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Particle Physics for specialists

Beyond Standard Model
Direct searches for New Physics

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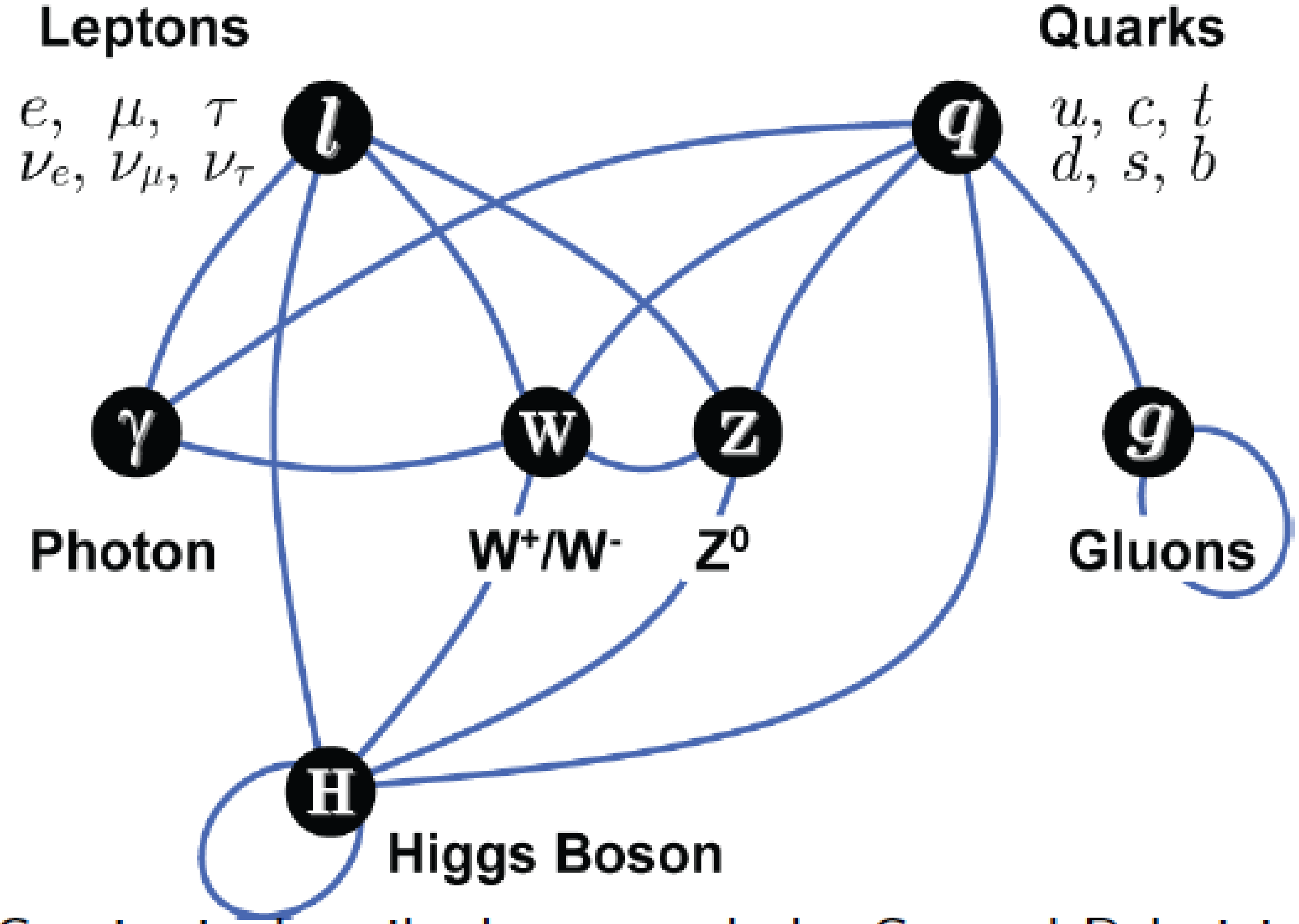
Some slides stollen from Anna Kaczmarska and Glen Cowan

State of the art…

The Standrad Model is the combination of the Gauge groups

$SU(3)_C \times SU(2)_L \times U(1)_Y$

including the Higgs Mechansism



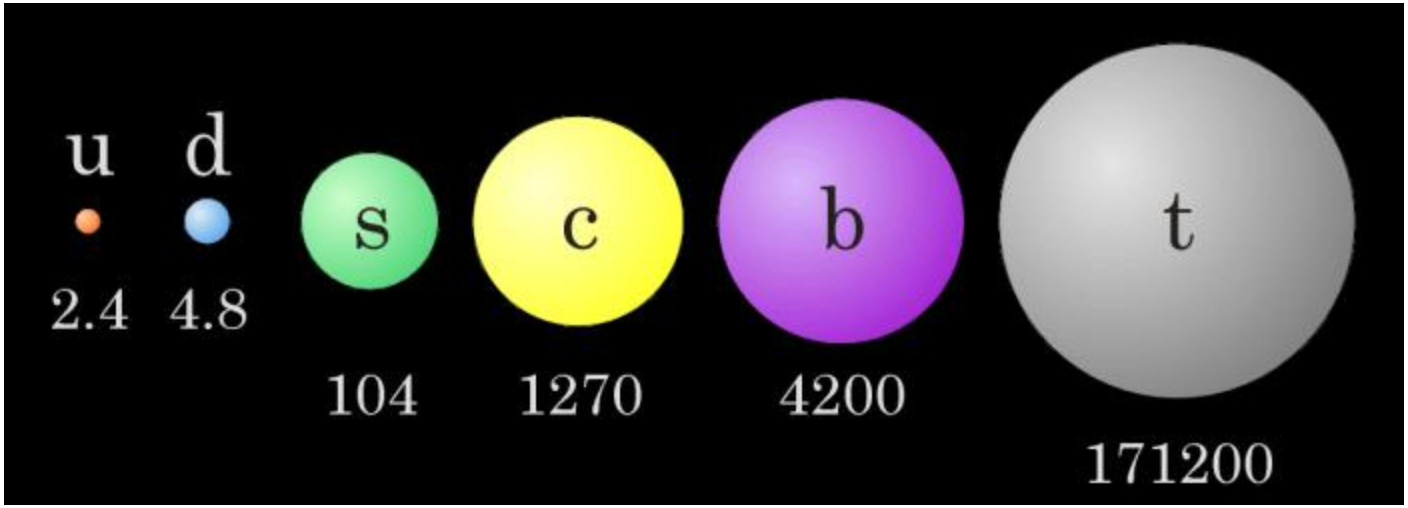
Gravity is described separately by General Relativity

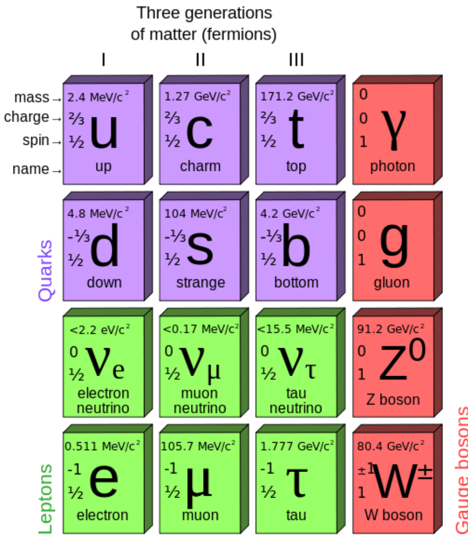
SM complete. End of the story?

- The Standard Model successfully describes all existing particle physics data (though question marks over the neutrino sector)

- But: many (too many? At least 19…) input parameters:
  - Quark and lepton masses
  - Quark charge
  - Couplings
  - Quark (+ neutrino) generation mixing, etc.
- And: many unanswered questions:
  - Why so many free parameters?
  - Why only 3 generations of quarks and leptons?
  - Why is the neutrino mass so small and the top quark mass so large (mass hierarchy)?
  - Higgs naturalness?
  - Why are the charges of the p and e identical?
  - What is responsible for the observed matter-antimatter asymmetry?
  - How can we include gravity?
  - Etc.

The mass hierarchy…




Three generations of matter (fermions)

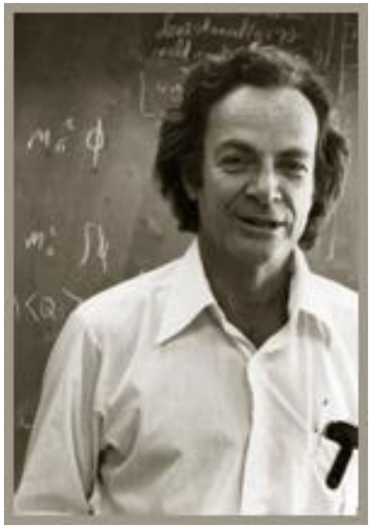
	I	II	III	
mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

Gauge bosons

- Do you want to be famous?
- Do you want to be a king?
- Do you want more than the Nobel Prize?

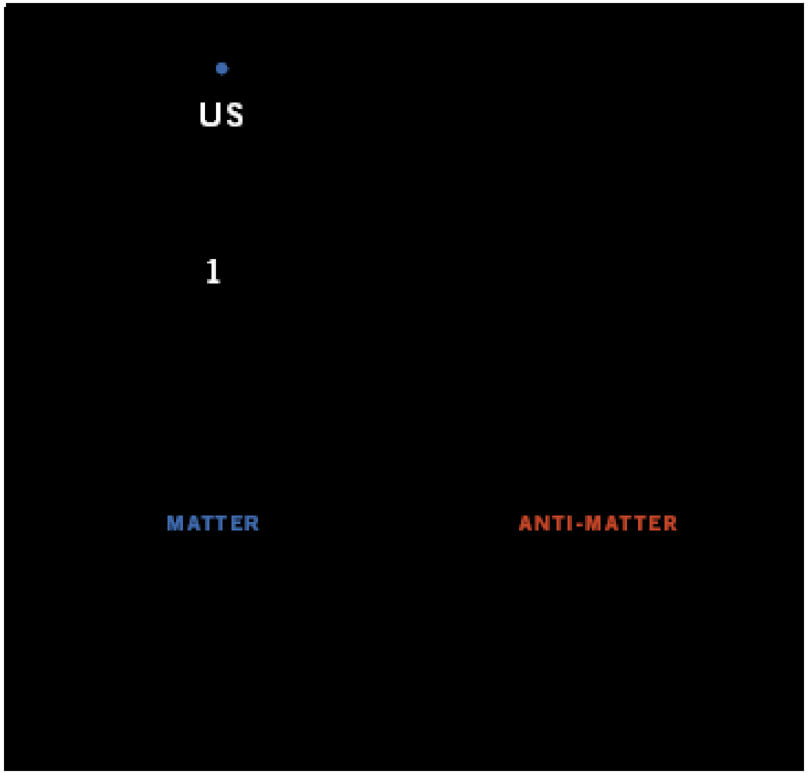
- Then solve the mass problem –

R.P. Feynman



Why are we there in the first place?

We exist because there is no antimatter around us !!!



- The Big Bang should have created equal amounts of matter and antimatter in the early universe.
- If matter and antimatter are created and destroyed together, it seems the universe should contain nothing but leftover energy
- Nevertheless, a tiny portion of matter – about one particle per billion – managed to survive. This is what we see today.
- The laws of nature do not apply equally to matter and antimatter!
  - CP violation we observe in kaons and B mesons systems seem to be not enough…
  - There has to be New Physics to explain that asymmetry!

„Fine Tuning”?
Higgs naturalness problem

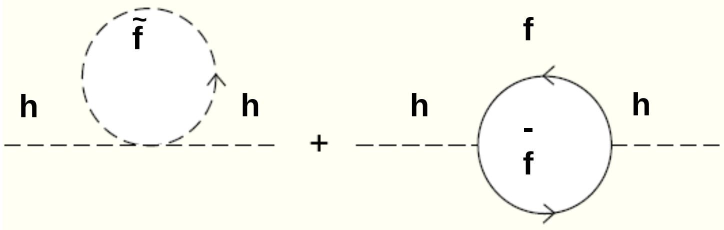
- Scalar quantum fields (like Higgs boson) get corrections terms to their masses which are sensitive to physics at arbitrarily high energies
- Quadratically divergent loop contributions to the Higgs mass drive the Higgs mass to unacceptably large values unless the tree level mass parameter is finely tuned to cancel the large quantum corrections.

$$m^2_{H_{\mathrm{SM}}}(\mathrm{phys}) \simeq m^2_{H_{\mathrm{SM}}} + \frac{c}{16\pi^2}\Lambda^2$$

If $\Lambda \sim 10^{16}$ GeV, then fine-tuning to 1 part in 10^{26} needed

Alternatively, if $\Lambda \sim 1$ TeV, then no fine-tuning, but then SM is valid only below 1 TeV scale

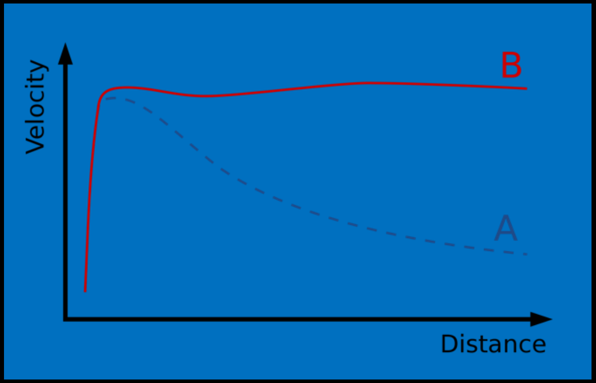
Fermionic and bosonic loops with the same coupling constants do cancell exactly!



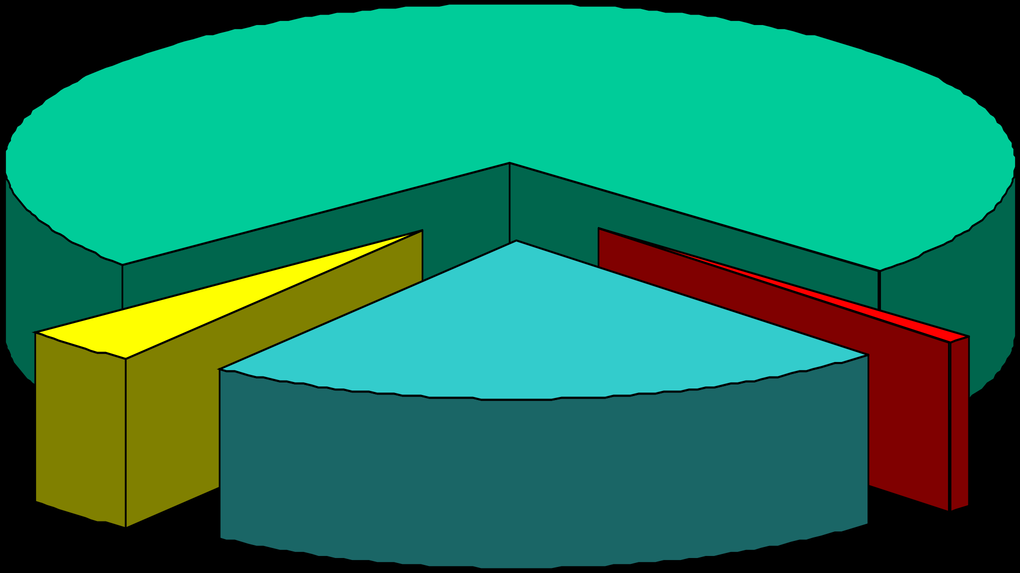
BUT in order for the mechanism to work one needs bosonic partners with reasonably low masses - *O*(TeV).

Cosmos is NOT stars & planets!

Galaxy rotation curves
Gravitational lensing
CMB pattern



DARK ENERGY73%
(DRIVES THE EXPANSION)



BARYONIC MATTER 4%
(SHINING MATTER
ONLY ~0.4%)

DARK
MATTER 23%

NEUTRINOS
0.1-2%

Is the 125 GeV scalar what we assume?

So far the Higgs…
looks like SM,
sounds like SM,
smells like SM.

T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs

But:

CONSISTENT with SM ≠ INCOMPATIBLE with BSM

- ❖ Essential questions:
  - ➢Is the 125 GeV Higgs the only one (extended sector)?
  - ➢Is it responsible for all the particle mass?
  - ➢Is it fundamental?
- ❖ Need to define models of interest. Most popular are additional EW singlet, 2HDM, NMSSM, additional Higgs Triplet, Three dublets, Composite Higgs, etc.
- ❖ All allow for SM-like light Higgs phenomenology with smaller or larger coupling modifications.

Is the 125 GeV scalar what we assume?

ROADMAP

Explore the 125 GeV Higgs

- Production rates (ggH, WH,ZH, VBF, ttH, HH, tH, bbH)
- Decay widths ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, $\mu\mu$, Zγ, fg, rg, etc.)
- Couplings to SM particles
- Spin and parity
- LFV, H->$\alpha\alpha$, H->inv, $\gamma+\not{E}$, etc.

Directly search for BSM scalars

- Heavy neutral CP-even and CP-odd states ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, HH, HZ, tt)
- Charged Higgs ($\tau\nu$, tb, WZ, cs, etc.)
- Doubly-charged Higgs
- Any deviations from SM backgrounds?

How much of the BSM scenarios can current data exclude?

2HDM models

- ❖ Generic class implementing a second Higgs doublet.
- ❖ After EWSB left with 5 physical states:

Three neutral: CP-even **h**, **H**, CP-odd **A**, two charged **H$^+$, H$^-$**

$$\tan\beta \equiv v_2/v_1 \qquad g^{2HDM}_{hVV}/g^{SM}_{hVV} = \sin(\beta-\alpha)$$

$$v_1^2 + v_2^2 = v^2 \approx (246\ \mathrm{GeV})^2 \qquad g^{2HDM}_{HVV}/g^{SM}_{HVV} = \cos(\beta-\alpha)$$

❖In order to prevent flavour-changing neutral currents, one is left with four coupling schemes:

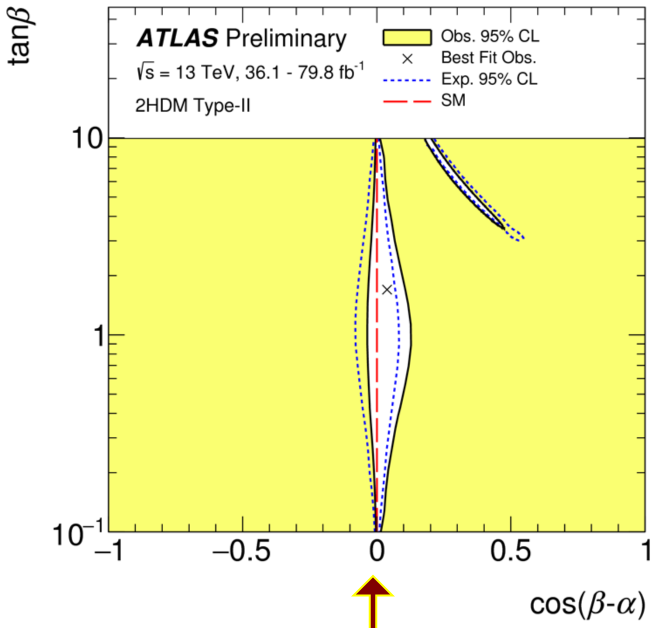
Type I: Only one doublet couples to all SM fermions.

Type II: one doublet couples to up-type quarks, the other to down-type quarks and leptons: „MSSM -like”

Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II.

Flipped: couplings to quarks as in the Type II model and to leptons as in Type I.

Constraints from Higgs coupling measurements

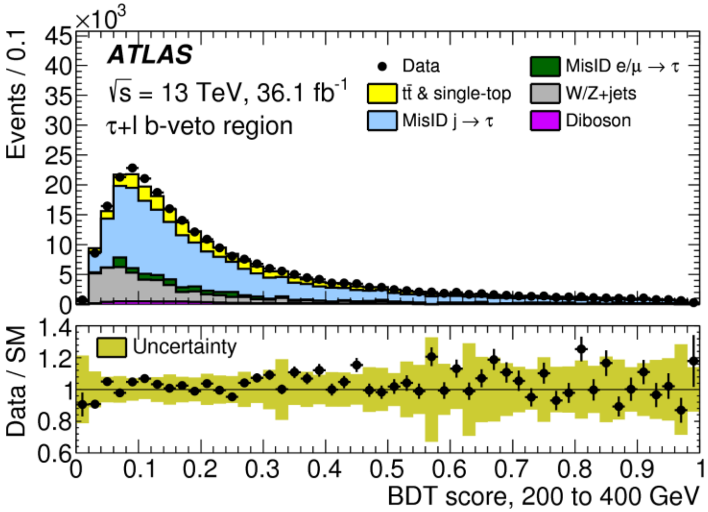


alignmet limit

Data Analysis in a nutshell

Typical workflow in BSM searches

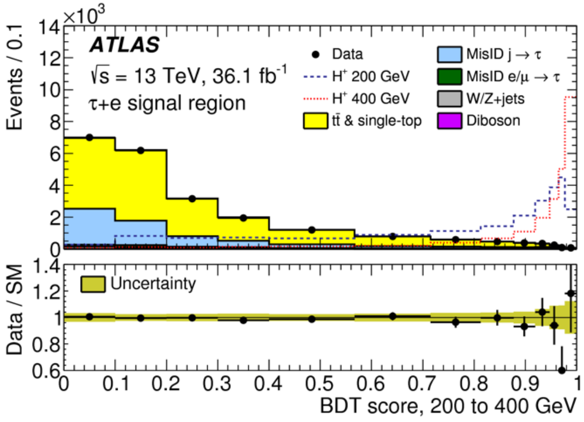
- Assume the signal model we want to search for and prepare the corresponding Monte Carlo simulation (MC).
- Construct the complete Standard Model background model using MC and/or data-driven techniques.
- Identify selection cuts defining so-called Signal Region (SR).
- Identify the test statistics – variable(s) – bearing discrimination between signal and background. Nowadays, often a MVA discriminant (Machine Learning)
- Validate background modelling in the Control Regions (CR - typically similar to SR but with suppressed contribution from the signal).

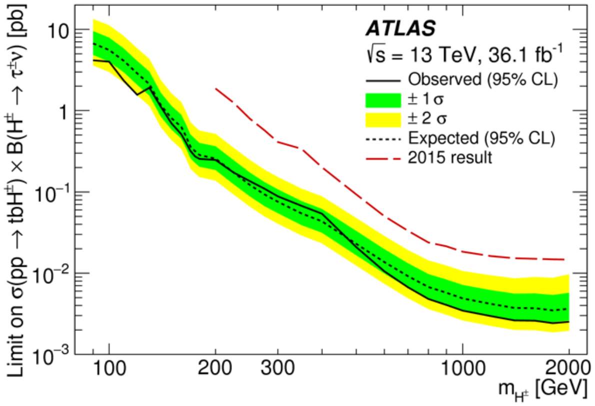


Data Analysis in a nutshell

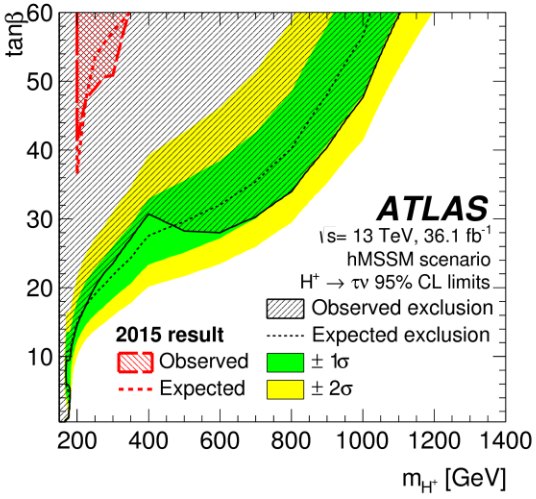
Typical workflow in BSM searches

- Perform statistical analysis of the test statistic in order to claim discovery or exclude signal strength μ exceeding certain value.





- The above needs to account for all possible systematic uncertainties
- Interpret the result within assumed model(s)

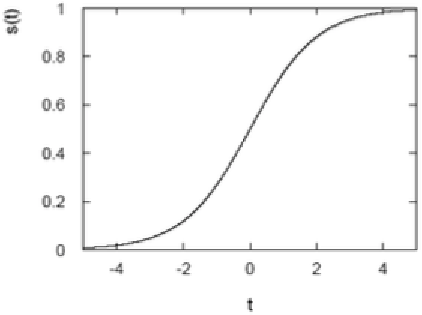


Artificial Neural Networks

The multi-layer perceptron

Use e.g. logistic sigmoid activation function,

$$s(u) = \frac{1}{1+e^{-u}}$$

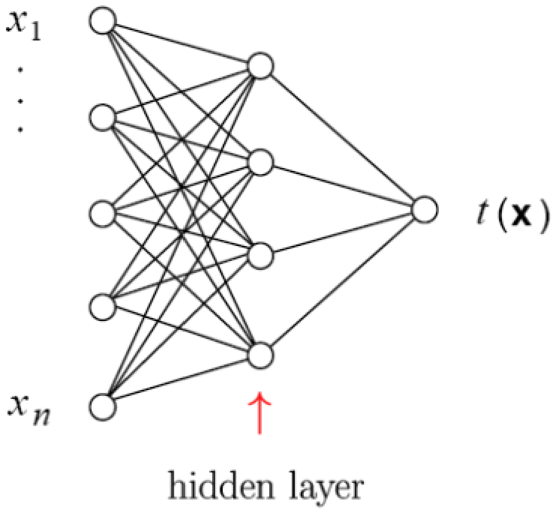


Define values for ‘hidden nodes’

$$h_i(\vec{x}) = s\left(w_{i0} + \sum_{j=1}^{n} w_{ij}x_j\right)$$

The network output is given by

$$t(\vec{x}) = s\left(a_0 + \sum_{i=1}^{n} a_i h_i(\vec{x})\right) .$$

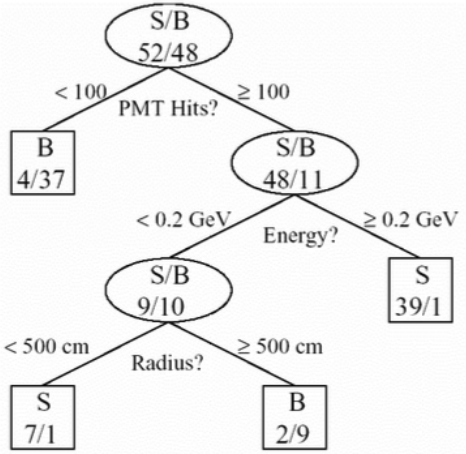


Trained on (simulated) data, usually by *backward propagation*, to minimize a specific *loss function*

(Boosted) Decision Trees

A training sample of signal and background data is repeatedly split by successive cuts on its input variables.

Order in which variables used based on best separation between signal and background.



Iterate until stop criterion reached, based e.g. on purity, minimum number of events in a node.

Resulting set of cuts is a ‘decision tree’.

Tends to be sensitive to fluctuations in training sample.

BOOST:
increase the weights of misclassified events and reconstruct the tree

Iterate → forest of trees (perhaps > 1000). For the mth tree,

$$T_m(\vec{x}) = \begin{cases} 1 & \vec{x} \text{ in signal acceptance region} \\ -1 & \text{otherwise} \end{cases}$$

Define a score α_m based on error rate of mth tree.

Boosted tree = weighted sum of the trees: $T(\vec{x}) = \sum_m \alpha_m T_m(\vec{x})$

Statistical analysis

Searching for BSM signal

Search for signal in a region of phase space; result is a histogram of some variable *x* with bin counts:

$$\mathbf{n} = (n_1, \ldots, n_N)$$

where bin contents depends on existence of the sought for signal (signal strength μ):

$$E[n_j] = \mu s_j + b_j$$

The Likelihood function:

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)}$$

Signal strength

Nuisance parameters

both s_j and b_j generally depend on nuisance parameters

Statistical analysis

Searching for BSM signal

The **profile likelihood ratio** provides an optimal test (Neyman-Pearson lemma):

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

maximizes for
a given μ

maximize *L*

The maximum Likelihood Ratio (LR) should be a near-optimal estimator for μ with nuisance parameters θ.

A monotonic function of LR is equally good.
In practice, minimise test statistic q:

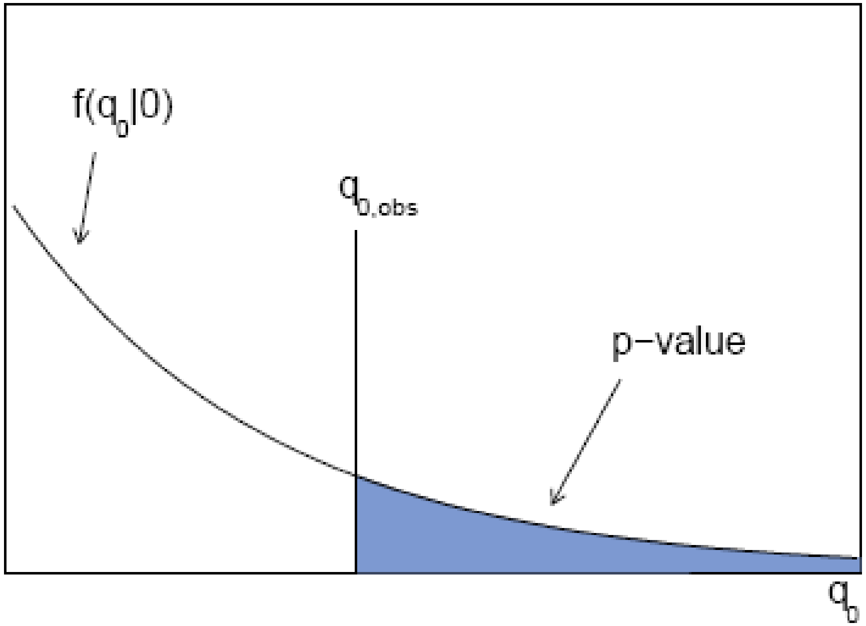
$$q = -2\ln\lambda(\mu)$$

Statistical analysis

p-value for discovery

Large q_0 means increasing incompatibility between the data and hypothesis, therefore *p*-value for an observed $q_{0,\mathrm{obs}}$ is

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$



From *p*-value get equivalent significance,

$$Z = \Phi^{-1}(1-p)$$

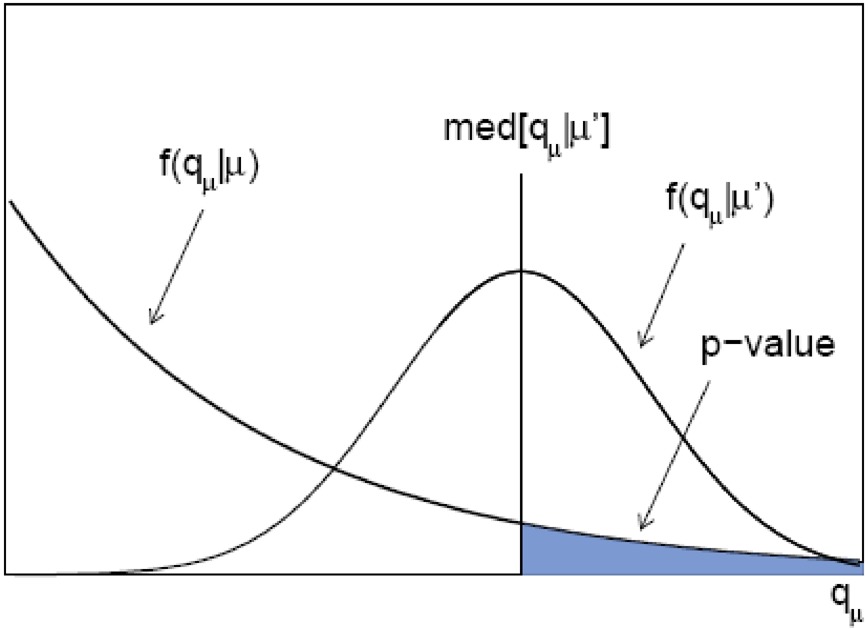
where Φ is the cumulative of standard Gaussian.

Statistical analysis

Expected (or median) significance / sensitivity

When planning the experiment, we want to quantify how sensitive we are to a potential discovery, e.g., by given median significance assuming some nonzero strength parameter μ′.

So for *p*-value, need $f(q_0|0)$, for sensitivity, will need $f(q_0|\mu')$.



Approximation due to Wald (1943):

$$-2\ln\lambda(\mu) = \frac{(\mu-\hat{\mu})^2}{\sigma^2} + \mathcal{O}(1/\sqrt{N})$$

$$\hat{\mu} \sim \text{Gaussian}(\mu', \sigma)$$

i.e., $E[\hat{\mu}] = \mu'$

σ from covariance matrix V, use, e.g.,

$$V^{-1} = -E\left[\frac{\partial^2 \ln L}{\partial\theta_i \partial\theta_j}\right]$$

(RCF limit)

Statistical analysis

discovery / upper limit

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

Discovery:

Try to reject background-only (μ = 0) hypothesis using:

$$q_0 = \begin{cases} -2 \ln \lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0 \; .$$

Upper limit:

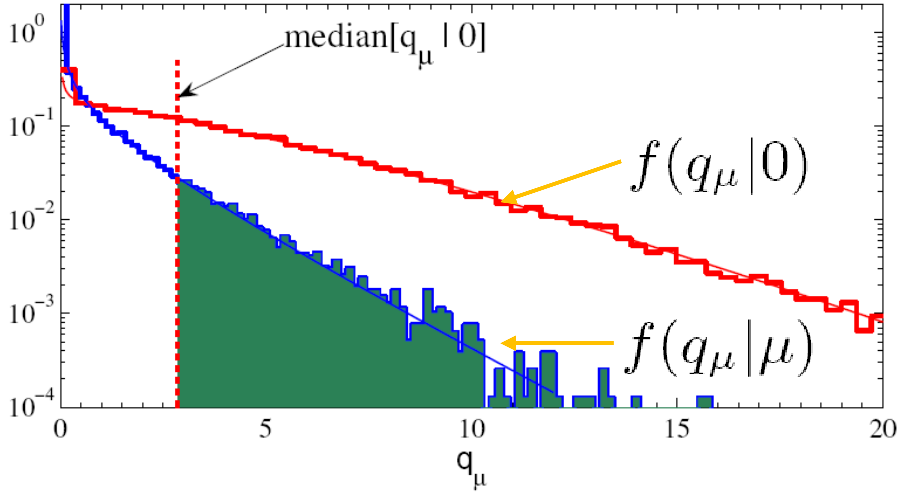
For purposes of setting an upper limit on μ use:

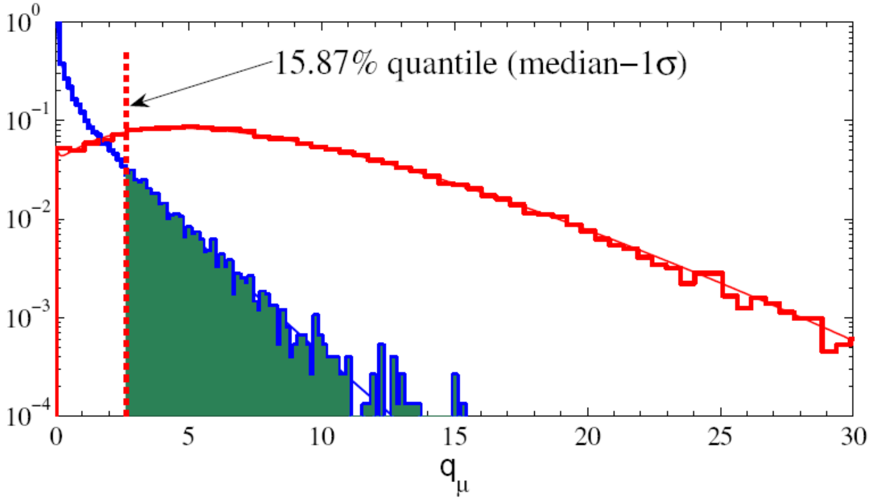
$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

$$p_\mu = \int_{q_{\mu,\mathrm{obs}}}^{\infty} f(q_\mu|\mu)\, dq_\mu$$

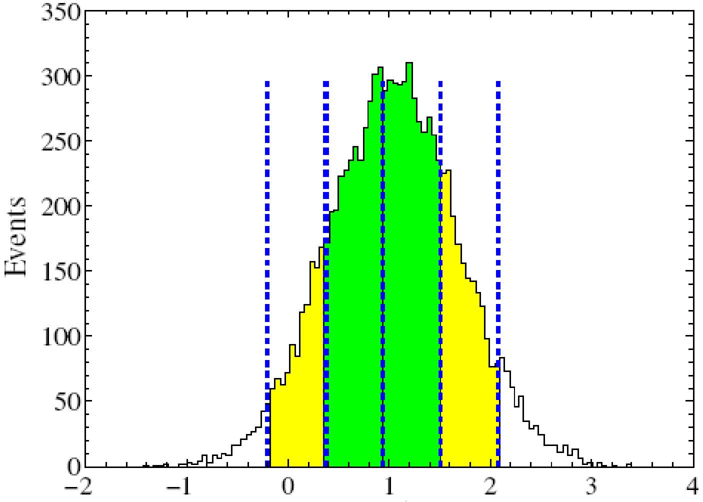
Statistical analysis

upper limit – example

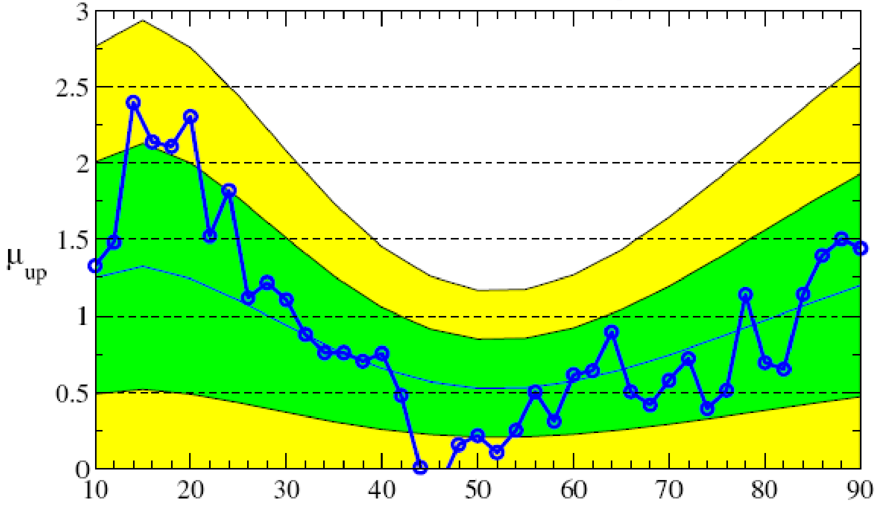




N statistically independent trials



The “Brazilian” plot

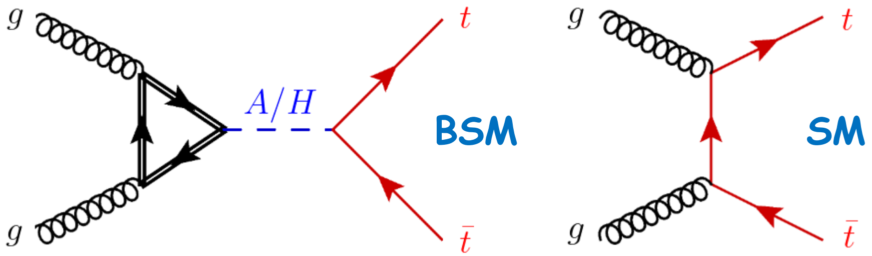


Systematic uncertainties on background (& signal) description generally weaken the limit and increase its error.

Life is not always this easy…

$A/H \rightarrow t\bar{t}$

(l, ll_{OS} final state)



- Strong **interference** with $t\bar{t}$ continuum.
- Simple limit on μ not feasible ☹

- **Search stage:** Fit $\sqrt{\mu}$

$$\mu S + \sqrt{\mu} I + B = (\mu - \sqrt{\mu})\boldsymbol{S} + \sqrt{\mu}(\boldsymbol{S} + \boldsymbol{I}) + \boldsymbol{B}$$

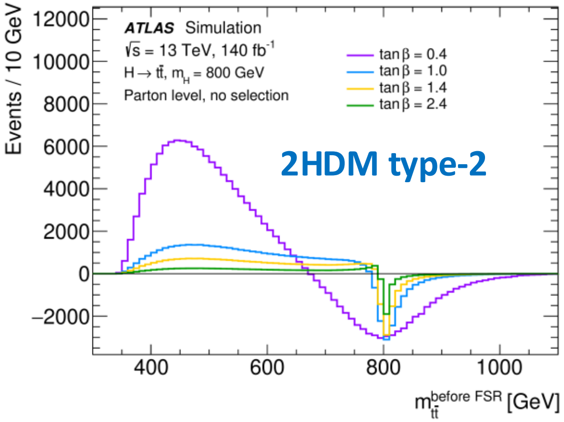
for each mass/width hypothesis.

Goal: potential rejection of $\mu = 0$ hyp.

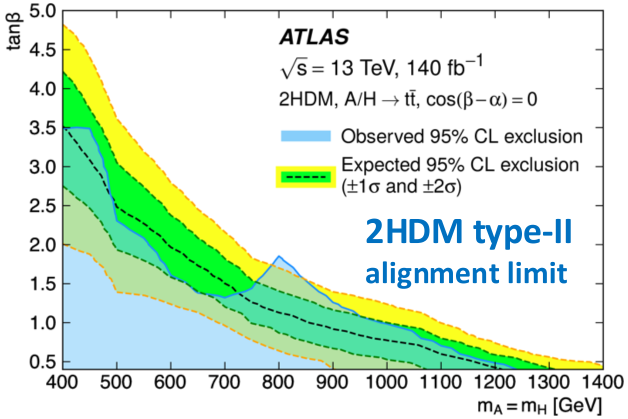
- **Exclusion stage:** $q = -2\ln(\mathcal{L}_1/\mathcal{L}_0)$

Goal: reject $\mu = 1$ hyp. against $\mu = 0$ one.

- Nonlinear dependence of $\mathcal{L}$ on $\sqrt{\mu}$! Disjoint exclusions possible. Full scan of phase space!



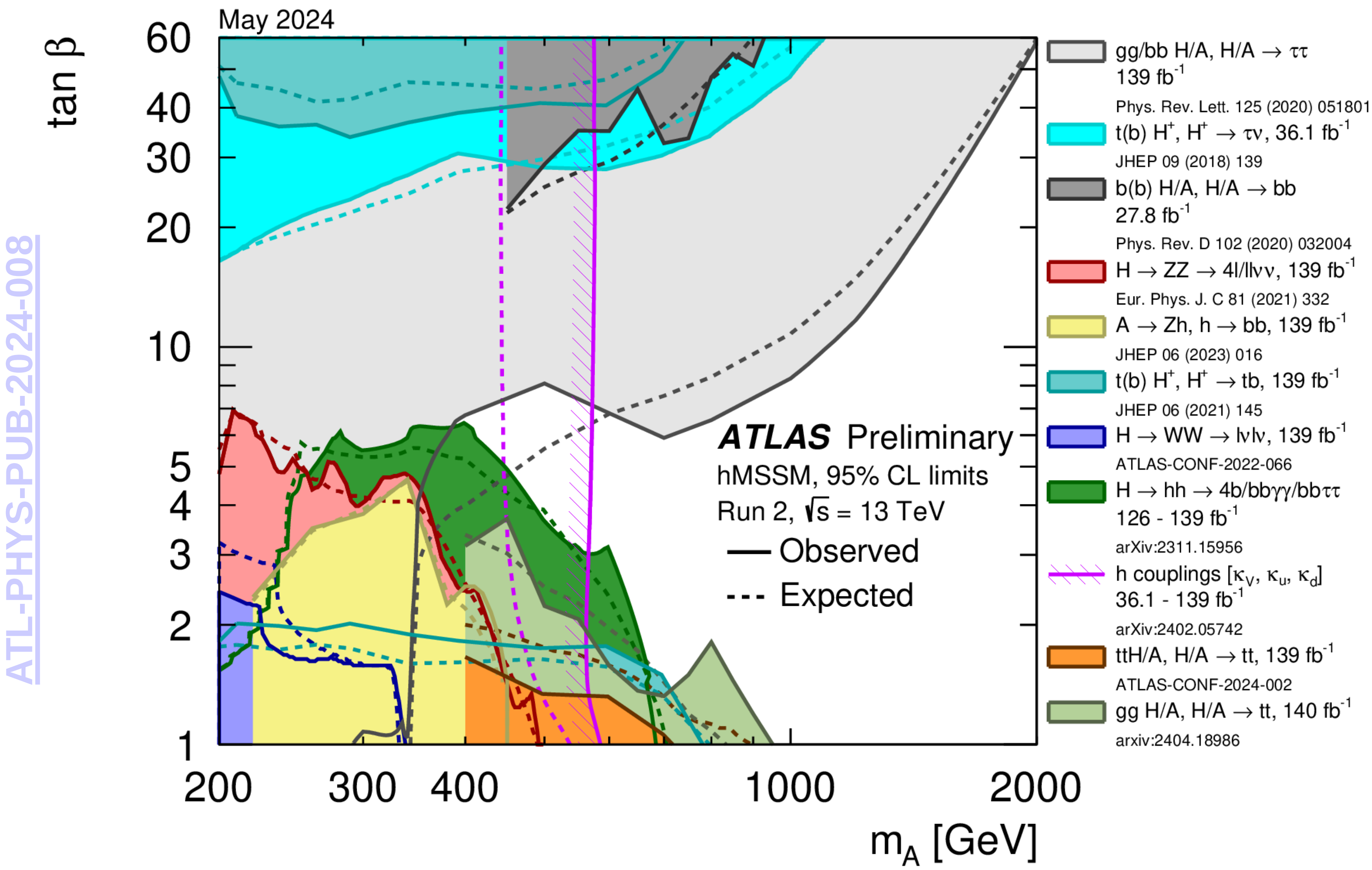
2HDM type-2



2HDM type-II alignment limit

arXiv:2404.18986

BSM higgs searches and constraints on hMSSM

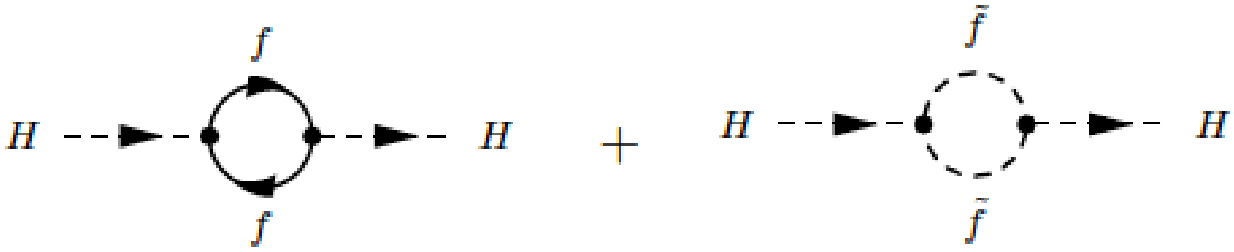


Supersymmerty

- Attractive solution: introduce a new symmetry, “supersymmetry” which links fermions and bosons
- Each fermion has a boson partner, and vice versa, with the same couplings.

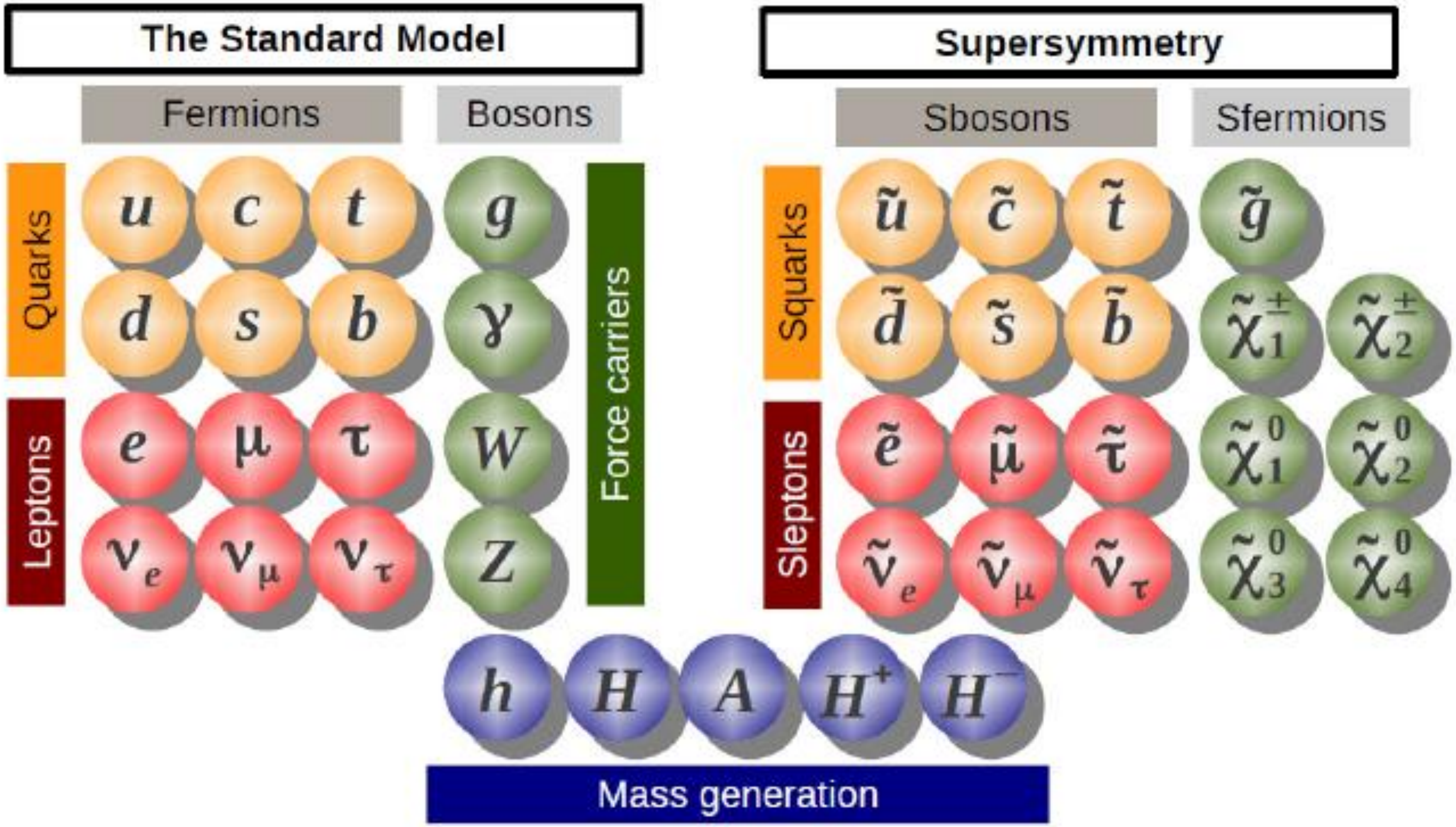
Ex. :	q (s=1/2)	→	$\boxed{\tilde{q}}$ (s=0)	skwark
	g (s=1)	→	$\boxed{\tilde{g}}$ (s=1/2)	gluino

- Boson and fermion loops contribute with opposite sign, giving a natural cancellation in their effect on the Higgs mass



- Must be a broken symmetry, because we clearly don't see bosons and fermions of the same mass
- However, this doubles the particle content of the model, and introduces lots of new unknown parameters

Supersymmetric family



$$\mathrm{SM}: \; W^\pm,\; W^0,\; B \xrightarrow{\text{mixing}} W^\pm,\; Z,\; \gamma$$

$$\mathrm{SUSY}: \; \tilde{H}_u^0,\; \tilde{H}_d^0,\; \tilde{W}^0,\; \tilde{B}^0 \xrightarrow{\text{mixing}} \tilde{\chi}_1^0,\; \tilde{\chi}_2^0,\; \tilde{\chi}_3^0,\; \tilde{\chi}_4^0$$

neutralinos

$$\tilde{H}_u^+,\; \tilde{H}_d^-,\; \tilde{W}^+,\; \tilde{W}^- \xrightarrow{\text{mixing}} \tilde{\chi}_1^\pm,\; \tilde{\chi}_2^\pm$$

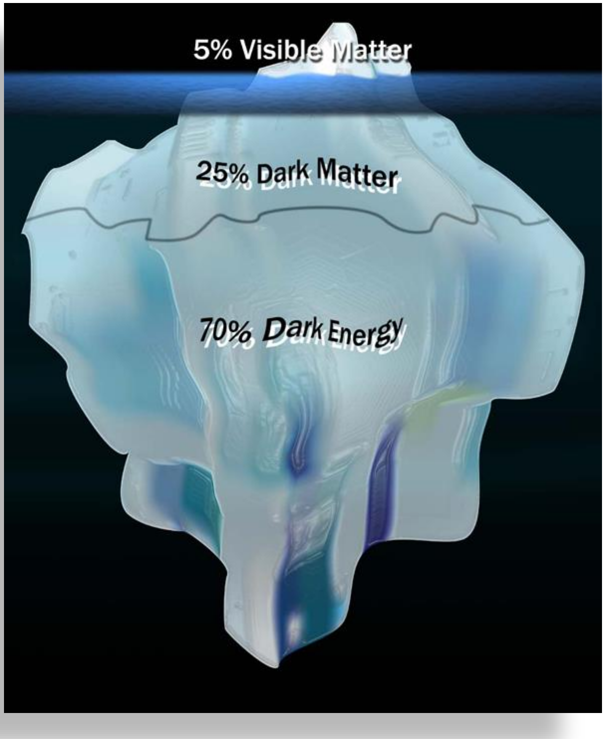
charginos

Supersymmerty & DM

- Impose *B* & *L* conservatiobn => R-parity

$$R_p = (-1)^{3(B-L)+2S} \qquad \text{S: Spin}$$

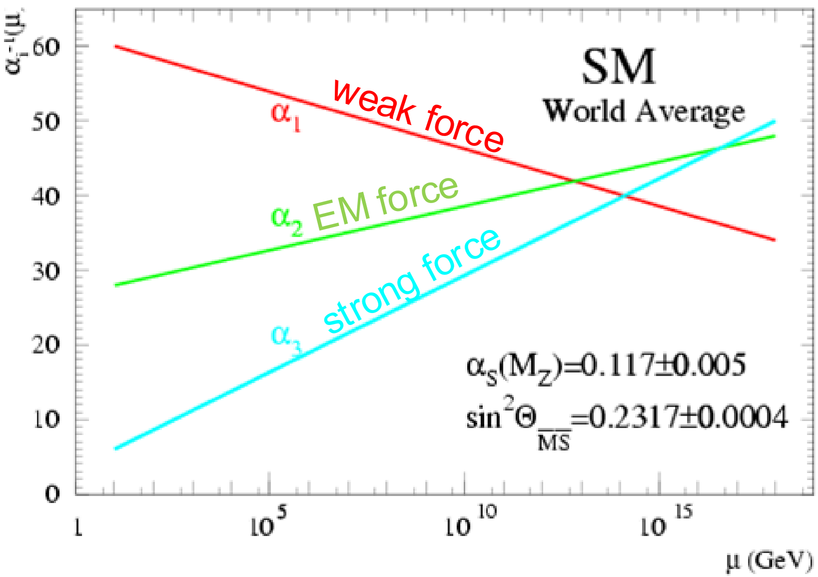
- SM particles R=+1
- SUSY particles R=-1
- Multiplicative number
- Two important consequences if R-parity is preserved:
  - Superpartners are pair-produced
  - Lightest superpartner is stable (LSP)
  - Proton is stable (in general SUSY allows for non conservation of L and B)

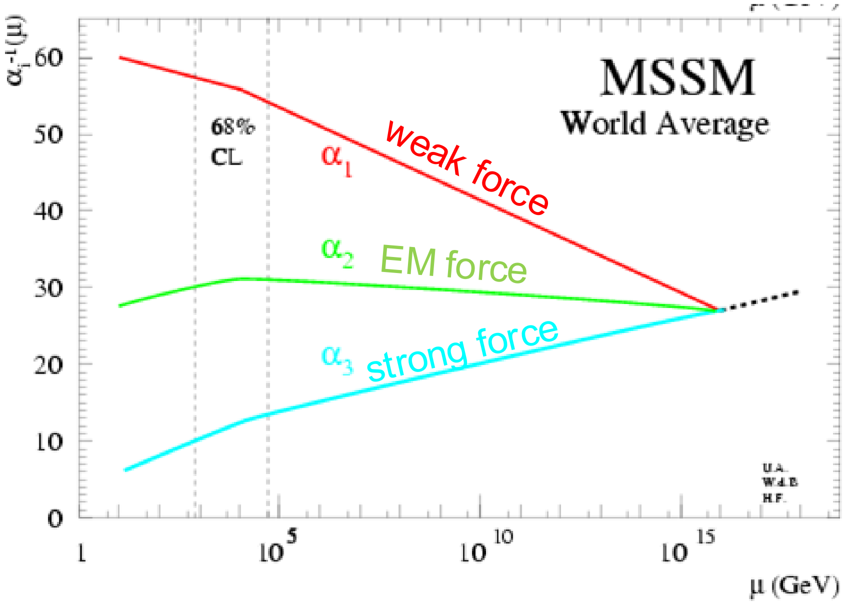


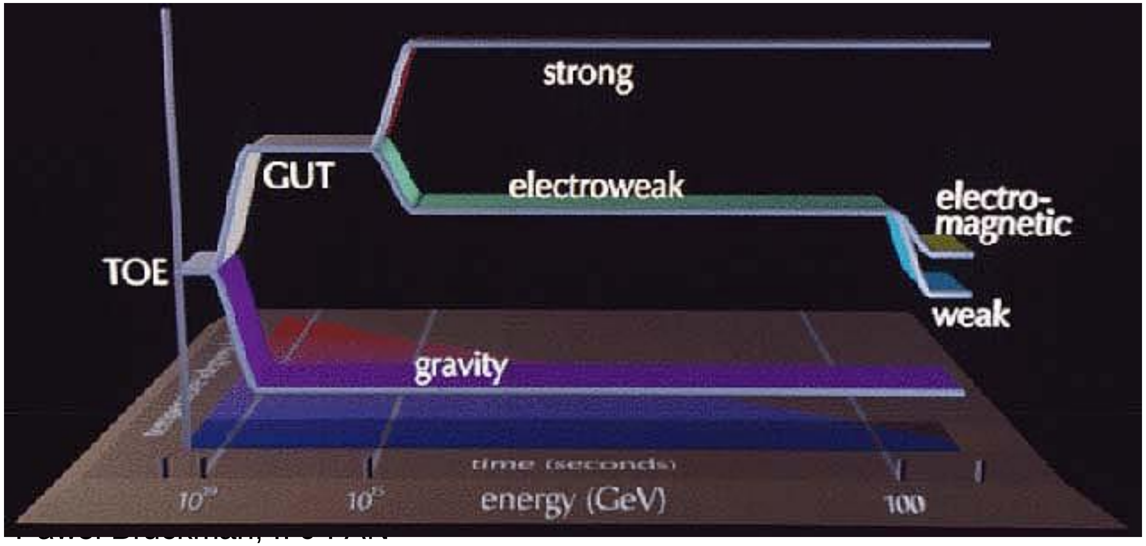
- LSP is good candidate for Dark Matter particle
  - neutralino (mix of bino, wino and higgsino)
  - Very hard to detect!

- Ordinary matter (~5%)
  – the only thing we knew until recently
- Dark matter (~25%)
  – does not emit light, but seen with gravity
- Dark energy (~70%)
  – do not know what it is; explains accelerated expansion

Supersymmerty & Grand Unification







- In the Standard Model, the interaction strengths are not quite unified at very high energy

- Add SUSY, the running of the couplings is modified, because sparticle loops contribute as well as particle loops

Why we would like Supersymmetry? summary

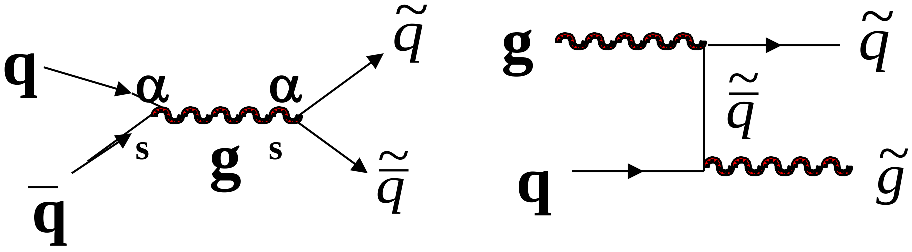
- Solution to „fine tuning problem”
- Dark matter candidate
- Coupling constants unification < M_P
- Simply beautiful extension of SM ☺
- ...and many others

Possible production and decay of SUSY particles @ LHC

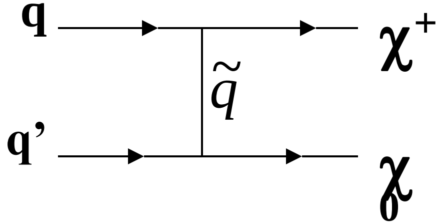
Basic scenario: R-parity conserved :

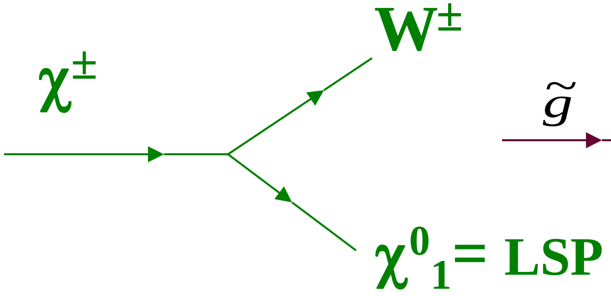
- SUSY is pair produced
- LSP at the end of the cascade decay (missing energy signature)

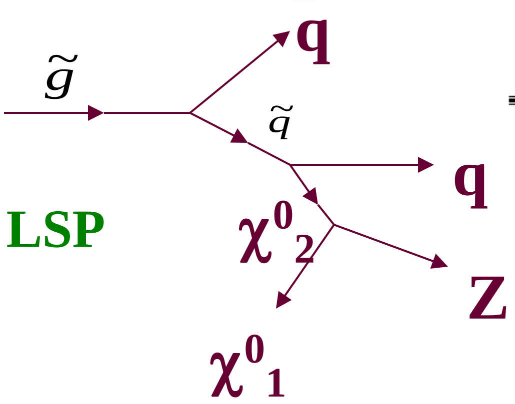
skwarks & gluinos (strong int.)



charginos & neutralinos (weak int.)

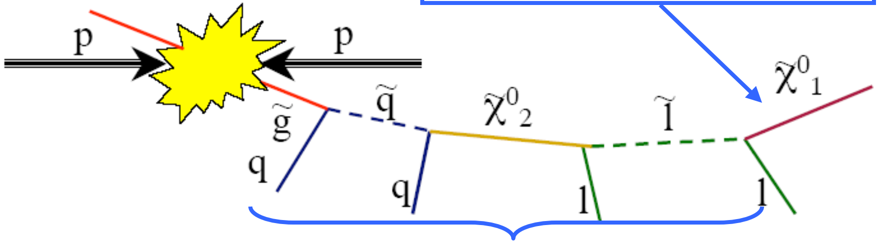






Understanding of SM backgrounds essential!

The cascade decay always ends with an LSP! (RPC) => Missing Transverse Energy.

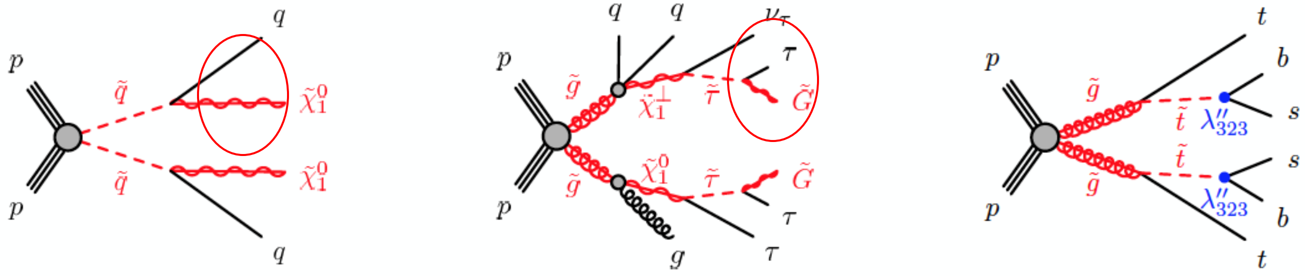


Lots of high p_T jets and leptons

SUSY & LHC?

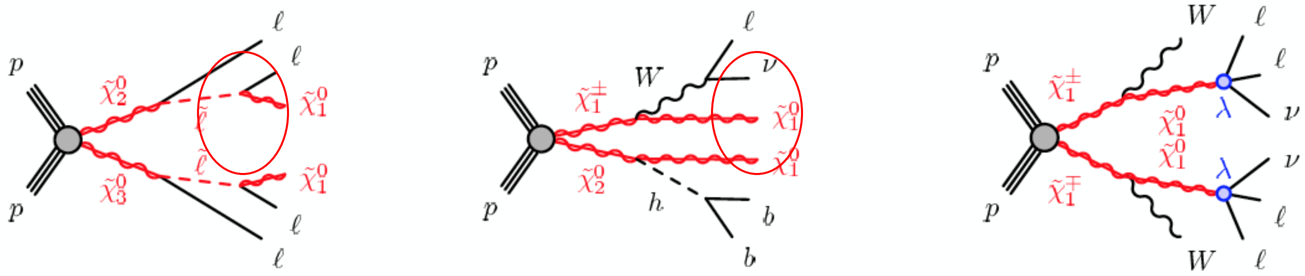
A lot of signatures!

- Strong production… (large cross-section)



- … or weak production

RPV



Important and difficult experimental observable:

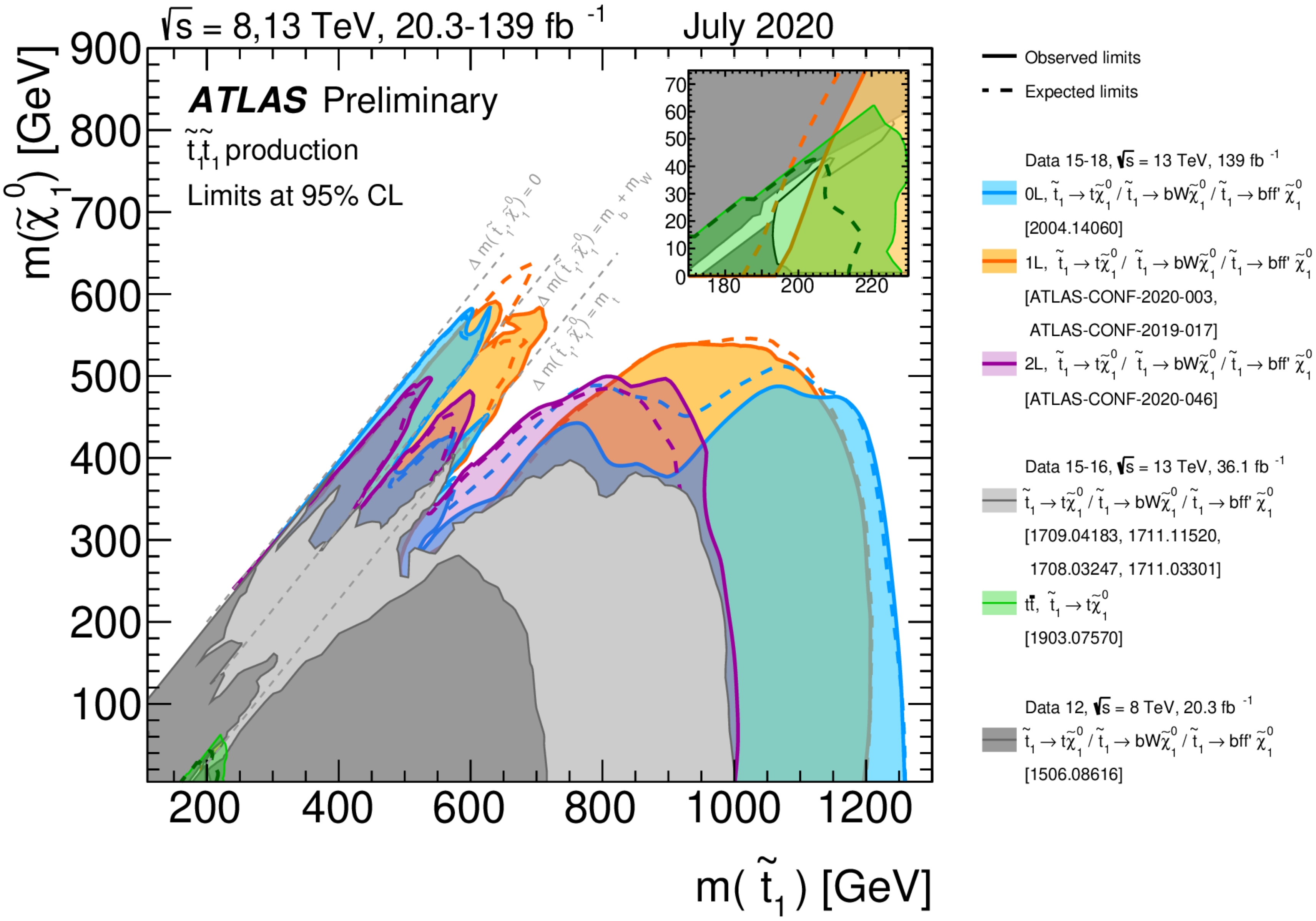
- Σ (all) => Missing Energy

In experiment we have to understand "all" with high precision!

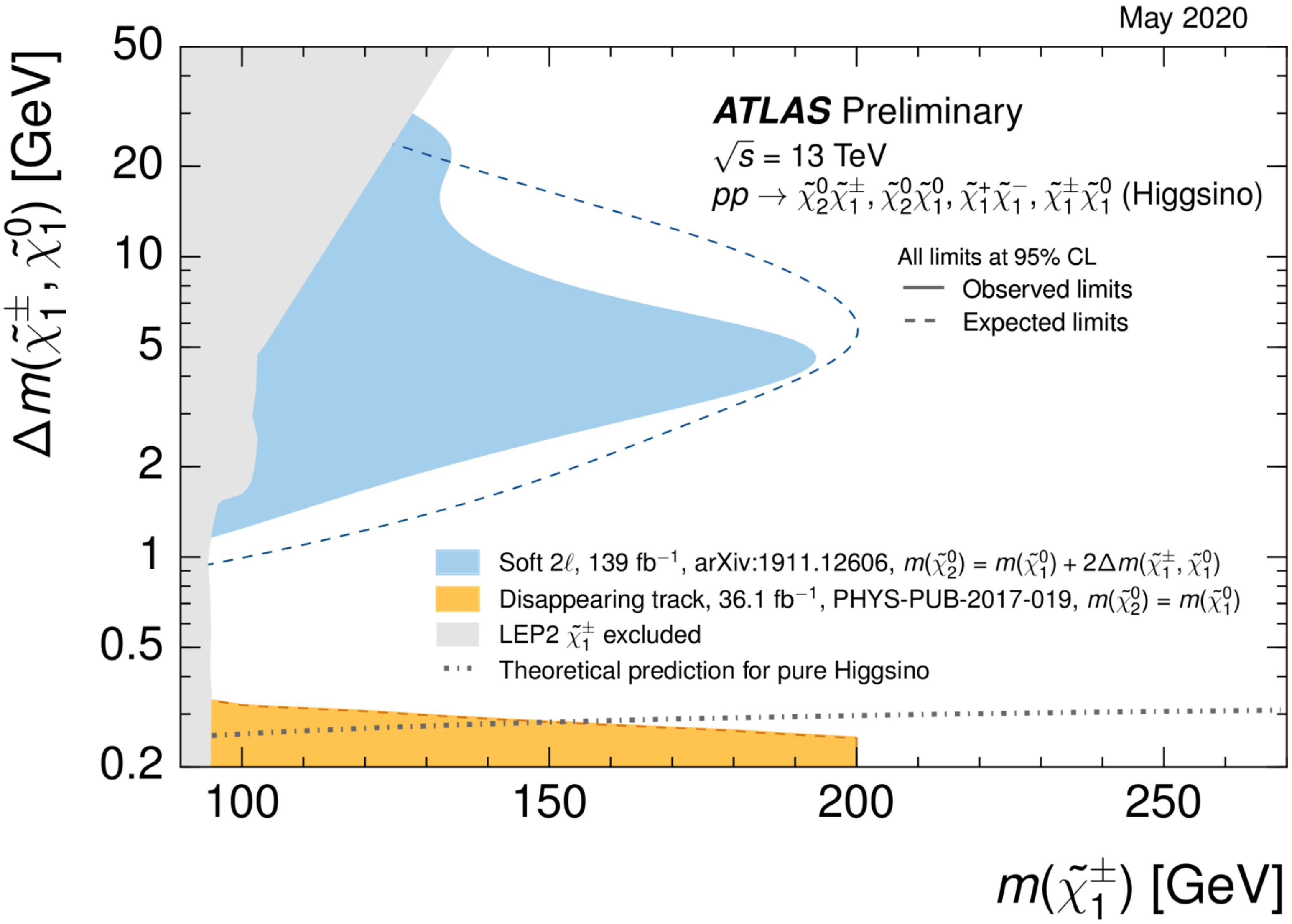
Richness of SUSY (new particles, production and decay channels) has its price

- Even Minimal Supersymmetric Standard Model has 124 free parameters
- Usually we introduce "scenarios" with additional relations between parameters (from mechanism of SUSY breaking)
  - In that case we work with fewer parameters

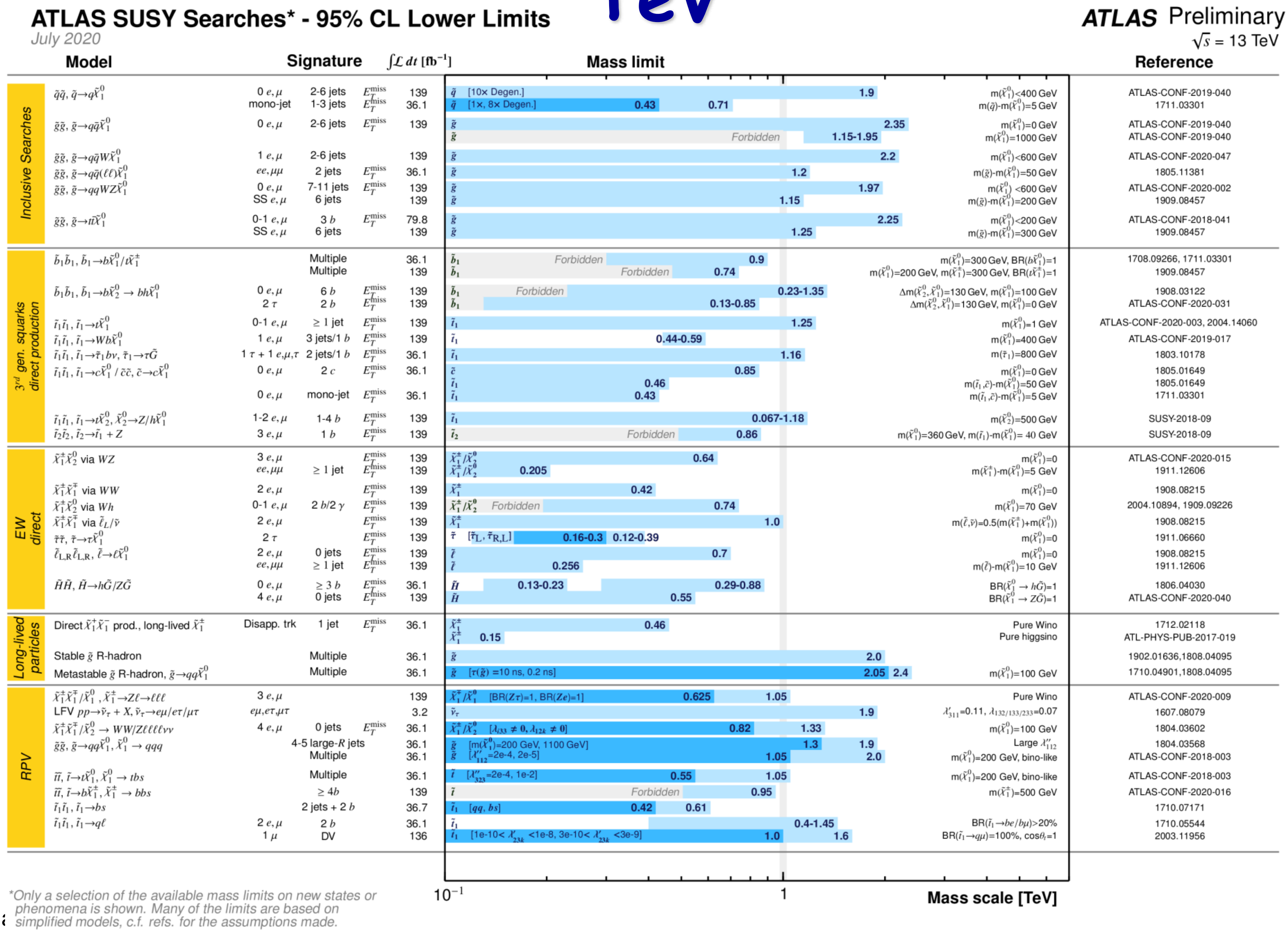
Example exclusion limits from ATLAS



Example exclusion limits from ATLAS



However, no sign of SUSY up to ~1 TeV

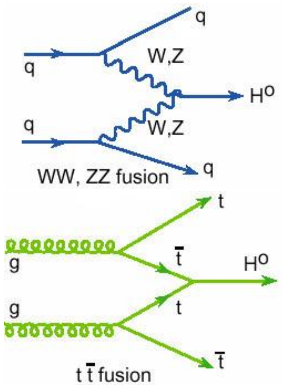


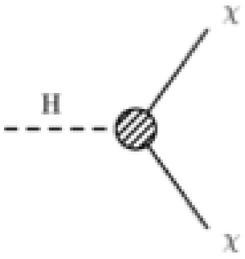
Dark matter revisited

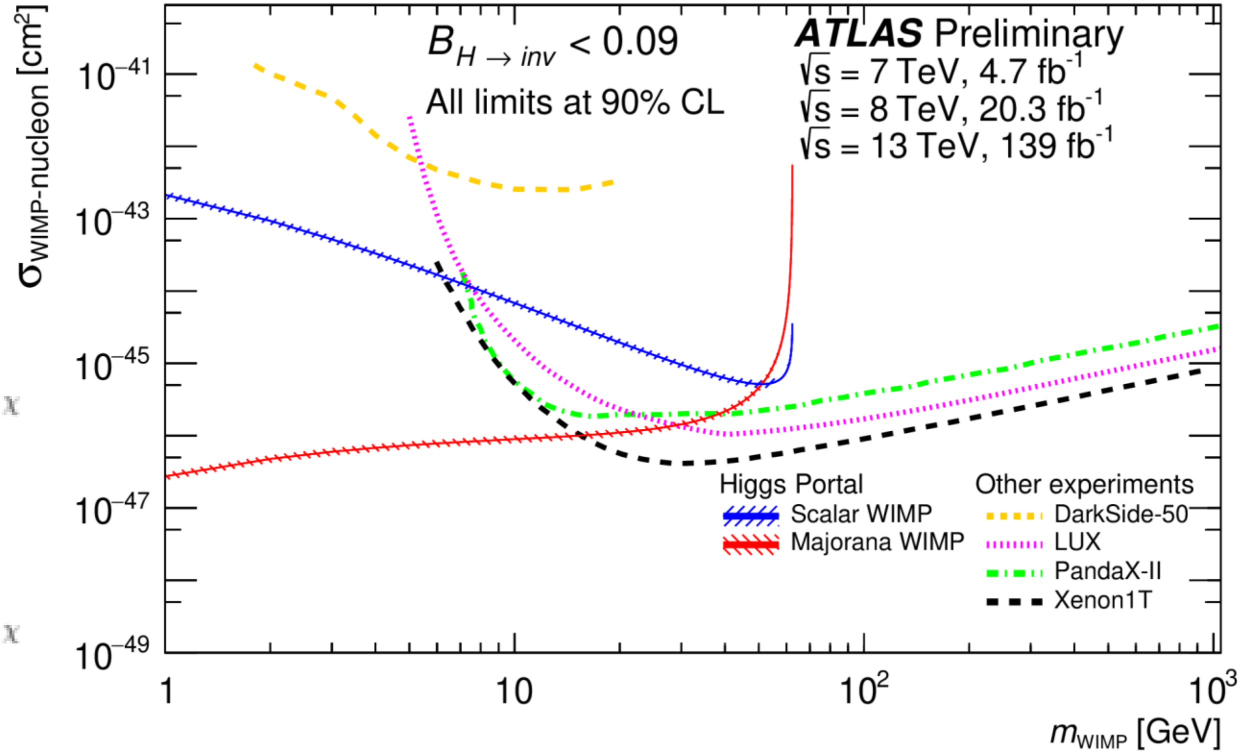
Higgs portal to Dark Sector

Direct searches for WIMP’s are complemented by constraints on invisible Higgs decays.
In the context of Higgs portal to DS models, invisible decays occure via 125 GeV Higgs mixing to a DS Higgs which subsequently decays to WIMPs.
The x-section limit can be converted to a limit on WIMP-nucleon cross-section for either Scalar or Majorana WIMP. Sensitivity up to $m_{WIMP}<m_H/2$!

VBF Higgs production and top-associated production are investigated.
Missing energy is the main signature.



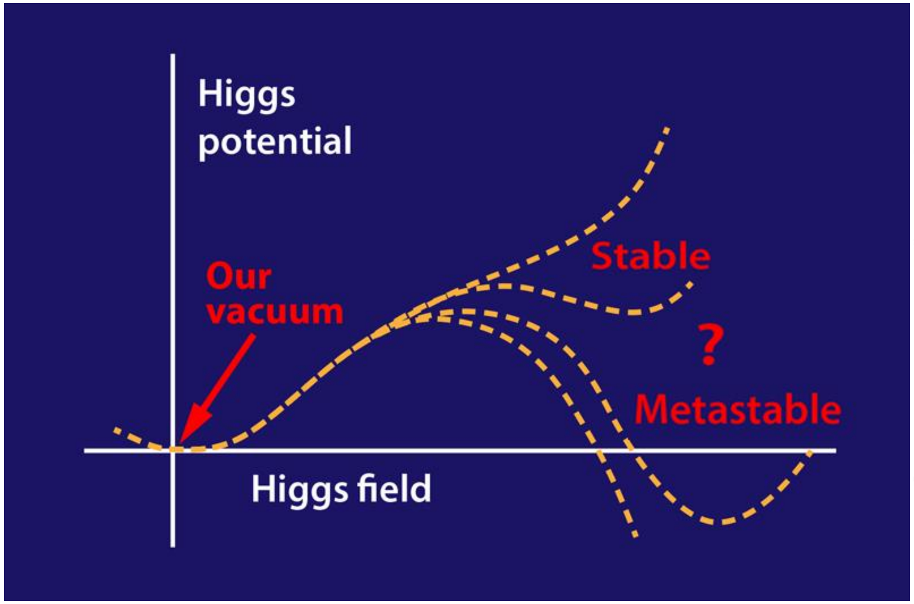


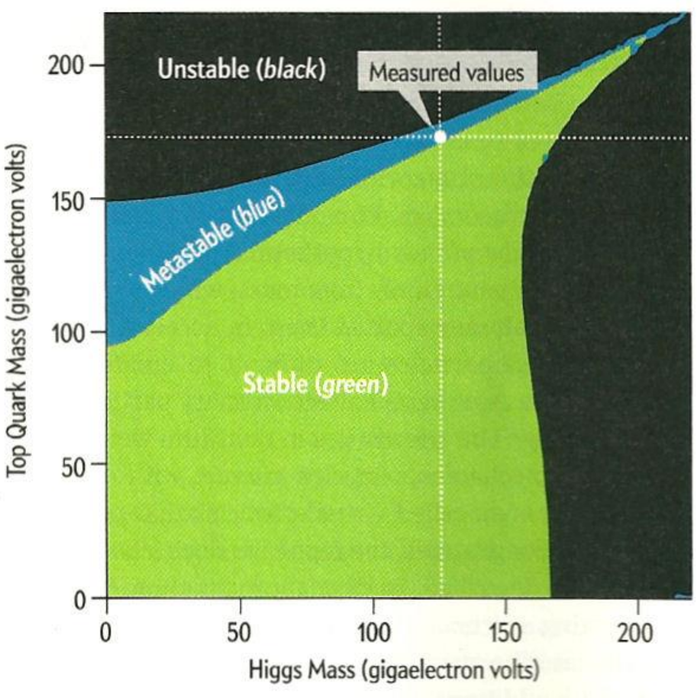


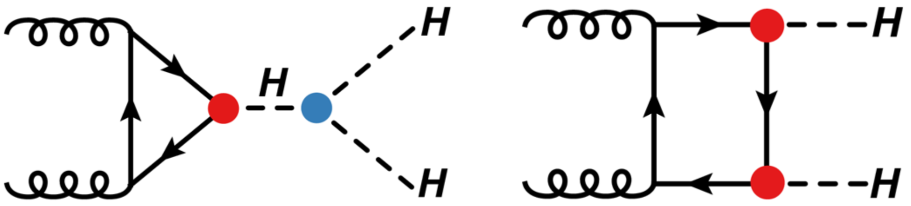
What is out fate?

Higgs potential and self-couplings

The confirmed BEH mechanism depends barely on the local expansion of the Higgs potential





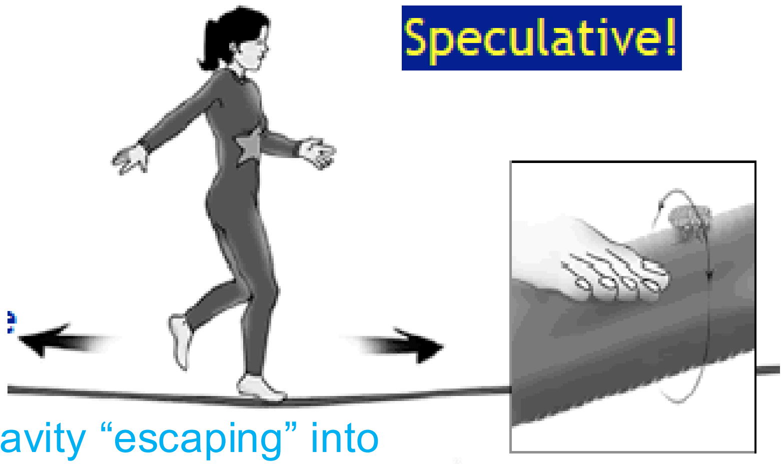


Higgs self-interaction probed e.g. via the di-Higgs production (0.1% of pp->H x-section).
Currently not observable, unless New Physics contributes!

Why gravity so weak? Extra Dimensions?

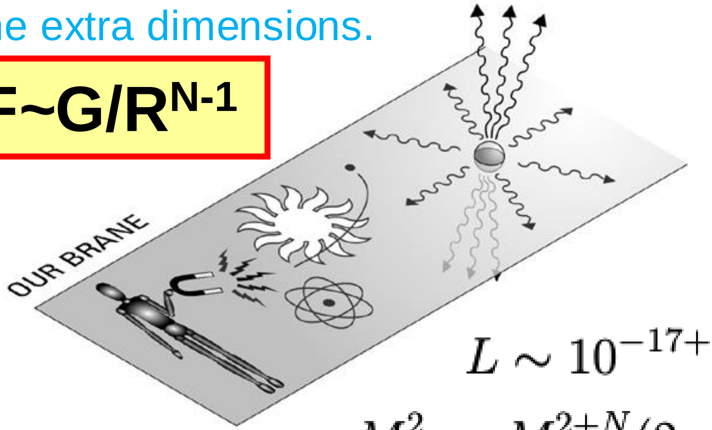
- The ultimate unification of the forces should include gravity (TOE)
- But gravity very much weaker than other forces
- Most particles (and us) can only travel in the regular 3 space + 1 time dimensions
- Gravitions - the bosons which propagate gravity - can travel in the Extra Dimensions (Arkhani-Hamed Dimopoulos Dvali -1998)
- The real gravitational constant is larger than the effective one we see
- They have to be small extra dimensions, otherwise we'd have seen them already
- If the dimensions are big enough we might see their effects at the LHC!

Speculative!



Gravity "escaping" into the extra dimensions.

F~G/R^{N-1}

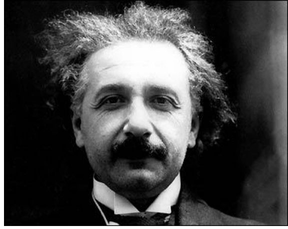


$$L \sim 10^{-17+30/N}$$

$$M_{\rm Pl}^2 = M_*^{2+N}(2\pi L)^N$$

- Mini black hole production at the LHC would be an observable consequence of extra space-time dimensions
- Black hole will decay very quickly (~10^{-26} s) via Hawking radiation: particles emitted isotopically

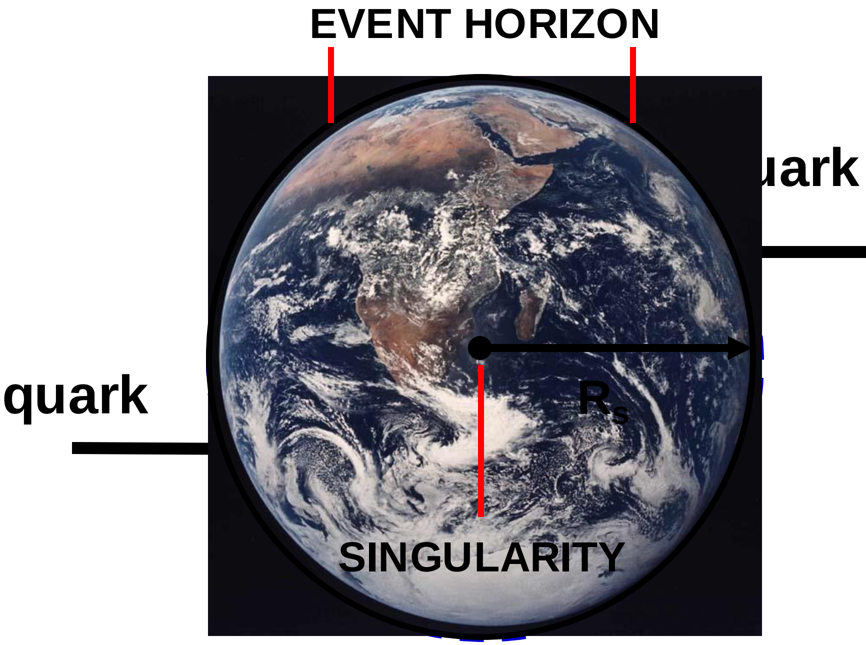
Production & decay of Black Holes



Bring mass closer than its Schwarzschild Radius, R_S,

$$\boxed{R_S = \frac{2GM}{c^2}}$$

and a black hole will form!



- BH lifetime @ LHC~ 10^{-27}–10^{-25} s

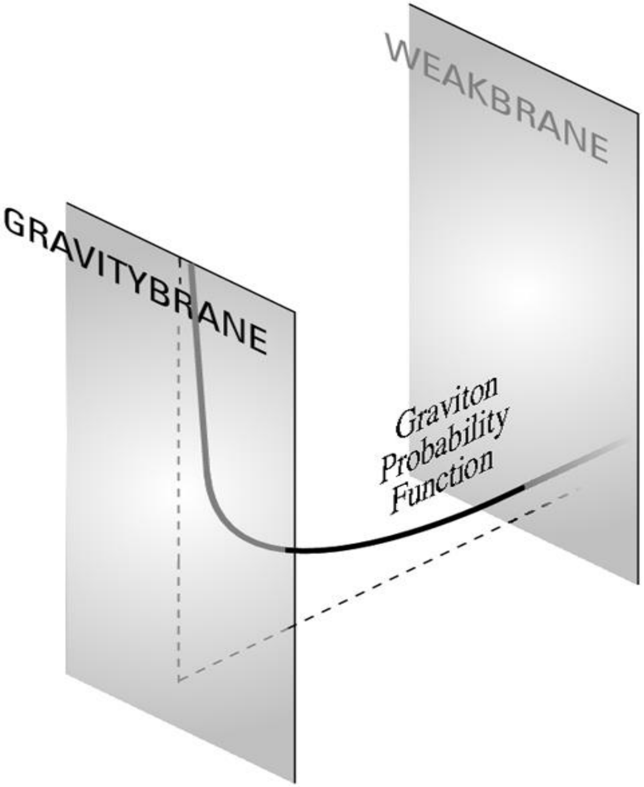
due to Hawking radiation

- Decays with equal probability to all particles.

$$\boxed{R_S^{Earth} = 8.8\text{mm}}$$

A micro Black Hole could look like this:

Randall-Sundrum models (RS)



$$ds^2 = g_{MN}\, dx^M dx^N = e^{-2\sigma} \eta_{\mu\nu}\, dx^\mu dx^\nu - dy^2 \,,$$

- All particles but graviton live on the TeV (weak) brane
- Small probability for graviton to be near the Weak-brane
- Graviton coupling suppressed by $1/M_{Pl}$
- If we live anywhere but the Gravity-brane, gravity will seem weak
- Natural consequence of warped geometry

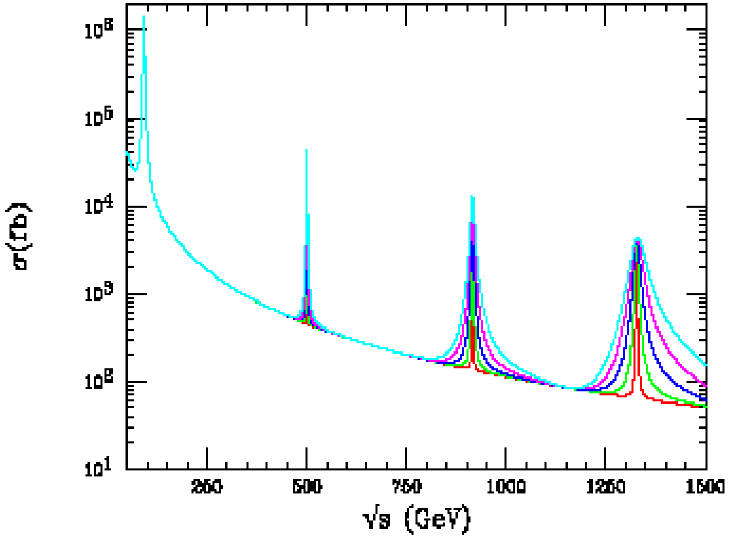
(Randall Sundrum – 1999)

Consequence
KK excitations

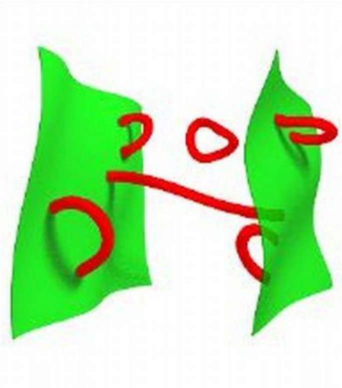
- All partricles living in the bulk will have Kaluza-Klein excitations!
- Those manifest in 4D as heavier mass states (the entire spectrum!)

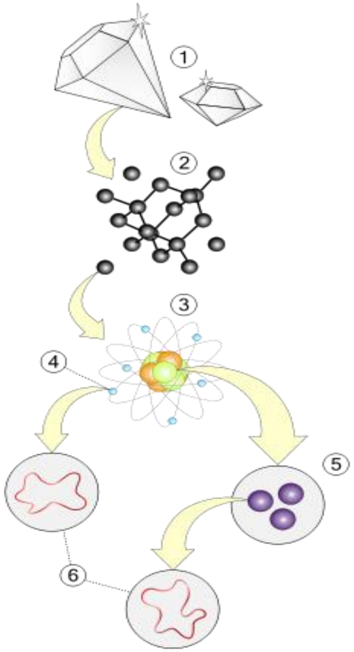
Protons collide

- ✘ **Produce a Kaluza-Klein particle**
- ✘ **Which Decays**
- ✘ **Definite mass spectrum and “spin”-2 (if a graviton!)**



TOE – super-strings?





- The most famous candidate is the (super)string theory
  - Goal: marriage of gauge theories with gravity!
- Basic building blocks are not point-like particles, but 1-D objects – the strings
- Emission or absorption of a particle corresponds to breaking up or merging strings
- Particles are string excitations, from a distance look like point-like objects.
- String theories require 9(10) space dimensions + one time dimension.
- Due to spontaneous symmetry breaking only 3D are large. The others remain small and curved.
- The theory remains „secure” as there is no way to validate or falsify it experimentally.

Summary

- The discovery of the Higgs boson finally completes the Standard Model of particle physics.
- The fundamental 125 GeV scalar exhibits all properties expected from SM Higgs.
- Neither Supersymmetry nor large Extra Dimensions have been observed at LHC.
- SM holds strong while BSM hides cleverly from us.
- But this is not the the end of our quest.
- The Higgs sector remains exquisitely attractive tool to search for BSM phenomena.
- A lot of crucial questions still unanswered.
- Like never before, the breakthrough will be driven by experimental evidence.
- Many options on the market to address the vital puzzles.

- We are in a particularly exciting moment.

HEP needs you!!!