Perugia, 31 Gennaio '08

Lo Standard Model all'inizio del LHC

Una impressionistica (e impressionante) rassegna dello stato dello SM oggi

G. Altarelli

Universita' di Roma Tre
CERN

QCD

QCD stands as a very solid building block of the SM

Comparison with experiment is excellent

Steady progress in techniques to extract precise predictions (higher order perturbative, resummation, event simulation, non perturbative, ...)

Very important for the LHC preparation: understanding QCD processes is a prerequisite for all possible discoveries

How do we get predictions from QCD?

- Non perturbative methods

•Lattice simulations (great continuous progress)

•Effective lagrangians

  * Chiral lagrangians
  * Heavy quark effective theories
  * SCET
  * NRQCD
  * AdS/CFT correspondence ••••••

•QCD sum rules

•Potential models (quarkonium)

- Perturbative approach

Based on asymptotic freedom.

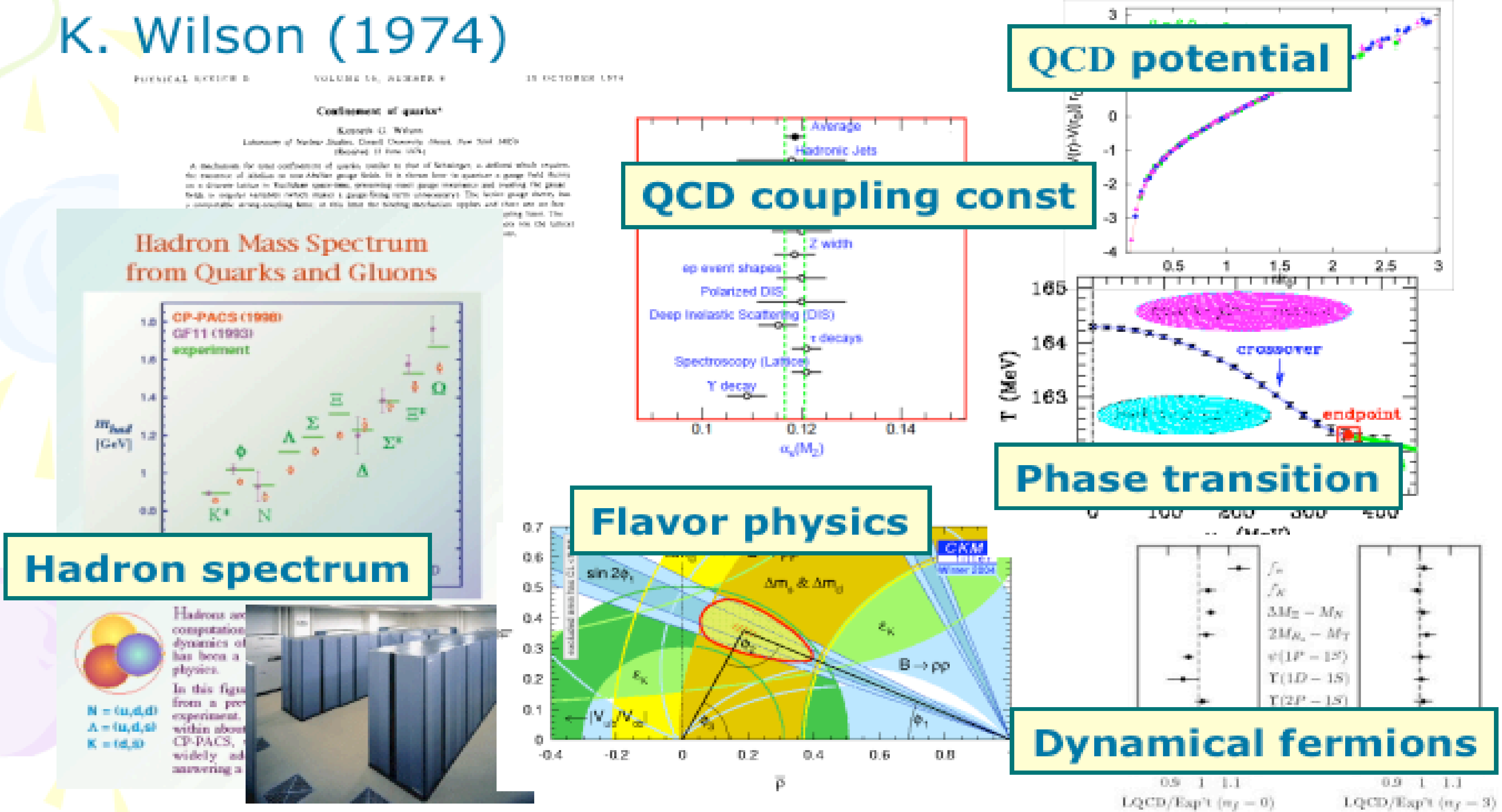
It still remains the main quantitative connection to experiment.

The main tool for non perturbative QCD in continuous progress

Hashimoto, ICHEP'04

30 years of lattice QCD

K. Wilson (1974)



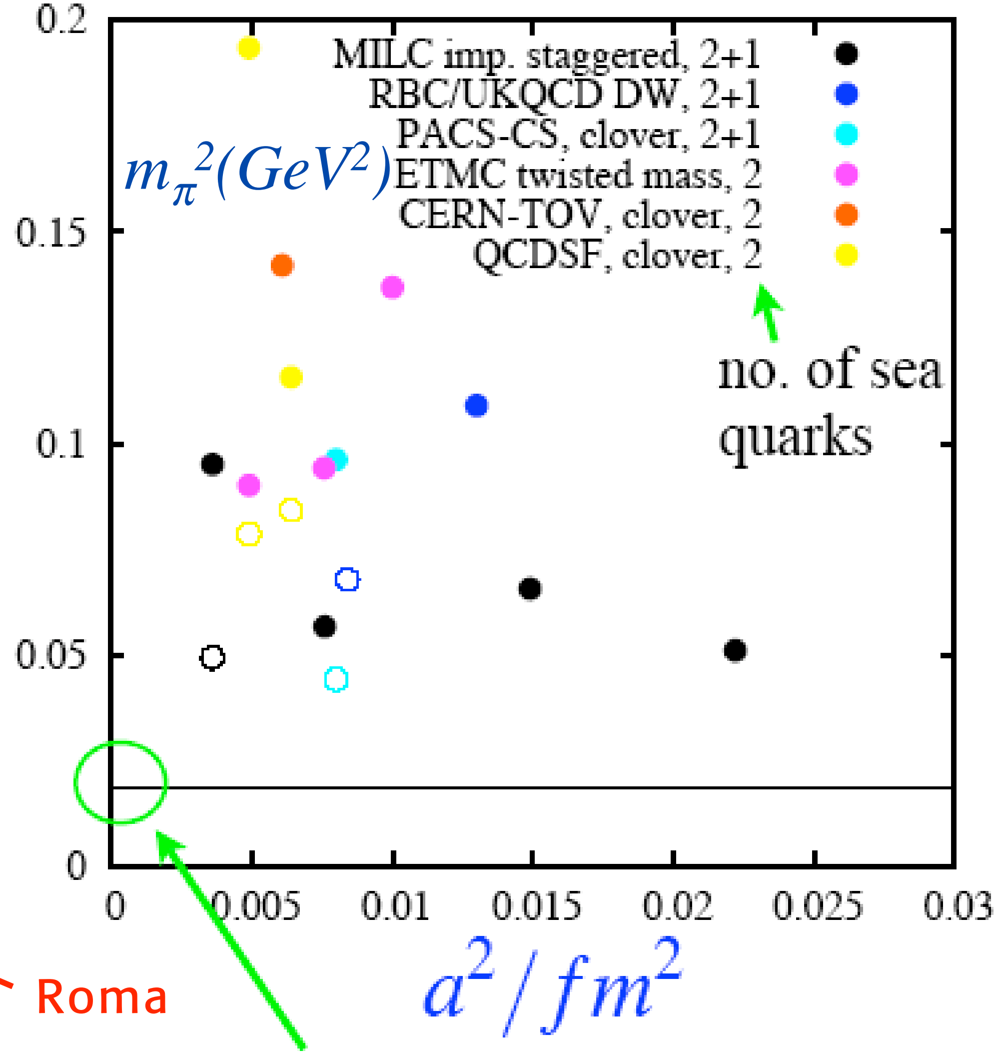
Lattice calculations have shown great progress

Unquenched fermions
Chiral logs control
Simulation techniques
Many-teraflop computers

Davies LP'07

	speed	chiral symm.	collab.
imp.stagg. (asqtad)	fast	OK	MILC/ HPQCD/ FNAL
domain wall	slow	good	RBC/ UKQCD
clover	fast	bad	PACS-CS QCDSF CERN-TOV
twisted mass	fast	OK	ETMC

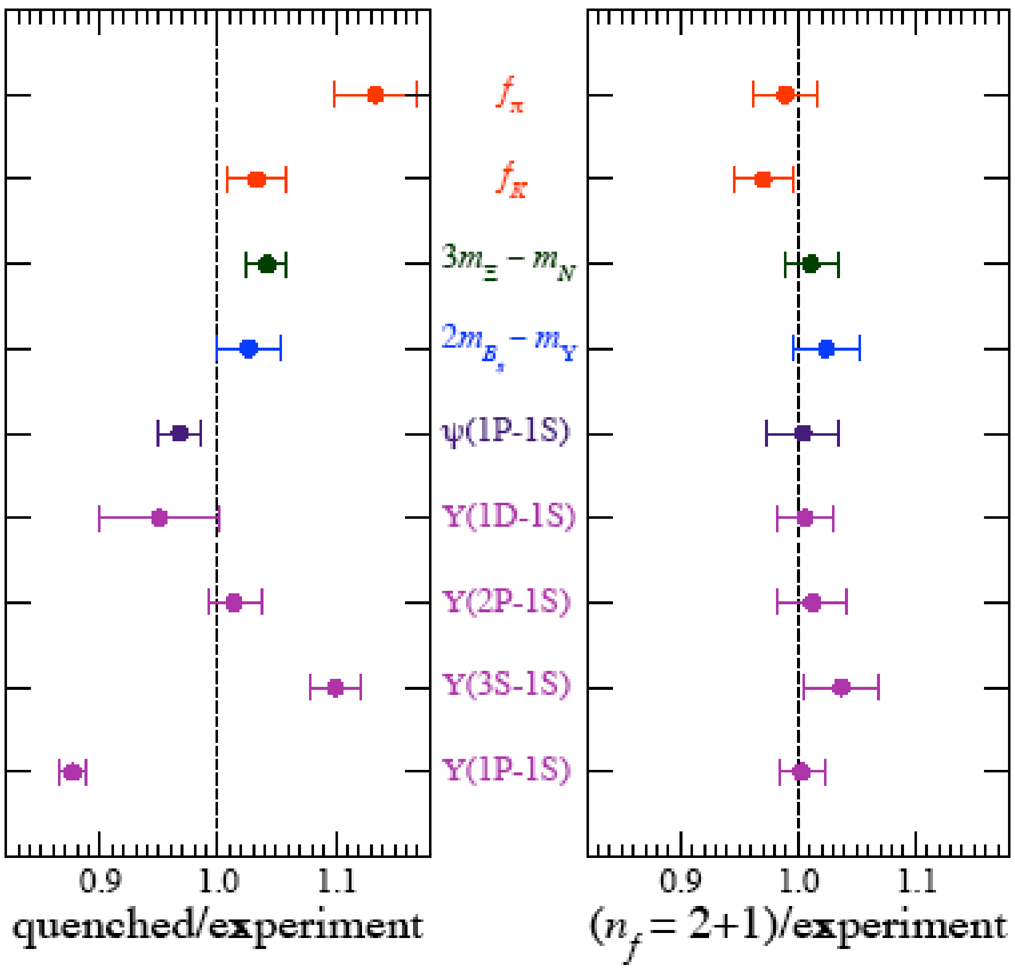
Roma



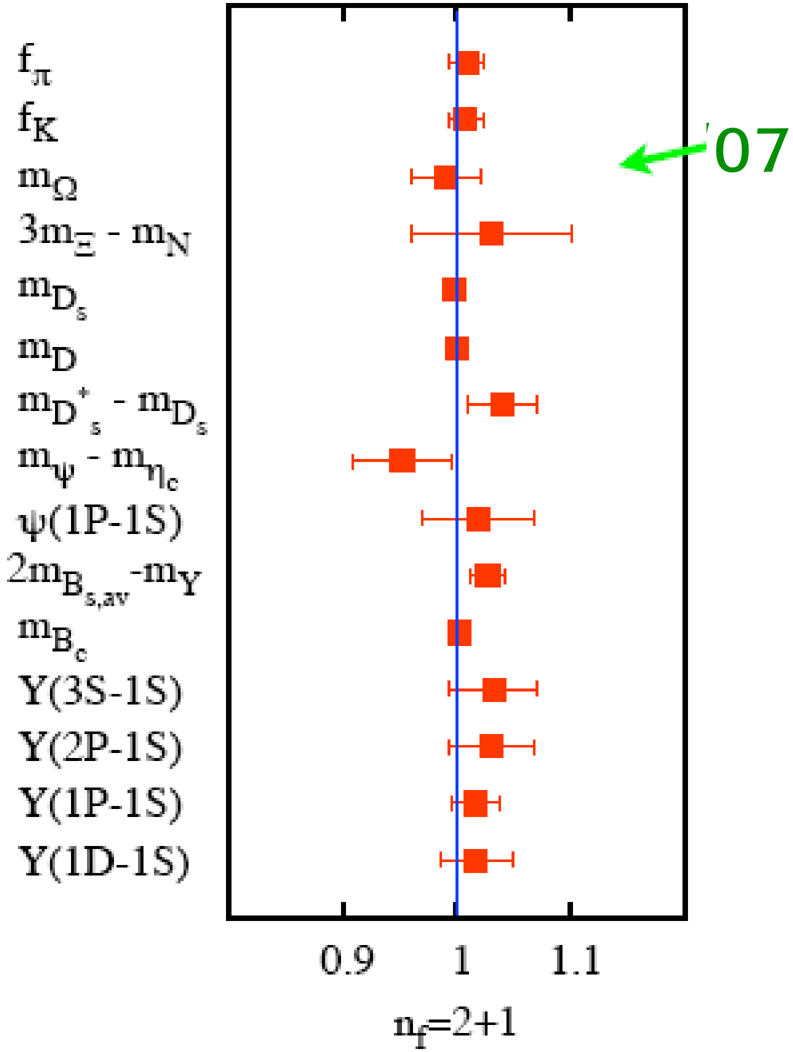
The quenched approximation (QA) is finished: what was rough agreement in QA is now precise with unquenching

old

quenched unquenched



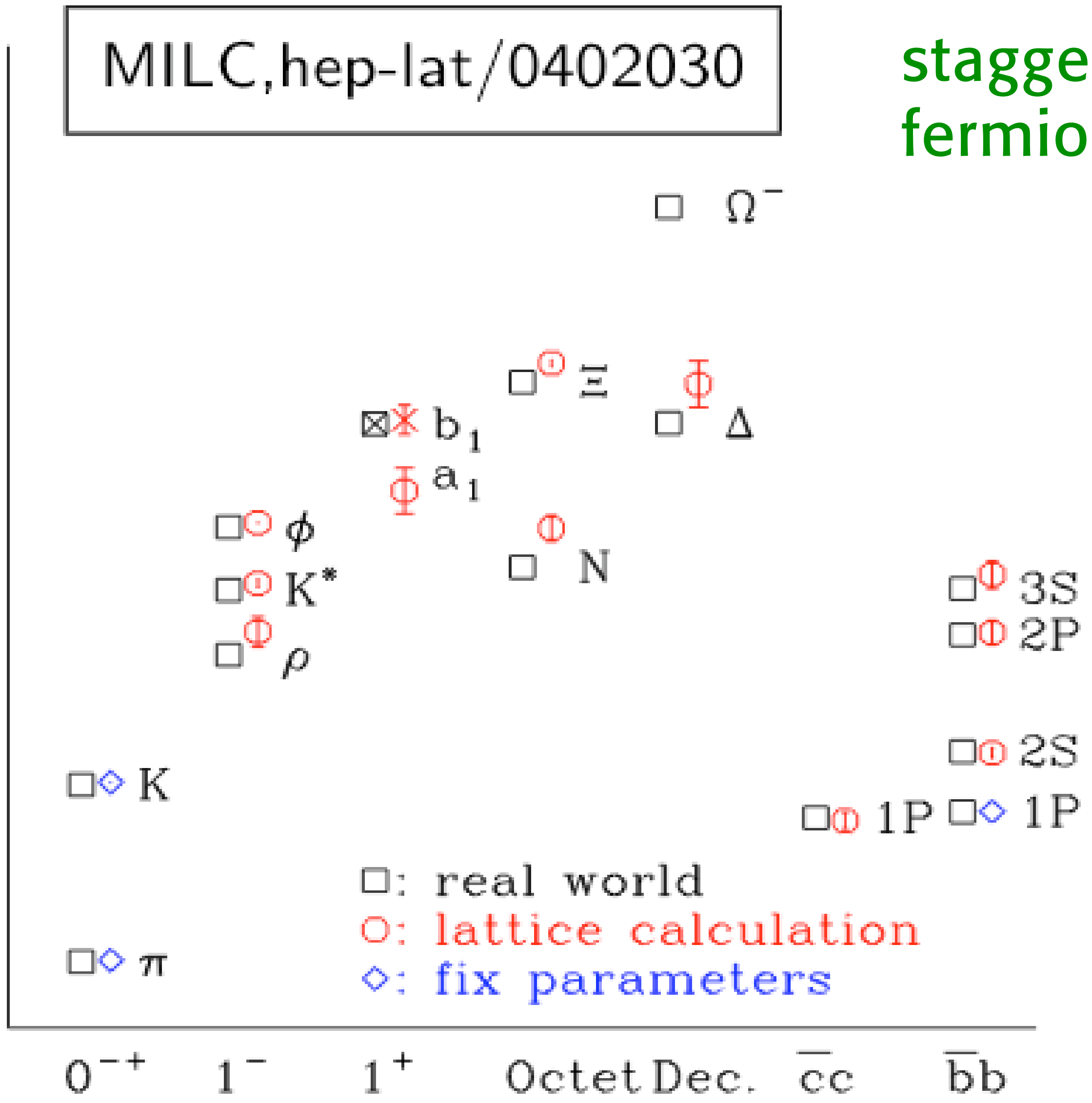
new



Unquenched lattice simulations reproduce spectrum well

Ukawa

Note:
p/ρ ~ 1.2
not 1.5
as from
3q/2q



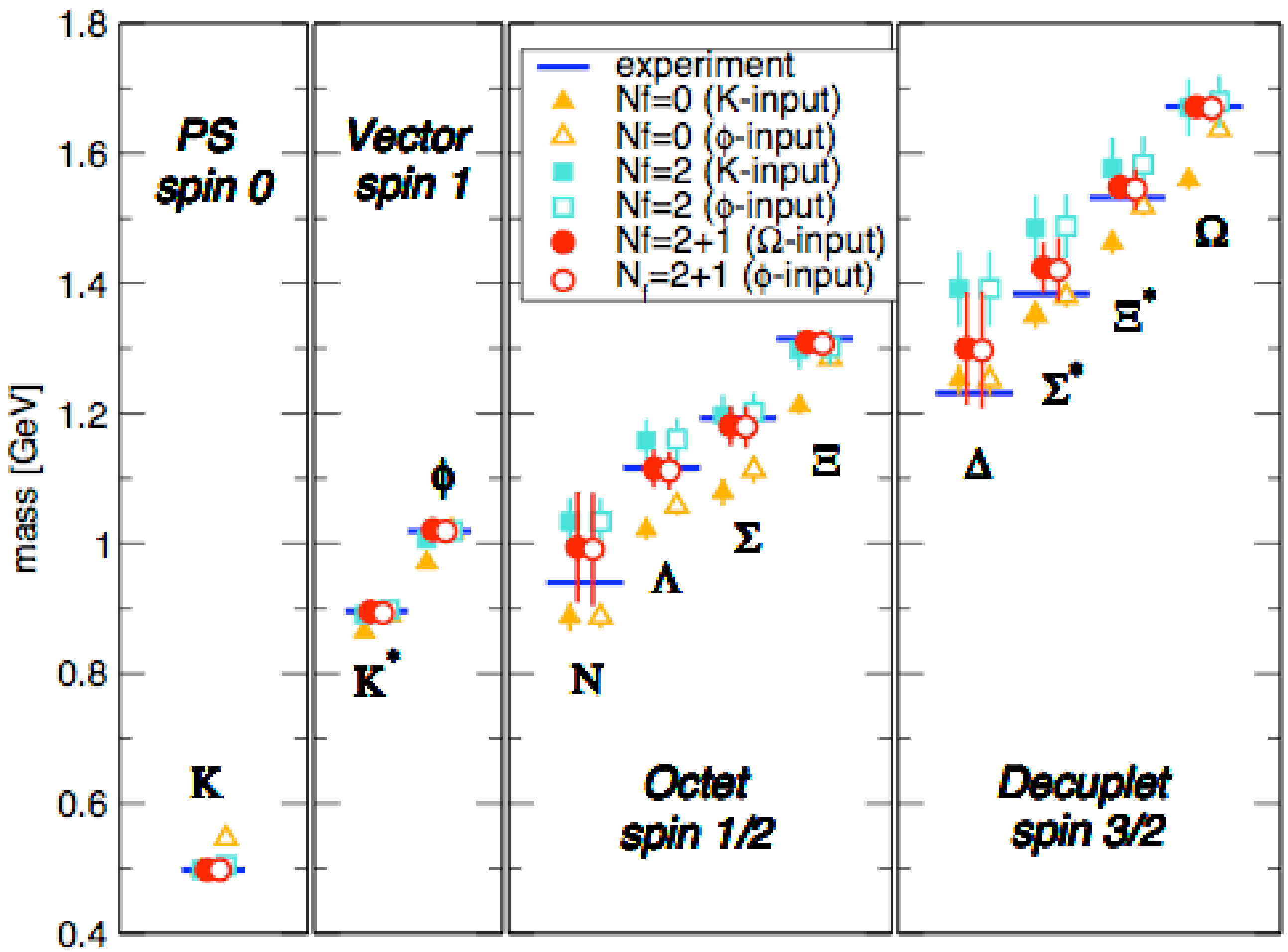
staggered
fermions

Unquenched lattice simulations reproduce spectrum well

Kuromashi'07

Wilson N_f=2+1

Here the focus is on strange particles



Kronfeld

Chiral extrapolation

- Lattice simulation is limited in a heavier quark mass region $m_q \sim (0.5\text{-}1) m_s$.

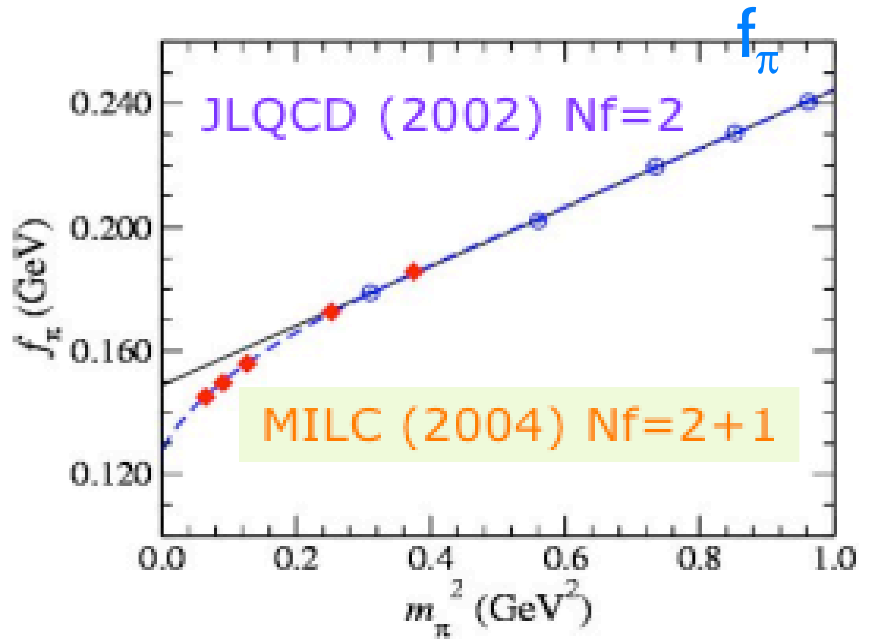
ChPT predicts the chiral log near the chiral limit.

$$c \log(m_q/1\text{GeV})$$

with a fixed coefficient.

Staggered simulation can push the quark mass much lower.

$$\langle 0|\partial^\mu A_\mu|\pi\rangle = f_\pi m_\pi^2$$



Pseudoscalar constants

Mackenzie, FPCP'06

f_D, f_{Ds}

$$f_D = 201(03)_{\rm sta}(17)_{\rm sys}\ \mathrm{MeV}$$

$$f_{D_s} = 249(03)_{\rm sta}(16)_{\rm sys}\ \mathrm{MeV}$$

Fermilab/MILC, 05. n_f=2+1 staggered light quarks.
Fermilab heavy quarks.

Compare with CLEO-c

f_{D+} = (223±17±3) MeV

$$f_D^{n_f=2} = 202(12)_{\rm sta}(^{+20}_{-25})_{\rm sys}$$

$$f_{D_s} = 238(11)_{\rm sta}(^{+07}_{-27})_{\rm sys}\ \mathrm{MeV}$$

CP-PACS, 05. n_f=2 clover light quark.
"RHQ" heavy quarks.

f_B, f_{Bs}

Using $|V_{ub}|$ = $(4.38\pm0.33)\times10^{-3}$ from HFAG

$$f_B = 0.176^{+0.028}_{-0.023}(\mathrm{stat})^{+0.020}_{-0.018}(\mathrm{syst})\ \mathrm{GeV}$$

Compare with new Belle result for f_B:

f_B = 0.216±0.022 GeV (HPQCD)

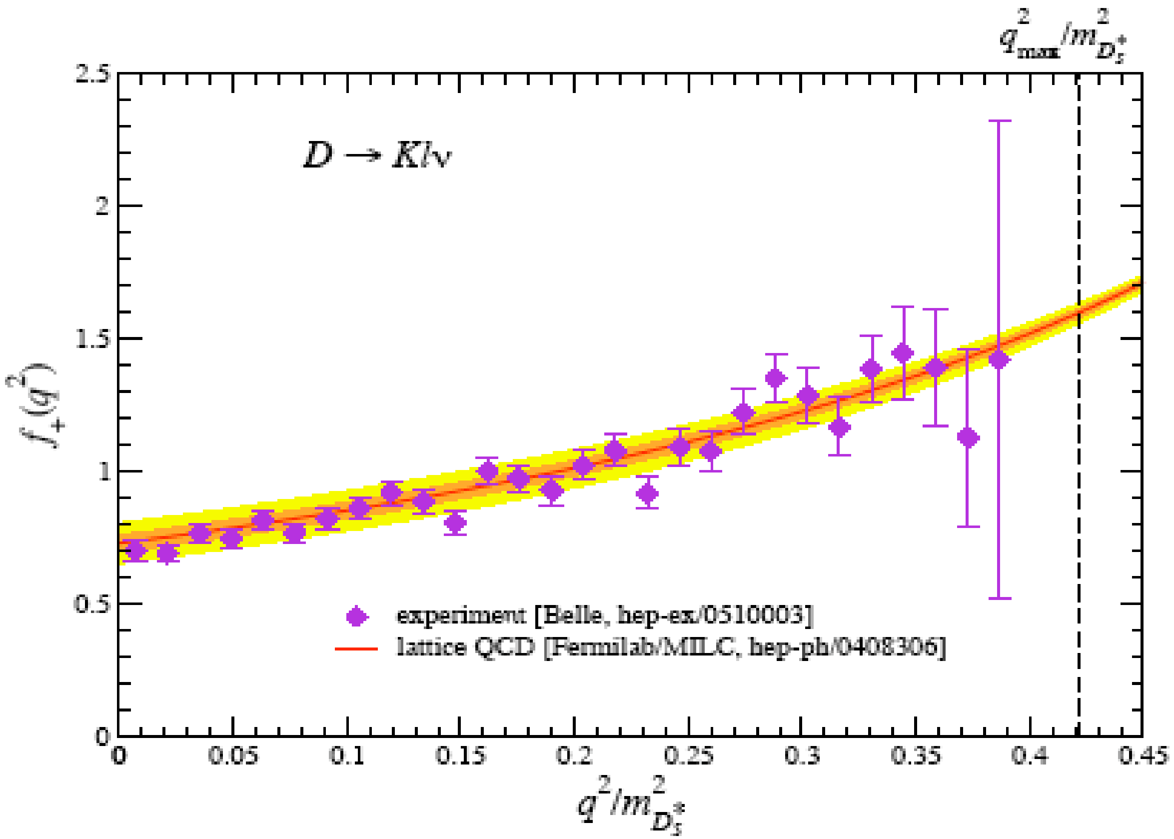
Phys. Rev. Lett. 95, 212001 (2005)

from post- to pre-diction!

$D \to \{K, \pi\} l\nu$

Mackenzie, FPCP'06

A prediction: shape of the $D \to K\, l\nu$ form factor.



CLEO-c is threatening to drastically improve. → More stringent tests.

Lattice is playing an increasingly important role in flavour physics

Davies LP'07

Lattice inputs
(2+1 sea quarks):

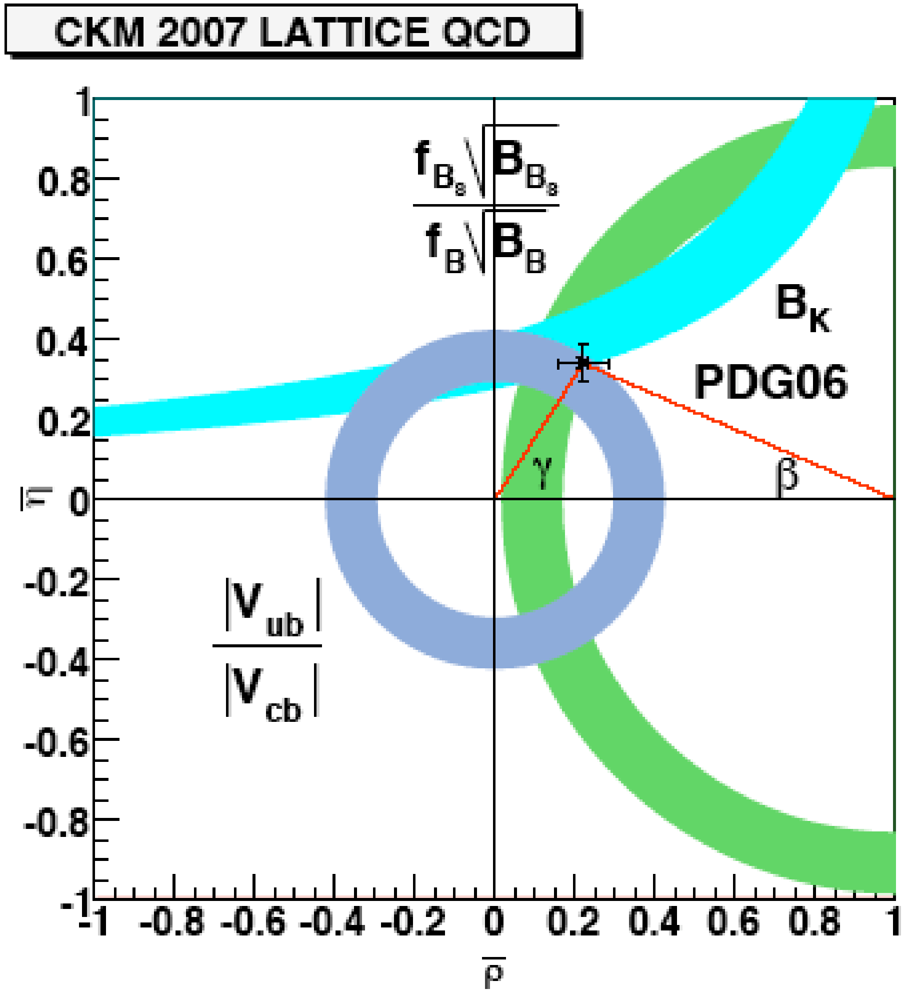
B_K

$f_K/f_\pi\ ,\ f_+(K\to\pi l\nu)$

$F(B\to D^* l\nu)$

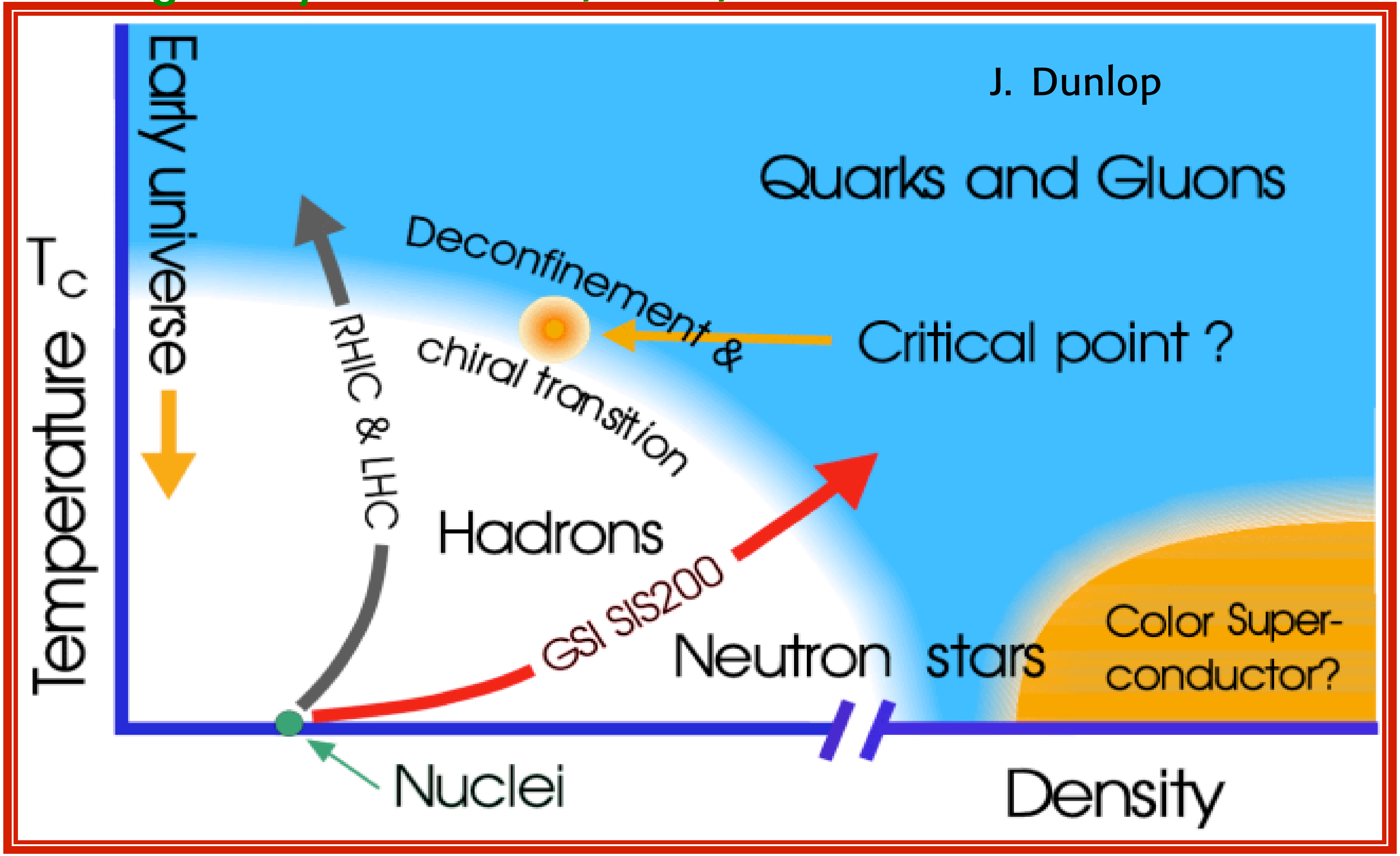
$f_+(B\to\pi l\nu)$

$$\frac{f_{B_s}\sqrt{B_{B_s}}}{f_B\sqrt{B_B}}$$



The QCD phase diagram

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

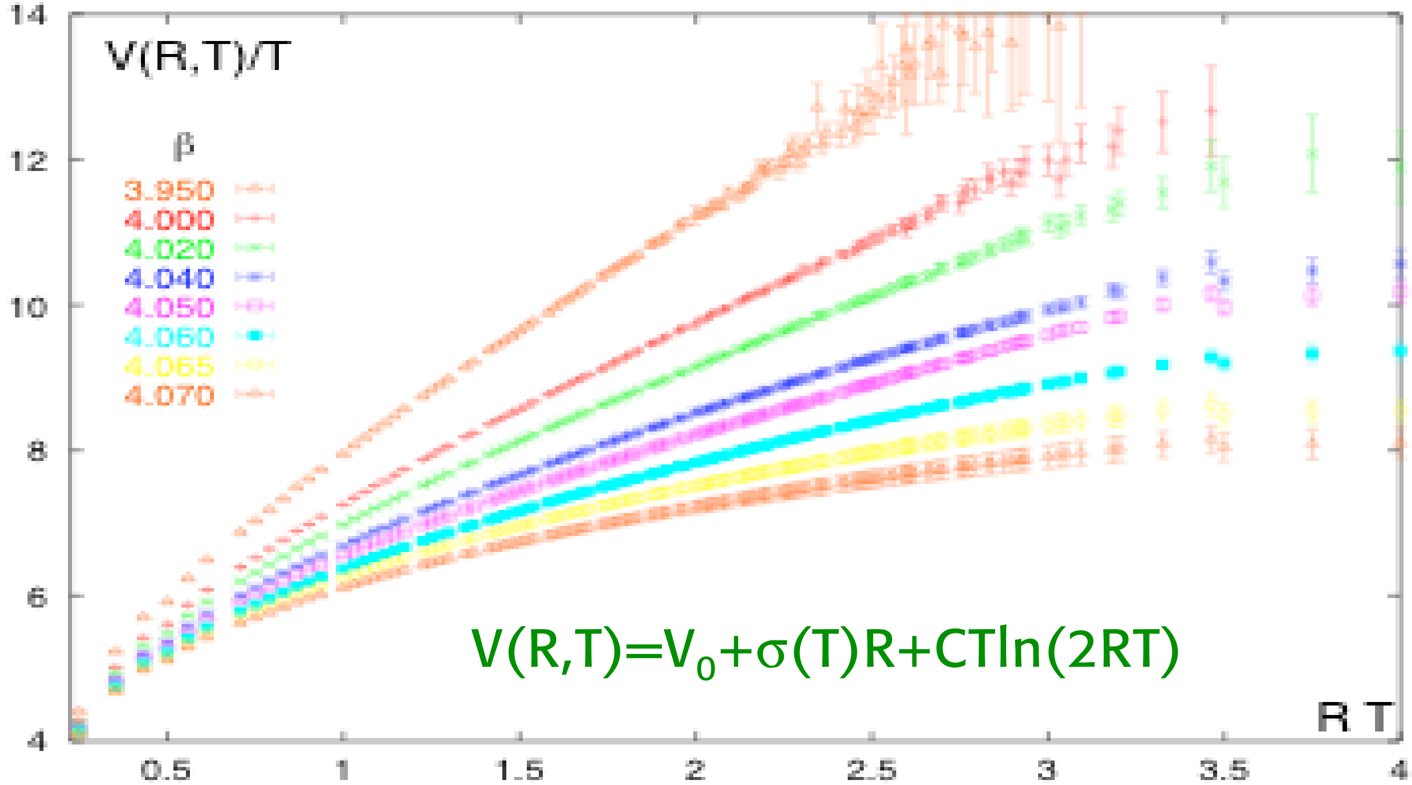


Confinement on the lattice

Potential between static quarks on the lattice

Kaczmarek, Karsch, Laermann, Lutgemeier '00

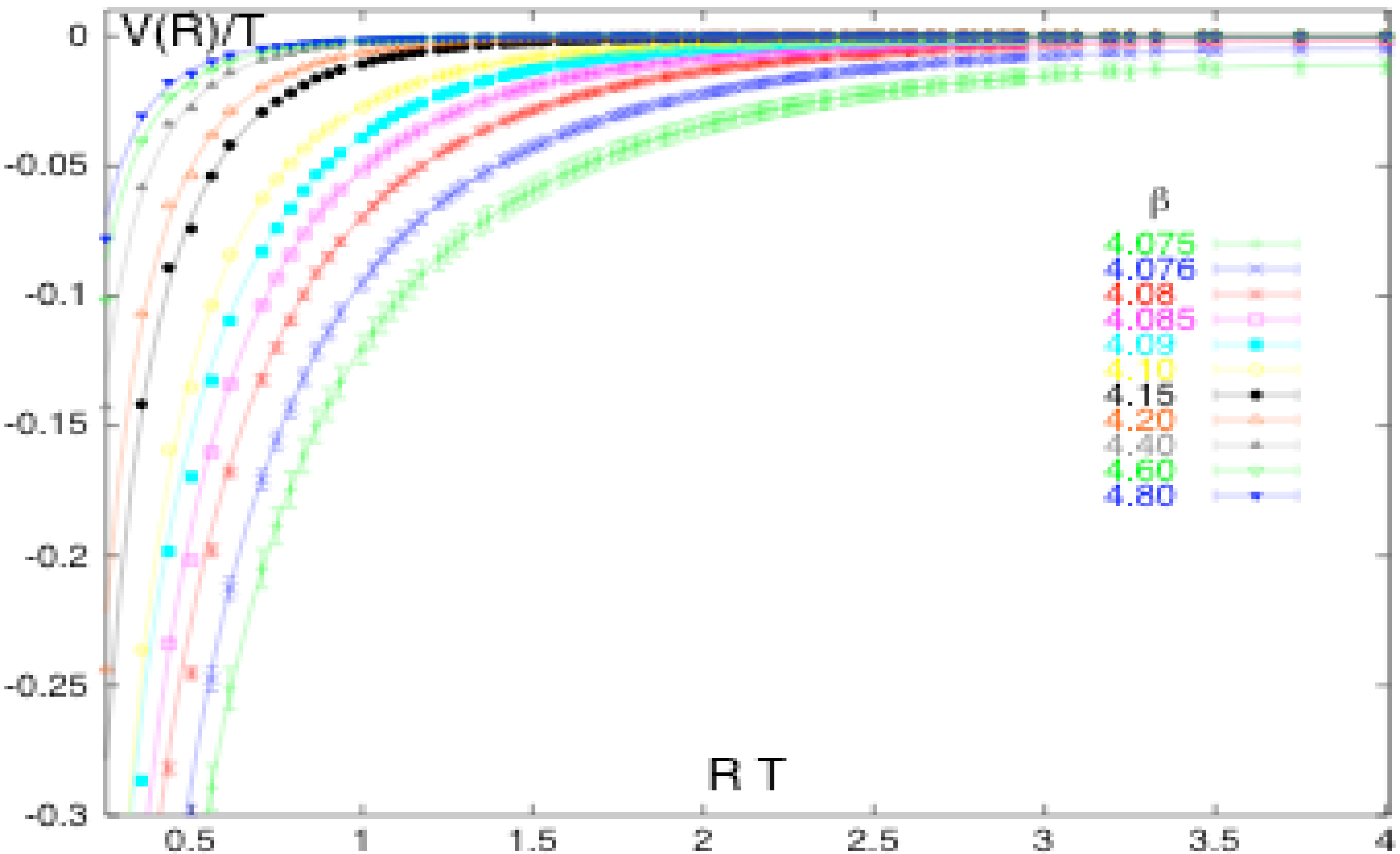
quenched approx.



Potential in units of kT (k=1) as function of R in units 1/T, for different $\beta=1/T$

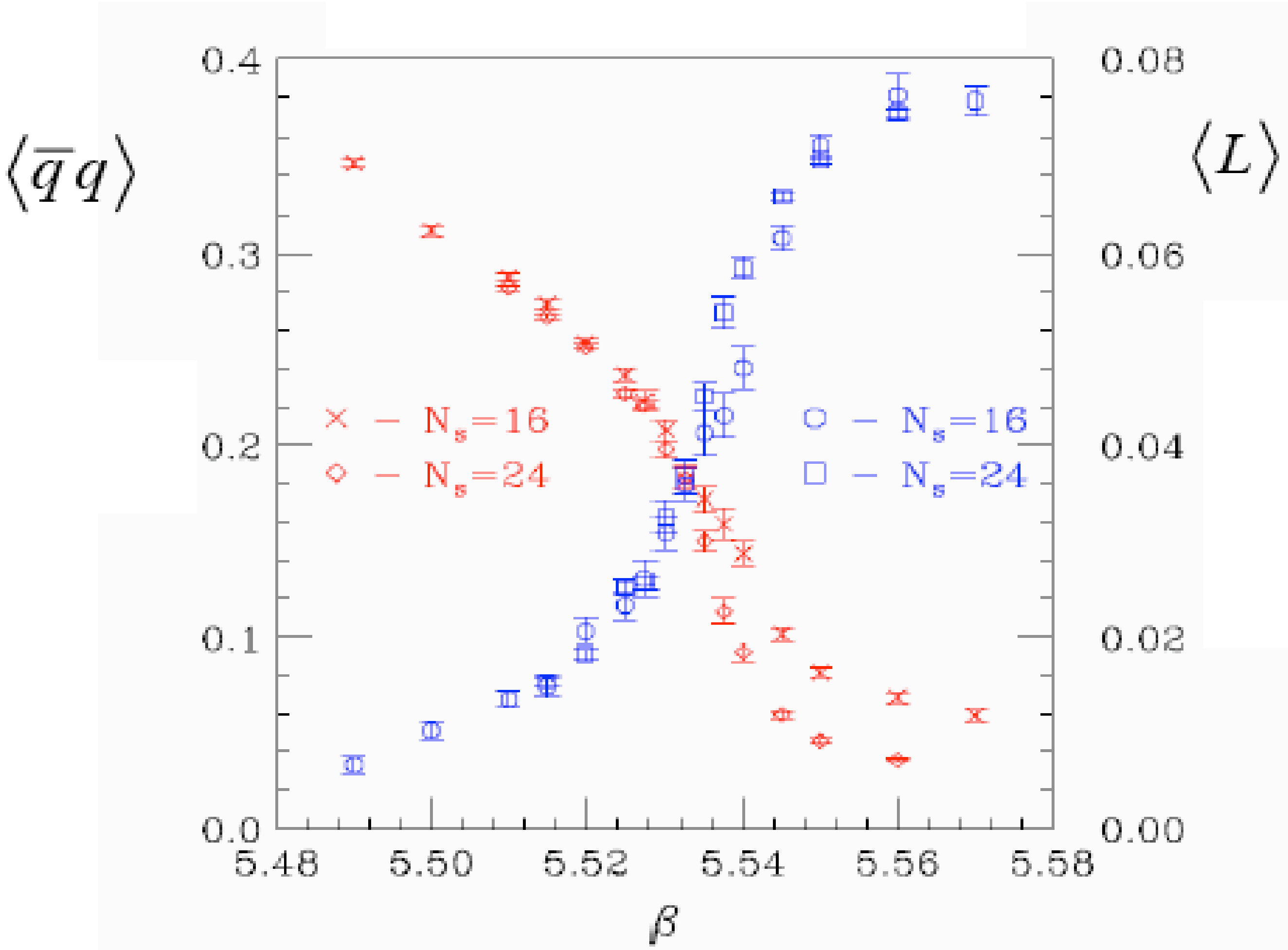
The linearly rising term slope vanishes at T_C

At $T>T_c$ the slope at large R remains zero



T_c depends on the number of quark flavours

Lattice QCD predicts a rapid transition, with correlated deconfinement and chiral restauration



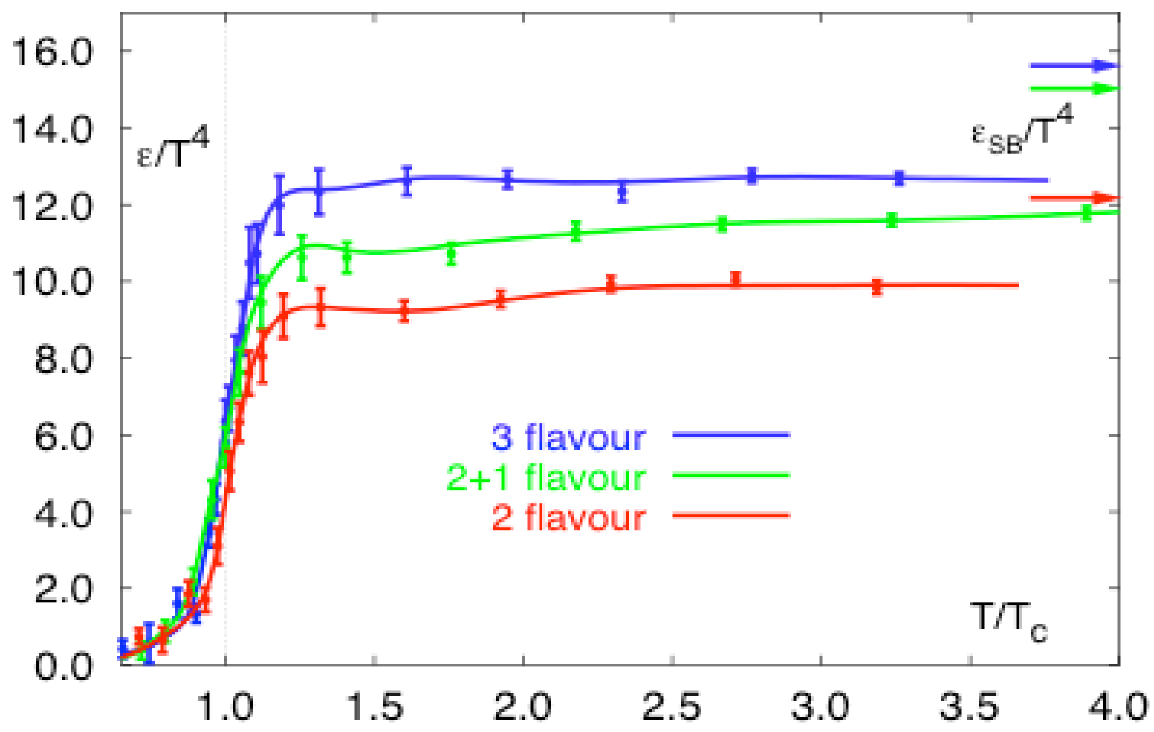
$$\langle L \rangle = \left\langle \mathrm{tr} \exp\left(i \int_0^{1/T} A_4 \, d\tau \right) \right\rangle$$

$$\sim \exp(-F_Q / T)$$

N_f=2, χQCD

Kogut and Sinclair, hep-lat/0408003

- **energy density increases sharply by the latent heat of deconfinement**

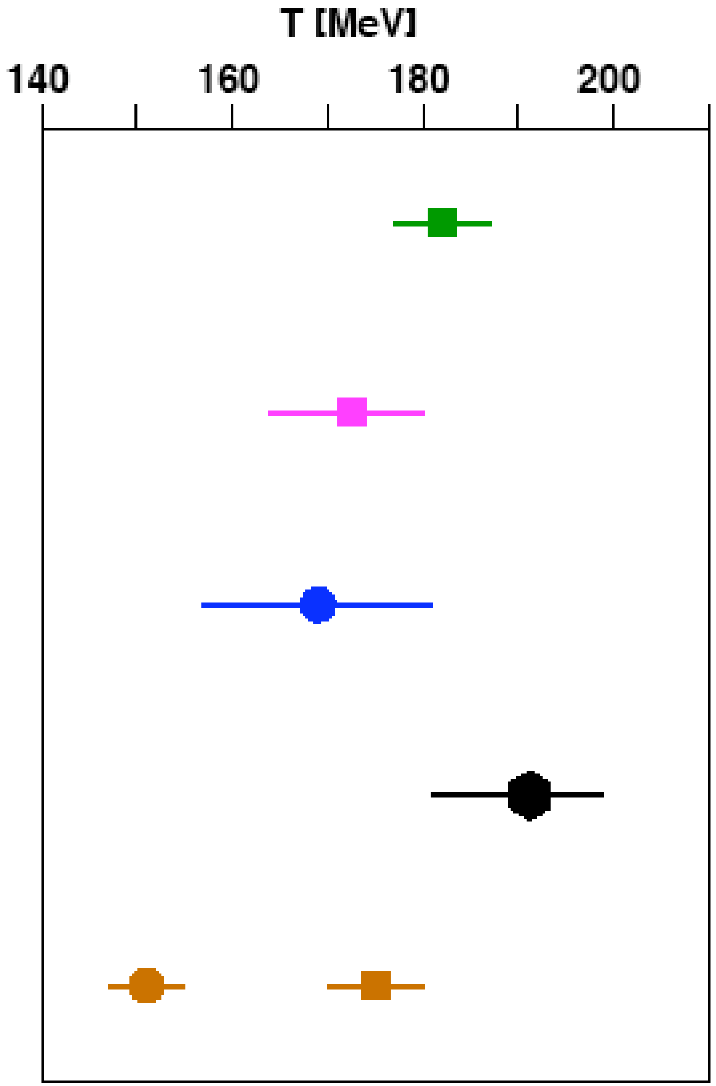


For $N_f = 2, 2+1$:

$T_c \simeq$ 175 MeV

$\epsilon(T_c) \simeq 0.5 - 1.0\ \mathrm{GeV/fm^3}$

Summary of recent results on T_c



use T=0 scale: r0=0.469fm

Karsch LAT'07

Nf=2:

V.G. Bornyakov et al, POS Lat2005, 157 (2006)
(improved Wilson, Nt=8, 10; input: r0=0.5 fm)
(added Nt=12, Lattice'07) (rescaled to r0)

Y. Maezawa et al., hep–lat/0702005 (QM'2006)
(improved Wilson, Nt=4, 6; input: m–rho)
(no cont. exp. yet)

Nf=2=1:

C. Bernard et al., Phys.Rev. D71, 034504 (2005)
(improved staggered (asqtad), Nt=4,6,8, input r1)
(rescaled to r0)

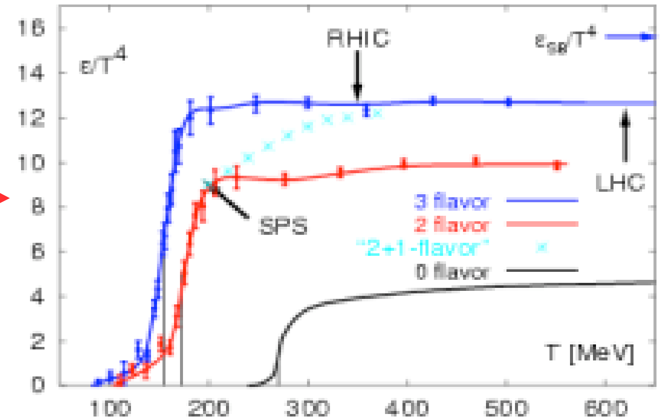
M. Cheng et al., Phys.Rev D74, 054507 (2006)
(improved staggered (p4), Nt=4,6; input r0)

Y. Aoki et al., Phys. Lett. B643, 46 (2006)
(staggered (stout), Nt=4,6,8,10; input fK)
(converted to r0)

● chiral ■ deconfinement ⬢ chiral+deconfinement

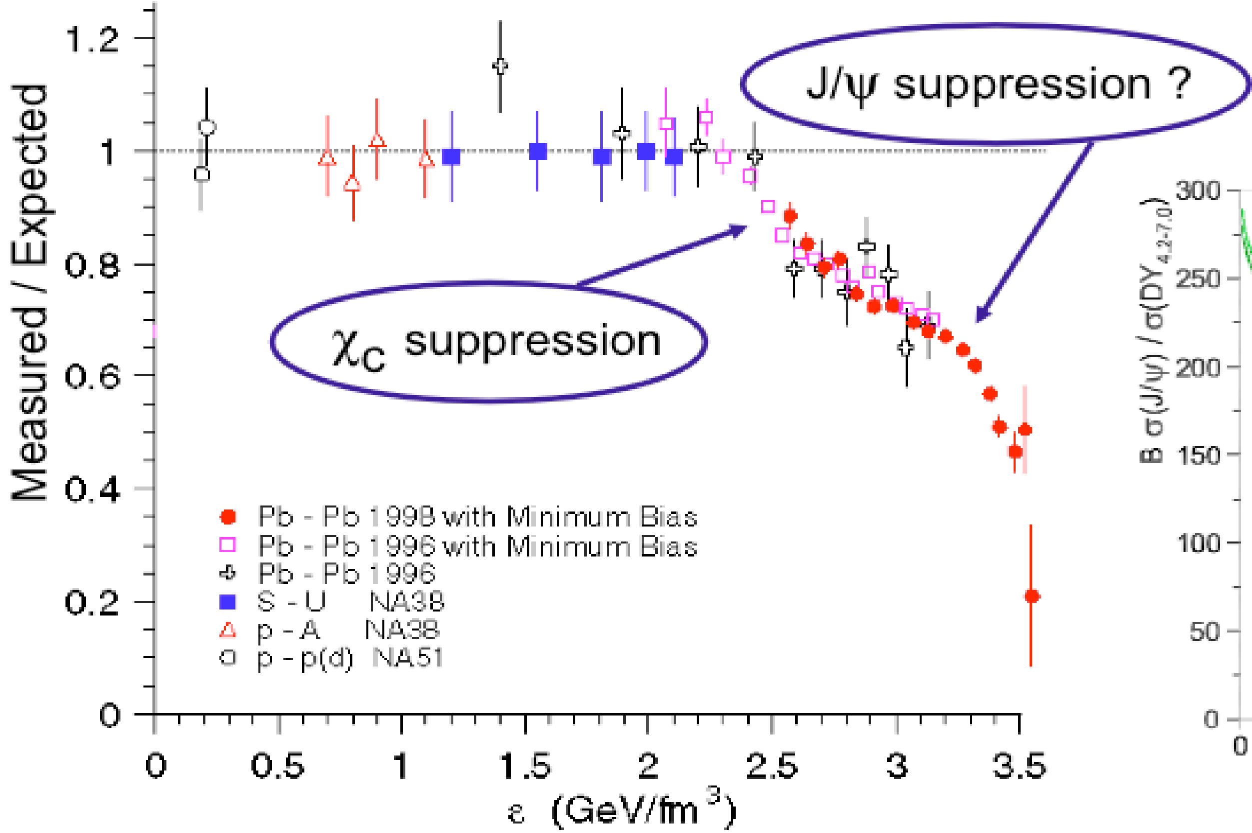
Experimental signals? CERN

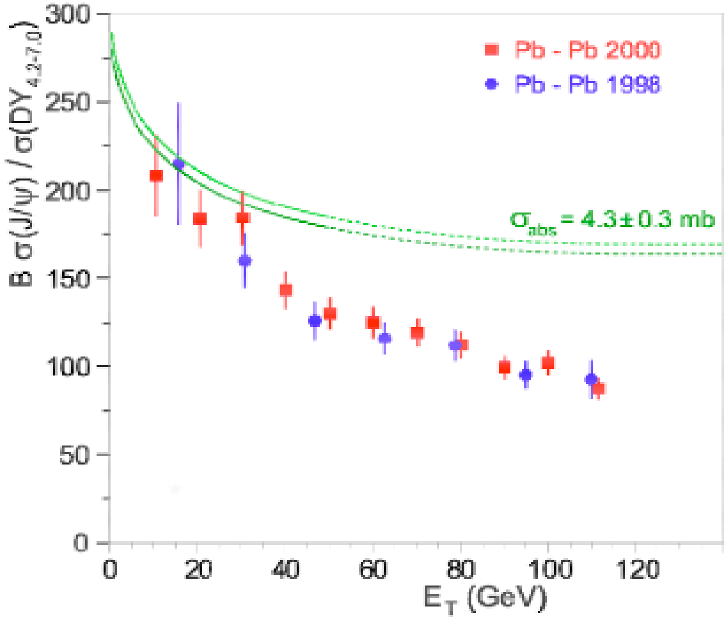
Apparently the SPS is well positioned to probe the transition region



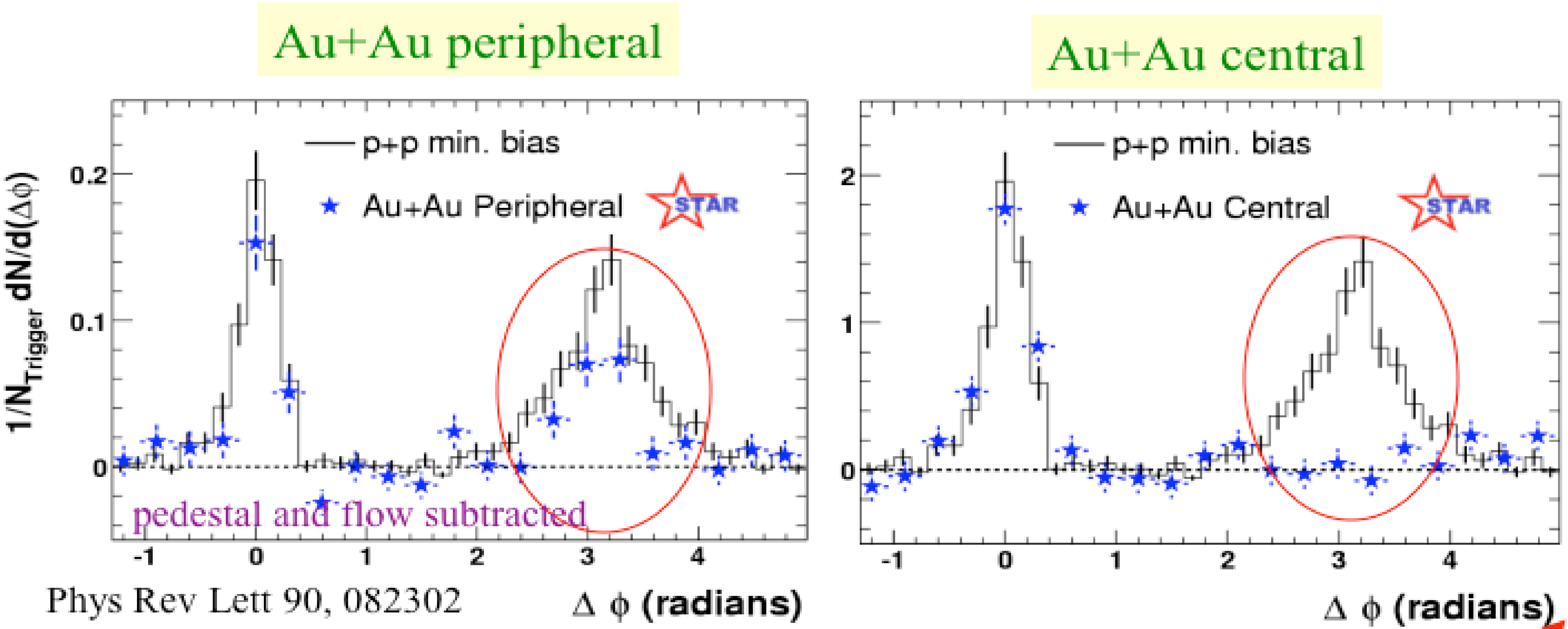
J/ψ suppression from p-A to Pb-Pb collisio

- The J/ψ production is suppressed in Pb-Pb collisions with respect to the yields extrapolated from proton-nucleus data → evidence for a deconfined QCD phase





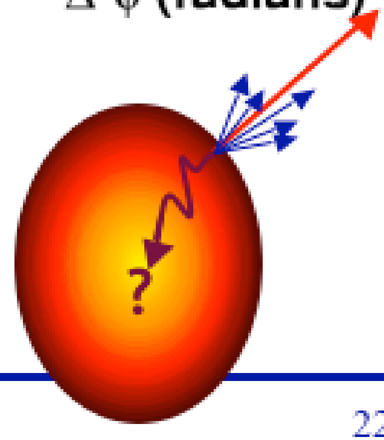
Azimuthal distributions in Au+Au



Phys Rev Lett 90, 082302

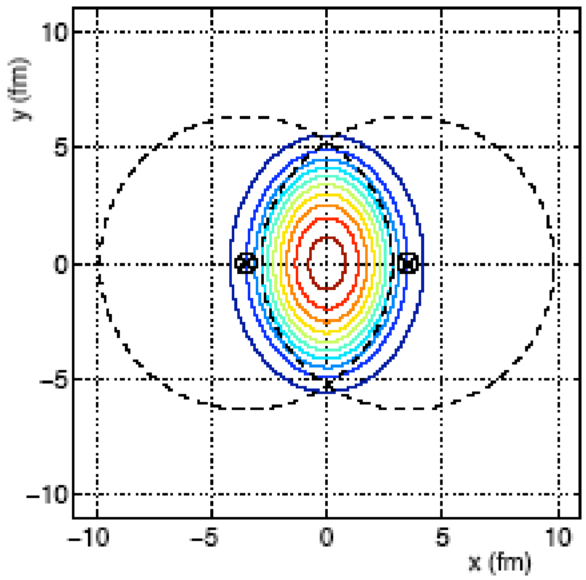
Near-side: peripheral and central Au+Au similar to p+p

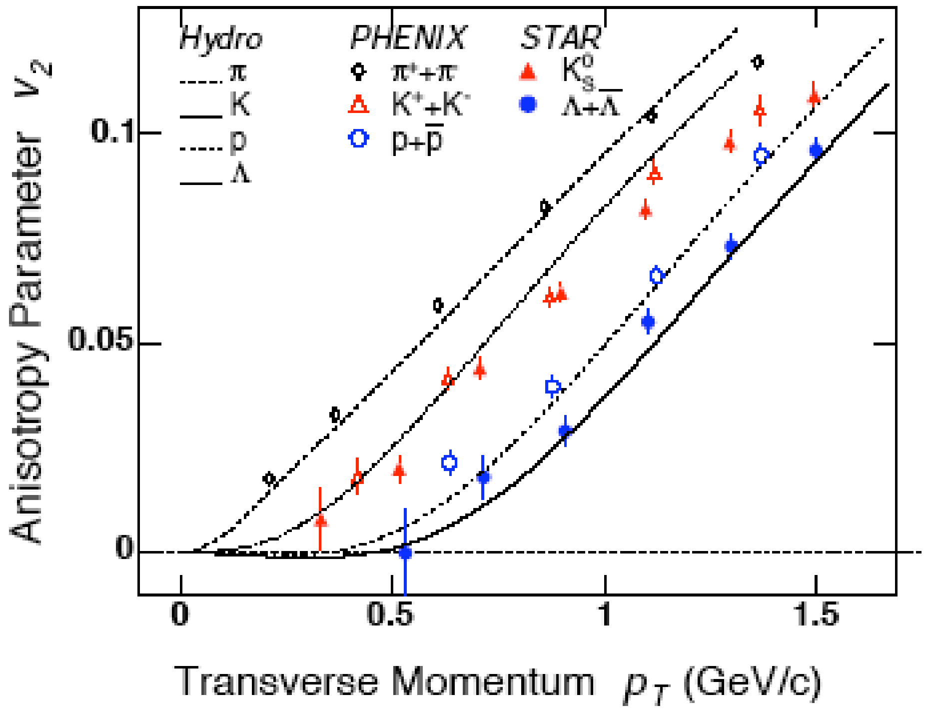
Strong suppression of back-to-back correlations in central Au+Au



Elliptic flow: a tool to study the primeval final state

Jacobs, Wang



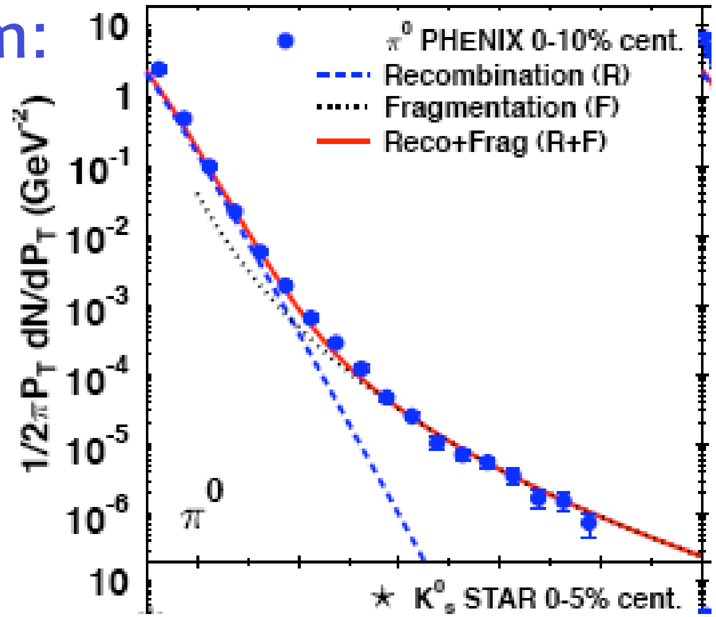


$$\frac{dN}{d\phi} \sim \left(1 + 2v_2 \cos\left[2\left(\phi - \phi_0\right)\right] + \ldots\ldots\right)$$

dominant anisotropy parameter

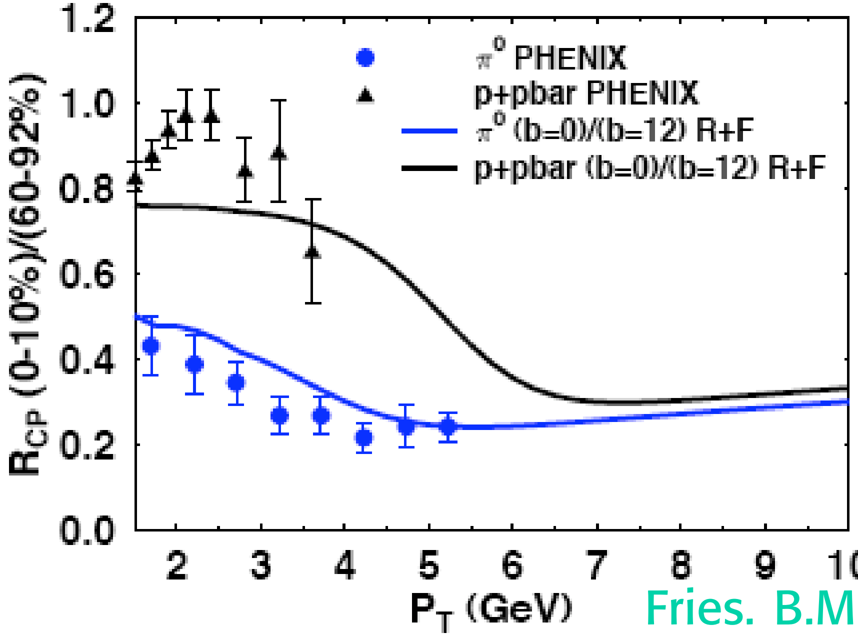
Hydrodynamic calculations are based on a phase made up of coloured partons

A 2-component hadronisation mechanism: coalescence and fragmentation

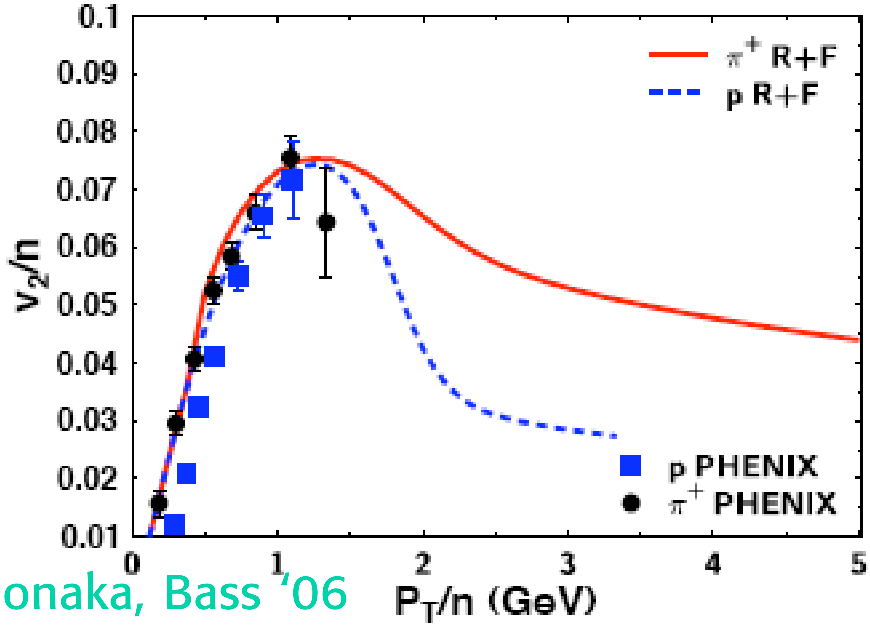


Early produced partons with high density have an exp falling in p_T: they produce hadrons by joining together.
At large p_T fragmentation with power behaviour survives

large p/π ratio



scaling: n constituent number



Fries. B.Muller, Nonaka, Bass '06

Elliptic flow, inclusive spectra, partonic energy loss in medium, strangeness enhancement, J/ψ suppression

....

are all suggestive of early production of a coloured partonic medium with high energy density (ε~5-10 GeV/fm^3) and temperature (T~170-180 MeV) then expanding as a near ideal fluid

Elliptic flow, inclusive spectra, partonic energy loss in medium, strangeness enhancement, J/ψ suppression

....

are all suggestive of early production of a coloured partonic medium with high energy density (ε~5-10 GeV/fm^3) and temperature (T~170-180 MeV) then expanding as a near ideal fluid

but only suggestive!

Perturbative QCD: A time of very difficult computations

Since α_s is not too small, $\alpha_s(m_Z^2) \sim 0.12$, the need of high order perturbative calculations, resummation of logs at all orders .... is particularly acute

Ingenious new computational techniques and software have been developed and many calculations have been realized that only a decade ago appeared as impossible.
Some examples follow:

Splitting functions

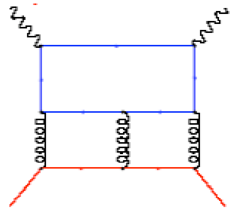
In 2004 the calculation of the NNLO splitting functions has been totally completed $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + \alpha_s^3 P_3 + \ldots\ldots$

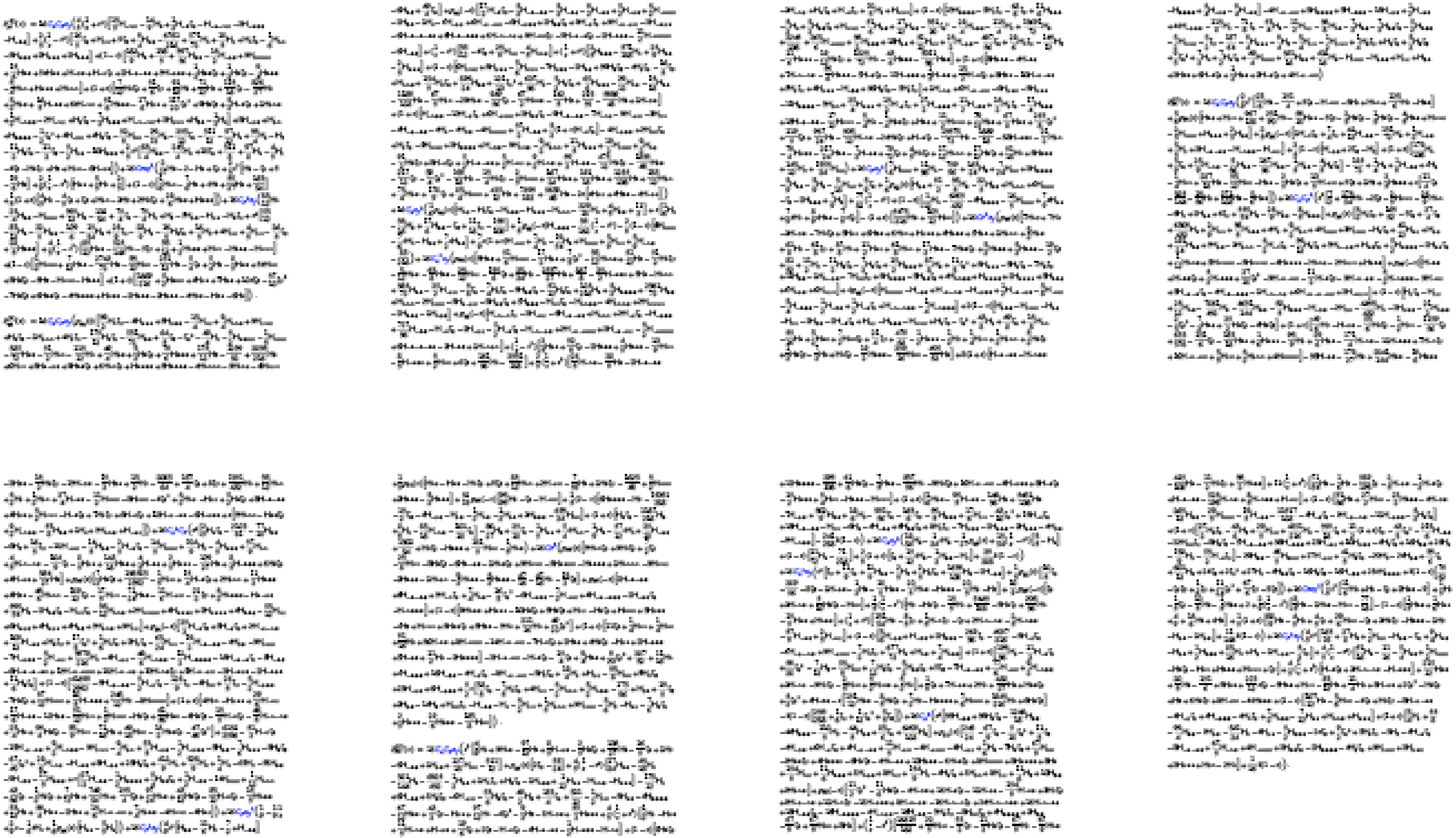
Moch, Vermaseren, Vogt

A really monumental, fully analytic, computation

NNLO singlet splitting functions

9607 3-loop diagrams





3rd order coeff. functions also computed Moch, Vermaseren, Vogt'05

Inclusive hadronic Z and τ decay at $o(\alpha_s^4)$ (NNNLO!!)

Baikov, Chetyrkin, Kuhn '08 ~20.000 diagrams

τ decay complete, Z decay only non singlet $\Sigma_f Q_f^2$ terms

(singlet terms $(\Sigma_f Q_f)^2$ small at $o(\alpha_s^3)$)

$$R(Q^2)=3\,\Sigma_f Q_f^2\,[1+a_s+1.4097a_s^2-12.76709a_s^3-80.0075a_s^4+\ldots]$$

$n_f=5$, $a_s=\alpha_s(Q^2)/\pi$

Can be used to improve α_s from τ and from Z

$\alpha_s(m_Z^2)=$ 0.1185---> 0.1190$\pm$0.0026

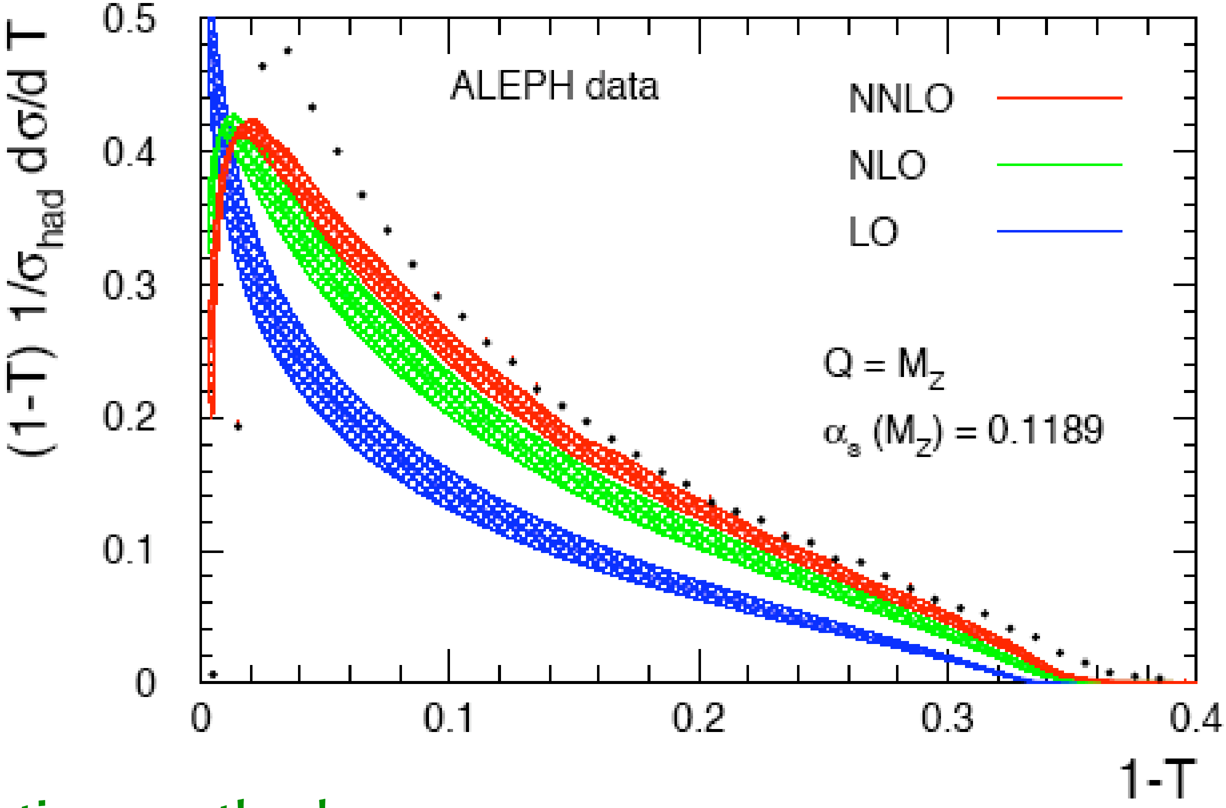
$\alpha_s(m_\tau^2)=$ 0.3455---> 0.332$\pm$0.016 or $\alpha_s(m_Z^2)=$ 0.1202$\pm$0.0019

As a result, the two come closer!

Hadronic event shapes at NNLO in e^+e^- annihilation

Gehrmann-De Ridder, Gehrmann, Heinrich '07

LO	$\gamma^* \to q\,\bar{q}g$	tree level
NLO	$\gamma^* \to q\,\bar{q}g$	one loop
	$\gamma^* \to q\,\bar{q}\,gg$	tree level
	$\gamma^* \to q\,\bar{q}\,q\bar{q}$	tree level
NNLO	$\gamma^* \to q\,\bar{q}g$	two loop
	$\gamma^* \to q\,\bar{q}\,gg$	one loop
	$\gamma^* \to q\,\bar{q}\,q\,\bar{q}$	one loop
	$\gamma^* \to q\,\bar{q}\,q\,\bar{q}\,g$	tree level
	$\gamma^* \to q\,\bar{q}\,g\,g\,g$	tree level

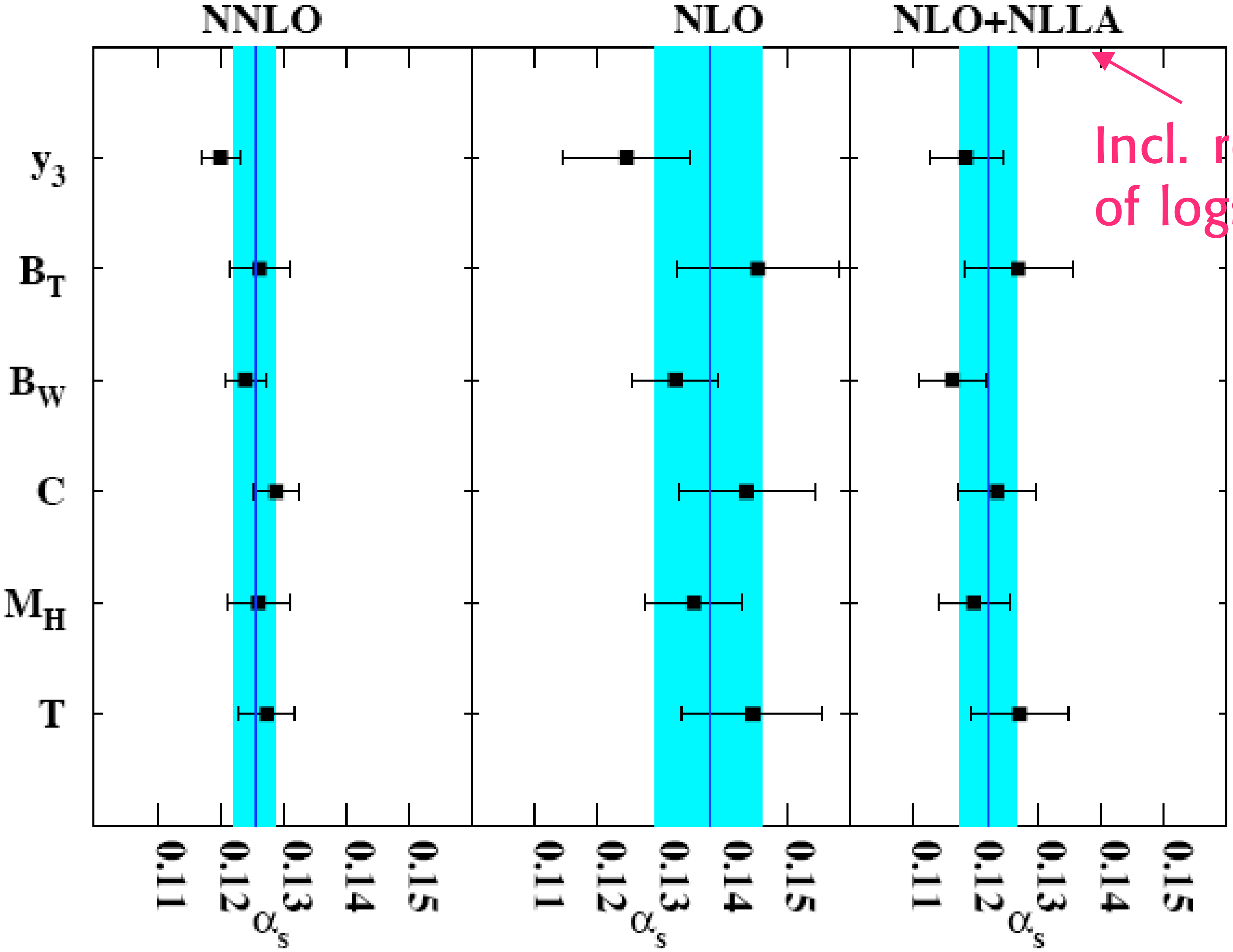


Based on the antenna subtraction method

Kosower; Campbell, Cullen, Glover

Application to α_s: $\alpha_s(m_Z^2) = 0.1240 \pm 0.0034$

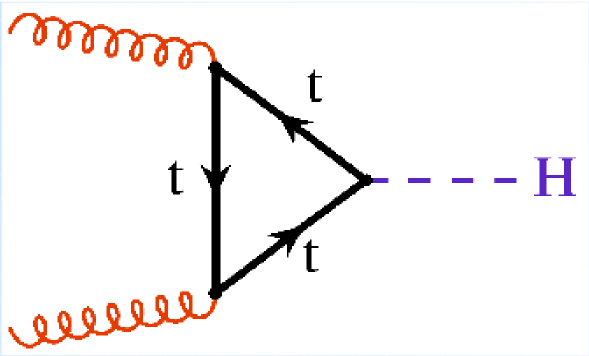
Dissertori, Gehrmann-De Ridder, Gehrmann, Heinrich, Stenzel '07



Incl. resumm. of logs

Higgs production via g+g -> H

Very important for the LHC



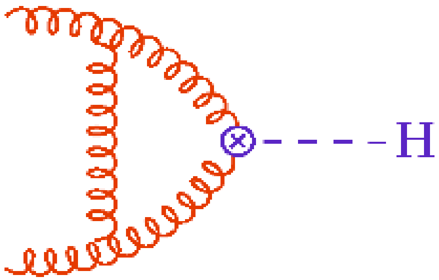
Effective lagrangian (m_t -> infinity)

$$\mathscr{L} = C_1 \, H \, G^{\mu\nu} G_{\mu\nu}$$

C_1 known to α_s^4

Chetyrkin, Kniehl, Steinhauser'97

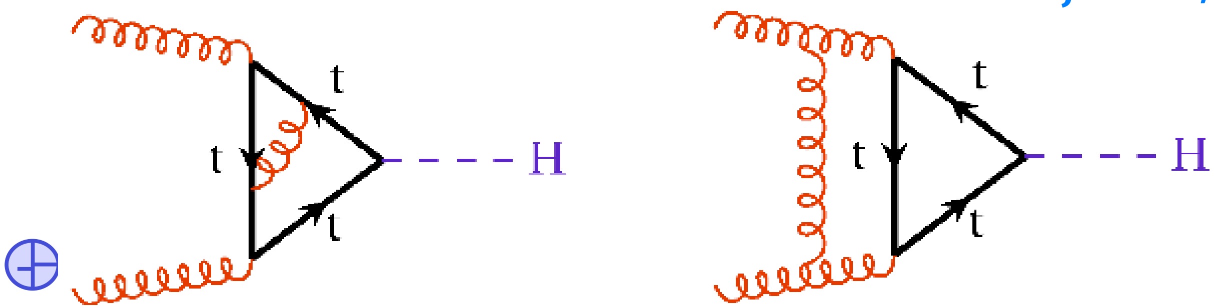
NLO corr.s computed with effective lagrangian



Dawson

Djouadi, Spira, Graudenz, Zerwas

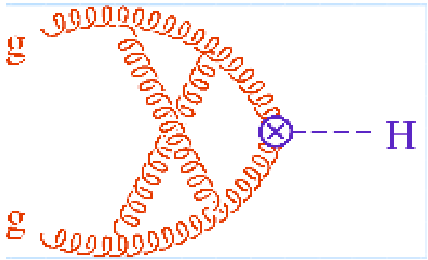
AND the full theory

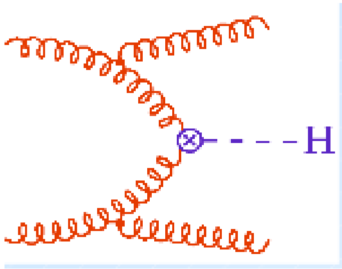


Djouadi, Spira, Graudenz, Zerwas

They agree very well

More recently the NNLO calculation was completed (analytic)

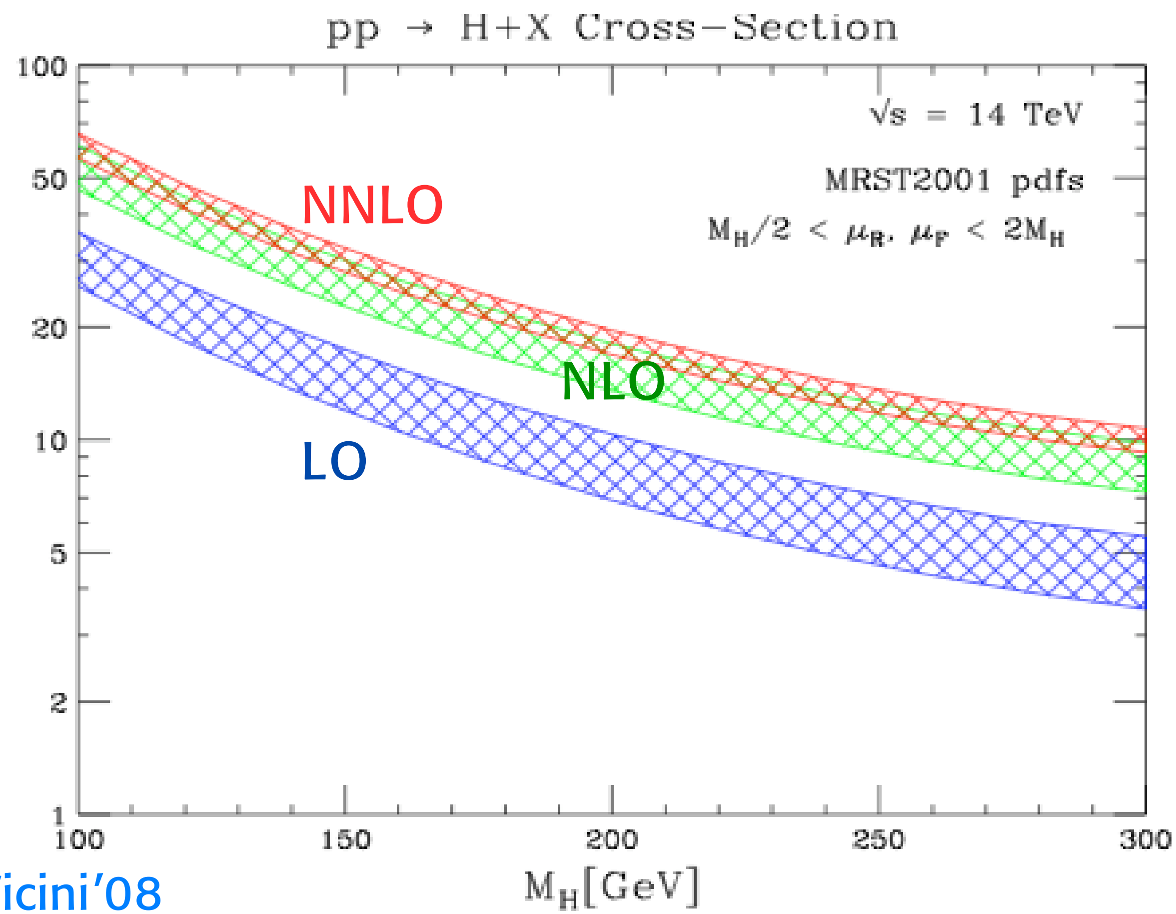




Catani, de Florian, Grazzini '01.
Harlander, Kilgore '01, '02
Anastasiou, Melnikov'02
Ravindran, Smith, van Neerven '03

Also NLO y and p_T distributions have been computed

De Florian, Grazzini, Kunszt '99
Glosser, Schmidt'02
Anastasiou, Melnikov, Petriello'05
Ravindran, Smith, van Neerven'06



Recent progress:
Resummation of large partonic-energy logs

DeMarzani, Ball, Del Duca, Forte, Vicini'08

Higgs p_T distribution: $[\log(p_T/m_H)]^n$ resummed

Bozzi, Catani, De Florian, Grazzini'03-'08

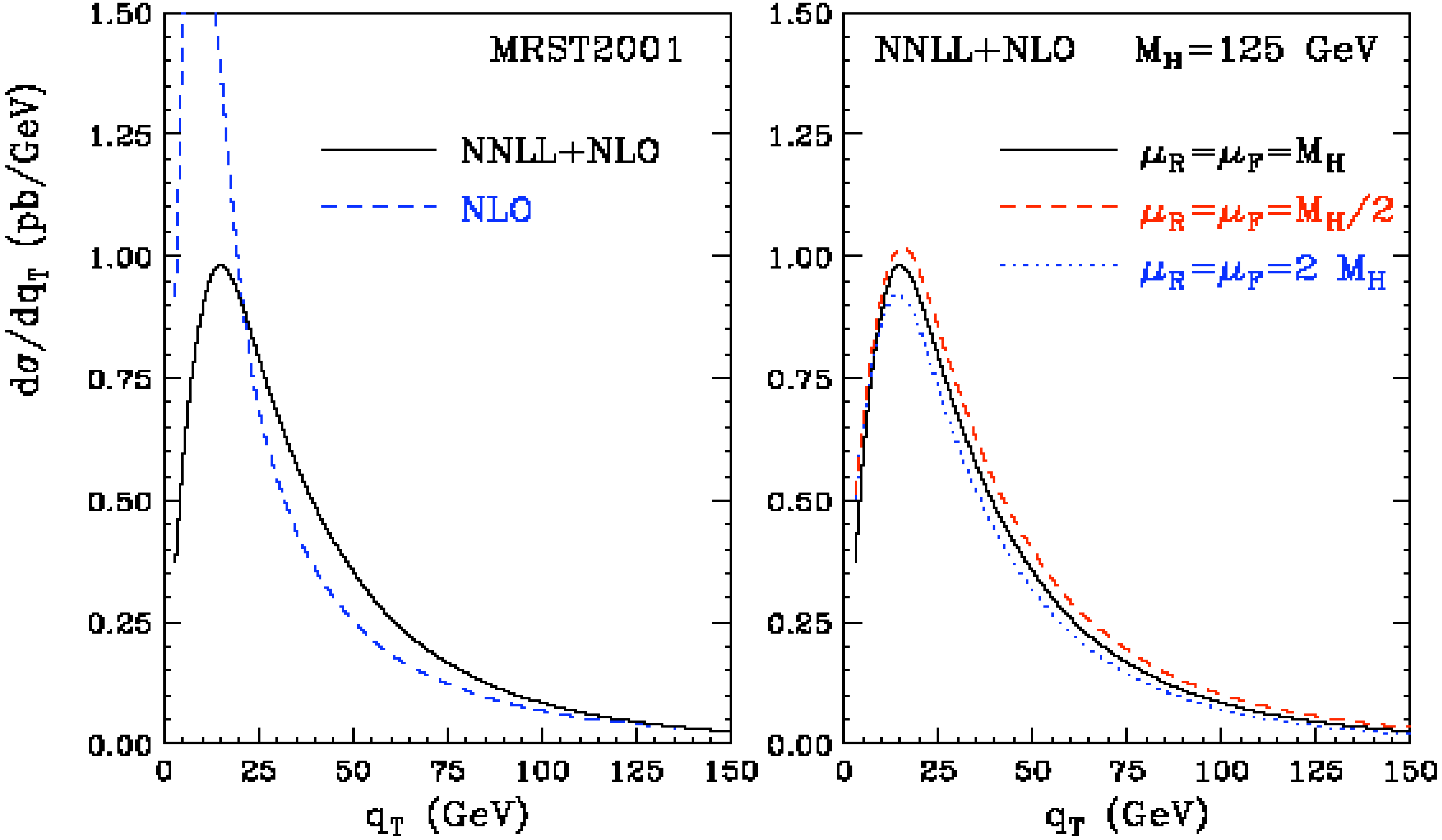
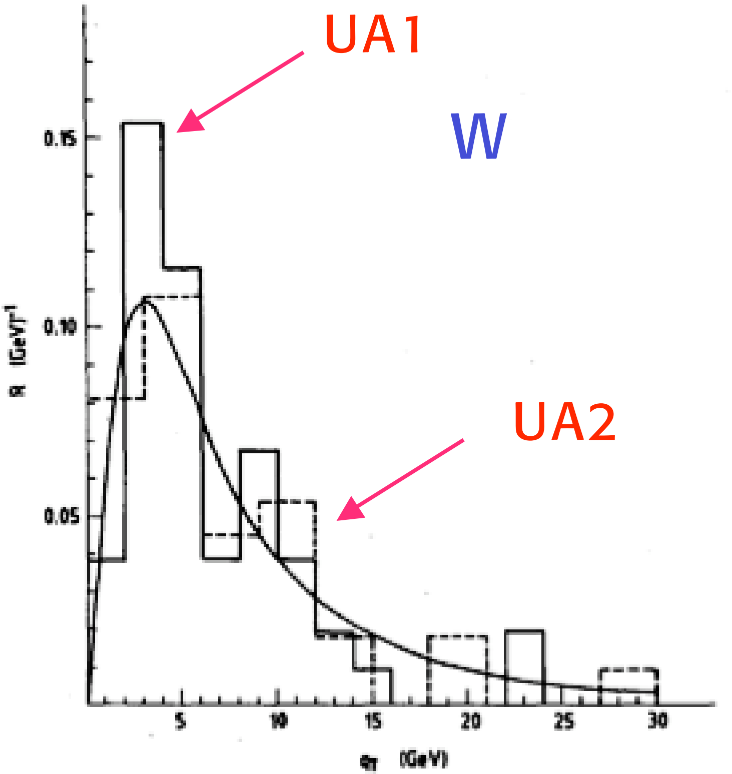


Figure 7. Resummed pQCD prediction for the Higgs transverse momentum distribution at the LHC, from Bozzi *et al.*[25]

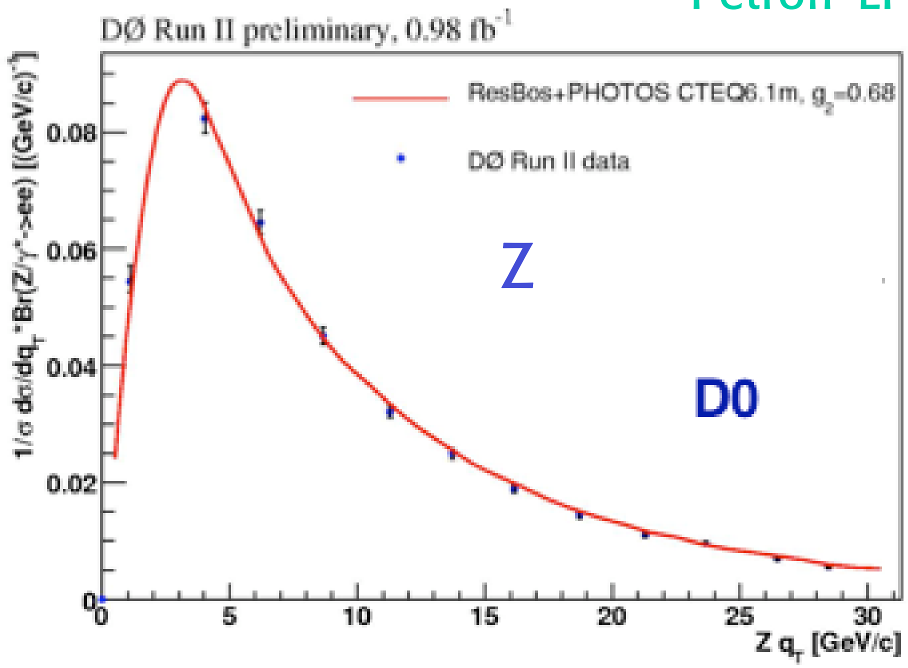
~25 years ago I started at CERN by computing the W and Z p_T distribution in QCD



GA, K.Ellis, M. Greco, G.Martinelli '84

Yesterday the W&Z
today the Higgs!

Petroff LP'07



In agreement with perturbative QCD augmented by Collins-Soper-Sterman (CSS) resummation at low q_T

J. Collins, D. Soper, G. Sterman, Nucl. Phys. B250 (1985) 199.

ResBos describes data well up to ~ 30 GeV

F. Landry, R. Bock, P.Nadolsky, C.P. Yuan
Phys. Rev. D 67, 073016 (2003)

NNLO describes better above 30 GeV

K. Melnikov and F. Petriello Phys. Rev. D74 114017 (2006)

$B \to X_s\gamma$ at NNLO: a great achievement by many theorists

A main constraint on new physics models

- Inclusive rate at NNLO almost exactly completed

Misiak et al '06

$$\mathcal{B}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\,\mathrm{GeV}} = \mathcal{B}(\bar{B} \to X_c e\bar{\nu})^{\mathrm{exp}} \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to ce\bar{\nu})}\right]_{\mathrm{LO\,EW}} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)}\right) \times$$

$$\times \left\{1 + \underset{\substack{\mathrm{NLO} \\ \sim 25\%}}{\mathcal{O}(\alpha_s)} + \underset{\substack{\mathrm{NNLO} \\ \sim 7\%}}{\mathcal{O}(\alpha_s^2)} + \underset{\sim 4\%}{\mathcal{O}(\alpha_{\mathrm{em}})} + \underset{\sim 1\%}{\mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right)} + \underset{\sim 3\%}{\mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right)} + \underset{<\sim 5\%}{\mathcal{O}\left(\frac{\alpha_s \Lambda}{m_b}\right)}\right\}$$

- Effect of photon cut at NNLO evaluated

$\Gamma(E_\gamma > E_0) = \Gamma(B \to X_s\gamma)F(E_0)$

Becher, Neubert '06

$B[B \to X_s\gamma, E_0 = 1.6\ \mathrm{GeV}](10^{-4}) = 3.15 \pm 0.23$ (pert. th)

$= 2.98 \pm 0.26$ ($F(E_0)$ non pert. OPE)

EXP: 3.55 ± 0.26 $\sim 1.5\ \sigma$

Singlet splitting function at small x

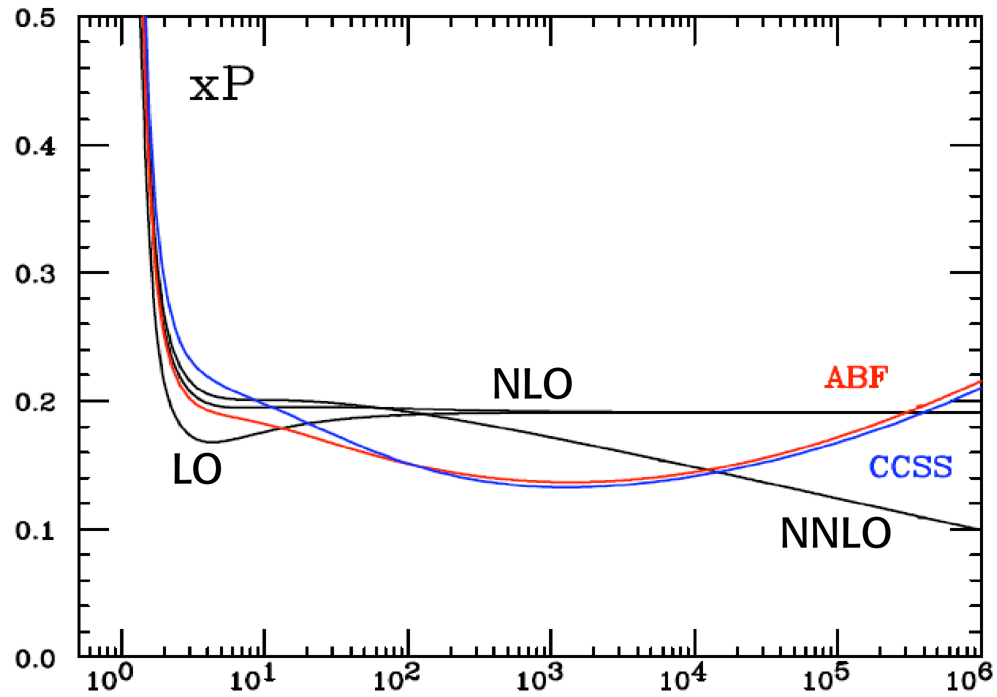
The problem of correctly including BFKL at small x has been solved

Ciafaloni, Colferai, Salam, Stasto (CCSS)
Altarelli, Ball, Forte (ABF)

Momentum cons.+ symmetry + running coupling effect

→ soft simple pole in anom. dim

- BFKL sharp rise tamed
- resummed result close to NLO in HERA region
- new expansion stable



Bulk of data

1/x

Makes the ground solid for LHC predictions (eg b production)

QCD event simulation

A big boost in the preparation to LHC experiments

General algorithms for computer NLO calculations

eg the dipole formalism — Catani, Seymour,.....

the antenna pattern — Kosower....

Matching matrix elements and parton showers

e.g. MC@NLO based on HERWIG — Frixione, Nason, Webber

POWHEG — Nason, Ridolfi

Perturbative (+ resumm.s)

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

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

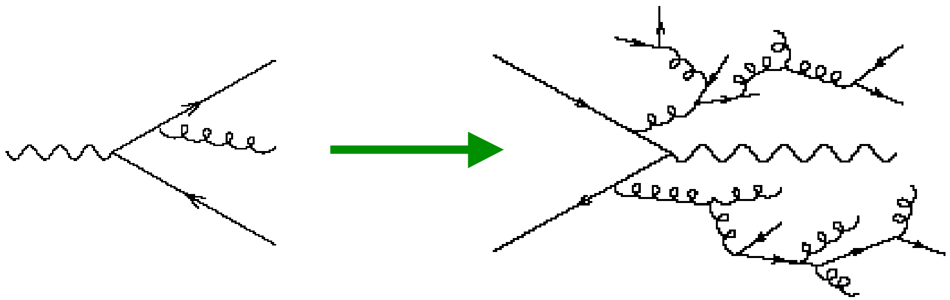
Complementary virtues:
the hard skeleton plus
the shower development
and hadronization

Parton showers

collinear emissions factorize

$$d\sigma_{q\bar{q}g} = d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t} P_{qq}(z) dz \frac{d\varphi}{2\pi}$$

$$t = (p_q + p_g)^2 \longrightarrow 0$$



hadronization added

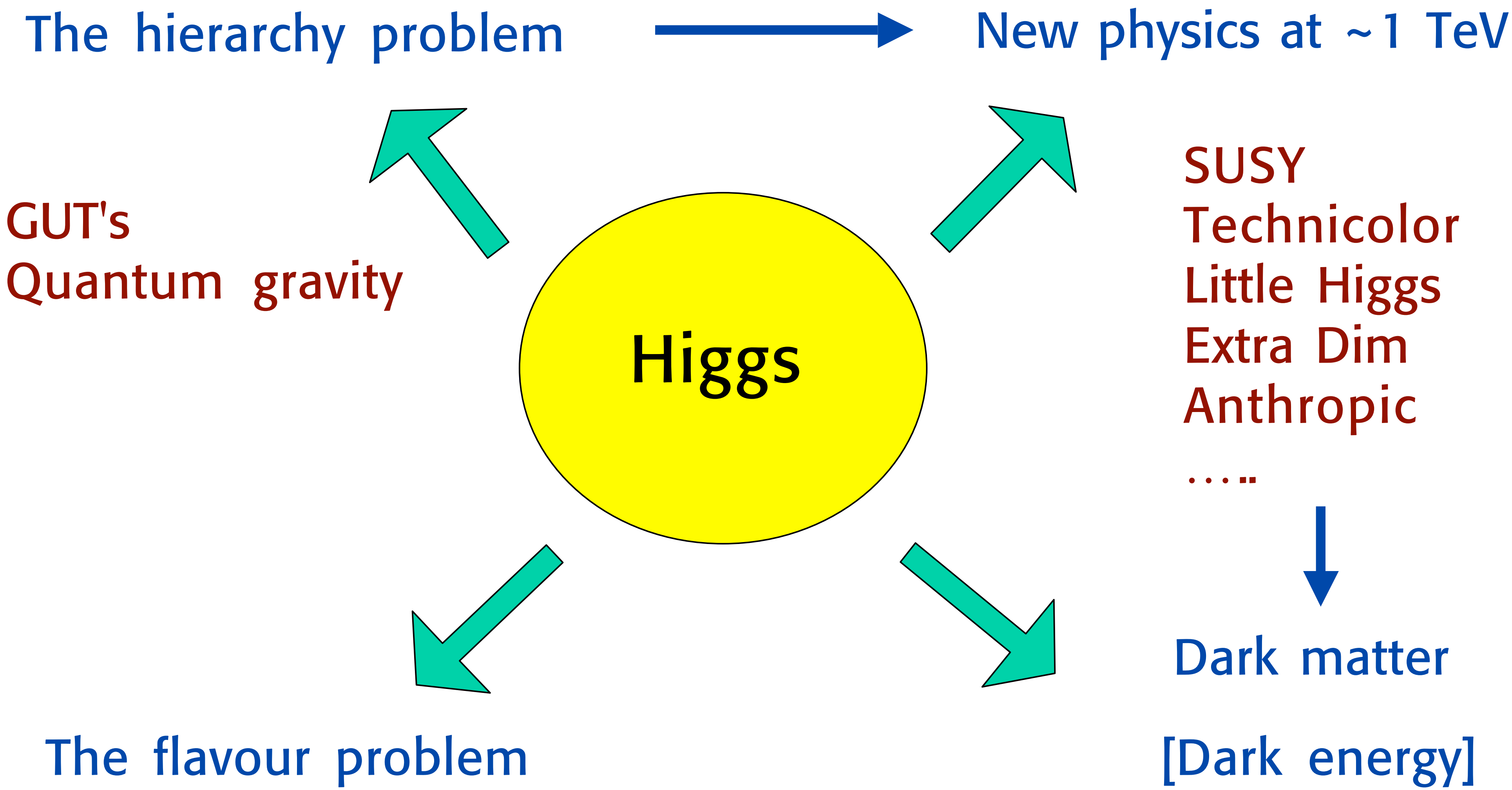
QCD is remarkably successful

A great amount of work has been made over the years to prepare for the LHC

The main conceptual problems in particle physics for the LHC to solve are in the electroweak sector, in particular in the Higgs sector

$\Longrightarrow$ **EW Interactions**

The Higgs problem is central in particle physics today



The Standard EW theory: $\mathcal{L} = \mathcal{L}_{\text{symm}} + \mathcal{L}_{\text{Higgs}}$

$$\mathcal{L}_{symm} = -\frac{1}{4}[\partial_\mu W_\nu^A - \partial_\nu W_\mu^A - ig\varepsilon_{ABC} W_\mu^A W_\nu^B]^2 +$$

$$-\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 +$$

$$+\overline{\psi}\gamma^\mu [i\partial_\mu + g W_\mu^A t^A + g' B_\mu \frac{Y}{2}]\psi$$

$$\mathcal{L}_{Higgs} = \left|[\partial_\mu - ig W_\mu^A t^A - ig' B_\mu \frac{Y}{2}]\phi\right|^2 +$$

$$+ V[\phi^\dagger\phi] + \overline{\psi}\Gamma\psi\phi + \mathrm{h.c}$$

with $\quad V[\phi^\dagger\phi] = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$

$\mathcal{L}_{\text{symm}}$: well tested (LEP, SLC, Tevatron…), $\mathcal{L}_{\text{Higgs}}$: ~ untested

All we know from experiment about the SM Higgs:

Rad. corr's -> $m_H < 182$ GeV (95%cl, incl. direct search bound)
but no Higgs seen -> $m_H > 114.4$ GeV (95%cl)

$v = \langle\phi\rangle = \sim 174$ GeV ; $\quad m_W = m_Z \cos\theta_W \longrightarrow$ doublet Higgs

That some sort of Higgs mechanism is at work has already been established

The questions are about the nature of the Higgs 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

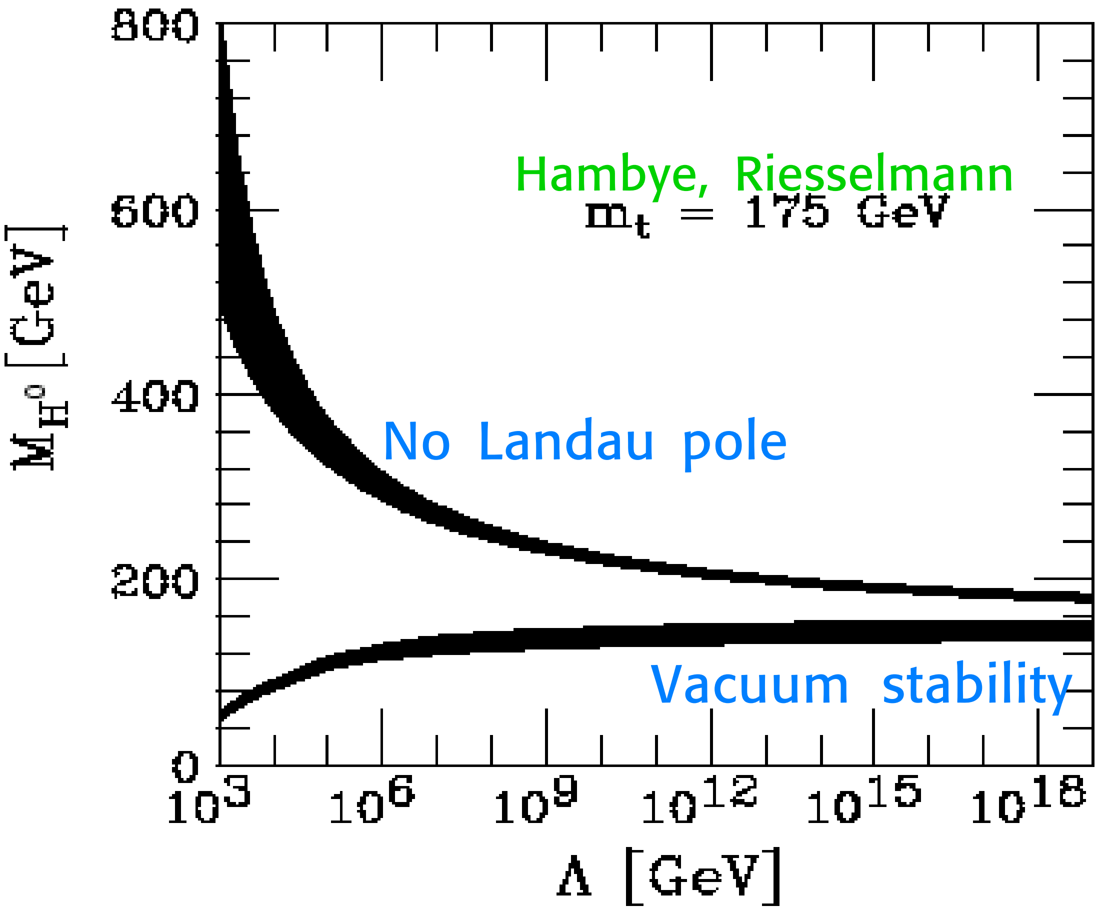
Theoretical bounds on the SM Higgs mass

Λ: scale of new physics beyond the SM

Upper limit: No Landau pole up to Λ

Lower limit: Vacuum (meta)stability

The LHC was designed to cover the whole range



If the SM would be valid up to M_{GUT}, M_{Pl} then m_H would be limited in a small range

Lower now because of m_t → $128\ \text{GeV} < m_H < 180\ \text{GeV}$

Additional argument against heavy Higgs:

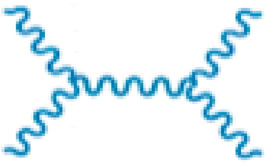
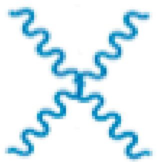
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

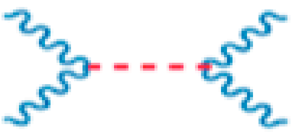
Zwirner

Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; …]

An example: $\mathcal{A}(W_L^+ W_L^- \longrightarrow Z_L Z_L) \quad (s \gg m_W^2)$

  $i\dfrac{s}{v^2}$

 $-i\dfrac{s^2}{v^2(s-m_h^2)}$

$$\rightarrow \quad -i\frac{m_h^2}{v^2}\frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

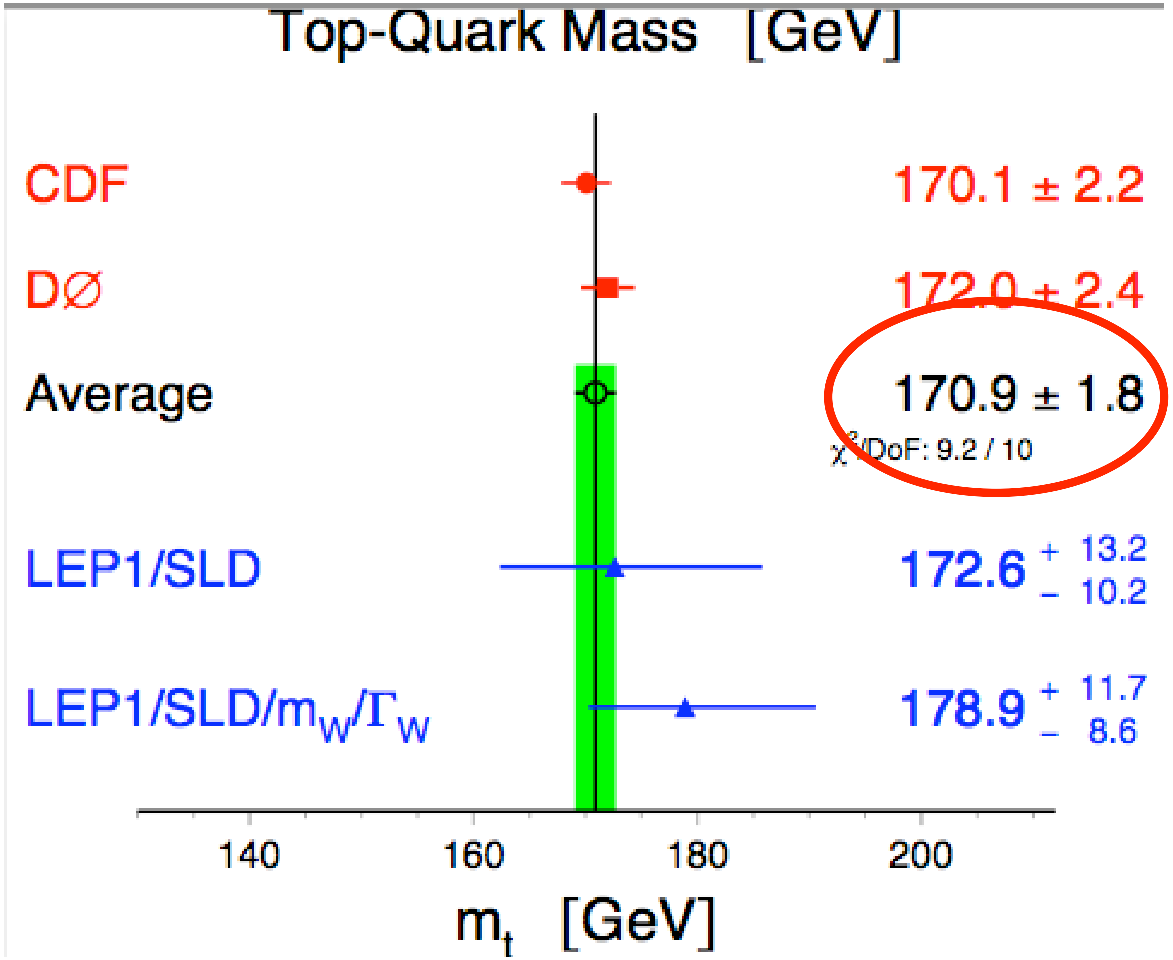
Precision Tests of SM

The only recent development in this domain is the decrease of the experimental value of m_t from CDF& D0 Run II

The error went also much down!

(Run I value: 178.0±4.3 GeV)

Winter'07



This has a small effect on the quality of the SM fit and on the m_H bounds

$m_t \Downarrow$: $m_H \Downarrow$

quality $\Downarrow$

Winter '07

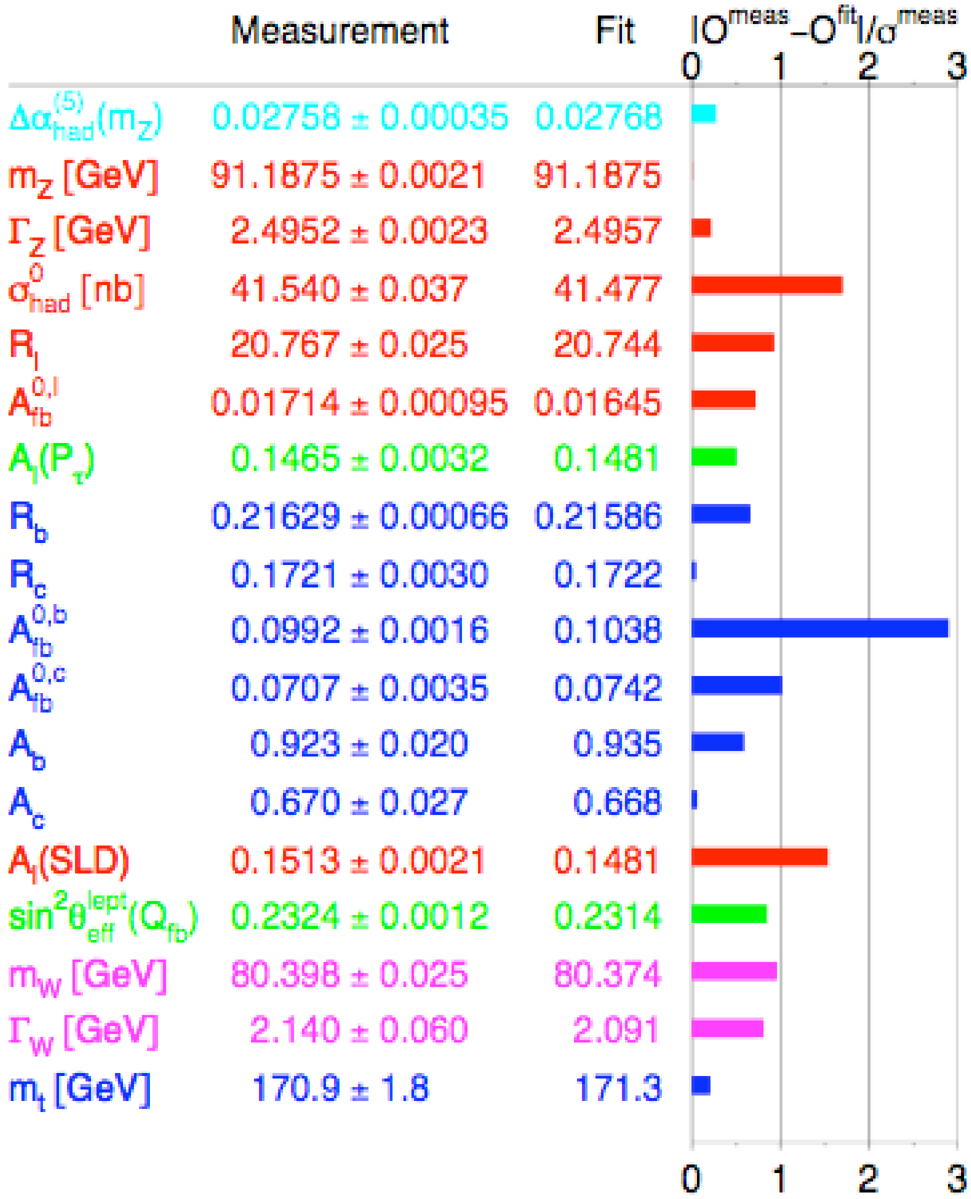
Overall the EW precision tests support the SM and a light Higgs.

The χ^2 is reasonable:

χ^2/ndof~18.2/13 (~15.1%)

Note: does not include NuTeV, APV, Moeller and $(g-2)_\mu$

a_μ ~3σ deviation?



Electron g-2: A recent measurement

Odom, Hanneke, D'Urso, Gabrielse '06

$a_e = (g-2)/2 = 11596521808.5(7.6)\ 10^{-13}$

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$
$$+ a_{\mu\tau} + a_{\text{hadronic}} + \cancel{a_{\text{weak}}},$$

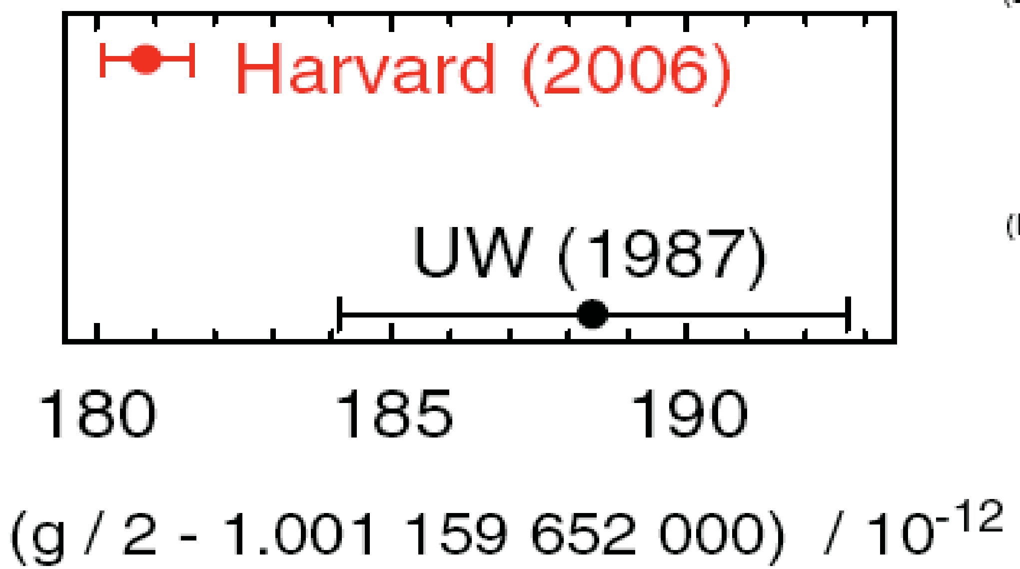
δa_h small

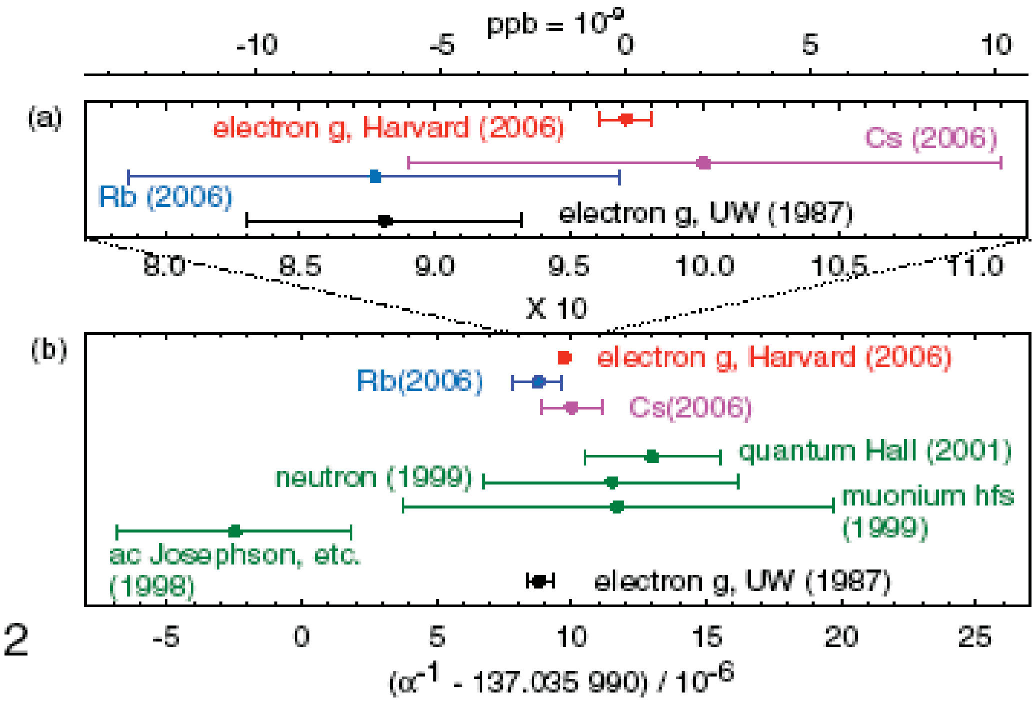
Best determination of α_{QED}

$\alpha^{-1} = 137.035999070(98)$

Value given in Aoyama et al '07, after a theory error was corrected

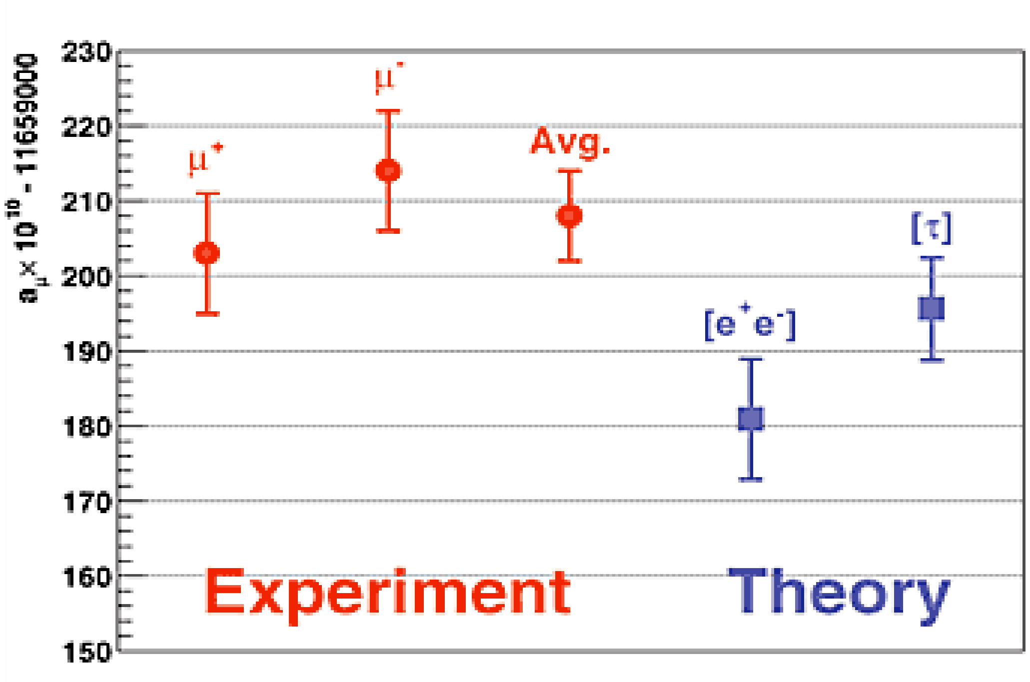
$$a(\text{hadron}) = 1.671\,(19) \times 10^{-12}$$
$$a(\text{weak}) = 0.030\,(01) \times 10^{-12}$$



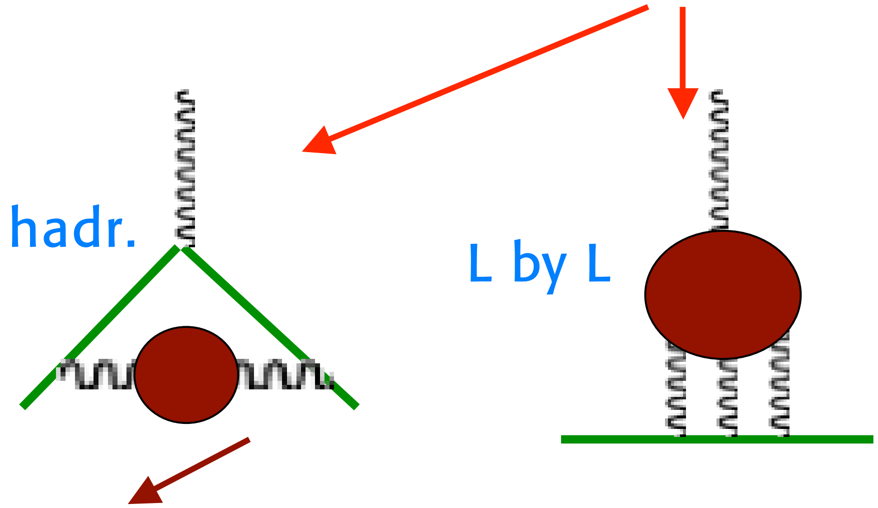


Muon g-2: more sensitive to new physics by $(m_\mu/m_e)^2 \sim 2\ 10^4$

BNL '04-'06: $a_\mu = (11659208.0 \pm 6.3)\ 10^{-10}$



$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}$$



$$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds\, \frac{R(s)\,K(s)}{s^2},$$

$$R(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

From the latest value of a_e (G. Gabrielse et al., 2006):
$\alpha^{-1} = 137.035999710(96)$,
$a_\mu^{\mathrm{QED}} = (116584718.09 \pm 0.14 \pm 0.08) \cdot 10^{-11}$.

Eidelmann, ICHEP'06

Contribution	$a_\mu, 10^{-10}$
Experiment	11659208.0 ± 6.3
QED	11658471.94 ± 0.14
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.5 ± 5.6
Exp.–Theory	27.5 ± 8.4 (3.3σ)

Mostly VP-LO
VP-NLO = -9.8±0.1
LbyL = 12.0±3.5

Knecht, Nyffeler'02
Melnikov, Veinshtein'04
Davier, Marciano '04

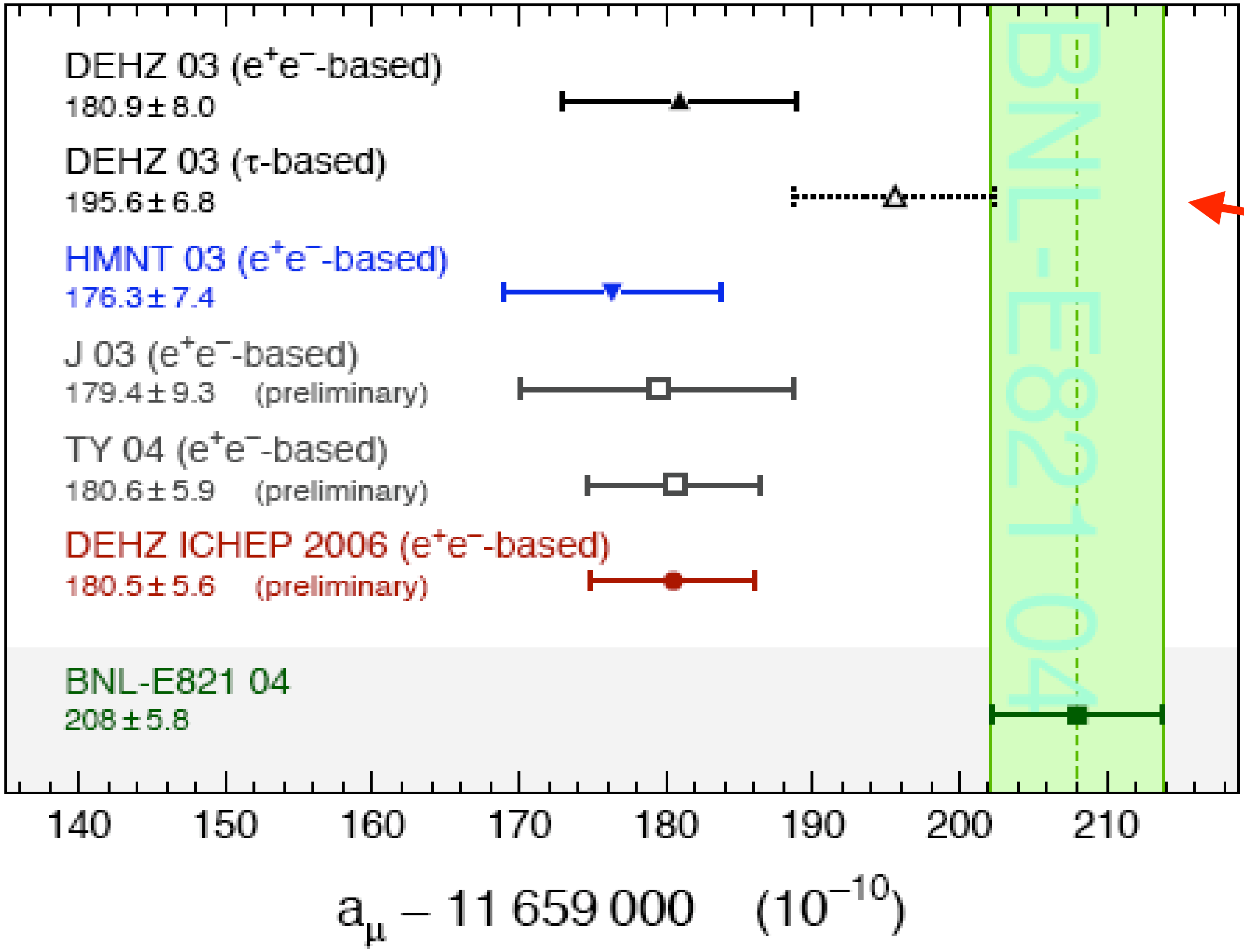
From e+e- data: ~3.3 σ

Observed Difference with Experiment:

$$a_\mu^{exp} - a_\mu^{SM} = (27.5 \pm 8.4) \times 10^{-10}$$

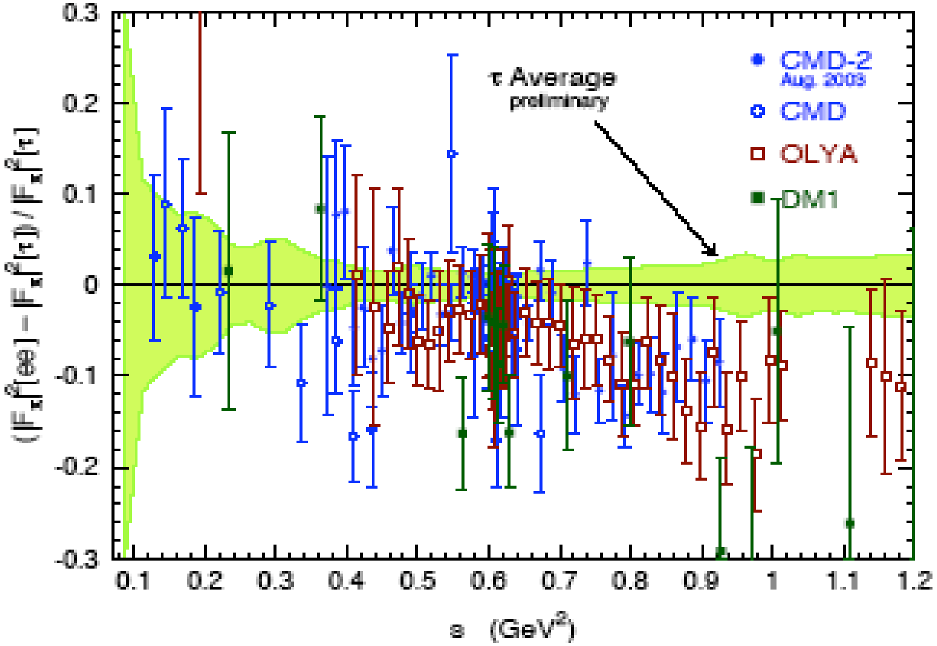
➡ 3.3 "standard deviations"

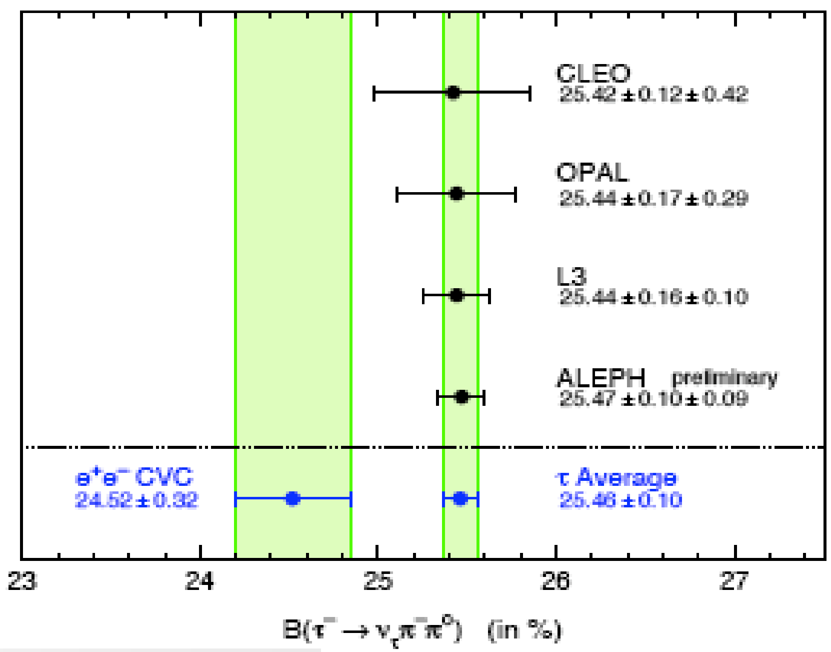
Davier/Hocker



Hadronic contr. from data.
τ vs e+e- discrepancy

CVC in the 2π Channel. e^+e^- vs. τ





Difference: BR[τ] – BR[e^+e^- (CVC)]:

Mode	$\Delta(\tau - e^+e^-)$	"Sigma"
$\tau^- \to \pi^-\pi^0\nu_\tau$	$+0.92 \pm 0.21$	4.5
$\tau^- \to \pi^-3\pi^0\nu_\tau$	-0.08 ± 0.11	0.7
$\tau^- \to 2\pi^-\pi^+\pi^0\nu_\tau$	$+0.91 \pm 0.25$	3.6

e^+e^- data on $\pi^-\pi^+\pi^0\pi^0$ not satisfactory

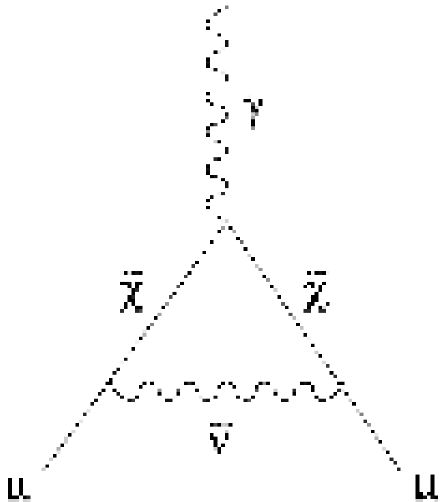
Observed Difference with Experiment:

$$a_\mu^{\exp} - a_\mu^{SM} = (27.5 \pm 8.4) \times 10^{-10}$$

➡ 3.3 "standard deviations"

Could be new physics
eg light SUSY

$$\delta a_\mu = 13 \cdot 10^{-10} \left(\frac{100 GeV}{M_{SUSY}} \right)^2 tg\beta$$



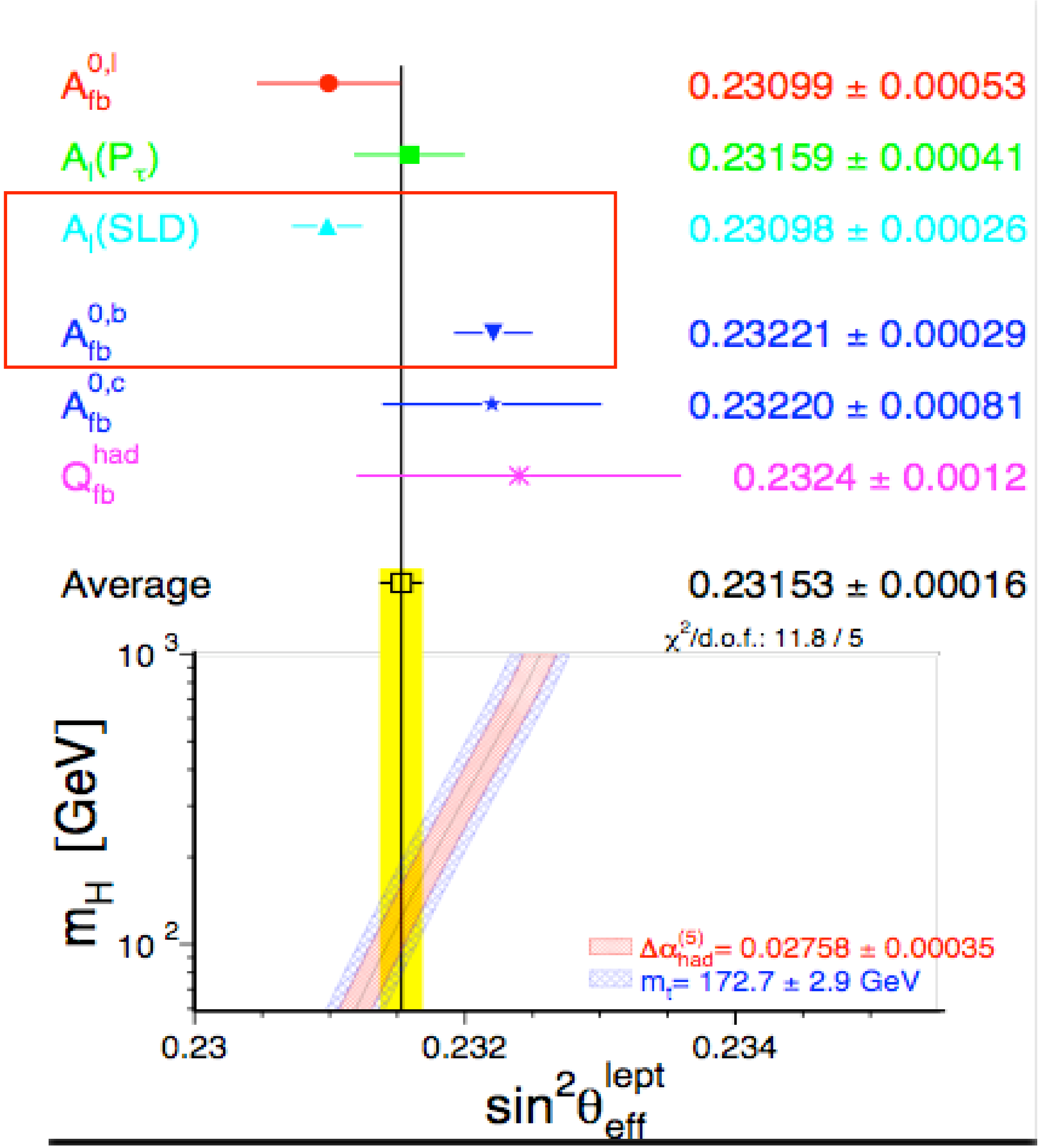
a_μ is a plausible
location for a
new physics signal!!

But the e-τ discrepancy is not understood:
theoretical errors underestimated?

$\sin^2\theta_W$

The two most precise measurements do not really match!

This unfortunate fact makes the interpretation of precision tests less sharp.

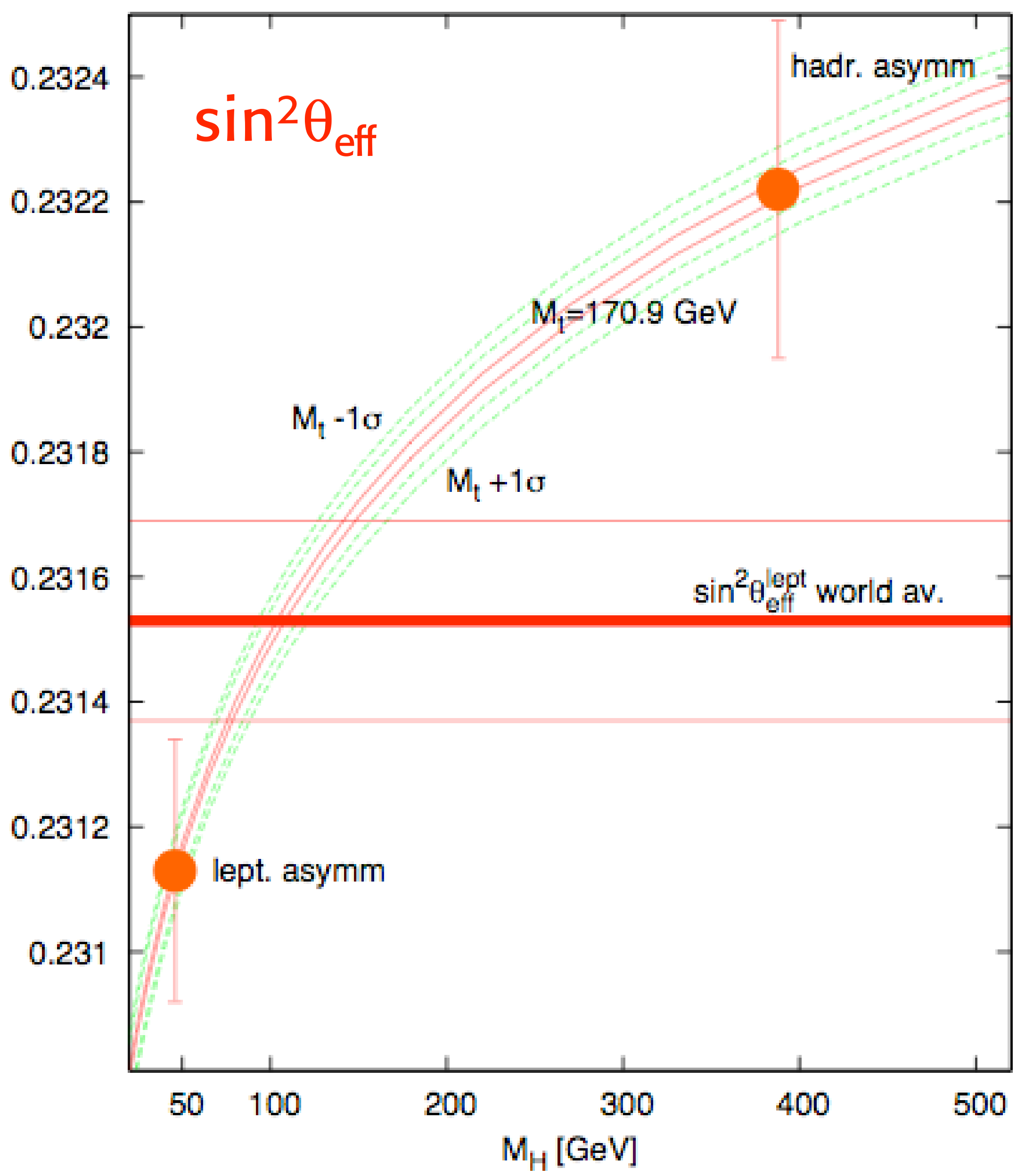


Plot $\sin^2\theta_{eff}$ vs m_H

P. Gambino

Exp. values are plotted at the m_H point that better fits given m_{texp}

Clearly leptonic and hadronic asymm.s push m_H towards different values



A^b_{FB} vs $[\sin^2\theta]_{lept}$: New physics in Zbb vertex?

After all the 3rd generation is somewhat special

The difficulty is that:

- No deviations are seen in A_b (SLD) and R_b
- A quite large shift in g_R, the Zbb right-handed coupling is needed (by ~30%: a tree level effect)

$$A^b_{FB} = \frac{3}{4} A_e A_b \qquad A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}$$

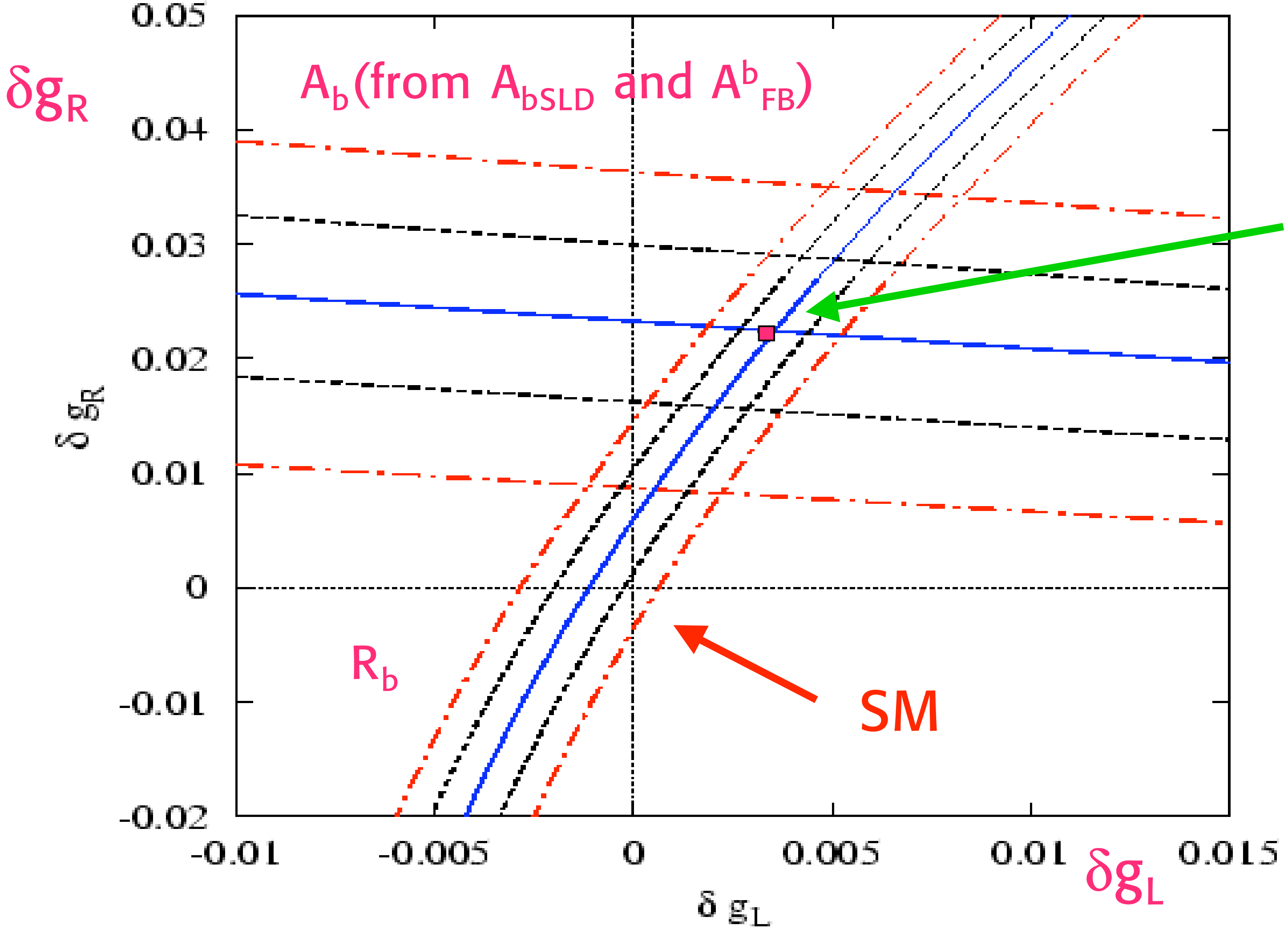
SM: $g_L^2 \approx 0.72 >> g_R^2 \approx 0.02$ $\qquad (A_b)_{SM} \approx 0.936$

from A^b_{FB} → $(A_b)_{SM} - A_b = 0.055 \pm 0.018$ -> ~3 σ

But note: $(A_b)_{SLD} = 0.923 \pm 0.020$, $\qquad R_b \sim g_L^2 + g_R^2$

also $R_b = 0.21629 \pm 0.00066$ ($R_{bSM} \sim 0.2157$)

Choudhury, Tait, Wagner '01



0.992 g_L(SM), 1.26 g_R(SM)

Too large for a loop effect. Needs a ad hoc tree level effect

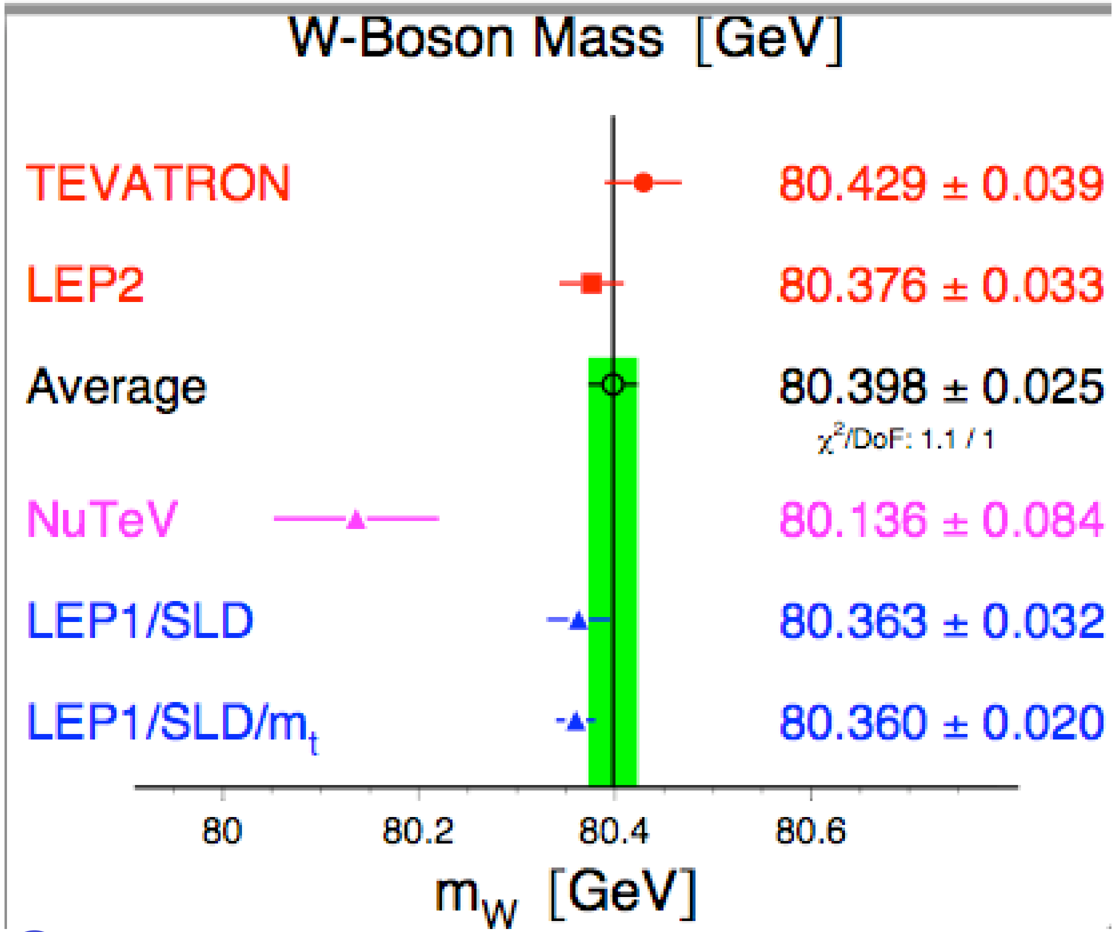
Mixing of the b quark with a vectorlike doublet (ω,χ) with charges (2/3, -1/3) or (-1/3, -4/3)? CTW'01

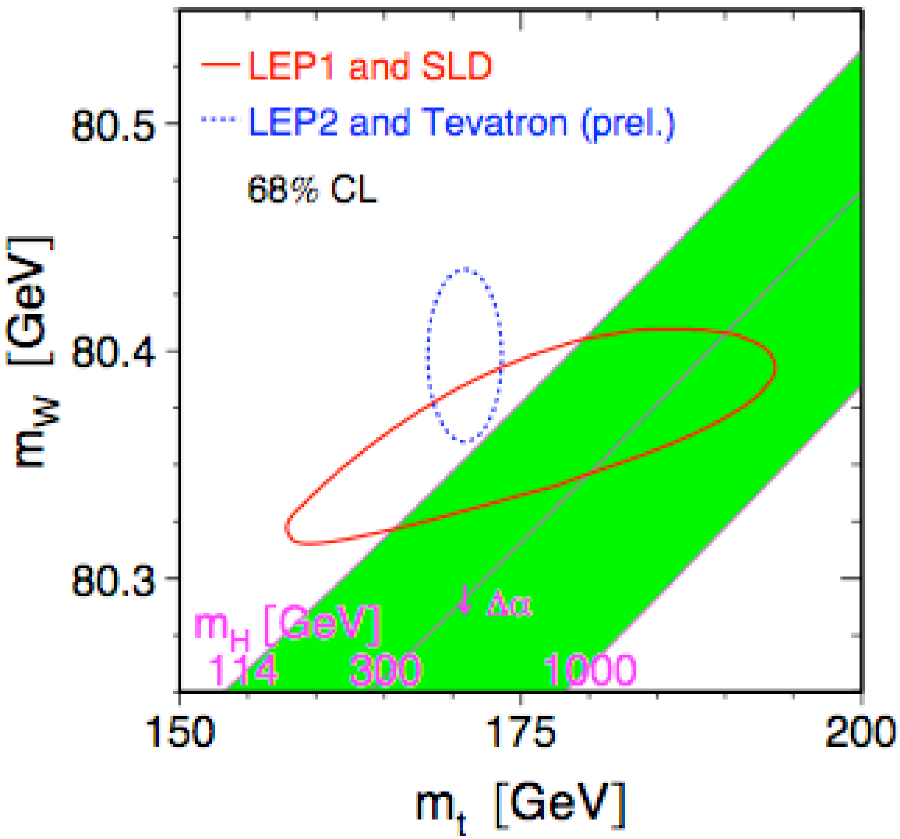
Or mixing of Z with Z' and KK recurrences in extra dim models? Agashe, Contino, Pomarol '06; Djouadi, Moreau, Richard '06

- The measured value of m_W is a bit high (given m_t)

(now came a little bit down from 80.420 -> 80.398)

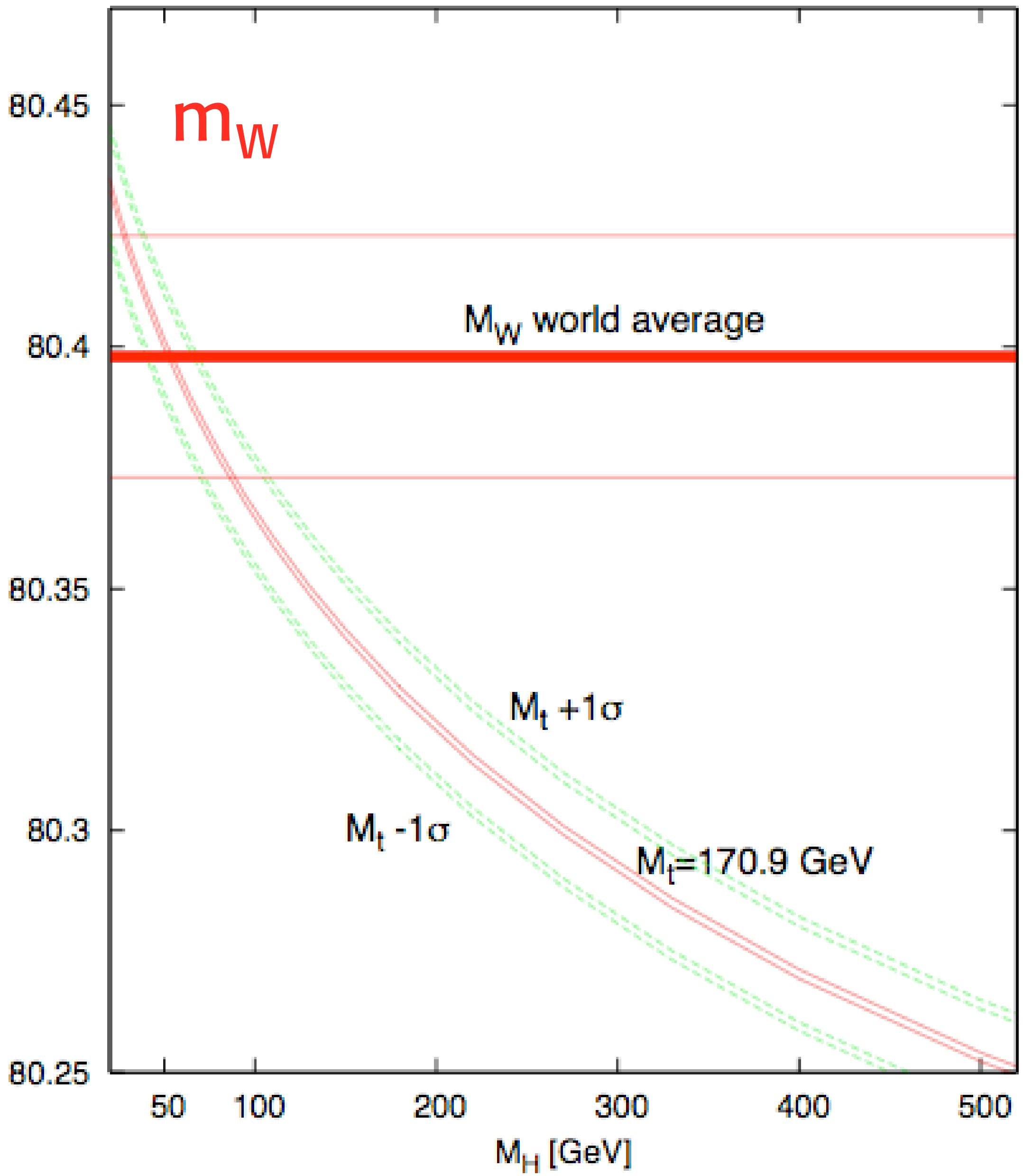
Winter '07





Plot m_W vs m_H

P. Gambino



m_W points to a light Higgs!

Like $[\sin^2\theta_{eff}]_l$

Fit results

Here only m_W and not m_t is used: shows m_t from rad. corr.s

Winter '07

	only m_W	only m_t	m_W, m_t
m_t(GeV)	178.9+12-9	170.9±1.8	171.3±1.7
m_H(GeV)	145+240-81	99+52-35	76+33-24
log[m_H(GeV)]	2.16±0.39	2.00 ± 0.19	1.88± 0.16
$\alpha_s(m_Z)$	0.1190(28)	0.1189 (27)	0.1185 (26)
χ^2/dof	17.4/12	16.0/11	18.2/13
m_W(MeV)	80385(19)	80360(20)	80374(15)

WA: m_W=80398(25)

Rad. corr.'s predict m_t and m_W very well. May be also m_H!

Status of the SM Higgs fit

Winter '07

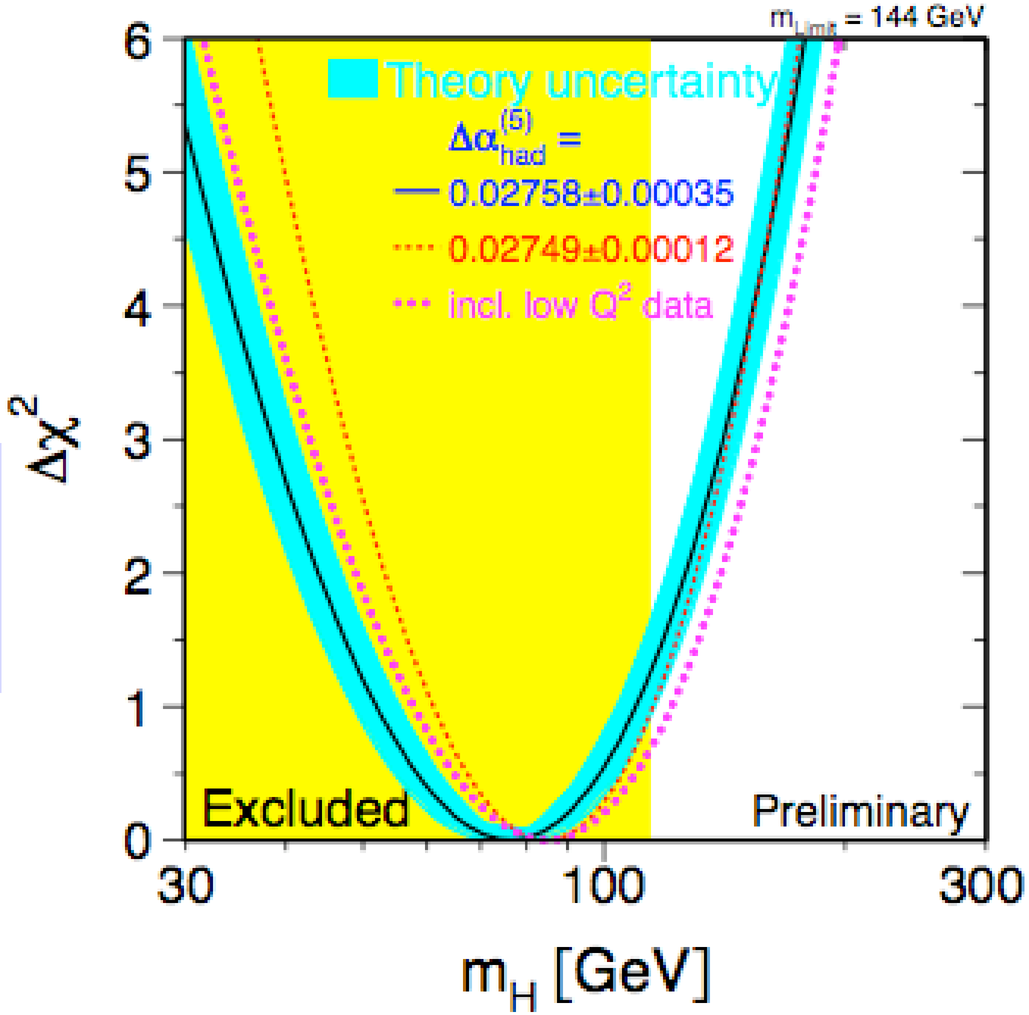
Sensitive to log m_H

Rad Corr.s ->

$\log_{10} m_H(\text{GeV}) = 1.88 \pm 0.16$

This is a great triumph for the SM: ~right in the narrow allowed range $\log_{10} m_H$ ~2 - 3

Direct search: $m_H > 114.4$ GeV



At 95% cl

$m_H < 144$ GeV (rad corr.'s)

$m_H < 182$ GeV (incl. direct search bound)

$\log_{10} m_H \sim 2$ is a very important result!!

Drop H from SM -> renorm. lost -> divergences -> cut-off Λ

$$\log m_H \to \log\Lambda + \text{const}$$

Any alternative mechanism amounts to identify the physics of Λ and the prediction of finite terms.

The most sensitive to $\log m_H$ are $\varepsilon_1 \sim \Delta\rho$ and ε_3 (or T&S):

$\log_{10} m_H \sim 2$ means that $f_{1,3}$ are compatible with the SM prediction

$$\varepsilon_1 = -\underbrace{\frac{3G_F m_W^2}{4\pi^2\sqrt{2}}\mathrm{tg}^2\theta_W}_{-1.2\ 10^{-3}}\left[\log\frac{m_H}{m_Z} + f_1\right]$$

New physics can change the bound on m_H (different $f_{1,2}$): well possible!

Some conspiracy is needed to simulate a light Higgs

$$\varepsilon_3 = \underbrace{\frac{G_F m_W^2}{12\pi^2\sqrt{2}}}_{0.45\ 10^{-3}}\left[\log\frac{m_H}{m_Z} + f_3\right]$$

Is it possible that the Higgs is not found at the LHC?

Looks pretty unlikely!!

The LHC range is large enough:
$m_H < \sim 1$ TeV
the Higgs should be really heavy!

Rad. corr's indicate a light Higgs (whatever its nature)

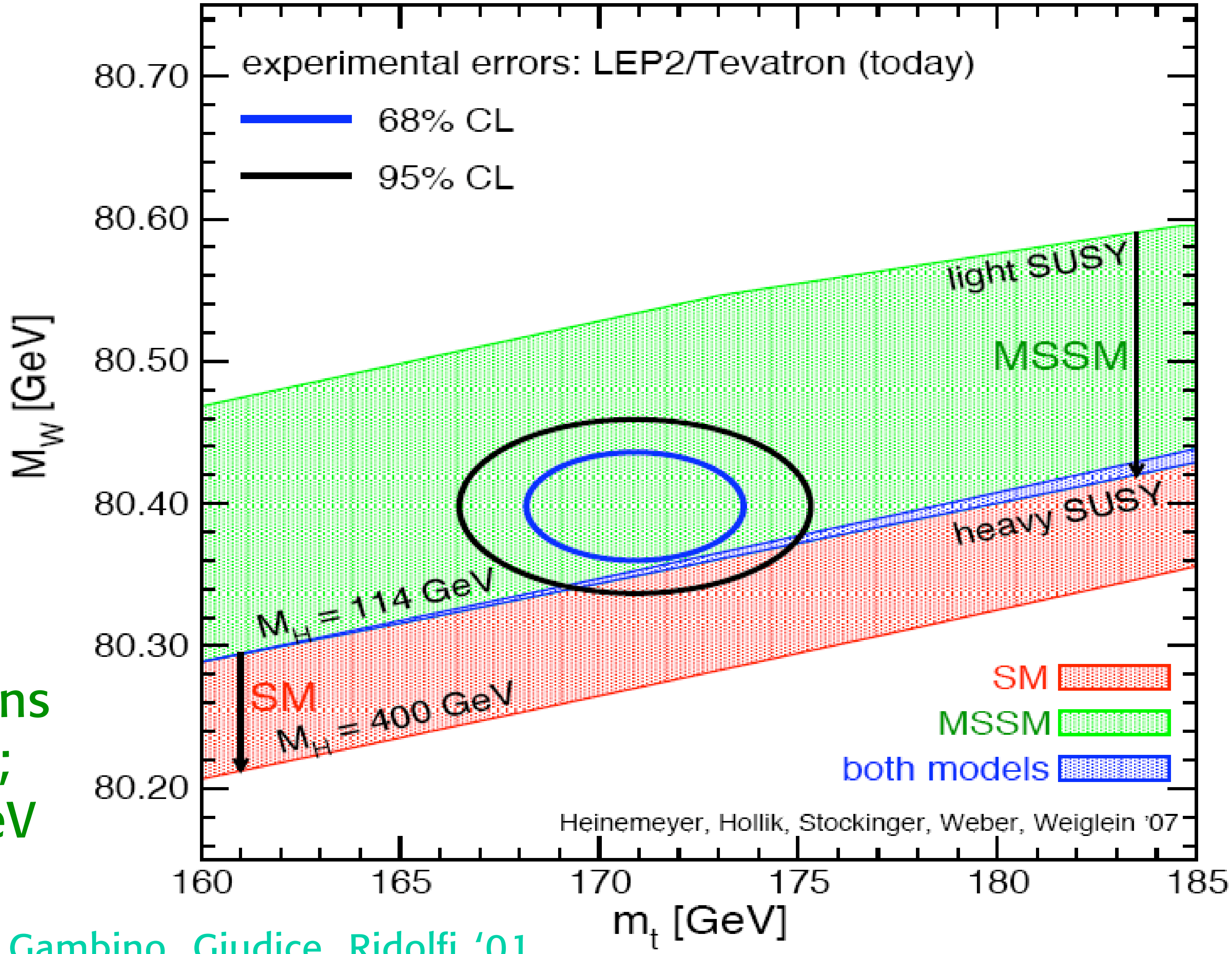
Such a heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > 0.8$ TeV)

e.g. strongly interacting WW or WZ scattering

Such nearby collapse of pert. th. is very difficult to reconcile with EW precision tests plus simulating a light Higgs

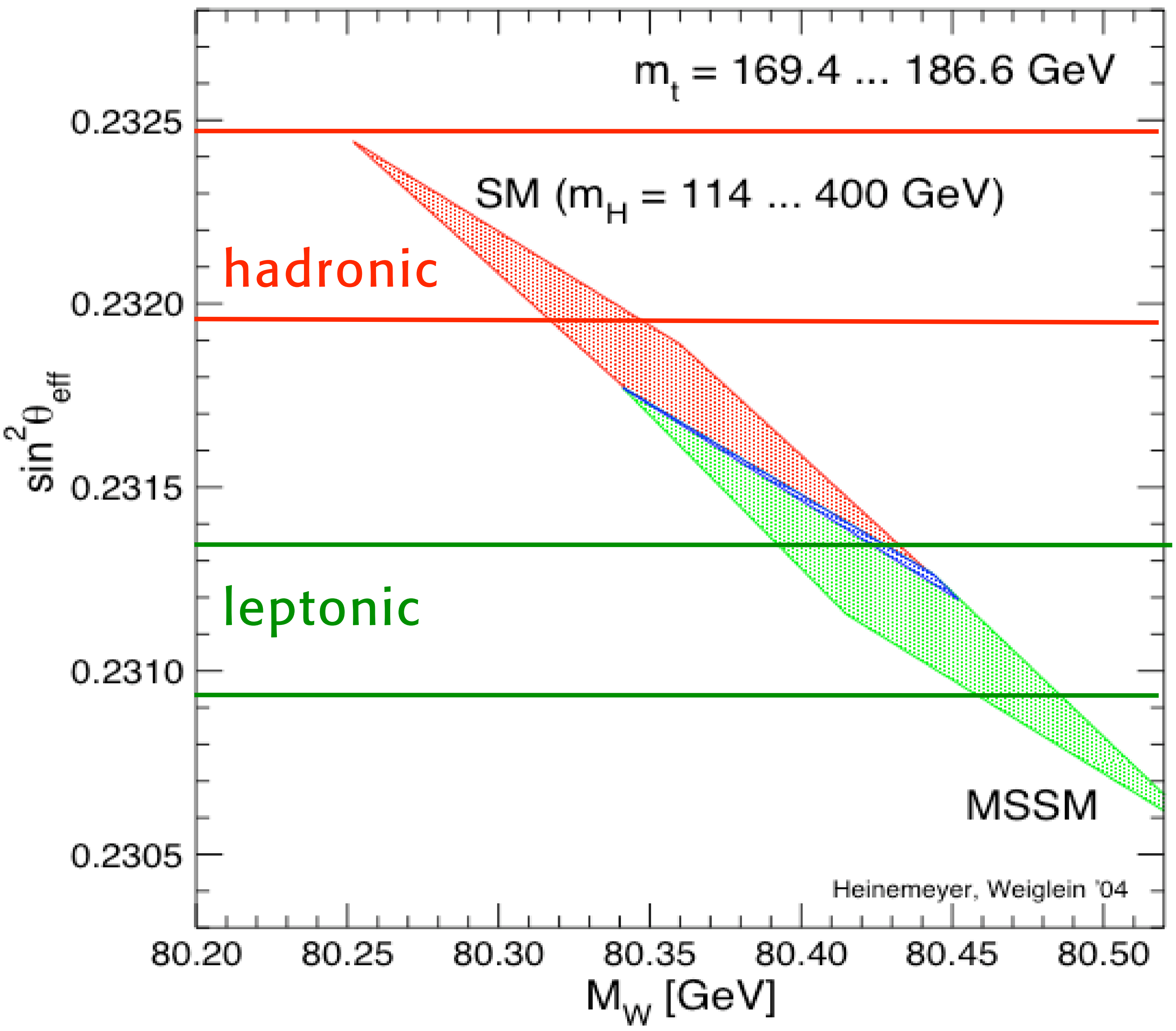
The SM perfect agreement with the data favours forms of new physics that keep at least some Higgs light

SUSY effects could modify the SM fit



"light SUSY"=
= light s-leptons
and charginos;
s-quarks ~1 TeV

G.A, Caravaglios, Gambino, Giudice, Ridolfi '01 sin²θ is unfortunately ambiguous



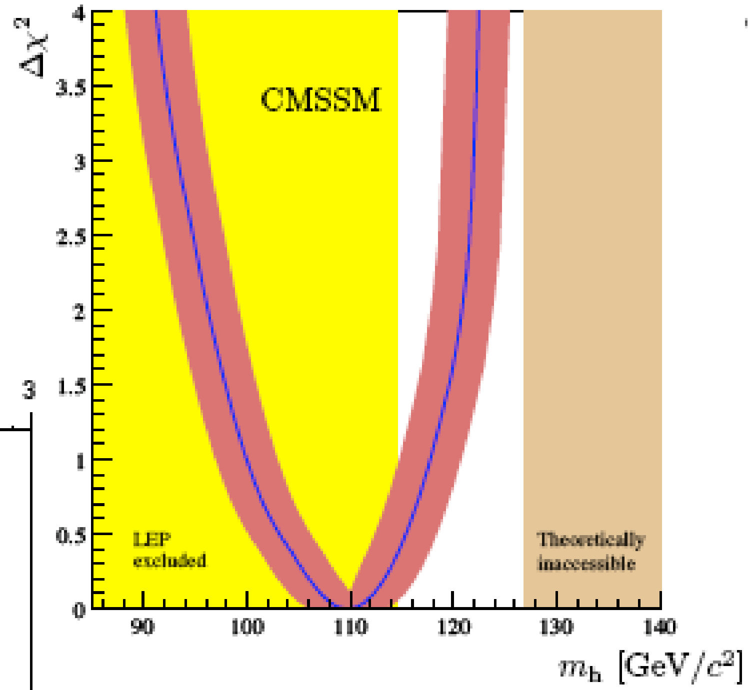
A recent study indicates that m_h goes up in CMSSM when b->sγ, a_μ, Ω_{DM} are added

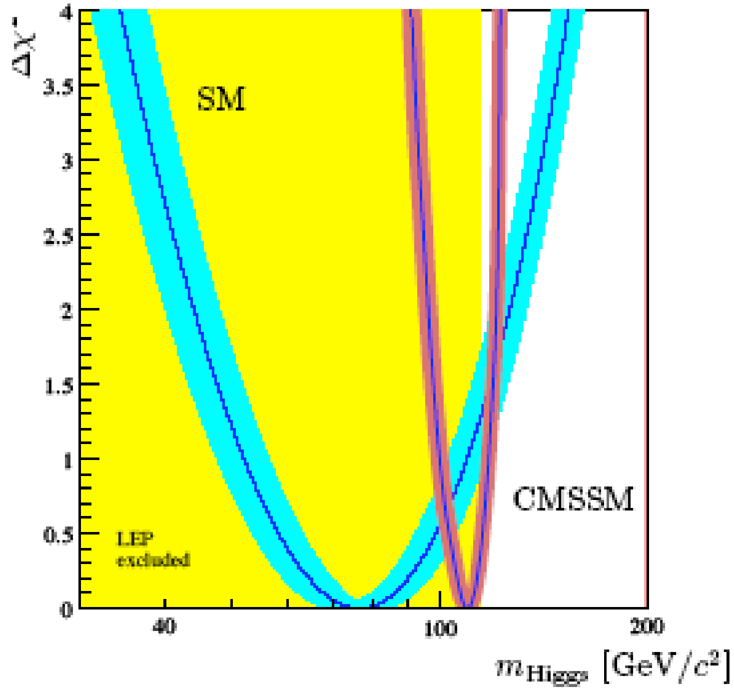
O. Buchmuller et al '07

also:
J. Ellis et al '07

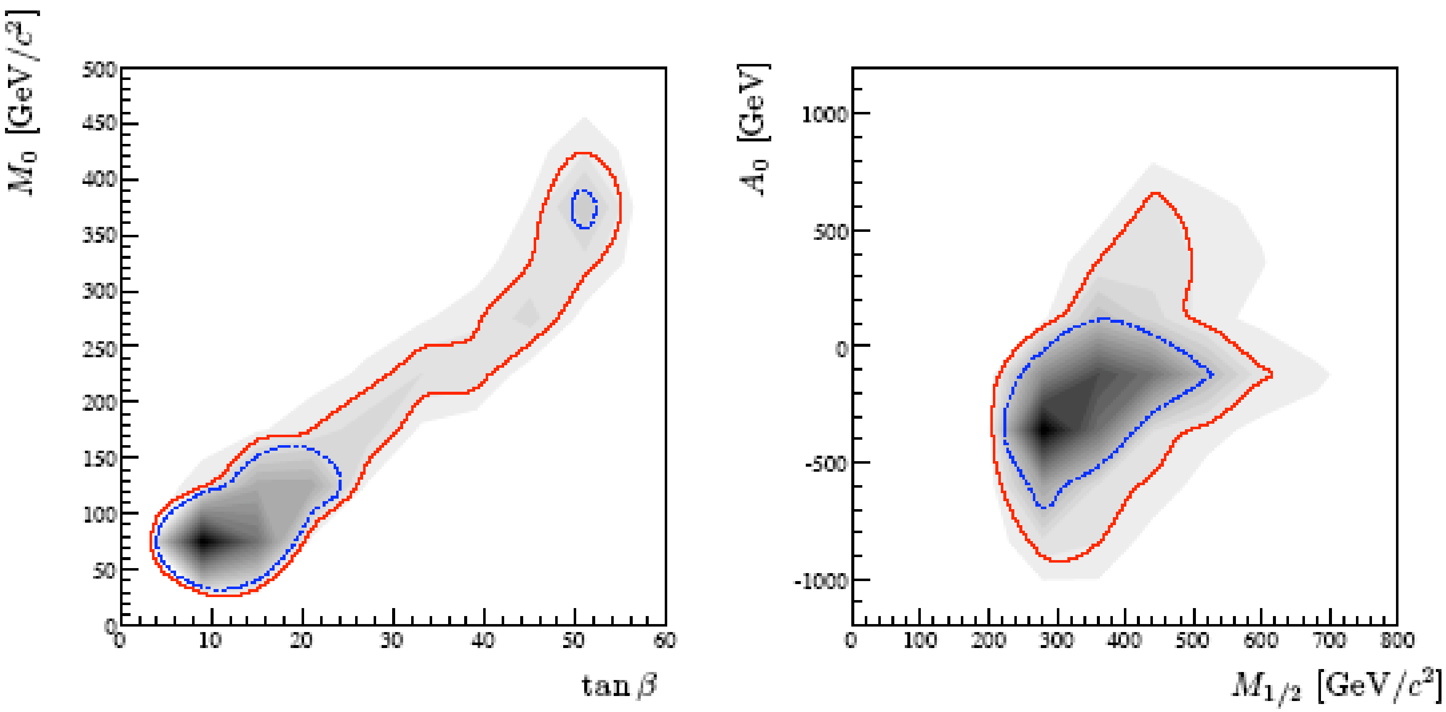
CMSSM

Variable	Measurement	Fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$ (0 1 2 3)
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758± 0.00035	0.02774	
m_Z [GeV]	91.1875± 0.0021	91.1873	
Γ_Z [GeV]	2.4952± 0.0023	2.4952	
σ^0_{had} [nb]	41.540± 0.037	41.486	
R_l	20.767± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465± 0.0032	0.1479	
R_b	0.21629± 0.00066	0.21613	
R_c	0.1721± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707± 0.0035	0.0741	
A_b	0.923± 0.020	0.935	
A_c	0.670± 0.027	0.668	
A_l(SLD)	0.1513± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324± 0.0012	0.2314	
m_W [GeV]	80.398± 0.025	80.382	
m_t [GeV]	170.9± 1.8	170.8	
$R(b\to s\gamma)$	1.13± 0.12	1.12	
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times 10^{-9}$]	2.95± 0.87	2.95	
Ωh^2	0.113± 0.009	0.113	





O. Buchmuller et al ’07



The Standard Model works very well

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

First, you have to find it!

→ LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- •••••

and experimental clues:

- Coupling unification
- Neutrino masses
- Baryogenesis
- Dark matter
- Vacuum energy
- •••••

$\boxed{\text{Some of these problems point at new physics at the weak scale: eg Hierarchy Dark matter}}$

With new physics at Λ the low en. th. is only an effective theory.
After integration of the heavy d.o.f.:

$\mathcal{L}_i$: operator of dim i

$$\mathcal{L} = \underbrace{o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4}_{\text{Renorm.ble part}} \quad \underbrace{+\, o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6}_{\text{Non renorm.ble part}} + \ldots$$

In absence of special symmetries or selection rules,
by dimensions $c_i\mathcal{L}_i \sim o(\Lambda^{4-i})\mathcal{L}_i$

$\mathcal{L}_2$: Boson masses ϕ^2. In the SM the mass in the Higgs potential is unprotected: $c_2 \sim o(\Lambda^2)$

$\mathcal{L}_3$: Fermion masses $\bar{\psi}\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \to m\log\Lambda$

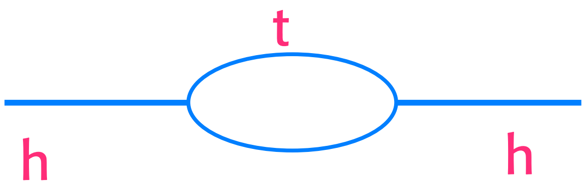
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$

$\mathcal{L}_{i>4}$: Non renorm.ble: suppressed by $1/\Lambda^{i-4}$ e.g. $1/\Lambda^2\bar{\psi}\gamma^\mu\psi\bar{\psi}\gamma^\mu\psi$

For the low energy theory: 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 so close but its effects were not visible at LEP

And also are not visible in flavour physics

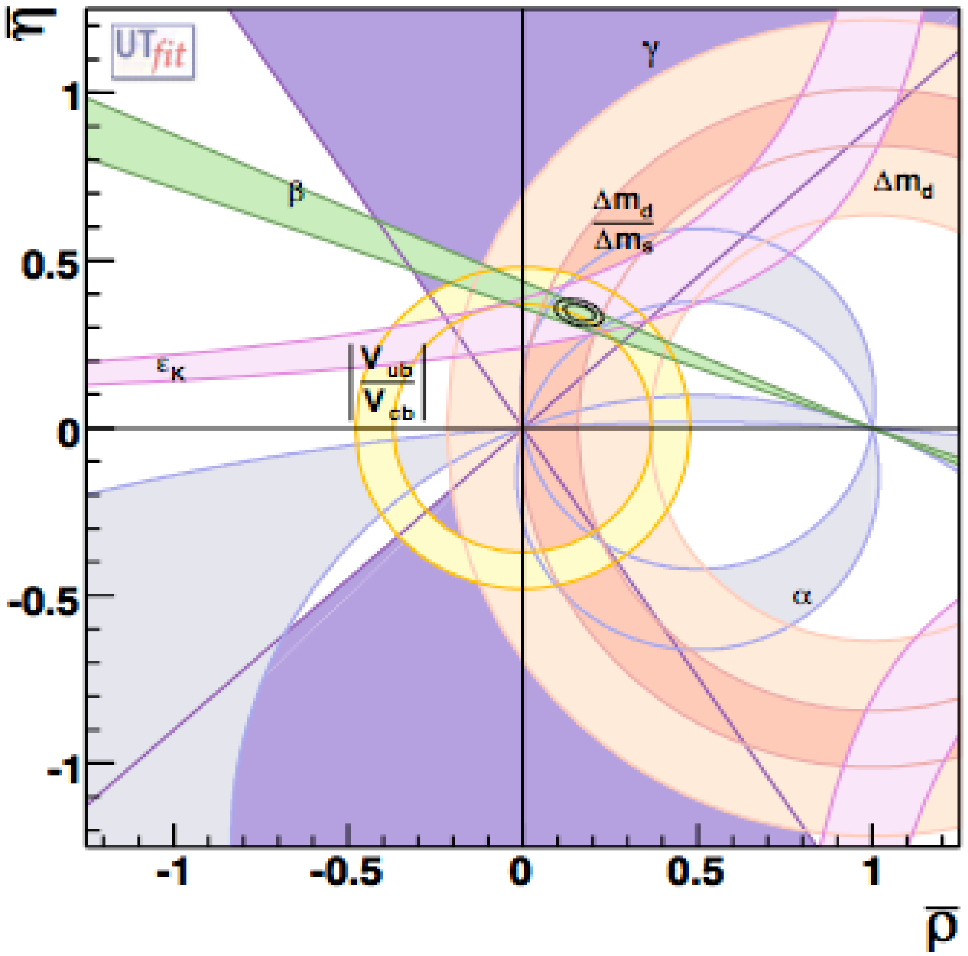
Precision Flavour Physics

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

- Light Higgs -> New physics at ~ few TeV
- But all effective non rinorm. vertices for FCNC have bounds above a few TeV

Apparently the SM suppression of FCNC and the CKM mechanism for CP violation is only mildly modified by new physics:
an intriguing mystery and a major challenge for models of new physics

The study of B decays (BaBar, Belle, CDF...) has revealed no signs of new physics



The LHCb experiment at the LHC will go further in this direction

Adding effective operators to SM generally leads to very large Λ

$$M(\mathrm{B_d}\text{-}\overline{\mathrm{B}}_\mathrm{d}) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\,\frac{1}{\Lambda^2}$$

Isidori

c_{NP}:

- $\sim 1 \xrightarrow{\text{tree / strong + generic flavour}} \Lambda \gtrsim 2{\times}10^4$ TeV [K]
- $\sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2{\times}10^3$ TeV [K]
- $\sim (y_t V_{ti}{}^* V_{tj})^2 \xrightarrow{\text{tree / strong + MFV}} \Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5$ TeV [K & B]

But the hierarchy problem demands Λ in the few TeV range

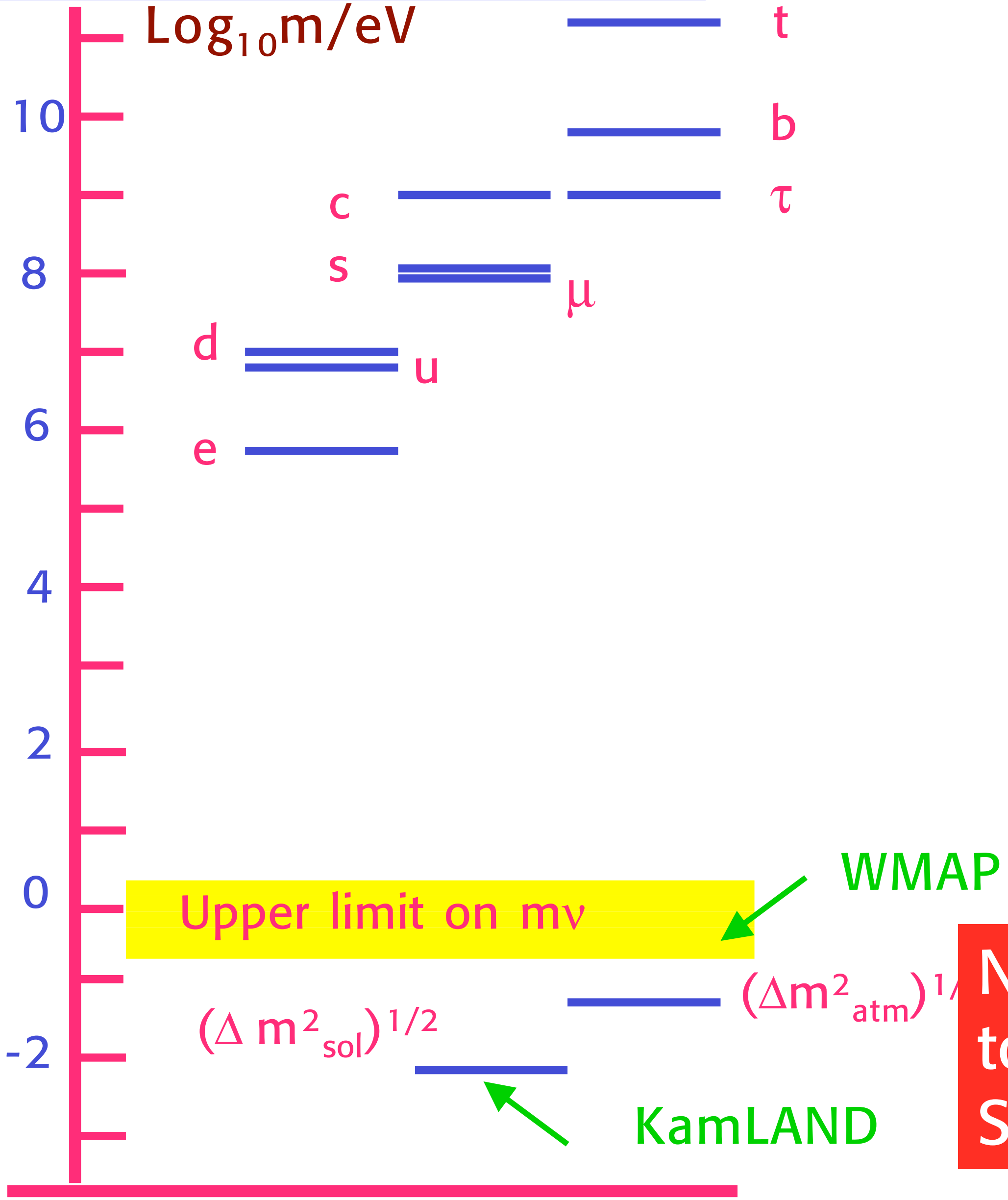
only assuming $c_{NP} \sim (y_t V_{tb}{}^* V_{td})^2$ (or anyway small)

we get a bound on Λ in the TeV range

eg in Minimal Flavour Violation (MFV) models

D'Ambrosio, Giudice, Isidori, Strumia'02

ν masses and mixings are new flavour physics!



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Neutrino masses point to M_{GUT}, well fit into the SUSY picture and in GUT's

See-Saw Mechanism

Minkowski; Yanagida;
Gell-Mann, Ramond , Slansky;
Glashow; Mohapatra, Senjanovic…..

$M\nu^T{}_R\nu_R$ allowed by SU(2)xU(1)

Large Majorana mass M (as large as the cut-off)

$m_D\bar{\nu}_L\nu_R$

Dirac mass m from Higgs doublet(s)

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & m_D \\ \nu_R & m_D & M \end{array}$$

$M \gg m_D$

Eigenvalues

$$\nu_{light} = \frac{-m_D^2}{M}, \quad \nu_{heavy} = M$$

sign conventional
for fermions

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m: \leq m_t \sim v \sim 200$ GeV

M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV

$m \sim v \sim 200$ GeV

$M \sim 10^{14} - 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

A signal in $0\nu\beta\beta$ would be an essential confirmation

Conclusion

Goals of LHC and the SM

- Complete the SM: clarify the Higgs sector
- Probe the limitations of the SM and search for new physics (dark matter?)