New resonances at the LHC

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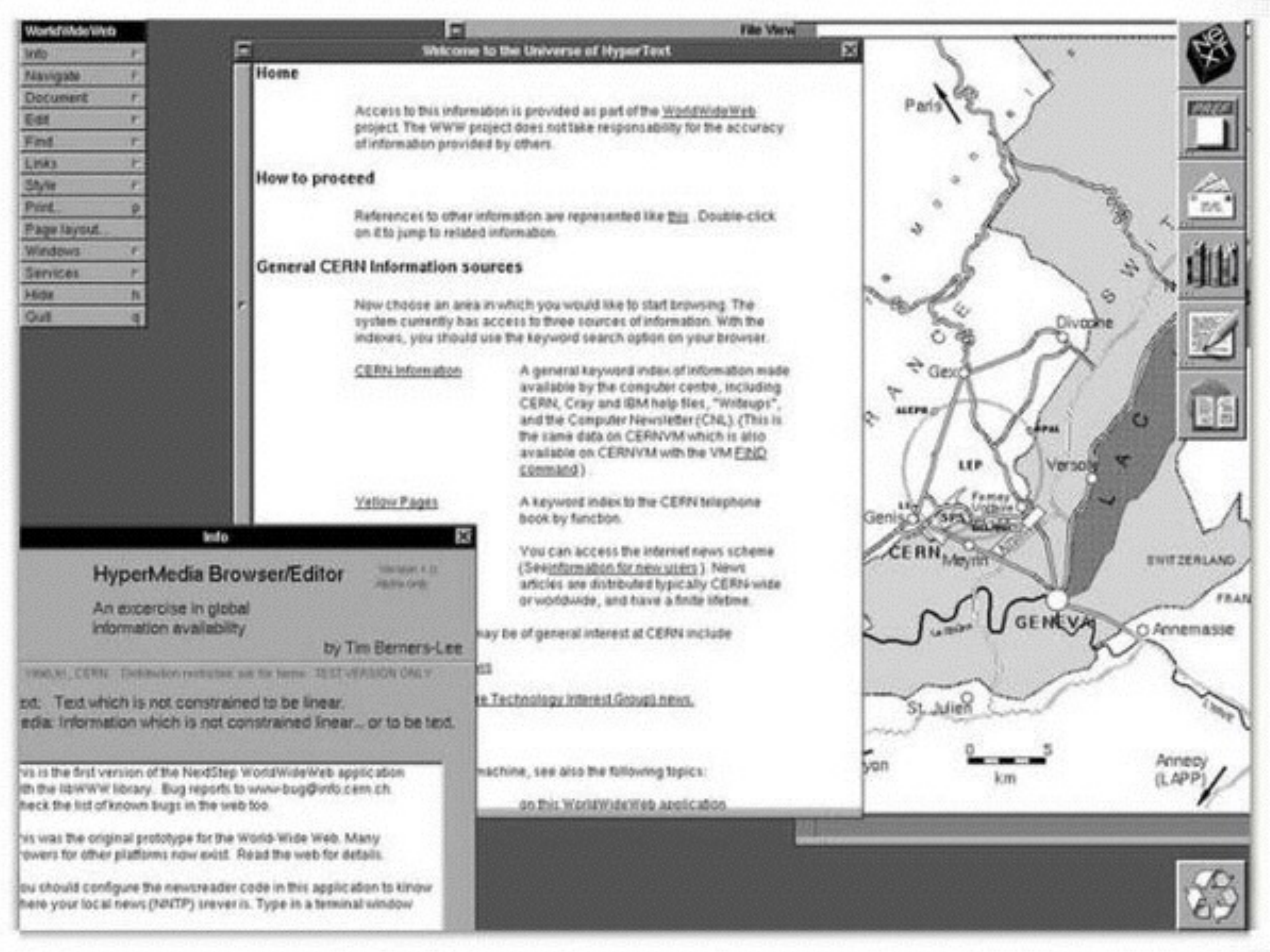
Yonsei Univ. & KIAS

The 12th Saga-Yonsei workshop
Dec. 21, 2015@ Yonsei University

25 years ago today, the first web page went online @CERN



Welcome to the Universe of HyperText

Home

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References to other information are represented like this . Double-click on it to jump to related information.

General CERN Information sources

Now choose an area in which you would like to start browsing. The system currently has access to three sources of information. With the indexes, you should use the keyword search option on your browser.

CERN Information	A general keyword index of information made available by the computer centre, including CERN, Cray and IBM help files, "Writeups", and the Computer Newsletter (CNL). (This is the same data on CERNVM which is also available on CERNVM with the VM FIND command)
Yellow Pages	A keyword index to the CERN telephone book by function.
	You can access the internet news scheme (See information for new users). News articles are distributed typically CERN-wide or worldwide, and have a finite lifetime.

nay be of general interest at CERN include

e Technology Interest Group) news.

nachine, see also the following topics:

on this WorldWideWeb application

Info

HyperMedia Browser/Editor

An excercise in global information availability

by Tim Berners-Lee

xt: Text which is not constrained to be linear.
edia: Information which is not constrained linear... or to be text.

is is the first version of the NextStep WorldWideWeb application
th the libWWW library. Bug reports to www-bug@info.cern.ch
heck the list of known bugs in the web too.

is was the original prototype for the World-Wide Web. Many
owers for other platforms now exist. Read the web for details.

ou should configure the newsreader code in this application to know
here your local news (NNTP) srever is. Type in a terminal window

After then,the world
changed completely
in an irreversible way

Some say we should invest
our money to where
economical return is high

Probably the best place is
PURE SCIENCE where
new ideas are born.

Particle physics

- The forefront of human’s understanding about Nature
- Looking for ‘fundamental principles’ which govern how Nature works, what Universe is composed with
- We look into elementary particles because we think we can learn the fundamental principles from them most efficiently!
- NOT BECAUSE we are interested in small things

Cosmology

- Indeed, we are interested in ‘Large things’ too
- Universe -our patch universe-, is the largest physical object we are interested in
- used to be ‘small’ 13.7b years ago
- Particle physics provides very useful framework to understand Universe itself!

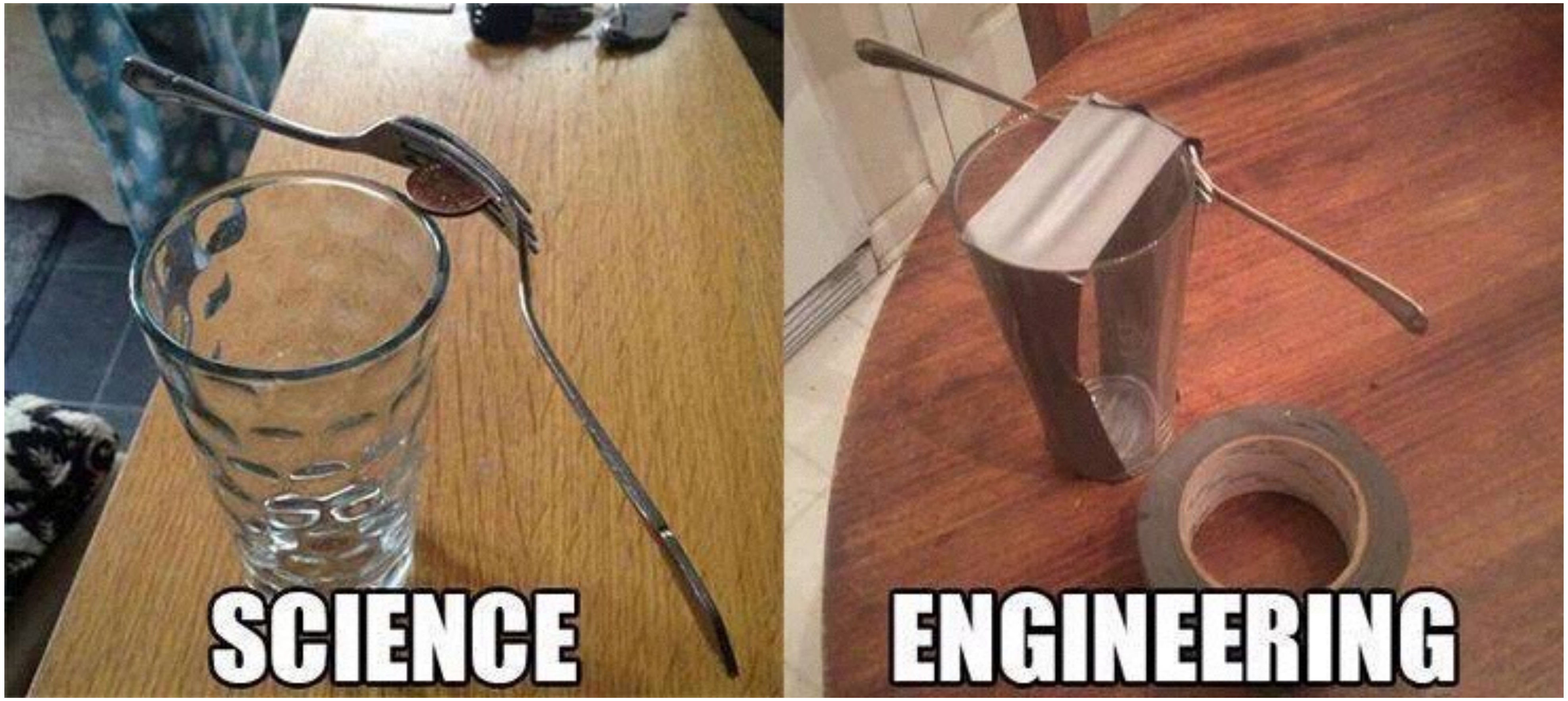
for students

- Don’t forget that we are looking for fundamental principles

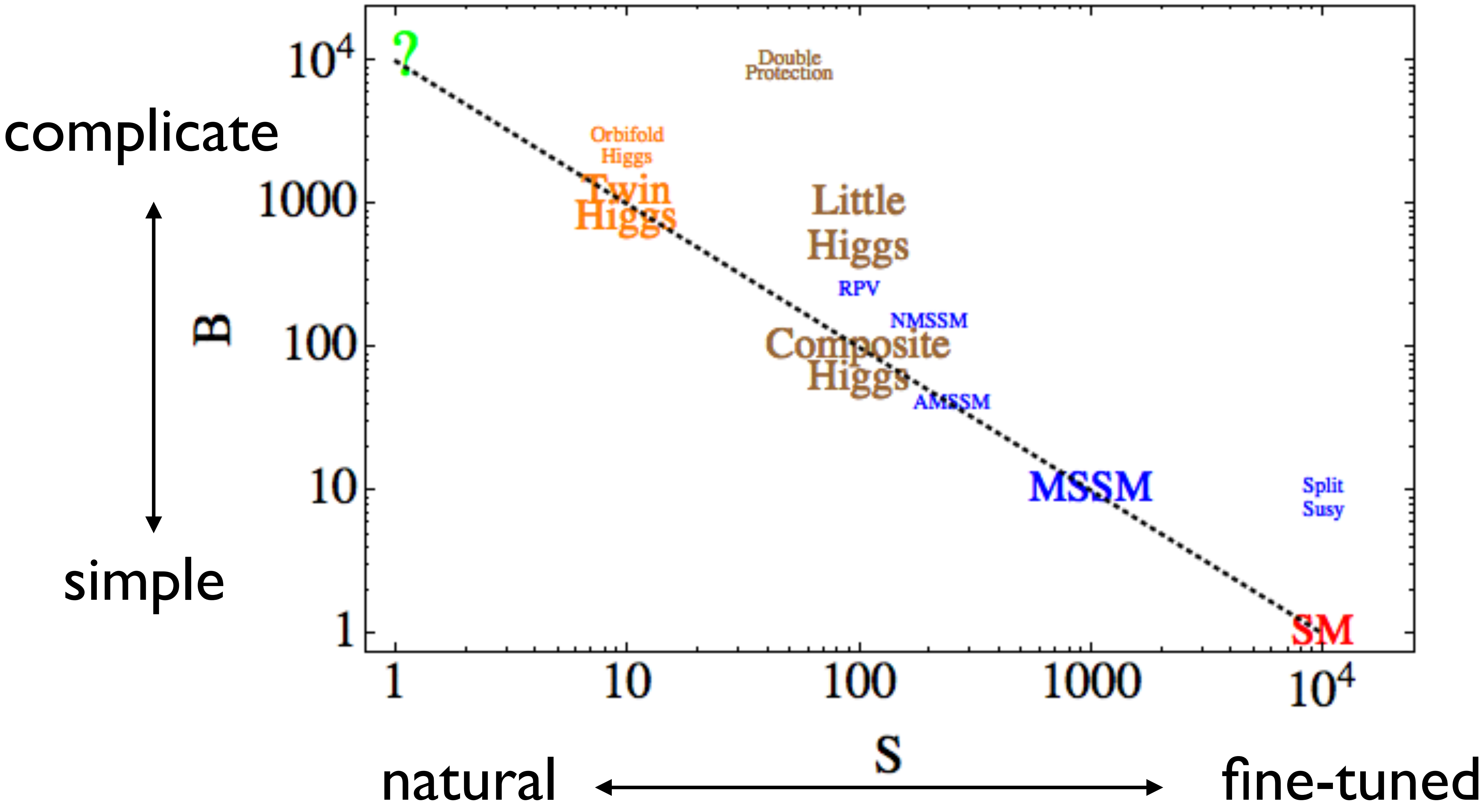
- This is NOT a small goal but probably the toughest goal

- We should be humble in front of Nature but you’d better be ambitious, work hard and think hard

What are we doing here?



BS diagram



complicate

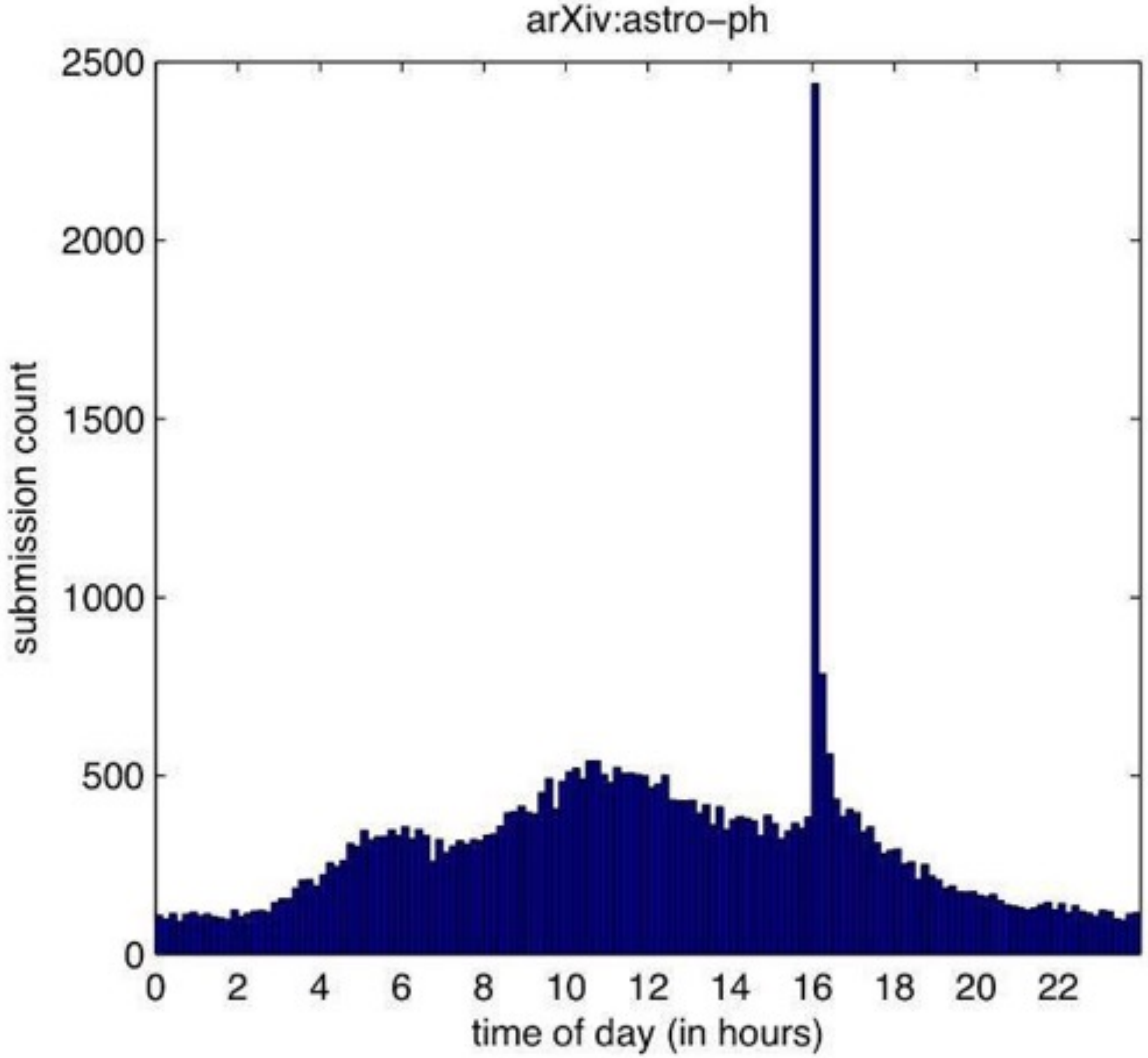
simple

natural

fine-tuned

credit: A. Falkowski

Resonance tells us a lot about what behind



US/EST

arXiv:0907.4740

Today's topics

- Top-philic resonance

Nicolas Greiner, Kyoungchul Kong, Jong-Chul Park, ***SCP***, Jan-Christopher Winter
JHEP 1504 (2015) 029

- Diboson resonance

Doojin Kim, Kyoungchul Kong, Hyun Min Lee, ***SCP***
JHEP 1511 (2015) 150

- Diphoton resonance @750 GeV coming soon

Part 1

Top-Philic Resonance at the LHC

Nicolas Greiner, Kyoungchul Kong, Jong-Chul Park, **SCP**, Jan-Christopher Winter
JHEP 1504 (2015) 029

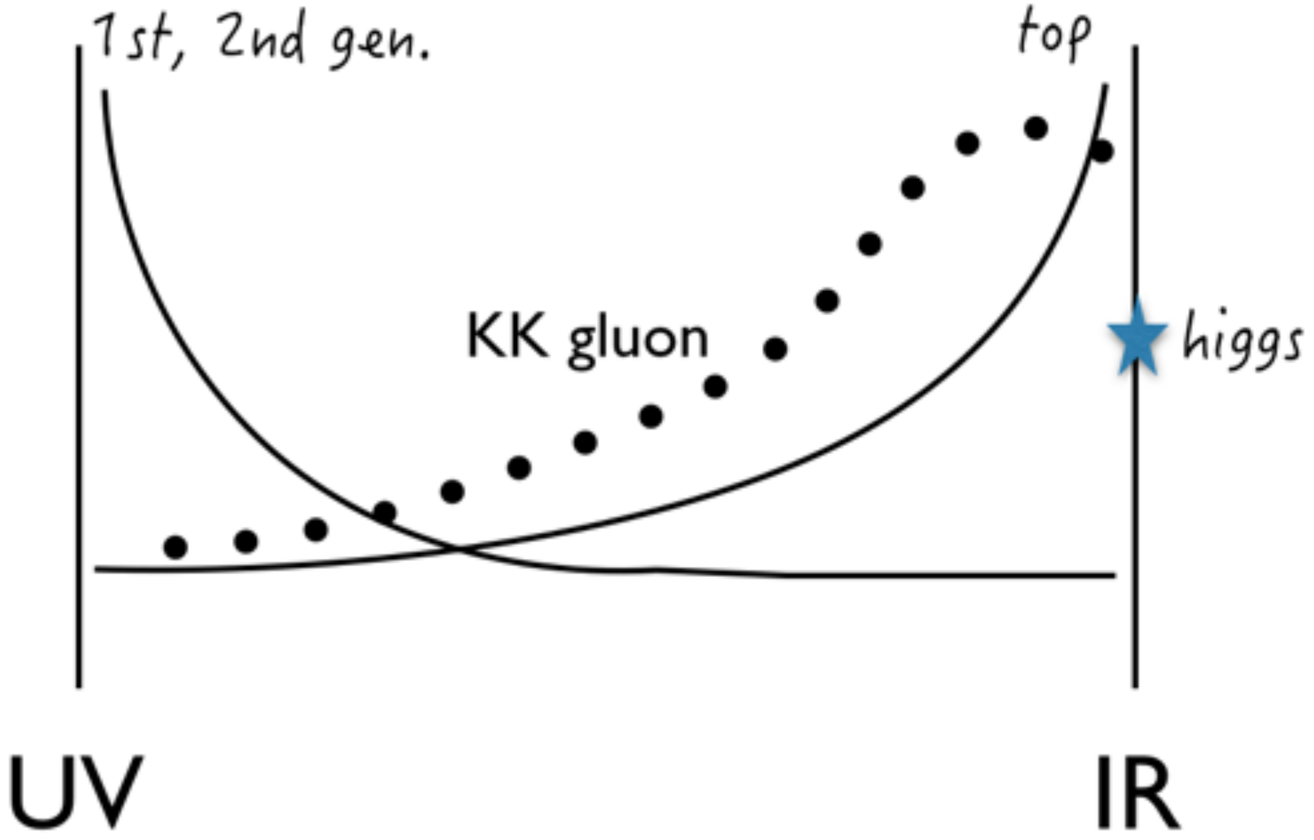
Top-philic resonance (TPR)

- New physics may have a sizable coupling only with top quark
- LHC is not the best place for this kind of new physics!

$$PDF(Q^2, x; top) = 0$$

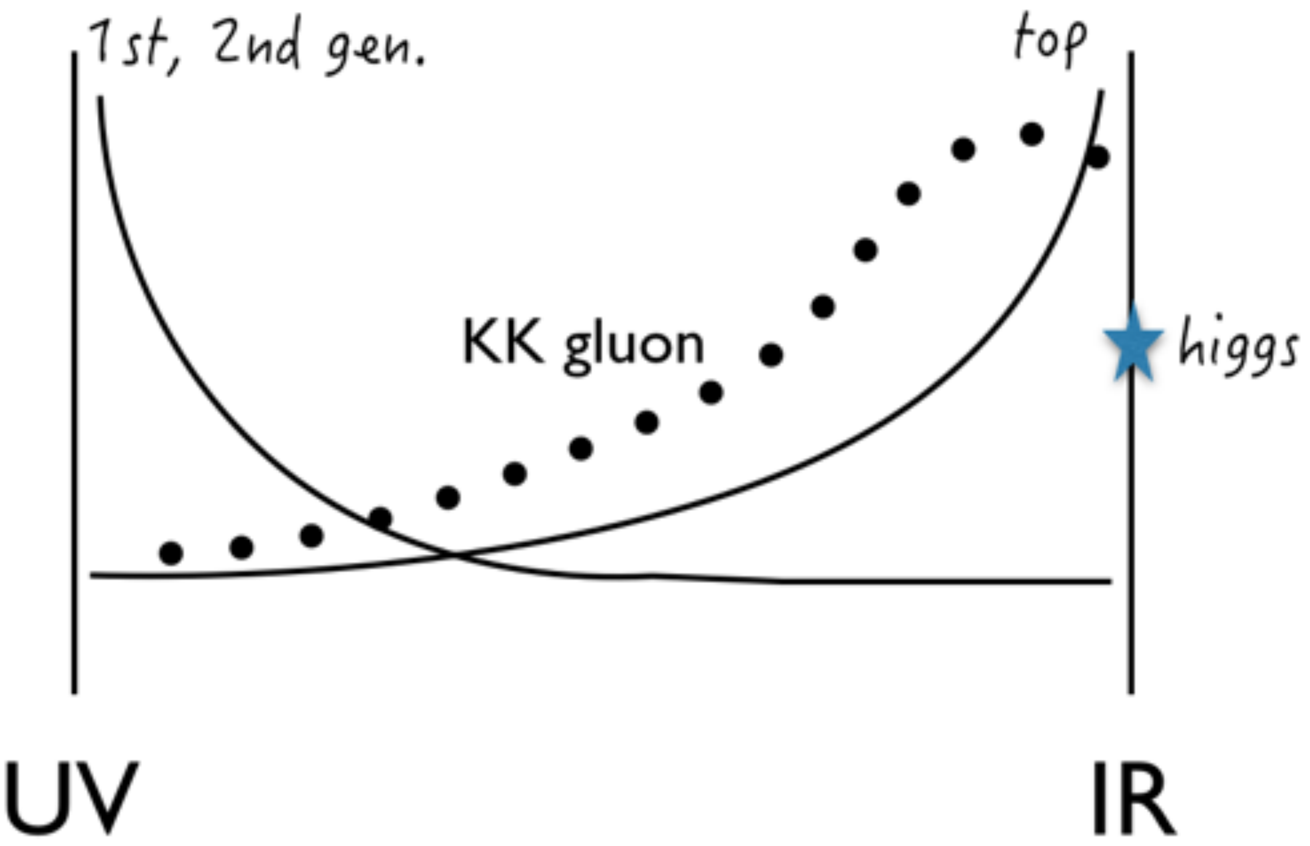
- We need to be clever to probe this kind of new physics

A model for TPR



effective coupling=wave function overlap

$$c_t = \int dy f_{G_3} f_t f_t$$



$$c_t \gg c_{u,d,\cdots}$$

“top-philic vector boson"

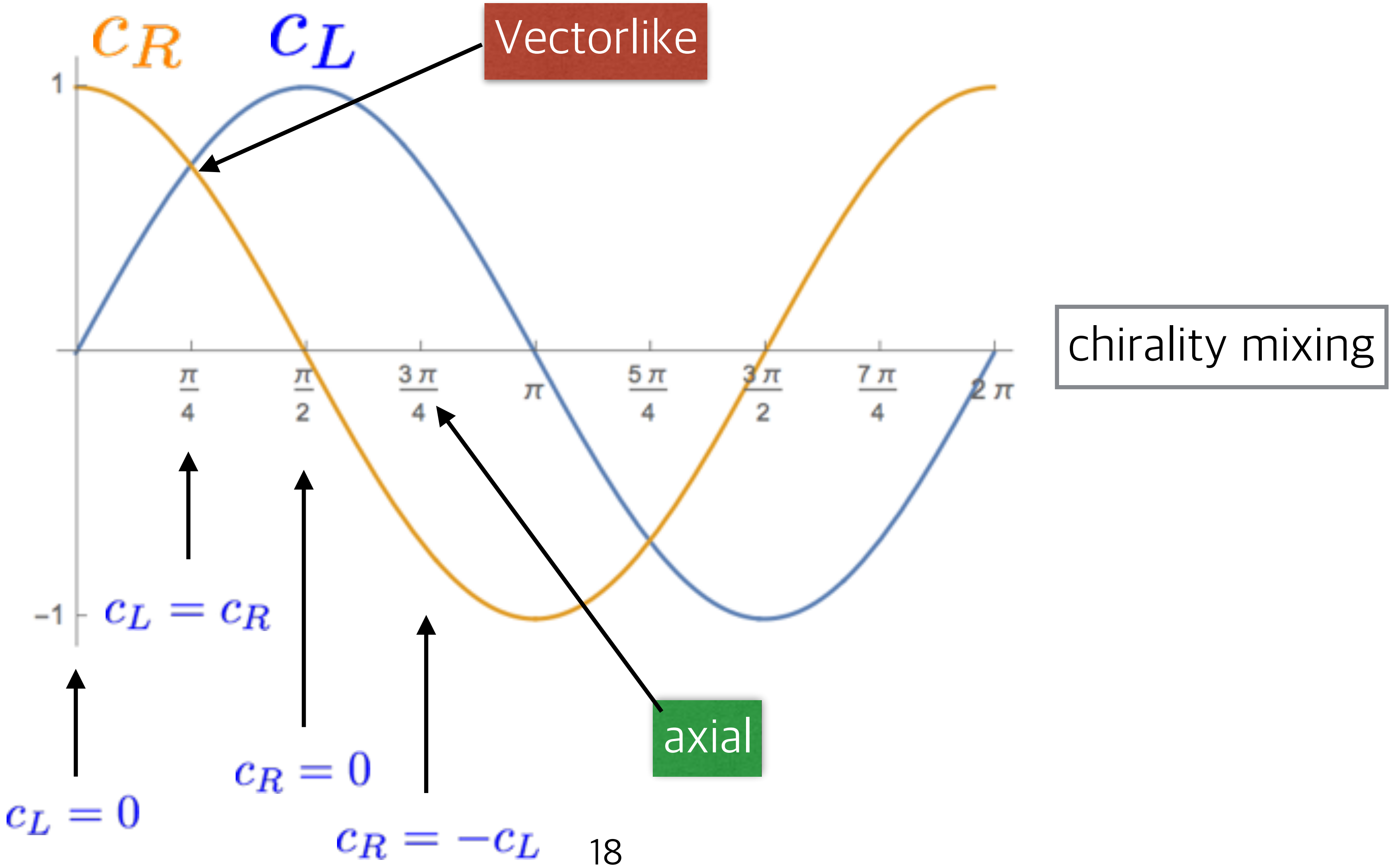
An effective Lagrangian

$$\begin{aligned} \mathcal{L} &= \bar{t}\,\gamma_\mu\Big(c_L P_L + c_R P_R\Big)t\,G_3^\mu\ , \\ &= c_t\,\bar{t}\,\gamma_\mu\Big(\cos\theta\,P_L + \sin\theta\,P_R\Big)t\,G_3^\mu \end{aligned}$$

- “theta” : generic chiral structure
- “c_t” : coupling strength ~O(1)

Chirality structure for G_3

$$\begin{aligned}\mathcal{L} &= \bar{t}\gamma_\mu\Big(c_L P_L + c_R P_R\Big)t\,G_3^\mu\,,\\ &= c_t\,\bar{t}\gamma_\mu\Big(\cos\theta\,P_L + \sin\theta\,P_R\Big)t\,G_3^\mu\end{aligned}$$



Vectorlike

chirality mixing

$c_L = c_R$

$c_L = 0$

$c_R = 0$

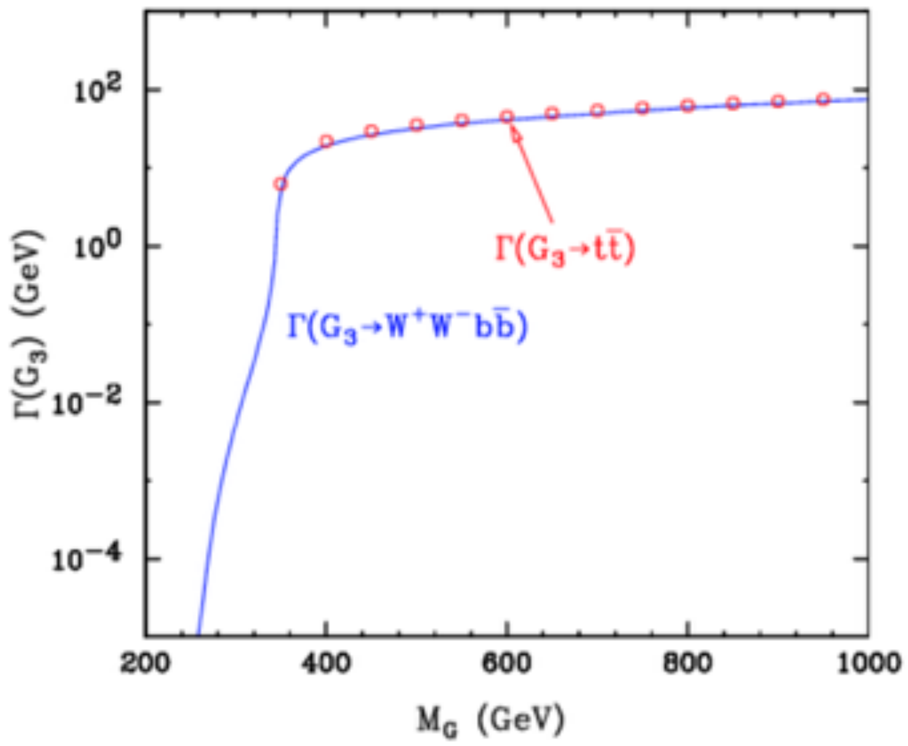
$c_R = -c_L$

axial

Decay of G_3

$$\begin{aligned}\Gamma\left(G_3\to t\bar{t}\right) &= \frac{c_t^2\,M_G}{8\pi}\sqrt{1-\frac{4\,m_t^2}{M_G^2}}\left[1+\frac{m_t^2}{M_G^2}\left(3\sin 2\theta-1\right)\right]\\ &\approx \frac{c_t^2\,M_G}{8\pi} \qquad \text{for } m_t \ll M_G\ .\end{aligned}$$

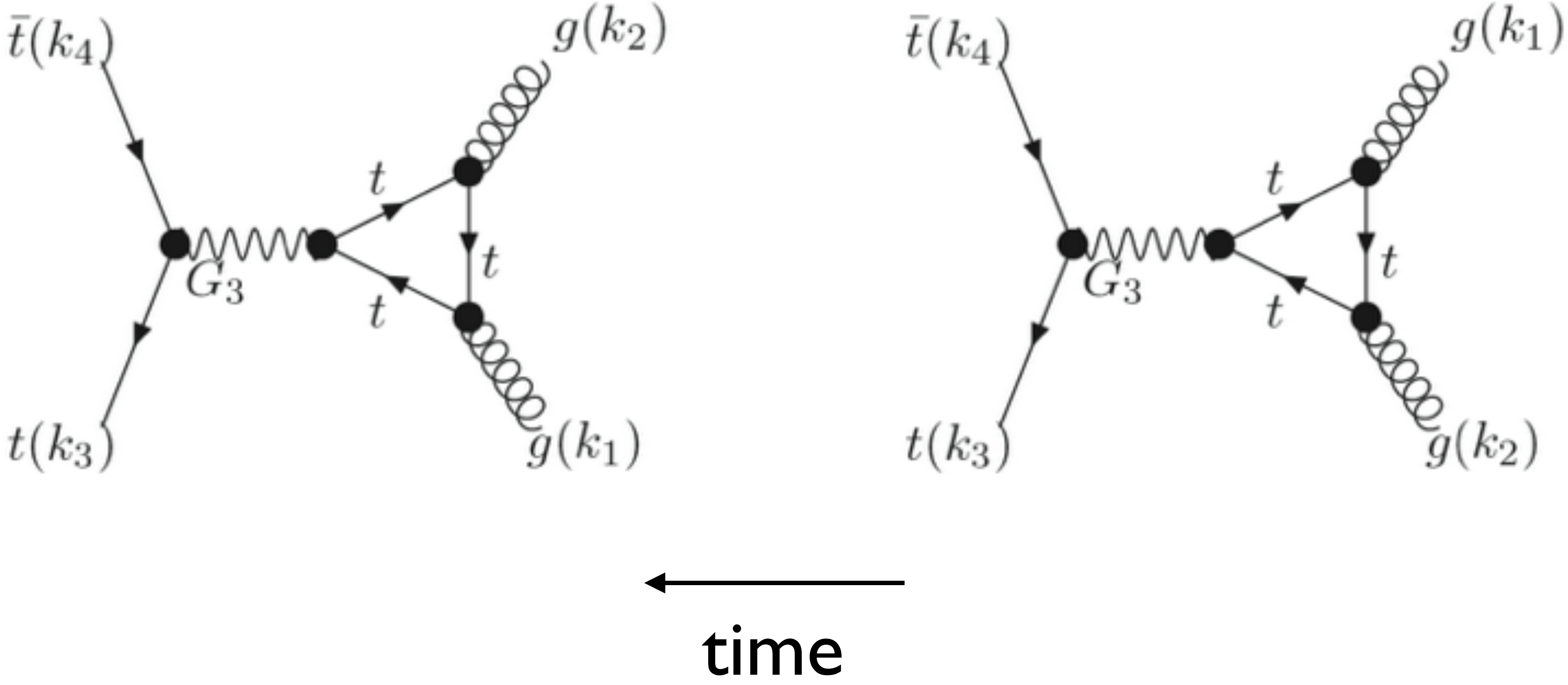
- **Decay is simple**
  Br(G_3->t t) =100%
  - Br(G_3->bb) makes the case more interesting…



Production mechanism

- **LHC: Proton (u,d,g,…) + Proton(u,d,g…)**
- **No direct contact with TPR**
- **but…**

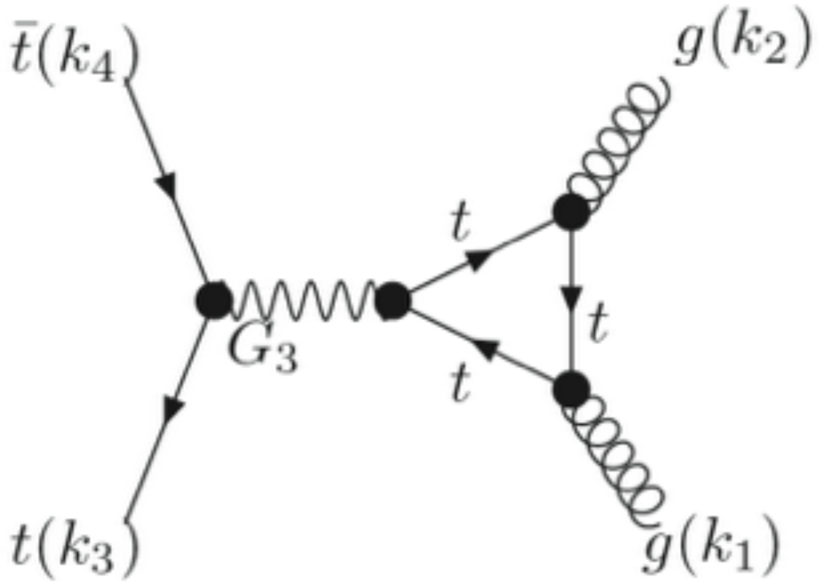
$g\ g \to G_3$
1-loop

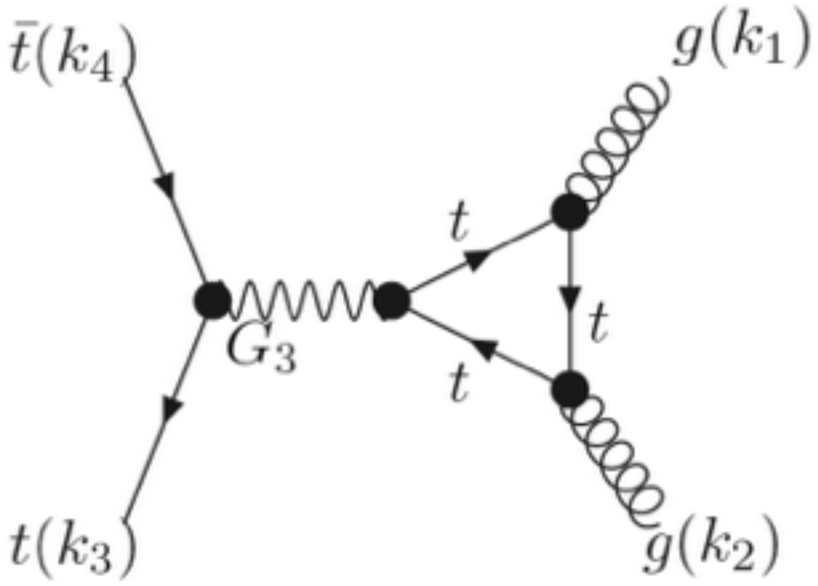


NOTE:

Landau-Yang theorem forbids on-shell production of vector G_3

Landau-Yang: A massive vector cannot decay into two massless photons and vice versa



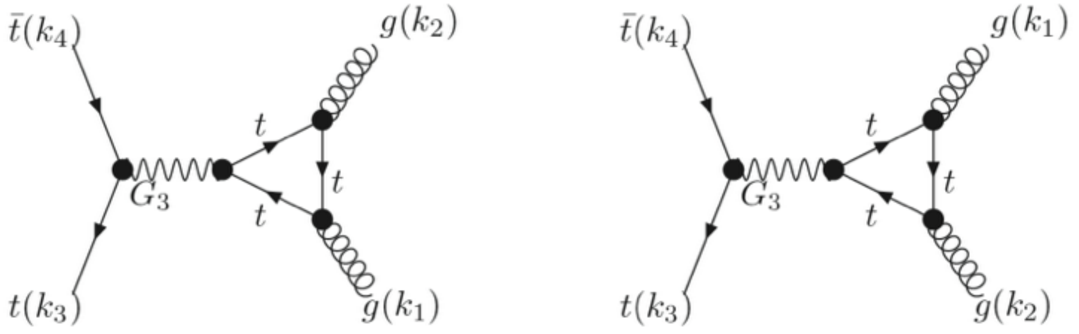


Furry's theorem

For any odd number n

$$\langle \Omega | T[j^{\mu_1}(x_1) \cdots j^{\mu_n}(x_n)] | \Omega \rangle = 0$$

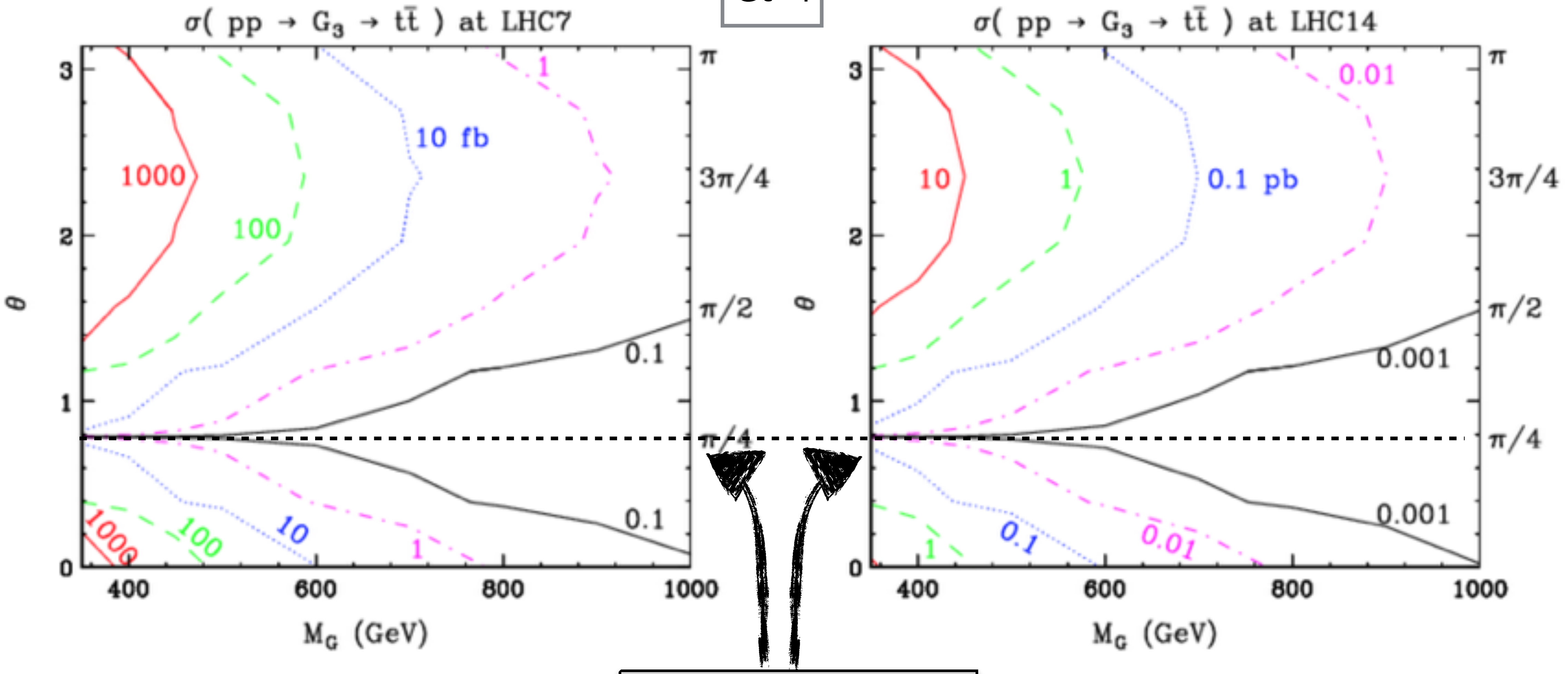
where j~ vector current



=0 for vector current interactions
i.e. theta =pi/4

Production cross section

Ct=1

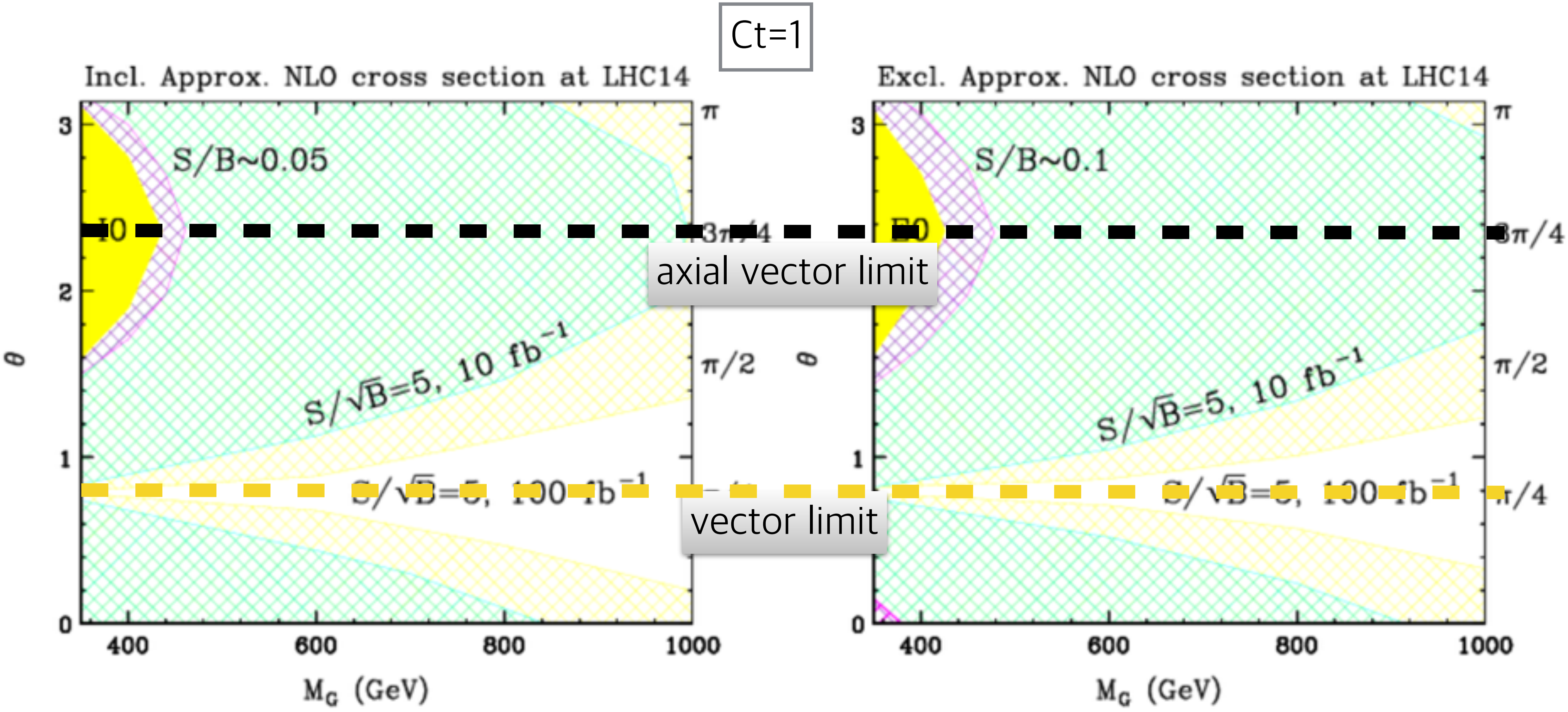


$$\theta = \pi/4$$

$$c_L = c_R$$

‘vectorlike’

LHC Run-2 expectation for t+tbar



Ct=1

axial vector limit

vector limit

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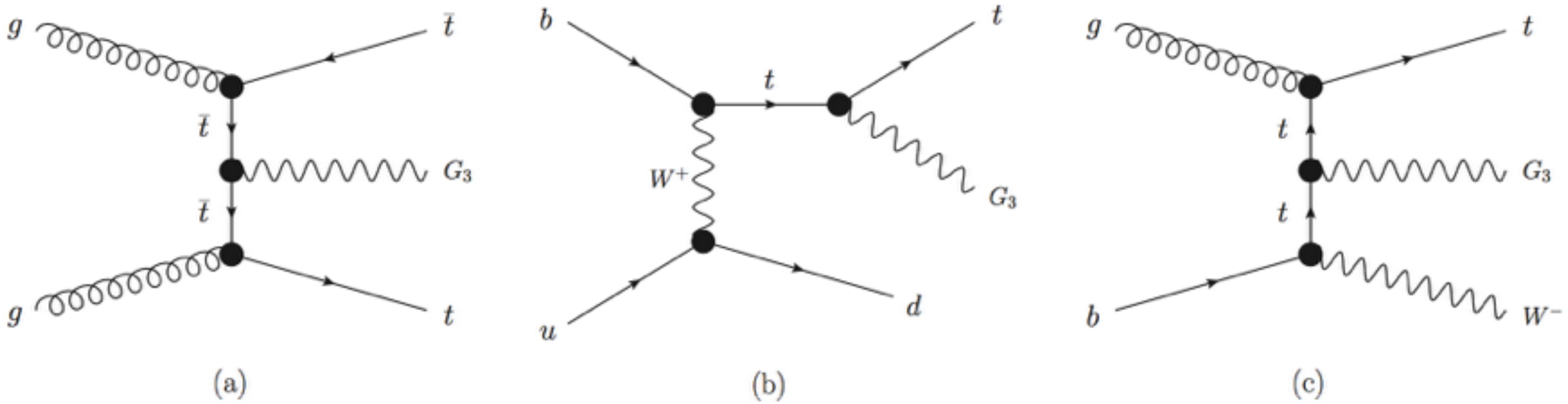
JHEP 1504 (2015) 029]

Tree level production channels



G3 t t

G3 t j

G3 t W

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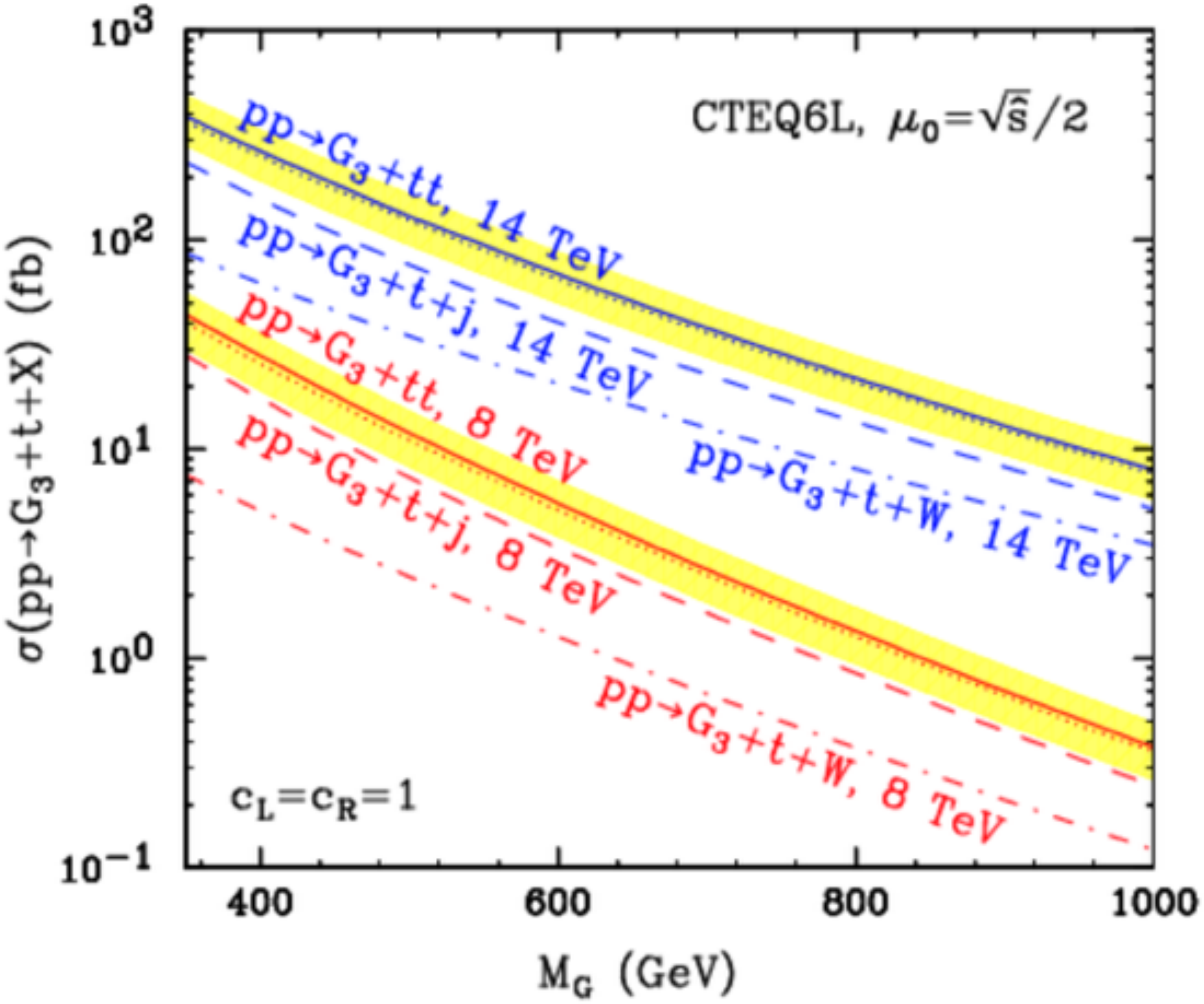
Cross sections



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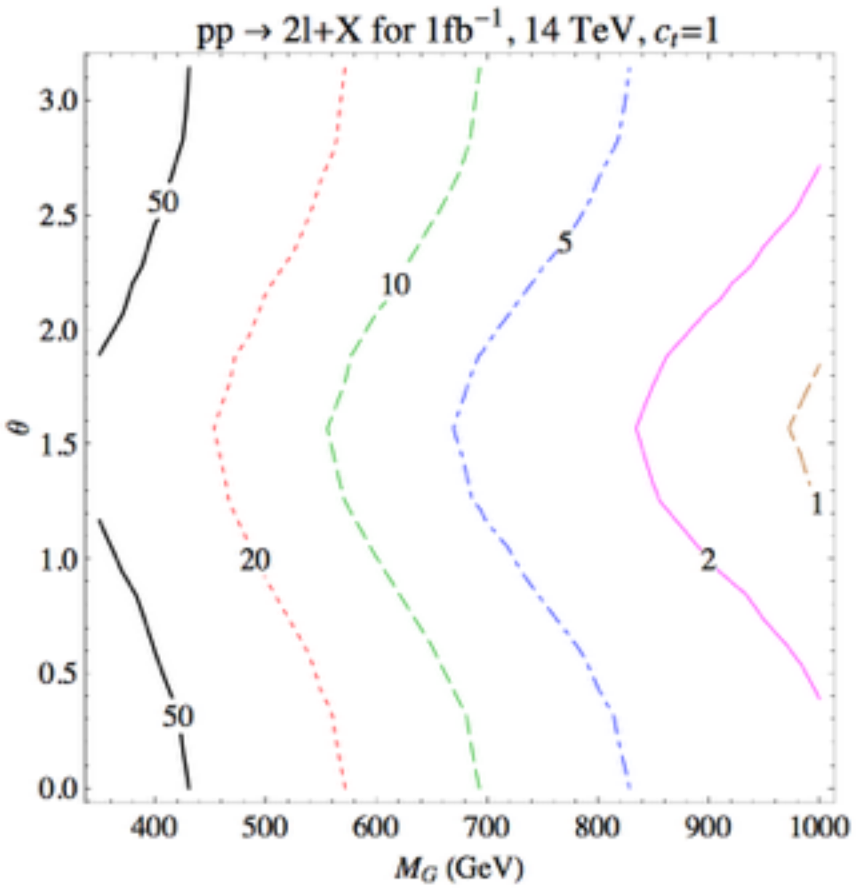
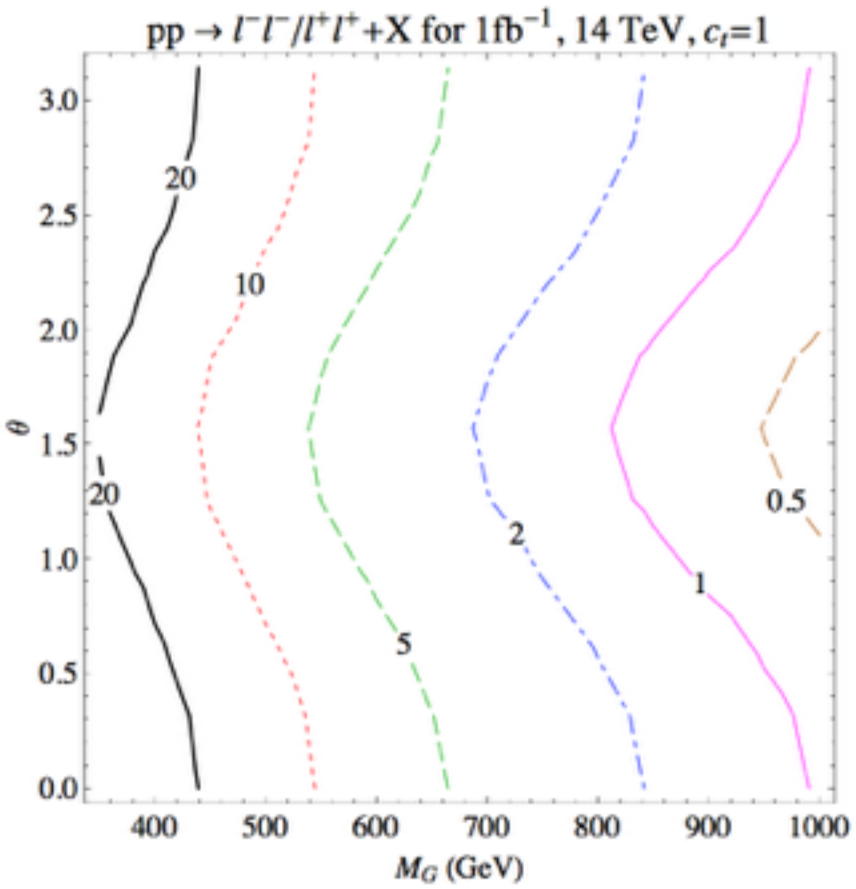
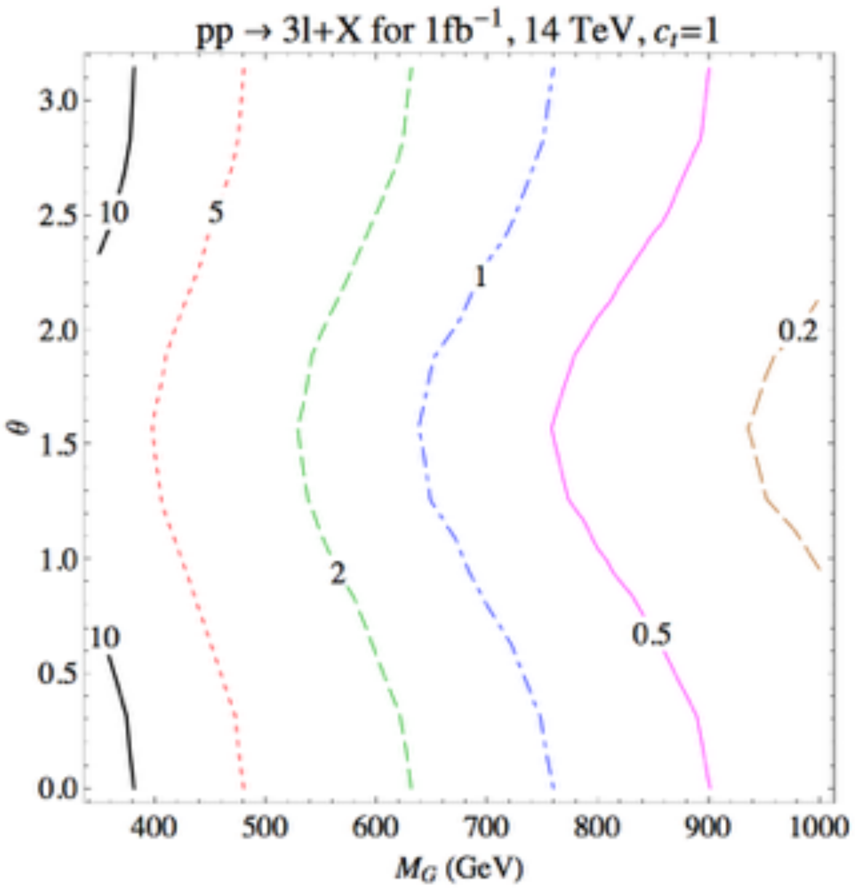
Expected # of events with leptonic final states



di-leptons +X



same-sign di-leptons +X



tri-leptons+X

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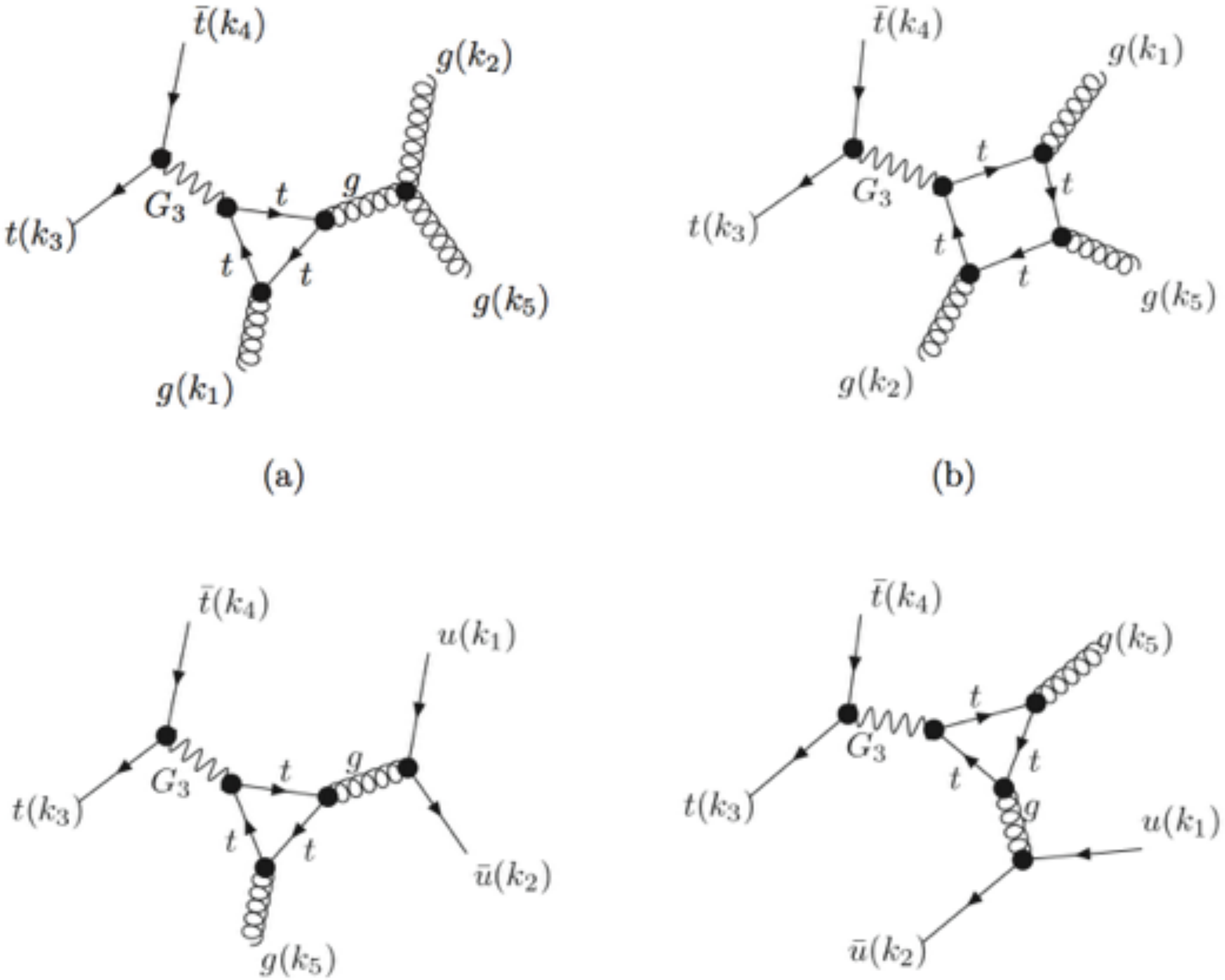
G_3+jet



(a) (b)

(c) (d)

G3 j

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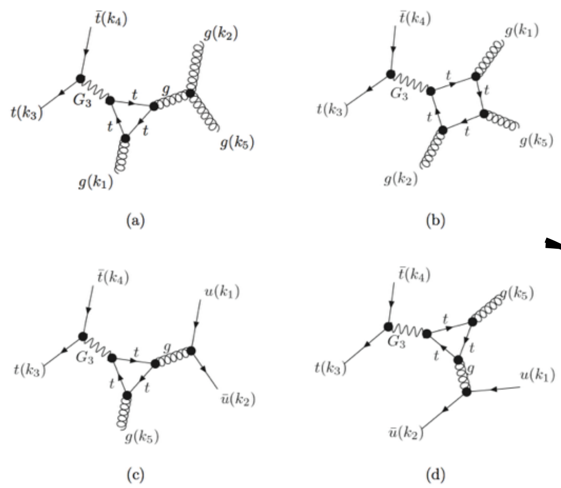
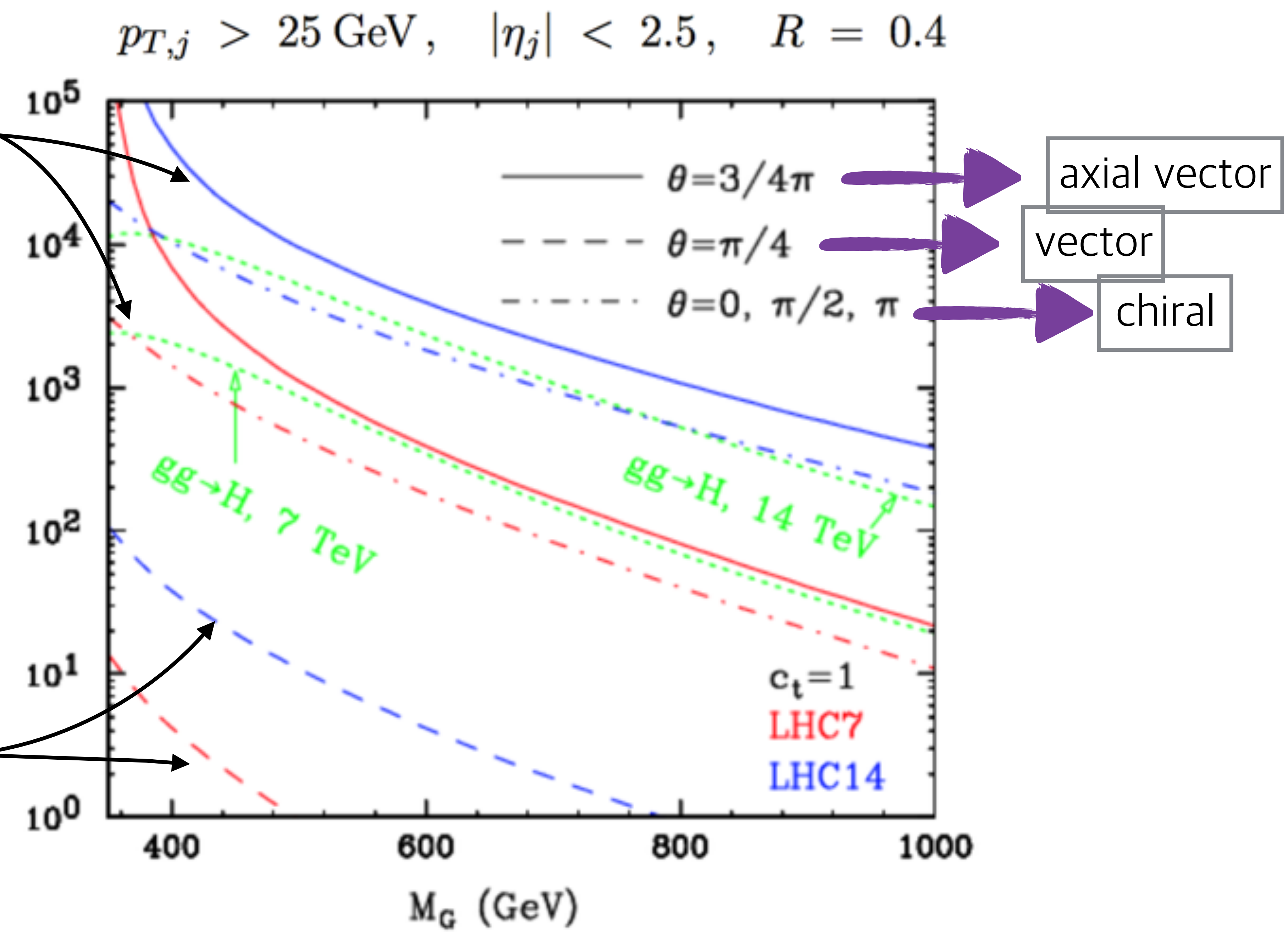
Cross sections: **G₃+jet**



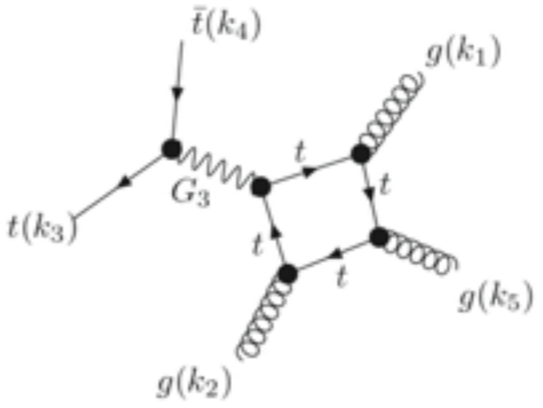


axial vector

vector

chiral

at furry limit



Nicolas Greiner, Kyoungchul Kong, Jong-Chul Park, ***SCP***, Jan-Christopher Winter
JHEP 1504 (2015) 029]

summary of Part-1

- We found several production mechanisms for TRP (tree as well as loop-level), which sometimes turned out to be much larger than what we naïvely expected! Here chirality structure plays important roles.

- G3+tt (or 4 tops), G3+j (or t tbar jet), G3+t+W (or 3t+W) are ~(1-1000) fb cross sections for <1TeV mass, which may be seen at LHC Run-2!

- We are now working with our experimentalist friends for the LHC run-2. Stay tuned!

‘Observation’

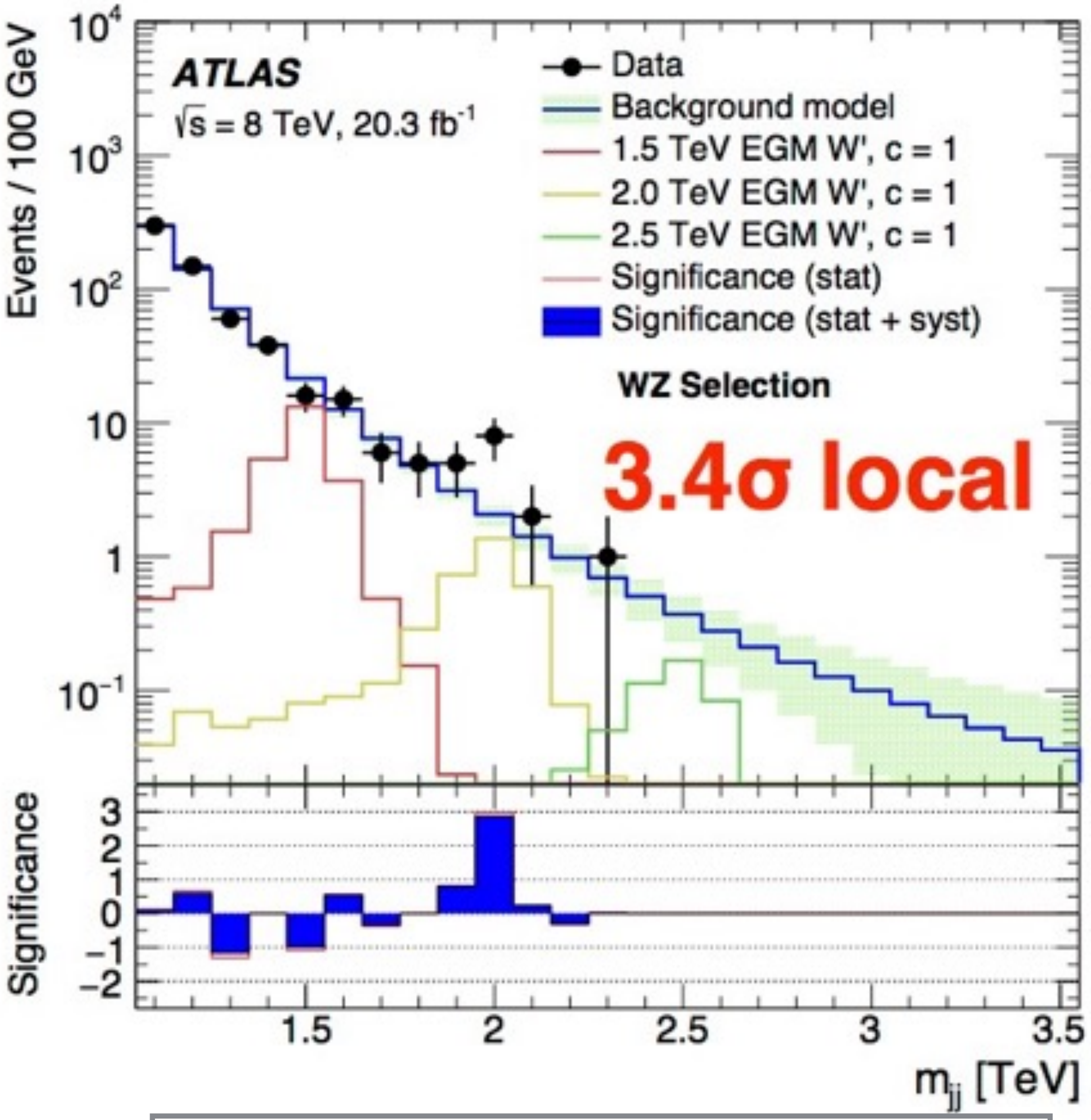
Part 2

Diboson resonances at the LHC and EFT approach

this is how I understand

Doojin Kim, Kyoungchul Kong, Hyun Min Lee, ***SCP***
JHEP 1511 (2015) 150

ATLAS recently reported diboson resonance in WZ

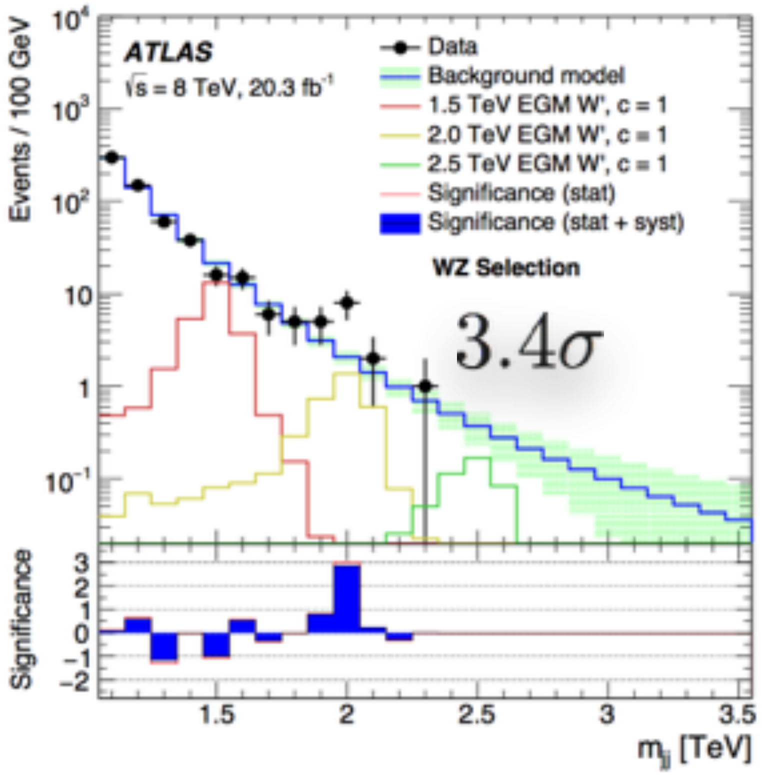


ATLAS collaboration arXiv:1506.00962

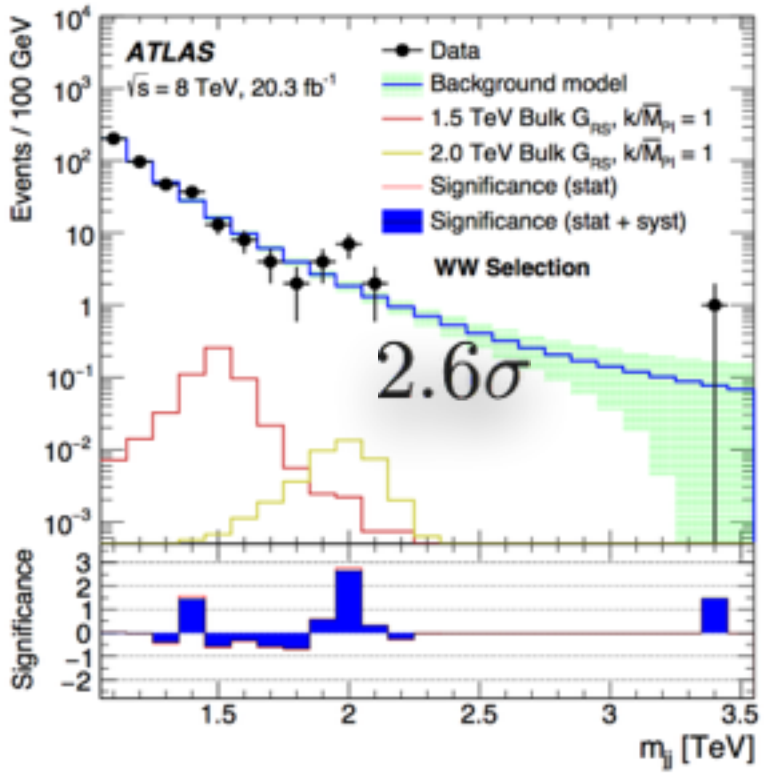
- hadronic decay of W, Z are considered. W&Z are boosted and tagged as “**fat-Jets**”
- “jet substructure technique” used to reduce background.
- still there are uncertainties in identifying W and Z

Not only in WZ but in WW, ZZ, too

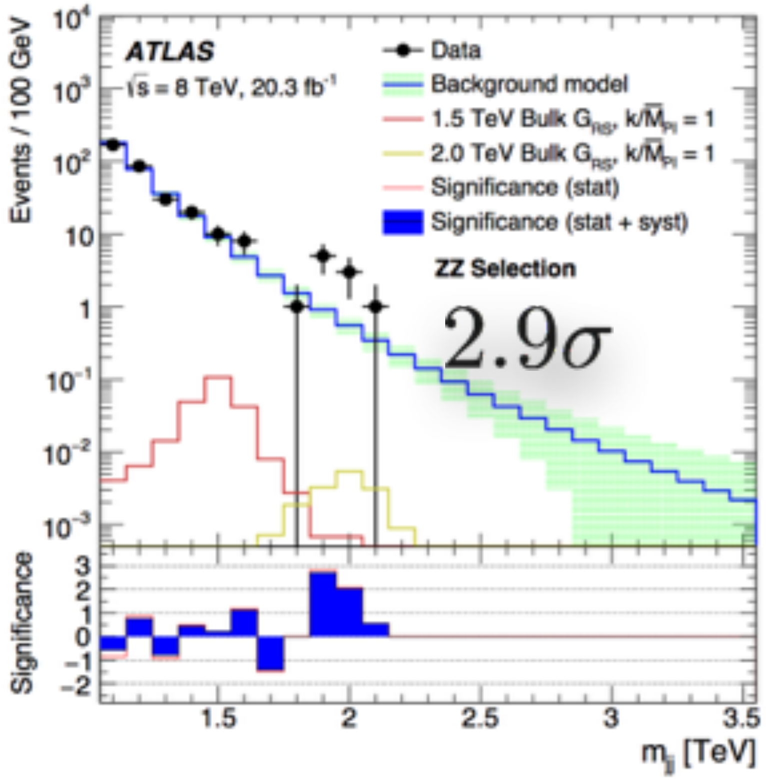
ATLAS collaboration arXiv:1506.00962



(a)



(b)



(c)

overall significance is < 3 sigma

but they are all at the same energy!

A mail from CMS

Hello,

Congratulations on an interesting paper "ATLAS Diboson Excesses Demystified in Effective Field Theory Approach". We at CMS would like to bring your attention to two other papers published over one year ago that address the same final state as the ATLAS X->VV all hadronic channel. In fact, **in our all-hadronic channel we also see a moderate excess at the same position.** We would appreciate a proper scientific treatment where you could address our results in the paper and citation. In fact this will strengthen the scientific case for your paper, since there is more evidence in favor of an excess.

The published papers are :

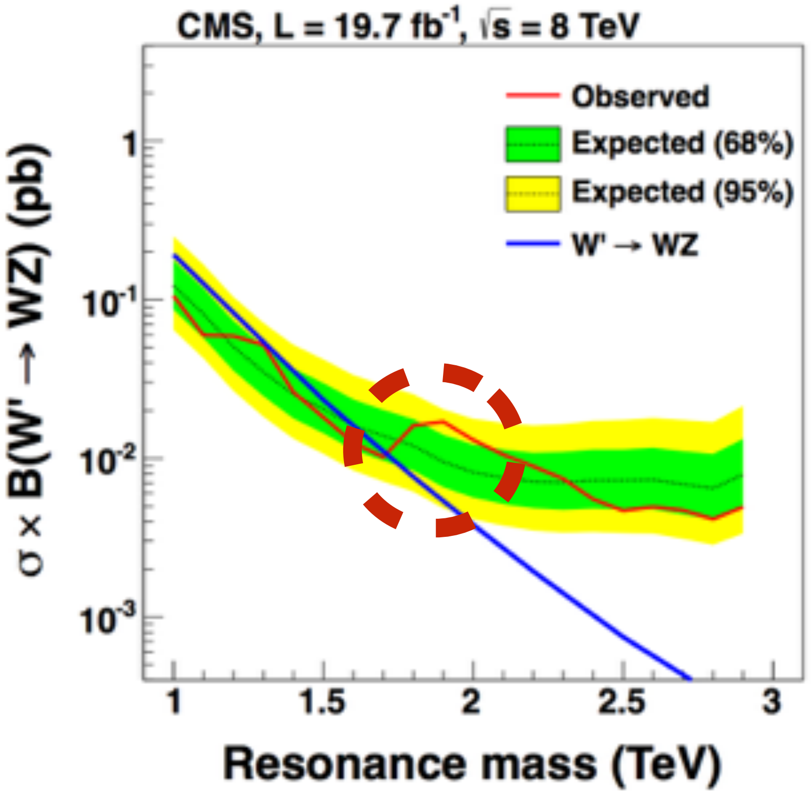
http://inspirehep.net/record/1294937
http://inspirehep.net/record/1296080

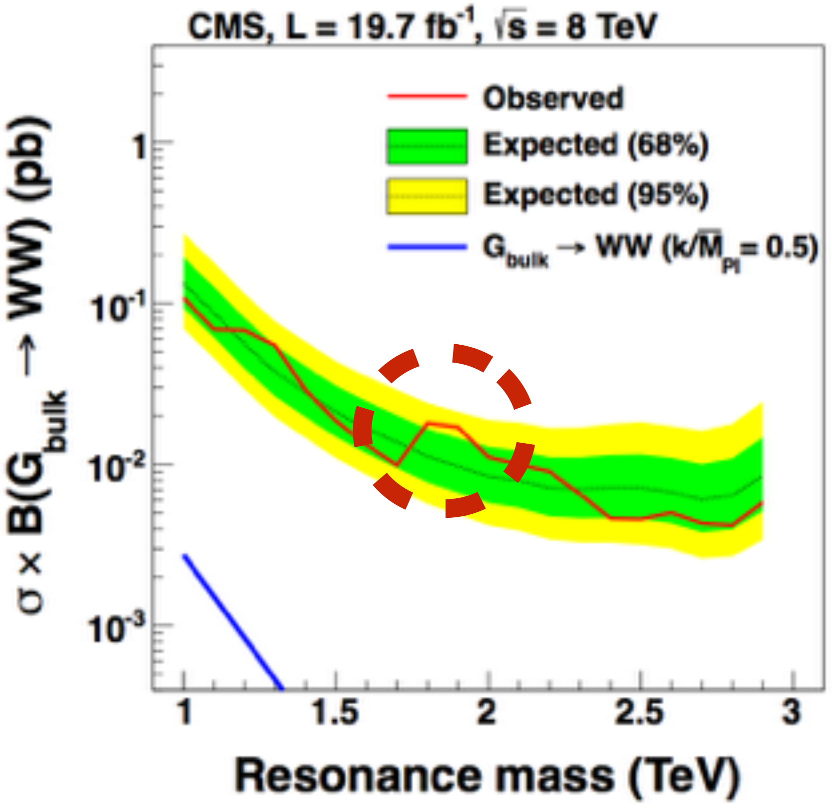
Many thanks for your consideration in this matter.

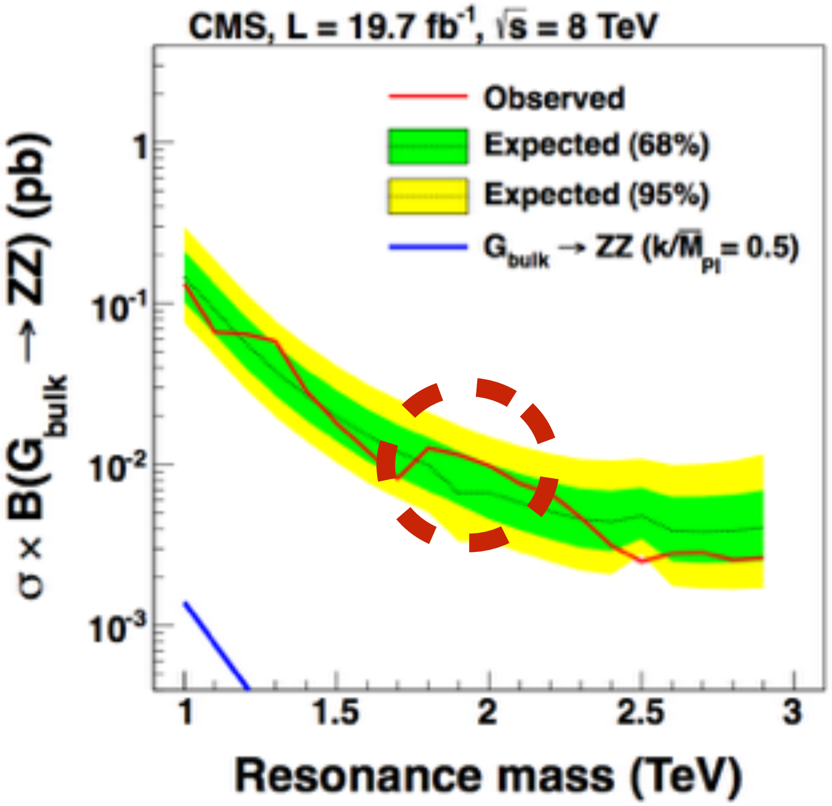
Sincerely,
Salvatore Rappoccio for the CMS Collaboration

Well, they are indeed 'visible' even though they are not significant…

CMS 1405.1994

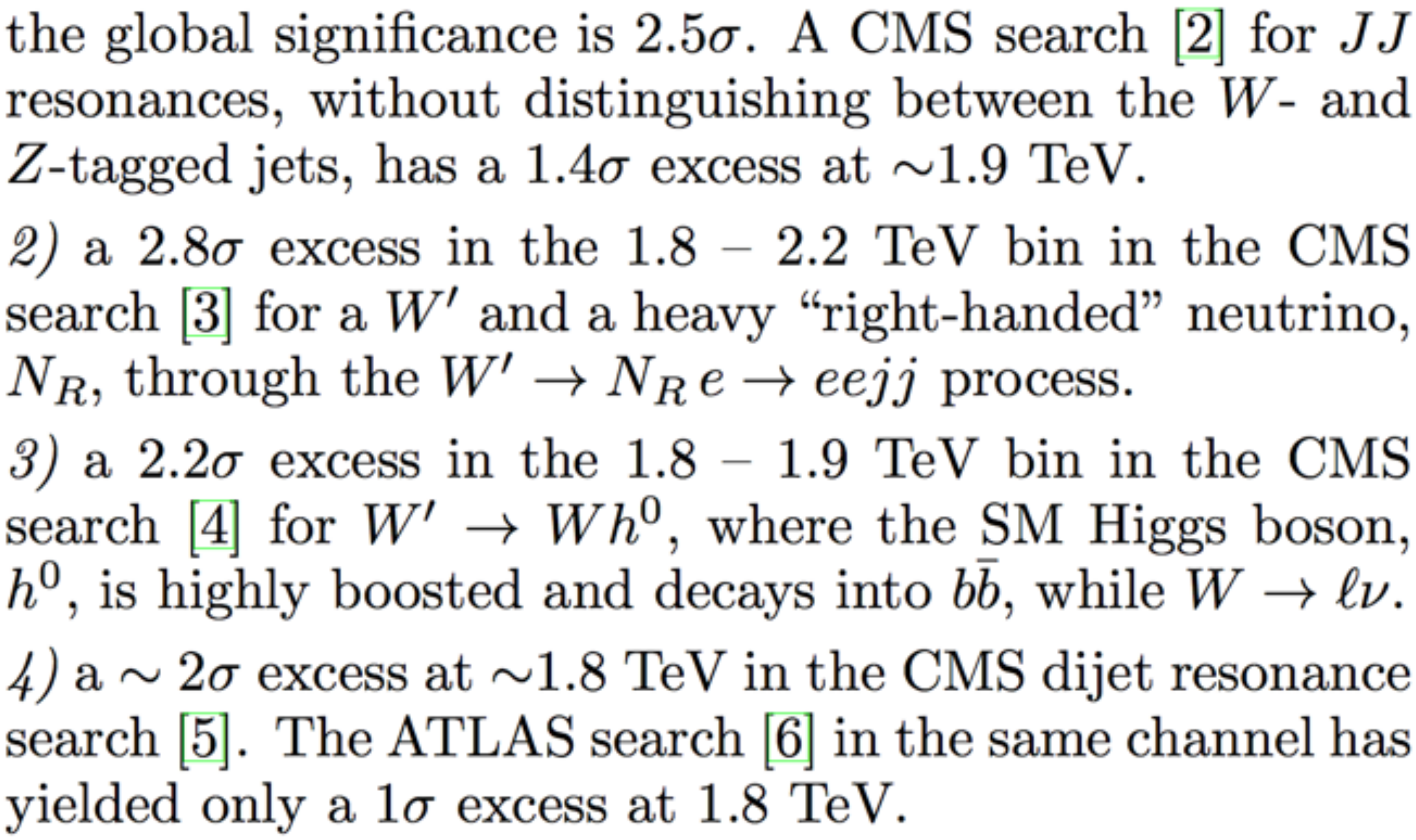






CMS ‘excesses’

summarized by [Dobrescu, Liu 1506.06736]



the global significance is 2.5σ. A CMS search [2] for JJ resonances, without distinguishing between the W- and Z-tagged jets, has a 1.4σ excess at $\sim$1.9 TeV.

2) a 2.8σ excess in the 1.8 – 2.2 TeV bin in the CMS search [3] for a W' and a heavy “right-handed” neutrino, N_R, through the $W' \to N_R\, e \to eejj$ process.

3) a 2.2σ excess in the 1.8 – 1.9 TeV bin in the CMS search [4] for $W' \to Wh^0$, where the SM Higgs boson, h^0, is highly boosted and decays into $b\bar{b}$, while $W \to \ell\nu$.

4) a $\sim 2\sigma$ excess at $\sim$1.8 TeV in the CMS dijet resonance search [5]. The ATLAS search [6] in the same channel has yielded only a 1σ excess at 1.8 TeV.

CMS 1405.1994

CMS
1407.3683

CMS
PAS-EXO-14-010

CMS 1501.04198

ATLAS 1407.1376

**In short,
not only ATLAS but also CMS
saw the similar excesses
all at the same energy ~2 TeV!**

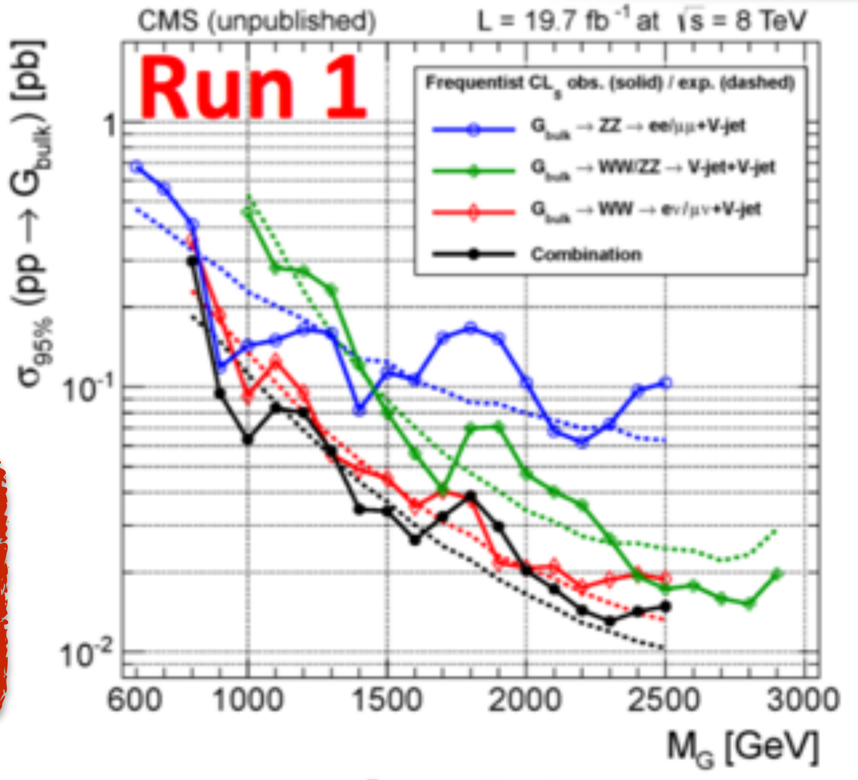
We want to understand
this 2 TeV ‘diboson’ resonance
in EFT approach

new!! Talk by Jim Olsen Dec. 15

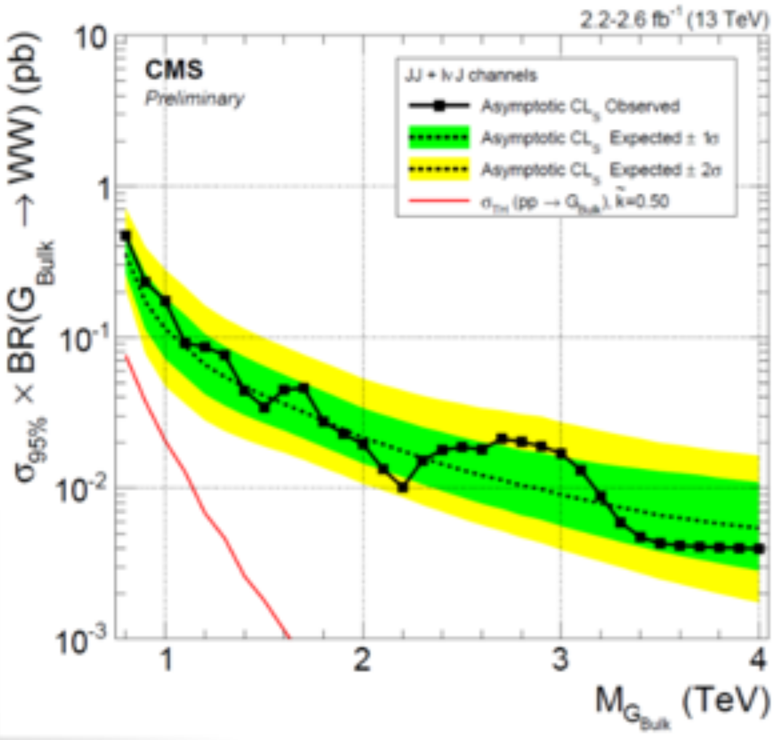
EXO-15-002

Search for diboson resonances

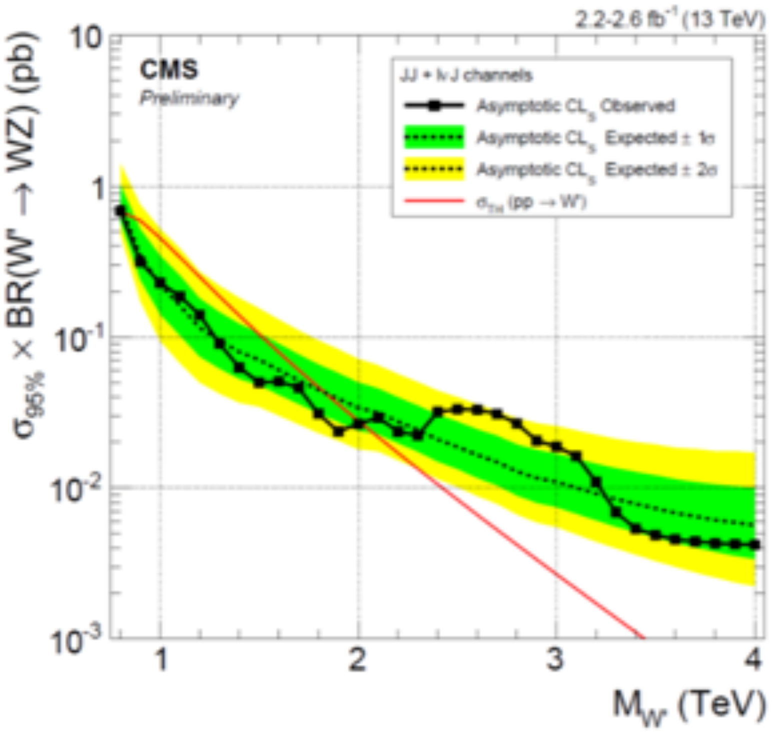
- **Run 1: CMS $\sim 2\sigma$ excess near 1.8-2.0 TeV**
- Repeat search at 13 TeV using most sensitive channels: $l\nu J$, JJ
- **Analysis categorized in dijet mass** for optimal sensitivity to WW, WZ, ZZ signals
- **13 TeV: no excess observed in the region of interest near 2 TeV**
  - More data needed to fully exclude Run 1 excess



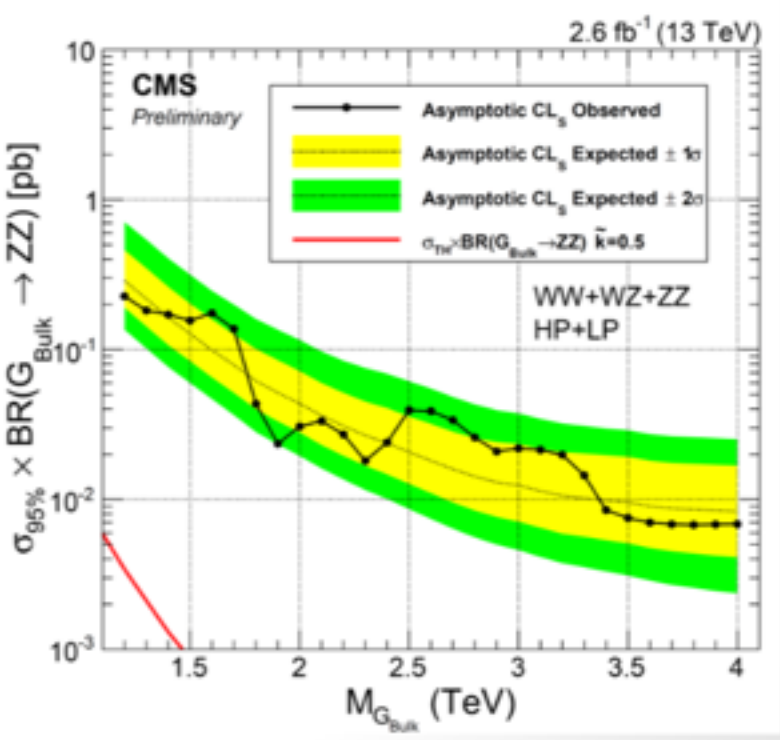
$G_{Bulk} \to WW$ ($l\nu J$+JJ)



W' → WZ ($l\nu J$+JJ)



$G_{Bulk} \to ZZ$ (JJ)



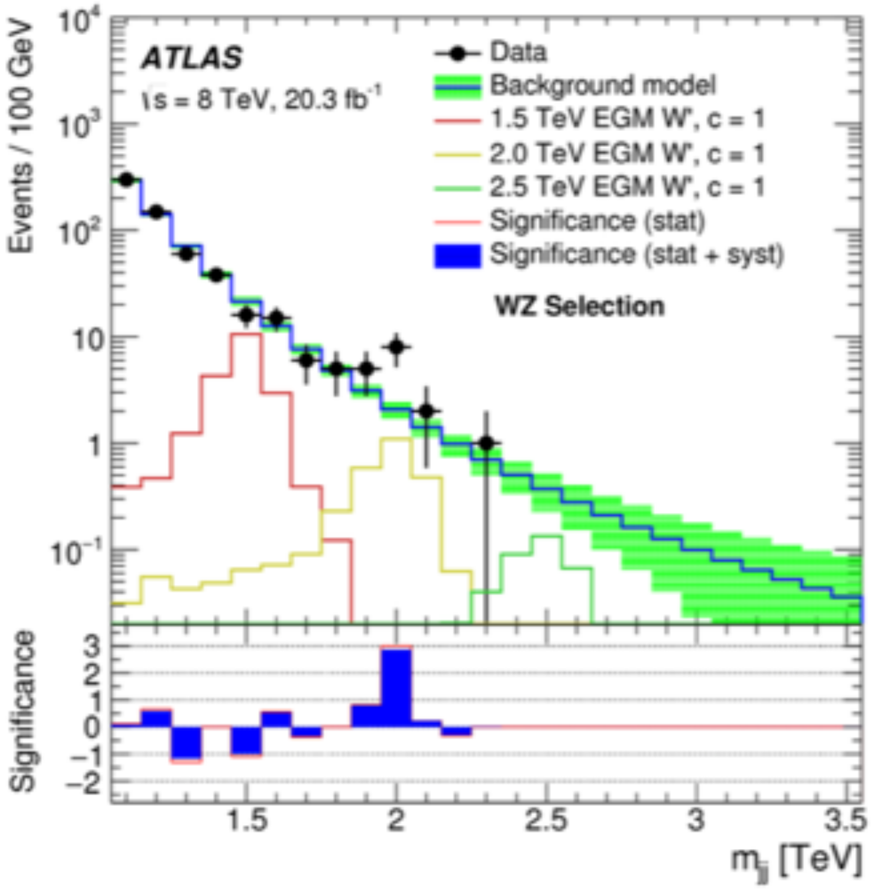
new!! Talk by M. Kado Dec. 15

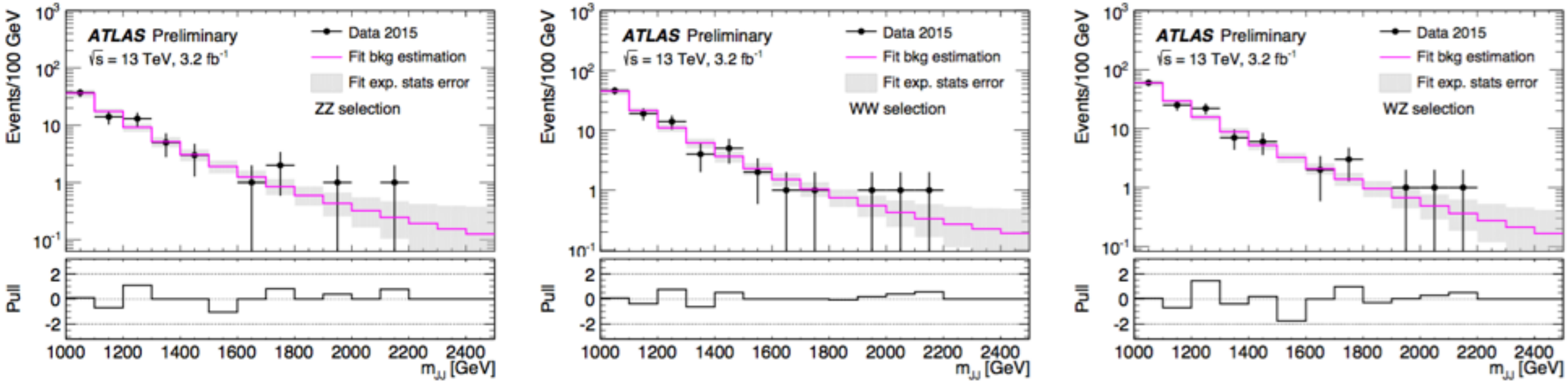
ATLAS-CONF-2015-073

Fully Hadronic **JJ Diboson** searches

- **Modest excess at Run-1: 3.4σ** local / **2.5σ global**
- **Analysis very similar to Run 1**, with functional fit of the background
- **No significant excess is observed** however sensitivity not high enough for conclusive probe of the Run 1 excess

Run-1





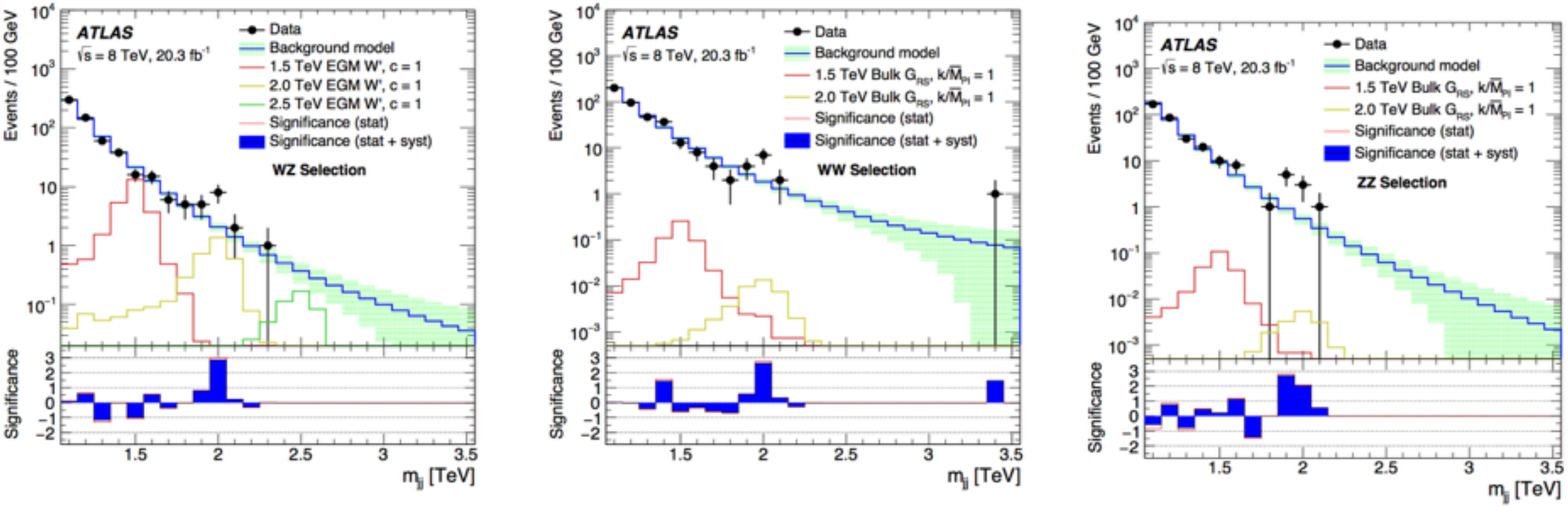
my interpretation

- Run-1 result for 2 TeV diboson resonance is not confirmed by Run-2 data.

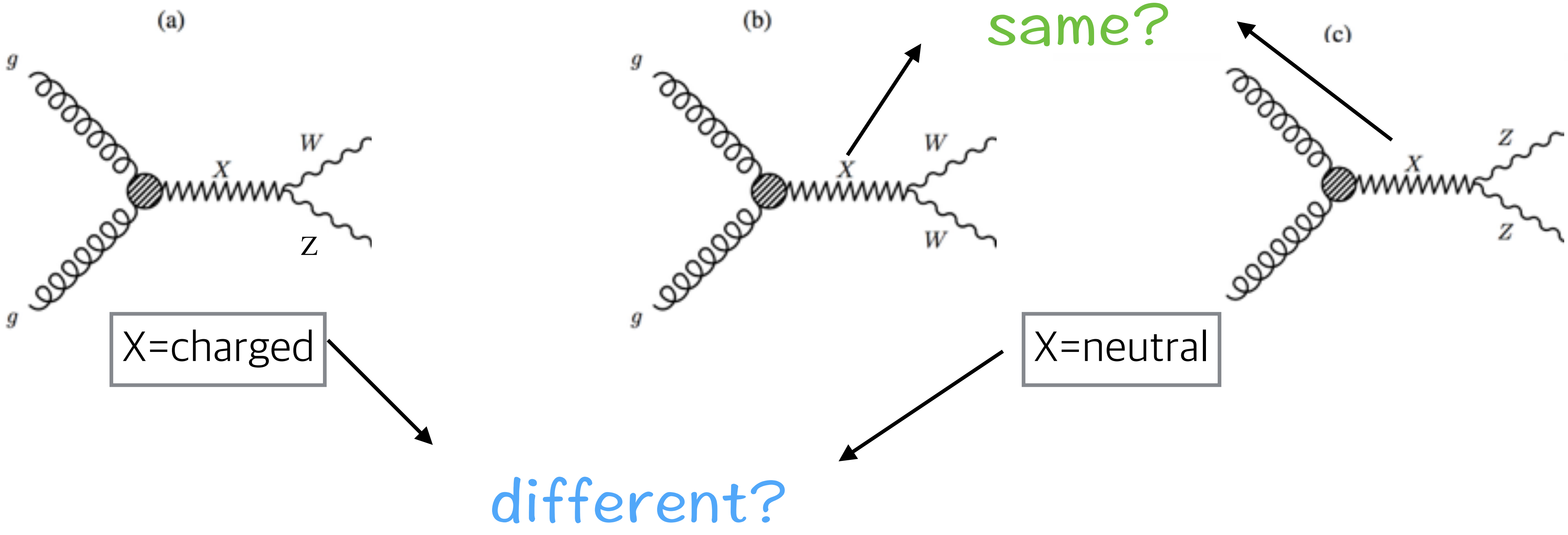
- but it is premature to exclude it and we need more data!

- so, I reserve my conclusion for the future.

Q. One or Two (or Three?)



(a) (b) (c)



same?

X=charged

X=neutral

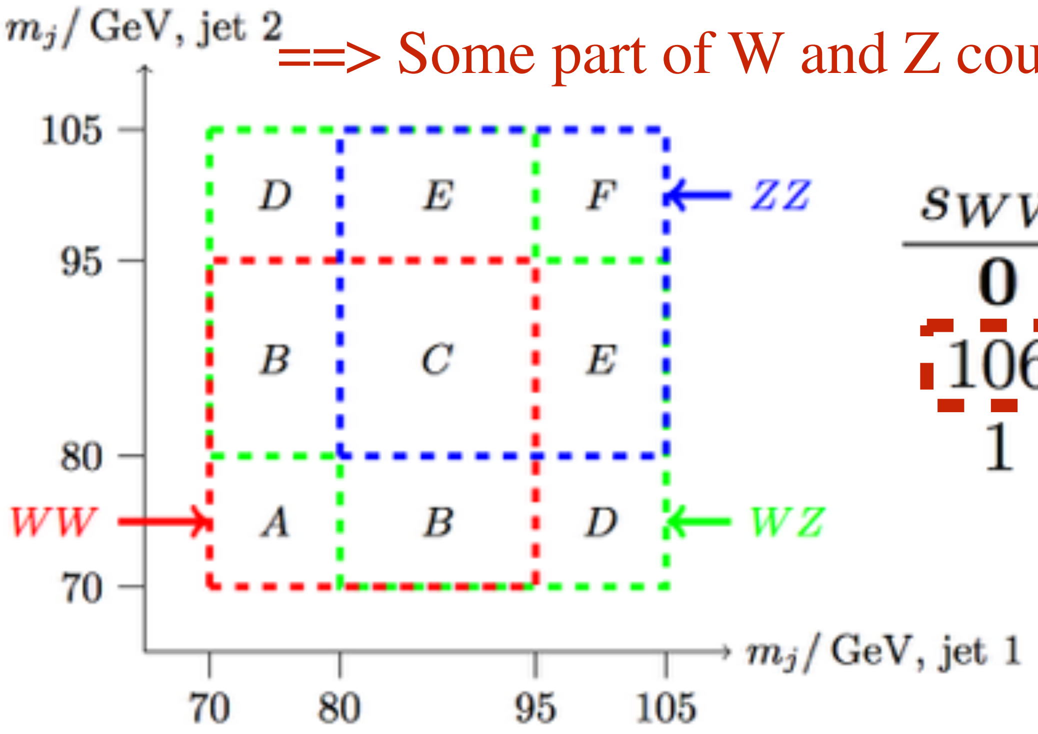
different?

Maybe one [Allanach et al, 1507.01638]

The likelihood analysis for ZZ, WW and WZ performed.

20% of the events in at least one signal region (C) belong to all three categories

==> Some part of W and Z could be misidentified!



s_{WW}	s_{WZ}	s_{ZZ}	μ_{WW}	μ_{WZ}	μ_{ZZ}	$\Delta\chi^2$
0	119	86	12.0	16.1	8.2	0.4
106	**0**	118	13.0	16.2	8.1	0.0
1	223	**0**	13.0	16.6	7.4	0.8

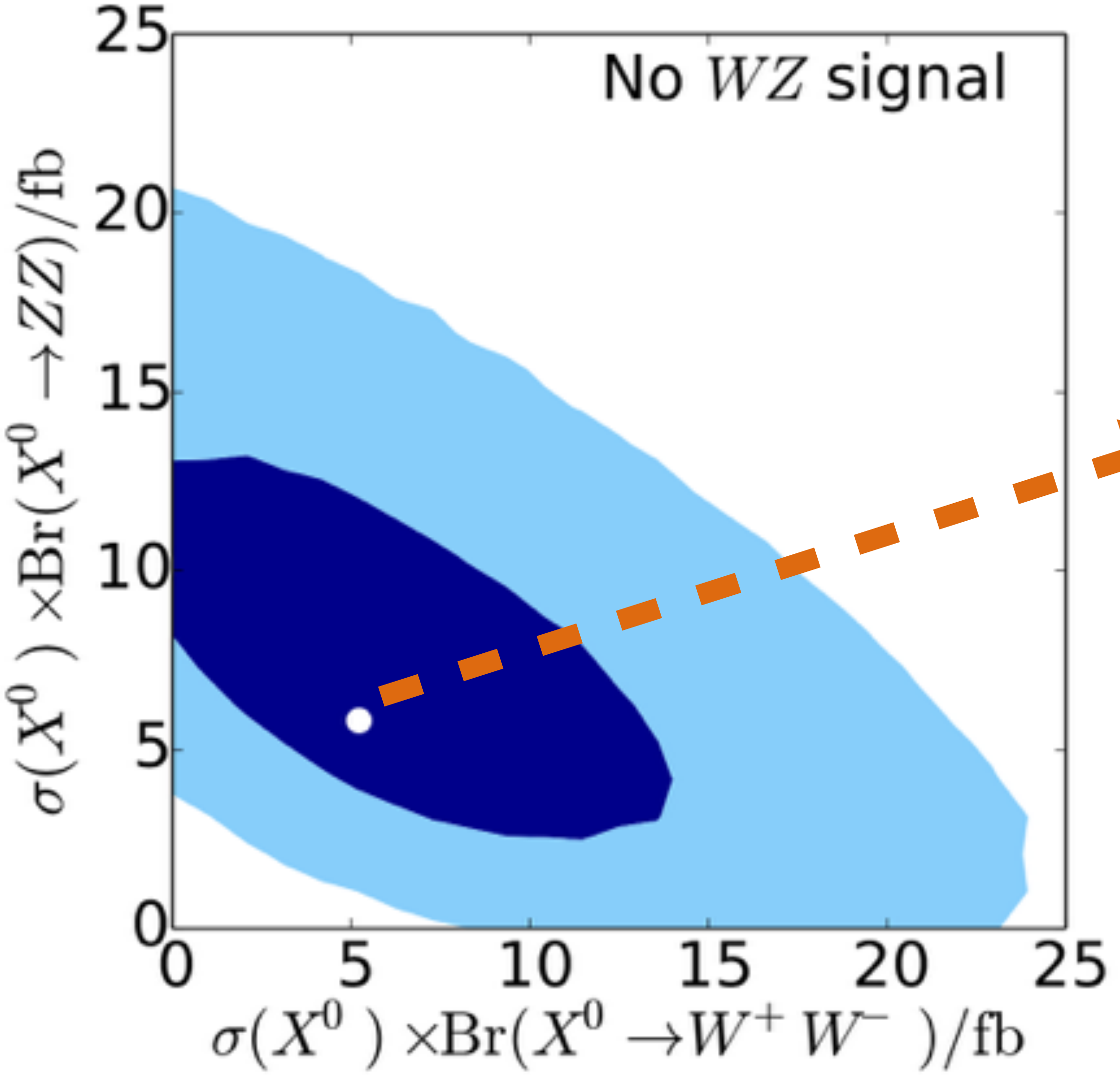
'best fit'

LESSON:

The best fit suggests that WZ may be just mis-identified WW or ZZ!

‘best fit’ with a single resonance

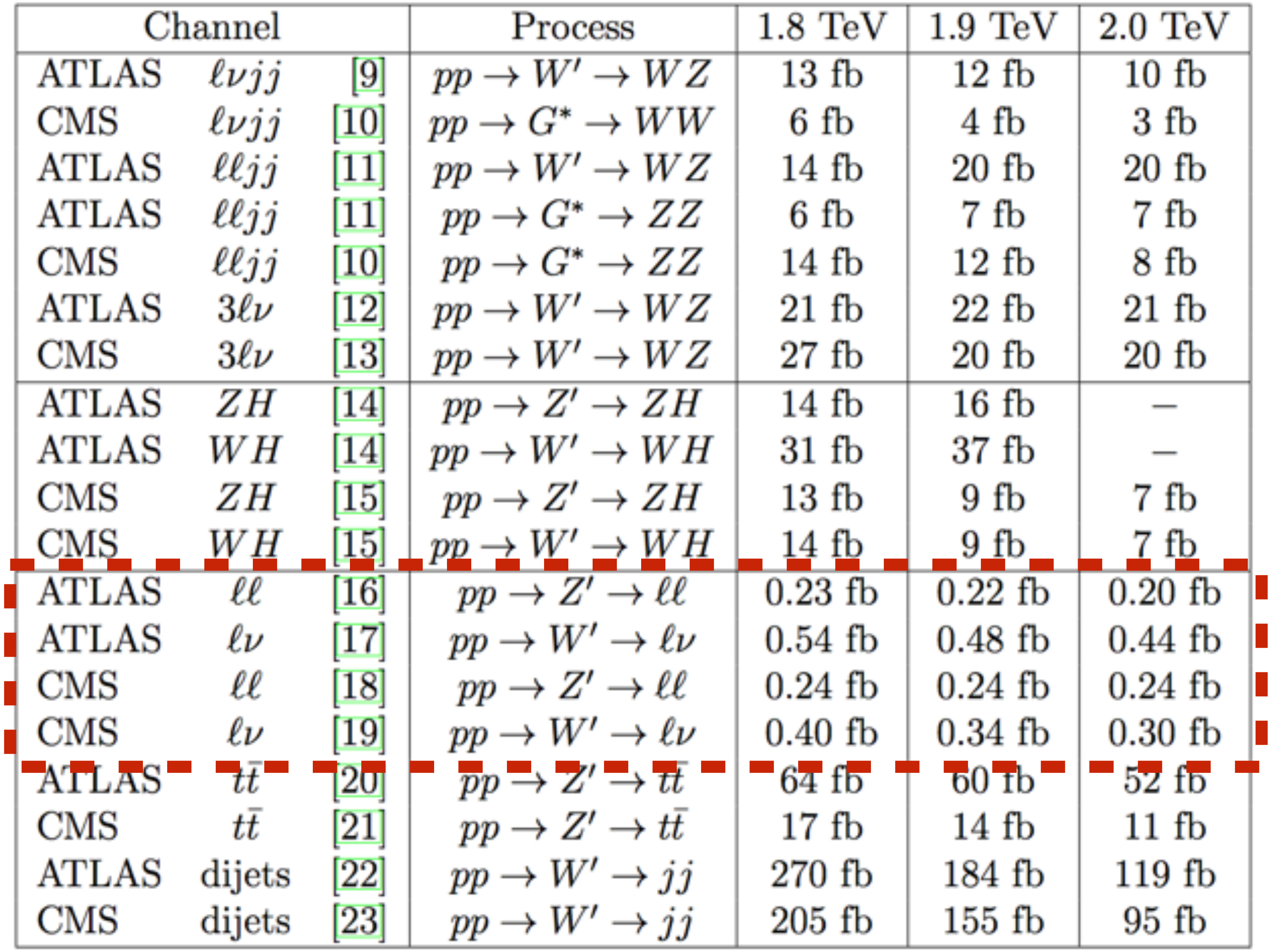
[Allanach et al, 1507.01638]



‘best fit’: WZ~0fb, ZZ~6 fb, WW~5 fb
95% limits: WW+ZZ ~ 4-24 fb

Limits from other searches

[Carmona, Delgado, Quiros, Santiago 1507.01914]

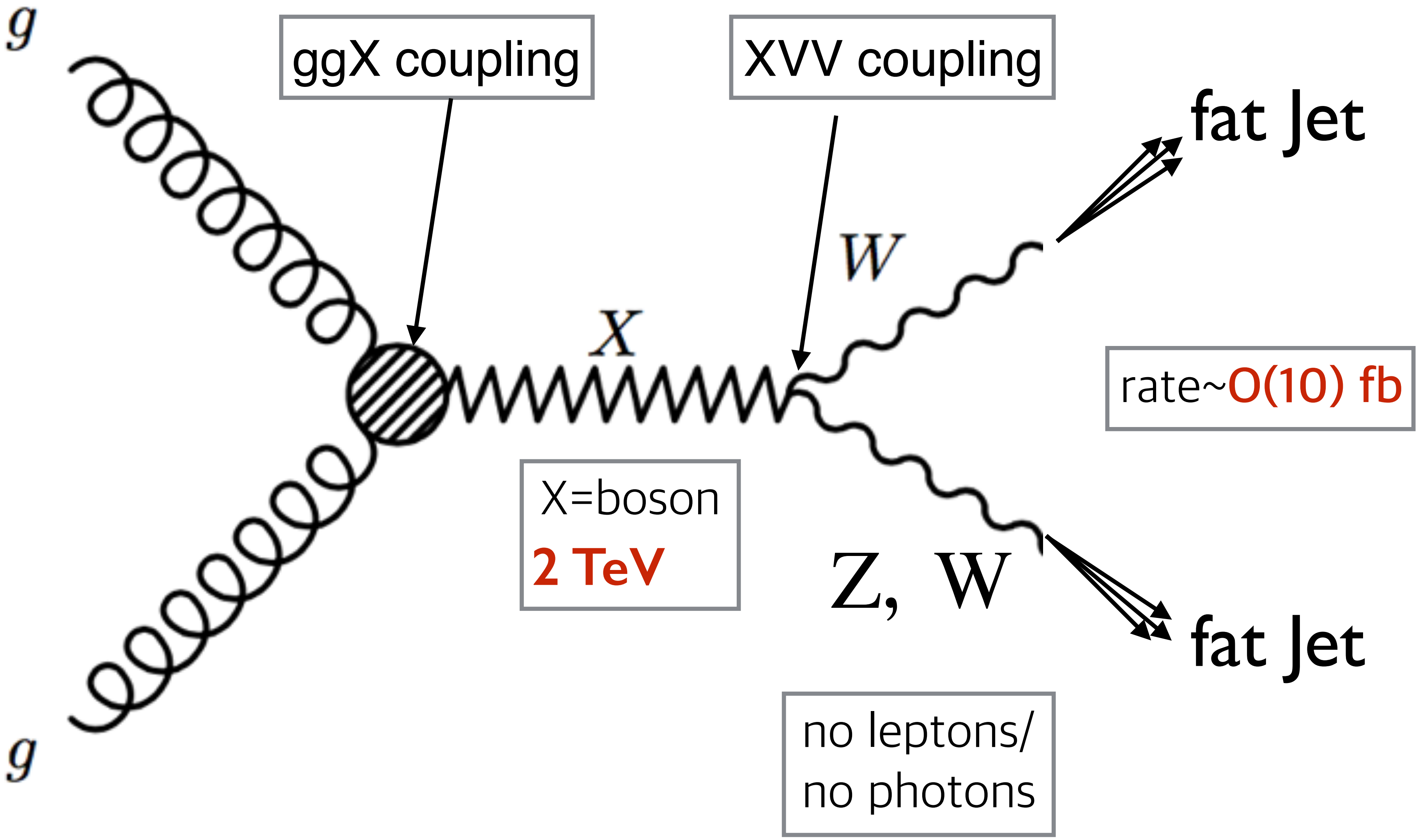


Channel			Process	1.8 TeV	1.9 TeV	2.0 TeV
ATLAS	$\ell\nu jj$	[9]	$pp \to W' \to WZ$	13 fb	12 fb	10 fb
CMS	$\ell\nu jj$	[10]	$pp \to G^* \to WW$	6 fb	4 fb	3 fb
ATLAS	$\ell\ell jj$	[11]	$pp \to W' \to WZ$	14 fb	20 fb	20 fb
ATLAS	$\ell\ell jj$	[11]	$pp \to G^* \to ZZ$	6 fb	7 fb	7 fb
CMS	$\ell\ell jj$	[10]	$pp \to G^* \to ZZ$	14 fb	12 fb	8 fb
ATLAS	$3\ell\nu$	[12]	$pp \to W' \to WZ$	21 fb	22 fb	21 fb
CMS	$3\ell\nu$	[13]	$pp \to W' \to WZ$	27 fb	20 fb	20 fb
ATLAS	ZH	[14]	$pp \to Z' \to ZH$	14 fb	16 fb	–
ATLAS	WH	[14]	$pp \to W' \to WH$	31 fb	37 fb	–
CMS	ZH	[15]	$pp \to Z' \to ZH$	13 fb	9 fb	7 fb
CMS	WH	[15]	$pp \to W' \to WH$	14 fb	9 fb	7 fb
ATLAS	$\ell\ell$	[16]	$pp \to Z' \to \ell\ell$	0.23 fb	0.22 fb	0.20 fb
ATLAS	$\ell\nu$	[17]	$pp \to W' \to \ell\nu$	0.54 fb	0.48 fb	0.44 fb
CMS	$\ell\ell$	[18]	$pp \to Z' \to \ell\ell$	0.24 fb	0.24 fb	0.24 fb
CMS	$\ell\nu$	[19]	$pp \to W' \to \ell\nu$	0.40 fb	0.34 fb	0.30 fb
ATLAS	$t\bar{t}$	[20]	$pp \to Z' \to t\bar{t}$	64 fb	60 fb	52 fb
CMS	$t\bar{t}$	[21]	$pp \to Z' \to t\bar{t}$	17 fb	14 fb	11 fb
ATLAS	dijets	[22]	$pp \to W' \to jj$	270 fb	184 fb	119 fb
CMS	dijets	[23]	$pp \to W' \to jj$	205 fb	155 fb	95 fb

leptophobic!
also
photophobic

Table 1: Summary of the relevant 95% C.L. observed bounds.

So, the minimum requirement for the ATLAS resonances is this



ggX coupling

XVV coupling

X=boson
2 TeV

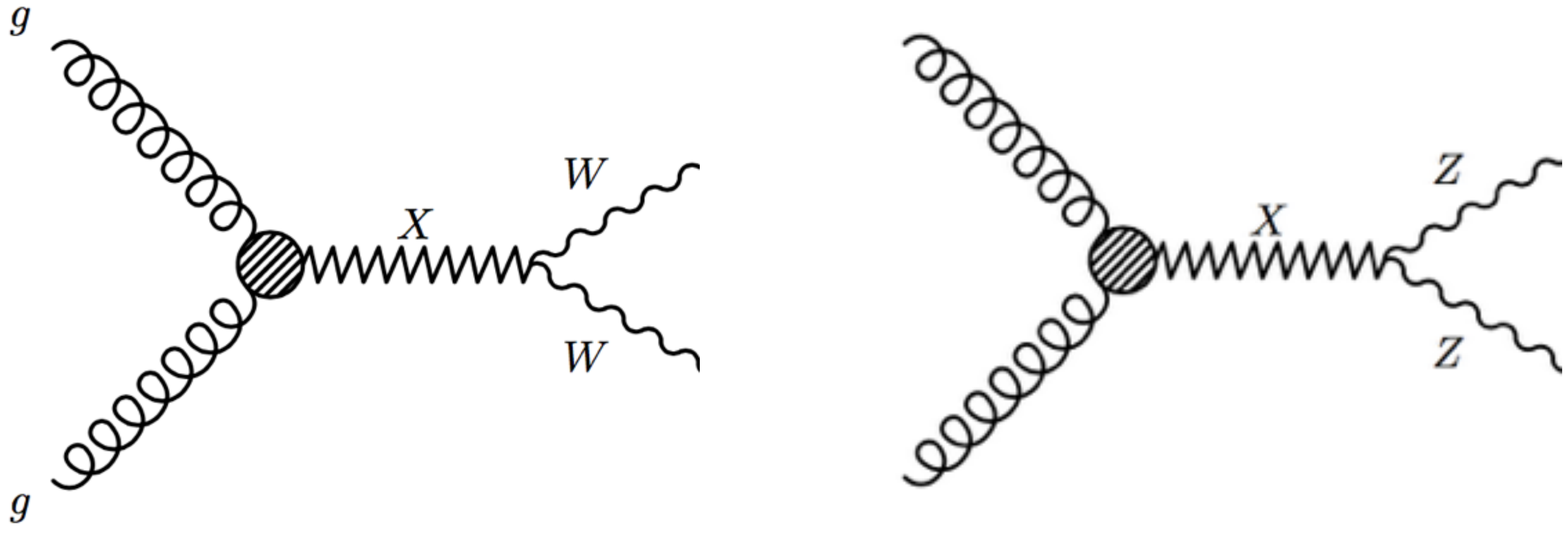
rate~O(10) fb

no leptons/
no photons

Our interpretation

- A single resonance is sufficient (WZ are mis-tagged fakes). We need to explain WW & ZZ via a neutral resonant state.
- Mass = 2 TeV
    - the total decay width <10% of the mass of the resonance. (Thanks to Kingman, personal communication)
    - the signal production cross section ~several fb
    - spin = 0 , 1 or 2 (or higher spin ?)
    - CP property is unknown
    - leptophobic, photophobic
- **O(4-8) fb $< \sigma$ x BR(ww) + σ x BR(ZZ) <O(20-24) fb**

Our EFT approach



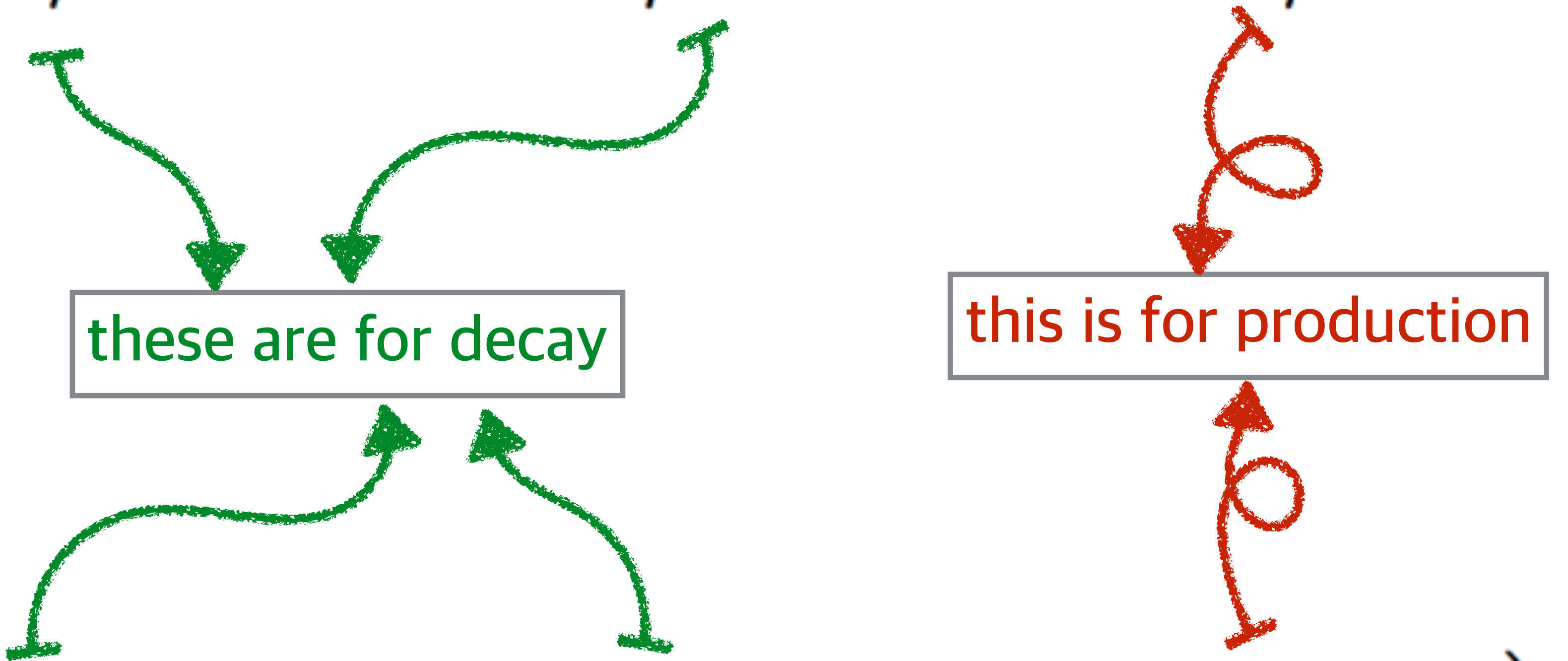
- Introduce a minimal set of effective operators which generate the absolutely necessary interactions
  - for production : pp → Resonance (gluon-gluon-R or q-q-R)
  - for decay : Resonance → WW / ZZ
  - Resonance can be (S, A, V, PV, T, PT)

Scalar

CP even

$$\mathcal{L}_s = -\frac{1}{\Lambda} S\left(s_1 F^{Y}_{\mu\nu} F^{Y\mu\nu} + s_2 F^{W}_{\mu\nu} F^{W\mu\nu} + s_3 G^{a}_{\mu\nu} G^{a\mu\nu}\right)$$

$$\boxed{\begin{array}{c} s_3 = 1 \\ \Lambda \sim 10 \text{ TeV} \\ m_S = 2 \text{ TeV} \end{array}}$$



these are for decay

this is for production

CP odd

$$\mathcal{L}_a = -\frac{1}{\Lambda} A\left(a_1 F^{Y}_{\mu\nu} \tilde{F}^{Y\mu\nu} + a_2 F^{W}_{\mu\nu} \tilde{F}^{W\mu\nu} + a_3 G_{\mu\nu} \tilde{G}^{\mu\nu}\right)$$

[Doojin Kim, Kyoungchul Kong, Hyun Min Lee, SCP 1507.06312]

Gauge invariance dictates the form of interactions

$$\mathcal{L}_s = -\frac{1}{\Lambda} S\left(s_1 F^Y_{\mu\nu} F^{Y\mu\nu} + s_2 F^W_{\mu\nu} F^{W\mu\nu} + s_3 G^a_{\mu\nu} G^{a\mu\nu}\right)$$

this should be small

$$s_{\gamma\gamma} = s_1 \cos^2\theta_W + s_2 \sin^2\theta_W ,$$

$$s_{Z\gamma} = (s_2 - s_1)\sin 2\theta_W ,$$

$$s_{ZZ} = s_2 \cos^2\theta_W + s_1 \sin^2\theta_W , \quad (2)$$

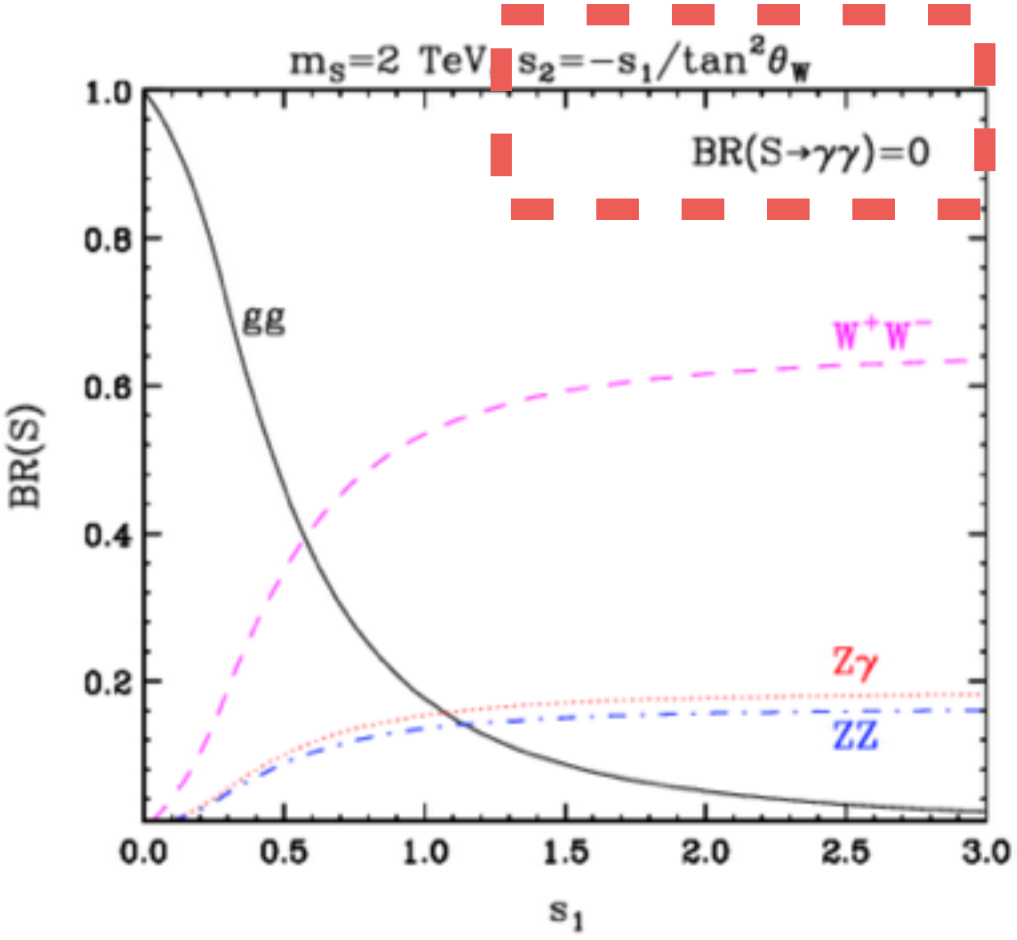
$$s_{WW} = 2 s_2$$

$$s_{gg} = s_3 ,$$

$$\mathcal{L} = -\frac{S}{\Lambda}\left(s_{\gamma\gamma} A\cdot A + s_{Z\gamma} Z\cdot A + s_{ZZ} Z\cdot Z + s_{WW} W\cdot W + s_{gg} G\cdot G\right)$$

Partial decay width

$$\begin{cases}
\Gamma_S(\gamma\gamma) = \frac{|s_{\gamma\gamma}|^2 m_S^3}{4\pi\Lambda^2}\,, & s_{\gamma\gamma} = s_1\cos^2\theta_W + s_2\sin^2\theta_W\,, \\
\Gamma_S(Z\gamma) = \frac{|s_{Z\gamma}|^2 m_S^3}{8\pi\Lambda^2}\left(1 - x_Z^S\right)^3, & s_{Z\gamma} = (s_2 - s_1)\sin 2\theta_W\,, \\
\Gamma_S(ZZ) = \frac{|s_{ZZ}|^2 m_S^3}{4\pi\Lambda^2}\sqrt{1-4x_Z^S}\left(1 - 4x_Z^S + 6(x_Z^S)^2\right), & s_{ZZ} = s_2\cos^2\theta_W + s_1\sin^2\theta_W\,, \\
\Gamma_S(W^+W^-) = \frac{|s_{WW}|^2 m_S^3}{8\pi\Lambda^2}\sqrt{1-4x_W^S}\left(1 - 4x_W^S + 6(x_W^S)^2\right), & s_{WW} = 2s_2 \\
\Gamma_S(gg) = \frac{2|s_{gg}|^2 m_S^3}{\pi\Lambda^2}\,, & s_{gg} = s_3\,,
\end{cases} \tag{2}$$



Photophobic decay

$$\begin{aligned}
&BR(W^+W^-) : BR(ZZ) : BR(Z\gamma) : BR(gg) \\
&\approx \frac{|s_1|^2}{4\tan^4\theta_W} : \frac{|s_1|^2\cos^2 2\theta_W}{8\sin^4\theta_W} : \frac{|s_1|^2}{4\tan^2\theta_W} : 1.
\end{aligned}$$

Vector (model dependent)

$$\mathcal{L}_{D4} = -g_X Z'_\mu \bar{q} \gamma^\mu (c_L P_L + c_R P_R) q - \frac{1}{2} \epsilon F^Y_{\mu\nu} F^{X\mu\nu} - \Big(i\eta D^\mu a_X \left(H^\dagger D_\mu H\right) + \text{c.c.} \Big)$$

$$\begin{aligned}
\mathcal{L}_{\text{CP-even}} = {} & \kappa_1 \epsilon^{\mu\nu\rho\sigma} Z'_\mu Z_\nu F_{\rho\sigma} + \hat{\kappa}_1 \epsilon^{\mu\nu\rho\sigma} Z'_\mu Z_\nu (\partial_\rho Z_\sigma - \partial_\sigma Z_\rho) \\
& + \Big(\kappa_2 \epsilon^{\mu\nu\rho\sigma} Z'_\mu W^-_\nu (\partial_\rho W^+_\sigma - \partial_\sigma W^+_\rho) + i\hat{\kappa}_2 Z'^\mu W^{-\nu} (\partial_\mu W^+_\nu - \partial_\nu W^+_\mu) + \text{c.c.} \Big) \\
& + \frac{\kappa_3}{\Lambda} Z'^\mu \partial^\nu h \, F_{\mu\nu} + \frac{\hat{\kappa}_3}{\Lambda} Z'^\mu \partial^\nu h \, (\partial_\mu Z_\nu - \partial_\nu Z_\mu)
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\text{CP-odd}} = {} & \alpha_1 Z'^\mu Z^\nu F_{\mu\nu} + \hat{\alpha}_1 Z'^\mu Z^\nu (\partial_\mu Z_\nu - \partial_\nu Z_\mu) \\
& + \Big(\alpha_2 Z'^\mu W^{-\nu} (\partial_\mu W^+_\nu - \partial_\nu W^+_\mu) + i\hat{\alpha}_2 \epsilon^{\mu\nu\rho\sigma} Z'_\mu W^-_\nu (\partial_\rho W^+_\sigma - \partial_\sigma W^+_\rho) + \text{c.c} \Big) \\
& + \frac{\alpha_3}{\Lambda} \epsilon^{\mu\nu\rho\sigma} Z'_\mu \partial_\nu h \, F_{\rho\sigma} + \frac{\hat{\alpha}_3}{\Lambda} \epsilon^{\mu\nu\rho\sigma} Z'_\mu \partial_\nu h \, (\partial_\rho Z_\sigma - \partial_\sigma Z_\rho) \, ,
\end{aligned}$$

gauge invariance

$$\alpha_2 = \frac{m_W}{m_Z} \Big(\alpha_1 \sin\theta_W + \hat{\alpha}_1 \cos\theta_W \Big), \quad \hat{\alpha}_2 = -\frac{m_W}{\Lambda} \Big(\alpha_3 \sin\theta_W + \hat{\alpha}_3 \cos\theta_W \Big)$$

tensor CP-even

$$\mathcal{L}^{\mathcal{G}}_{\mathrm{CP-even}} = \frac{1}{\Lambda} \mathcal{G}_{\mu\nu} T^{\mu\nu} \qquad \Lambda \sim 10 \text{ TeV}$$

$$T_{\mu\nu} = c_1 F^Y_{\mu\lambda} F^{Y\lambda}{}_{\nu} + c_2 F^W_{\mu\lambda} F^{W\lambda}{}_{\nu} + c_3 G_{\mu\lambda} G^{\lambda}{}_{\nu}$$

(~ energy momentum tensor)

gauge invariance:

$$c_{\gamma\gamma} = c_1 \cos^2\theta_W + c_2 \sin^2\theta_W$$

$$c_{Z\gamma} = (c_2 - c_1)\sin(2\theta_W)$$

$$c_{ZZ} = c_2 \cos^2\theta_W + c_1 \sin^2\theta_W$$

$$c_{WW} = 2c_2$$

$$c_{gg} = c_3\,,$$

Effective operator :CP odd tensor

$$\mathcal{L}^{\mathcal{G}}_{\rm CP-odd} = \frac{1}{\Lambda}\mathcal{G}_{\mu\nu}\tilde{T}^{\mu\nu} \qquad \Lambda \sim 10 \text{ TeV}$$

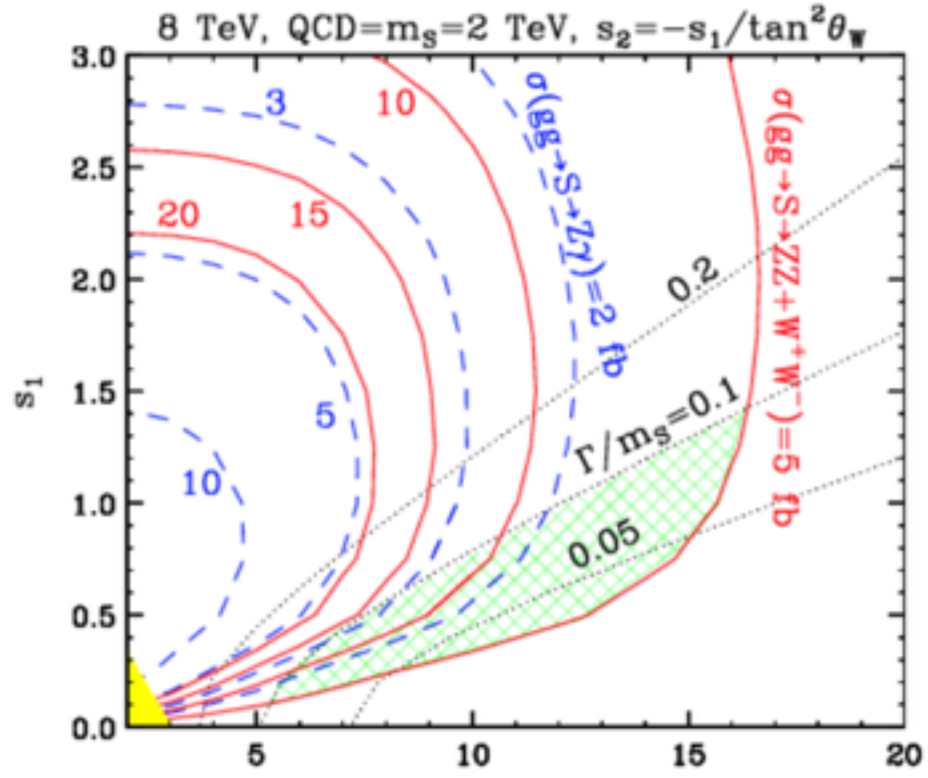
$$\begin{aligned}
\tilde{T}_{1,\mu\nu} = {} & a_1\,\epsilon_{\mu\lambda\rho\sigma}\partial^\lambda Z_\nu F^{\rho\sigma} + \hat{a}_1\,\epsilon_{\mu\lambda\rho\sigma}\partial^\lambda Z_\nu(\partial^\rho Z^\sigma - \partial^\sigma Z^\rho) \\
& + \Big(a_2\,\epsilon_{\mu\lambda\rho\sigma}\partial^\lambda W^-_\nu(\partial^\rho W^{\sigma+} - \partial^\sigma W^{\rho+}) + i\hat{a}_2\partial^\lambda W^-_\nu(\partial_\mu W^+_\lambda - \partial_\lambda W^+_\mu) + \text{c.c.}\Big) \\
& + \frac{a_3}{\Lambda}\,\partial^\lambda\partial_\nu h\, F_{\mu\lambda} + \frac{\hat{a}_3}{\Lambda}\,\partial^\lambda\partial_\nu h\,(\partial_\mu Z_\lambda - \partial_\lambda Z_\mu), \\
\tilde{T}_{2,\mu\nu} = {} & \frac{i}{2}a_q\,\bar{q}\gamma^5(\gamma^\mu\partial^\nu + \gamma^\nu\partial^\mu)q - \frac{i}{2}a_q((\partial^\mu\bar{q})\gamma^5\gamma^\nu + (\partial^\nu\bar{q})\gamma^5\gamma^\mu)q.
\end{aligned}$$

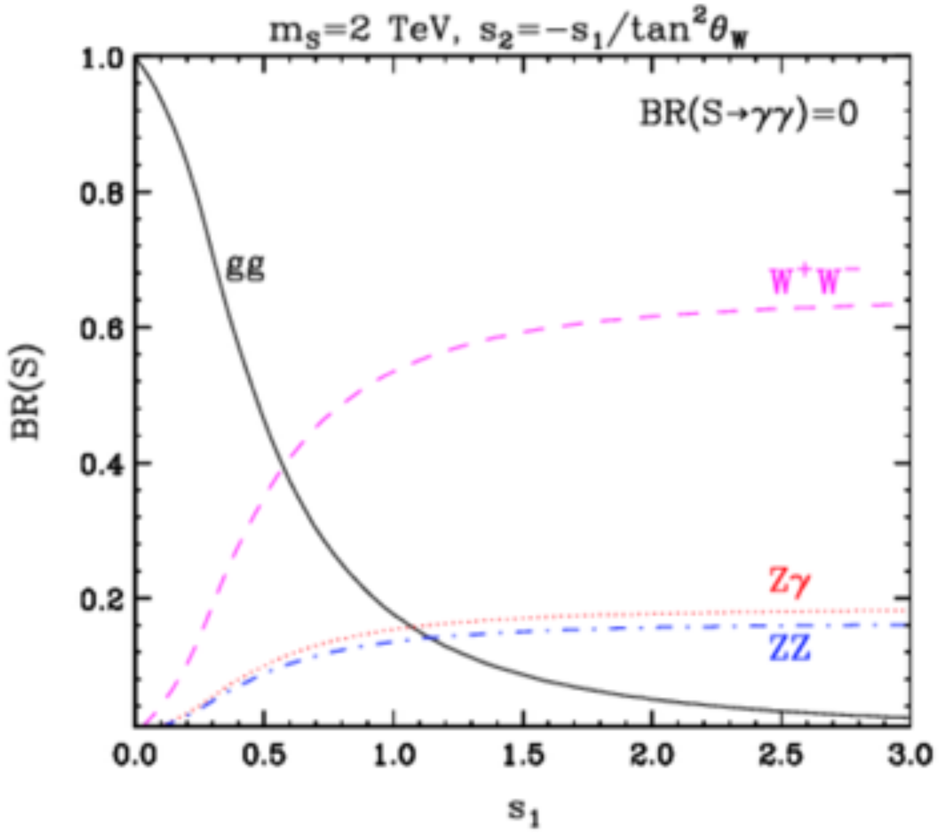
gauge invariance

$$a_2 = \frac{m_W}{m_Z}\Big(a_1\sin\theta_W + \hat{a}_1\cos\theta_W\Big), \quad \hat{a}_2 = -\frac{m_W}{\Lambda}\Big(a_3\sin\theta_W + \hat{a}_3\cos\theta_W\Big).$$

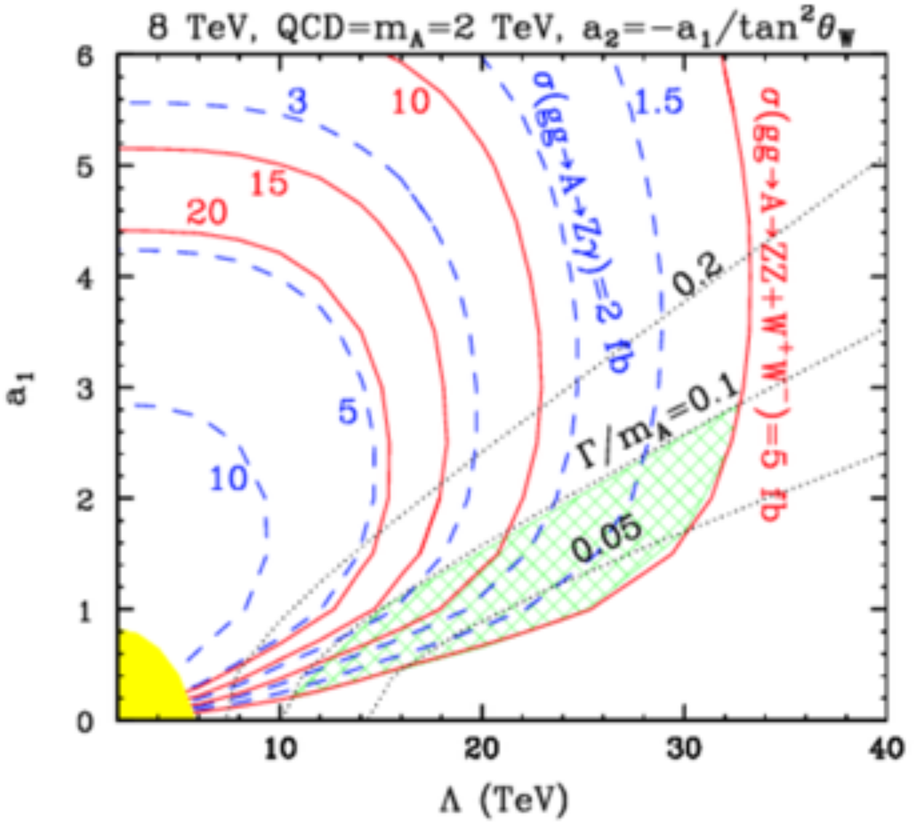
Parameter space for scalar

CP even



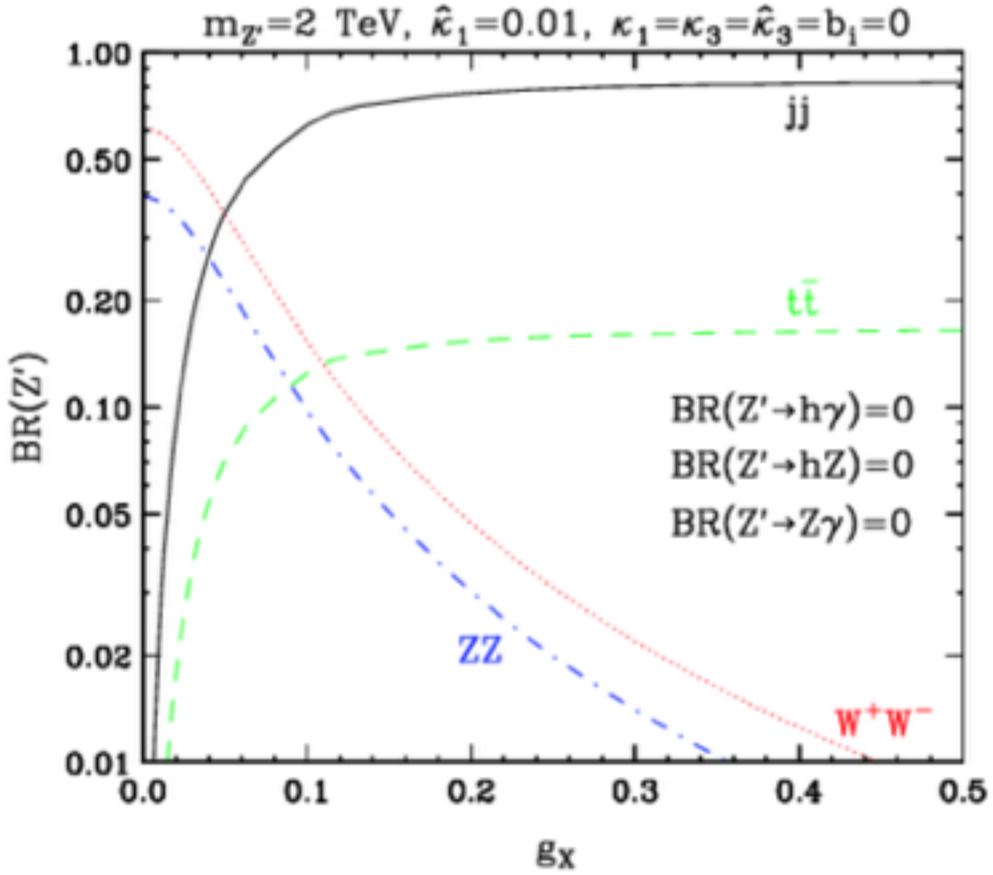


CP odd

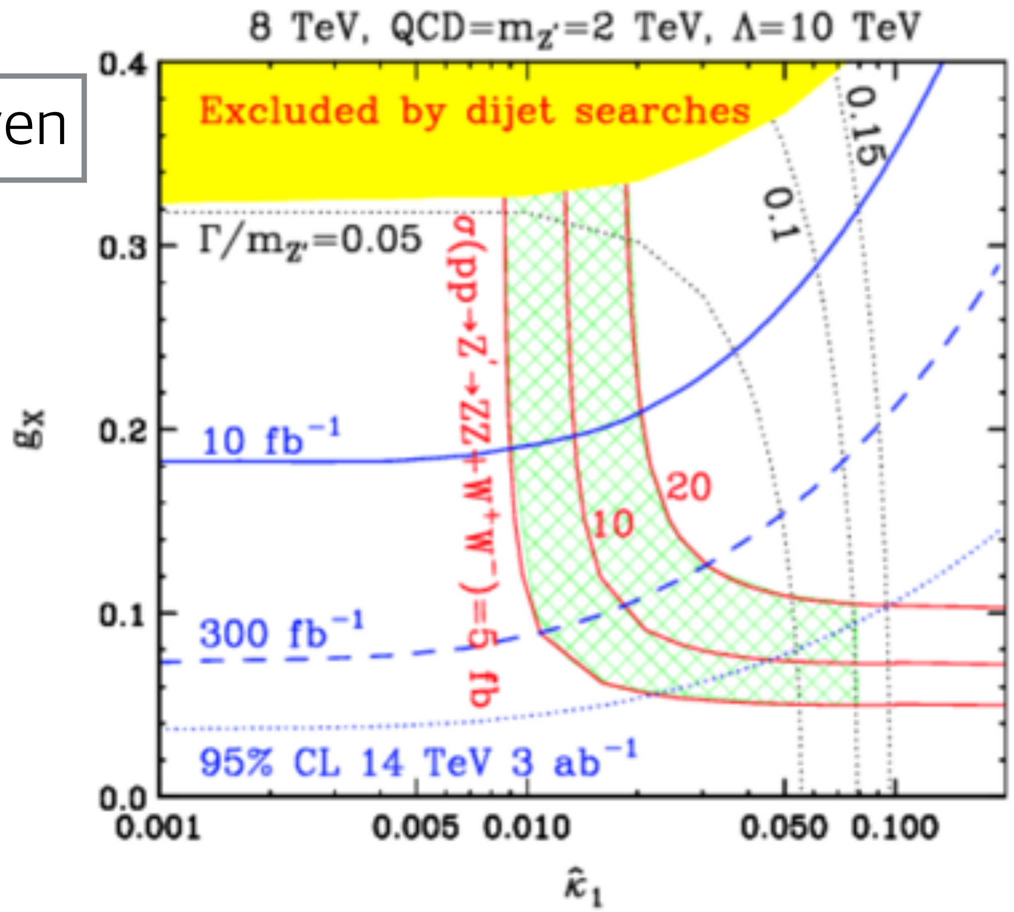


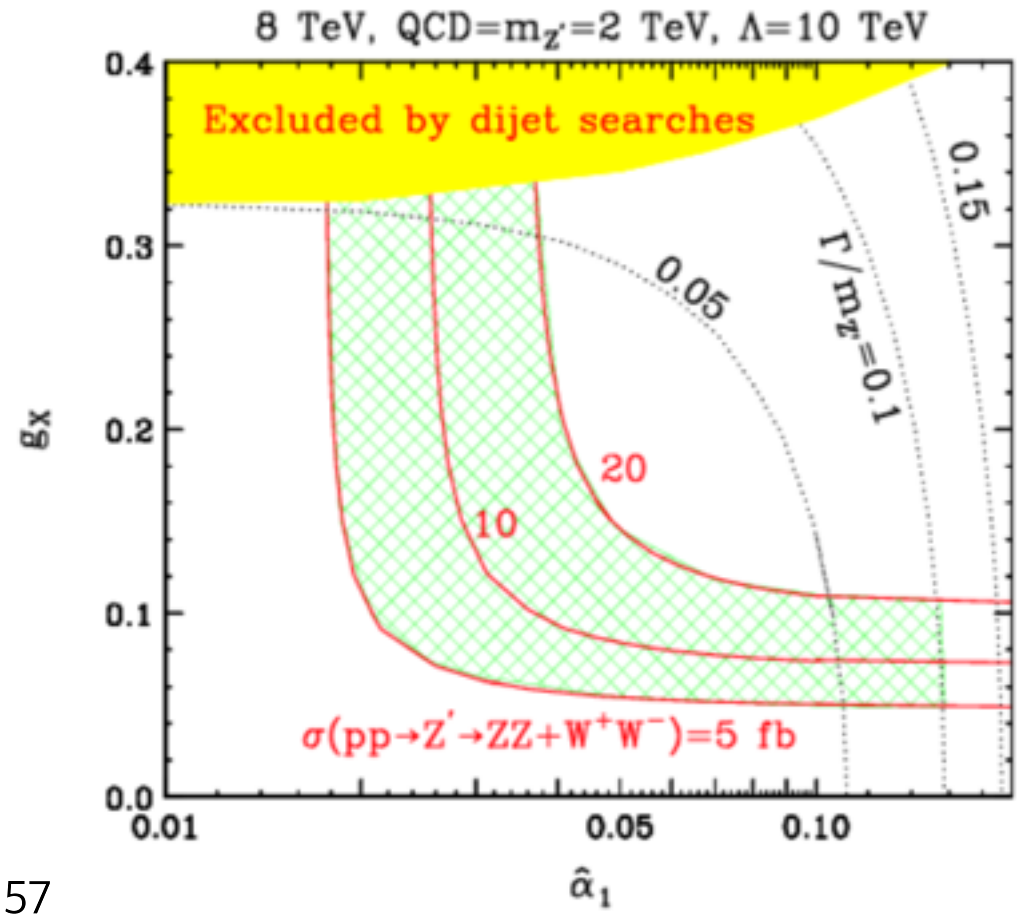
very similar

vector



CP even

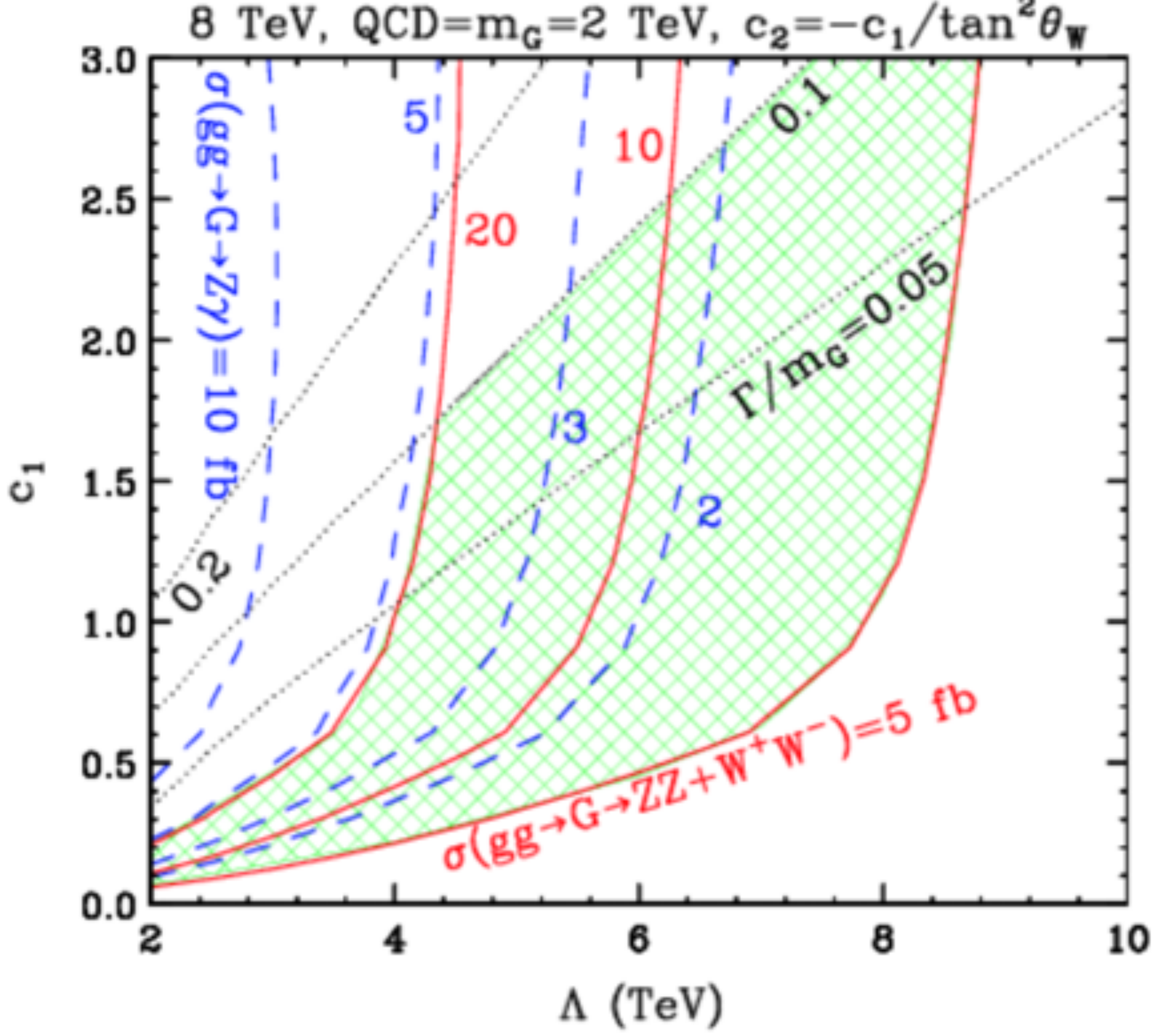




CP odd

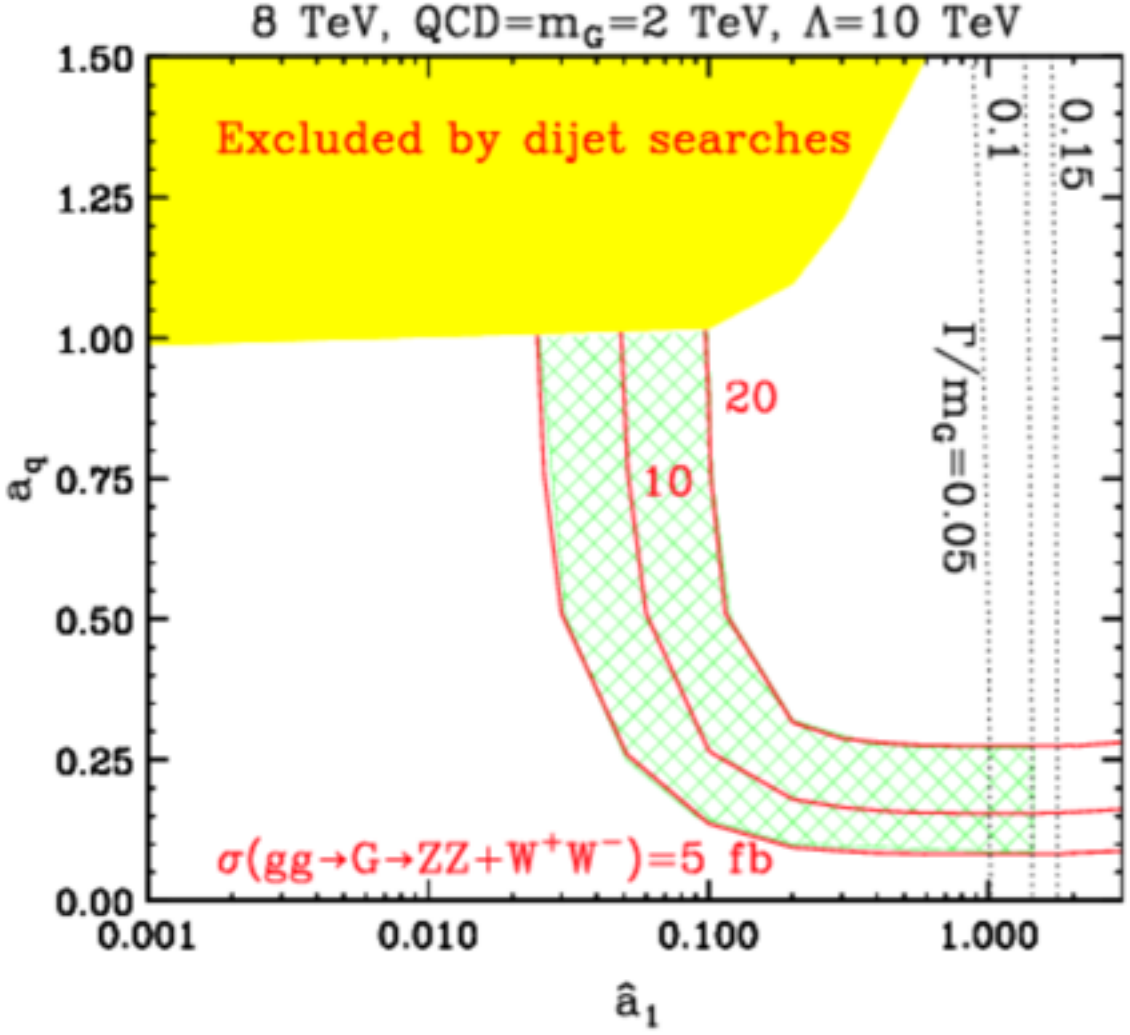
tensor

CP even



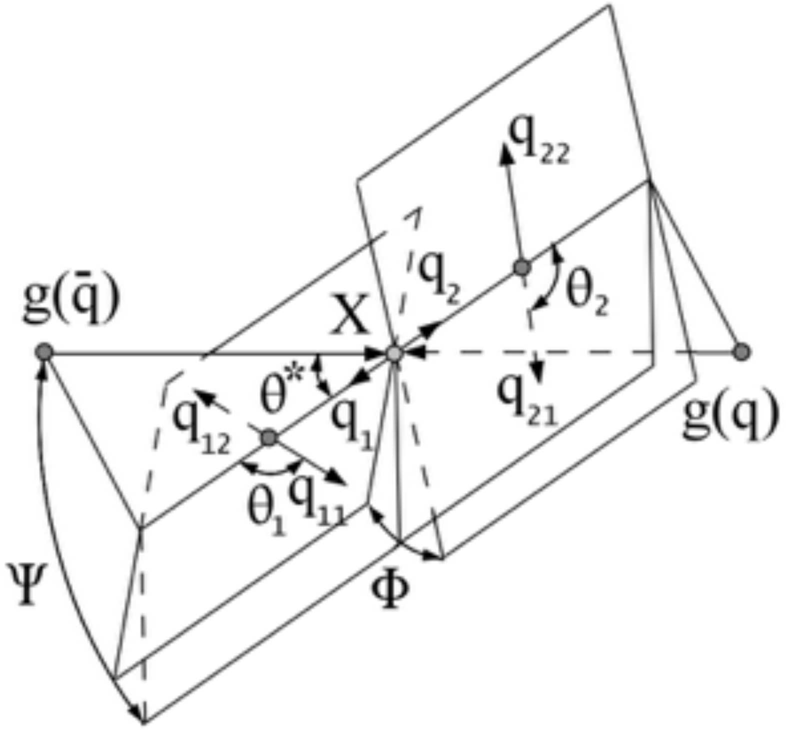
BR~similar to scalar

CP odd



BR~similar to vector

How to distinguish? see the angles!



$$\hat{\boldsymbol{n}}_1 = \frac{\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}}{|\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}|}, \qquad \hat{\boldsymbol{n}}_2 = \frac{\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}}{|\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}|}, \quad \text{and} \quad \hat{\boldsymbol{n}}_{\rm sc} = \frac{\hat{\boldsymbol{n}}_z \times \boldsymbol{q}_1}{|\hat{\boldsymbol{n}}_z \times \boldsymbol{q}_1|}.$$

$$\Phi = \frac{\vec{P}_1 \cdot (\hat{n}_1 \times \hat{n}_2)}{|\vec{P}_1 \cdot (\hat{n}_1 \times \hat{n}_2)|} \cos^{-1}(\hat{n}_1 \cdot \hat{n}_2) \text{ with } \hat{n}_i = \frac{\vec{u}_i \times \vec{v}_i}{|\vec{u}_i \times \vec{v}_i|},$$

$$\Phi_1 = \frac{\vec{P}_1 \cdot (\hat{n}_1 \times \hat{n}_{sc})}{|\vec{P}_1 \cdot (\hat{n}_1 \times \hat{n}_{sc})|} \cos^{-1}(\hat{n}_1 \cdot \hat{n}_{sc}) \text{ with } \hat{n}_{sc} = \frac{\hat{z} \times \vec{P}_1}{|\hat{z} \times \vec{P}_1|},$$

$$\cos\theta^* = \frac{\vec{P}_1 \cdot \hat{z}}{|\vec{P}_1|},$$

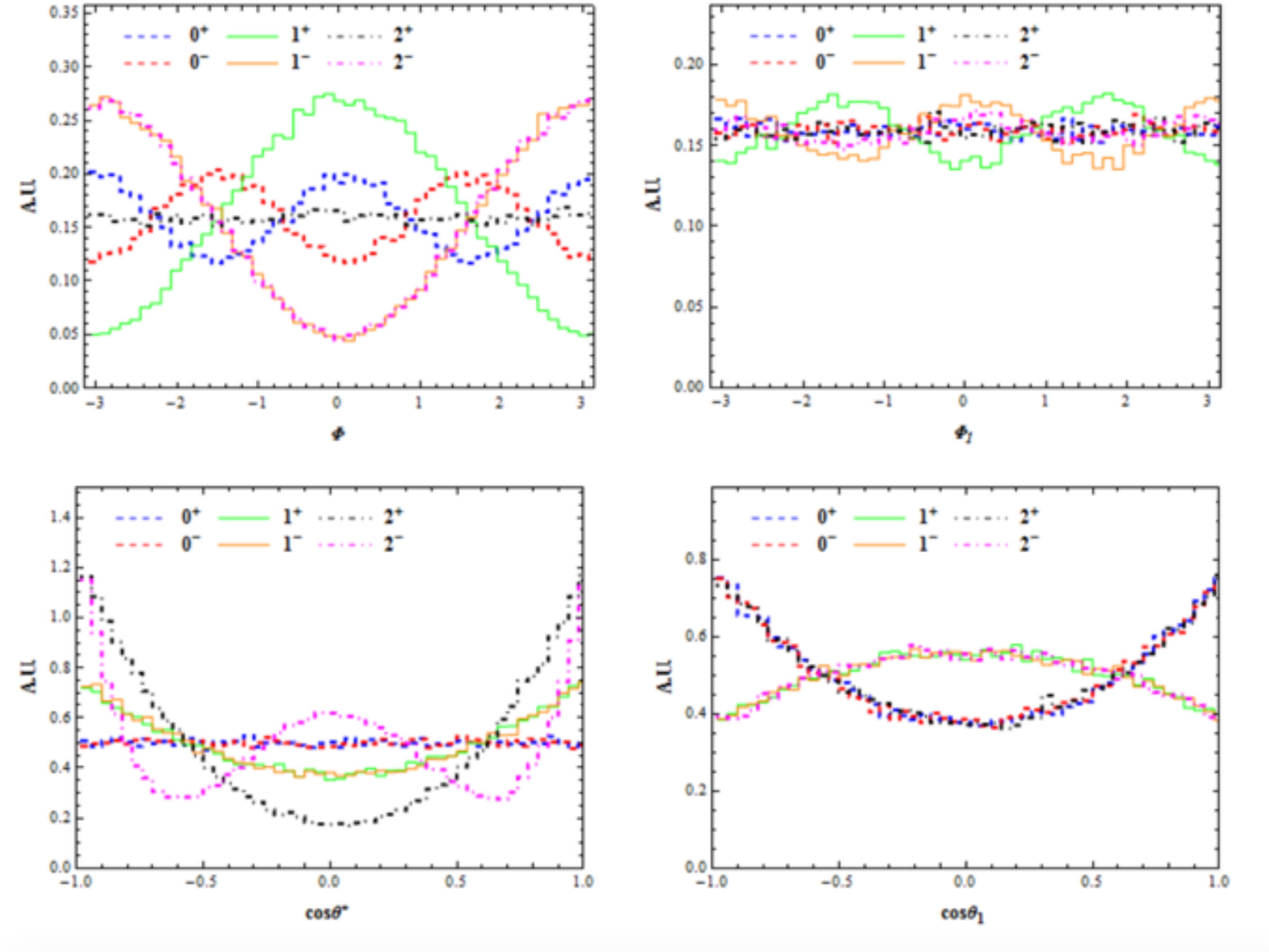
$$\cos\theta_1 = -\frac{\vec{P}_2 \cdot \vec{u}_1}{|\vec{P}_2||\vec{u}_1|}.$$

Scattering angle dependence

Scattering angle dependence:

$$\frac{d\sigma}{d\cos\theta^*} \sim \begin{cases} 1\,, & \text{for } gg \to 0^+\,,0^- \to W^+W^- \\ 1+\cos^2\theta^*\,, & \text{for } q\bar{q} \to 1^+\,,1^- \to W^+W^- \\ 1+6\cos^2\theta^* + \cos^4\theta^*\,, & \text{for } gg \to \quad 2^+ \quad \to W^+W^- \\ 1-3\cos^2\theta^* + 4\cos^4\theta^*\,, & \text{for } q\bar{q} \to \quad 2^- \quad \to W^+W^- \end{cases} .$$

Distributions may tell us more about spin & CP properties



summary & outlook

- **In PART-1:** We consider “top-philic resonance” as an interesting example and suggest a way of examining it in a model independent way at the LHC run-2.

- **In PART-2:** motivated by ATLAS diboson anomalies in WW, WZ, ZZ at 2 TeV, we consider a possible minimal EFT approach taking Spin-0, 1 and 2 with CP-even and odd states.

- Further experiments (LHC13) with measurement of angular distributions would be essential to confirm the signal and identify its spin and CP properties. (will learn more this winter?)

- For DM model builders: **‘Top-portal’** and **‘Diboson-portal’** could be interesting paths to go beyond the current analysis.