

LHC Precision Challenges - the BSM perspective

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Plan

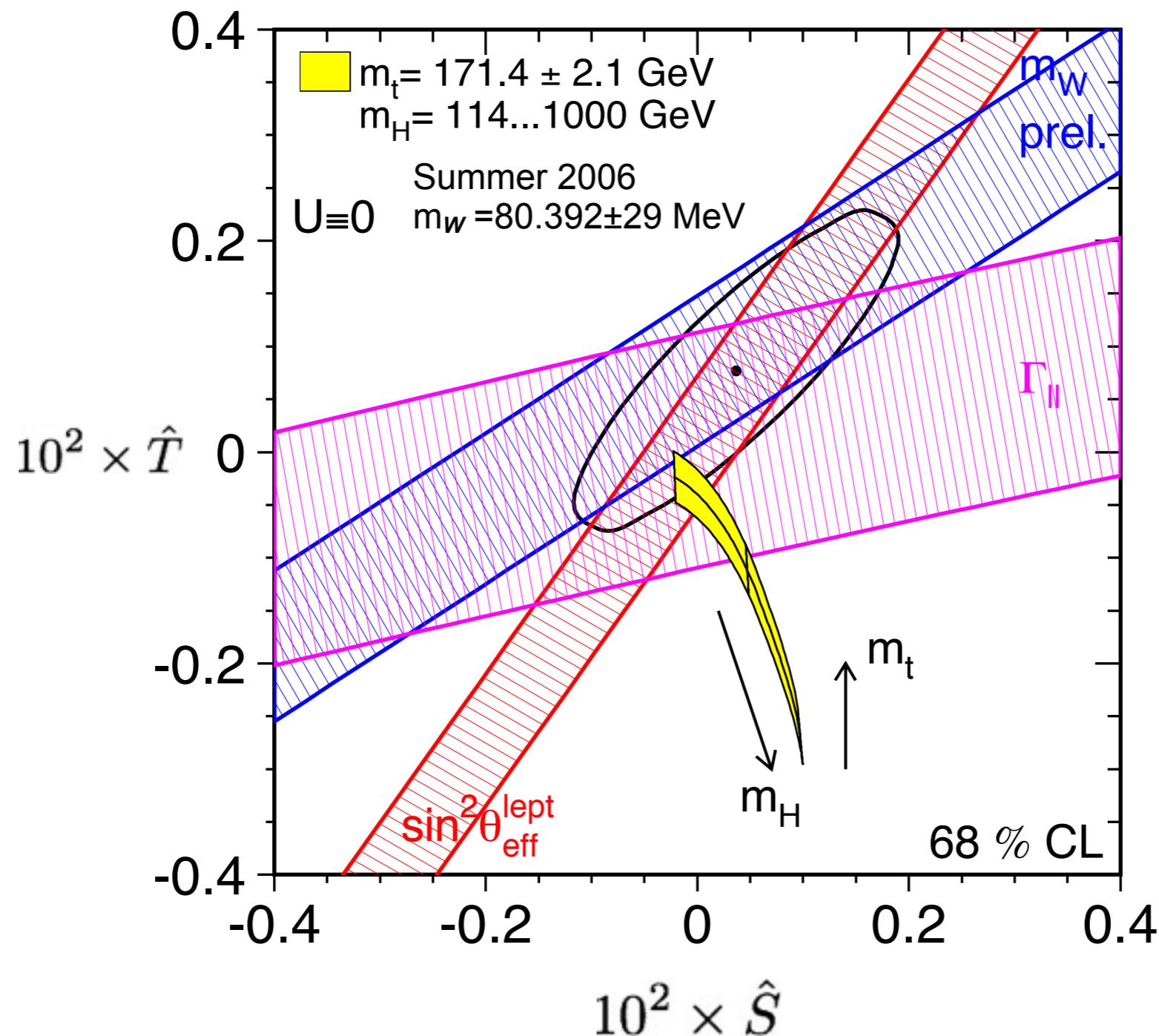
- W
- B
- t
- H
- ??

Theory motivation behind selected measurements

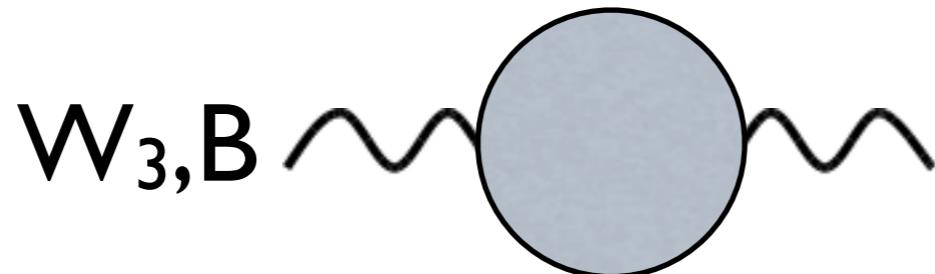
W

- W mass
- cubic couplings
- quartic couplings

W mass

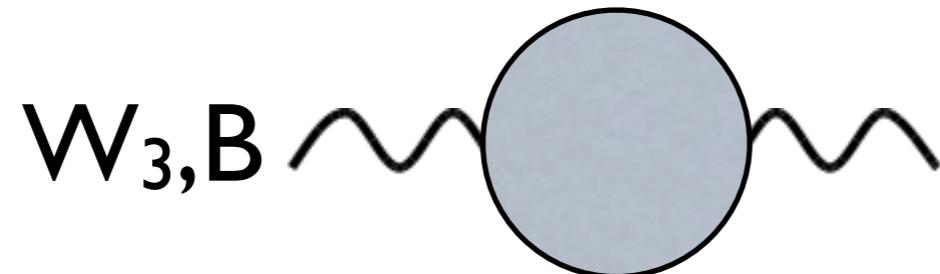


Oblique corrections



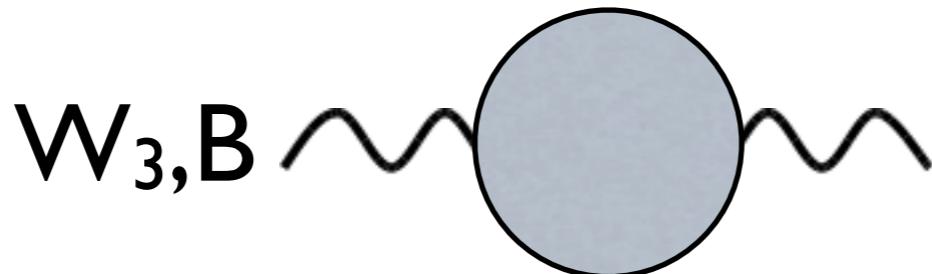
$$\begin{aligned}\mathcal{L} = & W_{\mu\nu}^+ W_{\mu\nu}^- + W_{\mu\nu}^3 W_{\mu\nu}^3 + B_{\mu\nu} B_{\mu\nu} \\ & + c_W^2 M_Z^2 W_\mu^+ W_\mu^- + M_Z^2 (Z_\mu)^2\end{aligned}$$

Oblique corrections



$$\begin{aligned}\mathcal{L} = & (1 + \hat{U}) W_{\mu\nu}^+ W_{\mu\nu}^- + W_{\mu\nu}^3 W_{\mu\nu}^3 + B_{\mu\nu} B_{\mu\nu} - \hat{S} B_{\mu\nu} W_{\mu\nu}^3 \\ & + (1 + \hat{T}) \textcolor{blue}{c}_W^2 M_Z^2 W_\mu^+ W_\mu^- + \textcolor{blue}{M}_Z^2 (Z_\mu)^2\end{aligned}$$

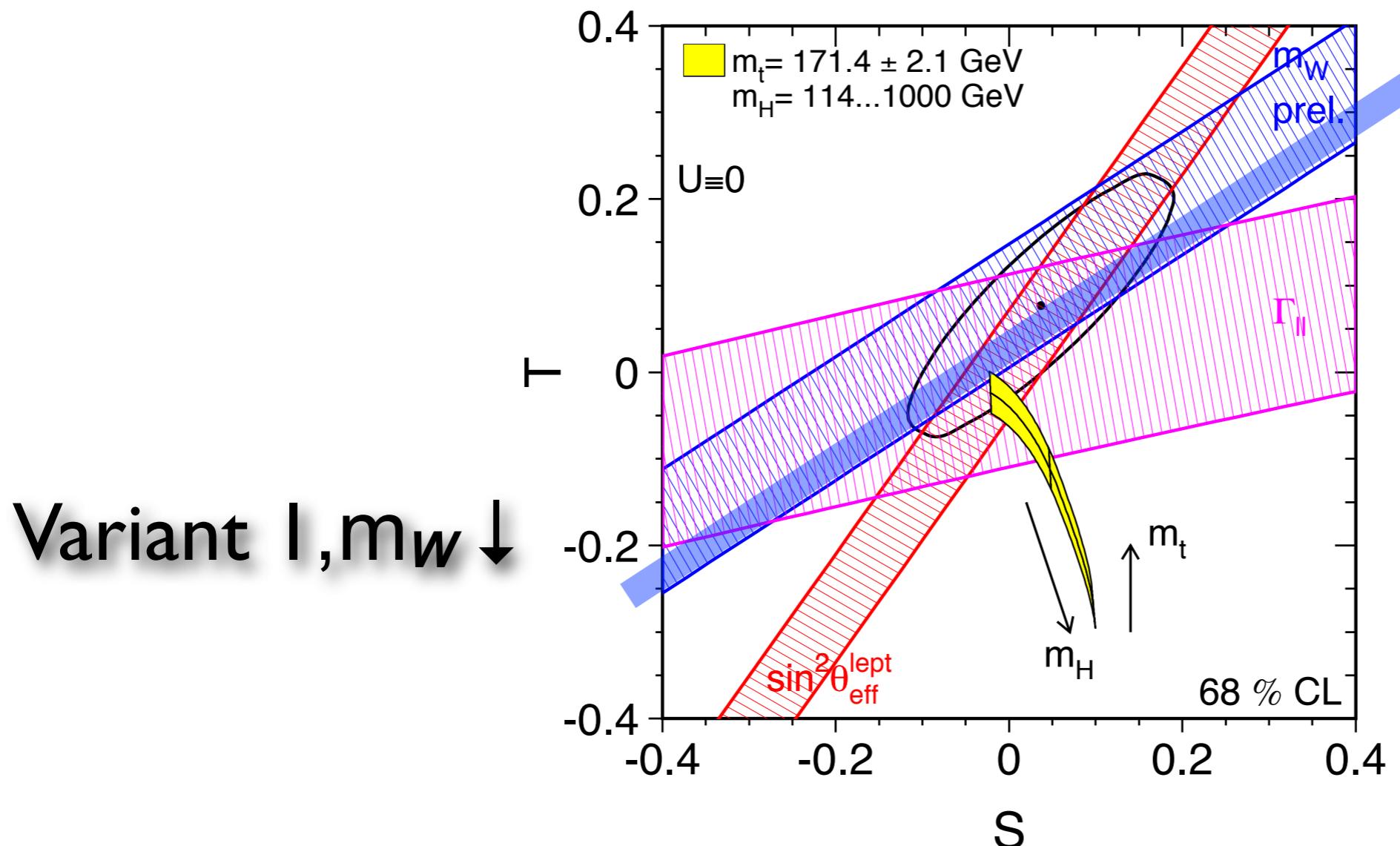
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- $\Gamma_{ll}, \sin^2 \theta_{\text{eff}} \dots \longleftrightarrow \hat{T}, \hat{S}$
- $M_W, \hat{T}, \hat{S} \longleftrightarrow \hat{U}$
- In SM, \hat{U} shows \sim no dependence on m_H

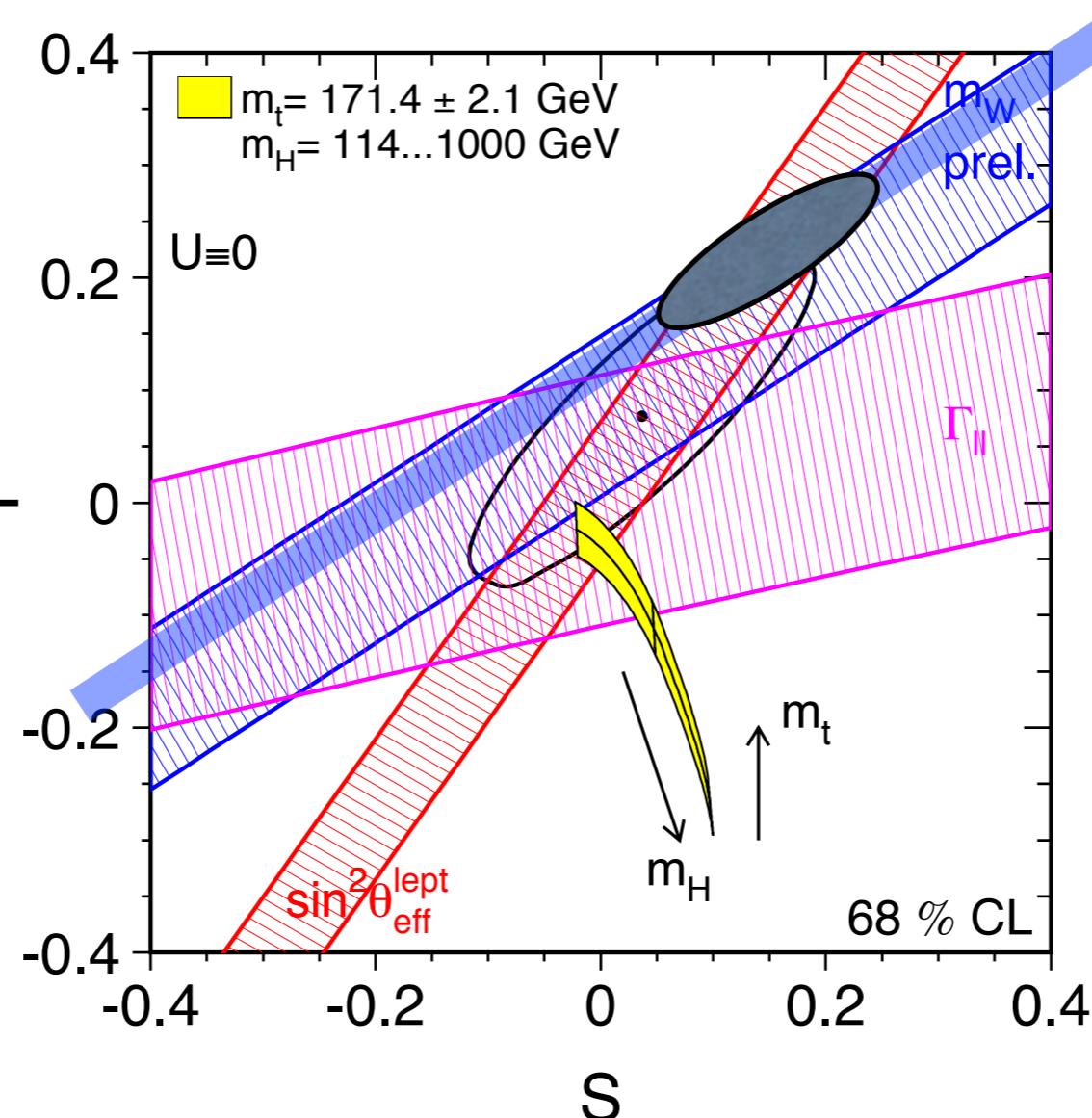
Impact of $\delta m_W < 10$ MeV



Fit perfectly consistent for a light Higgs

Impact of $\delta m_W < 10$ MeV

Variant 2, $m_W \uparrow$



Possible BSM explanations:

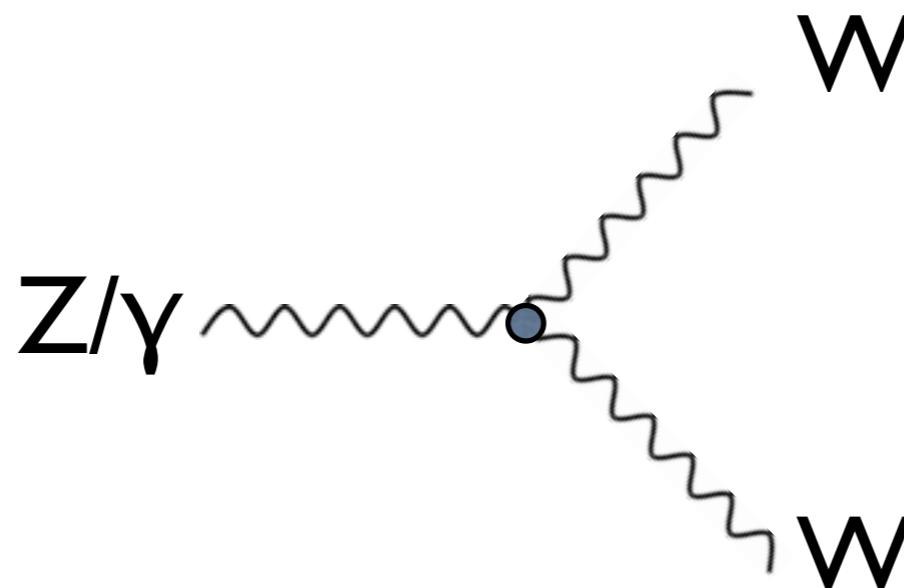
- (a) Loops of light particles (~ 100 GeV) (ex: charginos/neutralinos)
- (b) Tree-level mixing with \sim TeV vector resonances (ex: Z')

Statement on 4th generation

- There may well be new heavy **vectorlike** quarks (ex: top partners in composite Higgs scenarios), **but** an extra **chiral** generation seems rather unlikely
- While consistent with Z pole data in a small region of parameter space, *typical* contributions to the ρ parameter (T) is order of magnitude above needed

Cubic W couplings

Importance of longitudinal W,Z



- Deviation - sign of EW gauge boson compositeness
- Likely involves W_L (\in EWSB sector)
- $\Rightarrow W_\mu^+ W_\nu^- Z^{\mu\nu}$ (2L1T, known as $g^{Z/\gamma}$)
and not (field strength) 3 (3T, known as λ 's)

Impact on the scale of new physics

$$\mathcal{L} = |D_\mu H|^2 + \frac{ig_{SM}}{\Lambda_{UV}^2} (D_\mu H)^\dagger (D_\nu H) \times W_{\mu\nu} (\text{or } B_{\mu\nu})$$

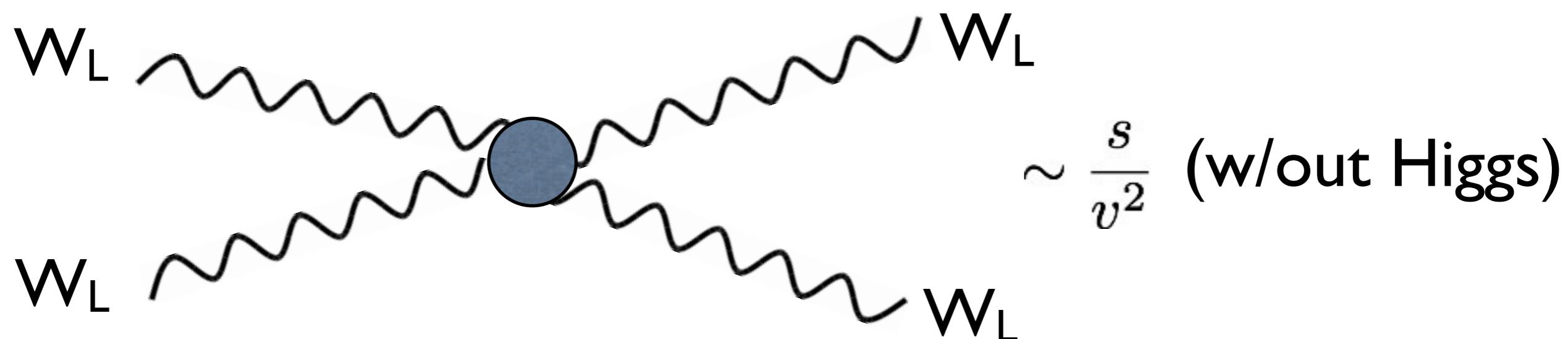
Scale of resonances in
the strong EWSB sector

⇒ Expect $\frac{\delta g_{WWZ}}{g_{WWZ}^{SM}} \sim \frac{M_W^2}{\Lambda_{UV}^2}$

- LEP legacy bounds $O(2\%) \Rightarrow \Lambda_{UV} \geq 500 \text{ GeV}$
- LHC improvement to $O(1\%)$ with $\text{few} \times 10 \text{ fb}^{-1} ??$

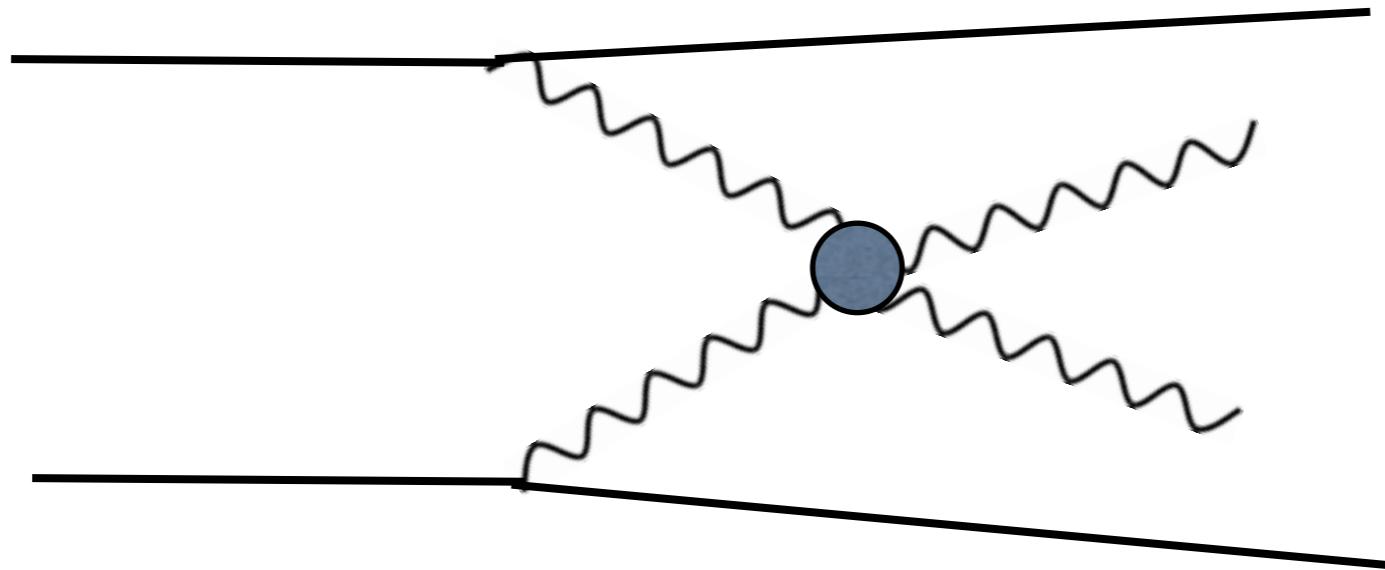
Quartic W couplings

Strong WW scattering



(While $T\bar{T} \rightarrow T\bar{T}$ only $f(t/s) \sim O(1)$)

$PP \rightarrow jjWW$



Difficult because $T\bar{T} \rightarrow T\bar{T}$ background
enhanced by $\mathcal{O}(10^3)$ numerical factor

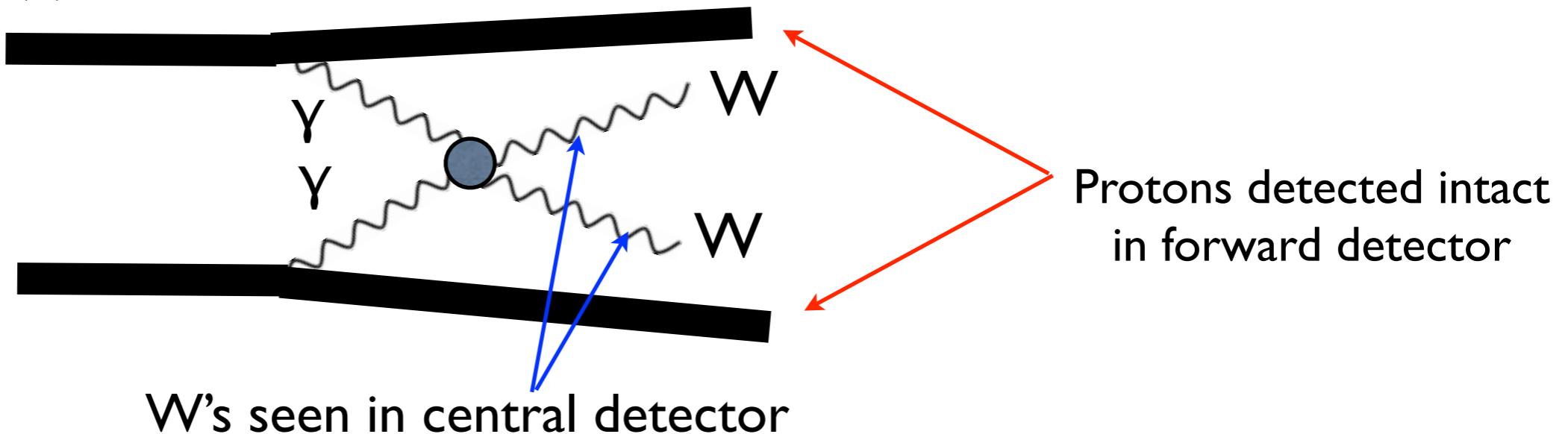
- ⇒ need $M_{inv} \geq 1 \text{ TeV}$ cut to get decent S/B
- ⇒ $\sigma_{\text{signal}} \sim \text{few fb}$ in leptonic channel
- ⇒ $\mathcal{O}(100 \text{ fb}^{-1})$ for a discovery

Jet substructure to save hadronic channels?

Anomalous $\gamma\gamma WW$ coupling ?

C.Ryon et al (Saclay)

$pp \rightarrow ppWW$

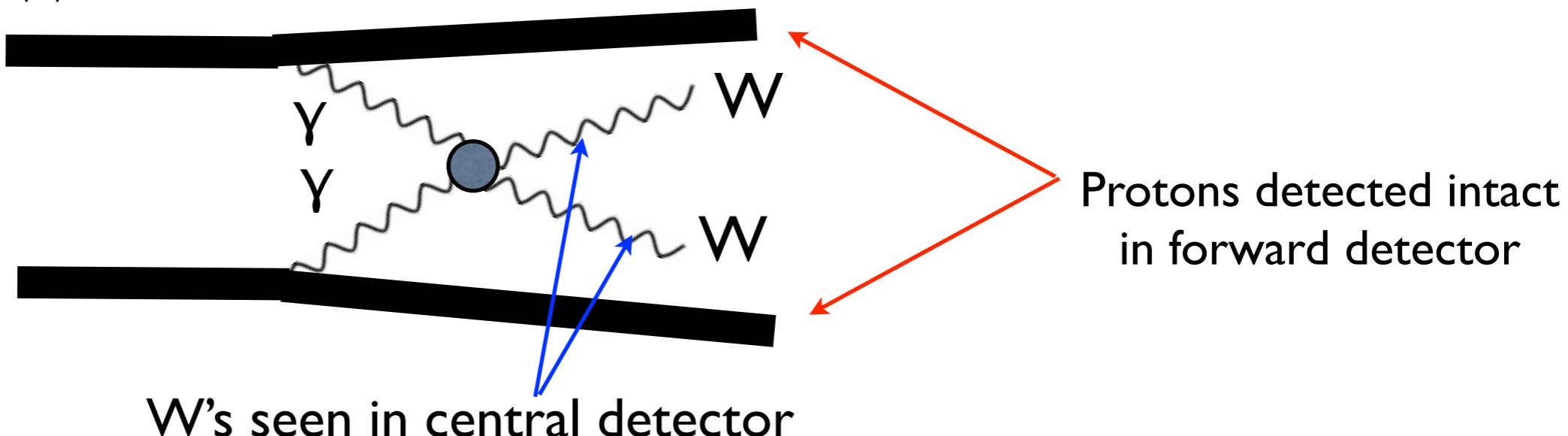


$$\sigma_{SM, \text{diffr}}(WW) \sim 100 \text{ fb}, \quad \sigma_{SM, \text{diffr}}(W > 1 \text{ TeV}) \sim \text{few fb}$$

Anomalous $\gamma\gamma WW$ coupling ?

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$pp \rightarrow ppWW$



$$\sigma_{SM, \text{diff}}(WW) \sim 100 \text{ fb}, \quad \sigma_{SM, \text{diff}}(W > 1 \text{ TeV}) \sim \text{few fb}$$

- In models of strong EWSB expect anomalous couplings

$$\delta \mathcal{L} \sim \frac{e^2 g_{SM}^2}{16\pi^2 \Lambda_{UV}^2} (F_{\mu\nu})^2 W_\alpha^+ W_\alpha^-$$

- With 100 fb^{-1} sensitive only to $\Lambda_{UV} \sim 100 \text{ GeV}$
⇒ seems extremely unlikely

B physics

Status quo

- CKM picture confirmed with no significant deviations (apart from a couple $2\text{-}3 \sigma$ anomalies)
- ⇒ TeV-scale physics (if exists) must have a non-generic flavor structure
 - ▶ Minimal Flavor Violation (ex: SUSY)
 - ▶ Partial compositeness (ex: composite Higgs models)

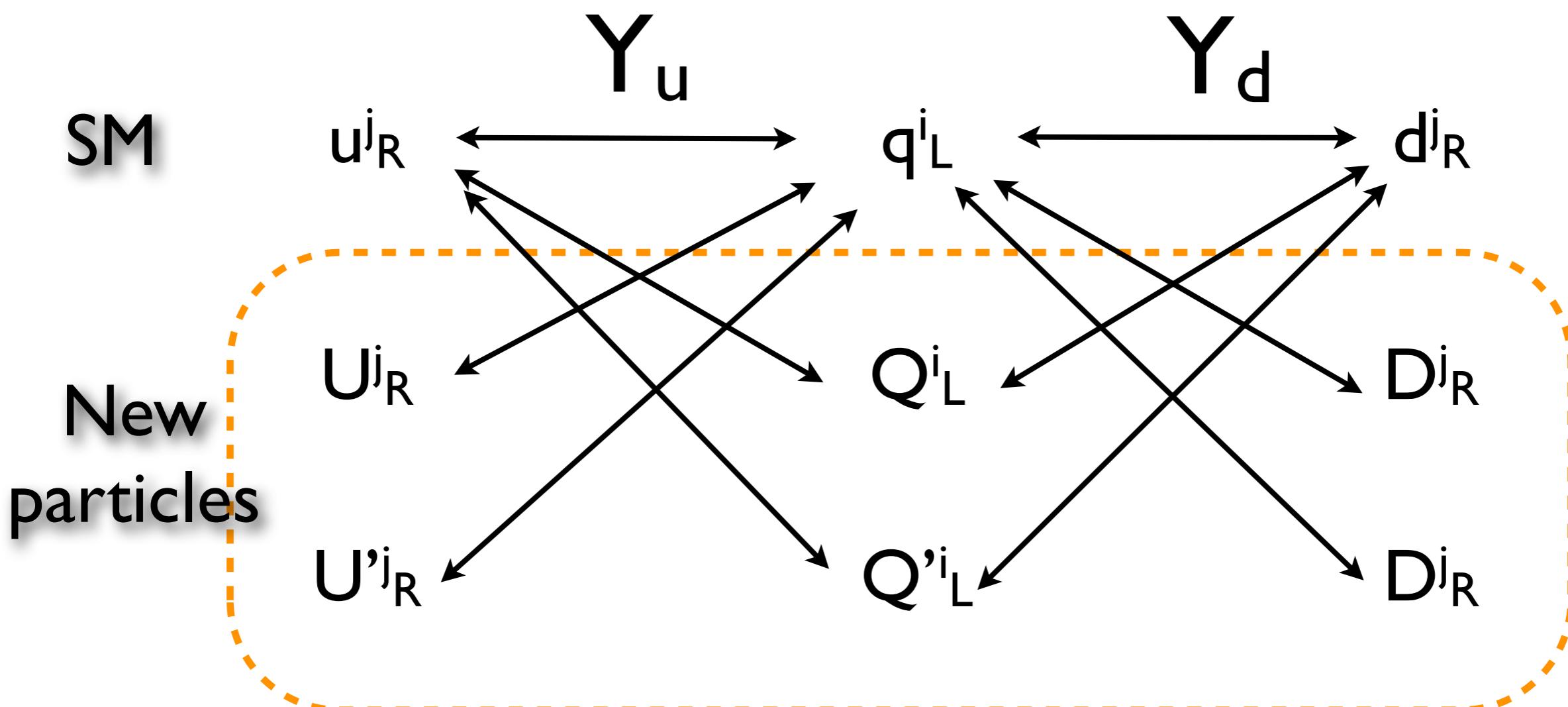
MFV

- Think in terms of Yukawa matrices Y_u, Y_d

$$\text{SM} \quad u^j_R \longleftrightarrow Y_u \quad q^i_L = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \longleftrightarrow Y_d \quad d^j_R$$

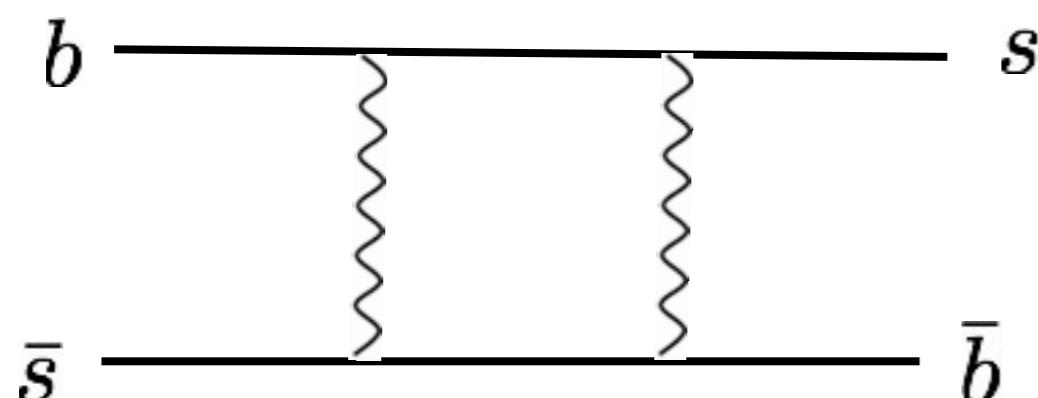
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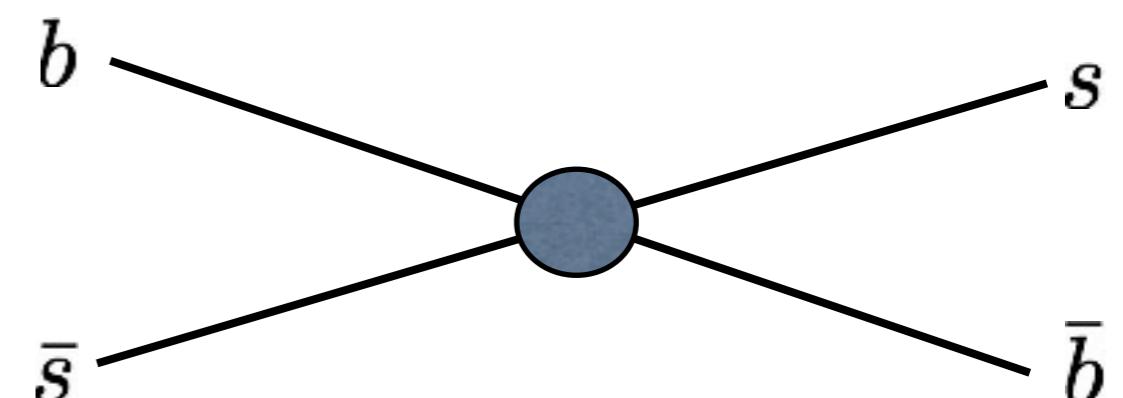


MFV

⇒ New physics contributions to FCNC have
the same CKM suppression as in SM



$$\sim \frac{(V_{tb} V_{ts})^2}{16\pi^2 m_W^2}$$

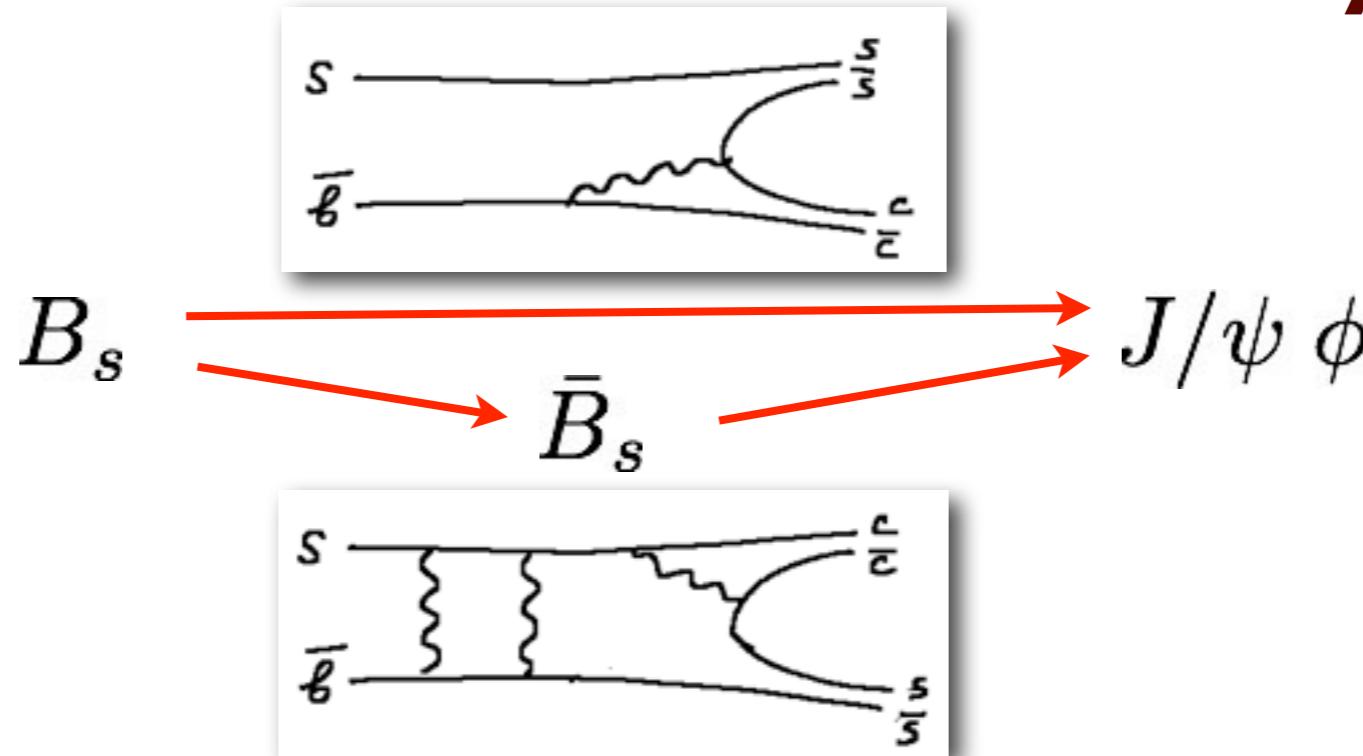


$$\sim \frac{(\mathbf{Y}_\mathbf{u}^\dagger \mathbf{Y}_\mathbf{u})^2}{\Lambda^2} \sim \frac{(V_{tb} V_{ts})^2}{\Lambda^2}$$

B-physics @ LHC

1. CP violation in B_s decays
2. $B_s \rightarrow \mu^+ \mu^-$
3. ...

CP violation in B_s decays



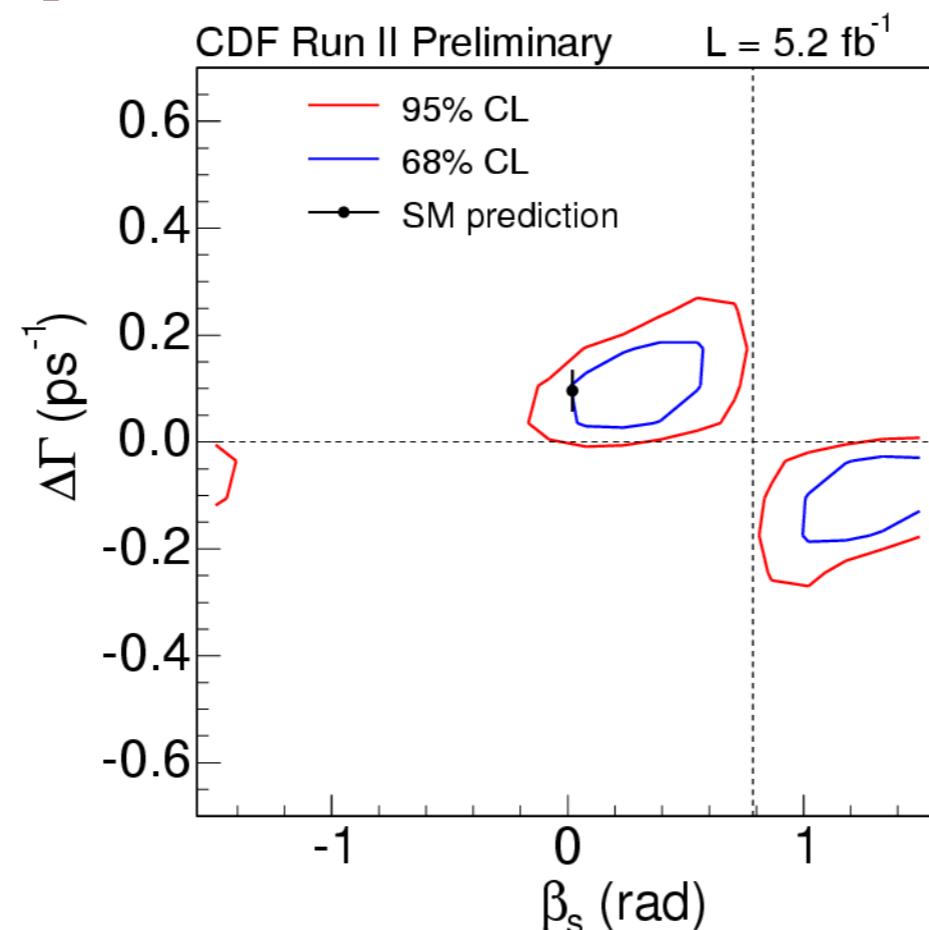
$$\frac{\mathcal{A}(B_s \rightarrow J/\psi \phi)}{\mathcal{A}(\bar{B}_s \rightarrow J/\psi \phi)} = e^{i2\beta_s}$$

In Standard Model:

$$\beta_s^{\text{SM}} = \arg \left(\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) \simeq 0.02$$

Experimental situation

ICHEP2010

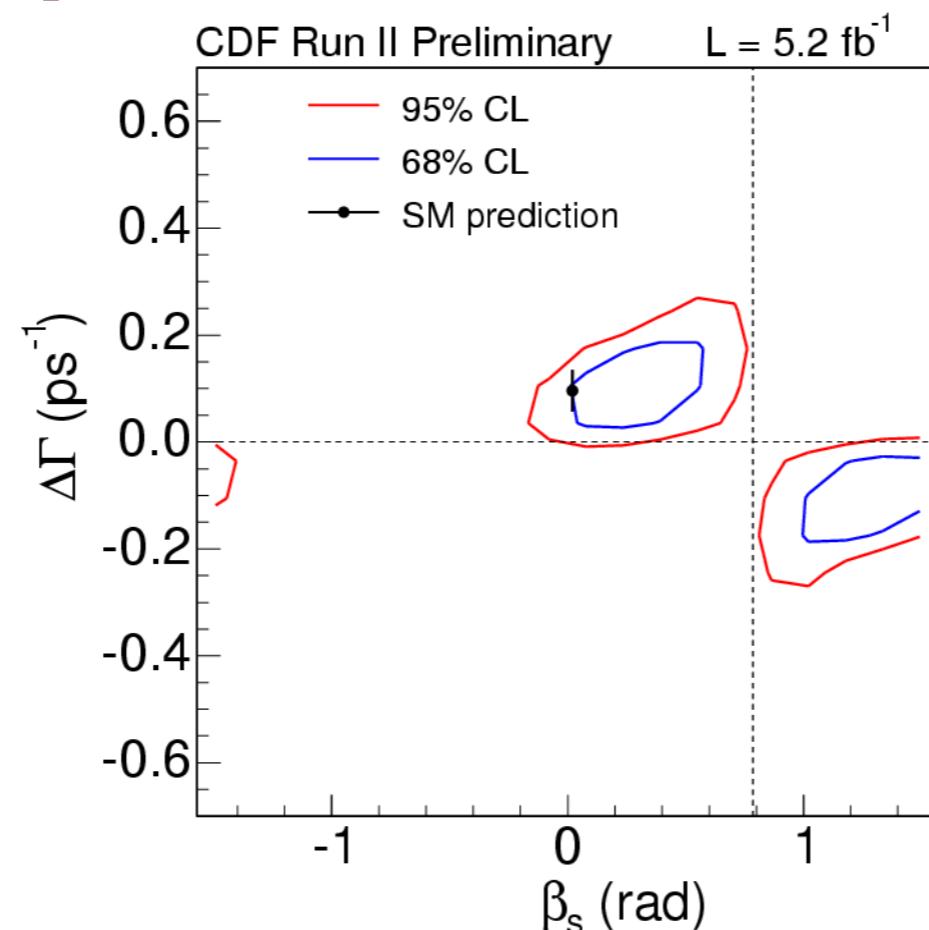


$$(\delta\beta_s)_{\text{exp}} \sim 0.2 \text{ rad}$$

LHCb: $\delta\beta_s \rightarrow 0.015$ with few fb^{-1}

Experimental situation

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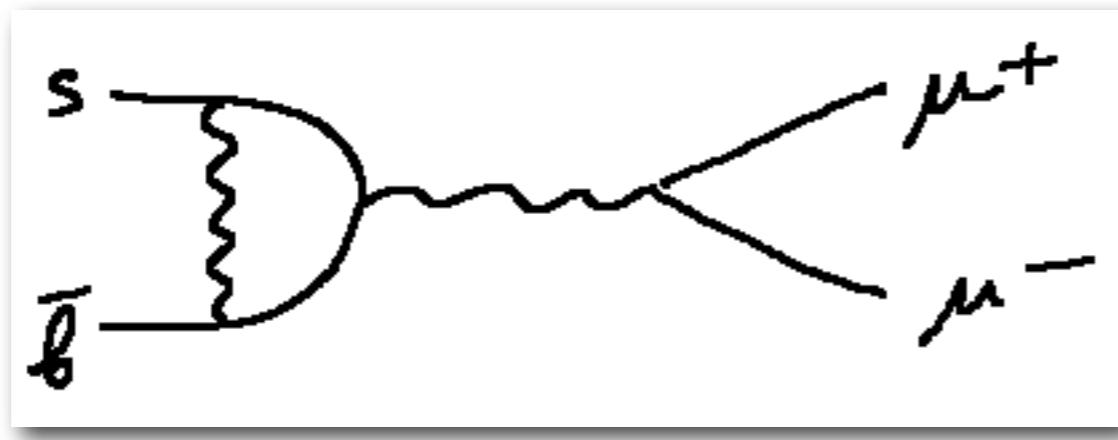


$$(\delta\beta_s)_{\text{exp}} \sim 0.2 \text{ rad}$$

LHCb: $\delta\beta_s \rightarrow 0.015$ with few fb^{-1}

Deviation from SM in this channel will imply presence
of new, flavor blind, sources of CP violation
(ex: CP violation in 2 Higgs doublet model)

$B_s \rightarrow \mu^+ \mu^-$



$$\mathcal{A} \sim \frac{V_{tb} V_{ts}}{16\pi^2 m_Z^4} \frac{m_\mu}{m_B}$$

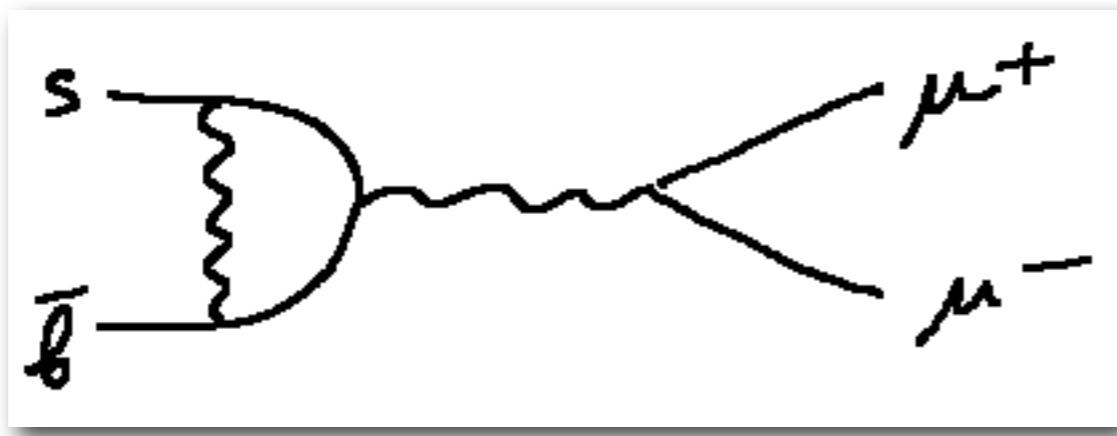
(helicity suppressed)

$$\text{BR}_{\text{SM}} \sim 3 \times 10^{-9}$$

$$\text{BR}_{\text{exp}} < 5.8 \times 10^{-8}$$

LHCb will observe this decay at 3σ with a few fb^{-1}

$$B_s \rightarrow \mu^+ \mu^-$$



$$\mathcal{A} \sim \frac{V_{tb} V_{ts}}{16\pi^2 m_Z^4} \frac{m_\mu}{m_B}$$

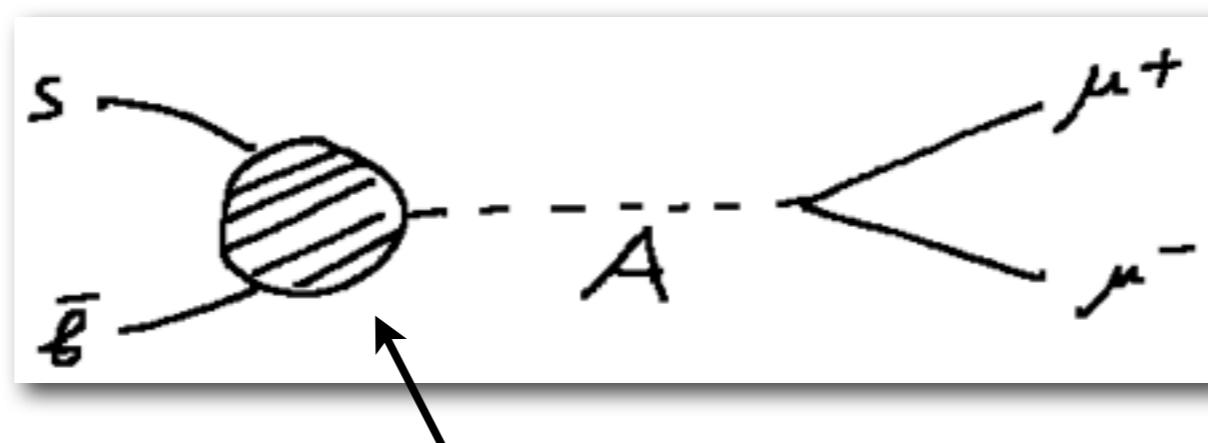
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Enhancement expected in MFV scenarios with large $\tan \beta$ (ex: SUSY)

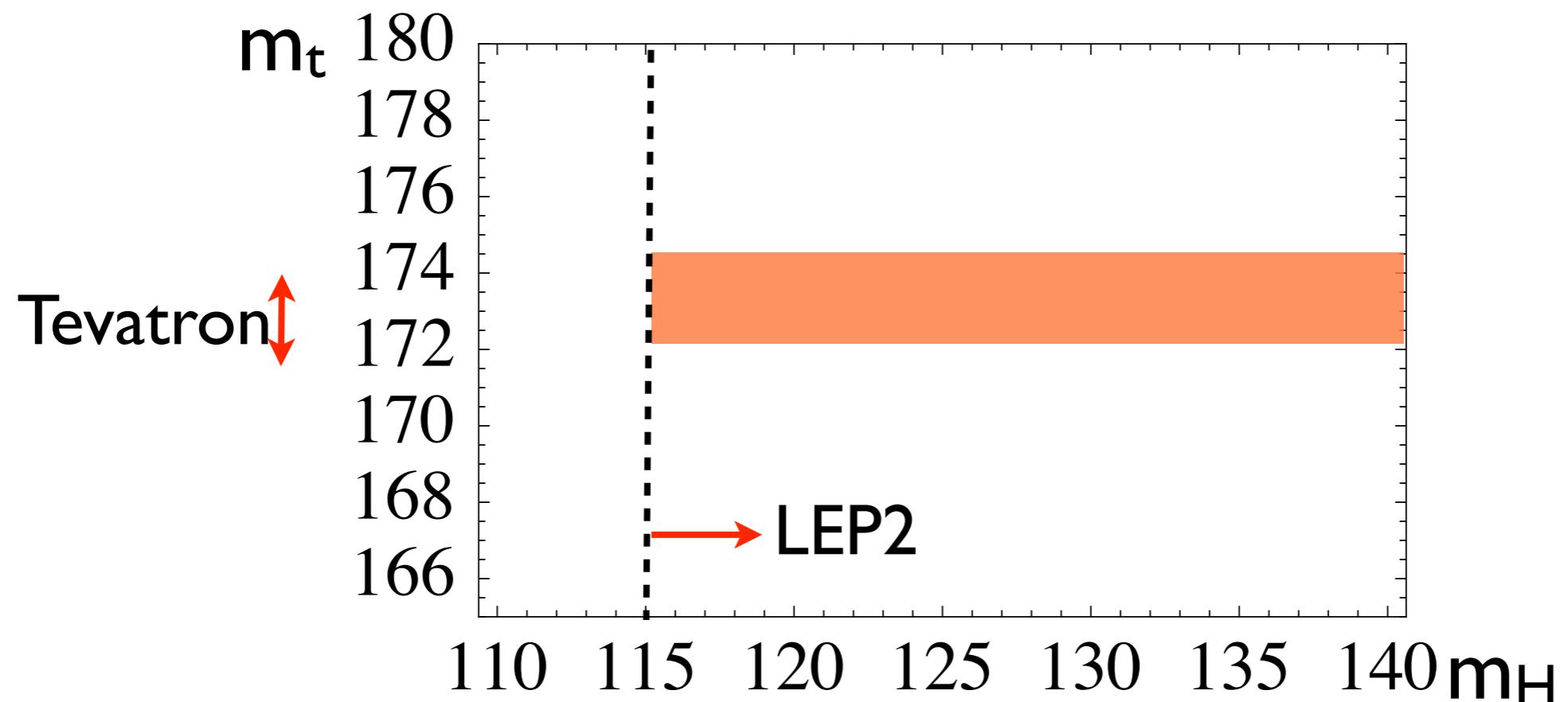


stop-chargino loop

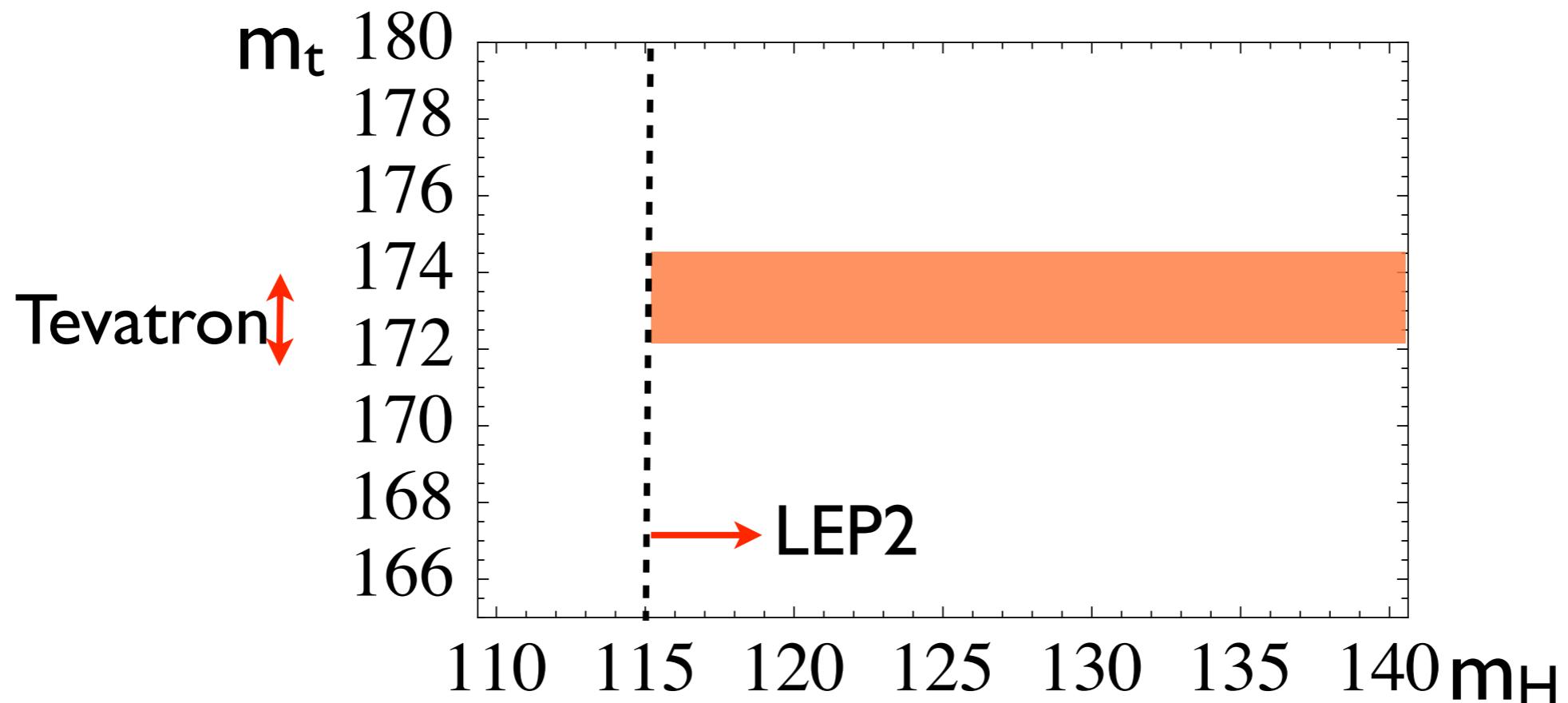
Top

1. top mass
2. top compositeness
3. top FCNC decays

Top mass



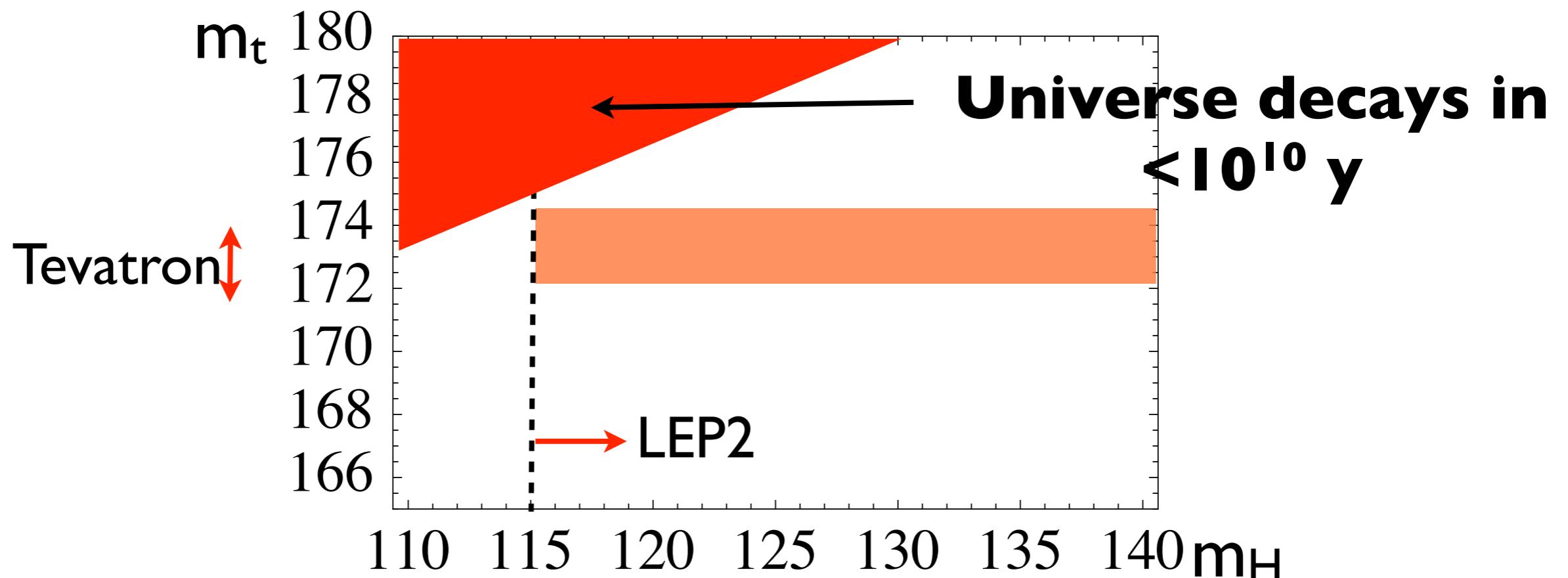
Top mass



In SM, heavy top + light Higgs \Rightarrow vacuum instability

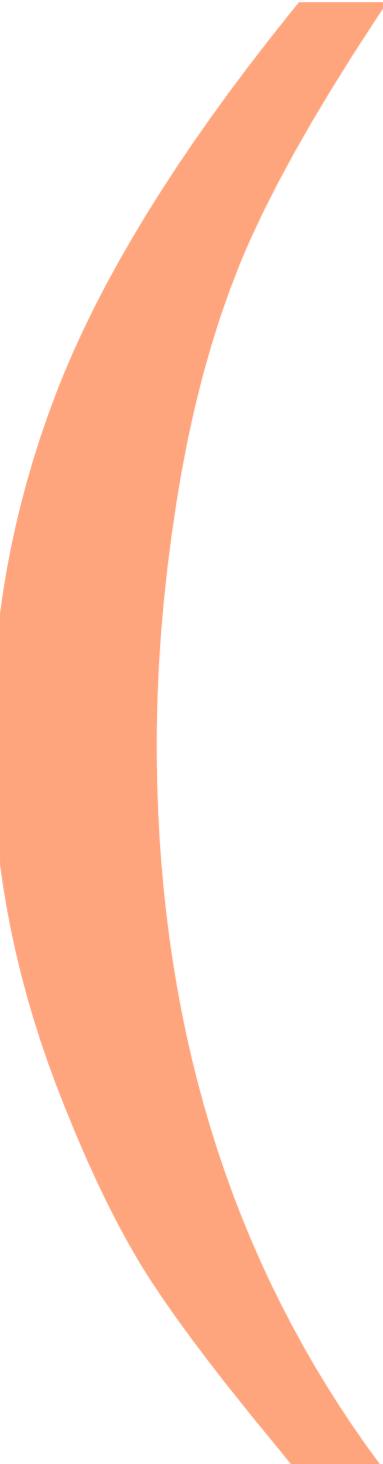
$$\frac{d\lambda_{\text{Higgs}}}{d \log E} = -3 \frac{y_{\text{top}}^2}{16\pi^2} + \dots$$

Top mass



In SM, heavy top + light Higgs \Rightarrow vacuum instability

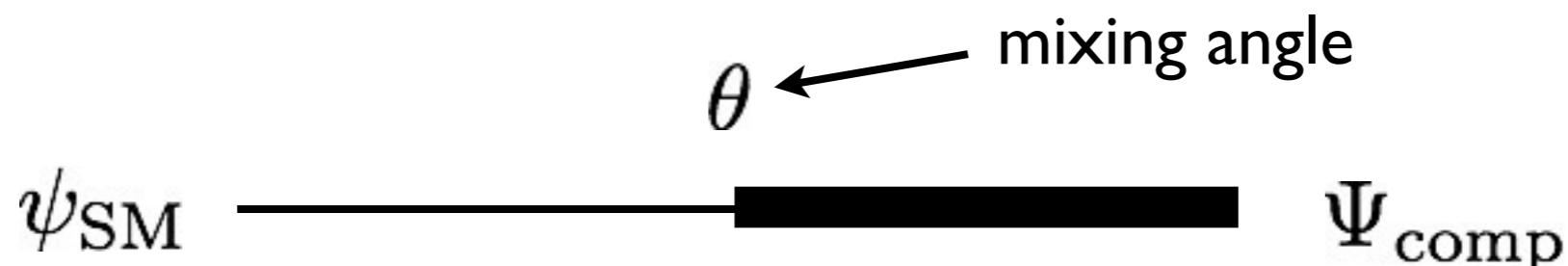
$$\frac{d\lambda_{\text{Higgs}}}{d \log E} = -3 \frac{y_{\text{top}}^2}{16\pi^2} + \dots$$



Partial compositeness

(ex: composite Higgs models, warped extra dimensions, Randall-Sundrum,...)

SM fermions get masses by mixing with heavy, vectorlike, “composite fermions”

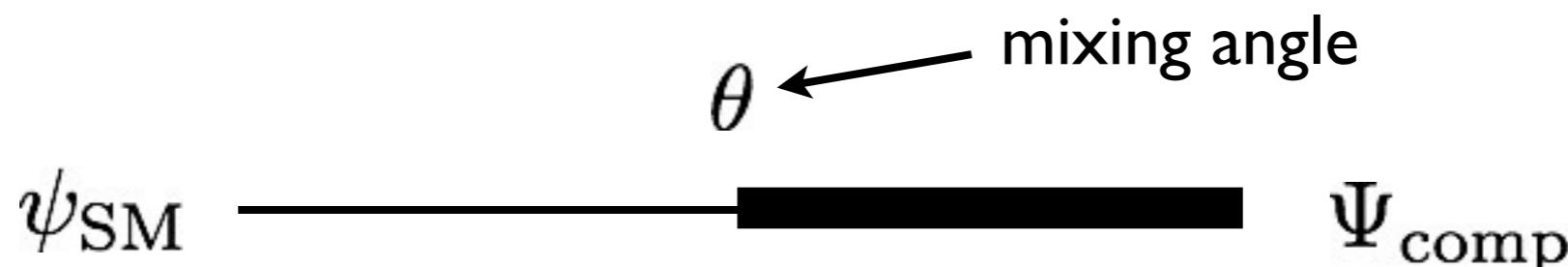


$$m_\psi = \theta_L \theta_R M_\Psi$$

$$\theta_1 \ll \theta_2 \ll \theta_3$$

$$V_{ij}^{\text{CKM}} \sim \frac{\theta_{Li}}{\theta_{Lj}} \quad (i \leq j)$$

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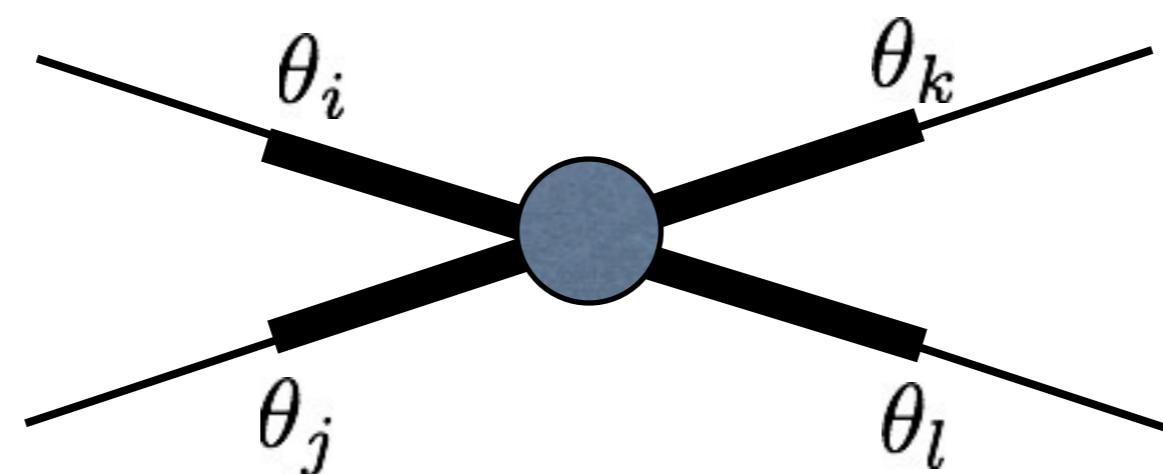
$$\theta_1 \ll \theta_2 \ll \theta_3$$

$$V_{ij}^{\text{CKM}} \sim \frac{\theta_{Li}}{\theta_{Lj}} \quad (i \leq j)$$

⇒ Effective Yukawa matrices @ low energy

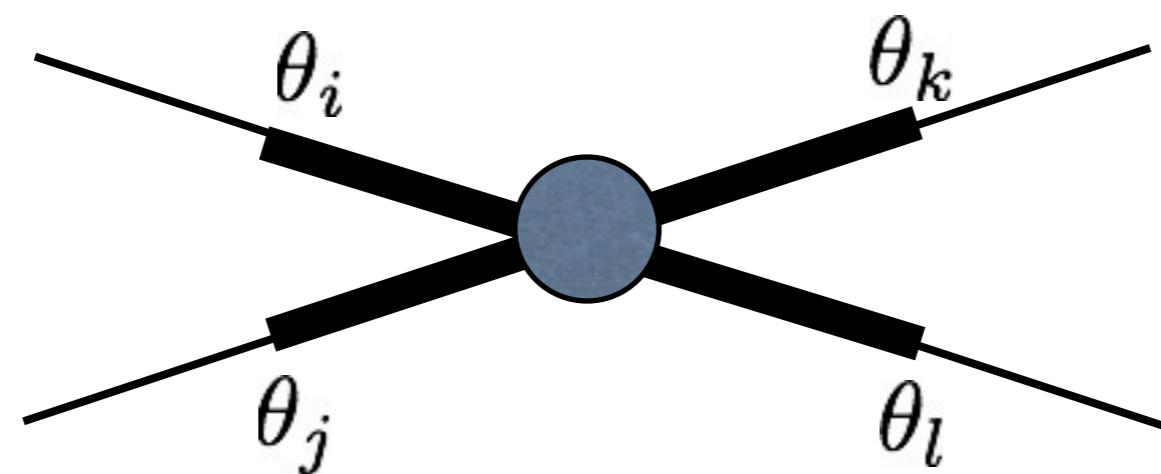
*Hierarchy of fermion masses and mixings
‘explained’ via degree of compositeness*

FCNC in partial compositenes

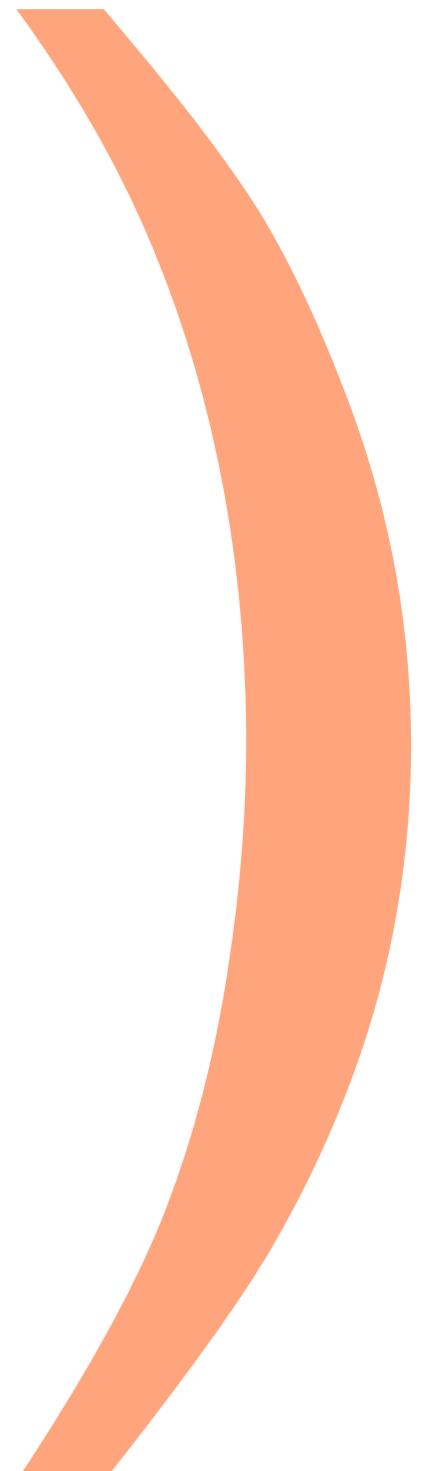


FCNC suppressed by mixing angles
(small for light quarks)

FCNC in partial compositenes



FCNC suppressed by mixing angles
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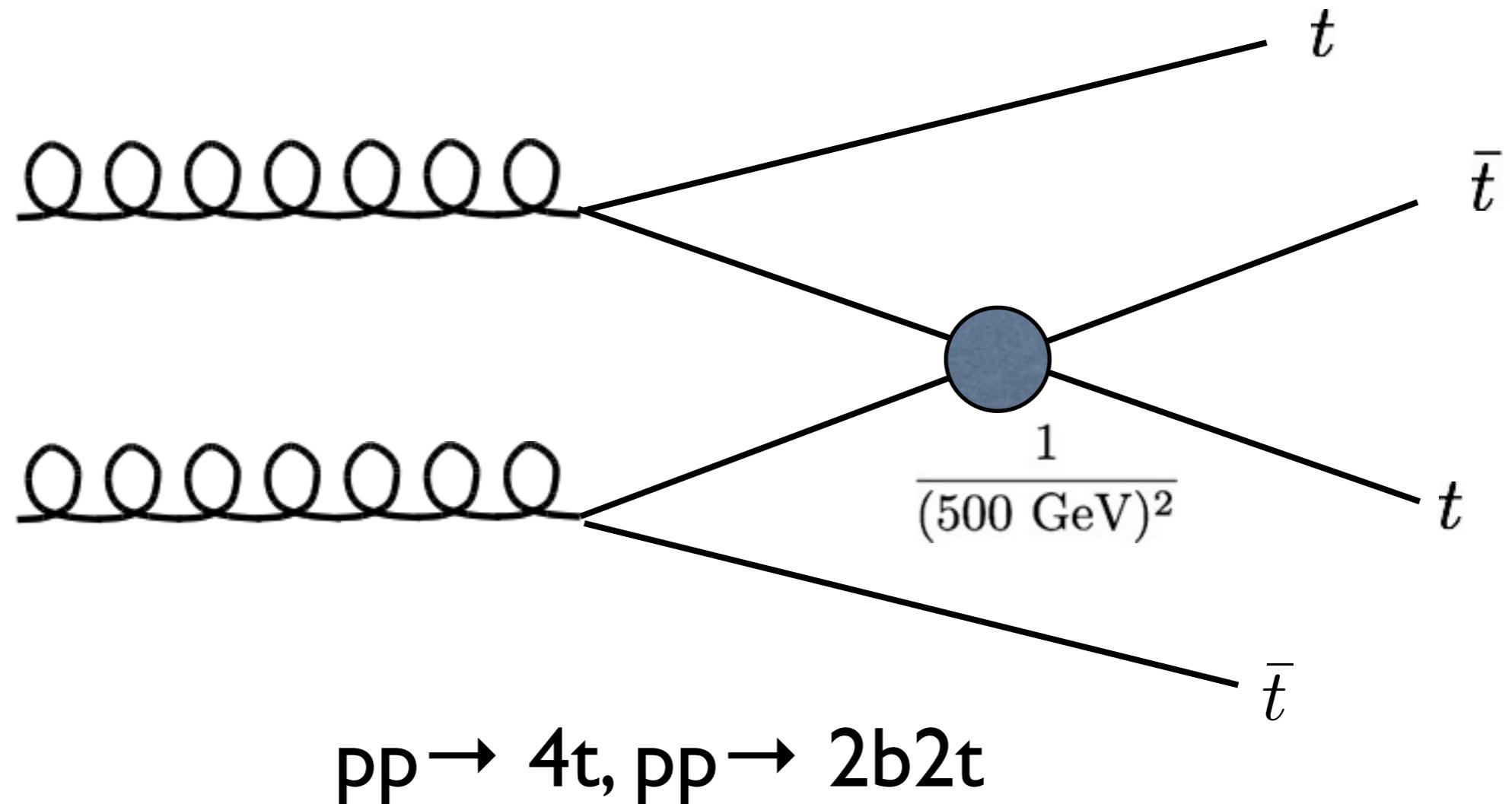
Top compositeness

- In *partial compositeness* framework,
top is “most composite” of all SM fermions
- Focus on extreme case when
TopLeft or TopRight is maximally composite
(easiest to detect)

$$\frac{16\pi^2}{\Lambda_{\text{UV}}^2} (\bar{t}_R \gamma^\mu t_R)^2 \quad \text{or} \quad \frac{16\pi^2}{\Lambda_{\text{UV}}^2} (\bar{q}_L^3 \gamma^\mu q_L^3)^2$$

$$\Lambda_{\text{UV}} \sim 5 \text{ TeV}$$

Top compositeness @ LHC



Lillie, Shu, Tait 2008

Pomarol, Serra 2008

FCNC top decays ($t \rightarrow c Z$)

$$\frac{16\pi^2}{\Lambda_{\text{UV}}^2} (H^\dagger D_\mu H)(\bar{t}_R \gamma^\mu t_R)^2$$

requires Higgs compositeness will have small charm admixture $\mathcal{O}(\sqrt{v_{cb}})$

$$BR(t \rightarrow cZ) \sim \text{few} \times 10^{-5} \left(\frac{5 \text{ TeV}}{\Lambda_{\text{UV}}} \right)^2$$

At the border of LHC sensitivity ?

Higgs

1. mass
2. couplings

Higgs mass per se

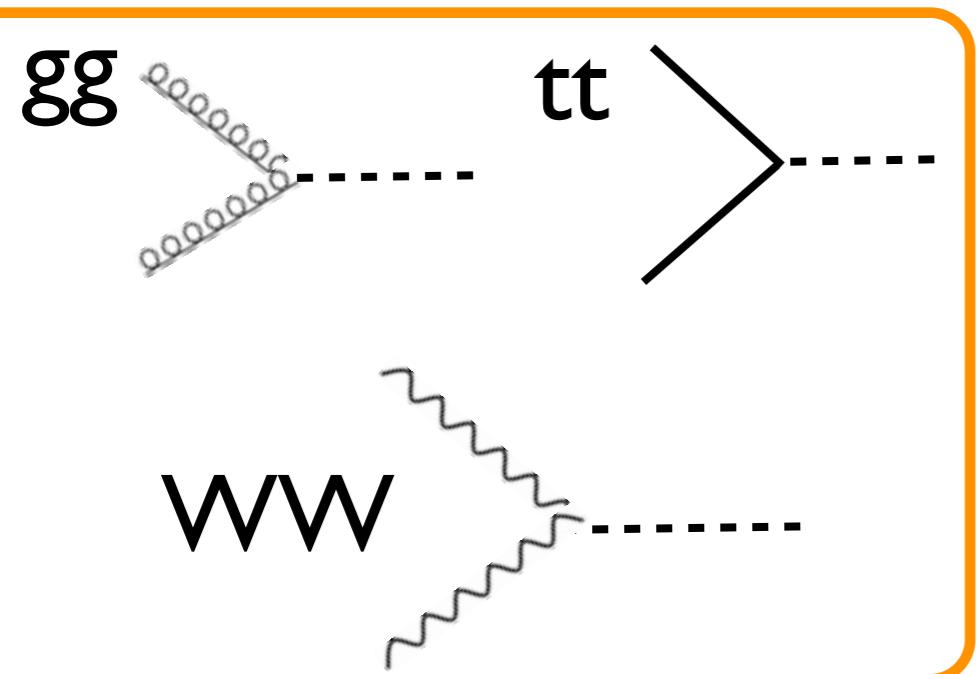
Interesting in:

- SUSY (see talk by Pietro Slavich)
- in the context of SM vacuum stability

Higgs couplings

vast subject...

Composite Higgs couplings

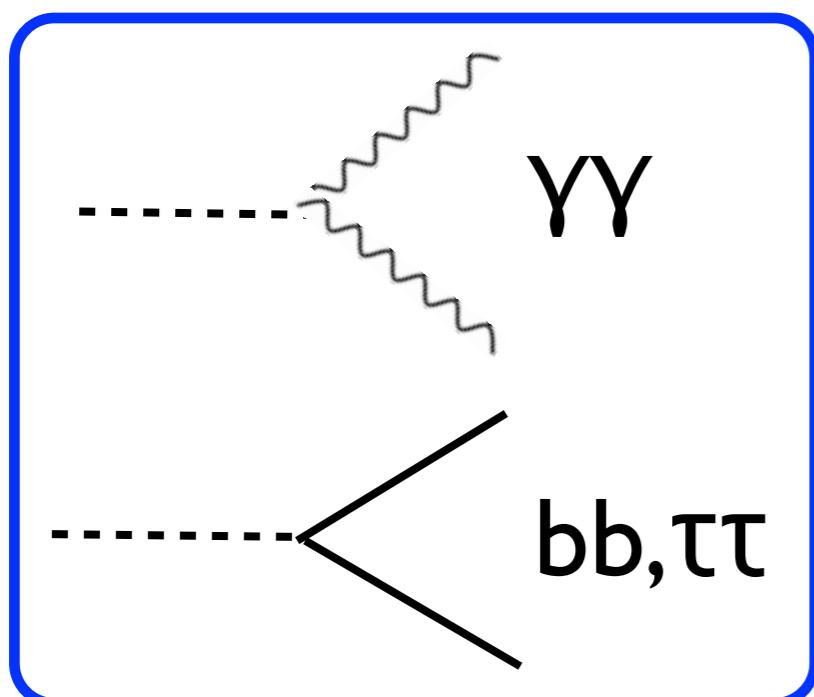


suppressed w.r.t. SM by $\mathcal{O}(10\%)$

ε_1

ε_2

$A \varepsilon_1 + B \varepsilon_2$



ε_3 ($\neq \varepsilon_1$ if top is composite)

Strategy

Measure $\sigma \times \text{BR}$ in various channels

production: GF, VBF, topstrahlung, associated
decay into: b, τ , γ , (virtual) W

Existing studies \Rightarrow 20%-40% precision on $\sigma \times \text{BR}$

Conclusions

- LHC is a discovery machine
- Were new physics to hide just outside the LHC energy range, LHC experiments would have potential to probe its existence indirectly
- Most fruitful if cross-check precision/direct detection
- In many interesting cases, detailed studies are lacking