Contemporary High Energy Physics
— Where We Are ?

Tao Han
Univ. of Wisconsin - Madison

ILC Workshop/Summer School,
TsingHua University, Beijing, China
(July 15 – 20, 2005)

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Our "Theory Bank"
Physics in the LHC Era
Synergy of the LHC and ILC

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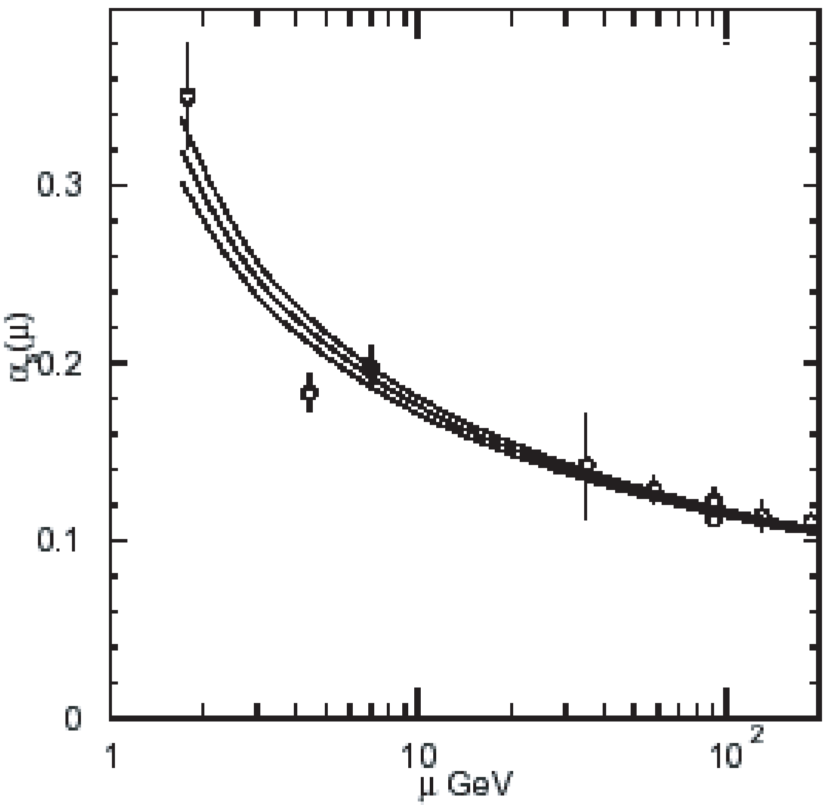
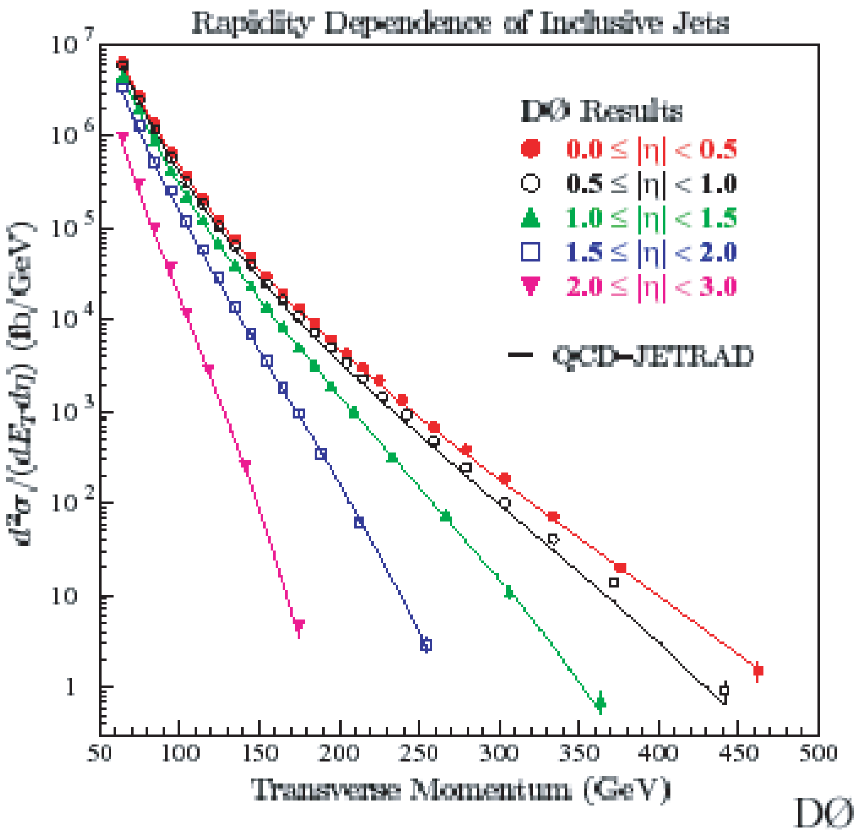
The Standard Model

as a Low-Energy Effective Theory

- $SU_c(3)$ QCD as the theory of strong interactions:





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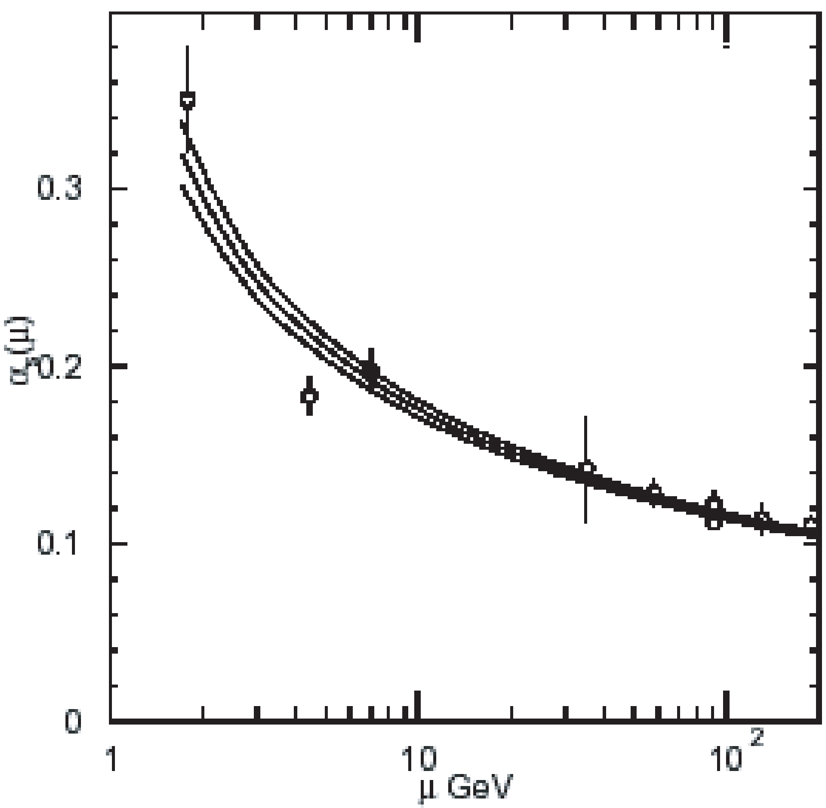
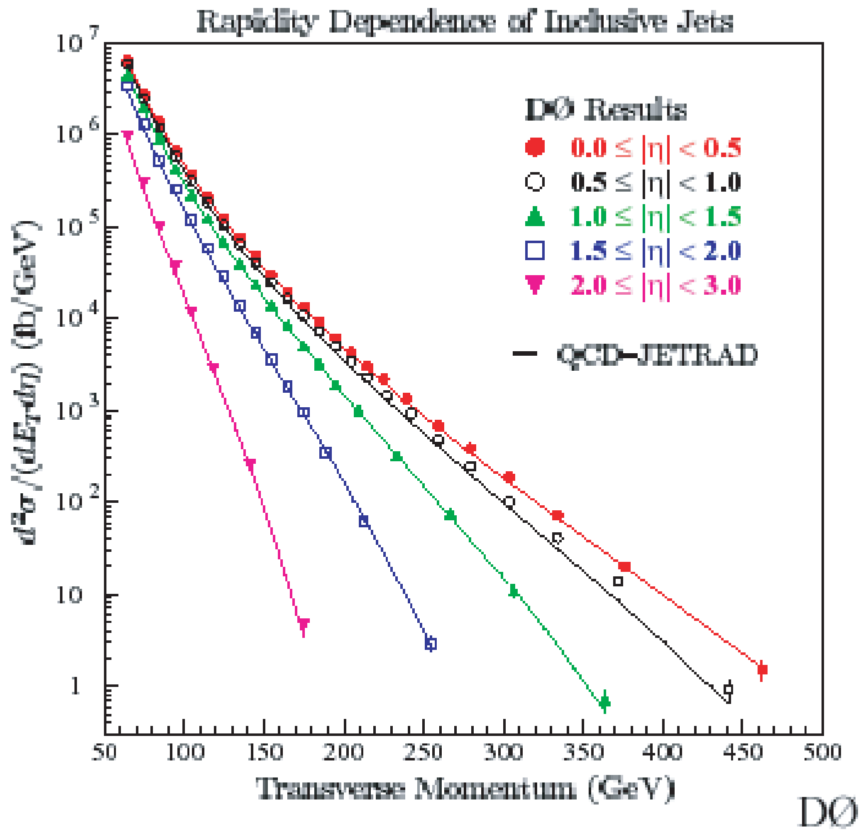


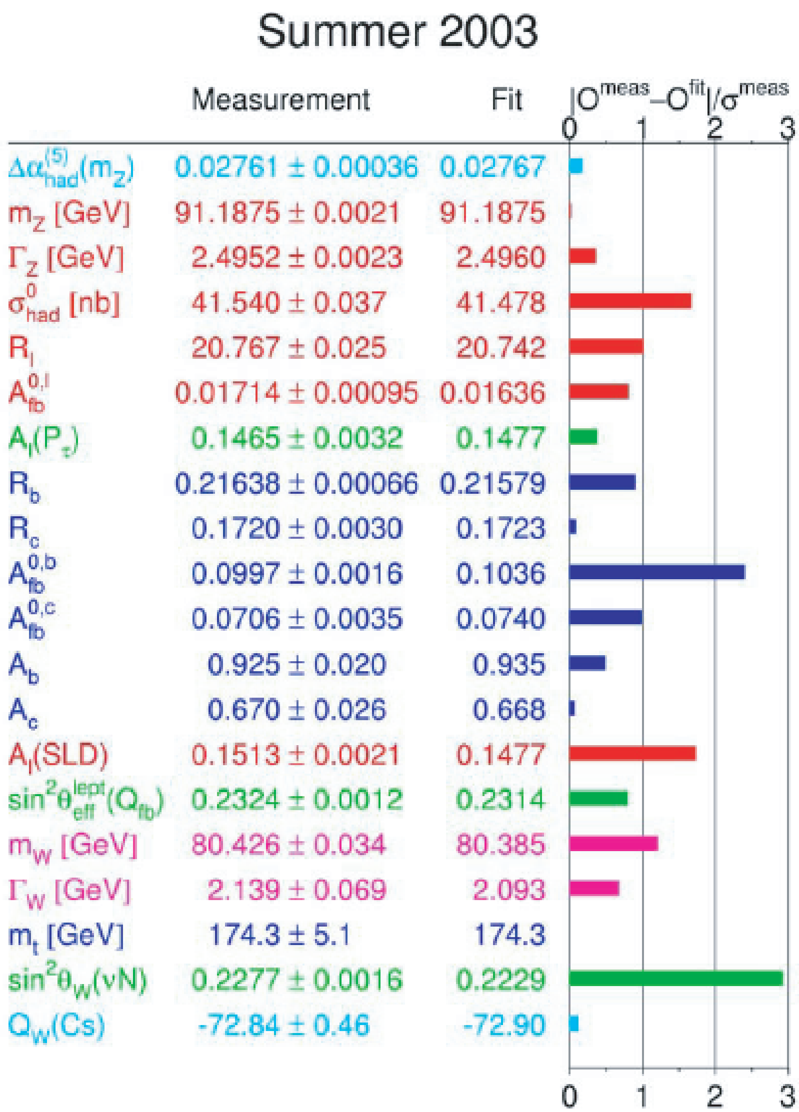


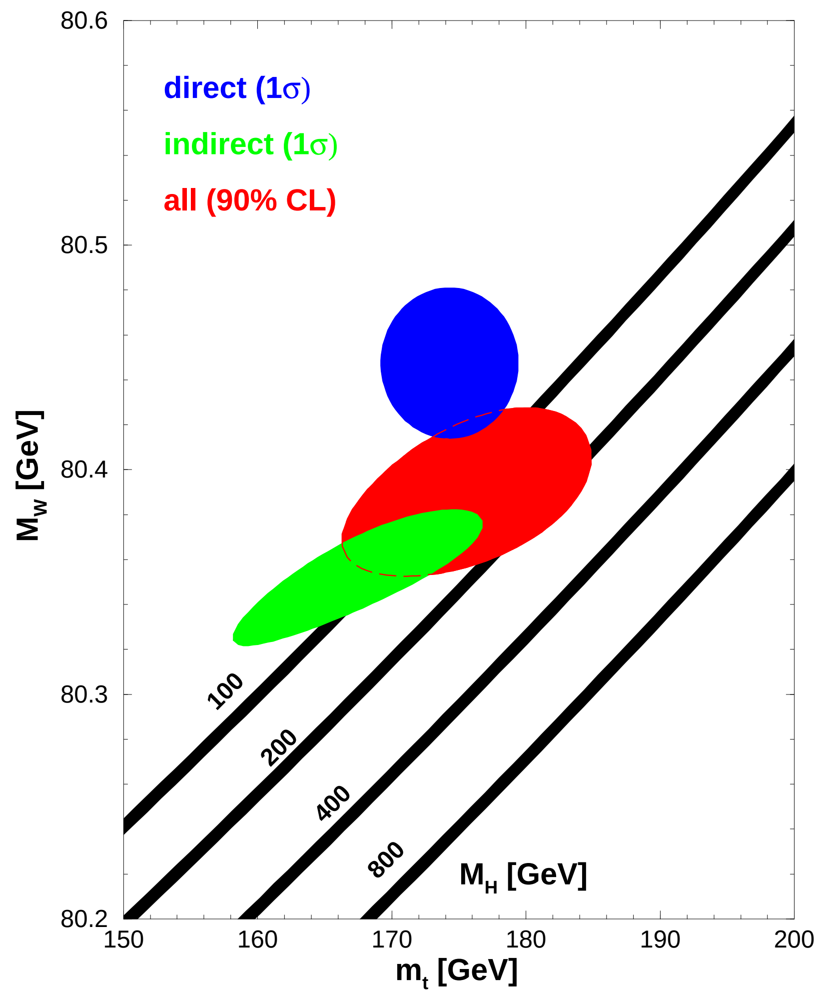
QCD remarkably successfful:

Perturbative QCD well tested and formed foundation for HEP;

Significant progress in lattice gauge calculatioins.

- $SU_L(2) \otimes U_Y(1)$ EW theory and precision measurements:





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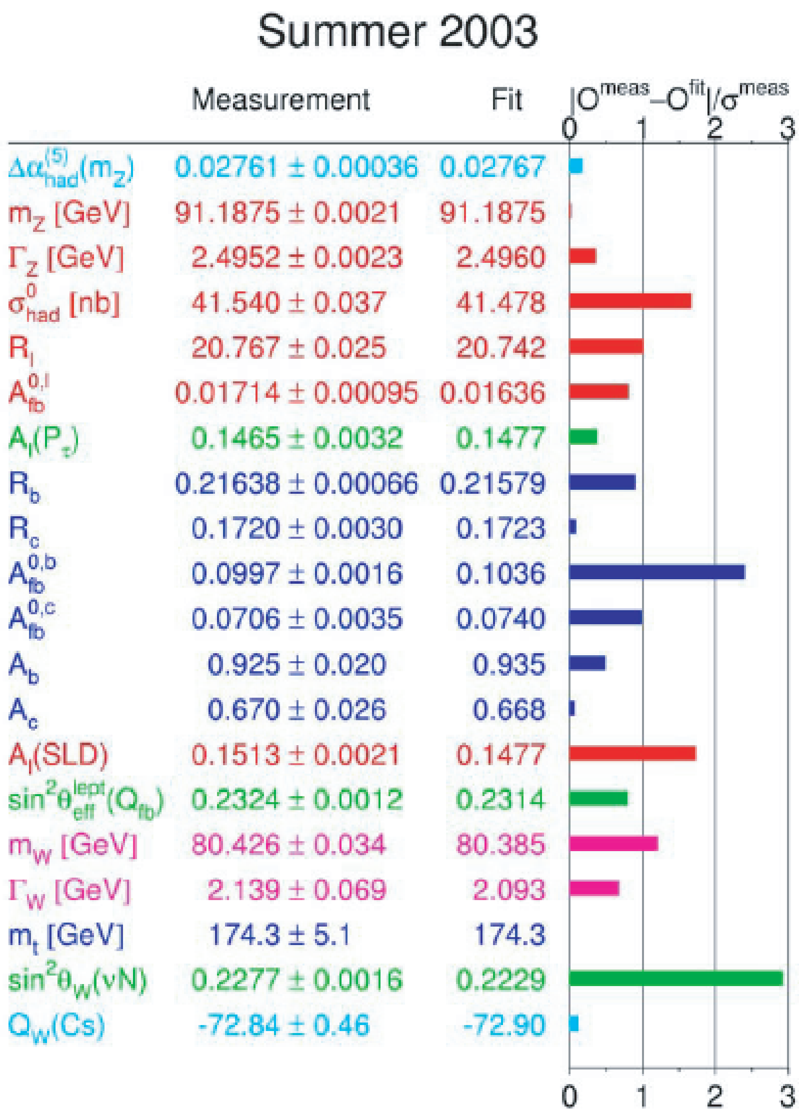
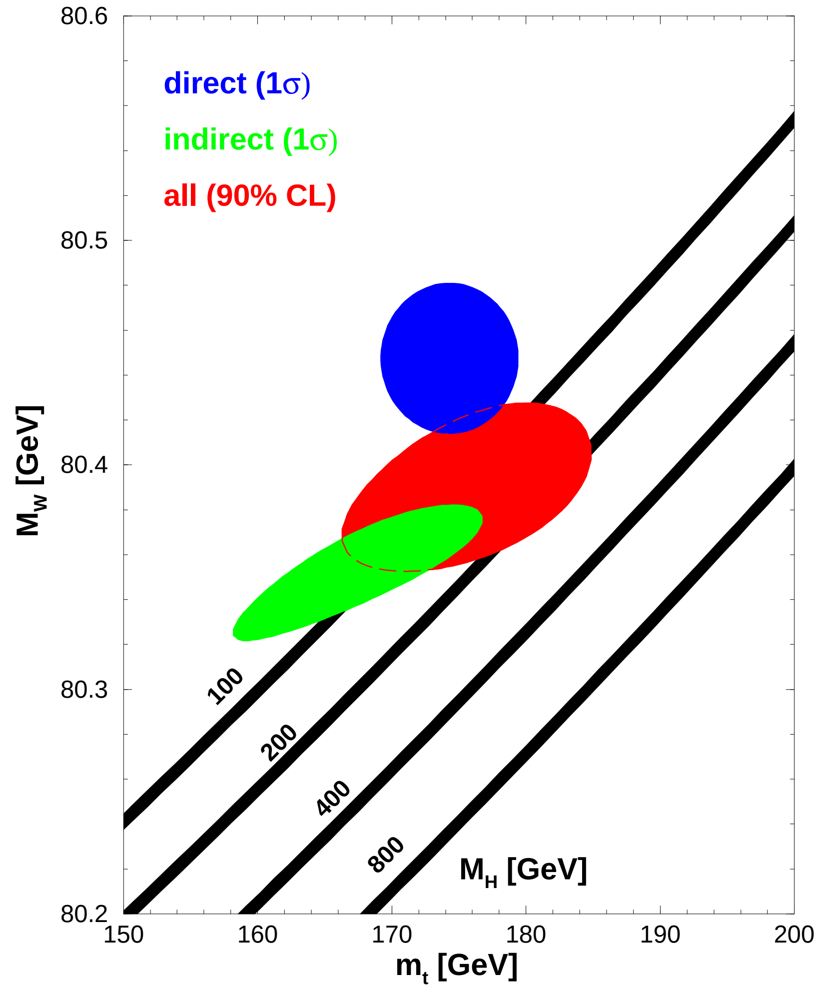


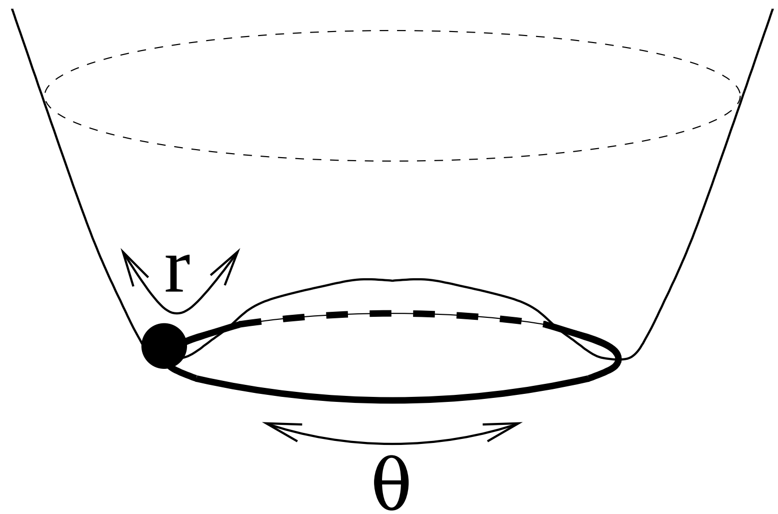


EW precision data: $m_H < 251$ GeV at 95% CL with $m_t = 178$ GeV.

- SM as an effective theory ?

$$V = -\mu^2\Phi^2 + \lambda\Phi^4,$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} iw^+ \\ \frac{H^0 + iz^0}{\sqrt{2}} \end{pmatrix}, \quad \langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{2\lambda}} \end{pmatrix}.$$



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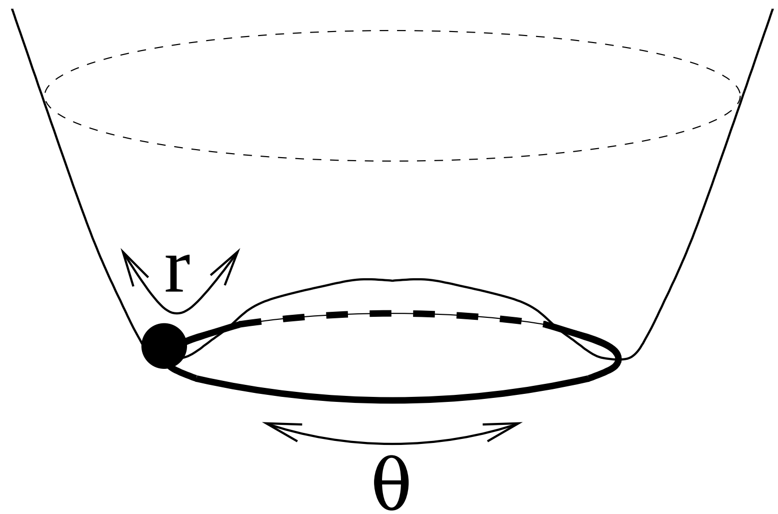

All masses in place:

$$M_{W,Z} = \frac{1}{2} g_V v, \quad m_f = \frac{g_f}{\sqrt{2}}\, v, \quad v^{-2} = \sqrt{2}\; G_F.$$

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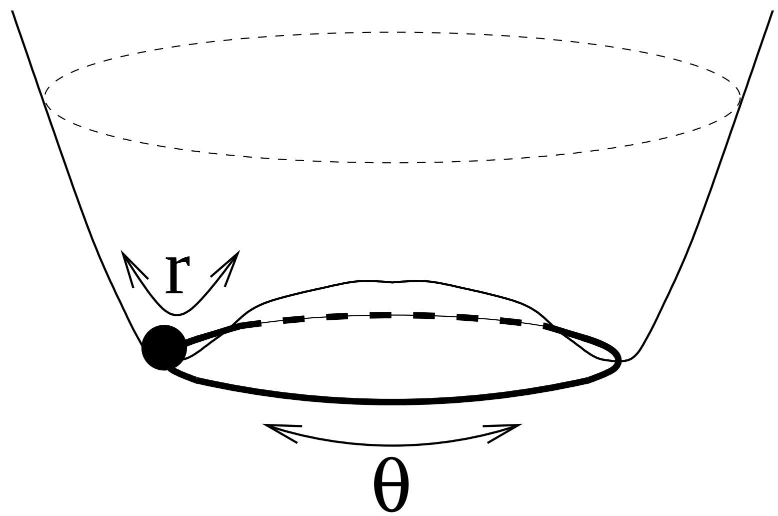

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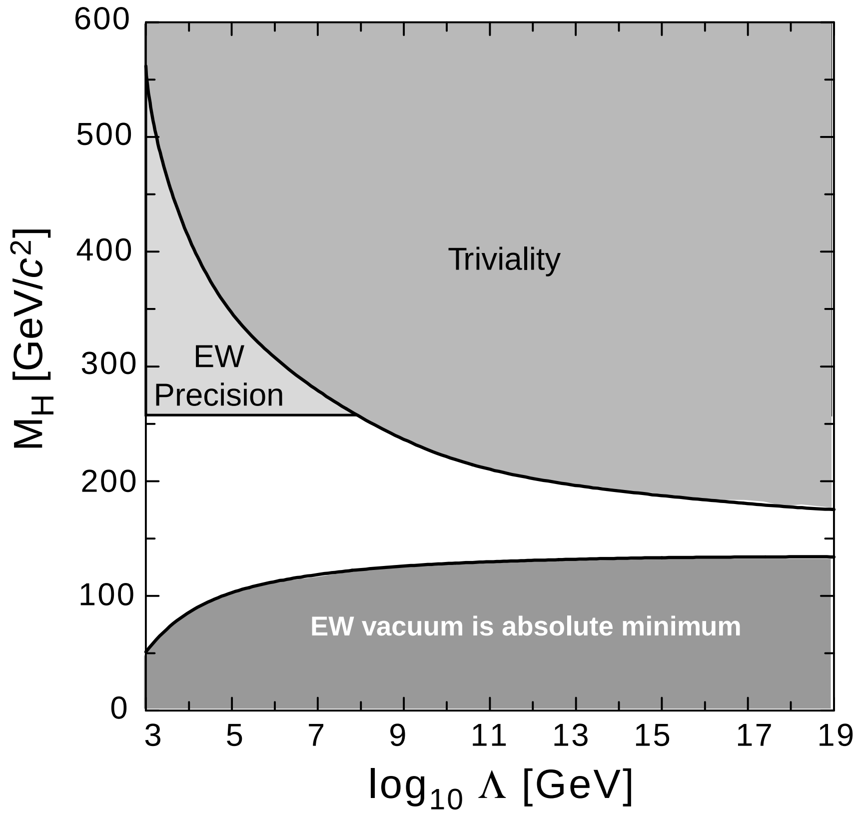
except the predicted, yet elusive Higgs H:

$$m_H = \sqrt{2\lambda}\, v.$$

Consider the m_H dependence on the theory cutoff Λ, below which the SM is valid.



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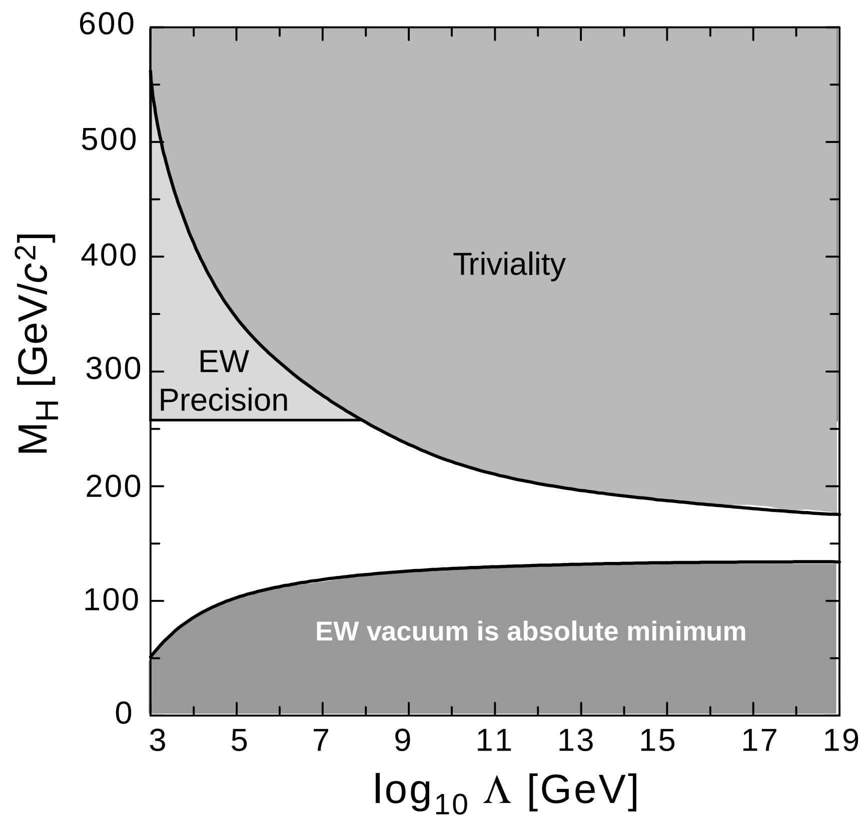


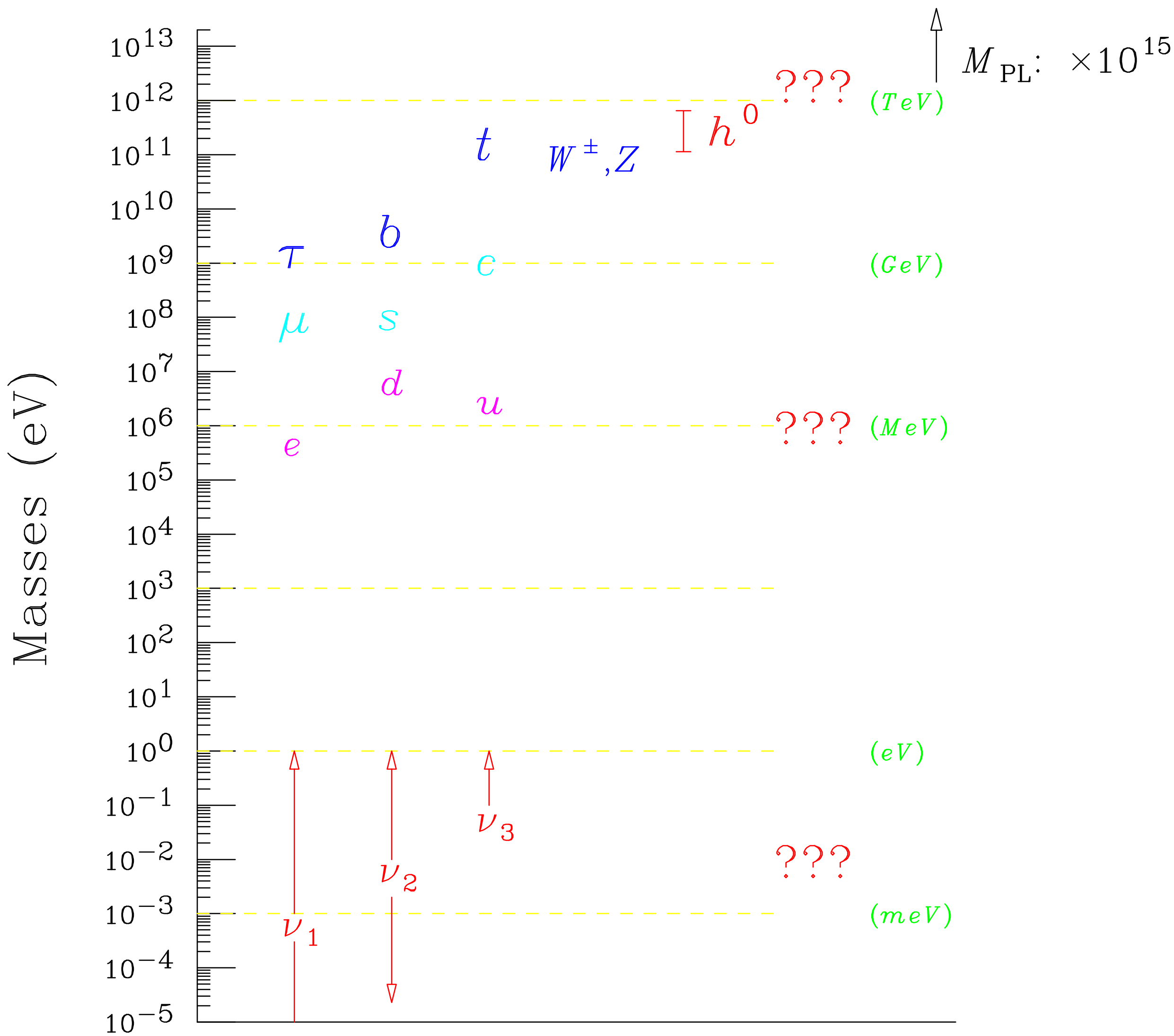
SM with a light H could be an *effective theory* up to $\Lambda \sim M_{pl}$:

SM: a stable vacuum; non-trivial interactions; renormalizability ...

Q: Would you need physics beyond the Standard Model?

The Need For Going Beyond SM ?

Mass Spectrum in a Wide Range:



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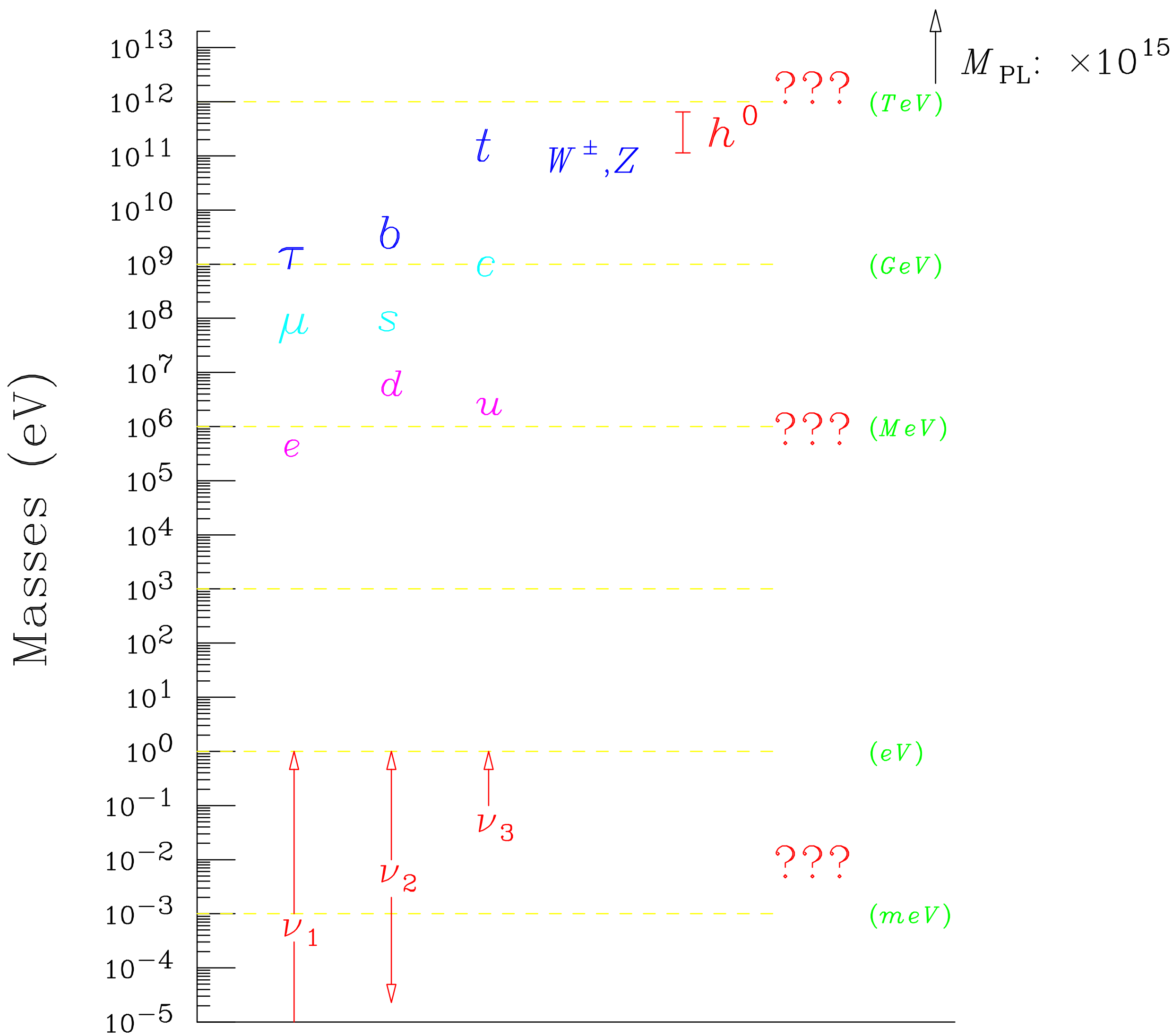

EW scale: $v \approx \mathcal{O}(1\ \text{TeV})$; m_ν : 10^{-15} down ? M_{pl} : 10^{15} up ?.

Vastly Separated Scales for Fundamental Interactions:

- QCD condensate: f_π

  At the scale Λ_{QCD}, the interaction becomes non-perturbative:

$$\alpha_s(Q^2) = \frac{1}{b\ln(Q^2/\Lambda^2)} \;\Rightarrow\; \Lambda_{QCD} \sim \Lambda\ \exp(-\frac{1}{2b\alpha_s}),$$

$$f_\pi \propto \langle \bar{q}_L q_R \rangle_0^{1/3} \sim 100\ \text{MeV}.$$

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  Empirically (Fermi's weak interaction) and theoretically (EWSB):

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- Quantum Gravity?

$$M_{Pl} = \hbar c/\sqrt{G_N} \approx 10^{19} \text{ GeV}.$$

  We have NO clue about it ...

Nontrivial fermion pattern: (observed)

Three fermion generations;

Quark small mixing;

Neutrino masses and (nearly) maximal mixing;

CP violation...

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Gauge interactions;

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Gravity and Planck scale physics;
Particle cosmology:
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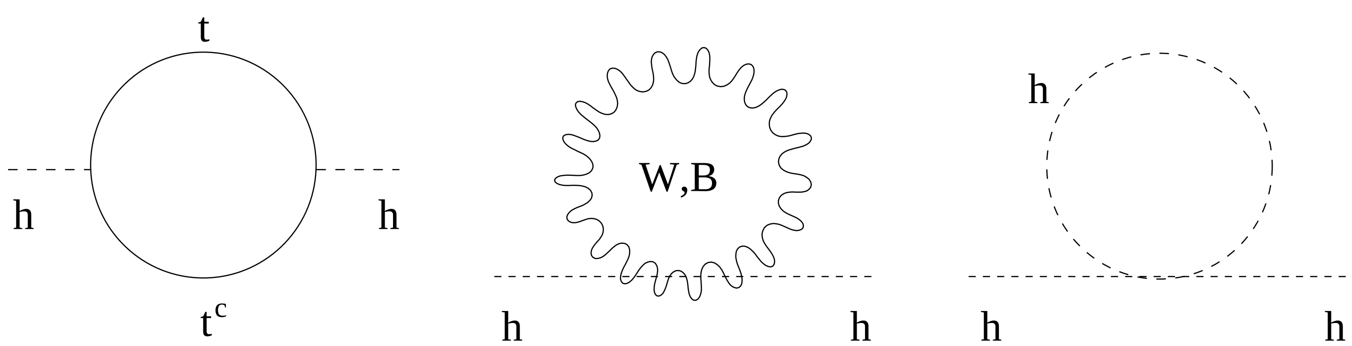
$\Longrightarrow$ All indicate the need for physics beyond the SM.

Most concerned: the naturalness problem

Due to quantum corrections, the Higgs mass is quadratically sensitive to the new physics (cutoff) scale: $\sim \Lambda^2$:



(a) (b) (c)

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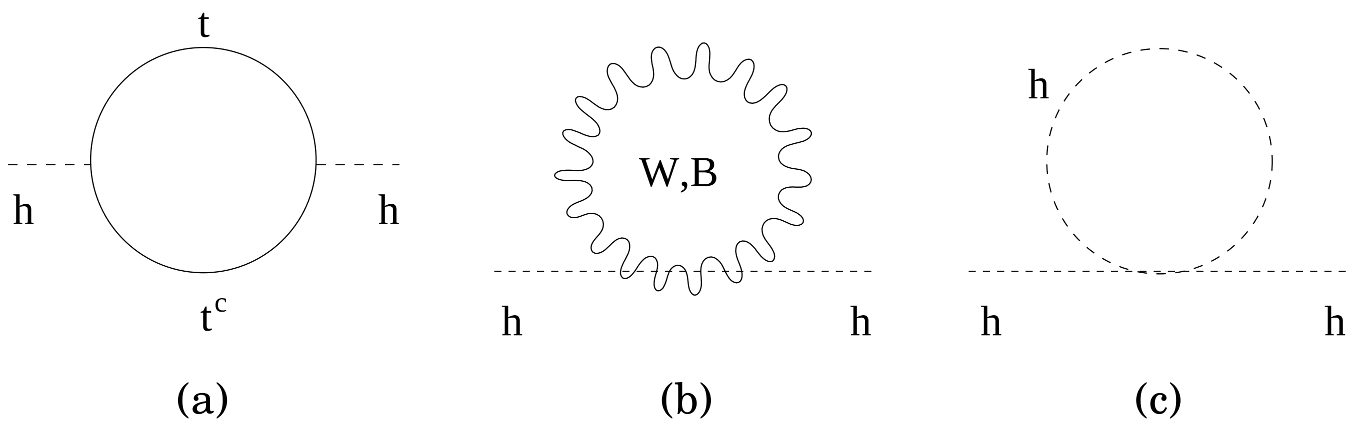

$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

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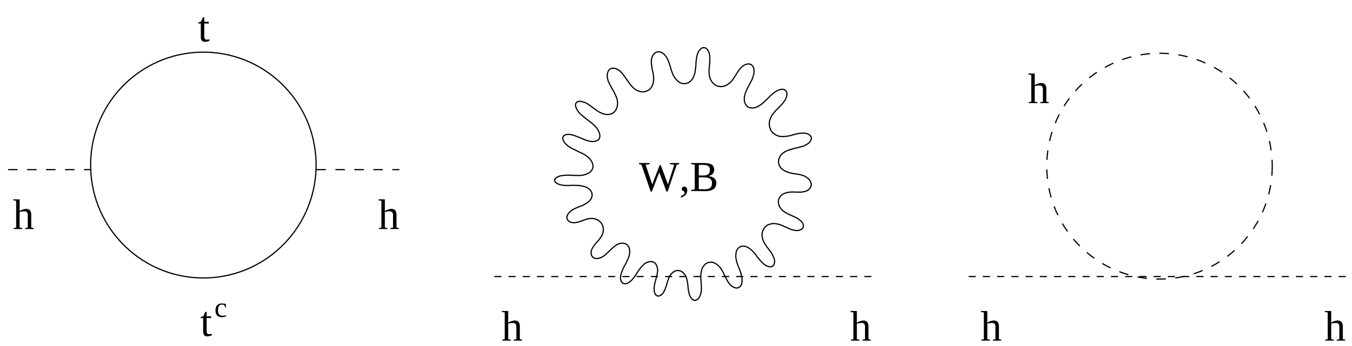

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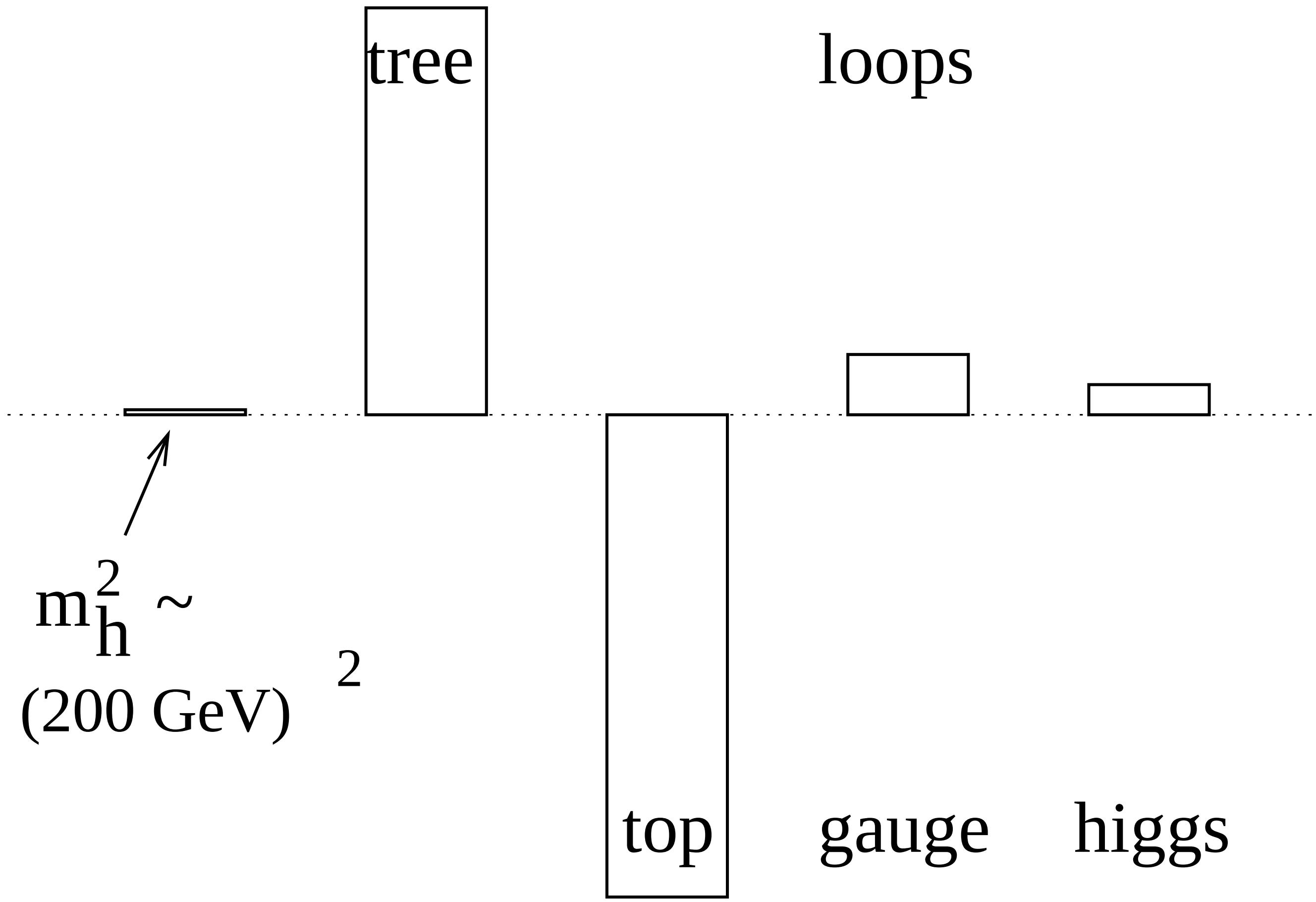
$$(200\ \text{GeV})^2 = m_{H0}^2 + \left[-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2 \right] \left(\frac{\Lambda}{10\ \text{TeV}} \right)^2$$


tree
loops
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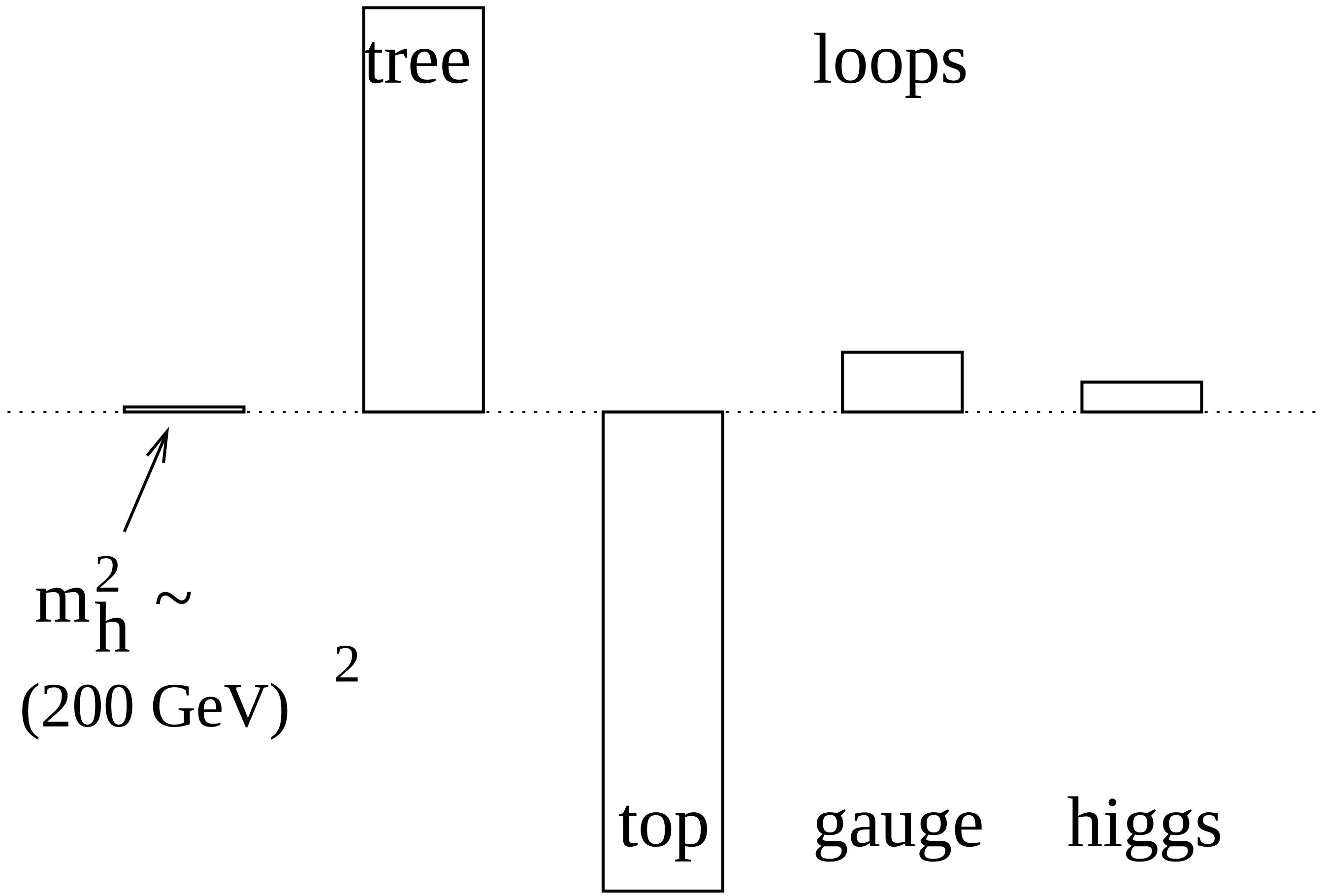
top
gauge
higgs



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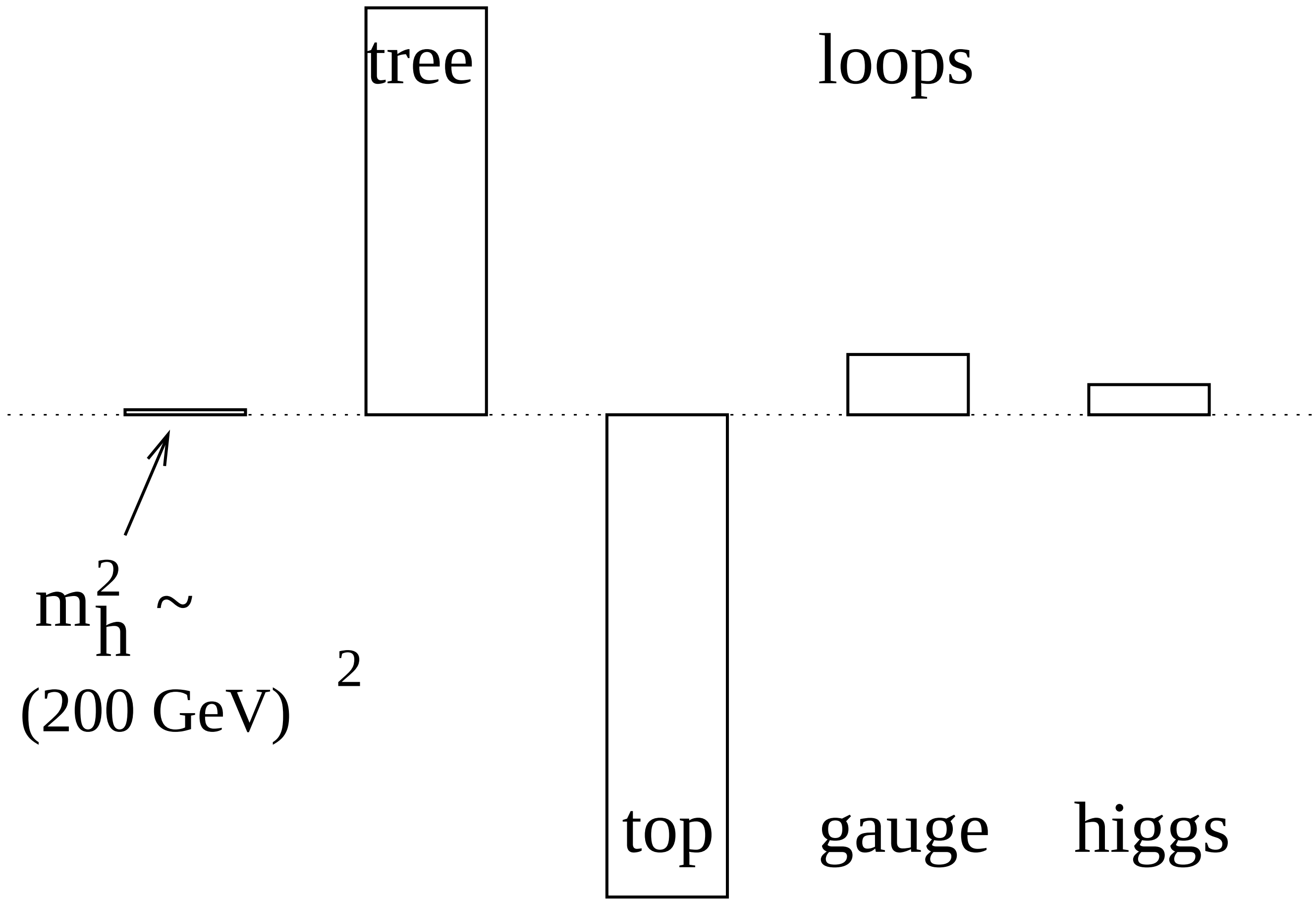

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Naturalness requirement: less than 90% cancellation on m_H^2

$$\Lambda_t \lesssim 3\ \text{TeV} \quad \Lambda_W \lesssim 9\ \text{TeV} \quad \Lambda_H \lesssim 12\ \text{TeV}$$

Our "theory bank"

The EWSB sector: The key to new physics.

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The EWSB sector: The key to new physics.

(A). Supersymmetry:

Weak scale SUSY stabilizes the hierarchy $M_W - M_{pl}$

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\frac{\lambda_f^2}{16\pi^2}\ln\left(\frac{\Lambda}{M_{SUSY}}\right).$$

if the "soft-SUSY breaking": $M_{SUSY} \sim \mathcal{O}(M_{SM})$.

Predict TeV scale new physics:
light Higgs bosons $H^0,\ A^0,\ H^\pm$;
SUSY partners $\tilde{W}^\pm ...,\ \tilde{g},\ \tilde{q},\ \tilde{l}^\pm ...$

Lead to rich physics at the electroweak scale at colliders;
Accommodate SUSY GUTs $M_{GUT} \sim 5 \times 10^{16}$ GeV.

(B). Dynamical approach for mass generation:

- Technicolor and alike: a lesson from QCD

  SU(N_{TC}) gauge theory, TC fermions $Q = U, D, ...$

  EWSB by TC-fermion condendation at Λ_{TC}:

  $$v \sim \langle \overline{Q_L} Q_R \rangle^{1/3} \sim 246 \text{ GeV}.$$

  Predicts new strong dynamics at the TeV scale: $\pi_T,\ \eta_T,\ \rho_T,\ \omega_T ...$

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- "Topcolor/Top-seesaw": Top quark special ?

  $$m_t \approx v/\sqrt{2} = 174 \text{ GeV}.$$

Introducing an additional fermion pair $\chi_L,\ \chi_R$

to generate the condensation $H \sim (\bar{\chi}_R t_L,\ \bar{\chi}_R b_L)$

Lead to a heavy Higgs $m_H \sim 1$ TeV,

a SM t, and a heavy state χ, $M_\chi \approx 4$ TeV.

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- A less ambitious approach: Little Higgs Models

  Accept the existence of a light Higgs;

  keep the Higgs boson "naturally" light (at 1-loop level).

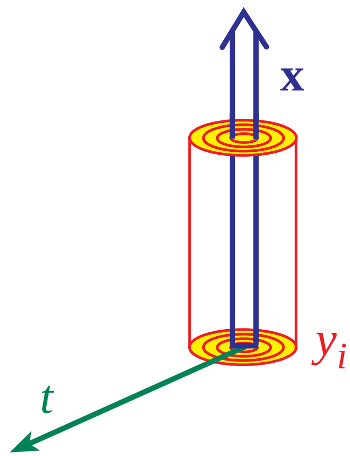
  Predicts new "partner particles":

  $$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(C). Extra-dimensions:
A new approach to the hierarchy problem

- Large Extra-dimension Scenario; ADD*

In a world with $D = 4 + n$ dimensions, n of them compactified,



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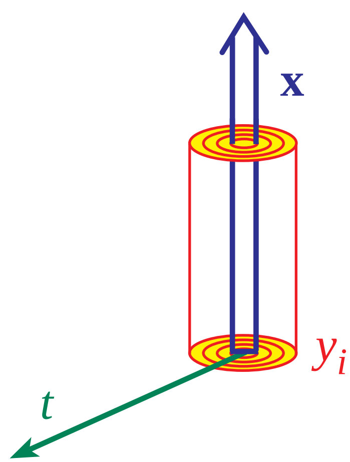

the 4-dim Planck scale is related to the D-dim one M_D as

$$M_{PL}^2 \sim M_D^{n+2} \int dx^n = M_D^{n+2} V_n.$$

Thus the fundamental scale in the theory:

$$M_D \sim (M_{pl}^2 / V_n)^{1/n+2} \longrightarrow \mathcal{O}(1 \text{ TeV}).$$

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- Extra dimensions and KK particles:

If an extra dimension y becomes compact (a circle of radius R), then all fields (gravitational, electromagnetic etc.) in y-dimension are periodic functions :

$$F(x,y) = \sum_{n=-\infty}^{\infty} F^n(x)\ e^{in\cdot y/R}.$$

Equation of motion:

$$(\partial^\mu \partial_\mu - \partial^y \partial_y) F(x,y) \Rightarrow (\partial^\mu \partial_\mu + \frac{n^2}{R^2}) F^n(x)$$

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$$\Delta M_{KK} = 1/R.$$

No γ_{KK}, e^-_{KK}, ... found $\Rightarrow$ R^{-1} large; or γ, e^- ... don't go there.

- The Randall-Sundrum Scenario

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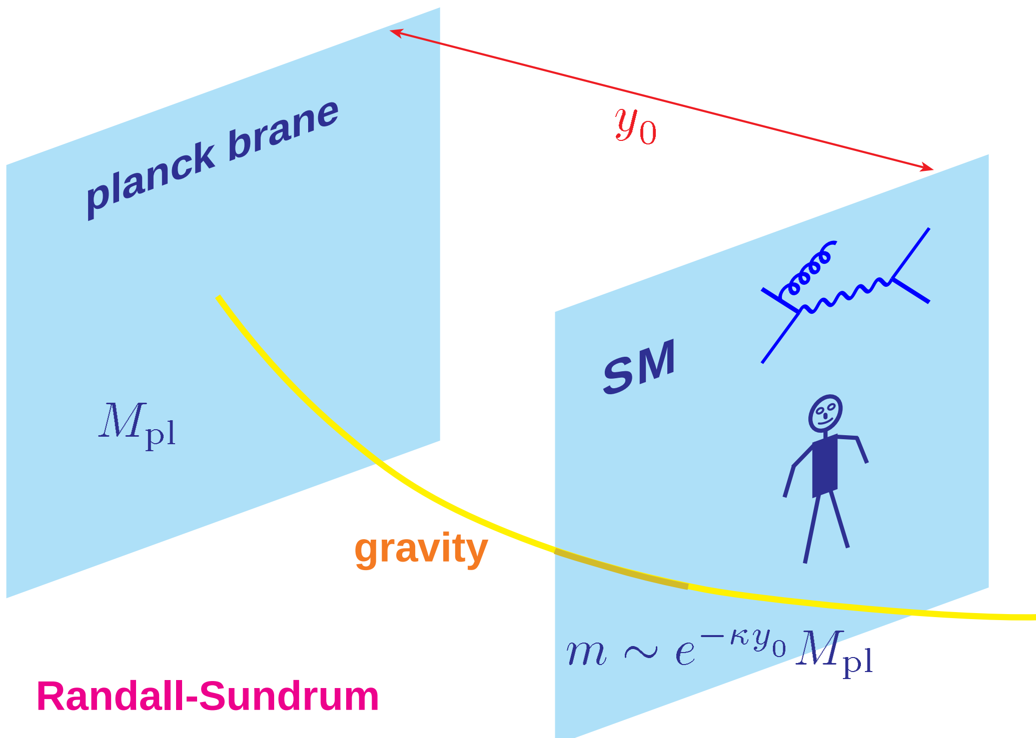
The extra dimension y is "warped":

$$ds^2 = e^{2A(y)}\ \eta_{\mu\nu}\ dx^\mu dx^\nu - dy^2,$$

where the "warp" factor $A(y) = -ky$,
with k the curvature scale in the 5^{th}-dim.



So the masses of the KK states are *not* equally-spaced.

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Electroweak precision constraints;

K/B rare decays and CP violation: $B \to X_s\gamma$; $J/\psi K_S$, ϕK_S, $\eta' K_S$...;

Neutrino masses and mixing;

muon $g-2$; $\mu \to e\gamma$...; neutron/electron EDMs;

Nucleon stability;

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Yet more to come:

Tevatron: ($p\bar{p}$ at 1.96 TeV, current)

EW, top sector, new particle searches, Higgs (?) ...

LHC: (pp at 14 TeV, 2007)

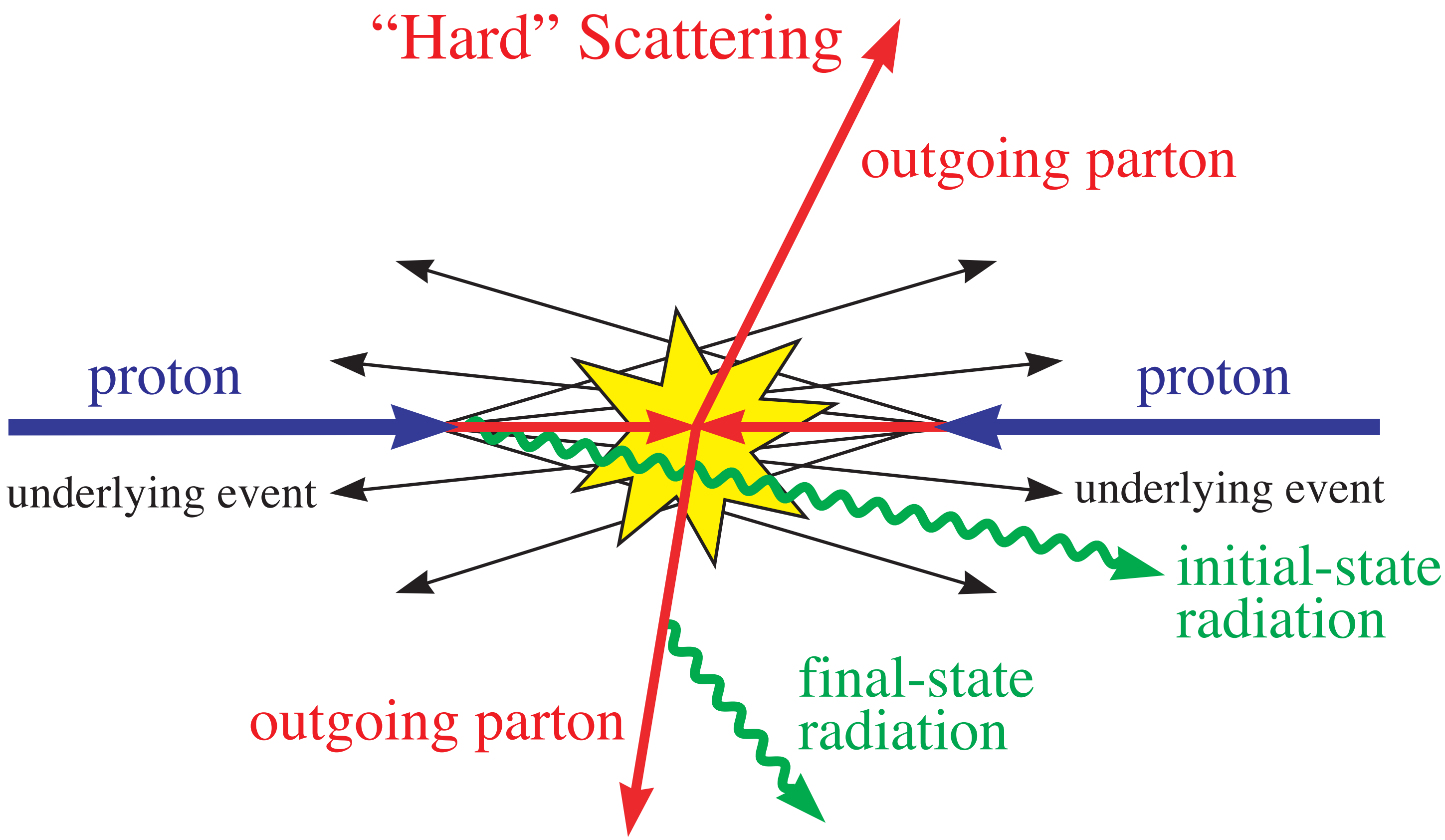
comprehensive Higgs studies, extensive new particle searches...

ILC: (e^+e^- at 500 GeV – 1 TeV)

more on top sector, precision Higgs and new light particles...

New Physics Search in the LHC Era:

In high-energy hadron collisions,



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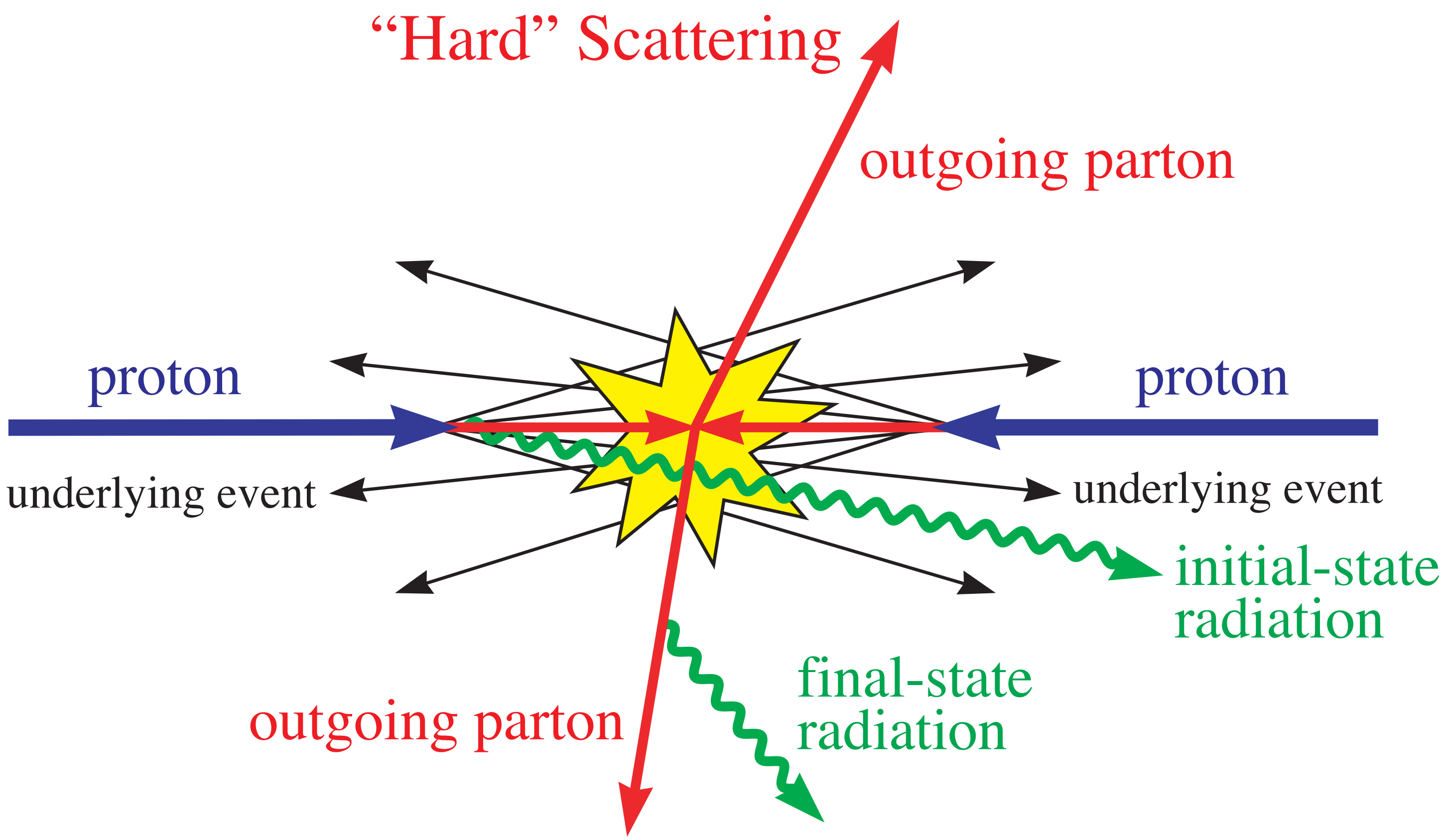
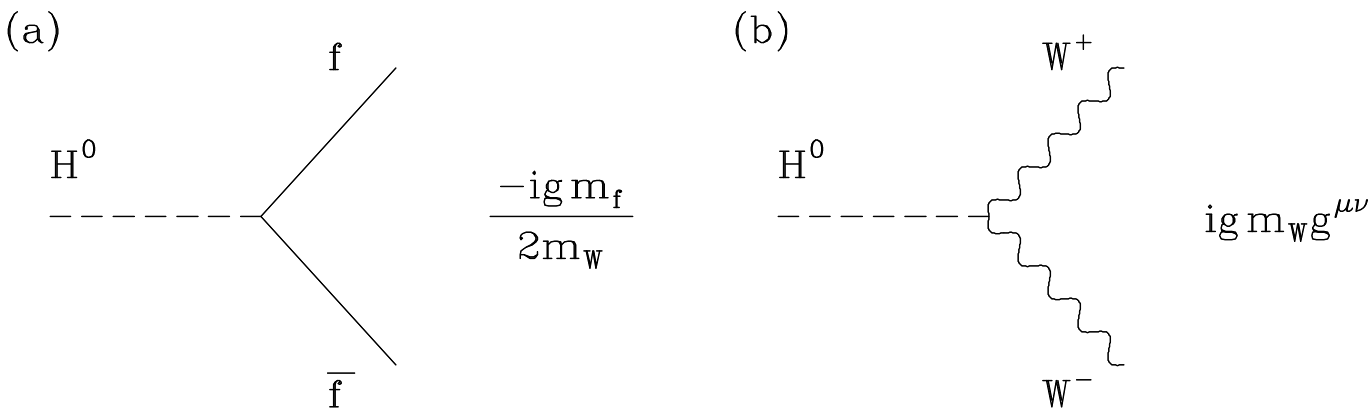


- Higher energy threshold: $M_{new} \sim \sqrt{s}$.
- multiple (strong, electroweak) channels: $q\bar{q},\ gg,\ qg,\ b\bar{b},\ WW\ \ldots$

Higgs Searches at the LHC:

The crucial features: Couplings proportional to masses.



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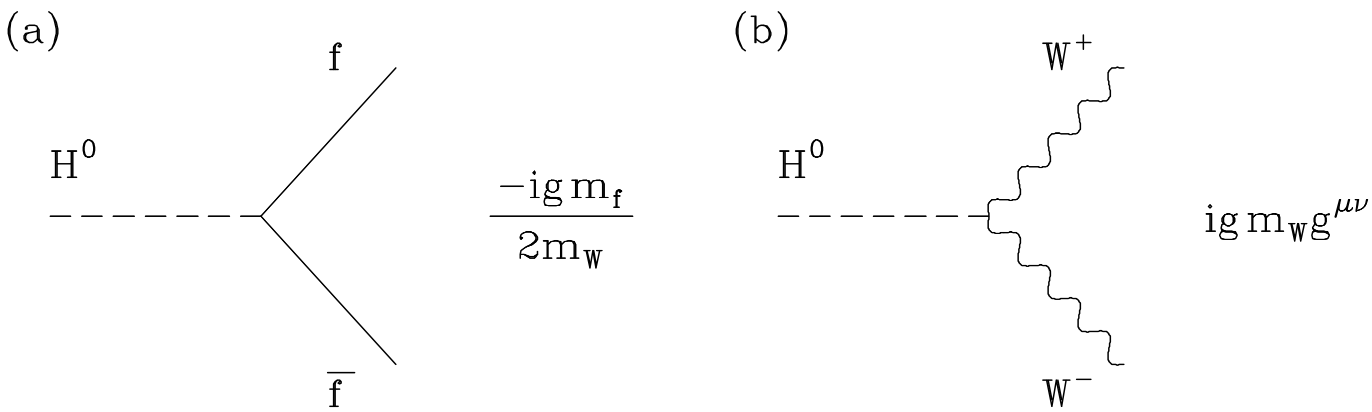
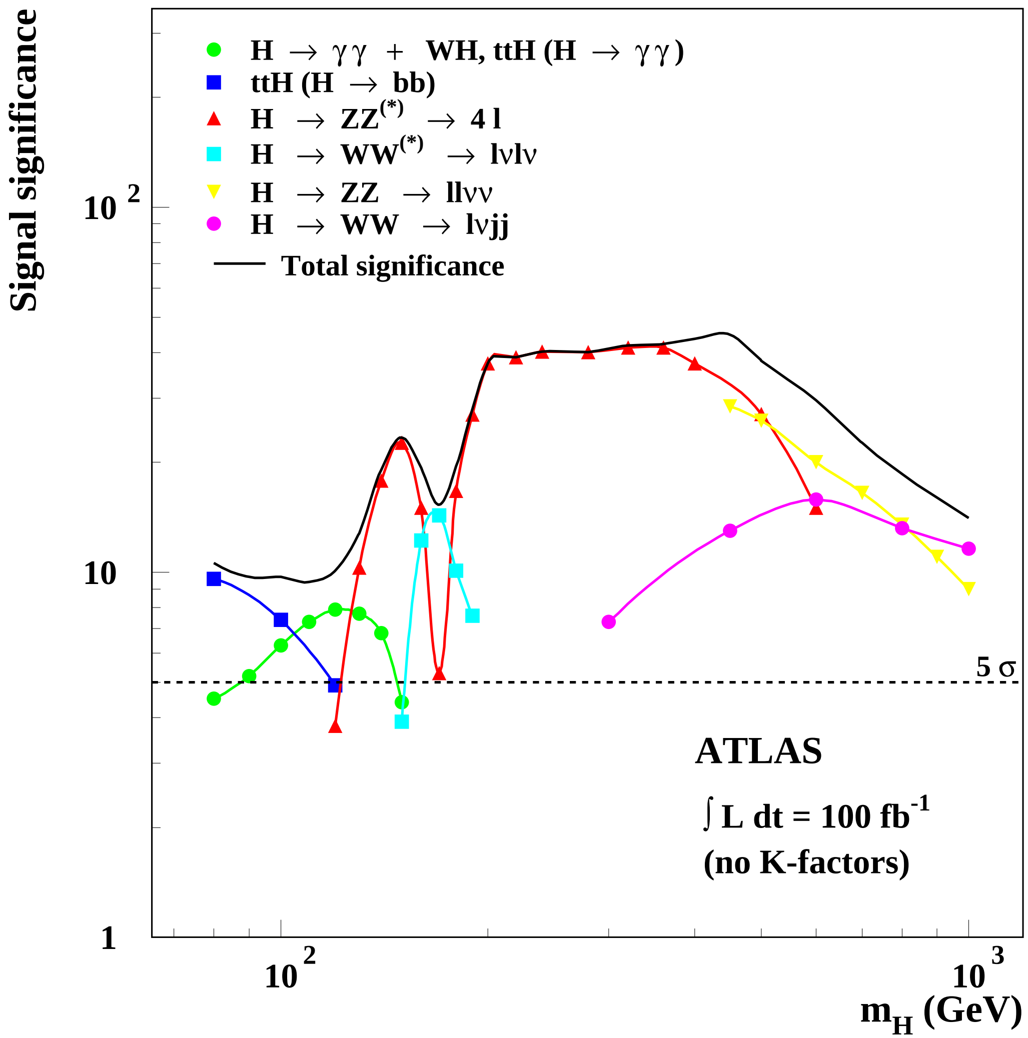


- At the LHC: hundreds of thousand may be produce,
  for $m_h \lesssim 700$ GeV, 100 fb^{-1}.
- Decay preferably to heavier particles.

- SM Higgs fully covered at the LHC:

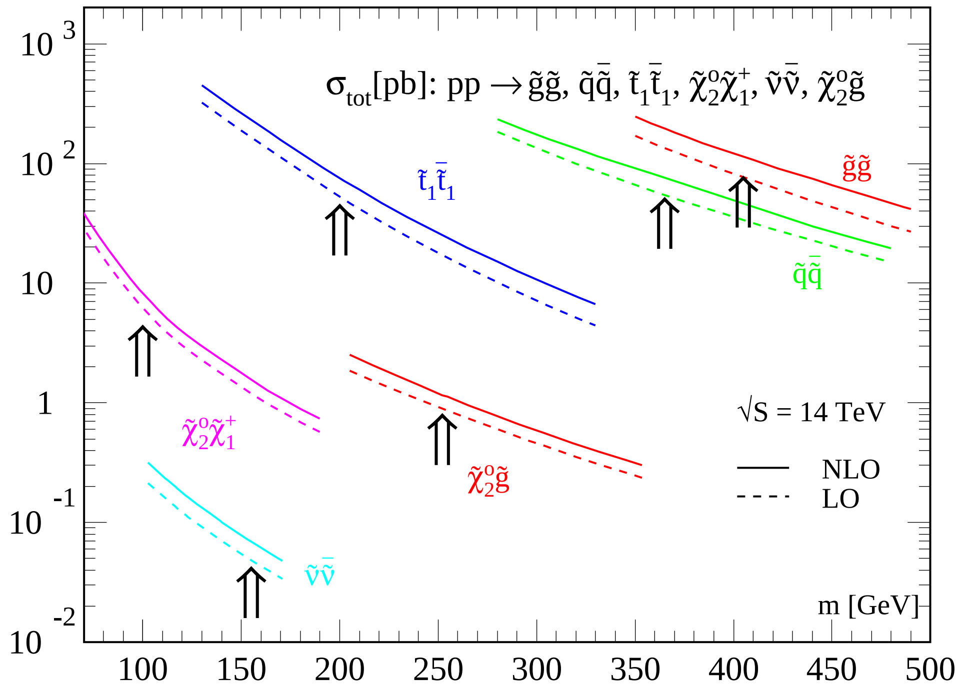


- ATLAS report: combining multiple channels, 10σ observation achievable.
- SUSY Higgs fully covered at the LHC:

Weak Scale Supersymmetry

- Hadron colliders can be a S-particle factory:

QCD production: $q\bar{q},\ gq,\ gg \to \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}.$
E.W. production: $q\bar{q} \to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^0,\ \tilde{\chi}_1^\pm\tilde{\chi}_2^0.$



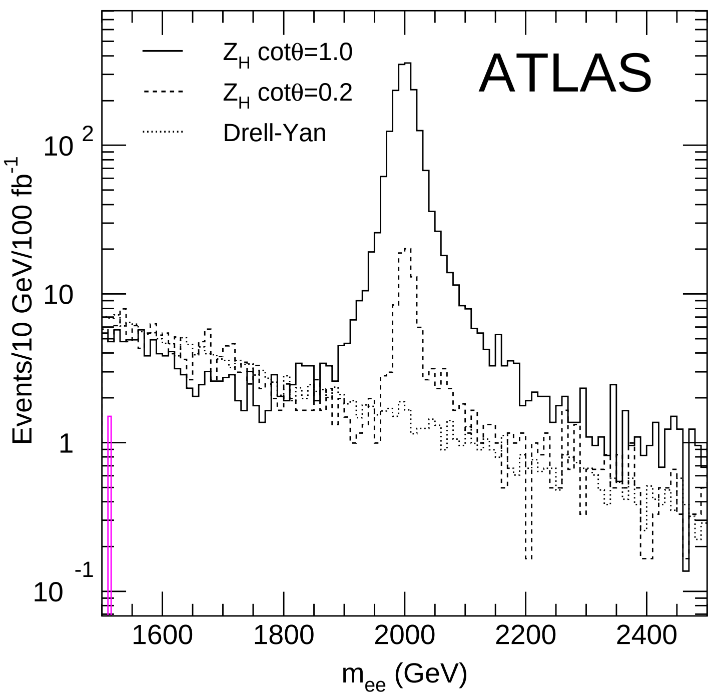
Typically,

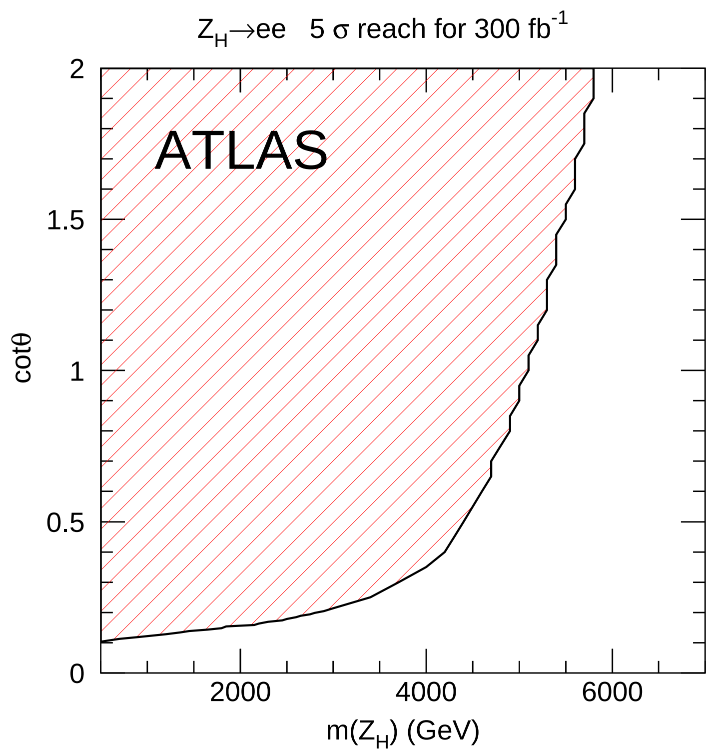
$\sigma(Tevatron) \approx \mathcal{O}(0.1 - 1\ \text{pb});\quad \sigma(\text{LHC}) \approx \mathcal{O}(10 - 100\ \text{pb}).$
LHC :$m_0 > 4000$ GeV, $m_{1/2} > 1400$ GeV, $\tan\beta \gtrsim 45$.

New gauge bosons and heavy fermions

New gauge bosons and heavy fermions

ATLAS simulations for $Z \to \ell^+\ell^-$:





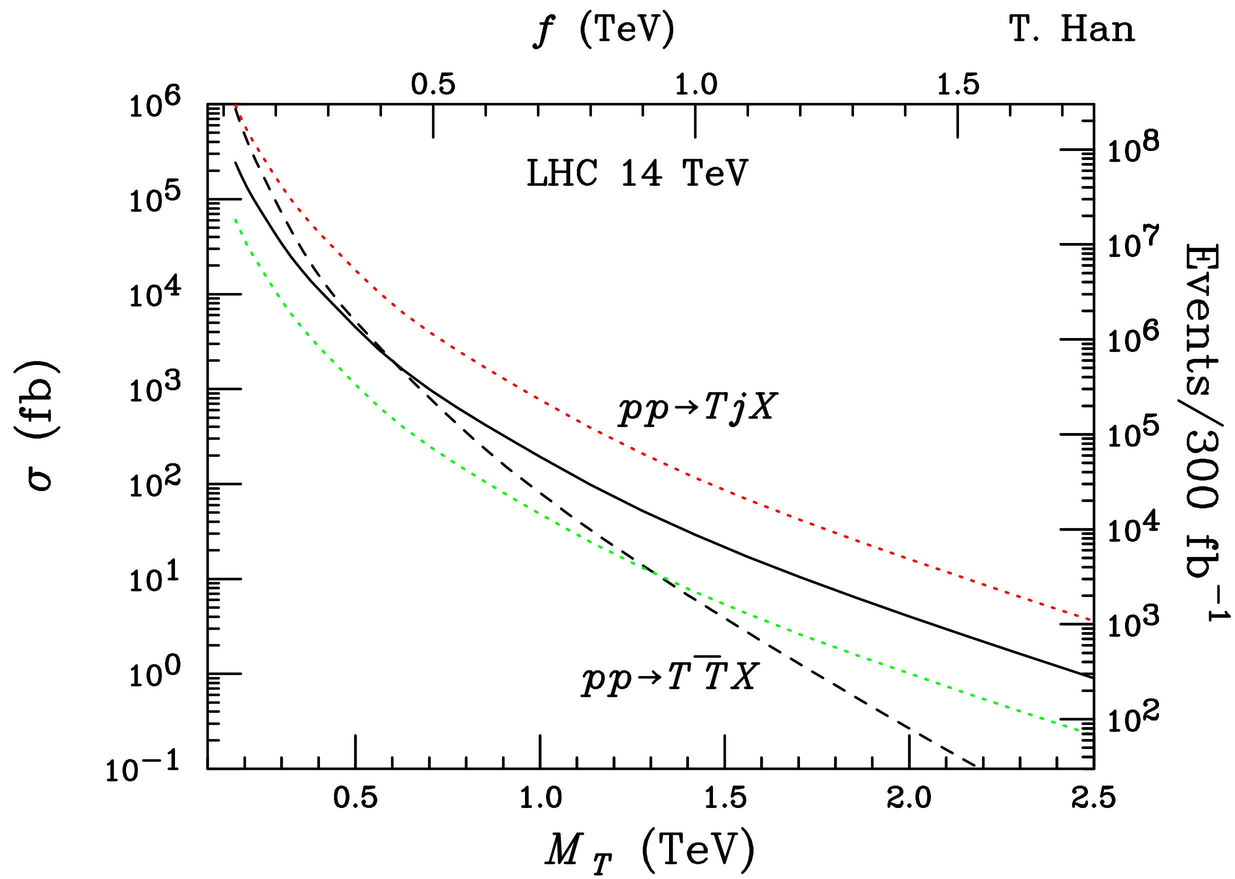
Little Higgs models as an example:

Reach $M_{Z_H} \sim$ several TeV for $\cot\theta > 0.1$:

Cross-sectiions measure $\cot\theta$: $N(\ell^+\ell^-)$ versus $N(Zh)$.

Mass peak M_{Z_H} determines f.

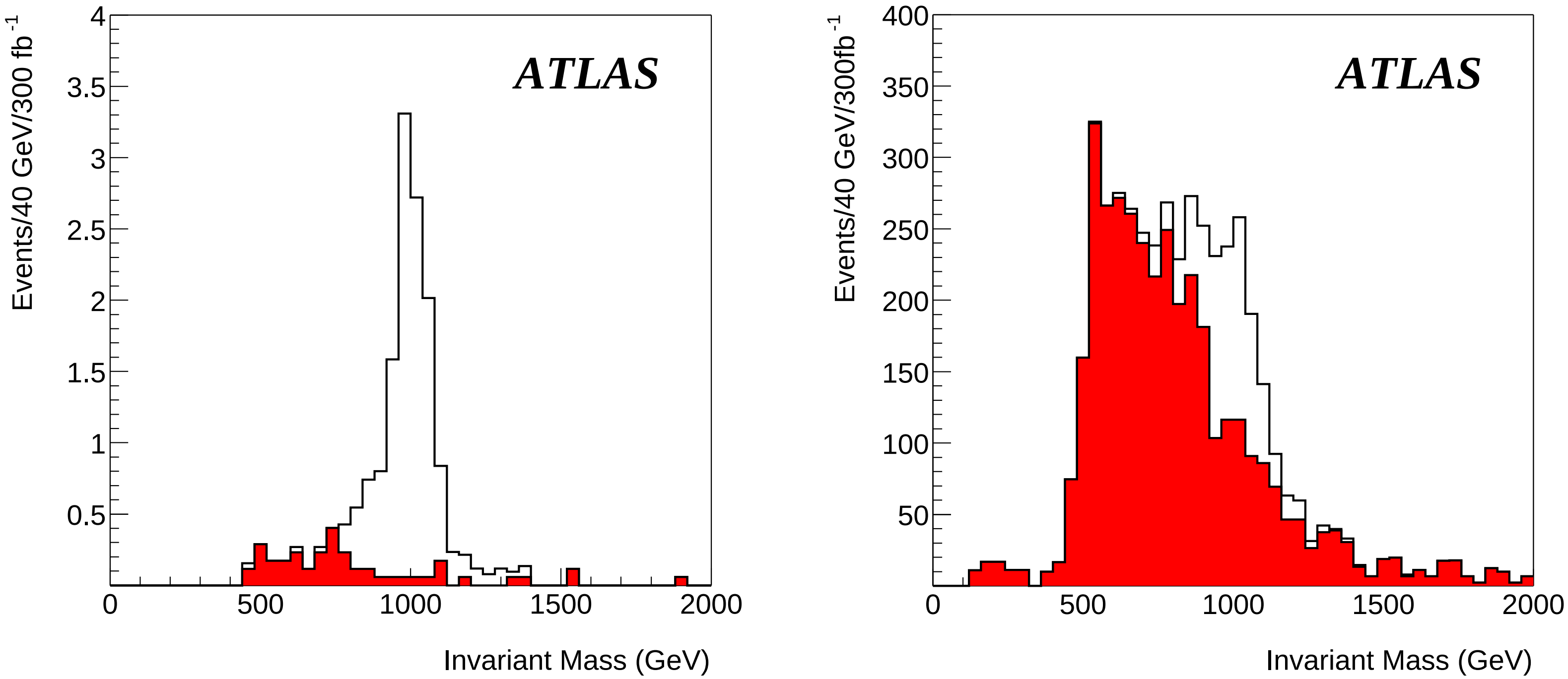
The heavy T signal at the LHC



$gg \to T\bar{T}$ phase-space suppression;

$qb \to q'T$ via t-channel $W_L b \to T$.

ATLAS simulations for $T \to tZ,\ bW$:



Reach $M_T \sim 1\ (2)$ TeV for $x_\lambda = 1\ (2)$.

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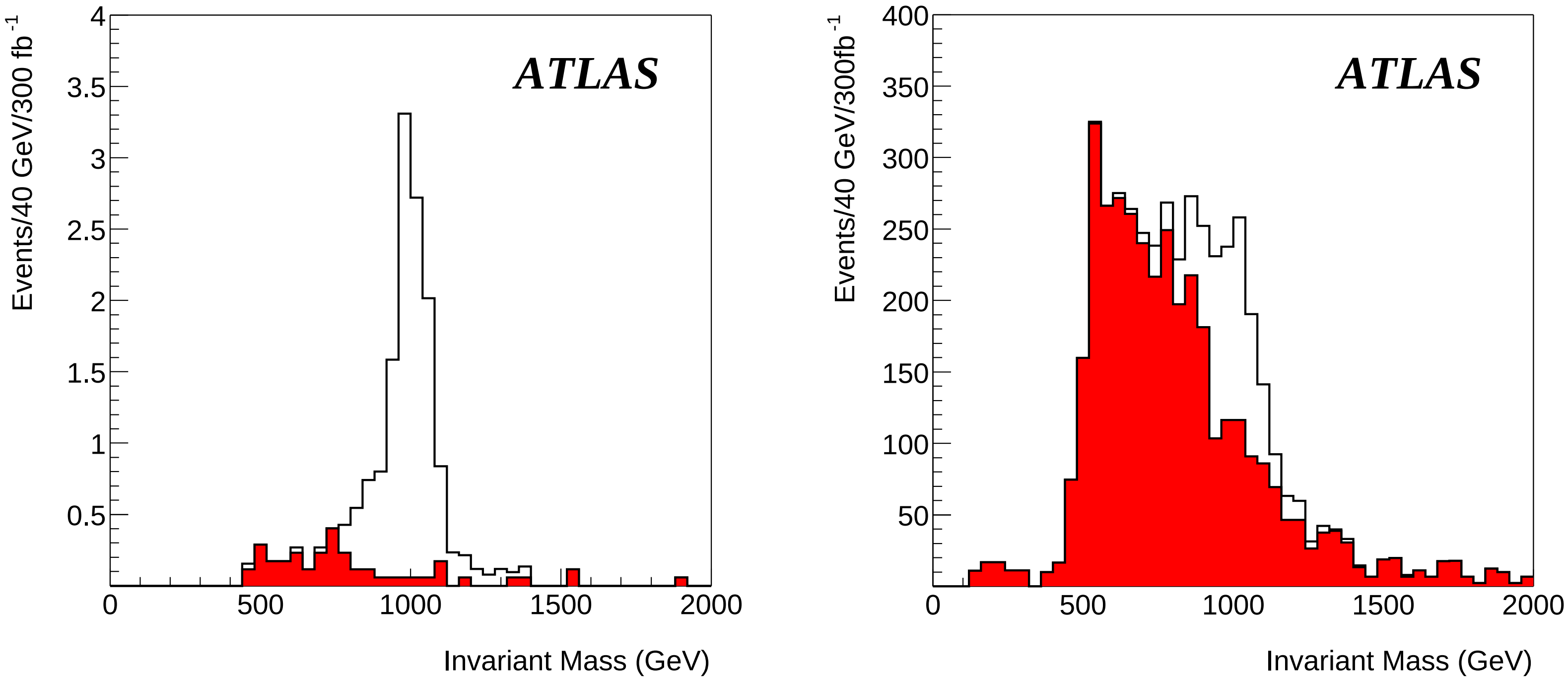

Reach $M_T \sim 1\ (2)$ TeV for $x_\lambda = 1\ (2)$.

Cross-sectiions measure coupling x_λ.

Mass peak M_T determines $f:\ v/f = m_t/M_T(x_\lambda + x_\lambda^{-1})$

$\Longrightarrow$ check consistency with f from M_{Z_H}.

Deep into extra-dimensions at the LHC:

- Observable signatures for extra-dim models:

▷ At "low" energies

† "very low": $E \ll 1/R,\ M_D$:

4d effective theory: as the Standard Model; weak effects from gravity.

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$(4+n)-$dim physics directly probed, and gravity effects observable: mainly via light KK gravitons of mass

$$m_{KK} \sim 1/R, \Leftarrow \text{discrete states in 5d viewpoint.}$$

or whatever propagate there $\Rightarrow$ an effective theory (SM+KK).

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▷ Intermediate energy regime $E \sim M_D$: stringy states significant: s-channel poles as resonances:

$$\mathcal{M}(s,t) \sim \frac{t}{s - M_n^2}, \quad M_n = \sqrt{n} M_S.$$

▷ At "trans Planckian" energies $E > M_D, M_S$:
$(4 + n)$−dim physics directly probed;
gravity dominant: black hole production*

$$\sqrt{s} = M_{BH} > M_D \text{ for } b < r_{bh}.$$

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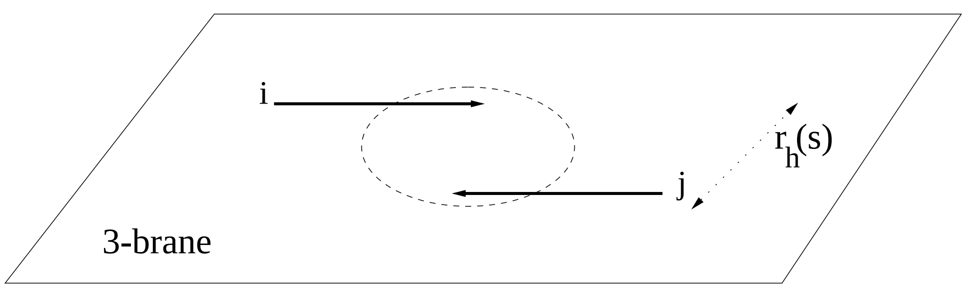
$$r_{bh} = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{BH}}{M_D} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right) \right]^{\frac{1}{n+1}} \rightarrow M_{BH}/M_{pl}^2 \text{ in 4d}$$

$$\sigma = \pi r_{bh}^2.$$



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- Collider Searches for Extra Dimensions:

A. Collider Signals I (ADD)

Real KK Emission: Missing Energy Signature

b. $p\bar{p} \rightarrow jet + KK$ (mono-jet+missing energy)

n – dim :	at Tevatron	at LHC
$n = 4$	$M_S > 900$ (GeV)	3400
$n = 6$	$M_S > 810$ (GeV)	3300

D. Stringy States at Colliders

Future colliders may reach the TeV string threshold thus directly produce the “stringy” resonant states.

Amplitude factor near the resonance

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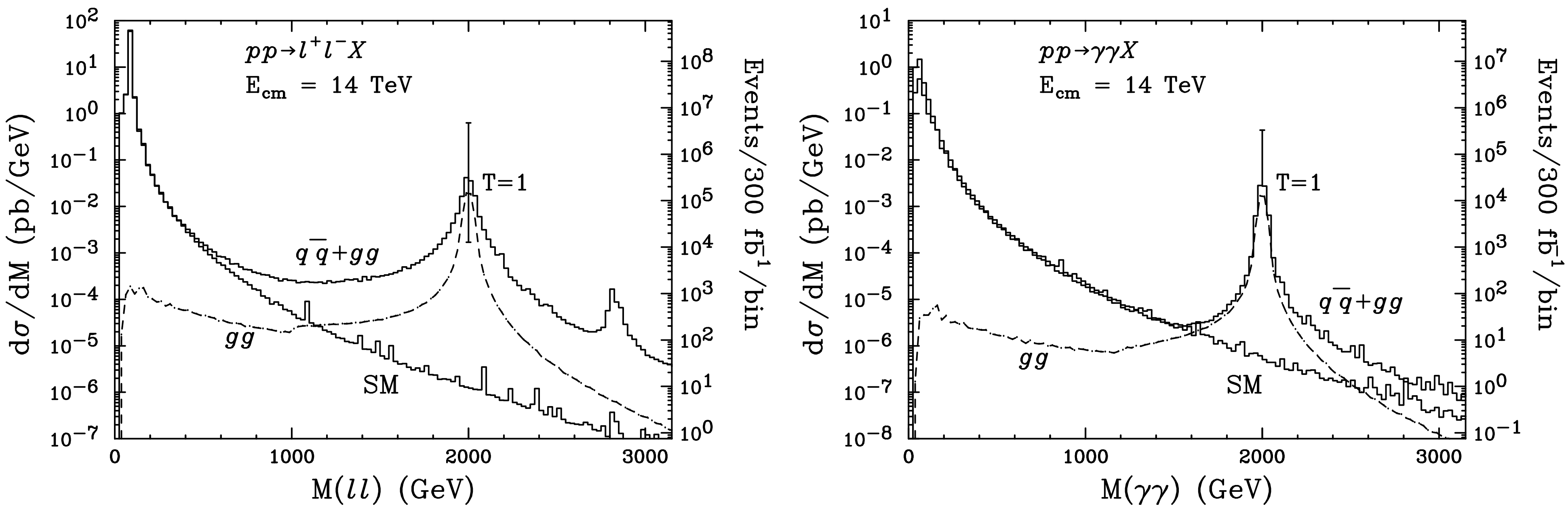

where T is an unkown gauge factor (Chan-Simon factor), typically $1-4$.

E. Black Hole Production at Colliders

For a black hole of mass M_{BH}, its size is

$$r_{bh} \approx \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}} \rightarrow \frac{M_{BH}}{M_{pl}^2} \text{ in 4d.}$$

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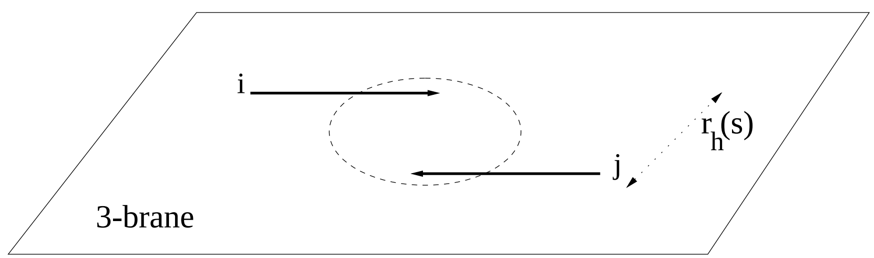
At higher energies and shorter distances (impact parameter)

$$E_{cm} > M_{BH} > M_D, \quad b_{impact} < r_{bh},$$

black holes formation is the dominant quantum gravity phenomena.



Black holes copiously produced at the LHC energies,

M_{BH}	$n = 4$	$n = 6$
5 TeV	1.6×10^5 fb	2.4×10^5 fb
7 TeV	6.1×10^3 fb	8.9×10^3 fb
10 TeV	6.9 fb	10 fb

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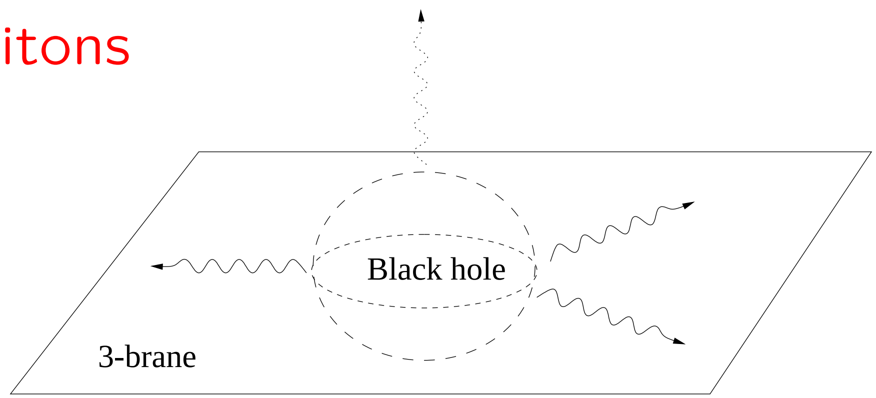
Black holes "decay" via Hawking radiation:

$\gamma,\ \nu,\ e^{\pm},\ hadrons, \ldots\ W^{\pm},\ Z\ldots,$ gravitons



Spectacular events:

- very luminous in the detector!
- lepton-number/baryon-number violation (?)
- spherical/angular momentum orientation (?) ... ...

Synergy of the LHC and ILC:

The need of the ILC

Consider the following scenarios:

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The need of the ILC

Consider the following scenarios:

LHC finds MANY new states, then the ILC ...

- Detailed spectroscopy:
  - ∗ Masses from kinematics and threshold m ∼a few 100 GeV;
  - ∗ Spins from threshold and decay patterns.

- Precise measurements for interactions:
  - ∗ Coupling strengths from cross sections and branching fractions.

- $\gamma\gamma$ option:
  - ∗ To sort out the scalar sector m ∼a few 100 GeV: CP property ...

Sufficient to distinguish different models: SUSY, TC, extra dimensions ...

LHC finds a light Higgs state (only) $m_h < 200$ GeV ...

- Precision measurements for its properties:
  * Coupling strengths, cross sections, and branching fractions.
  * SM-like, SUSY, or extended Higgs sector ?

$$e^+e^- \to Zh, \quad WWh, \quad t\bar{t}h, \quad b\bar{b}h.$$

- $\gamma\gamma$ collider for measuring m_h and

$$\Gamma(h \to \gamma\gamma)\ BR(h \to b\bar{b}) \quad \text{at} \quad 5\% \quad \text{level.}$$

- $Giga - Z$ factory to check consistency.

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LHC finds a heavy Higgs state (only) $m_h > 200 - 800$ GeV ...

- Precision measurements for its properties via

$$e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}h, \;\; e^+e^-Z^*Z^* \to e^+e^-h.$$

- Search and confirm NOTHING else.
- $\gamma\gamma$ collider for measuring m_h and $\Gamma(h \to \gamma\gamma)\ BR(h \to b\bar{b})$
- $Giga - Z$ factory to check consistency.

LHC finds NOTHING, not even h (?) ...

- Conclusive search and confirm it by

$$e^+e^- \to Zh, \quad \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}h, \; e^+e^-Z^*Z^* \to e^+e^-h.$$

- "Bread and butter" Precision physics

$$e^+e^-, \; \gamma\gamma \to t\bar{t}, \quad WW, \quad WWZ...$$

- $Giga - Z$ factory to check consistency.

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  uncover new signatures
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Go for the LHC !

Synergy with the ILC crucial !