Probing μτ flavor violating solutions for the muon g-2 anomaly at Belle II

IPA2022 Vienna
Sept. 5–9, 2022

Syuhei Iguro

・Inspire
・Web page

Karlsruher Institut für Technologie

Based on

JHEP 09 (2020) 144 with Y. Omura, M. Takeuchi

See also for the relevant works
JHEP 1911 (2019) 130 with Y. Omura, M. Takeuchi,
Phys.Rev.D 101 (2020) 7, 075011 with C.-P. Yuan, A. Kirtmaan,
JHEP 06 (2020) 040 with M. Endo, T. Kitahara,

Thanks for the invitation

Key words: Flavor, collider experiment, lepton flavor violation

Menu

- Introduction of the muon g-2 and status
- Our simplified model
  -- scalar with LFV interactions
- Collider signal
  -- Belle II prospect
- Summary

Our SM is a very good theory to describe almost all measurements

,,,,

However, large part of theorists is not satisfied with the SM.

Mysteries of the SM

Dark Matter, neutrino masses, matter vs antimatter asymmetry, strong CP problem, fine turning of Higgs mass, Yukawa hierarchy,,,,,

Each problem has several New Physics (NP) solutions and we need further hints to specify the scenario!

Deviations in flavor physics may be a hint for NP?

muon g-2 anomaly

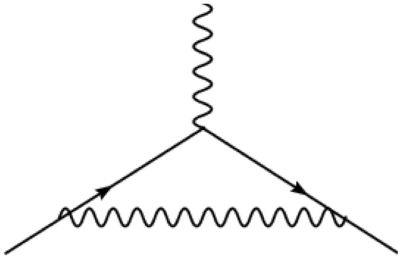
Overview: yesterday by Carlo Ferrari

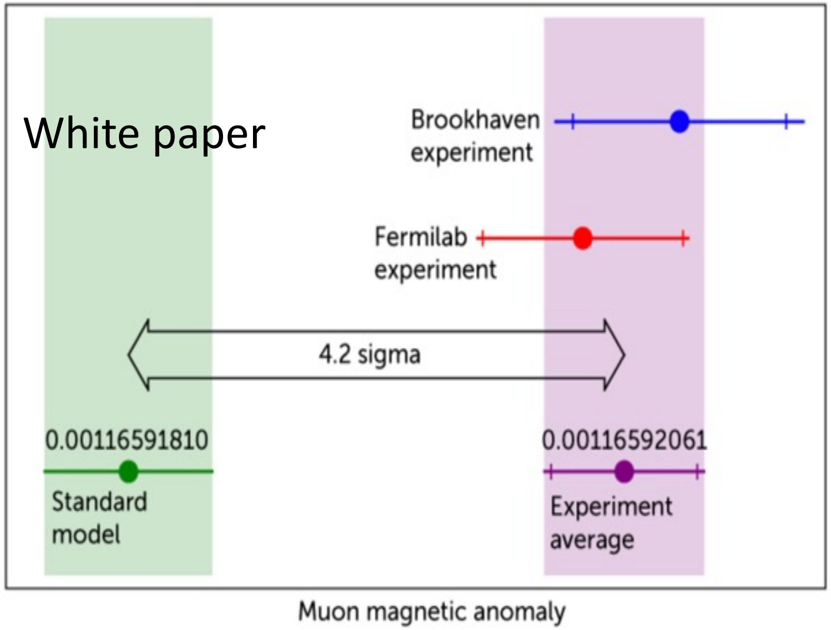
$$\vec{\mu} = -g\frac{e}{2m}\vec{S}$$

$\vec{\mu}$: Magnetic moment of the muon

g=2: tree level corresponds to 2 freedoms (spin up and down)

Anomalous magnetic moment: $\alpha_\mu = (g-2)/2$





Many developments

Theoretical calculation:
5-loop QED, lattice calculation,
Hadronic Light-by-Light,
Hadronic Vacuum Polarization,,,

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} \sim 2.5\times10^{-9}$$

Recent lattice favors smaller gap but
new problem arises in the EW fit, $e^+e^- \to 2\pi$
2003.04886, 2006.12666

Hint for BSM?

If this anomaly is true, we have a hint for new physics!

g-2

My criteria of the anomaly

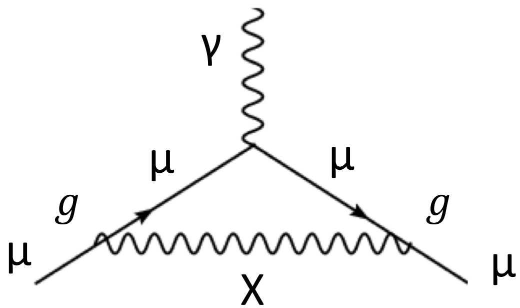
- Long standing? -> yes. 20 years old
- Multiple experiments? -> yes but need J-PARC
- Statistical significance? -> yes, 4.2σ

$R_{D,}$ R_K

What kind of new physics you need?

Naïve new physics scale to explain muon g-2 anomaly.

$$L \sim \frac{e\Delta a_\mu}{m_\mu} \mu_L \sigma^{\mu\nu} \mu_R F_{\mu\nu}$$



If new particle X appear at 1-loop with a flavor conserving coupling

$g \sim g_W = 0.66$

$$\Delta a_\mu \sim \frac{g^2}{16\pi^2}\frac{m_\mu^2}{m_X^2} \sim 3\times 10^{-9}\left(\frac{100\text{GeV}}{m_X}\right)^2$$

EW scale！

No signal in LHC so far

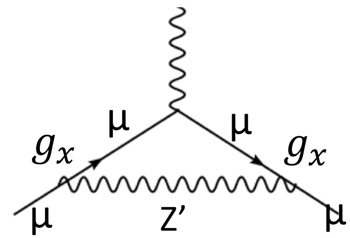
What kind of new physics scenarios are still allowed?

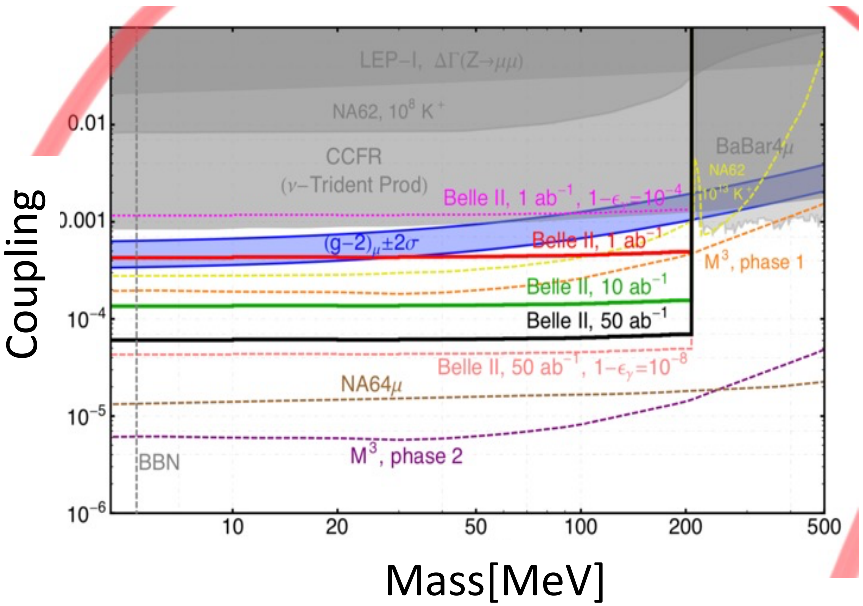
Light particle is available.

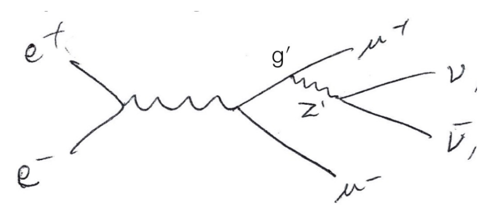
flavor conserving regime

e.g. Z’: $L_\mu - L_\tau$ (global U(1)).

particle	$L_2 = (\nu_{\mu L}, \mu_L)$	$L_3 = (\nu_{\tau L}, \tau_L)$	$(\mu_R)^c$	$(\tau_R)^c$	$(\nu_{\mu R})^c$	$(\nu_{\tau R})^c$	others
charge	$+1$	-1	-1	$+1$	-1	$+1$	0

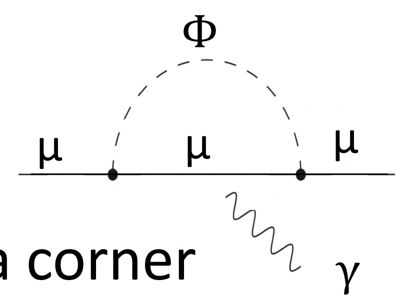






1904.13053:2μ+missing

The scenario will be explored soon in Belle II!



also

Heavy scenario like muon specific 2HDM is driven into a corner and will be fully probed at LHC in near future.

1705.01469 and S. Iguro w.i.p

What's else?

If there is some mechanism to enhance the contribution of Δa_{μ}, heavier mass and/or smaller coupling are enough for muon g-2.
Then it is more easy to evade constraints.

$$\Delta a_{\mu} \sim \frac{g^2}{16\pi^2}\frac{m_{\mu}^2}{m_X^2} \sim 3\times 10^{-9}\left(\frac{100\mathrm{GeV}}{m_X}\right)^2$$

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One solution is

Chirality enhancement

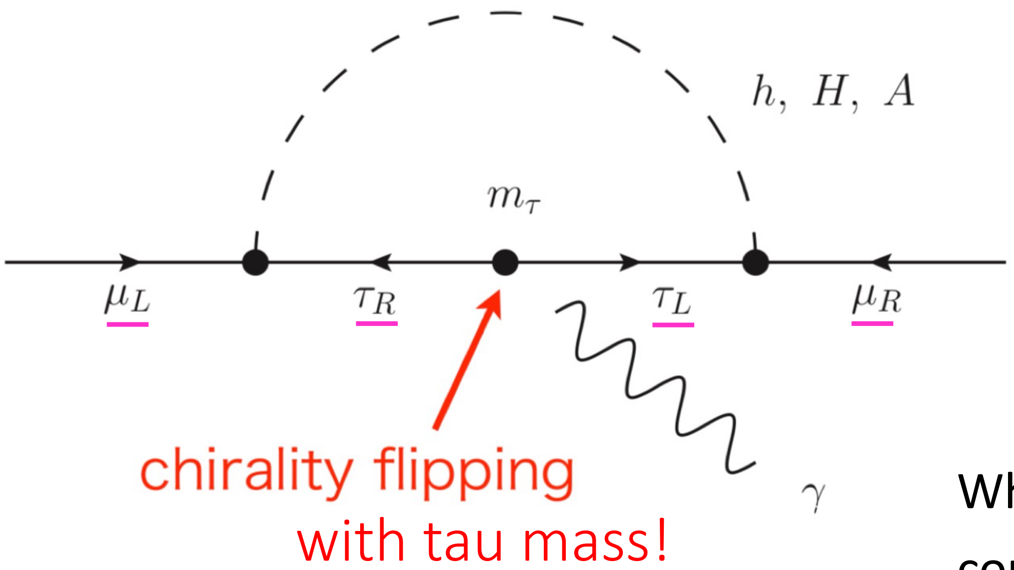
Chirality enhancement

$$\frac{e\Delta a_\mu}{m_\mu}\mu_L\sigma^{\mu\nu}\mu_R F_{\mu\nu}$$

$\Delta a_\mu \propto m_\mu^2$ for common scenarios

Chirality flip with a heavy internal fermion mass(>> m_μ)

e.g. flip with tau mass



$$\frac{m_\tau}{m_\mu}\sim 17$$

When $\Delta a_\mu \propto coupling^2$,
coupling can be smaller by $\sqrt{17}$

Such a particle can explain muon g-2 with smaller couplings

Model examples

- τμ flavor violating scalars S. Nie and M. Sher 9875376
- τμ flavor violating gauge boson,

  Soni,et al 1607.06832

τ mass enhancement

$m_\tau/m_\mu \sim 17$

- Scalar leptoquark (LQ) is also discussed

  Bauer,Neubert 1511.01900

Top mass enhancement

$m_t/m_\mu \sim 1600$

- Mixing with heavy vector like leptons

  Czarnecki,Marciano0102122

Heavy lepton mass enhancement

$m_L/m_\mu \sim 10 \times m_L$[GeV]

Menu

- Introduction
- Simple Model
- Belle II signal
- Summary

One realistic model

Tsumura, Abe,Toma 1904.10908

$(SU(3)_c, SU(2)_L)_{U(1)_Y}$ Discrete symm.

Particle	SM	Z_4
(L_e, L_μ, L_τ)	$(1,2)_{-1/2}$	$(1, i, -i)$
(e_R, μ_R, τ_R)	$(1,1)_{-1}$	$(1, i, -i)$
H	$(1,2)_{1/2}$	1
New entry Φ	$(1,2)_{1/2}$	-1

$$\Phi = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

Additional neutral scalars: H,A

Extra singlet scalar is needed for the neutrino masses

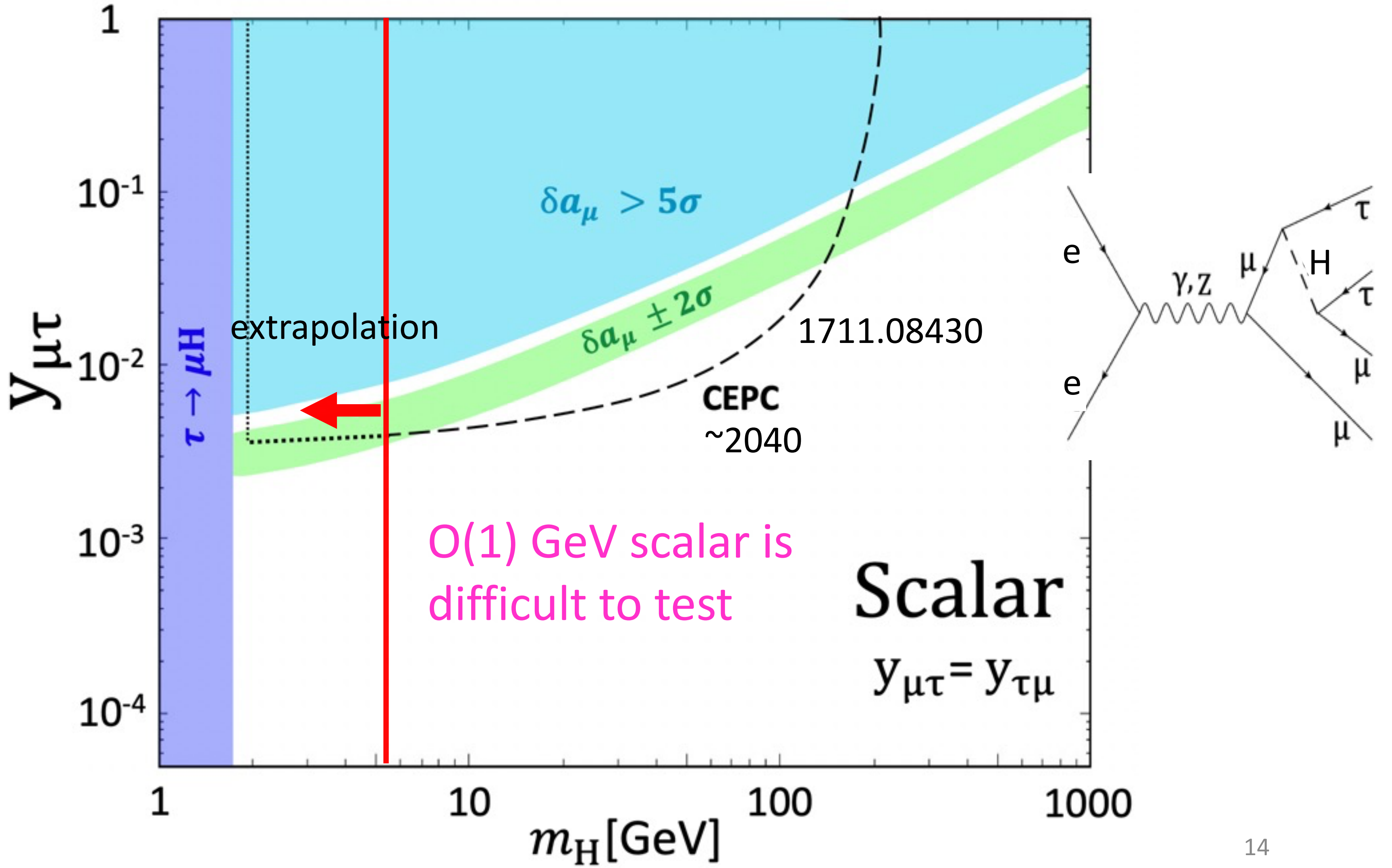
$$-\mathcal{L}_{Z_4}^{\text{yukawa}} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & y_{\mu\tau}\Phi^\dagger \\ & y_{\tau\mu}\Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

Additional scalars in Φ can only couple to $\mu\tau$. $m_H << m_A = m_{H+}$

We only consider a scalar (H) as a demonstration

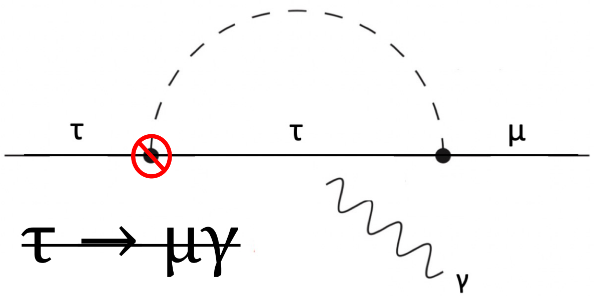
muon $g-2$ in μτ philic scalar model

2002.12728 S. Iguro et al

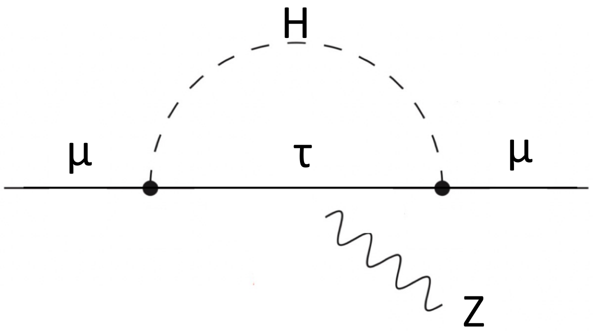


Other constraints?

Diagonal coupling is prohibited by Z_4 symmetry



~~$\tau \to \mu\gamma$~~



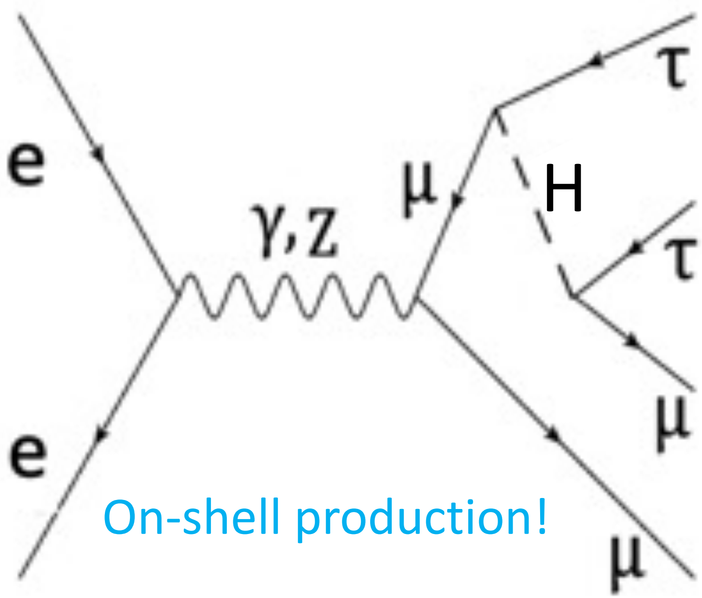
If only LFV couplings are sizable,
it is difficult to test in flavor physics.

・1-loop contribution to $Z \to \mu\mu$ is small.
=> the correction is 1-2 order smaller than LEP sensitivity.

・Additional scalar does not talk to quarks.
$\Rightarrow$ LHC production cross section is small and difficult for a GeV order scalar due to threshold (interesting for EW scale scenario (Discussed later)).

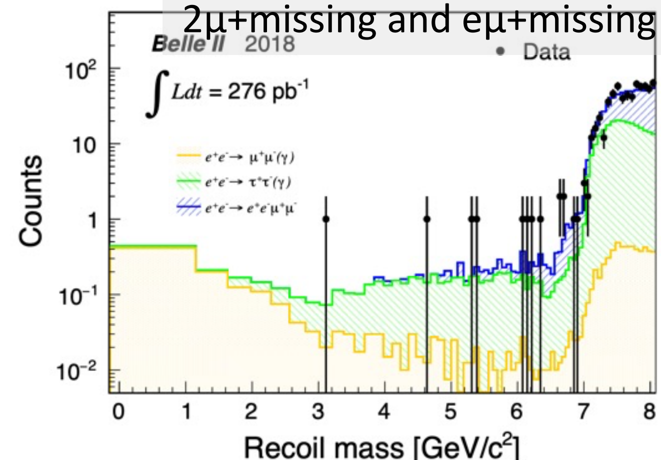
How we test the light scenario?

Proposal: $\mu^{\mp}\mu^{\mp}\tau^{\pm}\tau^{\pm}$ final state in Belle II

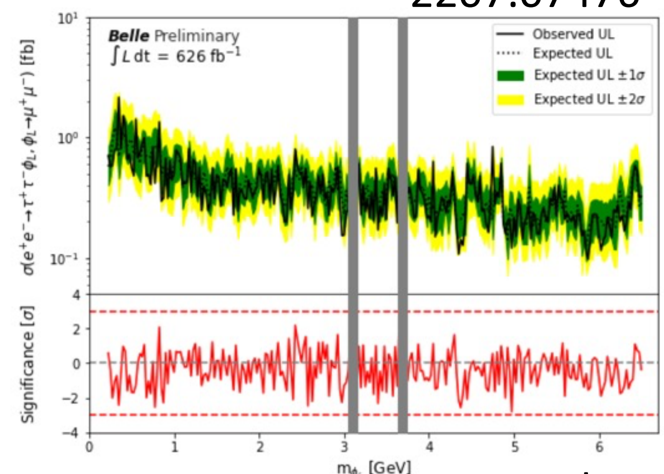


On-shell production!

Similar to Belle II 1912.11276
2μ+missing and eμ+missing



2207.07476



2τ+2l

Distinctive features of our signal

- μτ LFV resonance
- same sign lepton pairs

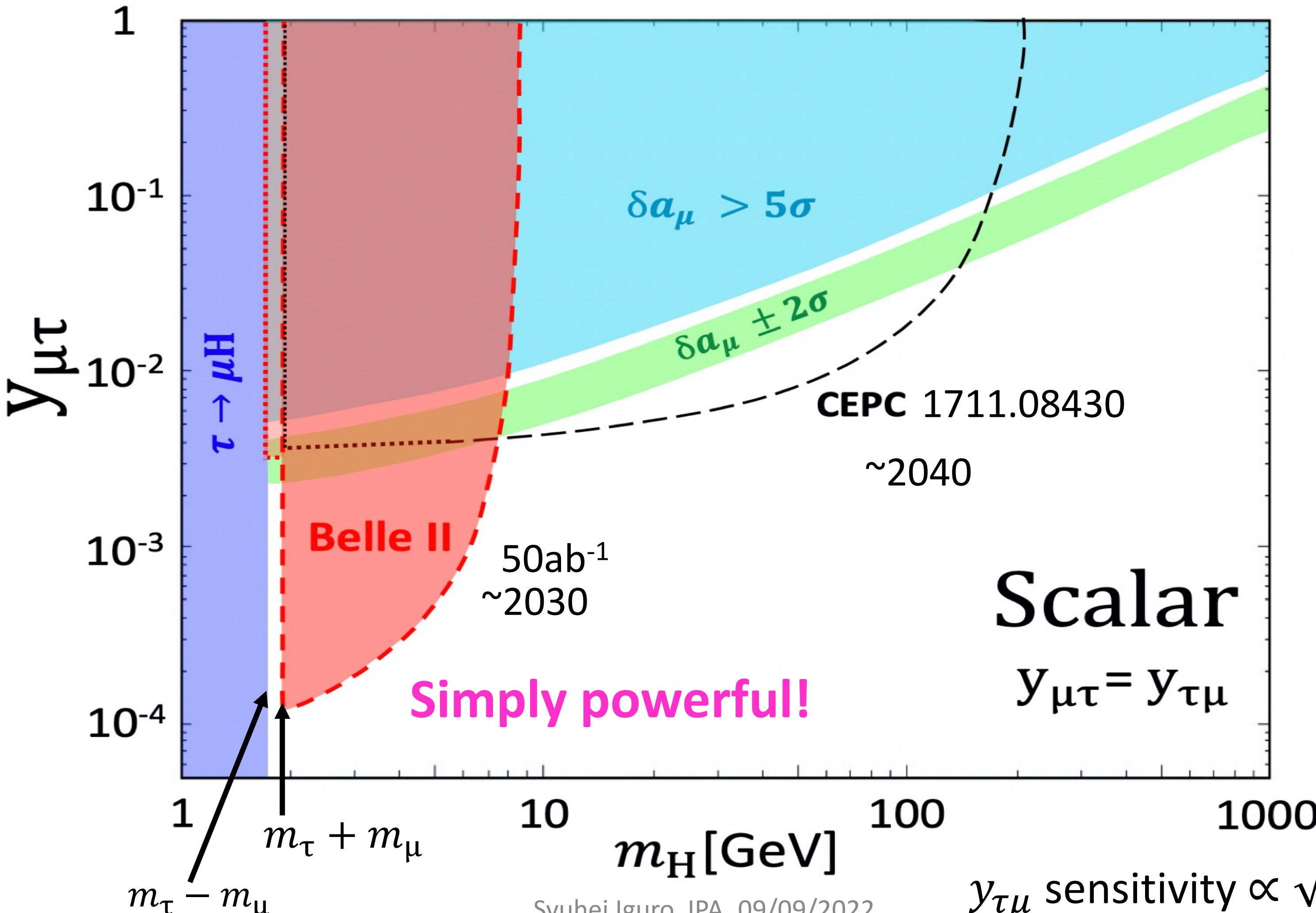
We required that all the visible particles are within the detector

Madgraph + Pythia 8

assuming BG free

$g-2$ in μτ-philic scalar model at Belle II

2002.12728 S. Iguro et al



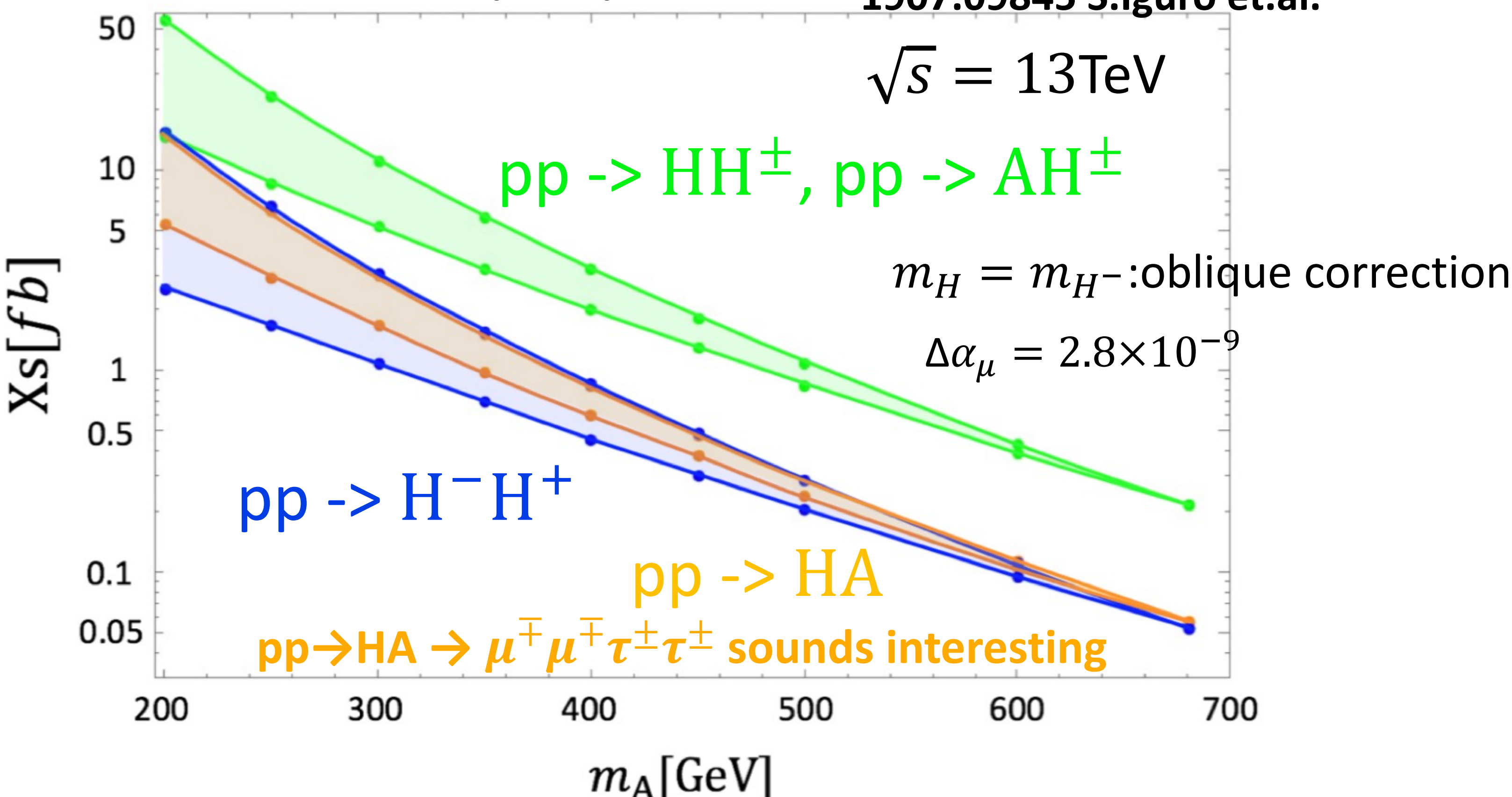
$y_{\tau\mu}$ sensitivity $\propto \sqrt{L}$

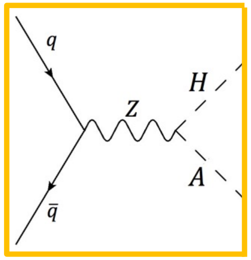
Heavy scalar scenario

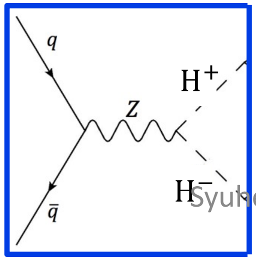
Electroweak production in LHC

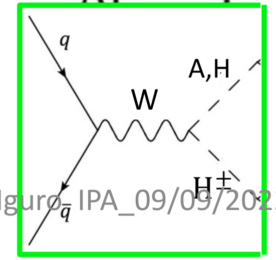
- Maximum mass gap in H and A is given as $m_H^2 = m_A^2 + \lambda_5 v^2 = m_A^2 + v^2$ (for $\lambda_5 < 1$)
- Minimum mass gap is given by $|y_e^{\mu\tau}|, |y_e^{\tau\mu}| < 1$.

1907.09845 S.Iguro et.al.









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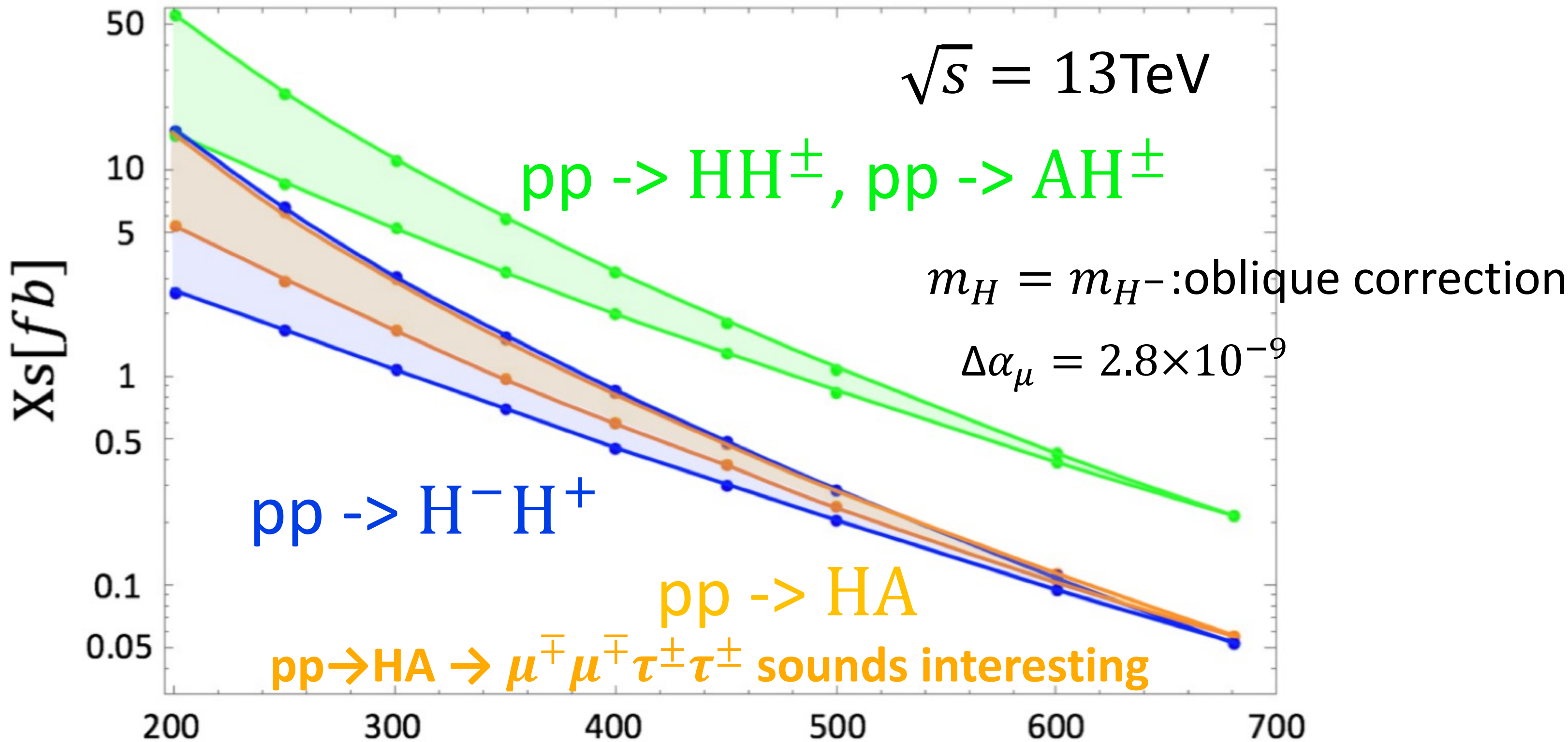
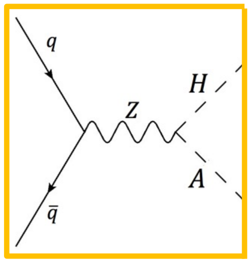




Run 2 data is sensitive up to 500 GeV.

HL-LHC is sensitive up to 1150 GeV.

S. Iguro and M. Blanke (KIT) coming soon.

Summary

$\mu\tau$ lepton flavor violating scalars can explain the muon g-2 discrepancy.

The model predicts distinctive $\mu^{\mp}\mu^{\mp}\tau^{\pm}\tau^{\pm}$ final state in colliders.

Belle II with $50ab^{-1}$ can test the scenario when the mass is O(1) GeV.

LHC is also important for the heavy scenario.

Comment: However, I skipped in this talk, the $\mu\tau$ LFV scalar model can explain the dark matter and neutrino masses with singlet scalars in type-I seesaw. See, 2205.08998 for model setup.

Thank you!

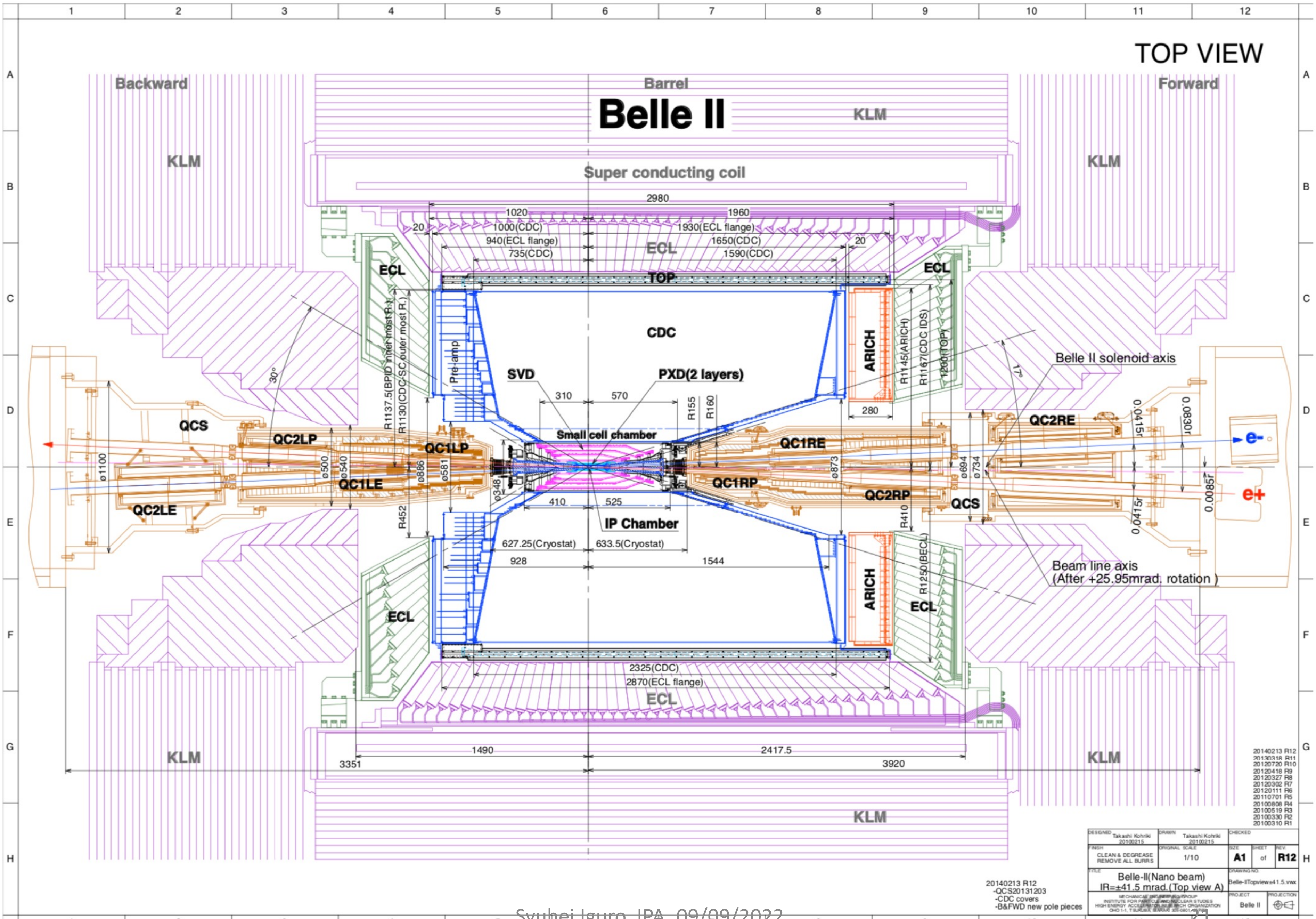

TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
TOP
CDC
ARICH
SVD
PXD(2 layers)
Small cell chamber
IP Chamber
Pre-amp
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC1RE
QC1RP
QC2RE
QC2RP
Belle II solenoid axis
Beam line axis
(After +25.95mrad. rotation)
e-
e+
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)
20140213 R12
-QCS20131203
-CDC covers
-B&FWD new pole pieces

Table 17: Summary of the detector components.

Purpose	Name	Component	Configuration	Readout channels	θ coverage
Beam pipe	Beryllium		Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm paraffin, 0.4 mm Be		
Tracking	PXD	Silicon Pixel (DEPFET)	Sensor size: 15×(L1 136, L2 170) mm^2, Pixel size: 50×(L1a 50, L1b 60, L2a 75, L2b 85) μm^2; two layers at radii: 14, 22 mm	10M	[17°;150°]
	SVD	Silicon Strip	Rectangular and trapezoidal, strip pitch: 50(p)/160(n) - 75(p)/240(n) μm, with one floating intermediate strip; four layers at radii: 38, 80, 115, 140 mm	245k	[17°;150°]
	CDC	Drift Chamber with He-C_2H_6 gas	14336 wires in 56 layers, inner radius of 160mm outer radius of 1130 mm	14k	[17°;150°]
Particle ID	TOP	RICH with quartz radiator	16 segments in ϕ at $r \sim 120$ cm, 275 cm long, 2cm thick quartz bars with 4×4 channel MCP PMTs	8k	[31°;128°]
	ARICH	RICH with aerogel radiator	2×2 cm thick focusing radiators with different n, HAPD photodetectors	78k	[14°;30°]
Calorimetry	ECL	CsI(Tl)	Barrel: $r = 125 - 162$cm, end-cap: $z = -102 - +196$cm	6624 (Barrel), 1152 (FWD), 960 (BWD)	[12.4°;31.4°], [32.2°;128.7°], [130.7°;155.1°]
Muon ID	KLM	barrel:RPCs and scintillator strips	2 layers with scintillator strips and 12 layers with 2 RPCs	θ 16k, ϕ 16k	[40°;129°]
	KLM	end-cap: scintillator strips	12 layers of (7-10)×40 mm^2 strips	17k	[25°;40°], [129°;155°]

Muon specific 2HDM is available.

flavor conserving

1705.01469, Abe et al.

$$H_1 = \begin{pmatrix} H^+ \\ \frac{H + iA + v'}{\sqrt{2}} \end{pmatrix} \quad H_2 = \begin{pmatrix} G^+ \\ \frac{v'' + h + iG}{\sqrt{2}} \end{pmatrix}$$

tanβ=v''/v' $\quad v = \sqrt{v'^2 + v''^2}$

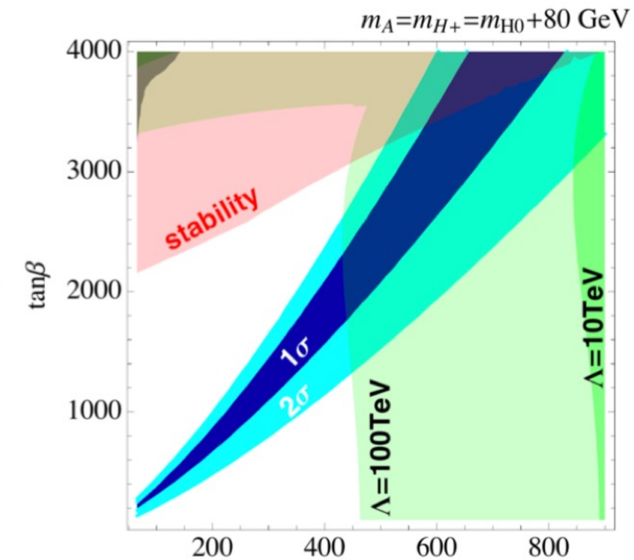
Table I: Particle contents and the charge assignment.

	q_L^j	u_R^j	d_R^j	ℓ_L^e	ℓ_L^τ	ℓ_L^μ	e_R	τ_R	μ_R	H_1	H_2
$SU(3)_c$	3	3	3	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	2	2	1	1	1	2	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1/2	−1/2	−1	−1	−1	1/2	1/2
Z_4	1	1	1	1	1	i	1	1	i	−1	1

$i = e^{i\frac{\pi}{2}}$

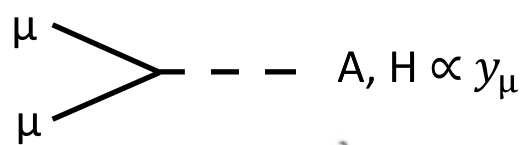
H_1 only couples to μμ

$$\mathcal{L}^{\text{Yukawa}} = -\bar{q}_L \tilde{H}_2 Y_u u_R - \bar{q}_L H_2 Y_d d_R - \bar{L}_L H_1 Y_{\ell 1} E_R - \bar{L}_L H_2 Y_{\ell 2} E_R + (h.c),$$

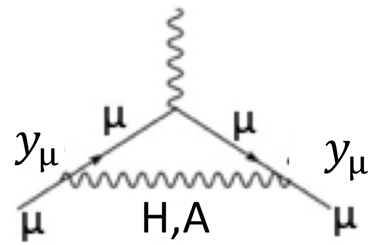


$$Y_{\ell 1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\mu \end{pmatrix}$$

$$y_\mu = \frac{\sqrt{2} m_\mu}{v} \sqrt{1 + t_\beta^2} \simeq 0.6 \left(\frac{t_\beta}{1000} \right)$$



$$m_\mu = \frac{v}{\sqrt{2}} \frac{y_\mu}{\sqrt{1 + t_\beta^2}}, \quad m_f = \frac{v}{\sqrt{2}} \frac{y_f t_\beta}{\sqrt{1 + t_\beta^2}} \quad \text{others}$$



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flavor conserving

1705.01469

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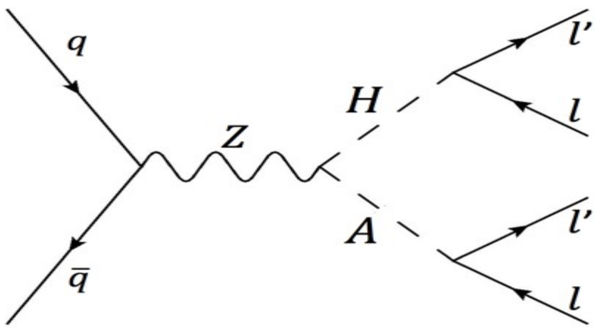
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1/2	−1/2	−1	−1	−1	1/2	1/2
Z_4	1	1	1	1	1	i	1	1	i	−1	1

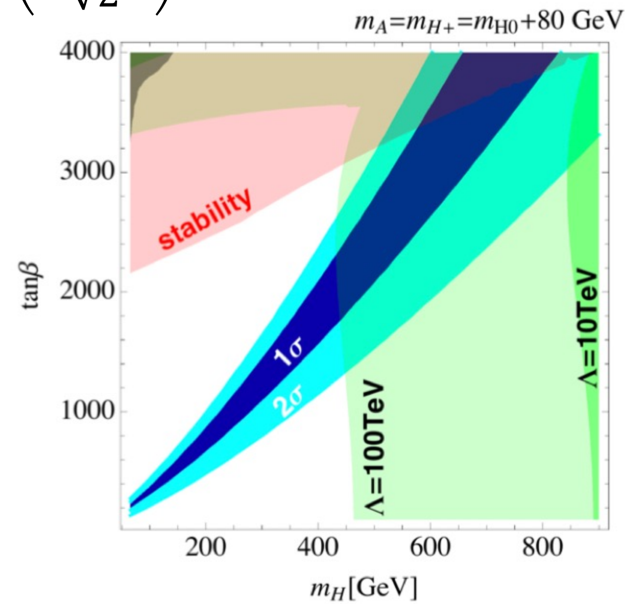
$$H_1 = \begin{pmatrix} H^+ \\ \frac{H + iA}{\sqrt{2}} \end{pmatrix}$$ in large tanβ limit

H_1 only couples to μμ

$$\mathcal{L}^{\text{Yukawa}} = -\bar{q}_L \tilde{H}_2 Y_u u_R - \bar{q}_L H_2 Y_d d_R - \bar{L}_L H_1 Y_{\ell 1} E_R - \bar{L}_L H_2 Y_{\ell 2} E_R + (h.c),$$

$$Y_{\ell 1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\mu \end{pmatrix}$$





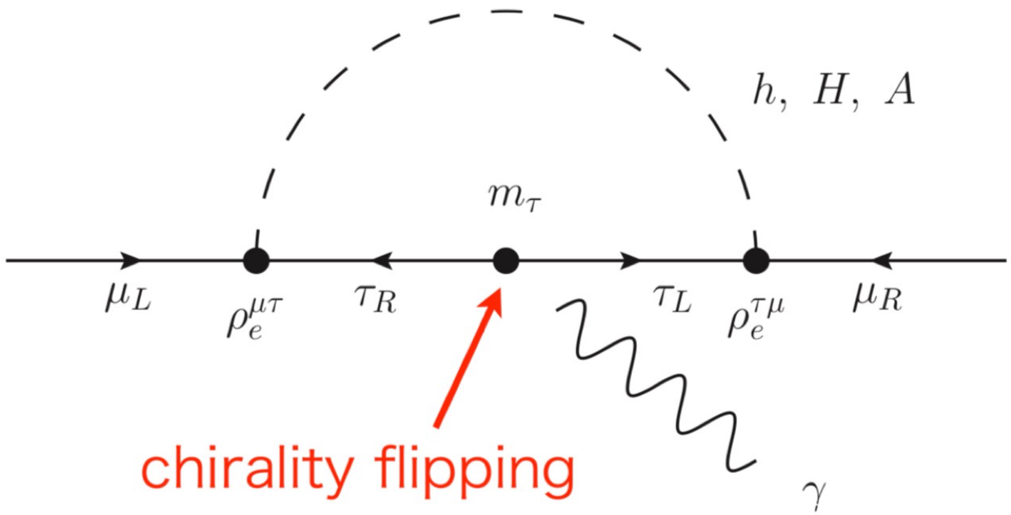
Multi lepton search in LHC(36fb^-1)

$m_H \lesssim 640$ GeV is excluded at 95% CL

The scenario will be explored in LHC!

Light pseudo scalar scenario in 2HDM is also available (Barr-Zee)

g-2 contribution



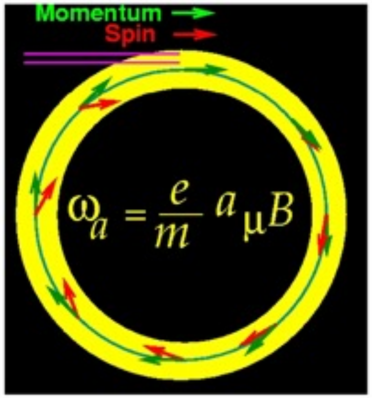
Notation: y <-> ρ

$O\left(\frac{m_\tau}{m_\mu}\right)$ enhancement

$$\Delta a_\mu \simeq \frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{16\pi^2}\left(\frac{\ln\frac{m_H^2}{m_\tau^2}-\frac{3}{2}}{m_H^2}-\frac{\ln\frac{m_A^2}{m_\tau^2}-\frac{3}{2}}{m_A^2}\right)$$

muon g-2 and EDM measurements

In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0



general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL E821 approach
γ=30 (P=3 GeV/c)

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

FNAL E989

J-PARC approach
E = 0 at any γ

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

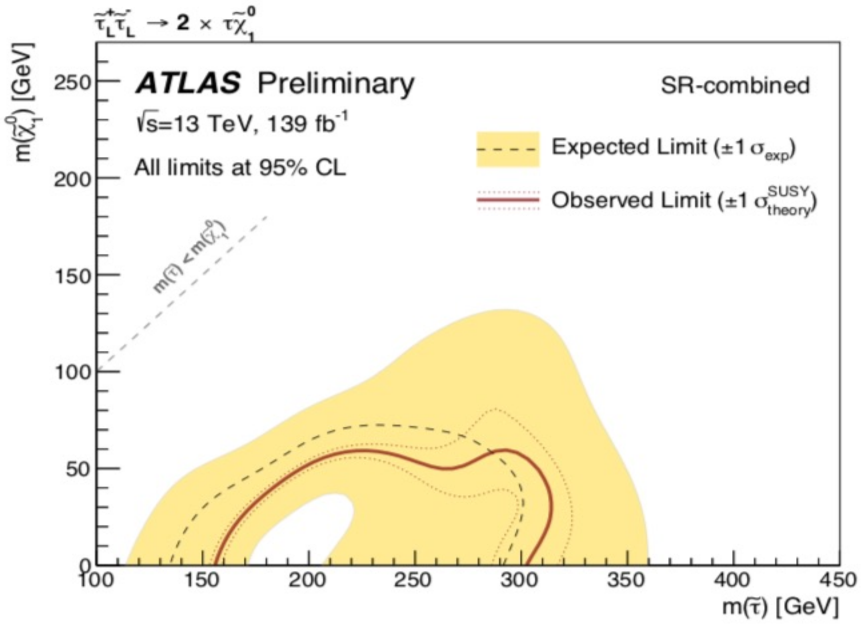
J-PARC E34

Slide by Mibe-san

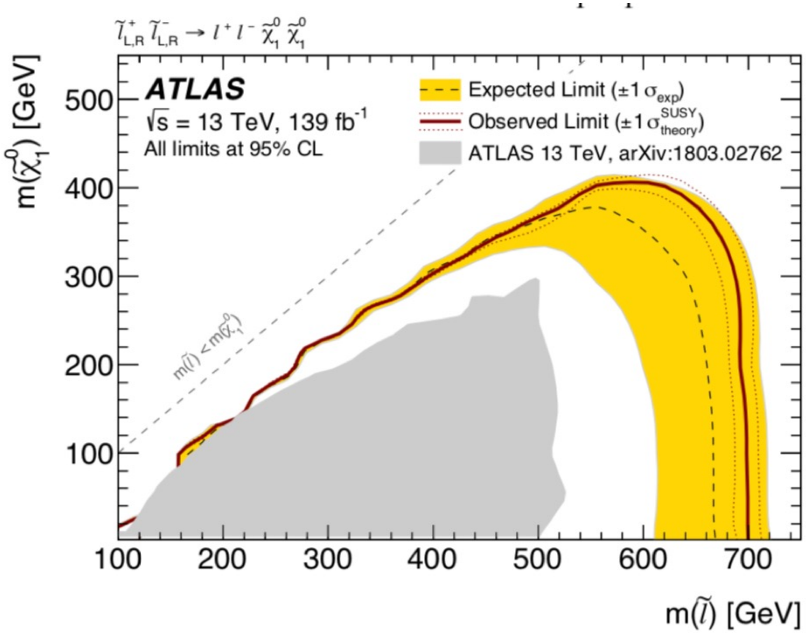
Slepton search

Left-handed slepton has the same quantum number as H^+ has.

stau



smuon



150-300 GeV with BR($H^- \to \tau\nu$)=1
Is excluded

All $\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L$ and $\tilde{\mu}_R$ are combined

We still have room for m_{H^+}= 120 GeV

Concern

- SMBG from 4τ？