Connecting Particles with the Cosmos

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DESY Hamburg, Auditorium

Landesexzellenzinitiative Hamburg

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New Physics at Colliders

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Outline

- Lessons from the past: Successful strategies of NP searches
  - Historic examples reminding us of the principles of searches for New Physics
- Status quo: The ever surviving Standard Model
  - Precision tests of the SM and consequences for the (B)SM physics theories
- The future: Application of the successful methods at future colliders
  - The next major machine: The LHC
  - … and a short look beyond the LHC
- Summary of the research area “collider experiments” in Hamburg

Disclaimer:

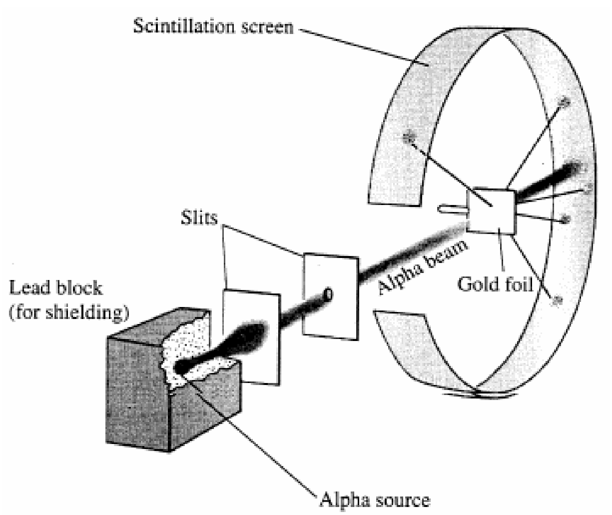
- By definition a 30’-talk on “New Physics at colliders” is incomplete
- Try to avoid overlap with other talks and focus on results obtained in HH

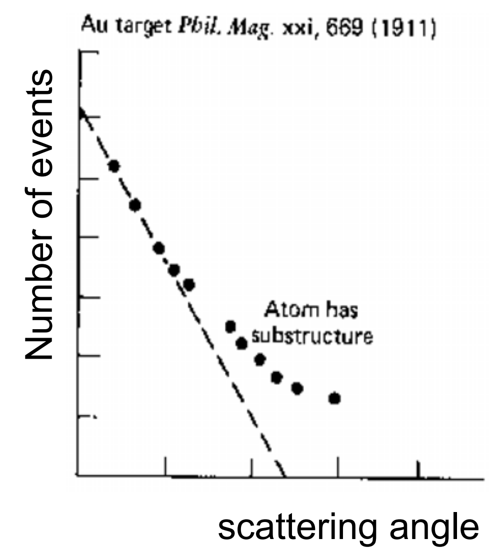
For illustration I label results with strong Hamburg involvement

The very beginning

- Searches for New Physics in HEP started almost 100 years ago
- Rutherford, Geiger, Marsden (1911)
  Scattering of α-particles on Au-target
  - E ~ 4.4 MeV
- Experimental result:
  - Excess of α's at large scattering angles
- Interpretation: New Physics!
  - Atoms have a nucleus !
    - 10^{-14}m, positively charged
    - Carries almost the full mass of the atom

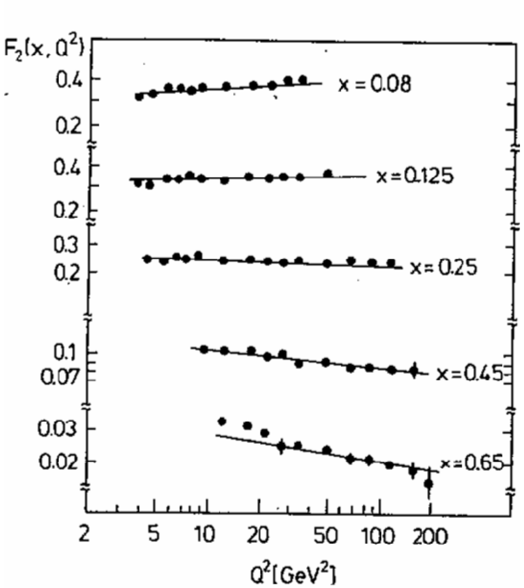
- Successful strategy: scattering experiments





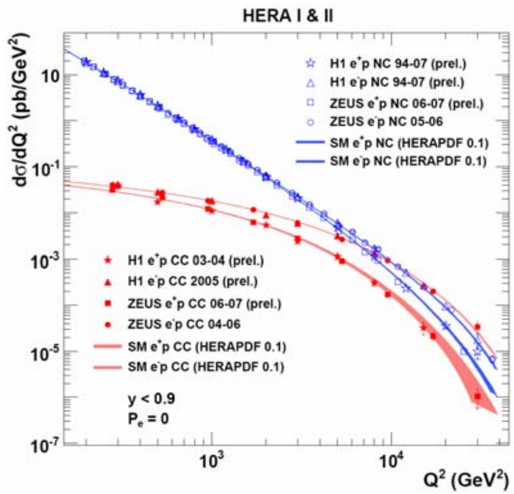
One particular successful example

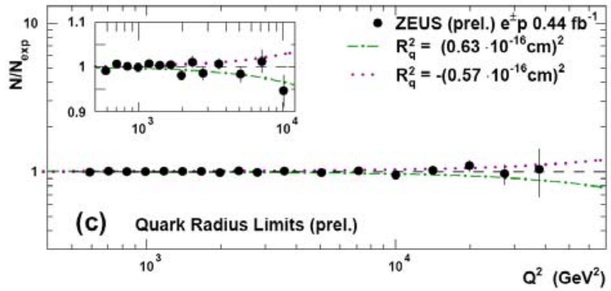
- SLAC 1967:
  Scattering of electrons on protons
  - Beam energies up to 20 GeV
- Experimental result:
  - Proton structure (F_2) is independent of momentum transfer (Q^2)
- Interpretation: New Physics!
  - Proton consists of point-like partons (quarks) !
- Successful strategy: scattering experiments
  1. Use fundamental particles as probes
  2. Use highest energy ($\sqrt{s}$)
  - Heisenberg: momentum transfer determines resolution $\Delta x = \hbar / \Delta p$
  - Einstein: high energy allows production of high mass particles $E = mc^2$



Deep Inelastic Scattering at its best

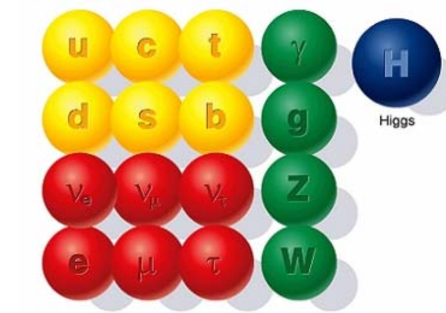
- Following this path rigorously
- HERA, Hamburg (1992-2007)
  Scattering of electrons (fundamental!) on moving (energy → resolution !) protons
  - Energies: $\sqrt{s}$= 320 GeV
- Experimental result:
  - Precision measurement of proton structure
- Interpretation:
  - Precise confirmation of QCD
  - Constraints on New Physics
    e.g. quark are point-like: $R<0.6\cdot10^{-18}$m
- Successful strategy: scattering experiments
  1. Use highest energy ($\sqrt{s}$)
  2. Use fundamental particles as probes
  3. Use highest luminosity (L)





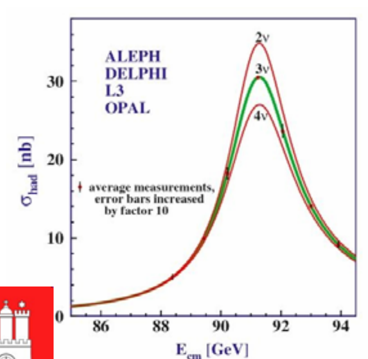
The Standard Model

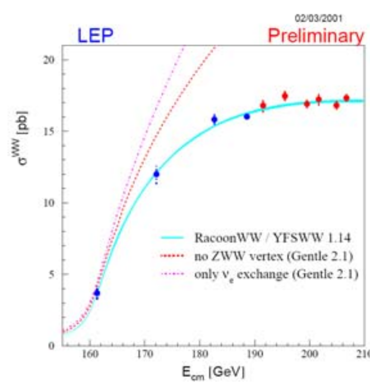
- Successful strategy of HEP: scattering experiments
  1. Highest energy ($\sqrt{s}$)
  2. Highest luminosity (L)
  3. Fundamental particles as probes

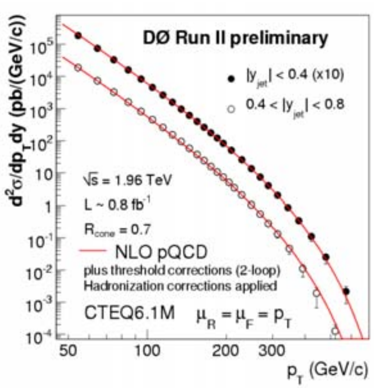


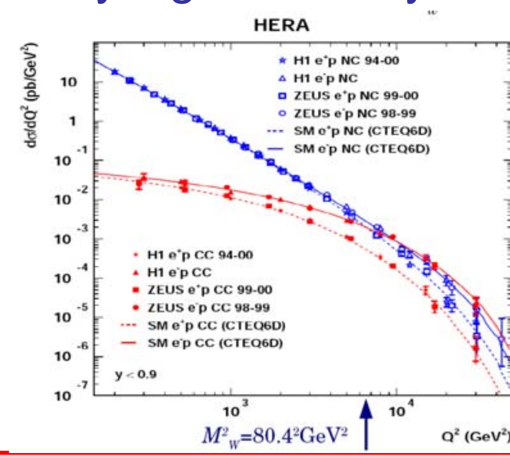
- Result after (for) decades: Standard Model, $SU(3)_C x SU(2)_L x U(1)_Y$ gauge theory
  - Matter: fermions (J=½) quarks and leptons in 3 families
  - Interactions: vector bosons (J=1) el.-mag. (γ), weak (W/Z) and strong (g)
  - Mass: scalar boson (J=0) Higgs (H), undetected

- The theory describes <u>all</u> HEP measurements with incredibly high accuracy



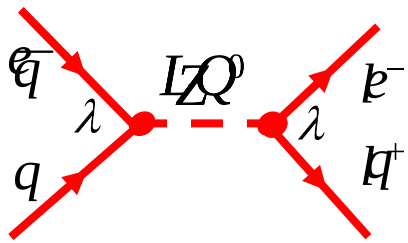




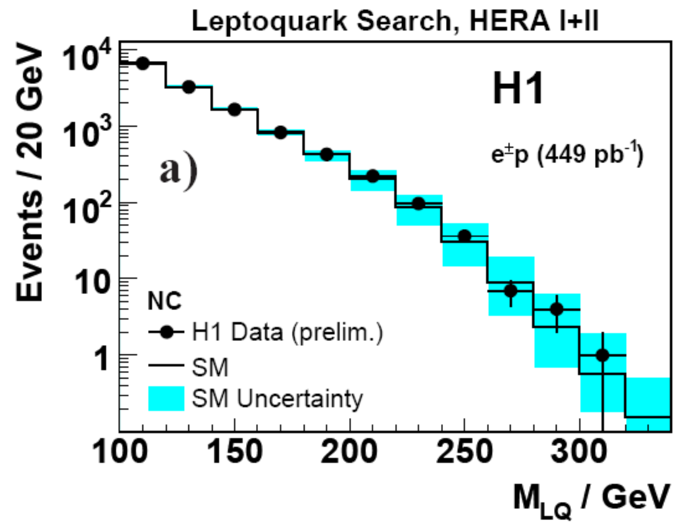


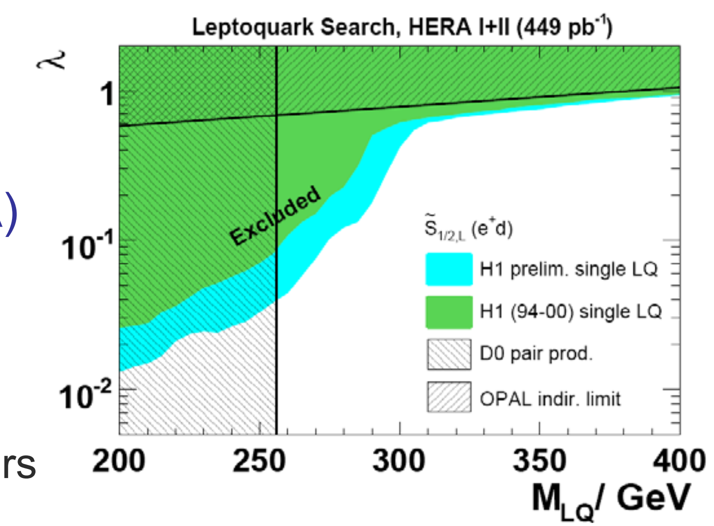
Successful techniques of NP searches

- Technique 1: <u>Direct searches</u>
  - Search for real production of new particles (*M*)
  - "on mass shell", requirement: $M <= \sqrt{s}$
  - Clean signal in kinematic distributions of decay products (e.g. invariant mass)
- Past example: Z^0 discovery at $Sp\bar{p}S$ (1983)
  - Clean peak in M_{ll} spectrum



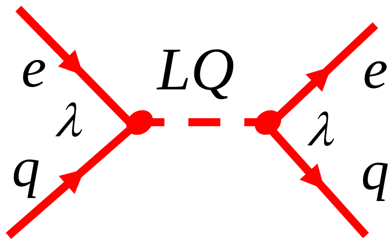
- Today's example: search for leptoquarks (HERA)
  - LQs couple to electrons and quarks with λ
  - Expect peak in *eq* invariant mass spectrum
  - <u>Result</u>: no peak over NC background
  - <u>Interpretation</u>: exclusion limits on model parameters (M_{LQ}, λ).
    - Particularly strong inside kinematic reach ($M<\sqrt{s}$)

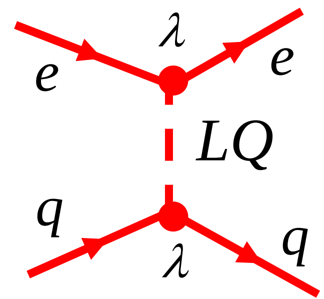




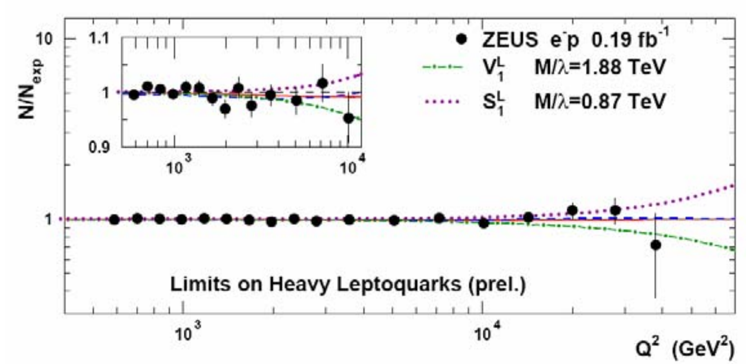
Successful techniques of NP searches

- Technique 2: indirect searches
  - Make use of small contributions of NP entering via virtual corrections
  - Even physics far beyond √s can contribute, i.e. *M*»√*s* is accessible via precision!
  - Precision needed to resolve the virtual corrections
- Again a HERA example: virtual contribution to NC cross-section by heavy LQs





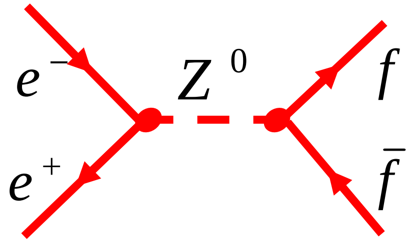
  - Expect deviation from SM at high Q^2
  - No deviation → exclusion limits for scales of new physics » √s

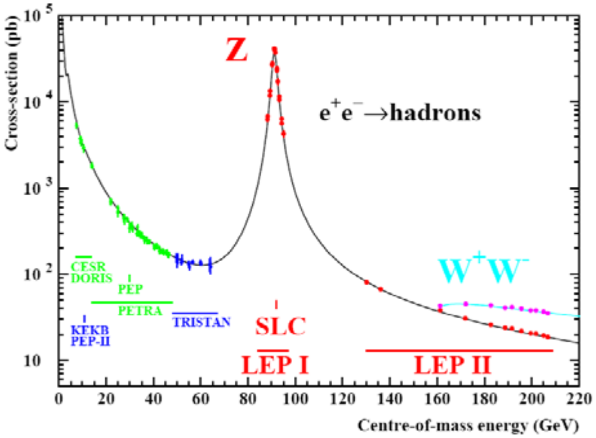


- Current HEP data agree with SM → indirect techniques are a major topic today
  - This will change once we open a new kinematic reach again (LHC)

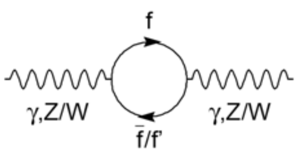
Precision Measurements of the SM

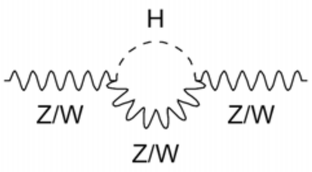
- Most famous example for indirect approach: precision measurements on the Z^0 pole in e^+e^- collisions (LEP, SLC)





- Comparison with SM prediction sensitive to virtual corrections
  - Dependence on particles with M » $\sqrt{s}$
  - SM: ~m_t^2 und ~lnM_H



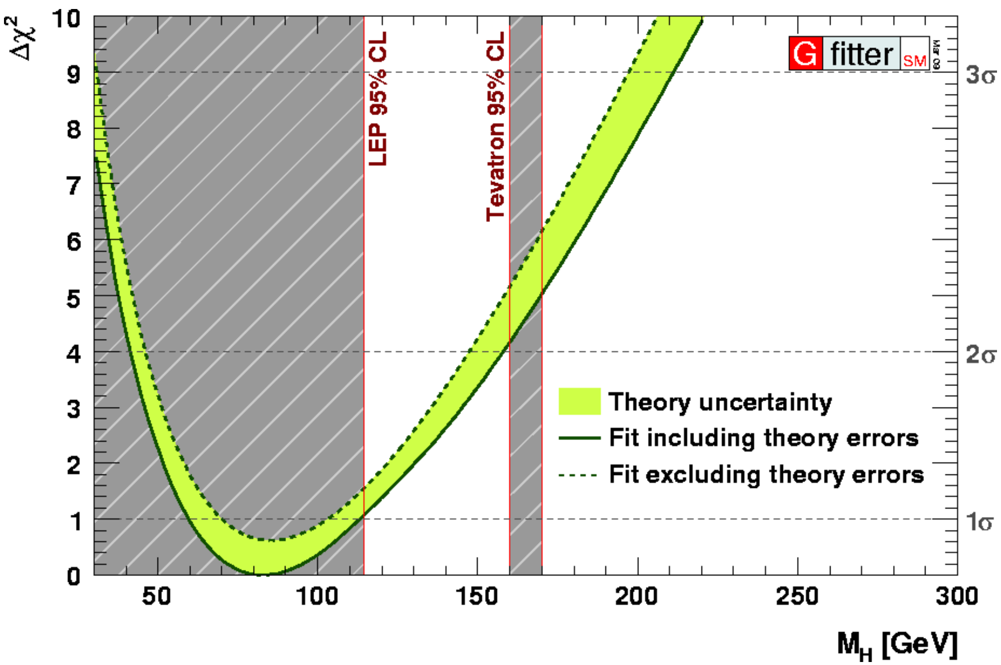


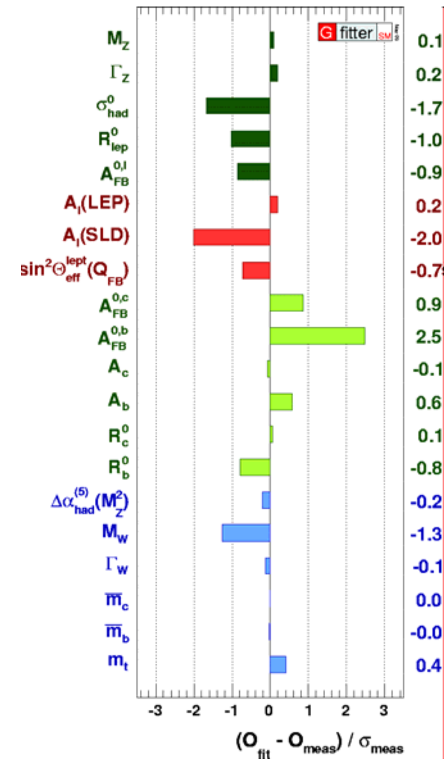
- Comparison performed using a χ^2 fit:
  - Check the consistency of the SM prediction with the measurement
  - Constraint the model parameters (e.g. in SM: M_H)

$$\chi^2 = \sum_i \frac{\left(x_{i,\text{mes}} - x_{i,\text{theo}}(y)\right)^2}{\sigma_i^2}$$

SM fits and indirect constraints

- Fit uses all sensitive observables available
  - Fit converges with $\chi^2/\text{ndf}=16.3/13 \rightarrow p\text{-value}=23\%$
- Overall good agreement of data with SM fit
  - Largest deviation (A^b_{FB}) 2.5σ known from the past
- Study most important SM parameter: M_H
  - $\Delta\chi^2=\chi^2-\chi^2_{min}$ as function of M_H



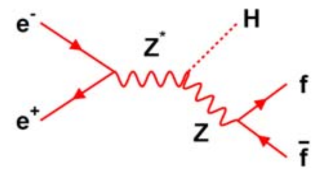


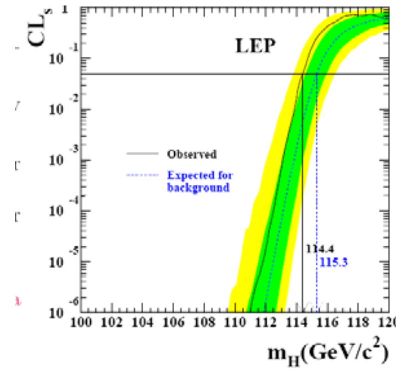
- Minimum at $M_H = 83^{+30}_{-23}$ GeV
- 2σ interval: [42,158] GeV
- 3σ interval: [29, 212] GeV

- Light Higgs preferred by precision observables

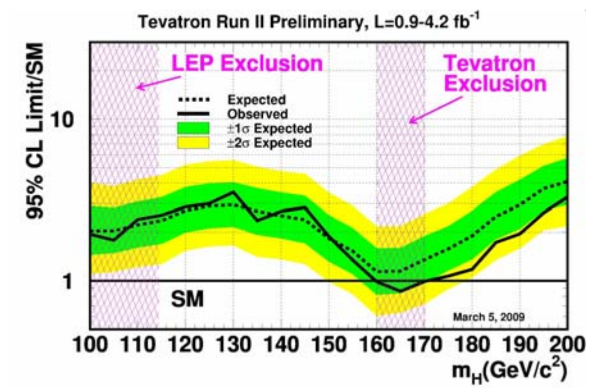
Direct searches for the SM Higgs

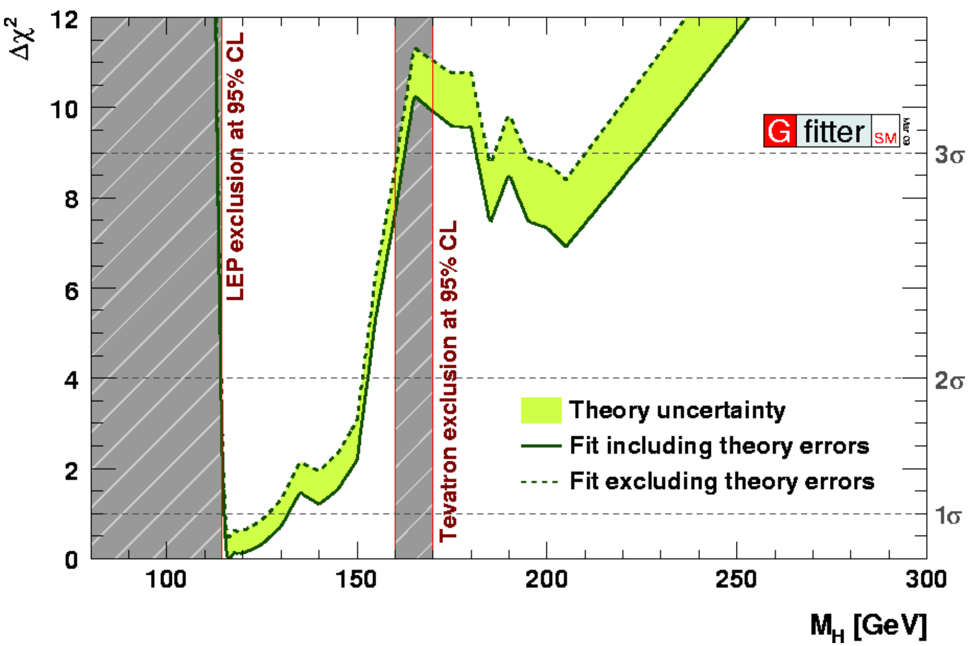
- In e^+e^- collisions at LEP:
  - Production via Higgsstrahlung
    - Cross section falls steeply for $M_H > \sqrt{s} - M_Z$
  - Result:
    - Very strong exclusion for $M_H < 113$ GeV
    - No exclusion for $M_H > 116$ GeV





- In $p\bar{p}$ collisions at TeVatron:
  - Variety of channels sensitive up to M_H~200 GeV
  - Exclusion for (cross section limit/ SM) < 1

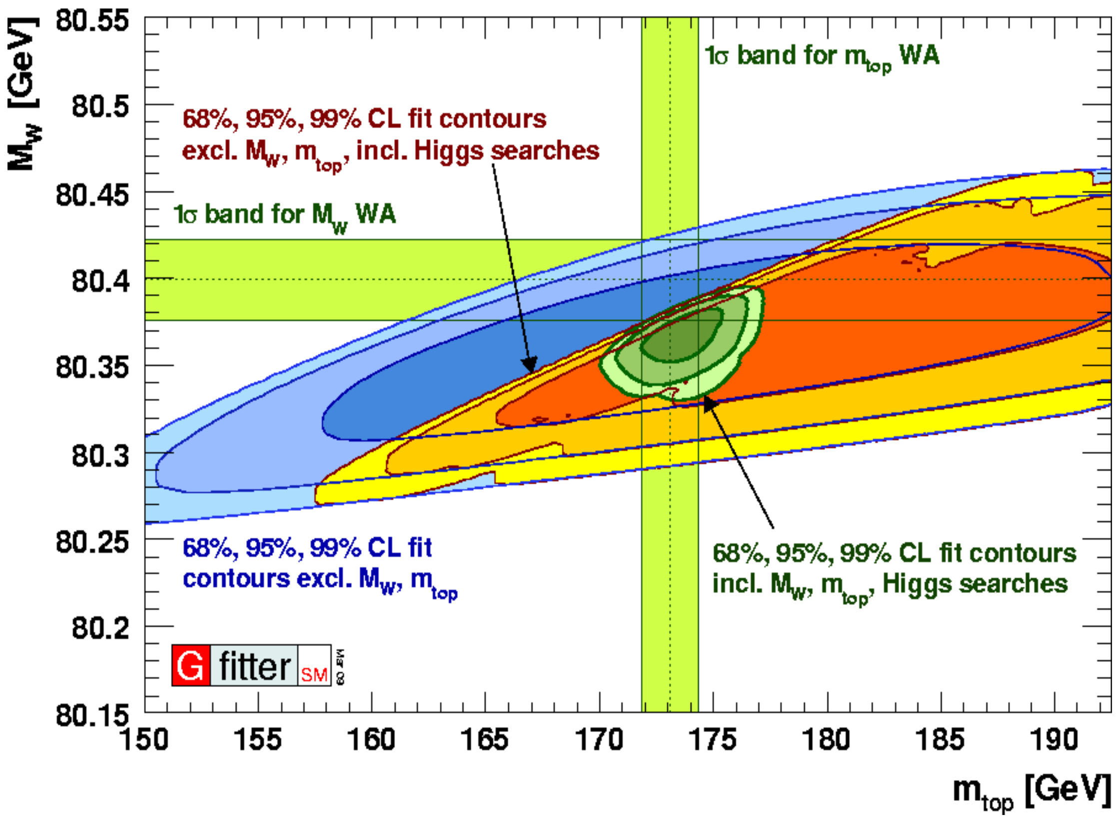




- Combination with indirect fit provides most precise value of M_H in SM:
  - Minimum at $M_H = 116^{+15.6}_{-1.3}$ GeV
  - 2σ interval: [114,153] GeV

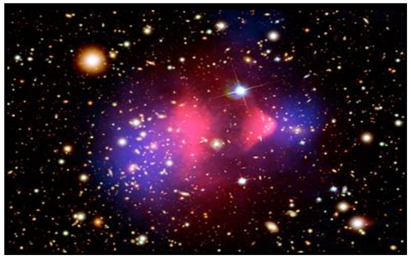
Internal consistency of the SM

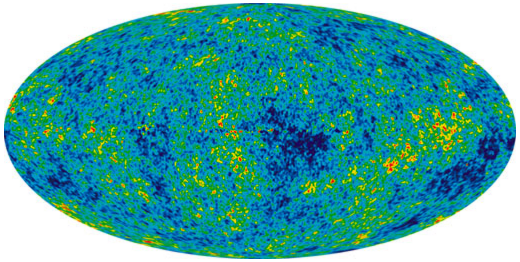
- Direct measurements and fit predictions agree well

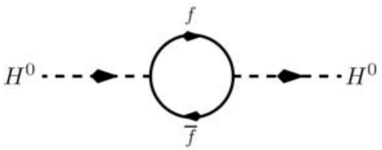


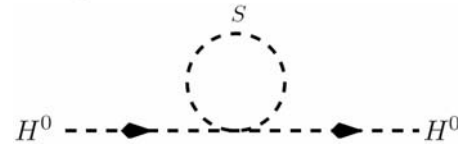
Why new physics then?

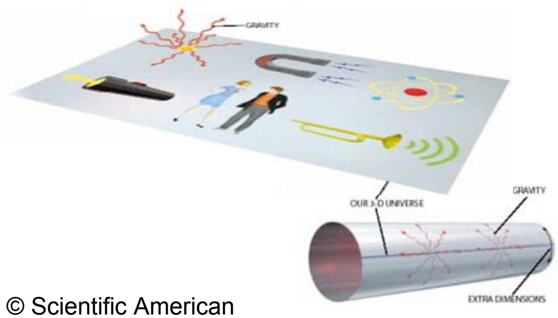
- SM has several limitations and shortcomings
  - Outside of HEP: hints for Dark Matter (Galaxy kinetics, Gravitational lensing, Fluctuations of CMB, …)
  - Hierarchy problem due to weakness of gravitation
    - Masses of scalar particles (H in the SM) unstable in presence of large scale hierarchies ($E_{ew} \ll E_{Planck}$)
- Example solutions proposed
  - Models without fundamental scalar particle
    - Techicolor, …
  - New physics between E_{ew} and E_{Planck} to regularise the M_H divergence
    - e.g. supersymmetric extensions of the SM, little Higgs, …
  - Gravity is not weak but acts in more than 4 space dimensions, ie. it is only diluted in our 4D world
    - models with extra space dimensions (ADD, RS, UED)
- Many of those SM extensions offer a Dark Matter candidate
  - e.g. the LSP in supersymmetric models







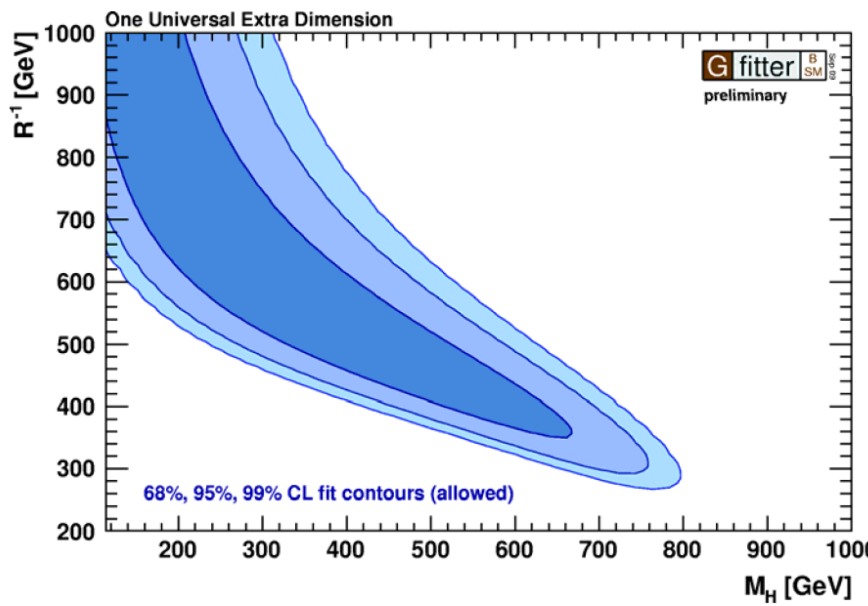




Precision data and constraints on new physics

- Precision data usable to constrain new physics models (indirect technique)
- New particles → new contributions to vacuum polarization
- Model independent procedure: *STU* parameters [Peskin and Takeuchi, Phys Rev. D46, 1 (1991)]
  - Parametrize loop effects in model independent way
    - *S*: isospin violating corrections
    - *T*: remainder in Z pole observables
    - *U*: additional corrections to M_W (often: U=0)

- Example: Models with Universal Extra Dimensions with radius *R*
  - Additional loop contributions from KK-top and KK-Higgs
  - For large R^{-1}, i.e. small radius, large scales: allowed region identical to SM
  - For small R^{-1}:, i.e. large radius, small scales: new effects can be compensated by larger M_H



  - In summary: allowed area in UED: R^{-1}>300GeV and M_H<800 GeV

Precision data and constraints on SUSY models

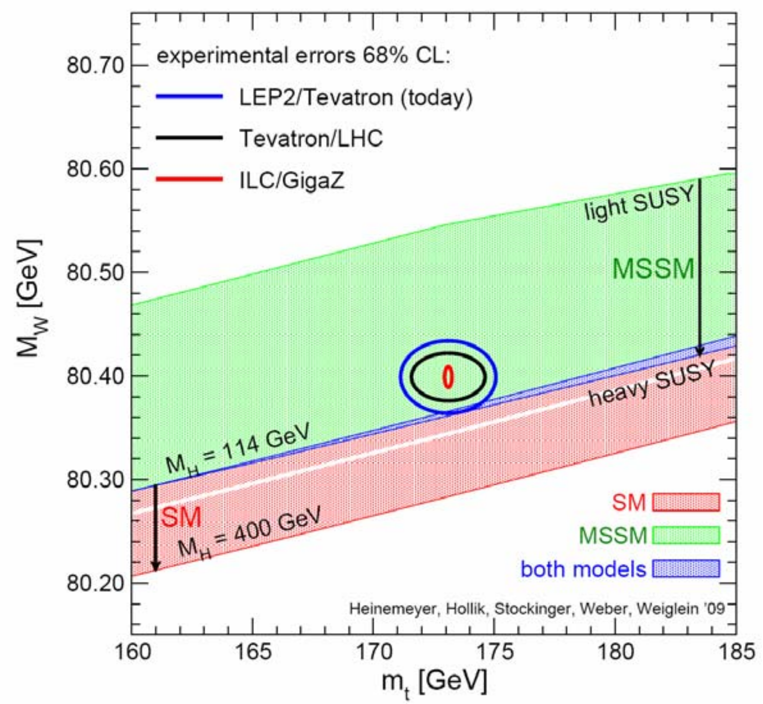
- Corrections from supersymmetric particles can be fully calculated

→ Fits of SUSY models to electroweak precision data can be done

- SUSY (MSSM) is a decoupling theory
  → Heavy SUSY (M~2TeV) looks exactly like the SM

- Overlap region with MSSM: region in SM with a light Higgs

- Current measurements are consistent with the SM with a slight preference to SUSY

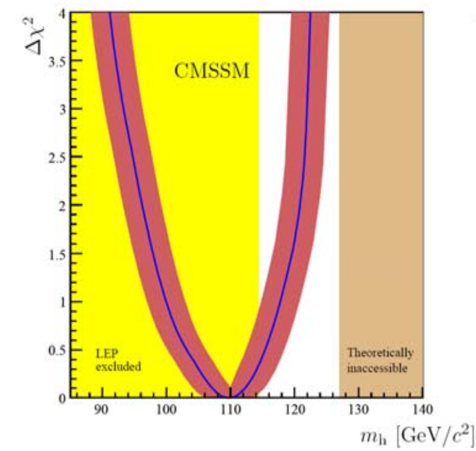


- However, no constraints on SUSY can be derived from precision collider data alone

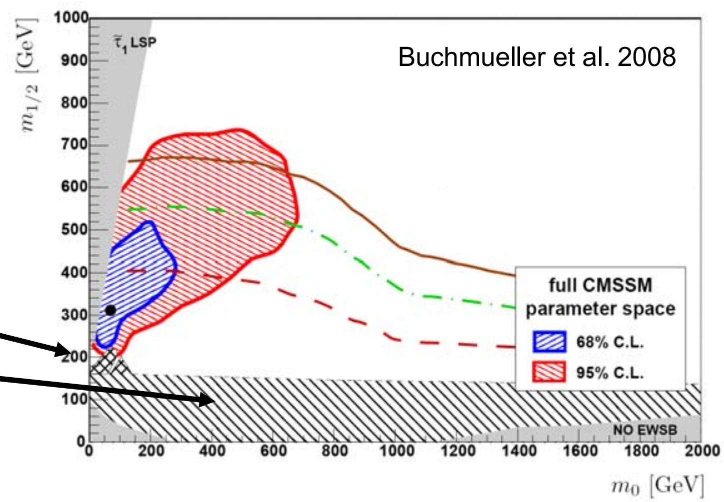
Indirect constraints on SUSY models

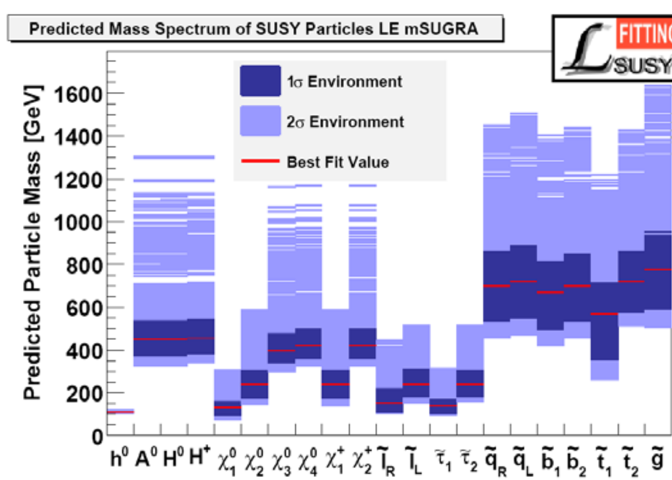
- Recent fits include additional observables in SUSY fits; mainly:
  - Relic density of Cold Dark Mater: $\Omega_{CDM}h^2$ LSP candidate for CDM
  - Anomalous magnetic moment of the muon: $(g\text{-}2)_\mu$ virtual SUSY contributions
    - Currently: 3.5σ away from SM (real effect?)
- CMSSM (mSUGRA): more precise prediction of M_h
  - Minimum close to LEP limit ! $M_h = 110^{+8}_{-10}\,(\text{exp.}) \pm 3\,(\text{theo.})\ \text{GeV}$
    - Corrections still ~ln M_h ,
    - But M_h dependent on SUSY parameters (and m_t)
      → constraint at low M_h
- Allowed regions in mSUGRA parameter space:
  - Low m_0 and low $m_{1/2}$ preferred → "small" SUSY masses

Buchmueller et al. 2007



Excluded from direct searches:
- Trileptons at Tevatron
- $\chi^\pm$ at LEP





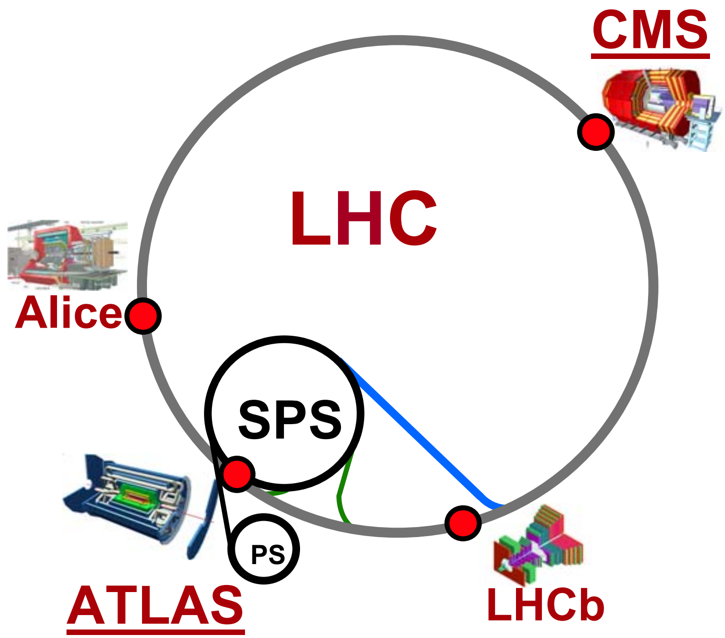
The Large Hadron Collider

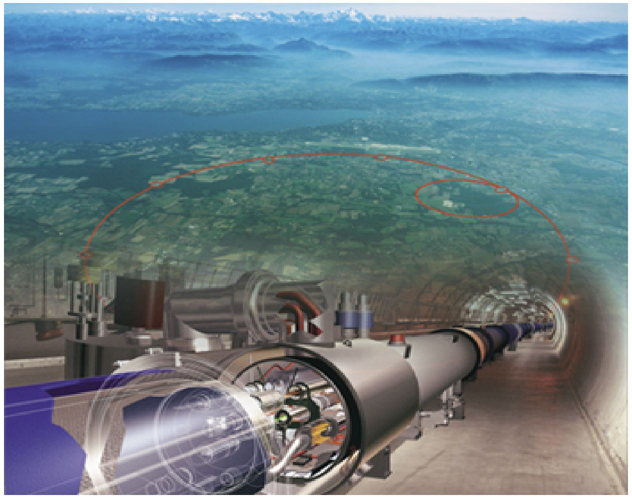
- Remember our old concept of success:
  $\sqrt{s}\uparrow$ and $L\uparrow$

- LHC follows this concept "par excellence"
  - 7x energy and 100x luminosity of the Tevatron

- Achieved with the following nominal machine parameters:

machine parameter	LHC
luminosity [$cm^{-2}s^{-1}$]	10^{34}
$\sqrt{s}$ [TeV]	14
BC interval [ns]	25
BC rate [MHz]	40
# bunches	2835 (3564)
# protons per bunch	$1.1 \cdot 10^{11}$

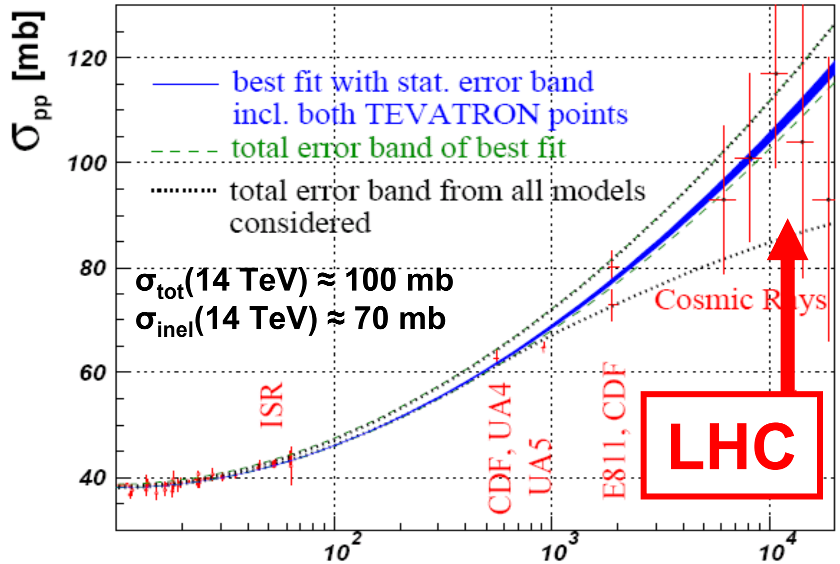




- The high centre-of-mass energy and the high luminosity enable the direct production of NP processes at the terascale.
  - Examples: Higgs, LQs, ED, heavy gauge bosons, 4th generation quarks, SUSY (later more) …
- … but this comes at a certain price
  - High $\sqrt{s}$ → high cross section
  - High luminosity

→ ~25 interactions/bunch crossing
→ ~1700 particles/ bunch crossing

total pp- cross-section



centre-of-mass energy (GeV)

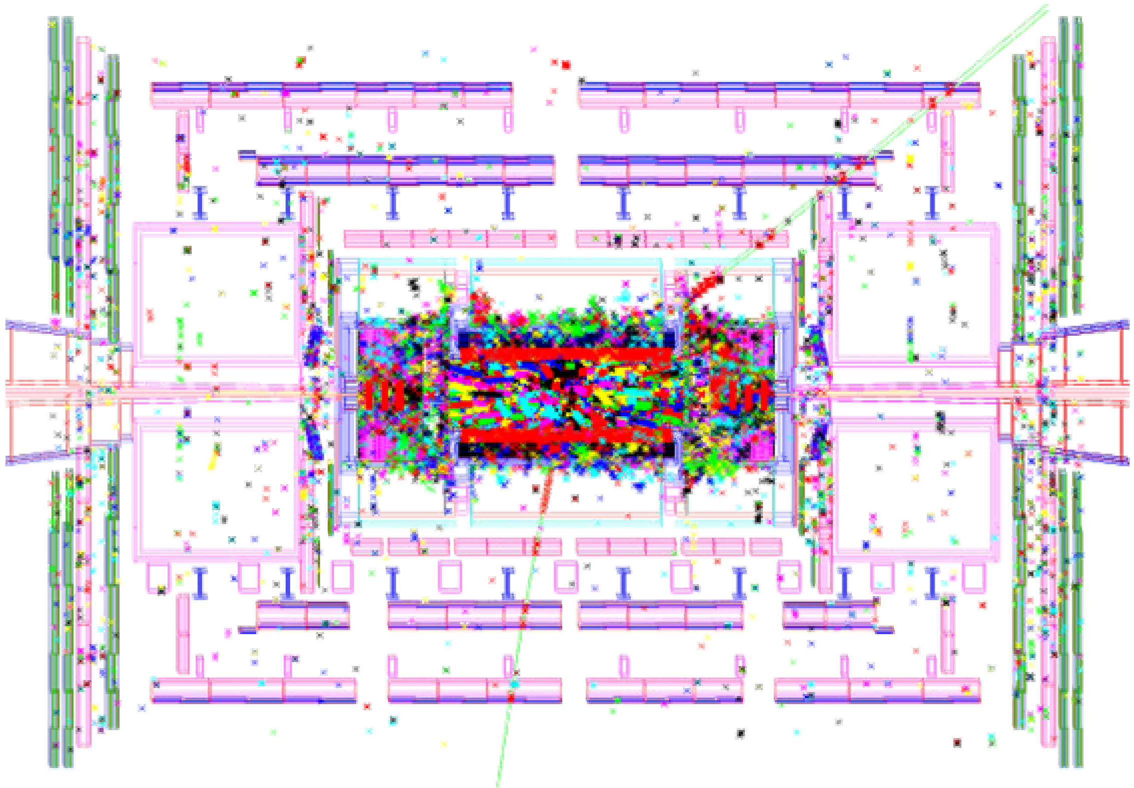
- Interesting numbers. But what does it mean for the experiments?

Conditions at the LHC

H → ZZ → 2e+2μ

~25 inelast. pp-interactions

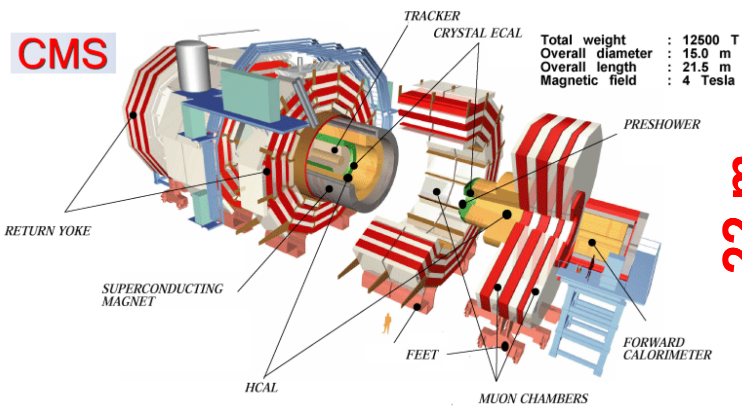
40 MHz !!

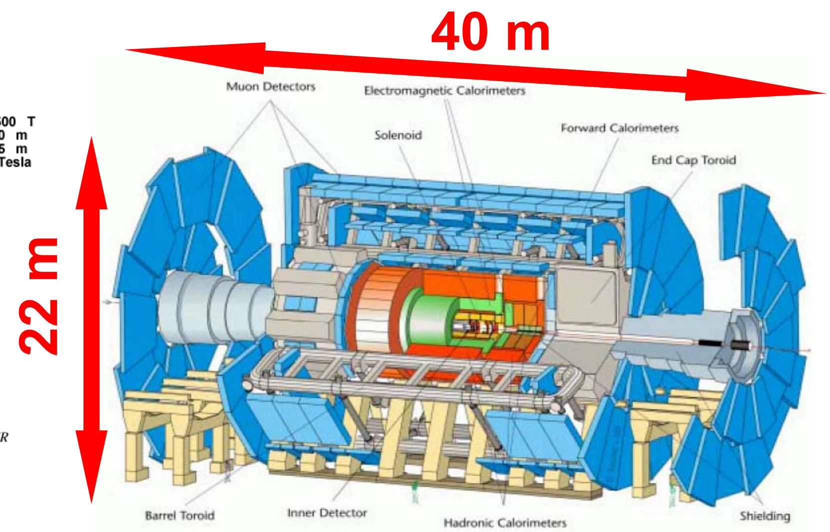


- Challenge for experimentalists: Design and construction of detectors that can cope with these conditions

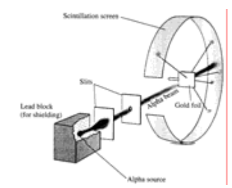
The LHC experiments

- Huge detectors with high granularity and fast readout to avoid pile-up





for comparison:



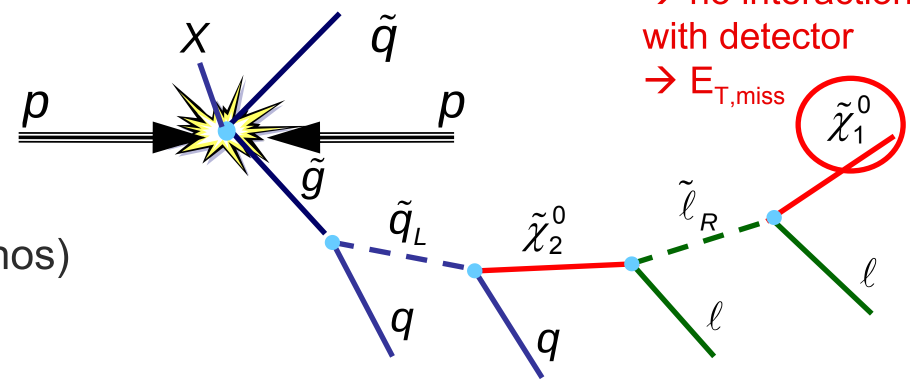
Rutherford to students: “There is no money for apparatus, we shall have to use our heads!”

- Highly selective trigger systems:
  - Selection of interesting events
    - Only 1 of ~200.000 inelastic events
  - Multilayer systems
    - Dedicated hardware and filter farms
  - Output: ~100 Hz
  - Crucial for physics reach

Direct searches at the LHC: example SUSY

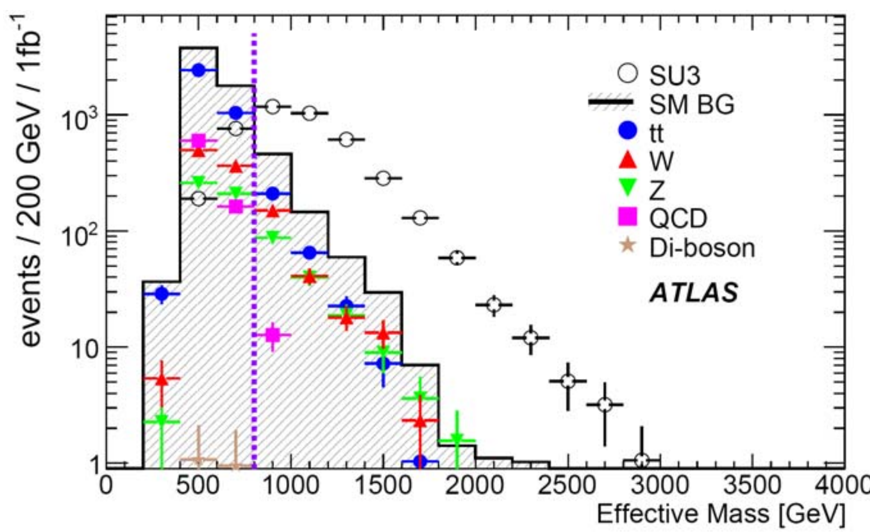
- Production of supersymmetric particles at the LHC
  - Pair-production of squarks and gluinos via the strong interaction:

$$gg, q\bar{q}, qq, qg \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$$

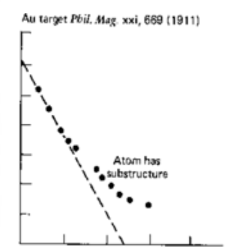


- Long decay chains to LSP:
  - Jets (from initial squarks and gluinos)
  - Missing transverse energy (LSP)
  - Leptons
- Exact topology strongly model-dependent → inclusive selection:
  - At least 4 hard jets
  - $E_{T,miss}$>100 GeV
- Choose a sensitive observable to compare with SM

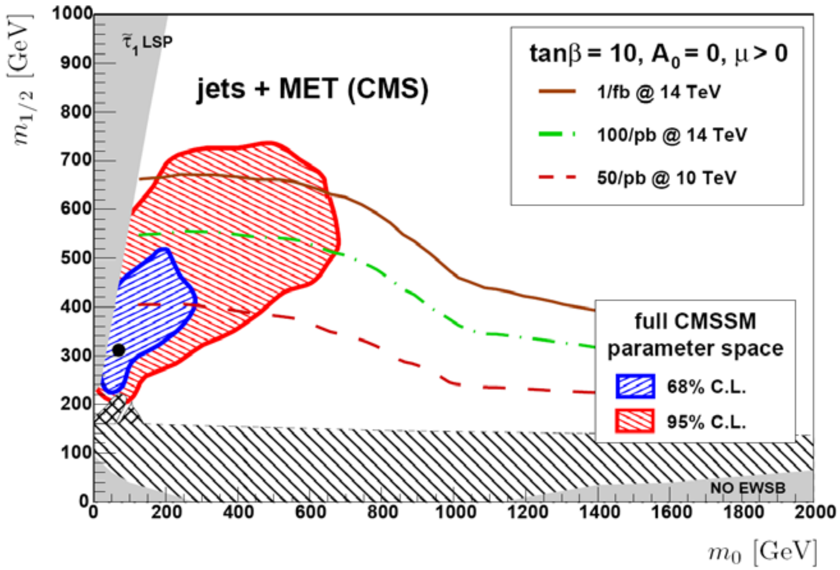
$$M_{\text{eff}} \equiv \sum_i |p_{T(i)}| + E_T^{\text{miss}}$$



For comparison:

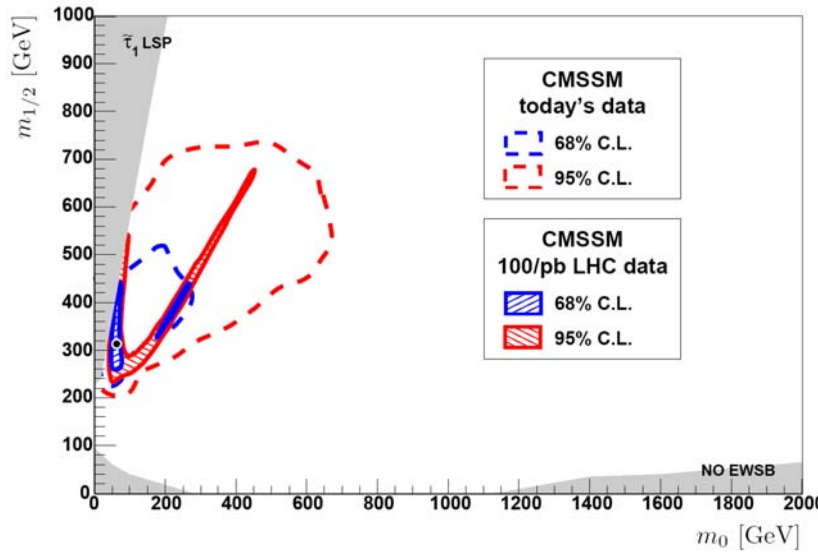


- Expected discovery reach of the LHC in the mSUGRA parameter space:
  - Early analysis using $\int Ldt$=50-200 pb^{-1} with $\sqrt{s}$=10TeV
    - Reach up to $M_{squarks}$~ 750 GeV
  - Mid-term analysis using $\int Ldt$=1fb^{-1} with $\sqrt{s}$=14TeV
    - Reach up to $M_{squarks}$~1.5 TeV
  - Preferred regions covered by early analyses

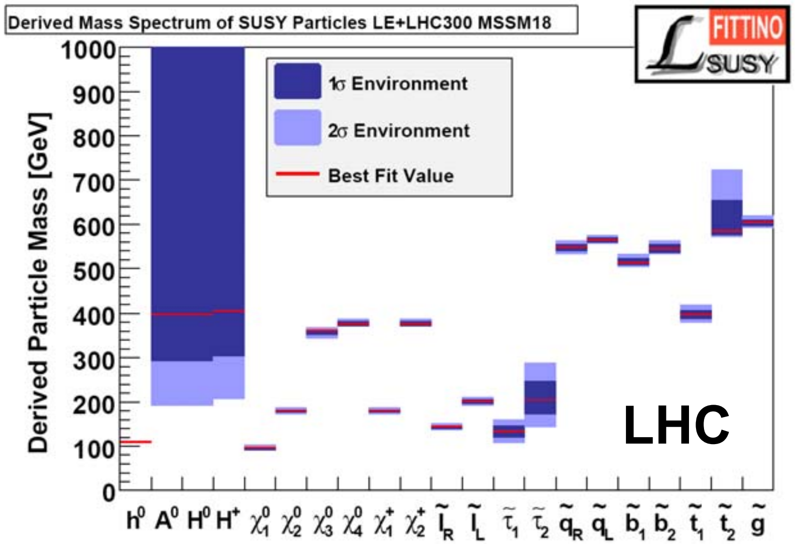


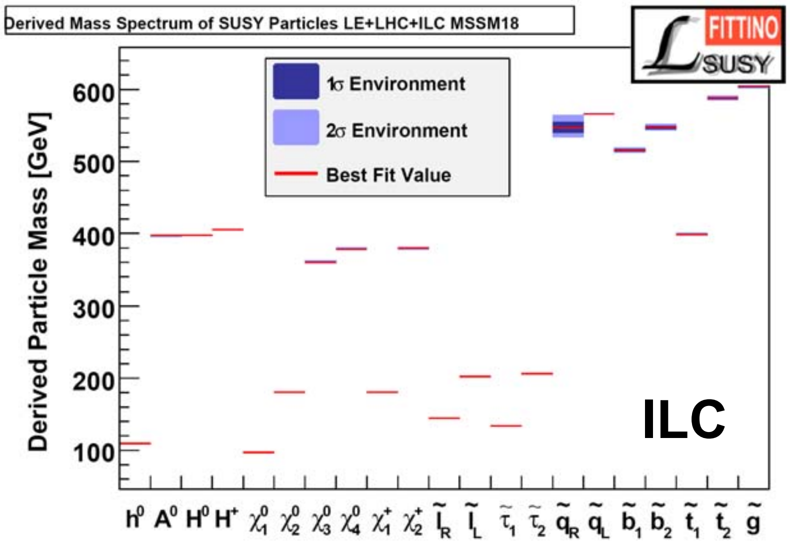
- Once SUSY *directly* discovered → measurements to enable *indirect* approach.
  - 2 escaping LSPs → model independent mass reconstruction impossible
  - Instead: kinematic endpoints and model dependent interpretation
    - E.g. measurement of the dilepton edge (±3 GeV) would significantly reduce the allowed region

$$\left(m_{ll}^2\right)^{edge} = \left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\cdot\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)/m_{\tilde{l}_R}^2$$



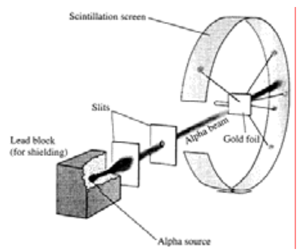
- The LHC follows two of our success principles: $\sqrt{s}\uparrow$ and $L\uparrow$
- But it does not collide fundamental particles rather protons
  - Experimental measurements will have quite some uncertainties
  - LHC gives huge uncertainties for more realistic SUSY models (e.g. MSSM18)

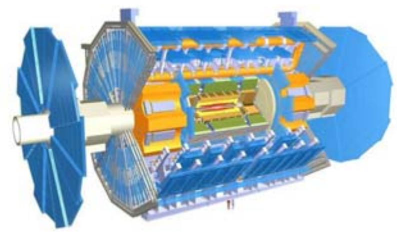




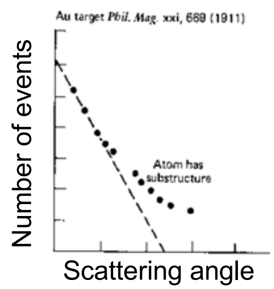
- An electron-positron linear collider as a next step …
  - … would allow precision measurements of the new physics theory
  - … would enable us to obtained a detailed knowledge of the new model as we have today for the SM ("LEP for SUSY or other BSM physics").

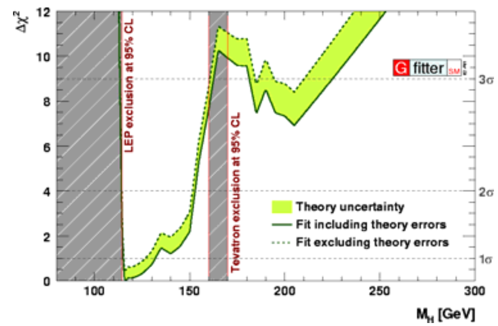
- Enormous development of scattering experiments over the last century





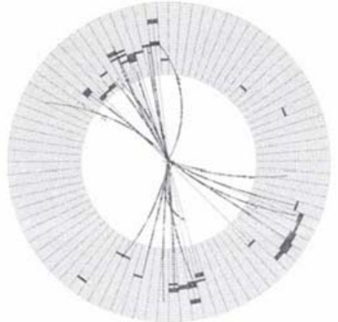
- Enormous development of our knowledge of the laws of nature



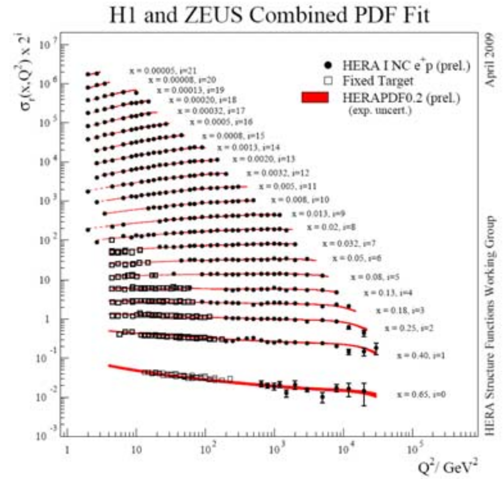


- This development continues!
- Next step is imminent: first data from the LHC!
- Truly *Exciting Times* for fundamental physics

Research area "collider experiments" in Hamburg



- <u>World-class contributions</u> in the last decades
  - Establishment of the Standard Model
  - Hamburg has been a primary driving force in the field, e.g.
    - e^+e^- collisions at PETRA: study of electroweak effects and QCD (discovery of the gluon!)
    - $e^{\pm}p$ collisions at HERA: study of the structure of the proton and QCD



- <u>Excellent opportunities</u> via strong LHC+ILC involvement for the years to come
  - First exploration of the Terascale
  - Hamburg participates in ATLAS, CMS and ILC
    - Next two years: SM processes at LHC (W,Z, top, QCD)
    - Next decade: search for/measurement of New Physics

- Hamburg offers a unique environment for the research area "collider experiment".