# From HERA to the LHC

John Ellis,

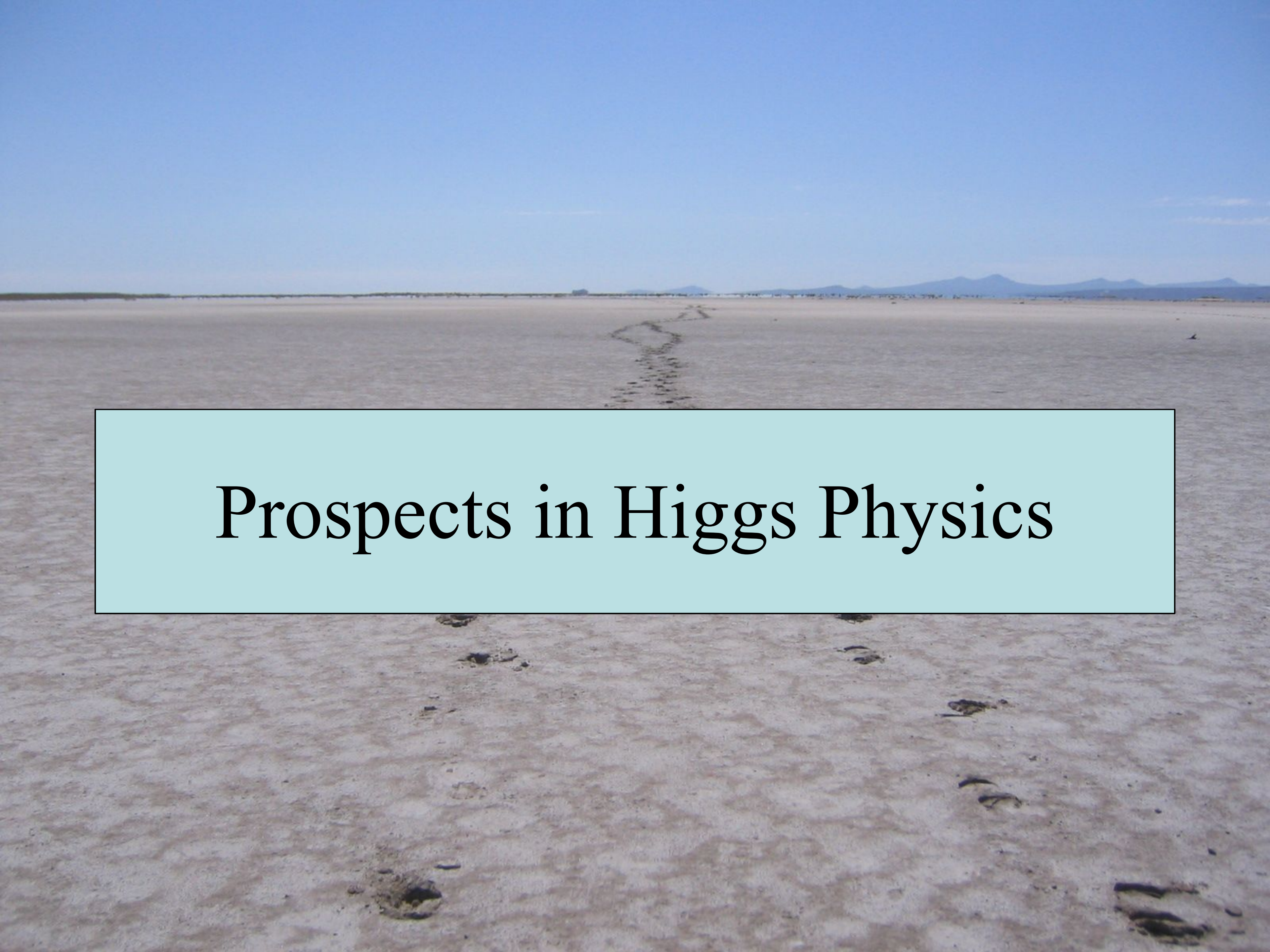
DESY,

March 23rd, 2005

# Preview

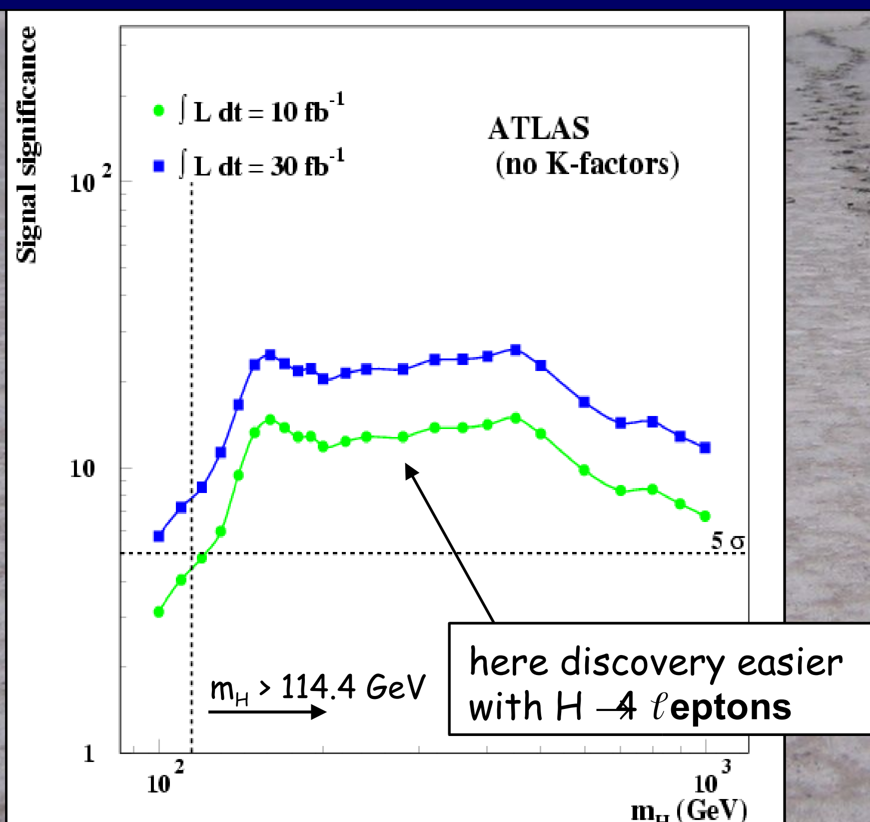
- LHC's 'core business': Higgs & Susy
- Importance of understanding QCD
- Parton saturation, RHIC and the CGC
- UHECRs & Forward physics @ LHC
- Diffractive Higgs production @ LHC

# Prospects in Higgs Physics

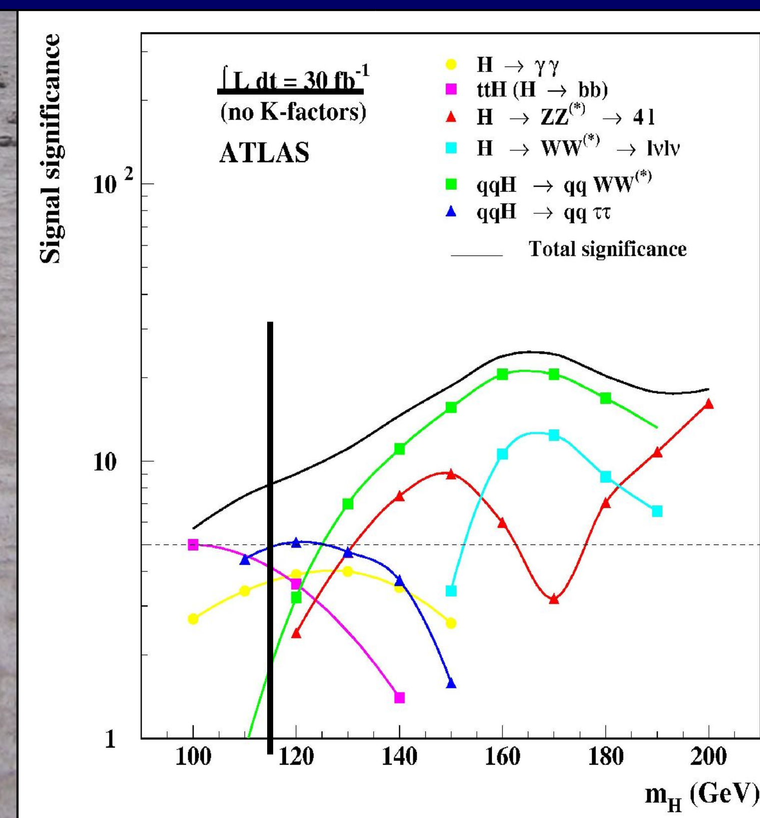


# Higgs Detection at the LHC

The Higgs may be found quite quickly …



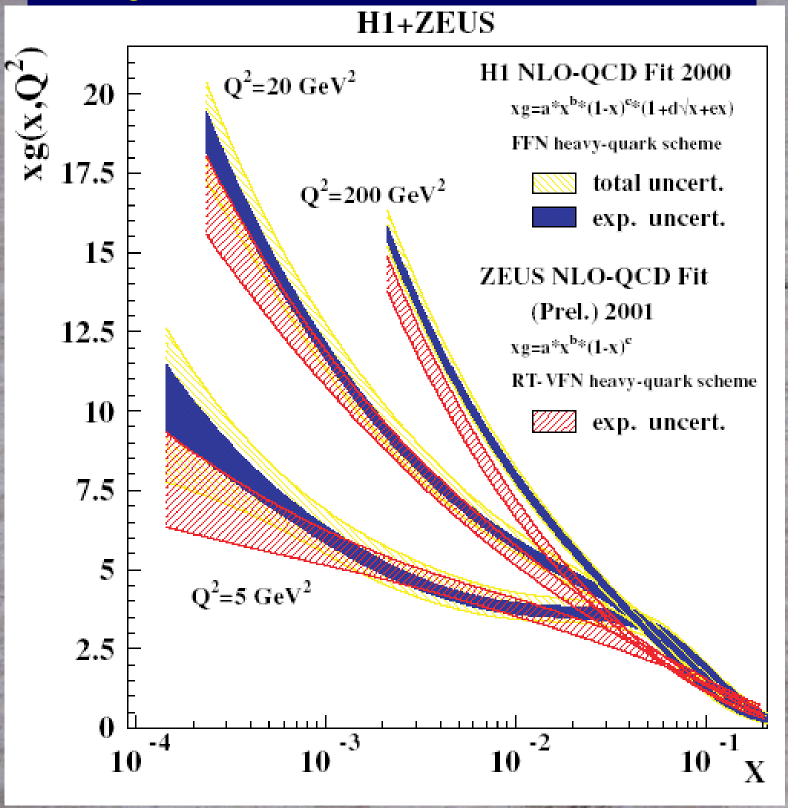

… in several different channels



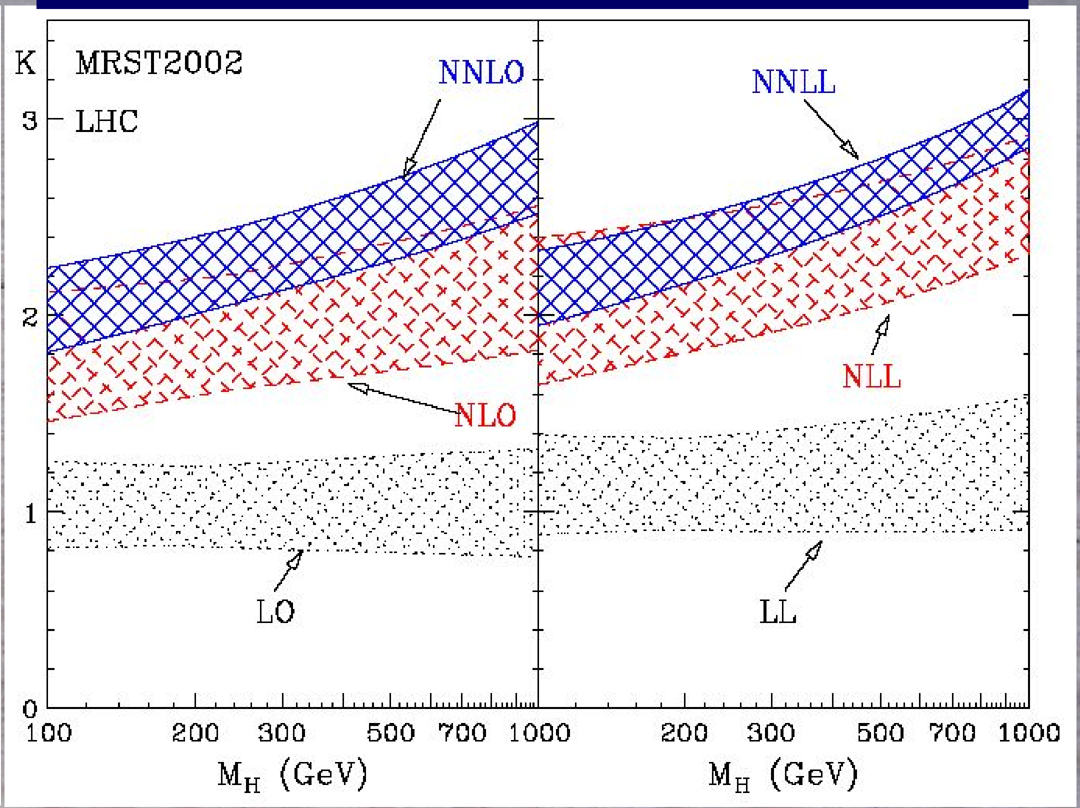
# How Accurately can the Higgs Cross Section be Calculated?

Glover

Need gluon distribution @ $x_g \sim 10^{-2}$, $Q^2 \sim 10^4$ GeV$^2$

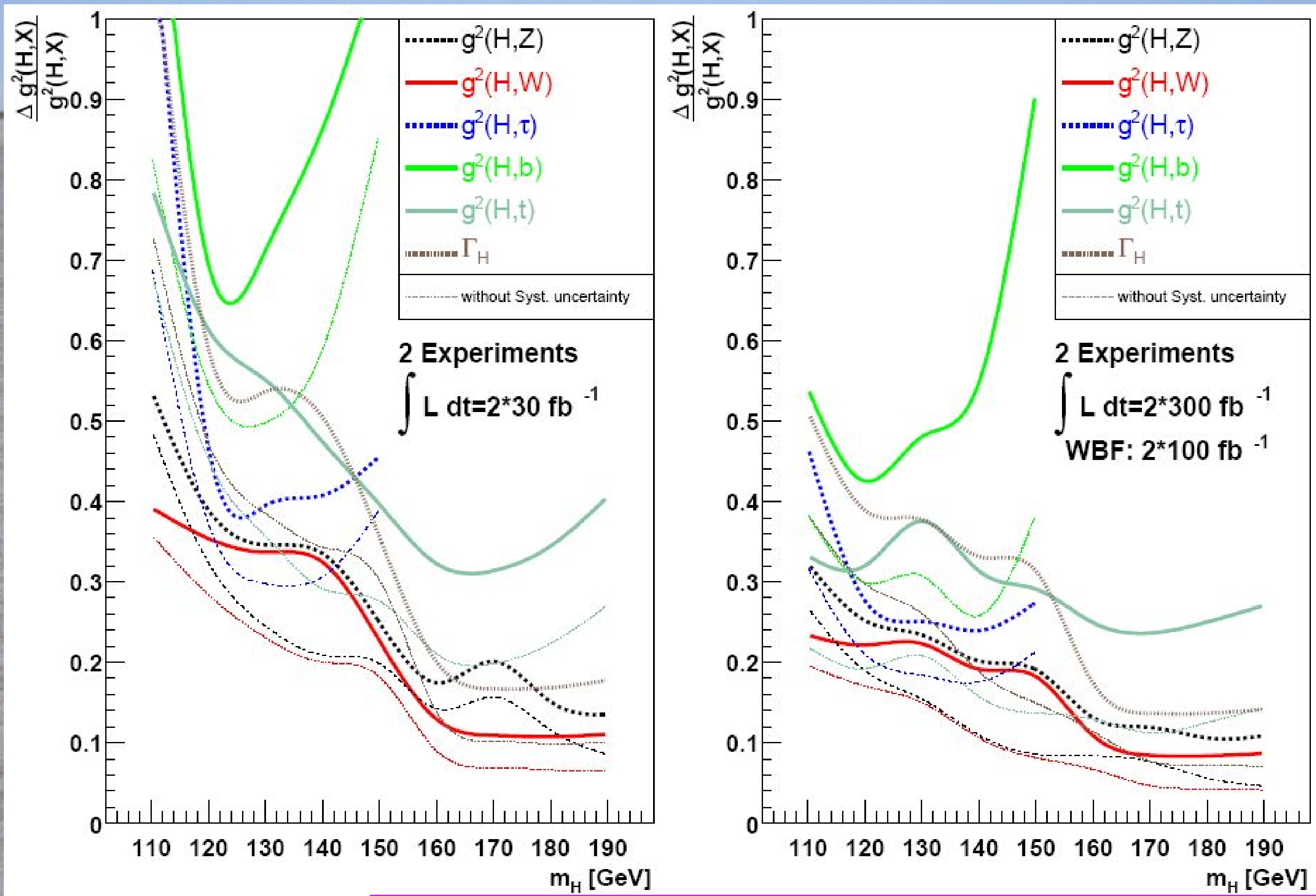



Resumming next-to-next-to-leading logarithms: 10% uncertainty




Catani + de Florian + Grazzini + Nason

# Accuracy in LHC Determinations of Higgs Couplings




Duhrssen + Heinemeyer + Logan + Rainwater + Weiglein + Zeppenfeld

# Theorists getting Cold Feet

- Composite Higgs model?
  conflicts with precision electroweak data
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra `Top', gauge bosons, `Higgses'
- Higgsless models?
  strong WW scattering, extra D?

# Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2 (\frac{\Lambda}{400GeV})^2$$

with new heavy T quark $m_T > 2\lambda_t f \sim 2f$ $f > 1$ TeV

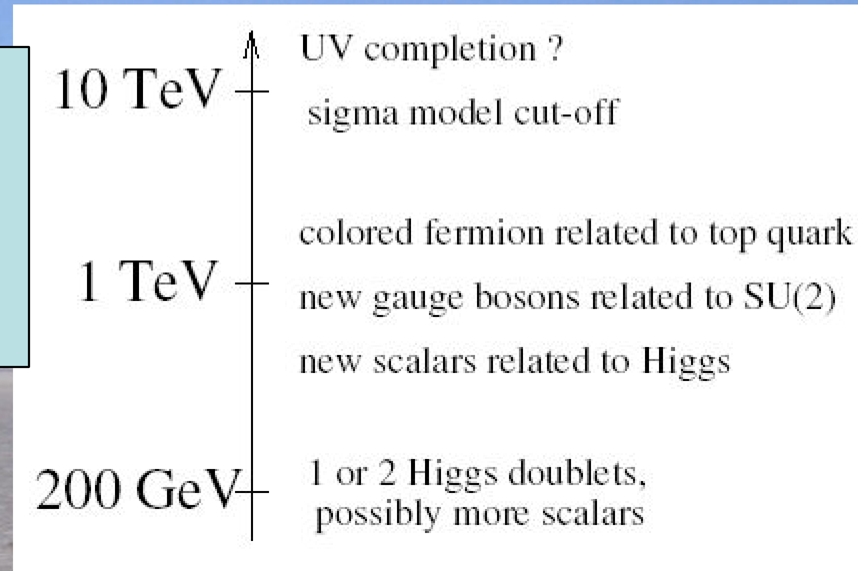
$$\delta m^2_{H,top}(LH) \sim \frac{6 G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log \frac{\Lambda}{m_T} \gtrsim 1.2 f^2$$

- New gauge bosons, Higgses
- Higgs light, other new physics heavy

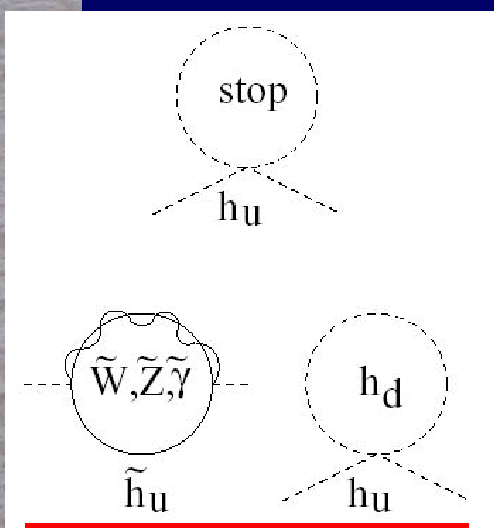
$M_T < 2$ TeV $(m_h$ / 200 GeV$)^2$
$M_{W'} < 6$ TeV $(m_h$ / 200 GeV$)^2$
$M_{H++} < 10$ TeV

Not as complete as susy: more physics > 10 TeV

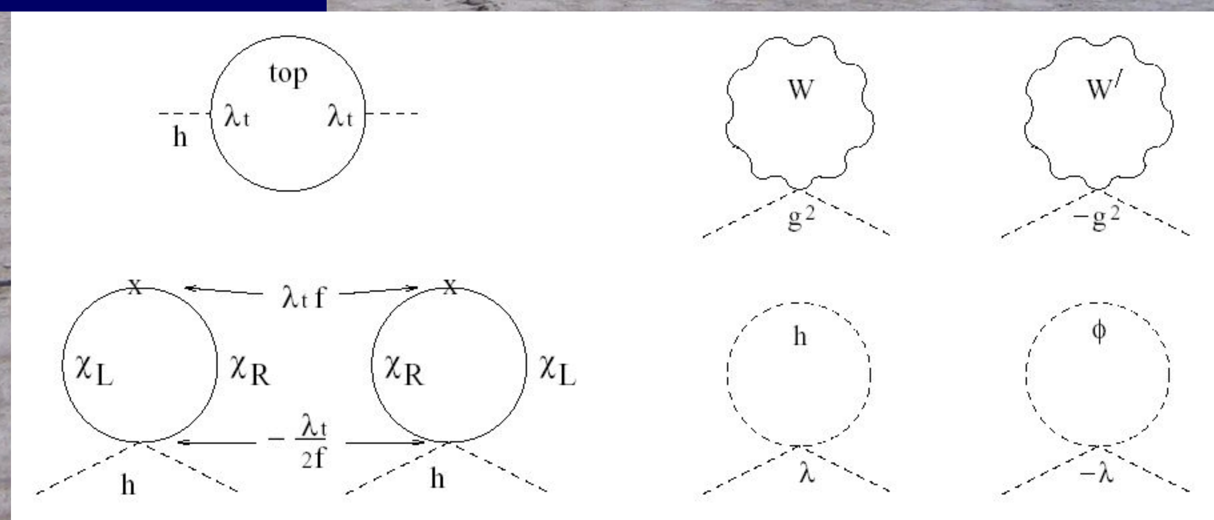
# Generic Little Higgs Spectrum




## Loop cancellation mechanisms

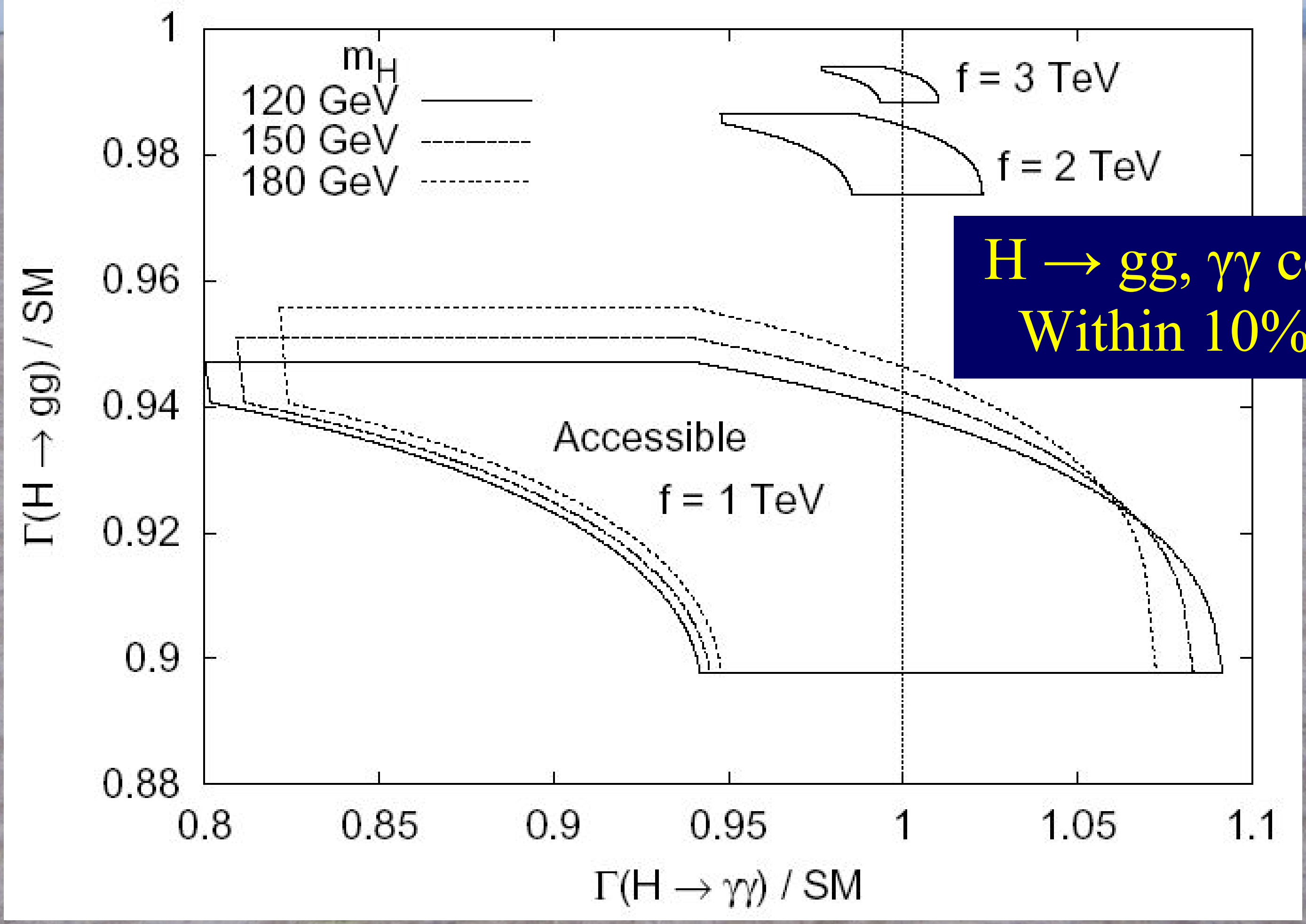



Supersymmetry




Little Higgs

# Measuring Little Higgs Couplings




$H \to gg, \gamma\gamma$ couplings
Within 10% of SM

# Supersymmetry

# Why Supersymmetry (Susy)?

- Hierarchy problem: why is $m_W << m_P$ ?

  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is

  $G_F = 1/ m_W^2 >> G_N = 1/m_P^2$ ?
- Or, why is

  $V_{Coulomb} >> V_{Newton}$ ? $e^2 >> G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?

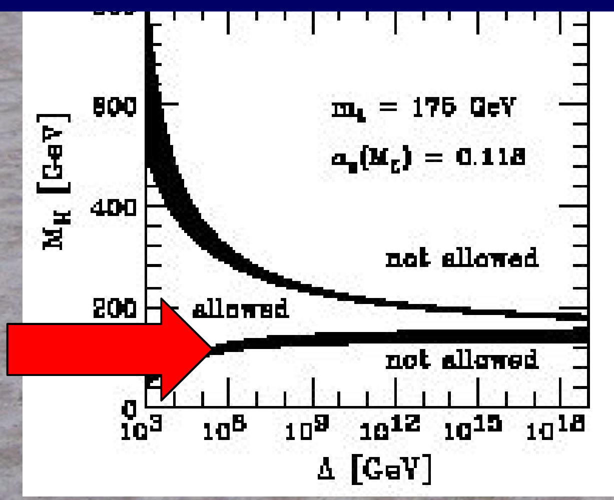
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops     fermions
- Need     $| m_B^2 - m_F^2| < 1$ TeV$^2$

# Other Reasons to like Susy

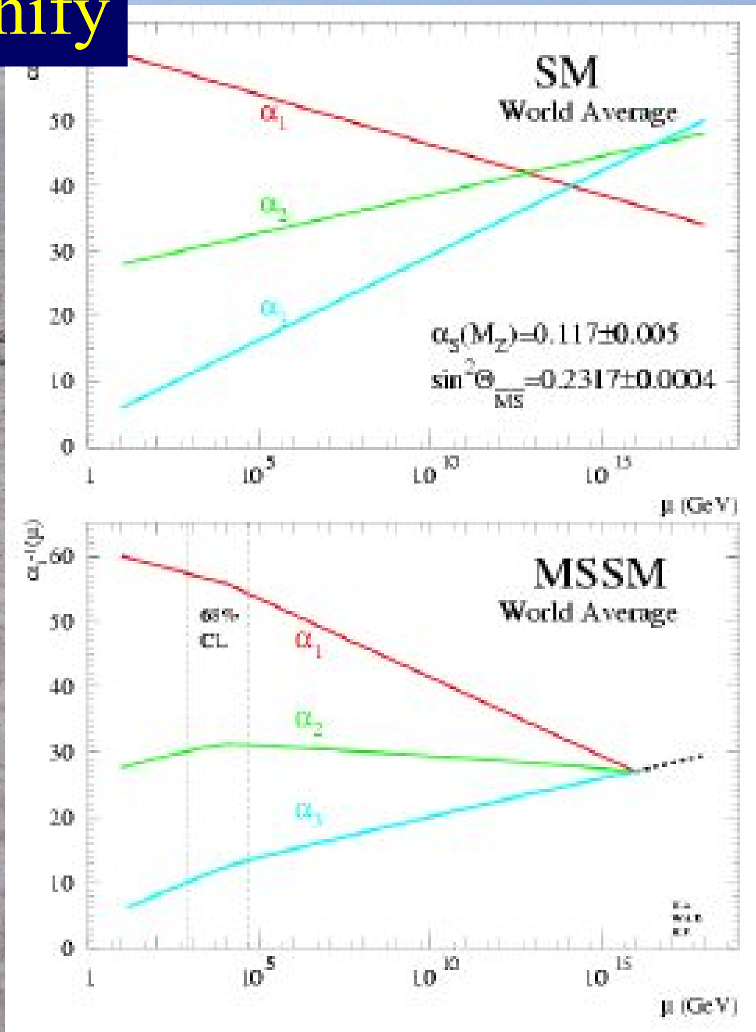
It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV

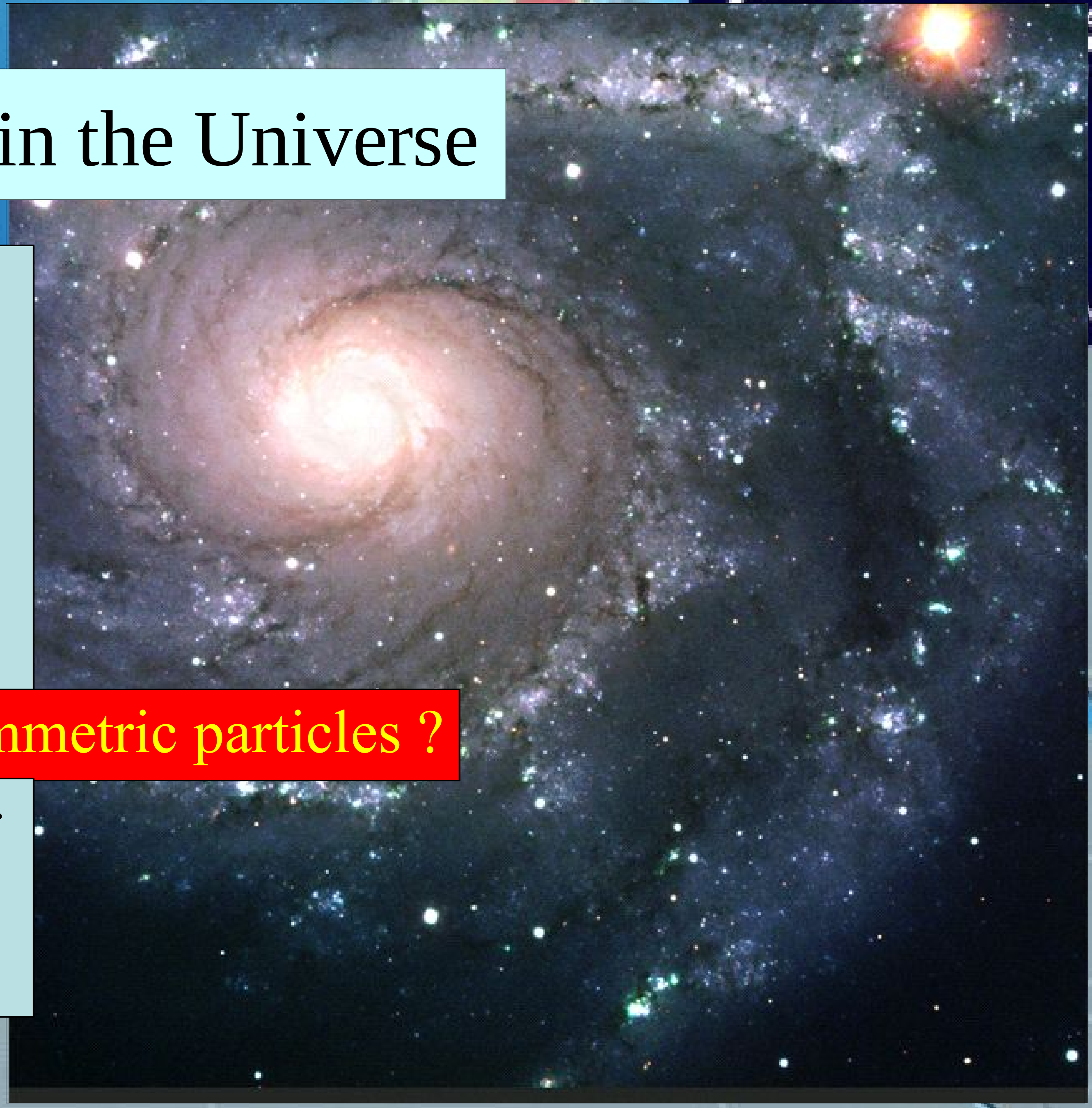
It stabilizes the Higgs potential for low masses




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

# Constraints on Supersymmetry

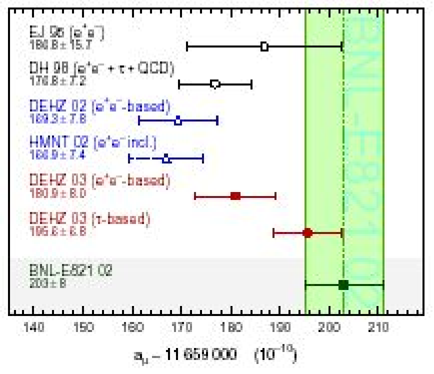
- Absence of sparticles at LEP, Tevatron

    selectron, chargino > 100 GeV

    squarks, gluino > 250 GeV

- Indirect constraints

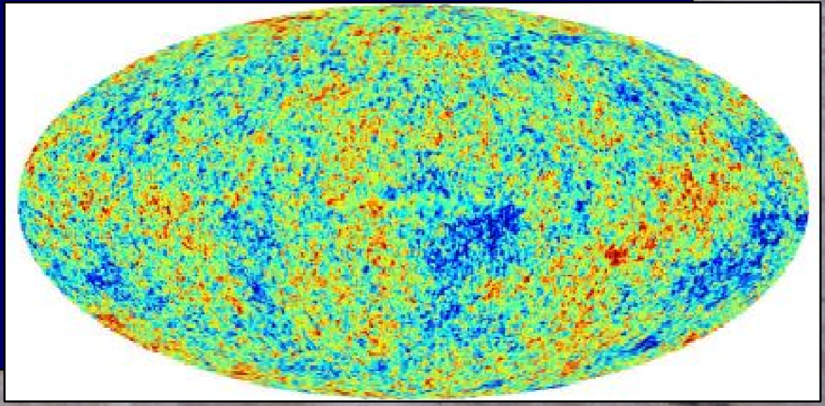
    Higgs > 114 GeV, b -> s $\gamma$  $g_\mu$ - 2




- Density of dark matter

    lightest sparticle $\chi$:

WMAP: $0.094 < \Omega_\chi h^2 < 0.124$



# Current Constraints on CMSSM

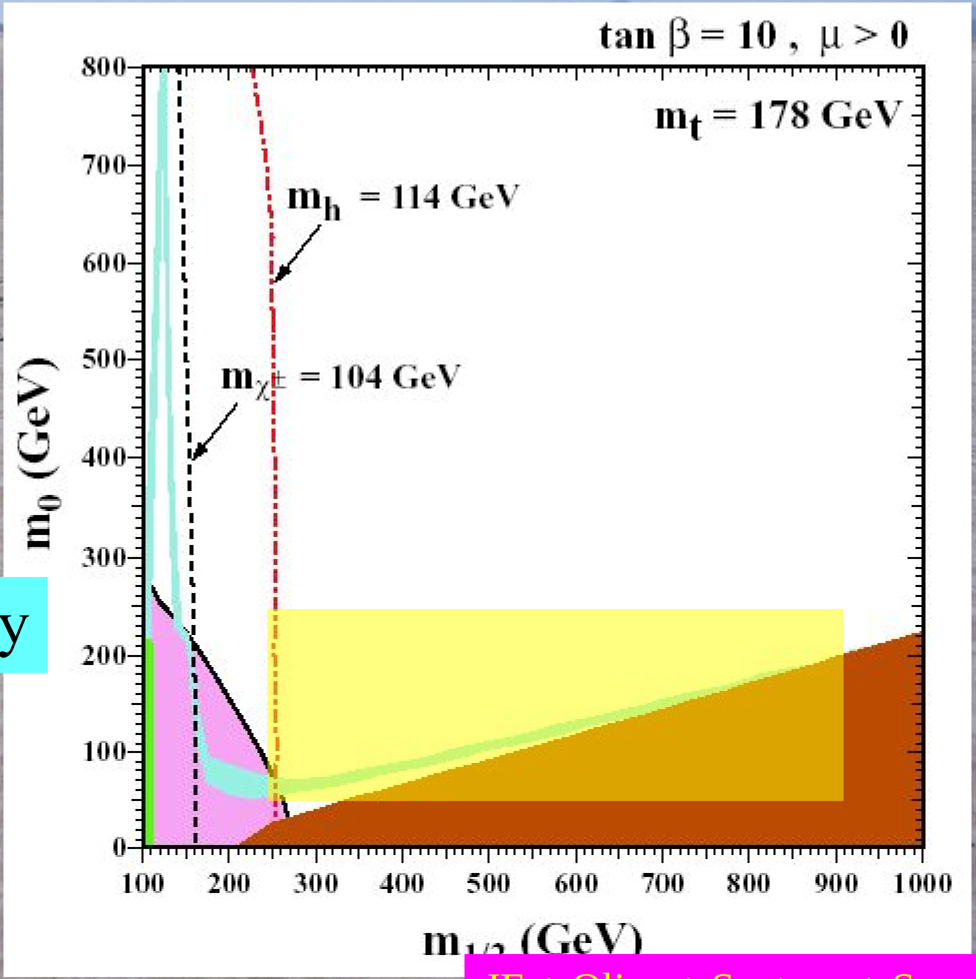
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b s gamma

WMAP constraint on relic density

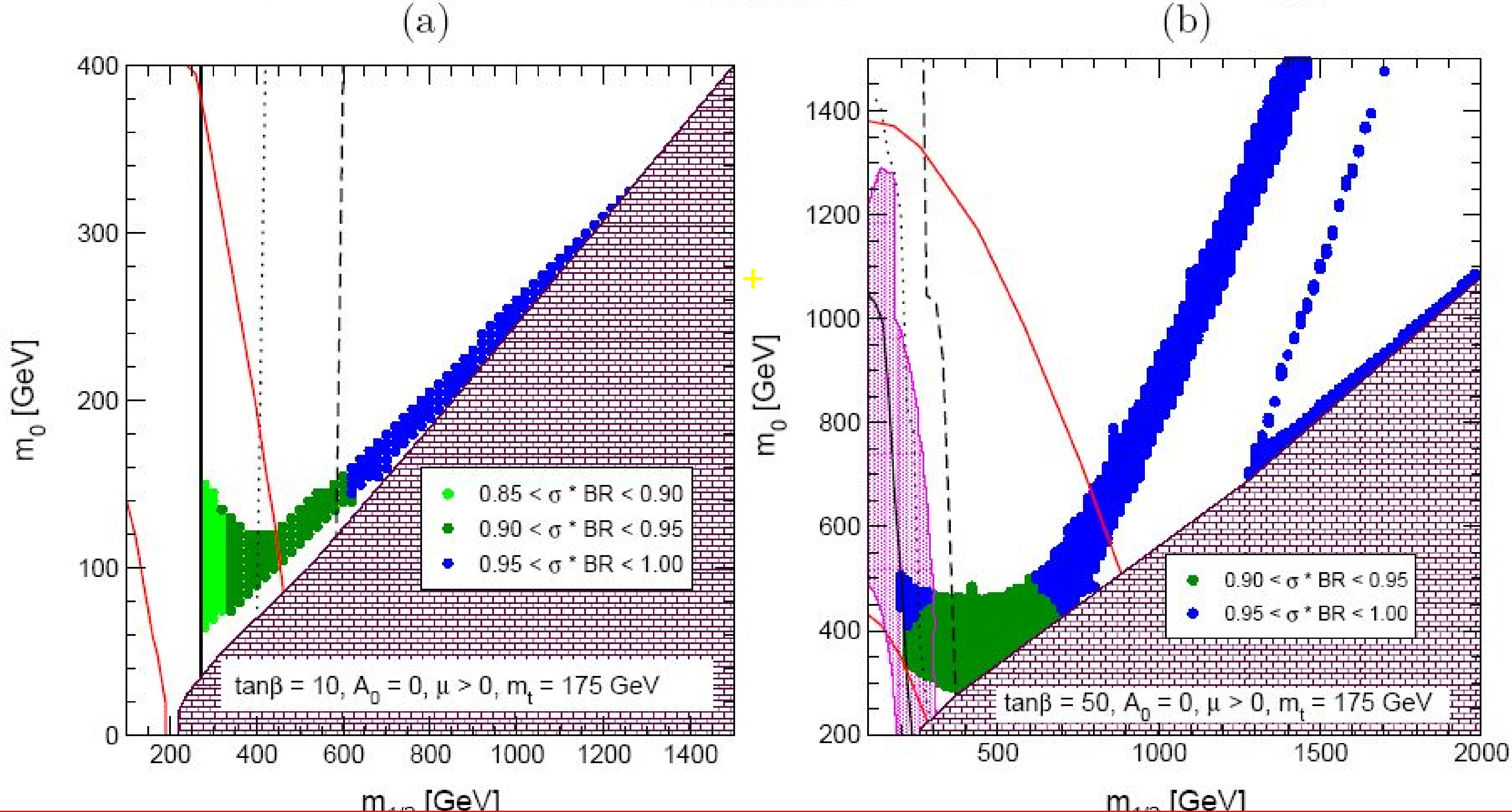
Excluded (?) by latest g - 2




JE + Olive + Santoso + Spanos

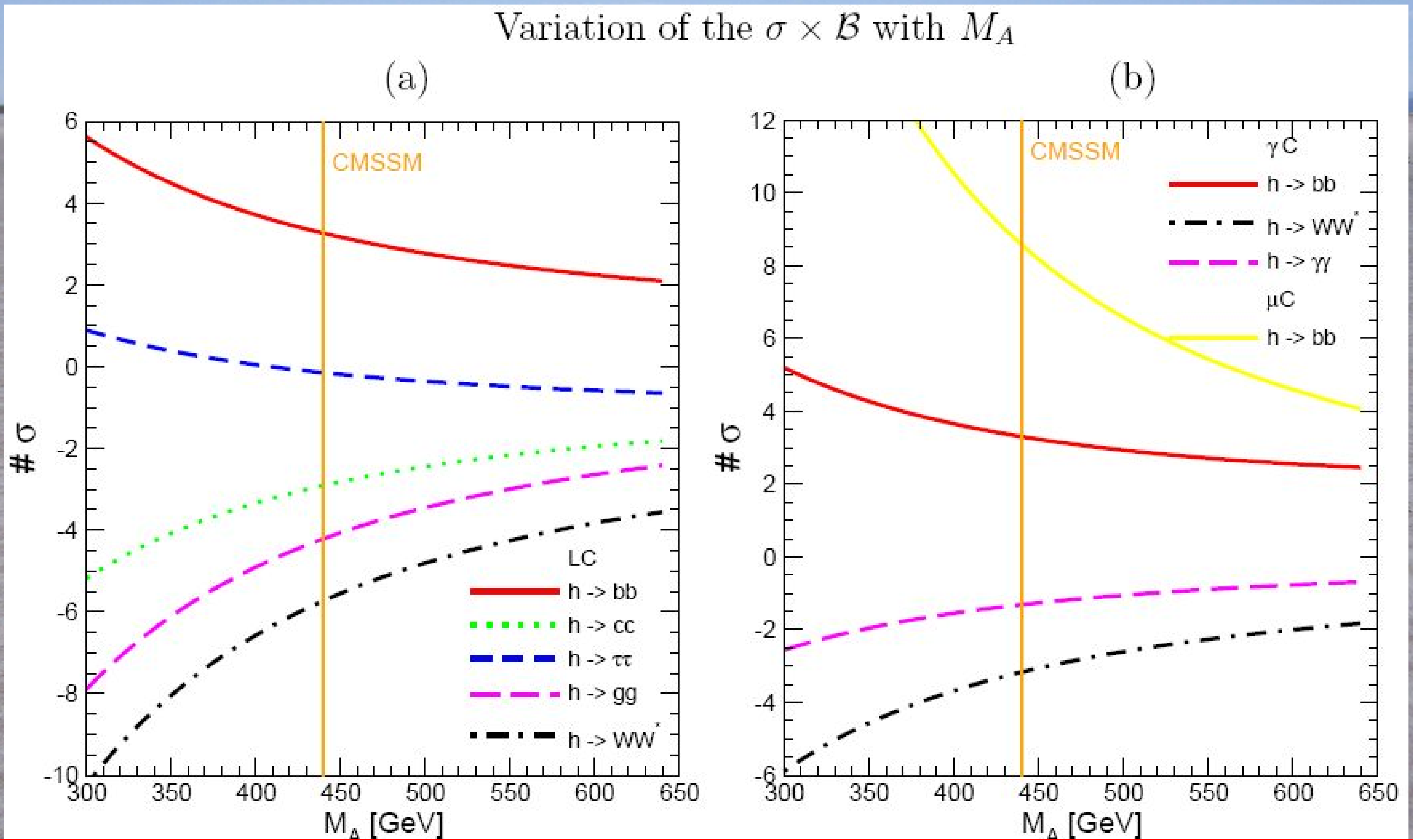
# Higgs Production: CMSSM vs SM

$$\left[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\right]_{\text{CMSSM}} / \left[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\right]_{\text{SM}}$$




**Good news: no suppression – Bad news: cannot distinguish CMSSM**

# CMSSM vs SM @ LC, γγ Collider




**Good news: can hope to distinguish CMSSM from Standard Model**

# Possible CP-Violating Asymmetries

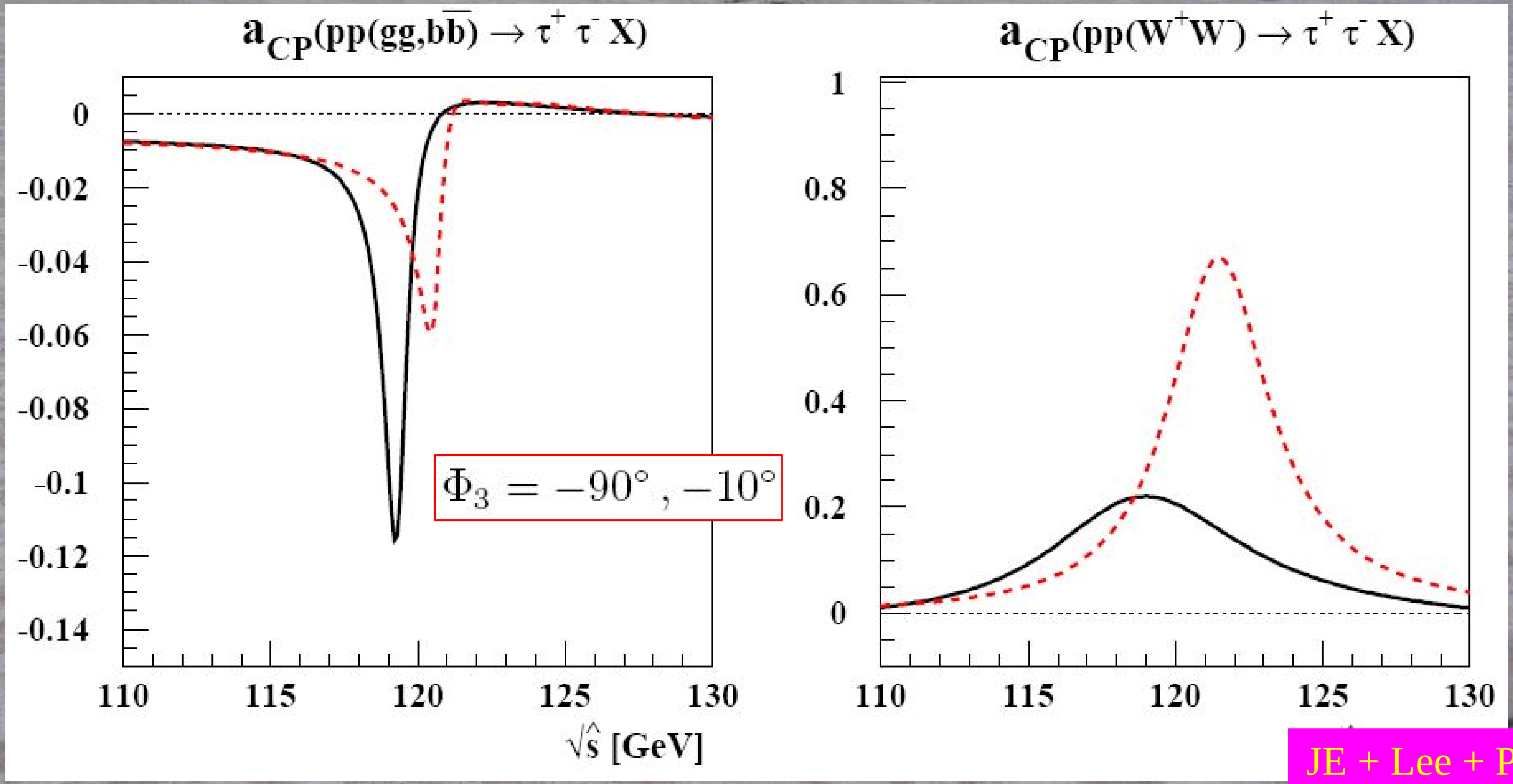
in CP-violating scenario with three-way mixing:

$\tan\beta = 50,\quad M_{H^\pm}^{\rm pole} = 155\ \ {\rm GeV},$

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY} = 0.5\ \ {\rm TeV},$

$|\mu| = 0.5\ \ {\rm TeV},\quad |A_{t,b,\tau}| = 1\ \ {\rm TeV},\quad |M_2| = |M_1| = 0.3\ \ {\rm TeV},\quad |M_3| = 1\ \ {\rm TeV},$

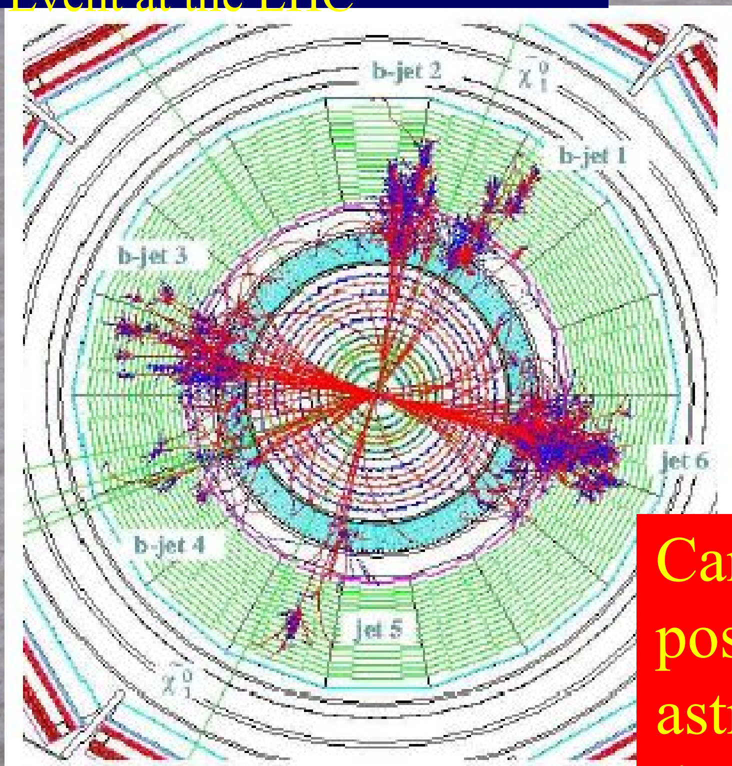
$\Phi_\mu = 0^\circ,\quad \Phi_A = \Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau} = 90^\circ,\quad \Phi_1 = \Phi_2 = 0^\circ,$



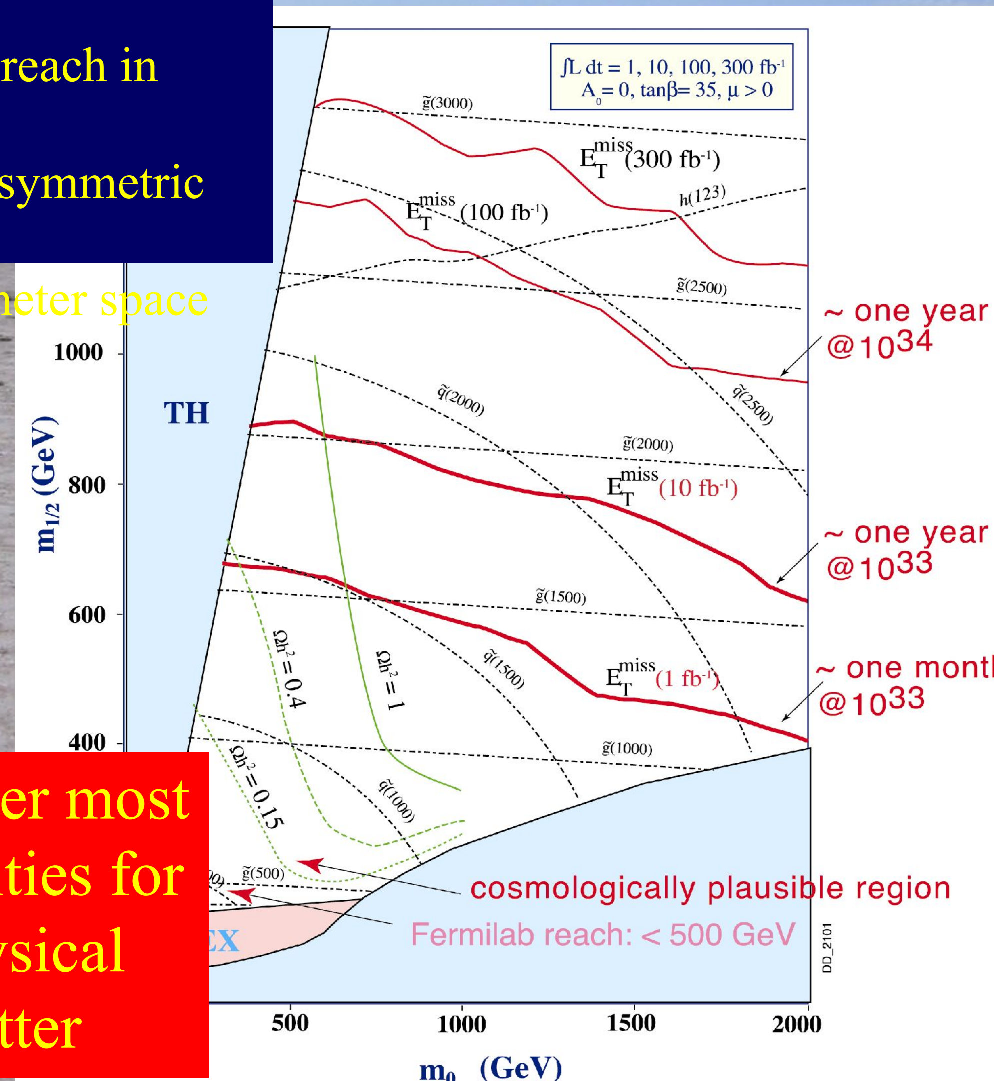

JE + Lee + Pilaftsis

# Supersymmetry Searches at LHC

`Typical' supersymmetric Event at the LHC



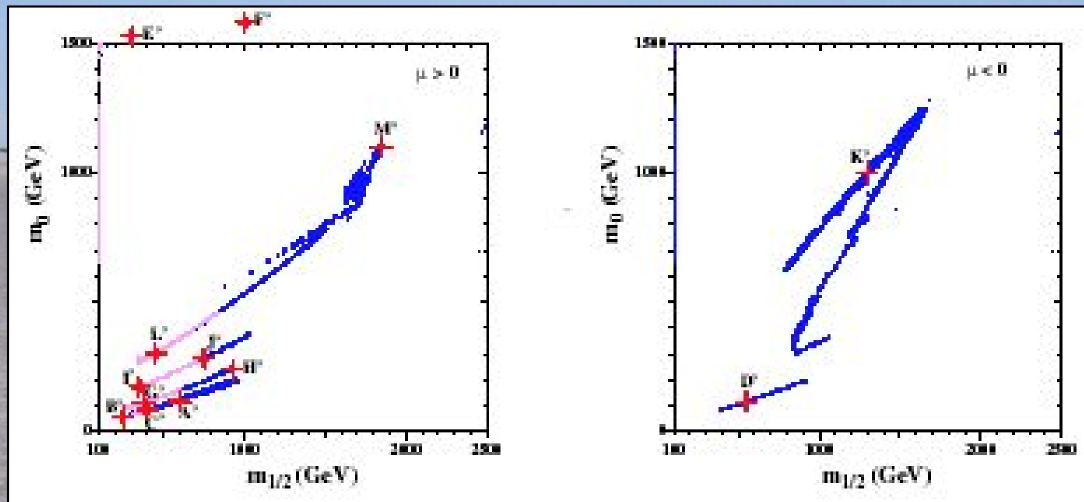

LHC reach in supersymmetric parameter space




Can cover most possibilities for astrophysical dark matter

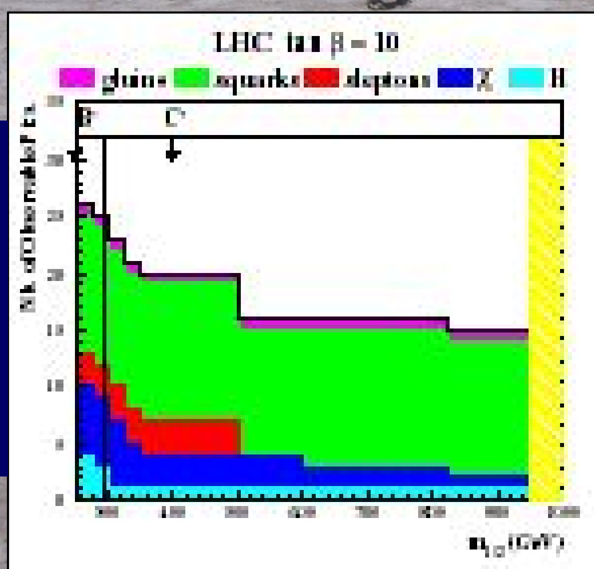
# Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

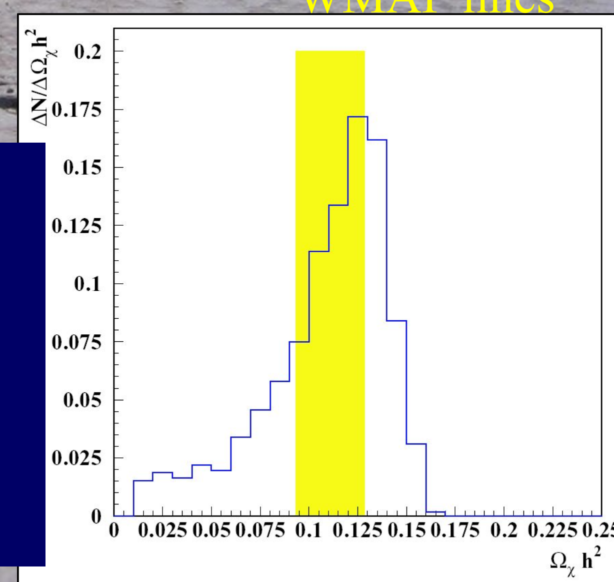



Specific benchmark Points along WMAP lines

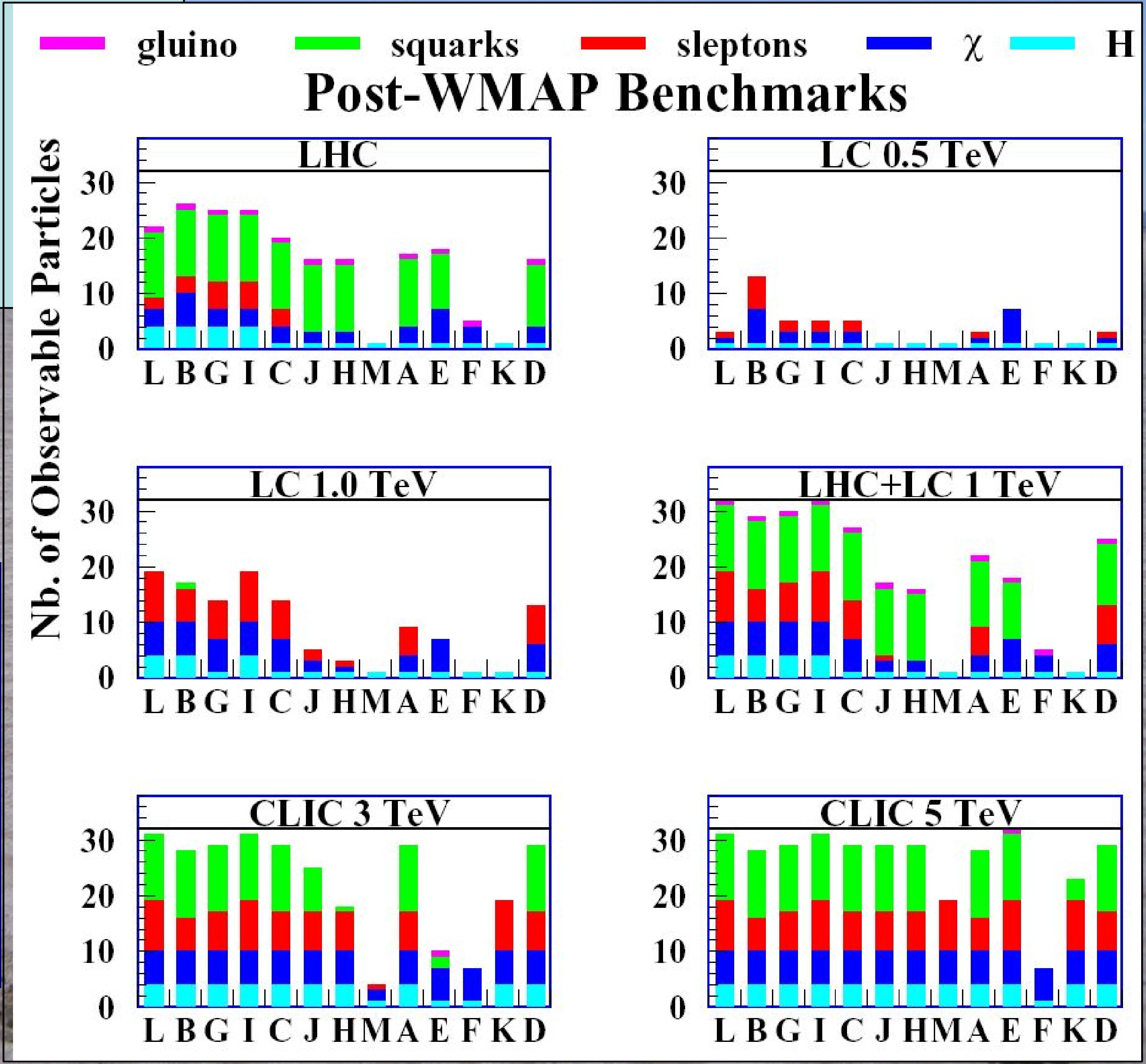
Sparticle detectability Along one WMAP line




Calculation of relic density at a benchmark



# Summary of LHC Scapabilities … and Other Accelerators




LHC almost

`guaranteed'

to discover

supersymmetry

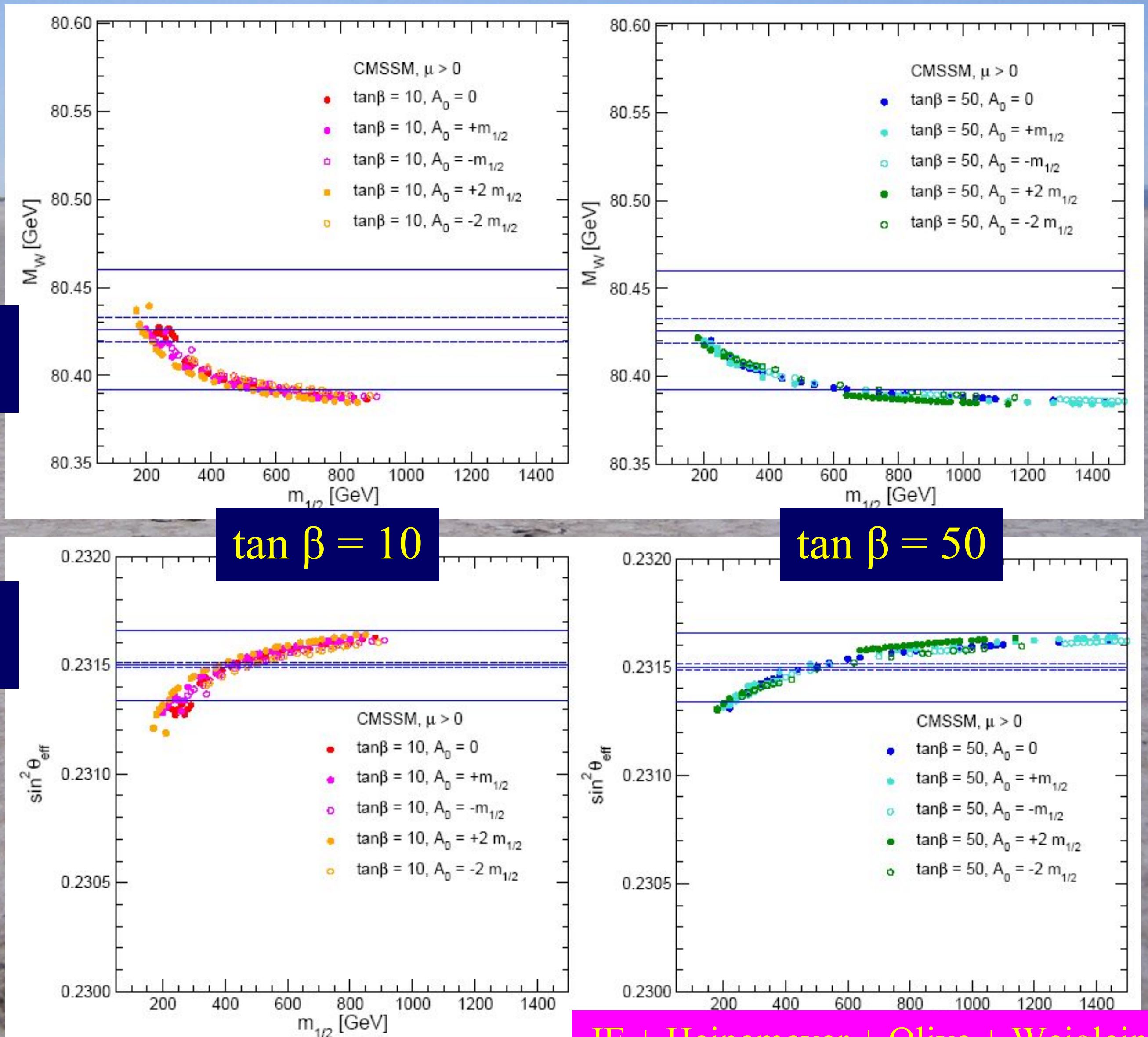
if it is relevant

# Precision Observables in Susy

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

$m_W$

$\sin^2\theta_W$




tan β = 10

tan β = 50

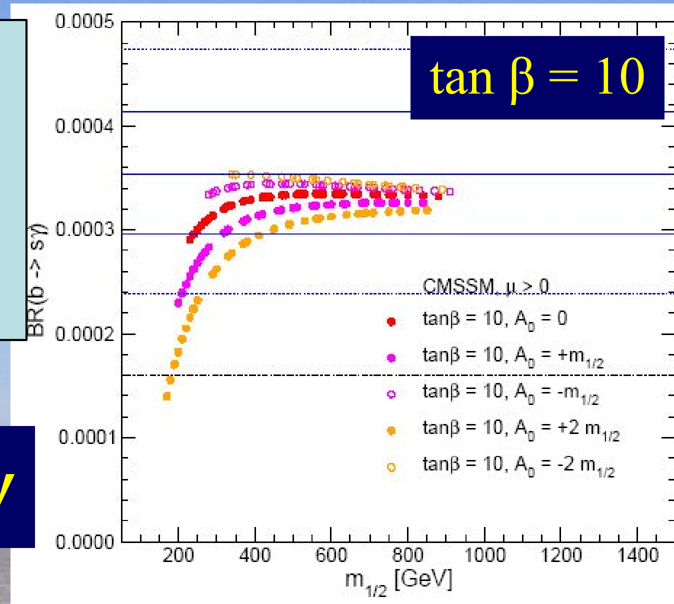
Present & possible future errors

JE + Heinemeyer + Olive + Weiglein

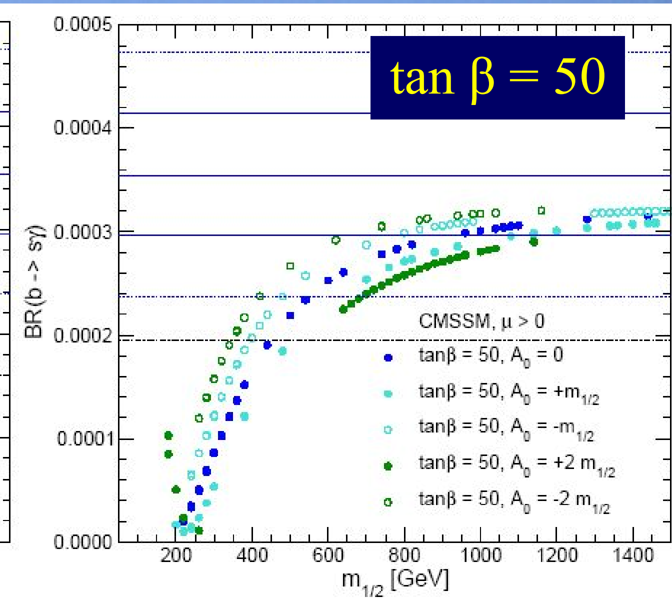
# More Observables

$b \to s\gamma$

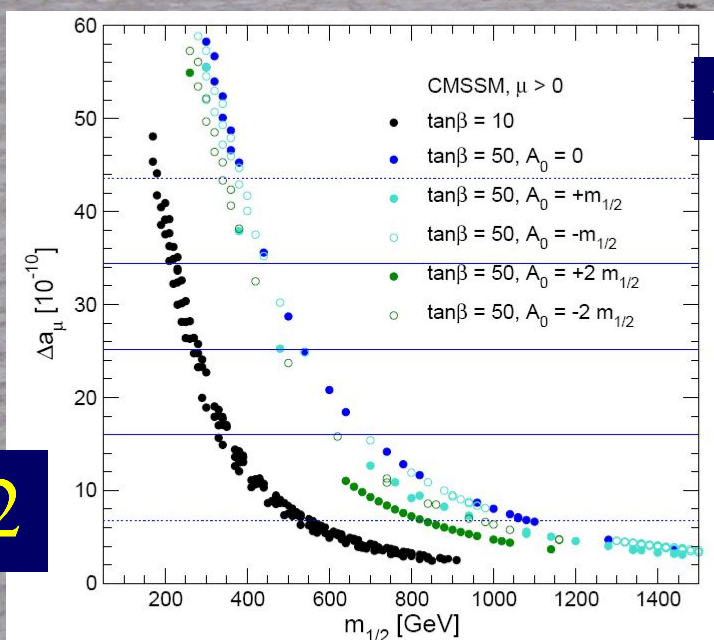
$\tan\beta = 10$




$\tan\beta = 50$

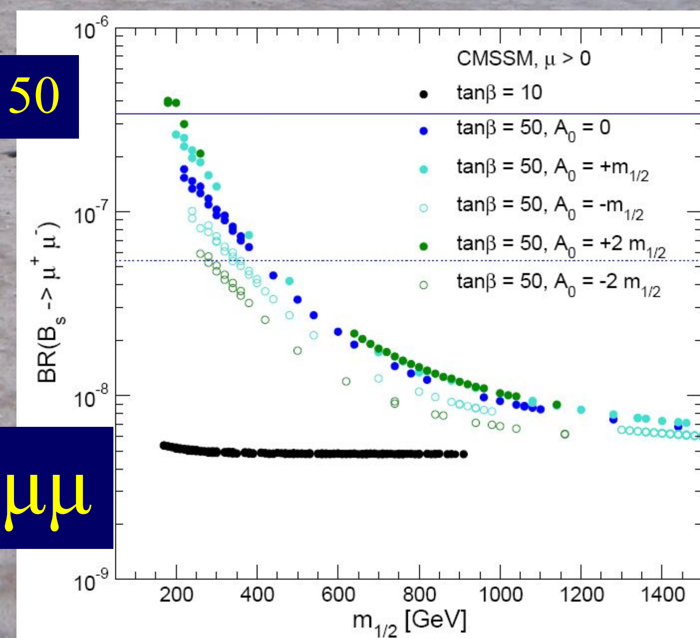



$g_\mu - 2$




$\tan\beta = 10, 50$

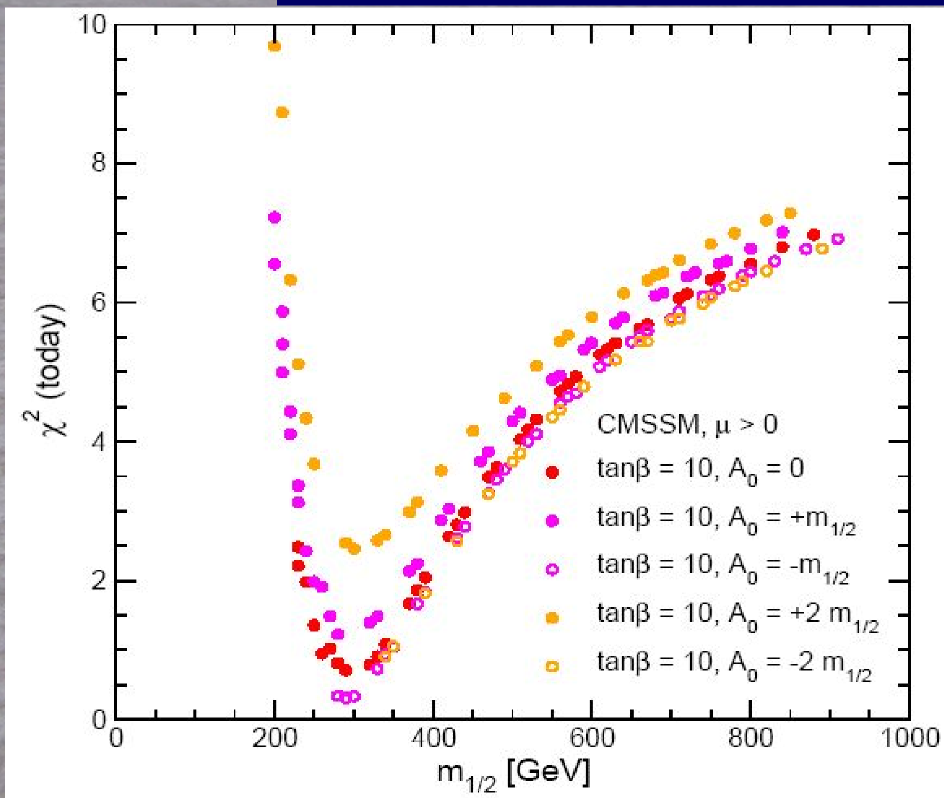
$B_s \to \mu\mu$

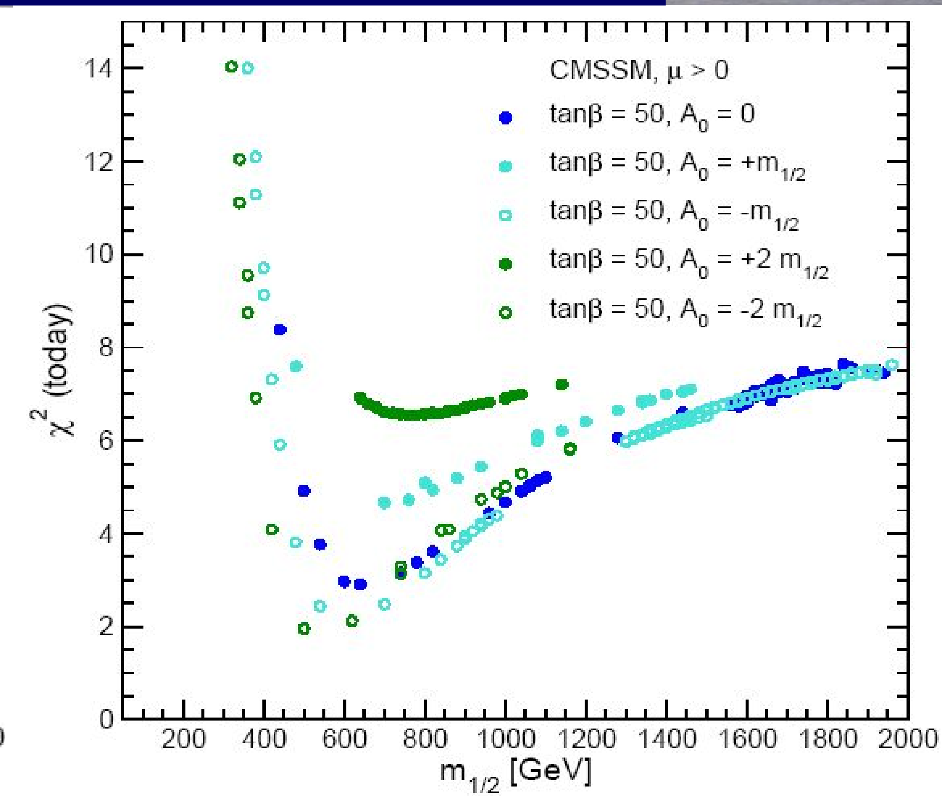



JE + Heinemeyer + Olive + Weiglein

# Global Fits to Present Data

As functions of $m_{1/2}$ in CMSSM for tan β = 10, 50

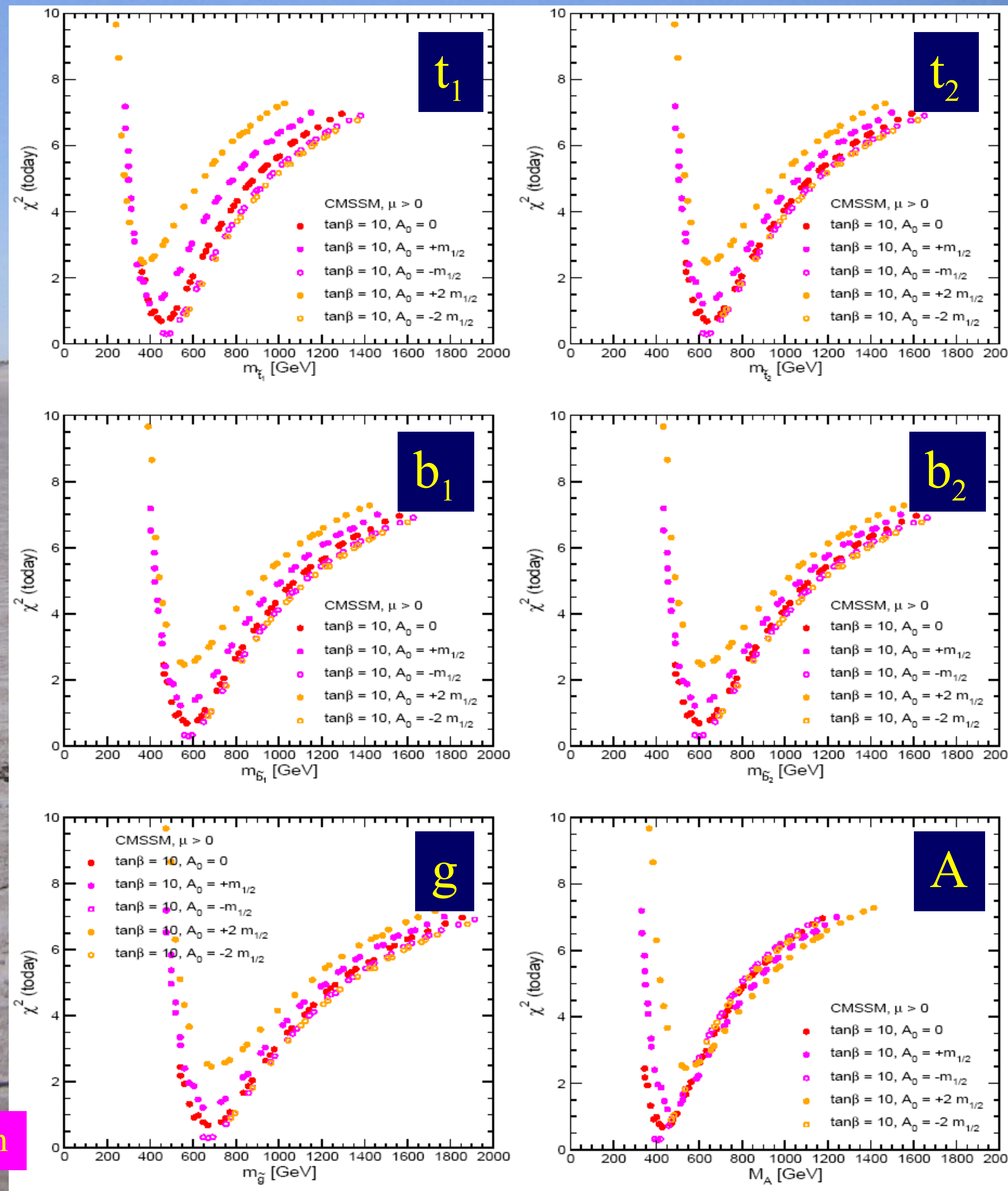



JE + Heinemeyer + Olive + Weiglein

# Global Fits to Present Data

Preferred sparticle masses for tan β = 10




JE + Heinemeyer + Olive + Weiglein

# Minimal Supergravity Model

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

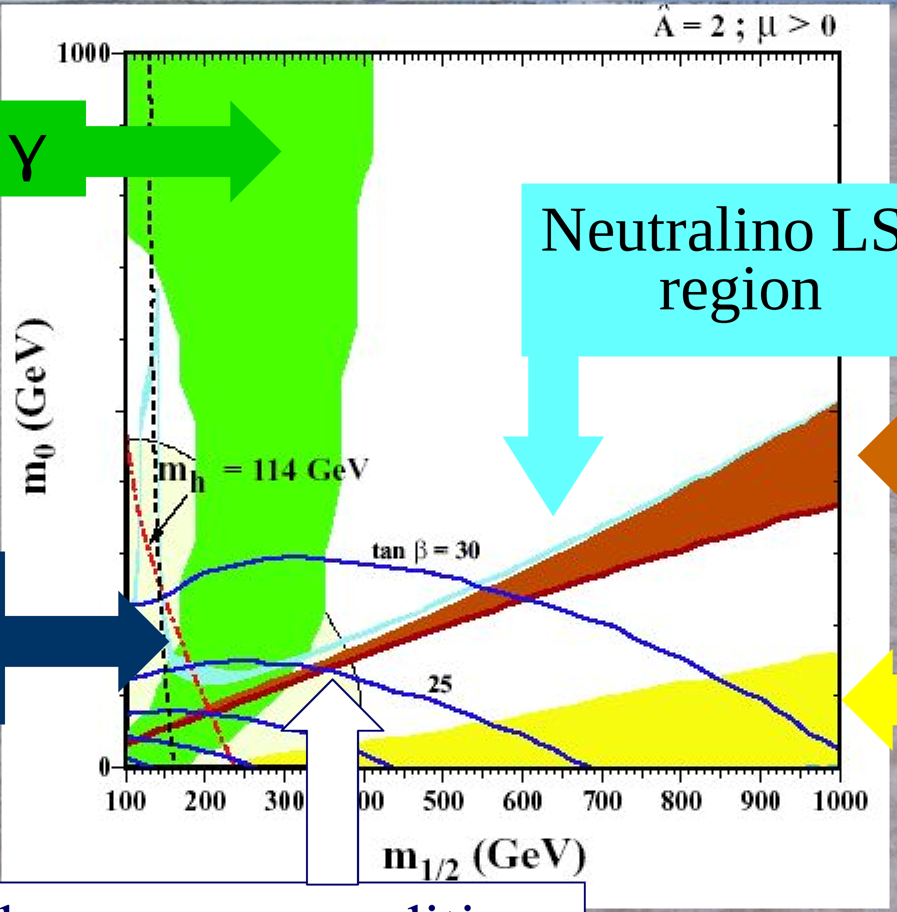
Excluded by b    s γ

Neutralino LSP region

stau LSP (excluded)

LEP constraints On $m_h$, charginc

Gravitino LSP region




tan β fixed by vacuum conditions

JE + Olive + Santoso + Spanos

# Slepton Trapping at the LHC?

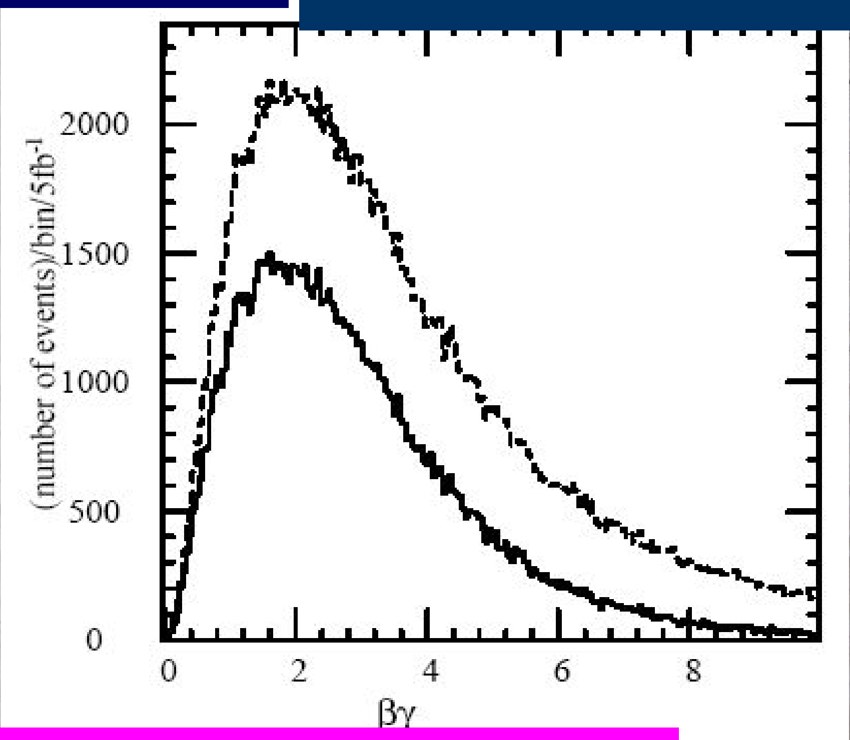
If stau next-to-lightest sparticle (NLSP)

may be metastable

may be stopped in detector/water tank

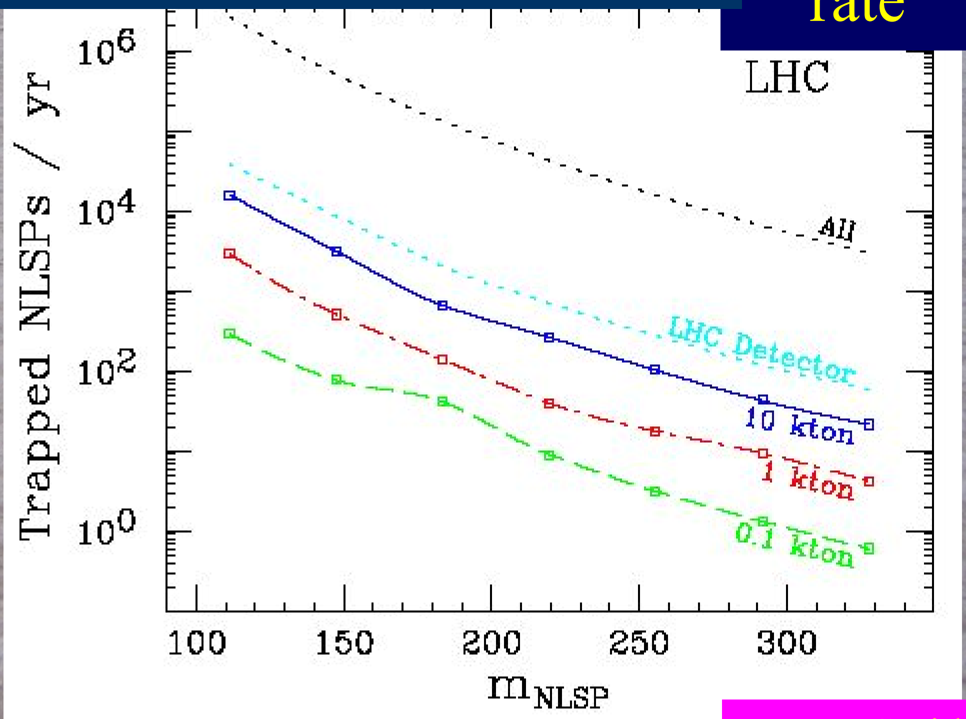
wait for them to decay: days, weeks, …?

Kinematics




Hamaguchi + Kuno + Nakaya + Nojiri

Trapping rate

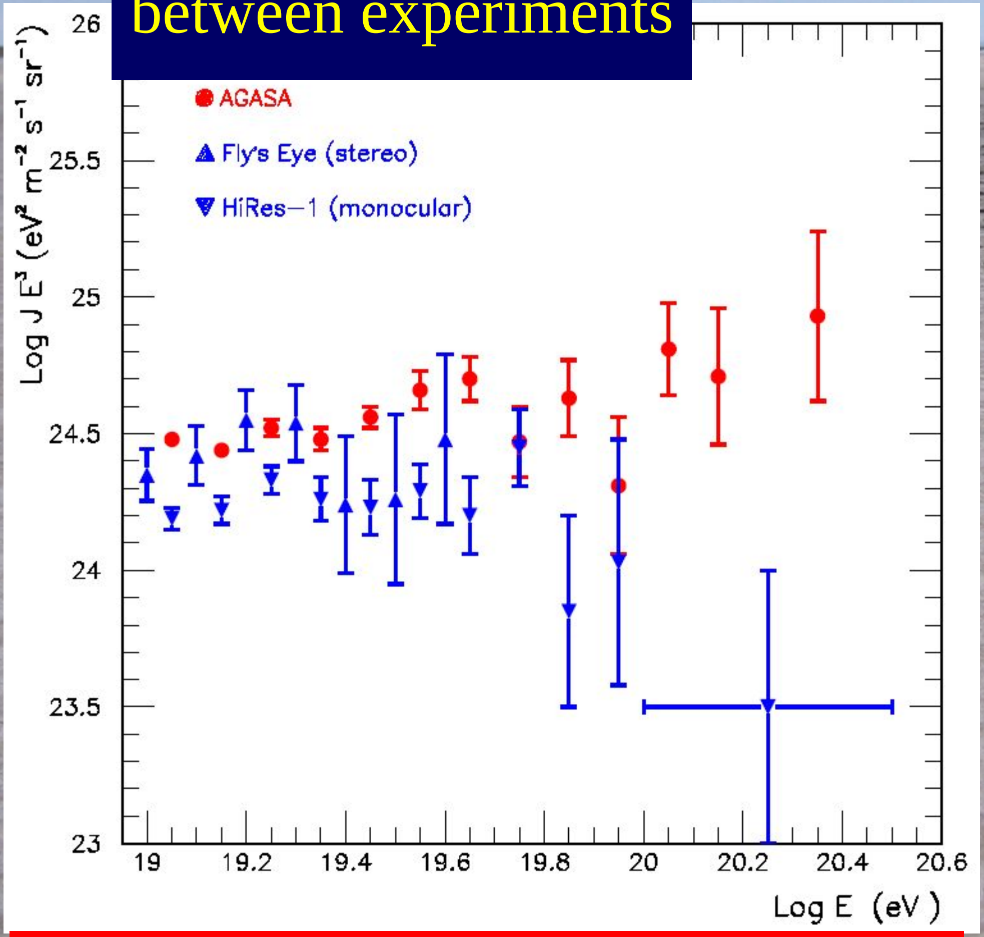



Feng + Smith

# Something completely different

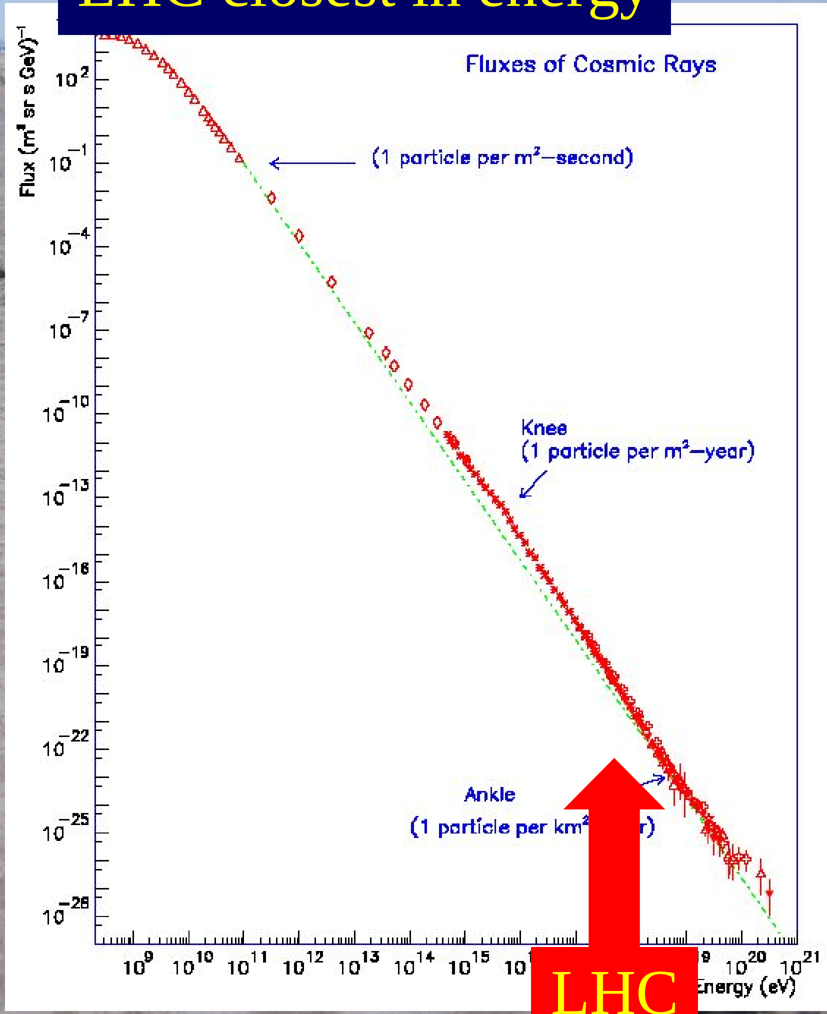
# Ultra-High-Energy Cosmic Rays

Discrepancies between experiments



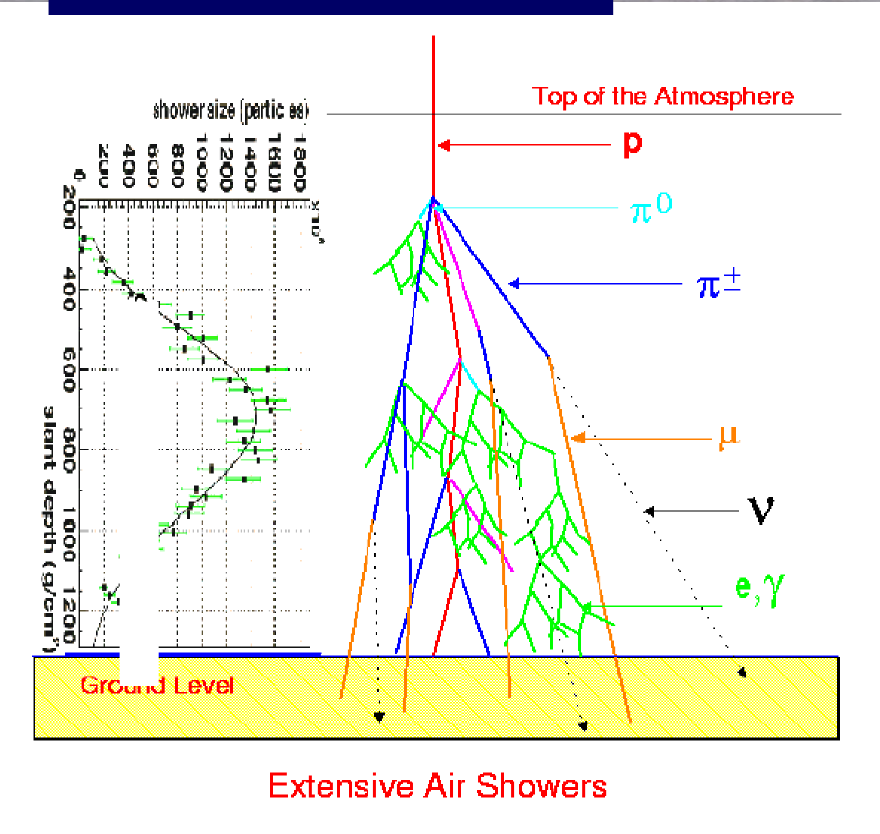

To be resolved by Auger laboratory

LHC closest in energy

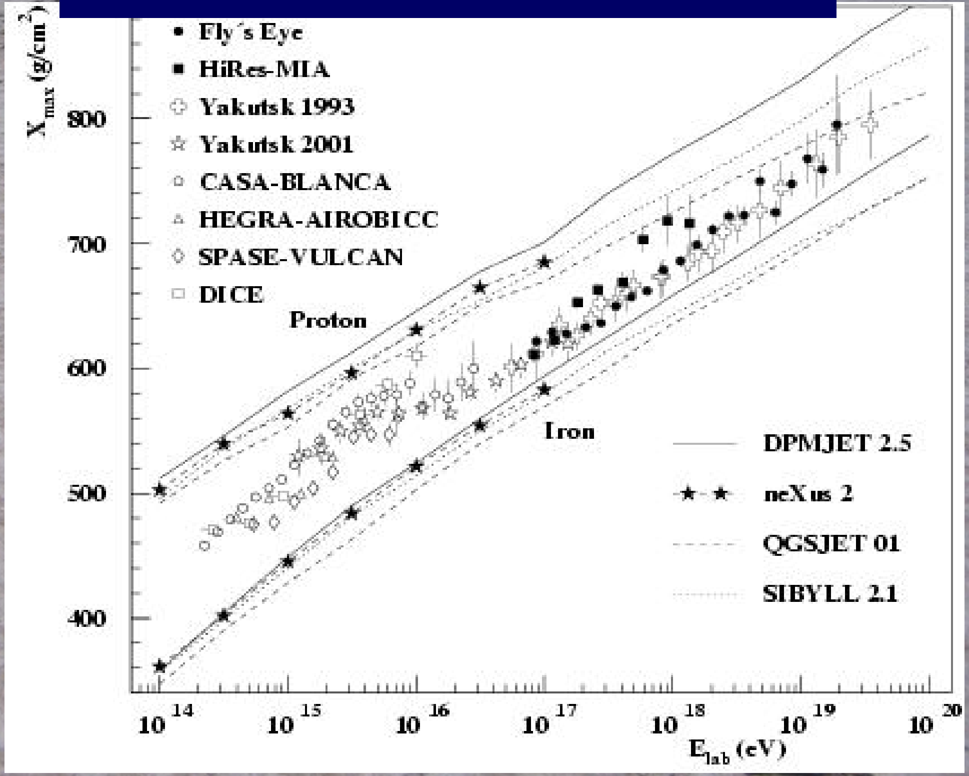


# Understanding High-Energy Cosmic Rays

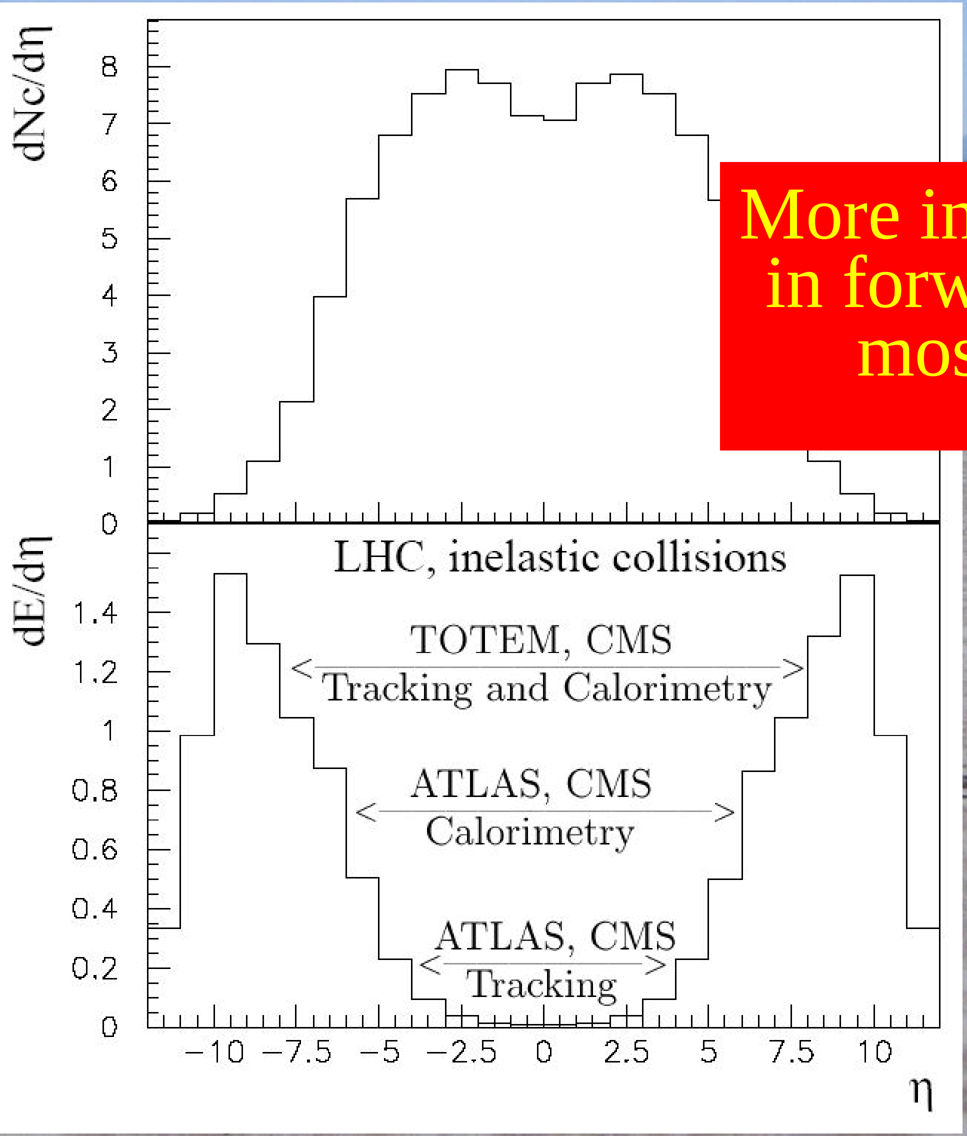
## Development of extensive air shower




## Uncertainties in composition due to model dependence



# (Lack of) Coverage by LHC Detectors




More instrumentation in forward direction most welcome

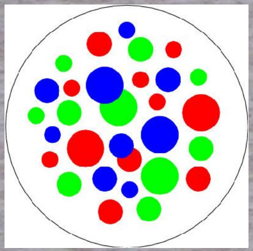
# Back to forward QCD

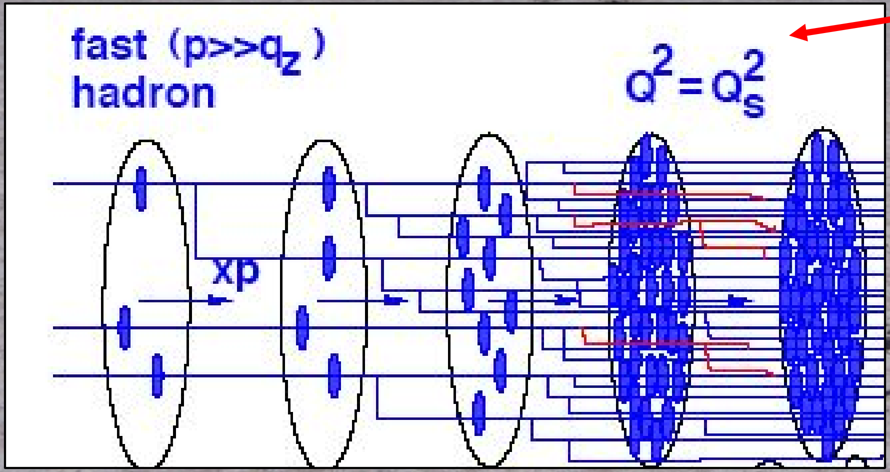
# Parton Saturation Effects

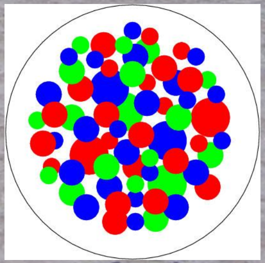
High energies s open access to small $x = Q^2/s$

Boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

large x





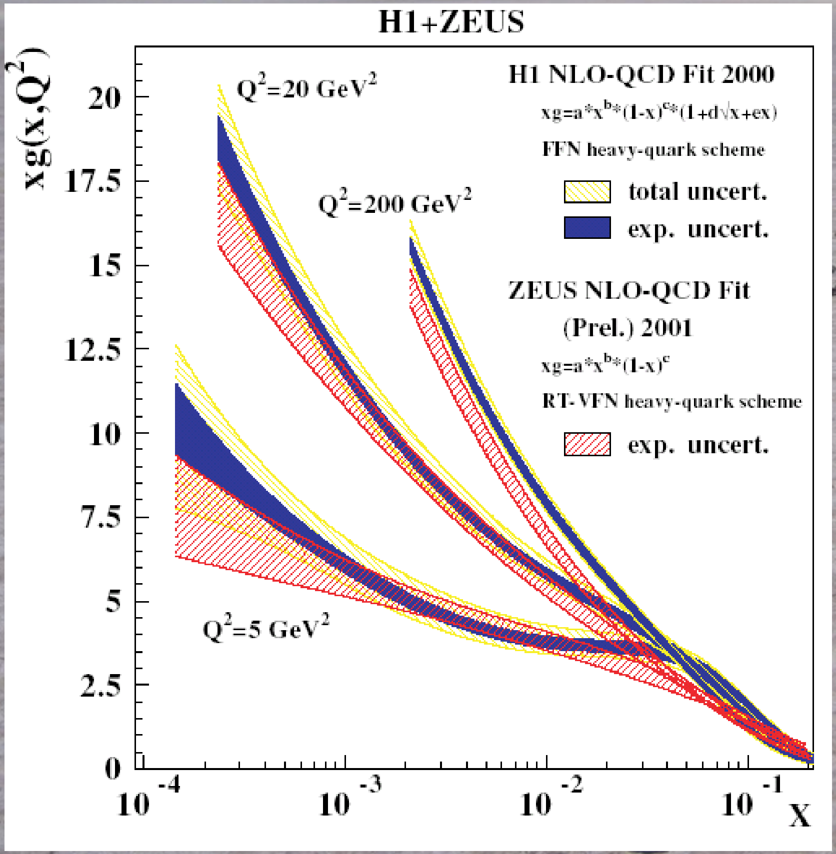
small x

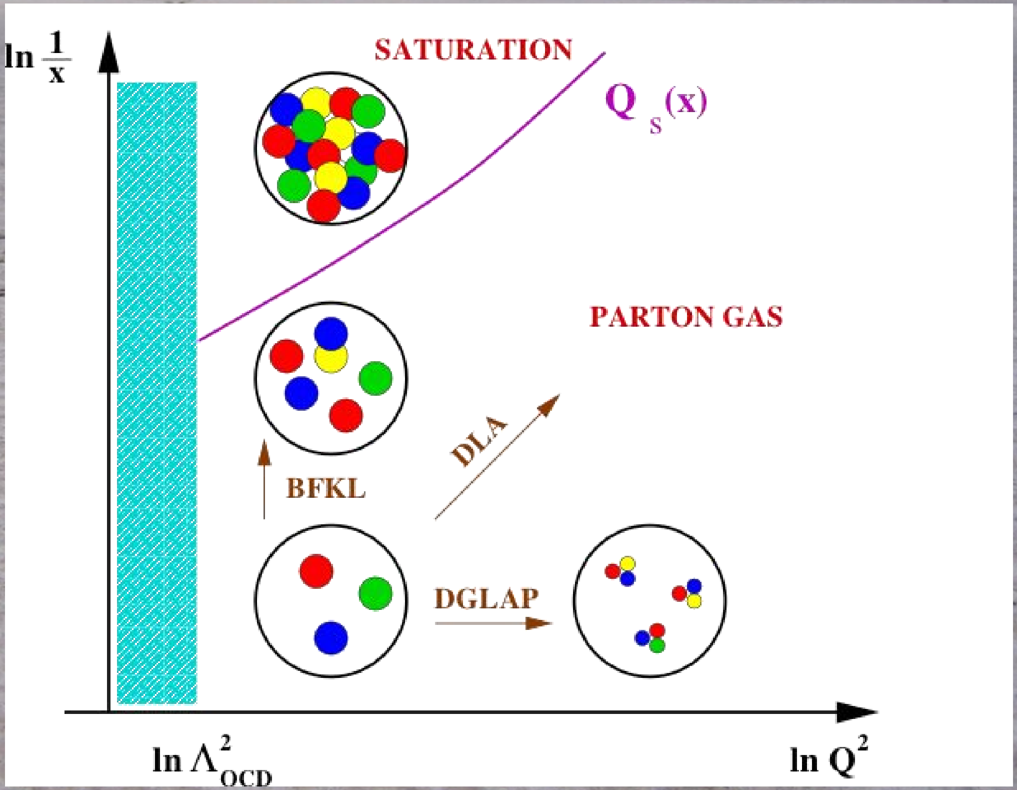
Large probability to emit an extra gluon ~ $\alpha_s \ln(1/x) \sim 1$:
number of gluons at small x grows, transverse area limited
Transverse density becomes large

# Non-linear QCD evolution and population growth

Linear evolution:

maximum population density

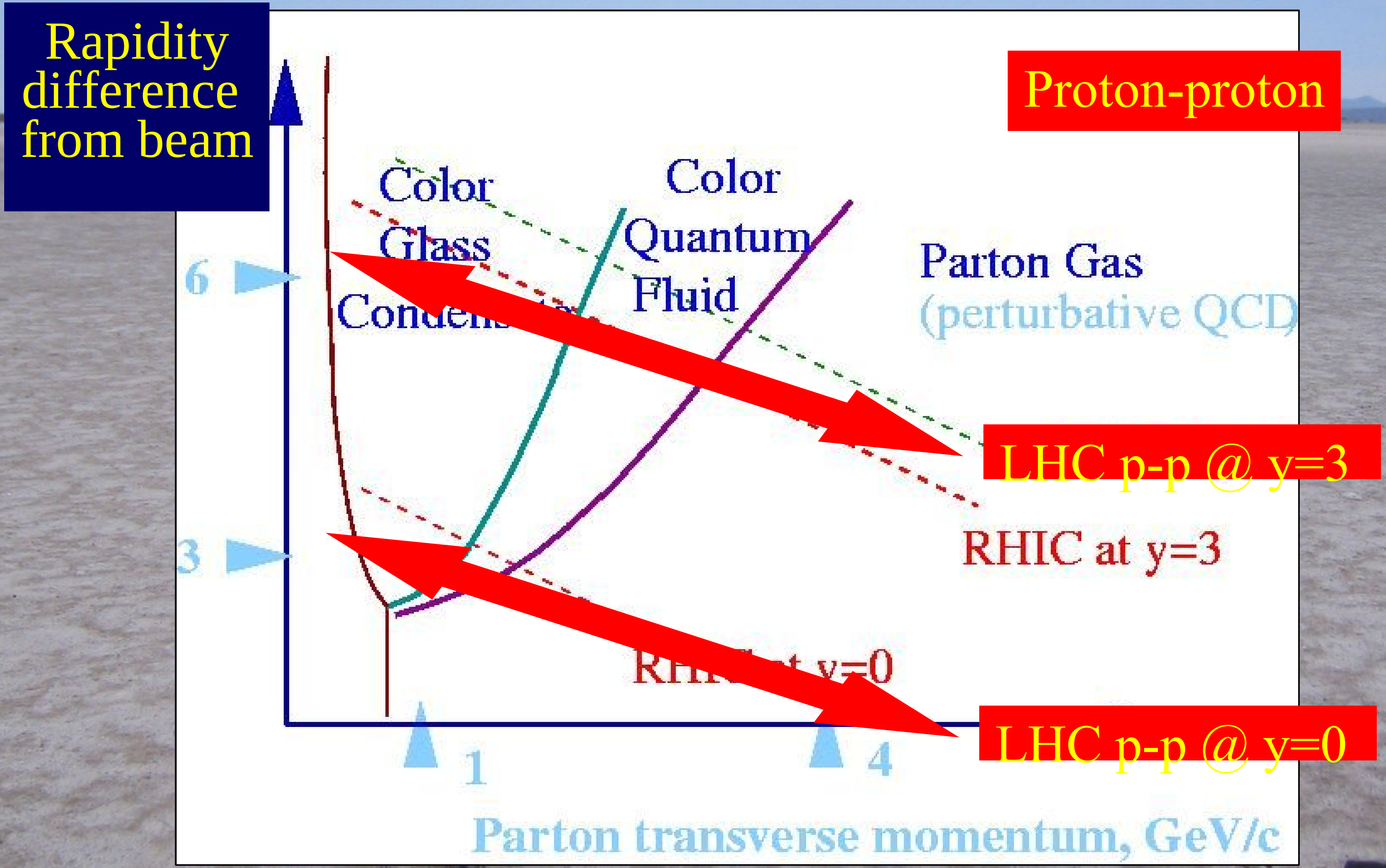


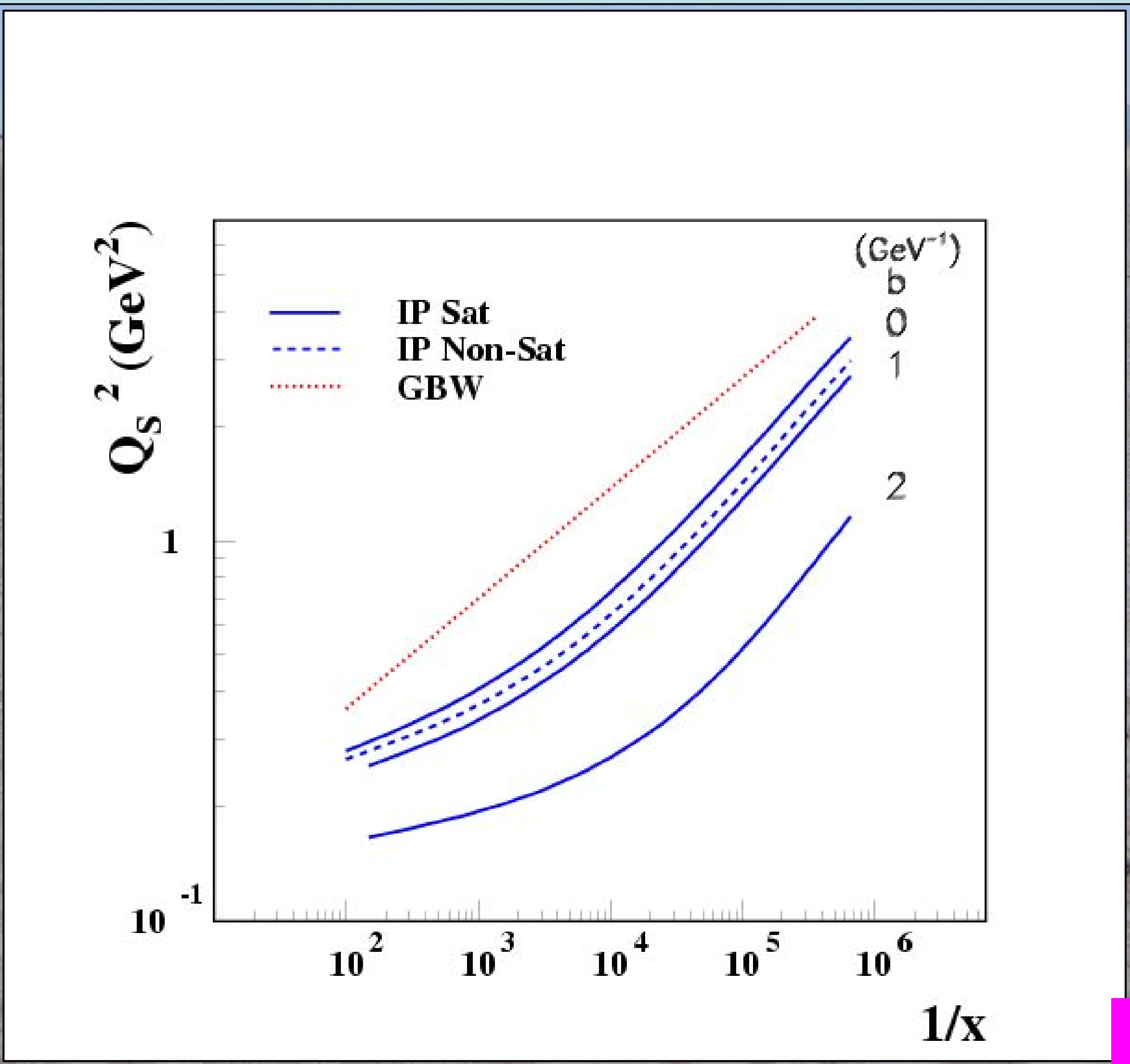

Malthus

Color glass condensate

# Phase diagram of high energy QCD



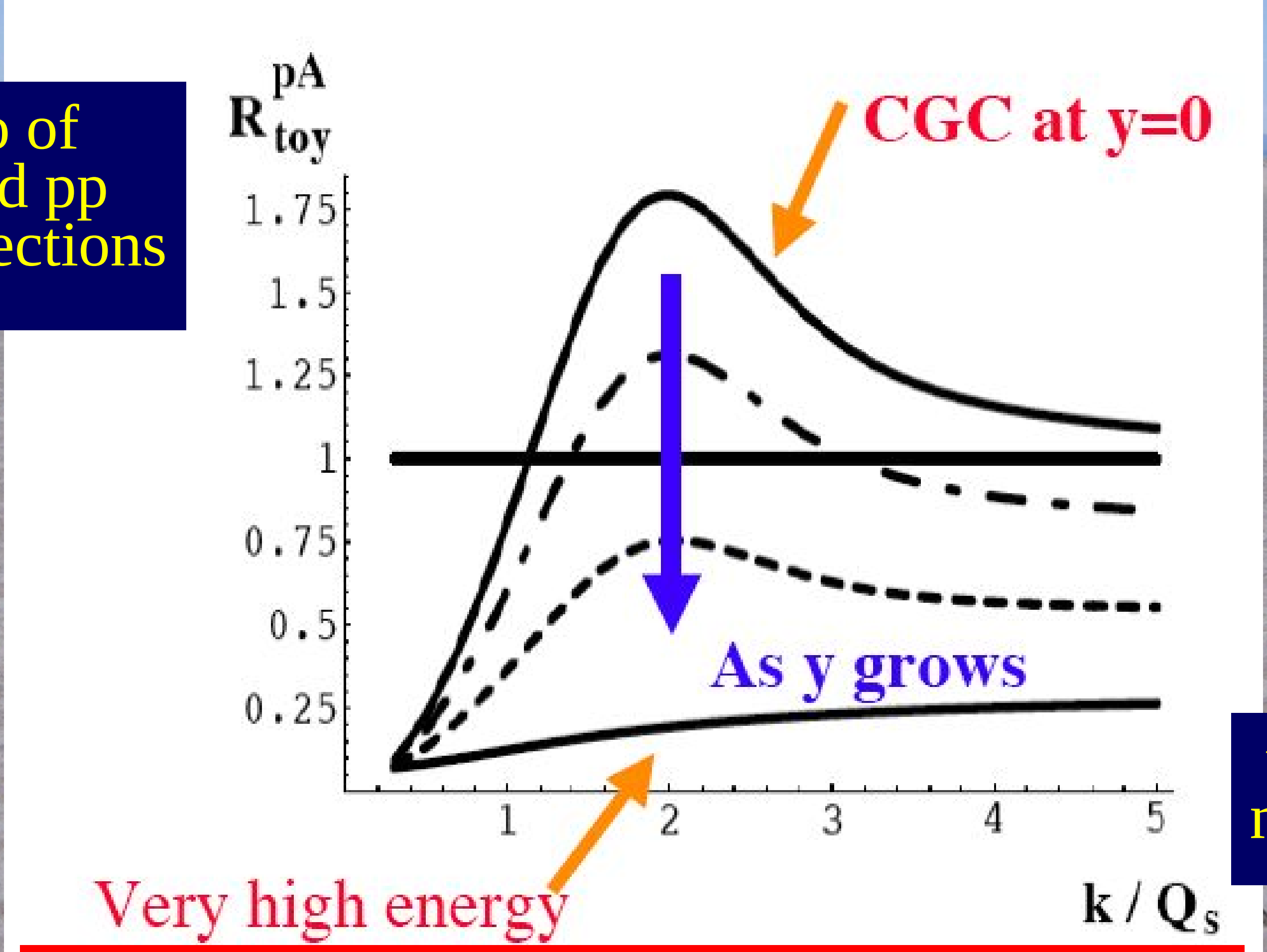
# Extraction of Saturation Scale from HERA Data




Kowalski + Teaney

# Gluon multiplication in a limited (nuclear) environment

Ratio of pA and pp Cross sections

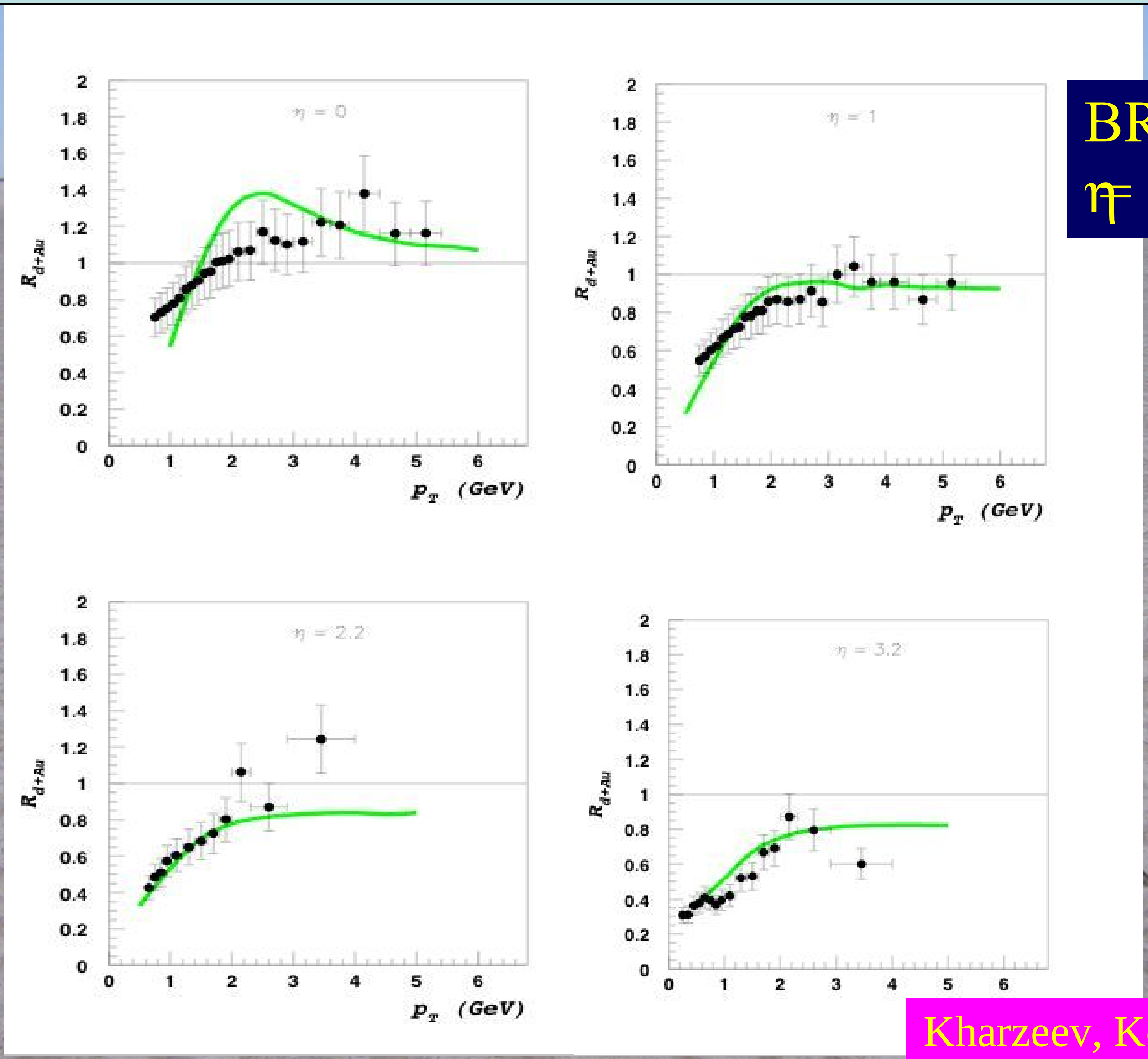



transverse momentum

At large rapidity y (small angle) expect suppression of hard particles

# Color Glass Condensate: confronting the data

BRAHMS data:
η = 0, 1, 2.2, 3.2




Kharzeev, Kovchegov, Tuchin

# New Physics in Diffraction?

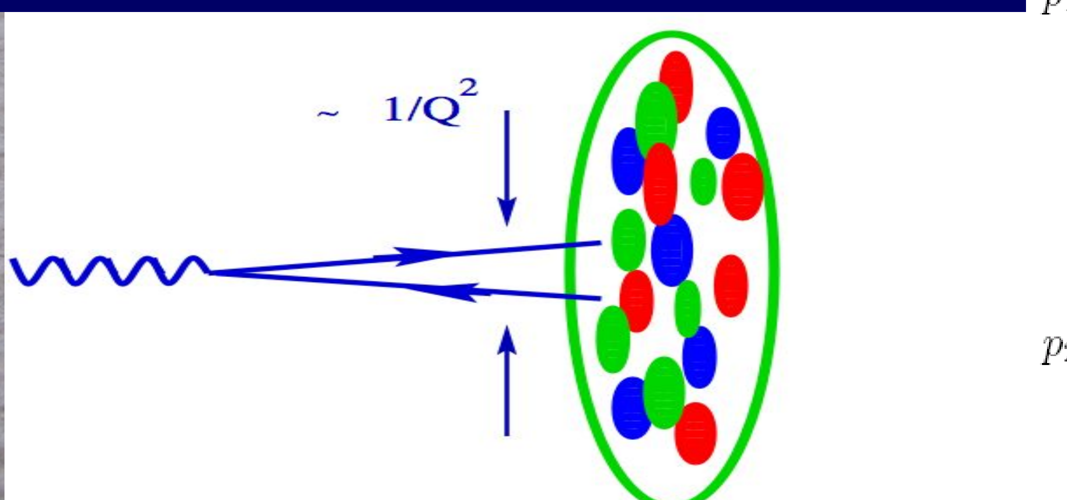
Cox

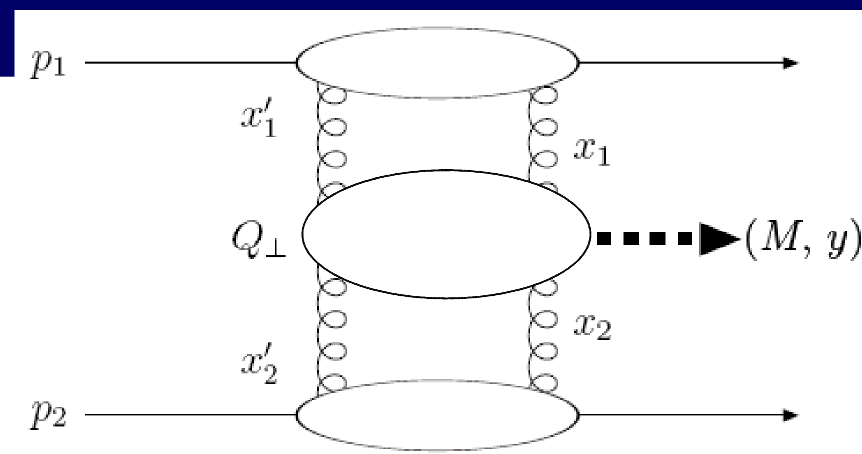
# The Diffractive Menagerie

- Soft diffraction dissociation:
Peripheral proton-proton collision dissociate proton → low-mass system

- Soft double diffraction:
Peripheral proton-proton collision produces low-mass central system

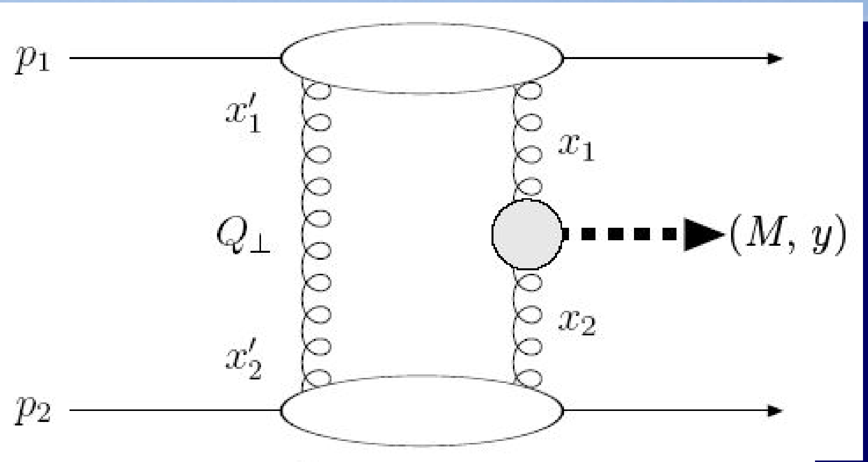
- Hard diffraction:
Small colour dipole penetrates proton produces very high-mass system



# Diffractive Higgs Production

- Double-diffractive Higgs production mechanism:

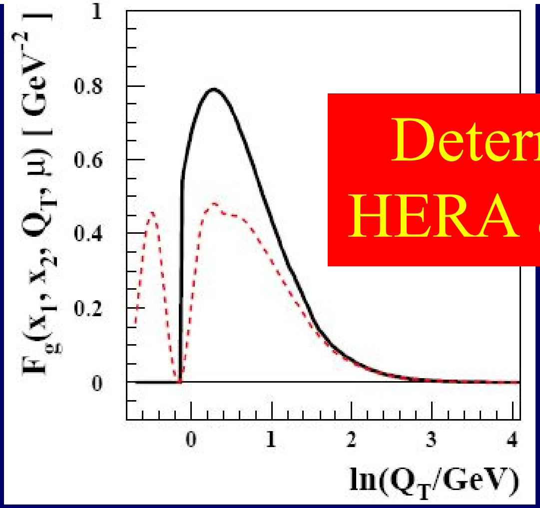



- Effective luminosity:

$$M^2 \frac{\partial^2 \mathcal{L}}{\partial y \partial M^2} = 4.0 \times 10^{-4} \left[ \frac{\int_{\ln Q_{\min}}^{\ln \mu} F_g(x_1, x_2, Q_T, \mu)\, \mathrm{d}\ln Q_T}{\mathrm{GeV}^{-2}} \right]^2 \left( \frac{\hat{S}^2}{0.02} \right) \left( \frac{4}{b\ \mathrm{GeV}^2} \right)^2 \left( \frac{R_g}{1.2} \right)^4$$

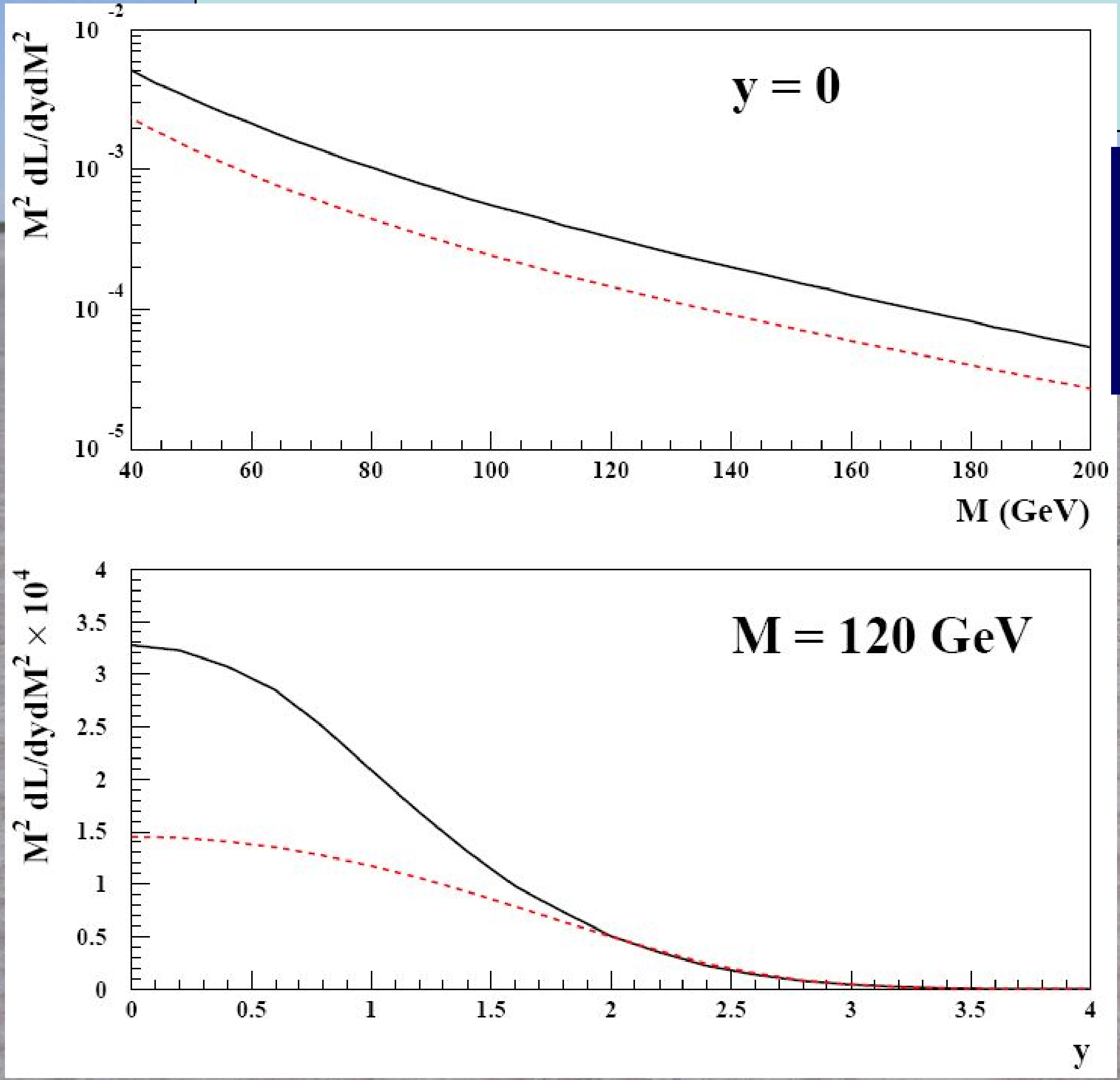
for nominal values of other inputs

- Gluon collision factor for different PDFs:

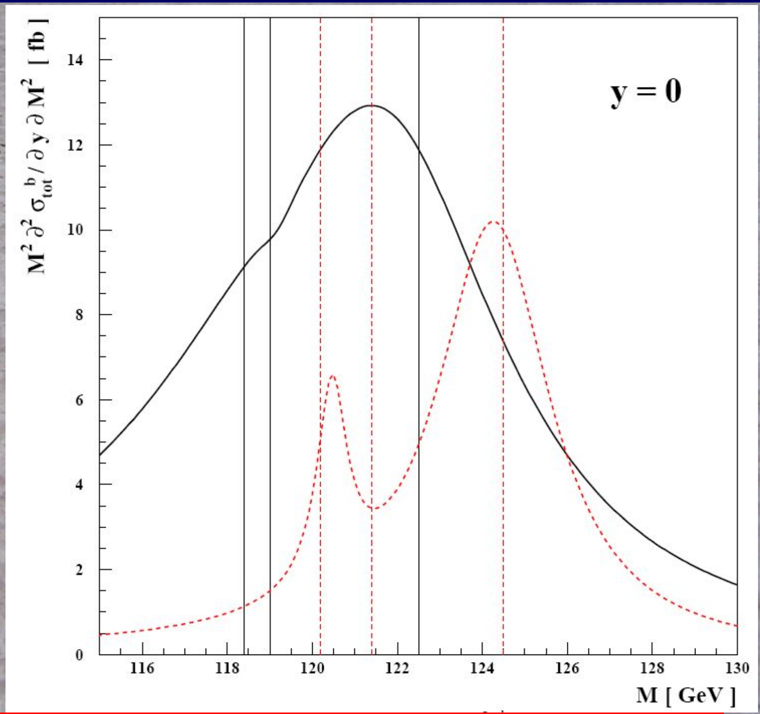



Determine using HERA & LHC data!

# Effective Luminosity: Double-Diffractive Higgs production



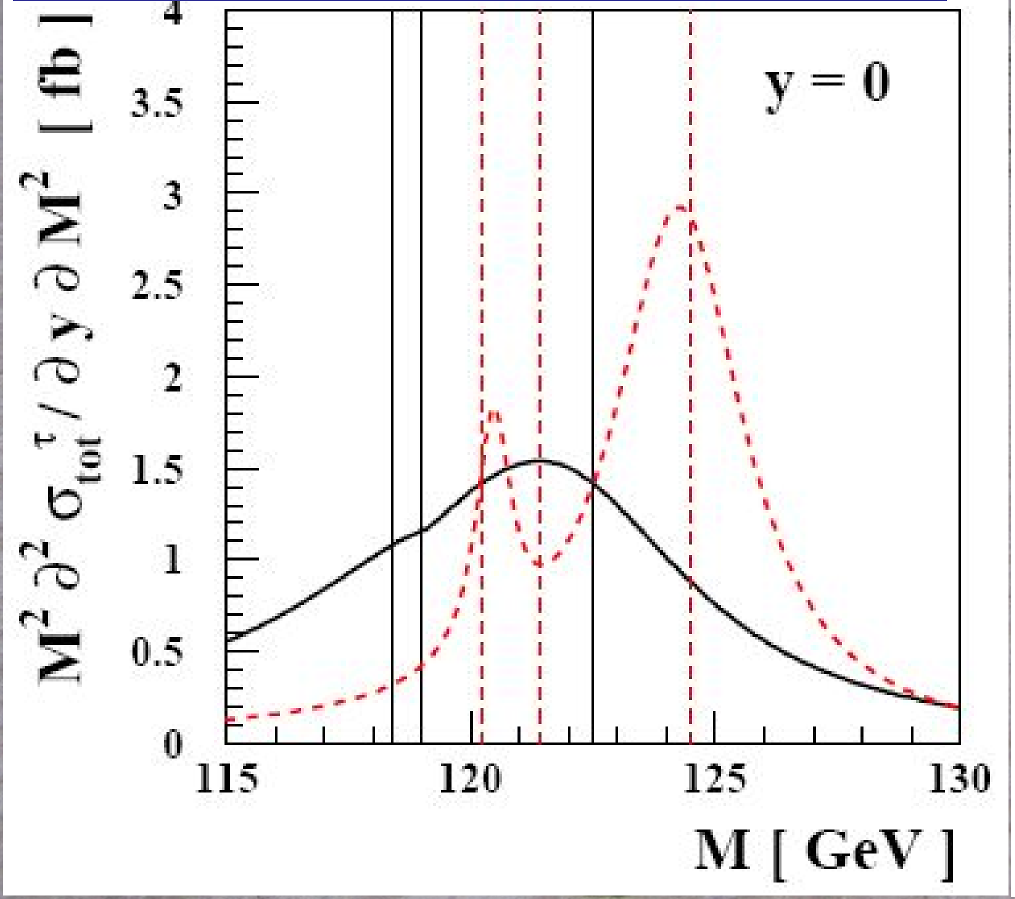

Cross section in CP-violating scenario: three-way mixing $\tan\beta = 50$, $m_{H^\pm} = 155$ GeV



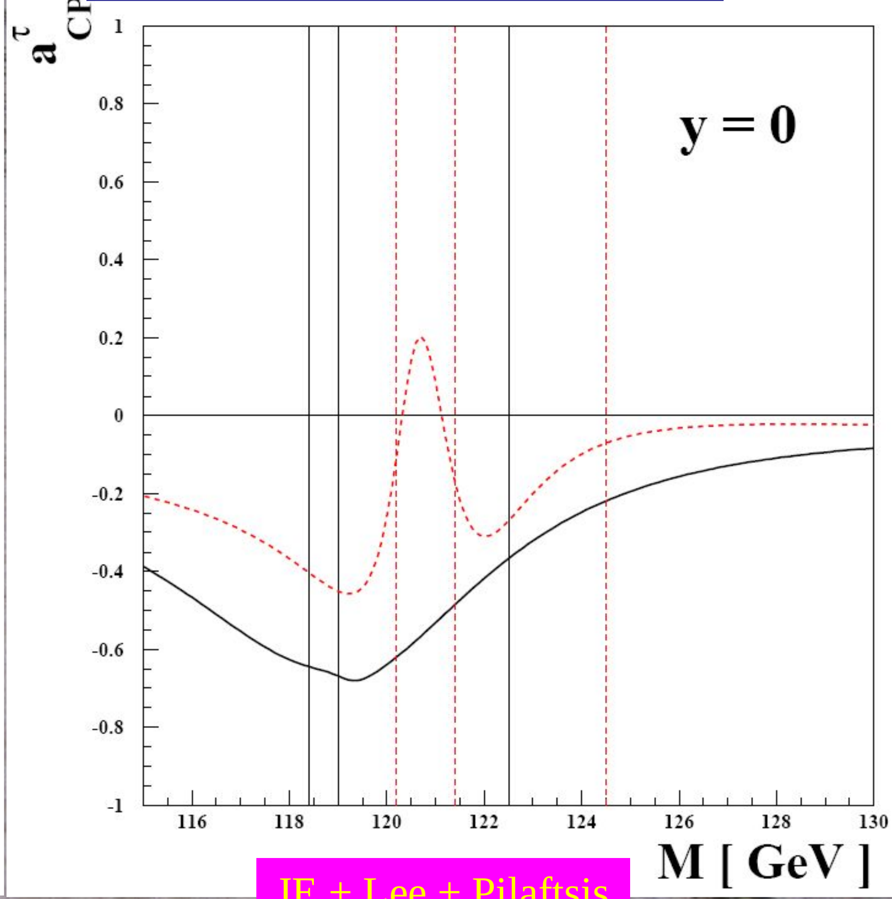

Can hope to measure line-shape using forward proton measurements?

# Cross Section, CP-Violating Asymmetry for $H_i \rightarrow \tau^+\tau^-$

Cross section peaks not at poles …



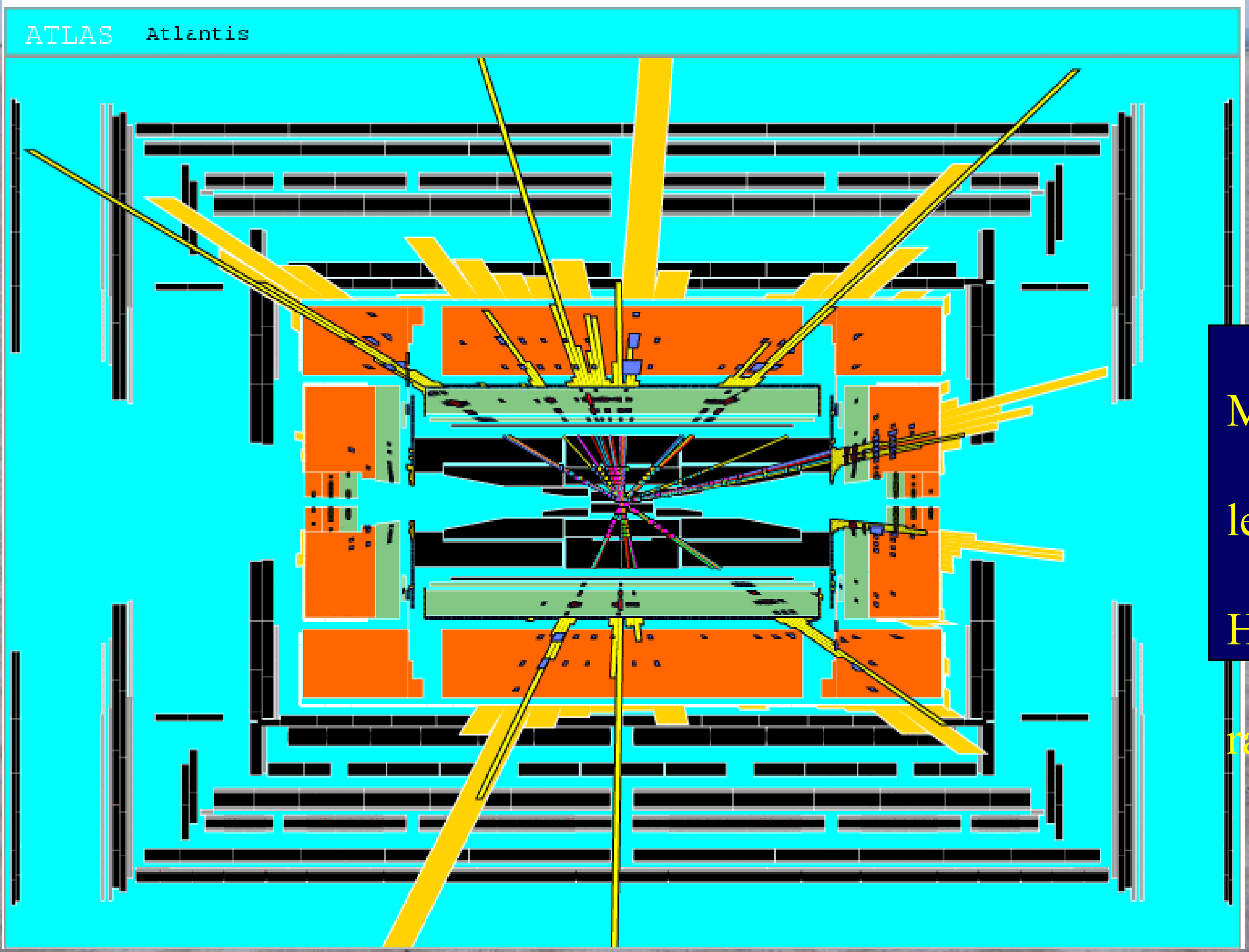

… nor are asymmetries




JE + Lee + Pilaftsis

Perhaps none of the above?

# Black Hole Production at LHC?




Multiple jets,

leptons from

Hawking

radiation

# Summary

- We do not know what the LHC will find
- But HERA physics provides crucial inputs:

  Parton distributions

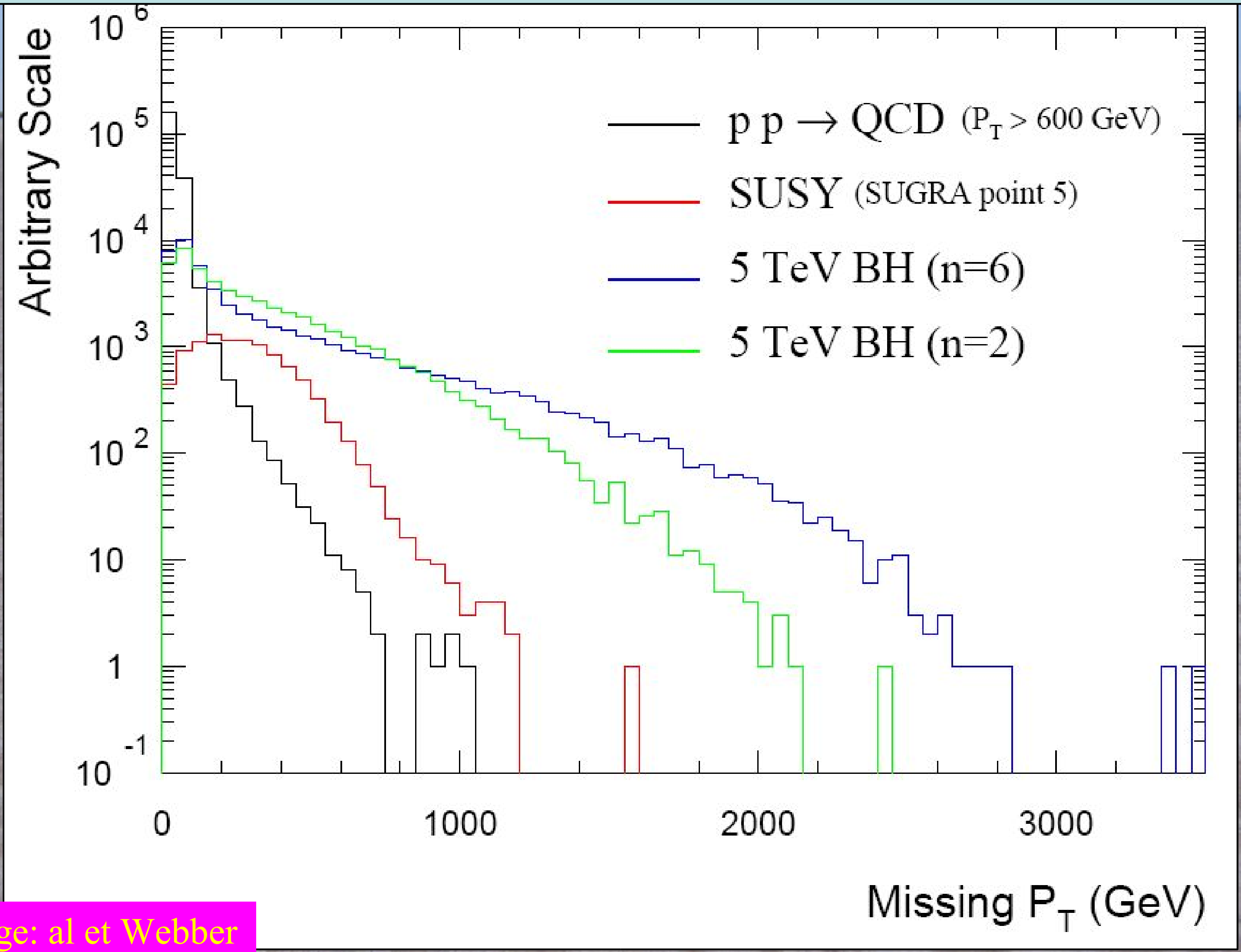
  Saturation effects
- Forward physics is potentially exciting area not covered by present detectors

  Colour glass condensate

  UHECRs

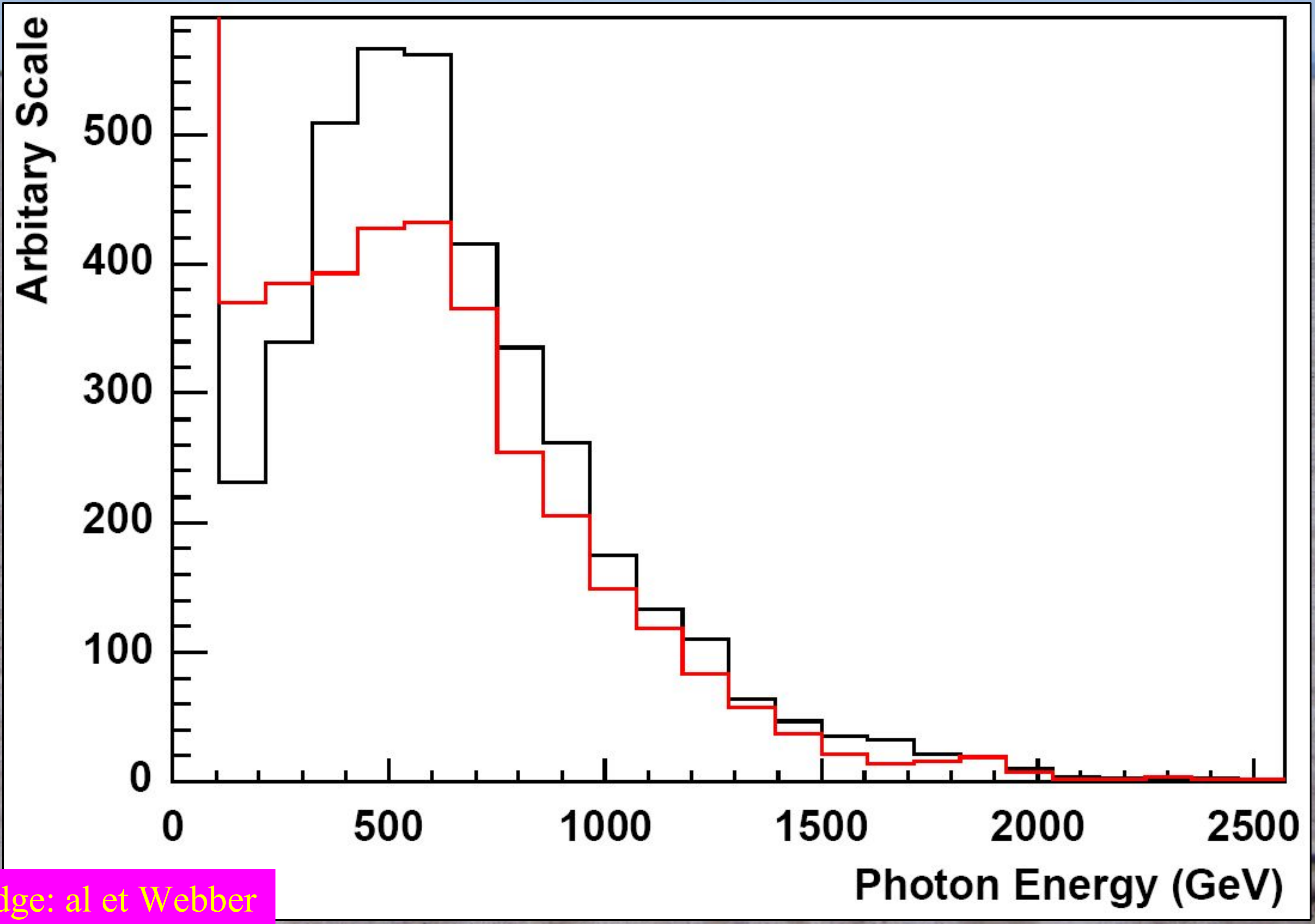
  Diffractive Higgs production?

# Black Hole Production



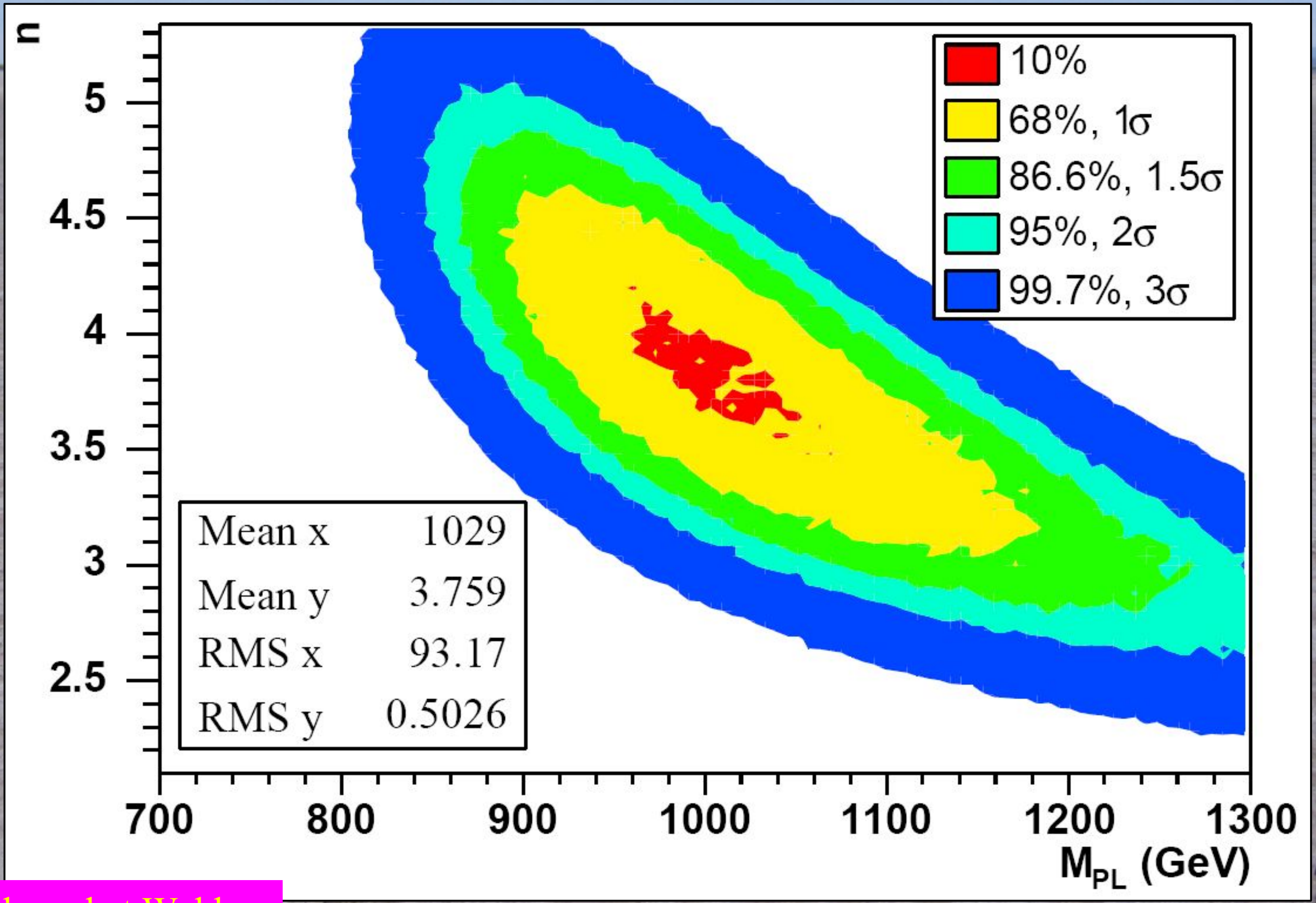

Cambridge: al et Webber

# Black Hole Decay Spectrum



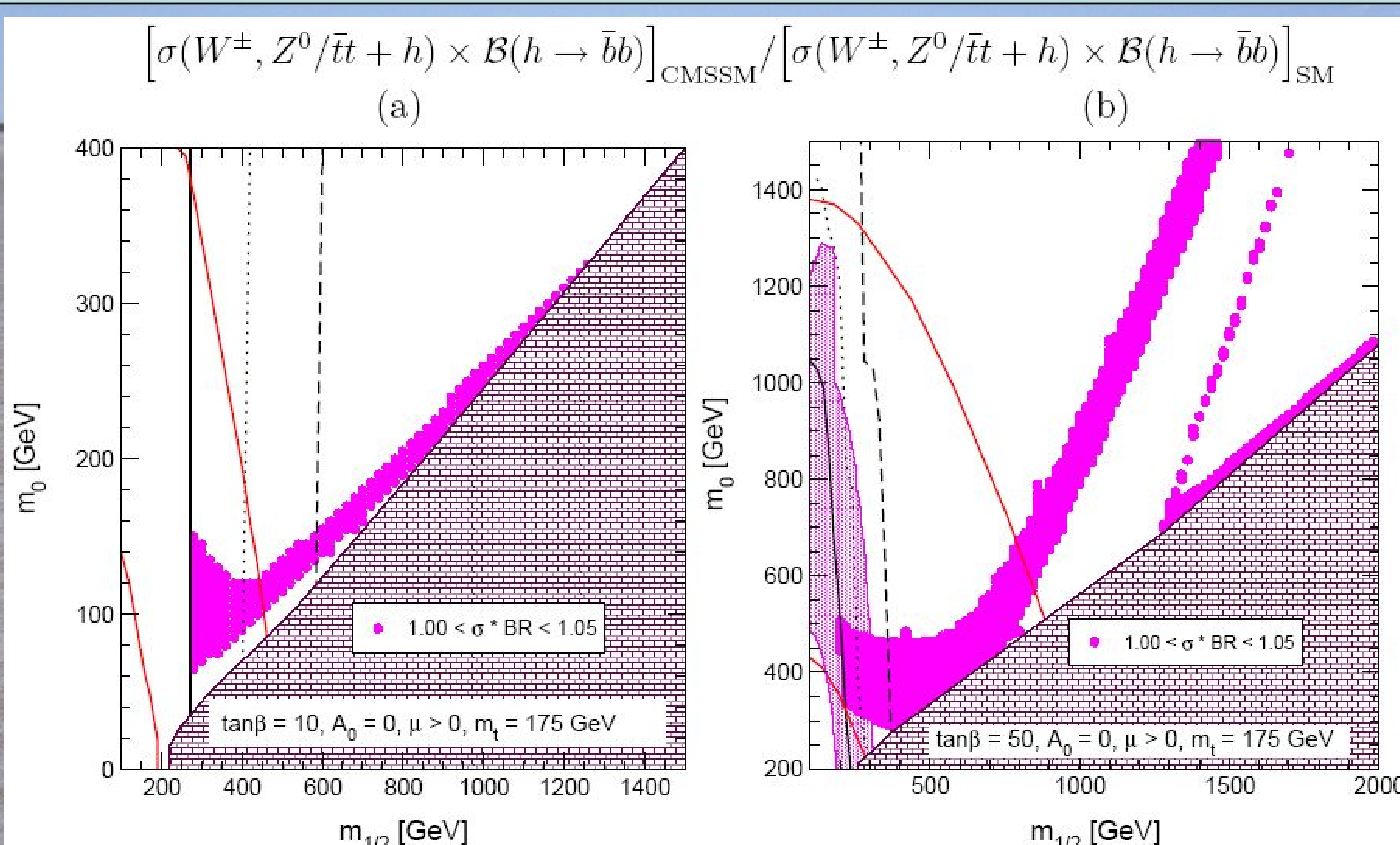

Cambridge: al et Webber

# Measuring Extra Dimensions




Cambridge: al et Webber

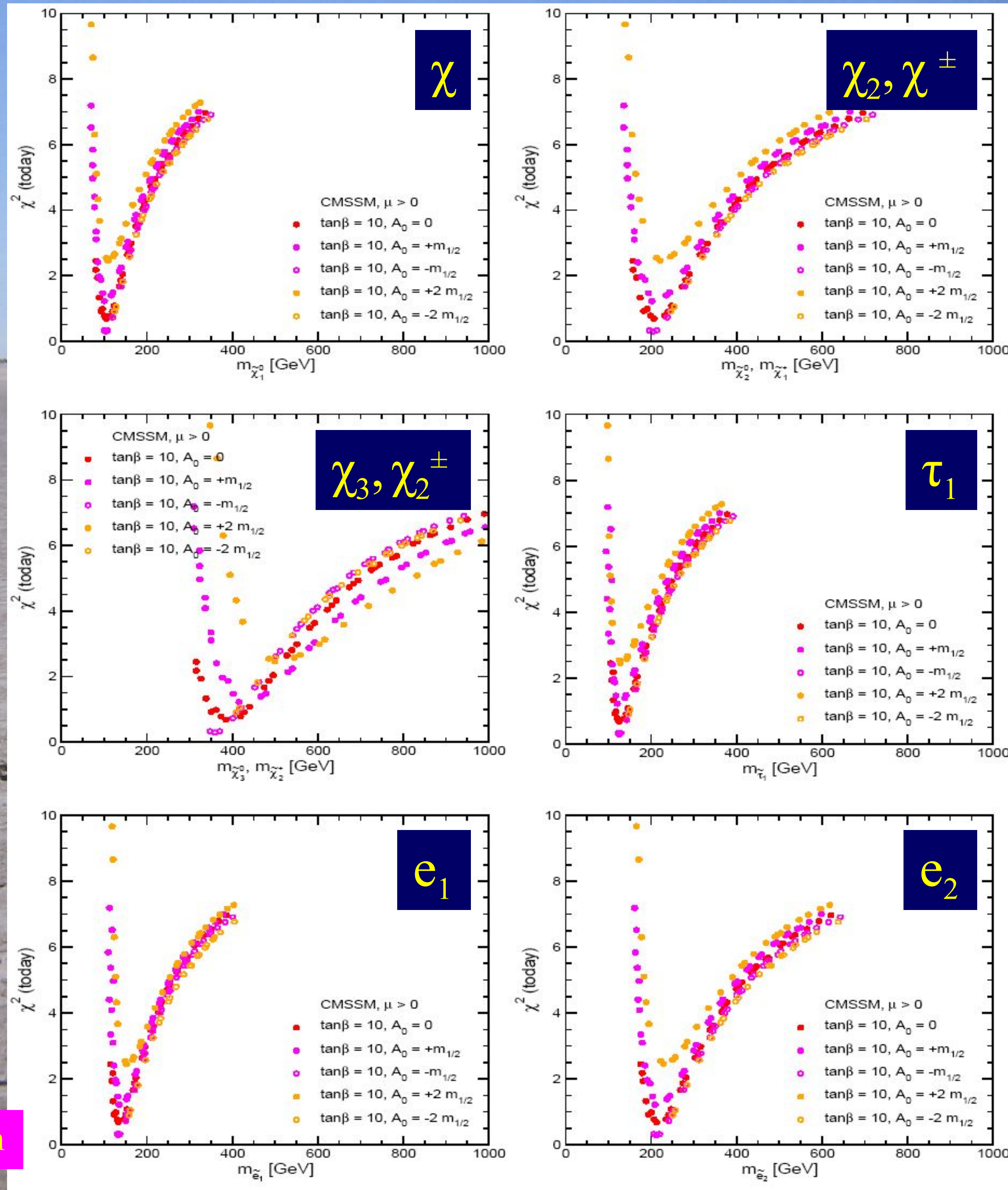
# Higgs Production: CMSSM vs SM




Good news: no suppression – Bad news: cannot distinguish CMSSM

# Global Fits to Present Data

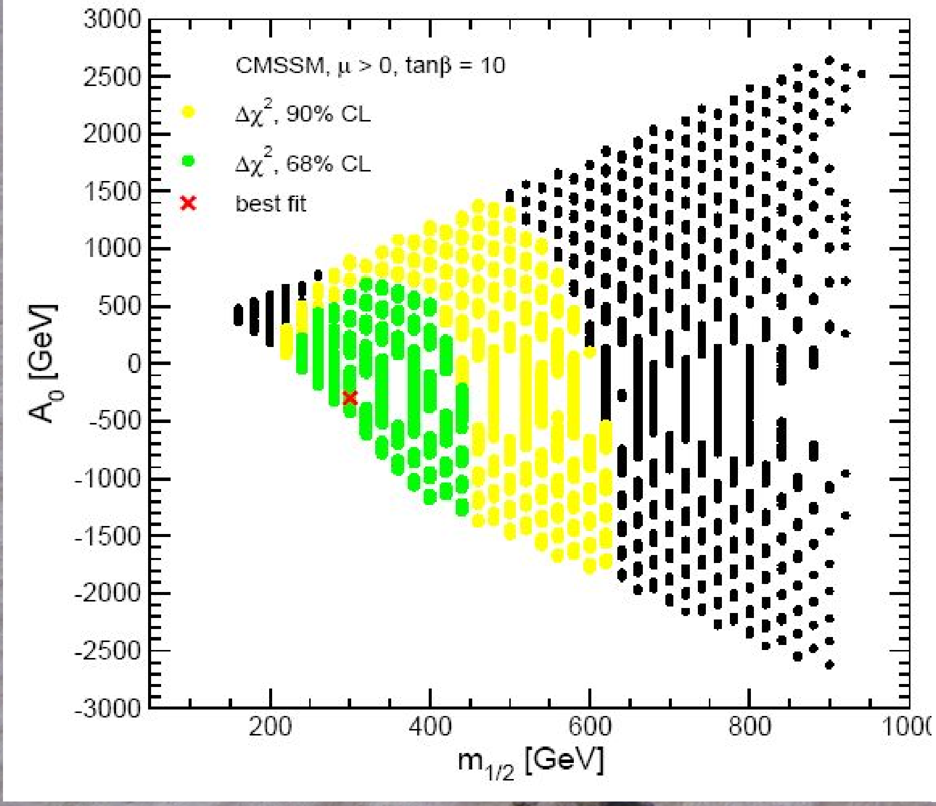
Preferred sparticle masses for tan β = 10

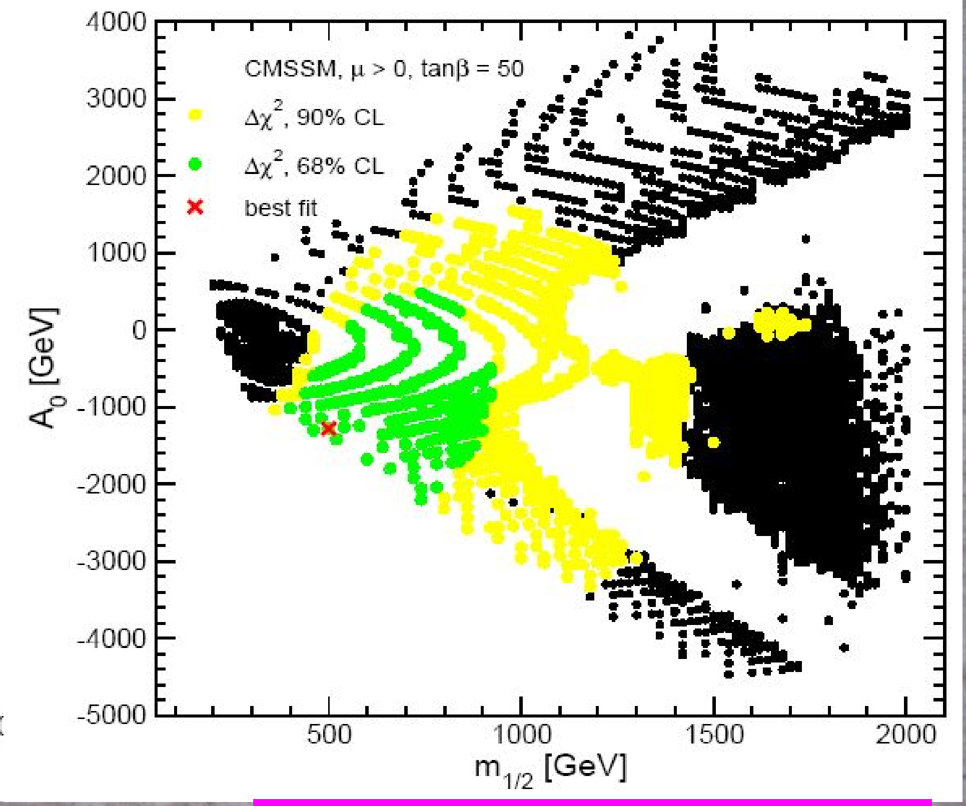



JE + Heinemeyer + Olive + Weiglein

# Global Fits to Present Data

($m_{1/2}$, $A_0$) planes in CMSSM for tan β = 10, 50



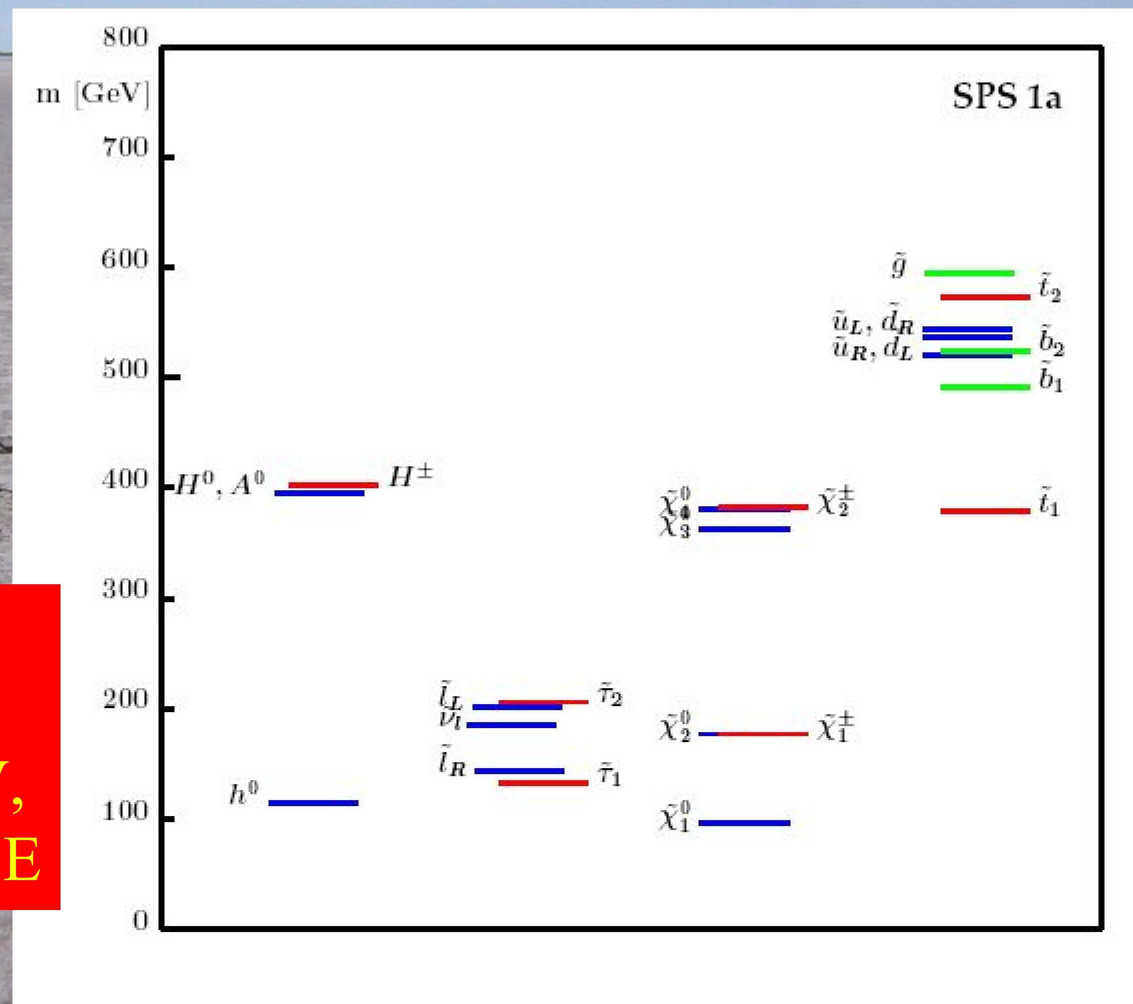




JE + Heinemeyer + Olive + Weiglein

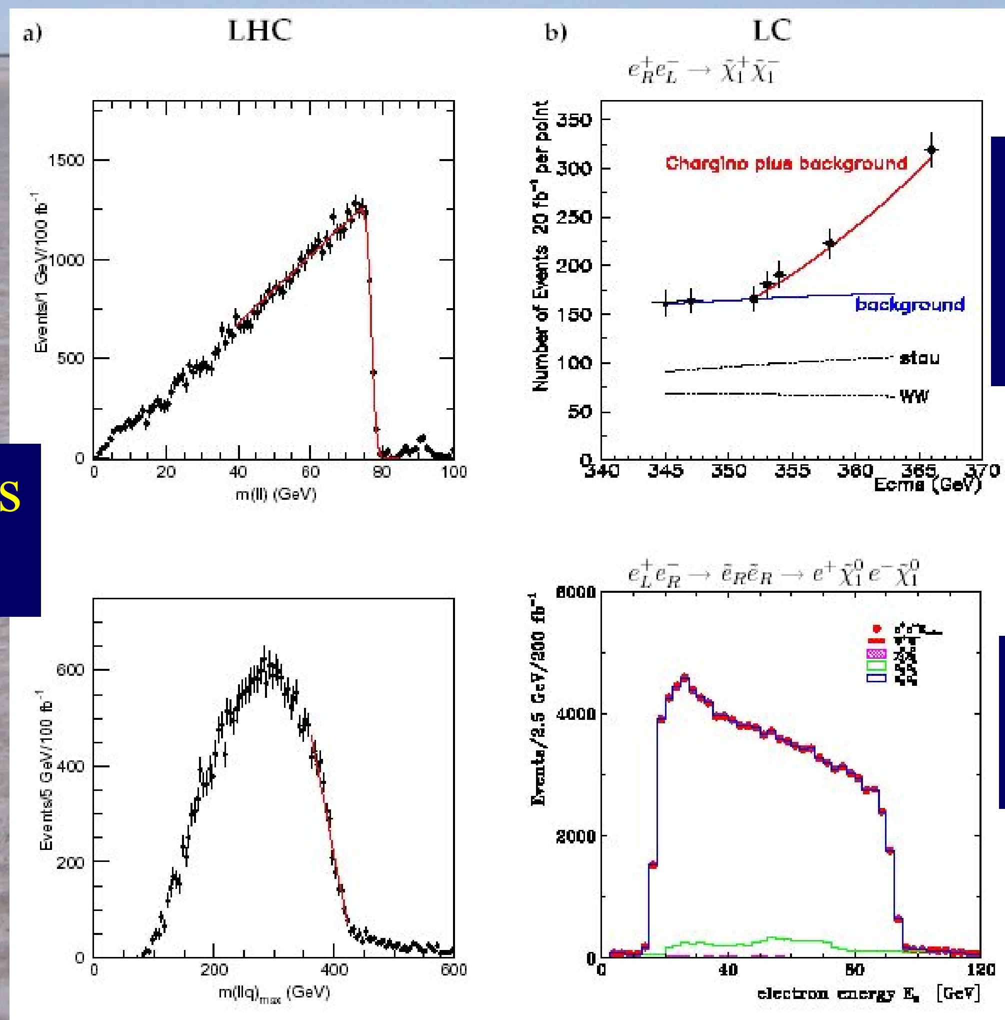
# Example of Benchmark Point

Spectrum of
Benchmark SPS1a
~ Point B of
*Battaglia et al*

Several sparticles
at 500 GeV LC,
more at 1000 GeV,
some need higher E



# Examples of Sparticle Measurements




Spectrum edges @ LHC

Threshold excitation @ LC

Spectra @ LC

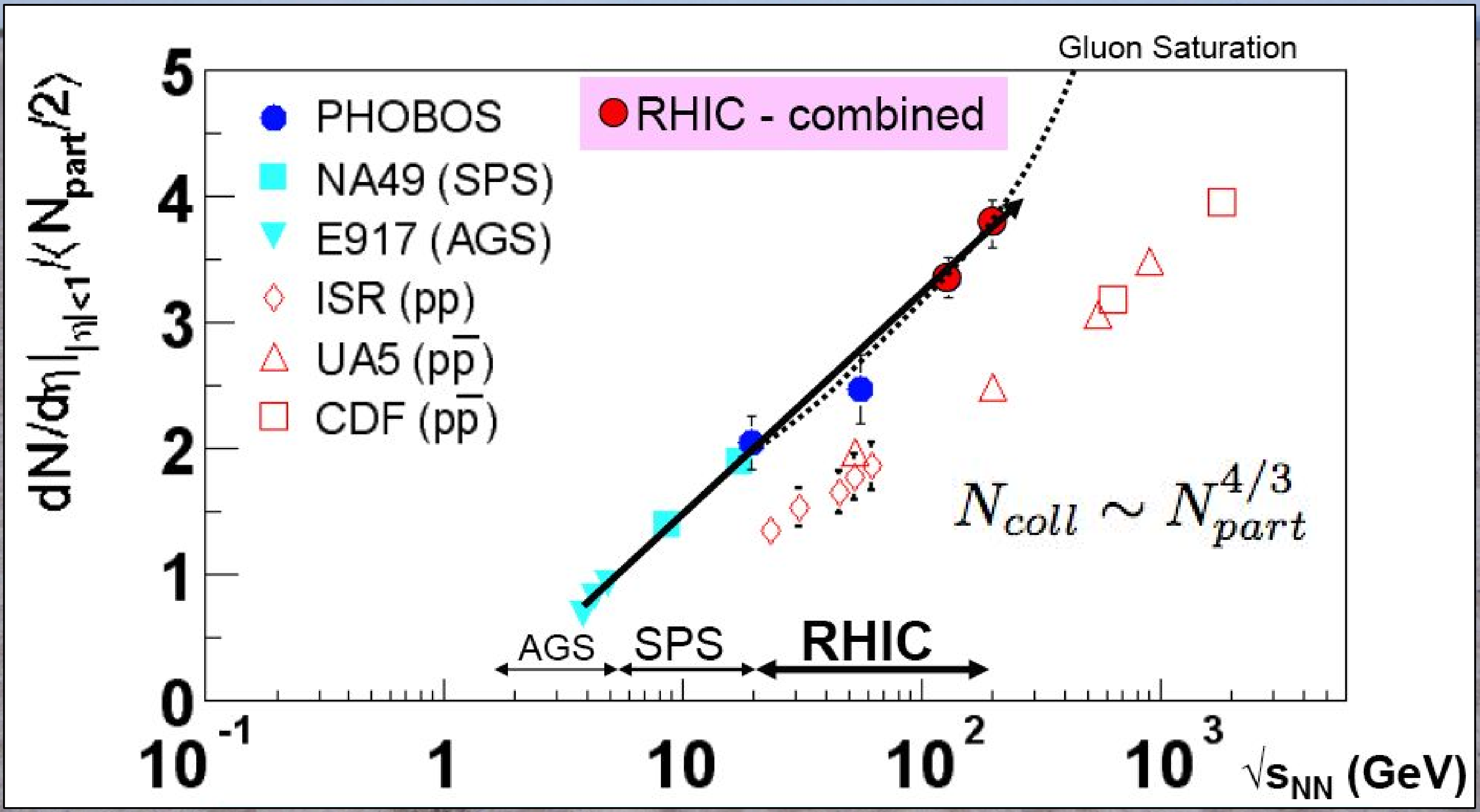
# Added Value of LC Measurements

| | $m_{SPS1a}$ | LHC | LC | LHC+LC | | $m_{SPS1a}$ | LHC | LC | LHC+LC |
|---|---|---|---|---|---|---|---|---|---|
| $h$ | 111.6 | 0.25 | 0.05 | 0.05 | $H$ | 399.6 | | 1.5 | 1.5 |
| $A$ | 399.1 | | 1.5 | 1.5 | $H+$ | 407.1 | | 1.5 | 1.5 |
| $\chi_1^0$ | 97.03 | 4.8 | 0.05 | 0.05 | $\chi_2^0$ | 182.9 | 4.7 | 1.2 | 0.08 |
| $\chi_3^0$ | 349.2 | | 4.0 | 4.0 | $\chi_4^0$ | 370.3 | 5.1 | 4.0 | 2.3 |
| $\chi_1^\pm$ | 182.3 | | 0.55 | 0.55 | $\chi_2^\pm$ | 370.6 | | 3.0 | 3.0 |
| $\tilde{g}$ | 615.7 | 8.0 | | 6.5 | | | | | |
| $\tilde{t}_1$ | 411.8 | | 2.0 | 2.0 | | | | | |
| $\tilde{b}_1$ | 520.8 | 7.5 | | 5.7 | $\tilde{b}_2$ | 550.4 | 7.9 | | 6.2 |
| $\tilde{u}_1$ | 551.0 | 19.0 | | 16.0 | $\tilde{u}_2$ | 570.8 | 17.4 | | 9.8 |
| $\tilde{d}_1$ | 549.9 | 19.0 | | 16.0 | $\tilde{d}_2$ | 576.4 | 17.4 | | 9.8 |
| $\tilde{s}_1$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 17.4 | | 9.8 |
| $\tilde{c}_1$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] |
| $\tilde{e}_1$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| $\tilde{\mu}_1$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| $\tilde{\tau}_1$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| $\tilde{\nu}_e$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

## Determination of CMSSM parameters

| | SPS1a | StartFit | LHC | $\Delta_{LHC}$ | LC | $\Delta_{LC}$ | LHC+LC | $\Delta_{LHC+LC}$ |
|---|---|---|---|---|---|---|---|---|
| $M_0$ | 100 | 500 | 100.03 | 4.0 | 100.03 | 0.09 | 100.04 | 0.08 |
| $M_{1/2}$ | 250 | 500 | 249.95 | 1.8 | 250.02 | 0.13 | 250.01 | 0.11 |
| $\tan\beta$ | 10 | 50 | 9.87 | 1.3 | 9.98 | 0.14 | 9.98 | 0.14 |
| $A_0$ | -100 | 0 | -99.29 | 31.8 | -98.26 | 4.43 | -98.25 | 4.13 |

# Hadron multiplicities: the effect of parton coherence



# Nuclear Modification of Hard Parton Scattering