带电轻子味破坏实验展望

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提纲

- 引言
- 带电轻子味破坏
- 实验进展简介
- 展望和总结

Standard Model for particle physics

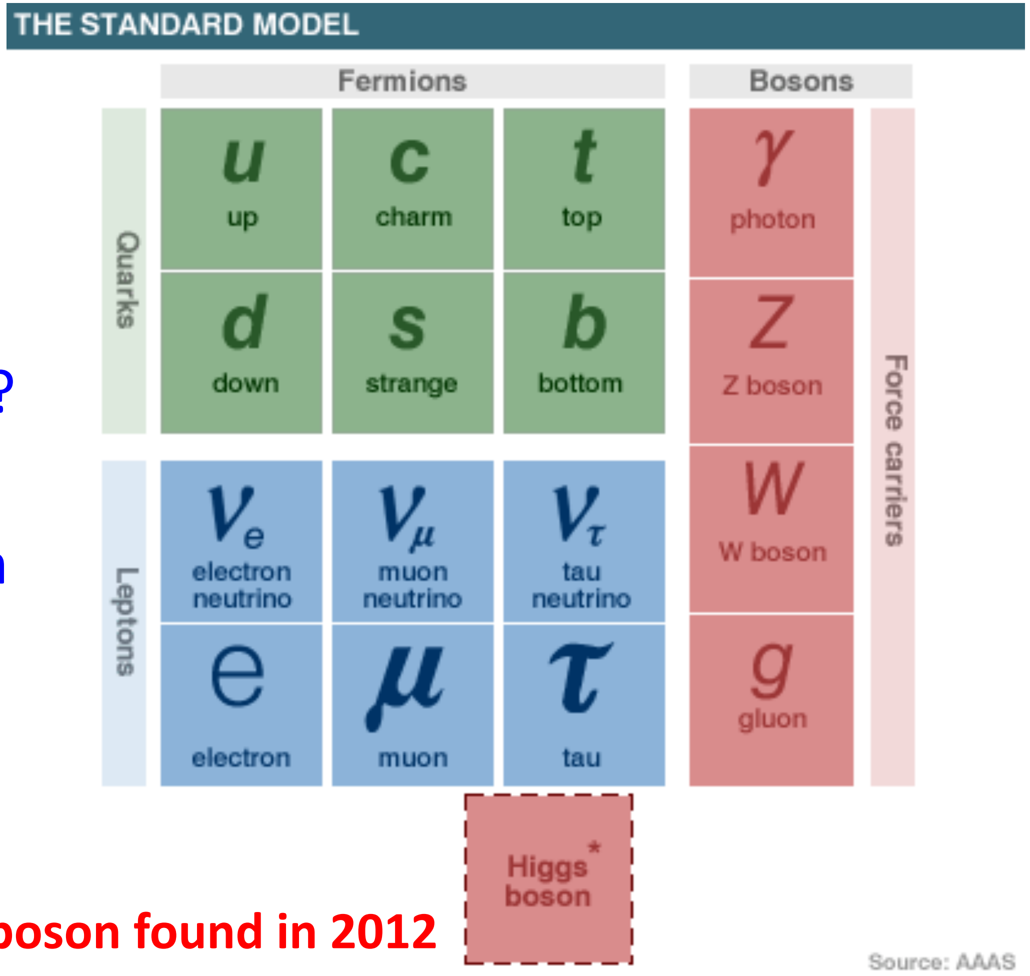
2012: Higgs boson discovered by ATLAS and CMS at LHC

No any signal of New Physics was found in lab, however,

- Dark matter candidates?
- Strong mass hierarchy?
- CP violation in universe vs. CKM phase?

…

indicate that new physics must be hidden somewhere in a corner!



Higgs boson found in 2012

实验上发现新物理的途径

- 类卢瑟福散射实验 – 物质深层次的结构
- 精确测量基本粒子的内禀性质：磁矩、电偶极矩…
- 测量高阶“精细”量子效应
- 测量正反物质不对称
- 测量稀有的标准模型禁戒的跃迁过程
- 更高能量发现新的粒子： 大型强子对撞机
- 观测宇宙线： 暗物质、轴子观测
- 集团效应：原子物理、凝聚态物理 [里德堡原子、量子干涉]

味物理：粒子物理基本问题

GIM

Flavor changing neutral current (FCNC)

夸克

轻子

2008年诺贝尔奖

小林、益川混合矩阵CKM

轻子味转换：
中微子震荡

梶田隆章，阿瑟·麦克唐纳
2015诺贝尔奖

是否存在带电轻子味改变的中性流？

Prof. A.J. Buras
TUM, Germany.

A.J. Buras的新物理“基因(DNA)”矩阵

FCNC: 味道改变的中性流

Models ⟶

Observables ↓

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Altmannshofer, Buras, Gori, Paradisi, Straub
Nucl. Phys. **B 830**, 17 (2010)

（charged） Lepton-flavor violation

Decay $\mu \to e\gamma,\ \mu \to eee,\ \tau \to \mu\gamma,\ \tau \to \mu\mu\mu,\ \tau \to \mu hh,$

$B_s \to e\mu, e\tau, \mu\tau,\ D^0 \to e\mu, e\tau,\ B \to Ke\mu,\ D \to Ke\mu$

$H \to \mu\tau, e\tau,\ Z \to e\mu, e\tau, \mu\tau,\ J/\psi \to e\mu, e\tau, \mu\tau$

Conversion $\mu + A \to e + A$

Oscillation $\nu_e \leftrightarrow \nu_\nu \leftrightarrow \nu_\tau,\ M(\mu^- e^+) \leftrightarrow M(\mu^+ e^-)$

Number violation $0\nu 2\beta,\ B^- \to \pi^+ \mu^- \mu^-,\ D^- \to \pi^+ e^- e^- ...$

Non-Universality $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu \,\mathrm{vs}\, \bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau,\ D_s^- \to \tau^-\bar{\nu}_\tau \,\mathrm{vs}\, D_s^- \to \mu^-\bar{\nu}_\mu,\ (g-2)_\mu$

Anomalies in Flavor

Before 2019

(HFLAV) (2019), arXiv:1909.12524.

$$\mathcal{R}_D = \frac{\mathcal{B}(\bar{B} \to D\tau^-\nu)}{\mathcal{B}(\bar{B} \to D\ell^-\nu)} = 0.340 \pm 0.027 \pm 0.013 \text{ (expt.)} \;\; [\textbf{SM}: \; 0.299 \pm 0.003]$$

$$\mathcal{R}_{D^*} = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\nu)}{\mathcal{B}(\bar{B} \to D^*\ell^-\nu)} = 0.295 \pm 0.011 \pm 0.008 \text{ (expt.)} \;\; [\textbf{SM}: \; 0.258 \pm 0.005].$$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \qquad R_{K^*} = \frac{\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^{*+}e^+e^-)}$$

$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central $Q^2 \in [1.0, 6.0]\,\text{GeV}/c^2$ — 2.6σ

$R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low $Q^2 \in [0.045, 1.1]\,\text{GeV}/c^2$ — $2.1\sigma - 2.3\sigma$

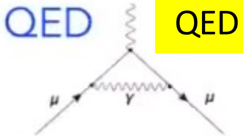
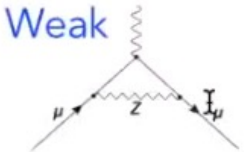
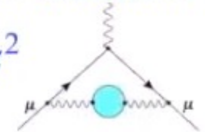
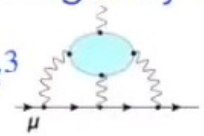
$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central $Q^2 \in [1.1, 6.0]\,\text{GeV}/c^2$ — $2.4\sigma - 2.5\sigma$

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

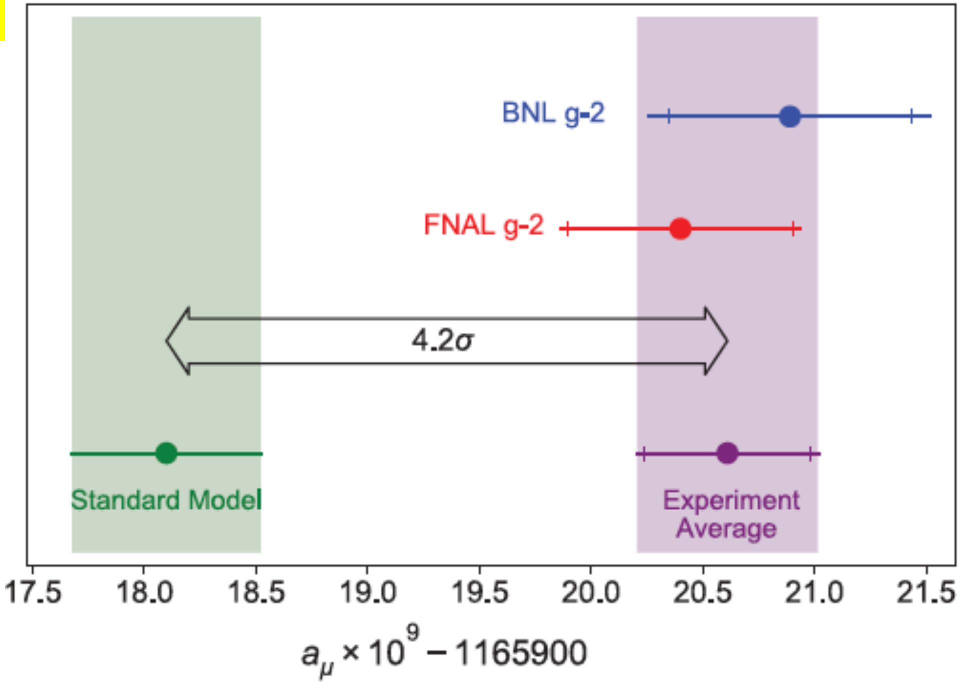
Muon反常磁矩(g-2)测量现状

$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

From Xu Feng

QED  +...	QED corrections	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
Weak  +...	Weak	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
Hadronic...	QCD contributions		
...Vacuum Polarization (HVP) α^2  +...		$6845\,(40) \times 10^{-11}$ [0.6%]	0.37 ppm
...Light-by-Light (HLbL) α^3  +...		$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm

B. Abi *et al.* (Muon g−2 Collaboration)
Phys. Rev. Lett. **126**, 141801, 2021



$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (251 \pm 59) \times 10^{-11}$$

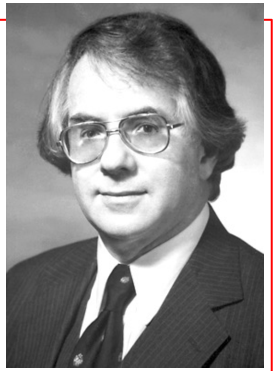
FNAL experiment targets on precision of 0.14 ppm ! HVP with error 0.2-0.3%

BESIII

美国未来粒子物理实验方向
个人观点

Boston University

arXiv:1305.5482[hep-ph] slg@bu.edu



格拉肖
1979年
诺贝尔奖

Snowmass 2013

ABSTRACT: *I present my views on the future of America's program in particle physics. I discuss a variety of experimental initiatives that do have the potential to make transformative impacts on our discipline and should be included in our program, as well as others that do not and should not.*

未来具有革命性发现的领域:
(1) Dark matter & Dark Energy
(2) Testing Global symmetry
(3) Testing Flavor symmetry with muon （缪轻子）
(4) Electric Dipole moments
(5) Neutrino Physics

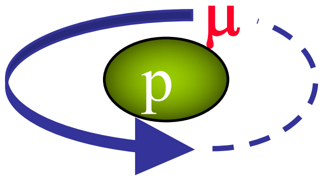
带电轻子味破坏
(CLFV)实验研究

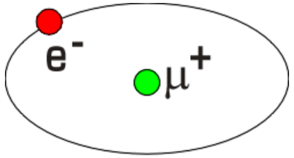
除去LHC和宇宙观测等实验！高精度测量也不可忽视。

Muon轻子简介

张文裕所长（1978-1984），高能所第一任所长， 科大近物系主任，1947年在普林斯顿大学巴尔默实验室发现muonic atom。

- 1936年Anderson and Neddermeyer 发现muon轻子
- 与电子质量关系： $m_\mu = 207 \cdot m_e$
- 弱衰变导致： “long” lifetime (2.2 微秒)→ beam and probe
- 主要衰变 $\mu \rightarrow e\ \nu_e\ \nu_\mu$ (parity violating)
- 极化束流： muon beam from pion decay
- Muon束缚态 (muon原子： $\mu^- p$, $\mu^- d$; muonium: $\mu^+ e^-$; dimuon: $\mu^+ \mu^-$)



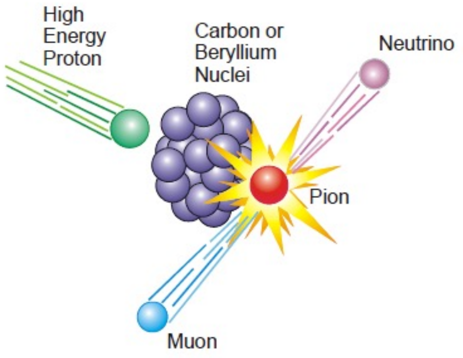


- 对新物理更敏感 $(m_\mu/m_e)^2 \approx 40{,}000$
- Lepton flavor violation ($\mu \rightarrow e$) extremely small in SM
- 容易被探测: $P_{detection} \approx 1$

世界上正在运行或批准的muon源

中国目前还没有高强度的muon源

质子束流：
连续(CW)
脉冲(Pulsed)



$p + p \rightarrow p + n + \pi^+$

$$\pi^+ \rightarrow \mu^+ + \nu_u$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

表面muon ≈28 MeV 100%极化
DIF muon > 30 MeV

China Spallation Neutron Source (CSNS)

基础muon实验物理

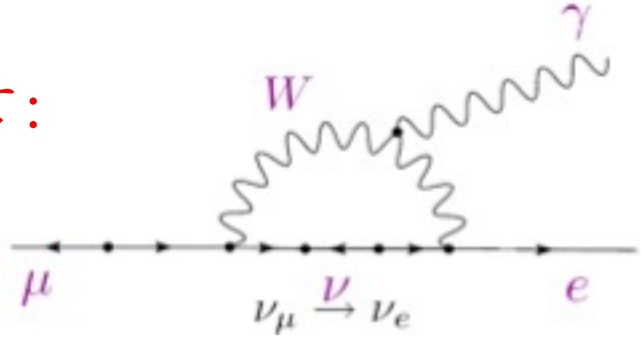
- 寿命 – 费米常数精确测量
  - MuLan & FAST at PSI
- 有关衰变常数的测量(ρ, δ, η, P_mξ...)
  - TWIST at TRIUMF and polarization measurements at PSI
- Muon俘获
  - MuCap at PSI: g_P, pseudoscalar coupling
  - MuSun at PSI: basic EW interaction in 2N system
- 轻子味破坏
  - μ→eγ MEG at PSI
  - μ→e e e mu3e at PSI
  - μ→e conversion: SINDRUM, Mu2e (FNAL), COMET, DeeMee (J-PARC)
- 反常磁矩 (g-2)
  - E821 at BNL and Muon g-2 at FNAL & J-PARC
- 电偶极距／磁偶极距
  - FNAL & J-PARC
- 洛伦兹 / CPT 破坏检验
  - FNAL & J-PARC
- 质子荷电半径
  - Muonic Lamb shift (CREMA), MuSE at PSI
- Muon偶素谱学和精细结构
  - Muonium hyperfine at LAMPF & MuSEUM at J-PARC
- ...

过去实验
正在运行
未来实验

带电轻子味破坏过程：muon→electron

考虑到中微子微小质量后标准模型预言：

$$B(\mu \to e\gamma) = \frac{\alpha}{2\pi}\left|\sum_k U_{ek}U^*_{\mu k}\frac{m^2_{\nu_k}}{m^2_W}\right|^2 < 10^{-54}$$



标准模型

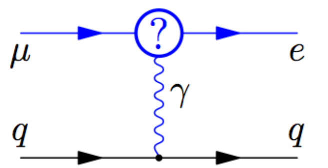
很多新物理模型可以给出可测量的预言！

对比夸克味改变的中性流过程，带电轻子味改变的中性流没有强相互作用本底。有精确的理论预言，是探测新物理的理想探针。

寻找缪轻子到电子转换过程（cLFV):

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

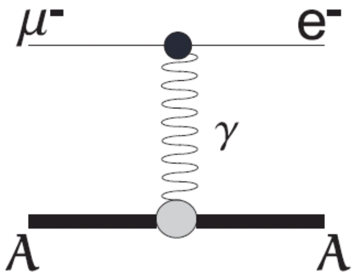
Recoil off a nucleus

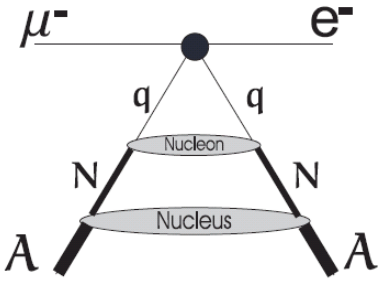


Coherent transition: 缪型原子在1S态-→跃迁机率98%→1S原子末态。电子动量为单能：105 MeV/c, 信号简单、易于测量！

对新物理的敏感度

$$L_{\mathrm{CLFV}} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\mathrm{R}}\sigma^{\mu\nu}e_{\mathrm{L}}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\mathrm{L}}\gamma^{\mu}e_{\mathrm{L}})(\bar{q}_{\mathrm{L}}\gamma_{\mu}q_{\mathrm{L}})$$

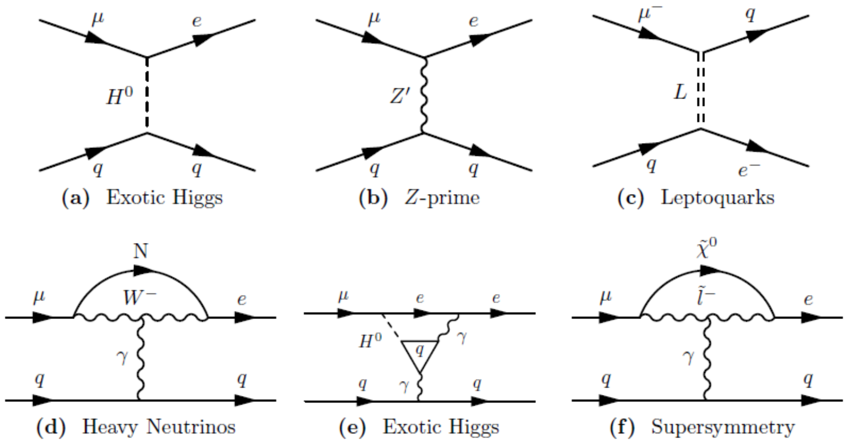


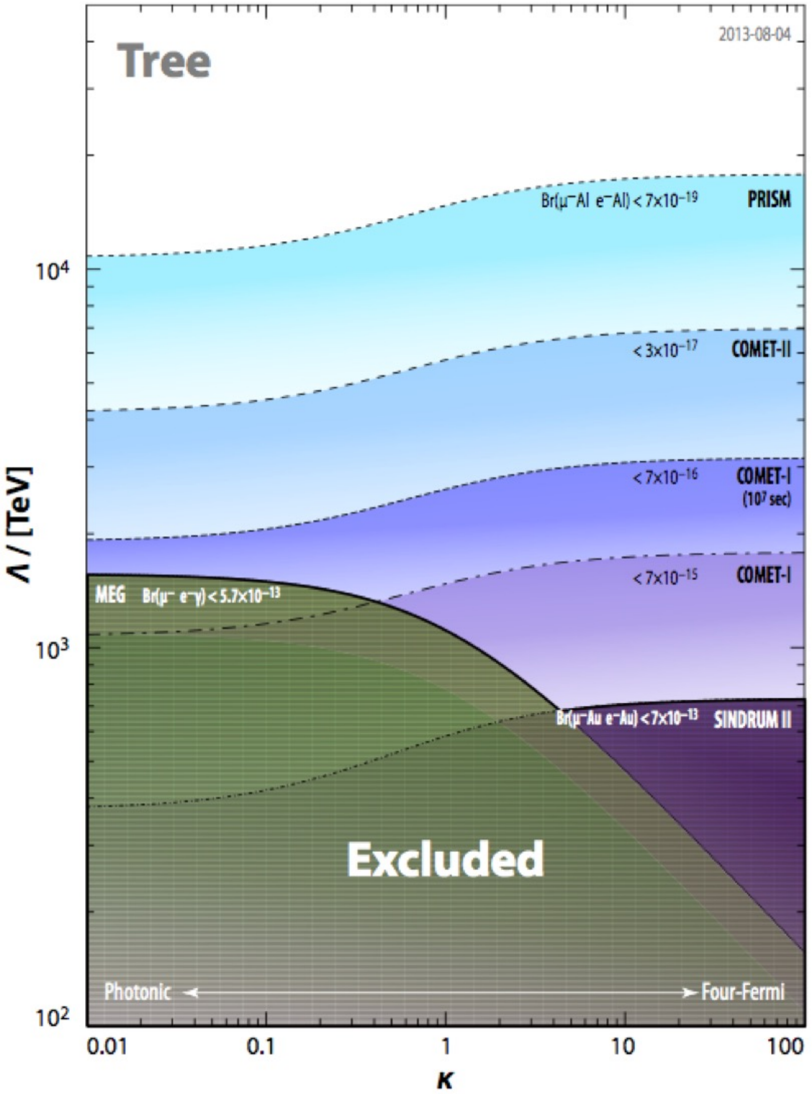


Dipole interaction
Loops dominate
for $\kappa \ll 1$

Contact terms
dominate for $\kappa \gg 1$

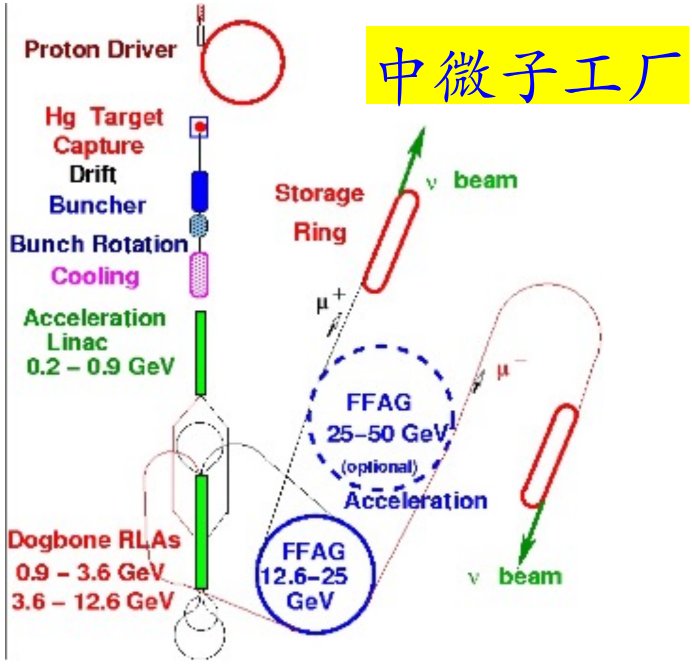
CLFV实验新物理模型的有力剃刀

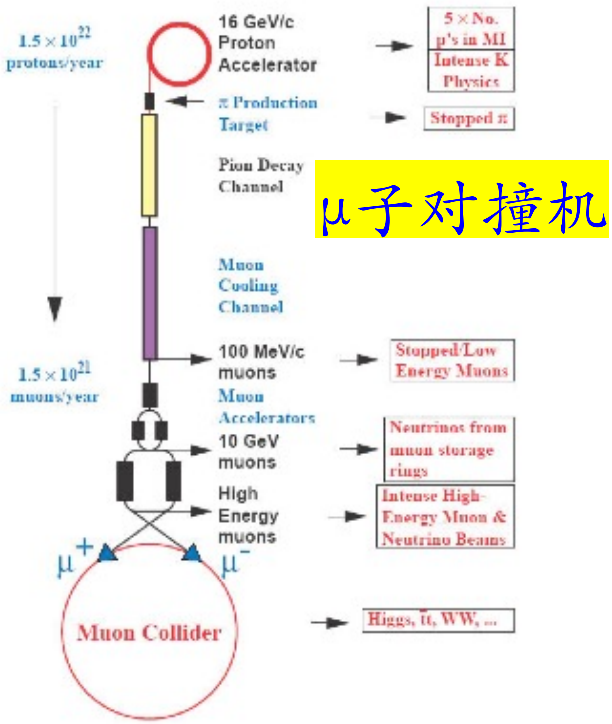




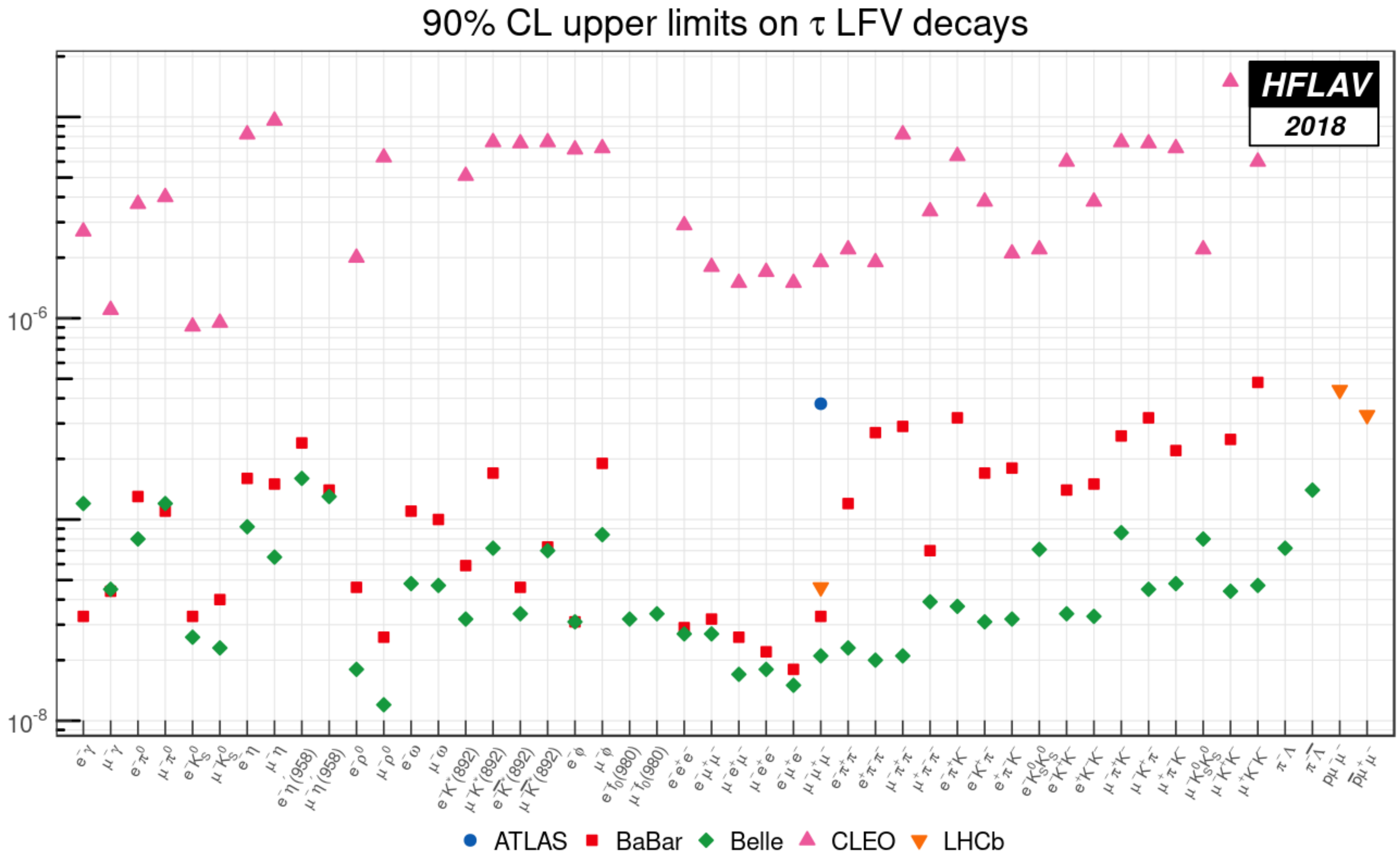
μ轻子与τ轻子的产额

- B工厂可以产生2 τ轻子/sec，超级B工厂可以产生100 τ轻子/sec 。
- 当前实验μ子数是 10^{8} muons/sec，下一代实验预期要实现10^{11}-10^{12} muons/sec。
- 未来MW以上质子束流： 10^{13}-10^{14} muons/sec。





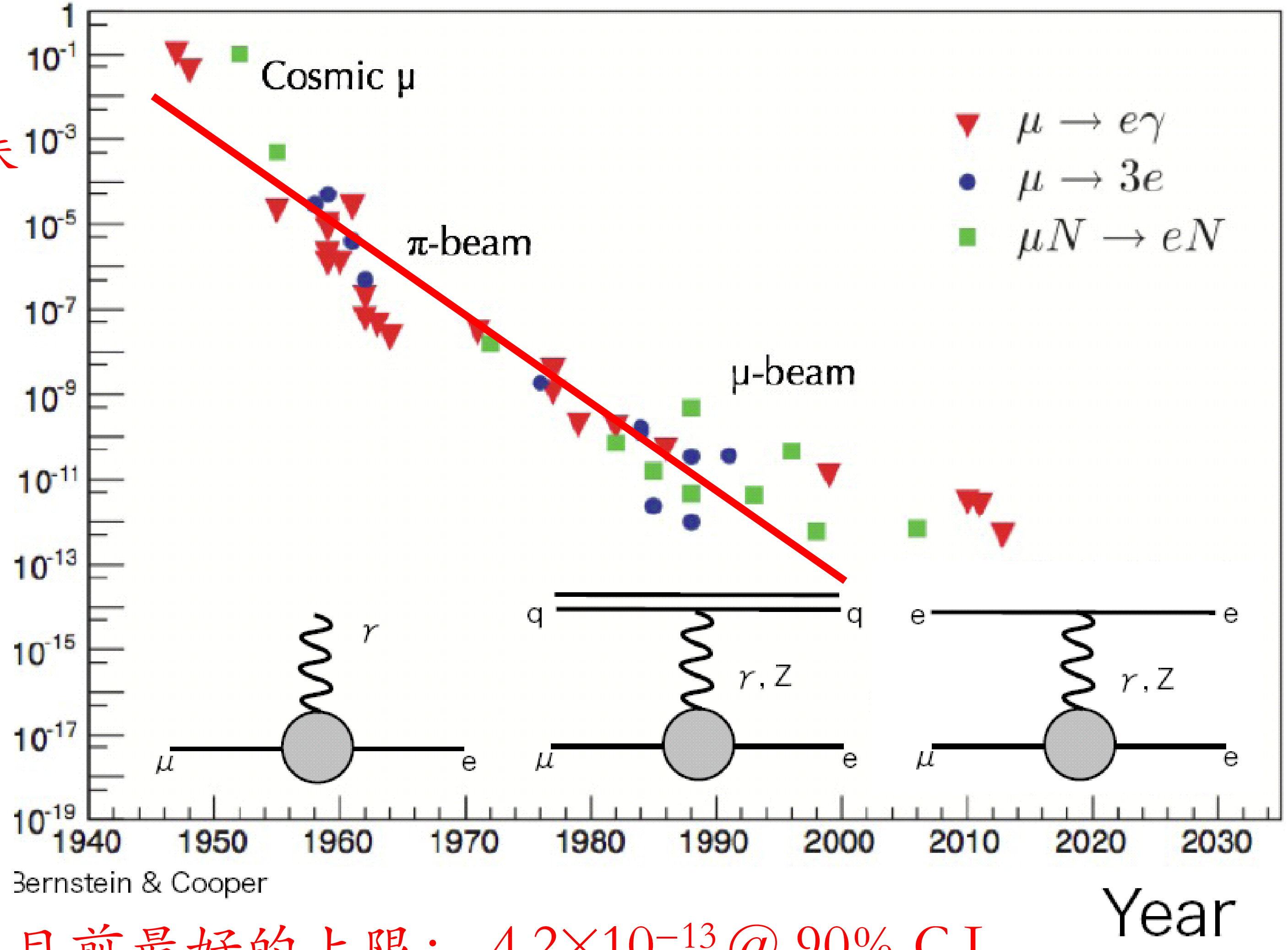
CLFV: τ 轻子衰变中的敏感度



Belle-II starts data-taking in 2019,
Belle-II will reach 10^{-9} for $\tau \rightarrow \mu\gamma$.

实验现状: muon→electron

1947年：庞蒂科夫

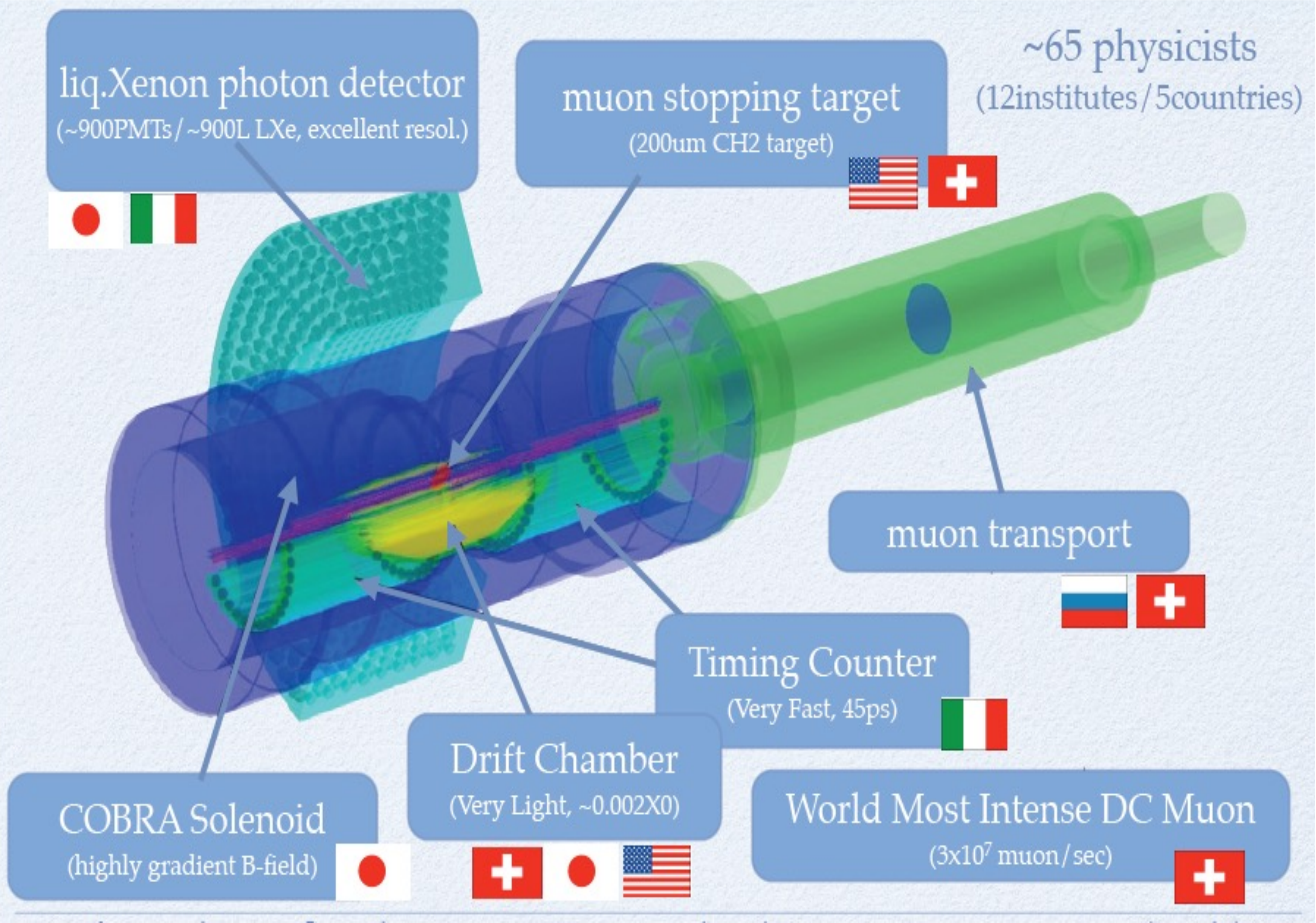


目前最好的上限： 4.2×10^{-13} @ 90% C.L.

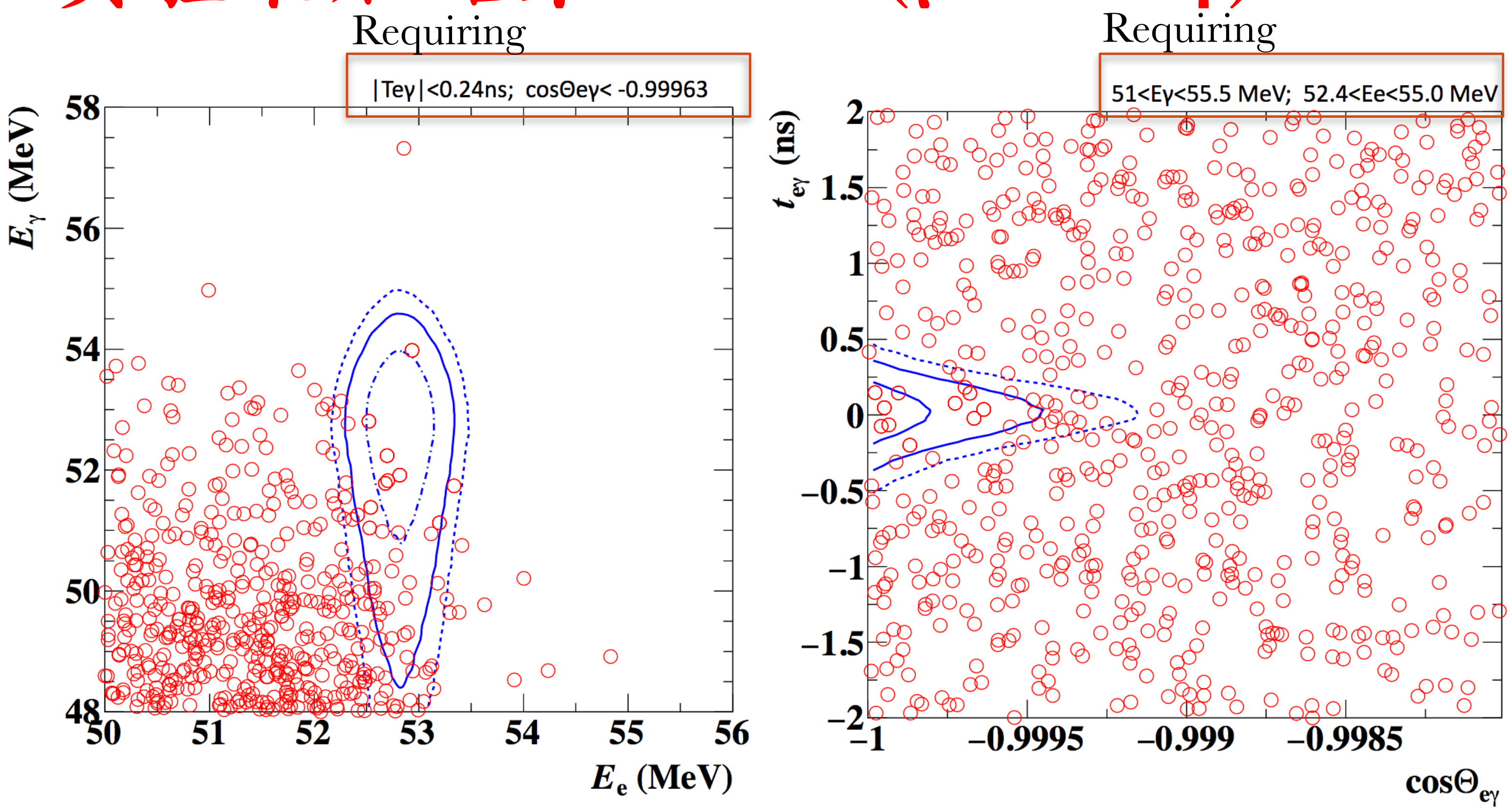
MEG: arXiv:1605.05081

瑞士Paul Scherrer Institute (PSI)的MEG实验：$\mu^+ \to e^+\gamma$ 寻找

PSI：多学科实验室。连续质子束流590MeV,流强2.2mA，连续缪束流$2\times\mathbf{10^8}\boldsymbol{\mu^+/s}$



MEG实验最后结果： BR ($\mu^+ \to e^+ \gamma$)



1σ, 1.64σ, 2σ contours are shown

New constraint on the $\mu \to e\gamma$ decay set by the MEG experiment with its final dataset: 7.5×10^{14} stopped μ^+

BR ($\mu \to e\gamma$) < 4.2x 10^{-13} at 90% C.L.

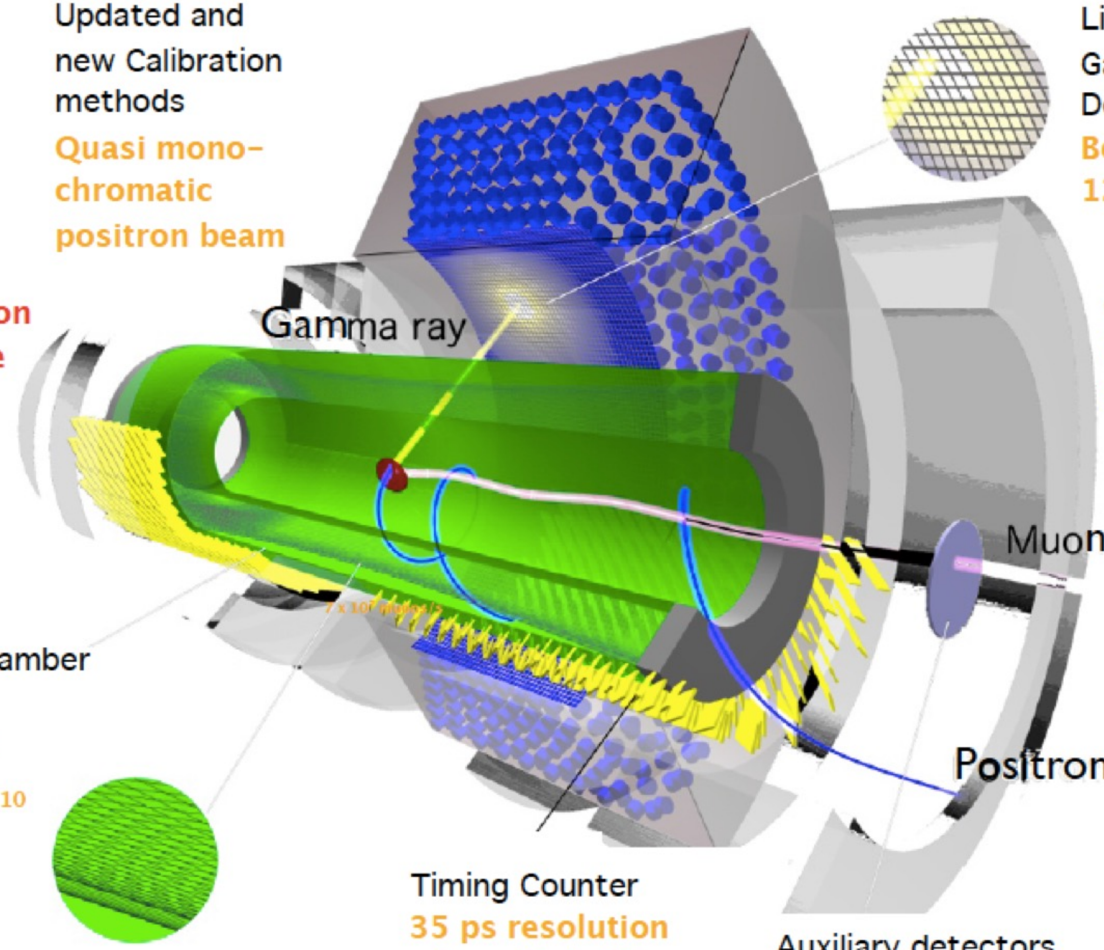
MEG: arXiv:1605.05081

MEG实验升级计划: MEG-II at PSI

2013	2014	2015	2016	2017-20
Design	Construction	PreEng Run	Eng. Run	Run

MEGII detector concept

Sensitivity [2017-20] ~ 4 x 10^{-14}



Wavedream
~9000 channels at 5GSPS

Updated and new Calibration methods
Quasi mono-chromatic positron beam

Liquid Xenon Gamma-ray Detector
Better uniformity w/ 12x12 VUV SiPM

x2 resolution everywhere

Cobra magnet
Gradient B field up to 1.3 T

Muon Beam and target
Full available stopped beam intensity
7 x 10^7

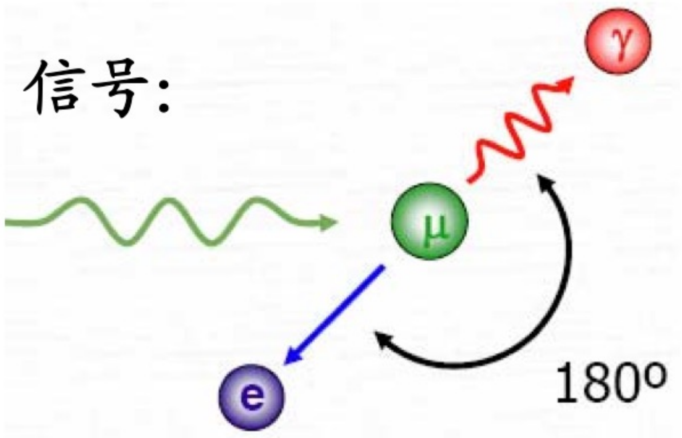
Drift Chamber
Single volume
$He:iC_4H_{10}$

Timing Counter
35 ps resolution w/ multiple hits

Auxiliary detectors
Background rejection

$\mu^+ \to e^+\gamma$衰变实验的局限性

$\mu^+ \to e^+\gamma$ 衰变：MEG实验@PSI

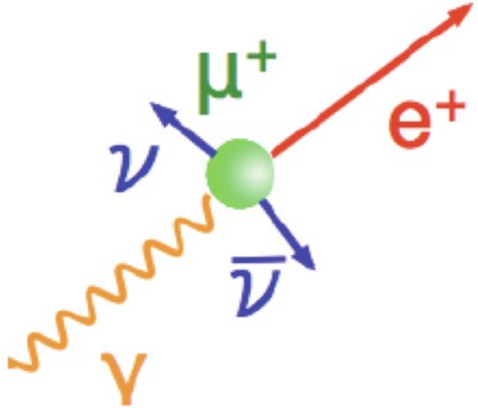


受到随机本底的限制，
提高束流强度无济于事，
最好的预期测量到 10^{-14}。

BR ($\mu \to e\gamma$) < 4.2x 10^{-13} at 90% C.L.
MEG: arXiv:1605.05081
MEGII预期： $4\text{x}10^{-14}$

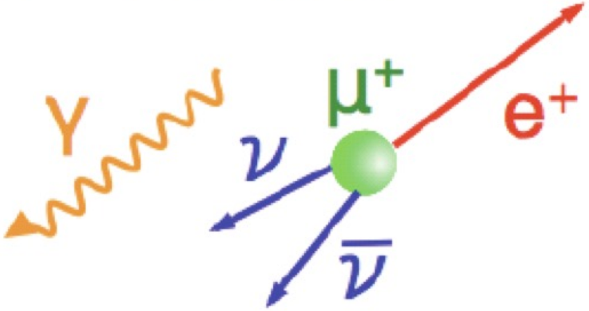
本底较大：

Radiative μ decay: $\mu \to e\nu\nu\gamma$



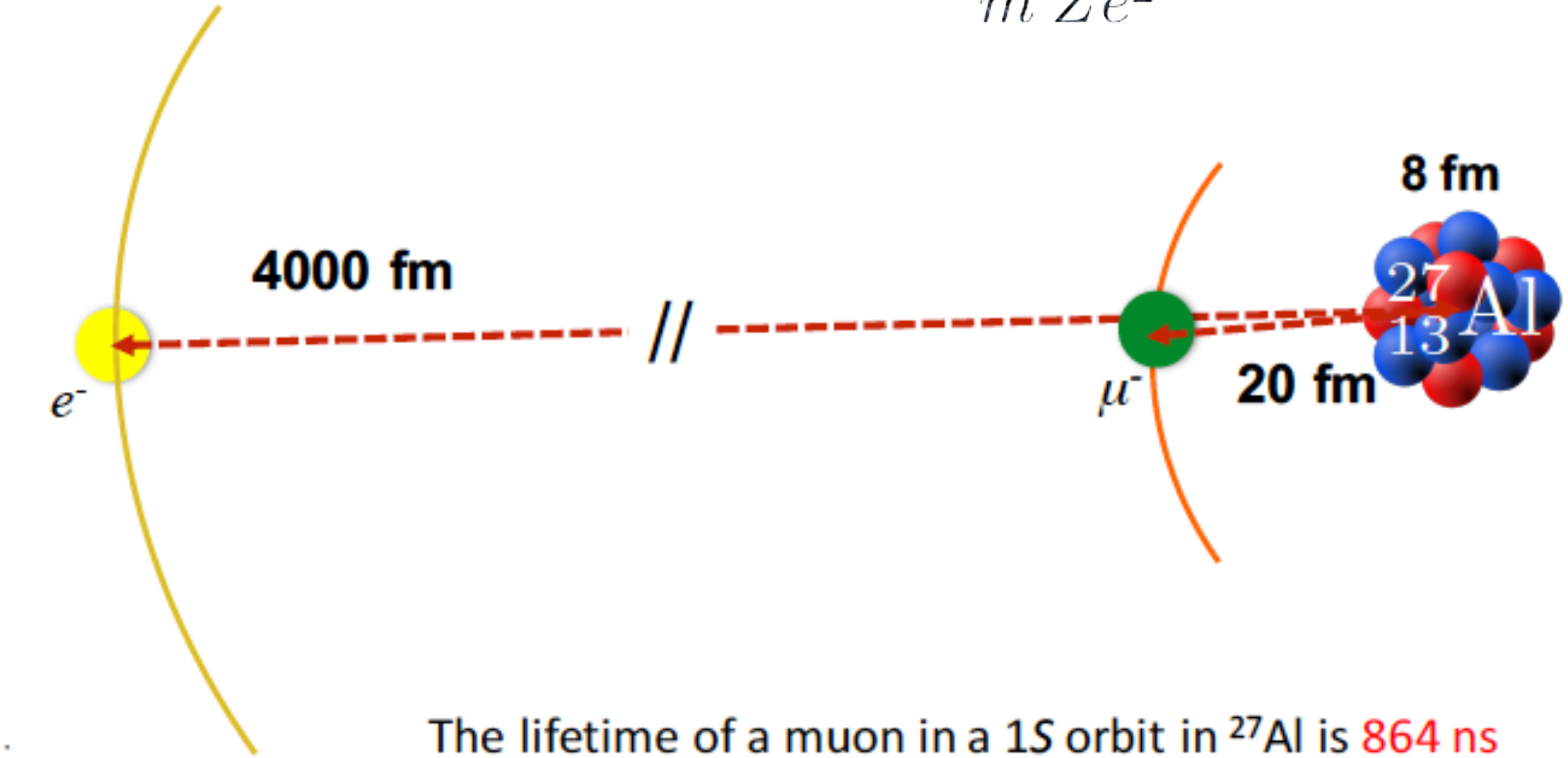
随机本底：

$\mu \to e\nu\nu$ + 随机γ光子



Muonic atoms

- A muon stopped in a target is captured in a high atomic orbit and then typically cascades quickly to the 1*S* ground state, emitting a series of X-rays
- The Bohr radius of the 1*S* ground state: $a_0 \sim \frac{1}{m} \frac{\hbar^2}{Ze^2}$

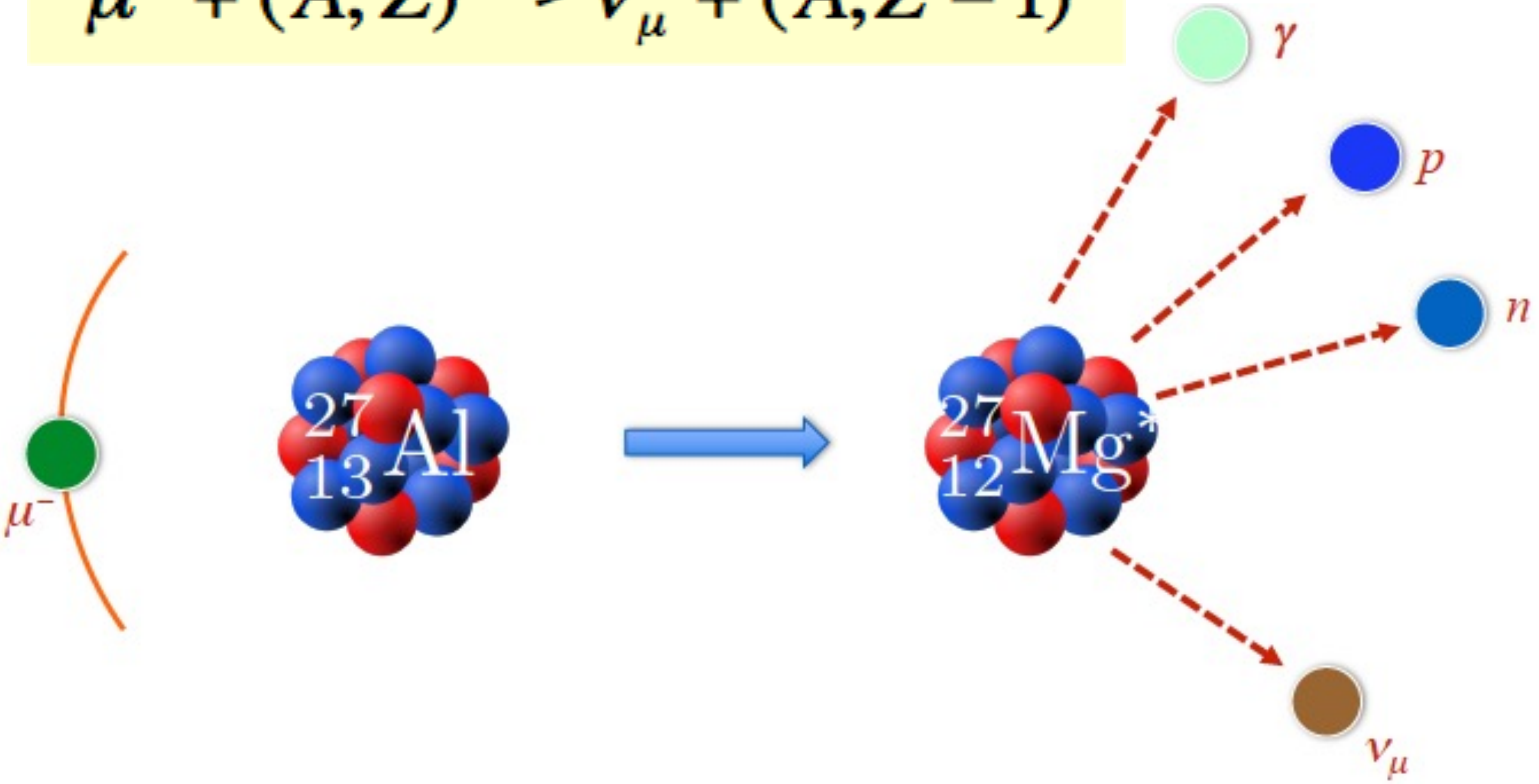


The lifetime of a muon in a 1*S* orbit in ^{27}Al is 864 ns

Muonic atoms

61% of 1S bound muons on Al undergo nuclear capture

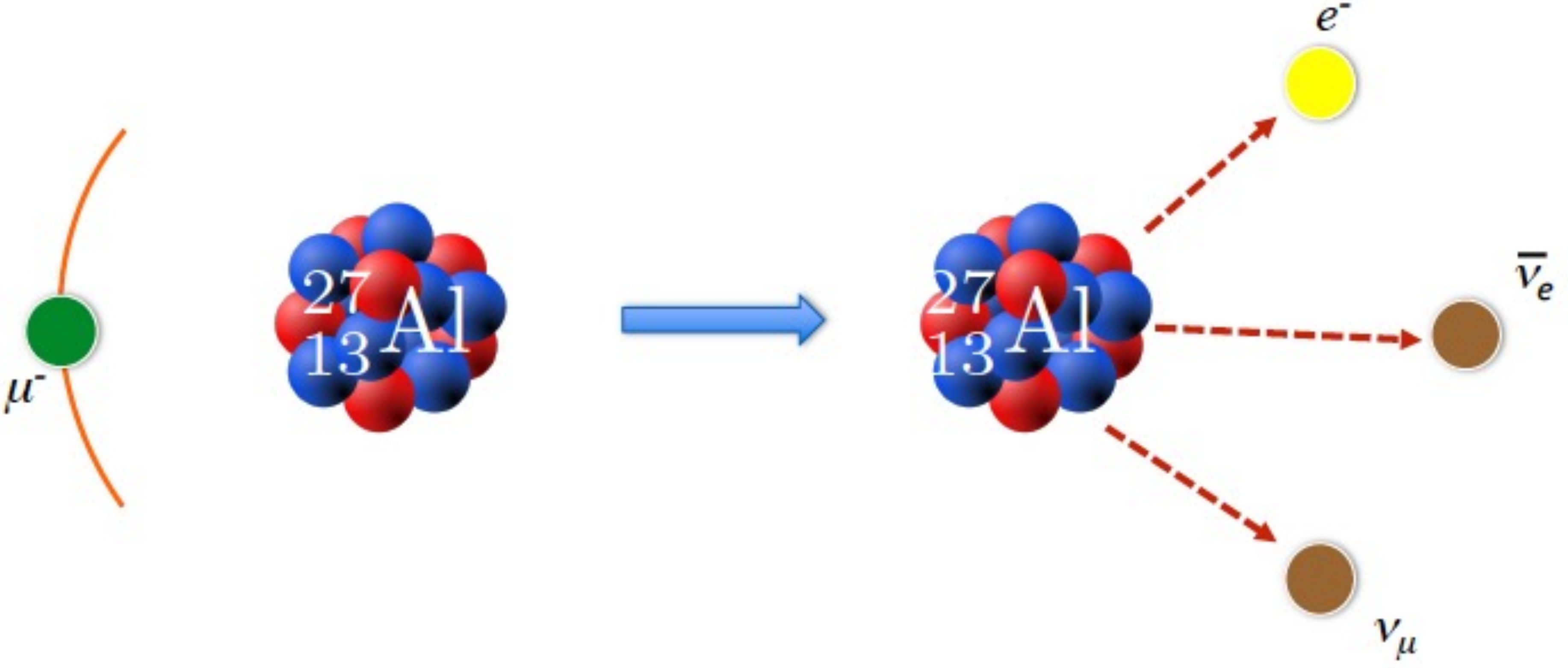
$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$



Muonic atoms

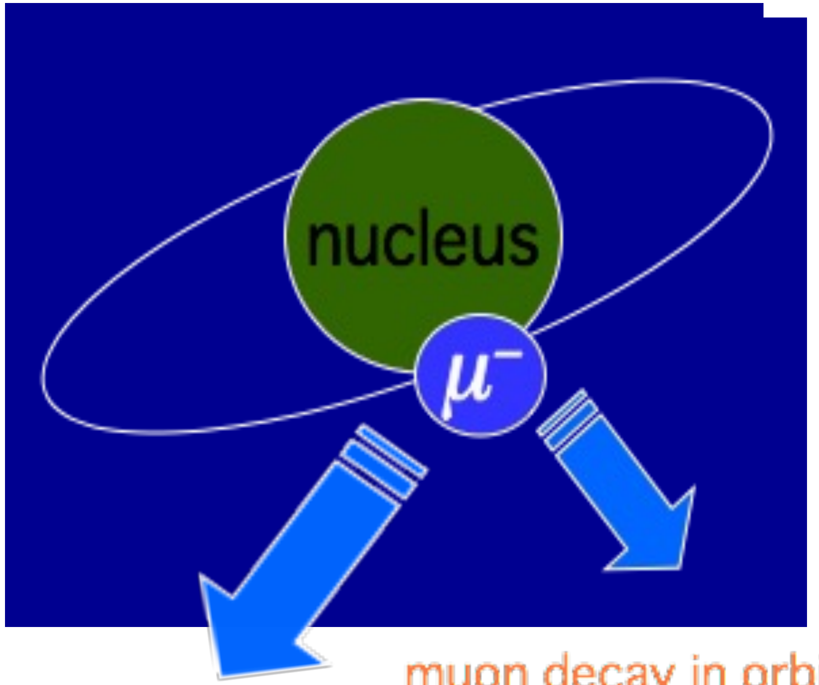
39% of 1S bound muons on Al decay, called Decay-In-Orbits (DIO)

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$



μ-e 转化过程

μ子原子基态



muon decay in orbit

In SM

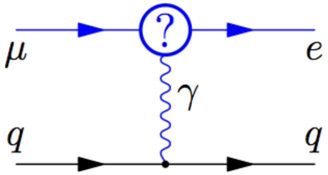
$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

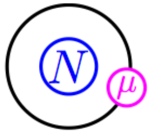
New Physics

Recoil off a nucleus

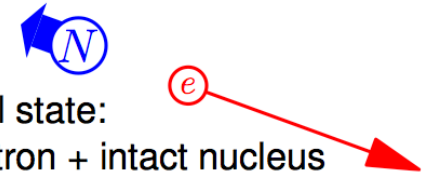


无中微子的μ子俘获

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$



Initial state:
muonic atom at rest



Final state:
electron + intact nucleus

- Kinematically allowed
- Violates lepton flavor conservation
- Signal is monoenergetic electron

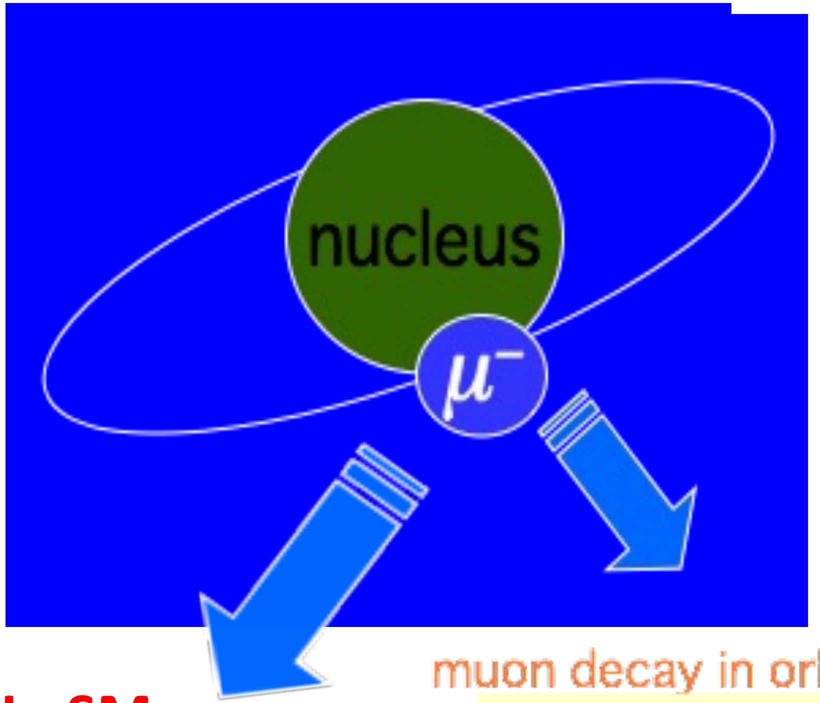
$$E_e = m_\mu - E_b - E_{\text{recoil}} \approx 104.97 \text{ MeV for Al}$$

- Conventional normalization to report results:

$$R_{\mu e} = \frac{\Gamma[\mu^- + N \rightarrow e^- + N]}{\Gamma[\mu^- + N \rightarrow \text{all captures}]}$$

μ-e 转化过程

μ子原子基态



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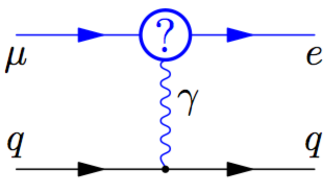
Recoil off a nucleus



无中微子的μ子俘获

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

信号事例特征：

105 MeV的单能单电子

主要本底：

(1) 物理本底

如在轨道衰变 (DIO)

(2) 束流相关本底

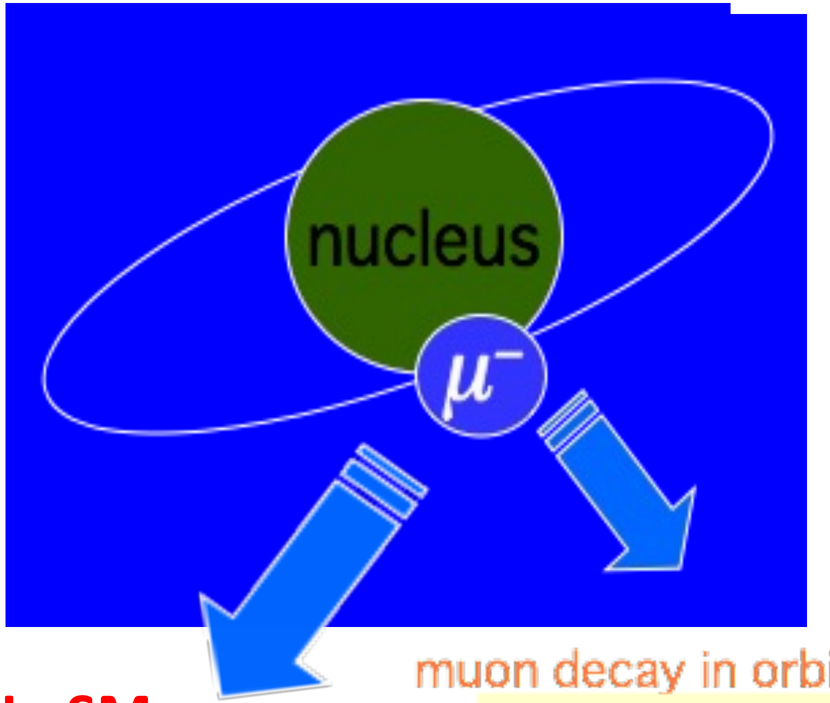
如π的辐射俘获，μ子飞行中衰变

(3) 偶发本底

如宇宙线，误寻迹

μ-e 转化过程

μ子原子基态



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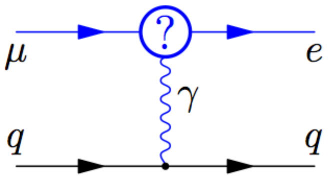
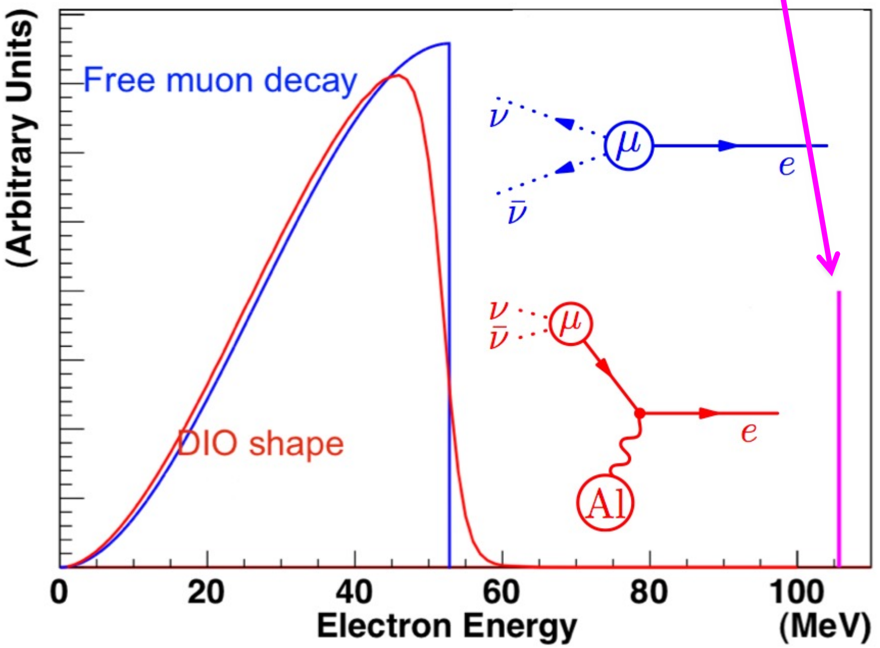
Recoil off a nucleus



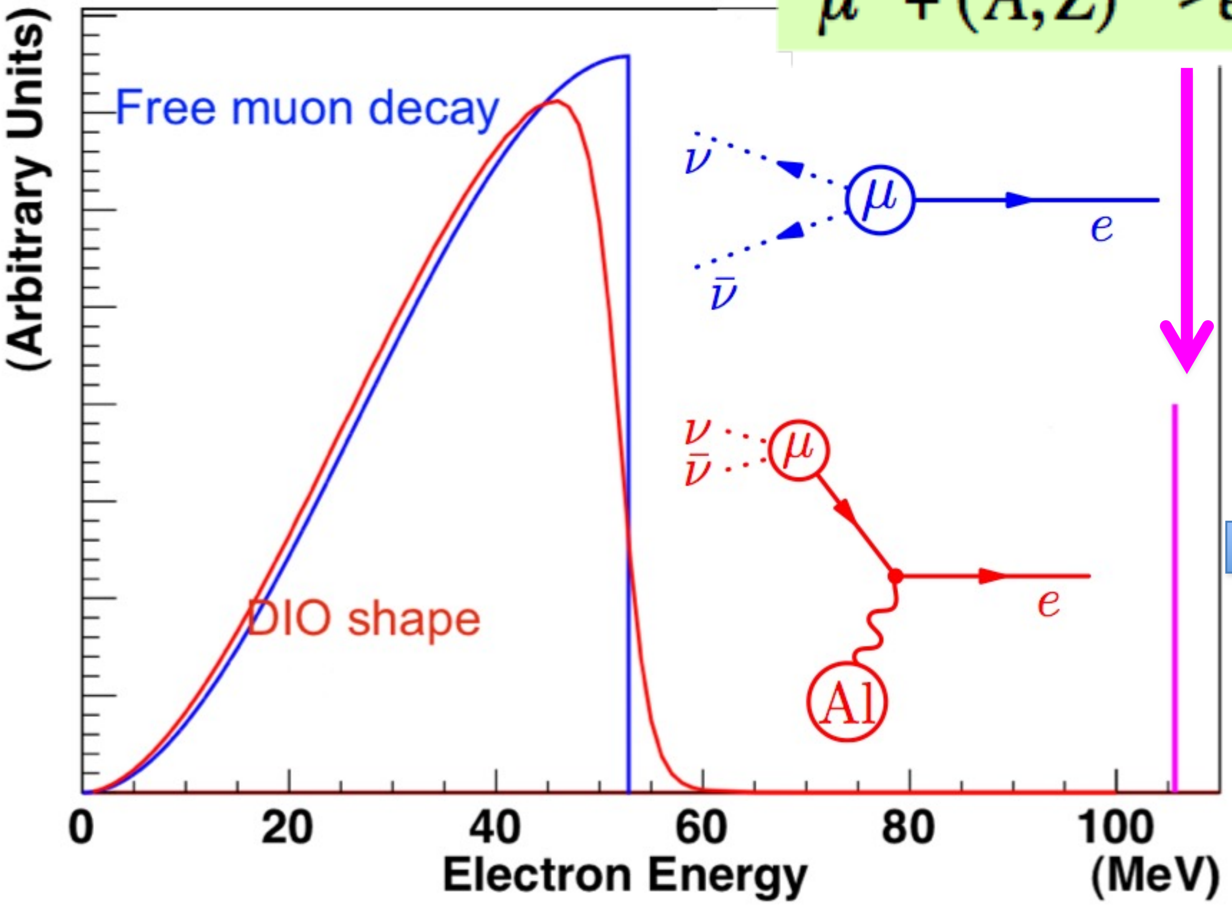
无中微子的μ子俘获

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

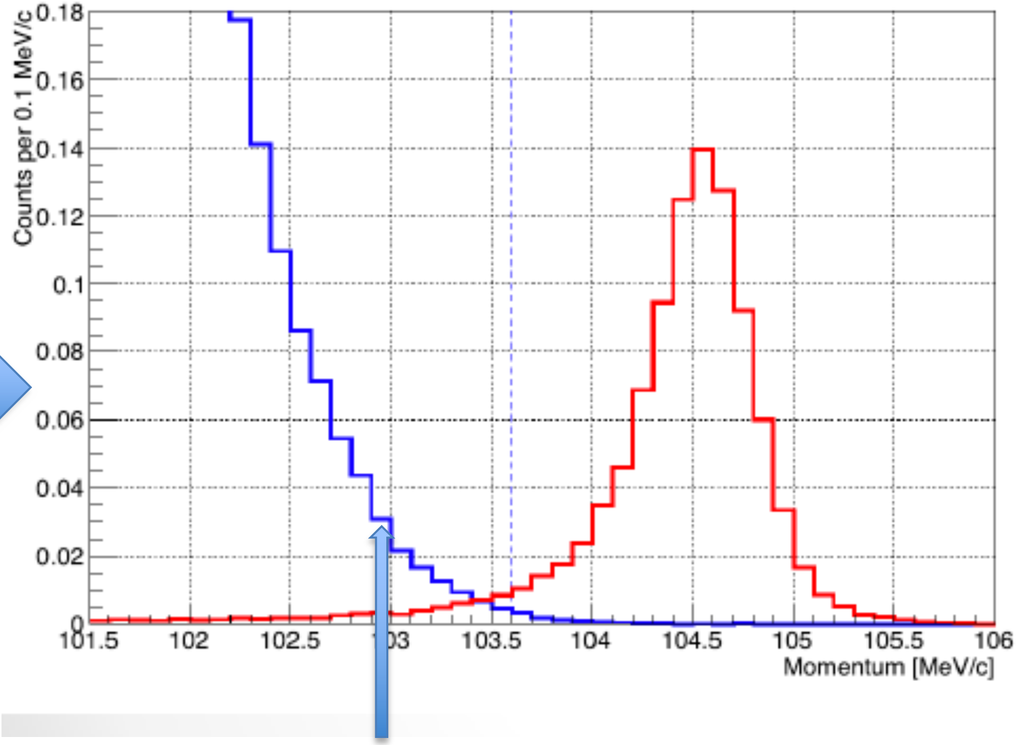


μ-e转化与μ子的Michel衰变可以很好地区分开

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$



考虑到探测器分辨后DIO本底会对信号有污染

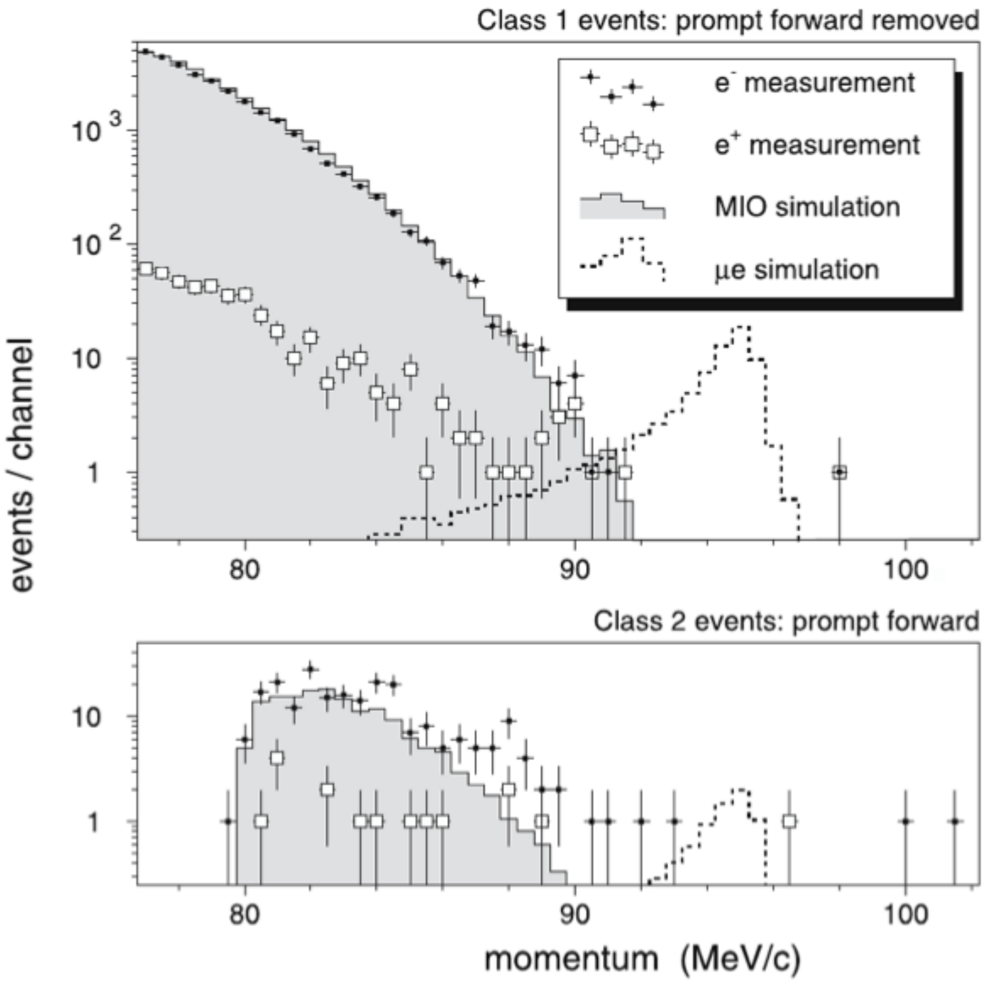


TWIST Collaboration PRD 80, 052012 (2009)

目前最好的 μN → eN 限制
SINDRUM II experiment at PSI

Conversion on gold:
$R_{\mu e} < 7 \times 10^{-13}$ 90% CL
[Eur.Phys.J C47(2006)]

Single event sensitivity
$S^1_{\mu e} = 2.5 \times 10^{-13}$



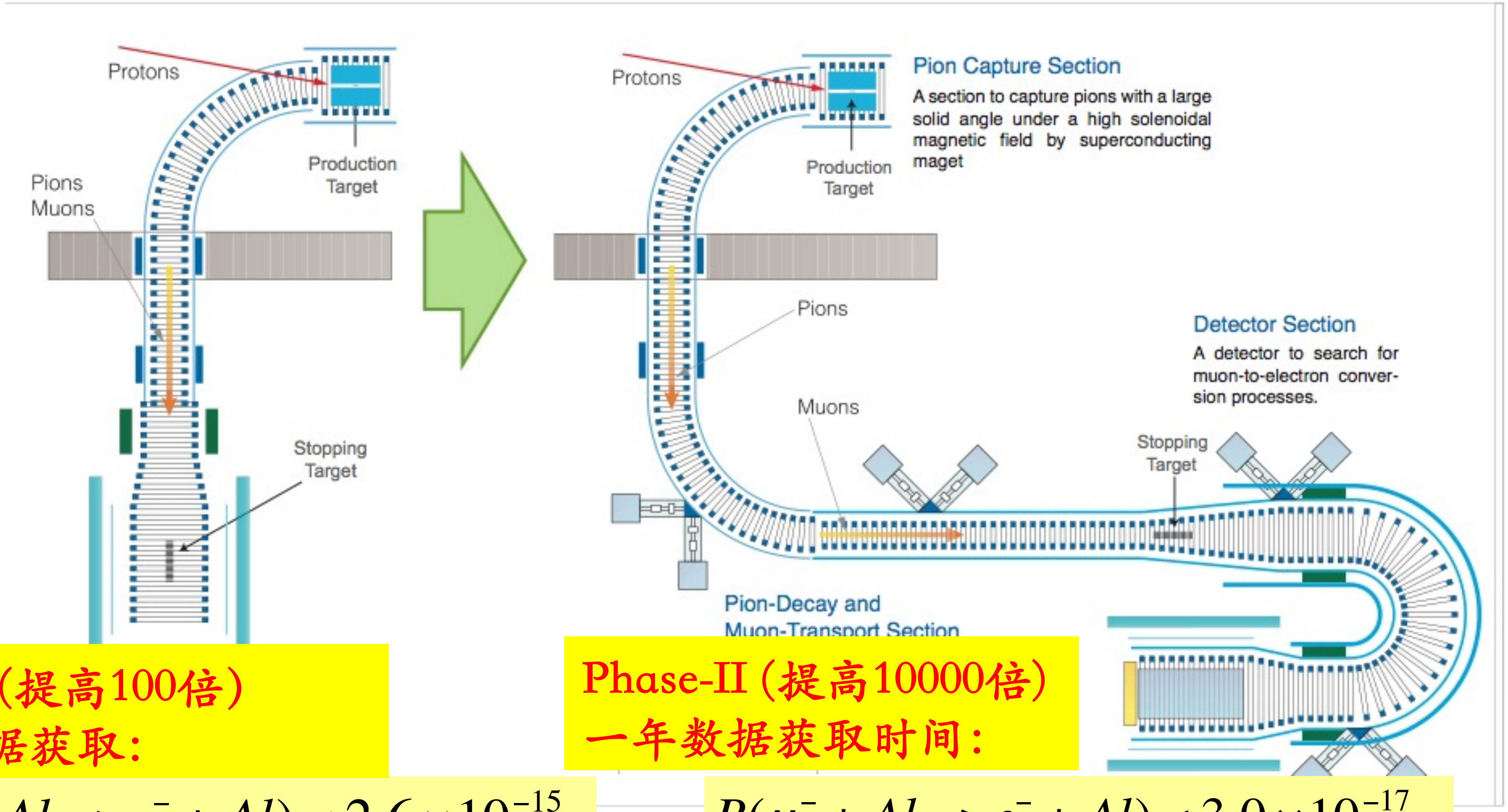
日本J-PARC COMET (E21) 实验

8 GeV, 0.4 mA, 3.2 kW：
石墨靶, 10^9 muon stops/s

8 GeV, 7.0 mA, 56 kW
钨靶, 10^{11} muon stops /s

COMET Phase-I

COMET Phase-II



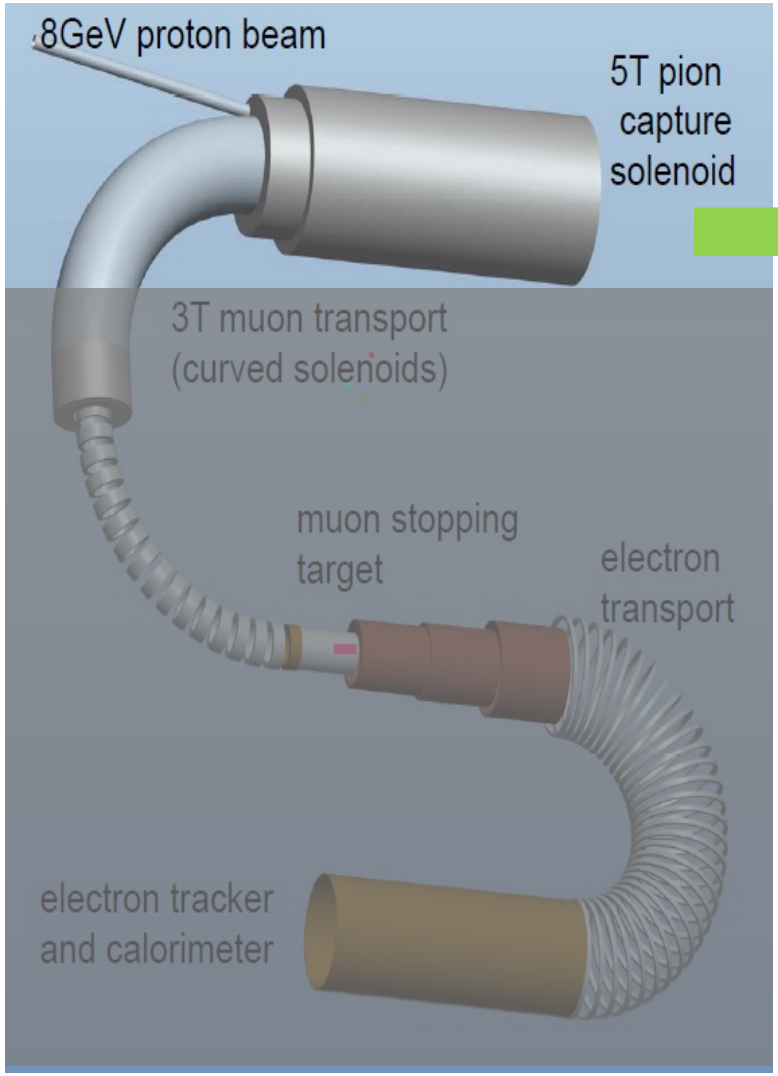
Phase-I (提高100倍)
半年数据获取：

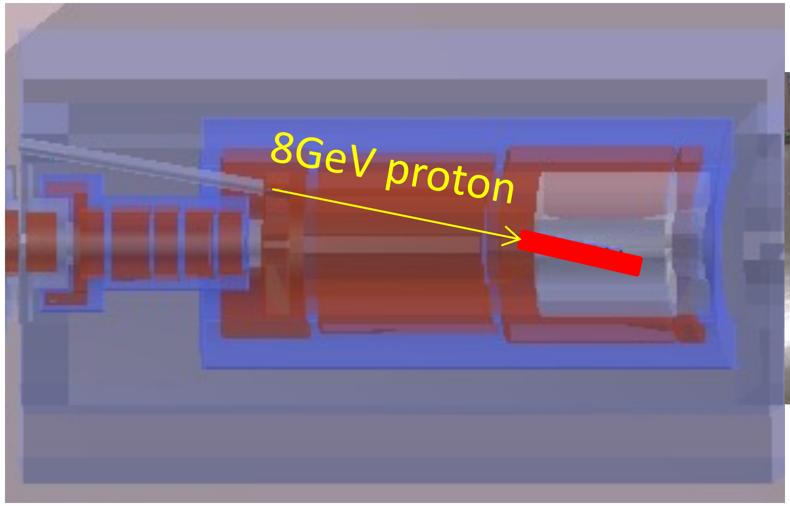
$$B(\mu^- + Al \to e^- + Al) < 2.6 \times 10^{-15}$$

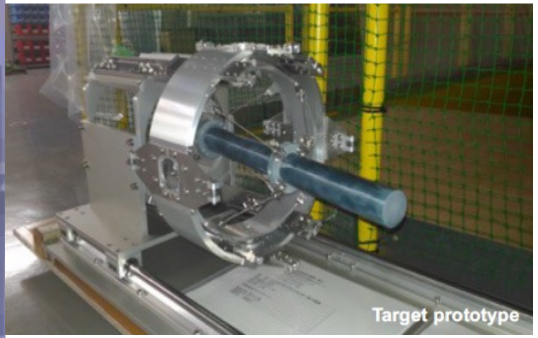
Phase-II (提高10000倍)
一年数据获取时间：

$$B(\mu^- + Al \to e^- + Al) < 3.0 \times 10^{-17}$$

Production target and the capture magnet





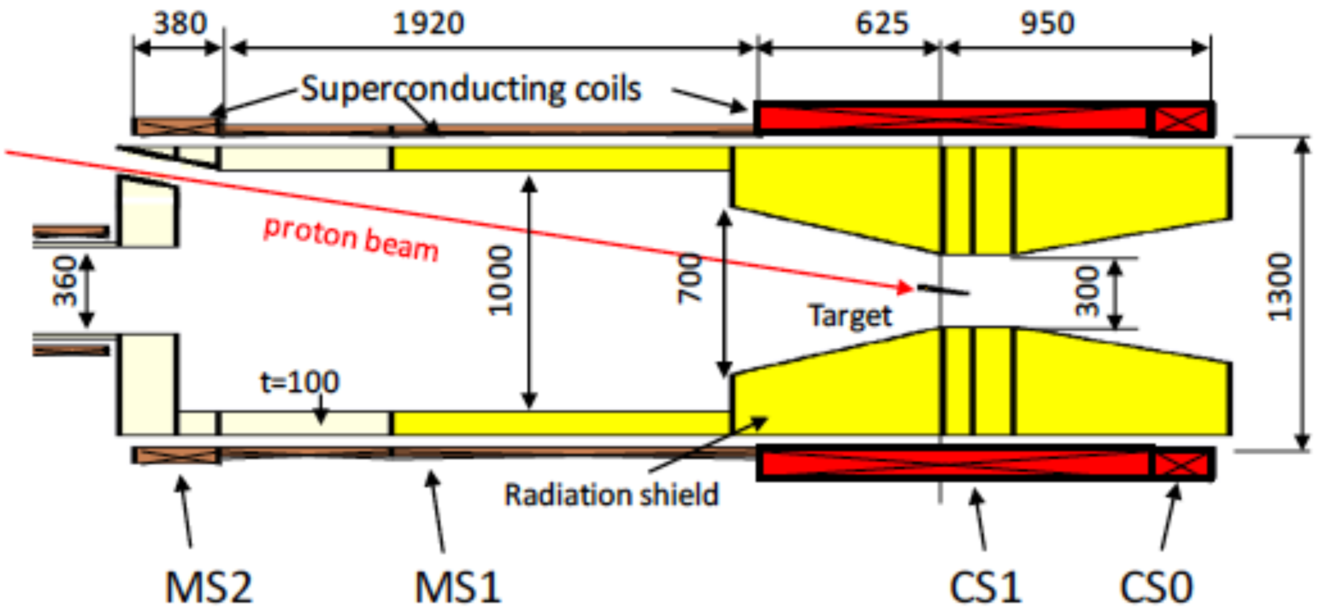


- 8 GeV 56 kW proton beam
- Thick target with 1~2 hadron interaction length
- Powerful capture magnet: 5 T
  - Large inner bore to fit in the shielding
  - Adiabatic decreasing field: focusing
- Expected muon yield: 10^{11} muon/sec! $(10^8\ @\ PSI)$

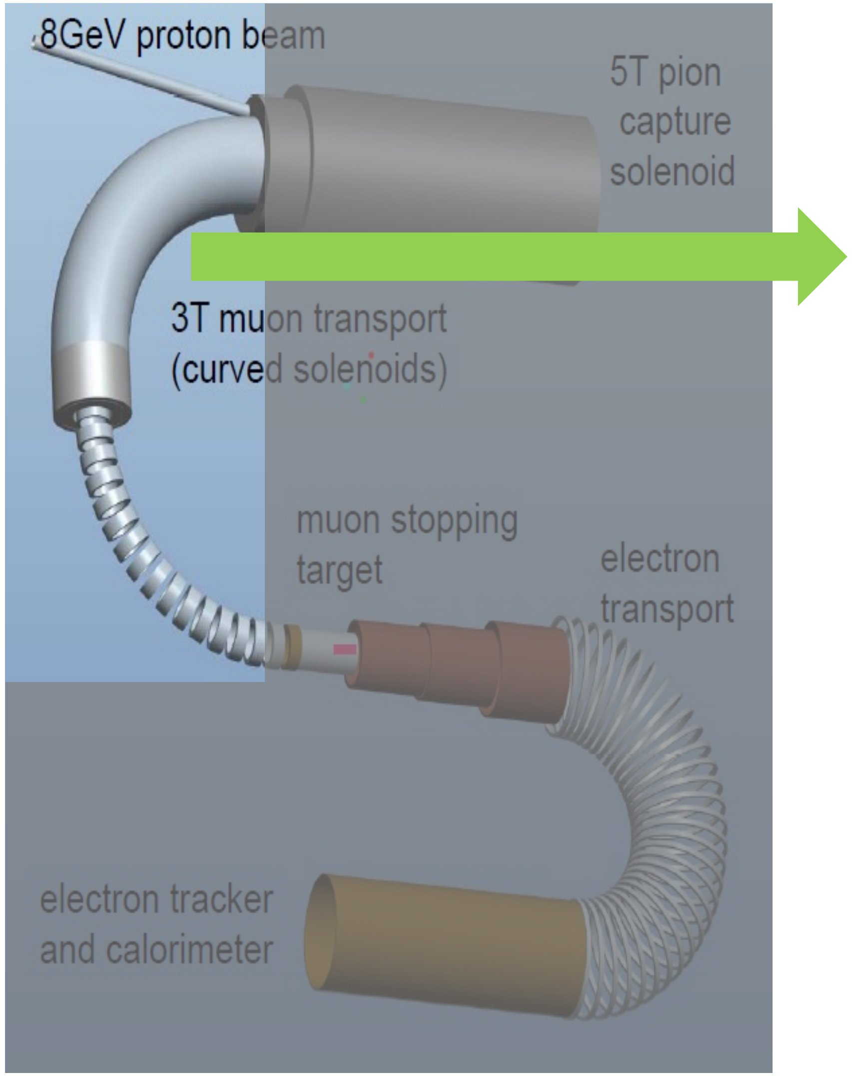
COMET capture solenoid

- Superconducting solenoid magnets with Al-stabilized conductor
- High field 5T to capture π^-
- Large bore 1300mm
- High radiation environment
- Decreasing field to focus trapped pions
- Thick radiation shielding 450mm
- Proton beam injection tilted at 10°
- Simple mandrel

	CS0	CS1	MS1	MS2
Length (mm)	175	1350	1800	380
Diameter (mm)	662	662	662	662
Layer	9	9	5	8
Thickness (mm)	144	144	80	128
Current density (A/mm²)	35	35	35	35
Maximum field (T)		5.7	4.0	3.9
Hoop stress (MPa)		59	51	30

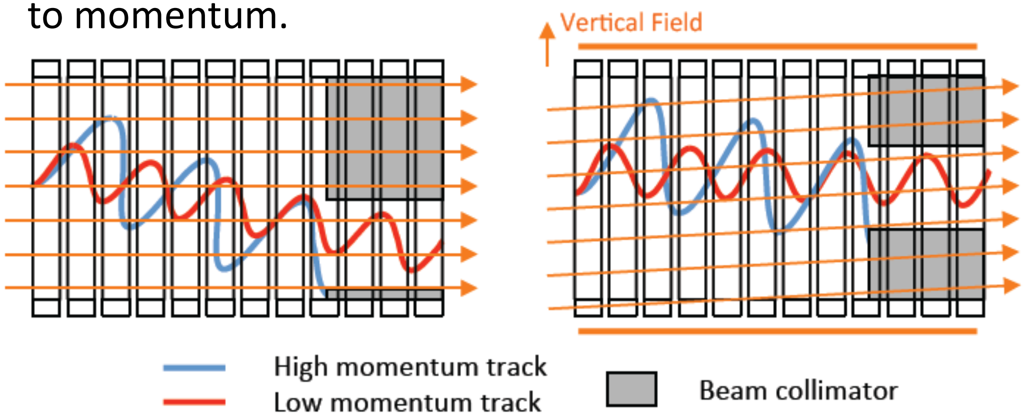


Transportation solenoid



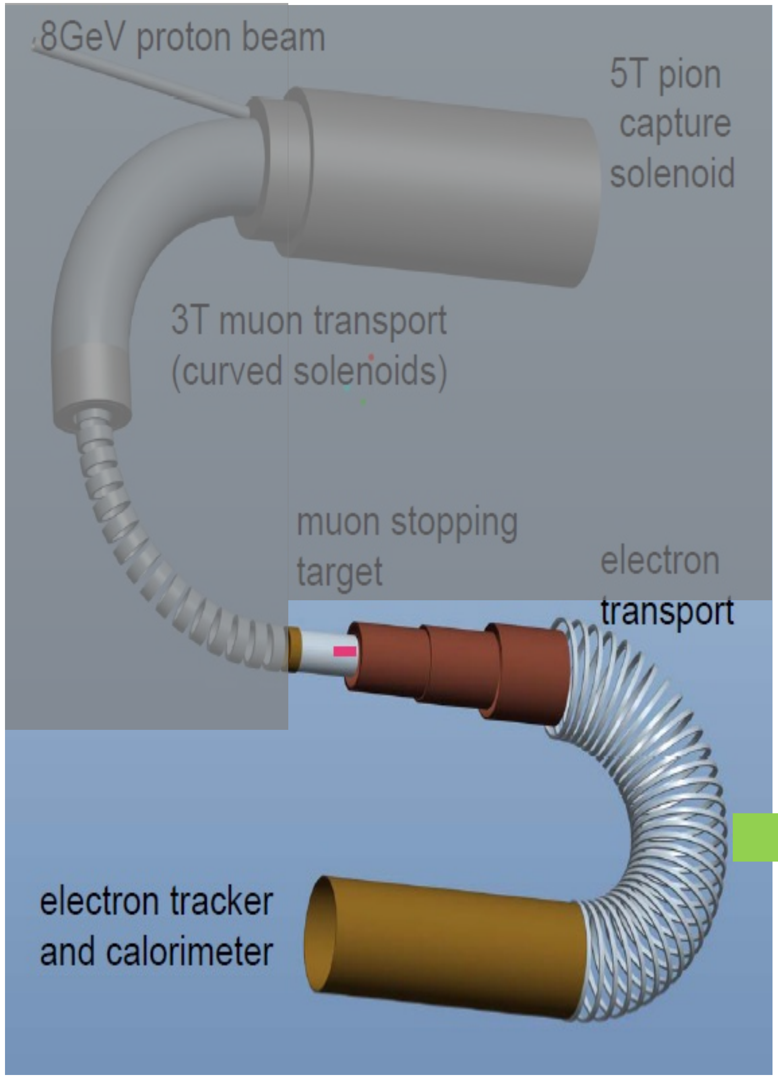
Drift vertically, proportional to momentum.

Vertical field as "correction"

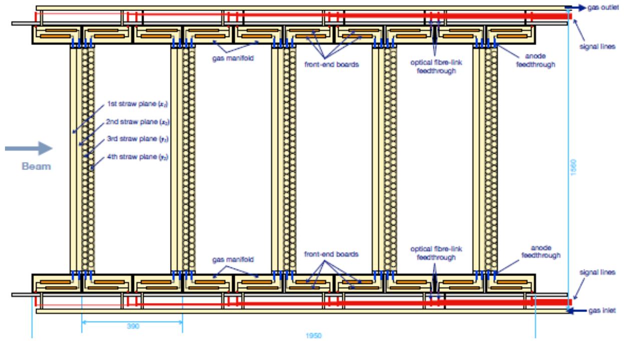


- Use **C shape** curved solenoid
  - Beam gradually disperses
    - Charge & momentum
  - Dipole field to pull back muon beam
    - Can be used to tune the beam
  - Collimator placed in the end
    - Utilize the dispersion in 180 degrees

COMET Phase-II: 探测器系统



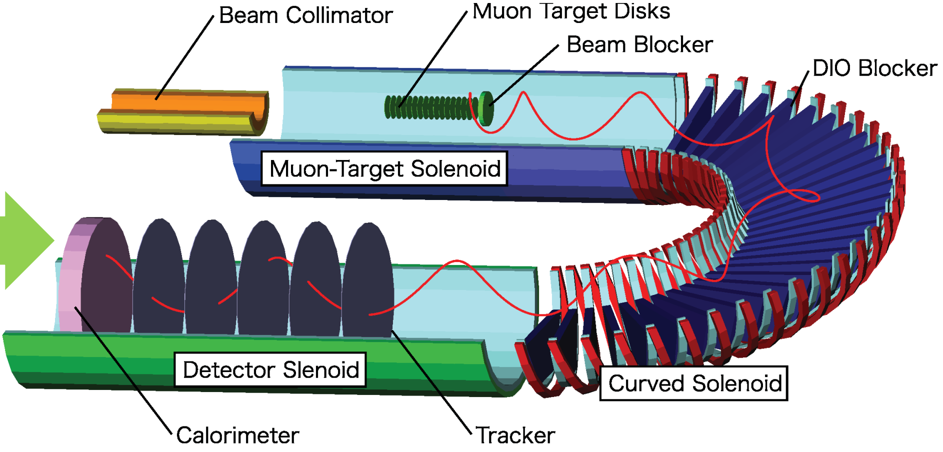
- Use straw tracker to measure the momentum
  - Really light: put in vacuum, **12 micro** meter thin straw



Tracker with Straw-tubes

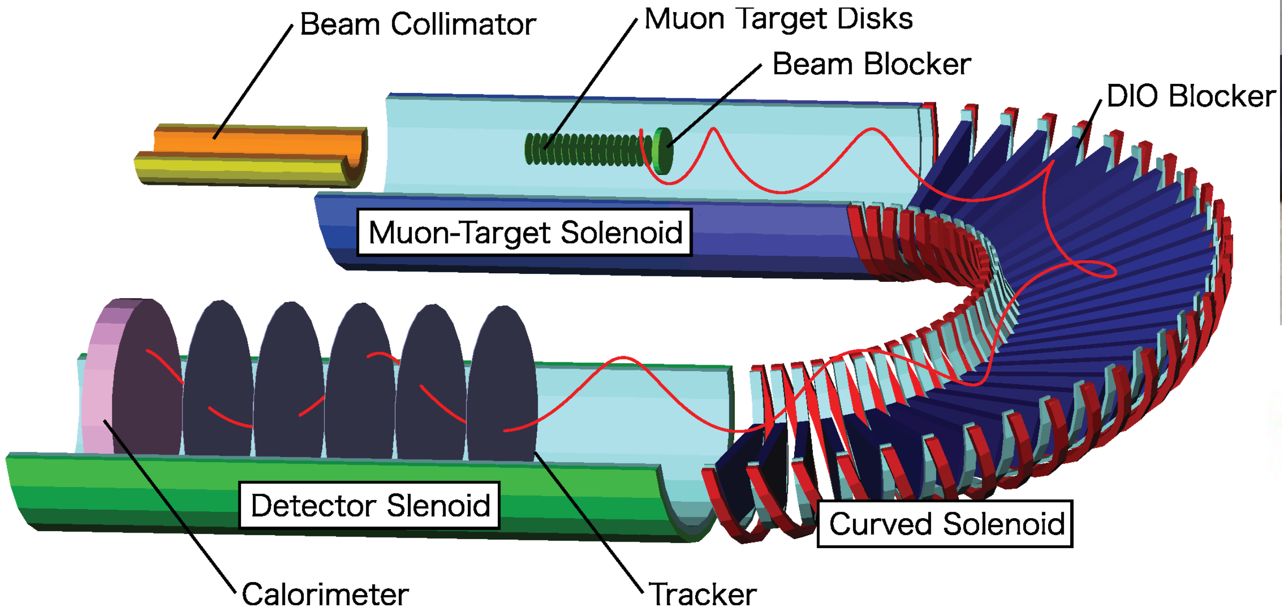
- ➢ Operational in vacuum in 1T
- ➢ Δp = 150~200 keV/c (for p=105 MeV/c)
- ➢ Straw tube
  - 20 µm thick, 9.75 mm diameter for Phase-I
  - 12 µm thick, 5 mm diameter for Phase-II
- ➢ More than 5 stations (xx'yy'>5)
- ➢ Ar:C_2H_6 (50:50)

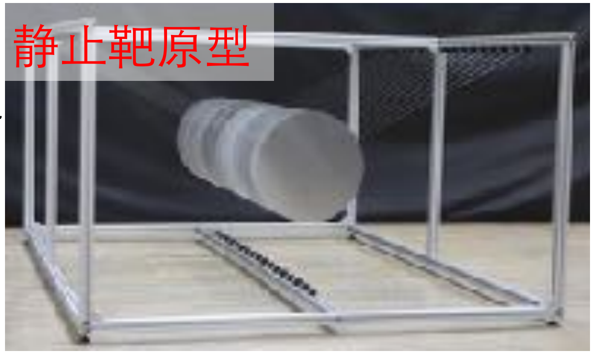
- Electromagnetic calorimeter
  - Providing trigger, TOF and PID

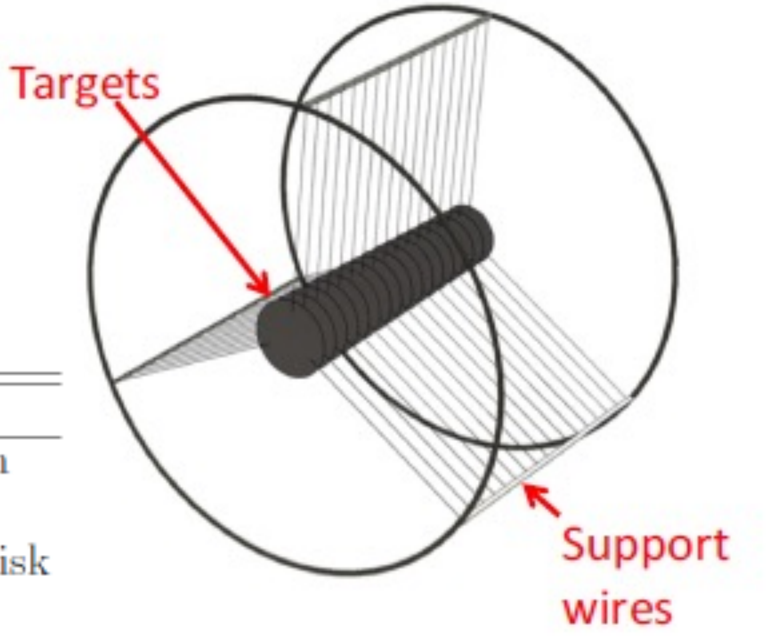


- ➢ 1,920 LYSO crystals
  - 2×2×12 cm (10.5 radiation length)
- ➢ ΔE/E = 5% (for E=105 MeV)
- ➢ 40-ns decay time
- ➢ APD + read-out(EROS)

COMET muon 停止靶







- 缪子停留在静止靶内。
- 束流通过另一端C型螺线管进行筛选
- 探测器系统位于C型螺线管的另一端。

Item	
Material	aluminium
Shape	flat disk
Radius	100 mm disk
Thickness	200 µm
Number of disks	17
Disk spacing	50 mm

从SINDRUM-II实验到COMET & Mu2e
J-PARC　Fermi Lab

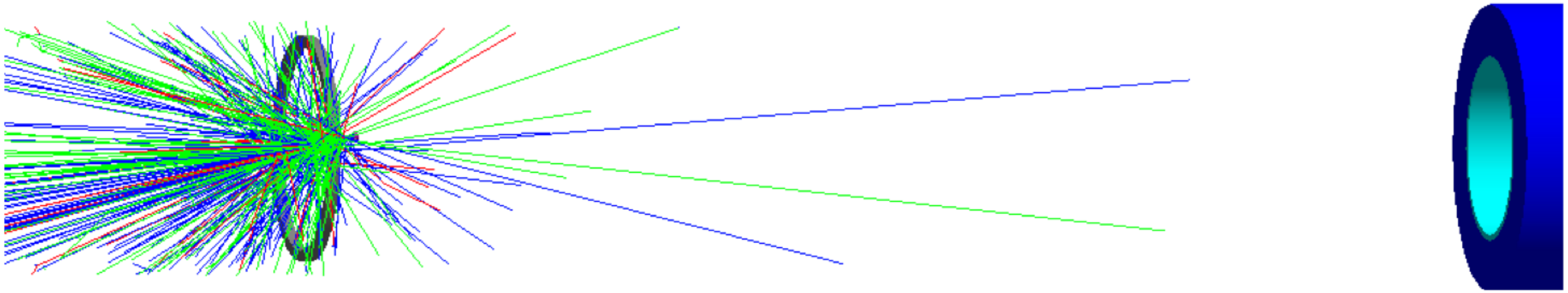
COMET & Mu2e实验单事例灵敏度：1.0 (2.5) $\times 10^{-17}$
比SINDRUM-II实验敏感度提高一万倍!
需要 $\mathcal{O}(10^{18})$ muons stopped per year，也就是
10^{11} muons stopped / sec.
（对应需要8.5 $\times 10^{20}$ 打靶质子/年）

而目前SINDRUMII实验: $\mathcal{O}(10^{8})$ muons stopped/second
一千年的数据获取.

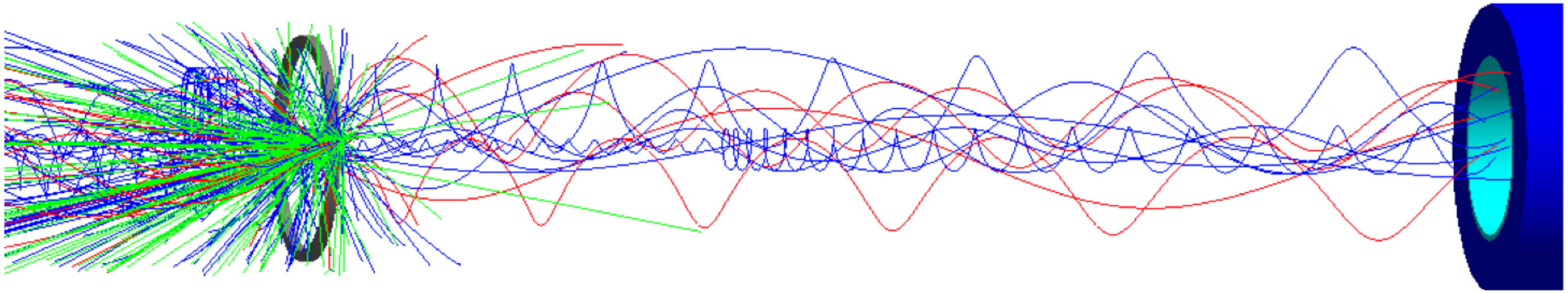
提高muon 流强方案

R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys **49**, 384 (1989)

Instead of this



Do this

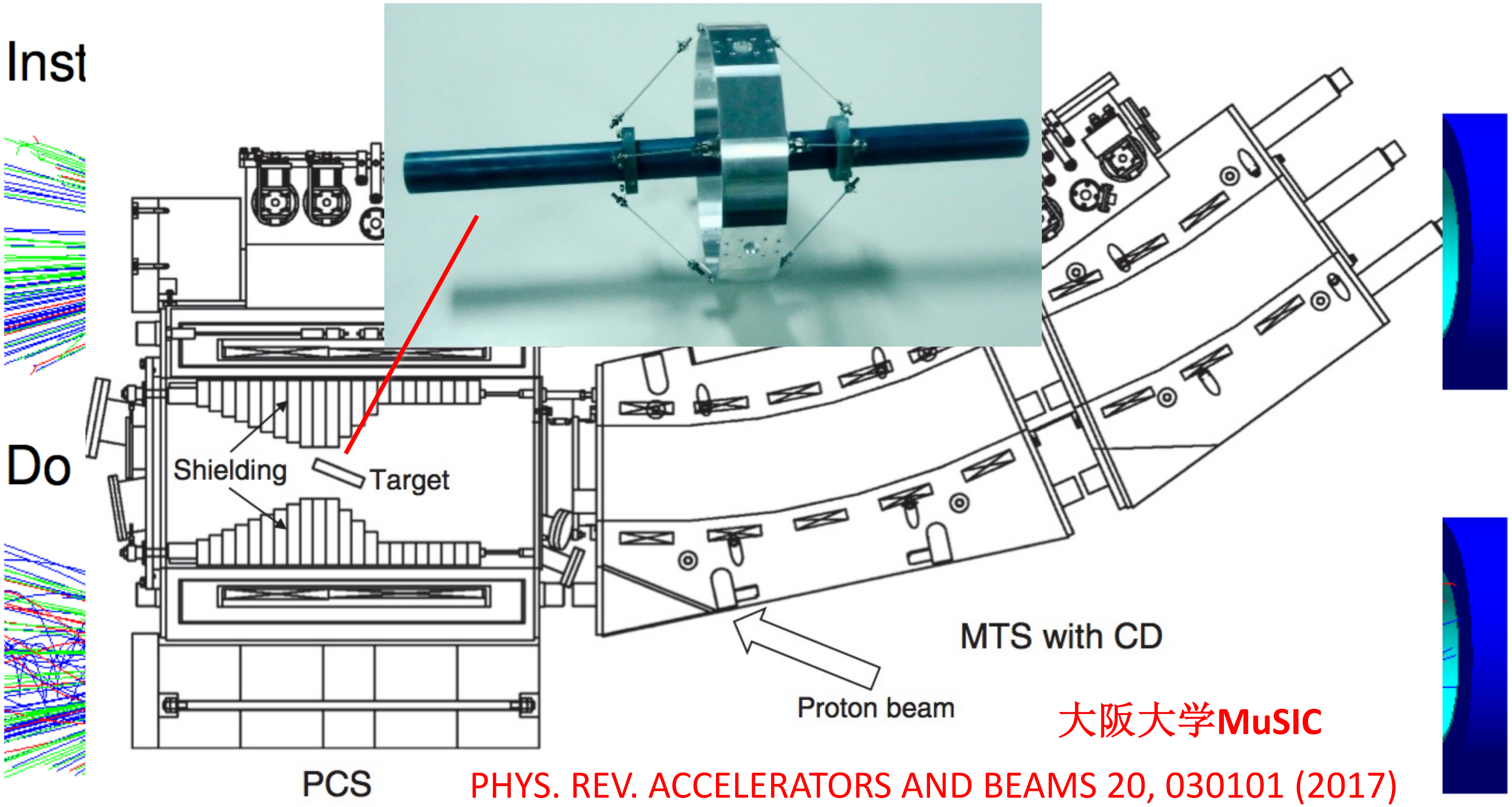


螺线管型超导磁场聚焦软pion介子，收集muon轻子

COMET： 10^{11} muon/s for 54kW of protons

提高muon 流强

R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys **49**, 384 (1989)

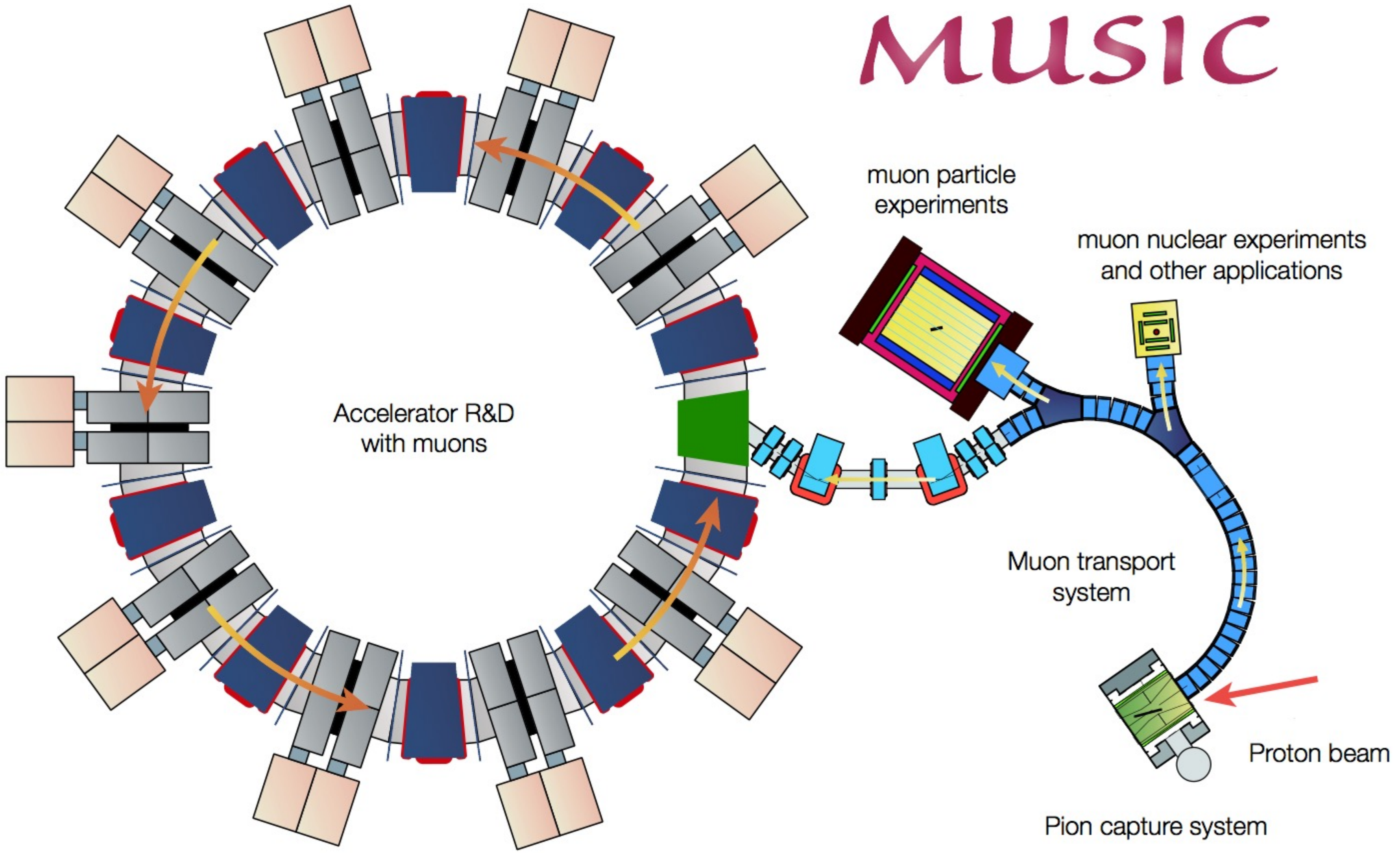


PHYS. REV. ACCELERATORS AND BEAMS 20, 030101 (2017)

螺线管型超导磁场聚焦软pion介子，收集muon轻子

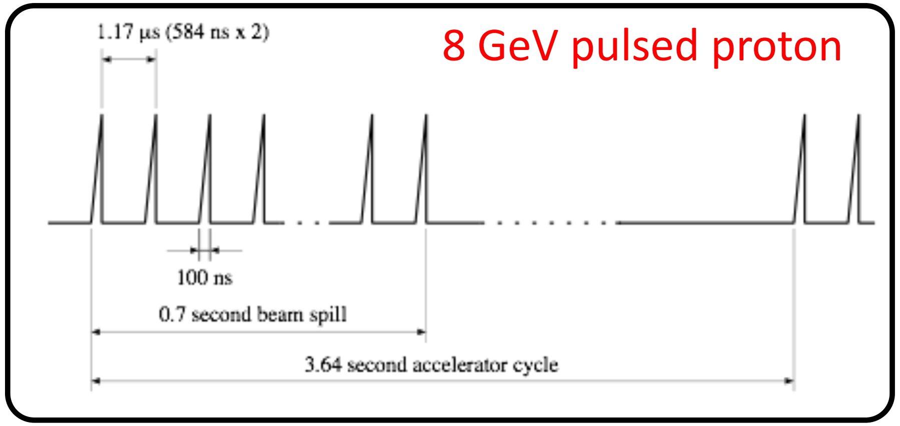
COMET： 10^{11} muon/s for 54kW of protons

大阪大学：MuSiC



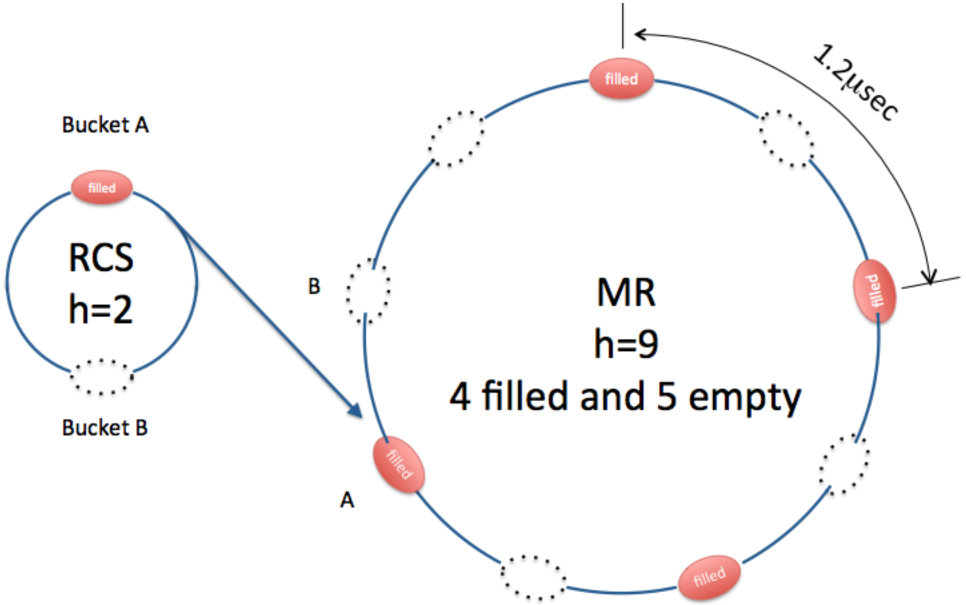
muon particle experiments
muon nuclear experiments and other applications
Accelerator R&D with muons
Muon transport system
Proton beam
Pion capture system

COMET实验需要的质子束流时间结构



TWIST Collaboration PRD 80, 052012 (2009)

τ(muonic Al)=0.865μs



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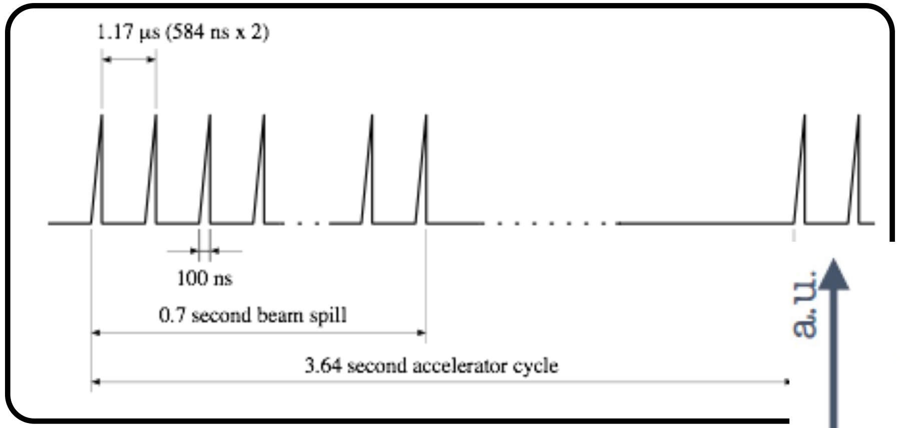

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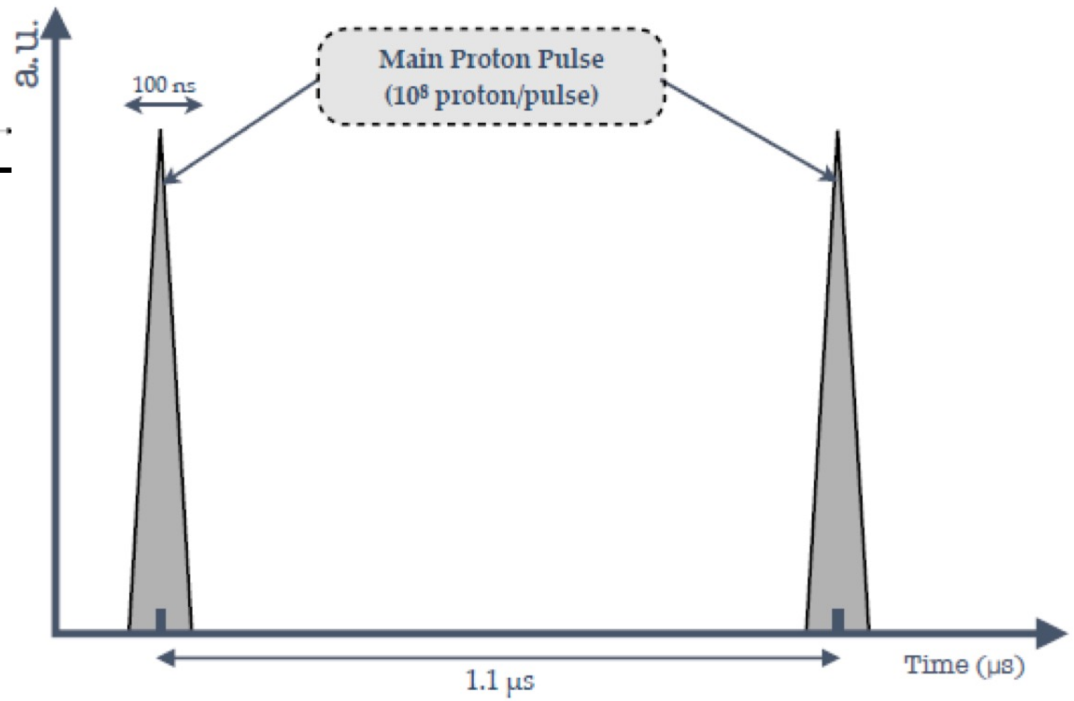

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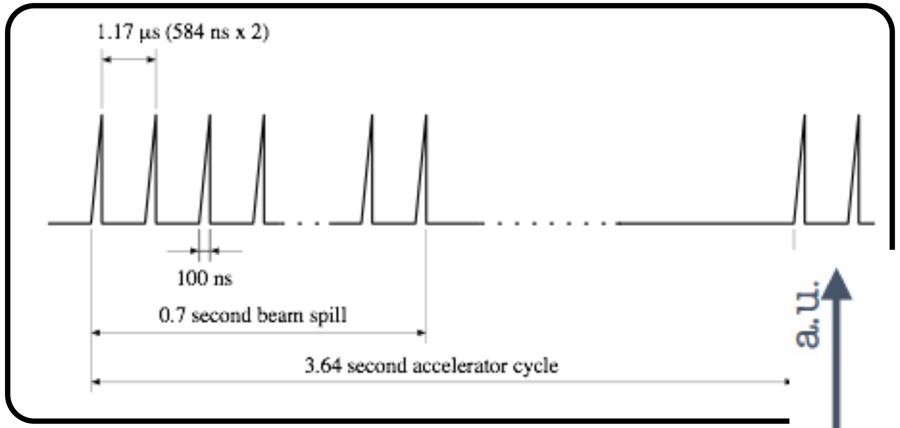

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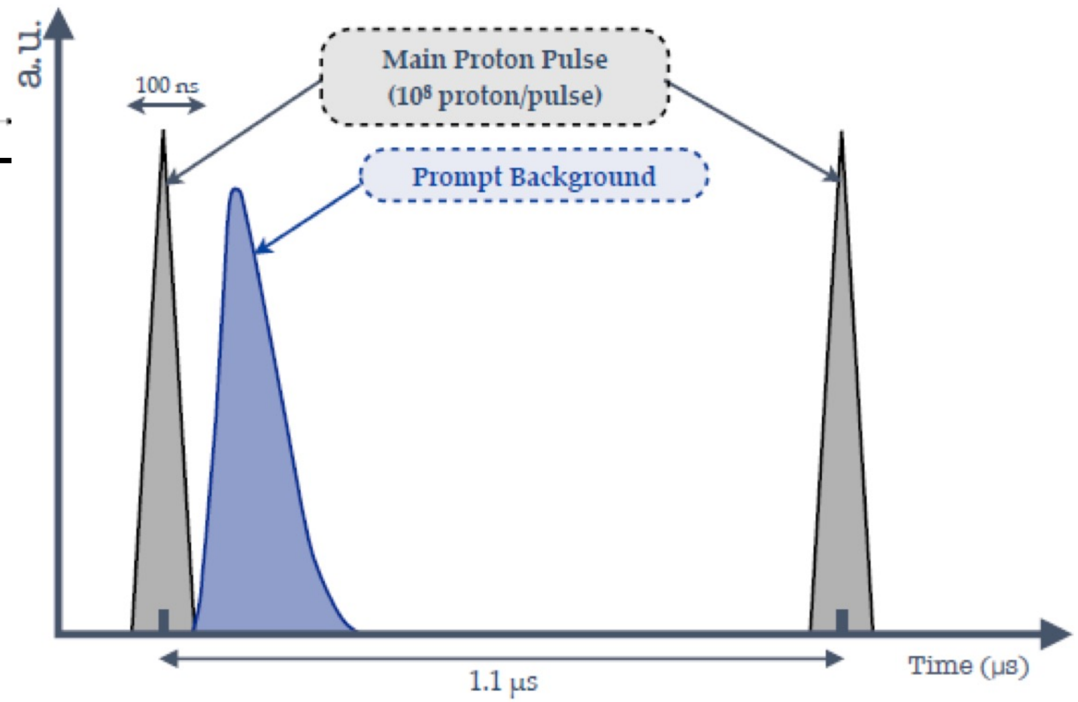
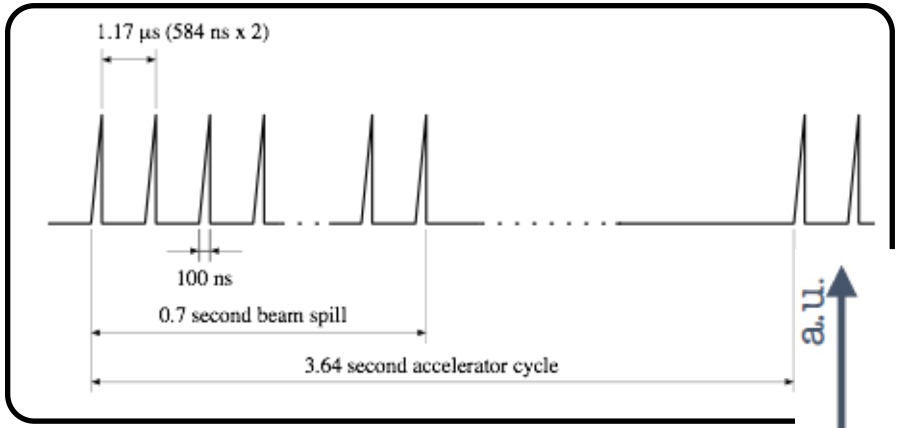


COMET实验需要的质子束流时间结构



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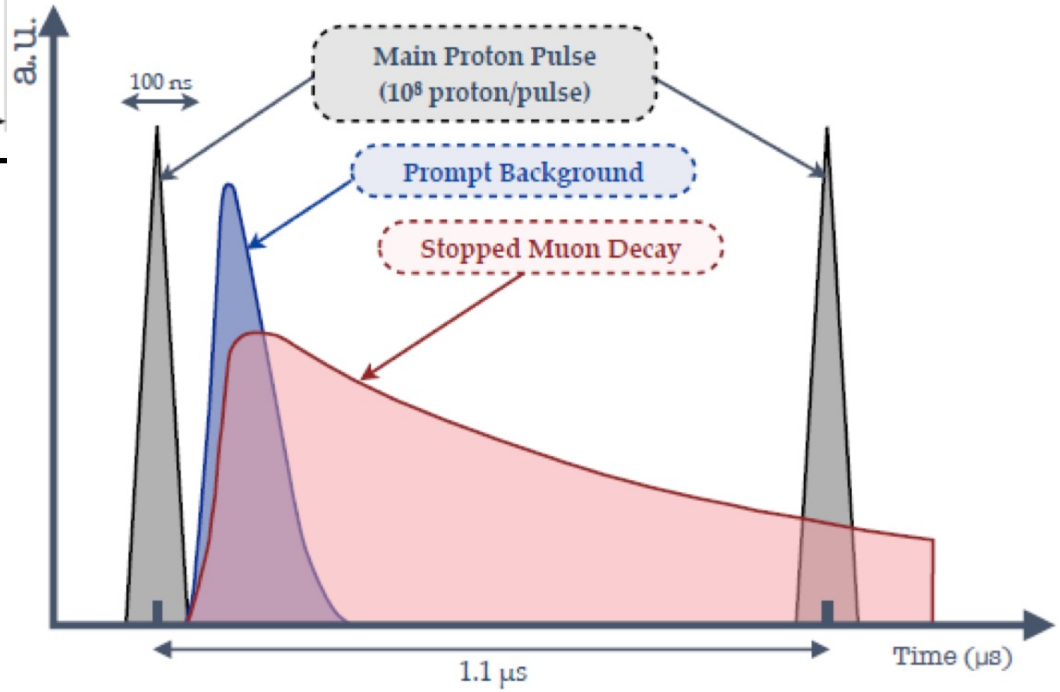

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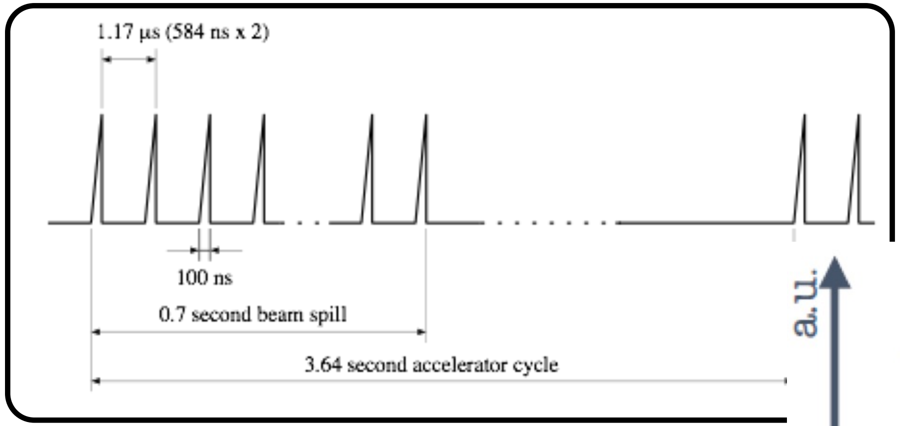

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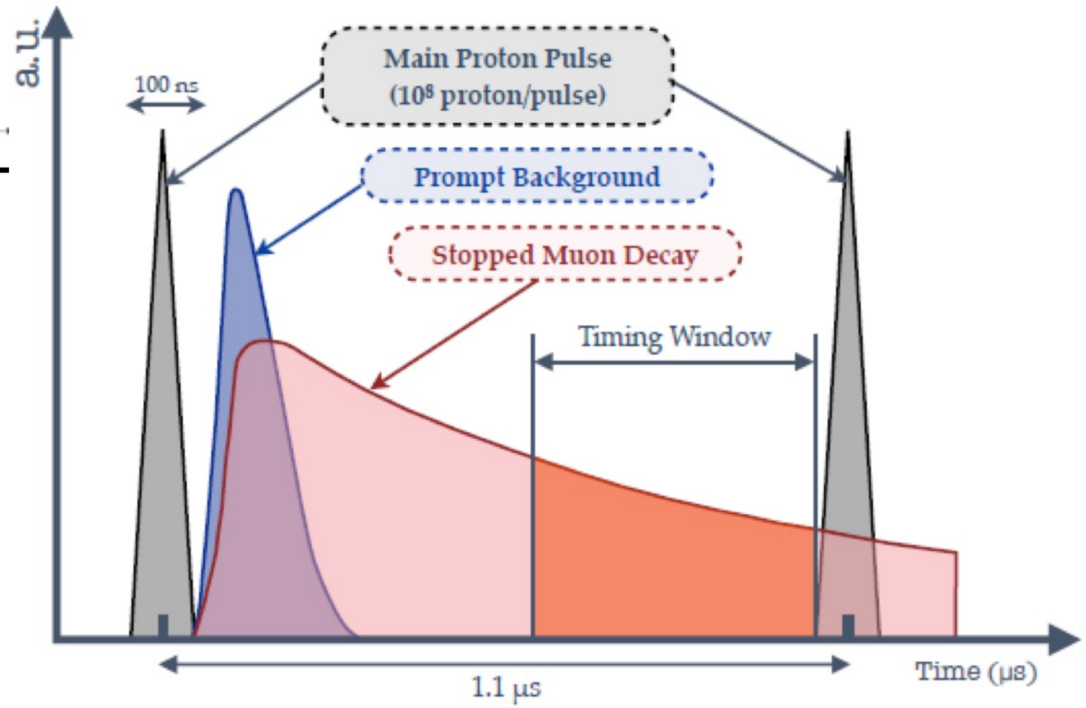
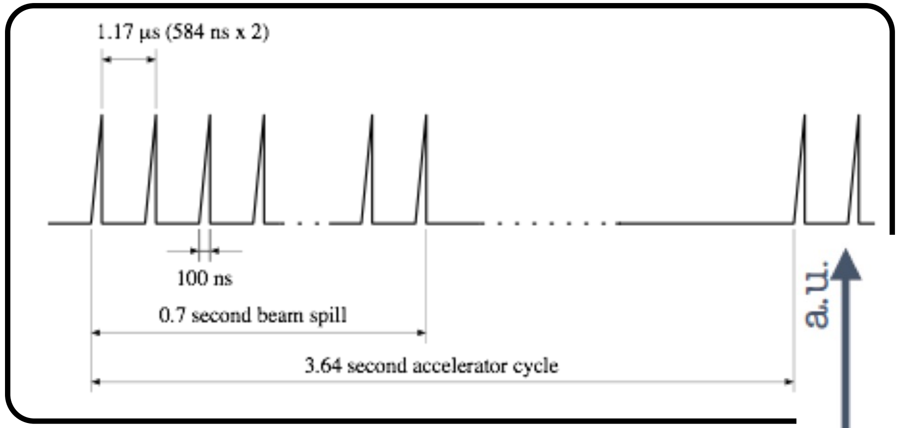


COMET实验需要的质子束流时间结构



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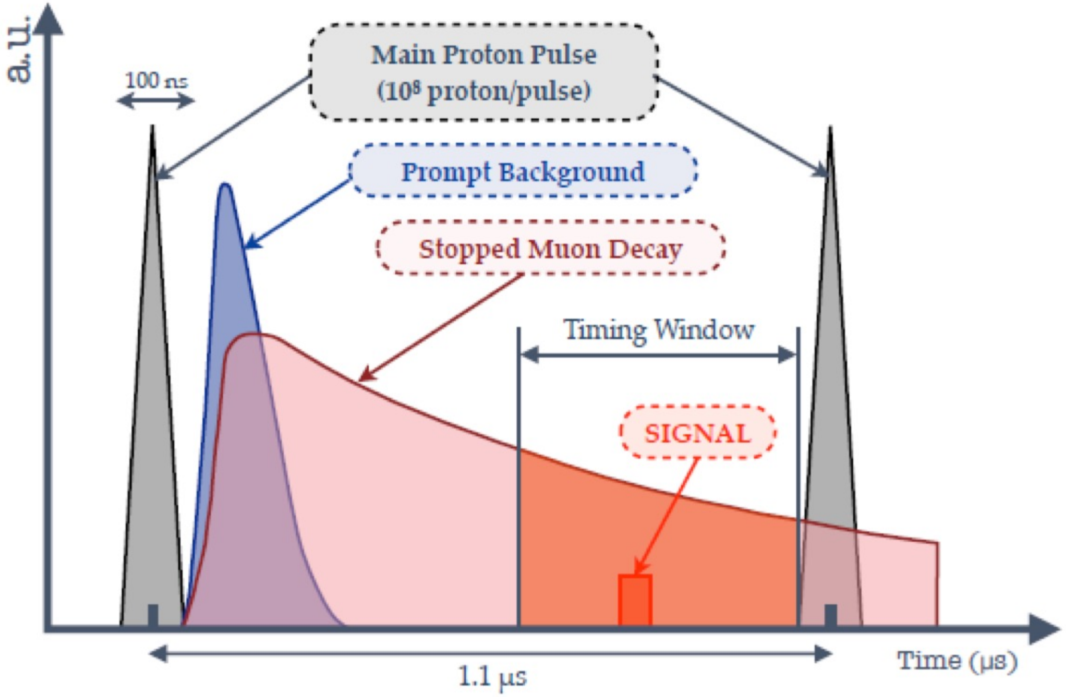


质子绝止率

$$R_{extinction} = \frac{N\ of\ protons\ between\ the\ pulses}{N\ of\ protons\ in\ the\ pulse}$$

$$R_{extinction} \sim 10^{-11}$$

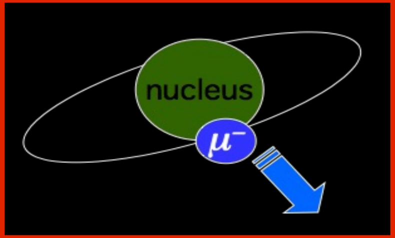
J-PARC: COMET Phase-I实验

Coherent Muon to Electron Transition (COMET)

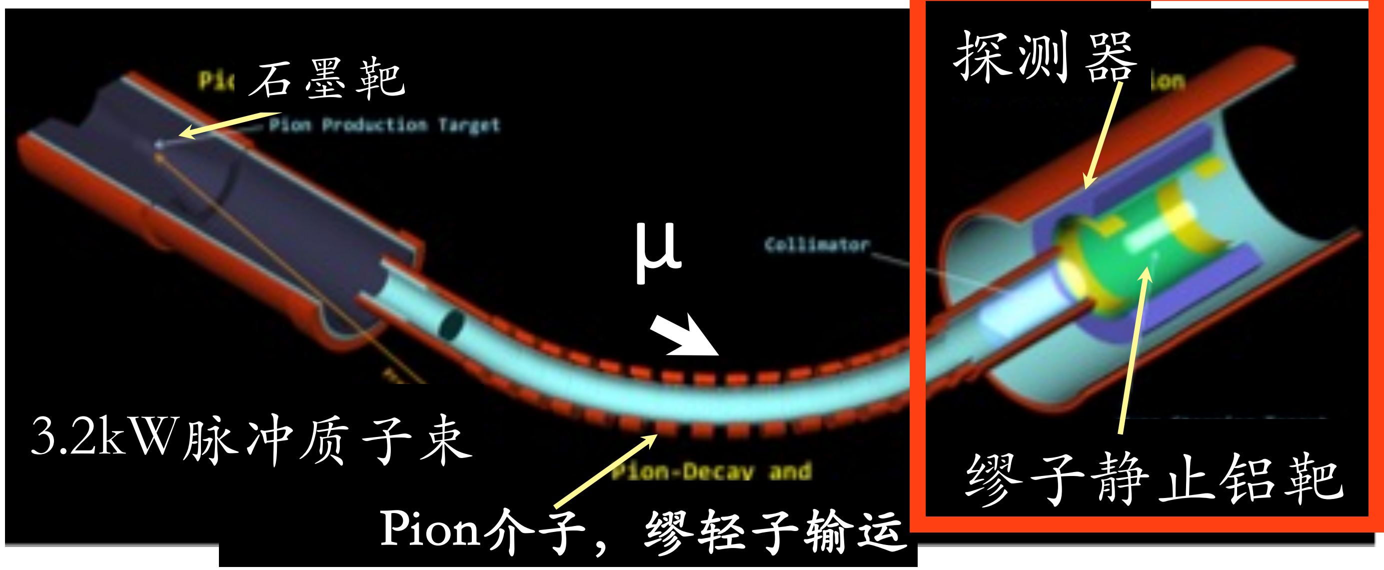
缪轻子到电子转换过程?

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

缪轻子被原子俘获形成1S态缪原子，在轨道上发生缪轻子到电子转换，释放105 MeV/c单能电子。



COMET Phase-I



实验方法：每年约10^{16}个带负电缪轻子被铝靶停止，形成1S态缪原子。

COMET 国际合作组

Oct 2018, COMET collaboration at Tbilisi

~200 members,
41 institutes from 17 countries

Still growing!

COMET 实验Phase-I设计技术报告

COMET Phase-I

COMET

Technical Design Report
INTERNAL VERSION
January 2018

COMET Phase-I 实验技术设计报告已经完成，共364页。

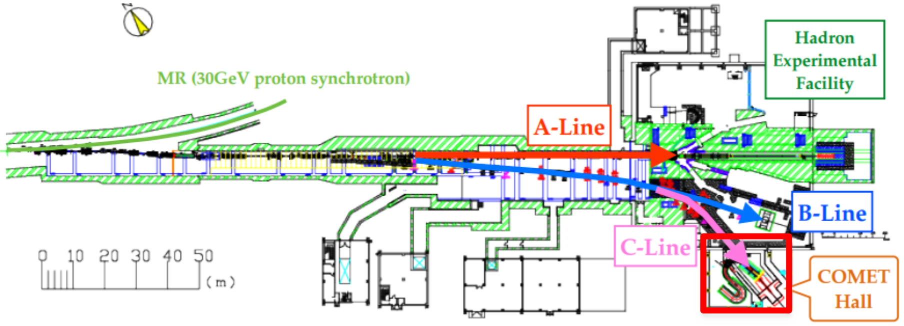
中方主要负责：

1） CDC探测器和电子学部分
2） Phase-I 本底分析部分
3） Phase-I 预期本底部分

arXiv:1812.09018, **PTEP 2020 (2020) no.3, 033C01**

COMET实验设施现状

质子束流线已全部完成。2022年将有质子束流到达COMET实验区。Phase alpha于2023年2月取数。

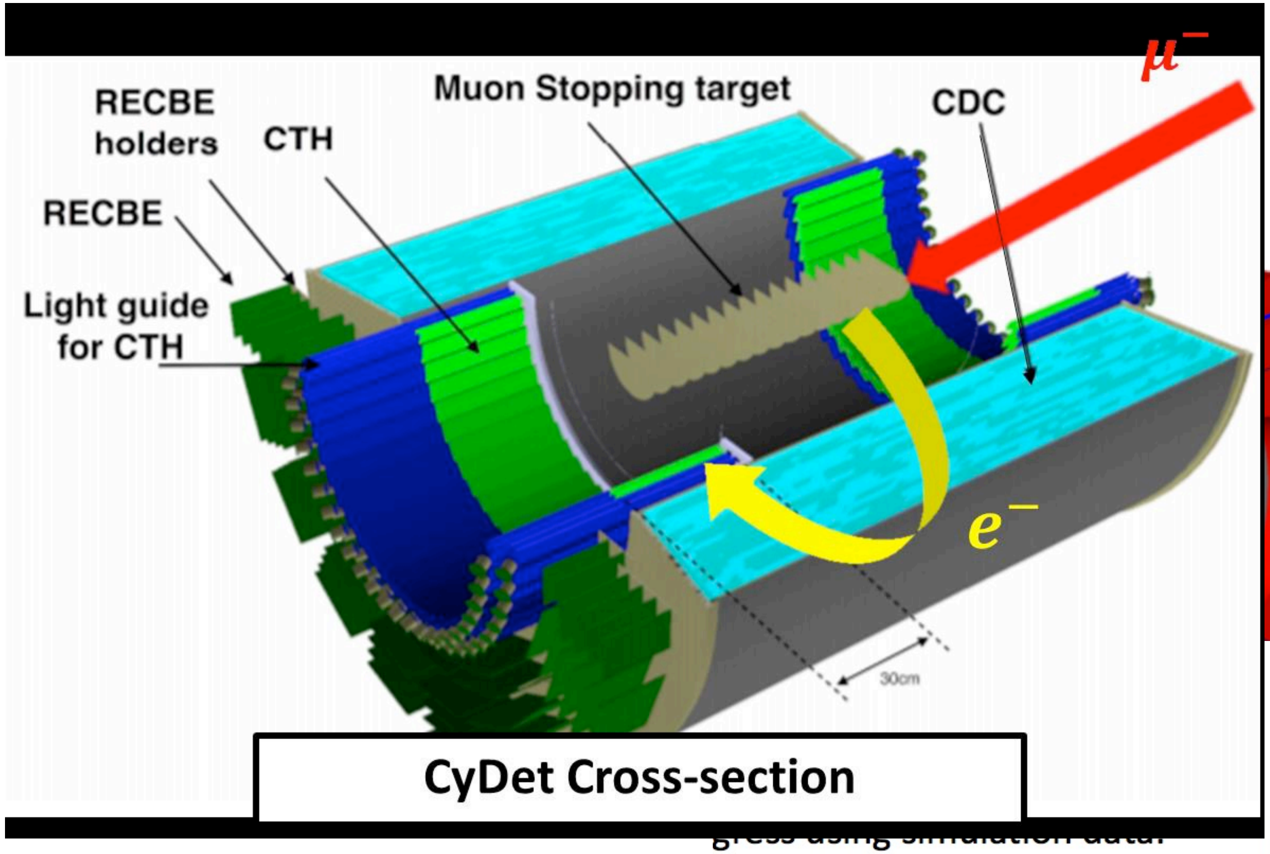


COMET探测器侧正在搭建电子学平台。

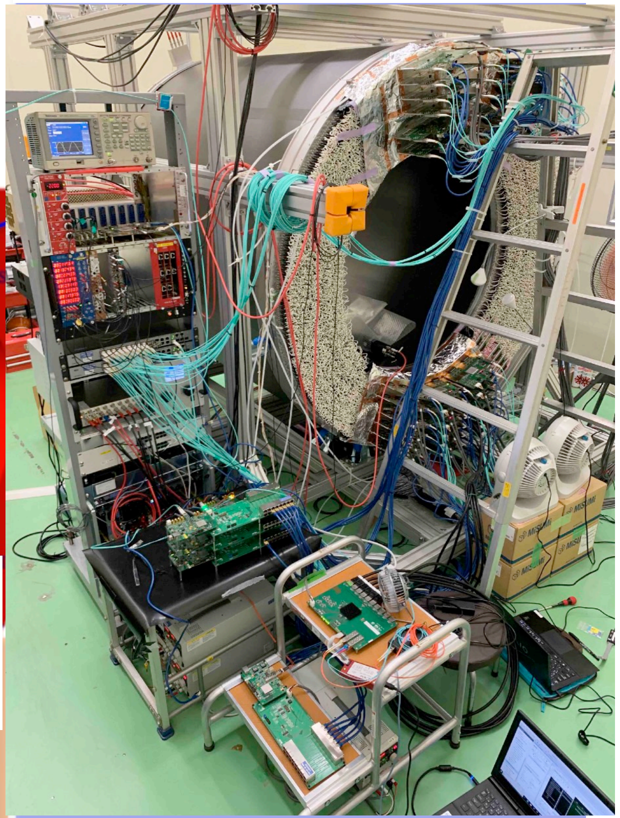
实验大厅从2015年投入使用

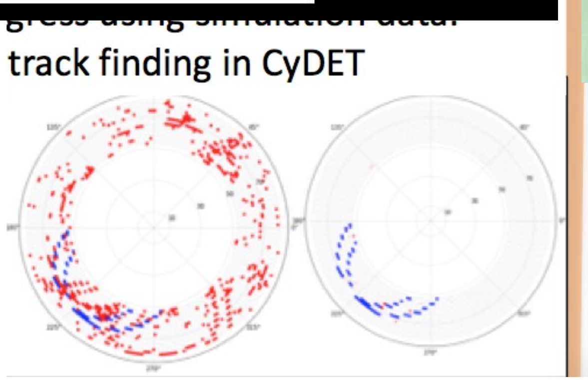
缪子输运线完成安装和辐射屏蔽。

COMET Phase-I 探测器准备：中心漂移室



中心漂移室(CDC)



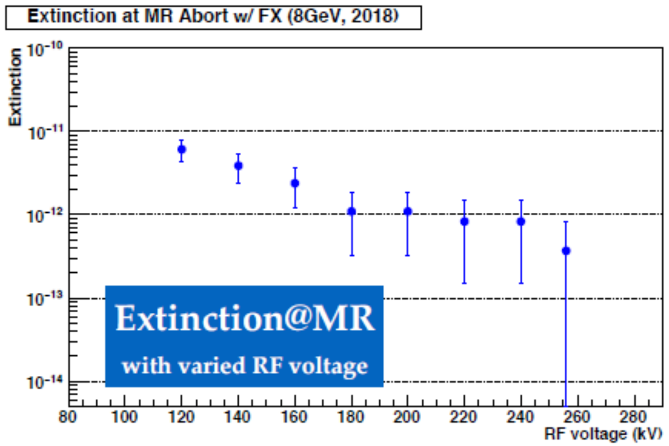


基于GEANT4对探测器
区域的模拟，分析框架和模拟数据
CDC径迹重建（高嫩所）。

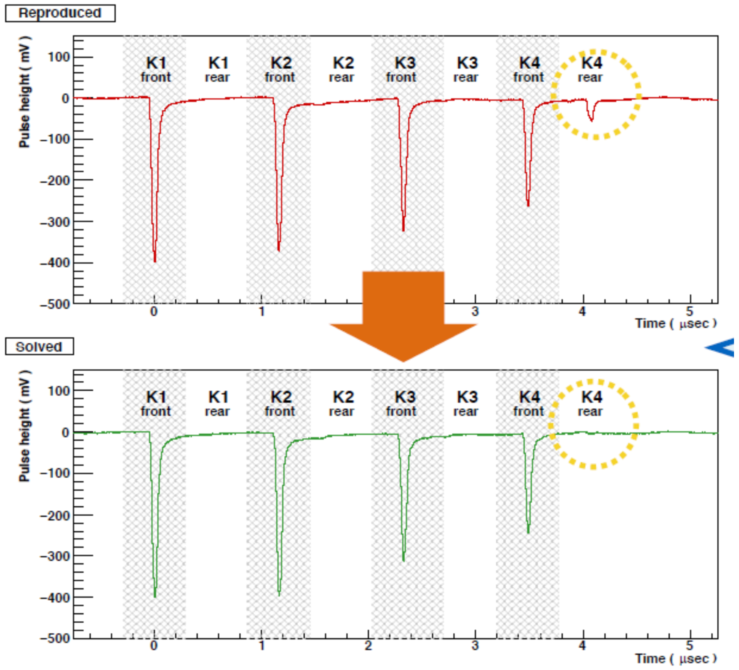
高能所负责的
CDC电子学读出

J-PARC质子束流测试

J-PARC主环的质子绝止率可以到达10^{-12}以下。这是一个里程碑

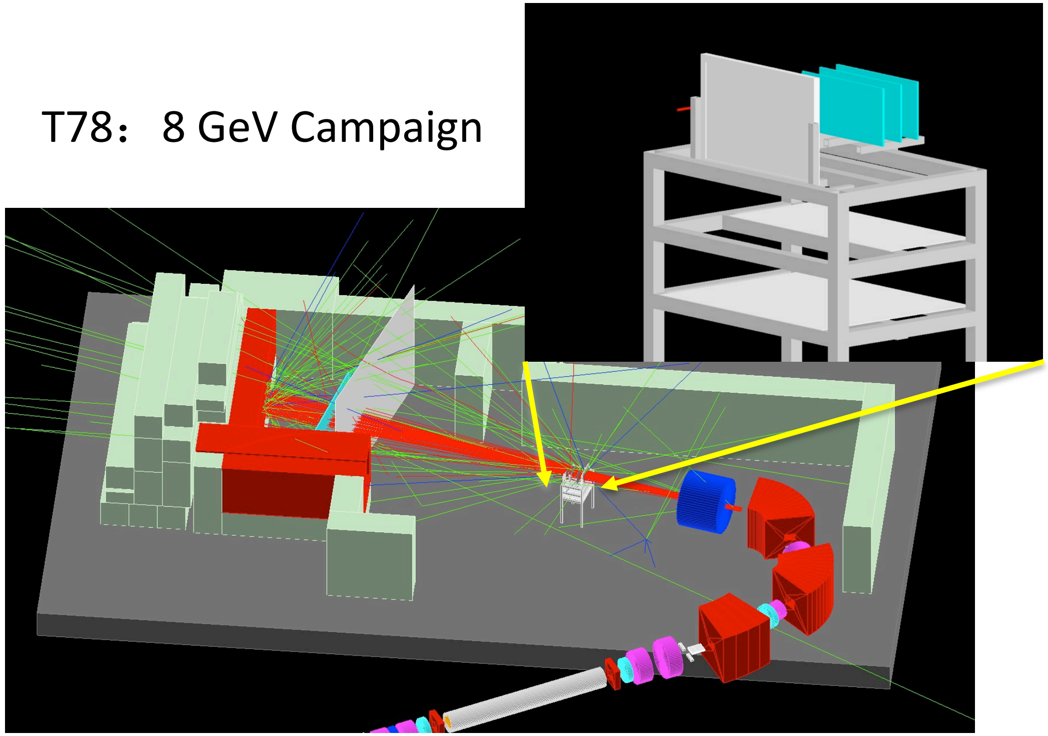


2018年束流测试，K4束团远端观察到泄漏。通过修改Kicker相位等方案解决。



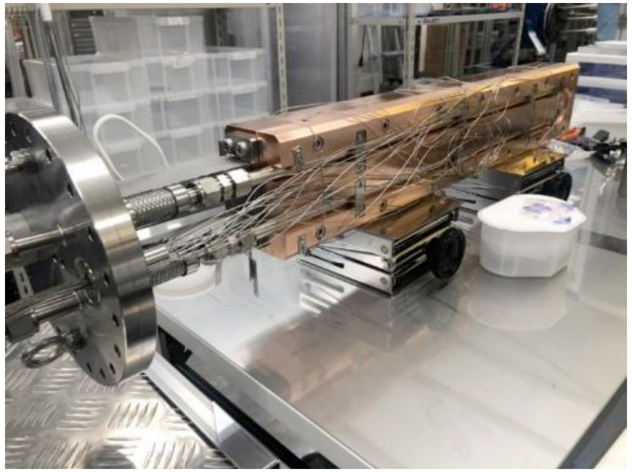
2021年，T78实验在在COMET慢速提取模式下验证了多种解决K4束团远端泄漏的方案可行。
初步结果表明，慢速提取质子束流的绝止率在90%置信度下不高于10^{-10}，达到实验要求。

T78：8 GeV Campaign

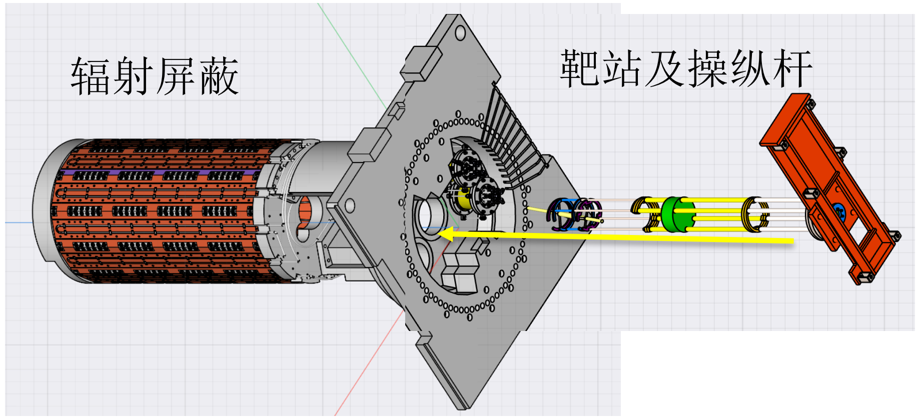


COMET 质子靶和辐射屏蔽现状-关键部件

Phase-I，铜屏蔽，空气制冷测试中。

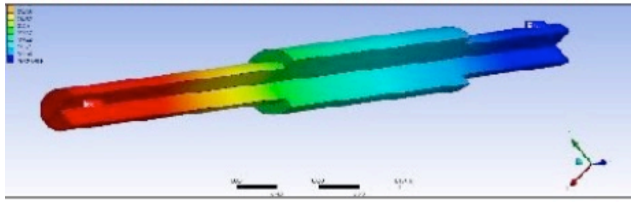


可远程操控的靶站设计。



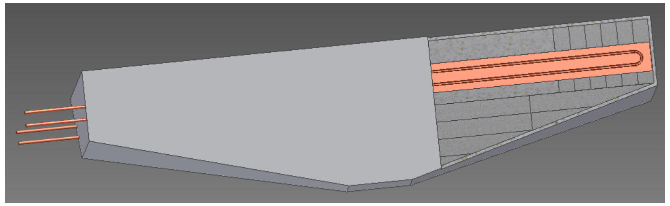
Phase-I，石墨靶，辐射冷却，温度在245摄氏度以内。

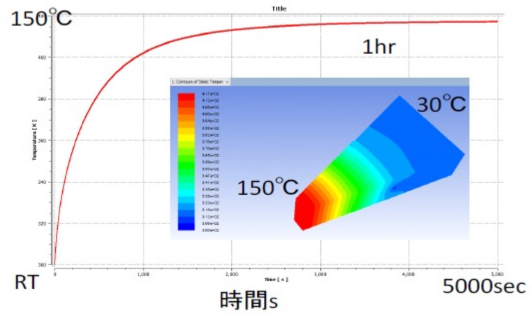
Graphite
Diameter: 26 mm and 40 mm, Length: 700 mm



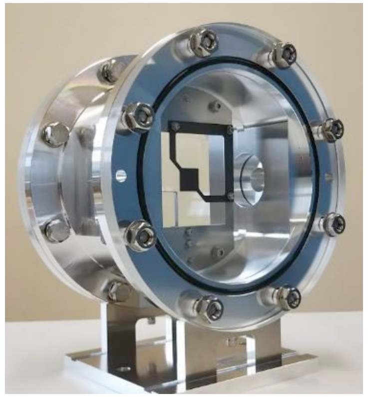
FEM simulation is completed. Max. temp. 245 degC.

Phase-II，钨屏蔽，水冷系统设计。

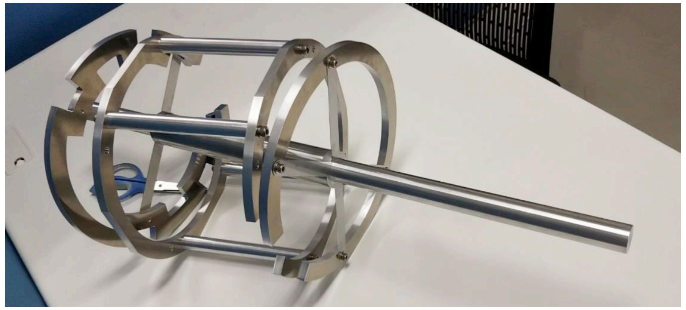




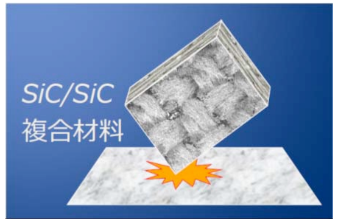
Phase-alpha靶已就绪。

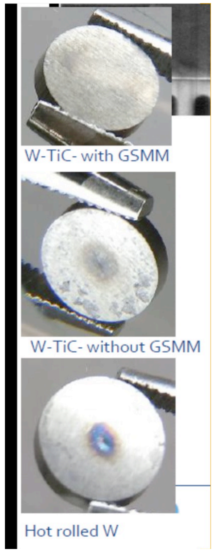


Phase-I靶固定环。



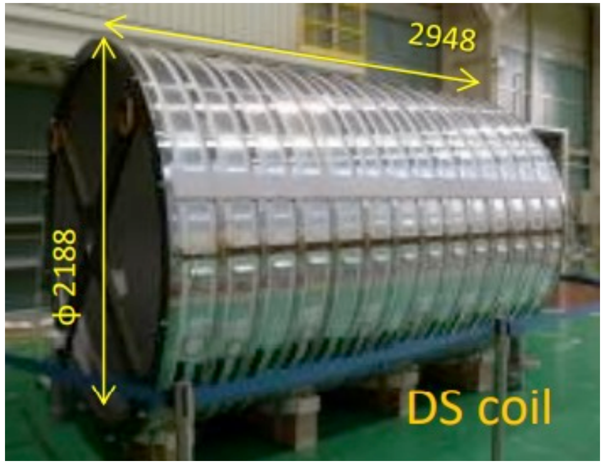
Phase-II计划使用钨靶，水冷。正在研究新型材料做靶的可能性。如W-TIC，SiC/SiC。





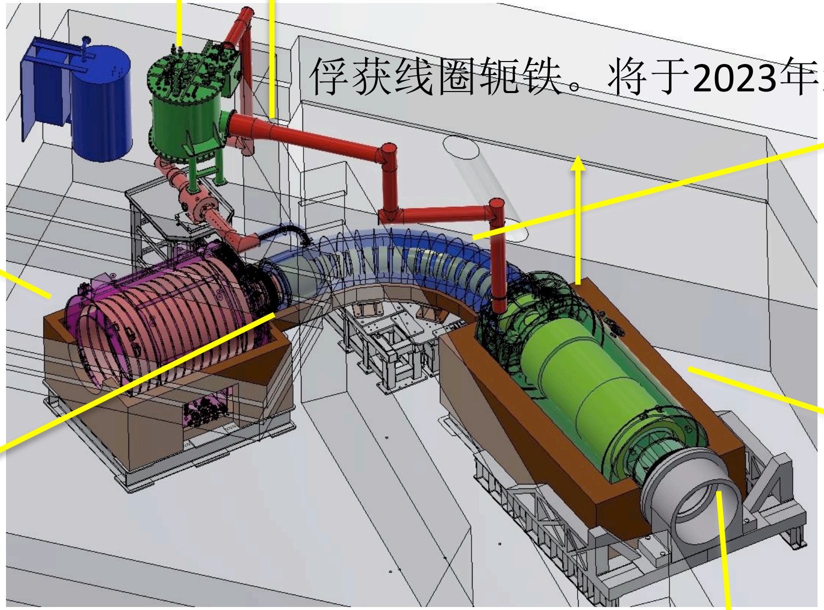
COMET 超导系统现状- COMET实验关键部件

探测器线圈。2015年交付。

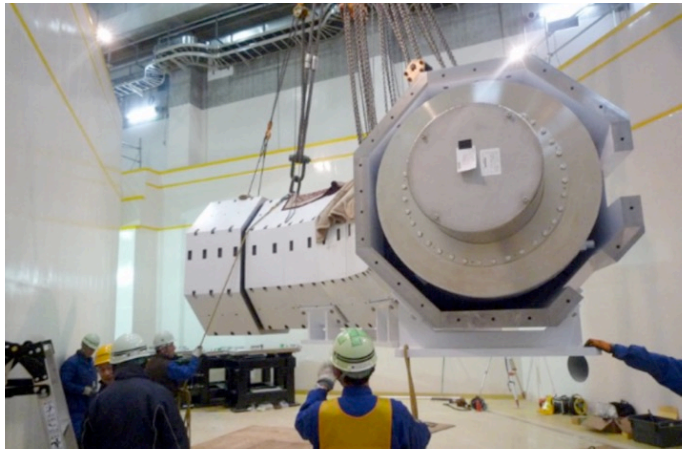


3000 A 俘获线圈的冷却系统于2021年测试成功。

俘获线圈轭铁。将于2023年组装完毕。

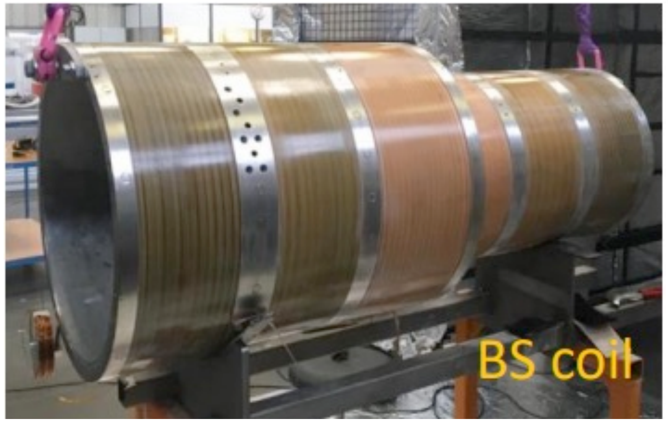


输运线圈及轭铁。2015年交付。
2022年计划系统测试，并测量磁场。

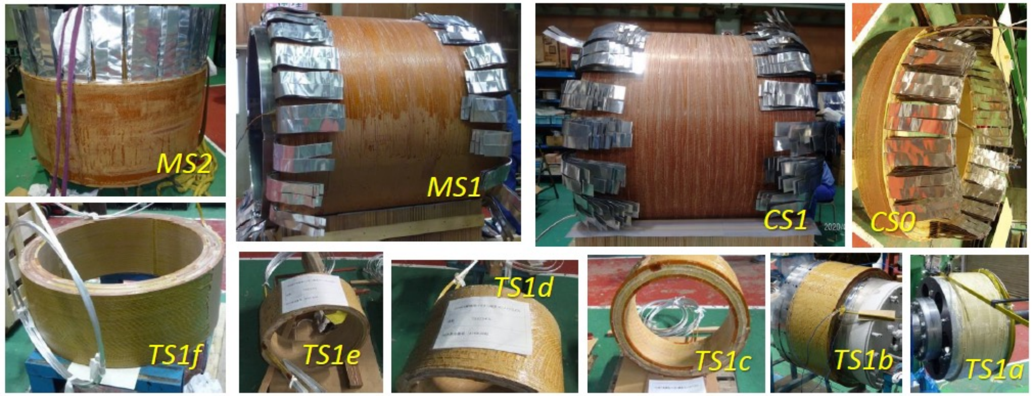


俘获线圈支撑系统。2021年组装完毕。

桥接线圈。2018年交付。

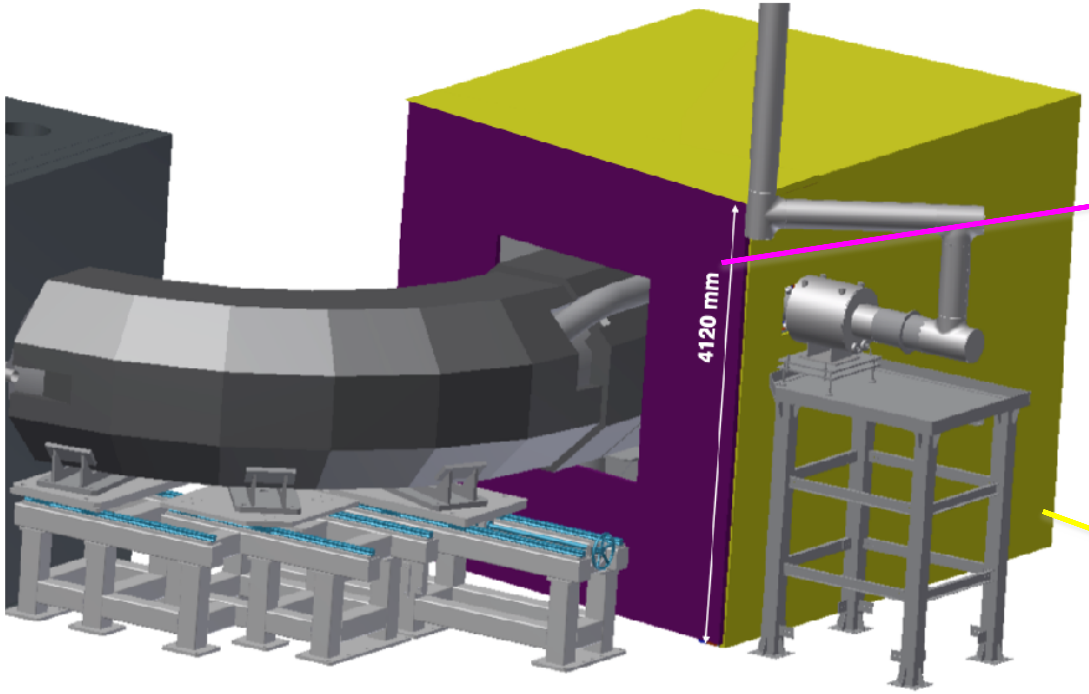


俘获线圈，2020年交付。



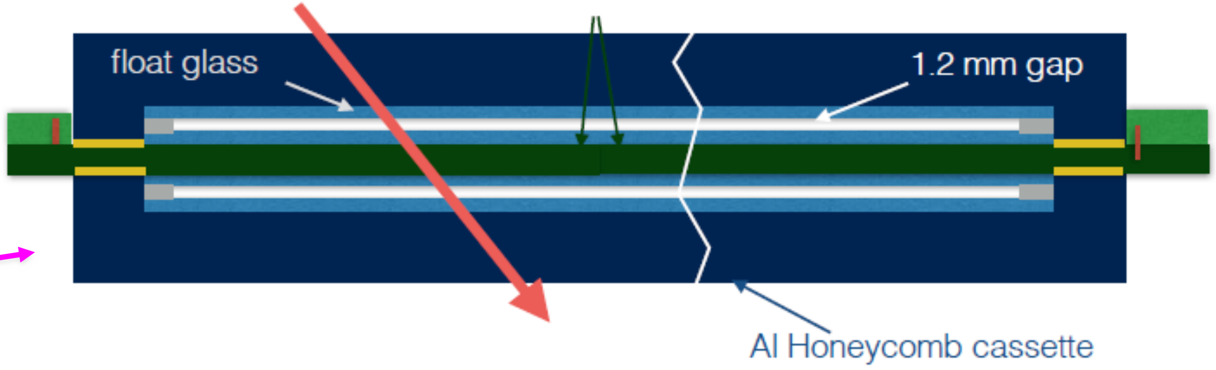
COMET Phase-II宇宙线反触发系统现状

COMET Phase-I反触发系统整体设计 。
黄色部分：塑料闪烁体（四层）
紫色部分：GRPC探测器。

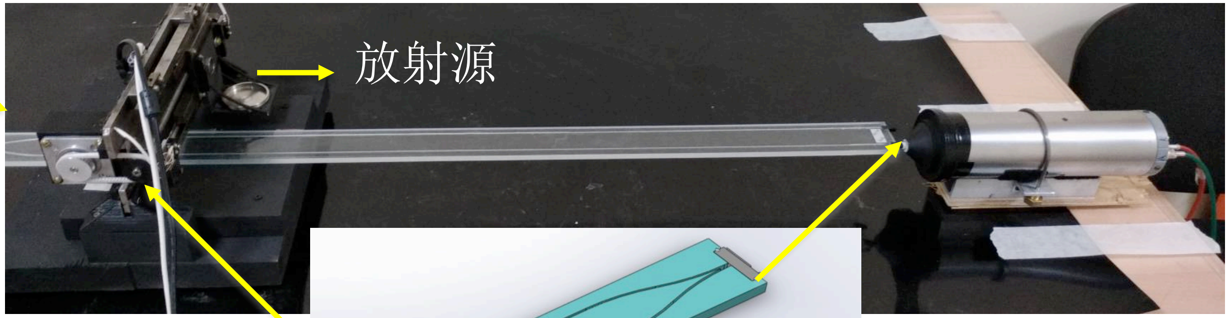


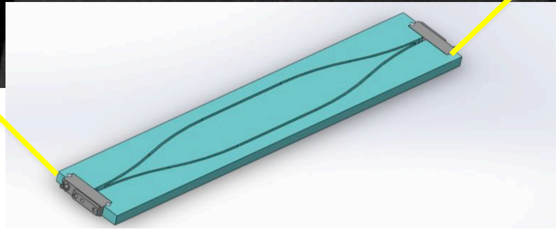
反触发系统设计指标：缪子探测效率高于99.99%。
目前塑料闪烁体测试性能：99.69%（初步结果）
漂移室配合反触发的方案正在研究。

近上游束流端，采用GRPC探测器，耐辐射，响应快。
具体方案仍在设计中。



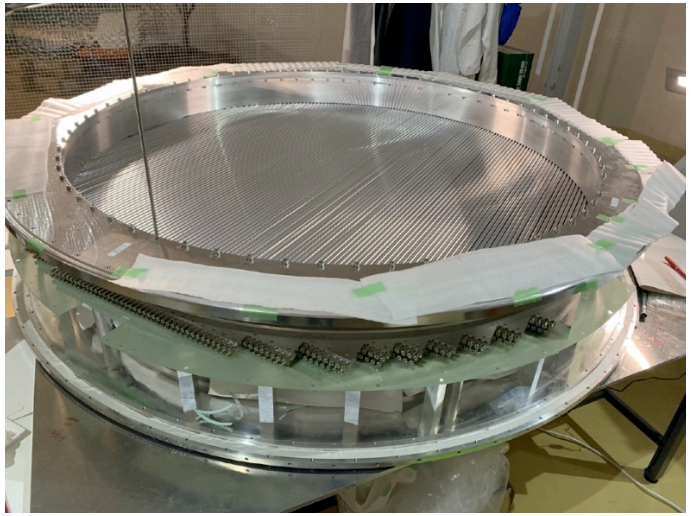
其他部分使用塑料闪烁体。利用光纤配合SiPM读数。
2021年完成设计测试。2022年投入量产。

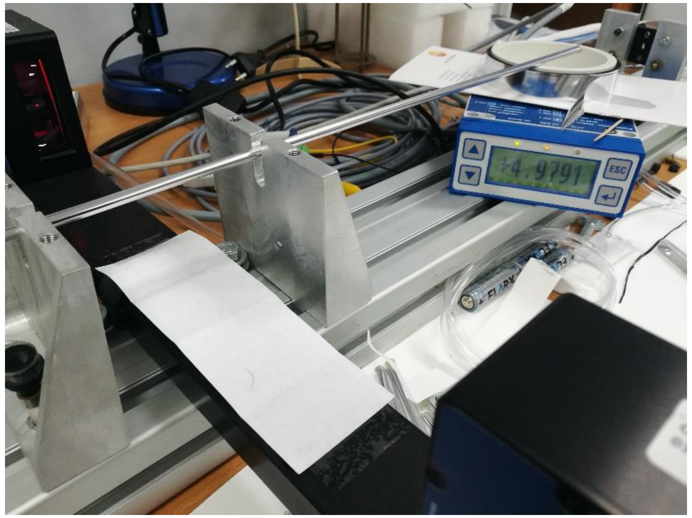




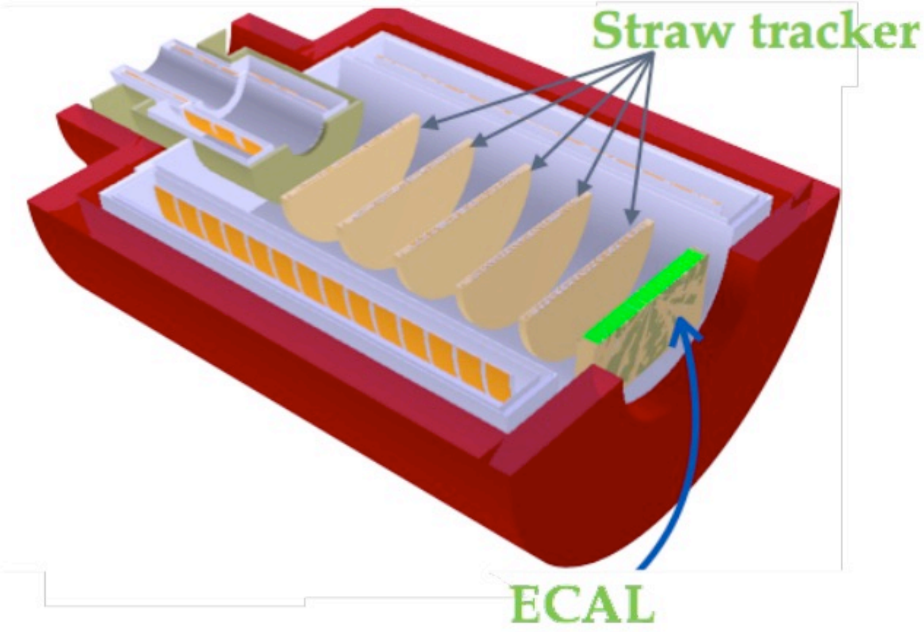
COMET Phase-II StrEcal现状

用于Phase-I的10mm直径，20um厚度的稻草管探测器一号站已搭建完毕。二号站接近完工。

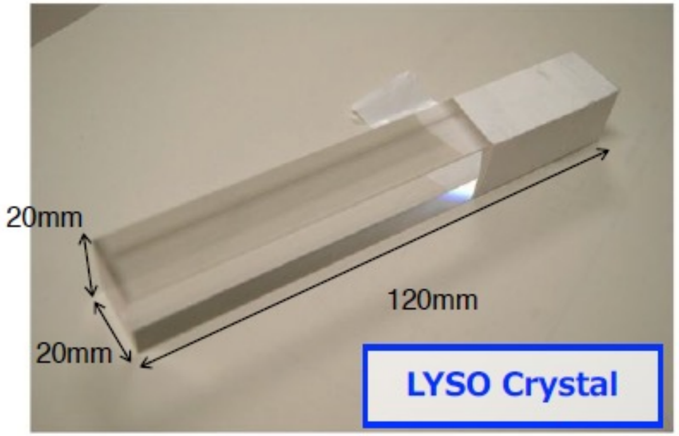




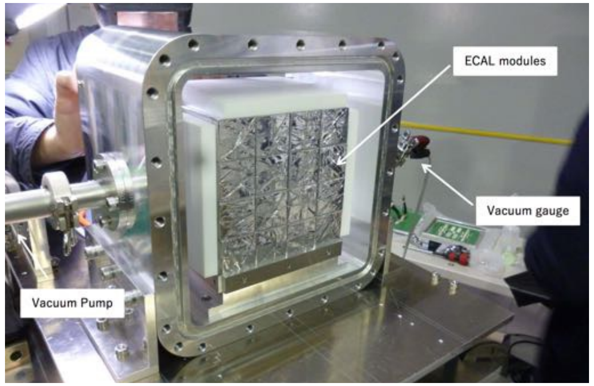
Phase-I中的StrEcal设计。用于直接测量缪子束流。采用5个稻草管站和~500个LYSO晶体



用于Phase-II的5mm直径，12um厚度的稻草管探测器于2019年研发成功。4倍压力测试成功。直径变化范围在120um以内。后续研究正在进行。



LYSO晶体原型机测试已完成。对105 MeV电子束流，能量分辨4%，位置分辨<6mm，时间分辨0.5 ns。
Phase-I的布局设计已完成。
~500块LYSO晶体已就位。



本底清单

物理本底

Intrinsic physics backgrounds

1	Muon decays in orbit (DIO)	Bound muons decay in a muonic atom
2	Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A' + \gamma$, followed by $\gamma \to e^- + e^+$
3	Radiative muon capture (internal)	$\mu^- + A \to \nu_\mu + e^+ + e^- + A'$,
4*	Neutron emission after muon capture	$\mu^- + A \to \nu_\mu + A' + n$, and neutrons produce e^-
5*	Charged particle emission after muon capture	$\mu^- + A \to \nu_\mu + A' + p$ (or d or α), followed by charged particles produce e^-

束流相关的快速／延迟本底

Beam related prompt/delayed backgrounds

6	Radiative pion capture (external)	$\pi^- + A \to \gamma + A'$, $\gamma \to e^- + e^+$
7	Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$
8	Beam electrons	e^- scattering off a muon stopping target
9	Muon decay in flight	μ^- decays in flight to produce e^-
10	Pion decay in flight	π^- decays in flight to produce e^-
11	Neutron induced backgrounds	neutrons hit material to produce e^-
12	$\overline{p}$ induced backgrounds	$\overline{p}$ hits material to produce e^-

其他本底：宇宙线、环境中子、偶然假径迹

Other backgrounds

14	Cosmic-ray induced backgrounds
15	Room neutron induced backgrounds
16	False tracking

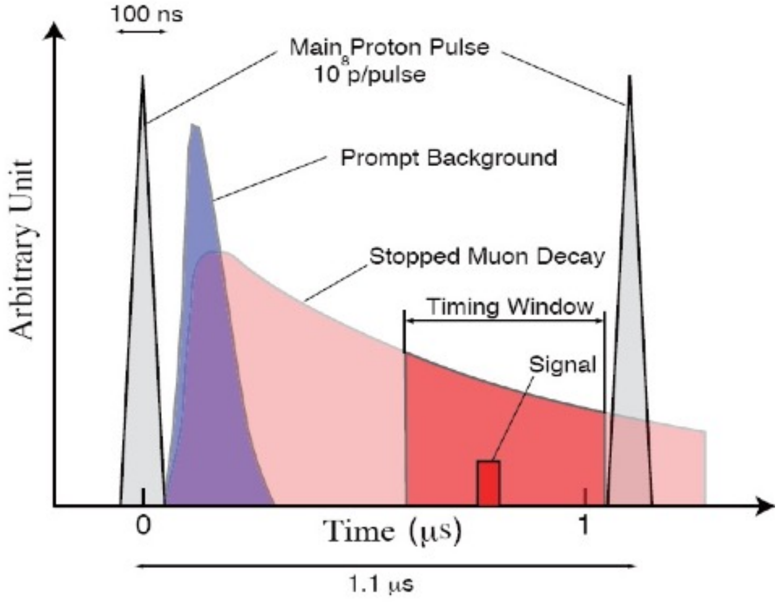
本底清单

Intrinsic physics backgrounds

1	Muon decays in orbit (DIO)	Bound muons decay in a muonic atom
2	Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A' + \gamma$, followed by $\gamma \to e^- + e^+$
3	Radiative muon capture (internal)	$\mu^- + A \to \nu_\mu + e^+ + e^- + A'$,
4*	Neutron emission after muon capture	$\mu^- + A \to \nu_\mu + A' + n$ and neut
5*	Charged particle emission after muon capture	$\mu^- + A$ - followed

Beam related prompt/delayed backgrounds

6	Radiative pion capture (external)	$\pi^- + A$ -
7	Radiative pion capture (internal)	$\pi^- + A$ -
8	Beam electrons	e^- scatte
9	Muon decay in flight	μ^- decay
10	Pion decay in flight	π^- decay
11	Neutron induced backgrounds	neutrons
12	$\bar{p}$ induced backgrounds	$\bar{p}$ hits ma...



Other backgrounds

14	Cosmic-ray induced backgrounds	
15	Room neutron induced backgrounds	
16	False tracking	

COMET Phase-I 预期本底

Table 20.8: *Summary of the estimated background events for a single-event sensitivity of* 3×10^{-15} *in COMET Phase-I with a proton extinction factor of* 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

Single Event Sensitivity

- Single Event Sensitivity $= \dfrac{1}{N_\mu \times f_{cap} \times f_{gnd} \times A_{\mu e}}$

N_μ = number of muons stopping on the target

0.61 f_{cap} = fraction of muon capture

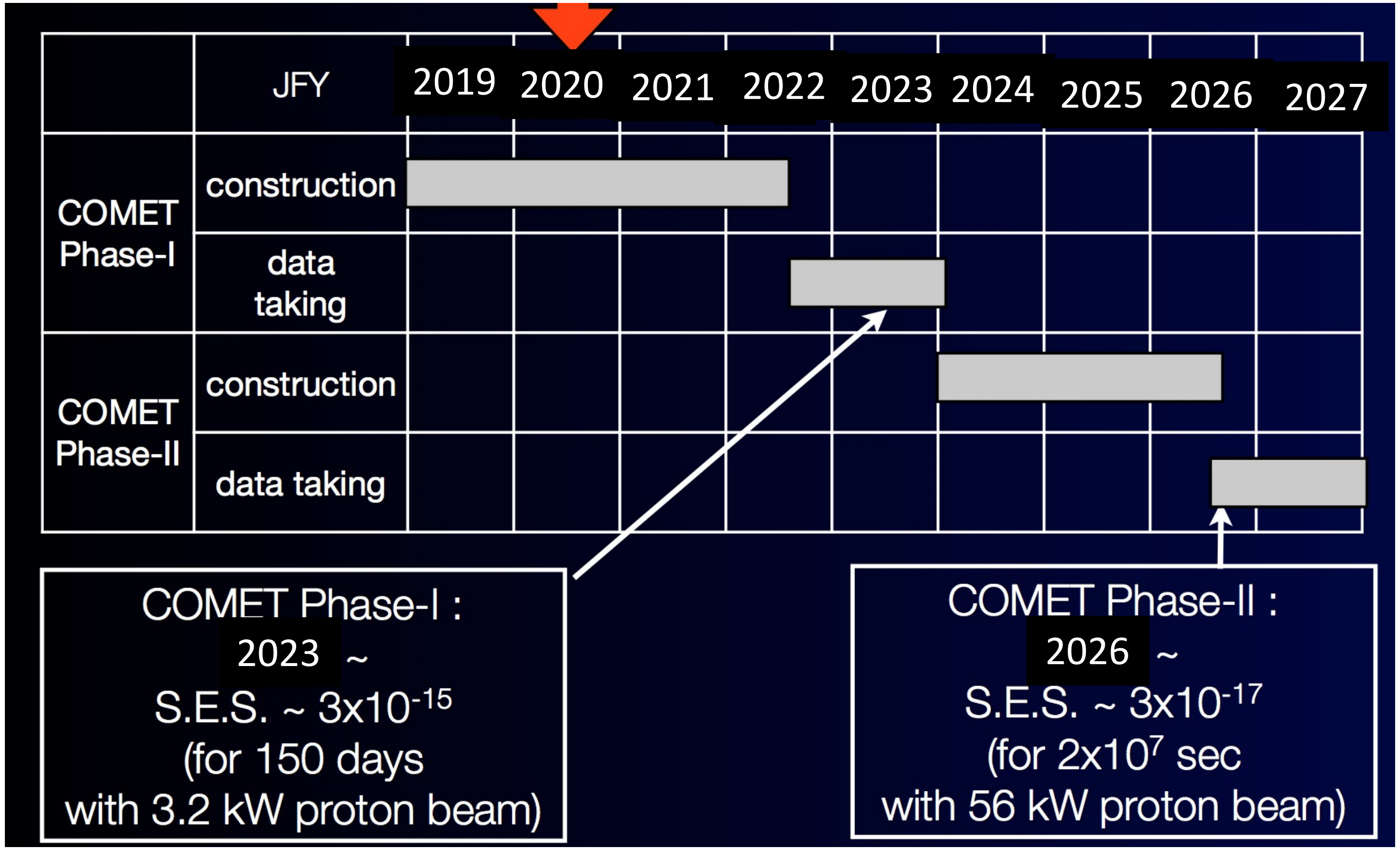
0.98 f_{gnd} = fraction of nucleus which is not excited by μ-e conv.

0.041 $A_{\mu e}$ = Total Acceptance for e^- from μ-e conv.

	Phase I	Phase II
Beam power	3.2 kW	56 kW
Protons on target	3×10^{19}	3×10^{21}
Stopped muons on target	1.5×10^{16}	1.5×10^{18}
Running time	~ 5 months	~ 1 year
S.E.S	$\mathbf{3 \times 10^{-15}}$	$\mathbf{2.6 \times 10^{-17}}$

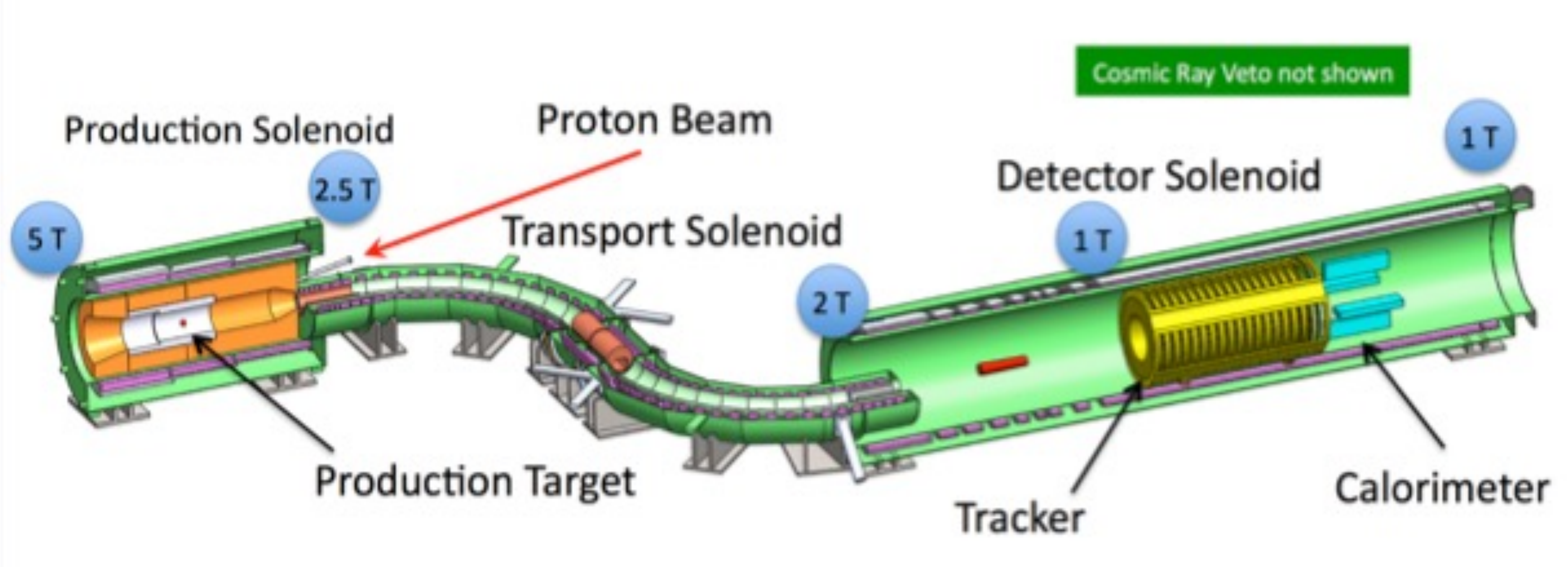
c.f. SIMDRUM-II: BR(μ^- Au→e^- Au) < $\mathbf{7 \times 10^{-13}}$

COMET时间表



The COMET Collaboration will have its detector systems commissioned and tested by the end of JFY 2019, to be ready for the beam which will arrive subsequently. Beam studies in the "B-line" proton beam line which supplies COMET will commence at this time.

μ-e转化： 费米实验室的Mu2e实验



$$B(\mu^- + Al \to e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \to e^- + Al) < 10^{-16} \quad \text{(90\%C.L.)}$$

在单事例灵敏度$3x10^{-19}$:寻找μ-e转化
PRISM (FFAG: μ子存储环)

PRISM

FFAG:固定磁场交变梯度

4 MW beam,
钨靶：10^{13} muon stops/s

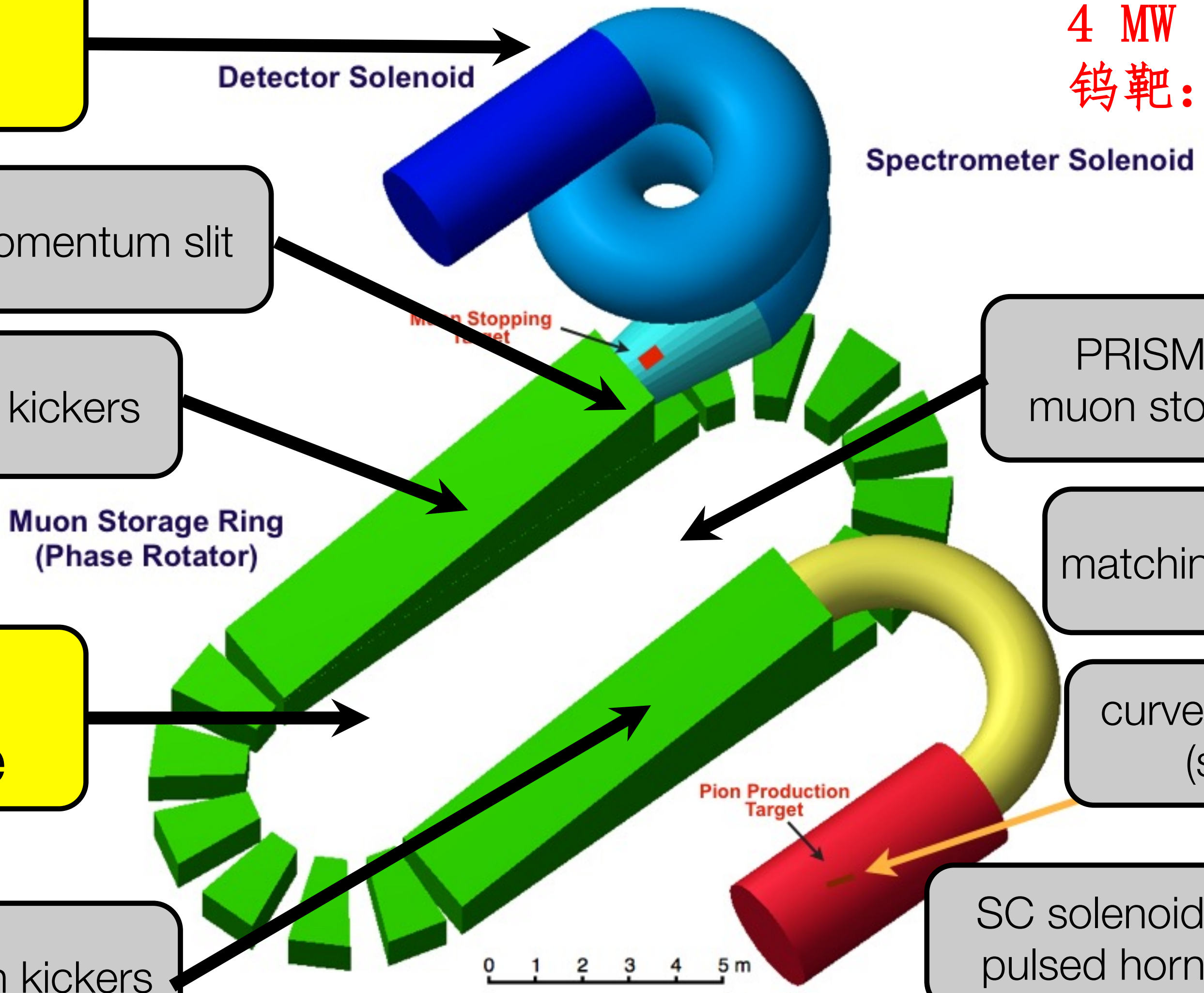
PRIME detector

momentum slit

extract kickers

PRISM beamline

injection kickers



PRISM-FFAG muon storage ring

matching section

curved solenoid (short)

SC solenoid / pulsed horns

PRISM-FFAG: μ子存储环 预研究(大阪大学)

phase rotation的展示实验已经完成

muon物理关键技术

参加COMET以及后续实验合作：

- 高流强缪子产生靶
- 大口径高场高热负荷超导磁铁制造相关技术
- 高流强质子束引出与废束收集
- 极高热负荷辐射屏蔽与冷却
- 缪束流收集与储存
- Muon粒子输运线设计与制造：中微子实验，muon对撞机等
- 缪束流收集与储存（FFAG）： muon子对撞机，中微子工厂，g-2等

掌握这些技术对中国的加速器中微子实验物理，以及未来国际中微子工厂和Muon子工厂合作具有重要意义。基于散裂中子源4kW强流质子束流，我国已经开始模拟高强度实验muon源。

日本J-PARC: Muon源科学目标

Muon Science

There are a wide variety of potential applications for muons provided by J-PARC MUSE, ranging from fundamental physics to applied science. The MUSE Facility is expected to be the world center of excellence for those research fields.

基础科学

Condensed Matter Physics
- High Tc cuprate superconductors
- Quantum criticality
- Vortex state of superconductors
- Hydrogen centers in semiconductors

Chemistry
- Radical chemistry
- Reaction dynamics of hydrogen
- Chemistry of supercritical phase

Particle Physics
- Supersymmetry and rare decay
- Quantum electrodynamics

交叉学科

μCatalyzed Fusion
- Alpha sticking and medium effect
- Effect of hyperfine interaction
- Muonic Atoms/Molecules

Biophysics
- Biological materials
- Function of molecules in view of electronic state

应用

Noninvasive Analysis
- Bulk-sensitive elemetal analysis
- Tomography
- Radiography

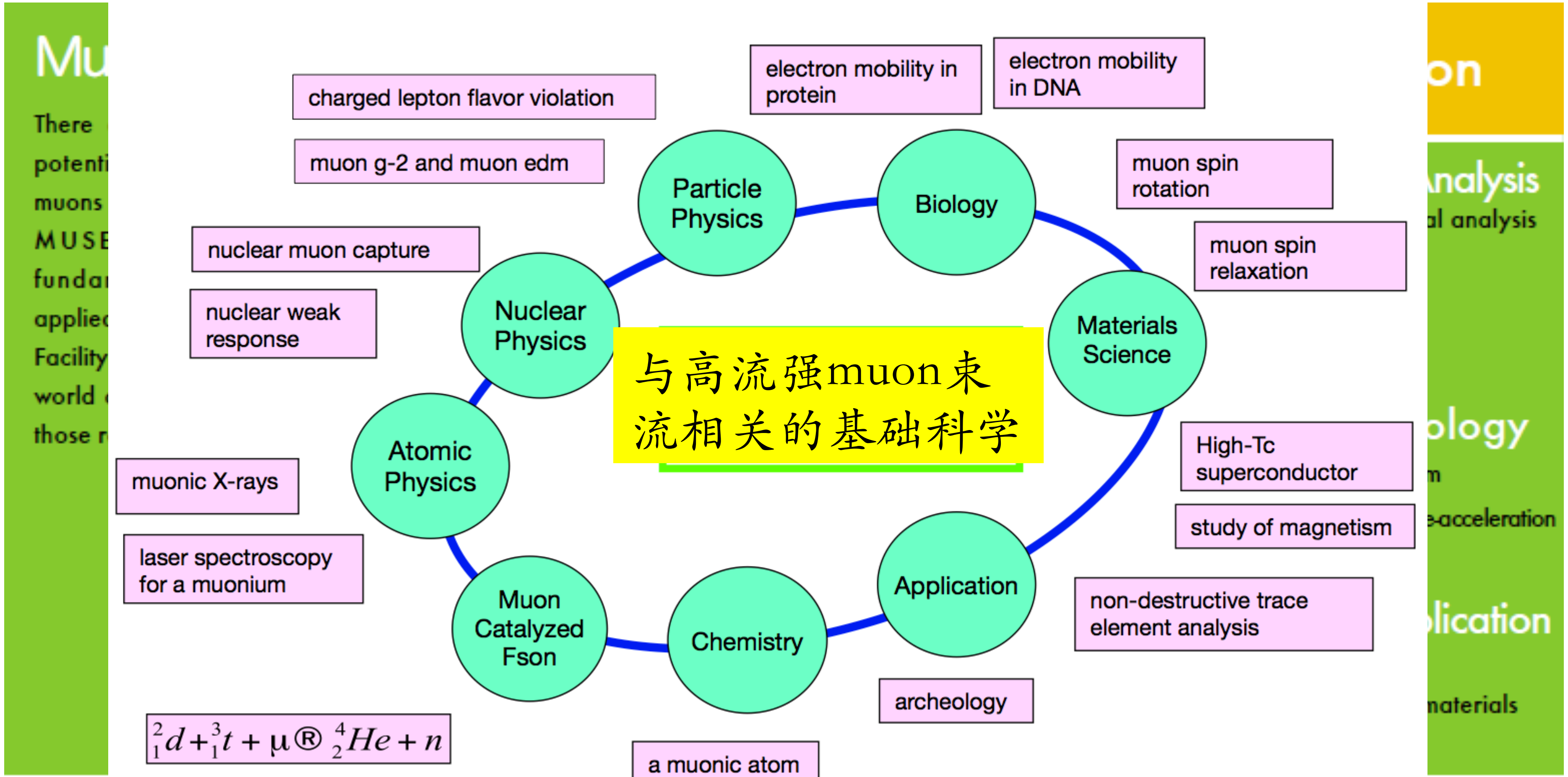
Beam Technology
- Ultraslow muon beam
- Muon beam cooling/re-acceleration

Industrial Application
- Hydrogen energy
- Testing of magnetic materials

Science and technology based on muon sources

（Courtesy: J-PARC/MUSE）

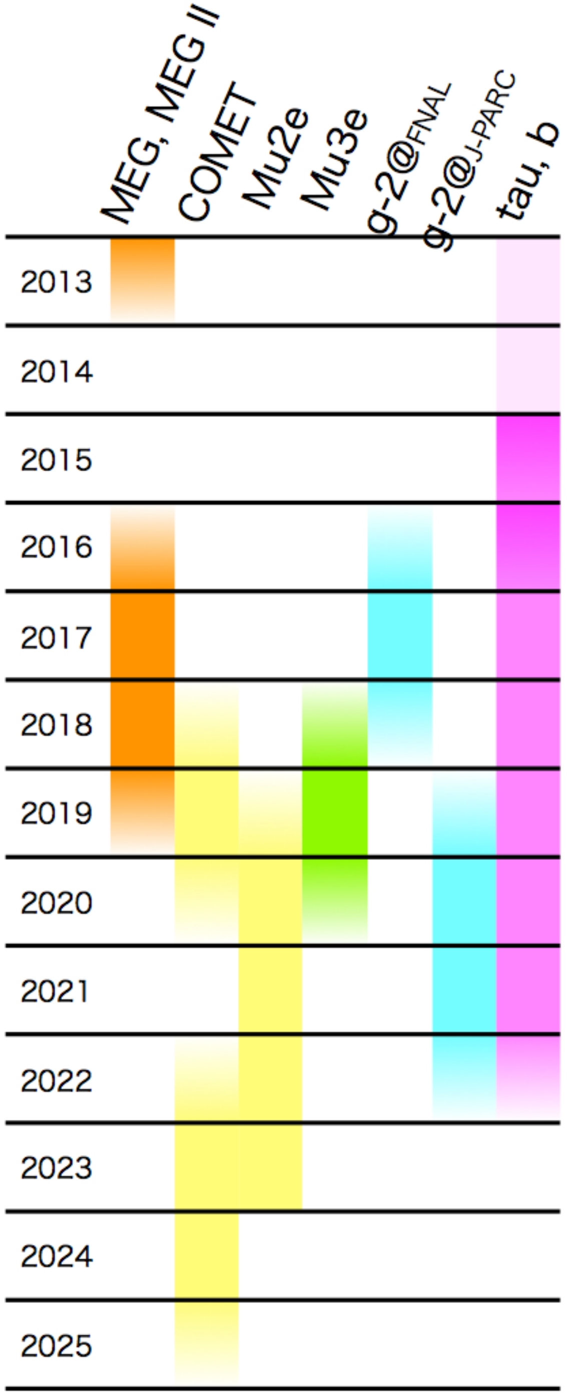
日本J-PARC: Muon源科学目标



粒子物理对科学技术进步的推动

总结

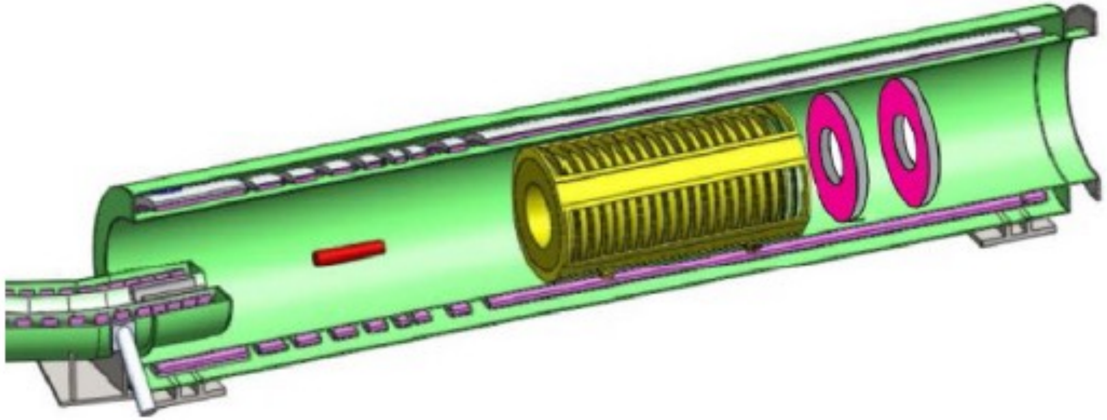
- CLFV是寻找新物理的最佳途径之一
- μ-e转化过程是寻找新物理的黄金过程
- COMET Phase-II预期单事例灵敏度将达到$3x10^{-17}$，计划2023年开始
- COMET Phase-I：$3x10^{-15}$的单事例灵敏度，已经开始建造，2023年开始取数
- Mu2e: 费米实验室，目前计划2022年左右开始
- 我国的CSNS和ADS将提供强流质子束流
- 考虑在CSNS上的muon源将为物理、化学、材料科学、生命科学提供平台。



谢谢大家！

Choosing the stopping targets

- The probability of of exchanging a virtual particle with the nucleus goes up with Z, *however*
- The muon lifetime in atomic orbit is *shorter* for high Z
  - This decreases the useful live window

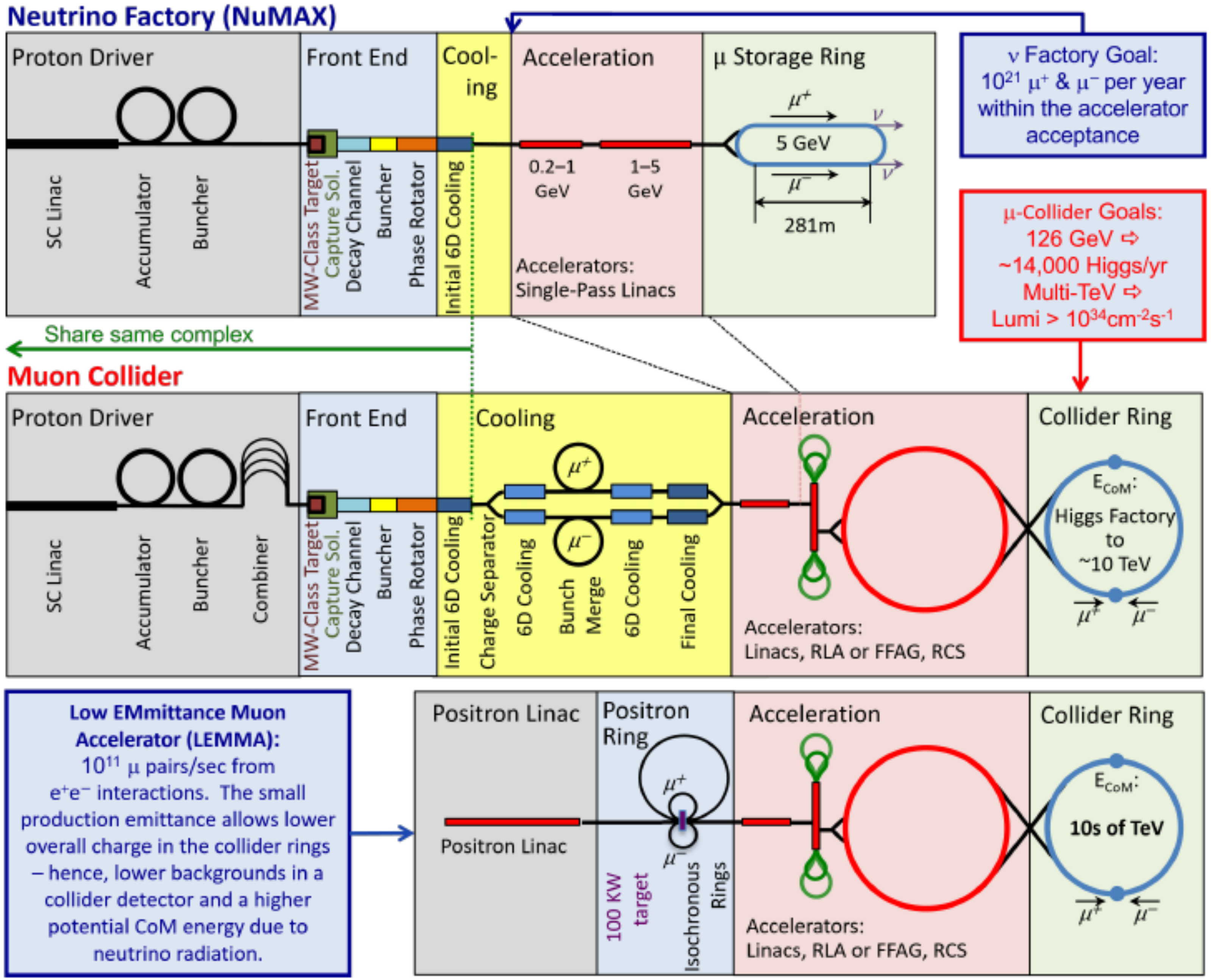


Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

Previous experiments used Ti, Pb and Pb targets
C or SiC is the target for DeeMe
Aluminum is the initial choice for Mu2e and COMET Phase I

Muon coliders

arXiv: 1808.01858



arXiv:1905.05747

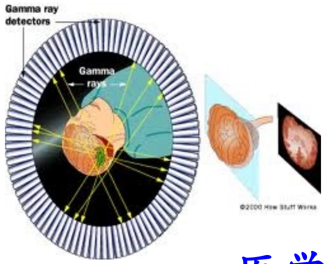
Positron driven muon source for a muon collider

10^{16}/s positron on target

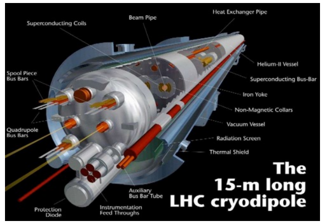
粒子物理对技术进步的推动

互连网，WWW，
网格计算，大数据
获取，传输和处理

加速器技术
辐照探测技术
快微电子学技术
海量数据技术
……



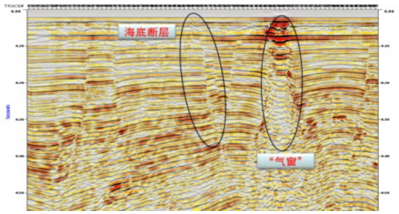
医学成像
放射性治疗



快／微电子学
大型超导磁铁

大型高精度，机械加工

国土安全



石油物探
海洋监测

"…此领域的研究不仅极大地推进了人类对自身所处的客观世界起源和发展的了解，而且在这些领域研究过程中所派生出来的技术还强有力地推动着其它领域的发展，成为许多高新技术产业的源头和至关重要的支撑平台，直接改善了人类生存和生活条件，是国家安全不可或缺的基础和国家综合实力的具体表现。" 《国家自然科学基金"十五"优先资助领域》，国家自然科学基金委员会，2001

Muon的基本性质

Table 1: Summary of Measured Muon Properties and Selected Decay Rates and Limits

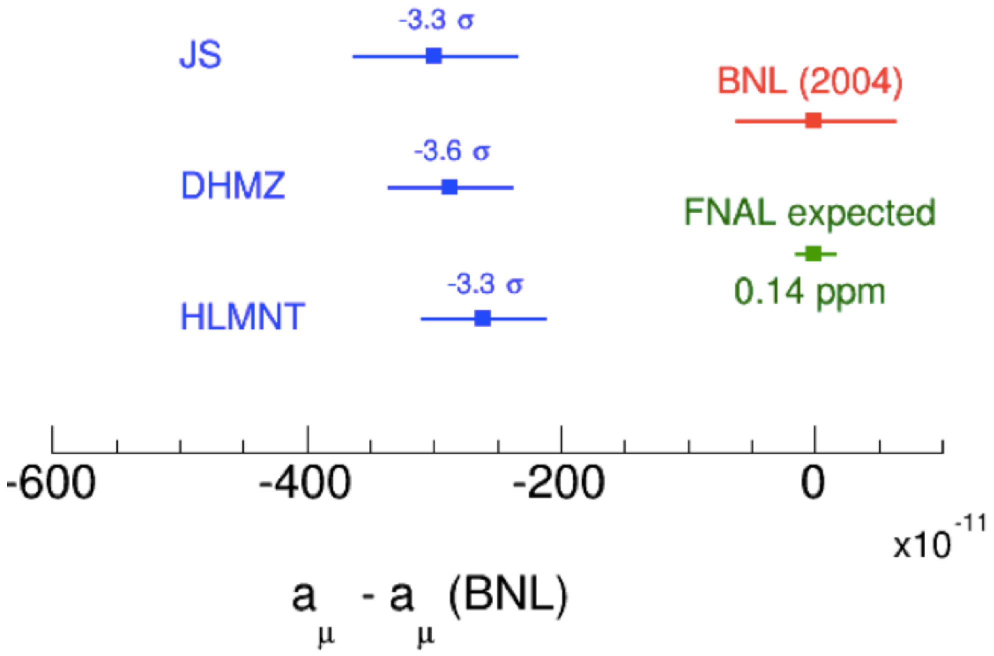
Property	Symbol	Value	Precision	Ref.
Mass	m_μ	105.658 3715(35) MeV	34 ppb	[4]
Mean Lifetime	τ_μ	$2.196\,9811(22) \times 10^{-6}$ s	1.0 ppm	[5]
Anom. Mag. Moment	a_μ	$116\,592\,091(63) \times 10^{-11}$	0.54 ppm	[4, 6]
Elec. Dipole Moment	d_μ	$< 1.9 \times 10^{-19} e\cdot$cm	95% C.L.	[7]
Branching Ratios	**PDG average**	**B.R. Limits**	**90% C.L.**	**Ref.**
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	$\approx 100\%$	$\mu^- \to e^- \gamma$	5.7×10^{-13}	[8]
$\mu^- \to e^- \bar{\nu}_e \nu_\mu \gamma$	1.4(4)%	$\mu^- \to e^- e^+ e^-$	1.0×10^{-12}	[9]
$\mu^- \to e^- \bar{\nu}_e \nu_\mu e^+ e^-$	$3.4(4) \times 10^{-5}$	$\mu^- \to e^-$ conversion	7×10^{-13}	[10]

Muon反常磁矩测量现状

- Most precise measurement performed at BNL (1999-2001)
- Accuracy of ~0.5 ppm

$$a_\mu^{exp} = 116\,592\,089\,(0.54)_{st}(0.33)_{sy}(0.63)_{tot} \times 10^{-11}$$

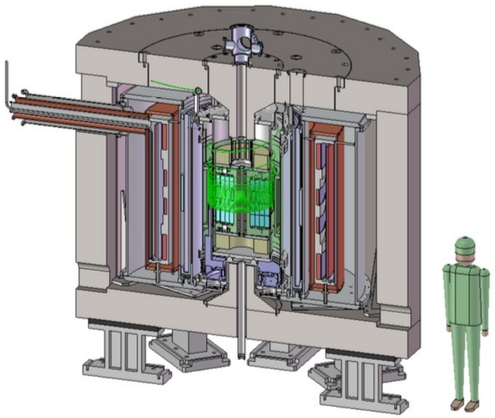
- Uncertainty is dominated by statistics

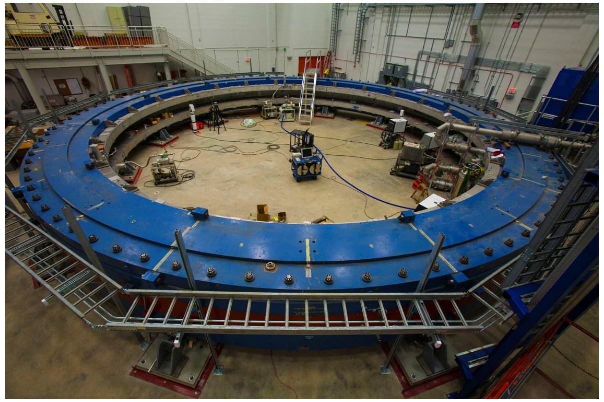


- Measurement differs from theory by ~3.5 σ

$$\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$$

The new Muon g-2 experiments: A comparison





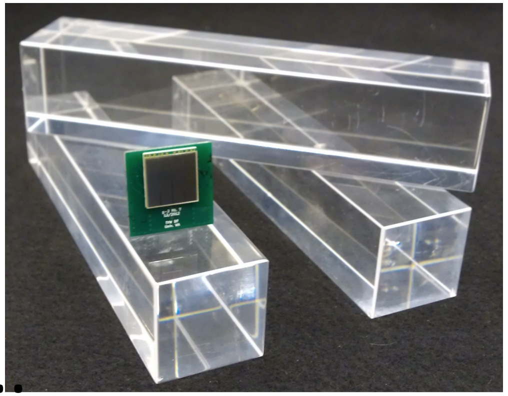
	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/C)
Polarization	P_{max} = 50%	$P \approx 97\%$
Magnet	MRI-like solenoid ($r_{storage}$ = 33cm)	Storage ring (7m radius)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Electron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	0.400 ppm	0.140 ppm

g-2 at Fermilab: Getting ready for data taking 2017

- Many improvements on entire experiment to reach 140 ppb
- New segmented PbF_2 electron calorimeter
- Precision alignment to reach dipole gradients of $\Delta B < \pm 25$ ppm
  - 72 poles
  - 840 wedge shims
  - 9000 thin iron foils

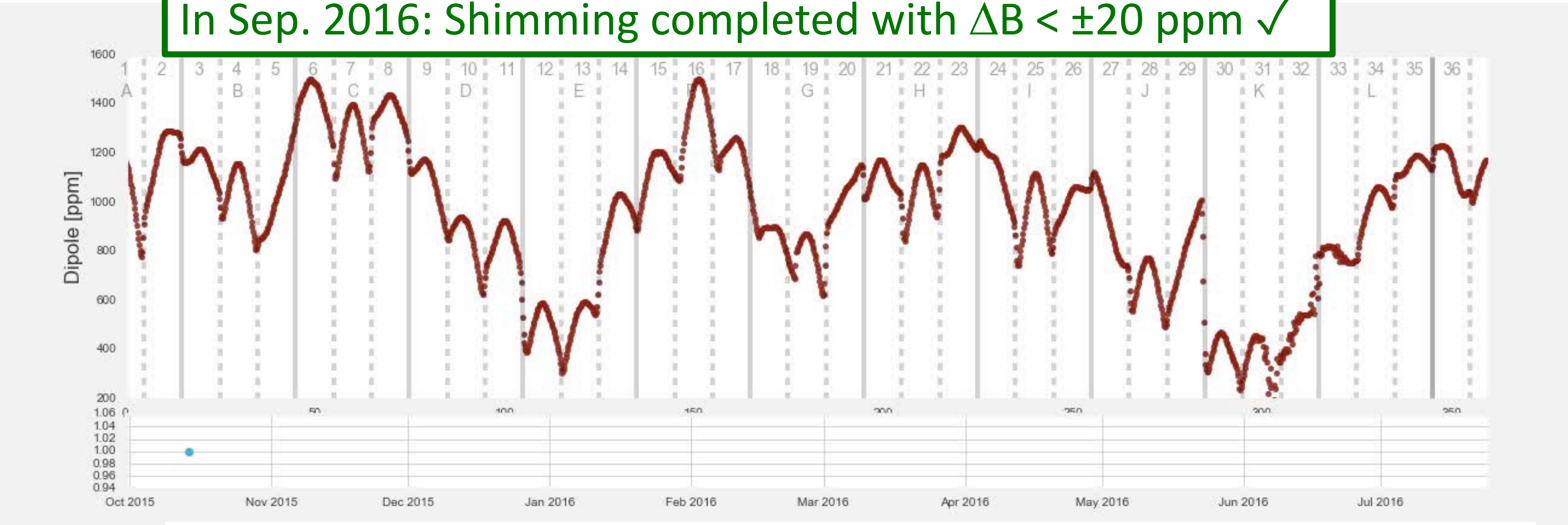
Peter Winter NuFact16

PbF_2 crystals and SiPM



10 months of improving the dipole field…

In Sep. 2016: Shimming completed with $\Delta B < \pm 20$ ppm ✓



Calibrations Poles Wedges Laminations

实验单事例灵敏度

Event selection	Value	
Online event selection efficiency	0.9	
DAQ efficiency	0.9	
Track finding efficiency	0.99	
Geometrical acceptance + Track quality cuts	0.18	
Momentum window ($\varepsilon_{\mathrm{mom}}$)	0.93	$103.6 < p_e < 106.0$ MeV/c
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3	$700 < t_e < 1170$ ns
Total	0.041	

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}},$$

Number of muons stopped inside targets

Fraction of μ-e conversion to the ground state = 0.9

Fraction of muons to be captured by Al target = 0.61

- 3×10^{-15} S.E.S. achievable in ~150 days of DAQ time corresponds to $N_\mu=1.5\times10^{16}$

日本计划的PRISM实验科学目标

PRISM

Aims:

- Address the technological challenges in realising an FFAG-based muon-to-electron conversion experiment,
- Strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.

Areas of work:

- the physics of muon to electron conversion,
- proton driver,
- pion capture,
- muon beam transport,
- injection and extraction for PRISM-FFAG ring,
- FFAG ring design including the search for a new improved version,
- FFAG hardware systems R&D.

CLFV: BESIII

J/ψ → eμ at BESIII (4)

Phys. Rev. D 87 (2013) 112007

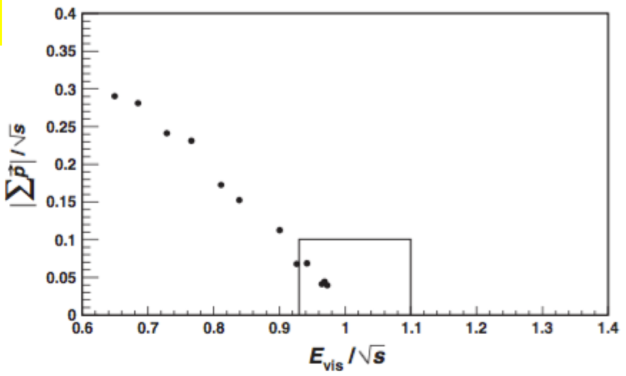


FIG. 3. A scatter plot of $E_{vis}/\sqrt{s}$ versus $|\Sigma\vec{p}|/\sqrt{s}$ for the J/ψ data. The indicated signal region is defined as $0.93 \leq E_{vis}/\sqrt{s} \leq 1.10$ and $|\Sigma\vec{p}|/\sqrt{s} \leq 0.1$.

TABLE I. Summary of systematic uncertainties (%).

Sources	Error
$e^{\pm}$ tracking	1.00
$\mu^{\pm}$ tracking	1.00
$e^{\pm}$ ID	0.62
$\mu^{\pm}$ ID	0.04
Acollinearity, acoplanarity	5.36
Photon veto	1.19
$N_{J/\psi}$	1.24
Total	5.84

$B(J/\psi \to e\mu) < N^{UL}_{obs}/(N_{J/\psi}\varepsilon) < 1.6\times10^{-7}$ @ 90% C.L.

100亿J/ψ

J/ψ→eμ

10^{-10}

J/ψ→μτ

10^{-9}

Simulated based on BESIII software and hardware systems

- $J/\psi \to \mu\tau$, $\tau \to e\upsilon_e\upsilon_\tau$
- Event topology: two opposite charged tracks, two missing tracks
- Most of the backgrounds are from $J/\psi \to \pi^+K_LK^-$, $J/\psi \to K_LK_L$, $J/\psi \to K^{*0}K^0$
- After background suppression, the detection efficiency is estimated to be 19%

With 1300 M J/ψ data

$B(J/\psi \to \mu\tau)^{sensitivity} < N^{UL}_{obs}/(N_{J/\psi}\varepsilon) < 7.3\times10^{-8}$ @ 90% C.L.

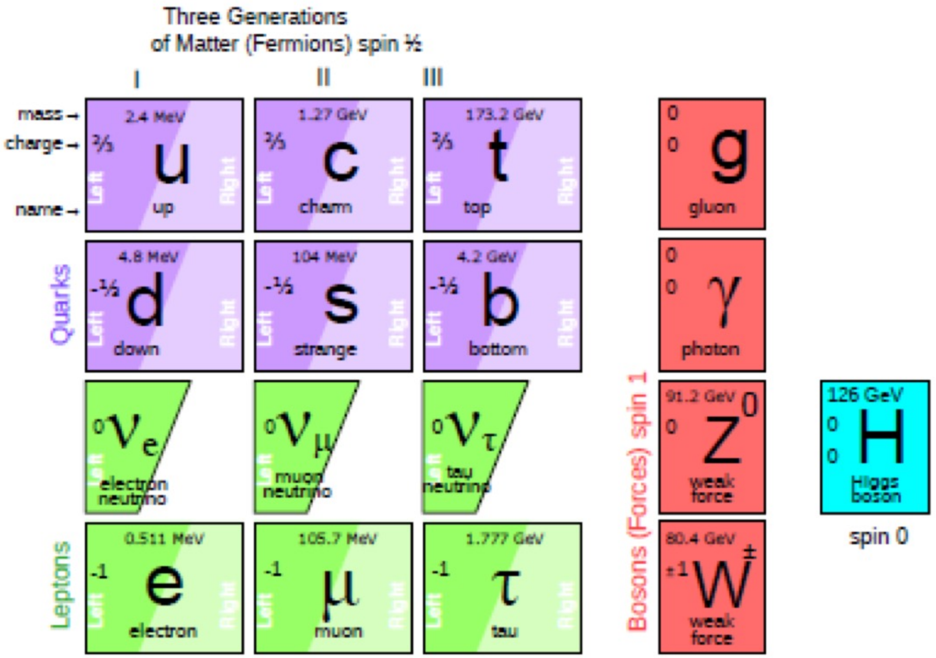
Flavor at the *Z pole*: the lepton Physics Case

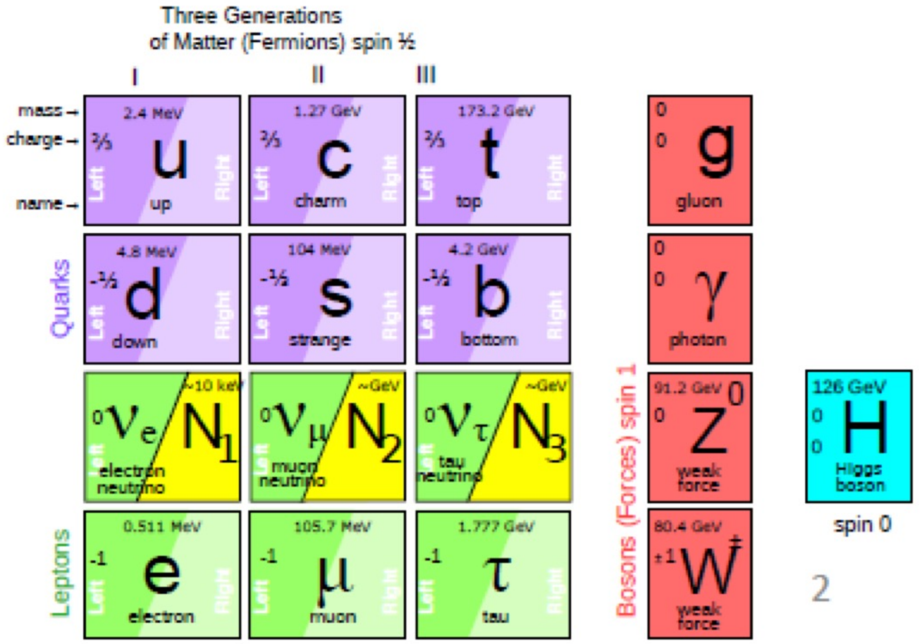
A. Blondel 2013

- Yukawa for charged fermions

$$\mathcal{L}_Y = Y^d_{ij}\bar{Q}_{Li}\phi d_{Rj} + Y^u_{ij}\bar{Q}_{Li}\tilde{\phi} u_{Rj} + Y^\ell_{ij}\bar{L}_{Li}\phi \ell_{Rj} + +\text{h.c.}$$

- Most general Lag. form for neutrals $\mathcal{L}_N = \frac{M_{ij}}{2}\bar{N}^c_i N_j + Y^\nu_{ij}\bar{L}_{Li}\phi N_j$





Flavor at the Z: the lepton Physics Case

Direct search:

$$e^+e^- \to Z \to \nu N$$
$$N \to l^+l'^-\nu, q\bar{q}'l, q\bar{q}\nu$$

Blondel, Graverinib, Serrab, Shaposhnikov arXiv:1411.5230

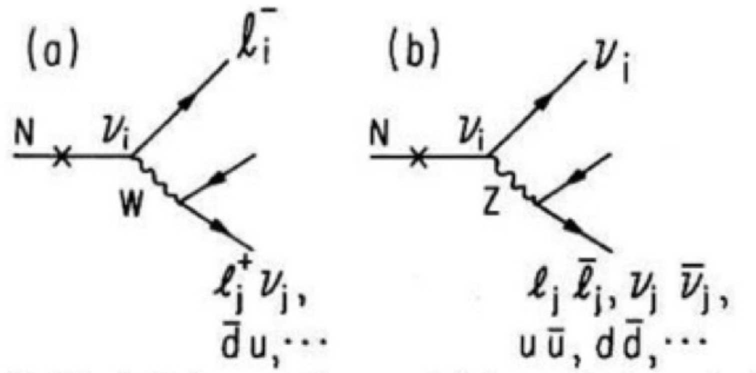


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

See next slides for constraint on mass-coupling

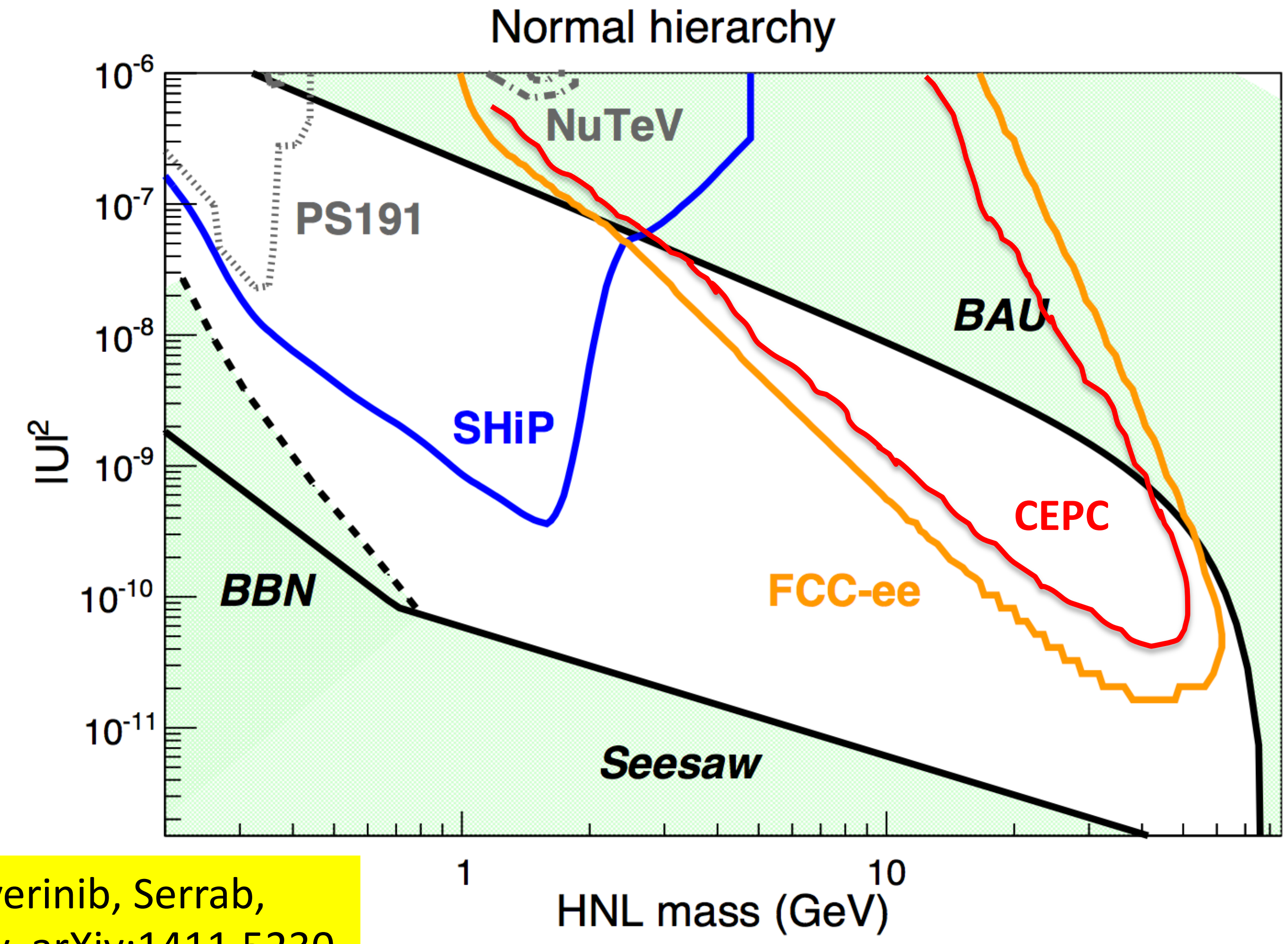
Indirect search: $e^+e^- \to Z \to NN \to l^+l^+h^-h^- + c.c.$

LNV processes to identify Majorana neutrinos

Sensitivity: 10^{-11} at CEPC.

Flavor at the *Z*: the lepton Physics Case

The parameter space which can be accessed [sensitivity figure supposing so far background-free reconstruction].



Blondel, Graverinib, Serrab, Shaposhnikov arXiv:1411.5230

(a) Decay length 10-100 cm, 10^{12} Z^0

Flavor at the Z: the lepton Physics Case

- Lepton Flavor-violating Z decays in the SM with lepton mixing are typically:

$$B(Z \to \mu e) \sim B(Z \to \tau e) \sim 10^{-54} \qquad B(Z \to \tau\mu) \sim 10^{-60}$$

- Any observation of such a decay would be an indisputable evidence for New Physics.

- Current limits at the level of ~10^{-6} (from LEP and recently ATLAS, *e.g*. DELPHI, Z. Phys. C73 (1997) 243 ATLAS, CERN-PH-EP-2014-195 (2014))

- The CEPC high luminosity Z factory would allow to gain up to five/six orders of magnitude: 10^{-11} — 10^{-12}
- Complementary to the direct search for steriles.

The following plots are based on a work from V. De Romeri et al.

Flavor at the Z: the lepton Physics Case

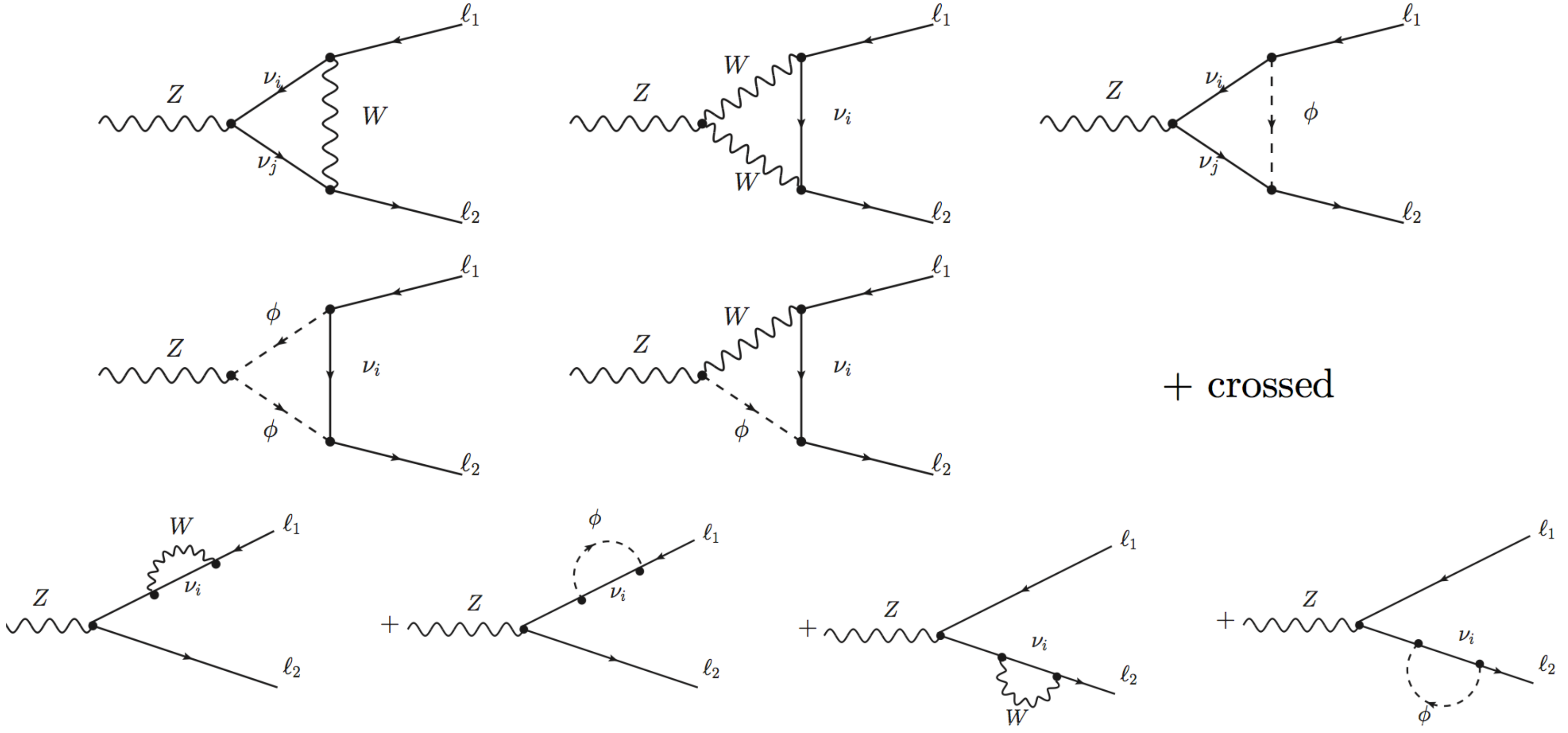
Low energy constraint: $B(\tau \rightarrow \mu\mu\mu) < 2.1 \times 10^{-8}$

$B(\mu \to e\gamma) < 5.2 \times 10^{-13}$ -> $B(Z \rightarrow \mu e) < 10^{-10}$

No strong constraint on $Z \rightarrow \tau\mu$ and τe A. Abada et al. arXiv:1412.6322

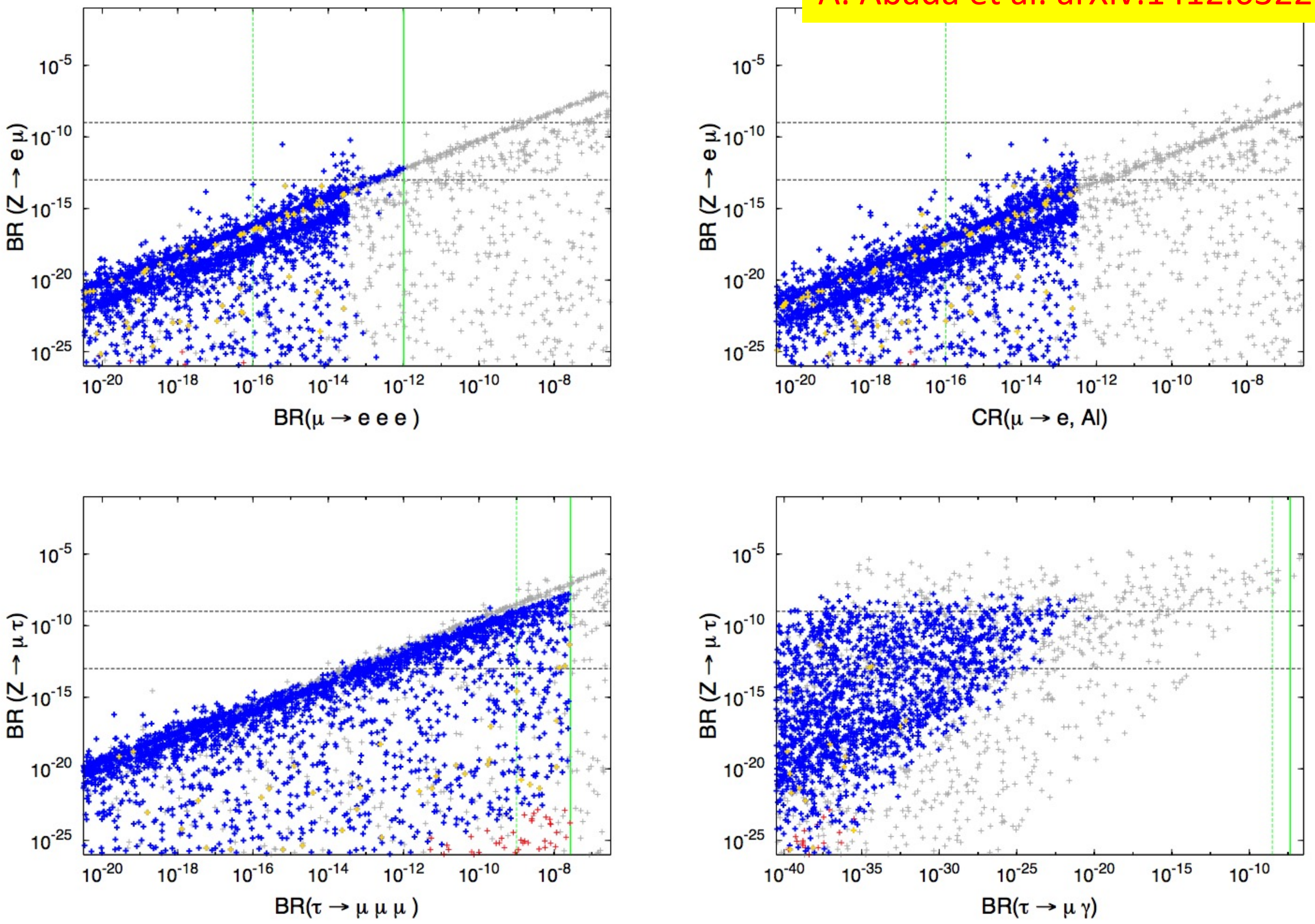
S. Davidson et al. JHEP 1209 (2012) 092

Examples of model realizations: physical states: 3 + N extra Majorana



Flavor at the *Z*: the lepton Physics Case

A. Abada et al. arXiv:1412.6322



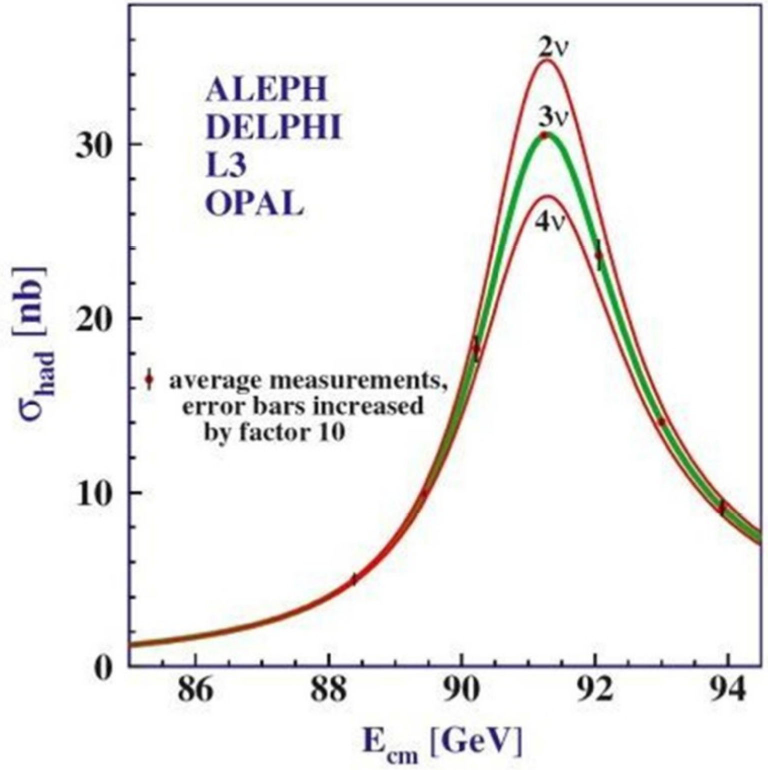
Flavor at the Z: the lepton Physics Case

Direct search: $$n_\nu = \left(\frac{\Gamma_{inv}}{\Gamma_{lept}}\right)^{meas} / \left(\frac{\Gamma_{inv}}{\Gamma_{lept}}\right)^{SM}$$

$$n_\nu = 2.9840 \pm 0.0082$$ LEP

0.004 CEPC

Limited by uncertainty due to calculation of Bhabha scattering. Improved by a factor of 2-3 at CEPC



Direct search: one year run at E=105 GeV

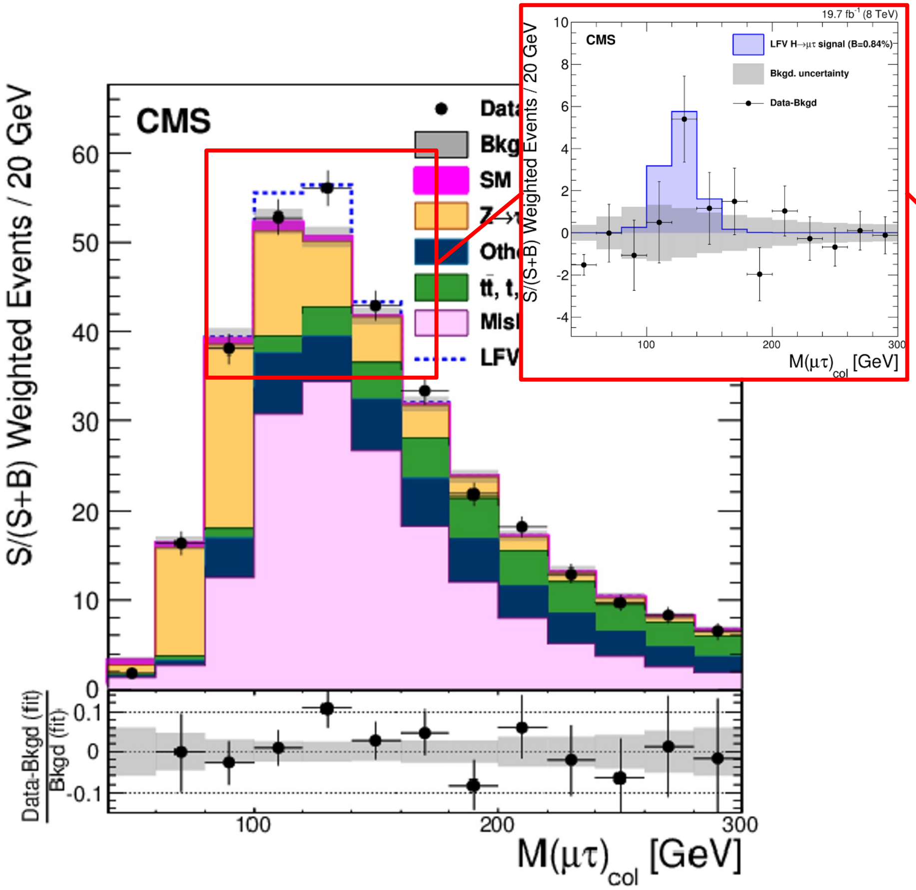
$$n_\nu = \left(\frac{e^+e^- \to \gamma Z_{inv}}{e^+e^- \to \gamma Z_{lept}}\right)^{meas} / \left(\frac{\Gamma_{inv}}{\Gamma_{lept}}\right)^{SM}$$

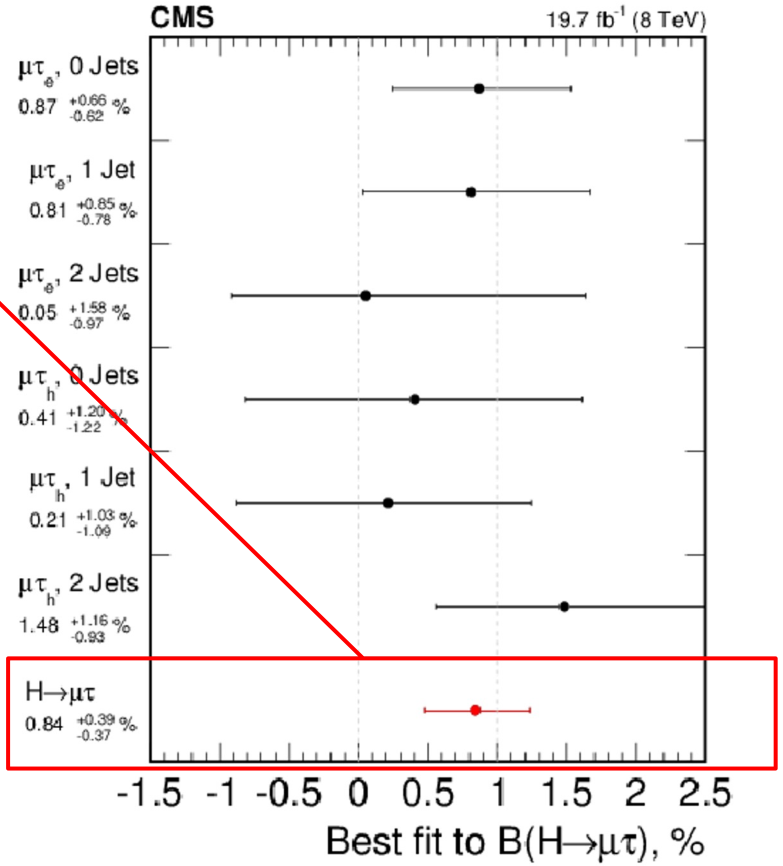
$$\Delta n_\nu = \pm 0.0008$$

Blondel, Graverinib, Serrab, Shaposhnikov arXiv:1411.5230

寻找轻子味破坏的汤川耦合 H→μτ at CMS (8 TeV)

Excess: ~2.4σ excess
Best Fit B(H→μτ)=0.84±0.39%

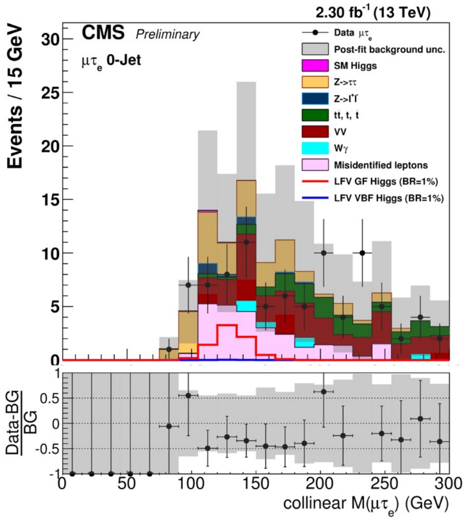


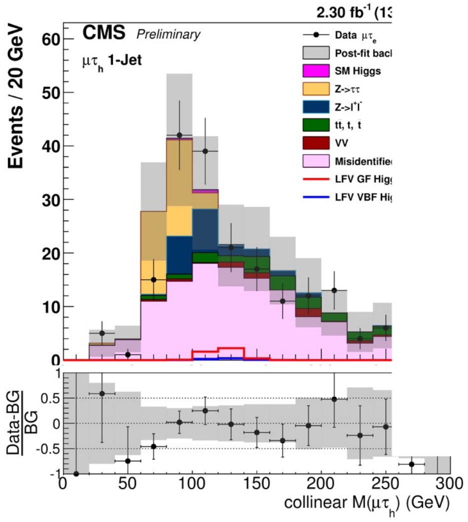


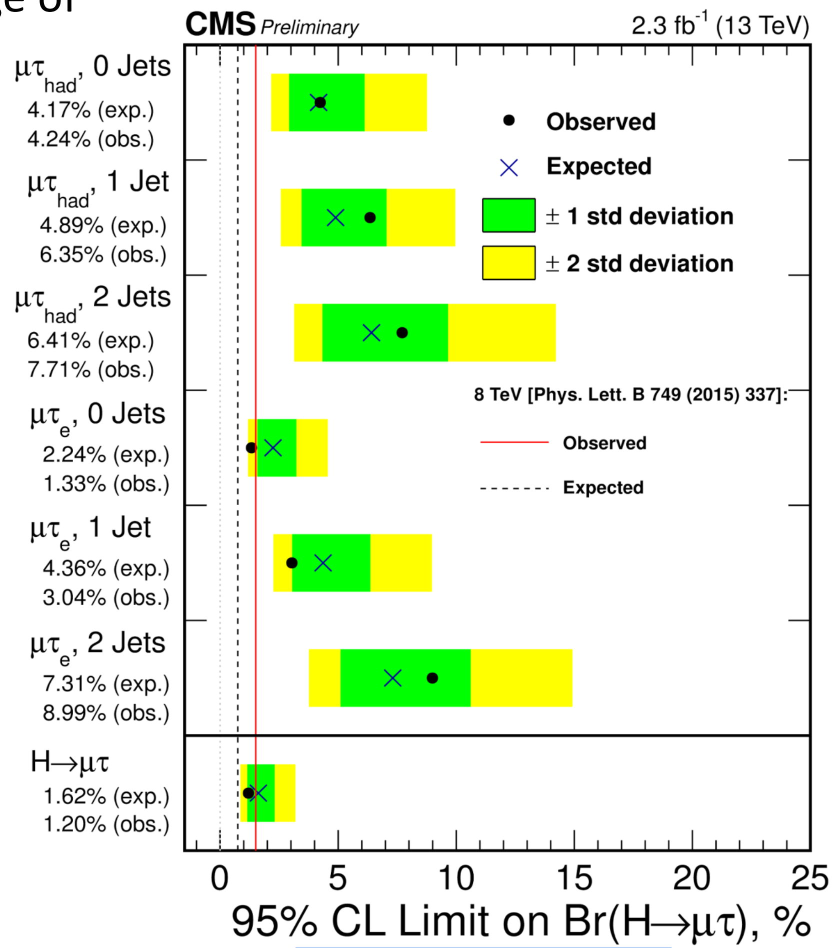
Phys. Lett. B 749 (2015) 337

寻找轻子味破坏的汤川耦合 H→μτ at CMS (13 TeV)

- Repetition of 8TeV H→μτ analysis: no change of strategy and kinematic cuts
- **Slight excess of 8TeV analysis could not be confirmed so far, but also not excluded!**
- Updated B(H→μτ) Limit: B(H→μτ)<1.2% observed (1.62% expected)







CMS-PAS-HIG-16-005

CLFV 唯象模型

Kazuhiro Tobe CLFV2016

Some models motivated by the exp. data

(sorry for only incomplete list of Refs)

★ Lepton-specific (type X) two Higgs doublet model

A. Crivellin, J. Heeck, P. Stoffer, PRL 116, 081801 (2016)

"muon g-2"+ $R(D^{(*)})$ (+"h→$\mu\tau$") → light H, t→Hc, ($\tau\to\mu\gamma$)…

★ $L_\mu - L_\tau$ model

W. Altmannshoher, M. Carena, A. Crivellin, 1604.0822

"muon g-2"+ "h→$\mu\tau$"+" R_K " → $\tau\to 3\mu$, h→$\mu\mu$, …

★ Leptoquark model

S. Baek, K. Nishiwaki, PRD93, 015002 (2016)

"muon g-2"+ "h→$\mu\tau$" → $\tau\to\mu\gamma$, …

★ General (type-III) two Higgs doublet model

Y. Omura, E. Senaha, K. Tobe, 1511.08880, JHEP 1505, 028 (2015)

"muon g-2"+ "h→$\mu\tau$" → $\tau\to\mu\gamma$, tau decay, …