Highlights in Physics Today

One Hundred Years After the Birth of Beppo Occhialini

Aula Magna - Università degli Studi - Milano
Via Festa del Perdono 7

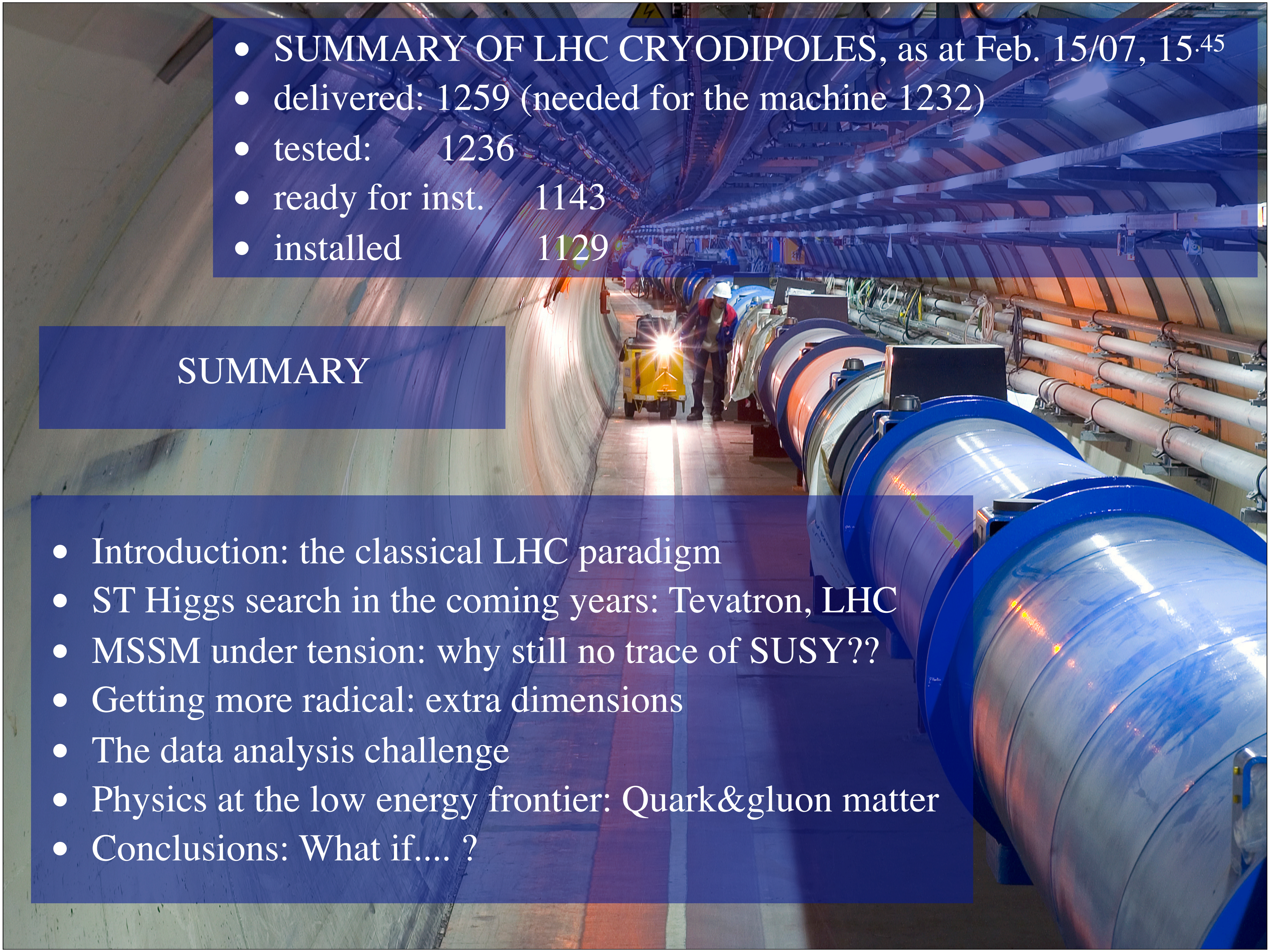
Experiments and Theory with the LHC: a personal view.

Luciano MAIANI, Universita’ di Roma, “La Sapienza”

Topics

. Highlights and outlook in Elementary Particles
. Astroparticles
. Astrophysics

Speak

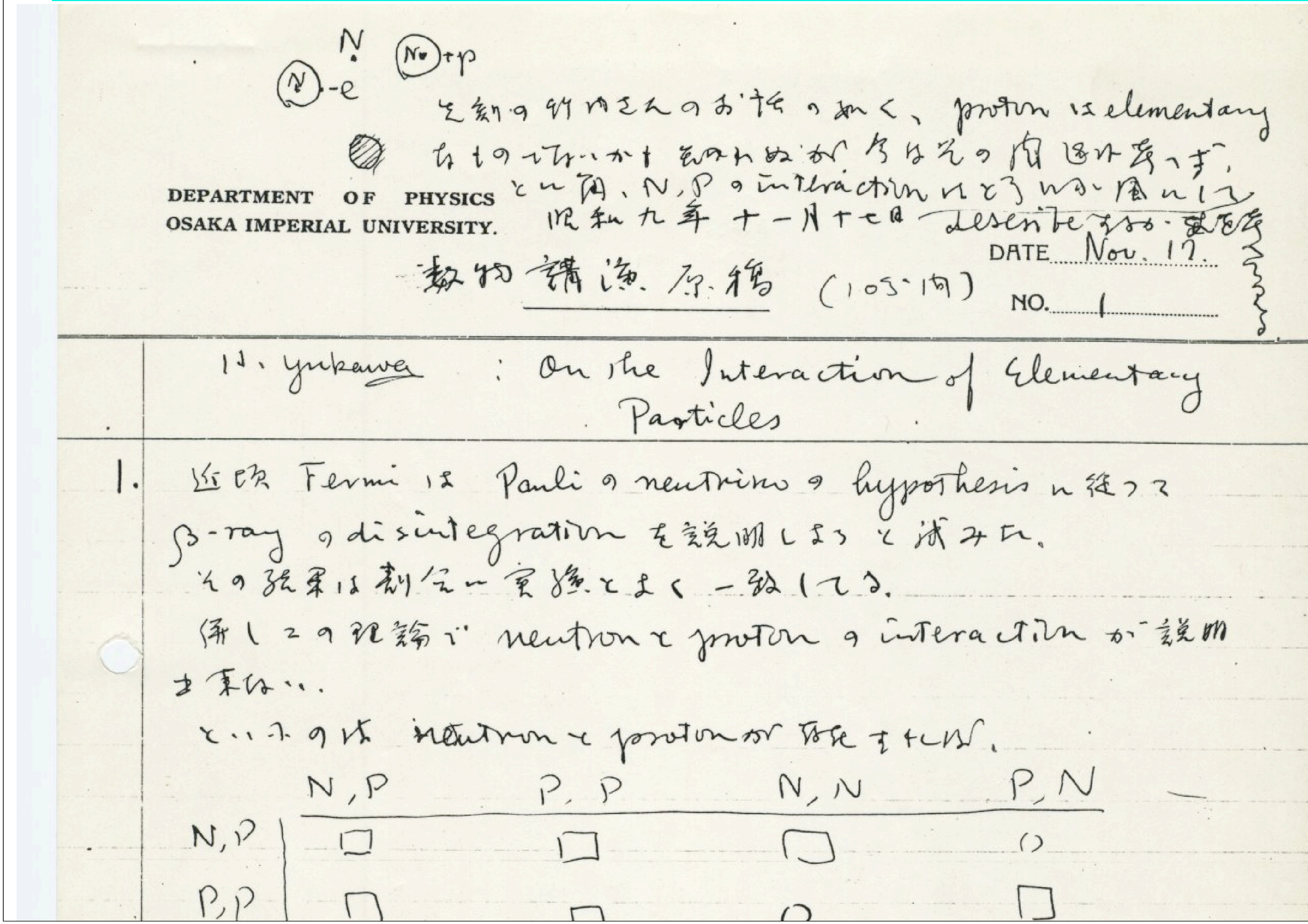


- SUMMARY OF LHC CRYODIPOLES, as at Feb. 15/07, 15.45
- delivered: 1259 (needed for the machine 1232)
- tested: 1236
- ready for inst. 1143
- installed 1129

SUMMARY

- Introduction: the classical LHC paradigm
- ST Higgs search in the coming years: Tevatron, LHC
- MSSM under tension: why still no trace of SUSY??
- Getting more radical: extra dimensions
- The data analysis challenge
- Physics at the low energy frontier: Quark&gluon matter
- Conclusions: What if.... ?

The missing particle of the 30's and 40's



DEPARTMENT OF PHYSICS
OSAKA IMPERIAL UNIVERSITY.

昭和九年十一月十七日

DATE Nov. 17.

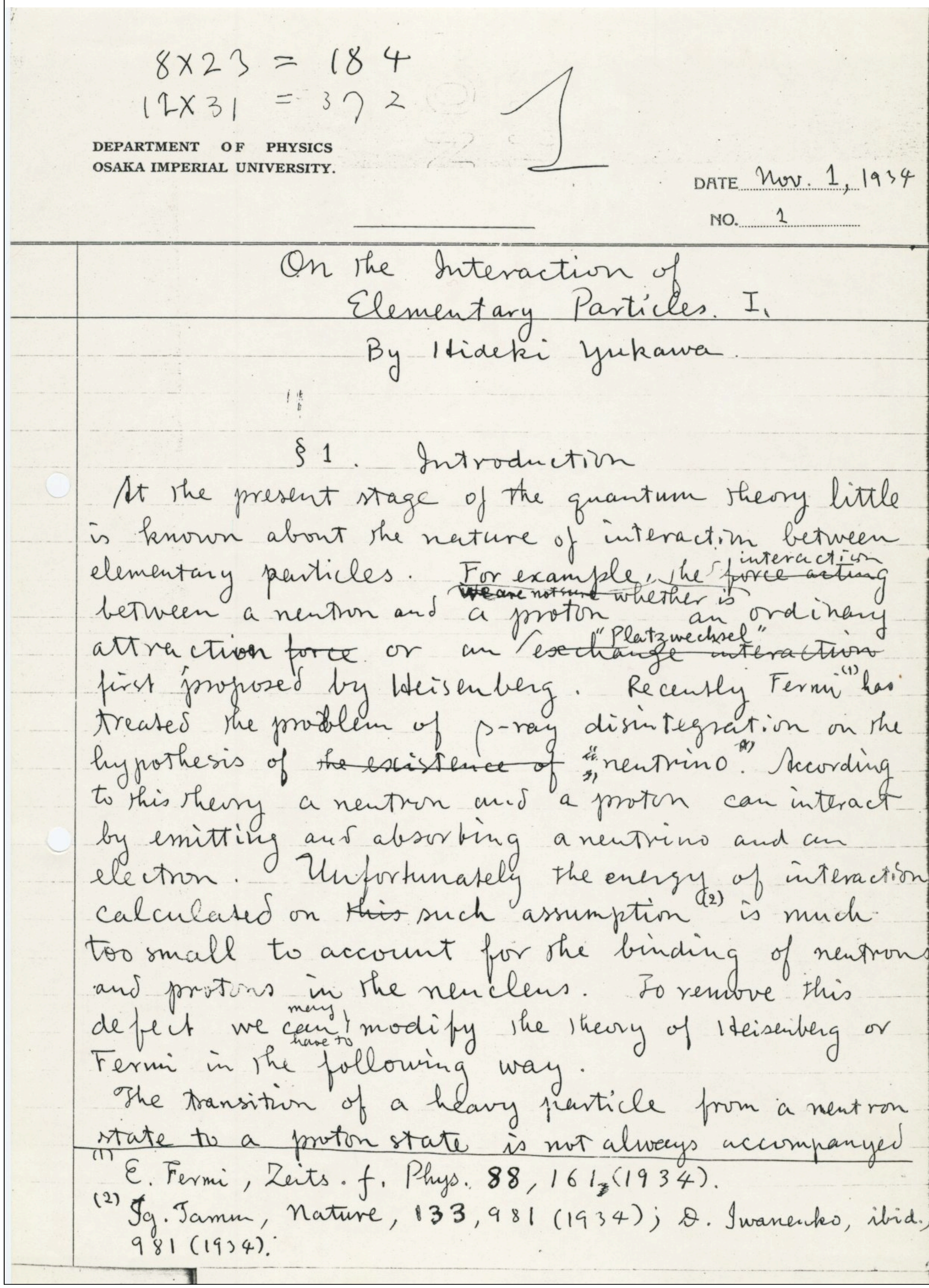
数物講演原稿 (10分間)

NO. 1

H. Yukawa : On the Interaction of Elementary Particles

1. 近頃 Fermi は Pauli の neutrino の hypothesis に従って β-ray の disintegration を説明しようと試みた。
その結果は割合に実験とよく一致してる。
併しこの理論で neutron と proton の interaction が説明出来ない。

	N, P	P, P	N, N	P, N
N, P	□	□	□	○
P, P	□	□	○	□


8×23 = 184
12×31 = 372

DEPARTMENT OF PHYSICS
OSAKA IMPERIAL UNIVERSITY.

DATE Nov. 1, 1934
NO. 1

On the Interaction of Elementary Particles. I.

By Hideki Yukawa

§1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction between elementary particles. For example, the interaction ~~force acting~~ between a neutron and a proton ~~We are not sure~~ whether is an ordinary attraction ~~force~~ or an "Platzwechsel" ~~exchange interaction~~ first proposed by Heisenberg. Recently Fermi(1) has treated the problem of β-ray disintegration on the hypothesis of ~~the existence of~~ "neutrino". According to this theory a neutron and a proton can interact by emitting and absorbing a neutrino and an electron. Unfortunately the energy of interaction calculated on ~~this~~ such assumption(2) is much too small to account for the binding of neutrons and protons in the nucleus. To remove this defect we can many have to modify the theory of Heisenberg or Fermi in the following way.

The transition of a heavy particle from a neutron state to a proton state is not always accompanied

(1) E. Fermi, Zeits. f. Phys. 88, 161 (1934).
(2) Ig. Tamm, Nature, 133, 981 (1934); D. Iwanenko, ibid. 981 (1934).

- the pion...
  at first identified with the muon; hypothesis discarded after: M. Conversi, E. Pancini and O. Piccioni, *Phys.Rev.* 71, 209 (1947).
- finally found by C.Lattes, H.Muirhead, G.Occhialini and C.Powell, *Nature* 159, 694 (1947).

This discovery opened the way to modern Elementary Particle Physics

The classical LHC Paradigma. Task#1: find the elementary scalars

Particle Physics in one page

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi$$ *The gauge sector* (1)

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$ *The flavor sector* (2)

$$+|D_\mu h|^2 - V(h)$$ *The EWSB sector* (3)

$$+N_i M_{ij} N_j$$ *The ν-mass sector (if Majorana)* (4)

- Do elementary scalars exist?
- Do they trigger spontaneous symmetry breaking, i.e. fermion and gauge boson masses?
- Task #1: find the Higgs boson(s) anywhere in the mass range allowed by the Standard Theory (ST).

Supersymmetry in the TeV range

- TeV scale for SUSY particles is indicated by hierarchy problem:
  - quadratic divergences in the Electroweak corrections to the Higgs potential would make theory "unnatural" at TeV scale (or bring M_{Higgs} to M_{Planck}) 't-Hooft, 1980

$$\delta V(\varphi) = \frac{\alpha}{\pi} C\{\sum_J (-1)^{2J}(2J+1)\Lambda^4 + \sum_J (-1)^{2J}(2J+1)M(\varphi)_J^2\Lambda^2 + \ldots\}$$

$n_{boson} - n_{fermion}$

=0 in softly Broken SUSY!

SUSY can solve the gauge hierarchy problem

[Weinberg; Maiani; Veltman; Witten; …]

thanks to its special renormalization properties

[Wess-Zumino; Iliopoulos-Zumino; Ferrara-Girardello-Palumbo; Grisaru et al;…]

In (many) supersymmetric extensions of the SM:

[qualitative here, more details below]

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

$$\Lambda^2 \rightarrow \Delta M_{SUSY}^2$$

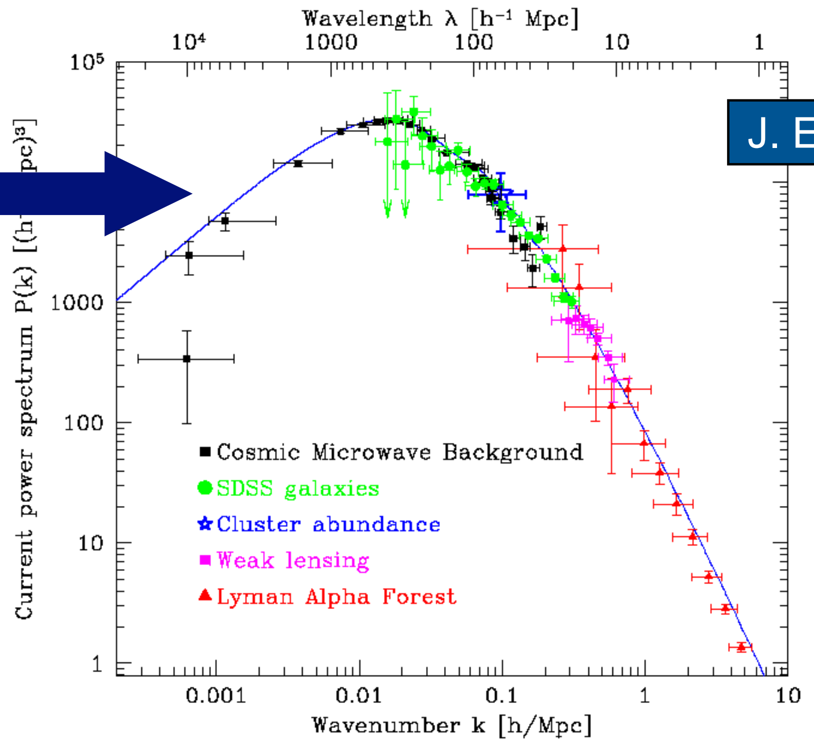
Phenomenology of SUSY pioneered by Pierre Fayet and widely explored by many others!

Power-dependence on SUSY-breaking masses
only mild logarithmic dependence on cutoff

The classical LHC Paradigma.
Task#2: find the SUSY partners

- SUSY requires two Higgs doublets (i.e 5 physical particles)
- m_H <150 GeV
- The case for TeV scale supersimmetry is reinforced by the Dark Matter problem: the LSP provides a good candidate for the Cold Dark Matter required by many Cosmological and Astrophysical facts

Flat Universe:
$\Omega_{Tot} = 1$,
Cold dark matter:
$\Omega_{CDM} \sim 0.25$,
No hot dark matter,
Few baryons:
$\Omega_b \sim 0.05$,
Dark energy:
$\Omega_\Lambda \sim 0.7$



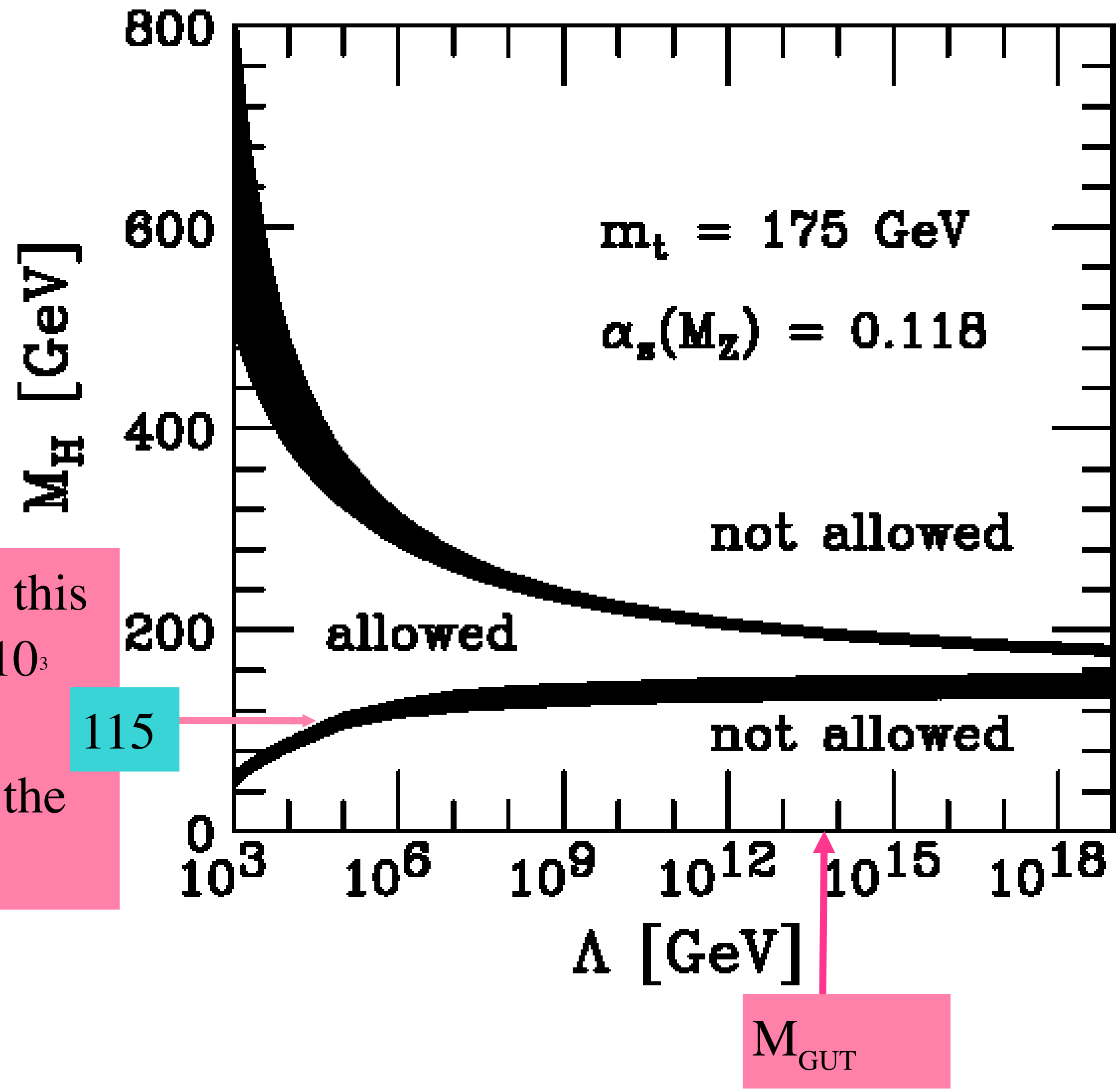
J. Ellis

Stability Conditions on the Higgs potential

stability until M_{GUT} requires:

136 GeV < m_H < 174 GeV

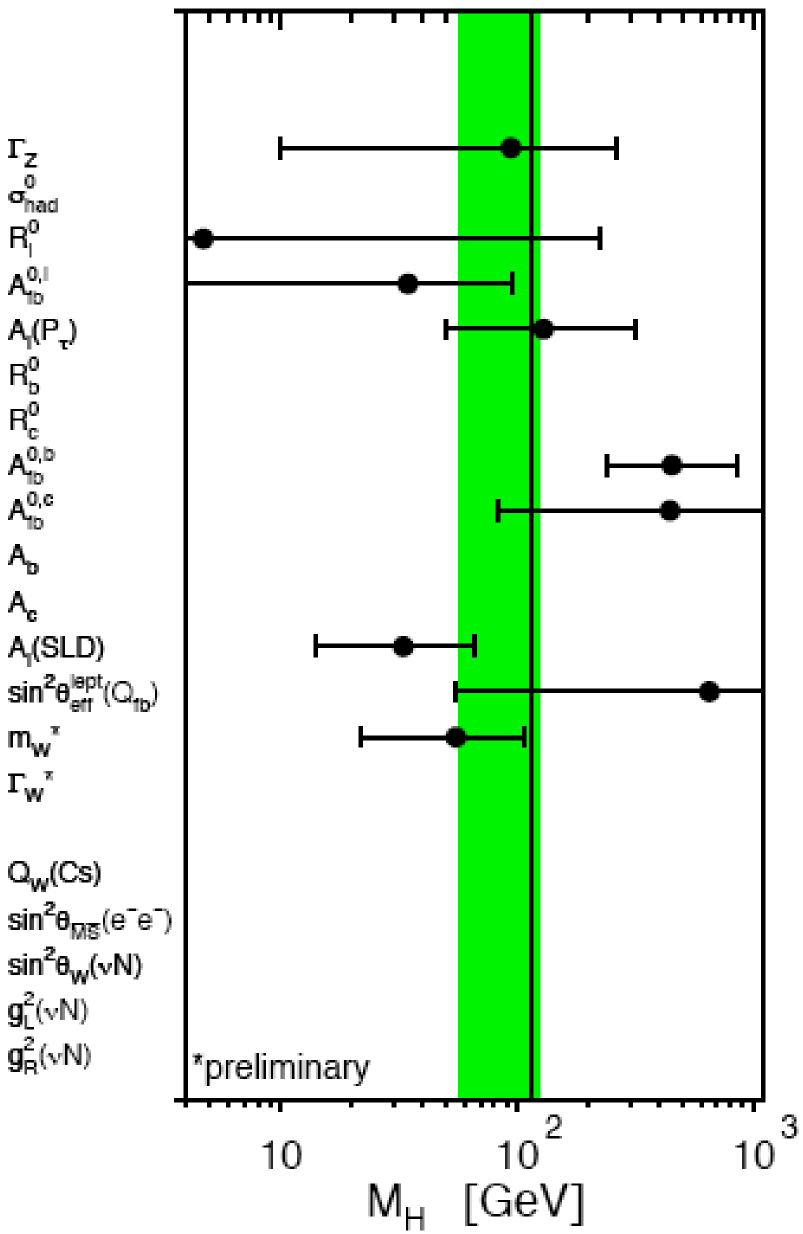
see P.Q. Hung and G. Isidori, Hep-ph/9609518



If the Higgs boson is found below this range, **bosonic** corrections at $\Lambda < 10^3$ TeV correlated to the top-quark correction, are needed to stabilise the potential up to M_{GUT}

On the SM Higgs boson

R. BARBIERI



$$m_h = 85^{+39}_{-28}\ GeV$$

$m_h < 166\ GeV$ *at 95% CL*

(with consistency between direct and indirect determinations, heavily relying on A^b_{FB})

LEPEWWG - Summer 2006

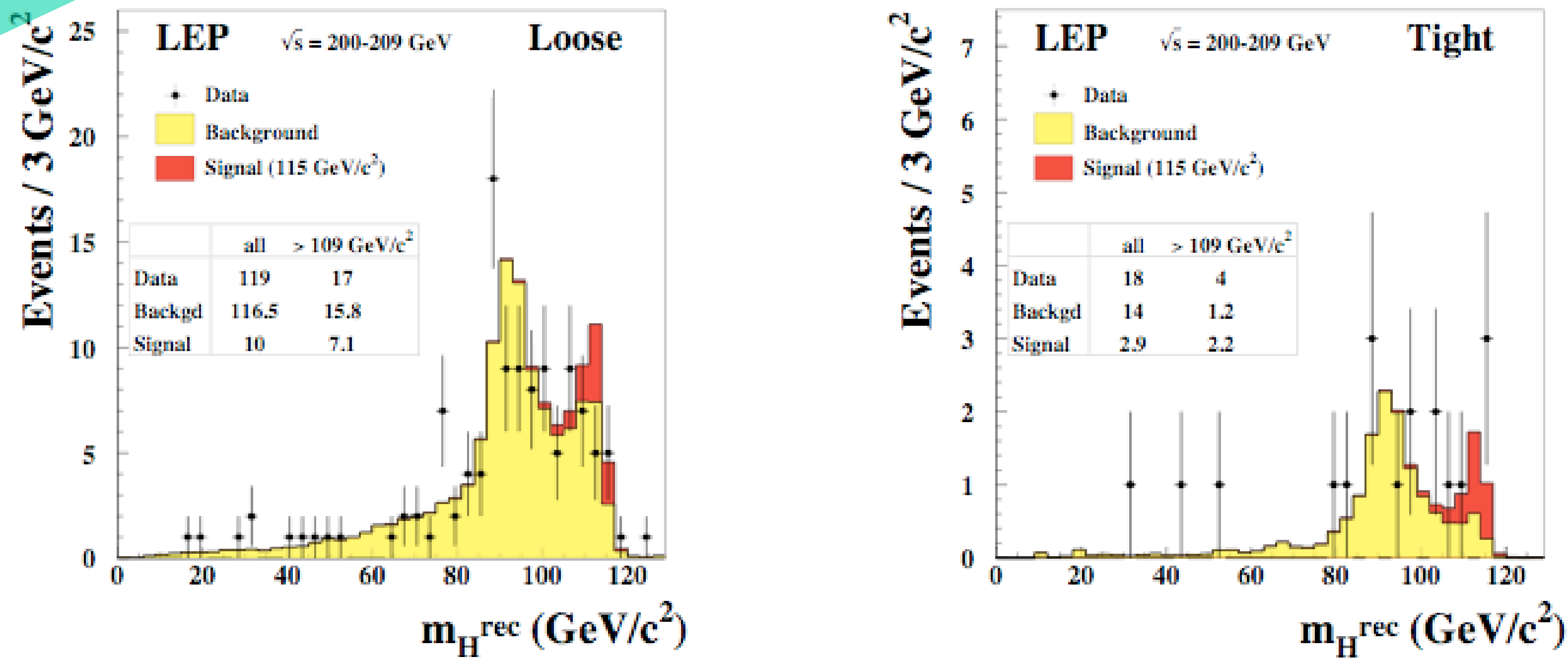
(Tevatron $m_t = 171.4 \pm 2.1\ GeV$ *)*

A HINT ??

Search for the Standard Model Higgs Boson at LEP

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP Working Group for Higgs Boson Searches[1]

CERN-EP/2003-011
13 March 2003



In the region of $m_{\rm H}$ above 115 GeV/c^2 the approximate value of 0.09 translates into 1.7 standard deviations from the background hypothesis. This deviation, although of low significance, is compatible with a Standard Model Higgs boson in this mass range while being also in agreement with the background hypothesis. Note that the value of $1-{\rm CL_b}$ would change in this region from about 0.09 to about 0.08 if the systematic errors were ignored.

2. ST Higgs search in the coming years: Tevatron, LHC

TeVatron Highlights

Jean-François Grivaz

(LAL-Orsay)

for the CDF and DØ Collaborations

J.-F. Grivaz FRIF - November 13, 2006 1

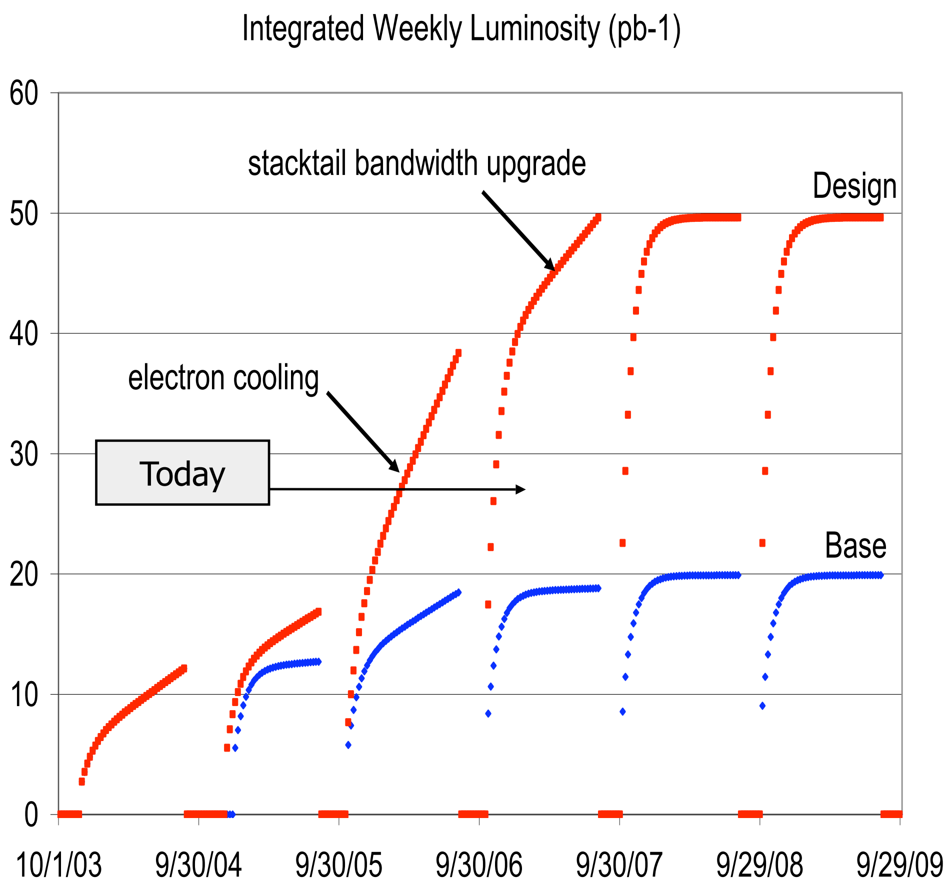
Tevatron Long Term Luminosity Plan

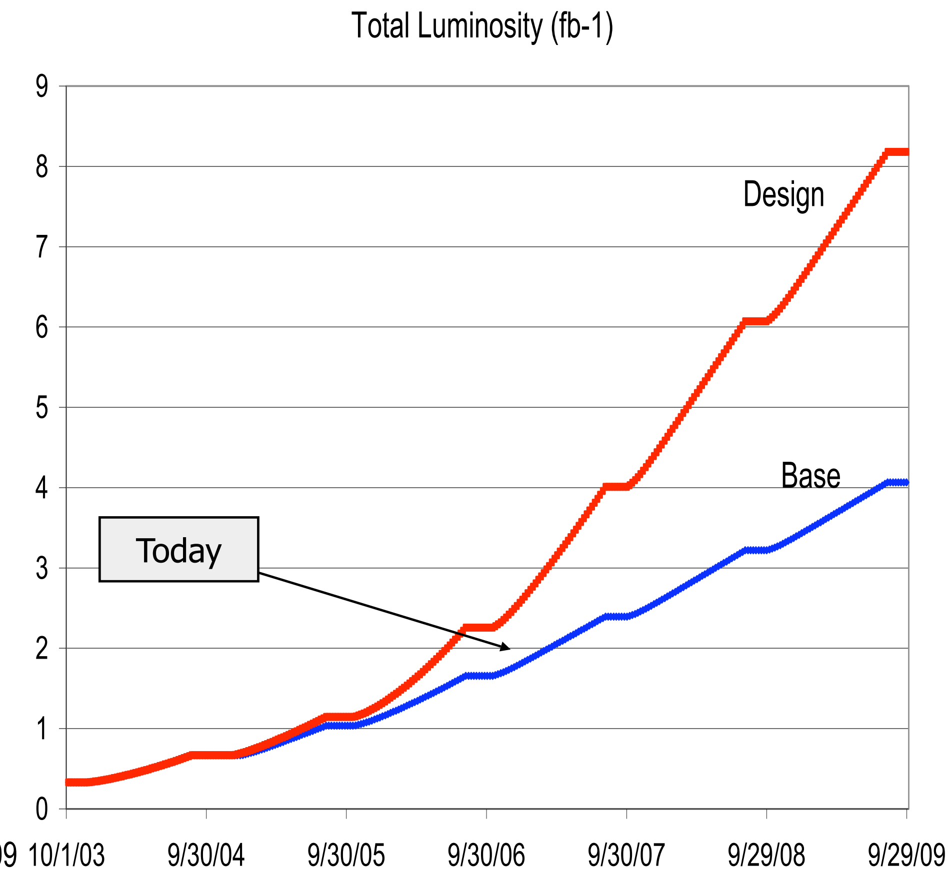
Increase in number of antiprotons
→ key for higher luminosity

Expected peak luminosity
→ $3 \cdot 10^{32}$ $cm^{-2}sec^{-1}$ by 2007

Currently expecting delivered luminosity to each experiment

→ 4 - 8 fb^{-1}
by the end of 2009



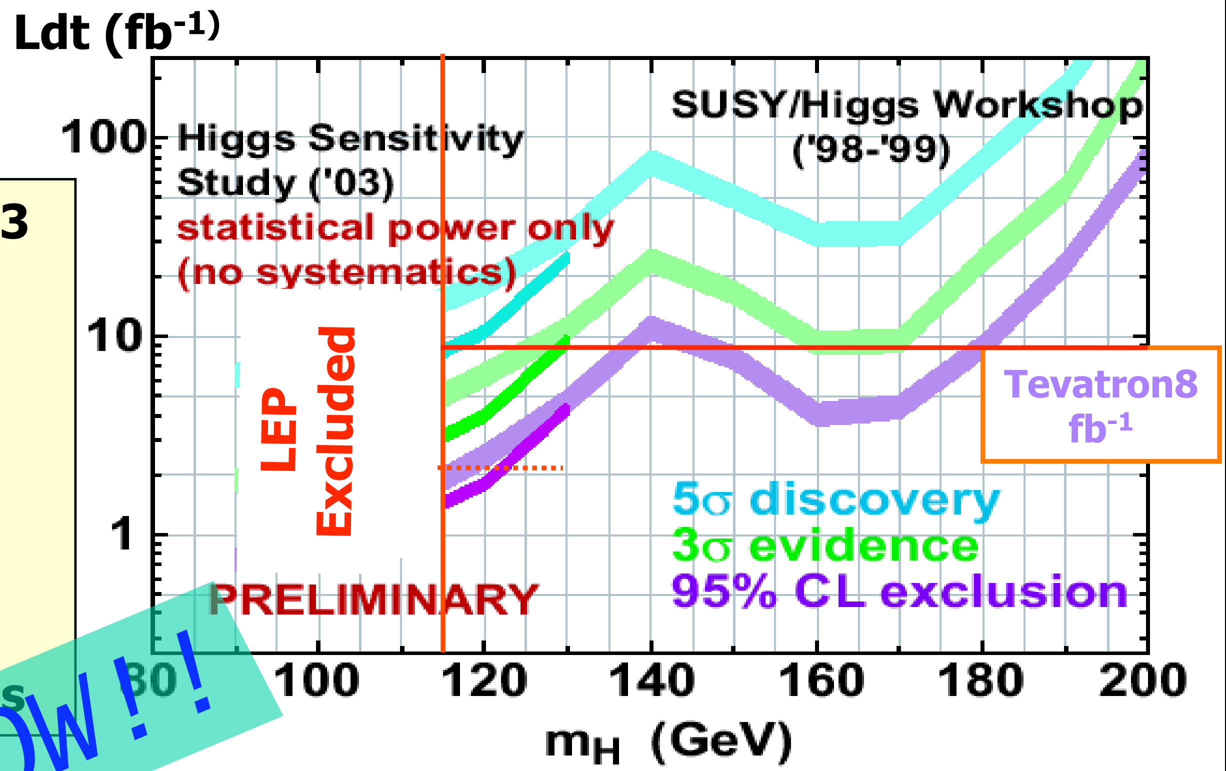


Tevatron SM Higgs Search: Outlook

Prospects updated in 2003 in the low Higgs mass region

W(Z) H→ lν(νν,ll) bb

→ better detector understanding
→ optimization of analysis



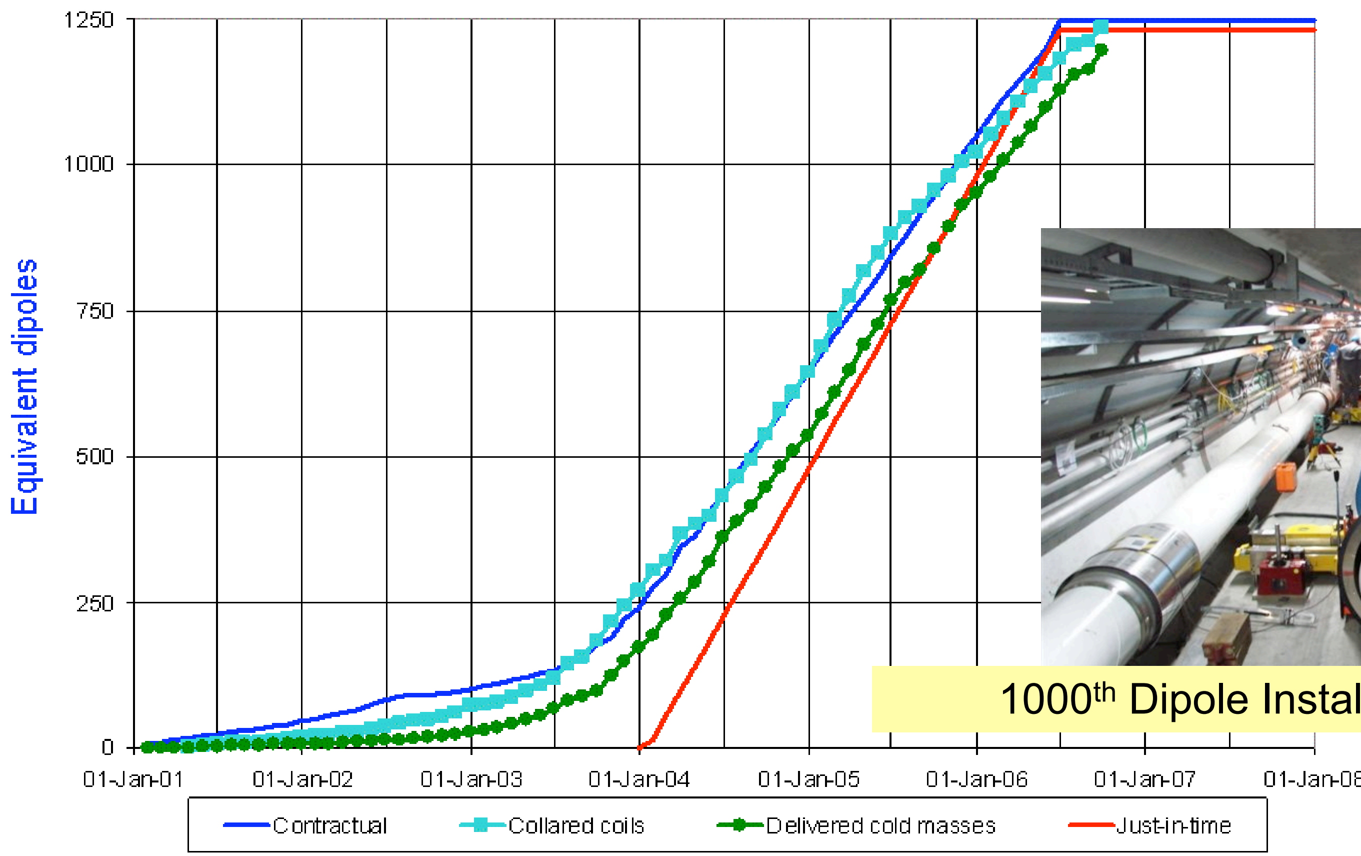
TO FOLLOW !!

Sensitivity in the mass region above LEP limit (114 GeV) starts at ~2 fb^{-1}
With 8 fb^{-1}: exclusion 115-135 GeV & 145-180 GeV,
5 - 3 sigma discovery/evidence @ 115 – 130 GeV

LHC Progress Dashboard

Accelerator Technology Department

Dipole cold masses



1000th Dipole Installed (sep 5)

Updated 30 Sep 2006 Data provided by F. Savary AT-MAS

(Revised) LHC schedule

as presented to CERN Council on 23 June 2006

- Last magnet installed : March 2007
  Machine and experiments closed : 31 August 2007
- First collisions ($\sqrt{s}$ = 900 GeV, L~10^{29} cm^{-2} s^{-1}) : November 2007
  Commissioning run at injection energy until end 2007, then shutdown (3 months ?)
- First collisions at $\sqrt{s}$=14 TeV (followed by first physics run): Spring 2008

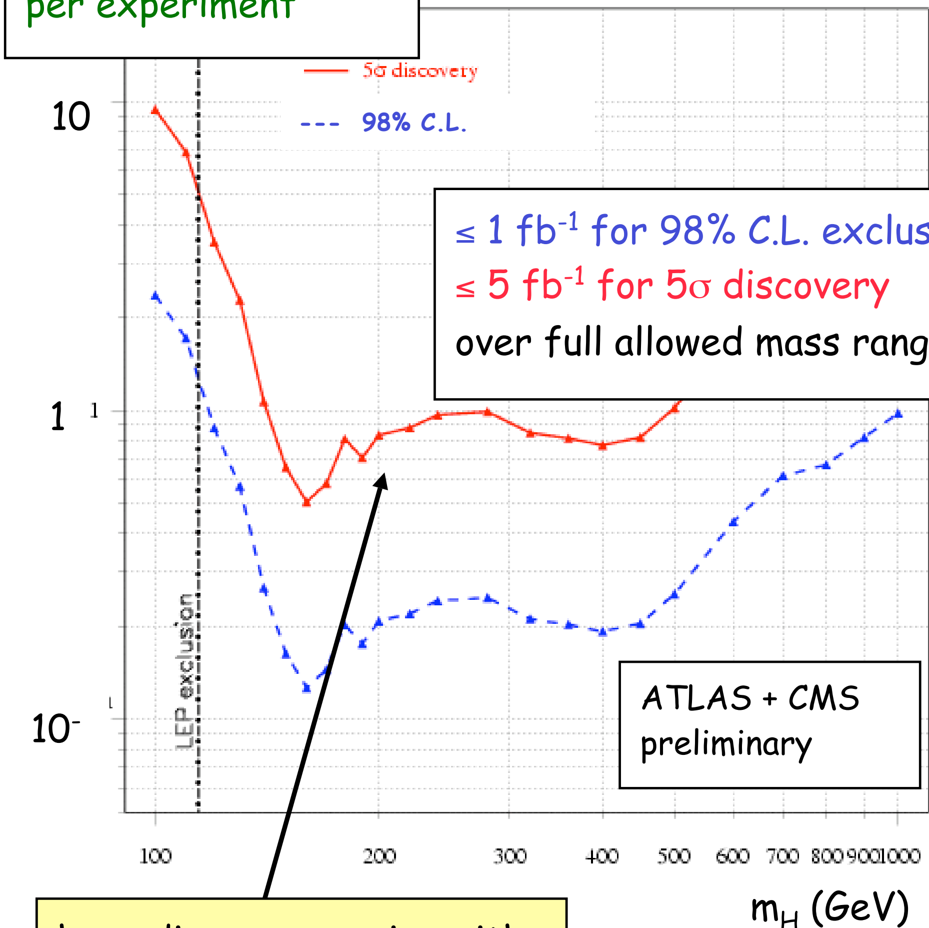
L. Evans,
CERN Council,
23/6/2006

- Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007.
  If we continue to commission the other sectors up to 7 TeV,
  we will not get circulating beam in 2007.
- The other sectors will be commissioned up to the field needed for de-Gaussing.
- Initial operation will be at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors.
- Full commissioning up to 7 TeV will be done in the winter 2008 shutdown

What about the SM Higgs boson ?

F. GIANOTTI. ICHEP 06

Needed $\int Ldt$ (fb^{-1}) per experiment



$\leq$ 1 fb^{-1} for 98% C.L. exclusion

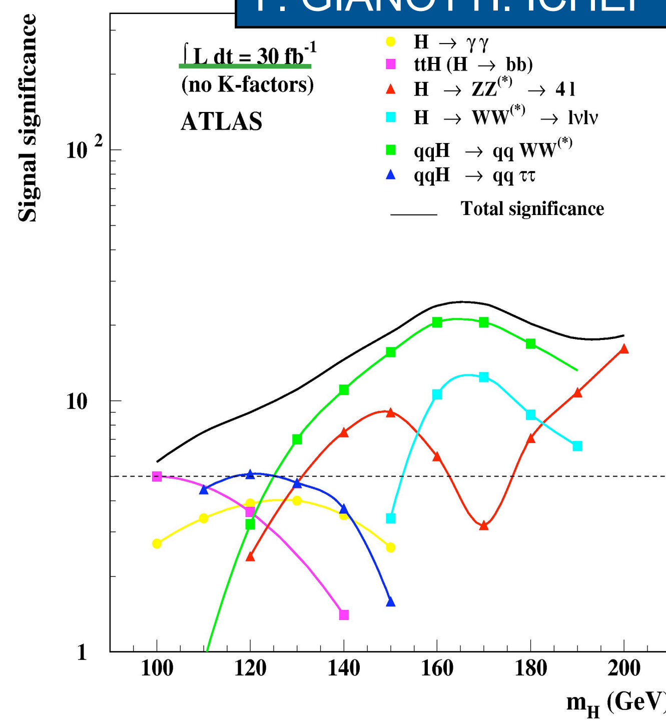
$\leq$ 5 fb^{-1} for 5σ discovery

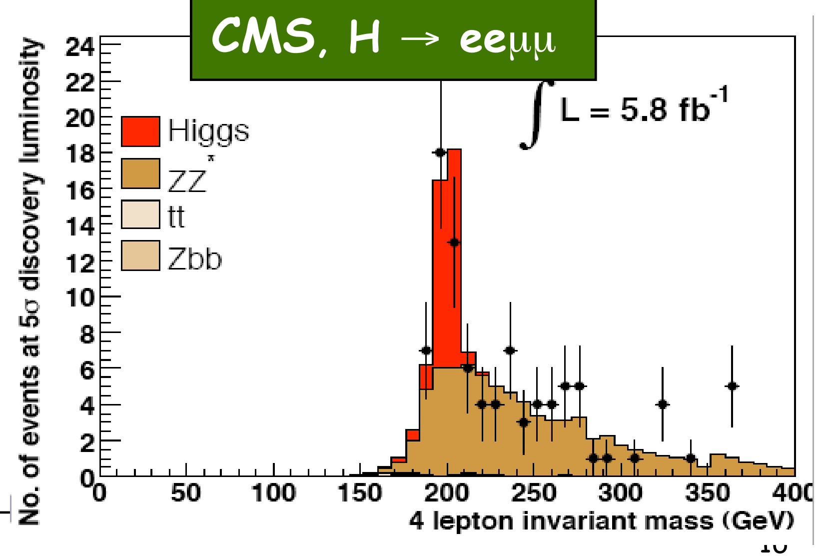
over full allowed mass range

ATLAS + CMS preliminary

here discovery easier with gold-plated $H \to ZZ \to 4l$

→ by end 2008 ?





$H \to 4l$: narrow mass peak, small background

$H \to WW \to l\nu l\nu$ (dominant at the Tevatron): counting channel (no mass peak)

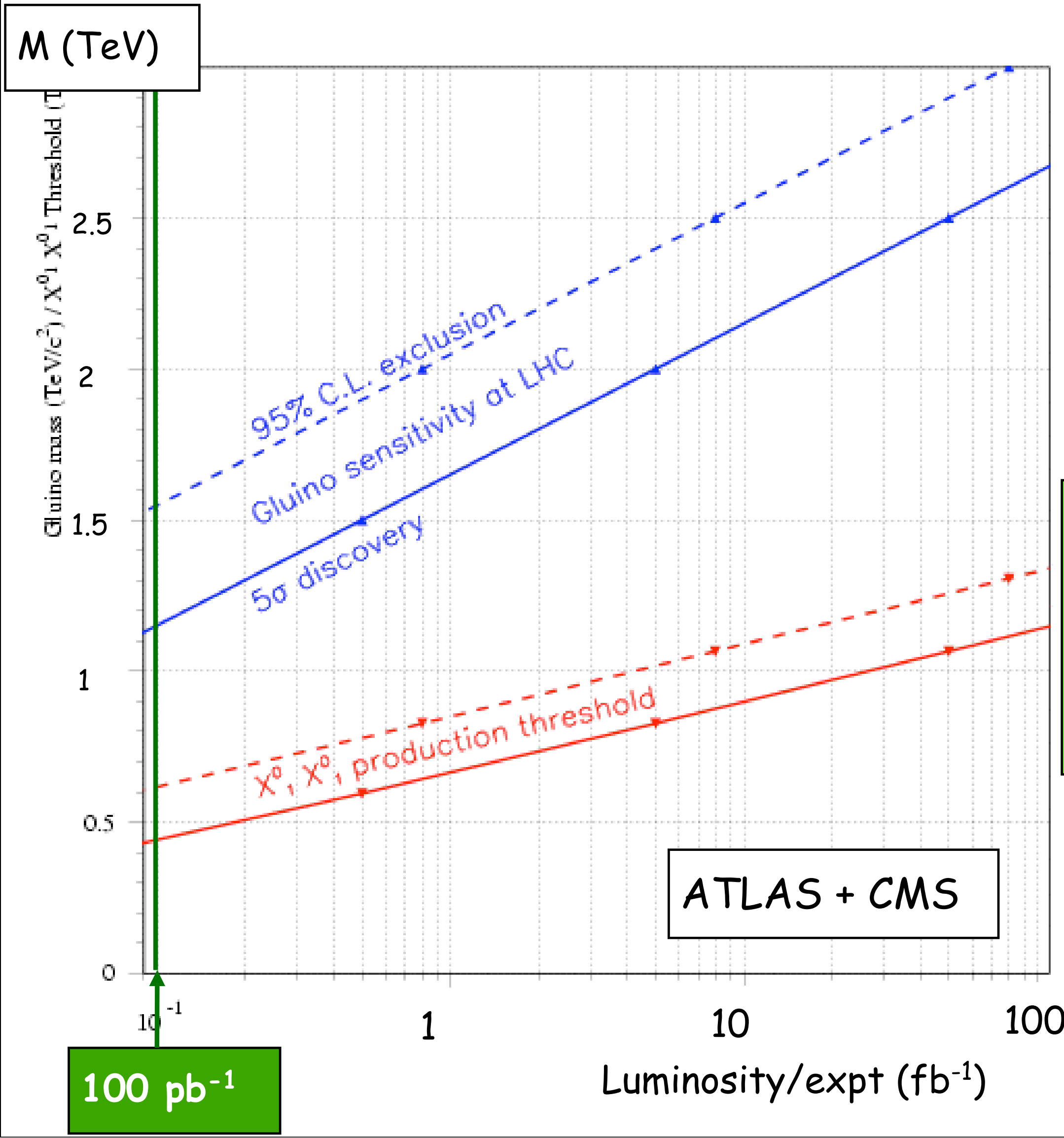
Example of "early" discovery: Supersymmetry ?

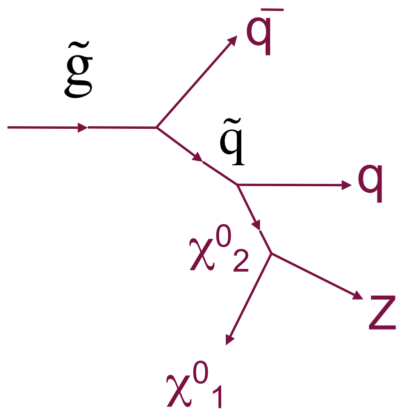
F. GIANOTTI. ICHEP 06

If SUSY at TeV scale → could be found "quickly" .... thanks to:

- large $\tilde{q},\tilde{g}$ cross-section → ≈ 10 events/day at 10^{32} for
- spectacular signatures (many jets, leptons, missing E_T)

$m(\tilde{q},\tilde{g}) \sim 1$ TeV





Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 (good) pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

BUT: understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.

3. MSSM under tension: why still no trace of SUSY??

Today's puzzle

F. ZWIRNER

[stressed, e.g., by Barbieri and Strumia: little hierarchy problem]

SM with light Higgs is in precise agreement with data

Naturalness pushes for a low scale of new physics:

$$\Lambda_{NP} < O(500)\ GeV$$

Precision tests push for a high scale of new physics:

$$\mathcal{L}_{eff}^{NP} = \frac{1}{\Lambda_{NP}^2}[c_1(\bar{e}\gamma^\mu e)^2 + c_2 W^I_{\mu\nu}B^{\mu\nu}H^\dagger\sigma^I H + \ldots]$$

$$c_i = O(1) \quad \Rightarrow \quad \Lambda_{NP} > \text{several } TeV$$

Conflict avoided with weakly coupled new physics affecting low-energy observables only via loops (and decoupled from flavour-violating operators)

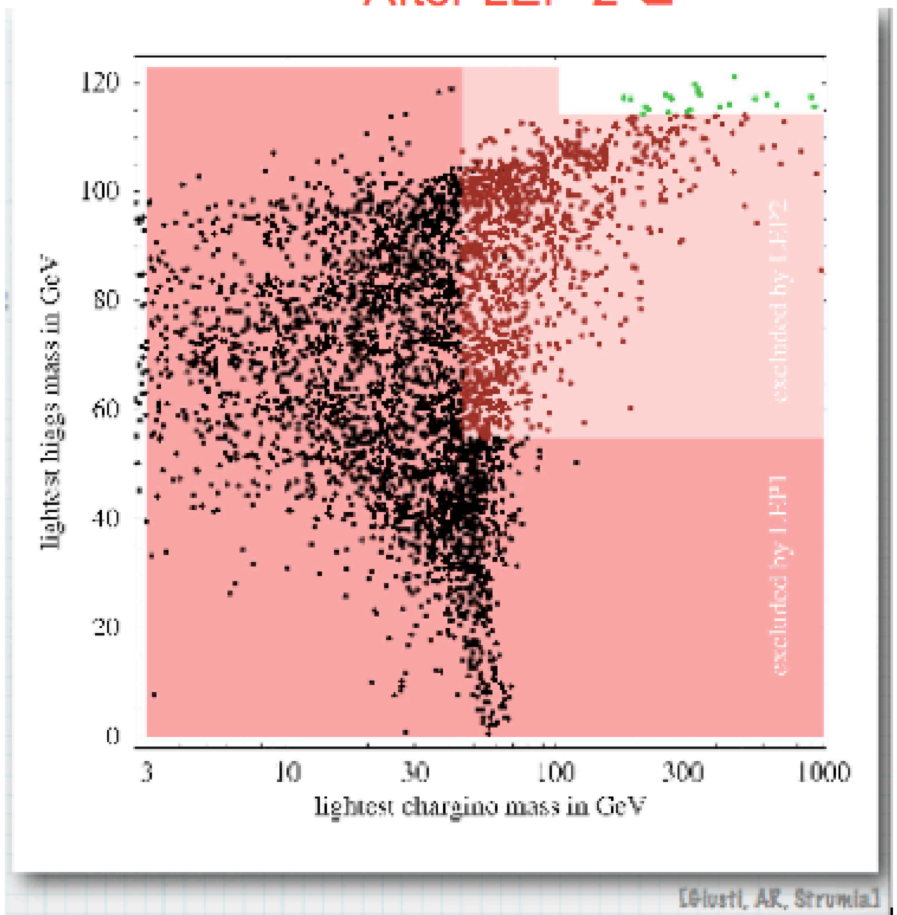
$$c_i \sim \frac{\alpha}{2\pi} \quad and \quad \Lambda_{NP} \sim O(500)\ GeV$$

F. ZWIRNER

An empirical measure of fine-tuning

After LEP-2 ↘

lightest Higgs mass (GeV)



← After LEP-1

lightest chargino mass (GeV)

F. ZWIRNER

4. (My temporary) conclusions

- Naturalness can still be used as a guiding principle
- It unambiguously predicts new physics at the LHC scale
- Precision tests: new physics must have special properties
- Supersymmetry still the most plausible candidate, even if we would have expected it to have been found already
- We may be missing important aspects of susy breaking
- Healthy to have alternatives for new physics at the LHC, some may merge with supersymmetry at a deeper level (e.g. extra dimensions & strongly interacting EW sector)

and, most importantly:

THE ERA OF SPECULATIONS ON WEAK SCALE IS AT ITS END: THE LHC VERDICT IS COMING!

5. Getting more radical: extra dimensions

From P. Derendinger in "High Energy Physics at the LHC Era: Theoretical and Experimental Perspectives"
Paris, October 2006

- String theories have more than four space-time dimensions (i.e. D=10 with fermionic states): need to compactify (or decouple) the extra dimensions.
- Uses supersymmetry and comes out naturally as an extension of the MSSM.
- However, many ways to break supersymmetry. Even at the Planck/string scale.
- Compactification radii and string scales are not necessarily Planck size [May be large].

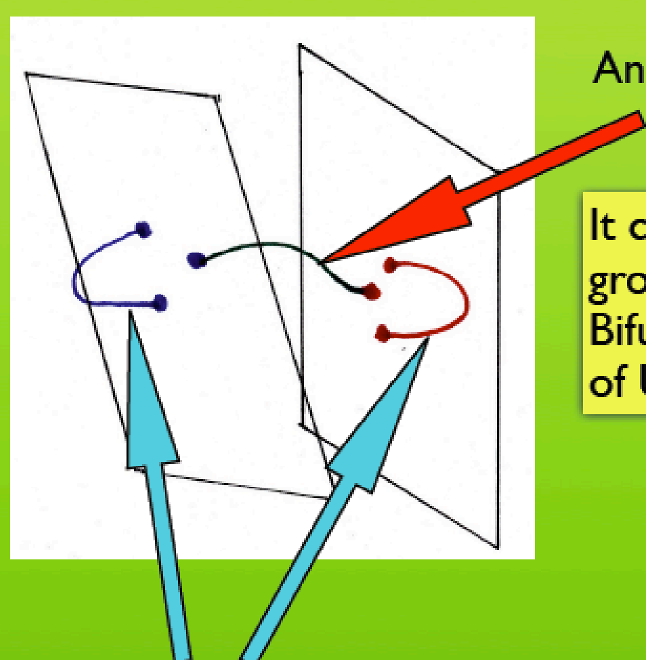
What if $1/R_D = M_D$ = electroweak mass scale ????

Arkhani-Ahmed, Dimopoulos,...

D-branes and open strings

A new ingredient: string solutions with a certain arrangement of D-branes on which open strings may end: new states in the spectrum to be used in string extensions of the Standard Model: "brane-world models", "intersecting brane models", "magnetized brane models"...

D-branes are not objects artificially introduced in space-time, they are *solutions of the string background equations*.



An open string stretching between two D-branes

It carries charges under both U(N) groups living on each brane: Bifundamental of U(N) x U(N)

What is needed for quarks, leptons, Higgses.

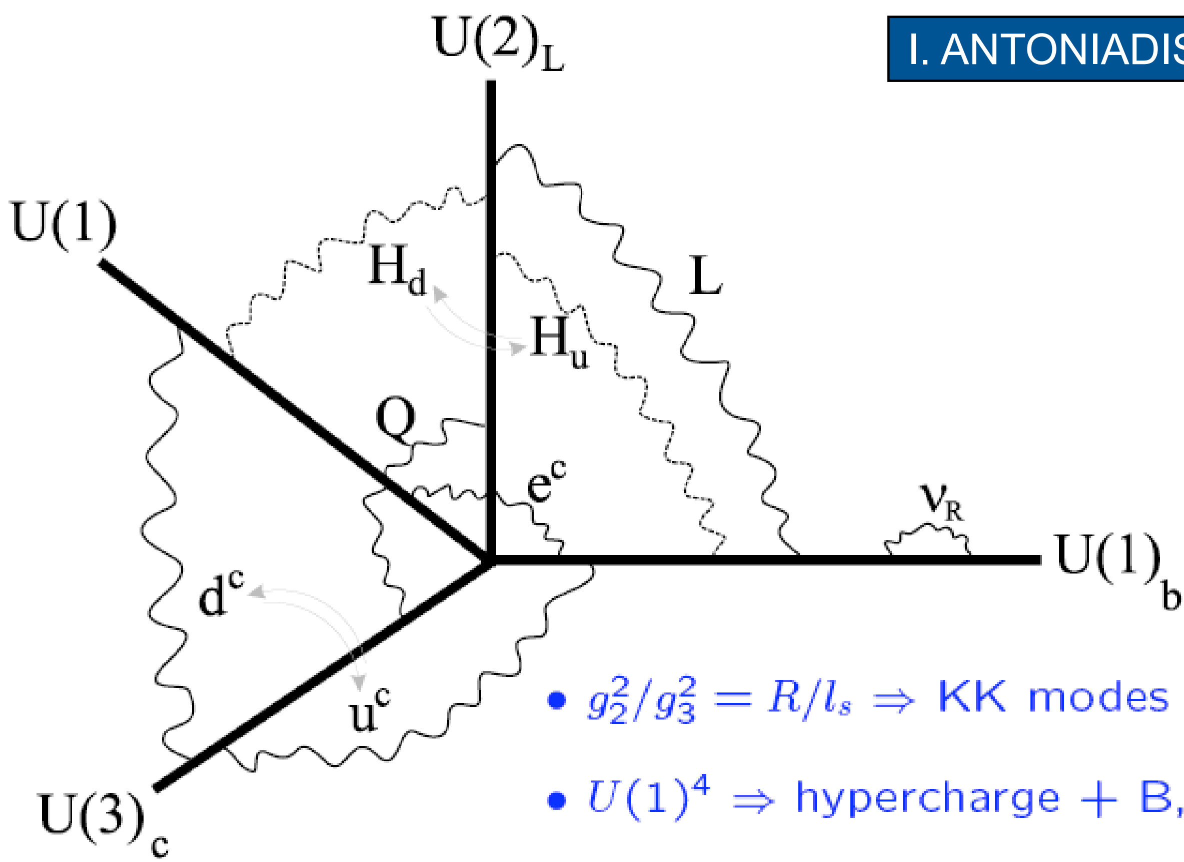
Adjoints of both U(N)'s: give the gauge bosons (and gauginos)

Overcoming the Quantum Field picture

Stringy picture of the Standard Theory ??

Standard Model on D-branes

I. ANTONIADIS



- $g_2^2/g_3^2 = R/l_s \Rightarrow$ KK modes for $SU(2)_L$
- $U(1)^4 \Rightarrow$ hypercharge + B, L, PQ global
- $U(1)$ on top of $U(2)$ or $U(3) \Rightarrow$ prediction for $\sin^2\theta_W$
- ν_R in the bulk $\Rightarrow$ small neutrino masses

The multidimensional physicist's kit:

What are M_D and/or R?

Recall: $$R = \frac{1}{M_D}\left(\frac{M_{Planck}}{M_D}\right)^{\frac{2}{D}}$$

Micro :

$M_D = M_{Planck} = 10^{18}$ GeV $\Rightarrow R \approx 10^{-35} cm (Planck - radius)$

Mini (D=2) :

$M_D = M_{GUT} = 10^{16}$ GeV $\Rightarrow R \approx 10^{-33} cm$

Coupling unif.
ν mass...

Midi :

$M_D = 10^7$ TeV(D=2)

10^4 TeV(D=6)

$\Rightarrow R \approx 10^{-17} cm (TeV - scale)$

Maxi :

$M_D = M_{Weak} = 1$TeV

$\Rightarrow R \approx 1 mm$ (D=2)

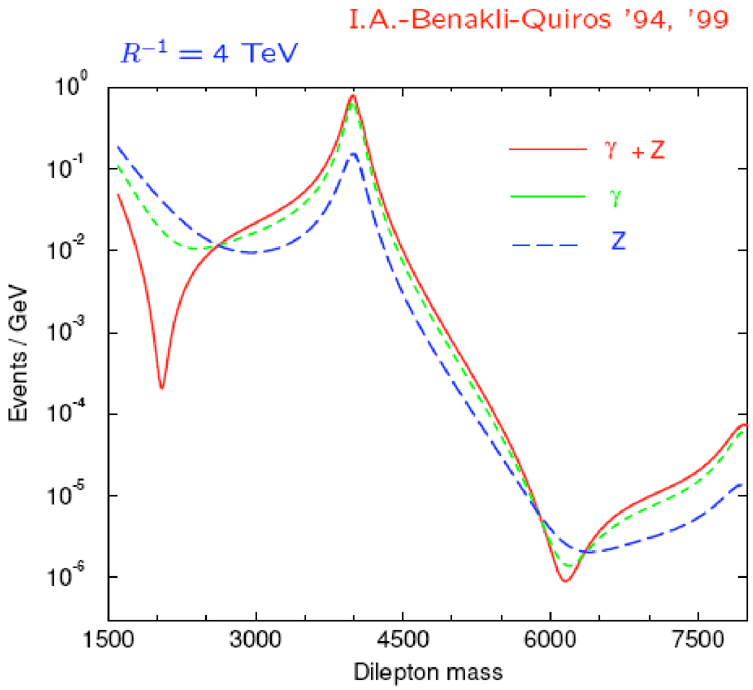
$\Rightarrow R \approx 10^{-2}\ \mu m$ (D=3)

Signatures of extra dimensions

- Kaluza-Klein excitations of known particles

$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

$\Rightarrow$ excited states of photon, $W^{\pm}$, Z, gluons



Correlated resonances in different channels would give very convincing evidence

virtual effects

Massive string vibrations $\Rightarrow$ indirect effects

virtual exchanges $\Rightarrow$ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

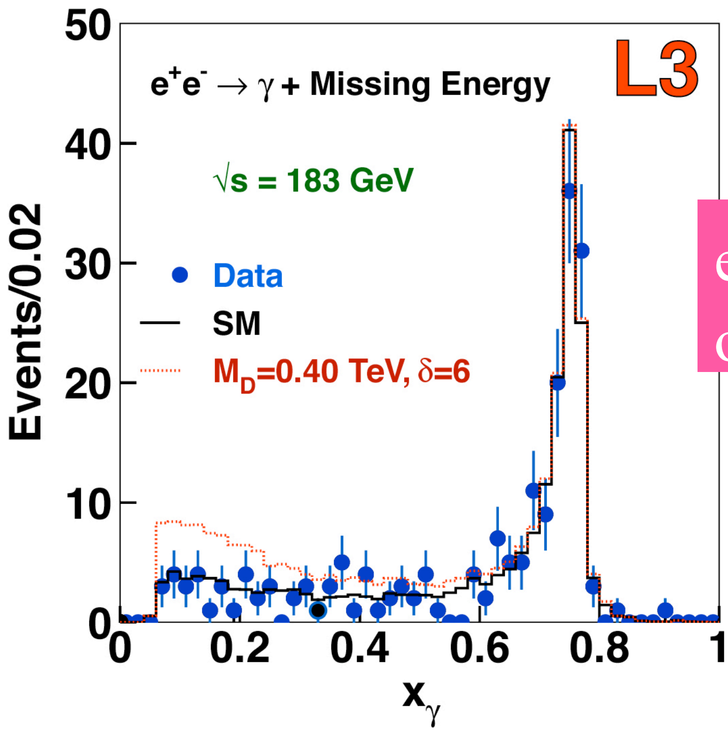
- same set of branes $\Rightarrow M_s \gtrsim 500$ GeV

dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$ Cullen-Perelstein-Peskin '00

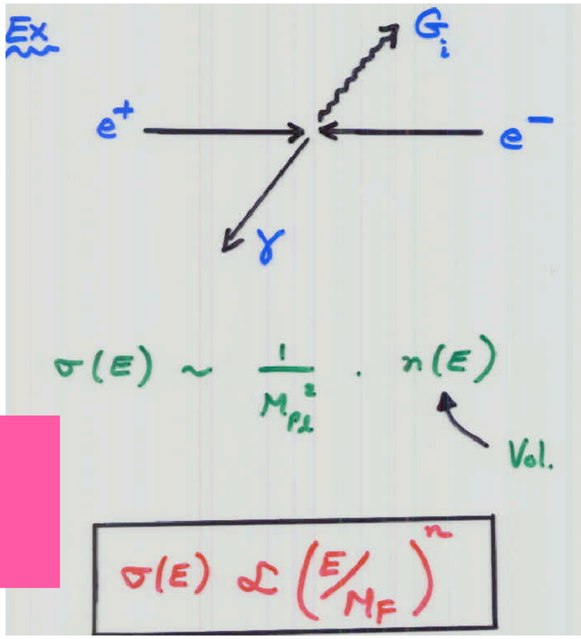
- brane intersections $\Rightarrow M_s \gtrsim 2-3$ TeV

dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$ I.A.-Benakli-Laugier '00

invisible energy

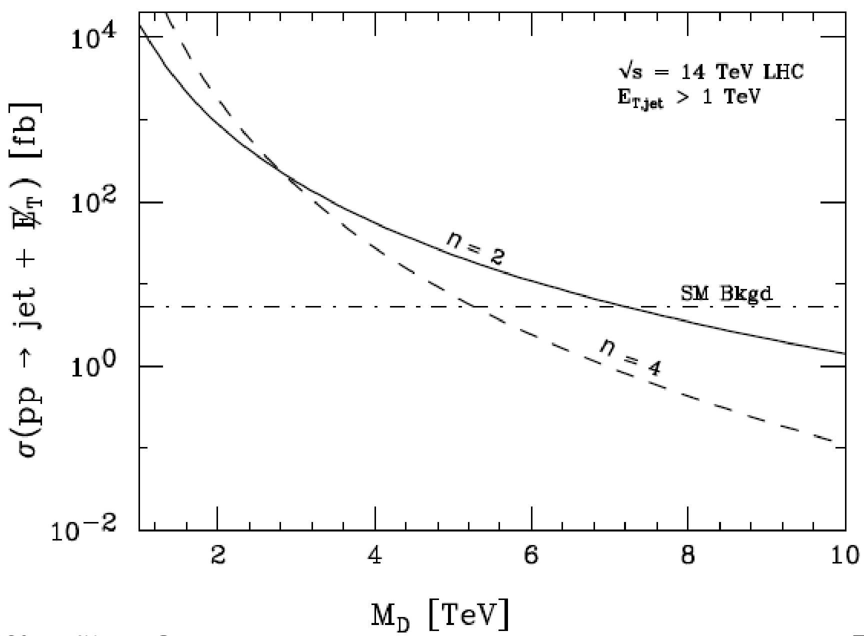


$e^+e^- \to \gamma$ + KK tower of Gravitons



Giudice-Rattazzi-Wells '98

- with LHC we can do better



Symmetry Breaking from twisted boundary conditions ??

- Initiated by Kawamura in the context of GUT
- could be used for SUSY breaking ???

Triplet-Doublet Splitting, Proton Stability and an Extra Dimension

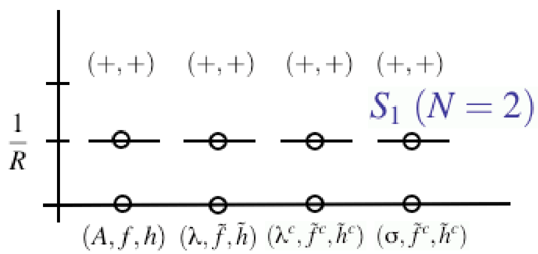
Yoshiharu KAWAMURA*)

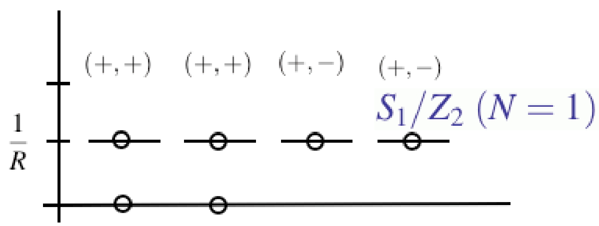
Department of Physics, Shinshu University, Matsumoto 390-8621, Japan

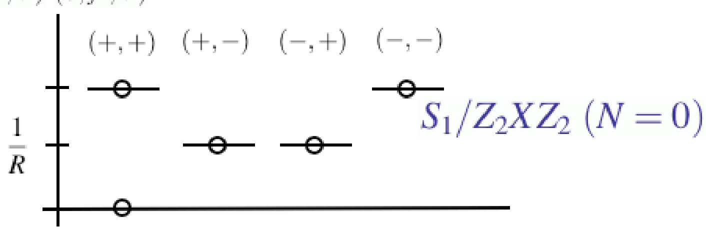
eived December 11, 2000)

Supersymmetry broken by B.C. on 5th dimension

a' la Scherk-Schwarz







1 single parameter 1/R, fixed by $G_F^{-1/2}$ *after rad. corr.*

$$\Rightarrow \frac{1}{R} = 450 \pm 100\ GeV \qquad m_h = 127 \pm 8\ GeV$$

B, Hall, Nomura

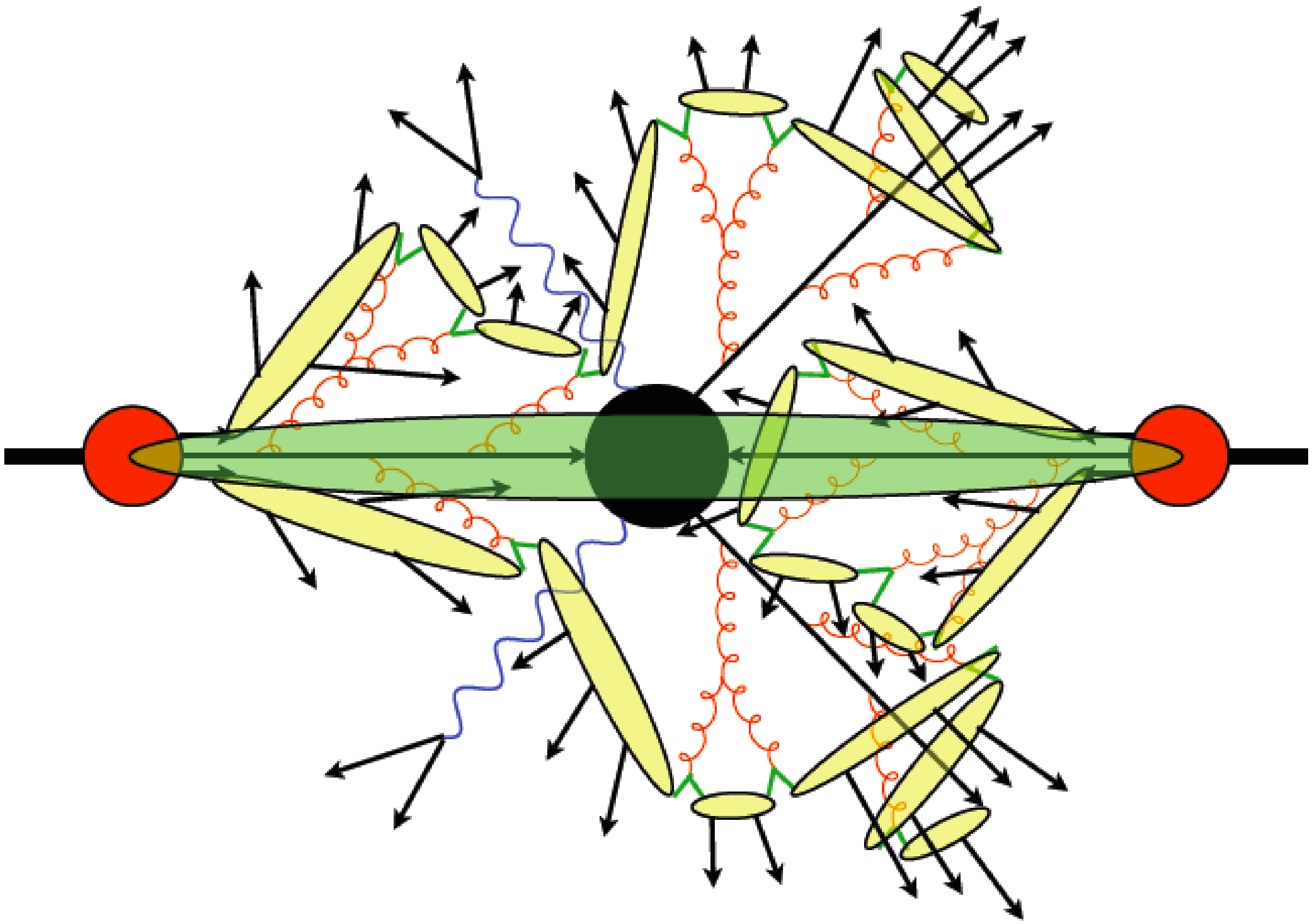
- Theory non renormalizable in 5 dimensions
- a large departure from field theory anyway !!!!
- a shot in the dark ???

Extra dimensions, gravity at low mass....

- Exciting possibility
- very clear signatures
- however:
- critical dependence from n makes predictions quite variable
- indirect effects are already pushing M_D up....20 TeV ???
- where have all GUT predictions gone ?? (neutrino mass, unification of couplings...):
- interesting attempts to recover them ...but still a lot of arbitrariness.

6. The data analysis challenge

Bryan Webber, University of Cambridge
'LHC Era' Workshop, Paris, 13-17 Nov 2006



2

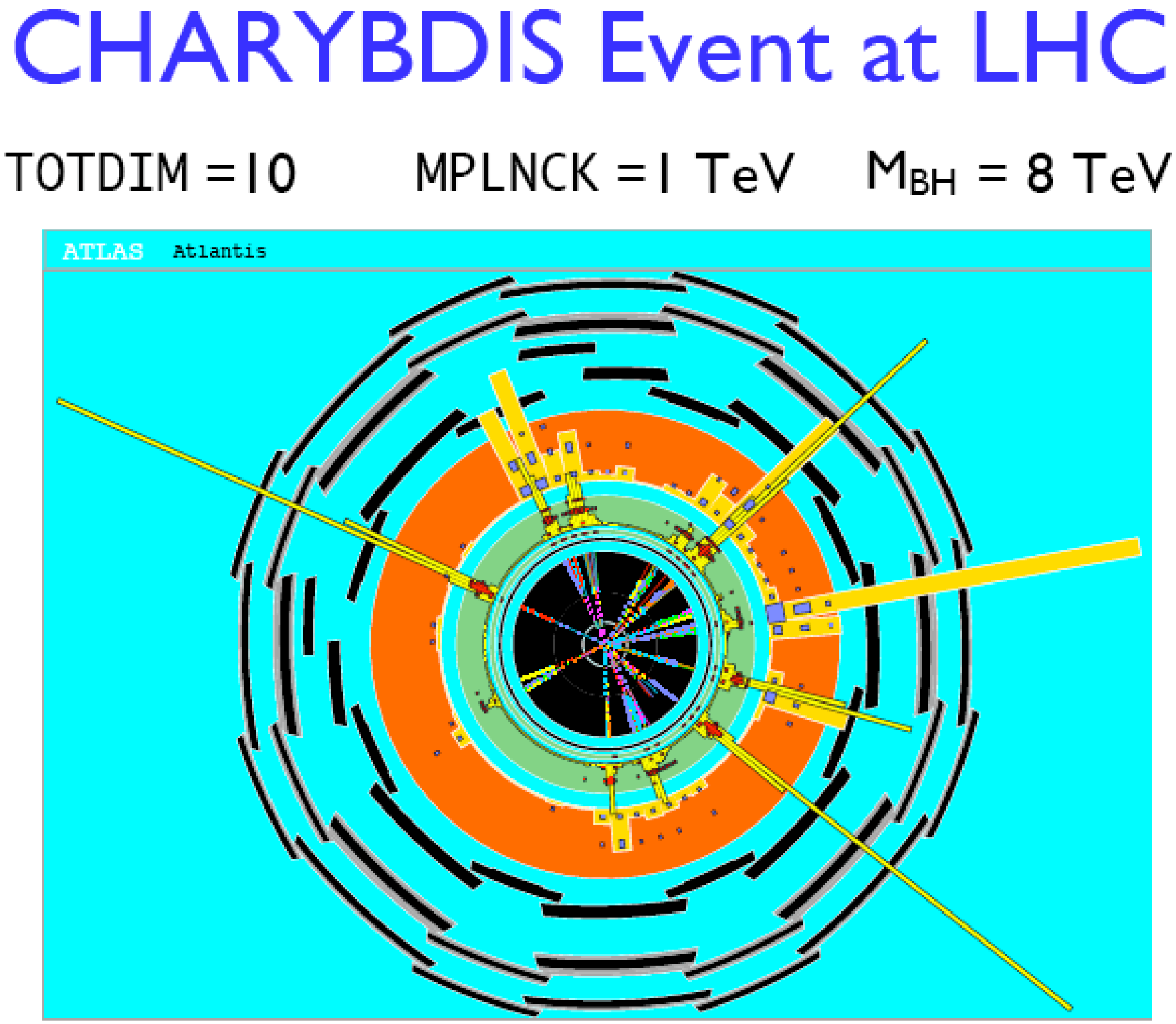
you give the parton-level process....

General-Purpose Event Generators

- PYTHIA
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran; v8 C++
- HERWIG
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++
- SHERPA
  - Virtuality-ordered shower, string/cluster hadronization
  - C++

even something rather strange should happen..

simulation of a mini black-hole event@ LHC (B. Webber)



- Adequate tools are in place
- exploration of the “classical LHC paradigm” should be possible to search for
- as for the unknown....

...a reminder...

All bunch crossings not selected by the on-line selection system are lost forever

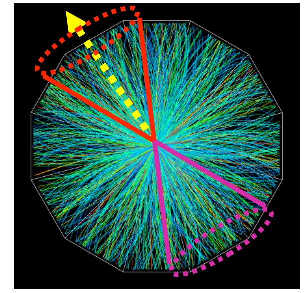
(only ~100 out of 40 000 000 bunch crossings available for repetitive (offline) physics analyses)

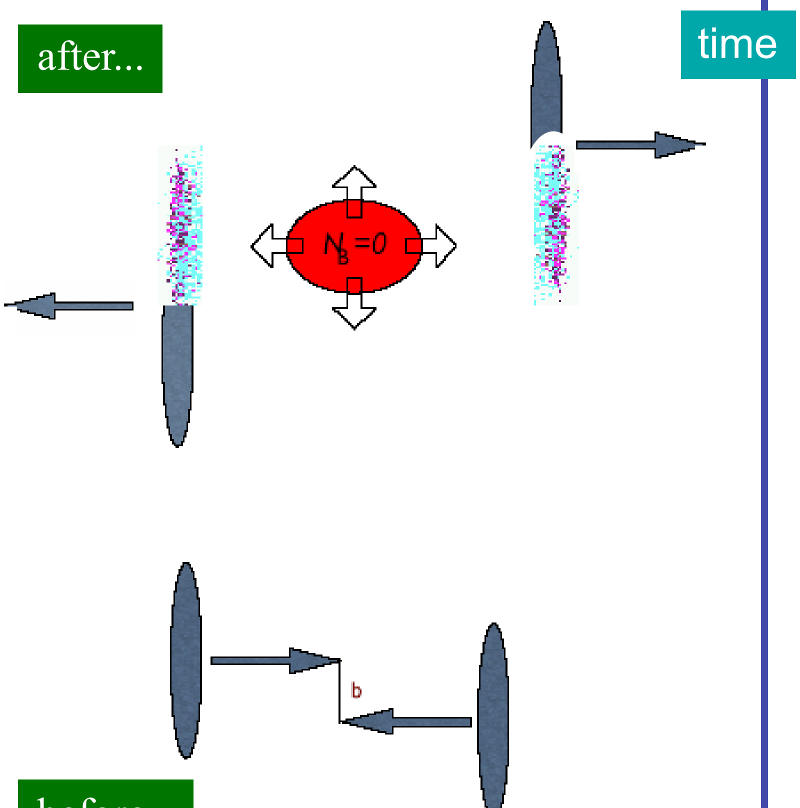
Mieczyslaw Witold Krasny, Pierre et Marie Curie University, Paris

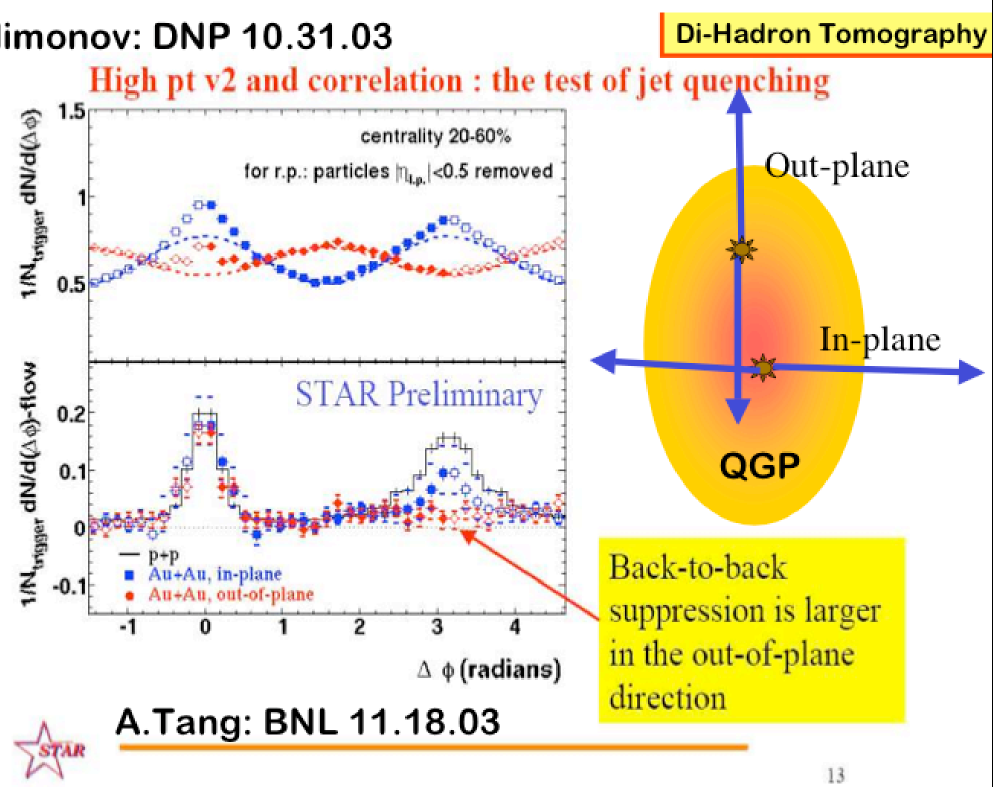
Reminiscent of the Eddington fisherman’s net:
Are we bound to find only what we are looking for??

- see LHC detectors as a “single pass” facility
- when new ideas will come, change appropriately the trigger menu and run the LHC again

7. Physics at the low energy frontier: hadrons from Quark&gluon matter

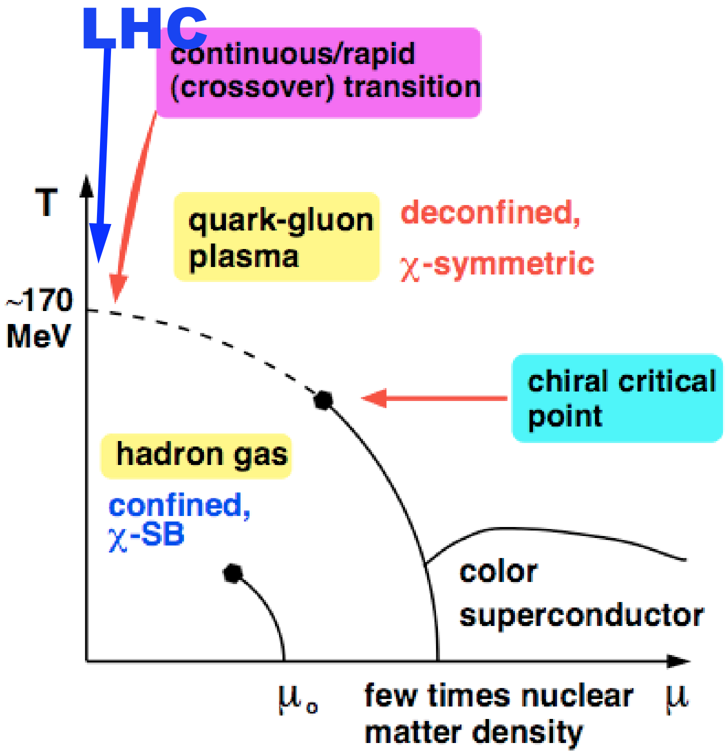






SPS: Pb-Pb 17 GeV/A
RHIC: Au-Au 200 GeV/A
LHC: Pb-Pb 5 TeV/A

Fancy, facts and calculations

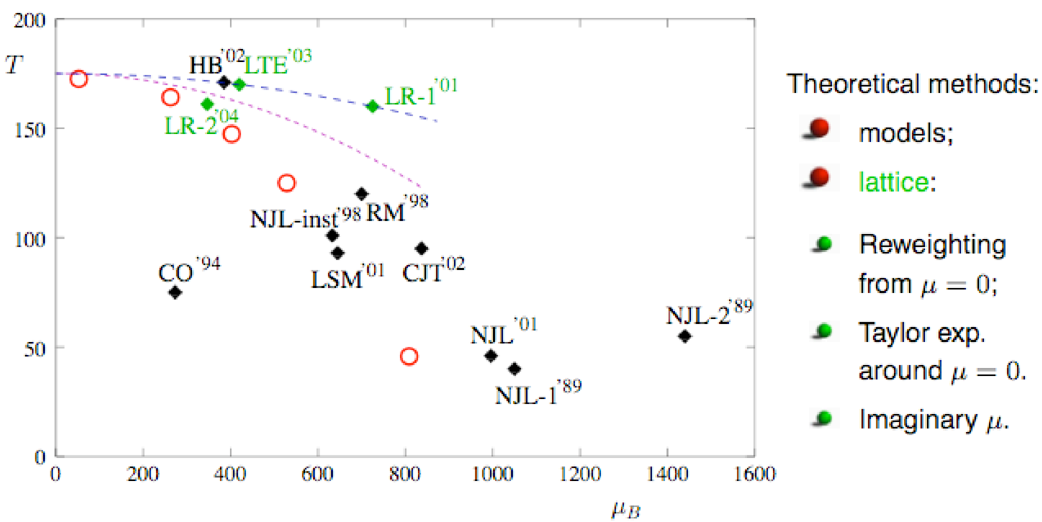


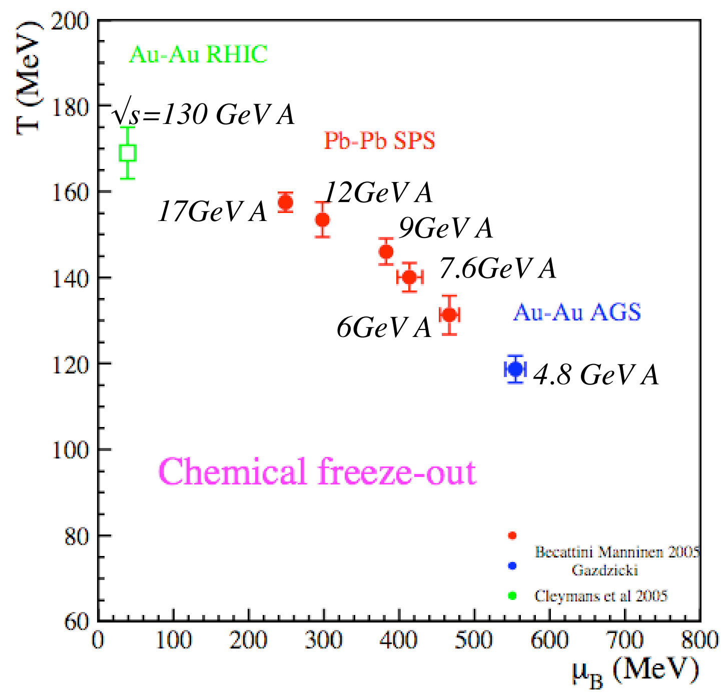
continuous transition for small chemical potential and small quark masses

2nd order phase transition;
Ising universality class
$T_c(\mu)$ under investigation

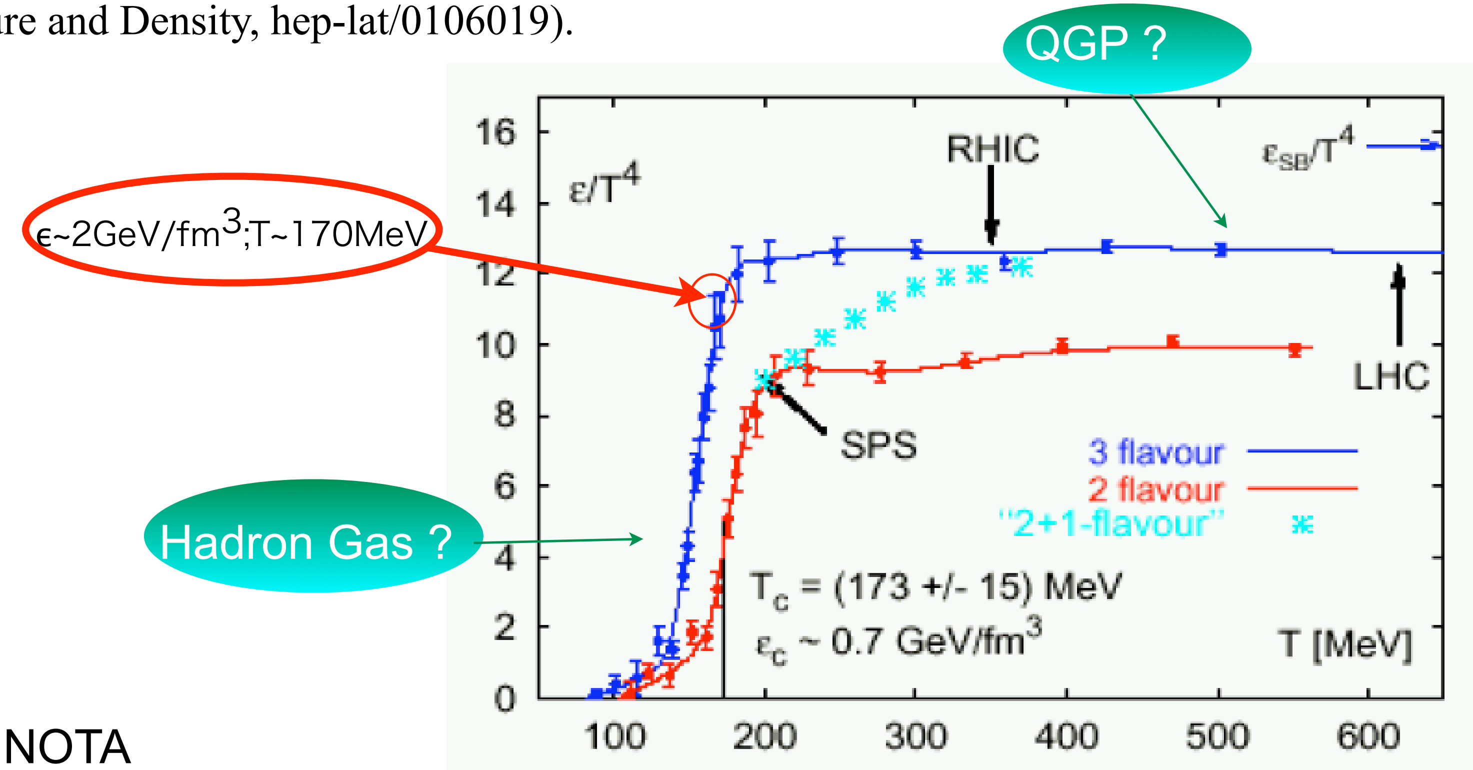
location of CCP uncertain:
volume and quark mass dependence

Locating the QCD critical point





Lattice QCD calculations of the energy density of hadronic matter vs. T (F. Karsch, Lattice QCD at High Temperature and Density, hep-lat/0106019).



NOTA

$$1\ fm = 10^{-13} cm \rightarrow\ 1(fm)^{-3} = 10^{-39} cm^{-3}$$
$$1 GeV = 1\ massa\ protone \simeq 10^{-24} gr$$
$$2GeV/fm^3 \simeq\ 10^9 ton/cm^3$$

(b) Elliptic flow

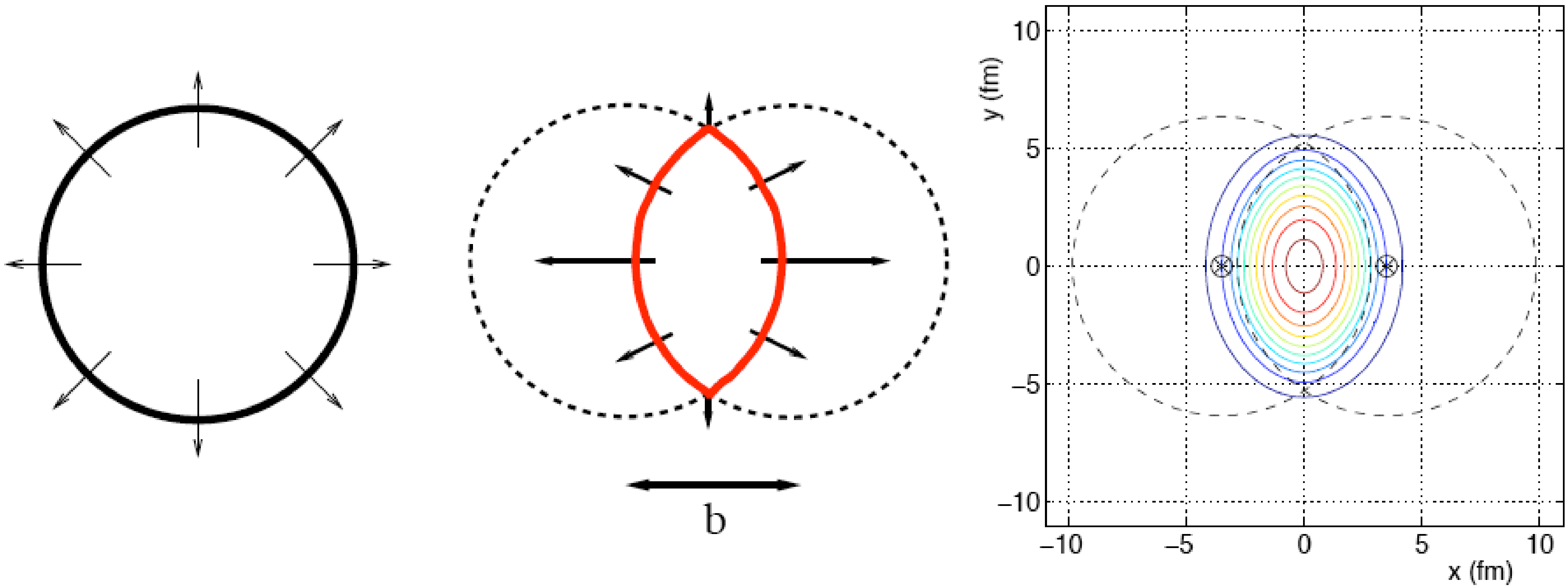


Fig. 12: Left and center panels: Schematic picture of radial and elliptic flow. Right panel: Initial energy density contours in the transverse plane for a Au+Au collision at impact parameter $b = 7\,\mathrm{fm}$. The dashed circles indicate transverse projections of the colliding nuclei.

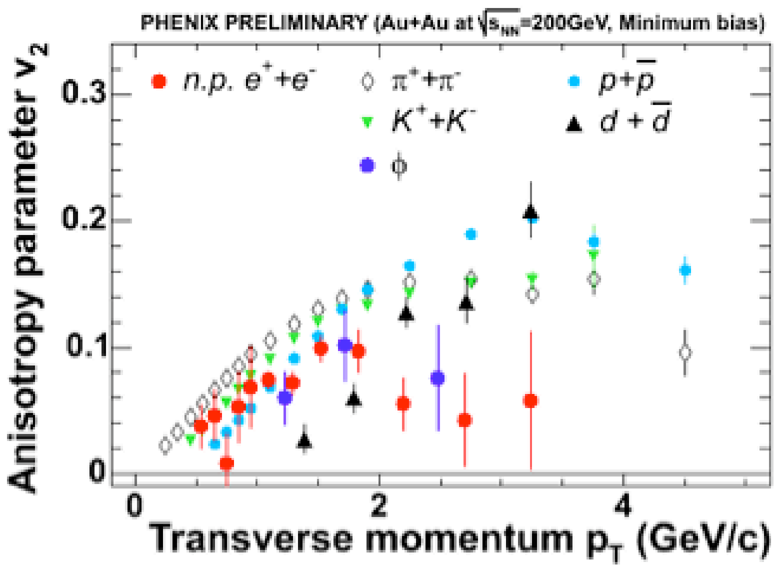
A collective phenomenon !!

Space eccentricity → Momentum anisotropy

$$\varepsilon_x(b) = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \neq 0 \qquad \varepsilon_p(\tau) = \frac{\int dxdy\,(T^{xx} - T^{yy})}{\int dxdy\,(T^{xx} + T^{yy})}.$$

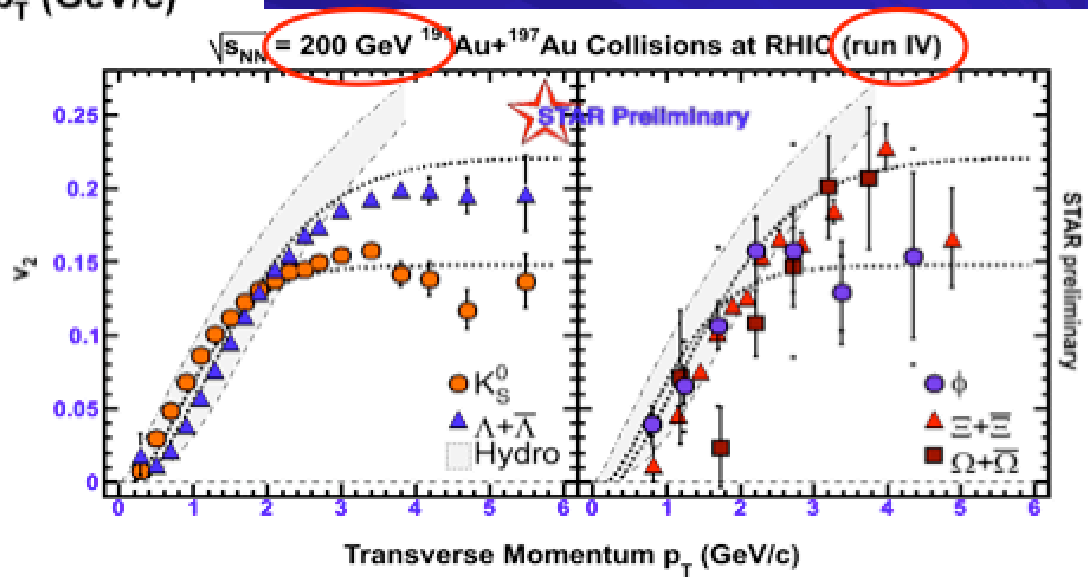
A tour in RHIC&SPS data (QM05, I. Tserruya)

Every particle flows



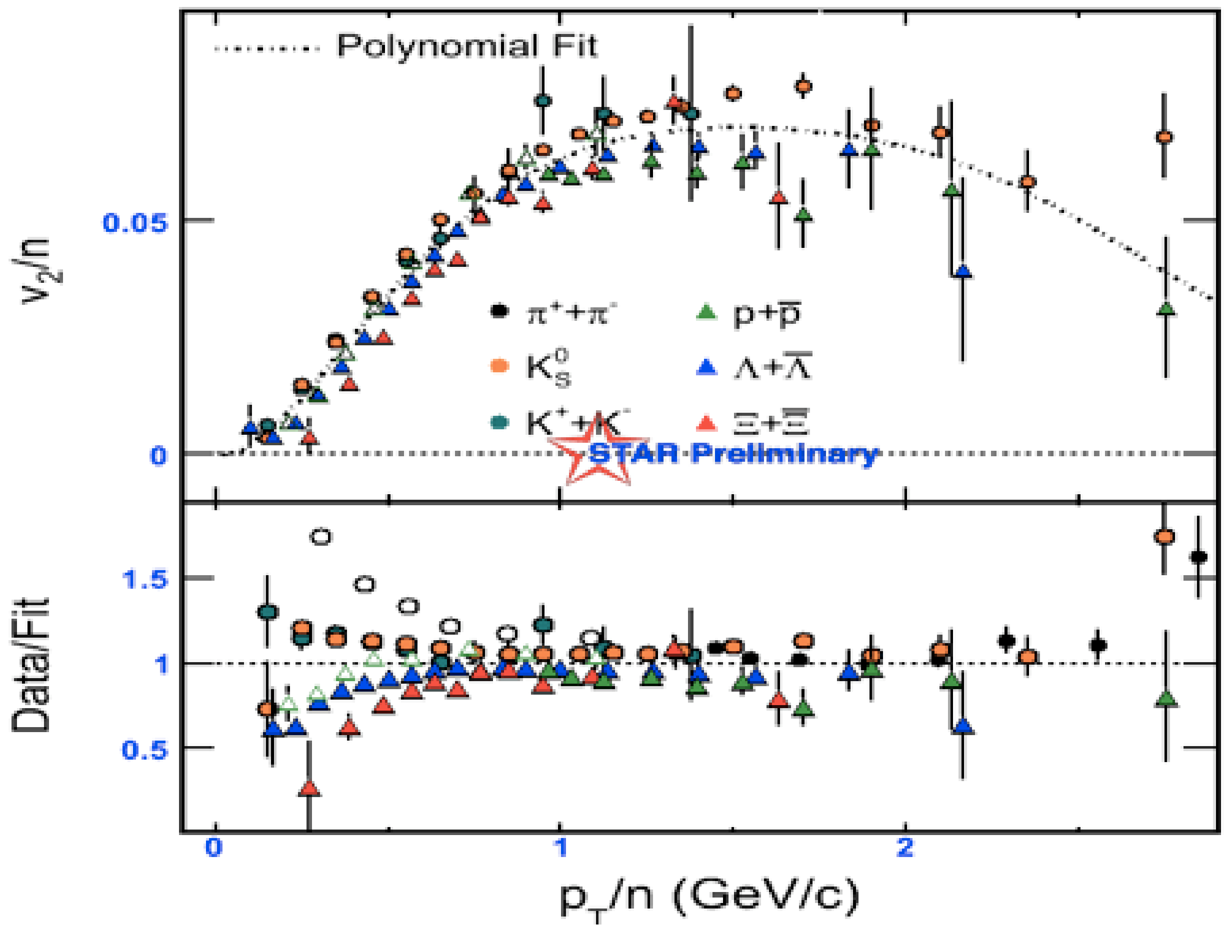
- Large v_2 of heavier particles: ϕ, Ξ, Ω, d.
- Even open charm flows (measured through single electrons)
- Strong interactions at early stage → early thermalization.

Itzhak Tserruya



Quark Counting in Heavy Ion Collisions

The elliptic-flow counting

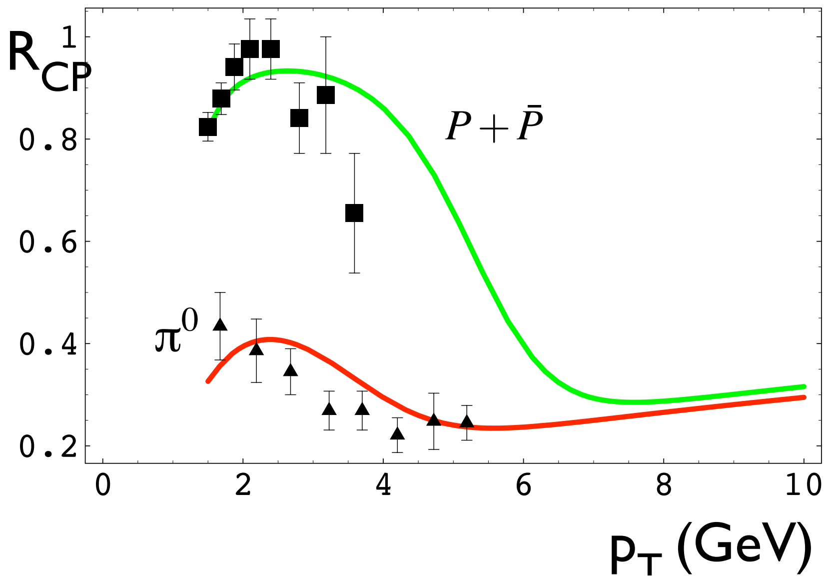


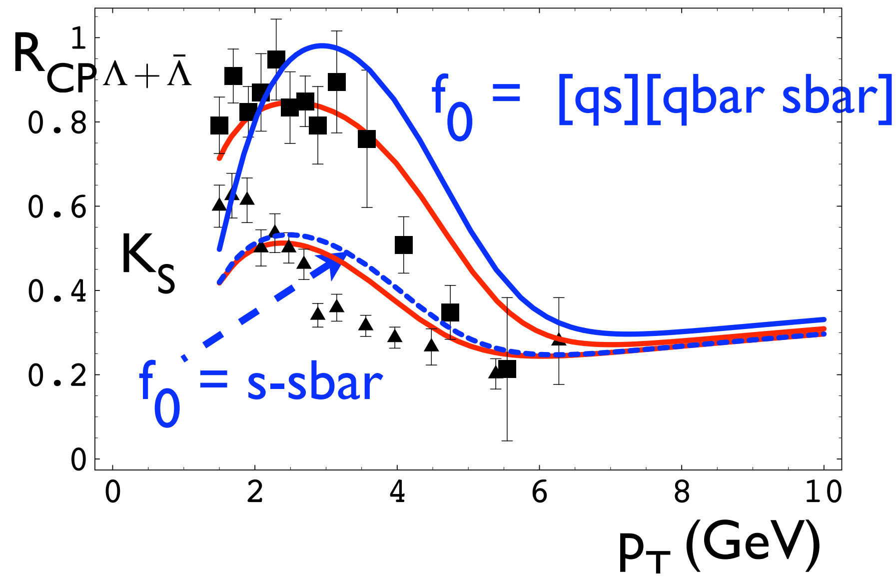
All this strengthens the case for sQGP with *early thermalization* of partonic matter made of *constituent quarks*

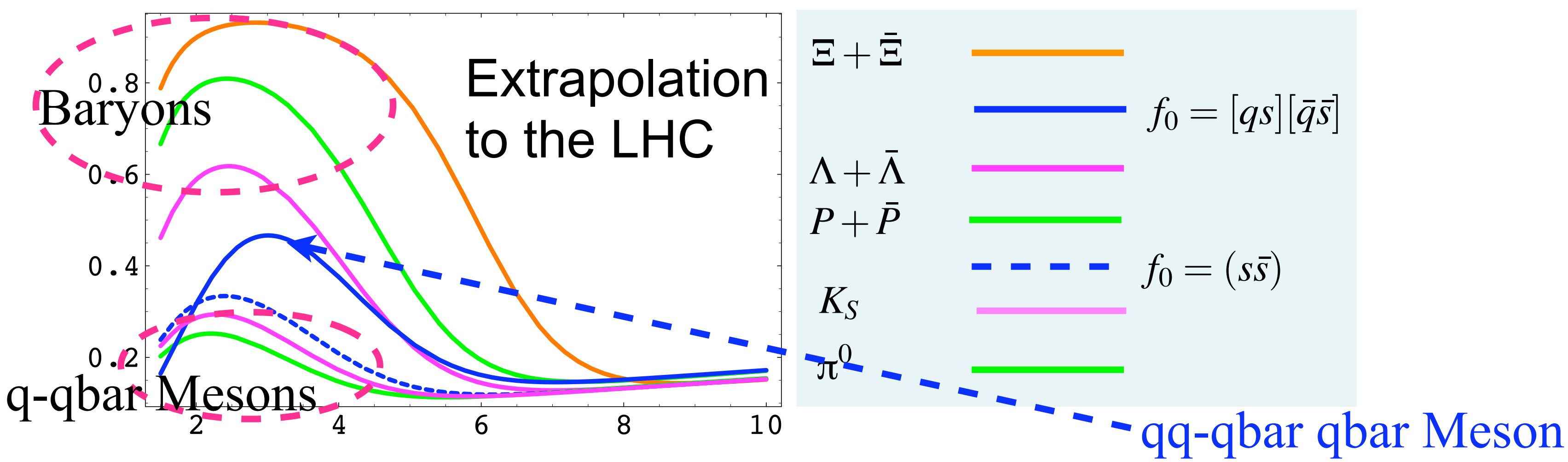
Ratio: CP(RHIC, Au-Au)

L. M., A. Polosa, V. Riquer, C. Salgado

$$R^H_{CP} = \frac{\frac{1}{N_{coll}}\frac{dN_H}{d^2p_\perp}(b=0)}{\frac{1}{N_{coll}}\frac{dN_H}{d^2p_\perp}(b=12)}$$







Useful probes @ LHC

- initial state quanta:
  - hard jets
  - hard, heavy quarks (what about top?)
  - Higgs
- bulk properties of QGP:
  - jet tomography
  - collective motion, hydrodynamical flow..
  - quarkonia will form from recombination: enhancement!

big surprises are possible!

Conclusions: what if...?

- We seem to be well-equipped for the next round of High Energy Physics
- tools to look for Higgs, SUSY and most simple alternatives are in place
- The LHC is confirmed to be in “the right place”, an energy region whise exploration ***is a must*** for Particle Physics
- what if no Higgs and no SUSY?
- Higgs: we know there is symmetry breaking, there must be a substitute in the TeV, e.g. W-W strong interactions
- LHC can see at least valid hints !
- ***I am confident LHC can say something conclusive about EW symmetry breaking***

Conclusions: what if...? (cont'd)

- SUSY may be more difficult: problems with an elementary scalar can be sent to some higher scale, 20 TeV or so ...
- the present lore: a 0.5-1 TeV LC can see virtual effects...but think of g-2 !!!
- a very politically ***uncorrect***, personal vew: the option of another exploratory machine like Eloisatron..or the "old" SSC should be kept
- an El/SSC type Hadron Collider has to be built in the US (there is no space at CERN) by a global collaboration (no alternative)
- Europe/CERN could aim, later, at a high-precision LC, from 90 GeV (Z factory) to multi TeV (CLIC).

....let's think about that...in time.