Composite Higgs

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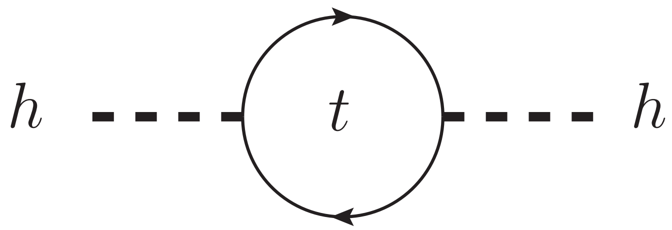
SNS Pisa

22 May 2014

Introduction: The Hierarchy Problem

- Higgs mass is unstable under radiative corrections



$$\delta m_h^2 \simeq \frac{g^2}{16\pi^2} \Lambda^2$$

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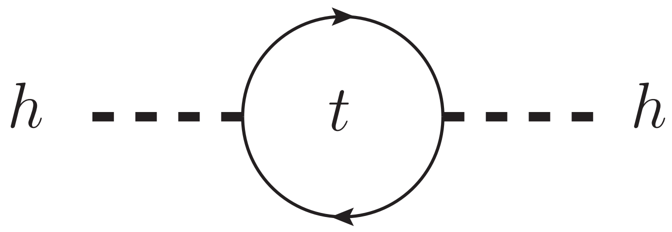

$$\delta m_h^2 \simeq \frac{g^2}{16\pi^2} \Lambda^2$$

$$\Lambda \sim M_{Planck}$$

$$\text{tuning} \sim \frac{M_{Planck}^2}{m_h^2} \sim 10^{32}$$

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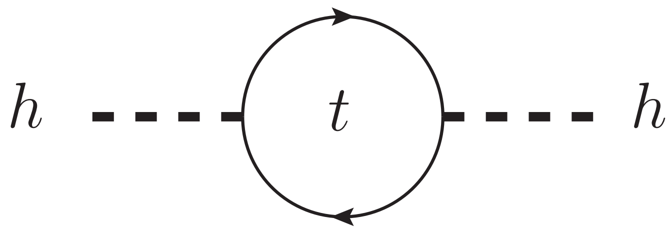

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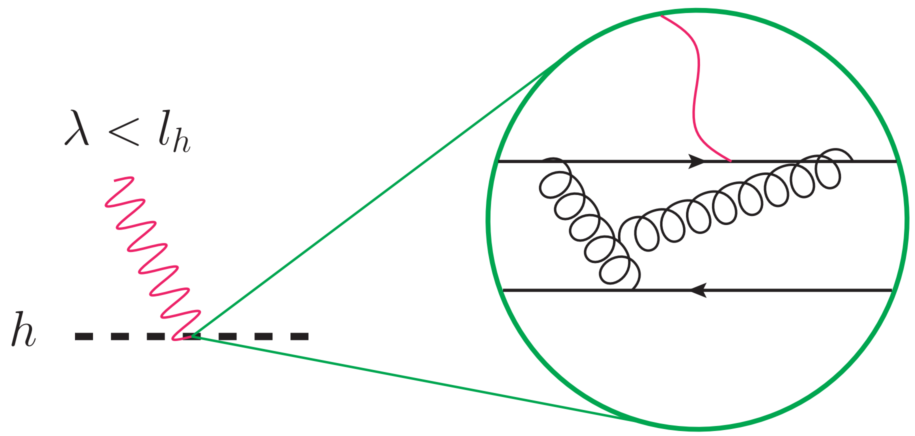
- new strong dynamics limits the UV sensitivity



$$\delta m_h^2 \simeq \frac{1}{l_h^2} \simeq m_\rho^2$$

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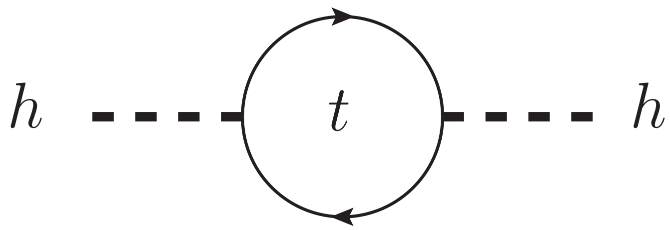

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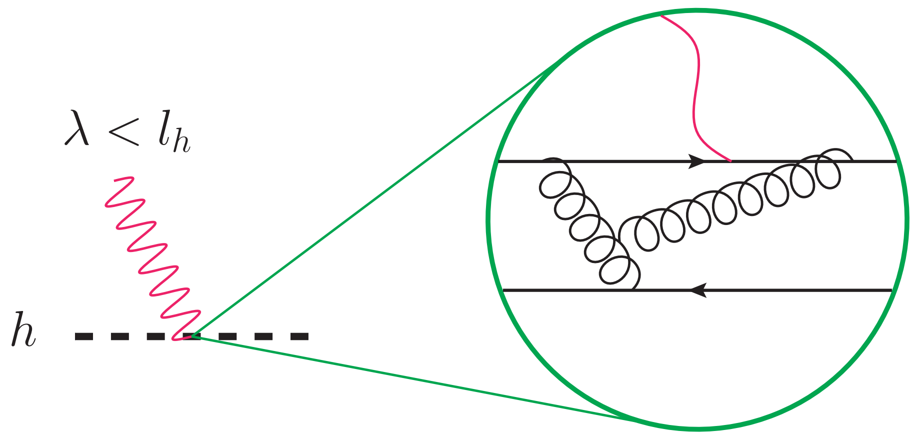

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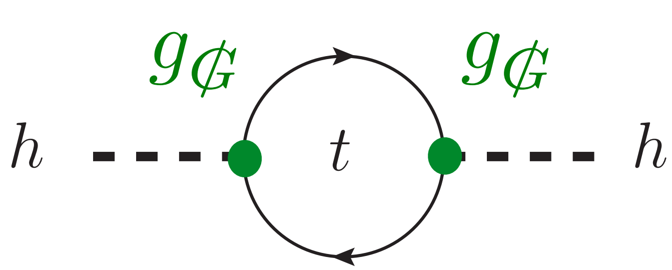
- Higgs realized as a Goldstone boson can be naturally light



$$\delta m_h^2 \simeq \frac{g_{\not G}^2}{16\pi^2}\,m_\rho^2$$

[Georgi,Kaplan]

Introduction: Composite Higgs

- Higgs realized as a Goldstone boson can be naturally light

Introduction: Composite Higgs

- Higgs realized as a Goldstone boson can be naturally light

minimal <u>spontaneous</u> symmetry breaking pattern in the strong sector:

$$SO(5) \rightarrow SO(4) \quad \text{at a scale } f$$

- $SO(4) \sim SU(2)_L\ SU(2)_R$ of the SM
- 4 Goldstone bosons in the 4 of SO(4) ~ Higgs doublet
- strong sector doesn't break custodial symmetry

Introduction: Composite Higgs

- Higgs realized as a Goldstone boson can be naturally light

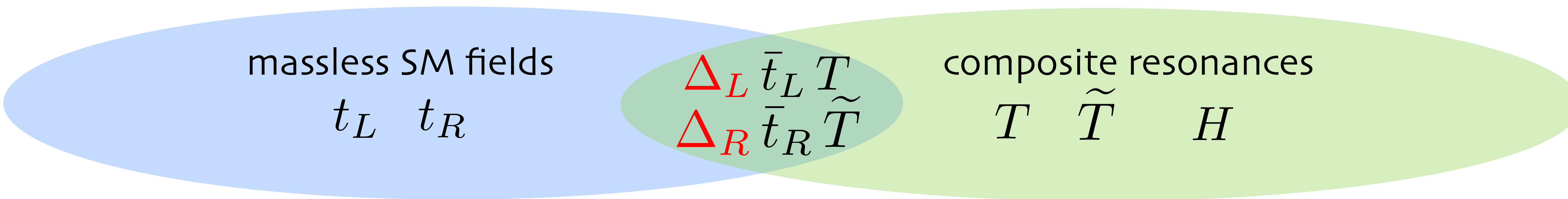
<u>explicit</u> SO(5) breaking via interactions with SM fermions and gauge bosons

- Higgs acquires potential which fixes its VEV $v < f$ and provides a mass

- Higgs mass is proportional to the strength of external perturbations

Partial Compositeness

- explicit breaking & partial compositeness
  - elementary and composite sector communicate via <u>linear</u> mixing of elementary and composite states



[Kaplan'91;Agashe,Contino,Pomarol'05]

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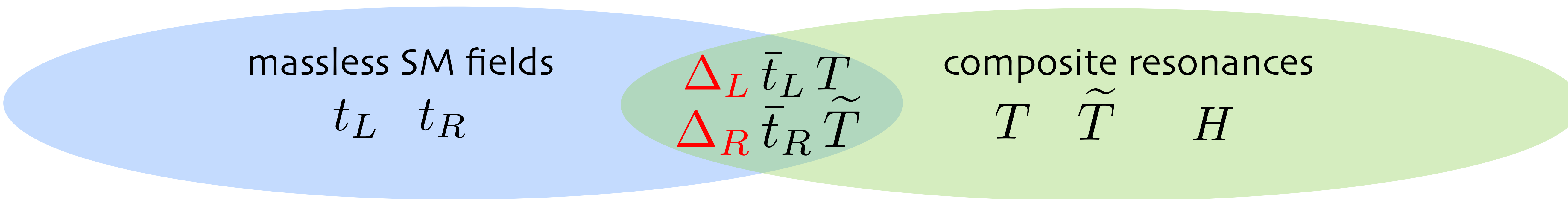
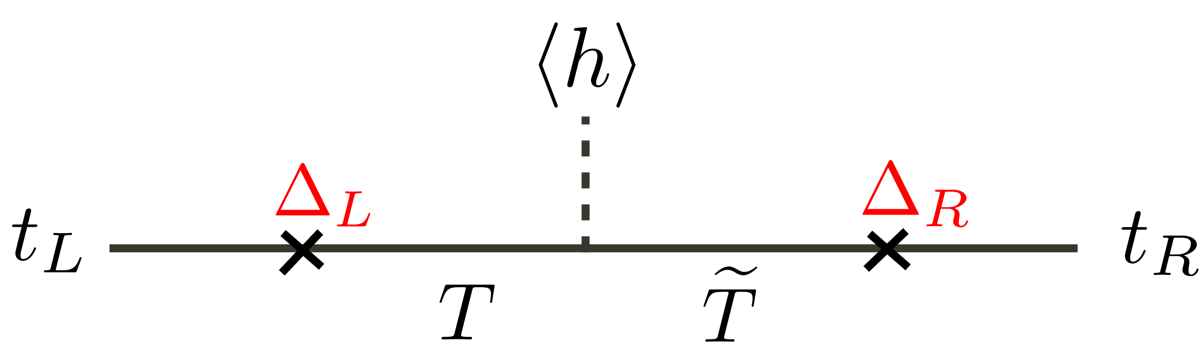


  - SM fermions mass generation:



$$m_q \sim \frac{\Delta_L \Delta_R}{\min(M_T, M_{\tilde{T}})} \frac{\langle h \rangle}{f}$$

top mixings are the most sizable !

Partial Compositeness

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massl … nances

H

SM fermions become "partially composite"

$$t_L = \cos\phi_L \, t_L + \sin\phi_L \, T_L$$

with a degree of compositeness

$$\sin\phi_L \simeq \frac{\Delta_L}{M_T}$$

- SM fermion

$$m_q \sim \frac{\Delta_L \Delta_R}{\min(M_T, M_{\tilde{T}})} \frac{\langle h \rangle}{f}$$

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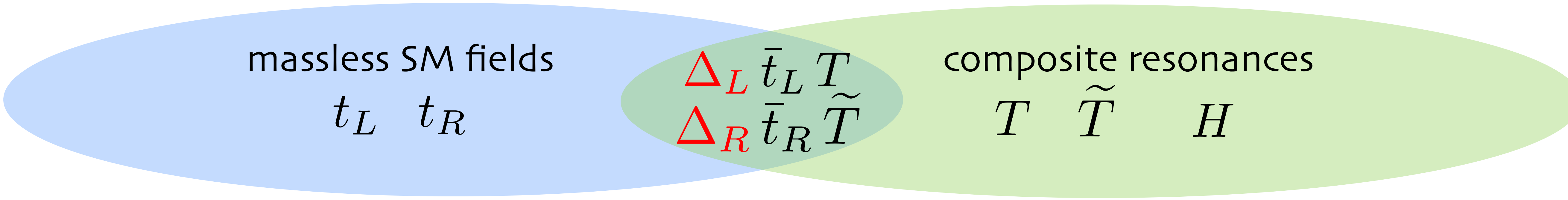

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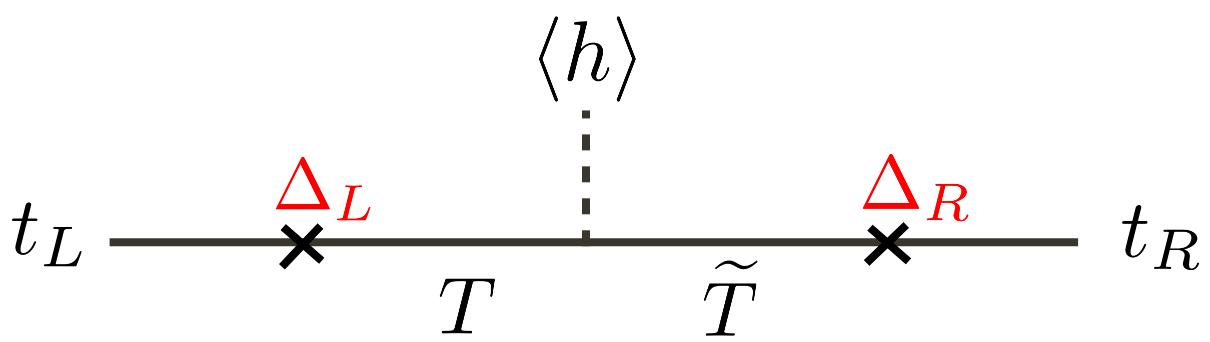

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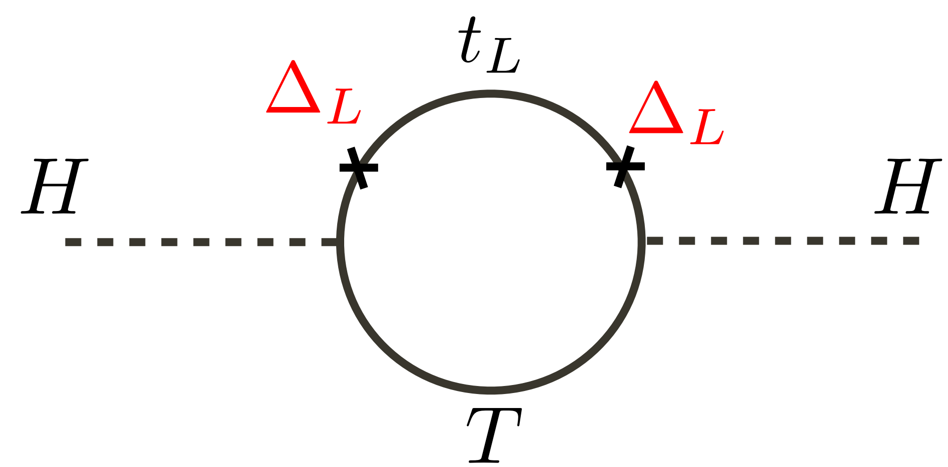
- Higgs mass generation



$$m_h \sim \Delta^n$$

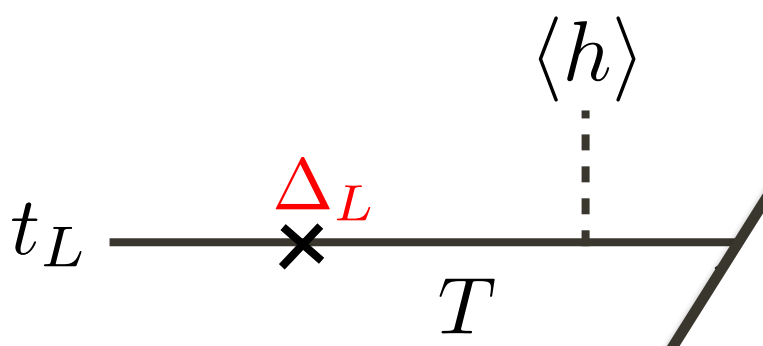
Partial Compositeness

▸ explicit breaking & partial compositeness

- elementary and composite sector communicate via <u>linear</u> mixing of elementary and composite states

massless SM fields	mixing	composite resonances
$t_L \quad t_R$	$\Delta_L \, \bar{t}_L \, T$ $\Delta_R \, \bar{t}_R \, \widetilde{T}$	$T \quad \widetilde{T} \quad H$

- SM fermions mass generation:



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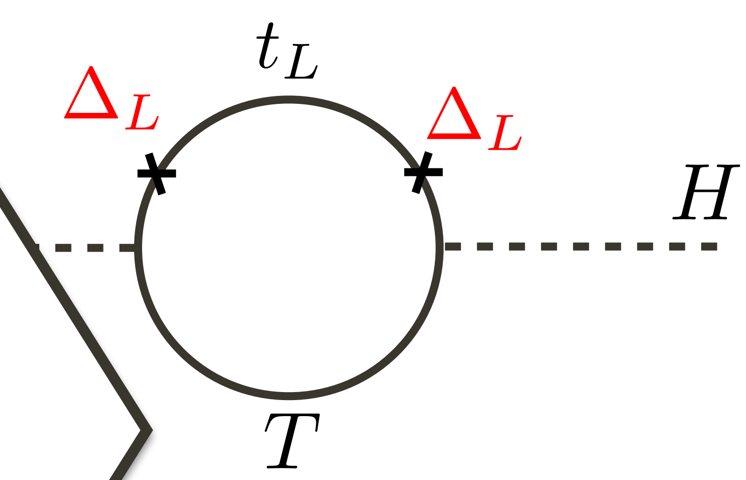


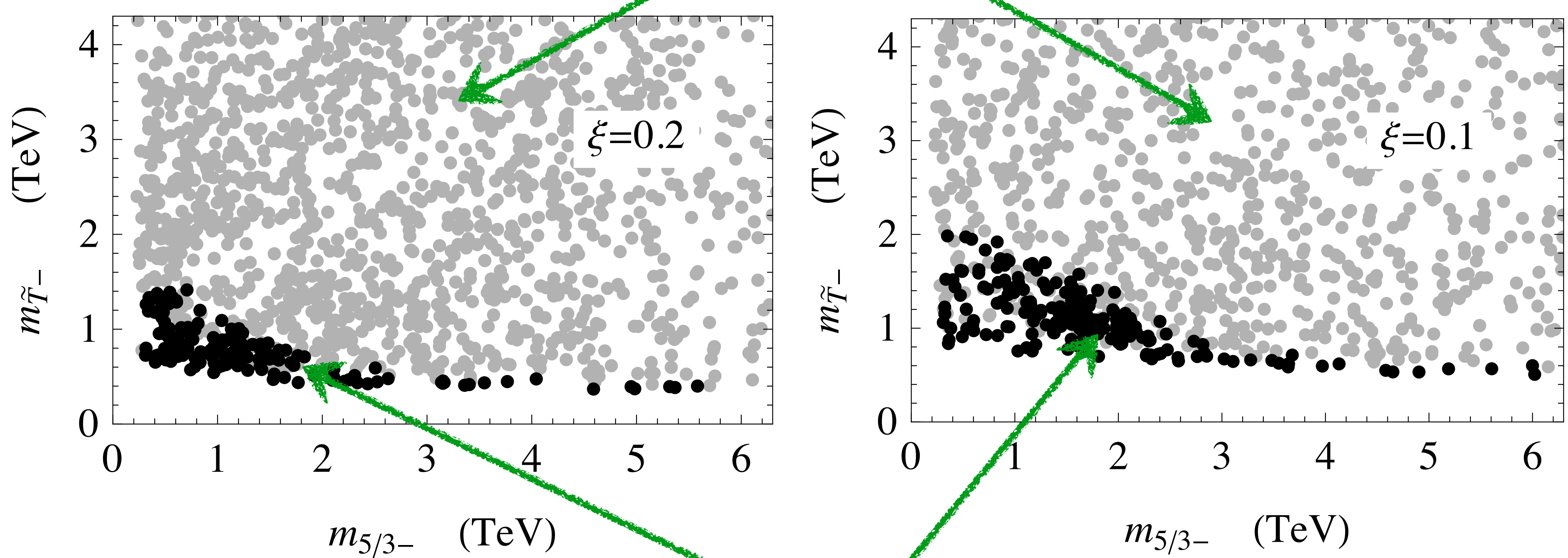
$$m_h \sim \Delta^n$$

composite Higgs needs light top partners

Partial Compositeness

▸ Results in concrete calculable models:

● Higgs is too heavy



● $m_h \simeq 125\, GeV$

20% tuning

m < 1.2 TeV

10% tuning

m < 1.7 TeV

[OM,Panico,Wulzer]

top mixings are the most sizable !

Testing CH

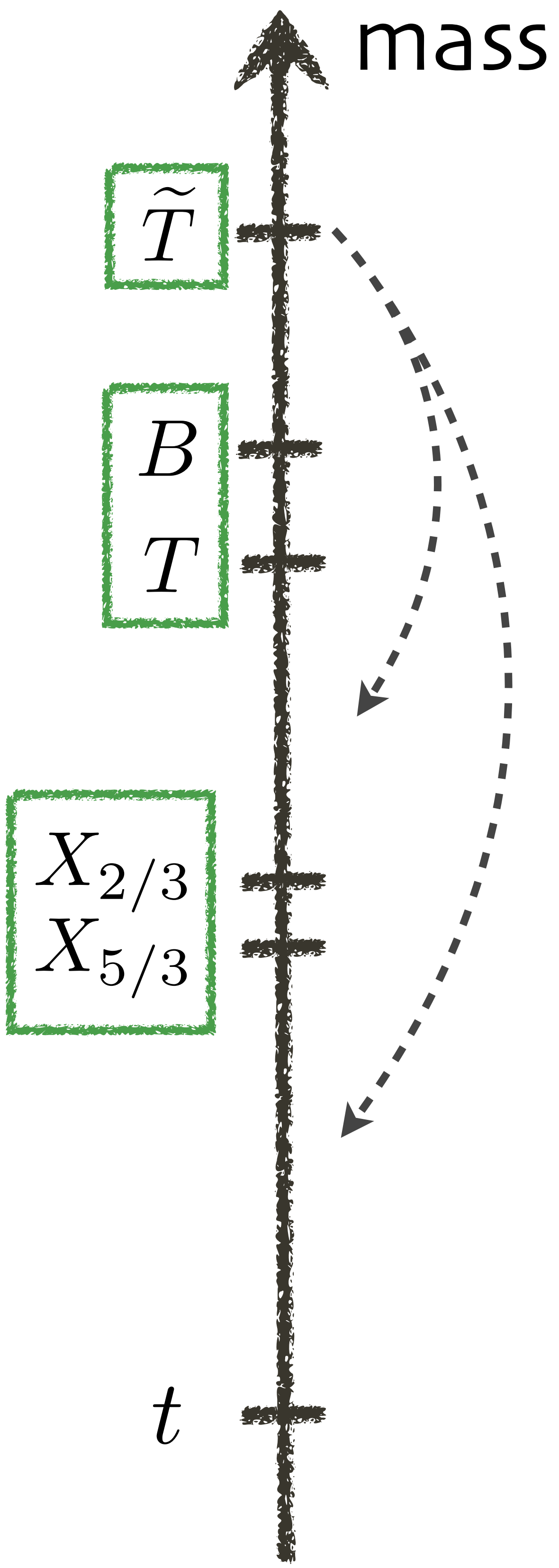
- Higgs partial widths
- Longitudinal gauge boson scattering
- Searches for SM fermion compositeness
- Flavour
- Electroweak precision tests
- Direct searches
- ...

Fermionic Top Partners

- $SO(4) \sim SU(2)_L \times SU(2)_R$ symmetry -> composite resonances are SO(4) multiplets

- singlet ψ_1 $\quad \tilde{T}$
- 4-plet ψ_4 $\quad \begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}$
- 9-plet ψ_9 $\quad X_{8/3} \ldots Z_{-4/3}$
- ...

Mass spectrum



Couplings to SM

Top partners are charged under SM gauge groups:

- color triplets -> interactions with gluons the same as for SM quarks
- charged under broken SU(2)xU(1)y

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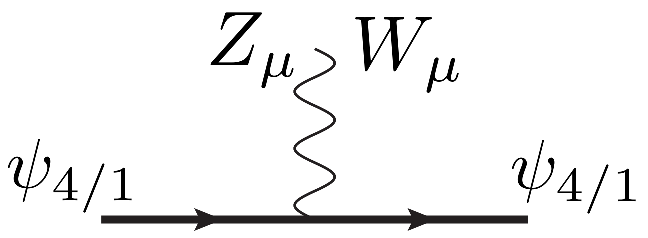

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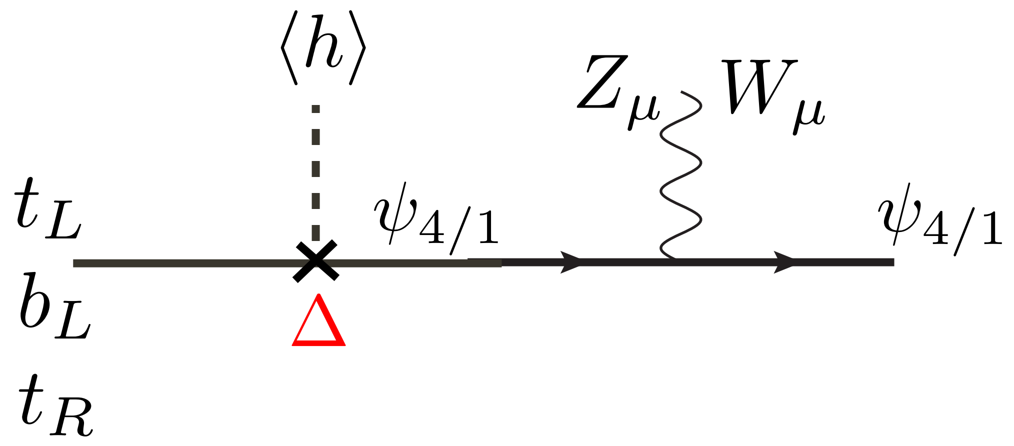

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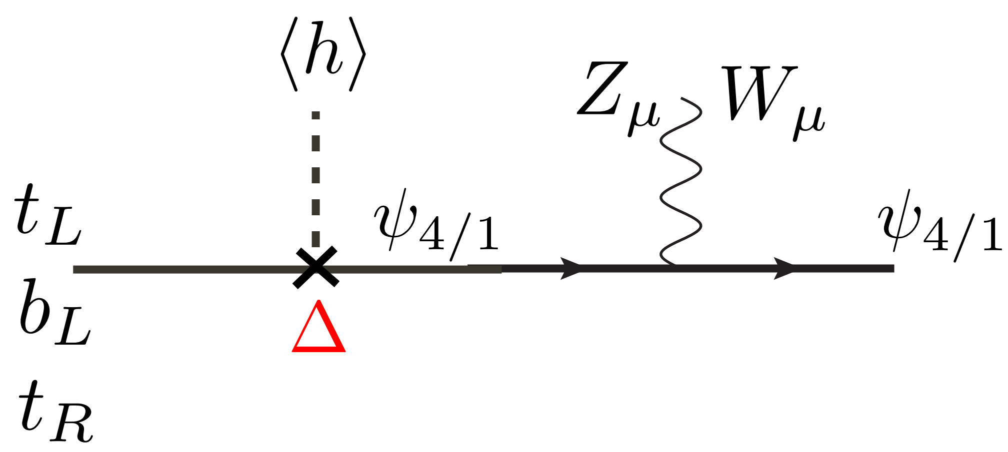

dominant couplings are defined by quantum numbers:

T $X_{5/3}$ B $X_{2/3}$ prefer t_R

$\widetilde{T}$ prefers t_L b_L

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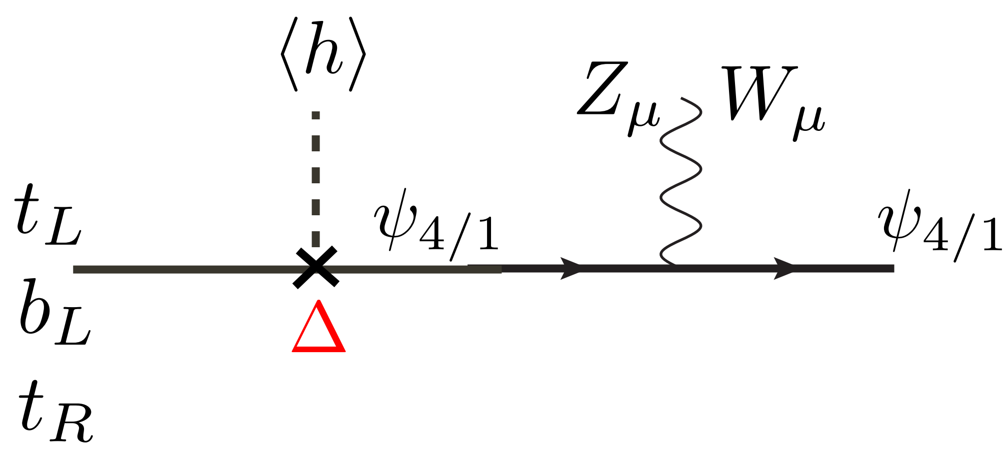

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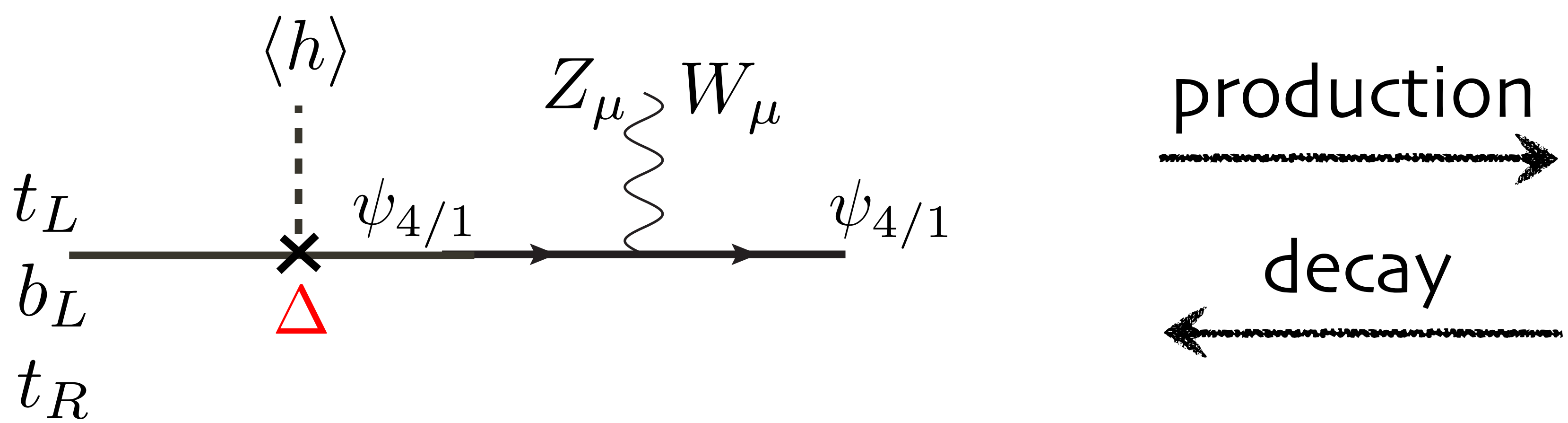

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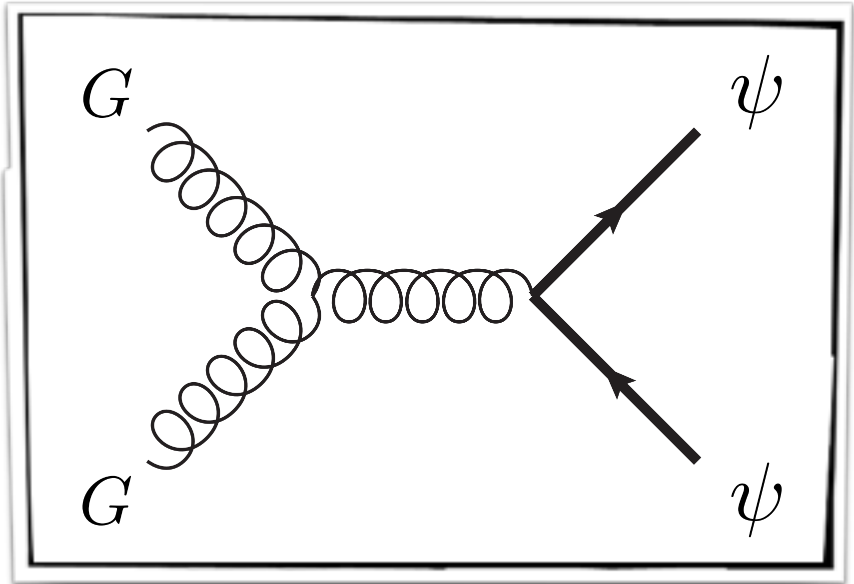
Production mechanisms

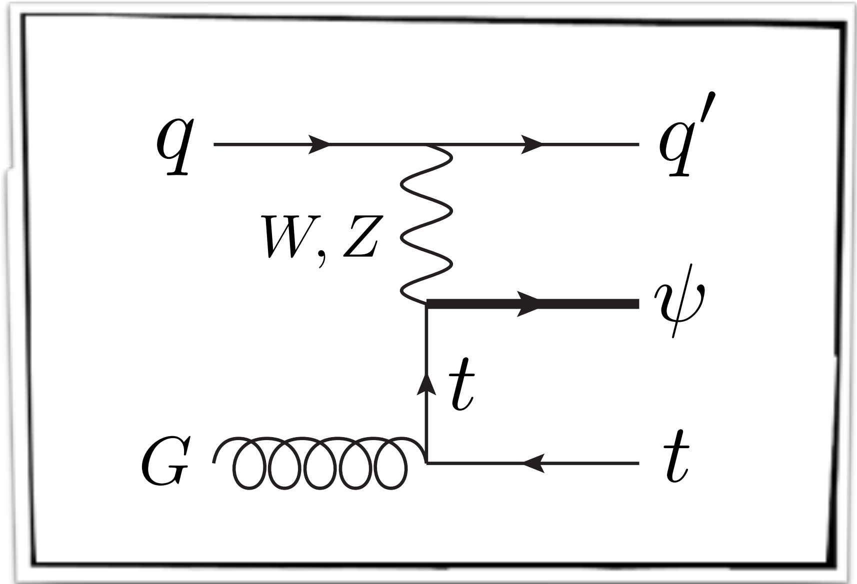
pair production

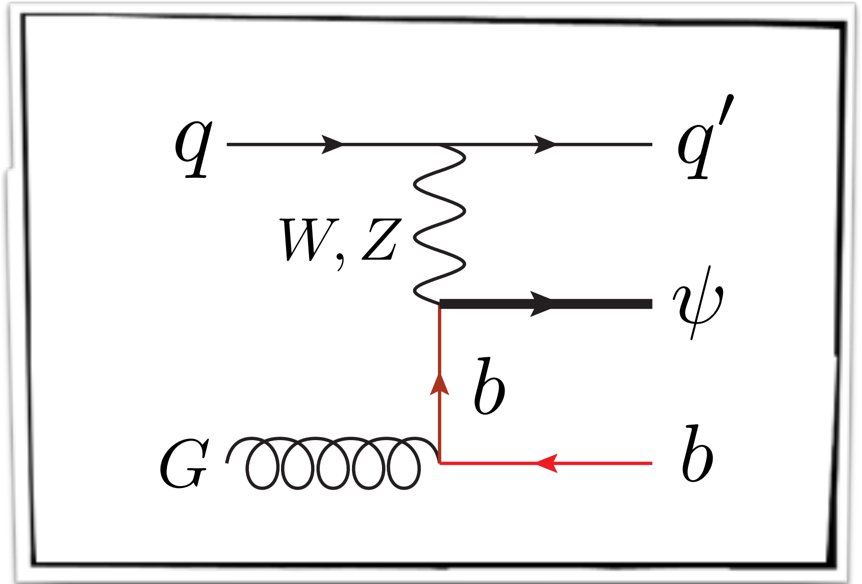
single production

with a top quark

with a bottom



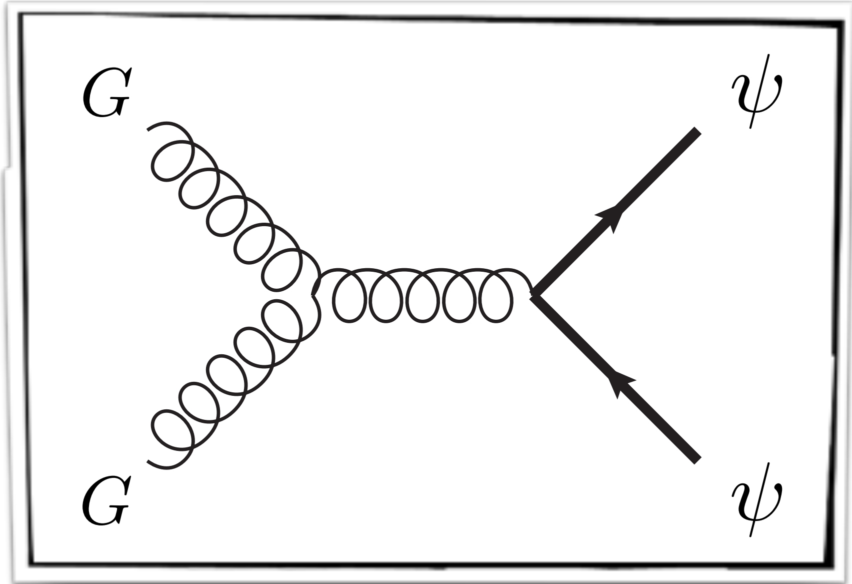




[Contino,Servant;Mrazek,Wulzer]

Production mechanisms

pair production



single production

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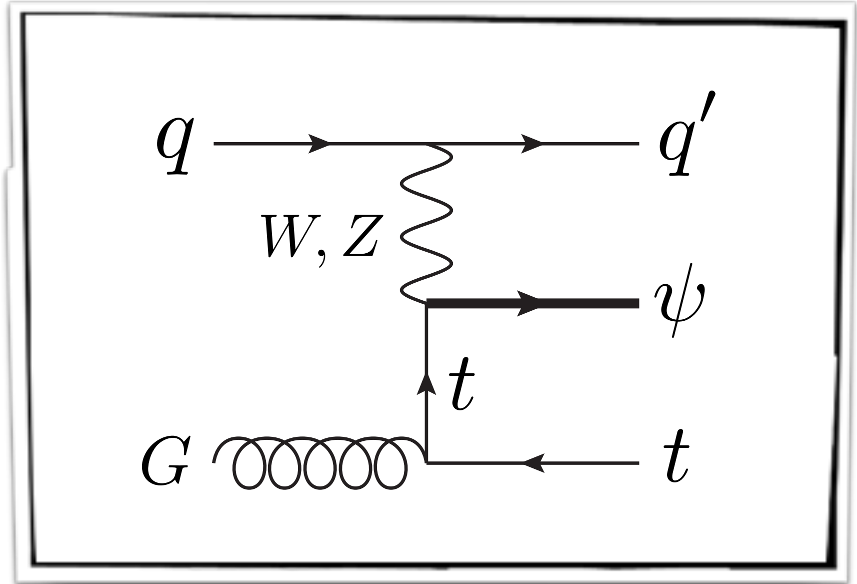
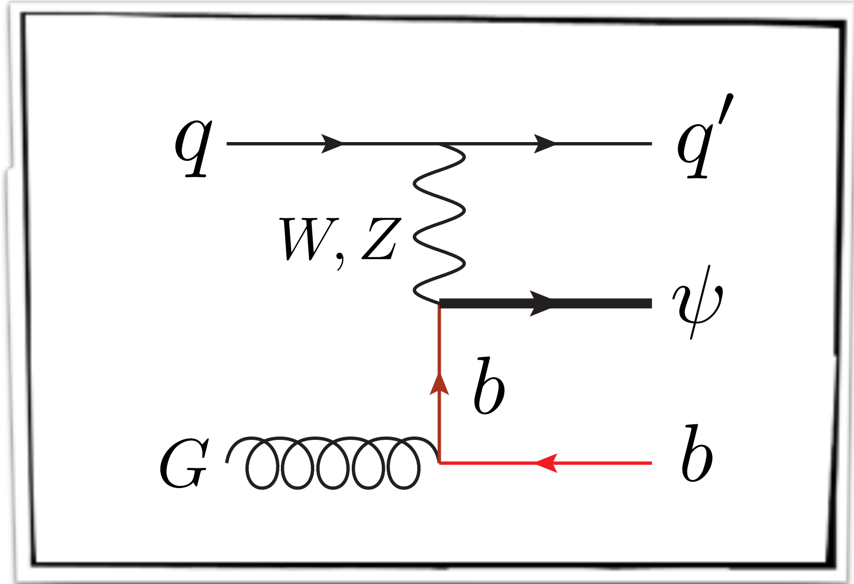


with a bottom



- two heavy states
- a lot of high-pt final states
- only QCD
- model independent

- only one heavy state
- less final states
- involves weak coupling
- additional test of a model structure

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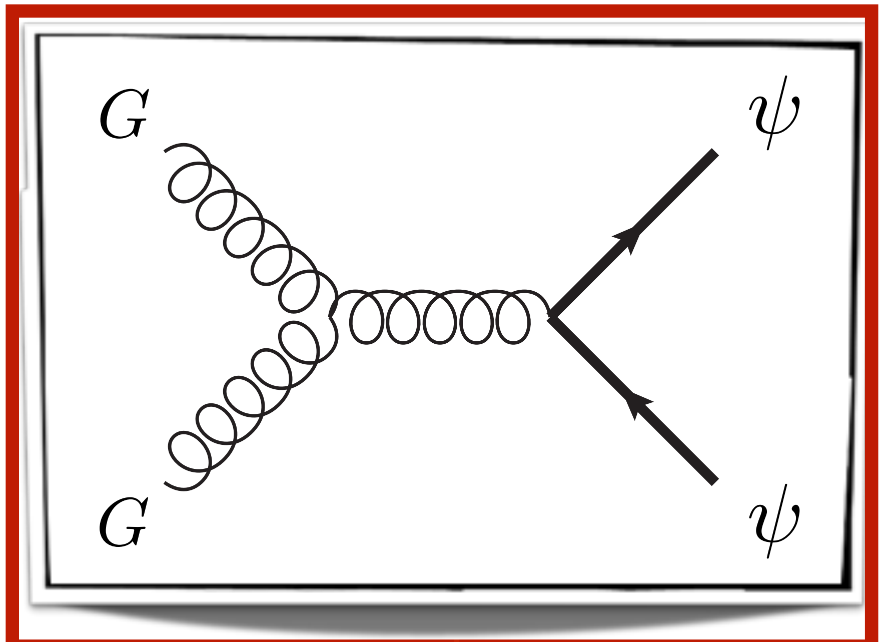

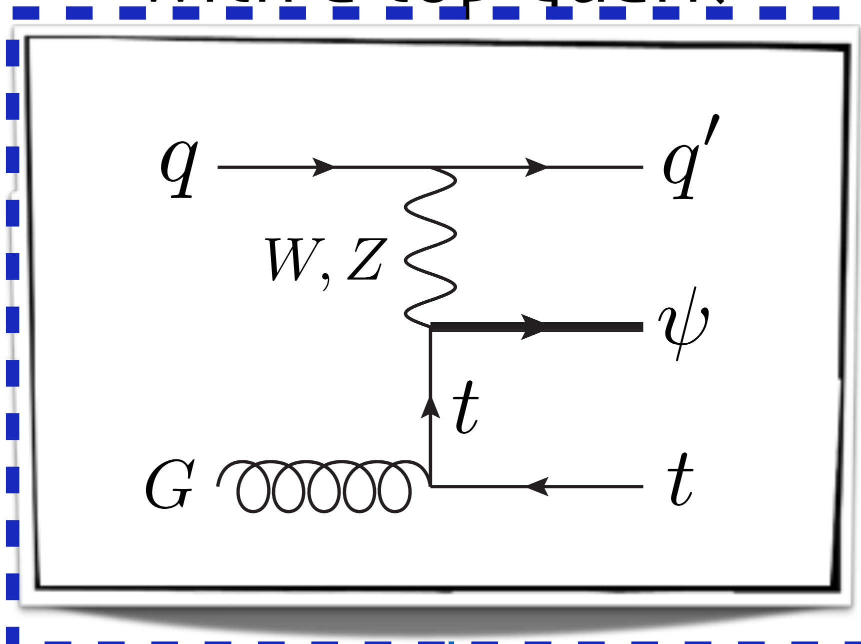

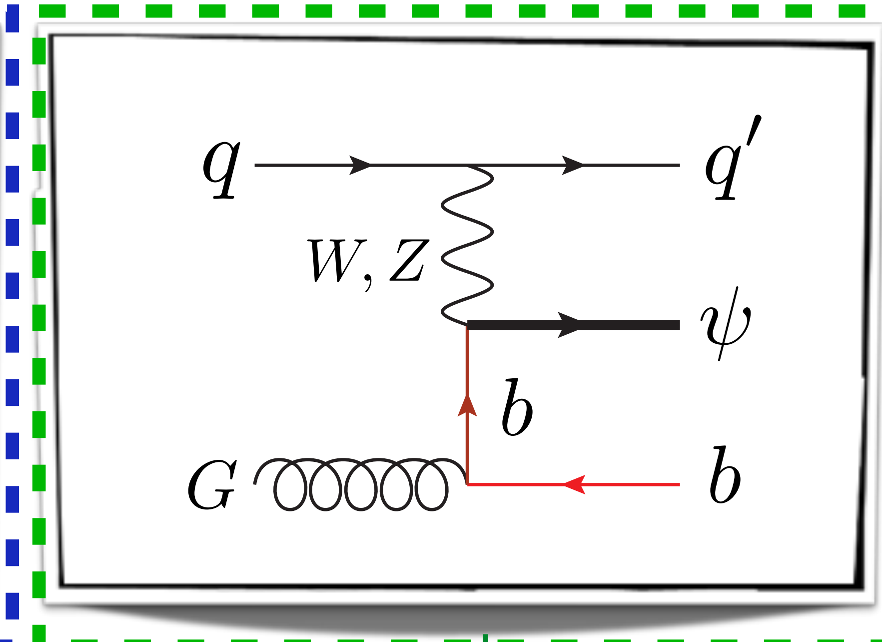

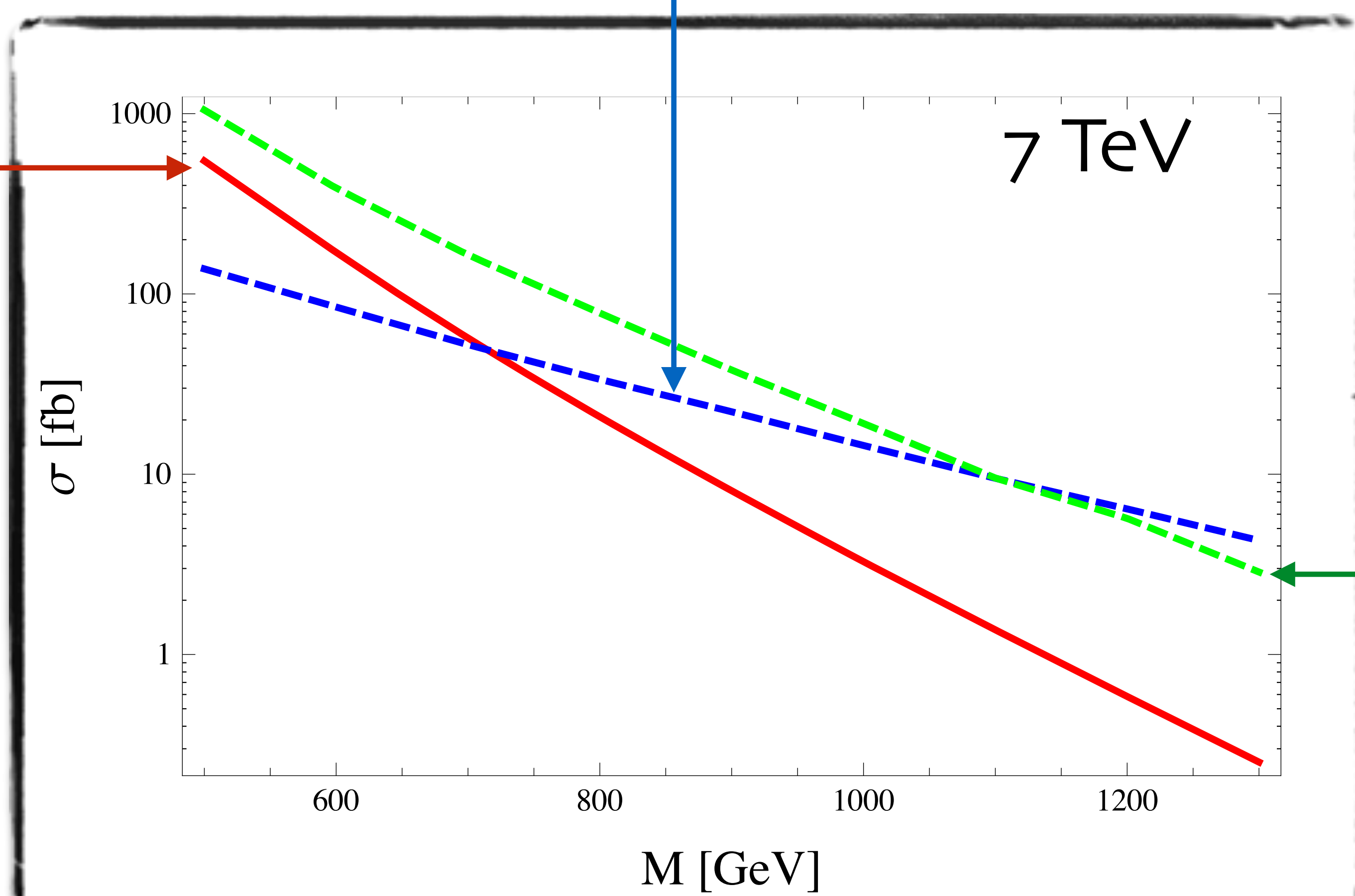

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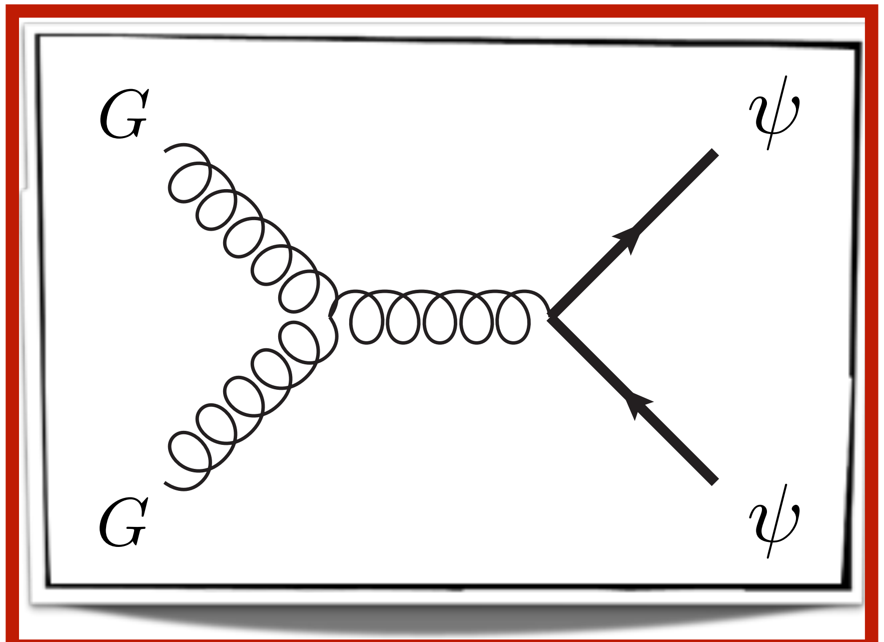
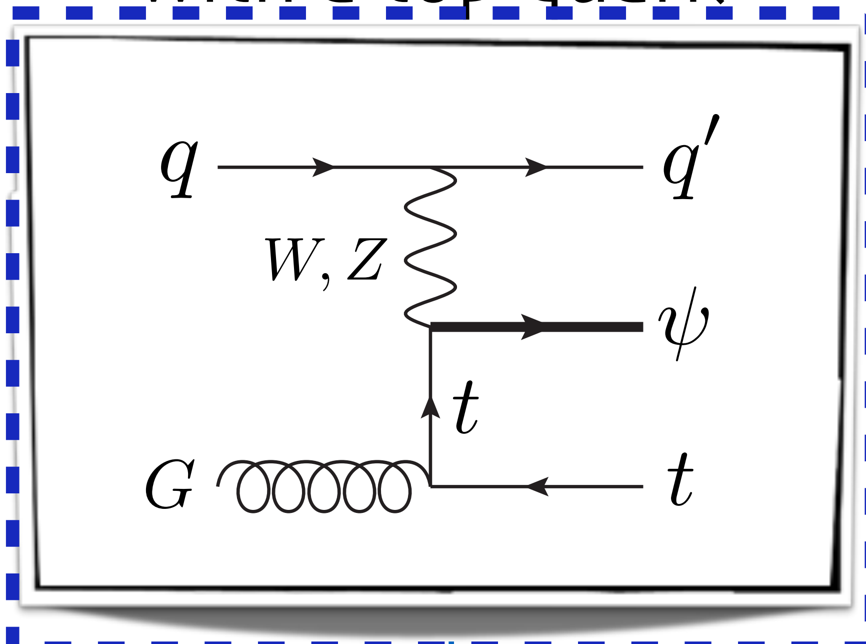
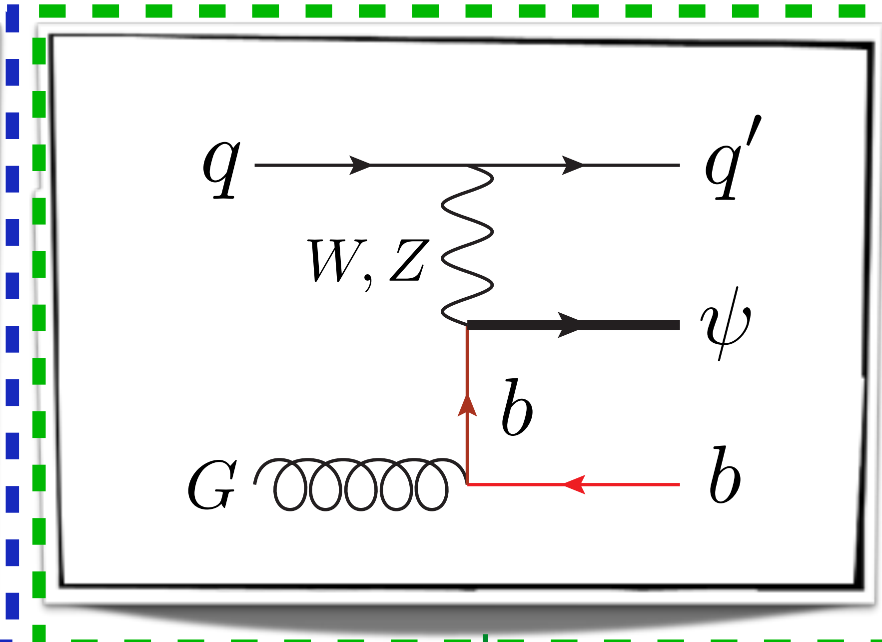
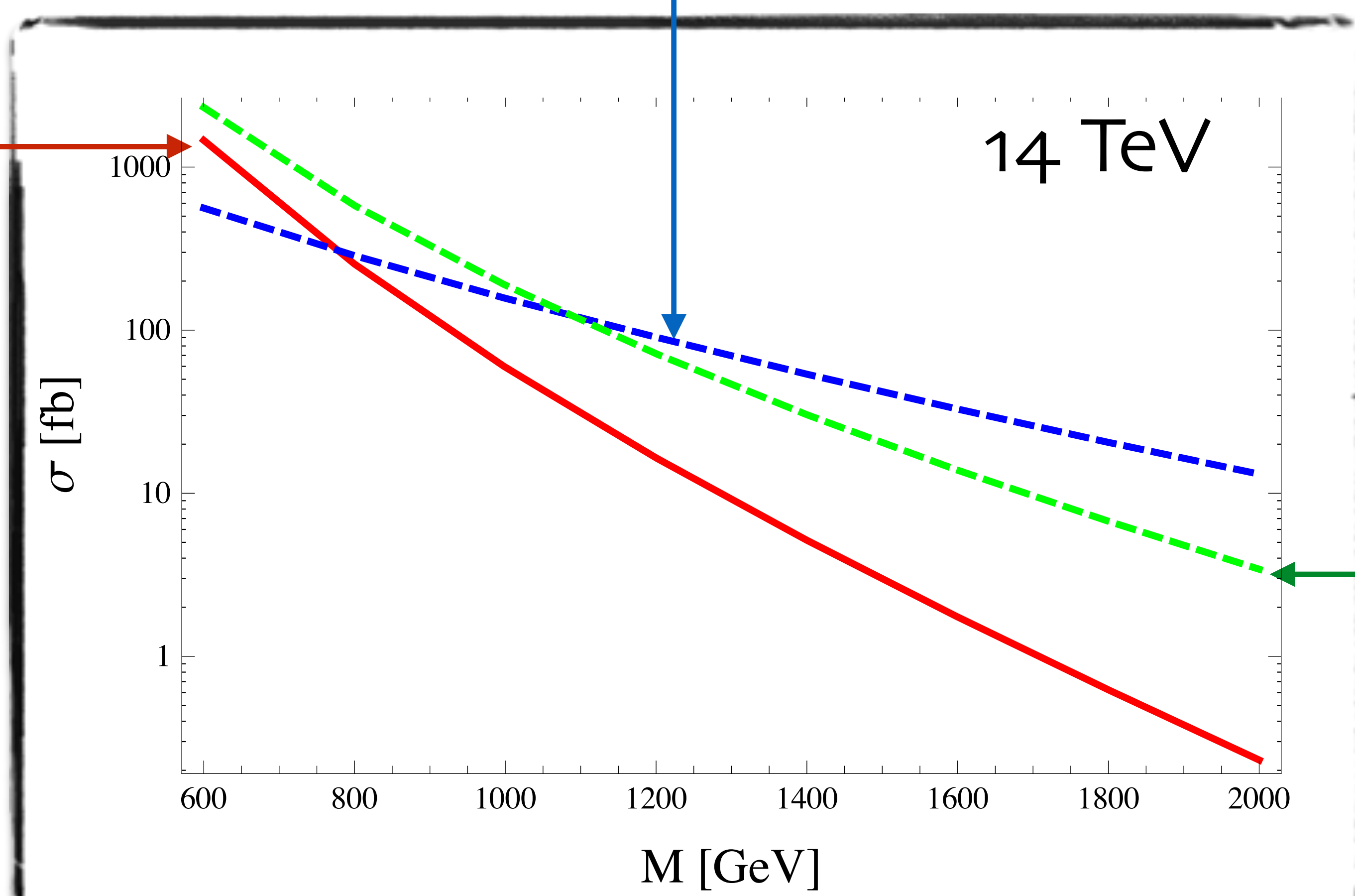








Connecting theory and experiment

Th:

preferred types of top partners single production
decay channels

coupling strength is model dependent

particles come in multiplets increasing the number of signal events

mass splitting is model dependent

...

...

Connecting theory and experiment

Exp:

level 1

most universal thing: test the typical channels and provide maximum of information needed for recast:

simple parametrization for the signal to account for BR's, different production channels and a pile-up from different partners

Th

bound on

$$\sigma_{signal} = \sum_{\psi_i} br\,\epsilon\,\sigma_{pair} + br\,\epsilon\,\alpha\,\sigma^0_{single}$$

Exp

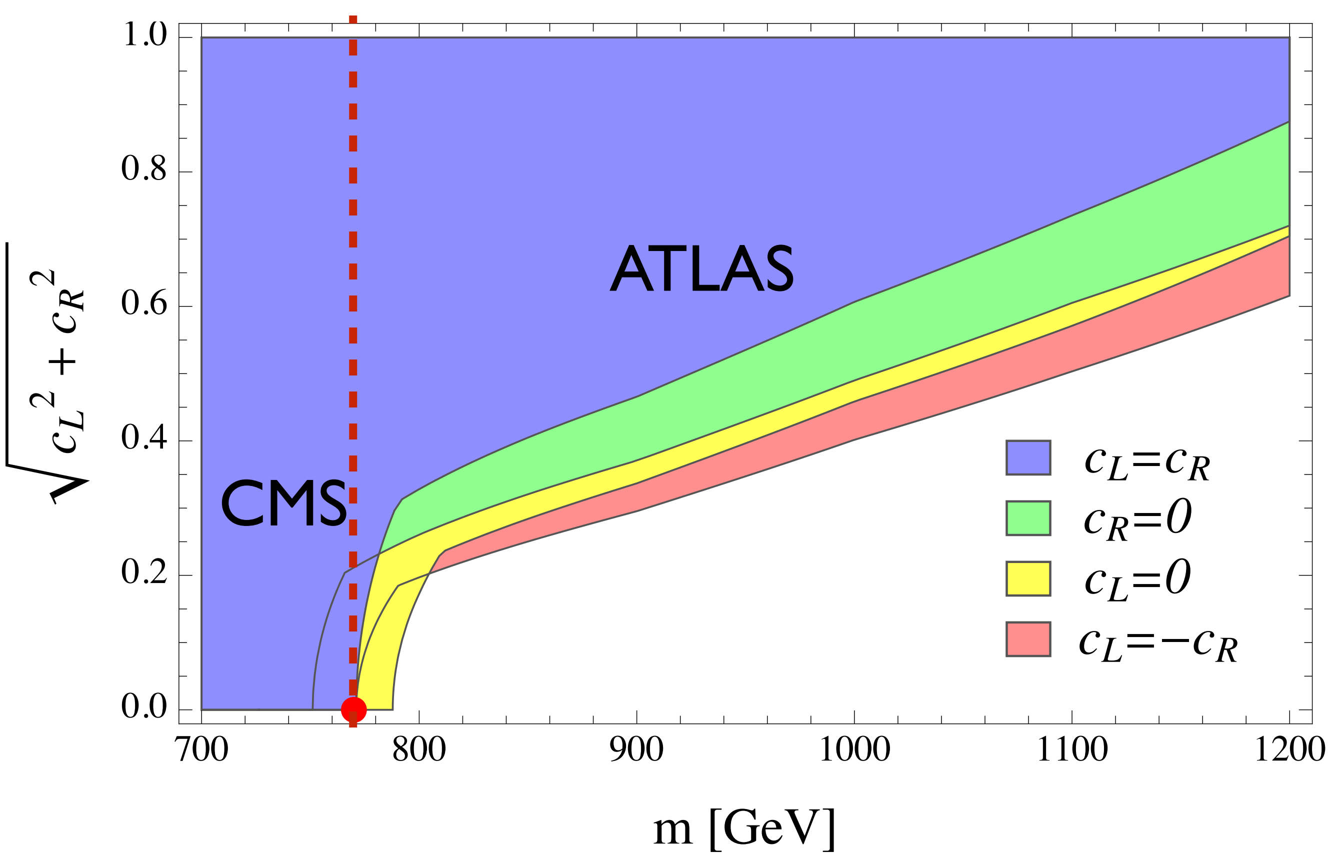
Connecting theory and experiment

Exp:

level 2

exclusion in terms of parameters of a simplified model
(such as http://hepmdb.soton.ac.uk/hepmdb:0214.0153)

$$\sigma_{\rm sing}(X\bar{t}) = \left(c_R^2 + c_L^2\right)\sigma_{Wt}(m_X) + 2\,c_R\,c_L\left(\frac{m_t}{m_X+m_t}\right)\sigma'_{Wt}(m_X)$$



one 5/3 charge state

recast of [ATLAS-CONF-2013-051,CMS PAS B2G-12-012]

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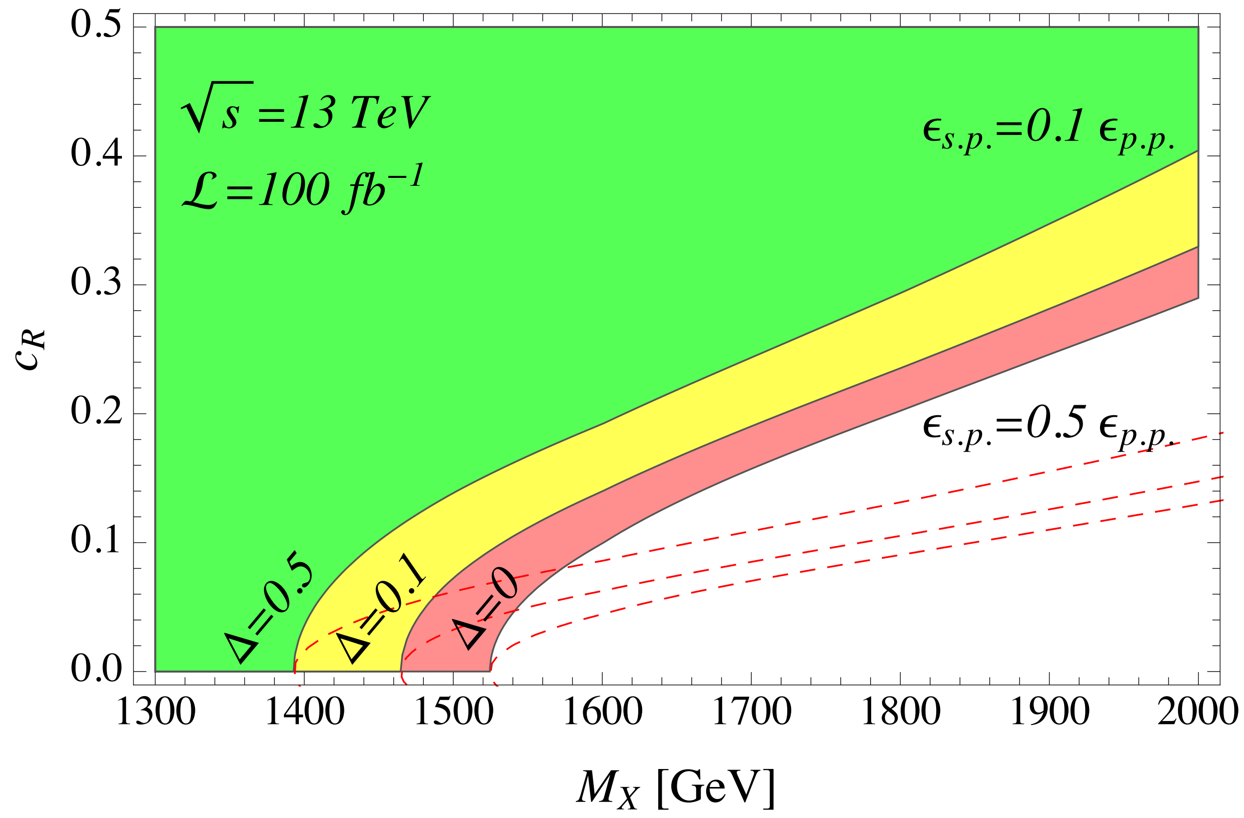


charge 5/3 and -1/3

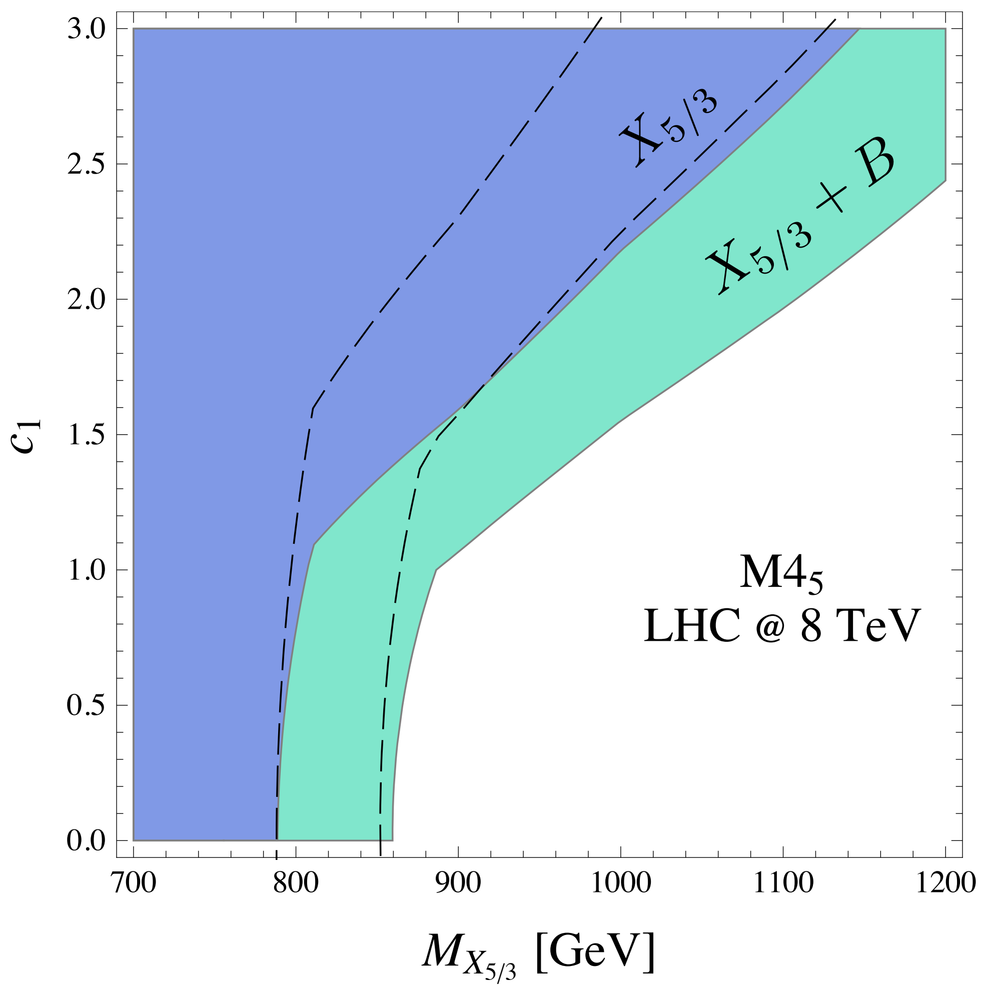
recast of [Avetisyan,Bose arXiv:1309.2234v1 [hep-ex]]

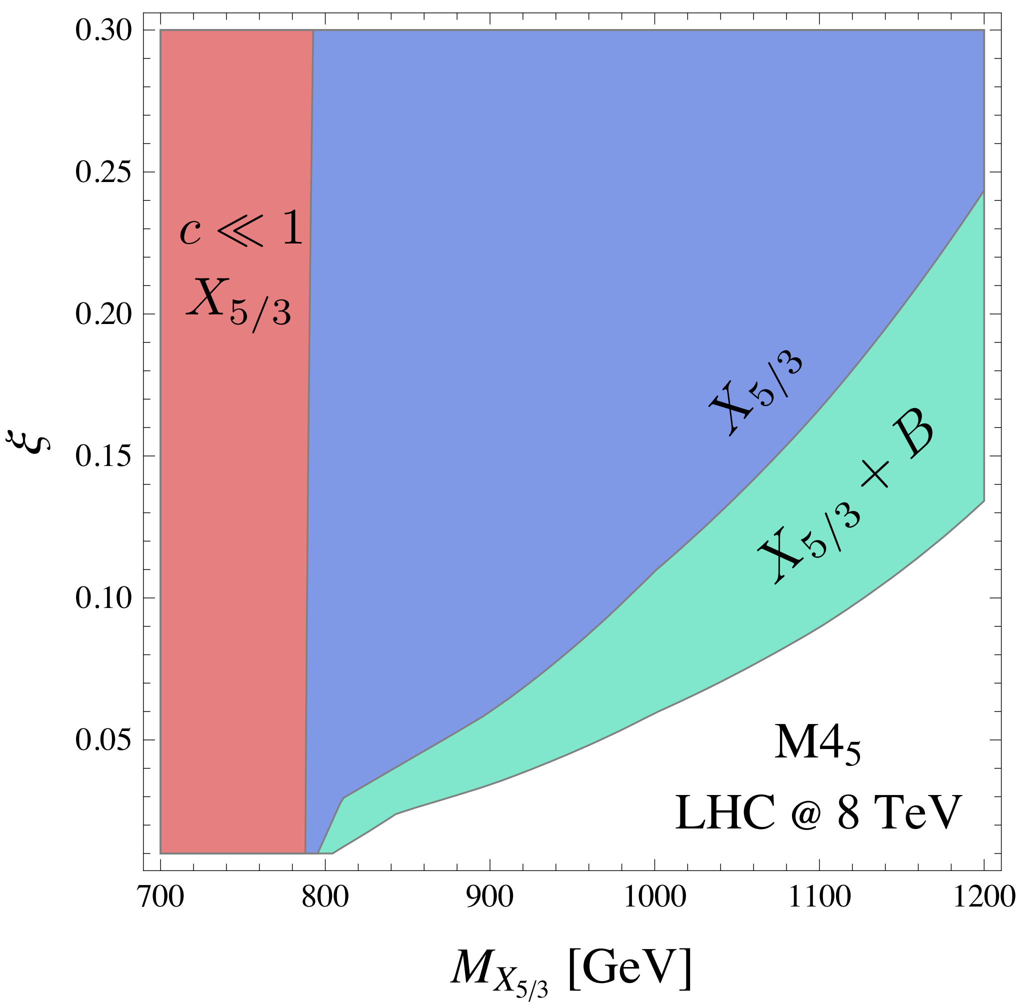
Connecting theory and experiment

Exp:

level 3

bounds on a parameter space of some more complete model





CH model of [arXiv:1211.5663]

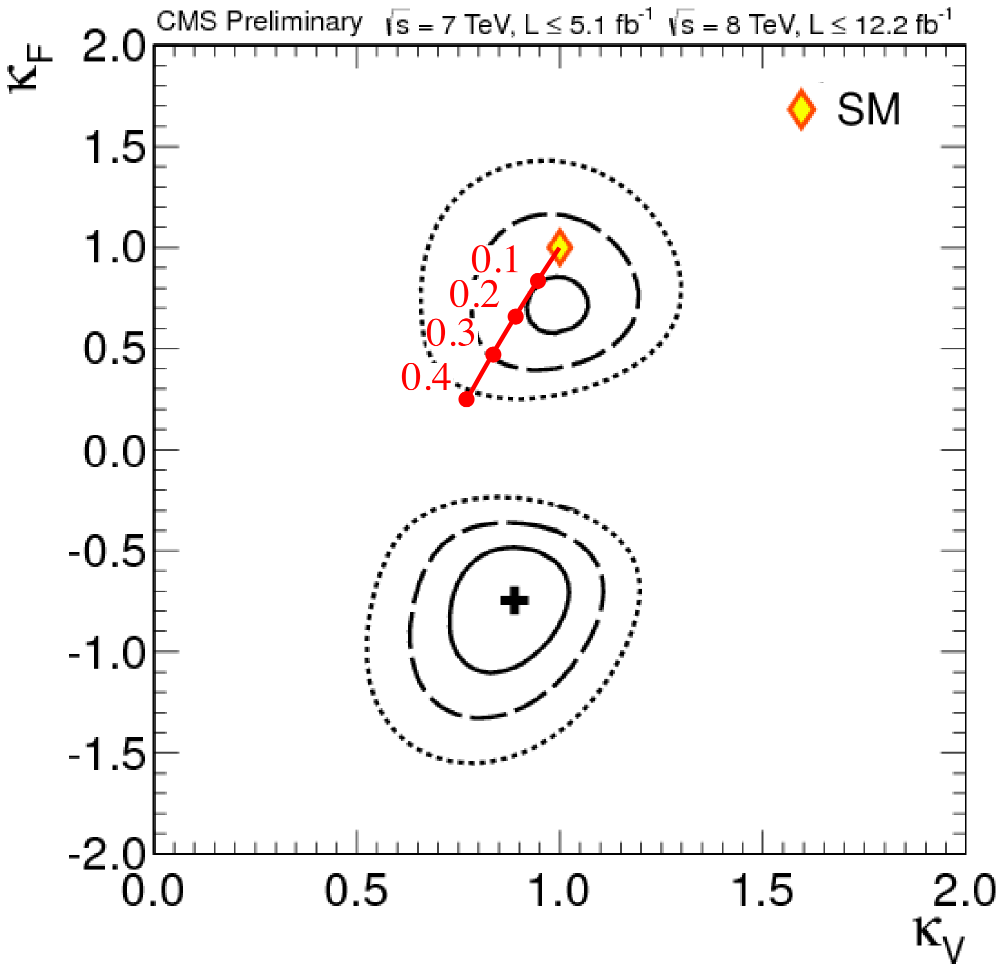
Summary

- Hierarchy problem motivates searches for the Higgs compositeness.

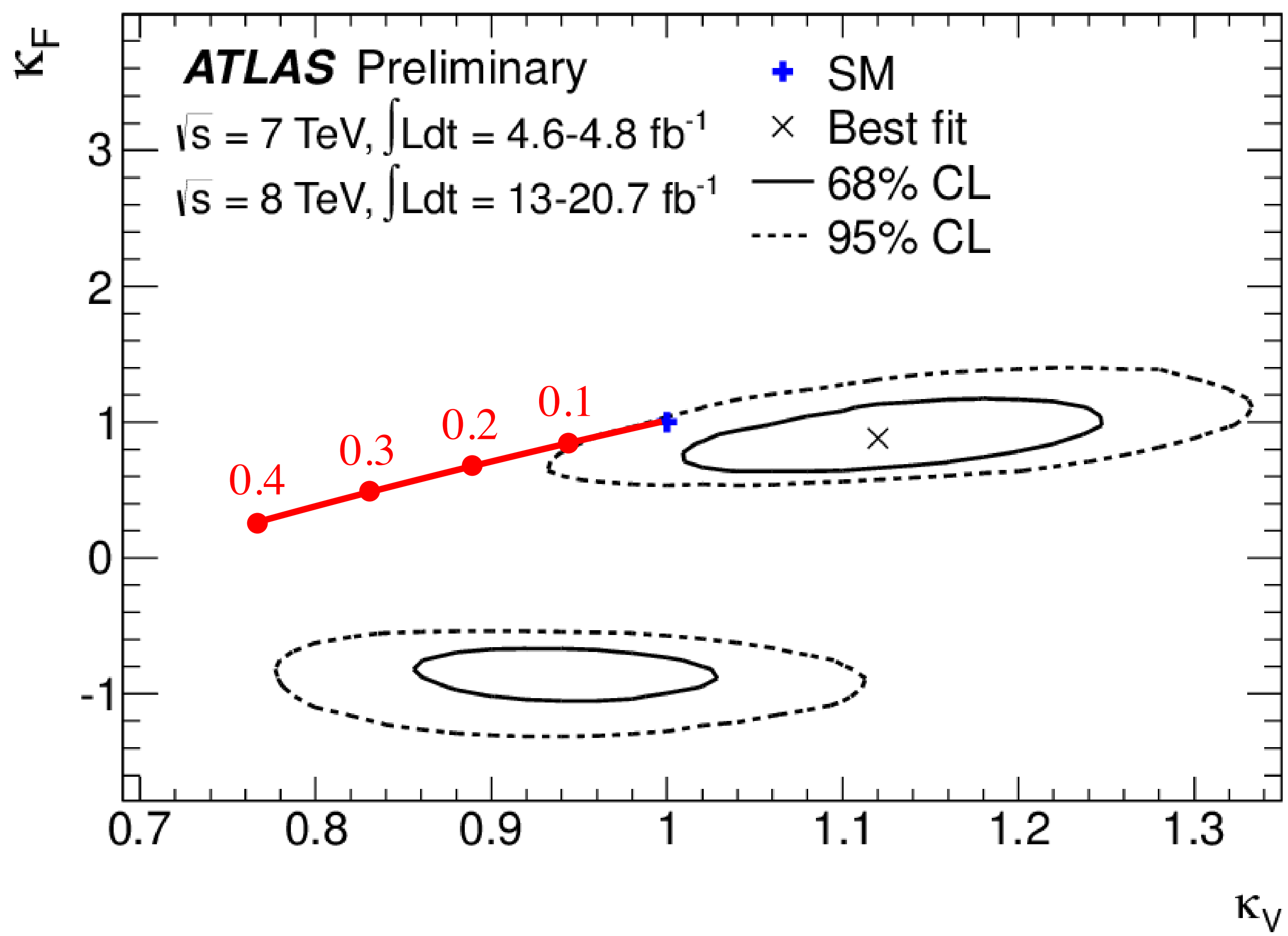
- Observed value of the Higgs mass implies a presence of composite fermionic resonances lighter than ~1.5 TeV.

- LHC has already started probing a natural region of the CH parameter space. 13 TeV LHC will be sensitive to new production channels important for the full exploration of the natural region of parameters.

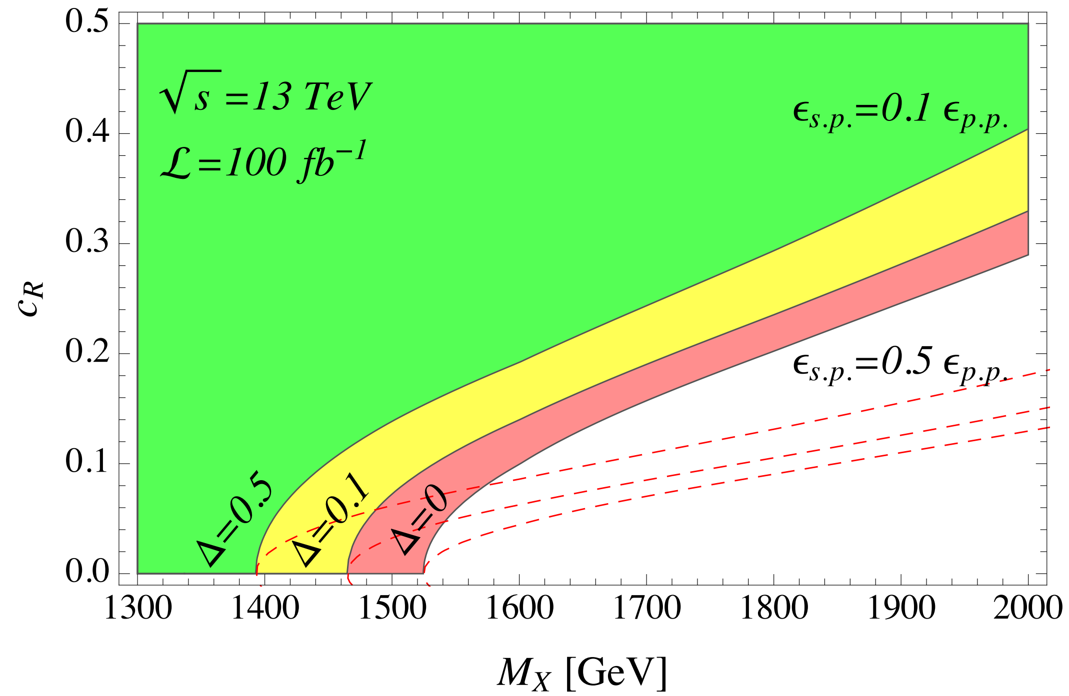
back-up slides



CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
SM
0.1
0.2
0.3
0.4
κF
κV

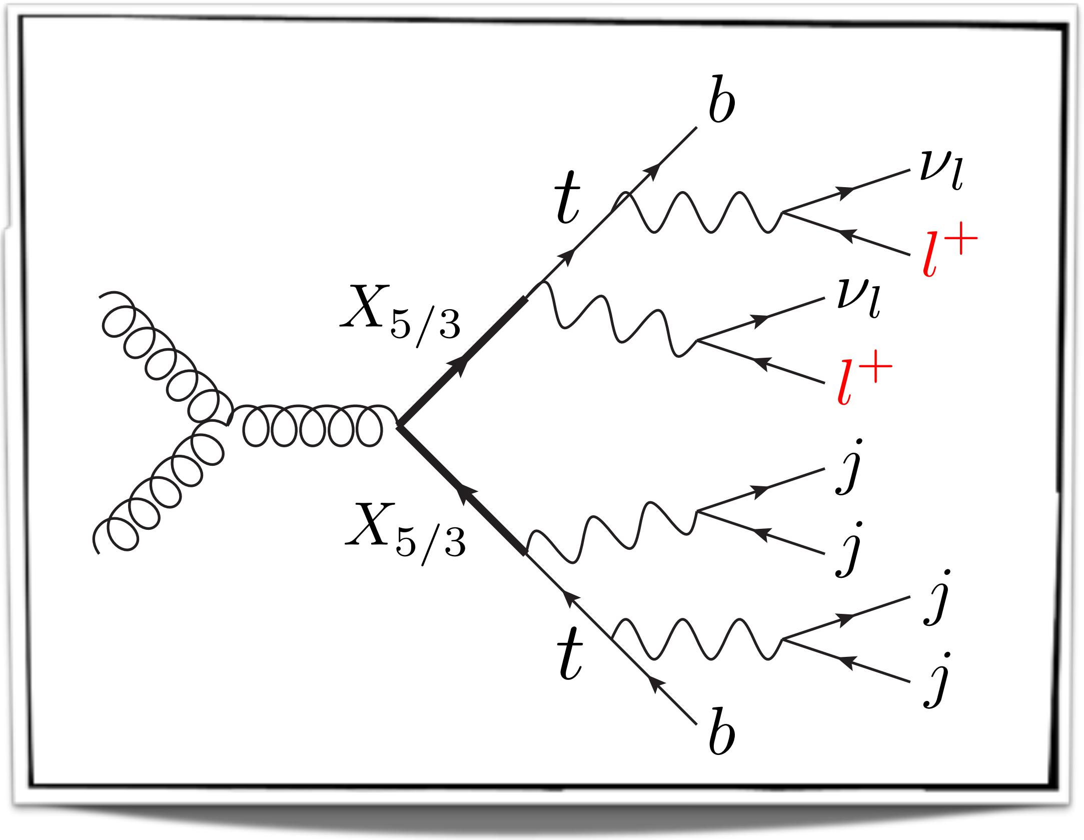


ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV, ∫Ldt = 13-20.7 fb-1
SM
Best fit
68% CL
95% CL
0.1
0.2
0.3
0.4
κF
κV



$\sqrt{s}$ =13 TeV
$\mathcal{L}$=100 fb^{-1}
$\epsilon_{s.p.}$=0.1 $\epsilon_{p.p.}$
$\epsilon_{s.p.}$=0.5 $\epsilon_{p.p.}$
Δ=0.5
Δ=0.1
Δ=0
c_R
M_X [GeV]
0.0
0.1
0.2
0.3
0.4
0.5
1300
1400
1500
1600
1700
1800
1900
2000

Recast of experimental searches: $X_{5/3} \to Wt$



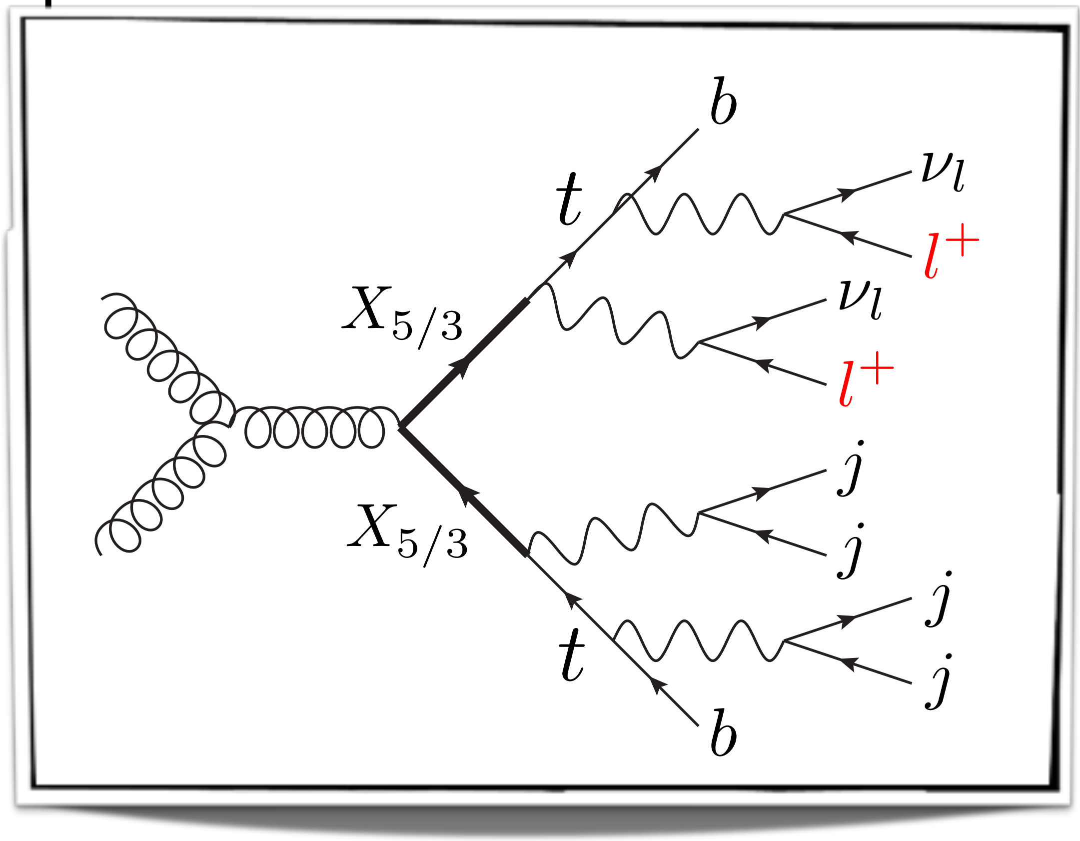
features:

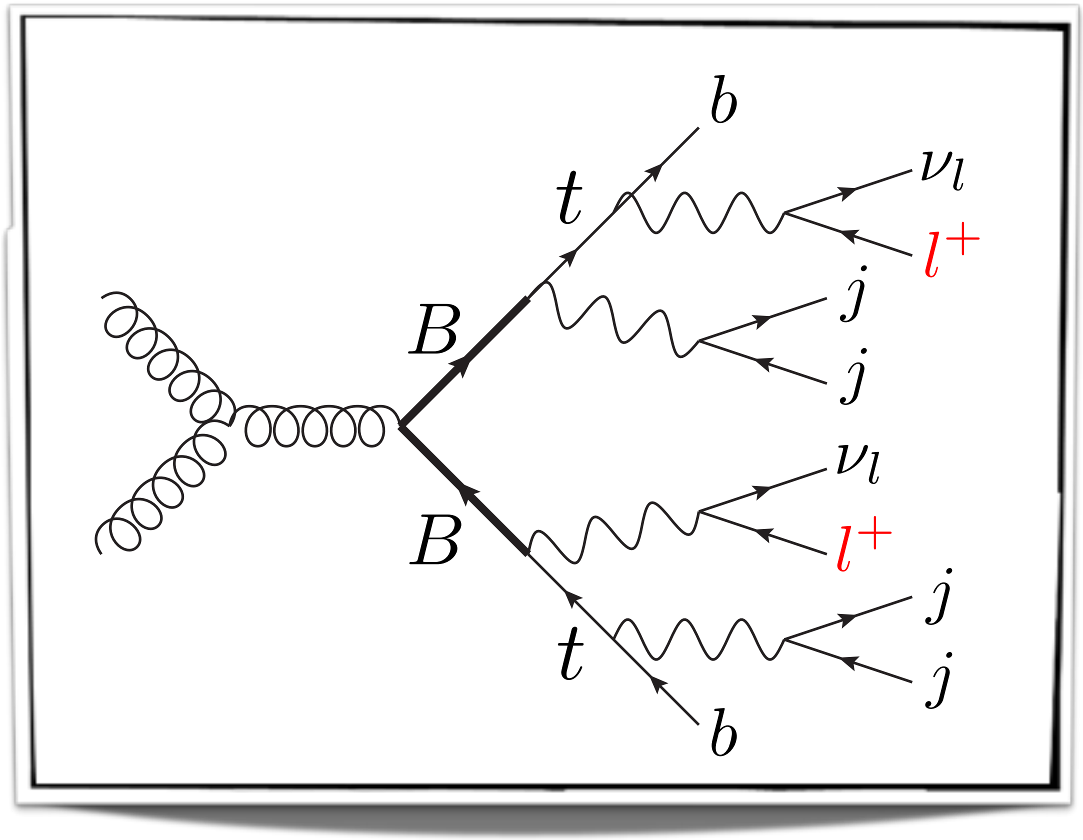
- pair produced X5/3
- 2 same sign leptons
- (b-tag)
- at least N (=2 for ATLAS and 5 for CMS) jets

[ATLAS-CONF-2013-051, CMS PAS B2G-12-012]

Recast of experimental searches: $X_{5/3} \to Wt$

- 2 particles contribute to the same final states





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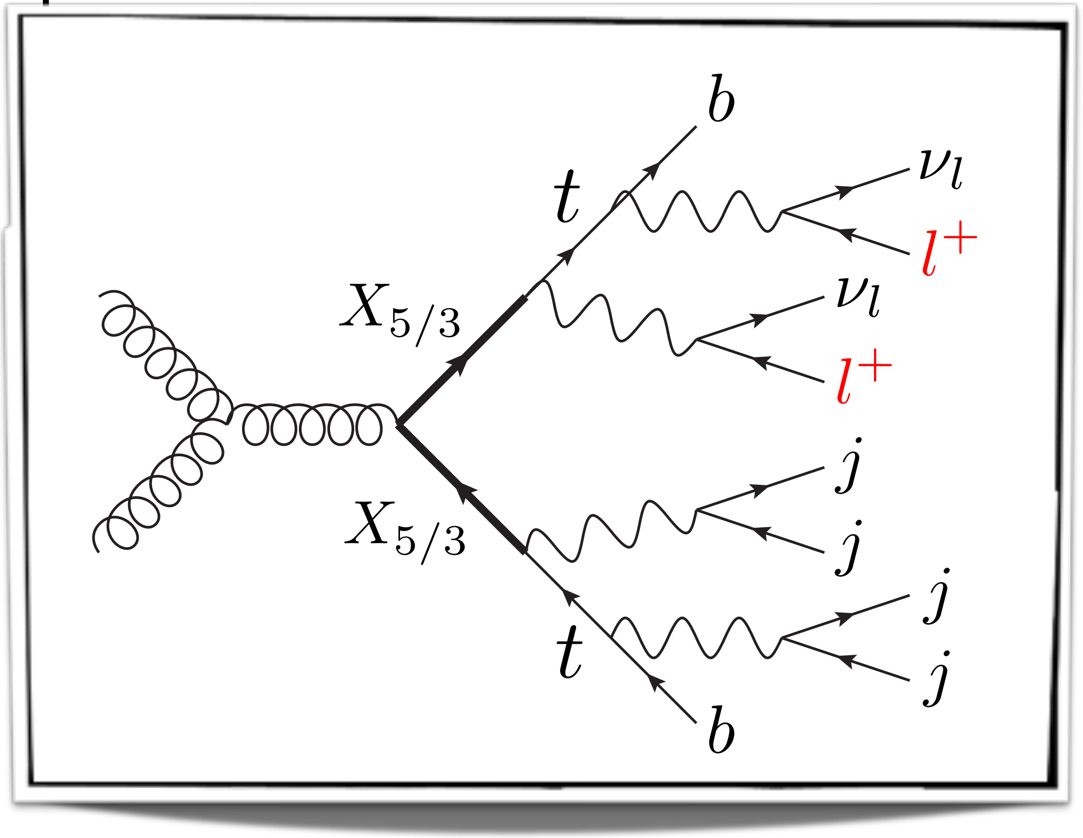
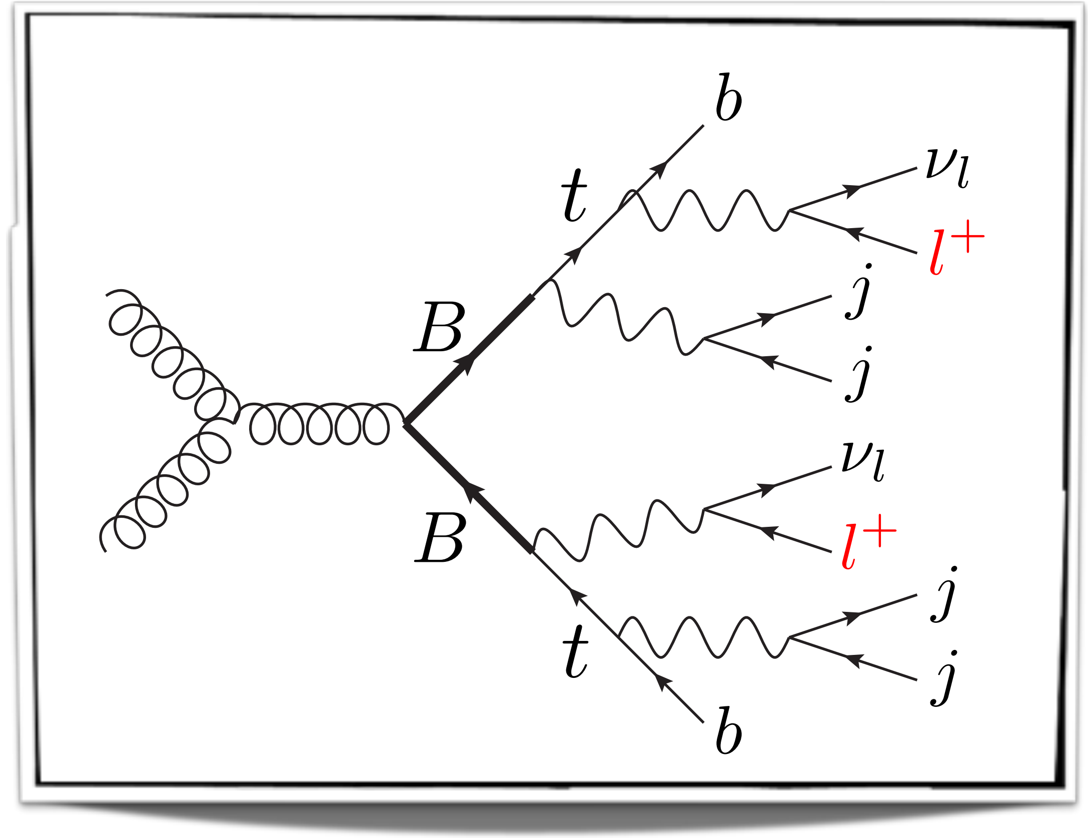
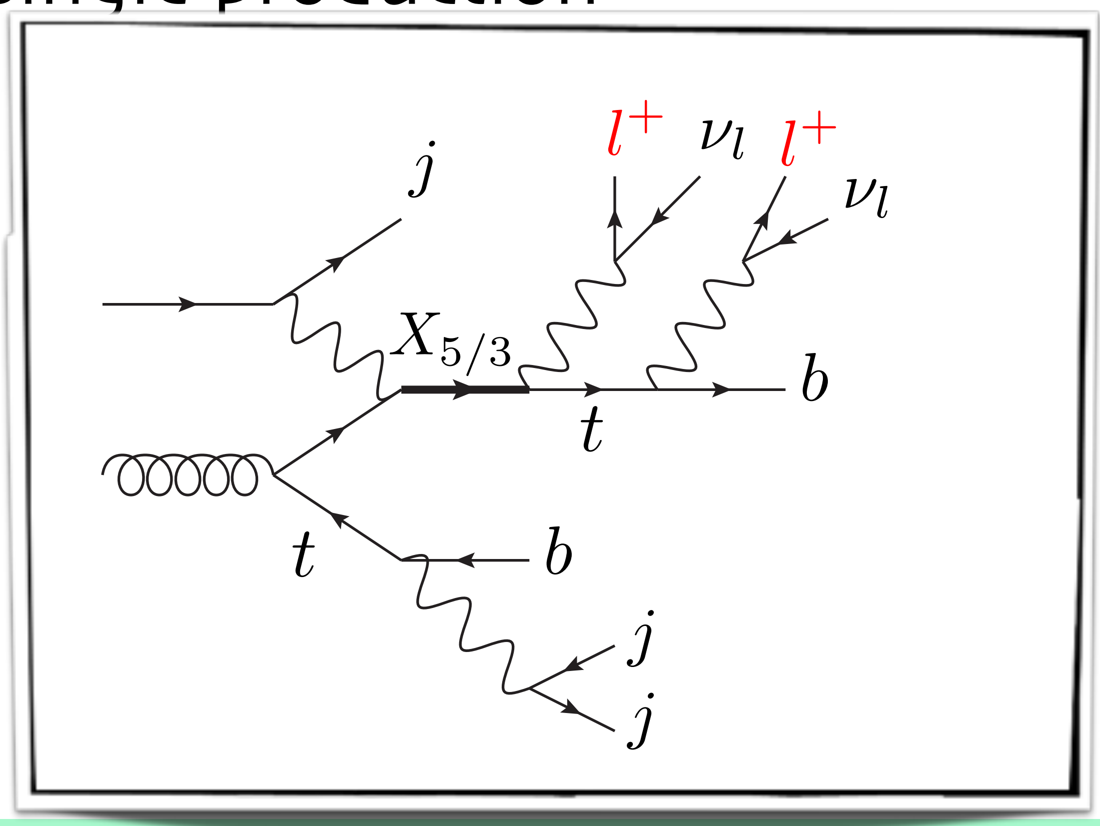
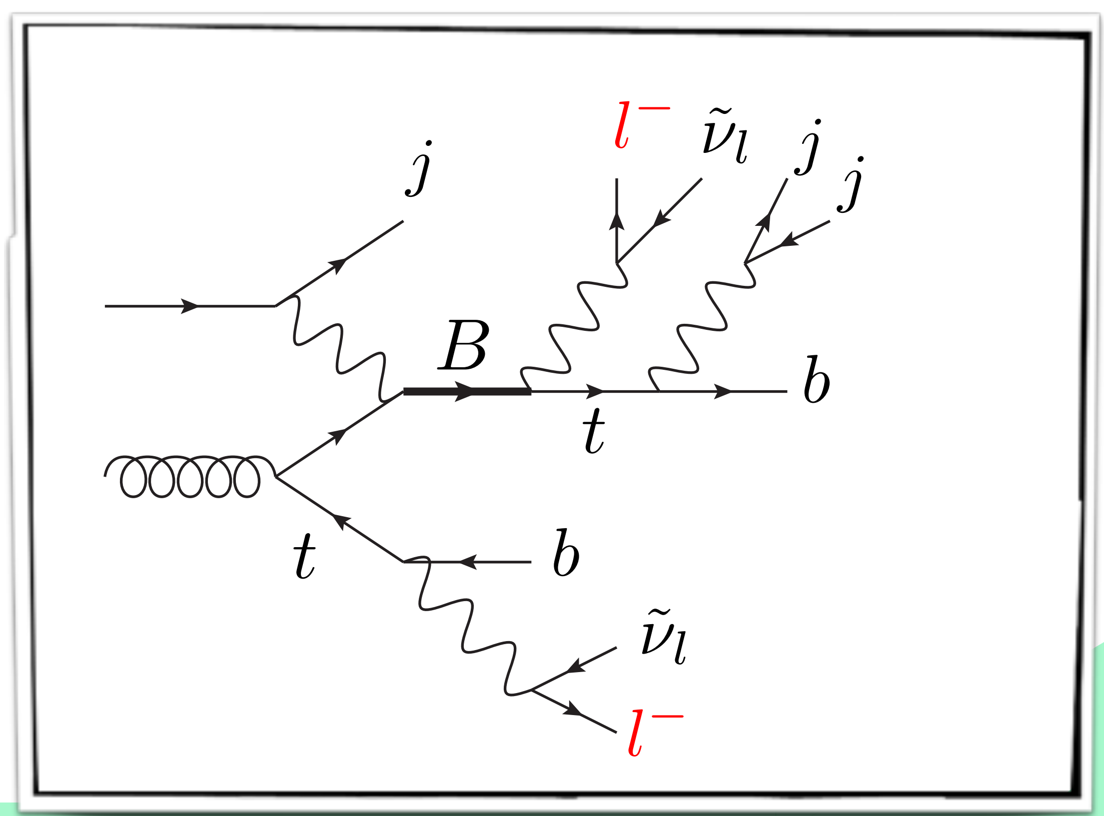
- 2 particles contribute to the same final states



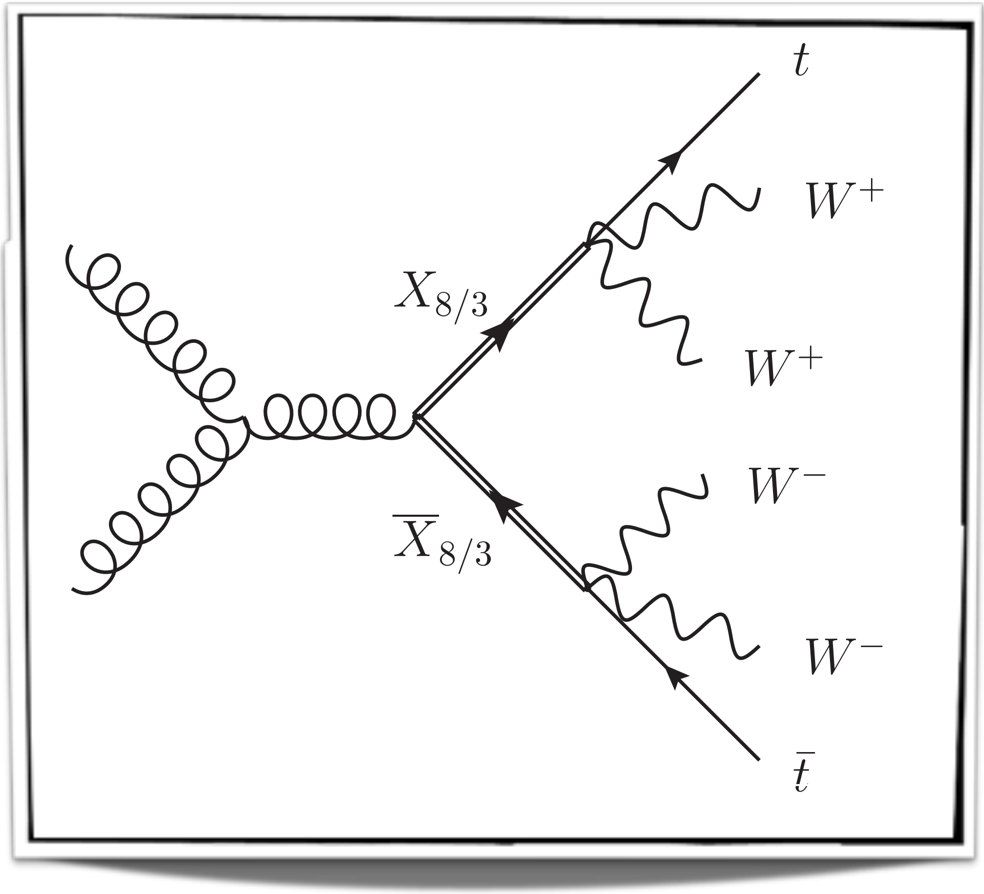


- single production

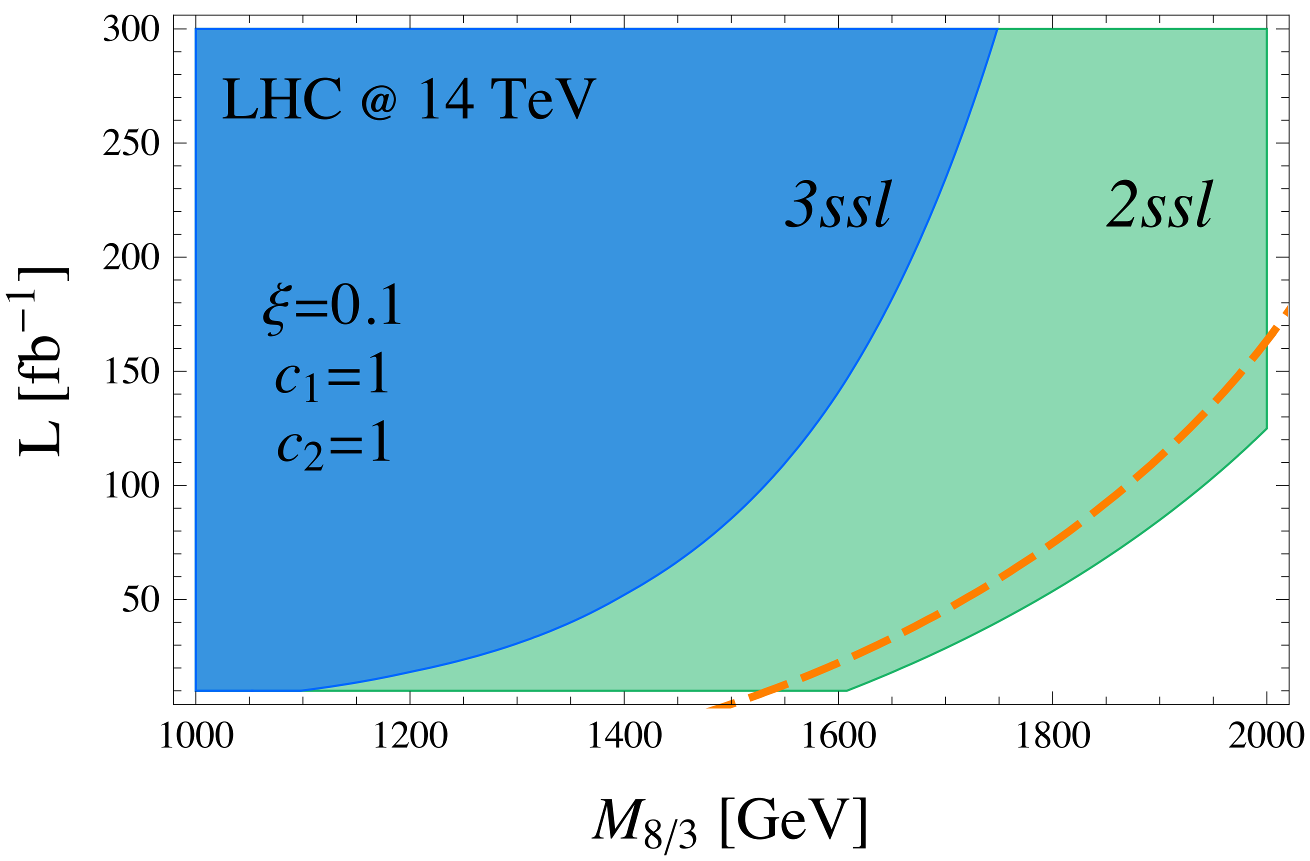




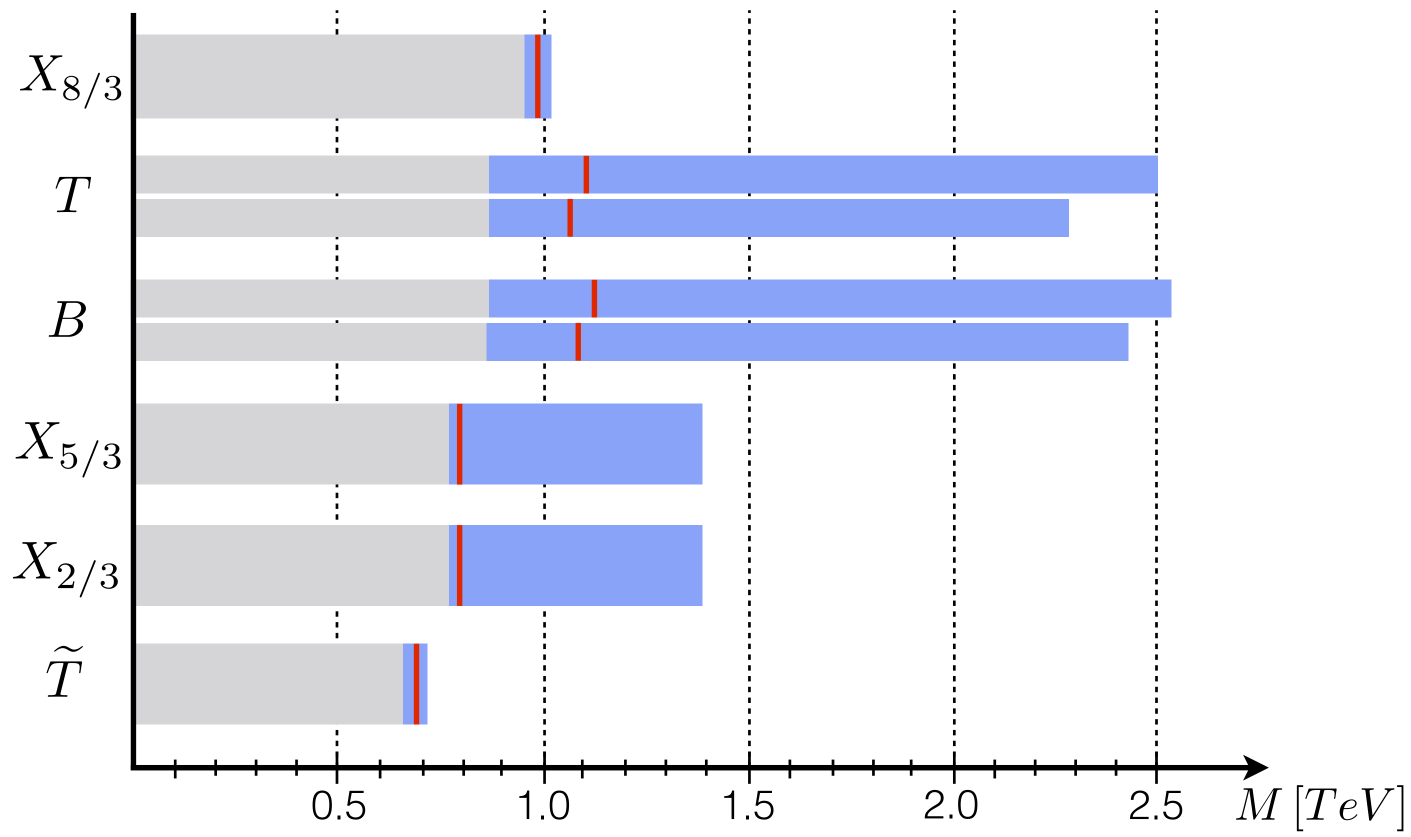
Bounds on charge-8/3 state



2, 3 same-sign leptons



Summary of Exclusions

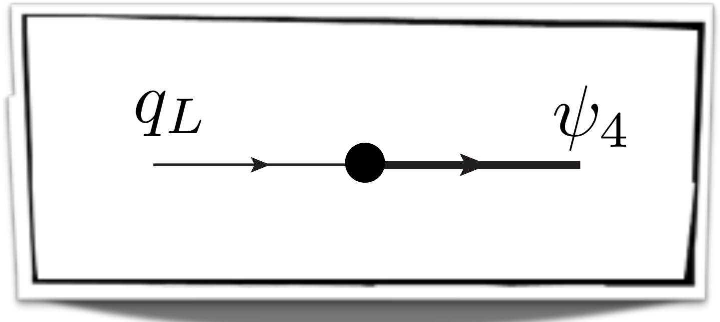


EFT for composite fermions

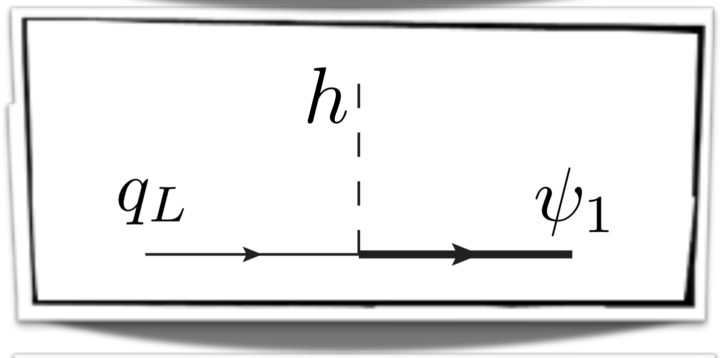
Goldstone matrix $U = \exp\left[\phi^{\hat{a}} T^{\hat{a}} / f\right]$

fourplet

$$L_{mixing} = y_{L4}\, f\, \bar{q}_L\, U\, \psi_4$$

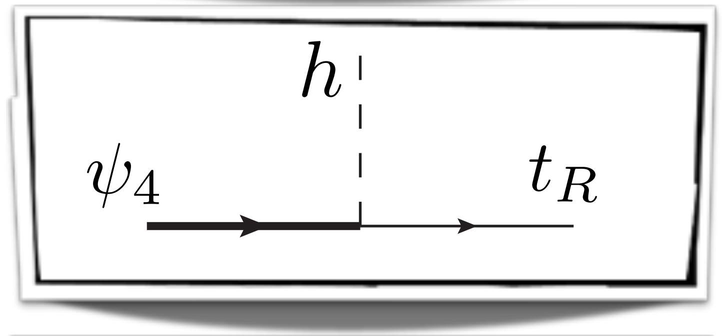


$$y_{L1}\, f\, (\bar{q}_L U)_5\, \psi_1$$

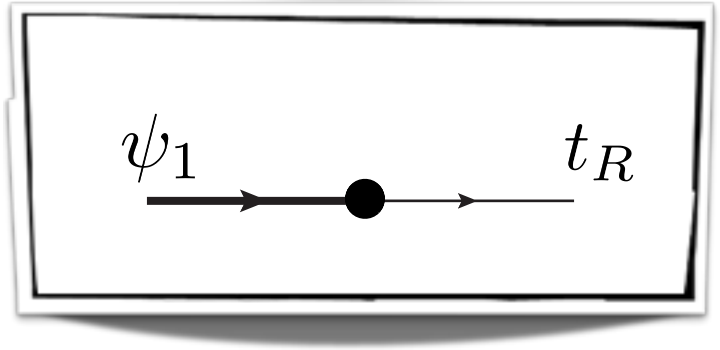


singlet

$$y_{R4}\, f\, \bar{t}_R\, U\, \psi_4$$



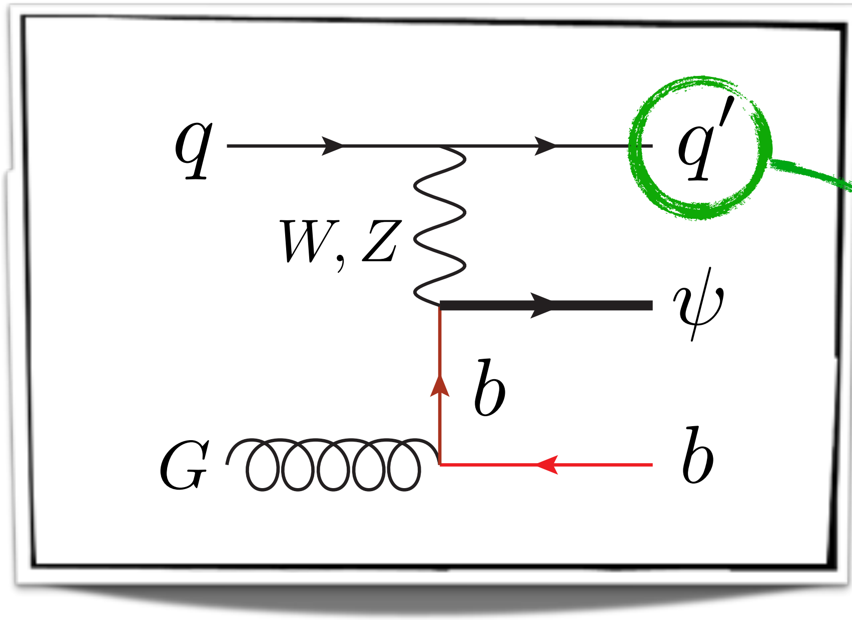
$$y_{R1}\, f\, (\bar{t}_R\, U)_5\, \psi_1$$



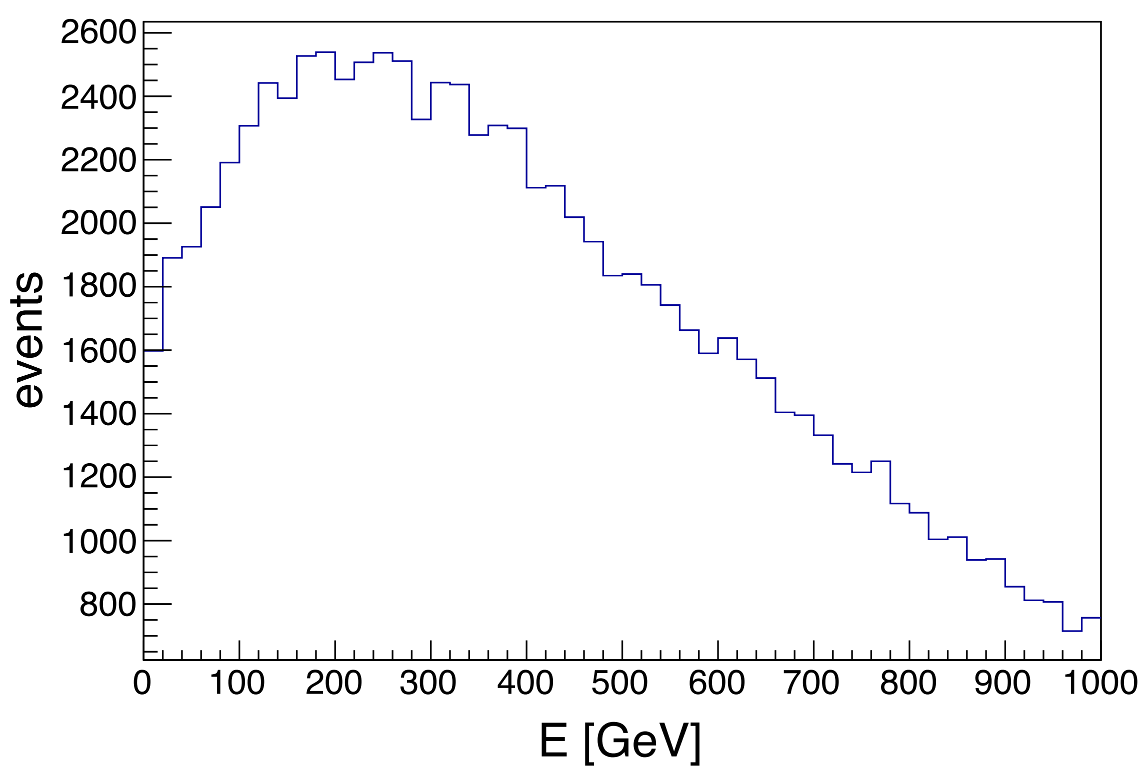
embeddings break the Goldstone symmetry

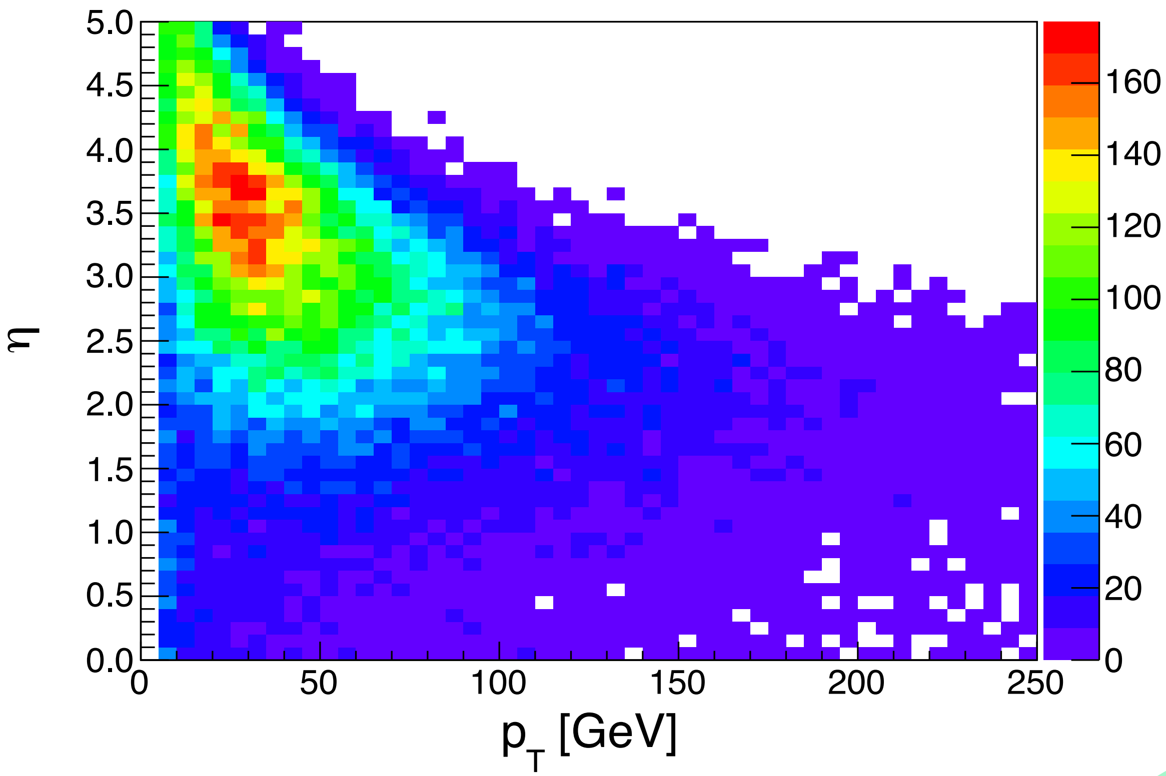
Production mechanisms

single production



energetic forward jet



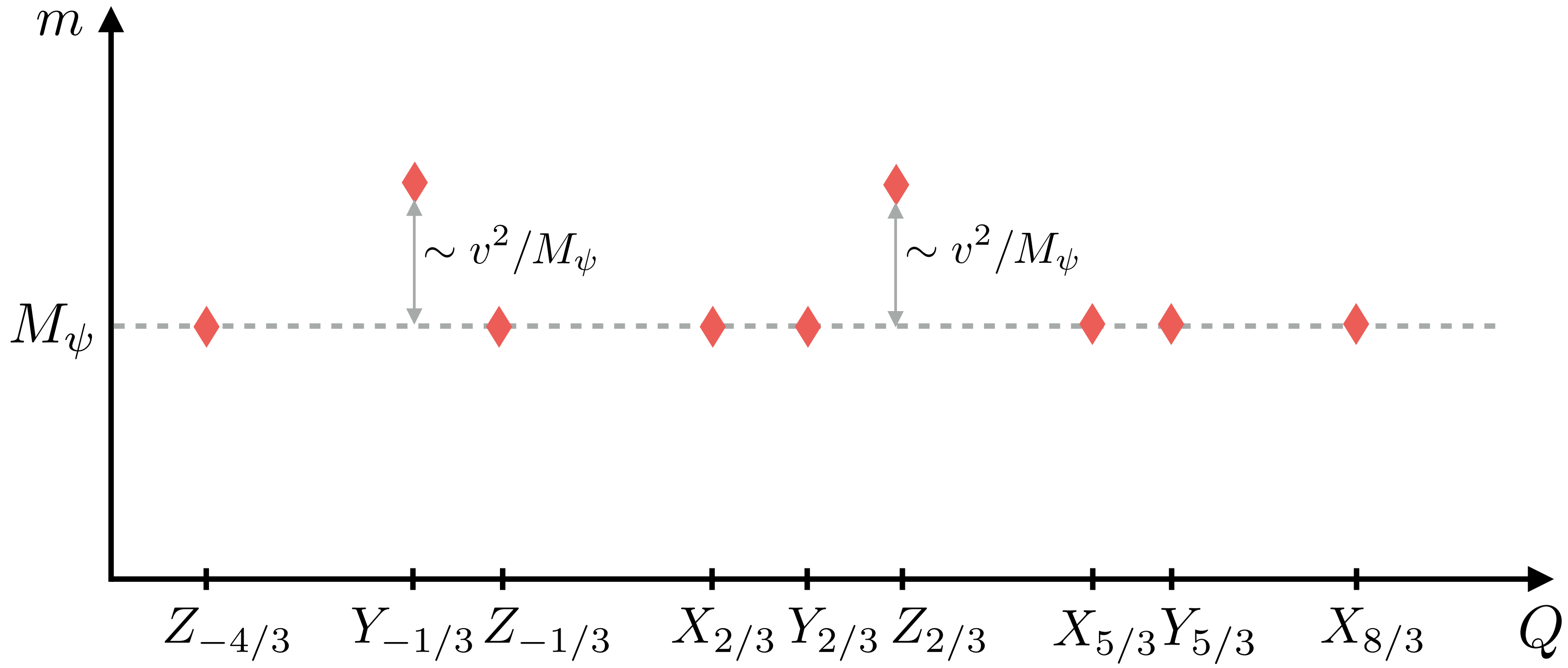


EFT for composite fermions

	$r_{\mathcal{O}} = \mathbf{5_{2/3}}$	$r_{\mathcal{O}} = \mathbf{14_{2/3}}$	SO(5)
$r_\Psi = \mathbf{9_{2/3}}$	–	$\mathbf{M9}_{14}$	
$r_\Psi = \mathbf{4_{2/3}}$	$\mathbf{M4}_5$	$\mathbf{M4}_{14}$	
$r_\Psi = \mathbf{1_{2/3}}$	$\mathbf{M1}_5$	$\mathbf{M1}_{14}$	
SO(4)			

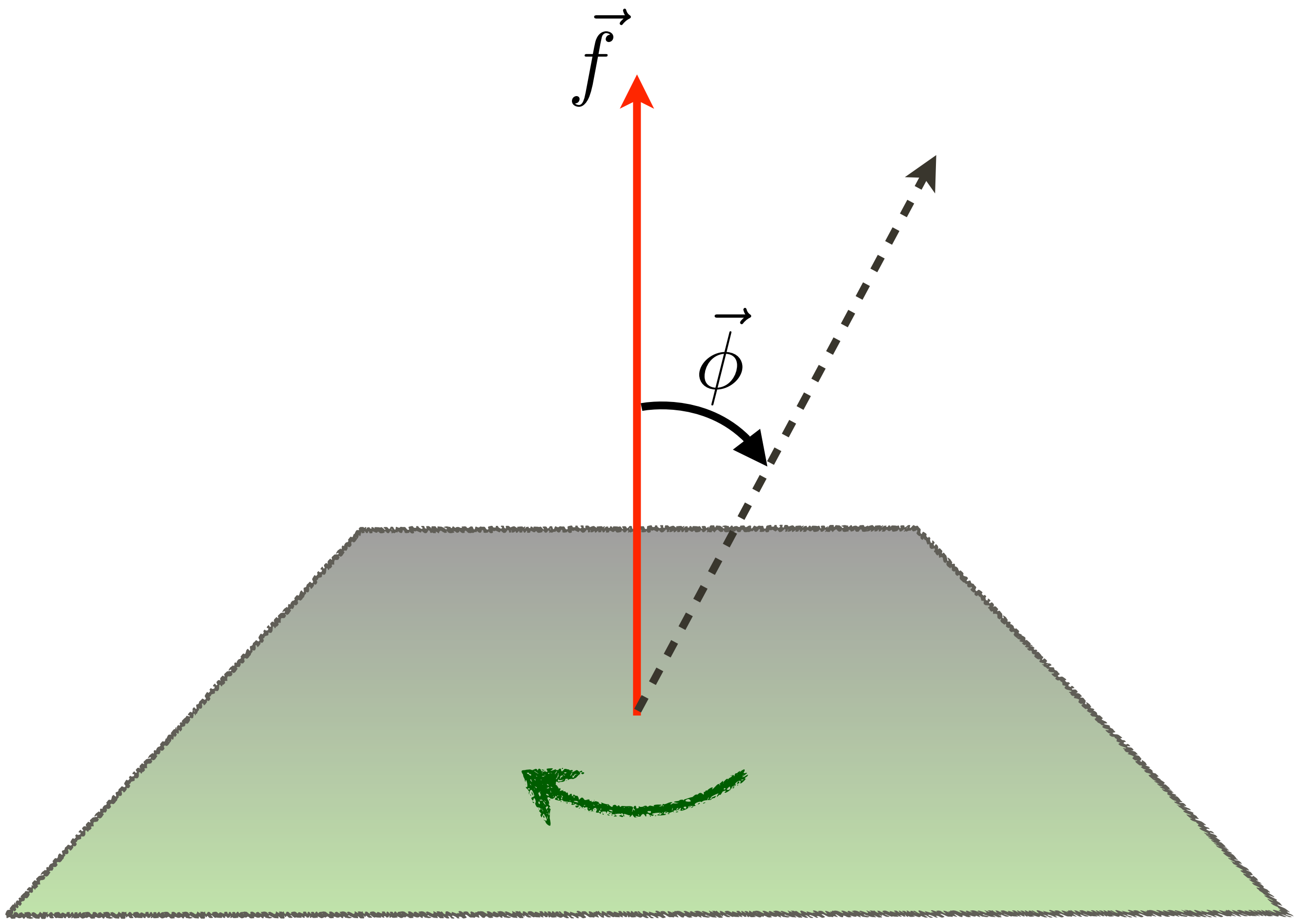
- singlet ψ_1 $\quad \widetilde{T}$
- 4-plet ψ_4 $\quad \begin{pmatrix} T \\ B \end{pmatrix} \quad \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}$
- 9-plet ψ_9 $\quad X_{8/3}\ , \quad \ldots$

Mass spectrum: 9-plet



Introduction: Composite Higgs

- simplified example: SO(3)/SO(2)

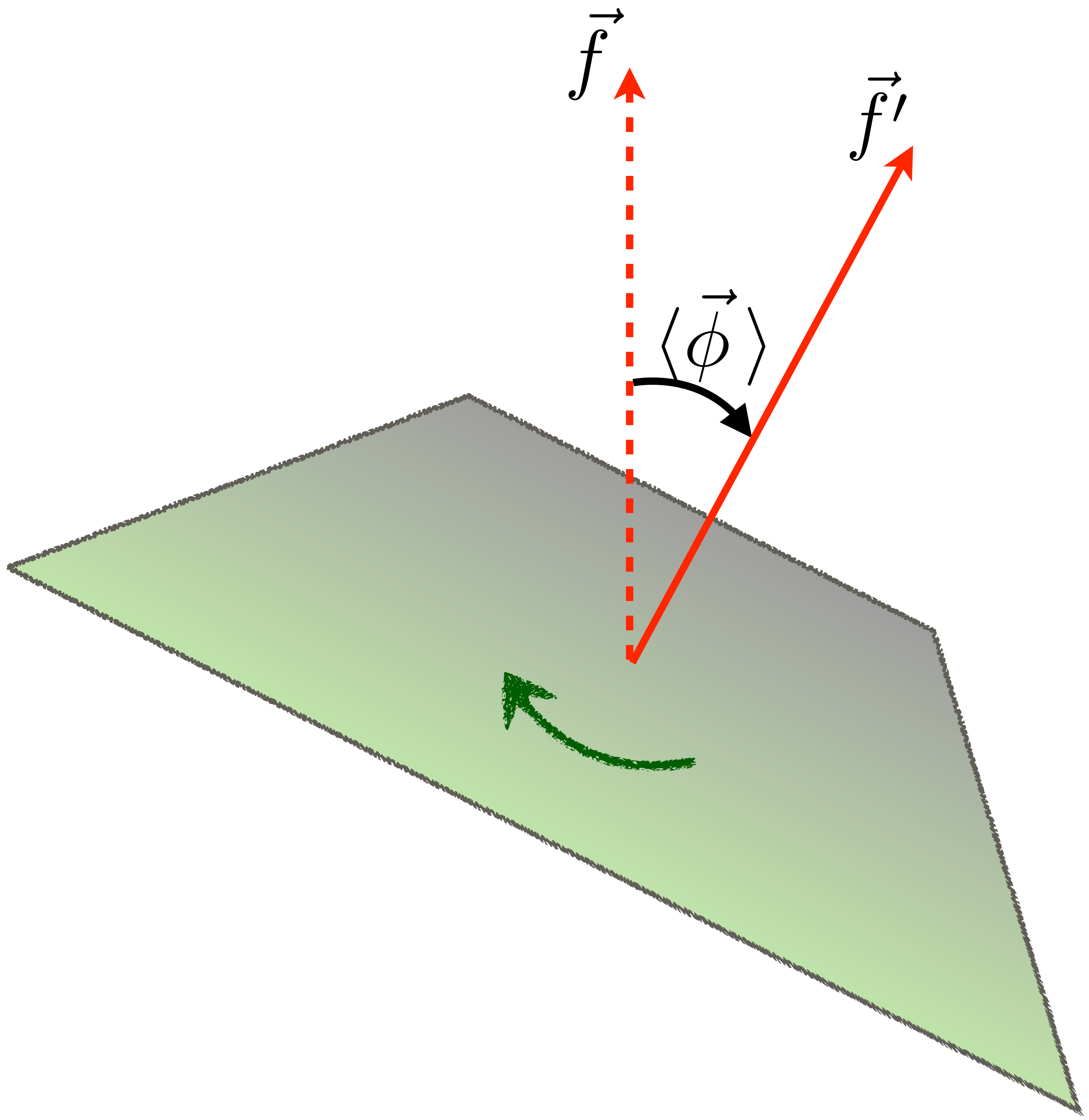


$\vec{f}$ is a non-SO(3) symmetric vacuum state

$\vec{\phi}$ - 2 goldstone bosons corresponding to excitations along broken rotations

Introduction: Composite Higgs

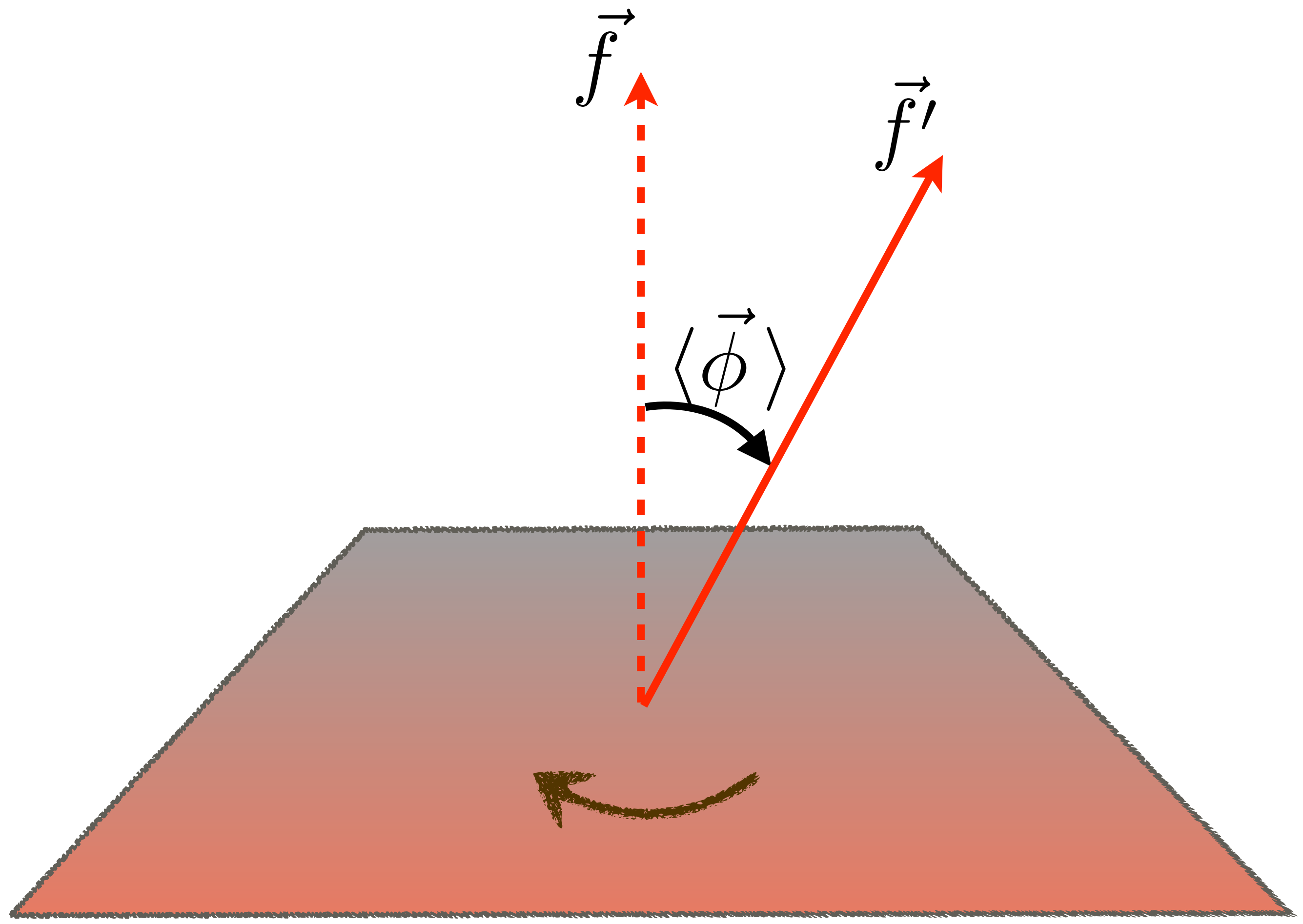
- simplified example: SO(3)/SO(2)



position of the SO(2) inside of SO(3) is not fixed, goldstone fields have no potential

Introduction: Composite Higgs

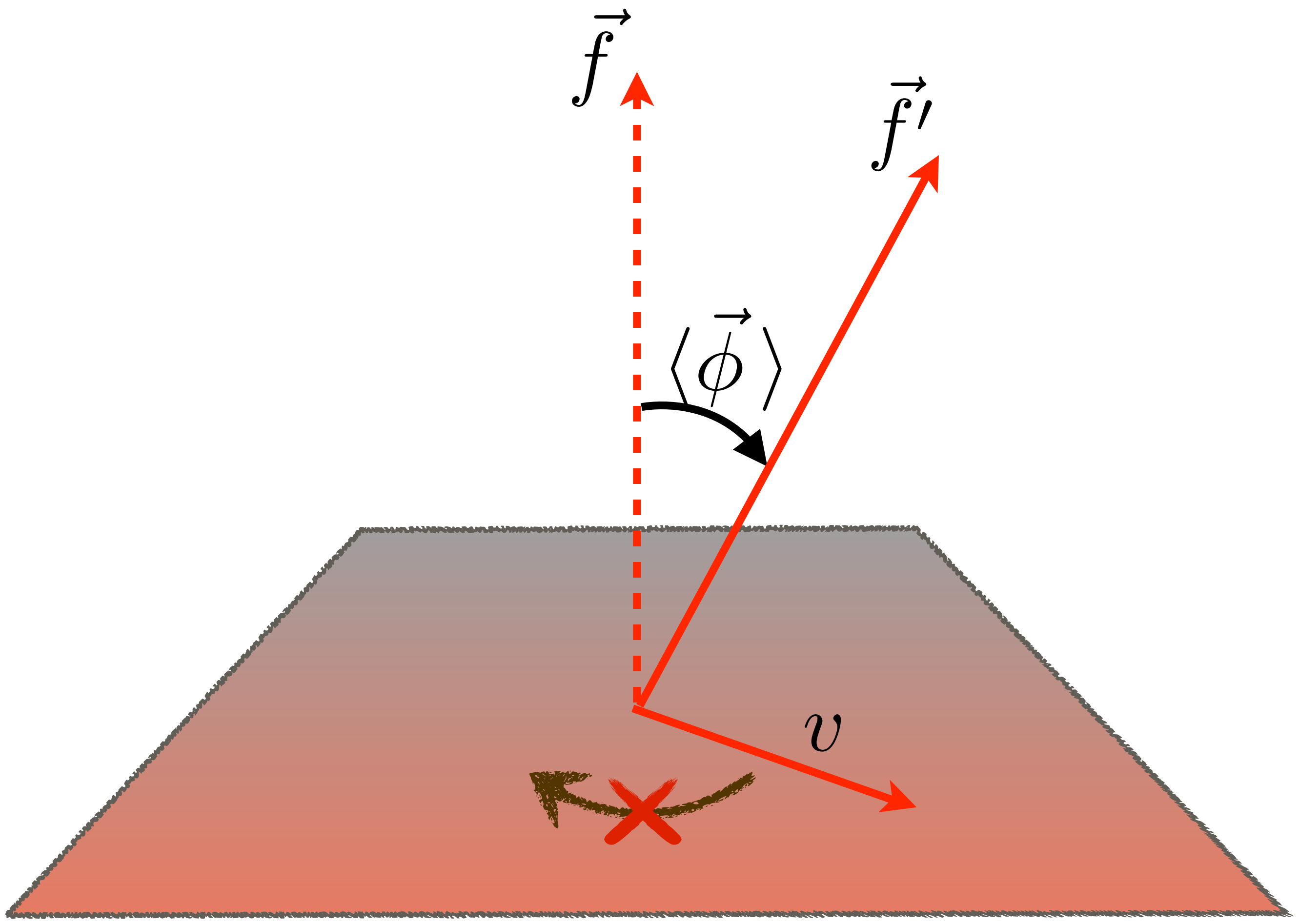
- simplified example: SO(3)/SO(2)



explicit weak breaking of SO(3) by external source

Introduction: Composite Higgs

- simplified example: SO(3)/SO(2)



- projection of the strong sector condensate breaks the symmetry of the external source
- breaking scale of the external symmetry is <u>lower</u>: $v_{SM} = f sin\langle\phi\rangle \quad \left(\phi \to \frac{\langle h \rangle}{f}\right)$
- Higgs mass is proportional to the strength of external perturbation