flavor anomalies meet the LHC

Before coming here

FCCP Capri, Italy
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Based on
[2202.10468](), [2201.06565](), [1907.09845](),
[2111.04748](), [2011.02486](), [1810.05843](), [1708.06176]()

・Inspire
・Web page

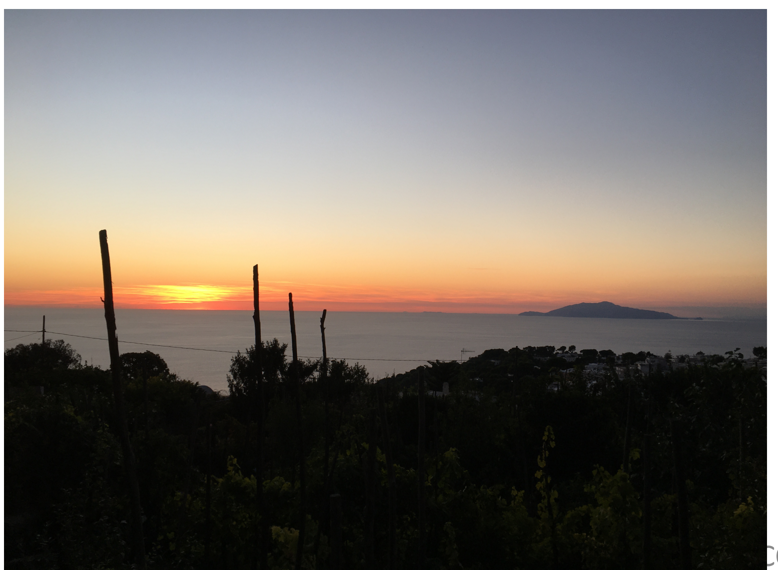
With Motoi Endo(KEK), Michihisa Takeuchi(Osaka), Teppei Kitahara(Nagoya, KMI), Kazuhiro Tobe(Nagoya)
Yuji Omura(Kindai), Ryoutaro Watanabe(Pisa), Hantian Zhang(KIT), Monika Blanke(KIT)

Thanks for the invitation

Key words: Flavor anomalies, collider probe, lepton flavor violation, Leptoquarks,,,,

Great memories

On site meeting is great



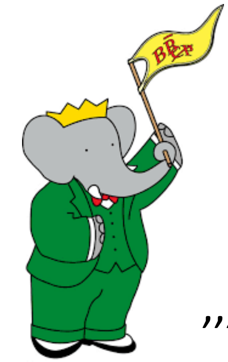
Messages in this talk

Flavor anomalies may be a hint of the new physics.

Motivated by the discrepancies, many developments for collider physics are made in the last decade.

Collider physics is also a very important tool to probe a new particle possibly behind the discrepancy.

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

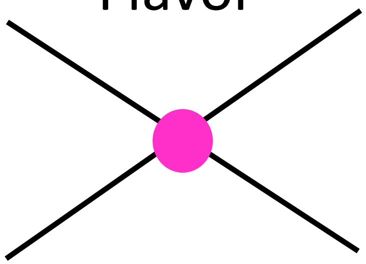
Dark Matter, matter vs antimatter asymmetry, strong CP problem, fine turning of Higgs mass, Yukawa hierarchy, Neutrino masses,,,,

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?

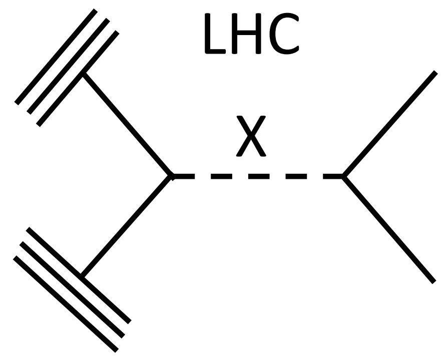
Fact

- No concrete NP signal at the high energy frontier
- Flavor physics is sensitive to higher NP scale.

Flavor



vs.



Kaon physics is sensitive up to 10^5 TeV depending on the flavor structure of a mediator

$\sqrt{s} = 13\text{TeV}$

Since a proton is not elementary particle, m_{NP}<13TeV can be produced

For me it sounds more natural to find something in flavor physics first and confirm at the direct searches.

Fact

No concrete NP signal at the high energy frontier so far,

however, as Kobayashi-Maskawa proposed a model
with more than 3rd generation, an experimental hint is very important.

Caution

Although there are many flavor anomalies on the market,
statistically and historically saying, most of them would not be true.

I started particle physics in 2016 and have seen disappearance,,,

$h \to \mu\tau$ | δa_e | ε'/ε | $W \to \tau\nu$

2017 | 2020 | 2020 | 2021

Additional data | Lattice | New data

Many excesses in LHC

e.g. di-tau, di-γ (95GeV),
di-di jets(1TeV)

At the same time many new discrepancies appeared!

$b \to cuq$ | CAA | $B_c \to J/\psi\tau\nu$ | Charm ΔA_{CP}

LHC data will come regardless of the status of the flavor discrepancies.
Independent cross check is interesting

I will interplay between collider physics
and following discrepancies

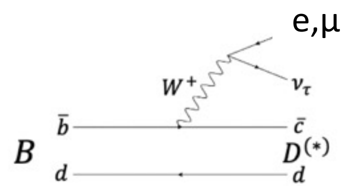
- b->cuq puzzle

- $R_{D^{(*)}}$ anomaly

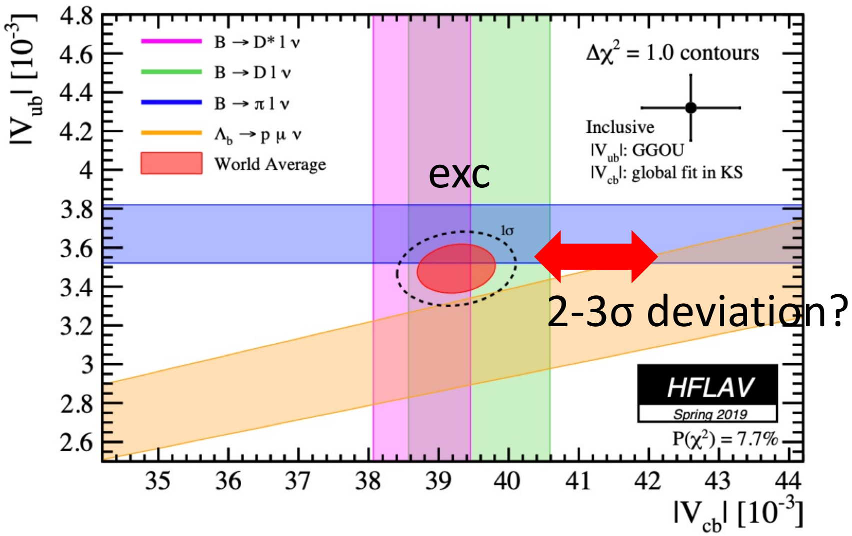
- Muon g-2 discrepancy(?) Depending on the time

Current status of B anomalies (b->c)

V_{cb} puzzle



$b \to c\bar{u}q$ puzzle



inclusive Vcb: determined from B->Xc lν mode

Xc: all hadronic state containing a charmed hadron.

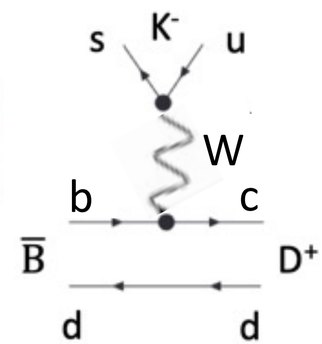
exclusive Vcb: determined from B->D$^{(*)}$ l ν mode

l=e, μ

New

$b \to c\bar{u}d$ $\quad$ $b \to c\bar{u}s$

	$BR^{exp} \times 10^3$	$BR^{SM,QCDF} \times 10^3$	
$\bar{B}_s \to D_s^+ \pi^-$	3.00 ± 0.23	4.09 ± 0.21	**3.5σ**
$\bar{B}^0 \to D^+ K^-$	0.186 ± 0.020	0.303 ± 0.015	**4.7σ**
$\bar{B}_s \to D_s^{*+} \pi^-$	2.0 ± 0.5	4.46 ± 0.22	**4.5σ**
$\bar{B}^0 \to D^{*+} K^-$	0.212 ± 0.015	0.327 ± 0.016	**5.3σ**
	PDG	2109.10811	

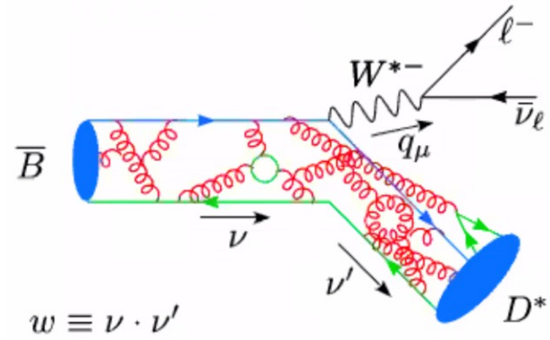


Tree level W

Amplitude ∝ B->D Form Factor
SM prediction updated in 2007.10338.

20% amplitude suppression is favored compared to QCDF prediction

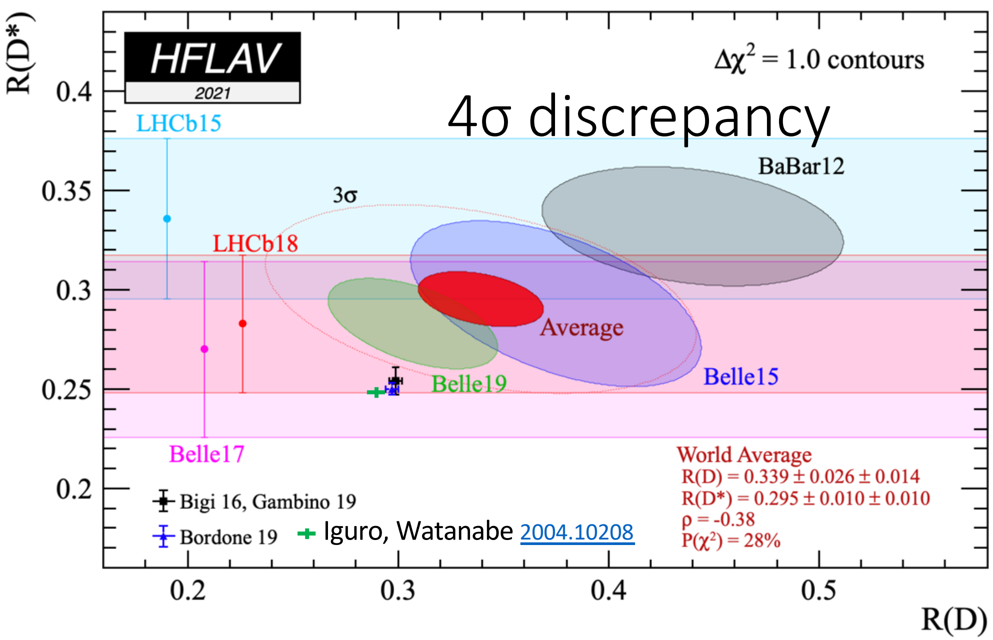
$R_{D^{(*)}}$ anomaly



Lepton flavor universality is a key prediction of the SM

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)} \tau \nu)}{BR(B \to D^{(*)} l \nu)}, \quad l = \mu, e$$

Taking ratio greatly cancels uncertainty in the hadronic matrix element



Several deviations

$$F_L^{D^*} = \frac{\mathrm{BR}(B \to D_L^* \tau \nu)}{\mathrm{BR}(B \to D^* \tau \nu)}$$

$F_{L\,SM}^{D^*} = 0.46 \pm 0.01$ 1.7σ

$F_{L\,exp}^{D^*} = 0.60 \pm 0.09$ Belle: 1903.03102

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi \tau \nu)}{BR(B_c \to J/\psi \mu \nu)}$$

$R_{J/\psi}^{SM} = 0.24 \pm 0.01$ 1.8σ

$R_{J/\psi}^{exp} = 0.71 \pm 0.25$ Belle: 1711.05623

One striking news: LHCb released the new data 2201.03497

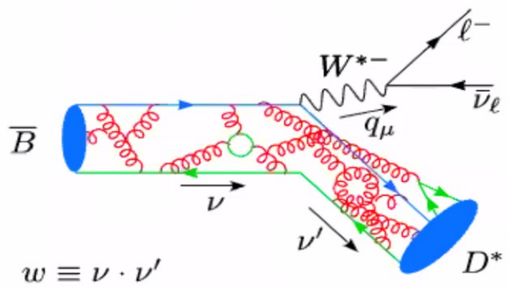
$$R(\Lambda_c) = \mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu}) / \mathcal{B}(\Lambda_b \to \Lambda_c \mu \bar{\nu})$$ Smaller than the SM

$R_{\Lambda c}^{exp} = 0.24 \pm 0.08$, $R_{\Lambda c}^{SM} = 0.324 \pm 0.004$ Consistent with SM within 1σ

However, systematic uncertainty is still large to say something

B decays involve hadron physics
B->D$^{(*)}$ form factor is important .

Non-perturbative information extracted from
Lattice, experiments, QCDSR,,,,



- V_{cb} puzzle **BR(B->D lν)∝|Vcb × FFs|^2**
- $b \to c\bar{u}q$ anomaly **BR(B->DK) ∝ | Vcb × FFs |^2**
- $R_{K^{(*)}}$ anomaly See, talk by Nazila
- $R_{D^{(*)}}$ anomaly **BR(B->Dlν)∝|Vcb × FFs|^2** $\frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}l\nu)}$

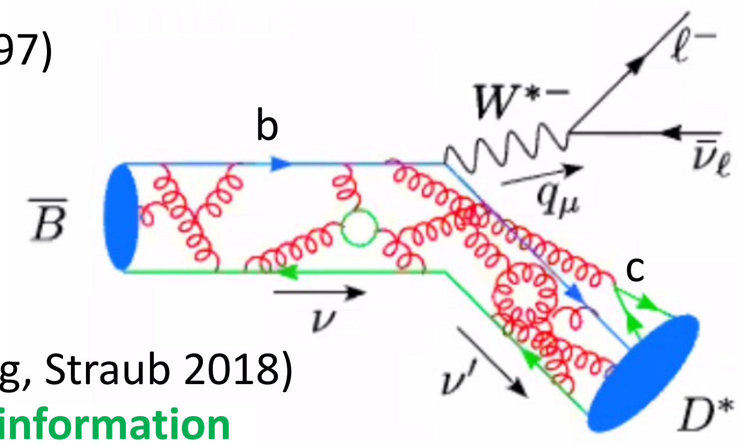
B->D form factor is very important

,,,,,,,, We have updated FF (HQET) using experimental input from Belle
Iguro, Watanabe JHEP **08 (2020) 08, 006**

Form Factors in B->D,D* transition

Conventional parametrization

- CNL parametrization (Caprini, Lellouch, Neubert 1997)
  -> too much simplified
- BGL parametrization (Boyd, Grinstein, Lebed 1997)
  -> too general to use for the NP analysis



Our approach

- General Heavy Quark Effective Theory(GHQET) (Jung, Straub 2018)

QCD information

$$\langle D|\bar{c}\gamma^\mu b|B\rangle_{\mathrm{HQET}} = \sqrt{m_B m_D}\left[h_+(v+v')^\mu + h_-(v-v')^\mu\right],$$

SM

$$\langle D^*|\bar{c}\gamma^\mu\gamma^5 b|B\rangle_{\mathrm{HQET}} = \sqrt{m_B m_{D^*}}\left[h_{A_1}(w+1)\epsilon^{*\mu} - (\epsilon^*\cdot v)\left(h_{A_2}v^\mu + h_{A_3}v'^\mu\right)\right],$$

$$v^\mu = p_B^\mu/m_B,\ v'^\mu = p^\mu_{D^{(*)}}/m_{D^{(*)}},\ w = v\cdot v' = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}}),$$

Main difference: h_+, h_-, h_{A1}… are described by common parameters

We want to determine h_x precisely.

Recent progress

L. Zoltan et al 2017

$$\hat{h}_X = \hat{h}_{X,0} + \frac{\alpha_s}{\pi}\delta\hat{h}_{X,\alpha_s} + \frac{\bar{\Lambda}}{2m_b}\delta\hat{h}_{X,m_b} + \frac{\bar{\Lambda}}{2m_c}\delta\hat{h}_{X,m_c} + \left(\frac{\bar{\Lambda}}{2m_c}\right)^2\delta\hat{h}_{X,m_c^2},$$

0.1   0.05   0.2   0.04

M. Bordone et al. EPJC 2020

Three kinds of constraints (input of the fit)

- Lattice (6)

• prediction for large q^2
• unstable particles (D*) are problematic
-> hard to predict FF for B->D*

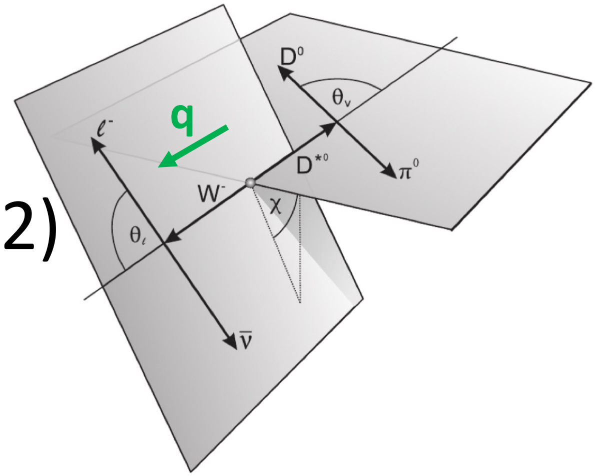
- Theory (45)

e.g. QCDSR
LCSR
Unitarity bound

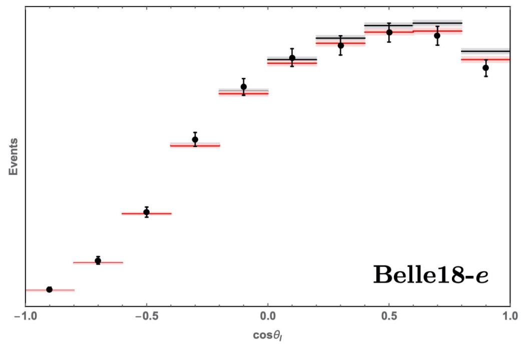
• prediction for small q^2
we newly included QCDSR constraints on higher derivative terms

- Experiment (132)

Belle 17,18



Experimental data from Belle
we also newly included data of angular distribution in 1809.03290

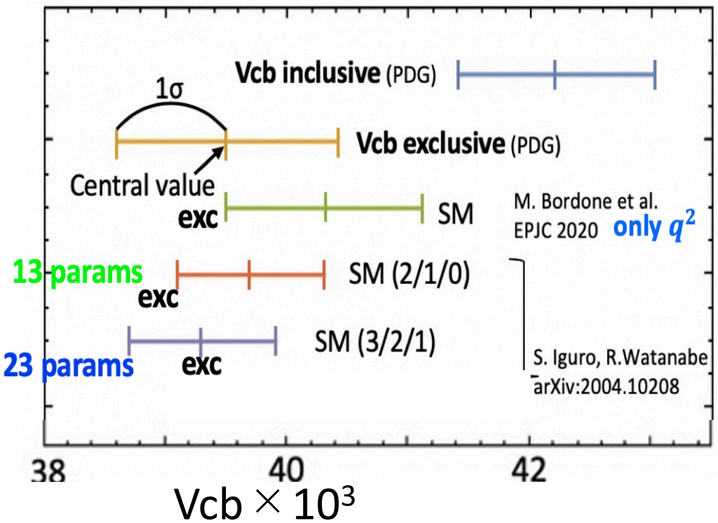


～180 constraints

full kinetic (q^2, θ_l, θ_V , χ) distributions of B → D* l ν

Latest status with our form factor

Vcb puzzle remains



b->cuq puzzle

	$BR^{exp}\times10^3$	$BR^{SM,QCDF}\times10^3$	
$\overline{B}_s \to D_s^+\pi^-$	3.00 ± 0.23	4.09 ± 0.21	3.5σ
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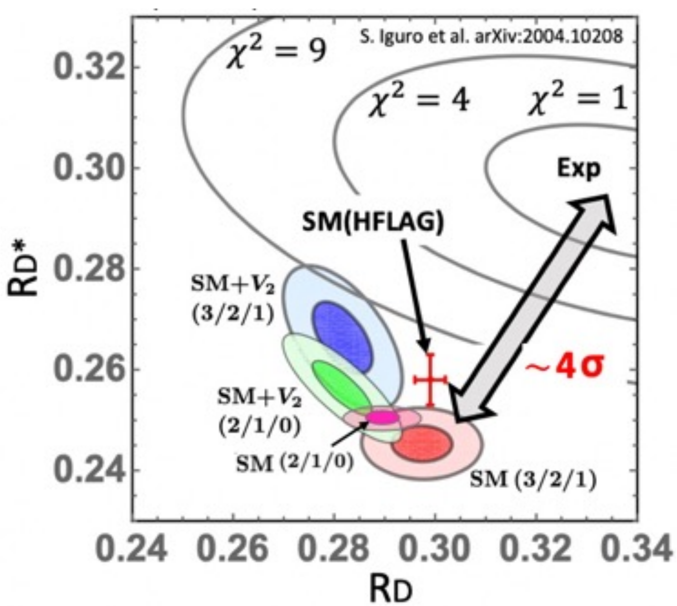


We got the smaller RD* value.
-> Now ~~3~~ 4σ discrepancy again.
Even if we have new physics in b->clv transition, the anomaly remains.

$$R_{D^{(*)}} = \frac{BR(B\to D^{(*)}\tau\nu)}{BR(B\to D^{(*)}l\nu)}\ ,\ l = \mu, e$$

NP in τ mode is necessary.

NP possibilities of b->cuq puzzle ?

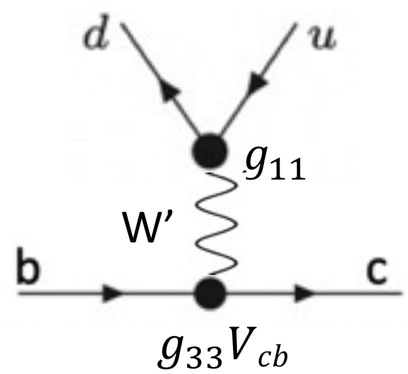
In order to explain the discrepancy,
O(10)% downward shift from the SM amplitude is necessary.

Interestingly such a large shift is still allowed by flavor observables.

Lenz et al 1912.07621.

We need a charged mediator (for instance W', not LQ)
The naïve NP scale for this puzzle is estimated as

$$\left|\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}}\right| \sim 10\% = \frac{g_{11}\times g_{33}}{M_V^2}\frac{1}{4\sqrt{2}G_F} = \frac{g_{11}\times g_{33}}{1}\frac{(400\text{GeV})^2}{M_V^2}$$



Our model 2008.01086 Iguro, Kitahara

We will focus on the $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model

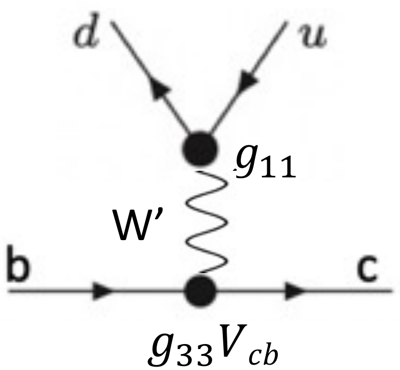
See also for other NP analyses, Bordone et al 2103.10332, Cai et al 2103.04138..

The model contains heavy vector-like quarks and
heavy SU(2) gauge multiplet.

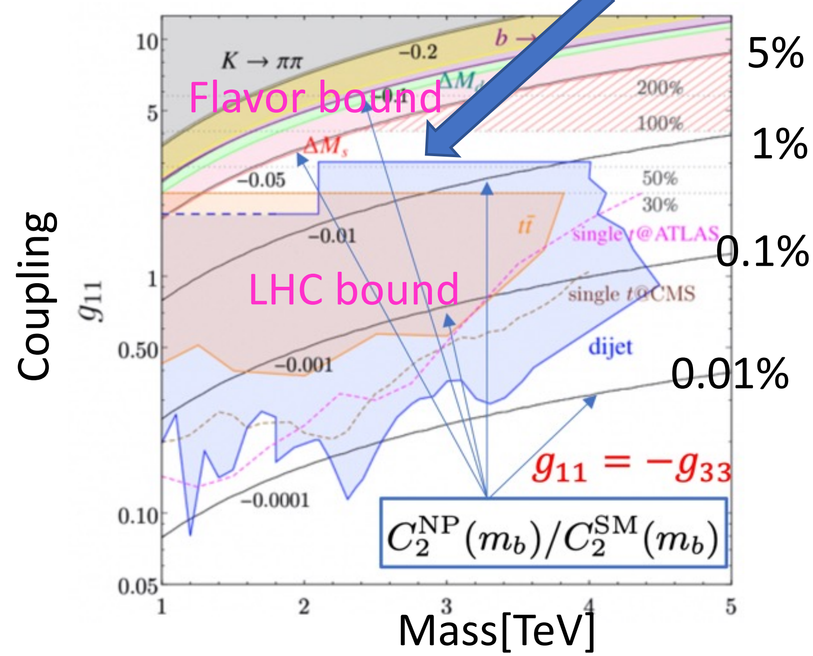
Goal: 20% shift

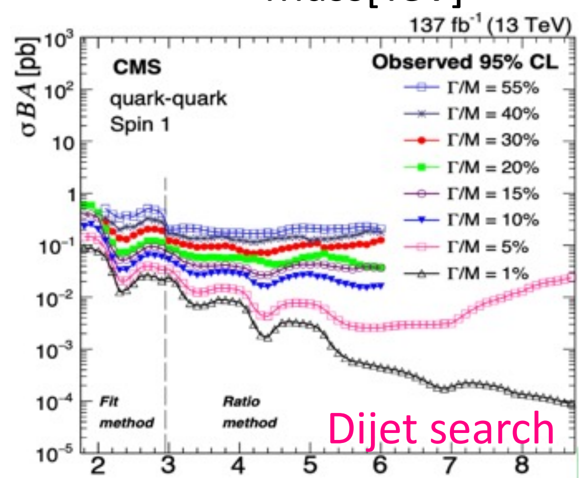
$b \to c\bar{u}q$ puzzle and LHC

$$\mathcal{L} = + \frac{g_{ij}}{2} Z'_\mu \bar{d}^i_L \gamma^\mu d^j_L - \frac{(VgV^\dagger)_{ij}}{2} Z'_\mu \bar{u}^i_L \gamma^\mu u^j_L - \frac{(Vg)_{ij}}{\sqrt{2}} W'^+_\mu \bar{u}^i_L \gamma^\mu d^j_L + \text{H.c.}\,,$$



$$g_{ij} = \begin{pmatrix} \underline{g_{11}} & 0 & 0 \\ 0 & \underline{g_{11}} & g_{23} \\ 0 & g_{23} & \underline{g_{33}} \end{pmatrix}$$





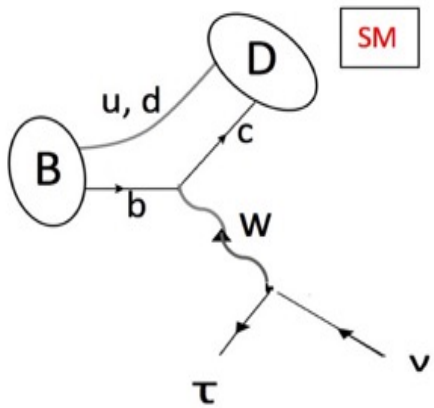
1911.03947

LHC bounds are very stringent.
Possible deviation is 100 times smaller.

-> NP explanation is difficult.

What kind of New physics is implied by $\boldsymbol{R_{D^{(*)}}}$?

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)} \tau\nu)}{BR(B \to D^{(*)} l\nu)}, \quad l = \mu, e$$



- New physics in b -> cτν is necessary.
- We need to enhance $BR(B \to D^{(*)}\tau\nu)$ by 20%.

Tree level W exchange describes the SM amplitude

O(1) TeV tree level NP is necessary

It is natural to test NP scenarios at the LHC

Faroughy et al 1609.07138, Altmannshofer et al 1704.06659 Iguro-Tobe 1708.06176, Abdullah et al 1805.01869, Becirevic et al 1806.05689, Iguro-Omura-Takeuchi 1810.05843, Mandal et al 1811.03561, Greljo 1811.07920, Baker et al 1901.10480, Marzocca 2008.07541, Iguro-Watanabe-Takeuchi 2011.02486, Iguro et al 2111.04748, Jaffedo 2112.14604 Iguro-Zhang-Blanke 2202.10468

Bunch of works!

Effective Lagrangian for b → c τ ν

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{VL}) O_{VL} + C_{VR} O_{VR} + C_{SR} O_{SR} + C_{SL} O_{SL} + C_T O_T \right]$$

Operator basis

$$\left.\begin{aligned} O_{SR} &= (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) \\ O_{SL} &= (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) \end{aligned}\right\} \text{Scalar}$$

$$\left.\begin{aligned} O_{VL} &= (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu_\tau) \\ O_{VR} &= (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu_\tau) \end{aligned}\right\} \text{Vector}$$

$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau) \quad \text{Tensor}$$

We focus on models with $\nu_{\tau,L}$

Possible candidate

H^- $B_c^- \to \tau\bar{\nu}$

W'_L Bs mixing & bb > ττ

LQ

Recent progress in BR($B_c^- \to \tau\bar{\nu}$)

$\Gamma_{Bc} \propto m_Q^5$ + large error in charm mass

-> large error for Γ_{Bc}

Previous constraint

$< 30\%$ R.Alonso et al 1611.06676

$< 10\%$ A.G.Akeroyd et al 1708.04072

Current constraint

$< 63\%$ B.Grinstein et al 2105.02988

M.Blanke et al 1811.09603

Tera Z factory is important, Manqui et al(CEPC), Olcyr et al(FCC-ee)

3 types of LQs are known to explain R_D, R_{D^*} anomalies

R_2, S_1 and U_1

A. Angelescu, et al. 1808.08179

$(SU(3)_c, SU(2)_L, U(1)_Y)$

R_2 : $(3, 2, 7/6)$ scalar

$C_{S_L}(\mu_{LQ}) = 4C_T(\mu_{LQ})$

X. Q. Li, et al. 1605.09308

S_3 with $(\bar{3}, 3, 1)$ is needed for R(K)

I. Dorsner,et al. 1701.08322

S_1 : $(\bar{3}, 1, 1/3)$ scalar

$C_{S_L}(\mu_{LQ}) = -4C_T(\mu_{LQ}), C_{V_L}(\mu_{LQ})$

Y. Sakaki, et al. 1309.0301

$S_1 - S_3$ combination is considered

A. Crivellin, et al. 1703.09226

U_1: $(3, 1, 2/3)$ vector

$C_{S_R}(\mu_{LQ}), C_{V_L}(\mu_{LQ})$

R(K) is also possible

UV completion is needed

e.g. Pati Salam

Calibbi, et al. 1709.00692

Heeck, et al. 1808.07492

Grinstein, et al. 1812.01603

Iguro, et al. 2103.11889,2201.04638

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$SU(4)_C \to SU(3)_C \times U(1)_{B-L}$$

Massive vector LQ appear (Z' also)

Recently 4321 model is most popular

See Gino, et al. 2203.01952 toward UV completion

From the flavor side, τ polarization in $B \to D\tau\nu$ is the best angular observable

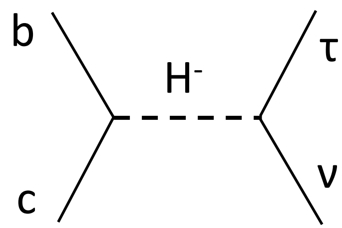
Iguro, et al. 2018

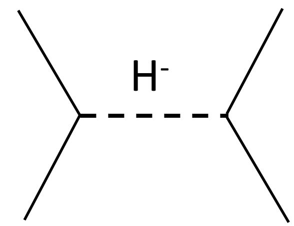
Key feature of the NP signal at the LHC

$R_{D^{(*)}}$ | LHC

s-channel

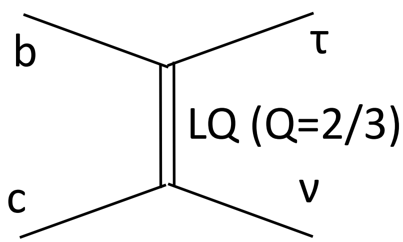
- Charged Higgs



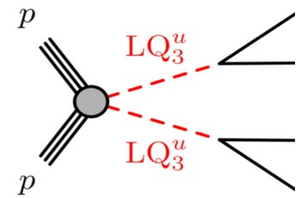


τν resonance

- Leptoquarks

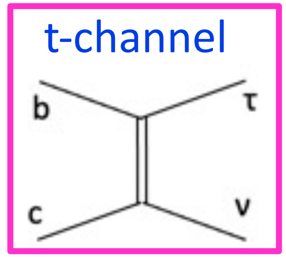


Various channels



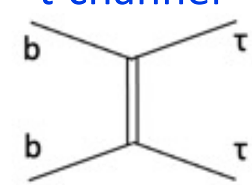
Pair production
τb τb search

t-channel



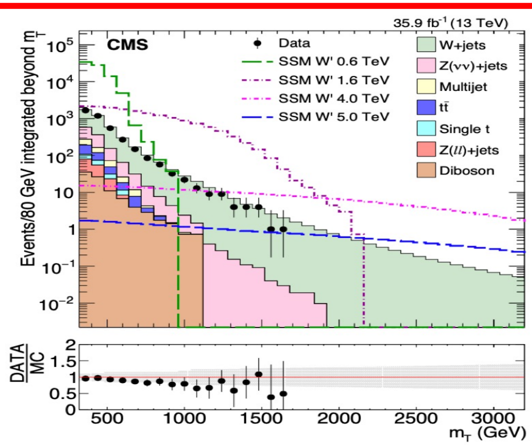
Mono tau search

t-channel



di-τ search

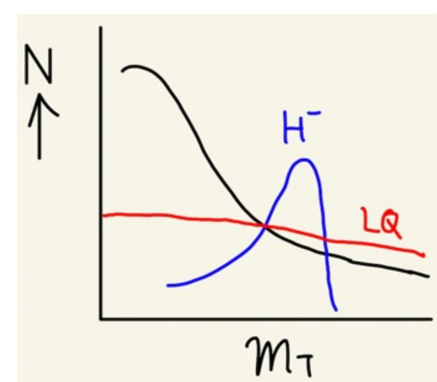
High pT tails



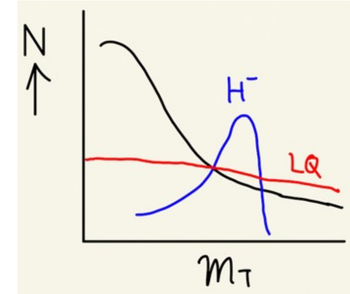
signal shape on the mT plane
s-channel : cliff
t-channel : plateau (t<0)

$$m_T = \sqrt{2 p_T^{\ell} E_T^{\rm miss} (1 - \cos\theta_{\ell\nu})}$$

Main SM BG: pp -> qq->W->lν

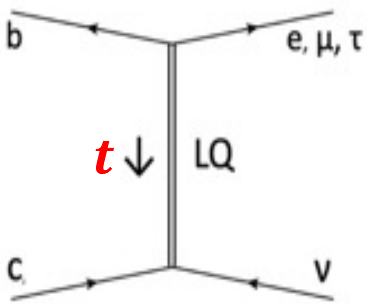


LHC implication in LQ cases



High p_T τ events are sensitive to the scenarios

In some papers EFT limit is taken.



propagator

EFT limit

$$\frac{1}{t - m_{LQ}^2} \Rightarrow \frac{1}{m_{LQ}^2}$$

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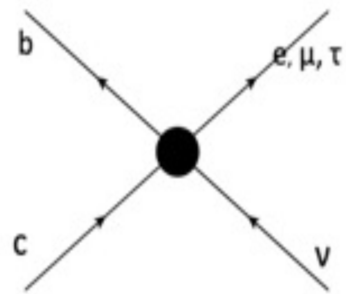
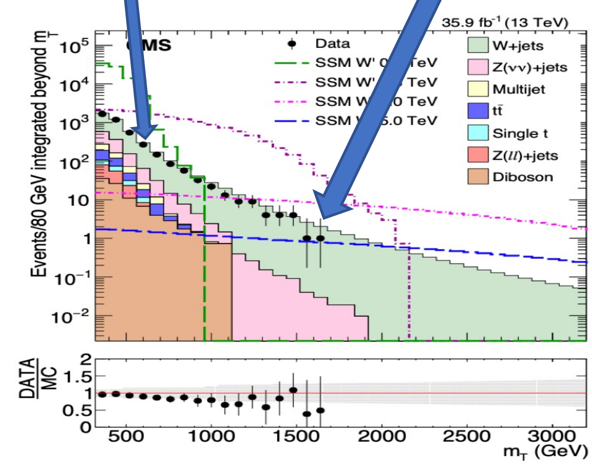


Huge BG from W

High p_T region is sensitive to NP



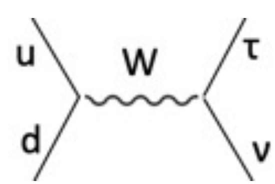
$$t = (p_b - p_c)^2 \sim -2 p_b \cdot p_c < 0$$

Large t is the source of the large transverse momentum.

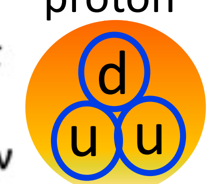
We found up to 50% sensitivity mass dependence in terms of WC Iguro et al [2011.02486](https://arxiv.org/abs/2011.02486)

EFT limit is always aggressive for LQ models since t<0.

Main BG : pp→W→τν. N(W^+) > N(W^-) means collecting τ^- event improves the sensitivity



proton



Further improvement of τν mode

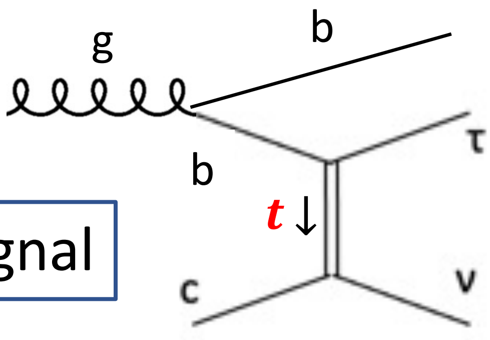
An additional b-tagging

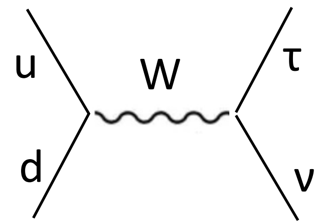
A. Soni et al 1704.06659, Iguro-Tobe 1708.06176

Importance of b-tagging

1. smaller BG, 2. different BG → semi-independent cross check
3. specifying interaction: one of quarks in 4-fermi is b

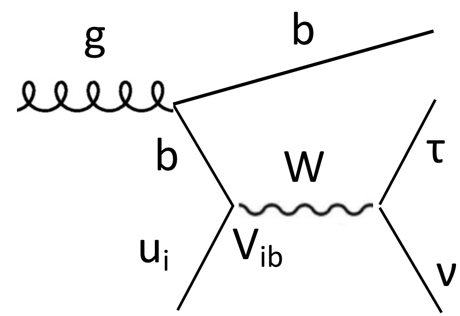
Signal



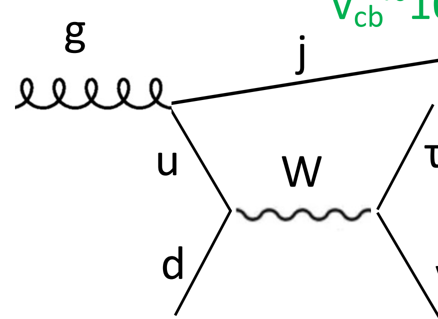


No b-jet
previous

BG



V_{cb}~10^{-2}, V_{ub}~10^{-3}



j->b mis tag less than 1%

Within the EFT framework,
an additional b-jet tagging improve WC sensitivity
by 30-40% Minho et al 2008.07541

WZ, single t ,,, are
also important

We keep mediator mass dependence
even with b-jet tagging Iguro et al 2111.04748

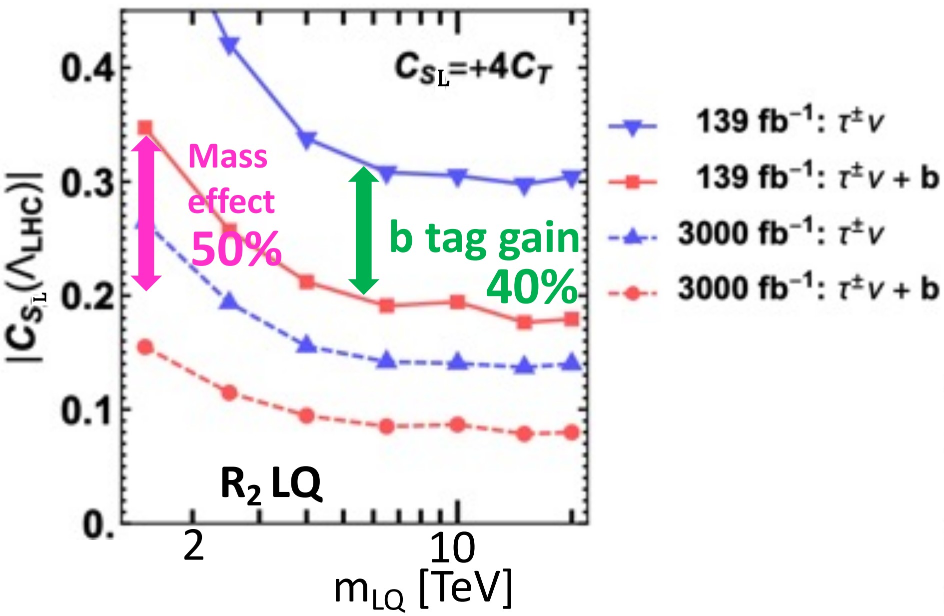
τ ν +b with mass dependence

2111.04748

We observed the significant mass dependence

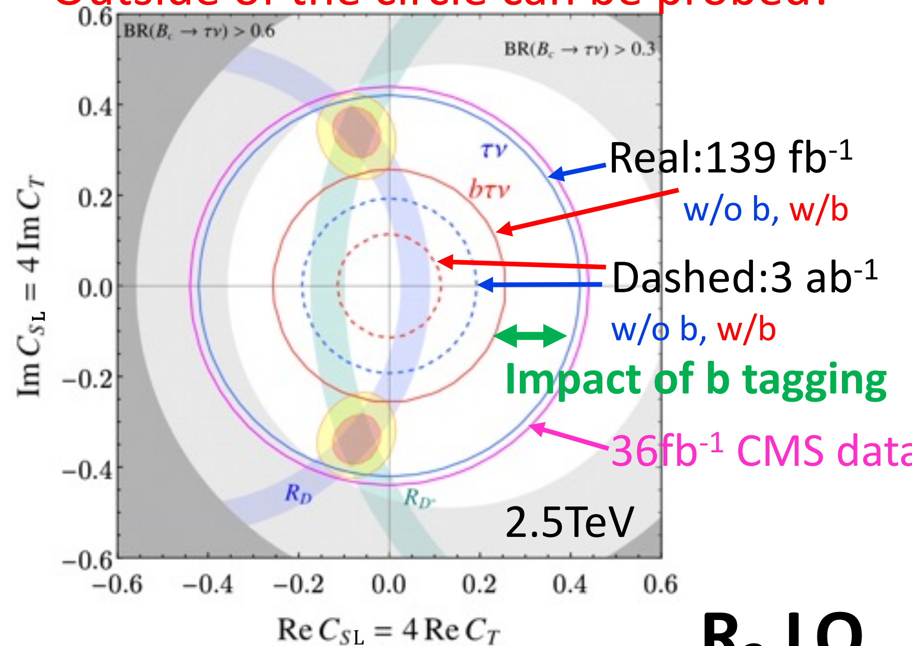
t parameter dependence is large in small mass region

Sensitivity to WC

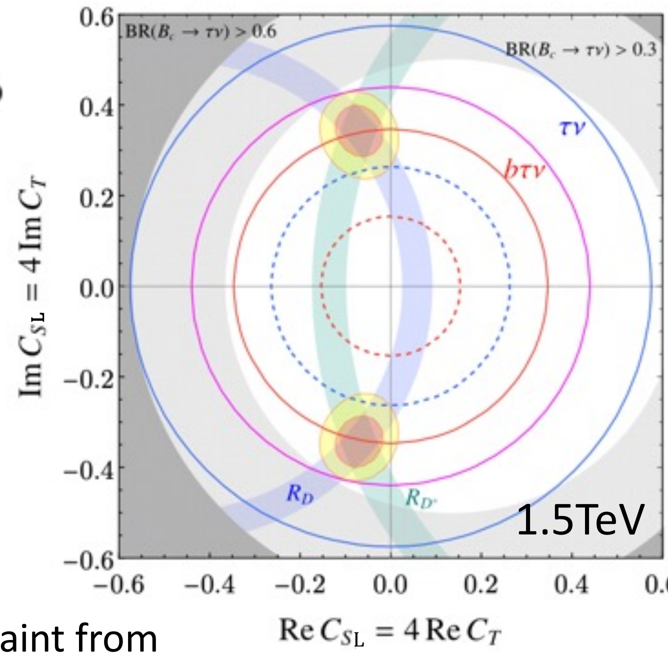


Charge ID of b-jet would improve the sensitivity since the main BG does not come from the genuine b+τν event.

Outside of the circle can be probed!



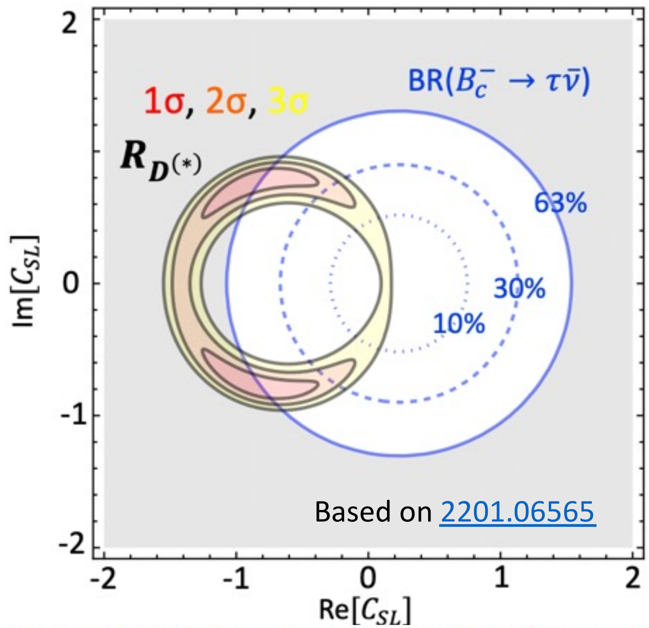
R$_2$ LQ



pT dependence of tau tagging efficiency will relax constraint from 36fb^{-1} CMS data Jaffedo 2112.14604 but problem is fixed for139fb^{-1}!

We can test the scenario soon!

H^+ revived



Thanks to the relaxed upper bound from $B_c^- \to \tau\bar{\nu}$ scalar scenario is still viable!

Only scalar can enhance $F_L^{D^*}$

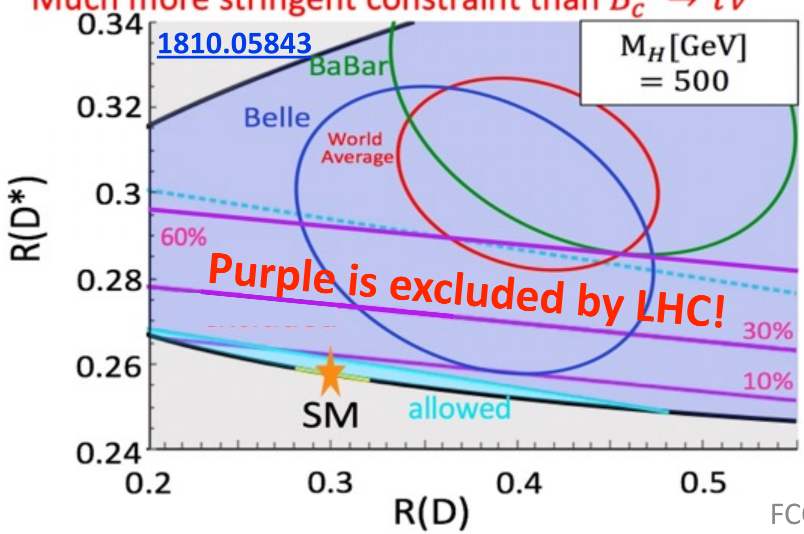
$$F_{L\,exp}^{D^*} = 0.60 \pm 0.09, \quad F_{L\,SM}^{D^*} = 0.46 \pm 0.01$$

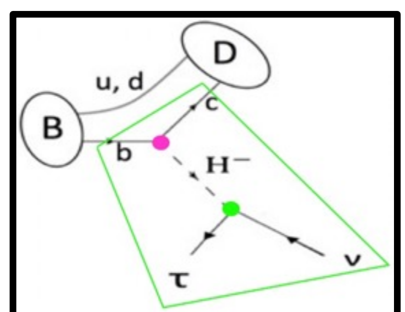
We need complex WC

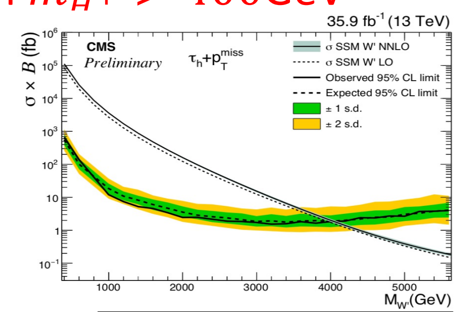
=> Complex Yukawa in type III (General) 2HDM

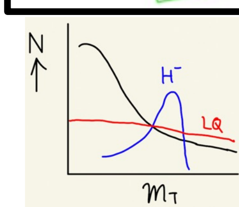
Reinterpreting **τν resonance search** from the CMS(36fb^{-1}) excludes the scenario with $m_{H^+} > 400$GeV

Much more stringent constraint than $B_c^- \to \tau\bar{\nu}$

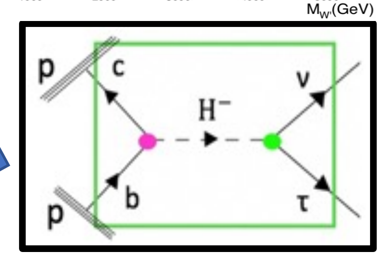








correlation

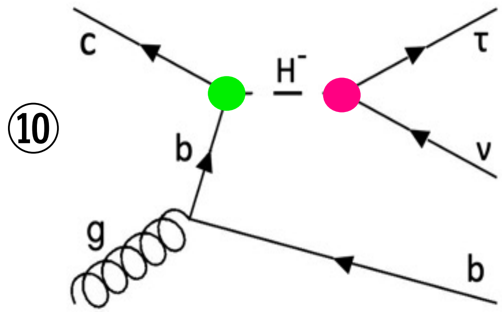


There is no data available for $m_{H^+} < 400$GeV

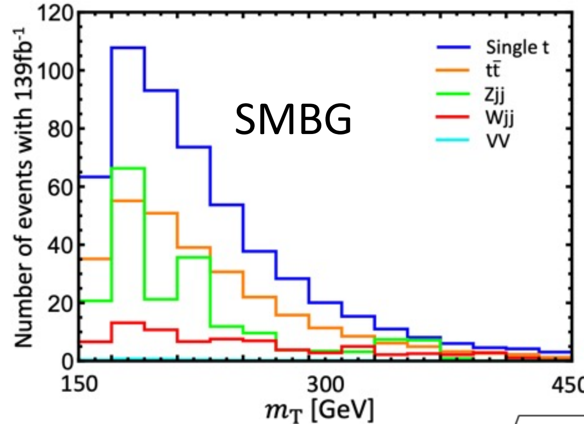
Additional b-jet would suppress the trigger rate

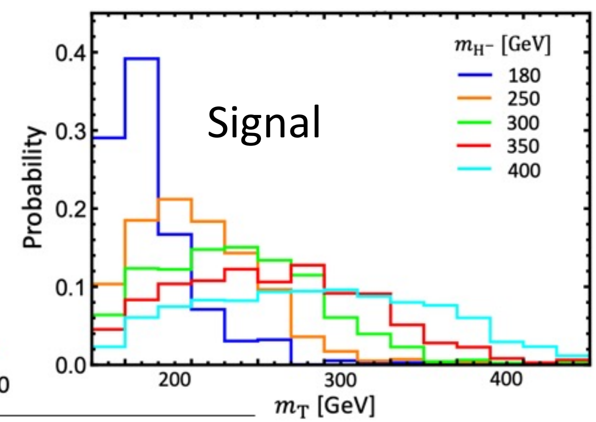
Closing the low mass window with τν+b search! $180\text{GeV} < m_{H^+} < 400\text{GeV}$

Iguro, Hantian, Blanke 2202.10468



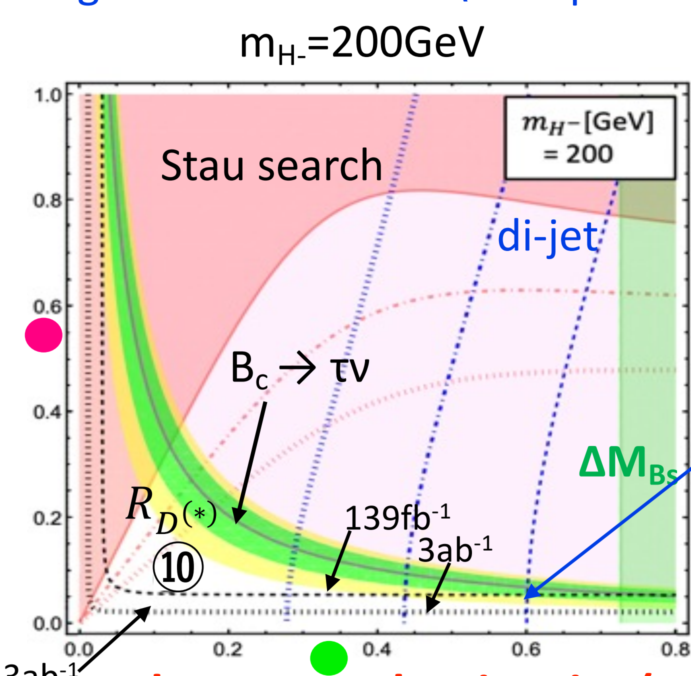
b-tagging suppress the SMBG

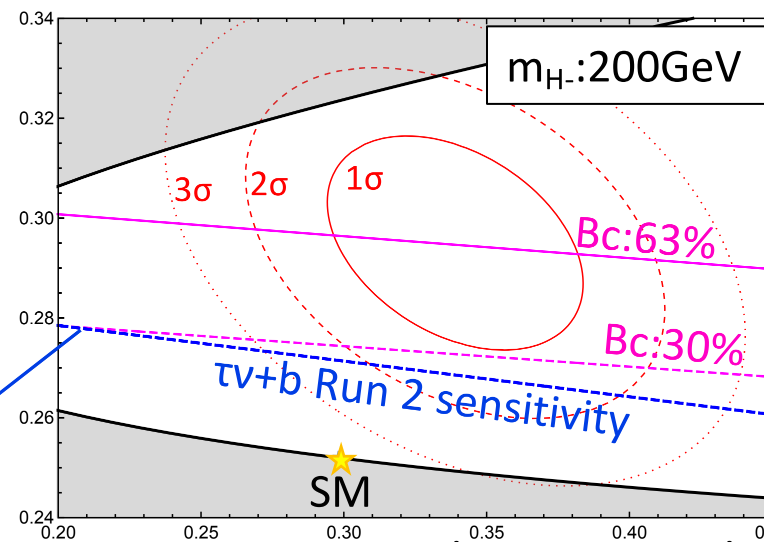




$$m_T = \sqrt{2 p_T^{\ell} E_T^{\rm miss} (1 - \cos\theta_{\ell\nu})}$$

NP signal event number (with parameters to explain the anomaly) is comparable with SMBG!





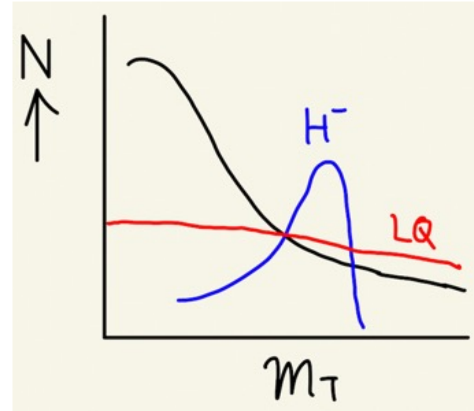
conservative syst. error is assigned

Heavier scenario is more easy due to smaller BG!

The current luminosity (139fb^{-1}) is already enough to judge the model!

Check list at the LHC

$b \to c\tau\nu$ interaction



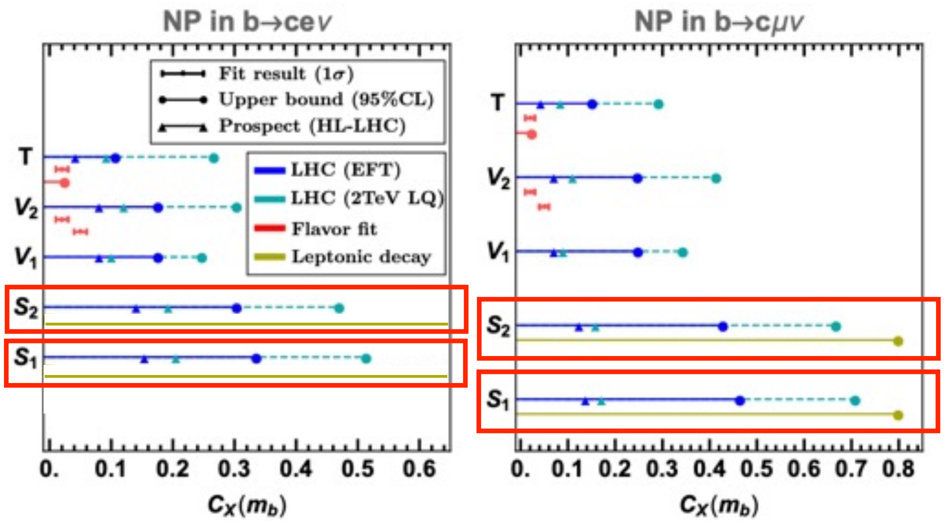
Signal / channel		$\tau\nu$	$\tau\nu$ +b	Mass dependence $\tau\nu$	Mass dependence $\tau\nu$ +b
H^+	S	Iguro et al 1810.05843 **Done**	Iguro et al 2202.10468 **Done**		
LQ	t	Greljo et al 1811.07920 **Done**	Minho et al 2008.07541 **Done**	Iguro et al 2011.02486 **Done**	Iguro et al 2111.04748 **Done**

Finally completed the table!

+b category is always more sensitive

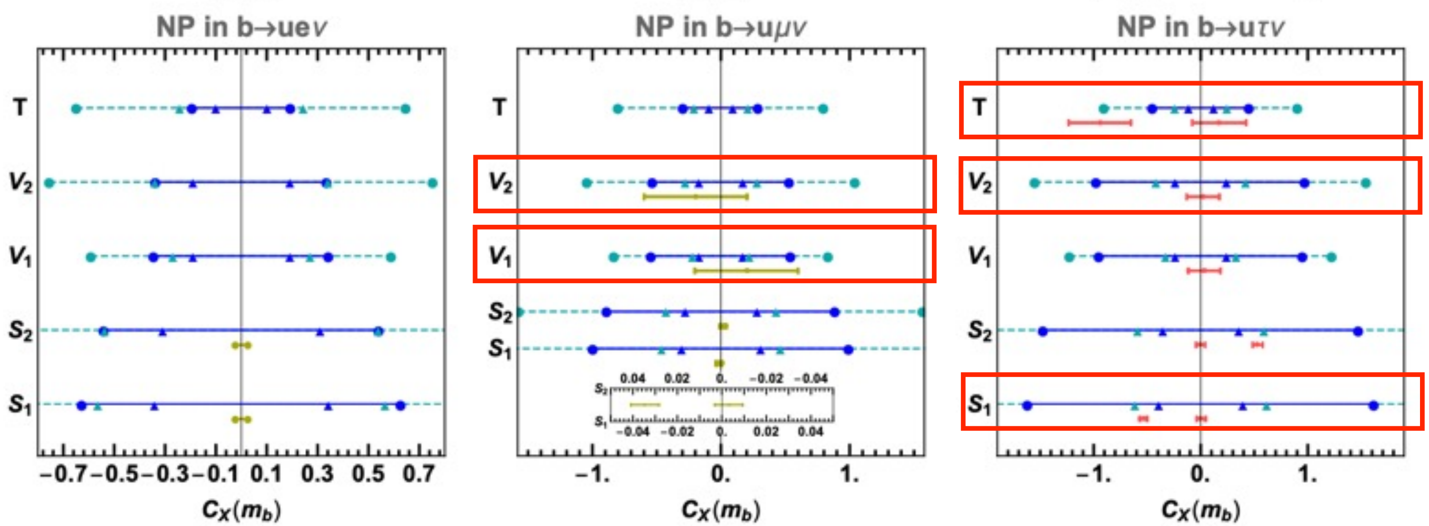
High pT collider physics is also sensitive to $b \to c\, l\, \nu$ and $b \to u\, l\, \nu$.

Iguro, et al. 2011.02486



$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{u_ib} \begin{bmatrix} (1+C_{VL})O_{VL} + C_{VR}O_{VR} \\ +C_{SR}O_{SR} + C_{SL}O_{SL} + C_T O_T \end{bmatrix}$$

$$O_{SR(1)} = (\bar{u}_i P_R b)(\bar{l} P_L \nu_l)$$
$$O_{SL(2)} = (\bar{u}_i P_L b)(\bar{l} P_L \nu_l)$$
$$O_{VL(1)} = (\bar{u}_i \gamma^\mu P_L b)(\bar{l} \gamma^\mu P_L \nu_l)$$
$$O_{VR(2)} = (\bar{u}_i \gamma^\mu P_R b)(\bar{l} \gamma^\mu P_L \nu_l)$$
$$O_T = (\bar{u}_i \sigma^{\mu\nu} P_L b)(\bar{l} \sigma_{\mu\nu} P_L \nu_l)$$



LHC is comparable with flavor sensitivity

Summary

We need more data to confirm/reject flavor anomalies.

LHC provides a powerful and independent cross check the new physics scenario.

Let’s independently conclude scenarios before the arrival of the new data.

muon g-2 anomaly

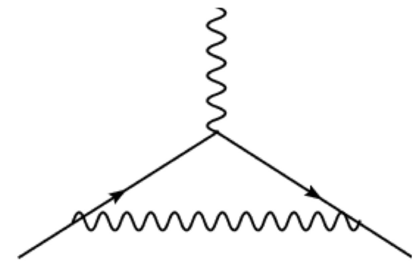
Many talks 1^{st} and 2^{nd} days

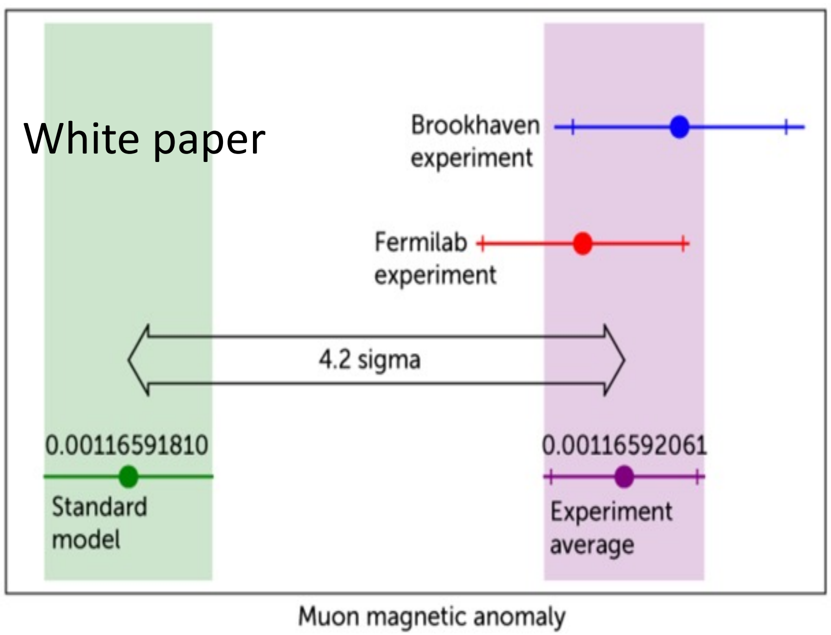
$$\vec{\mu} = -g\frac{e}{2m}\vec{S}$$

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

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

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





Many developments

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

$$\Delta a_\mu = a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} \sim 2.5\times 10^{-9}$$

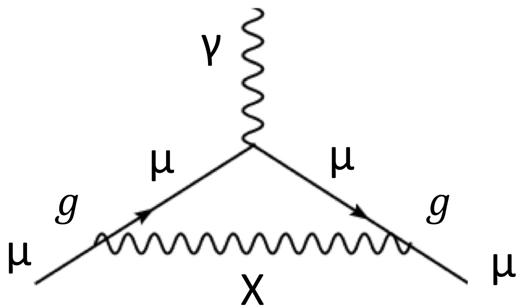
Recent lattice favors smaller gap but
new problem arises in $e^+e^- \to 2\pi$ and the EW fit(slightly).

The situation is not fixed

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?

Muon g-2 and LHC

Because of the size and sign available scenarios are **limited** for the model with simple extension

2104.03691: Single field extension

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\mathrm{BNL}}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.3.
6	0	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$	Excluded: LEP lepton mixing
13	1/2	$(\mathbf{1}, \mathbf{2}, -3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	UV completion problems
18	1	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: LHC searches
19	1	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	UV completion problems
20	1	$(\bar{\mathbf{3}}, \mathbf{1}, -5/3)$	Excluded: LHC searches
21	1	$(\bar{\mathbf{3}}, \mathbf{2}, -5/6)$	UV completion problems
22	1	$(\bar{\mathbf{3}}, \mathbf{2}, 1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\bar{\mathbf{3}}, \mathbf{3}, -2/3)$	Excluded: proton decay

Two Higgs doublet model

S_1 leptoquarks

See, talk by Olcyr

R_2 leptoquarks

Dark photon

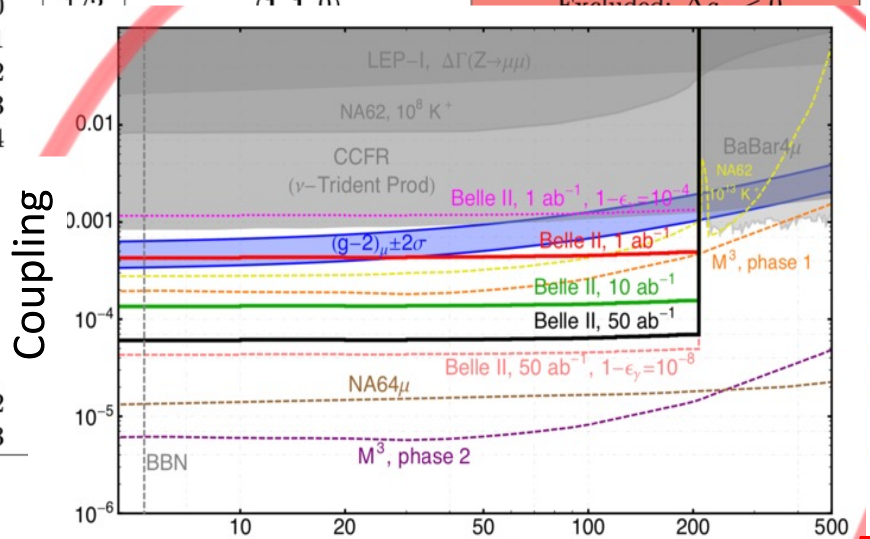
Many models are already killed by LHC

LHC data will come regardless of the HVP status.
If the LHC exclude all the simple model NP pheno people (at least me) can move to other things.

Muon g-2 and LHC

2104.03691: Single field extension

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\rm BNL}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.3.
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11			
12			
13			
14			
1			
1			
1			
1			
1			
2			
2			
22			
23			



1904.13053:2μ+missing

Mass[MeV]

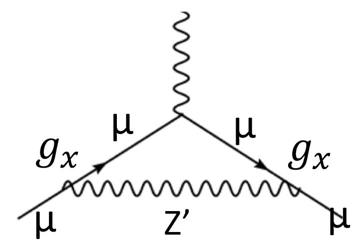
Two Higgs doublet model

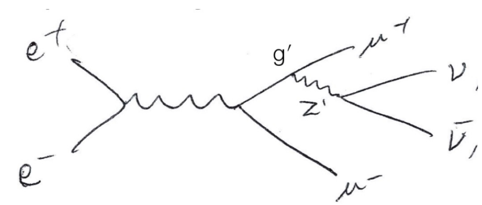
S_1 leptoquarks

See, talk by Olcyr

R_2 leptoquarks

Dark photon





The scenario will be explored soon in Belle II, NA64!

Possibilities (1,2,-1/2)

- Muon specific 2HDM 1504.07059 T. Abe, et al.
- Flavor aligned 2HDM 1502.04199 V. Ilisie
- Type-X 2HDM 1409.3199 M. Passera, et al.
- μτ2HDM

Focus of this talk

LHC physics

SU(2) doublet : EW pair production

Final state

- Muon specific 2HDM multi-muon

  1504.07059 T. Abe, et al.

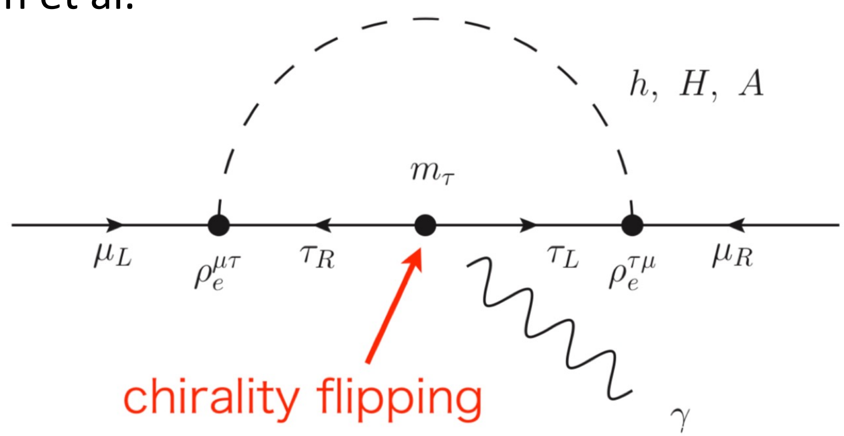
- Flavor aligned 2HDM multi-tau

- Type-X 2HDM multi-tau

  1507.08067 Chun et al.

- μτ2HDM $\mu^+ \mu^+ \tau^- \tau^-$

Even if the size of the deviation decrease, those signals are always important.



New scalars are accessible even with enhancement

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

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

Scenario can explain the dark matter and neutrino masses with singlet scalars in type-I seesaw. See, 2205.08998.

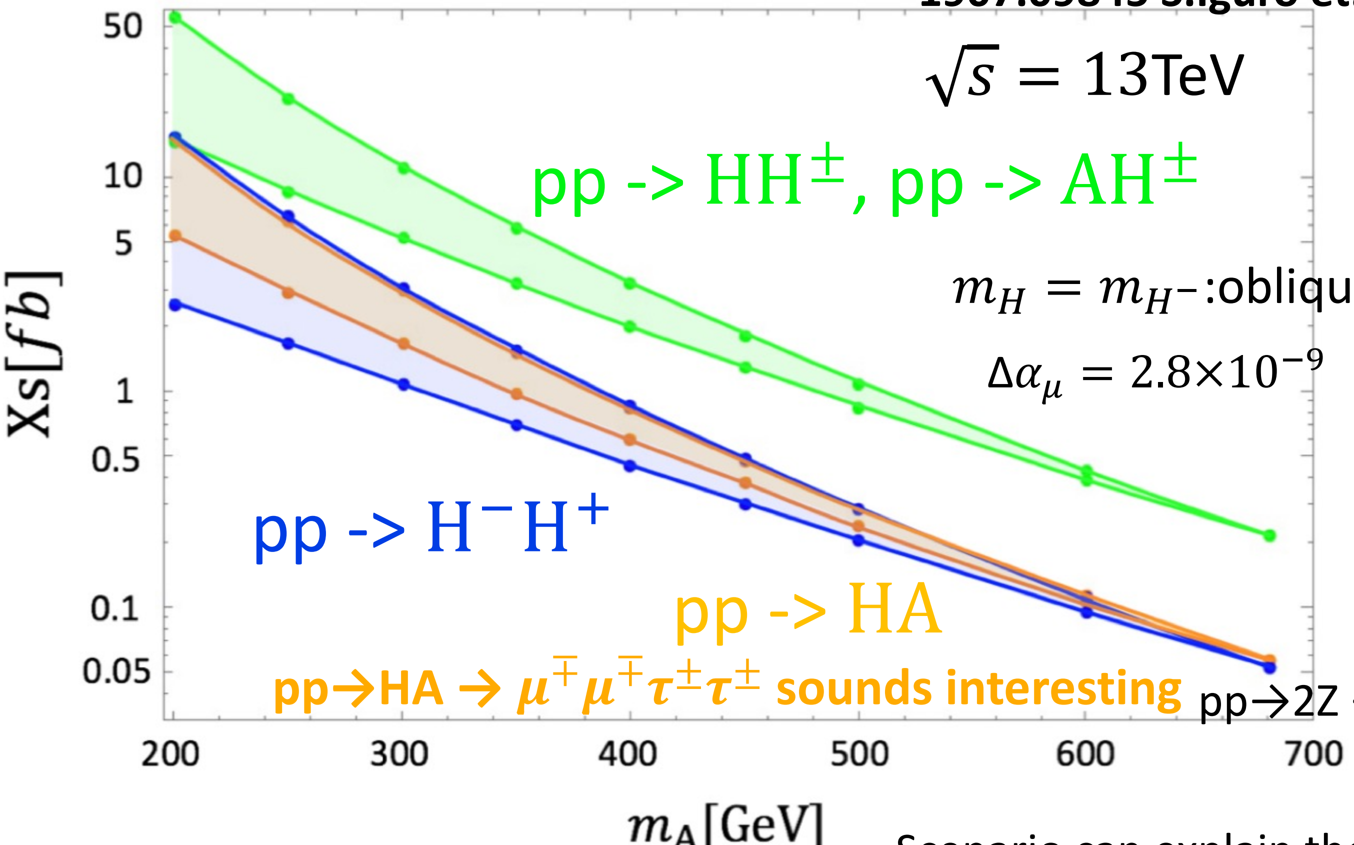
$$-\mathcal{L}^{\text{yukawa}}_{Z_4} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & \underline{y_{\mu\tau}} \Phi^\dagger \\ & \underline{y_{\tau\mu}} \Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

Additional scalars in Φ can only couple to μτ.

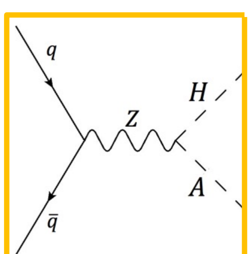
Electroweak production in LHC

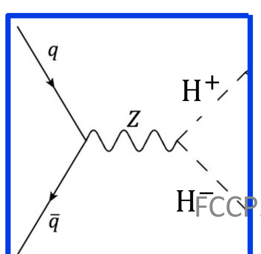
- Maximum mass gap in H and A is given as $m_H^2 = m_A^2 + \lambda_5 v^2 = m_A^2 + v^2$ (for $\lambda_5 < 1$)
- Minimum mass gap is given by $|y_e^{\mu\tau}|, |y_e^{\tau\mu}| < 1$.

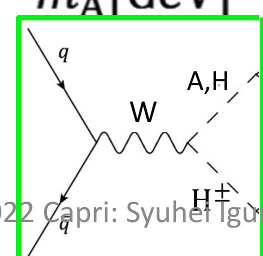
1907.09845 S.Iguro et.al.



pp→2Z →4τ BG is small







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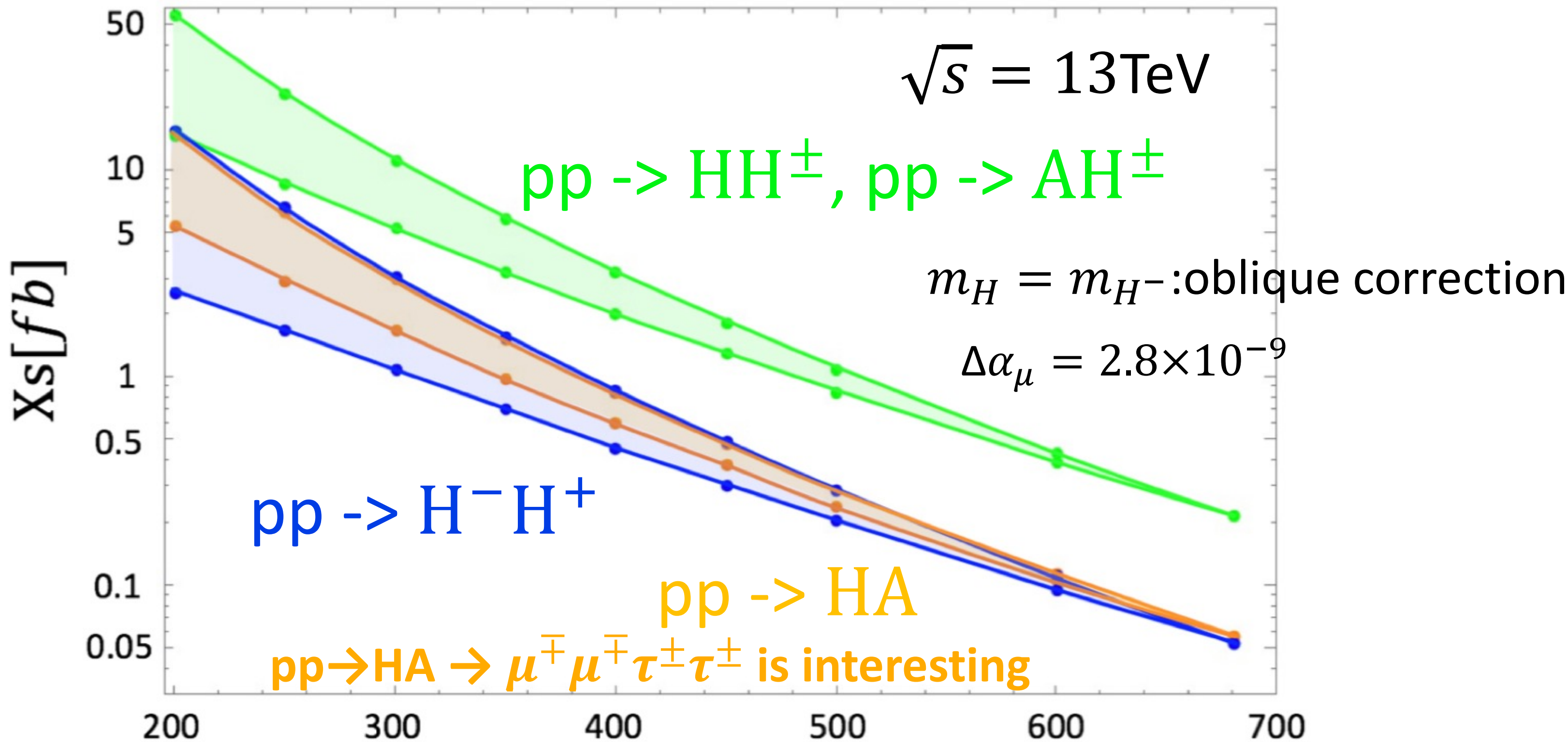
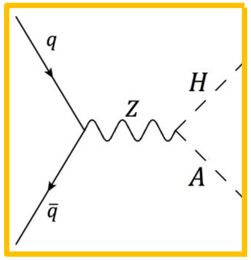
- Maximum mass gap in H and A is given as $m_H^2 = m_A^2 + \lambda_5 v^2 = m_A^2 + v^2$ (for $\lambda_5 < 1$)
- Minimum mass gap is given by $|y_e^{\mu\tau}|, |y_e^{\tau\mu}| < 1$.





Run 2 data is sensitive up to 500 GeV.

HL-LHC is sensitive up to 1150 GeV.

S. Iguro and M. Blanke, coming soon.

Bonus

Nice to meet you!

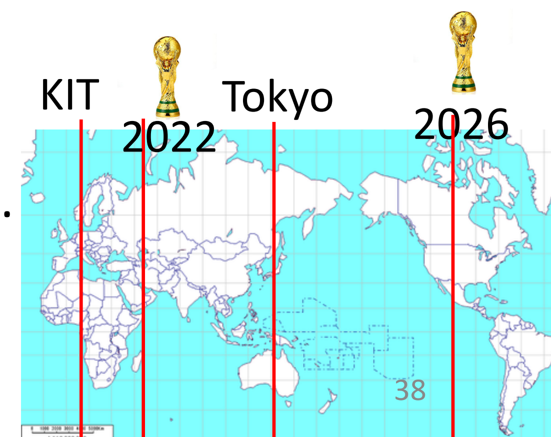
I am a Postdoc at KIT for three years!

Oct. 2021 – September 2024

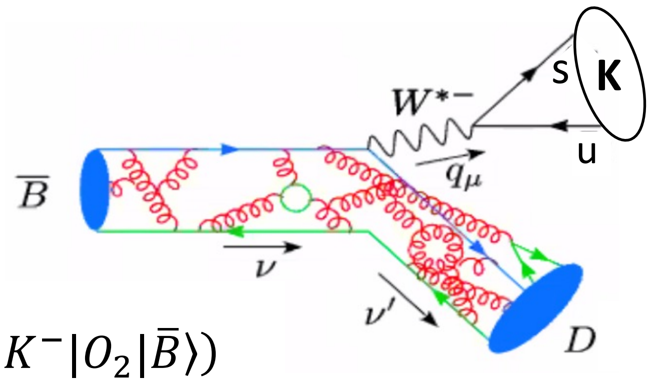
- Name: Syuhei Iguro
- Position: Postdoc
- Birth place: Japan, Tokyo
- Interests: Flavor, Collider, Dark Matter, Neutrino.....

Especially for interplay between flavor physics and collider physics

- I love football! I came to EU since time gap is smaller between here and Qatar 2022 W cup. I will go to U.S. since we have the next one in U.S.
- For more info: https://igurosyuhei.wixsite.com/mysite



Factorization amplitude



$$A(\bar{B} \to D^+K^-) = \frac{G_F V_{us}^* V_{cb}}{\sqrt{2}} (C_1 \langle D^+K^- | O_1 | \bar{B} \rangle + C_2 \langle D^+K^- | O_2 | \bar{B} \rangle)$$

The non factorizable soft gluon exchange contribution between BD system and K is suppressed. *Bjorken (89)*

Soft collinear effective theory shows the contribution is absent at leading order

$a_1 = C_1 + \frac{C_2}{N}$ (LO) Bauer et al. 0107002

$$= \frac{i\, G_F V_{us}^* V_{cb}}{\sqrt{2}} (m_B^2 - m_D^2) a_1(D^+K^-) f_K\, F_0^{B\to D}(m_K^2)$$

$a_1(D^+K^-)$ is calculated in pQCD at NNLO. See also Beneke et al 2107.03819 for QED correction

$$a_1(D^+K^-) = (1.069^{+0.009}_{-0.012}) + \left(0.046^{+0.023}_{-0.015}\right) i$$ *Huber et al, 1606.02888*

Uncertainty in f_K and V_{us} is negligible

$V_{cb} \times F_0^{B\to D}(m_K^2)$: LCSR, Belle data, QCDSR, Lattice Iguro Watanabe 2004.10208.

LCSR dominance at $q^2 = m_K^2$

Missing piece?

- *V_{cb}, B-> D, D** form factor?

  We use the result from Iguro Watanabe 2004. 10208: V_{cb}^{exc}=0.397(6),,,.

  Adopting $V_{cb}^{inc} > V_{cb}^{exc}$ makes the situation worse!

- *$O(\Lambda_{QCD}/m_b)$ sub-leading power corrections* ?

  Expected to be small: O(0.1)% Bordone et al 2007.10338 $\ll$10%

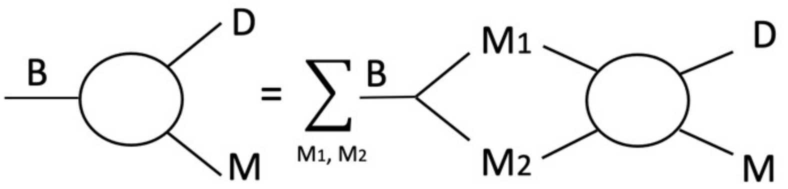
  - $O(\Lambda_{QCD}/m_b)$ chirality enhanced contribution is absent
  - correction to LCDA is $O(\alpha_s \Lambda^2/m_b^2)$
  - Contribution from soft gluon exchange between BD system and light meson is small

- *Other corrections beyond QCDF?*

  meson-meson rescattering contribution is tested

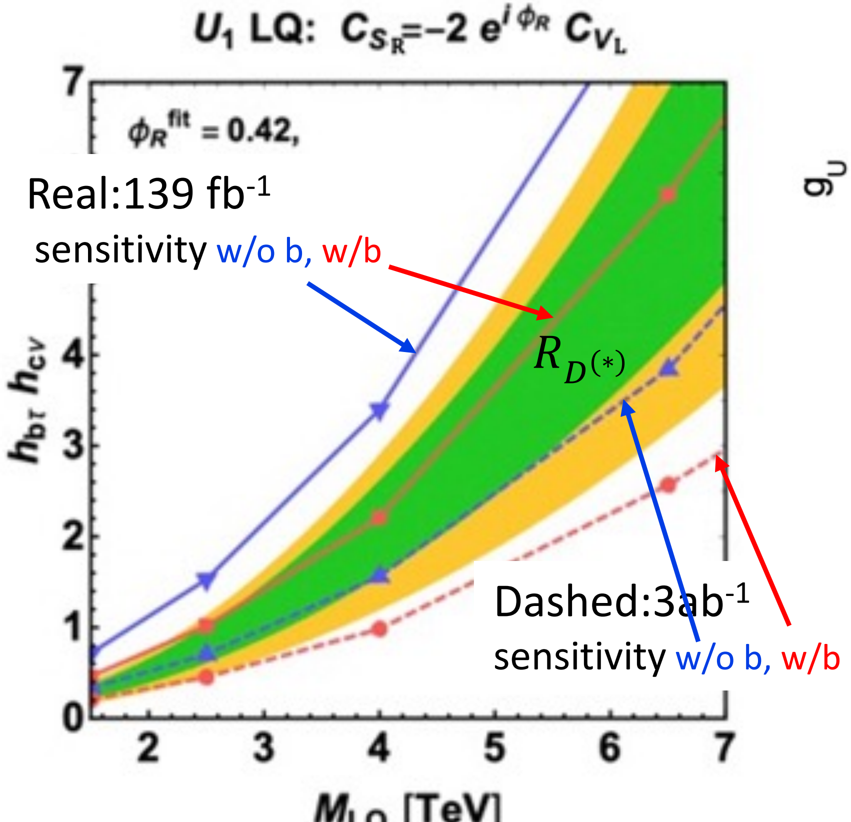
  Iguro, Endo, Mishima 2109.10811

  We can not explain within the SM

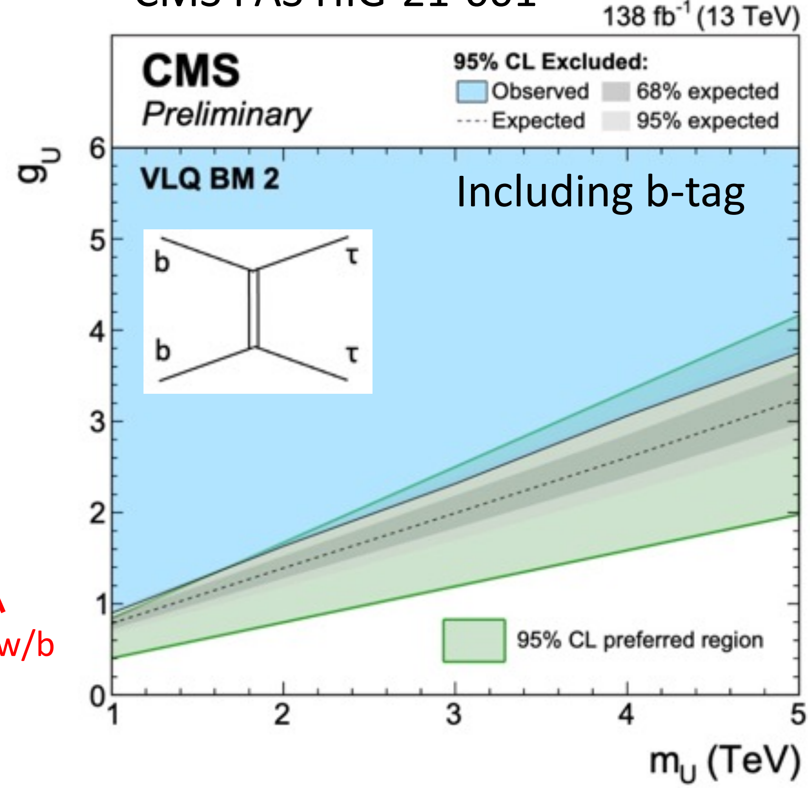


Other scenarios: U_1 LQ with U(2) flavor symmetry

2111.04748



CMS PAS HIG-21-001



We assigned the conservative uncertainty corresponding to the one with 36 fb^{-1} to estimate the sensitivity with 139 fb^{-1} → our sensitivity is conservative.

We can touch the interesting region with the LHC.

Clear mass dependence, importance of an additional b-tagging are found

Small comment: not explicitly mentioned on 1st day

Key observable for Belle II

	$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
R$_2$ LQ	[0.442, 0.447]	[0.336, 0.456]	[−0.464, −0.424]	1 σ data	1 σ data
S$_1$ LQ	[0.436, 0.481]	[−0.006, 0.489]	[−0.512, −0.450]	1 σ data	1 σ data
U$_1$ LQ	[0.440, 0.459]	[0.156, 0.422]	[−0.542, −0.488]	1 σ data	1 σ data
SM	0.46(4)	0.325(9)	−0.497(13)	0.299(3)	0.258(5)
data	0.60(9)	-	−0.38(55)	**0.340(30)**	**0.295(14)**
Belle II	0.04	3%	0.07	3%	2%

Iguro et al 2018

λ_τ: Spin of τ

$$P_\tau^D = \frac{\Gamma\left(\lambda_\tau = \frac{1}{2}\right) - \Gamma\left(\lambda_\tau = -\frac{1}{2}\right)}{\Gamma\left(\lambda_\tau = \frac{1}{2}\right) + \Gamma\left(\lambda_\tau = -\frac{1}{2}\right)}$$

P_τ^D **is a good quantity to distinguish LQ models.**

Statistical error is dominant in polarization observables.

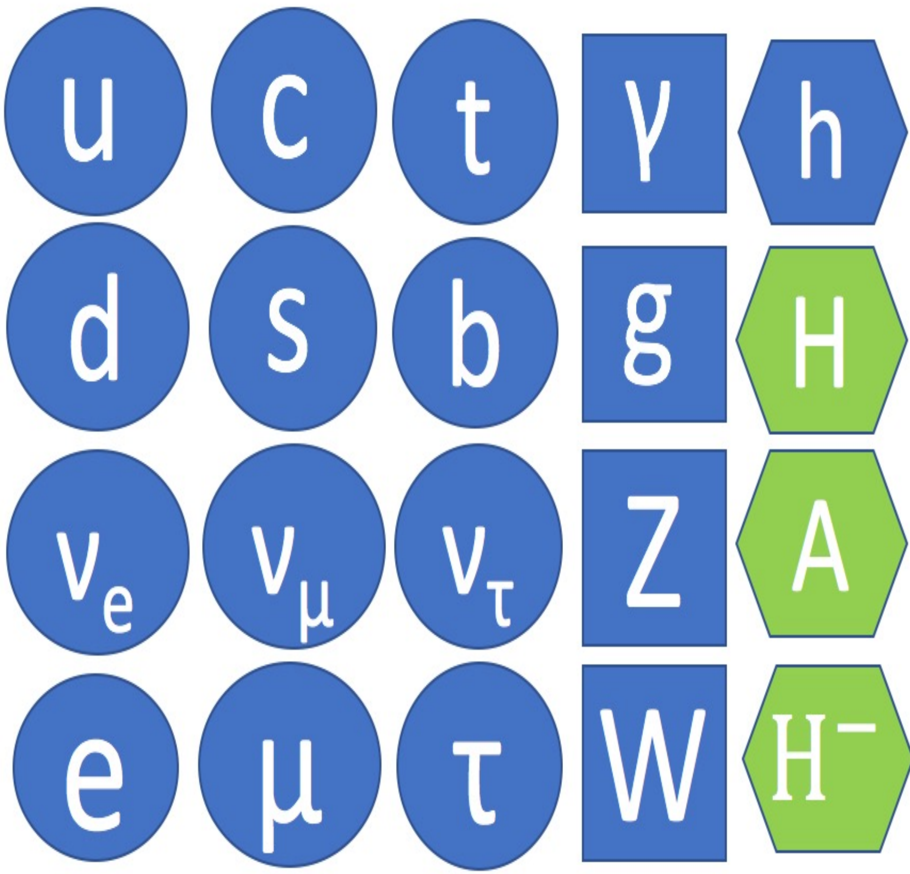
Let's wait Belle II for the new data!

Additional contents for H^- part

Our Model

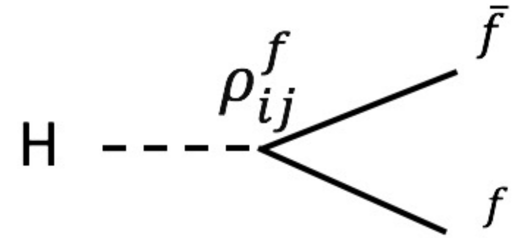
Iguro-Tobe [1708.06176](1708.06176)

Particle set in G2HDM



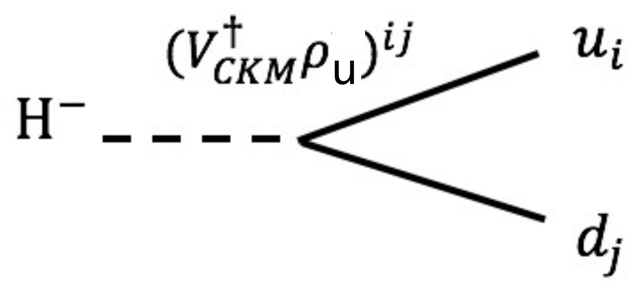
Neutral Scalar

$$\frac{1}{\sqrt{2}}\rho_f^{ij}\mathrm{H}\overline{f_L^i}f_R^j \quad (f=u,d,e,\nu)$$



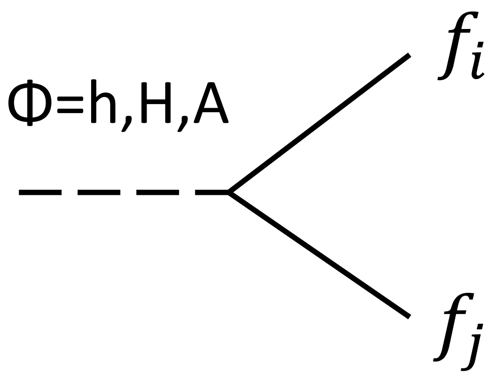
Charged Scalar

$$(\mathrm{V_{CKM}}\rho_d)^{ij}\mathrm{H}^-\overline{u_L^i}d_R^j+(V_{CKM}^\dagger\rho_u)^{ij}\mathrm{H}^-\overline{d_L^i}u_R^j$$



Model: G2HDM

Yukawa couplings between a neutral scalar and fermions



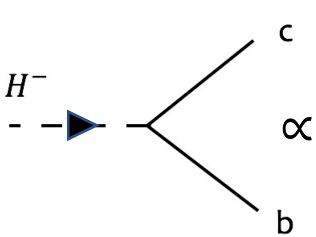
$$\approx i(y^f_{\Phi ij}\,P_R + y^{f*}_{\Phi ji}\,P_L)$$

$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

$$y^f_{Aij} = \begin{cases} -\dfrac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = u \\ +\dfrac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = d, e, \end{cases}$$

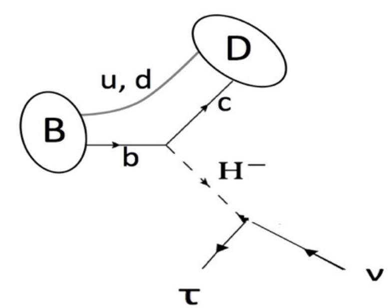
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

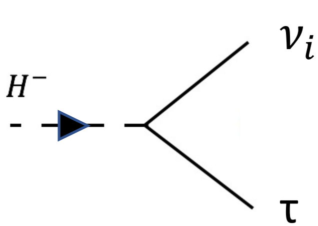
Yukawa interactions relevant to $R(D^{(*)})$



$$\propto (V_{CKM}\rho_d P_R - \rho_u^\dagger V_{CKM} P_L)^{cb} \approx \rho_d^{sb} P_R - \rho_u^{tc*} P_L$$

ρ_d^{sb}<<1:Bs Mixing





$$\propto \rho_e^{\tau\tau}$$

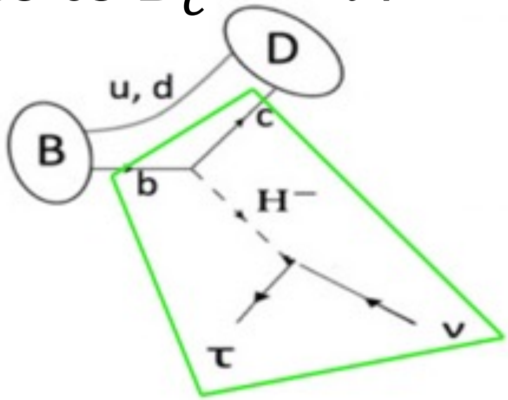
$$\boxed{\text{Yukawa interactions relevant to } R(D^{(*)}) \quad \rho_u^{tc} \times \rho_e^{\tau\tau}}$$

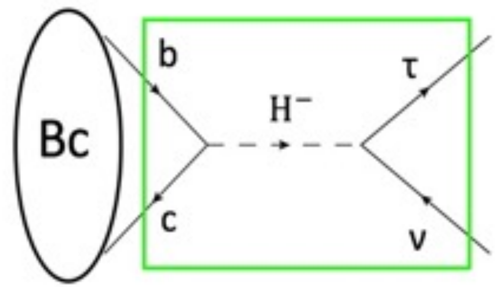
ρ_u^{tc} can be O(1) Nierste et al 2019, George-Hou 2018

Constraint

Recent update

Vector and scalar operators for $\mathrm{R}(\mathrm{D}^{(*)})$ automatically contributes to $B_c^- \to \tau\bar{\nu}$





BR($\mathrm{B}_c^- \to \tau\nu$)=

$$\mathrm{BR}(\mathrm{B}_c^- \to \tau\bar{\nu})_{\mathrm{SM}} \times \left| 1 + C_{V1} - C_{V2} + \boxed{\frac{m_{Bc}^2}{m_\tau(m_b + m_c)}} (C_{S1} - C_{S2}) \right|^2$$

~ 4.2

$\mathrm{BR}(\mathrm{B}_c^- \to \tau\bar{\nu})_{\mathrm{SM}} = 2\%$

Scalar operator drastically enhances

BR($\mathrm{B}_c^- \to \tau\bar{\nu}$)

Γ ∝ mQ^5 × G_F^2. large pT depemdence
large error in mc in fragmentation
-> large error for ΓBc function fBc/fB

Previous constraint

$< 30\%$ R.Alonso et al. 1611.06676

$< 10\%$ A.G.Akeroyd.et al. 1708.04072

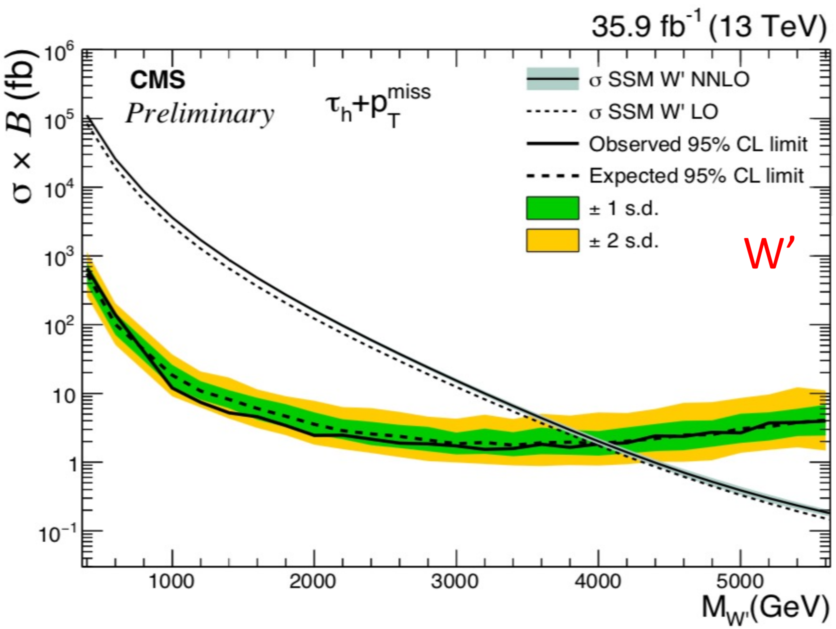
Current constraint

B.Grinstein 2105.02988

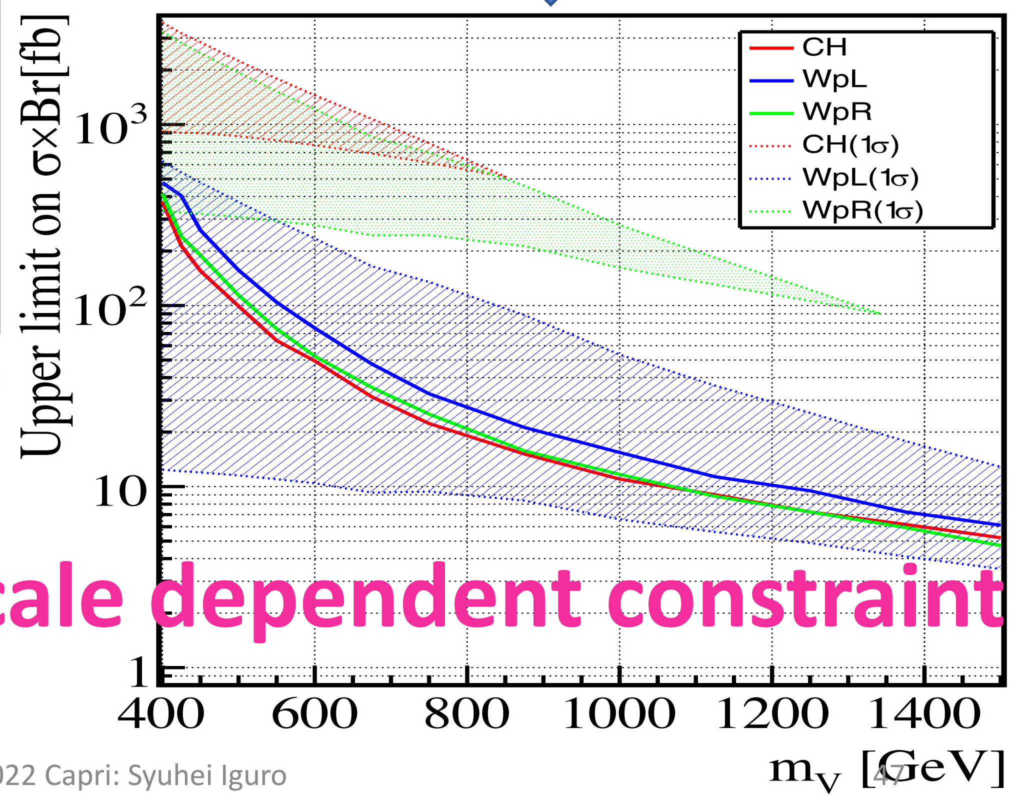
$< 63\%$ M.Blanke.et al. 1811.09603

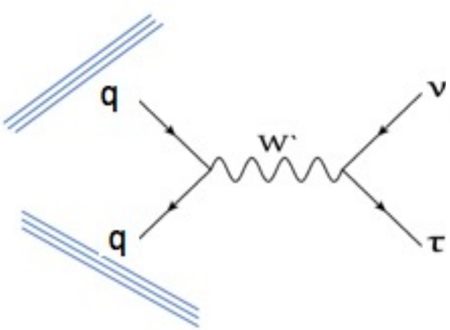
Large coefficient (large coupling) allows the collider search!

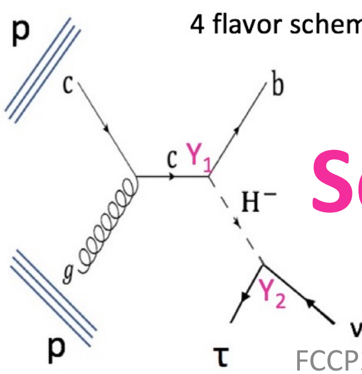
$\tau\nu$ resonance (+j) search in LHC can give a stringent limit.
But, the limit is for W'. CMS-PAS-EXO-17-008



We reinterpreted this limit into
H$^-$ by the collider simulation.



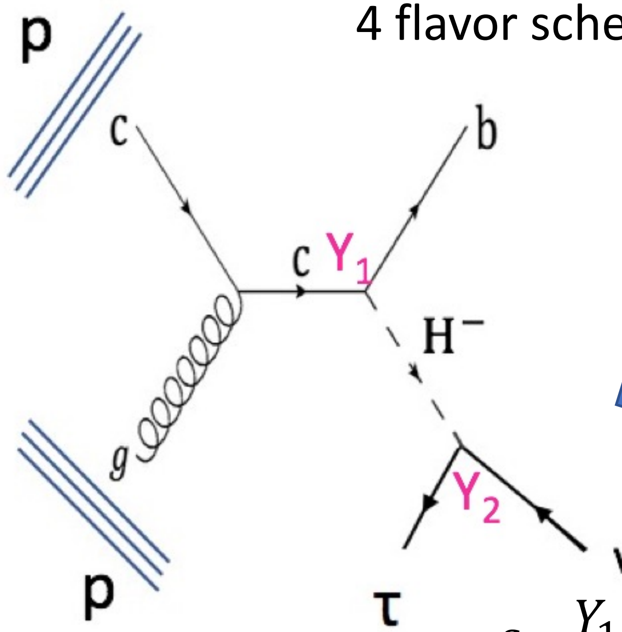




Scale dependent constraint!

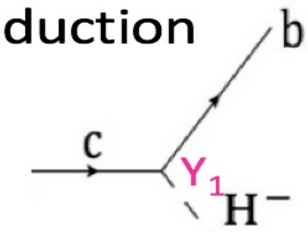
$\sigma\times$ Br in G2HDM

4 flavor scheme



$$C_R'^S \sim \frac{Y_1 Y_2}{m_{H^-}^2}$$

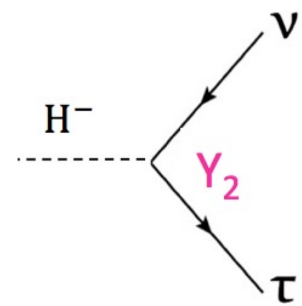
Production



depending on H$^-$ mass

$\sigma = X_{H^-}|Y_1|^2$

Branching ratio



$$\mathrm{BR}(\mathrm{H}^- \to \tau\nu) \approx \frac{|Y_2|^2}{3|Y_1|^2+|Y_2|^2}$$

$$\boxed{\sigma\times\mathrm{BR} = \frac{X_{H^-}|Y_1|^2\ |Y_2|^2}{3|Y_1|^2+|Y_2|^2}}$$

Combination 1 : $Y_1 = 1$, maximizing denominator.
less events, weaker constraint.

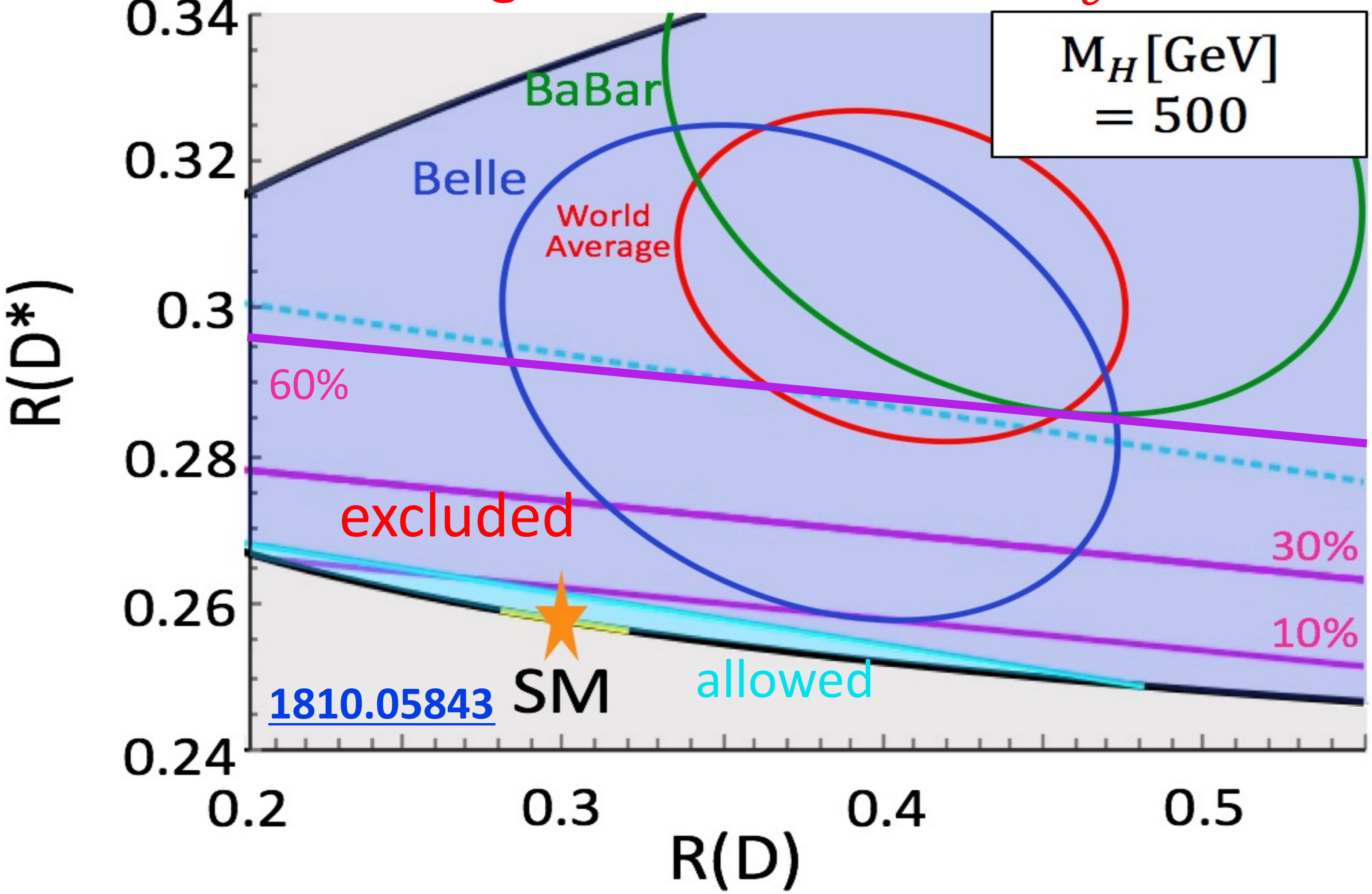
Combination 2 : $Y_2 = \sqrt{3}Y_1$, minimizing denominator.
more events, severe

We set $|Y_1|, |Y_2| < 1$: narrow resonance $\tau\nu$ search.

$\Gamma(\mathrm{H}^- \to bc) \sim 0.06|Y_1|^2 m_{H^-}$, $\Gamma(\mathrm{H}^- \to \tau\nu) \sim 0.02|Y_2|^2 m_{H^-}$, then $\Gamma/m_{H^-} < 0.1$

Result

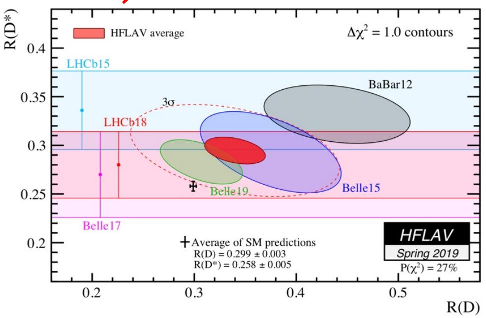
Much more stringent constraint than $B_c^- \to \tau\bar{\nu}$



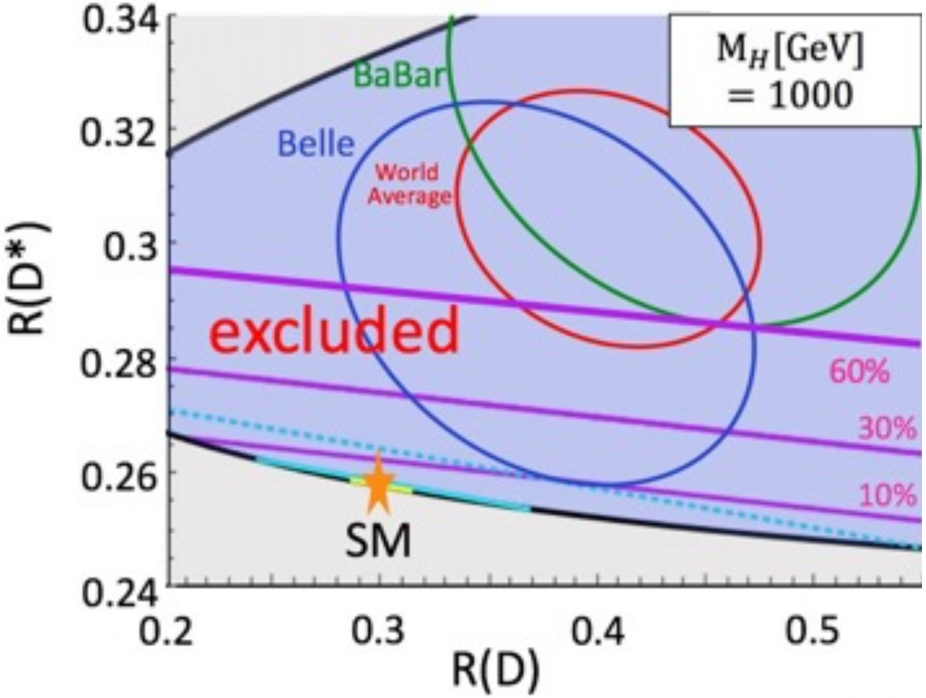
Result

Heavier H^-, more severe constraint.

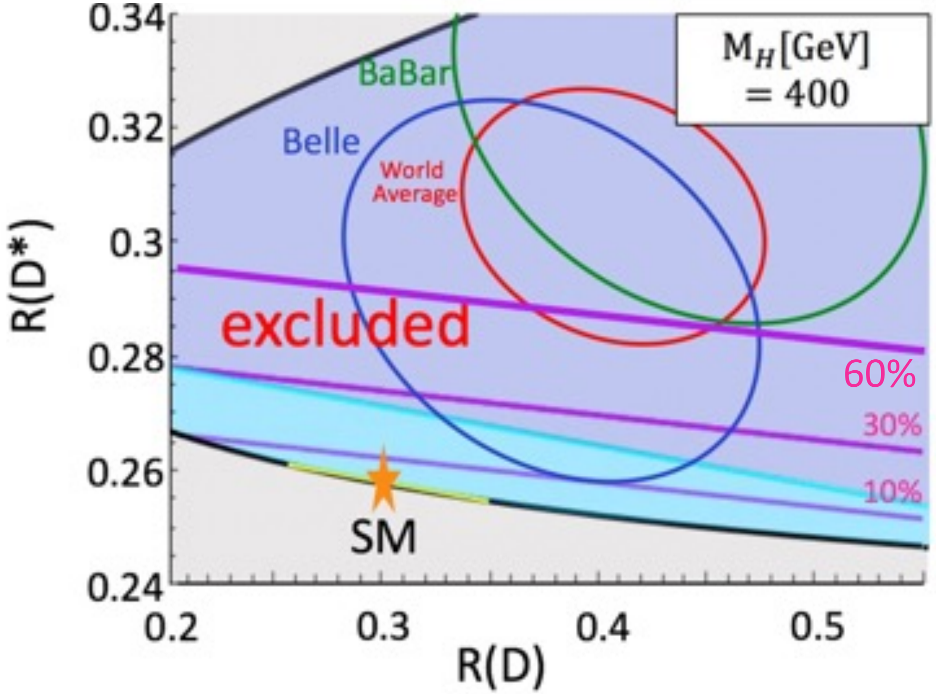
[1810.05843]



heavier



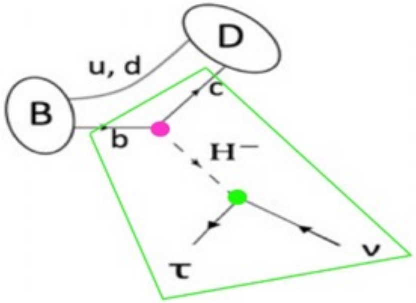
lighter

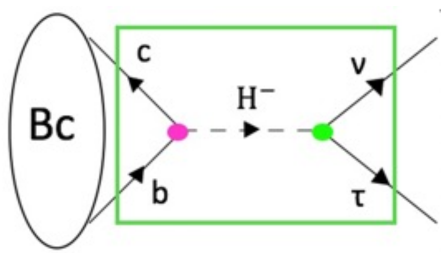


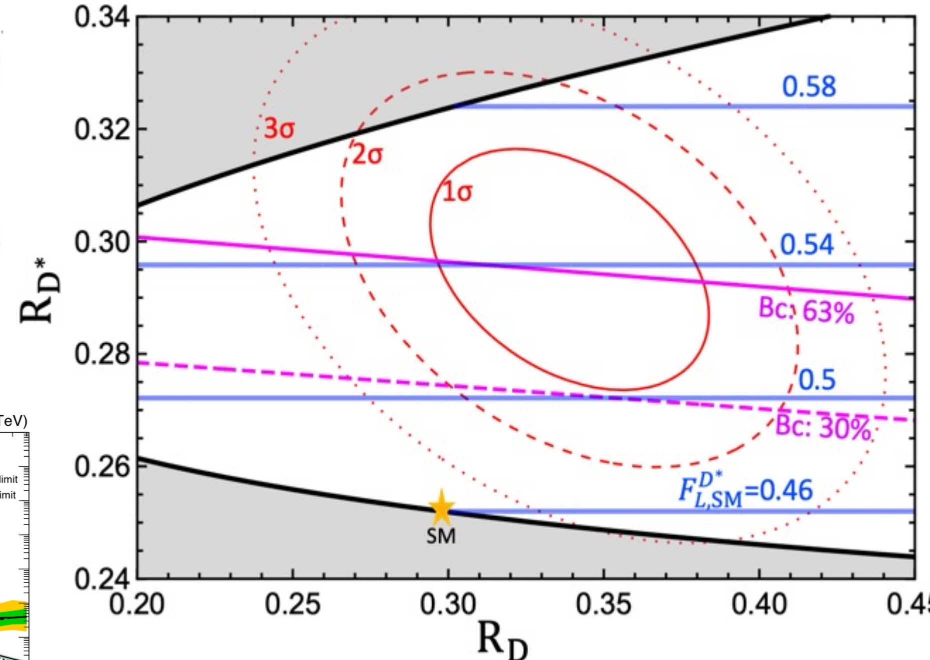
Better sensitivity for heavy $\tau\nu$ resonances: experimentally $\tau\nu$ resonance search for W' is more sensitive to a heavier resonance because of the low background from W→ $\tau\nu$.

H^- interpretation of R_D , R_{D^*} anomalies silently revived

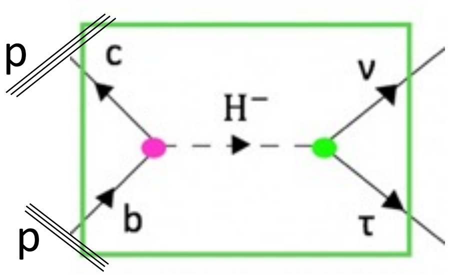
Summary of the status and prospect are discussed Syuhei Iguro, **2201.06565**

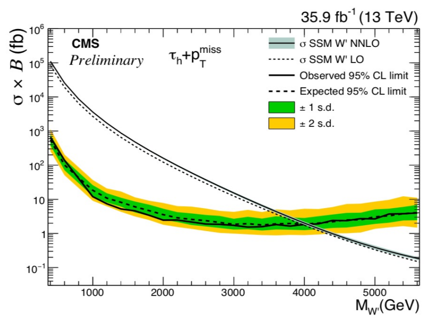






Due to the charm mass scheme dependence,
The bound is relaxed BR(Bc→τν)<63% Grinstein 2021





τν resonance search at LHC gives more stringent constraint for m_{H-} > 400GeV Iguro 2018

$F_{L,SM}^{D^*}$=0.46, $F_{L,Belle}^{D^*}$=0.60 ± 0.09
Only scalar can enhance $F_L^{D^*}$

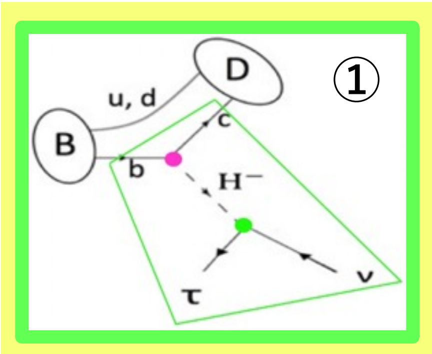
τν resonance search result for m_{H-} < 400GeV is not available at $\sqrt{s}$=13TeV probably because

- they originally search for W' in SSM and wanted to push up the lower bound on $m_{W'}$
- SMBG (W-> τν tail) is huge at low mT

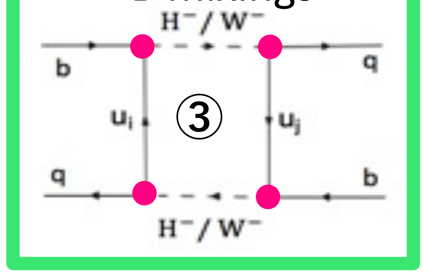
How is the situation and prospect for m_{H-} < 400GeV ?

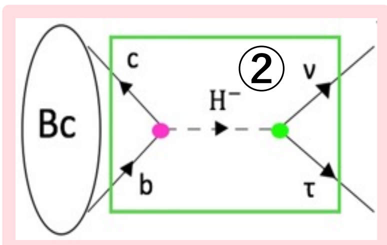
Various bounds are very complementary

HL-LHC can probe large parameter space!

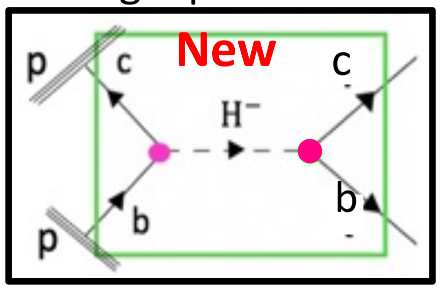


B mixings





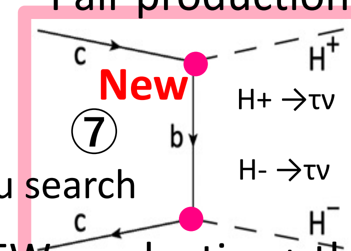
Single production



3 categories of bounds

1. **right to left e.g. ③, ④, ⑤**
2. **above to bellow ⑦**
3. **constrain ↙ e.g. ②**

Pair production



Stau search

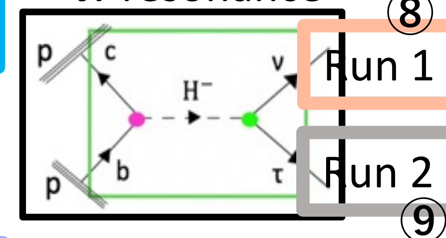
EW production+ this

bb resonance search
$\sqrt{s}$=8TeV ④

bb + photon search
$\sqrt{s}$=13TeV ⑤

Flavor inclusive di-jet
$\sqrt{s}$=13TeV ⑥

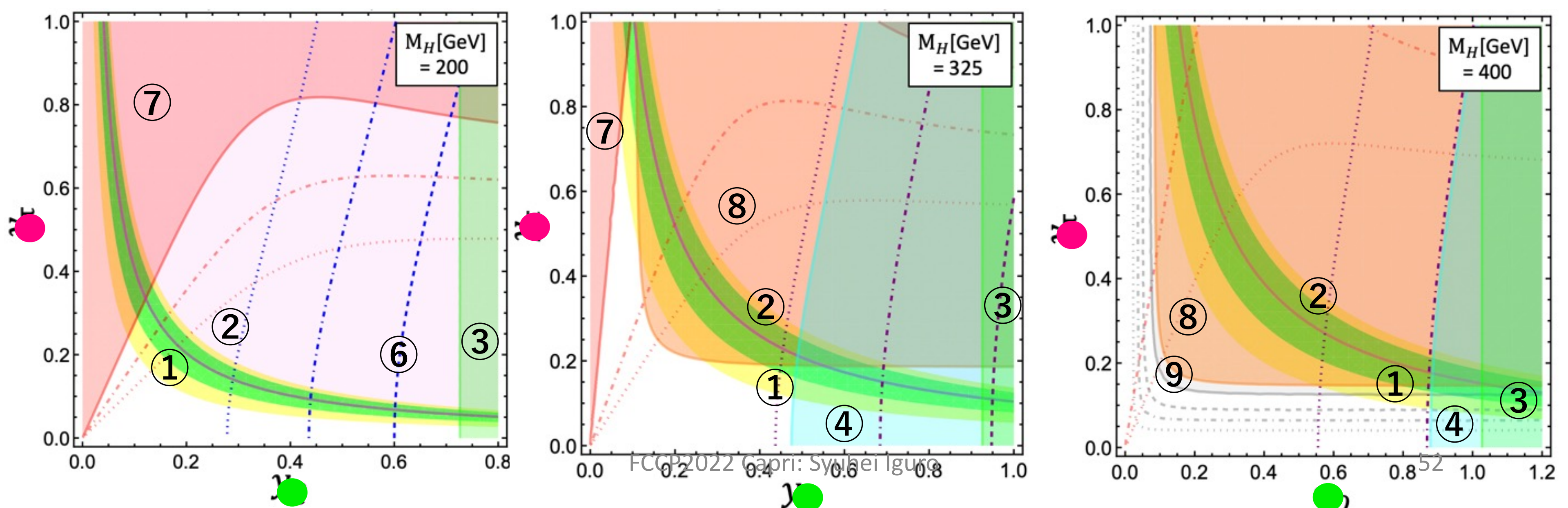
τν resonance



Luminosity

Current — · · 500fb^{-1}

- - ·139fb^{-1} ········· 3ab^{-1}



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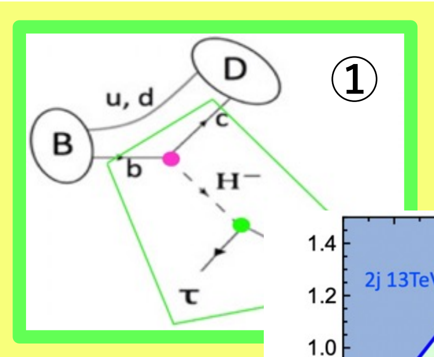
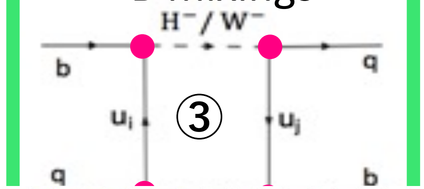
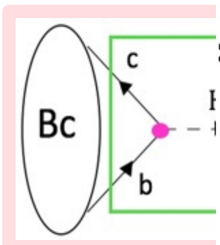
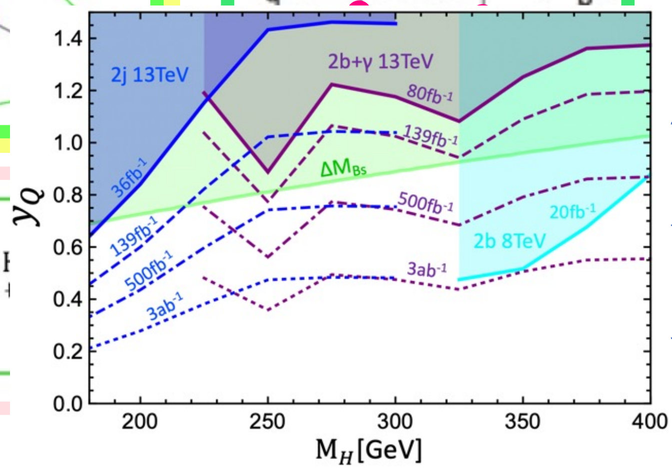


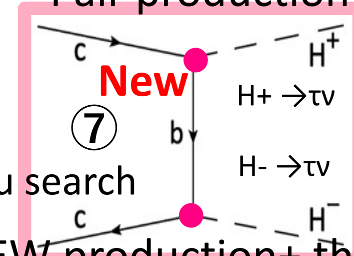
B mixings







Pair production



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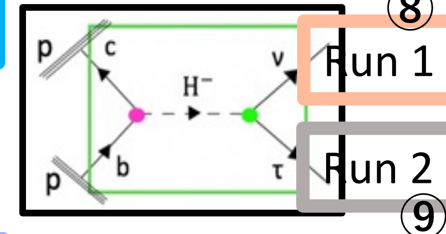
$\sqrt{s}$=13TeV ⑥

τν resonance



Luminosity

—— Current — · · 500fb⁻¹

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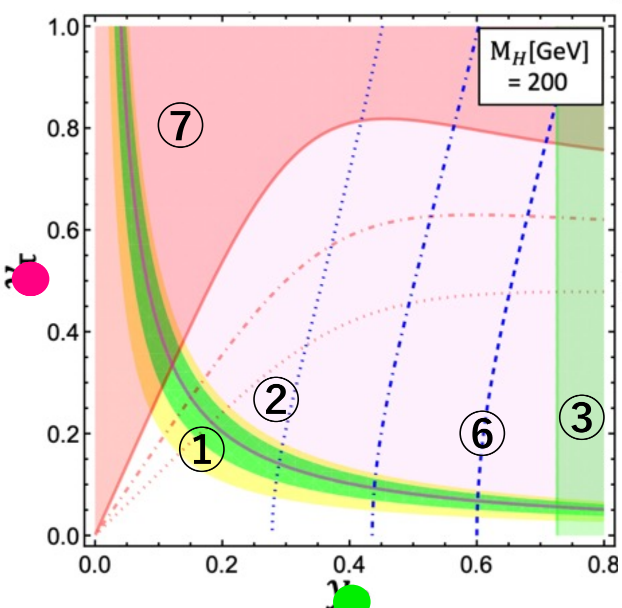
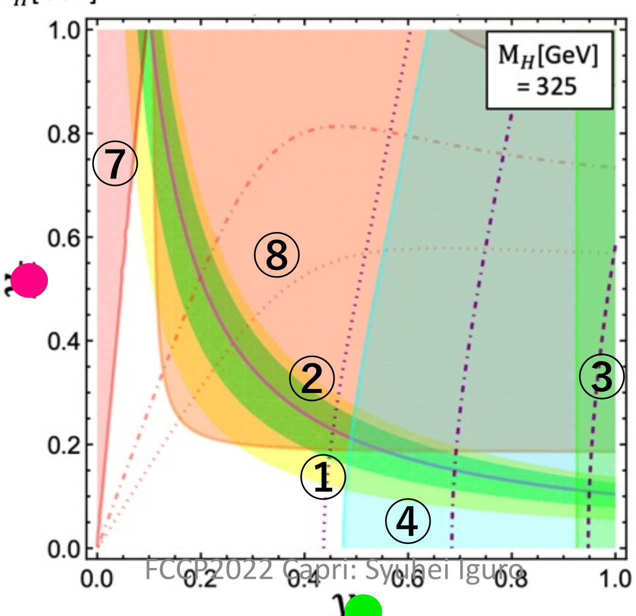
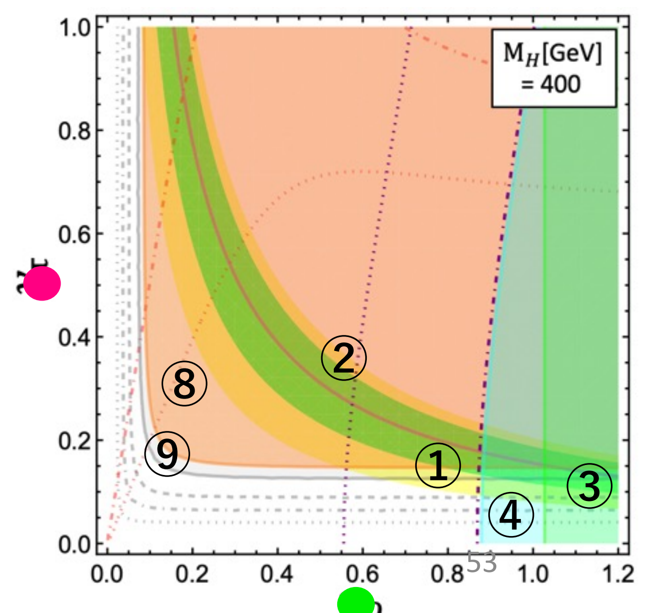


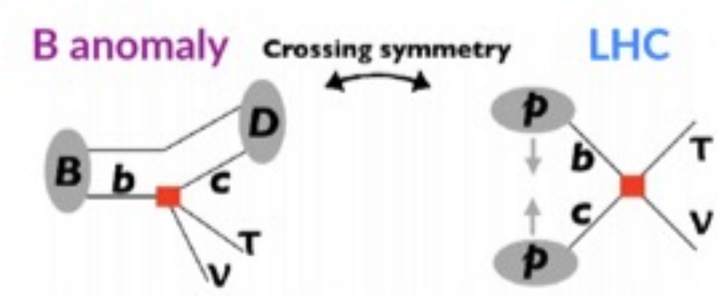




Additional contents for LQ part

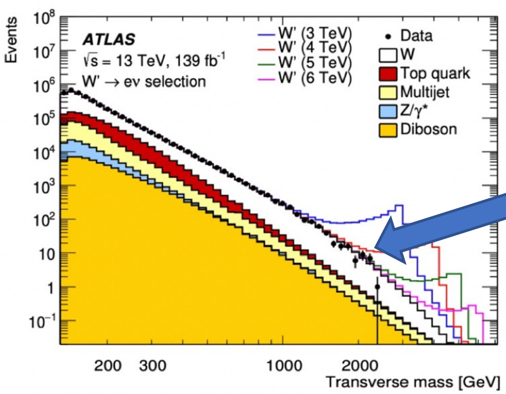
Several works in the literature

t-channel mediator: Leptoquark (LQ)

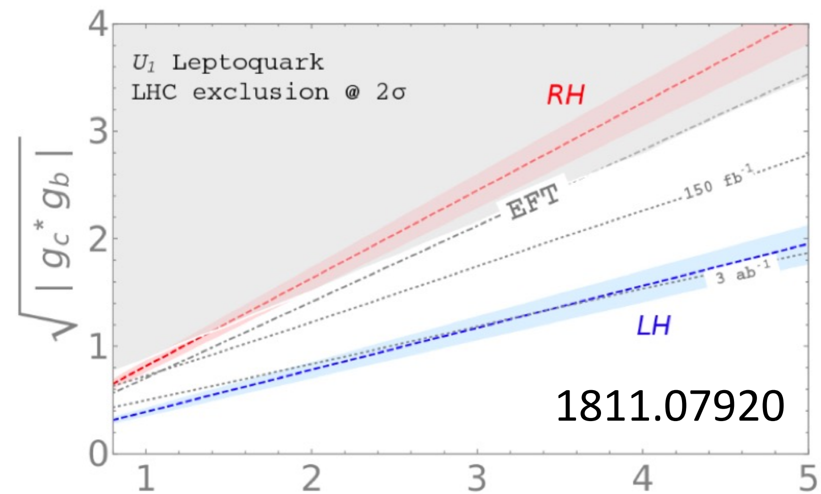


HL LHC can test LH scenario!

signal shape on the MT plane
t-channel : plateau



Look into the high pT region



1811.07920

$$m_T = \sqrt{2p_{\rm T}^{\ell} E_{\rm T}^{\rm miss}(1-\cos\theta_{\ell\nu})}$$

$$\mathcal{L}^{\rm LE}_{\rm eff} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\tau)(\bar{\tau}\gamma_\mu P_L \nu_\tau)(\bar{c}\gamma^\mu P_L b)$$ LH

Authors of 1811.07920 also worked within EFT and set the limit on WCs

TABLE II. 2σ upper bounds for the absolute value of the WCs of semi-tauonic cb transitions at $\mu = m_b$.

Data set	Vector	Scalar	Tensor
ATLAS (36.1 fb^{-1})	0.55	0.93	0.26
CMS (35.9 fb^{-1})	0.25	0.45	0.12
LHC combined	0.32	0.57	0.16
LHC (150 fb^{-1})	0.21	0.37	0.10
HL-LHC	0.10	0.17	0.05

	Best fit	1σ range
ϵ_L^τ	0.07	(0.05, 0.09)
ϵ_T^τ	−0.03	(−0.04, −0.02)
$\epsilon_{S_L}^\tau$	0.08	(0.01, 0.14)
$\epsilon_{S_R}^\tau$	0.14	(0.08, 0.20)

HL LHC is sensitive to the currently favored NP.

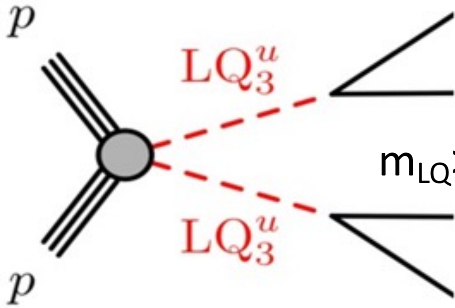
According to them, we can apply the EFT limit for m_{LQ} > 2-3 TeV.

However, this is not good approximation.

The difference is crucial to judge the model

LHC implication in LQ cases

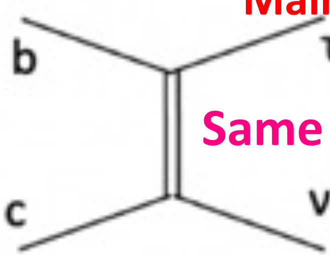
Gino et al 1901.10480

① 

m_{LQ}>1.6TeV

② t-channel

Main focus

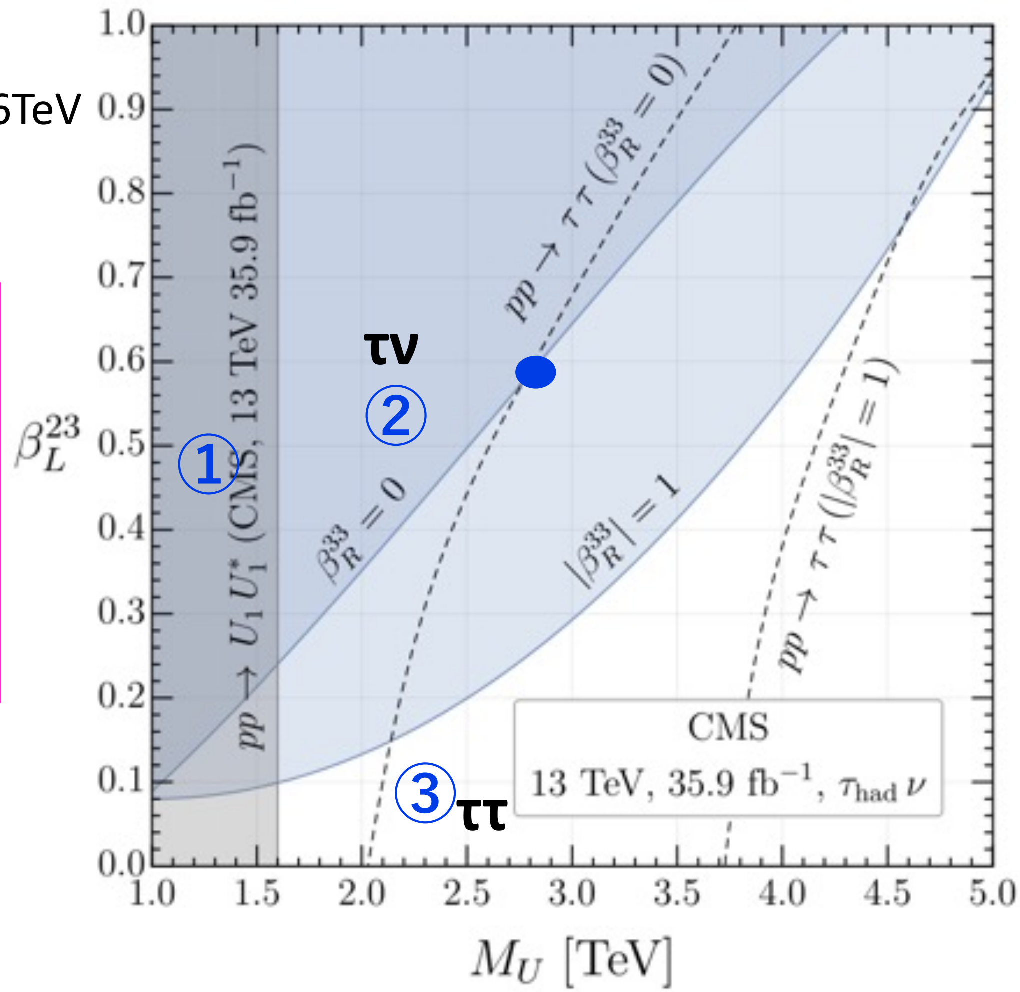


Same as R_D

Model independent

③ t-channel

Single production is also important



β_R: additional parameter

Significant mass dependence

Effective Lagrangian for b ->c τ ν

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[(1+C_{V1})O_{V1} + C_{V2}O_{V2} + C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T\right]$$

At mb=4GeV

Operator basis 5 operators

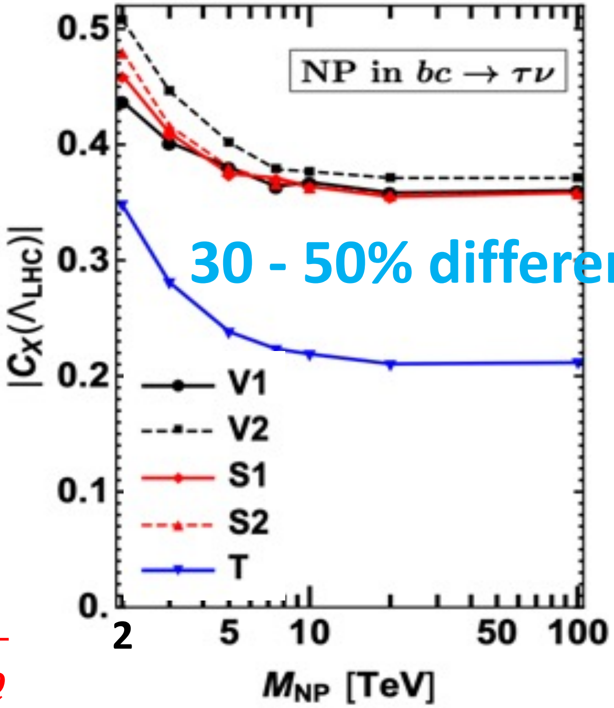
$$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L\nu_\tau)$$
$$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L\nu_\tau)$$
Scalar

$$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L\nu_\tau)$$
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L\nu_\tau)$$
Vector

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L\nu_\tau)$$
Tensor

$$\frac{1}{t - m_{LQ}^2}$$

Upper limit on WC



30 - 50% difference

***t* can not be neglected for the high pT mono tau region.**

BG cut flow

BG (**cut a**)	Wjj	$Zjj\,(Z \to \nu\bar{\nu})$	$t\bar{t}$	$Z, \gamma\,$DY	VV	single t
τ cut (a-1)	4613.3	562.0	241.8	1236.4	72.2	52.4
lepton cut (a-2)	4609.1	561.9	230.3	744.1	65.5	50.1
MET cut (a-3)	2933.0	471.9	190.8	83.9	42.8	42.6
back-to-back (a-4)	777.0	184.6	9.85	52.5	12.1	1.09
$0.7 < m_T < 1$ TeV	70.5	20.1	0.34	3.03	1.30	0.02
1 TeV $< m_T$	16.9	5.1	0.06	0.56	0.32	0.02
1 TeV $< m_T$ [25]	22 ± 6.2	0.9 ± 0.5	< 0.1	< 0.1	0.7 ± 0.1	< 0.1
1 TeV $< m_T$ [34]	18	5.2	0.44	0.0025	1.7	0.1

Table 9. Cut flows of the SM background events in the **cut a** category (the $\tau^{\pm}\nu$ search). The expected number of events corresponding to $\int \mathcal{L}dt = 35.9\,\text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV are shown. The last two rows show the results by Refs. [25] and [34]. See, the main text for the detail.

BG cut flow

BG (**cut b**)	Wjj	$Zjj\,(Z \to \nu\bar{\nu})$	$t\bar{t}$	Z,γ DY	VV	single t
number of jets	6693.4	235099	346.7	1813.2	125.8	151.8
number of τ	3173.5	5617.1	73.9	894.9	59.7	34.0
number of b	90.6	305.5	35.9	163.9	5.28	18.8
isolated lepton	90.5	305.5	29.7	10.4	1.38	17.0
τ kinematics	78.8	20.8	23.6	9.19	1.13	14.0
MET cut	71.2	4.62	20.9	2.52	0.98	12.7
back-to-back	7.84	3.61	1.67	0.57	0.18	0.54
$0.7 < m_T < 1$ TeV	0.58	0.37	0.056	0.28	0.018	0.029
1 TeV $< m_T$	0.16	0.06	0.01	0.007	0.005	0.005
1 TeV $< m_T$ [34]	0.18(5)	0.21(12)	0.29(3)	$4.2(4)\times10^{-5}$	0.35(5)	0.067(7)

Table 10. Same as Table 9 but for **cut b** (the $\tau^\pm\nu + b$ search). The last row shows the results by Ref. [34]. Note that their b-tagging efficiencies are different from ours (see, the footnote #3).