Status and Prospects on Flavor Physics

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Flavor Physics Mini-Workshop

Yonsei University, Aug 29 (Thu) 2024

Contents

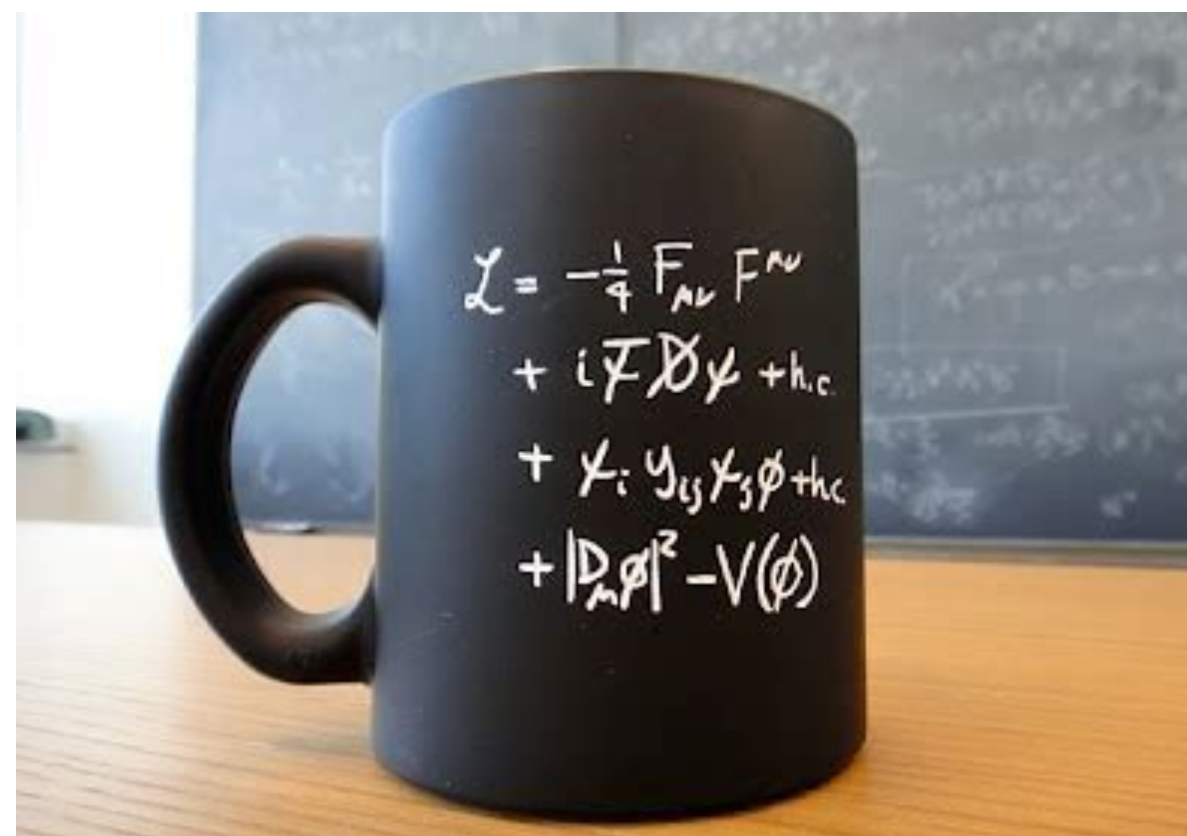
- Flavor physics for (B)SM
- GIM, Flavor/CPV in quarks and charged lepton sectors
- Muon g-2
- Example w/ light dark sector for light DM, muon g-2 and Belle II $B^+ \to K^+ \nu \bar{\nu}$ data
- Old wine in a new bottle : flavor problem in multi-Higgs doublet model in flavored multi-Higgs doublet models

Reappraisal of SM

SM

- Poincare symmetry : $E, \overrightarrow{P}, \vec{J}$ conservations & Boost
- Local gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$
- SM fermions: chiral ($L \neq R$)
- Global symmetries (B, L_i, L) : Accidental symmetry of the SM → Reasons for longevity of proton and very small neutrino masses

- Gauge interaction: Universality
- Schematically looks like this!



SM for particle physics

$$\mathcal{L}_{MSM} = -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu}$$
$$-\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R$$
$$+|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i$$
$$+\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2$$
$$-\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) .(1)$$

Renormalizable part

+ ∞ # of higher dim (nonrenormalizable) operators
(why neutrinos are light, proton lives very long)

QFT + conservation laws (symmetries):

- $E, \vec{p}, \vec{J}$ + Special Relativity : Poincare sym
- Exact charge conservation : local gauge sym
- No global symmetries imposed : accidental

Current Status of SM

- Only Higgs (~SM) and Nothing Else so far at the LHC
- Yukawa & Higgs self couplings to be measured and tested
- Nature is described by Quantum Local Gauge Theories
- Unitarity and gauge invariance played key roles in development of the SM

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Exp's
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Accidental Sym’s of SM

- Renormalizable parts of the SM Lagrangian conserve baryon #, lepton # : broken only by dim-6 and dim-5 op’s $\longrightarrow$“longevity of proton” and “lightness of neutrinos” becoming Natural Consequences of the SM (with conserved color in QCD)

- QCD and QED at low energy conserve P and C, and flavors

- In retrospect, it is strange that P and C are good symmetries of QCD and QED at low energy, since the LH and the RH fermions in the SM are independent objects

- What is the correct question ? “P and C to be conserved or not ?” Or “LR sym or not ?”

How to do Model Building

- Specify local gauge sym, matter contents and their representations w/o any global sym
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- You may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

Motivations for BSM

Pheno'cal Motivations

- Neutrino masses and mixings
- Baryogenesis

Leptogenesis

- Inflation (inflaton)

Starobinsky & Higgs Inflations

?

- Nonbaryonic DM

Many candidates

- Origin of EWSB and Cosmological Const ?

Can we attack these problems ?

Theoretical Motivations

- Fine tuning problem of Higgs mass parameter : SUSY, RS, ADD, etc.
- Critical comments in the Les Houches Lecture by Aneesh Manohar (arXiv:1804.05863)
- Standard arguments :
  - Electron self-energy in classical E&M vs. QED
  - Δm_K without/with charm quark
  - $\Delta m^2 = m_{\pi^\pm}^2 - m_{\pi^0}^2$ without/with ρ mesons
  - They are simply wrong !

No-lose theorem for LHC

- Before the Higgs boson discovery, rigorous arguments for LHC due to the No-Lose theorem

- W/o Higgs boson, $W_L W_L \to W_L W_L$ scattering violates unitarity, which is one of the cornerstones of QFT

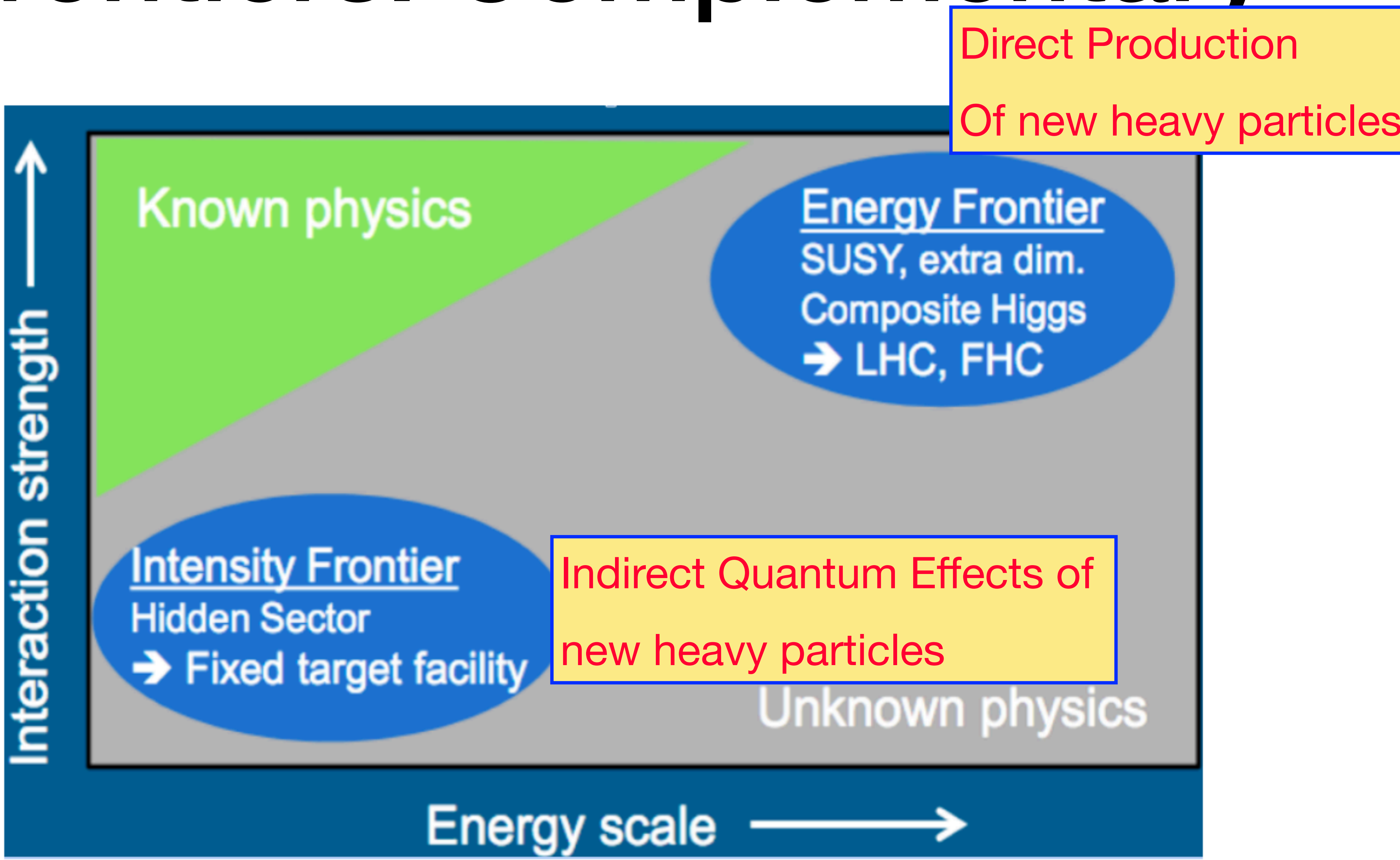
- Unitarity will be restored by
  - Elementary Higgs boson
  - Infinite tower of new resonances (KK tower)
  - New resonances for strongly interacting EWSB sector
  - Higgs is there, but not observable if it decays into DM (2007,2011,..)

My Personal Viewpoints

- Traditionally, Fine Tuning or Naturalness problem was the driving force for many BSM, and predicted many signatures @ LHC
- No signatures @ LHC means that the traditional motivation is not that well motivated
- Mathematical and Theoretical Consistency : more important for BSM model buildings
- Unitarity is one of the Holy Grails in EFT approach

Flavor Physics for (B)SM

Energy vs. Intensity Frontiers: Complementary



What is “Flavor”?

- https://en.wikipedia.org/wiki/Flavour_(particle_physics)

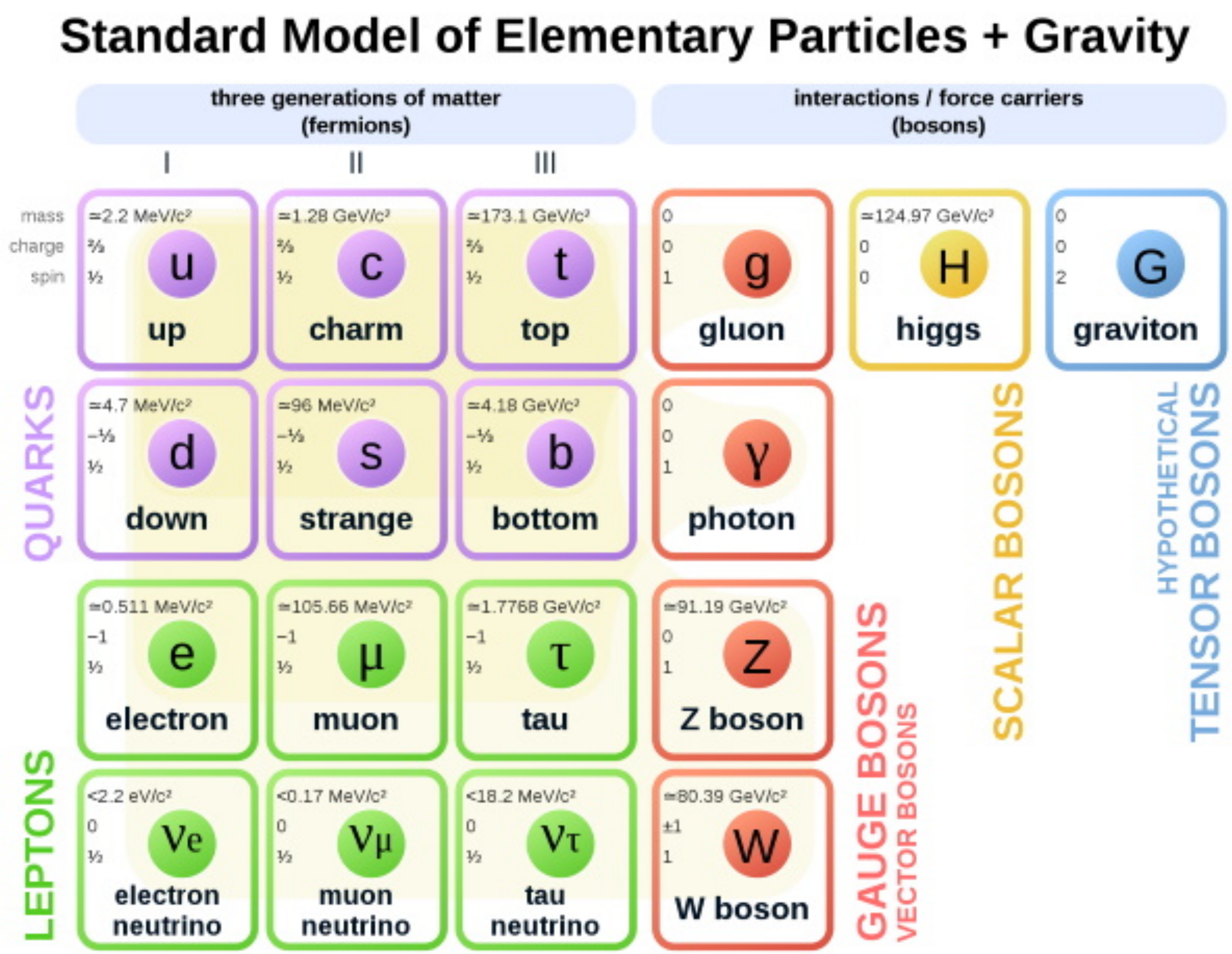
In particle physics, **flavour** or **flavor** refers to the *species* of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles. They can also be described by some of the family symmetries proposed for the quark-lepton generations.

- Flavor is defined in the mass eigenstate basis for quarks and charged leptons
- Neutrino flavors: SU(2) partners of charged leptons

Key Roles in Shaping SM

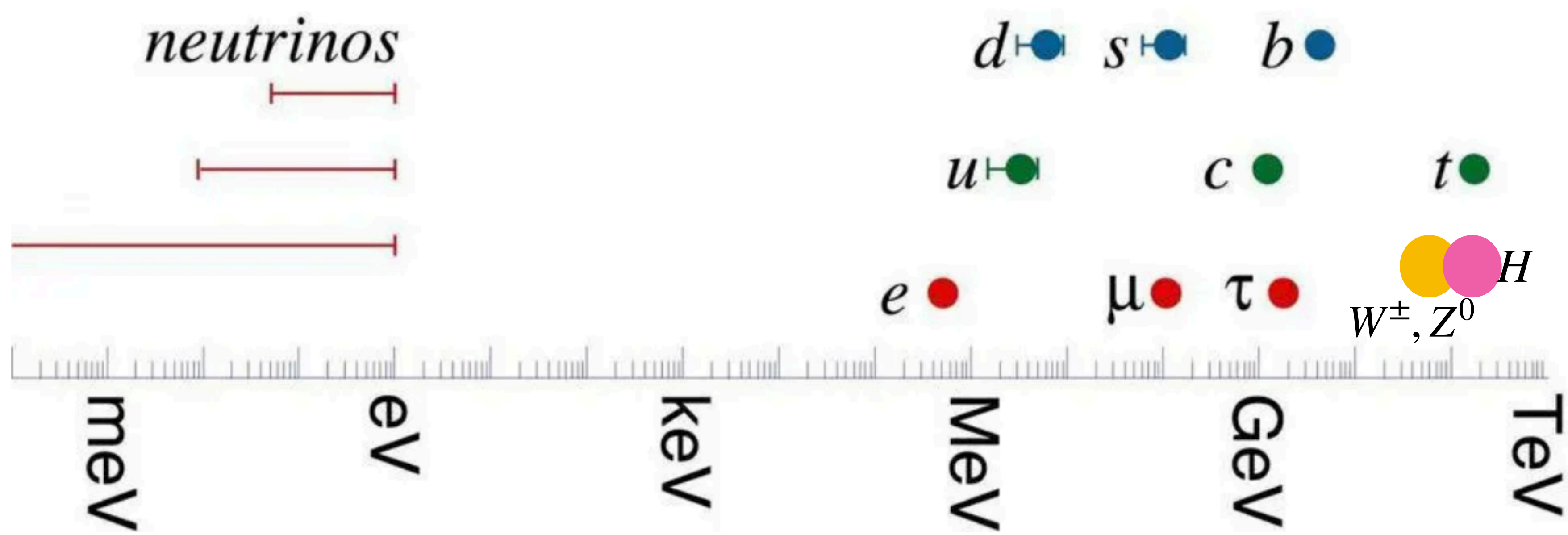
- Discoveries of muon, tau, charm, bottom, top, etc.
- Parity and C-conjugation violation (Maximal) in Charged Current Weak Interactions (T.D.Lee and C.N. Yang,1956)
- CP violations in the mixing ($K_L \to 2\pi$, ϵ_K) (Cronin, Fitch, 1964) and decay ($K_2 \to 2\pi$, $\mathrm{Re}(\epsilon^{'}/\epsilon_K)$) (NA31, 1993)
- Chiral structures and universality in charged current weak interactions → Basis for the SM (with CKM)

Periodic Table for SM



DM can be considered as another flavor, since its property is the same as the neutrinos (upto mass and spin).

Mass Spectra



- Can we understand this mass spectra ?
- Why neutrinos are much lighter than other charged particles ?
- Photon, gluon, graviton: massless

CKM Mixing

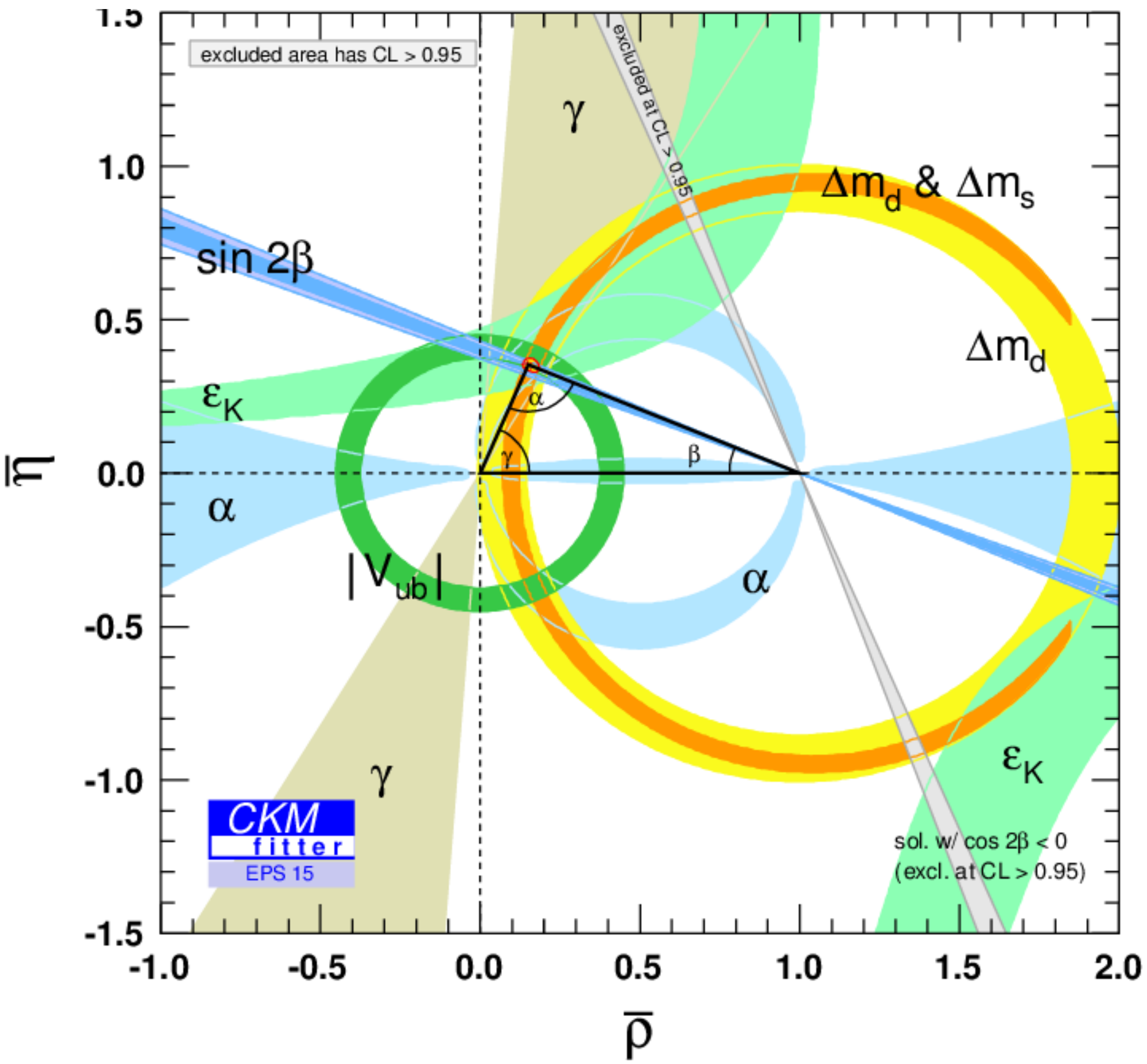
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4) .$$

Wolfenstein parametrization

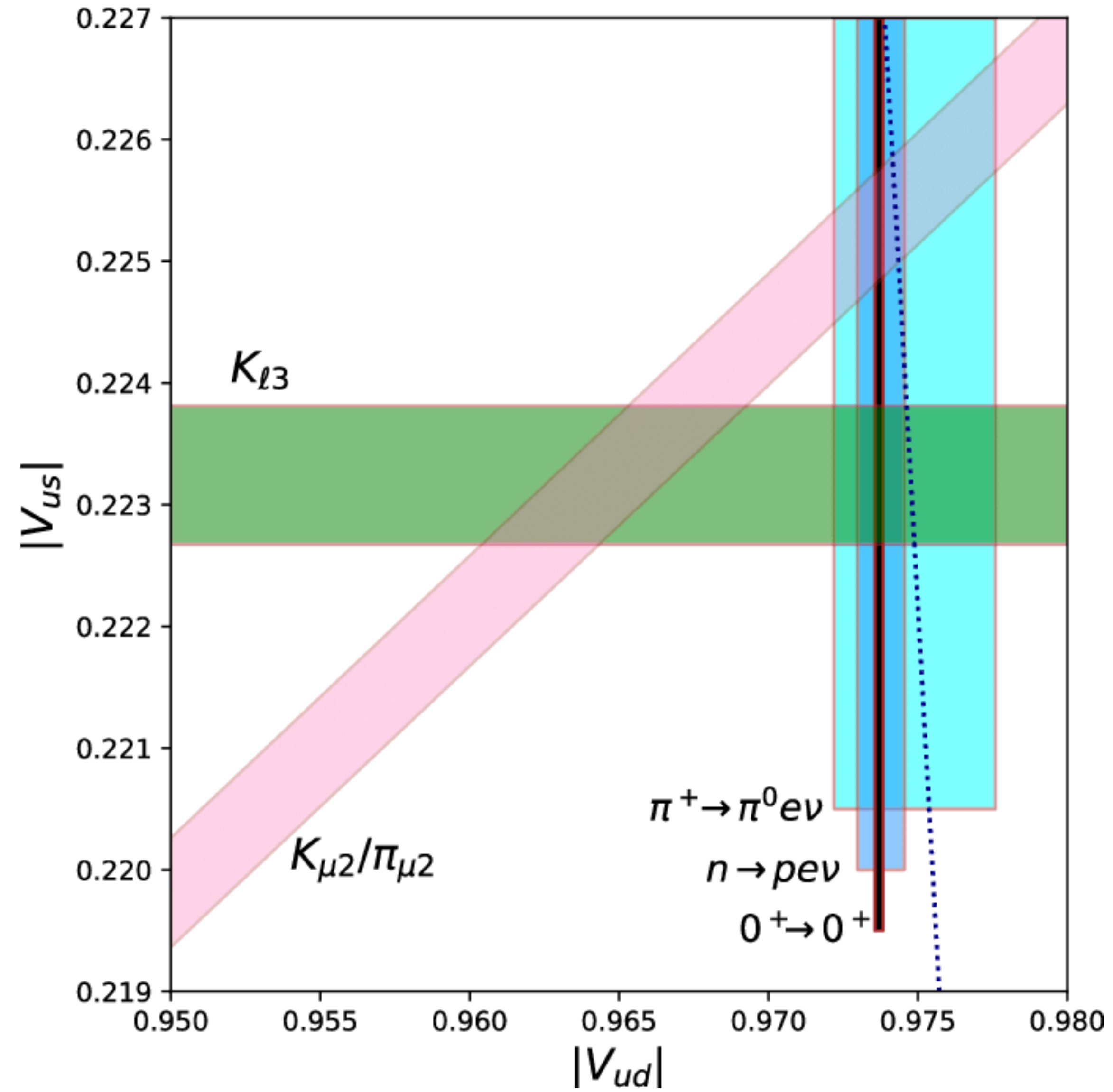
- CKM: 3X3 Unitary Matrix : $V^\dagger V = VV^\dagger = 1$
- $$\sum_{k=1,2,3} |V_{ik}|^2 = \sum_{k=1,2,3} |V_{kj}|^2 = 1\ , \quad \sum_{k=1,2,3} V_{ik}V_{jk}^* = 0$$
- 3 mixing angles and 1 CPV phase
- $\lambda = 0.2257\,^{+0.0009}_{-0.0010}$, $A = 0.814\,^{+0.021}_{-0.022}$, $\rho = 0.135\,^{+0.031}_{-0.016}$, and $\eta = 0.349\,^{+0.015}_{-0.017}$

CKMology

Strong Constraints on BSM @ TeV Scale



Unitarity Triangle



Cabibbo Angle Anomaly

(P)MNS Mixing

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix} = \begin{bmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.779 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{bmatrix}$$

The value of $\delta_{CP} = 197^{\circ}{}^{+42^{\circ}}_{-25^{\circ}}$ is very difficult to measure, and is the object of ongoing research; however the current constraint $169^{\circ} \leq \delta_{CP} \leq 246^{\circ}$ in the vicinity of 180° shows a clear bias in favor of charge-parity violation.

- Pattern is very different from CKM. Why ?
- Neutrino masses ? Mass ordering ? Majorana or Dirac ?

Flavor Problems

- Who ordered muon ? Why 3 families of SM fermions ?
- What determine flavor mixings (CKM vs. MNS) ?
- Origin of masses and mixings (including neutrinos) ?
- Flavor (or family) dependent gauge interaction ?
- Proton decays ? Neutron lifetime puzzle ?
- Many unanswered questions out there, with many suggestions and creative ideas ! (FN, Flavor Symmetry, etc.)

ArXiv:2309.07788 with S. Baek, J. Kersten, L. Vellasco-Sevilla

GIM, Flavor/CPV in Quarks and Charged Lepton Sectors

Before GIM (1970)

- If there were only three familes with

$$\begin{pmatrix} u_L \\ d_L \cos\theta_C + s \sin\theta_C \end{pmatrix}, u_R, d_R, s_R,$$

  there would be huge contribution to $K^0 \to \mu^+\mu^-$ mediated by W^0 gauge boson of $SU(2)_L$

- Precition vs. Data:

$$\frac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^+ \to \mu\nu_\mu)} = O(1), \quad vs. \quad \sim 3 \times 10^{-7}(\mathrm{Data})$$

- In nature (in the kaon system), FCNC is highly suppressed
- What is wrong ? How to cure the theory ?

GIM (1970)

- GIM introduced another quark called "charm" ($\equiv c$) with the orthogonal coupling to the down type quarks

$$\begin{pmatrix} u_L \\ d_L \cos\theta_C + s \sin\theta_C \end{pmatrix}, \quad \begin{pmatrix} c_L \\ -d_L \sin\theta_C + s \cos\theta_C \end{pmatrix}, \quad u_R, d_R, s_R$$

- Then W^0 coupling is flavor diagonal, and no tree level contribution to $K_L \to \mu\mu$
- FCNC processes can occur only at one-loop or higher loops
- $m_c \sim 1.5$ GeV will explain Δm_K (Gaillard, Lee, Rosner 1974)
- Charm quark discovered in 1975
  $\to$ "Triumph of Theoretical Physics"

In retrospect, large FCNC is a wrong prediction of anomalous gauge theory for 3 quark flavors, which is not a healthy theory [ABJ anomaly in 1969]

GIM Mechanism

- No tree level flavor-changing neutral current (FCNC)
- FCNC generated at loops in the SM, and sensitive to particle masses in the loop
- FCNC Amplitude for $i \to j \propto \sum_{k=1,2,3} V_{ik} V^*_{jk} f(m_k^2)$

$= 0$, if $m_k = m_0$ independent of k

$$= \sum_{k=1,2,3} V_{ik} V^*_{jk} \left[f(m_k^2) - f(m_1^2) \right] \propto \Delta m_{k1}^2$$

GIM

- Larger loop amp for FCNC of down-type quarks, since the quarks in the loop are up-type, $\propto m_t^2$
- Smaller loop amp for top FCNC, since the quarks in the loop are down-type, $\propto m_b^2$
- Top FCNC is highly suppressed in the SM → A nice probe of BSM with large FCNC [T. Kim's talk]
- B FCNC is not that much suppressed in the SM → Nice test grounds of the SM at loops, and BSM since new particles also appear at one loop order [Y. Kwon's talk]

Tree-level FCNC ?

- Severely constrained by exp data
- General 2HDM models have large FCNC problem mediated by neutral (pseudo)scalar bosons
- Glashow-Weinberg proposed a way out of this, by assuming ……. → Type I, II, X, Y , by imposing softly broken Z_2 symmetry ($H_1 \to H_1,\, H_2 \to -H_2$)
- $Z_2 \to U(1)_H$: Ko, Omura, Yu (2012) → New window open for 2HDM model buildings

Muon g-2

[M. Lee's talk]

Magnetic Moment in Classical E&M

- General Physics : Current Loop $\rightarrow \vec{\mu} = IA\vec{n}$

- Slowly varying EM field couples to

  Total electric charge $Q = \int d^3x\ \rho(\vec{x})$

  Quadratic moment Q_{ij} :

$$Q_{ij} = \int d^3x\ \rho(\vec{x})(x_i x_j - \frac{1}{3}\ \delta_{ij}\vec{x}^2)$$

  Magnetic dipole moment $\vec{\mu}$

- Low Energy Theorem

Magnetic Moment in QFT

- Fundamental Properties of a particle :
  - Mass M
  - Spin s : Bosons and Fermions with Diff. Statistics
  - Charge Q : integral multiples of e_p
  - Magnetic Dipole Moment (MDM) μ
- MDM vs. Spin

$$\vec{\mu} = g\frac{e\hbar}{2mc}\,\vec{s}$$

- Pointlike Dirac particle : $g = 2$ (e.g., electron, muon, quark etc.)

  cf. $g = 2.79 \ \ (-1.86)$ for proton (neutron)

  $\rightarrow$ Indicate p and n are composite particles

- Quantum Corrections modifies g at loop levels.

$$a_\mu \equiv \left(\frac{g-2}{2}\right)_\mu$$

$\rightarrow$ Anomalous Magnetic Dipole Moment

- Theoretically well understood
  (except for the hadronic contibutions)
- Measured with high precisions
- Indirect Probe of New Physics Beyond the SM

How to measure it ?

- Relativistic Muon in a Ring with $\vec{B}$ field
- Cyclotron Frequency :

$$\omega_c = \frac{eB}{mc\gamma} = \frac{2\mu_B B}{\hbar\gamma}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \qquad \beta = |\vec{\beta}| = |\frac{\vec{v}}{c}|$$

- Spin Precession Frequency (BMT equation) :

  [V. Bargmann, L. Michel and V.L. Telegdi,

  Phys. Rev. Lett. **2**, 435 (1959)]

$$\omega_s = \frac{eB}{mc\gamma}\left[1 + \left(\frac{g-2}{2}\right)\gamma\right]$$

- Additional Precession due to $\vec{E}$ field

$$\Delta\omega_a = \frac{e}{mc}\left(\frac{1}{\gamma^2-1} - a\right)\vec{\beta}\times\vec{E}$$

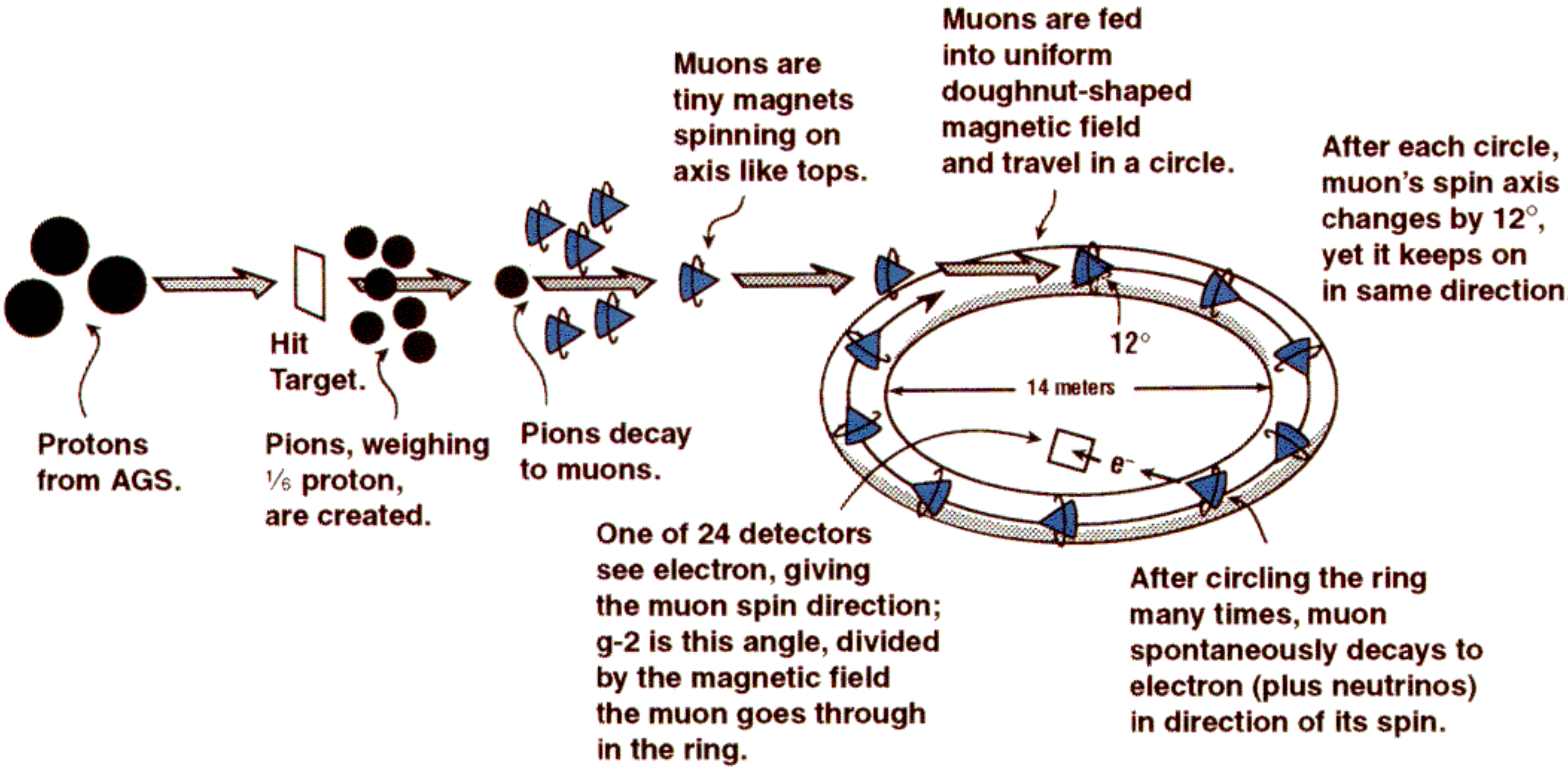
$\rightarrow$ Can be made zero by choosing $\gamma^2 = 1 + 1/a$

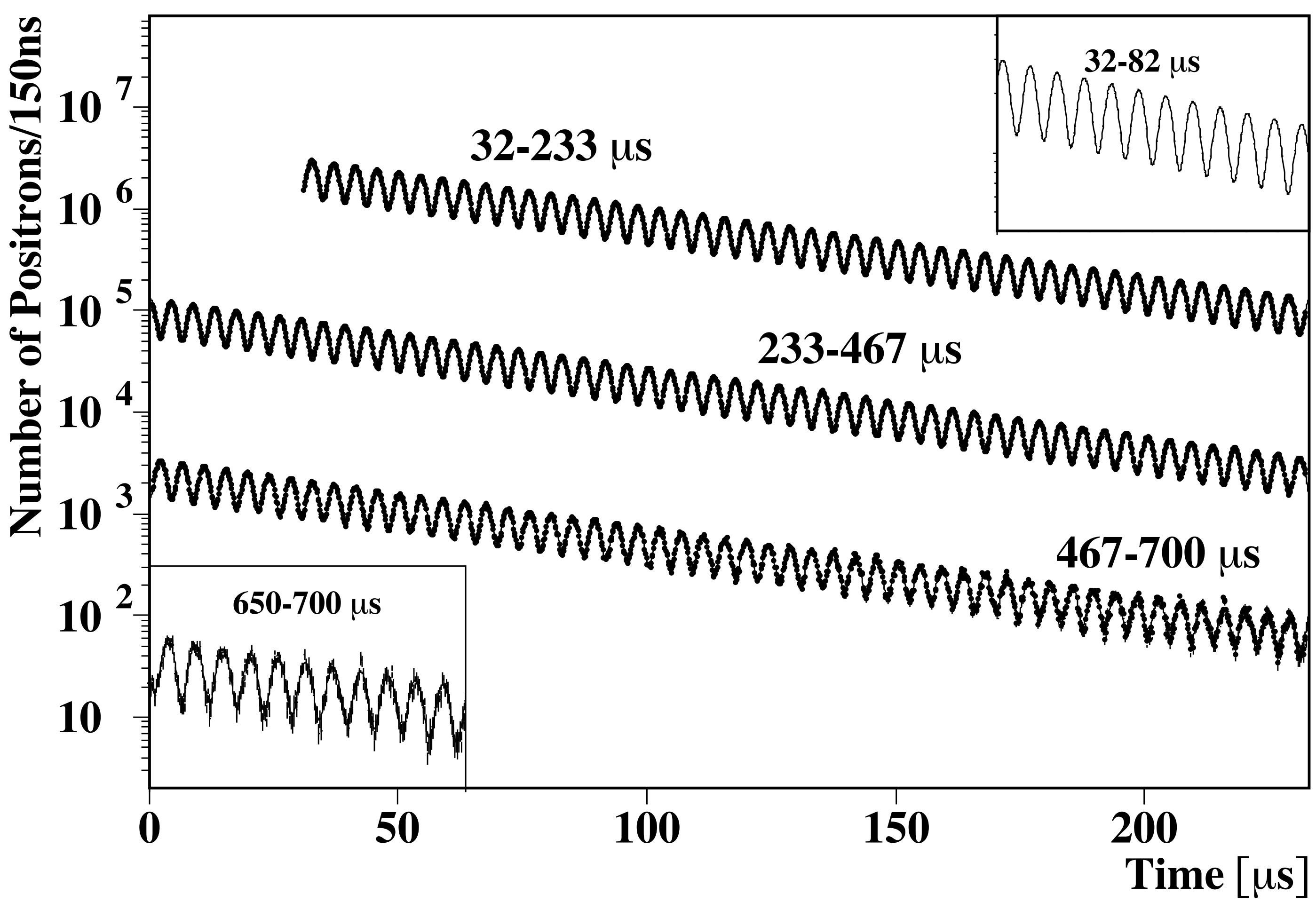
Magic Muon Momentum

3.1GeV/c, a.k.a. magic momentum, with $\gamma \approx 29.3$

- Muon decay distribution carries the informations of the muon polarization
  - $(V-A)\times(V-A)$ Nature of Muon Decay
  - The highest energy electron tends to come along the muon polarization

LIFE OF A MUON:
THE g-2 EXPERIMENT





Number of Positrons/150ns
10 7
10 6
10 5
10 4
10 3
10 2
10
0
50
100
150
200
Time [μs]
32-233 μs
233-467 μs
467-700 μs
32-82 μs
650-700 μs

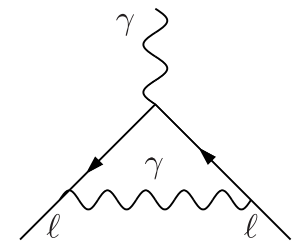


Fig. 8. The universal lowest order QED contribution to a_ℓ.

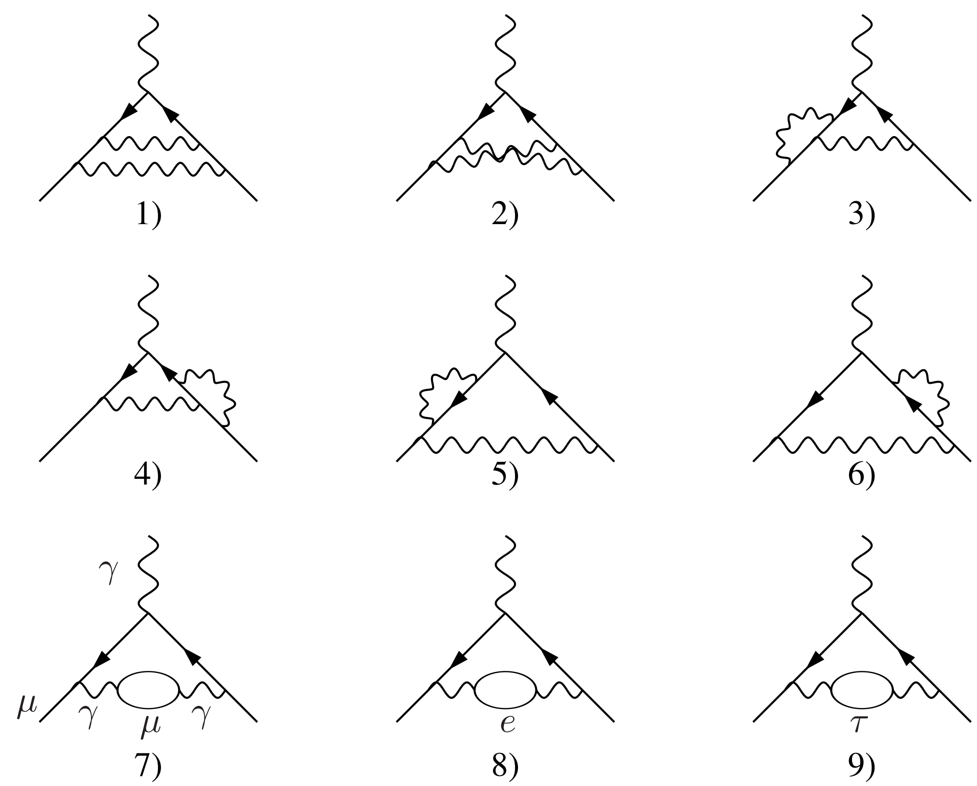


Fig. 9. Diagrams 1-7 represent the universal second order contribution to a_μ, diagram 8 yields the "light", diagram 9 the "heavy" mass dependent corrections.

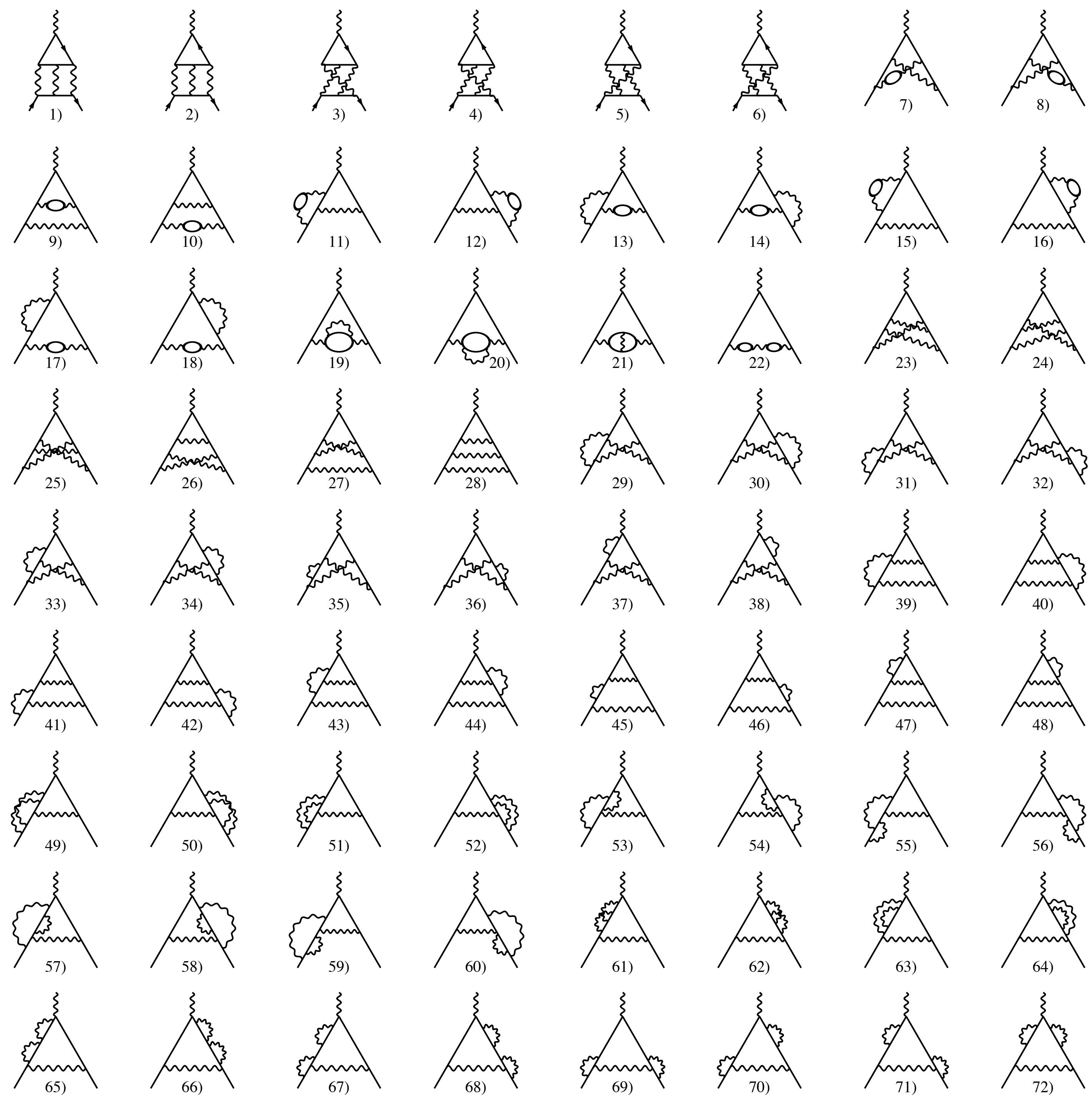


Fig. 10. The universal third order contribution to a_μ. All fermion loops here are muon–loops. Graphs 1) to 6) are the light–by—light scattering diagrams. Graphs 7) to 22) include photon vacuum polarization insertions. All non–universal contributions follow by replacing at least one muon in a closed loop by some other fermion.

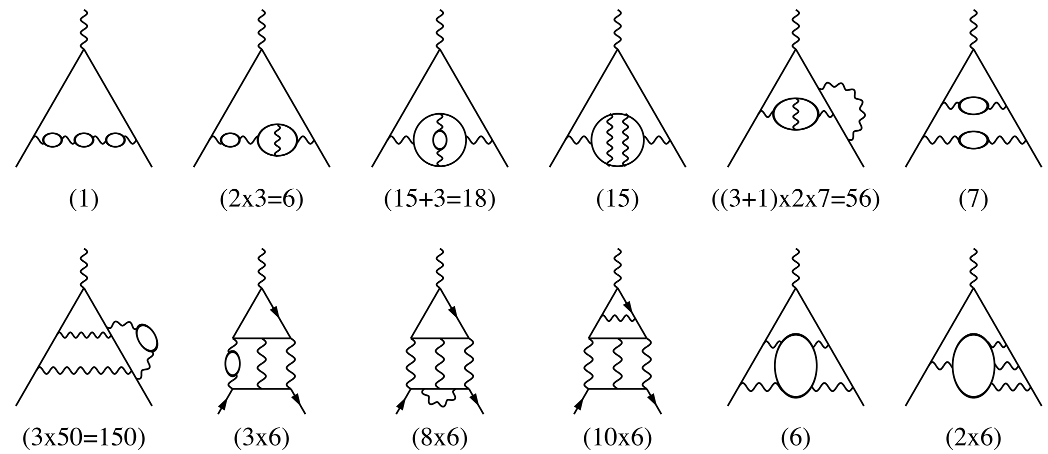


Fig. 11. Some typical eight order contributions to a_ℓ involving lepton loops. In brackets the number of diagrams of a given type if only muon loops are considered. The latter contribute to the universal part.

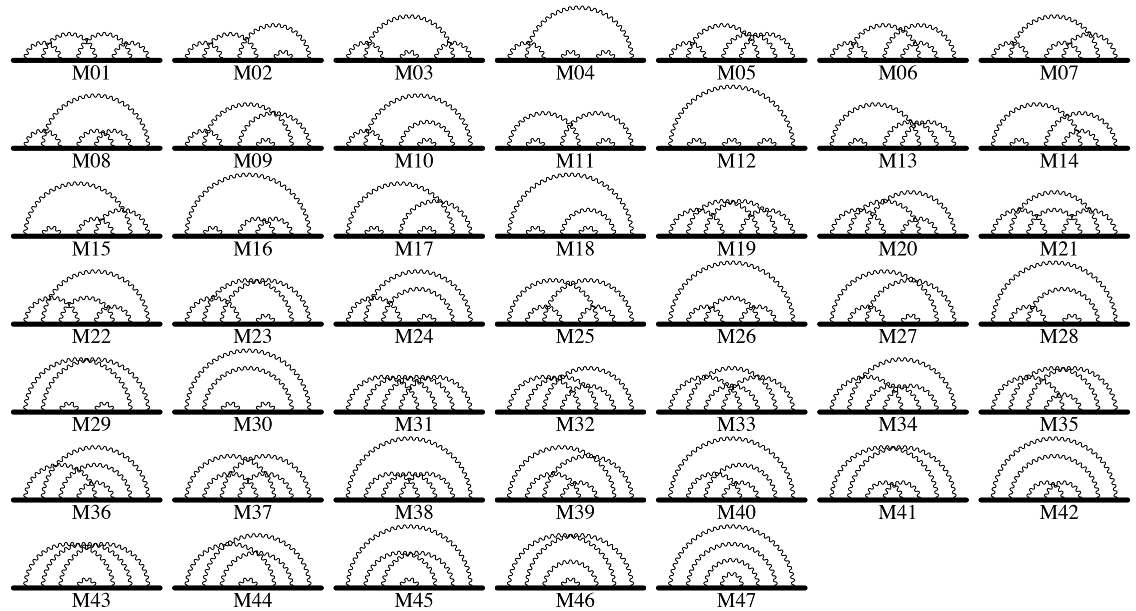


Fig. 12. 4-loop Group V diagrams. 47 self-energy-like diagrams of $M_{01} - M_{47}$ represent 518 vertex diagrams [by inserting the external photon vertex on the virtual muon lines in all possible ways]. Reprinted with permission from [108]. Copyright (2007) by the American Physical Society].

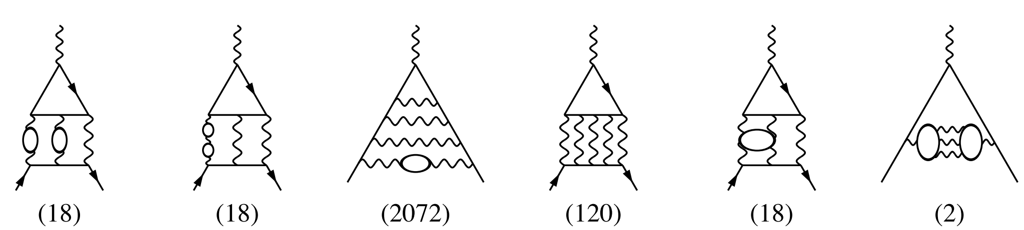


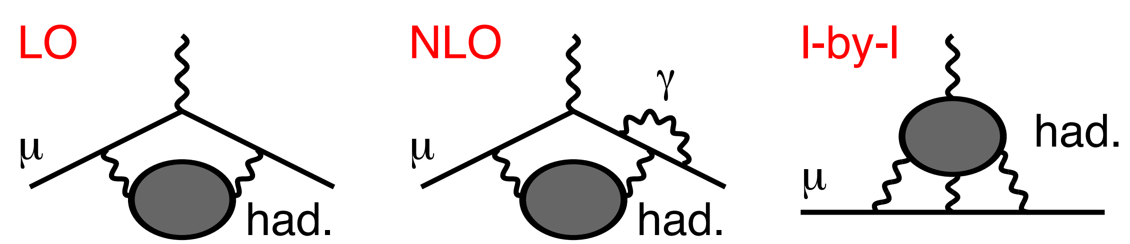
Fig. 13. Typical tenth order contributions to a_ℓ including fermion loops. In brackets the number of diagrams of the given type.

Standard Model Prediction for Muon $g-2$

QED contribution	11 658 471.809 (0.016) $\times 10^{-10}$	Kinoshita & Nio
EW contrib.	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contrib.		
LO hadronic	**689.4 (4.0)** $\times 10^{-10}$	HLMNT09
NLO hadronic	-9.8 (0.1) $\times 10^{-10}$	HLMNT09
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 177.3 (4.8)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**31.6 (7.9)** $\times 10^{-10}$	**4.0 σ discrepancy**

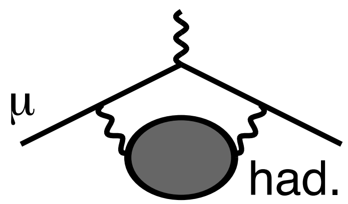
(Numbers taken from HLMNT09 (`arXiv:1001.5401`))

n.b.: hadronic contributions:

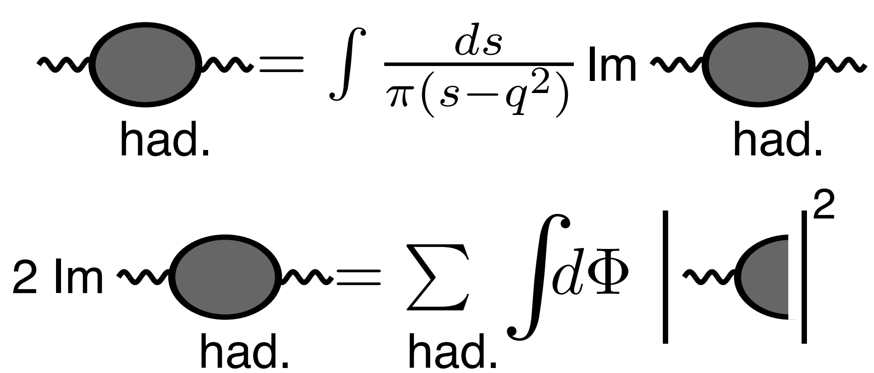


LO Hadronic Contribution

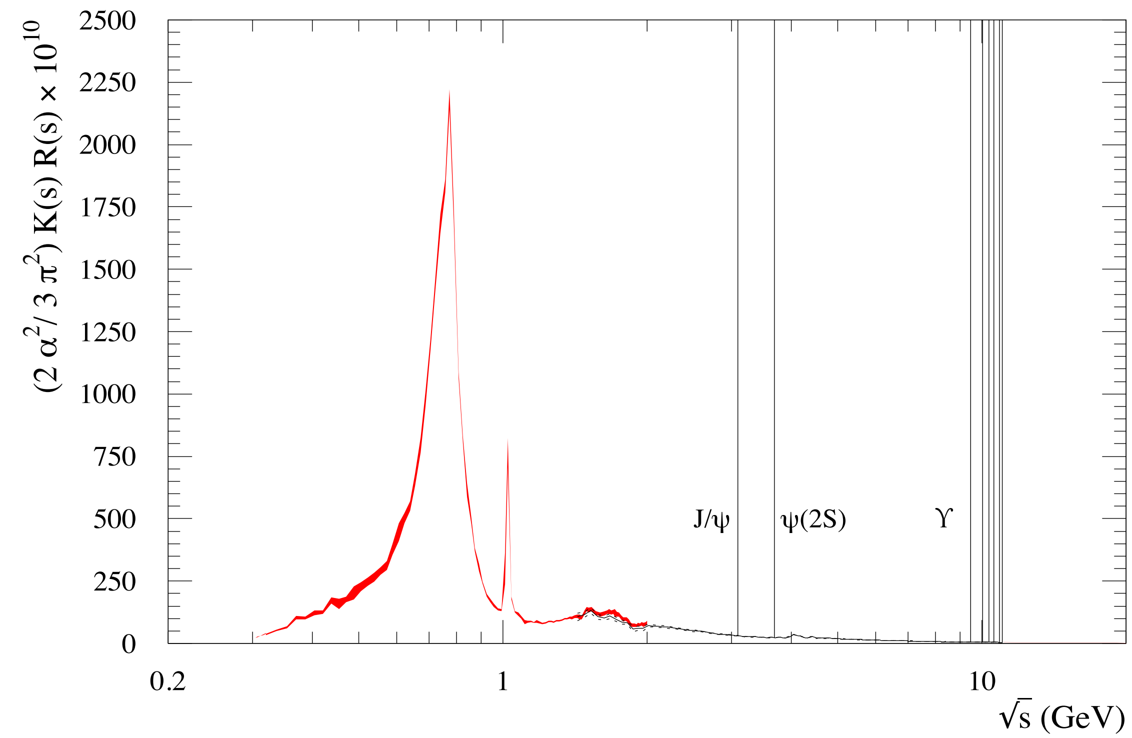
The diagram to be evaluated:



pQCD not useful. Use the dispersion relation and the optical theorem.

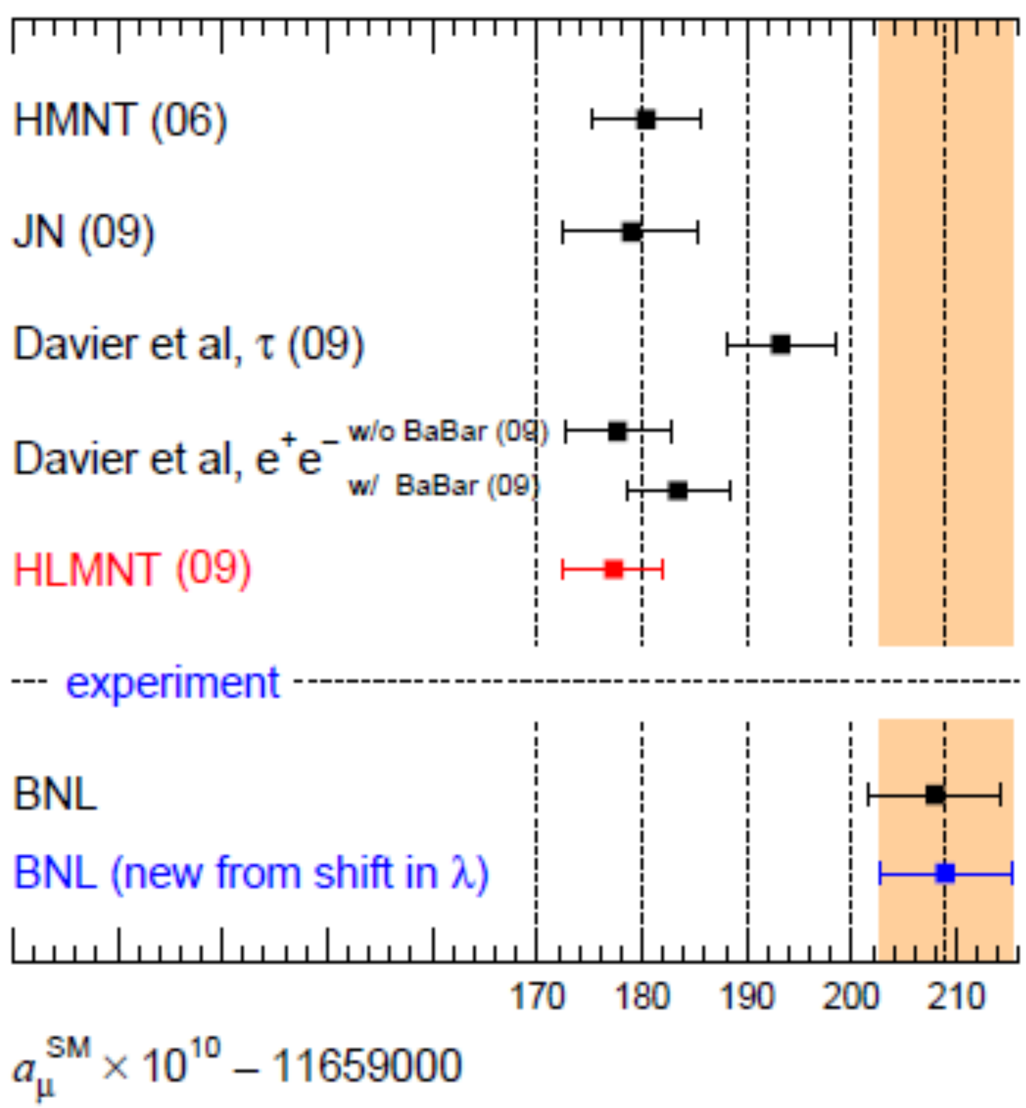


$$a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\text{th}}}^{\infty} ds\, \frac{1}{s} \hat{K}(s) \sigma_{\text{had}}(s)$$



- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s \Longrightarrow$ Lower energies more important
- We have to rely on exp. data for $\sigma_{\text{had}}(s)$ $\Longrightarrow$ Good data crucial

a_μ^{SM} compared to BNL world av.



Davier et al.: $1.8/3.9/3.1\,\sigma$

JN 09: $3.2\,\sigma$ $[179.0 \pm 6.5]$

Recent changes

TH: Improved LO hadronic (from e^+e^-):

[New data from CMD-2, SND, KLOE, BaBar, CLEO, BES. Combination of excl. (BaBar RadRet) and incl. data below 2 GeV.]

$(6894 \pm 46) \cdot 10^{-11} \longrightarrow (6894 \pm 40) \cdot 10^{-11}$

TH: Use of recent L-by-L compilation [PdeRV]: $a_\mu^{\mathrm{L-by-L}} = (10.5 \pm 2.6) \cdot 10^{-10}$

EXP: Small shift of BNL's value due to CODATA's shift of muon to proton magn. moment ratio:

Was $a_\mu = 116\,592\,080(63) \times 10^{-11}$

$\rightarrow a_\mu = 116\,592\,089(63) \times 10^{-11}\ (0.5ppm)$

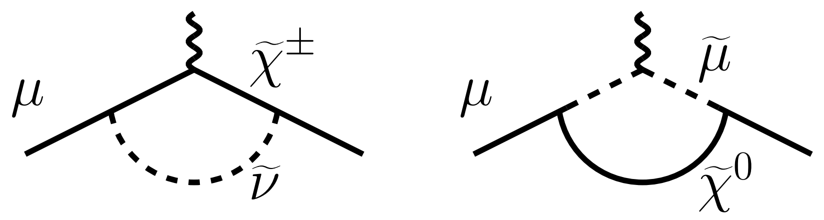
▶ With this input HLMNT get:

$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{TH}} = (31.6 \pm 7.9) \cdot 10^{-10}$, $\sim 4.0\sigma$

BSM @ Weak Scale

Is the 4.0σ deviation due to SUSY?

Dominant **SUSY contributions**:



which is, very roughly, given by

$$a_\mu^{\rm SUSY} = ({\rm sgn}\ \mu)\frac{\alpha(M_Z)}{8\pi\sin^2\theta_W}\frac{m_\mu^2}{\widetilde{m}^2}\tan\beta,$$

where $\widetilde{m}$ is the SUSY scale.

Numerically,

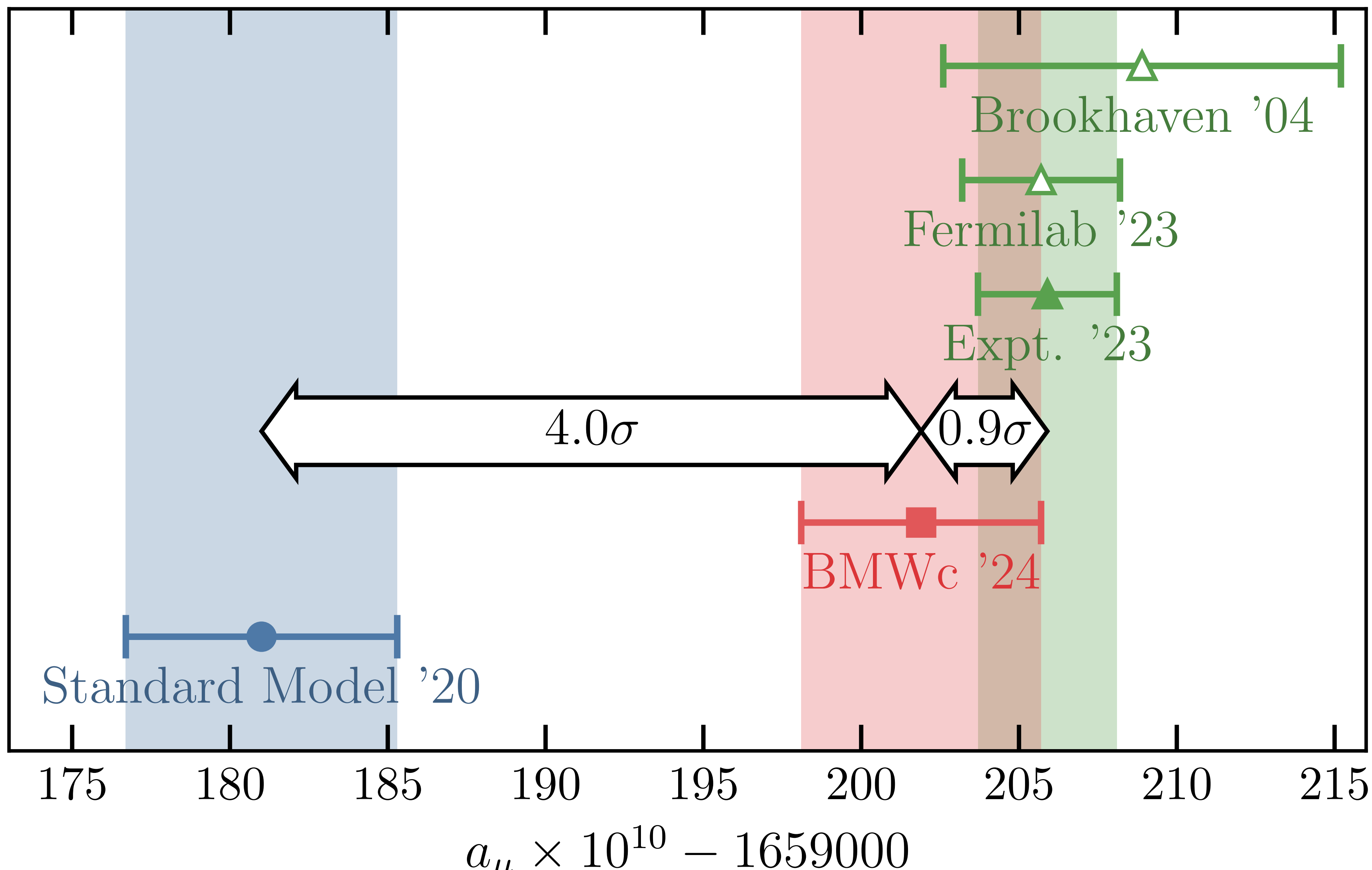
$$a_\mu^{\rm SUSY} = ({\rm sgn}\mu)\times 13\times 10^{-10} \times\left(\frac{100{\rm GeV}}{\widetilde{m}}\right)^2\tan\beta$$

In order for this to be $15.8 \le a_\mu^{\rm SUSY}\times 10^{10} \le 47.4$ (2 σ range),

$$\boxed{\widetilde{m} = \mathbf{170 - 640}\ \text{GeV}}$$

for $\tan\beta = 10 - 50$. (**Rough estimates**)

News from Lattice QCD



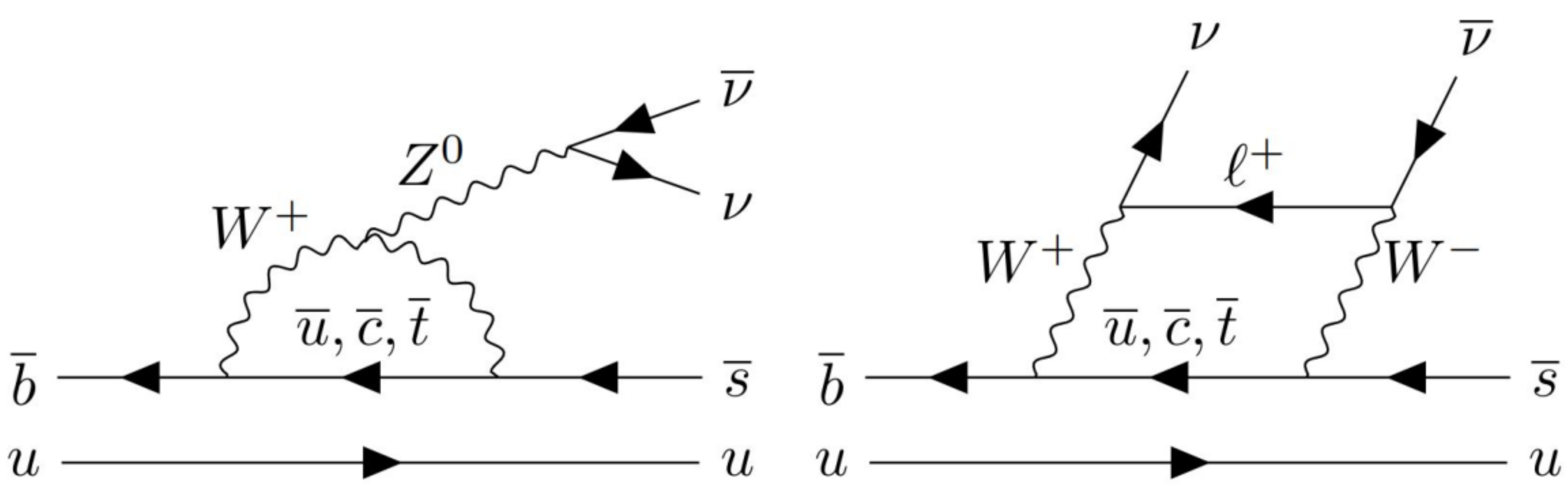
Plenary talk by Finn M. Strokes @ QCHSC2024, Cairns, Australia

Example with light dark sector for light DM, muon g-2 and Belle II $B^+ \to K^+\nu\bar{\nu}$

Based on arXiv:2204.04889, arXiv:2401.10112

$B^+ \to K^+\nu\bar{\nu}$ in the SM

- The $B^+ \to K^+\nu\bar{\nu}$ process is known with high accuracy in the SM:
  - $Br(B^+ \to K^+\nu\bar{\nu}) = (4.97 \pm 0.37) \times 10^{-6}$ HPQCD, PRD 2023



- $$\mathcal{L}_{b\to s\nu\bar{\nu}} = -C_\nu \bar{s}_L\gamma^\mu b_L \bar{\nu}\gamma^\mu \nu$$

$$C_\nu = \frac{g_W^2}{M_W^2}\frac{g_W^2 V_{ts}^* V_{tb}}{16\pi^2}\left[\frac{x_t^2+2x_t}{8(x_t-1)} + \frac{3x_t^2-6x_t}{8(x_t-1)^2}\ln x_t\right],$$

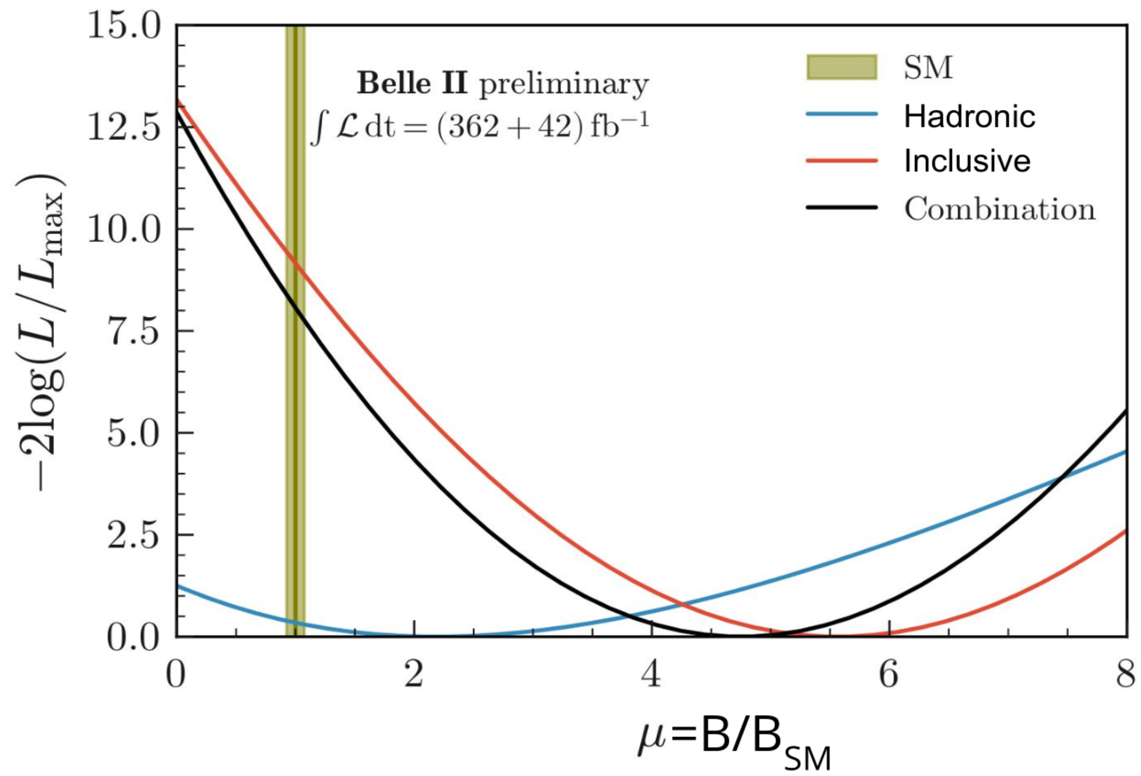
where $x_t = m_t^2/M_W^2$.

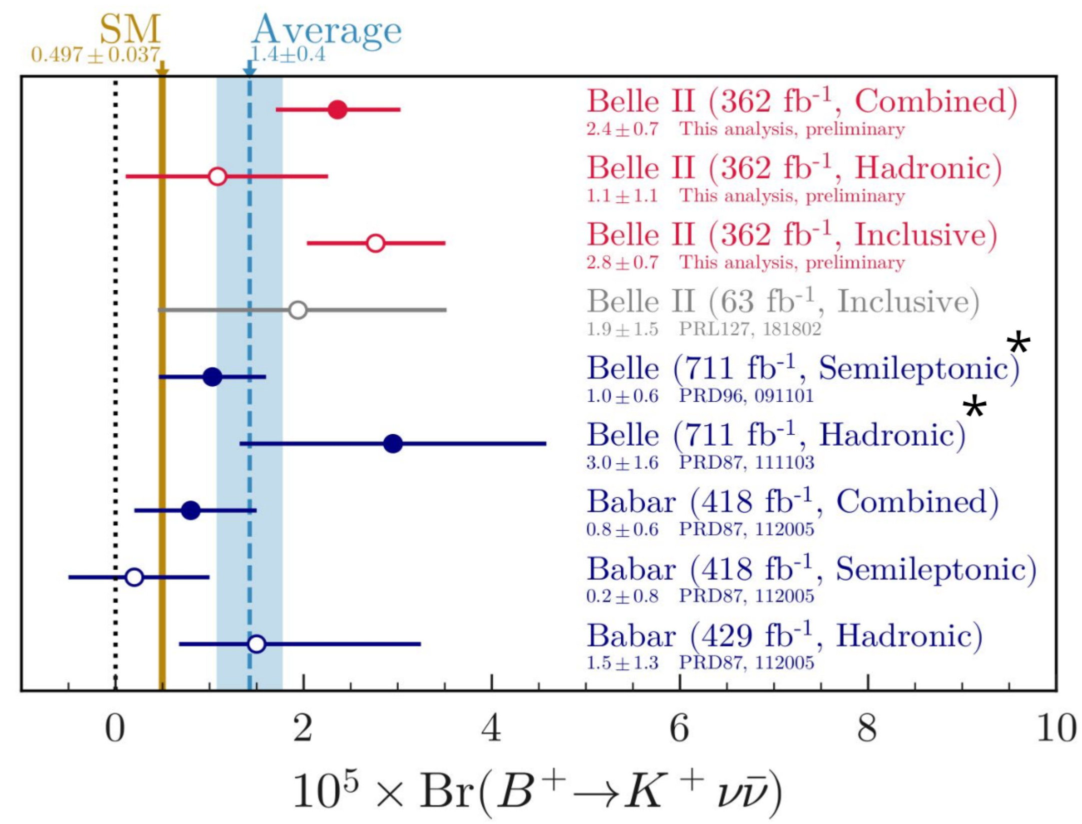
Measurement of $B^+ \to K^+\nu\bar{\nu}$

- Challenges in reconstructing the events
  - Searches for $B \to K^{(*)}\nu\bar{\nu}$ have only been performed at the B factories Belle and BaBar

- Using the same techniques in Belle, BaBar
  - Semileptonic tagged analyses
  - Hadronic-tagged analyses

- Inclusive tag analysis (Belle & BelleII)
  - Allow one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon



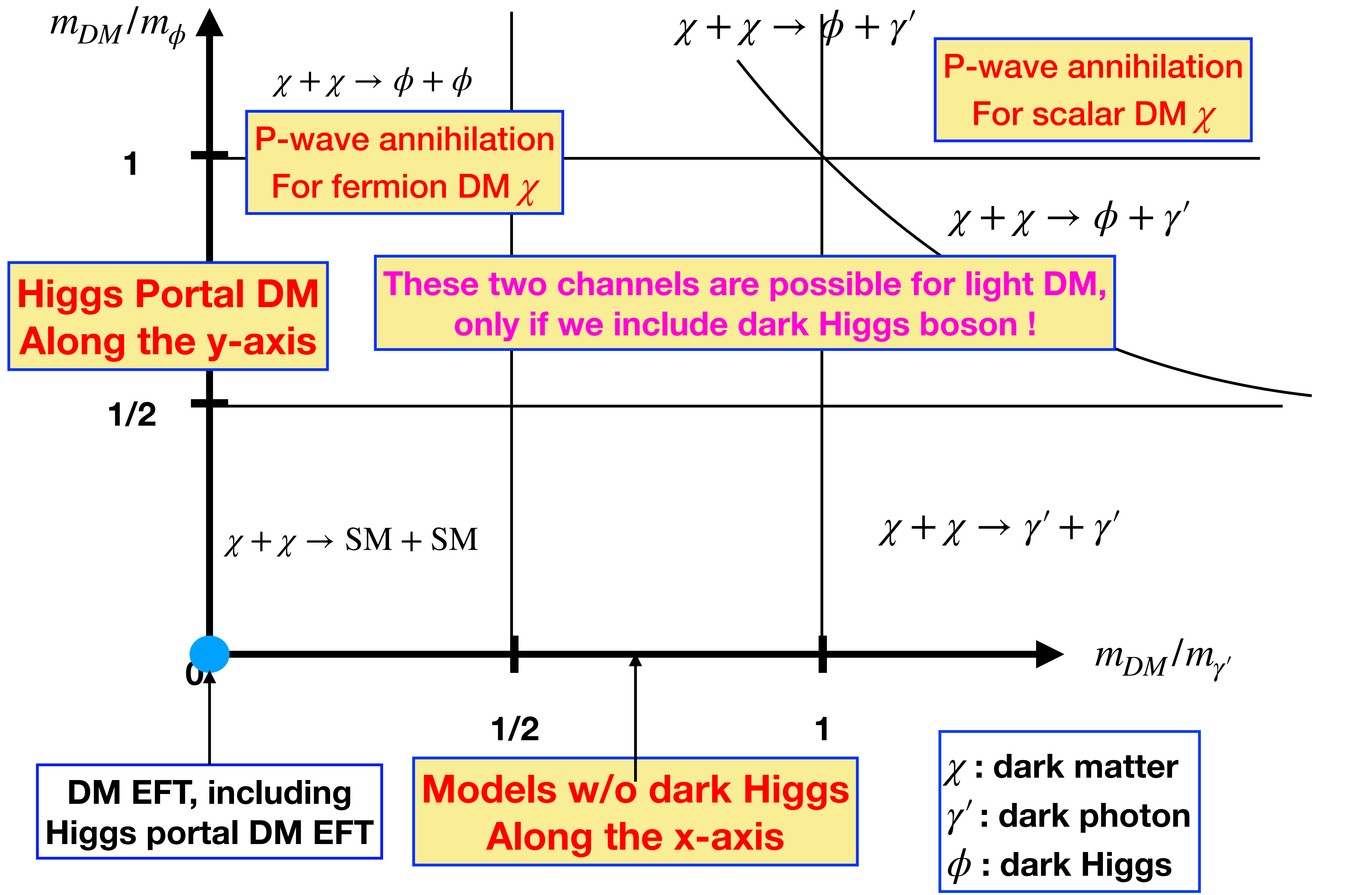


- $Br(B^+ \to K^+ \nu\bar{\nu}) = (2.4 \pm 0.7) \times 10^{-5}$
  - Significance of observation is 3.6σ
  - 2.8σ tension with the SM prediction
- $Br(B^+ \to K^+ E_{\mathrm{miss}})_{NP} = (1.9 \pm 0.7) \times 10^{-5}$
- Indicate not only the presence of NP in the $b \to s\nu\bar{\nu}$ transitions but even the presence of new light states (particles in dark sector?)

Questions ?

- Can we explain this mild excess in terms of new physics with light particles ?
- Light DM ? Something that decays mostly into neutrinos ?
- New light d.o.f. may have connections with other puzzles in particle physics and cosmology….
- Muon g-2, Hubble tension, etc.
- Answer : Yes, within $U(1)_{L_\mu - L_\tau}$ models with light complex scalar DM and light dark Higgs boson

Dark sector parameter space for a fixed m_{DM}



$U(1)_{L_\mu - L_\tau}$ -charged DM

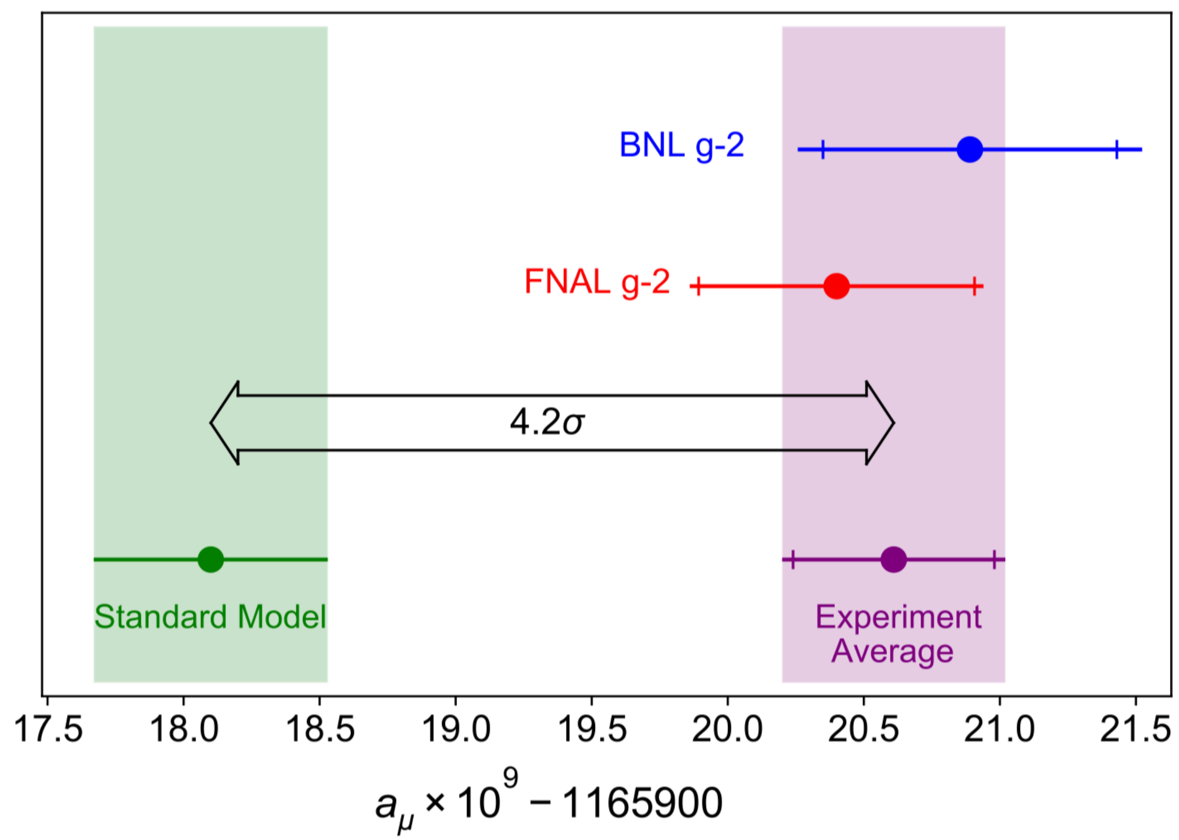
: Z' only vs. $Z' + \phi$

arXiv:2204.04889 [hep-ph]
With Seungwon Baek, Jongkuk Kim

SM+$U(1)_{L_\mu - L_\tau}$ gauge sym

- He, Josh, Lew, Volkas, PRD 43, 22; PRD 44, 2118 (1991)
- One of the anomaly free gauge groups without extension of fermion contents
- The simplest anomaly free U(1) extensions that couple to the SM fermions directly
- Can affect the muon g-2, PAMELA e^+ excess, (and B anomalies with extra fermions : Not covered in this talk)

Muon g-2



The Muon g-2 Collaboration, 2104.03281

Excellent example for graduate students

- Relativistic E&M (spinning particle in EM fields)
- Special relativity (time dilation)
- (V-A) structure of charged weak interaction

Muon (g-2) in $U(1)_{\mu-\tau}$ Model

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$
\begin{array}{llll}
L_L^e: & (1,2,-1)(0) & e_R: & (1,1,-2)(0) \\
L_L^\mu: & (1,2,-1)(2a) & \mu_R: & (1,1,-2)(2a) \\
L_L^\tau: & (1,2,-1)(-2a) & \mu_R: & (1,1,-2)(-2a).
\end{array}
$$

$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha'}{2\pi}\frac{2m_\mu^2}{3M_{Z'}^2}$$

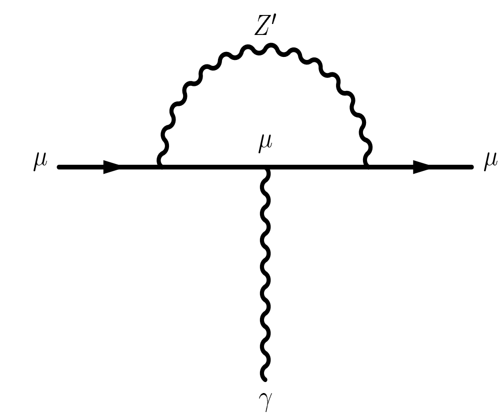
$$Z' \to \mu^+\mu^-, \tau^+\tau^-, \nu_\alpha\bar{\nu}_\alpha \text{ (with } \alpha = \mu \text{ or } \tau), \ \psi_D\overline{\psi}_D$$

$$\Gamma(Z' \to \mu^+\mu^-) = \Gamma(Z' \to \tau^+\tau^-) = 2\Gamma(Z' \to \nu_\mu\bar{\nu}_\mu) = 2\Gamma(Z' \to \nu_\tau\bar{\nu}_\tau) = \Gamma(Z' \to \psi_D\bar{\psi}_D)$$

if $M_{Z'} \gg m_\mu, m_\tau, M_{\rm DM}$. The total decay rate of Z' is approximately given by

$$\Gamma_{\rm tot}(Z') = \frac{\alpha'}{3} M_{Z'} \times 4(3) \approx \frac{4(\text{or } 3)}{3} \text{ GeV} \left(\frac{\alpha'}{10^{-2}}\right) \left(\frac{M_{Z'}}{100\text{GeV}}\right)$$

$$
\begin{aligned}
q\bar{q} \text{ (or } e^+e^-) &\to \gamma^*, Z^* \to \mu^+\mu^- Z', \tau^+\tau^- Z' \\
&\to Z^* \to \nu_\mu\bar{\nu}_\mu Z', \nu_\tau\bar{\nu}_\tau Z'
\end{aligned}
$$



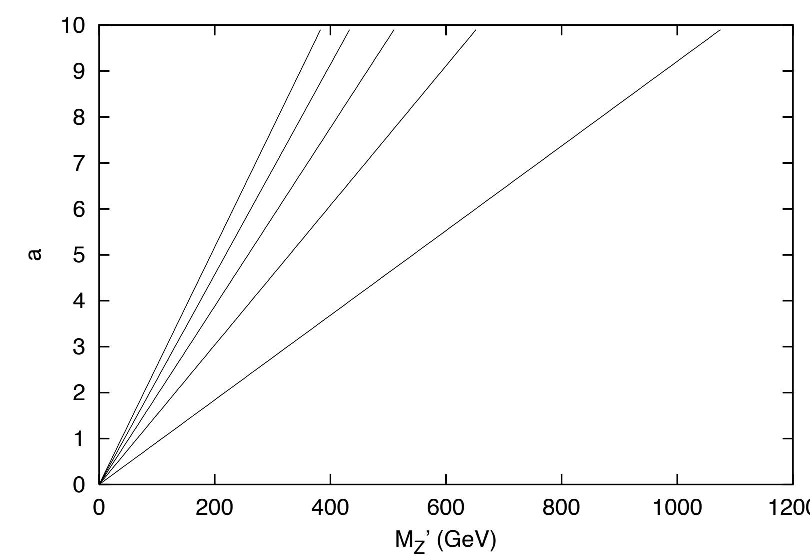


FIG. 2. Δa_μ on the a vs. $m_{Z'}$ plane in case b). The lines from left to right are for Δa_μ away from its central value at $+2\sigma, +1\sigma, 0, -1\sigma$ and -2σ, respectively.

Baek and Ko, arXiv:0811.1646, for PAMELA e^+ excess

$$\mathcal{L}_{\rm Model} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm New}$$
$$\mathcal{L}_{\rm New} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \overline{\psi_D} i D \cdot \gamma \psi_D - M_{\psi_D} \overline{\psi_D} \psi_D + D_\mu \phi^* D^\mu \phi$$
$$-\lambda_\phi (\phi^* \phi)^2 - \mu_\phi^2 \phi^* \phi - \lambda_{H\phi} \phi^* \phi H^\dagger H.$$

Here we ignored kinetic mixing for simplicity

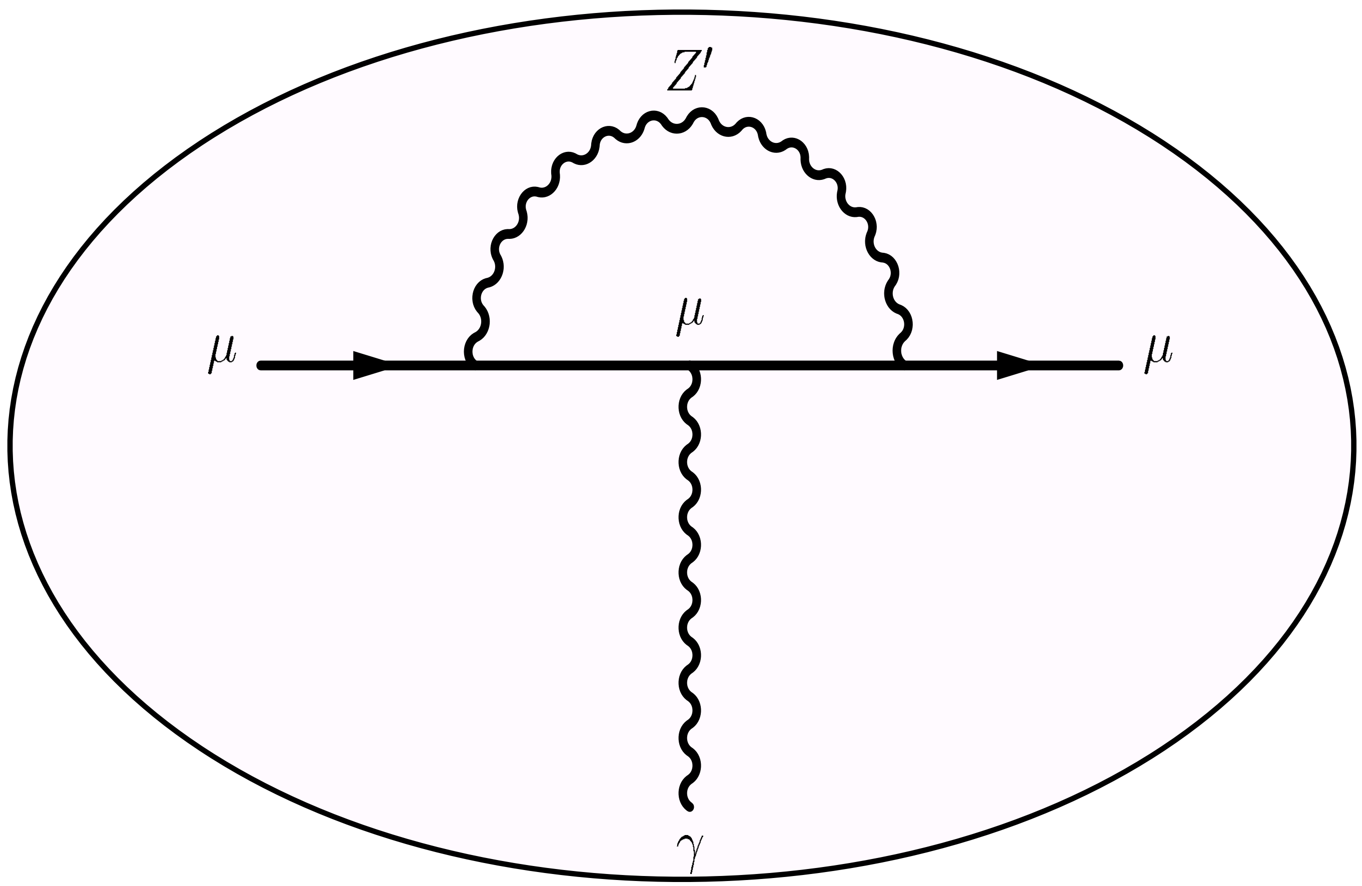
$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{e}{s_W c_S}(I_3 - s_W^2 Q) Z_\mu + ig' Y' Z'_\mu$$

muon g-2, Leptophilc DM, Collider Signature

Muon (g-2)

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (302 \pm 88) \times 10^{-11}.$$



$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x) M_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2m_\mu^2}{3M_{Z'}^2}$$

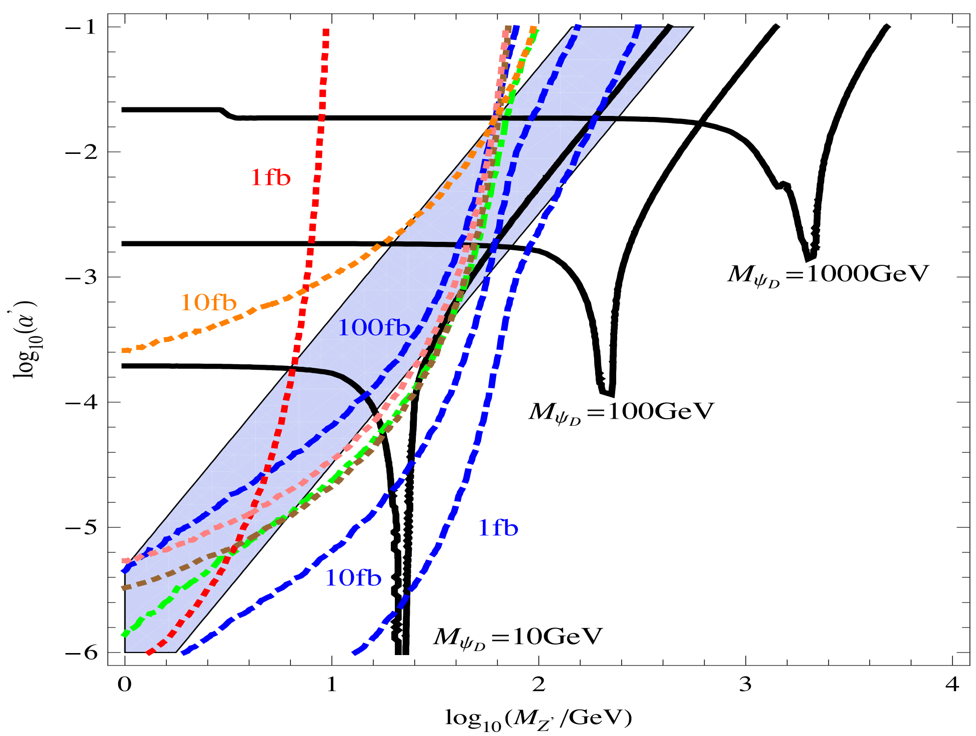


Figure 1: The relic density of CDM (black), the muon $(g-2)_\mu$ (blue band), the production cross section at B factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the Z^0 decay width (2.5×10^{-6} GeV, brown dotted) in the $(\log_{10}\alpha', \log_{10}M_{Z'})$ plane. For the relic density, we show three contours with $\Omega h^2 = 0.106$ for $M_{\psi_D} = 10$ GeV, 100 GeV and 1000 GeV. The blue band is allowed by $\Delta a_\mu = (302 \pm 88)\times 10^{-11}$ within 3 σ.

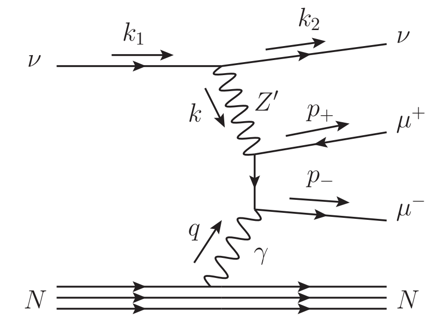


FIG. 1. The leading order contribution of the Z′ to neutrino trident production (another diagram with μ^+ and μ^- reversed i ... in g'

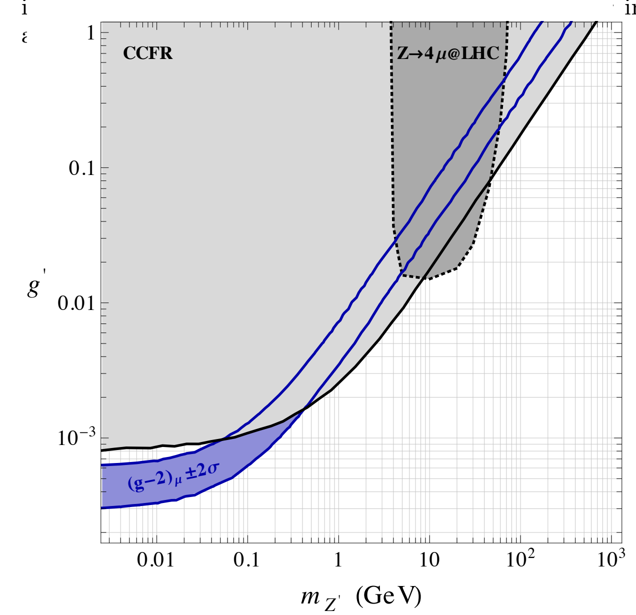


FIG. 2. Parameter space for the Z′ gauge boson. The light-grey area is excluded at 95% C.L. by the CCFR measurement of the neutrino trident cross-section. The grey region with the dotted contour is excluded by measurements of the SM

Seungwon Baek, Pyungwon Ko, arXiv:0811.1646, JCAP(2009) about PAMELA e^+ excess

Altmannshofer et al. arXiv:1406.2332 [hep-ph]

Neutrino trident puts strong constraints on this model

One can evade the neutrino trident constraint, if one introduces New fermions and generate muon g-2 at loop level w/ new fermions !

Z' Only

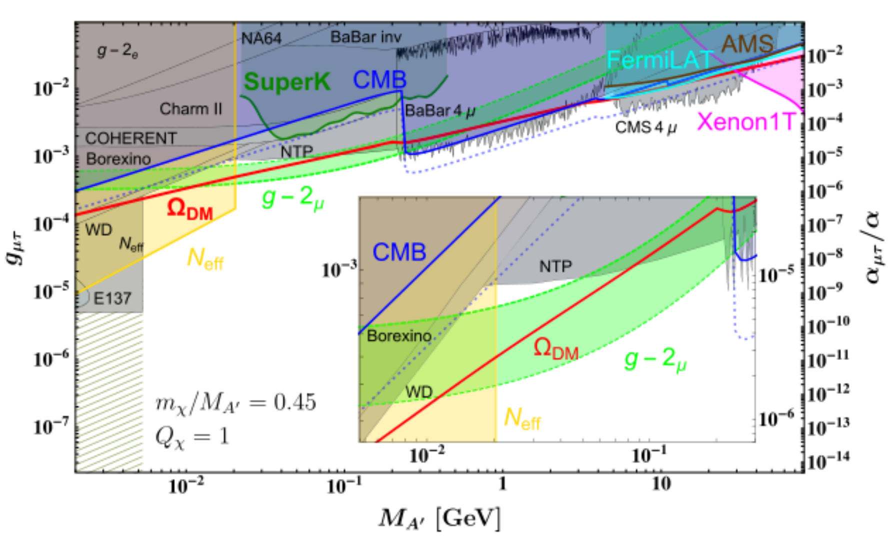
- Consider light Z' and $g_X \sim (\text{a few}) \times 10^{-4}$ for the muon g-2. Then
- $\chi\bar{\chi} \to Z'^{*} \to f_{\rm SM}\bar{f}_{\rm SM}$: dominant annihilation channel
- $g_X \sim 10^{-4}$ is too small for $\chi\bar{\chi} \to Z'Z'$ to be effective for $\Omega_\chi h^2$
- $m_{Z'} \sim 2m_{\rm DM}$ with the s-channel Z' resonance for the correct relic density
- Many recent studies on this case:

- Asai, Okawa, Tsumura, 2011.03165
- Holst, Hooper, Krnjaic, 2107.09067
- Drees and Zhao, arXiv:2107.14528
- And some earlier papers

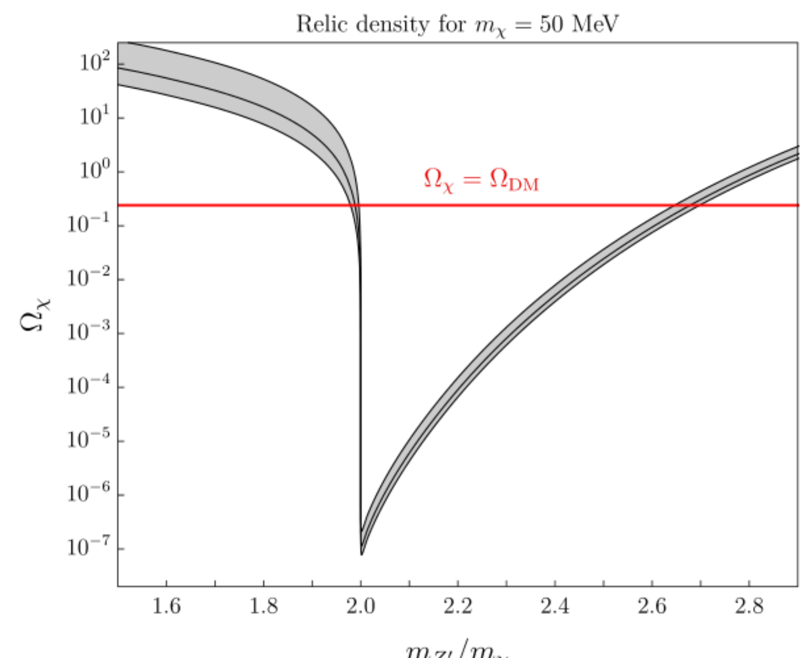
Leptophilic Z' model + DM

- $\chi\bar{\chi}(X\bar{X}) \to Z'^{*} \to \nu\bar{\nu}$: dominant annihilation channels
  - $M_{Z'}$~$2M_{\chi}$ with the **s-channel Z' resonance** only gives the correct relic density

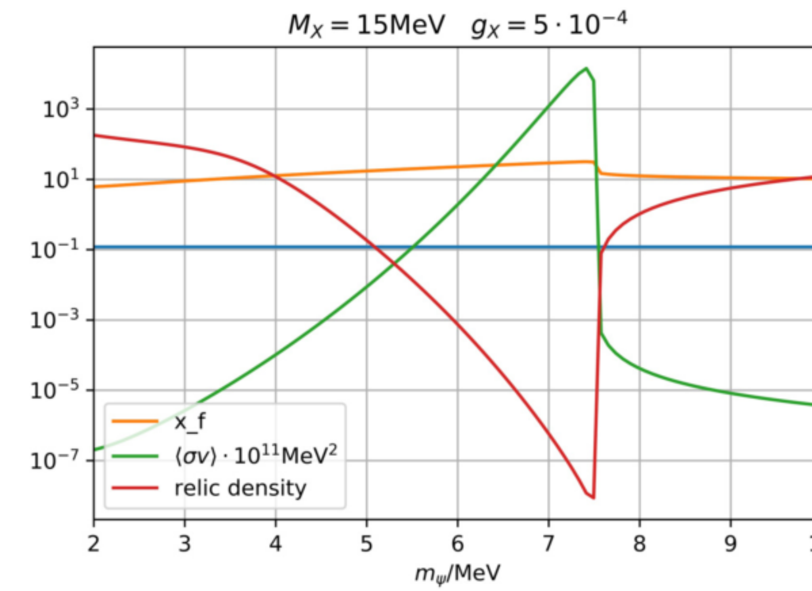
P. Foldenauer, PRD 2019



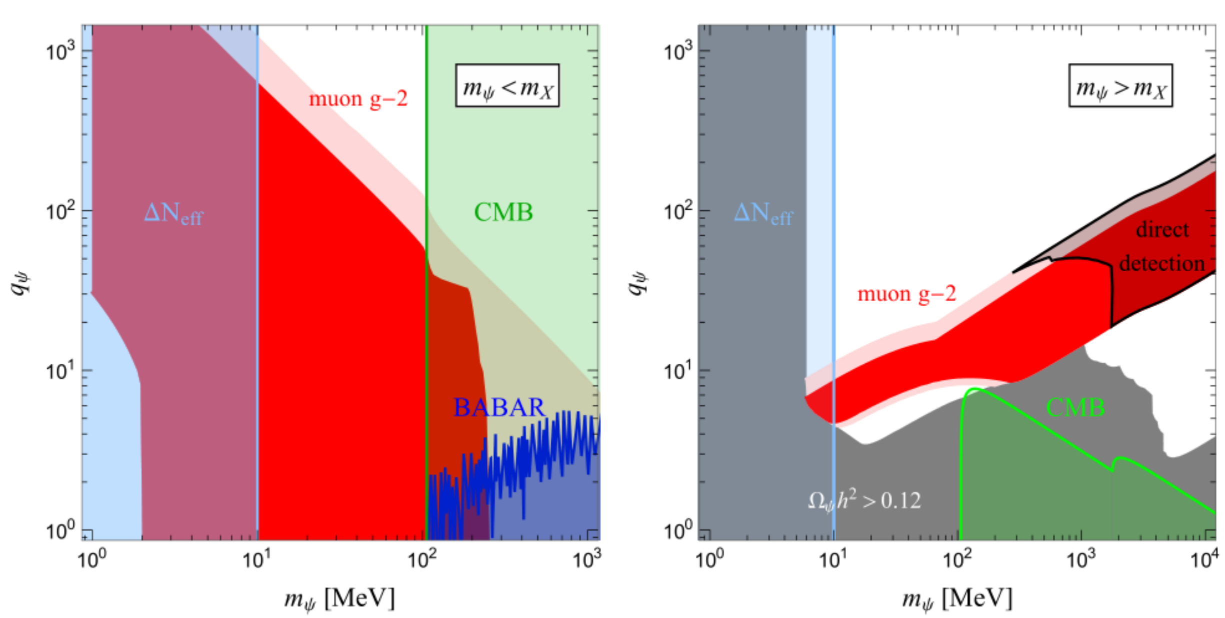
I. Holst. D. Hooper, G. Krnjaic, PRL 2022

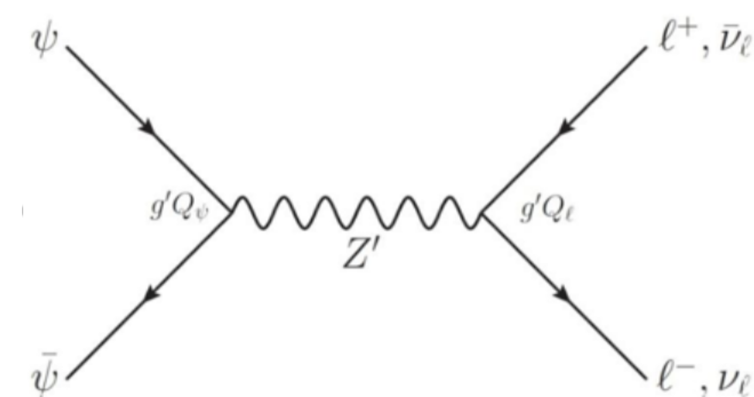


M. Drees, W. Zhao, PLB 2022



Asai, Okawa, Tsumura, JHEP 2021





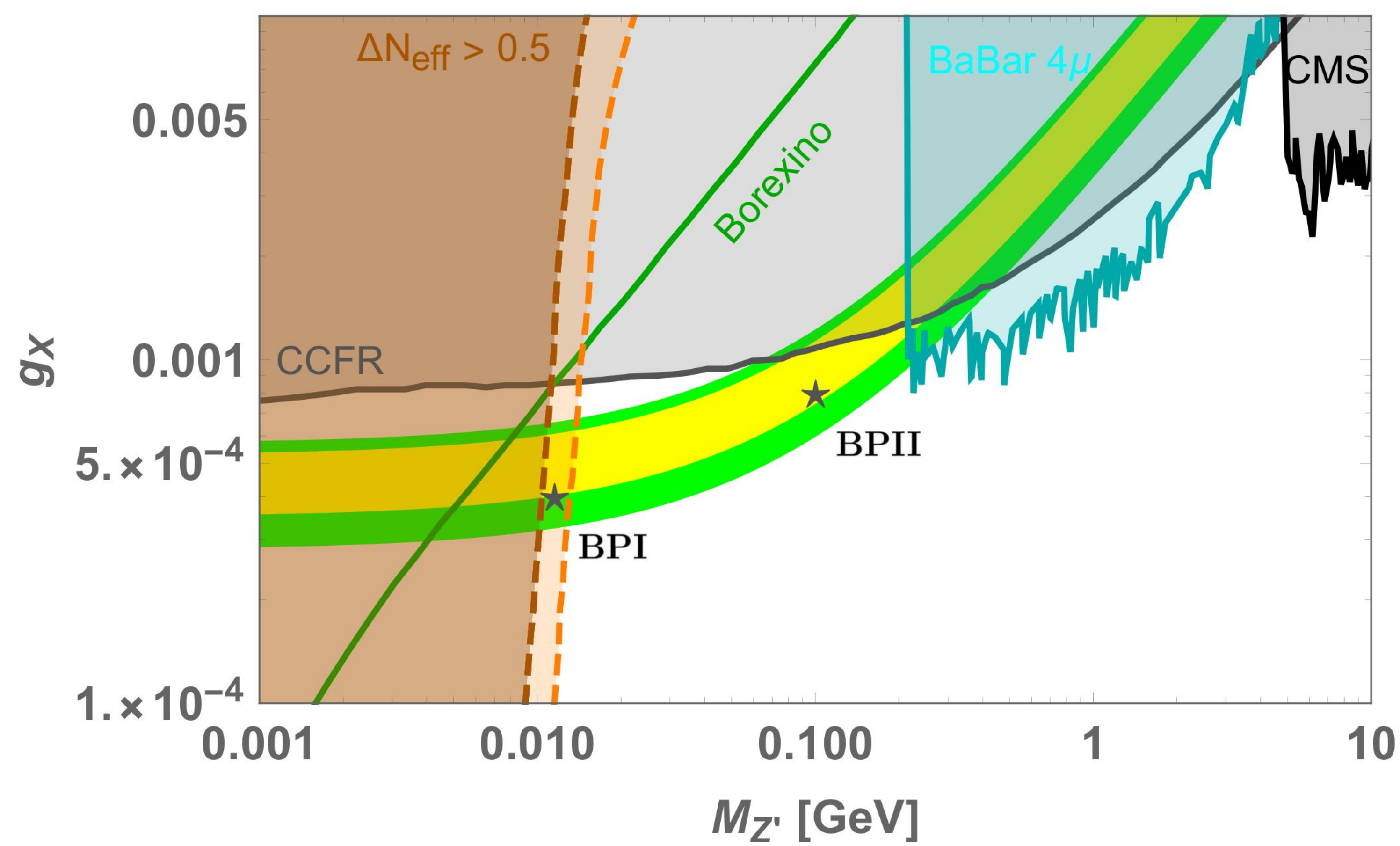


FIG. 1. Regions inside the yellow and Green shaded areas by the Δa_μ are allowed at 1σ and 2σ C.L.. Cyan, black, and orange regions are excluded by other experimental bounds. Above green solid line is ruled out by the Borexino experiment. Region inside the orange area can resolve the Hubble tension. We take two Benchmark Points (BP) $(M_{Z'}, g_X)$ as **BPI** $=(11.5\,\mathrm{MeV}, 4\times10^{-4})$ and **BPII** $=(100\,\mathrm{MeV}, 8\times10^{-4})$.

$U(1)_{L_\mu - L_\tau}$ -charged DM

: Z' only vs. $Z' + \phi$

cf: Let me call Z' , $U(1)_{L_\mu - L_\tau}$ gauge boson,

"dark photon", since it couples to DM

Models with Φ

TABLE I: $U(1)$ charge assignments of newly introduced particles and SM particles. The other SM particles are singlet.

Field	Z'_μ	$X(\chi)$	Φ	$L_\mu = (\nu_{L\mu}, \mu_L), \mu_R$	$L_\tau = (\nu_{L\tau}, \tau_L), \tau_R$
spin	1	0 (1/2)	0	1/2	1/2
$U(1)$ charge	0	$Q_X(Q_\chi)$	Q_Φ	+1	-1

We Consider Both Complex Scalar (X) and Dirac Fermion DM (χ)

- Physics depends on Q_Φ , Q_X and Q_χ
- $Q_\Phi = 2Q_{X(\chi)}$ and $3Q_X$ need special cares, since there are extra gauge invariant op's that break $U(1) \to Z_2$, Z_3 after $U(1)$ is spontaneously broken by nonzero VEV of Φ

Complex Scalar DM (generic with $Q_{\Phi} \neq Q_X, etc$)

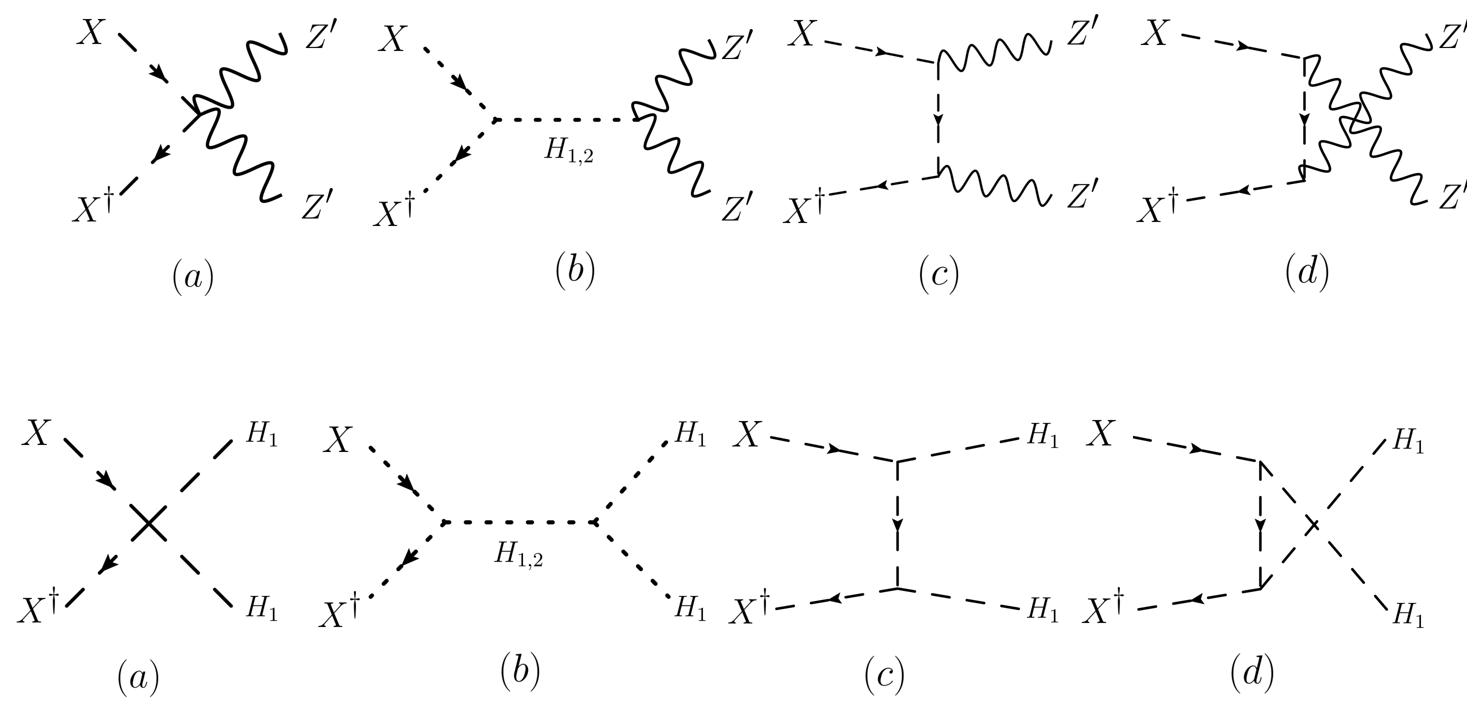


FIG. 2. (*Top*) Feynman diagrams for Complex scalar DM annihilating to a pair of Z' bosons. (*Bottom*) Feynman diagrams for Complex scalar DM annihilating to a pair of H_1 bosons.

$H_2 \simeq H_{125}$ and $H_1 \simeq \phi$ (dark Higgs)

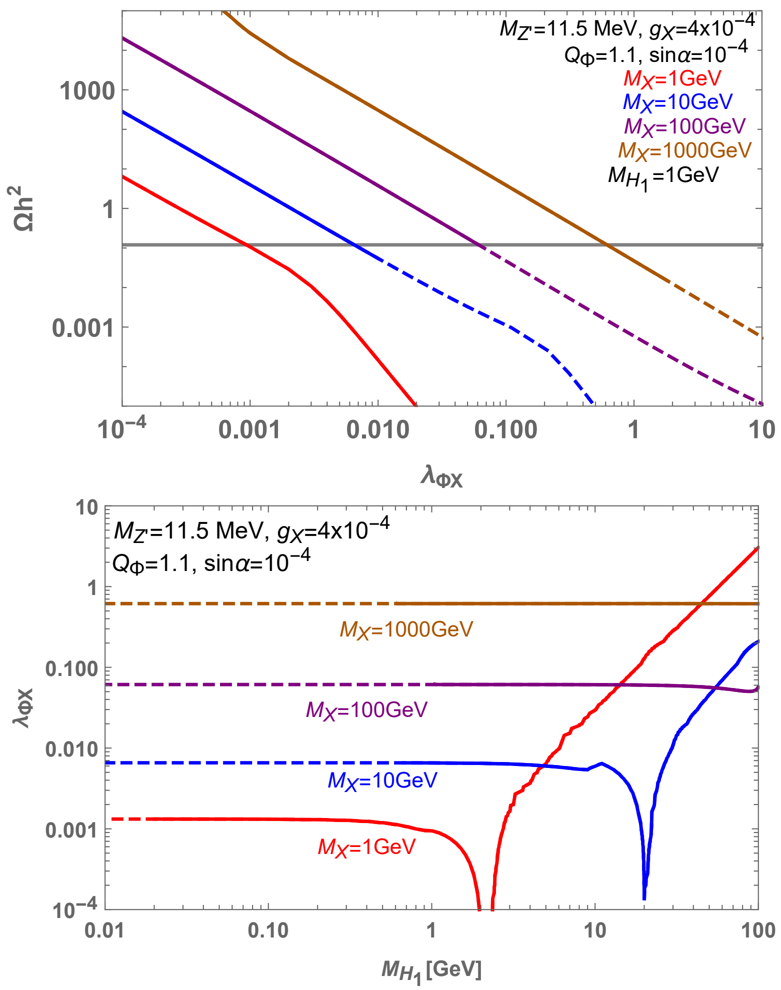


FIG. 3. *Top*: relic abundance of complex scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] for $M_X = 1,\ 10, 100,\ 1000\text{GeV}$, respectively. We assumed $Q_\Phi = 1.1$, $M_{H_1} = 1\text{GeV}$, and $\sin\alpha = 10^{-4}$. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$.

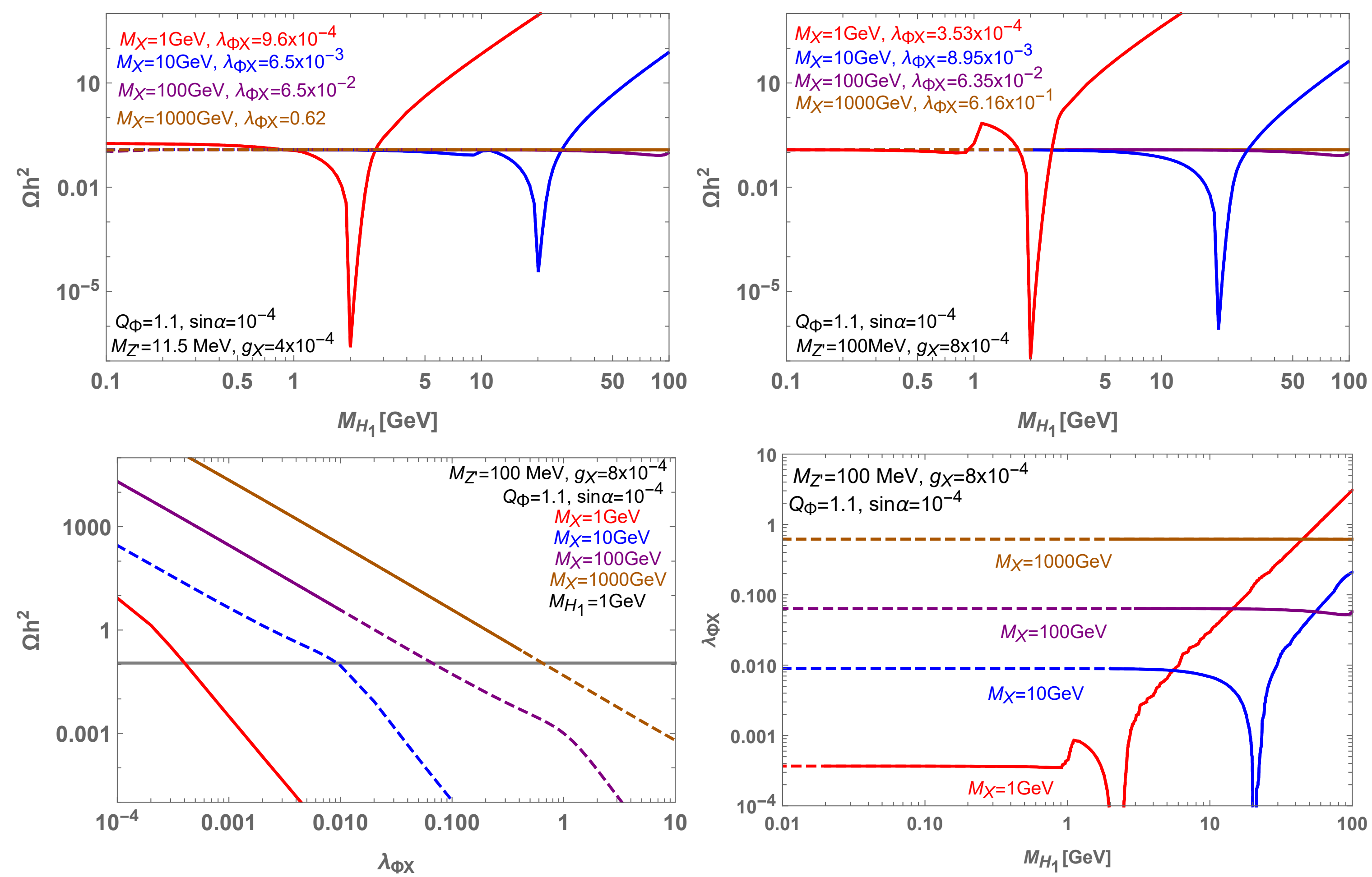


FIG. 7. The (*Top*) plots show the relic abundance of complex scalar DM for $Q_\Phi = 1.1$ as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*). The (*Bottom*) plots show the relic density as functions of $\lambda_{\Phi X}$ (*Left*) and the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$ (*Right*) for [**BPII**] . We take four different DM masses, $M_X = 1,\ 10, 100,\ 1000\text{GeV}$, respectively. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$
due to dark Higgs boson contributions

Complex Scalar DM: $U(1)_{L_\mu - L_\tau} \to Z_2\ (Q_\Phi = 2Q_X)$

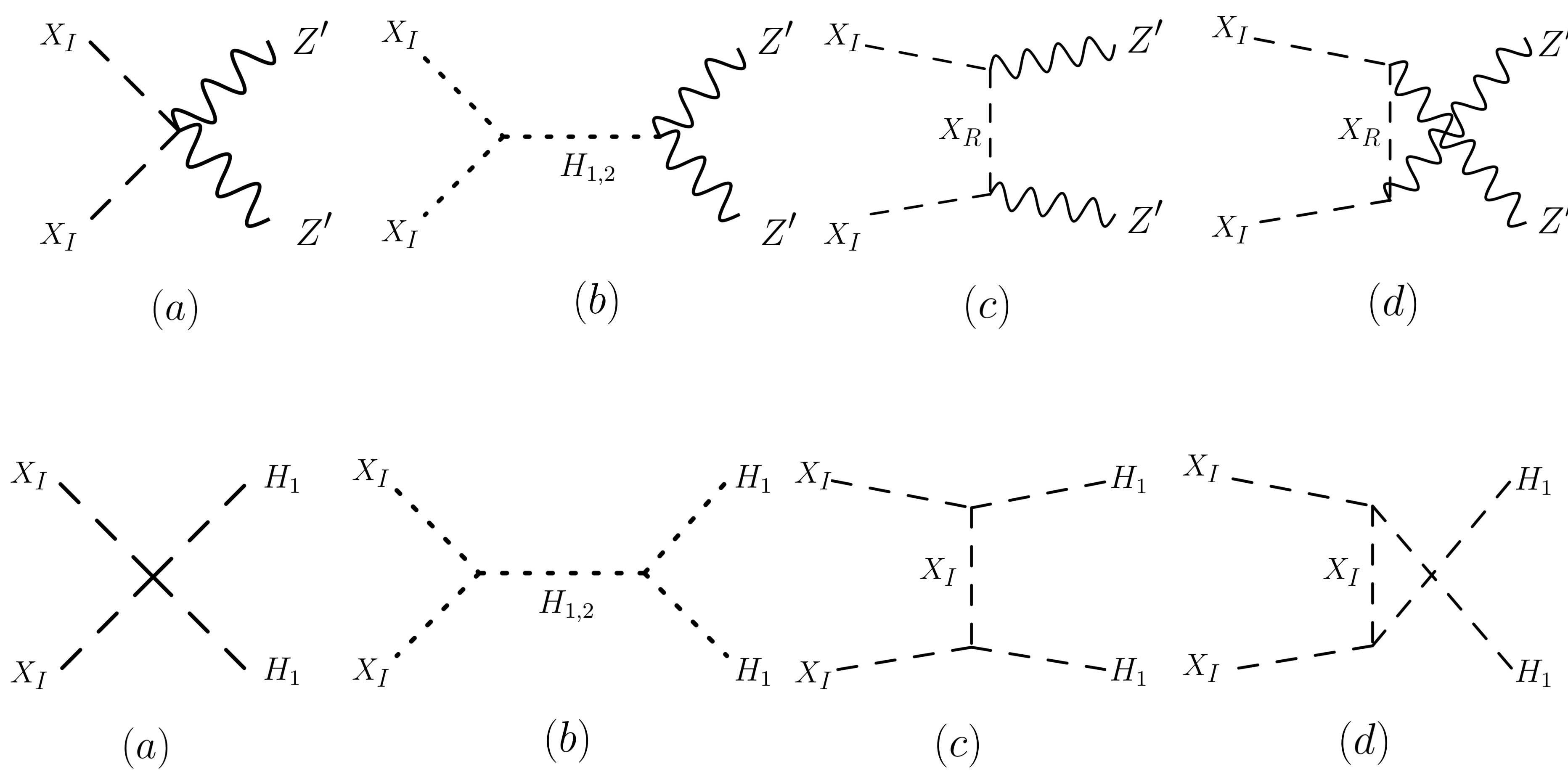


FIG. 8. (*Top*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of Z' bosons. (*Bottom*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of H_1 bosons, which is mostly dark Higgs-like.

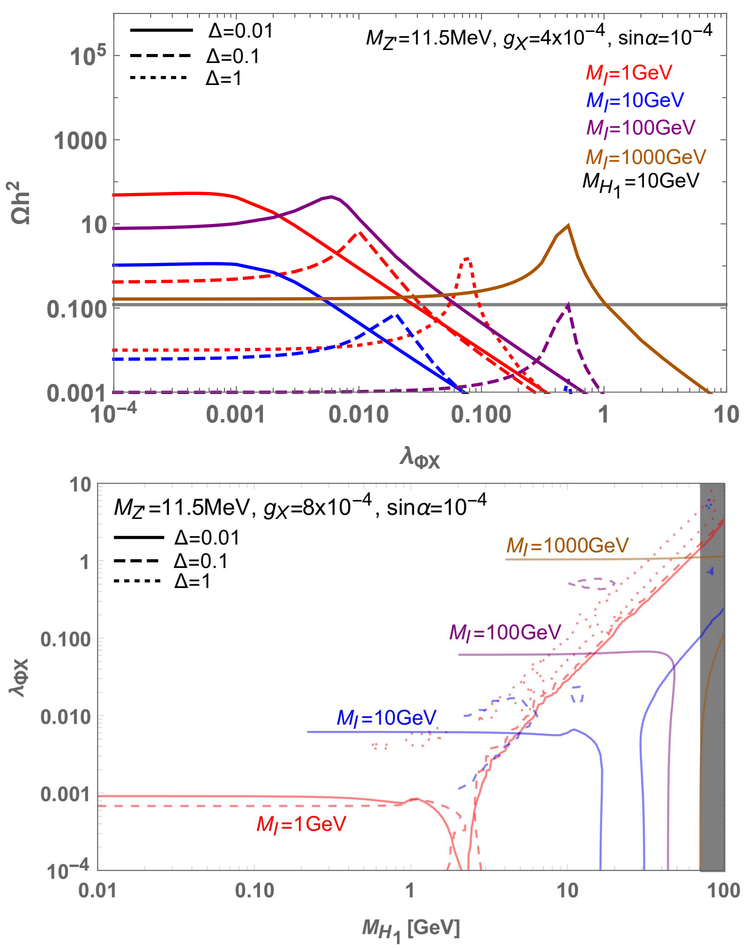


FIG. 4. *Top*: Relic abundance of local Z_2 scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] and different values of mass splittings (Δ). We take $\lambda_{HX} = 0$, $M_{H_1} = 10\text{GeV}$, and $s_\alpha = 10^{-4}$. All the curves satisfy the DM direct detection bound. *Bottom*: The preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for different values of Δ. The gray area is excluded by the perturbative condition.

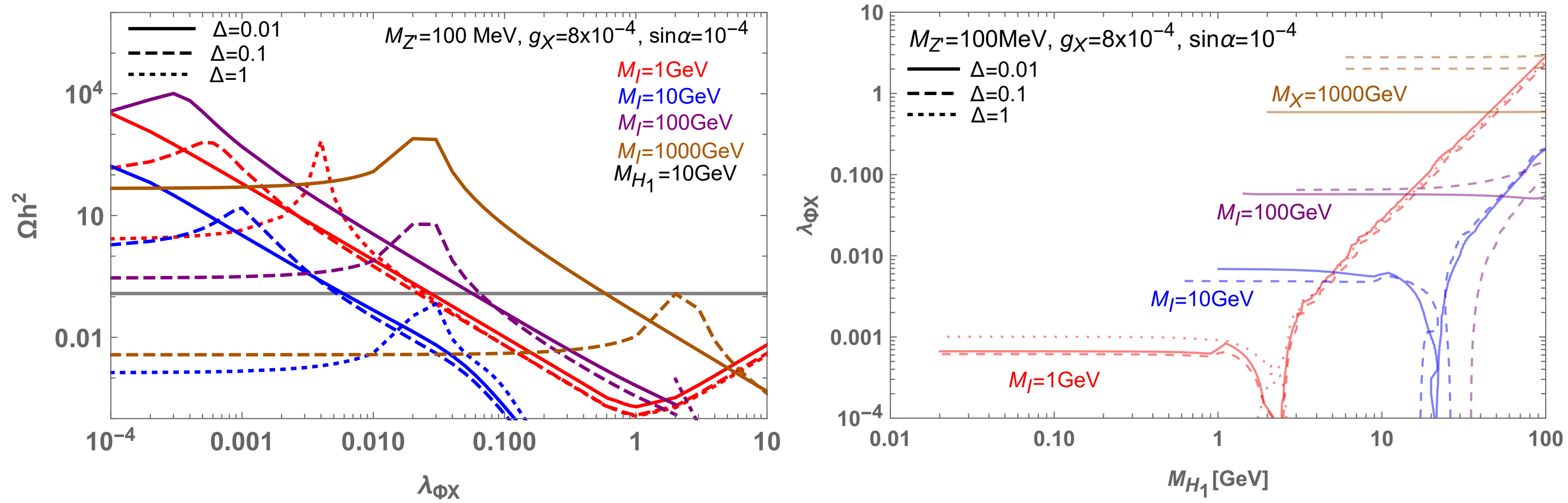


FIG. 9. (*Left*) Relic abundance of local Z_2 scalar DM in case of [**BPII**]. We take $\lambda_{HX} = 0$, $M_{H_1} = 10\text{GeV}$, and $s_\alpha = 10^{-4}$. All the lines satisfy the DM direct detection bound. (*Right*) Relic abundance of local Z_2 scalar DM in the $(M_{H_1}, \lambda_{\Phi X})$ plane.

DM mass : much wider range than $m_{Z'} \sim 2m_{\mathrm{DM}}$ due to dark Higgs boson contributions

Dirac fermion DM: $U(1)_{L_\mu - L_\tau} \to Z_2 \; (Q_\Phi = 2Q_\chi)$

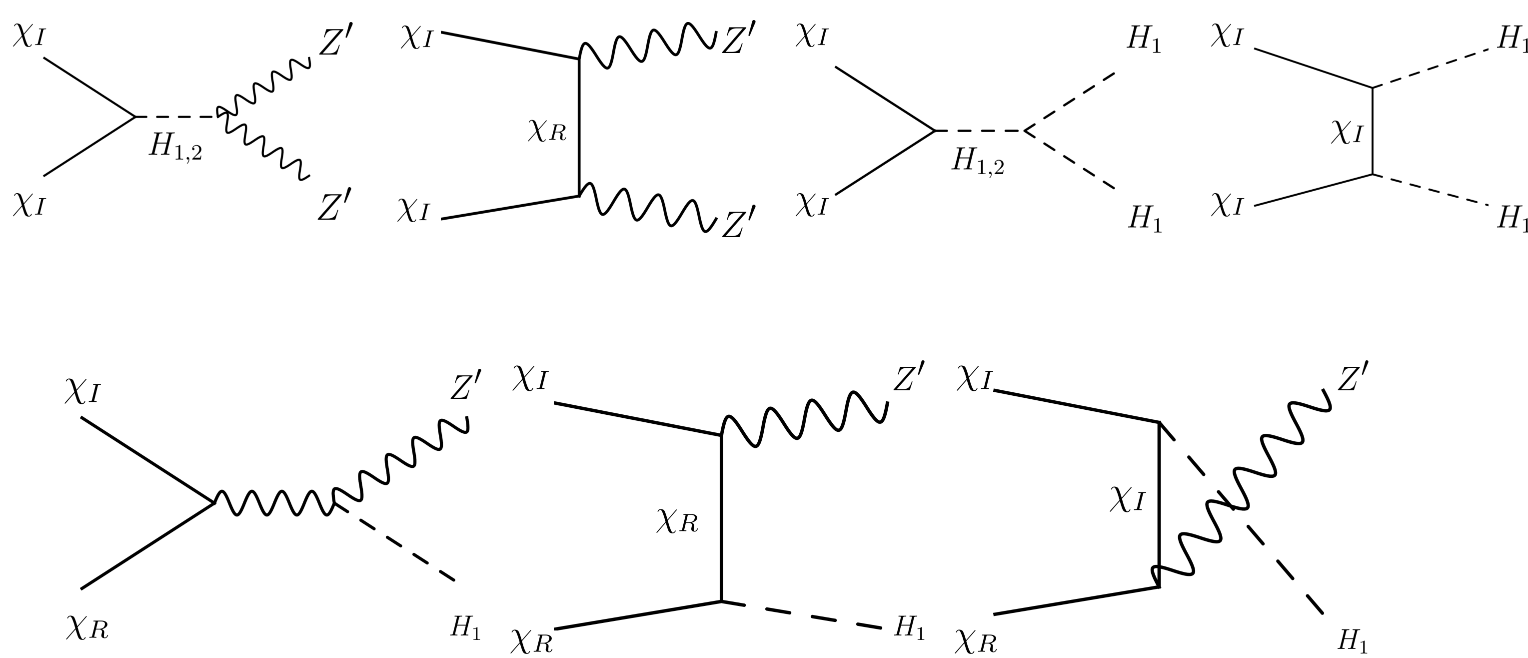


FIG. 5. Feynman diagrams of local Z_2 fermion DM (co-)annihilating into a pair of Z' bosons and H_1 bosons (*Top*), and $Z' + H_1$ (*Bottom*).

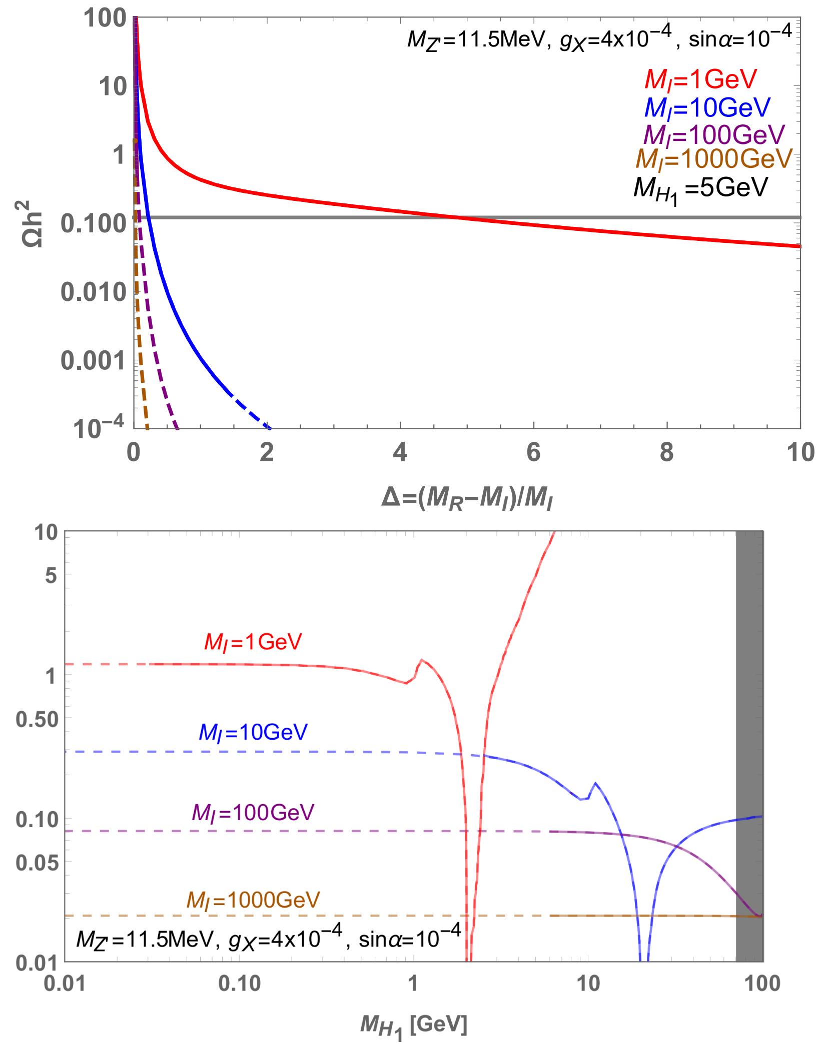


FIG. 6. *Top*: Dark matter relic density as functions of mass splitting Δ for [**BPI**] and for different values of DM mass, $M_I = 1, 10, 100, 1000$GeV. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: Preferred parameter space in the (M_{H_1}, Δ) plane for different DM masses. The gray region is ruled out by the perturbativity condition on λ_Φ.

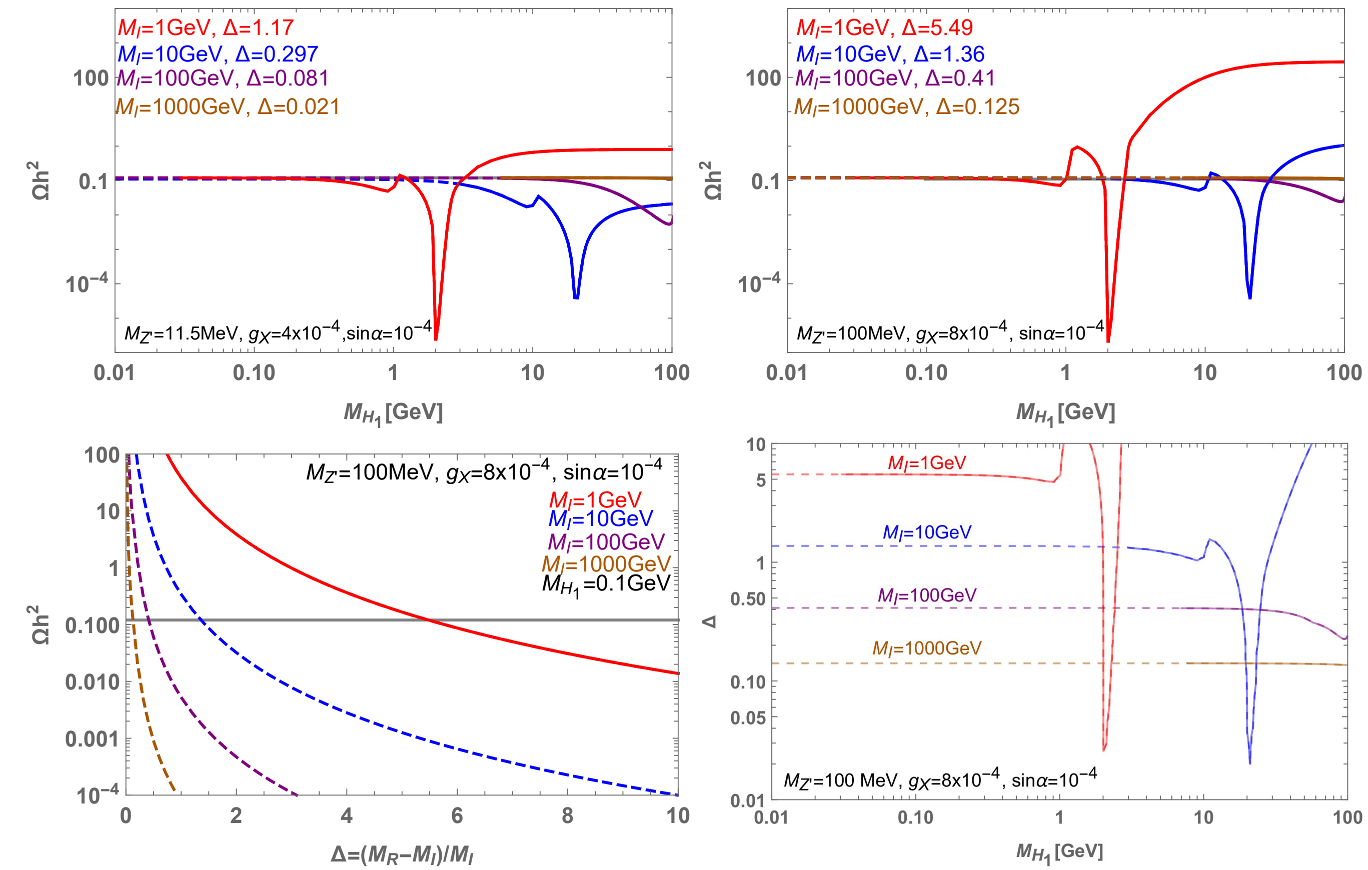


FIG. 11. (*Top*) Dark matter relic density as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*) (*Bottom-Left*) Dark matter relic density as functions of Δ for [**BPII**], and *(Bottom-right)* Preferred parameter region in the (Δ, M_{H_1}) plane. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$ due to dark Higgs boson contributions

Summary of this part

- DM physics with massive dark photon can not be complete without including dark gauge symmetry breaking mechanism, e.g. dark Higgs field ϕ, which have been largely ignored by DM community (or some ways other than dark Higgs to provide dark photon mass)

- Many examples show the importance of ϕ in DM phenomenology, astroparticle physics and cosmology

- Once ϕ is included, can accommodate the muon g-2 and thermal DM without the s-channel resonance condition $m_{Z'} \sim 2m_{\rm DM}$

- $m_{\rm DM}$: essentially free, whereas $m_{Z'} \sim O(10-100)$ MeV and $g_X \sim O(10^{-4})$ can explain the muon (g-2)

On Recent Belle II data on $B^+ \to K^+ \nu \bar{\nu}$

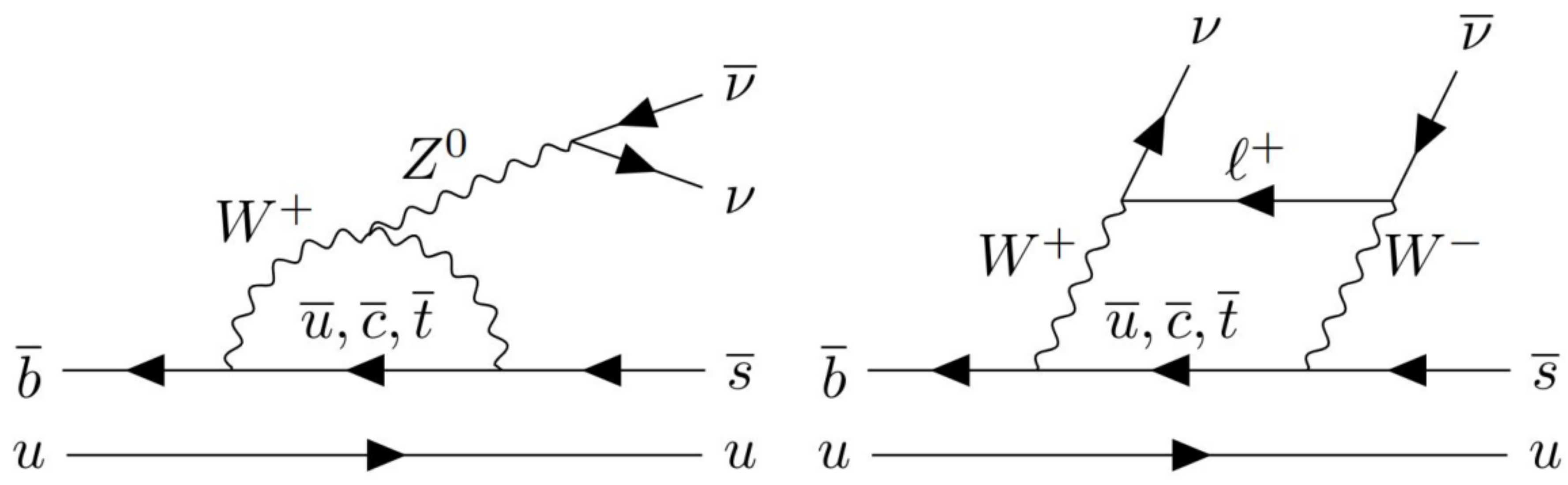
arXiv:2401.10112

With Shu-Yu Ho, Jongkuk Kim

$B^+ \to K^+\nu\bar{\nu}$ in the SM

- The $B^+ \to K^+\nu\bar{\nu}$ process is known with high accuracy in the SM:
  - $Br(B^+ \to K^+\nu\bar{\nu}) = (4.97 \pm 0.37) \times 10^{-6}$

HPQCD, PRD 2023



- $$\mathcal{L}_{b\to s\nu\bar{\nu}} = -C_\nu \bar{s}_L \gamma^\mu b_L \bar{\nu}\gamma^\mu \nu$$

$$C_\nu = \frac{g_W^2}{M_W^2}\frac{g_W^2 V_{ts}^* V_{tb}}{16\pi^2}\left[\frac{x_t^2 + 2x_t}{8(x_t - 1)} + \frac{3x_t^2 - 6x_t}{8(x_t - 1)^2}\ln x_t\right],$$

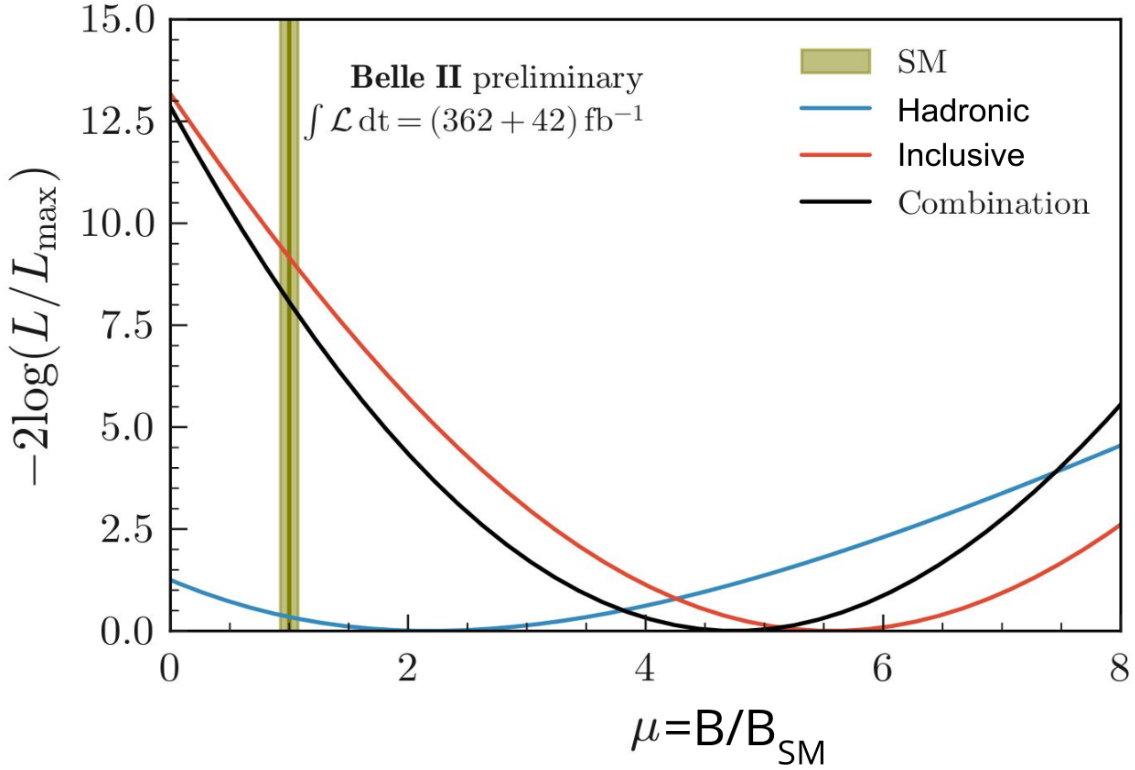
where $x_t = m_t^2/M_W^2$.

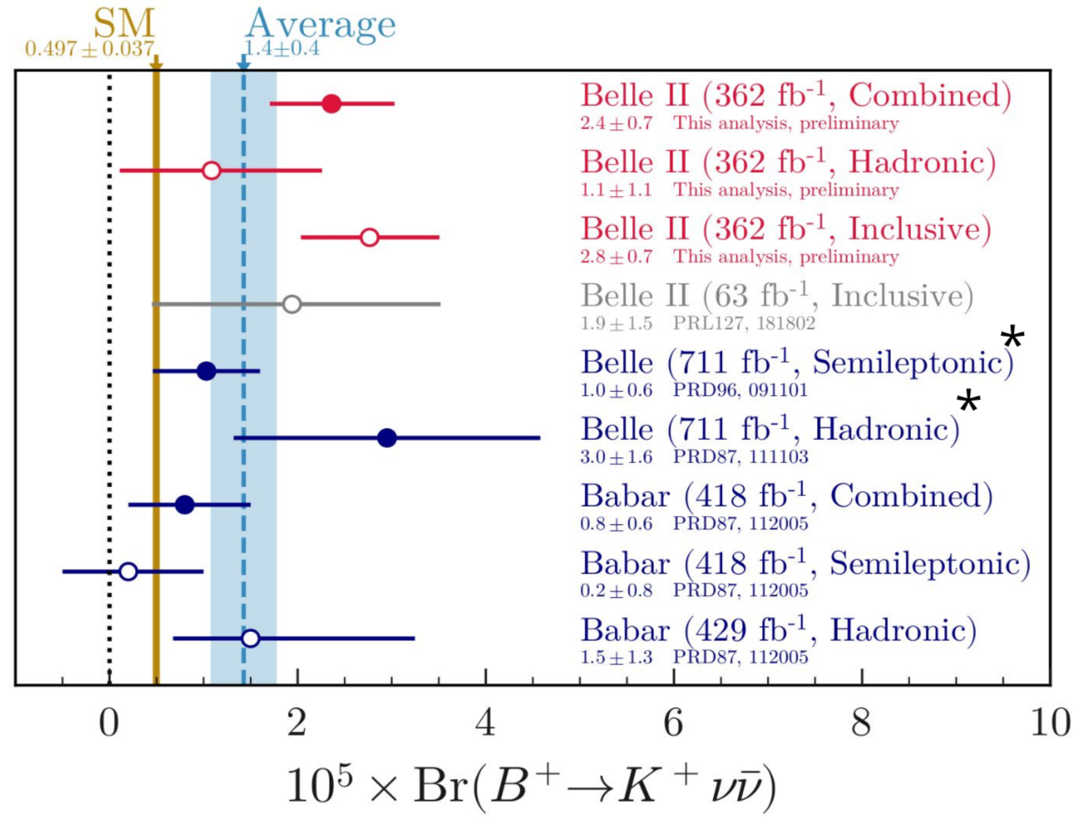
Measurement of $B^+ \to K^+\nu\bar{\nu}$

- Challenges in reconstructing the events
  - Searches for $B \to K^{(*)}\nu\bar{\nu}$ have only been performed at the B factories Belle and BaBar

- Using the same techniques in Belle, BaBar
  - Semileptonic tagged analyses
  - Hadronic-tagged analyses

- Inclusive tag analysis (Belle & BelleII)
  - Allow one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon





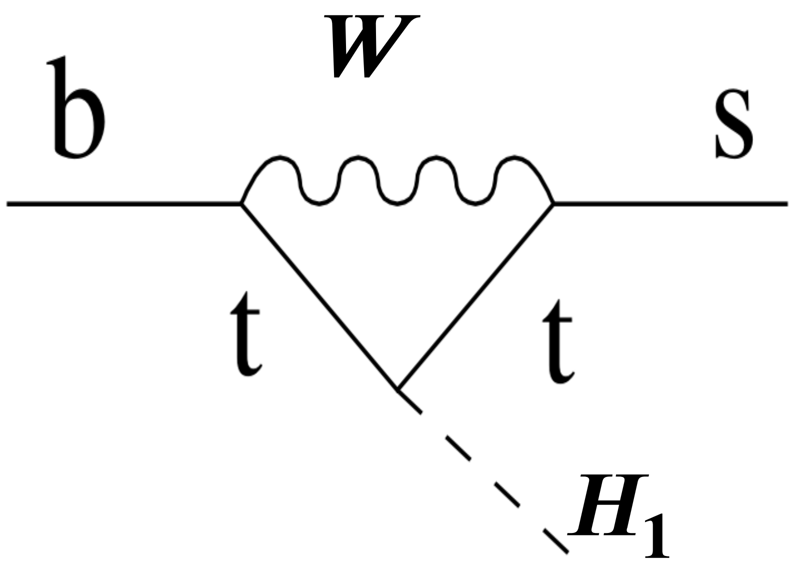
- $Br(B^+ \to K^+ \nu\bar{\nu}) = (2.4 \pm 0.7) \times 10^{-5}$
  - Significance of observation is 3.6σ
  - 2.8σ tension with the SM prediction
- $Br(B^+ \to K^+ E_{\text{miss}})_{NP} = (1.9 \pm 0.7) \times 10^{-5}$
- Indicate not only the presence of NP in the $b \to s\nu\bar{\nu}$ transitions but even the presence of new light states (particles in dark sector?)

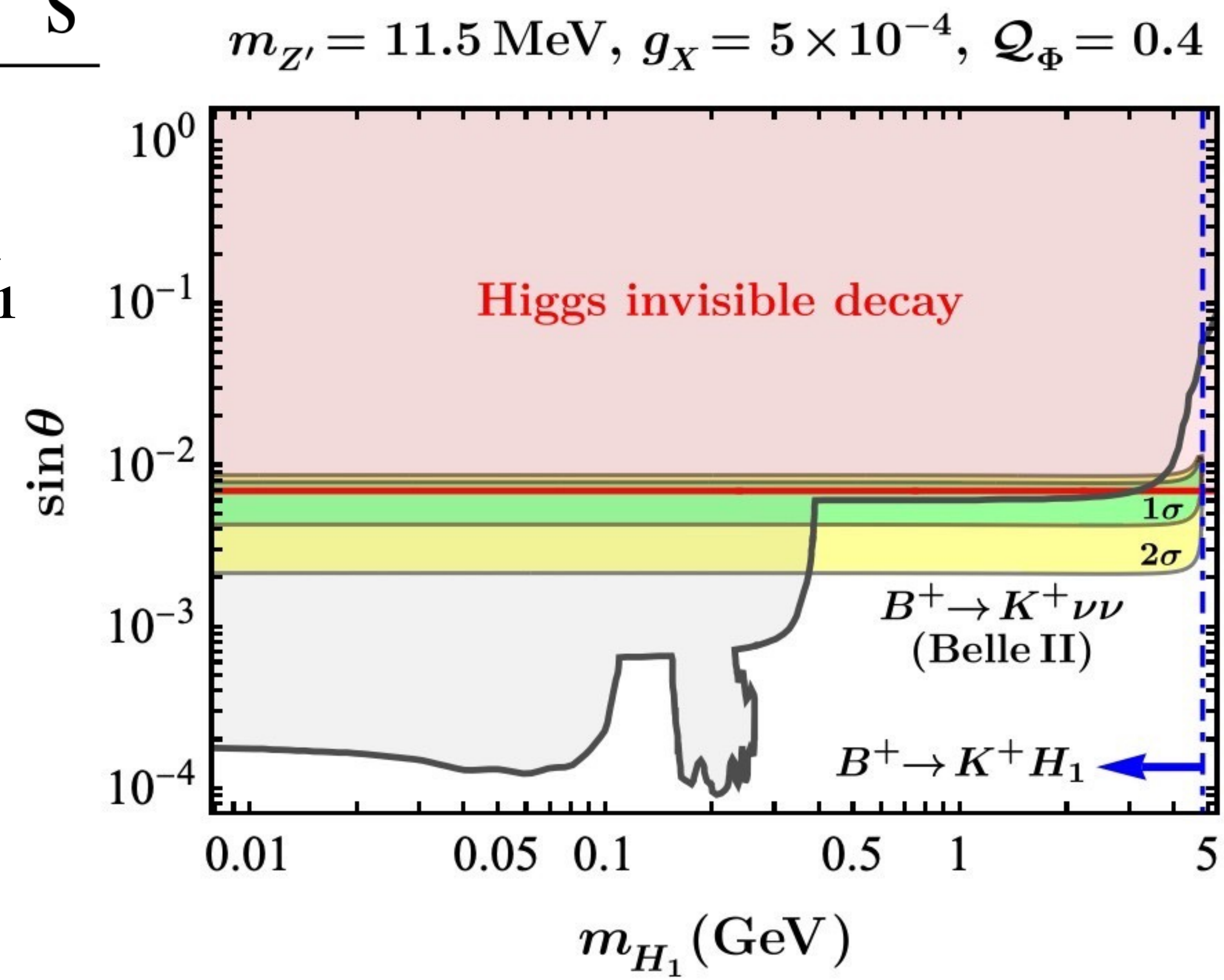
CMB constraints

- Dominant DM annihilation channel
  - Before resonance, $XX^* \to Z'Z', h_1h_1$
  - Near resonance, $XX^* \to Z'h_1$
  - After resonance, $XX^* \to Z'Z'$
- h_1 dominantly decays into a pair of either Z' or DM (kinematically open when $m_{h_1} > 2m_X$)
- We can avoid the stringent CMB bound thanks to invisible decay of both h_1 and Z'

Belle II anomaly: two-body decay

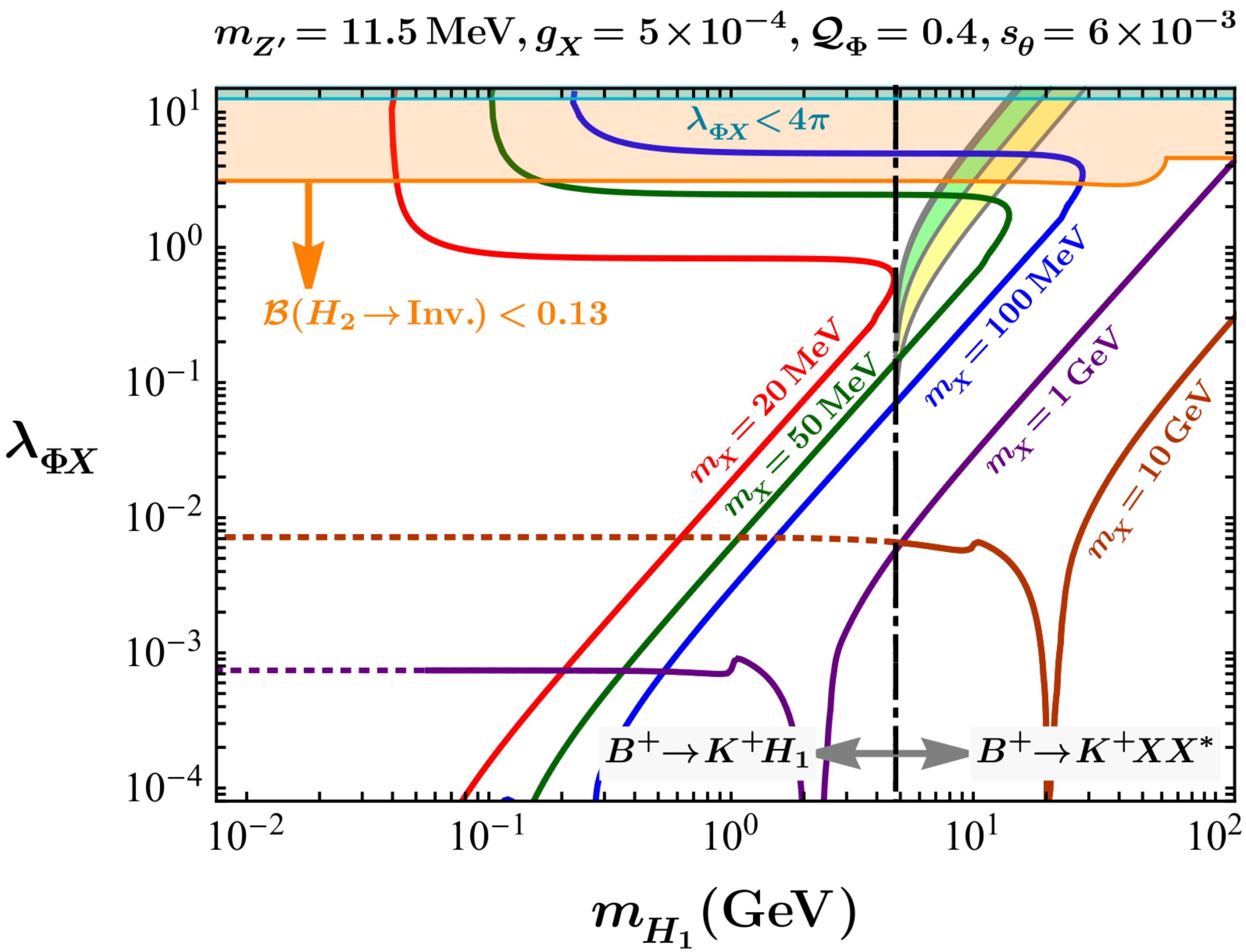
- When $m_{H_1} < m_B - m_K$, two-body decay





Belle II anomaly: three-body decay

- When $m_{H_1} > m_B - m_K$, H_2 is off-shell → three-body decay
  - Two-body decay: $m_X \lesssim 6.5\text{GeV}$ $(m_{H_1} = 2\text{GeV})$
  - Three-body decay: $20\text{MeV} < m_X \lesssim 60\text{MeV}$ $(m_{H_1} > m_B - m_K)$



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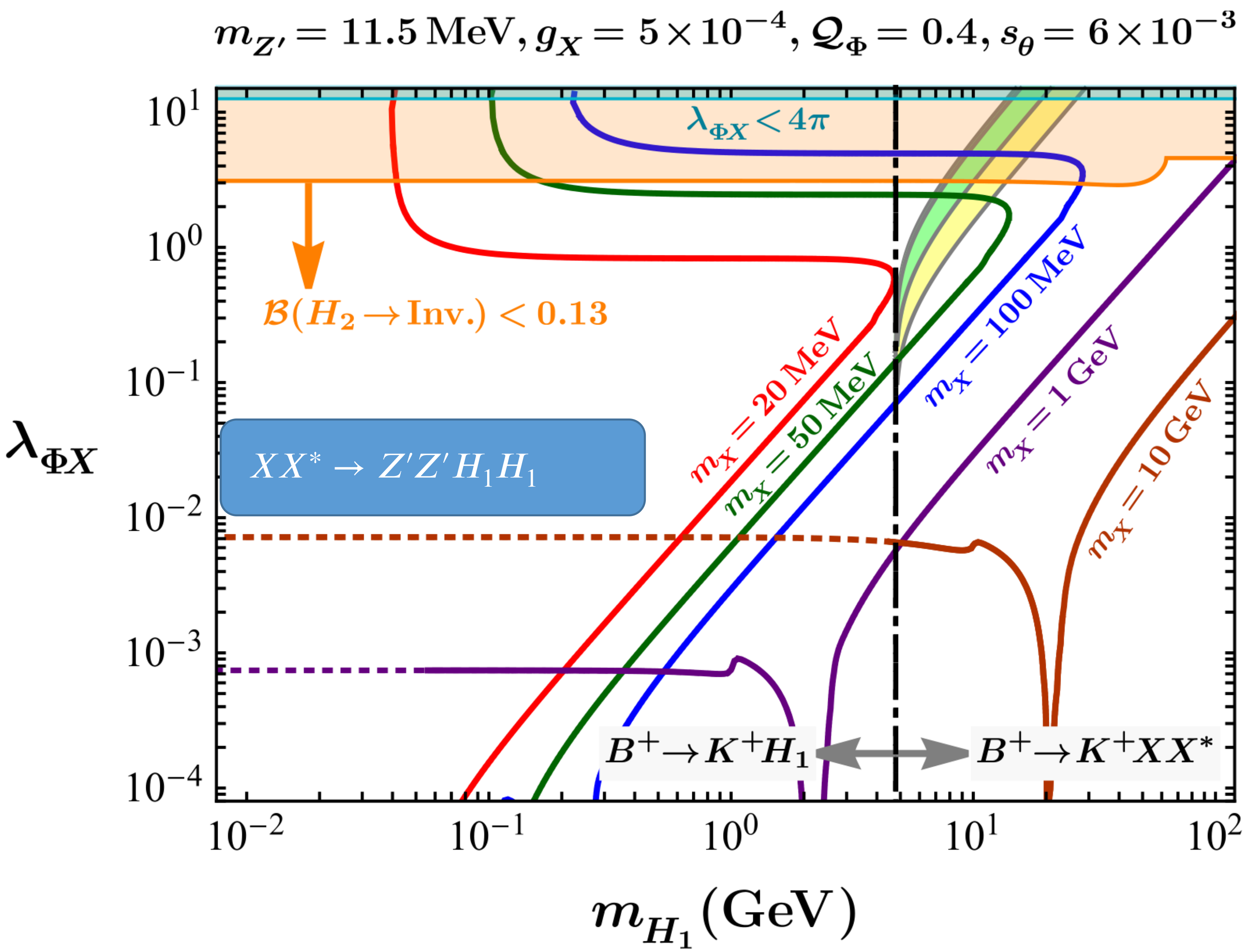

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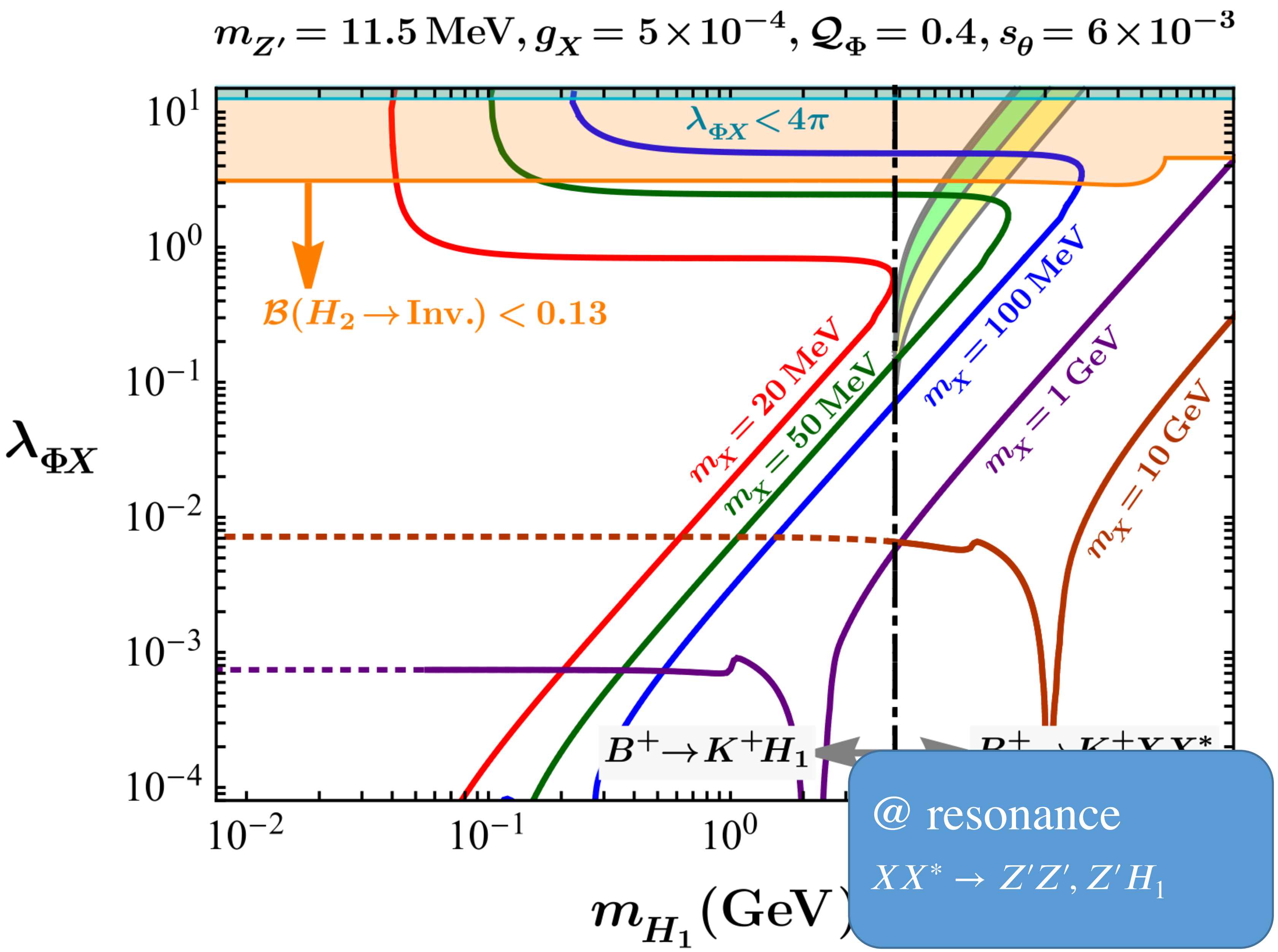

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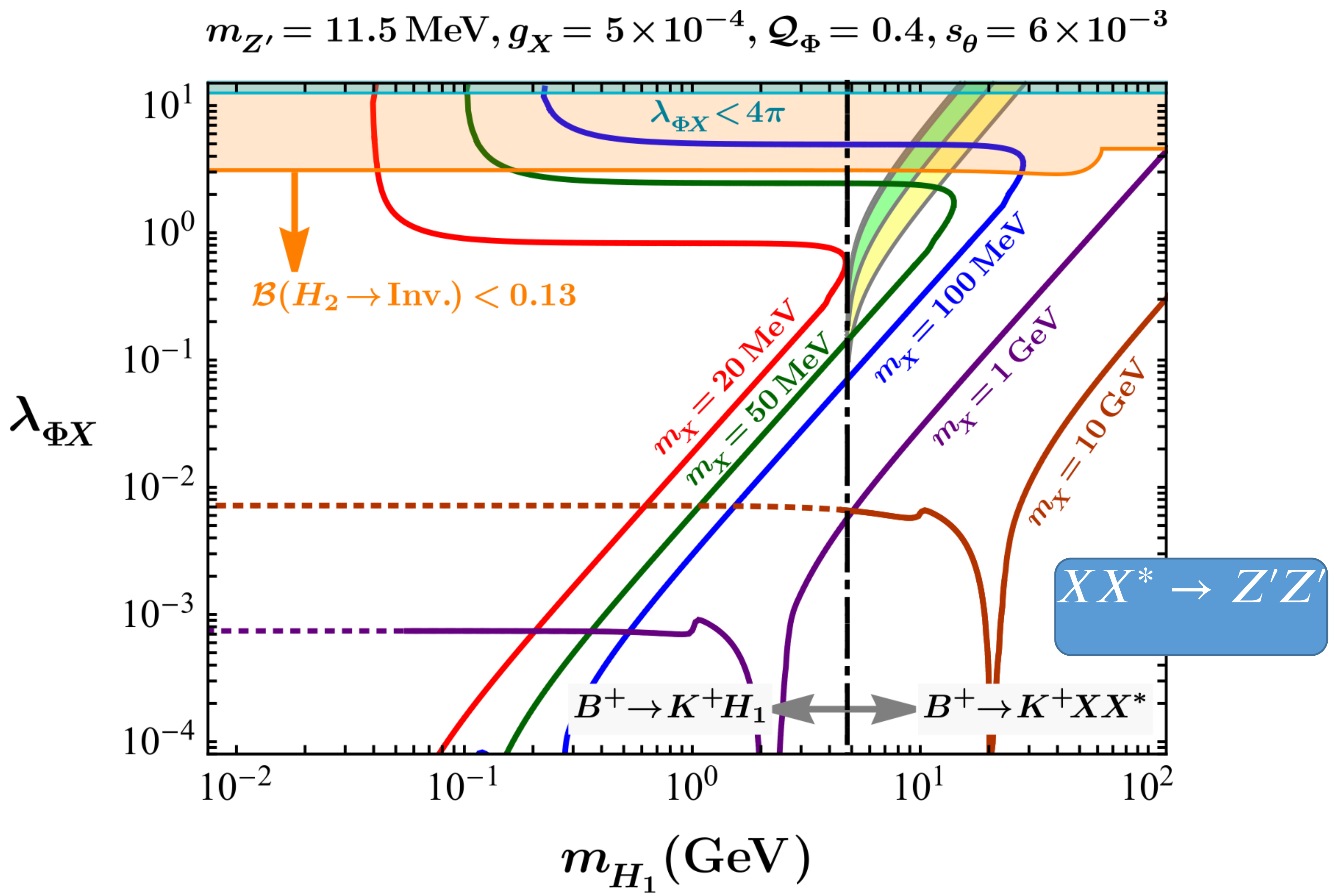
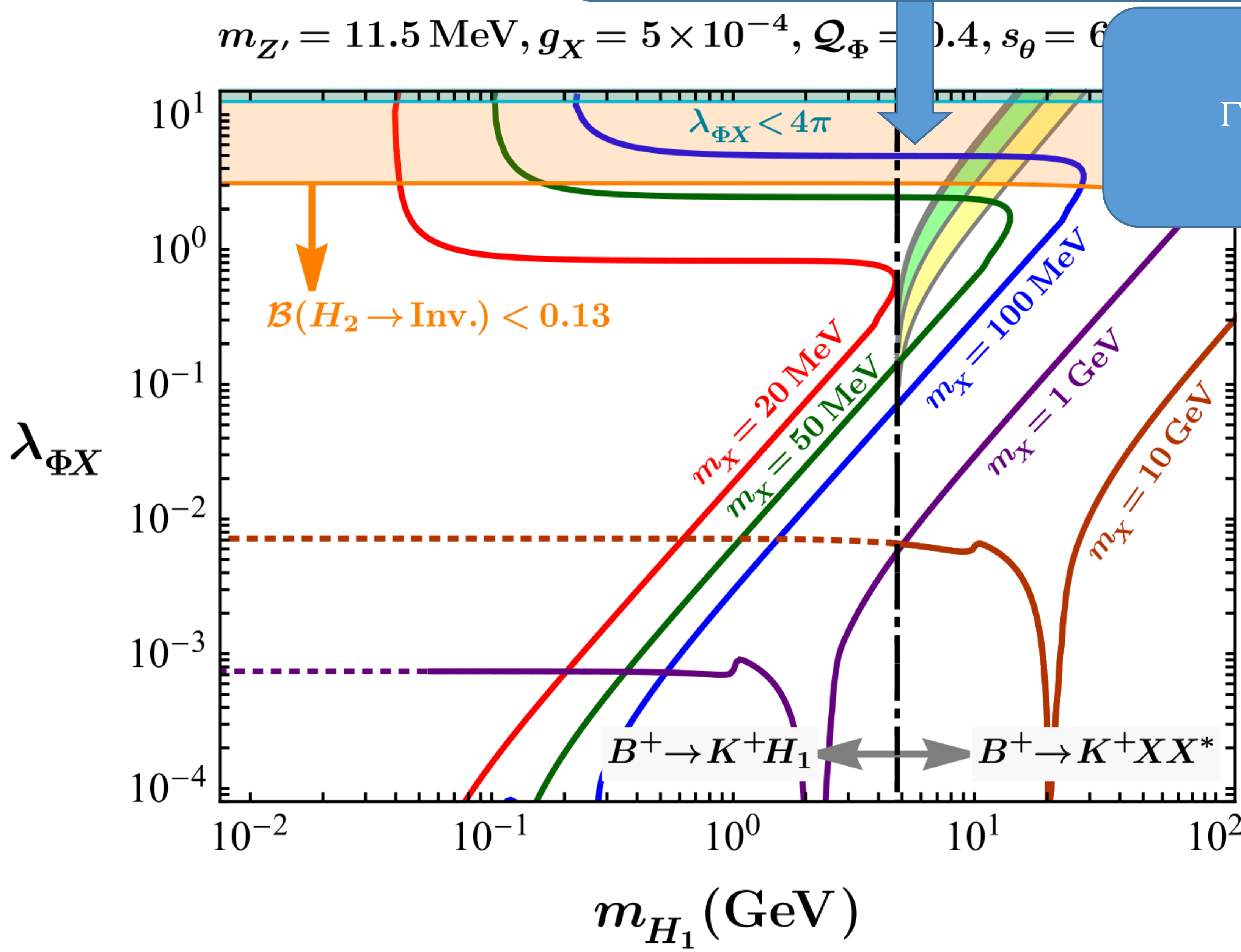


Belle II anomaly: three-body decay

- When $m_{H_1} > m_B - m_K$, H_2 is off-
  - Two-body decay: $m_X \lesssim 6.5\text{GeV}$ (
  - Three-body decay: $20\text{MeV} < m_X$

$$\sigma v \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2} \frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(4m_X^2 - m_{H_1}^2)^2 + m_{H_1}^2 \Gamma_{H_1}^2} \sqrt{1 - \frac{m_{Z'}^2}{m_X^2}}$$

$$\Gamma_{H_1} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}} \sqrt{1 - \frac{4m_X^2}{m_{H_1}^2}}$$



Belle II anomaly: three-body decay

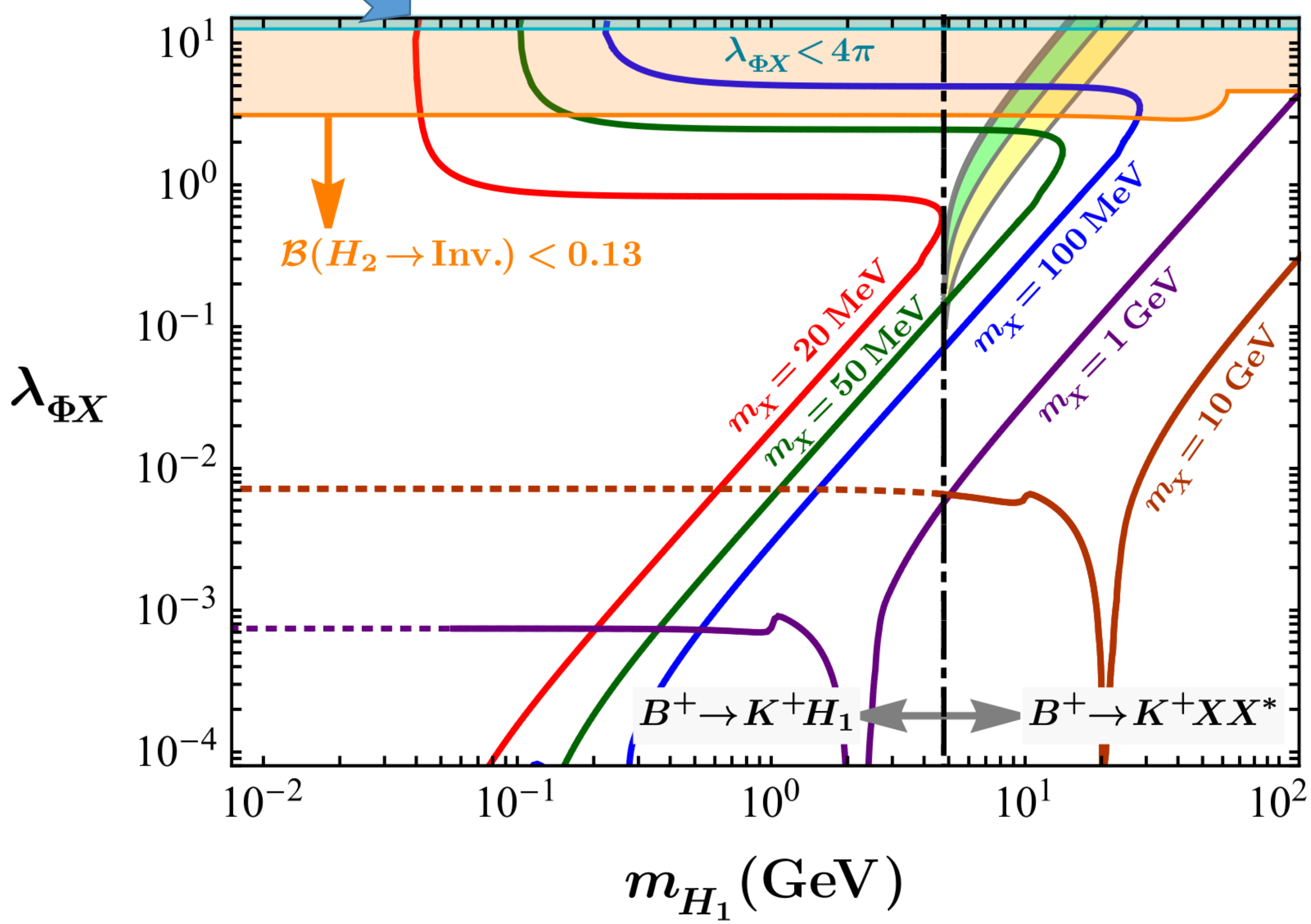
$$\Gamma_{H_1} = \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}} \sqrt{1 - \frac{4m_X^2}{m_{H_1}^2}} \qquad \sigma v \propto \frac{\lambda_{\Phi X}^2}{m_{H_1}^2 \Gamma_{H_1}^2}$$

Phase-space suppression

ee-body decay

$_B - m_K)$

$m_{Z'}$ ... 1.5 MeV, $g_X = 5\times 10$ ..., $Q_\Phi = 0.4$, $s_\theta = 6\times 10^{-3}$



Conclusion

- Belle II data shows a mild excess of $B^+ \to K^+ \nu \bar{\nu}$ over the SM prediction

- This mild excess can be interpreted as $B^+ \to K^+$ + dark sector particles through a dark Higgs portal: a pair of scalar DM, a pair of Z' decaying into a pair of neutrinos, both of which are invisibles in $U(1)_{L_\mu - L_\tau}$ models with complex scalar DM

- Can accommodate the muon g-2, and relax the tension in the Hubble parameter with extra dark radiation

Back Up

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability
  (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in "local gauge symmetry" without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- "(Chiral) dark gauge theories without any global sym"
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT,

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (Strongly interacting hidden sector (DQCD), dark pions and dark baryons : Ko et al (2007))
- Kinematically long-lived if DM is very light (axion, sterile ν_s , etc..)

Old wine in a new bottle: Flavored multi-Higgs doublet models

Flavor (or Family) dependent Gauge Interactions ?

- What if there is a flavor(family) dependent new gauge interactions ?

- For example, what if the RH quarks couple to new massive spin-1 particle (Z') ?

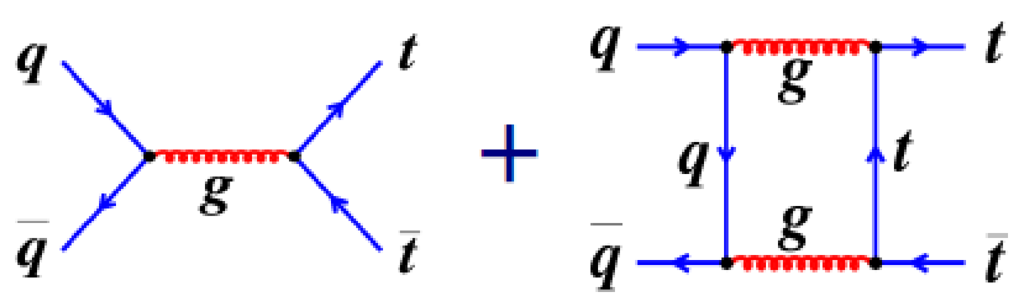
- What would be the minimal setup for such model, mathematically / theoretically consistent and realistic ?

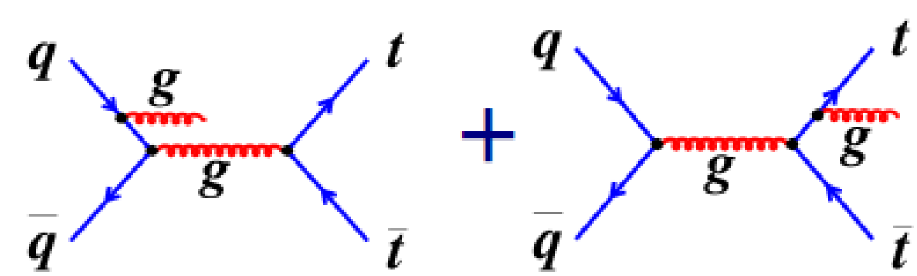
- As an example, I will discuss an extra U(1) model that couples only to t_R in the interaction basis [Top FBA]

Top Charge Asym in QCD (Muller@ICHEP2012)

NLO QCD: interference of higher order diagrams leads to asymmetry for $t\bar{t}$ produced through $q\bar{q}$ annihilation:

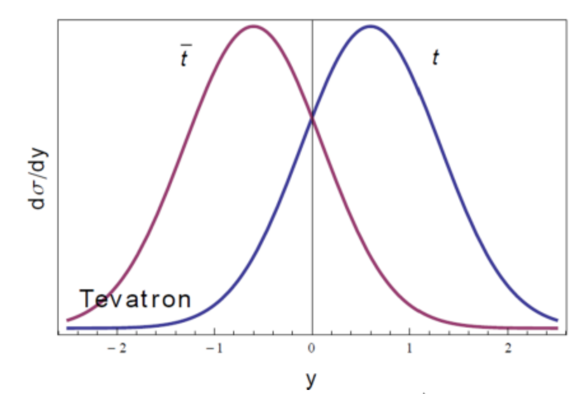
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





- At Tevatron: define forward-backward asymmetry

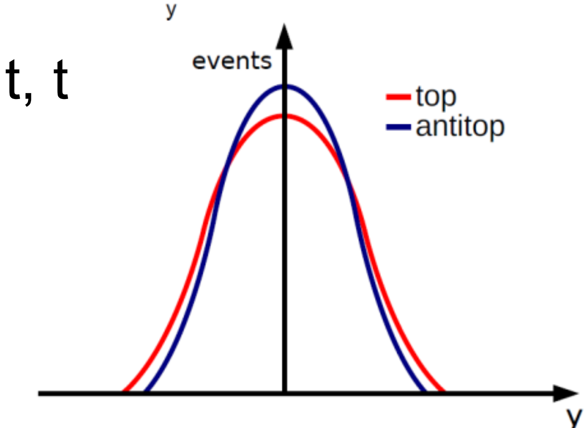
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



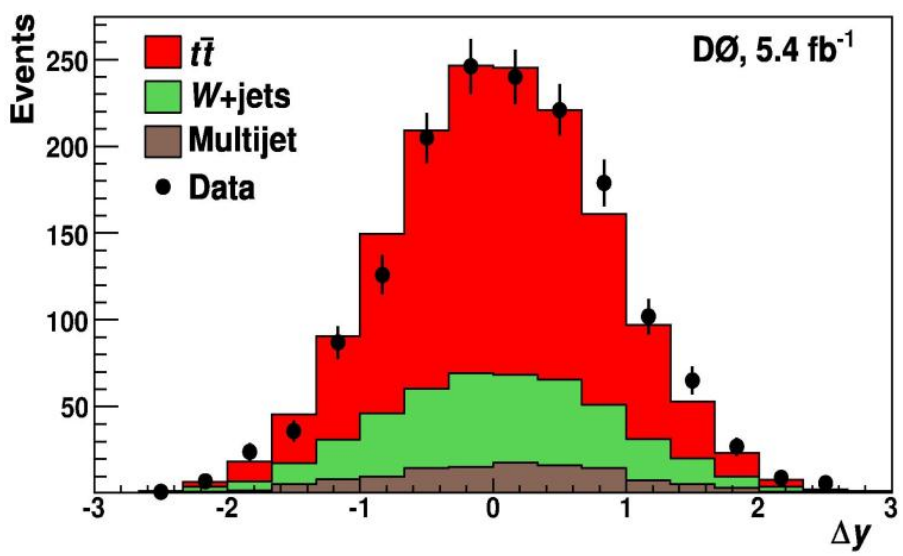
- At LHC: define asymmetry in the widths of rapidity distributions of t, t

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



ICHEP 2012 : Top FBA (Muller's talk)



Δy in the lepton-jets channel

Measured asymmetry on detector level after bkg subtraction:

A_{FB} det = 0.092 ± 0.037 (stat+syst)

MC@NLO: A_{FB} det = 0.024 ± 0.007

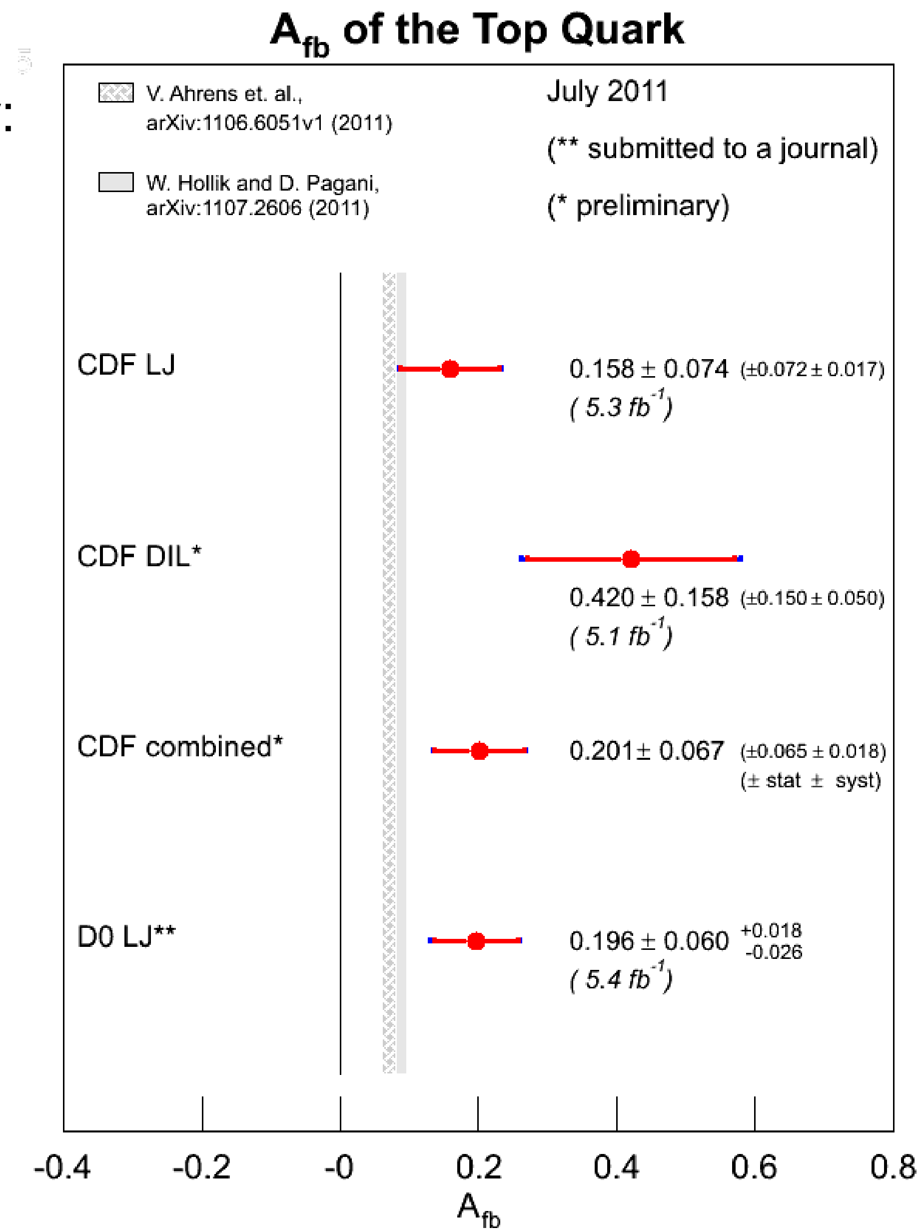
Measured asymmetry on parton level:

A_{FB} = 0.196 ± 0.065 (stat+syst)

D0 results in the di-lepton channel:

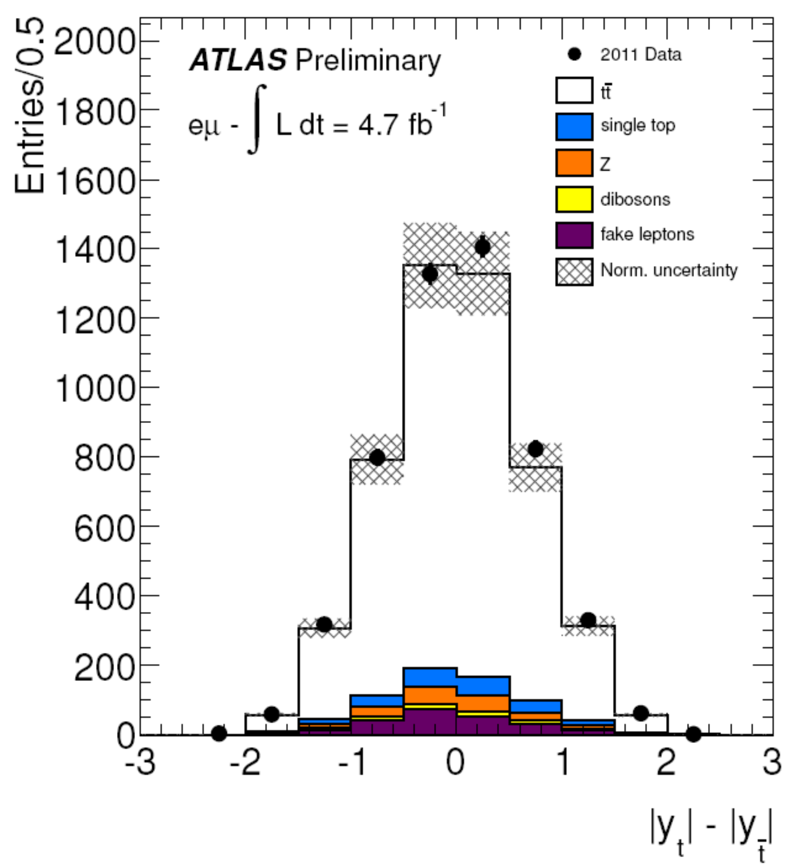
A_{FB} = 0.118 ± 0.032

Summary:

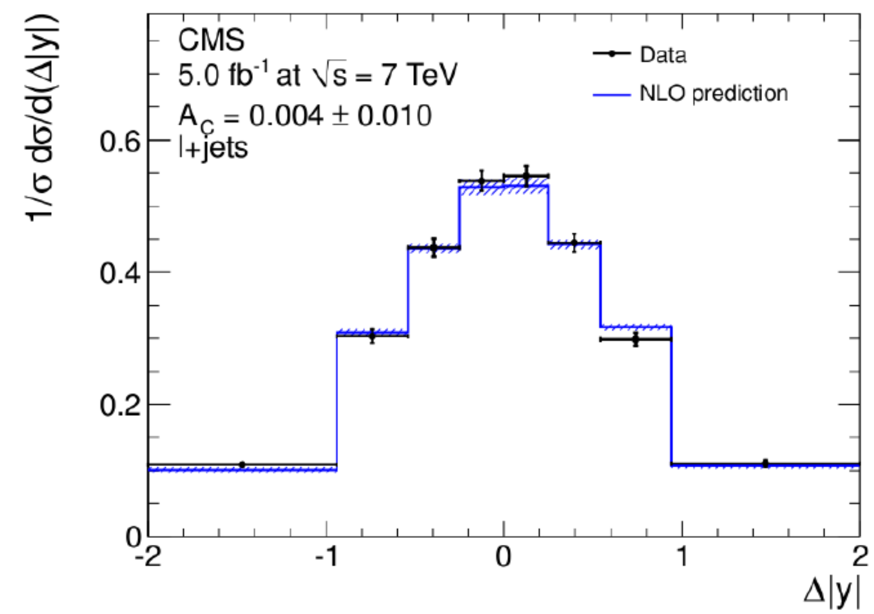


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

ICHEP 2012 : Top C Asym (Muller's talk)



ATLAS-CONF-2012-057

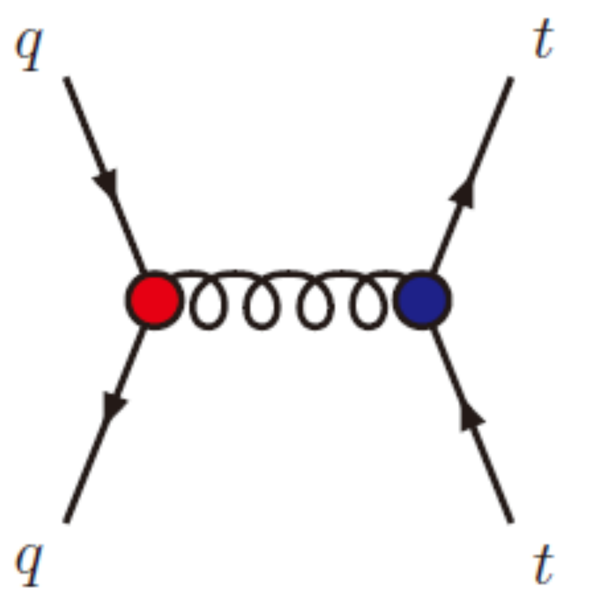


CMS PAPER TOP-11-030

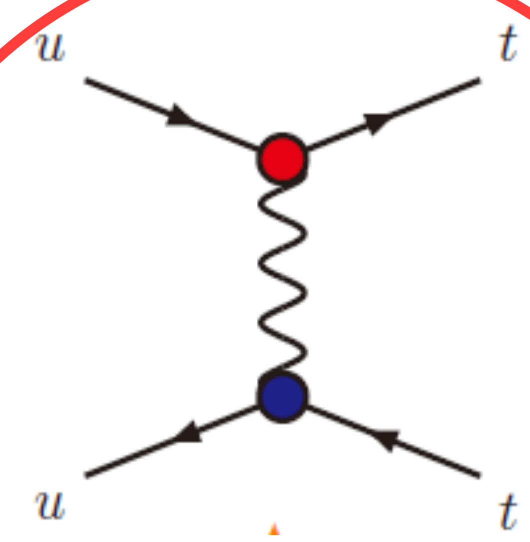
- ATLAS: A_C = 0.029 +- 0.018 (stat.) +- 0.014 (syst.)
- CMS: Corrected: A_C = 0.004 +- 0.010 (stat.) +- 0.011 (syst.)

- Theory (Kühn, Rodrigo): A_C = 0.0115 +- 0.0006

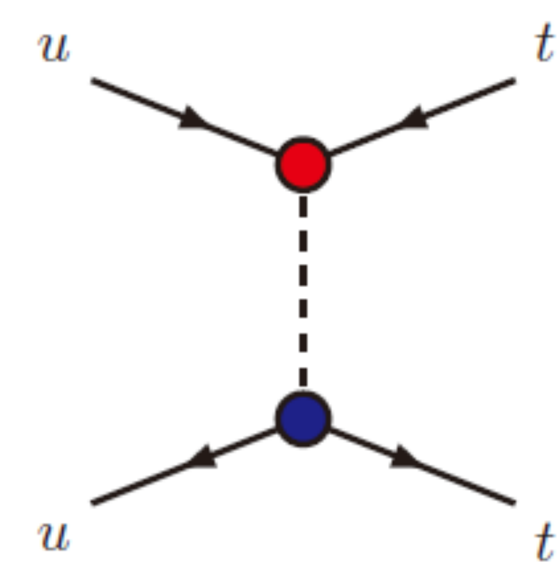
New physics models for top A_{FB}



s-channel: coloured resonance $\mathcal{G}_\mu$



t-channel: Z', W', ϕ



u-channel: exotic scalars

(new) heavy VB

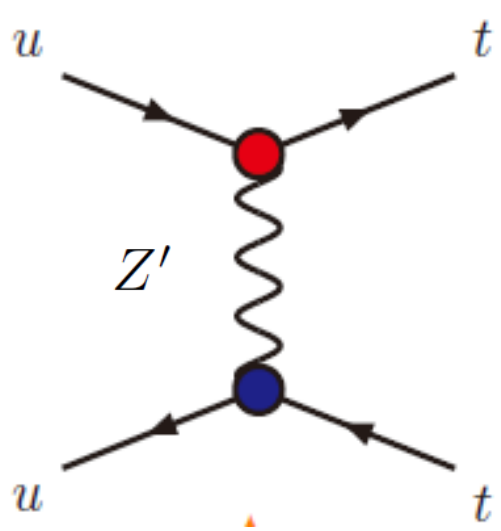
4-fermion interaction

Ko et al (2009), (2010);
Degrande et al (2010); etc.

- flavor dependent.
- challenging to construct a realistic model.
  - anomaly free, renormalizable, and realistic Yukawa couplings.

Z′ model

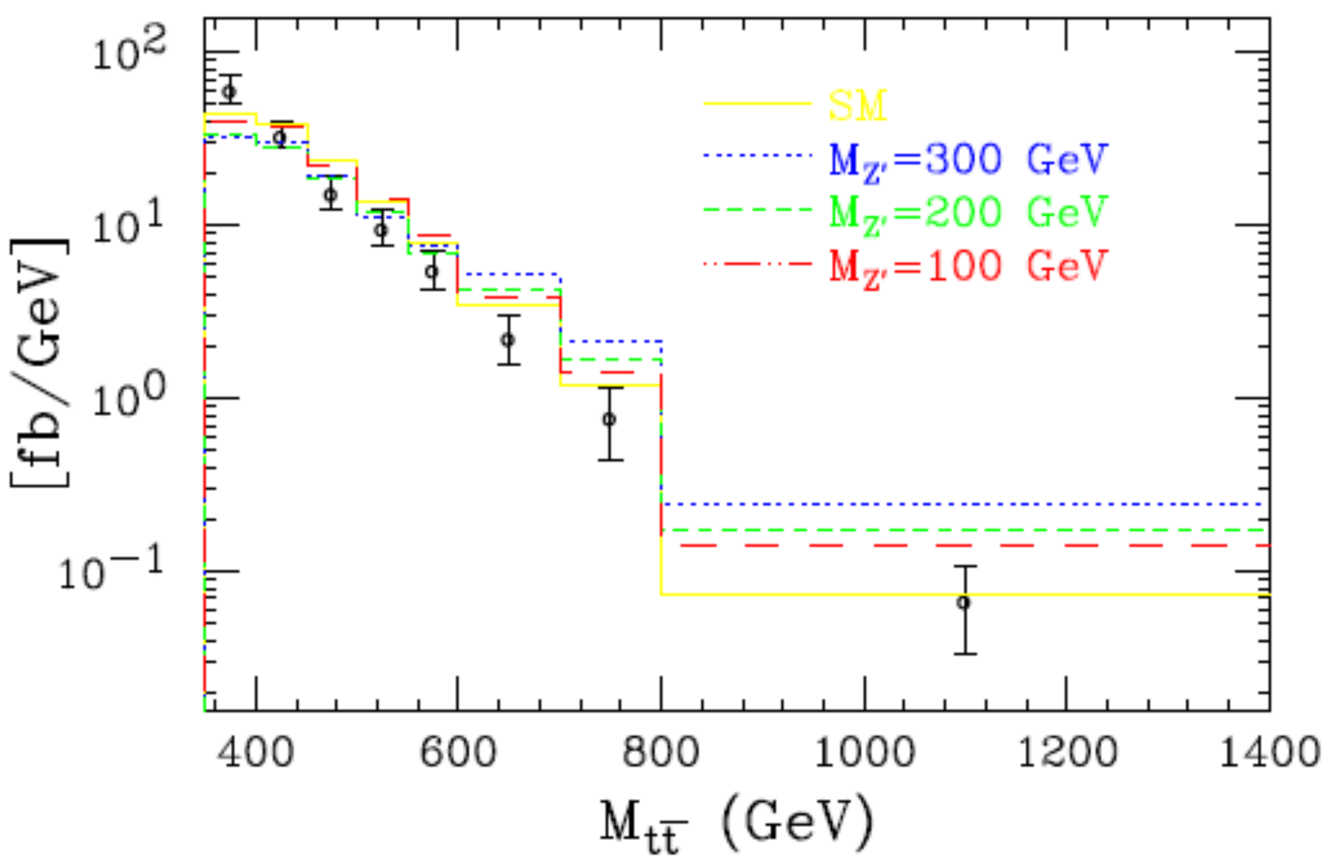
Jung, Murayama, Pierce, Wells, PRD81



- assume large flavor-offdiagonal coupling and small diagonal couplings.

$$\mathcal{L} \ni g_X Z'_\mu \bar{u} \gamma^\mu P_R t + h.c.$$

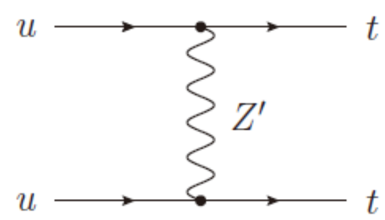
- In general, could have different couplings to the top and antitop quarks.



- light Z′ is favored from the M_{tt} distribution.

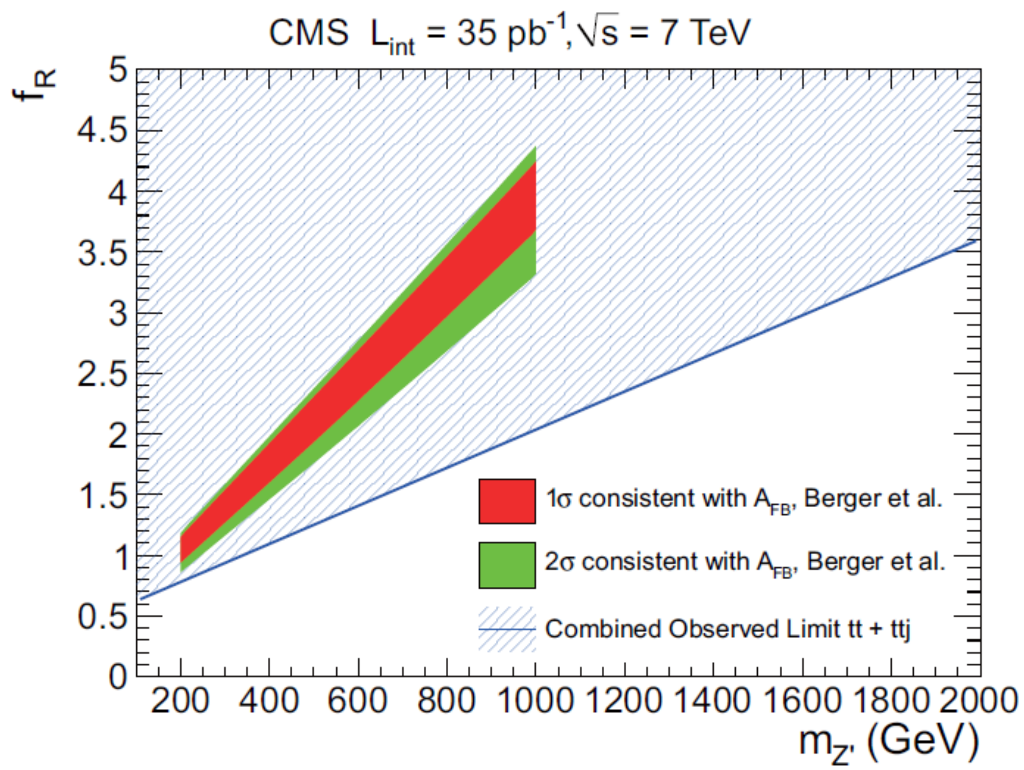
- severely constrained by the same sign top pair production.
  - the t-channel scalar exchange model has a similar constraint.

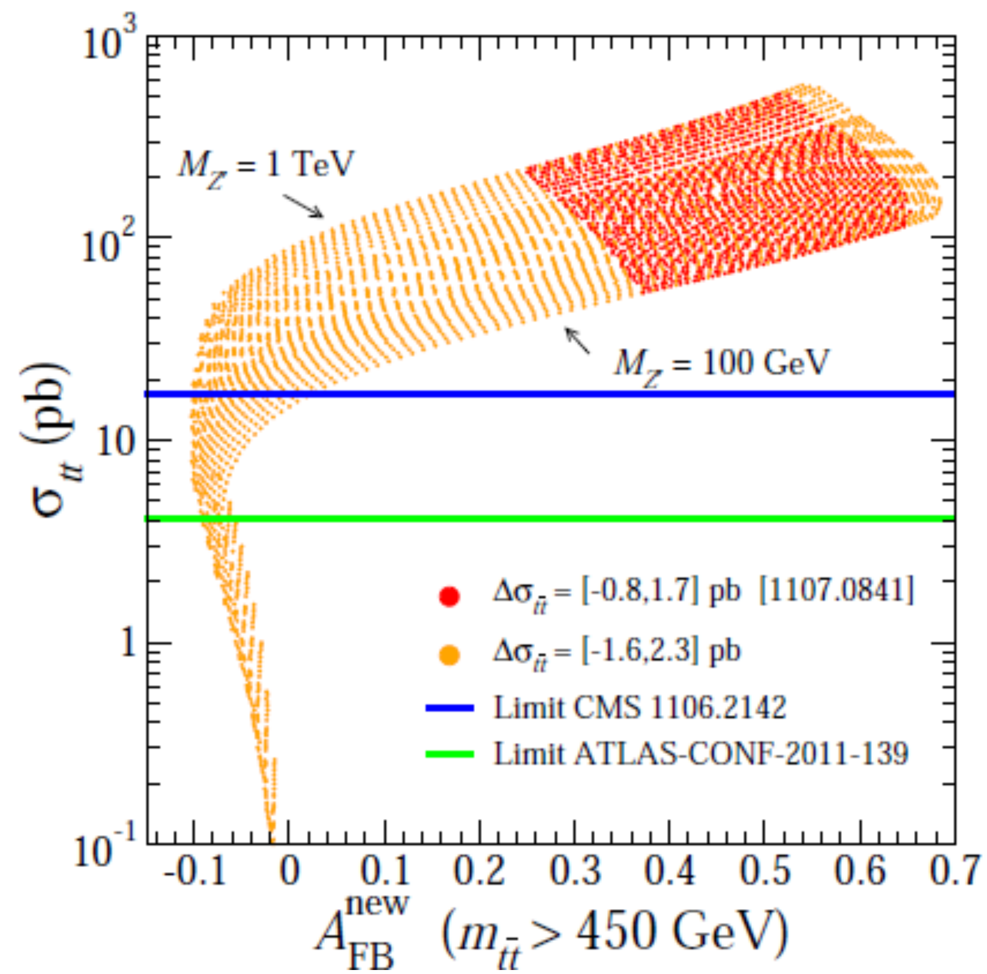
Same sign top pair production at LHC



$$\mathcal{L} = g_W \bar{u} \gamma^{\mu} (f_L P_L + f_R P_R) t Z'_{\mu} + \text{h.c.},$$

General exclusion plot





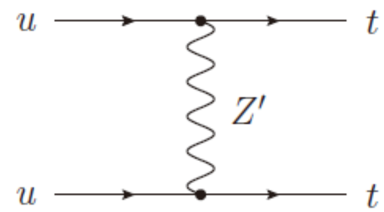
CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

CMS, JHEP1108; ATLAS-CONF-2011-169

Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded?

Same sign top pair production at LHC



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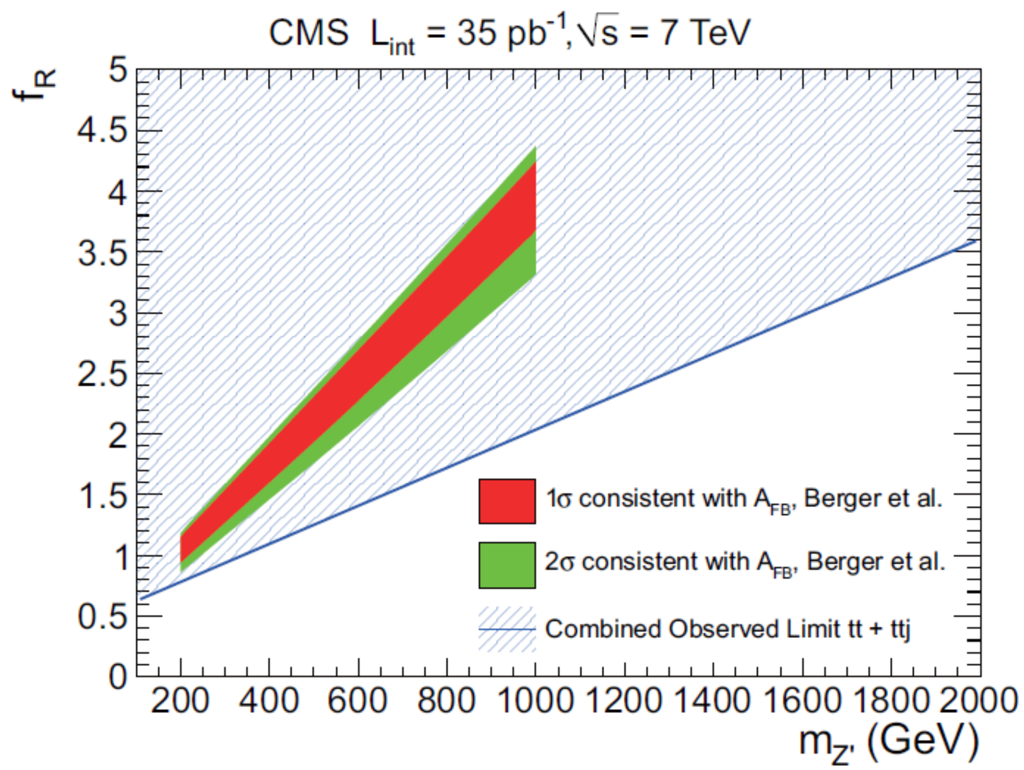

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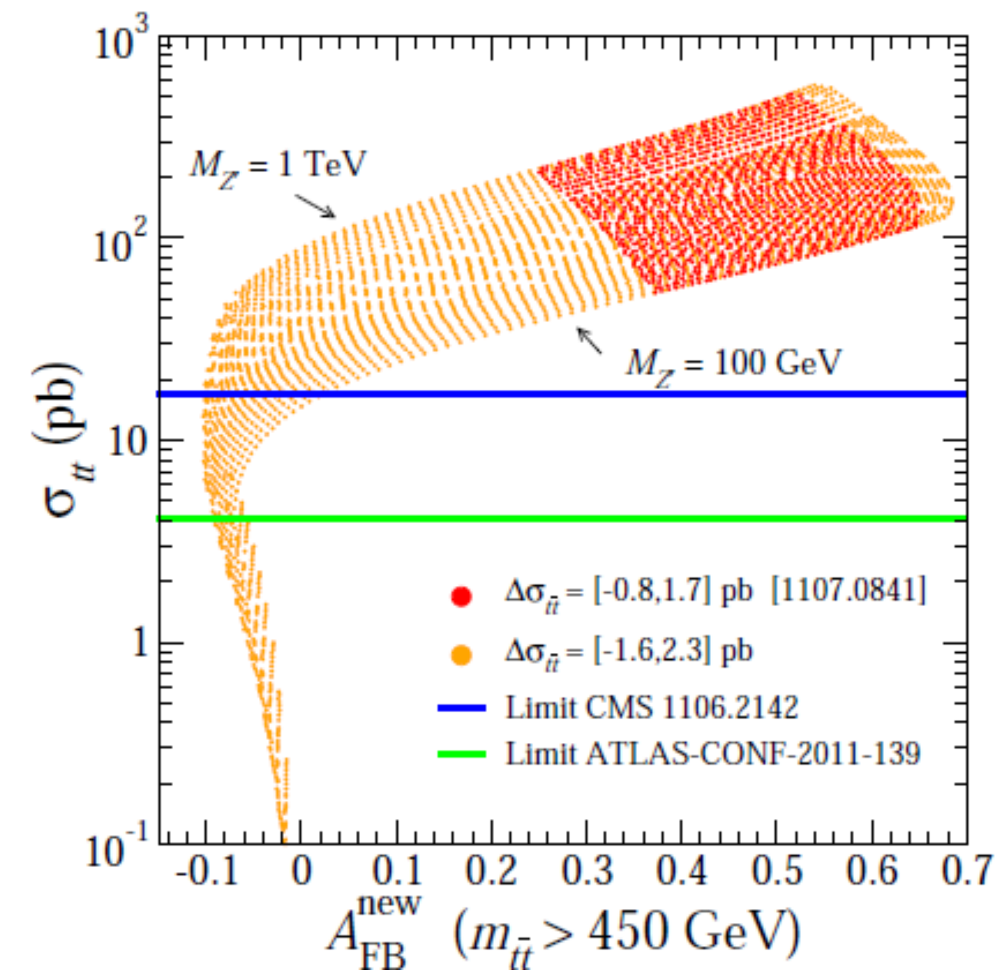


Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded?
- the answer is NO.

Is the Z' model for top FB asym excluded by the same sign top pair production ?

Is the Z' model for top FB asym excluded by the same sign top pair production ?

NO !

NOT YET !

However, the story is not so simple for models with vector bosons that have chiral couplings with the SM fermions !

Chiral U(1)' model (Ko, Omura, Yu)

(1) arXiv:1108.0350, PRD (2012)
(2) arXiv:1108.4005, JHEP 1201 (2012) 147
(3) arXiv:1205.0407, EPJC 73 (2013) 2269
(4) arXiv:1212.4607, JHEP 1303 (2013) 151

What is the problem of the original Z' model ?

- Z' couples to the RH up type quarks : leptophobic and chiral : ANOMALY ?
- No Yukawa couplings for up-type quarks : MASSLESS TOP QUARK ?
- Origin of Z' mass
- Origin of flavor changing couplings of Z'

What is the problem of the original Z' model ?

$$\mathcal{L}_Y = -Y_{ij}^U \overline{Q_{Li}} \tilde{H} U_{Rj} - Y_{ij}^D \overline{Q_{Li}} H D_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

No Yukawa's for up-type quarks:
MASSLESS TOP QUARK !

How to cure this problem ?

This problem is independent of top FCNC

Answer : Extend Higgs sector

$$\mathcal{L}_Y = -Y^U_{ij}\overline{Q_{Li}}\tilde{H}U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

$$\mathcal{L}_Y = -Y^U_{ijk}\overline{Q_{Li}}\tilde{H}_k U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

$H_k : U(1)$ charged

Mandatory to extend Higgs sector!
Z' only model does not exist!

# of U(1)'-charged new Higgs doublets depend on U(1)' charge assigments to the RH up quarks

Flavor-dependent U(1)′ model

- Charge assignment : SM fermions

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	1/6	q_L
Q_2	3	2	1/6	q_L
Q_3	3	2	1/6	q_L
$\overline{D_1}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{D_2}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{D_3}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{U_1}$	$\overline{3}$	1	$-2/3$	u_1
$\overline{U_2}$	$\overline{3}$	1	$-2/3$	u_2
$\overline{U_3}$	$\overline{3}$	1	$-2/3$	u_3
H	1	2	1/2	0

LH quarks and RH down-type quarks have universal couplings.

Flavor-dependent

Higgs

Flavor-dependent U(1)′ model

- Charge assignment : Higgs fields

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	$-q_L - u_1$
H_2	1	2	1/2	$-q_L - u_2$
H_3	1	2	1/2	$-q_L - u_3$
Φ	1	1	1	$-q_\Phi$

- introduce three Higgs doublets charged under U(1)′ in addition to the S M Higgs which is not charged under U(1)′.

$$\begin{aligned} V_y &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} \overline{D_j} Q_i i\tau_2 H^\dagger \\ &+ y^e_{ij} \overline{E_j} L_i i\tau_2 H^\dagger + y^n_{ij} H \overline{N_j} L_i . \end{aligned}$$

- The U(1)′ is spontaneously broken by U(1)′ charged complex scalar Φ.

Anomaly Cancellation : Sol. I

- Anomaly cancelation requires extra fermions I: SU(2) doublets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	1/6	$-(q_1+q_2+q_3)$
D'_R	3	1	$-1/3$	$-(d_1+d_2+d_3)$
U'_R	3	1	2/3	$-(u_1+u_2+u_3)$
L'	1	2	$-1/2$	0
E'	1	1	-1	0
l_{L1}	1	2	$-1/2$	Q_L
l_{R1}	1	2	$-1/2$	Q_R
l_{L2}	1	2	$-1/2$	$-Q_L$
l_{R2}	1	2	$-1/2$	$-Q_R$

one extra generation

$SU(2)_L{}^2 \cdot U(1)'$

vector-like pairs

$U(1)'^2 \cdot U(1)$

a candidate for CDM

Anomaly Cancellation : Sol. II

• Anomaly cancelation requires extra fermions II: $SU(3)_c$ triplets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
q_{L1}	3	1	$-1/3$	Q_L
q_{R1}	3	1	$-1/3$	Q_R
q_{L2}	3	1	$-1/3$	$-Q_L$
q_{R2}	3	1	$-1/3$	$-Q_R$

• introduce the singlet scalar X to the SM in order to allow the decay of th e extra colored particles.

$$V_m = \lambda_i X^\dagger \overline{D_{Ri}} q_{L1} + \lambda_i X \overline{D_{Ri}} q_{L2}$$

a candidate for CDM

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

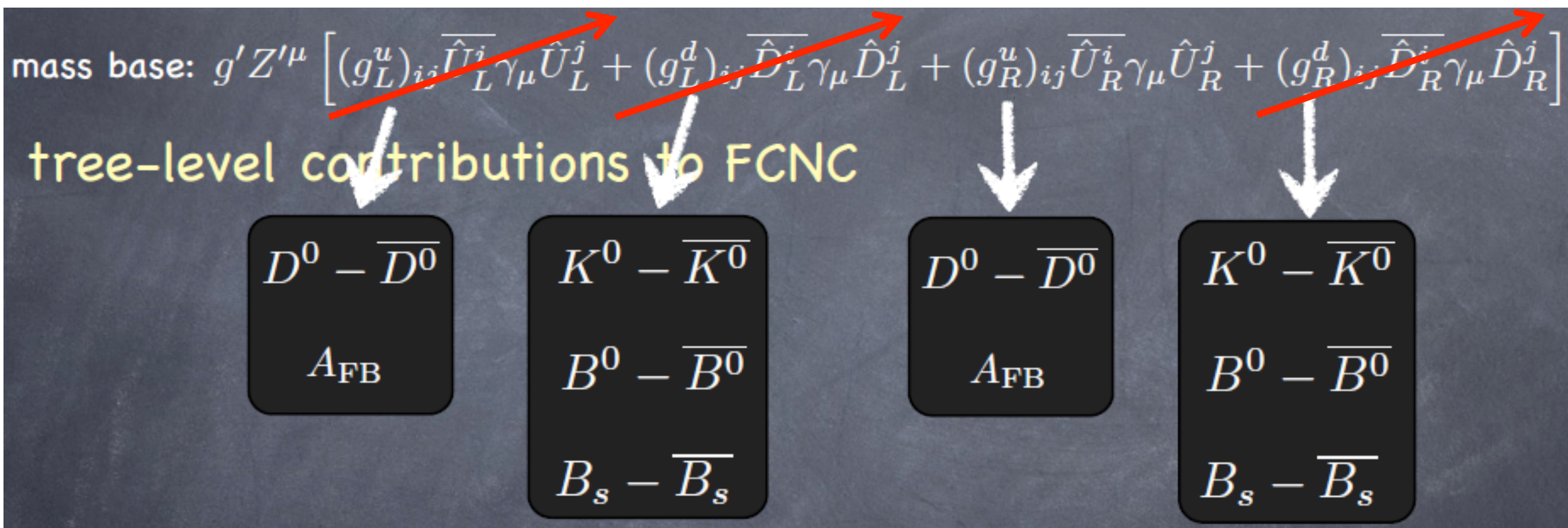
- Z′ interacts only with the right-handed up-type quarks

$$g' Z'^{\mu} \sum_{i,j=1,2,3} (g_R^u)_{ij} \overline{U_R}^i \gamma_\mu U_R^j \longleftarrow g' Z'^{\mu} \sum_{i=1,2,3} u_i \overline{U'_{Ri}} \gamma_\mu U'_{Ri}$$

- The 3 X 3 coupling matrix g_R^u is defined by

$$(g_R^u)_{ij} = (U_R^u)_{ik} u_k (U_R^u)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix



Flavor-dependent U(1)′ model

- 2 Higgs doublet model : $(u_1, u_2, u_3) = (0, 0, 1)$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	1	q_Φ

$$
\begin{aligned}
V_y &= y^u_{i1}\overline{Q_i}\widetilde{H}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H}U_{Rj} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{Rj} \\
&\quad + y^d_{ij}\overline{Q_i}HD_{Rj} + y^e_{ij}\overline{L_i}H\overline{E_j} + y^n_{ij}\overline{L_i}\widetilde{H}N_j .
\end{aligned}
$$

$$
V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,
$$

$$
\begin{aligned}
Y^u_{ij} &= \frac{m^u_i \cos\alpha}{v\cos\beta}\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta), \\
Y^d_{ij} &= \frac{m^d_i \cos\alpha}{v\cos\beta}\delta_{ij},
\end{aligned}
\quad \Bigg\} \propto \text{ the fermion mass}
$$

Flavor-dependent U(1)′ model

- 3 Higgs doublet model: $(u_1, u_2, u_3) = (-q, 0, q)$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	q
H_2	1	2	1/2	0
H_3	1	2	1/2	$-q$
Φ	1	1	0	-1

$$\begin{aligned} \mathcal{L}_{\rm Y} &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} H_2^\dagger \overline{D_j} Q_i + y^e_{ij} H_2^\dagger \overline{E_j} L_i + y^n_{ij} H_2 \overline{N_j} L_i . \end{aligned}$$

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

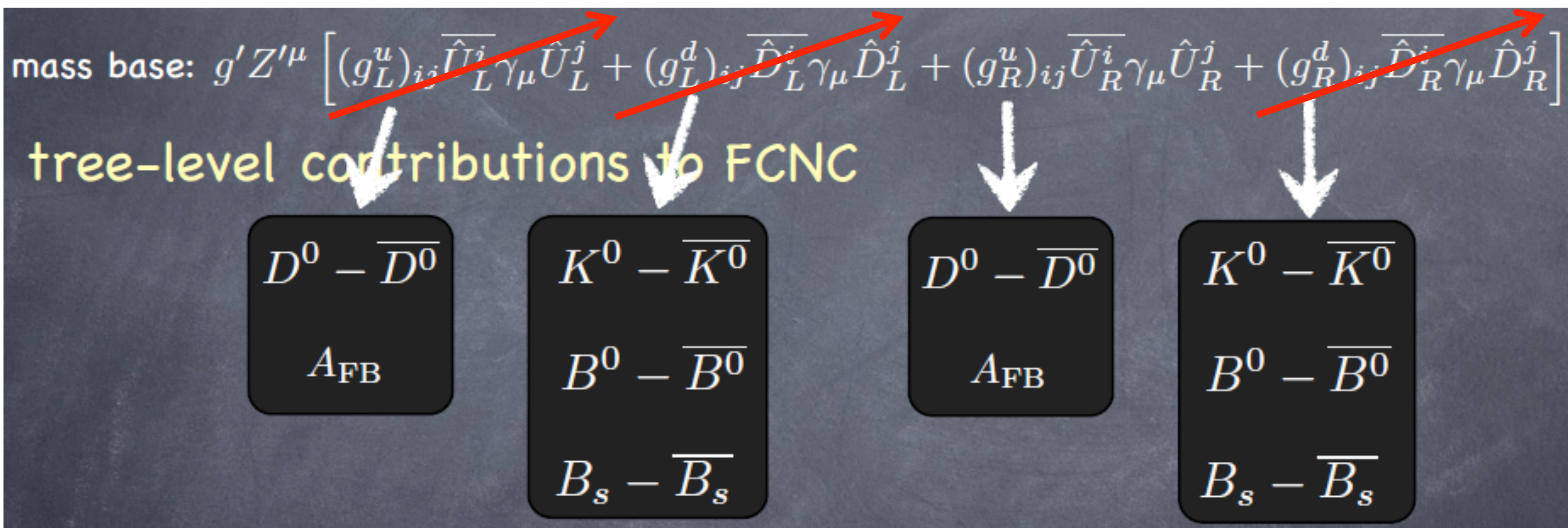
- Z′ interacts only with the right-handed up-type quarks

$$g' Z'^{\mu} \sum_{i,j=1,2,3} (g_R^u)_{ij} \overline{U_R}^i \gamma_\mu U_R^j \longleftarrow g' Z'^{\mu} \sum_{i=1,2,3} u_i \overline{U'_{Ri}} \gamma_\mu U'_{Ri}$$

- The 3 X 3 coupling matrix g_R^u is defined by

$$(g_R^u)_{ij} = (U_R^u)_{ik} u_k (U_R^u)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix



Flavor-dependent U(1)′ model

- Yukawa coupling in the mass base (2HDM)

- lightest Higgs h:

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}h + Y^e_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}h + h.c.,$$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi,$$

$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi\delta_{ij},$$

$$Y^e_{ij} = \frac{m^l_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi\delta_{ij},$$

- lightest charged Higgs h$^+$:

$$V_{h^\pm} = -Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- + Y^{d+}_{ij}\overline{\hat{U}_{Li}}\hat{D}_{Rj}h^+ + h.c.,$$

$$Y^{u-}_{ij} = \sum_l (V_{\rm CKM})^*_{li}\left\{\frac{\sqrt{2}m^u_l\tan\beta}{v}\delta_{lj} - \frac{2\sqrt{2}m^u_l}{v\sin 2\beta}(g^u_R)_{lj}\right\},$$

$$Y^{d+}_{ij} = (V_{\rm CKM})_{ij}\frac{\sqrt{2}m^d_j\tan\beta}{v},$$

- lightest pseudoscalar Higgs a:

$$V_a = -iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a + iY^{ad}_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}a + iY^{ae}_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}a + h.c.,$$

$$Y^{au}_{ij} = \frac{m^u_i\tan\beta}{v}\delta_{ij} - \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij},$$

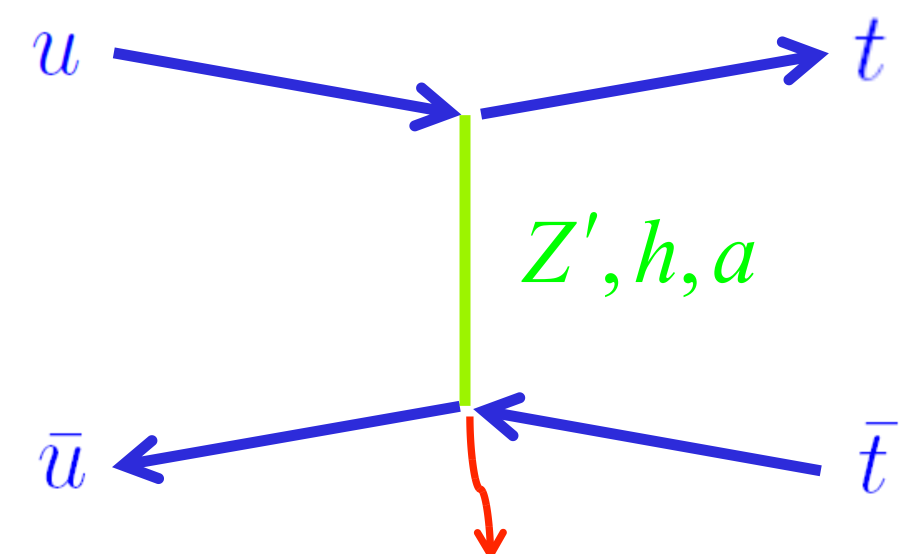
$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

$$Y^{ae}_{ij} = \frac{m^l_i\tan\beta}{v}\delta_{ij}.$$

Top-antitop pair production

1. Z′ dominant scenario

cf. Jung, Murayama, Pierce, Wells, PRD81(2010)♪



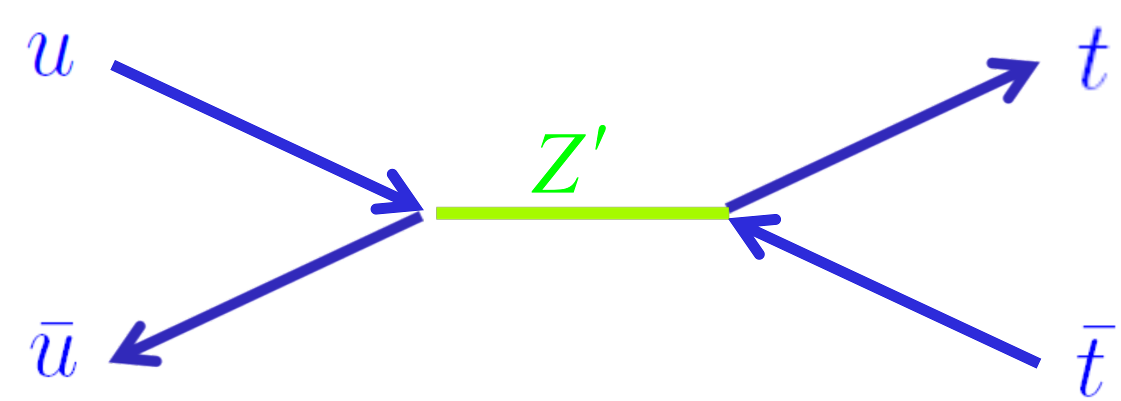
$$\alpha_X = \frac{(g' g^u_{Rut})^2}{4\pi}, Y_{tu}, Y^a_{tu}$$

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

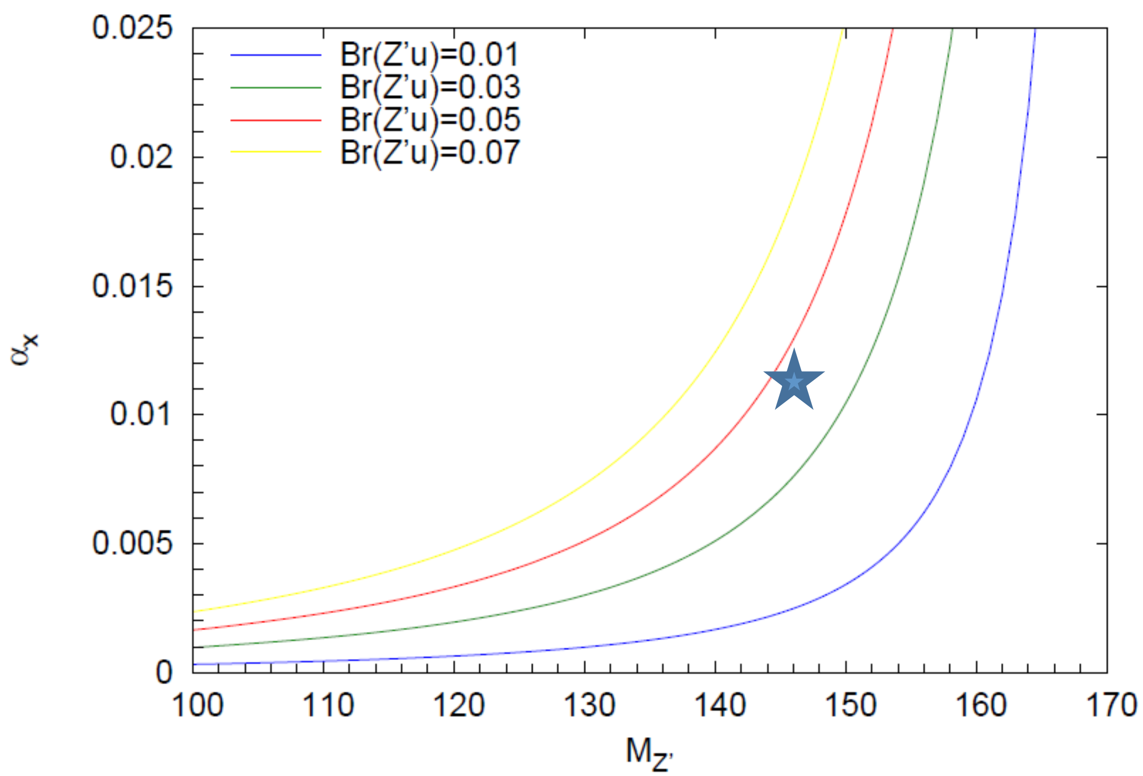
3. Mixed scenario

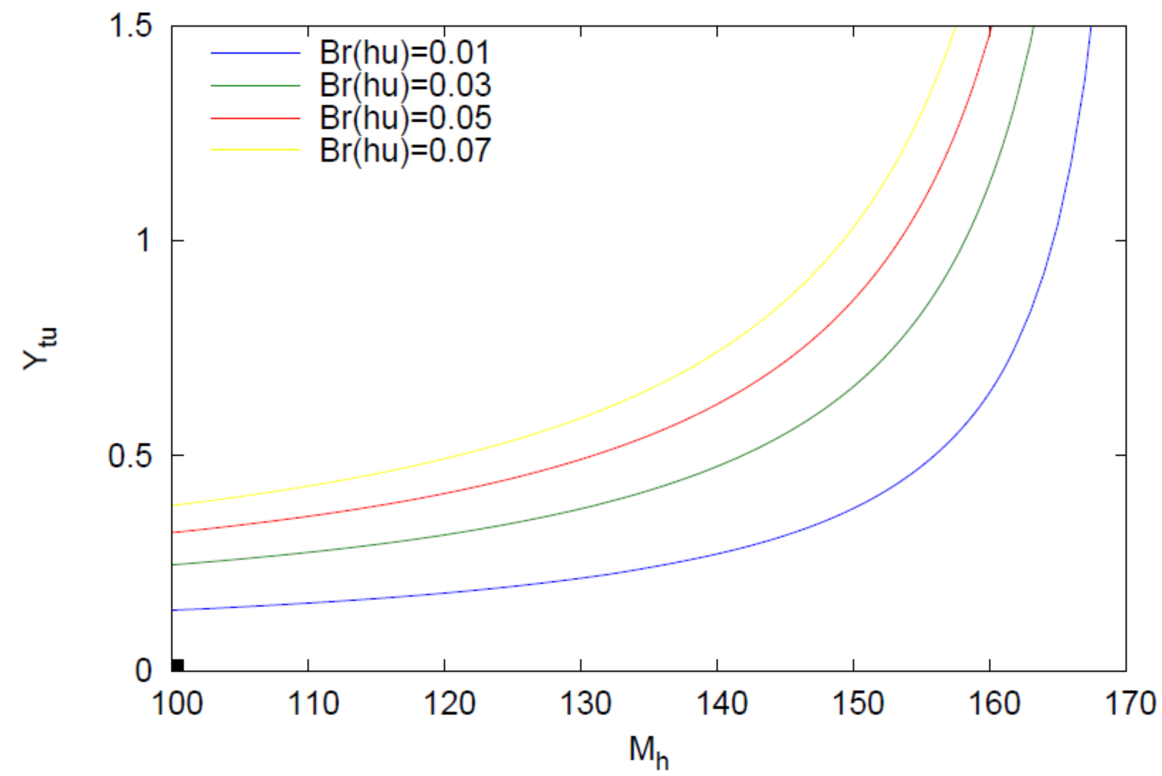
Destructive interference between Z' and h,a for the same sign pair production (Ko, Omura, Yu)



Top quark decay

- decay into W+b in SM : Br(t→Wb)~100%.
- If the top quark decays to $Z' + u$ or $h + u$, Br(t→Wb) might significantly be changed.

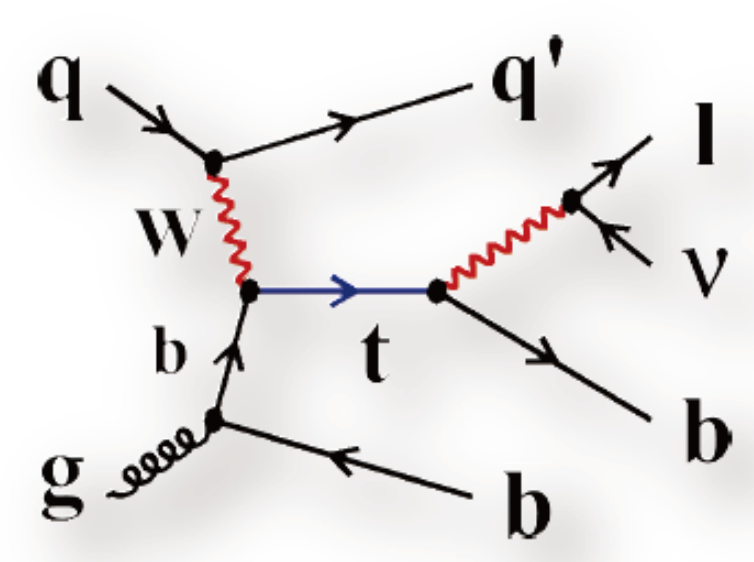




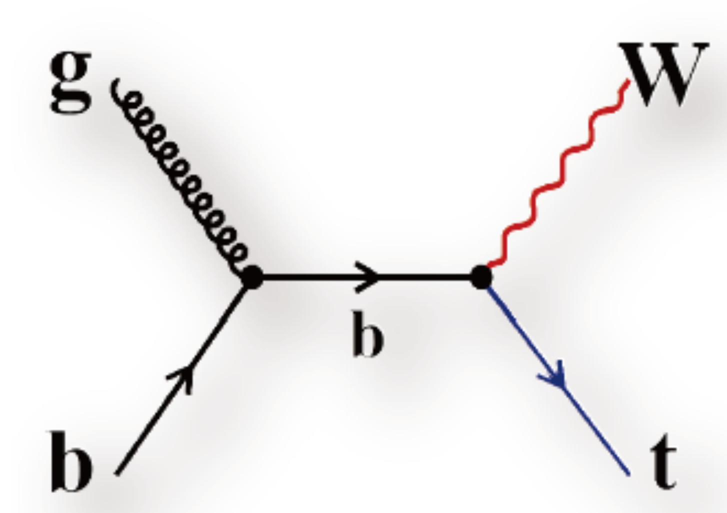
- requires Br(t →non-SM)<5% .
- choose either $m_{Z'} < m_t$ or $m_h < m_t$.

Single top quark production

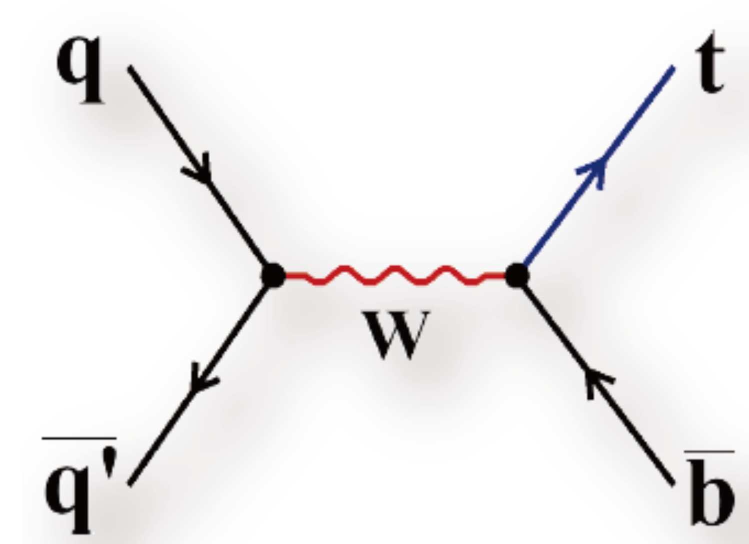
t channel



Wt channel



s channel



- D0 D0, 1105.2788

$$\sigma(p\bar{p} \to tbq) = 2.90 \pm 0.59 \text{ pb}$$

In the SM,

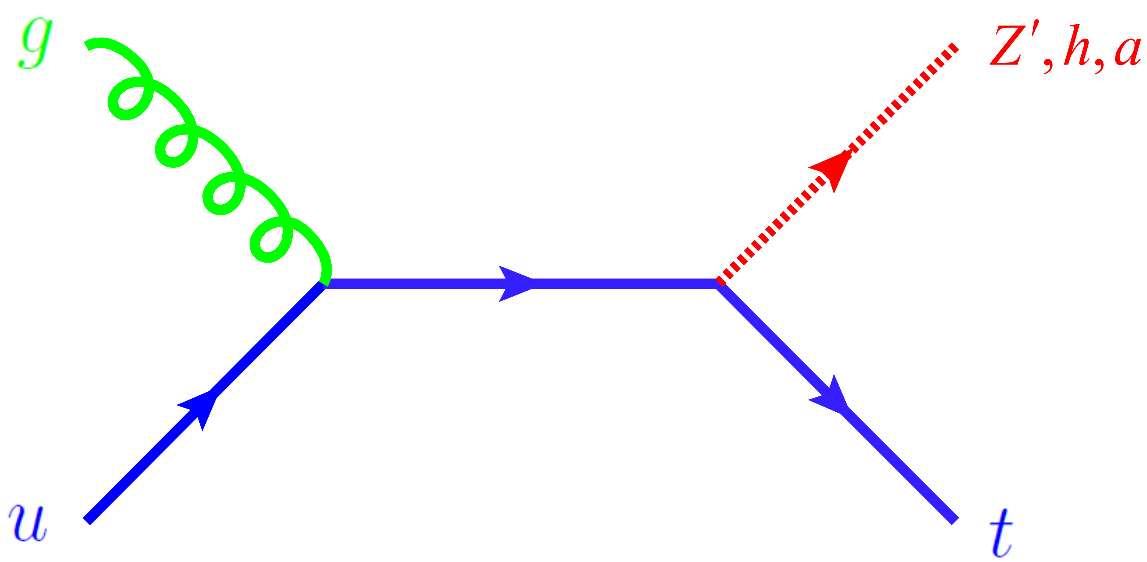
$$\sigma(p\bar{p} \to tbq) = 2.26 \pm 0.12 \text{ pb}$$

- CMS CMS, 1106.3052

$$\sigma(pp \to tbq) = 83.6 \pm 29.8 \pm 3.3 \text{ pb}$$

$$\sigma(pp \to tbq) = 64.3^{+2.1+1.5}_{-0.7-1.7} \text{ pb}$$

Single top quark production



$\Rightarrow$ no b quark or W boson in the final state

- D0 D0, 1105.2788♪

$$\sigma(p\bar{p} \to tbq) = 2.90 \pm 0.59 \text{ pb}$$

- CMS CMS, 1106.3052♪

$$\sigma(pp \to tbq) = 83.6 \pm 29.8 \pm 3.3 \text{ pb}$$

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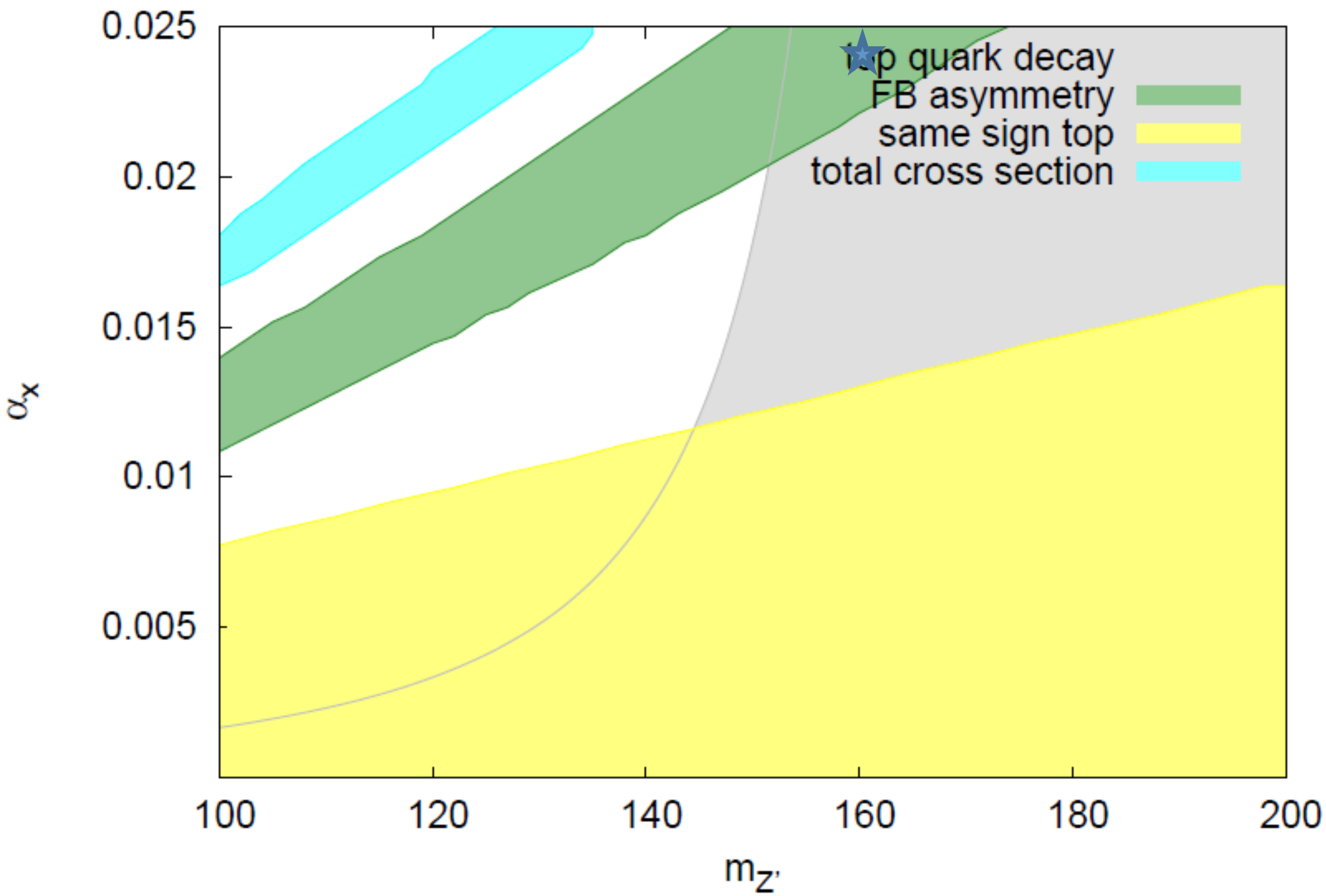
Favored region

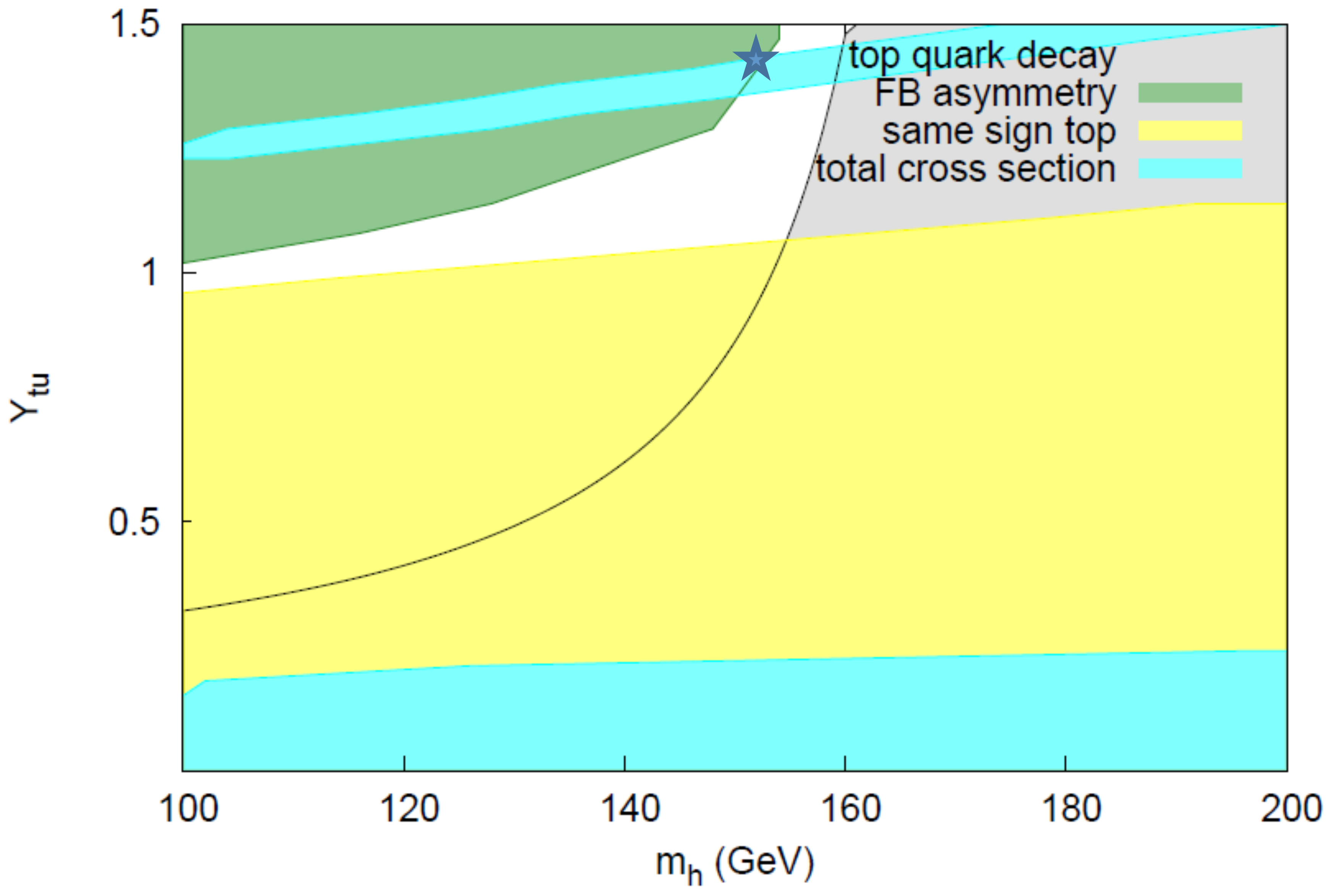
Z′ dominant case



★= similar to Jung, Murayama, Pierce, Wells' model (PRD81)

Favored region

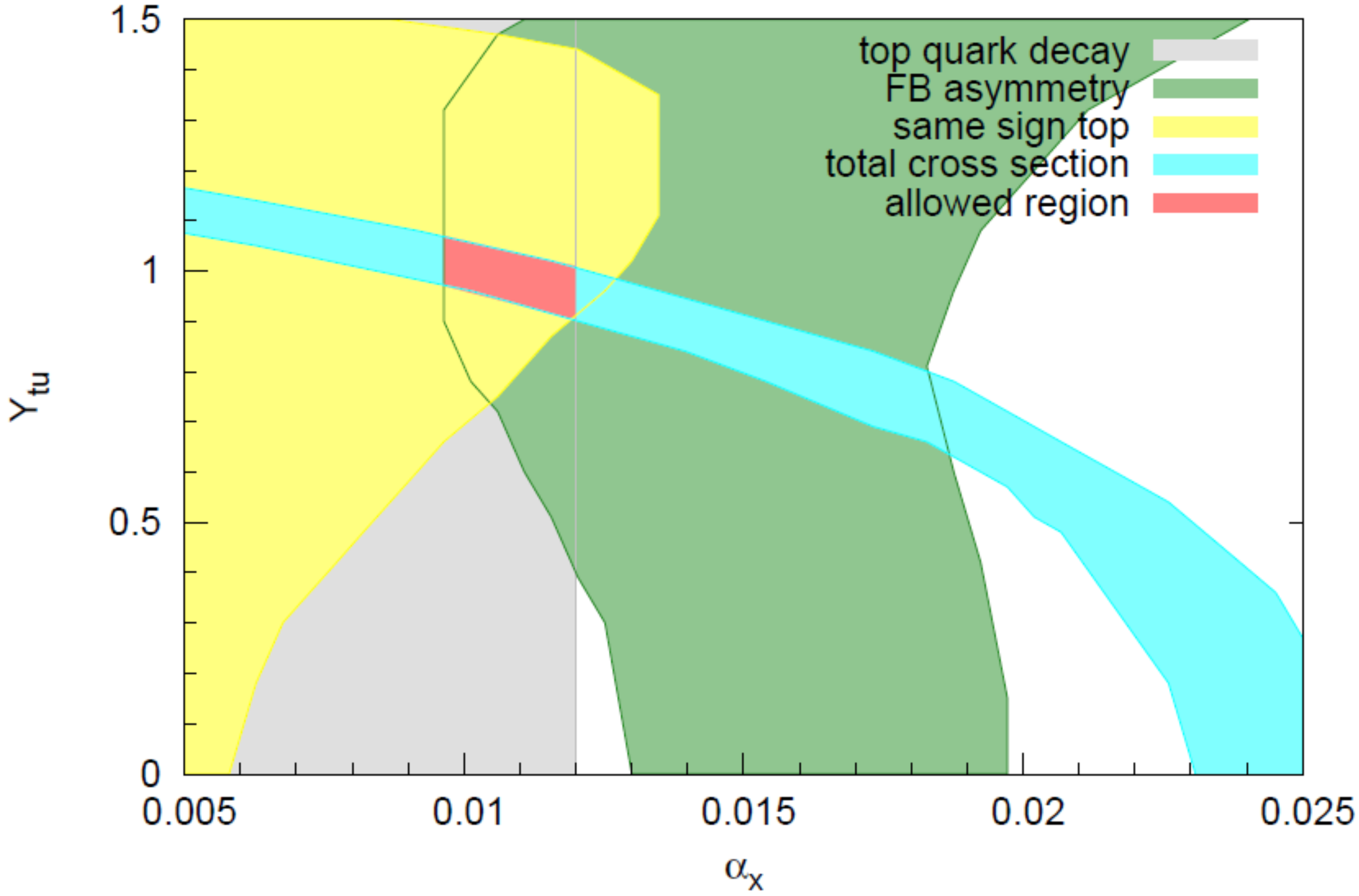
Scalar Higgs (h) dominant case



★ = similar to Babu, Frank, Rai's model (PRL107)

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

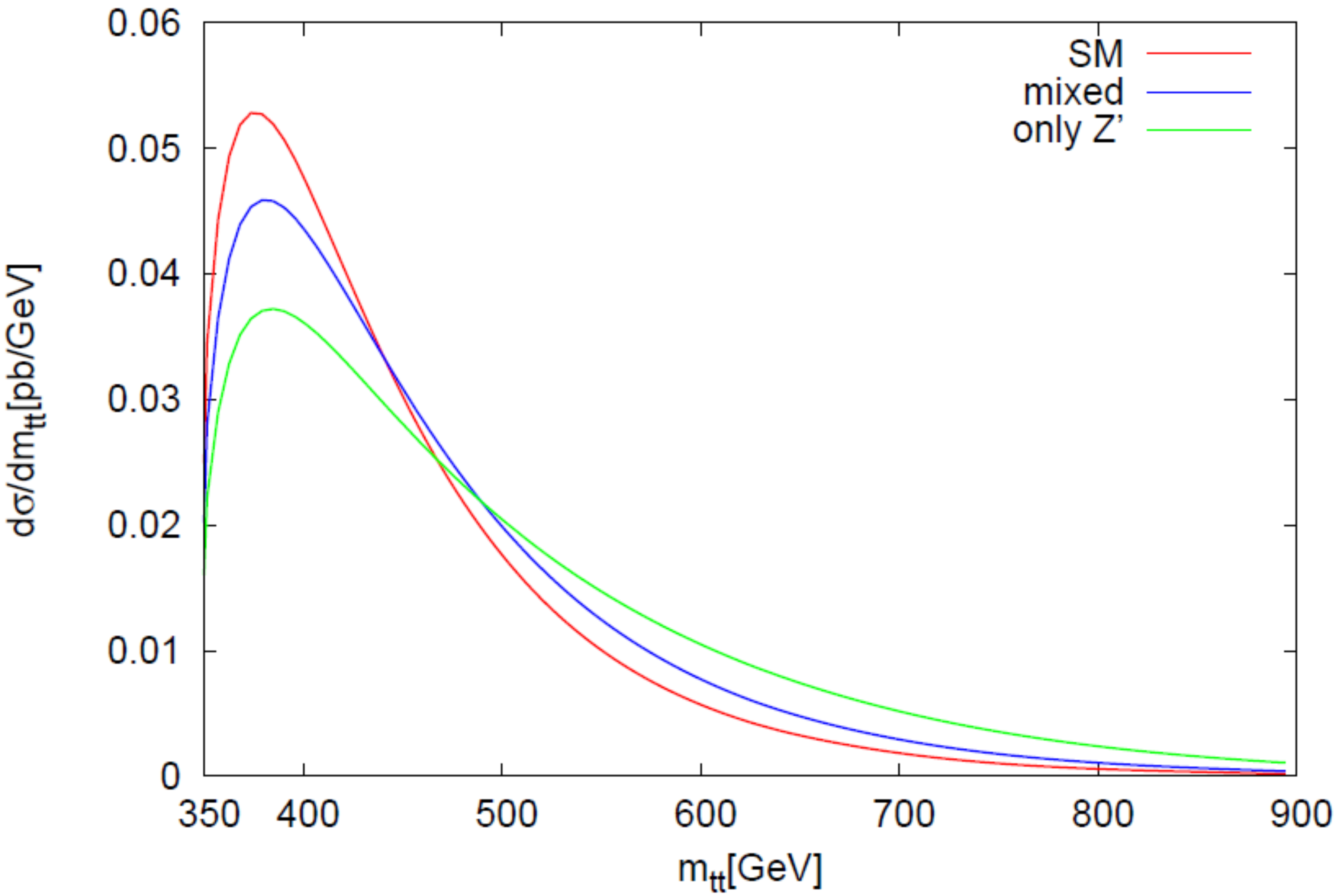
$m_h = 180$ GeV

$m_a = 300$ GeV

$Y_{tu}^a = 1.1$

- destructive interference between Z and Higgs bosons in the same signe top pair production.
- consistent with the CMS bound, but not with the ATLAS bound.

Invariant mass distribution



Only Z′ case

$m_{Z'} = 145$ GeV

$\alpha_x = 0.029$

mixed case

$m_{Z'} = 145$ GeV

$m_h = 180$ GeV

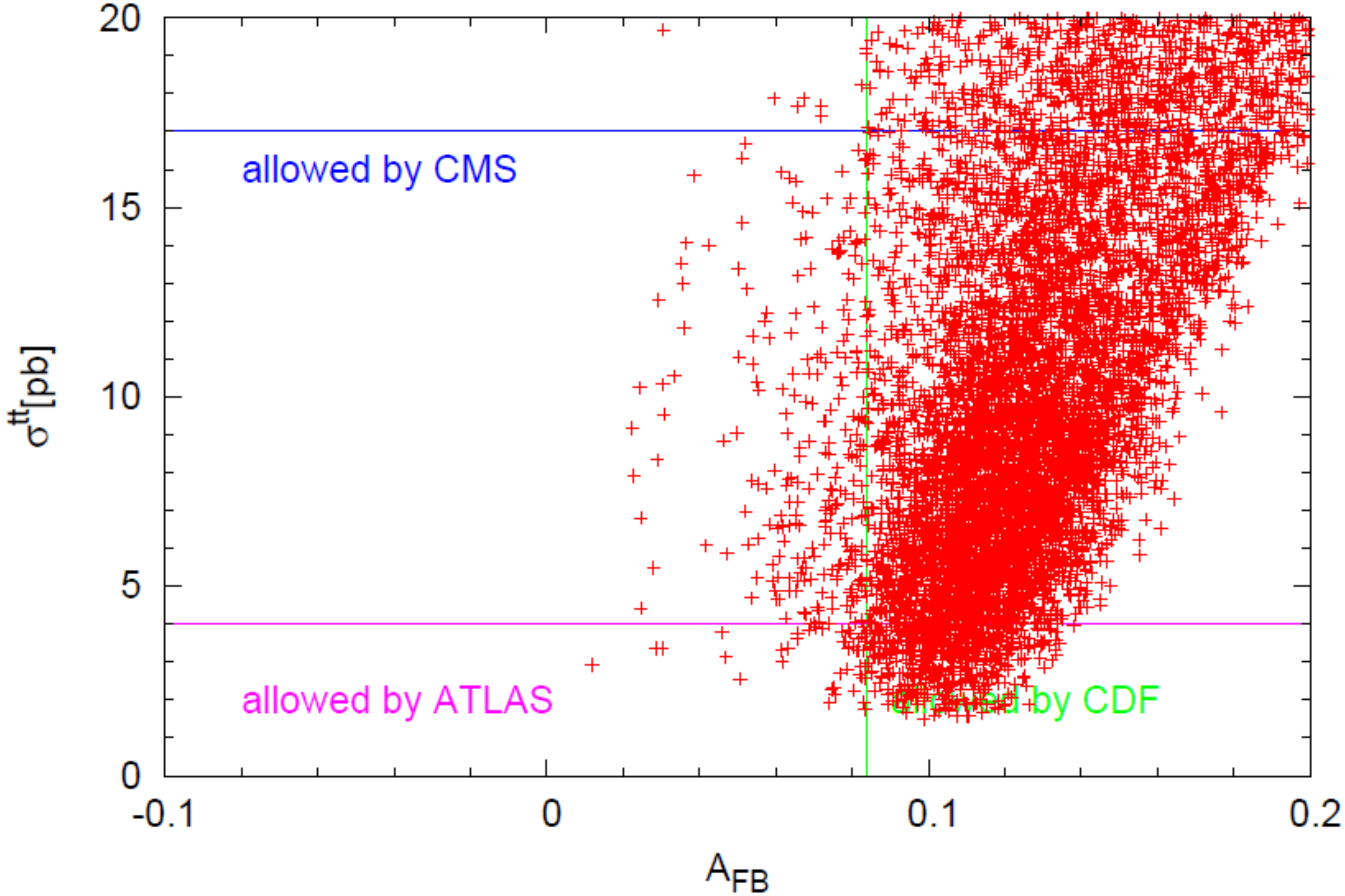
$m_a = 300$ GeV

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

180 GeV$< m_a < 1$ TeV

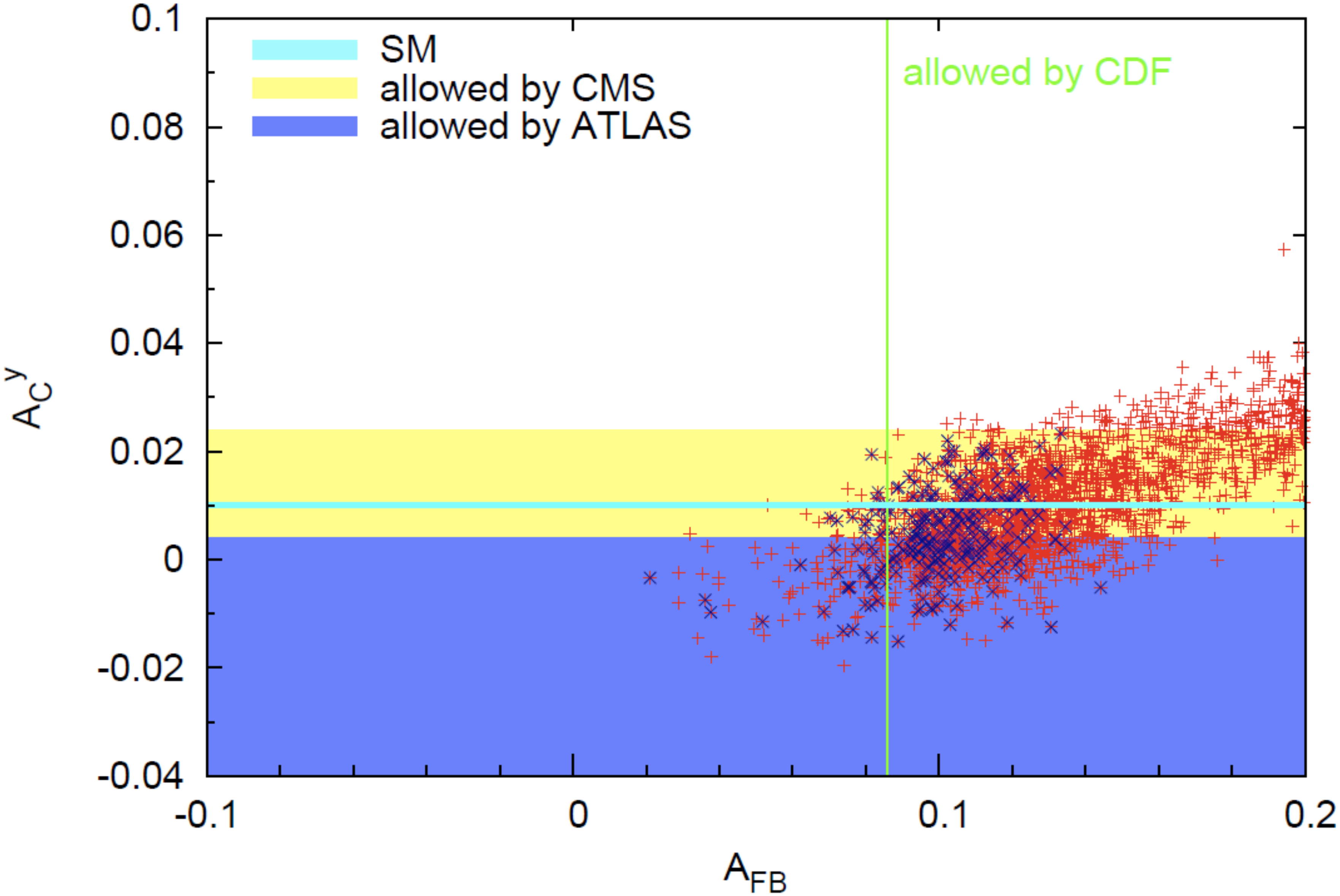
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}{}^{a} < 1.5$

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus A_C^y



$m_{Z'} = 145$ GeV

180 GeV $< m_h < 1$ TeV

180 GeV $< m_a < 1$ TeV

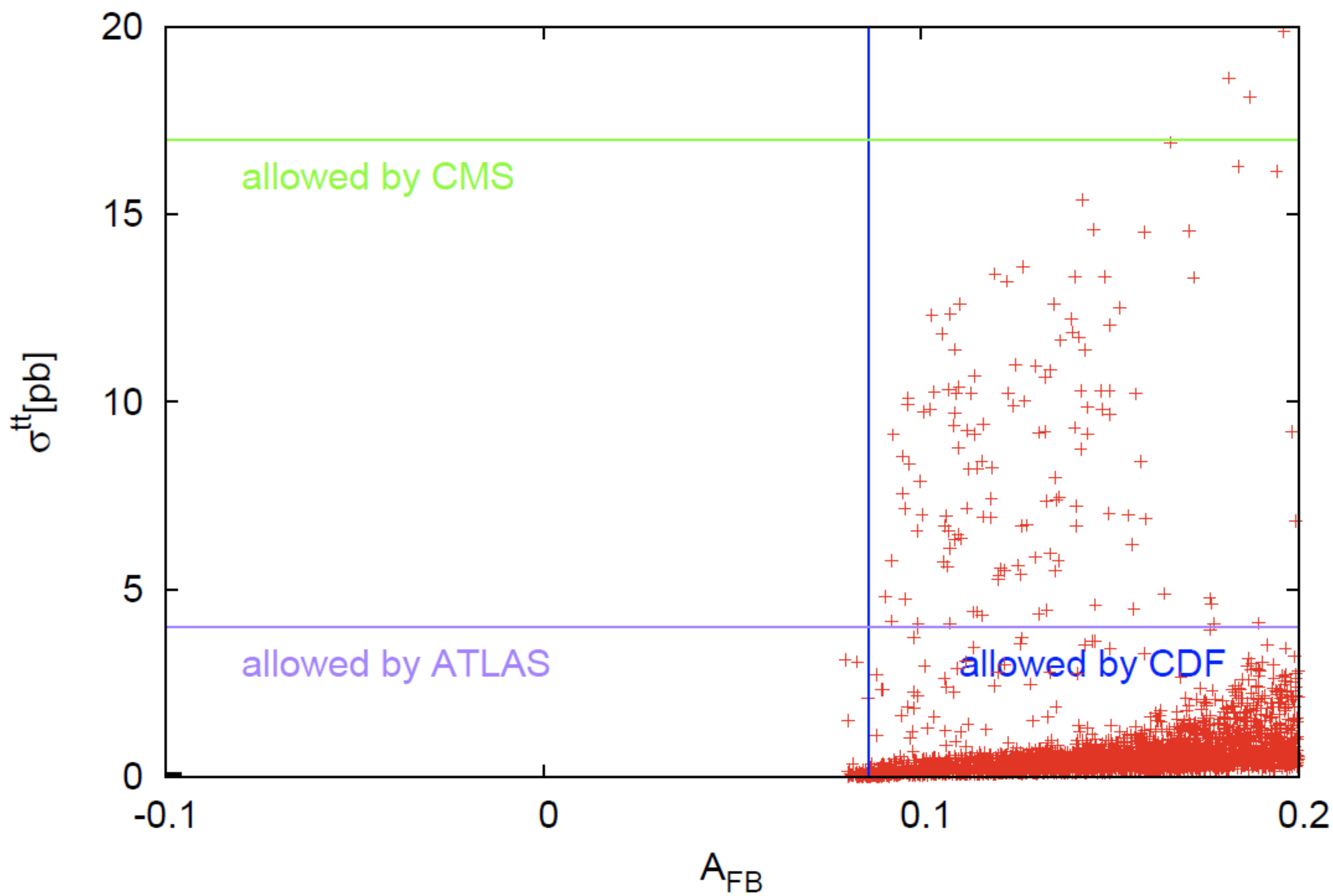
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}^a < 1.5$

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus σ_{tt}



$m_h = 126$ GeV

180 GeV$< m_{Z'} < 1.5$ TeV

180 GeV$< m_a < 1$ TeV

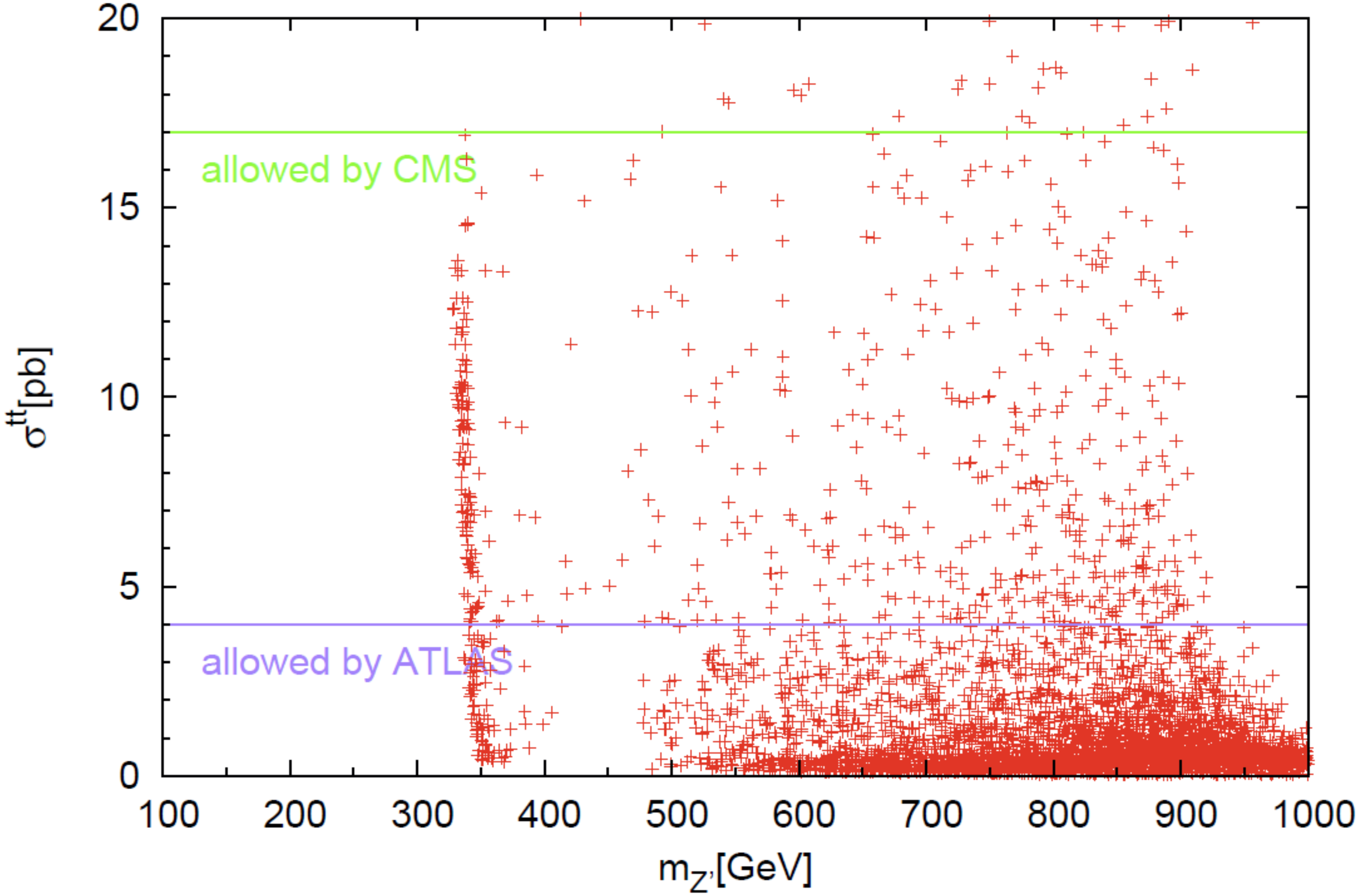
$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

$0.1 < Y_{tu}^{a} < 1.5$

Still OK with new CMS data < 0.39 pb

$m_{Z'}$ versus σ_{tt}



$m_h = 126$ GeV

180 GeV$< m_{Z'} < 1.5$ TeV

180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

$0.1 < Y_{tu}^a < 1.5$

Still OK with new CMS data < 0.39 pb

Conclusions

- We constructed realistic Z' models with additional Higgs doublets that are charged under U(1)' : Based on local gauge symmetry, renormalizable, anomaly free and realistic Yukawa
- New spin-one boson (Z') with chiral couplings to the SM fermion requires a new Higgs doublet that couples to the new Z'
- This is also true for axigluon, flavor SU(3)_R, W', etc.
- Our model can accommodate the top FB Asym @ Tevatron, the same sign top pair production, and the top CA@LHC

- Meaningless to say "The Z' model is excluded by the same sign top pair production."
- Important to consider a minimal consistent (renormalizable, realistic, anomaly free) in order to do phenomenology
- Flavor issues in B and charm systems were also studied (w/ Yuji Omura and C. Yu)
- Top longitudinal pol (which is zero in QCD because of Parity) could be another important tool for resolving the issue (Ko et al, Godbole et al, Degrande et al, etc)