Joint ECFA-EPS Session, Grenoble, 23 July 2011

Particle theory: recent progress and medium-term prospects

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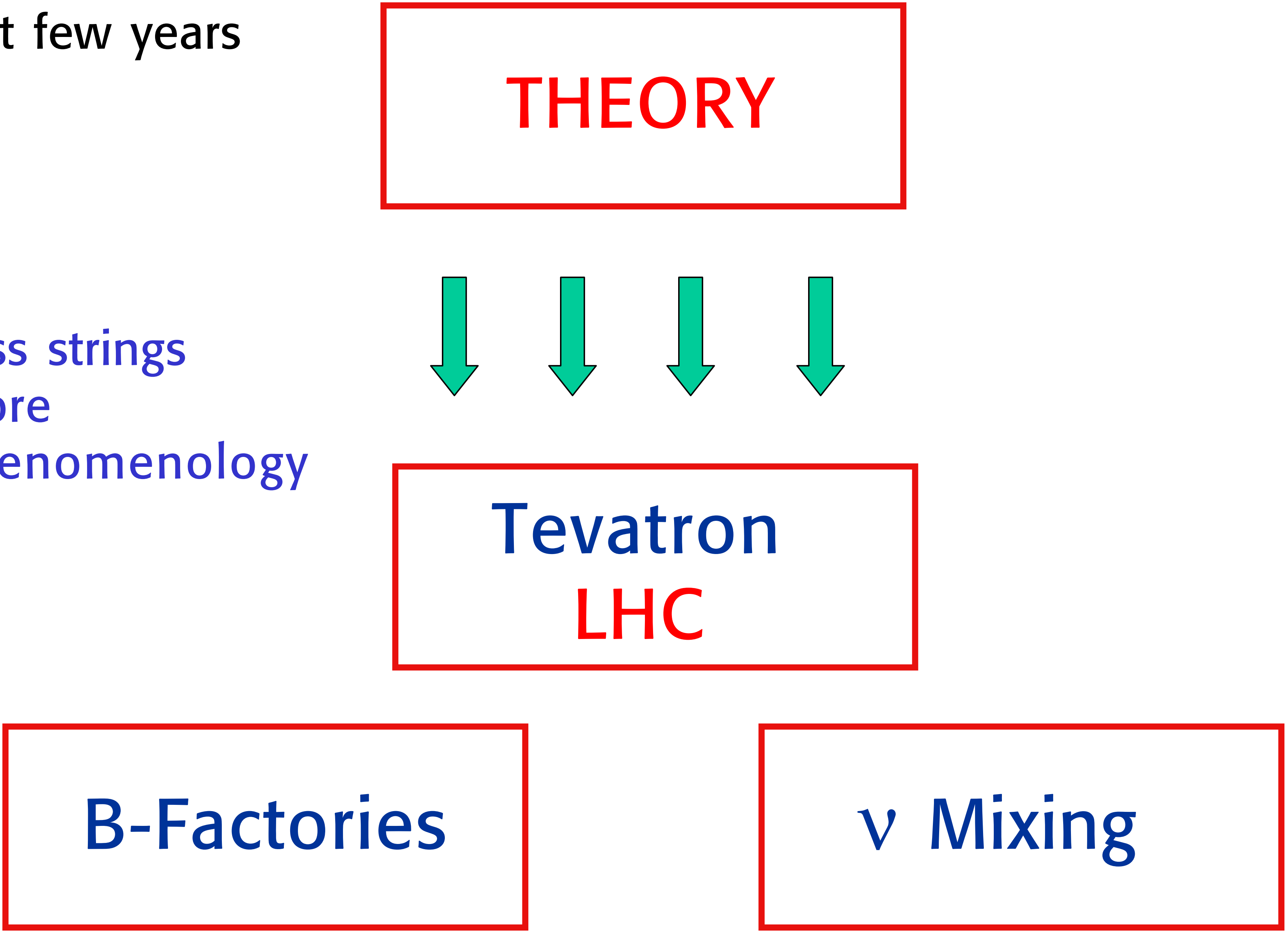
The trend in the
last few years



THEORY

Less strings
more
phenomenology

Tevatron
LHC

B-Factories

ν Mixing

We concentrate on the phenomenological side

A large amount of theoretical work was devoted to directly prepare the interpretation of LHC experiments

- New and improved generators for event simulation
- Advanced QCD and EW calculations
- Signals and interpretation

  e.g. the top quark FB asymmetry at the Tevatron has generated much work (axi-gluons, FC Z'...)

In this class one can also include

- QCD lattice calculations for flavour physics and heavy ion experiments

QCD event simulation A big boost in view of the LHC

General algorithms for computer NLO calculations

the dipole Catani, Seymour,..... FKS formalisms Frixione, Kunszt, Signer

the antenna pattern Kosower....

Matching matrix elements and parton showers

LO ME: ALPGEN, MadGraph, MLM, (L)-CKKW Mangano.....

NLO ME: MC@NLO Frixione, Webber.....
POWHEG, MENLOPS Frixione, Nason, Oleari.....
Hamilton, Nason

Beyond
general purpose
HERWIG
PYTHIA, SHERPA

Perturbative (+ resumm.s)

$$d\sigma = A\alpha_S^N [\, 1 + (c_{1,1}L + c_{1,0})\alpha_S + (c_{2,2}L^2 + c_{2,1}L + + c_{2,0})\alpha_S^2 + \dots\,]$$

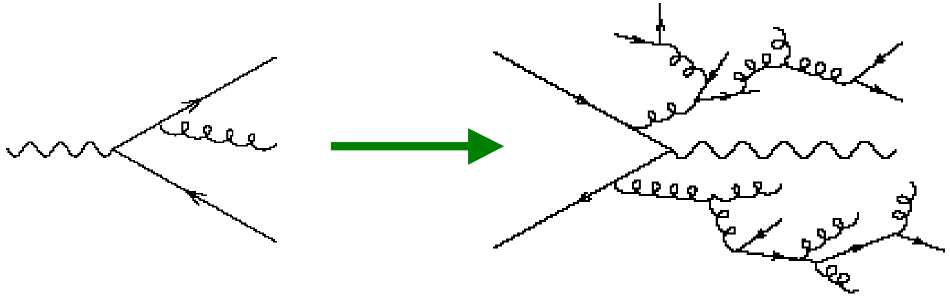
L= large log eg L=log(p_T/m)

Complementary virtues:
the hard skeleton plus
the shower development
and hadronization

Parton showers

collinear emissions factorize

$$\begin{aligned} d\sigma_{q\bar{q}g} &= d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi} \\ t &= (p_q + p_g)^2 \longrightarrow 0 \end{aligned}$$



hadronization added

On going progress in automatisation

QCD for LHC: very difficult calculations needed

New powerful techniques for loop calculations

Basic idea: Loops can be fully reconstructed from their unitarity cuts

First proposed by Bern, Dixon, Kosower ‘93-‘97
Revived by Britto, Cachazo, Feng ’04
Perfected by Ossola, Papadopoulos, Pittau ’06

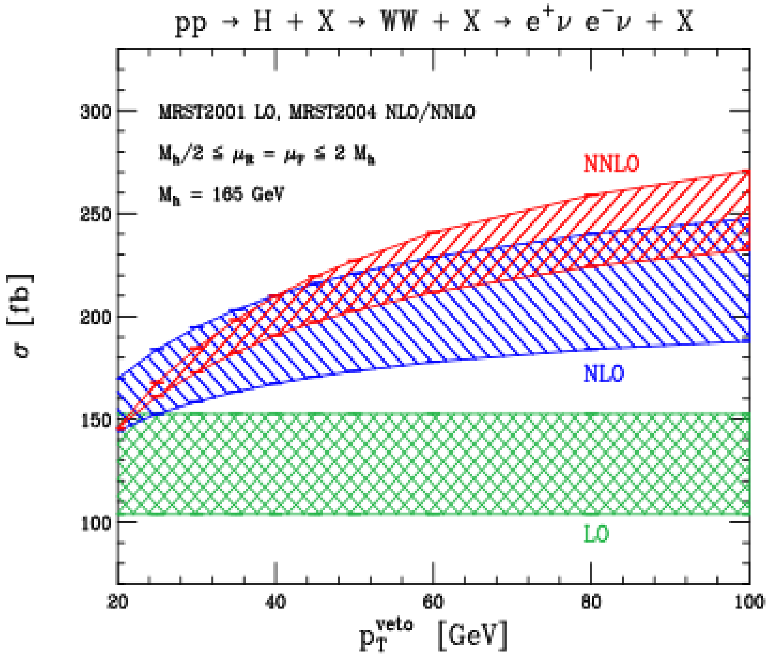
Generalized d-dimension unitarity
K. Ellis, Giele, Kunszt, Melnikov ‘08-’09

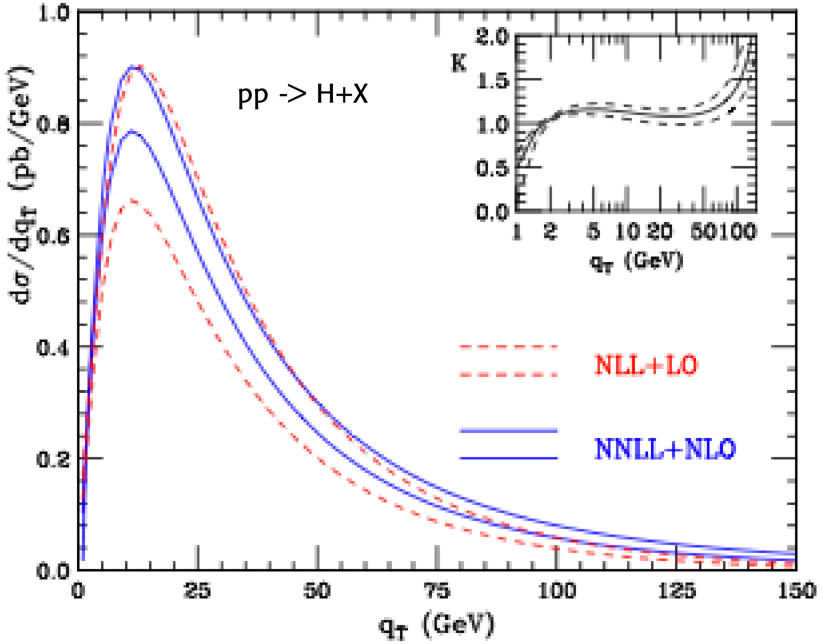
Examples of recent NLO calculations in pp collisions

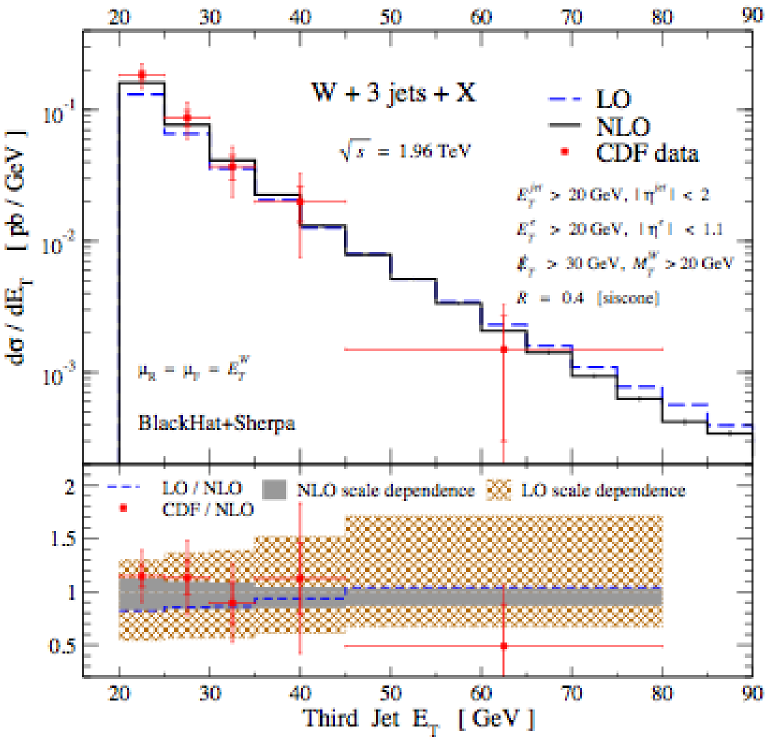
ttbb Bredenstein et al ‘09-’10, Bevilacqua et al ‘09
W+3jets Berger et al ‘09, R.K.Ellis , Melnikov, Zanderighi ‘09,
Z,γ^* +3jets Berger et al ‘10
WW+2jets Melia et al ‘10-’11
WWbb Denner et al ‘10
tt+2jets Bevilacqua et al ‘10-’11
bbbb Greiner et al ‘11
W+4jets Berger et al ‘11

And the Higgs cross section and distributions are known to NNLO Harlander, Kilgore ‘02; Anastasiou, Melnikov ‘02; Ravindran et al ‘03; Anastasiou, Melnikov, Petriello ‘04, Bozzi et al ‘07

A terrific amount of work by QCD theorists for LHC

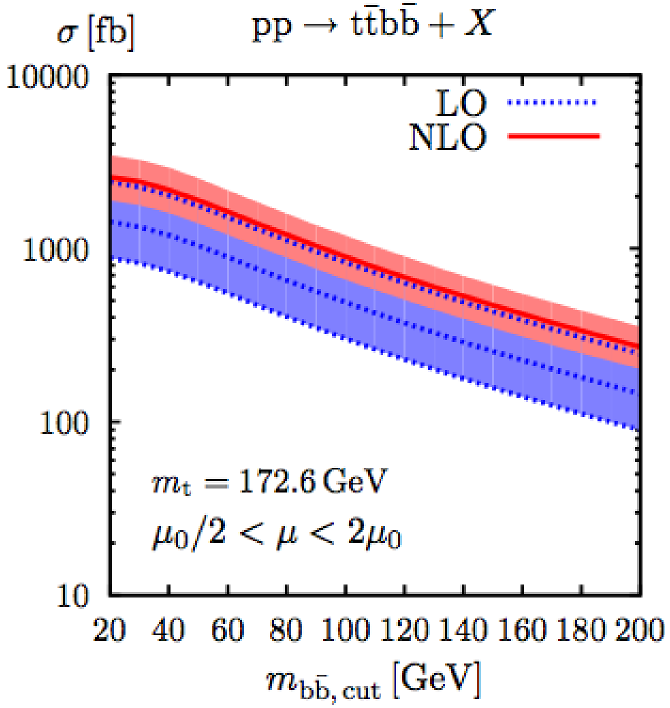




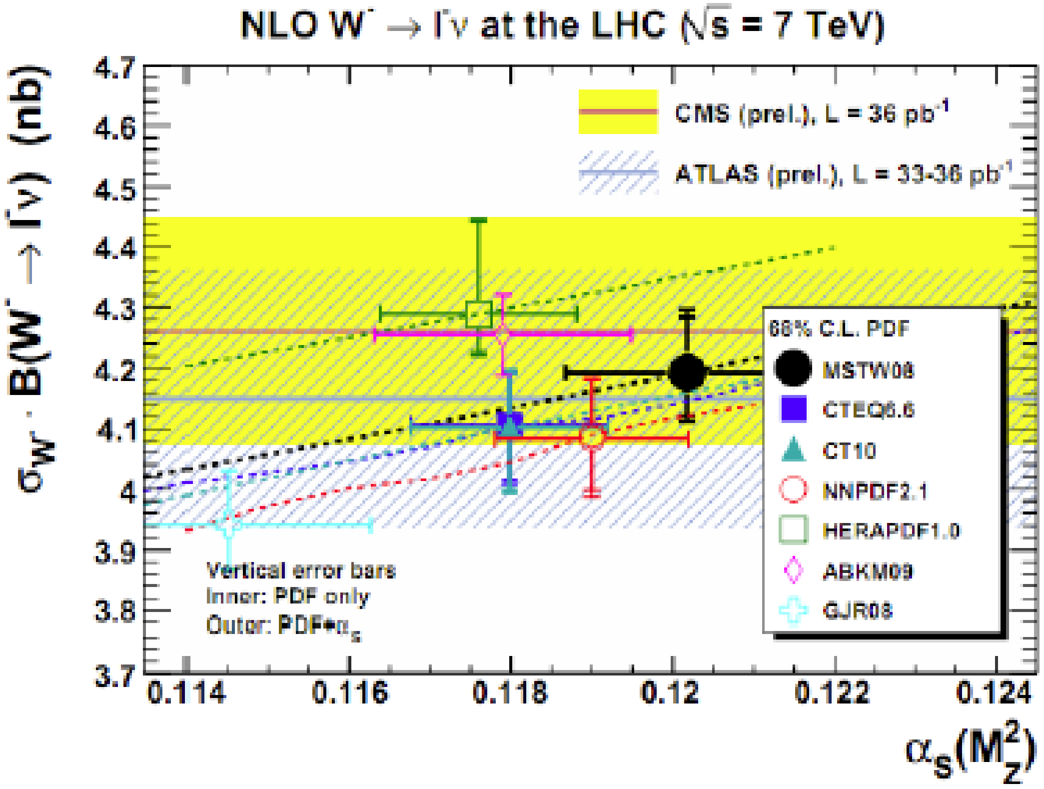


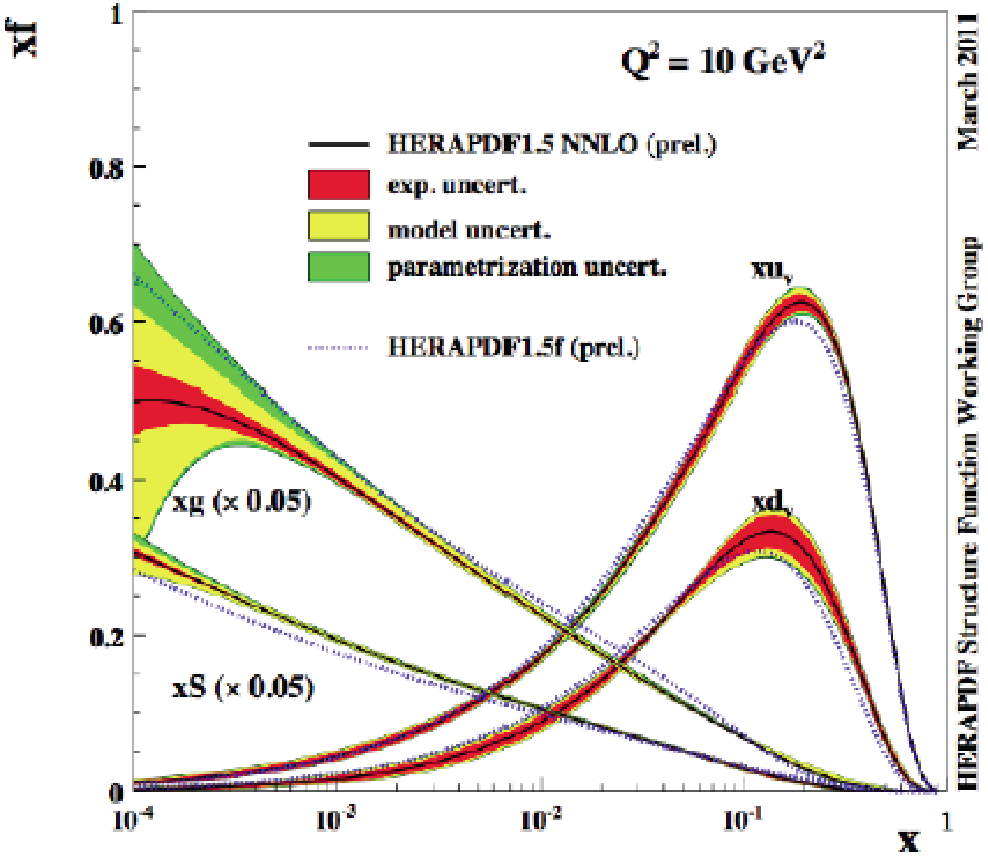
Fantastic technical skill!!

Essential for the LHC



An important task: preparing the optimal pdf's for the LHC



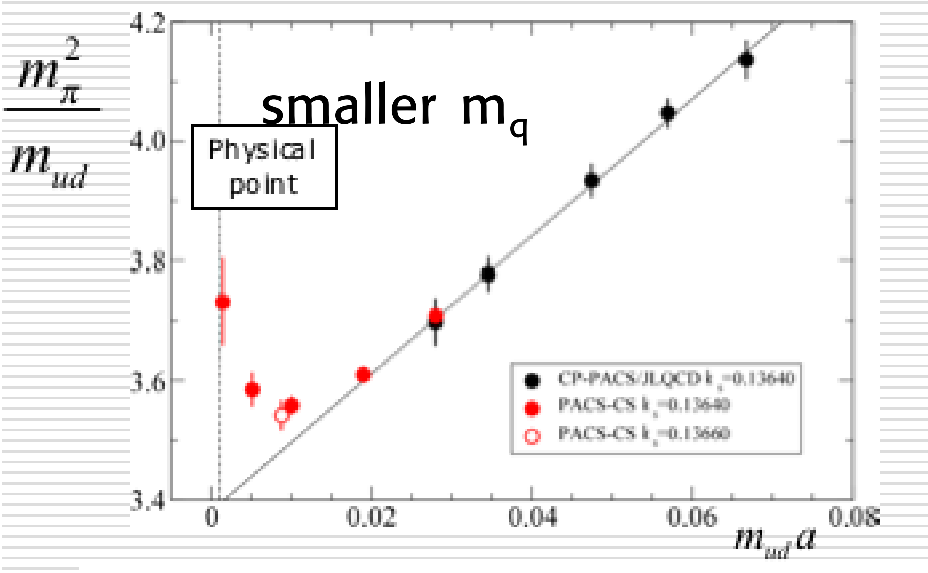


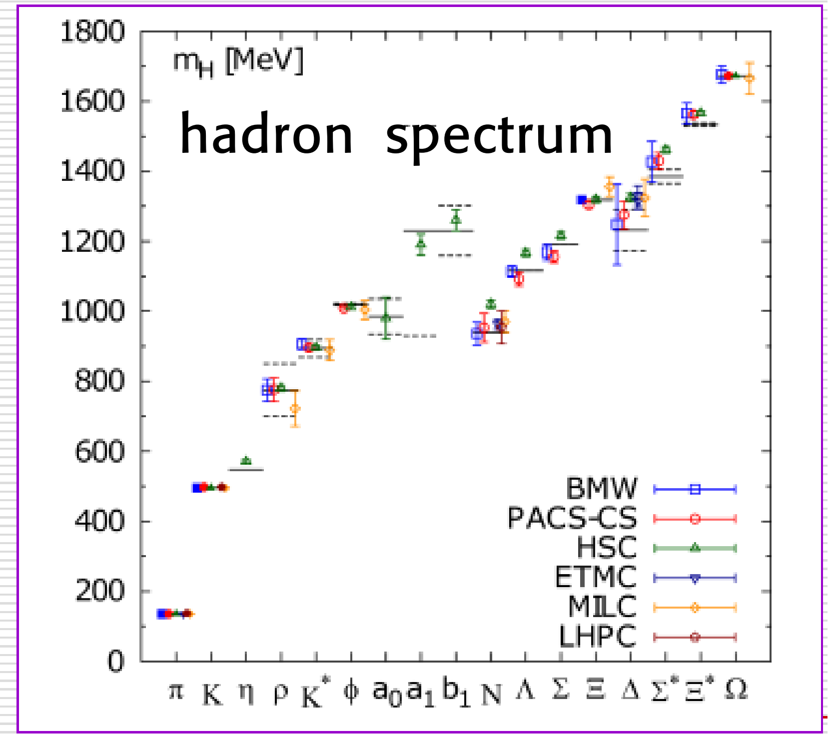
Dedicated groups
MSTW, CTEQ, NNPDF, HERAPDF,.....

LHeC and the continuation of DIS physics
⊕ may become precious in this domain in the future

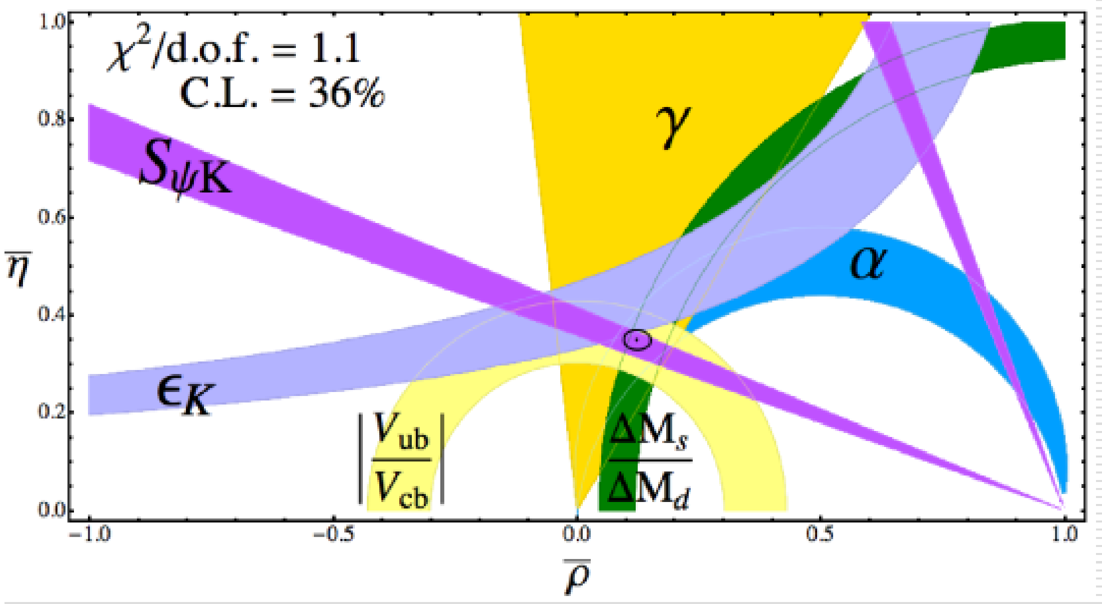
Great progress in lattice QCD

From postdiction to prediction





A crucial role in flavour physics



Unquenching

a -> smaller

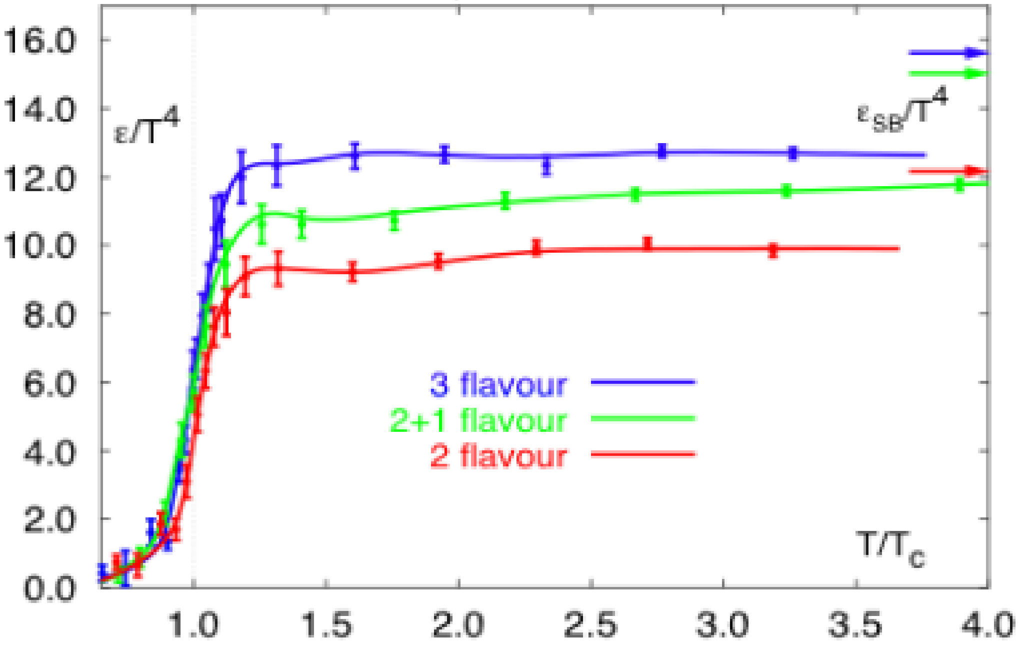
L -> larger

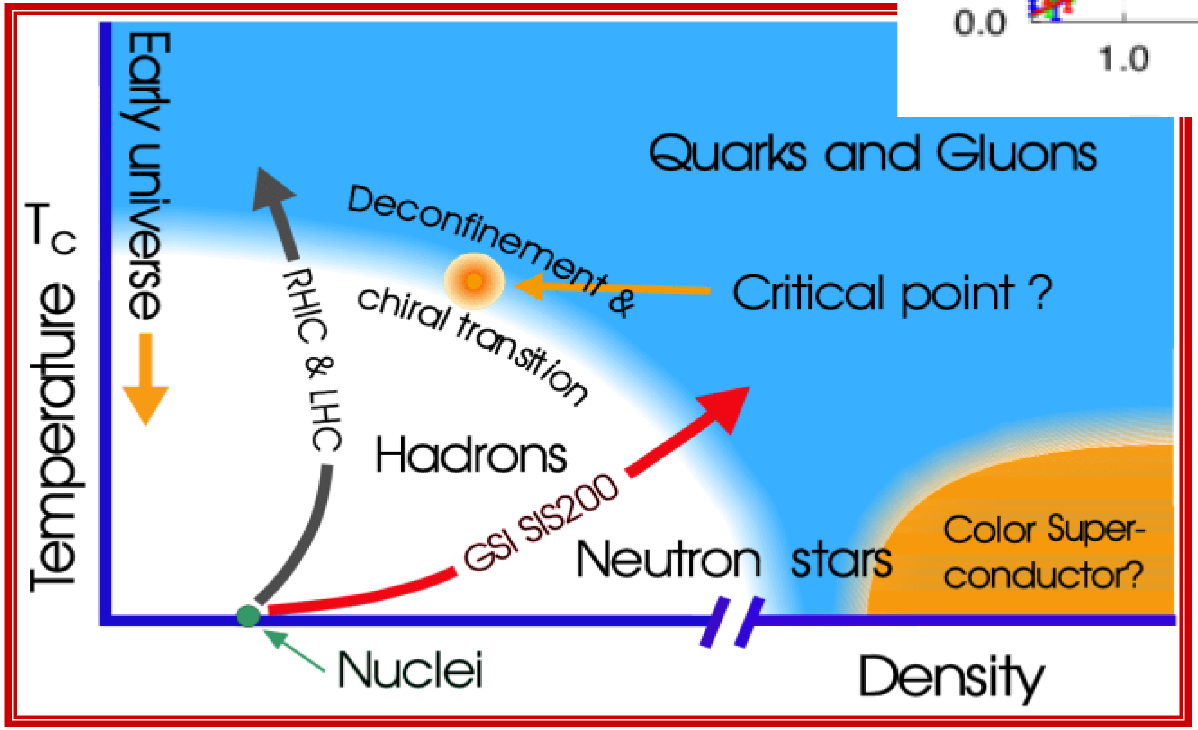
m_q -> 0

The QCD phase diagram

Studied on the lattice
and probed by
colliding heavy ions
at SPS, RHIC, LHC

high T and density





Establishing confinement
Studying deconfinement
& chiral restoration
Quark-gluon plasma

Particle physics at a glance

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable, hence highly predictive.
And is well supported by the data.

However, we expect corrections from higher energies

certainly from the GUT or Planck scales
but also from the TeV scale (LHC!)

In fact even just as a low energy effective theory
the SM is not satisfactory

QCD + the gauge part of the EW theory are fine,
but the Higgs sector is so far only a conjecture and
is problematic

The Higgs problem is central in particle physics today

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi \right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0\mathrm{exp}} \sim (2.10^{-3}\ \mathrm{eV})^4$

Origin of quadratic divergences.
Hierarchy problem

Possible instability depending on m_H

The flavour problem:
large unexplained ratios of Y_{ij} Yukawa constants

The Higgs sector of the SM is just a minimal conjecture
The reality could be more complicated

That some sort of spontaneous symmetry breaking mechanism is at work has already been established (couplings symmetric, spectrum totally non symmetric)

The question is on the nature of the Higgs mechanism/particle(s)

- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Alternative forms of EW symmetry breaking

A vast literature

Examples:

- SUSY Higgs
- Little Higgs
- Higgs from Extra Dim's
- Higgsless models
- Composite Higgs

• • •

Crosstalk with string theory:

Extra dimensions (large, warped), branes,
AdS/CFT correspondence

Except for SUSY,
common ingredients:
the Higgs a pseudo
Goldstone boson of an
enlarged symmetry --->
new vector bosons

Z', W', ρ'...

Non perturbative sectors
limit predictivity and
all need
an UV completion

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson
  - W′, Z′
  - KK recurrences
  - resonances from a strong sector
  - ……

LHC scenarios

Catastrophic: No Higgs, no new physics

Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

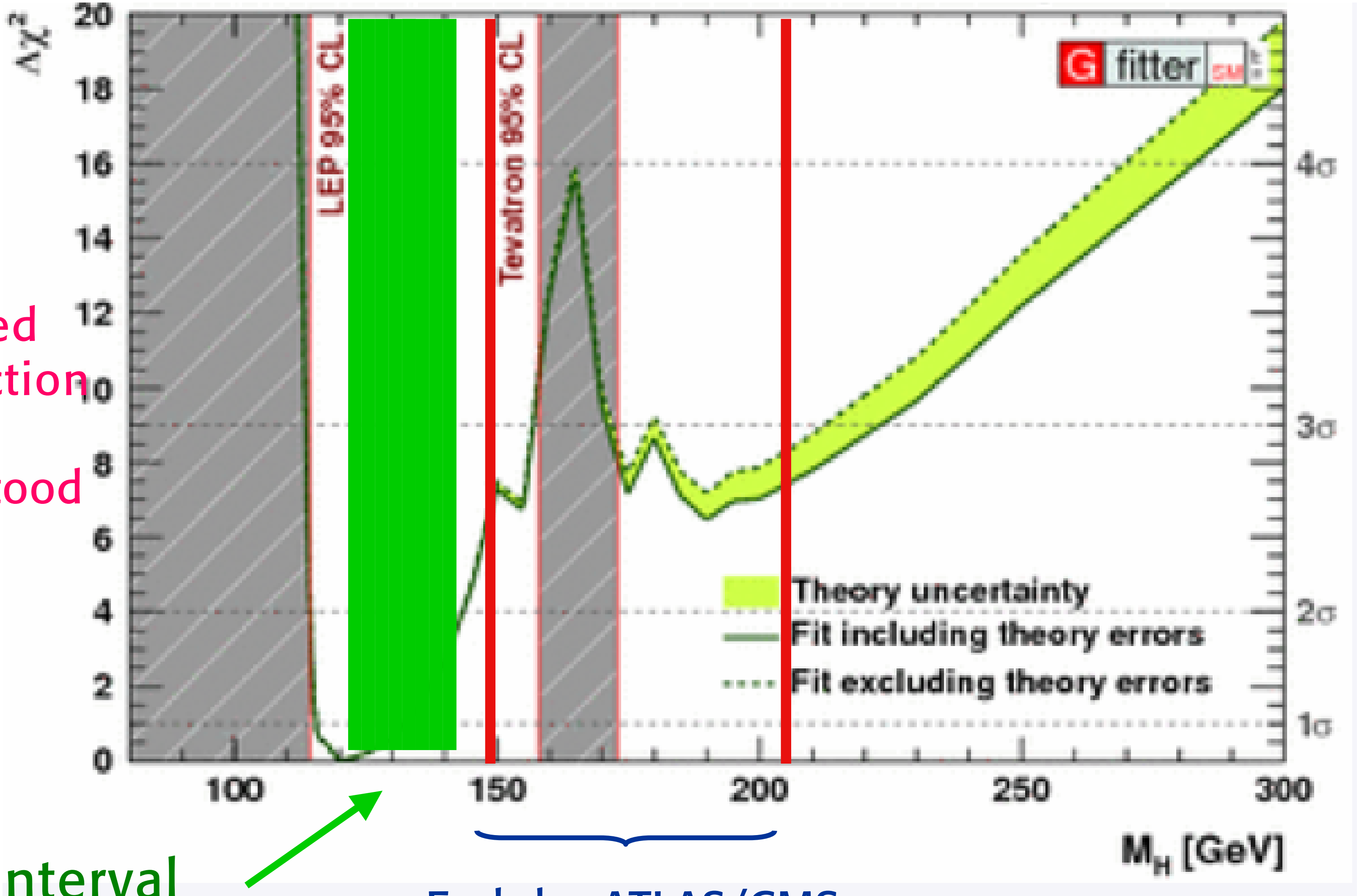
The EW precision tests point to a light Higgs. In most of the alternative models the Higgs is still light and the LHC sensitivity range is large

So the Higgs should not be missed at the LHC

Actually the results presented at this Conference show that the search for the SM Higgs has made a lot of progress!

The SM Higgs is close to be observed or excluded

This fig.
is a non
authorized
reproduction
of what
I understood



interval
with excess
~2.5 σ

Excl. by ATLAS/CMS

also $300 < m_H < 450$ GeV
is excluded

If a Higgs signal is observed

This would be a triumph for the LHC

The next challenge for experiment would be to measure its couplings in order to see whether it is the SM Higgs or an exotic Higgs
The ILC would be boosted

If a Higgs signal is excluded then some new physics must be responsible for the EW symmetry breaking

Experiments must find it

LHC scenarios

Catastrophic: No Higgs, no new physics

Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

Theorist projection: non standard Higgs and new physics

A lot of model building in this direction

The Standard Model works very well

So, why not find the Higgs and declare
particle physics solved?

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle

.....

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy
- some experimental anomalies: $(g-2)_\mu$, ...

Some of these problems
point at new physics
at the weak scale: eg
Hierarchy
Dark matter (perhaps)

insert here
your
preferred
hints

Dark Matter

WMAP, SDSS, 2dFGRS….

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.045$, $\Omega_m \sim 0.27$

Most is Dark Matter and Dark Energy

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: eg Neutralinos (--> LHC)
Also Axions are still viable (introduced to solve strong CPV)
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

LHC has good chances because it can reach any kind of WIMP:

WIMP: Weakly Interacting Massive Particle
with m ~ 10^1-10^3 GeV

For WIMP’s in thermal equilibrium after inflation the density is:

$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\mathrm{Pl}}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}}$$

can work for typical weak cross-sections!!!

This “coincidence” is a good indication in favour of a WIMP explanation of Dark Matter

A crucial question for the LHC

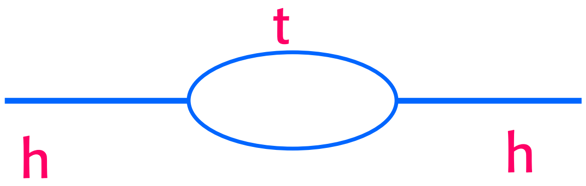
Is Dark Matter a WIMP?

LHC will tell yes or no to WIMPS

Laboratory experiments on Dark Matter are also very important (including the search for axions, a non WIMP solution)

The “little hierarchy” problem

e.g. the top loop (the most pressing):



$m_h^2 = m^2_{bare} + \delta m_h^2$

$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

$\Lambda \sim o(1\text{TeV})$

This hierarchy problem demands new physics near the weak scale

Λ: scale of new physics beyond the SM

- $\Lambda \gg m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

Precision Flavour Physics

Another area where the SM is good, too good.....

With new physics at ~ TeV one would expect
the SM suppression of FCNC and the CKM
mechanism for CP violation to be sizably modified.

But this is not the case

an intriguing mystery and a major challenge for models of
new physics

LHCb and its upgrade, super B-factories are needed to look
for small deviations from the SM

The continuation of flavour physics is essential

Quarks

- K, D, B decay
- CKM matrix
- CP violation
- FCNC
- 4th generation

Example of refined theor. calculations:

Br(b -> s γ)

exp: $(3.55 \pm 0.26)\ 10^{-4}$

th: $(3.15 \pm 0.23)\ 10^{-4}$

at NNLO Misiak et al '07

LHC can say yes or no

Leptons

- neutrino mass and mixing
- leptonic FCNC processes ($\mu \to e\gamma$ is very important)
- $(g-2)_\mu$, edm's
- τ decays

ν masses and mixings

- ν's are not all massless but their masses are very small

- probably masses are small because ν's are Majorana particles

- then masses are inv. prop. to the large scale M of L n. viol.

- M~ $m_{\nu R}$ is empirically close to 10^{14}-10^{15} GeV ~ M_{GUT}
  -> ν masses fit well in the GUT picture

- decays of ν_R with CP & L violation can produce a B-L asymm.
  -> baryogenesis via leptogenesis

- detecting $0\nu\beta\beta$ would prove ν's are Majorana and L is viol.

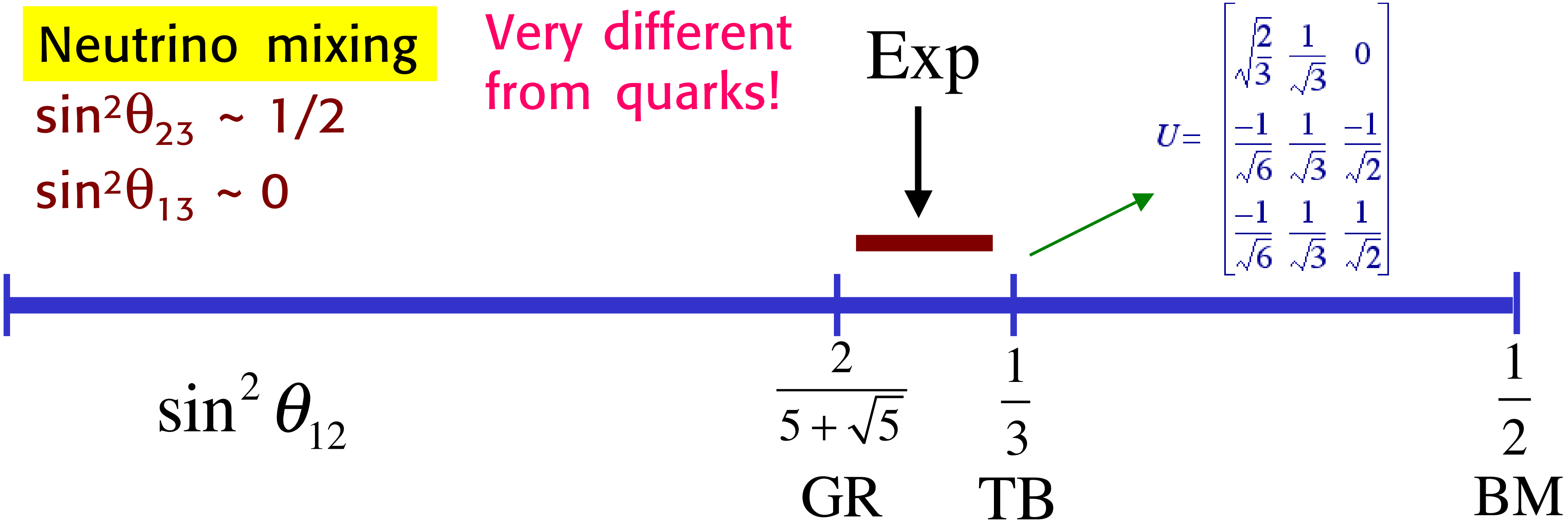
- ⊕ ν's are not a significant component of dark matter in Universe

Neutrino mixing

$\sin^2\theta_{23} \sim 1/2$

$\sin^2\theta_{13} \sim 0$

Very different from quarks!



Exp

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

$\sin^2\theta_{12}$

TB: Group A4, S4..... A vast literature

GR: Golden Ratio - Group A5 Feruglio, Paris ’11

$\Big\}\ \theta_{13} \sim o(\theta_C^2)$

BM: Group S4 GA, Feruglio, Merlo ’09 $\theta_{13} \sim o(\theta_C)$

supported by MINOS T2K

A recent review of discrete flavour groups:

GA, F. Feruglio, ArXiv:1002.0211 (Review of Modern Physics)

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of Λ^2 in δm_h^2

  approximate (possible): $\Lambda \sim m_{SUSY} - m_{ord}$ → top loop $\Lambda \sim m_{stop}$

  The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

  Strongly disfavoured by LEP. Coming back in new forms

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

  "Little Higgs" models. Some extra trick needed to solve problems with EW precision tests

- Extra spacetime dim's that "bring" M_{Pl} down to o(1TeV)

Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top (SUSY)
- some new fermion
  - t′ (Little Higgs)
  - KK recurrences of the top (Extra dim.)
  - ……
- nothing dumps it and we accept the ever increasing fine tuning

Main results of this Conference

The Higgs comes closer

The new physics is pushed further away

Examples:

sequential W’: $m_{W'} > 2.15\text{-}2.27$ TeV
sequential Z’: $m_{Z'} > 1.8\text{-}1.9$ TeV
gluino: $m_{g} > \sim 1$ TeV
degenerate s-quarks: $m > \sim 1.2$ TeV

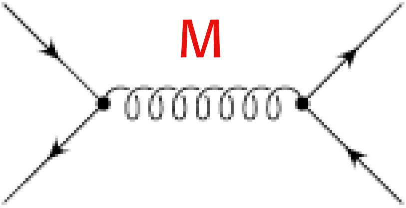
Not a single significant hint of new physics found

A lot of fine-tuning is imposed on us when our present theory is confronted with the data

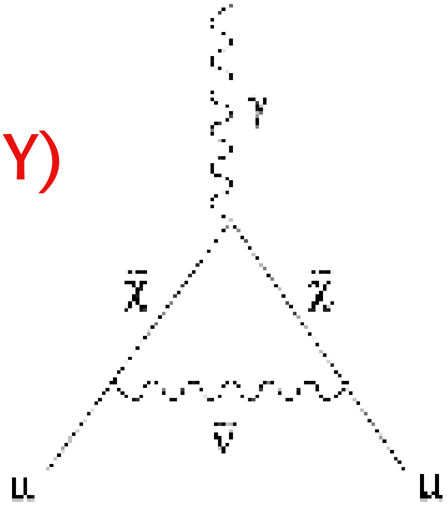
For naturalness we need new physics at ~ 1 TeV but we see no clear deviations in EW Precision Tests and in Flavour Physics and now at the LHC

Strong constraints on model building

Typical tree level NP effects too large



Avoided by R-parity (SUSY)
T-parity (Little Higgs) etc



Loop effects preferred

SUSY: boson fermion symmetry

The hierarchy problem: $\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$

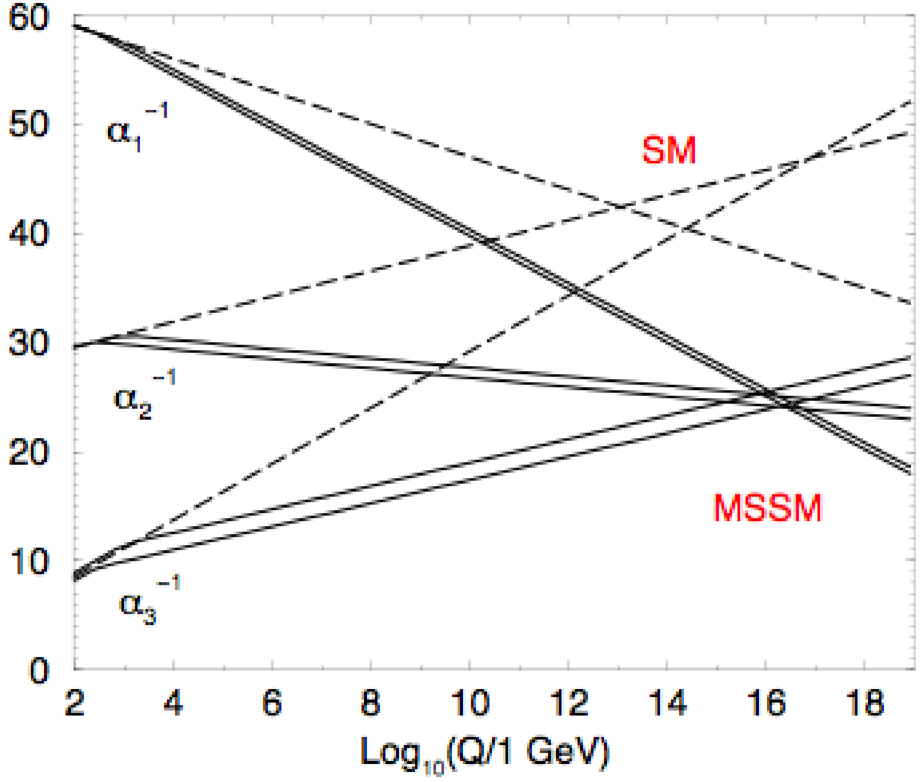
In broken SUSY Λ^2 is replaced by $(m_{stop}^2 - m_t^2)\log\Lambda$

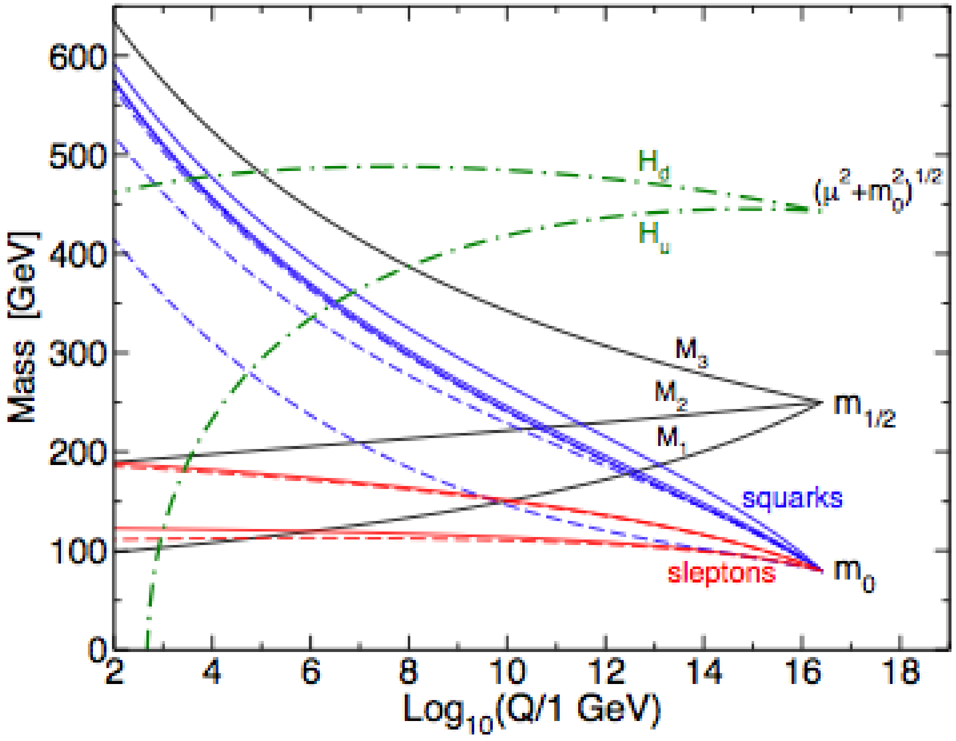
m_H>114.4 GeV, $m_{\chi+}$ >100 GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly on minimal realizations (MSSM, CMSSM…).

Yet SUSY is a completely specified, consistent, computable model, perturbative up to M_{Pl} quantitatively in agreement with coupling unification (GUT’s)
(unique among NP models)
and has a good DM candidate: the neutralino
(actually more than one).

Remains the reference model for NP

Beyond the SM SUSY is unique in providing a perturbative theory up to the GUT/Planck scale





Other BSM models (little Higgs, composite Higgs, Higgsless....) all become strongly interacting and non perturbative at a multi-TeV scale

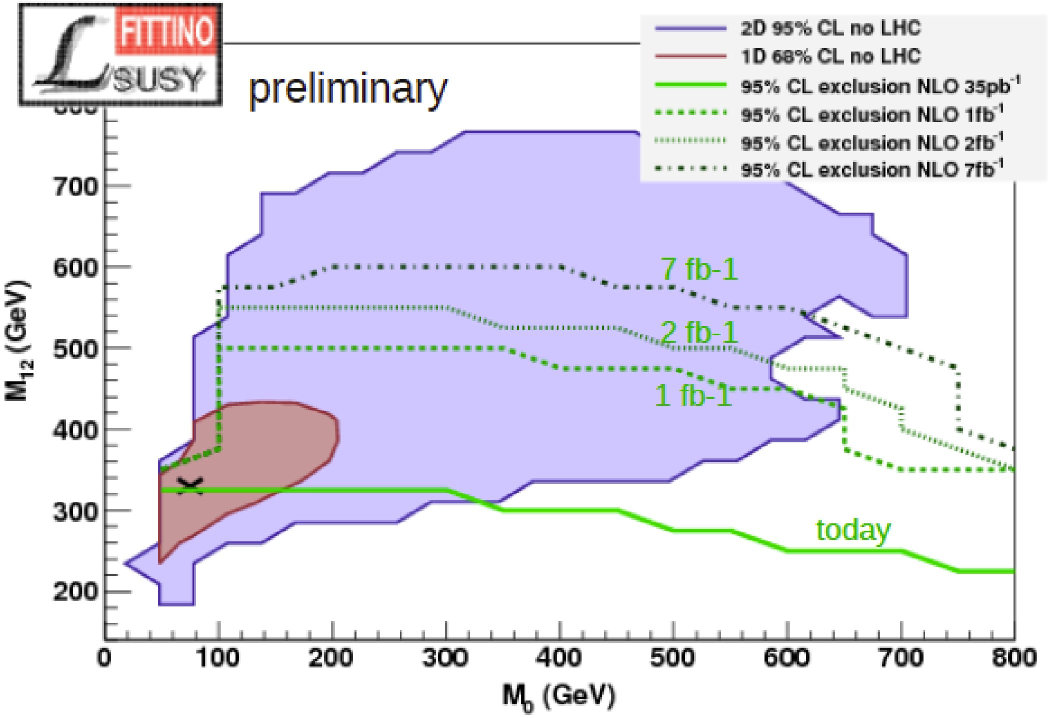
Tools to fit the data to the CMSSM

Lafaye et al

Bechtle et al

The best fit to the data
wants light SUSY.
But the LHC
now excludes it

The CMSSM is close
to be discarded



SUSY

With new data ever increasing fine tuning

Complicating SUSY beyond the (C)MSSM (essentially out)

There is still room for non minimal versions

- Heavy first 2 generations
- NMSSM
- Split SUSY
- More global symmetry
- More interactions
- • • •

LHC scenarios

Catastrophic: No Higgs, no new physics

Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

Theorist projection: non standard Higgs and new physics

A lot of model building in this direction

Pure SM: A light scalar Higgs, no new physics at the EW scale

If so, nature does not abhor fine tuning at all

This is the paradigm that experiment must try to falsify

Conclusion

The Higgs comes closer, New Physics is pushed further away

The LHC experiments are just at the start and much deeper layers can be reached in the next decade

Flavour physics maintains an essential role as a precision tool

Neutrino physics is very important for the theory of flavour and as a probe into the GUT scale (some large neutrino detectors can also do p decay)

"Small" experiments like those for $0\nu\beta\beta$, m_ν, μ->$e\gamma$, searches for Dark Matter, ... are extremely important