WHEPP, 3 January '06

2006: Particle Physics in the SM and beyond

G. Altarelli

CERN

The Standard Model

$$\underbrace{SU(3)}_{\text{Strong}} \otimes \underbrace{SU(2) \otimes U(1)}_{\text{Electroweak}}$$

add classical gravity (general relativity) to describe 99% of measurable phenomena

SU(3) colour symmetry is exact!

The EW symmetry is spont. broken down to $U(1)_Q$

Higgs sector (???)

Gauge Bosons

8 gluons g^A

$W^{\pm}, Z, \gamma$

Matter fields: 3 generations of quarks (coloured) and leptons

$$\begin{bmatrix} u & u & u & \nu \\ d & d & d & e \end{bmatrix}$$

+ 2 more replicas (???)

QCD

QCD stands as a very solid building block of the SM

The unbroken gauge symmetry of the SM is $SU(3)xU(1)_Q$

QCDxQED

For many years the field theory of reference was QED, now QCD is a more complex and intriguing framework

Due to asymptotic freedom, actually QCD is a better defined theory than QED

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
    ****

•QCD sum rules

•Potential models (quarkonium)

- Perturbative approach

Based on asymptotic freedom.

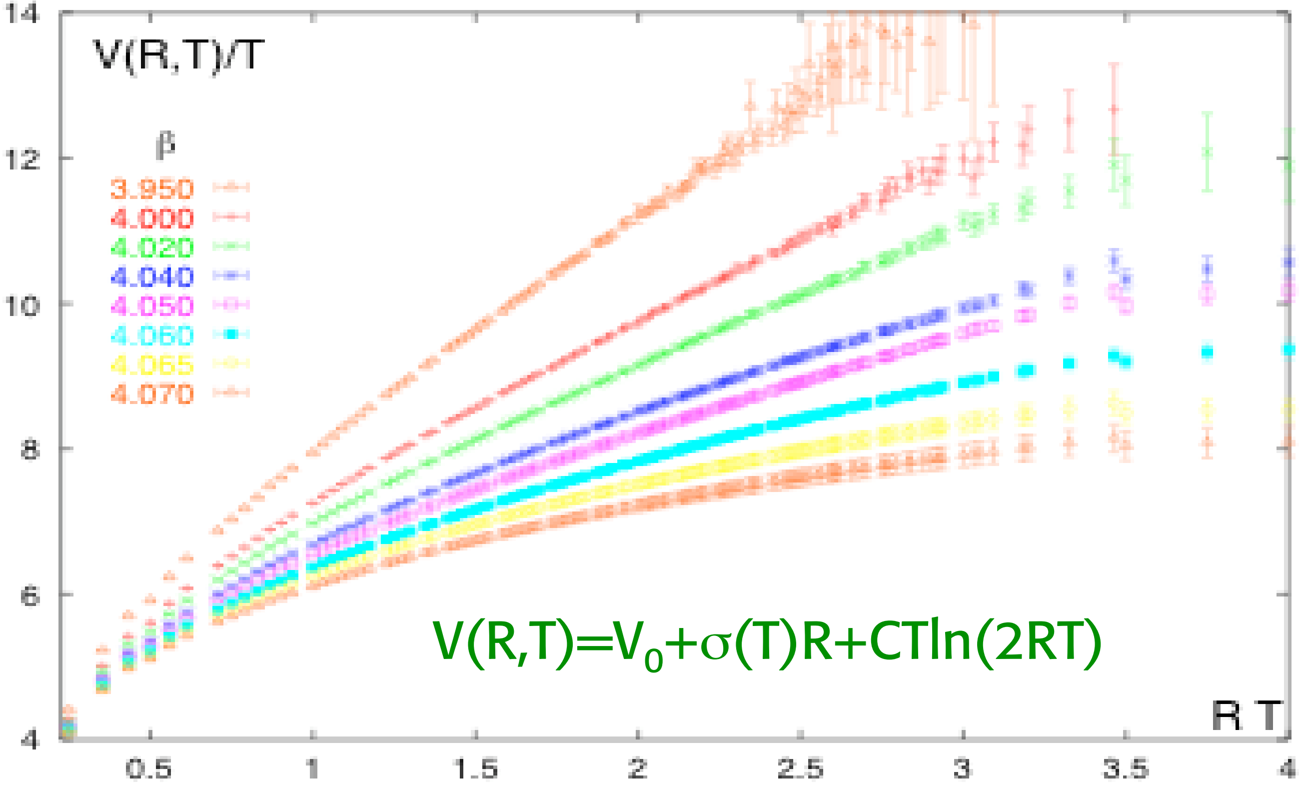
It still remains the main quantitative connection to experiment.

Confinement on the lattice

Potential between static quarks on the lattice

Kaczmarek, Karsch, Laermann, Lutgemeier ‘00

quenched approx.

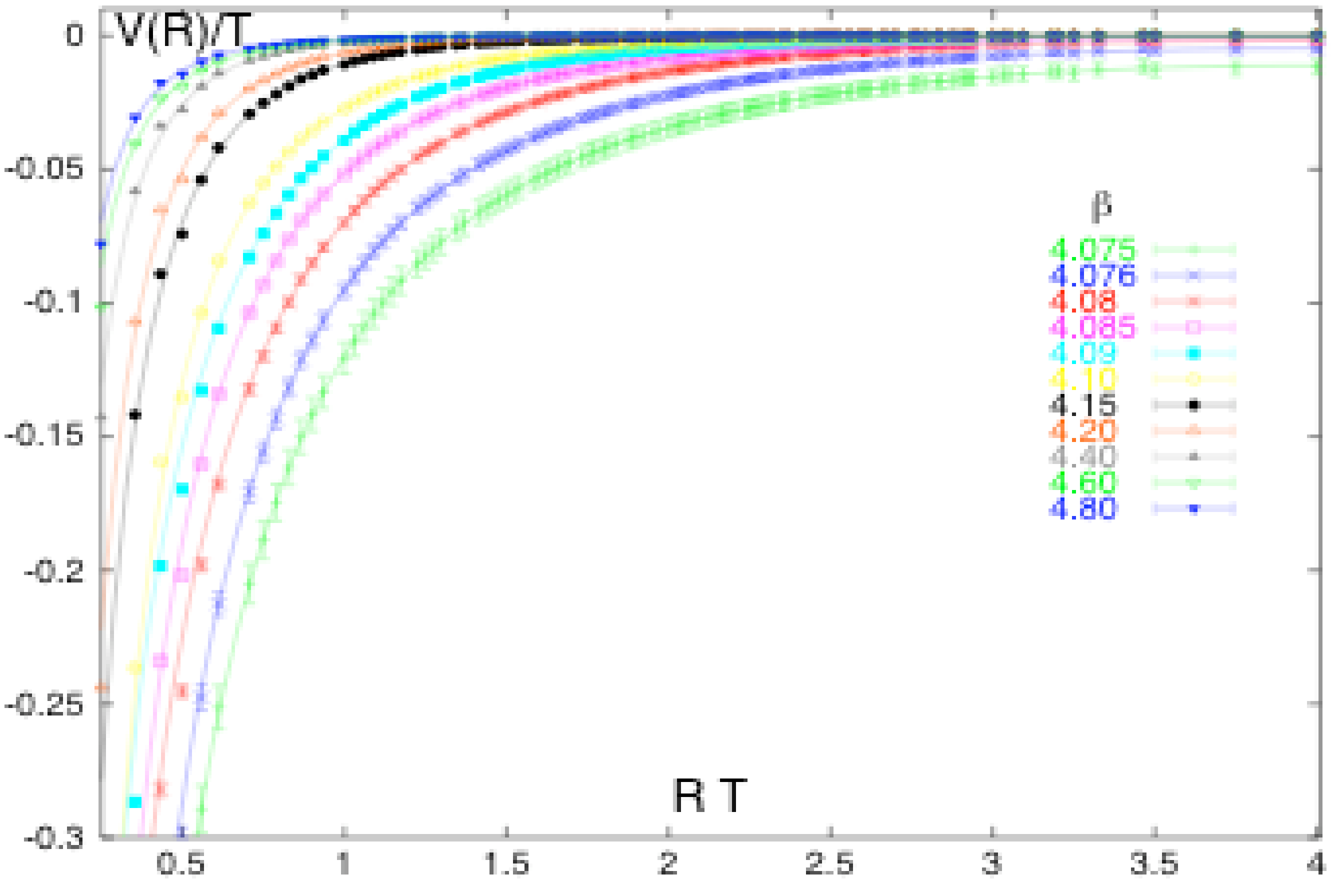


$V(R,T)=V_0+\sigma(T)R+CT\ln(2RT)$

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

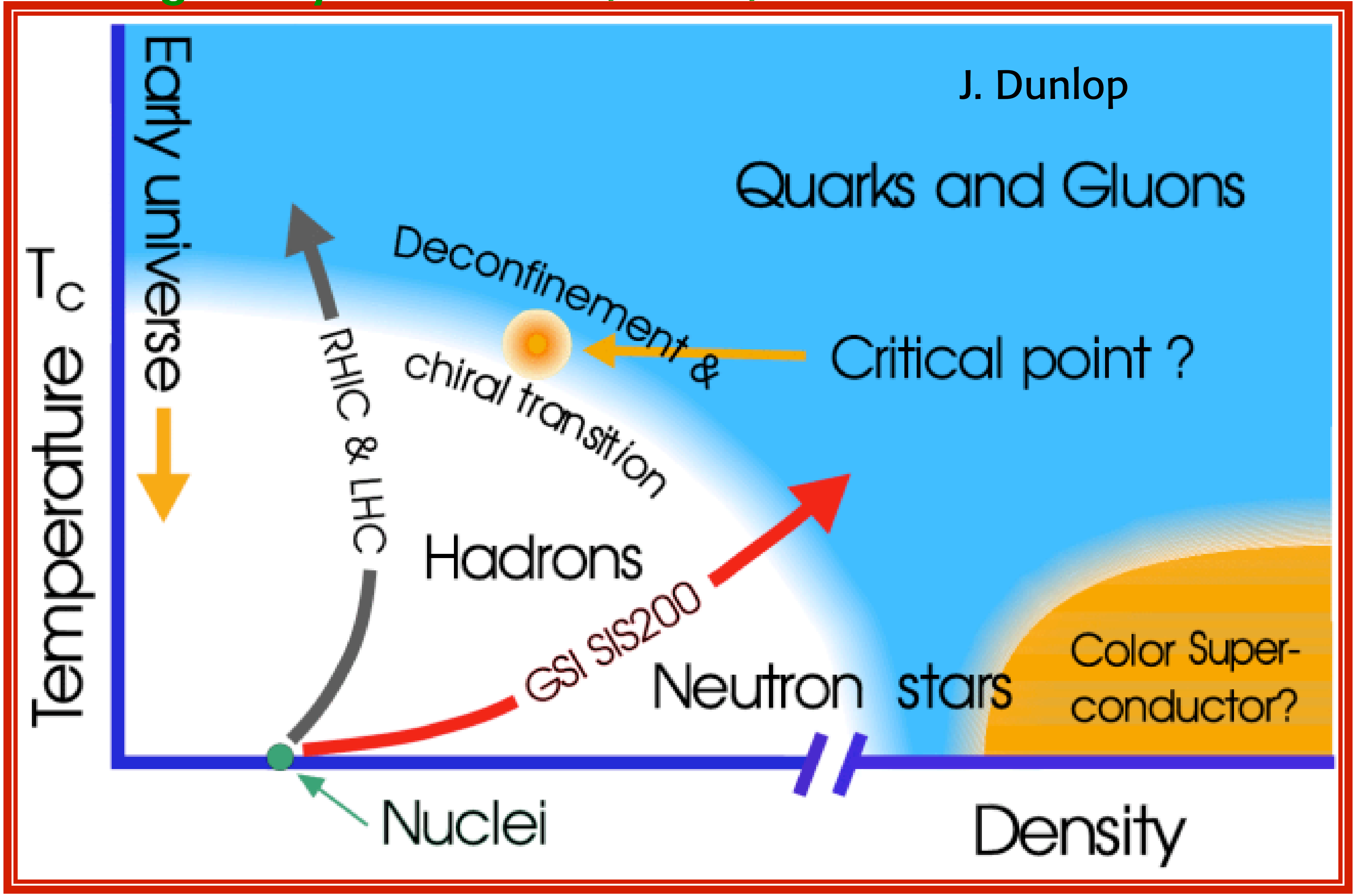
At $T > T_C$ the slope at large R remains zero



T_C depends on the number of quark flavours

The QCD phase diagram

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



2. Critical Behaviour in QCD

What happens to strongly interacting matter at high temperatures and/or densities?

- colour deconfinement

hadronic matter:

colourless constituents of hadronic dimension

⇓

quark-gluon plasma:

pointlike coloured constituents

- chiral symmetry restoration

hadronic matter:

quarks acquire effective mass $M_q \neq 0$

⇓

quark-gluon plasma:

$M_q \to m_q = 0$, chiral symmetry restored

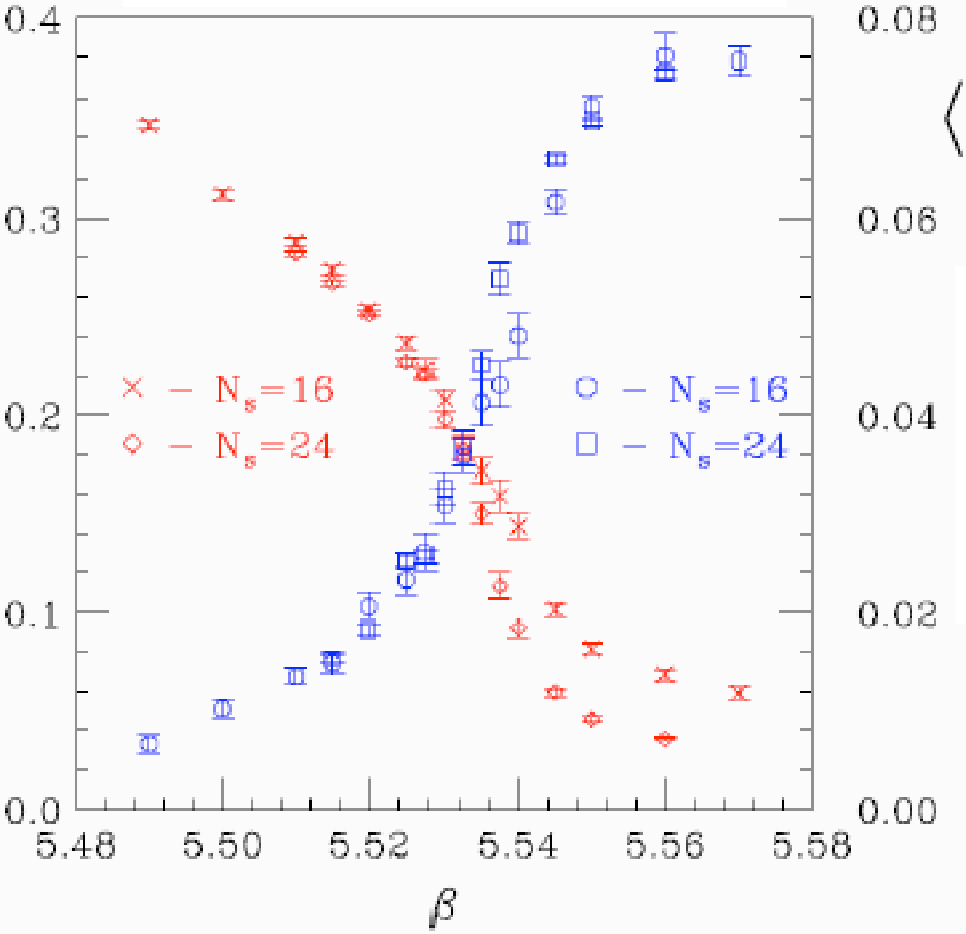
- colour superconductivity

deconfined quarks → coloured bosonic ‘diquarks’

diquark condensation → colour superconductor

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

$$\langle \bar{q} q \rangle$$



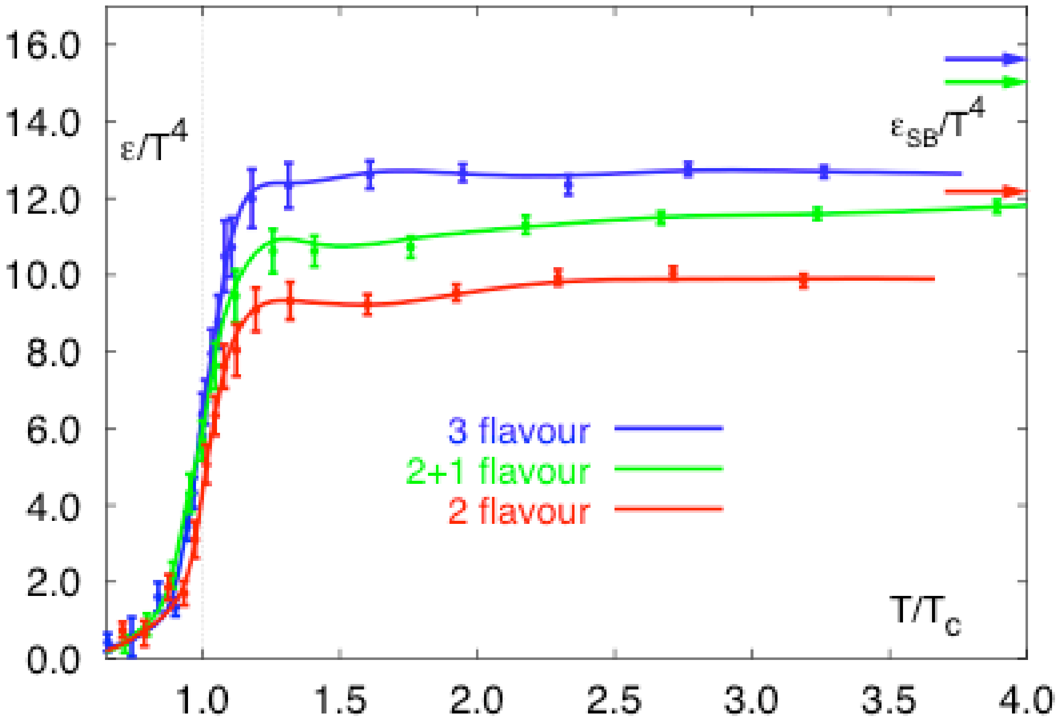
$$\langle L \rangle = \left\langle \mathrm{tr}\,\exp\left(i \int_0^{1/T} A_4\, d\tau\right) \right\rangle$$

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

N_f=2, χQCD

Kogut and Sinclair,
hep-lat/0408003

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

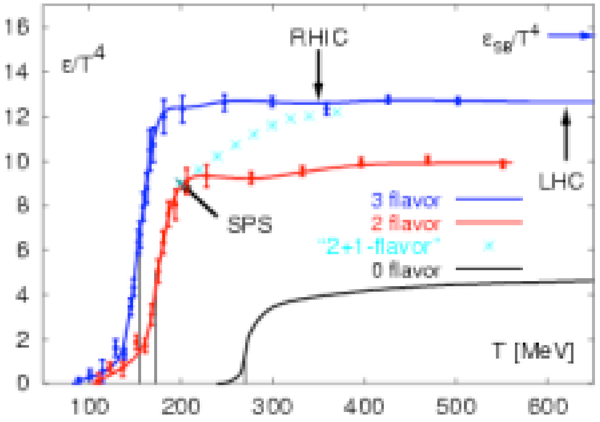


For $N_f = 2, 2+1$:

$$\boxed{\begin{array}{l} T_c \simeq \ 175 \text{ MeV} \\ \epsilon(T_c) \simeq 0.5 - 1.0 \text{ GeV/fm}^3 \end{array}}$$

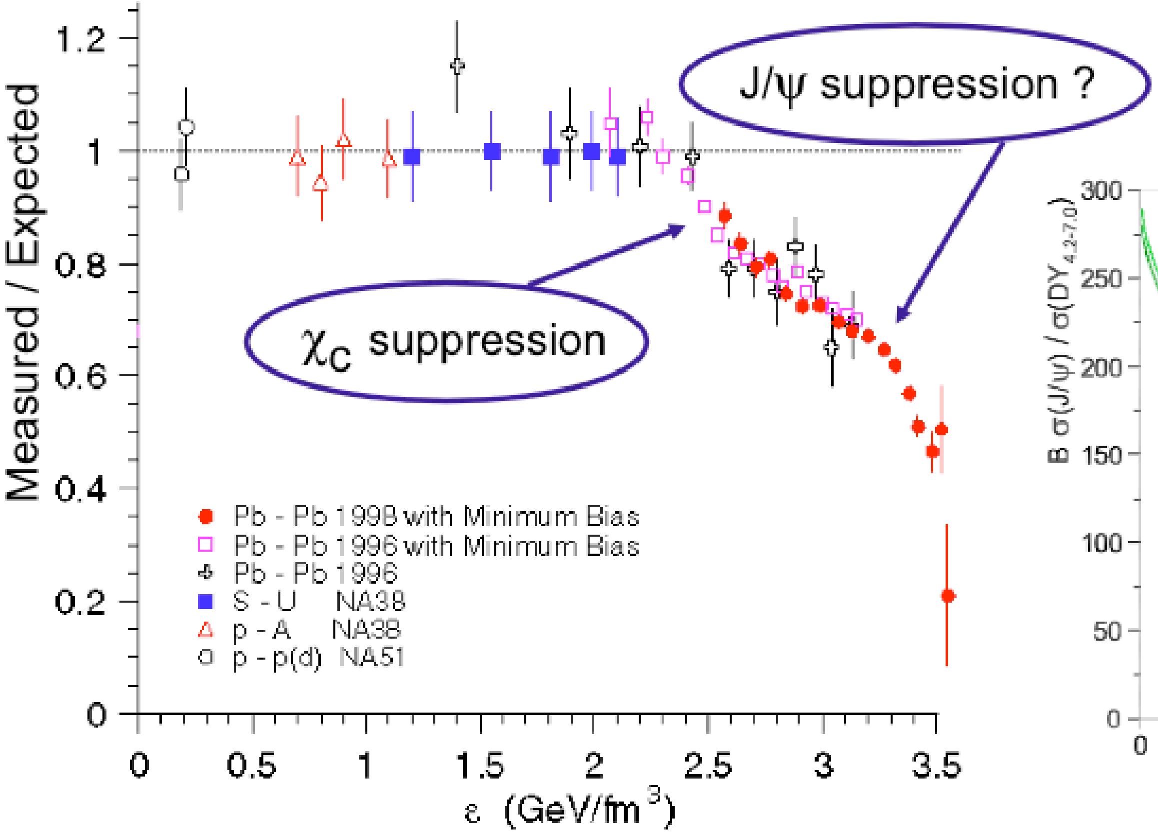
Experimental signals?   CERN

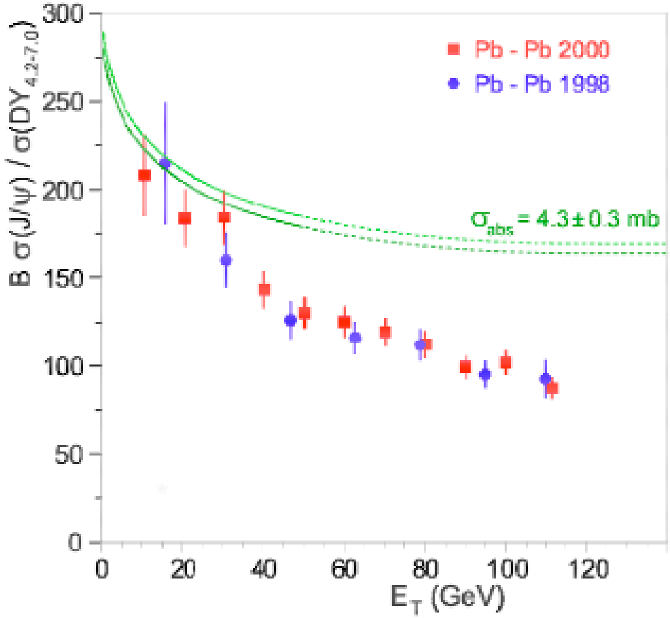
Apparently the SPS is well positioned to probe the transition region



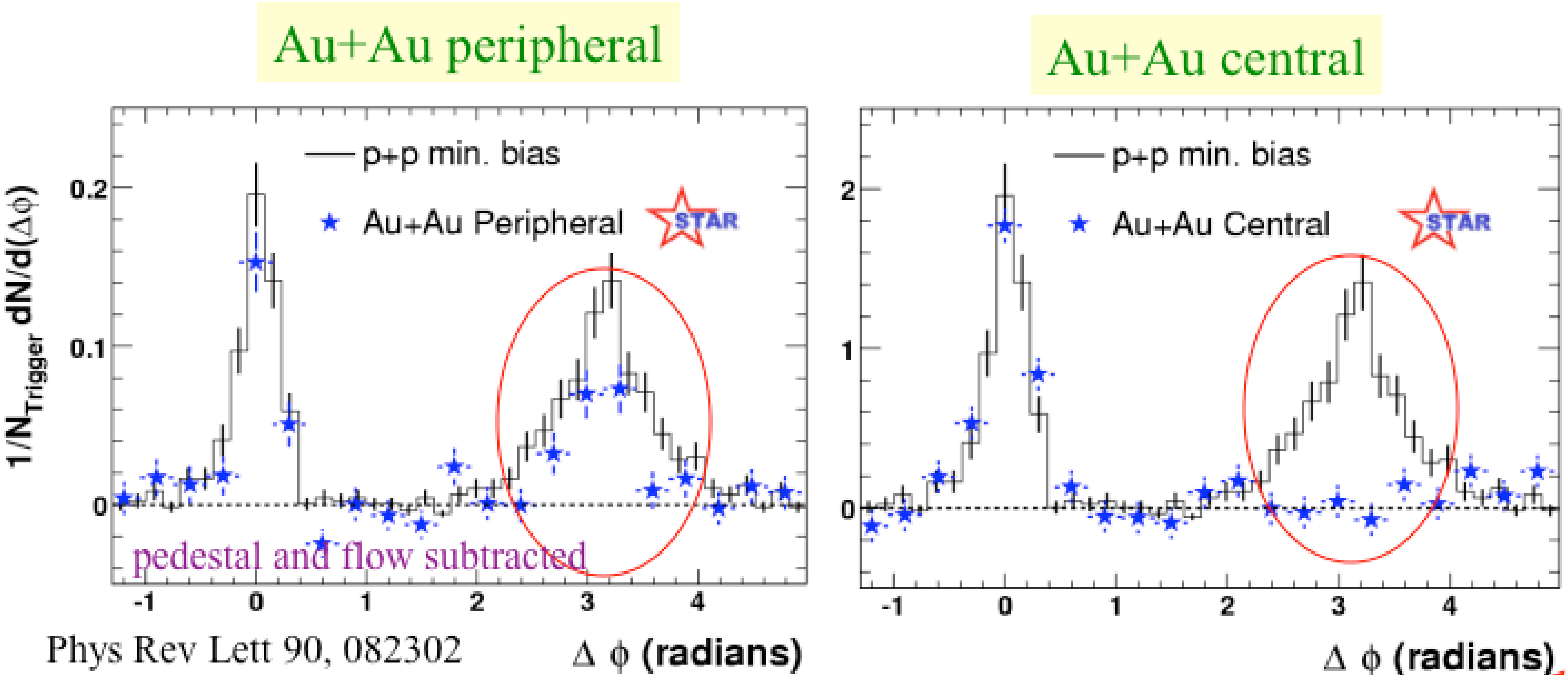
J/ψ suppression from p-A to Pb-Pb collisio

- 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

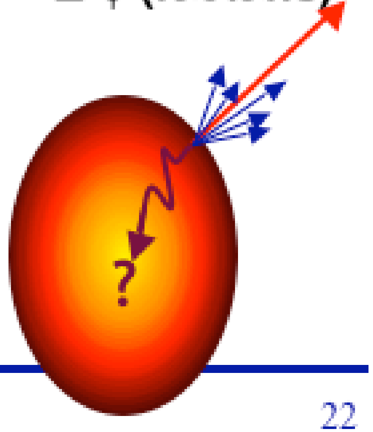




Azimuthal distributions in Au+Au



Phys Rev Lett 90, 082302



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

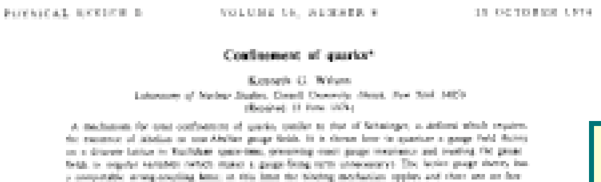
Strong suppression of back-to-back correlations in central Au+Au

The main tool for non perturbative QCD in continuous progress

Hashimoto, ICHEP'04

30 years of lattice QCD

K. Wilson (1974)



PHYSICAL REVIEW D VOLUME 10, NUMBER 8 15 OCTOBER 1974

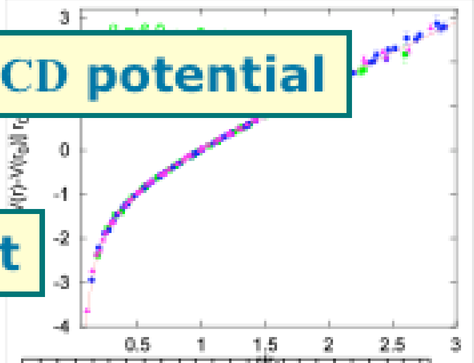
Confinement of quarks*

Kenneth G. Wilson

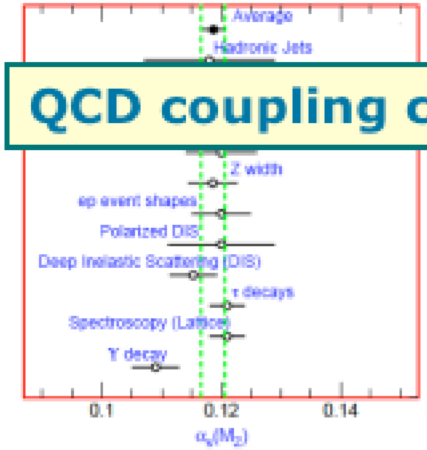
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

(Received 12 June 1974)

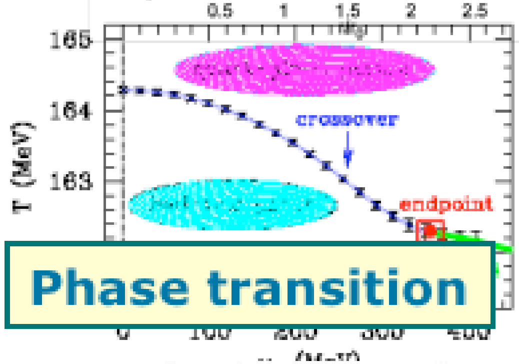
QCD potential



QCD coupling const

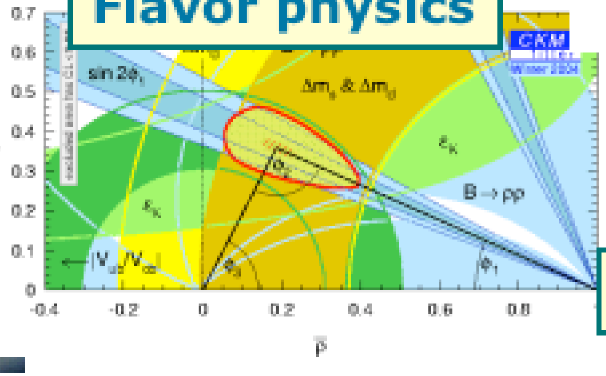


Phase transition

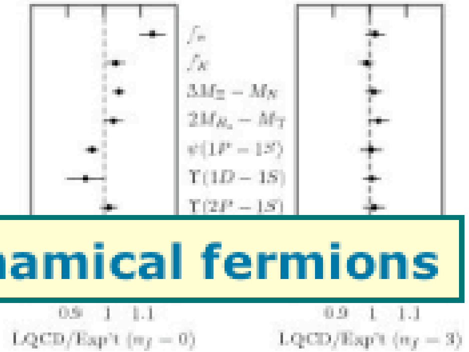


Hadron spectrum

Flavor physics



Dynamical fermions



Kronfeld

Today main lattice activities:

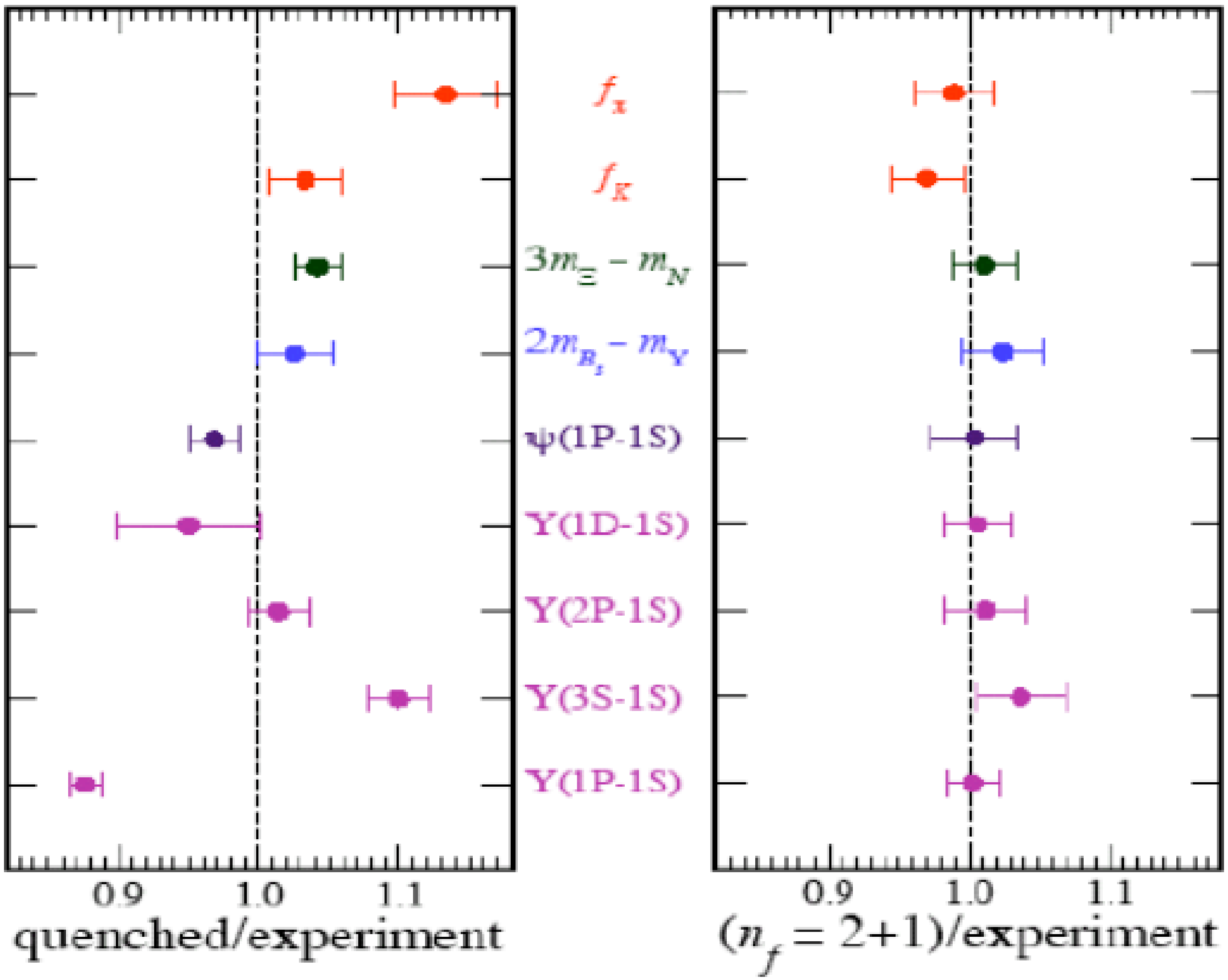
1. Issues in recent QCD simulations
   - Chiral extrapolation, fermion formulations…
2. Fundamental parameters
   - QCD coupling constant, quark masses
3. Kaon physics
   - Form factors, kaon B parameter
4. Heavy quarks
   - Decay constants, form factors…

$$\alpha^{(5)}_{\overline{\mathrm{MS}}}(M_Z) = 0.1177(13)$$

The big step is going from quenched (no dyn. fermions) to unquenched

PRL92, 022001 (2004)

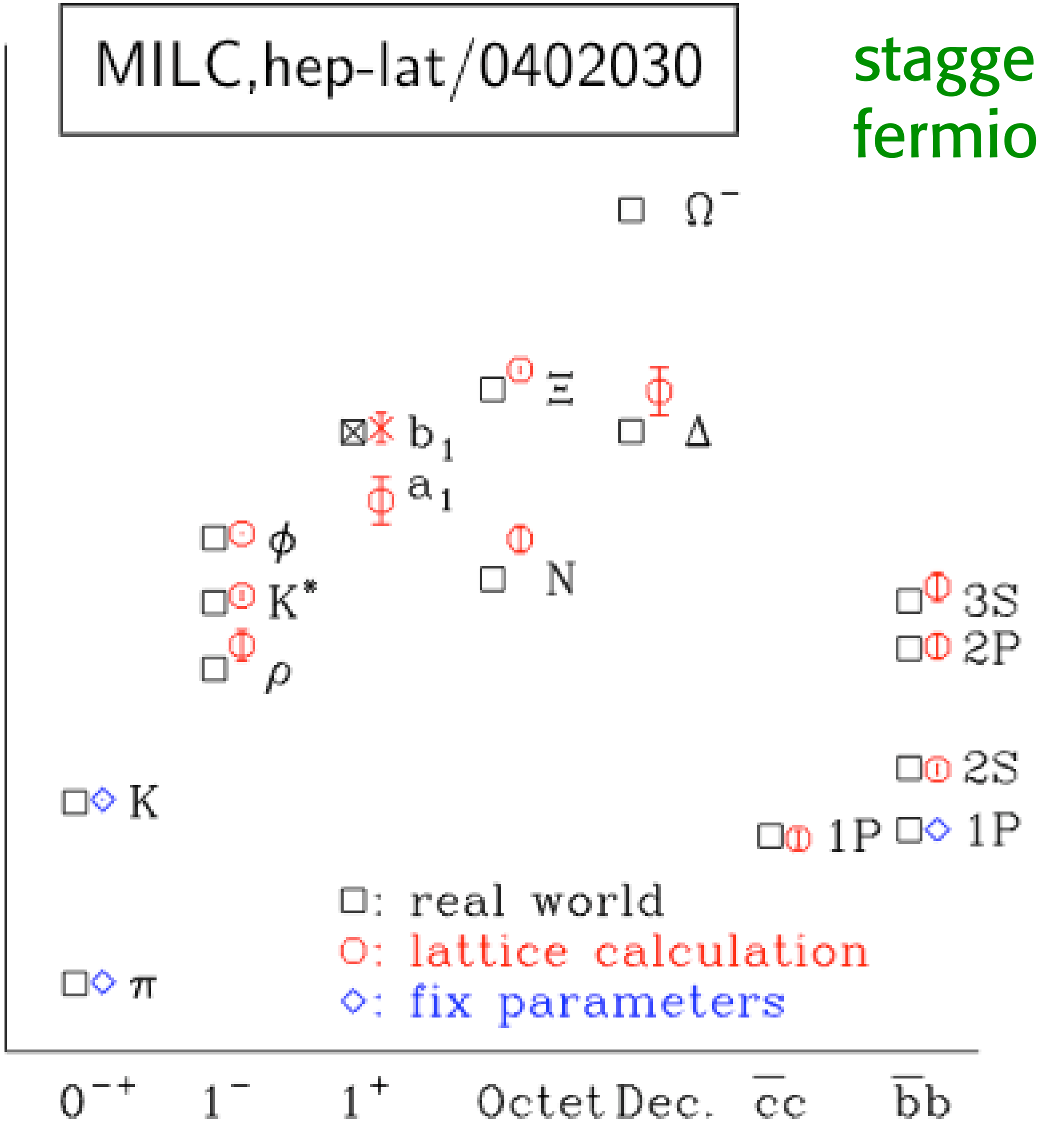
Evident improvement of predictions



Unquenched lattice simulations reproduce spectrum well

Ukawa

Note:
p/ρ ~ 1.2
not 1.5
as from
3q/2q



staggered
fermions

Chiral extrapolation

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

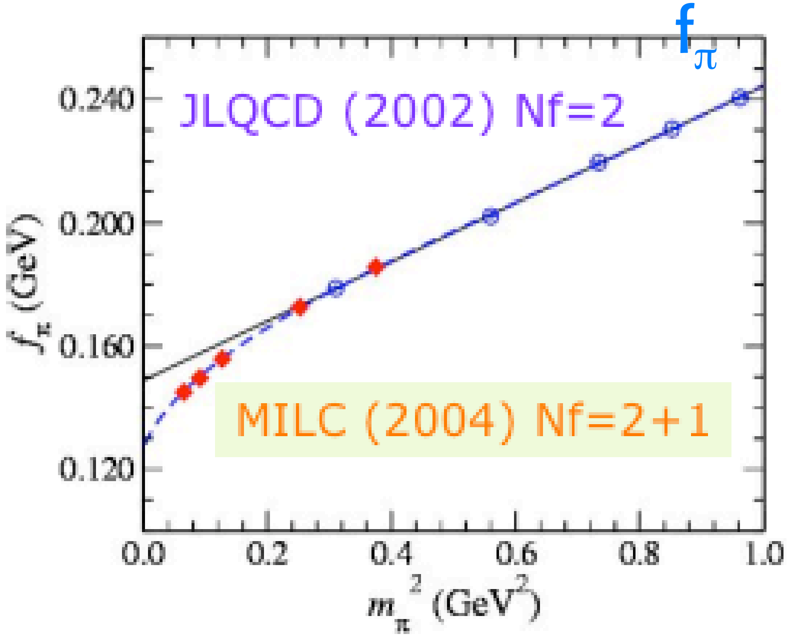
ChPT predicts the chiral log near the chiral limit.

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

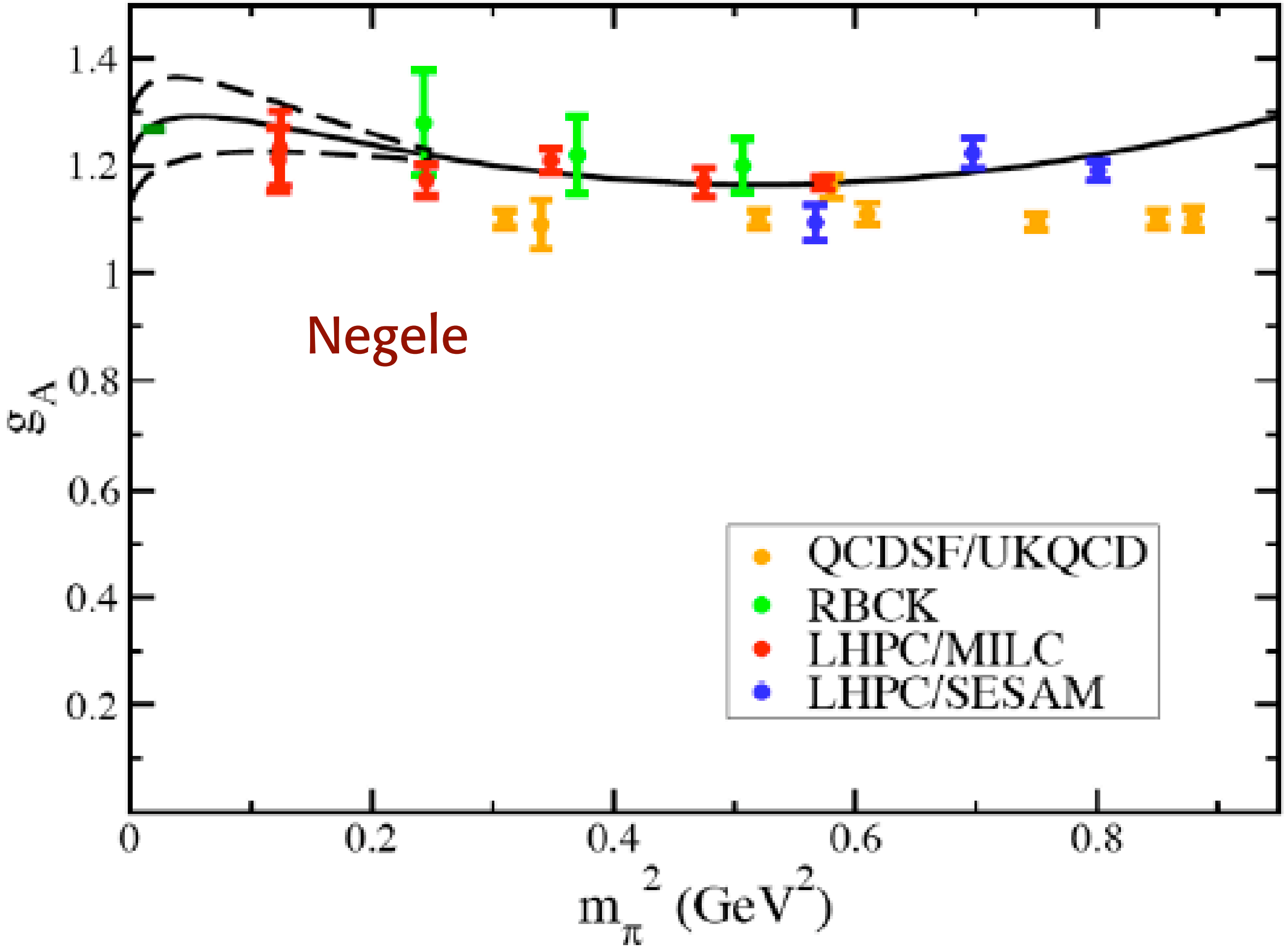
with a fixed coefficient.

Staggered simulation can push the quark mass much lower.

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

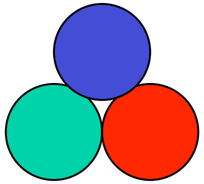


Nucleon axial charge g_A: all results

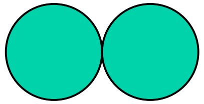


Hadron spectroscopy

All observed hadrons are colourless composites of quarks



Baryons: qqq



Mesons: $q\bar{q}$

For example:

Proton p: uud
Pion π^+: $u\bar{d}$

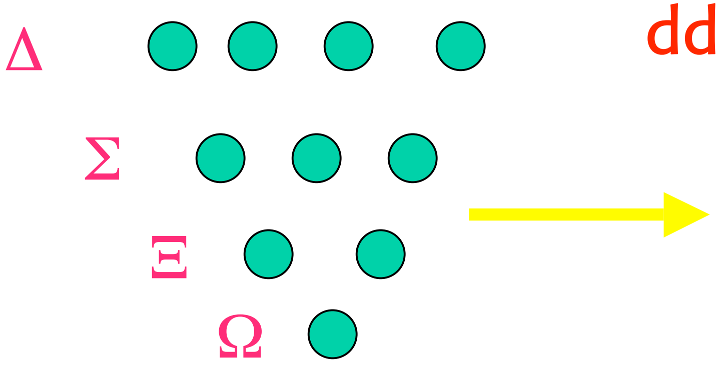
Colour is essential for Fermi statistics

The state Δ^{++} with spin 3/2 = u↑u↑u↑

is symmetric in space and spin but antisymm. in colour

and for explaining the observed spectrum

For example:
the "decuplet"



ddd ddu duu uuu

dds dus uus

dss uss

sss

New developments on exotic states

Glue-balls (gg) bound states predicted by lattice at M>~1.5 GeV have never been clearly identified (probably largely mixed).

Hybrid states ($qq^{bar}g$ or qqqg...) have also escaped detection

Recently new unexpected developments in hadron spectroscopy

New narrow states: $\Theta(1540)^+ \sim$ KN ~ $uudds^{bar}$

$D_{sJ}(2317)^+ \sim D_s\pi$, $D_{sJ}(2460)^+ \sim D_s{}^*\pi$, ...

$X(3872)^0 \sim \pi^+\pi^- J/\Psi$

widths < few MeV!

- Pentaquarks $[qq][qq]q^{bar}$
- Tetraquarks $[qq][q^{bar}q^{bar}]$

or

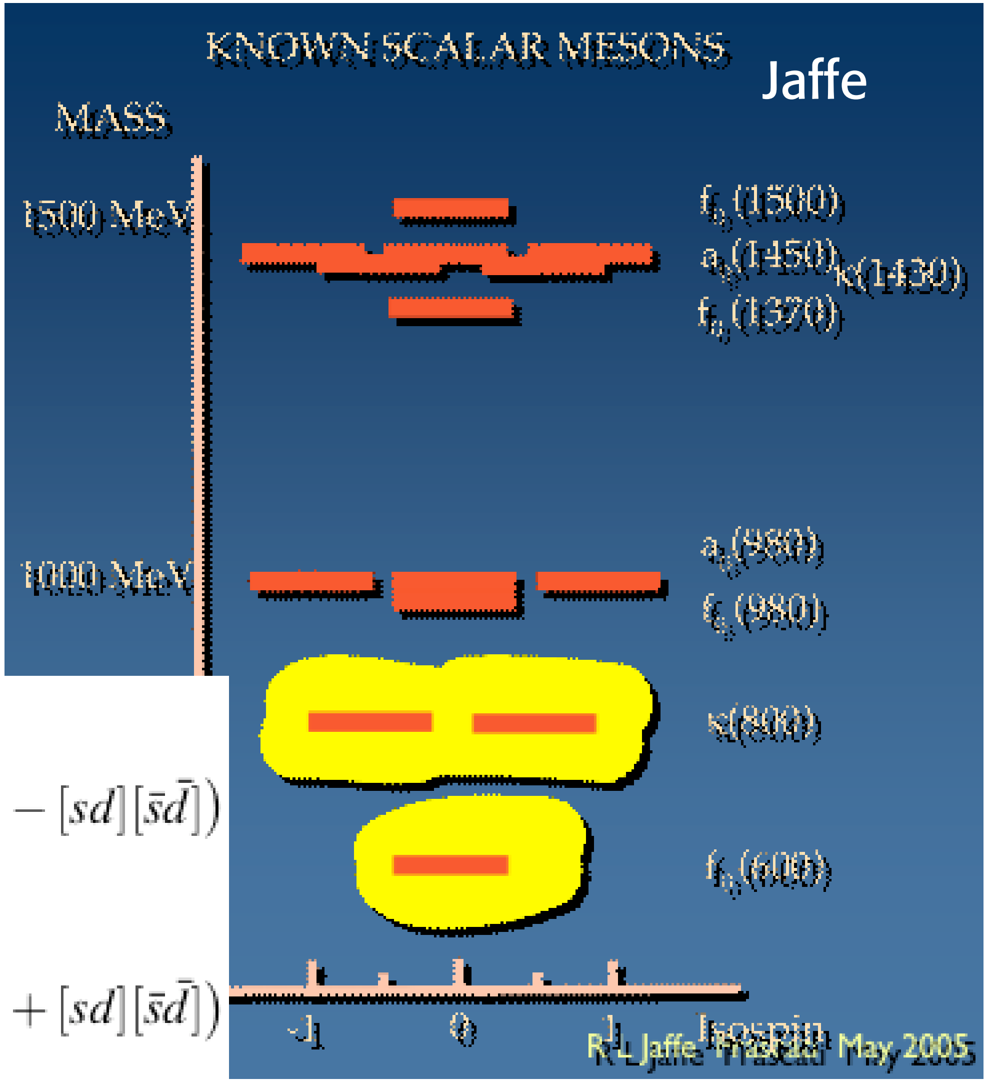
- Meson-meson molecules (eg $D\text{-}D^{*bar}$)
- Chiral solitons

based on diquarks [qq] spin 0,
colour antisymm. (3^{bar}),
flavour antisymm. (3^{bar})

Too many scalar mesons!!

The spectrum of light ones indicates tetraquarks

Jaffe
Maiani, Piccinini, Polosa, Riquer



Jaffe

$$\begin{aligned}
a^+(I=1,I_3=+1,S=0) &= [su][\bar s\bar d]\\
a^0(I=1,I_3=0,S=0) &= \frac{1}{\sqrt2}\left([su][\bar s\bar u]-[sd][\bar s\bar d]\right)\\
a^-(I=1,I_3=-1,S=0) &= [sd][\bar s\bar u]\\
f_\circ(I=0,S=0) &= \frac{1}{\sqrt2}\left([su][\bar s\bar u]+[sd][\bar s\bar d]\right)\\
\sigma_\circ(I=0,S=0) &= [ud][\bar u\bar d]
\end{aligned}$$

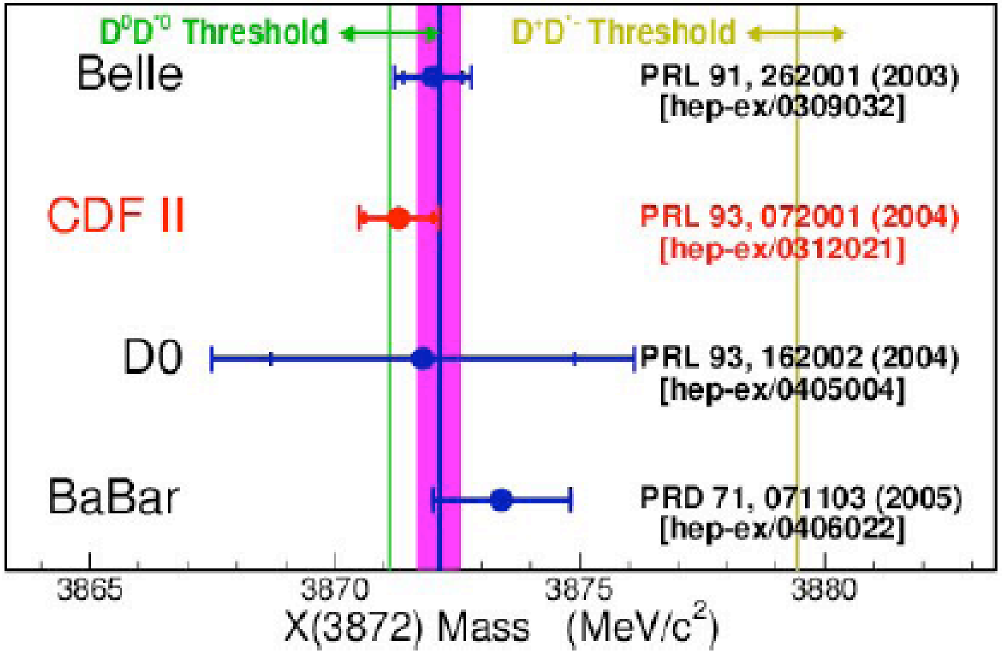
$$\begin{aligned}
\kappa(I=1/2,I_3=+1/2,S=+1) &= [ud][\bar s\bar d]\\
\kappa(I=1/2,I_3=-1/2,S=+1) &= [ud][\bar s\bar u]\\
\kappa(I=1/2,I_3=+1/2,S=-1) &= [us][\bar d\bar u]\\
\kappa(I=1/2,I_3=-1/2,S=-1) &= [ds][\bar d\bar u]
\end{aligned}$$

Also:
$D_{sJ}(2317)$, $D_{sJ}(2460)$
X(3872)
candidates for single and double c tetraquarks

DD* molecule Braaten, Kusonoki

or tetraquark? Maiani et al

$X(3872)\ Mass$



$m = 3871.9 \pm 0.5\,\mathrm{MeV}$ ($D^0\overline{D}^{*0}$ threshold is at 3871.3 ± 1.0)

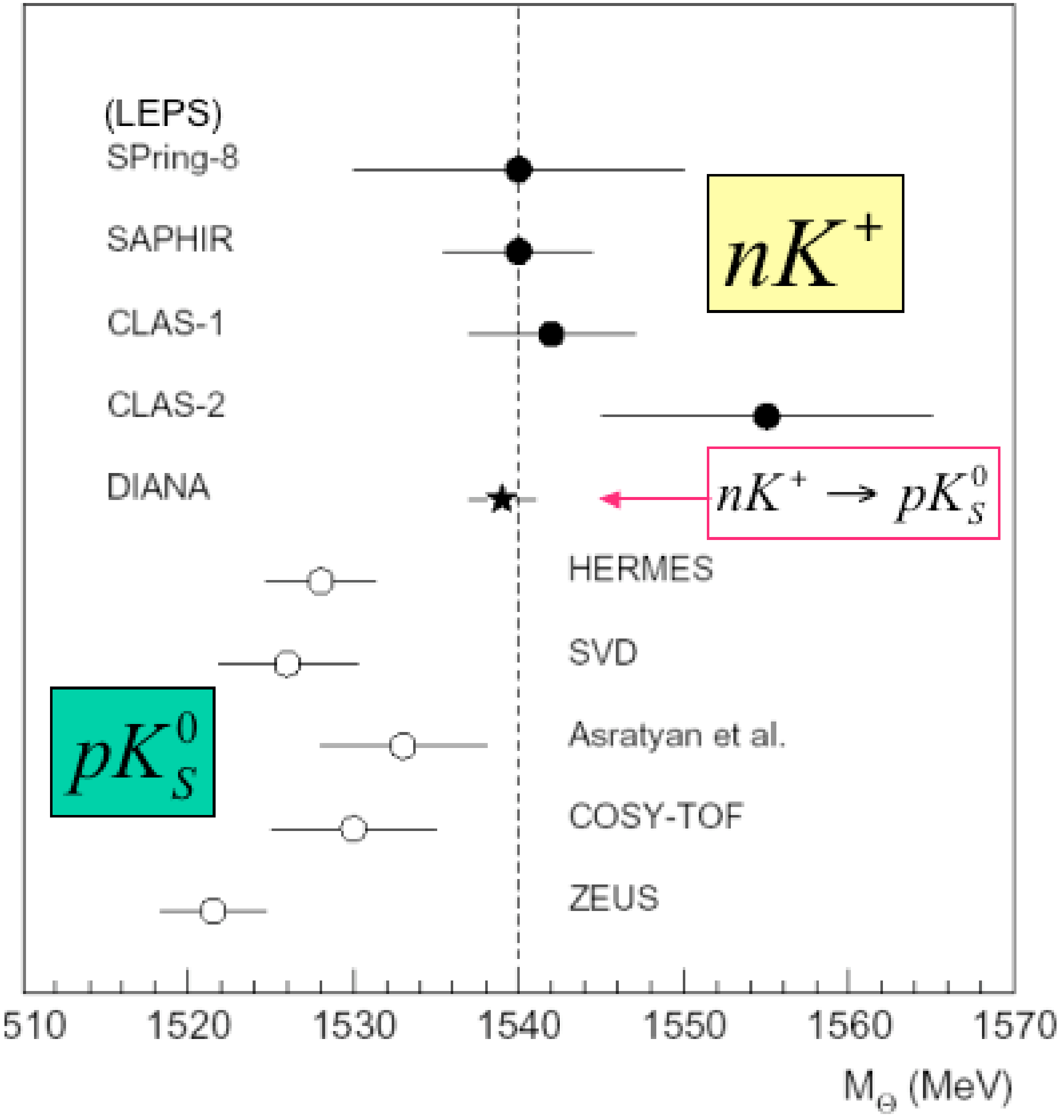
Narrow $\Gamma < 2.3\,\mathrm{MeV}$ @ 90 % CL.

Do pentaquarks really exist? Doubts are relevant

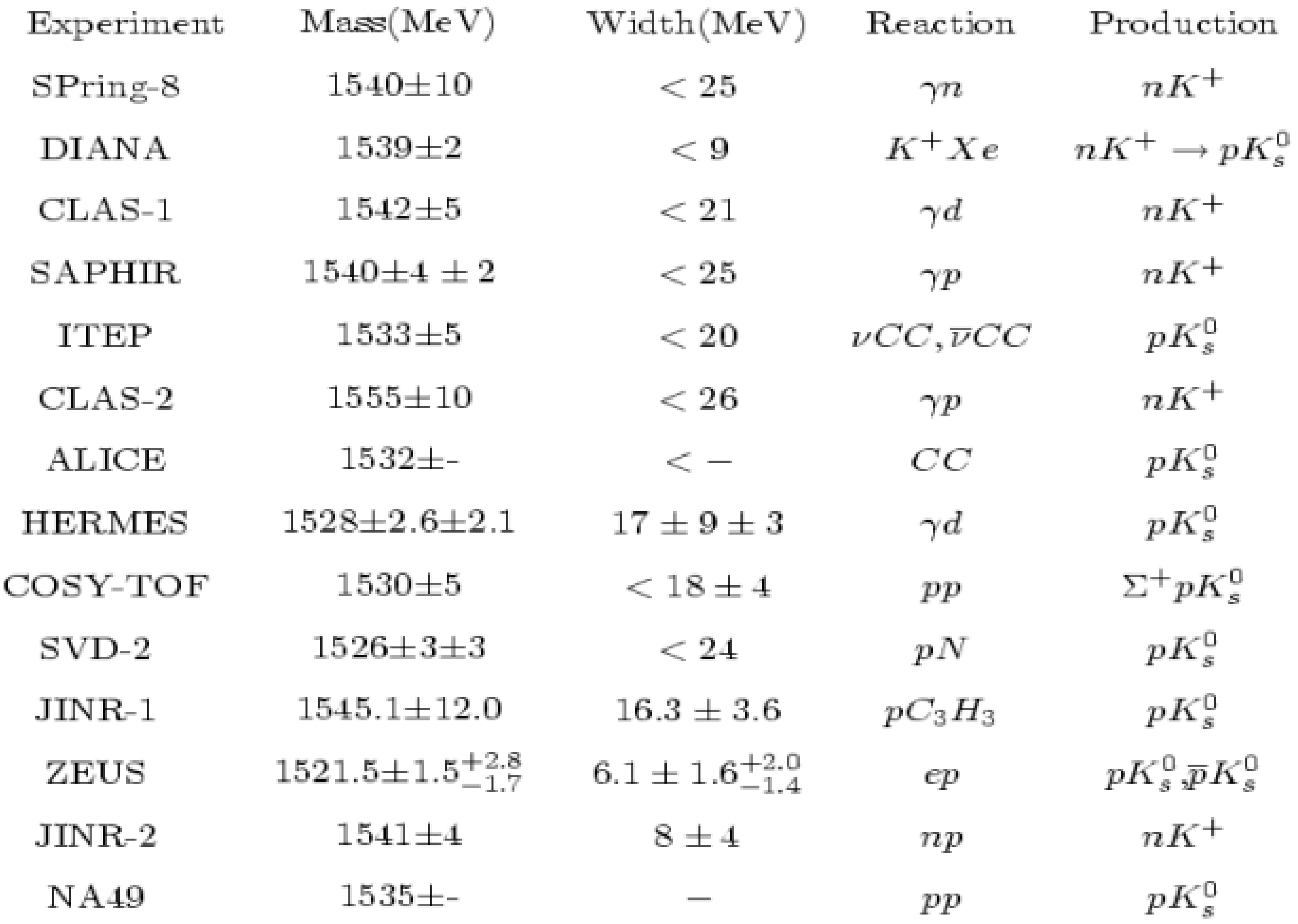
Mass inconsistencies

Tension between small width and large production

Exotic production mechanism to explain no evidence at larger energies

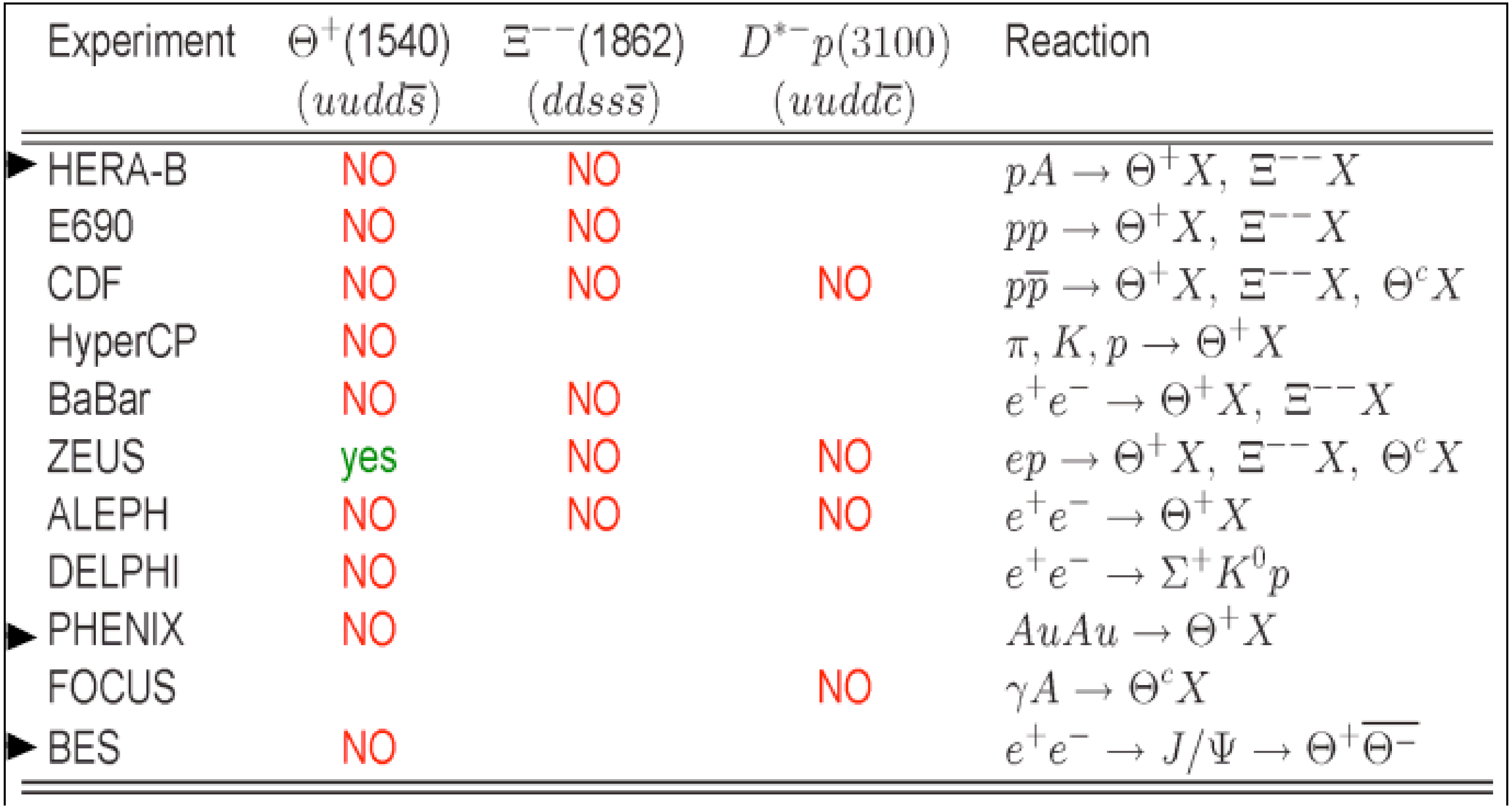


Evidence mostly from low energy, low statistics experiments



Experiment	Mass(MeV)	Width(MeV)	Reaction	Production
SPring-8	1540±10	< 25	γn	nK^+
DIANA	1539±2	< 9	K^+Xe	$nK^+ \rightarrow pK_s^0$
CLAS-1	1542±5	< 21	γd	nK^+
SAPHIR	1540±4 ±2	< 25	γp	nK^+
ITEP	1533±5	< 20	$\nu CC, \overline{\nu} CC$	pK_s^0
CLAS-2	1555±10	< 26	γp	nK^+
ALICE	1532±-	$< -$	CC	pK_s^0
HERMES	1528±2.6±2.1	$17 \pm 9 \pm 3$	γd	pK_s^0
COSY-TOF	1530±5	$< 18 \pm 4$	pp	$\Sigma^+ pK_s^0$
SVD-2	1526±3±3	< 24	pN	pK_s^0
JINR-1	1545.1±12.0	16.3 ± 3.6	pC_3H_3	pK_s^0
ZEUS	$1521.5 \pm 1.5^{+2.8}_{-1.7}$	$6.1 \pm 1.6^{+2.0}_{-1.4}$	ep	$pK_s^0, \overline{p}K_s^0$
JINR-2	1541±4	8 ± 4	np	nK^+
NA49	1535±-	$-$	pp	pK_s^0

Negative evidence from high energy, high statistics experiments



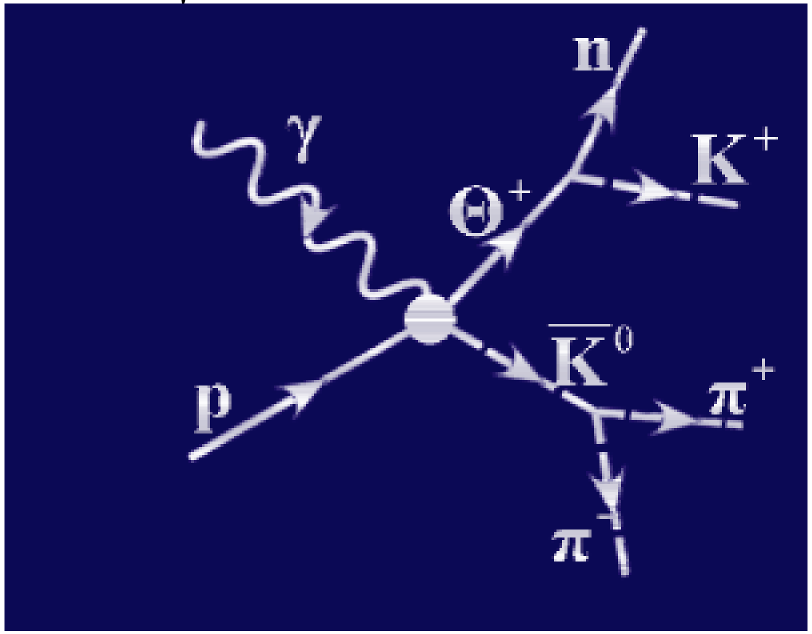
Experiment	$\Theta^+(1540)$ $(uudd\bar{s})$	$\Xi^{--}(1862)$ $(ddss\bar{s})$	$D^{*-}p(3100)$ $(uudd\bar{c})$	Reaction
► HERA-B	NO	NO		$pA \to \Theta^+ X,\ \Xi^{--} X$
E690	NO	NO		$pp \to \Theta^+ X,\ \Xi^{--} X$
CDF	NO	NO	NO	$p\bar{p} \to \Theta^+ X,\ \Xi^{--} X,\ \Theta^c X$
HyperCP	NO			$\pi, K, p \to \Theta^+ X$
BaBar	NO	NO		$e^+e^- \to \Theta^+ X,\ \Xi^{--} X$
ZEUS	yes	NO	NO	$ep \to \Theta^+ X,\ \Xi^{--} X,\ \Theta^c X$
ALEPH	NO	NO	NO	$e^+e^- \to \Theta^+ X$
DELPHI	NO			$e^+e^- \to \Sigma^+ K^0 p$
► PHENIX	NO			$AuAu \to \Theta^+ X$
FOCUS			NO	$\gamma A \to \Theta^c X$
► BES	NO			$e^+e^- \to J/\Psi \to \Theta^+ \overline{\Theta^-}$

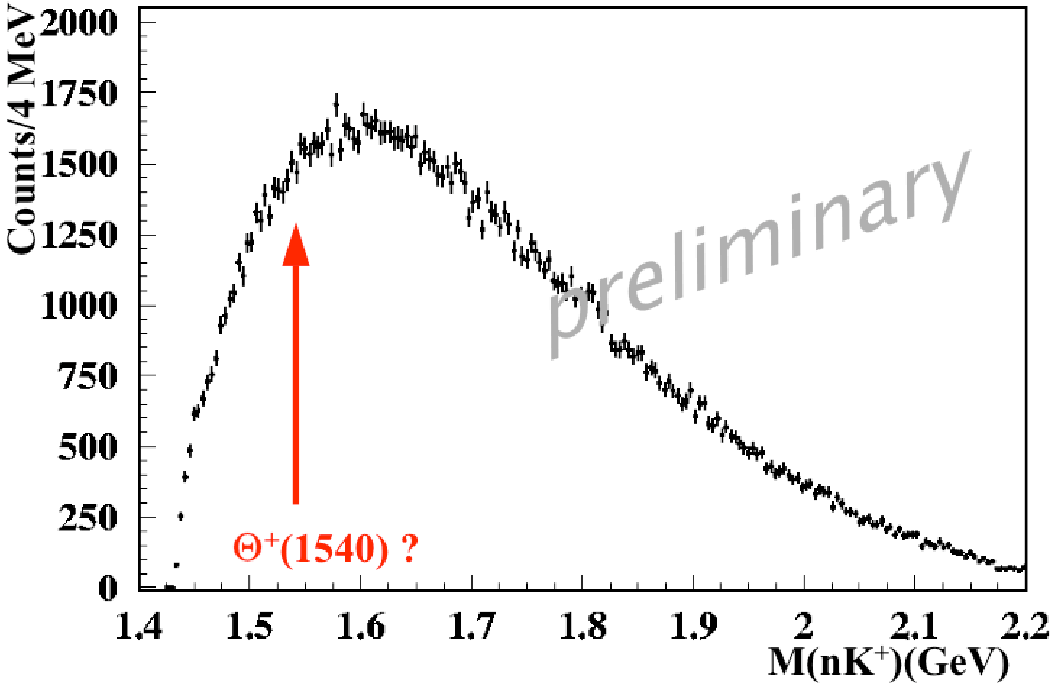
New

April '05: Negative result of CLAS g11@JLAB

No Θ^+ observed in dedicated high statistics search

A deadly blow?





Flatly contradicts previous results:

SAPHIR

$\sigma_{\gamma p \to \Theta^+ K^0} \sim 300$ nb

reanalysis 50 nb

CLAS

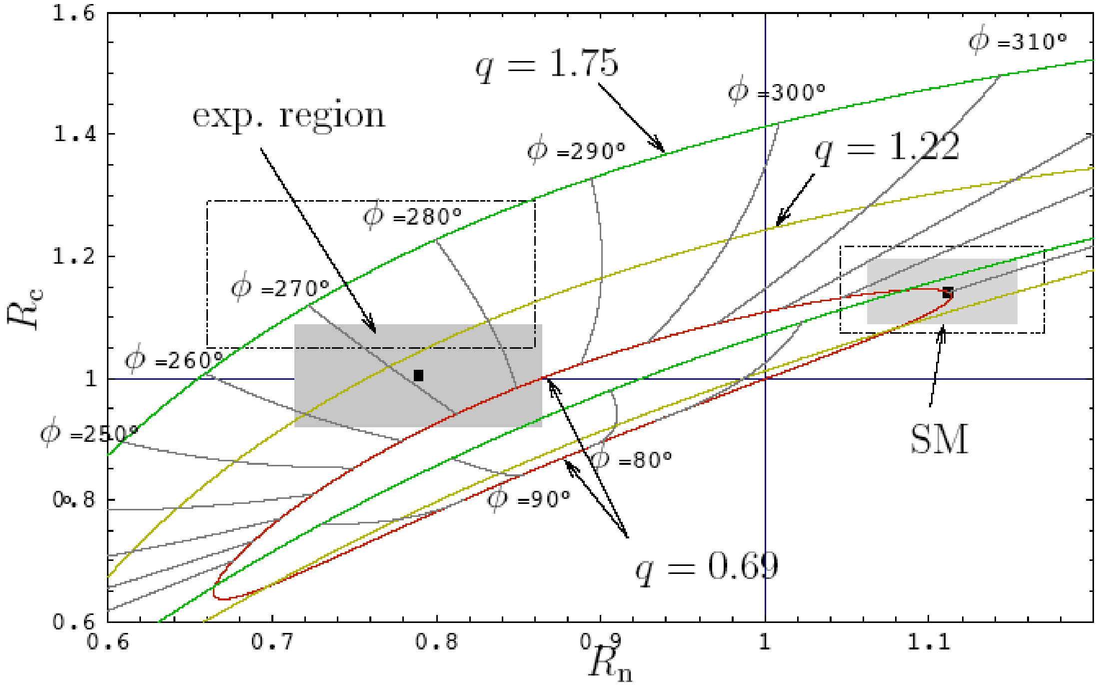
$\sigma_{\gamma p \to \Theta^+ K^0} < 1$- 4 nb

QCD plays an essential role in the interpretation of B decay (lattice, heavy Q eff. th, QCDF, SCET, pQCD)

$$R_c \equiv 2\left[\frac{\mathrm{BR}(B^+ \to \pi^0 K^+)+\mathrm{BR}(B^- \to \pi^0 K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0)+\mathrm{BR}(B^- \to \pi^- \bar{K}^0)}\right] \overset{\mathrm{Exp}}{=} 1.00 \pm 0.08$$

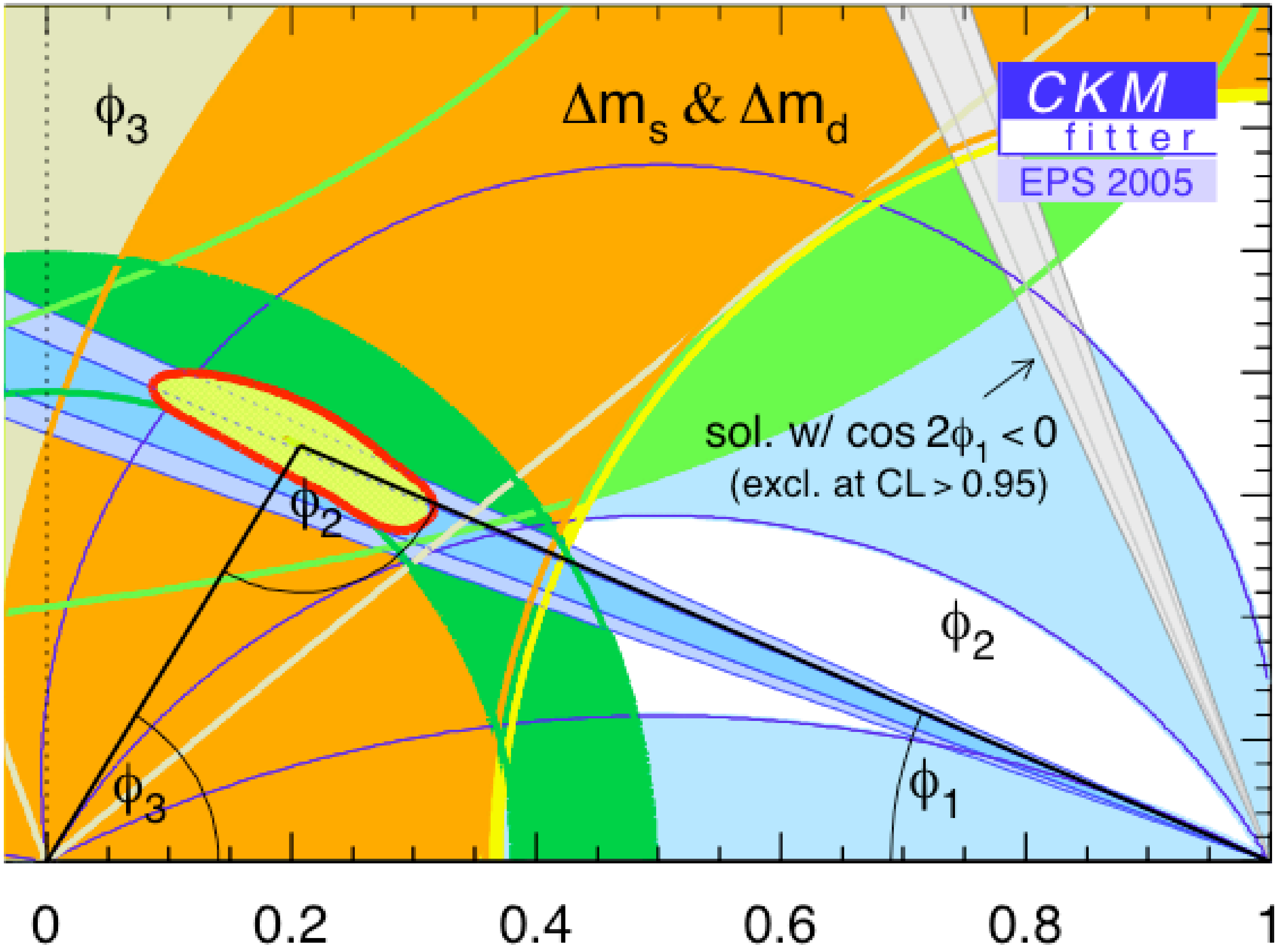
$$R_n \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+)+\mathrm{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\mathrm{BR}(B_d^0 \to \pi^0 K^0)+\mathrm{BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right] \overset{\mathrm{Exp}}{=} 0.79 \pm 0.08$$

Fleischer



Overall B-mixing and CP violation agree with SM. Here is a possible deviation in channels where penguins are dominant

The CKM picture of CP violation is supported by expt.
Deviations from new physics must be small: not trivial at all!!



Perturbative QCD

In the QCD lagrangian

$$L = -\frac{1}{4}\sum_{A=1}^{8} F^{A\mu\nu}F^{A}_{\mu\nu} + \sum_{j=1}^{n_f} \bar{q}_j(i\widehat{D} - m_j)q_j$$

quark masses are the only parameters with dimensions.

Naively we would expect massless QCD to be scale invariant (dimensionless observables should not depend on the absolute energy scale, but only on ratios of energy variables)

While massless QCD is finally not scale invariant, the departures from scaling are asymptotically small, logarithmic and computable (in massive QCD there are additional mass corrections suppressed by powers).

QCD is "asymptotically free". All and only non-abelian gauge th. are asymptotically free (in 4-dim.)

The running coupling $\alpha(Q^2)$ is the crucial quantity:

$$\frac{d\alpha(Q^2)}{d\log Q^2} = \beta[\alpha(Q^2)]$$

$$\boxed{\alpha(Q^2) = \frac{1}{b\log\frac{Q^2}{\Lambda^2_{QCD}}}(1 + ...)}$$

$$\beta(\alpha) = -b\alpha^2[1 + b'\alpha + ...] \quad (b>0)$$

$$b = \frac{11N_C - 2n_f}{12\pi}$$

MS, n_f=5: $\beta(\alpha) \cong -0.610\alpha^2\left[1 + 1.261\frac{\alpha}{\pi} + 1.475\left(\frac{\alpha}{\pi}\right)^2 + 9.836\left(\frac{\alpha}{\pi}\right)^3 + ...\right]$

4th: van Ritbergen, Vermaseren, Larin (1997)

~ 50.000 4-loop diagrams!!

Λ_{QCD} is the scale that breaks scale inv. in massless QCD

Λ_{QCD} = 218±24 MeV (N_f=5)

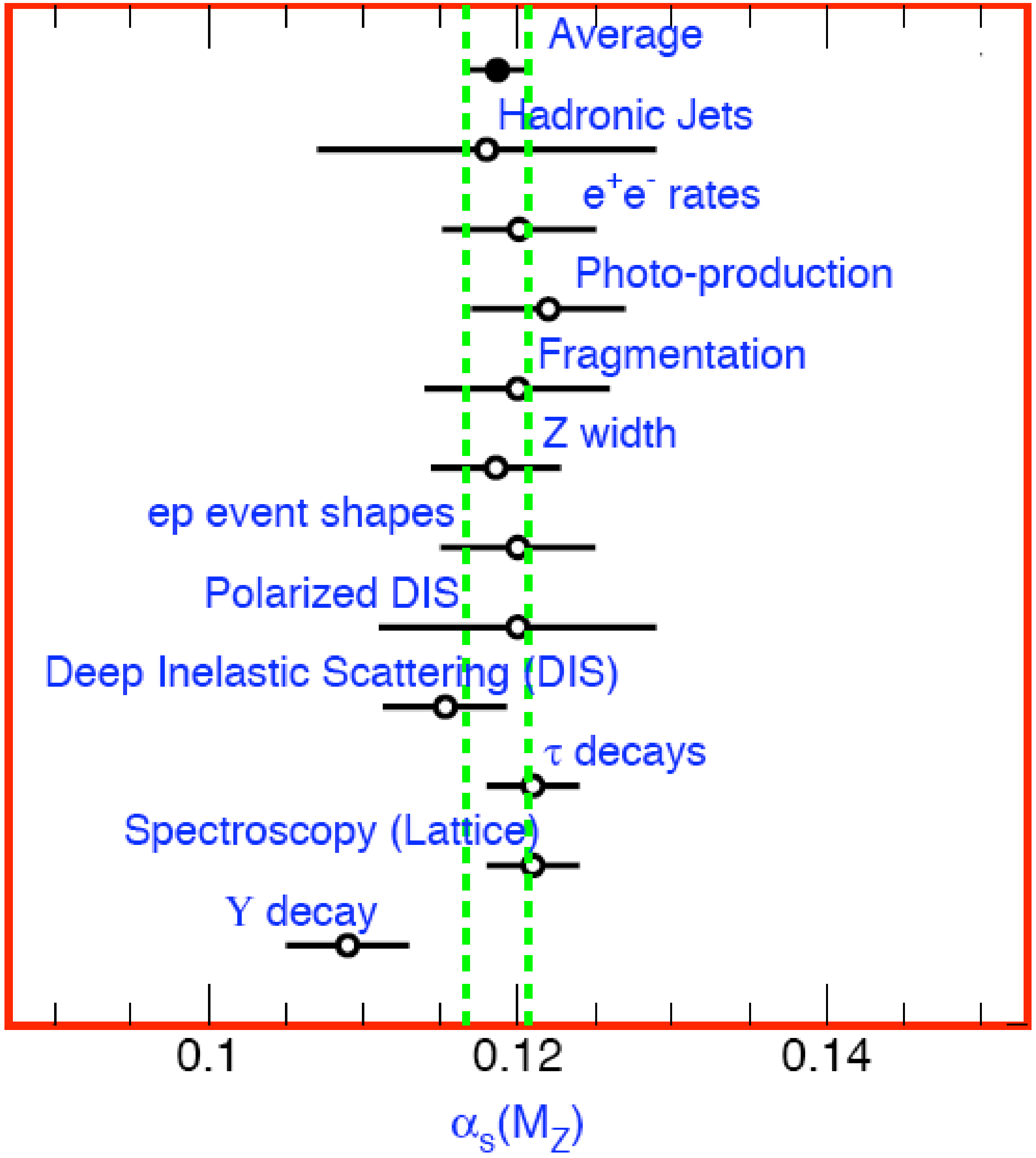
The ρ mass etc are due to Λ_{QCD} not to m_q

No hierarchy problem in QCD!

$$\Lambda_{QCD} = M_{Pl}\exp\left(\frac{-1}{2b\alpha(M^2_{Pl})}\right)$$

Measurements of $\alpha_s(m_Z)$

PDG'04 summary on $\alpha_s(m_Z)$ $\overline{\text{MS}}$



$\alpha_s(m_Z)=0.1187\pm0.002$

$\Lambda_5 = 218\pm24$ MeV

The agreement among many different ways of measuring α_s is a strong quantitative test of QCD

A time of very difficult computations

Splitting functions

For many years all splitting funct.s P have been known to NLO accuracy: $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + ...$

GLAP, Floratos et al; Gonzales-Arroyo et al; Curci et al; Furmanski et al

Then the complete, analytic NNLO results have been derived for the first few moments ($N<13,14$).

Larin, van Ritbergen, Vermaseren+Nogueira

Finally, in 2004, the calculation of the NNLO splitting functions has been totally completed $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + \alpha_s^3 P_3 + ...$

Moch, Vermaseren, Vogt

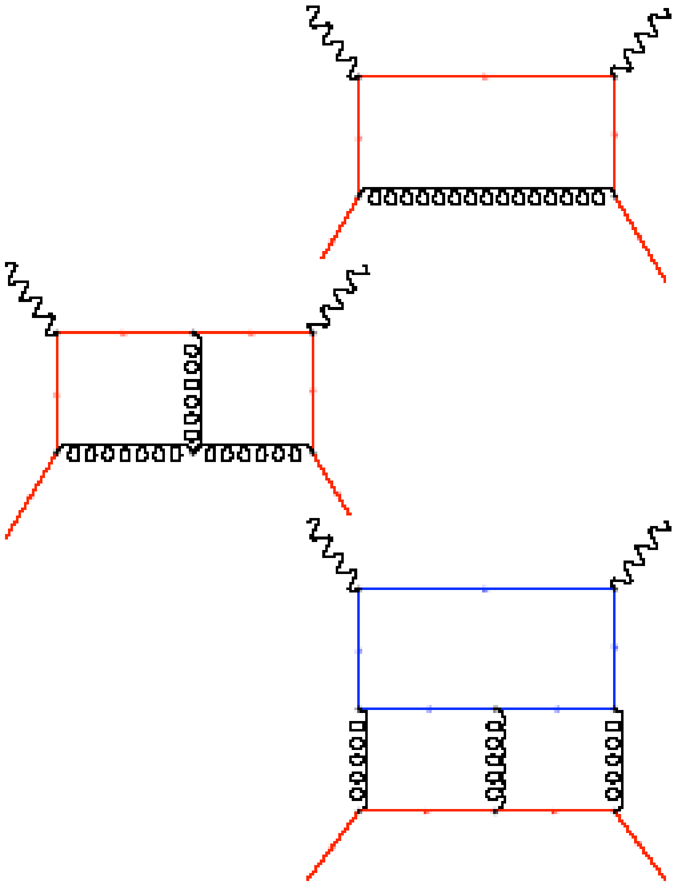
⊕ A really monumental, fully analytic, computation

The calculation (in a nut shell)

Moch

- Calculate anomalous dimensions (Mellin moments of splitting functions)
  $\longrightarrow$ divergence of Feynman diagrams in dimensional regularization $D = 4 - 2\varepsilon$

$$\gamma_{\rm ij}^{(n)}(N) = -\int_0^1 dx\, x^{N-1} P_{\rm ij}^{(n)}(x)$$



- **One-loop** Feynman diagrams
  $\longrightarrow$ in total 18 for $\gamma_{\rm ij}^{(0)}$ / $P_{\rm ij}^{(0)}$
  (pencil + paper)

- **Two-loop** Feynman diagrams
  $\longrightarrow$ in total 350 for $\gamma_{\rm ij}^{(1)}$ / $P_{\rm ij}^{(1)}$
  (simple computer algebra)

- **Three-loop** Feynman diagrams
  $\longrightarrow$ in total 9607 for $\gamma_{\rm ij}^{(2)}$ / $P_{\rm ij}^{(2)}$
  (cutting edge technology $\longrightarrow$ computer algebra system FORM Vermaseren '89-'04)

NLO singlet splitting functions

$$
\begin{aligned}
P^{(0)}_{\mathrm{ps}}(x) &= 0\\
P^{(0)}_{\mathrm{qg}}(x) &= 2n_f\, p_{\mathrm{qg}}(x)\\
P^{(0)}_{\mathrm{gq}}(x) &= 2C_F\, p_{\mathrm{gq}}(x)\\
P^{(0)}_{\mathrm{gg}}(x) &= C_A\Big(4p_{\mathrm{gg}}(x)+\frac{11}{3}\delta(1-x)\Big)-\frac{2}{3}n_f\,\delta(1-x)
\end{aligned}
$$

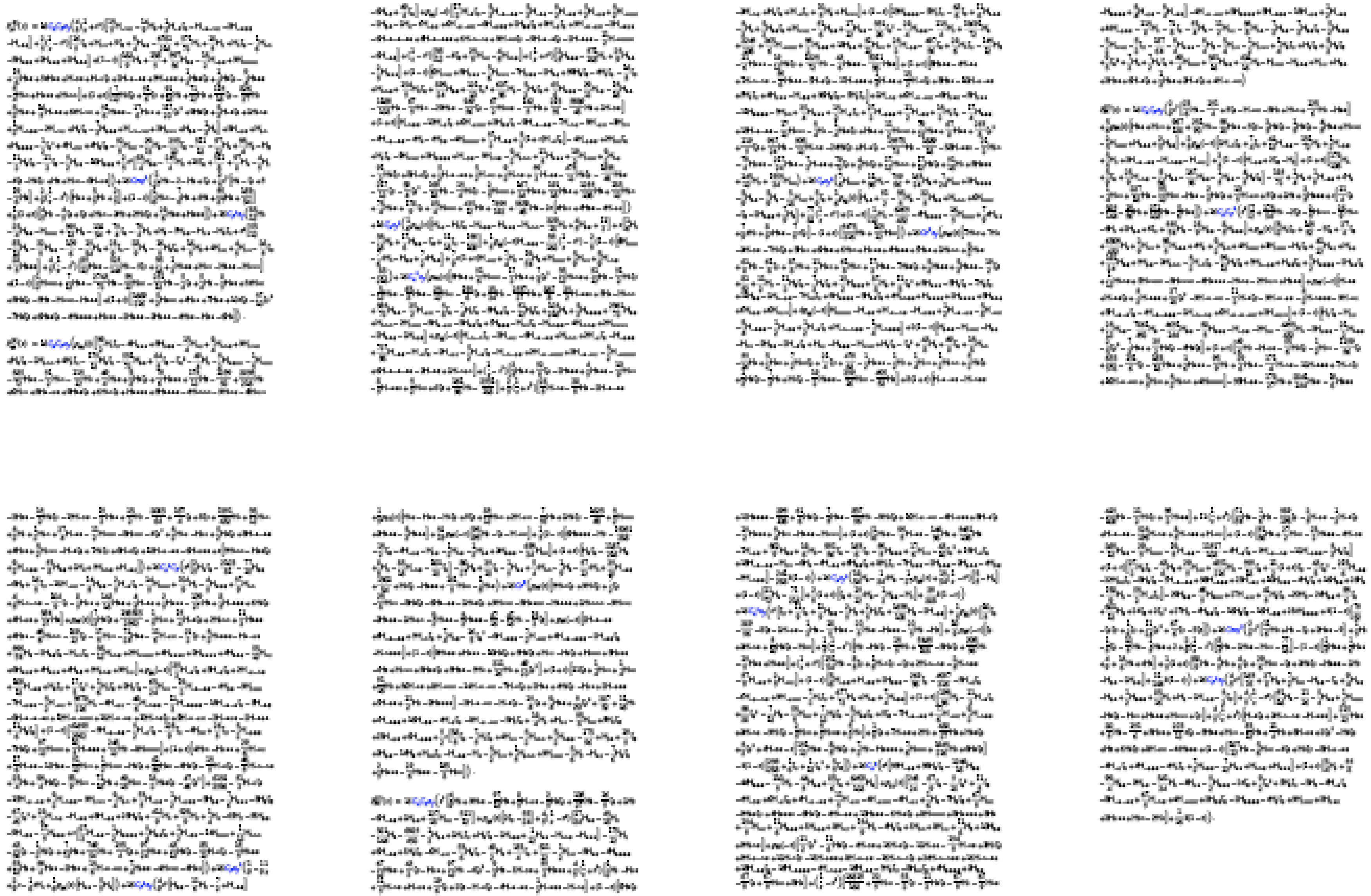
$$
P^{(1)}_{\mathrm{ps}}(x) = 4C_F n_f\Big(\frac{20}{9}\frac{1}{x}-2+6x-4\mathrm{H}_0+x^2\Big[\frac{8}{3}\mathrm{H}_0-\frac{56}{9}\Big]+(1+x)\Big[5\mathrm{H}_0-2\mathrm{H}_{0,0}\Big]\Big)
$$

$$
\begin{aligned}
P^{(1)}_{\mathrm{qg}}(x) = {}& 4C_A n_f\Big(\frac{20}{9}\frac{1}{x}-2+25x-2p_{\mathrm{qg}}(-x)\mathrm{H}_{-1,0}-2p_{\mathrm{qg}}(x)\mathrm{H}_{1,1}+x^2\Big[\frac{44}{3}\mathrm{H}_0-\frac{218}{9}\Big]\\
&+4(1-x)\Big[\mathrm{H}_{0,0}-2\mathrm{H}_0+x\mathrm{H}_1\Big]-4\zeta_2 x-6\mathrm{H}_{0,0}+9\mathrm{H}_0\Big)+4C_F n_f\Big(2p_{\mathrm{qg}}(x)\Big[\mathrm{H}_{1,0}+\mathrm{H}_{1,1}+\mathrm{H}_2\\
&-\zeta_2\Big]+4x^2\Big[\mathrm{H}_0+\mathrm{H}_{0,0}+\frac{5}{2}\Big]+2(1-x)\Big[\mathrm{H}_0+\mathrm{H}_{0,0}-2x\mathrm{H}_1+\frac{29}{4}\Big]-\frac{15}{2}-\mathrm{H}_{0,0}-\frac{1}{2}\mathrm{H}_0\Big)
\end{aligned}
$$

$$
\begin{aligned}
P^{(1)}_{\mathrm{gq}}(x) = {}& 4C_A C_F\Big(\frac{1}{x}+2p_{\mathrm{gq}}(x)\Big[\mathrm{H}_{1,0}+\mathrm{H}_{1,1}+\mathrm{H}_2-\frac{11}{6}\mathrm{H}_1\Big]-x^2\Big[\frac{8}{3}\mathrm{H}_0-\frac{44}{9}\Big]+4\zeta_2-2\\
&-7\mathrm{H}_0+2\mathrm{H}_{0,0}-2\mathrm{H}_1 x+(1+x)\Big[2\mathrm{H}_{0,0}-5\mathrm{H}_0+\frac{37}{9}\Big]-2p_{\mathrm{gq}}(-x)\mathrm{H}_{-1,0}\Big)-4C_F n_f\Big(\frac{2}{3}x\\
&-p_{\mathrm{gq}}(x)\Big[\frac{2}{3}\mathrm{H}_1-\frac{10}{9}\Big]\Big)+4{C_F}^2\Big(p_{\mathrm{gq}}(x)\Big[3\mathrm{H}_1-2\mathrm{H}_{1,1}\Big]+(1+x)\Big[\mathrm{H}_{0,0}-\frac{7}{2}+\frac{7}{2}\mathrm{H}_0\Big]-3\mathrm{H}_{0,0}\\
&+1-\frac{3}{2}\mathrm{H}_0+2\mathrm{H}_1 x\Big)
\end{aligned}
$$

$$
\begin{aligned}
P^{(1)}_{\mathrm{gg}}(x) = {}& 4C_A n_f\Big(1-x-\frac{10}{9}p_{\mathrm{gg}}(x)-\frac{13}{9}\Big(\frac{1}{x}-x^2\Big)-\frac{2}{3}(1+x)\mathrm{H}_0-\frac{2}{3}\delta(1-x)\Big)+4{C_A}^2\Big(27\\
&+(1+x)\Big[\frac{11}{3}\mathrm{H}_0+8\mathrm{H}_{0,0}-\frac{27}{2}\Big]+2p_{\mathrm{gg}}(-x)\Big[\mathrm{H}_{0,0}-2\mathrm{H}_{-1,0}-\zeta_2\Big]-\frac{67}{9}\Big(\frac{1}{x}-x^2\Big)-12\mathrm{H}_0\\
&-\frac{44}{3}x^2\mathrm{H}_0+2p_{\mathrm{gg}}(x)\Big[\frac{67}{18}-\zeta_2+\mathrm{H}_{0,0}+2\mathrm{H}_{1,0}+2\mathrm{H}_2\Big]+\delta(1-x)\Big[\frac{8}{3}+3\zeta_3\Big]\Big)+4C_F n_f\Big(2\mathrm{H}_0\\
&+\frac{2}{3}\frac{1}{x}+\frac{10}{3}x^2-12+(1+x)\Big[4-5\mathrm{H}_0-2\mathrm{H}_{0,0}\Big]-\frac{1}{2}\delta(1-x)\Big)\ .
\end{aligned}
$$

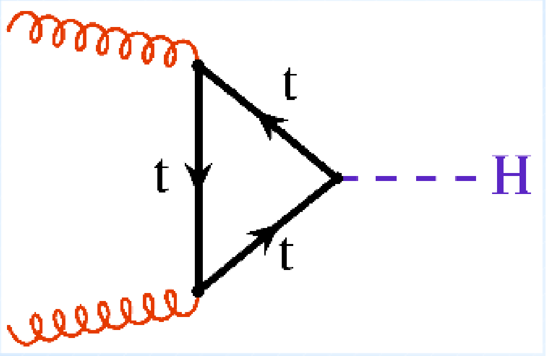
NNLO singlet splitting functions



Predictions for future tests

Higgs production via g+g -> H

Very important for the LHC



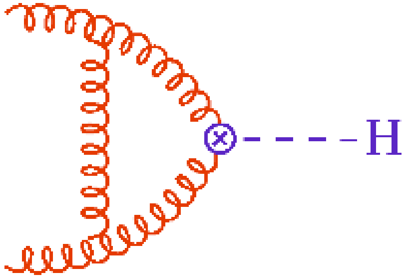
Effective lagrangian (m_t -> infinity)

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

C_1 known to α_s^4

Chetyrkin, Kniehl, Steinhauser

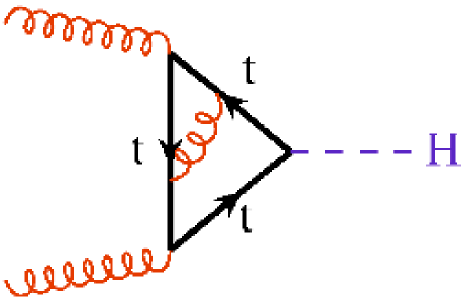
NLO corr.s computed with effective lagrangian

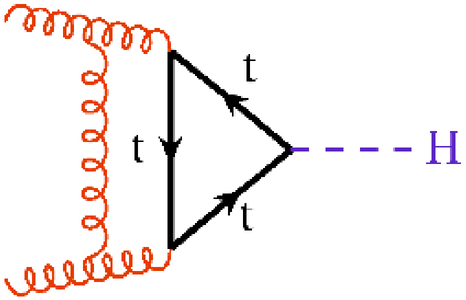


Dawson
Djouadi, Spira, Graudenz, Zerwas

AND the full theory

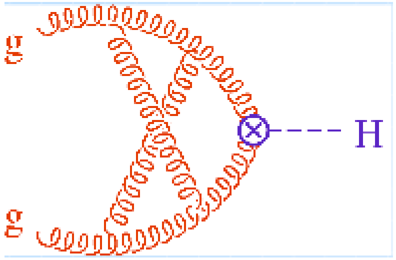
Djouadi, Spira, Graudenz, Zerwas

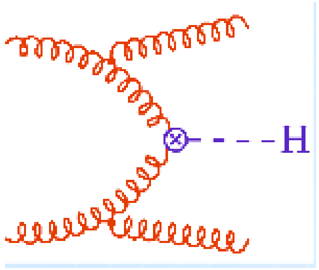




They agree very well

Recently the NNLO calculation has been completed (analytic)

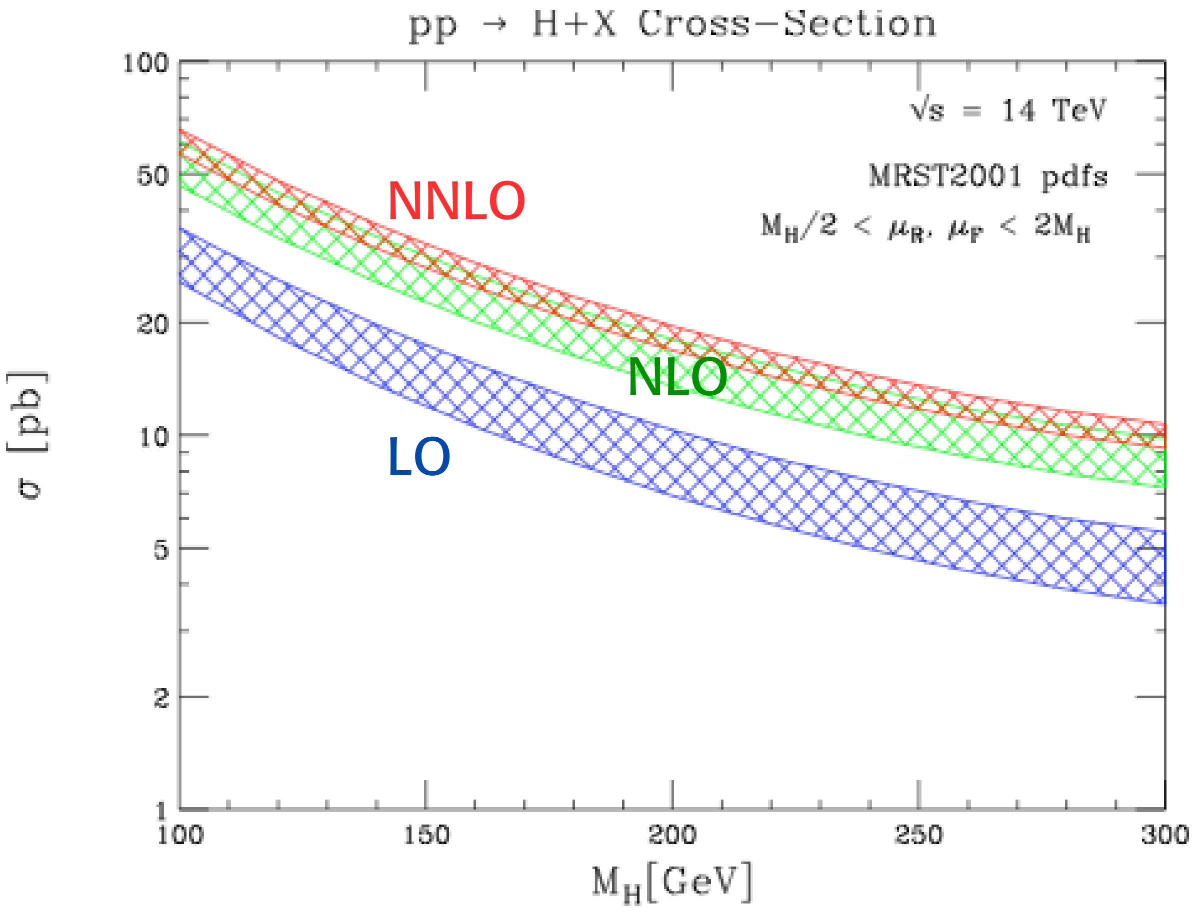




Harlander, Kilgore
Ravindran, Smith, van Nerven
Anastasiou, Melnikov

Also NLO y and p_T distributions have been computed

Anastasiou et al
De Florian, Grazzini, Kunszt
Ravindran, Smith, van Nerven
Glosser, Schmidt



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

Bozzi, Catani, De Florian, Grazzini

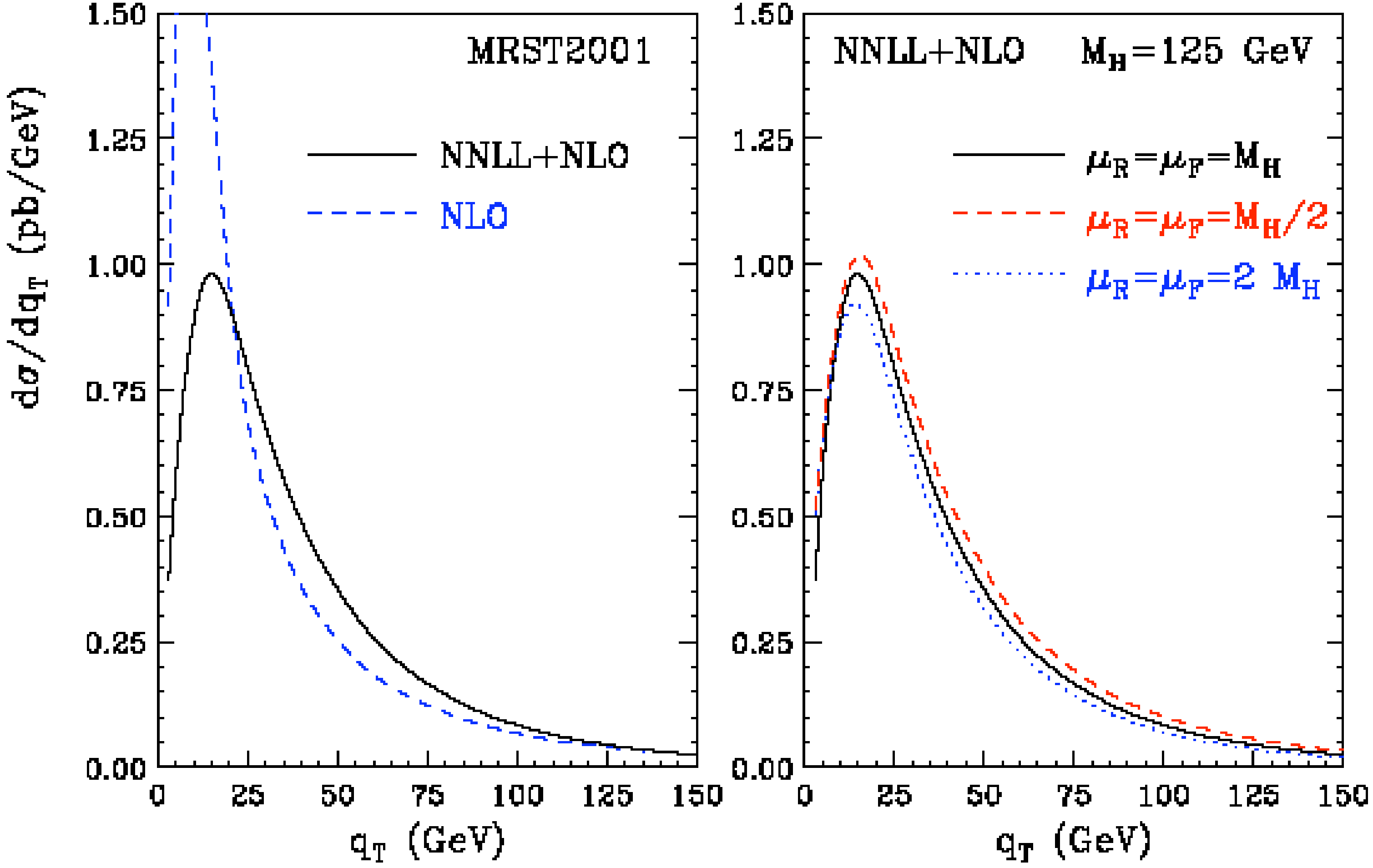


Figure 7. Resummed pQCD prediction for the Higgs transverse momentum distribution at the LHC, from Bozzi *et al.*[25]

QCD event simulation

A big boost in the preparation to LHC experiments

General algorithms for computer NLO calculations
eg the dipole formalism Catani, Seymour,..

Matching matrix elements and parton showers
e.g. MC@NLO-based on HERWIG Frixione, Nason, Webber

Perturbative (+ resumm.s)

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

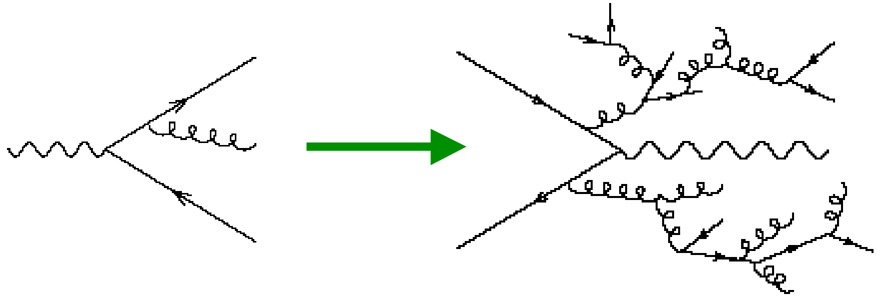
L= large log eg L=log(p_T/m)

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

Parton showers

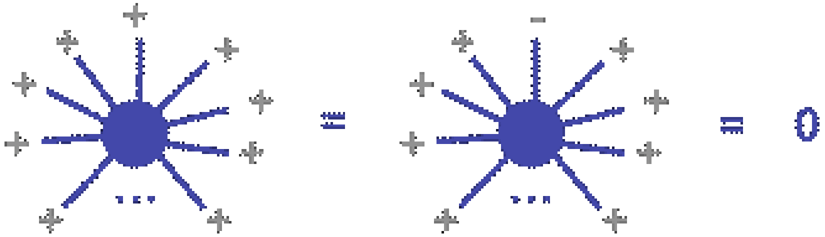
collinear emissions factorize

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



hadronization added

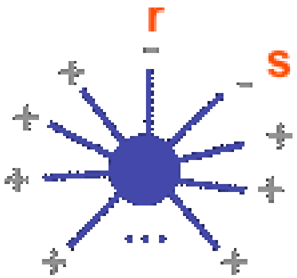
String theory improved QCD: a powerful breakthrough



Amplitudes of n incoming gluons with ±helicities

Parke, Taylor '86

Maximum
Helicity
Violating



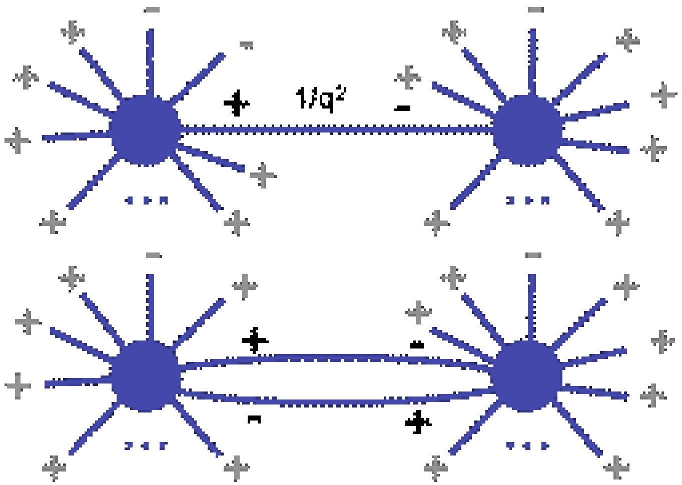
$$= i\, g_S^{n-2} \frac{\langle r, s\rangle^4}{\prod_{j=1}^{n} \langle j, j+1\rangle} \qquad \begin{cases} \langle i, j\rangle = u_-(p_i)\bar{u}_+(p_j) \\ |\langle i, j\rangle| = \sqrt{2 p_i \cdot p_j} \end{cases}$$

Relation between gauge th and string th in twistor space

Witten '03

allows to compute all helicity amplitudes (effective vertices and propagators).

Very compact results much faster than Feynman diagrams



Cachazo, Svrecek, Witten '04

Rapid progress: at tree level

Powerful recursion relations Britto, Cachazo, Feng; BCF, Witten

Inclusion of massless fermions Georgiou, Khoze

of external EW vector bosons Berne et al

of external Higgs Dixon, Glover, Khoze; Badger +GK

Already important for multijet events at the LHC

and also loops: QCD 1-loop

Bedford, Brandhuber, Spence and Travaglini; Bern, Dixon and Kosower; Bidder, Bjerrum-Bohr, Dunbar and Perkins

Looks very promising

Conclusion on QCD

QCD is a non abelian unbroken gauge quantum field theory of fundamental physical relevance

Its physics content is very large and our knowledge esp. in the non perturbative domain is still very limited but progress both from experiment (HERA, Tevatron, RHIC, LHC) and from theory is continuous

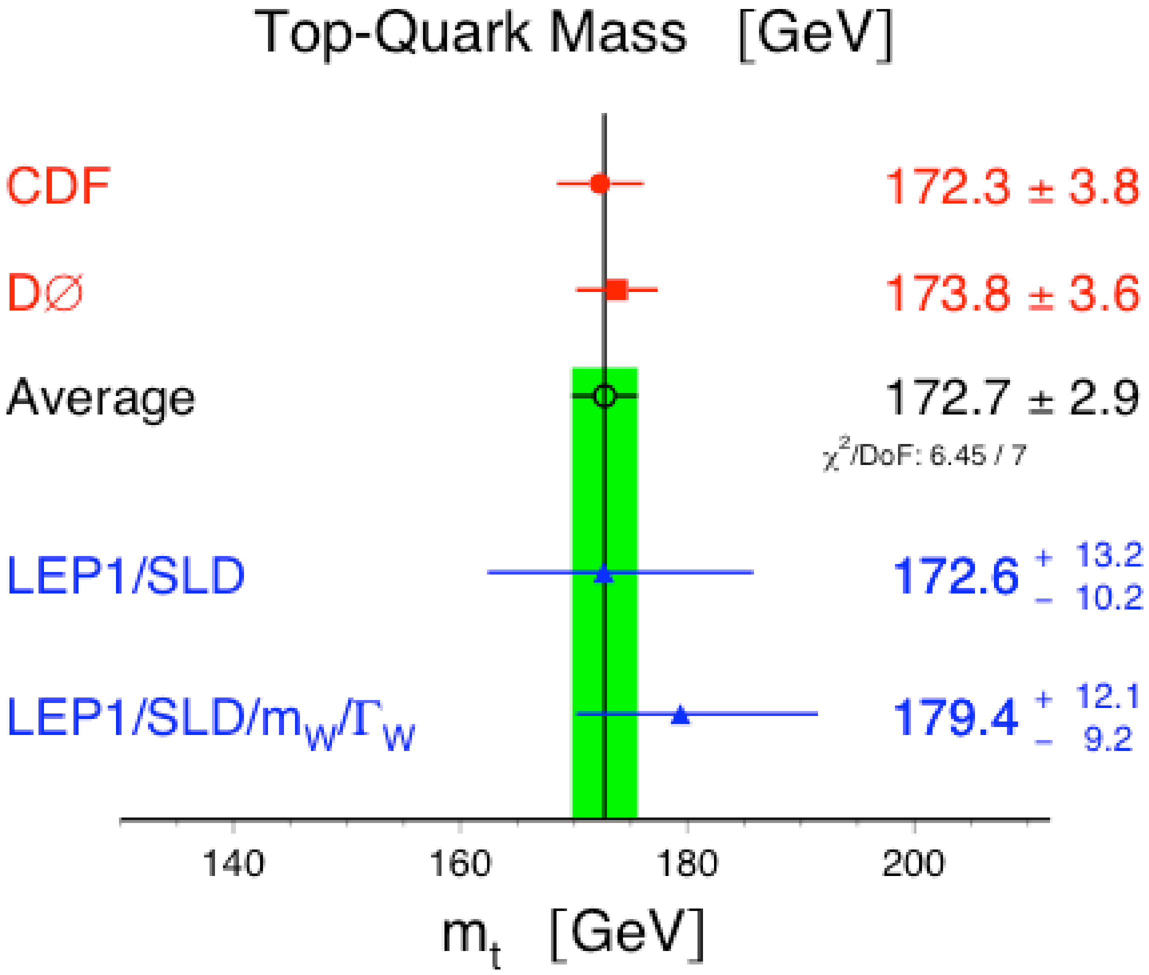
Very good agreement with experiment

Electro-Weak Theory: Precision Tests of SM

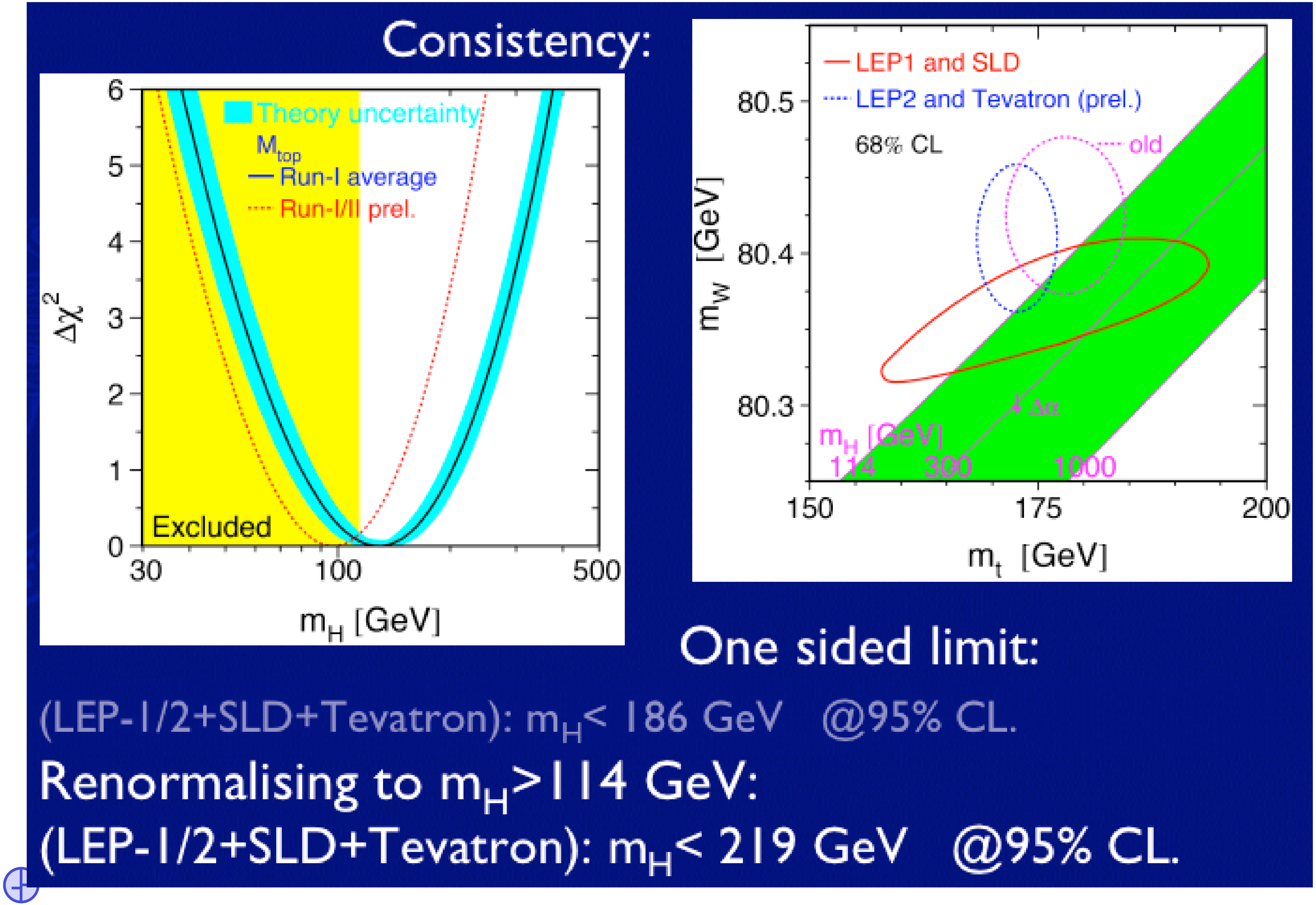
The only appreciable development in this domain is the decrease of the experimental value of m_t from CDF& D0 Run II
(Run I value: 178.0±4.3 GeV)

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

$m_t \downarrow \qquad m_H \downarrow$



de Jong-Lisbon Conf. July'05



Consistency:

One sided limit:

(LEP-1/2+SLD+Tevatron): m_H< 186 GeV @95% CL.

Renormalising to m_H>114 GeV:

(LEP-1/2+SLD+Tevatron): m_H< 219 GeV @95% CL.

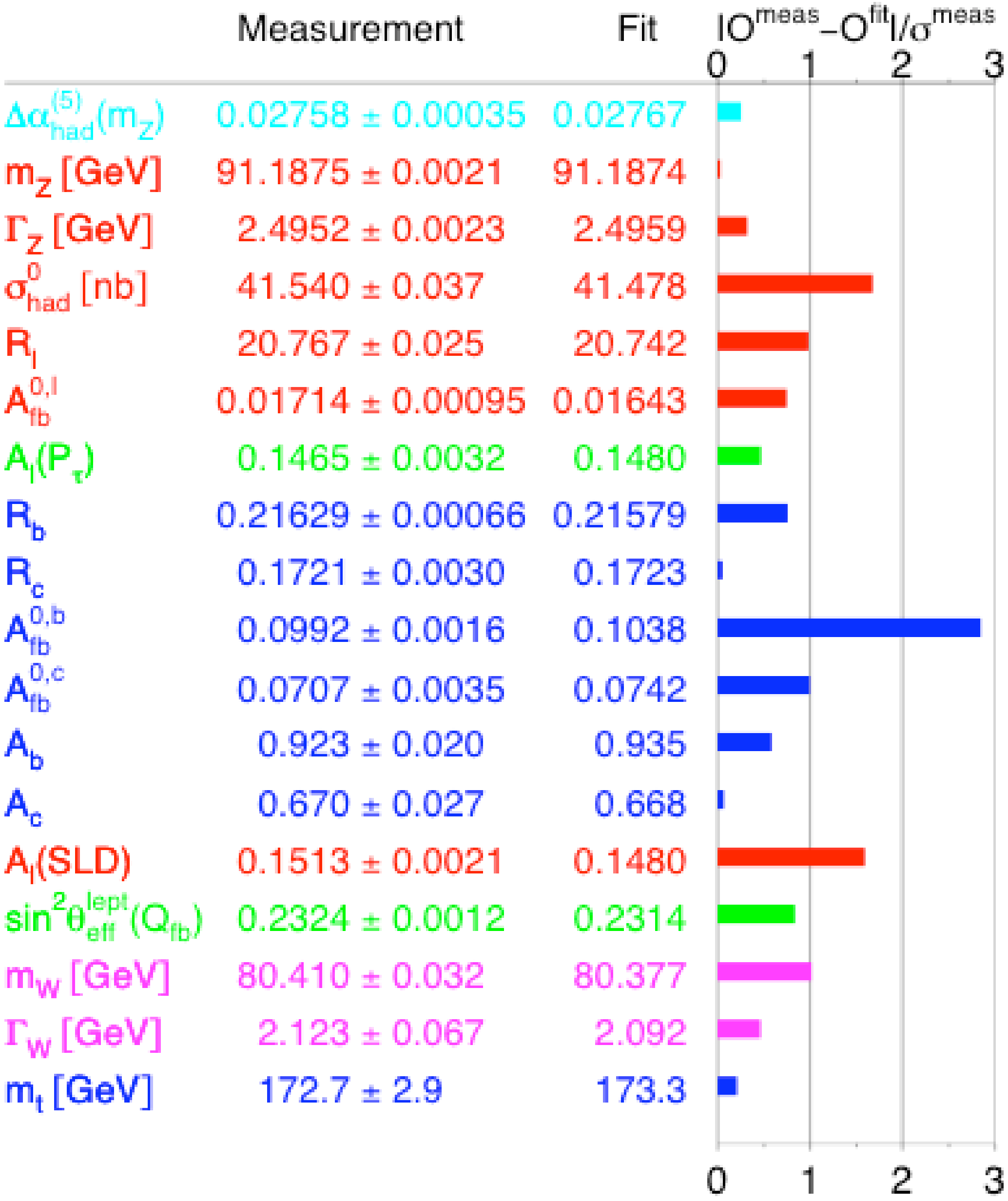
Overall the EW precision tests support the SM and a light Higgs.

The χ^2 is reasonable:

χ^2/ndof~18.6/13 (~14%)

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

Summer 2005



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3

Low Energy Experiments

~3σ away!?

	Observable	Measurement	SM fit
NuTeV	$\sin^2\theta_W$ (νN [10])	0.2277 ± 0.0016	0.2226
APV	$Q_W(\mathrm{Cs})$ (APV [11])	-72.84 ± 0.49	-72.91
Moeller	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (e^-e^- [12])	0.2296 ± 0.0023	0.2314

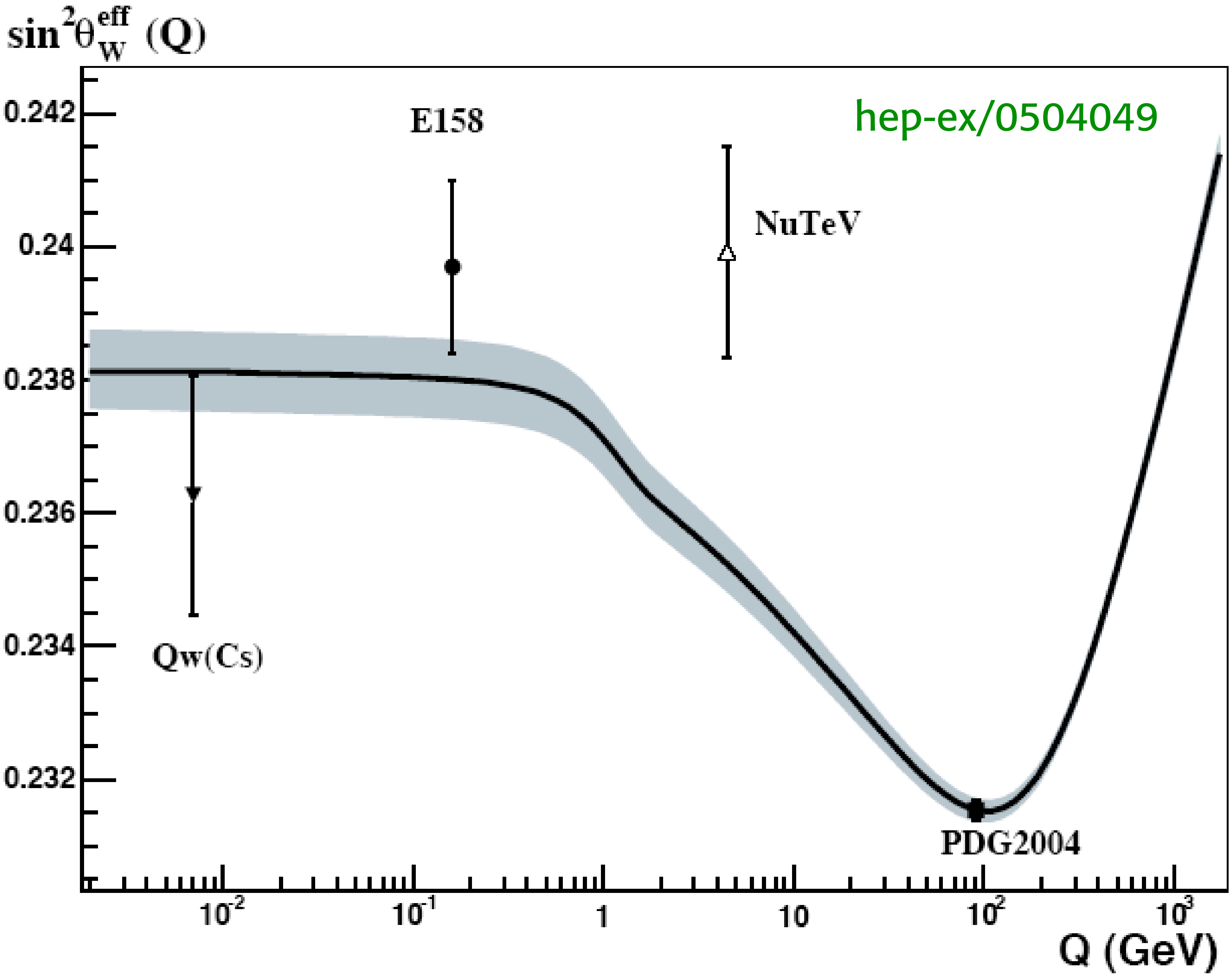
hep-ex/0504049: 0.2330±0.0015

New!!

$$\boxed{A_{PV} = \frac{(\sigma_R - \sigma_L)}{(\sigma_R + \sigma_L)}}$$

recall for comparison:
present WA
$\sin^2\theta_{\mathrm{eff}}$=0.23153 ± 0.00016

(g-2) not included here
[no m_H implications]



hep-ex/0504049

The NuTeV anomaly probably simply arises from a large underestimation of the theoretical error

- The QCD LO parton analysis is too crude to match the required accuracy
- A small asymmetry in the momentum carried by s-sbar could have a large effect

NuTeV claims to have measured this asymmetry from dimuons. But a LO analysis of s-sbar makes no sense and cannot be directly transplanted here

(α_s*valence corrections are large and process dependent)

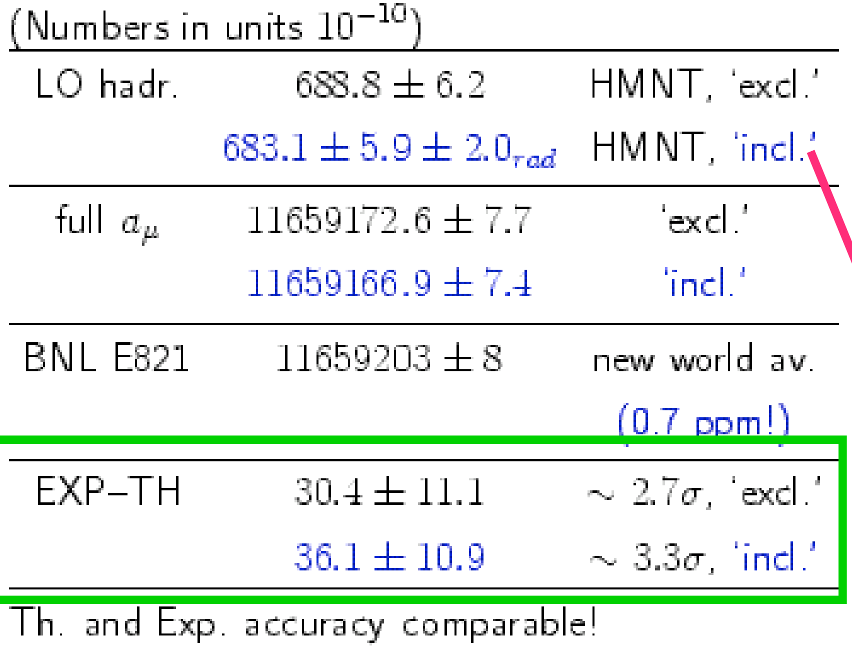
A recent CTEQ fit of s-sbar goes in the right direction.

- A tiny violation of isospin symmetry in parton distrib's can also be important.

S. Davidson, S. Forte, P. Gambino, N. Rius, A. Strumia

$(g-2)_\mu$ ~3σ discrepancy shown by the BNL'02 data

In 2002:



(Numbers in units 10^{-10})

LO hadr.	688.8 ± 6.2	HMNT, 'excl.'
	$683.1 \pm 5.9 \pm 2.0_{rad}$	HMNT, 'incl.'
full a_μ	11659172.6 ± 7.7	'excl.'
	11659166.9 ± 7.4	'incl.'
BNL E821	11659203 ± 8	new world av.
		(0.7 ppm!)
EXP−TH	30.4 ± 11.1	$\sim 2.7\sigma$, 'excl.'
	36.1 ± 10.9	$\sim 3.3\sigma$, 'incl.'

Th. and Exp. accuracy comparable!

EW ~ 15.2±0.4

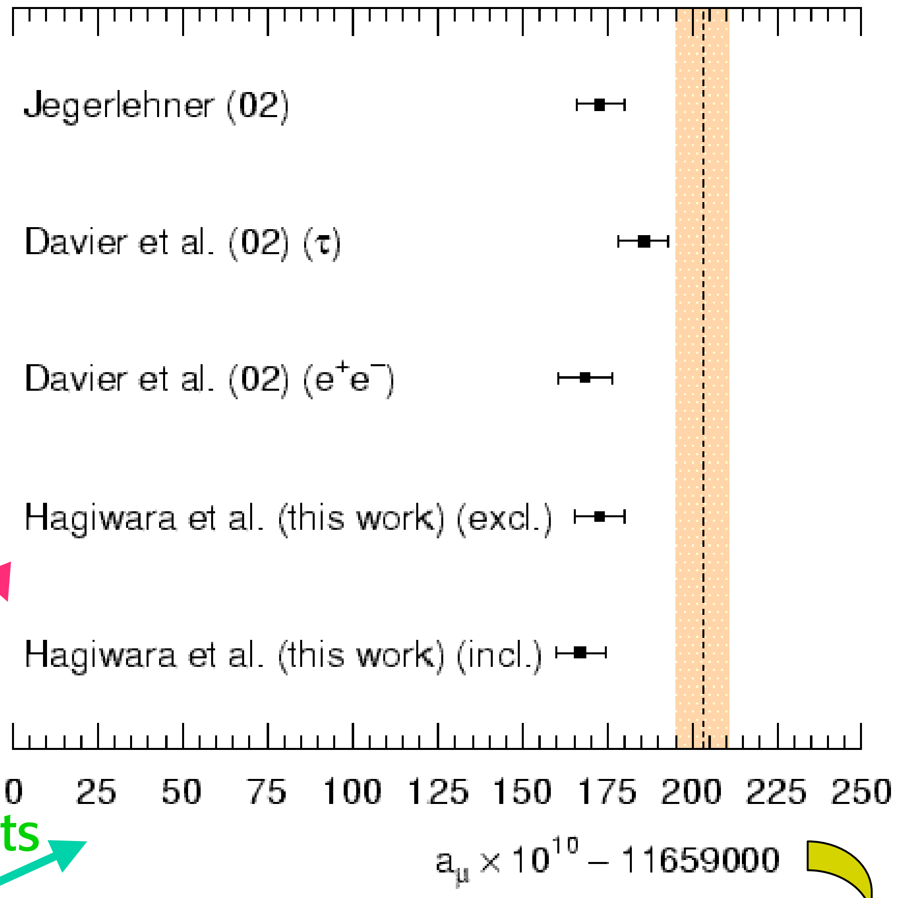
LO hadr ~ 683.1±6.2

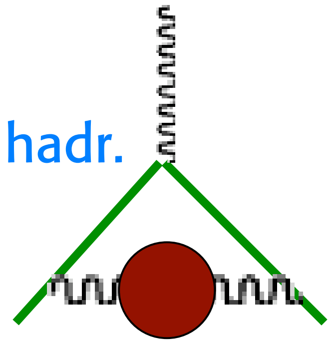
NLO hadr ~ -10±0.6

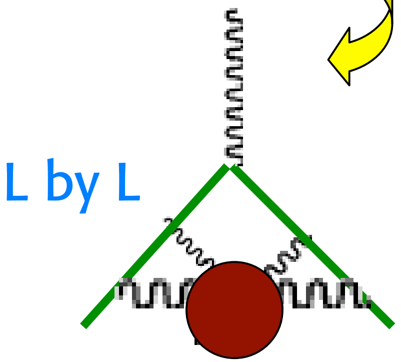
Light-by-Light ~ 8±4

(was ~ -8.5±2.5)

These units



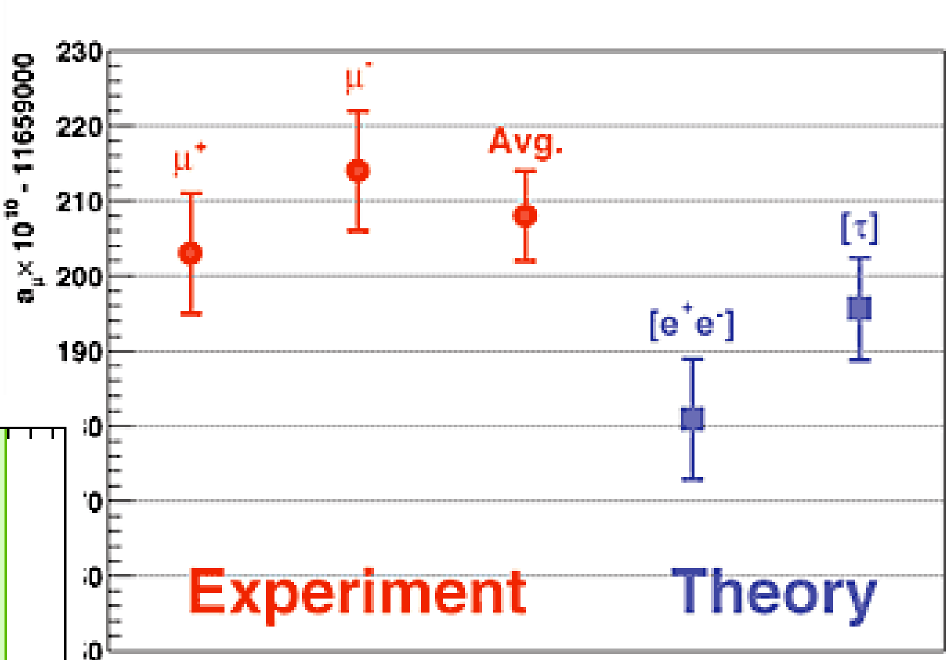


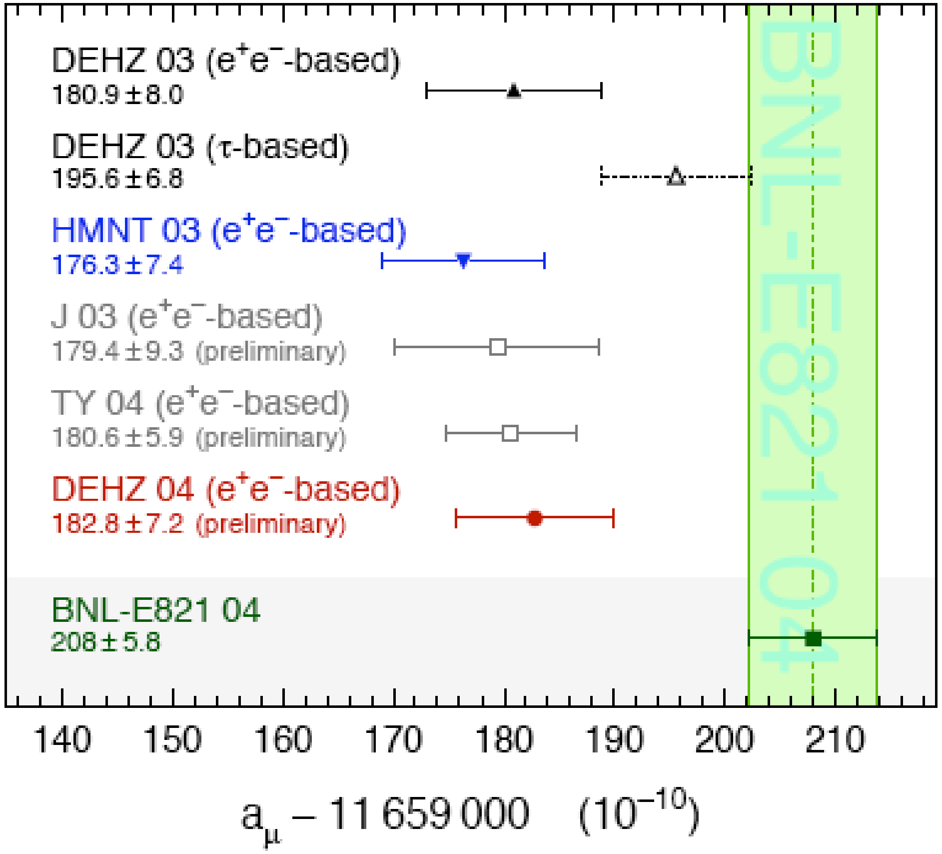


2004

New results from BNL

- μ^- measured
  (was μ^+)
- discrepancy up again
  to 2.7σ (e^+e^-)

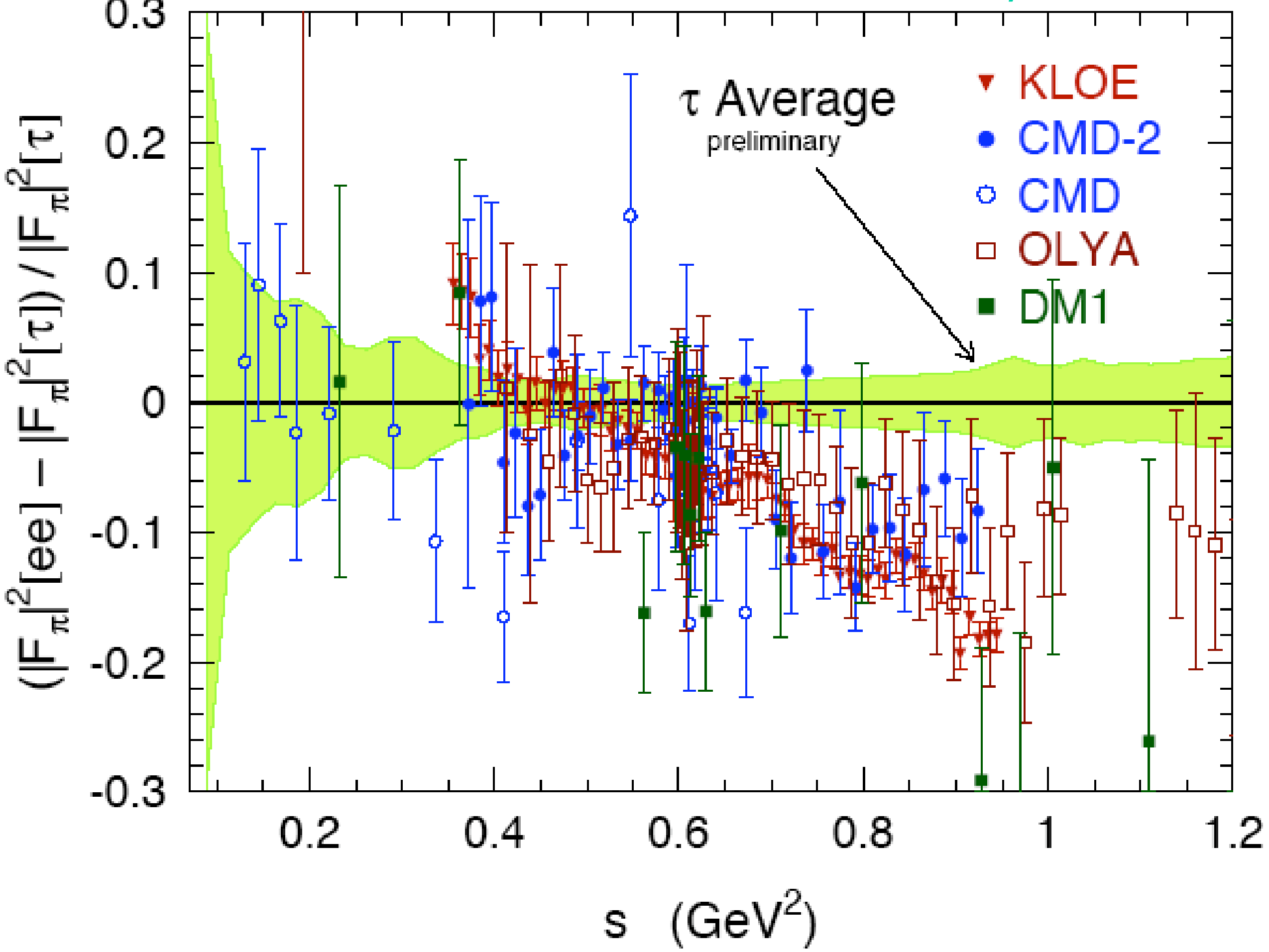




ICHEP'04

There is a persistent discrepancy between the τ and e+e- data (after correcting for V-A vs V, isospin rotation...)

Hocker, ICHEP'04



τ decay would indicate no significant deviation, while e+e- -> 2.7 σ (more direct)

Question Marks on EW Precision Tests

- The measured values of $\sin^2\theta_{eff}$ from leptonic (A_{LR}) and from hadronic (A^b_{FB}) asymmetries are $\sim 3\sigma$ away

- The measured value of m_W is a bit high

  (now worse because m_t went down)

- The central value of m_H ($m_H = 91+45-32$ GeV) from the fit is close to the direct lower limit ($m_H > 114.4$ GeV at 95%) [more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm. $m_H = 56+34-22$ GeV] (worse now than in the past)

A well known issue:

2001: Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Status of $\sin^2\theta_{eff}$

Combined lept. asymm.:

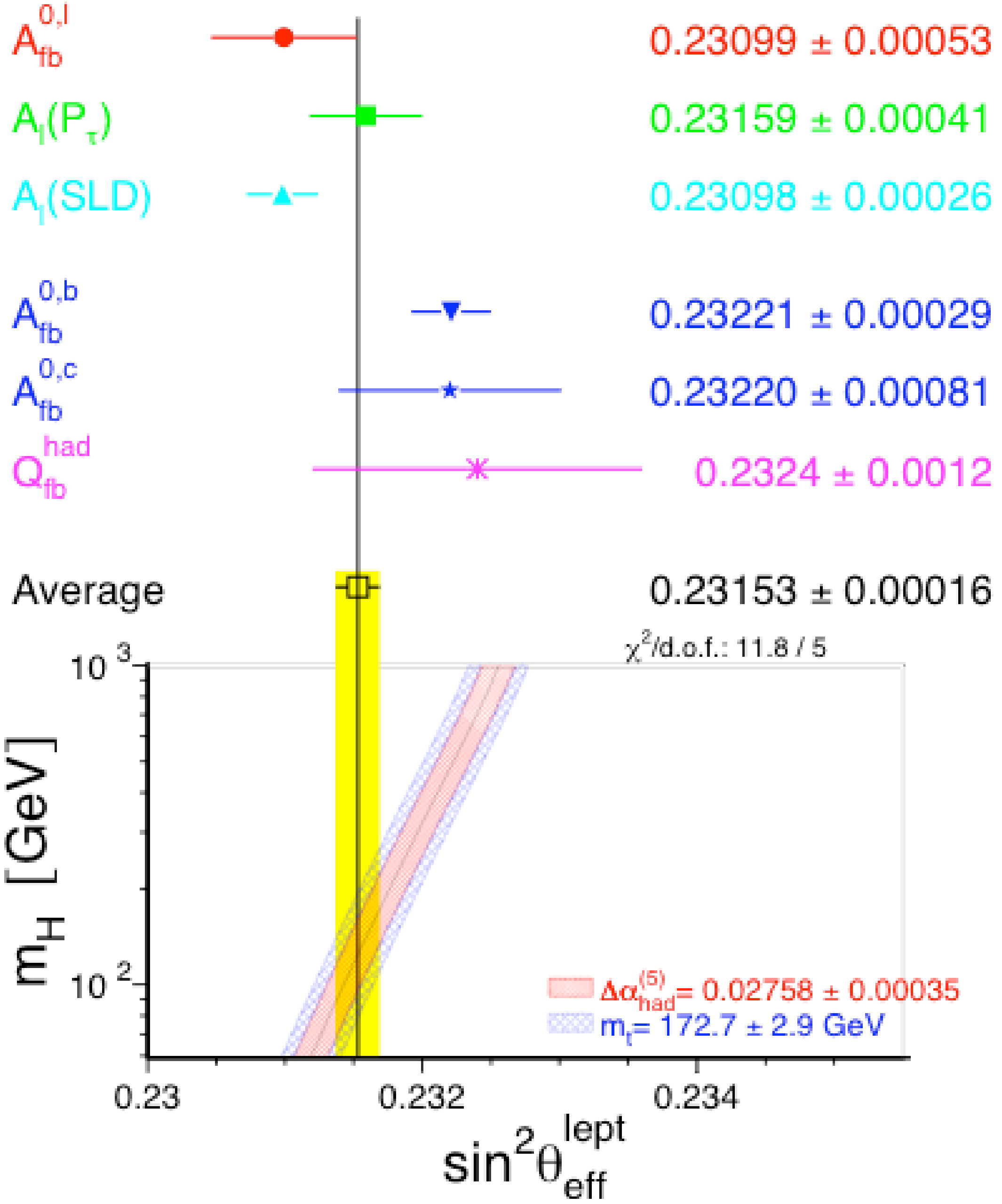
$[\sin^2\theta]_{lept}$=0.23113(21)

Combined hadr. asymm.:

$[\sin^2\theta]_{hadr}$=0.23222(27)

diff = 3.2 σ

Essentially the discrepancy is between A_l(SLC) & A_{fb}^{0b}



Recently the combined value of A^b_{FB} has moved a bit in the wrong direction

Cause: Discovery of omission in ZFITTER of a small 2- loop term for b-quarks

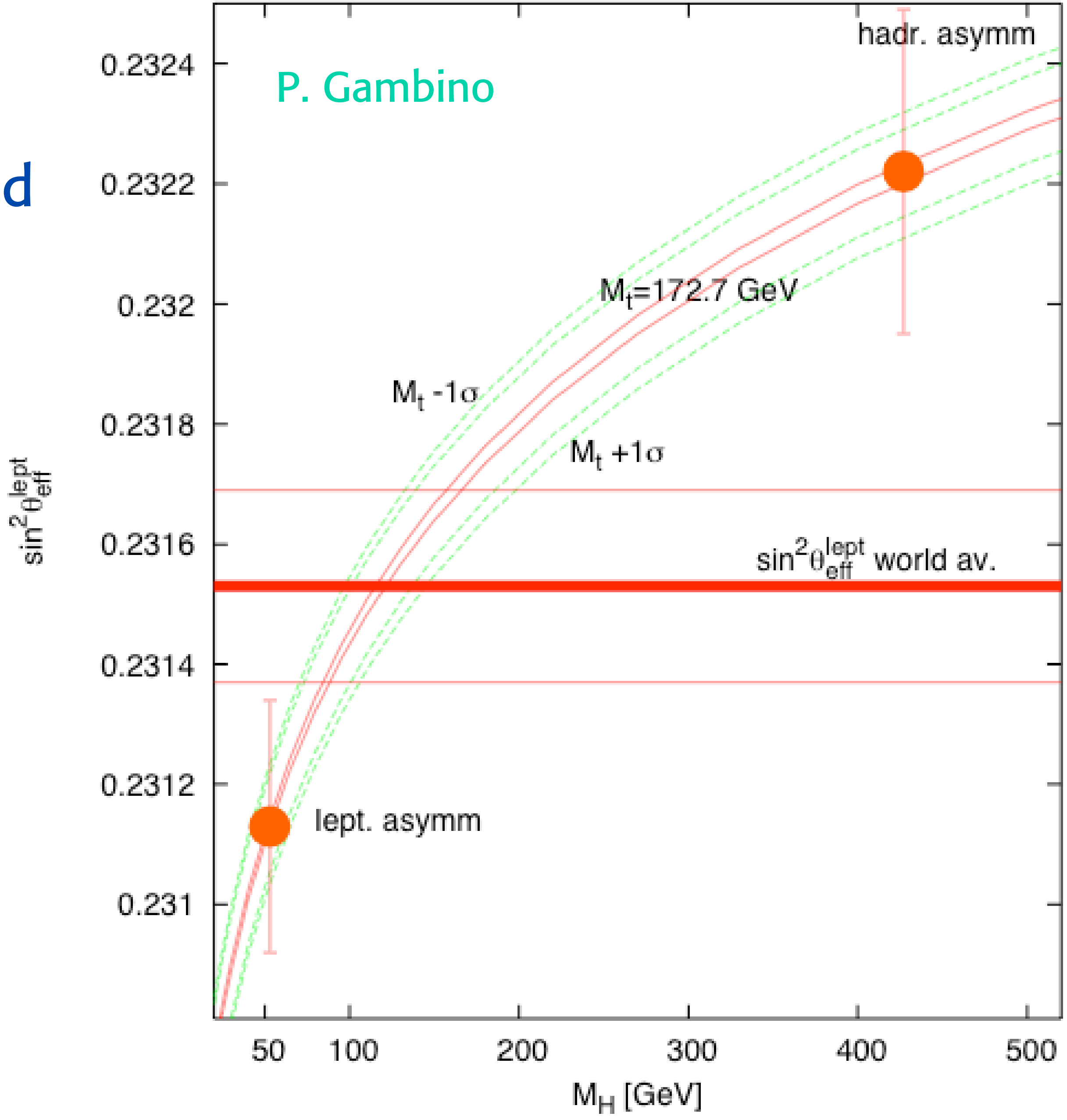
Effect: $A^b_{FB} = 0.0998 \pm 0.0017$ becomes 0.0992 ± 0.0016

The discrepancy $[\sin^2\theta]_{hadr}$-$[\sin^2\theta]_{lept}$ goes from 2.8 to 3.2σ

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

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



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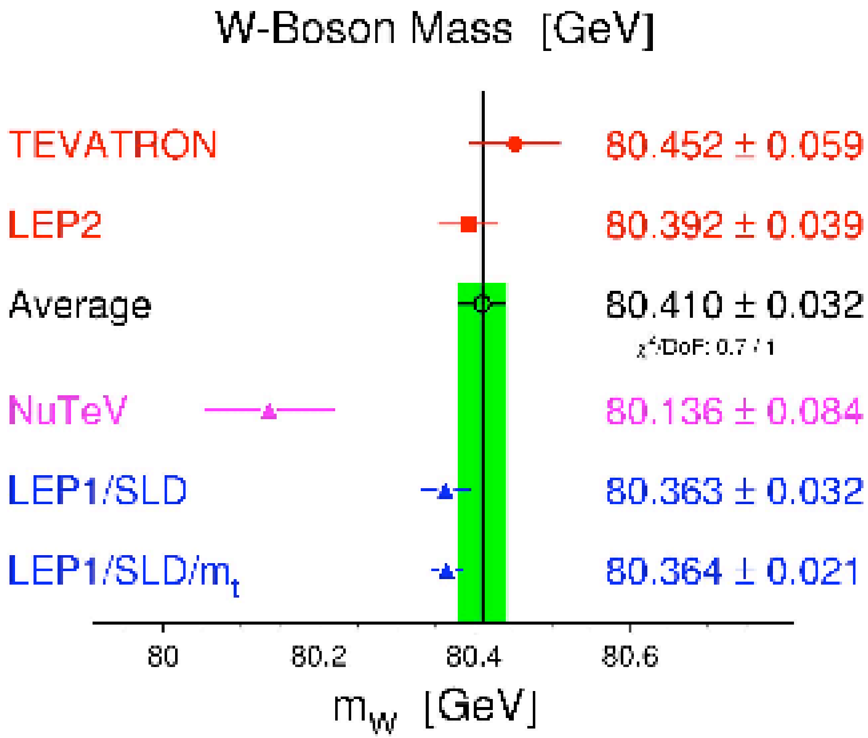
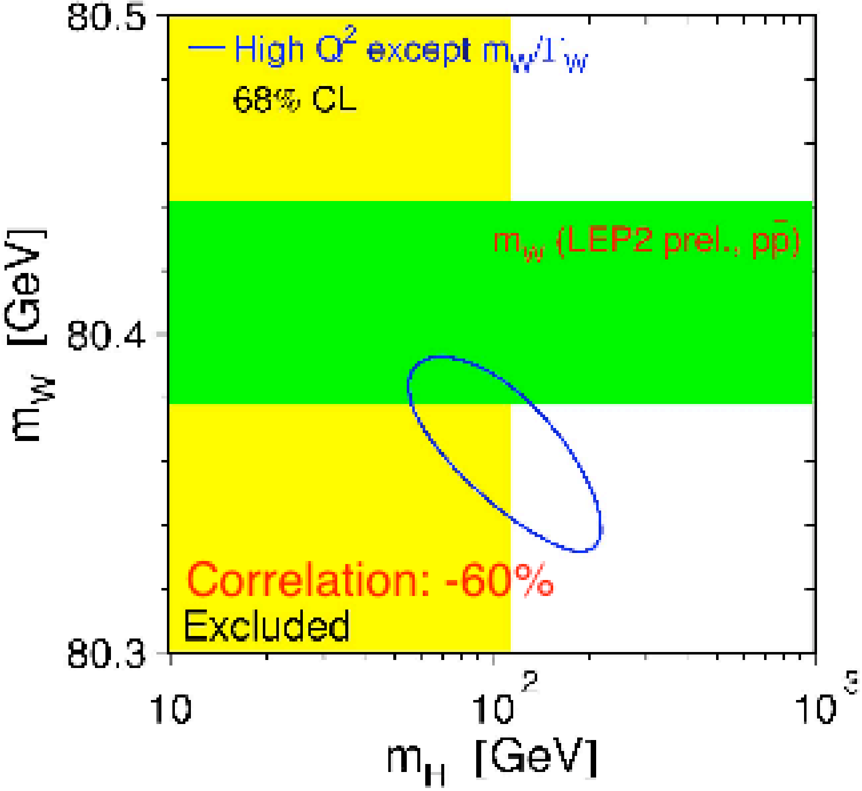
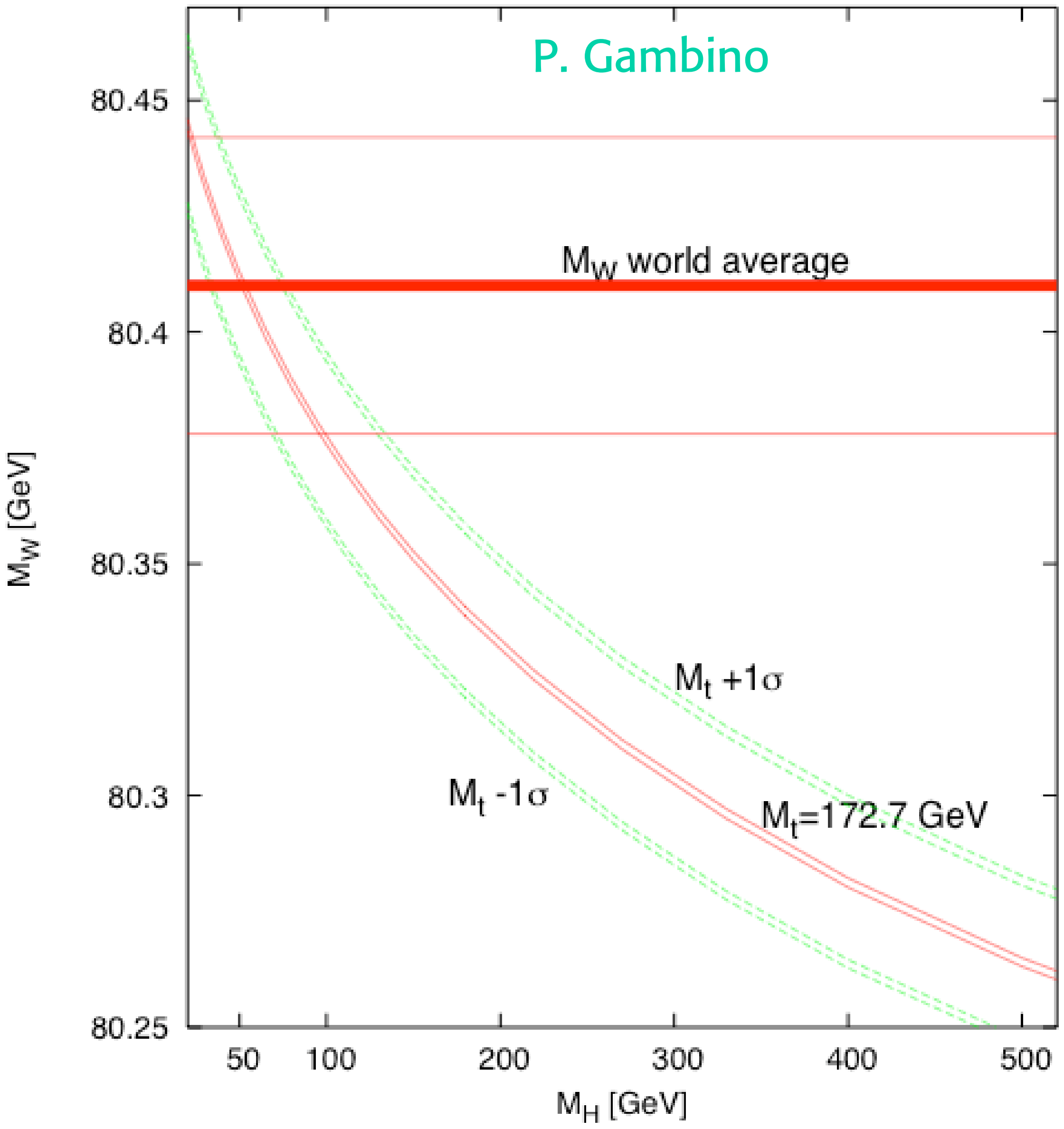




Plot m_W vs m_H

m_W points to a light Higgs!

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



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A well known issue:

2001: Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Not a significant indication of a problem

However, since new physics at the EW scale could well be around, one looks with interest at every possible hint

Status of the SM Higgs fit

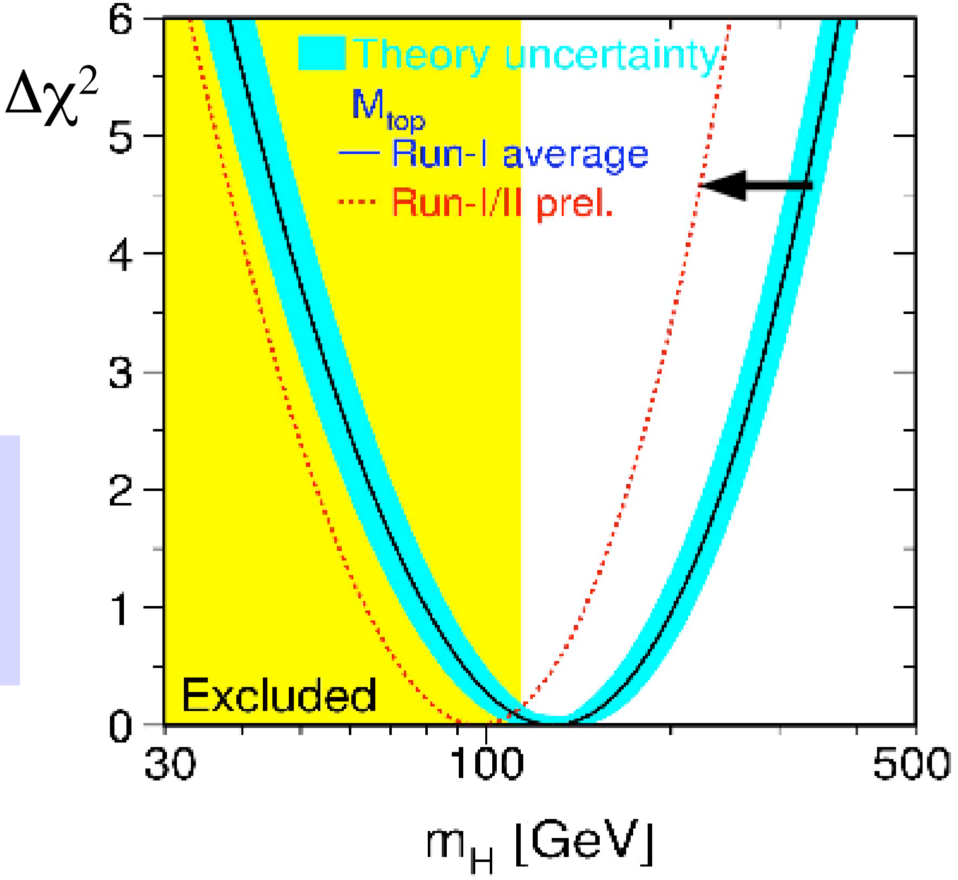
Summer '05

Sensitive to log m_H

Rad Corr.s ->
$\log_{10} m_H(\mathrm{GeV}) = 1.96 \pm 0.18$

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

Direct search: $m_H > 114$ GeV



At 95% cl
$m_H < 186$ GeV (rad corr.'s)
$m_H < 219$ GeV (incl. direct search bound)

Fit results

Summer '05

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

	m_W	m_t	m_W, m_t
m_t(GeV)	179.4±10.6	172.7±2.8	173.3±2.7
m_H(GeV)	148+248-83	112+62-41	91+45-32
log[m_H(GeV)]	2.17±0.39	2.05 ± 0.20	1.96± 0.18
$\alpha_s(m_Z)$	0.1190(28)	0.1190 (27)	0.1186 (27)
χ^2/dof	17.3/12	16.0/11	17.8/13
m_W(MeV)	80387(22)	80364(21)	80390(18)

WA: m_W=80425(34)

$\log_{10} m_H \sim 2$ 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 change the prediction of finite terms.

The most sensitive quantities to $\log m_H$ are $\varepsilon_1 \sim \Delta\rho$ and ε_3:

$\log_{10} m_H \sim 2$ 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 $f_{1,2}$)

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

The flavour problem

- Light Higgs -> New physics at ~ 1 TeV
- But all effective non rinorm. vertices for FCNC have bounds above a few TeV

Apparently the SM soppression of FCNC is only mildly modified by new physics:
an intriguing mystery and a major challenge for models of new physics

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
- •••••

If you take all these clues I think that SUSY is still the best known solution (vacuum energy is unsolved by all)

Conceptual problems of the SM

Most clearly:

- No quantum gravity ($M_{Pl} \sim 10^{19}$ GeV)
- But a direct extrapolation of the SM leads directly to GUT's ($M_{GUT} \sim 10^{16}$ GeV)

M_{GUT} close to M_{Pl}

- suggests unification with gravity as in superstring theories
- poses the problem of the relation m_W vs M_{GUT}- M_{Pl}

Can the SM be valid up to M_{GUT}- M_{Pl}??

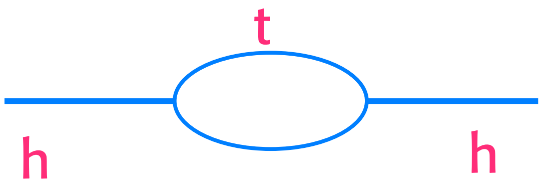
← The hierarchy problem

Not only it looks very unlikely, but the new physics must be near the weak scale!

For the low energy theory: the “little hierarchy” problem:

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

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



$$\delta m^2_{h|top} = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim (0.3\Lambda)^2$$

This hierarchy problem demands new physics near the weak scale

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

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: 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 are not directly visible

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of $\delta\mu^2$

  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

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

  "Little Higgs" models. Problems with EW precision tests

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

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

- Ignore the problem: invoke the anthropic principle

SUSY at the Fermi scale

- Many theorists consider SUSY as established at M_{Pl} (superstring theory).
- Why not try to use it also at low energy to fix some important SM problems.
- Possible viable models exists:
  - MSSM softly broken with gravity mediation
    - or with gauge messengers
    - or with anomaly mediation
    - …
- Maximally rewarding for theorists
  - Degrees of freedom identified
  - Hamiltonian specified
  - Theory formulated, finite and computable up to M_{Pl}

Unique!

Fully compatible with, actually supported by GUT's
Good Dark Matter candidates

But: Lack of SUSY signals at LEP + lower limit on m_H

→ problems for minimal SUSY

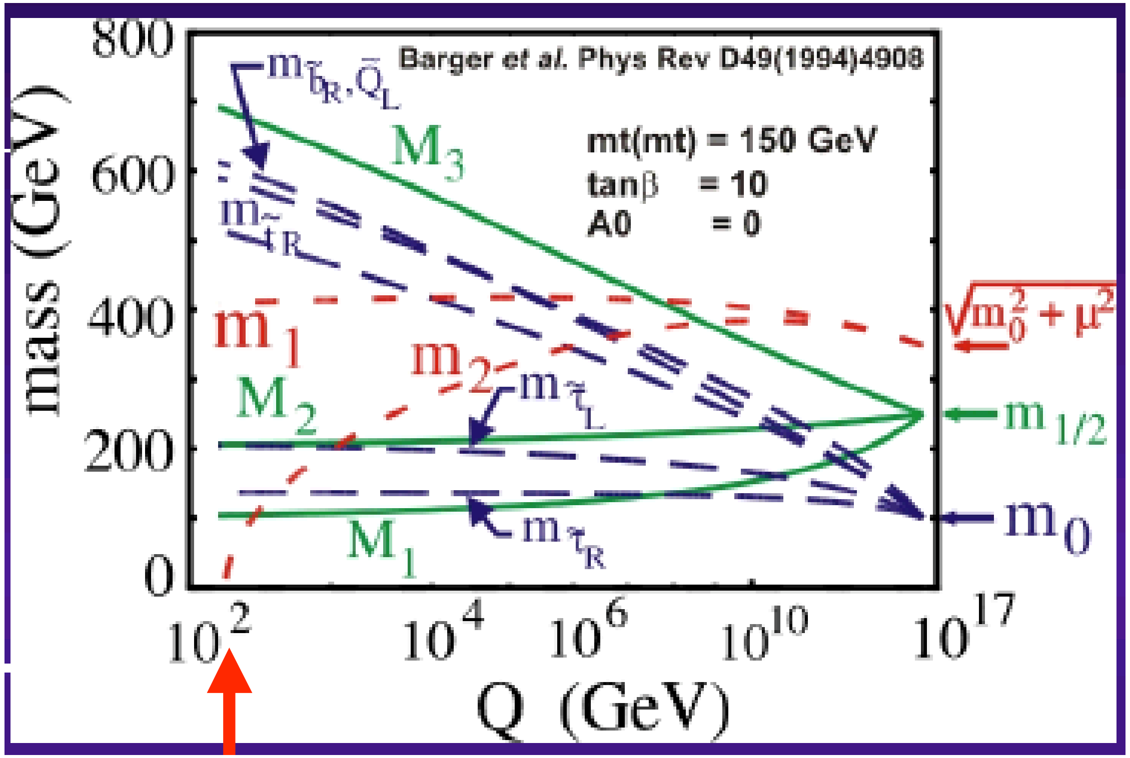
m_{stop} large tends to clash with $\delta m_h^2 \sim m_{stop}^2$

- In MSSM: $$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3\alpha_w m_t^4}{4\pi m_W^2 \sin^2\beta} \ln\frac{\tilde{m}_t^4}{m_t^4} < \sim 130 \text{ GeV}$$

So $m_H > 114$ GeV considerably reduces available parameter space.

- In SUSY EW symm. breaking is induced by H_u running

Exact location implies constraints



m_Z can be expressed in terms of SUSY parameters

For example, assuming universal masses at M_{GUT} for scalars and for gauginos

$$m_Z^2 \approx c_{1/2} m_{1/2}^2 + c_0 m_0^2 + c_t A_t^2 + c_\mu \mu^2$$

$c_a = c_a(m_t, \alpha_i, \ldots)$

Clearly if $m_{1/2}$, m_0,... >> m_Z: Fine tuning!

LEP results (e.g. $m_{\chi+}$ >~100 GeV) exclude gaugino universality if no FT by > ~20 times is allowed

Without gaugino univ. the constraint only remains on m_{gluino} and is not incompatible

$$m_Z^2 \approx 0.7 m_{gluino}^2 + \ldots$$

Barbieri, Giudice; de Carlos, Casas; Barbieri, Strumia; Kane, King; Kane, Lykken, Nelson, Wang......

[Exp. : m_{gluino} >~200GeV]

Residual FT could be alleviated by going to a non minimal model e.g adding an extra Higgs singlet (NMSSM)

SUSY fits with GUT's

- **Coupling unification:** Precise matching of gauge couplings at M_{GUT} fails in SM and is well compatible in SUSY

From $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$ measured at LEP predict $\alpha_s(m_Z)$ for unification (assuming desert)

Non SUSY GUT's
$\alpha_s(m_Z)=0.073\pm0.002$

SUSY GUT's
$\alpha_s(m_Z)=0.130\pm0.010$

Langacker, Polonski

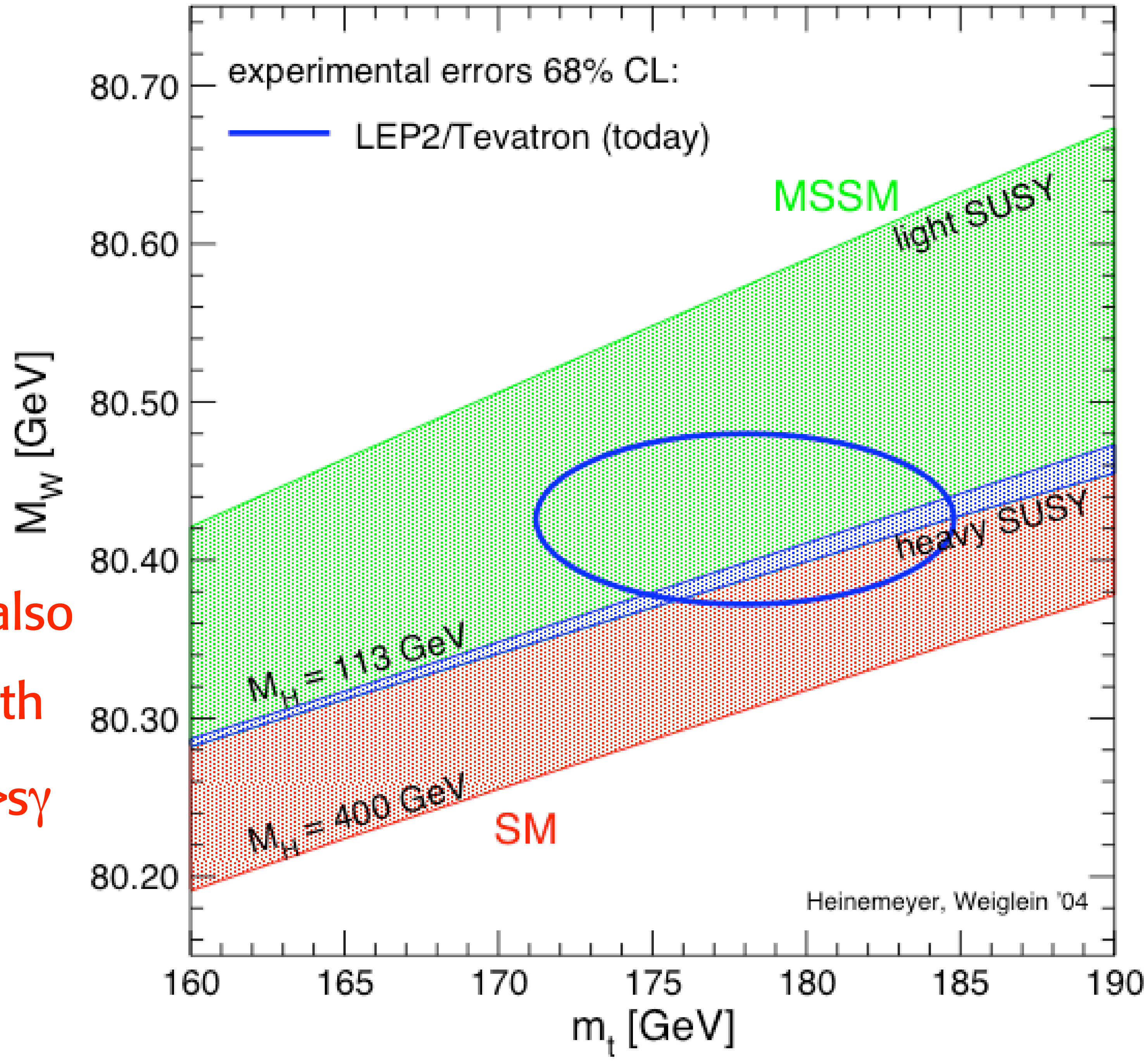
EXP: $\alpha_s(m_Z)=0.119\pm0.003$
Present world average

Dominant error:
thresholds near M_{GUT}

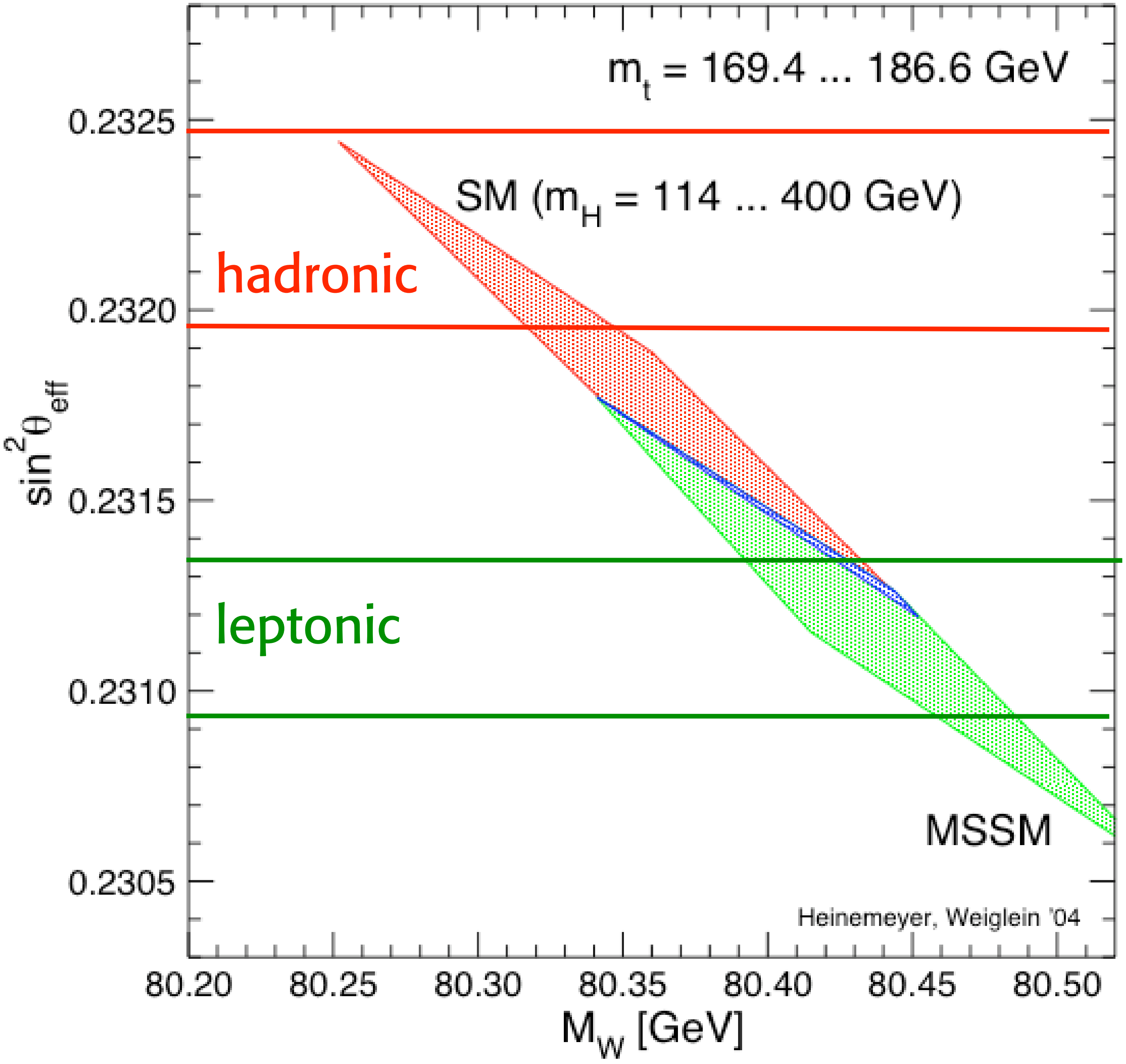
- **Proton decay:** Far too fast without SUSY

- M_{GUT} ~ 10^{15}GeV non SUSY ->10^{16}GeV SUSY
- Dominant decay: Higgsino exchange

While GUT's and SUSY very well match, (best phenomenological hint for SUSY!) in technicolor , large extra dimensions, little higgs etc., there is no ground for GUT's



Light SUSY is also compatible with $(g-2)_\mu$ and $b \to s\gamma$

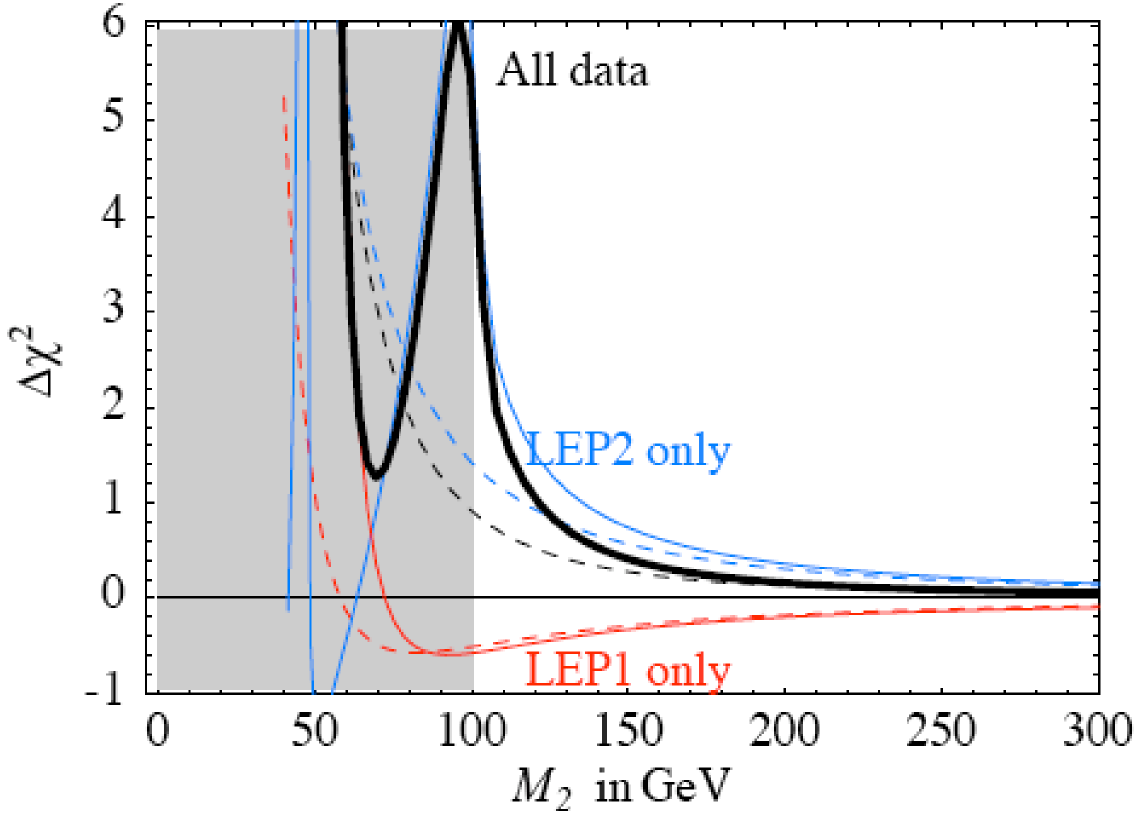

m_t = 169.4 ... 186.6 GeV
SM (m_H = 114 ... 400 GeV)
hadronic
leptonic
MSSM
Heinemeyer, Weiglein '04
$\sin^2\theta_{eff}$
0.2325
0.2320
0.2315
0.2310
0.2305
80.20
80.25
80.30
80.35
80.40
80.45
80.50
M_W [GeV]

Recent:

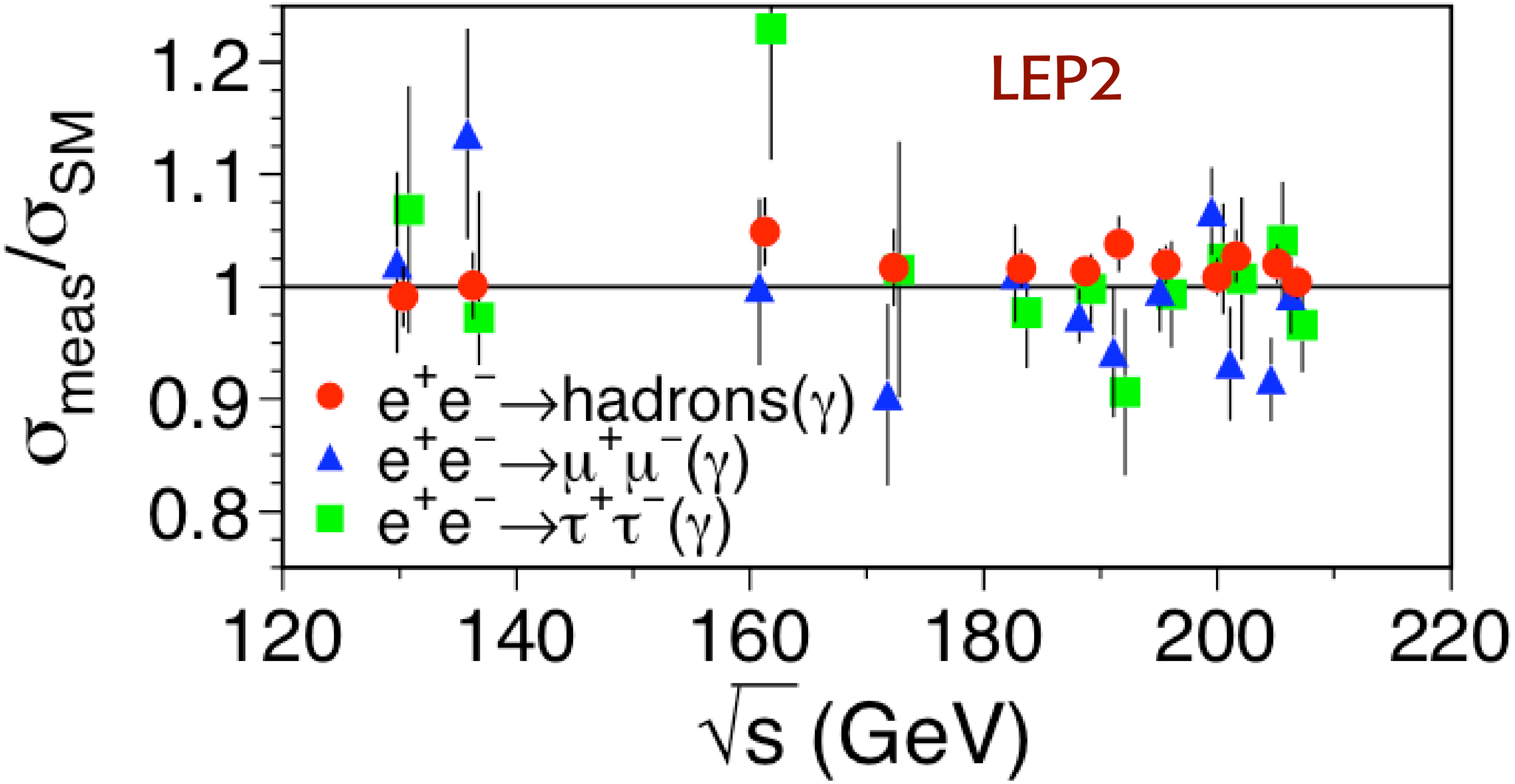
However, LEP2 data do not support the virtual effects of light SUSY Marandella, Shappacher, Strumia

When including LEP2: ε1, ε2, ε3 --> $\hat{S}, \hat{T}, W, Y$

Barbieri, Pomarol, Rattazzi, Strumia



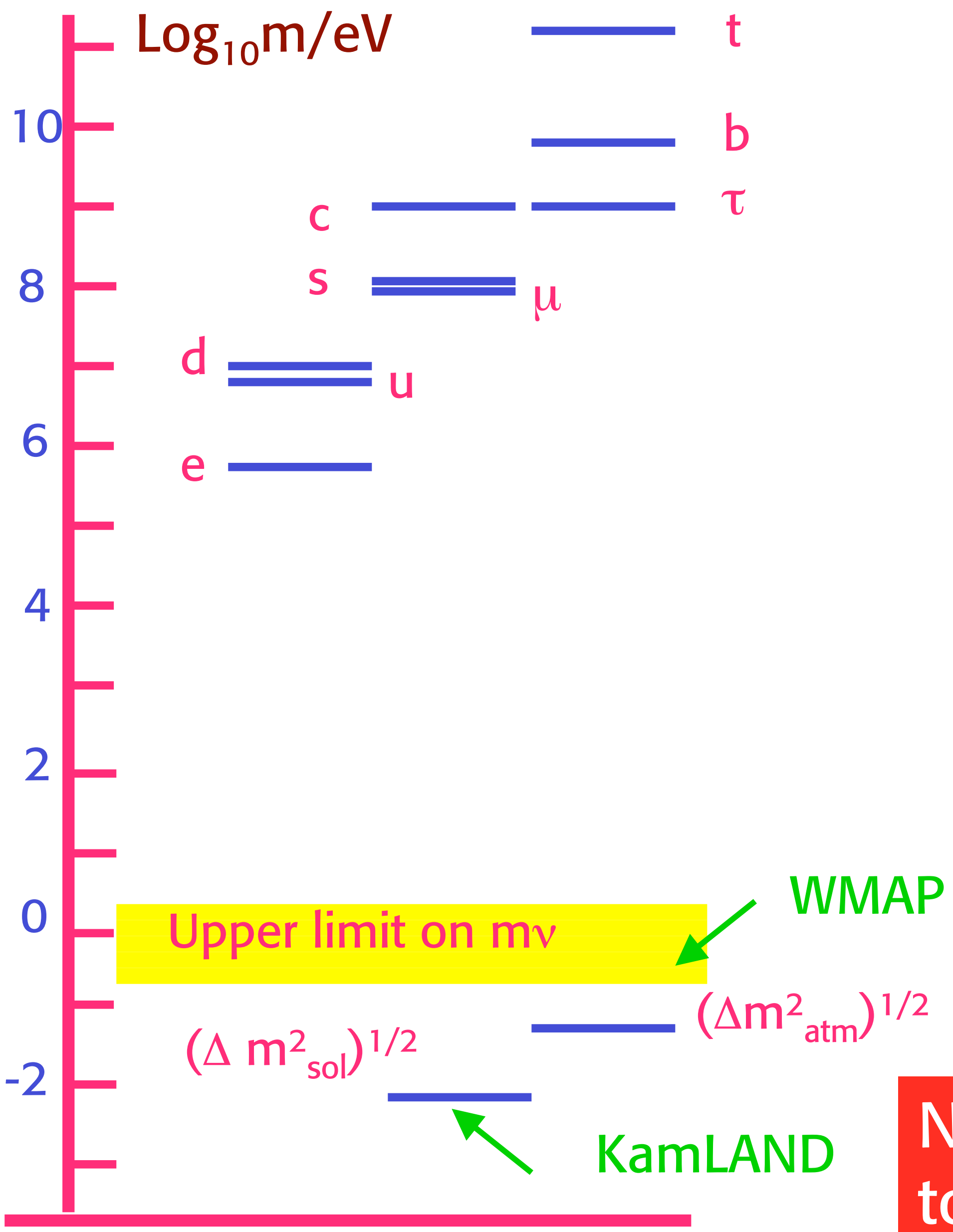
A 1.7σ excess in the hadronic cross-section at LEP2



Virtual light SUSY effects would go in the opposite direction.
But this effect looks too large to be a virtual SUSY effect
(a 2% effect is like increasing α_s by a factor 1.5)

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

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 $M \sim M_{GUT}$

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

$m \sim m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

$$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05 \text{ eV}$$
$$m \sim v \sim 200 \text{ GeV}$$

$$M \sim 10^{15} \text{ GeV}$$

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

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

indeed add considerable support to this idea.

Technicolor, Little Higgs, Extra dim….: nearby cut-off. Problem of suppressing

$$O_5 = \nu_L^T \frac{\lambda}{M} \nu_L HH$$

Another big plus of neutrinos is the elegant picture of baryogenesis thru leptogenesis

(after LEP has disfavoured BG at the weak scale)

Baryogenesis A most attractive possibility:

BG via Leptogenesis near the GUT scale

T ~ $10^{12\pm3}$ GeV (after inflation)

Buchmuller,Yanagida,
Plumacher, Ellis, Lola,
Giudice et al, Fujii et al
…..

Only survives if Δ(B-L)is not zero
(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R (M~10^{12} GeV)

L non conserv. in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from ν oscill's is compatible with BG via (thermal) LG

In particular the bound
was derived for hierarchy

$m_i < 10^{-1}$ eV

Buchmuller, Di Bari, Plumacher;
Giudice et al; Pilaftsis et al;
Hambye et al

Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

Dark Matter

WMAP

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.044$, $\Omega_m \sim 0.27$
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: $\Omega_\nu < 0.015$ (WMAP)

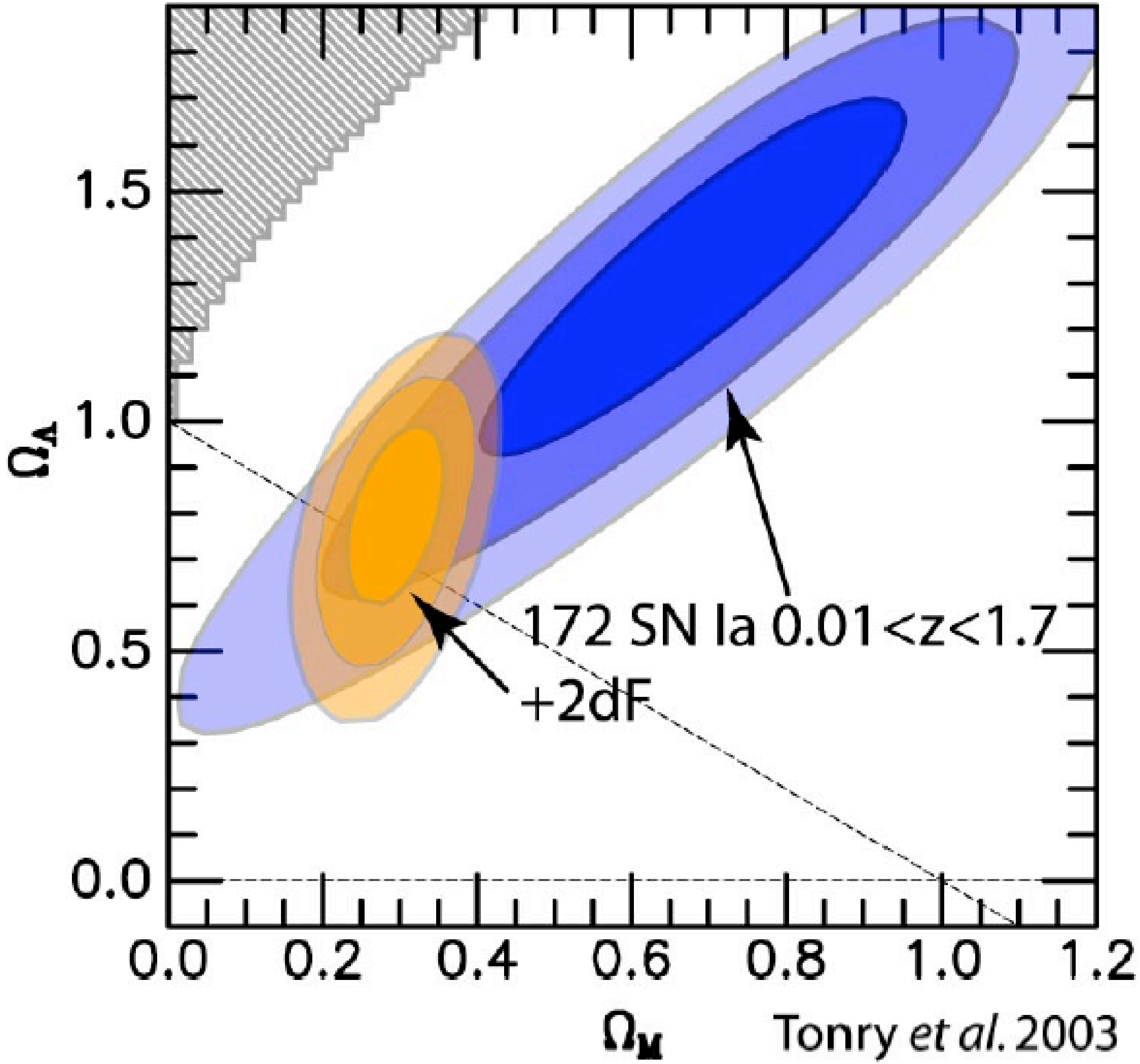
SUSY has excellent DM candidates: Neutralinos (--> LHC)
Also Axions are still viable
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

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

LHC?

Supernova
Cosmology
Project

High-z SN
Search Team



Tonry *et al.* 2003

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

WIMP: weakly interacting particle with m ~ 10^1-10^3 GeV

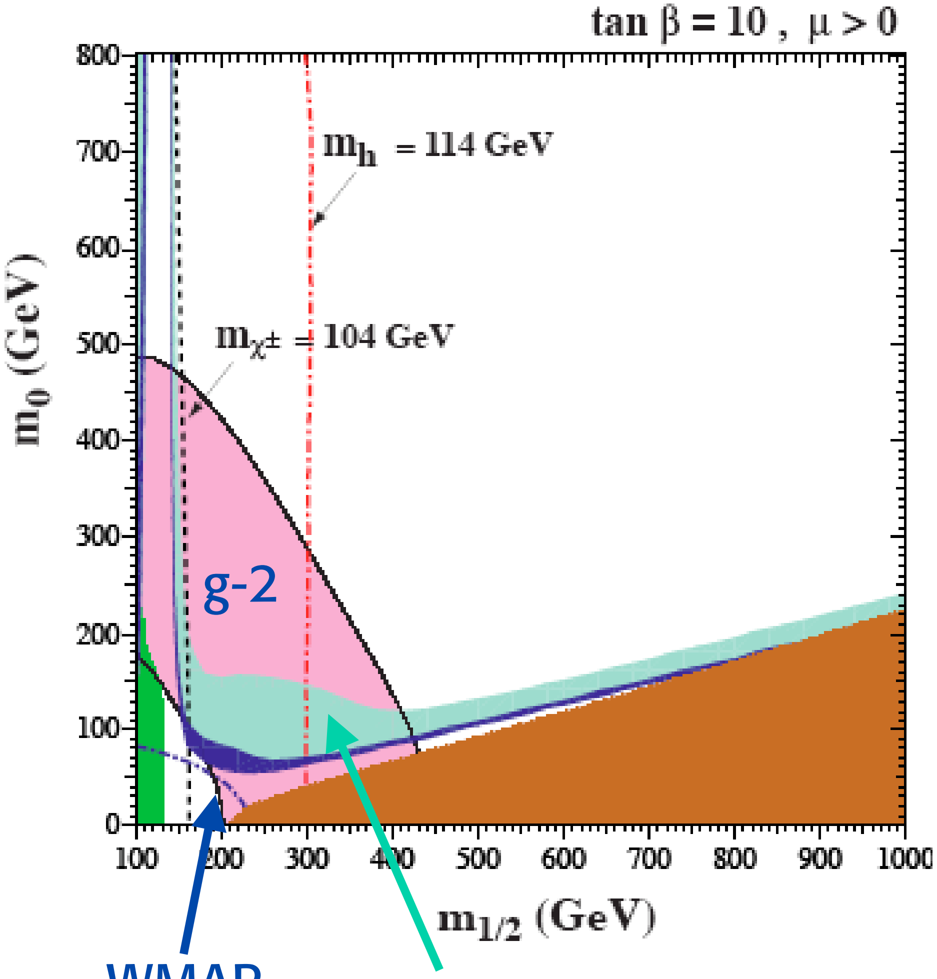
For WIMP's in thermal equilibrium after inflation the density is:

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

can work for typical weak cross-sections!!!

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

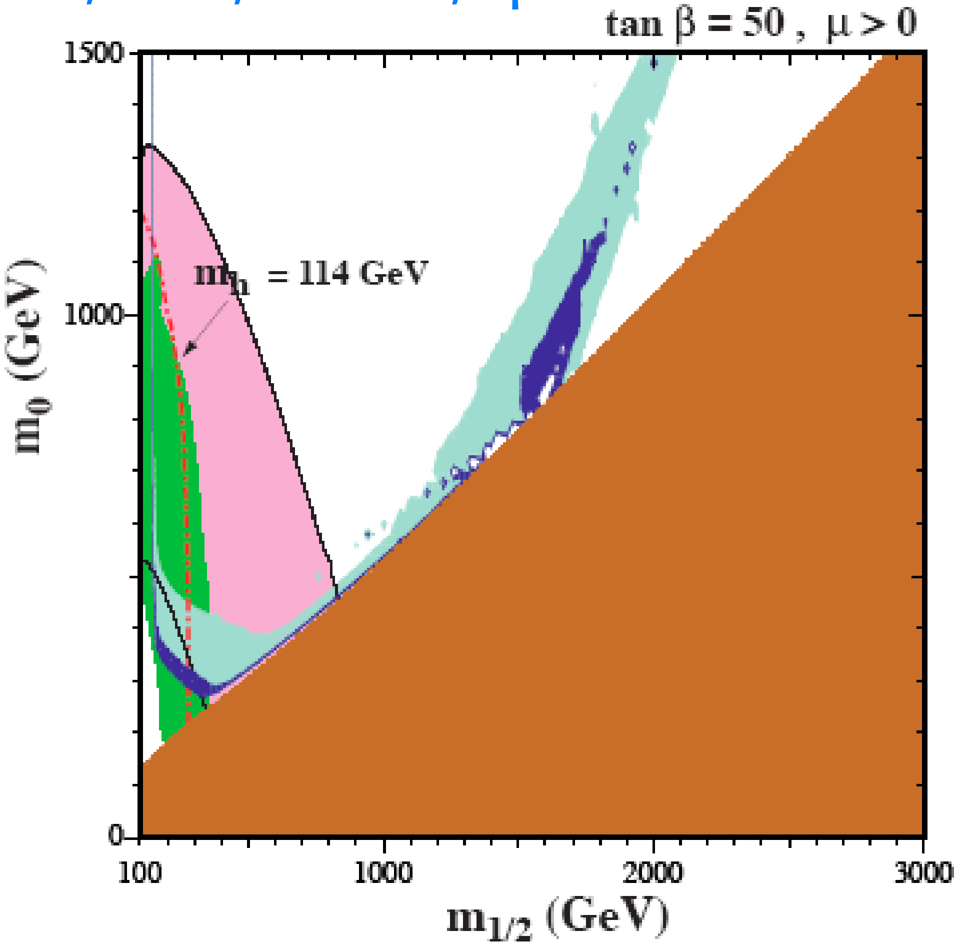
SUSY Dark Matter: we hope it is the neutralino



WMAP

$0.1<\Omega h^2<0.3$

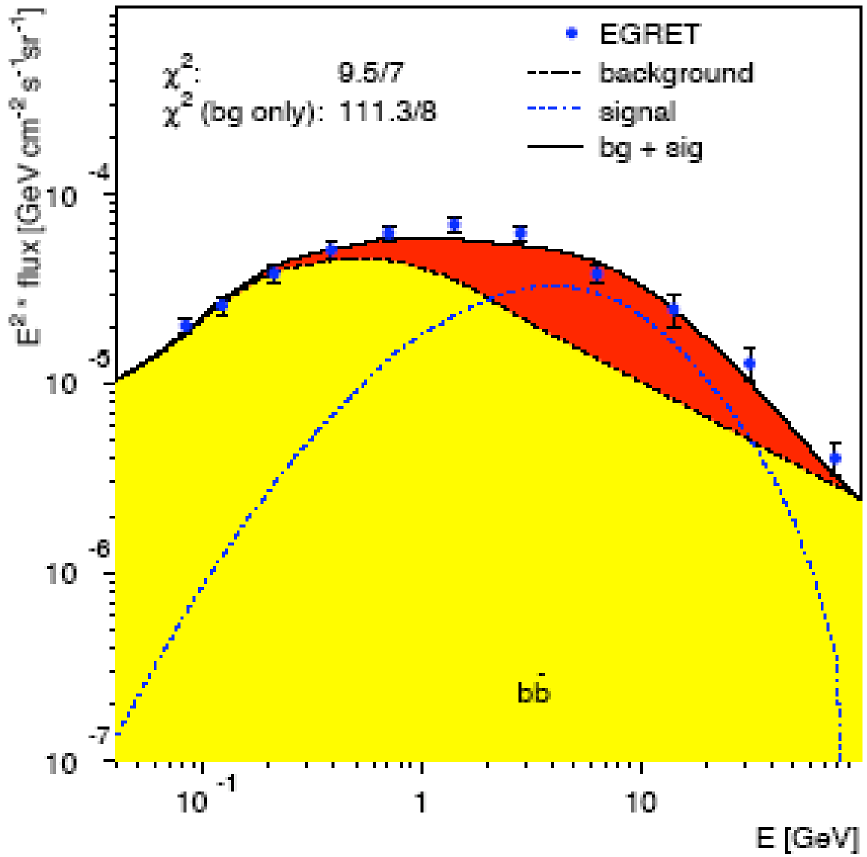
Ellis, Olive, Santoso, Spanos



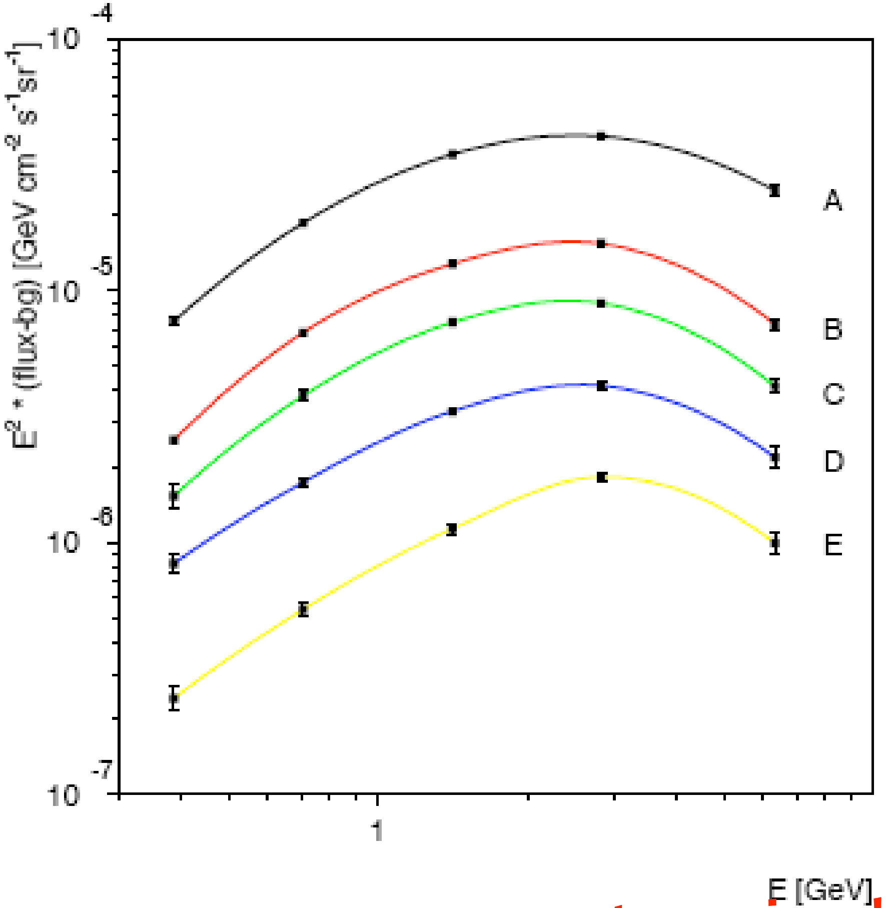
This is for the CMSSM
With less constraints more space

EGRET excess of diffuse gamma rays is compatible with neutralino Dark Matter

De Boer; De Boer, Herold, Sander, Zhukov

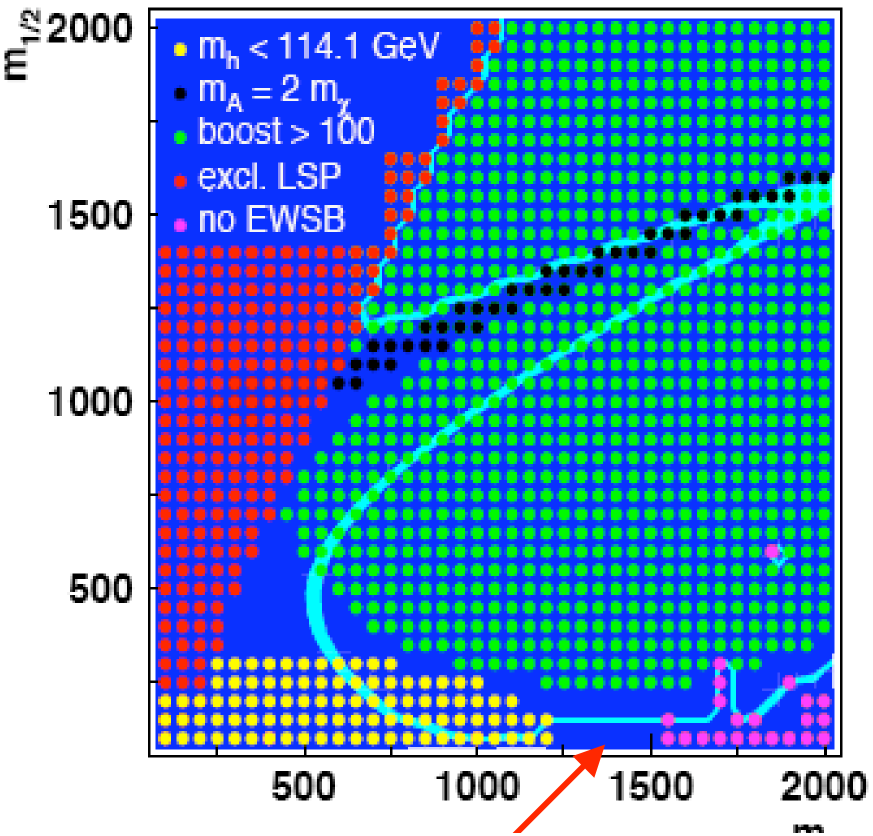


red: the DM contribution

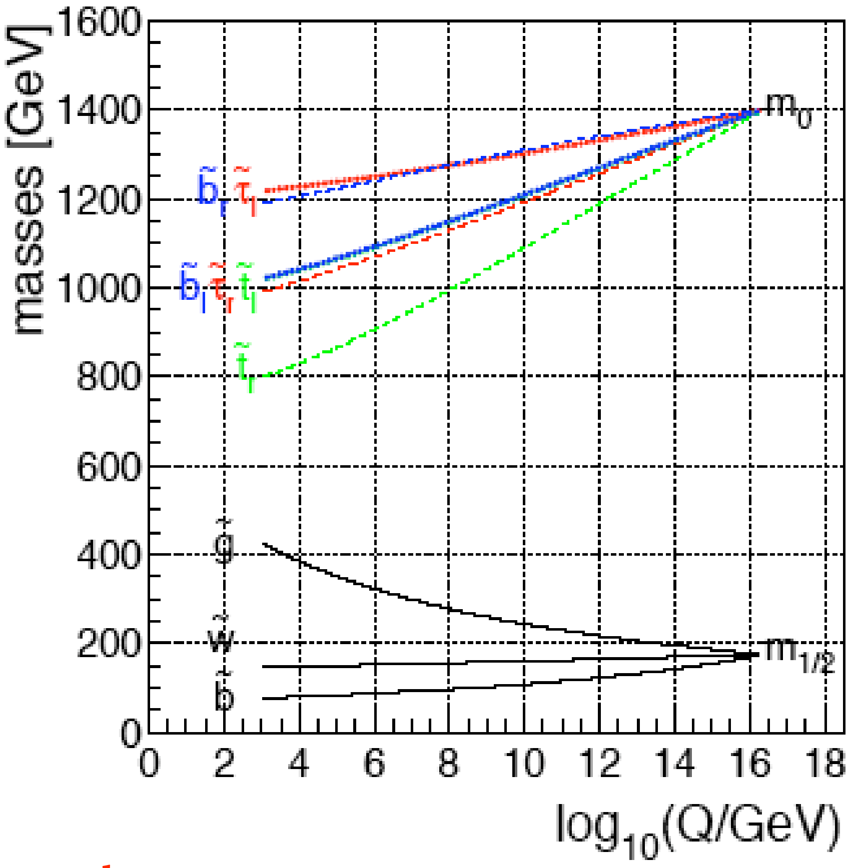


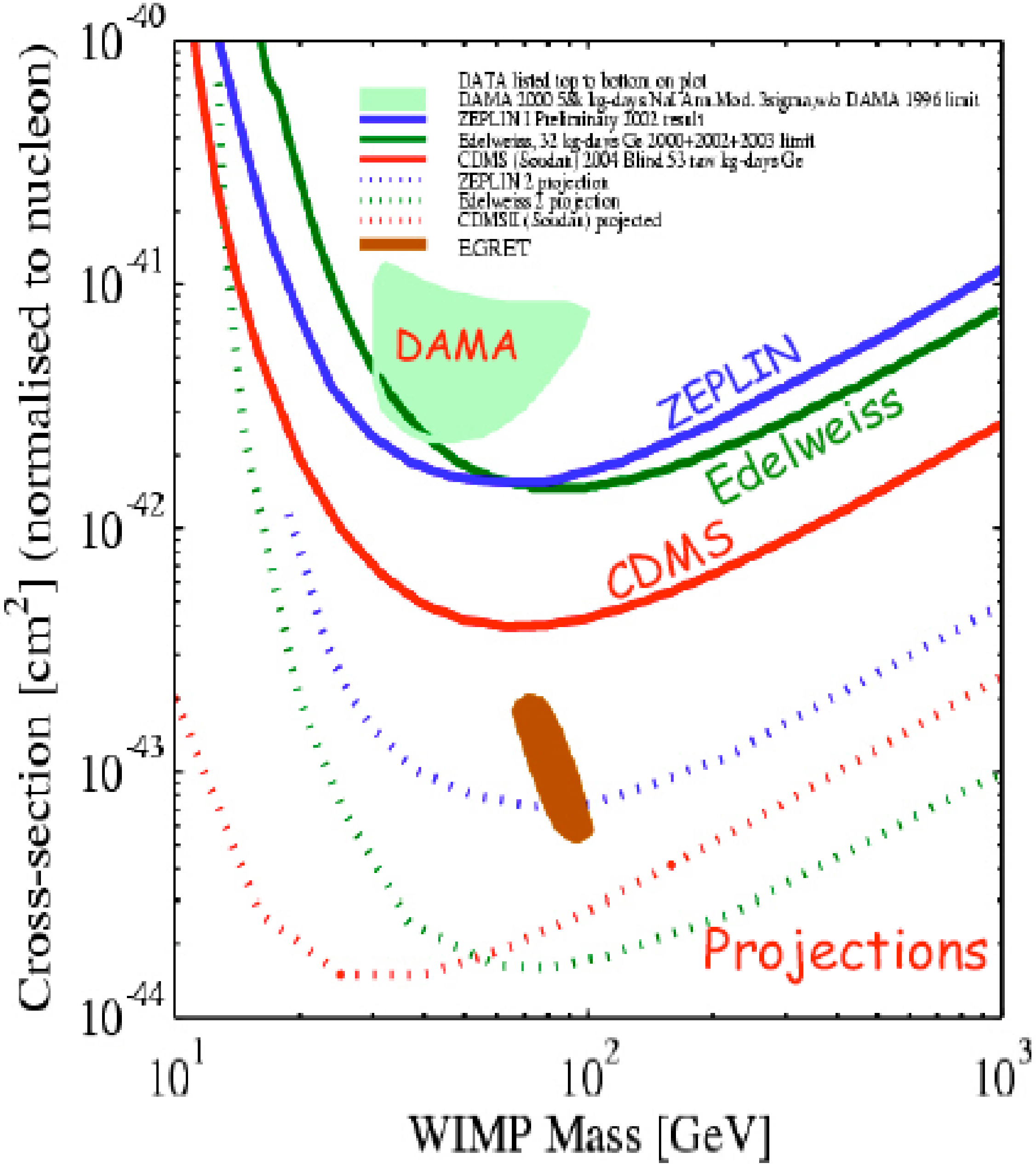
same excess spectrum in all regions

The excess is compatible with neutralinos: $m_\chi \sim$ 50-100 GeV, $m_0 \sim$ 1400 GeV, $m_{1/2} \sim$ 180 GeV, tg$\beta \sim$ 50



correct relic density (WMAP) and annihilation cross section




DATA listed top to bottom on plot
DAMA 2000 58k kg-days NaI Ann.Mod. 3sigma,w/o DAMA 1996 limit
ZEPLIN I Preliminary 2002 result
Edelweiss, 32 kg-days Ge 2000+2002+2003 limit
CDMS (Soudan) 2004 Blind 53 raw kg-days Ge
ZEPLIN 2 projection
Edelweiss 2 projection
CDMSII (Soudan) projected
EGRET
DAMA
ZEPLIN
Edelweiss
CDMS
Projections
Cross-section [cm^2] (normalised to nucleon)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^1
10^2
10^3
WIMP Mass [GeV]

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.65$ → $\rho_\Lambda \sim (2\ 10^{-3}\ \mathrm{eV})^4 \sim (0.1\mathrm{mm})^{-4}$ → Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

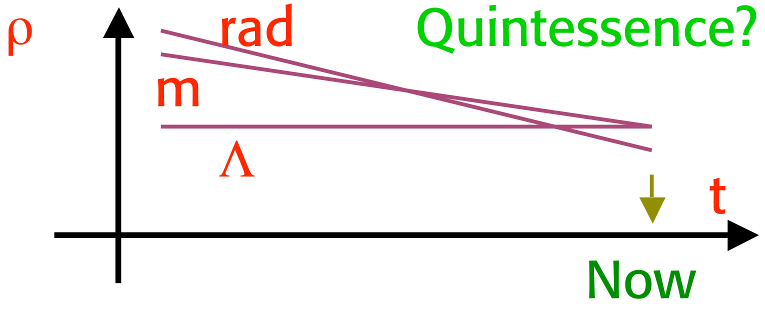
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\ \rho_{obs}$

Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 \sim 10^{59}\ \rho_{obs}$

It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{EW})^2/M_{Pl}$

Other problem:
Why now?



Quintessence?

Quintessence: the cosmological “constant” is actually a vev of a scalar field ϕ which evolves towards the minimum

Could explain smallness, but not “why now?”

To have $\rho_m / \rho_\Lambda \sim o(1)$ now means
$\rho / \rho_\Lambda \sim 10^9$ at recombination

For radiation: $\rho \sim R^{-4} \sim T^4$
For matter: $\rho_m \sim R^{-3} \sim T^3$
For const. Λ : $\rho_\Lambda \sim$ constant

A coupling of ν’s to Quintessence could explain “why now?”

Fardon, Nelson, Weiner; Peccei....

The Majorana mass M of ν_R could be $M(\phi)$ and the combined evolution could explain “why now?”

But: ad hoc potentials and energy scales

A new approach: introduce light ν_R’s coupled to ϕ PGB.
Explain $\Lambda \sim (m_\nu)^4$, but smallness of m_ν unexplained

Barbieri, Hall, Oliver, Strumia

The scale of vacuum energy poses a large naturalness problem!

So far no clear way out:
- A modification of gravity? (extra dim.)
- Leak of vac. energy to other universes (wormholes)?
- • • • •

Perhaps naturality irrelevant
- Anthropic principle: just right for galaxy formation

(Weinberg)

Perhaps naturality irrelevant also for Higgs: Arkani-Hamed, Dimopoulos; Giudice, Romanino '04, String Th. Landascapes '05

Split SUSY: a fine tuned light Higgs + light gauginos and higgsinos. all other s-partners heavy (a new scale) preserves coupling unification and dark matter

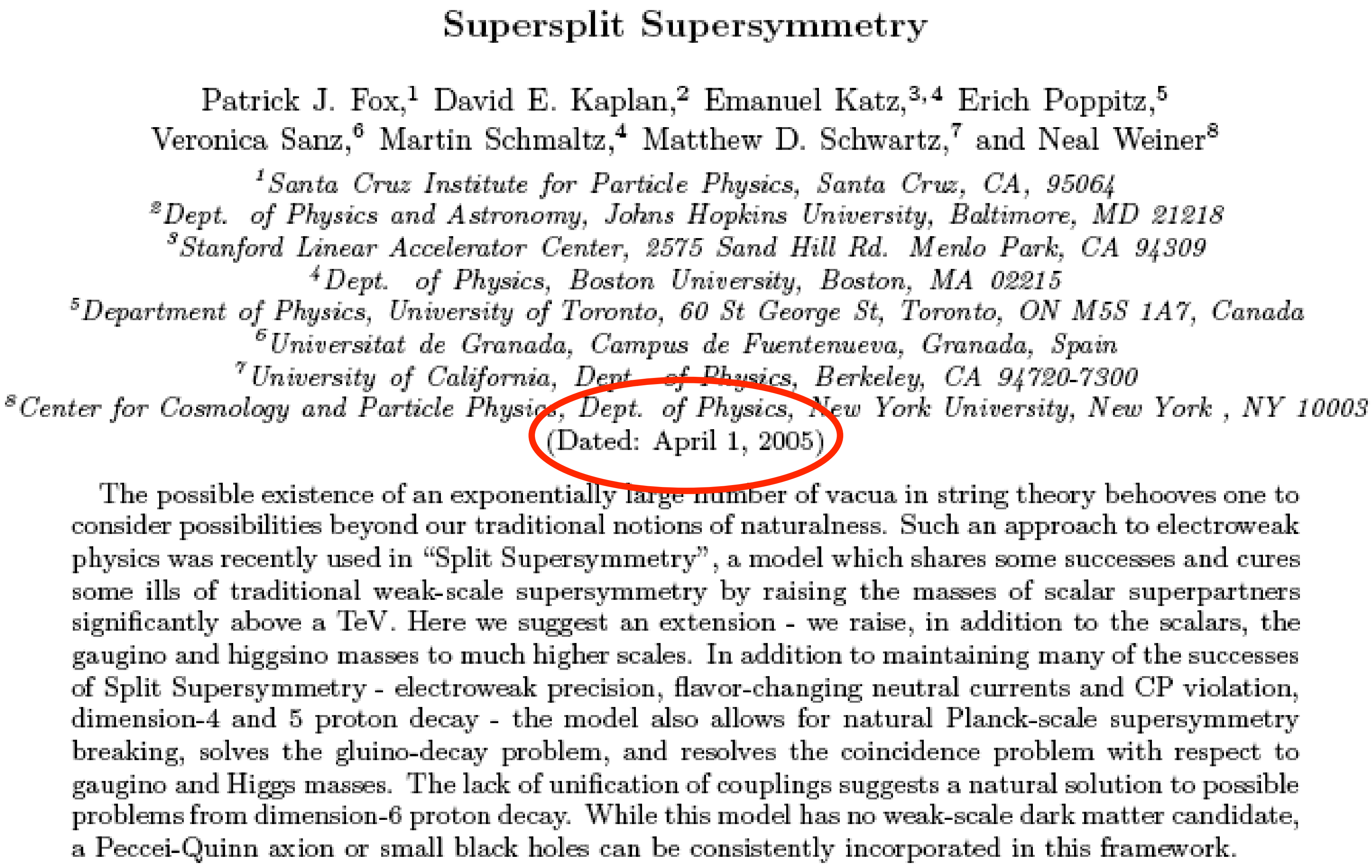
But then also a two-scale non-SUSY GUT with axions as DM

Normal SUSY, no SUSY, split SUSY? LHC will tell

An April 1st joke?

hep-th/0503249

The SM



Supersplit Supersymmetry

Patrick J. Fox,[1] David E. Kaplan,[2] Emanuel Katz,[3,4] Erich Poppitz,[5]
Veronica Sanz,[6] Martin Schmaltz,[4] Matthew D. Schwartz,[7] and Neal Weiner[8]

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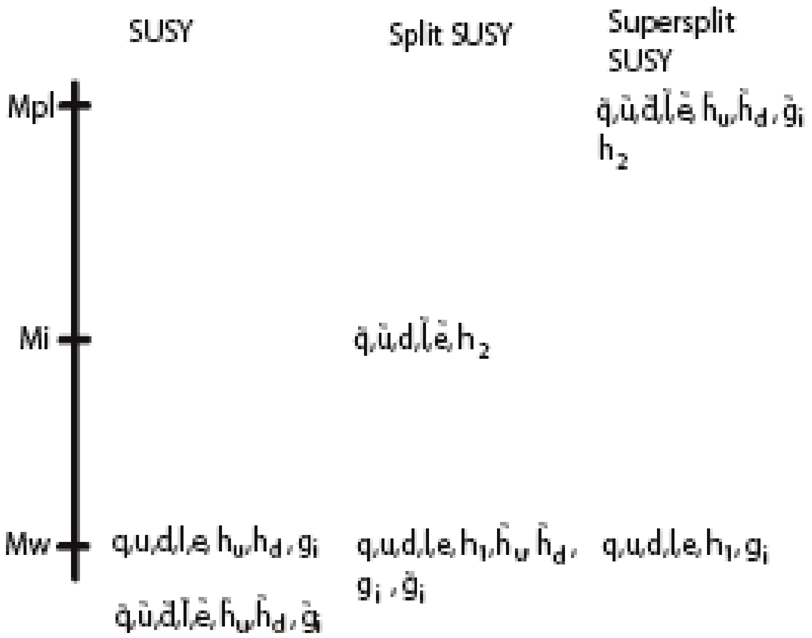
(Dated: April 1, 2005)

The possible existence of an exponentially large number of vacua in string theory behooves one to consider possibilities beyond our traditional notions of naturalness. Such an approach to electroweak physics was recently used in “Split Supersymmetry”, a model which shares some successes and cures some ills of traditional weak-scale supersymmetry by raising the masses of scalar superpartners significantly above a TeV. Here we suggest an extension - we raise, in addition to the scalars, the gaugino and higgsino masses to much higher scales. In addition to maintaining many of the successes of Split Supersymmetry - electroweak precision, flavor-changing neutral currents and CP violation, dimension-4 and 5 proton decay - the model also allows for natural Planck-scale supersymmetry breaking, solves the gluino-decay problem, and resolves the coincidence problem with respect to gaugino and Higgs masses. The lack of unification of couplings suggests a natural solution to possible problems from dimension-6 proton decay. While this model has no weak-scale dark matter candidate, a Peccei-Quinn axion or small black holes can be consistently incorporated in this framework.



Note added: While this work was being completed, we became aware of [18, 19, 20], a series of conference talks where a similar model was considered. While there are some similarities (specifically, field content and interactions), the philosophy is completely unrelated.

[18] S. Glashow, "Towards a Unified Theory - Threads in a Tapestry," Nobel Lecture, Dec 8, 1979.

[19] A. Salam, "Gauge Unification of Fundamental Forces," Nobel Lecture, Dec 8, 1979.

[20] S. Weinberg, "Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions," Nobel Lecture, Dec 8, 1979.

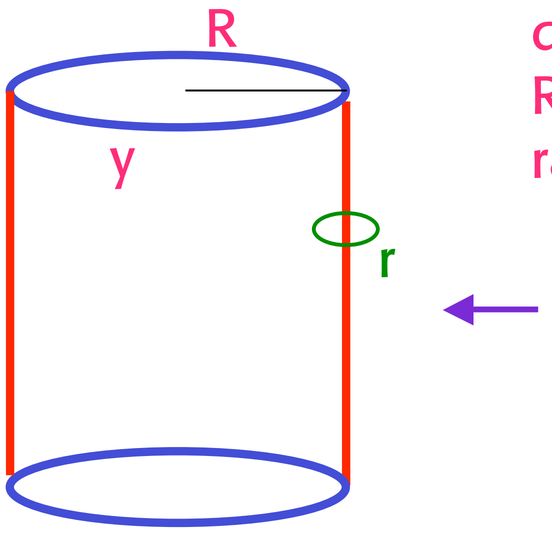
Large Extra Dimensions

Solve the hierachy problem by bringing gravity down from M_{Pl} to o(1TeV)

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis/ Randall,Sundrun…..

Inspired by string theory, one assumes:

- Large compactified extra dimensions
- SM fields are on a brane
- Gravity propagates in the whole bulk



y: extra dimension

R: compact'n radius

y=0 "our" brane (possibly with thickness r)

$G_N \sim 1/M^2_{Pl}$: Newton const.

M_{Pl} large as G_N weak

The idea is that gravity appears weak as a lot of lines of force escape in extra dimensions

Generic feature:

compact dim. → Kaluza-Klein (KK) modes

$p=n/R$ $m^2=n^2/R^2$ (quantization in a box)

Many possibilities:

- SM fields on a brane

The brane can itself have a thickness r:

$1/r >\sim 1\text{TeV}$ → $r <\sim 10^{-17}$ cm

→ KK recurrences of SM fields: W_n, Z_n etc

cfr:
- Gravity on bulk

$1/R >\sim 10^{-3}$ eV → $R <\sim 0.1$ mm

- Factorized metric:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}(y) dy^i dy^j$$

perhaps the most promising

- Warped metric: Randall-Sundrum (R-S)

$$ds^2 = e^{-2mR|\varphi|}\eta_{\mu\nu} dx^\mu dx^\nu - R^2\varphi^2$$

$m = M_{Pl}\exp(-2mR\pi)$ → $Rm \sim 10$

- Large Extra Dimensions is a very exciting scenario.

- However, by itself it is difficult to see how it can solve the main problems (hierarchy, the LEP Paradox)

$$\left(\frac{M_{Pl}}{m}\right)^2 = (Rm)^{d-4}$$

$$m = M_{Pl} \exp(-2mR\pi)$$

* Why (Rm) not 0(1)?

R-S better in this respect

Goldberger,Wise

* $\Lambda \sim 1/R$ must be small (m_H light)

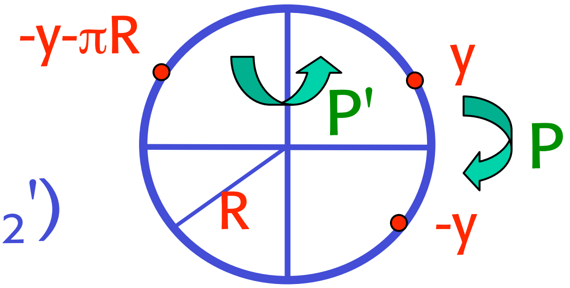
* But precision tests put very strong lower limits on Λ (several TeV)

In fact in typical models of this class there is no mechanism to sufficiently quench the corrections

- But could be part of the truth!

- Interesting directions explored ⇒

Symmetry breaking by orbifolding



$S/(Z_2 x Z_2')$

For $1/R \sim M_{GUT}$

Z_2-> P: y ⟺ -y

GUT's in ED: very appealing
SU(5), SO(10) in 5 or 6 dimensions

Z_2'-> P': y' ⟺ -y'
y'=y + πR/2
or y ⟺ -y- πR

Kawamura/GA, Feruglio/ Hall, Nomura;
Hebecker, March-Russell;
Hall, March-Russell, Okui, Smith
Asaka, Buchmuller, Covi
....

- No baroque Higgs system
- Natural doublet-triplet splitting
- Coupling unification can be maintained

● ● ● ●

$$\phi_{++}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{++}^{(2n)}(x_\mu)\cos\frac{2ny}{R}$$

$$\phi_{+-}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{+-}^{(2n+1)}(x_\mu)\cos\frac{2n+1}{R}y$$

$$\phi_{-+}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{-+}^{(2n+1)}(x_\mu)\sin\frac{2n+1}{R}y$$

$$\phi_{--}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{--}^{(2n+2)}(x_\mu)\sin\frac{2n+2}{R}y$$

Symmetry breaking at the weak scale

$1/R \sim o(\mathrm{TeV})$

- **SUSY Breaking**

Barbieri, Hall, Nomura.....Papucci, Marandella.

5D SUSY-SM compactified on $S/(Z_2\text{-}Z_2')$

•Z breaks N=2 SUSY, Z′ N=1 SUSY (Scherk-Schwarz)

effective theory non-SUSY (SUSY recovered at d<R)

- Higgs boson mass in principle computable

no invariant Higgs mass operator in 5-dim

rather insensitive to UV $m_H \sim 110 - 125$ GeV

$$\begin{tikzcd}
& \psi_M(+,+) \arrow[dl, dash] \arrow[dr, dash, dashed] & \\
\phi_M(+,-) \arrow[dr, dash, dashed] & & \phi_M^{c\dagger}(-,+) \arrow[dl, dash] \\
& \psi_M^{c\dagger}(-,-) &
\end{tikzcd}$$

matter

$$\begin{tikzcd}
& \psi_H(+,-) \arrow[dl, dash] \arrow[dr, dash, dashed] & \\
\phi_H(+,+) \arrow[dr, dash, dashed] & & \phi_H^{c\dagger}(-,-) \arrow[dl, dash] \\
& \psi_H^{c\dagger}(-,+) &
\end{tikzcd}$$

Higgs (only 1!)

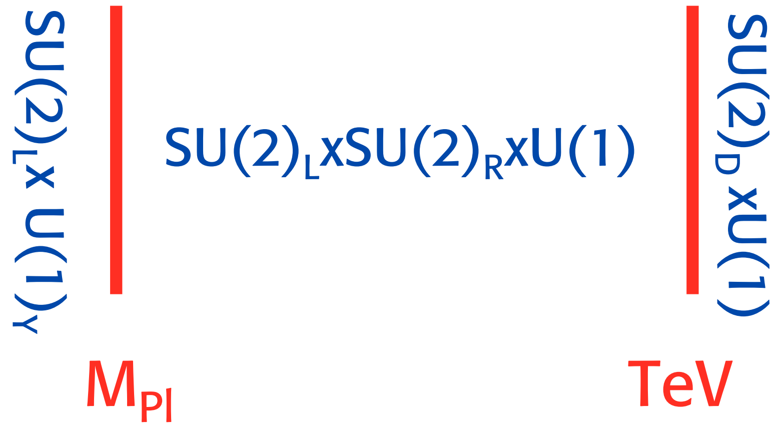
$$\begin{tikzcd}
& A^\mu(+,+) \arrow[dl, dash] \arrow[dr, dash, dashed] & \\
\lambda(+,-) \arrow[dr, dash, dashed] & & \psi_\Sigma(-,+) \arrow[dl, dash] \\
& \phi_\Sigma(-,-) &
\end{tikzcd}$$

gauge

all are in the bulk

• Gauge Symmetry Breaking (Higgsless theories)

Csaki et al/Nomura/Davoudiasl et al/Barbieri, Pomarol, Rattazzi;....



$SU(2)_L x\, U(1)_Y$

$SU(2)_L xSU(2)_R xU(1)$

$SU(2)_D xU(1)$

M_{Pl}

TeV

Warped R-S background

Symmetries broken by
Boundary Conditions (BC)
on the branes

Altogether only $U(1)_Q$ unbroken

- Unitarity breaking (no Higgs) delayed by KK recurrences

- Dirac fermions on the bulk (L and R doublets). Only one chirality has a zero mode on the interval

But: serious problems with EW precision tests

e.g. Barbieri, Pomarol, Rattazzi,Strumia, Chivukula et al

Boundary conditions allow a general breaking pattern
(for example, can lower the rank of the group)
equivalent to have generic Higgses on the brane

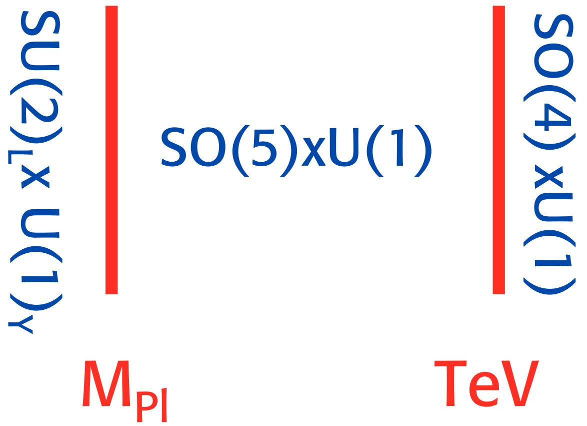
Breaking by orbifolding is more rigid
(the rank remains fixed)
corresponds to Higgs in the adjoint (A_5 the 5th A_M)

No realistic Higgsless model for EW symmetry breaking so far emerged

However be alerted of possible signals at the LHC:
no Higgs but KK recurrences of W, Z and additional gauge bosons

• Composite Higgs in a 5-dim AdS theory

Agashe, Contino, Pomarol



$SU(2)_L x\ U(1)_Y$

SO(5)xU(1)

SO(4) xU(1)

M_{Pl}

TeV

Warped R-S background

A new way to look at walking technicolor using AdS/CFT corresp.

As in Little Higgs models

The Higgs is a PGB and EW symmetry breaking is triggered by top-loop effects. In 4-dim the bulk appears as a strong sector

The 5-dim theory is weakly coupled so that the Higgs potential and EW observables can be computed

The Higgs is light: $m_H < 140$ GeV

Summarizing

- SUSY remains the Standard Way beyond the SM
- What is unique of SUSY is that it works up to GUT's .

  GUT's are part of our culture!
  Coupling unification, neutrino masses, dark matter, ...
  give important support to SUSY
- It is true that one expected SUSY discovery at LEP

(this is why there is a revival of alternative model building and of anthropic conjectures)

- No compelling, realistic alternative so far developed

(not an argument! Interesting models explored)

- Extra dim.s is a complex, rich, attractive, exciting possibility.
- Little Higgs models look as just a postponement

(both interesting to pursue)

Get the LHC ready fast; we badly need exp input!!!

The big problems:

- The Higgs
- The hierarchy problem
- The flavour problem
- Dark matter
- Dark energy

We hope that the LHC will bring important results on them