Physics at the LHC: from Standard Model to new discoveries

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Outline

- Standard Model
- LHC
- Higgs boson at the LHC
- Beyond the Higgs boson
- Conclusion

The Standard Model

- The Standard Model:
  - relativistic quantum renormalizable field theory;
  - gauge group $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_R$.
- Particle content:
  - leptons: $e, \mu, \tau; \nu_e, \nu_\mu, \nu_\tau$.
  - quarks: u, c, t; d, s, b.
  - bosons: $g, \gamma, Z, W; H$.
- All the particles but the Higgs boson H have been found.
- As a matter of principle, every fact that exists in sciences derives from the Standard Model.
- The Standard Model, as we know it, can not be the final theory; gravity is not included.

Experimental tests

- Collider tests: $E = mc^2$:
    - produce new (heavy) particles by increasing the energy of the colliding objects
    - LEP, Tevatron, LHC, ILC(?)
- Precision tests: $\Delta t \; \Delta E \sim \hbar$:
    - quantum fluctuations lead to testable imprints.
    - magnetic and dipole moments of elementary fermions, muon decay, atomic parity violation, CP-violation, flavor violation $\mu \to e\gamma$.
- The SM has been tested through energies $\sim 100 \ \mathrm{GeV}$ or distances $\sim 10^{-18} \ \mathrm{m}$.
- No sizable deviations from the Standard Model predictions found so far.
- Most of the facts that do not fit into the Standard Model come from cosmology/astroparticle physics:
    - dark matter;
    - dark energy;
    - baryon asymmetry;
    - neutrino masses.
- To accomodate those facts, modifications of the Standard Model are required.

Modifications of the Standard Model

- Empirical approach:
    - minimal modifications to accomodate established facts;
    - keep renormalizability as the guiding principle for building the theory;
- Aesthetic approach: forget about the rules of the game in the renormalizable quantum field theory – ask “Why?”
    - Why is gravity so weak? $M_{\mathrm{Planck}} \gg 1\ \mathrm{TeV}$
    - Why the Higgs boson mass is stable against radiative corrections?
    - Why are neutrino masses so close to the dark energy scale?
- extra dimensions, little Higgs, Higgsless models, landscape, variations of the above .
- supersymmetric extensions of the SM.
- To find the Higgs boson and to search for beyond the Standard Model physics, the Large Hadron Collider (LHC) is being built.

The LHC will find something

- Solid argument: either the SM Higgs boson is found at the LHC or something unexpected happens:
  - If $m_H < 1$ TeV, the LHC will see the Higgs;
  - If $m_H > 1$ TeV, the interaction of electroweak gauge bosons in the SM becomes strong at around 1 TeV.
- Less solid argument: hierarchy/naturallness problem.
  - It is not natural that the SM with the light Higgs boson is a valid theory up to an arbitrary large scale.
  - Assume SM is only valid up to a cut-off $\Lambda \sim 10$ TeV:

$$m_H^2 = m_{\rm tree}^2 - \frac{3\lambda_t^2\Lambda^2}{8\pi^2} + ... = m_{\rm tree}^2 - 100[200 \text{ GeV}]^2.$$

  - To have $m_H^2 \sim (200 \text{ GeV})^2$, a tuning of about 10^{-2} is required in $m_{\rm tree}^2$.
- The hierarchy/naturallness problem is solved in BSM models by introducing new forms of matter with mass about few TeV $\longrightarrow$ such particles will be, generically, found at the LHC.

The LHC

- The LHC parameters:
  - proton beams
  - collision energy 14 TeV → ×7 Tevatron
  - luminosity 10 fb^{-1} → ×100 Tevatron
  - Two major all purpose detectors: ATLAS and CMS.
- Increase in energy and luminosity leads to very high rates for SM processes

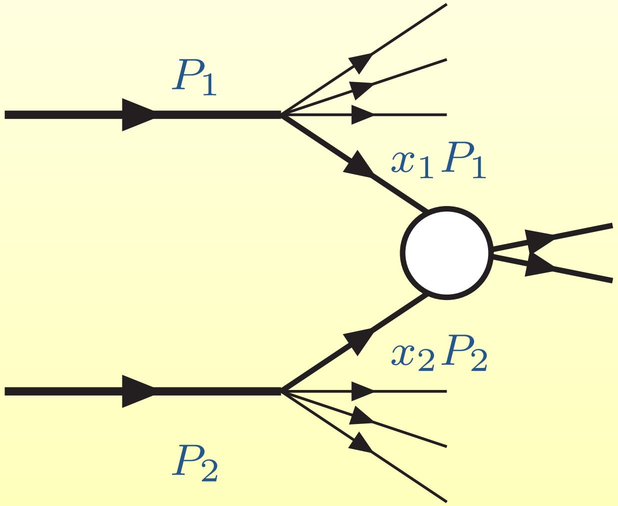
Process	σ (nb) $\equiv$ evts/s
Jets, $E_T > 0.1$ (2) TeV	10^3 (10^{-4})
$W^\pm \rightarrow e\nu_e$	20
$c\bar{c}$, $b\bar{b}$	8×10^6, 5×10^5
$t\bar{t}$	0.8

- A machine with unique potential and unique challenges.

The LHC: challenges

- Hadron collider: non-perturbative dynamics:
    - Factorization theorems → universal non-perturbative input;
    - Asymptotic freedom → applicability of perturbation theory;

$$\sigma = D \otimes \sigma_{\rm pert} \otimes F$$

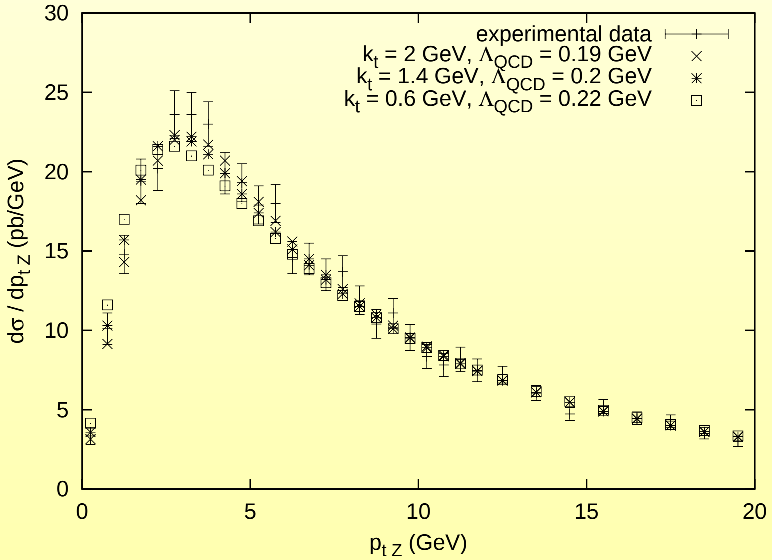


- F – parton distribution function; data;
- D – fragmentation models; data;
- $\sigma_{\rm pert}$ – hard scattering cross-section; theory.

- Fixed order perturbation theory often insufficient.

The LHC: challenges

- All orders treatment of QCD – non-trivial:
  - Perturbation theory ⟶ shower event generators ;
  - Shower event generators ⟶ hadronization models;
  - Hadronization models ⟶ detector response simulation.

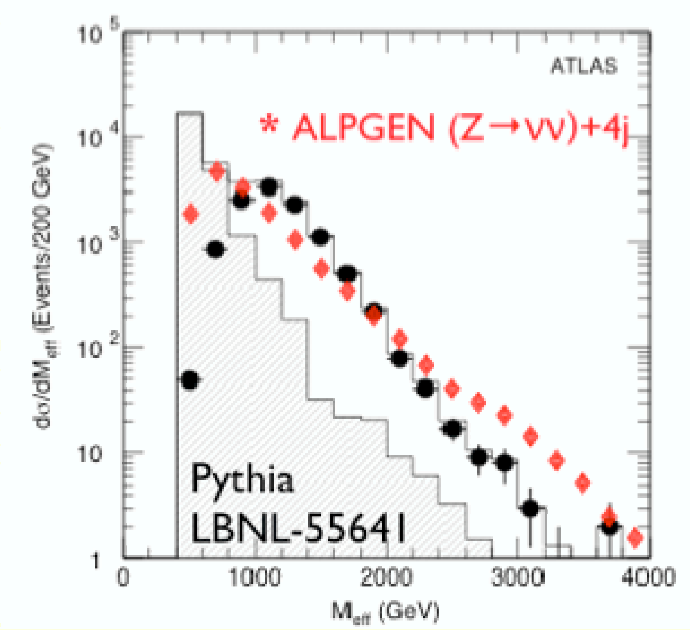


Non-trivial interplay of many ingredients may lead to puzzles:

- 1984 UA1 “discovery” of the top quark with $m_{\text{top}} = 40 \pm 10$ GeV.
- large $E_\perp$ jets at the Tevatron, Run I;
- B-meson production cross-section at the Tevatron, Run I.
- NuTeV $\sin^2\theta_W$.

- A particular important issue for the LHC is an accurate computation of hard multijet processes (backgrounds to New Physics searches).

The LHC: challenges

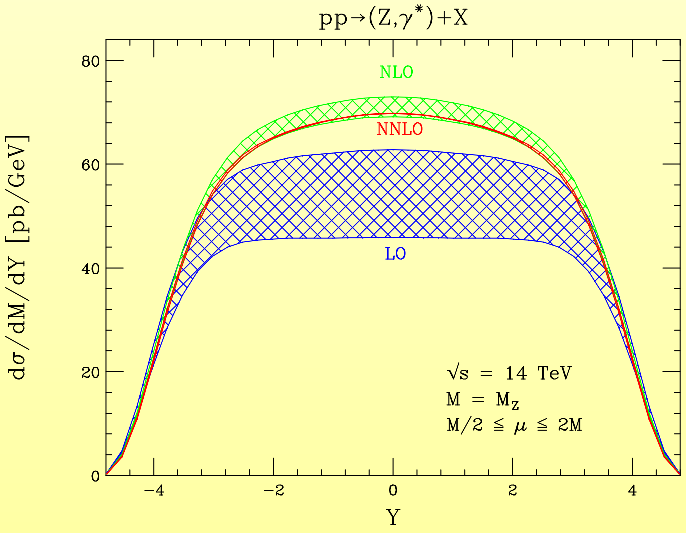


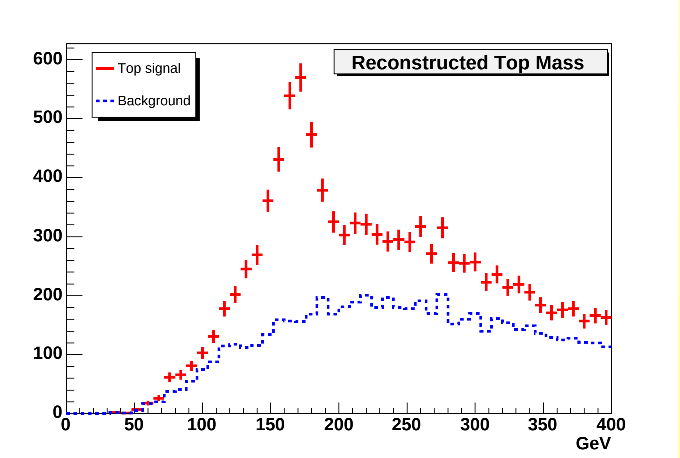
$$M_{\rm eff} = \sum_{\rm jets} p_\perp + E_\perp^{\rm miss}$$

- ALPGEN: exact matrix elements; correct hard emissions built in.
- PYTHIA: emulates hard emissions by producing large number of softer jets.
- PYTHIA underestimates the background significantly.
- Catani-Krauss-Kuhn-Webber procedure to combine shower event generators with exact matrix elements.

The LHC: rediscovering the Standard Model

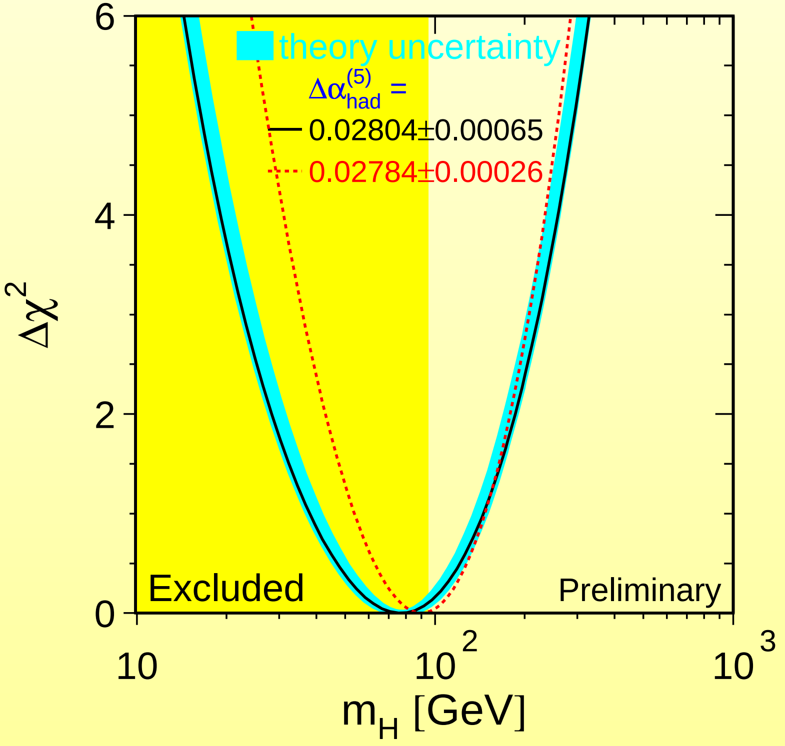
- The first priority of the two LHC collaborations is to test and verify their detector performances using basic Standard Model processes:
  - $Z \rightarrow l^+l^-, W \rightarrow l\nu$ lepton energy scale; tracking efficiency;
  - Z, W – parton distribution function, luminosity monitoring; M_W.
  - $t\bar{t}$ – b-tagging, jet energy scale
  - $W/Z +$ jets, QCD jets – verify theoretical tools.





Hunting the Higgs boson at the LHC

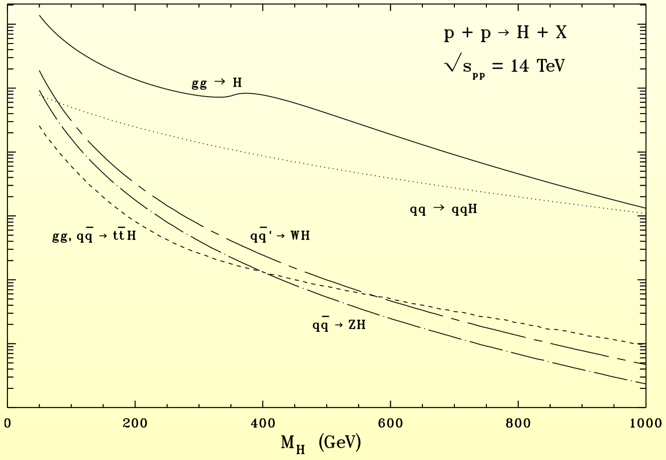
- Discovery of the Higgs boson is the most important goal of the LHC physics program:
  - test the mechanism of EWSB
  - find the last missing particle of the Standard Model
- Precision electroweak fits and direct bounds from LEP imply that the Higgs boson mass is $m_H \sim 100 - 200$ GeV.

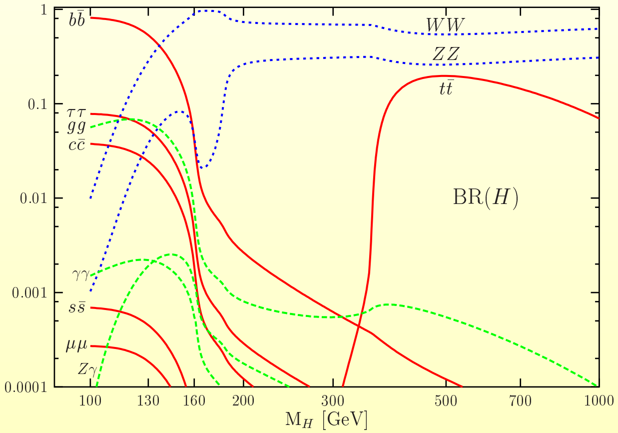


$$m_W = 80.3827 - 0.0579 \ln \frac{m_H}{100} - 0.008 \ln^2 \frac{m_H}{100}$$
$$-0.517 \left(\frac{\Delta\alpha_h^{(5)}}{0.0280} - 1 \right) + 0.543 \left[\left(\frac{m_t}{175} \right)^2 - 1 \right]$$
$$-0.085 \left(\frac{\alpha_s(m_z)}{0.118} - 1 \right) .$$

Hunting the Higgs boson at the LHC

- Higgs production processes and decay channels

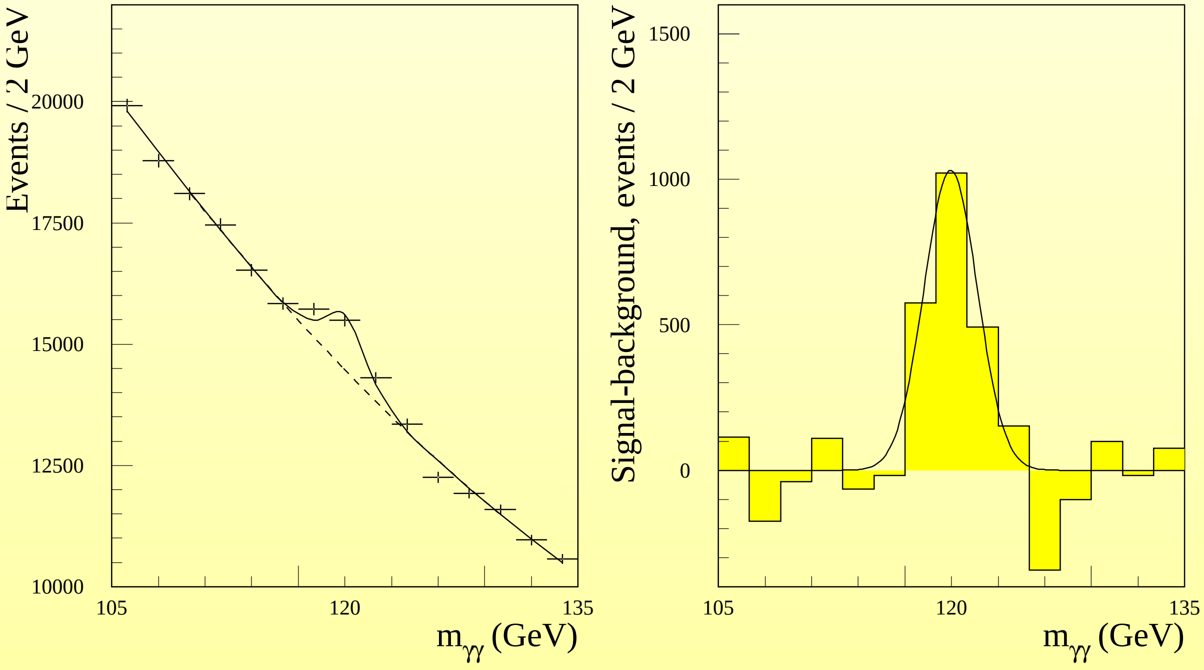




- The quality of the Higgs signal is determined by the relative magnitude of the signal and the background.
- Promising discovery channels
  - $pp \longrightarrow gg \longrightarrow H \longrightarrow \gamma\gamma;$
  - $pp \longrightarrow gg \longrightarrow H \longrightarrow ZZ \longrightarrow 4l;$
  - $pp \longrightarrow WH \longrightarrow l\bar{\nu}_e\gamma\gamma$
  - $pp \longrightarrow gg \longrightarrow H \longrightarrow W^+W^- \longrightarrow l^+l^-\nu_e\bar{\nu}_e.$

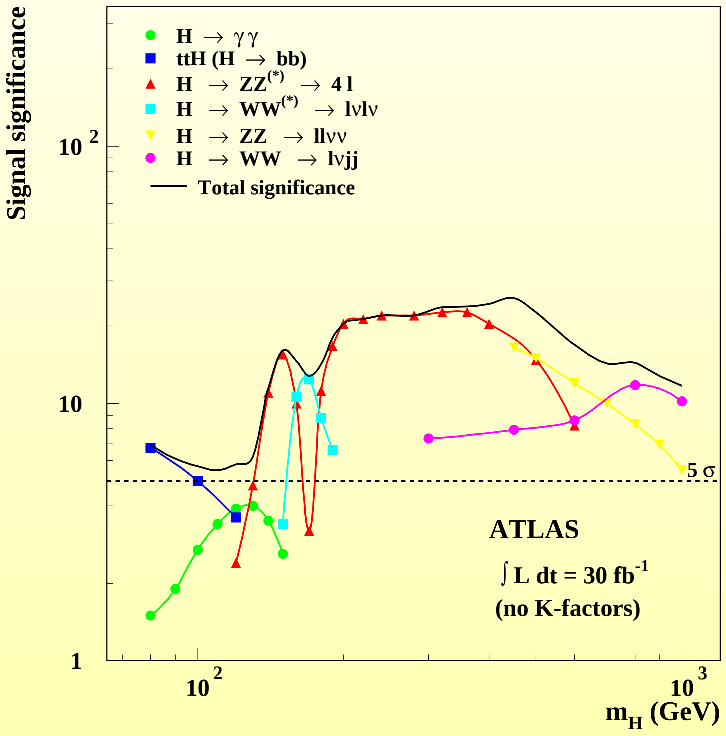
Hunting the Higgs boson at the LHC

- For the light Higgs boson, the $gg \longrightarrow H \longrightarrow \gamma\gamma$ is the most important channel. However:
  - The background from prompt photon production is overwhelming;
  - Excellent resolution on the photon energy is required;
  - Experimental studies of the background in signal-free regions.



Hunting the Higgs boson at the LHC

- The significance of the Higgs signal $S/\sqrt{B}$.



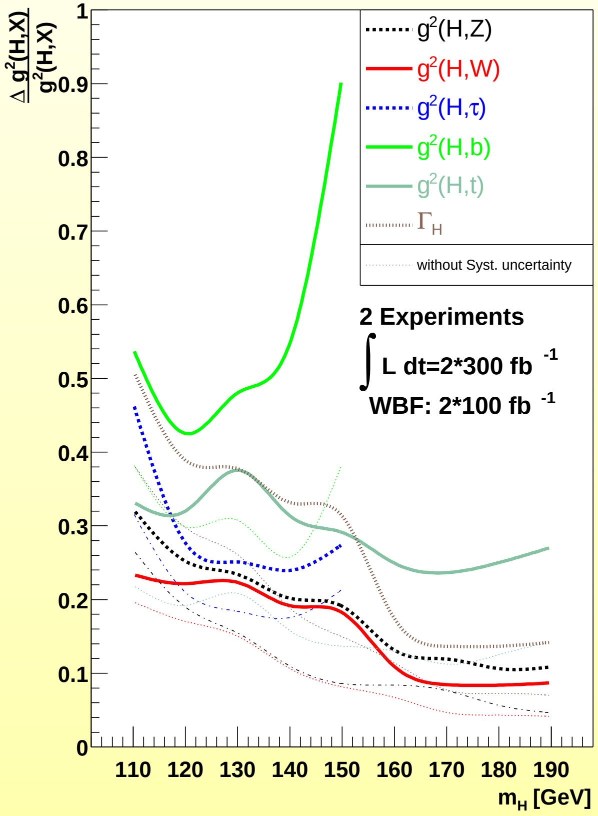
For $m_H = 115\ \mathrm{GeV}$, $L = 10\ \mathrm{fb}^{-1}$:

	$H \to \gamma\gamma$	$t\bar{t}H(b\bar{b})$	$qqH(\tau\tau)$
S	130	15	10
B	4300	45	10
$S/\sqrt{B}$	2	2.2	2.7

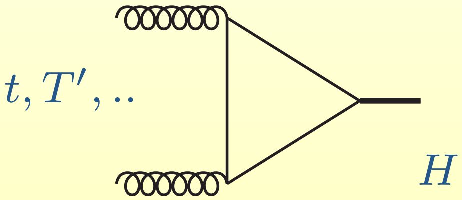
- ○ $H \to \gamma\gamma$ – electromagnetic calorimetry;
- ○ $t\bar{t}H(b\bar{b})$ – efficient b-tagging;
- ○ $qqH(\tau\tau)$ – efficient central jet veto.

Is this really the Higgs boson?

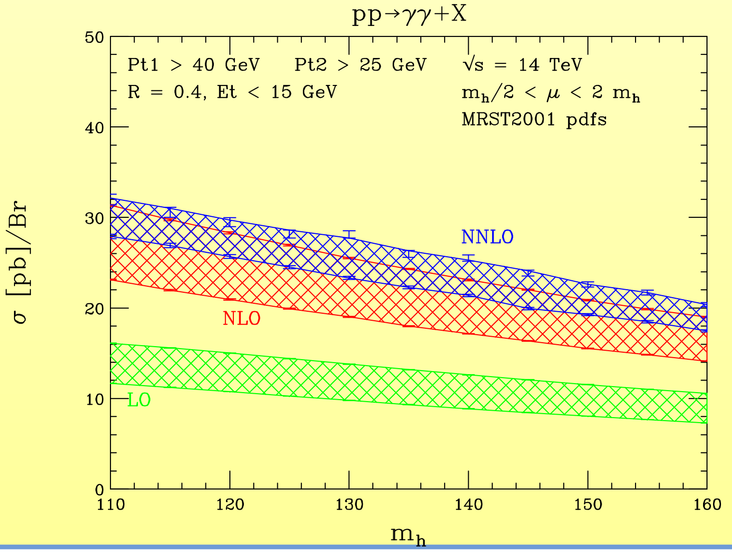
- The Standard Model Higgs has to couple to matter and gauge fields in a unique way



  - The Hgg coupling counts the number of ultra-heavy quarks:



  - QCD corrections $\sim 100\%$; challenge to theorists

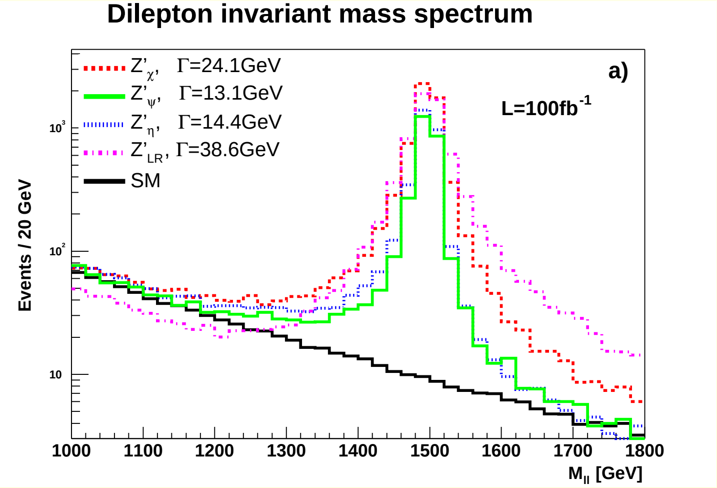


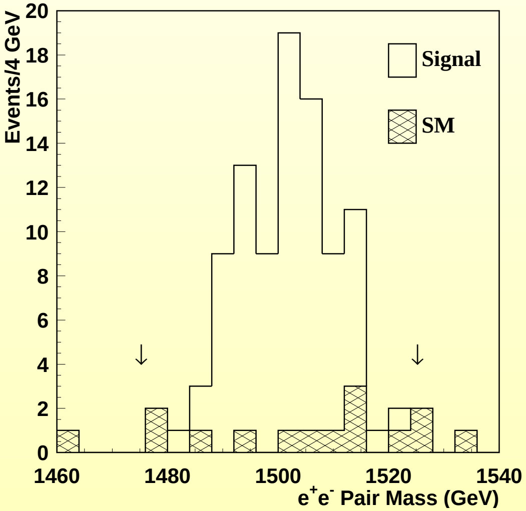
Searching for BSM physics

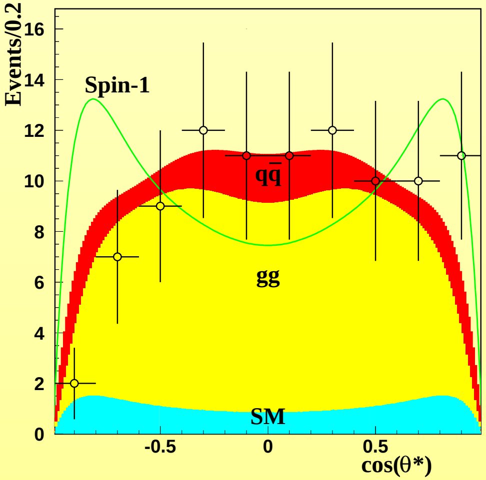
- When we search for New Physics, we do not know what we are loooking for.
- First, figure out that something is there; then, figure out what this is.
- Models ↔ collider signatures.
- Many models but relatively few signatures
    - New models ↔ new signatures ⟶ Important
    - New models ↔ old signatures ⟶ Less important
- Signatures, generic and not:
    - bump hunting (Z', W', extra dimensions, technicolor);
    - high $p_\perp$ jets and missing $E_\perp$ (SUSY).
    - monojets (extra dimensions);
    - long-lived new particles in the detector (split-SUSY).

Bump hunting

- Many BSM models predict the existence of new resonances (new $U(1)$ bosons, extra dimensional theories, technicolor)



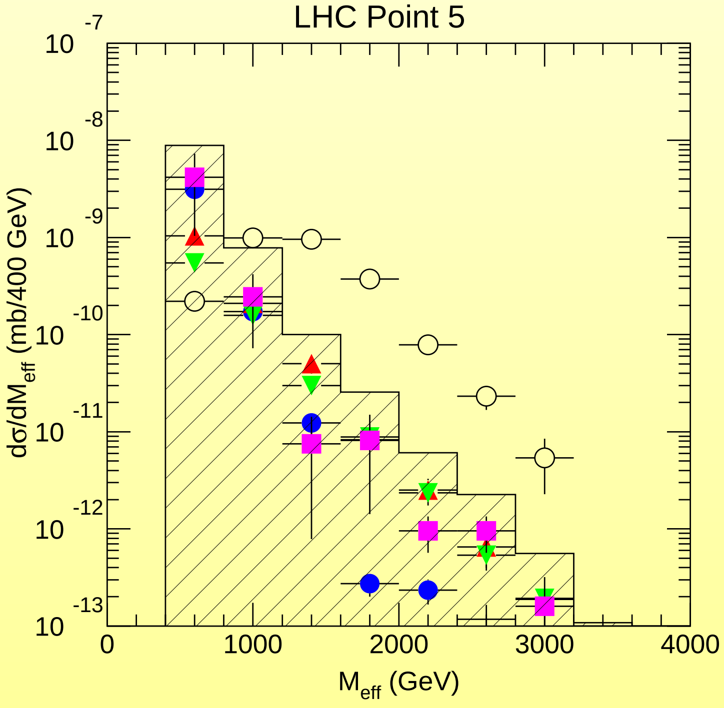


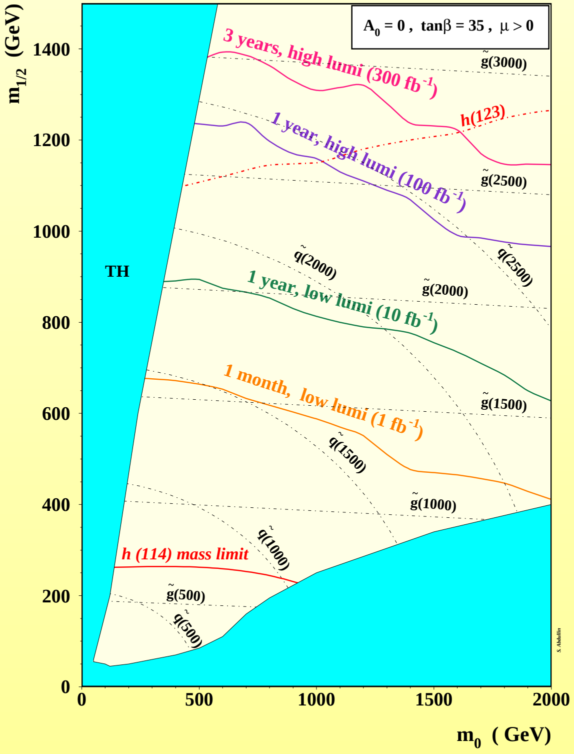


- ○ Techni-hadrons $VV \to \rho^T \to VV \to 4l$ are hard;
- ○ Spin of Z' vs. RS gravitons can be determined;

Jets + $E_\perp^{\text{miss}}$: SUSY at the LHC

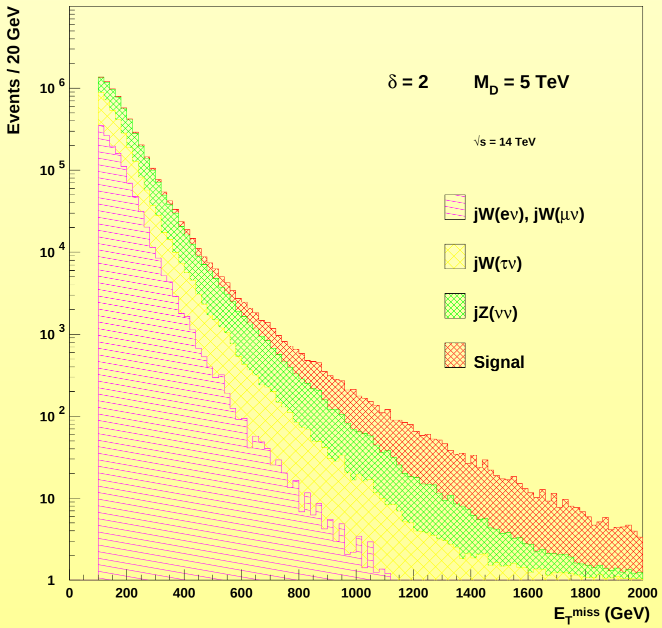
- In typical SUSY models, squark and gluino production cross-sections are large, ~ 10 pb.
- Decays of squarks and gluinos produce jets, leptons and missing energy.
- Heavy objects lead to larger values of $M_{\text{eff}} = \sum p_\perp + E_\perp^{\text{miss}}$ than in the SM.
- Mass scale of SUSY is determined from the position of the peak in M_{eff} distribution.
- Beyond that, determining the masses SUSY particles and establishing their properties is rather challenging.





Jets + $E_{\perp}^{\text{miss}}$: large extra dimensions

- The world may have more than $3+1$ dimensions:
  - Large extra dimensions, warped extra dimensions, universal extra dimensions, etc.
  - Models and phenomenology vary significantly; ranging from resonance-like excitations to missing energy.
- Large extra dimensions: SM on the brane, gravity in the bulk.
  - Natural scale for gravity $M_D \sim 1$ Tev;
  - $G_N \propto R^{-\delta} M_D^{-2-\delta}$;
  - $\delta > 2-3$, $M_D >$ few $\times$ 100 GeV (cosmology, astroparticle, Tevatron).



- Basic LHC signature: jet + $E_{\perp}^{\text{miss}}$ that originates from (multiple) graviton emission $gg \to G +$ jet.
- Backgrounds: $Z(\nu\bar{\nu}) +$ jet, $W(e\nu) +$ jets, etc.
- Reach: $M_D < 6$ TeV, $\delta = 2-4$.

Long-lived gluinos: split-SUSY

- Split-SUSY scenario:
  - all squarks have masses $\sim 10^6$ TeV;
  - gauginos and the SM Higgs boson is at electroweak scale.
- New phenomenology – long-lived gluinos: lifetimes between 10^{-12} sec to years.
- Signatures:
  - Displayed decays;
  - Delayed decays – events with beams off;
  - Energy deposition in hadronic calorimeter;

Conclusions

- The LHC opens up a new energy frontier which might be relevant for most fundamental physics questions of out time;
- The LHC will discover the Higgs boson within several years;
- The LHC will likely discover new forms of matter if their masses are within few TeV;
- The LHC will have a hard time in identifying the model → the ILC?
- The LHC physics is complex and interveined; requires different expertise and support from different components of particle physics community.