# Probing new physics behind flavor anomalies at the LHC

IBS and KMI joint workshop 2022


Syuhei Iguro


Based on
2202.10468, 2201.06565,
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)

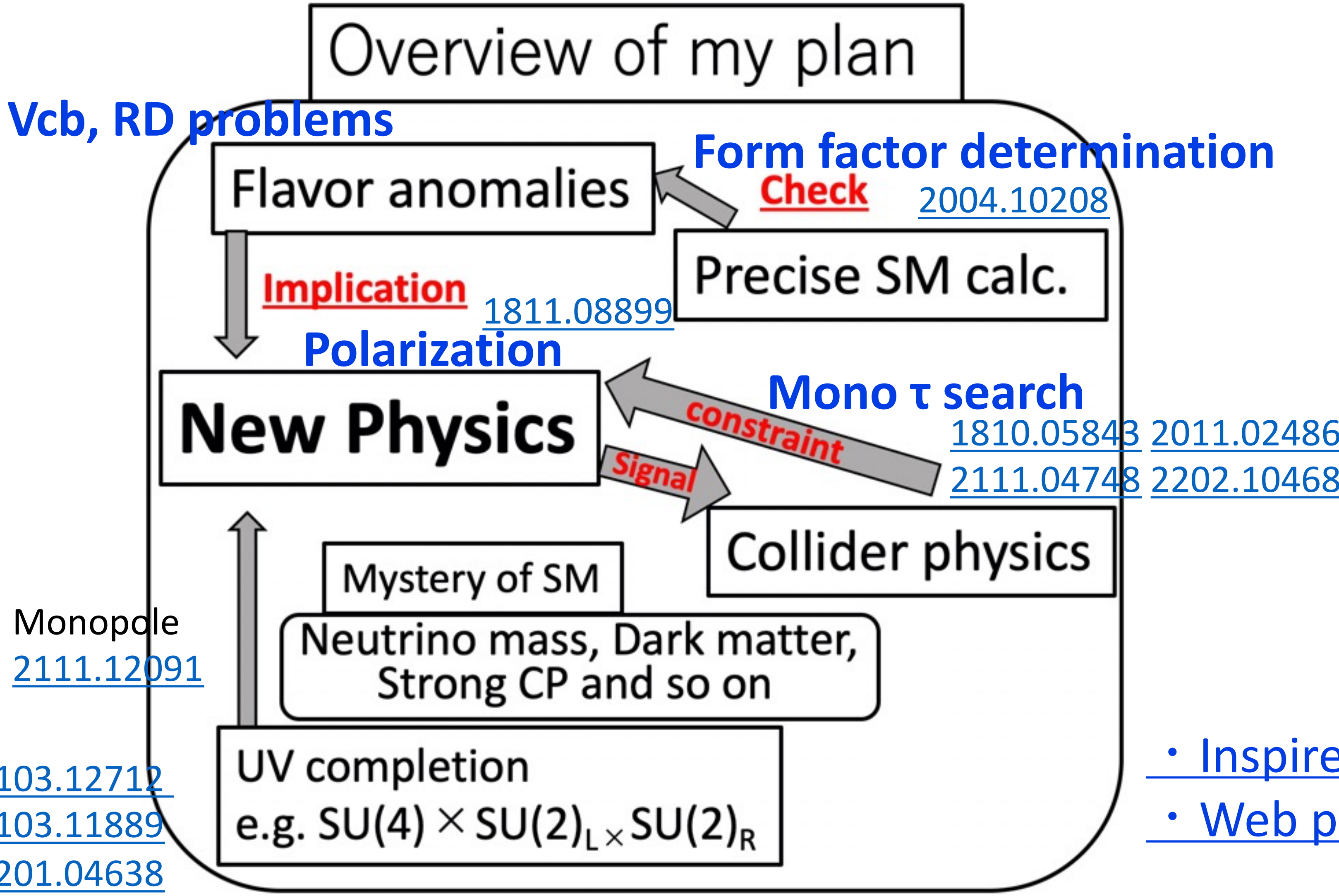

Thanks for inviting me!

# Messages in this talk

The LHC provides the unique window to access
the new physics possibly behind B anomalies.
Several developments are made in this 5 years.
e.g. leptoquark mass dependence,
an additional b-jet requirement,
charge asymmetry of the final state.

The b flavor physics and collider physics are very complementary.

# Summary of the my physics view

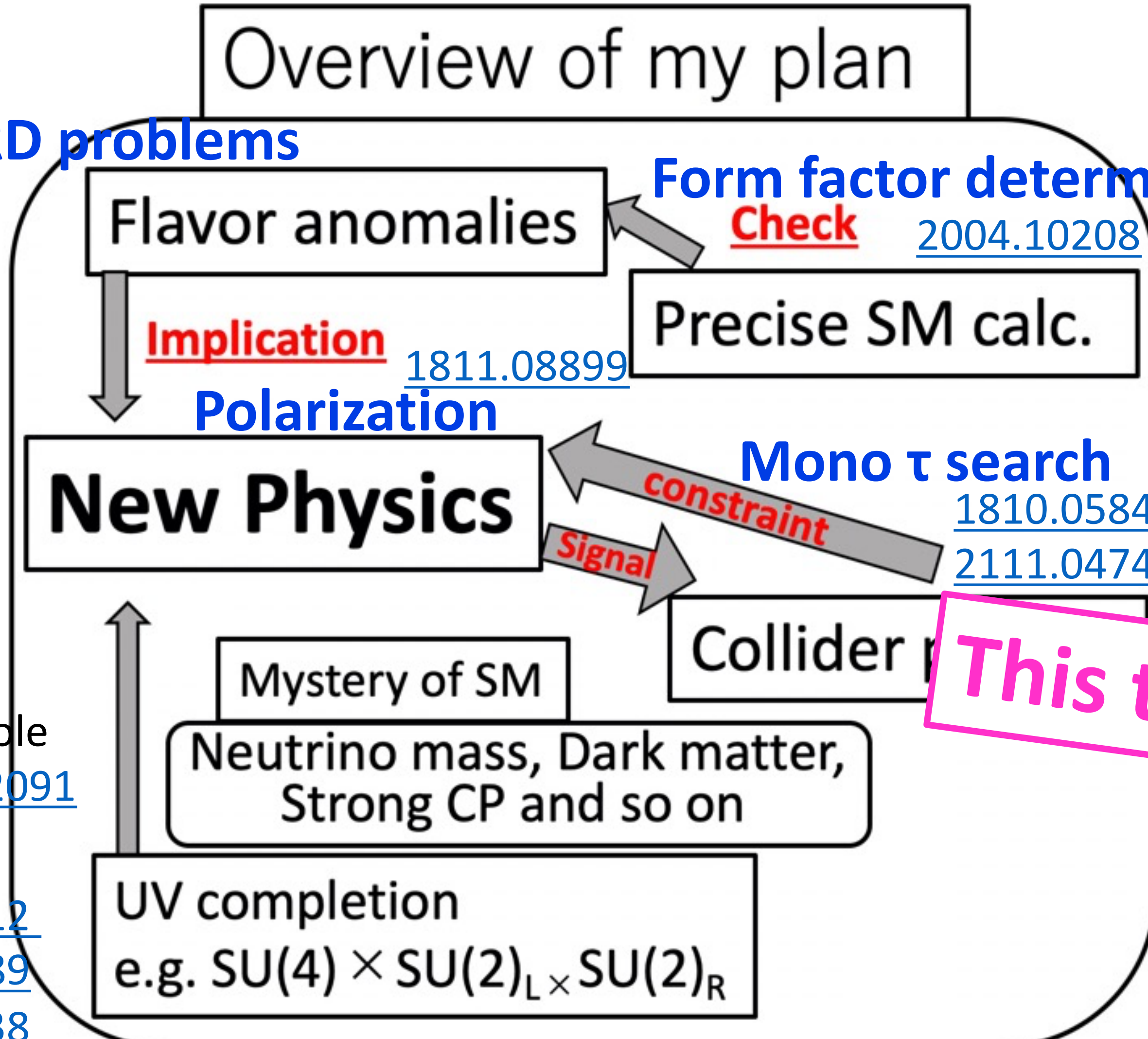



Monopole
2111.12091

2103.12712
2103.11889
2201.04638

・Inspire
・Web page

# Summary of the my physics view




**Vcb, RD problems**

**Form factor determination**

2004.10208

1811.08899

**Polarization**

**Mono τ search**

1810.05843 2011.02486

2111.04748 2202.10468

**This talk**

Monopole
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2103.11889
2201.04638

・ Inspire
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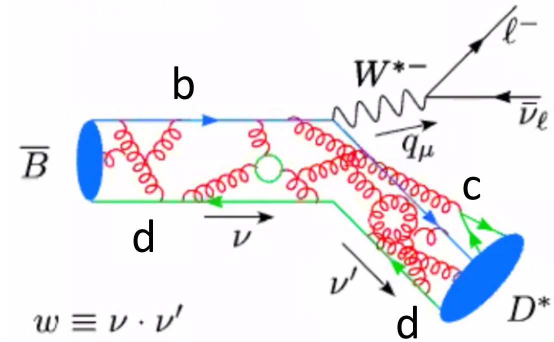
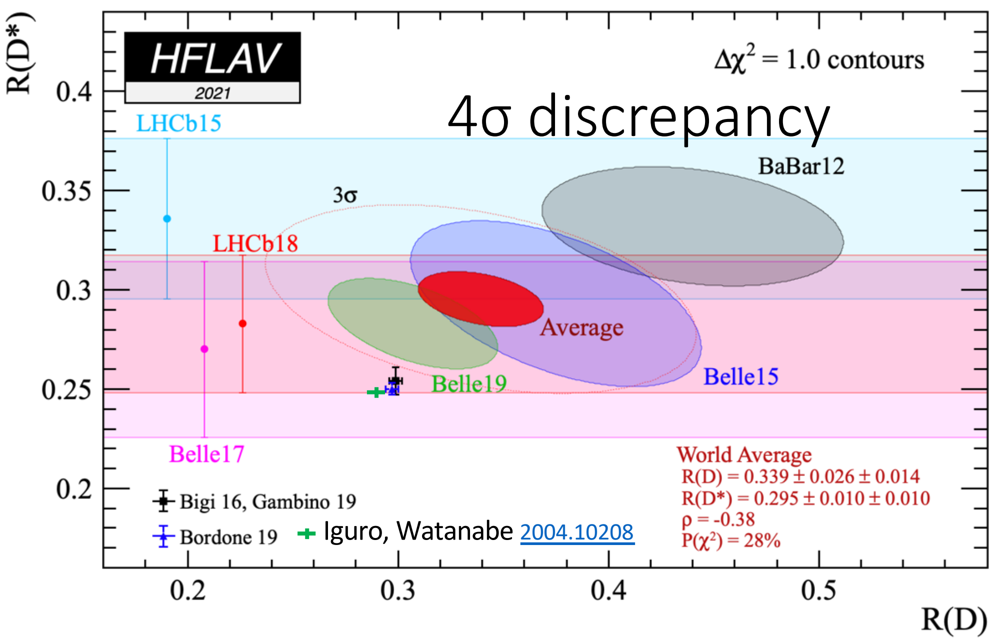
# $R_{D^{(*)}}$ anomaly




**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

Recent 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

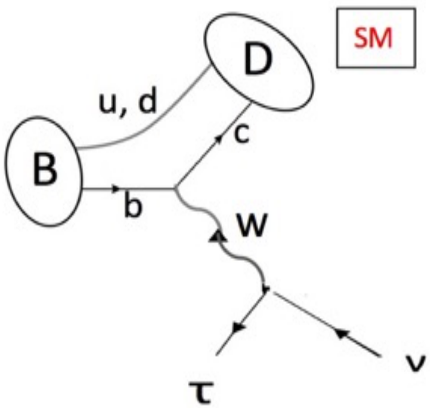
$R_{\Lambda c}^{exp} = 0.24 \pm 0.08$, $R_{\Lambda c}^{SM} = 0.324 \pm 0.004$

Consistent with SM within 1σ

However, systematic uncertainty is still large to say something

# What kind of New physics is implied?

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




- 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**

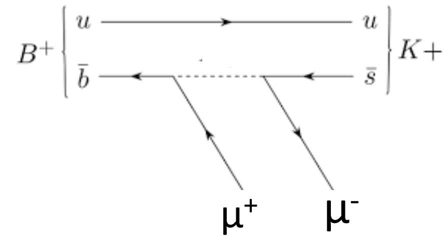
**It is natural to test NP scenarios at the LHC**

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

**Bunch of works!**

# $R_{K^{(*)}}$ anomaly $\quad b \to s\mu\bar{\mu}$

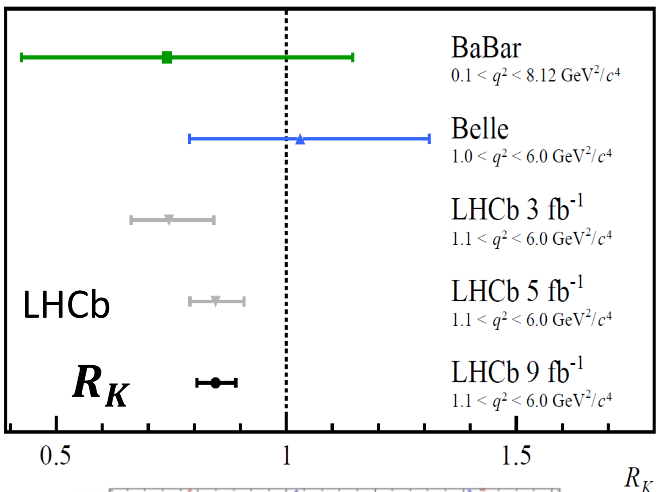
Leptoquark(LQ)

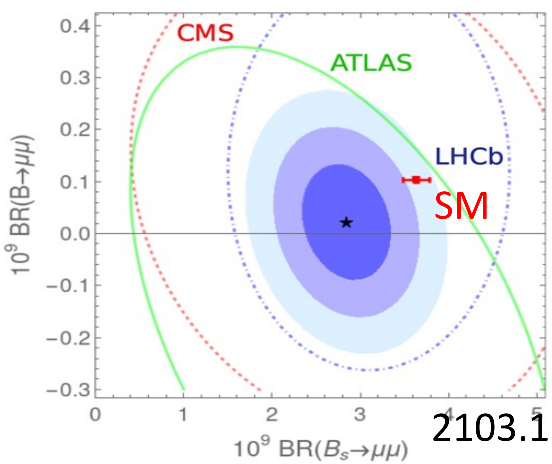



**Lepton flavor universality is a key prediction of the SM**

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\bar{\mu})}{BR(B \to K^{(*)}e\bar{e})}$$

Taking ratio greatly cancels uncertainty in the hadronic matrix element



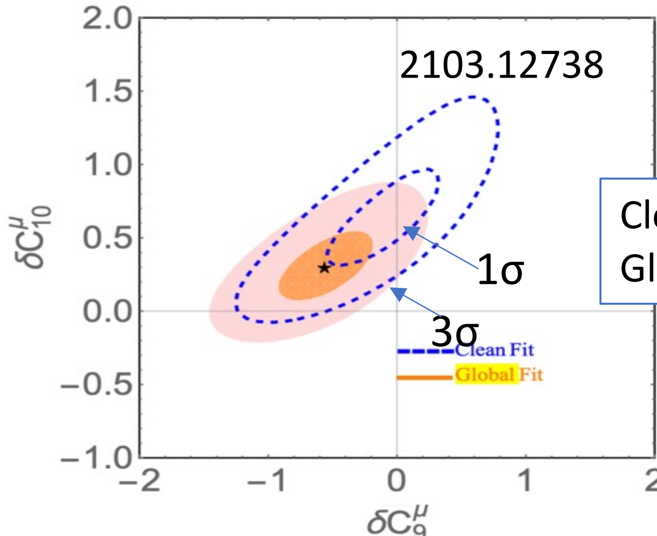




2103.12738

Global fit

$$\mathcal{H}_{\rm eff}^{\rm SM} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_{ps} \left( C_1 O_1^p + C_2 O_2^p + \sum_{i=3}^{10} C_i O_i \right) \quad \lambda_{ps} = V_{pb} V_{ps}^*$$

$$O_9^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell). \quad O_{10}^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell).$$




IBS-KMI 2022

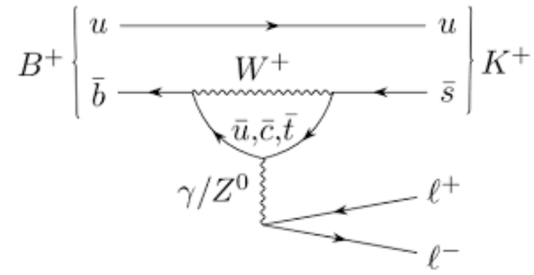
Clean obs. : $R_K$, $R_{K^*}$, $B_s \to \mu\bar{\mu}$.
Global obs.: Clean+ angular

Currently there is sizable deviation!

# What kind of New physics is implied?

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\bar{\mu})}{BR(B \to K^{(*)}e\bar{e})}$$

SM: Penguin




- New physics in $b \to s\mu\bar{\mu}$ is interesting.
- We need to reduce SM amplitude by 15%.

1-loop induced current describes the SM amplitude

**40 TeV tree level NP is enough**

**It is challenging to test NP scenarios at the LHC ($\sqrt{s}$ =13TeV)**

Kohda et al. 1803.07492, Afik et al. 1805.11402 Allanach et al. 1810.02166,
ATLAS 2105.13847, Greljo et al. 2205.13552,
Syuhei-Michi-Monika-Marco w.i.p.

**works on colliders!**

Discussion on 100TeV collider, muon collider

# Target of this talk

NP candidate behind the $\boldsymbol{R_{D^{(*)}}}$ anomaly.

However, the contents can be also applied to search for the NP contribution in the other process e.g.

$b \to u\, l\, \nu$.

Measurement of the $b \to ul\nu$ process was statistically limited, however, the Belle II experiment is on-going!

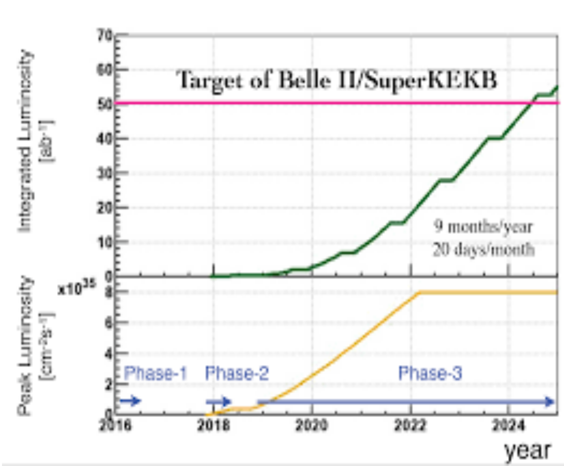
$|V_{cb}/V_{ub}|^2 = 100$

Interesting observables are waiting for the measurement.

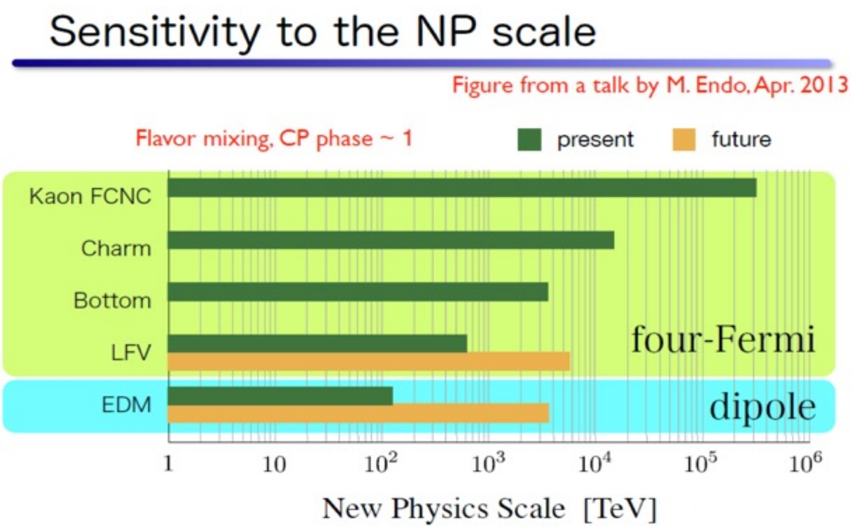
$$\boldsymbol{R}_{\pi} = \frac{\boldsymbol{BR(B\to\pi\tau\nu)}}{\boldsymbol{BR(B\to\pi l\nu)}} \simeq 1.05 \pm 0.51,\ R_{\pi}^{SM} = 0.64 \pm 0.02$$

$\pm 0.09$ with 50ab$^{-1}$ Belle II book

Even if the current B anomaly would disappear the LHC can provide the independent cross check.



# Usually flavor physics is much more sensitive to the high energy compared to LHC physics

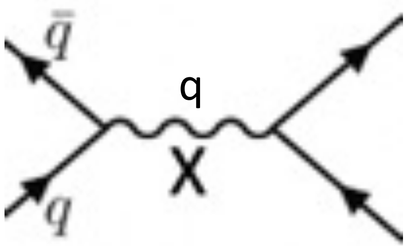



Especially

FCNC gives very good sensitivity.

However, semitaonic decay has an experimental difficulty (tau tagging) and collider sensitivity can be comparable!

# Low energy effective Hamiltonian




$$\frac{1}{q^2 - m_X^2 + i m_X \Gamma_X} \Rightarrow \frac{1}{m_X^2}$$

This method is valid when $q^2 \gg m_X^2$ is satisfied.

In the flavor physics, this approximation usually holds really well e.g. $m_W^2 \gg q^2 > m_B^2$ (B meson decay). Is this valid for the LHC?

# 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

$$O_{SR} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$
$$O_{SL} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$

Scalar

$$O_{VL} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$O_{VR} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

Vector

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

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 $\Gamma_{Bc}$

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


11

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

If time allows

We will discuss how to test LQ (and $\mathrm{H}^{-}$) solutions at the LHC.

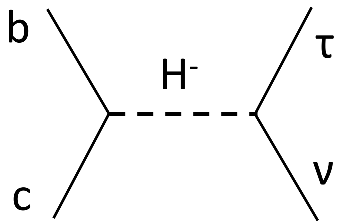
Then we discuss the sensitivity to

$b \to c\, l\, \nu$ and $b \to u\, l\, \nu$ at the end.

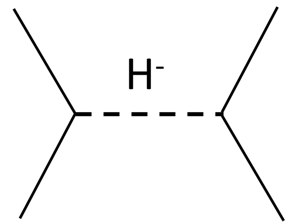
# Two NP categories for $R_{D^{(*)}}$ anomaly

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

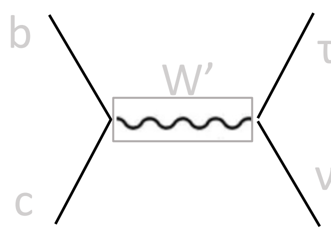
- Charged Higgs



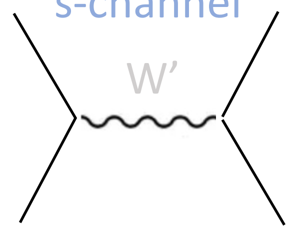

s-channel

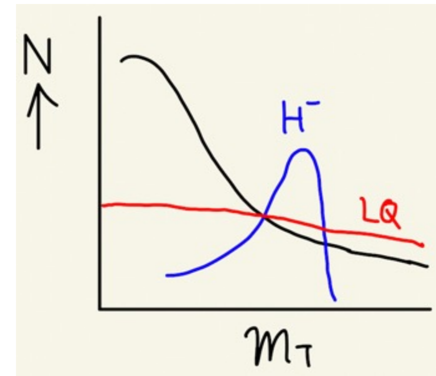



- W' (,Z')




s-channel



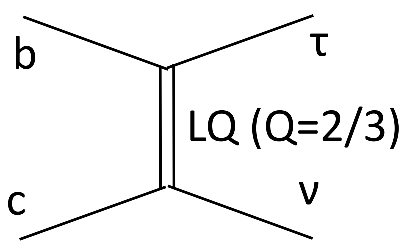

$m_T = \sqrt{2 p_T^{\ell} E_T^{\mathrm{miss}} (1 - \cos\theta_{\ell\nu})}$

:transverse mass

**τν resonance**

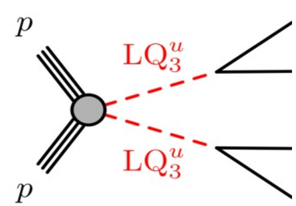
Excluded by ττ search (Z') and Bs meson mixing.

- Leptoquarks



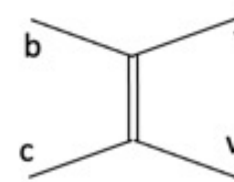

Vector can solve RK simultaneously

Various channels



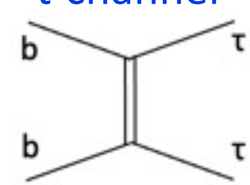

Pair production
τb τb search

t-channel




Mono tau search

t-channel

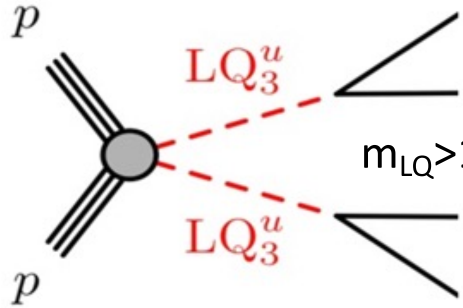



di-τ search

**High pT tails**

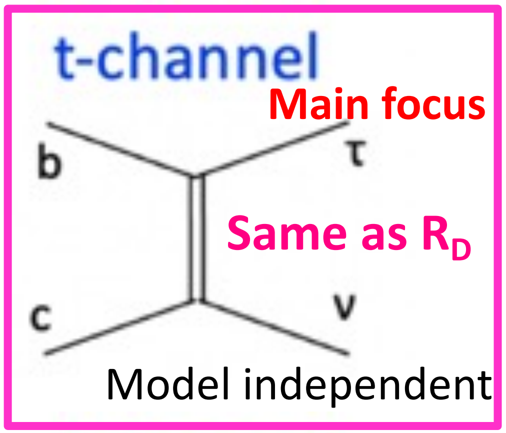
# LHC implication in LQ cases

①

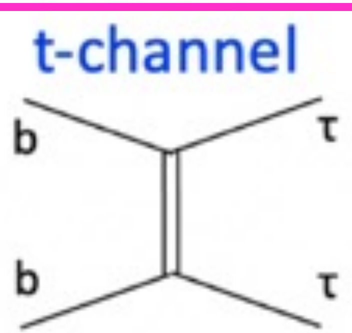



$m_{LQ}$>1.6TeV

②

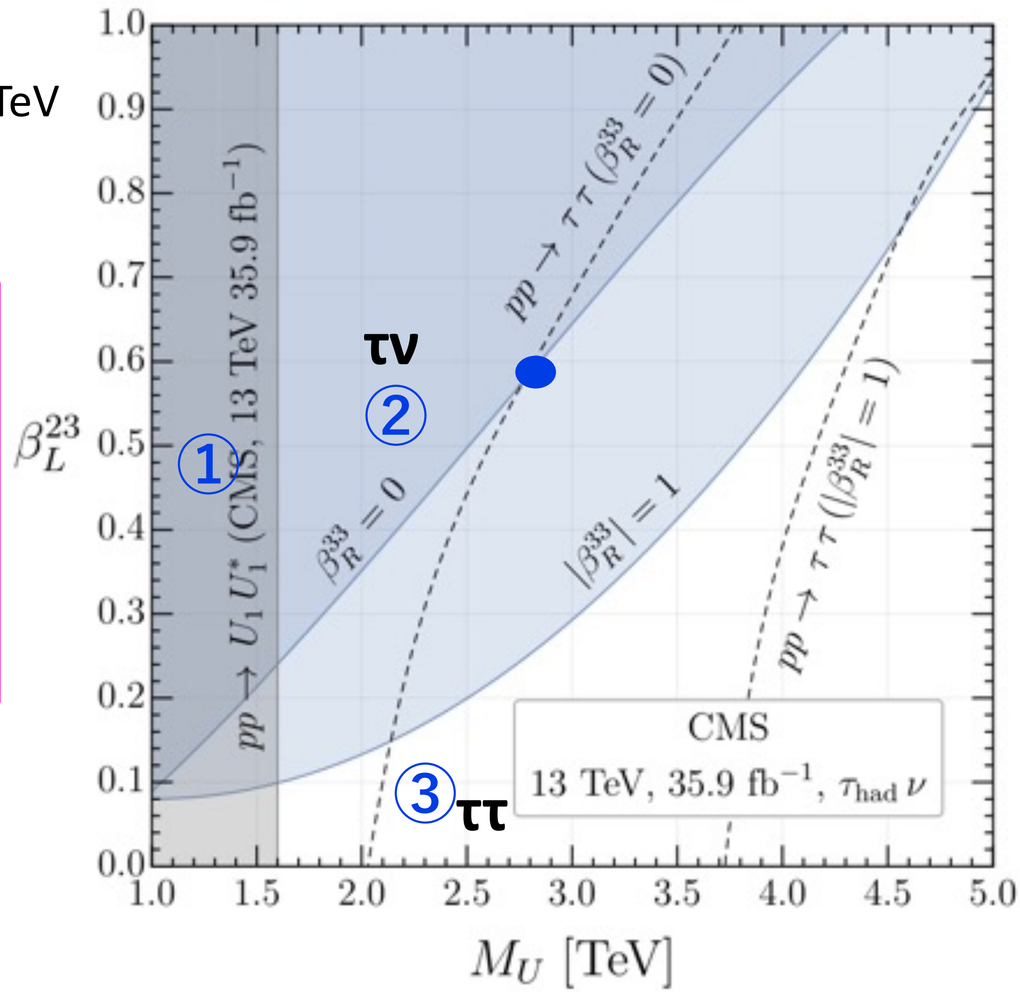



③



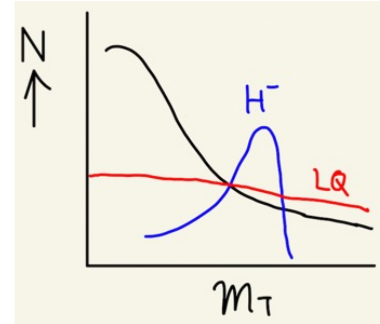

Single production is also important

Gino et al. 1901.10480



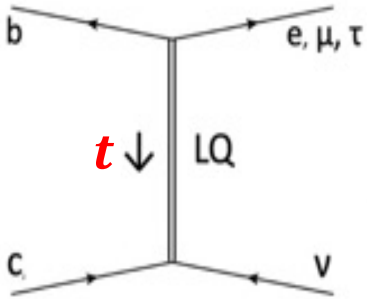

$\beta_R$: additional parameter

# LHC implication in LQ cases




## High $p_T$ τ events are sensitive to the scenarios

In some papers EFT limit is taken.

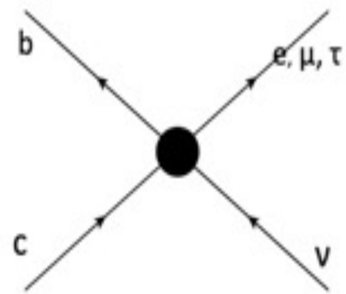



propagator

EFT limit

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

<

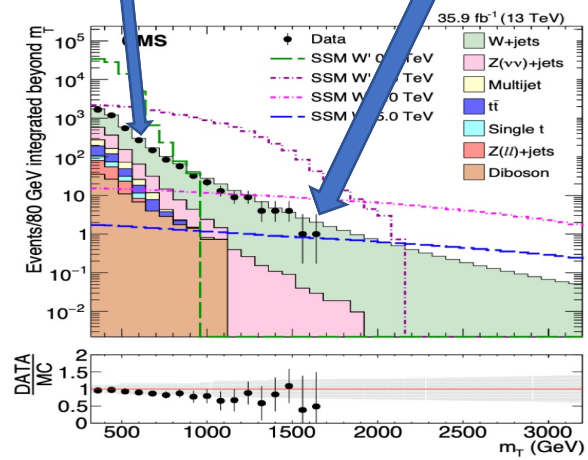



$$t = (p_b - p_c)^2 \sim -2 p_b \cdot p_c < 0$$

Large $t$ is the source of the large transverse momentum.

Huge BG from W

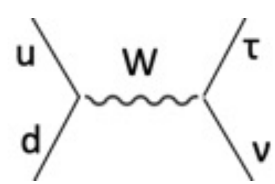
High $p_T$ region is sensitive to NP



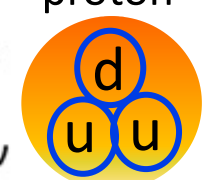

We found up to 50% mass dependence of sensitivity in terms of WC Iguro et al 2011.02486

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

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




proton



# Further improvement of τν mode

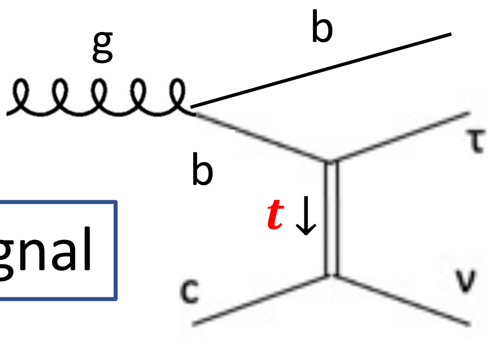
## an additional b-tagging

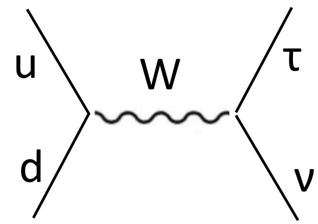
A. Soni et al. 1704.06659, Iguro-Tobe 1708.06176

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

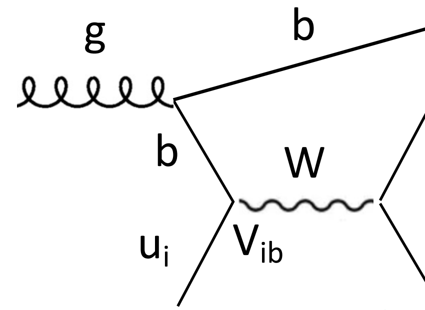
Signal



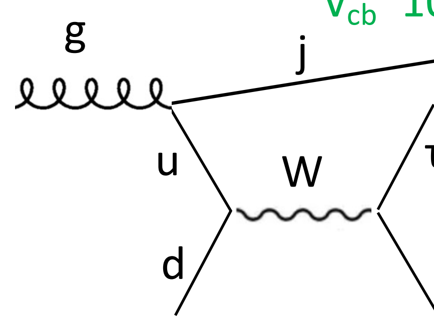




No b-jet previous

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 .

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

WZ, single t, 2t,, are also important

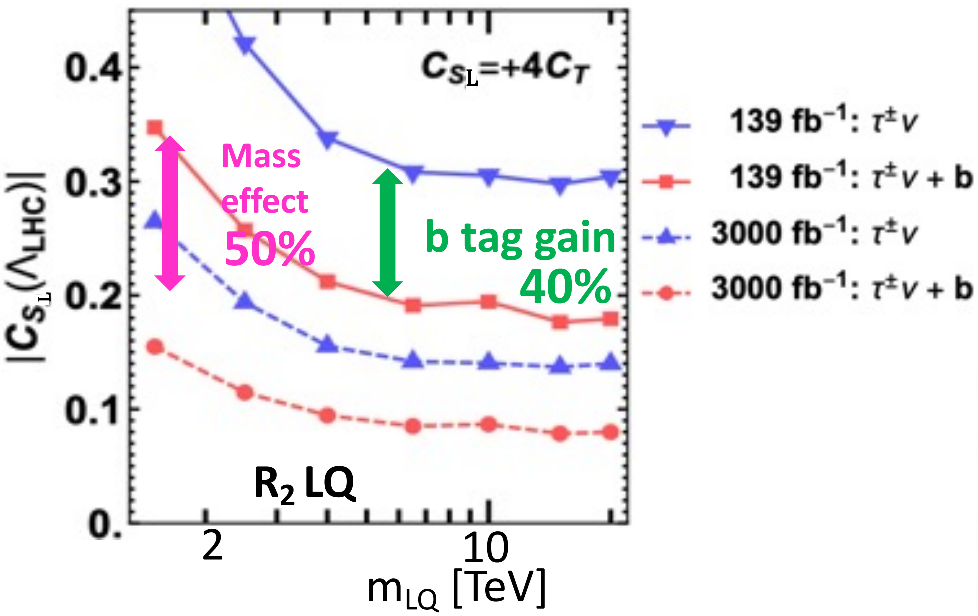
# τ ν +b with mass dependence

2111.04748

We observed the significant mass dependence

$t$ parameter dependence is large in small mass region.

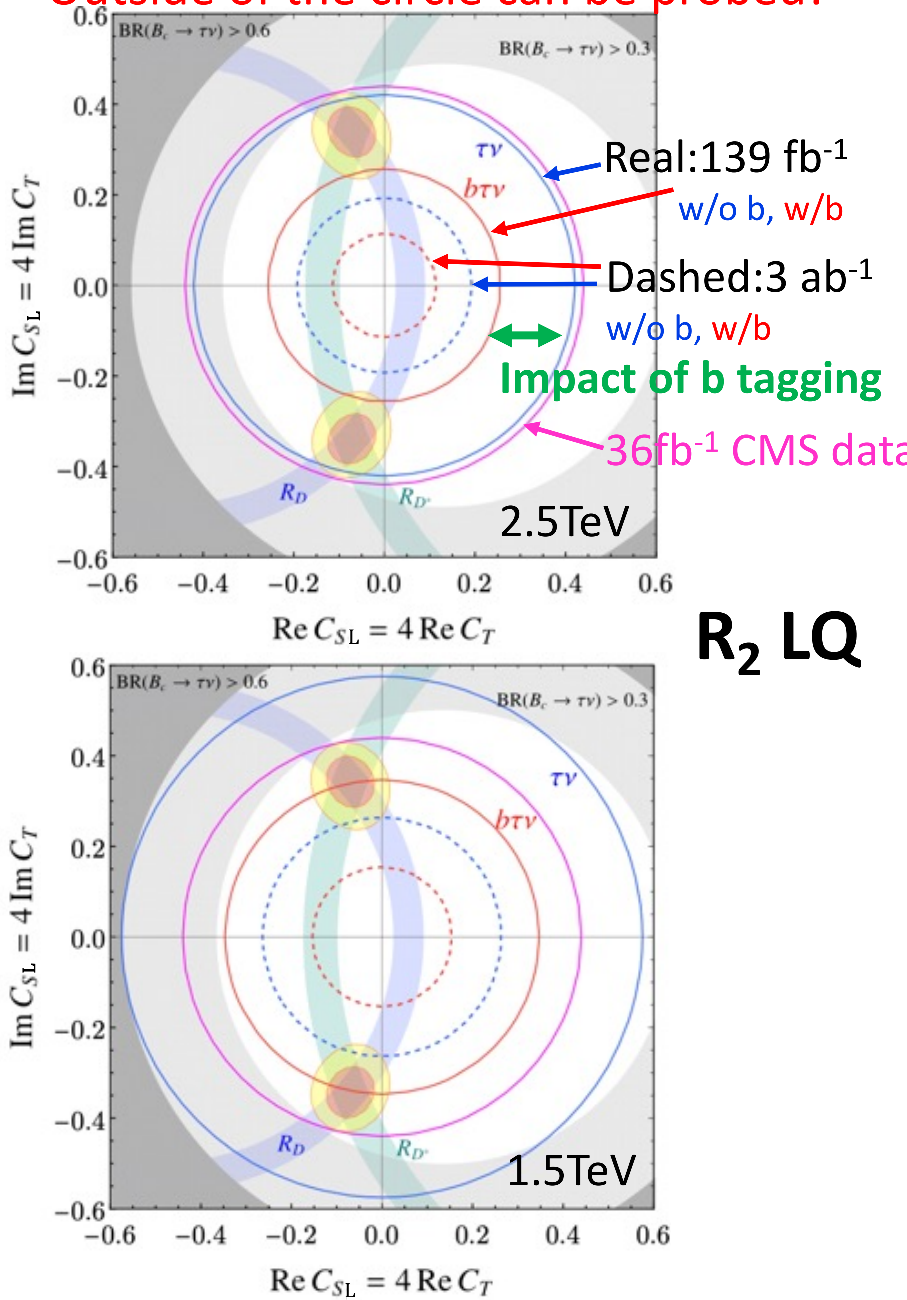
Sensitivity to WC




This dependence is common to other LQ scenarios

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!

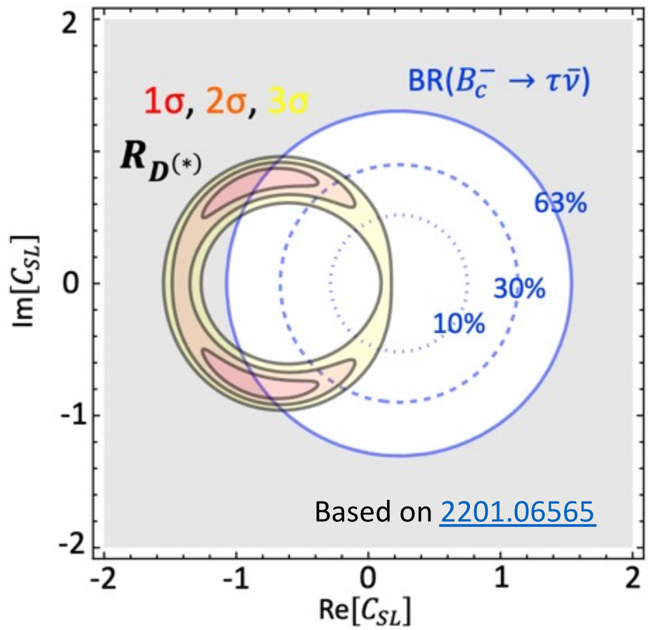



**$R_2$ LQ**

We can test the scenario soon!

$H^+$ interpretation of RD anomaly revived and we can test very soon at the LHC.

# Scalar operator revived




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

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

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

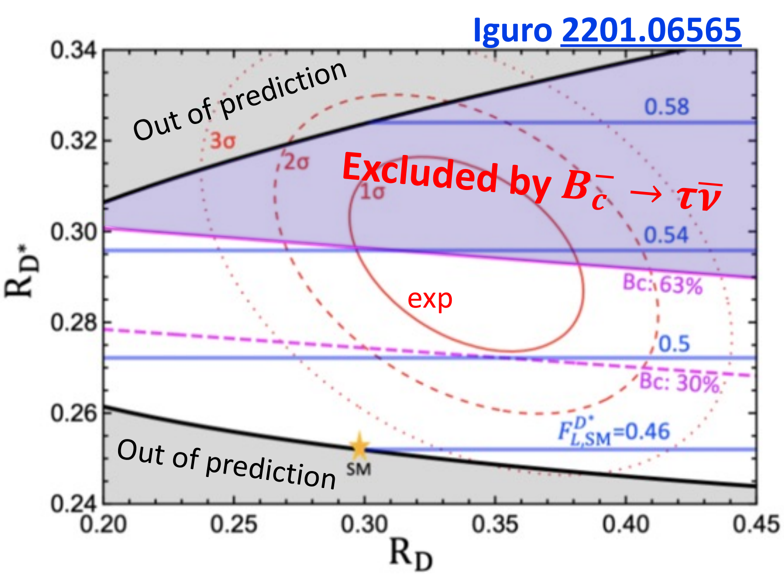
We need complex WC

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

Scenario 1 in Iguro-Tobe 1708.06176

Only top-charm flavor violating Yukawa coupling can provide sizable $C_{SL}$ without violating LHC, flavor, EDM constraints see also Nierste et al 2019, George-Hou 2018

**bb →ττ is less relevant to this model**

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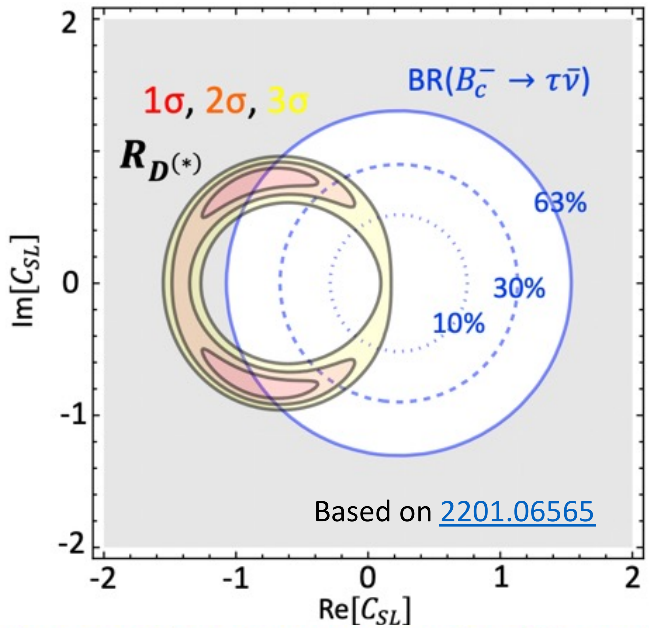


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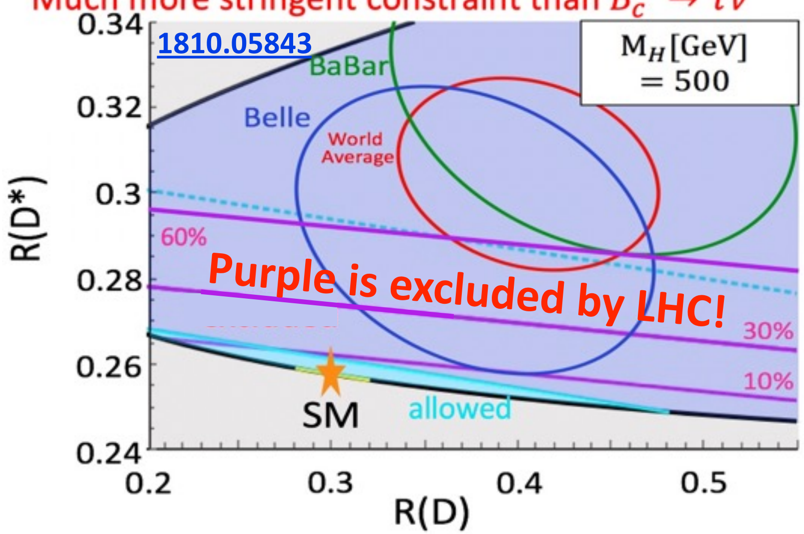
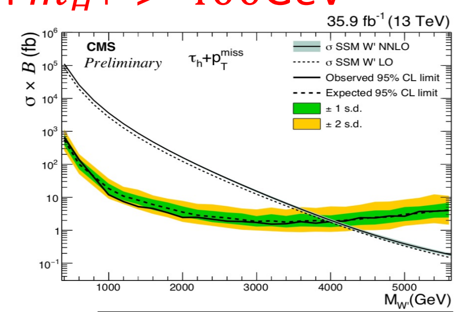
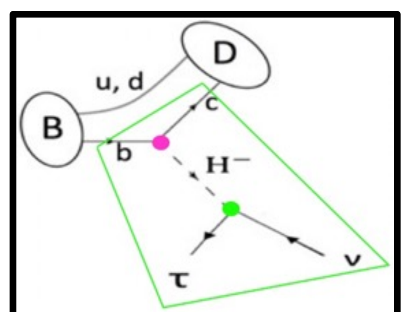
=> Complex Yukawa in type III (General) 2HDM

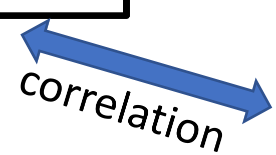
Much more stringent constraint than $B_c^- \to \tau\bar{\nu}$

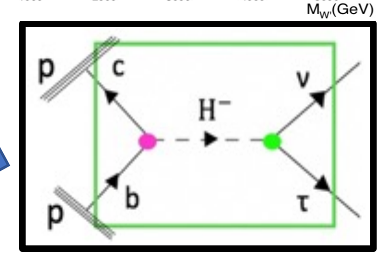



Reinterpreting **τν resonance search** from the CMS(36fb$^{-1}$) excludes the scenario with $m_{H^+} > 400$GeV



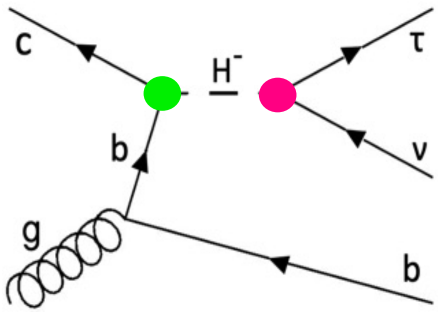




There is no data available for $m_{H^+} < 400$GeV

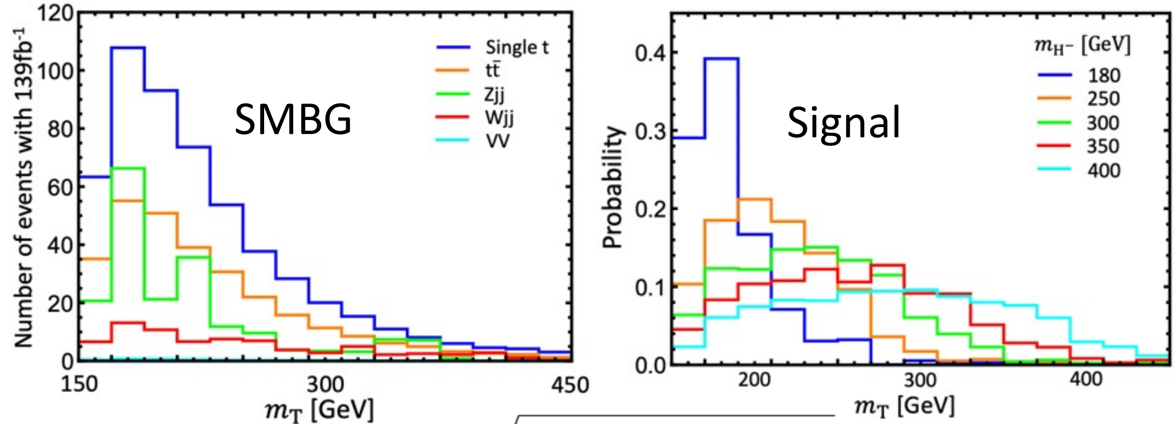
Additional b-jet would suppress the trigger rate

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

Iguro, Hantian, Blanke 2202.10468



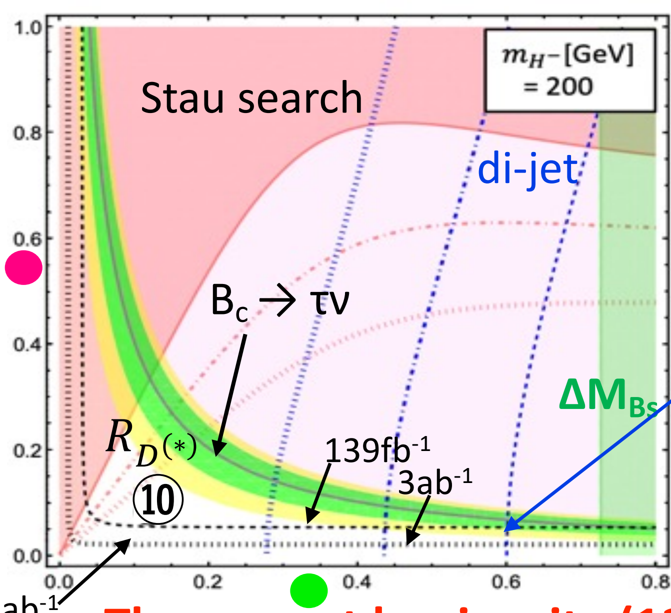

b-tagging suppress the SMBG

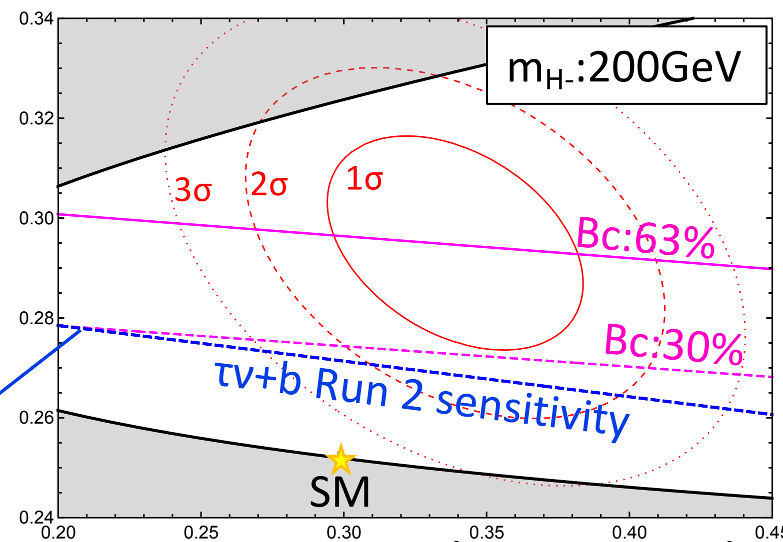



$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1-\cos\theta_{\ell\nu})}$$

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

$m_{H^-}$=200GeV



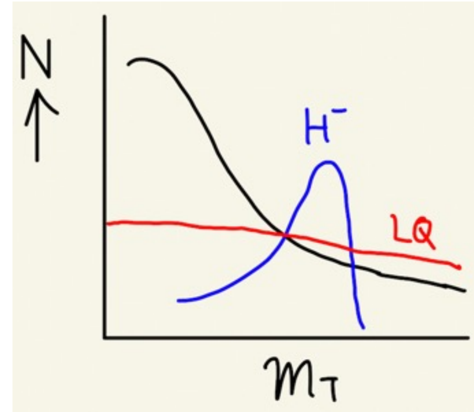

conservative syst. error is assigned

**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



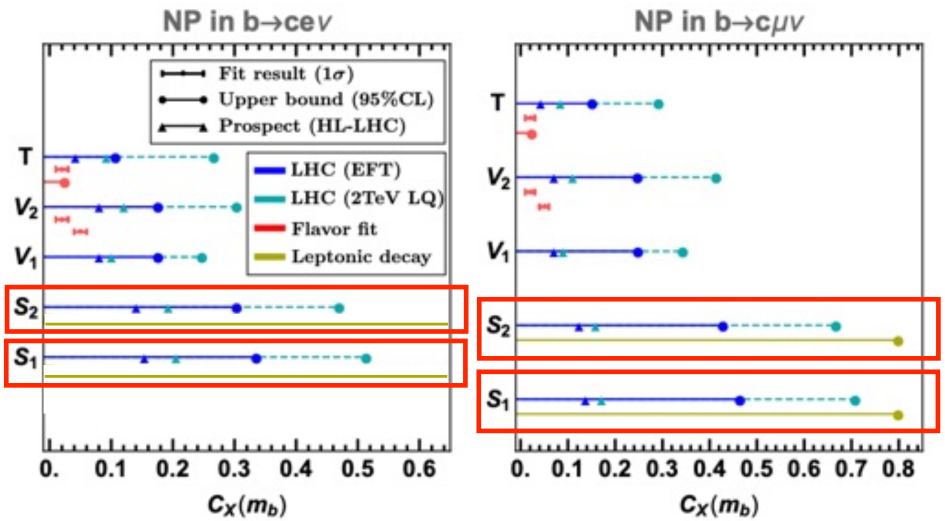

| Signal / channel | | $\tau\nu$ | $\tau\nu$ +b | Mass dependence $\tau\nu$ | Mass dependence $\tau\nu$ +b |
|---|---|---|---|---|---|
| $H^+$ | S | Iguro et al. 1810.05843 **Done** | Iguro et al. 2202.10468 **Done** | | |
| LQ | t | Greljo et al. 1811.07920 **Done** | Minho et al. 2008.07541 **Done**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

**Finally completed the table!**

**+b category is always more sensitive**

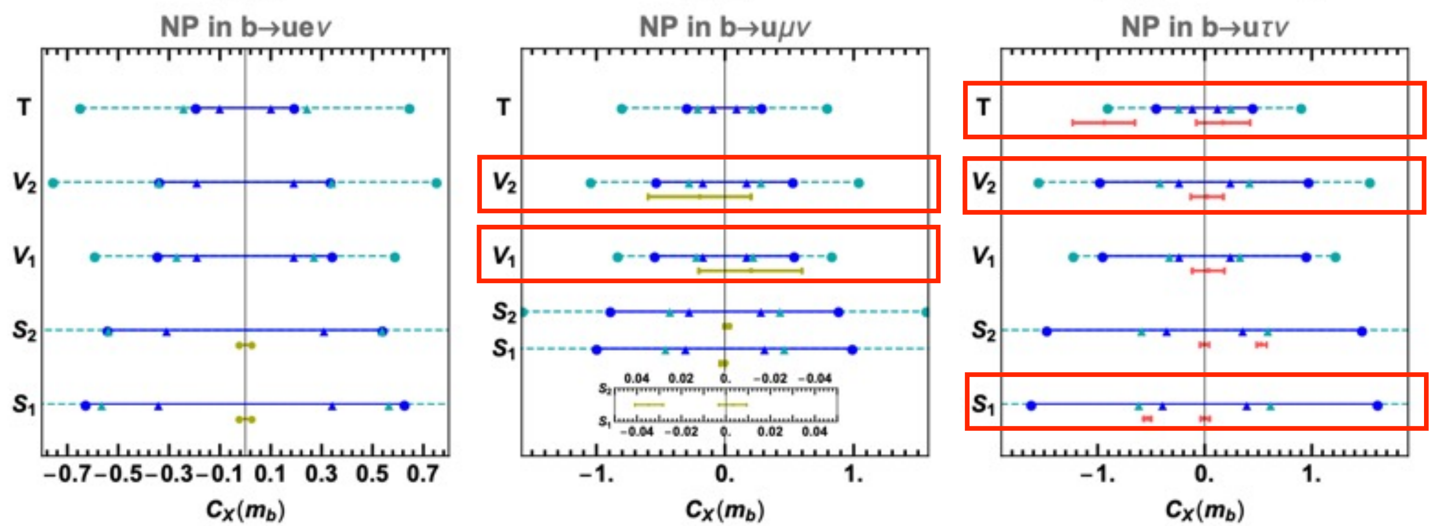
Iguro et al. 2011.02486

# Sensitivity to $b \to c\, l\, \nu$ and $b \to u\, l\, \nu$.




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

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




**LHC is important also in $b \to u\, l\, \nu$**

# Messages in this talk

The LHC provides the unique window to access
the new physics possibly behind B anomalies.

Several developments are made in this 5 years.

e.g. leptoquark mass dependence, 50%

an additional b-jet requirement, 40%

charge asymmetry of the final state.

The b flavor physics and collider physics are very complementary.

# Phenomenological consequence

- Leptoquark(LQ) sensitivity at the LHC can be improved with an additional b-jet tagging.
  LQ mass dependence is crucial to judge the model in the context of $R_{D^{(*)}}$ anomaly.

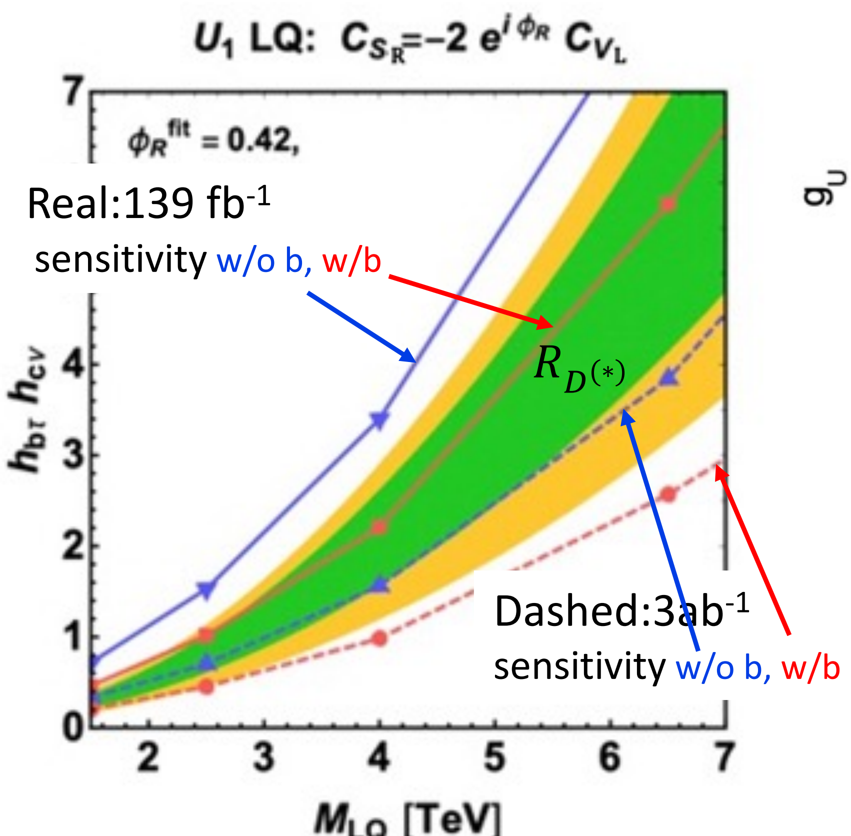
- H$^+$ interpretation of $R_{D^{(*)}}$ anomaly revived and we can test very soon at the LHC.

**Thank you for listening!**

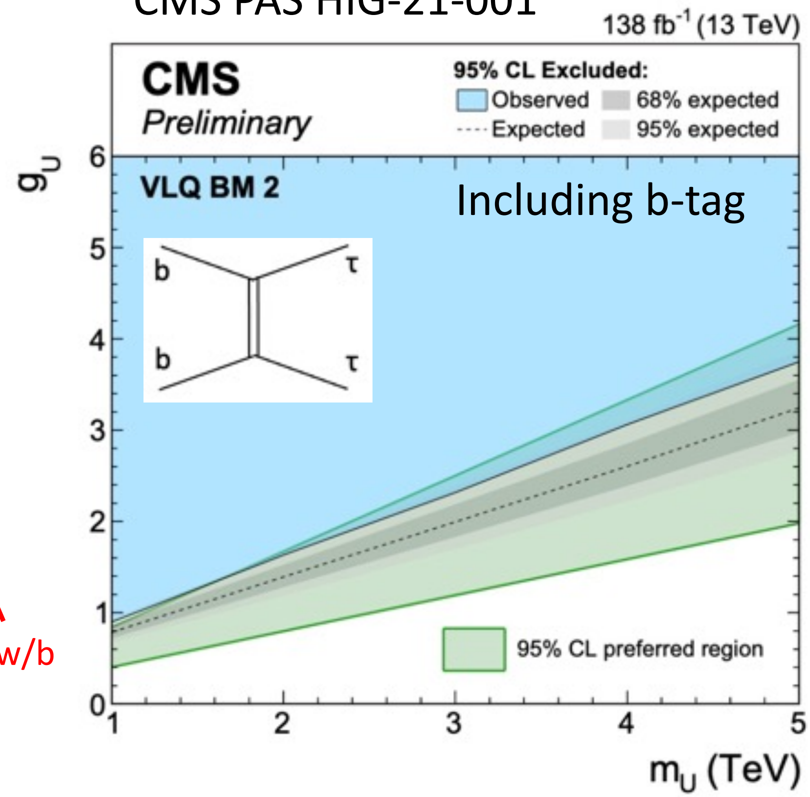
# Bonus

# 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

# Nice to meet you!

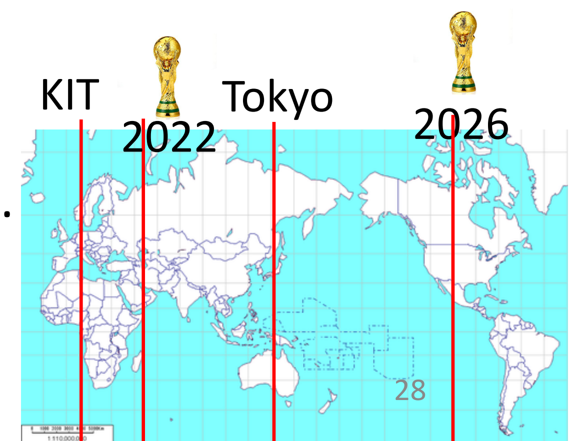
# I am a Postdoc at KIT for three years!

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



# 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!

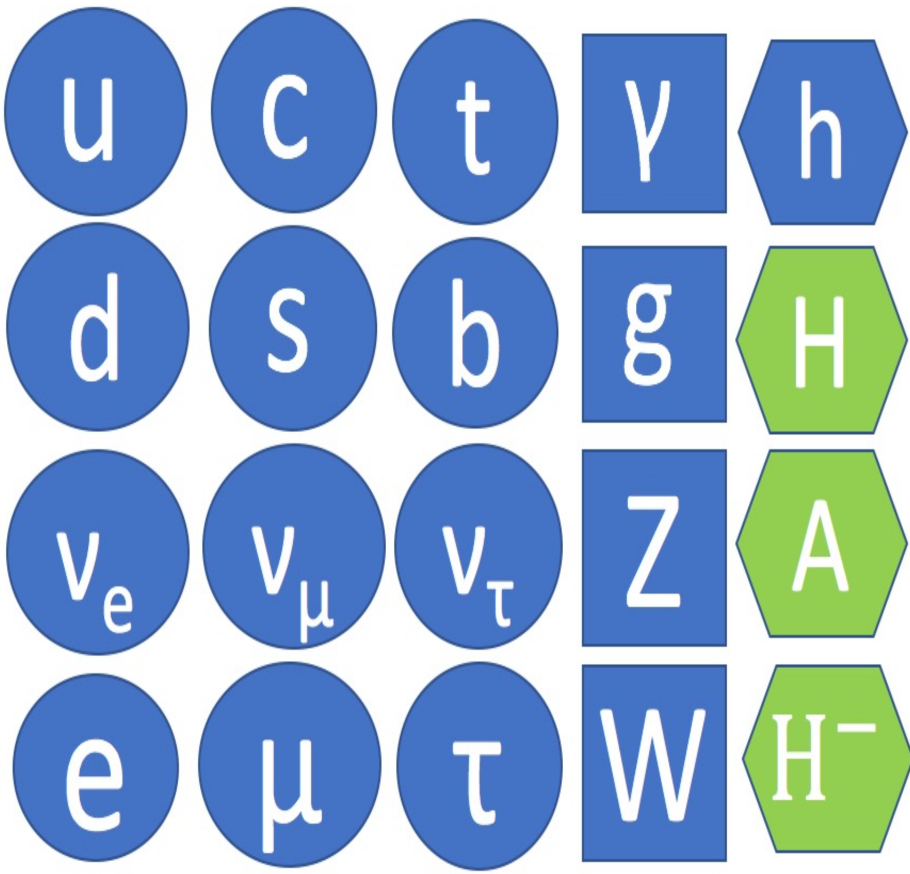
Deviations in flavor physics may be a hint for NP?

# Additional contents for $H^-$ part

# Our Model

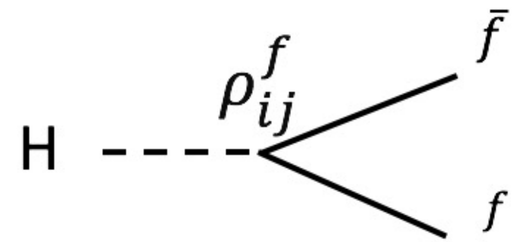
Iguro-Tobe 1708.06176

## Particle set in G2HDM



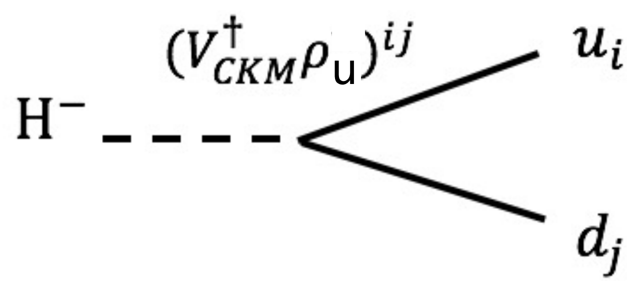

## Neutral Scalar

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



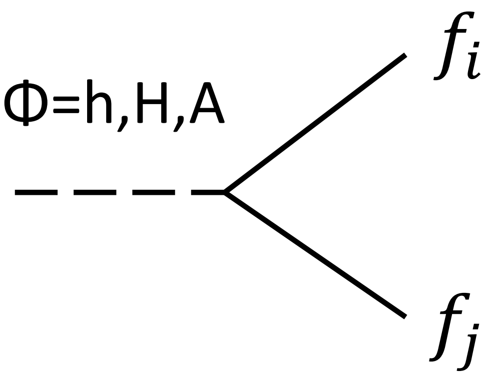

## Charged Scalar

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



# Model: G2HDM

## Yukawa couplings between a neutral scalar and fermions



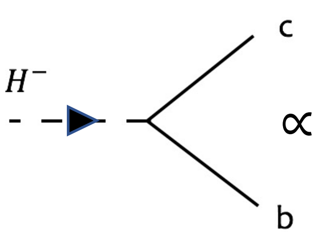

$$\approx i(y^{f}_{\Phi ij}\, P_R + y^{f*}_{\Phi ji}\, P_L)$$

$$y^{f}_{hij} = \frac{m^{i}_{f}}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_{f}}{\sqrt{2}} c_{\beta\alpha},$$

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

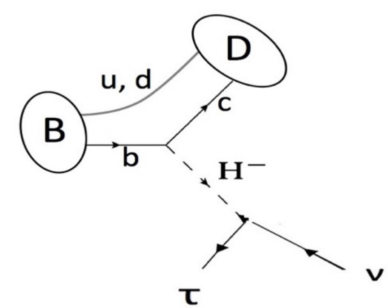
$$y^{f}_{Hij} = \frac{m^{i}_{f}}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_{f}}{\sqrt{2}} s_{\beta\alpha}$$

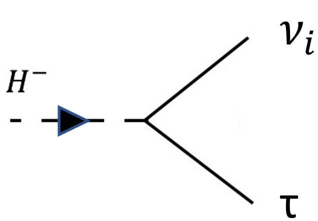
## Yukawa interactions relevant to $R(D^{(*)})$




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

$\rho_d^{sb}$<<1:Bs Mixing




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

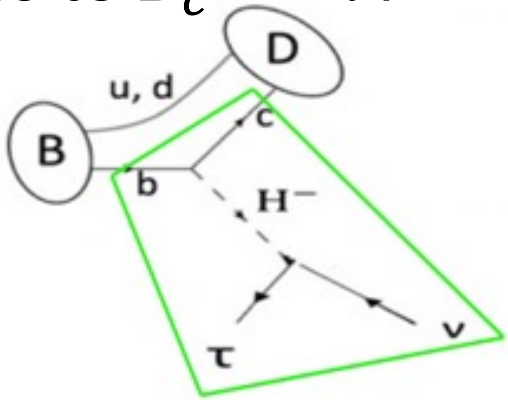
| Yukawa interactions relevant to $R(D^{(*)})$ |
|---|
| $\rho_u^{tc} \times \rho_e^{\tau\tau}$ |

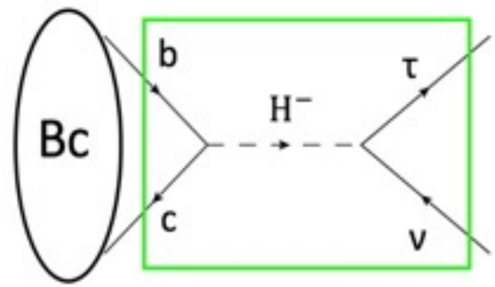
$\rho_u^{tc}$ can be O(1) Nierste et al 2019, George-Hou 2018

# Constraint

Recent update

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




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

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

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

$\sim 4.2$

**Scalar operator drastically enhances**

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

$\Gamma \propto mQ^5 \times G_F^2$.
large error in mc
-> large error for ΓBc

large pT depemdence
in fragmentation
function fBc/fB

Previous constraint

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

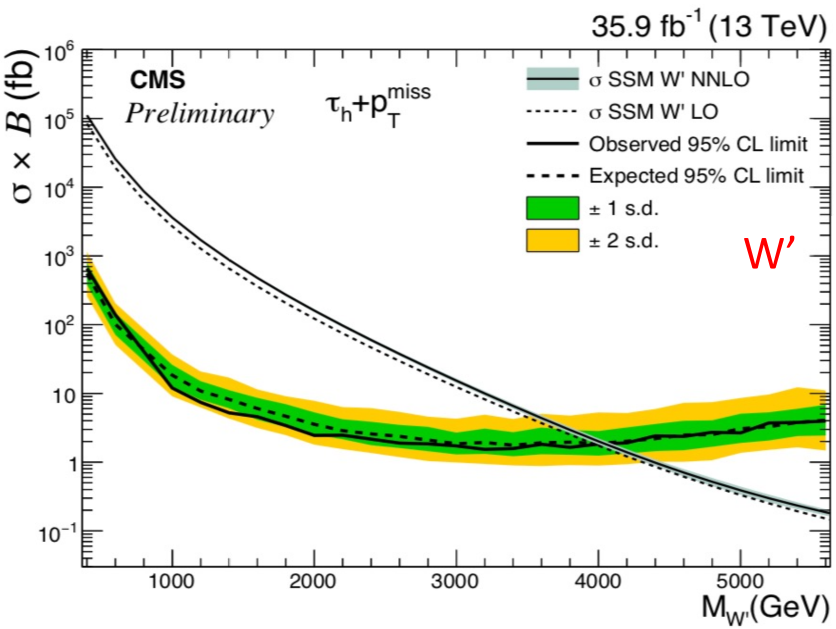
$< 10\%$ A.G.Akeroyd.et al. 1708.04072

**Current constraint**

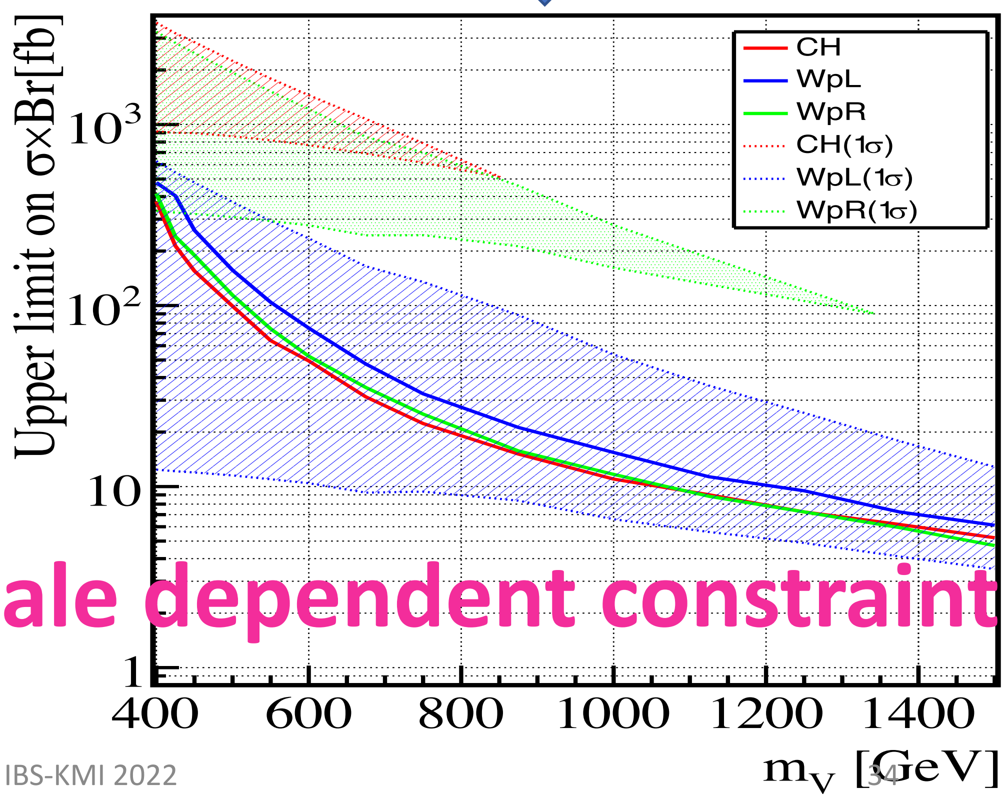
$< 63\%$ B.Grinstein 2105.02988
M.Blanke.et al. 1811.09603

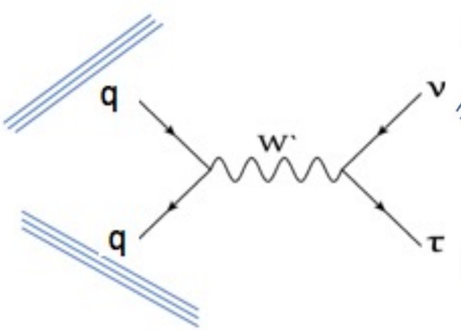
Large coefficient (large coupling) allows the collider search!

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

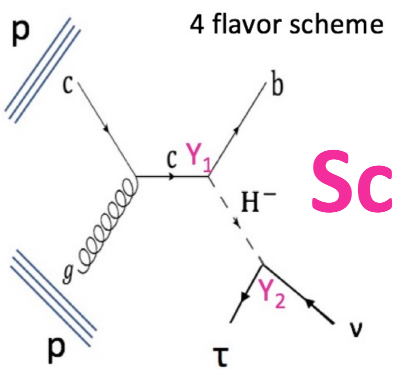



We reinterpreted this limit into $H^-$ by the collider simulation.



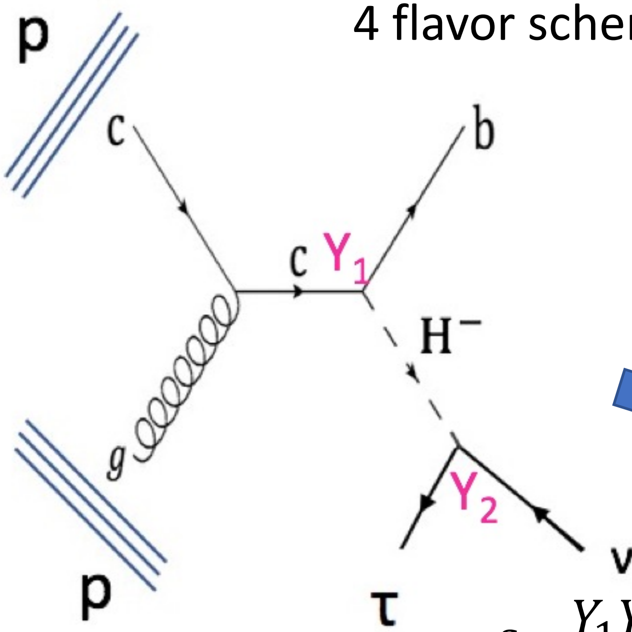

4 flavor scheme




**Scale dependent constraint!**

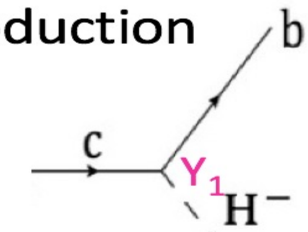
# σ × Br in G2HDM

4 flavor scheme



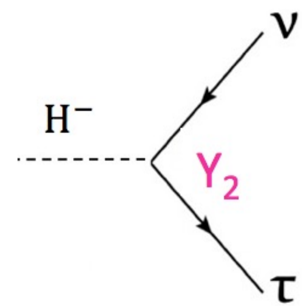

$$C_R'^S \sim \frac{Y_1 Y_2}{m_{H^-}^2}$$

Production




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

Branching ratio




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

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

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

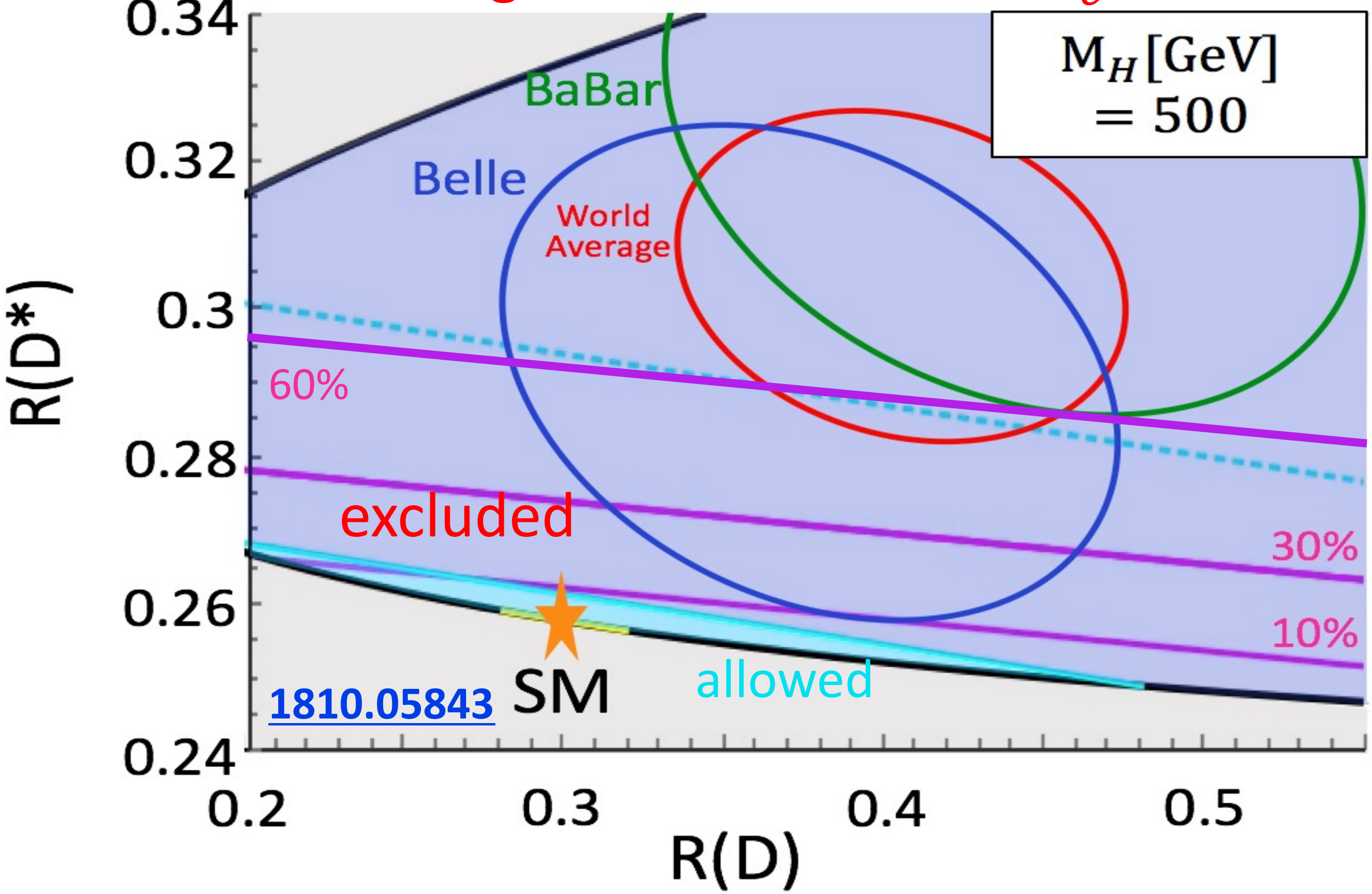
Combination 2 : $Y_2 = \sqrt{3} Y_1$, minimizing denominator.
more events, severe

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

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

# Result

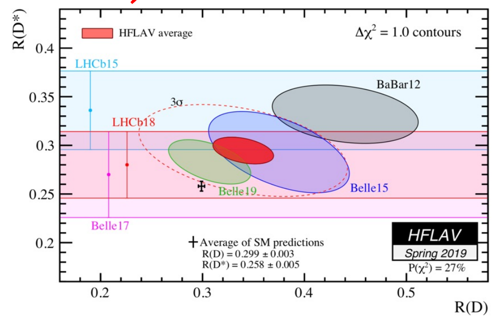
Much more stringent constraint than $B_c^- \to \tau\bar{\nu}$



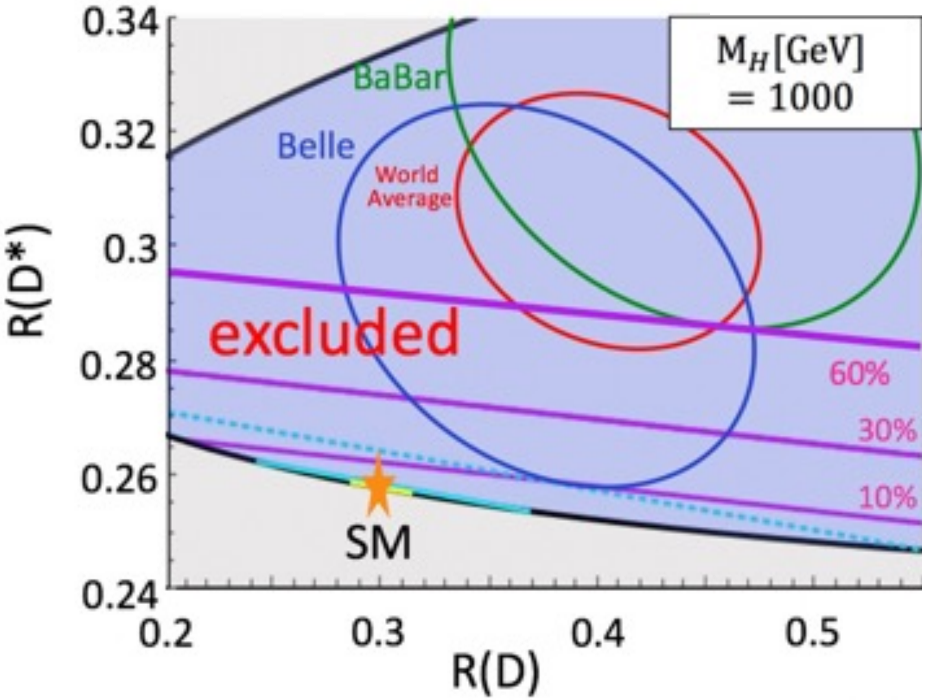
# Result

**Heavier $H^-$, more severe constraint.**

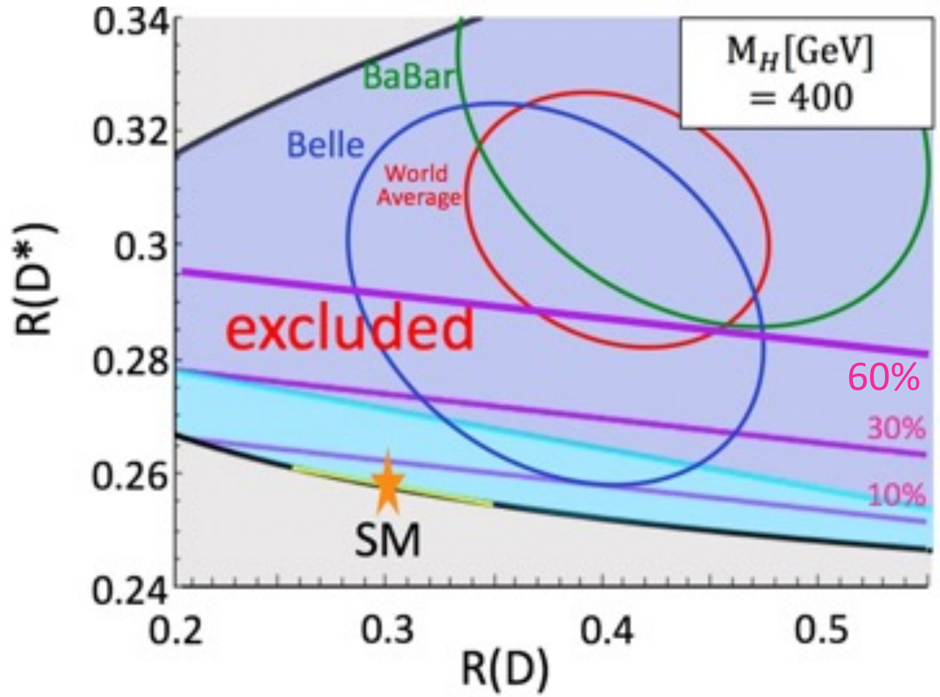
[1810.05843](1810.05843)




heavier



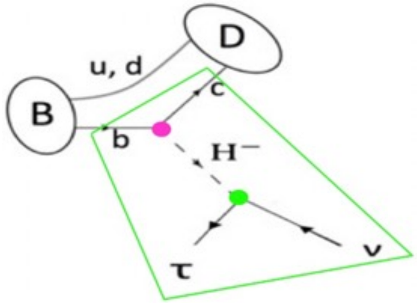

lighter

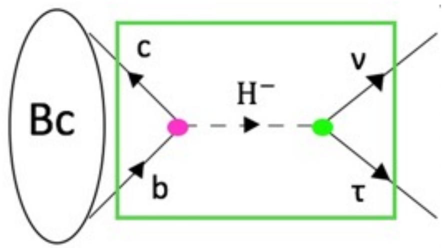



Better sensitivity for heavy $\tau\nu$ resonances: experimentally $\tau\nu$ resonance search for W' is more sensitive to a heavier resonance because of the low background from W→ $\tau\nu$.

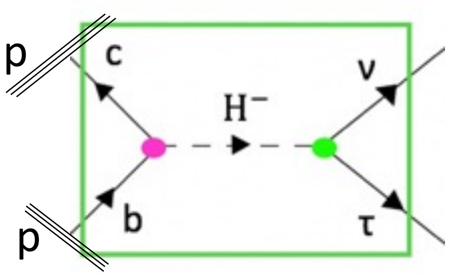
# $H^-$ interpretation of $R_D$ , $R_{D^*}$ anomalies silently revived

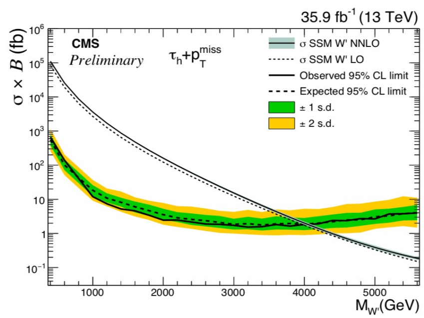
**Summary of the status and prospect are discussed** Syuhei Iguro, **2201.06565**



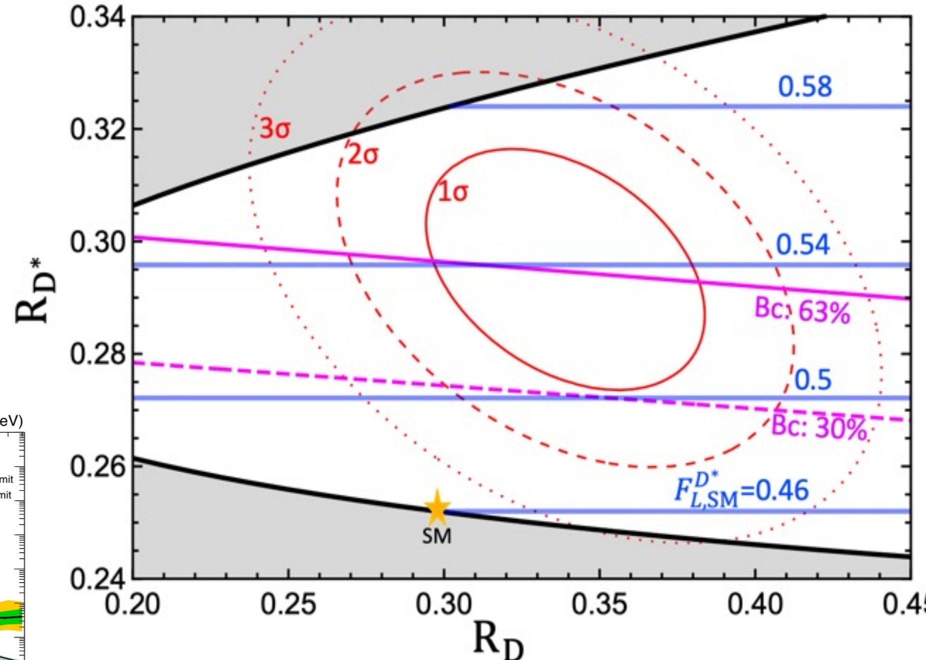




Due to the charm mass scheme dependence,
The bound is relaxed BR(Bc→τν)<63% Grinstein 2021




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




$F^{D^*}_{L,SM}$=0.46, $F^{D^*}_{L,Belle}$=0.60 $\pm$ 0.09

Only scalar can enhance $F^{D^*}_{L}$

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

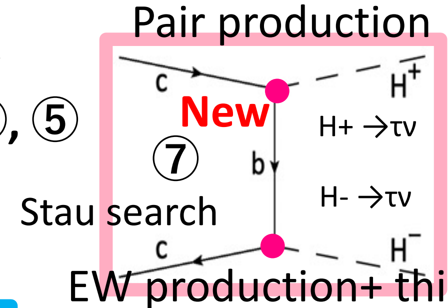
- they originally search for W' in SSM and wanted to push up the lower bound on $m_{W'}$
- SMBG (W-> τν tail ) is huge at low mT

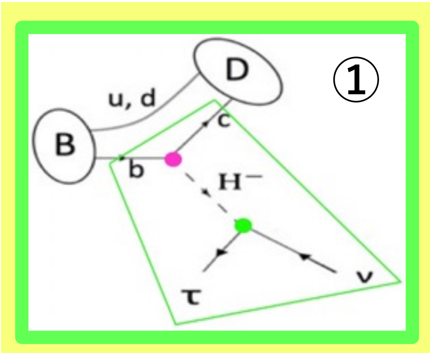
**How is the situation and prospect for $m_{H-}$ < 400GeV ?**

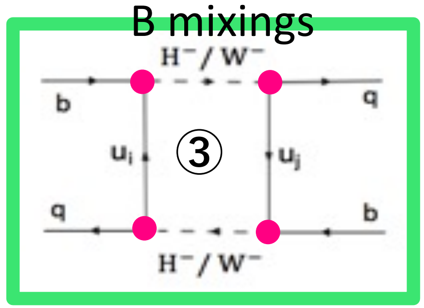
# Various bounds are very complementary
## HL-LHC can probe large parameter space!

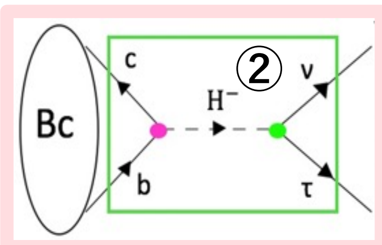
3 categories of bounds

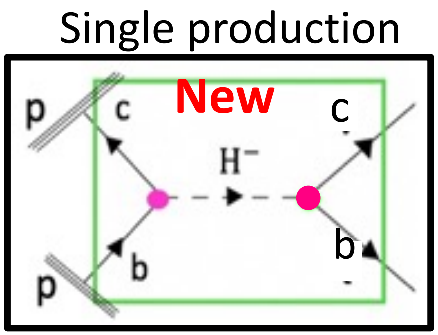
1. **right to left e.g. ③, ④, ⑤**
2. **above to bellow ⑦**
3. **constrain ↙ e.g. ②**



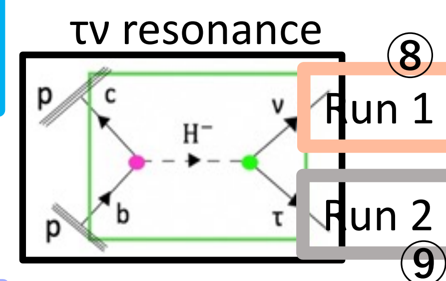



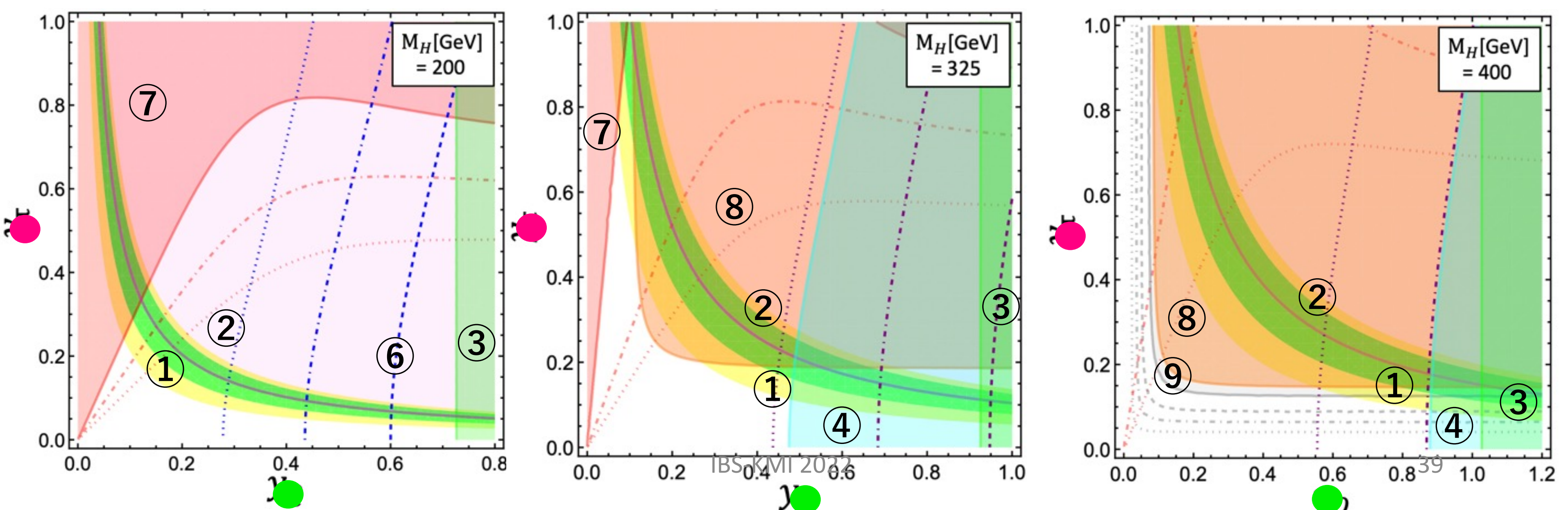

bb resonance search
$\sqrt{s}$=8TeV ④

bb + photon search
$\sqrt{s}$=13TeV ⑤

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

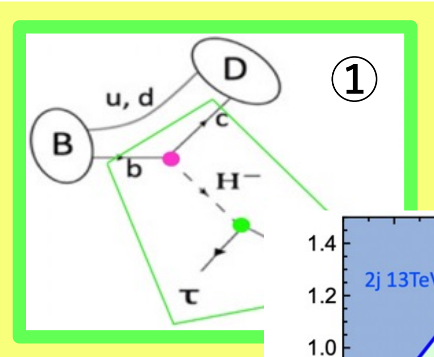



**Luminosity**
Current, 500fb$^{-1}$, 139fb$^{-1}$, 3ab$^{-1}$

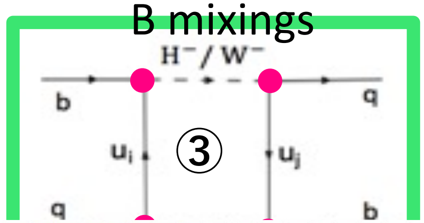


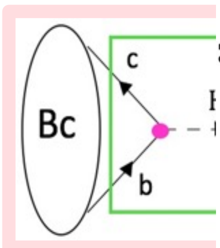
# Various bounds are very complementary

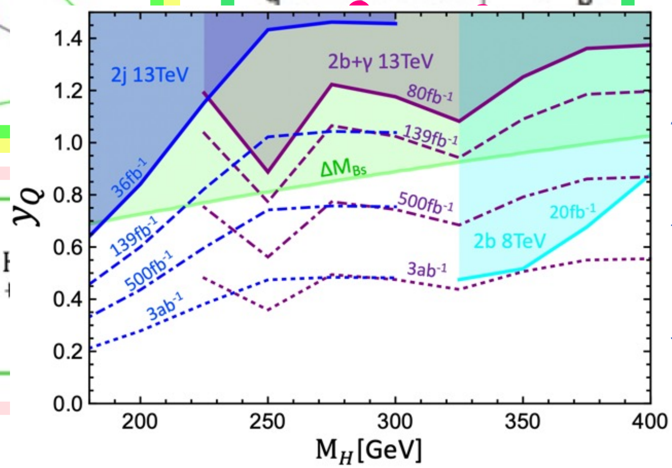
## HL-LHC can probe large parameter space!




B mixings



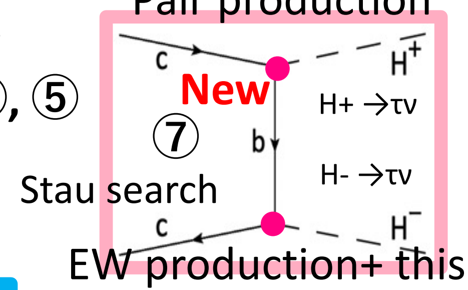




3 categories of bounds

**1. right to left e.g. ③, ④, ⑤**

**2. above to bellow ⑦**

**3. constrain ↙ e.g. ②**

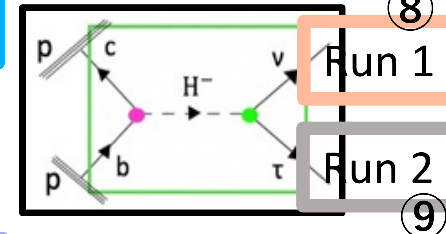



bb resonance search $\sqrt{s}$=8TeV ④

bb + photon search $\sqrt{s}$=13TeV ⑤

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

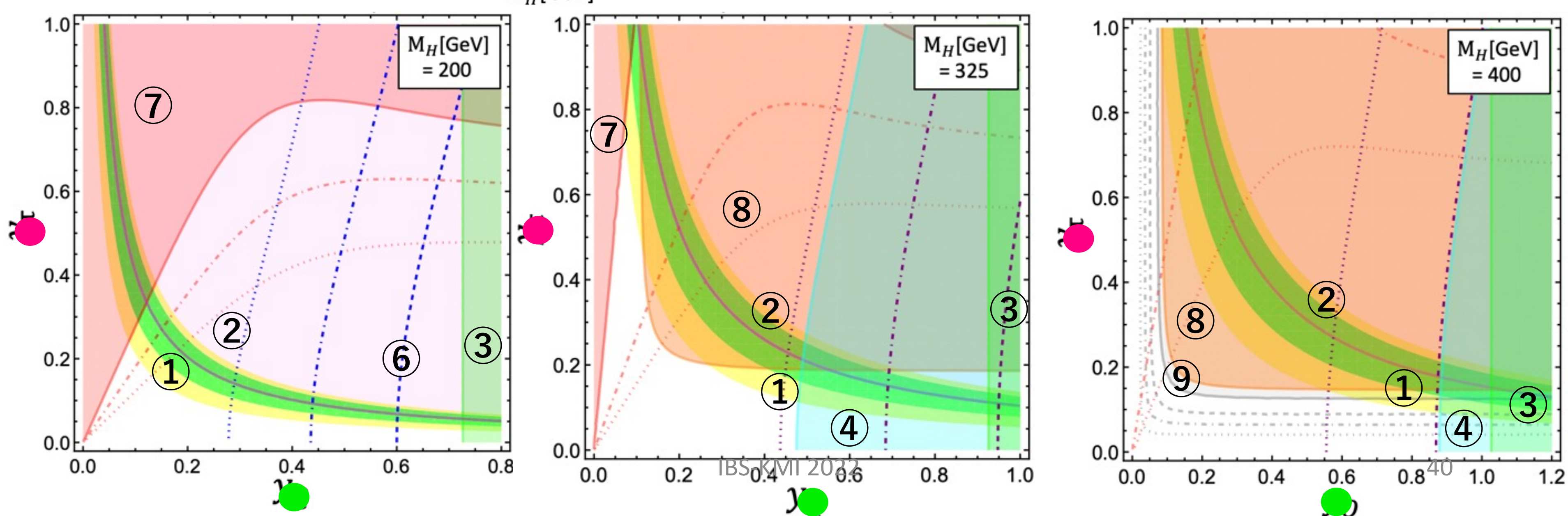
τν resonance




**Luminosity**

—— Current — · · 500fb⁻¹

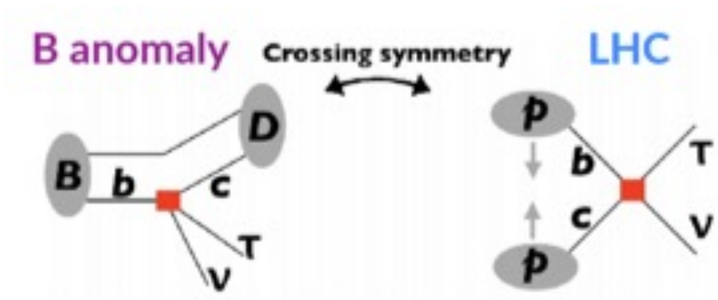
- - · 139fb⁻¹ ......... 3ab⁻¹



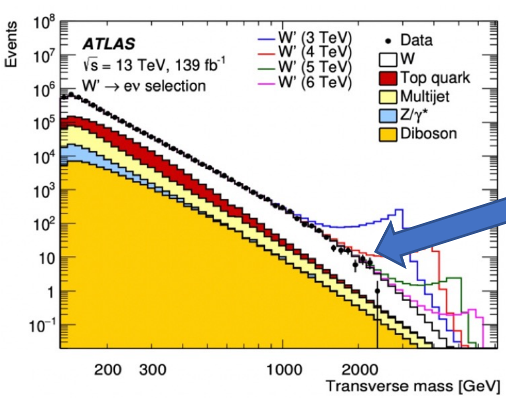
# Additional contents for LQ part

# Several works in the literature

## t-channel mediator: Leptoquark (LQ)



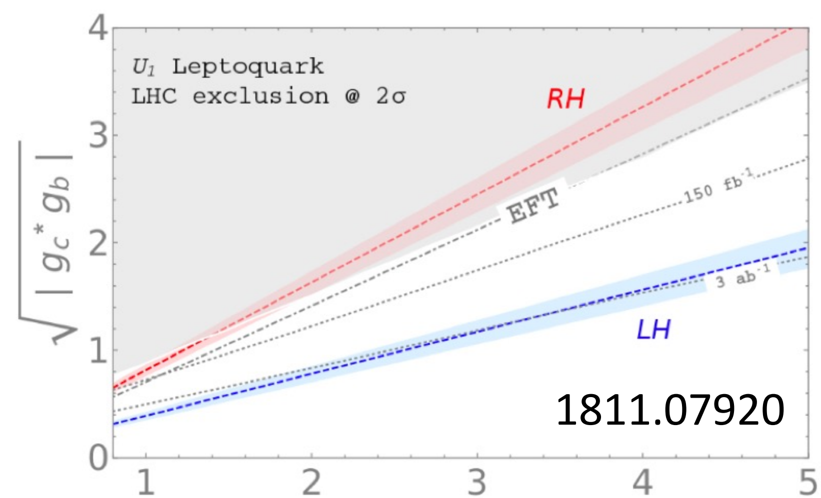

signal shape on the MT plane
t-channel : plateau




Look into the high pT region

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

HL LHC can test LH scenario!




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

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

TABLE II. $2\sigma$ 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 $\text{fb}^{-1}$) | 0.55 | 0.93 | 0.26 |
| CMS (35.9 $\text{fb}^{-1}$) | 0.25 | 0.45 | 0.12 |
| LHC combined | 0.32 | 0.57 | 0.16 |
| LHC (150 $\text{fb}^{-1}$) | 0.21 | 0.37 | 0.10 |
| HL-LHC | 0.10 | 0.17 | 0.05 |

| | Best fit | $1\sigma$ range |
|---|---|---|
| $\epsilon_L^\tau$ | 0.07 | (0.05, 0.09) |
| $\epsilon_T^\tau$ | −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

# 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

Scalar

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

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

Vector

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

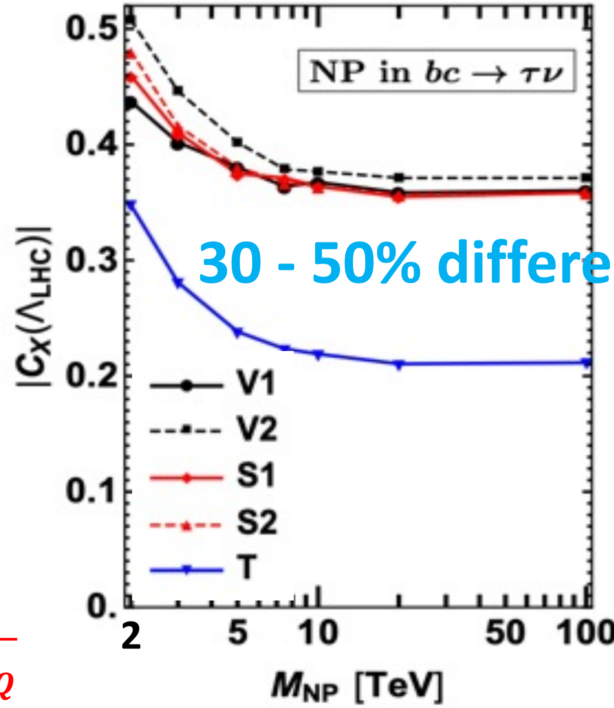
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

Tensor

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

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

Upper limit on WC




30 - 50% difference

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

# Are you happy with LQ?

More ambitious scenarios

- Addressing $R_{D(*)}$, $R_{K(*)}$, muon *g*−2 and ANITA anomalies in a minimal *R*-parity violating supersymmetric framework 2002.12910.

- A Minimal Explanation of Flavour Anomalies: B-Meson Decays, Muon Magnetic Moment, and the Cabbibo Angle 2104.05730

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1$$

- Unified framework for B-anomalies, muon *g*−2 and neutrino masses 2009.01771

# 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

Calibbi et al 1709.00692
Heeck et al 1808.07492
Grinstein et al 1812.01603
Iguro et al 2103.11889

e.g. Pati Salam

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

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

Massive vector LQ appear (Z' also)

## Recently 4321 model is most popular

See Gino et al 2203.01952 toward UV completion

# BG cut flow

| BG (**cut a**) | $Wjj$ | $Zjj\,(Z \to \nu\bar{\nu})$ | $t\bar{t}$ | $Z,\gamma\,$DY | $VV$ | single $t$ |
|---|---|---|---|---|---|---|
| $\tau$ 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] | $22 \pm 6.2$ | $0.9 \pm 0.5$ | $< 0.1$ | $< 0.1$ | $0.7 \pm 0.1$ | $< 0.1$ |
| 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**) | $Wjj$ | $Zjj\,(Z\to\nu\bar{\nu})$ | $t\bar{t}$ | $Z,\gamma$ DY | $VV$ | single $t$ |
|---|---|---|---|---|---|---|
| number of jets | 6693.4 | 235099 | 346.7 | 1813.2 | 125.8 | 151.8 |
| number of $\tau$ | 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 |
| $\tau$ 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).

# Key observable for Belle II

| | $F_L^{D^*}$ | $P_\tau^D$ | $P_\tau^{D^*}$ | $R_D$ | $R_{D^*}$ |
|---|---|---|---|---|---|
| $R_2$ LQ | [0.442, 0.447] | [0.336, 0.456] | [−0.464, −0.424] | 1 $\sigma$ data | 1 $\sigma$ data |
| $S_1$ LQ | [0.436, 0.481] | [−0.006, 0.489] | [−0.512, −0.450] | 1 $\sigma$ data | 1 $\sigma$ data |
| $U_1$ LQ | [0.440, 0.459] | [0.156, 0.422] | [−0.542, −0.488] | 1 $\sigma$ data | 1 $\sigma$ 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% |

After Moriond2019

$\lambda_\tau$: Spin of τ

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

$P_\tau^D$ **is a good quantity to distinguish LQ models.**

Statistical error is dominant in polarization observables.

Let’s wait Belle II for the new data!