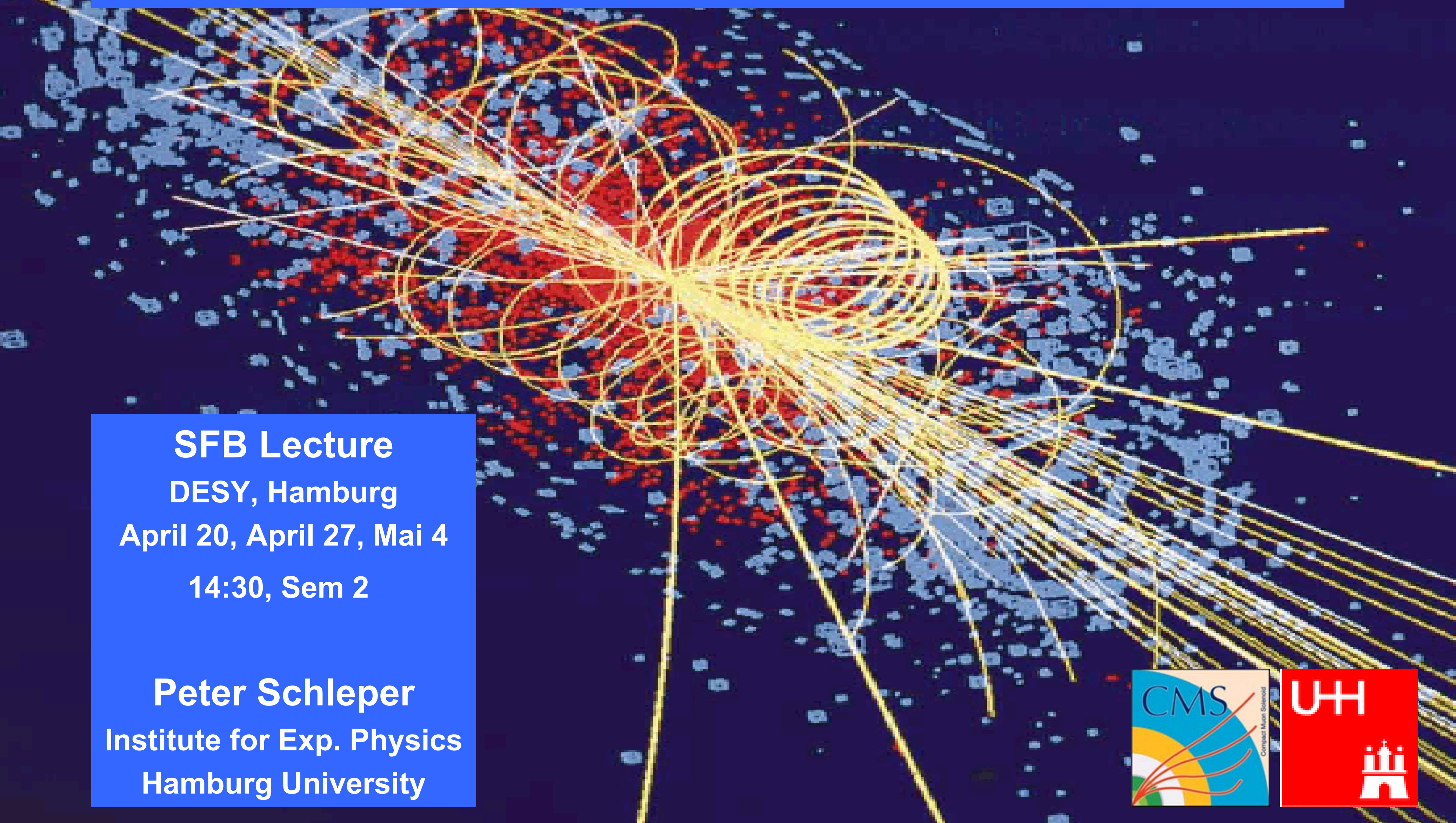
Early Bird Physics at the Large Hadron Collider



SFB Lecture

DESY, Hamburg

April 20, April 27, Mai 4

14:30, Sem 2

Peter Schleper

Institute for Exp. Physics

Hamburg University

Outline

Lecture 1

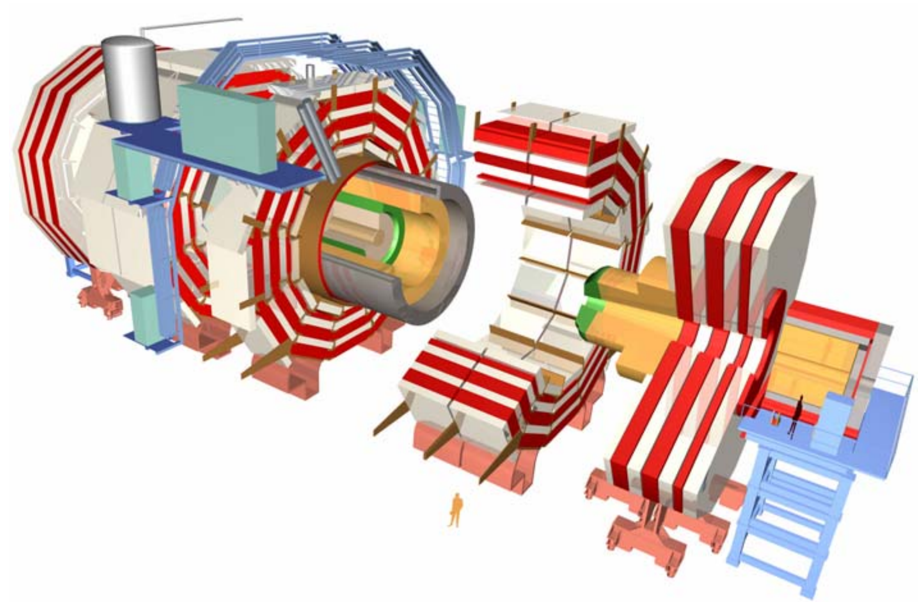
- Motivation
- LHC & Experiments
- Cross Sections
- Higgs

Lecture 2

- Experiments
- SUSY

Lecture 3

- SUSY
- Outlook: SLHC



No comprehensive overview

- Selected topics
- Experimental issues
- Focus on first 3 years of data taking

Literature

In detail:

CMS / ATLAS TDRs

Reviews:

GENERAL-PURPOSE DETECTORS FOR THE LARGE HADRON COLLIDER

Daniel Froidevaux and Paris Sphicas

Annu. Rev. Nucl. Part. Sci. 2006. 56:375–440

TASI 2004 Lecture Notes on Higgs Boson Physics

Laura Reina, hep-ph/0512377

Weak Scale Supersymmetry

H.Baer, X. Tata, Cambridge University Press

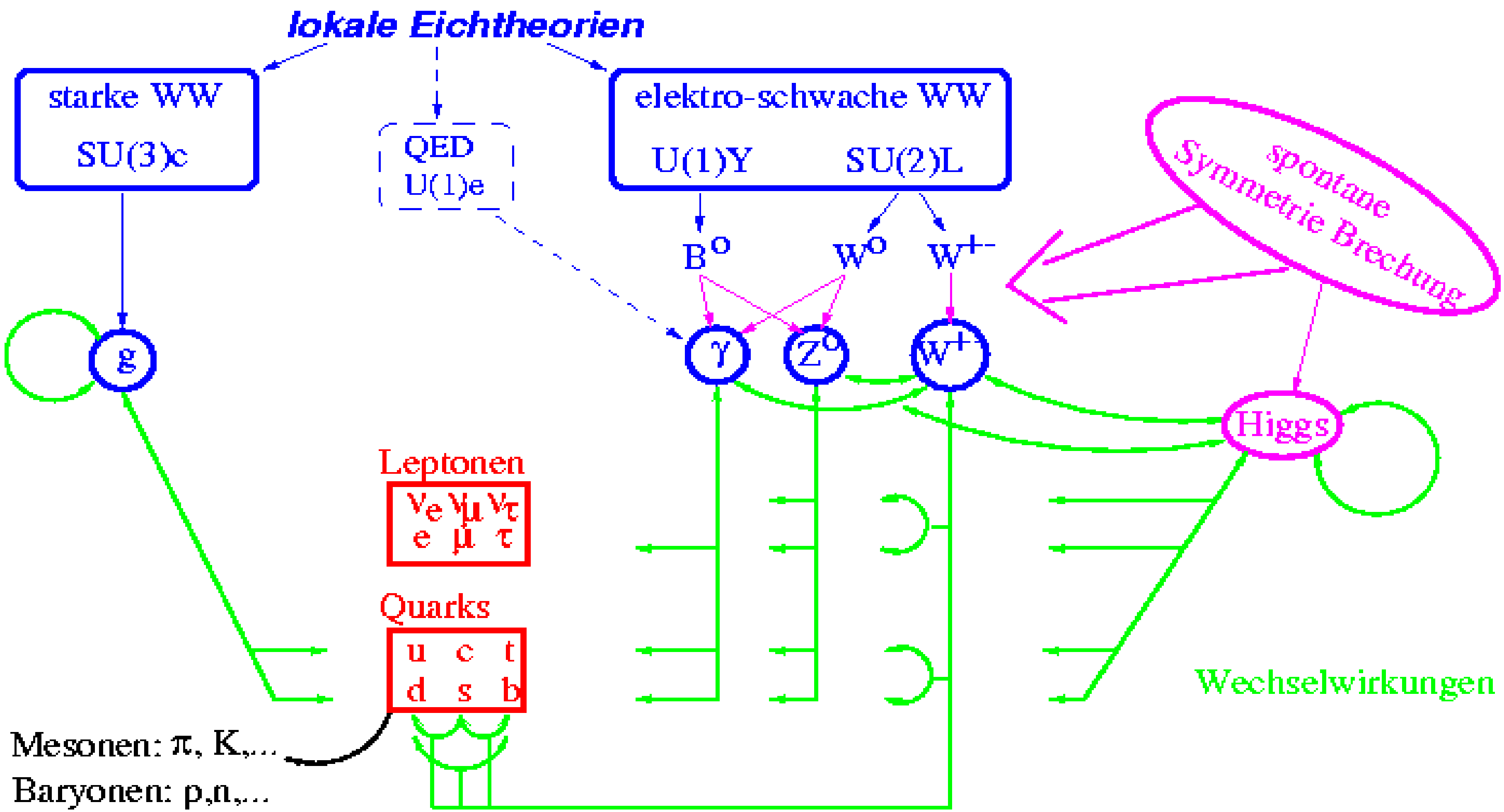
Supersymmetry facing experiment

L. Pape, D.Treille, Rep. Prog. Phys. 69 (2006) 2843-3067

Supersymmetry at LHC

G.Ridolfi, F. Gianotti, CERN academic lectures, 2003

The Standard-Modell



17 particles, 26 constants

The Standard Model

Theory

- U(1) x SU(2) x (SU(3)
- Local gauge field theory, EWSB
- Renormalizable
- Free of anomalies
- Predictive power:
  - W, Z, top, Higgs
  - running of couplings
- Arbitraryness:
  - Construction principle
  - 17 particles, 26 constants
- Incomplete:
  - Limited at High Energies (>1 TeV)
  - Hierarchy problem, M_H

→ GUT, SUSY, Gravity, …

→ SUSY: $M_{H,}$ $M_{GUT,}$ Dark matter

Experiment

- All (?) data correctly described
- Consistent picture of all interactions below 200 Ge

→ Outstanding success of the SM

- Higgs particle not discovered
- No experimental confirmation of EWSB
- Cosmology: Dark Matter, Dark Energy

Tension between experiment and theory

→ Time for a decisive experiment: LHC

LHC motivation

Principal Goals (J. Ellis)

- **Explore a new energy / distance scale**
  resolution 10^{-19} m

- **Look for 'the' Higgs boson**
  Standard Model Higgs / SUSY Higgs

- **Look for supersymmetry / extra dimensions, …**

- **Find something the theorists did not expect**

The LHC accelerator

History

- Planned and build since ~ 1985
- Collisions 2007/08 – 2015 ?

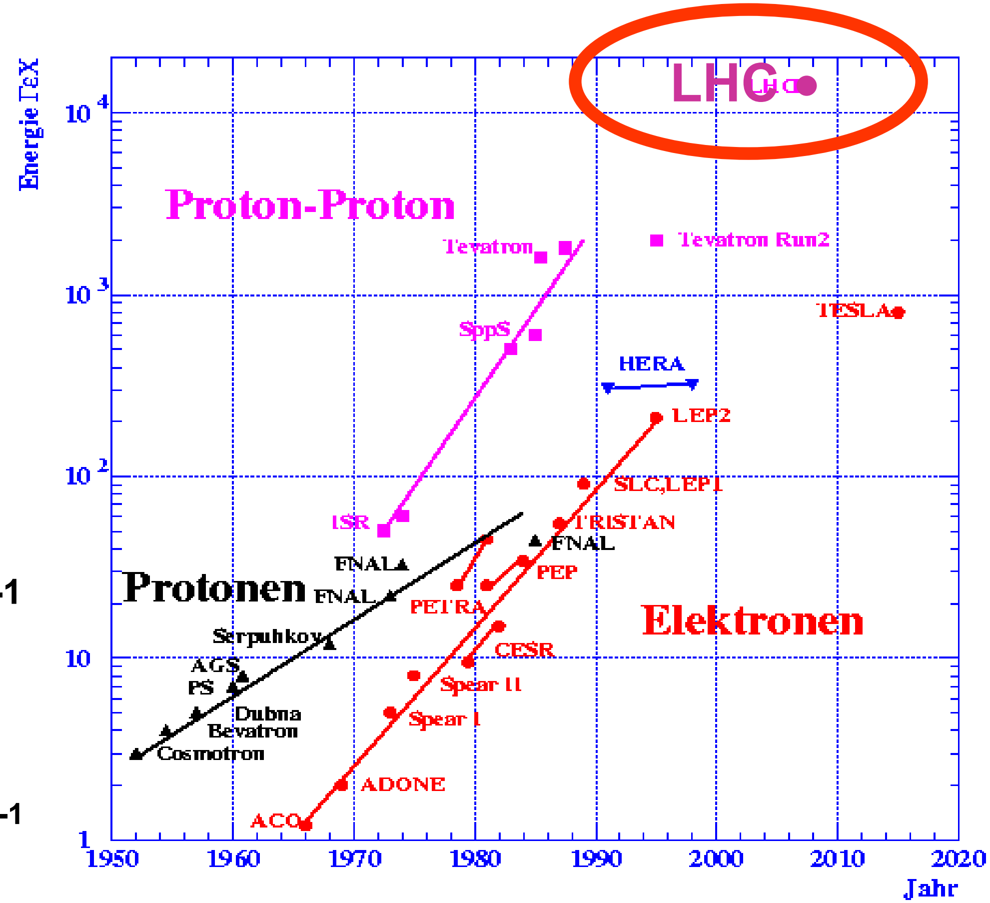
Design

- Proton-Proton at sqrt(s) = 14 TeV
- Luminosity up to L = 10^{34} cm^{-2} s^{-1}

  → per year L_{int} = 100 fb^{-1}

  → goal: L_{int} = 300 fb^{-1}

  Tevatron: now: 2.5 fb^{-1}, until 2009: 8 fb^{-1}



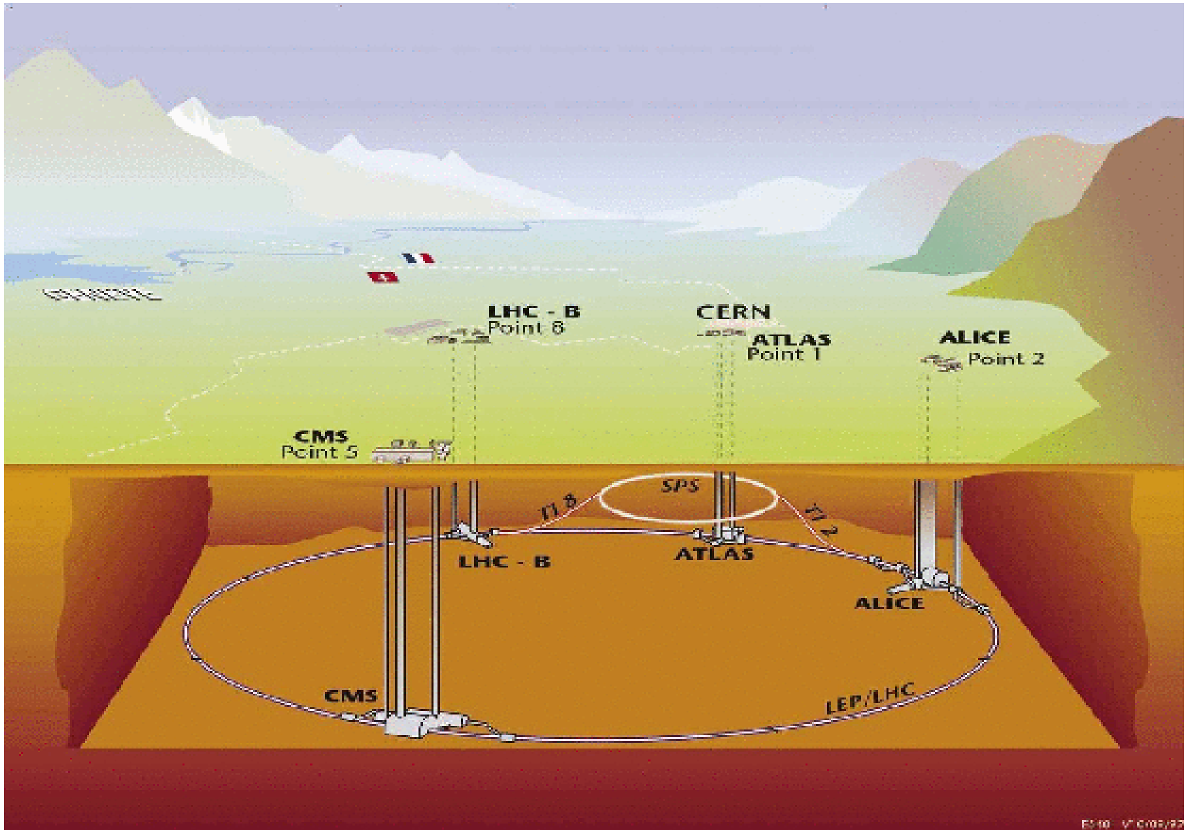
Experiments

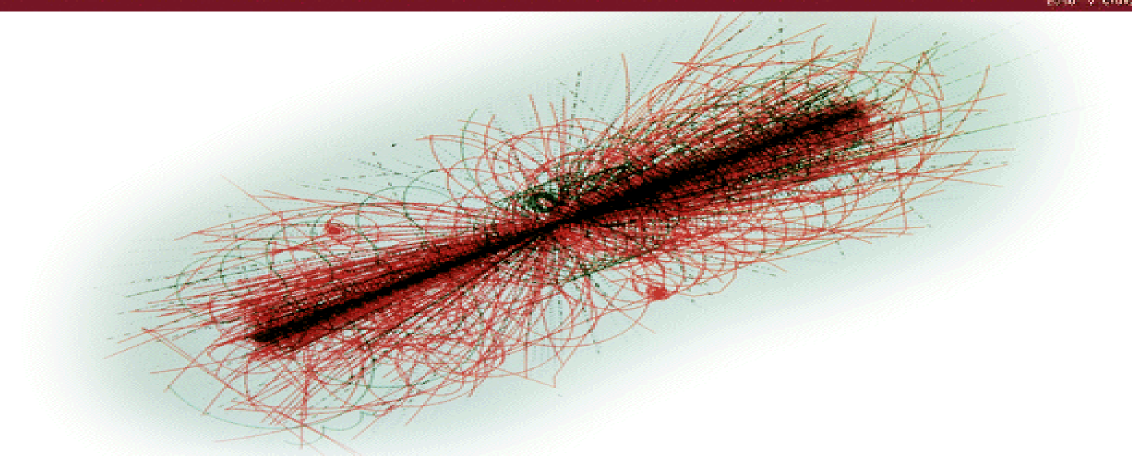
- ATLAS and CMS (+ LHC-B, ALICE)
- ~ 3000 scientists / experiment

Milestone for particle physics

- high expectations → high risk

The Large Hadron Collider (LHC)





- 26.6 km circumference
- 8 T magnets
- 2835*2835 bunches
- 10^{11} protons / bunch
- **Bunch separation:**
  25 ns (f = 40 MHZ)
  7.5 m
- Bunch: 7.5 cm •16 µm •16 µm
- **Luminosity L = 10^{34} cm^{-2} s^{-1}**

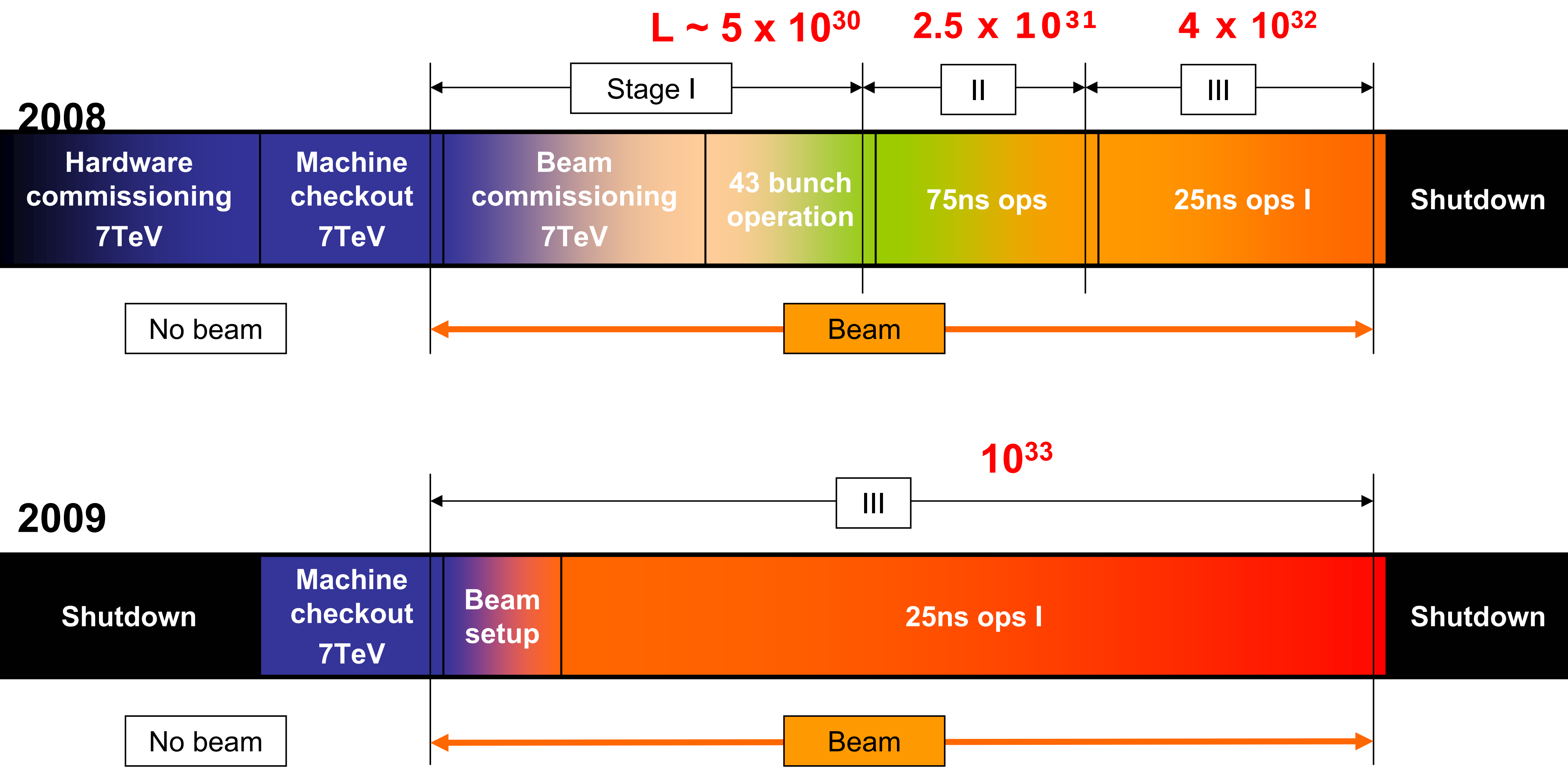
$$L = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

- **Total cross section**
  σ_{tot} = 10^8 nb
- **Interaction rate at full luminosity: 10^9 / s**

→ Overlay of 25 pp interactions within one bunch crossing
→ 1600 charged particles
→ very high demand on detectors

LHC plans

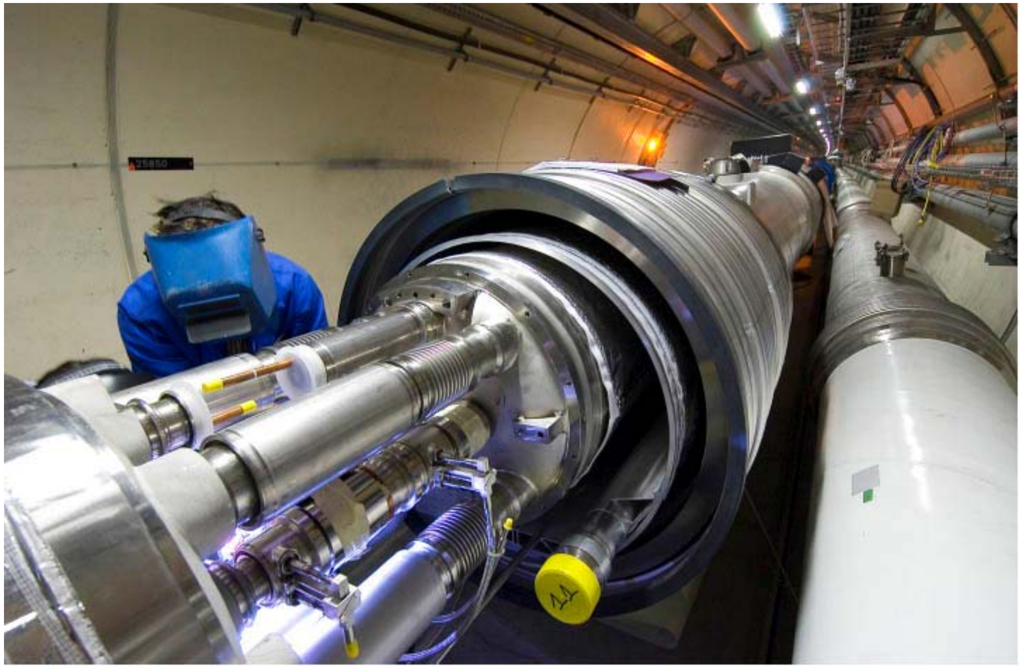
1 fb^{-1} = 120 effective days @ L ~ 10^{32} cm^{-2} s^{-1}



LHC plans

Startup

- Most major components available (?)
- No major problems seen so far
- 30 Aug 07 Beam-pipe closed
- Nov 2007 Pilot run at 900 GeV
- June 2008 Collisions at 14 TeV



Prospects for Luminosity

Low Luminosity period

- 2008 1 fb^{-1}
- 2009 5 fb^{-1}
- 2010 10 fb^{-1}

High Luminosity period

- > 2011 100 fb^{-1} per year
  @ $L = 10^{34}\ cm^{-2}\ s^{-1}$

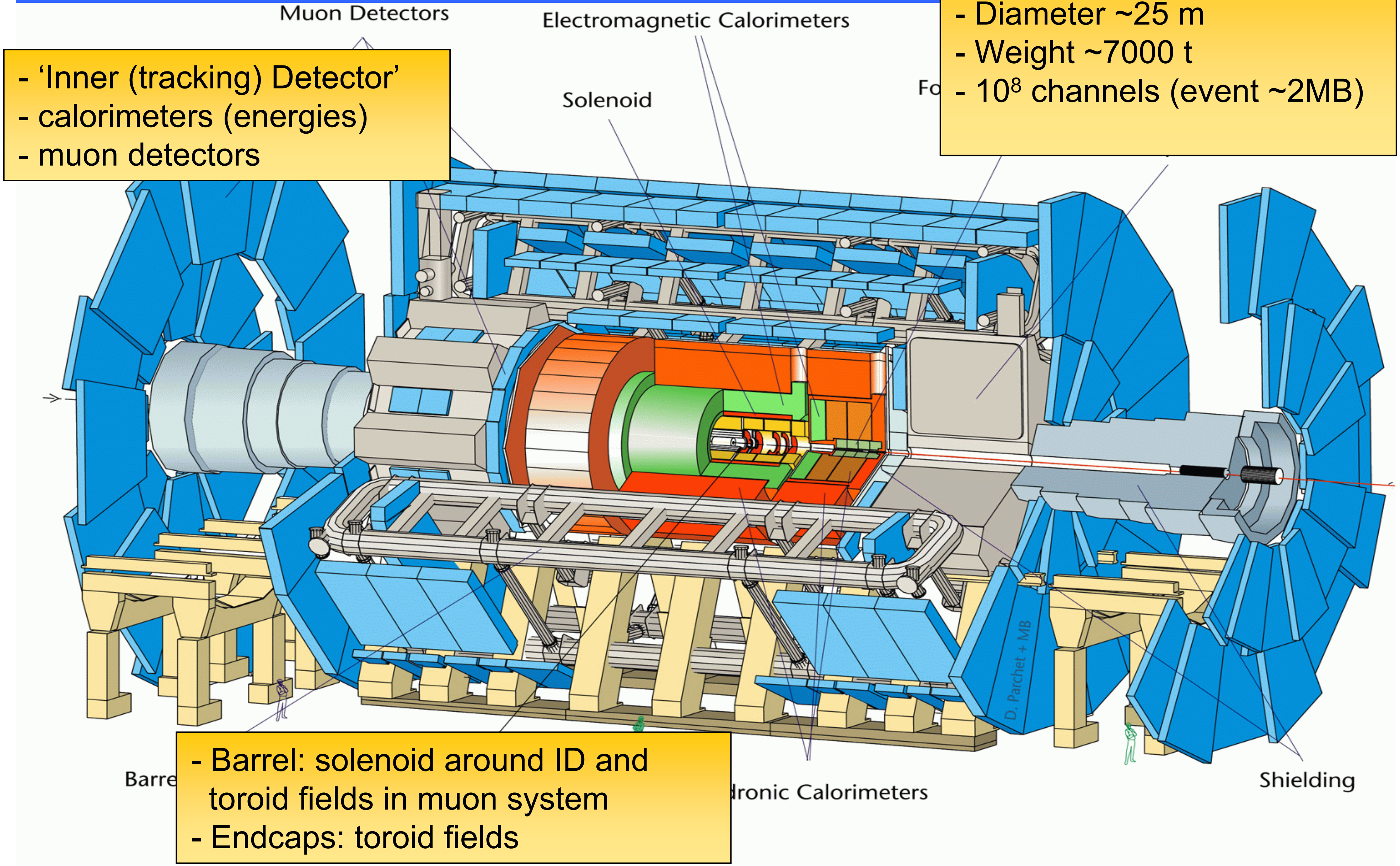
Slow startup of luminosity expected

- Experiments prepare for early physics program
- Much less reduced problems with overlay events

THE ATLAS EXPERIM

- Length ~40 m
- Diameter ~25 m
- Weight ~7000 t
- 10^8 channels (event ~2MB)

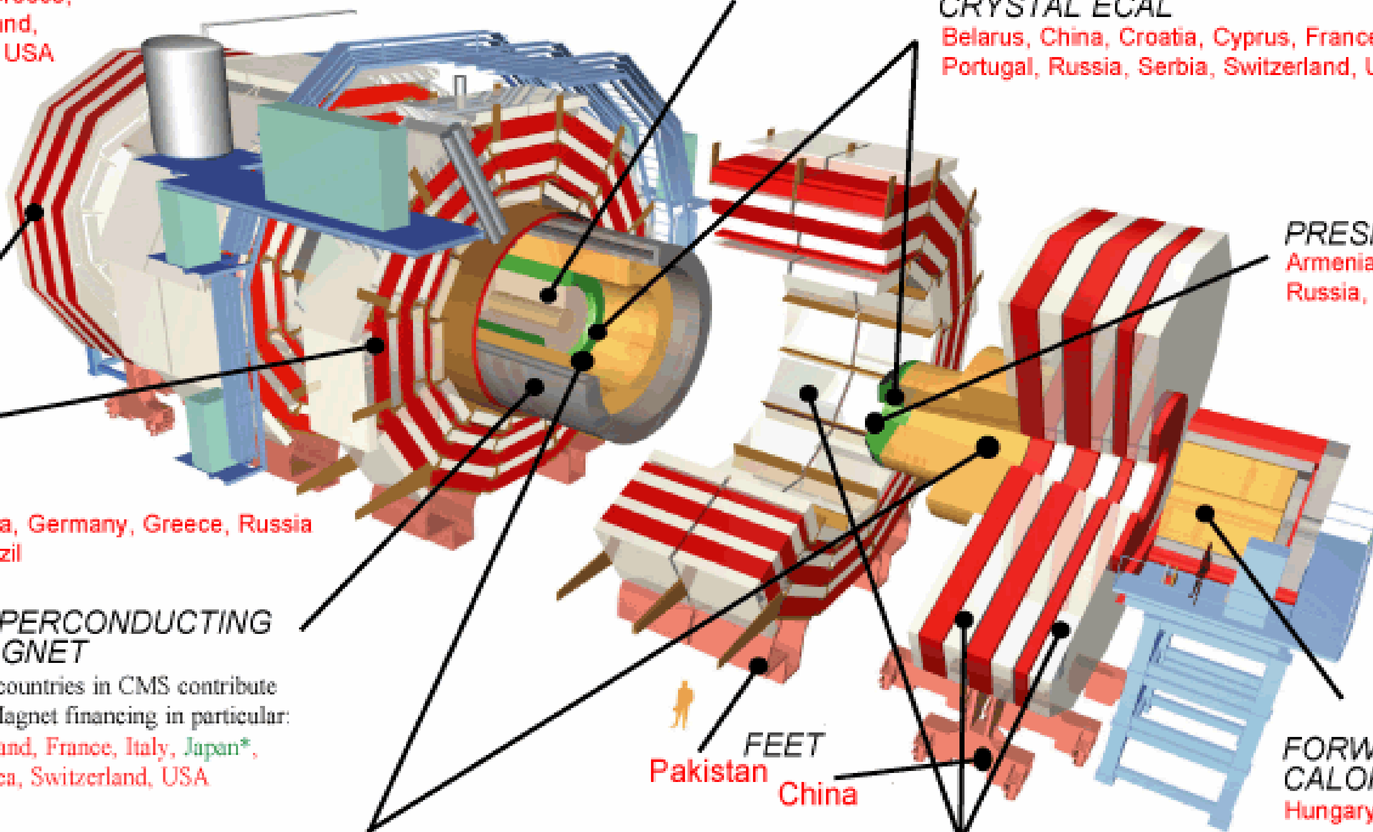
- 'Inner (tracking) Detector'
- calorimeters (energies)
- muon detectors



- Barrel: solenoid around ID and toroid fields in muon system
- Endcaps: toroid fields

CMS Collaboration

36 Nations, 159 Institutions, 1940 Scientists (February 2003)



TRIGGER & DATA ACQUISITION
Austria, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, Finland, France, Germany, Italy, Japan*, New Zealand, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Serbia, Switzerland, UK, USA

PRESHOWER
Armenia, Belarus, Greece, India, Russia, Taipei, Uzbekistan

RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA, Brazil

SUPERCONDUCTING MAGNET
All countries in CMS contribute to Magnet financing in particular: Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET
Pakistan
China

FORWARD CALORIMETER
Hungary, Iran, Russia,Turkey, USA

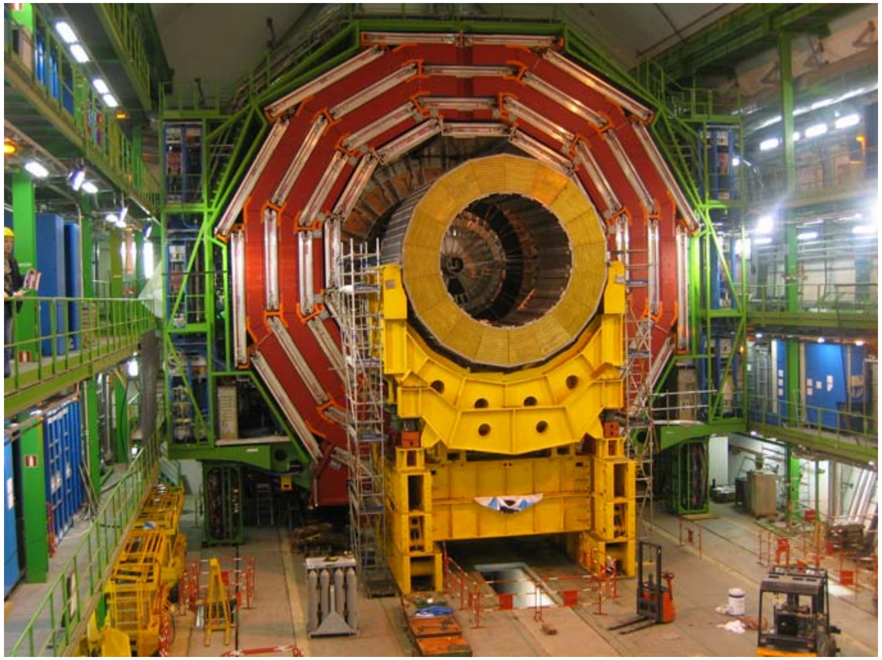
HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

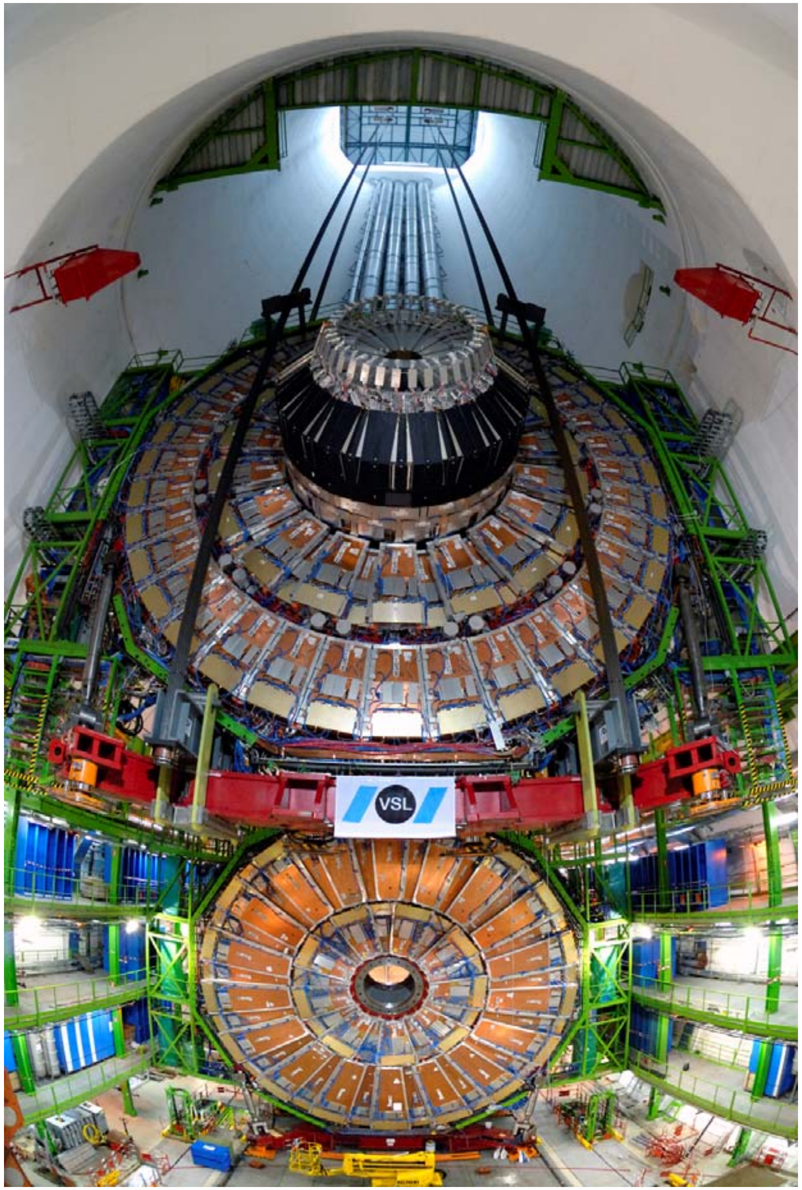
MUON CHAMBERS
Barrel: Austria, Bulgaria, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

Total weight	: 12500 T
Overall diameter	: 15.0 m
Overall length	: 21.5 m
Magnetic field	: 4 Tesla

* Only through industrial contracts

CMS Experiment Status





Experiment Status

CMS: mounted on surface

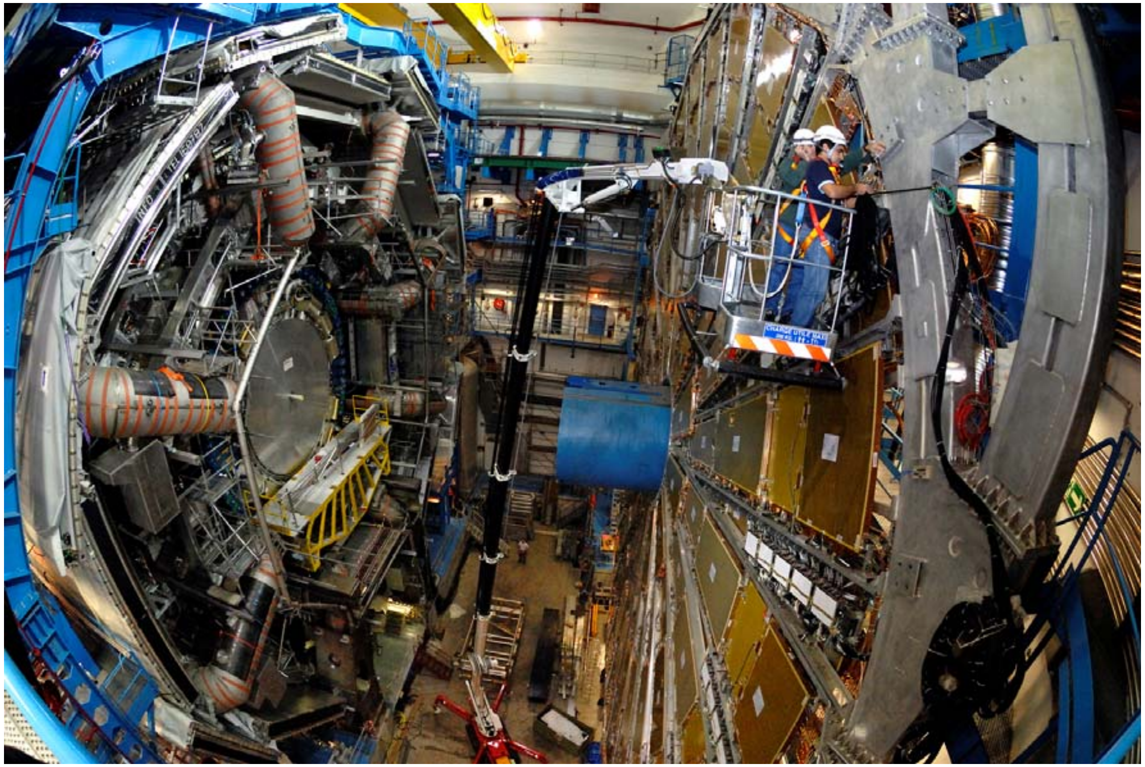
- lowered central part February 28th ,
- 2007: without ECAL endcap and pixels
- 2008: complete detector

ATLAS: mounted in cavern

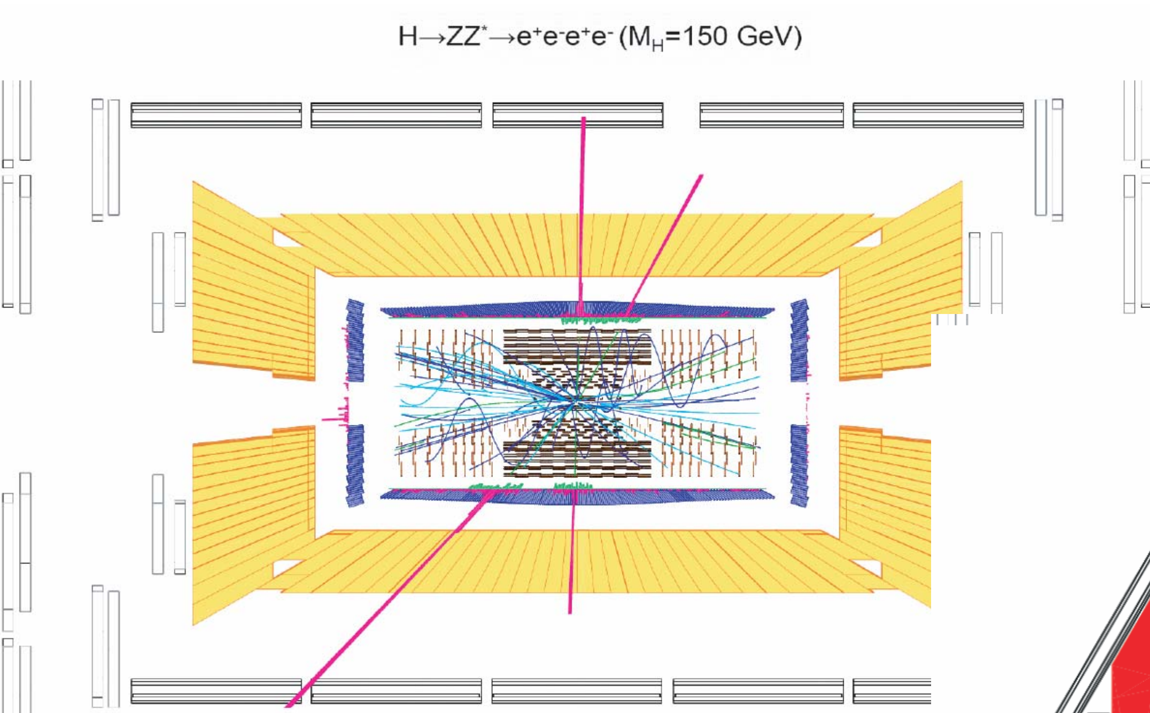
- 2007: almost complete
  (TRT, muon)
- 2008 complete detector

Both: reduced trigger/DAQ capabilities initially

ATLAS

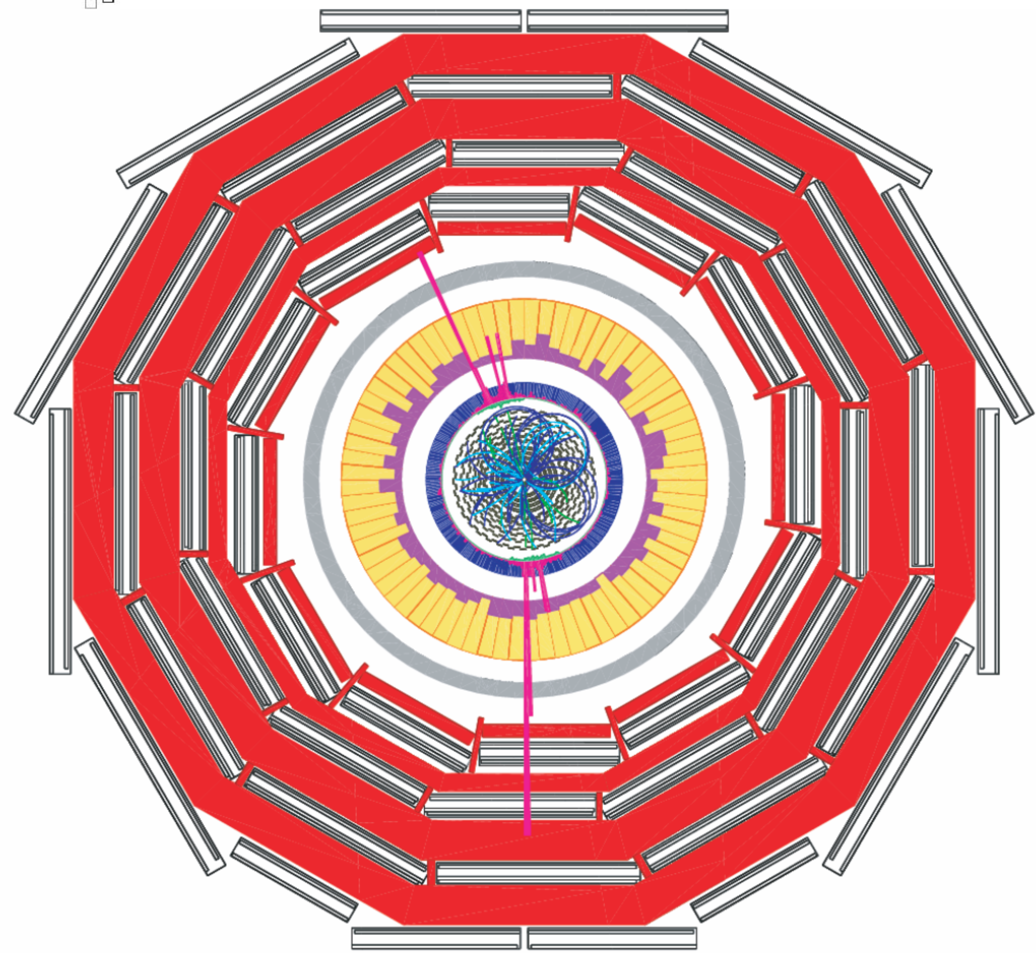


CMS Higgs Simulation



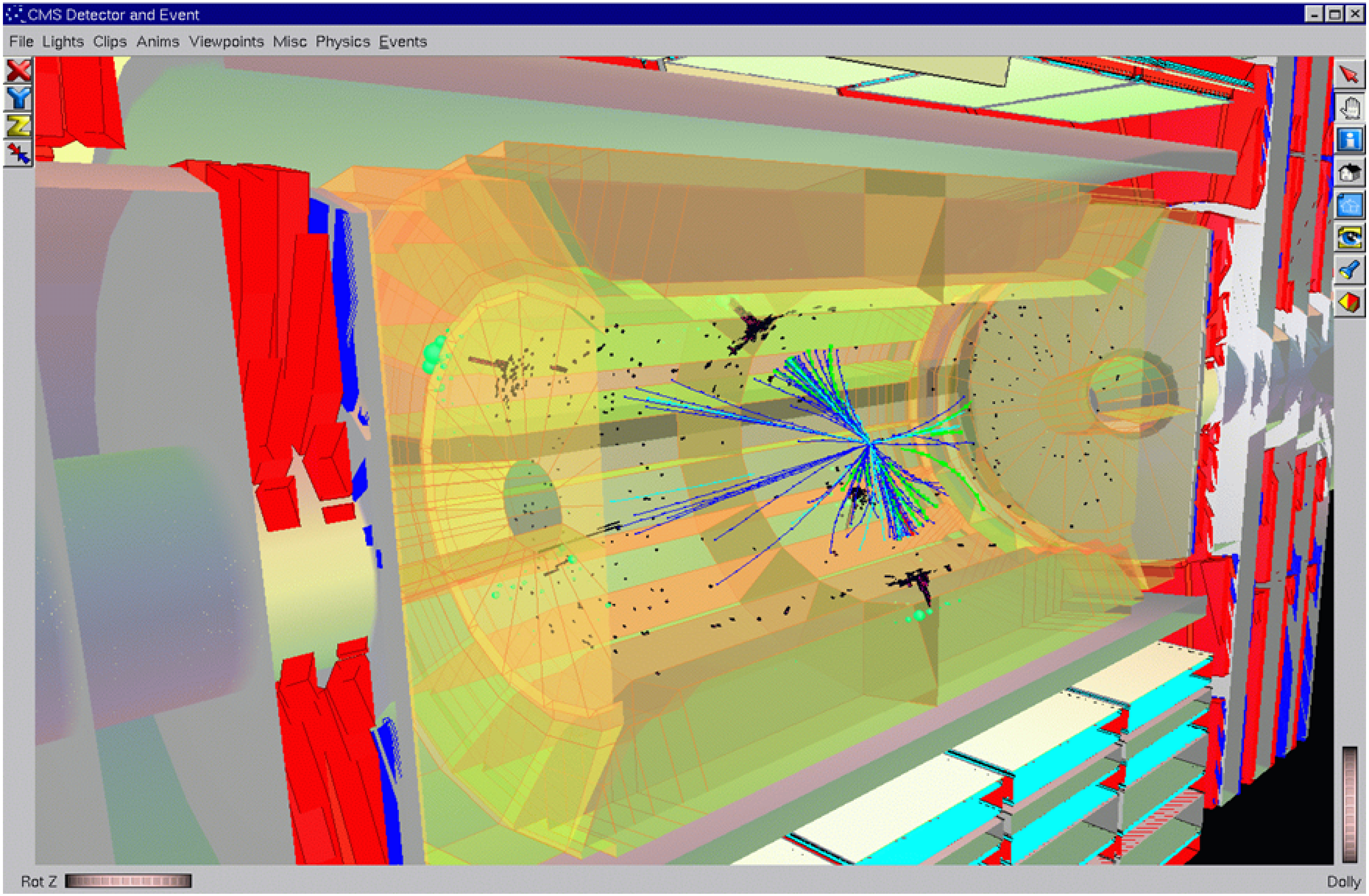
$H \to ZZ \to eeee$

$M_H = 150$ GeV



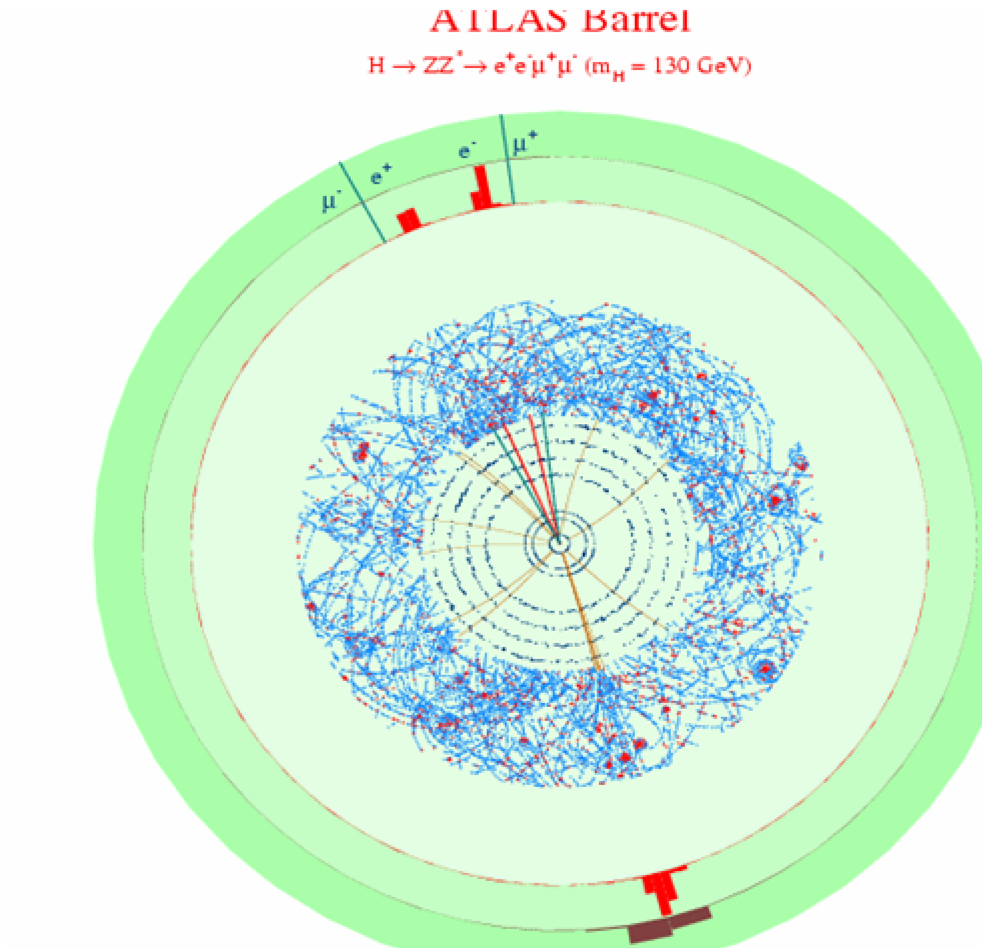
- **Large magnetic field**
- **Low momentum tracks**
- **vanish through beam pipe**

Simulation of event in the CMS detector: Low luminosity



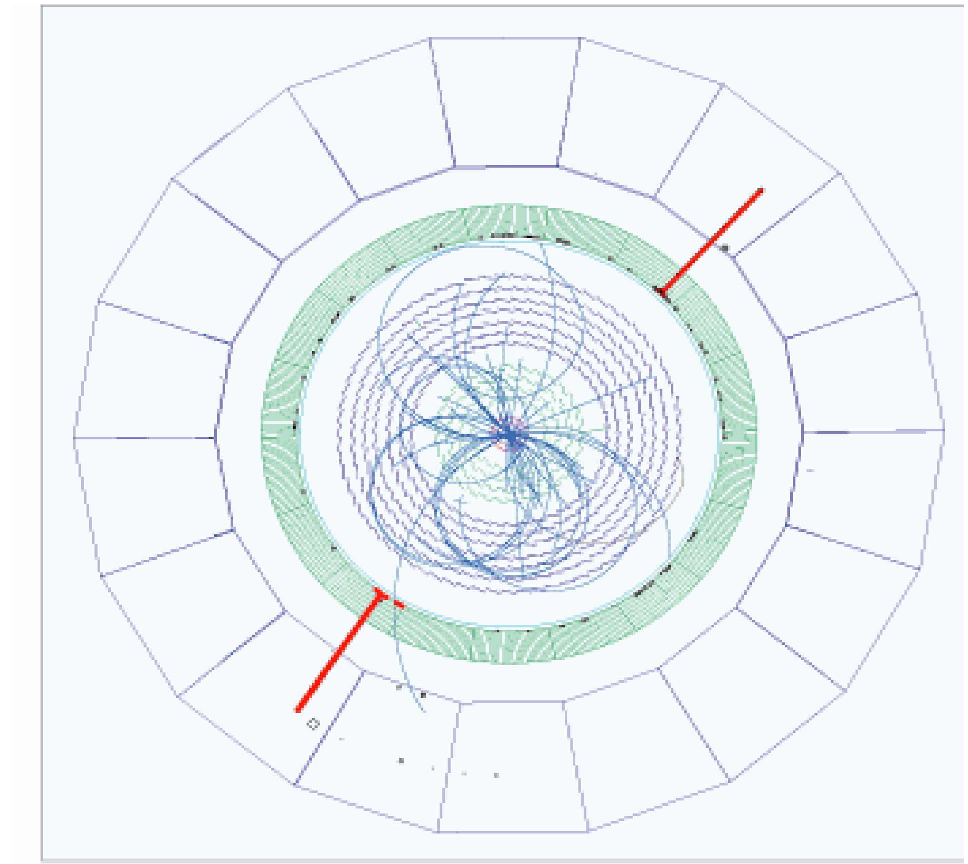
$H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^-$
(m_H = 130 GeV, L=10^{34} $cm^{-2}s^{-1}$)

$H \rightarrow \gamma\gamma$
(m_H = 130 GeV, L=10^{32} $cm^{-2}s^{-1}$)

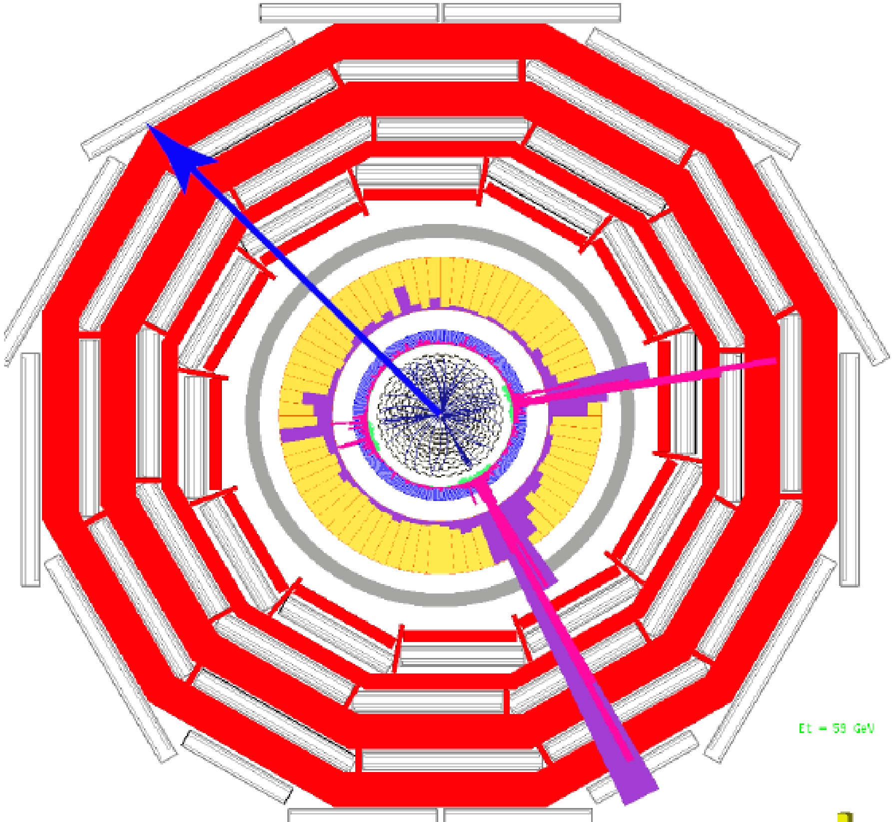


Hard interaction simultaneously
with 24 other interactions

CMS

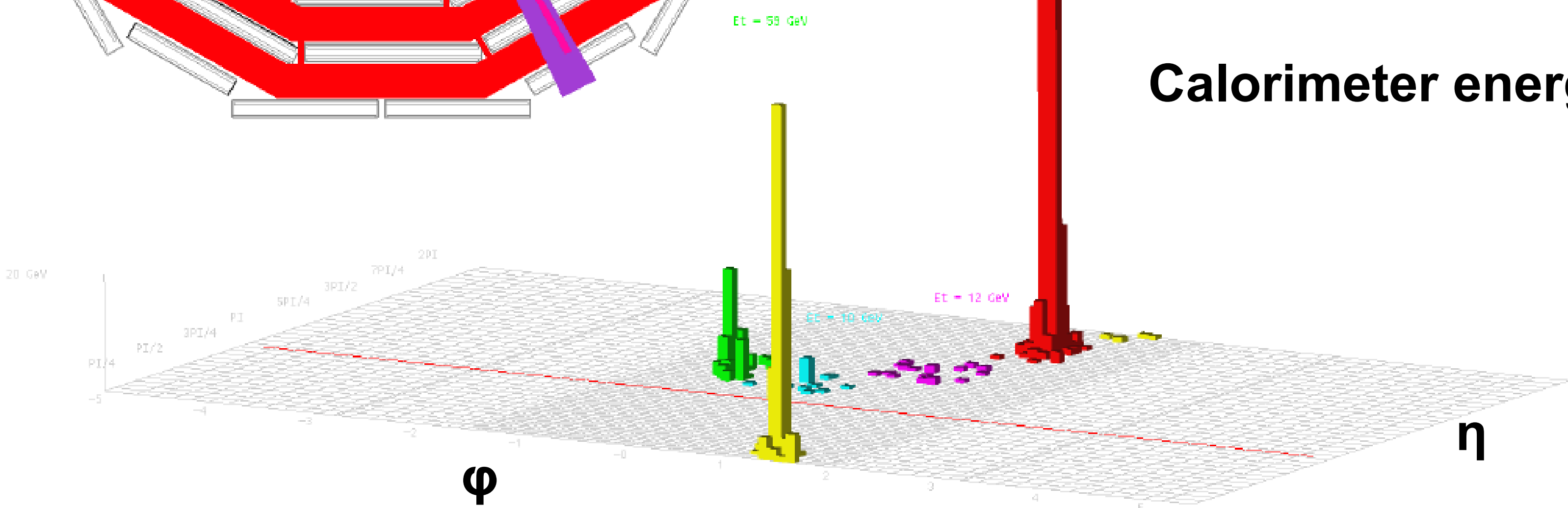


Supersymmetry event simulation



SUSY event: Squark production

- ETmiss = 360 GeV
- ETjet = 330, 140, 60 GeV

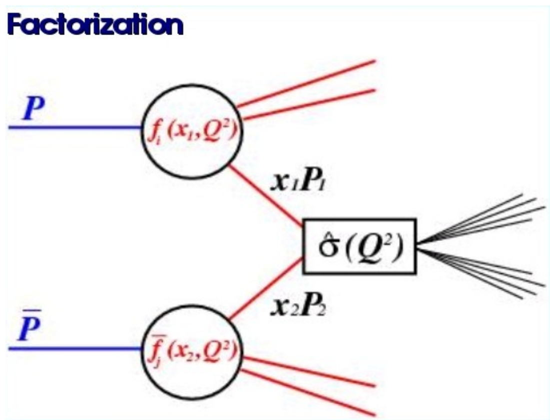


Calorimeter energies

φ

η

Cross sections



$$\sigma = \sum_{i,j} \int_0^1 \mathrm{d}x_1\, \mathrm{d}x_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}$$

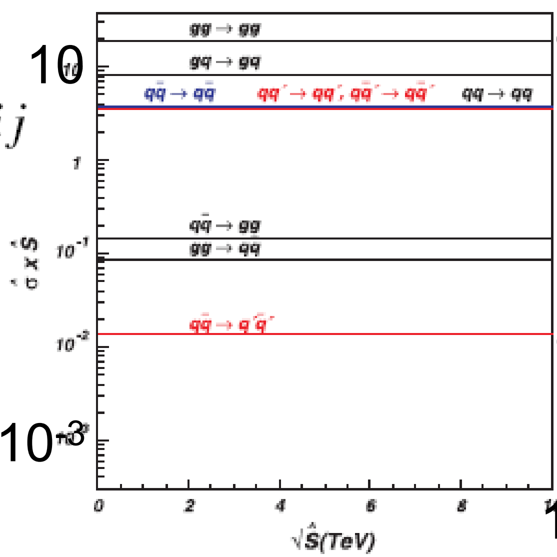
$$\sigma = \sum_{i,j} \int \left(\frac{\mathrm{d}\hat{s}}{\hat{s}}\,\mathrm{d}y\right) \left(\frac{\mathrm{d}L_{ij}}{\mathrm{d}\hat{s}\,\mathrm{d}y}\right) (\hat{s}\,\hat{\sigma}_{ij})$$

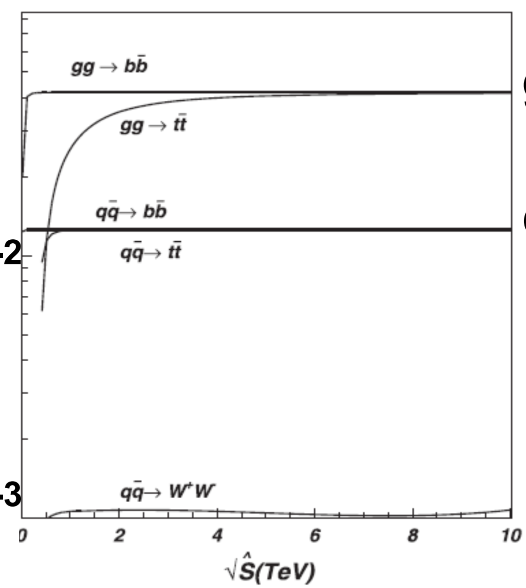
Parton Luminosity

$$\frac{\mathrm{d}L_{ij}}{\mathrm{d}\hat{s}\,\mathrm{d}y} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\,[f_i(x_1,\mu)\,f_j(x_2,\mu) + (1 \leftrightarrow 2)].$$

Partonic cross section

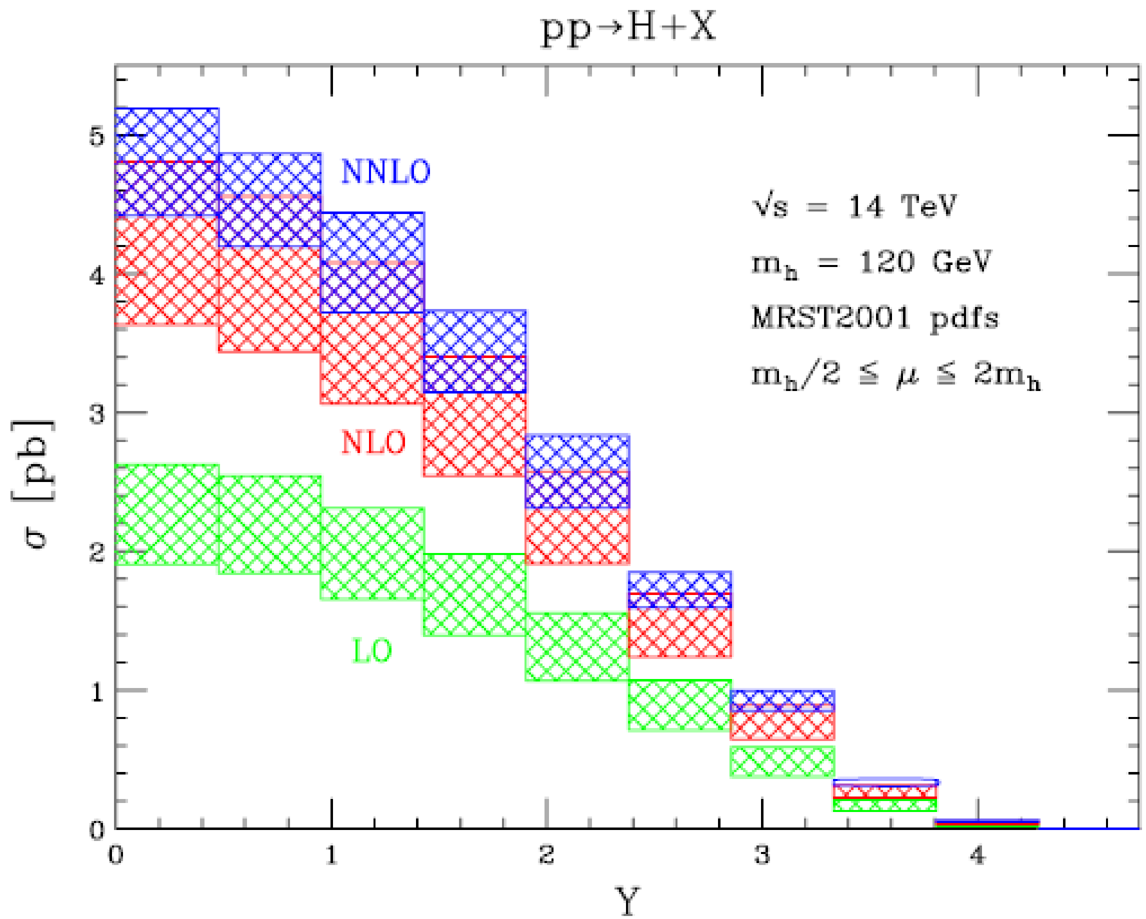
$\hat{s}\,\hat{\sigma}_{ij}$ = 10^{-3} ….20





Higher order calculations

Example: Higgs production



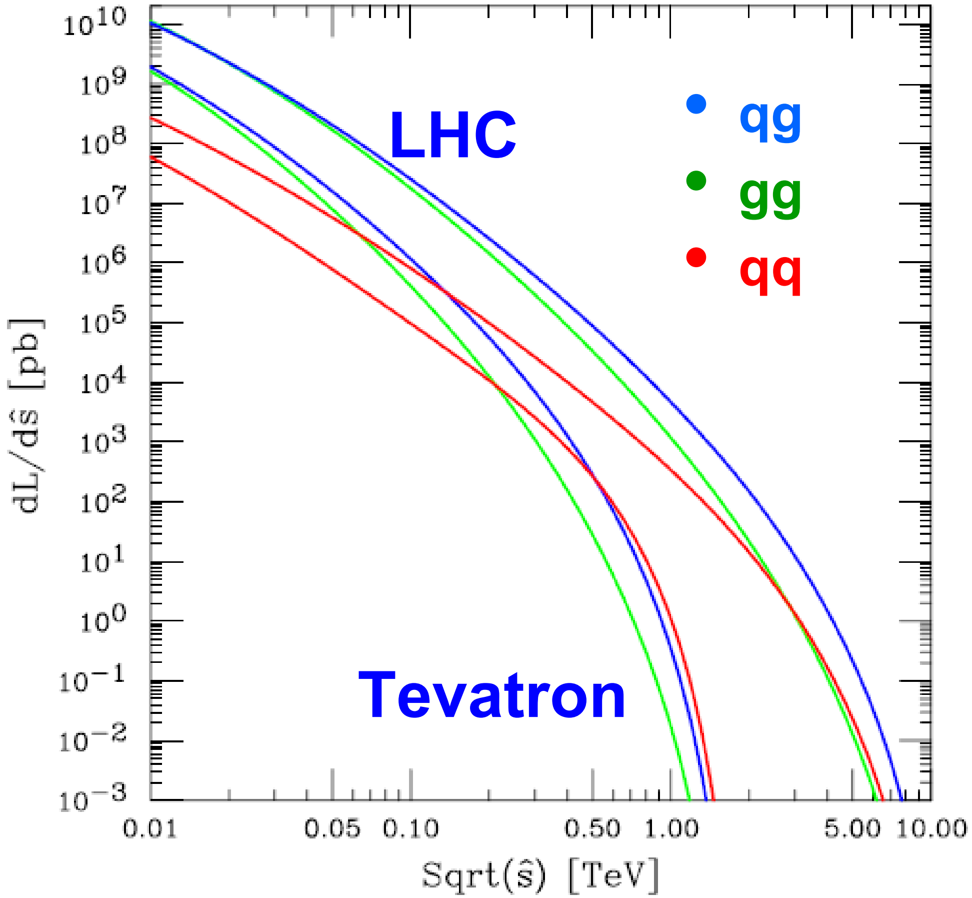
NLO wishlist

process ($V \in \{Z, W, \gamma\}$)

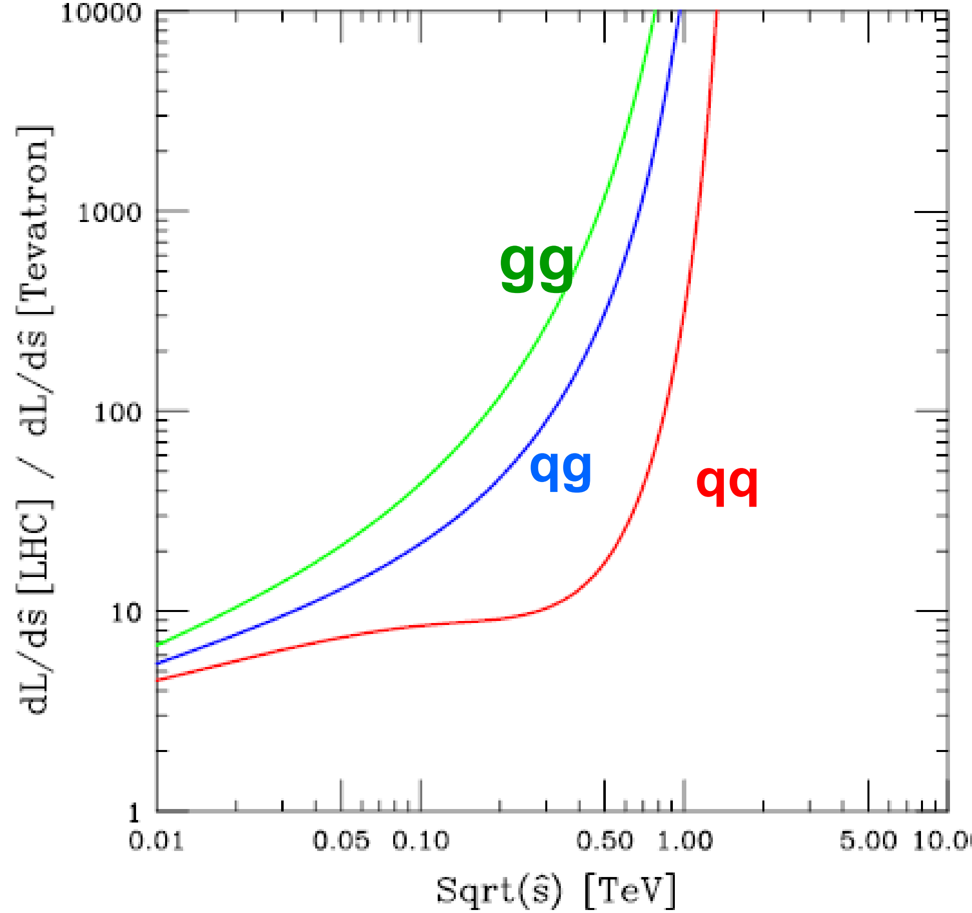
1. $pp \to V\,V + \text{jet}$
2. $pp \to H + 2$ jets
3. $pp \to t\bar{t}\,b\bar{b}$
4. $pp \to t\bar{t} + 2$ jets
5. $pp \to V\,V\,b\bar{b}$
6. $pp \to V\,V + 2$ jets
7. $pp \to V + 3$ jets
8. $pp \to V\,V\,V$

Parton Luminosity

Parton Lumi



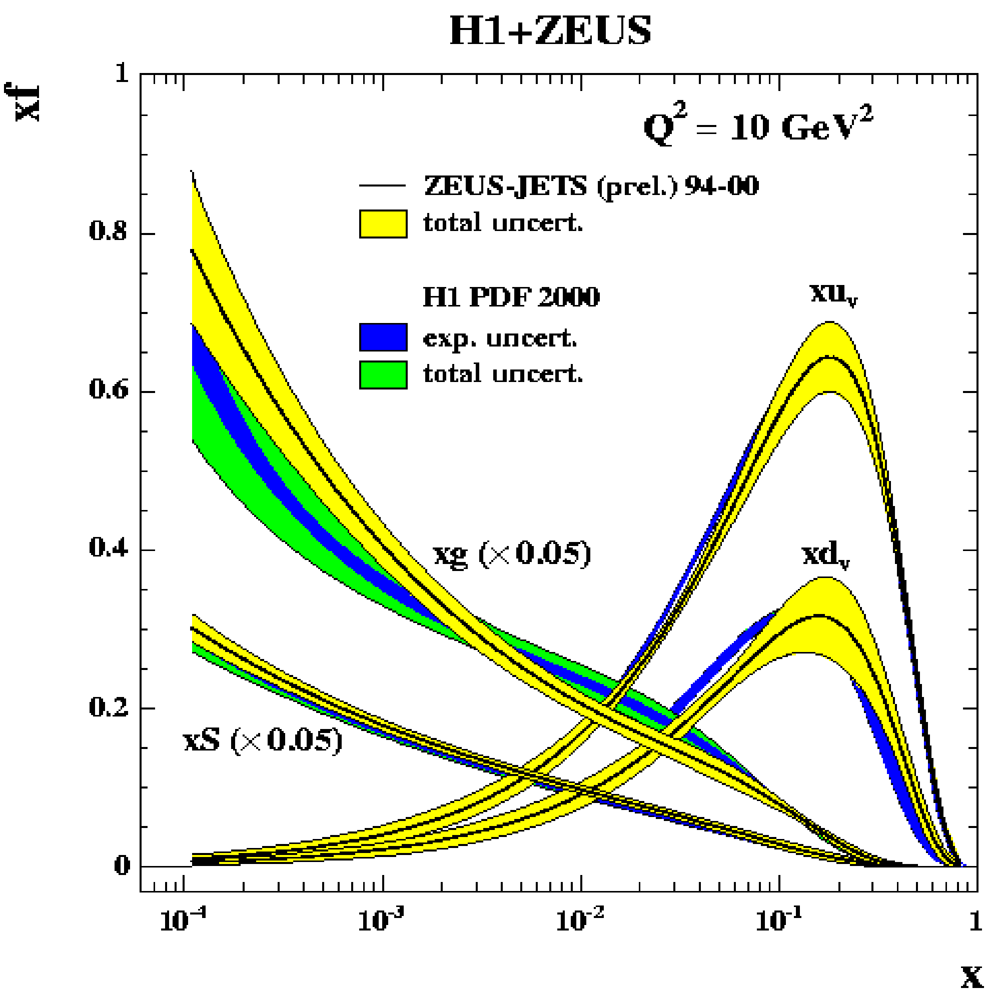
Ratio LHC / Tevatron:



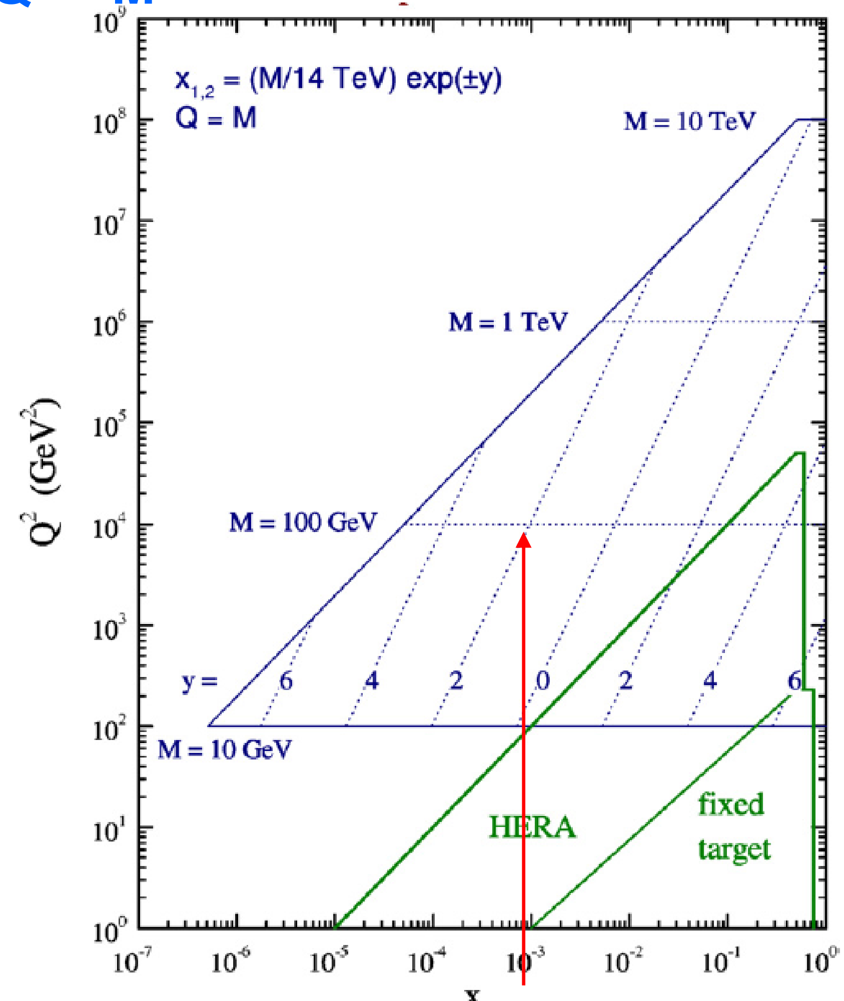
LHC / Tevatron: factor 40 for gg→ H @ M_H= 120 GeV

factor 10000 for gg→ XX @ M_X= 0.5 TeV

Parton densities



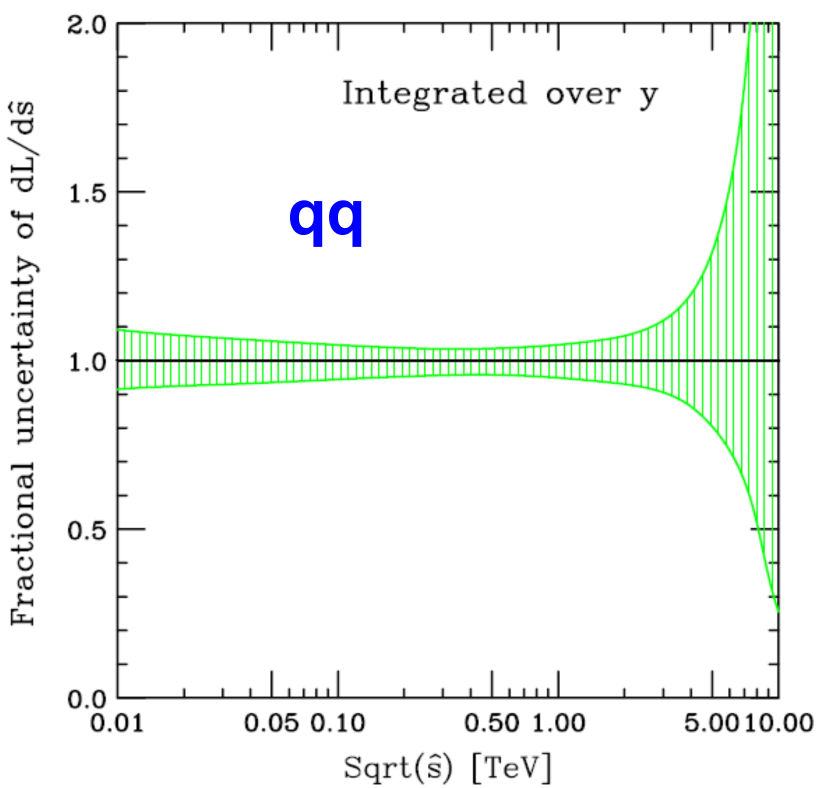
$Q^2 = M^2$

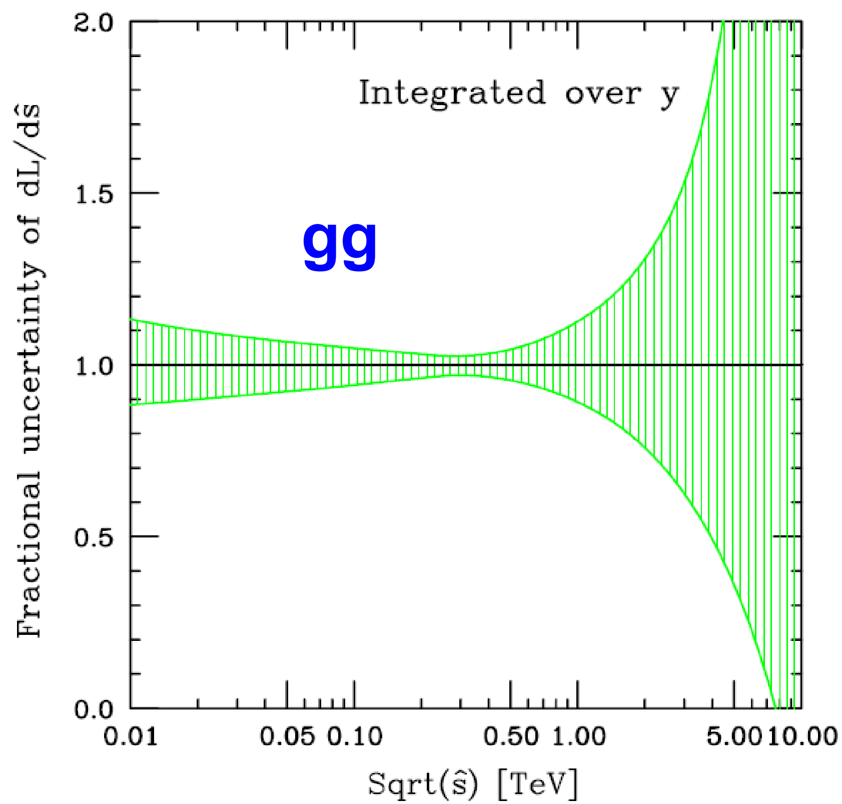


x 10^{-3}

- HERA data has major impact on LHC ($x > 10^{-3}$)
- extrapolation to large Q2 (M2) for LHC

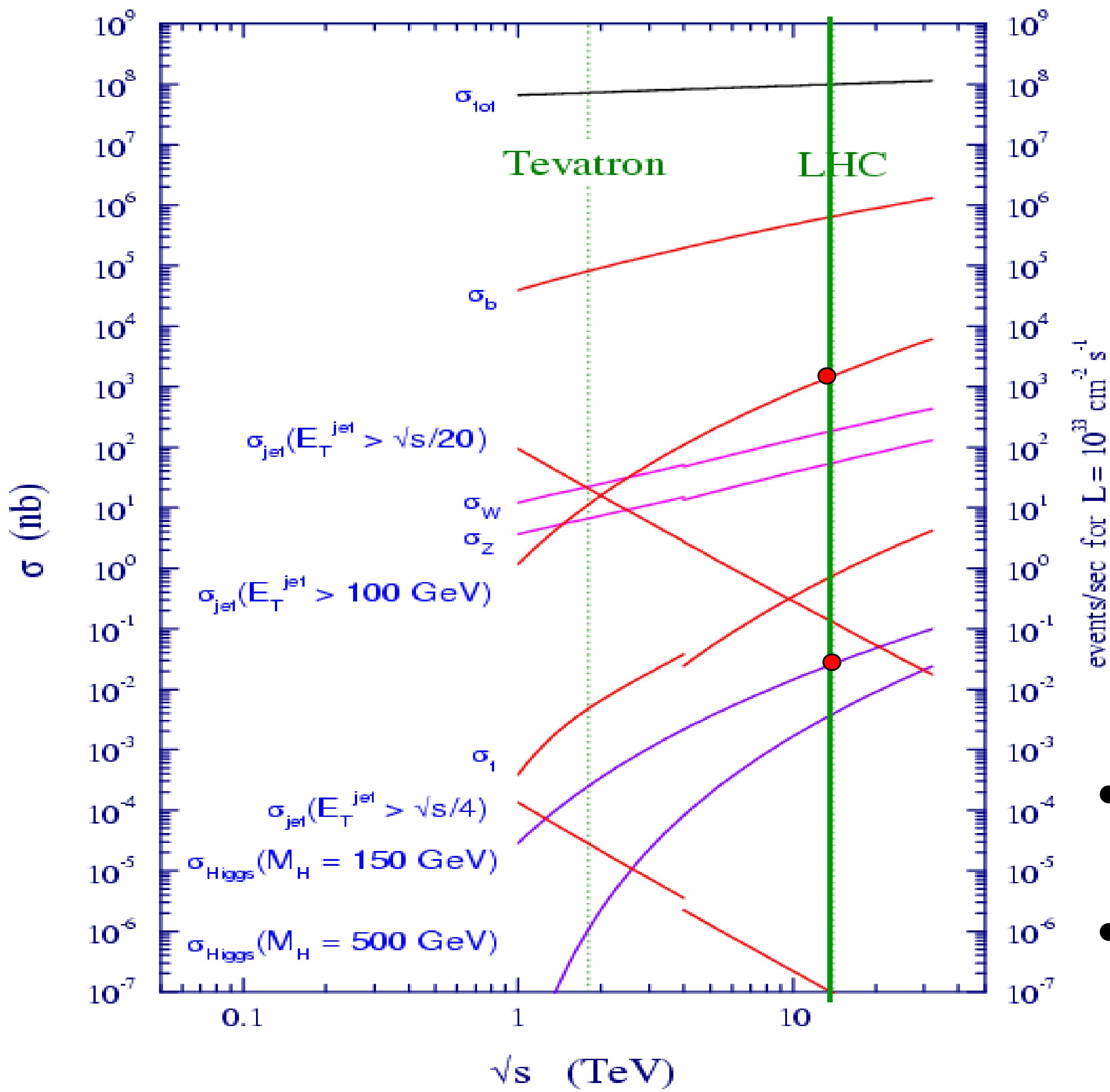
Uncertainty on Parton Luminosity





- **5 – 10 % error up to 2 TeV**
- **No precision for gg processes above ~ 3 TeV**

Cross Sections



10^8 Events per sec @10^{33} cm^{-2}s^{-1}

1000 jets / s (ET>100)

200 W /s 50 Z^0 /s

1 ttbar / s

1 Higgs /min M_H=150 GeV

- Huge event rates for Standard Model processes
- Jets >> W, Z, t , H

Higgs

- Required in the SM for mass terms for all fermions and bosons
- All interactions known: couplings ~ mass
- Not predicted: M_H

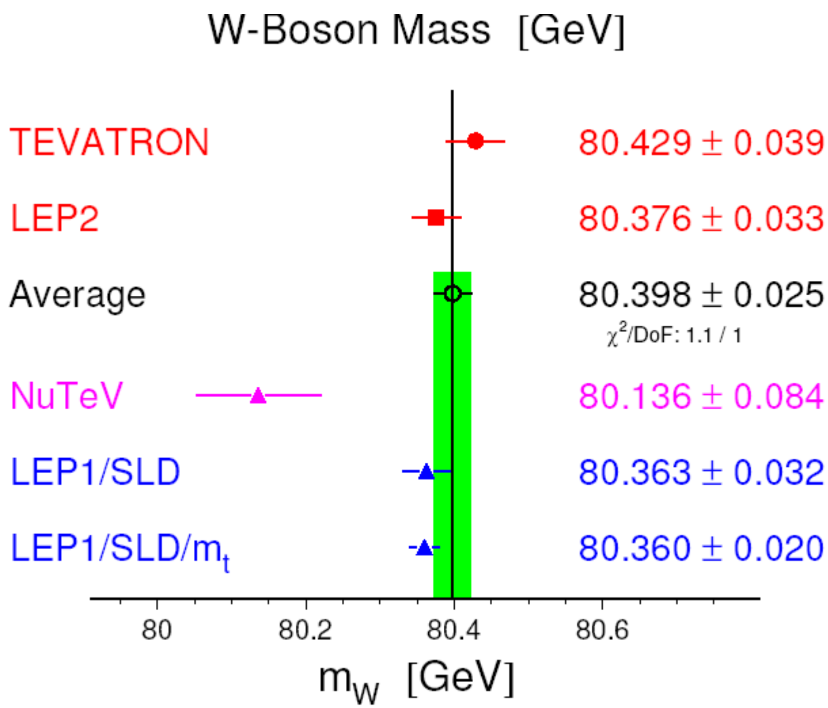
Discovery

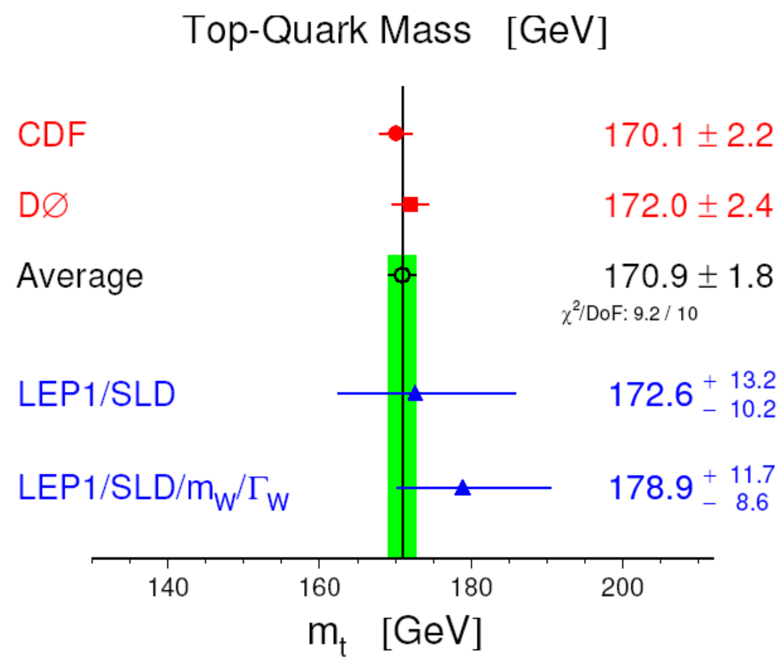
- Reveal the first scalar particle in nature
- Complete the SM
- Symmetry + spont. symmetry breaking
- Would lead the path to physics beyond the SM

→ **Primary goal of LHC**

Electroweak precision meas.: LEP-I final + LEP-II prel.

M_{top} and M_W: new results from Tevatron (Mar 07)





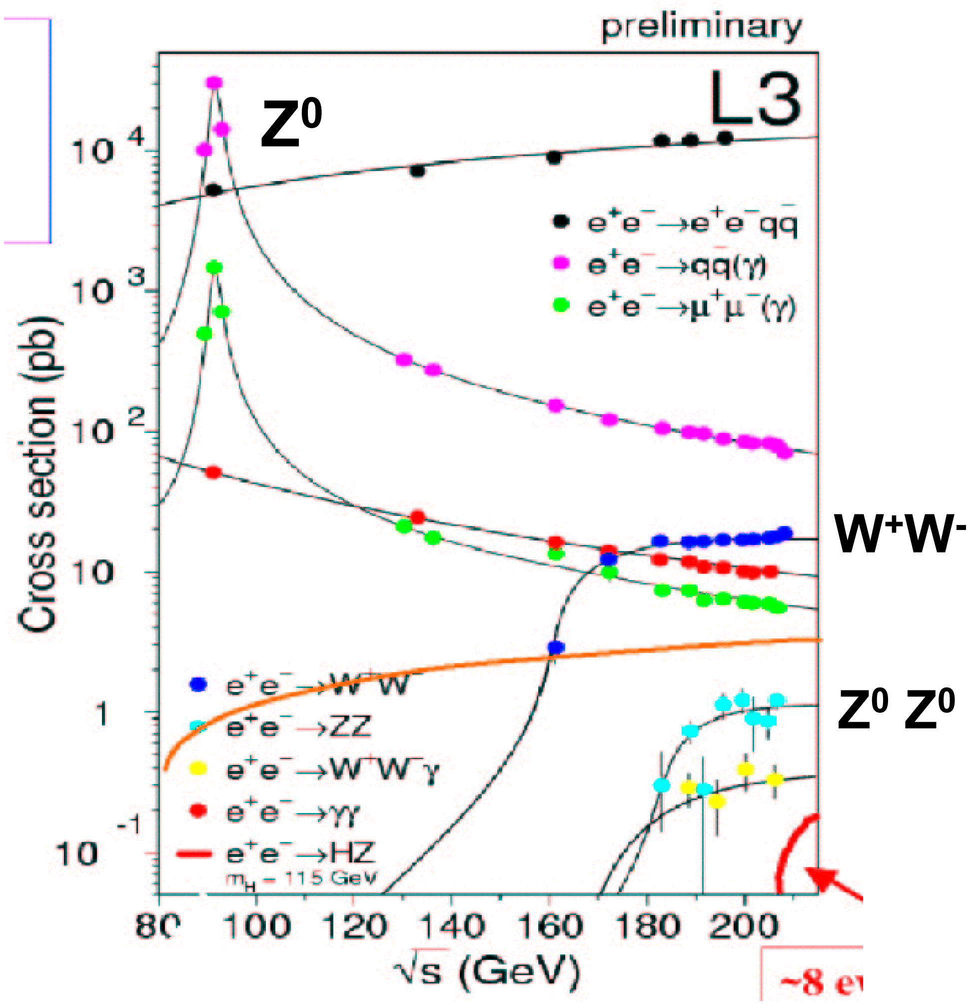
$M_W = 80.398 \pm 0.025\ \mathrm{GeV}/c^2$

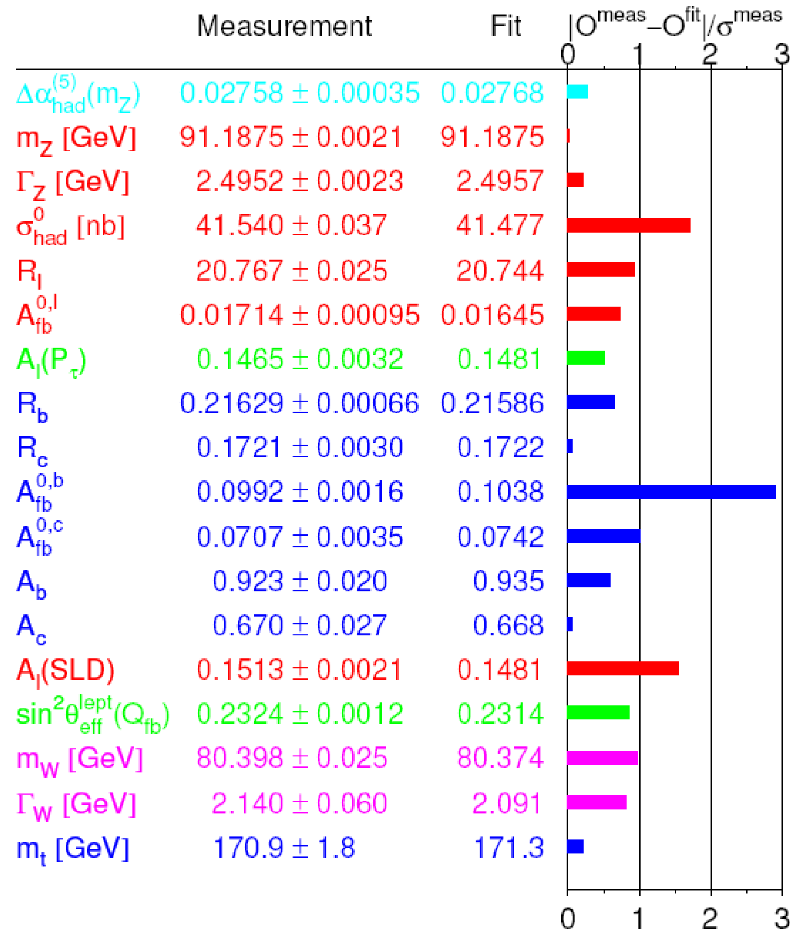
$M_{top} = 170.9 \pm 1.8\ \mathrm{GeV}/c^2$

Higgs mass constraints

LEP: $e^+e^- \rightarrow$ ….

Precision test of the SM

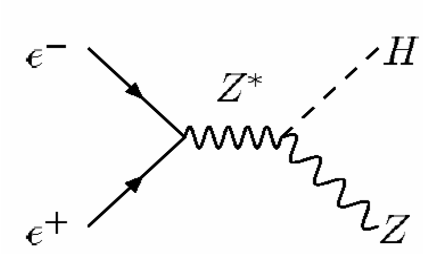


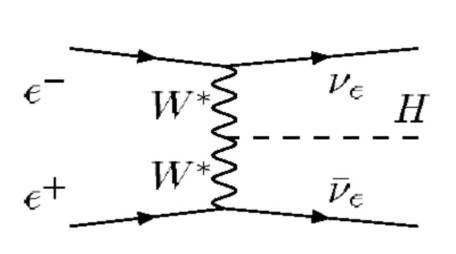


	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1875	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ^0_{had} [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21586	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.374	
Γ_W [GeV]	2.140 ± 0.060	2.091	
m_t [GeV]	170.9 ± 1.8	171.3	

Alle data consistent with the SM if M_H exists at low masses (Theoretical bounds: next lecture)

Higgs Mass Constraints



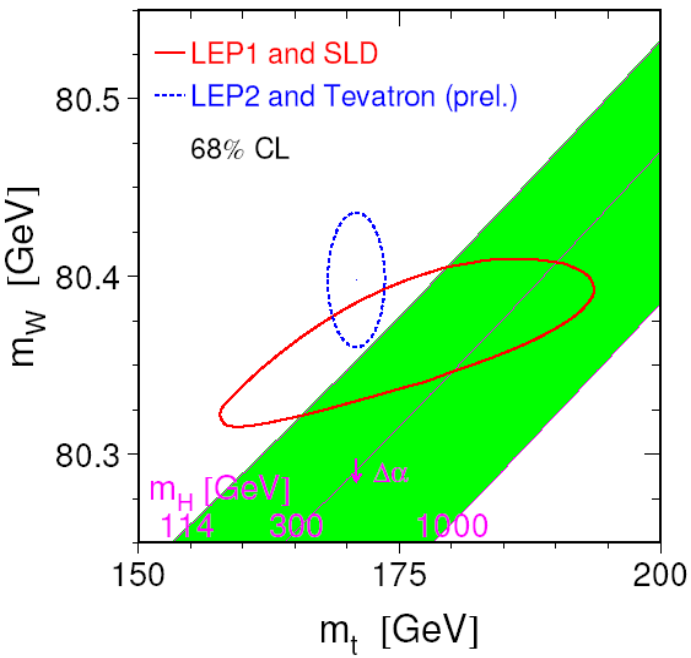


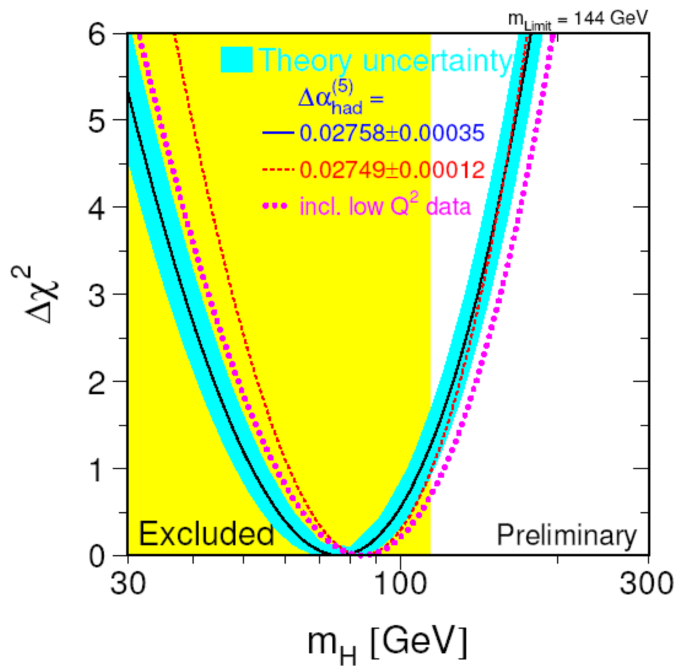
direkt search $e^+e^- \rightarrow Z\,H$

- MH > 114,5 GeV

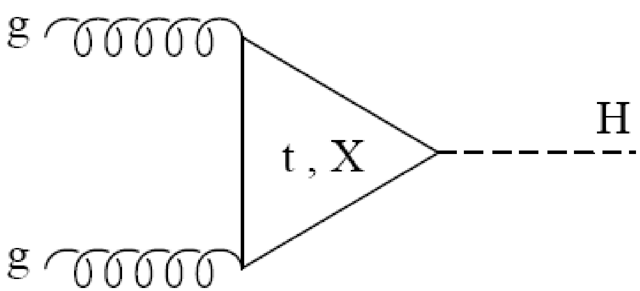
LEP / Tevatron indirect

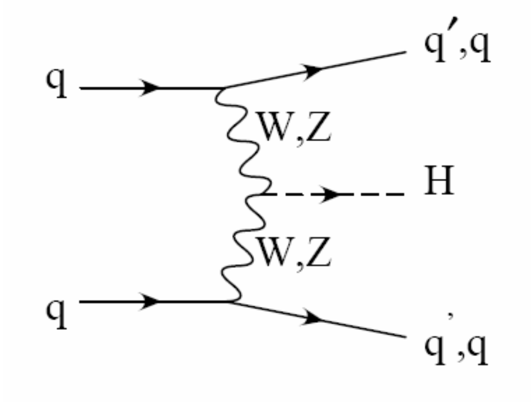
- M_H = 76 (+33 -24) GeV (exp., 68%C.L.)
- M_H < 144 GeV (95% C.L.)
- M_H < 188 GeV (95% C.L., incl. direct search)

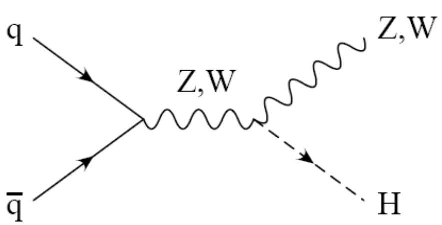


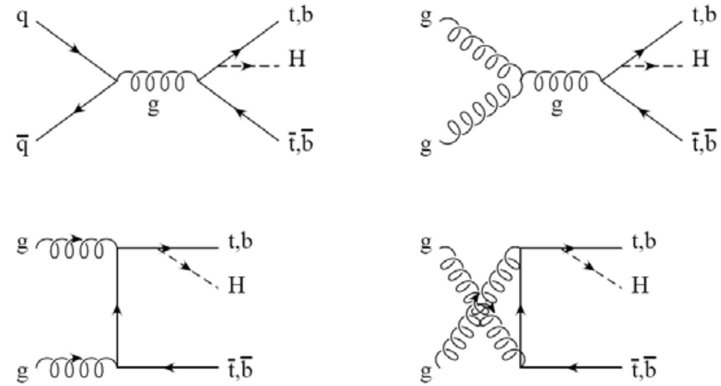


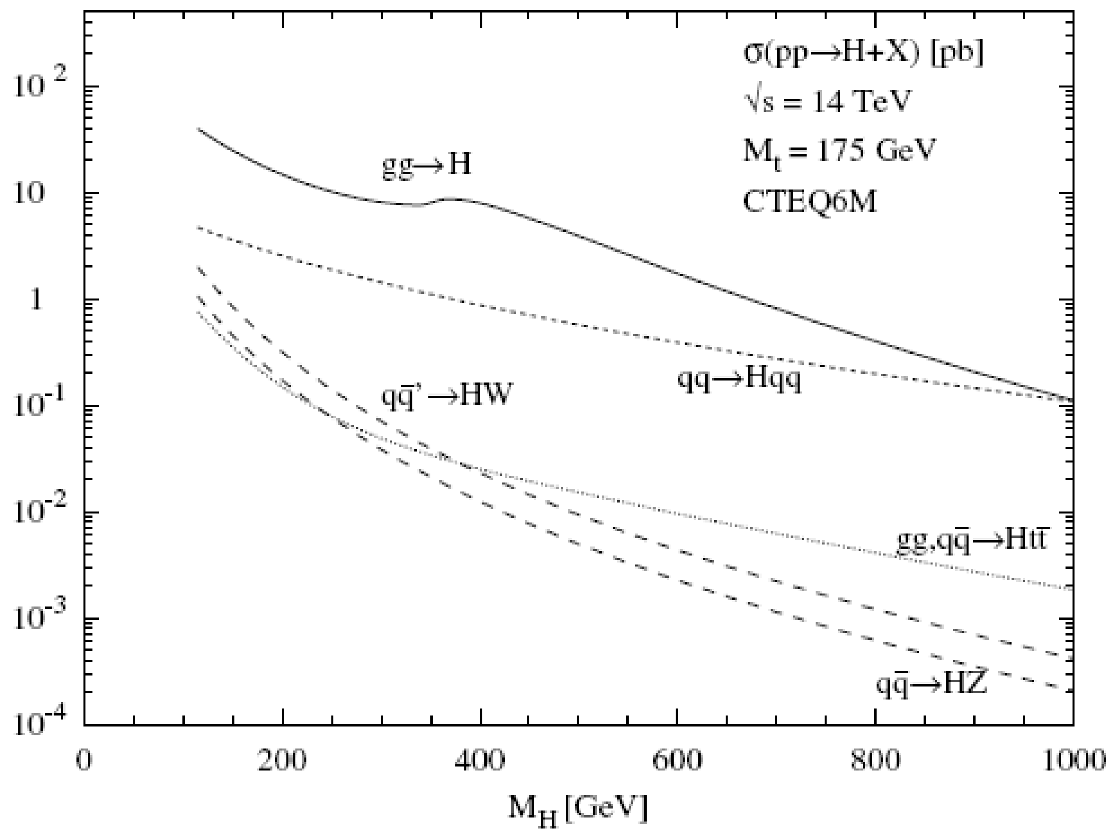
Higgs production at LHC



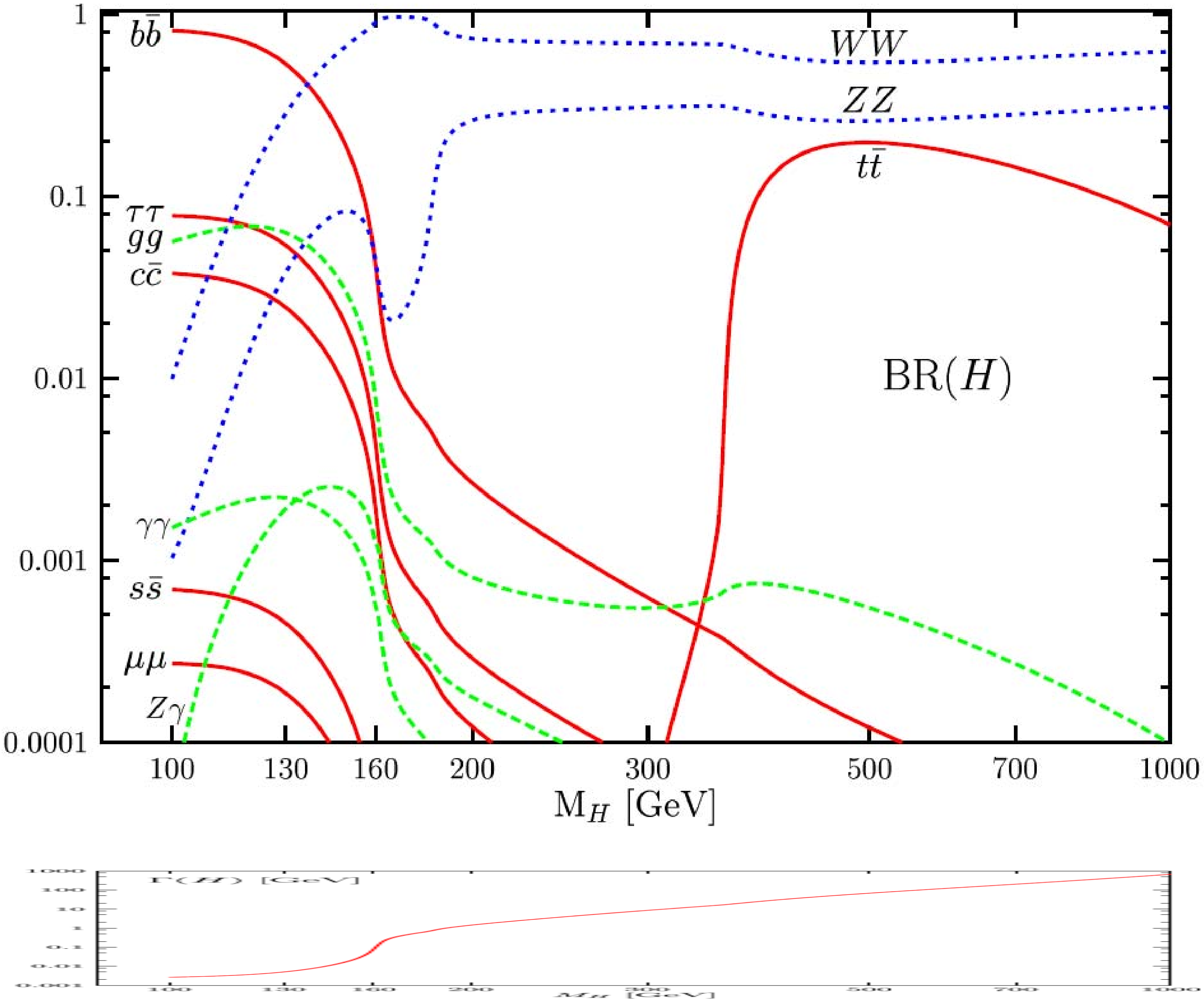




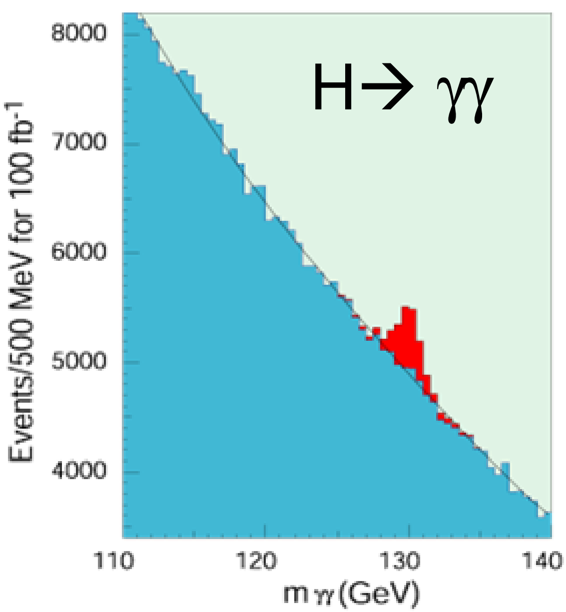


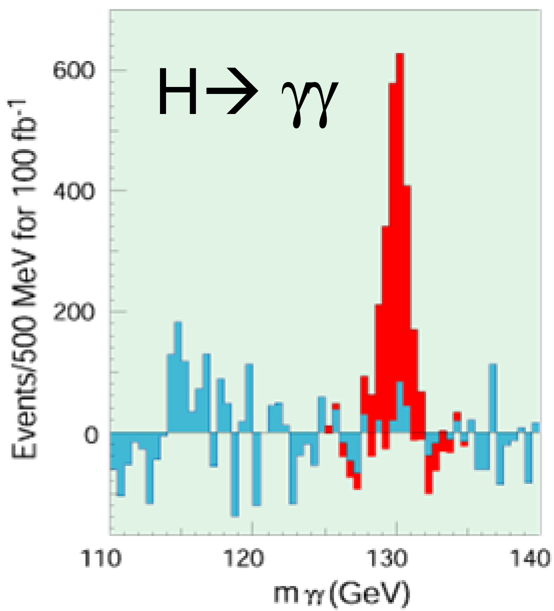


Higgs Branching Ratios



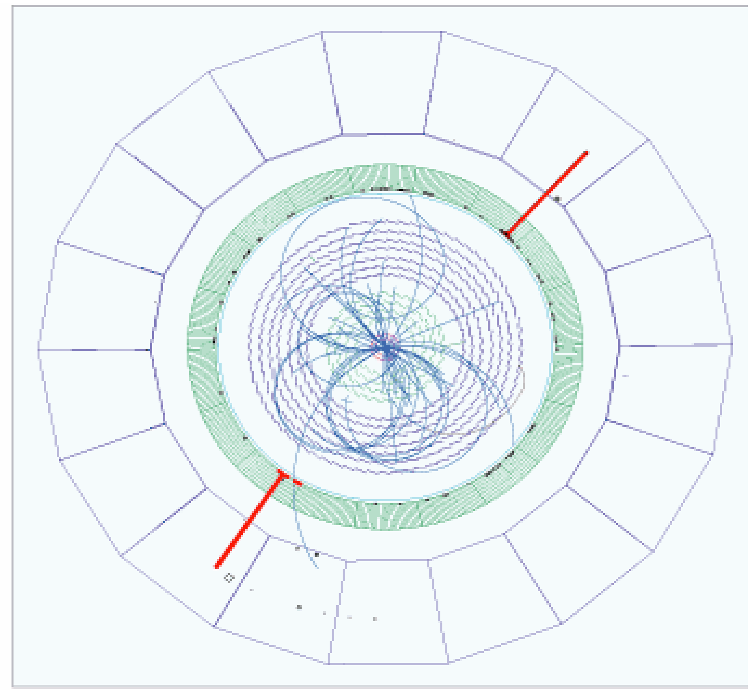
New CMS results
Fully detailed simulation and analysis





2-Photon Invariant Mass

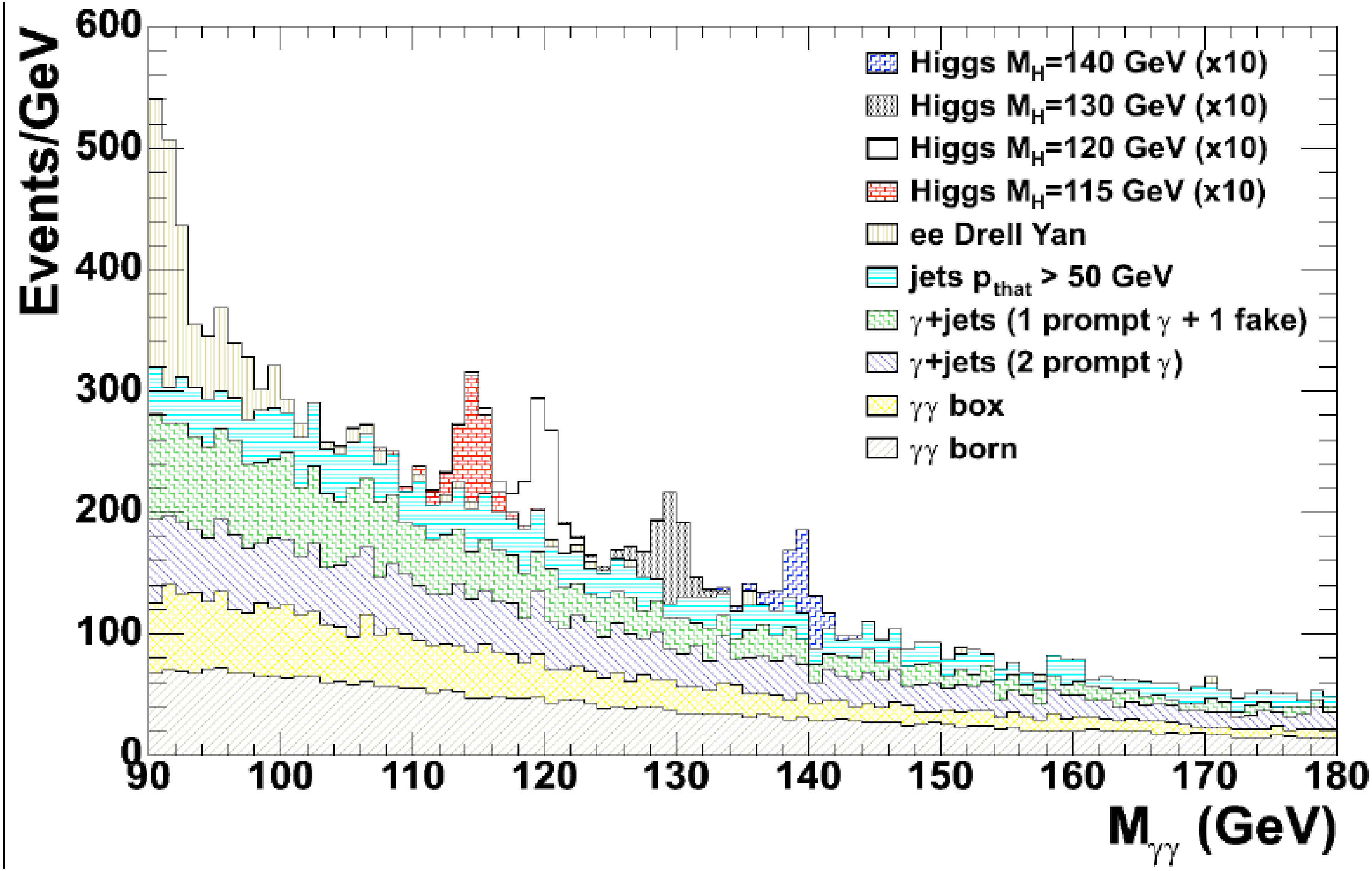
H→γγ Event



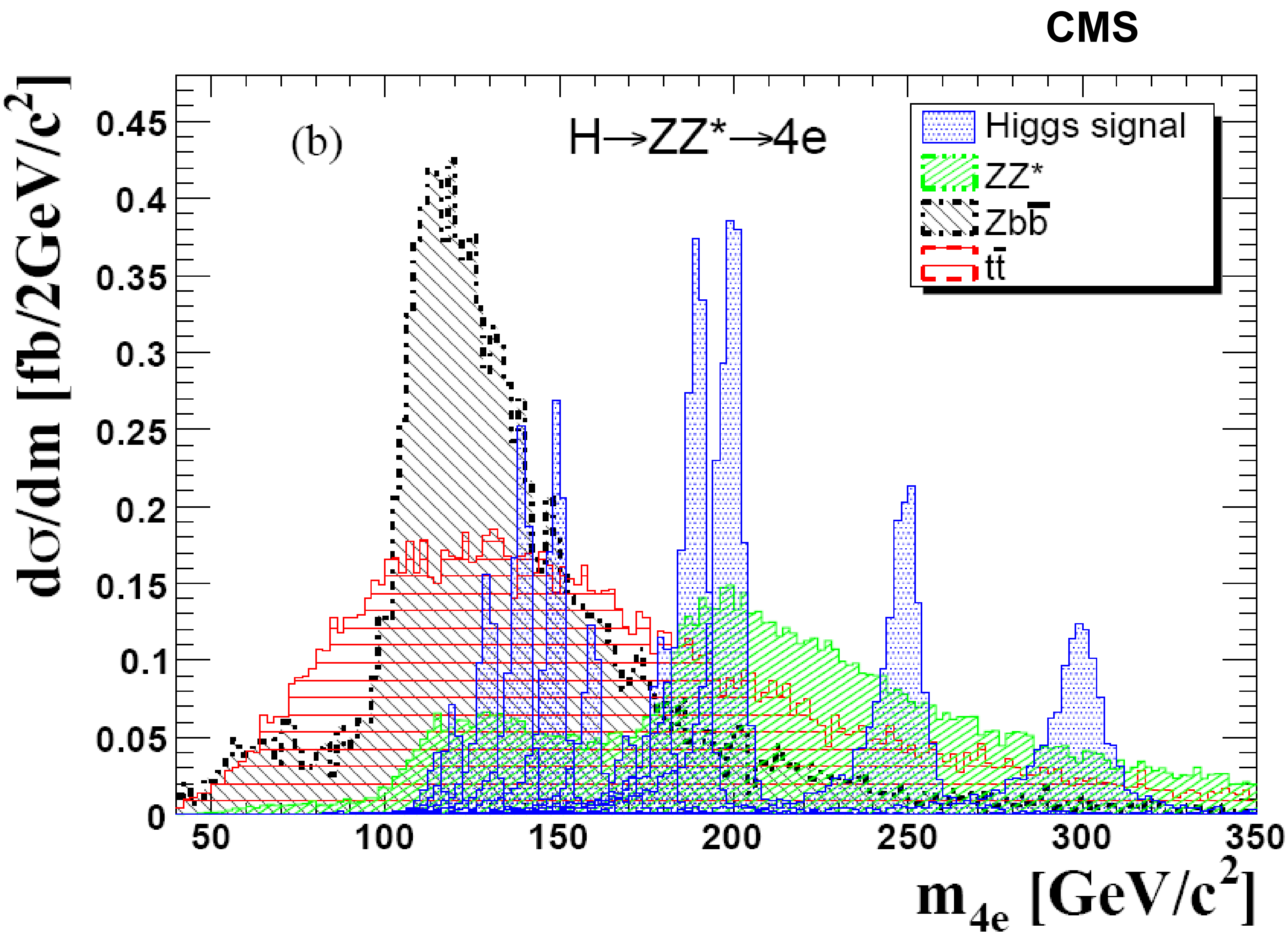
ECAL Design-energy Resolution:

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} + \frac{155\,MeV}{E} + 0.55\%$$

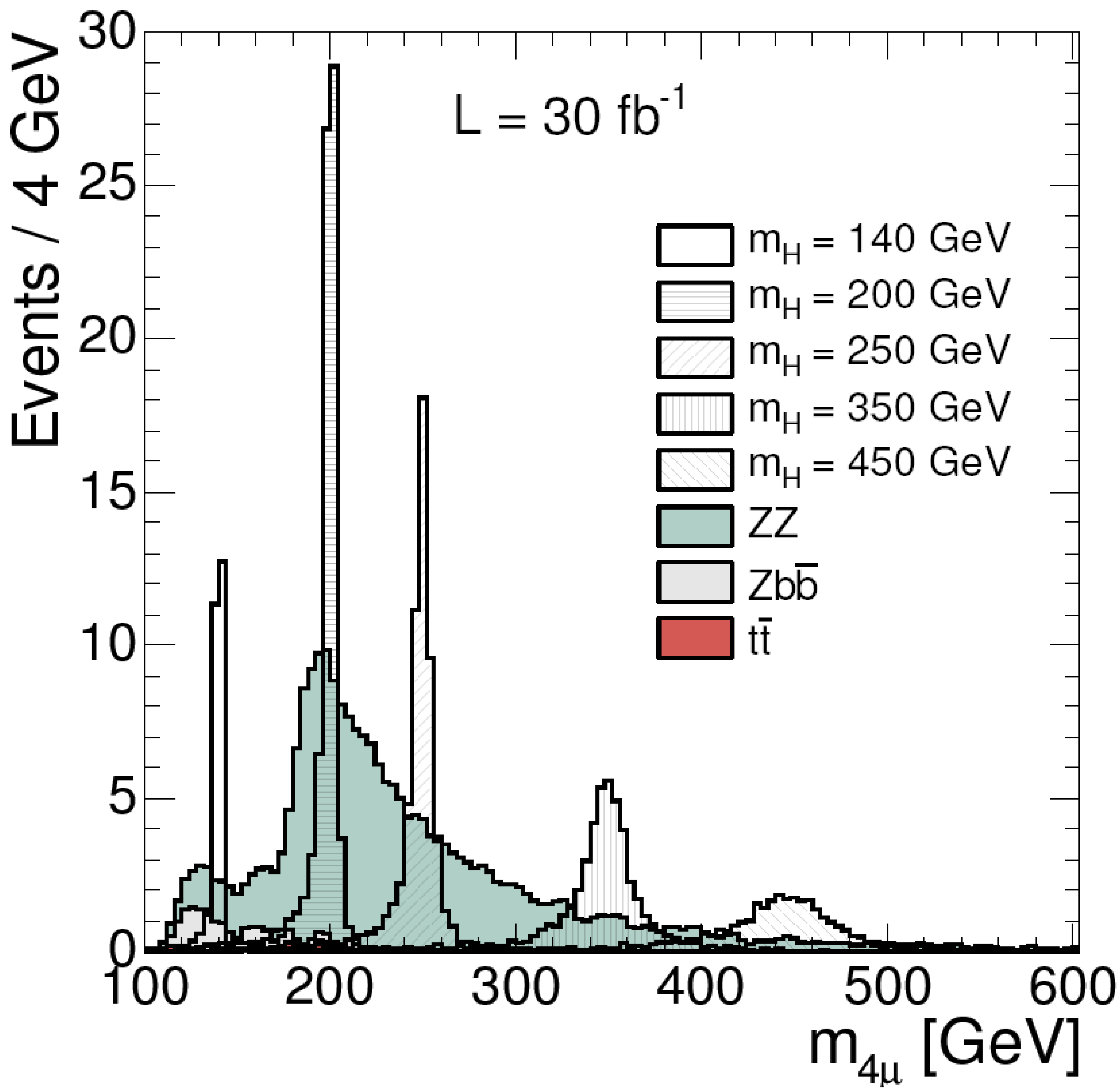
H → gamma + gamma



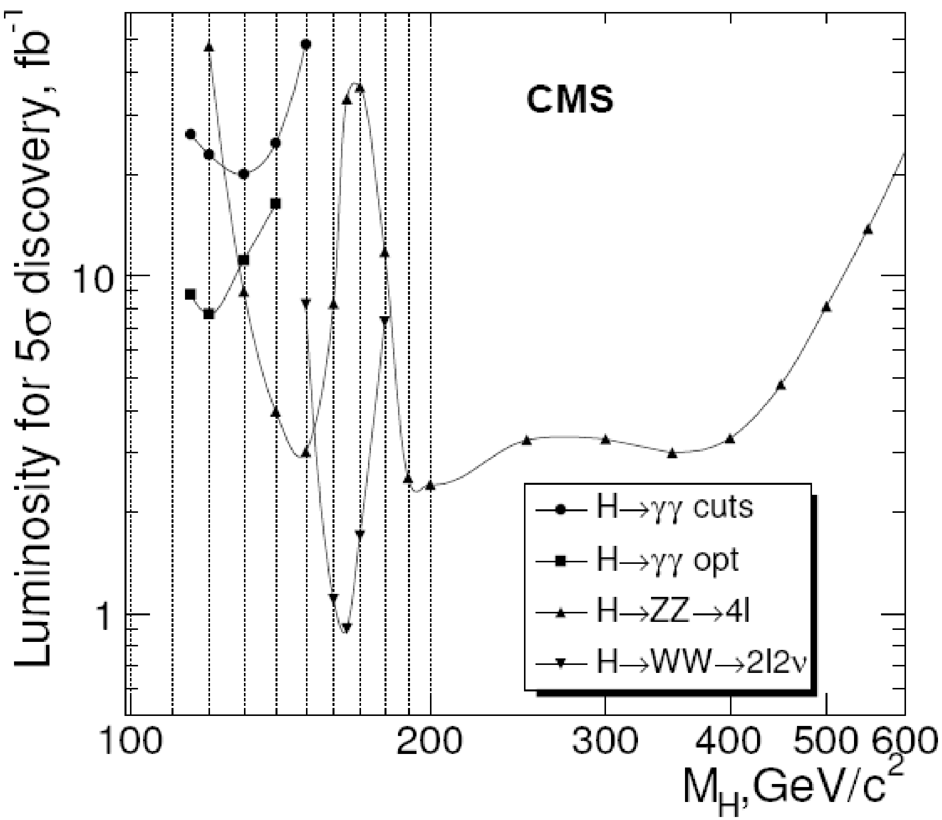
The golden channel
Higgs → 4 leptons

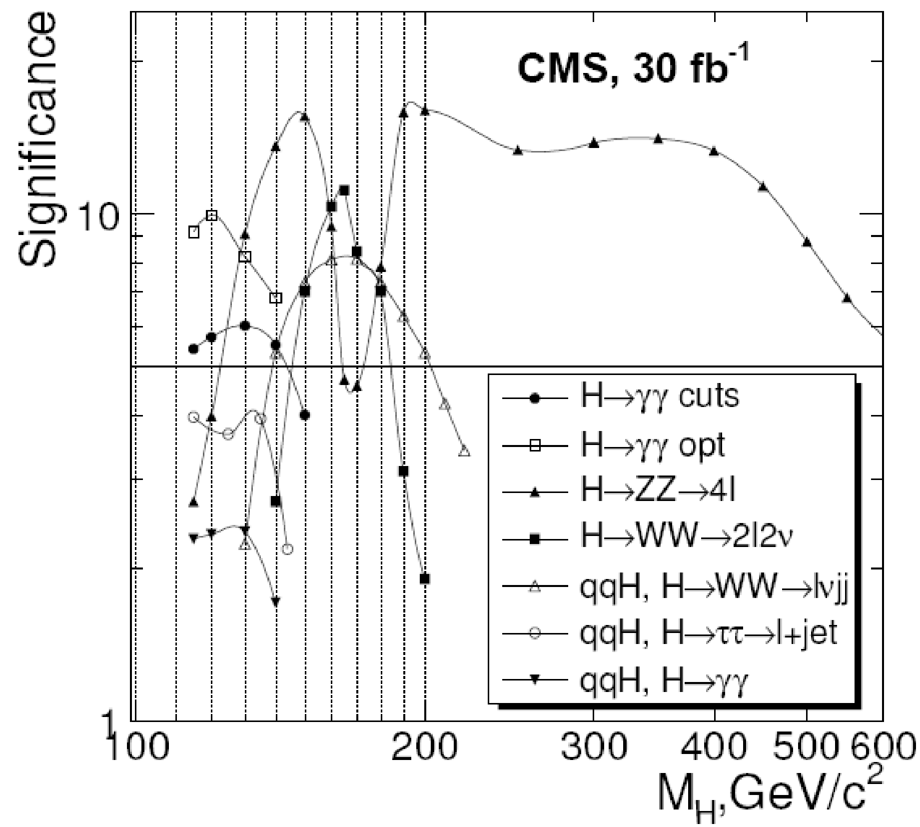


Higgs → 4 leptons



Higgs discovery potential

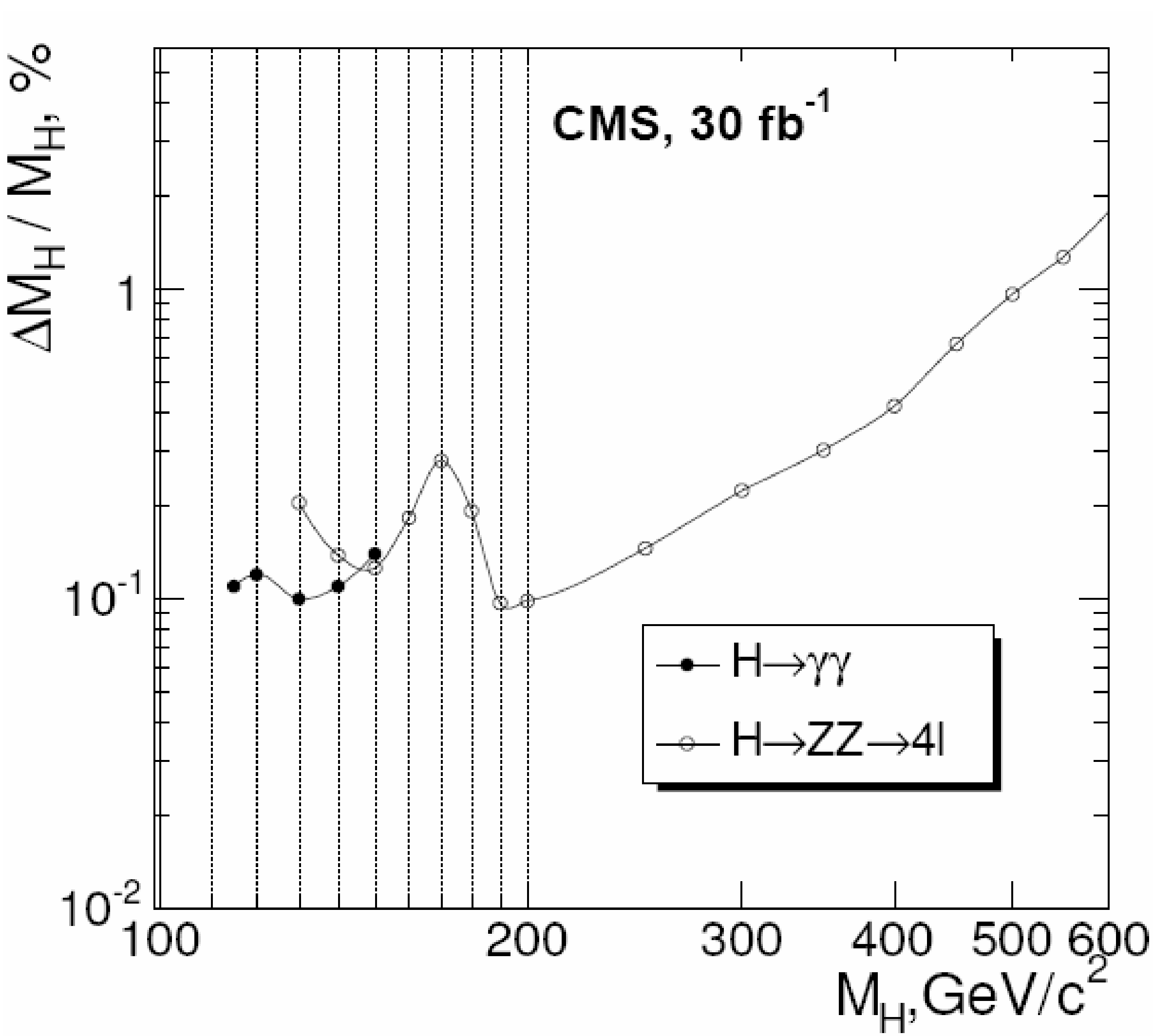




- **Early discovery (2008!) possible, if MH ~ 160-170 GeV**
- **10 sigma significance after 4 years**

→ Standard Model Higgs discovery is unavoidable
if LHC and Experiments function as expected

Higgs mass measurement

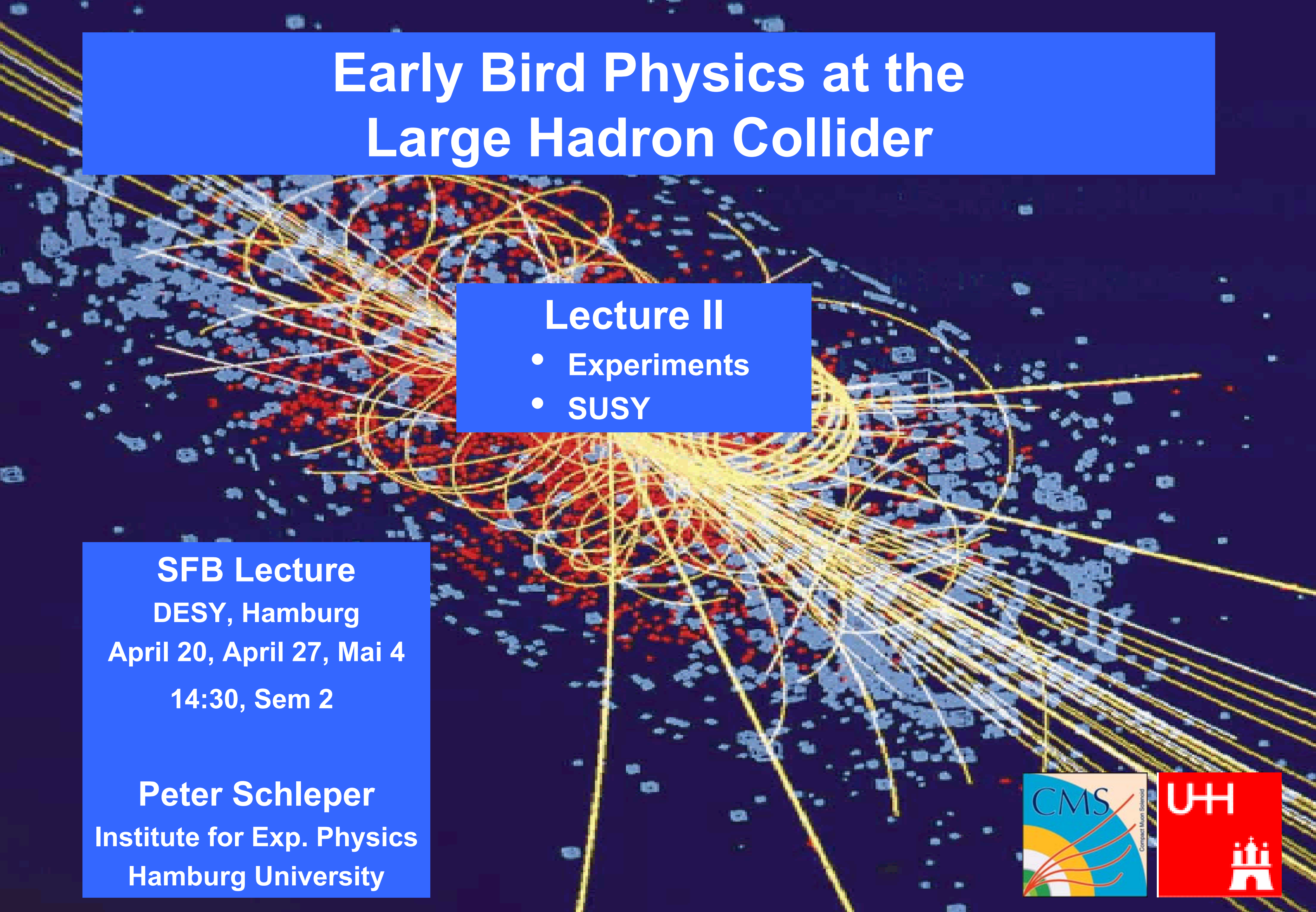


Major step for particle physics

Highly relevant also for SUSY

→ See next lecture

END lecture 1



Early Bird Physics at the Large Hadron Collider

Lecture II

- Experiments
- SUSY

SFB Lecture

DESY, Hamburg

April 20, April 27, Mai 4

14:30, Sem 2

Peter Schleper

Institute for Exp. Physics

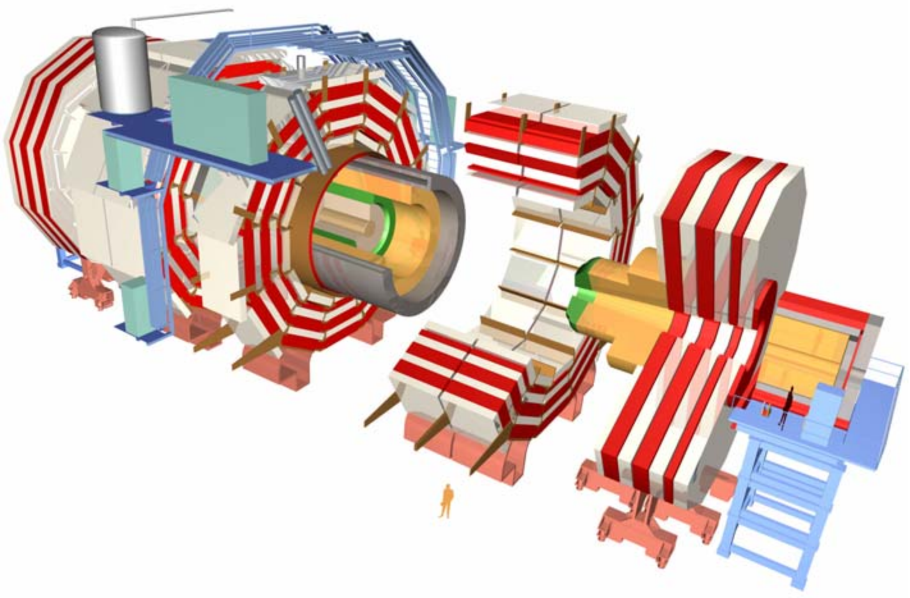
Hamburg University

Outline

Lecture 1
- Motivation
- LHC & Experiments
- Cross Sections
- Higgs

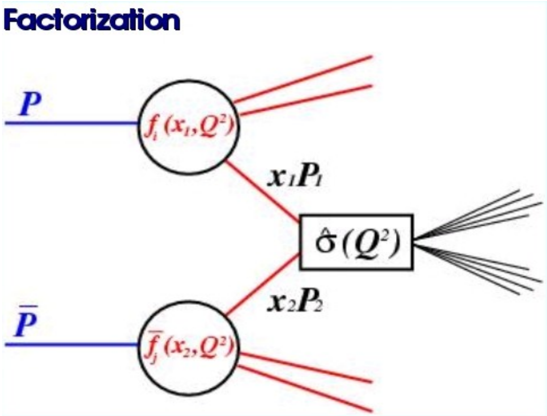
Lecture 2
- Experiments
- SUSY

Lecture 3
- SUSY
- Other exotics
- Outlook: SLHC



No comprehensive overview
- Selected topics
- Experimental issues
- Focus on first 3 years of data taking

Cross sections



$$\sigma = \sum_{i,j} \int_0^1 \mathrm{d}x_1\, \mathrm{d}x_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}$$

$$\sigma = \sum_{i,j} \int \left(\frac{\mathrm{d}\hat{s}}{\hat{s}}\,\mathrm{d}y\right) \left(\frac{\mathrm{d}L_{ij}}{\mathrm{d}\hat{s}\,\mathrm{d}y}\right) (\hat{s}\,\hat{\sigma}_{ij})$$

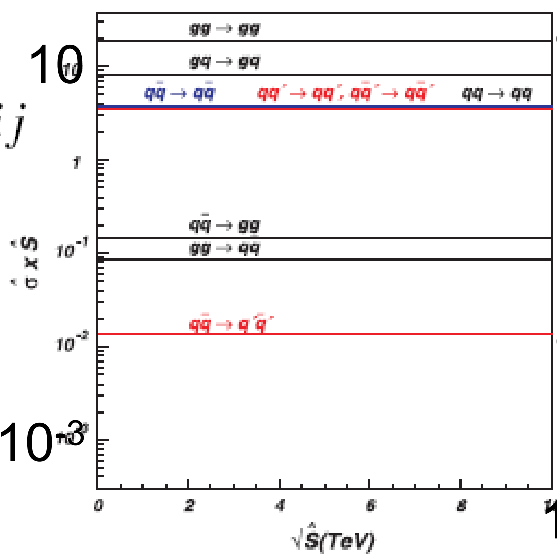
Parton Luminosity

$$\frac{\mathrm{d}L_{ij}}{\mathrm{d}\hat{s}\,\mathrm{d}y} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\,[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)].$$

Partonic cross section $\hat{s}\,\hat{\sigma}_{ij}$ = 10^{-3} ….20

$\hat{s}\,\hat{\sigma}_{ij}$

10



gg→gg

qq→q'q'

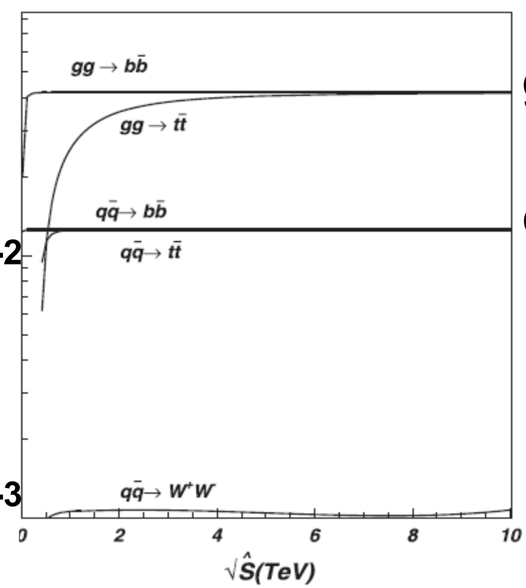
10^{-3}

10 TeV

$\hat{s}\,\hat{\sigma}_{ij}$

10^{-2}

10^{-3}



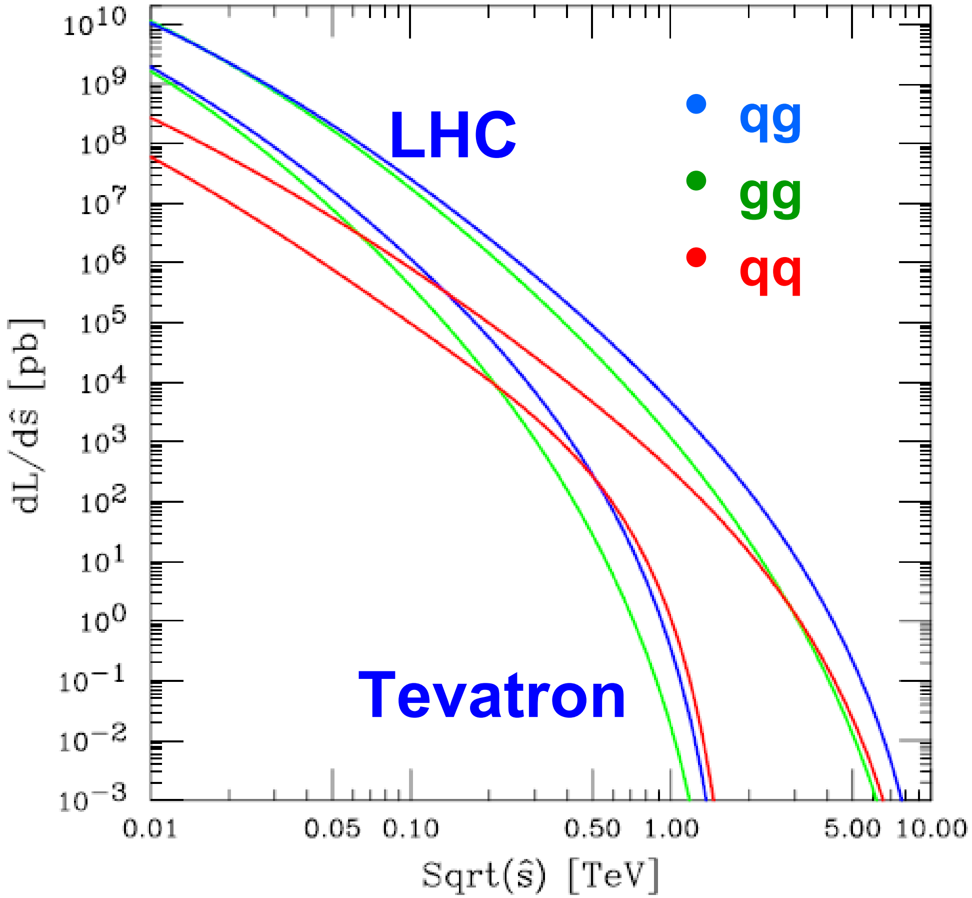
gg → bb, tt

qq → bb, tt

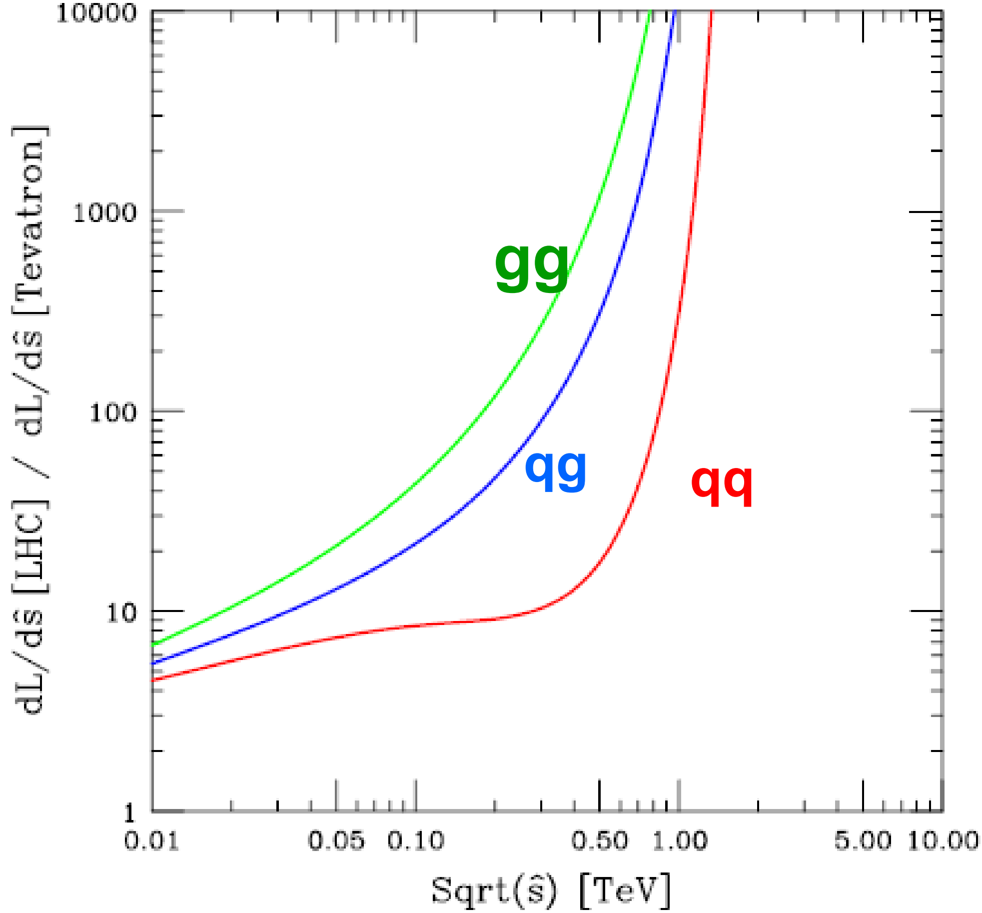
qq → WW

Parton Luminosity

Parton Lumi



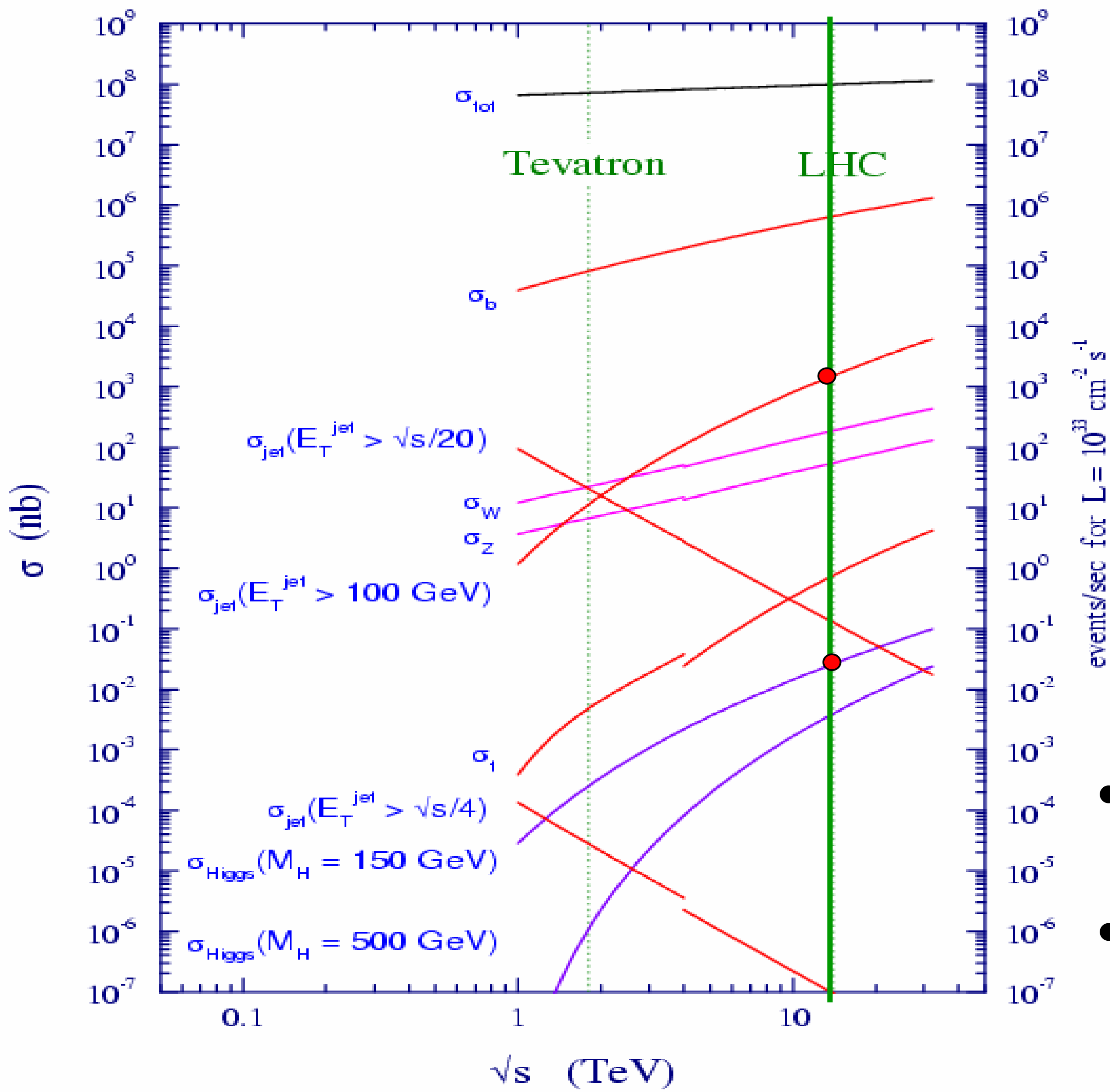
Ratio LHC / Tevatron:



LHC / Tevatron: factor 40 for gg→ H @ M_H= 120 GeV

factor 10000 for gg→ XX @ M_X= 0.5 TeV

Cross Sections



10^8 Events per sec
@10^{33} cm^{-2}s^{-1}

1000 jets / s (ET>100)

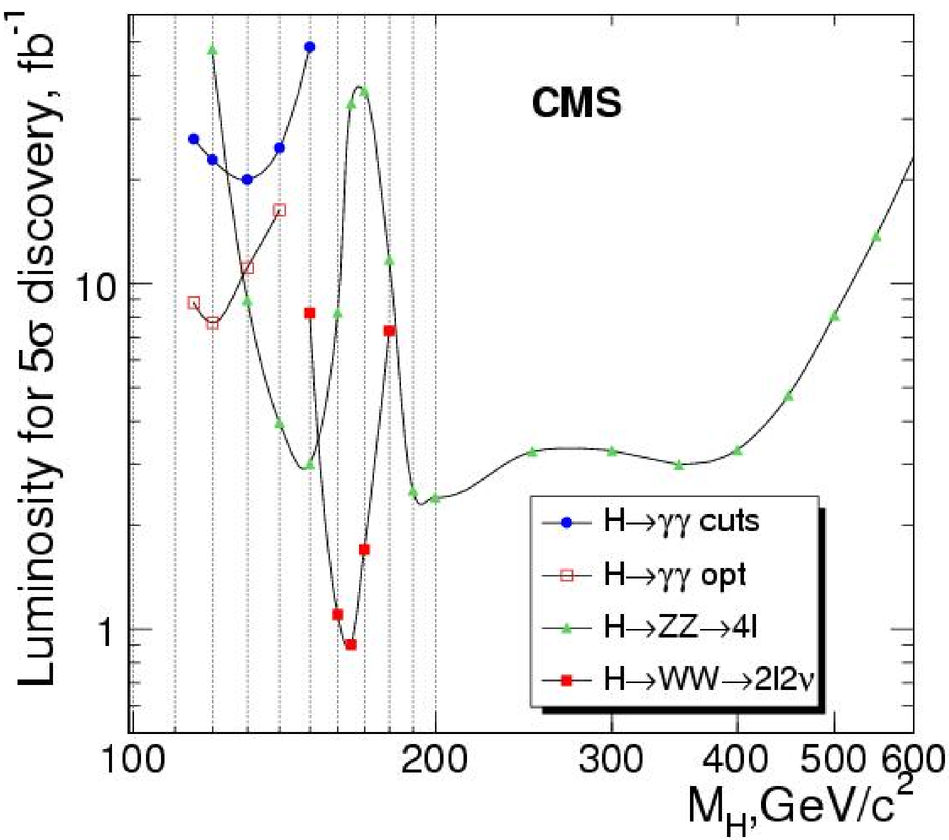
200 W /s 50 Z^0 /s

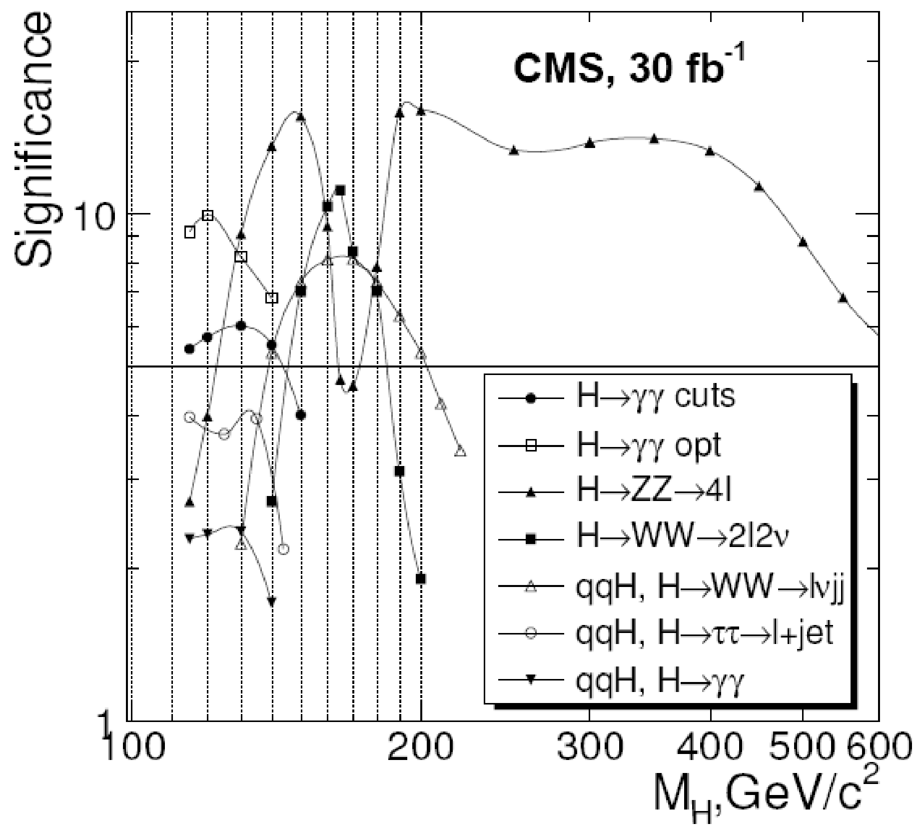
1 ttbar / s

1 Higgs /min M_H=150 GeV

- Huge event rates for Standard Model processes
- Jets >> W, Z, t , H

Higgs discovery potential





- **Early discovery (2008!) possible, if M_H ~ 160-170 GeV**
- **10 sigma significance after 4 years**

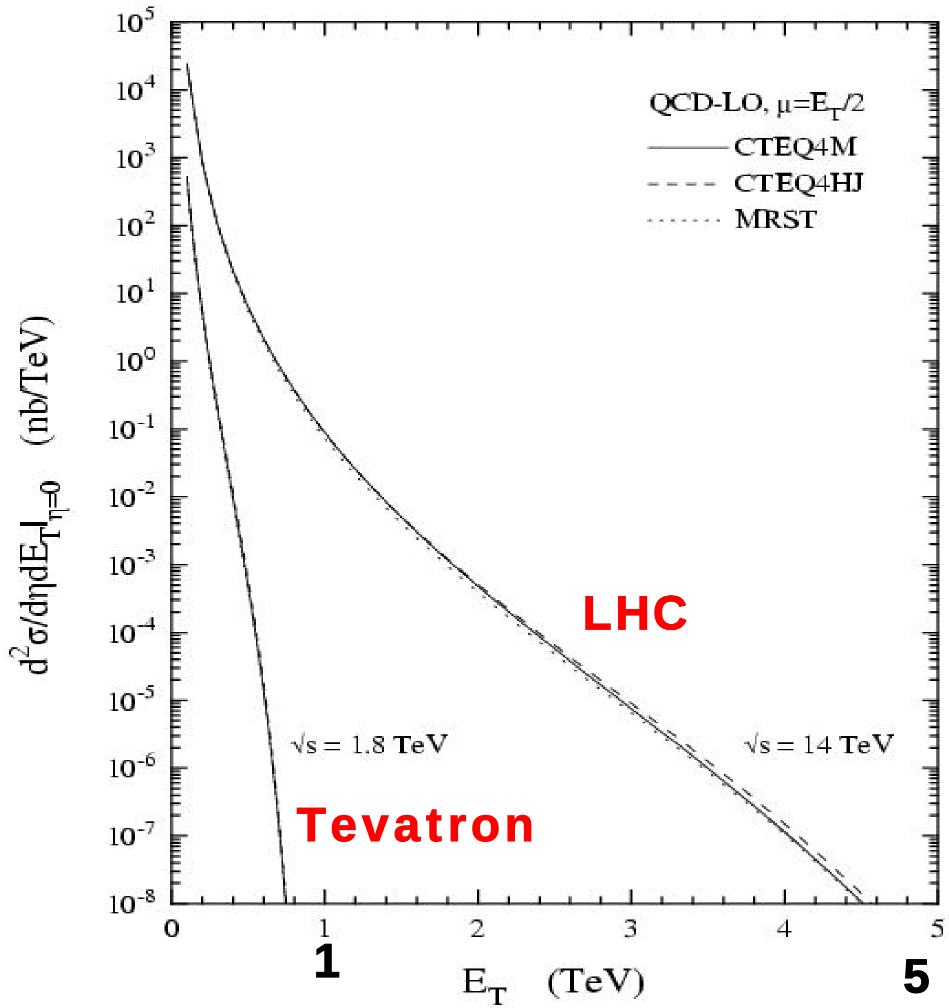
→ Standard Model Higgs discovery is unavoidable
if LHC and Experiments function as expected

LHC Event rates

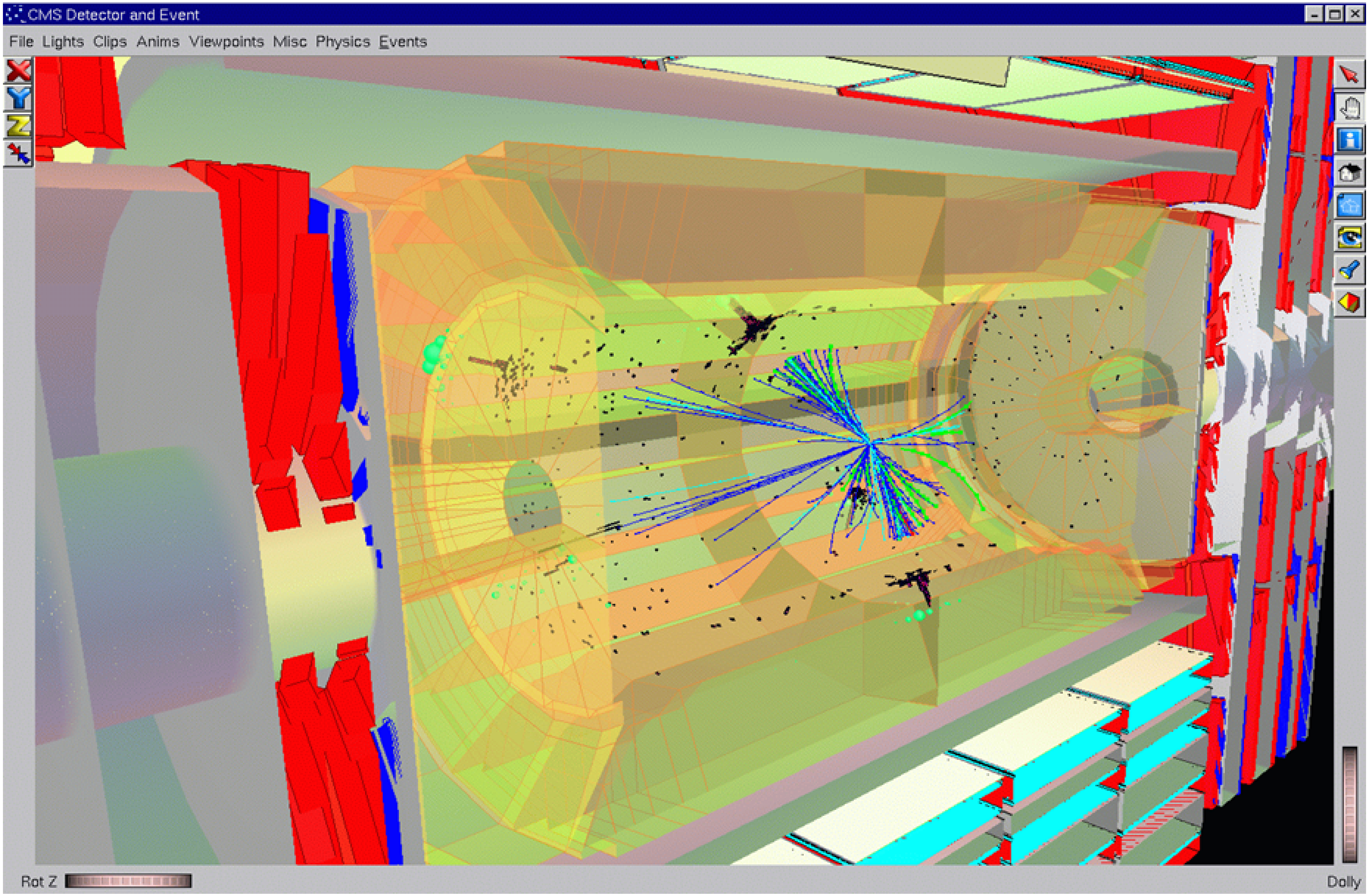
Expectations for 2008	Events $10^{32}\ cm^{-2}\ s^{-1}$	Events per 1 fb^{-1}
QCD jets E_T > 100 GeV	150 /sec	1.5×10^9
$W \to \mu\nu$	2 /sec	2×10^7
$Z \to \mu\mu$	*0.2 /sec*	2×10^6
t t	*0.1 /sec*	10^6
Higgs M_H = 125 GeV, 200 GeV	340 /day 115 /day	4×10^4 1.5×10^4
gluino-gluino M_{gluino} = 1 TeV	0.8 – 8 /day	10^2 to 10^3

E^T = 40 GeV: jets / leptons = 10^5

QCD jet crosssection



Simulation of event in the CMS detector: Low luminosity



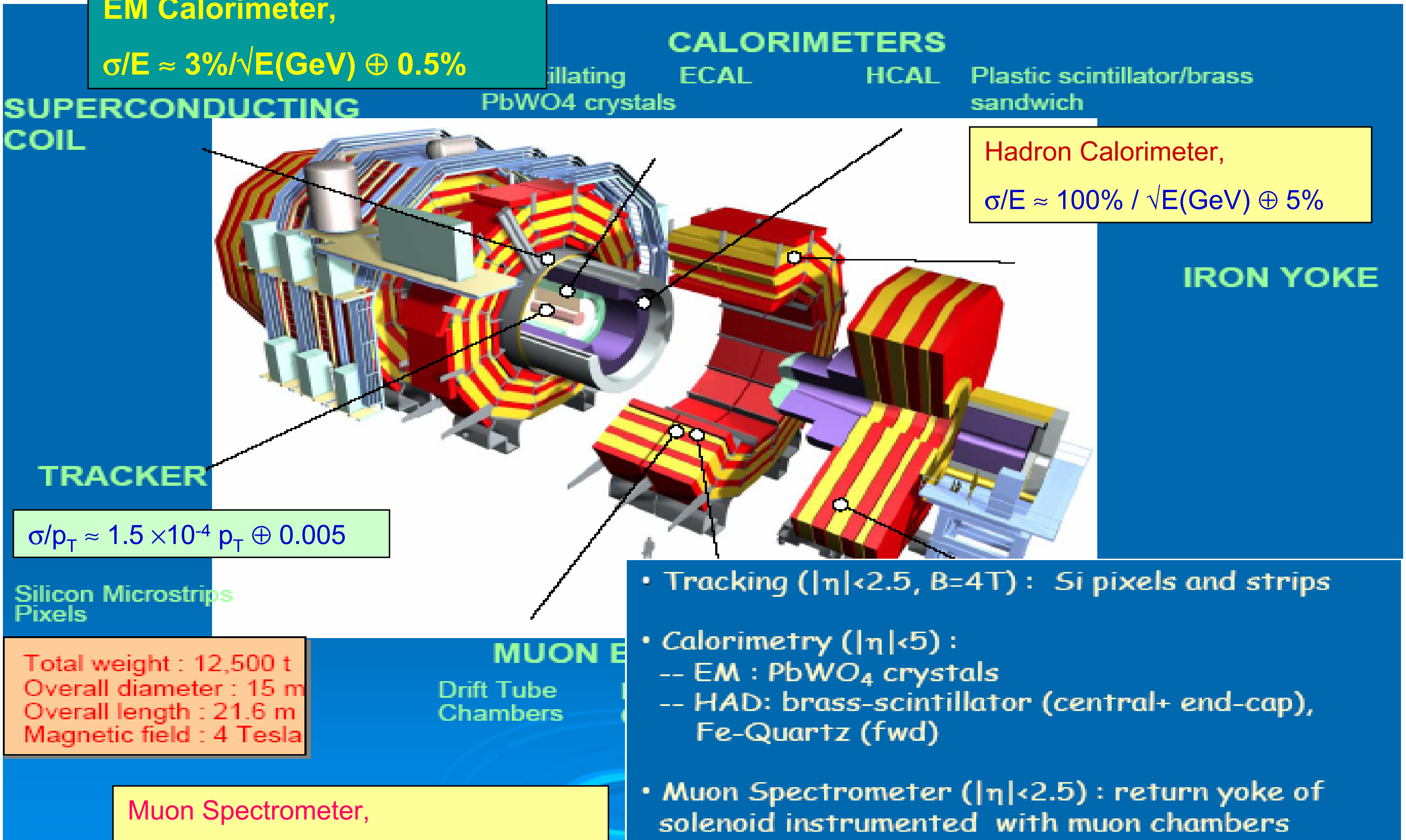
CMS Detector

EM Calorimeter,

$\sigma/E \approx 3\%/\sqrt{E(GeV)} \oplus 0.5\%$

Hadron Calorimeter,

$\sigma/E \approx 100\% / \sqrt{E(GeV)} \oplus 5\%$



$\sigma/p_T \approx 1.5 \times 10^{-4}\, p_T \oplus 0.005$

Muon Spectrometer,

$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

A Toroidal LHC Apparatus (ATLAS) DETECTOR

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(\mathrm{GeV})} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \to \gamma\gamma$)

Precision Muon Spectrometer,

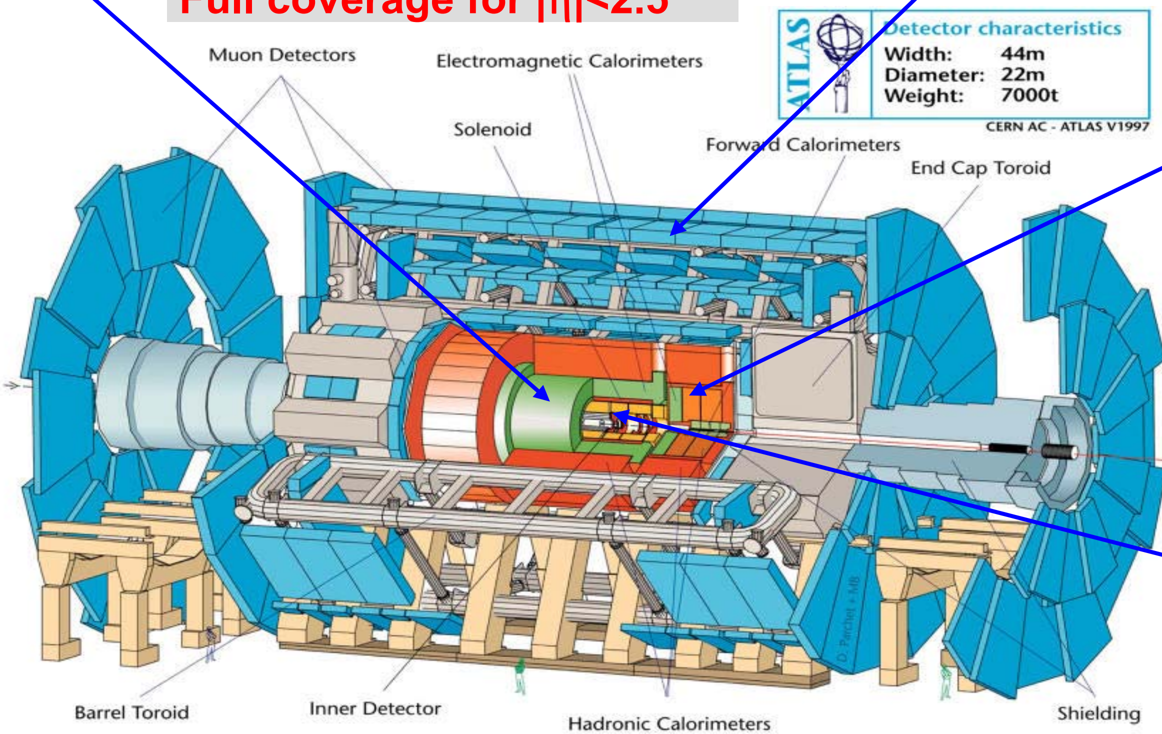
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \to \mu\mu$, $H \to 4\mu$)

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(\mathrm{GeV})} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \to \tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

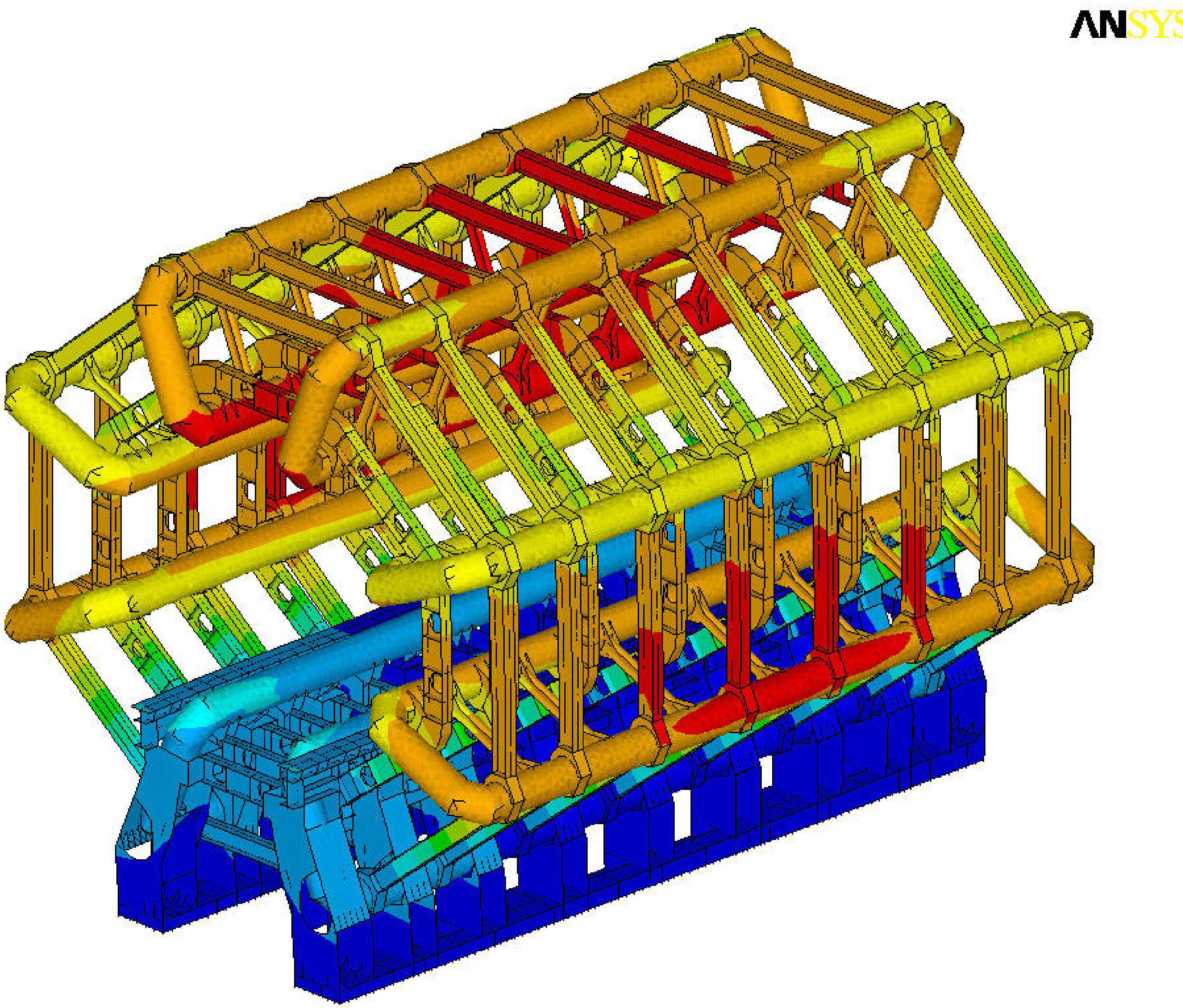
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)$=15μm@20GeV (e.g. $H \to bb$)

Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

ATLAS coils

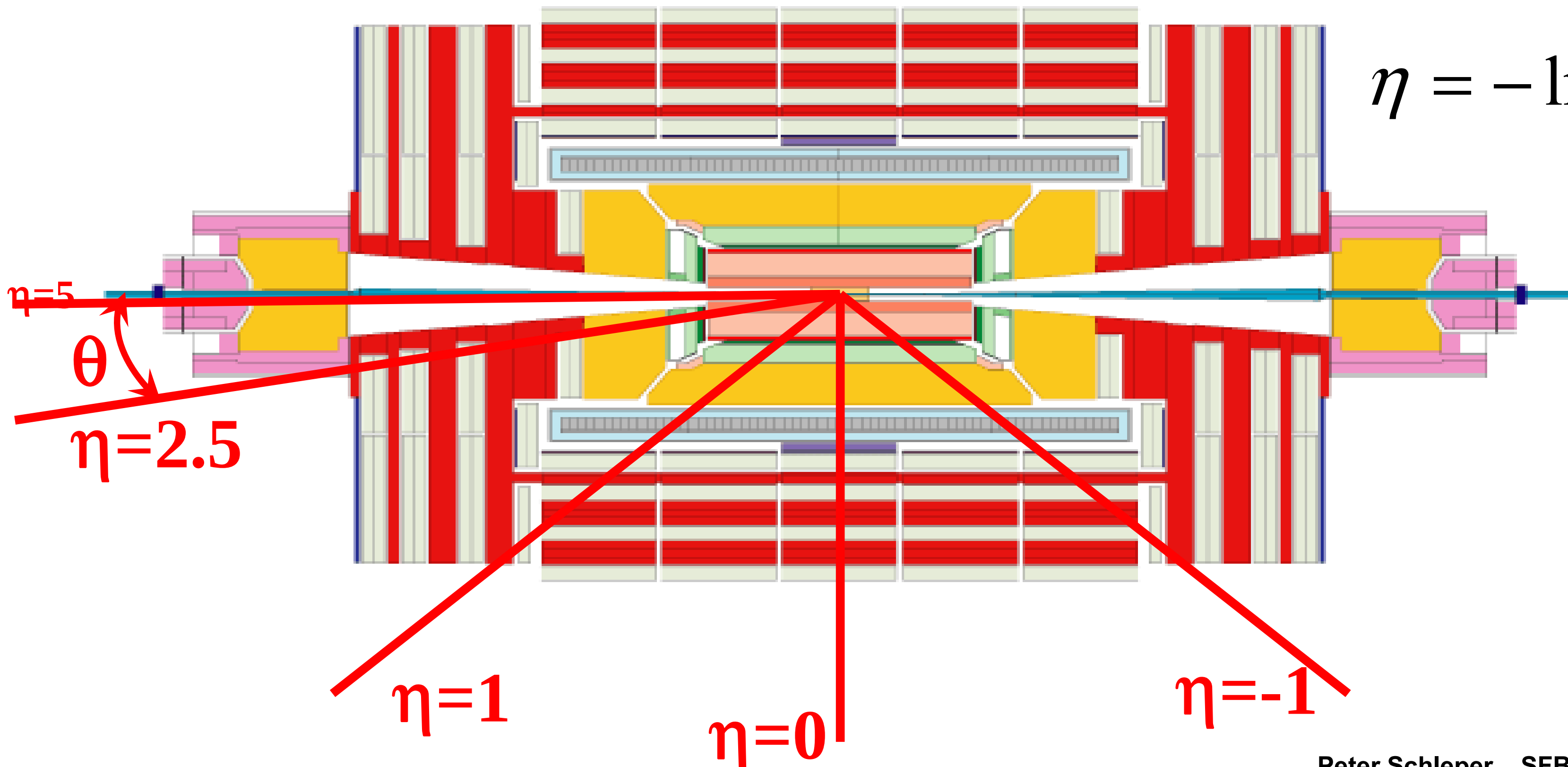


	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels + strips TRD B= 2T $\sigma/p_T \sim 5\times10^{-4}\ p_T(\mathrm{GeV}) \oplus 0.01$	Si pixels + strips B= 4T $\sigma/p_T \sim 1.5\times10^{-4}\ p_T\ (\mathrm{GeV}) \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ good longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ good lateral segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$ + …	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 7\ \%$ at 1 TeV standalone	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Detector Acceptance

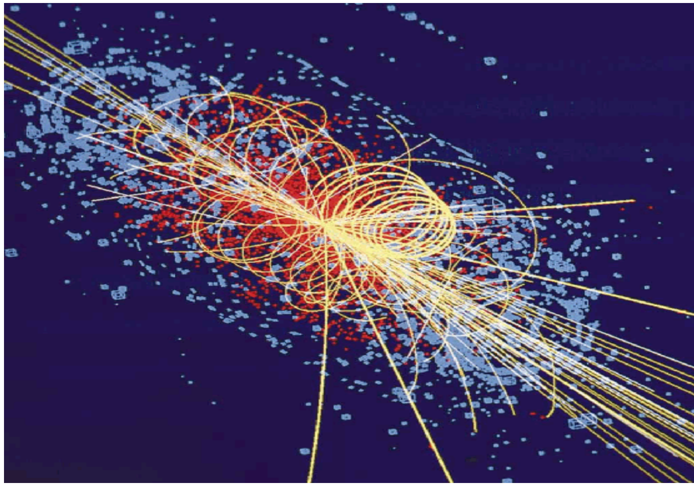
Acceptance η	Central (Barrel)	Forward (Endcap)
Tracking	< 1.5	< 2.4
Elektrons	< 1.2	< 2.5
Hadrons	< 1.2	< 2.5 → 5
Myons	< 1.2	< 2.5

$$\eta = -\ln\left(\tan\left(\theta/2\right)\right)$$



Pile-up and Underlying Events

Overlay of events from different processes at large luminosity



Pile – up in time

- From different bunch crossings (25 ns)
- Challenge for fast detector response & signal shapes
- ➨ typical response times achieved are 20-50 ns (!)
- ➨ remaining effect is small

Pile – up in space

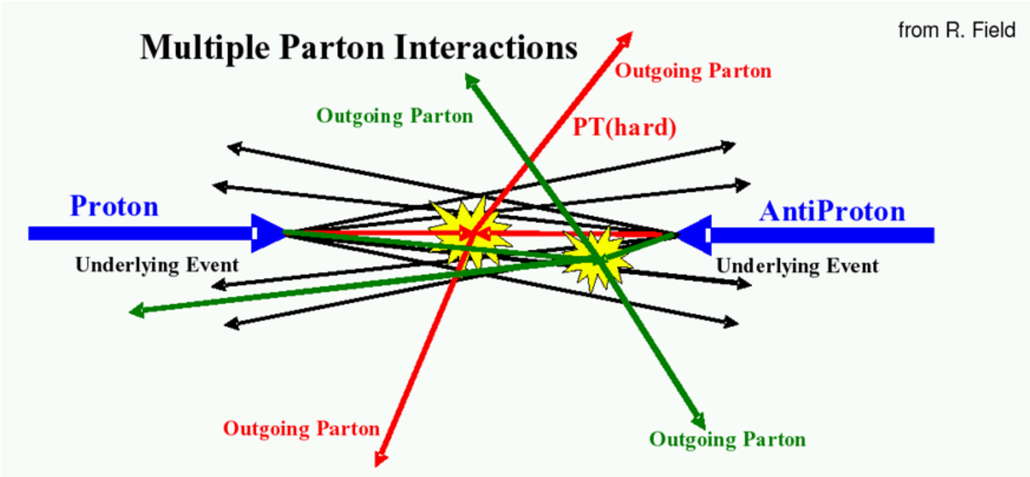
- From interactions of up to 25 protons from each bunch
- Up to 1600 low PT particles, close to IP: 10^8 particles /cm^2/s
- ➨ High granularity → large number of channels
  ATLAS: 100 million pixels,
  200000 cells in electr. calorimeter
- ➨ o.k. for muons, electrons, photons
- ➨ Pedestal of energy within jets
  momentum cut of at 0.5 .. 1 GeV against minimum bias events
  Vertexing to remove pile-up from minimum bias events ?
- ➨ Quality of measurements depends on instantaneous luminosity

Underlying event

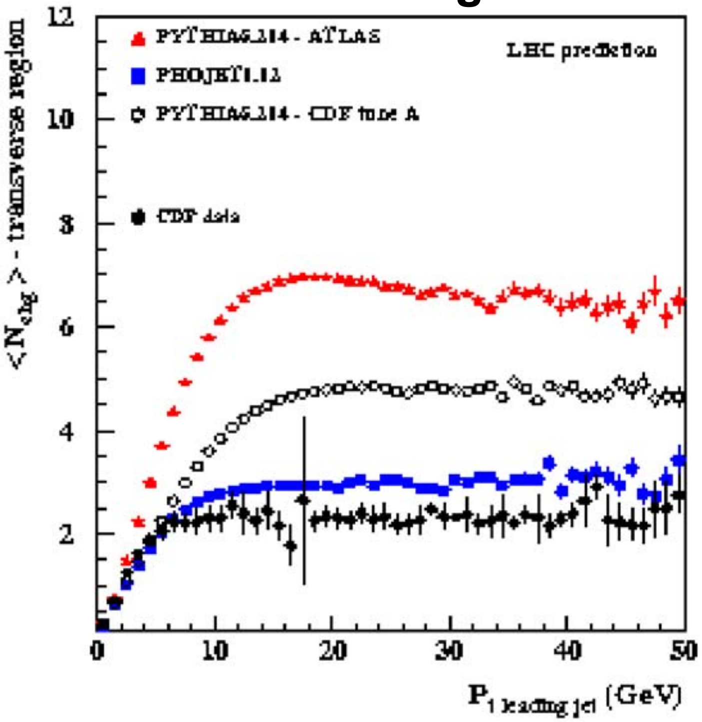
- From several parton-parton interactions within the same proton

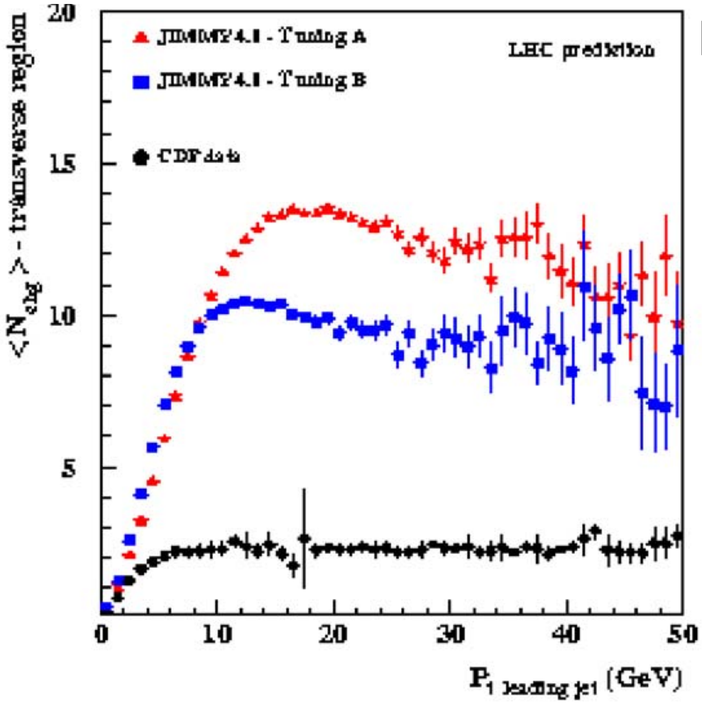
Underlying event

- **Models, no firm QCD predictions**
- **Large extrapol. uncertainties from Tevatron**



Number of charged tracks outside region of hard jet(s)





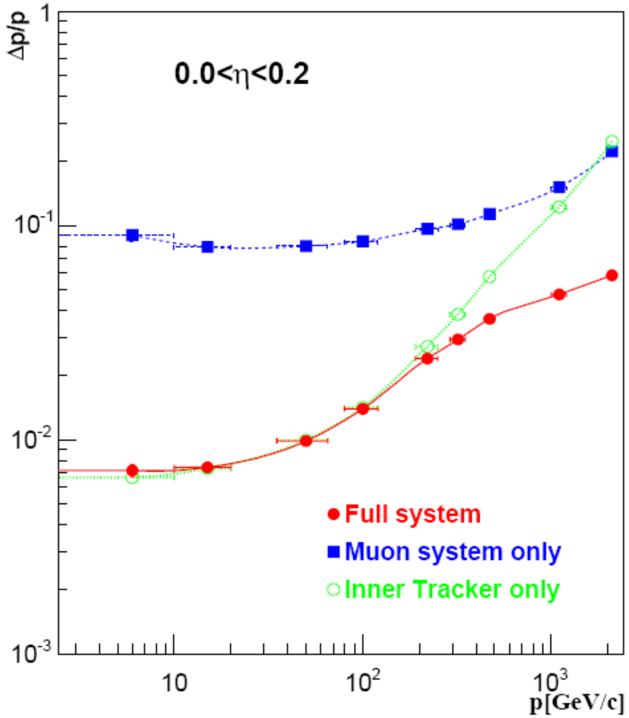
per unit area in eta-phi:

- **<Nch> ~ 1-2**
- **<PTch> ~ 1-2 GeV**
- **Fluctuations ?**

Needs to be measured in early data

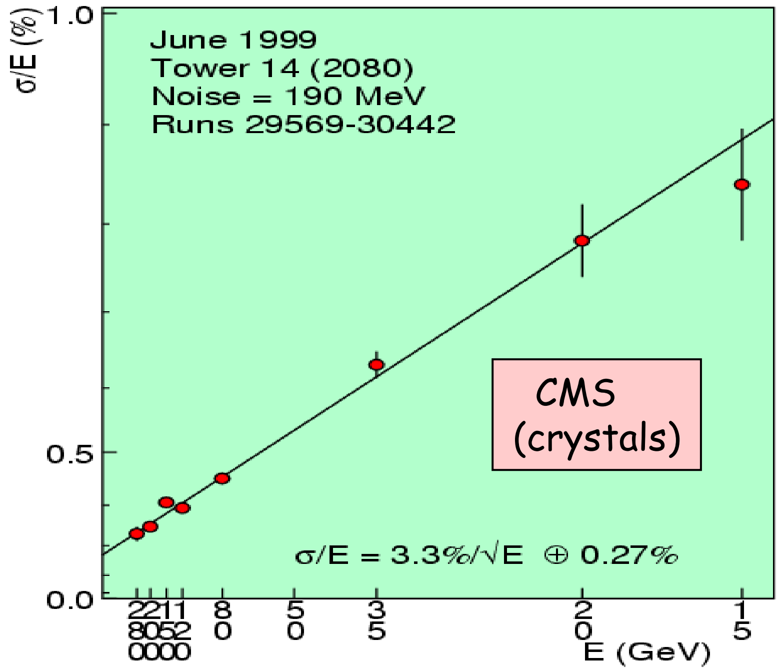
Detector properties

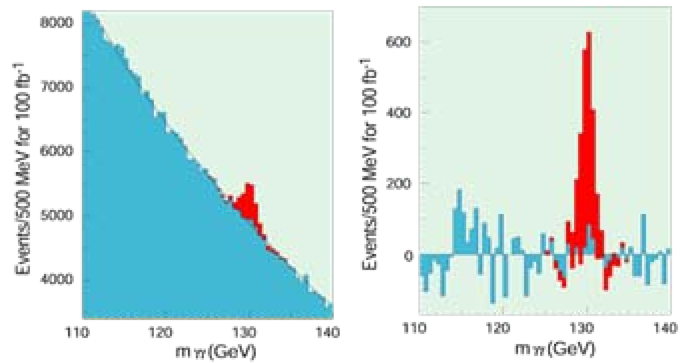
CMS tracking + muon



Tracking	ATLAS	CMS
σp_T for p_T=1GeV η=0	1.3%	0.7%
σp_T for p_T=100GeV η=0	3.8%	1.5%
Transverse σi.p. for p_T=1GeV	75μm	90μm
Longitunal σi.p. for p_T=1GeV	150μm	125μm

CMS Ecal





B-Tagging

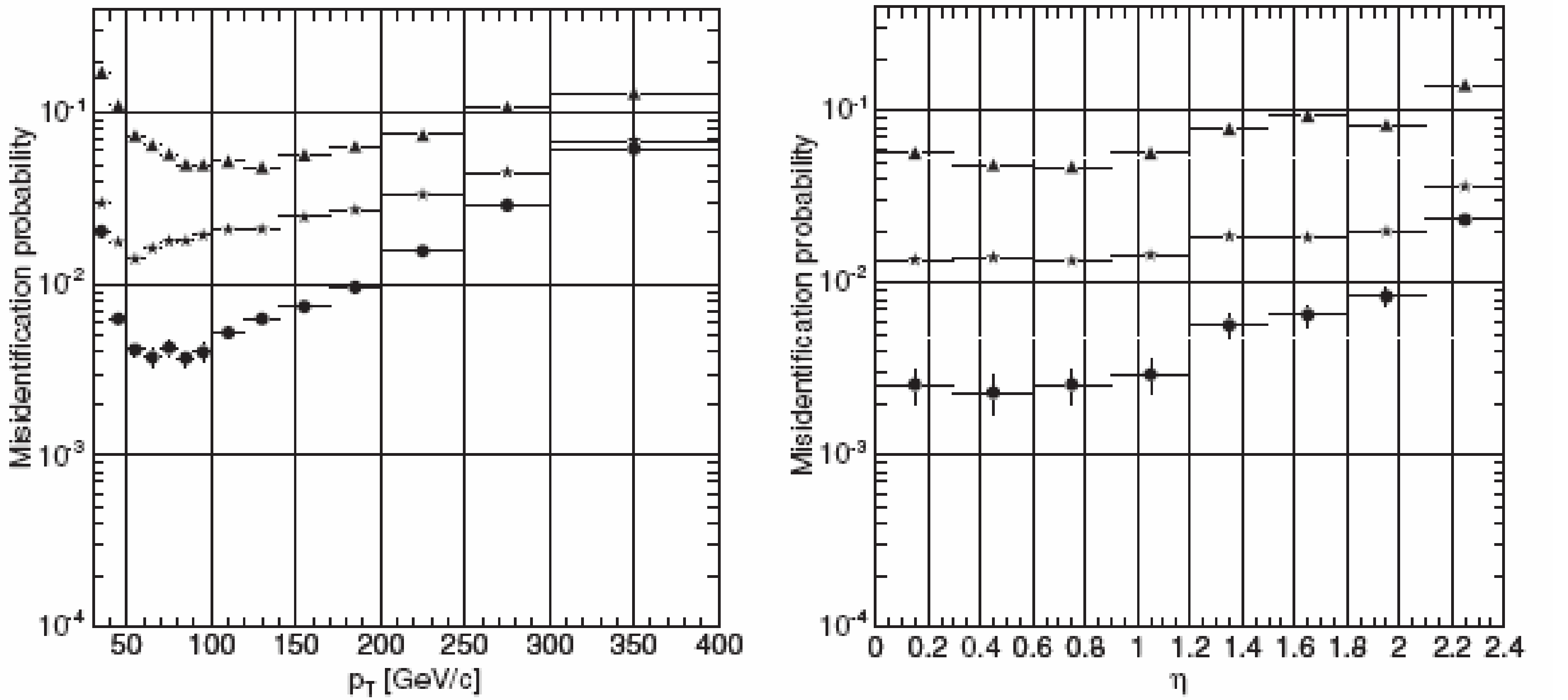
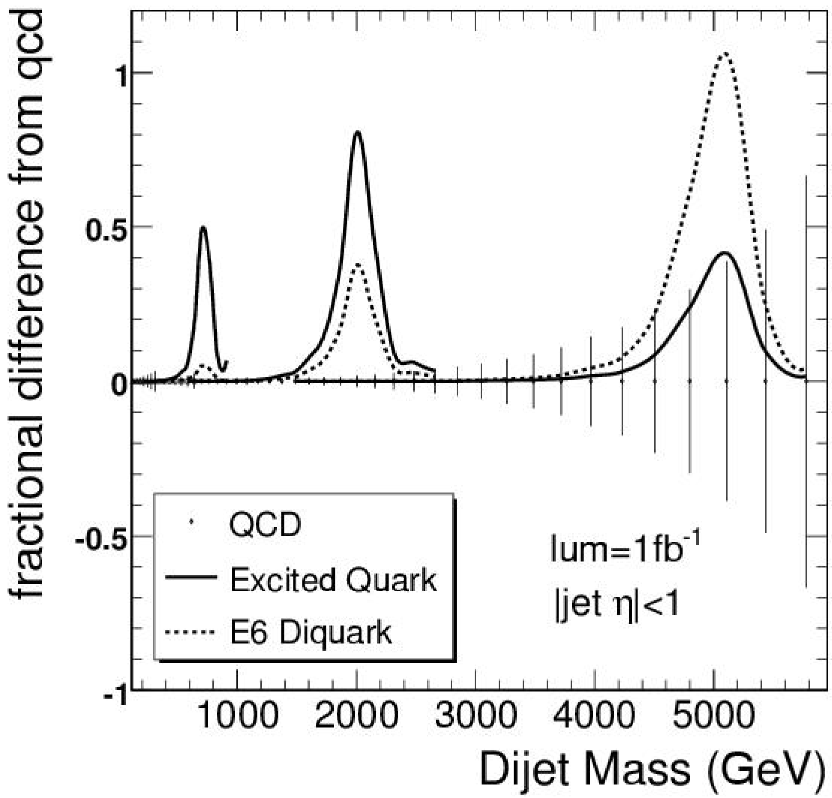
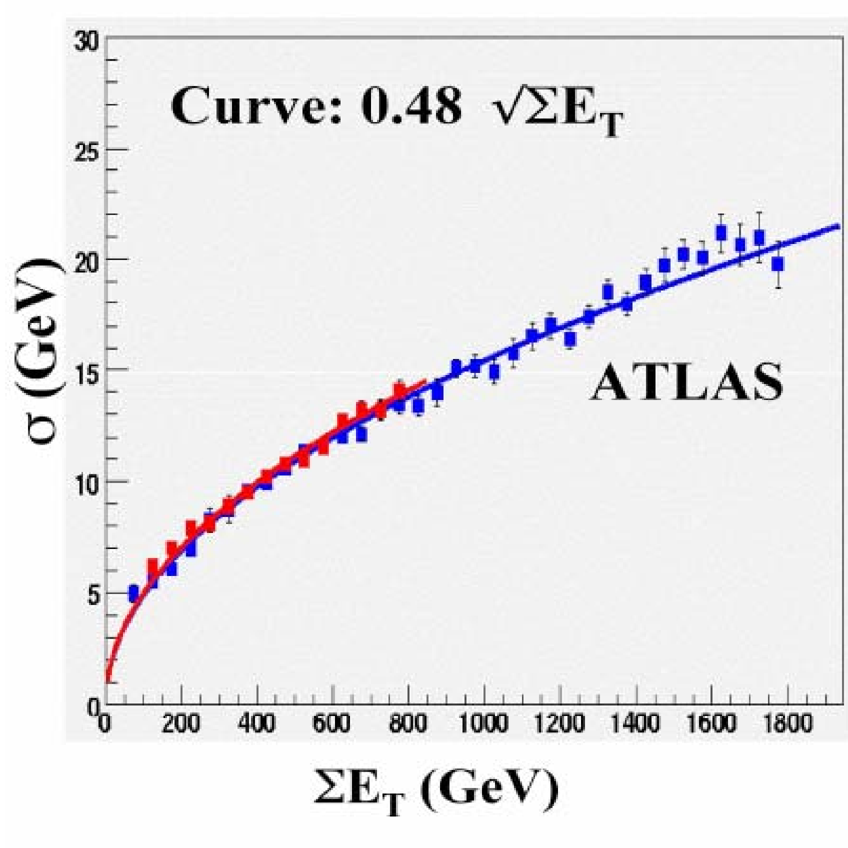


Figure 11 Illustration of the b-tagging performance expected for the CMS tracker using a combined impact parameter and secondary vertexing algorithm. The performance is shown for a fixed b-jet tagging efficiency of 50% as a function of the initial parton transverse momentum for $|\eta| < 2.4$ (*left*) and as a function of the jet pseudorapidity η for initial parton transverse momenta between 50 and 80 GeV (*right*). The vertical axis indicates the probability for misidentifying samples of c jets (*triangles*), gluon jets (*stars*), and light-quark jets (*circles*) as b jets.

CMS 2-jet invariant mass



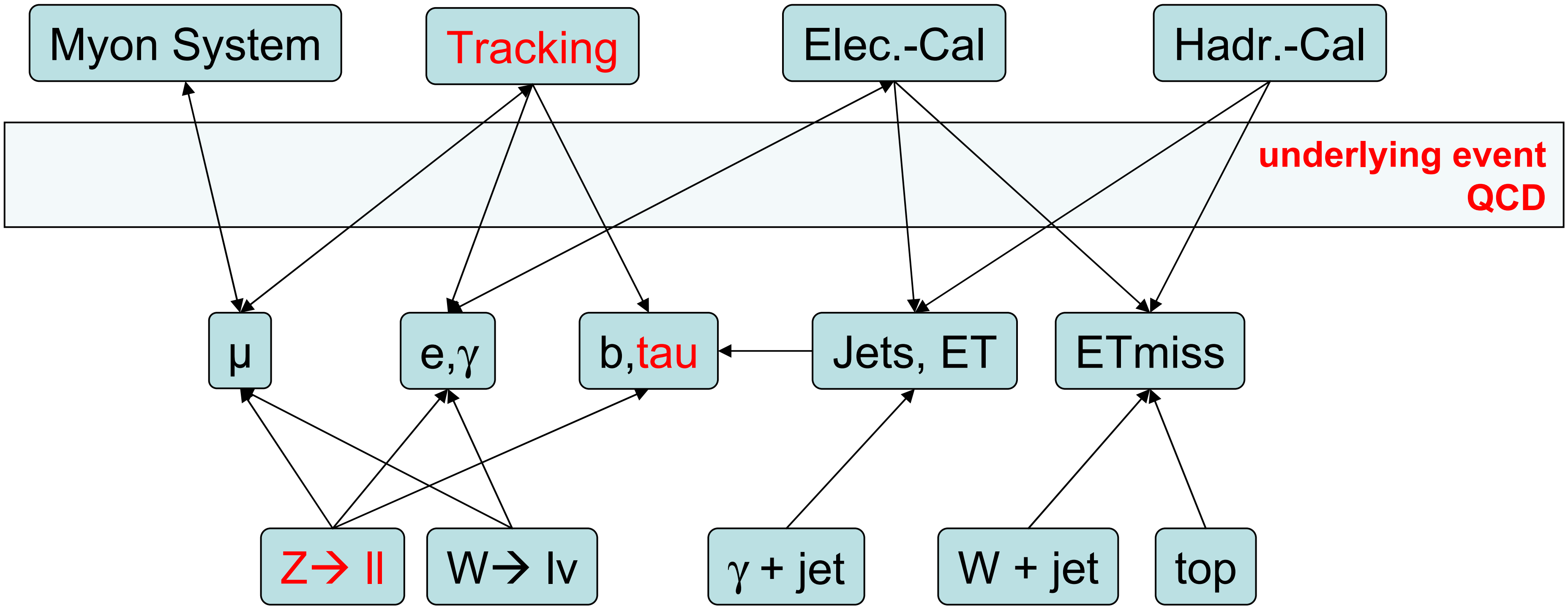
ATLAS ETmiss resolution



ETmiss: in QCD events:

dominated by jet resolution, acceptance losses, underlying event

SM monitor processes and detector monitoring



Standard Modell Processes:

- calibration and efficiencies of detector components
- background for all searches
- experimental and theoretical preparation ?

Energy / momentum scale calibration

Electrons: Z → ee

CMS: intercalibration with single electrons, min bias
uniformity 0.4 – 2.0% (from 4% at day-1)
absolute scale from Z: 0.05 – 0.1%

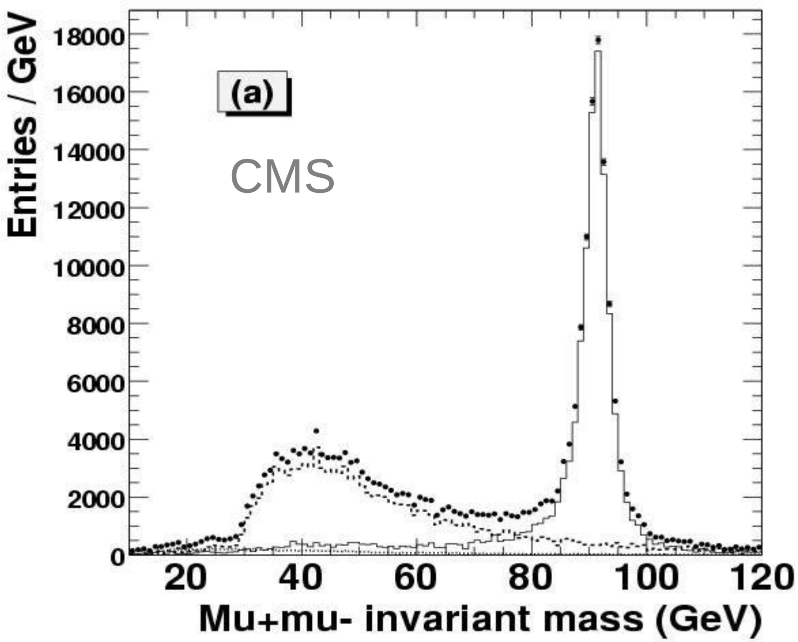
ATLAS: uniformity 1.0 → 0.4%, scale < 0.1%

Challenge: disentangle many effects with Z sample:
B-field, material, non-uniformity, alignment, response…
(so: also need top, J/ψ, Υ, minimum bias,…)

Muons: Z → μμ

1 month at 10^{32}:
$>10^5$ muon pairs

Momentum scale < 0.1%



Hadron energy scale from Top decays

Semileptonic top events!

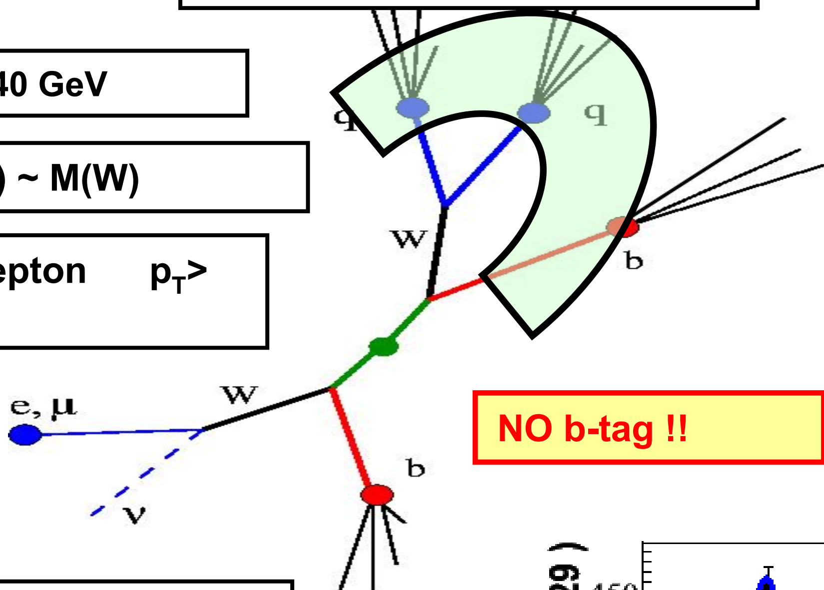
3 jets with largest $\sum p_T$

4 jets p_T> 40 GeV

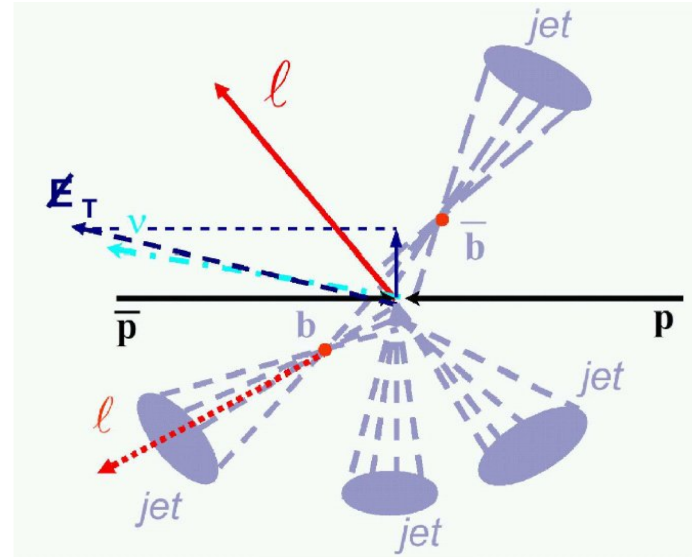
2 jets M(jj) ~ M(W)

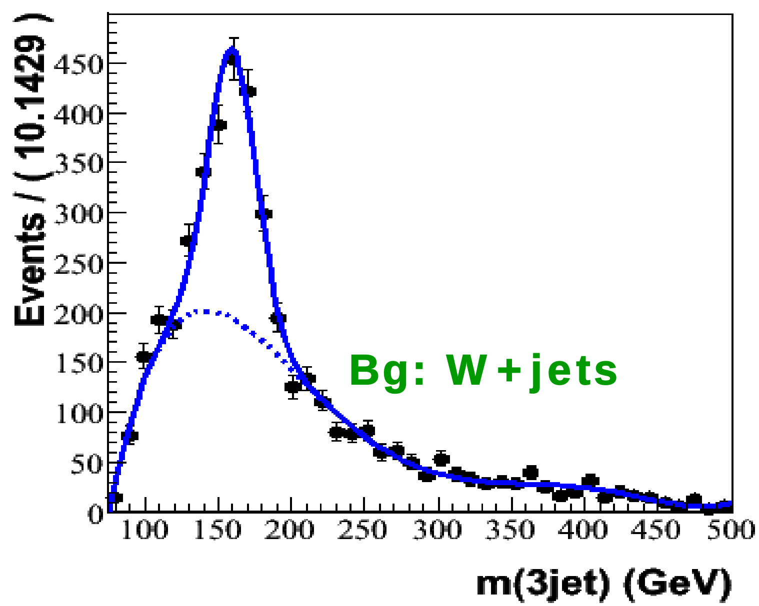
Isolated lepton p_T> 20 GeV

E_T^{miss} > 20 GeV



NO b-tag !!





-b jets
-E_T^{miss} calibration
-Hadronic W's
-p_T (top) studies

If b-tag works, cleaner selection

Also: isolated pions: E / P
radioactive sources

Detactor performance

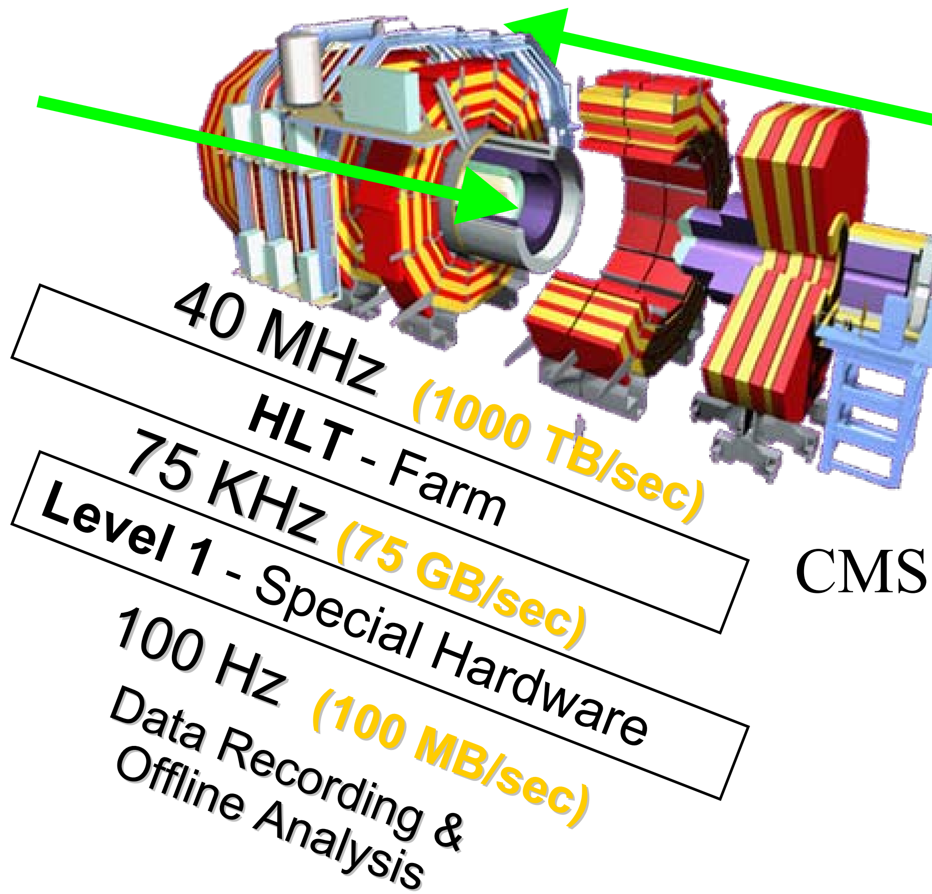
	Expected Day 0	Goals for Physics
ECAL uniformity	~ 1% ATLAS ~ 4% CMS	< 1%
Lepton energy scale	0.5—2%	0.1%
HCAL uniformity	2—3%	< 1%
Jet energy scale	<10%	1%
Tracker alignment	20—200 μm in Rϕ	O(10 μm)

Trigger

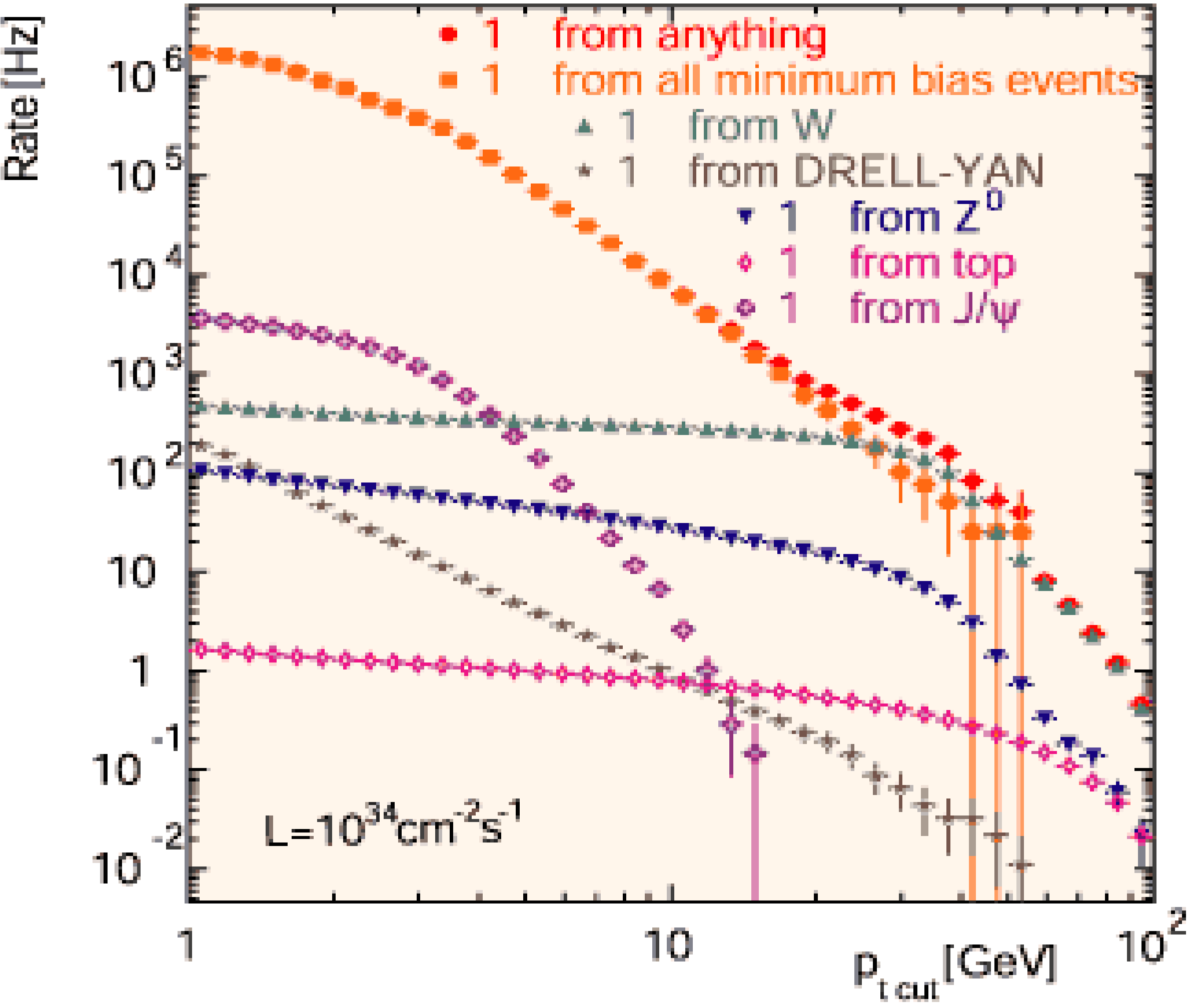
Trigger Level 1	ATLAS (GeV)	CMS (GeV)
Inclusive isolated e/γ	25	29
Two electrons/photons	15	17
Inclusive isolated muon	20	14
Two muons	6	3
Inclusive τ-jet	-	86
Two τ-jet	-	59
τ-jet and E^T_{miss}	25 and 30	-
1-jet, 3-jets, 4-jets	200,90,65	177,86,70
Jet and E^T_{miss}	60 and 60	
Electron and Jet		21 and 45
Electron-Muon	15*10	-
+calibration, monitoring…		

10^7 trigger rejection power

10^{13} analysis selection power



Muon rates



Small PT

- Minimum bias rates too high

> 20 GeV

- W-Zerfall
- Drell-Yan (qq→Z→μμ)
- Z-Zerfall
- top-Zerfall
- ??

High Level trigger

ATLAS Selection	$2 \cdot 10^{33}$ cm^{-2}s^{-1}	10^{34} cm^{-2}s^{-1}	Rates (Hz, low lumi)
Electron	e25i, 2e15i	e30i, 2e20i	~40
Photon	γ60i, 2γ20i	γ60i, 2γ20i	~40
Muon	μ20, 2μ10	μ20, 2μ10	~40
Jets	j400, 3j165, 4j110	j590, 3j260, 4j150	~25
jet+E_{tmiss}	j70+xE70	j100+xE100	~20
tau+E_{tmiss}	τ35+xE45	τ60+xE60	~5
B physics	2μ6 with $m_B/m_{J/\Psi}$	2μ6 with m_B	~20
Total			~200

Rate·Event size (1.6MB) → needed band widths / storage volume
Rate·CPU time → number of processors (500?)

Why physics beyond the Standard Model ?

Theory

- U(1) x SU(2) x (SU(3)
- Local gauge field theory, EWSB
- Renormalizable
- Free of anomalies
- Predictive power:
  - W, Z, top, Higgs
  - running of couplings
- Arbitraryness:
  - Construction principle
  - 17 particles, 26 constants
- Incomplete:
  - Limited at High Energies (>1 TeV)
  - Hierarchy problem, M_H

→ GUT, SUSY, Gravity, …

→ SUSY: $M_{H,}$ $M_{GUT,}$ Dark matter

Experiment

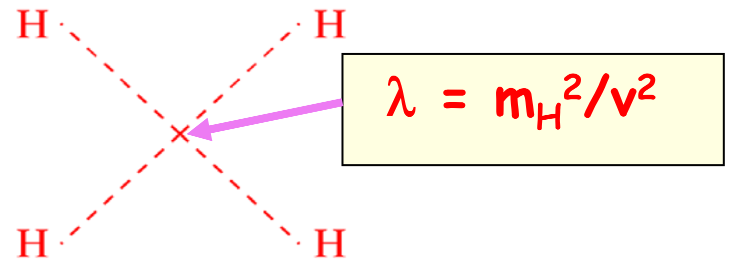
- All (?) data correctly described
- Consistent picture of all interactions below 200 Ge

→ Outstanding success of the SM

- Higgs particle not discovered
- No experimental confirmation of EWSB
- Cosmology: Dark Matter, Dark Energy

Tension between experiment and theory

→ Time for a decisive experiment: LHC



Cancellation of Chiral Anomalies:

- $Q_d = Q_e / 3$ for 3 colours required
- ➡ Hint for Grand Unification

$$0 \le \lambda(\Lambda) \le \infty$$

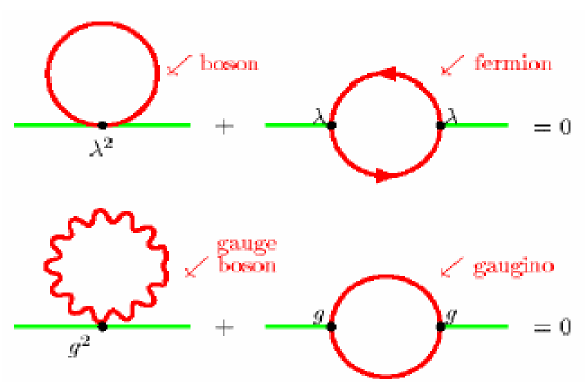
Hierarchy problem: M_{GUT} >> M

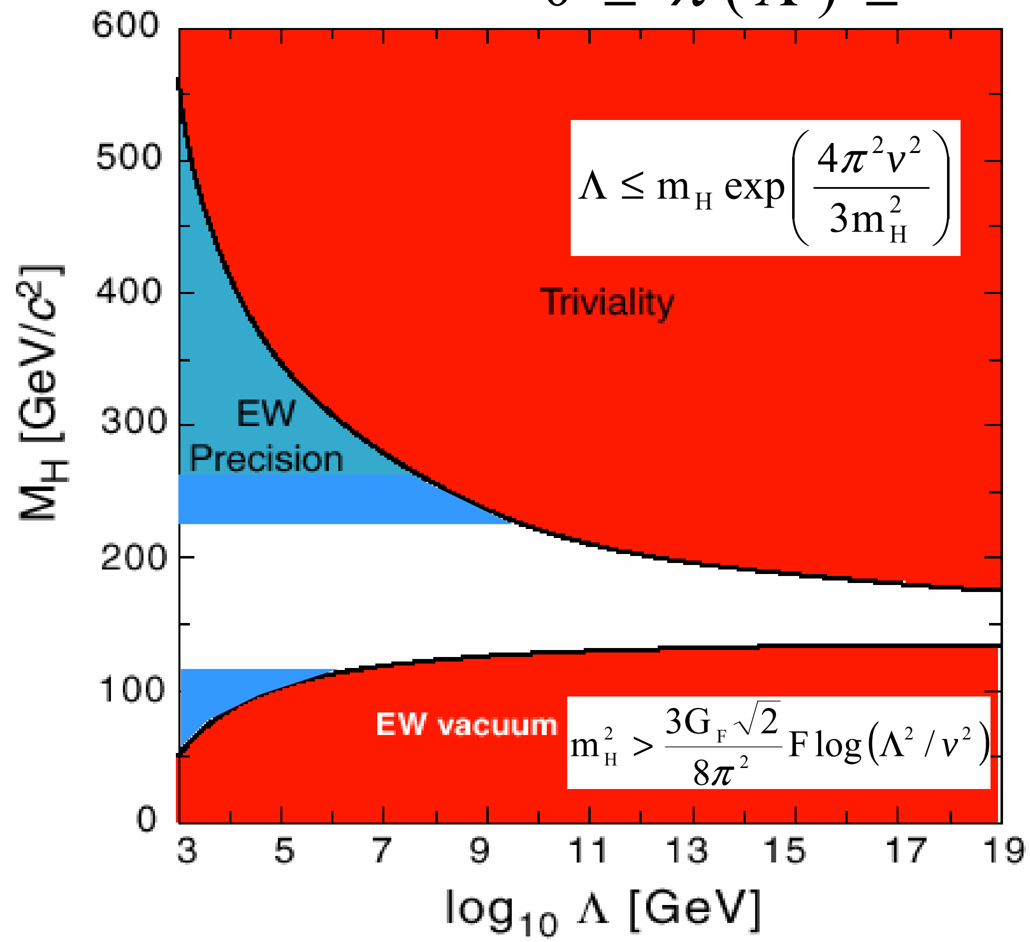
Extrapolation to large scales

- ➡ Higgs mass divergences

$$m^2_{H_{SM}}(\mathrm{phys}) \simeq m^2_{H_{SM}} + \frac{c}{16\pi^2}\Lambda^2$$

- ➡ Bounds on Higgs mass
- ➡ No divergence if symmetry between Fermions-Bosons





Supersymmetrie

Symmetry between fermions and bosons

Spin	Standardteilchen	Superpartner	Spin
1/2	Leptonen (e, ν_e, …) Quarks (u, d, …)	Sleptonen ($\tilde{e}$, $\tilde{\nu}_e$, …) Squarks ($\tilde{u}$, $\tilde{d}$, …)	0
1	Gluonen $W^{\pm}$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

Gauge couplings of partners are identical,
Masses of partners are different: SUSY is broken

Susy particles

Requires two Higgs doubles of opposite Hypercharge
(one for up-sector, one for down-sector)

$$\Phi_{(Y=-1)} = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \qquad \Phi_{(Y=+1)} = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

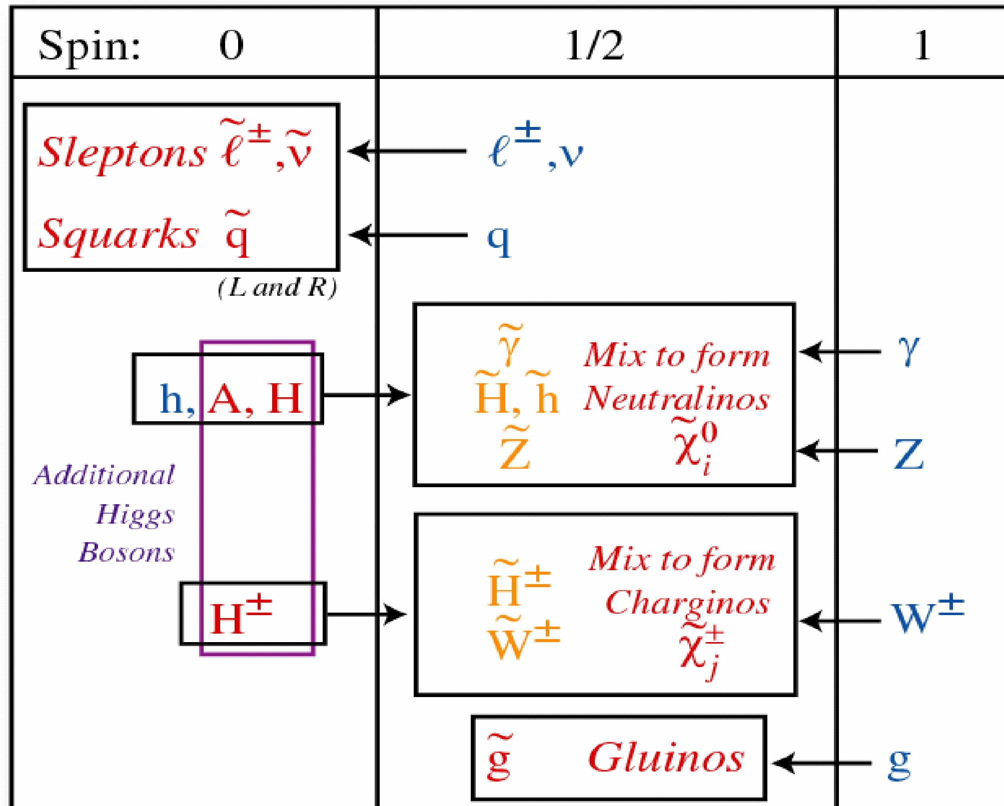
5 physical Higgs bosons

2 charged : H^+ and H^-
2 CP even neutral : H and h
1 CP odd neutral : A

Higgs masses derivable from MSSM parameters

H^+, H^-: $M^2 = M_W^2 + M_A^2$ (at tree-level)
h : $M < M_Z$ (at tree-level) → 130 GeV (rad. corr.)

Superpartners for all SM fields
(approximate doubling of physical particle spectrum)



Why SUSY at ~ 1 TeV ?

- stabilises the Higgs mass if

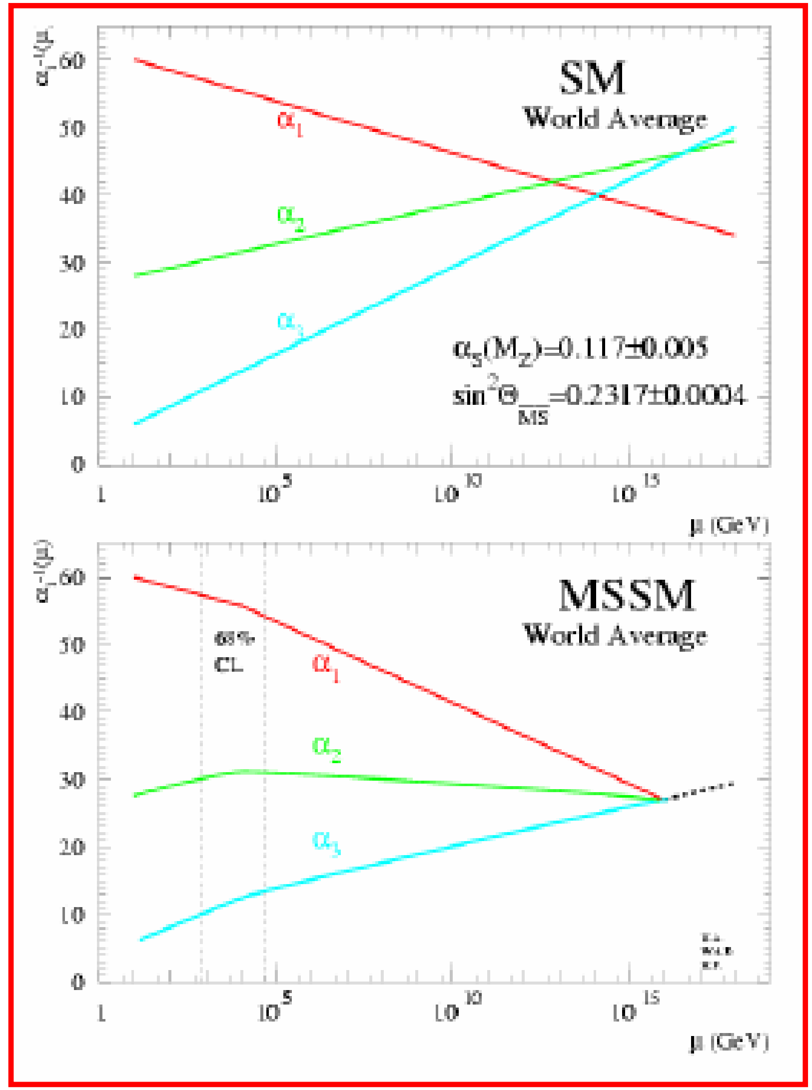
  $|m_F - m_B| < O(1\text{ TeV})$

- predicts a light Higgs $m_h < 130$ GeV
- predicts gauge coupling unification
- dark matter candidate:

  lightest SUSY particle can be stable

  LSP= neutralino, sneutrino, gravitino, axino ...

- consistent with all data



→SUSY at the TeV scale:

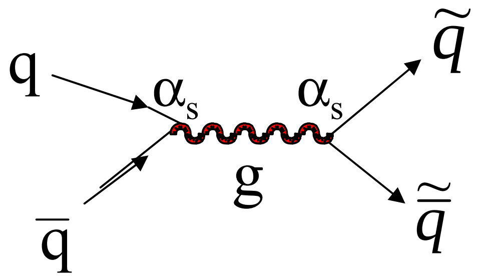
best candidate for physics beyond the Standard Model

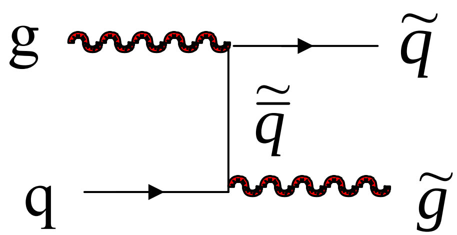
Sparticle production at LHC

from Gianotti

- **Squarks and gluinos** produced via strong processes $\rightarrow$ large cross-section

E.g.:



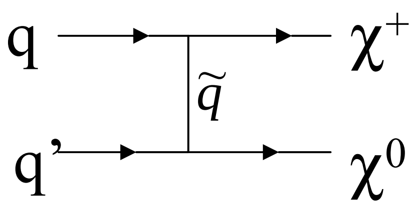


M (GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

- **Charginos, neutralinos, sleptons** direct production via electroweak processes

➡ much smaller rate (produced more abundantly in squark and gluino decays)

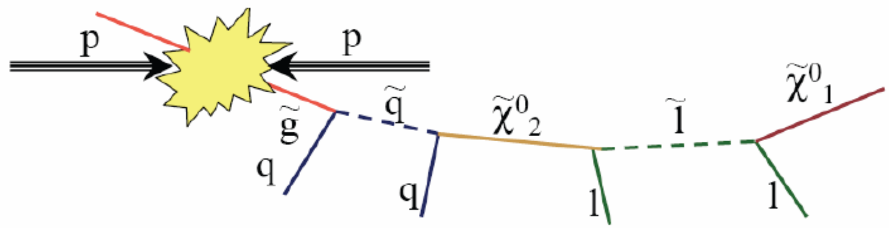
E.g.



$\sigma \approx$ pb $\quad m_\chi \approx 150$ GeV

$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ production are <u>dominant</u> SUSY processes at LHC (if accessible)

LHC: signal and background

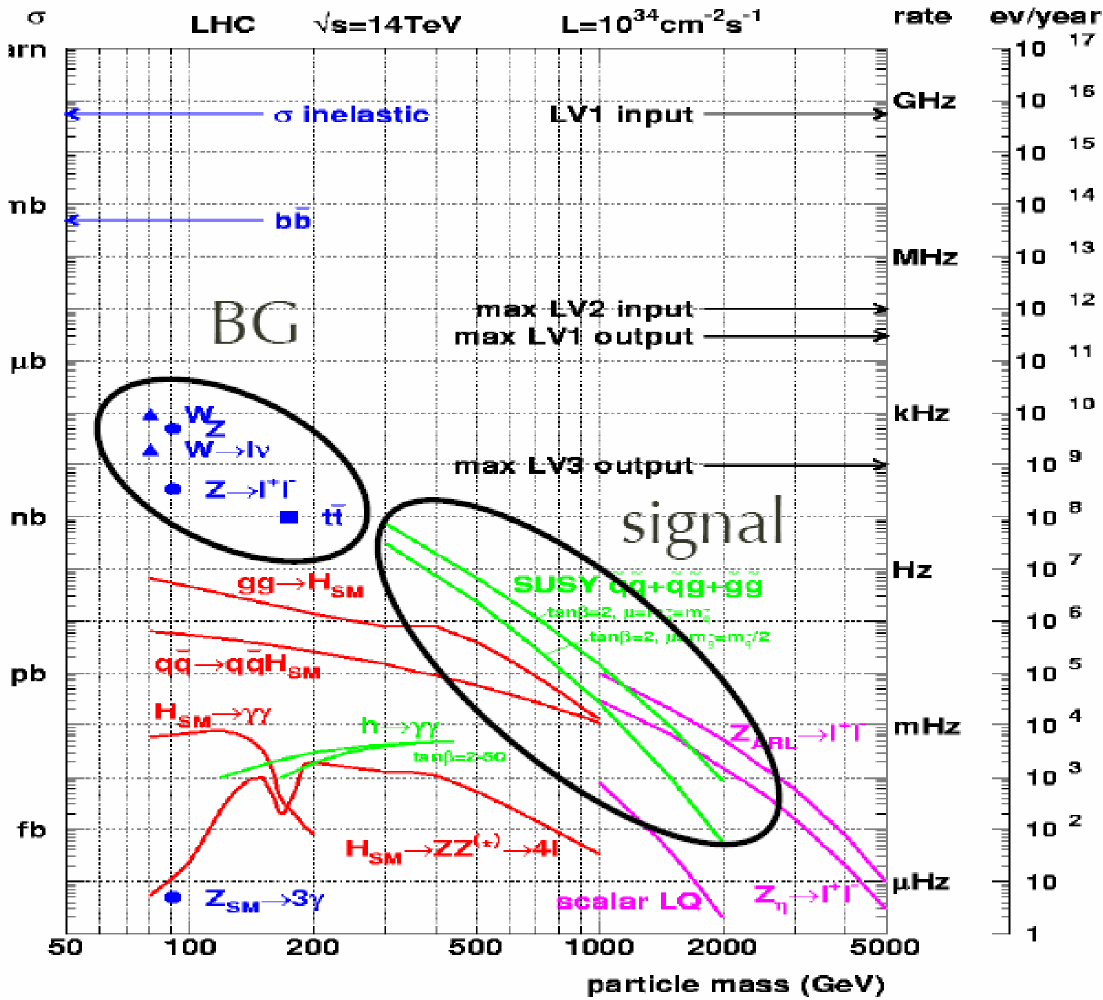


Dominant production of colored sparticles which will decay to leptons, jets + LSP

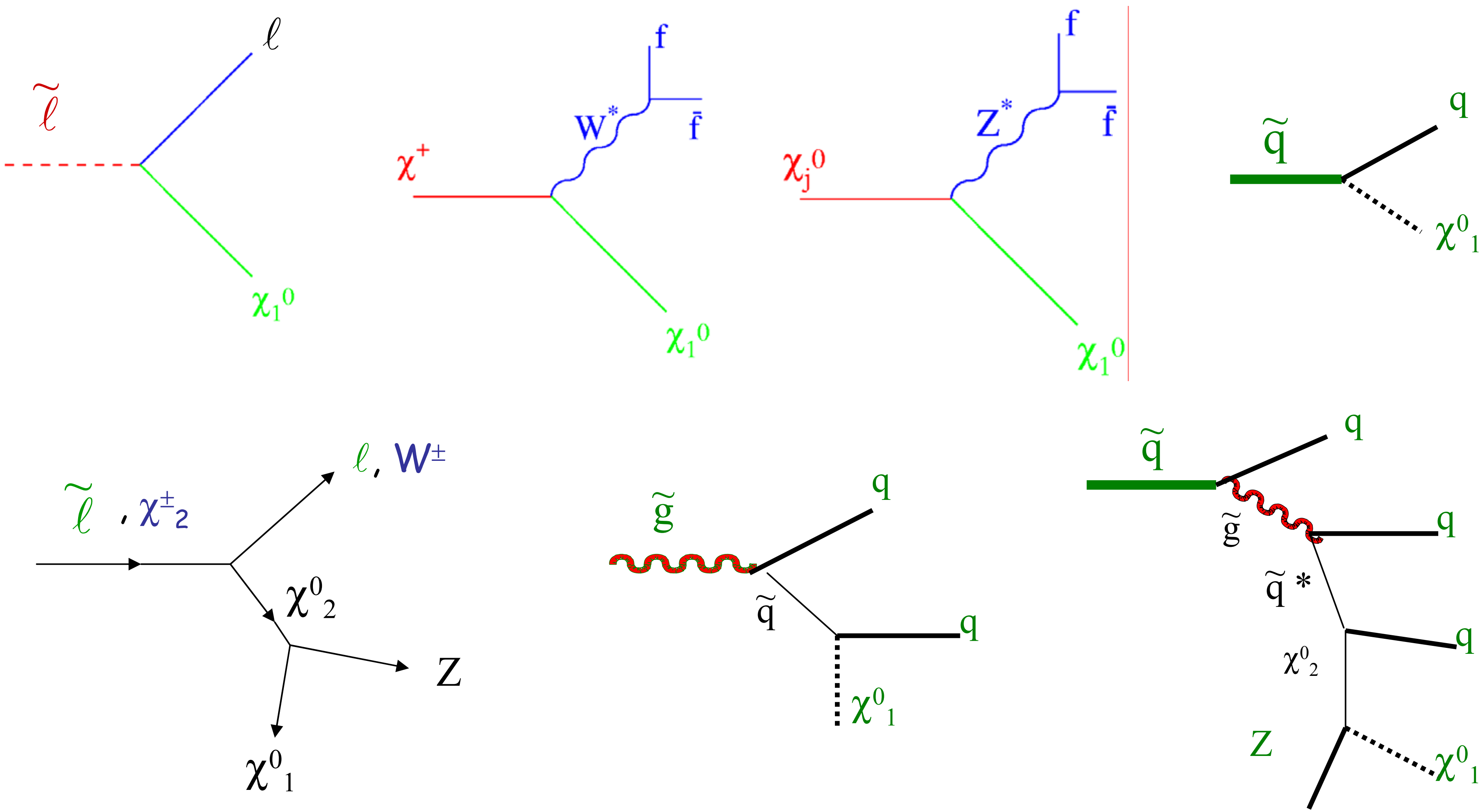
SUSY signal:
jets and leptons with large Pt
+ missing transverse energy
(typical e.g. for mSUGRA, GMSB)

BG from W, Z and tt production:
need strong rejection ~10^{-4}

Exploit kinematics to maximum extent:
mass reconstruction method



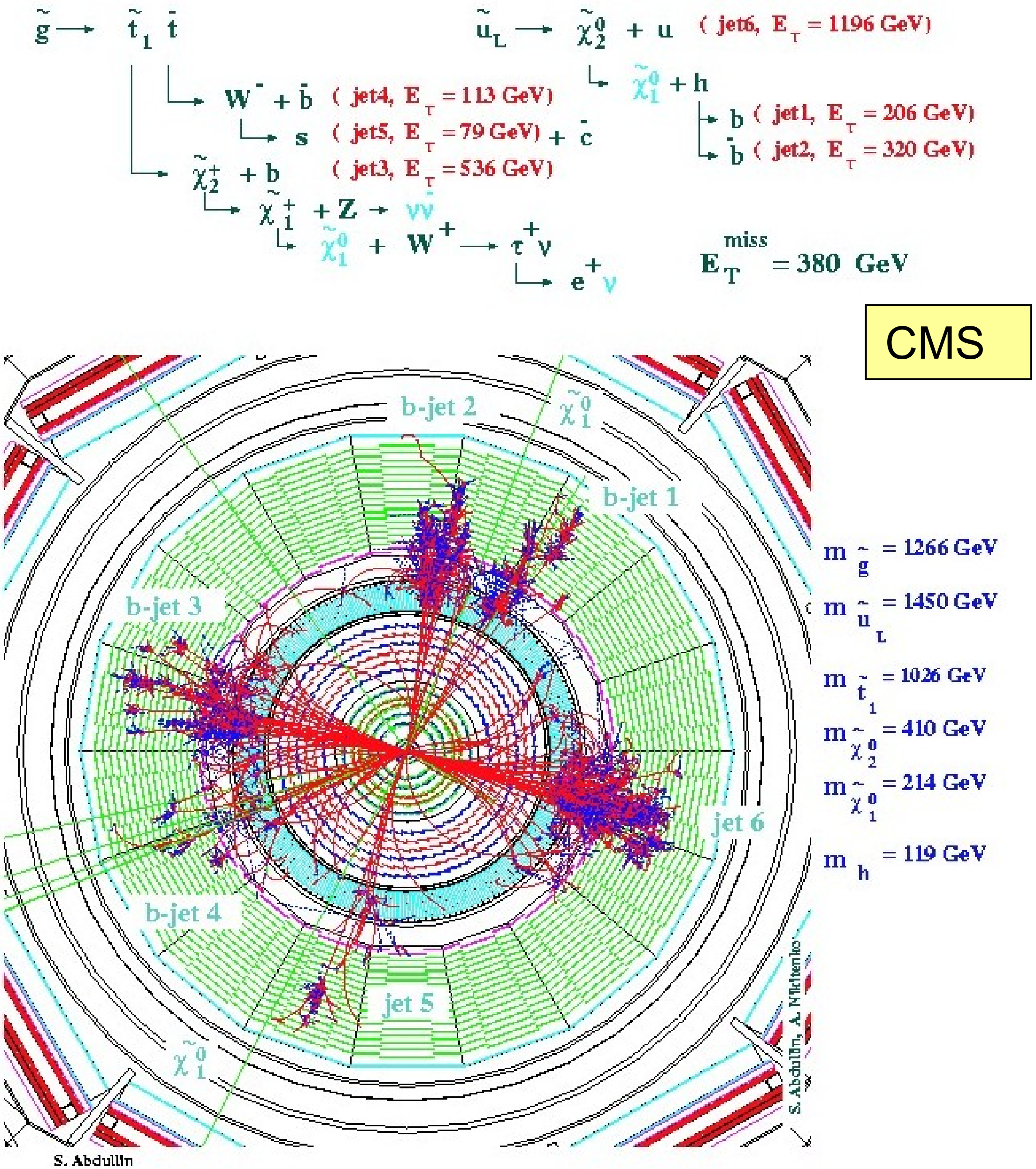
SUSY vertices and decay modes



Long decay chaines: **Jets + ETmiss**

(often + leptons, W,Z, …)

Example :



m_0 = 1000 GeV
$m_{1/2}$ = 500 GeV
$\tan\beta$ = 35 $\mu > 0$ $A_0 = 0$

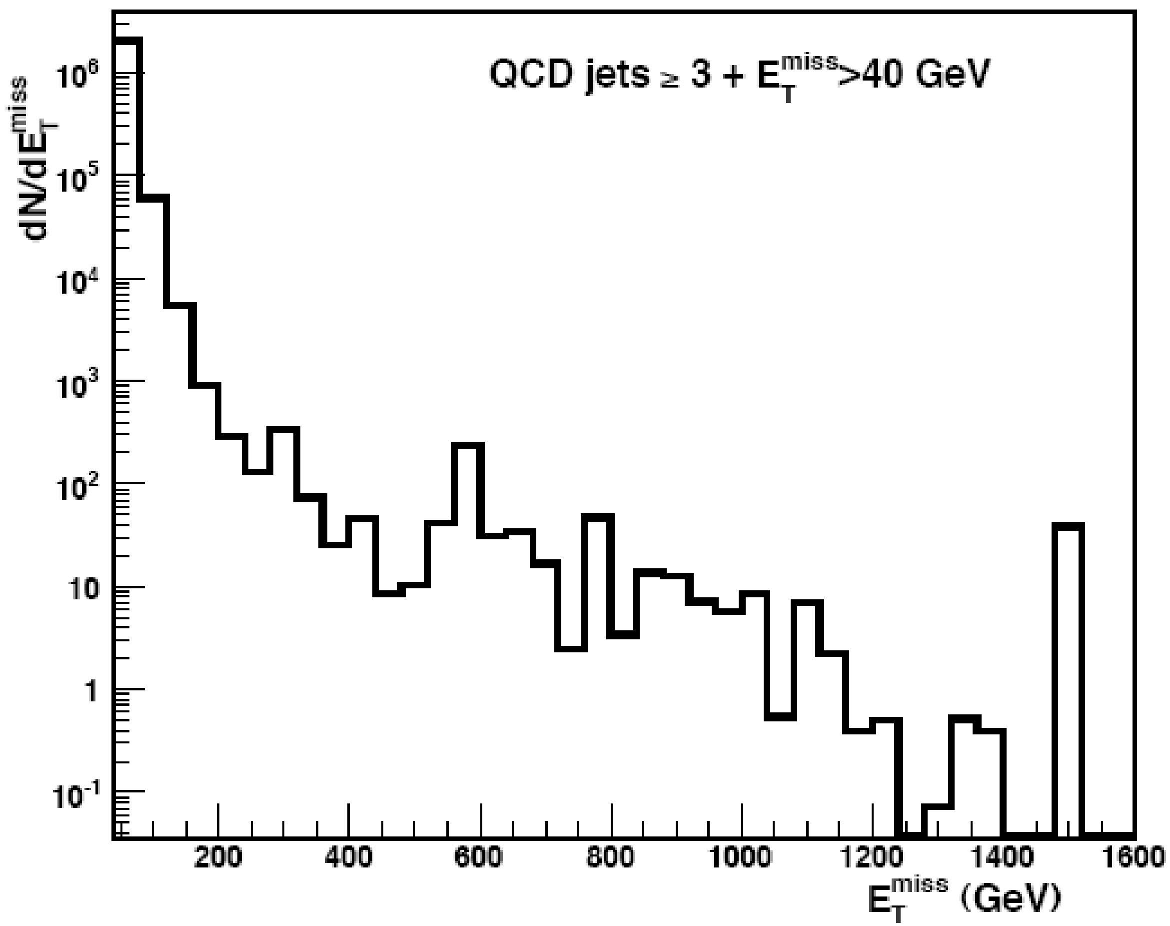
$$m(\tilde{q}, \tilde{g}) \sim 1\,\text{TeV}$$

→ spectacular signatures
→ easy to extract SUSY signal from SM backgrounds at LHC (in most cases …)

Eample Analysis

Problem:

- **ETmiss in QCD events**



LM1

Low mass SUSY

- **Gluinos: 600 GeV**
- **Squarks: 550 GeV**
- M0= 60 GeV
- M1/2=250 GeV
- tan beta=10

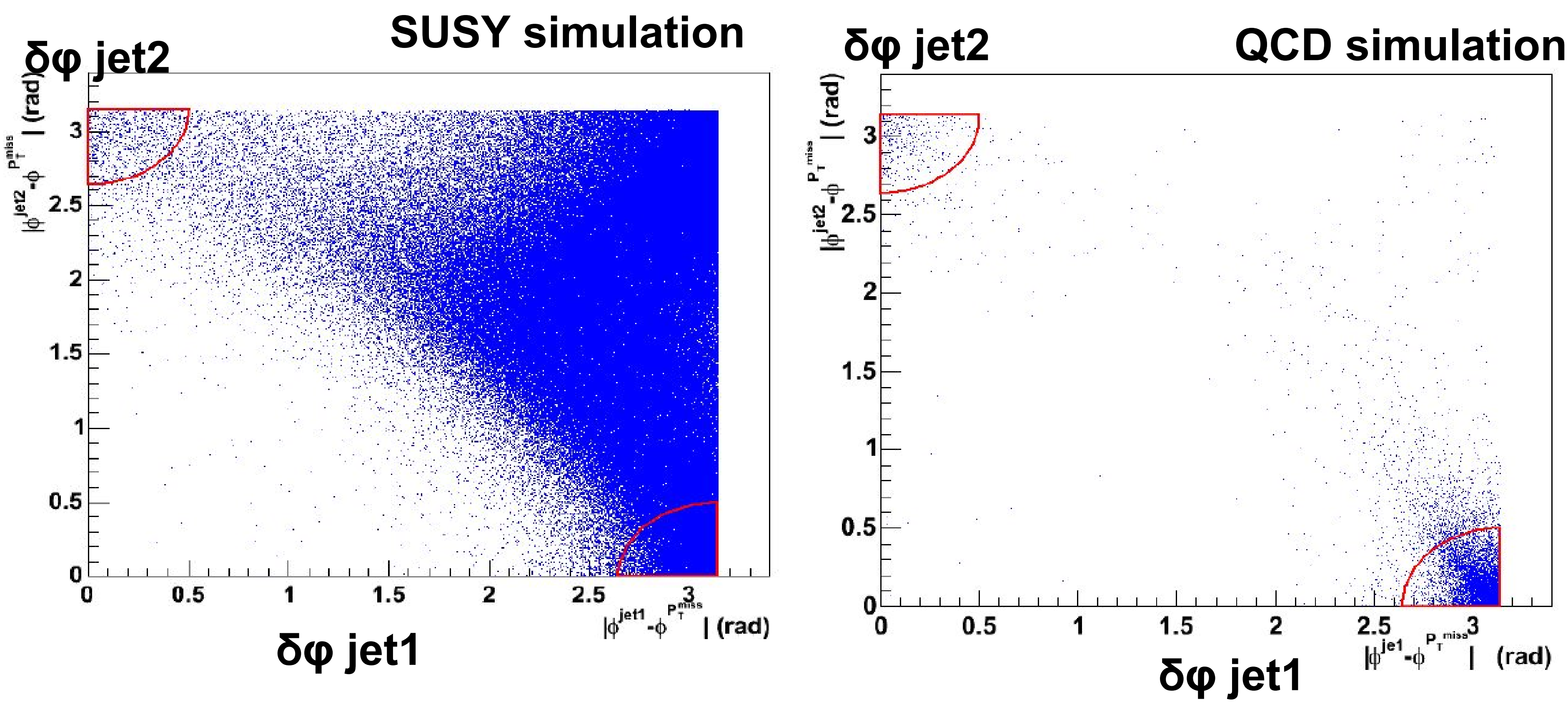
Full hadronic channel

- **several jets + ETmiss**
- **No leptons**

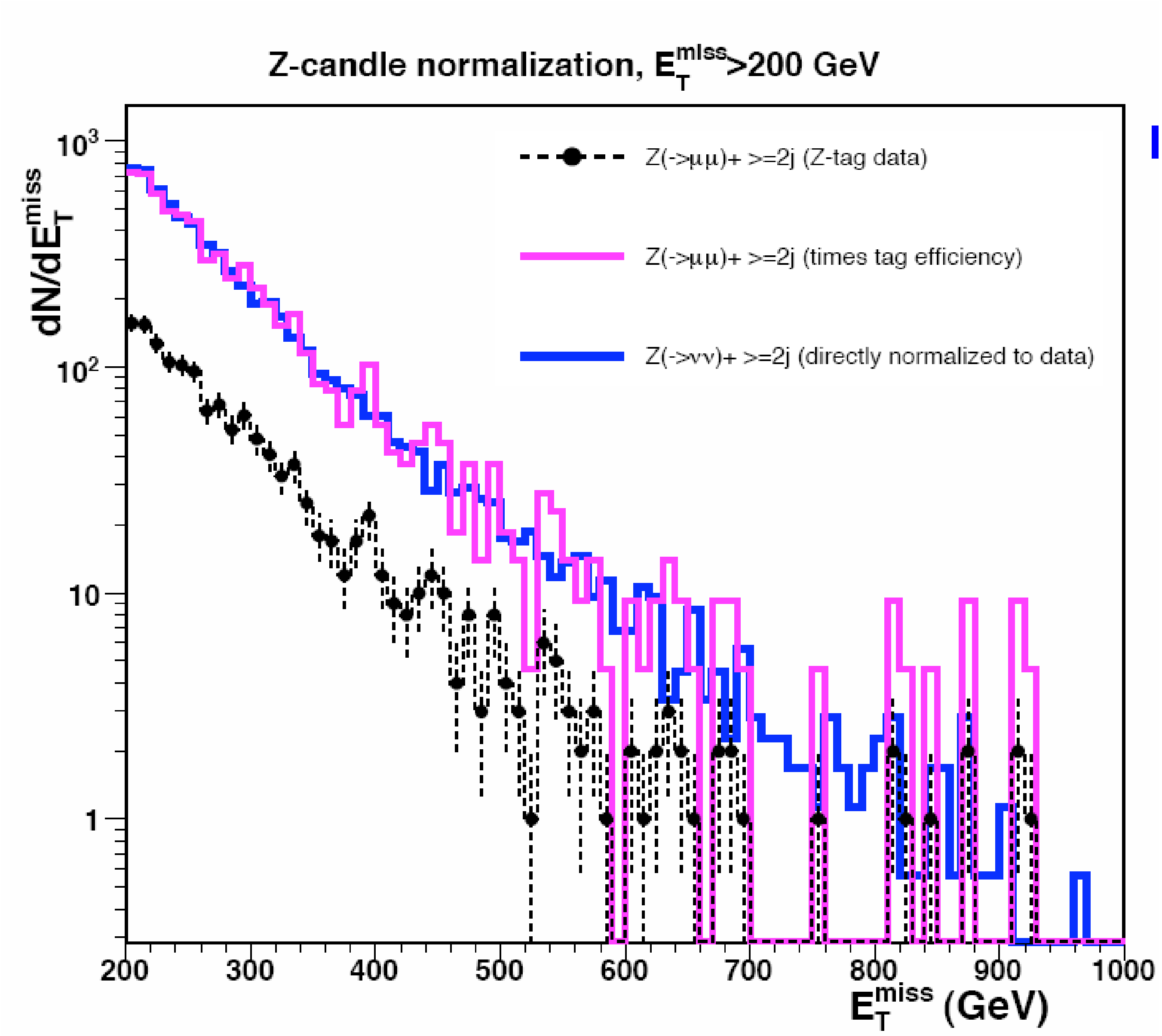
SUSY example analysis

QCD events: ETmiss dominated by jet resolution

- Study PTmiss direction w.r.t. jet direction
- Cut on



Background



Irreducible background

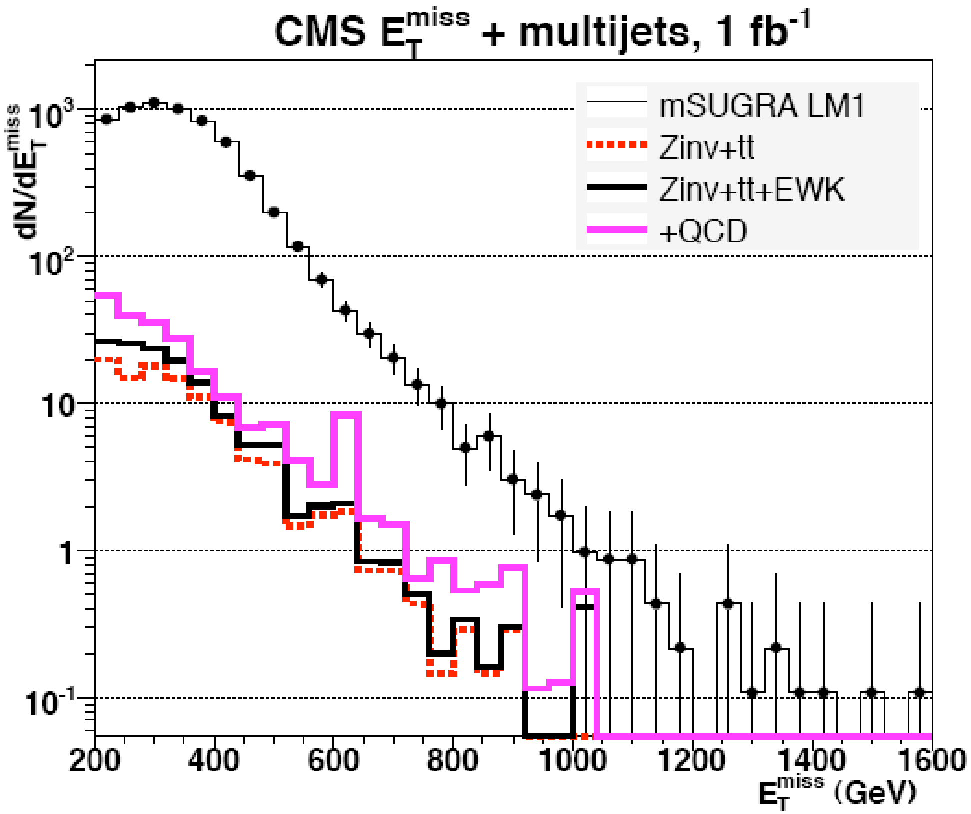
Zjj → ννjj

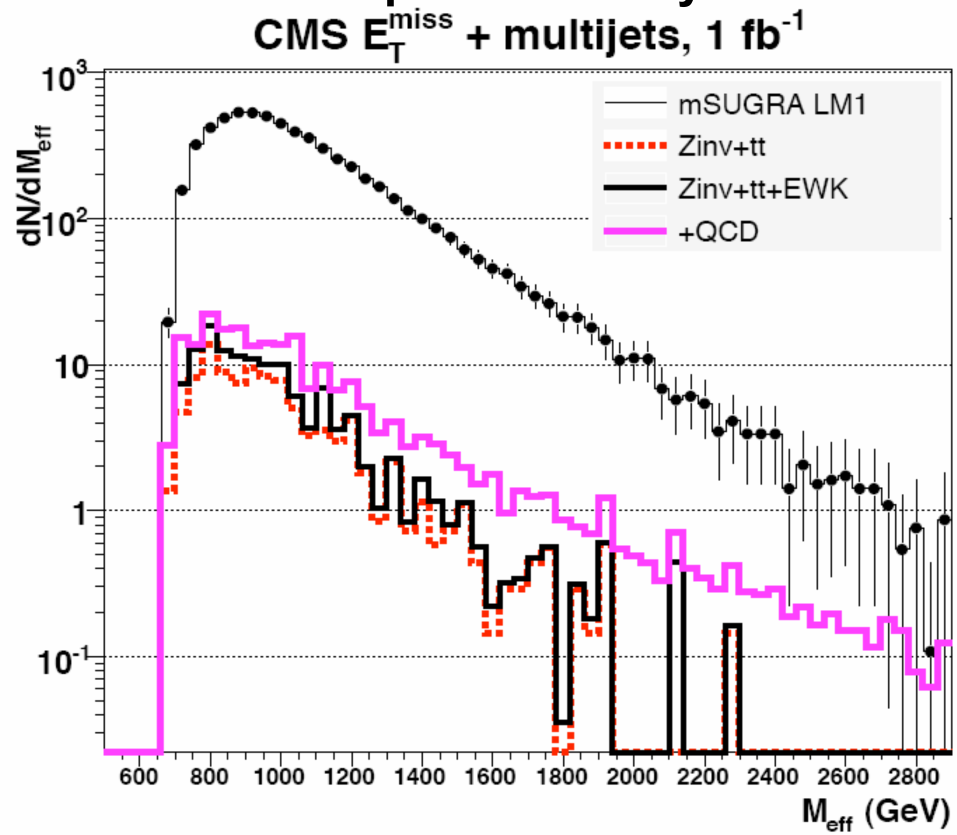
- **Determine background from data**
  Zjj → μμjj
- **Assume same ETmiss distribution**

Signal significance

Meff = ET + PTmiss

Measure of total energy released in sparticle decay: ~ MSUSY

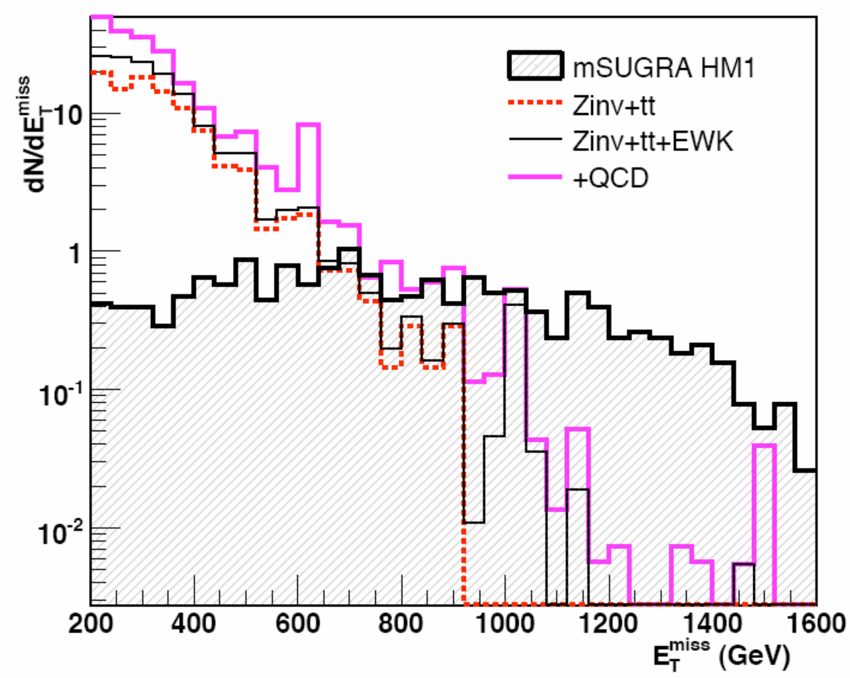


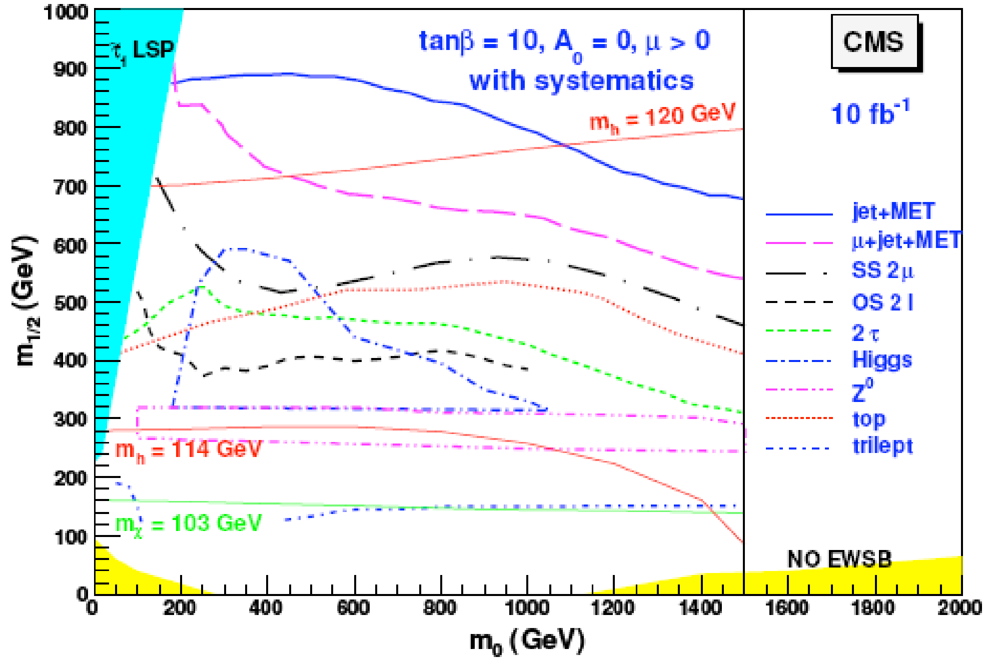


High signal / background ratio

- **Background uncertainty not too important**

High mass SUSY: HM1





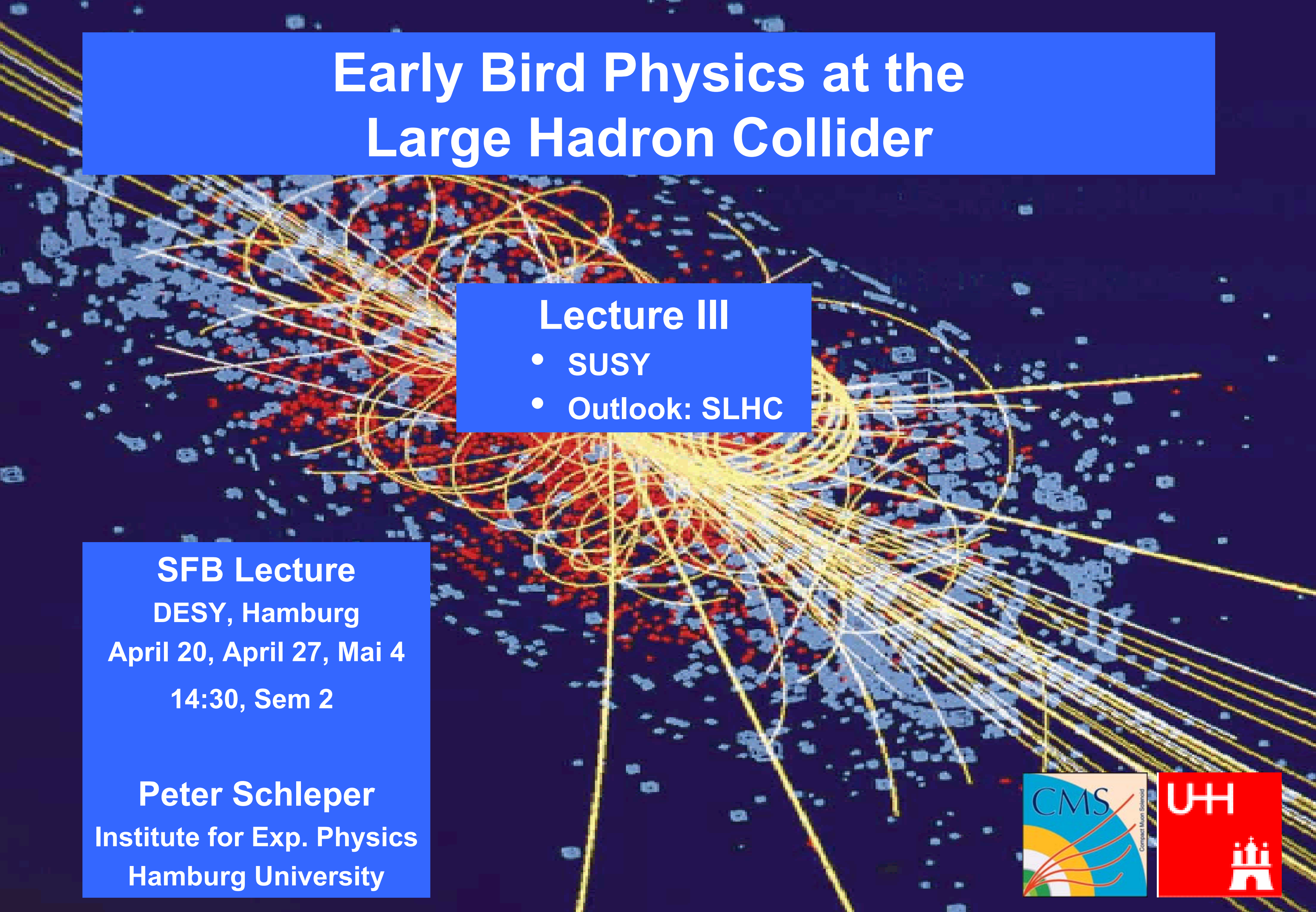
Low mass SUSY

- LM1: 6 pb^{-1}
- Typical: 0.1-1 fb^{-1}

High mass SUSY

- Ultimate reach:
- Squarks, Gluinos: 2500 GeV

END lecture 2



Early Bird Physics at the Large Hadron Collider

Lecture III

- SUSY
- Outlook: SLHC

SFB Lecture
DESY, Hamburg
April 20, April 27, Mai 4
14:30, Sem 2

Peter Schleper
Institute for Exp. Physics
Hamburg University

Susy particles

Requires two Higgs doubles of opposite Hypercharge
(one for up-sector, one for down-sector)

$$\Phi_{(Y=-1)} = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \qquad \Phi_{(Y=+1)} = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

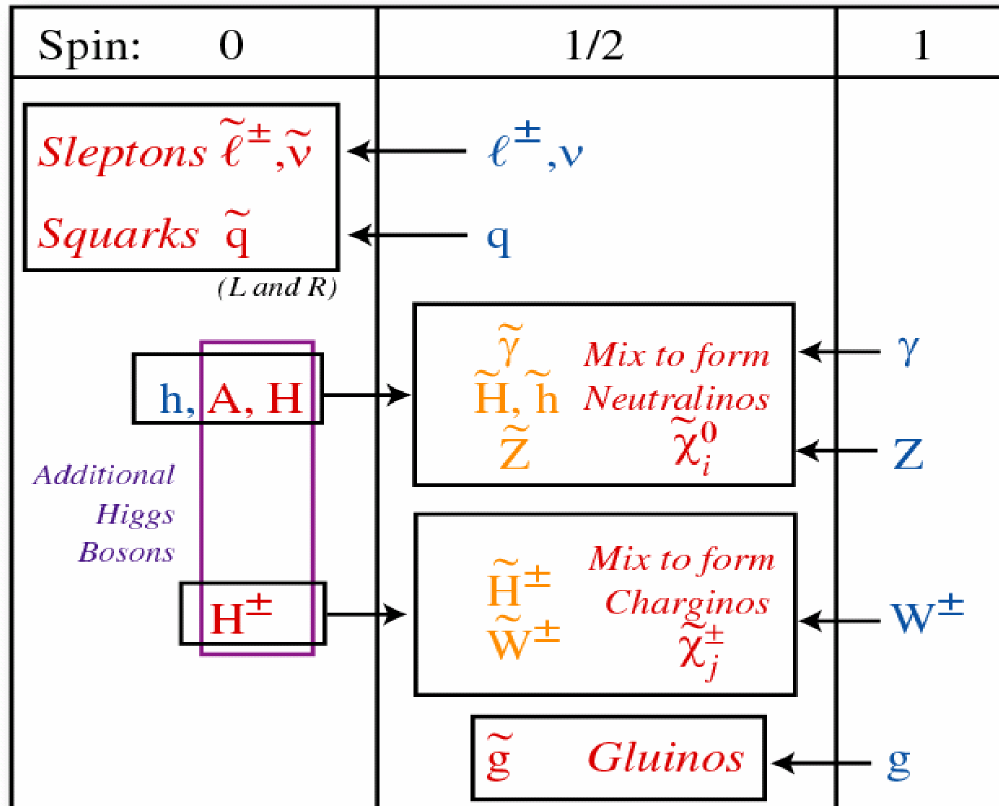
5 physical Higgs bosons

2 charged : H^+ and H^-
2 CP even neutral : H and h
1 CP odd neutral : A

Higgs masses derivable from MSSM parameters

H^+, H^-: $M^2 = M_W^2 + M_A^2$ (at tree-level)
h : $M < M_Z$ (at tree-level) → 130 GeV (rad. corr.)

Superpartners for all SM fields
(approximate doubling of physical particle spectrum)



SUSY Models and Parameters

MSSM: minimal susy standard model

- SM particles, 2 Higgs doublets → h,H,A,$H^{\pm}$
- SUSY partners
- Soft SUSY breaking (no quadratic div.)
- 126 parameters

  (masses, couplings, mixing param.)

  Higgs: $\tan\beta = vev_1 / vev_2$, m_A, μ

➡ Too complicated; no ? predictive power

Here: R-parity conservation

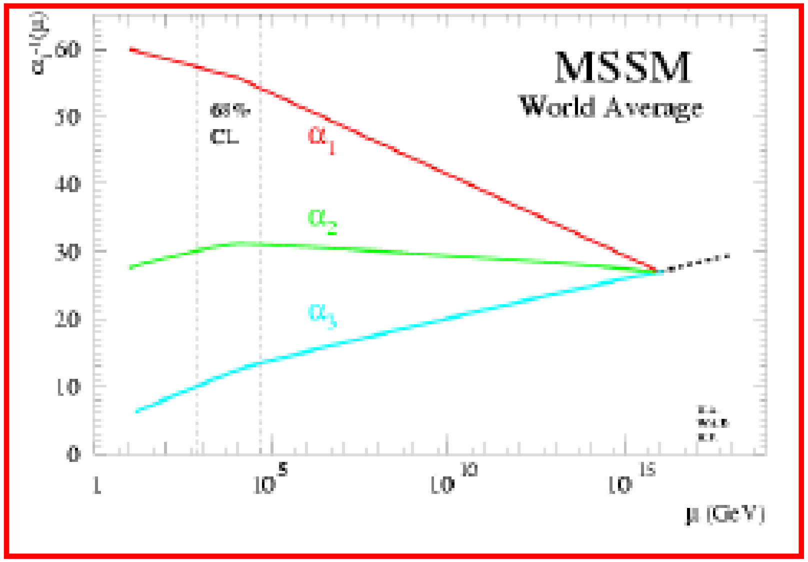
- no proton decay, LSP is stable

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = -\Big[& \tilde{Q}_i^{\dagger} \mathbf{m}^2_{Q_{ij}} \tilde{Q}_j + \tilde{d}^{\dagger}_{Ri} \mathbf{m}^2_{D_{ij}} \tilde{d}_{Rj} + \tilde{u}^{\dagger}_{Ri} \mathbf{m}^2_{U_{ij}} \tilde{u}_{Rj} \\
& + \tilde{L}_i^{\dagger} \mathbf{m}^2_{L_{ij}} \tilde{L}_j + \tilde{e}^{\dagger}_{Ri} \mathbf{m}^2_{E_{ij}} \tilde{e}_{Rj} + m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2 \Big] \\
& - \frac{1}{2} \left[M_1 \bar{\lambda}_0 \lambda_0 + M_2 \bar{\lambda}_A \lambda_A + M_3 \bar{\tilde{g}}_B \tilde{g}_B \right] \\
& - \frac{i}{2} \left[M_1' \bar{\lambda}_0 \gamma_5 \lambda_0 + M_2' \bar{\lambda}_A \gamma_5 \lambda_A + M_3' \bar{\tilde{g}}_B \gamma_5 \tilde{g}_B \right] \\
& + \left[(\mathbf{a_u})_{ij} \epsilon_{ab} \tilde{Q}_i^a H_u^b \tilde{u}^{\dagger}_{Rj} + (\mathbf{a_d})_{ij} \tilde{Q}_i^a H_{da} \tilde{d}^{\dagger}_{Rj} + (\mathbf{a_e})_{ij} \tilde{L}_i^a H_{da} \tilde{e}^{\dagger}_{Rj} + \text{h.c.} \right] \\
& + \left[(\mathbf{c_u})_{ij} \epsilon_{ab} \tilde{Q}_i^a H_d^{*b} \tilde{u}^{\dagger}_{Rj} + (\mathbf{c_d})_{ij} \tilde{Q}_i^a H^*_{ua} \tilde{d}^{\dagger}_{Rj} + (\mathbf{c_e})_{ij} \tilde{L}_i^a H^*_{ua} \tilde{e}^{\dagger}_{Rj} + \text{h.c.} \right] \\
& + \left[b H_u^a H_{da} + \text{h.c.} \right], \qquad (8.1
\end{aligned}
$$

Constrained MSSM (CMSSM)

use unification at the GUT scale:

- Gauge couplings: $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_{GUT} = 0.04$
- Gaugino masses: $m_{1/2} = M_1 = M_2 = M_3$
- Sfermion masses: m_0 = $m_{\tilde{\ell}_R}, m_{\tilde{\ell}_L}, m_{\tilde{\nu}_L}, m_{\tilde{q}_R}, m_{\tilde{q}_L}$
- Higgs Parameters $\tan\beta$, m_A, μ
- Squark/Slepton Mixing: A_t, A_b, A_τ



SUSY breaking models

mSUGRA: Minimal Supergravity at GUT scale

- Unify spin 0 sector: Higgs and sfermions
- Unify all trilinear couplings $A_t = A_b = A_\tau = A_0$
- Radiative EWSB → only sign of μ
  - $m_{1/2}$, m_0 , tan β, sign(μ), A_0
  - LSP = lightest neutralino

AMSB: anomaly mediated breaking

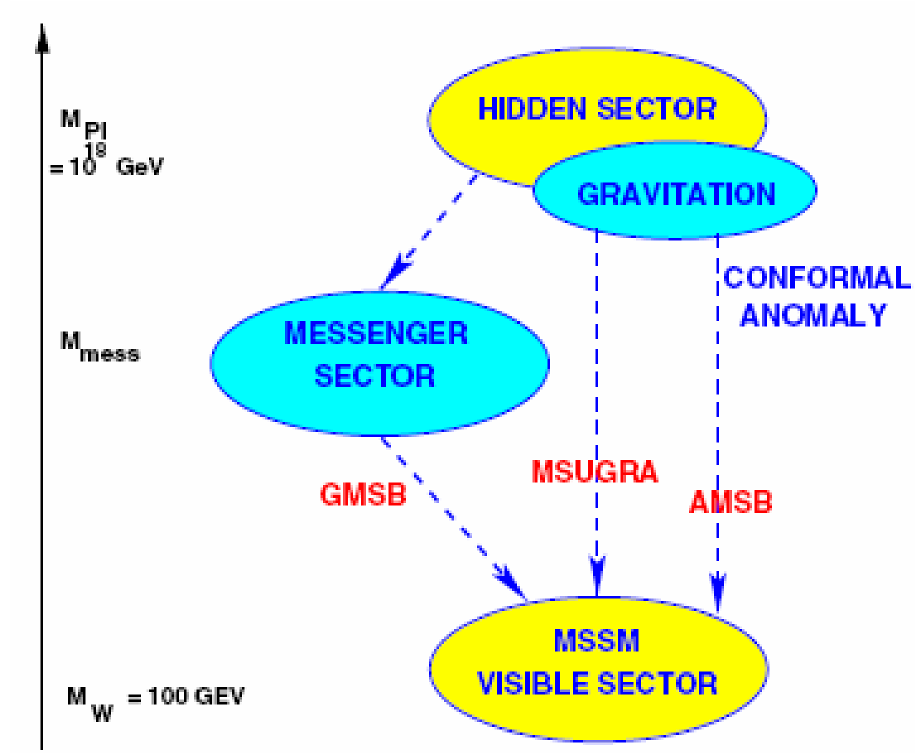
  - $m_{3/2}$, m_0 , tan β, sign(μ)
  - LSP = lightest neutralino

GMSB: Gauge mediated breaking

  - M, Λ, N, tan β, sign(μ)
  - LSP = Gravitino

Gaugino mediated breaking in extra dimens.

- vis. – gauginos -- hidden
  - $m_{1/2}$, M_c, tan β, sign(μ)
  - LSP = Gravitino



Running Masses

RGE evolution of SUSY masses

Gaugino masses:

$$\frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}$$

$$M_3 \equiv M_{\tilde{g}} \simeq 2.7 m_{1/2},$$
$$M_2(M_Z) \simeq 0.8 m_{1/2},$$
$$M_1(M_Z) \simeq 0.4 m_{1/2}.$$

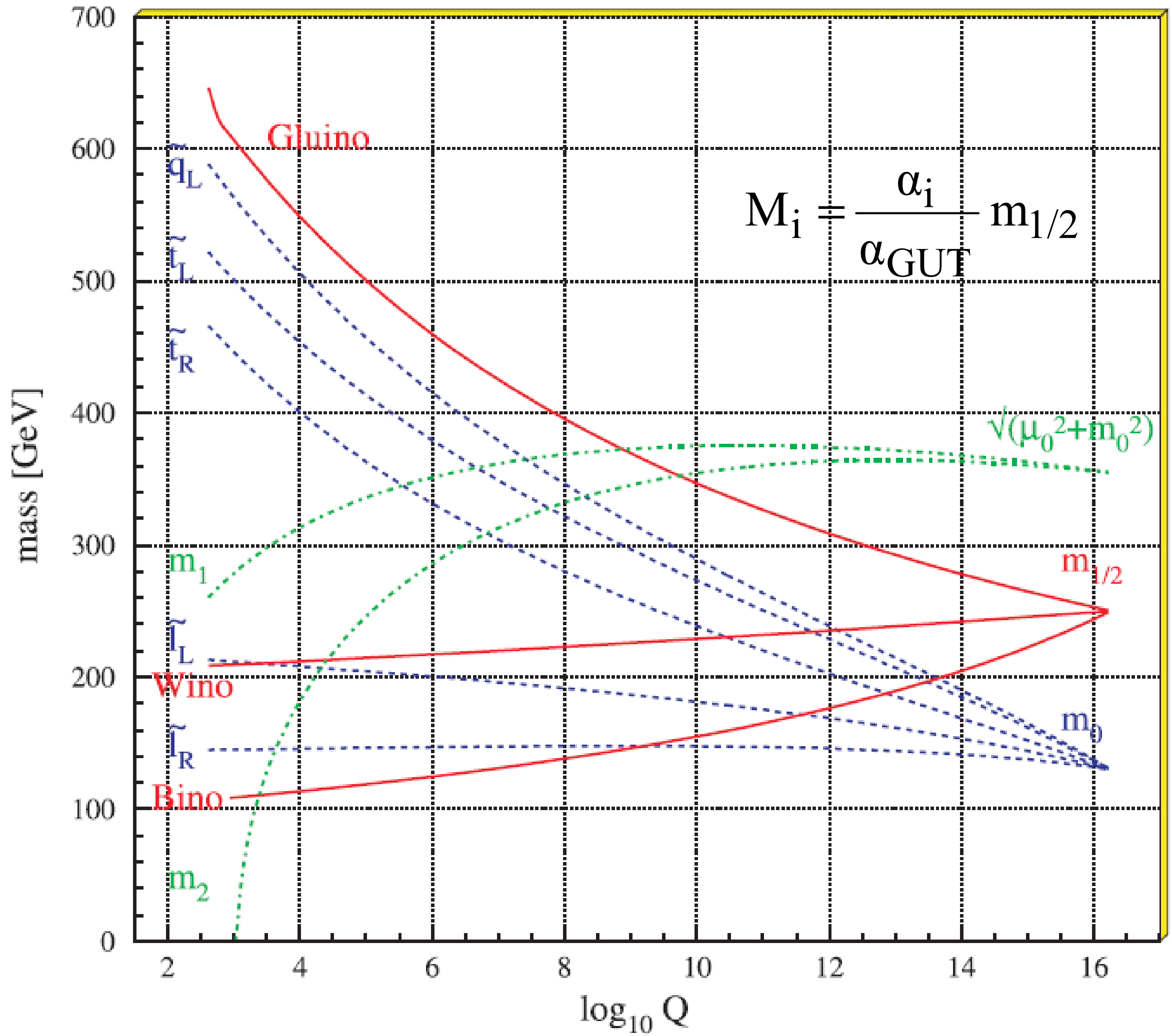
Sfermion masses:

$$m_{\tilde{l}} < m_{\tilde{q}} \simeq M_{\tilde{g}}$$

Higgs Masses:

- m_h < 130 GeV
- $m^2_{H,A,H\pm} \sim m^2_A + M^2_W$

mSUGRA



Neutralino & Chargino Mixing

Mass eigenstates depend on

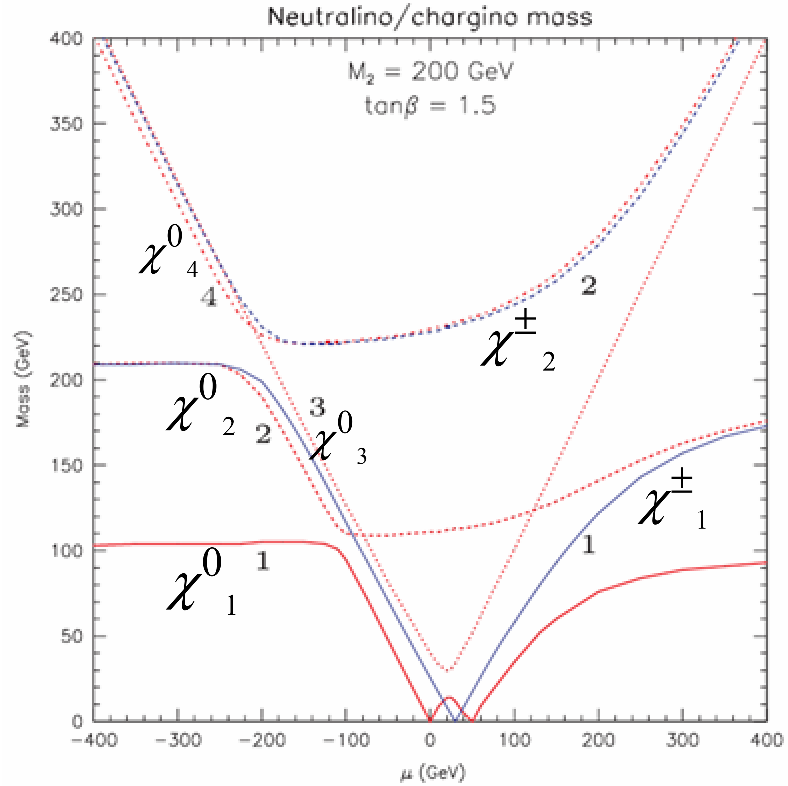
- M_1, M_2, tan β, μ
- M_Z, $\sin^2\theta_W$ EW mixing

Neutralino mixing $(\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u) \rightarrow \chi^0_{1,2,3,4}$

$$\begin{pmatrix} M_1 & 0 & -M_Z \cos\beta s_W & M_Z \sin\beta s_W \\ 0 & M_2 & M_Z \cos\beta c_W & -M_Z \sin\beta c_W \\ -M_Z \cos\beta s_W & M_Z \cos\beta c_W & 0 & -\mu \\ M_Z \sin\beta s_W & -M_Z \sin\beta c_W & -\mu & 0 \end{pmatrix}$$

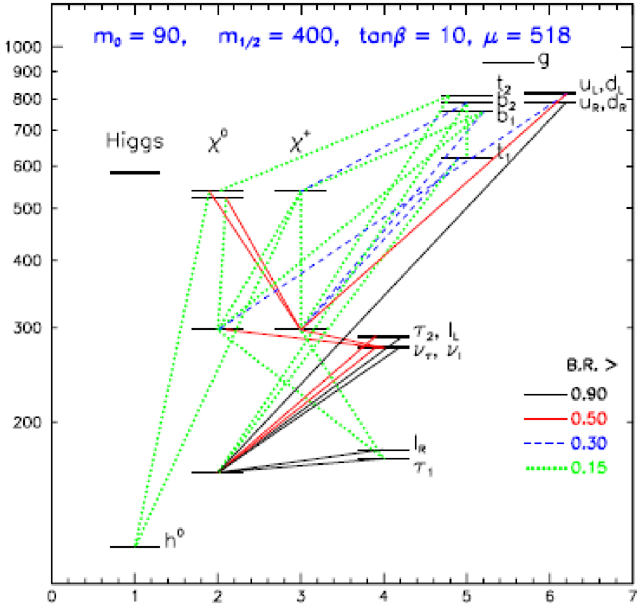
Chargino mixing $(\tilde{W}^+ \tilde{H}^+) \rightarrow \chi^\pm_{1,2}$

$$\begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & +\mu \end{pmatrix}$$

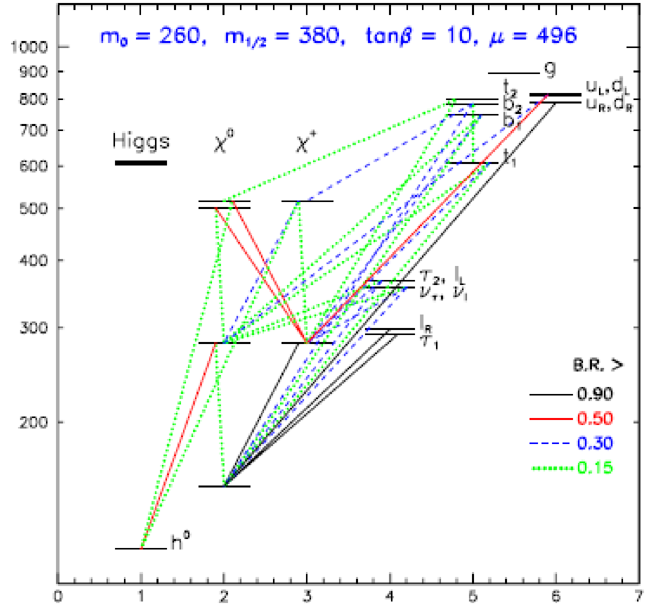


mSUGRA masses and decays

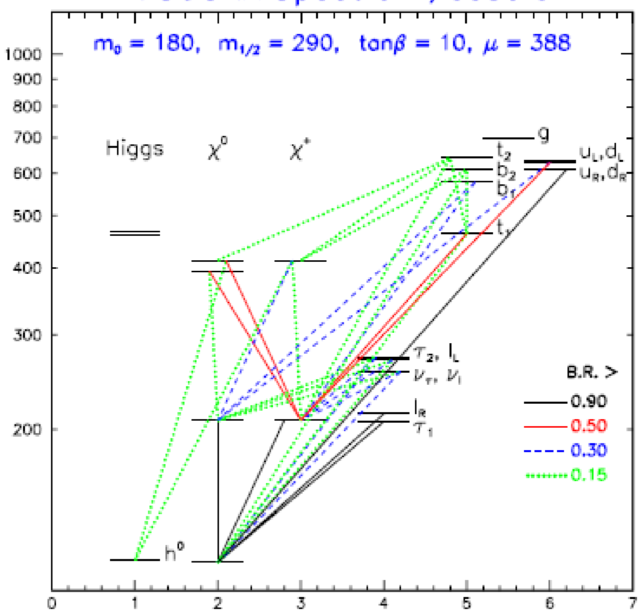
MSUGRA Spectrum, case 1



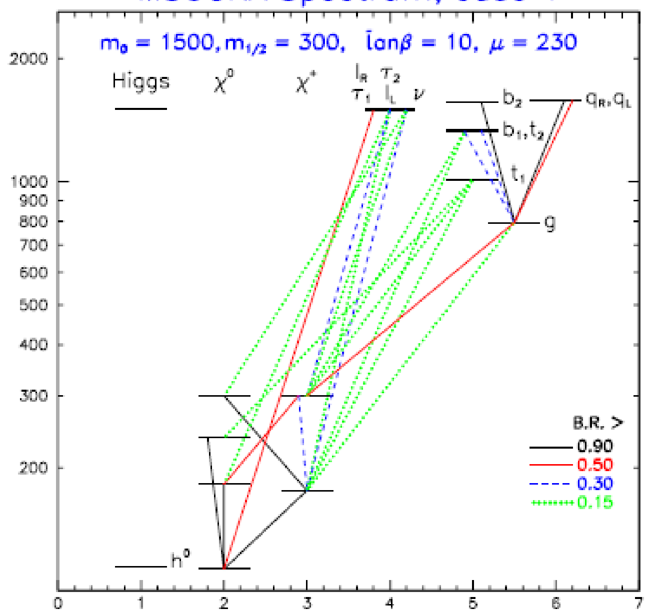
MSUGRA Spectrum, case 2



MSUGRA Spectrum, case 3



MSUGRA Spectrum, case 4



Mass differences

- $M_{Squark} >> M_{LSP}$
  → Large ET, Large ETmiss
  → model independent discovery
- $M_{slepton}$ close to M_{LSP}
  → leptons with low ET
  model dependent

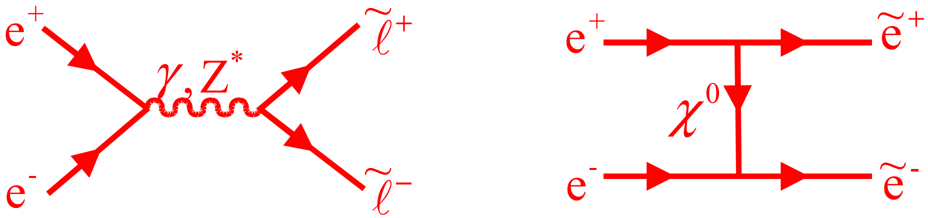
Decays patterns

- Parameter dependent
- Partially long decay chains
- Missing LSP
- Measure mass differences

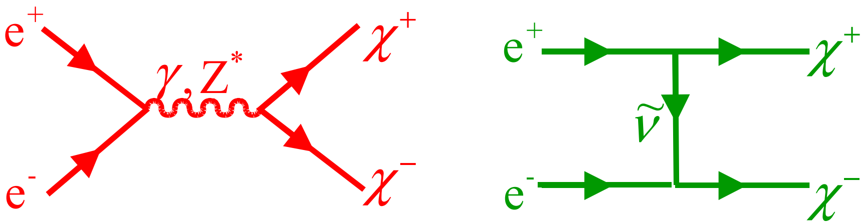
→ SUSY parameter measurements

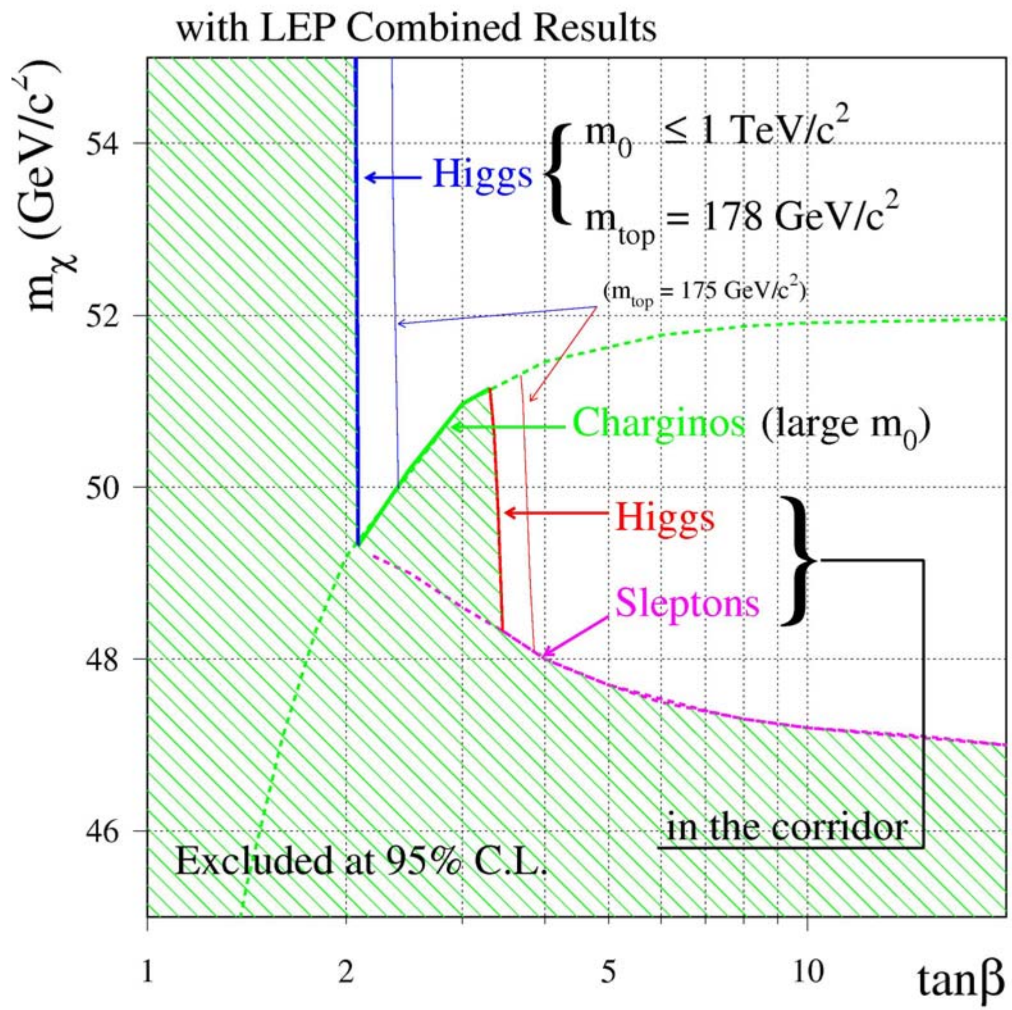
LEP searches

Slepton production



Chargino Production

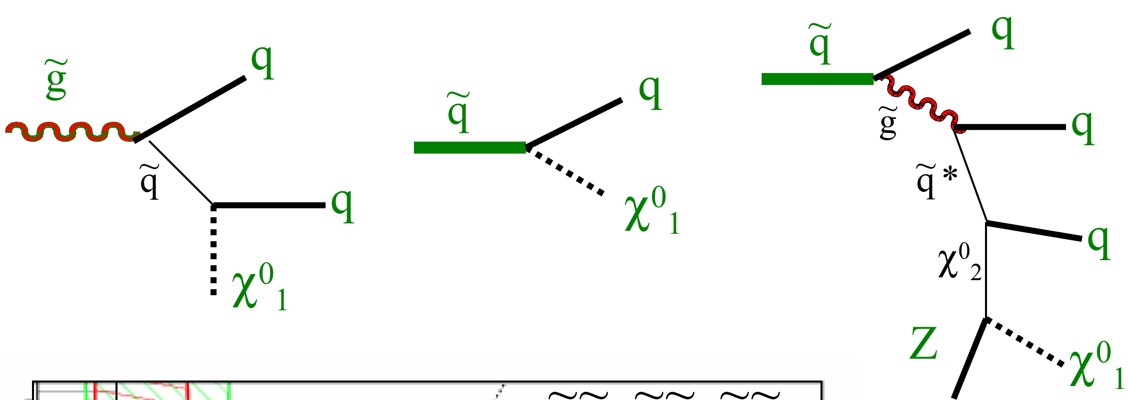




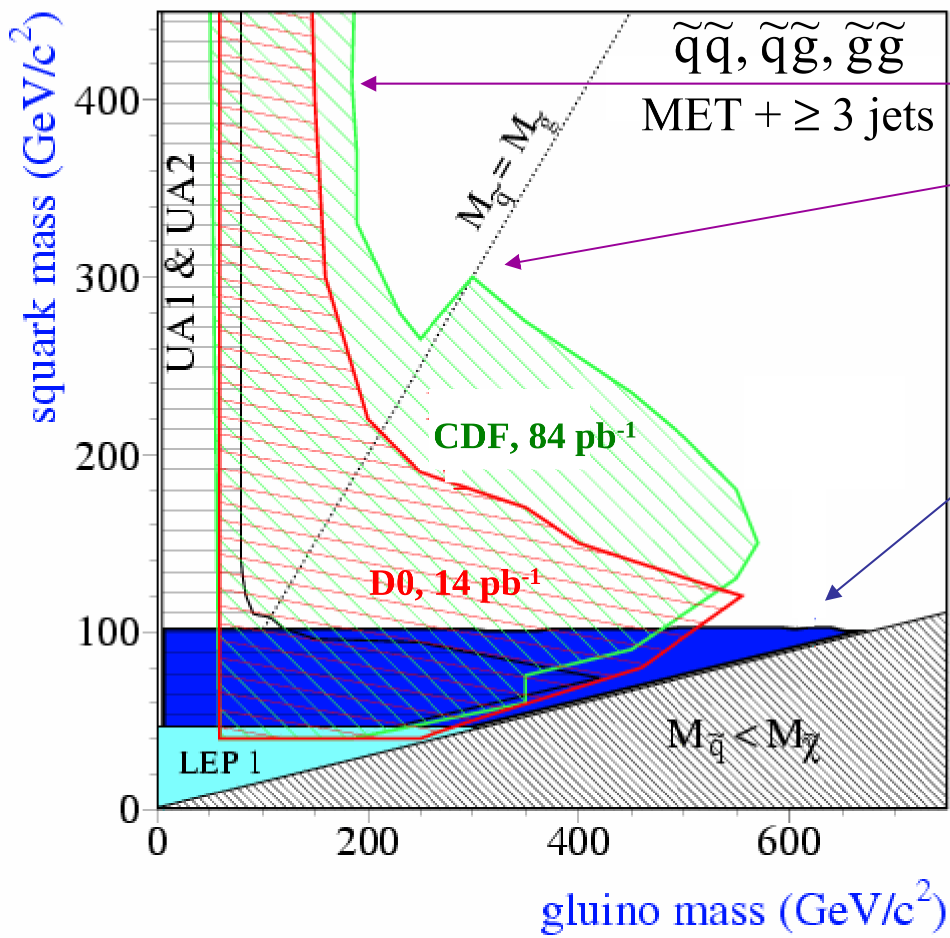
CMSSM:

- sfermions and charginos excluded for m < 80 … 104 GeV
- tan β > 1.4
- M_{LSP} > 47 GeV
- M_h > 114.5 GeV

Tevatron searches for Squarks & Gluinos



Signature:
E_T^{miss} + n jets + m leptons



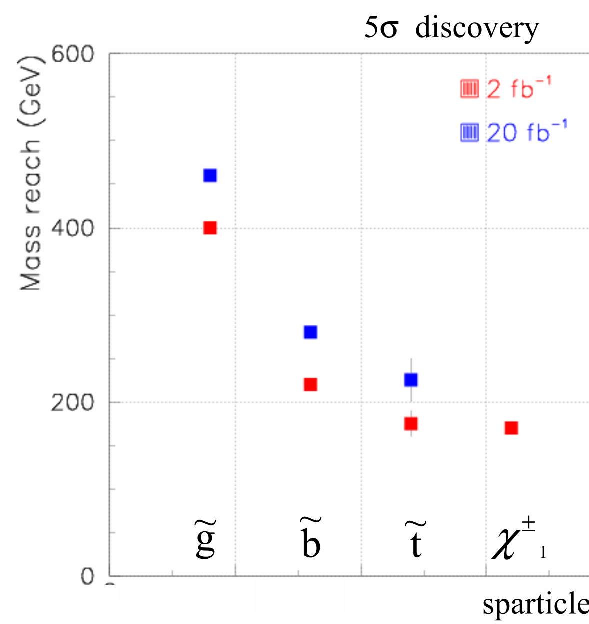
$m(\tilde{g}) > 195$ GeV

$m(\tilde{q}) \approx m(\tilde{g}) > 300$ GeV

$\tilde{q}\tilde{q}$ searches at LEP

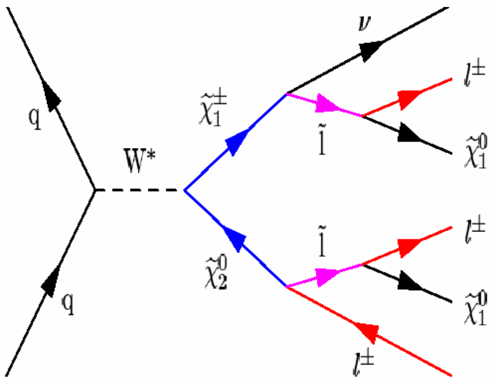
Tevatron not sensitive to

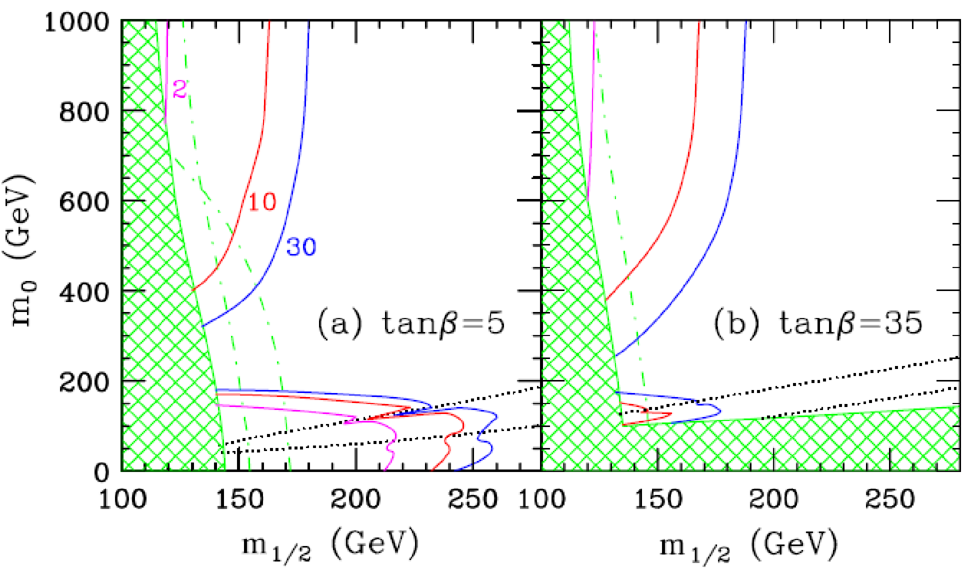
$\Delta m(\tilde{q} - \chi^0_1) < 25$ GeV



3-lepton search

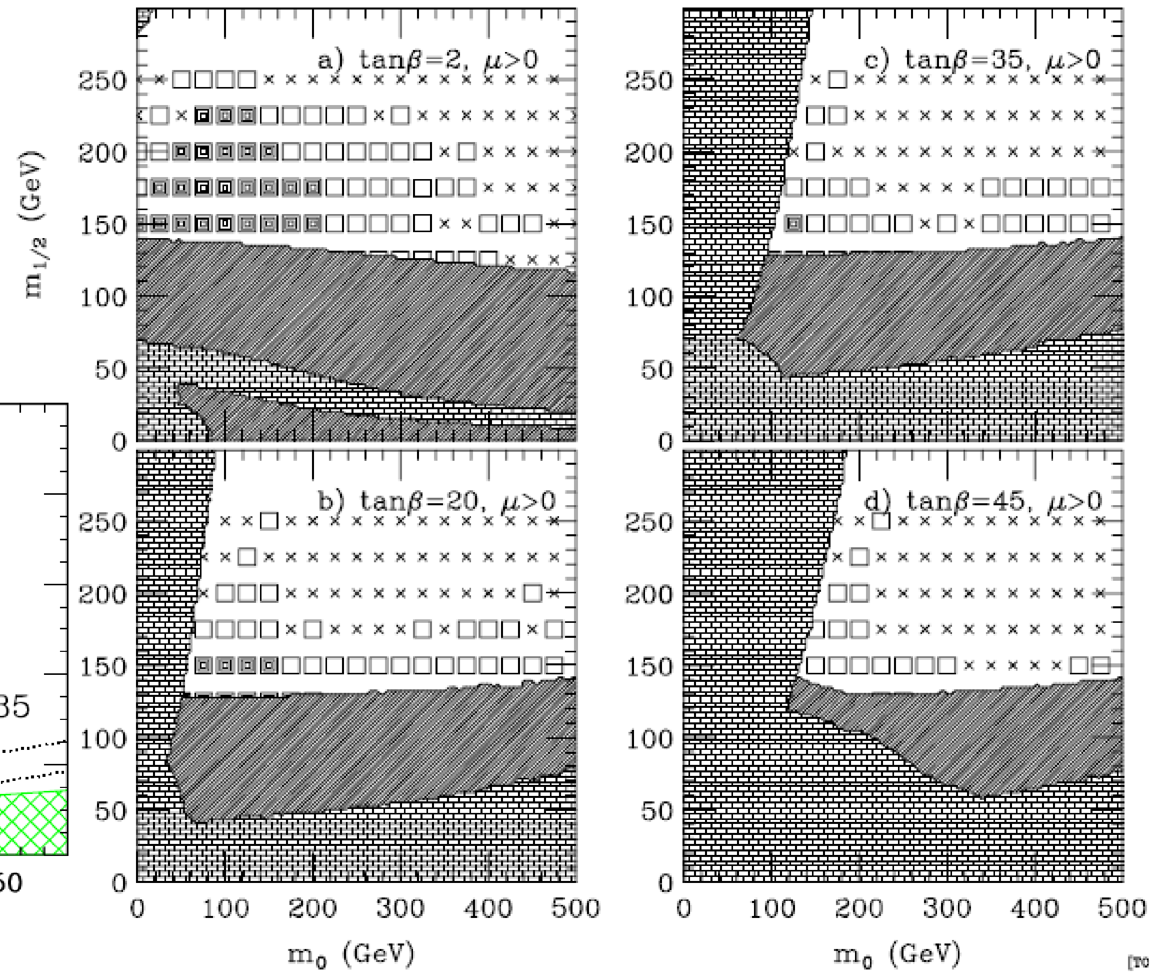
- 2, 10, 30 fb^{-1}



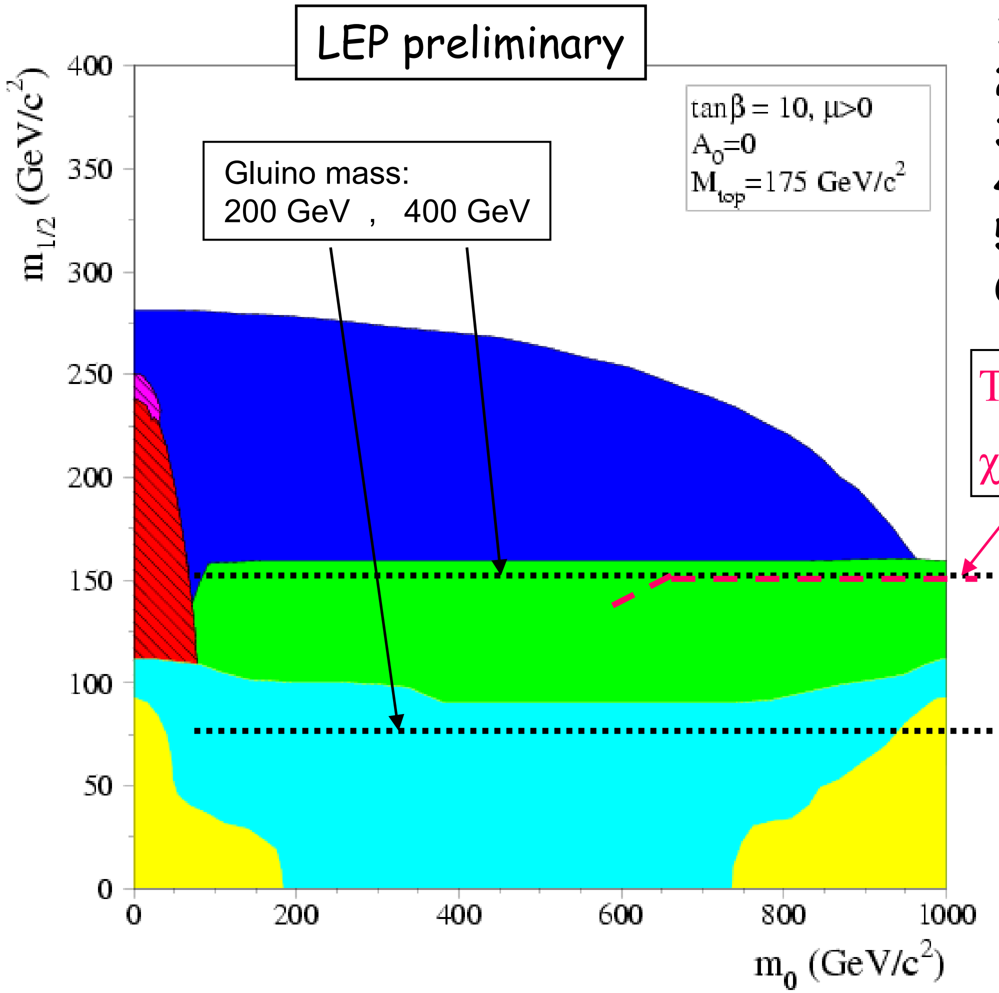


Squark / Gluino decays

- 2 fb^{-1} and 25 fb^{-1}



LEP and Tevatron in MSUGRA



Regions excluded by:

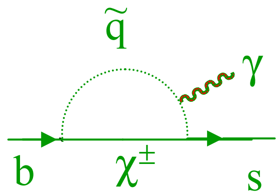
1. *Theory*
2. *Z width from LEP1*
3. *Charginos from LEP*
4. *Sleptons from LEP*
5. *Higgs from LEP*
6. *Stable staus from LEP*

Tevatron Run 2 (2 fb^{-1})

$\chi_1^+\chi_2^0 \rightarrow 3l^\pm$ + MET searches

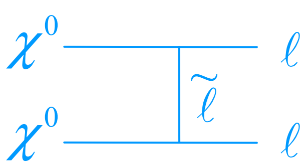
Rare Processes and Cosmology

- $B \rightarrow s\,\gamma$ excluded

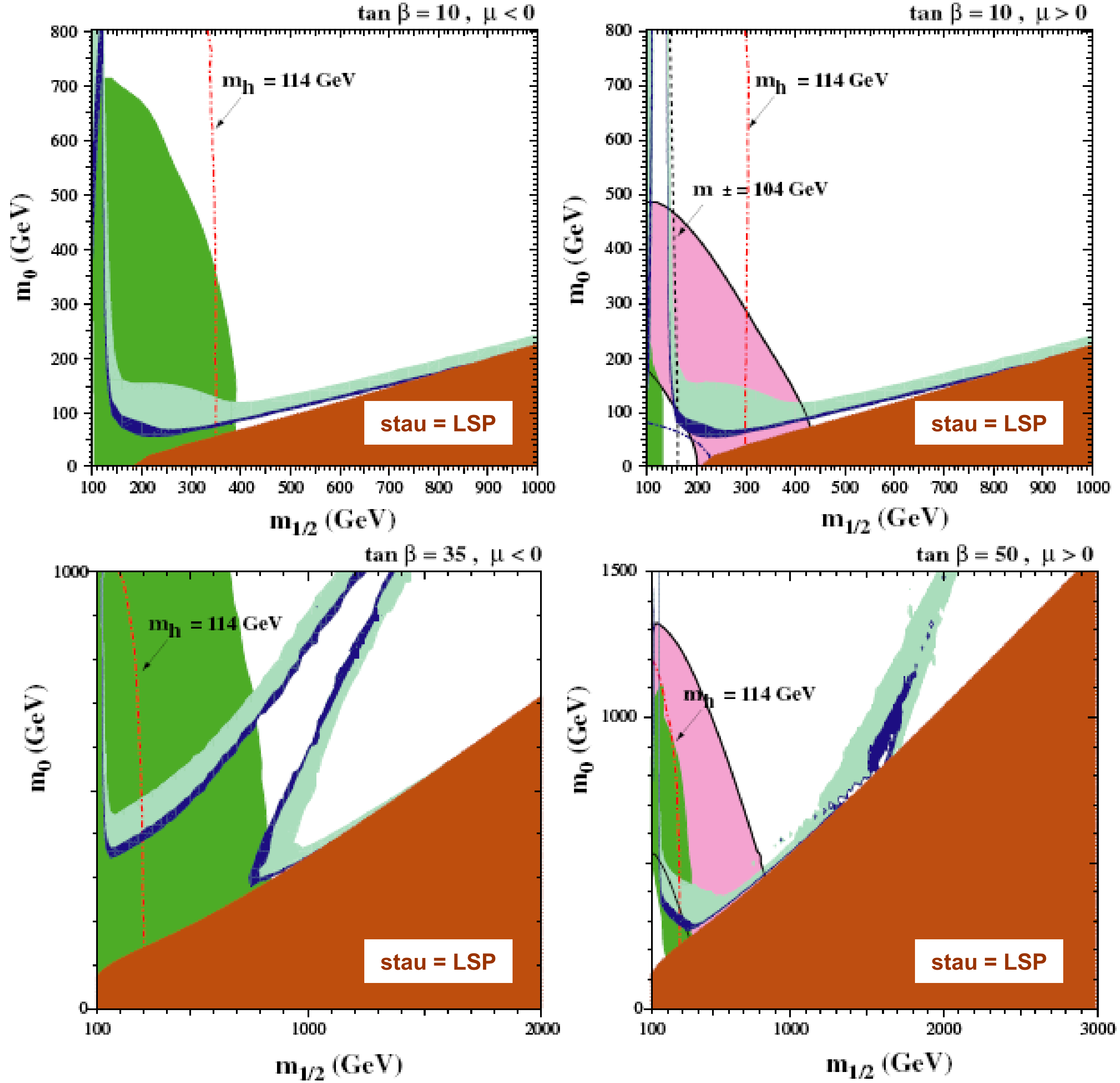


- g_μ-2 favoured

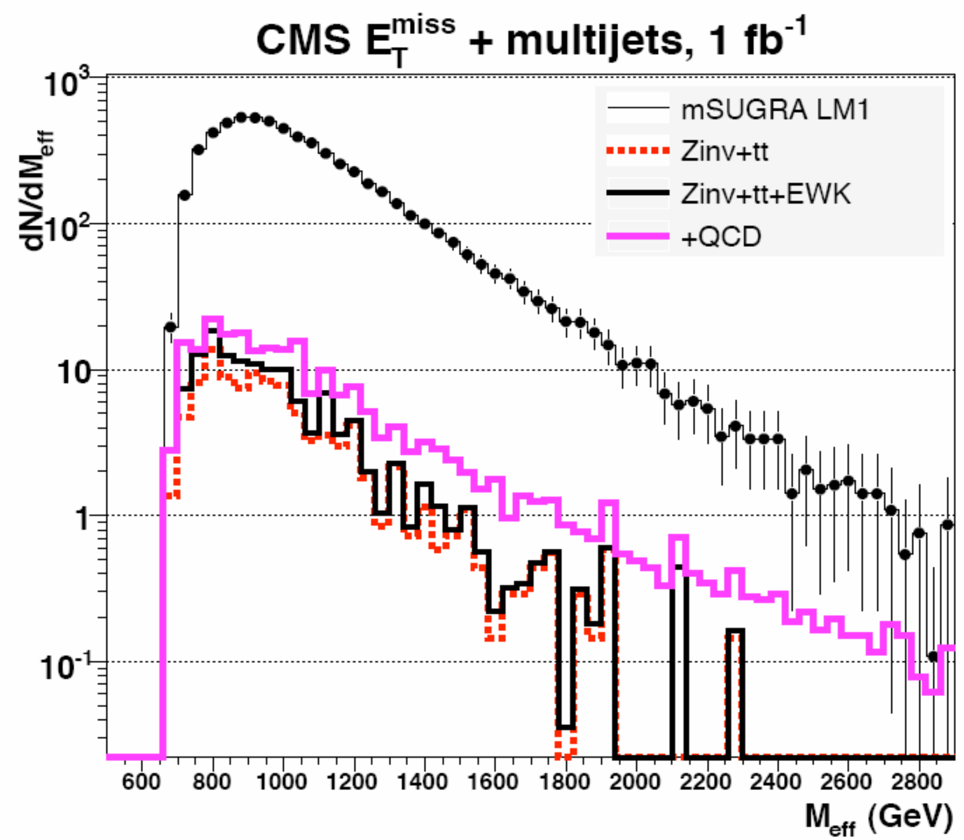
- Dark matter favoured

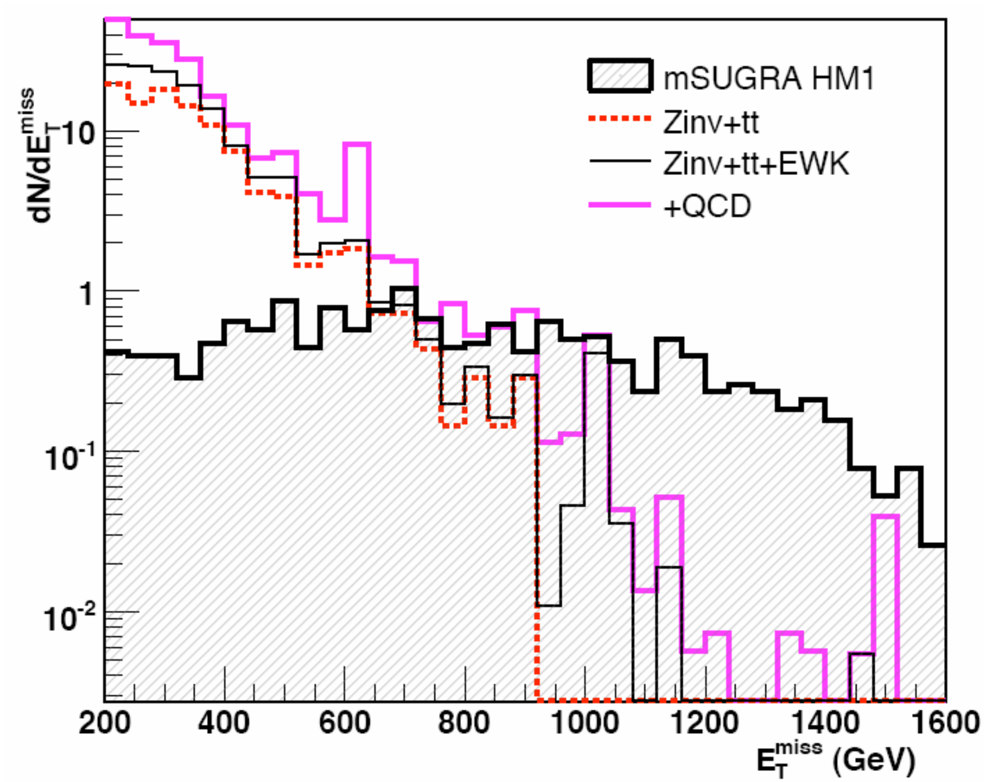


  - m_{LSP} < 500 GeV



Selection: high ET jets (70GeV) + ETmiss (200GeV)





Low mass SUSY

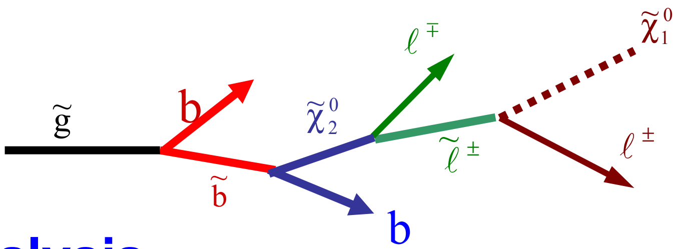
- LM1: 6 pb^{-1}
- Typical: need 0.1-1 fb^{-1}

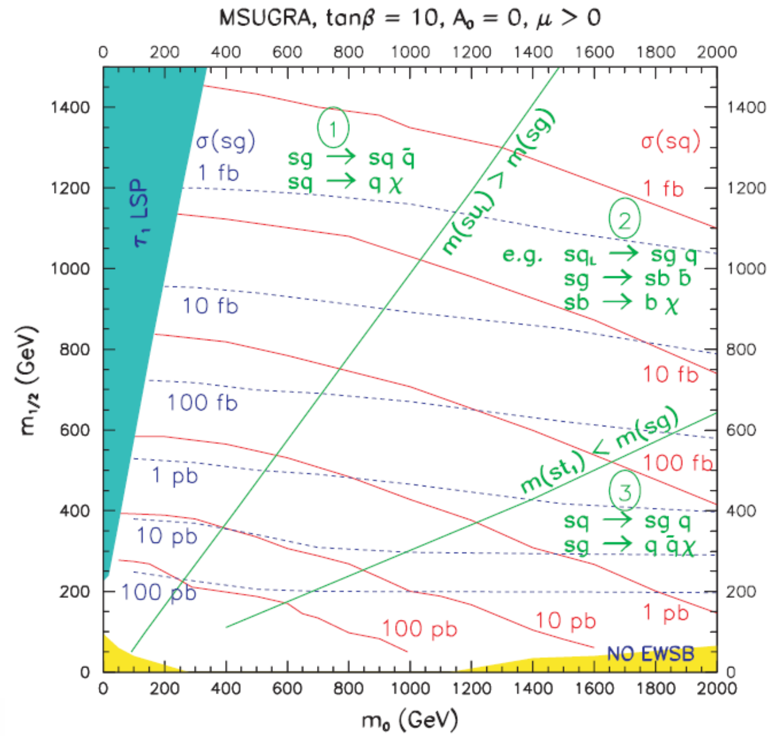
High mass SUSY

- Ultimate reach:

  Squarks, Gluinos: 2500 GeV

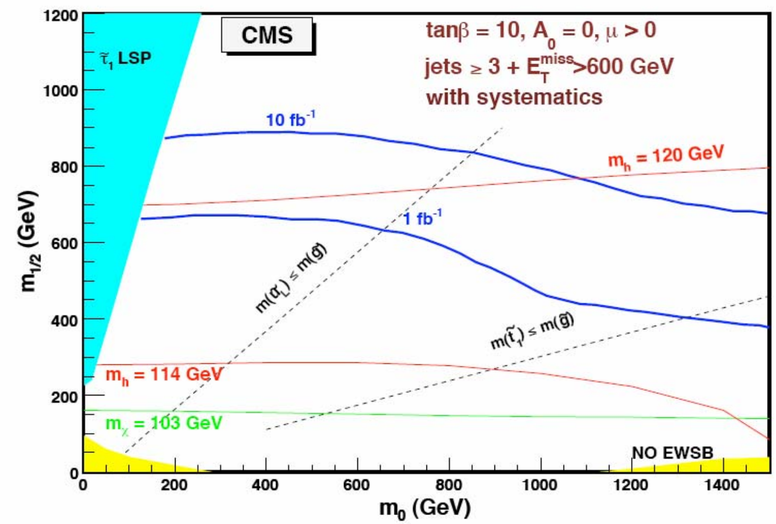
LHC SUSY analysis strategy





1) Inclusive analysis

- Jets + ETmiss
  - ➡ First evidence
  - ➡ use Meff, ETmiss, #jets, event rate
    - ➡ R_P
    - ➡ estimate squark+gluino mass,



2) Exclusive analysis

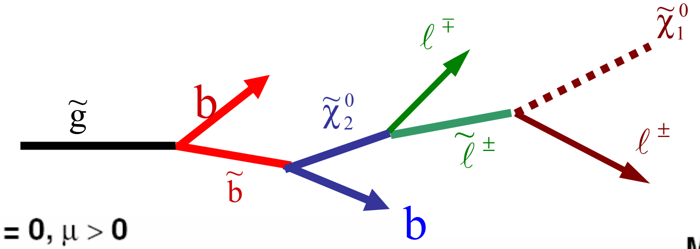
- check for e, mu, tau, gammas, Z0, W, top, higgs, heavy stable particles
  - ➡ kinematic analysis
  - ➡ estimate SUSY masses, BR

3) Higgs mass, SUSY higgs search

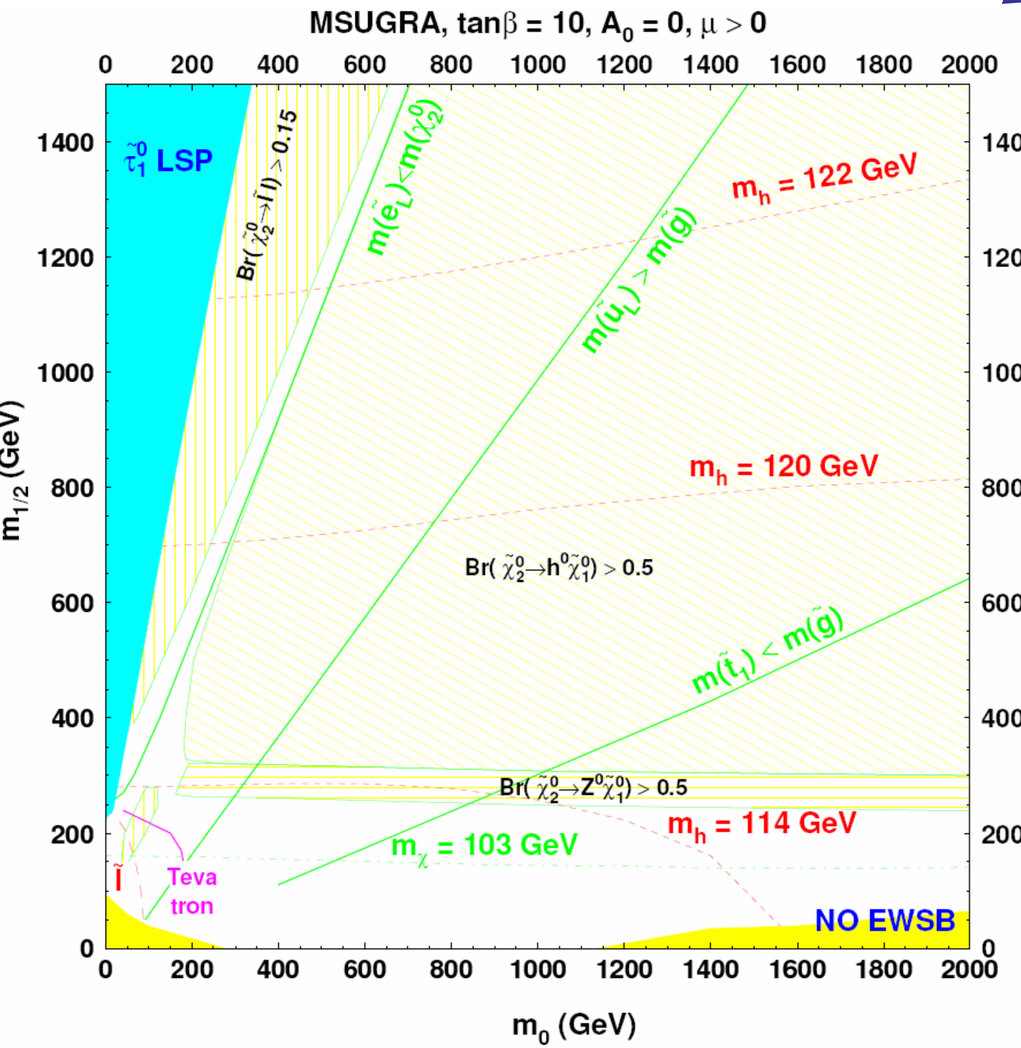
4) Check consistency at GUT scale

➡ Is it SUSY

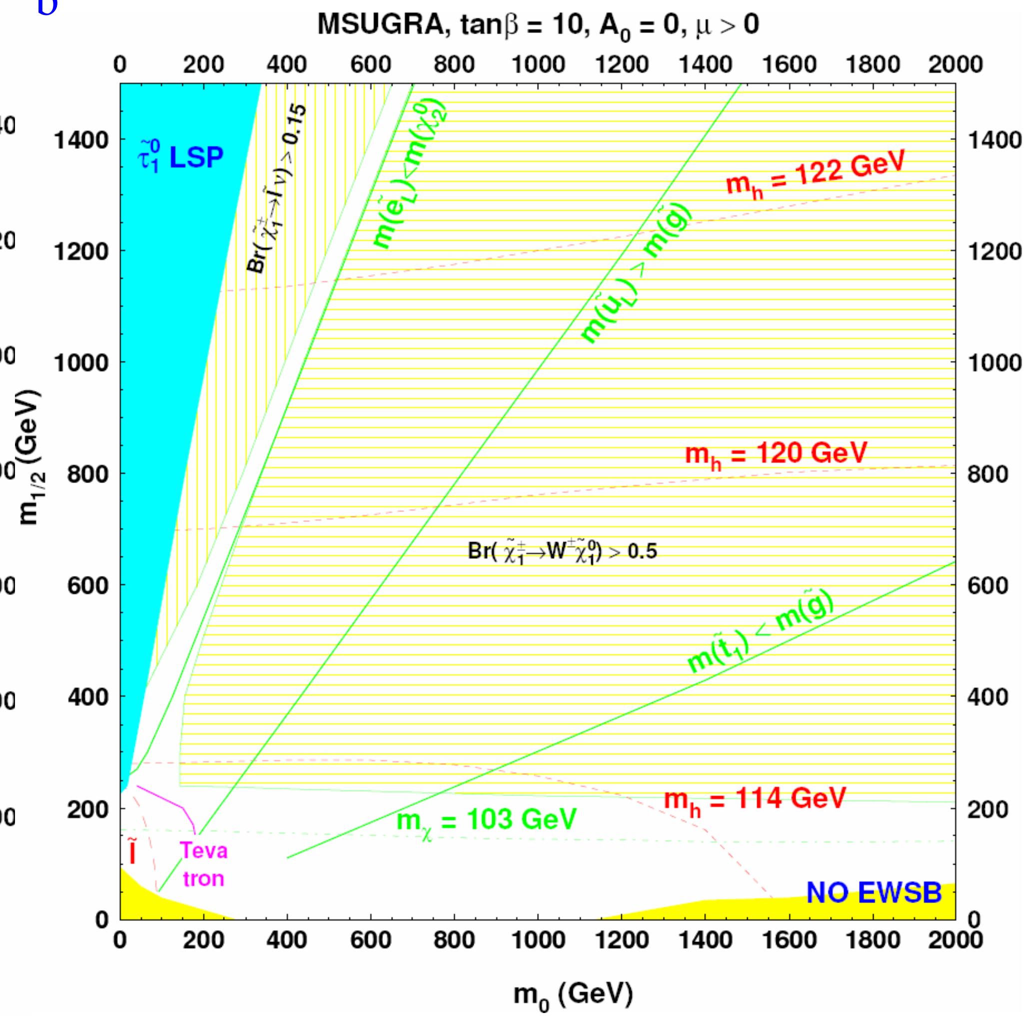
Gaugino decays



Neutralino $_2$



Chargino $_1$



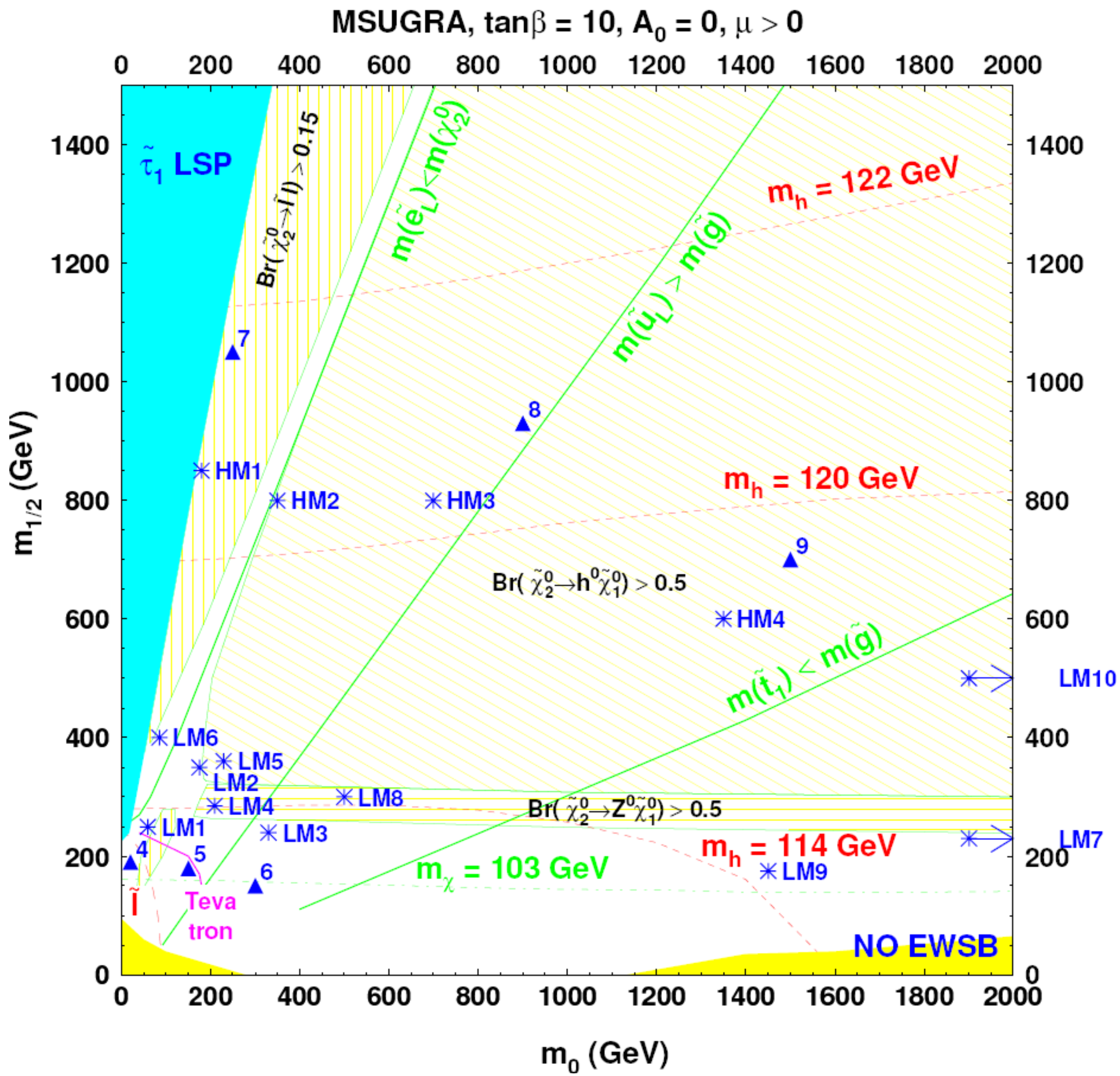
SUSY benchmark points

Studies of

SUSY Benchmark points

Finally:

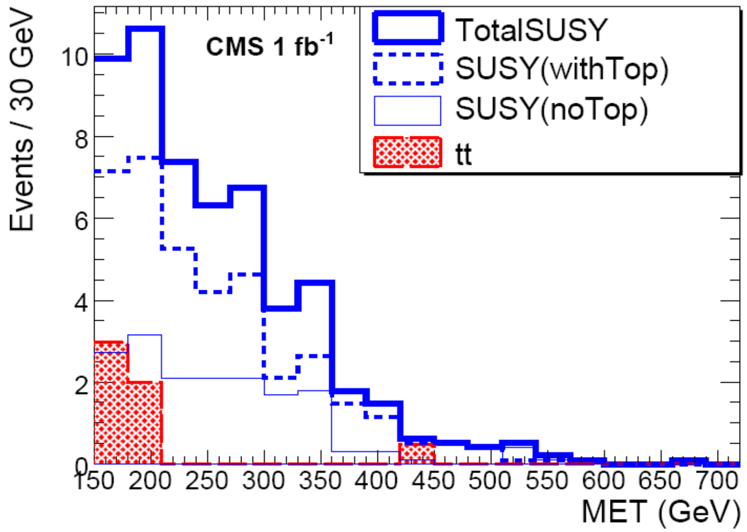
SUSY parameter scan

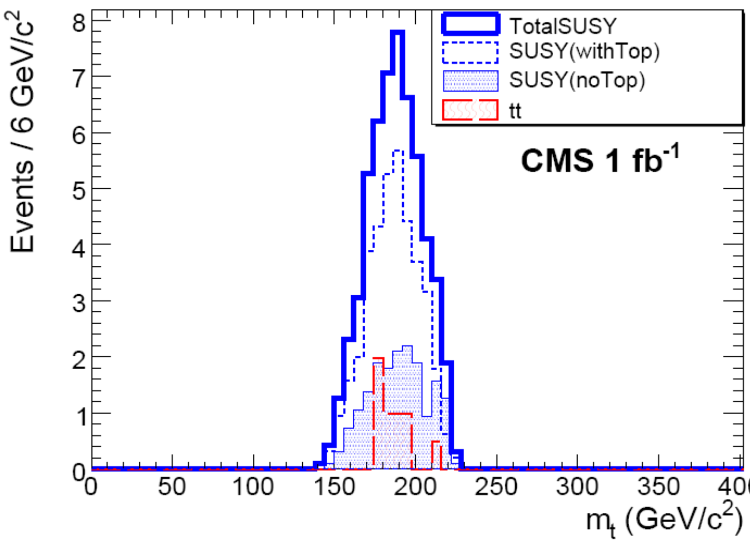


SUSY decays with top

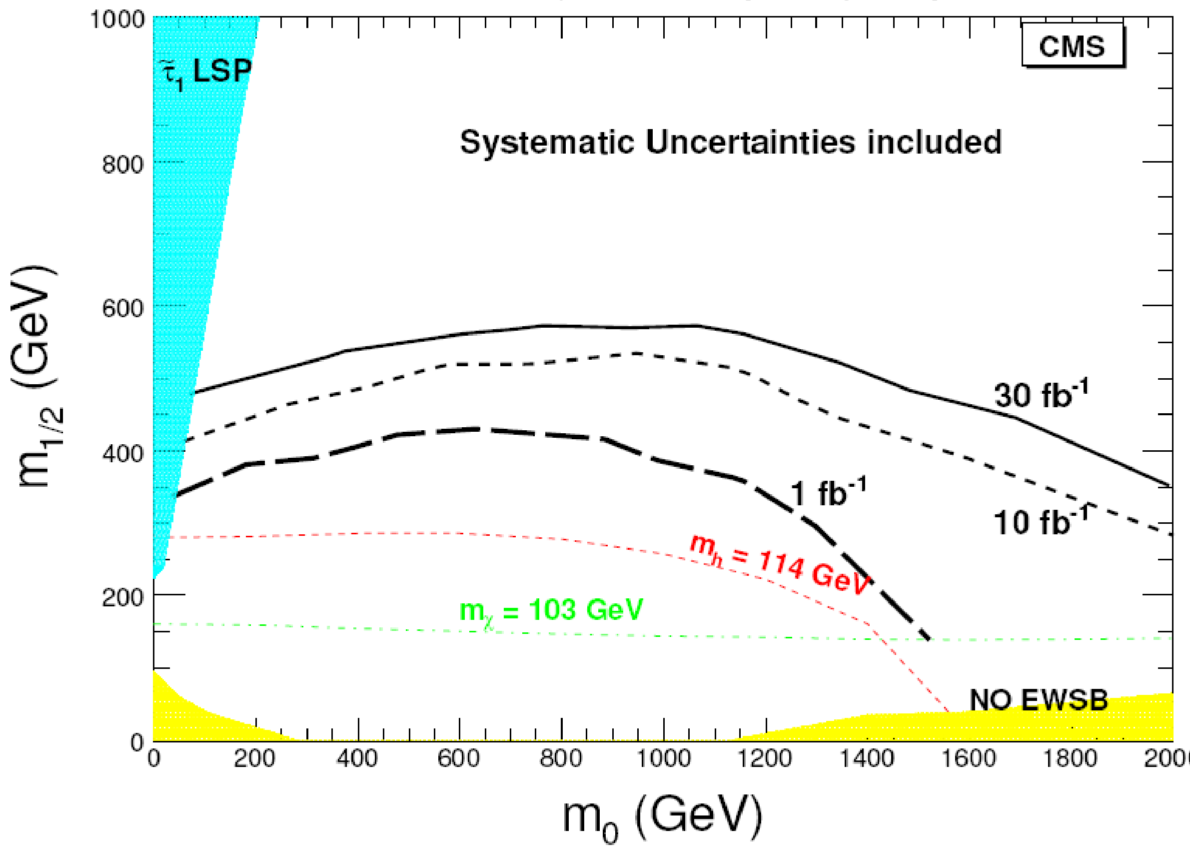
LM1

- $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant
- $B(\tilde{\chi}_2^0 \to \tilde{l}_R l) = 11.2\%$, $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 46\%$, $B(\tilde{\chi}_1^\pm \to \tilde{\nu}_l l) = 36\%$





Discovery reach (5 sigma)

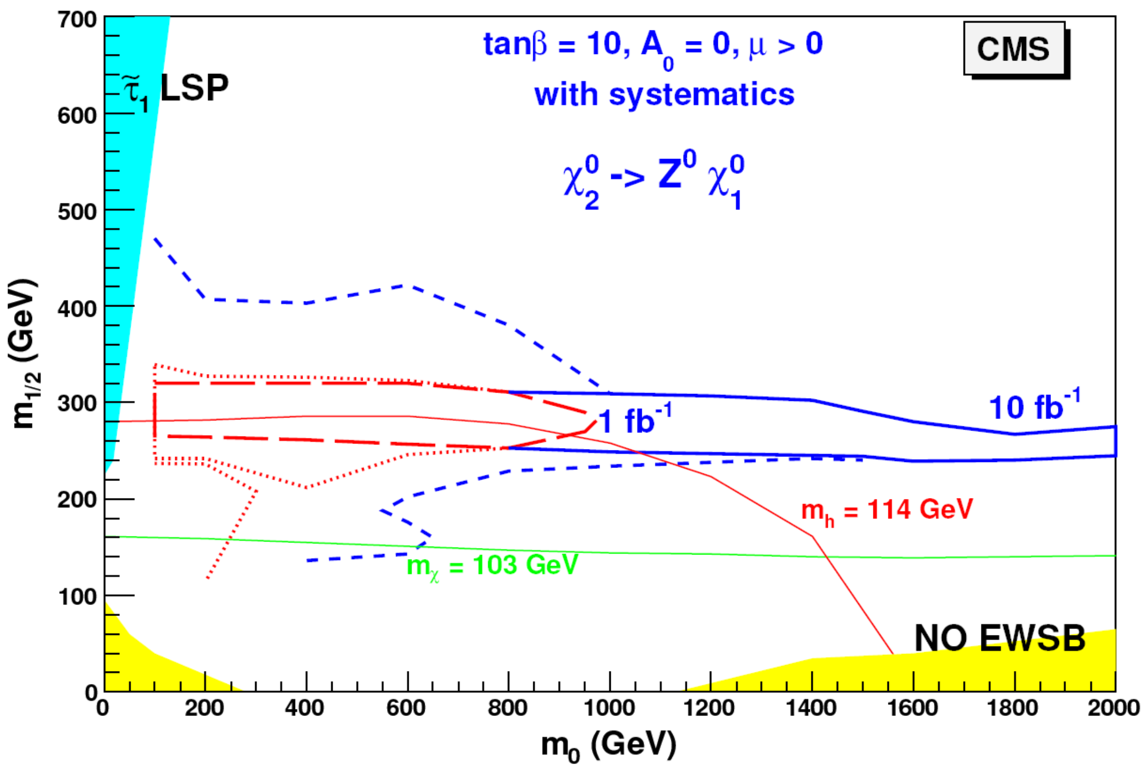


SUSY decays with Z^0

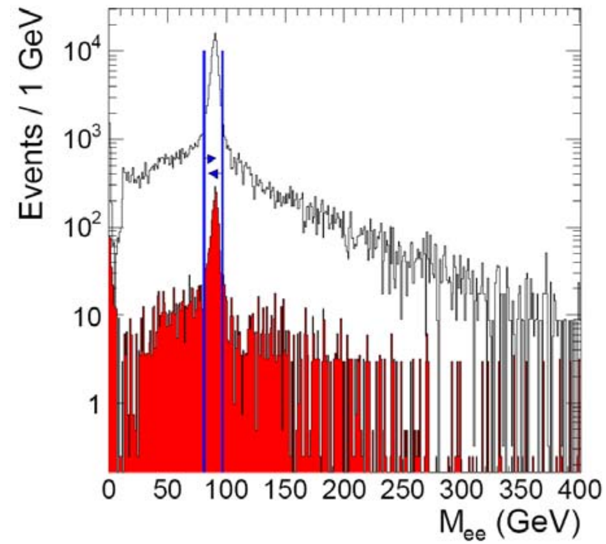
LM4: squark/ gluino production

decays to $\chi_2^0 \to Z^0 \chi_1^0$

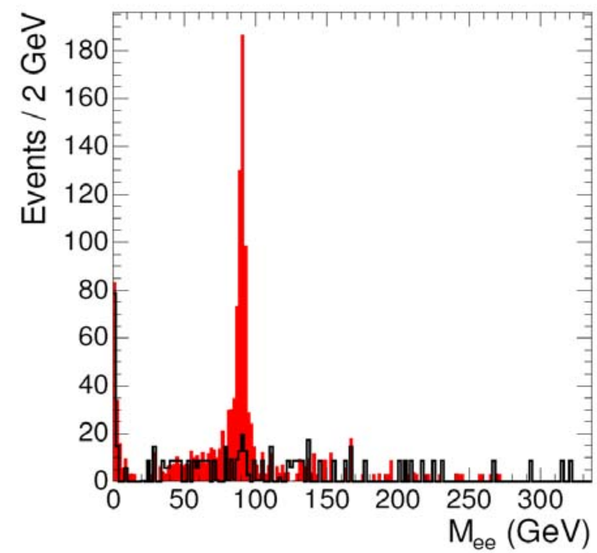
- $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant with $\tilde{g} \to \tilde{b}_1 b = 24\%$
- $B(\tilde{\chi}_2^0 \to Z^0 \tilde{\chi}_1^0) = 97\%$, $B(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = 100\%$



before ETmiss cut



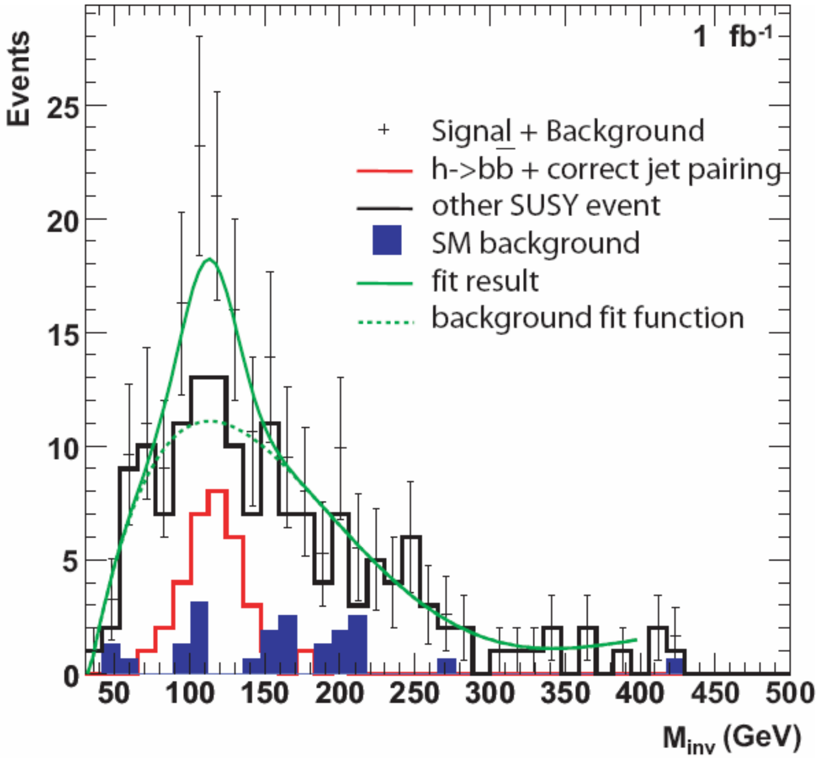
after ETmiss cut

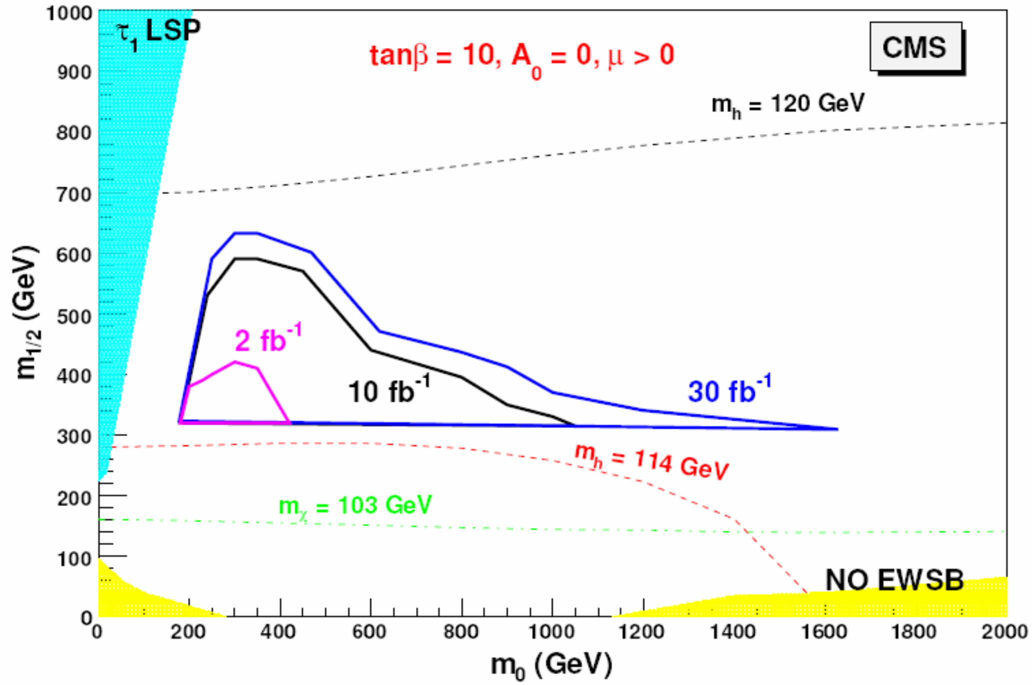


SUSY decays with Higgs h → bb

- $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant with $B(\tilde{g} \to \tilde{b}_1 b) = 19.7\%$ and $B(\tilde{g} \to \tilde{t}_1 t) = 23.4\%$
- $B(\tilde{\chi}_2^0 \to h^0 \tilde{\chi}_1^0) = 85\%$, $B(\tilde{\chi}_2^0 \to Z^0 \tilde{\chi}_1^0) = 11.5\%$, $B(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = 97\%$

LM5





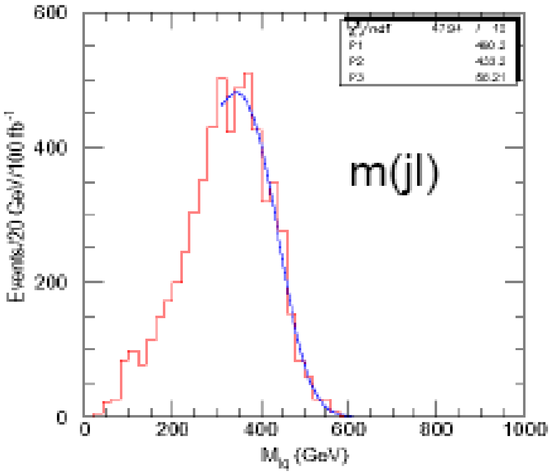
- **Dominant background to SUSY decays are other SUSY decay channels**
- **Measurement of Higgs mass and BR needs large luminosity !**

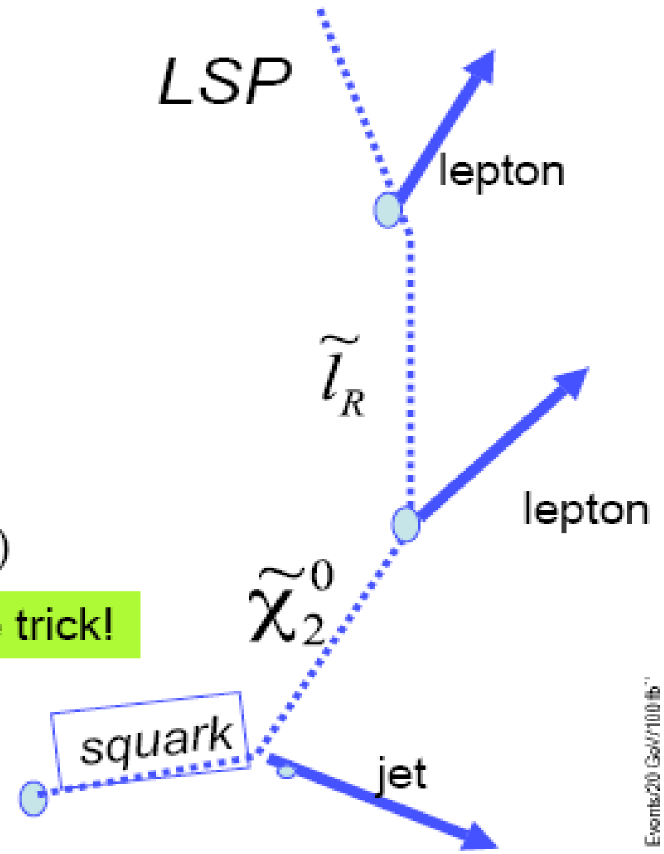
Mass reconstruction

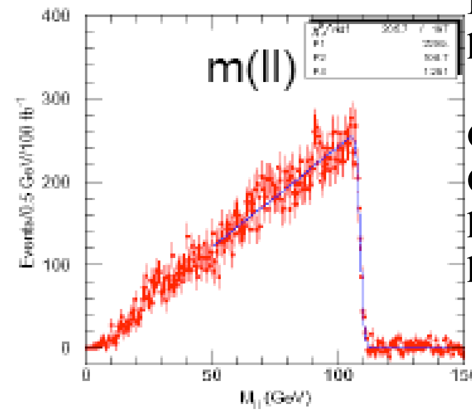
determination of the boundary of phase space
for mass determination.

Kawagoe,
Nojiri, Polesello
hep-ph/0410160

Gjelsten, Miller,
Osland
hep-ph/0410303
hep-ph/0511008

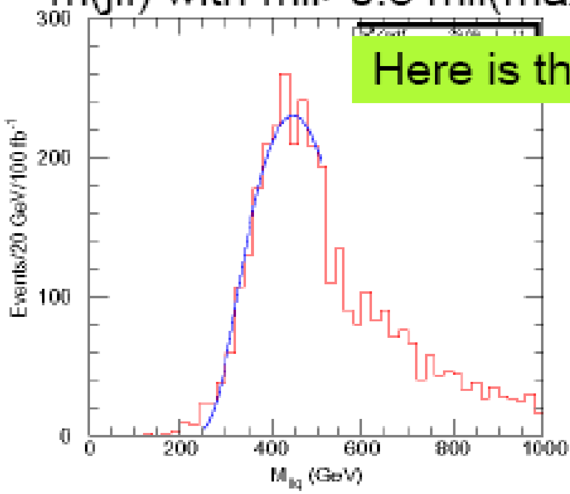




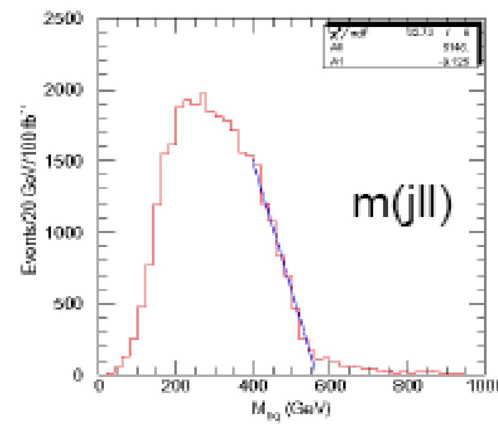


ee+μμ-eμ subtraction
is effective to select
single channel

m(jll) with mll>0.5 mll(max)

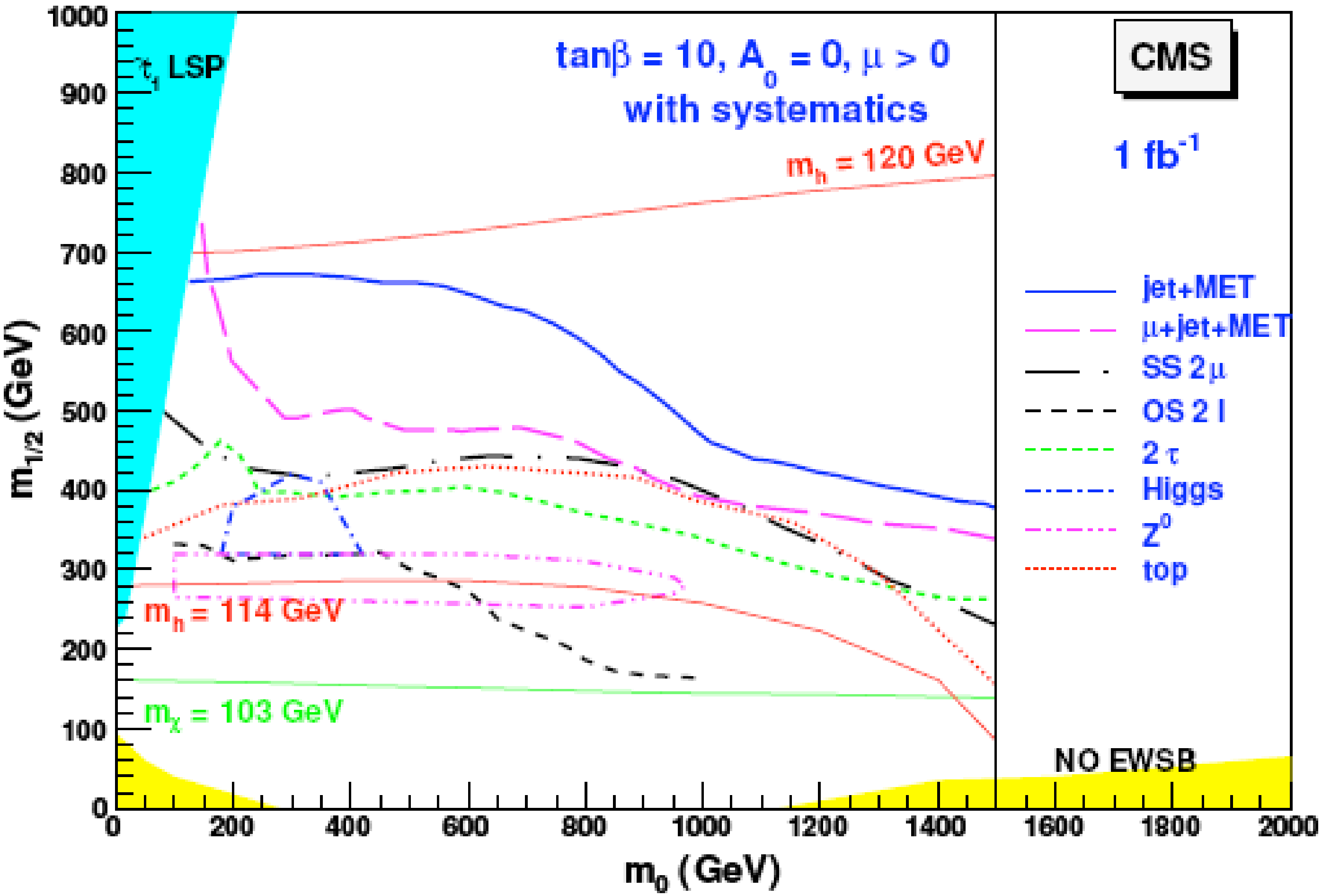


Here is the trick!



Nojiri, SUSY06

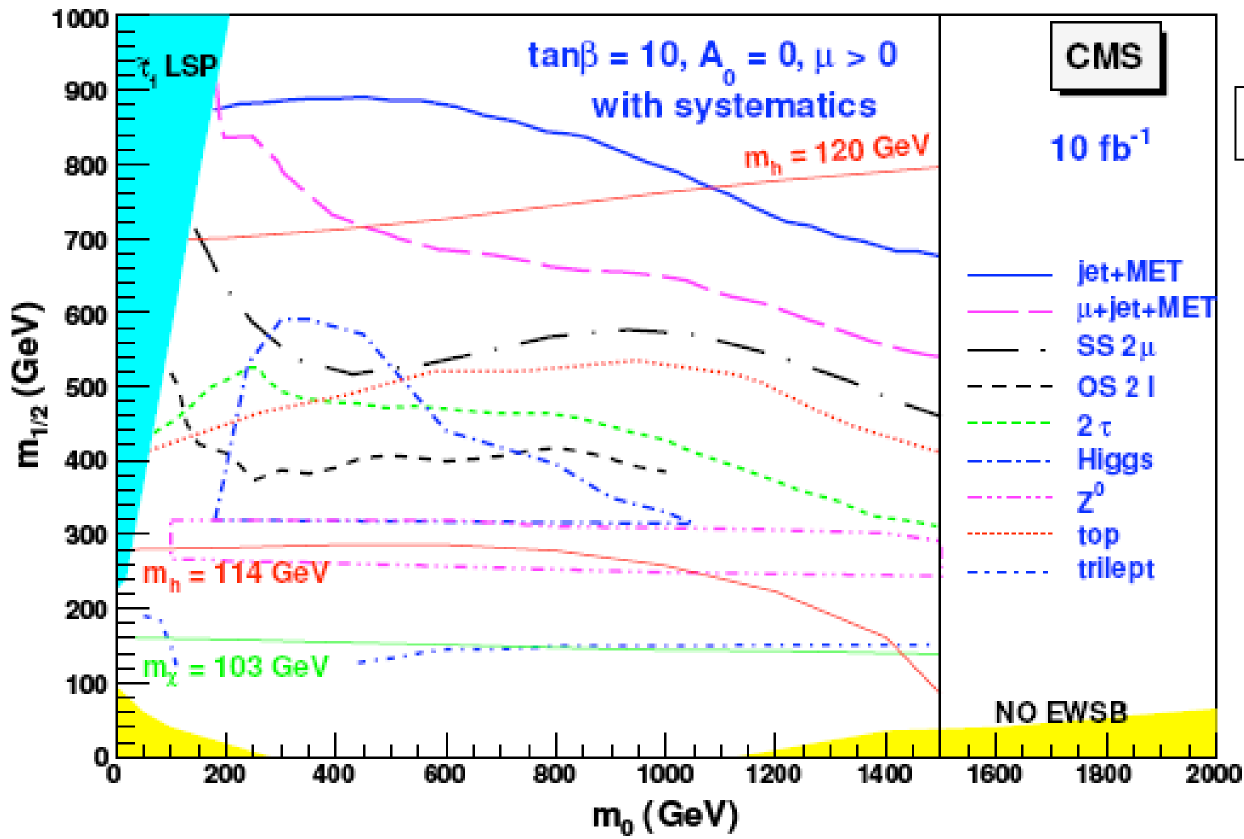
Early discovery at LHC ?



Jets + MET
gives highest reach
(most model-independent)

Lepton signatures are
more model-dependent
(e.g. a lot of τ's
at large tanβ)

SUSY discovery reach for CMS

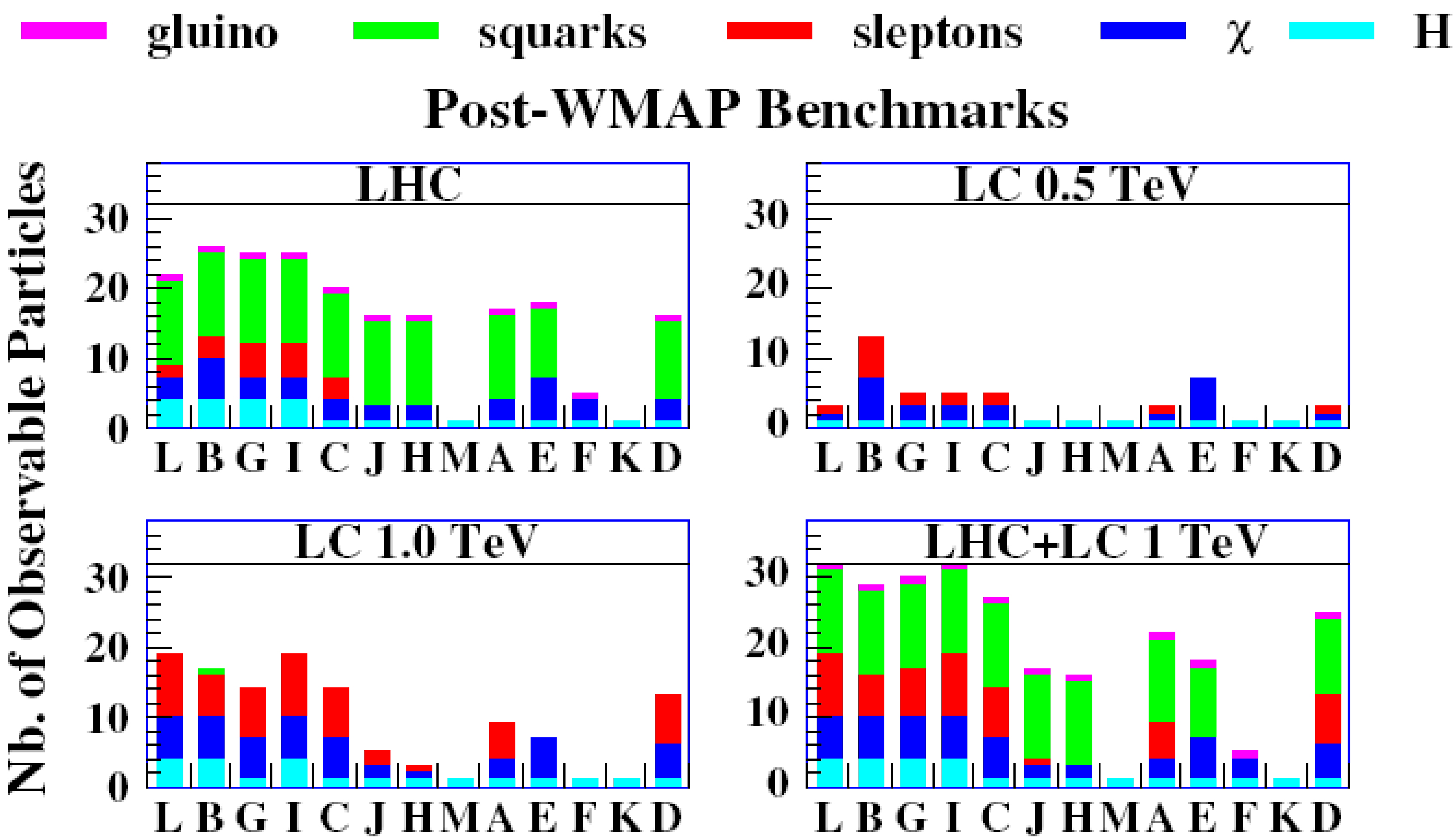


Discovery reach for squarks/gluinos

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

- **Large discovery potential already in the first year (2008)**
- **Reach at full luminosity: ~ 2 TeV for squark and gluino masses**
- **Interpretation very model dependent !**

SUSY particle detection



In some scenarios many (not all) SUSY particles can be detected

No full coverage (squarks/gluinos too heavy)

Reguires next machine ?!

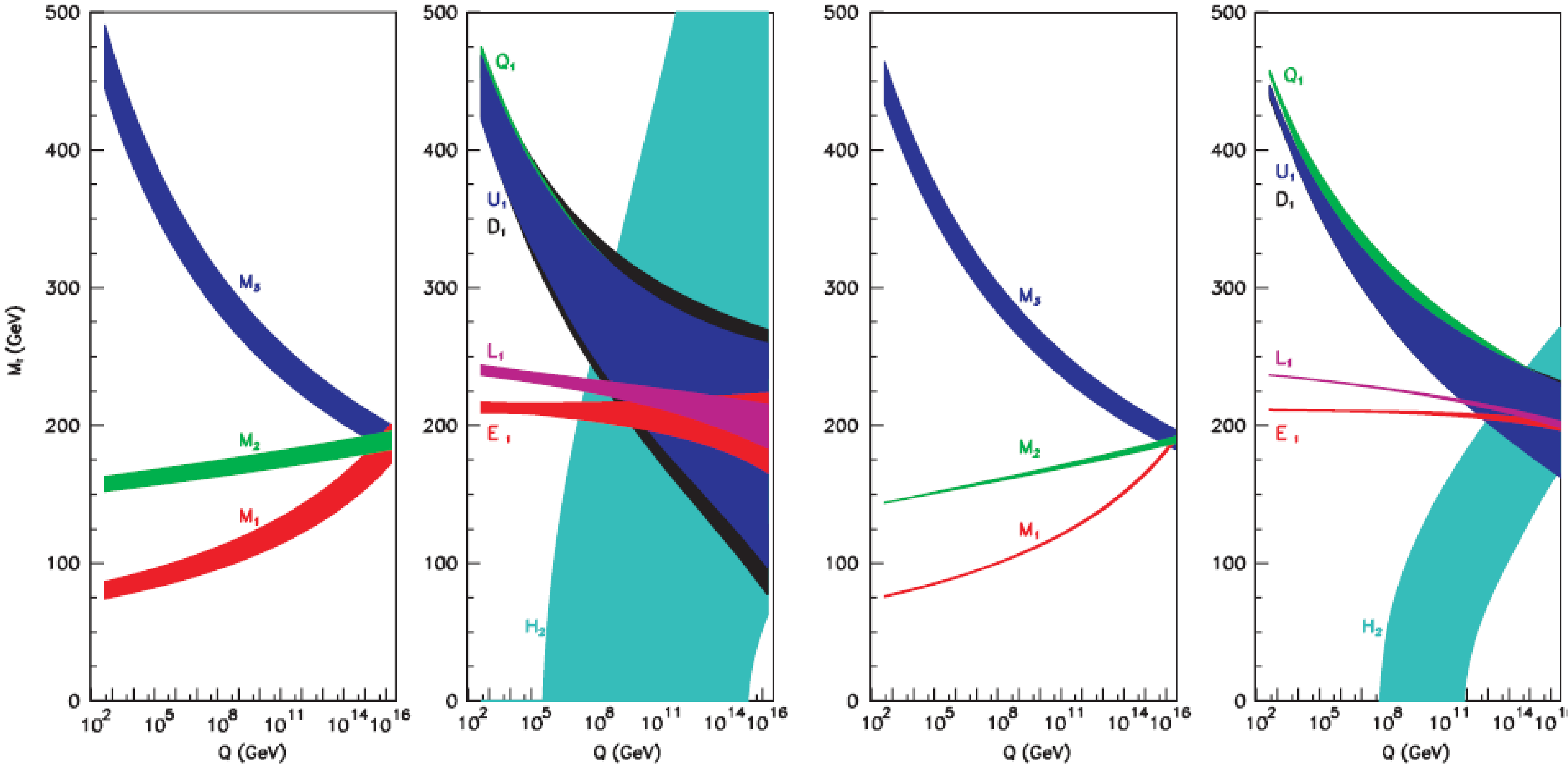
Physics at the GUT scale

Extrapolation of SUSY masses to high energy: Unification ?

LHC

- low mass point
- all particles visible

LHC + ILC



Summary: Unknowns

- **Performance of LHC:**

  Luminosity, stability

- **Background uncertainty**

  ~10 – 30 %

- **SUSY breaking models:**

  Masses of SUSY particles

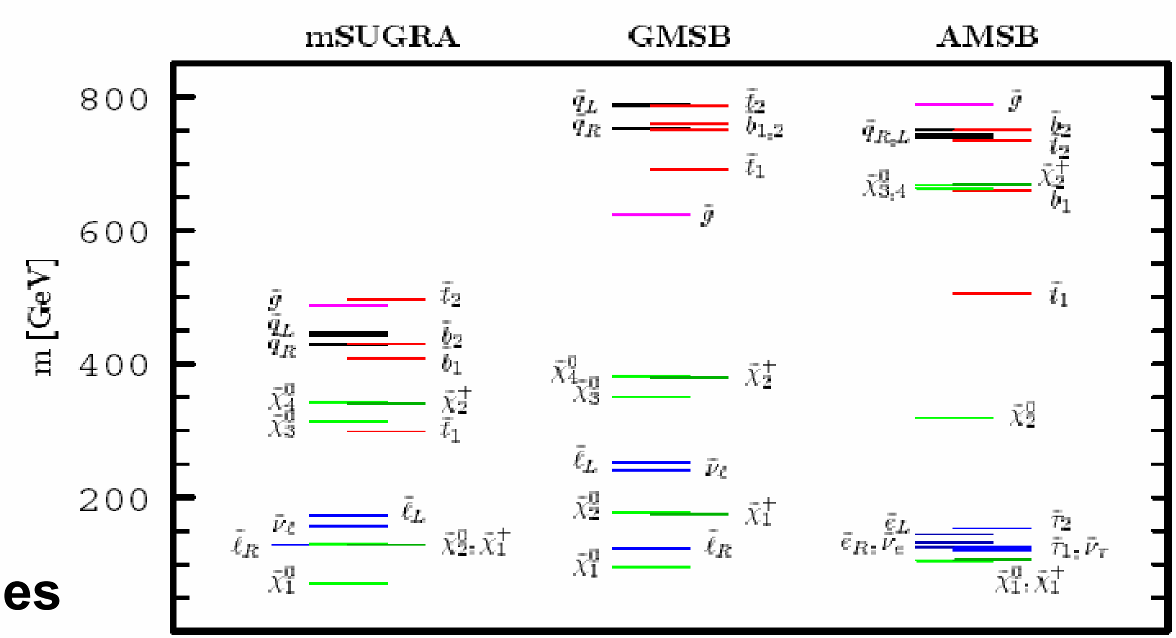
  Decay modes of SUSY particles

  → event signature

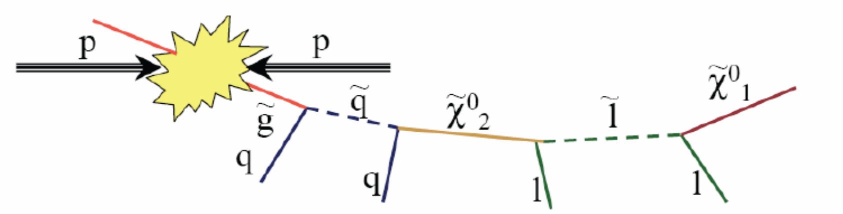
- **Squark/gluino cross section:**

  uncertainty ~10 %

- **Initial state and energy**
- **Missing final state particles (LSP)**
- **Performance of detector**



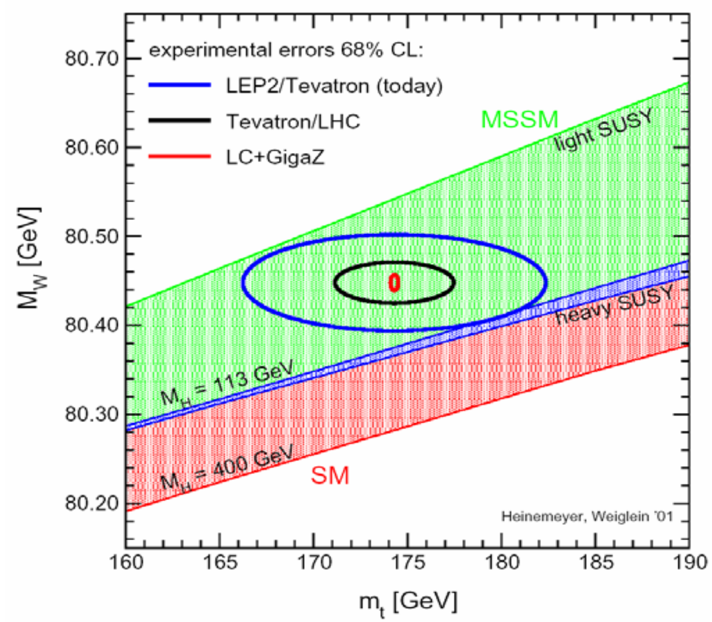
- **mass determination crucial to determine SUSY parameters**
- **Ambiguities**
- **often no unique solution**



Summary: Expected LHC results

Standard Model

- PDFs , QCD, ……
- δ M_{top} ~ 1.5 GeV (theory dominated)
  0.5 GeV (experimental)
  (Tevatron now: 1.7 GeV)
  - ➡ Higgs mass constraint
  - ➡ Discriminates between SM and SUSY ?

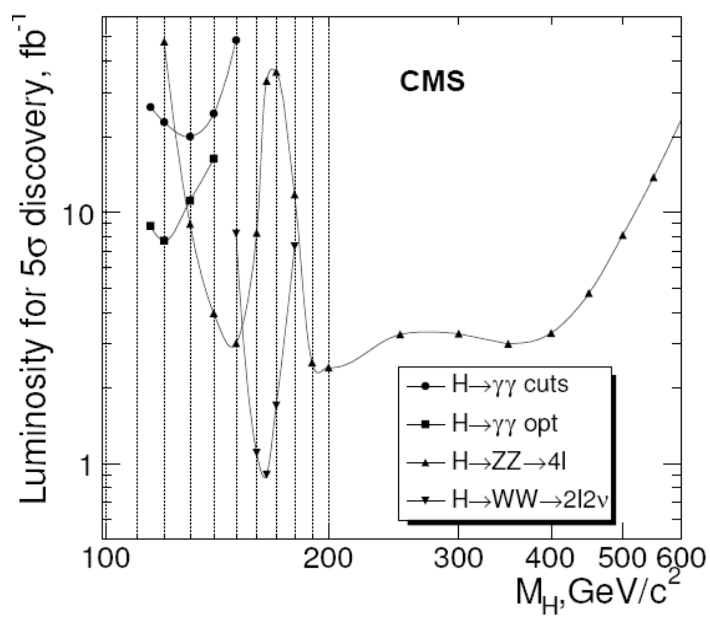


Higgs (SM)

➡ Luminosity needed for 5 sigma discovery

- M_H < 160 GeV @ 10 fb^{-1}
- M_H ~ 160 GeV @ 1 fb^{-1}
- M_H > 160 GeV @ 3 fb^{-1}

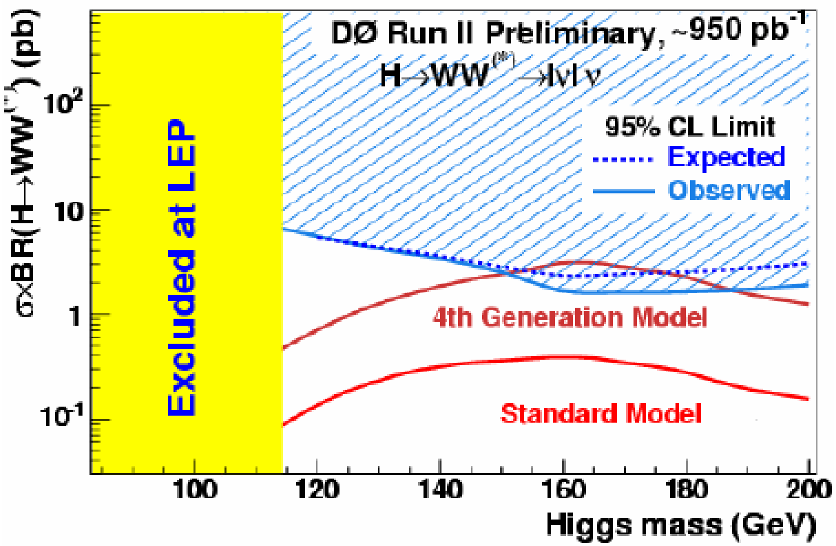
- Higgs mass: ~ 1 % uncertainty
- No Higgs found:
  new dynamics in WW scattering @ ~1 TeV

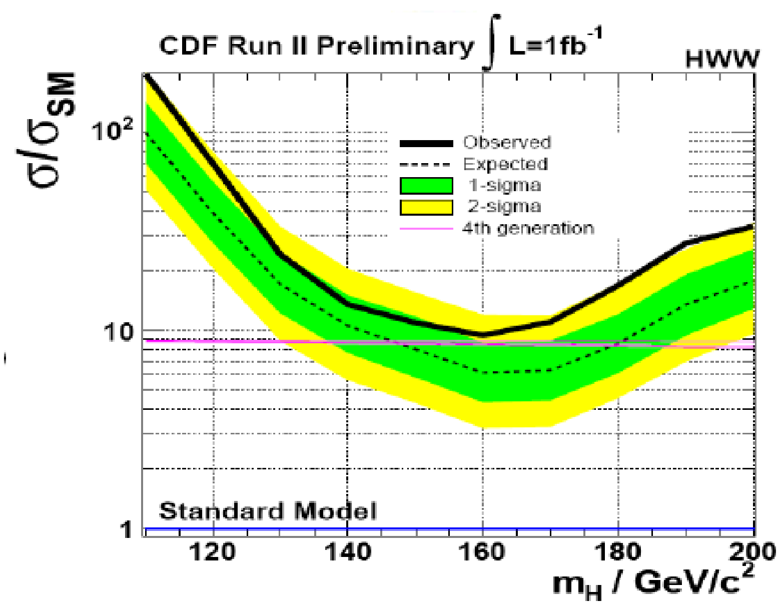


➡ **Fundamental insight into laws of nature at the TeV Scale**

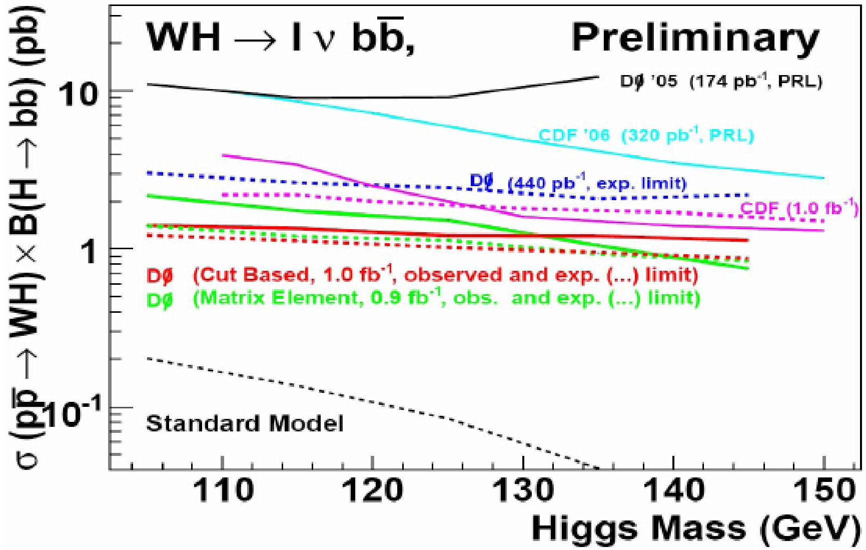
Tevatron Higgs

M_H > 135 GeV: gg → H → WW





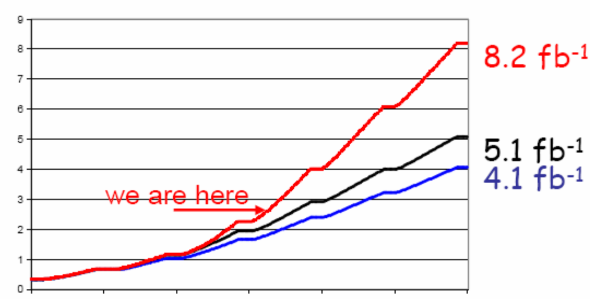
M_H < 135 GeV: qq → WH → Wbb



Status: limit > SM expectation

- factor 7.5 at m_H = 115 GeV
- factor 4 at m_H = 160 GeV

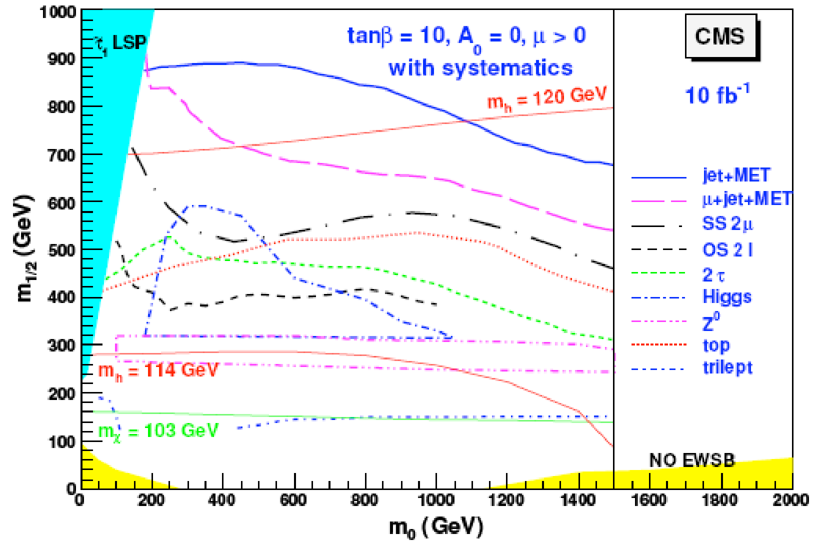
➡ $\sqrt{(2_{D0+CDF} * 8_{Lumi-09} * ?_{impr.})}$ > 4 needed



Summary: Supersymmetry

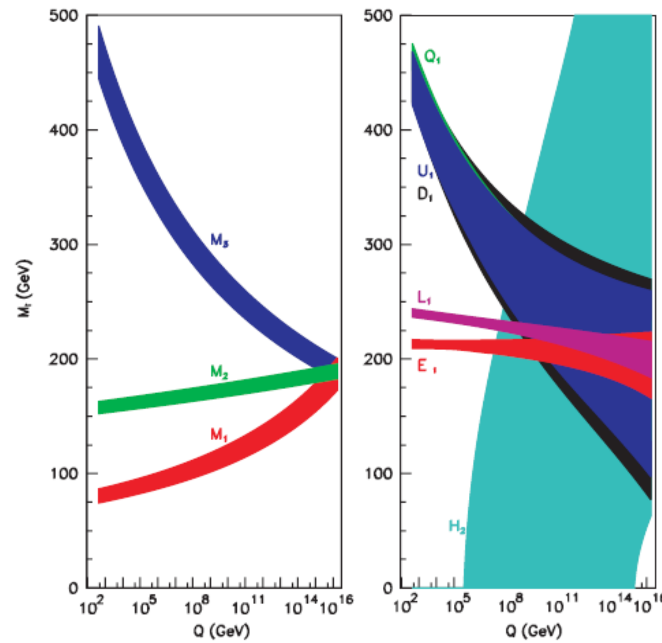
Supersymmetry
Limited by CMS energy and luminosity to Mass (Squarks/gluinos < 2.5 TeV)

- **Inclusive : discoveries**
- **Exclusive: Model determination**



Discovery would be a decisive step for physics

- **weak → SUSY → GUT**
- **Comparable to anti-matter discovery**



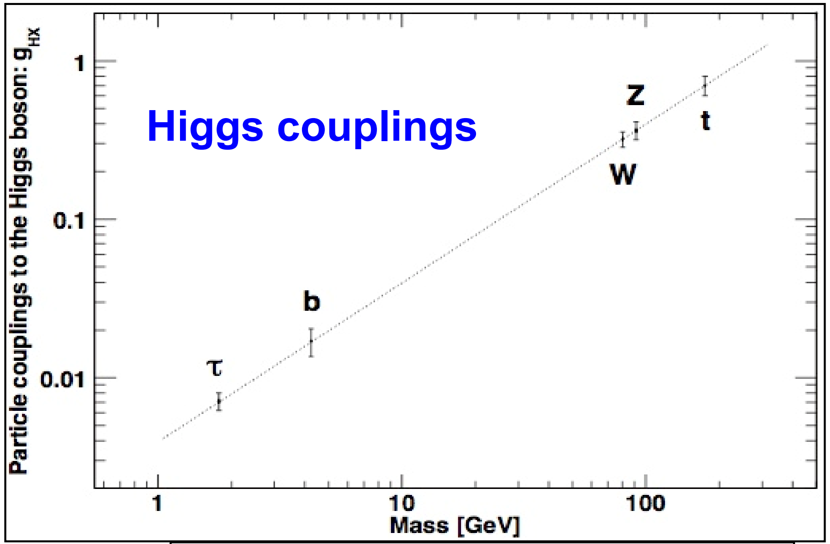
Many other extensions of SM studied for LHC for all QCD produced signatures

Super - LHC

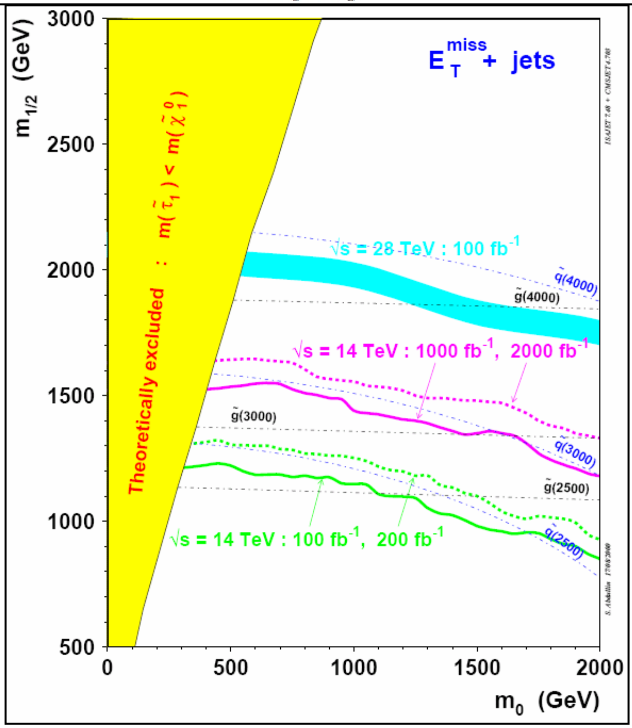
Super-LHC:

- Factor 10 luminosity
- Ecms=14 TeV
- Eeff larger (PDF)
  - Large particle flux
  - Radiation hardness
  - Segmentation

→New tracking
→New electronics
→New DAQ
→New trigger
→New computing issues
→expensive



SUSY reach



END lecture 3