Physics @ LHC

- **Principal Goals:**
- Explore a new energy/distance scale
- Look for 'the' Higgs boson
- Look for supersymmetry/extra dimensions, …
- Find something the theorists did not expect

*Concluding talk, ≠ **Summary***

Kraków, July 2006

John Ellis, TH Division, PH Department, CERN

The Big Particle Physics Match

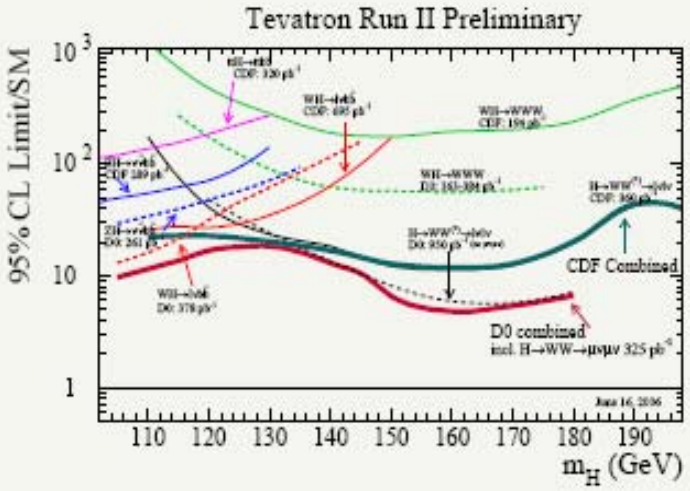
- **Training camp**
  - Tevatron, B factories, theoretical ideas & calculations
- **Warming up**
  - Installation, commissioning, pilot run
- **First half**
  - The first 1 to 30 fb^{-1}
- **Injury time**
  - Diffractive Higgs production
- **Second half**
  - On to 300 fb^{-1}
- **Extra time**
  - SLHC: 10^{35} $cm^{-2}s^{-1}$
- **Penalty shoot-out**
  - ILC vs CLIC vs DLHC vs TLHC

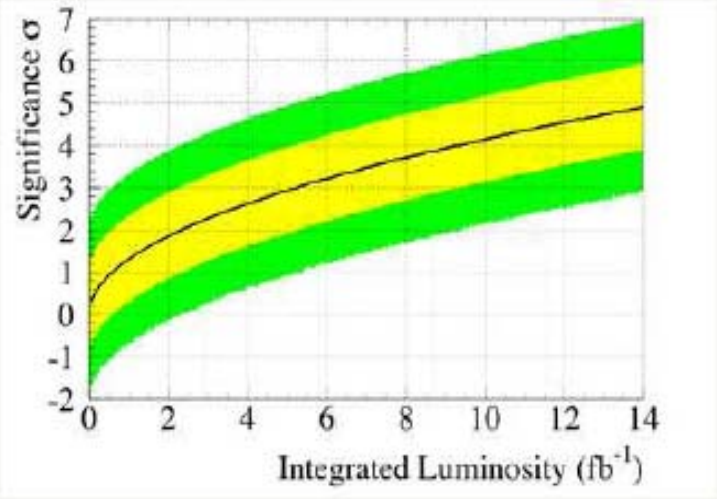
Training Camp

- Tevatron physics (& B factories)
  - QCD
  - B physics
  - Electroweak physics
  - Top physics
  - Searches for new particles, e.g., Higgs
- **They may find it!**
- Theoretical ideas & calculations

Summary of the SM Higgs at Tevatron

⇒ **Limits and expected significance (with improvements)**





⇒ **Need to work on further improvements, especially**

- Use of Neural-Networks for selecting events
- Dijet mass resolution
- Increase lepton accepance

⇒ **Need to accumulate more Integrated Luminosity** (increase of a factor 6-10 for Run II)

⇒ **Starting to combine in each experiment and plan to combine CDF and D0 results.**

⇒ **Chances of observing the Higgs for low masses (difficult range for LHC)**

EW @ Tevatron

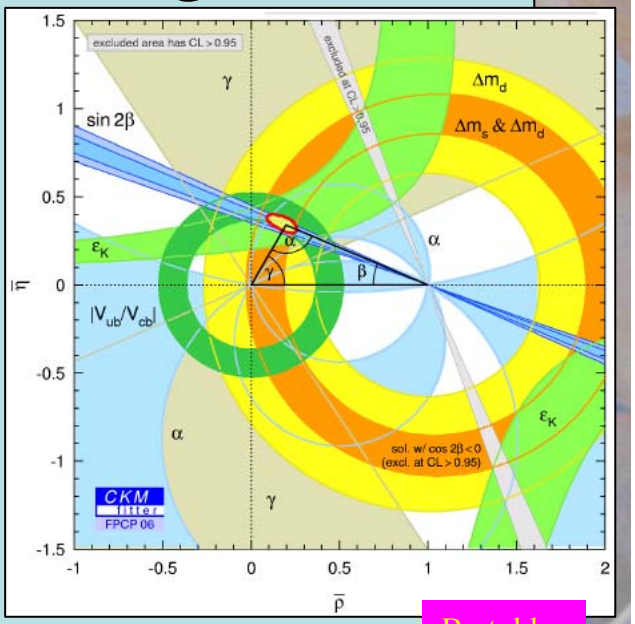
- W mass measurement:
  - Dominant errors: PDFs, lepton energy scale
- Multiple W/Z production:
  - WW @ 5 sigma, WZ @ 3.3 sigma
- All W production and decay details need careful understanding @ LHC
  - W+H important channel
  - W+jets important backgrounds

QCD, Top @ Tevatron

- QCD at Tevatron: photons, jets
  - backgrounds, tools for new physics
  - azimuthal angular distributions
  - should be able to describe corners of multijet phase space
- Top has charge 2/3, spin ½
- Mass = 172.5 ± 2.5 GeV:
  - put together with m_W, suggests light Higgs
- All-jet sample: see top and W peaks

B Physics @ Tevatron, B factories

- Predict B CPX from CP-conserving observables: CKM dominant
- Is CKM the Whole Story?
  - Problem with sin 2β?
  - J/ψK vs other modes?
  - improve α measurements
  - want better measurement of γ
- Windows on new physics: $B \rightarrow s\gamma$, Kl^+l^-
- B_s mixing and $B \rightarrow \tau\nu$ pressure SUSY



Bartoldus

What have theorists done for us lately?

- Simplifications of QCD: SUSY, twistors
- Still many processes uncalculated:

Les Houches 2005 wishlist (short version)

1. $pp \to VV$ jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to VV\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to VVV$	SUSY trilepton

Lykken

Theoretical Basis for Higgs Search

- Higgs physics very inspiring for theoretical developments
  → phase space integrations, higher order Monte Carlos, ...
- higher orders essential
  → $\sigma(gg \to H) \approx \sigma_{\rm LO}(1 + 0.7 + 0.3 + \cdots) \approx 2\sigma_{\rm LO}$
- clear understanding of theory opens new experimental windows
  → coupling measurements, CP properties, ...
- new conceptual understandings
  → bottom densities, higher order SUSY, ...
- exciting times ahead of us
  → (N)NLO era at hadron colliders has begun!
  → Higgs physics with data!

Harlander

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)

  Susy
- Why so many types of matter particles?

  matter-antimatter difference?

  LHC
- Unification of the fundamental forces?

  at very high energy ~ 10^{16} GeV?

  probe directly via neutrino physics, indirectly via masses, couplings

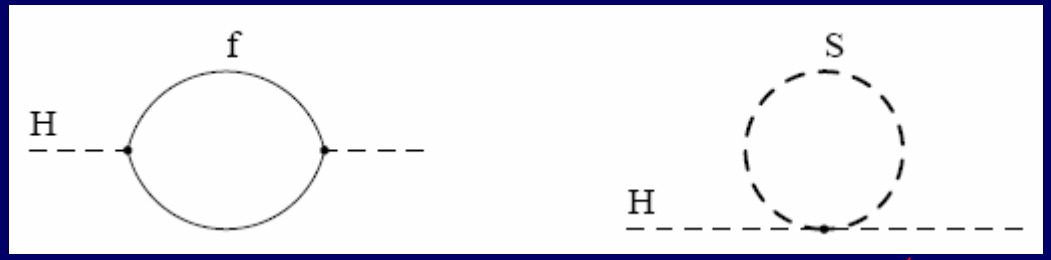
  Susy
- Quantum theory of gravity?

  (super)string theory: extra space-time dimensions?

  Susy

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

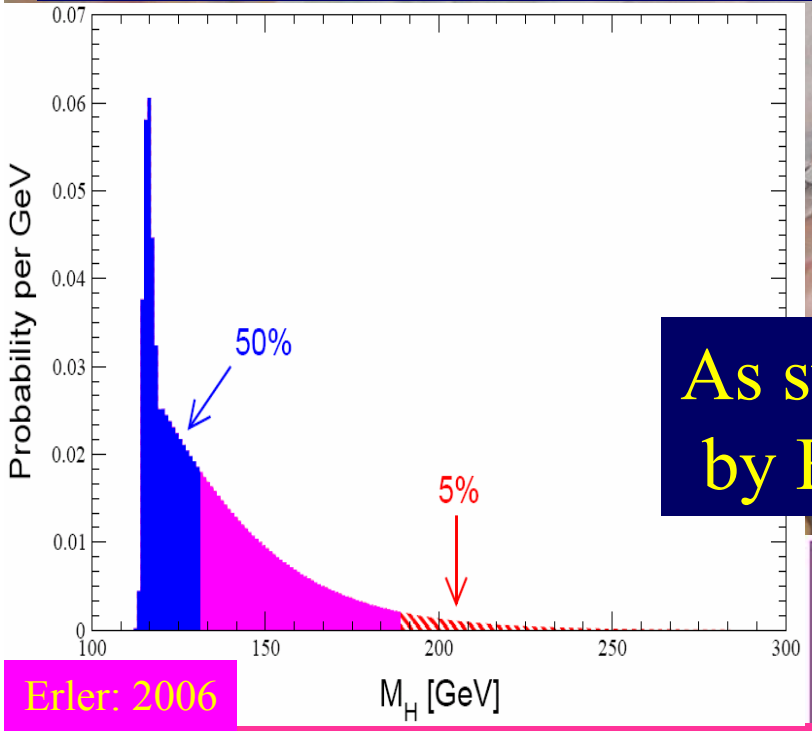
$$\lambda_S = y_f^2 \cdot 2$$

Supersymmetry!

Other Reasons to like Susy

It enables the gauge couplings to unify

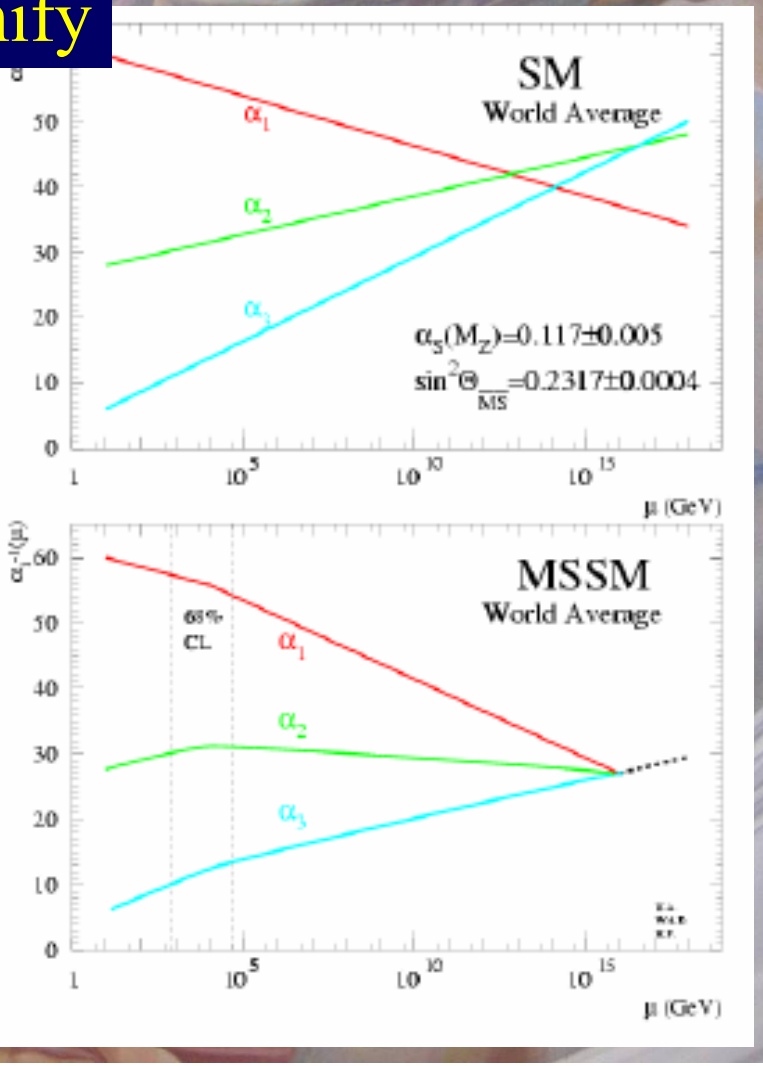
It predicts $m_H < 150$ GeV



Erler: 2006

As suggested by EW data

Approved by Fabiola Gianotti



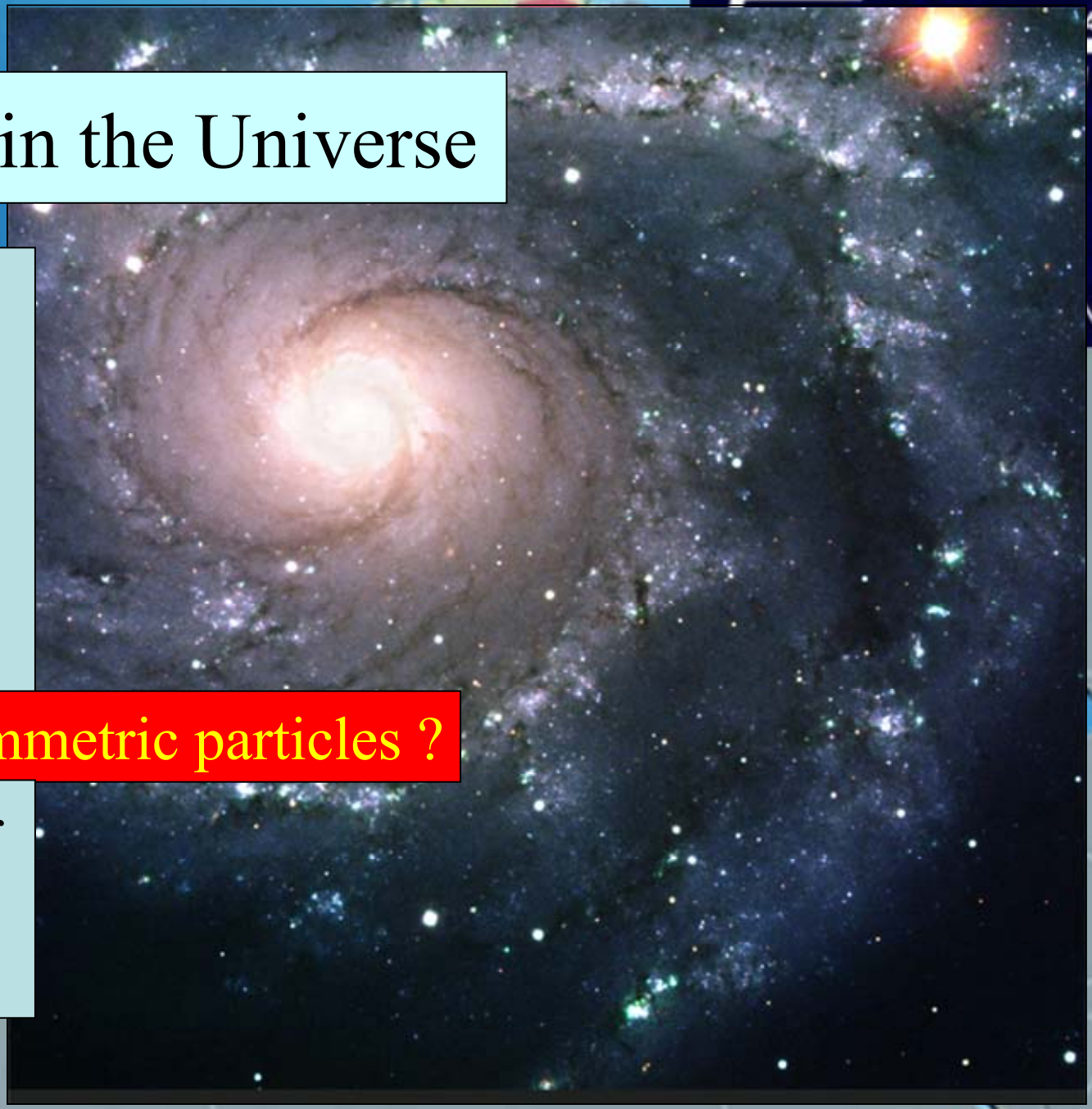
Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible

Dark Matter

Lightest Supersymmetric particles ?

We shall look for them with the LHC



Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ
  - Gravitino
    - (nightmare for astrophysical detection)

Current Constraints on CMSSM

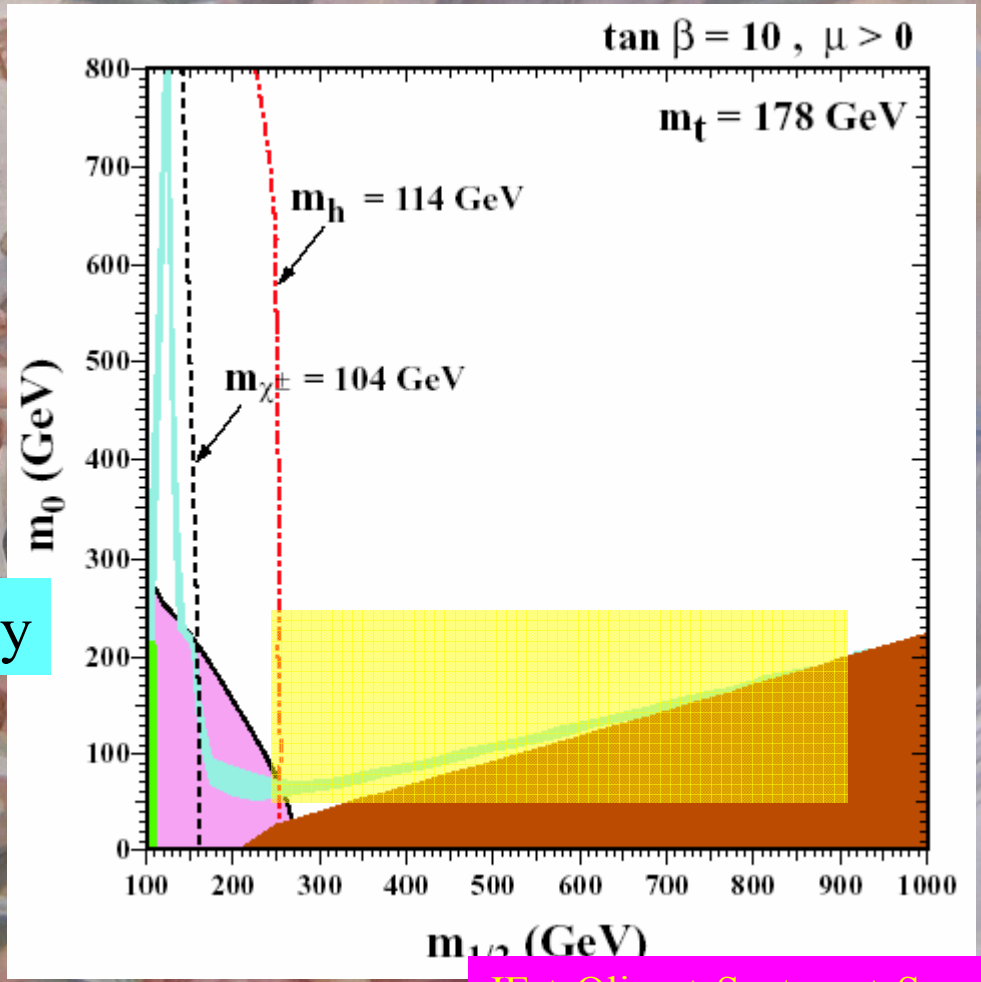
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Excluded (?) by latest g - 2



JE + Olive + Santoso + Spanos

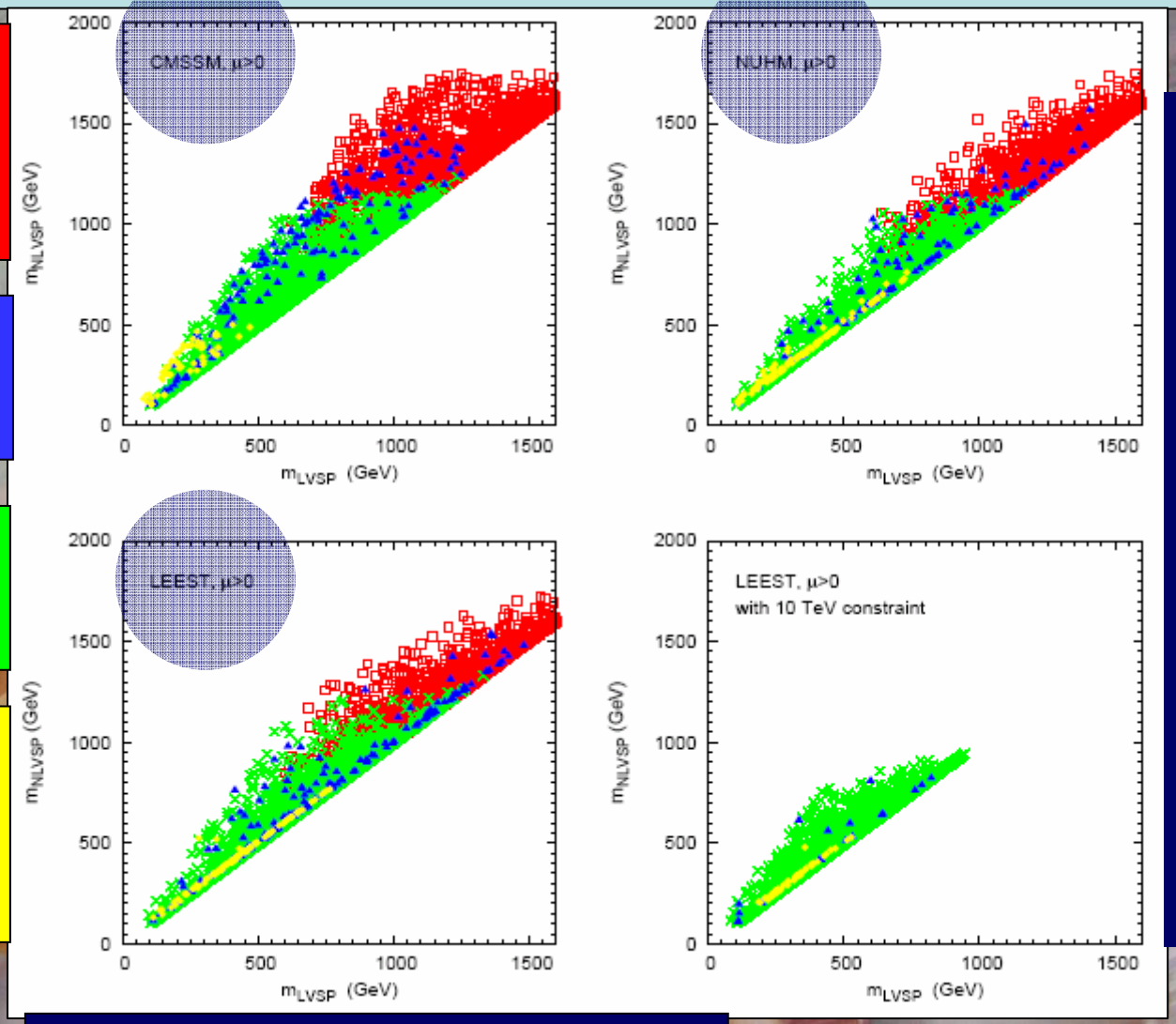
Sparticles may not be very light

Full Model samples

Provide Dark Matter

Detectable @ LHC

Dark Matter Detectable Directly



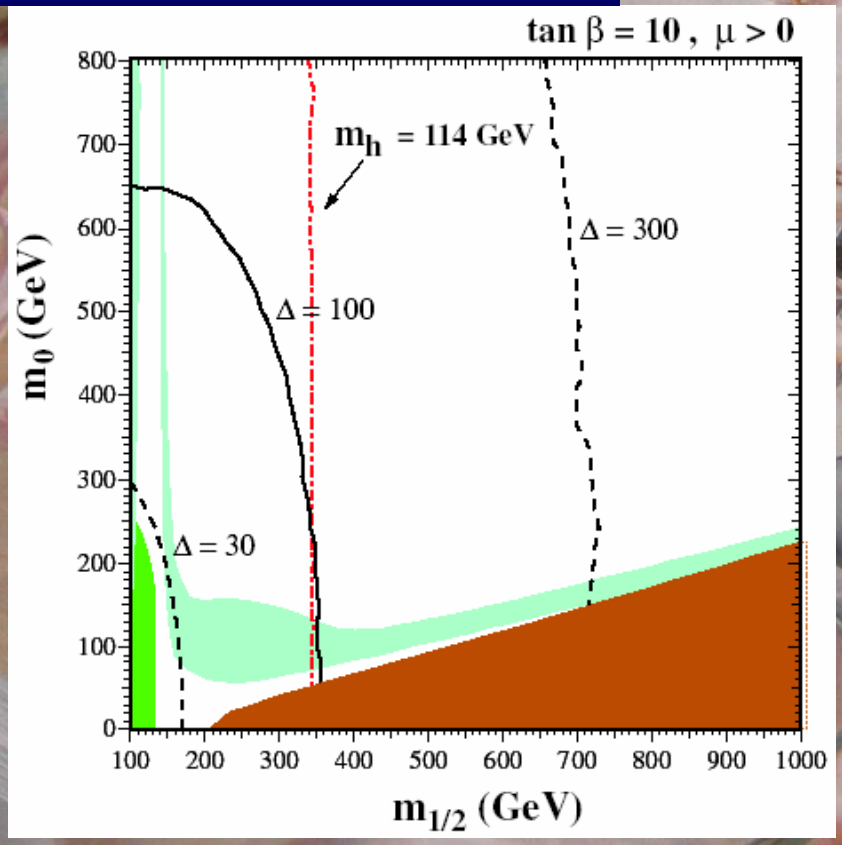
← Second lightest visible sparticle

Lightest visible sparticle →

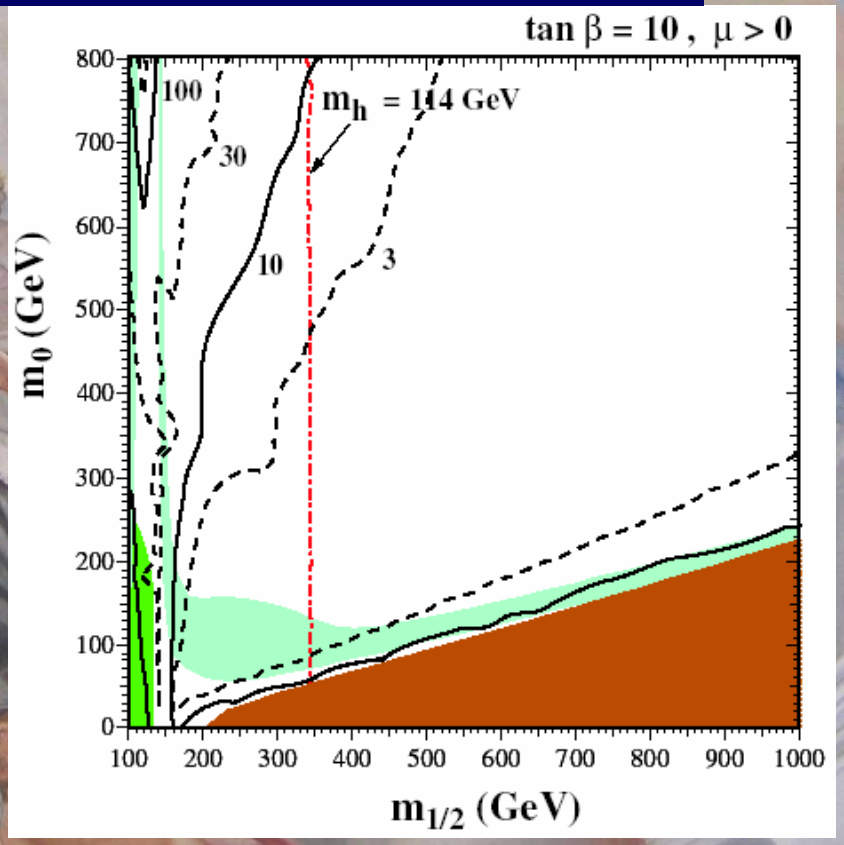
JE + Olive + Santoso + Spanos

How ‘Likely’ are Heavy Sparticles?

Fine-tuning of EW scale



Fine-tuning of relic density



Larger masses require more fine-tuning: but how much is too much?

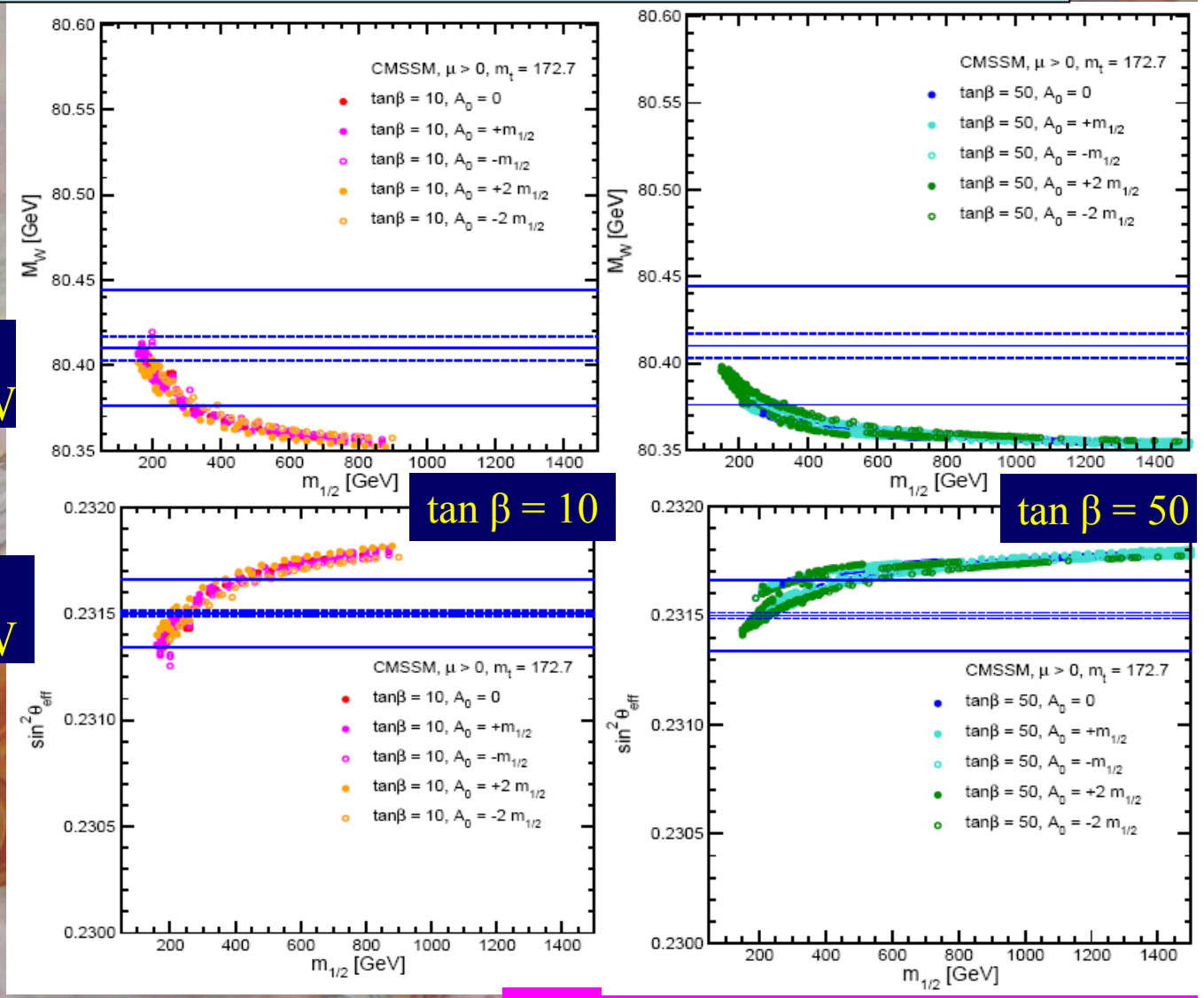
Can one estimate the scale of supersymmetry?

Precision Observables in Susy

Sensitivity to $m_{1/2}$ in CMSSM along WMAP lines for different A

m_W

$\sin^2\theta_W$

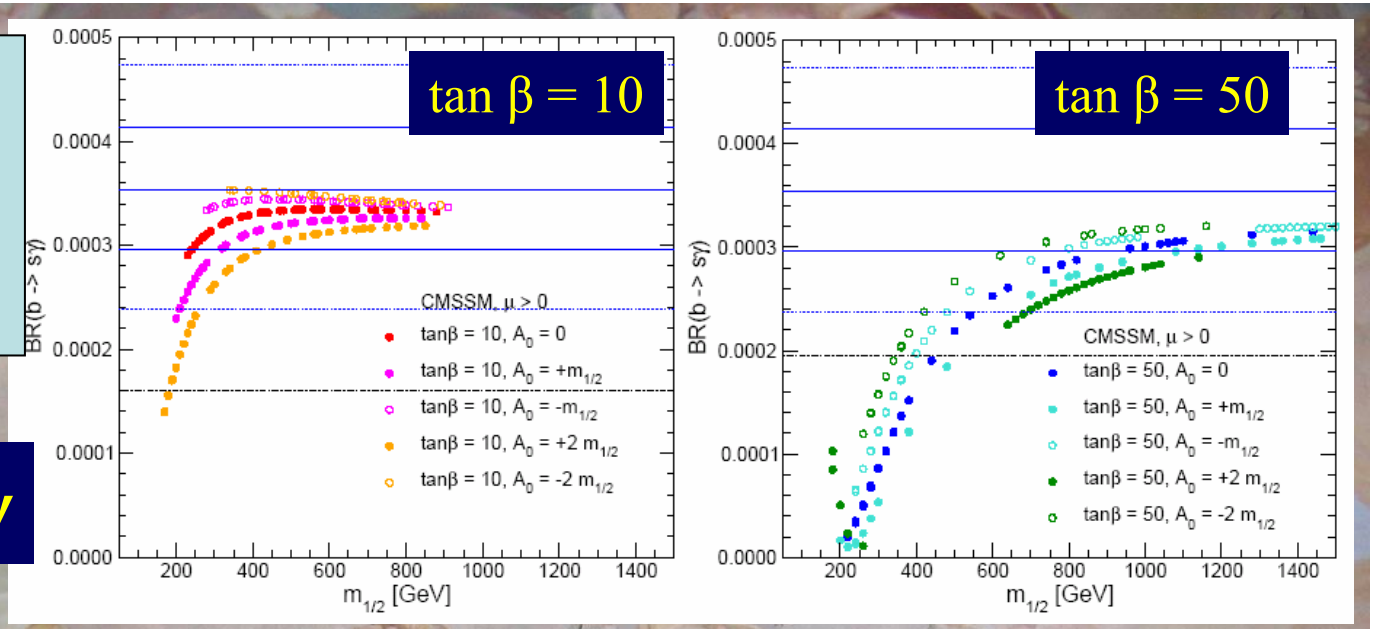


Present & possible future errors

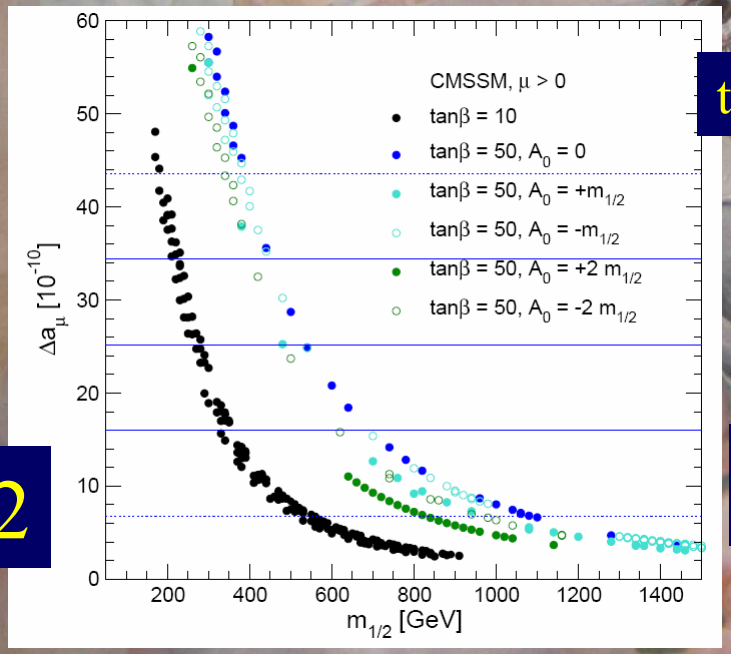
JE + Heinemeyer + Olive + Weiglein: 2006

More Observables

$b \rightarrow s\gamma$

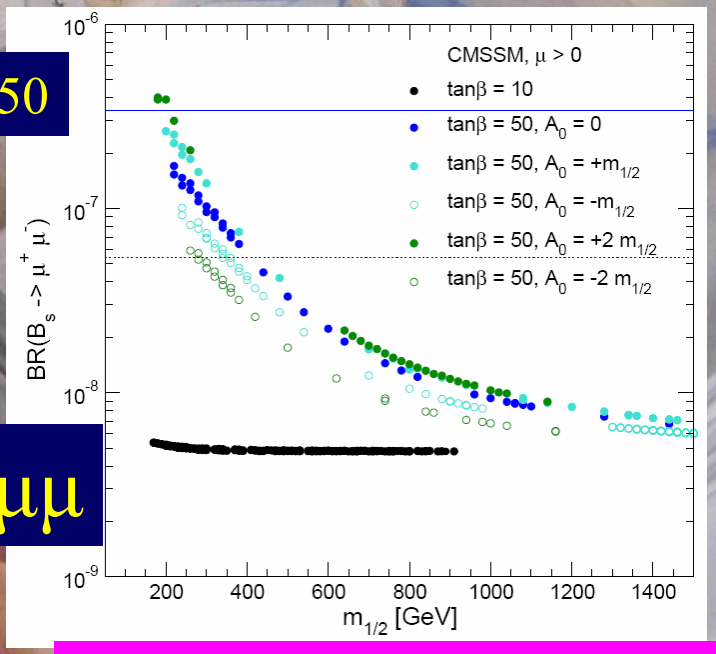


$g_\mu - 2$



tan β = 10, 50

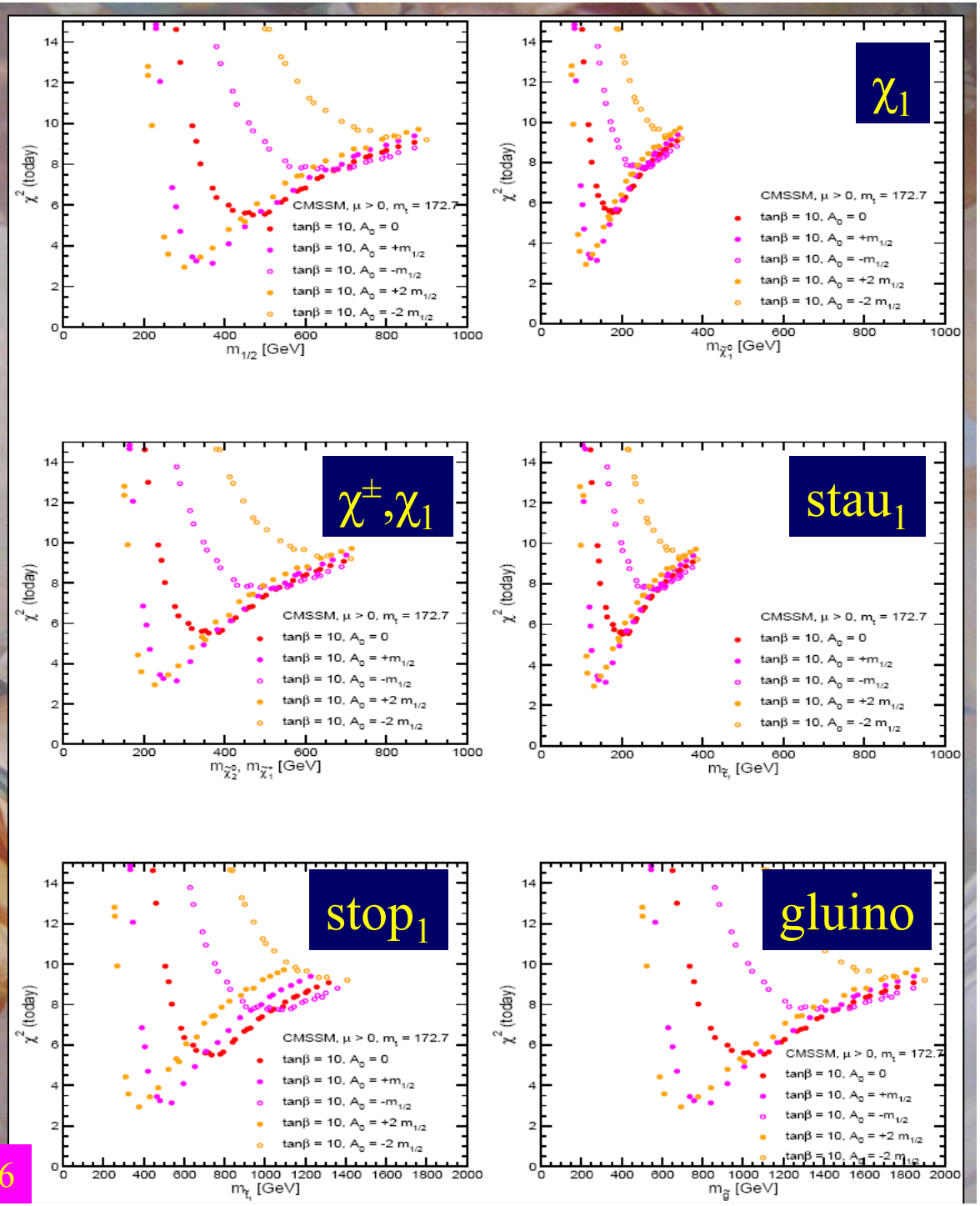
$B_s \rightarrow \mu\mu$



JE + Heinemeyer + Olive + Weiglein

Global Fits to Present Data

Preferred sparticle masses for tan β = 10



JE + Heinemeyer + Olive + Weiglein: 2006

Non-MSSM BSM

- Extra dimensions?
  - either low-scale: X EW data
  - or beyond reach of LHC?
  - rich alternative to SUSY phenomenology
- Little Higgs as dimensional deconstruction
  - Gauge-Higgs unification in larger groups
  - New fermions, heavy W, Z, γ
  - Fairly complicated and no leading competitor
  - another rich alternative to SUSY phenomenology

Pokorski

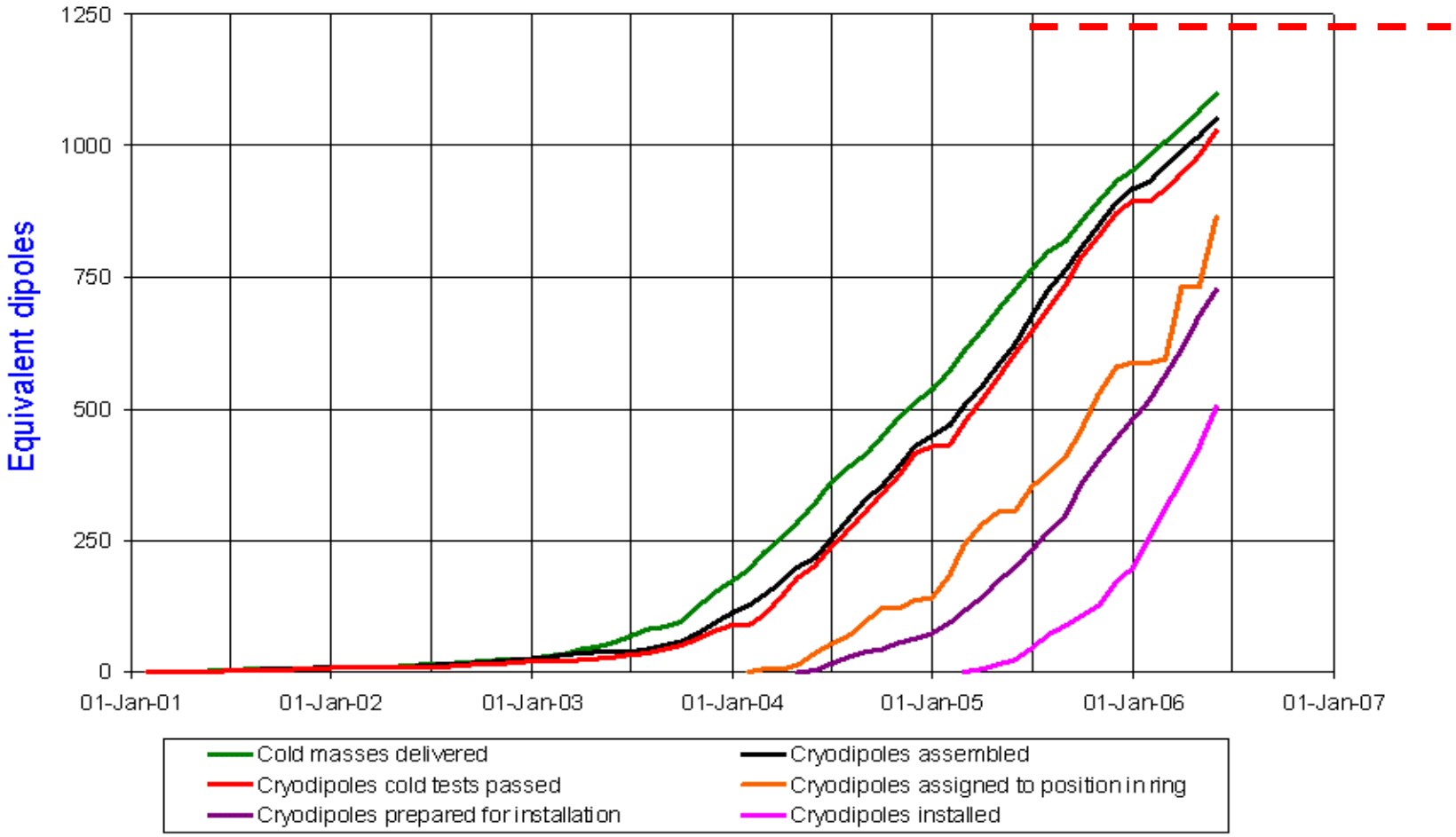
Warming Up

- Status of the LHC accelerator:
  - Installation
  - Commissioning
  - Pilot run
- Status of the LHC experiments
- Status of the LHC computing Grid

LHC Progress Dashboard

Accelerator Technology Department

Cryodipole overview



Updated 31 May 2006

Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM

Underground

Remaining LHC Milestones

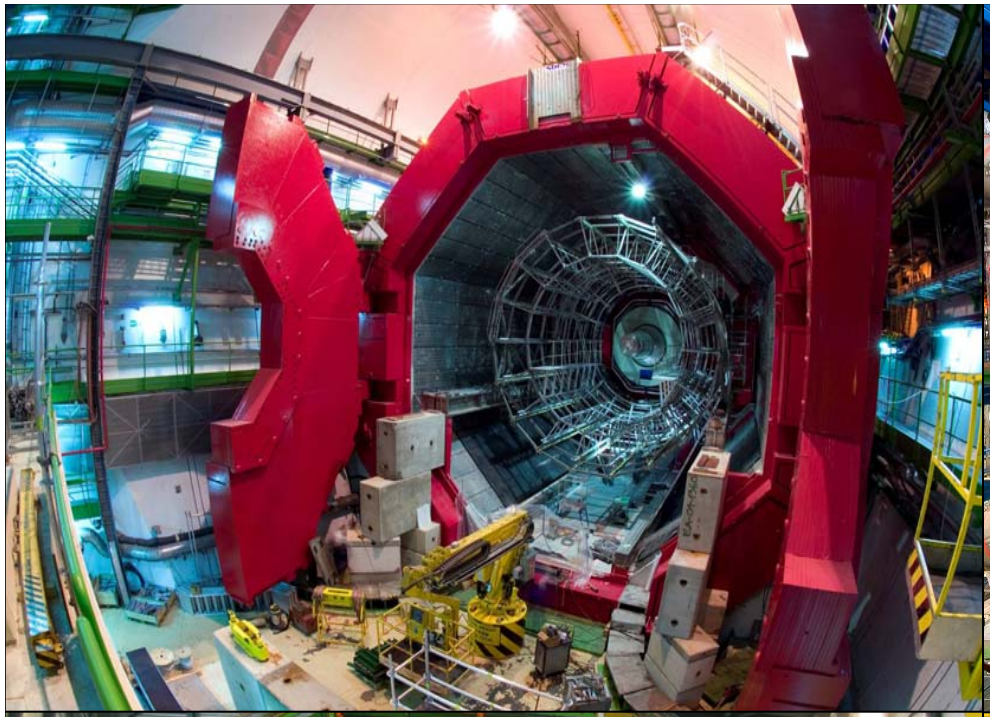
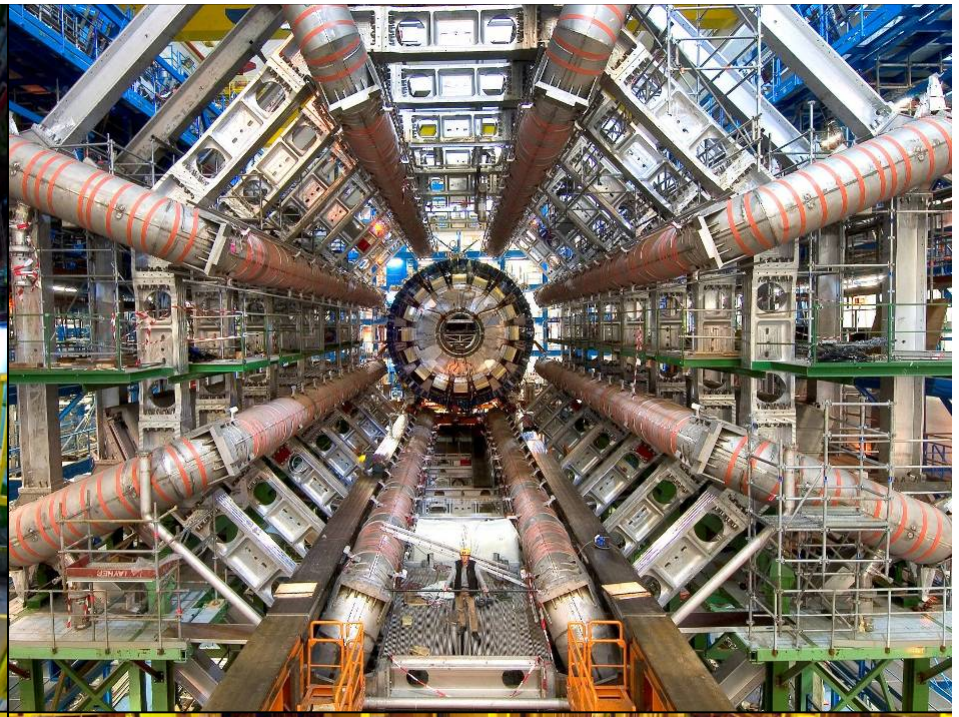
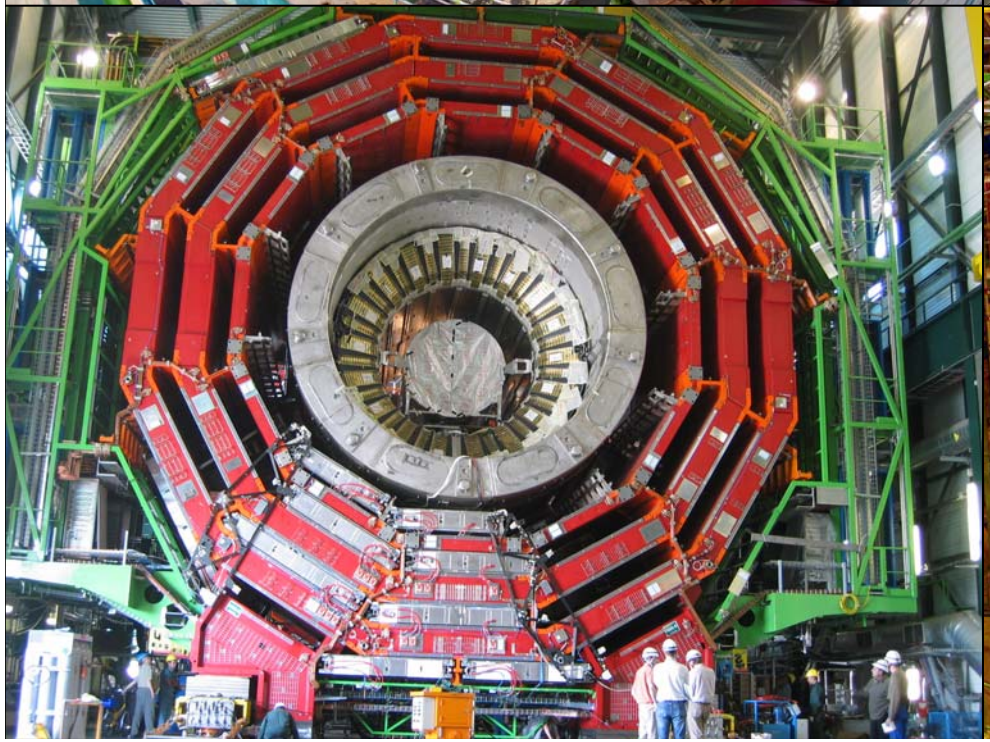
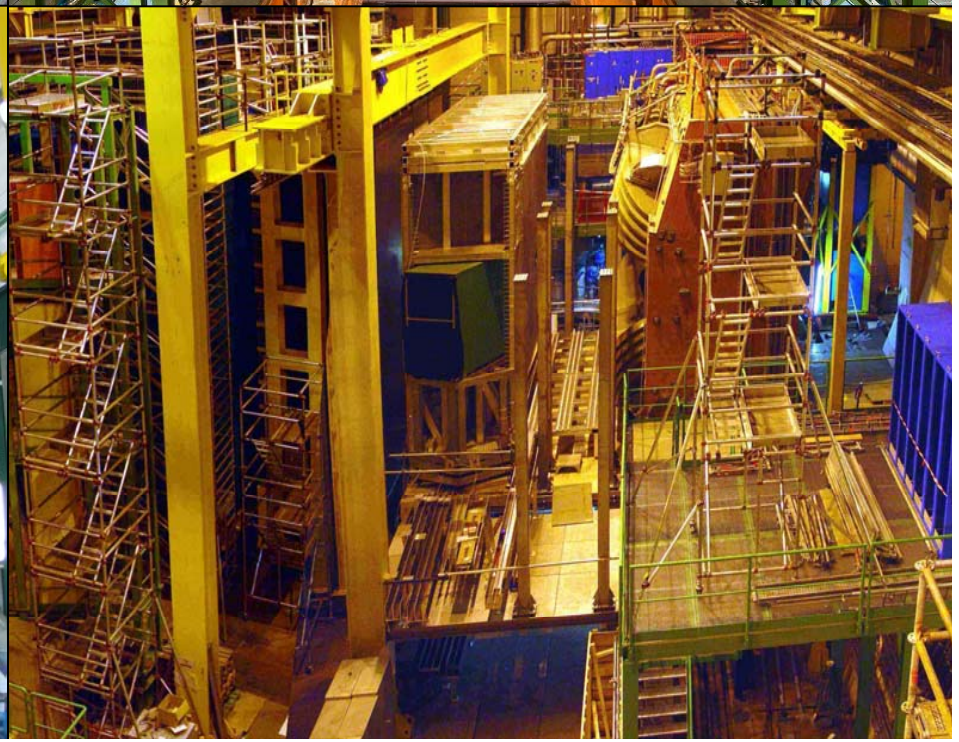
Engelen

Last magnet delivered	October 2006
Last magnet tested	December 2006
Last magnet installed	March 2007
Machine closed	August 2007
First collisions	November 2007

Machine commissioning

Engelen

- 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

First Half

- Measure and understand minimum bias
- Measure jets, start energy calibration
- Measure W/Z, calibrate lepton energies
- Measure top, calibrate jet energies & missing E_T
- First searches for Higgs:
  - Combine many signatures
  - need to understand detector very well
- First searches for SUSY, etc.

Standard Model @ LHC

- Jet multiplicity distributions from data: MCs disagree
- W, Z: theory uncertainties will dominate
- Hope to get error in $m_W < 10$ MeV
  - 5 MeV possible?
  - remember LEP!
- Hope to get error in $m_t < 1$ GeV
  - pile-up, jet E scale, underlying event
  - eventually ± 0.5 GeV?

Boonekamp

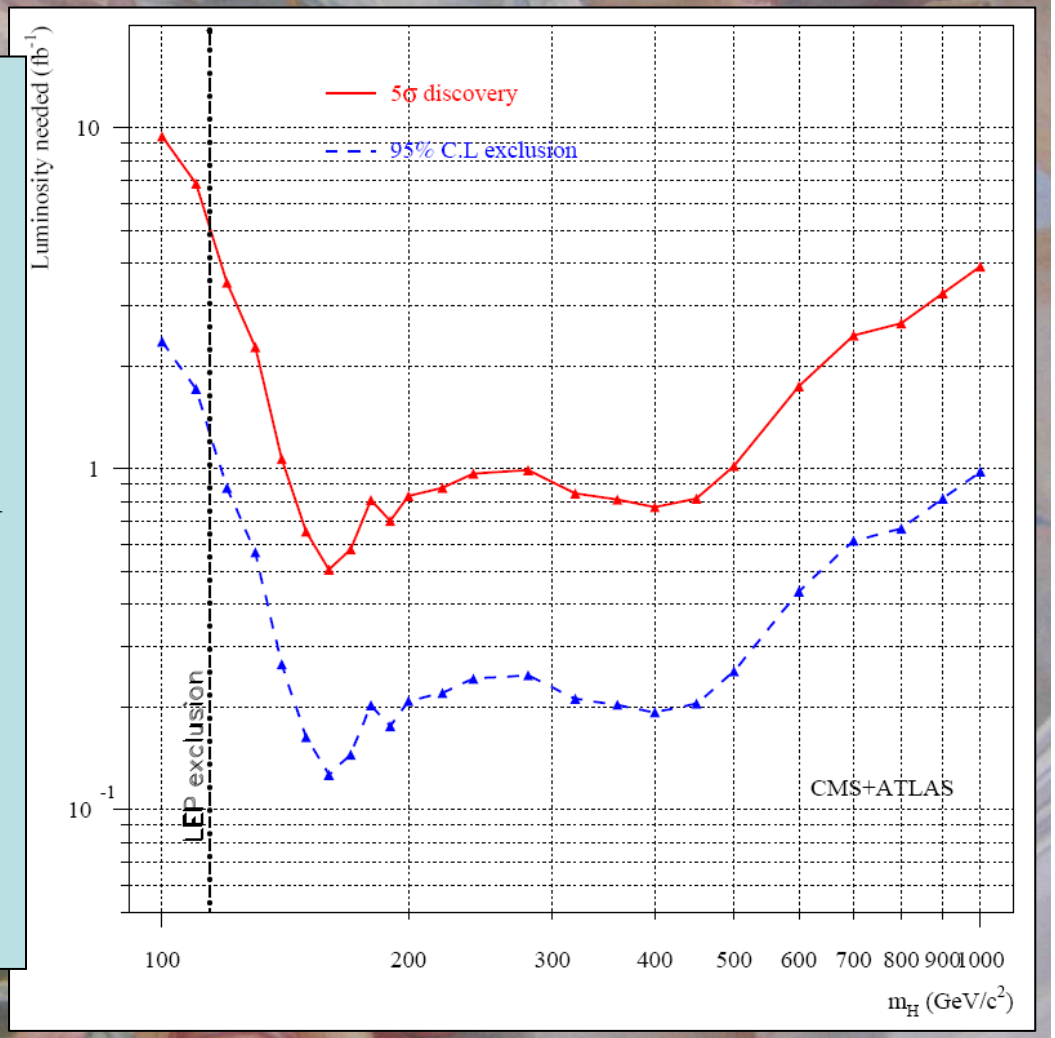
Duda

Looking for New Physics @ LHC

- Need to understand SM first:
  - calibration, alignment, systematics
- Searches for specific scenarios, e.g., SUSY, vs signature-based searches, e.g., monojets?
- False dichotomy!
- How to discriminate between models?
  - different Z′ models?
  - missing energy: SUSY vs UED?
    - higher excitations, spin correlations, spectra, …

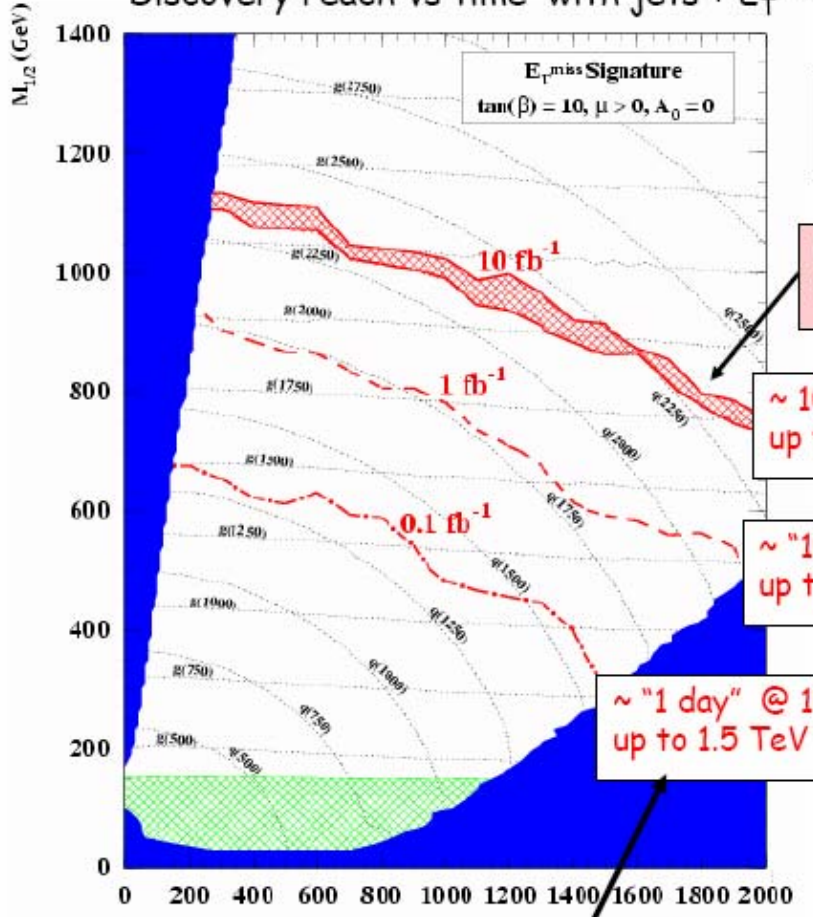
Potential of Initial LHC running

- A Standard Model Higgs boson could be discovered with 5-σ significance with $5fb^{-1}$, $1fb^{-1}$ would be sufficient to exclude a Standard Model Higgs boson at the 95% confidence level
- Signal would include ττ, γγ, bb, WW and ZZ
- Will need to understand detectors very well



How soon will we know?

Initial LHC Reach for Supersymmetry



ATLAS
5σ discovery curves

band indicates factor ± 2 variation in background estimate

~ 100 days : up to 2.3 TeV

~ "10 days" : up to 2 TeV

~ "1 day" @ 10^{33}: up to 1.5 TeV

Discovery reach for squarks/gluinos

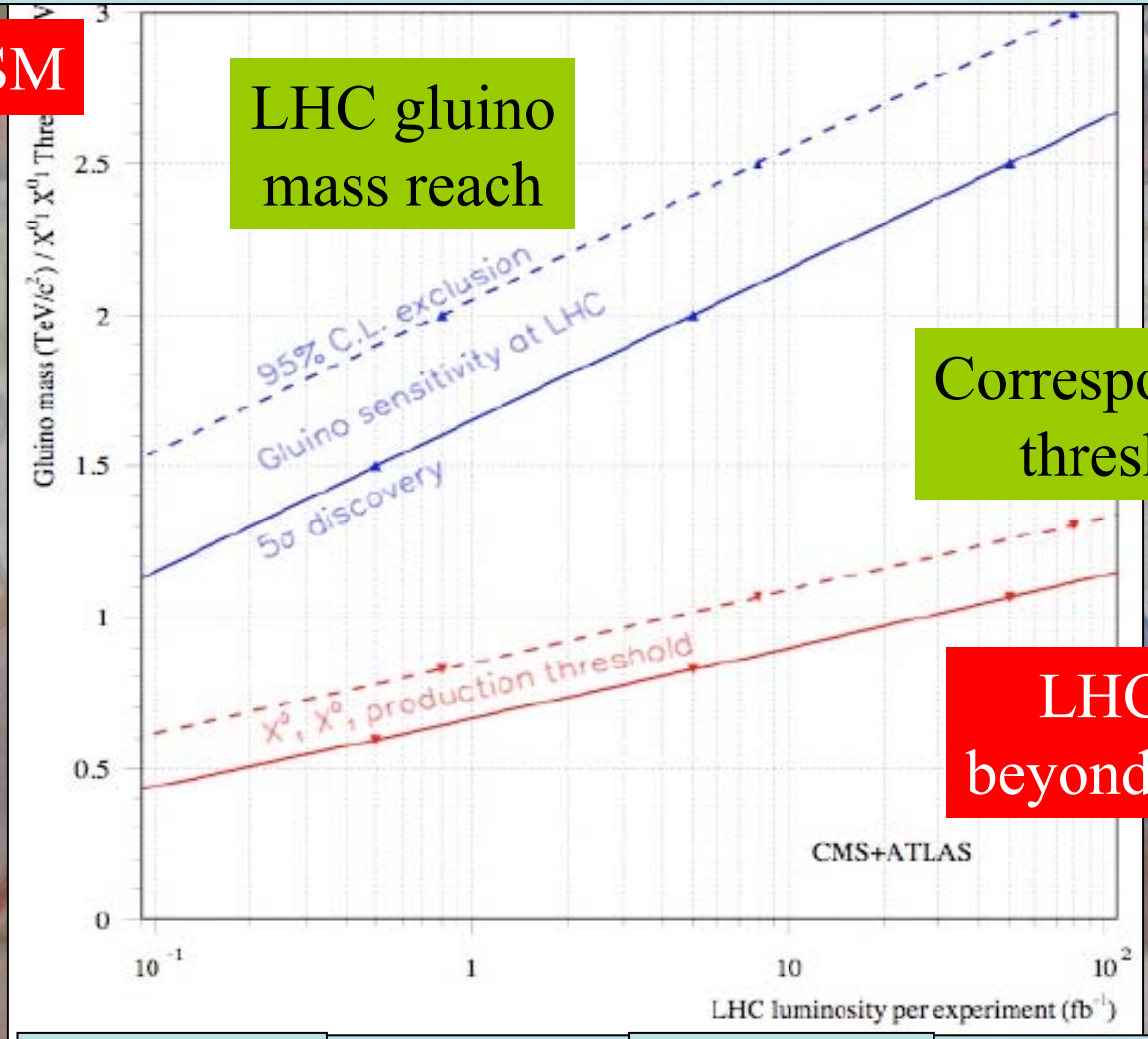
Time	mass reach
1 month at 10^{33}	~ 1.3 TeV
1 year at 10^{33}	~ 1.8 TeV
1 year at 10^{34}	~ 2.5 TeV
ultimate (300 fb^{-1})	~ 2.5-3 TeV

But : it will take a lot time to understand the detectors and the backgrounds ...

Implications of LHC Search for ILC

In CMSSM

LHC gluino mass reach



Corresponding sparticle thresholds @ ILC

LHC already sees beyond ILC 'at turn-on'

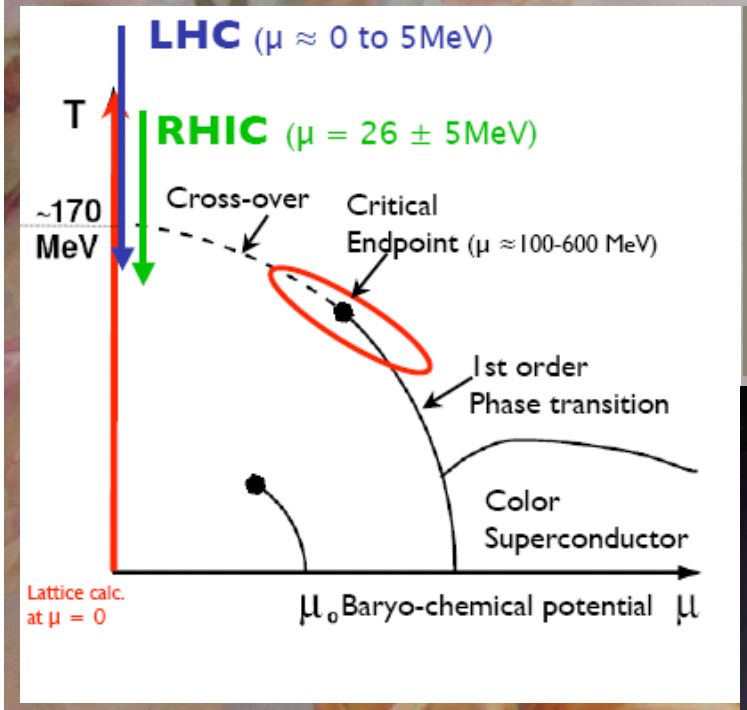
'month' @ 10^{32} | 'month' @ 10^{33} | 1 'year' @ 10^{33} | 1 'year' @ 10^{34}

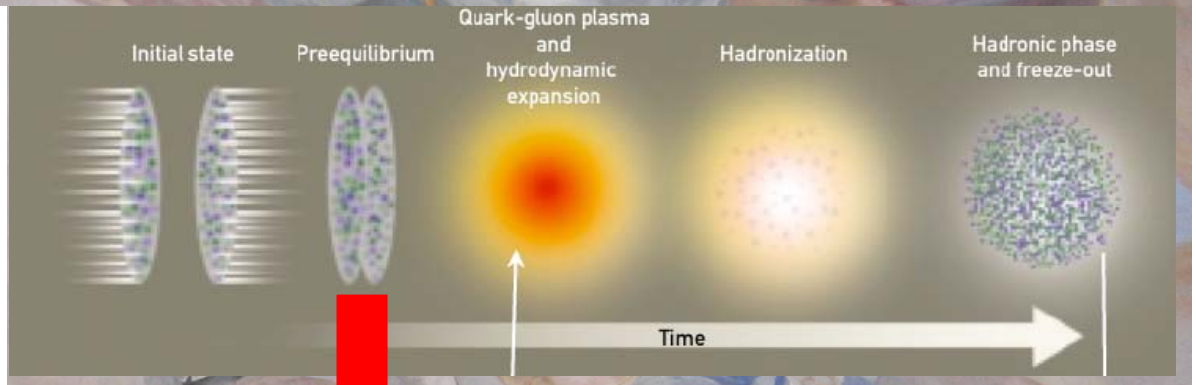
Blaising et al: 2006

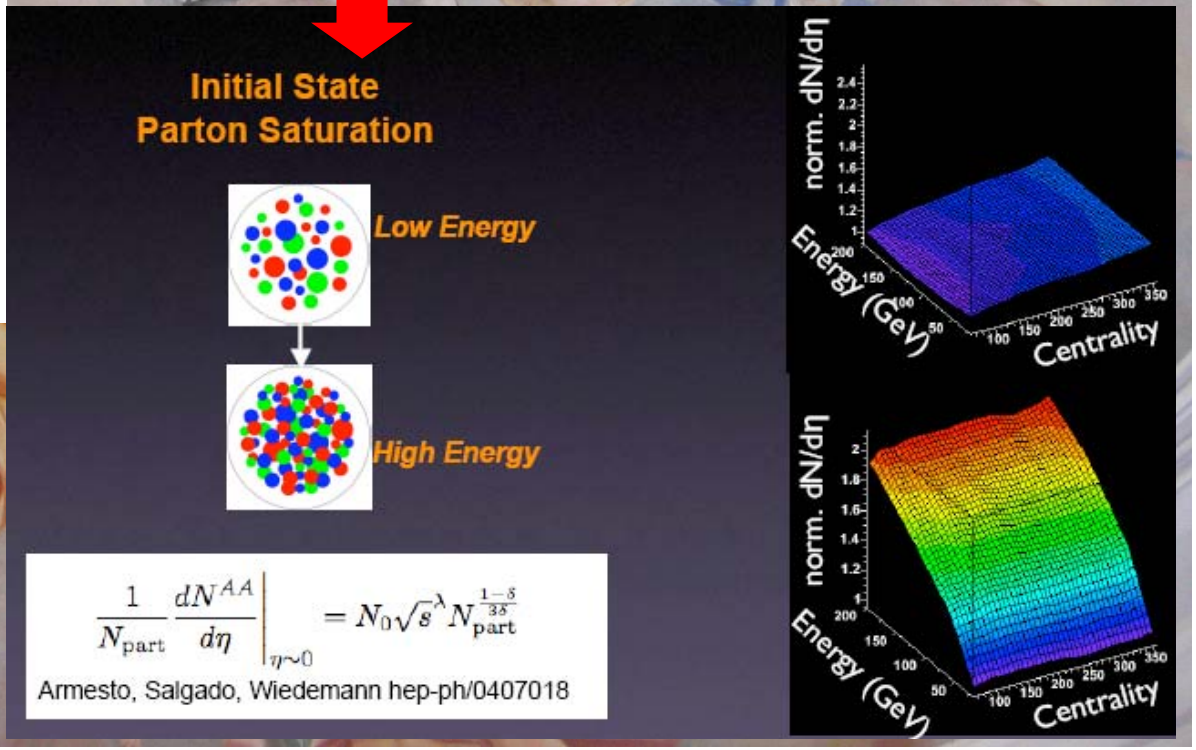
Heavy Ions @ LHC

- Observations/puzzles @ RHIC
  - Initial state: fast thermalization, saturation effects, geometric scaling
  - Medium: low-viscosity hydrodynamics, large transport coefficient
  - Final state: jet quenching, shock wave/Cerenkov radiation?
- New theoretical ideas:
  - CGC: thermalization, multiplicity
  - AdS/CFT correspondence: shock wave, transport coefficient
- New kinematic range @ LHC: cross-over, not phase transition

New State(s) of Hadronic Matter







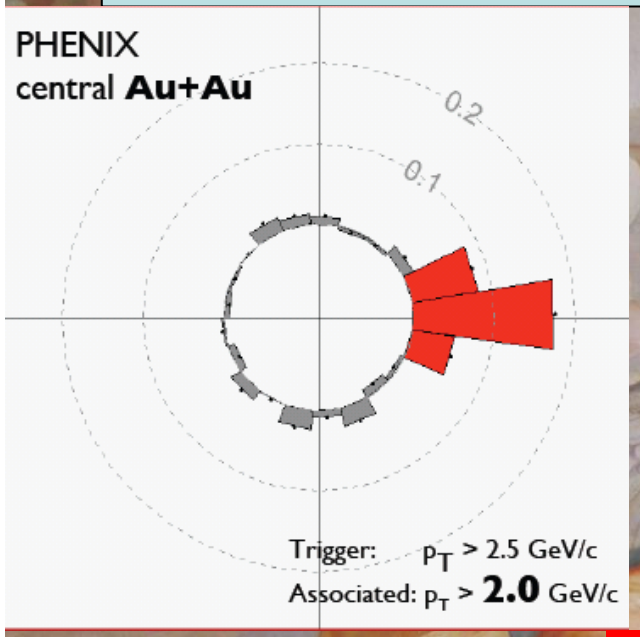
$$\left.\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

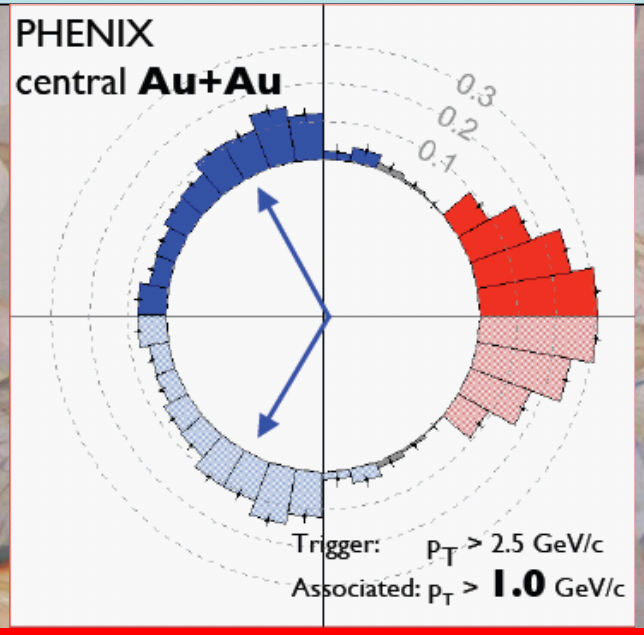
Armesto, Salgado, Wiedemann hep-ph/0407018

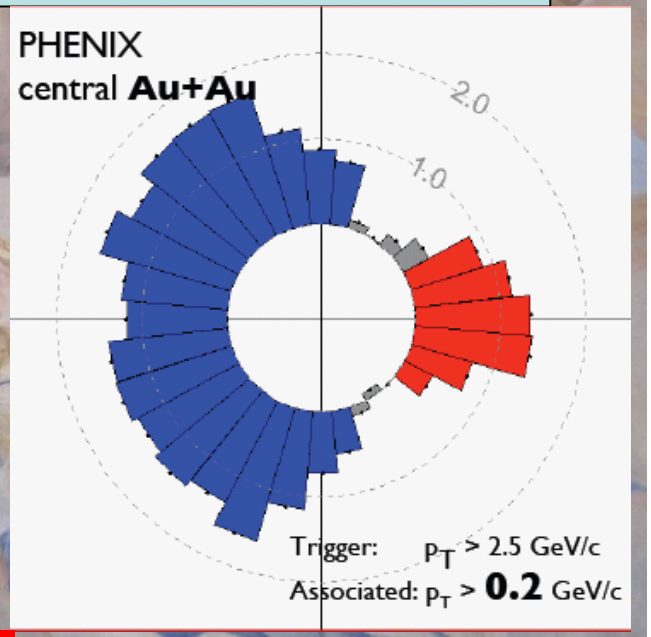
Phase diagram probed in heavy-ion collisions

Salgado, Roland

Jet Quenching: Antenna Pattern as Function of p_T







Where did jet go?

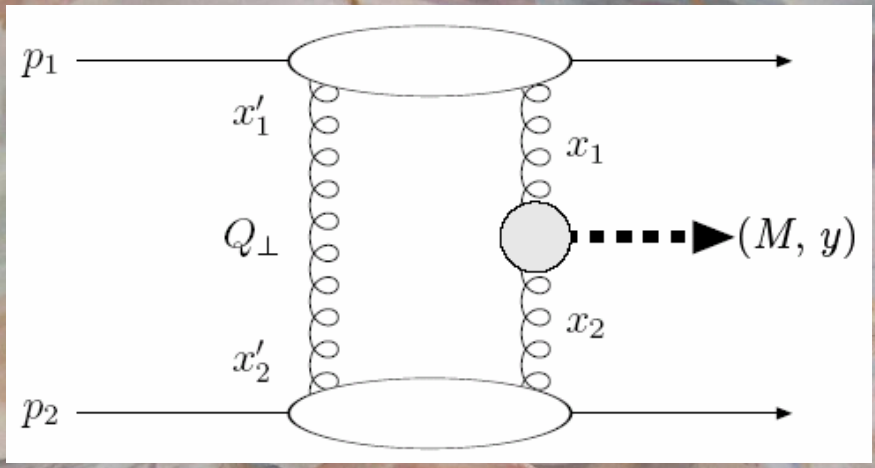
Non-trivial antenna pattern at medium p_T: Mach cone? Cerenkov radiation?

Many soft particles

What LHCb may tell us

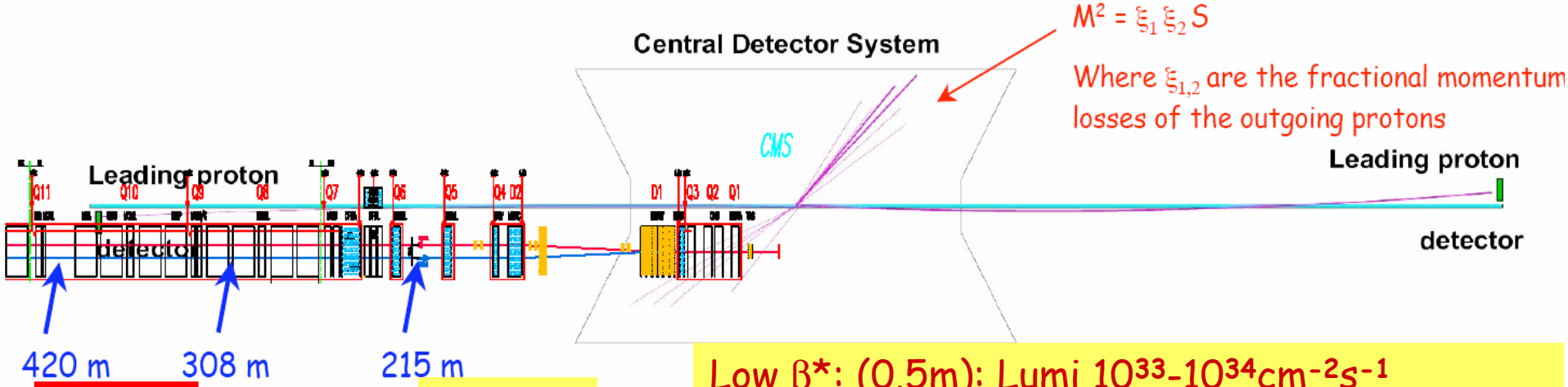
- Compare tree (pure CKM) and loops (may be contamination by New Physics)
- Measure CPV in B_s decays
- Improve measurements of α, β and γ
- Rare B decays
- No longer asking whether CKM 'right'
  - already know it is dominant
- Look for additional sources of CP violation
  - something is need for baryogenesis

Injury Time



Diffractive Higgs production?

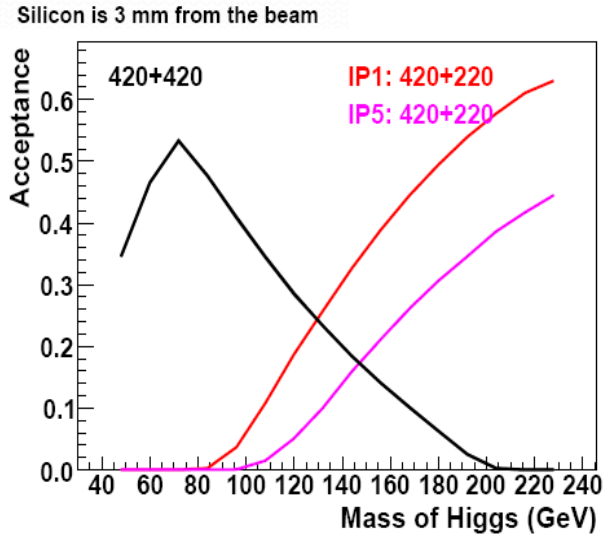
Detectors for Exclusive Higgs



FP420

TOTEM (ATLAS)

Low β^*: (0.5m): Lumi 10^{33}-10^{34}cm^{-2}s^{-1}
220m: $0.02 < \xi < 0.2$
300/400m: $0.002 < \xi < 0.02$
RPs in the cold region/needs cryostat redesign
Detectors at 420 are needed to access the low
ξ values for low Higgs mass acceptance



FP420 R&D Project
http://www.fp420.com
Contacts: A De Roeck/B. Cox

- Problem: 420m to late for CMS/ATLAS L1 trigger. Trigger on central activity

De Roeck

Second Half

- Physics with 300 fb^{-1}
- How much will we learn about Higgs?
- Maximum reach for new physics?
- How much will we learn about SUSY?
  - or whatever Nature chooses, …

Subsequent LHC Running

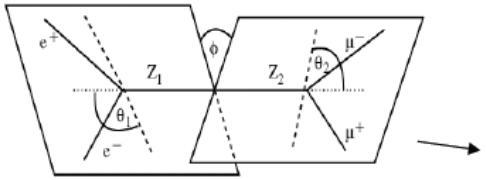
- Will be possible to determine spin of Higgs decaying to $\gamma\gamma$ or ZZ
- Can measure invisible Higgs decays at 15-30% level
- Will be possible to determine many Higgs-particle couplings at the 10-20% level

Spin,CP

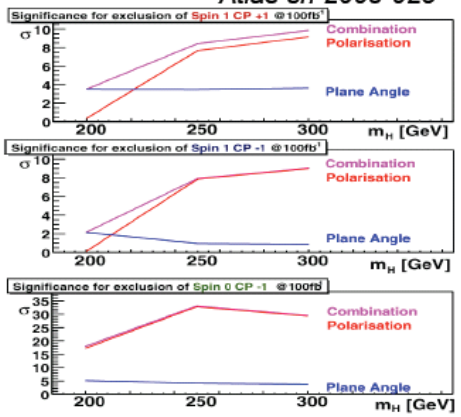
Observation of gg→H or H→$\gamma\gamma$ excludes spin 1

For M_H>200 GeV, study spin/CP from H→ZZ→4l

Atlas-sn-2003-025



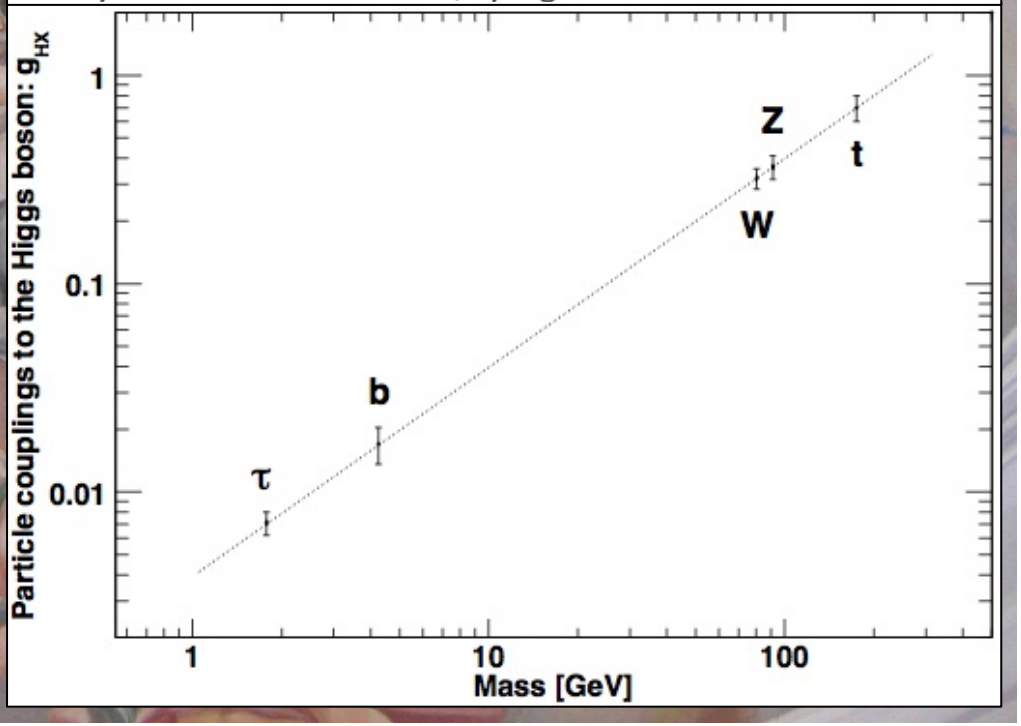
Θ→Z polariation
φ→plane angle



CP Properties of HWW coupling can be studied from VBF processes

cf talk by M.Bluj

3-July-2006 G.Unal, Physics@LHC 29

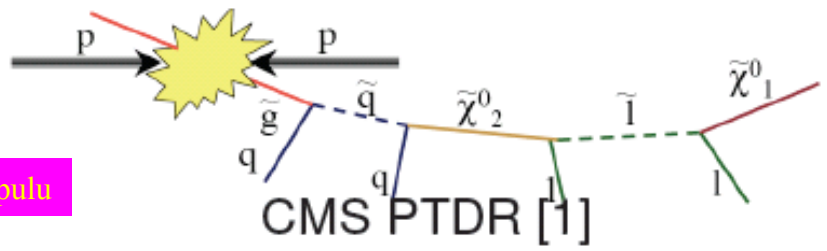


Summary of LHC Scapabilities … and Other Accelerators

LHC almost `guaranteed' to discover supersymmetry if it is relevant to the mass problem and measure many sparticles

Battaglia, De Roeck, Gianotti, JE, Olive, Pape

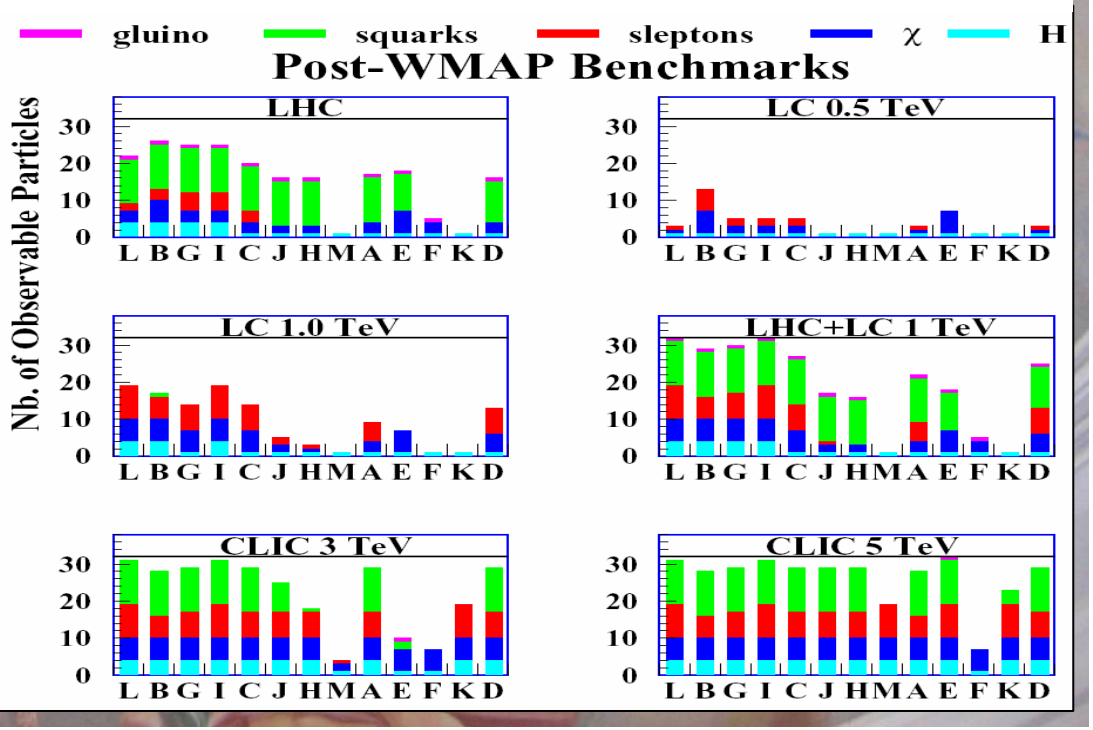
First Mass Clues (adding the jets)



Spiropulu

CMS PTDR [1]

	LM2 test point	
	measured	theory
$M(\tilde{\chi}^0_1)$ (GeV)	$147 \pm 23(\text{stat}) \pm 19(\text{sys})$	138.2
$M(\tilde{\chi}^0_2)$ (GeV)	$265 \pm 10(\text{stat}) \pm 25(\text{sys})$	265.5
$M(\tilde{\tau})$ (GeV)	$165 \pm 10(\text{stat}) \pm 20(\text{sys})$	153.9
$M(\tilde{q})$ (GeV)	$763 \pm 33(\text{stat}) \pm 58(\text{sys})$	753-783 (light $\tilde{q}$)



Possible Nature of SUSY Dark Matter

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ
  - Gravitino
    - (nightmare for astrophysical detection)

GDM: a bonanza for the LHC!

Possible Nature of NLSP if GDM

- NLSP = next-to-lightest sparticle
- Very long lifetime due to gravitational decay, e.g.:

$$\Gamma_{\tilde{\tau}\to\tilde{G}\tau} = \frac{1}{48\pi}\,\frac{1}{M_P^2}\,\frac{m_{\tilde{\tau}}^5}{m_{3/2}^2}\left(1-\frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$

- **Could be hours, days, weeks, months or years!**
- Generic possibilities:
  - lightest neutralino χ
  - lightest slepton, probably lighter stau
- Constrained by astrophysics/cosmology

Minimal Supergravity Model (mSUGRA)

More constrained than CMSSM: $m_{3/2} = m_0$, $B_\lambda = A_\lambda - 1$

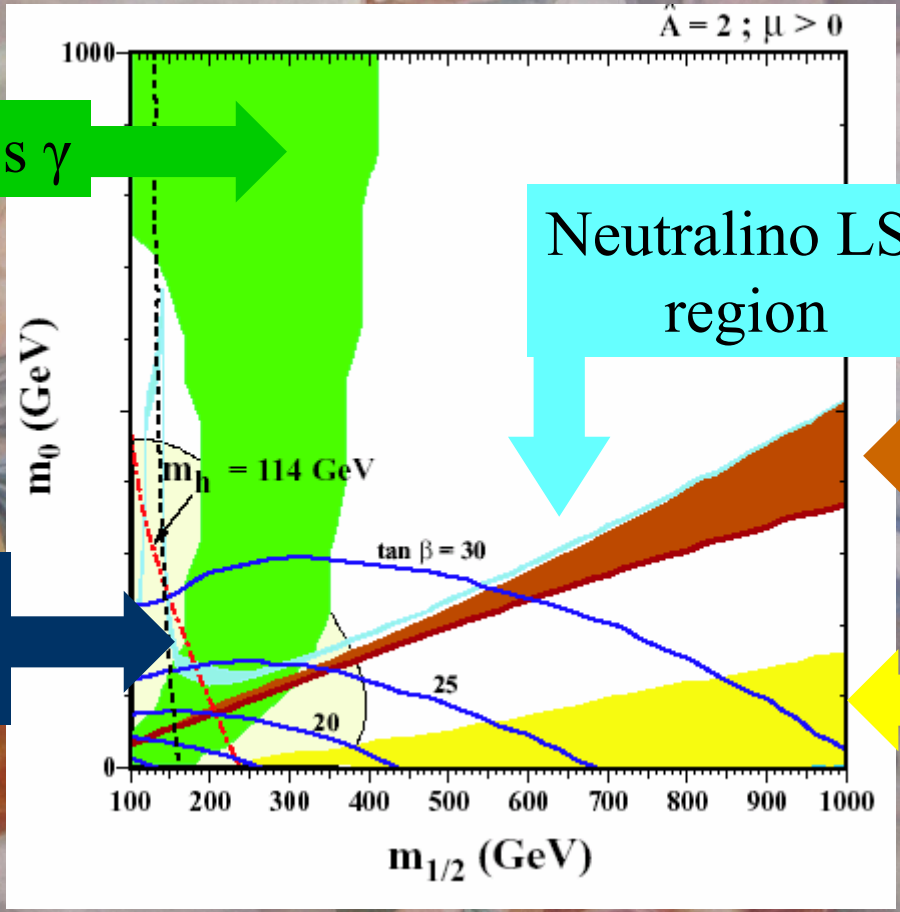
Excluded by b → s γ

Neutralino LSP region

stau LSP (excluded)

LEP constraints On m_h, chargino

Gravitino LSP region

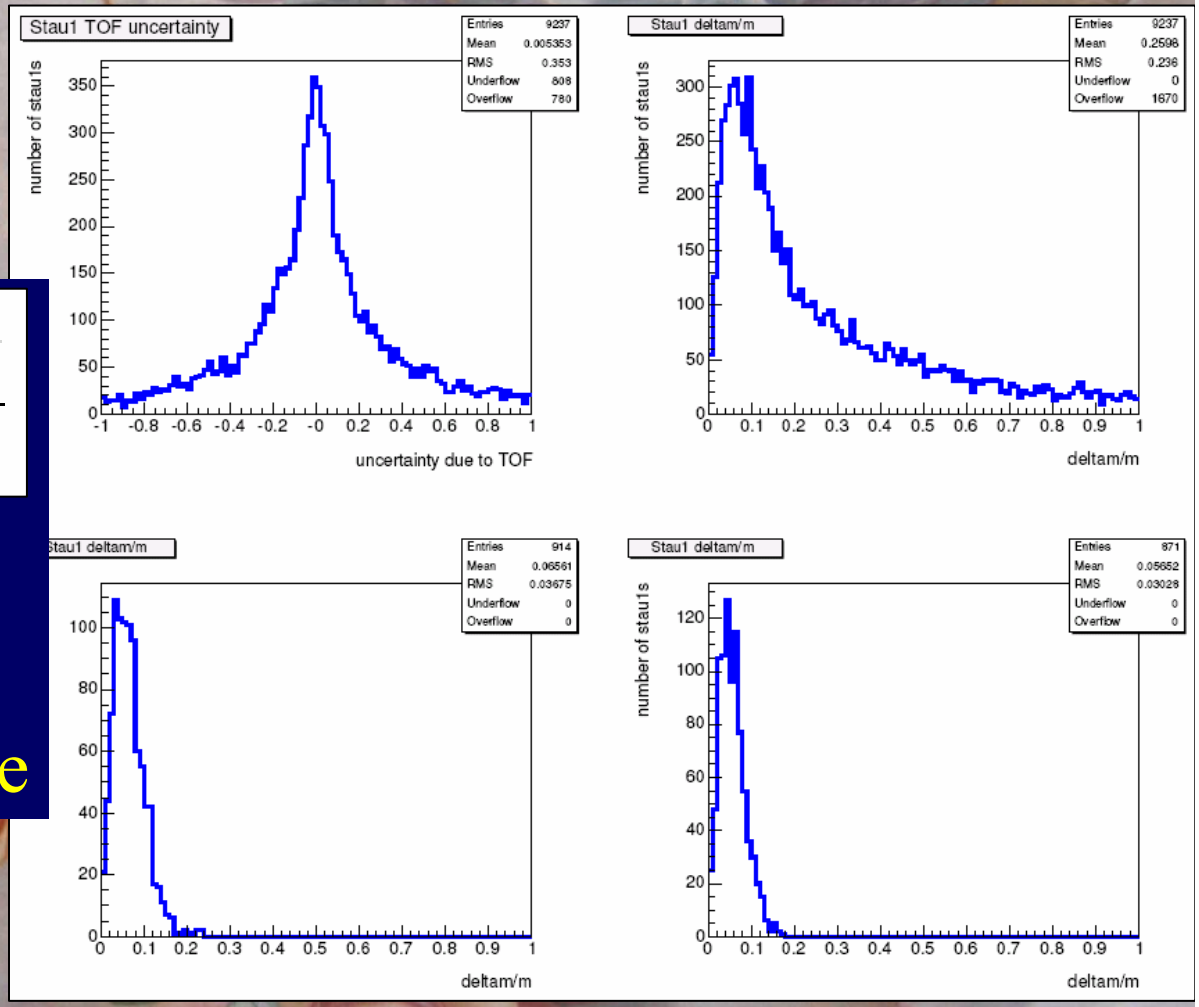


JE + Olive + Santoso + Spanos

Stau Mass Measurements by Time-of-Flight

$$\frac{\Delta M}{M} = \frac{\Delta p}{p} \bigoplus \beta\gamma^2 \frac{c\Delta t}{L}$$

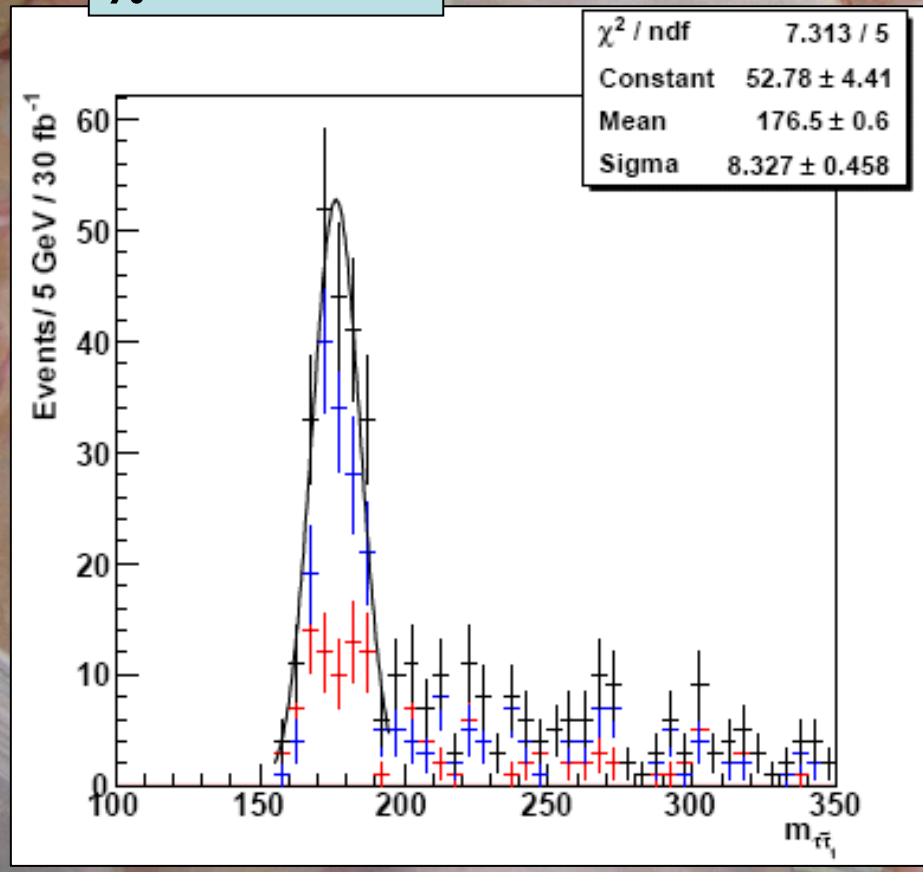
- Event-by-event accuracy < 10%
- < 1% with full sample



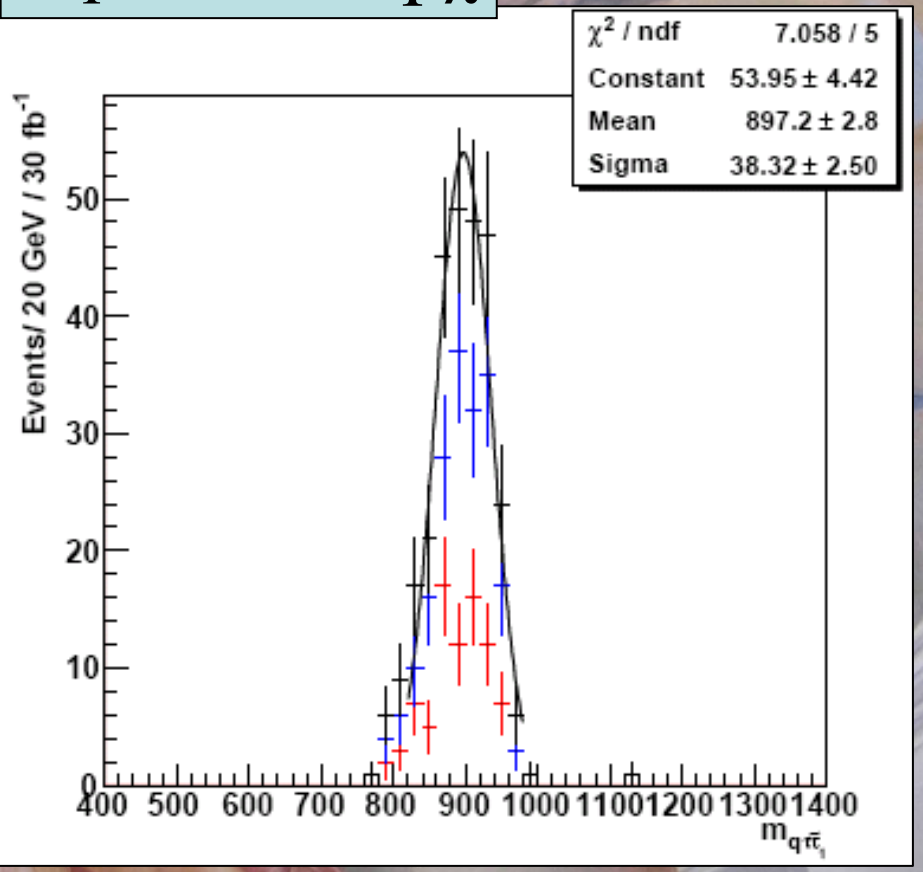
De Roeck, JE, Gianotti, Moortgat, Olive + Pape: hep-ph/0508198

Reconstructing GDM Events

$\chi \rightarrow$ stau τ



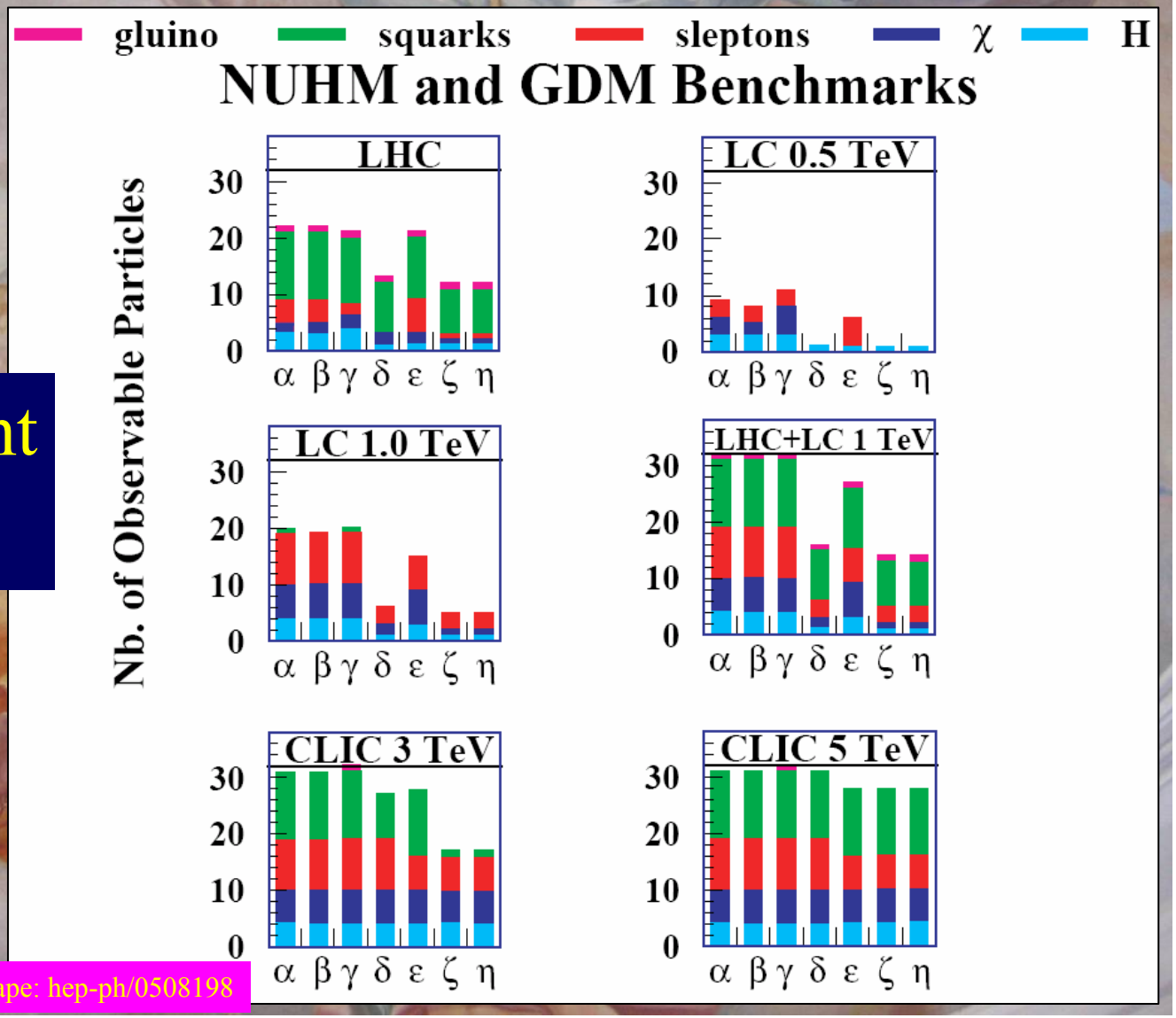
Squark $\rightarrow$ q χ



JE, Raklev, Øye: 2006

Numbers of Visible Sparticle Species

At different colliders

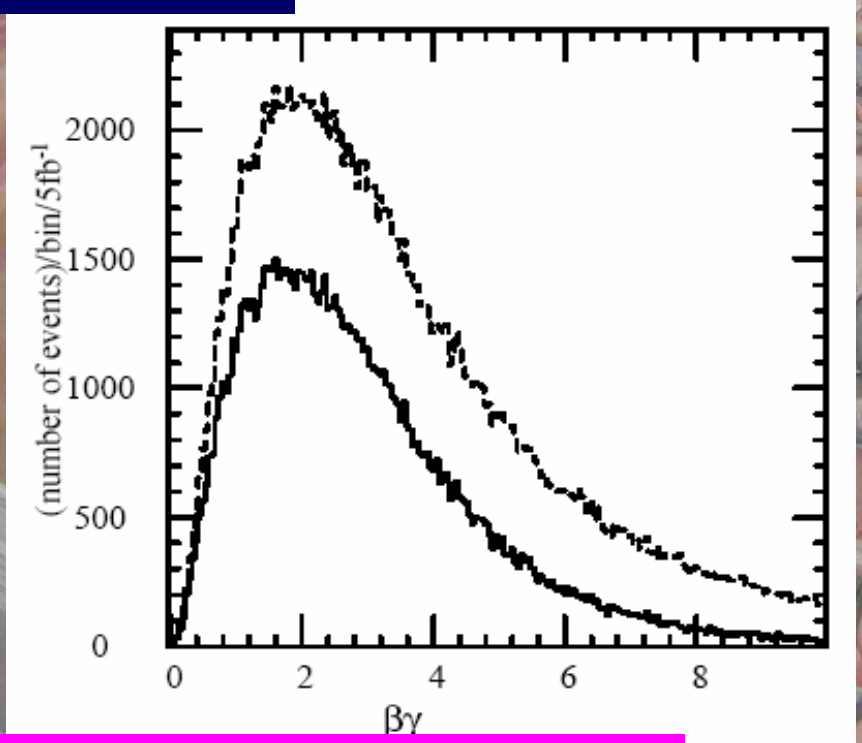


De Roeck, JE, Gianotti, Moortgat, Olive + Pape: hep-ph/0508198

Slepton Trapping at the LHC?

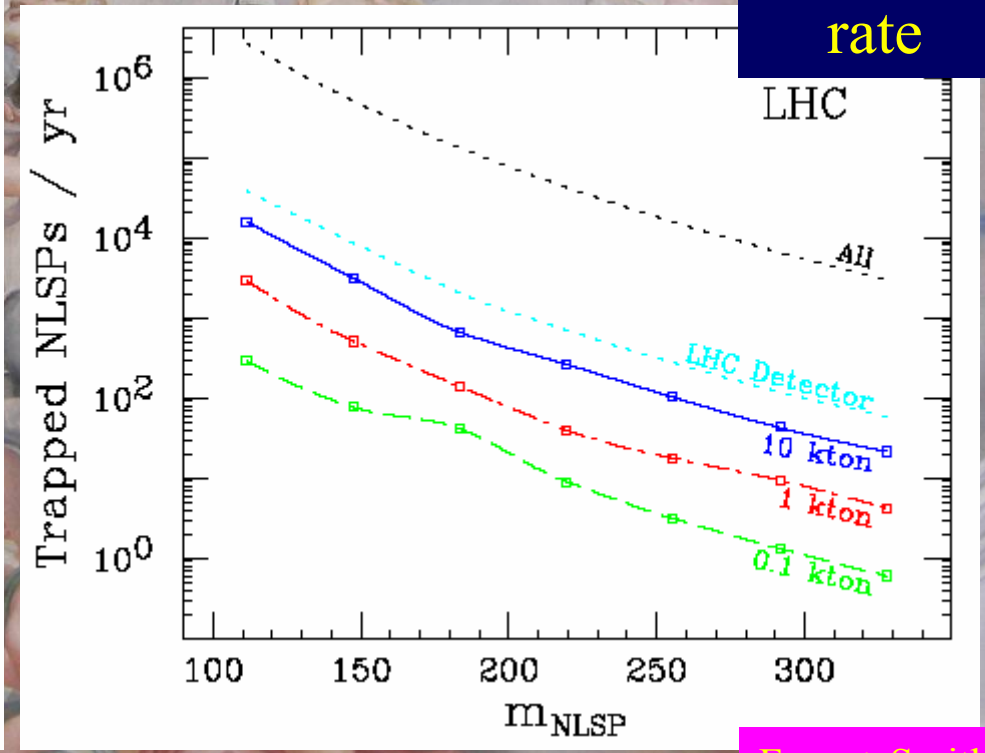
If stau next-to-lightest sparticle (NLSP)
may be metastable
may be stopped in detector/water tank?

Kinematics



Hamaguchi + Kuno + Nakaya + Nojiri

Trapping rate



Feng + Smith

Very little room for water tank in LHC caverns, only in forward directions where few staus

Extract Cores from Surrounding Rock?

- Use muon system to locate impact point on cavern wall with uncertainty < 1cm
- Fix impact angle with accuracy 10^{-3}
- Bore into cavern wall and remove core of size 1cm × 1cm × 10m = 10^{-3}m^3 ~ 100 times/year
- Can this be done before staus decay?

  Caveat radioactivity induced by collisions!

  2-day technical stop ~ 1/month
- Not possible if lifetime ~10^4s, possible if ~10^6s?

De Roeck, JE, Gianotti, Moortgat, Olive + Pape: hep-ph/0508198

Extra Time: LHC Luminosity Upgrade?

- **SLHC**: examples of physics @ 10^{35} $cm^{-2}s^{-1}$:
  - more sensitive studies of a light Higgs boson and better searches for a heavy Higgs boson,
  - triple-Higgs coupling
  - better electroweak measurements – e.g., of TGVs
  - searches for heavier new physics – e.g., supersymmetric particles and new gauge bosons
- Increasing LHC luminosity to 10^{35} $cm^{-2}s^{-1}$ would require major modifications to the ATLAS and CMS detectors
  - e.g., inner tracking systems
- Likely to cost 30 to 50% of the initial capital costs.

New Higgs Physics @ SLHC

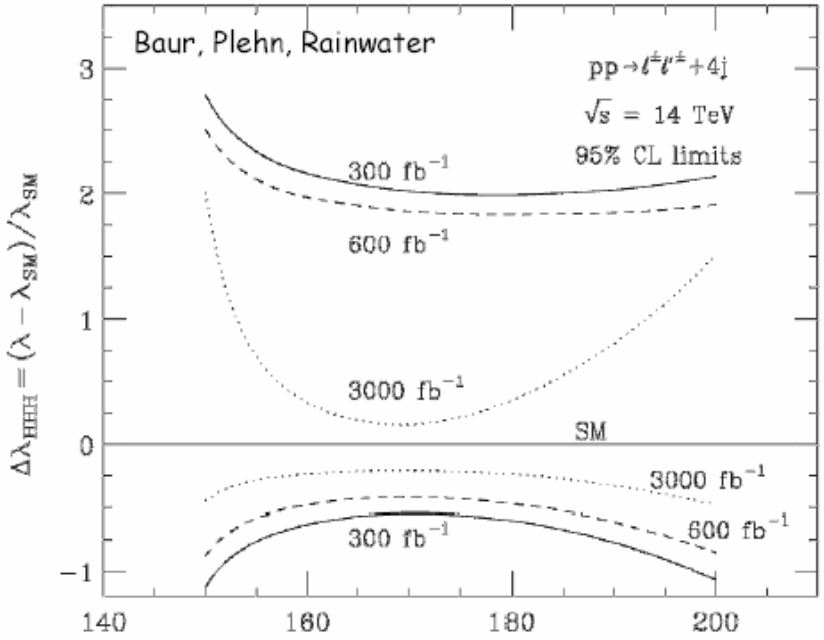
Rare Higgs decays at SLHC

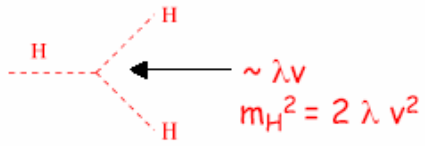
Channel	m_H	S/√B LHC (600 fb^{-1})	S/√B SLHC (6000 fb^{-1})
$H \to Z\gamma \to ll\,\gamma$	~ 140 GeV	~ 3.5	~ 11
$H \to \mu\mu$	130 GeV	~ 3.5 (gg+VBF)	~ 7 (gg)

BR ~ 10^{-4} both channels

→ additional coupling measurements : e.g. Γ_μ / Γ_W to ~ 20%

Higgs self-couplings at SLHC ?





$HH \to W^+ W^- W^+ W^- \to l^\pm\nu\ jj\ l^\pm\nu\ jj$

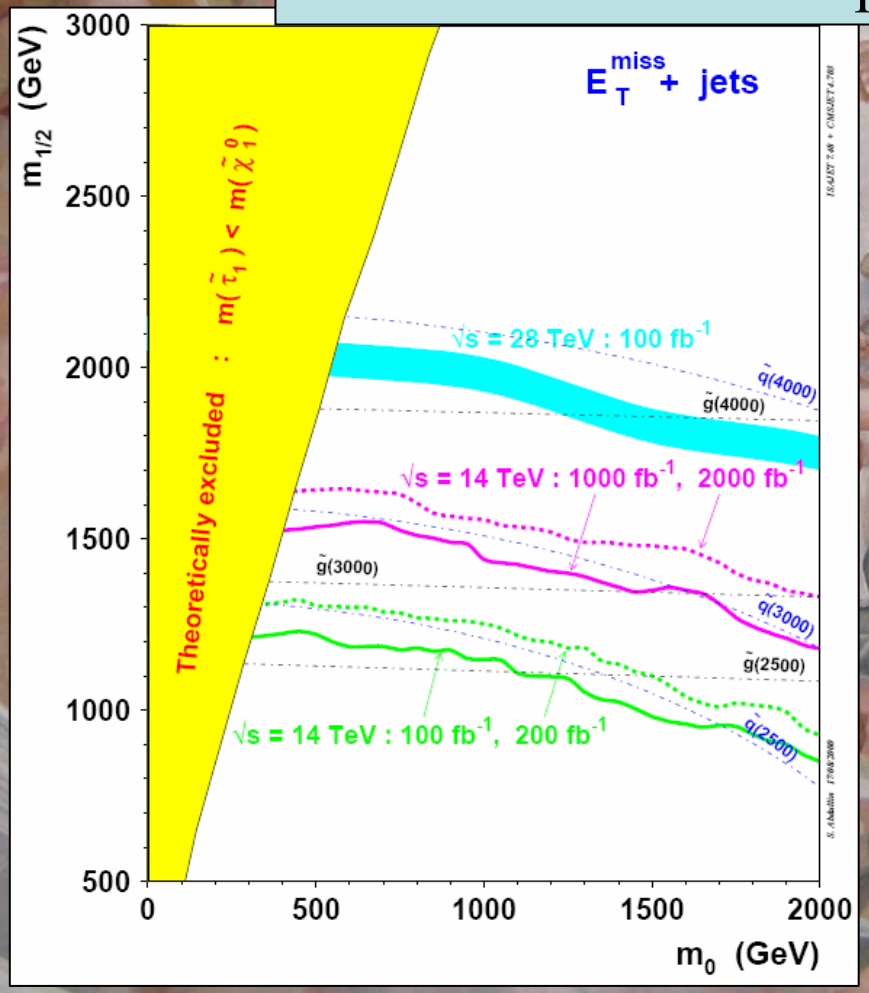
LHC: λ= 0 may be excluded at 95% CL.

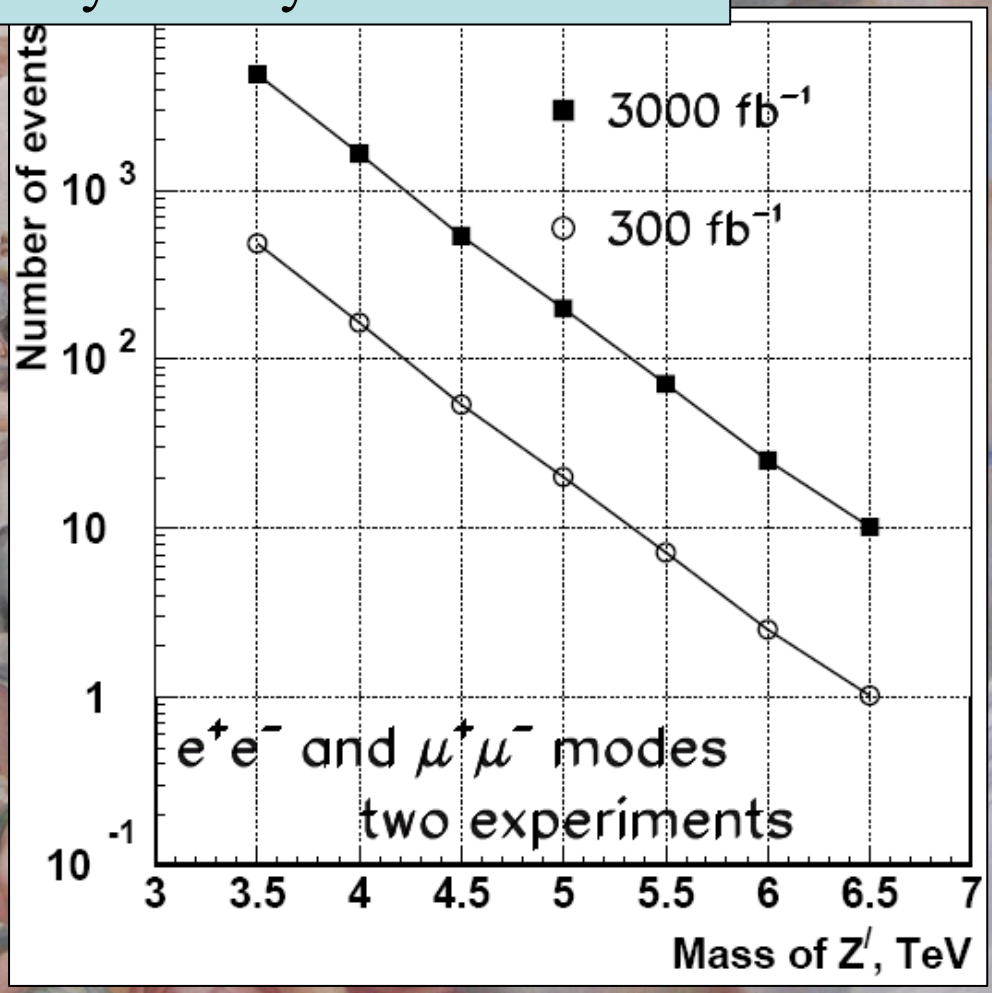
SLHC: λ may be determined to 20-30% (95% CL)

Comparable to √s = 0.5 TeV LC , not competitive with CLIC (precision up to 7%)

Examples of Searches for New Physics

Extended reach for supersymmetry and a Z' boson





Penalty Shoot-out

- What after the LHC?
  - SLHC?
  - ILC?
  - CLIC?
  - DLHC (double LHC energy)?
  - TLHC (triple LHC energy)?

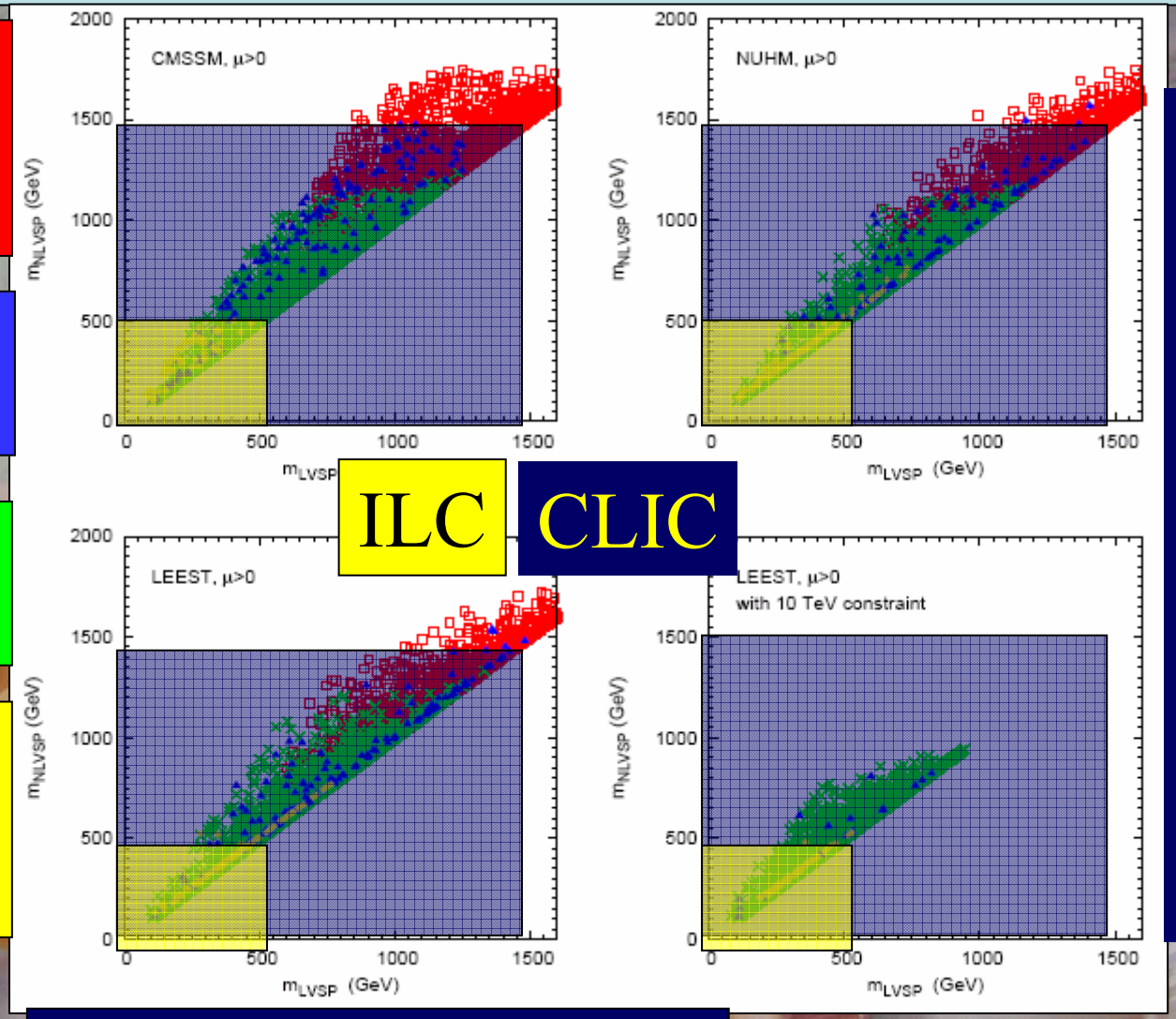
Sparticles may not be very light

Full Model samples

Provide Dark Matter

Detectable @ LHC

Dark Matter Detectable Directly



ILC

CLIC

← Second lightest visible sparticle

Lightest visible sparticle →

JE + Olive + Santoso + Spanos

Penalty Shoot-out

- What is next round after the LHC?
  - SLHC?
  - ILC?
  - CLIC?
  - DLHC (double LHC energy)?
  - TLHC (triple LHC energy)?
- Only the LHC can tell us
- **Answers available in '2010'**