Introduction to the "Beyond the Standard Model" session

JRJC 2015

Nov. 19th 2015

Samuel Calvet

Outline

- Why do we need “Beyond the Standard Model” (BSM) theories ?

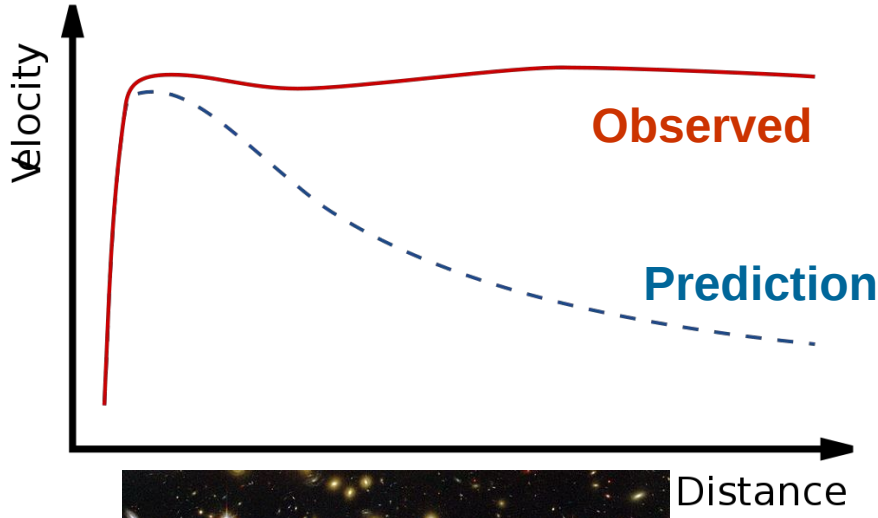
- BSM theories on the market : their predictions/particles
  - SuperSYmetry, Extra-dimensions, compositness, ...

Why do we need BSM theories ?

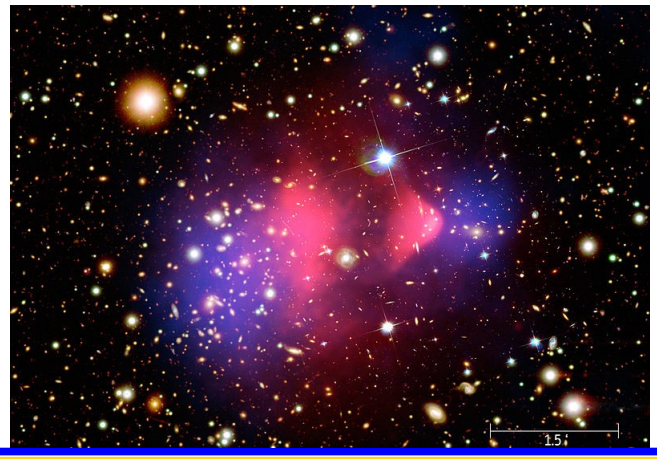
2 reasons (among others) that drive searches at LHC ?

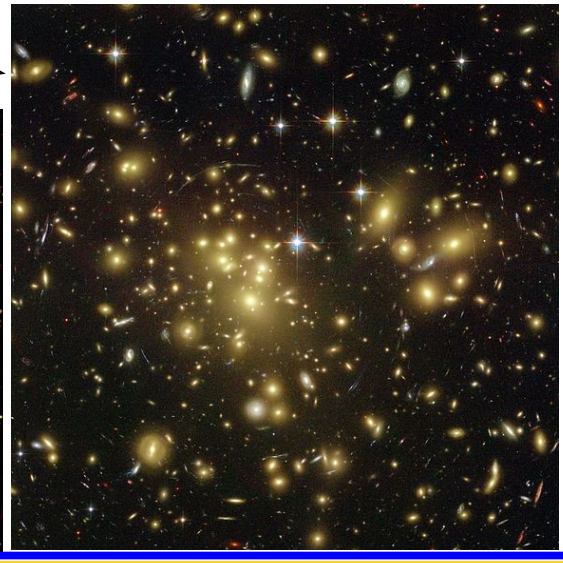
Dark matter

- Astrophysical observations in contradiction w/ the theories
  - Rotation of galaxies needs “extra mass”
  - Cluster of galaxies:
    - Same velocity issue
    - Gravitational lensing
    - Bullet cluster
    - ….



Cf Talk by Antje





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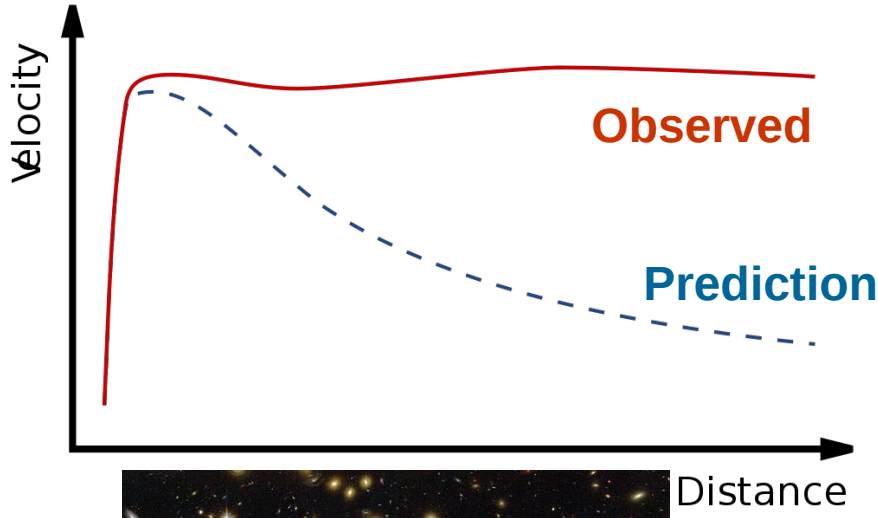
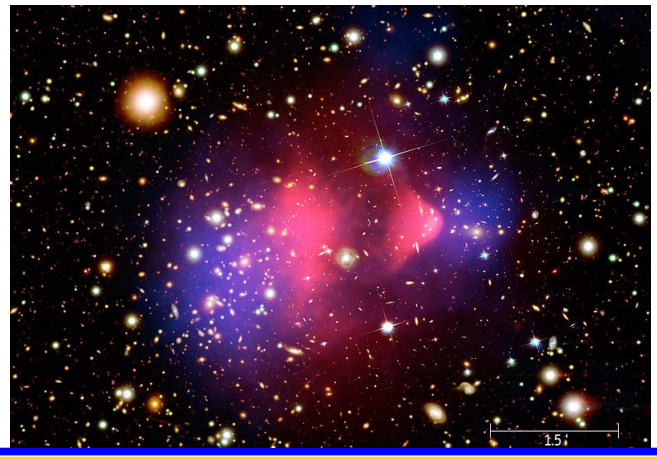
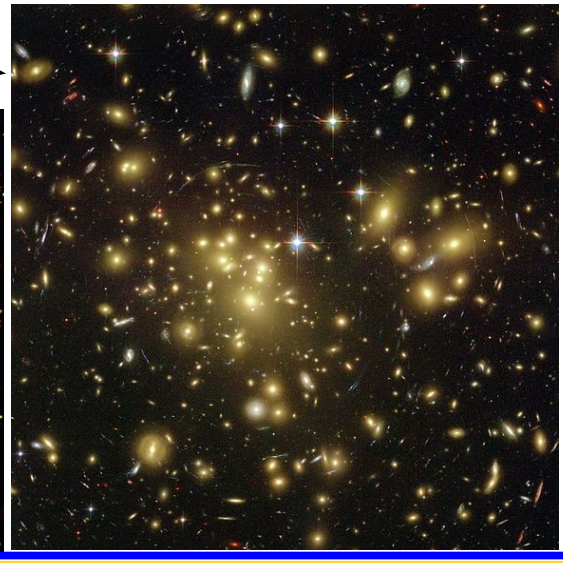






Cf Talk by Antje

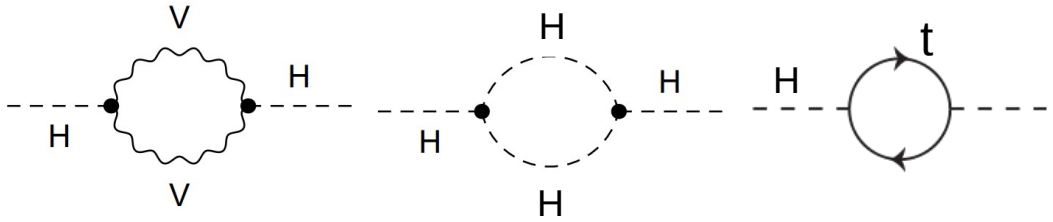
→ Need of neutral particles weakly interacting (dark matter)

Naturalness

- Higgs mass modified by quantum corrections

$$m^2_{h_{\mathrm{SM}}} = m_0^2 + \frac{3}{16\pi^2 v^2_{SM}}(2m_W^2 + m_Z^2 + m^2_{h_{\mathrm{SM}}} - 4m_t^2)\Lambda^2$$

Λ: scale of new physic



- If:
  - **Λ is large** (up to Planck scale to include the gravity ?)
  - No ultra precise cancellation of terms (→ fine tuning)

→ Large m_h

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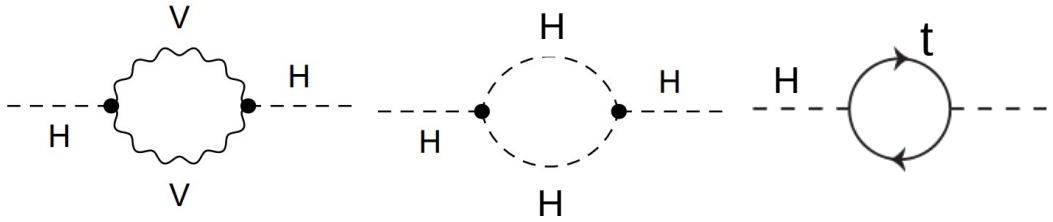

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- Observation : m_h~125GeV → light !

Not natural !

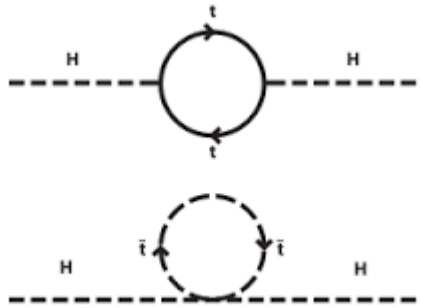
Solving naturalness issue

- Main ideas to solve the naturalness issue:

  - No ultra precise cancellation of terms (→ fine tuning)
  - Λ can be large (up to Planck scale to include the gravity ?)

- New symmetry
  - Each correction balanced by another (new) one
  - Protects m_H

    → supersymmetry



Solving naturalness issue

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  - No ultra precise cancellation of terms (→ fine tuning)
  - Λ can be large (up to Planck scale to include the gravity ?)

  - New symmetry

  - New spatial dimensions
    - Bring the Planck scale to lower value

      → Λ is small

Solving naturalness issue

- Main ideas to solve the naturalness issue:

  - No ultra precise cancellation of terms (→ fine tuning)
  - Λ can be large (up to Planck scale to include the gravity ?)

  - New symmetry
  - New spatial dimensions
  - Higgs boson is not the SM one
    - Higgs is a composite particle at scale Λ

      → naturalness issue disappears

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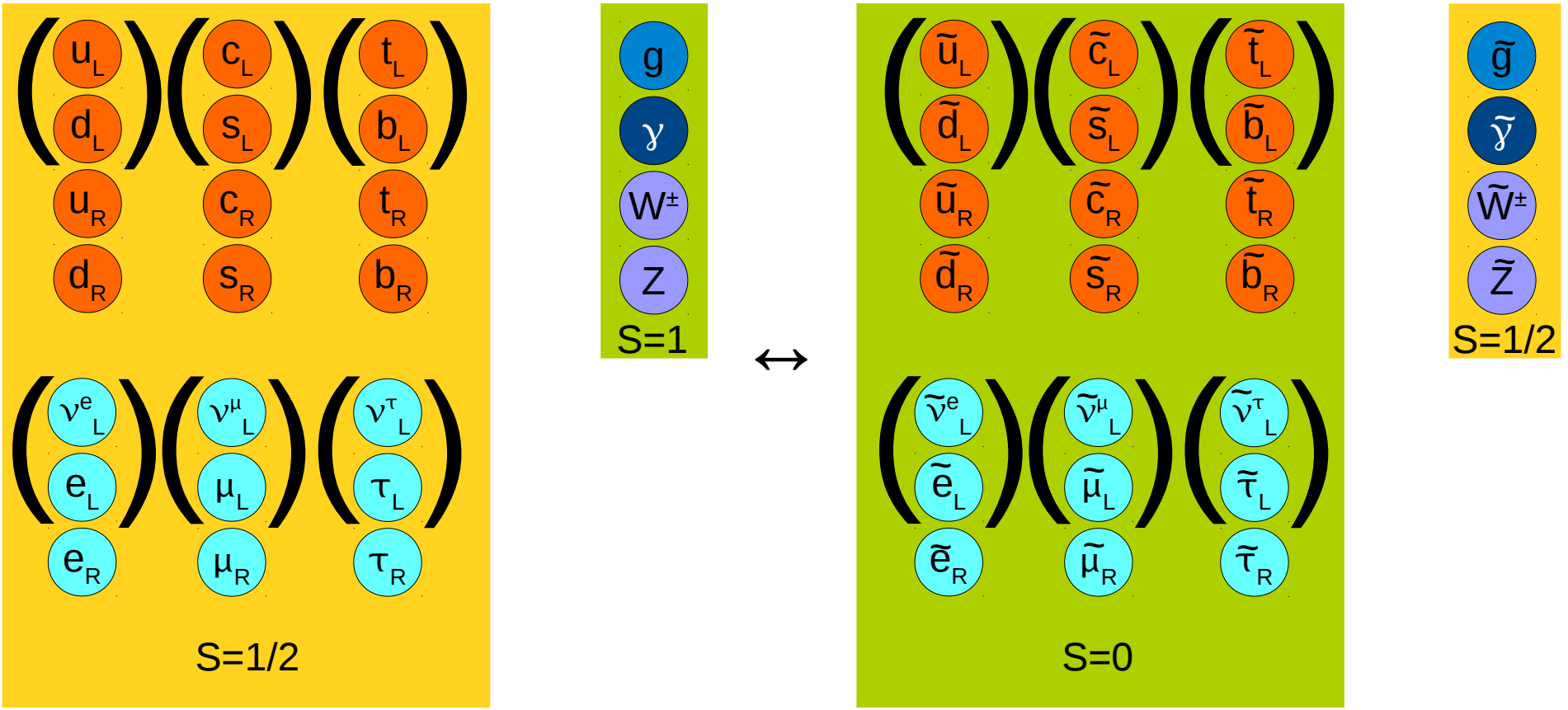
  } Have to appear at the TeV scale to be efficient

Supersymmetry

Supersymmetry

- Add new symmetry: fermion ↔ boson



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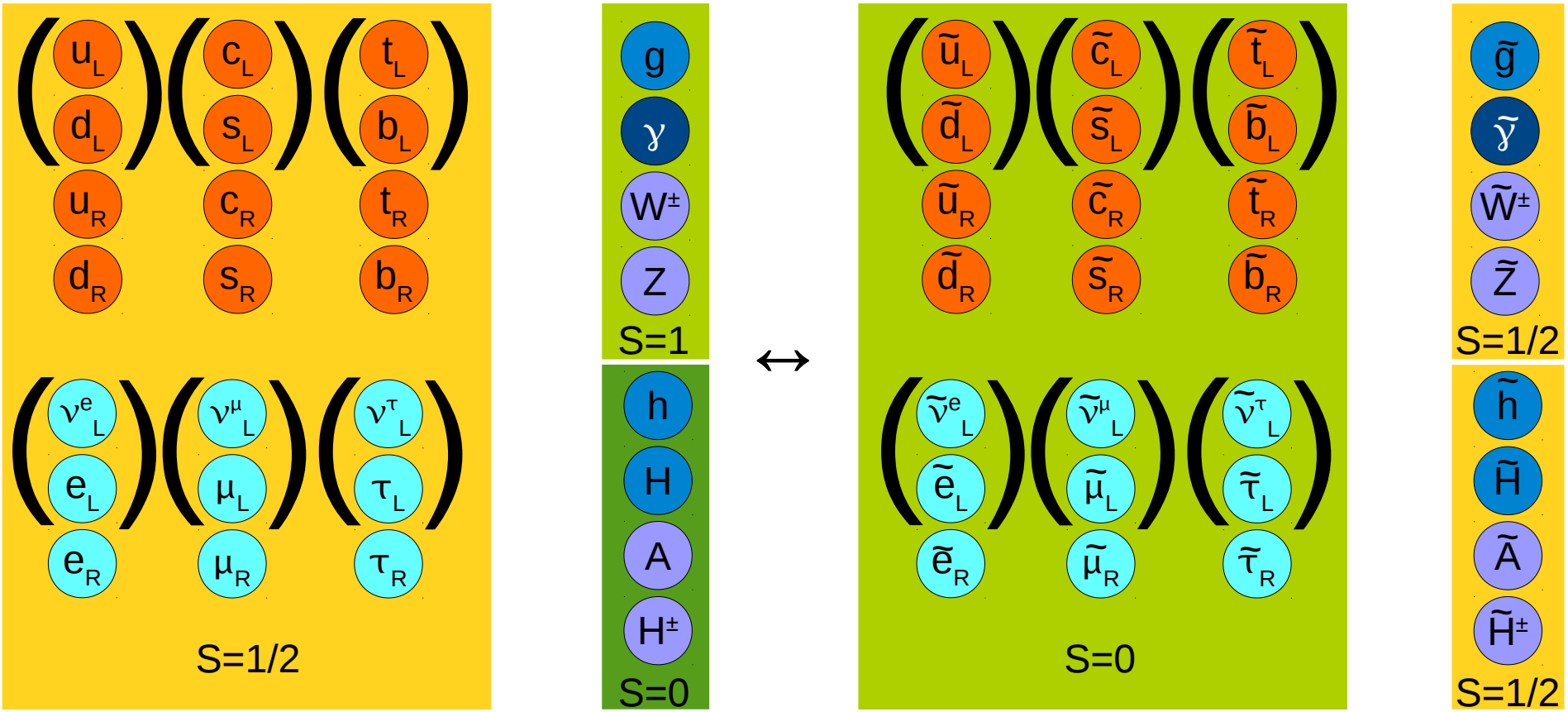
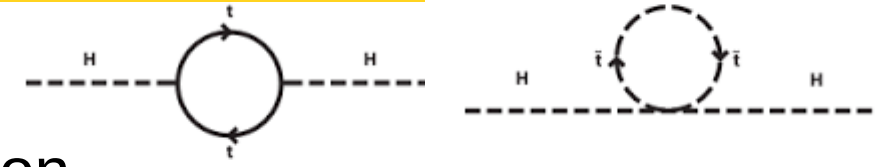


Extended Higgs sector

Supersymmetry



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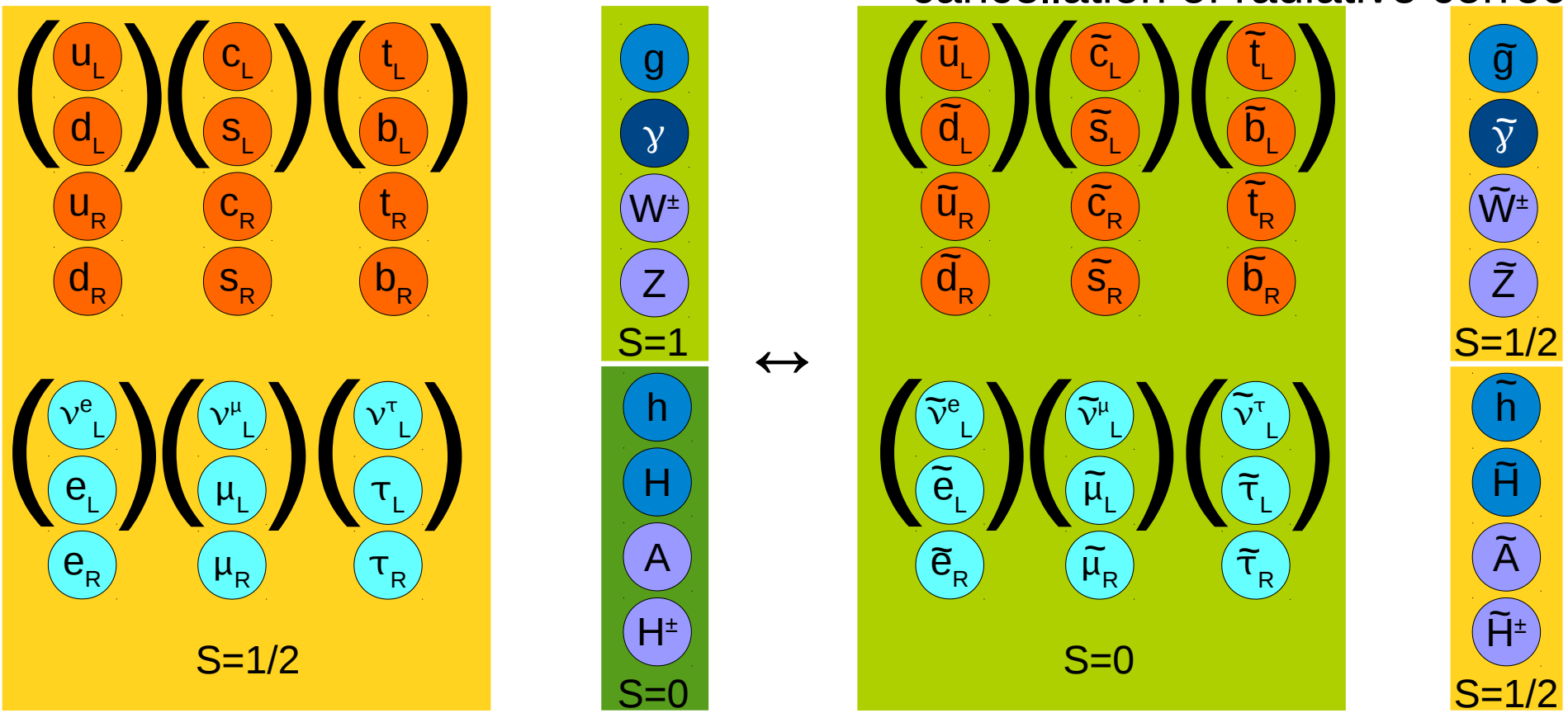
  → cancellation of radiative corrections



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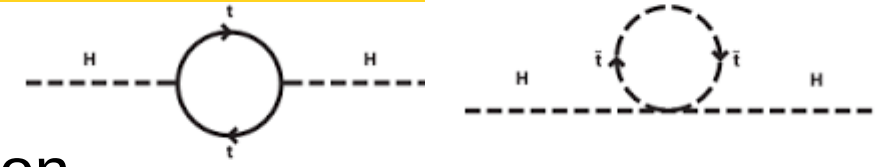

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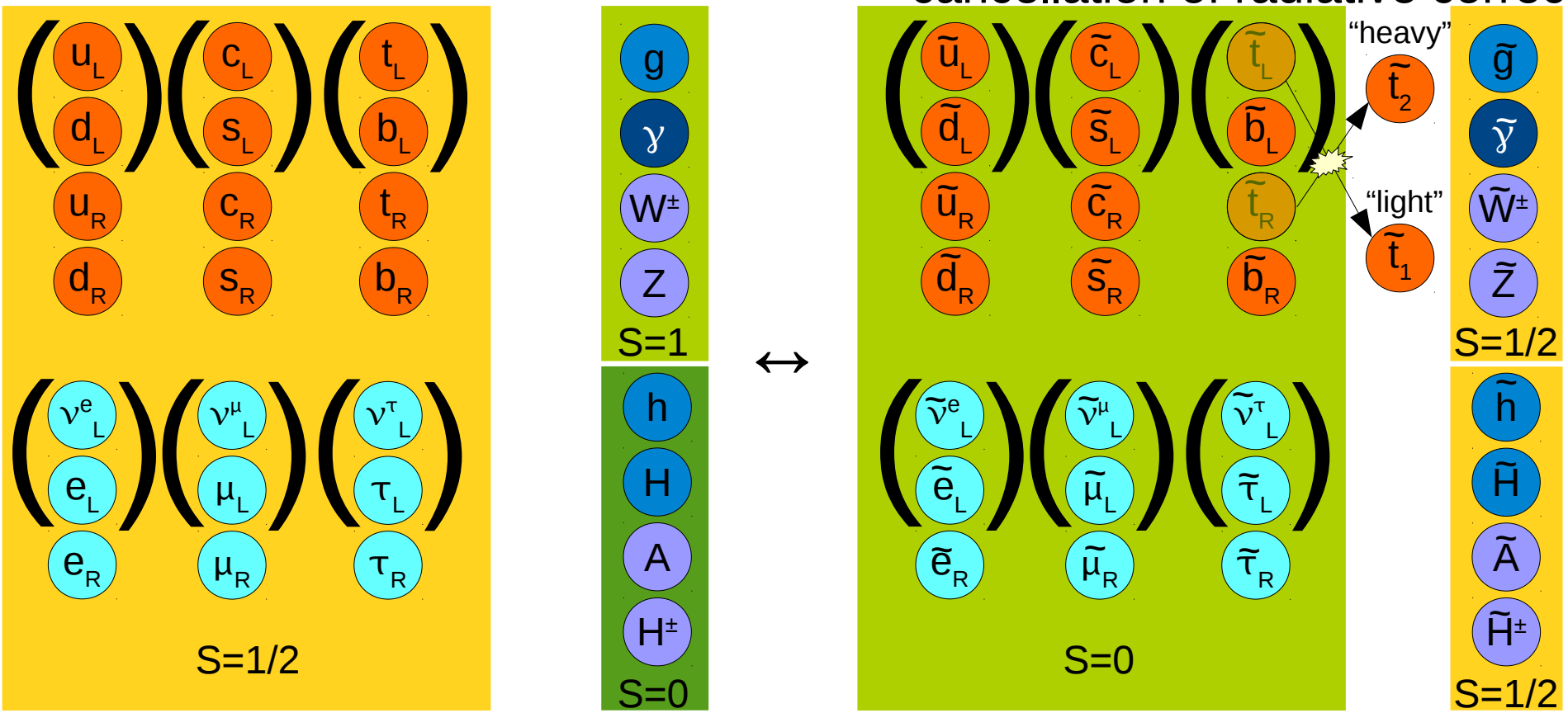
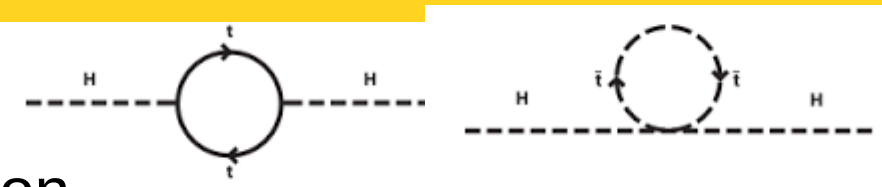


- Add a pinch of mixing

Supersymmetry



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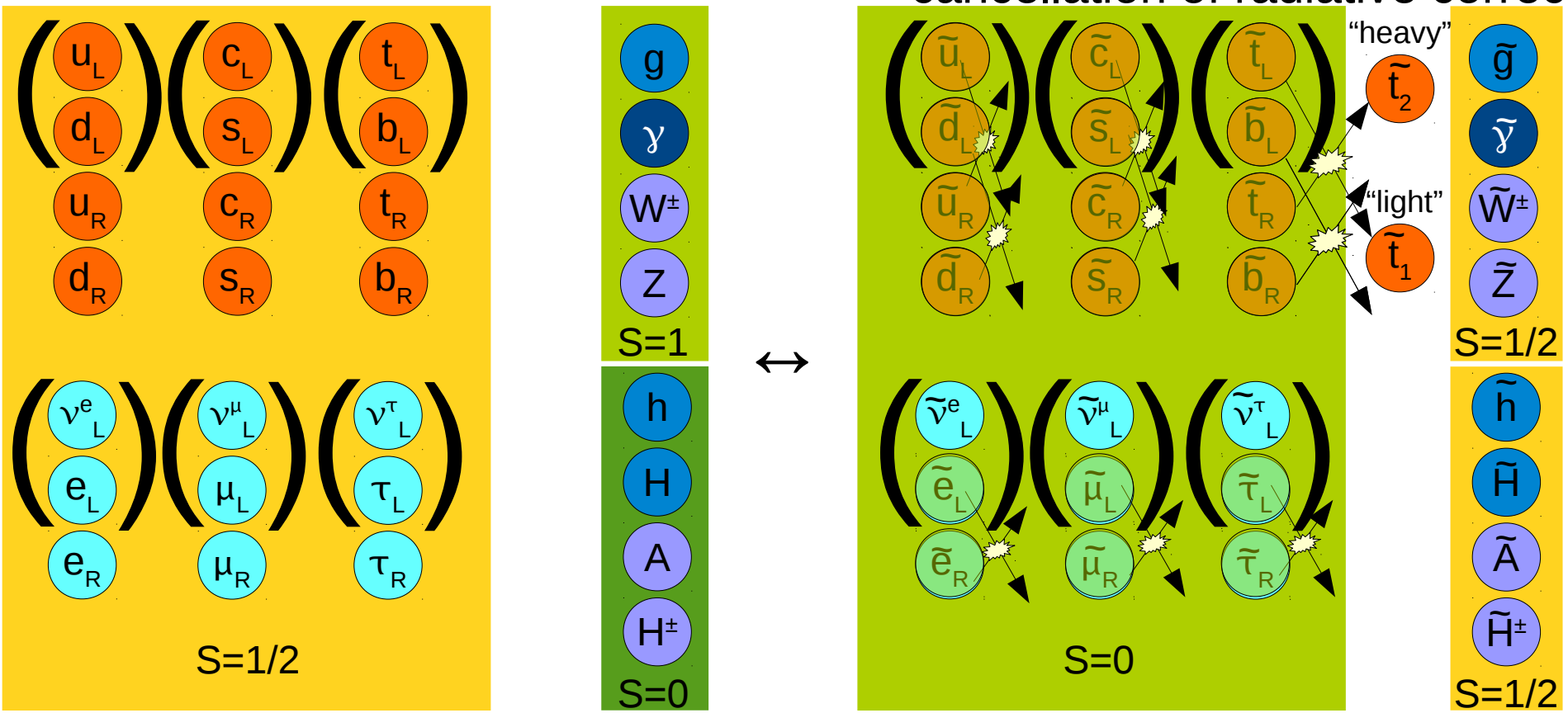

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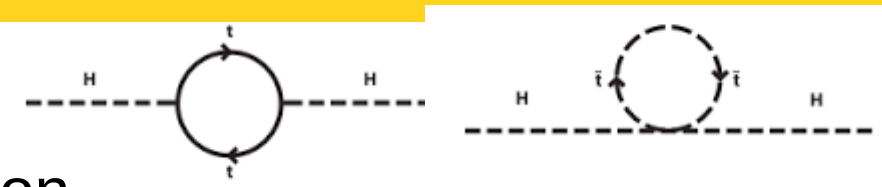

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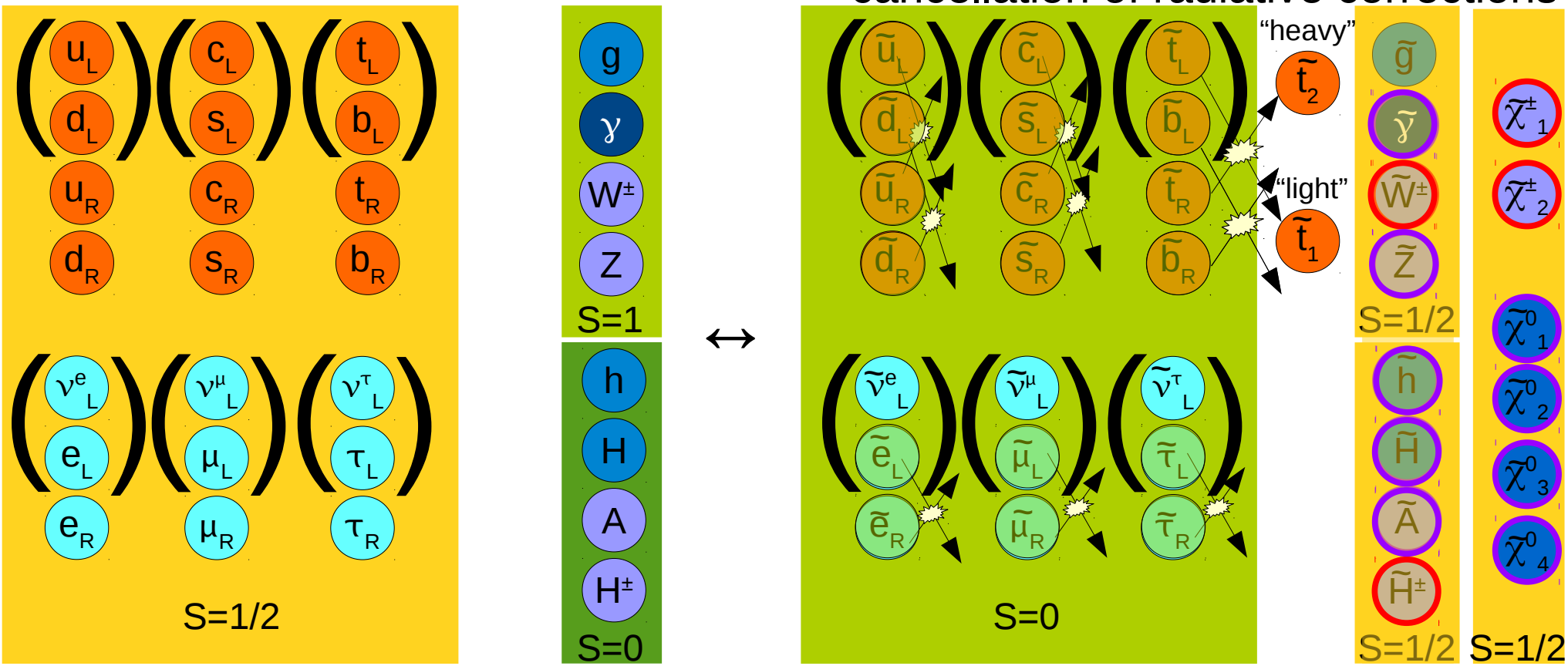

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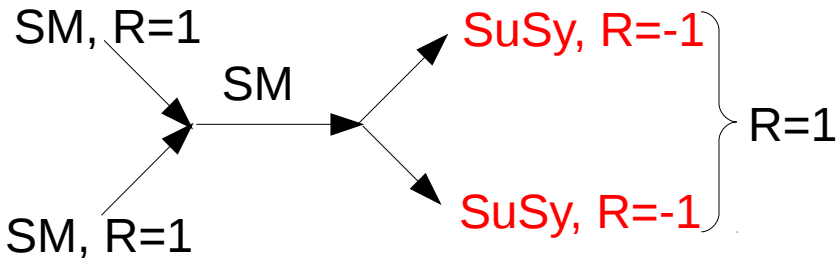
Supersymmetry: R-parity

- $R=(-1)^{L+3B+2J}$ L/B: leptonic/baryonic number, J:spin
  - +1 for SM particles
  - -1 for SuSy particles

- R-parity:
  - Assumed prefect or weakly violated (to preserve proton lifetime)
  - SuSy particle produced by pair



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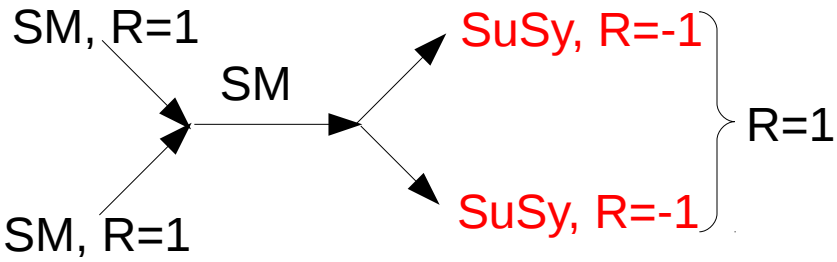
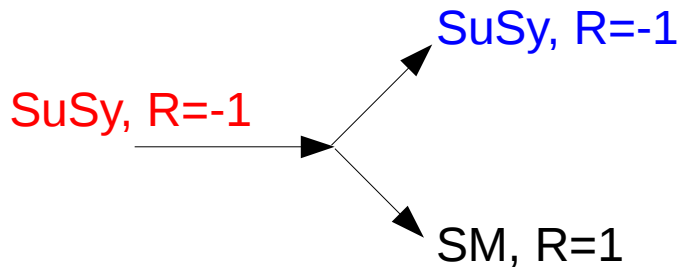
- R-parity:
  - Assumed prefect or weakly violated (to preserve proton lifetime)
  - SuSy particle produced by pair
  - Lightest SuSy particle (LSP) is stable → Dark matter candidate





Breaking SuSy

- Super-partners not yet observed → heavier than SM partners

- SuSy has to be **broken**
  - Unknown mechanism
  - Introduces many free parameters

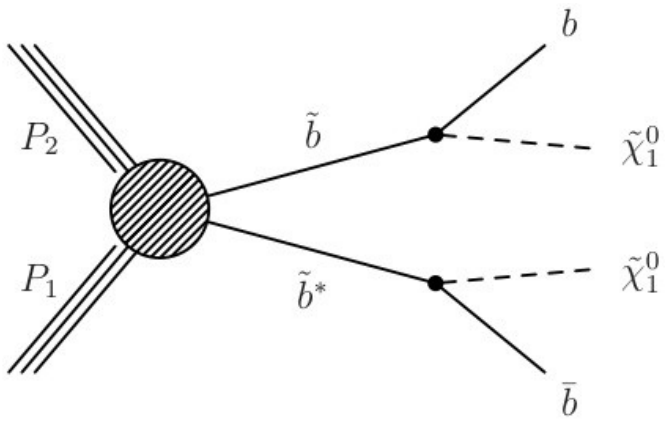
  → **Phenomenological assumptions** to express results
  (mSUGRA, MSSM, nMSSM, pMSSM, …)

  or

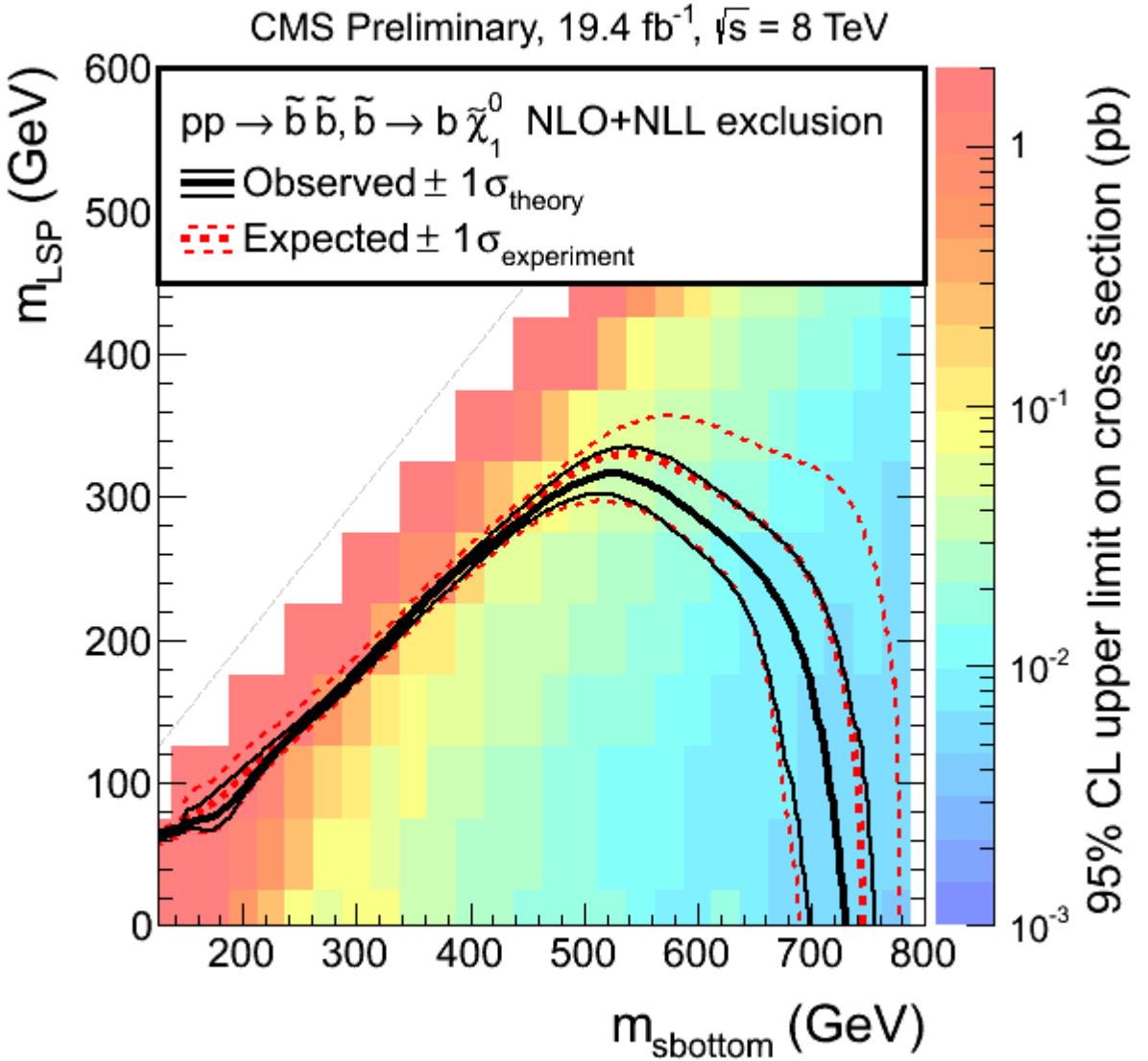
  → **Simplified models**:
    - branching ratio=100%
    - decouple other sparticles

A rich phenomenology

- A simple example

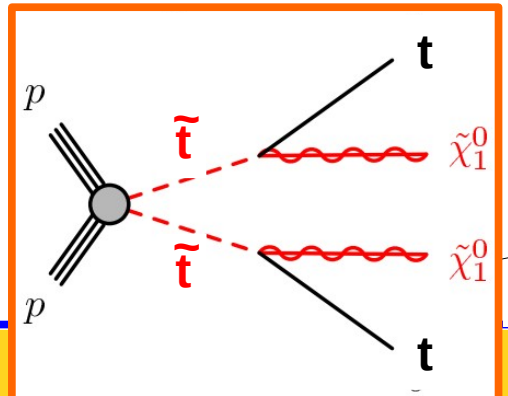


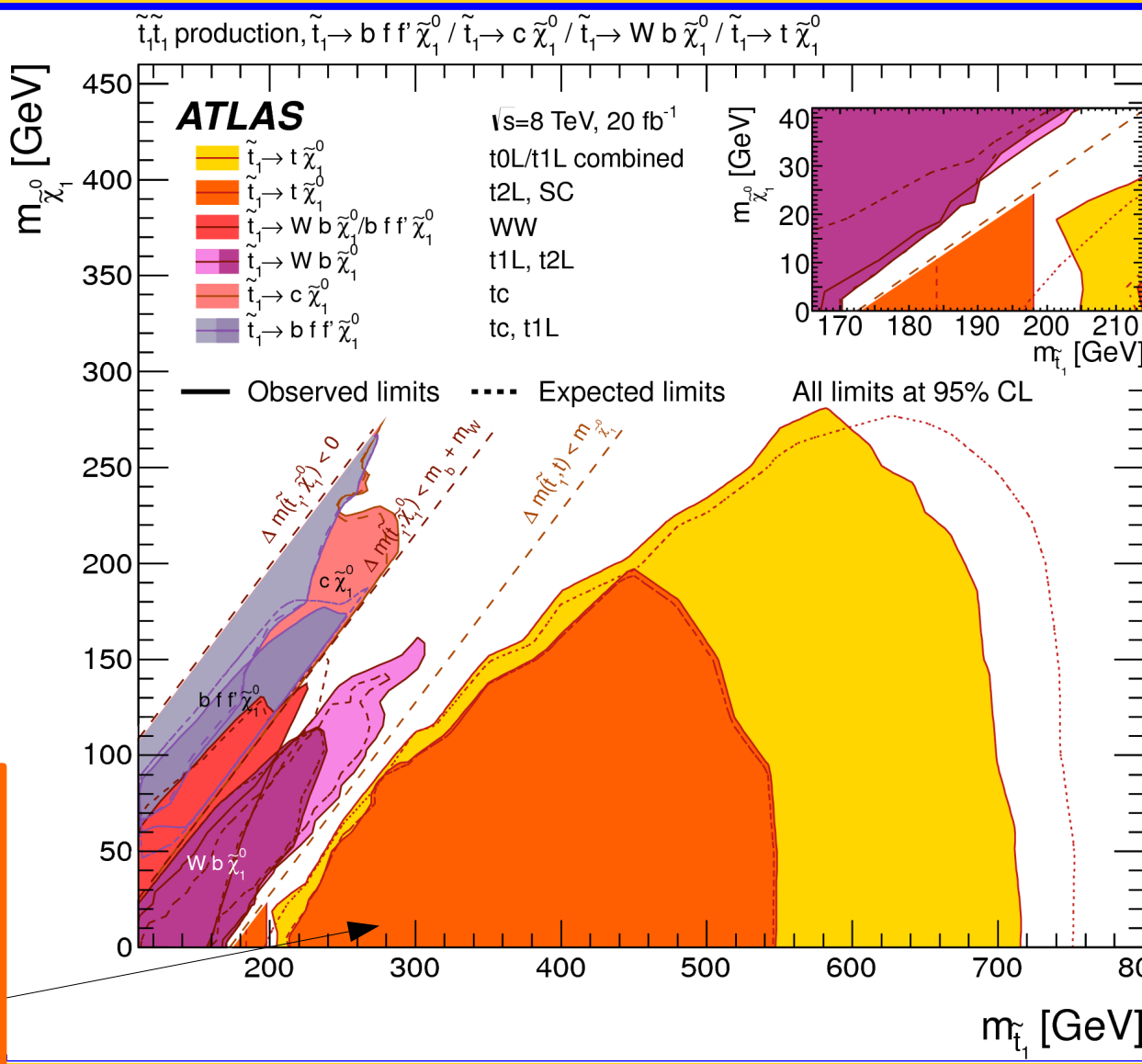
2 b + missing energy



A rich phenomenology

- A more complex one





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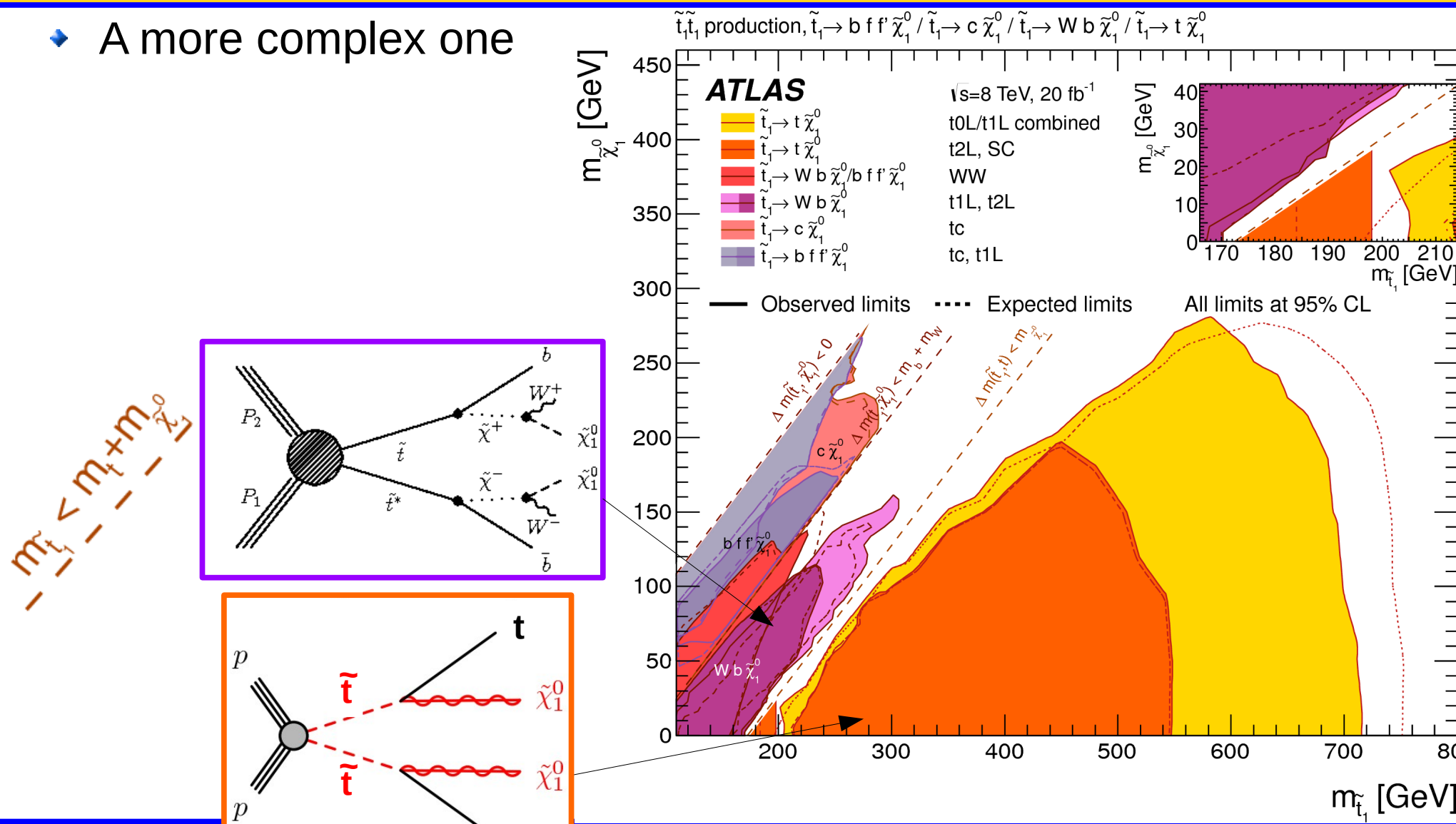

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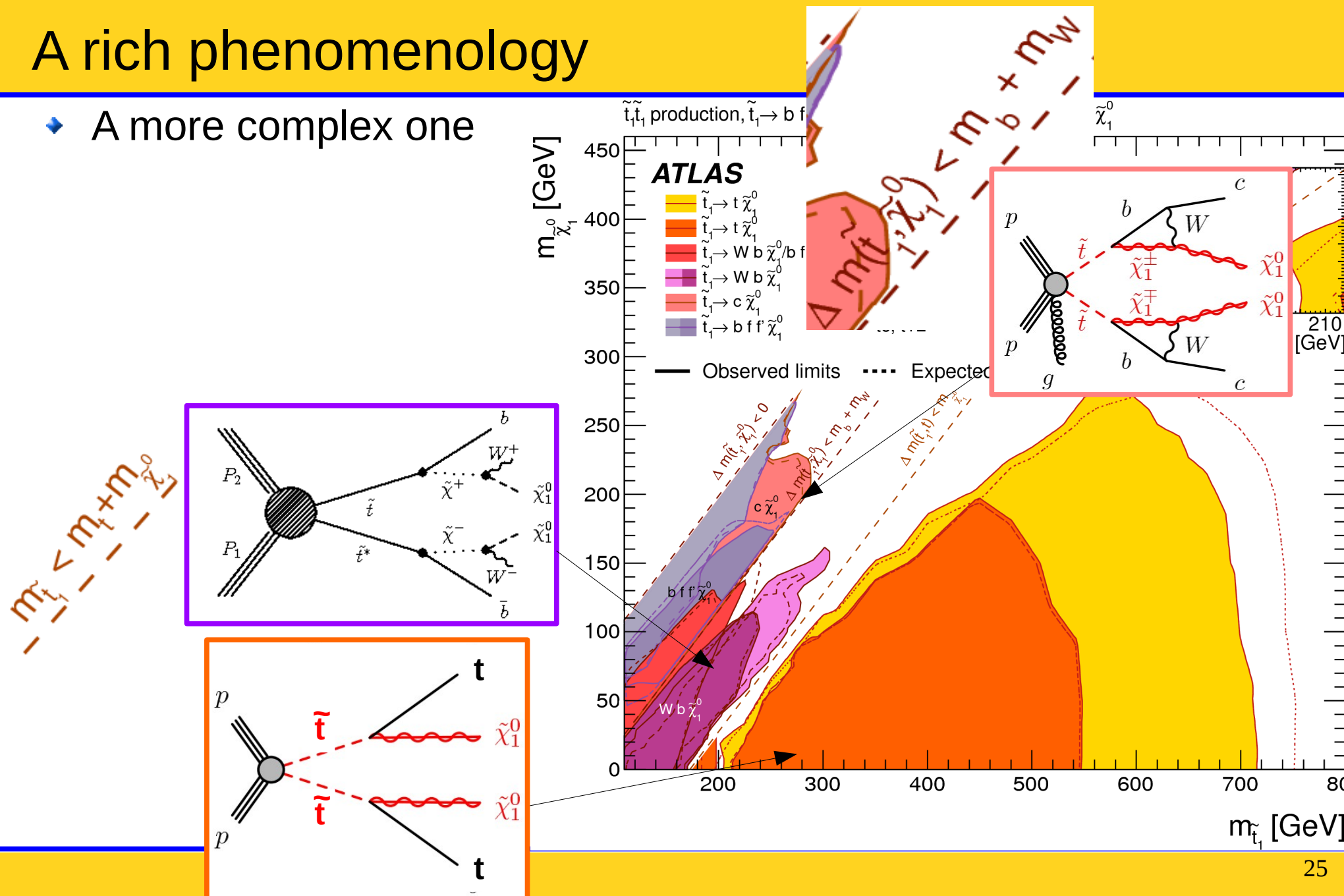

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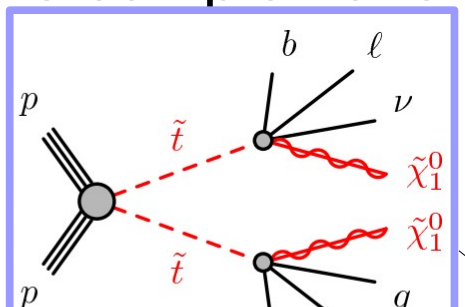
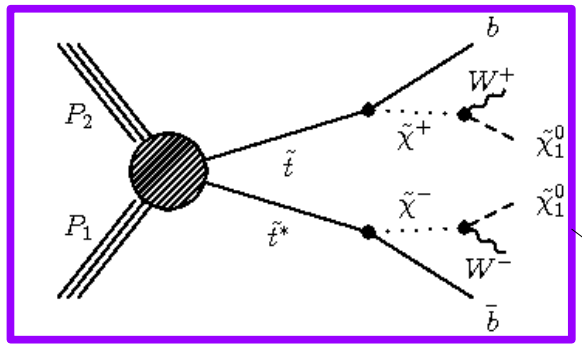
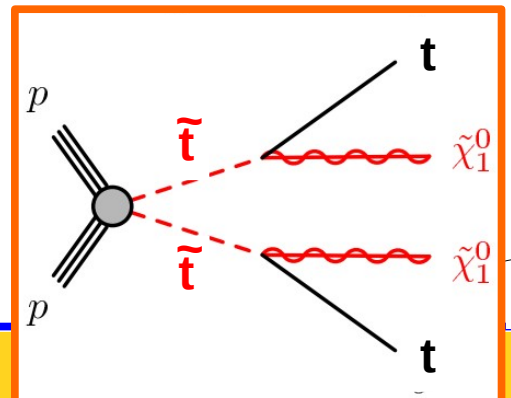
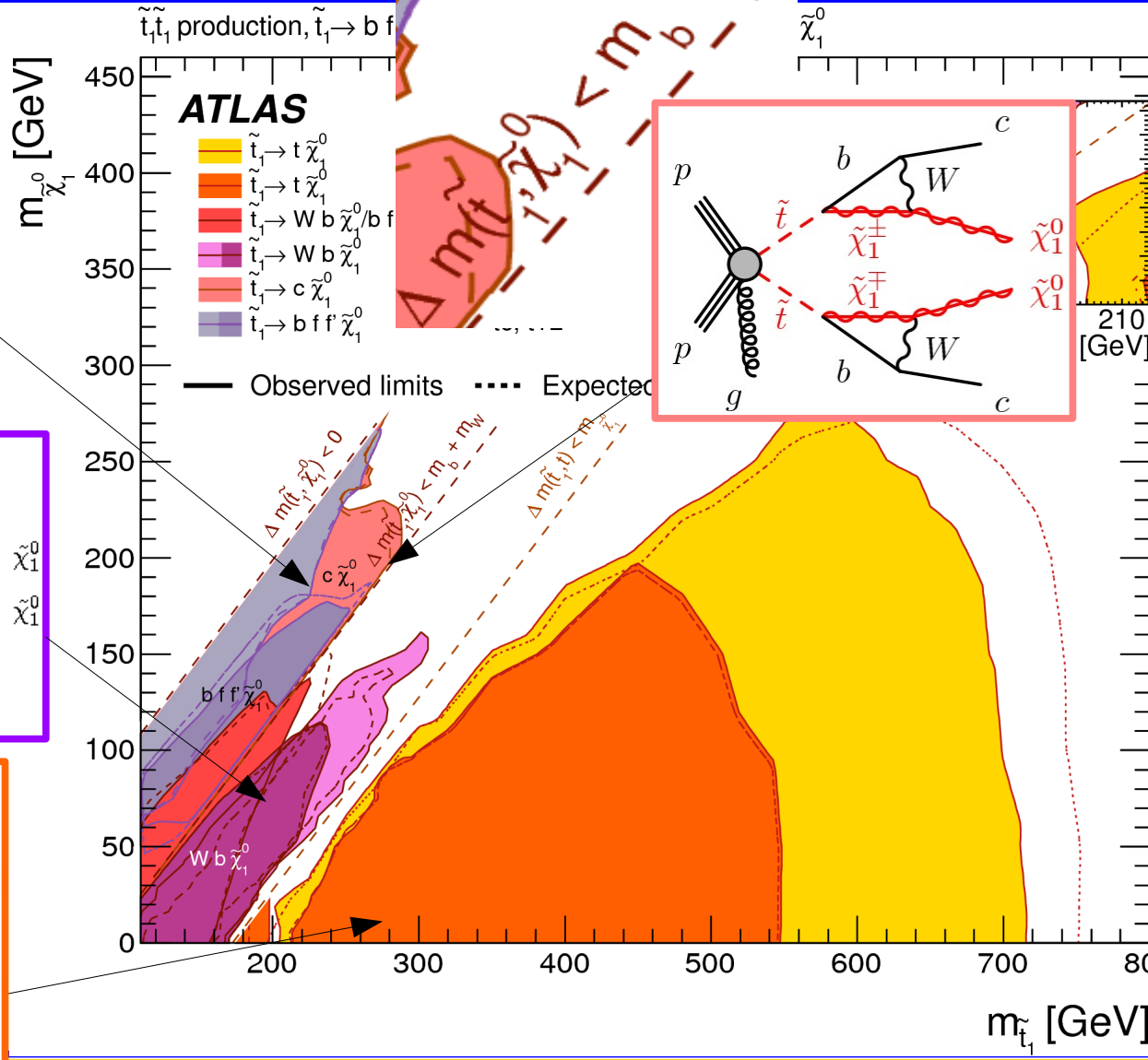






$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$



SuSy : summary

- Addresses naturalness & dark matter
- Very rich phenomenology
- A lot of free parameters

→ Difficult to “kill”

→ Baptiste's talk

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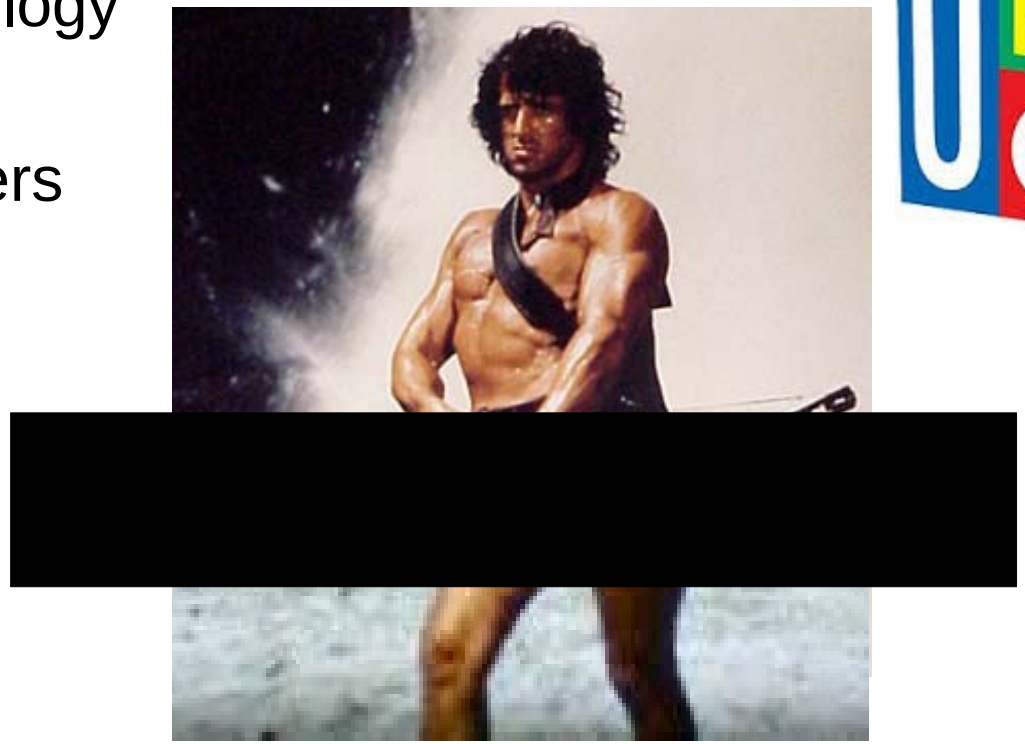


Extra-dimensions

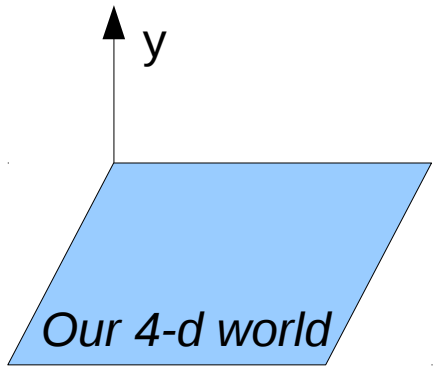
Nice ref: M. Besancon, Moriond EW 2010
Models & signatures of extra dimensions at the LHC

Kaluza–Klein excitations

- Add a space-dimension (*y*)

Flat (ie factorisable): $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

$\mu,\nu = 0, 1, 2, 3, \ldots D$



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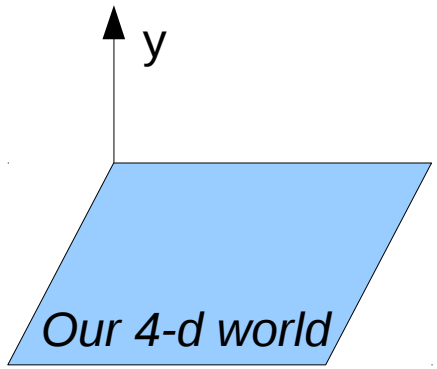
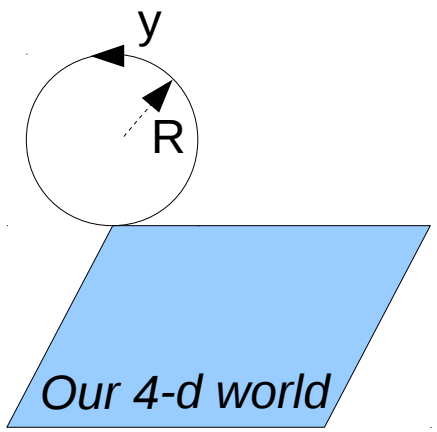


Compactification



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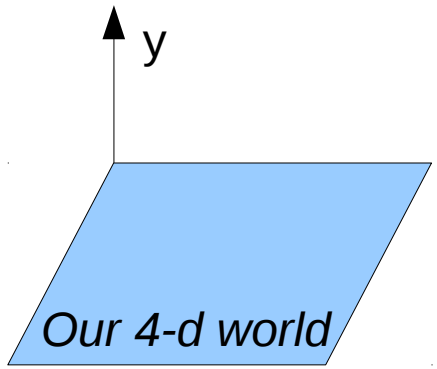

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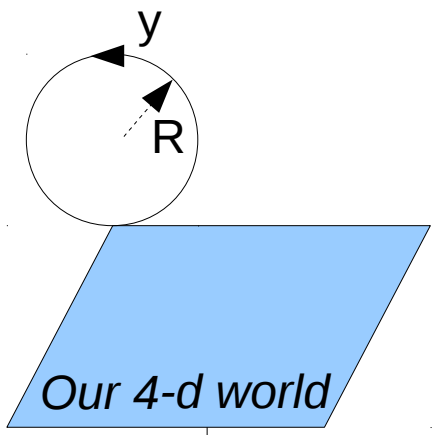

Fourier mode expansion

$\Phi(x,y)=\Sigma_k \Phi^{(k)}(x)e^{iky/R}$

Kaluza–Klein (KK) excitations

$m_k^2=m_0^2+k^2/R^2$

- Assume some fields can propagate along *y*
  - Momentum in new dimensions ↔ mass 4-D (Kaluza–Klein resonance)

Kaluza–Klein excitations

- Add a space-dimension (*y*)

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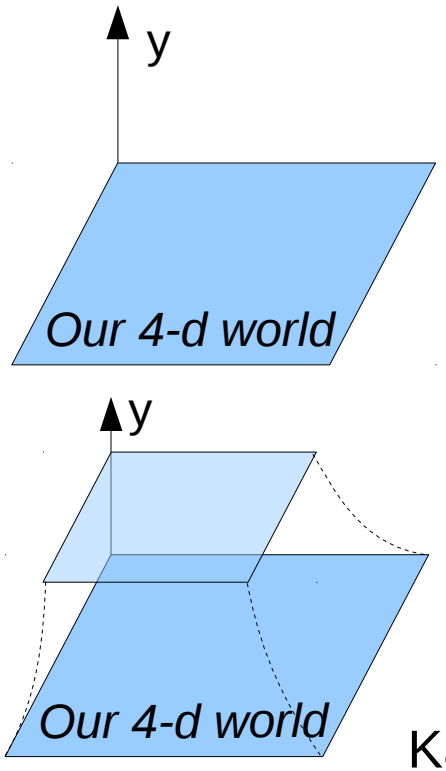
$\mu,\nu=0, 1, 2, 3, \ldots D$

Warped: $ds^2=a_{(y)}\,(g_{\mu\nu}dx^\mu dx^\nu) + dy^2$

$\mu,\nu=0, 1, 2, 3$



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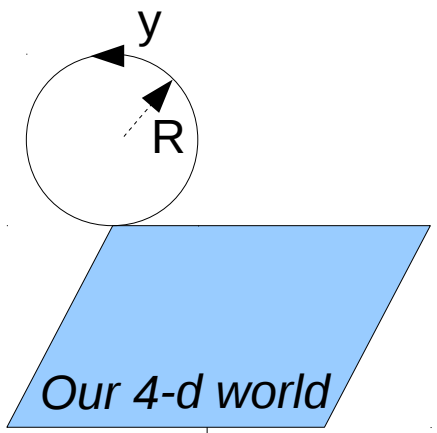

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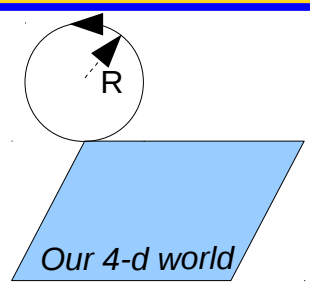
Adding extradimensions...

A lot of room to play...

	Topology	N extradim	Propagating fields
ADD	Flat	≥2	Graviton
mUED	Flat	≥1	V, fermions
RS1	Warped	1	Graviton
Bulk RS	Warped	1	Everything apart Higgs
...			

ADD (Arkani-Hamed, Dimopoulos and Dvali)

- *n* compactified flat extra-dimensions
- Only gravity propagates in the bulk
  - Dilution of the gravity



$$M_{Pl}^{2} \sim M_{D}^{2+n} R^{n}$$

Planck mass in 4+nD

Planck mass in 4D

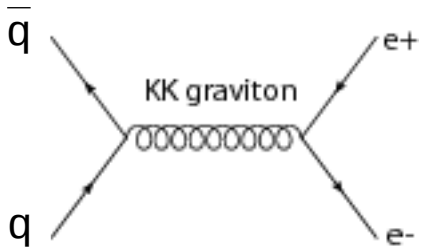
- If M_{Pl}=1TeV (to address the hierarchy problem):
  - ~~n=1 → R=10^{10}km~~
  - ~~n=2 → R=1mm~~
  - n=3 → R=1nm
  - ...

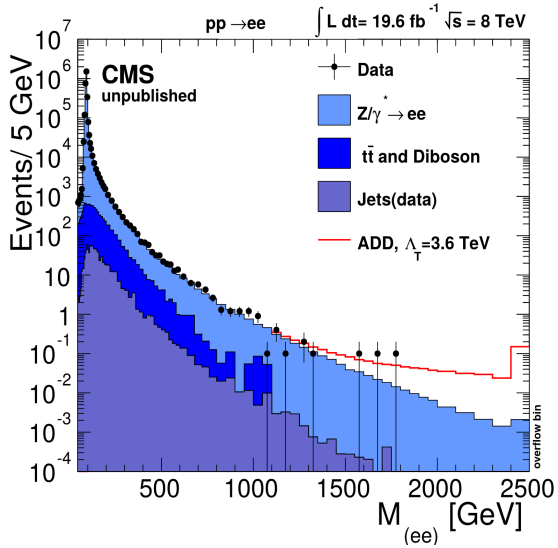
Gravity probed down to ~0.1mm

ADD signatures at colliders

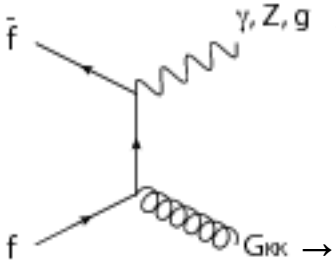
- "Large" R → states close to each other (Δm~eV) → continuum

- s-channel



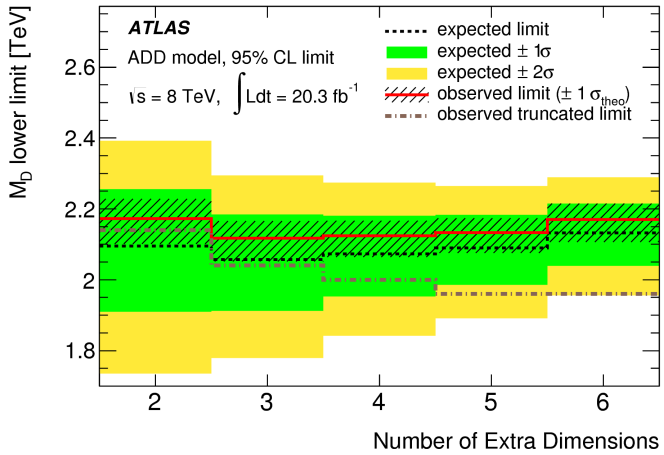


- KK graviton in final states



→ detected

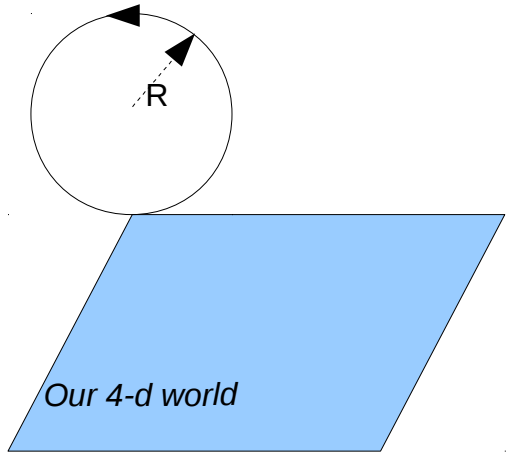
→ Missing Energy



Gamma+MET

UED

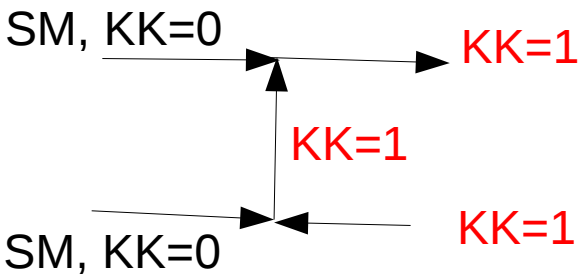
- **Universal Extra-Dimensions**

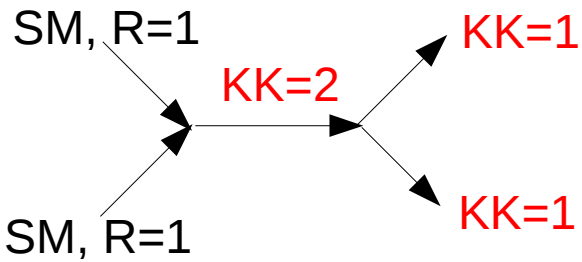


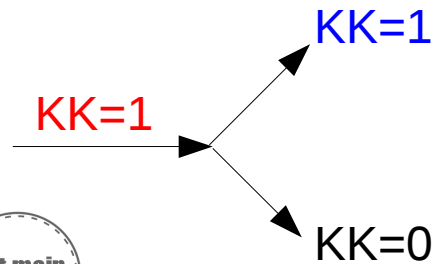
  - No gravity included
  - All the SM fields in the bulk
  - Assume momentum conservation in the bulk

    → KK-parity = $(-1)^{KK}$

    Similar effect than R-parity (pair production of 1st mode, dark matter candidate)





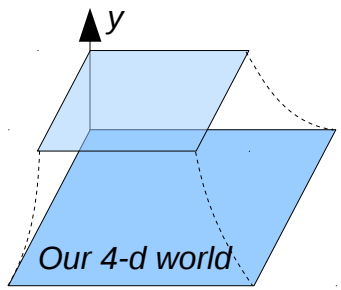


Randall–Sundrum (RS)

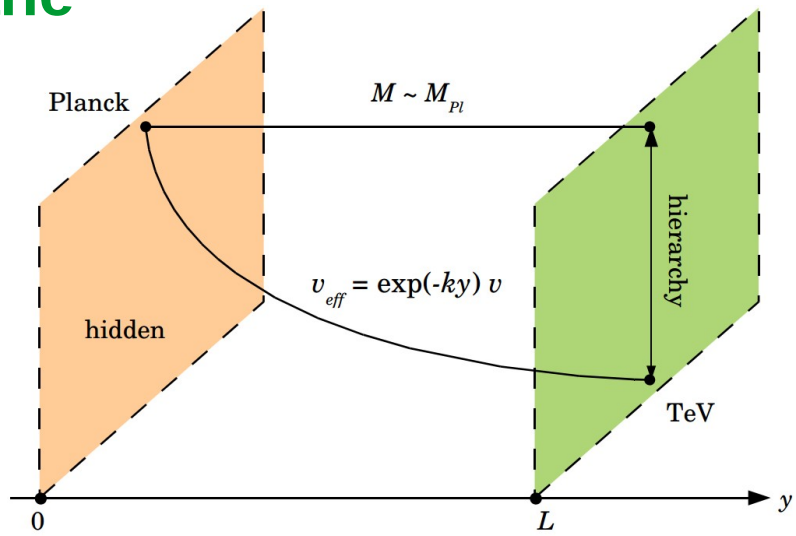
- Warped compacted 5D

$$ds^2 = e^{-2kRy}(g_{\mu\nu}dx^\mu dx^\nu) + R^2 dy^2 \qquad (\theta \in [0,\pi],\ k \sim M_{Pl})$$

Warp factor



- Warp generates **vev~O(TeV) on a brane** from **Planck scale on another brane**



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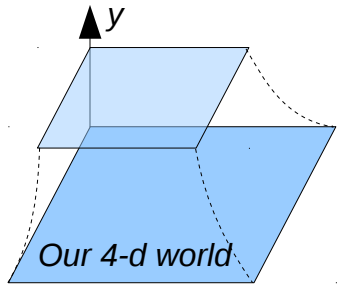

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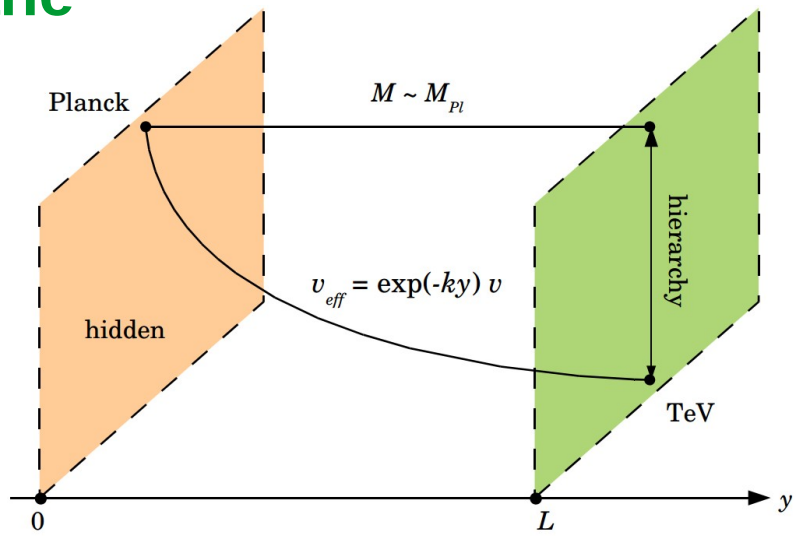

- **Bulk RS**
  - **Higgs** localized on/near **TeV brane**
    → Fix hierarchy problem

Randall–Sundrum (RS)

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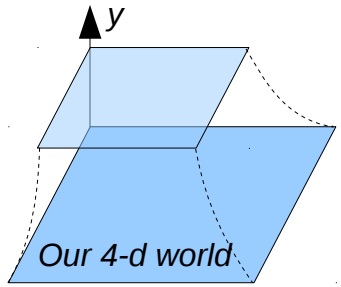

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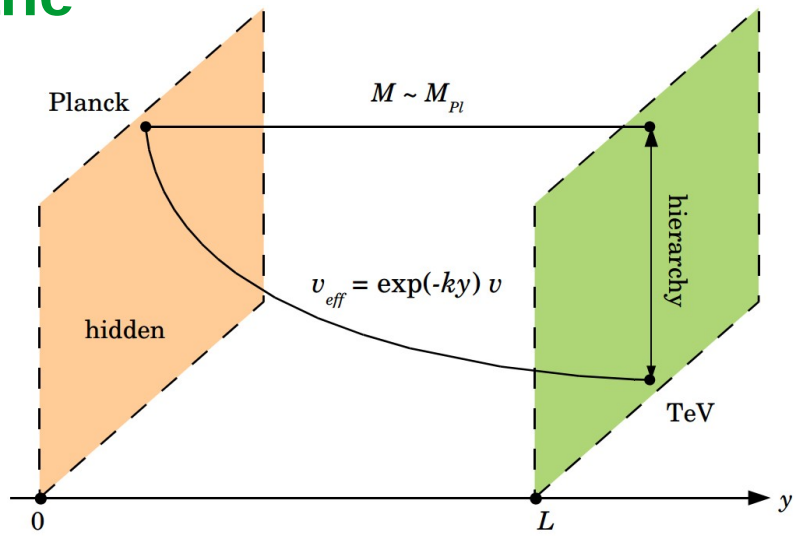

- **Bulk RS**
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    - **3rd generation: TeV brane**

    → ~large Yukawa → large 3rd gen. mass

Randall–Sundrum (RS)

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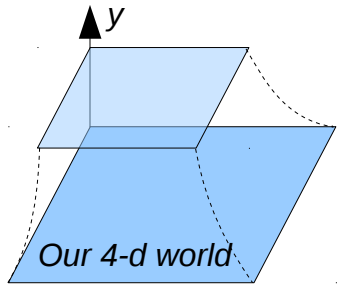

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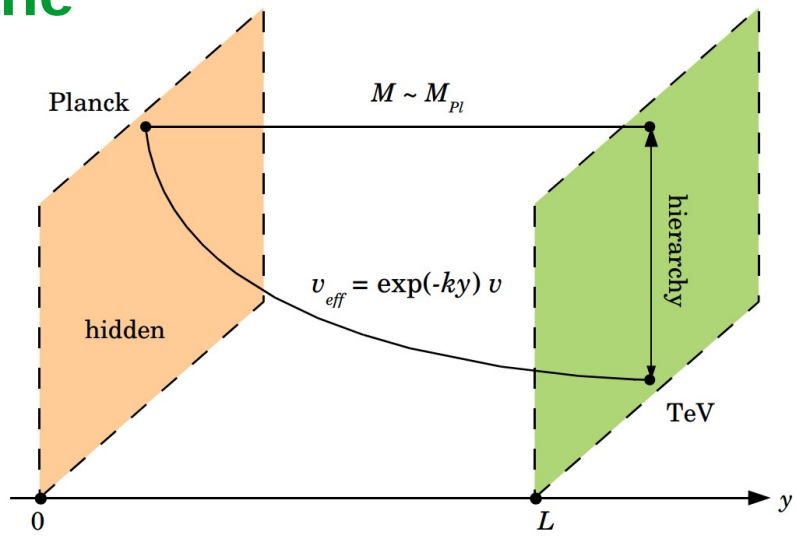

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    → Fix hierarchy problem
    - 1st and 2nd generations : Planck brane
    - **3rd generation: TeV brane**

    → ~large Yukawa → large 3rd gen. mass
  - Fields in bulk → KK resonances
  - Prediction of Vector-like quark (see next slides)

Extra-dimensions...

Various kinds of models addressing different issues

	Topology	N extradim	Propagating fields	Addresses...
ADD	Flat	≥2	Graviton	Naturalness
mUED	Flat	≥1	V, fermions	Dark matter
Bulk RS	Warped	1	Everything apart Higgs	Naturalness
...				

→ Kirill's talk

Compositness

Compositness

- Assume new Strong sector (QCD-like) at TeV-scale
  - SO(5) → SO(4) + 4 Goldstone bosons (=Higgs doublet)
    → Higgs boson is composite (like pion in QCD)

- Consequences:
  - Fix naturalness issue
  - Lagrangian modified as:

$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_f \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right) + \cdots$$

$$a = \sqrt{1 - \frac{v^2}{f^2}} \qquad b = 1 - \frac{2v^2}{f^2} \qquad c = \sqrt{1 - \frac{v^2}{f^2}}$$

Stolen to A. Pomarol

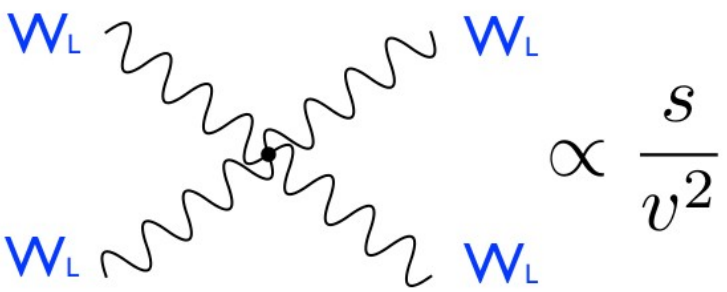
(SM: a=b=c=1)

Scale related to the composite-scale

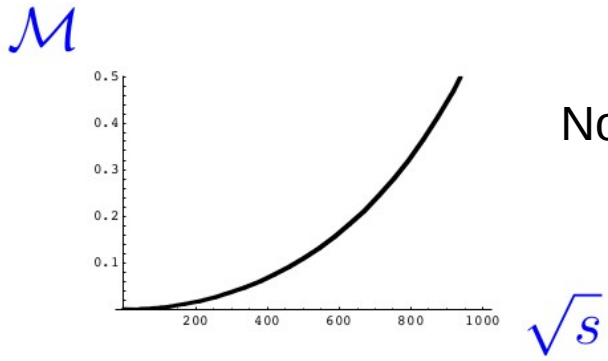
Compositness: consequence

- SM without Higgs

Cf Philipp Pigard's talk

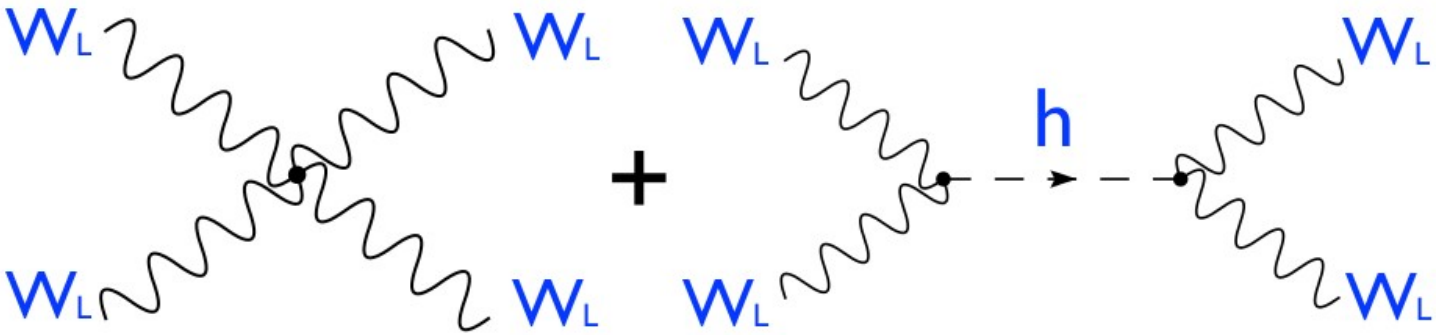


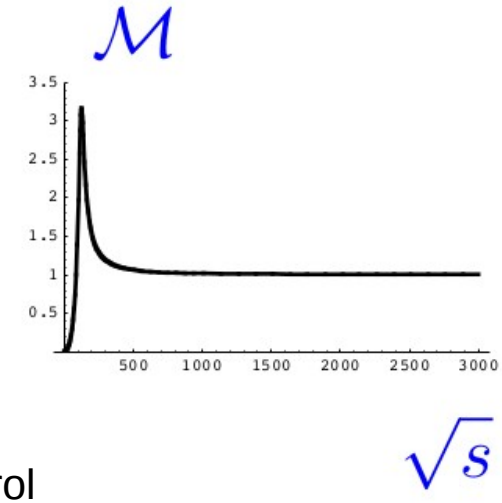
$$\propto \frac{s}{v^2}$$



No unitarity at high energy

- SM with Higgs: unitarity recovered

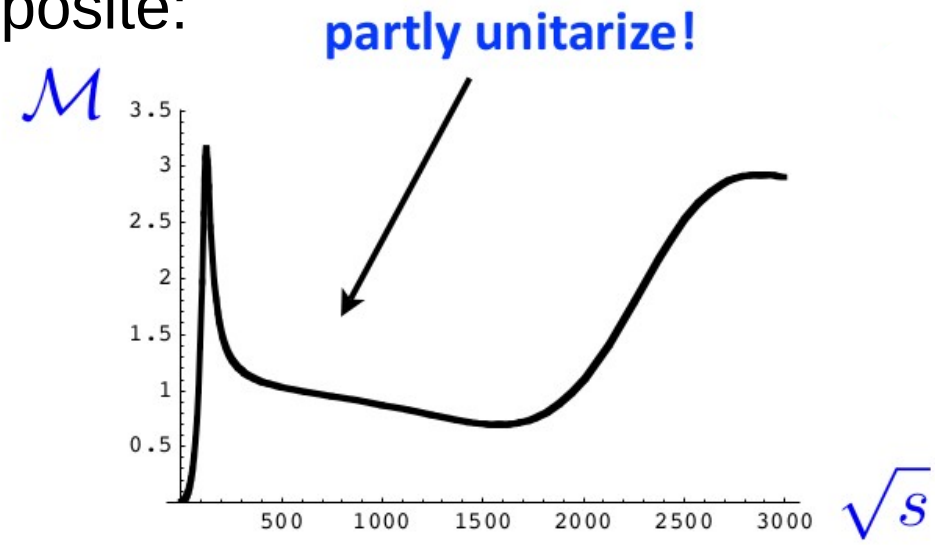




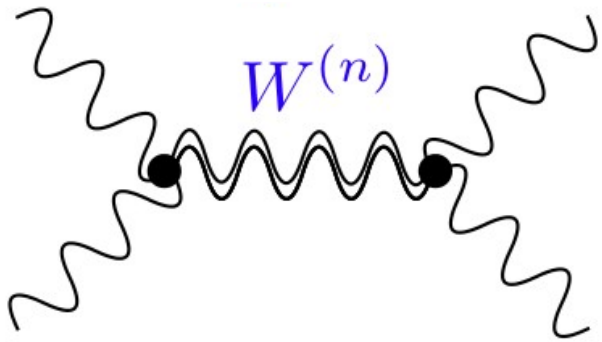
Figures stolen to A. Pomarol

Compositness: consequence

- If the Higgs is (partially) composite:



→ Need extra states:



$$M_{W^{(n)}} \simeq \frac{2 \text{ TeV}}{\sqrt{1-a^2}}$$

Figures stolen to A. Pomarol

- Also predicts Vector-Like Quarks (VLQ)

Vector-Like Quark (VLQ)

- Predicted by many theories
  - Extra-dimension, Compositness, Grand Unified Theory, …

- Vector-like ?

Vector-Like Quark (VLQ)

- Predicted by many theories
  - Extra-dimension, Compositness, Grand Unified Theory, …

- Vector-like ?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}\left(J^{\mu+}W^+_\mu + J^{\mu-}W^-_\mu\right)$$ Charged current Lagrangian

- SM chiral quarks: ONLY left-handed charged currents

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R \quad \text{with} \quad \begin{cases} J^{\mu+}_L = \bar{u}_L\gamma^\mu d_L = \bar{u}\gamma^\mu(1-\gamma^5)d = V-A \\ J^{\mu+}_R = 0 \end{cases}$$

- vector-like quarks: BOTH left-handed and right-handed charged currents

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

L. Panizzi

Vector-Like Quark (VLQ)

- Predicted by many theories
  - Extra-dimension, Compositness, Grand Unified Theory, …

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L. Panizzi

$\mathcal{L}_M = -M\bar{\psi}\psi$ Gauge invariant mass term without the Higgs

VLQ

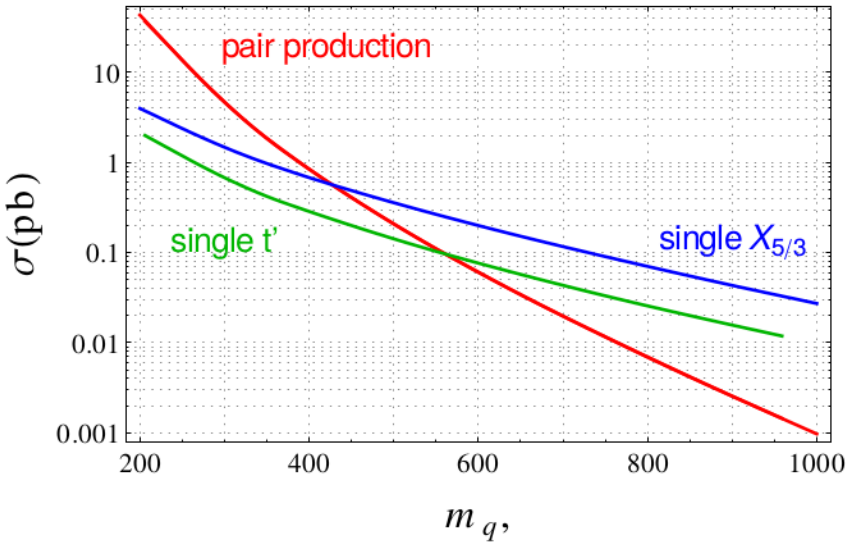
- VLQ mix with SM quarks
- … and interact through Yukawa interactions
- Various incarnation possible:

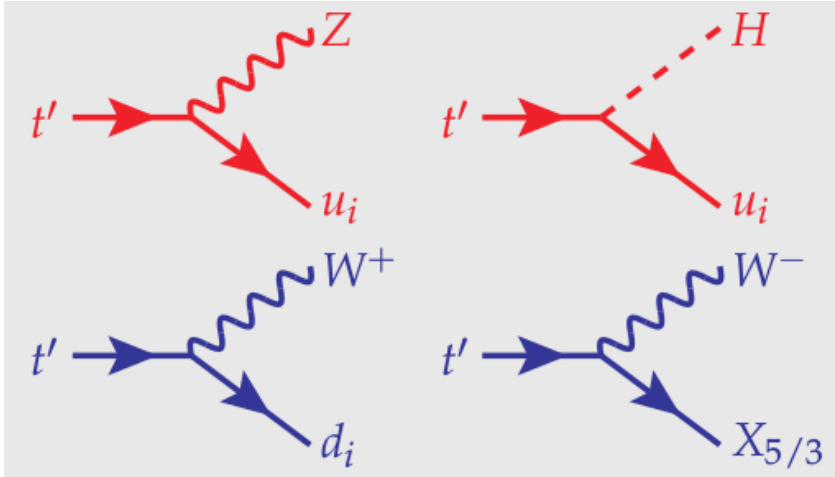
	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix} \begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix} \begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$

L. Panizzi

Searching for VLQ

- Production / decay





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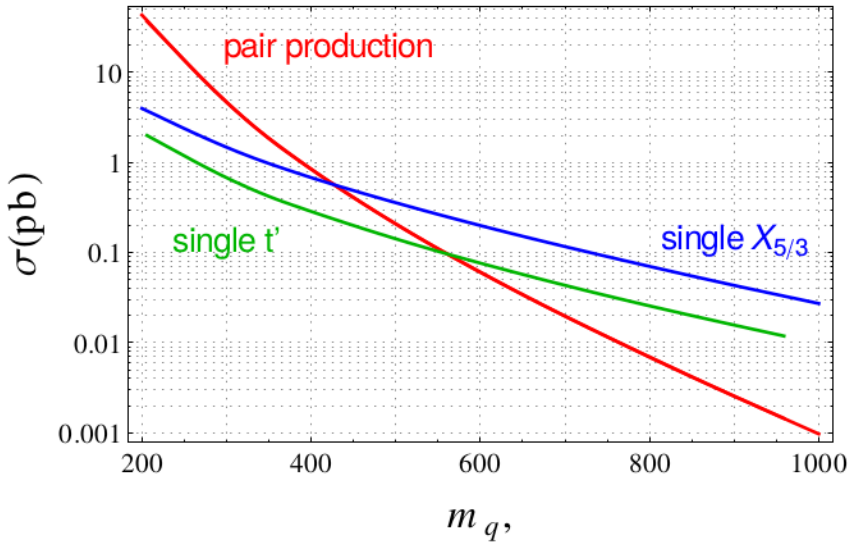

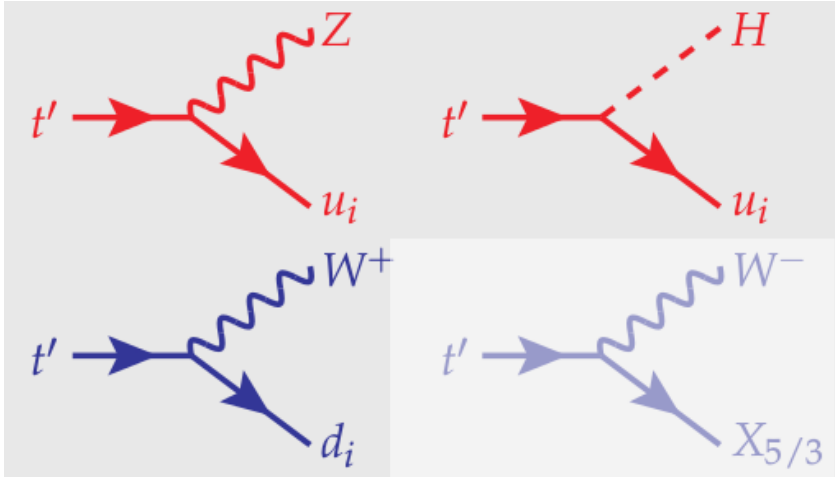

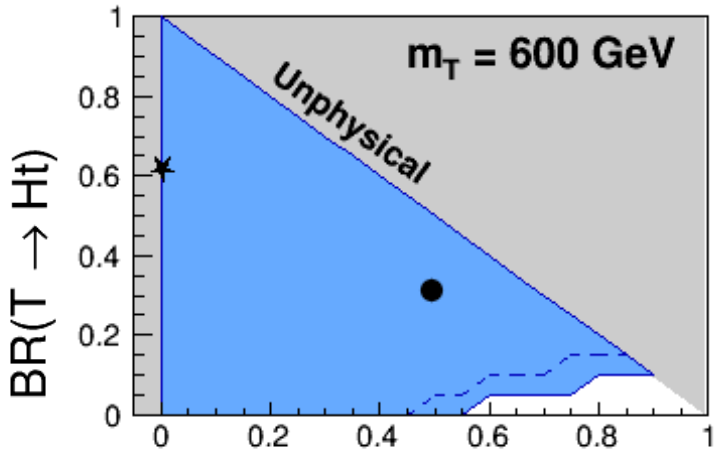

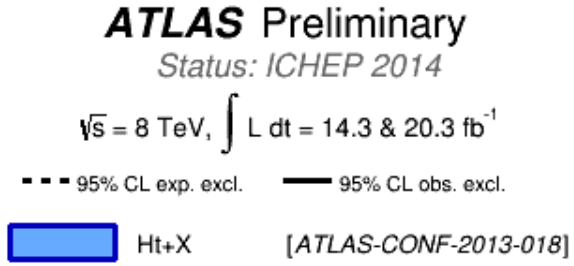

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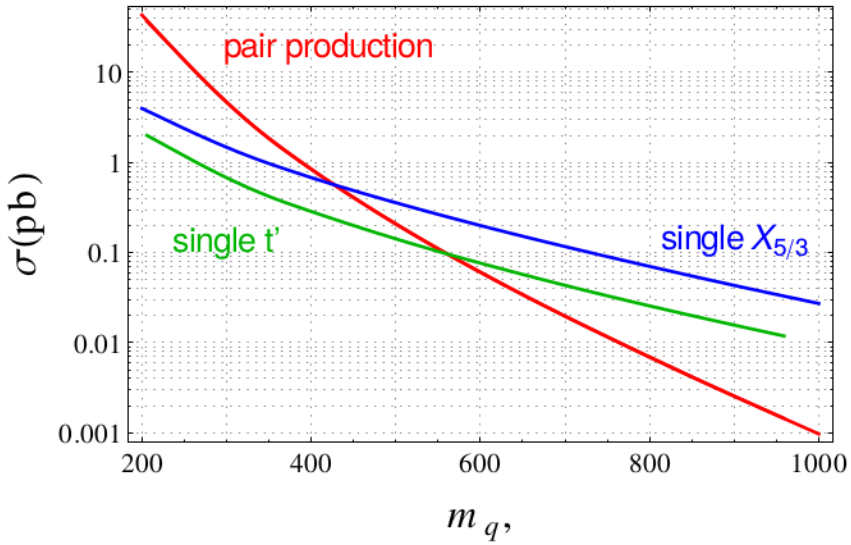

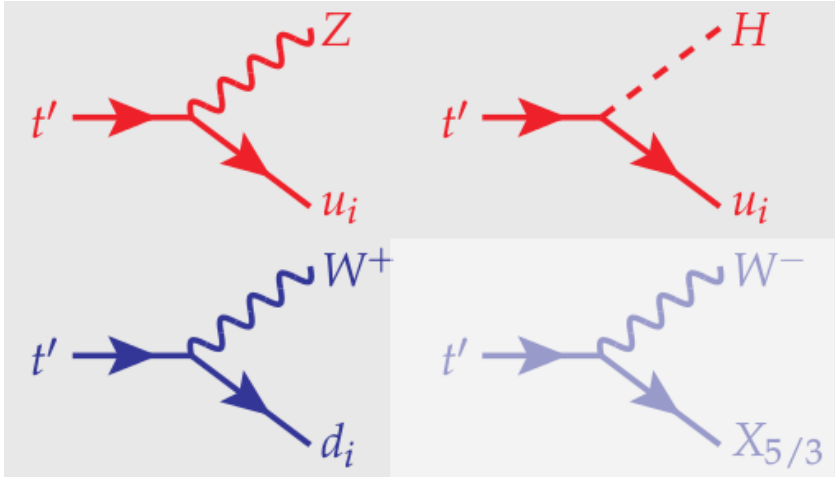

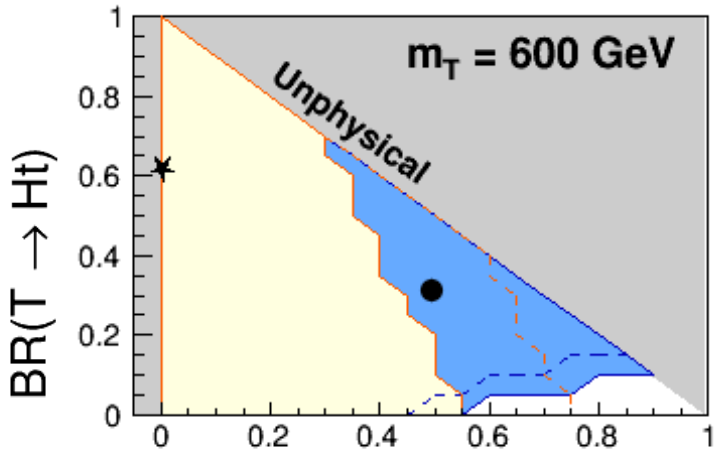

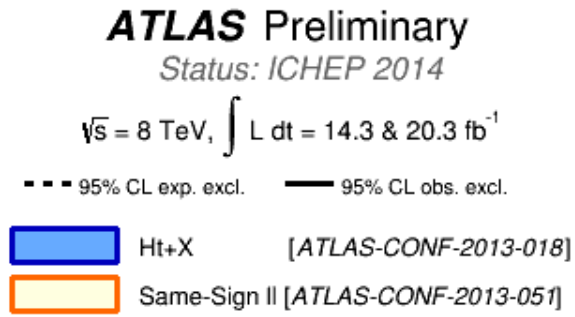

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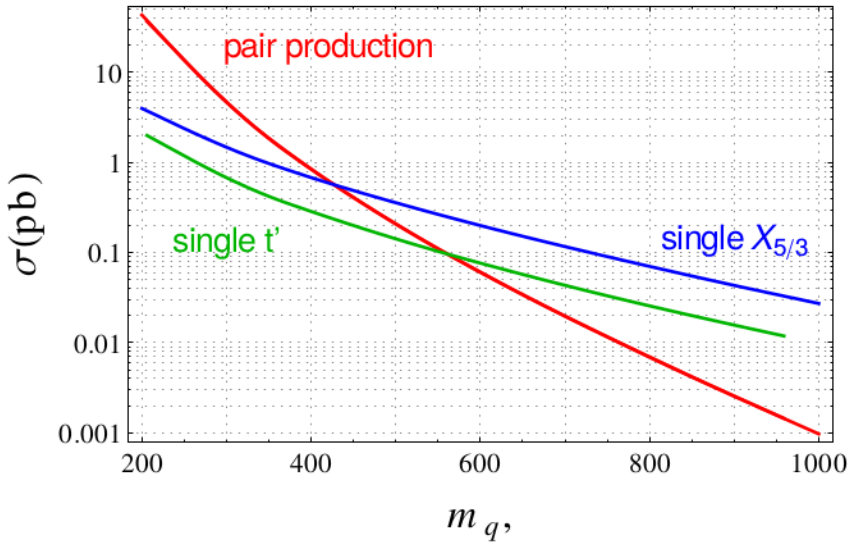

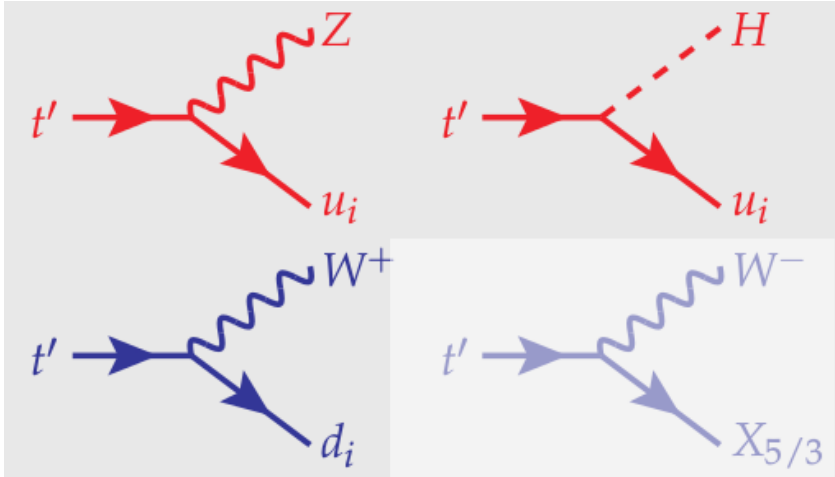

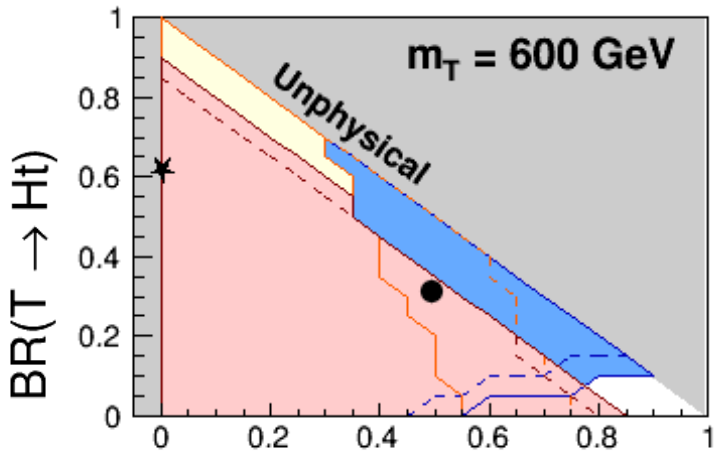

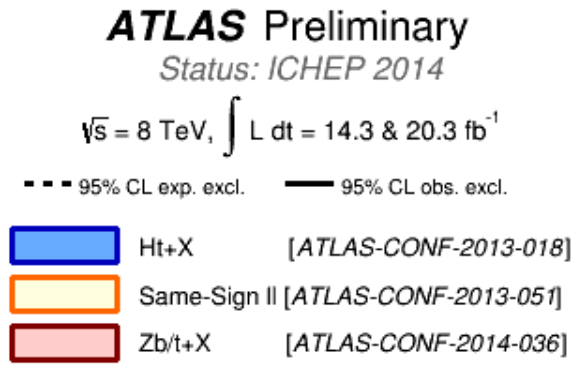

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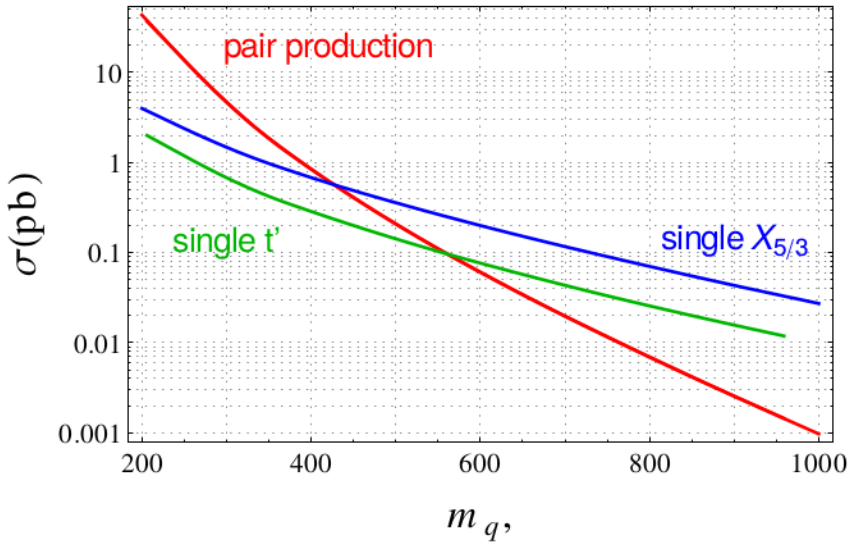
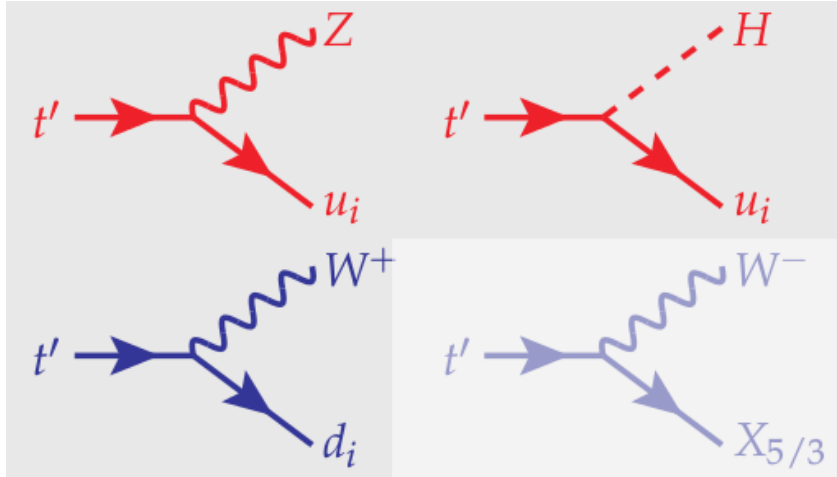
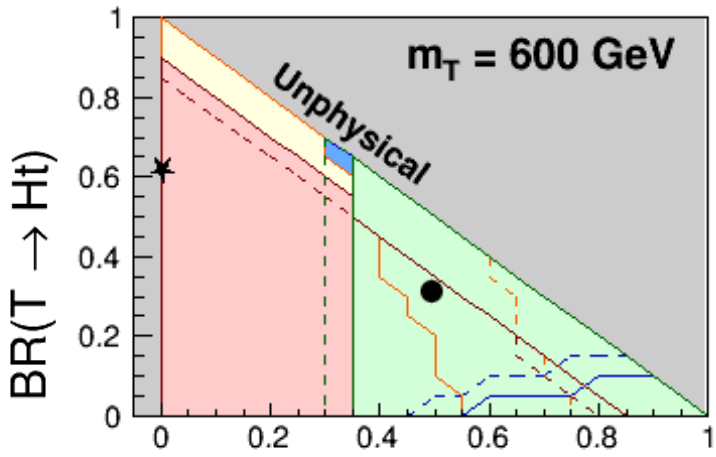
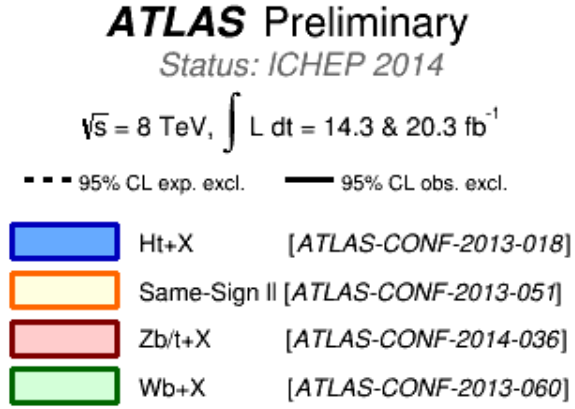




Cf Romain's talk





Conclusion

- Lots of models on the market

  … trying to address
  - dark matter
  - naturalness

- Of course, I could not present
  - many other models
  - many other problems (ν mass, ...)

Backup

Top-quark mass

- Important parameter of the SM
  - (meta-)stability of the Higgs field ?