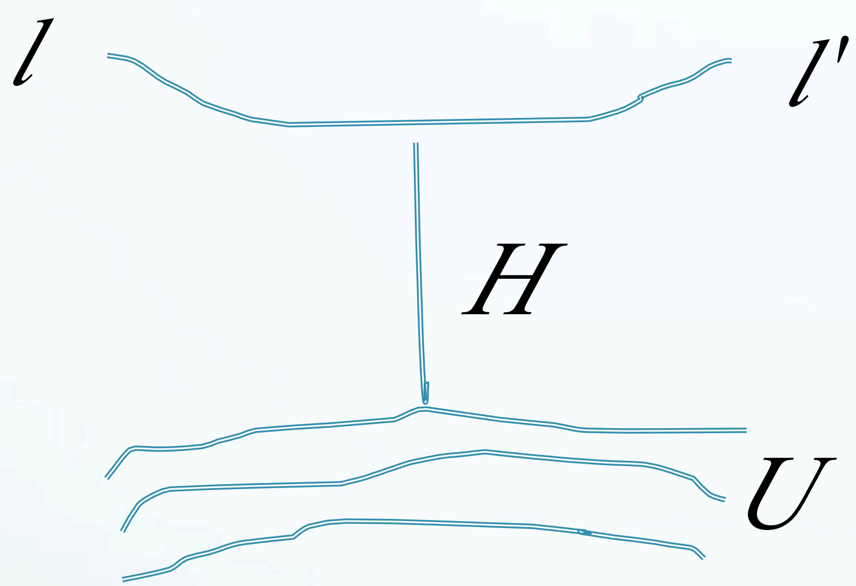
$$\varepsilon = \left(\frac{\Lambda_U}{M}\right)^{2(d_{UV}-d)} \left(\frac{Q}{M}\right)^{2(n+d-4)} = \left(\omega \cdot Q^{n+d-4}\right)^2$$

RESULT: any observable is predicted by the energy of a given experiment scaled by U-factor

Rare $l \to l'$

No explanation in the SM. Origin is unknown.

However, the transition $l \to l'$ is through H exchange in U-stuff cloud



$$At \quad v < \Lambda < Q < \Lambda_U$$

$$\sim const\ M^2 |H|^2 \frac{1}{\Lambda_U^d} O \cdot \left(\frac{\Lambda_U}{M}\right)^{d_{UV}} \quad (*)$$

- Higgs requires the v.e.v. v
- Operator $(*)$ introduces a scale in the CFT
- U-sector flows away from its conformal fixed point
- Conformal breaking below scale Λ. U-sector becomes a SM particle sector. No NP rare processes are seen.

Rare $l \to l'$

Conformal (scale) symmetry is breaking at scale

$$\Lambda^{4-d} = v^2 \frac{\Lambda_U^{d_{UV}-d}}{M^{d_{UV}-2}}$$

- NP are seen only in IR (or nearly conformal sector) where $Q \geq \Lambda$ for a given experiment

$$At \quad IR \quad * \left| H \right|^2 \to v^2$$

$$** \; const \;\; O \to \Lambda^d$$

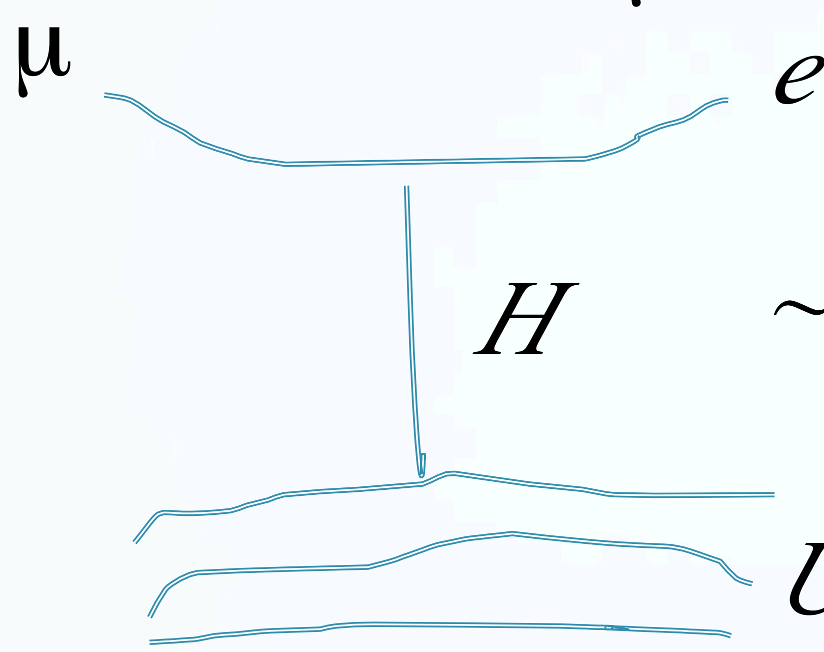
The effect of U-sector on observable is bounded by

$$\varepsilon < \frac{1}{v^4} \left(\frac{Q^n}{M^{n-2}} \right)^2$$

Important:

No UV and U-scaling dimensions of the CFT operators (P. Fox et al. (2007); G.K. , I. Gorbunov (2011))

Rare $\mu \to e$



$$\sim const\ M^2 |H|^2 \frac{1}{\Lambda_U^d} O \cdot \left(\frac{\Lambda_U}{M}\right)^{d_{UV}} \quad (*)$$

$$\Downarrow$$

$$\sim (\bar{\mu} H e) O \frac{\Lambda_U^{d_{UV}-d}}{M^{d_{UV}}}, \quad n=4$$

In IR $\quad M^2 |H|^2 \to M (\bar{\mu} e)\left(\frac{v}{M}\right), \quad n=3$

$$\varepsilon_{\mu e} < \frac{1}{v^4}\left(\frac{Q^n}{M^{n-2}}\right)^2 \left(\frac{v}{M}\right)^2$$

3 parameters only:

- Energy of experiment Q
- EW scale v
- UV scale M > EW scale

Estimation of $\varepsilon_{\mu e}$

COMET:

$$Q \sim E^{\pi}_{total}, \quad M > m_Z$$

$$p^{\pi}_{total} \approx \begin{matrix} 120\, MeV/c, \ Backward\ scattering \\ 200-400\, MeV/c \ \ Forward\ scattering \end{matrix}$$

Result I:

$$\varepsilon^{min}_{Fw,\mu e} < 5 \cdot 10^{-17}$$

$$\varepsilon^{max}_{Fw,\mu e} < 1.4 \cdot 10^{-15}$$

Compatible with the estimation for $BR\left(\mu^- + Al \to e^- + Al\right) \leq \left(2.6-6\right) \cdot 10^{-17}$ used for the muon-stopping target

Result II: Experimental energy Q has to be increased, so that the $U-$ stuff can couple strongly enough to the SM fields, and $\mu \to e$ transition will have to be seen more clearly.

COMET collaboration

23 October 2014

129 collaborators
28 institutes, 11 countries

The COMET Collaboration

R. Akhmetshin[3], K. Akuma[17], M. Aoki[22], R. B. Appleby[19], Y. Arimoto[12], Y. Bagaturia[7], W. Bertsche[19], A. Bondar[3], D. Bryman[2], B. Chiladze[5], M. Danilov[10], W. daSilva[16], P. Dauncey[8], G. Devidze[5], P. Dornan[8], A. Drutskoy[10], S. Dymov[11], A. Edmonds[25], L. Epshteyn[3], P. Evtoukhovich[11], G. Fedotovich[3], Y. Fukao[12], M. Gersabeck[19], D. Grigoriev[3], K. Hasegawa[12], I. H. Hasim[22], O. Hayashi[22], M. I. Hossain[18], Z. Ibrahim[17], F. Idris[17], Y. Igarashi[12], F. Ignatov[3], M. Ikeno[12], S. Ishimoto[12], T. Itahashi[22], S. Ito[22], T. Iwami[22], Y. Iwashita[13], X. Jiang[4], P. Jonsson[8], V. Kalinnikov[11], F. Kapusta[16], H. Katayama[22], K. Kawagoe[15], V. Kazanin[3], B. Khazin[3], A. Khvedelidze[11], M. Koike[26], G. Kozlov[11], B. Krikler[8], A. Kulikov[11], Y. Kuno[22], Y. Kuriyama[14], A. Kurup[8], B. Lagrange[14], M. Lancaster[25], H. B. Li[4], W. Li[4], A. Liparteliani[5], G. Macharashvili[11], Y. Makida[12], Y. Matsumoto[22], T. Mibe[12], S. Mihara[12], A. Moiseenko[11], Y. Mori[14], N. Mosulishvili[5], E. Motuk[25], Y. Nakai[15], T. Nakamoto[12], T. H. Nam[22], J. Nash[8], M. Nioradze[5], H. Nishiguchi[12], T. Numao[24], T. Ogitsu[12], K. Okamoto[22], C. Omori[12], K. Ooishi[15], T. Ota[23], H. Owen[19], R. Palmer[1], C. Parkes[19], J. Pasternak[8], A. Popov[3], V. Rusinov[10], A. Ryzhenenkov[3], B. Sabirov[11], N. Saito[12], H. Sakamoto[22], P. Sarin[6], K. Sasaki[12], A. Sato[22], J. Sato[23], D. Shemyakin[3], V. Shmakova[11], M. Sugano[12], W. Tajudeen[17], Y. Takubo[12], M. Tanaka[12], C. V. Tao[21], E. Tarkovsky[10], Y. Tevzadze[5], N. D. Thong[22], V. Thuan[9], J. Tojo[15], M. Tomizawa[12], I. Trekov[5], N. M. Truong[22], Z. Tsmalaidze[11], N. Tsverava[11], S. Tygier[19], T. Uchida[12], Y. Uchida[8], K. Ueno[12], S. Umasankar[6], E. Velicheva[11], A. Volkov[11], M. Warren[25], M. Wing[25], C. Wu[4], G. Xia[19], K. Yai[22], A. Yamamoto[12], M. Yamanaka[20], M. Yoshida[12], Y. Yoshii[12], K. Yoshimura[12], T. Yoshioka[15], Y. Yuan[4], Y. Yudin[3], Y. Zhang[4]

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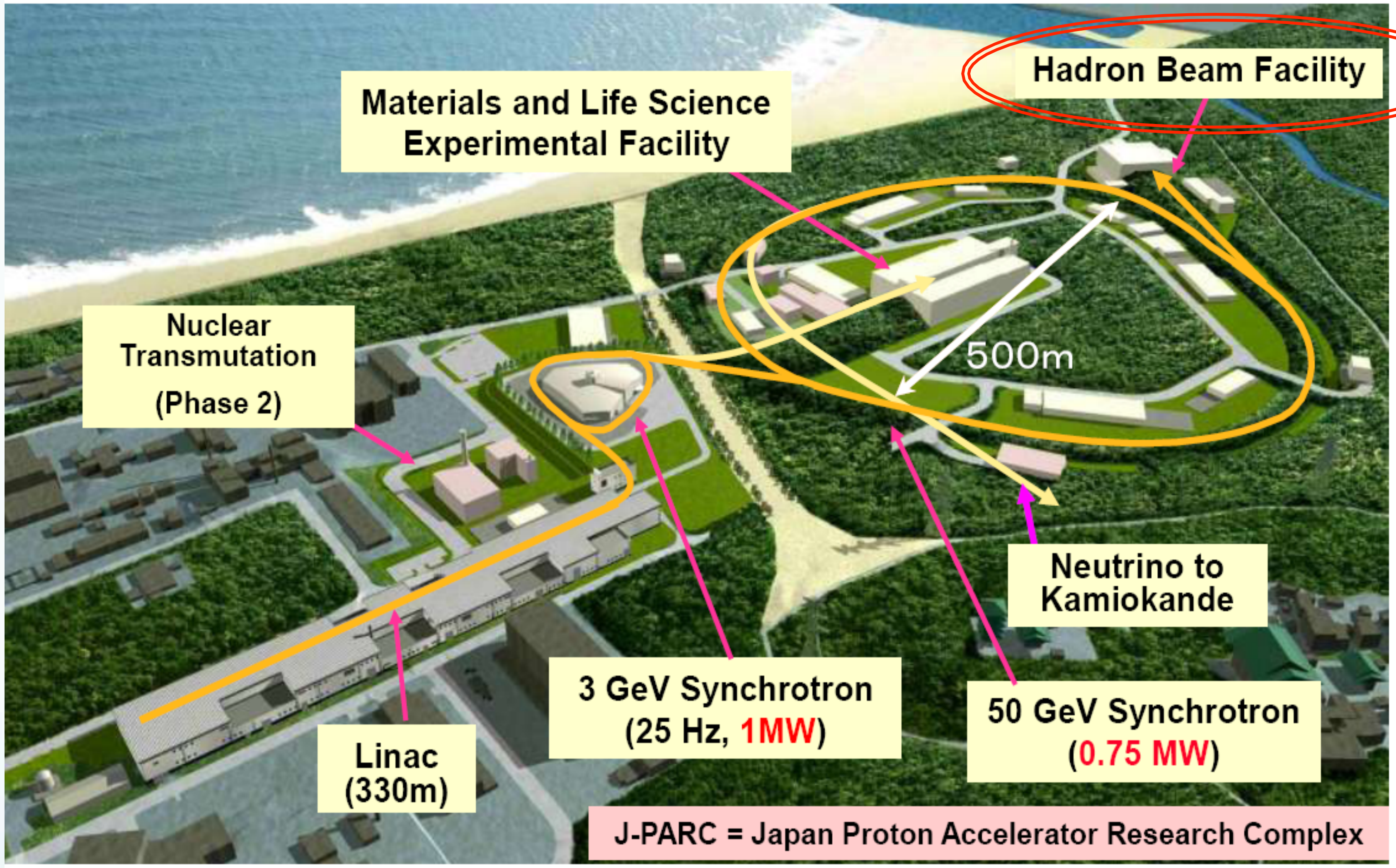
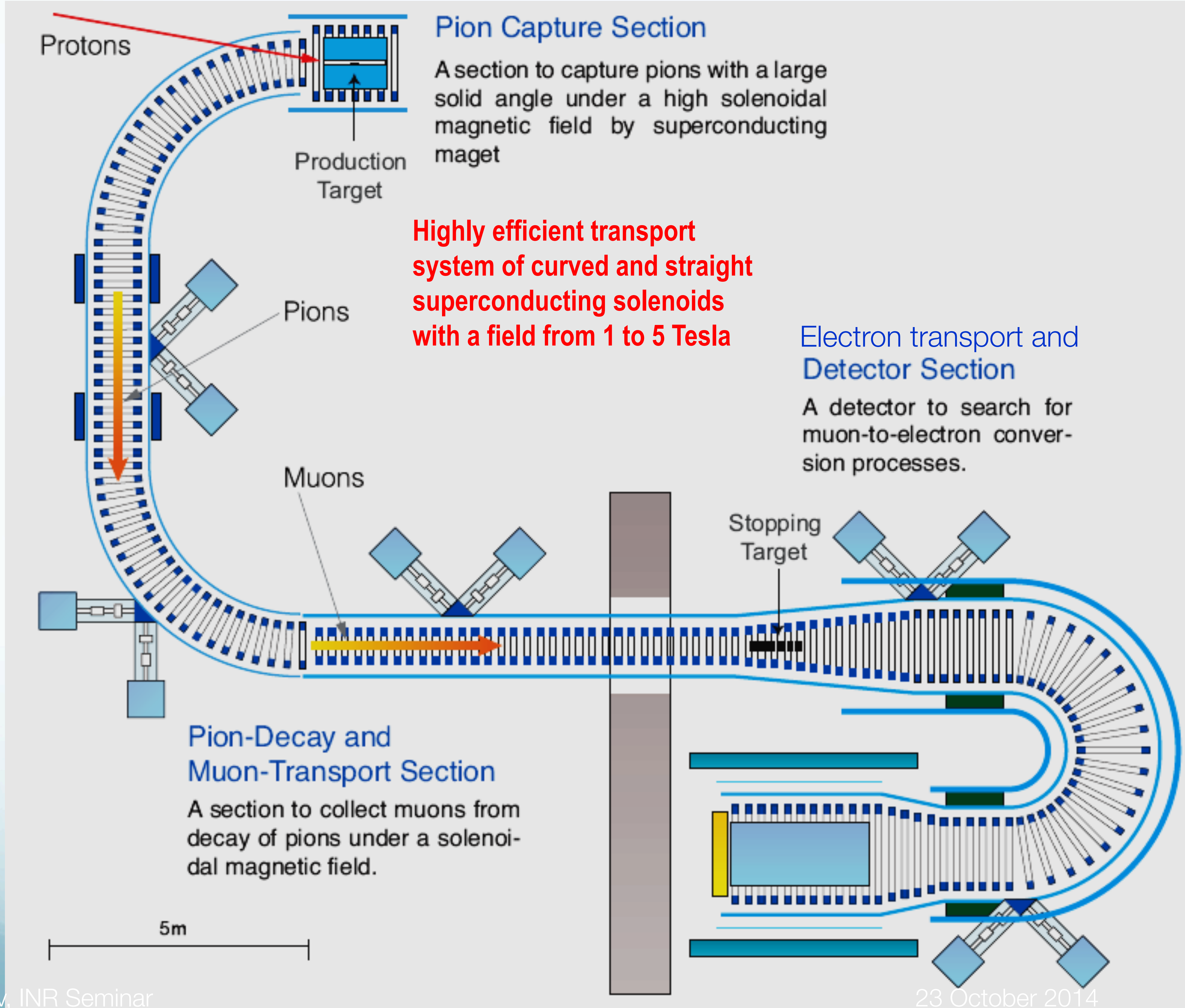
J-PARC Facility

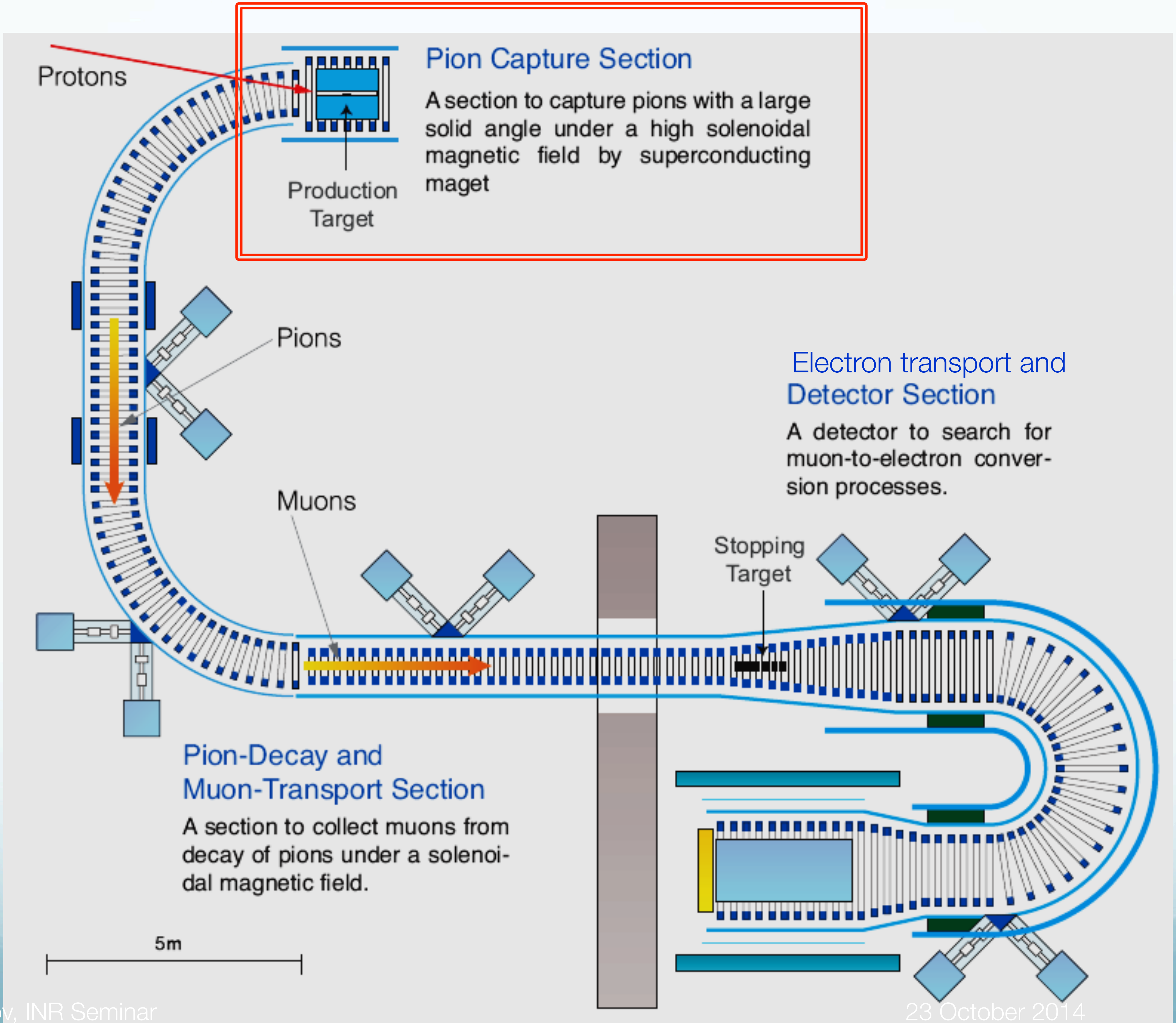


An effective pion capture and muon transport scheme will provide the muon beam of $10^{11}\ s^{-1}$ intensity, that is 3 orders of magnitude higher than the current world best.

Proton beam requirements for COMET:	J-PARC current (*nominal*) parameters
8 GeV energy	30 (*50*) GeV
beam power 56 kW	450 (*750*) kW

J-PARC beam is used not at full power


Protons
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget
Production Target
Highly efficient transport system of curved and straight superconducting solenoids with a field from 1 to 5 Tesla
Pions
Electron transport and Detector Section
A detector to search for muon-to-electron conver-sion processes.
Muons
Stopping Target
Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoi-dal magnetic field.
5m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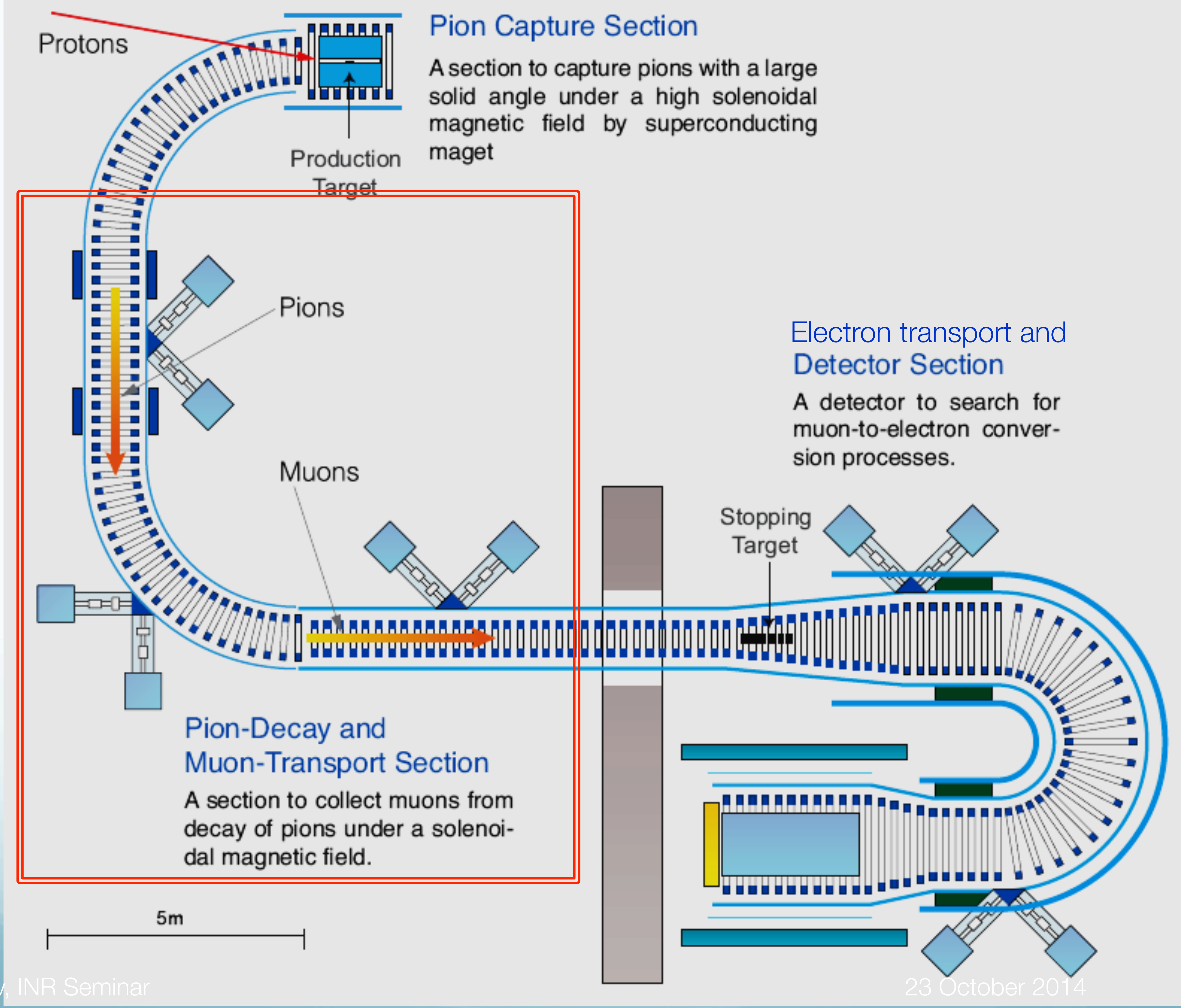
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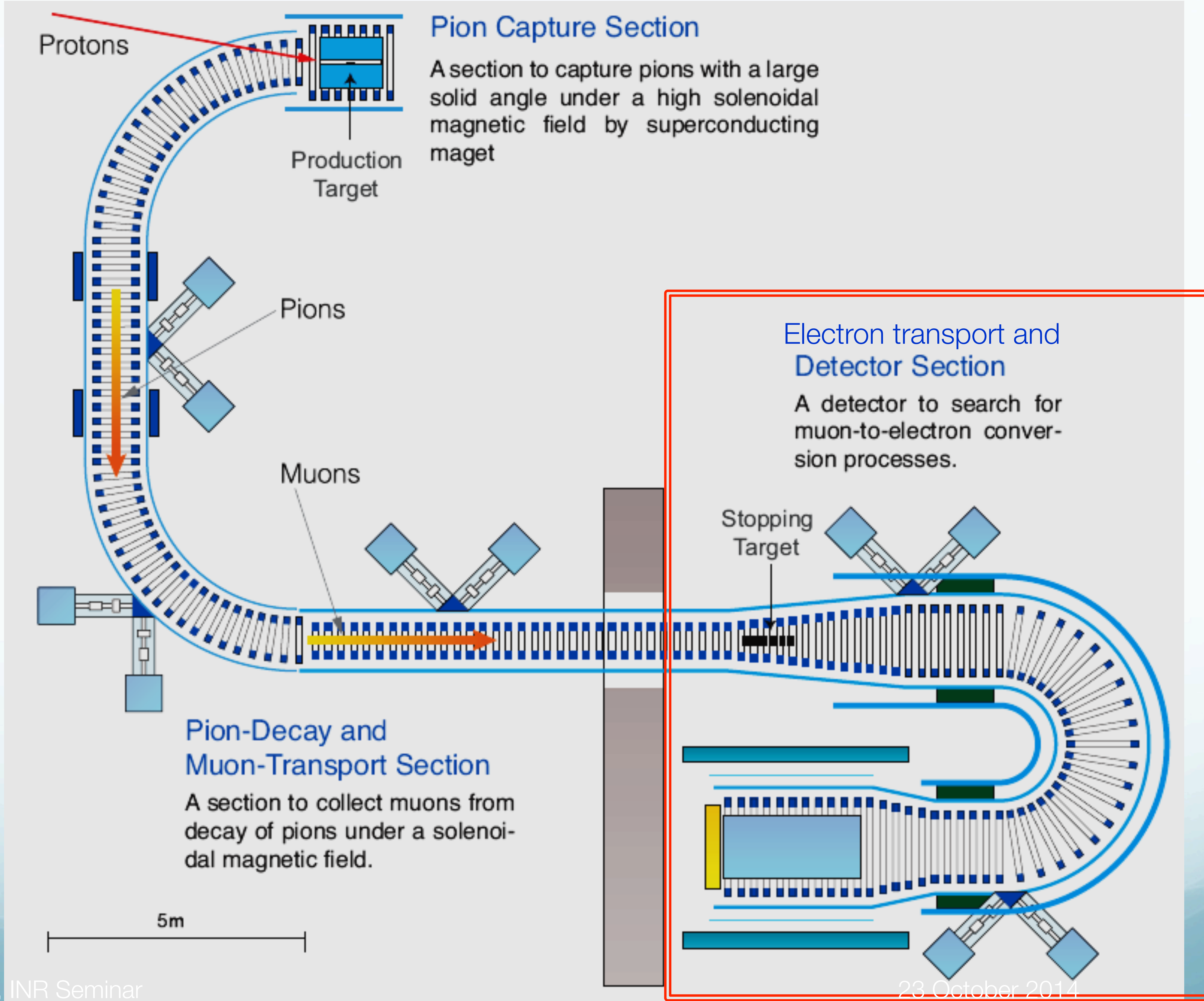
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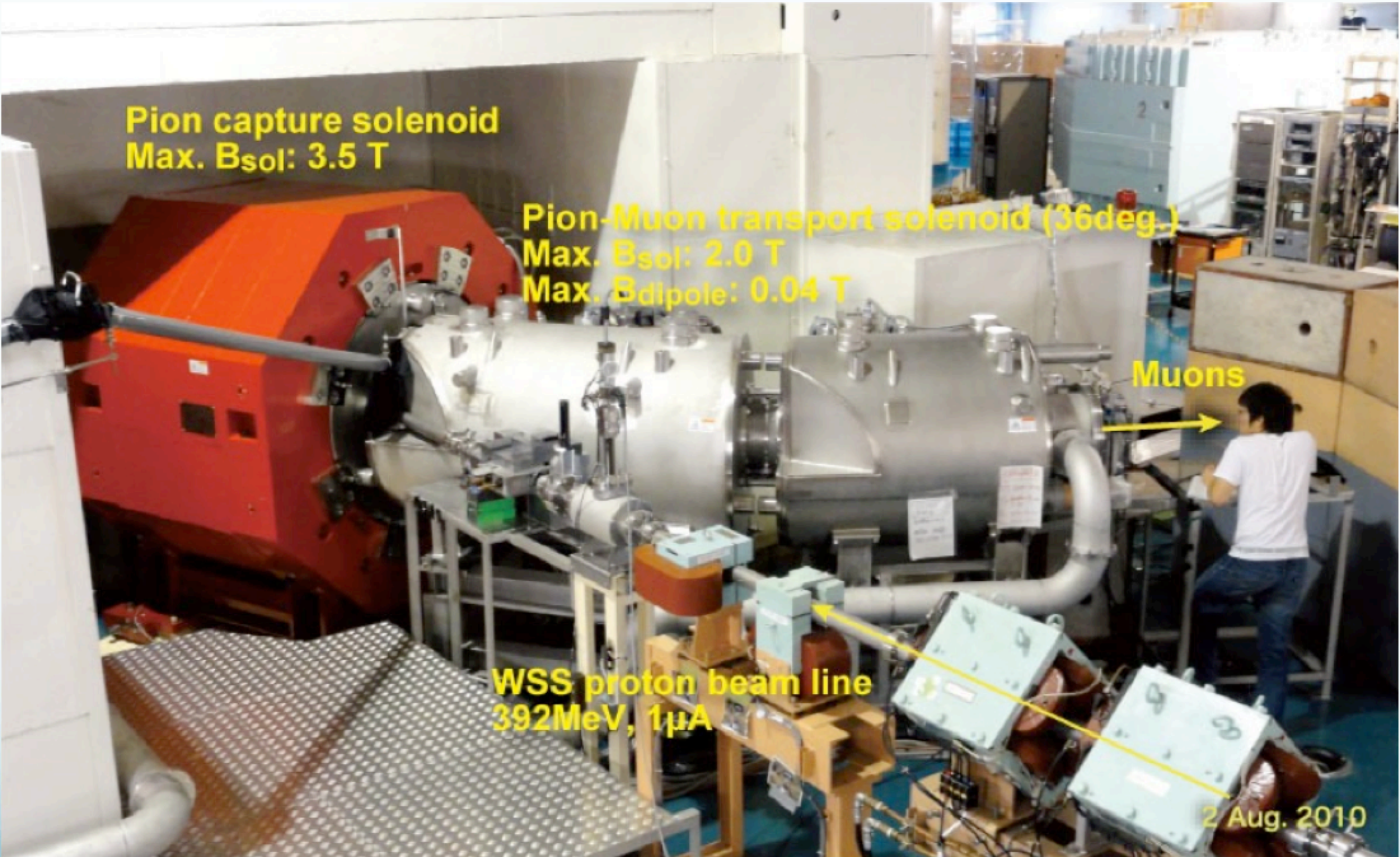
5m


Pion capture solenoid
Max. Bsol: 3.5 T
Pion-Muon transport solenoid (36deg.)
Max. Bsol: 2.0 T
Max. Bdipole: 0.04 T
Muons
WSS proton beam line
392MeV, 1μA
2 Aug. 2010

To reach the goal of increasing sensitivity by several orders of magnitude, it is extremely important to study experimentally all sources of background.

High-end technology of the muon beam line and performance of the detectors should be tested and well understood.

Two-phase approach in COMET.

Phase-I (since 2016 up to 2018) :

1) Direct measurement of potential background sources by using the actual COMET beam line.
2) A search for μ - e conversion at intermediate sensitivity $\sim 10^{-15}$ what is ~100 times better than the current SINDRUM-II limit.

For these two tasks different apparatus will be used

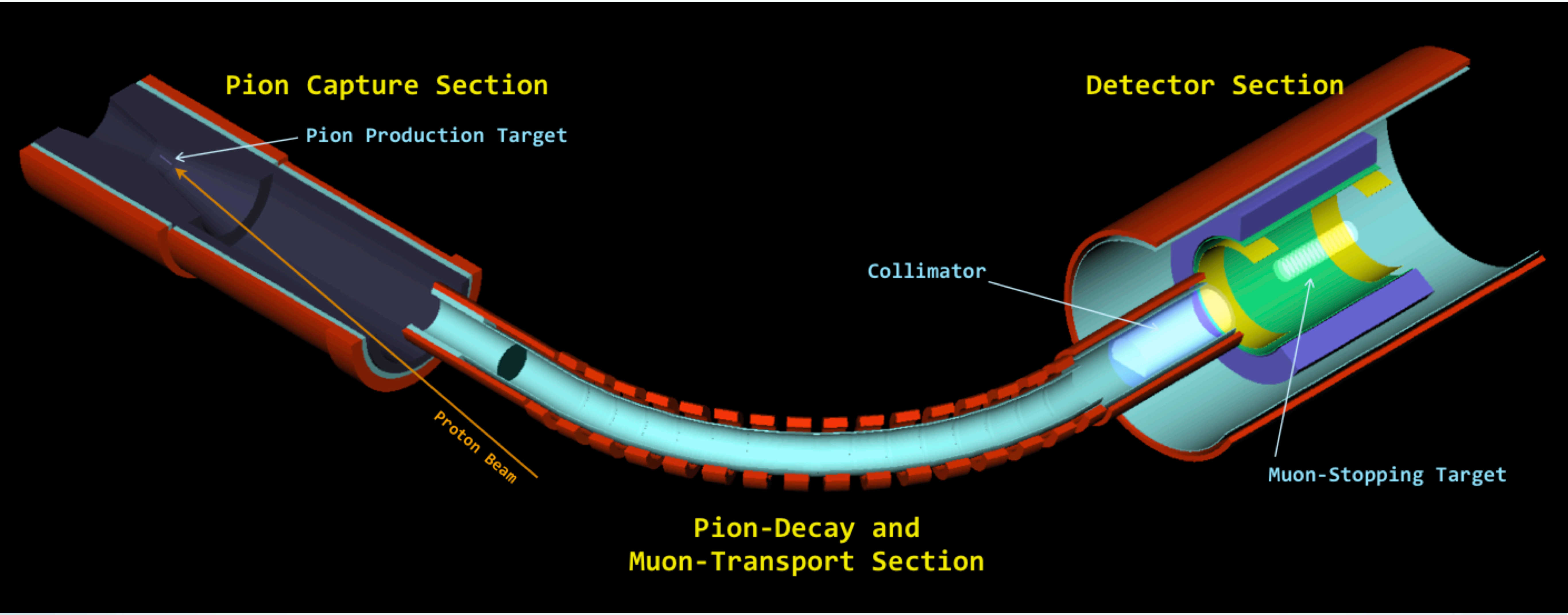
Phase-II (starting from 2019):

COMET experiment with the declared sensitivity of $\sim 10^{-17}$.

Summary of COMET Phase-I/Phase-II

	Phase-I	Phase-II
Experiment start	2016	2019
Proton beam power	3.2 kW (8 GeV)	56 kW (8 GeV)
Running time	1.5×10^{6} s (~ 1 month)	2×10^{7} s (~ 1 year)
# of protons	3.8×10^{18}	8.5×10^{20}
# of muon stops	8.7×10^{15}	2.0×10^{18}
Muon rate	5.8×10^{9} s^{-1}	1.0×10^{11} s^{-1}
# of muon stops/ proton	0.0023	0.0023
# of BG events	0.03	0.4
Single event sensitivity	3.1×10^{-15}	2.6×10^{-17}
Upper limit (90% C.L.)	7×10^{-15}	6×10^{-17}

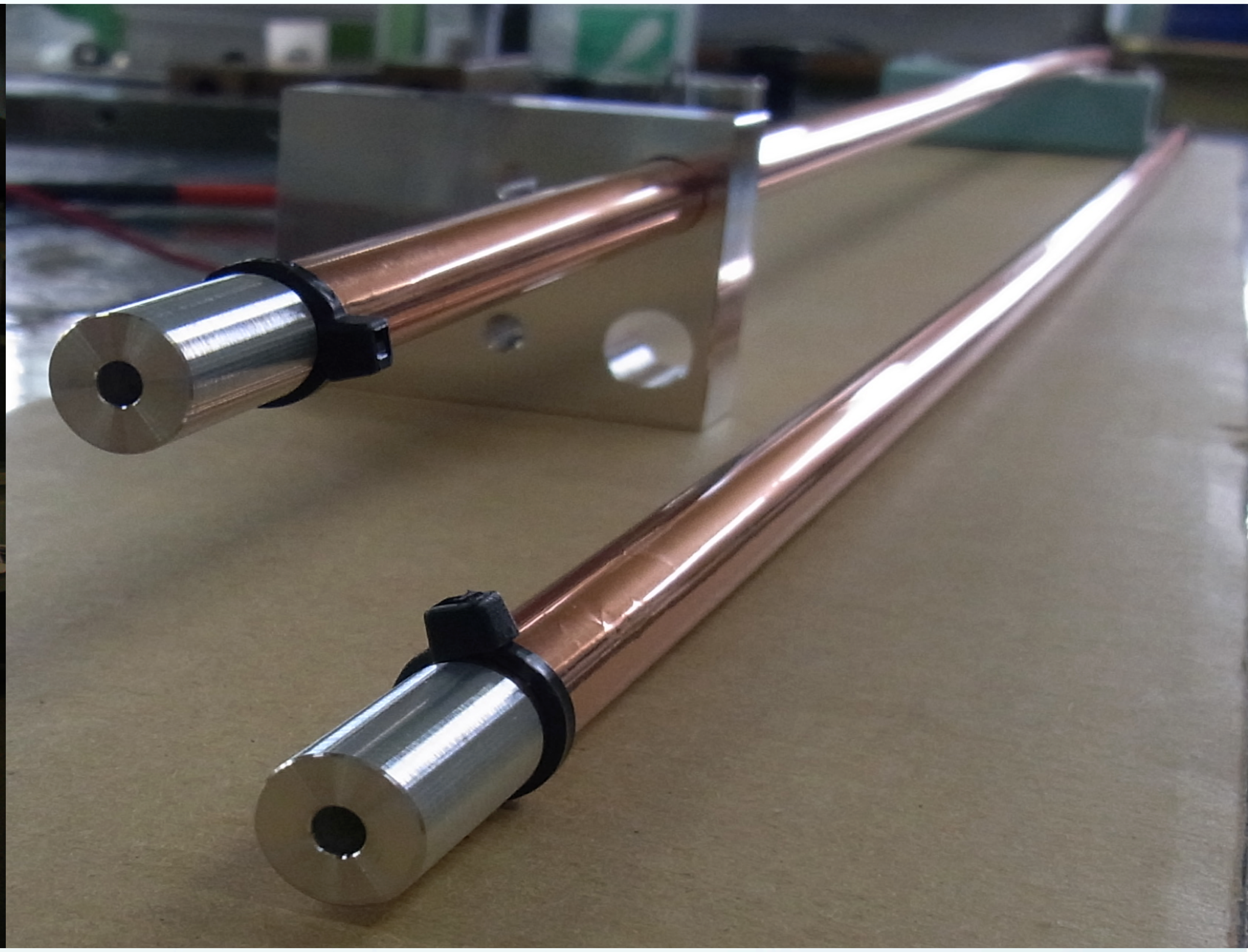
COMET, Phase I



JINR participation in COMET

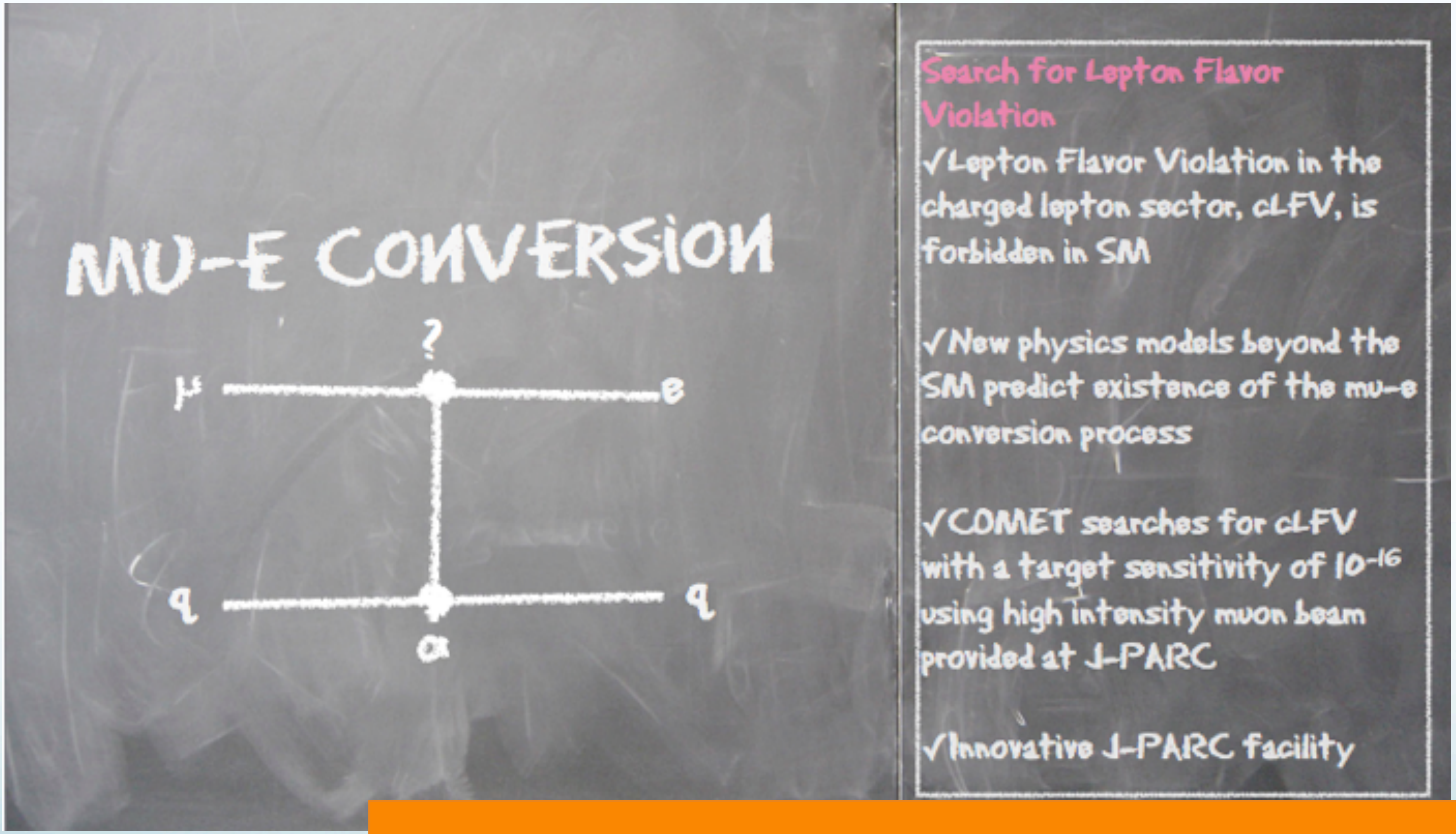
1. Electromagnetic calorimeter	start of realization
2. Straw tracker	start of realization
3. Simulations	start of realization
4. Data analysis	to be started later

JINR-KEK prototype assembly studies at the JINR VBLHEP straw production facility



Summary

Mu-e conversion at the level 10^{-17} would be the big challenge and the great discovery potential!



NP is approached soon!

MU-E CONVERSION

Search for Lepton Flavor Violation

✓Lepton Flavor Violation in the charged lepton sector, cLFV, is forbidden in SM

✓New physics models beyond the SM predict existence of the mu-e conversion process

✓COMET searches for cLFV with a target sensitivity of 10^{-16} using high intensity muon beam provided at J-PARC

✓Innovative J-PARC facility

Thank you for your attention!