Parametrizing BSM Physics

(Towards model independence)

Work since 2001 with:
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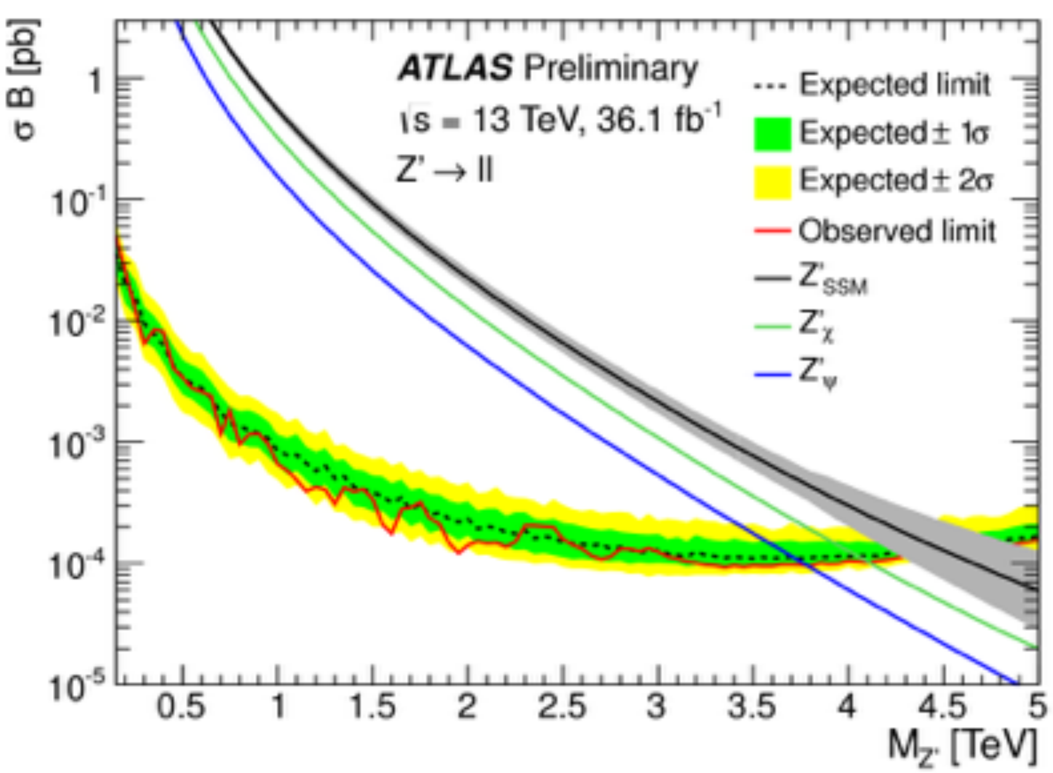
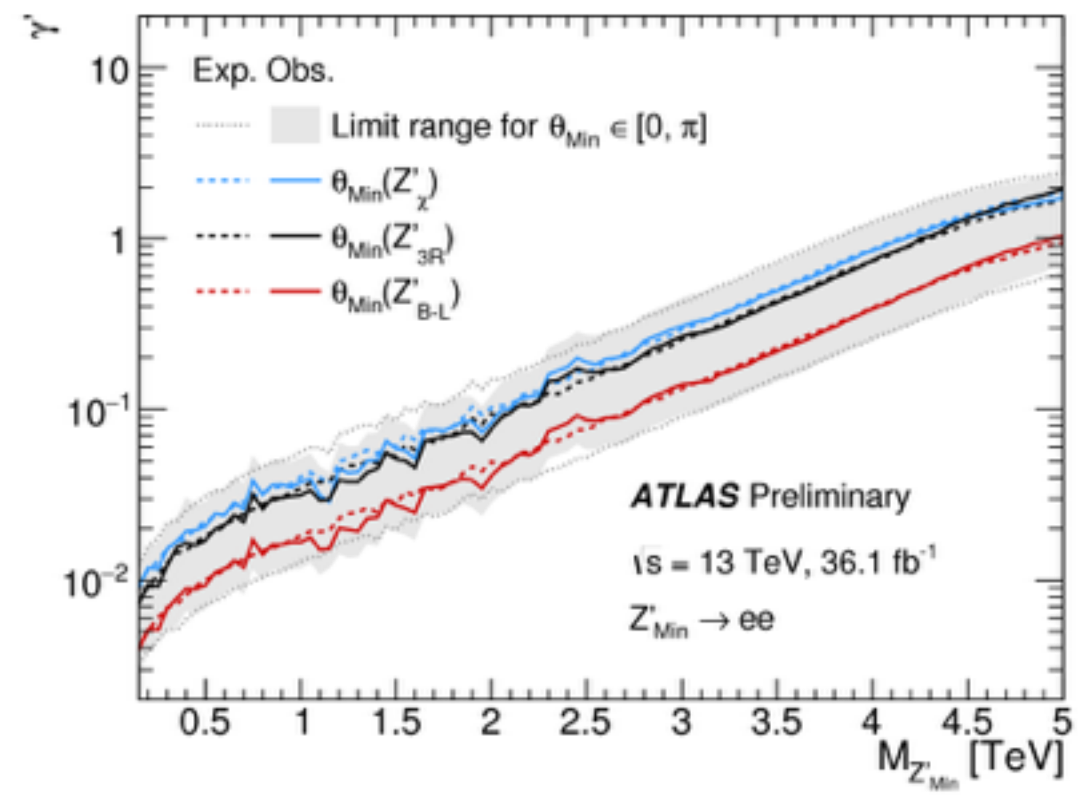
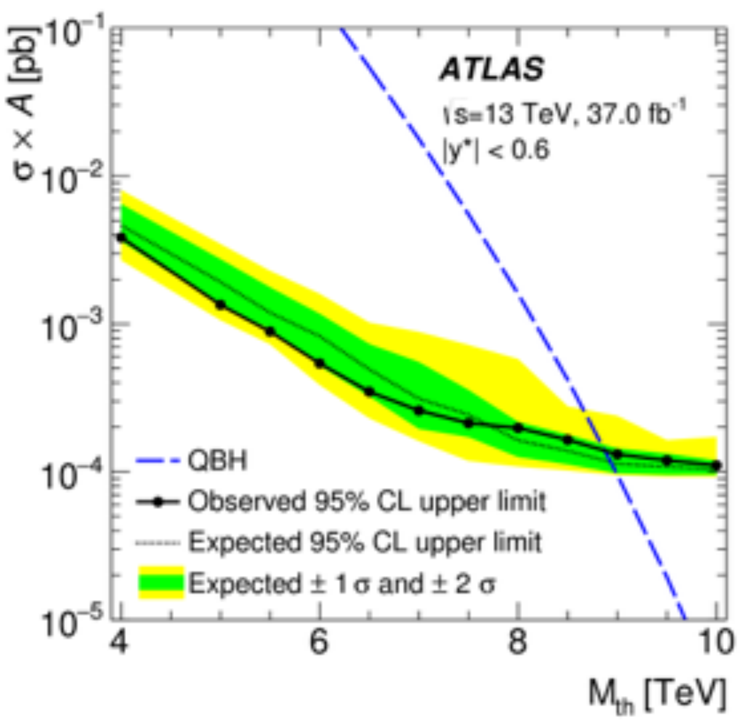
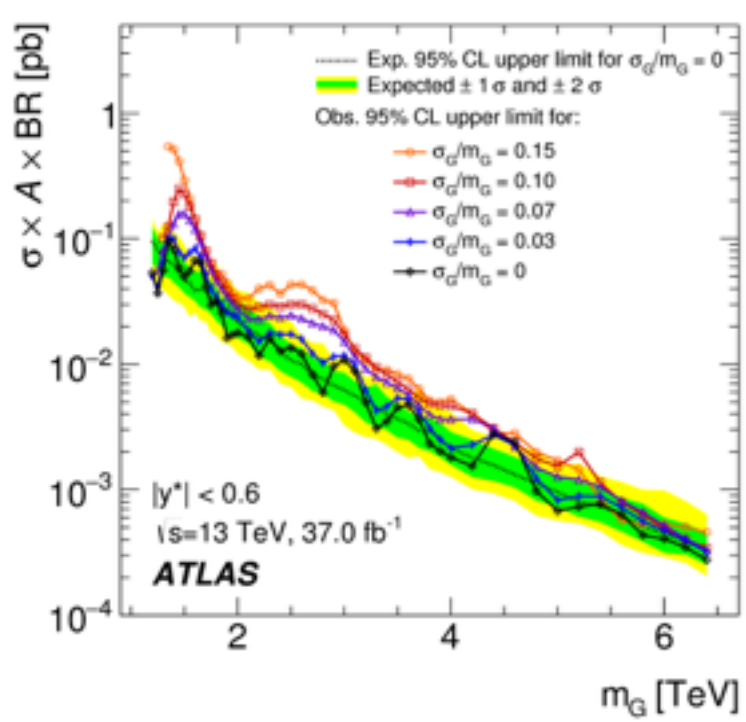
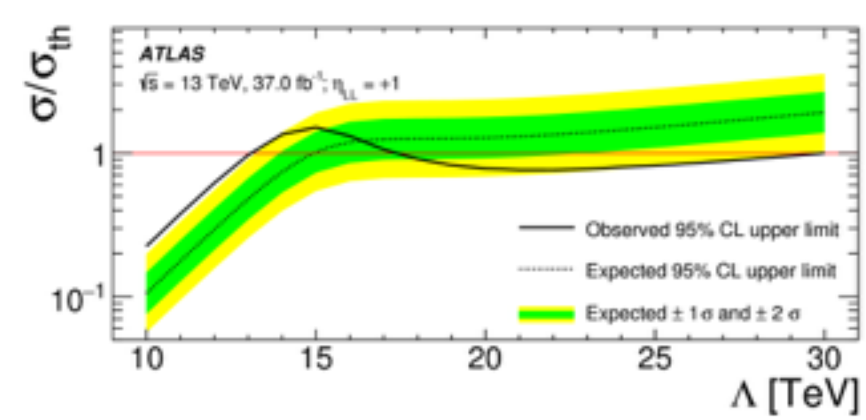
Searches of NP: line shapes, benchmarks, models, ...

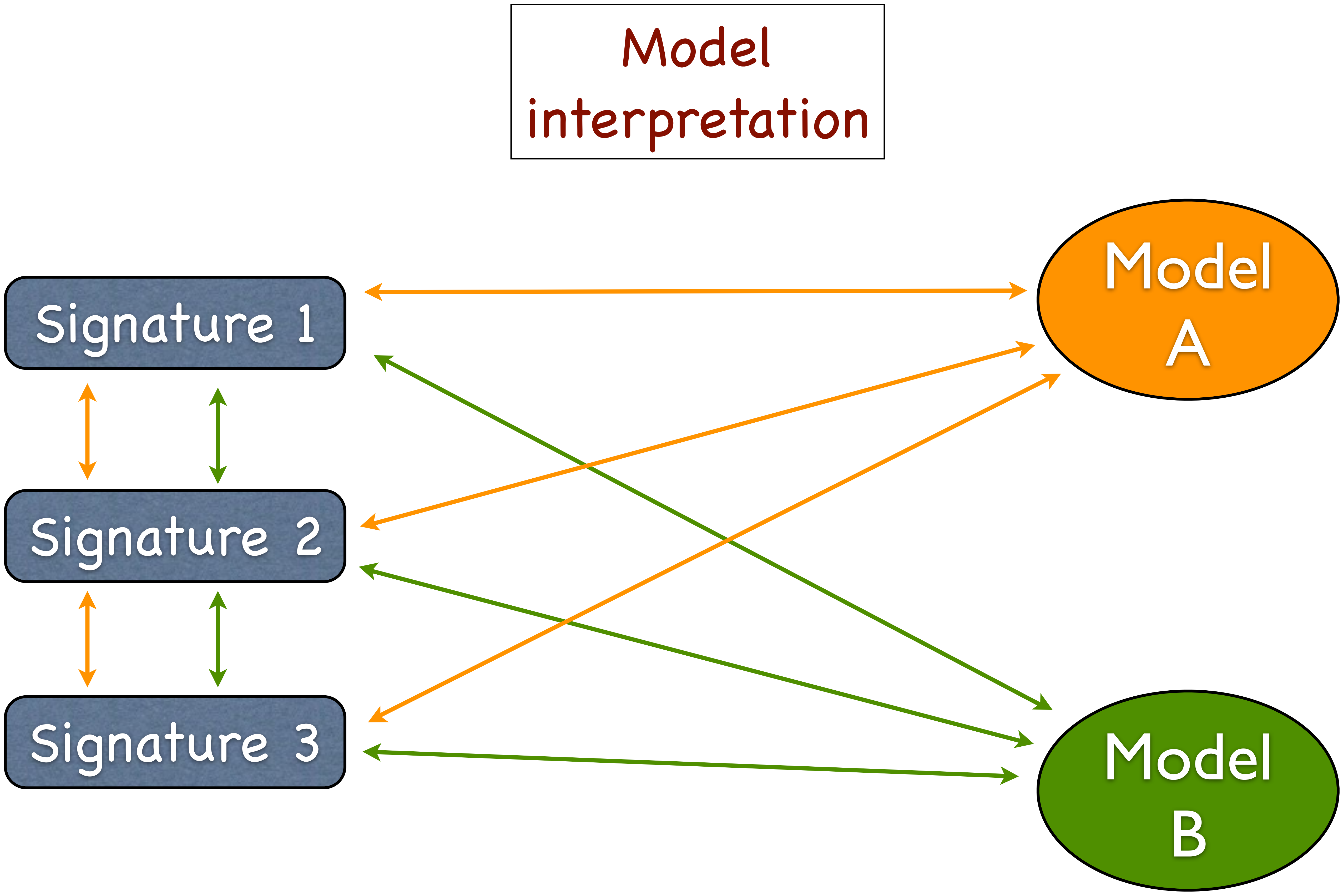






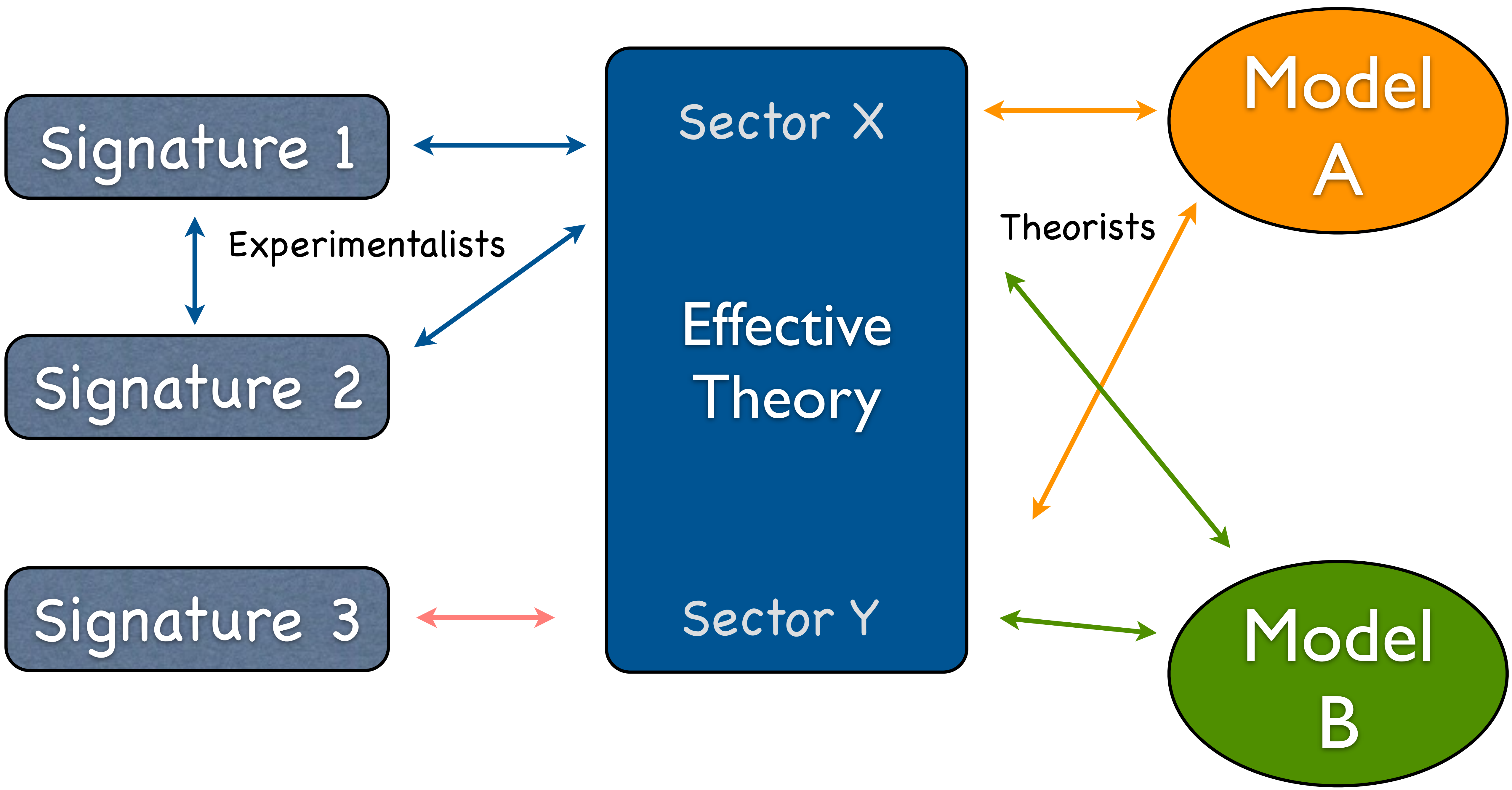






Model interpretation
Signature 1
Signature 2
Signature 3
Model A
Model B

Model-independent interpretation



Outline

- The General Effective Theory
  - Systematics
  - Usage
- Example: VL Quarks
- Conclusions

Framework:
Effective Quantum Field Theory

✓ Impose established symmetries: Lorentz, gauge, ...

✓ Assume "fundamental" scale Λ >> E

✓ Choose fields to describe d.o.f. below Λ

SM Effective Theory

Other effective theories

✓ Write all local symmetric operators of dim Δ with arbitrary coefficients of order $\Lambda^{4-\Delta}$

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Effective Quantum Field Theory

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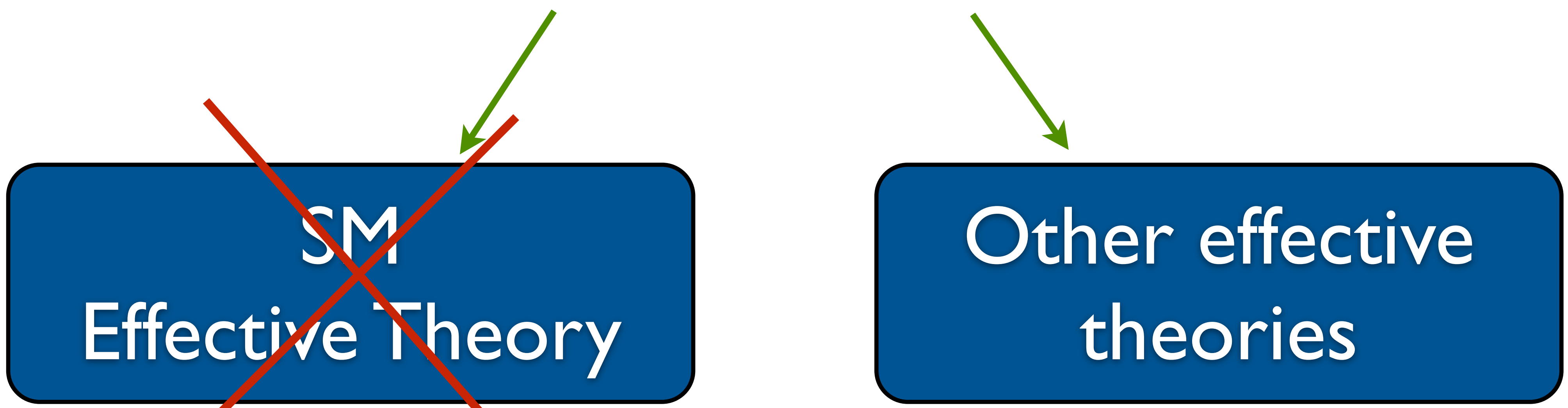


Resonant production
of new particles!

etric operators of dim Δ with arbitrary coefficients of order $\Lambda^{4-\Delta}$

General Effective Theory

- Symmetries: impose Lorentz and SU(3)xSU(2)xU(1) gauge invariance (+ EWSB)

- Field content: SM (w/ Higgs) + arbitrary irreps of

    - Lorentz: spin 0, 1/2, 1, 3/2, ...

    - SU(3)xSU(2)xU(1) gauge group

- Power counting: decoupling scenario ➔ start with renormalizable operators. Continue order by order in $\frac{1}{\Lambda}$

- Parameters: Allow for general couplings and masses M << Λ.

Infinite number of multiplets and parameters at each order

Need some additional organizational principle / assumption

Let us concentrate on generically-largest effects

Restriction:
New fields can have linear couplings to SM ops

- ✓ Single production at colliders
- ✓ Decay into SM particles
- ✓ Tree level contributions to D=6 SMEFT

irreps ⟷ SM ops ☞ finite possibilities at each order

Start at O(Λ^0) ⟶ linear couplings to SM renormalizable ops

Spin 0

Color Singlets

$S \in (1,1)_0$

$S_1 \in (1,1)_1$

$S_2 \in (1,1)_2$

$\varphi \in (1,2)_{\frac{1}{2}}$

$\Xi_0 \in (1,3)_0$

$\Xi_1 \in (1,3)_1$

$\Theta_1 \in (1,4)_{\frac{1}{2}}$

$\Theta_3 \in (1,4)_{\frac{3}{2}}$

Color Triplets

$\omega_1 \in (3,1)_{-\frac{1}{3}}$

$\omega_2 \in (3,1)_{\frac{2}{3}}$

$\omega_4 \in (3,1)_{-\frac{4}{3}}$

$\Pi_1 \in (3,2)_{\frac{1}{6}}$

$\Pi_7 \in (3,2)_{\frac{7}{6}}$

$\zeta \in (3,3)_{-\frac{1}{3}}$

Color Sextets

$\Omega_1 \in (6,1)_{\frac{1}{3}}$

$\Omega_2 \in (6,1)_{-\frac{2}{3}}$

$\Omega_4 \in (6,1)_{\frac{4}{3}}$

$\Upsilon \in (6,3)_{\frac{1}{3}}$

Color Octet

$\Phi \in (8,2)_{\frac{1}{2}}$

Spin 0

Color Singlets

$S \in (1,1)_0$

$S_1 \in (1,1)_1$

$S_2 \in (1,1)_2$

$\varphi \in (1,2)_{\frac{1}{2}}$

$\Xi_0 \in (1,3)_0$

$\Xi_1 \in (1,3)_1$

$\Theta_1 \in (1,4)_{\frac{1}{2}}$

$\Theta_3 \in (1,4)_{\frac{3}{2}}$

$$\left\{ \begin{array}{ll} \Xi_1^{++} & \Xi_1^{--} \\ \Xi_1^{+} & \Xi_1^{-} \\ \Xi_1^{0} & \Xi_1^{0\,\prime} \end{array} \right.$$

Color Triplets

$\omega_1 \in (3,1)_{-\frac{1}{3}}$

$\omega_2 \in (3,1)_{\frac{2}{3}}$

$(3,1)_{-\frac{4}{3}}$

$(3,2)_{\frac{1}{6}}$

$\Pi_7 \in (3,2)_{\frac{7}{6}}$

$\zeta \in (3,3)_{-\frac{1}{3}}$

Color Sextets

$\Omega_1 \in (6,1)_{\frac{1}{3}}$

$\Omega_2 \in (6,1)_{-\frac{2}{3}}$

$\Omega_4 \in (6,1)_{\frac{4}{3}}$

$\Upsilon \in (6,3)_{\frac{1}{3}}$

Color Octet

$\Phi \in (8,2)_{\frac{1}{2}}$

Spin 1/2

Leptons

$$N \in 1_0 \qquad E \in 1_{-1}$$

$$\begin{pmatrix} N \\ E^- \end{pmatrix} \in 2_{-\frac{1}{2}}$$

$$\begin{pmatrix} E^- \\ E^{--} \end{pmatrix} \in 2_{-\frac{3}{2}}$$

$$\begin{pmatrix} E^+ \\ N \\ E^- \end{pmatrix} \in 3_0$$

$$\begin{pmatrix} N \\ E^- \\ E^{--} \end{pmatrix} \in 3_{-1}$$

Quarks

$$U \in 1_{\frac{2}{3}} \qquad D \in 1_{-\frac{1}{3}}$$

$$\begin{pmatrix} X \\ U \end{pmatrix} \in 2_{\frac{7}{6}} \qquad \begin{pmatrix} D \\ Y \end{pmatrix} \in 2_{-\frac{5}{6}}$$

$$\begin{pmatrix} U \\ D \end{pmatrix} \in 2_{\frac{1}{6}}$$

$$\begin{pmatrix} X \\ U \\ D \end{pmatrix} \in 3_{\frac{2}{3}} \qquad \begin{pmatrix} U \\ D \\ Y \end{pmatrix} \in 3_{-\frac{1}{3}}$$

Spin 1

Color Singlets

$\mathcal{B}_\mu \in (1,1)_0$

$\mathcal{B}^1_\mu \in (1,1)_1$

$\mathcal{W}_\mu \in (1,3)_0$

$\mathcal{W}^1_\mu \in (1,3)_1$

$\mathcal{L}^1_\mu \in (1,2)_{\frac{1}{2}}$

$\mathcal{L}^3_\mu \in (1,2)_{-\frac{3}{2}}$

Color Triplets

$\mathcal{U}^2_\mu \in (3,1)_{\frac{2}{3}}$

$\mathcal{U}^5_\mu \in (3,1)_{\frac{5}{3}}$

$\mathcal{Q}^1_\mu \in (3,2)_{\frac{1}{6}}$

$\mathcal{Q}^5_\mu \in (3,2)_{-\frac{5}{6}}$

$\mathcal{X}_\mu \in (3,3)_{\frac{2}{3}}$

Color Sextets

$\mathcal{Y}^1_\mu \in (\bar{6},2)_{\frac{1}{6}}$

$\mathcal{Y}^5_\mu \in (\bar{6},2)_{-\frac{5}{6}}$

Color Octets

$\mathcal{G}_\mu \in (8,1)_0$

$\mathcal{G}^1_\mu \in (8,1)_1$

$\mathcal{H}_\mu \in (8,8)_0$

Writing the effective Lagrangian

- Write kinetic terms with SU(3)xSU(2)xU(1) - covariant derivatives
- Diagonalize kinetic terms
- Write explicit gauge-inv mass terms and diagonalize them
- Write all gauge-invariant renormalizable interactions with most general couplings
- Calculate and compare with experiment: constraints on masses and couplings + predictions
- Translate results to your favourite model (easy!)

Example: sector with extra scalars

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_\sigma \eta_\sigma \left[(D_\mu \sigma)^\dagger D^\mu \sigma - M_\sigma^2 \sigma^\dagger \sigma \right] - V(\{\sigma\}, \phi) - \sum_\sigma \left(\sigma^\dagger J_\sigma + \text{h.c.} \right) \quad + \ \ldots$$

$$\sim \overline{\psi_L} \otimes \xi_R \qquad \overline{\xi_R} \otimes \psi_L$$

E.g.

$(1,3)_1$

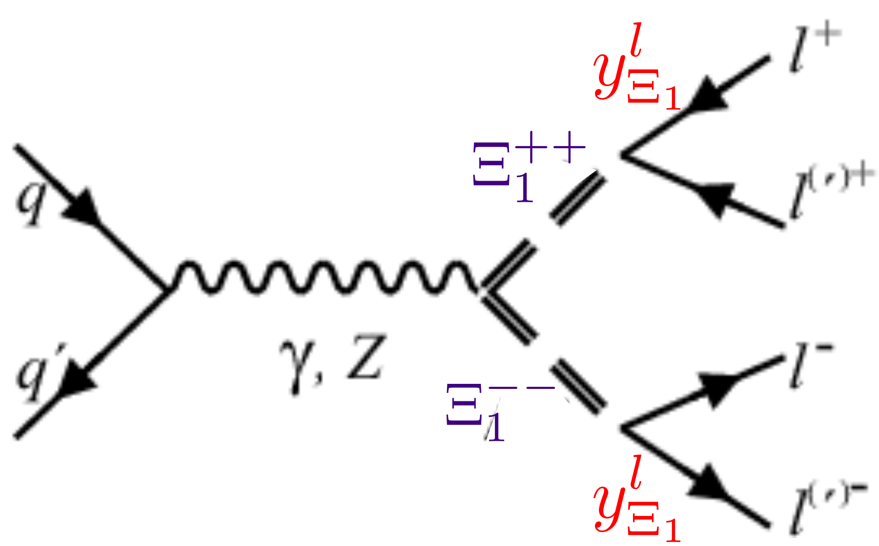
$$\mathcal{L} \supset (y^l_{\Xi_1})_{ij}\, \Xi_1^a \overline{l^i_L} \sigma_a \varepsilon l^{j\,c}_L + \text{h.c.} + \kappa_{\Xi_1} \Xi_1^{a\,\dagger} (\tilde{\phi}^\dagger \sigma_a \phi) + \text{h.c.} + \lambda_{\Xi_1} (\Xi_1^{a\,\dagger} \Xi_1^a)(\phi^\dagger \phi) + \tilde{\lambda}_{\Xi_1} \frac{i}{\sqrt{2}} \epsilon_{abc} (\Xi_1^{a\,\dagger} \Xi_1^b)(\phi^\dagger \sigma_c \phi) + \kappa^{ijk}_{\Xi_0 \Xi_1} \frac{i}{\sqrt{2}} \epsilon_{abc} \Xi^a_{0i} \Xi^{b\,\dagger}_{1j} \Xi^c_{1k}$$

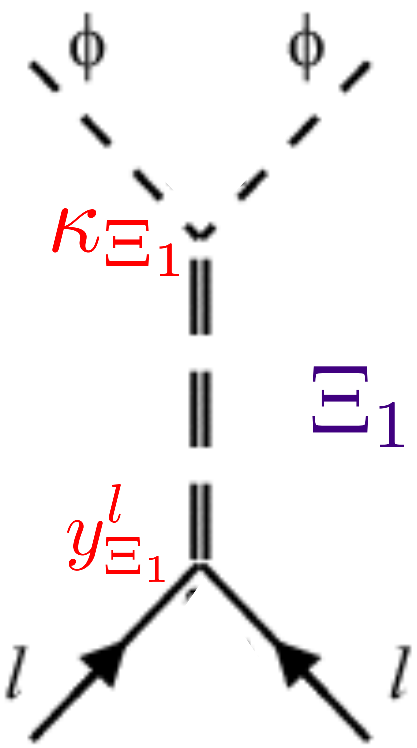
Example: sector with extra scalars

$$
\begin{aligned}
\mathcal{L} = \quad & \mathcal{L}_{\rm SM} \\
& + \sum_\sigma \eta_\sigma \left[(D_\mu \sigma)^\dagger D^\mu \sigma - M_\sigma^2 \sigma^\dagger \sigma \right] \\
& - V(\{\sigma\}, \phi) - \sum_\sigma \left(\sigma^\dagger J_\sigma + \text{h.c.} \right)
\end{aligned}
$$

E.g.

$(1,3)_1$

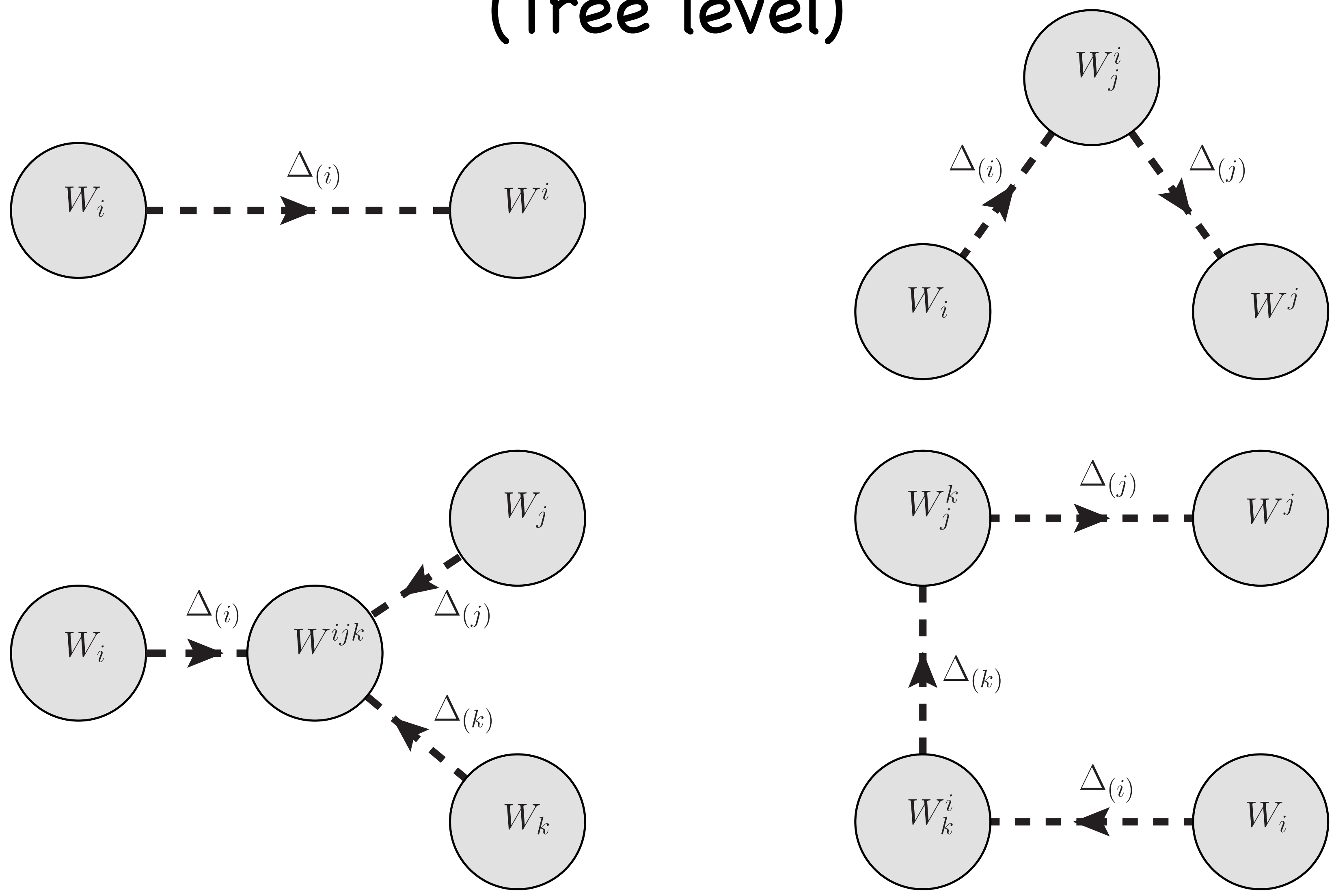




Indirect effects → Match to SMEFT in exact phase

$$\mathcal{L}_{\rm int} = -\sum_{m,n} \sigma^\dagger_{j_1} \cdots \sigma^\dagger_{j_n} W^{j_1 \ldots j_n}_{i_1 \ldots i_m} \sigma^{i_1} \cdots \sigma^{i_m}$$

(Tree level)



$$\Delta_{(i)} = -(D_i^2 + M_i^2)^{-1} = -\frac{1}{M_i^2}\left(1 - \frac{D_i^2}{M_i^2}\right) + \ldots$$

See talk by Juan Carlos Criado

- Integration of heavy fields in symmetric phase
- The new cutoff is the lowest mass of extra particles
- The coefficients of the SM effective theory are functions of the masses and couplings of the multiplets

Complete tree-level dictionary to D=6

General VL quarks → del Aguila, MPV, Santiago, hep-ph/0007316

General VL leptons → del Aguila, de Blas, MPV, 0803.4008

General vectors → del Aguila, de Blas, MPV, 1005.3998

General scalars → de Blas, Chala, MPV, Santiago, 1412.8480

Mixed contributions → de Blas, Chala, Criado, MPV, Santiago, 1706.xxxx

Loops in progress: Anastasiou, Carmona, Lazopoulos, Santiago

Resonant processes

Work in broken EW phase (diagonalise new masses,...)

In practice we can study only a few multiplets simultaneously

Strategies:

- (All multiplets appearing in a class of models)
- All multiplets contributing to process of interest (often, assume separated resonances)
- Simple models: one multiplet at a time
- Analyse, choose another one, repeat

We have a Lagrangian ⟹ can use QFT and do real calculations.

✓ Finite width

✓ Interference with SM amplitude

✓ Interference between amplitudes with new fields

✓ Angular distributions

✓ Radiative corrections

Electroweak multiplets with components of different charge

↓

Correlated contributions to different processes

Example:
Vector-like quarks

- Kinetic terms (couplings to gauge bosons)
- Yukawa interactions

SM-extra

$$\lambda_q \, \phi \, \bar{Q}_R \, q_L$$
$$\lambda_t \, \phi \, \bar{Q}_L \, t_R$$
$$\lambda_b \, \phi \, \bar{Q}_L \, b_R$$

singlets: λ_q
doublets: λ_t or/and λ_b
triplets: λ_q

extra-extra

$$\tilde{\lambda} \, \phi \, \bar{Q}_R \, Q'_L$$

the couplings $\lambda_{q,t,b}$, $\tilde{\lambda}$
are matrices in flavour space

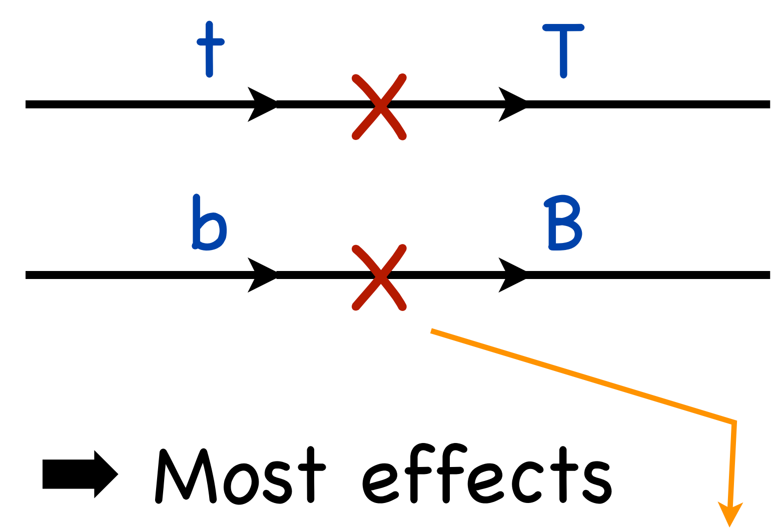
Mixing

Upon EWSB, the Yukawa couplings give rise to non-diagonal mass matrices for u,c,t,T^a and u,c,t,B^a

Diagonalize to go to mass-eigenstate base

Non diagonal interactions with
- Z and W bosons
- Higgs

  - light-light (modified)
  - heavy-heavy (modified/new)
  - light-heavy (new)



➡ Most effects associated with mixing angles

➡ Correlations

Example: doublet $\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$ coupled to third family

(X also called $T^{5/3}$)

2 parameters

M , λ_t

trade for →

Physical parameters:

Heavy mass m_T (or m_X)

Mixing angle $s_R = \sin\theta_R \sim \lambda_t \frac{v}{m_T}$

I'm ignoring a possible phase

heavy-light couplings

$X_L t_L W \rightarrow -s_L$

$X_R t_R W \rightarrow -s_R$

$T_L b_L W \rightarrow s_L$

$T_L t_L Z \rightarrow 2 s_L c_L$

$T_R t_R Z \rightarrow -s_R c_R$

$T_L t_R H \rightarrow s_R c_R$

$T_R t_L H \rightarrow \frac{m_t}{m_T} s_R c_R$

light-light couplings

$t_L b_L W \rightarrow c_L$

$t_L t_L Z \rightarrow c_L^2 - s_L^2$

$t_R t_R Z \rightarrow -s_R^2$

$ttH \rightarrow c_R^2$

s_L further suppressed and not independent:

$$\tan\theta_L = \frac{m_t}{m_T}\tan\theta_R$$

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$X_L t_L W \to -s_L$

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Correlations

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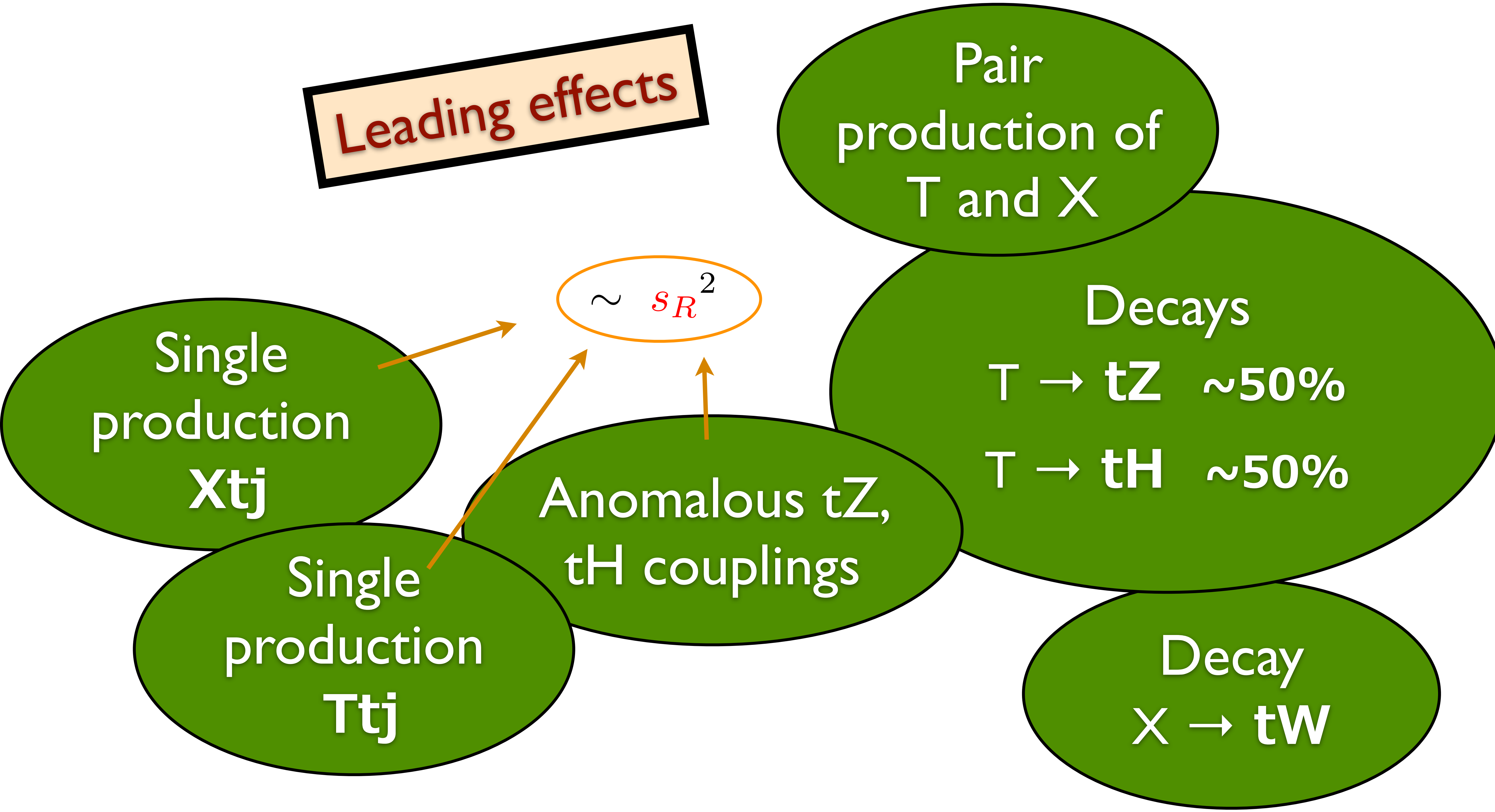
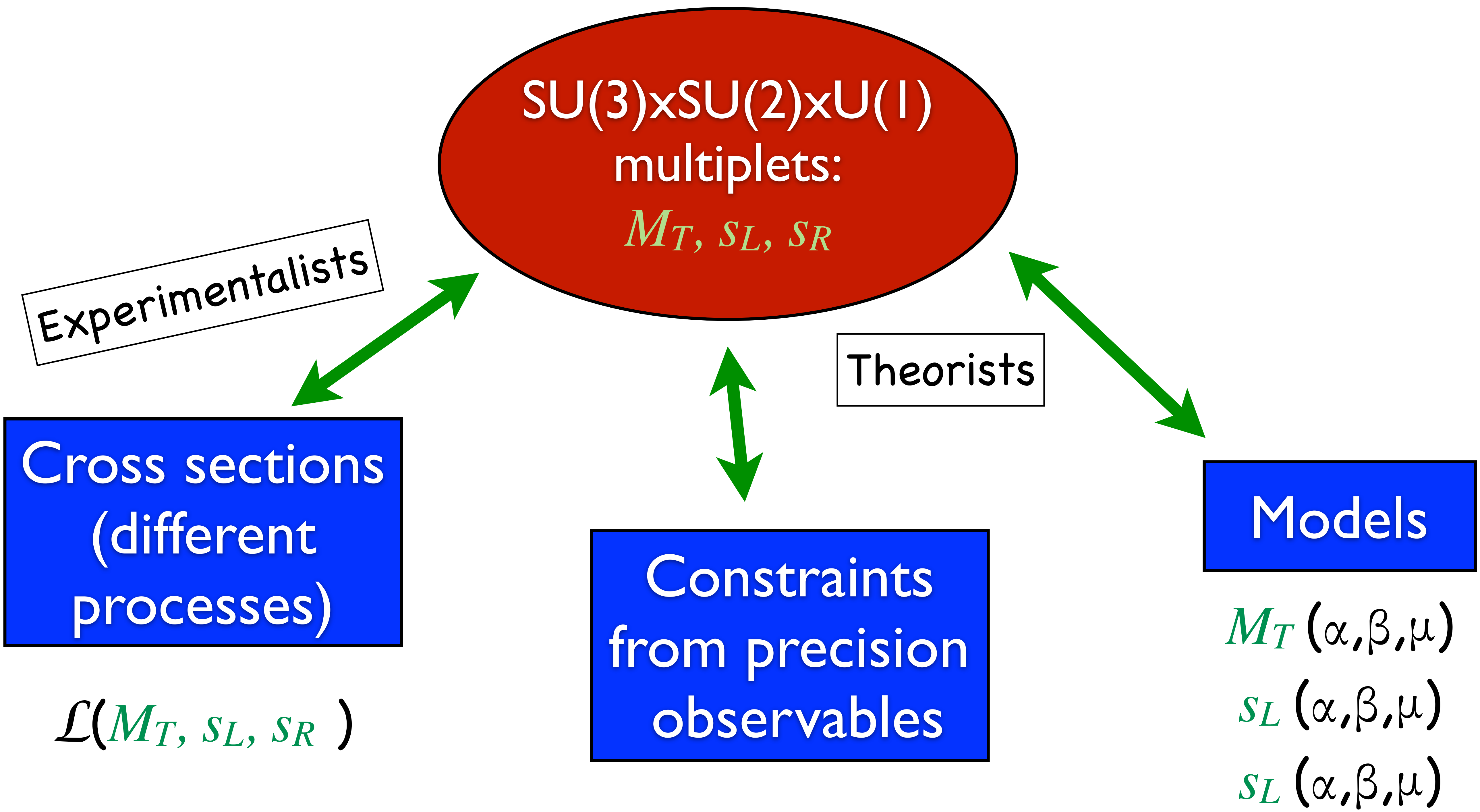


Summarising



Summarising

Advantages of the gauge-invariant framework:

- Full description (resonant production, interference)
- Correlations: can compare/combine final states
- Convenient for model discrimination
- Can take EWPT into account
- Straightforward comparison with models

(Other model-independent approaches fail in some of these points)

Final remarks

- Weak coupling of new particles to SM needed for predictivity
- But new particles can belong to strongly-coupled sector
- Extended Higgs sectors can be accommodated
- We need separation of scales (large enough Λ)
- Can incorporate higher-dimensional ops
- Difficult to remove the linear-coupling restriction without loosing generality

Backup

Example: SM + one scalar iso-triplet $(1,3)_1$

$$\mathcal{L}_{\text{eff}} \supset -2\frac{\kappa_{\Xi_1}(y^{l\,\dagger}_{\Xi_1})_{ij}}{M^2_{\Xi_1}}\ \overline{l^{i\,c}_L}\tilde{\phi}^*\tilde{\phi}^\dagger l^j_L$$

$$+\frac{(y^l_{\Xi_1})_{ki}(y^l_{\Xi_1})_{jl}}{M^2_{\Xi_1}}\ (\overline{l^i_L}\gamma_\mu l^j_L)(l^k_L\gamma^\mu l^l_L) \quad +2\frac{|\kappa_{\Xi_1}|^2 y^e_{ii}}{M^4_{\Xi_1}}\ (\phi^\dagger\phi)(\overline{l^i_L}\phi e^i_R)$$

$$+2\frac{|\kappa_{\Xi_1}|^2 y^d_{ii}}{M^4_{\Xi_1}}\ (\phi^\dagger\phi)(\overline{q^i_L}\phi d^i_R)\ +2\frac{|\kappa_{\Xi_1}|^2 V^\dagger_{ij} y^u_{jj}}{M^4_{\Xi_1}}\ (\phi^\dagger\phi)(\overline{q^i_L}\tilde{\phi} u^i_R)$$

$$+4\frac{|\kappa_{\Xi_1}|^2}{M^4_{\Xi_1}}\ (\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)\ +2\frac{|\kappa_{\Xi_1}|^2}{M^4_{\Xi_1}}\ (\phi^\dagger\phi)\Box(\phi^\dagger\phi)$$

$$-\frac{|\kappa_{\Xi_1}|^2}{M^4_{\Xi_1}}(2\lambda_{\Xi_1}-\sqrt{2}\tilde{\lambda}_{\Xi_1}-4\lambda_\phi)\ (\phi^\dagger\phi)^3$$

Example: SM + one scalar iso-triplet $(1,3)_1$

$$\mathcal{L}_{\rm eff} \supset -2\frac{\kappa_{\Xi_1}(y^{l\,\dagger}_{\Xi_1})_{ij}}{M^2} \overline{l^{i\,c}_L}\tilde{\phi}^*\tilde{\phi}^\dagger l^j_L$$

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$$-\frac{|\kappa_{\Xi_1}|^2}{M^4_{\Xi_1}}(2\lambda_{\Xi_1} - \sqrt{2}\tilde{\lambda}_{\Xi_1} - 4\lambda_\phi)(\phi^\dagger\phi)^3$$

ν mass

LEP2, Møller

Higgs-fermions

Higgs w.f.

T parameter

Higgs selfcoupling.

Bounds from

- $\not{B}$ & $\not{L}$

- Flavor physics (hadronic & leptonic)

- EWPD: Z-pole, low-energy, W mass & width, t and H mass, $\Delta\alpha_{\rm had}^{(5)}$, α_s , LEP2, CKM unitarity

- LHC non-resonant searches

- Higgs observables

- Neutrino physics

Consequences of generic mixing of general VLQ

Branco, Lavoura '86; Langacker, London '88; del Aguila, MPV, Santiago '00;
Choudhury, Tait, Wagner '01; Aguilar-Saavedra '02; Cacciapaglia et al. '12

- ✓ Mass splittings
- ✓ Light-heavy interactions ⇒ single production & decay
- ✓ Modified form of LH and RH neutral currents
- ✓ Including FCNC at tree level!
- ✓ Non-unitary CKM matrix
- ✓ RH charged currents
- ✓ New CP violating phases
- ✓ Higgs physics, oblique corrections, ...

Interesting effects, but strong constraints from flavour physics.

$t \to cZ$, ...

⇓

Usually, mixing with only one SM family

Phenomenology: simple models

Aguilar-Saavedra, Benbrik, Heinemeyer, MPV, 1306.0572

- Consider one multiplet at a time
  - ✓ Robust for direct searches (unless degenerate VLQ with same charge)
  - ✓ Care with indirect searches
- Mixing with 3rd generation only
  - ✓ Avoid flavour problems
  - ✓ Motivated by CKM, EWSB, hierarchy and (partial) top/bottom compositeness

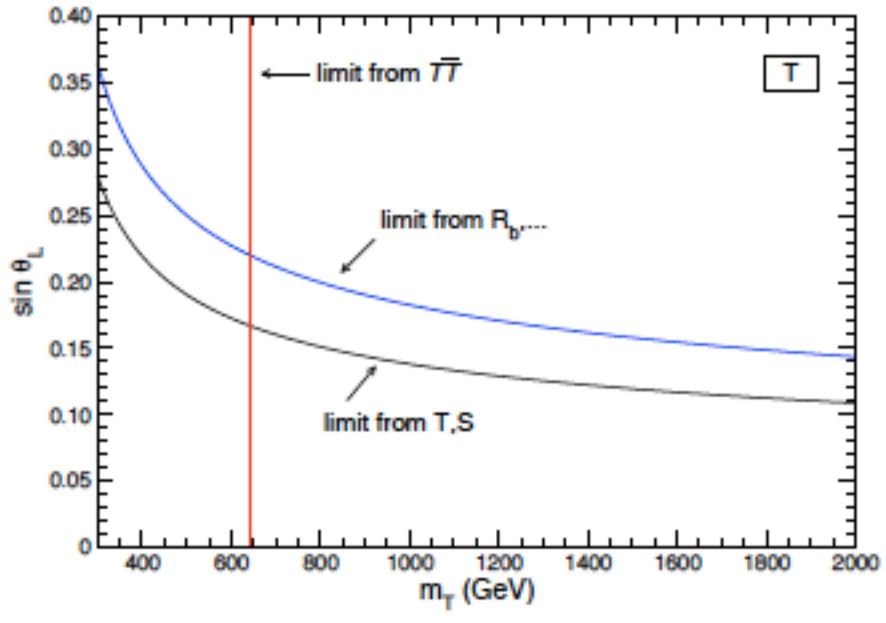
Indirect effects and constraints (coupling to third family)

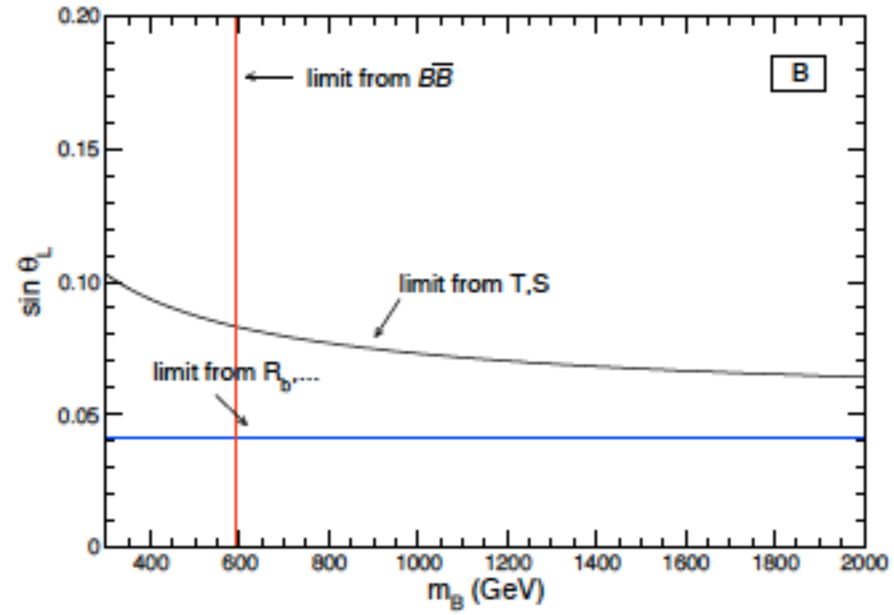
Modified t & b couplings

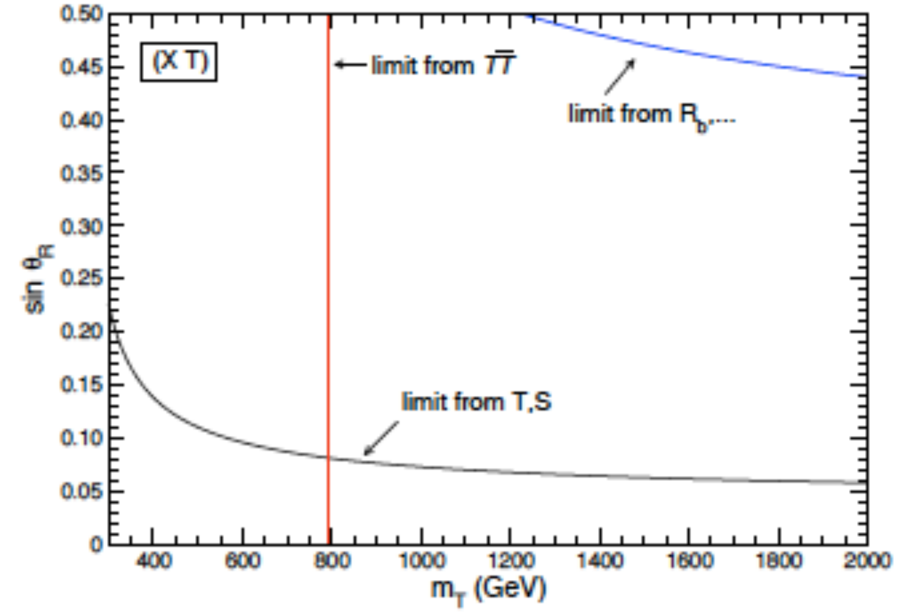
del Aguila, MPV, Santiago '00

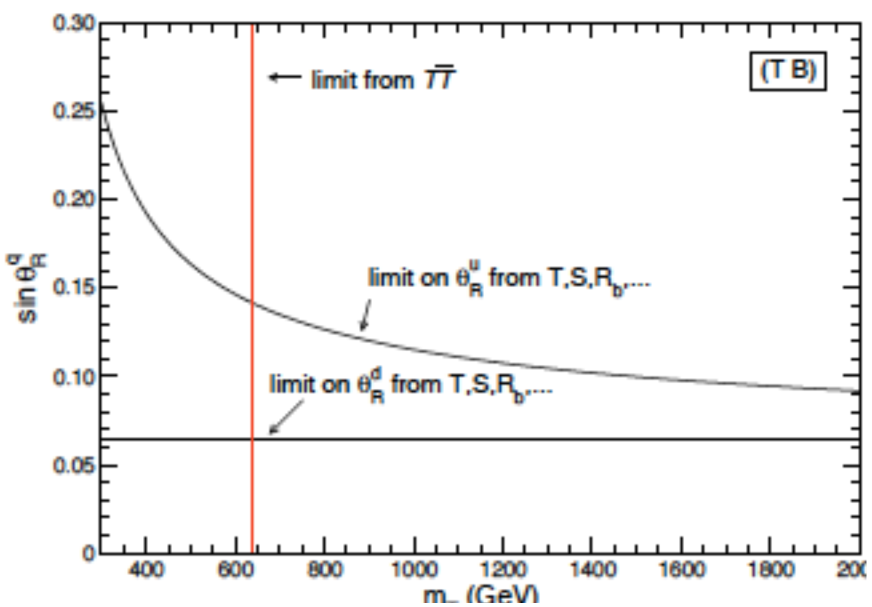
	# par	δW_{tb}^L	δW_{tb}^R	δX_t^L	δX_b^L	δX_t^R	δX_b^R	δY_t	δY_b
T	1	↓	—	↓	—	—	—	↓	—
B	1	↓	—	—	↓	—	—	—	↓
$\begin{pmatrix} T \\ B \end{pmatrix}$	2	—	↑	—	—	↑	↑	↓	↓
$\begin{pmatrix} X \\ T \end{pmatrix}$	1	—	—	—	—	↑	—	↓	—
$\begin{pmatrix} B \\ Y \end{pmatrix}$	1	—	—	—	—	—	↑	—	↓
$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	1	↑	—	↓	↑	—	—	↓	↓
$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$	1	↑	—	↑	↓	—	—	↓	↓

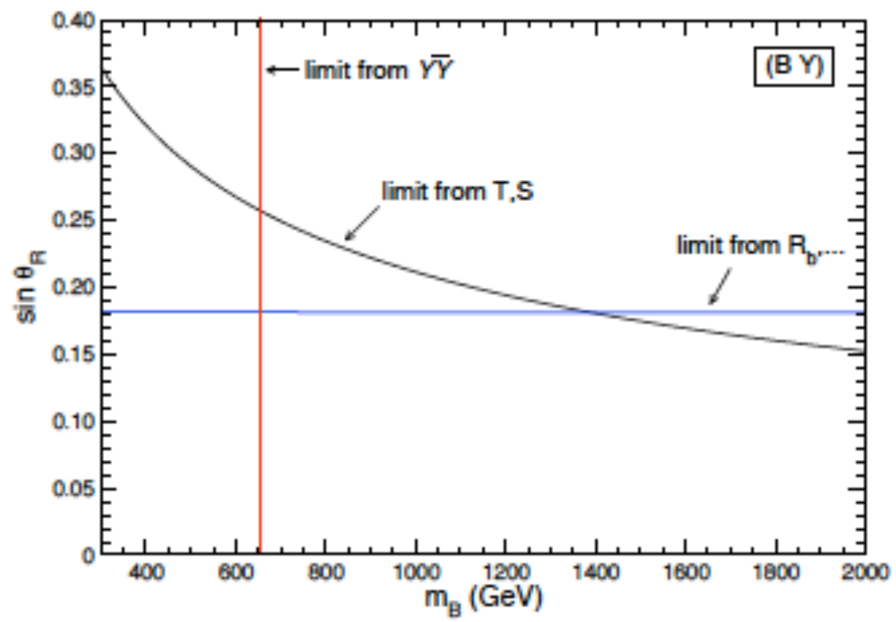
Electroweak precision limits

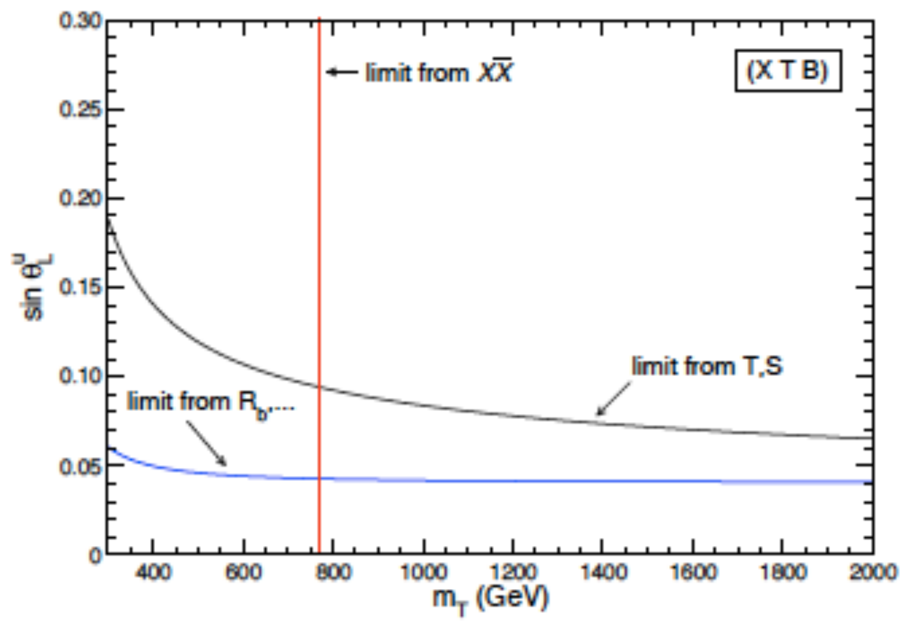


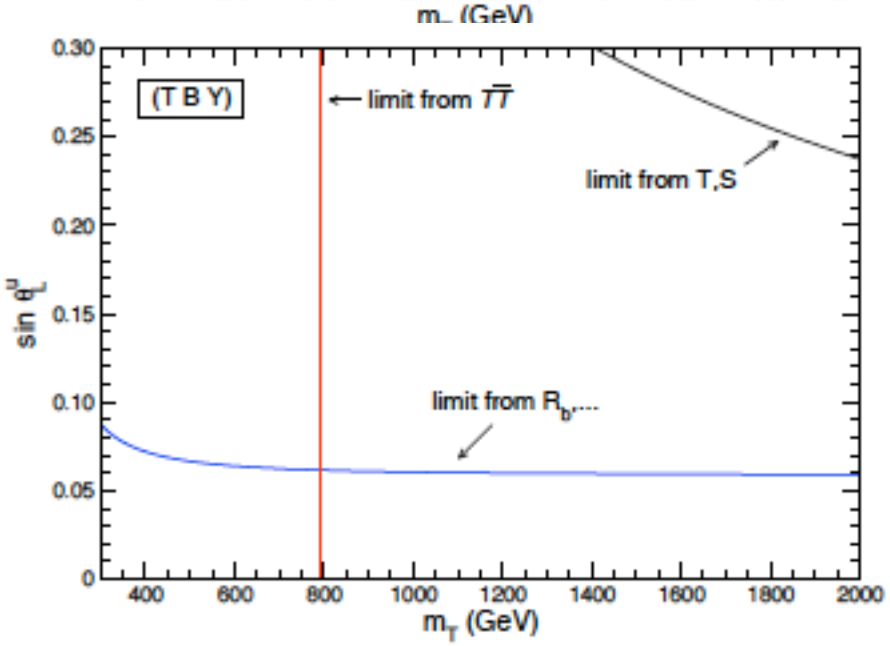












$$S,\ T$$

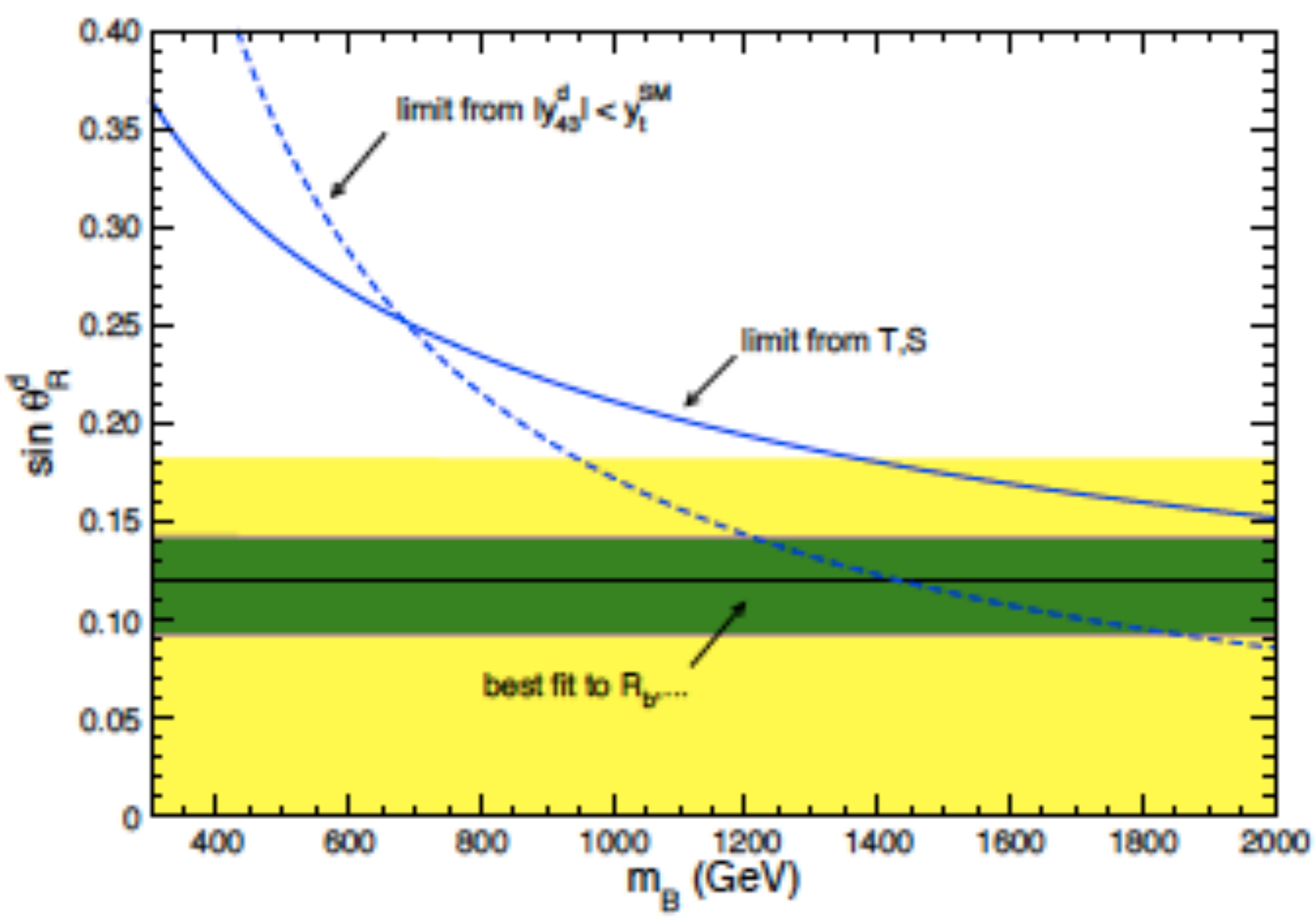
$$R_b,\ A_{FB}^b,\ A_b,\ R_c$$

Direct limits not updated

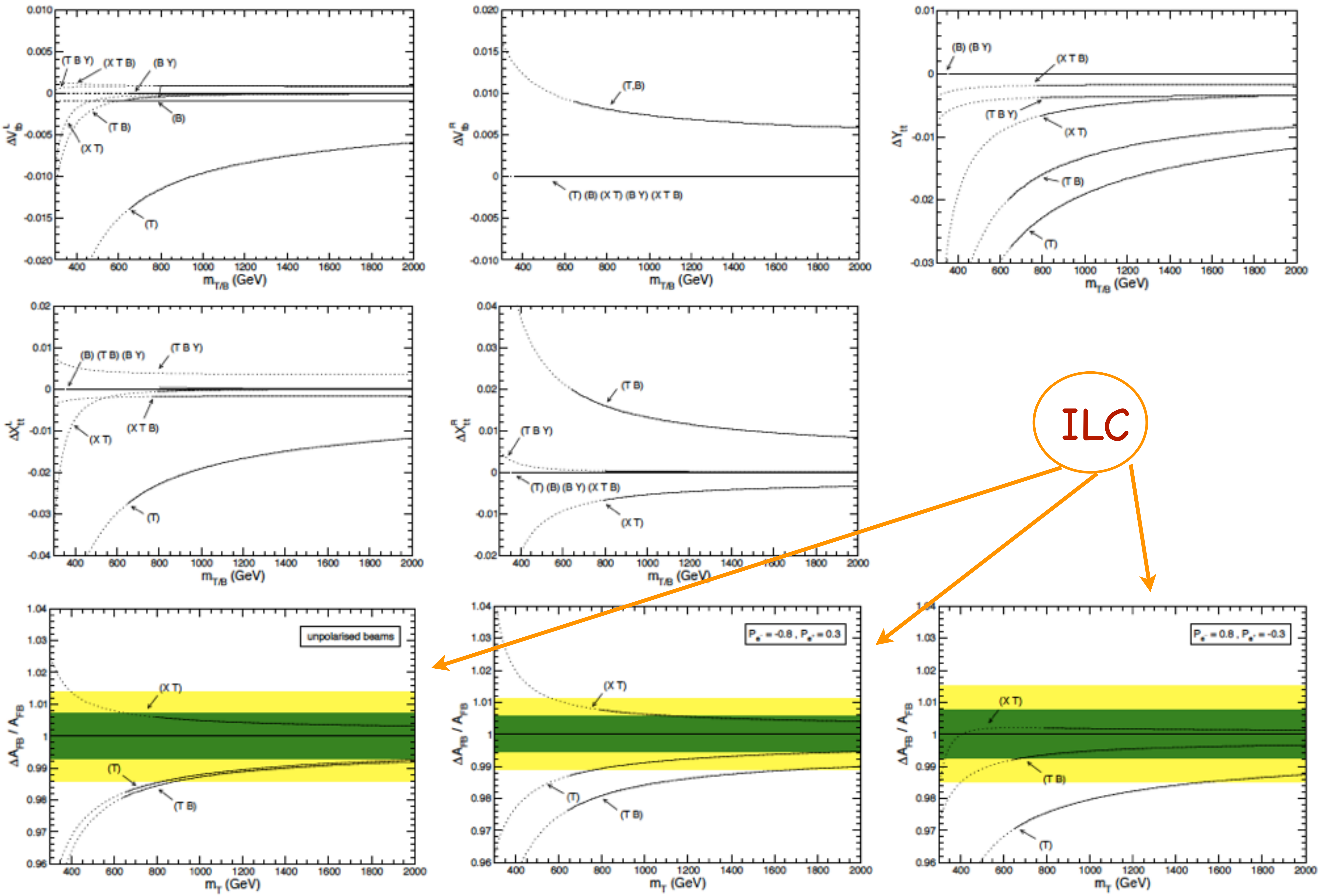
Electroweak precision limits

Improved fit for doublet $\begin{pmatrix} B \\ Y \end{pmatrix}$

(Beautiful mirrors, Choudhury, Tait, Wagner '01)



Anomalous top couplings



Higgs physics

$gg \to H, \quad H \to gg, \quad H \to \gamma\,\gamma$

- Cancellation in charge +2/3 sector between
  - T loop
  - t loop with modified top couplings

- Contribution of B loop proportional to mixing square

$H \to bb$

- Reduced width, enhanced BR into other final states

All together, ~ 10% effects at most when limits above apply

- Larger effects possible in presence of several multiplets with $\tilde{\lambda}$ couplings

Direct searches

Pair Production at LHC

Dominated by QCD (depends only on mass)

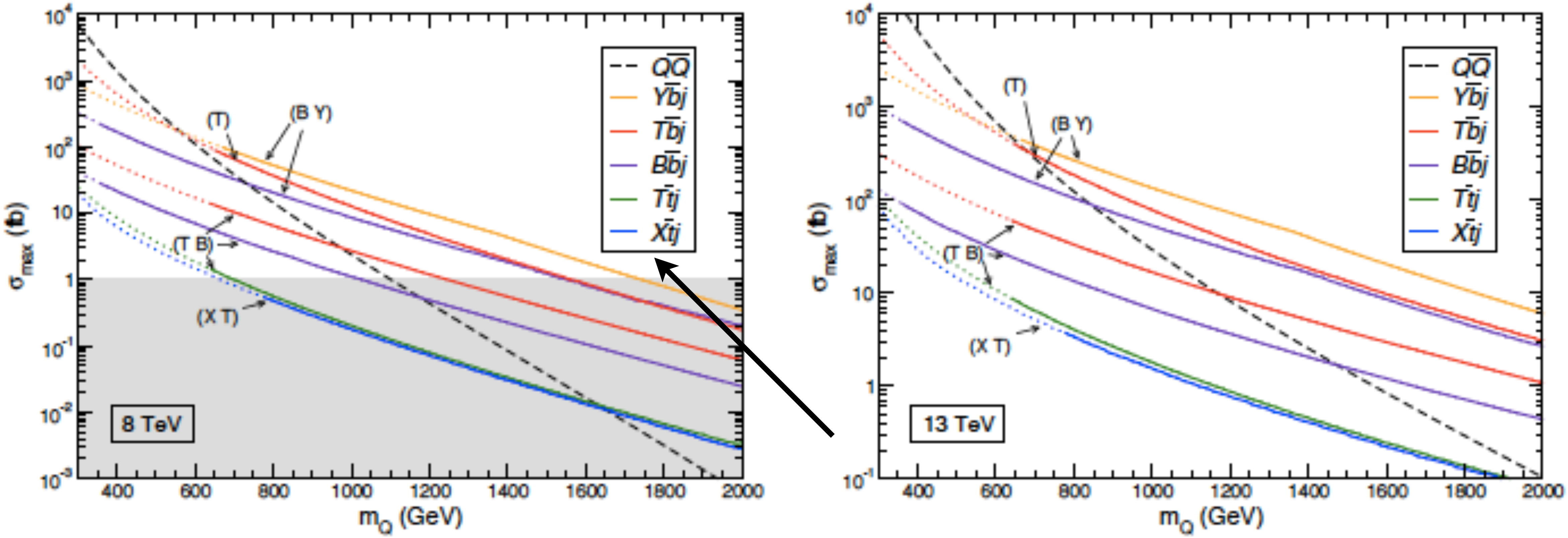
Very complete analysis of pair production for singlets and doublets in Aguilar-Saavedra '09

Single Production at LHC

Direct limits not updated

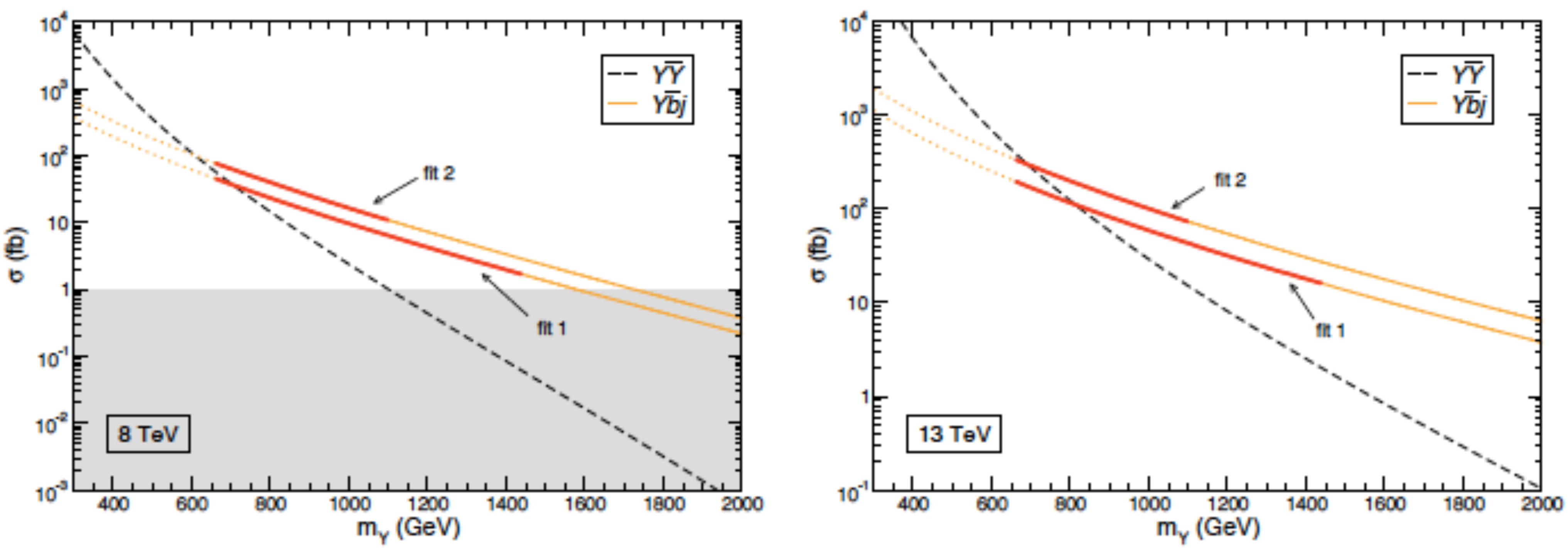
QCD-electroweak processes, similar to top single production

(proportional to mixing squared)



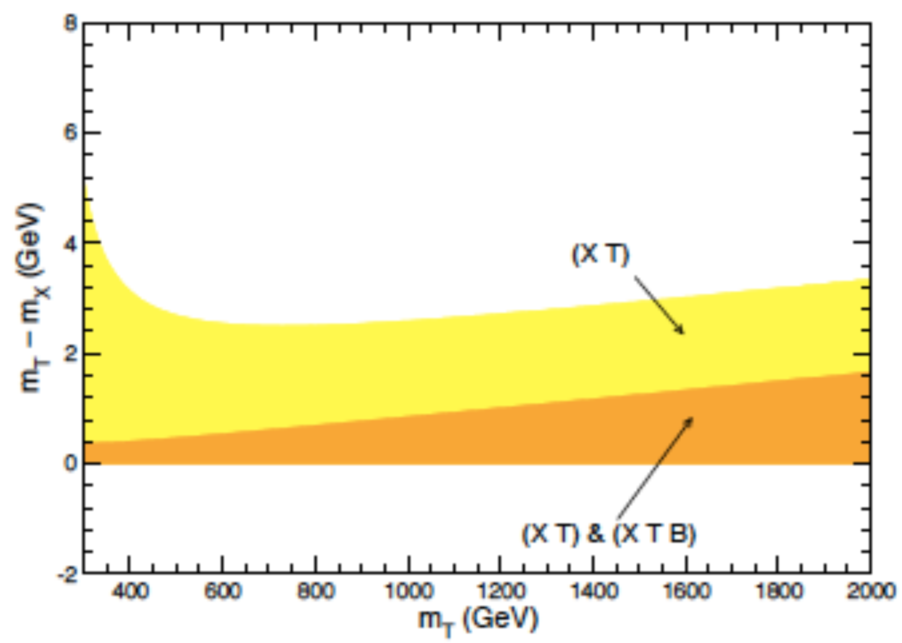
$\begin{pmatrix} B \\ Y \end{pmatrix}$:

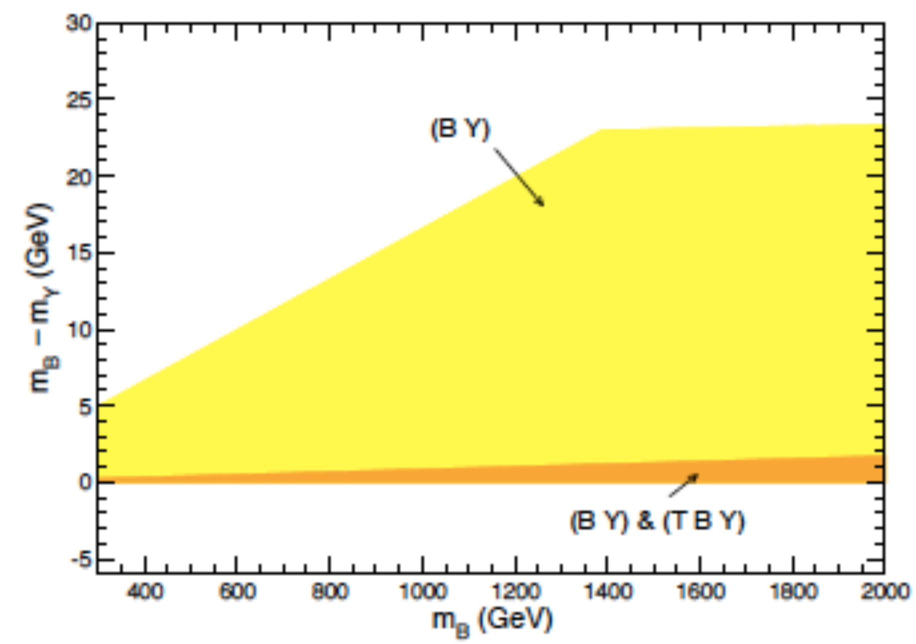
Single production for best-fit (1) mixing

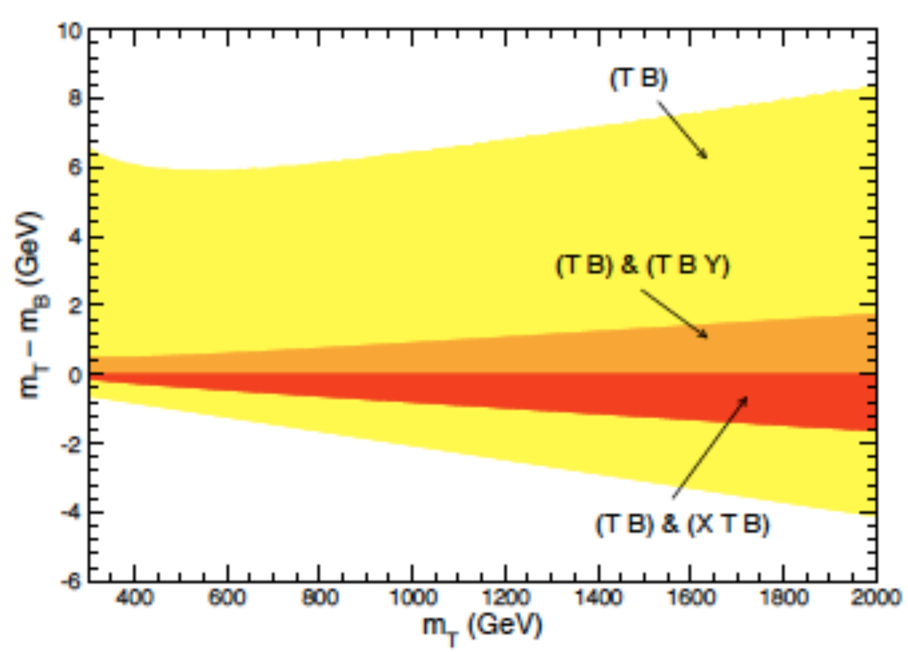


Mass splittings

(determined by M and mixings)







Very suppressed decays into heavy partners

Decays

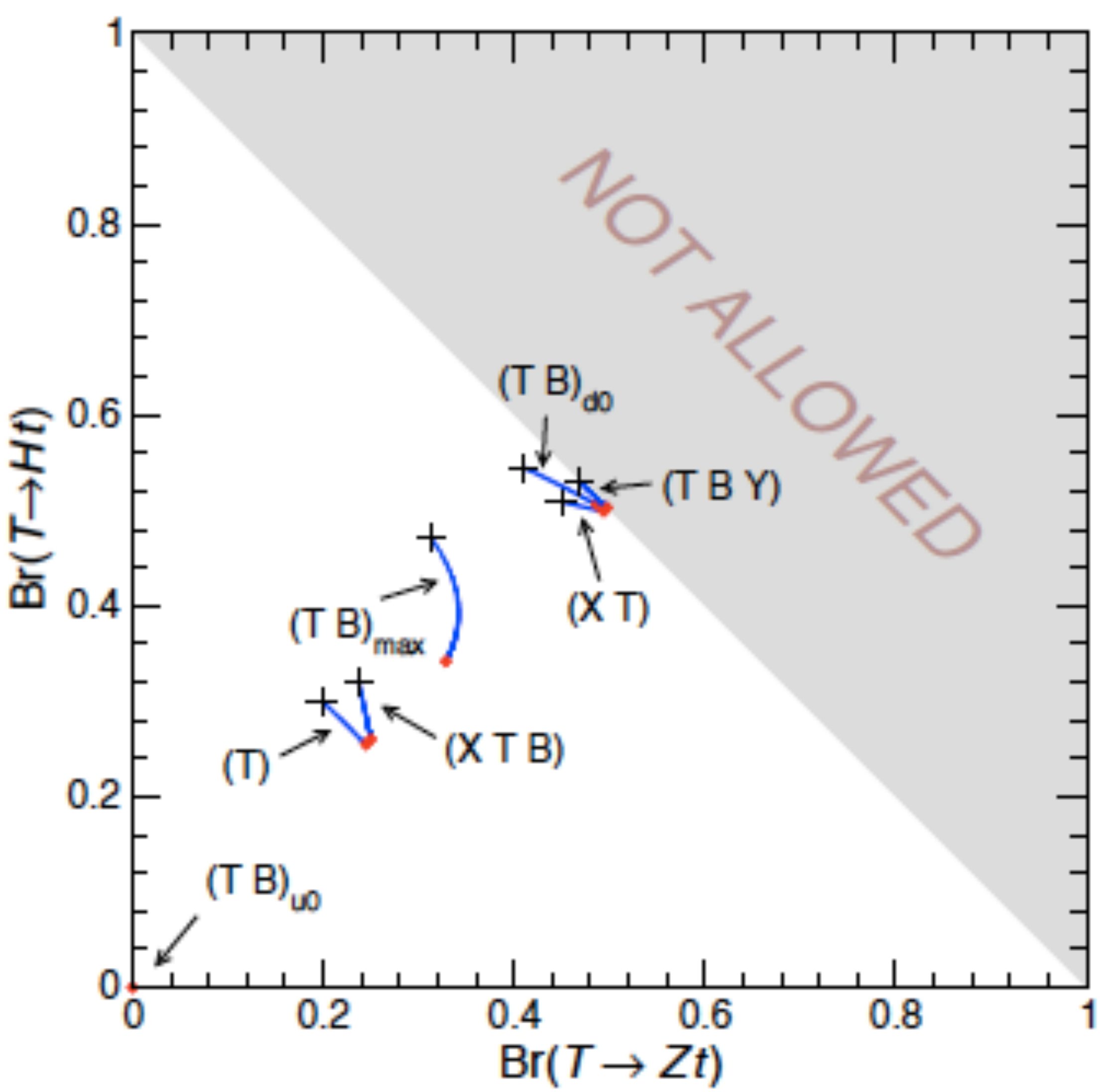
Charge +5/3: X → W t

Charge −4/3: Y → W b

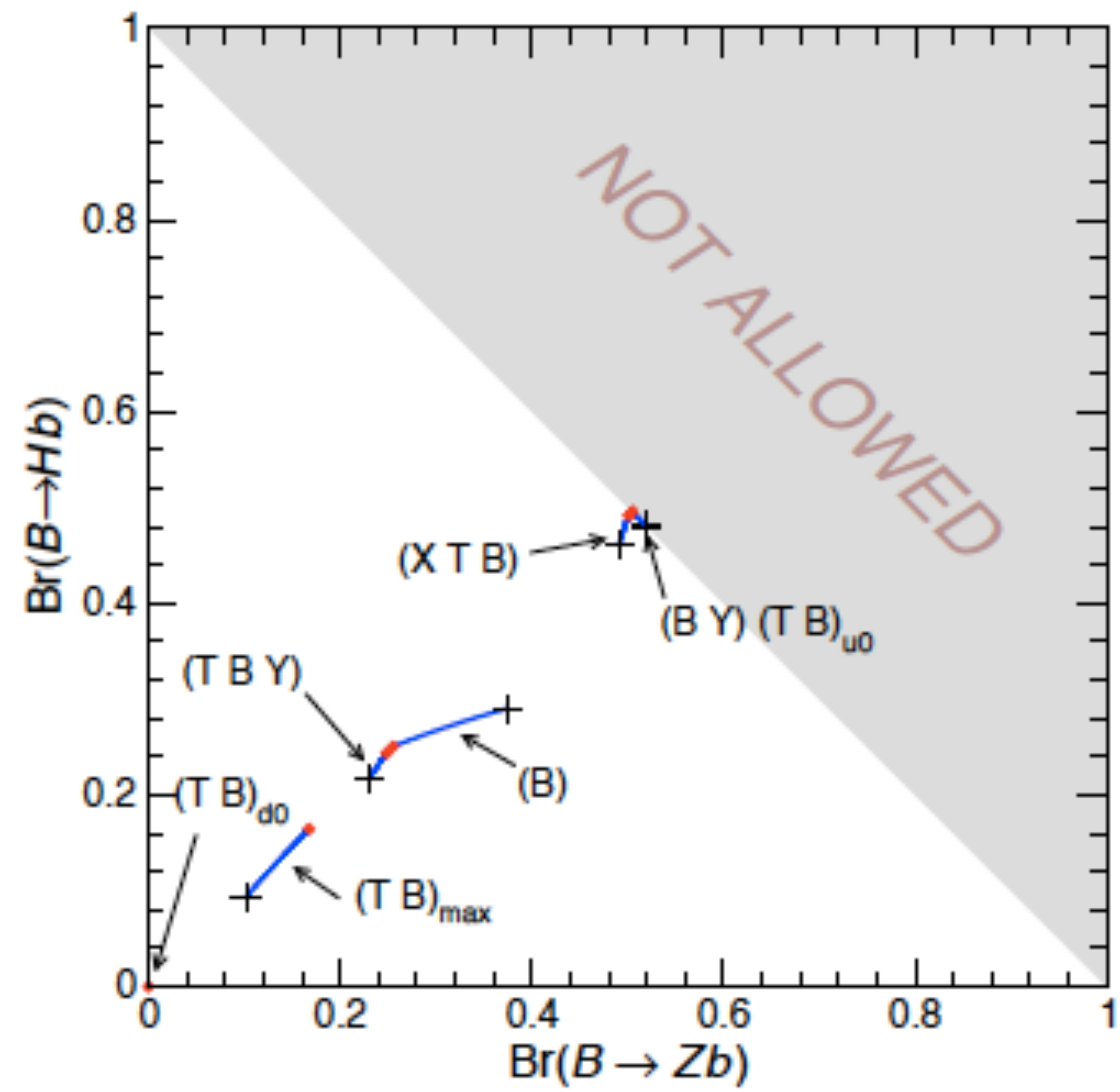
Charge +2/3: T → Wb, Zt, Ht

Charge −1/3: B → Wt, Zb, Hb

$$BR(T \to Wb) + BR(T \to Zt) + BR(T \to Ht) = 1$$

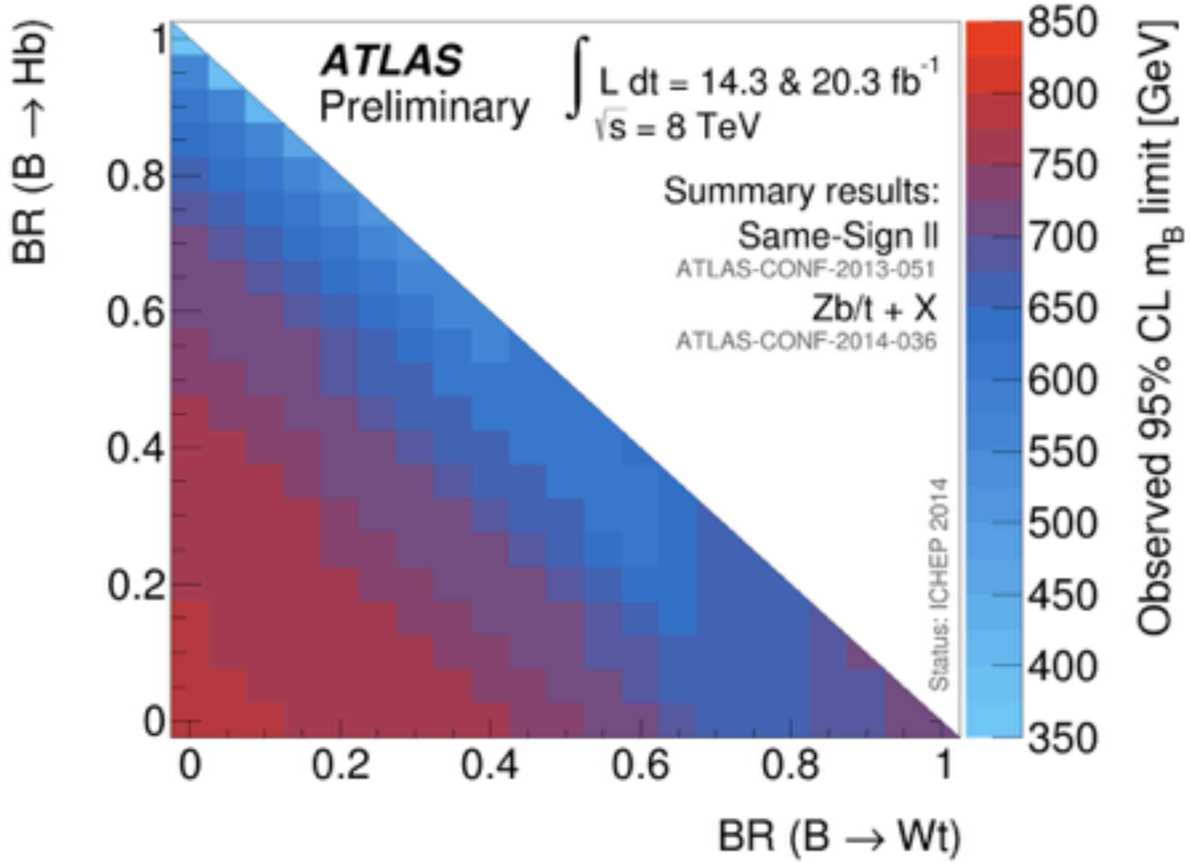


$$BR(B \to Wt) + BR(B \to Zb) + BR(B \to Hb) = 1$$



Decays

Old analysis



Charge -1/3: B → Wt, Zb, Hb