Y a-t-il un futur après le LHC ?

Oui, c'est un collisionneur leptonique

Pierre Lutz Irfu/SPP et IN2P3/LAL

Context of this talk

- The energy frontier : entering the terascale

Tevatron@Fermilab	A first glimpse	1.96 TeV
LHC @ CERN	exploration	7 → 14 TeV
Next collider	Zoom in to reveal the most important features	???

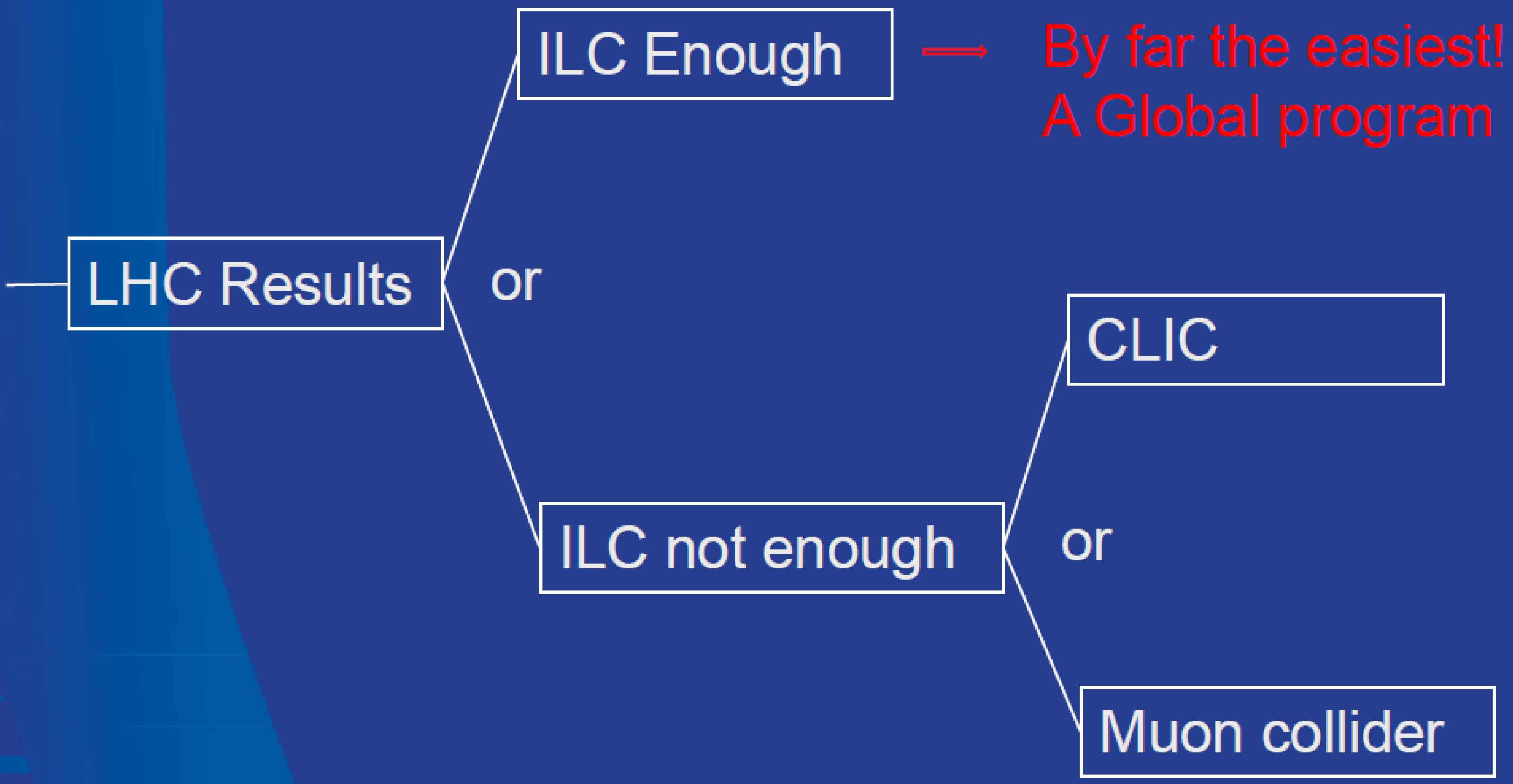
- LHC start-up : promises and limits
- The Standard Model is well alive ! But needs some modifications.

Summary

It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier; *there should be a strong well-coordinated European activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision, to be ready for a new assessment by Council around 2010.*

Unanimously approved by the CERN Council at the special Session held in Lisbon on 14 July 2006

Biggest decision of the decade !



Outlook

- Complementarity between hadron and lepton colliders
- Things we'll never do with the LHC
- LC Physics case as robust as ever
- Comments on different LC technologies
- The need for a vigorous detector R&D
- Irfu/SPP & SEDI studies

What do we expect to find ?

Certainly : the Higgs particle(s), or whatever takes its place

Possibly : provide the dark matter that fills the Universe

Perhaps : more distant cousins of these might even be responsible for the dark energy that drives the Universe apart

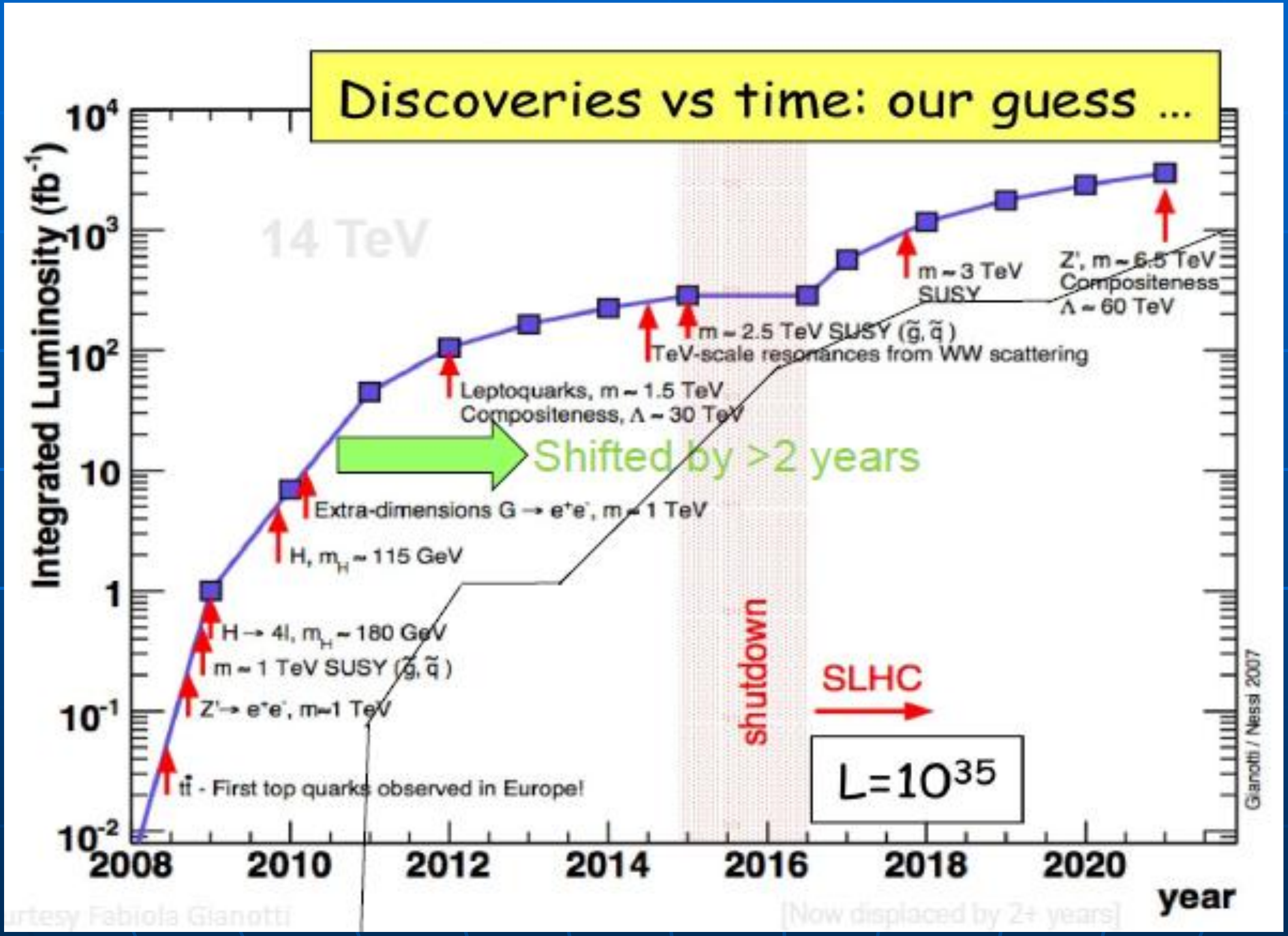
Clear connexion with the Cosmic Frontier

LHC and its 4 scenarios

i. A higgs particle (and anything else)
ii. No higgs particle (and anything else)
iii. Events with missing energy (SUSY)
iv. Some more exotic signal of new physics

Hard to imagine any LHC discovery which would not trigger the start of an e^+e^- program.

Timescale for the LHC



Gianotti 2007

Oddone 2010

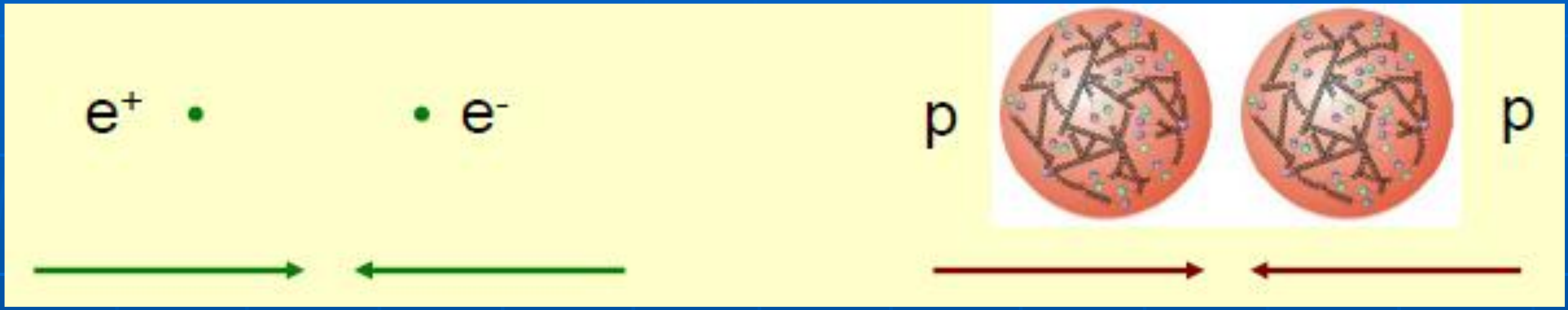
Hadron vs lepton collider

Why e^+e^- ?

- Two distinct and complementary strategies for advancing in particle physics with the help of colliders
- High energy : direct discovery of new phenomena
- High precision : quantum effects of new physics at high energies through precise measurements at lower scales
- Both strategies have worked well together : much more complete understanding.

Why e^+e^- ?

Key features of e+e- (what does not work with hadron collisions)

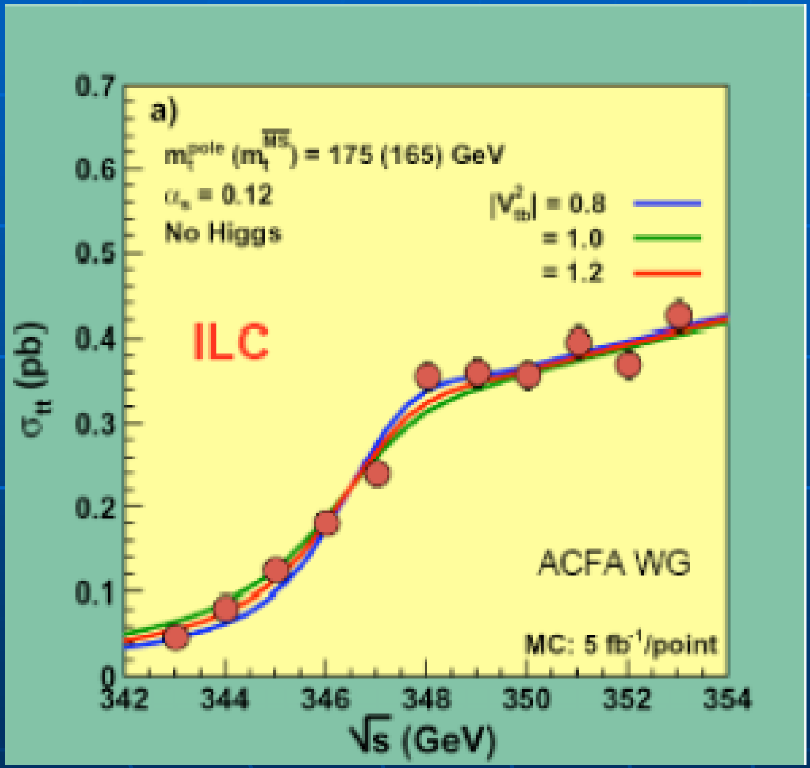


- ✓ precisely defined and known centre-of-mass energy of hard process
  (machine requirement : low beam energy spread, low beamstrahlung)
- ✓ tunable centre-of-mass energy
  (machine requirement : flexibility, high luminosity)
- ✓ polarized beams
  (machine requirement : do it ! - detectors : measure it !)
- ✓ clean, fully reconstructable events
  (detector requirement : jet flavour, lepton reconstruction, hermeticity)
- ✓ moderate backgrounds → no trigger → unbiased physics

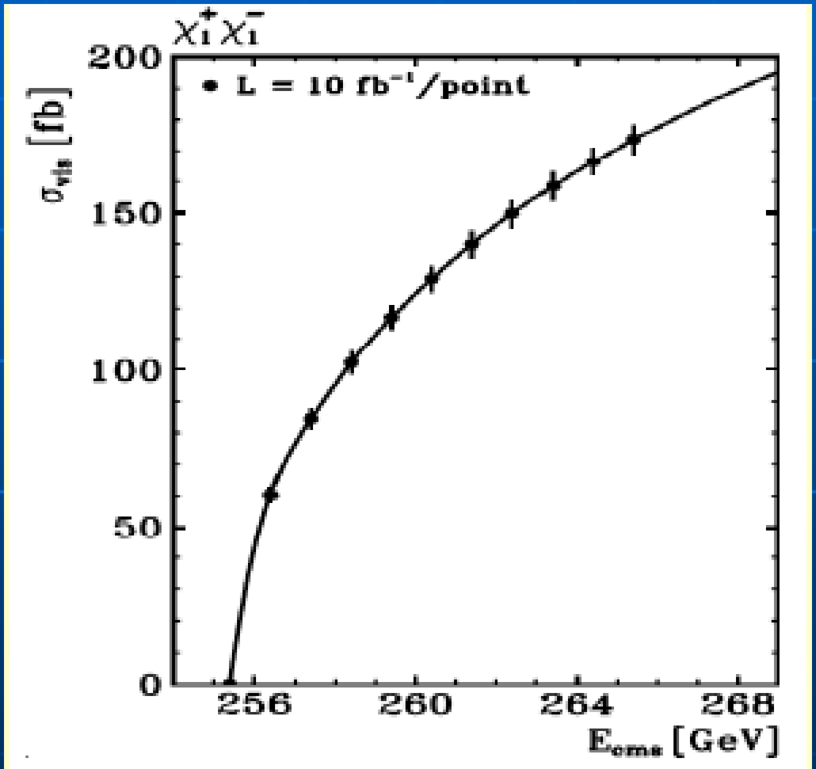
LC exclusive

Things we'll never do with LHC

1) Ultraprecise mass determinations from threshold scans



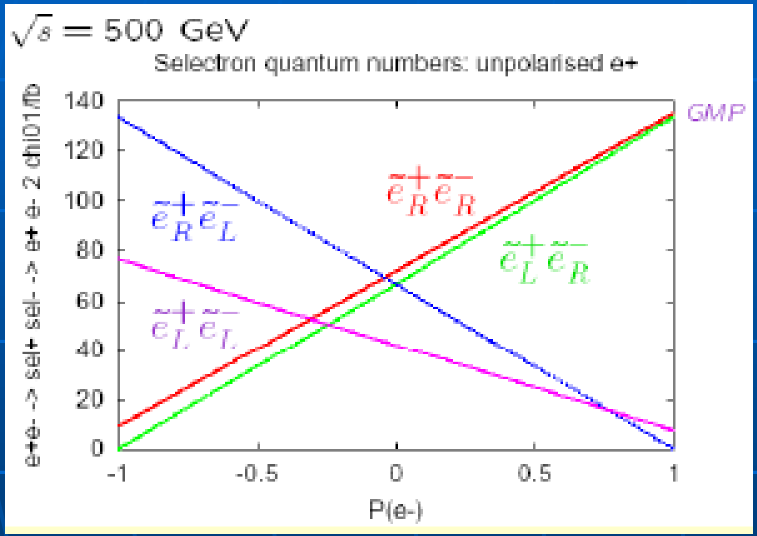
Top quark mass with ~100 Mev precision

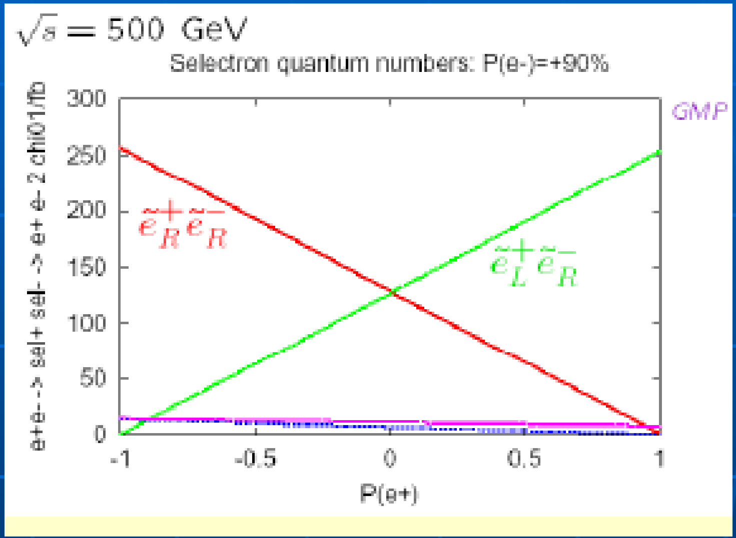


Chargino production at threshold

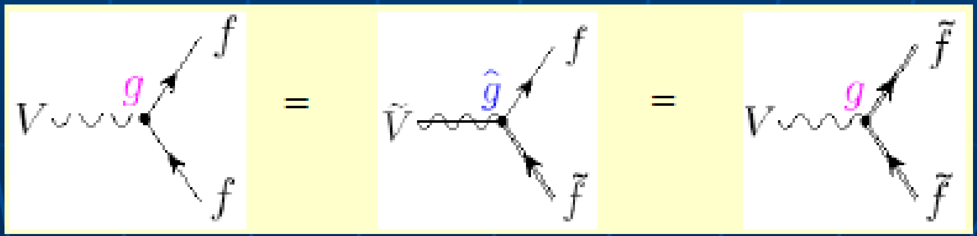
Things we'll never do with LHC

2) Directly disentangle chiral structure with polarized beams



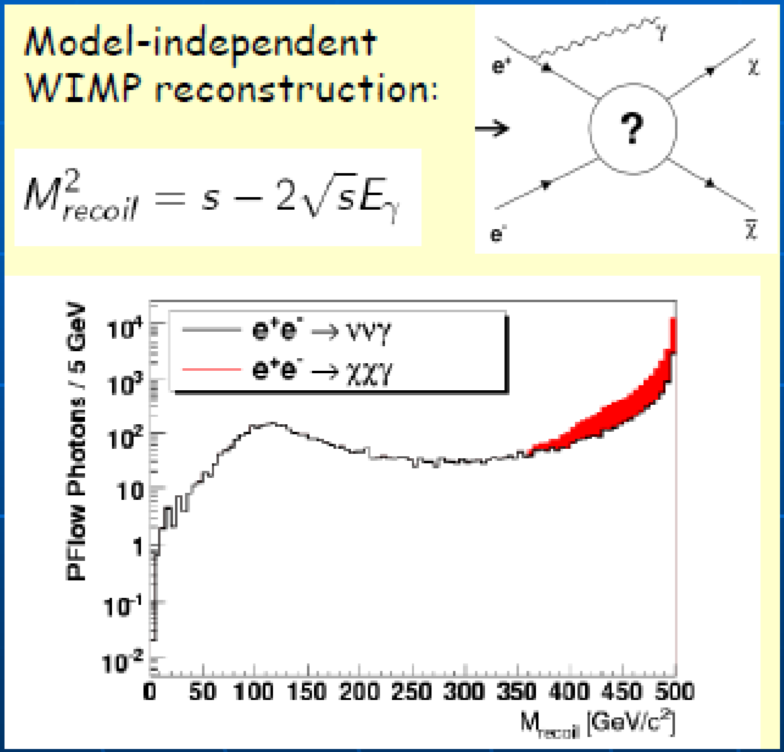


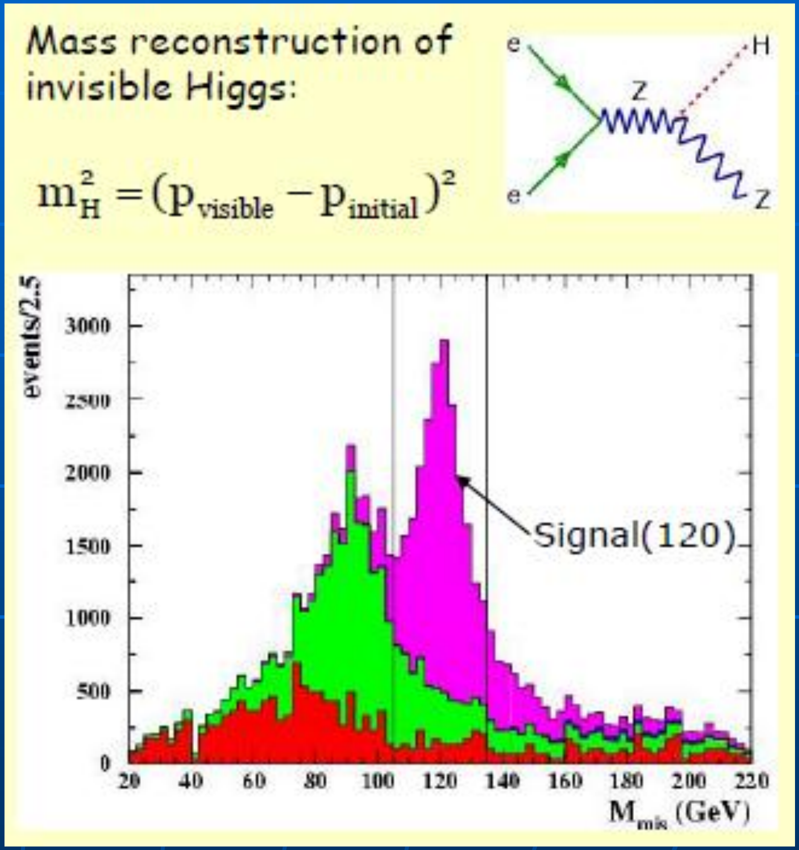
Test fundamental SUSY relations
[G. Moortgat-Pick]



Things we'll never do with LHC

3) Reconstruct the invisible





Recoil mass distribution for a 180 GeV spin 1 WIMP [J. List et al.]

[Schumacher and many others]

Constraints for the machine

What any LC needs to fulfill

- **The baseline** : e^+e^- LC operating from 150 to 500 GeV, tunable energy, e^- polarization 80%, beam energy stability and precision 10^{-3} or better at least 500 fb^{-1} in 4 years ($L \sim 2 \times 10^{34} cm^{-2} s^{-1}$)
- **Upgrade** : to ~1 TeV with 1 ab^{-1}/3-4 years
- **Options** :
  - e^+ polarization > 50%
  - GigaZ (high luminosity running at M_Z and $2M_W$)
  - $\gamma\gamma$, $e\gamma$, e^-e^- collisions

Choice of options depends on LHC+ILC results

What any LC needs to fulfill

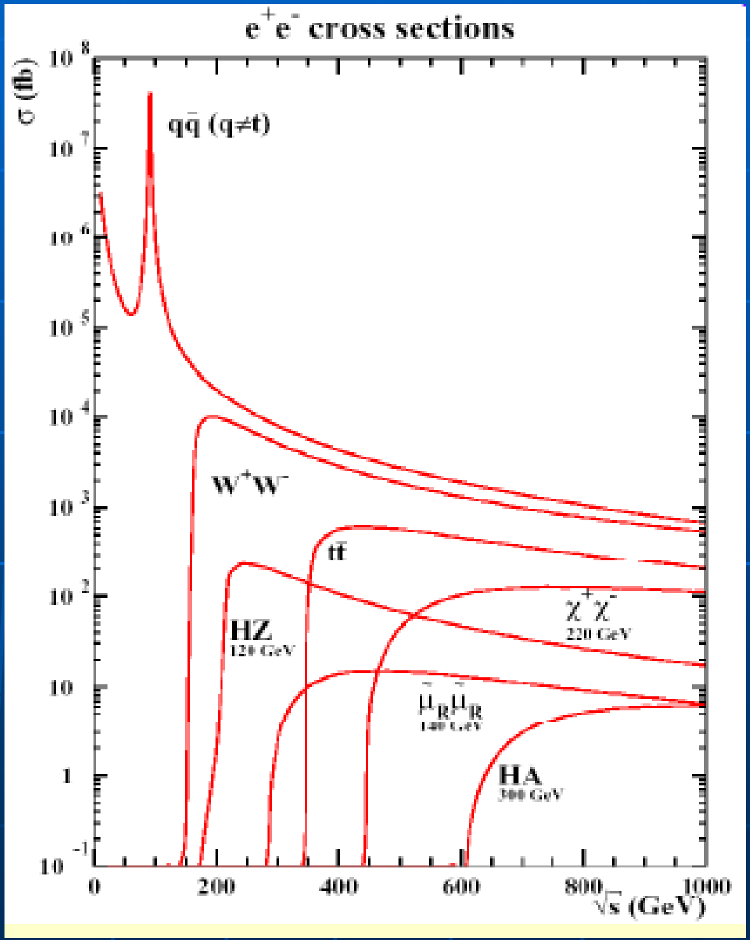
Luminosity requirement of 2×10^{34} is a lower limit

Remarks :
e^+e^- cross sections at 500 GeV are small : O(10-100 fb), and multi-fermion processes even smaller.

500 fb^{-1} at 500 GeV represent « only »
- 40000 HZ events
- 2500 HZ, with Z → ll
- 5000 smuon pairs (m = 140 GeV)
- 200 HHZ events

By far most measurements at LC will be statistics-limited

Possibly will have many thresholds to scan.



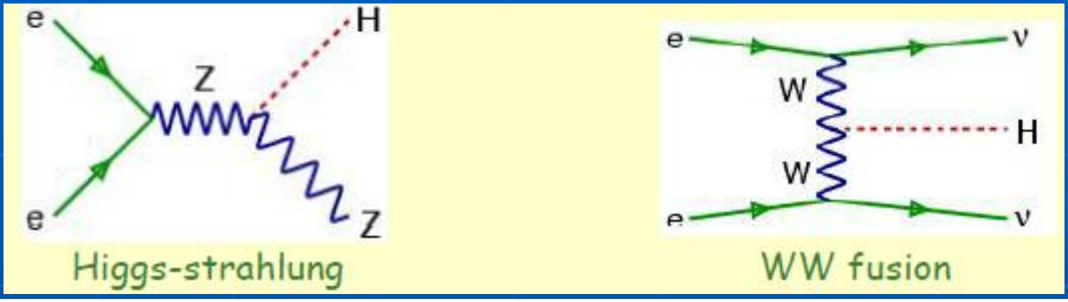
LC physics case

Higgs physics

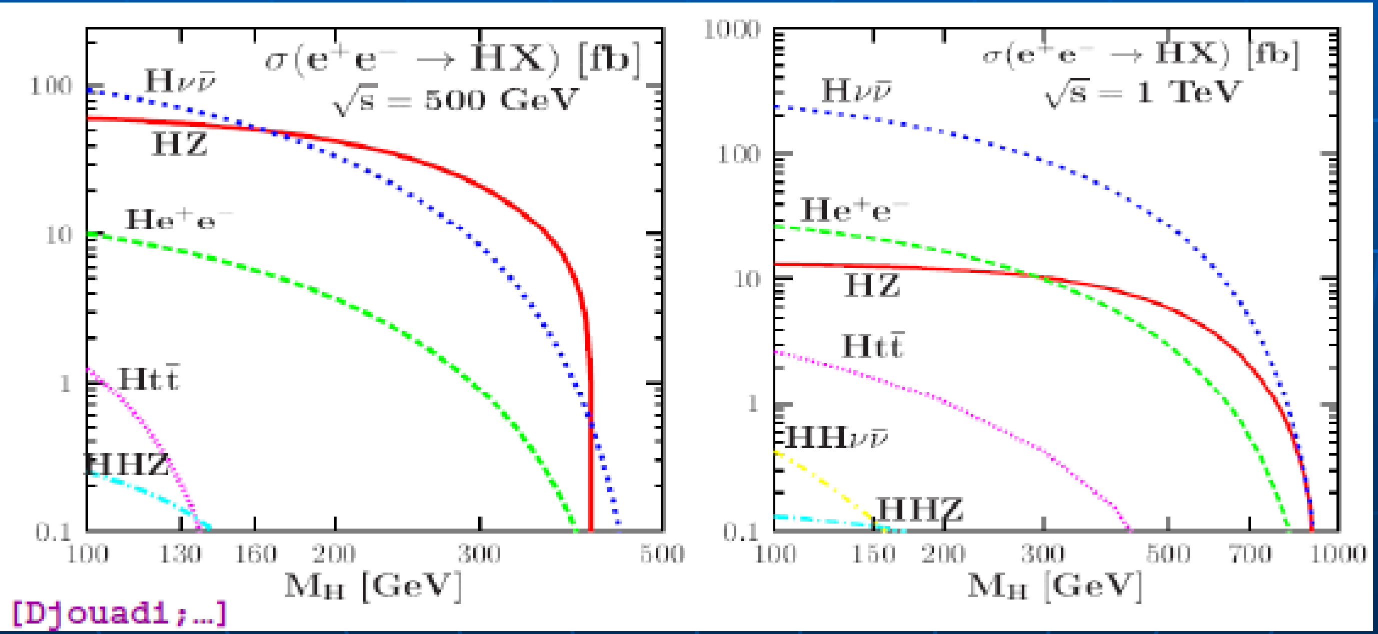
- LHC trigger :
  - ✓ Any discovery of a Higgs-like state
  - ✓ Or absence of Higgs and absence of strong WW interactions
- LC objective :
  - ✓ Precise and model-independent measurement of Higgs properties
  - ✓ Discrimination of different Higgs models
  - ✓ Consistency of visible Higgs sector with electro-weak precision measurements

Higgs physics

Dominant production processes at LC

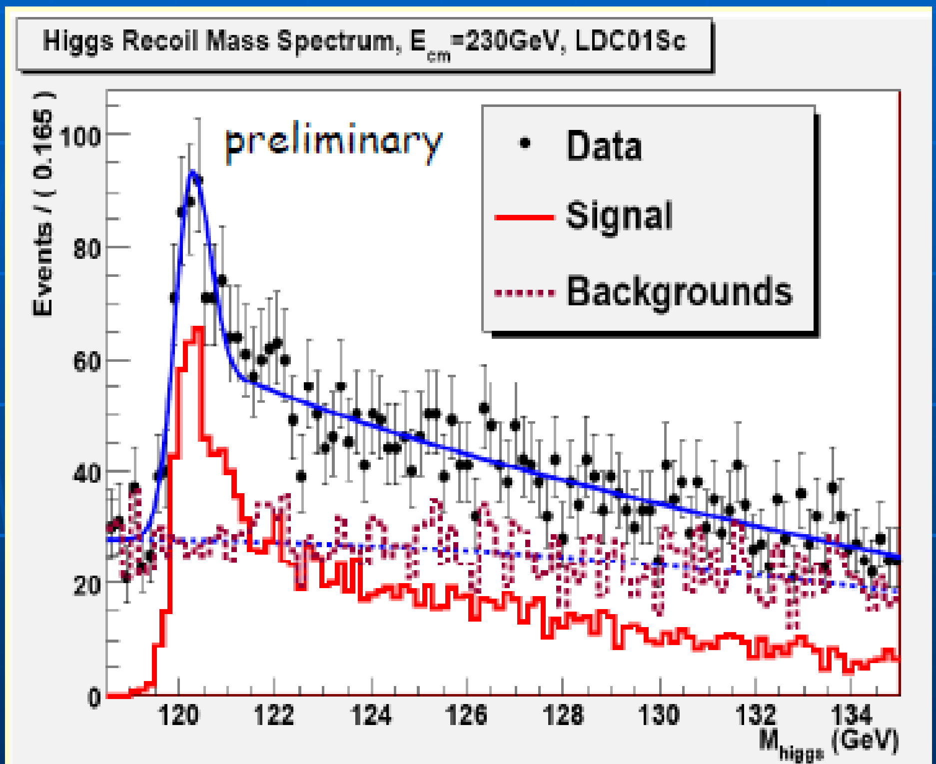


dominant at high energy



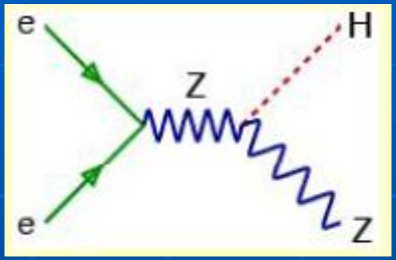
Higgs physics : model independent

Anchor of LC Higgs physics : why LC is qualitatively different from LHC



Full detector simulation & Analysis

[Li et al. 2009]



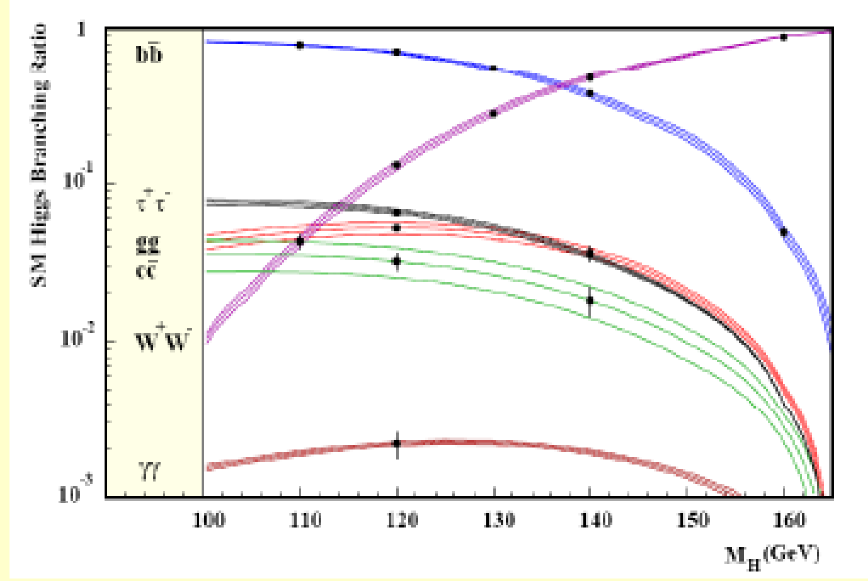
Select di-lepton events,
consistent with Z → ee/μμ
Calculate recoil mass

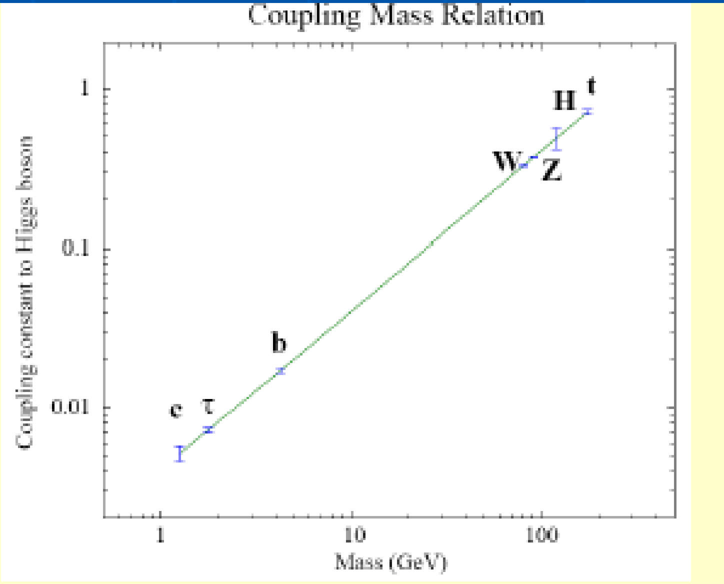
$$m_H^2 = (p_{\ell\ell} - p_{\text{initial}})^2$$

Model independent
Decay-mode independent

Higgs physics : precise measurements

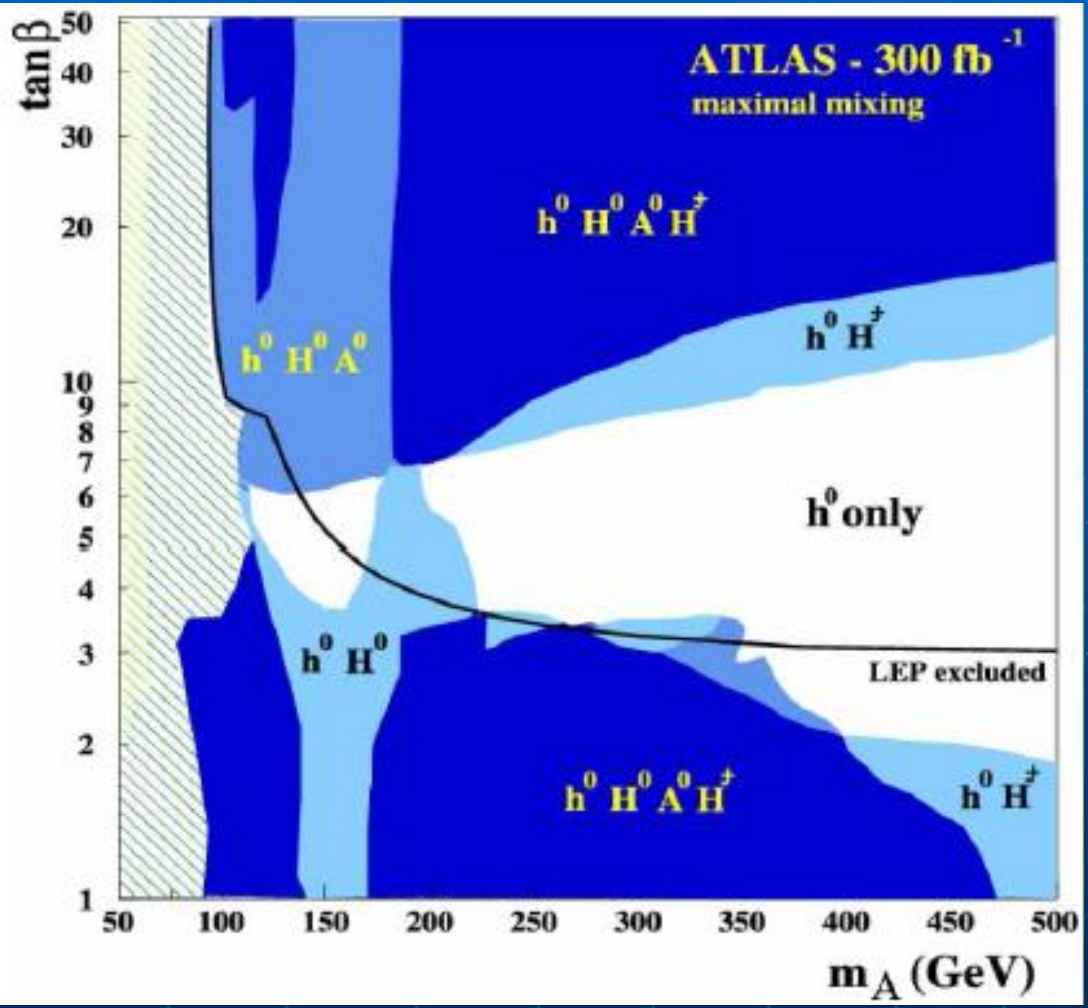
✓Couplings to bosons, up- and down-type fermions
✓Mass and total width
✓Quantum numbers J^{PC} (incl. sensitivity to CP violation)
✓Measurement of λ_{HHH} (not so precise, but unique)





[M.Battaglia, G.Borisov, and others]

Higgs physics – what precision is good for



For medium tanb LHC alone has a very limited reach for the heavy MSSM Higgs

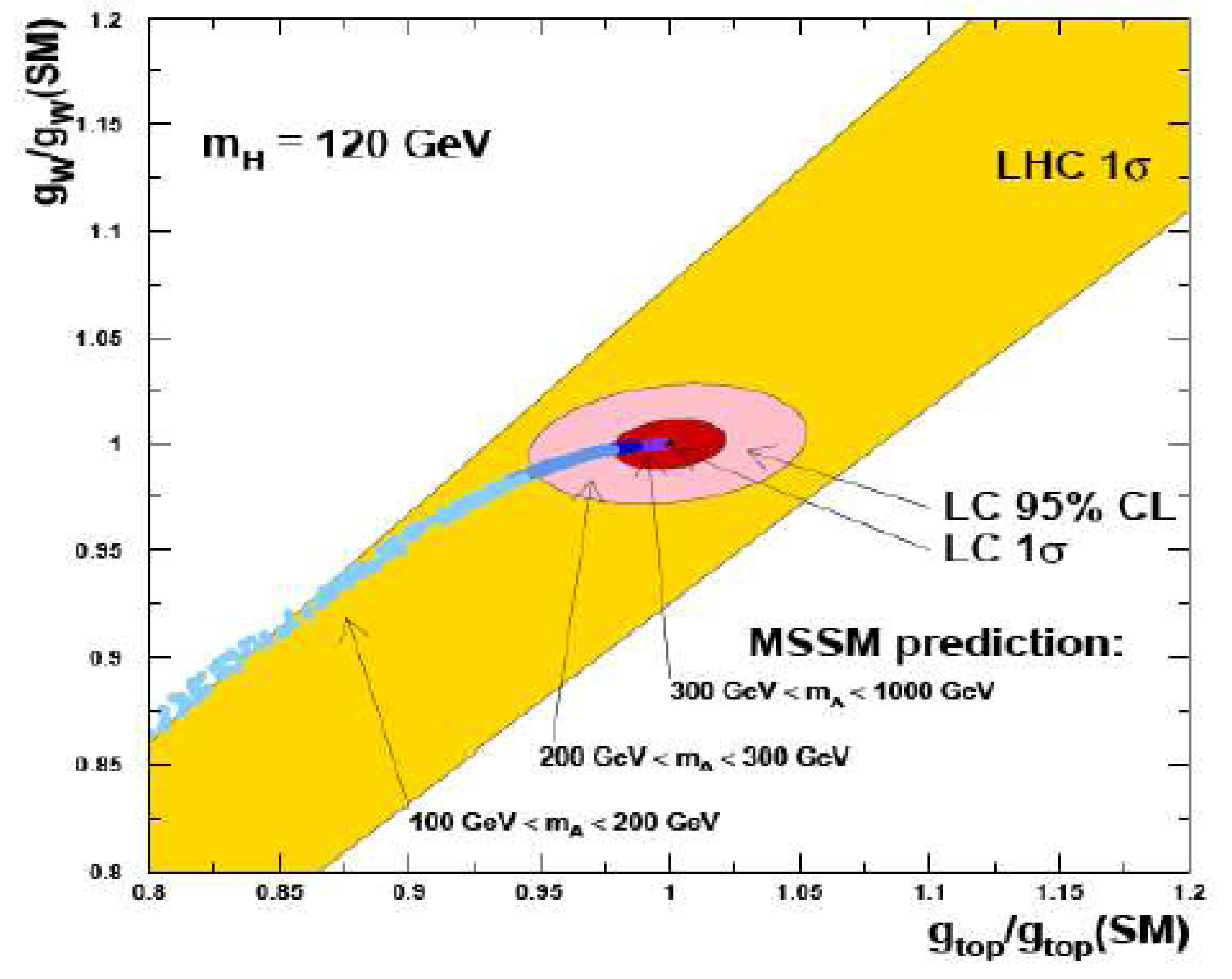
At e^+e^- colliders these bosons are visible up to (at least) $\sqrt{s}/2$

ILC500 is touching the interesting region

ILC1000 is covering large parts of it

The Higgs sector of the MSSM

The Higgs profile can be entirely determined, even close to the decoupling regime



Deviations of the couplings of the h from the SM predictions : 95% of all MSSM solutions can be distinguished

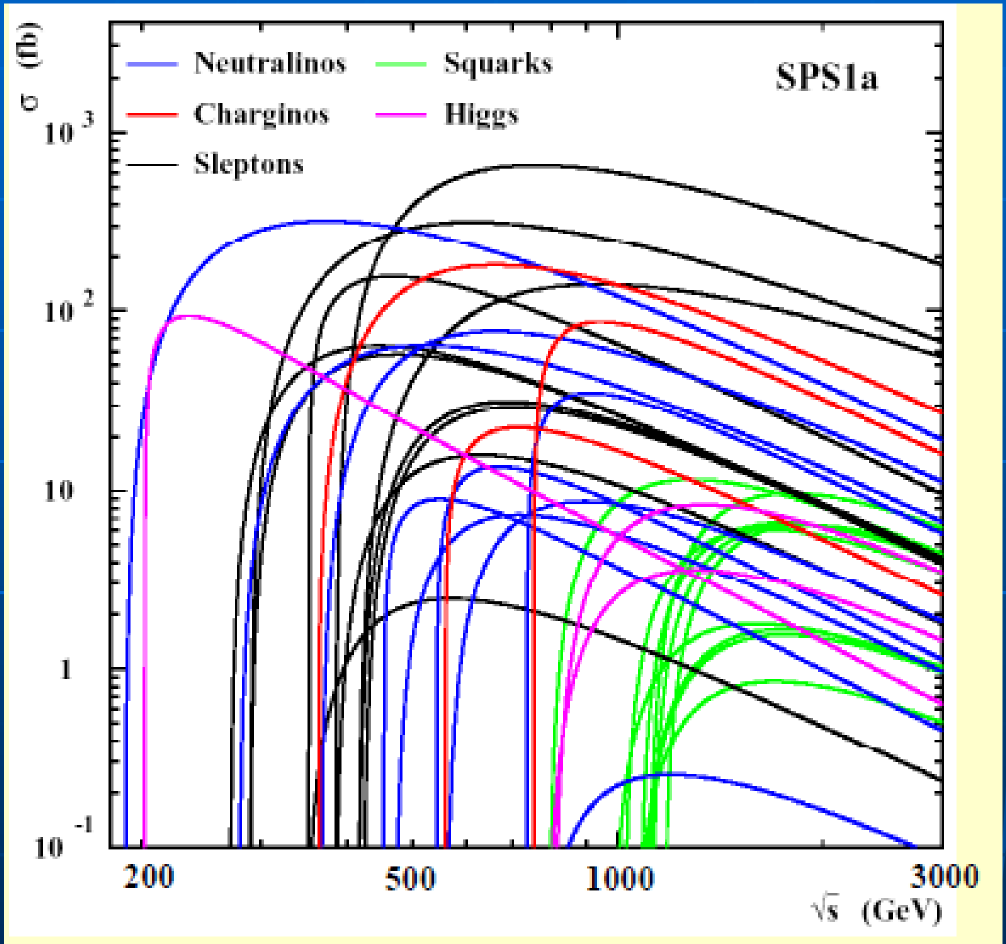
from the SM case if

M_A < 600 GeV

Supersymmetry

- <u>LHC trigger</u> :
  - ✓ Evidence for excess of missing energy events consistent with existence of new particles of mass < $E_{cms}/2$
  - ✓ Or observation (ie mass reconstruction) of RPV SUSY particles with mass < $E_{cms}/2$
- <u>LC objective</u> :
  - ✓ Precise and model-independant measurement of properties of (kin. accessible) sparticles.
  - ✓ Determine pattern of high-scale unification
  - ✓ Determine properties of datk matter candidate

Supersymmetry



May well be fun at LC in spite of all « Cassandre »

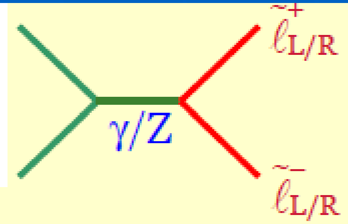
Cross sections are 10-1000fb

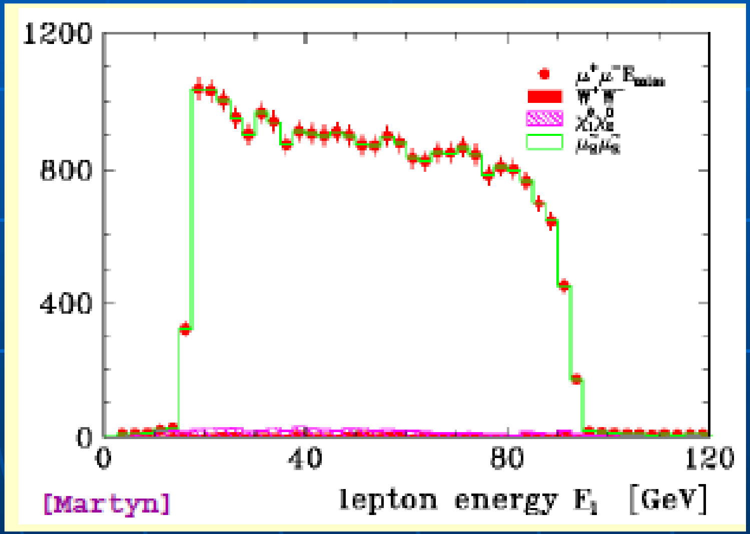
To disentangle this chaotic pattern, the various LC options are vital, in particular :

- ✓ tunable cms energy
- ✓ tunable beam polarization
- ✓ high luminosity

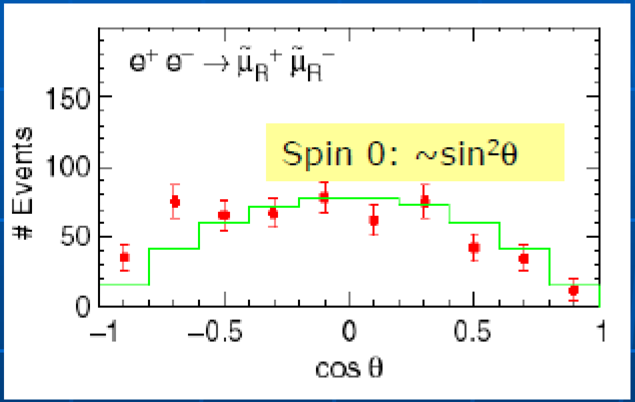
Supersymmetry : sleptons

Pair-production	
	$e^+e^- \rightarrow \tilde{e}_R\tilde{e}_R,\ \tilde{e}_L\tilde{e}_L,\ \tilde{e}_R\tilde{e}_L,\ \tilde{\nu}_e\bar{\tilde{\nu}}_e$
	$e^+e^- \rightarrow \tilde{\mu}_R\tilde{\mu}_R,\ \tilde{\mu}_L\tilde{\mu}_L,\ \tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu$
	$e^+e^- \rightarrow \tilde{\tau}_1\tilde{\tau}_1,\ \tilde{\tau}_2\tilde{\tau}_2,\ \tilde{\tau}_1\tilde{\tau}_2,\ \tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau$





Simple 2-body kin. and beam-constraint allow for mass meas. of both slepton and lightest neutralino



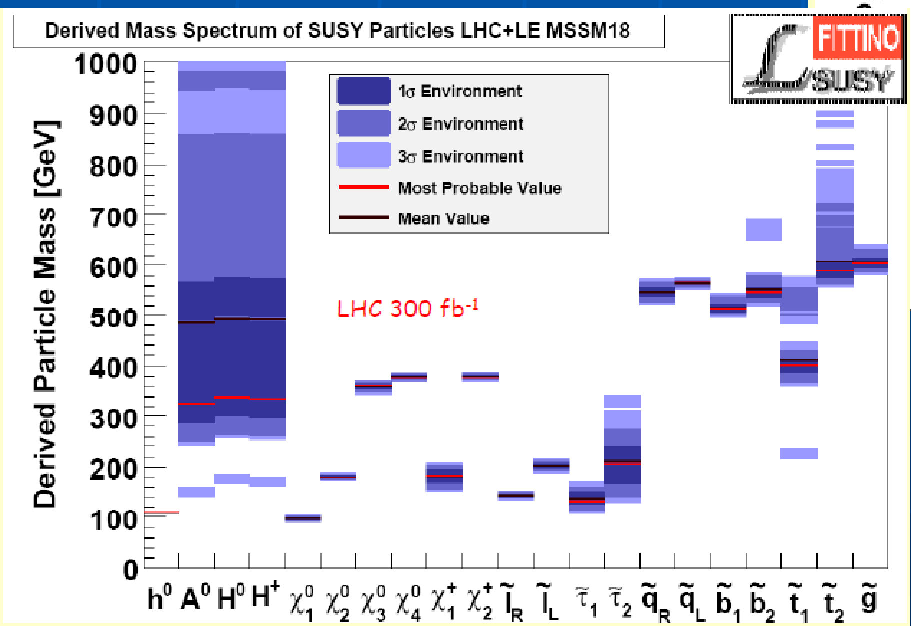
Easy spin measurement

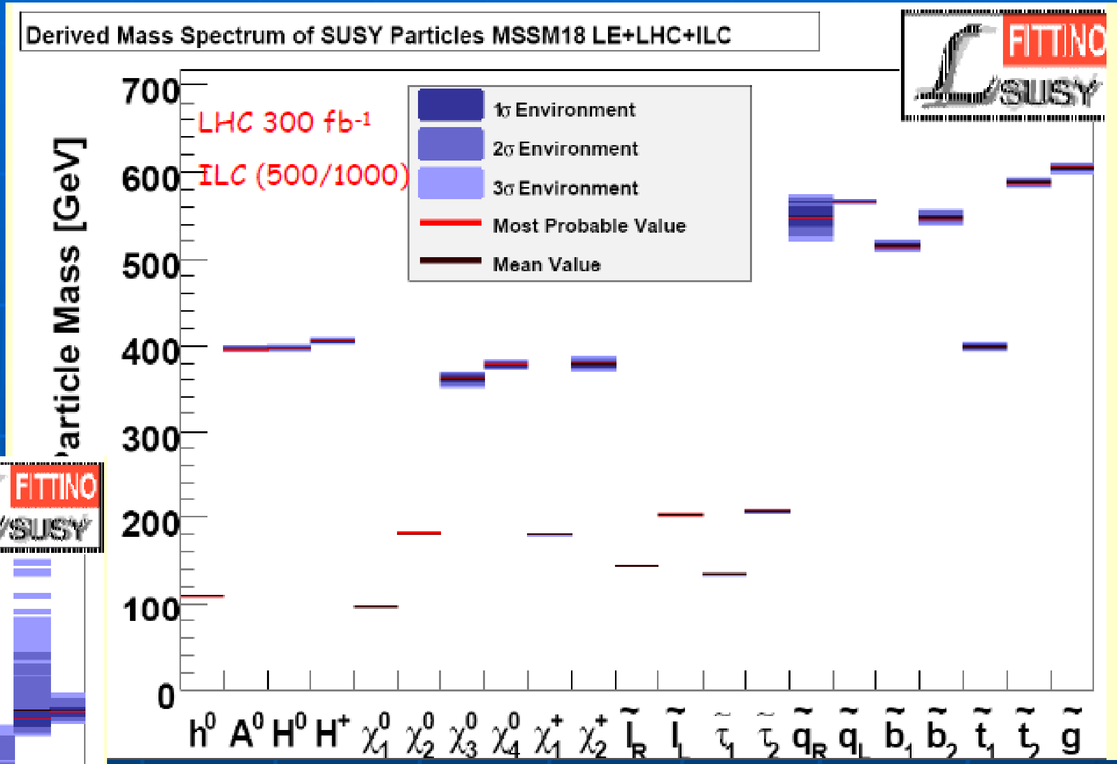
$$m_{\tilde{l}} = \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+}$$

$$m_{\tilde{\chi}} = m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}$$

Supersymmetry : precision

LHC alone



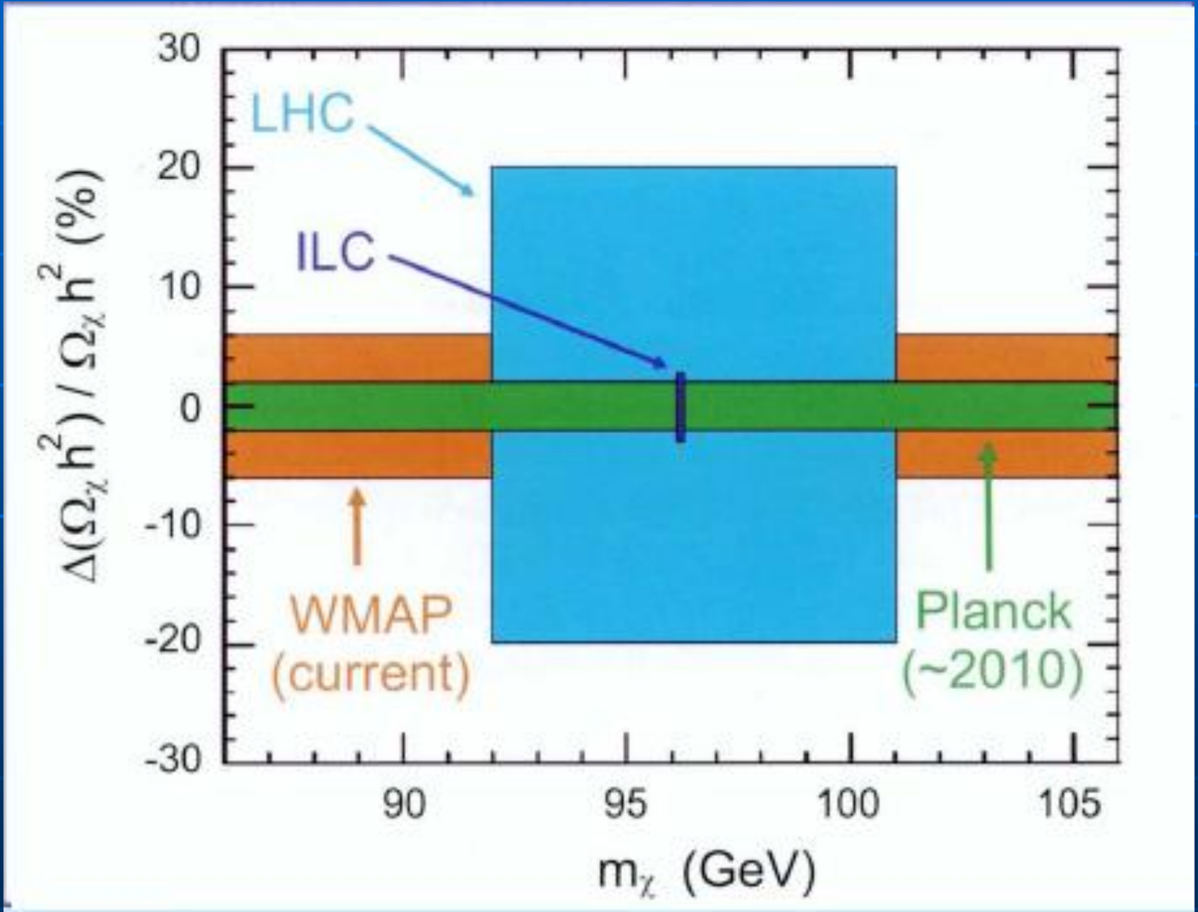


LHC and ILC

[Bechtle et al.]

SUSY and dark matter

Is dark matter linked to the Lightest Supersymmetric Particle (LSP) ?



Complementary views :

WMAP/Planck : sensitive to total density of dark matter

LC (and LHC) : identify DM particle and measures its mass.

Gauge bosons couplings

LHC trigger :

✓ discovery of heavy gauge boson (m <~5 TeV)

✓ or absence of Higgs boson and evidence for strong WW interactions

✓ or most other « surprises »

LC objective :

✓ (contribute to) determination of the properties of the new states

✓ new physics through loop-level tests of SM processes at all energies

✓ shine some light into the deep multi-TeV region

CLIC vs ILC

ILC vs CLIC : differences

- Timeline

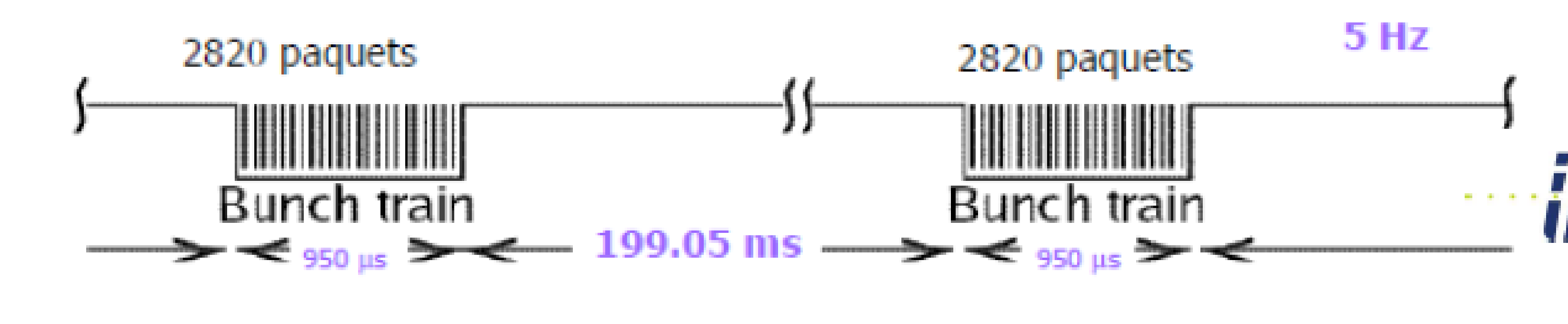
  ILC is « ready » : TDC in 2010/2012

  CLIC is not : preliminary TDR in ?
- Energy

  first phase at 500 GeV for both

  max energy : 1 TeV (ILC), 3 TeV (CLIC)
- Time structure
- Beam-induced background

Time structure



CLIC:	1 train = 312 bunches	0.5 ns apart	50 Hz
ILC:	1 train = 2820 bunches	337 ns apart	5 Hz

ILC : no hardware trigger !!!

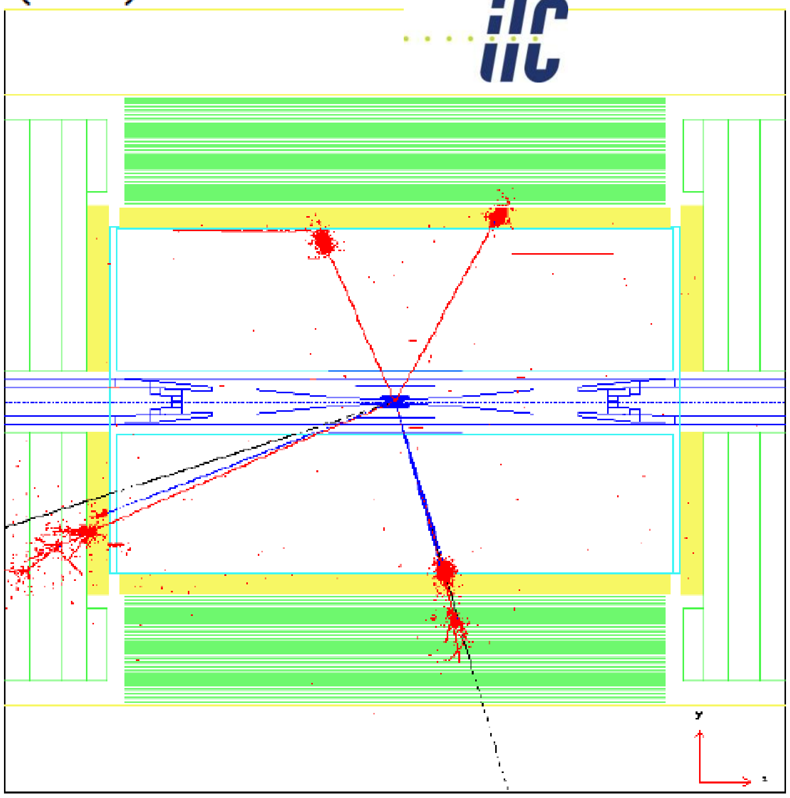
Consequences for CLIC detector:

- Assess need for detection layers with time-stamping
  - Innermost tracker layer with sub-ns resolution
  - Additional time-stamping layers for photons and for neutrons
- Readout electronics will be different from ILC
- Power pulsing at 50 Hz, instead of 5 Hz

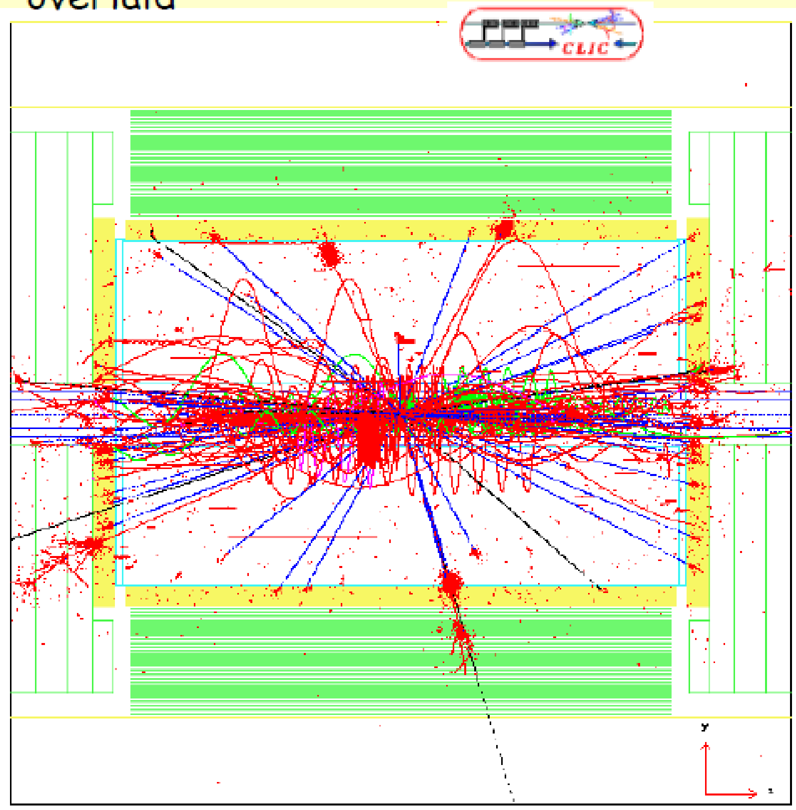
Does LC technology matter ?

HZ → ττee event

Without soft hadronic events overlaid (=ILC)

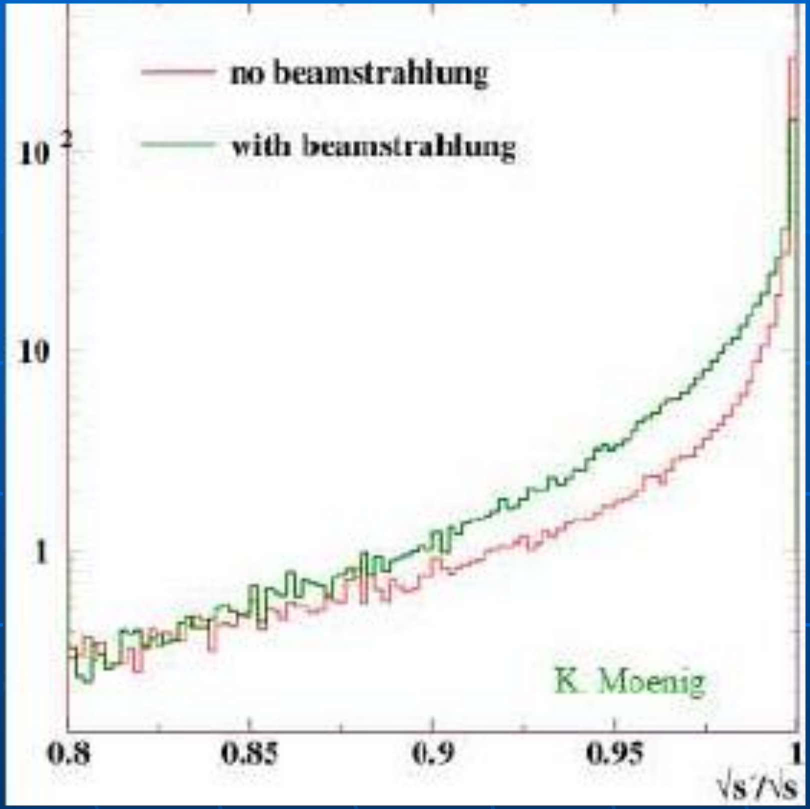


With 32 BX (=16 ns) „CLIC nominal 500" overlaid

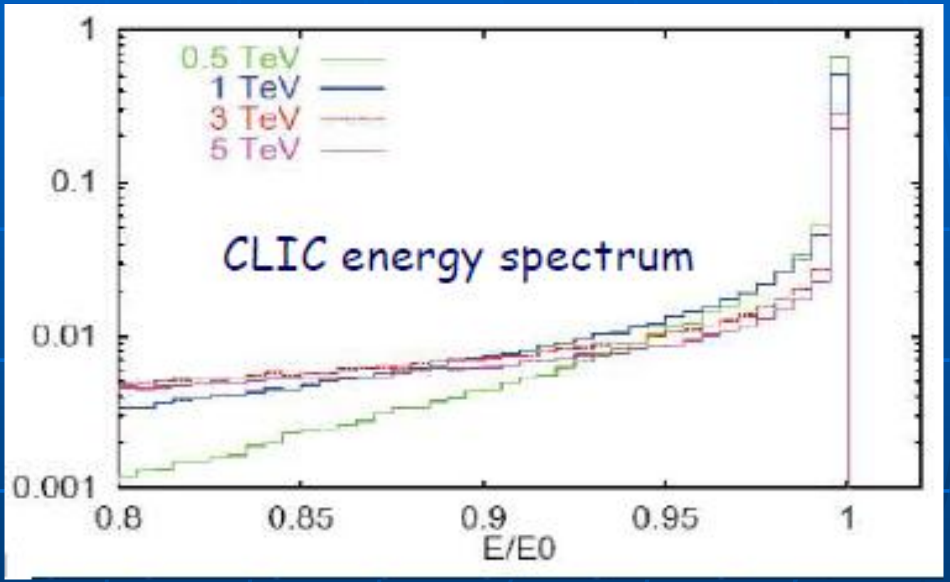


note: CLIC 3000 nominal has 14 times CLIC500 overlaid

The price of high lumi : beamstrahlung



ILC 500



$\Delta E/E$ = 2.4% / 7% / 29%
ILC500 / CLIC500 / CLIC3000

Impact on kinematic fits

Backgrounds

- Background sources are similar for CLIC and ILC
- Due to the higher beam energy and smaller bunch sizes, they are significantly more severe at CLIC
- VTX : O(10) times more bkgd at CLIC
- TPC : O(30) times more bkgd at CLIC

What about a muon collider

- No beamstrahlung !
- $\mu^+\mu^- \rightarrow H^\circ \rightarrow$ anything is accessible
- Incredible precision on m_H, perhaps not necessary
- You have experience (antiprotons) for collider based on a secondary beam : for muons, you must do it in 20 msec !

Constraints on detectors

Some detector design criteria

Requirement for ILC

- Impact parameter resolution

  $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)$

- Momentum resolution

  $\sigma\left(\frac{1}{p_T}\right) = 5\times10^{-5}\ (GeV^{-1})$

- Jet energy resolution goal

  ~~$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$~~ $\quad \frac{\sigma_E}{E} = 3-4\%$

- Detector implications:
  - Calorimeter granularity
  - Pixel size
  - Material budget, central
  - Material budget, forward

Compared to best performance to date

- Need factor 3 better than SLD

  $\sigma_{r\phi} = 7.7 \oplus 33/(p\sin^{3/2}\vartheta)$

- Need factor 10 (3) better than LEP (CMS)

- Need factor 2 better than ZEUS

  $\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$

- Detector implications:
  - Need factor ~200 better than LHC
  - Need factor ~20 smaller than LHC
  - Need factor ~10 less than LHC
  - Need factor ~ >100 less than LHC

Observation: LHC: staggering increase in scale, but modest extrapolation of performance
ILC: modest increase in scale, but significant push in performance

Vertex detector : b & c tagging

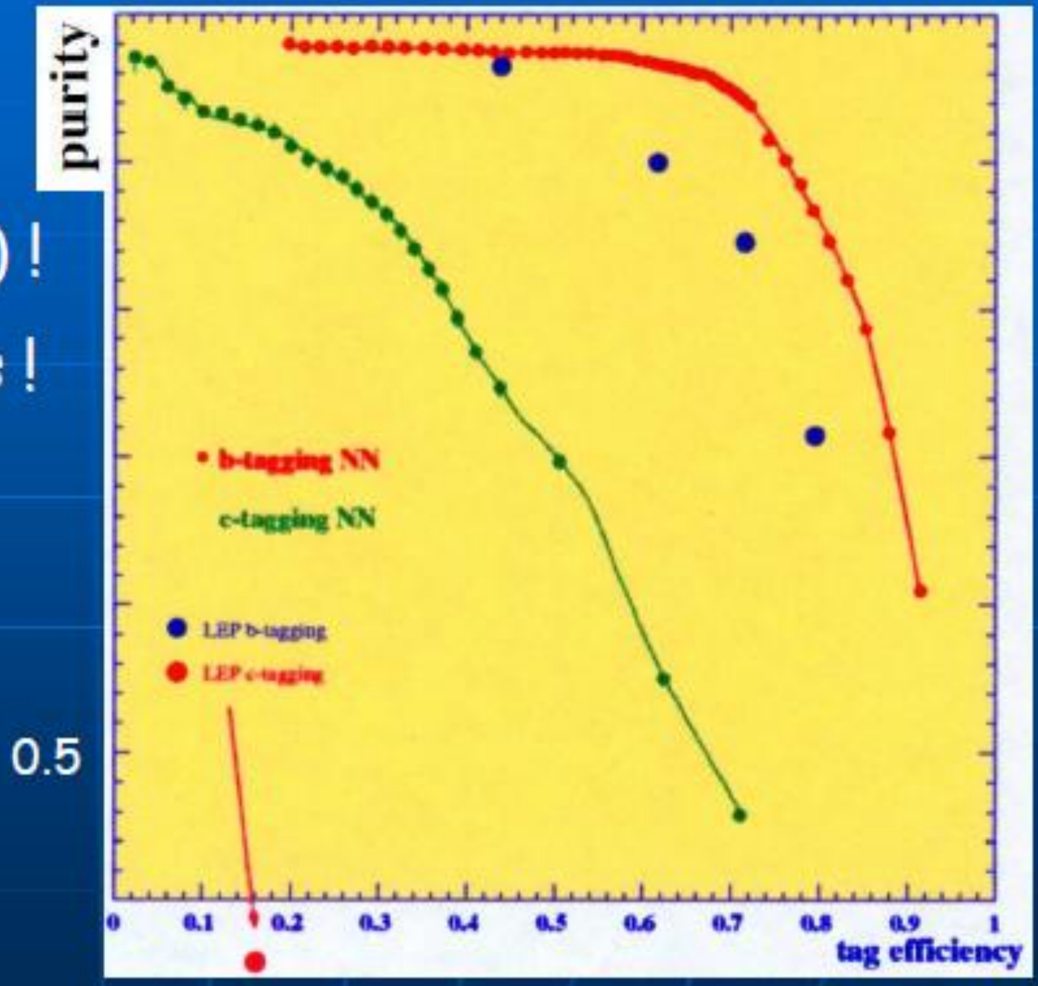
Want to measure BR(H→cc) !

Have to tag 4-b final states !

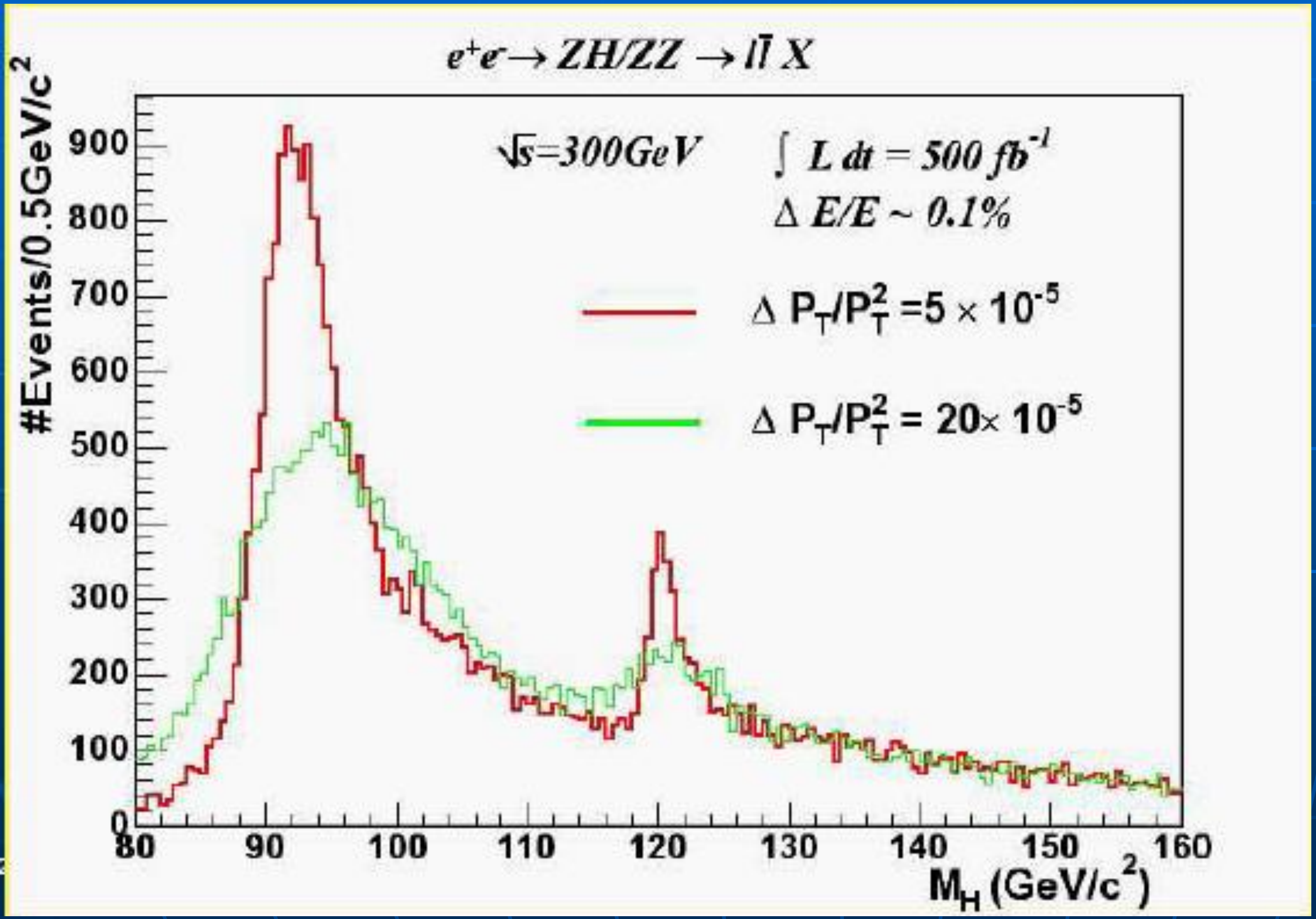
We do not know how to built such a VDET !

Many R&D on various technologies :

CCD, MAPS, Depfet, 3D



Tracker : momentum resolution

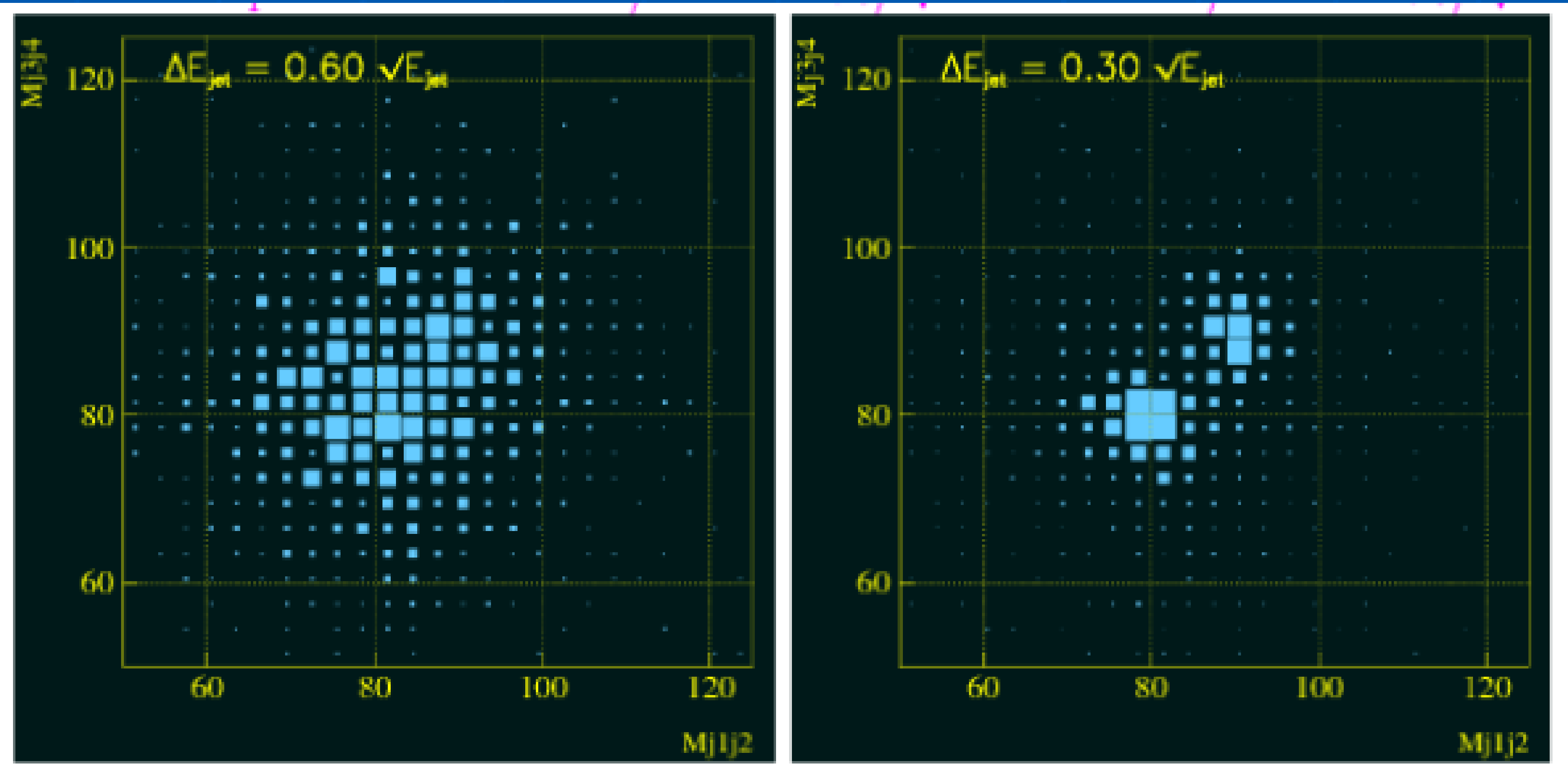


Example:

Recoil mass to a Z into 2 leptons

Calorimetry : the challenge

The W/Z separation, in processes like WWνν or ZZνν needs an unprecedented energy resolution (jet energy)



Calorimetry : particle flow

To be able to achieve the jet resolution can NOT simply use calorimeters as sampling devices.

~~$\frac{\sigma_E}{E} \simeq 0.30\frac{1}{\sqrt{E(GeV)}}$~~ $\frac{\sigma_E}{E} = 3-4\%$

Have to use "energy/particle flow (PFA)". Technique has been used to improve jet resolution of existing calorimeters.

Algorithm:

- use EM calorimeter (EMCAL) to measure photons and electrons;
- track charged hadrons from tracker through EMCAL,
- identify energy deposition in hadron calorimeter (HCAL) with charged hadrons & replace deposition with measured momentum (very good)
- When completed only E of neutral hadrons (K's, Lambda's) is left in HCAL. Use HCAL as sampling cal for that.

Require:
Imaging cal (use as tracker = like bubble chamber),
→ very fine transverse & longitudinal segmentation
Large dynamic range: MIP.... to .....shower
Excellent EM resolution

Does PFA work for high-energy jets ?

Mark Thomson CLIC08 using ILD detector description

- Traditional calorimetry $\sigma_E/E \approx 60\%/\sqrt{E/\mathrm{GeV}}$
- Does not degrade significantly with energy (but leakage will be important at CLIC)
- Particle flow gives much better performance at "low" energies
  - very promising for ILC

What about at CLiC ?

- PFA perf. degrades with energy
- For 500 GeV jets, current alg. and ILD concept:

$$\sigma_E/E \approx 85\%/\sqrt{E/\mathrm{GeV}}$$

- Crank up field, HCAL depth…

$$\sigma_E/E \approx 65\%/\sqrt{E/\mathrm{GeV}}$$

- Algorithm not tuned for very high energy jets, so can probably do significantly better

rms90 PandoraPFA v03-β

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	23.8 %	3.5 %
100 GeV	29.1 %	2.9 %
180 GeV	37.7 %	2.8 %
250 GeV	45.6 %	2.9 %
500 GeV	84.1 %	3.7 %
500 GeV	64.3 %	3.0 %

63 layer HCAL (8 λ_I)
B = 5.0 Tesla

Conclude: for 500 GeV jets, PFA reconstruction not ruled out

R&D at Irfu

Very small group
(only 2 permanents SPP)
TPC à lecture Micromegas
Monolithic Active Pixel Sensors

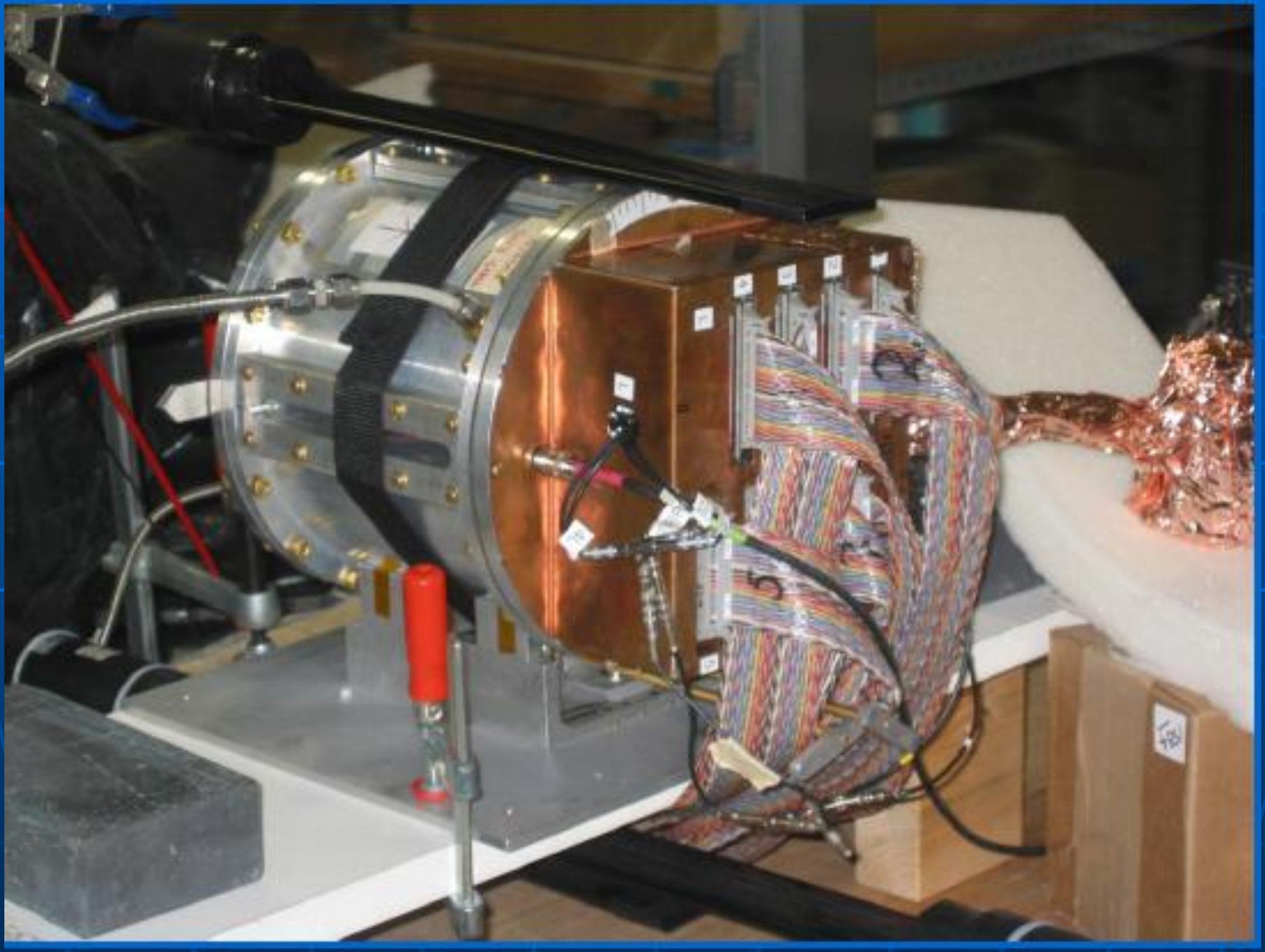
TPC à lecture Micromegas
Vers la résolution ultime

- Dans une TPC classique, la résol. est limitée (~180μm) par le ExB, et le problème du retour des ions complique les choses.
- Les premières TPC/Micromegas (coll. Dapnia/LAL/LBL et MP-TPC) (2002-2005) montrent qu'un seul pixel est touché (la résolution est alors pitch/$\sqrt{12}$), mais ExB et retour des ions excellents.
- 2 solutions : étaler la charge ou diminuer la taille des pixels.

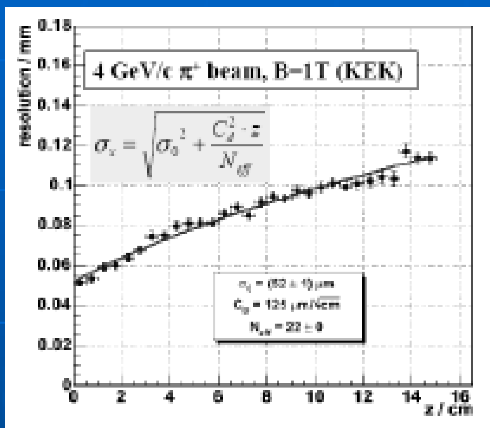
Etaler la charge : la feuille résistive

- Idée (M. Dixit) : étaler la charge sur plusieurs pads (après amplification), grâce à une feuille résistive collée sur les pads.
- Plusieurs solutions testées, avec des rayons cosmiques et/ou en faisceau (KEK et DESY) (coll. Carleton-Dapnia-LAL-Montréal)

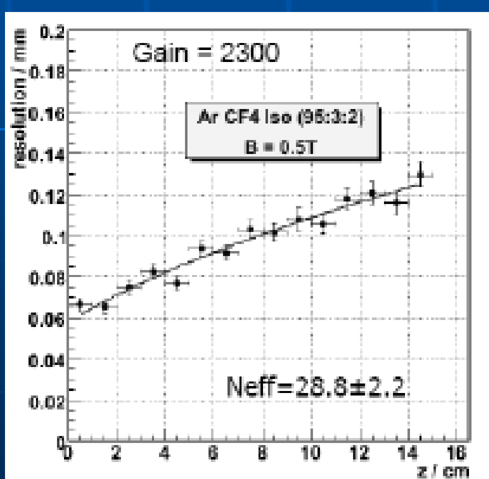
La TPC en test



La feuille résistive : résultats

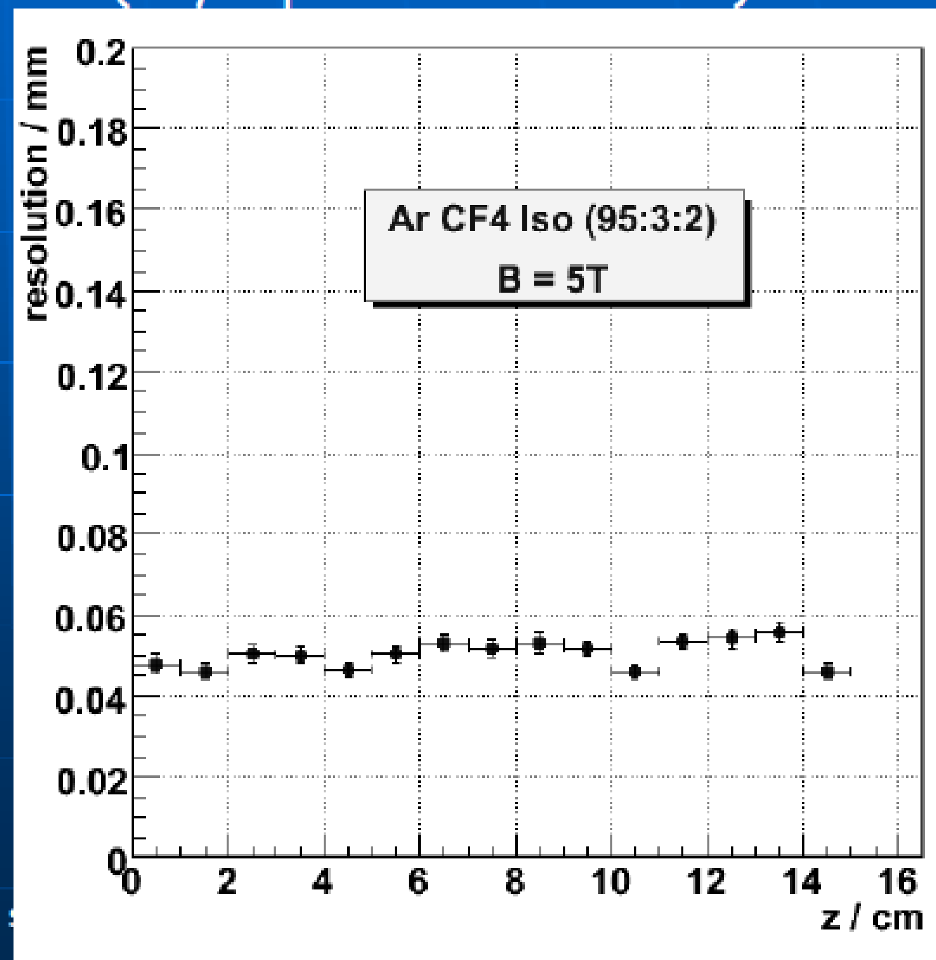


Résolution = 50µm pour toutes distances de dérive (80µm pour 2m de dérive)

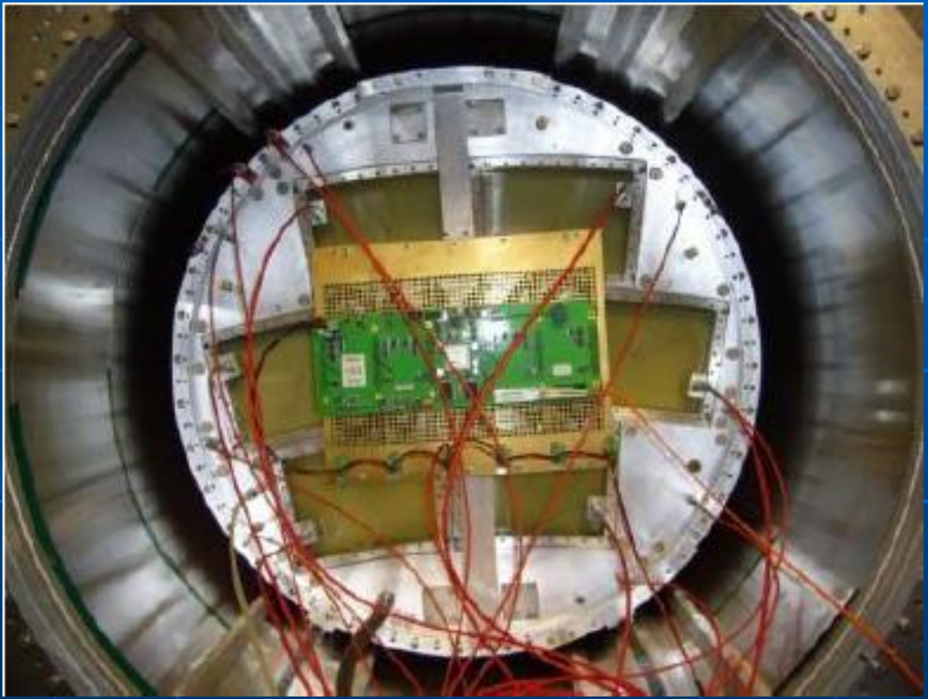


ANR ?

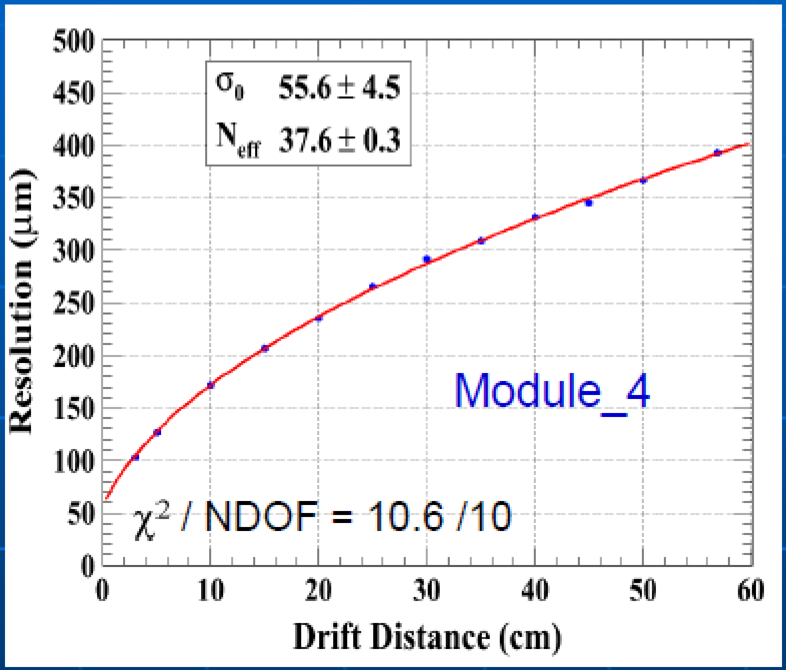
T2K ?

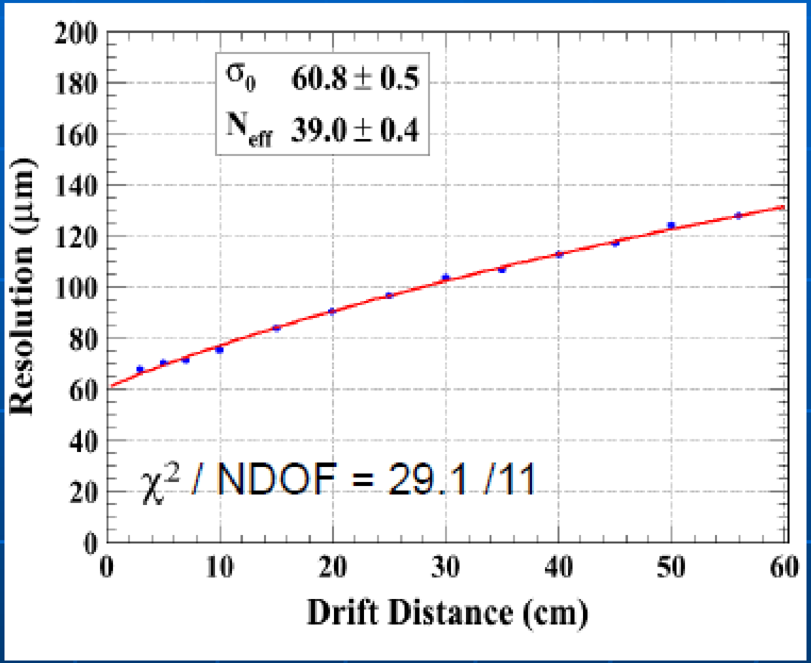


TPC : large prototype



Data analysis results





B = 0

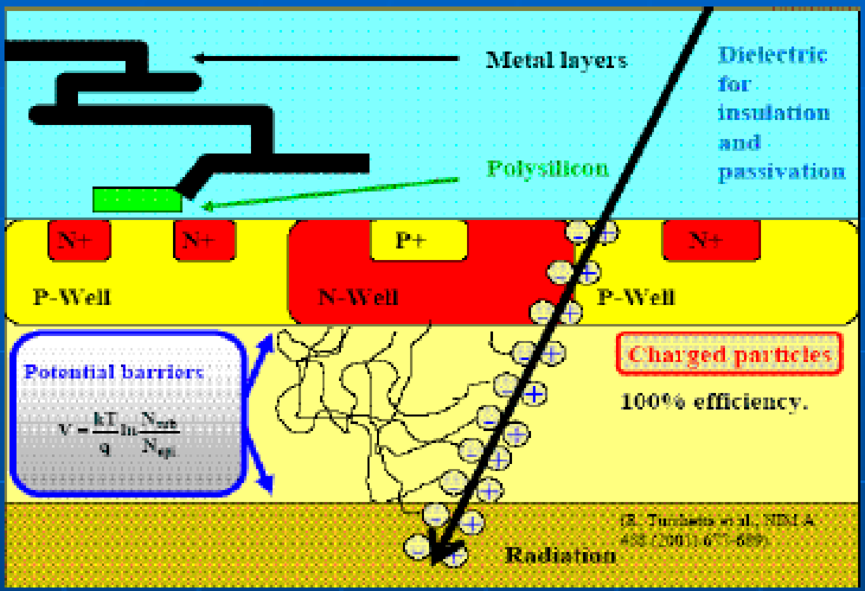
B = 1T

$$\sigma = \sqrt{\sigma_0^{\ 2} + \frac{C_d^2 \cdot z}{N_{eff}}}$$

σ_0 : the resolution at Z=0

N_{eff} : the effective number of electrons

Principe de base des MAPS



Silicium type p basse résistivité

Signal produit dans la couche épitaxiale (low doping)

Q ~ 80 e-h/µm   signal < 1000 e

Collection de la charge par la jonction p-epi   n-well
(propagation thermique et réflexions)

Avantages spécifiques :

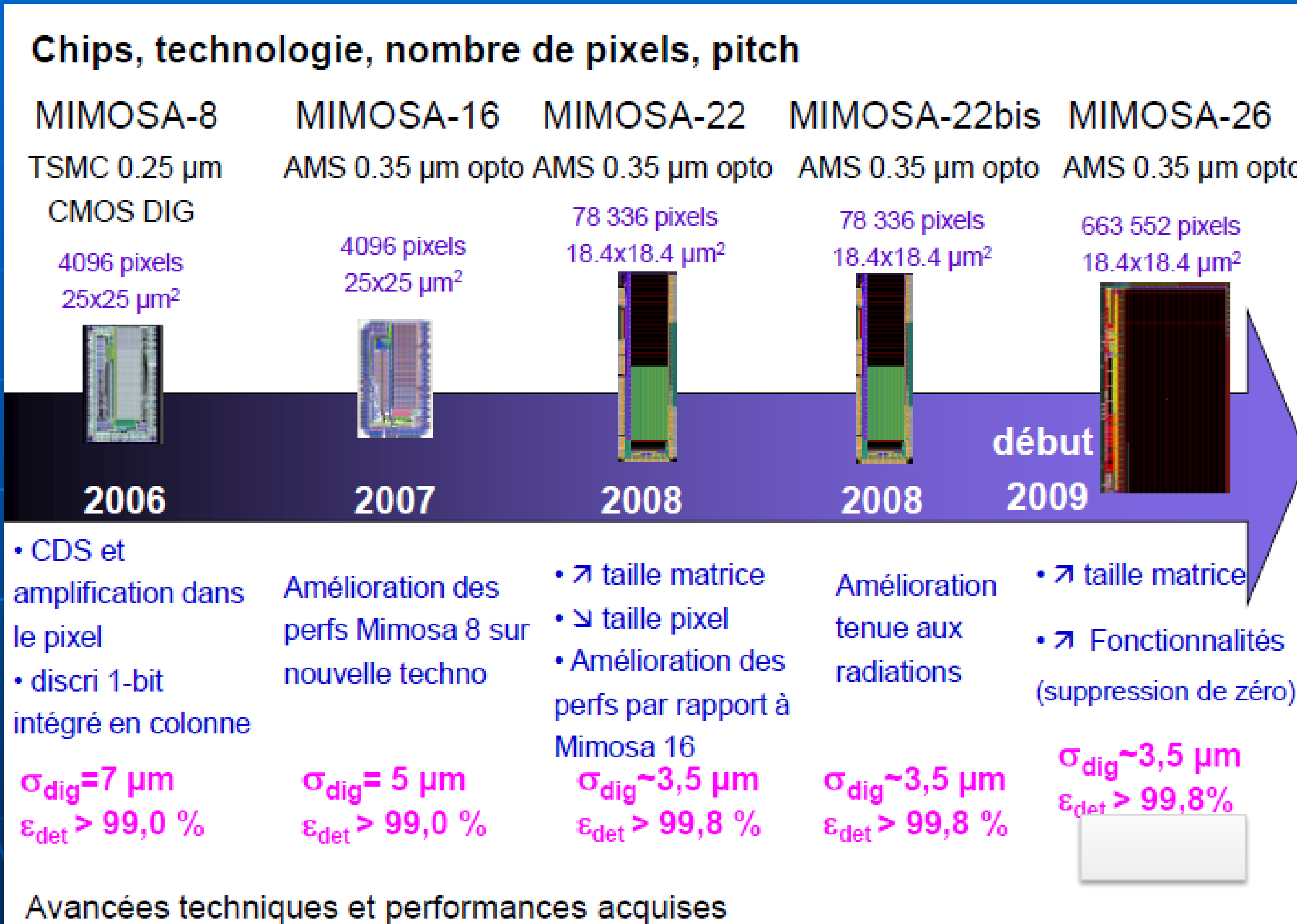
µcircuits intégrés sur le senseur (system-on-chip)   monolithique

Volume sensible (~couche épi) mince (<15µ)   amincissement OK

Standard CMOS   peu cher, mais dépendant techno

Les avantages des CCD, mais plus rapides et plus tolérants Rad.

Collaboration IPHC/IRFU



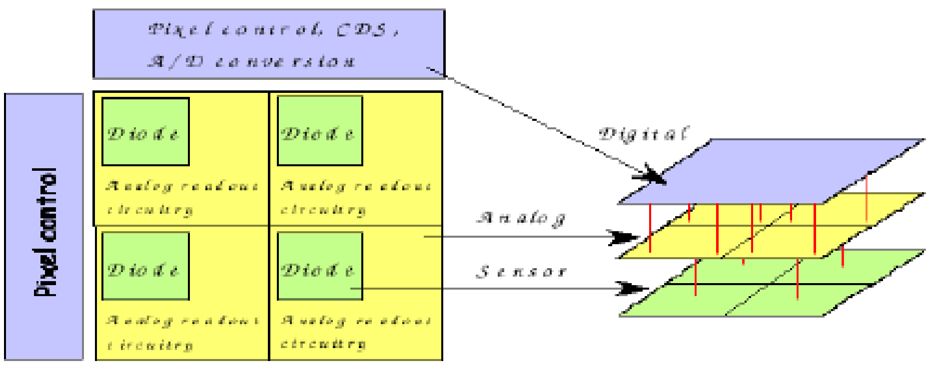
Next step : using 3DIT

- **3D Integration Techno.** allow integrating high density signal processing μcircuits inside small pixels

- **3DIT are expected to be particularly beneficial for CMOS sensors :**
  - ⁂ *combine different fab. processes*
  - ⁂ *alleviate constraints on transistor type inside pixel*

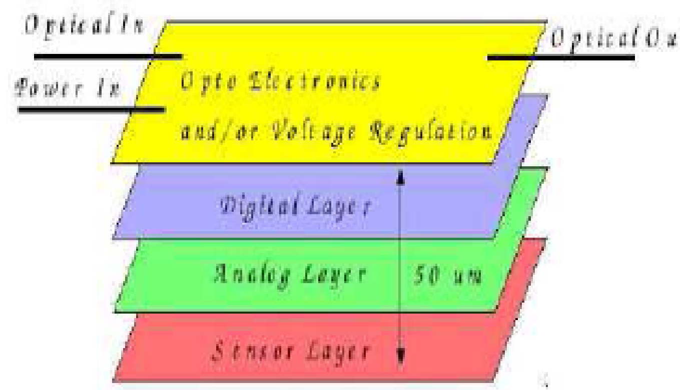
- **Split signal collection and processing functionnalities :**
  - ⁂ *Tier-1: charge collection system*
  - ⁂ *Tier-2: analog signal processing*
  - ⁂ *Tier-3: mixed and digital signal processing*
  - ⁂ *Tier-4: data formatting (electro-optical conversion ?)*

- **Use best suited technology for each Tier :**
  - ⁂ *Tier-1: epitaxy (depleted or not), deep N-well ?*
  - ⁂ *Tier-2: analog, low I_{leak}, process (nb of metal layers)*
  - ⁂ *Tier-3 & -4 : digital process (nb of metal layers), feature size $\rightarrowtail$ fast laser (VOCSEL) driver, etc.*



Conventional MAPS 4 Pixel Layout

3D 4 Pixel Layout

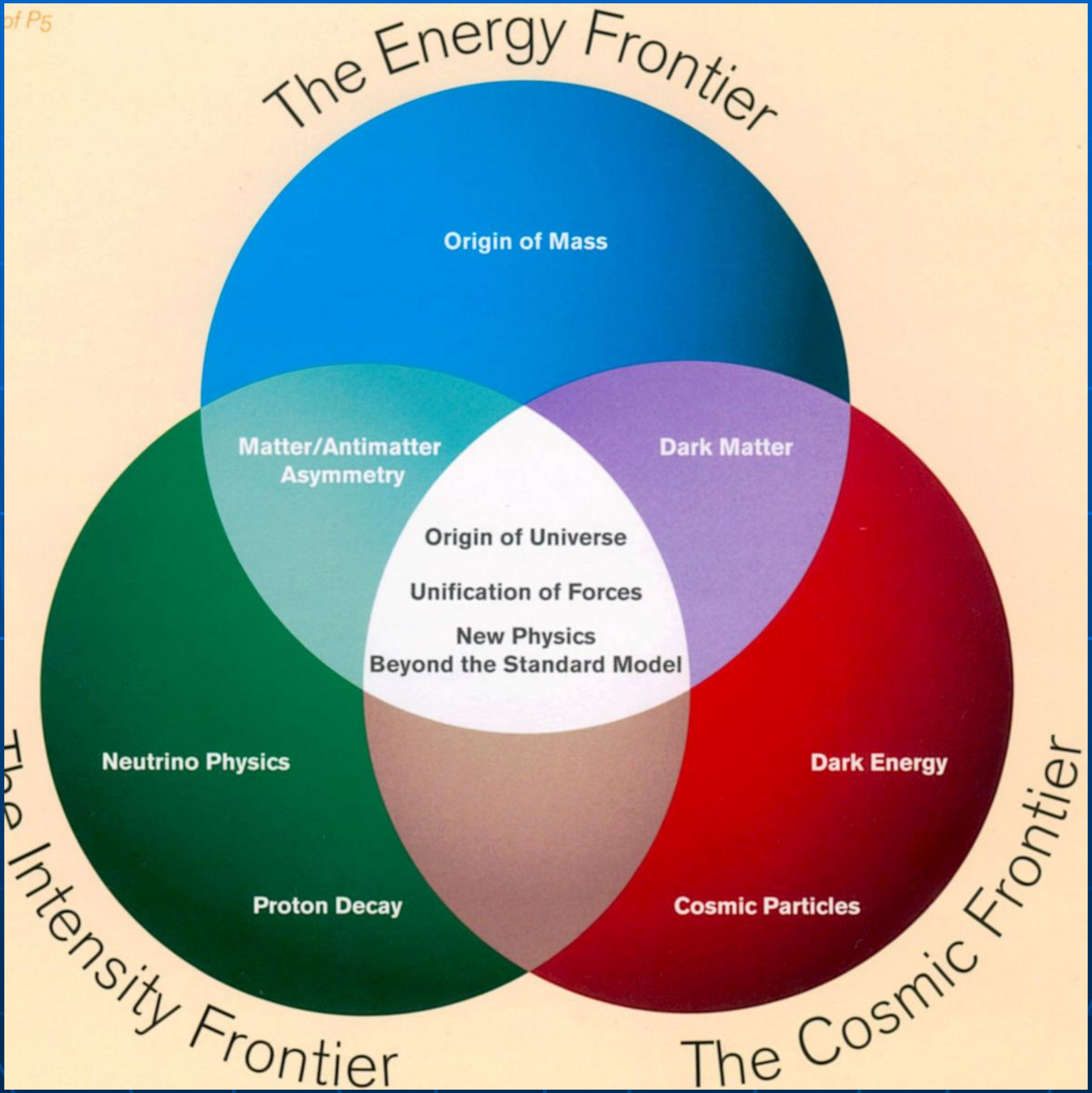


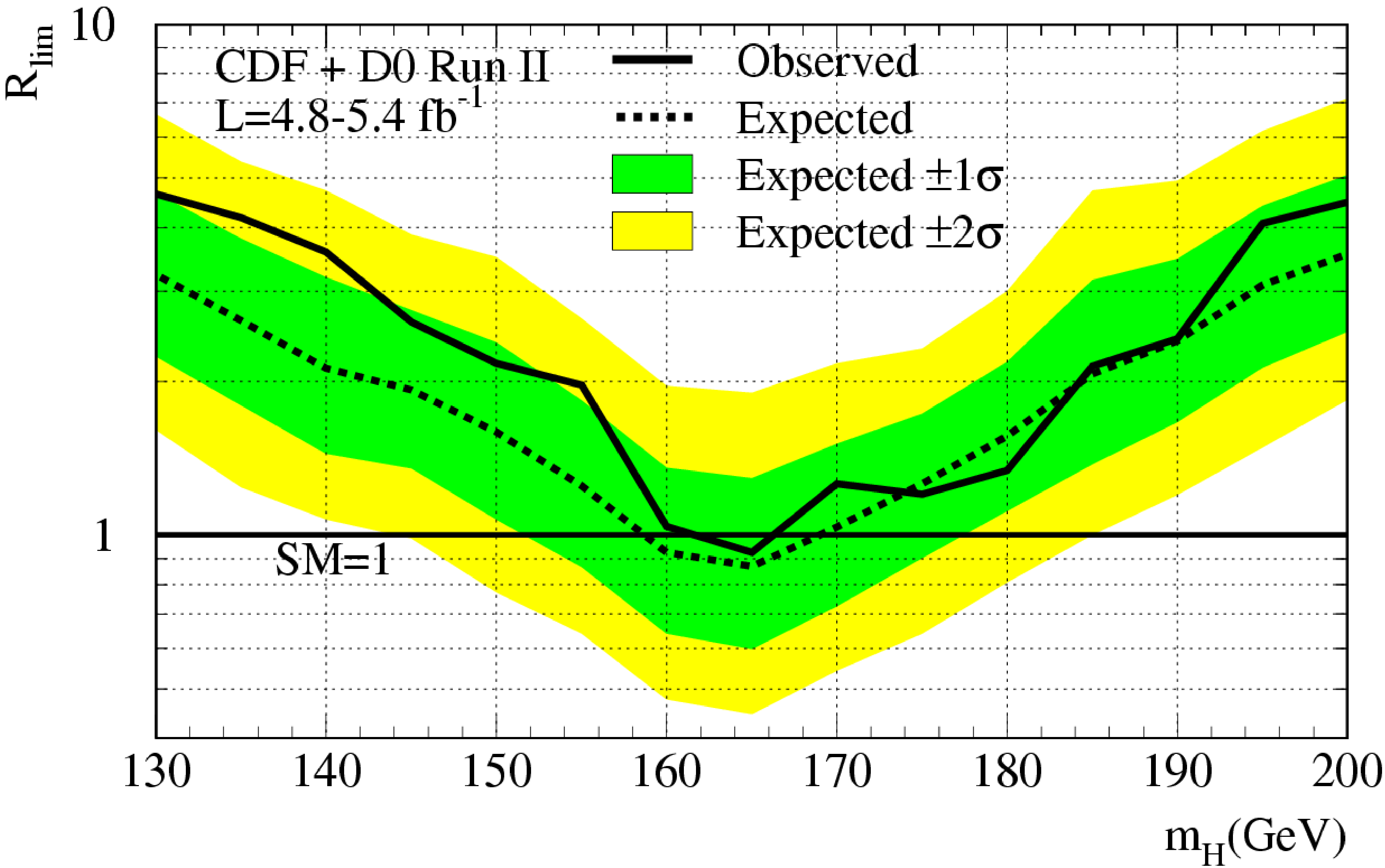
Conclusions

- Hard to imagine any LHC discovery which would not trigger the start of an e^+e^- programme
- Staged approach to LC seems politically more realistic and physically more sensible
- Watch out carefully for « tiny » differences between different collider technologies

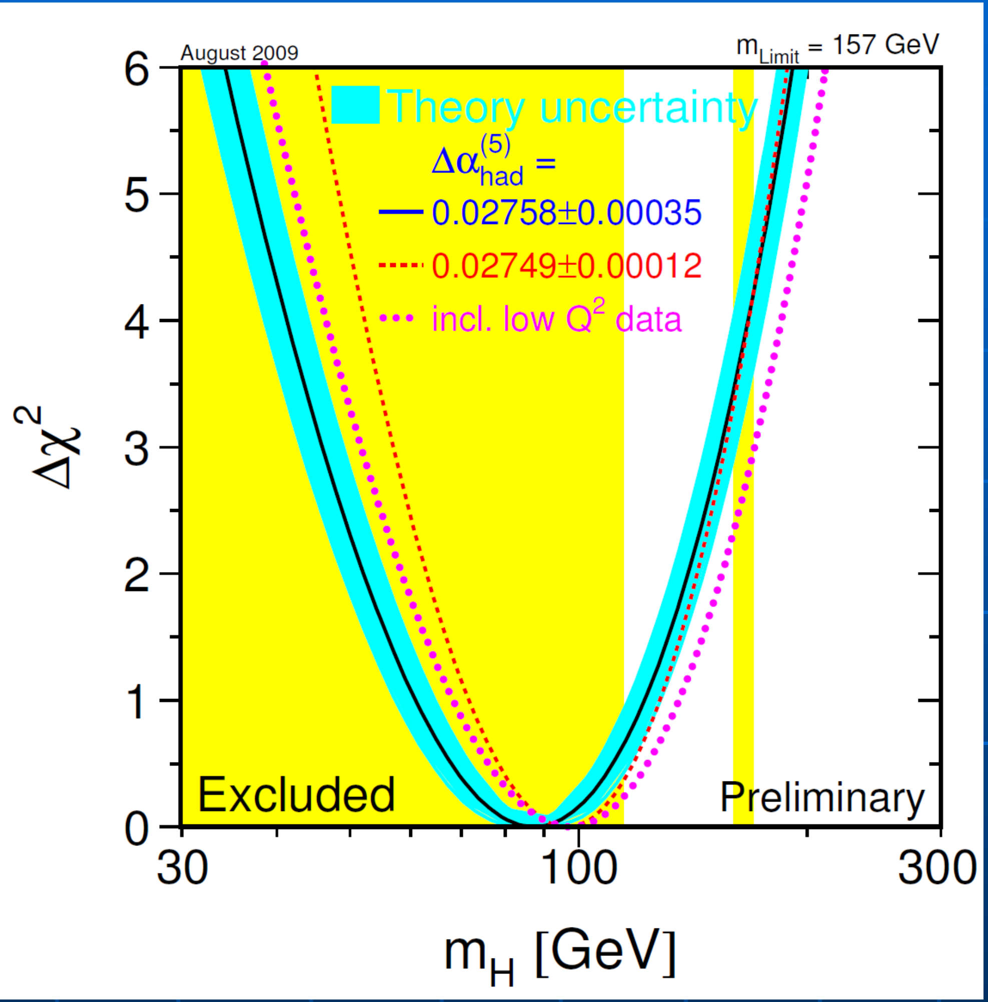
Backup

The three frontiers

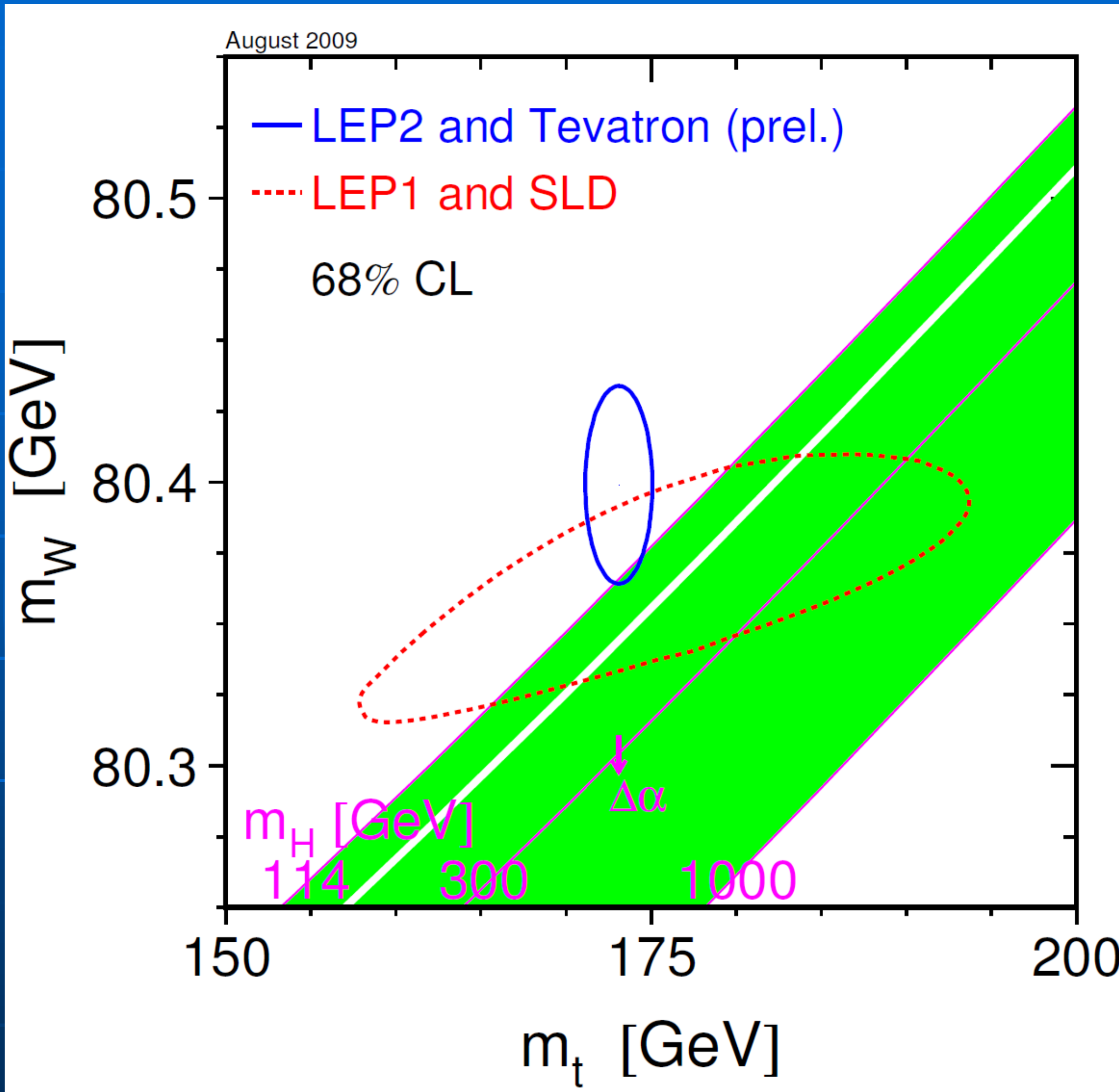




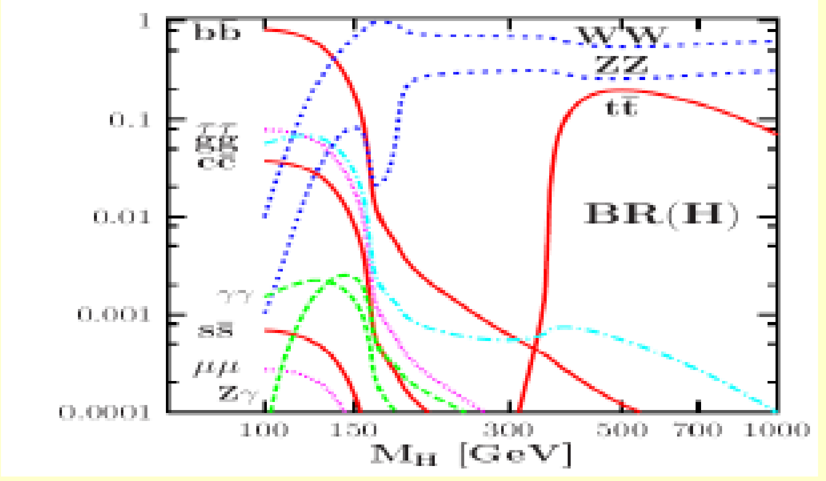
R_{lim}
10
1
CDF + D0 Run II
L=4.8-5.4 fb^{-1}
Observed
Expected
Expected ±1σ
Expected ±2σ
SM=1
130
140
150
160
170
180
190
200
m_H(GeV)



August 2009
m_{Limit} = 157 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]


August 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

Comments on m_H = 160 … 200+ GeV



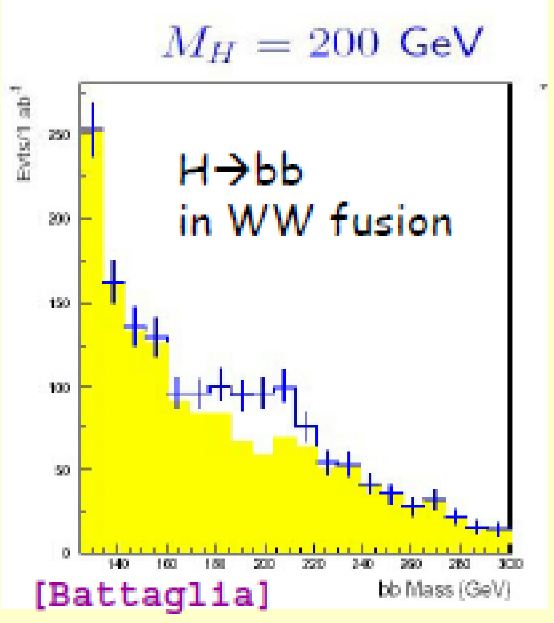
- Higgs phenomenology less rich
- Gauge boson couplings dominant
- LC vital to measure

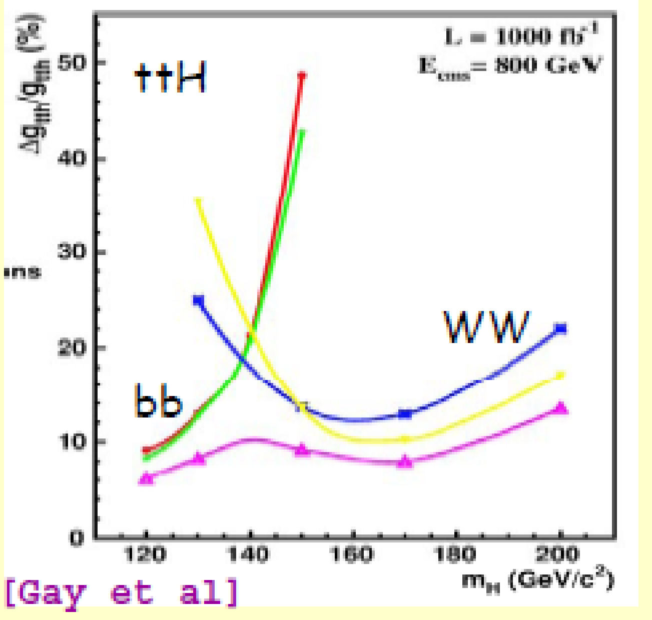
b-Yukawa coupling from H->bb

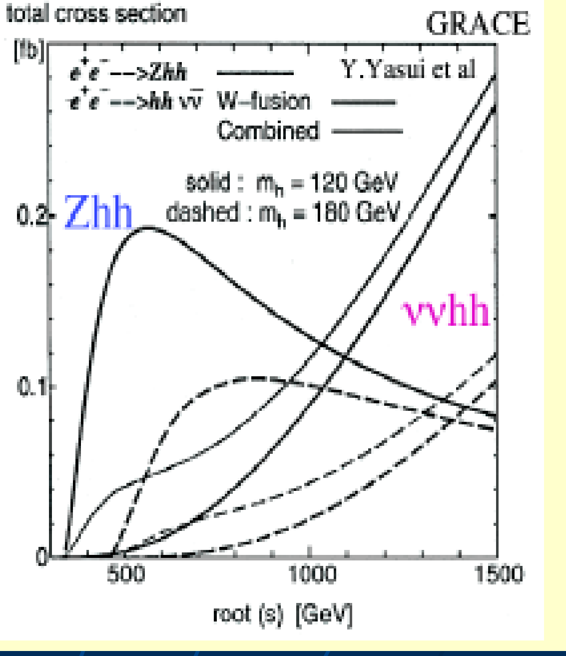
t-Yukawa coupling from ttH -> ttWW

total width from WW→H→WW + HZ→WWZ

selfcoupling? (maybe…)







Higgs physics - what precision is good for

a very recent example: catalog of deviations from SM Higgs partial widths

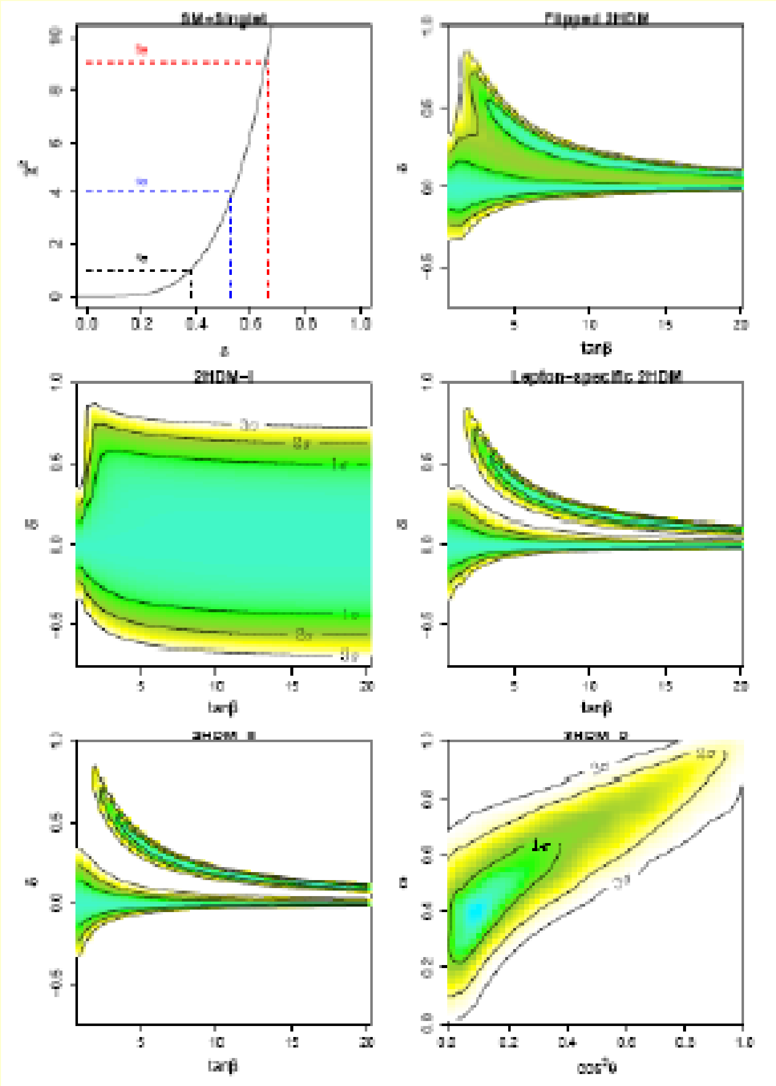
for various types of non-Standard Higgs sectors

Model	Γ_W^h/Γ_W^{SM}	Γ_d^h/Γ_d^{SM}	Γ_u^h/Γ_u^{SM}	$\Gamma_\ell^h/\Gamma_\ell^{SM}$
SM	1	1	1	1
SM+S	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$
2HDM-I	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
2HDM-II	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
2HDM-II+S	$1-\delta^2-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$	$1+2\delta/t_\beta-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$
2HDM-II+D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$
Flipped 2HDM	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
Lepton-specific 2HDM	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
MSSM	$1-\delta^2$	$1-2t'_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
3HDM-D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1+2\delta c_\gamma/t_\Omega$

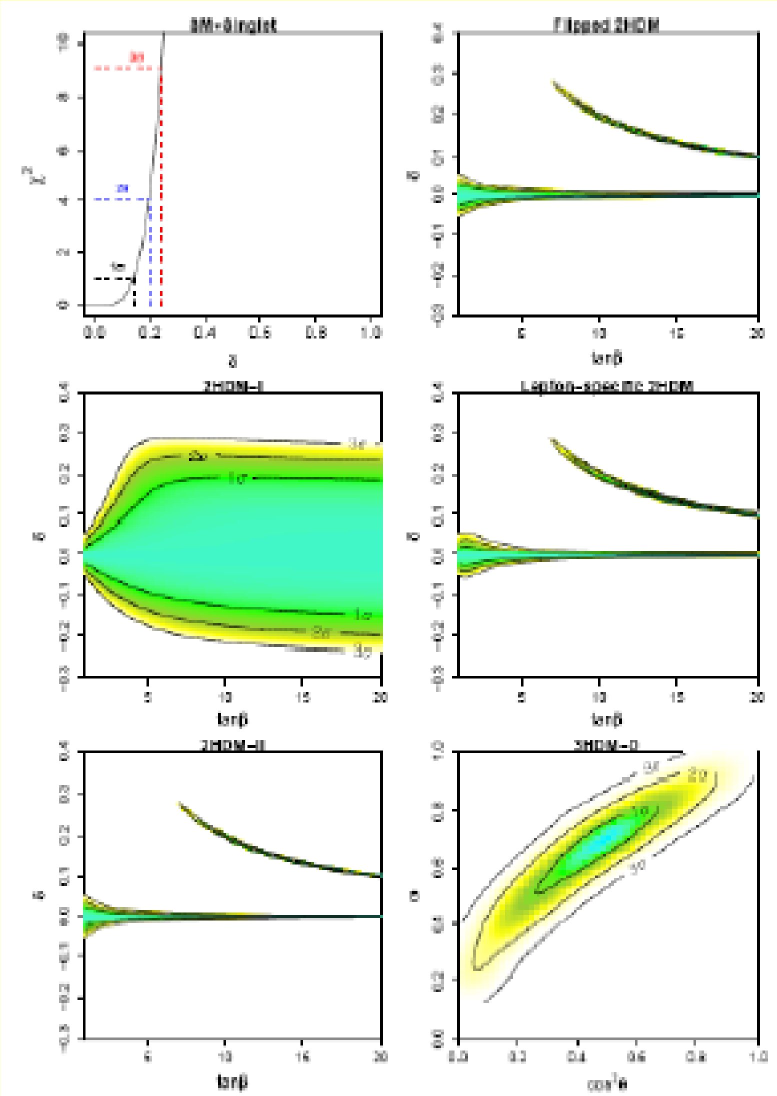
[Barger,Logan,Shaughnessy arXiv:0902.0170]

Higgs physics - what precision is good for

LHC

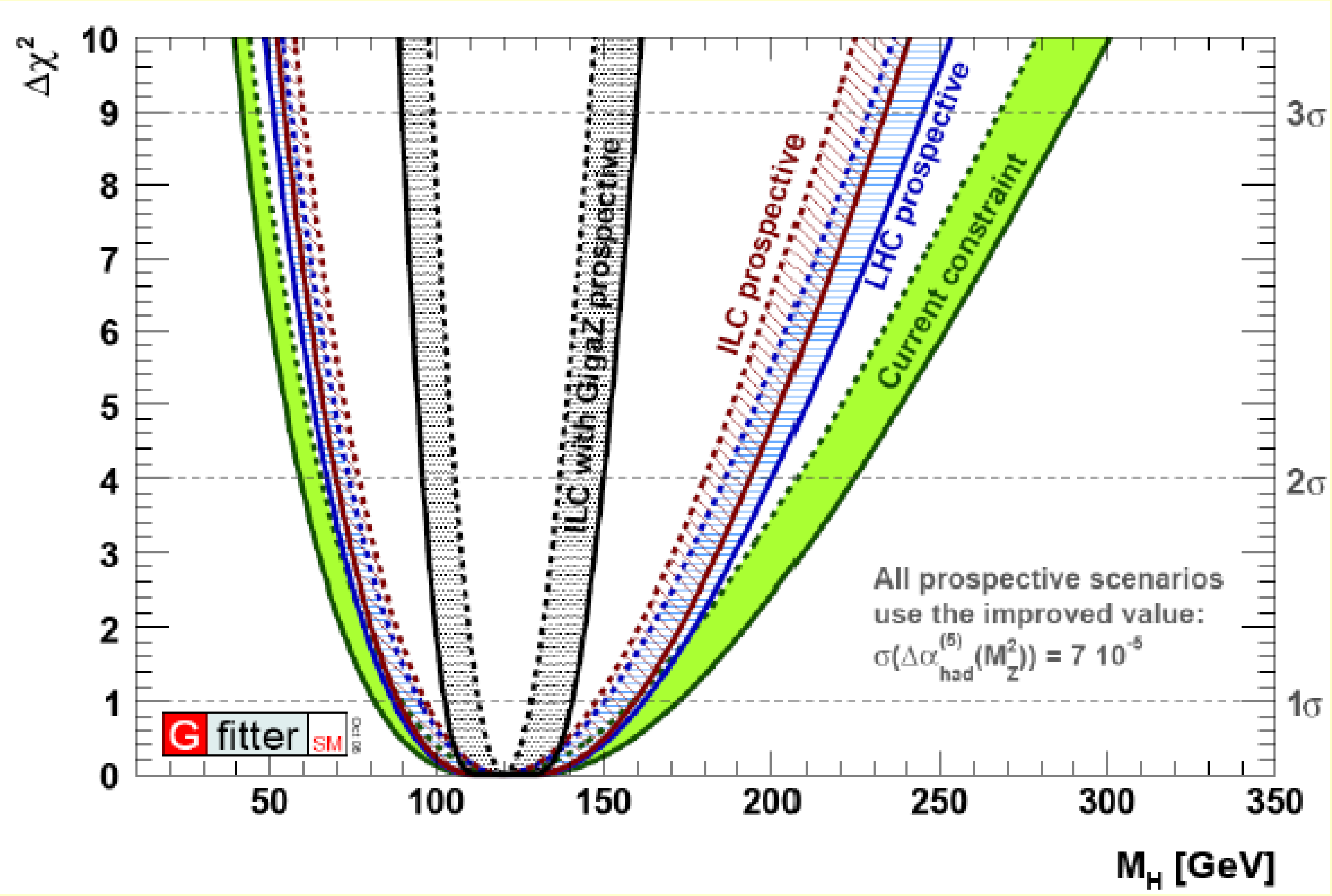


→ ILC



[Barger, Logan, Shaughnessy arXiv:0902.0170]   note different scale on most plots

Electro-weak fit with Giga-Z



[Flächer, Goebel, Haller, Höcker, Mönig, Stelzer 08]

On staging

Various „natural" stages (ordered in $\sqrt{s}$) for an e^+e^- collider:

91.2 GeV -- Giga-Z

~ 250 GeV -- maximum of HZ cross section

344 GeV -- ttbar threshold

2 m(LSP,LKP,...) + X -- model independent WIMP measurements

2 m(NLSP) + X -- SUSY spectroscopy (part I)

~ 800 GeV -- maximum of ttH cross section, HH coupling

m (Z′)

2 m (squarks) + X

3 TeV

Different stages (and when to reach them) will (hopefully) be known from LHC data

Main reports

ILC : ILC Reference design report, Vol. II, arXiv:0709.1893 [hep-ph]

CLIC : Physics at the CLIC multi-TeV linear collider, hep-ph/0412251

Muon Collider : Prospective study of Muon Storage Rings at CERN, CERN-99-02