Lessons from rise and falls of anomalies

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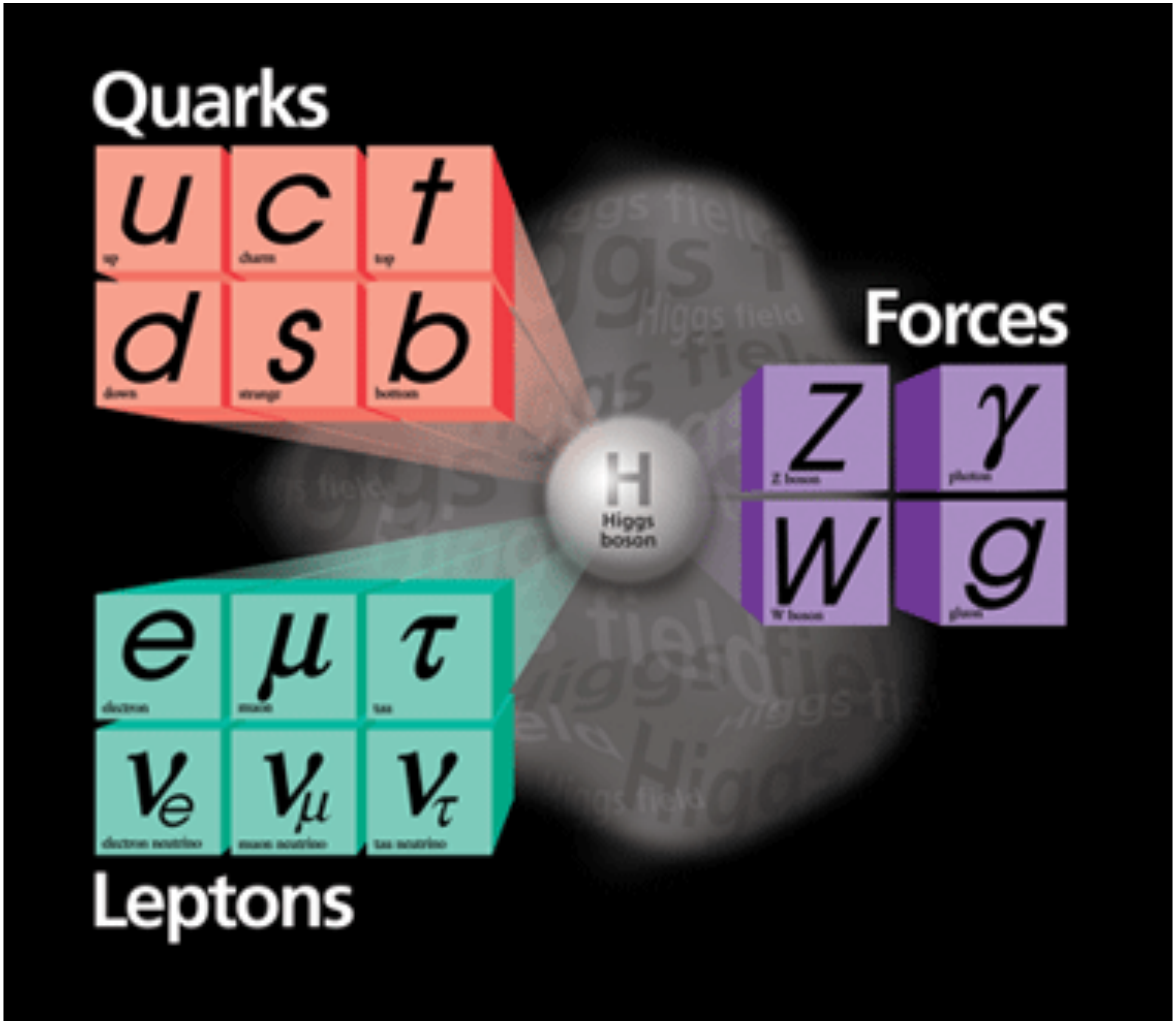
Standard Model of Particle Physics

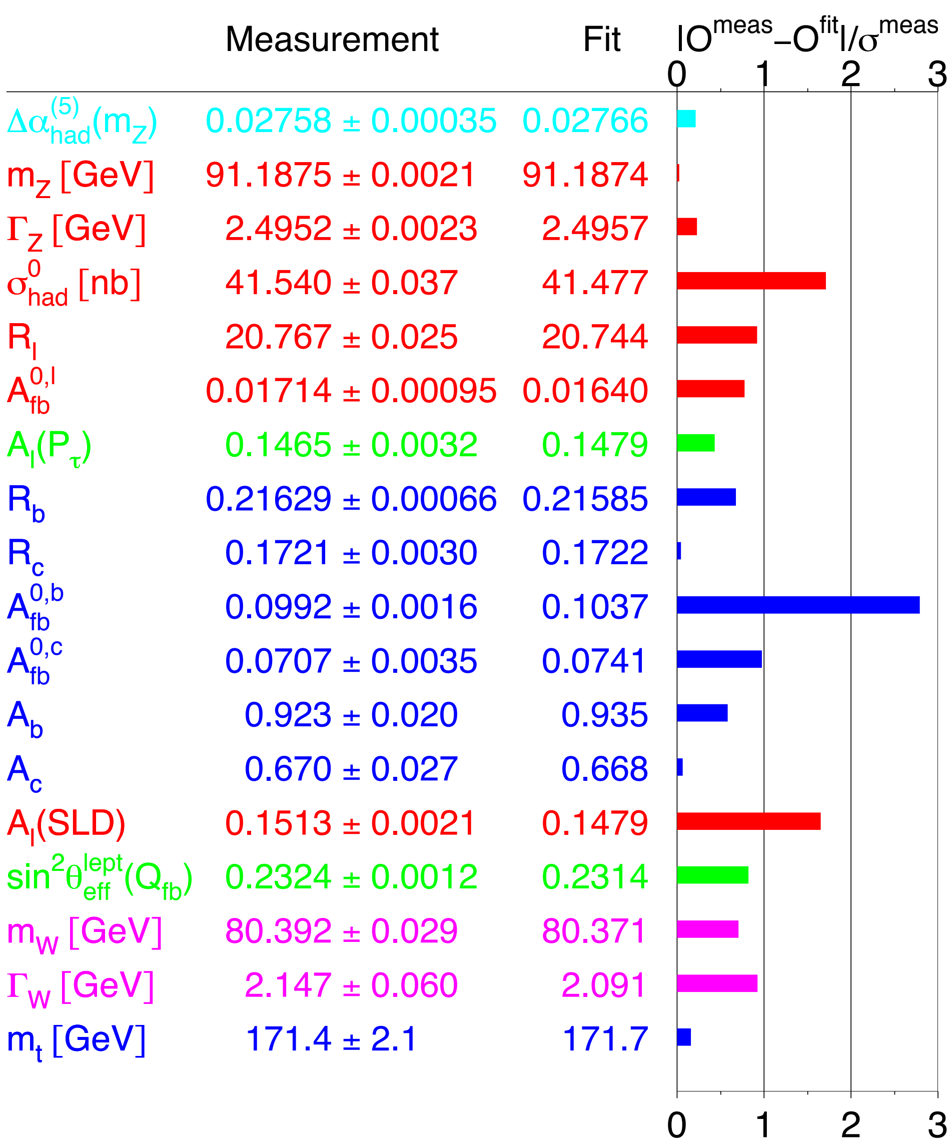


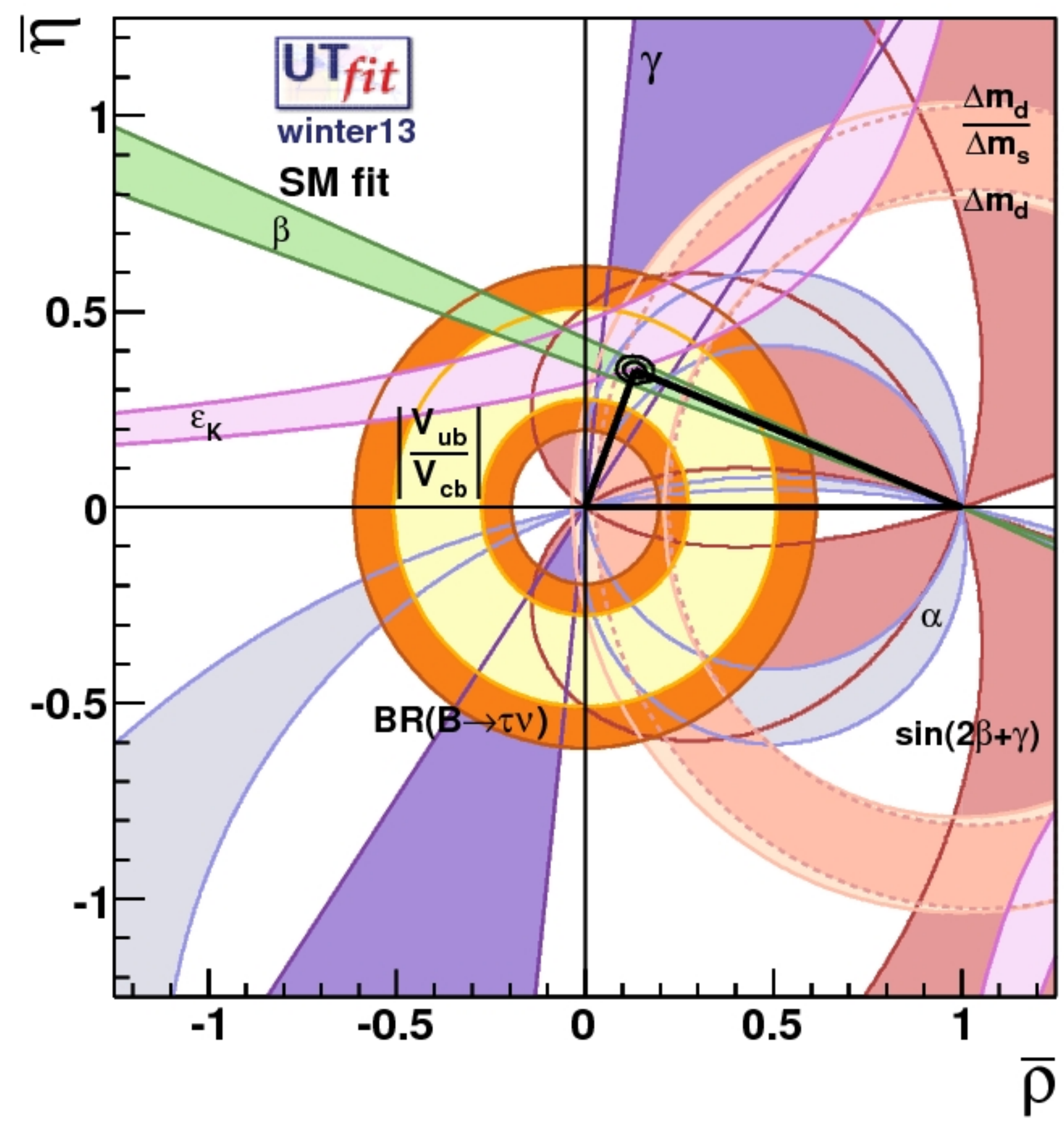
SM Lagrangian

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

Based on local gauge principle

EWPT & CKM





Almost Perfect !

Only Higgs (~SM) and Nothing Else So Far at the LHC

All the interactions except for gravity are described by Quantum Gauge Theories !

Success of SM

- 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
- proton longevity : baryon # is an accidental sym of the SM, and proton is a composite of 3 quarks
- No gauge singlets in the SM
- All the SM fermions chiral > we can understand the origin of their masses through the nonzero Higgs VEV

Lessons for Model Building

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries (B, Li)
- 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
- One 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

Occam's Razor

- A principle of parsimony, economy, or succinctness
- It states that among competing hypotheses, the one that makes the fewest assumptions should be selected
- SM with one Higgs doublet satisfies this principle, as we will see

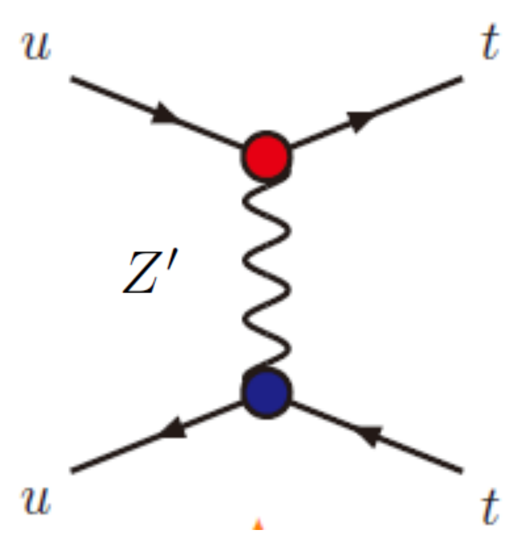
See wikipedia for more details

Totalitarian Principle

- In quantum mechanics, everything not forbidden is compulsory (Gell-Mann)
- Any interaction which is not forbidden by a small number of simple conservation laws is not only allowed, but *must* be included in the sum over all "paths" which contribute to the outcome of the interaction
- What can happen will happen

Z′ model

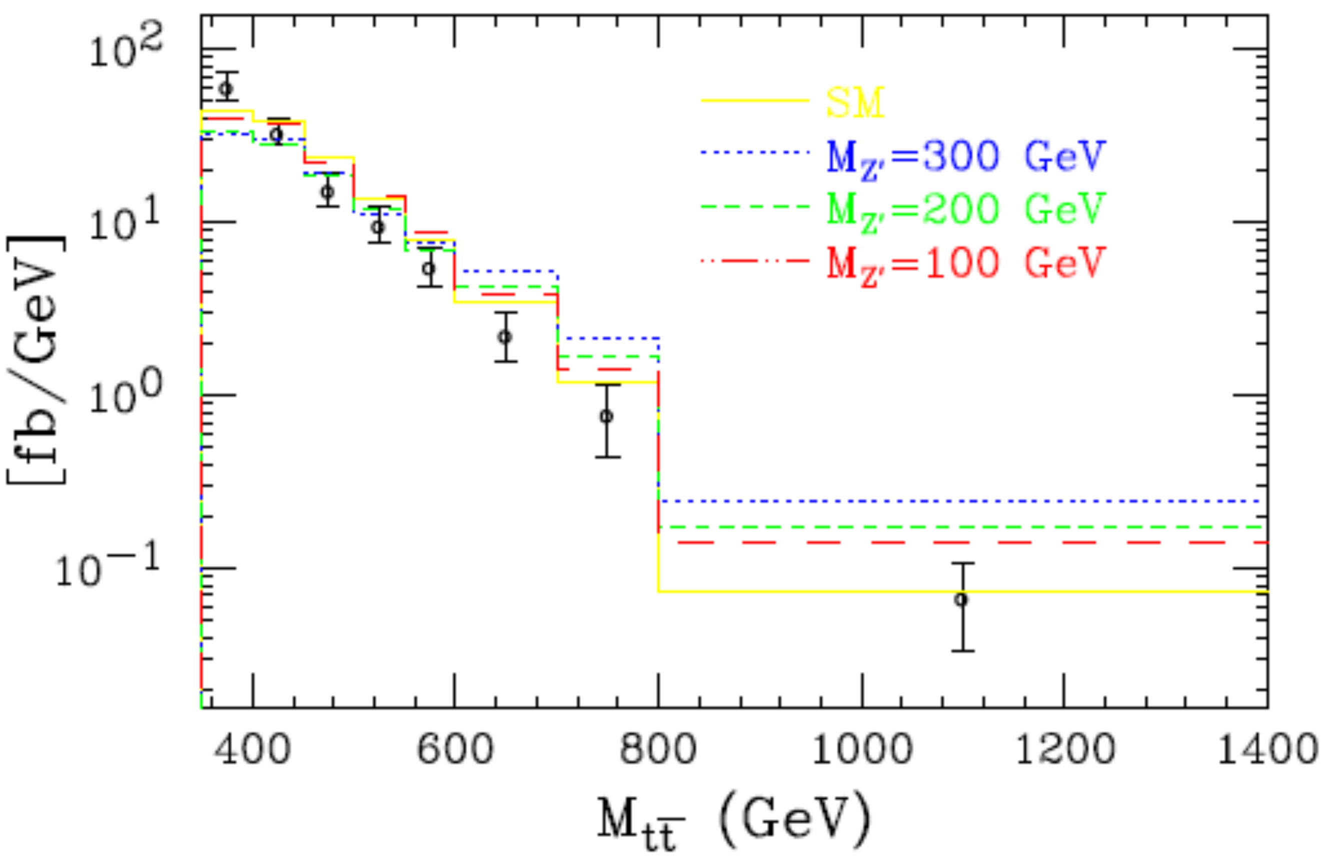
Jung, Murayama, Pierce, Wells, PRD81♪



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

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

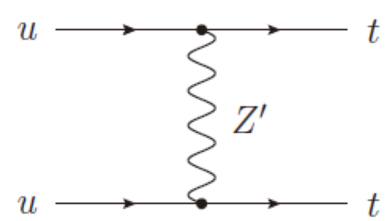
• In general, could have different couplings to the top and antitop quarks.



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

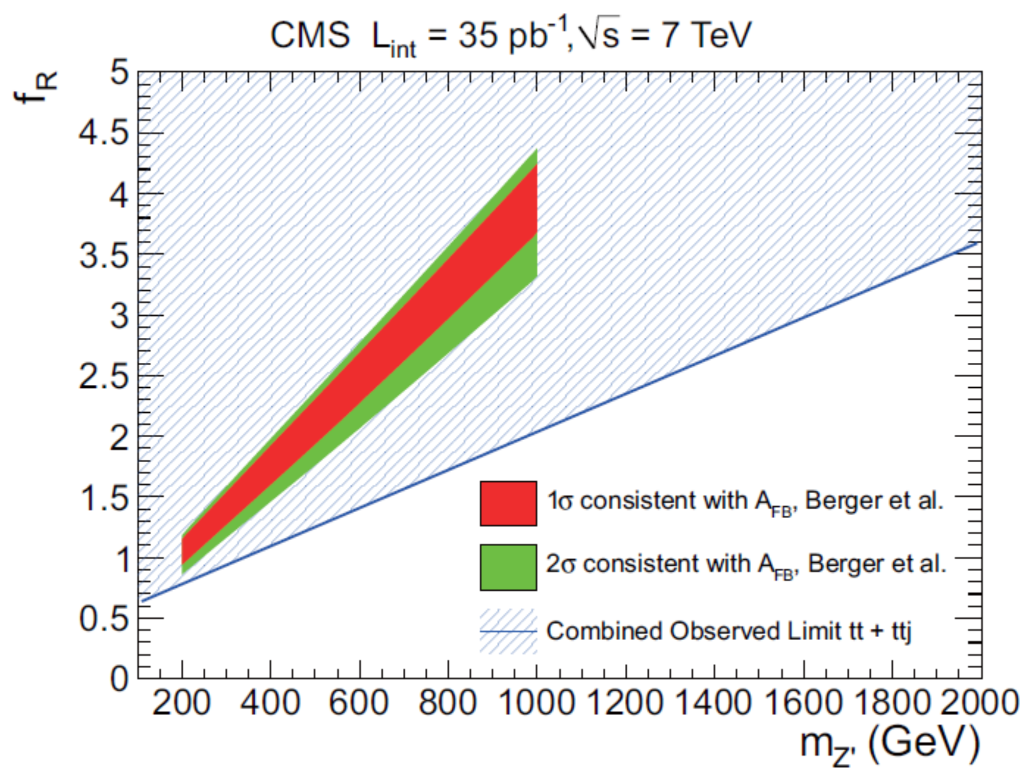
• severely constrained by the same sign top pair production.
- the t-channel scalar exchange model has a similar constraint.

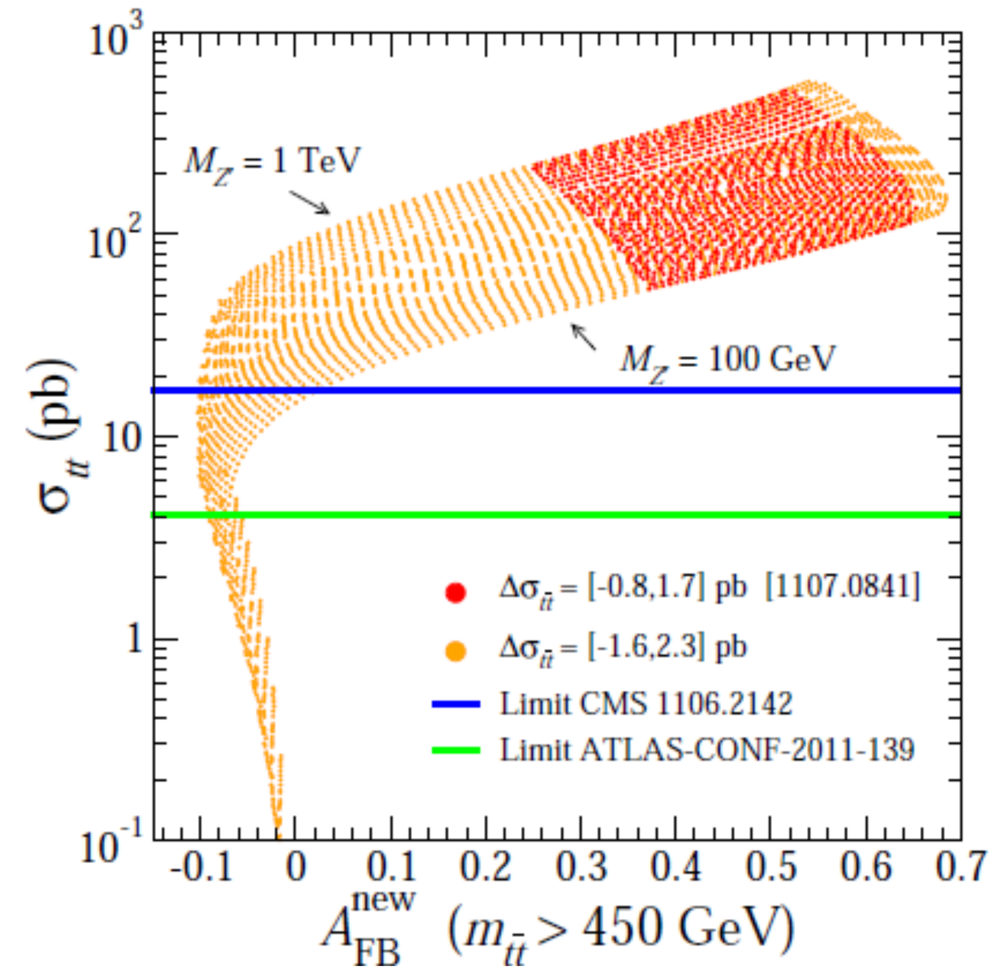
Same sign top pair production at LHC



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

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?
- the answer is NO.

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 ?

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

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!

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

$H_k : U(1)$ 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

- 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

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

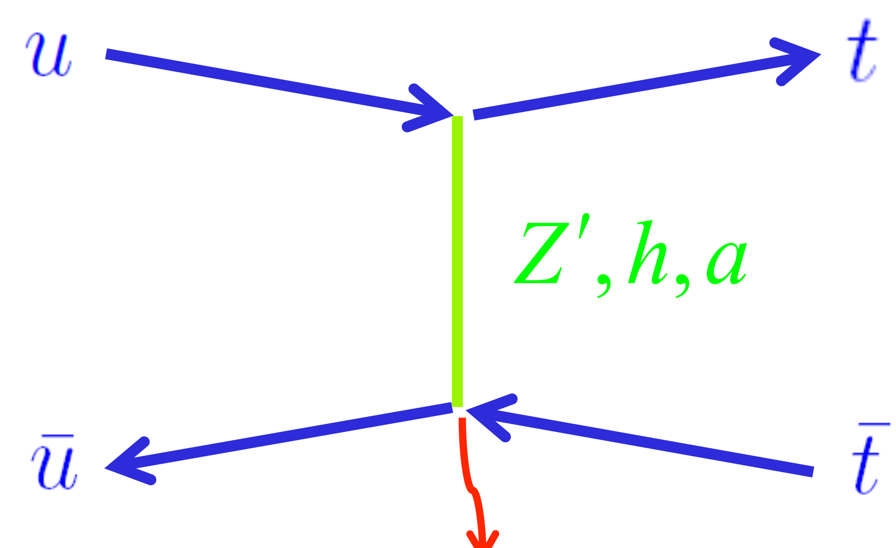
$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,$$

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

Top-antitop pair production

1. Z′ dominant scenario

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



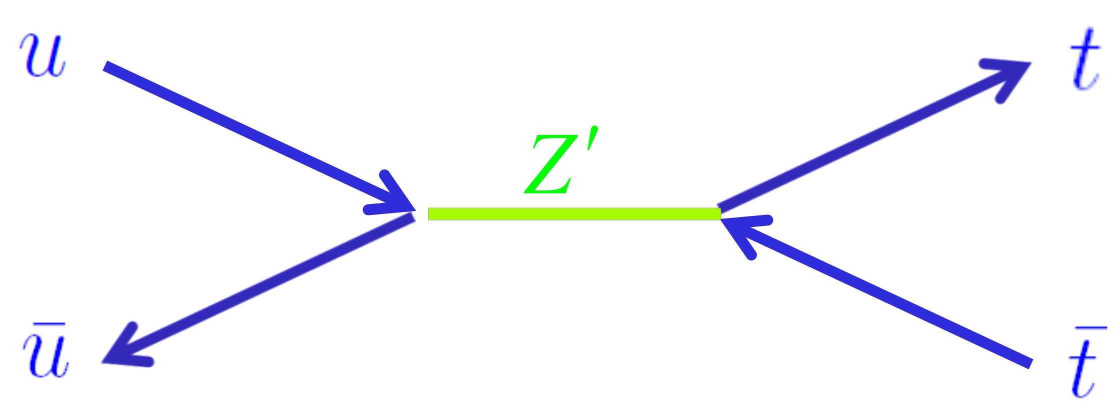
$$\boxed{\alpha_X = \frac{(g' g^u_{Rut})^2}{4\pi}, Y_{tu}, Y^a_{tu}}$$

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

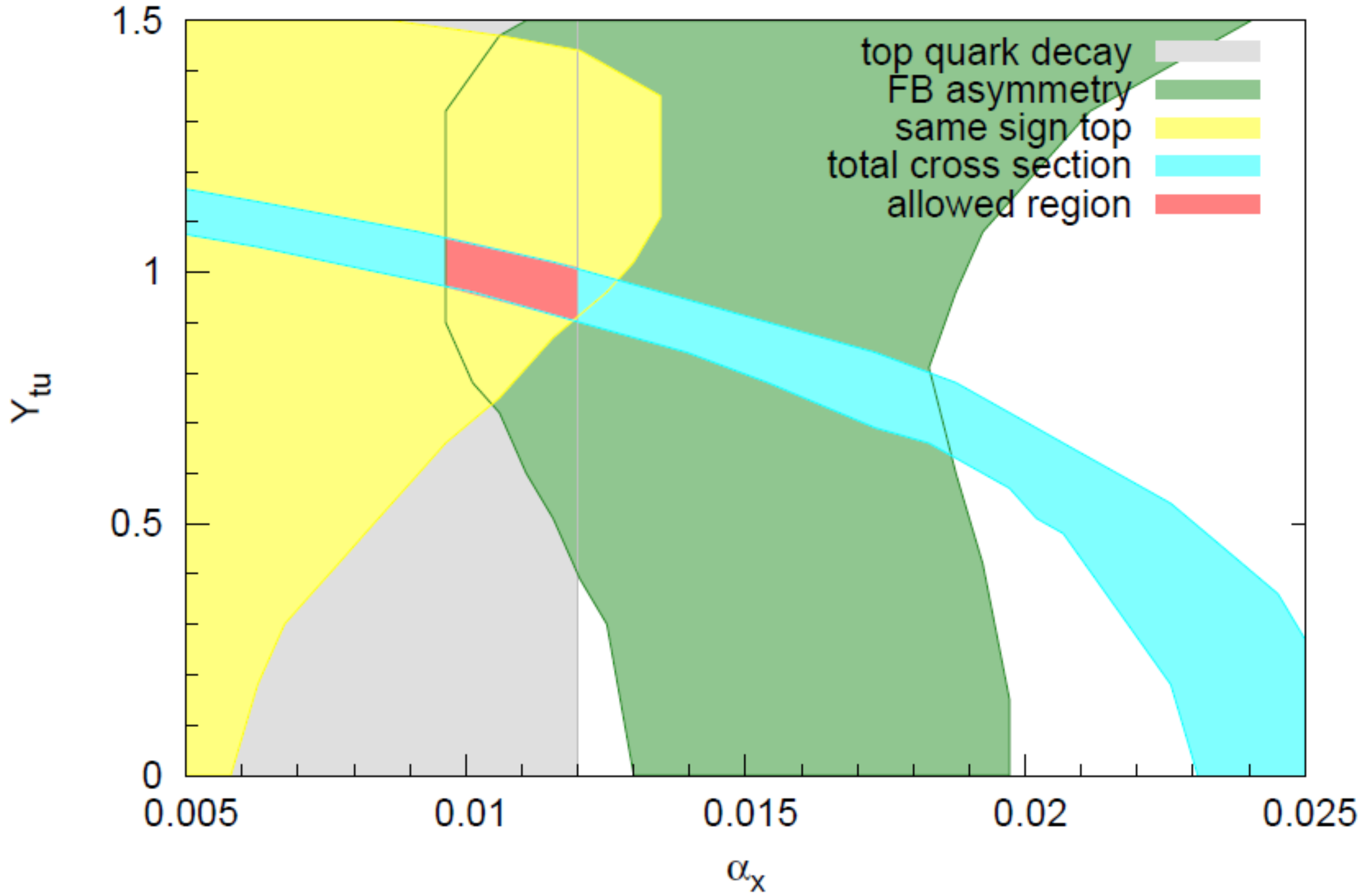
3. Mixed scenario

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



Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

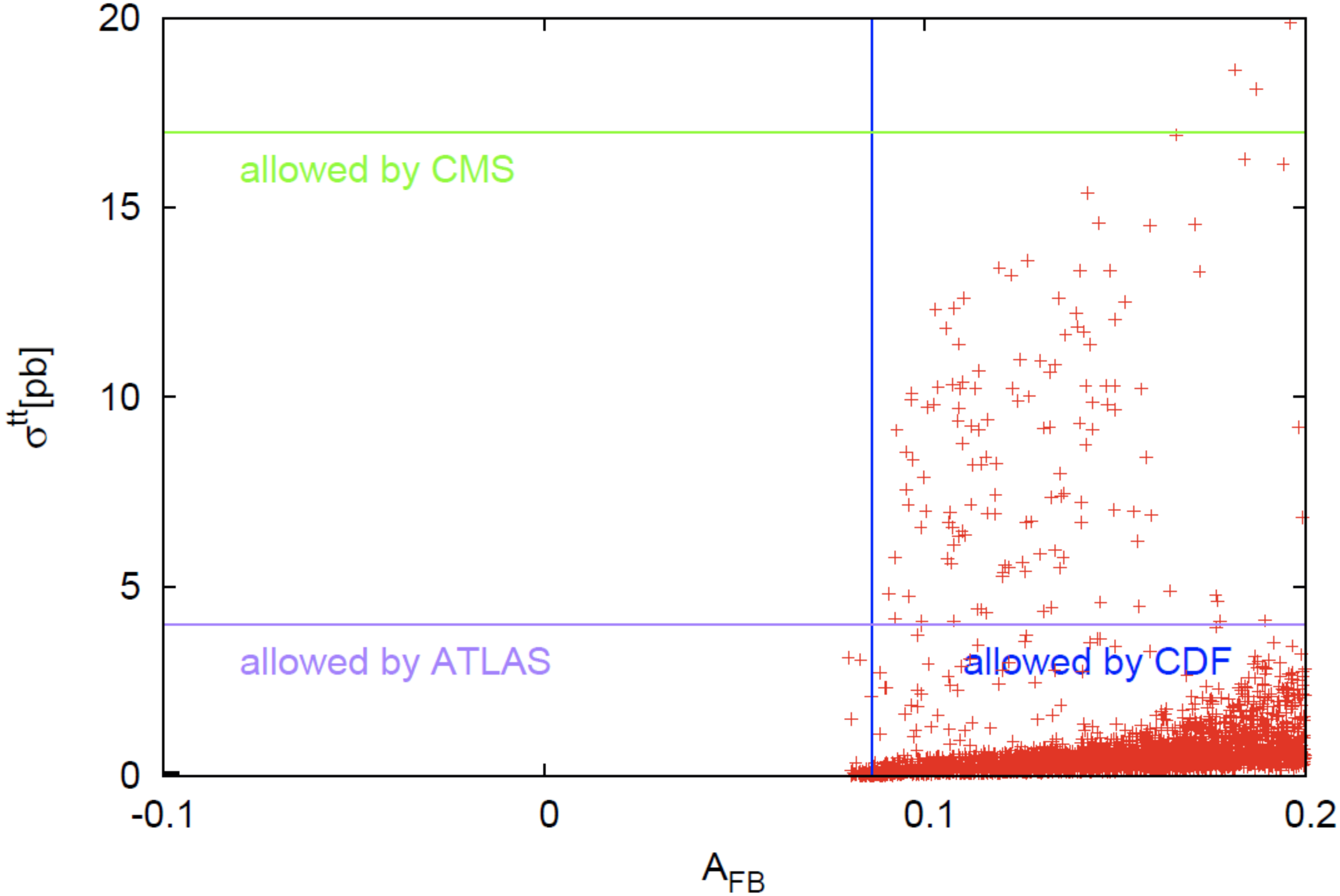
$m_h = 180$ GeV

$m_a = 300$ 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.

A_{FB} versus σ_{tt}



$\boxed{m_h = 126 \text{ GeV}}$

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

$180 \text{ GeV} < m_a < 1 \text{ TeV}$

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

Still OK with new CMS data < 0.39 pb

Summarizing

- 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

New insight for 2HDM

- 2HDM : very popular scenarios for BSM with extended Higgs sectors
- No good reasons : (i) why not ? (ii) tree-level rho parameter =1, (iii) Type II is motivated by MSSM, (iv) …
- 2HDM (and multi-HDM) could be natural if there are new chiral $U(1)_H$ symmetries (see hep-ph/1204.4588, PLB; 1309.7156, JHEP; 1405.2138, JHEP;1502.00262, JHEP; 1601.00586, JHEP, all with Yuji Omura and Chaehyun Yu)
- dim-2 soft Z2 breaking in the usual 2HDM is replaced by $U(1)_H$ symmetry breaking in this new approach

Some Thoughts

- Appraisal of local gauge symmetry : well tested in the SM, and could be relevant to DM physics
- Scale symmetry (?) : probably the only way to understand the origin of mass (especially the masses of scalar bosons and Dirac fermions)
- Pure gauge singlet (?) : all the known particles carry some gauge charges, and no singlet particle found yet in Nature
- Why is there no higher dim representation of gauge group for matter fields ? And why no scalars found other than H?

And of course a lot of questions you can ask !

DM searches @ colliders : Beyond the EFT and simplified DM models

- S. Baek, P. Ko, M. Park, WIPark, C. Yu, arXiv:1506.06556, PLB (2016)
- P. Ko and Hiroshi Yokoya, arXiv:1603.04737, JHEP (2016)
- P. Ko, A. Natale, M. Park, H. Yokoya, arXiv:1605.07058, JHEP(2017)
- P. Ko and Jinmian Li, arXiv:1610.03997, PLB (2017)
- and more recent works

Talk by Jinmian Li on Fri

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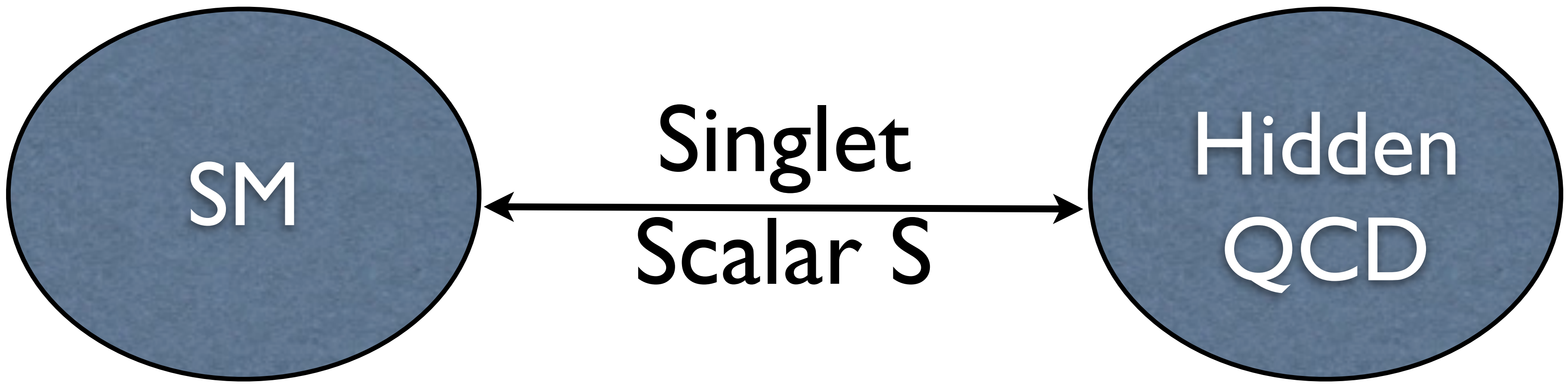
Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by “S”

Appraisal of Scale Invariance

- May be the only way to understand the origin of mass dynamically (including spontaneous sym breaking)
- Without it, we can always write scalar mass terms for any scalar fields, and Dirac mass terms for Dirac fermions, the origin of which is completely unknown
- Probably only way to control higher dimensional op's suppressed by Planck scale

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \\ &+ \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c.\Big)\end{aligned}$$

Hidden sector lagrangian with new strong interaction

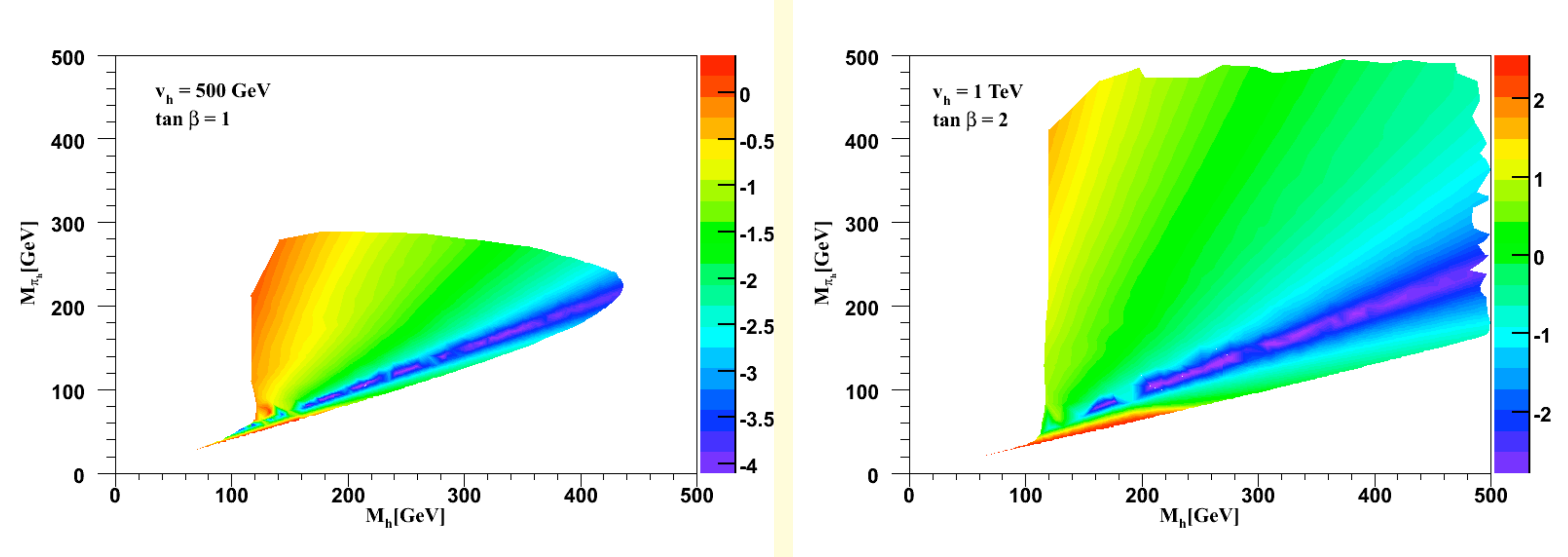
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}_{\rm hidden}^{\rm eff} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}_{\rm hidden}^{\rm eff} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

Relic density

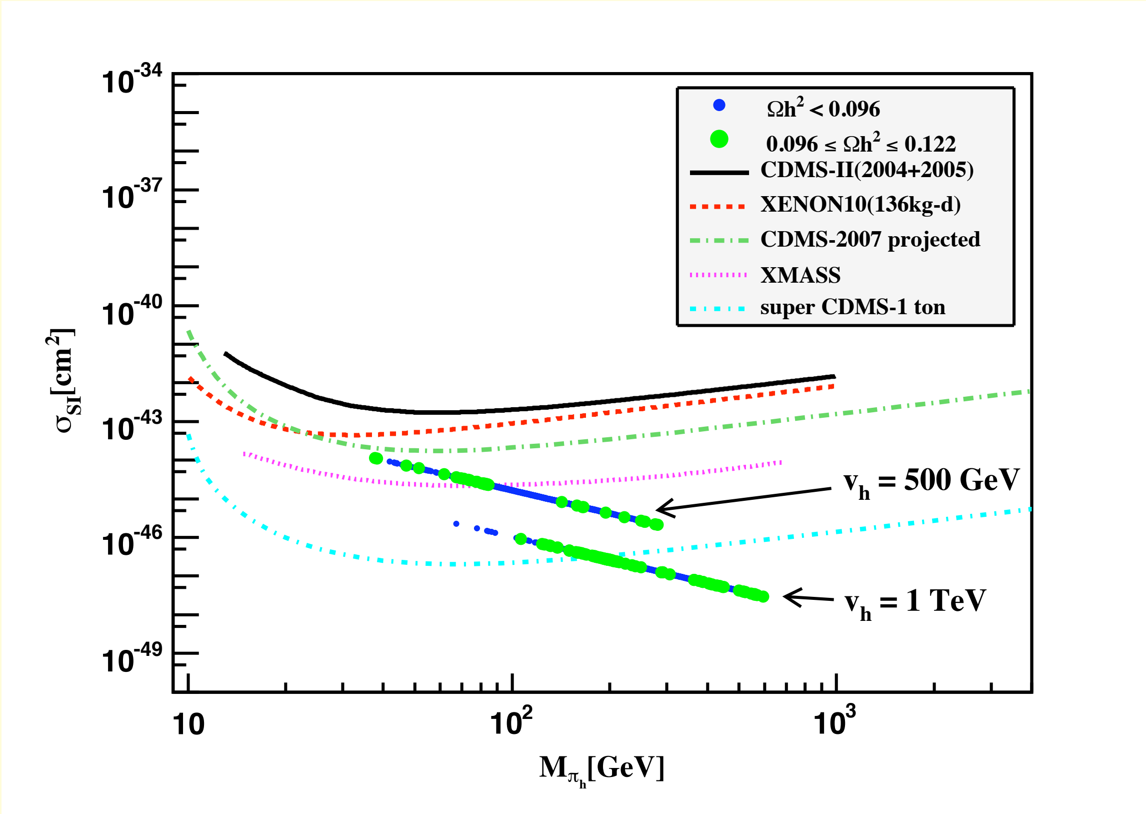


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

So far

- I discussed dark pion DM as WIMP
- SIMP scenario is also possible if we include Wess-Zumino-Witten term : talk by Alex Natale on Wed

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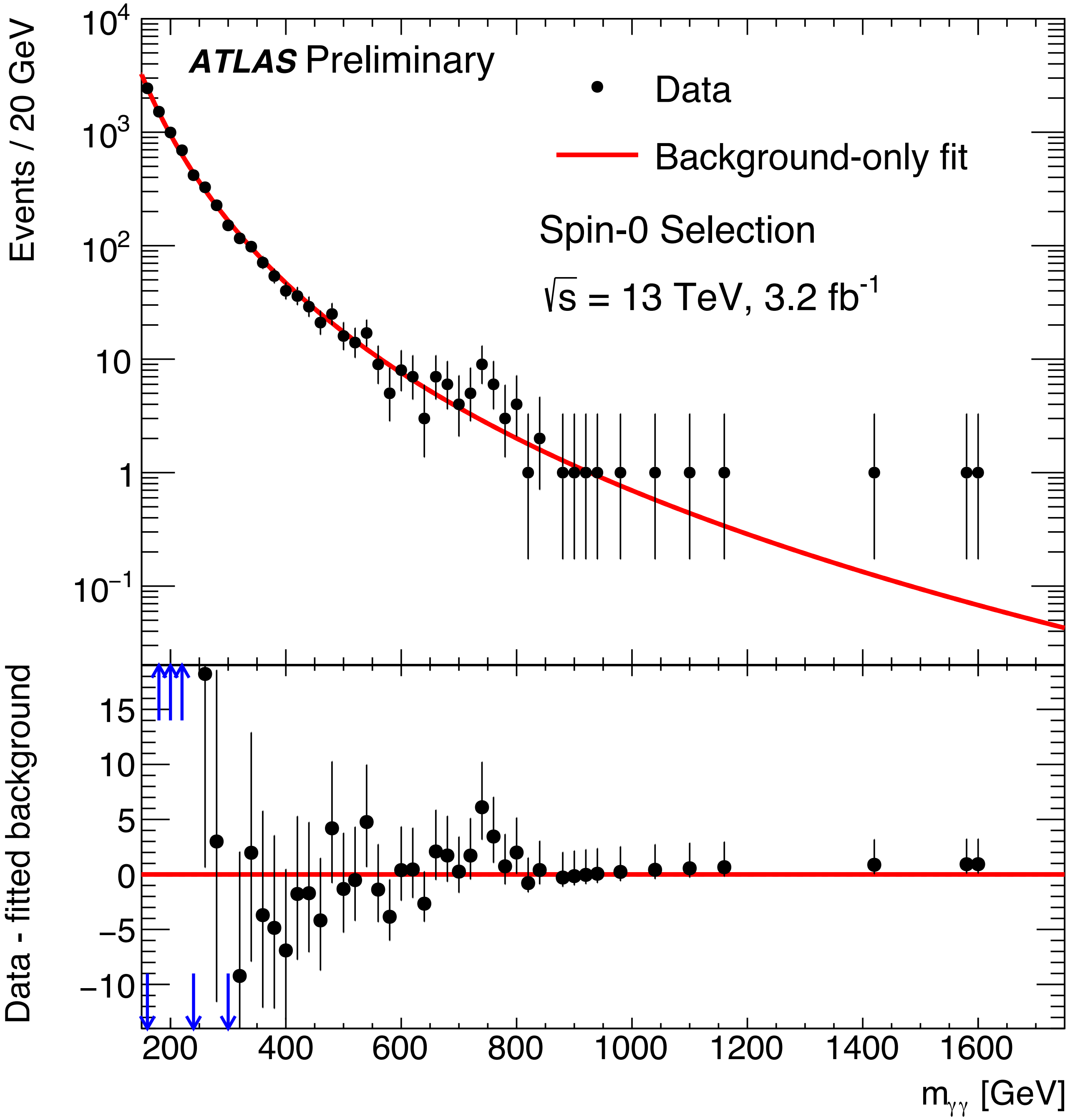
Results

SPIN-0 ANALYSIS

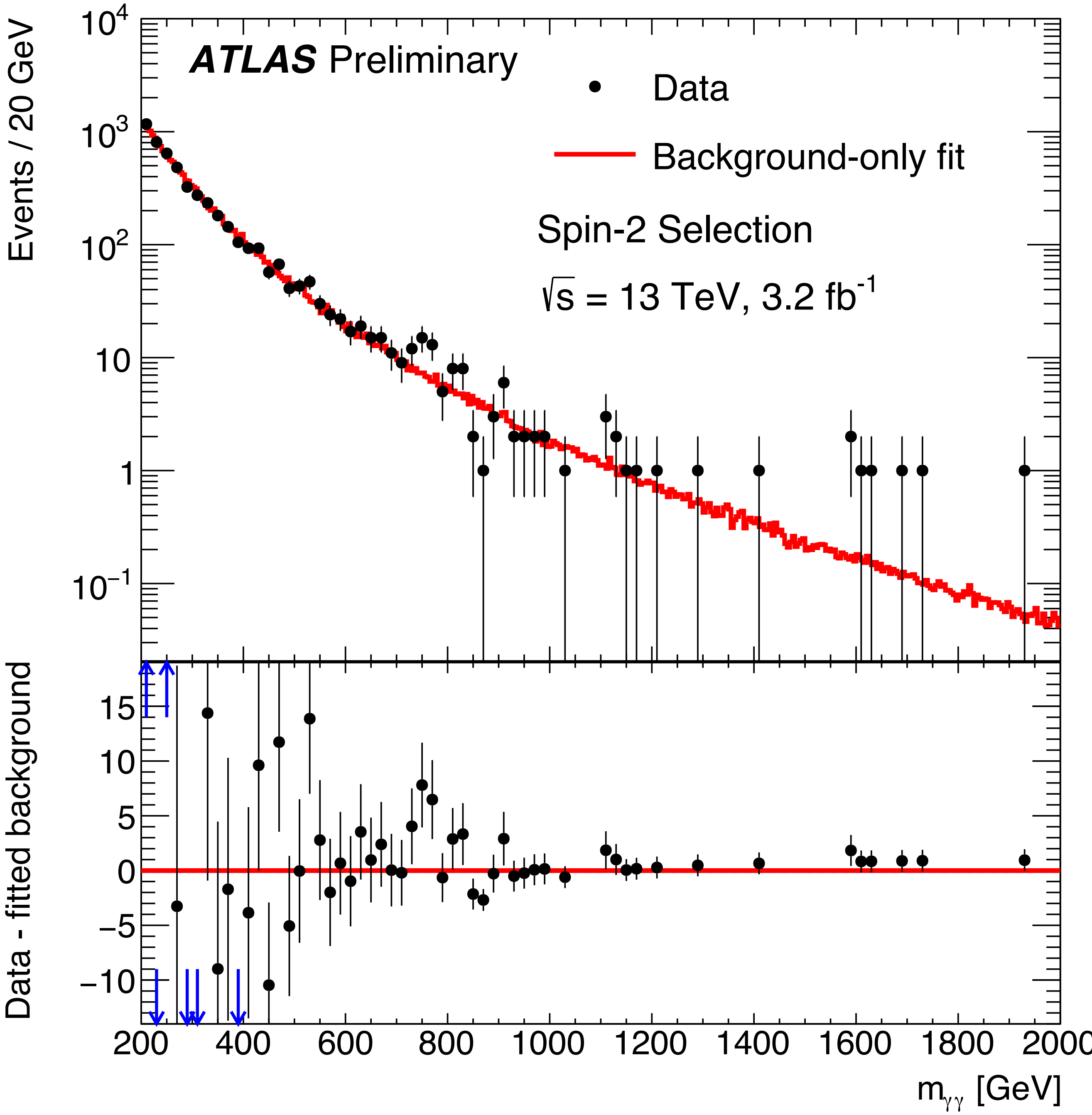
background-only fit



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

SPIN-2 ANALYSIS

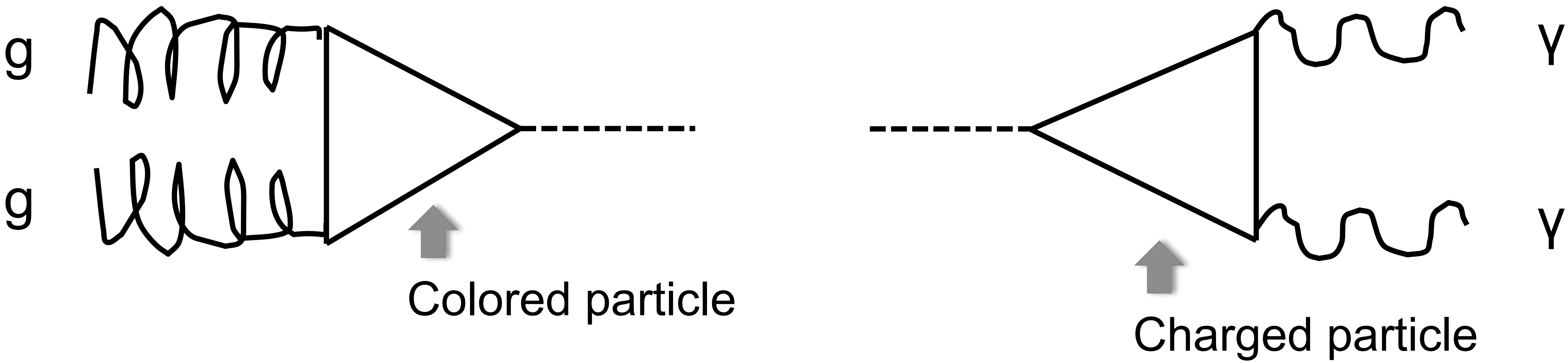
background-only fit



5066 events ($m_{\gamma\gamma}$ > 200 GeV)

One scenario: gluon fusion + diphoton decay via loop

Production: gluon fusion **Diphoton decay channel**



It is not easy to get $\sigma(gg \to \Phi_{New})BR(\Phi_{New} \to \gamma\gamma) \sim 5$ fb

Ex) Two Higgs doublet Model (Type-II) (Angelescu, Djouadi, Moreau arxiv:1512.0492)

$\sigma(gg \to H) \sim 850$ fb $\times \cot^2\beta$ $\sigma(gg \to A) \sim 850$ fb $\times 2\cot^2\beta$

$BR(H \to \gamma\gamma) \sim O(10^{-5})$ $BR(A \to \gamma\gamma) \sim O(10^{-5})$

We need exotic colored and/or charged particles

Let us discuss simple case of (SM) singlet scalar boson + exotic particles

Basic Questions

- Raison d'être of (fundamental?) singlet scalar and vector-like fermions ? Completely singlet particles ???

- Uncomfortable to have a completely singlet

- Two Options : Another new Higgs boson related with

- New spontaneously broken gauge symmetry, or

- Composite (pseudo)scalar boson

- Why vector like fermions have EW scale mass ?

Answers

- New chiral U(1)' symmetry broken by new singlet scalar (Higgs)
- 750 GeV excess ~ U(1)' breaking scalar (could be even dark Higgs)
- Vectorlike fermions : chiral under new U(1)' , anomaly cancellation, and get massive by new Higgs mechanism ~ EW scale mass
- Can we generate phi(750) decay width ~ 45 GeV without any conflict with the known constraints ?
- Yes, if phi(750) mainly decays into new particles
- Many examples : (i) Leptophobic U(1)' with fermions in the fundamental representation of E6, (ii) anther similar 2HDM + singlet model (iii) Dark U(1)' plus dark sector, Dark Higgs decay into a pair of Z'

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Cautions on EFT

$\pi^\pm \to \mu^\pm \nu, e^\pm \nu$ decay

- Naive guess does not work. WHY ?

$$\mathcal{L} = y\pi \bar{l}\nu$$

- This works better.

$$\mathcal{L} = \frac{1}{\Lambda}\partial_\mu \pi \bar{l}\gamma^\mu (1-\gamma_5)\nu$$

- This implies that the vector mediator between the leptonic current and the hadronic current
- Vector field $\sim$ gauge field couples to the conserved current and show the universality
- Note that $\tau(\pi^\pm) = 2.6 \times 10^{-8}$, vs. $\tau(\mu) = 2.2 \times 10^{-6}$
- Universality ?

$\pi^\pm \to \mu^\pm\nu, e^\pm\nu$ decay (cont'd)

- Eventually the correct answer is

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\bar{u}\gamma^\mu(1-\gamma_5)d\bar{l}\gamma^\mu(1-\gamma_5)\nu$$

  with $< 0|\bar{u}\gamma^\mu\gamma_5 d|\pi(q) >= i f_\pi q^\mu$ ($f_\pi = 93$ MeV)
- Vector interaction : gauge interaction which has Universality
- But gauge fields can couple to conserved currents
- Then K, η were discovered below proton mass :$SU(2)_f \to SU(3)_f$
- And ρ mesons were discovered in the $I = J = 1$ channel in the $\pi\pi$ scattering

Something for future ?

- Test SM as many ways as possible : need improved understanding of PQCD; measurements of Higgs self couplings, Yukawa couplings, etc.

- Resolve some current anomalies : muon g-2, proton radius in monic hydrogen, B physics anomalies, etc

- Cover the WIMP parameter space from LHC, DM (in)direct detection as much as possible

- Axion/axion-like particle search

- Complete (or better) understanding of neutrinos (Majorana vs. Dirac, CP phase, mass ordering, sterile neutrino, etc.)
- New particles around EW scale accessible at the LHC ? (SUSY, extra dim, new scalars/fermions/vectors, etc.)
- What would be the new or interesting energy scale, if nothing is found at the HL LHC ?
- Connection between particle physics & cosmology (collider, (in)direct DM search vs. gravitational wave, CMS, LSS, etc.)
- DE, DR, DM interactions (data vs. theory) ? (DM-DR interactions for relaxing the tension between H0 and sigma8 in 3 papers with Yong Tang ; 1608.01083, PLB;1609.02307, PLB;1706.05605, PLB(with Nagata))

Hope to see something new/unexpected from on-going experiments