John, and Beyond Known Physics at the LHC

Colloquium to mark the 65th birthday of
John Ellis
13th September 2011

Roadmap for Discoveries
(Part 2 of a common account
on LHC, together with Peter Jenni)

Image a la Sergio da Vittorio Veneto

A Theorist

Think of things for the experiments to look for, and hope they find something different

J. Ellis

Physics Focus of Attention in Early 1990's

1. Clarify the electroweak symmetry breaking sector! How is mass generated?

SM has an unproven element: the generation of mass

Higgs mechanism ? or other physics ?

Answer will be found at **LHC energies**

2. Identify particles that make up Dark Matter

Even if the Higgs exists, all is not completely well with SM alone: next question is "why is (Higgs) mass so low"?

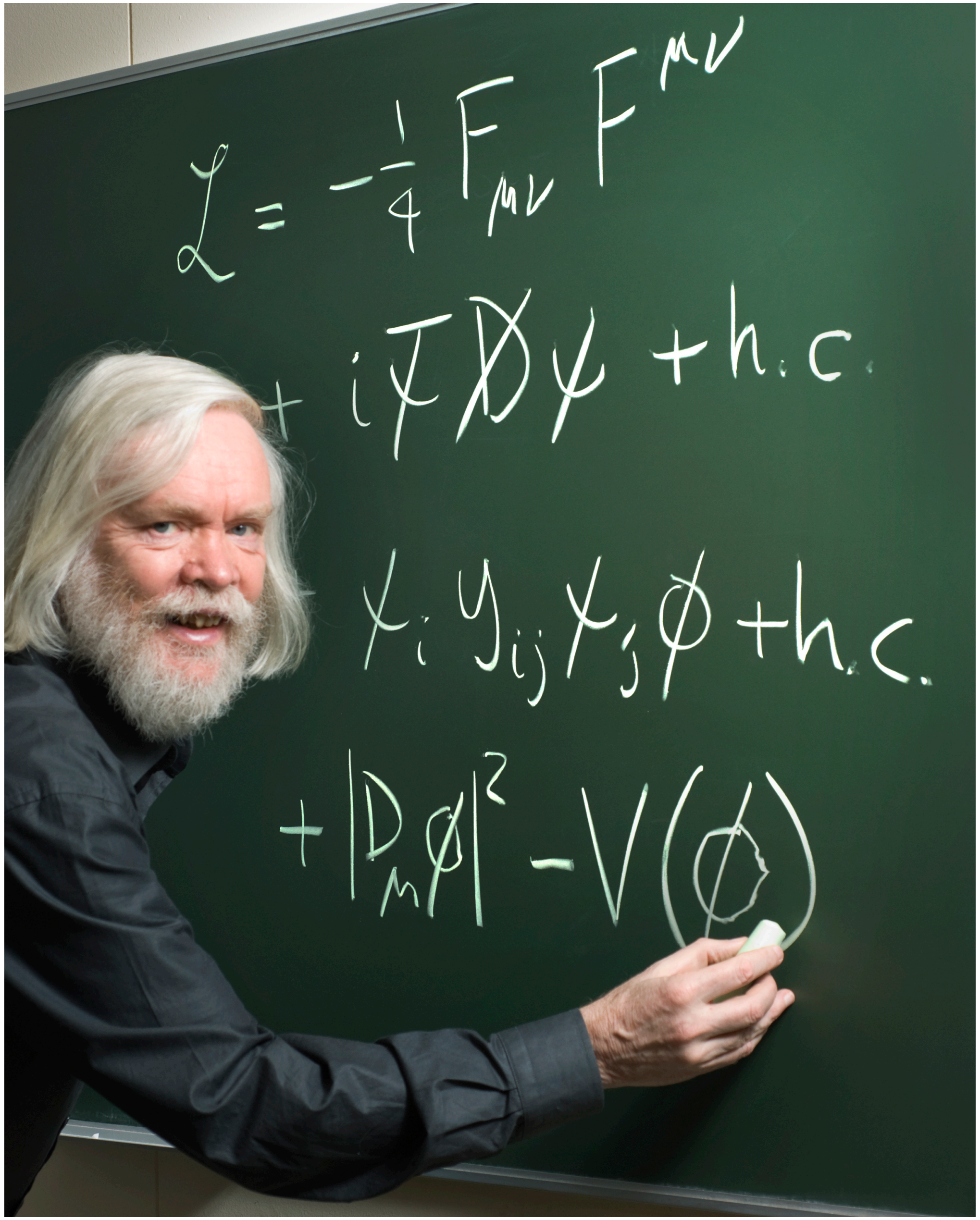
If a new symmetry (Supersymmetry) is the answer, it must show up at *O*(**1TeV)**

3. Search for new physics at the TeV scale

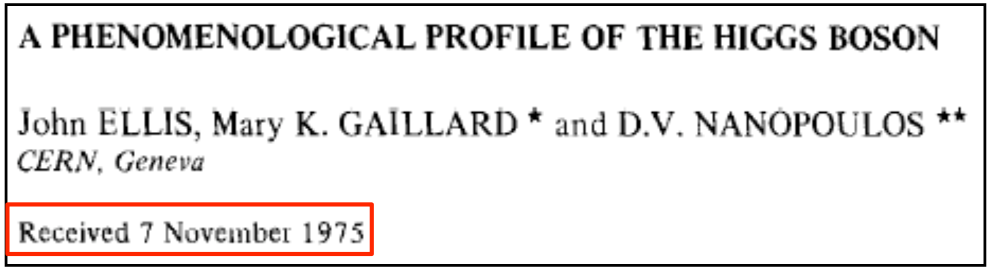
SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨ dramatic concepts: supersymmetry , (extra space-time dimensions) ?

Clarify the Electroweak Symmetry Breaking Sector



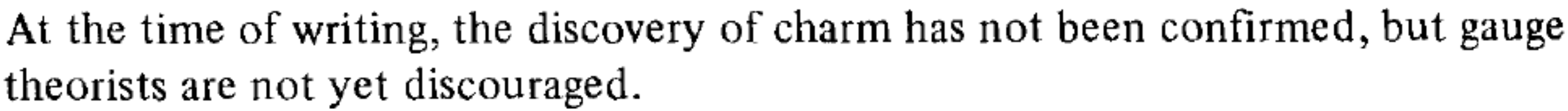
Clarify the Electroweak Symmetry Breaking Sector



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975



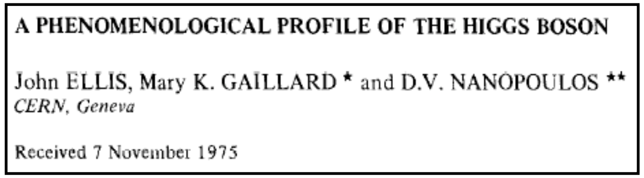
At the time of writing, the discovery of charm has not been confirmed, but gauge theorists are not yet discouraged.

Seminal Events just before the above paper:
Neutral currents (1973)
Charm (1974)
Heavy lepton τ (1975)
Much attention to search for $W^{\pm}$, Z^0

For these authors, the Big Issue: is there a Higgs boson?
Previously ~ 10 papers on Higgs bosons
$M_H > 18$ MeV
This paper presented the first attempt at a systematic survey

A Phenomenological Profile of the Higgs Boson

Higgs decay modes and searches in 1975:



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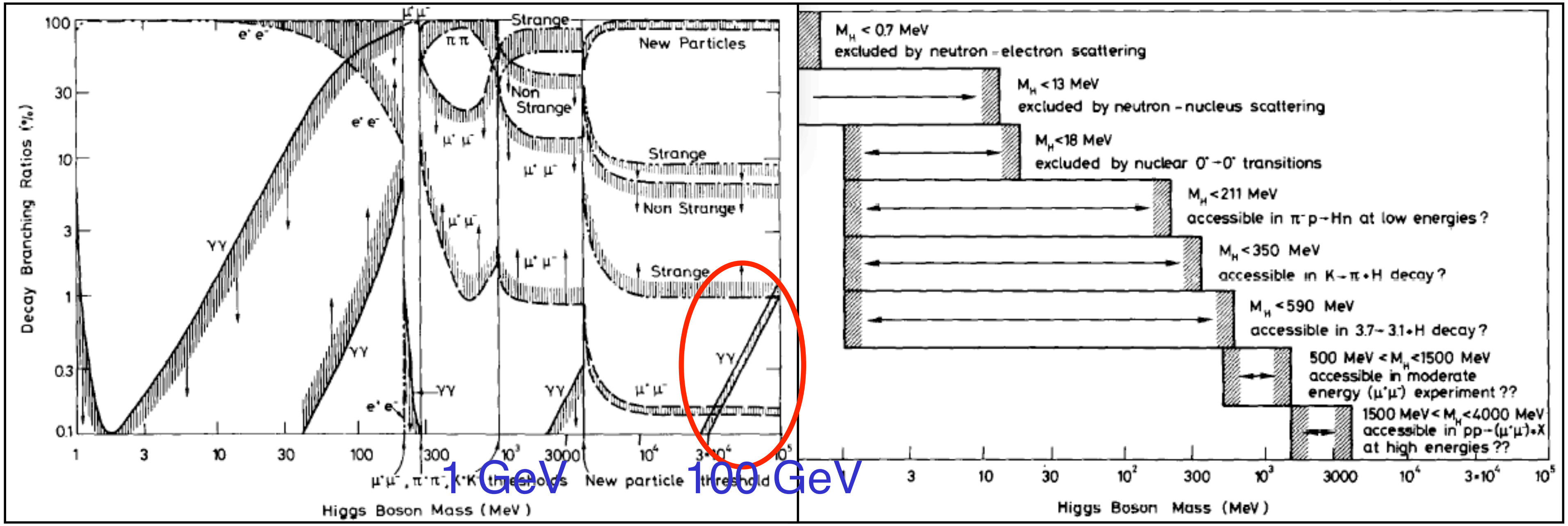
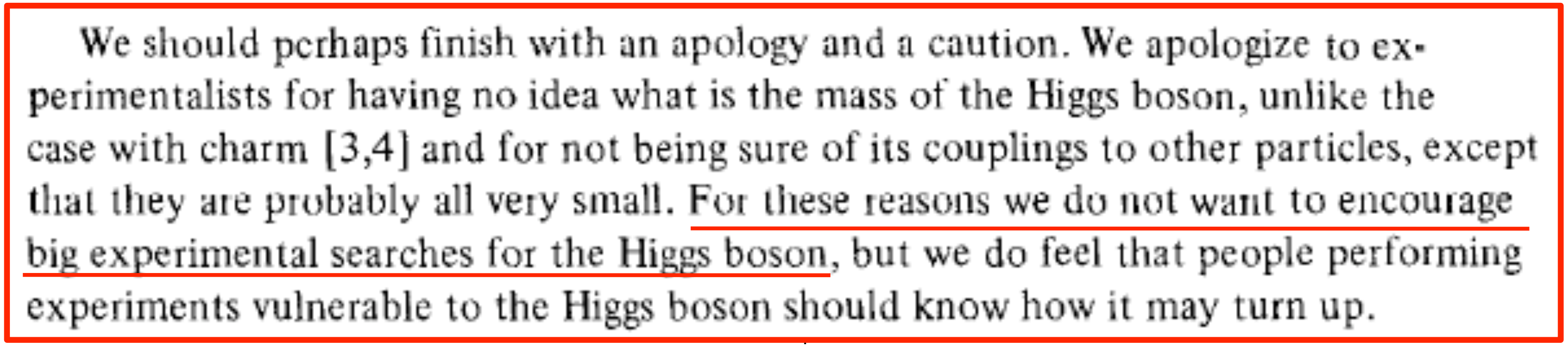
JE at HH11

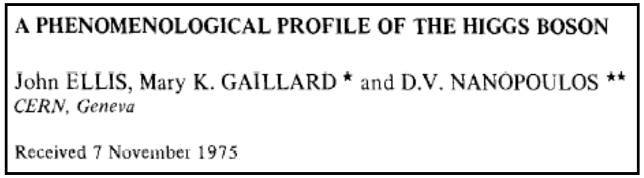




We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A Phenomenological Profile of the Higgs Boson

Higgs decay modes and searches in 1975:



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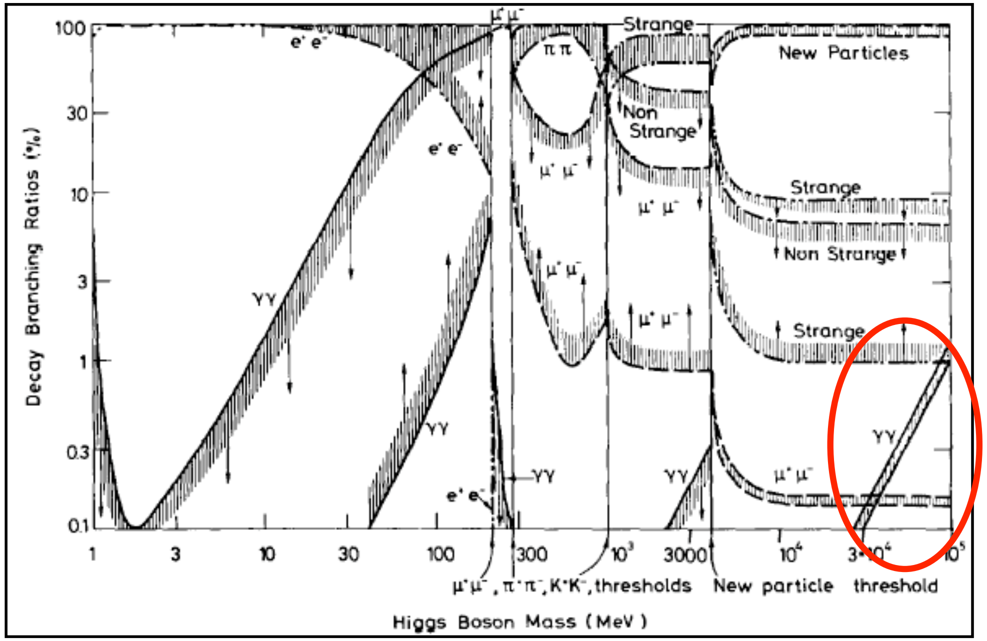

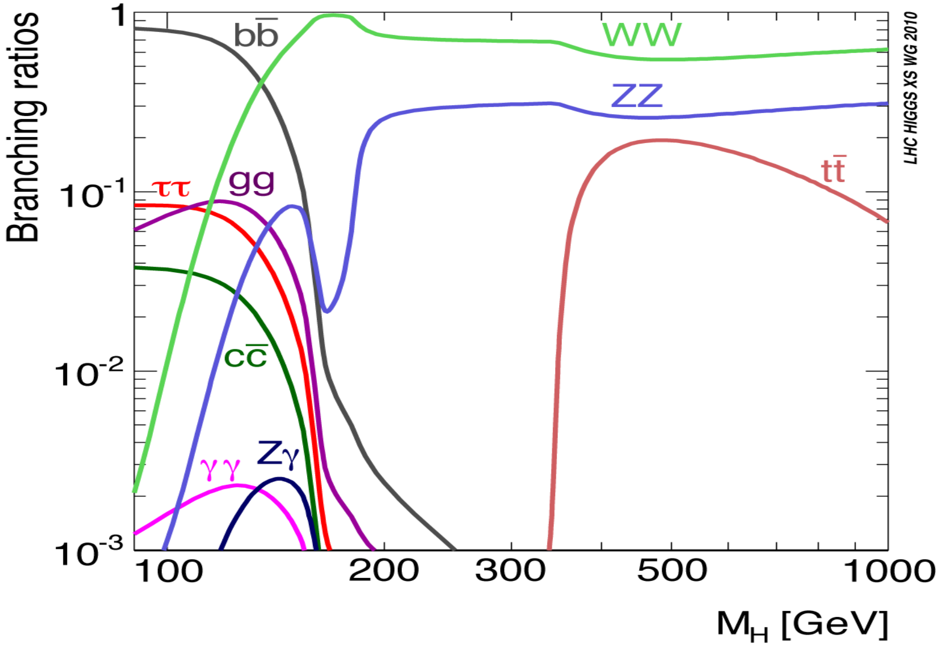

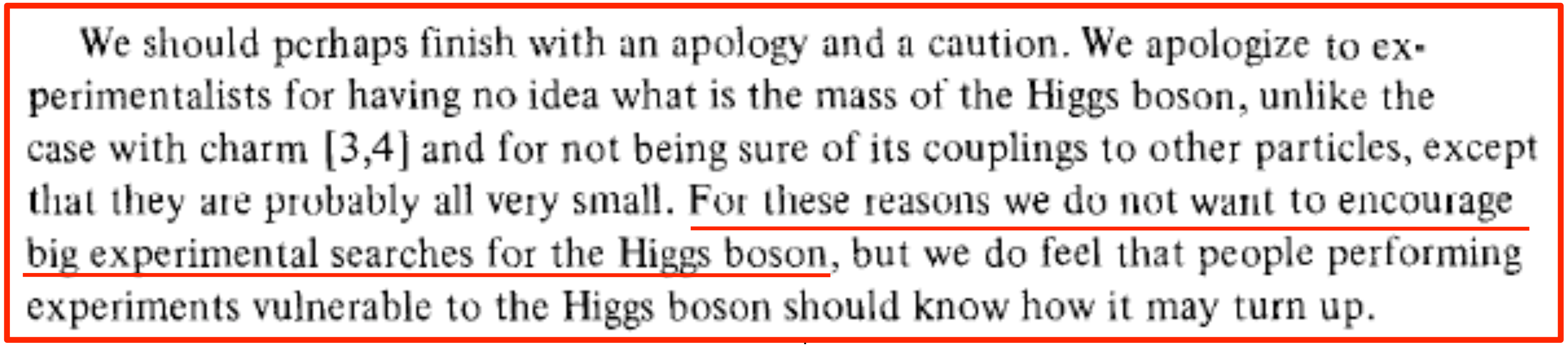

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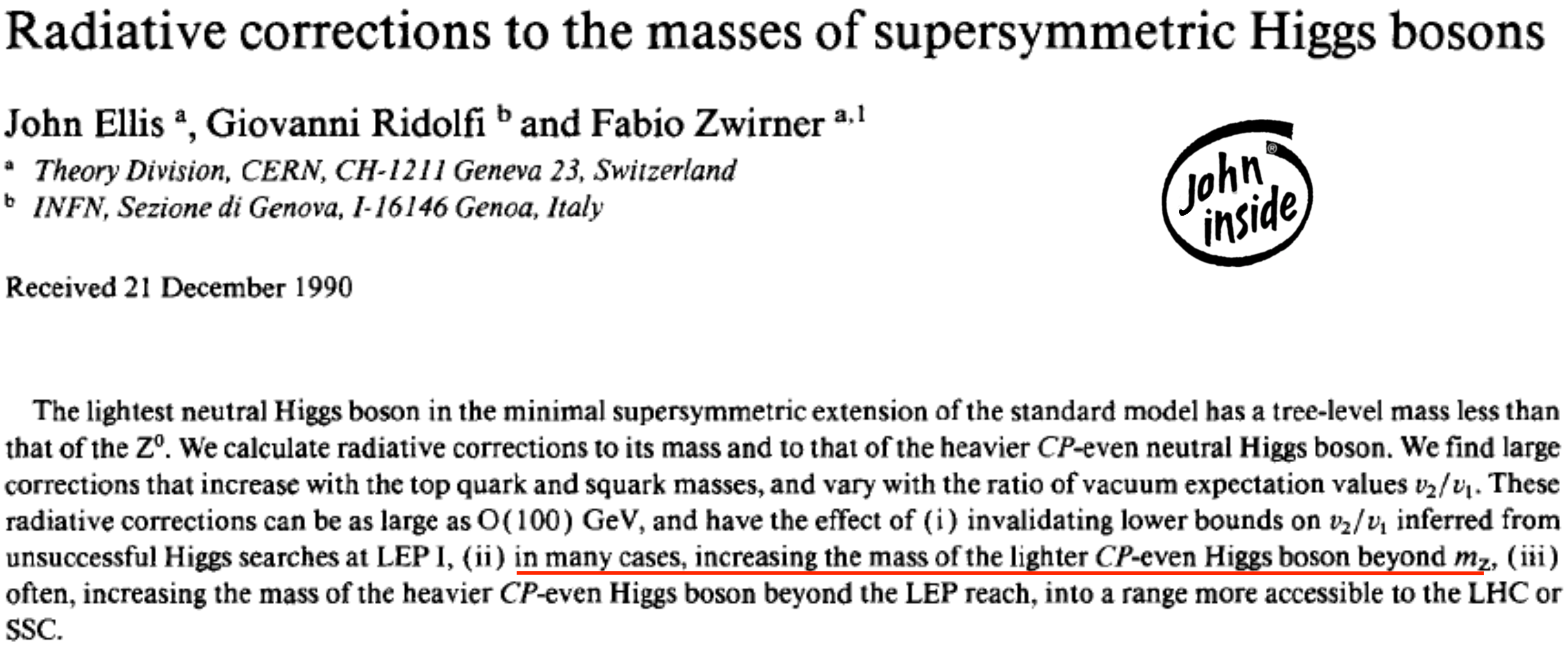
A Key Element that Drove LHC-GPD Designs



Radiative corrections to the masses of supersymmetric Higgs bosons

John Ellis [a], Giovanni Ridolfi [b] and Fabio Zwirner [a,1]

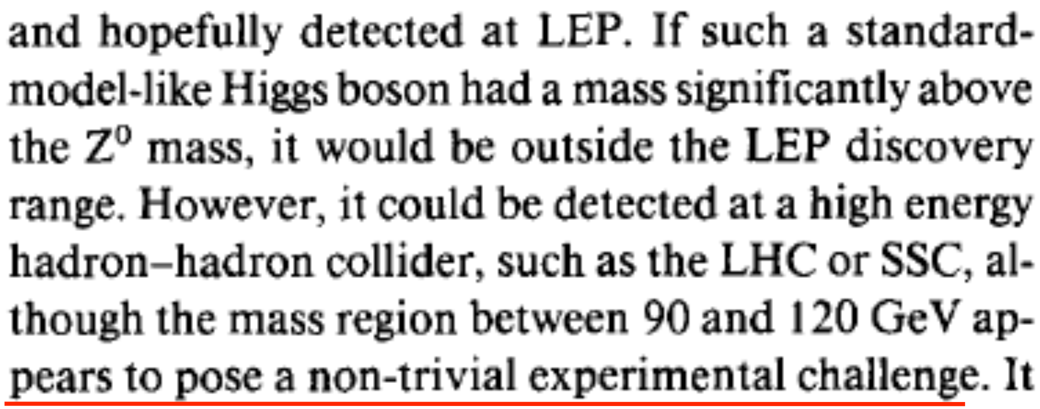
[a] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*

[b] *INFN, Sezione di Genova, I-16146 Genoa, Italy*

John inside

Received 21 December 1990

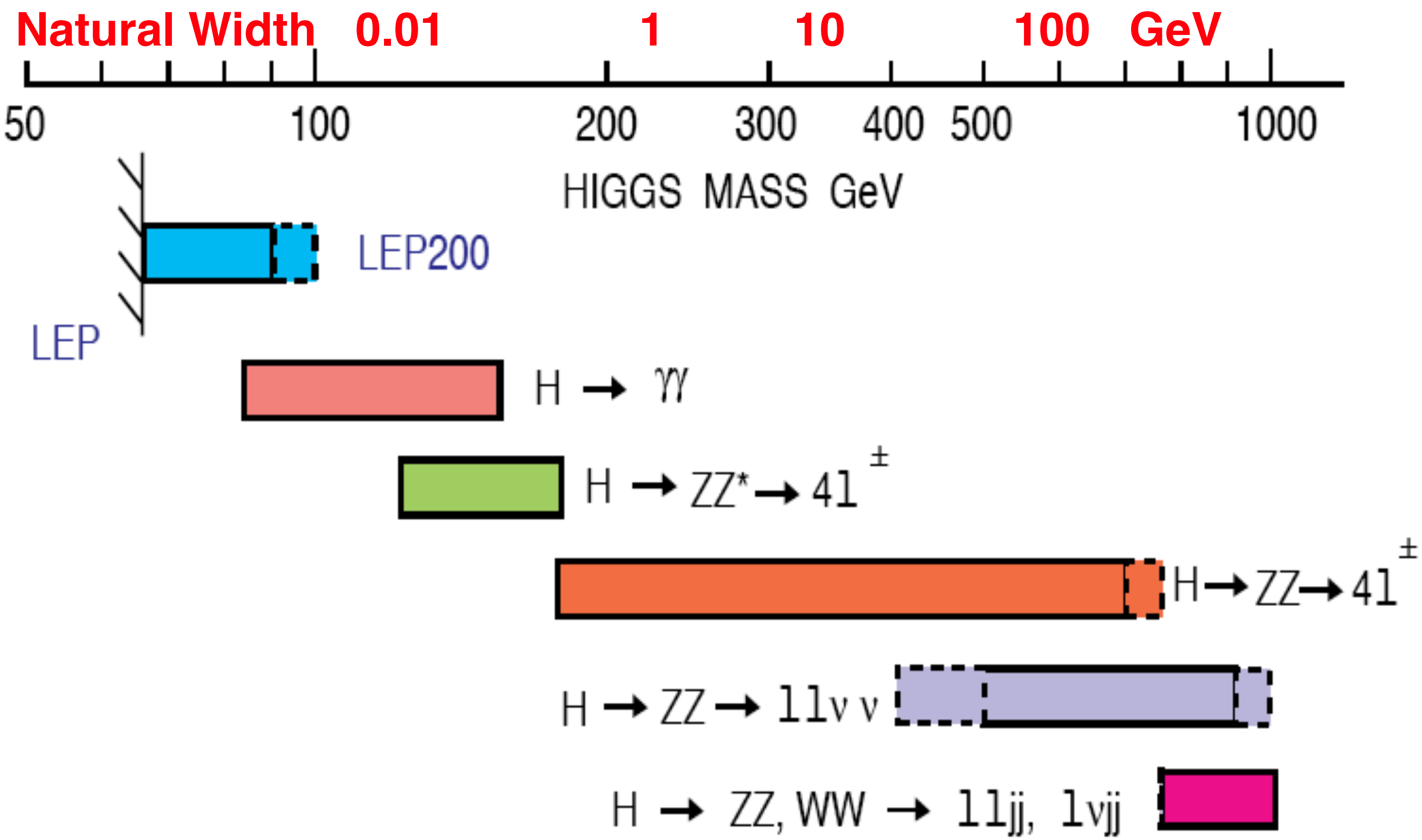
The lightest neutral Higgs boson in the minimal supersymmetric extension of the standard model has a tree-level mass less than that of the Z^0. We calculate radiative corrections to its mass and to that of the heavier *CP*-even neutral Higgs boson. We find large corrections that increase with the top quark and squark masses, and vary with the ratio of vacuum expectation values v_2/v_1. These radiative corrections can be as large as O(100) GeV, and have the effect of (i) invalidating lower bounds on v_2/v_1 inferred from unsuccessful Higgs searches at LEP I, (ii) in many cases, increasing the mass of the lighter *CP*-even Higgs boson beyond m_Z, (iii) often, increasing the mass of the heavier *CP*-even Higgs boson beyond the LEP reach, into a range more accessible to the LHC or SSC.



and hopefully detected at LEP. If such a standard-model-like Higgs boson had a mass significantly above the Z^0 mass, it would be outside the LEP discovery range. However, it could be detected at a high energy hadron–hadron collider, such as the LHC or SSC, although the mass region between 90 and 120 GeV appears to pose a non-trivial experimental challenge. It

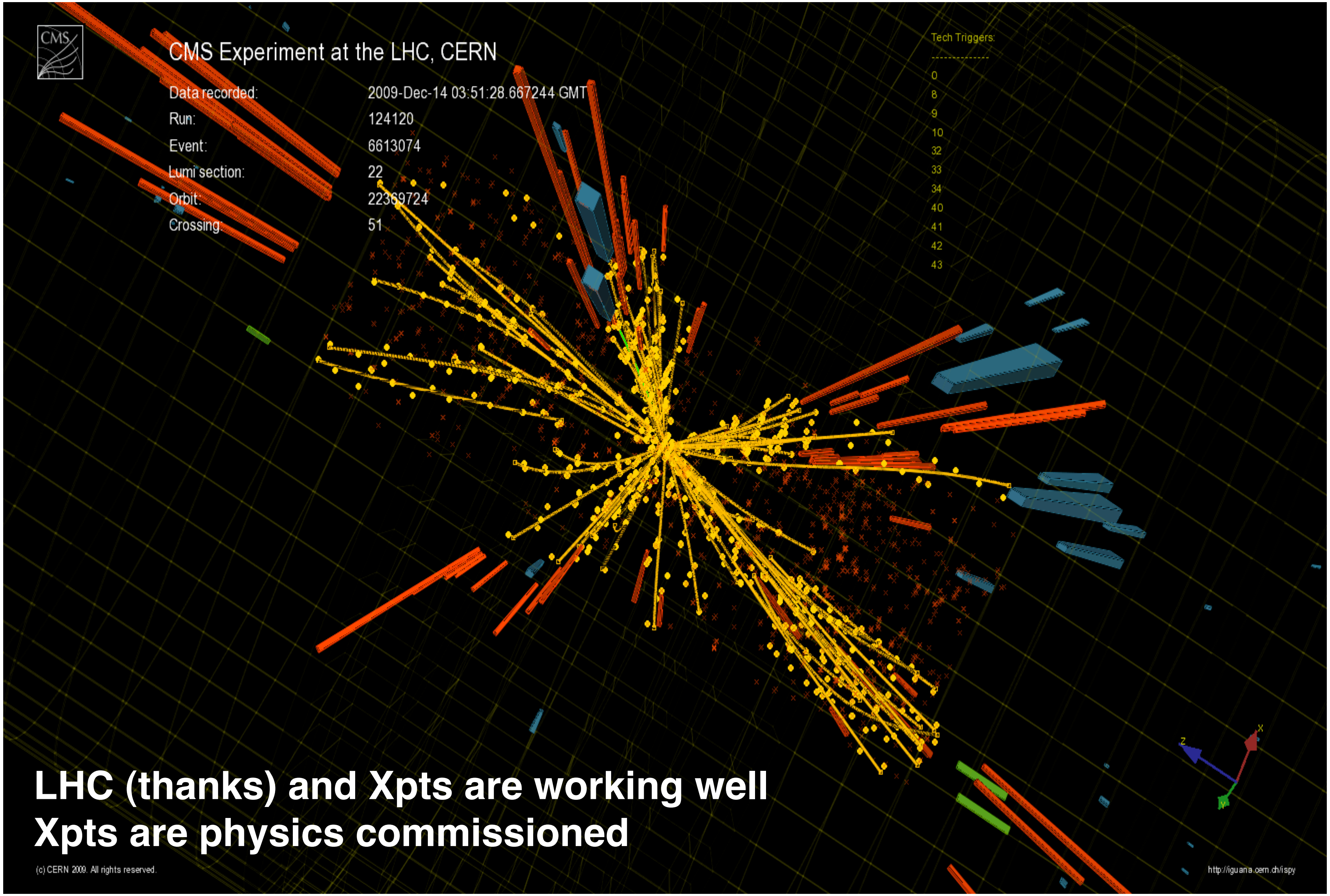
+ a few others

Physics Benchmark For Detector Design Production of SM Higgs Boson



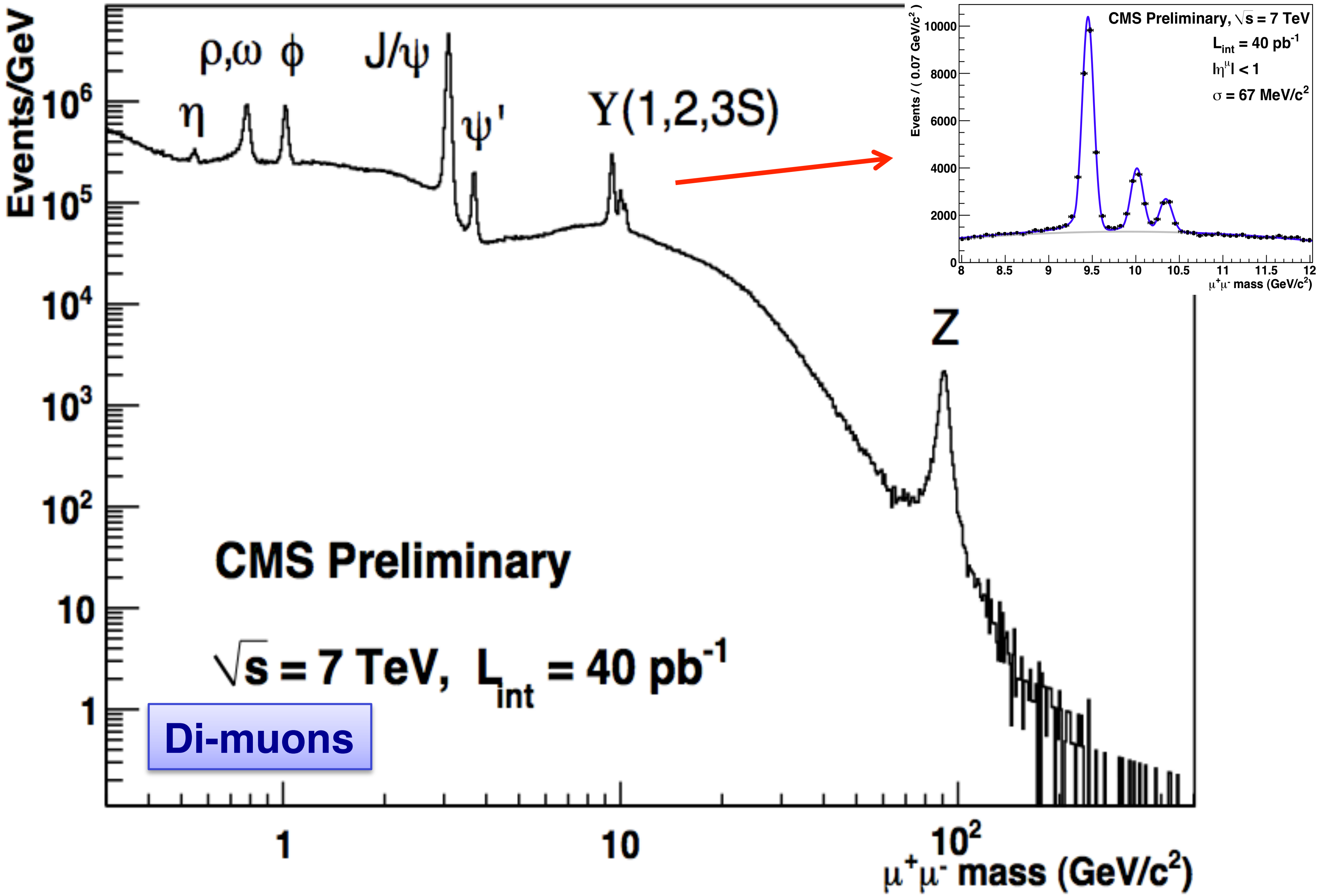
Transparency from the 90's

A Collision of Two Protons

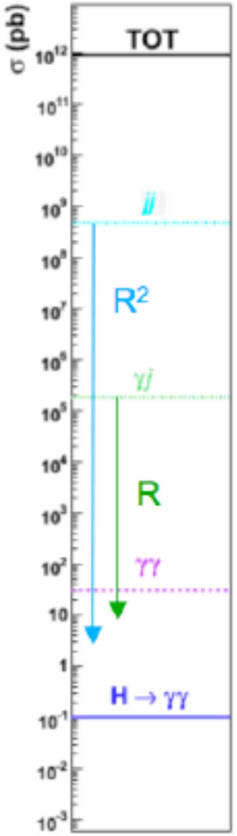


LHC (thanks) and Xpts are working well
Xpts are physics commissioned

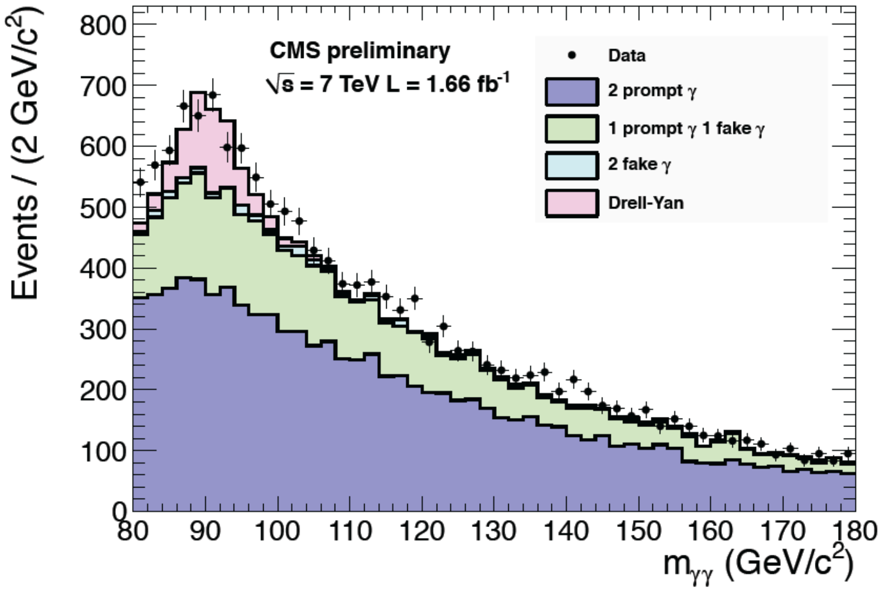
CMS Performance: Tracking and Muons

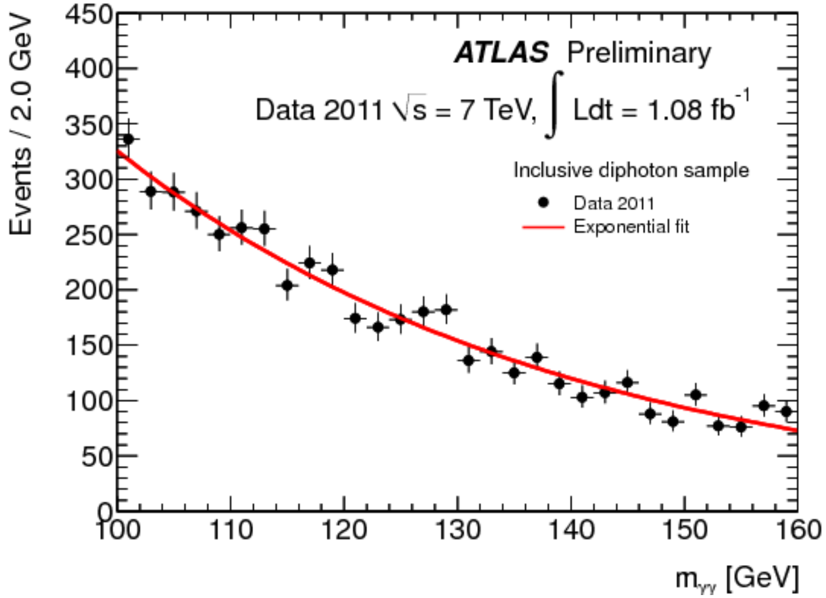


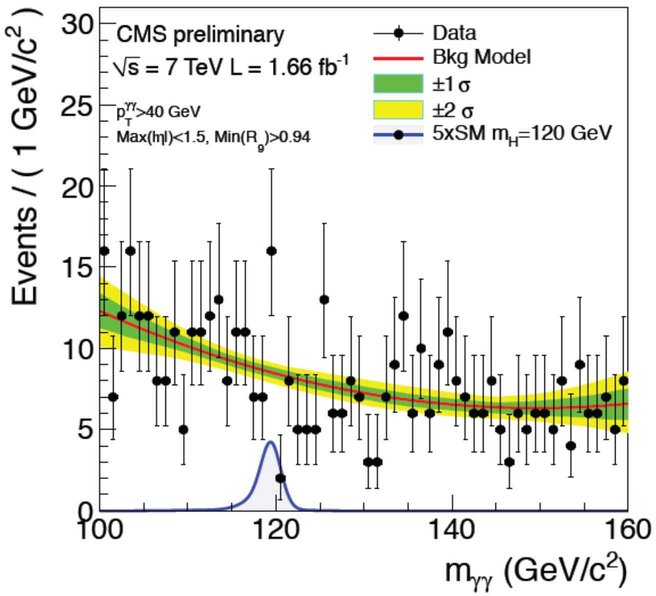
Search for the SM H → γγ



R ~ O(8000)







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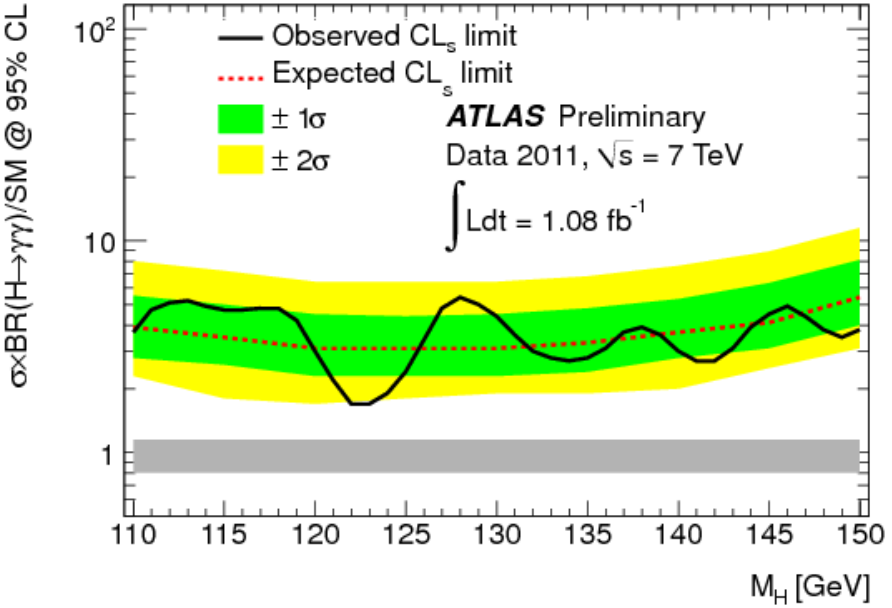
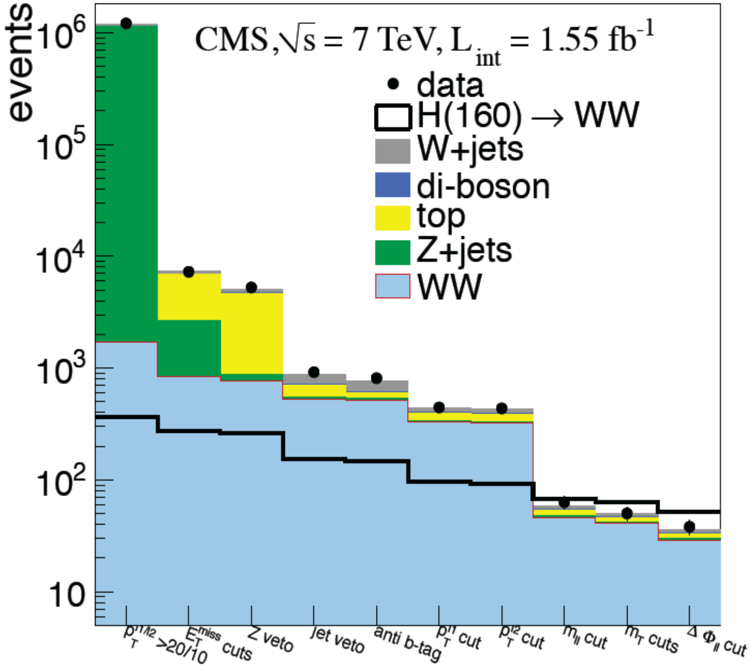
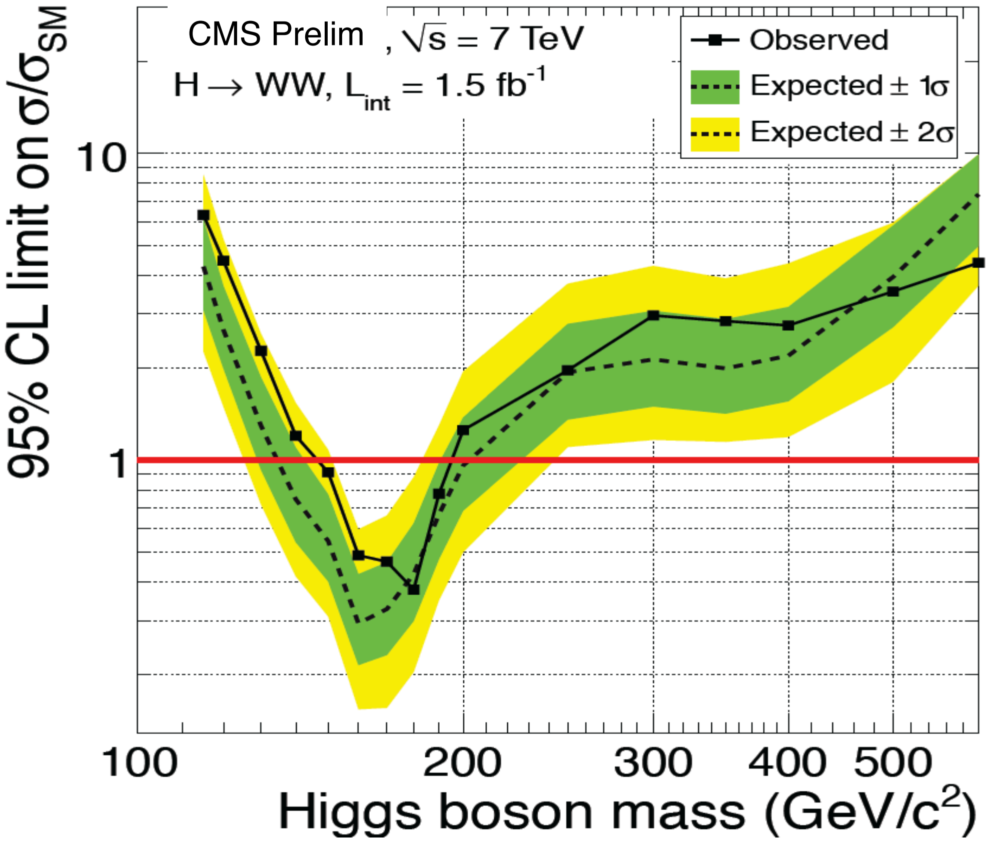
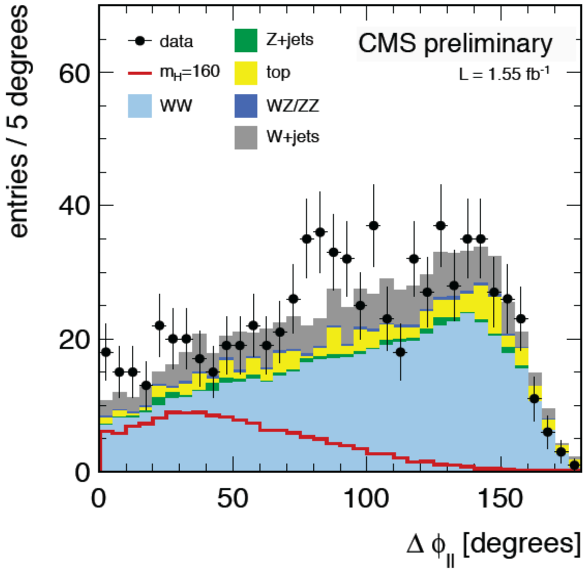


CMS: Search for the SM H →WW →llνν

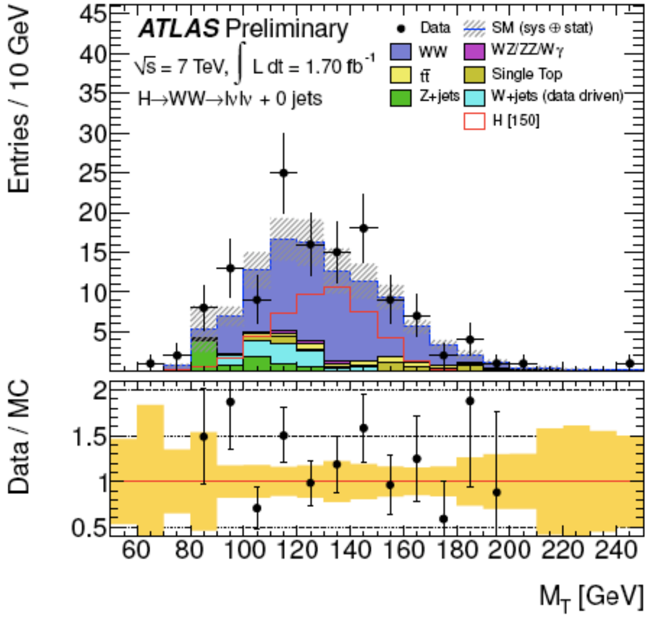


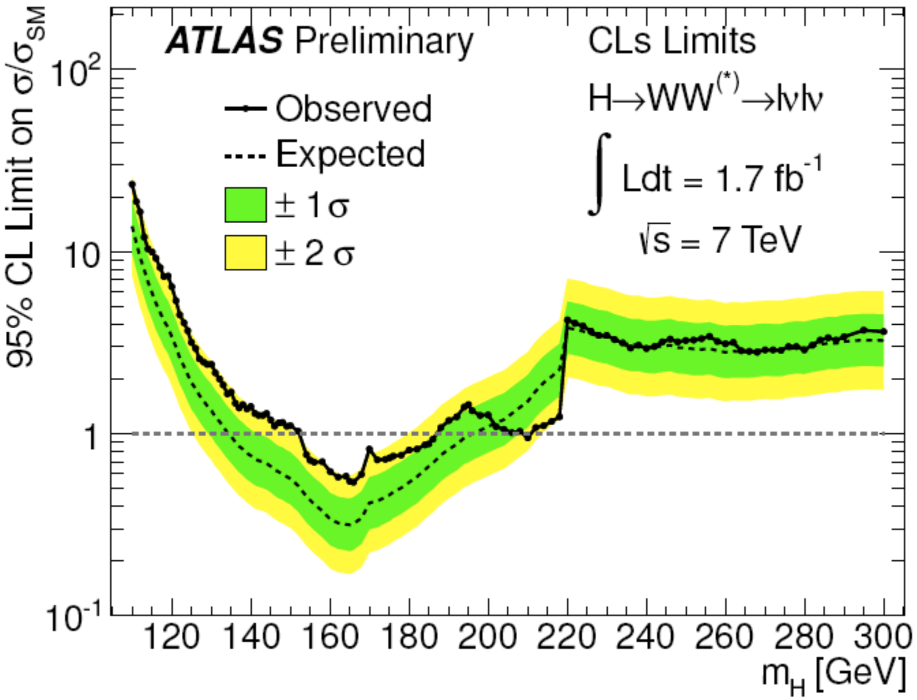




SM Higgs boson with mass
147 < M_H < 194 GeV is disfavoured at 95% CL.
Expected disfavoured mass range
136 < M_H < 200 GeV

ATLAS: Search for the SM H → WW → llνν





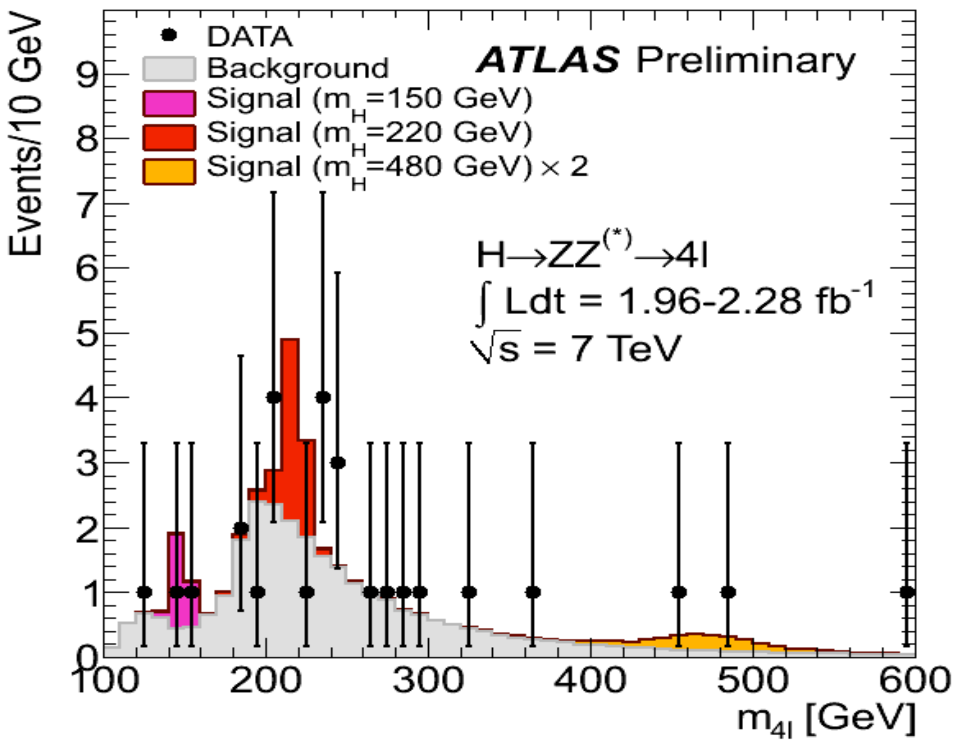
	WW	ttbar	Total SM bkg.	Data	Higgs m_H=150
0-jet	**43±6**	**2.2±1.4**	**53±9**	**70**	34±7
1-jet	**10±2**	**6.9±1.9**	**23±4**	**23**	12±3

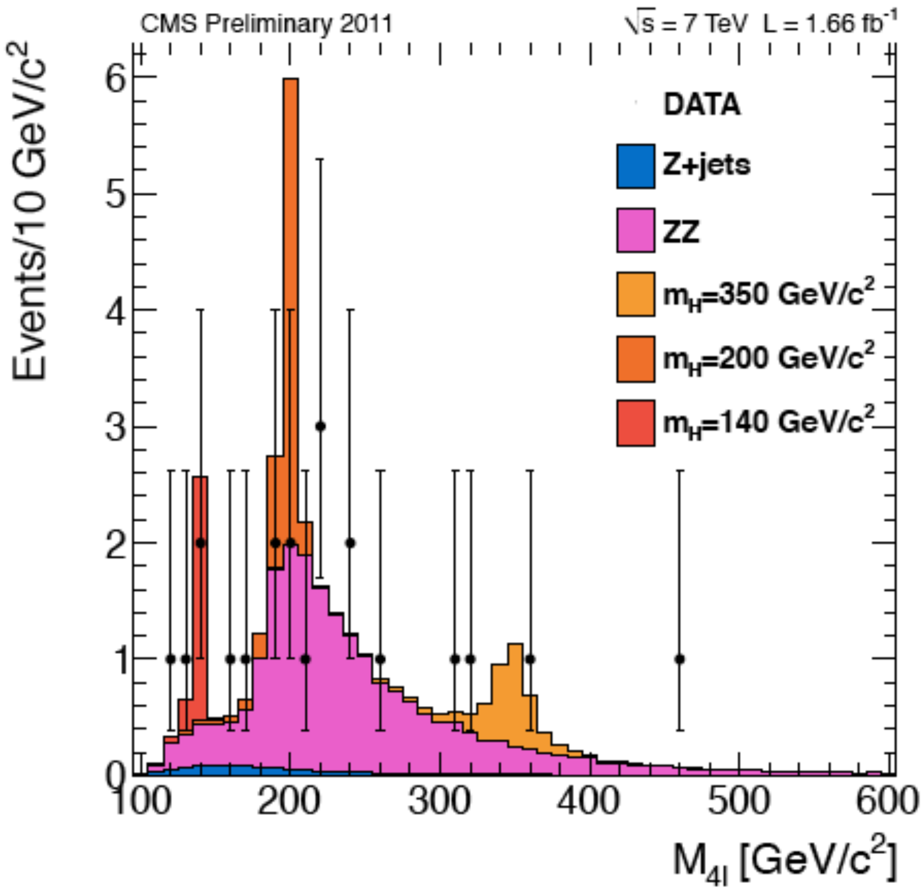
Final selection, optimized for m_H=150 GeV

A Standard Model Higgs boson with $154<m_H<186$ GeV is disfavoured at 95% C.L.

Expected disfavoured mass range is $135 < m_H < 196$ GeV

Search for the SM H → ZZ → 4l





ATLAS

Observe: 27 events

6ee, 9eμ, 12μμ events

Expected: 28 ± 4 events

CMS

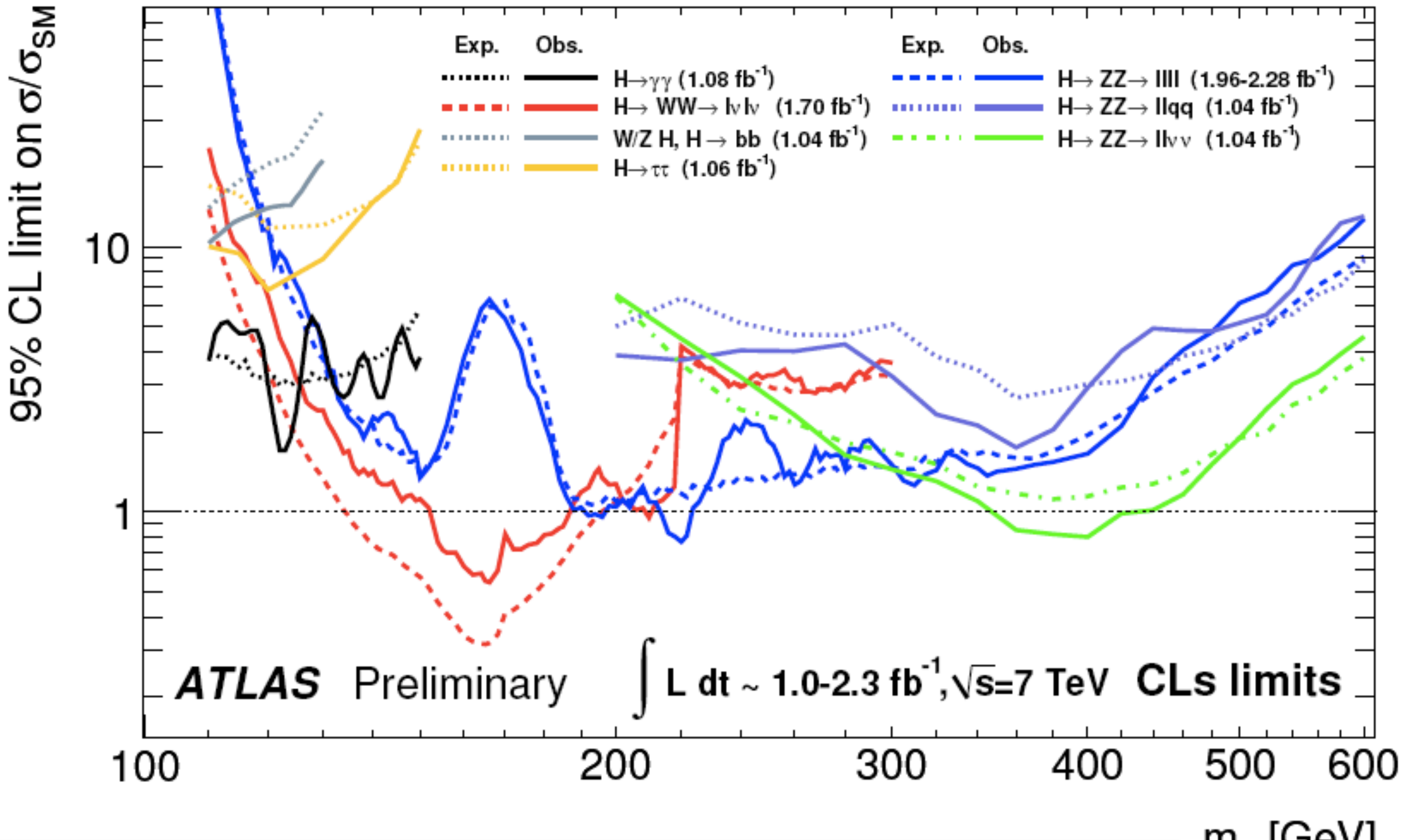
Observe: 21 events

5ee, 10eμ, 6μμ events

Expected: 21.2 ± 0.8 events

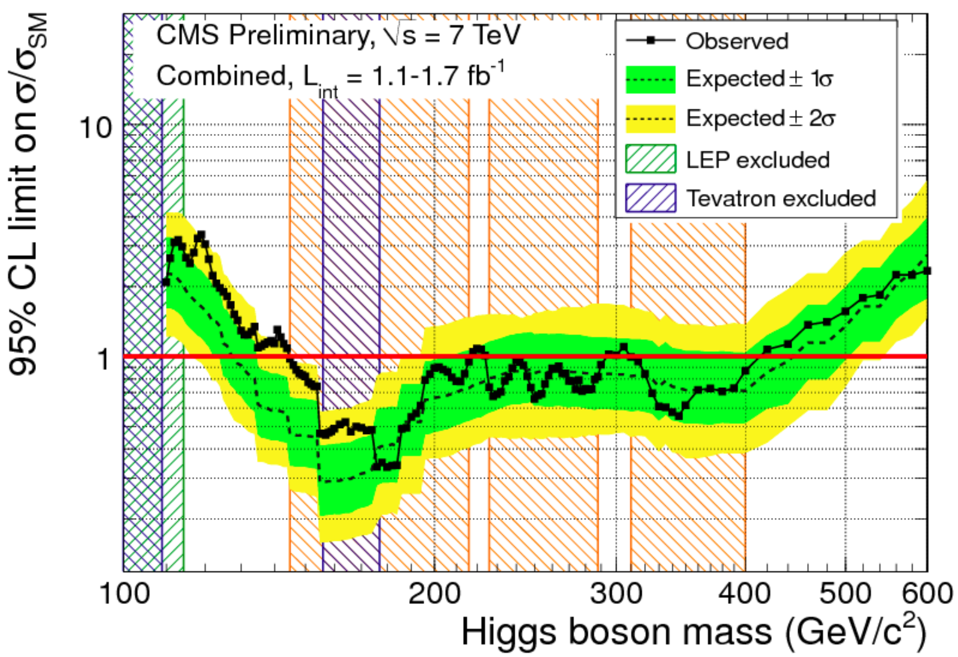
ATLAS: Search for the SM H Boson

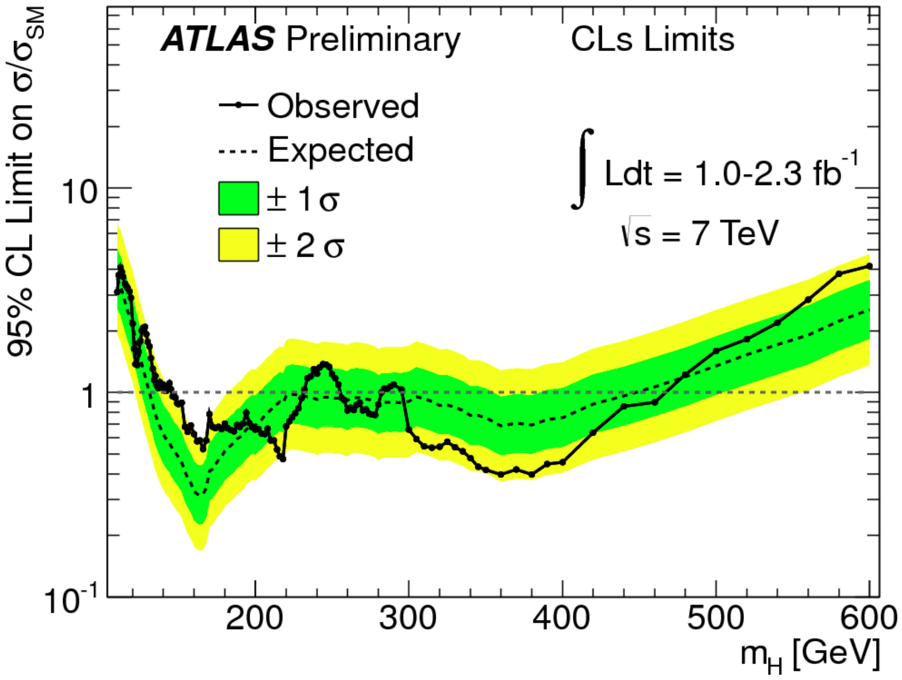
How the individual channels contribute

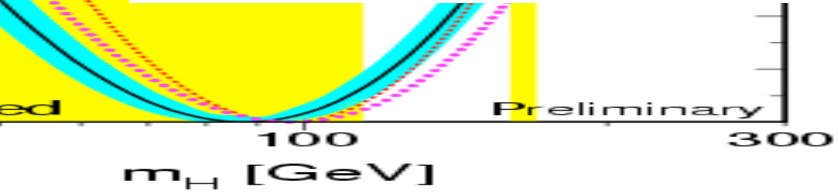


Solid lines = Observed limit; Dashed lines = Median Expected

Search for the SM Higgs Boson



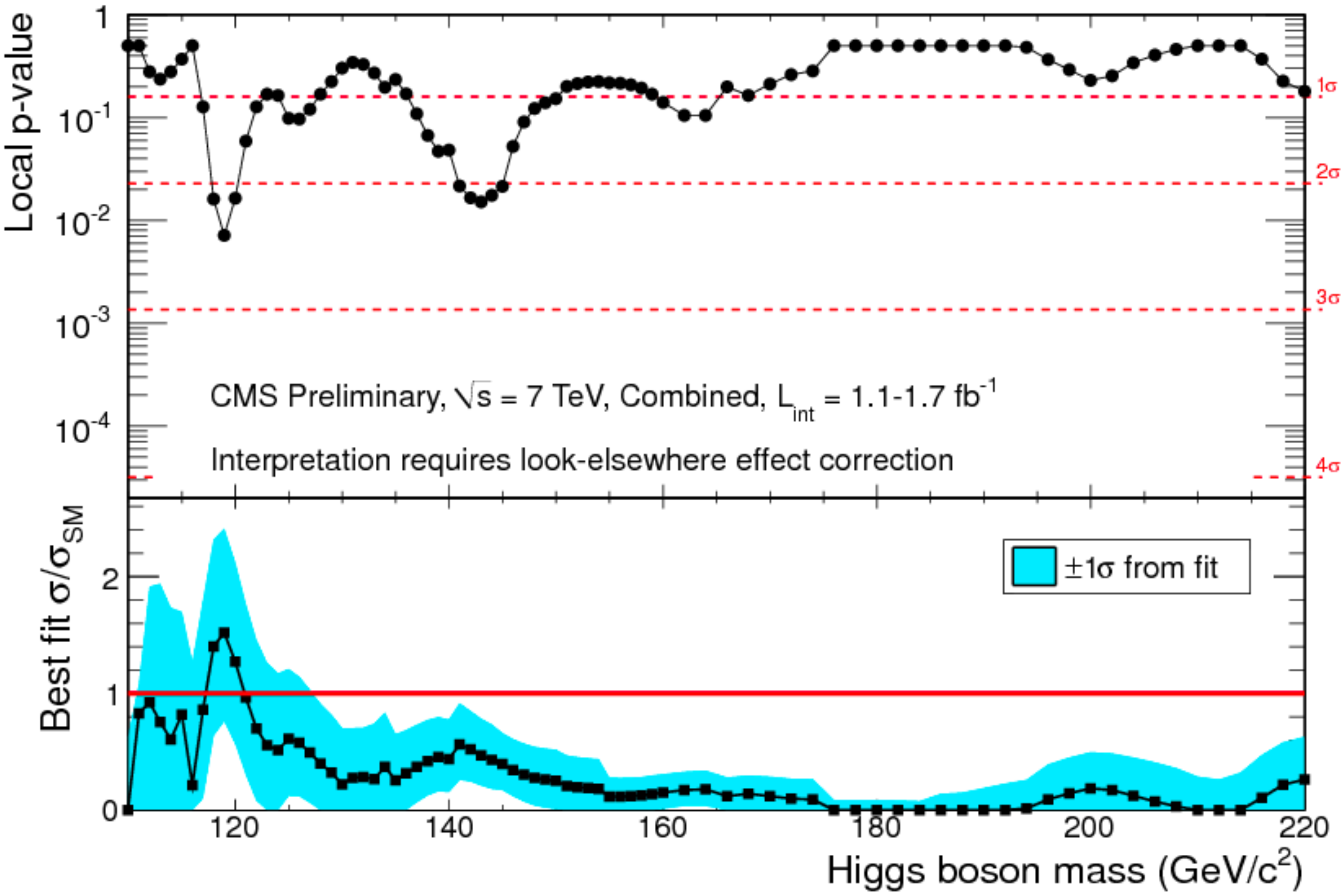




Observed disfavoured mass range at 95% CL:
CMS: 145-216, 226-288, 310-400 GeV
ATLAS: 146-232, 256-282, 296-466 GeV
ATLAS: 160-220, 300-420 GeV at 99% CL

Expected disfavoured mass range at 95% CL:
CMS: 130 – 440 GeV

CMS Combination: Search for the SM H Boson



Seeking Supersymmetry

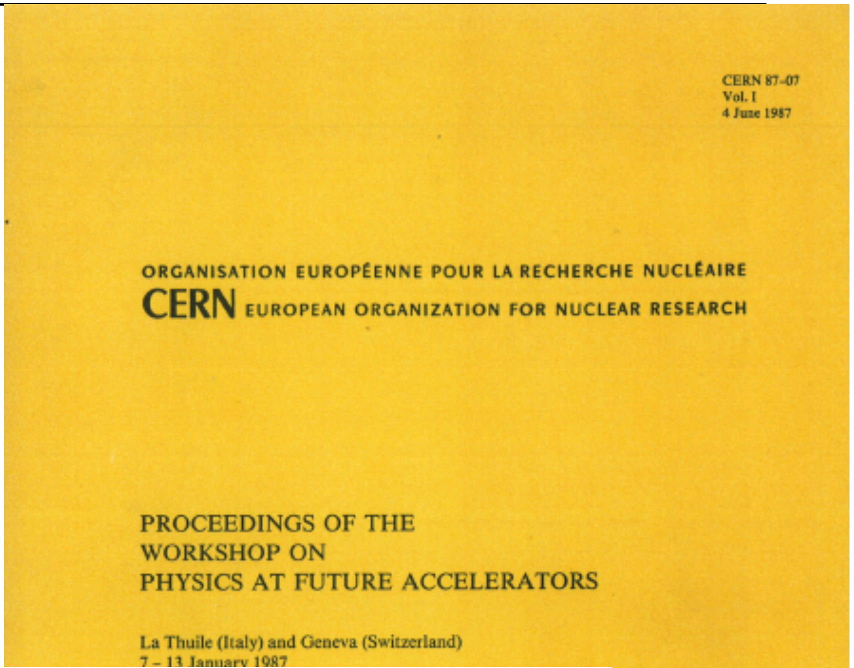
Image a la Sergio da Vittorio Veneto

Search for Physics Beyond the SM

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

La Thuile
7-13 January 1987

$\sqrt{s}$ = 17 TeV !

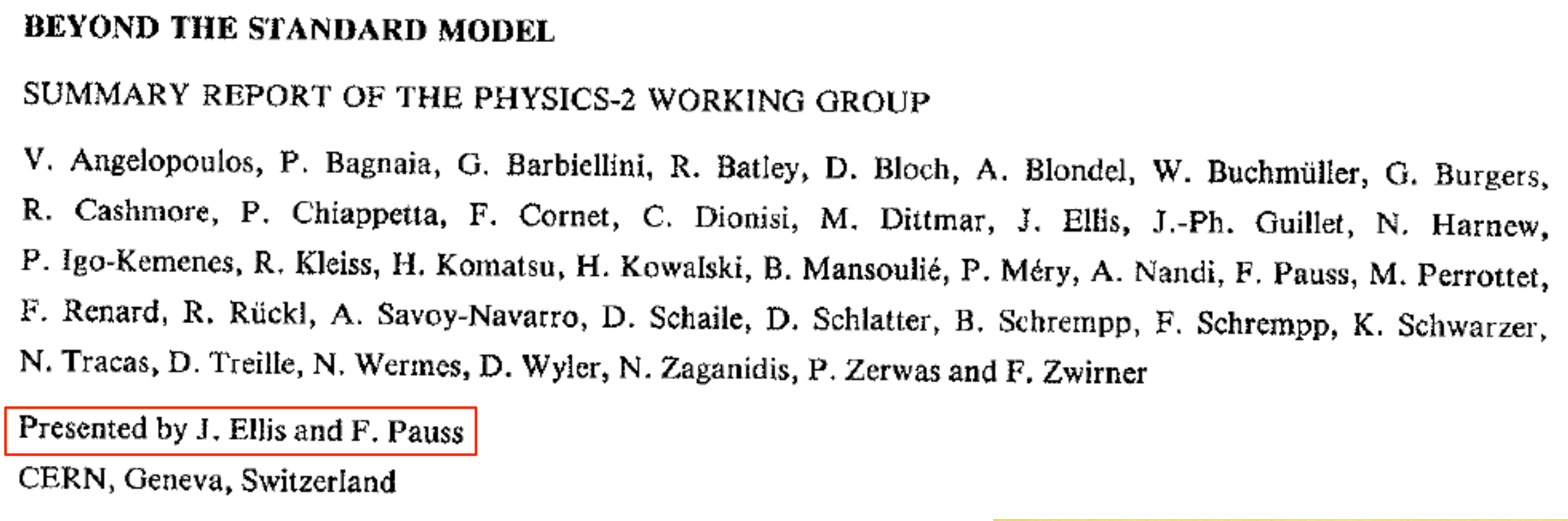


CERN 87-07
Vol. I
4 June 1987

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987



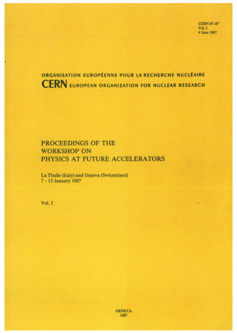
BEYOND THE STANDARD MODEL

SUMMARY REPORT OF THE PHYSICS-2 WORKING GROUP

V. Angelopoulos, P. Bagnaia, G. Barbiellini, R. Batley, D. Bloch, A. Blondel, W. Buchmüller, G. Burgers, R. Cashmore, P. Chiappetta, F. Cornet, C. Dionisi, M. Dittmar, J. Ellis, J.-Ph. Guillet, N. Harnew, P. Igo-Kemenes, R. Kleiss, H. Komatsu, H. Kowalski, B. Mansoulié, P. Méry, A. Nandi, F. Pauss, M. Perrottet, F. Renard, R. Rückl, A. Savoy-Navarro, D. Schaile, D. Schlatter, B. Schrempp, F. Schrempp, K. Schwarzer, N. Tracas, D. Treille, N. Wermes, D. Wyler, N. Zaganidis, P. Zerwas and F. Zwirner

Presented by J. Ellis and F. Pauss
CERN, Geneva, Switzerland

Search for Physics Beyond the SM



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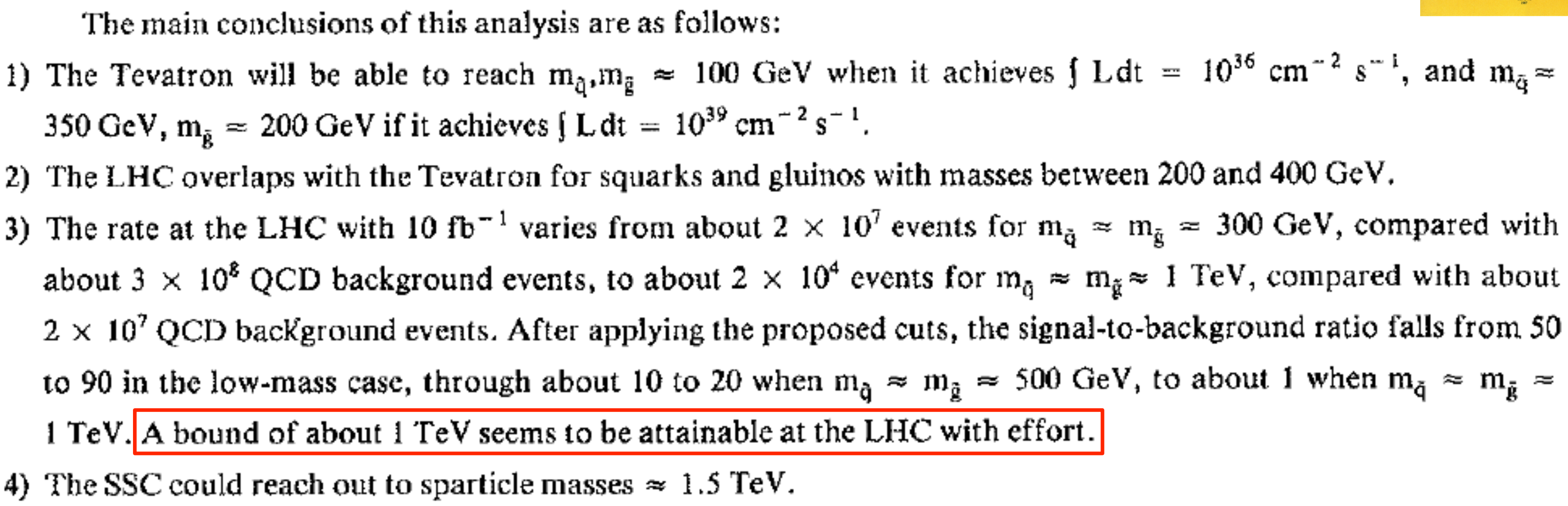
1987

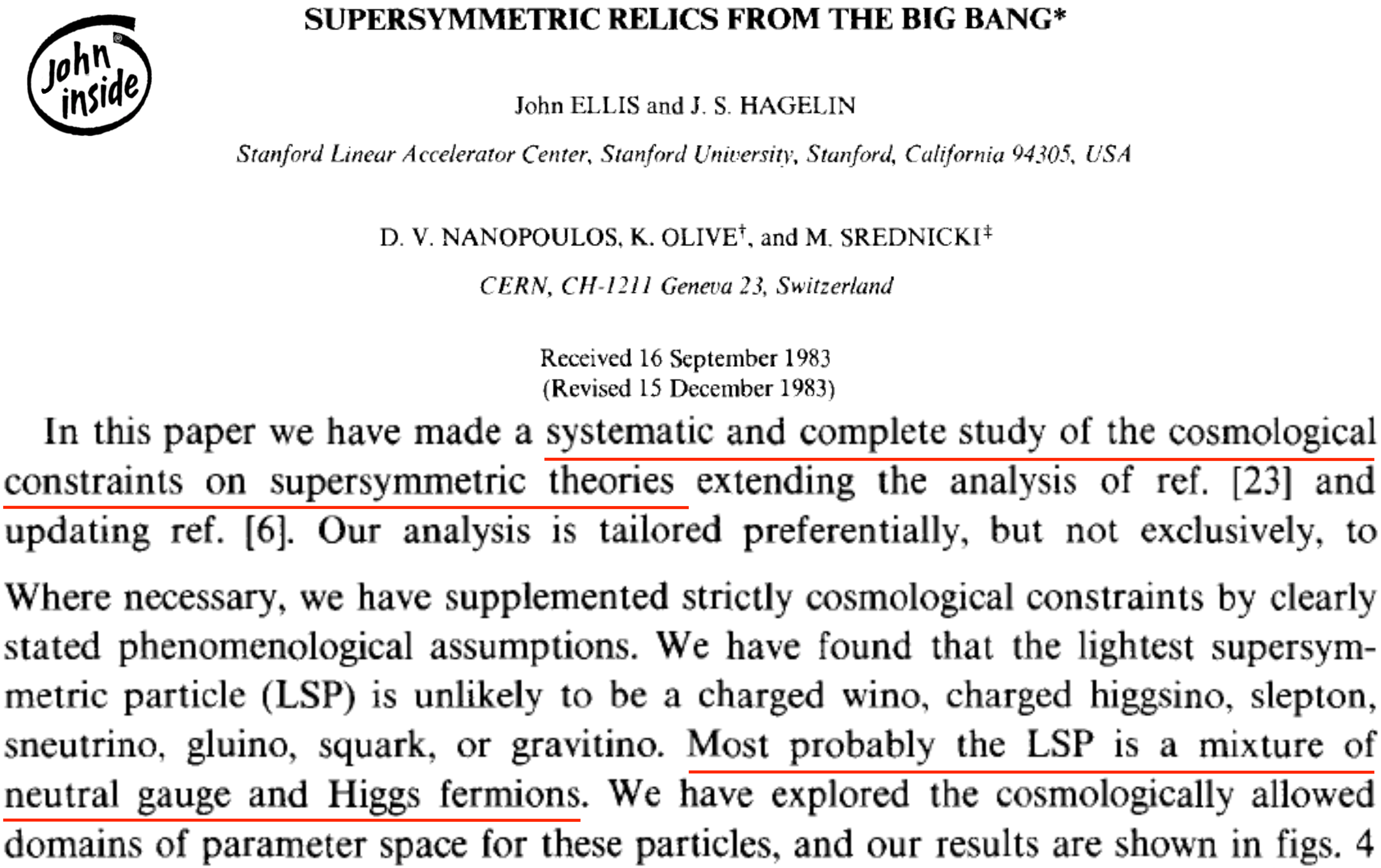
Supersymmetry



The main conclusions of this analysis are as follows:

1) The Tevatron will be able to reach $m_{\tilde{q}}, m_{\tilde{g}} \approx 100$ GeV when it achieves $\int L dt = 10^{36}$ $cm^{-2} s^{-1}$, and $m_{\tilde{q}} \approx 350$ GeV, $m_{\tilde{g}} \approx 200$ GeV if it achieves $\int L dt = 10^{39}$ $cm^{-2} s^{-1}$.
2) The LHC overlaps with the Tevatron for squarks and gluinos with masses between 200 and 400 GeV.
3) The rate at the LHC with 10 fb^{-1} varies from about 2×10^7 events for $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 300$ GeV, compared with about 3×10^8 QCD background events, to about 2×10^4 events for $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 1$ TeV, compared with about 2×10^7 QCD background events. After applying the proposed cuts, the signal-to-background ratio falls from 50 to 90 in the low-mass case, through about 10 to 20 when $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 500$ GeV, to about 1 when $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 1$ TeV. A bound of about 1 TeV seems to be attainable at the LHC with effort.
4) The SSC could reach out to sparticle masses $\approx$ 1.5 TeV.

Relics from Ancient Times



SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE[†], and M. SREDNICKI[‡]

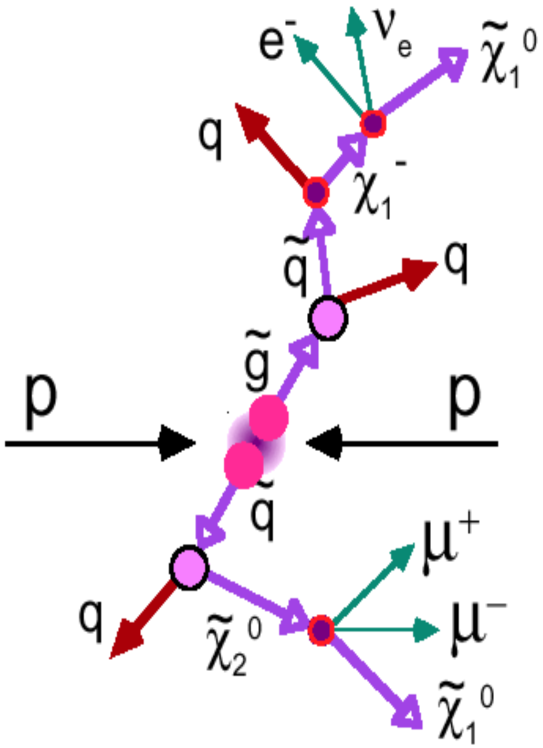
CERN, CH-1211 Geneva 23, Switzerland

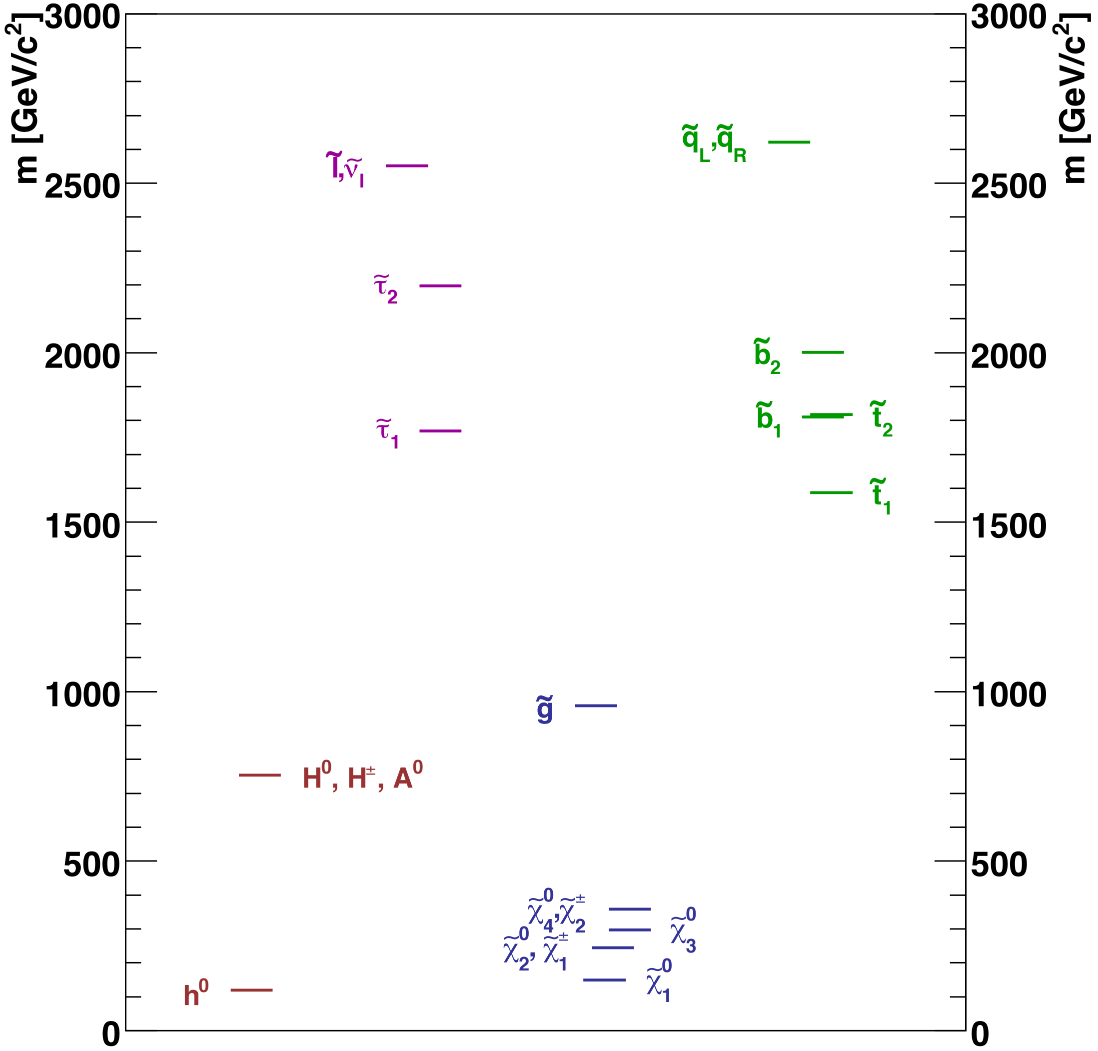
Received 16 September 1983
(Revised 15 December 1983)

In this paper we have made a systematic and complete study of the cosmological constraints on supersymmetric theories extending the analysis of ref. [23] and updating ref. [6]. Our analysis is tailored preferentially, but not exclusively, to

Where necessary, we have supplemented strictly cosmological constraints by clearly stated phenomenological assumptions. We have found that the lightest supersymmetric particle (LSP) is unlikely to be a charged wino, charged higgsino, slepton, sneutrino, gluino, squark, or gravitino. Most probably the LSP is a mixture of neutral gauge and Higgs fermions. We have explored the cosmologically allowed domains of parameter space for these particles, and our results are shown in figs. 4

Supersymmetry:
a New Zoology of Particles?



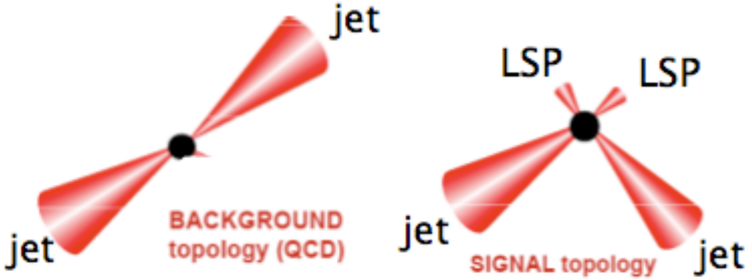


Searches require several (high-P_T) jets + (high) ME_T and charged leptons

b-jets can enhance sensitivity.

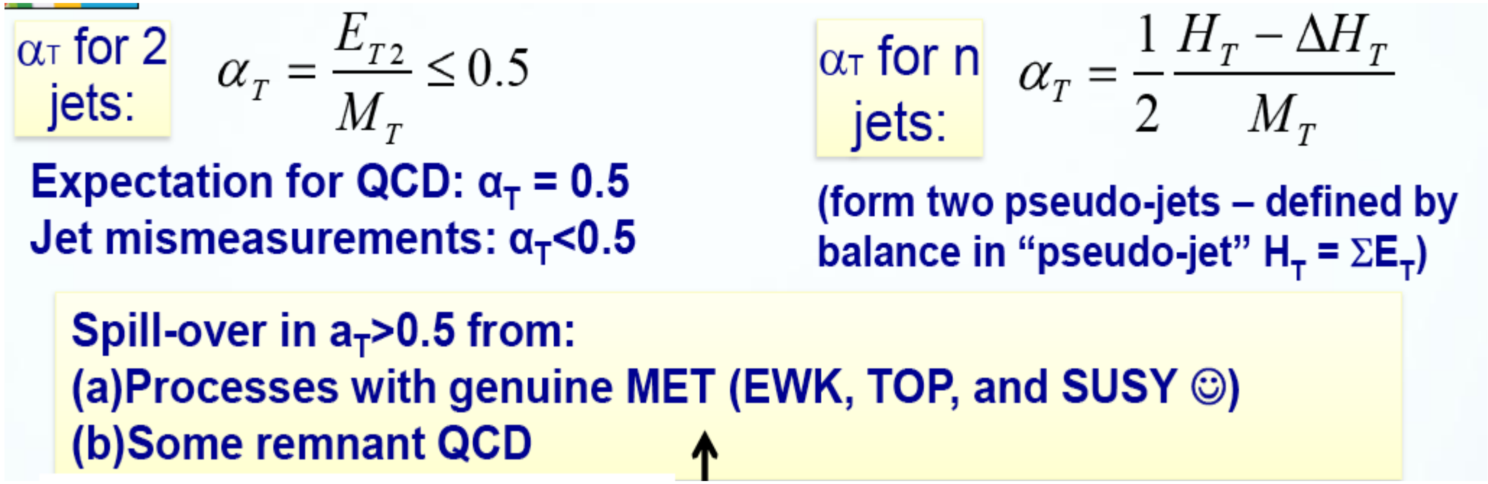
CMS: Early Search for Supersymmetry – an Example

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

- **No direct dependence on calorimetric MET**
- **Originally proposed for di-jets but now generalized for Njets**
- **Perfectly balanced events (QCD) have $\alpha_T = 0.5$ (cut at $\alpha_T > 0.5$)**
- **Due to built-in correlation α_T is very robust against jet mis-measurements**



α_T for 2 jets: $\alpha_T = \dfrac{E_{T2}}{M_T} \leq 0.5$

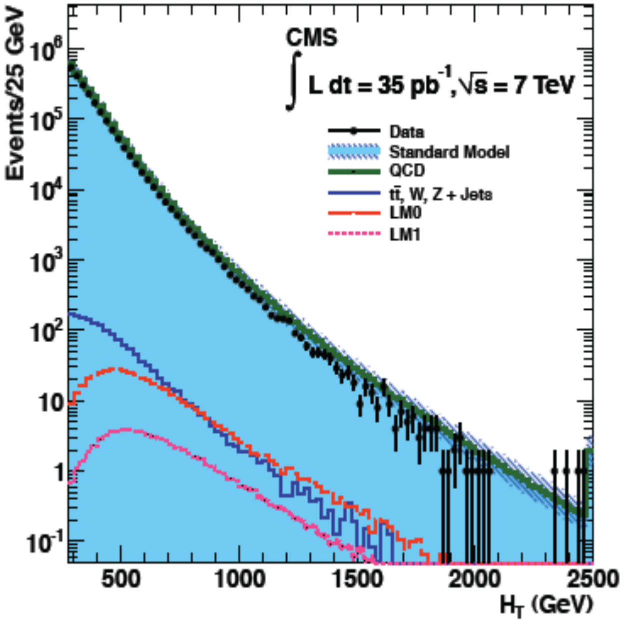
Expectation for QCD: $\alpha_T = 0.5$
Jet mismeasurements: $\alpha_T < 0.5$

α_T for n jets: $\alpha_T = \dfrac{1}{2}\dfrac{H_T - \Delta H_T}{M_T}$

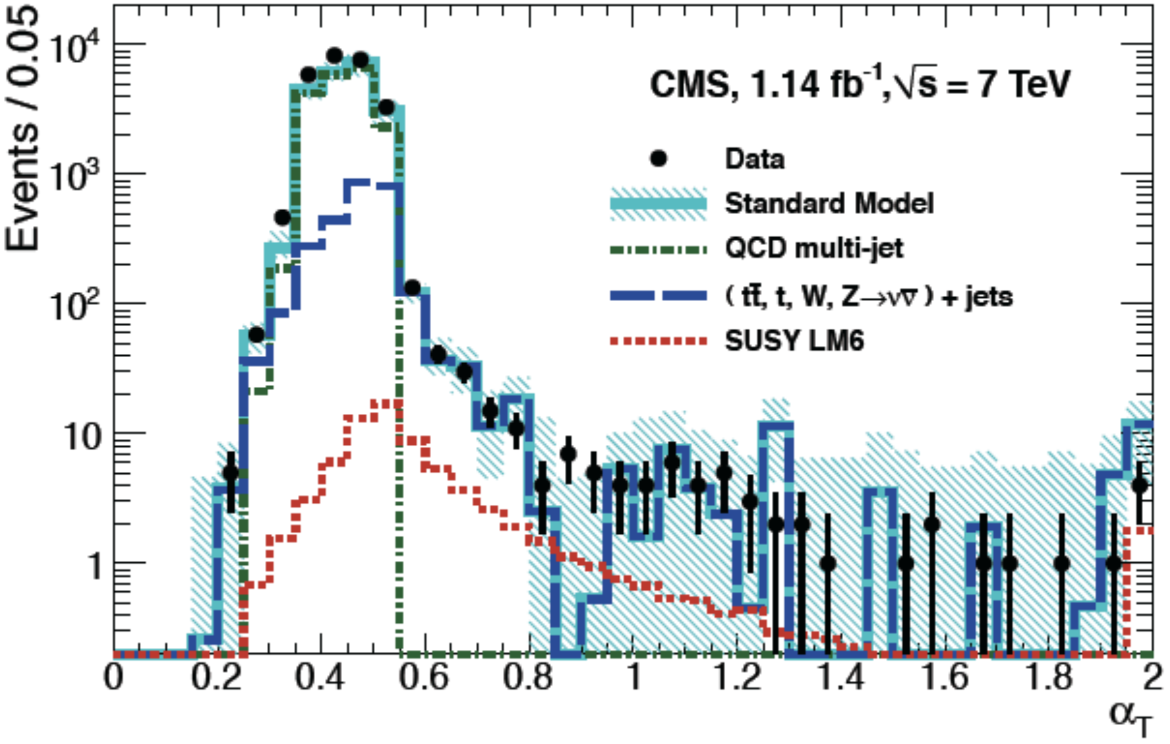
(form two pseudo-jets – defined by balance in "pseudo-jet" $H_T = \Sigma E_T$)

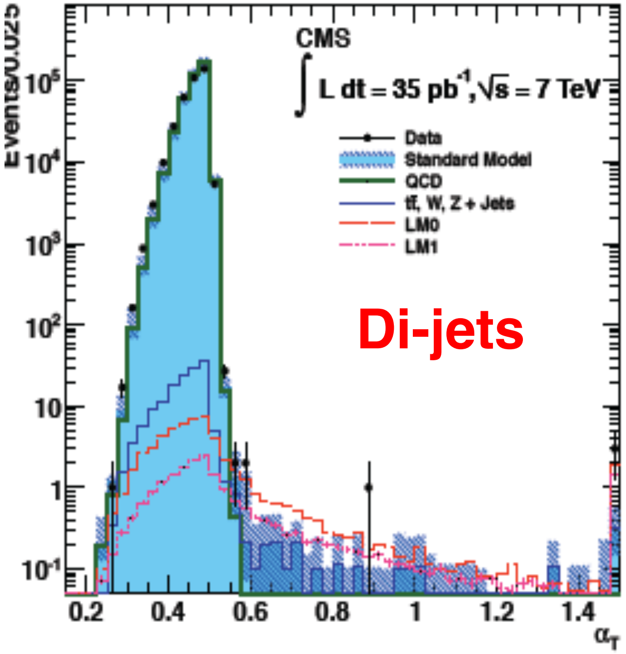
Spill-over in $a_T > 0.5$ from:
(a)Processes with genuine MET (EWK, TOP, and SUSY ☺)
(b)Some remnant QCD

CMS:Search for Supersymmetry - Update

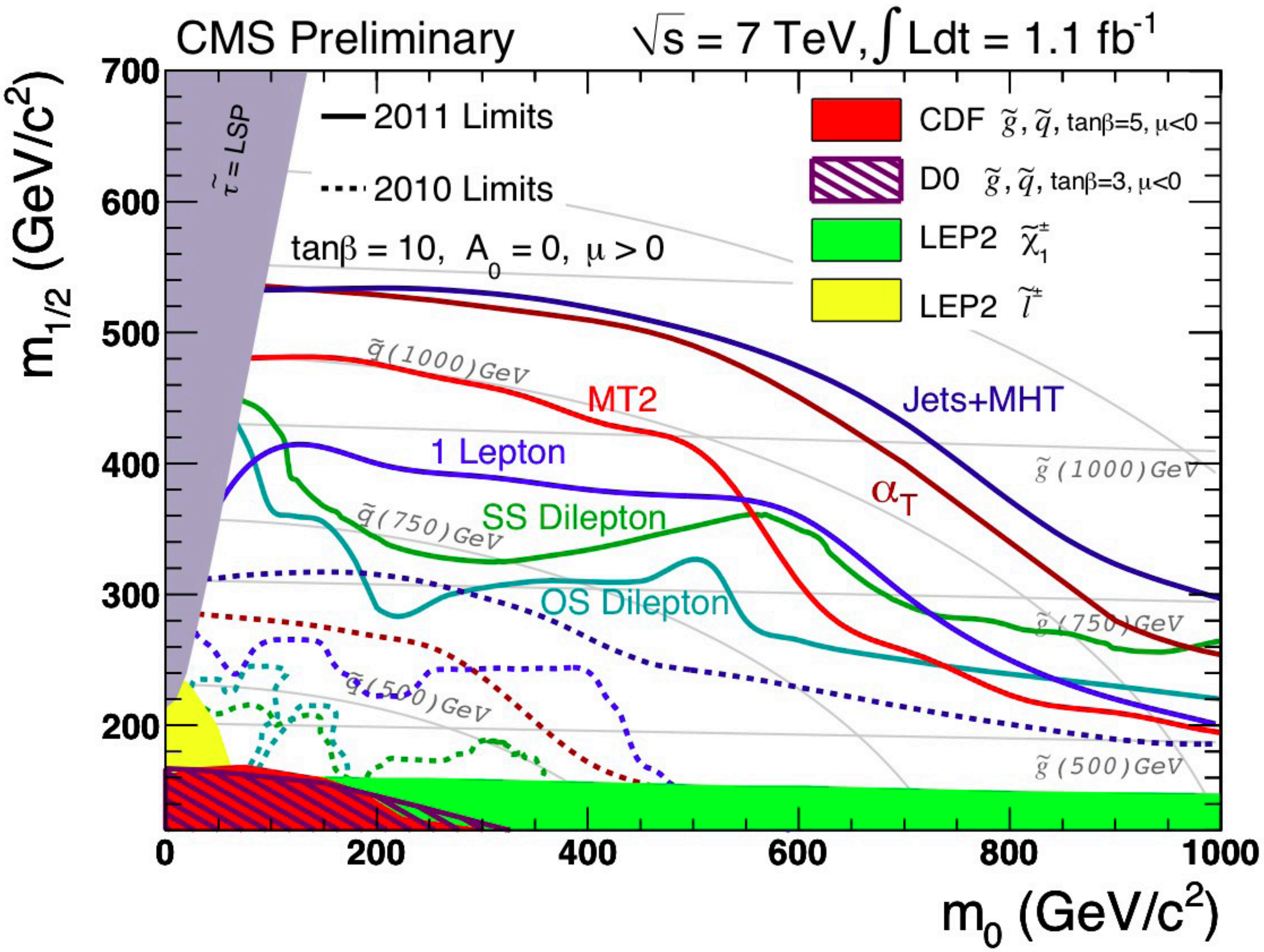


H_T>350 GeV, 2 Leading jets E_T>100GeV (|η|<2.5)
Other jets E_T>50 GeV (|η|<3

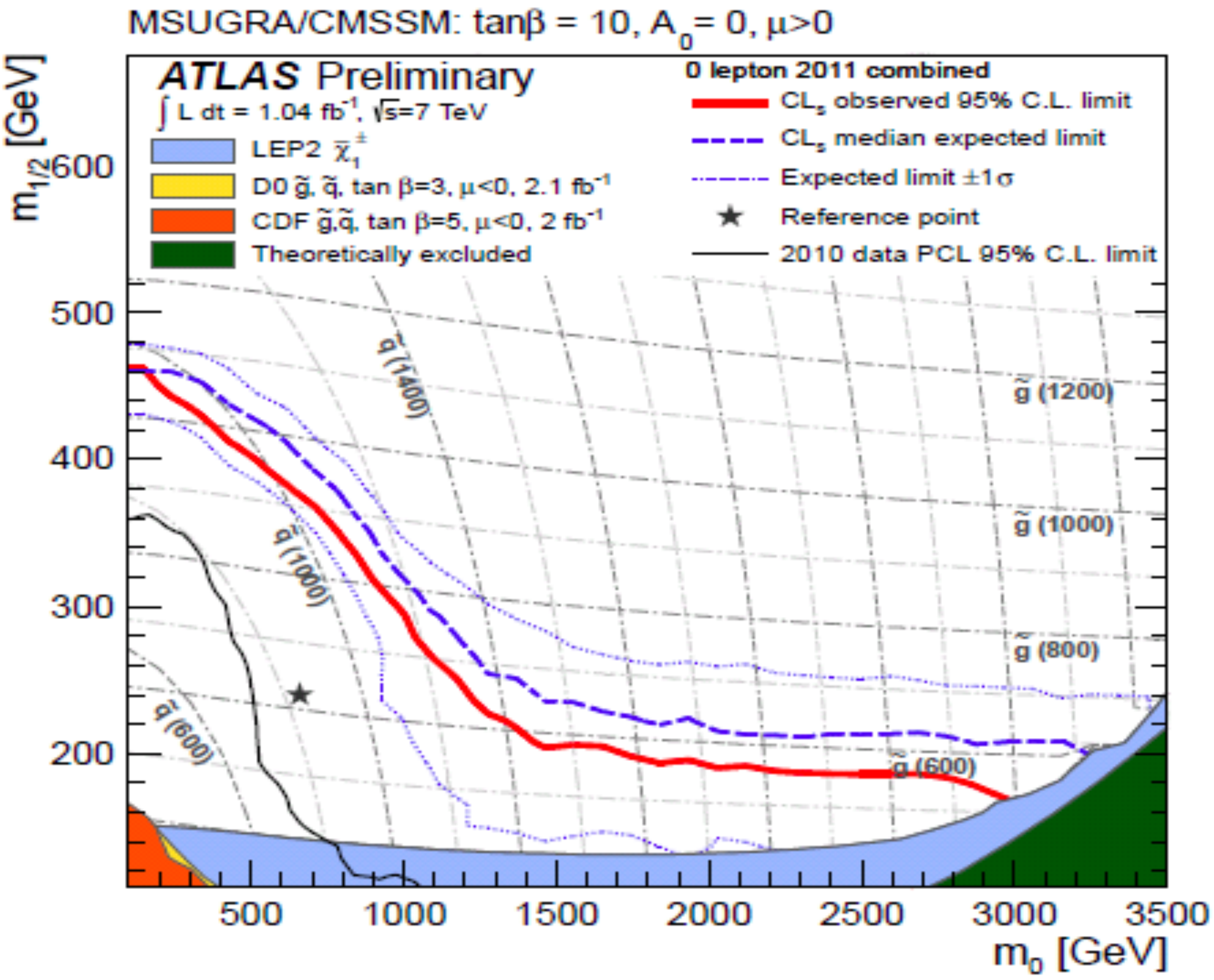




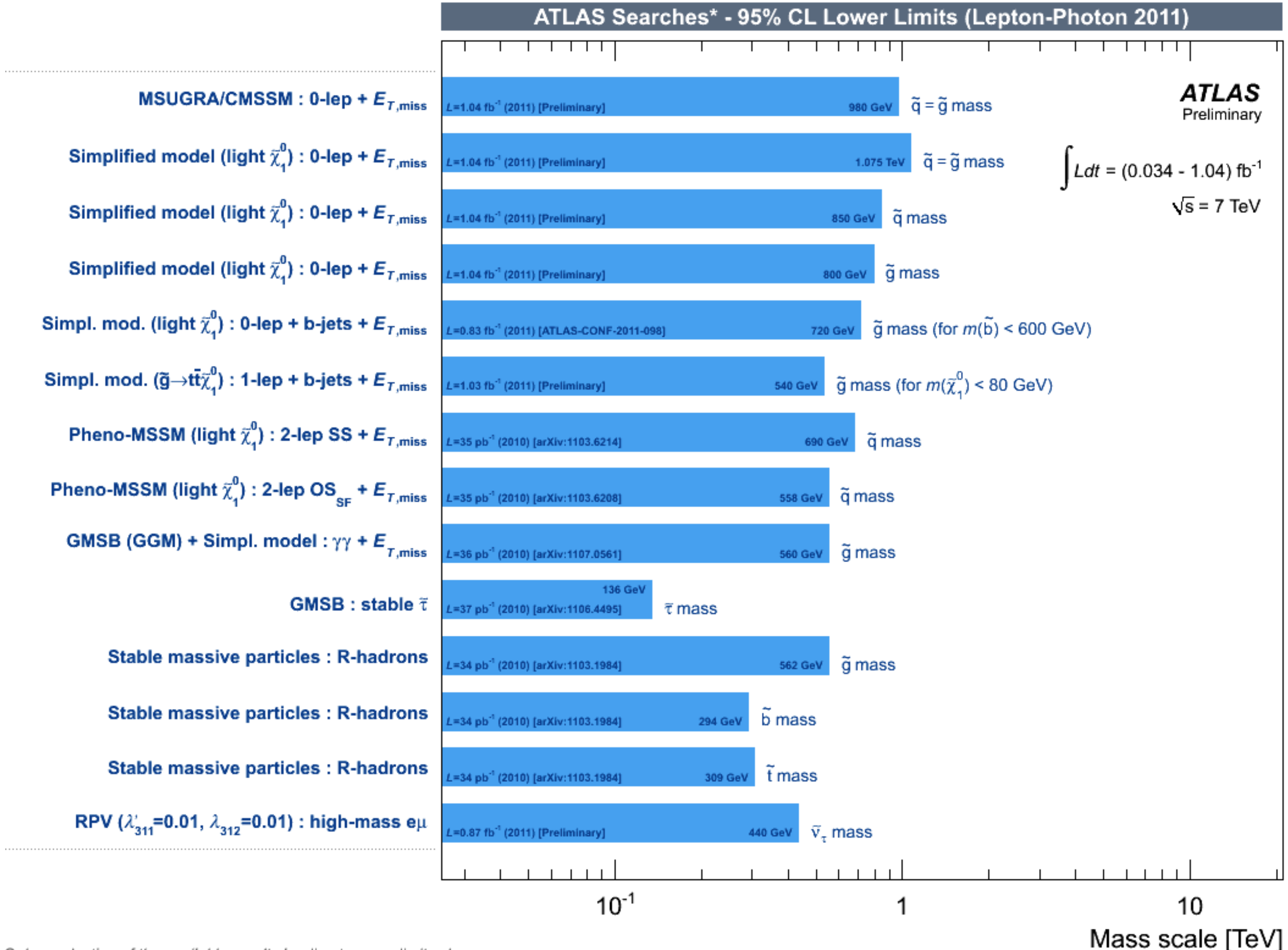
Summary of CMS Results on SUSY



Summary of ATLAS Results on SUSY

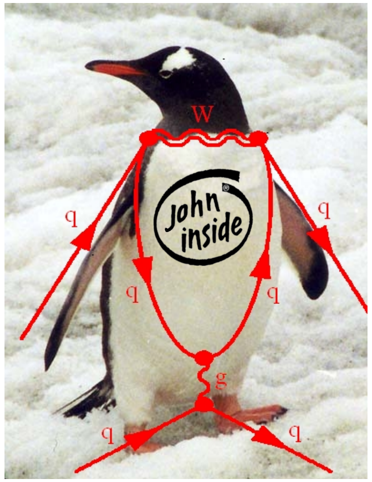


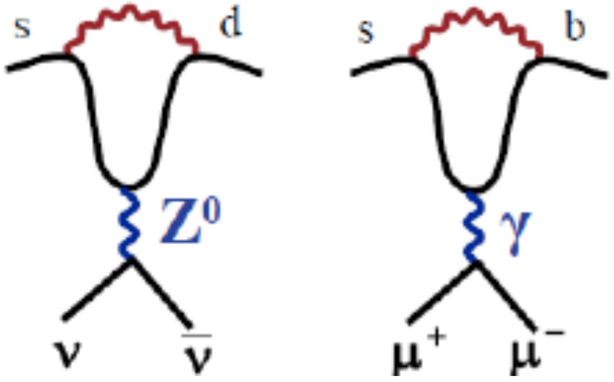
Another View of ATLAS Results on SUSY



Only a selection of the available results leading to mass limits shown

Labeling Penguins: B → μμ



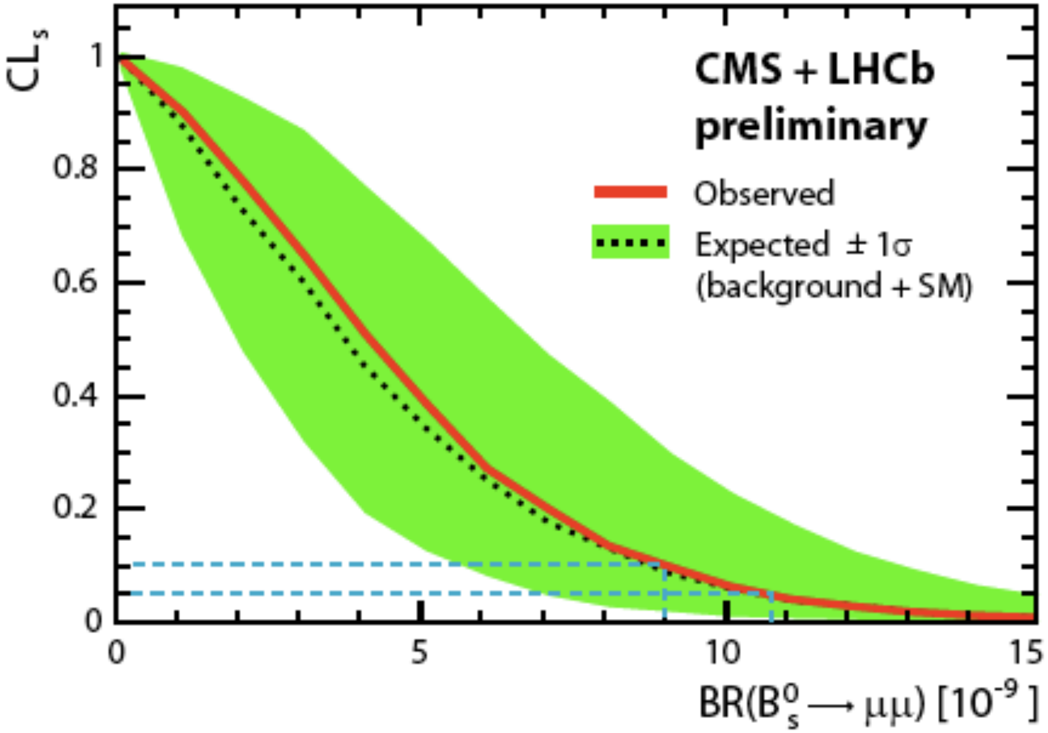


+ other diagrams

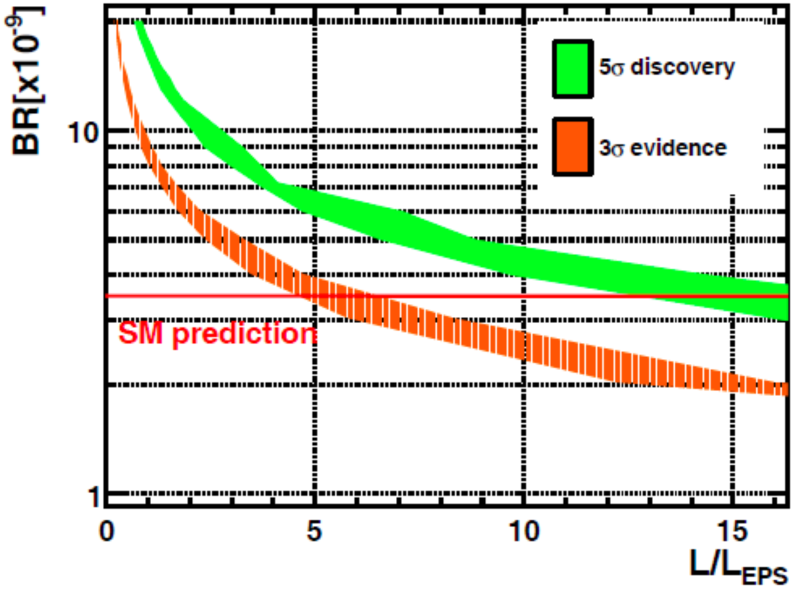
$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

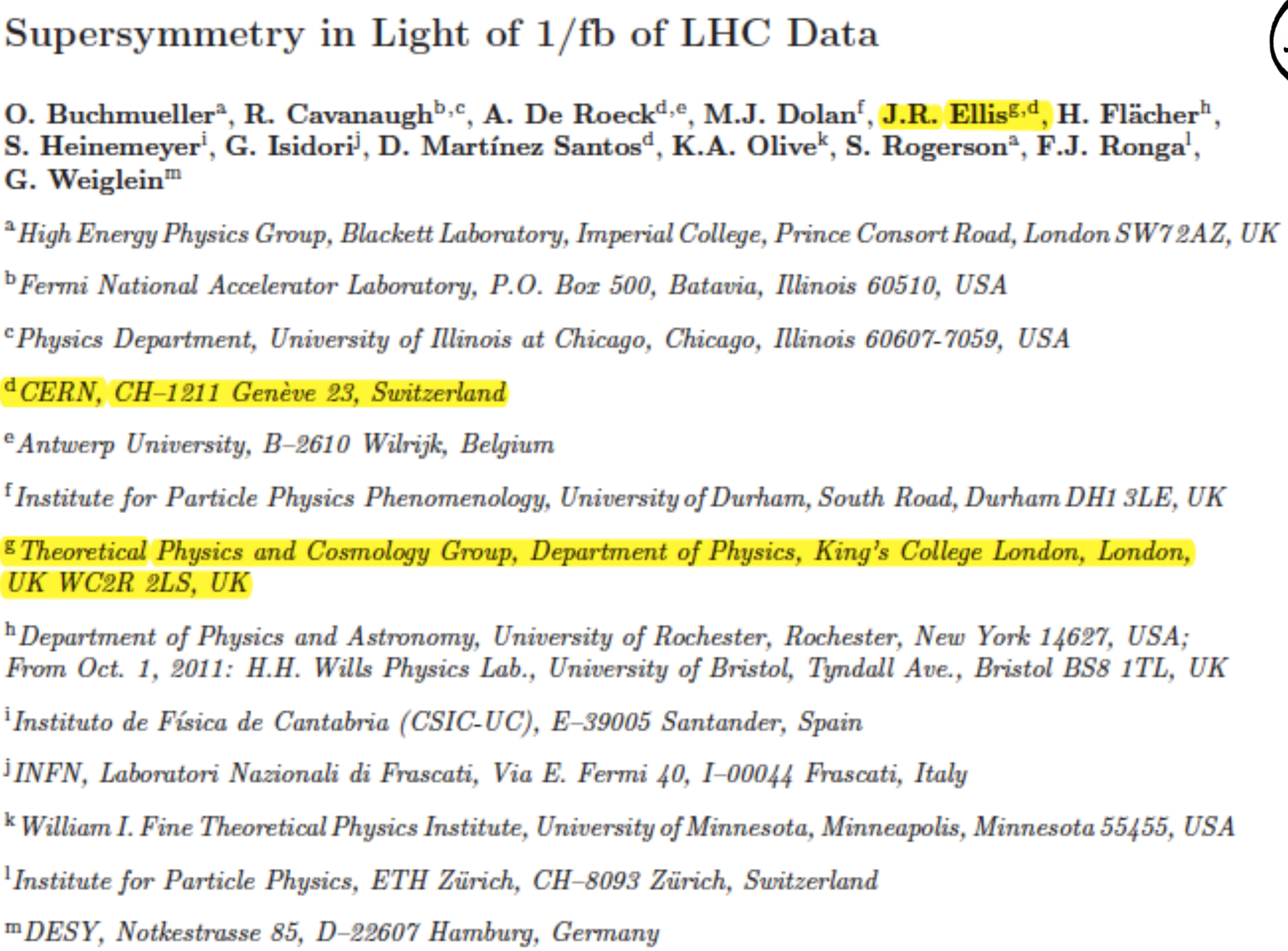
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \; < \; 1.08 \times 10^{-8}$ at 95 % CL,

$(B_s^0 \to \mu^+\mu^-) \; < \; 0.90 \times 10^{-8}$ at 90 % CL,



tsv





Supersymmetry in Light of 1/fb of LHC Data

O. Buchmueller[a], R. Cavanaugh[b,c], A. De Roeck[d,e], M.J. Dolan[f], J.R. Ellis[g,d], H. Flächer[h], S. Heinemeyer[i], G. Isidori[j], D. Martínez Santos[d], K.A. Olive[k], S. Rogerson[a], F.J. Ronga[l], G. Weiglein[m]

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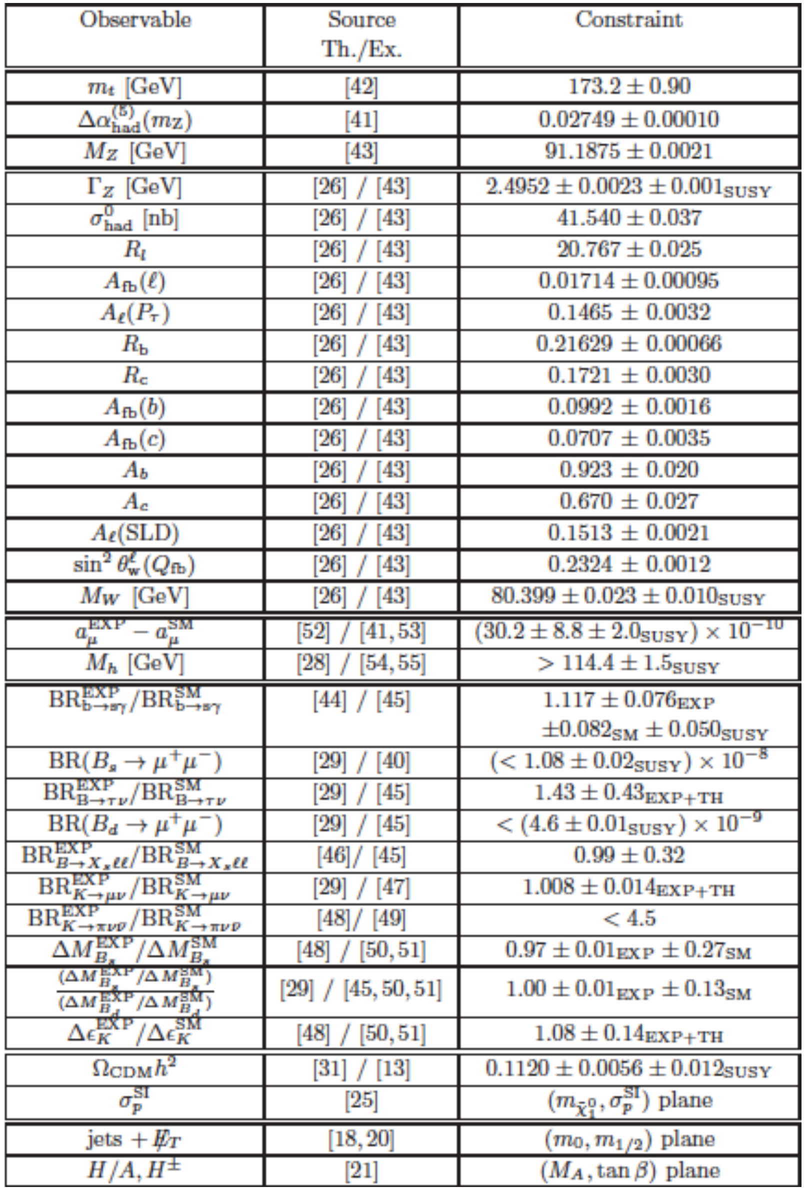
[m] *DESY, Notkestrasse 85, D–22607 Hamburg, Germany*

Global Fits: Putting it all together



Observable	Source Th./Ex.	Constraint
m_t [GeV]	[42]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[41]	0.02749 ± 0.00010
M_Z [GeV]	[43]	91.1875 ± 0.0021
Γ_Z [GeV]	[26] / [43]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[26] / [43]	41.540 ± 0.037
R_l	[26] / [43]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[26] / [43]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[26] / [43]	0.1465 ± 0.0032
$R_{\rm b}$	[26] / [43]	0.21629 ± 0.00066
$R_{\rm c}$	[26] / [43]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[26] / [43]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[26] / [43]	0.0707 ± 0.0035
A_b	[26] / [43]	0.923 ± 0.020
A_c	[26] / [43]	0.670 ± 0.027
A_ℓ(SLD)	[26] / [43]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[26] / [43]	0.2324 ± 0.0012
M_W [GeV]	[26] / [43]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[52] / [41,53]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M_h [GeV]	[28] / [54,55]	$> 114.4 \pm 1.5_{\rm SUSY}$
${\rm BR}^{\rm EXP}_{b\to s\gamma}/{\rm BR}^{\rm SM}_{b\to s\gamma}$	[44] / [45]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
${\rm BR}(B_s \to \mu^+\mu^-)$	[29] / [40]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
${\rm BR}^{\rm EXP}_{B\to\tau\nu}/{\rm BR}^{\rm SM}_{B\to\tau\nu}$	[29] / [45]	$1.43 \pm 0.43_{\rm EXP+TH}$
${\rm BR}(B_d \to \mu^+\mu^-)$	[29] / [45]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
${\rm BR}^{\rm EXP}_{B\to X_s\ell\ell}/{\rm BR}^{\rm SM}_{B\to X_s\ell\ell}$	[46]/ [45]	0.99 ± 0.32
${\rm BR}^{\rm EXP}_{K\to\mu\nu}/{\rm BR}^{\rm SM}_{K\to\mu\nu}$	[29] / [47]	$1.008 \pm 0.014_{\rm EXP+TH}$
${\rm BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/{\rm BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$	[48]/ [49]	< 4.5
$\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s}$	[48] / [50,51]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$	[29] / [45,50,51]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$	[48] / [50,51]	$1.08 \pm 0.14_{\rm EXP+TH}$
$\Omega_{\rm CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{\rm SUSY}$
$\sigma_p^{\rm SI}$	[25]	$(m_{\tilde\chi^0_1}, \sigma_p^{\rm SI})$ plane
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane

Impressive list of considered observables are combined in a χ^2 analysis:

$$
\begin{aligned}
\chi^2 = & \quad \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} & (1)\\
+ & \quad \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu)) & (2)\\
+ & \quad \chi^2(\text{SUSY search limits}) & (3)\\
+ & \quad \sum_i^M \frac{\left(f^{\rm obs}_{SM_i} - f^{\rm fit}_{SM_i}\right)^2}{\sigma\left(f_{SM_i}\right)^2} & (4)\\
+ & \quad \chi^2(\text{LHC} + \text{Xenon}) & (5)
\end{aligned}
$$

(1) – χ^2 term - measurements
(2) - limits (e.g. $M_{\rm higgs}$)
(3) - SUSY limits (LEP and Tevatron)
(4) - nuisances parameters like $M_{\rm top}$
(5) - recent limits from LHC and Xenon

The European Physical Journal
volume 71 number 8 august 2011
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Particles and Fields

John inside

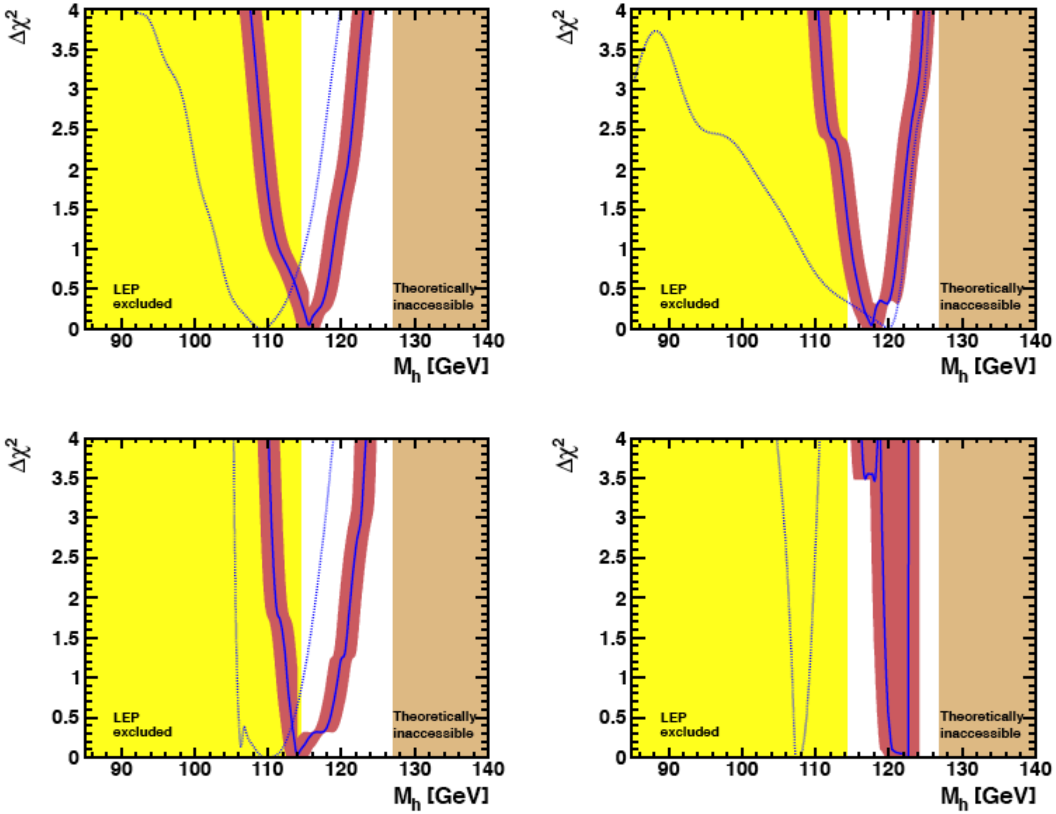
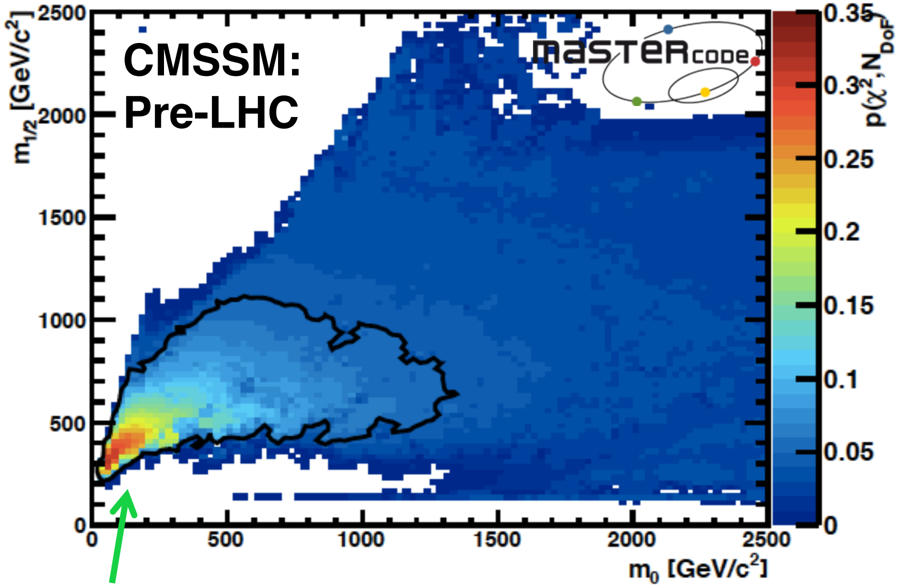


Figure 9. *The one-parameter* χ^2 *likelihood functions for the lightest MSSM Higgs mass* M_h *in the CMSSM (upper left), NUHM1 (top right), VCMSSM (lower left) and mSUGRA (lower right). In each panel, we show the* χ^2 *functions of the post-2010-LHC/Xenon100 constraints as solid lines, with a red band indicating the estimated theoretical uncertainty in the calculation of* M_h *of* ~ 1.5 GeV, *and the pre-LHC* χ^2 *function is shown as a dashed line.*

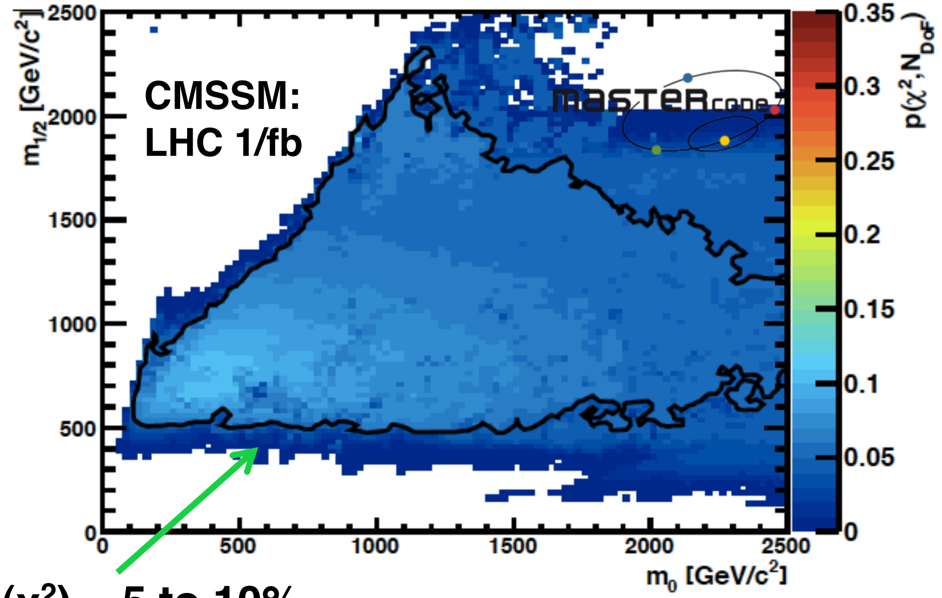
Impact of 1/fb LHC Searches on SUSY



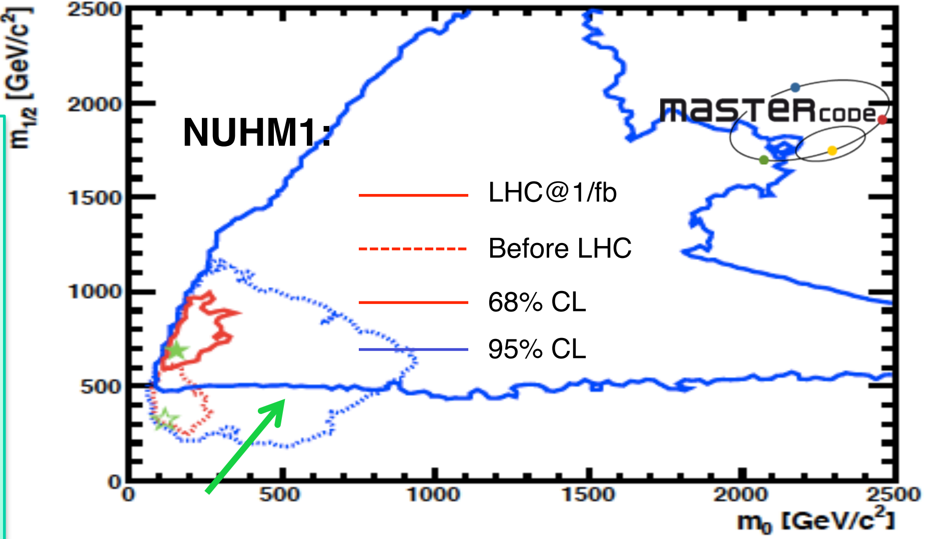
$P(\chi^2)$ ~ 30% hot spot

Goodness of Fit: $P(\chi^2)$

There is some disappointment in the air that the LHC has found no signs of SUSY in the first 1/fb of data.
The room for constrained SUSY models like CMSSM or NUHM is getting smaller but it needs more data to be fully conclusive.
We will know more later this year.

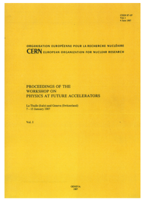


$P(\chi^2)$ ~ 5 to 10%
LHC searches excluded hot spot

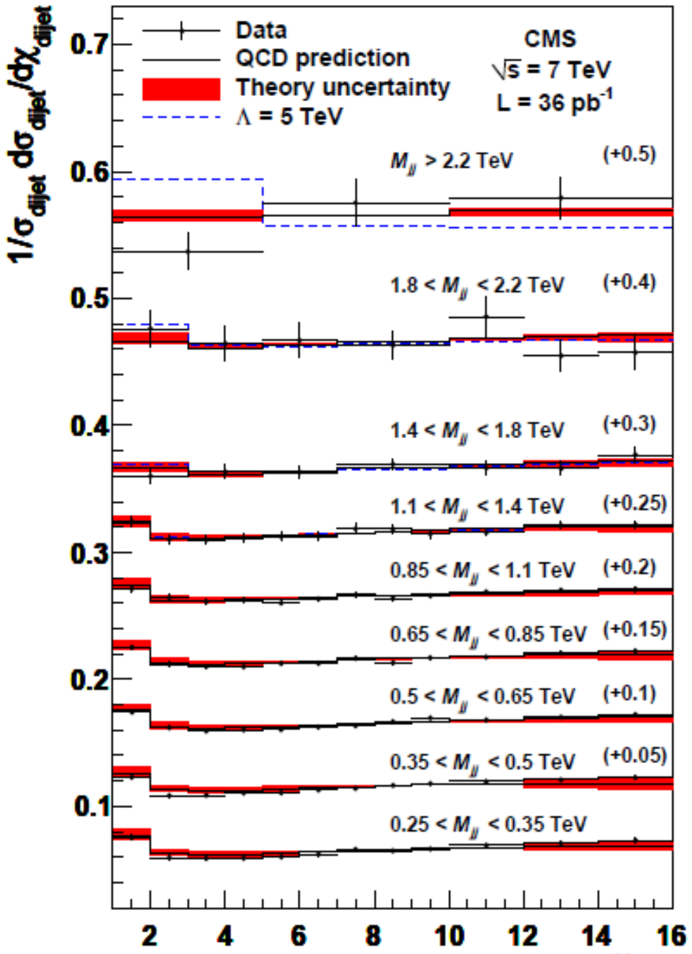


LHC searches: push to higher masses

Deviations from QCD in di-jet angular distributions

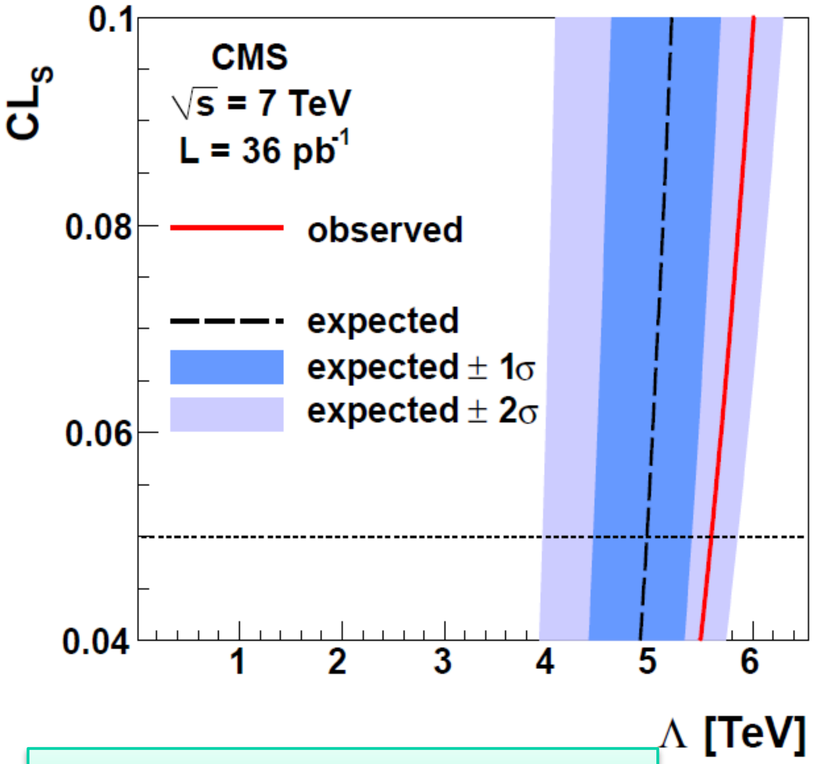


LHC with 10fb^{-1}
95% CL limit L ~ 12 TeV



$$\chi = \exp(|y_1 - y_2|) = \frac{1 + \cos\vartheta^*}{1 - \cos\vartheta^*}$$

Deviations from the QCD expectation could reveal a substructure of the quarks (‘compositeness’ at scale Λ) in analogy to the famous Rutherford scattering 100 years ago

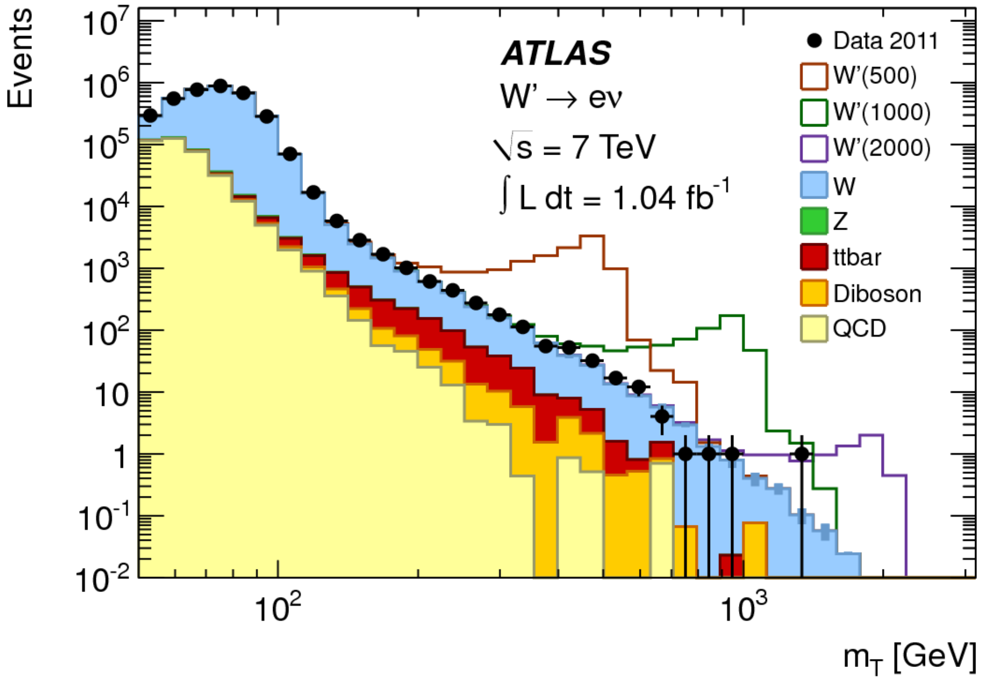


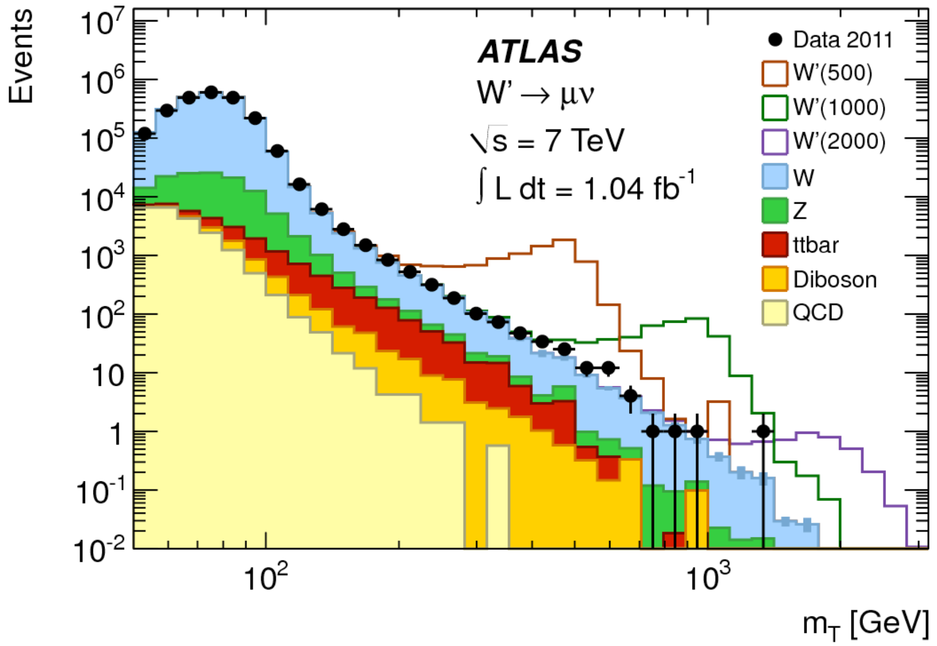
Λ > 6 TeV @ 95% C.L.

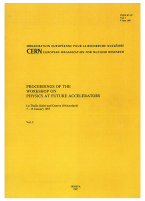
ATLAS: Search for W’ SSM

Electron + missing E_T

Muons + missing E_T







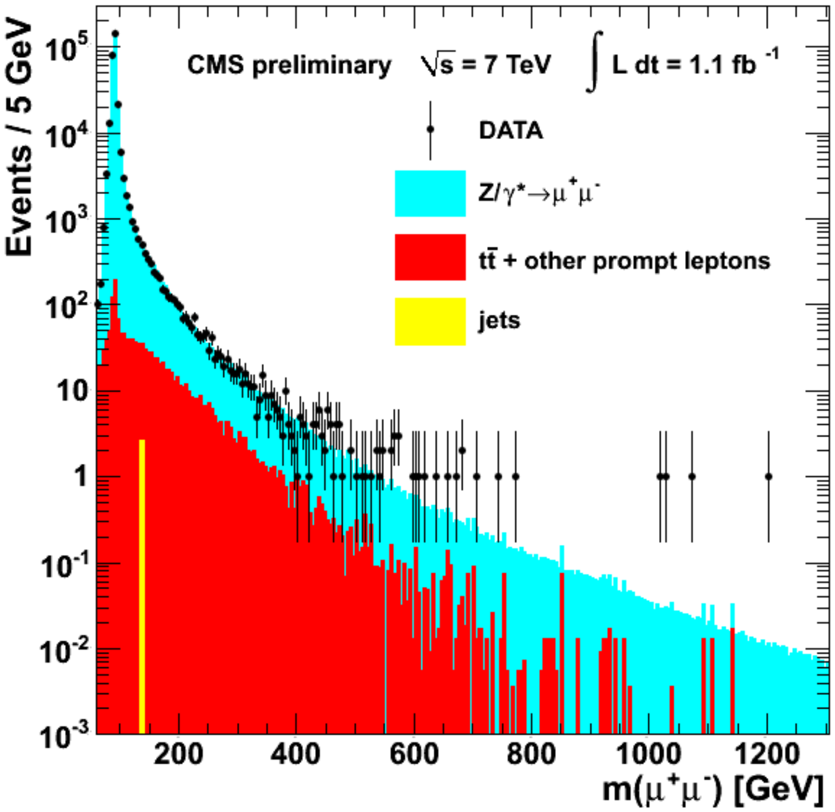
LHC with $10\mathrm{fb}^{-1}$
95% CL limit L ~ 4 - 5 TeV

ATLAS: $W' \to l\,\nu$

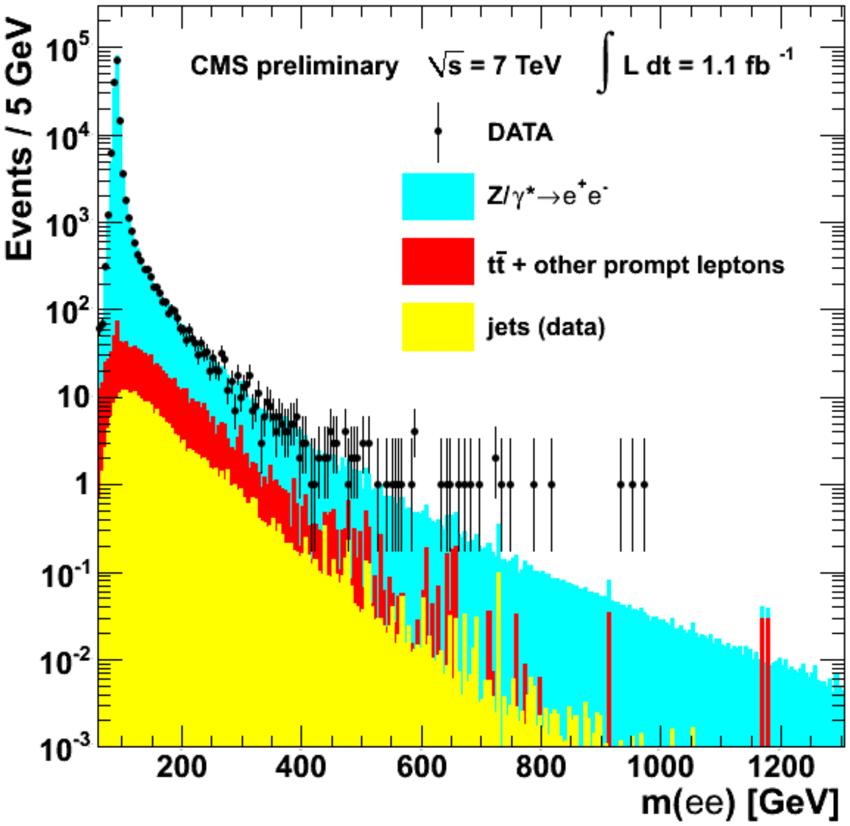
$M_{W'} > 2.15$ TeV 95% CL

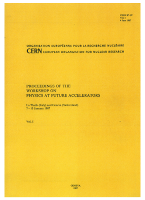
CMS: Search for Z’ (SSM)

Dimuons



Di-electrons





LHC with 10fb^{-1}
95% CL limit L ~ 4 - 5 TeV

CMS: ee and μμ
$M_{Z'}$ > 1.94 TeV 95% CL

Microscopic Evaporating Black Holes

THE signature of low-scale quantum gravity ($M_D << M_{Pl}$)

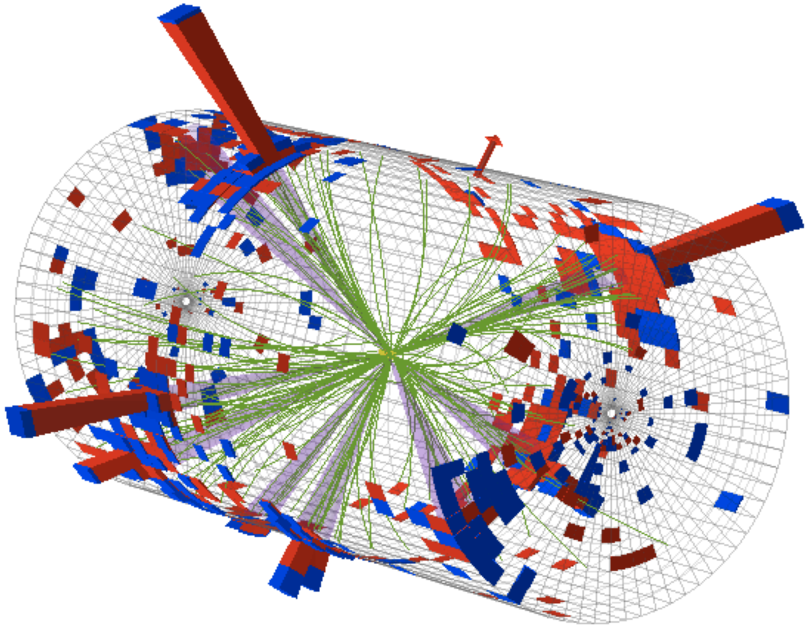
BH formation when the two colliding partons have distance smaller than R_S,, the Schwarzschild radius corresponding to their invariant mass

Cross section from geometry: $\sigma = \pi R_S^2 \sim \text{TeV}^{-2}$ (up to ~100 pb!)

Microscopic BHs decay instantaneously via Hawking evaporation

emitting “democratically” a large number of energetic quarks, gluons, leptons, photons, W/Z, h, etc.

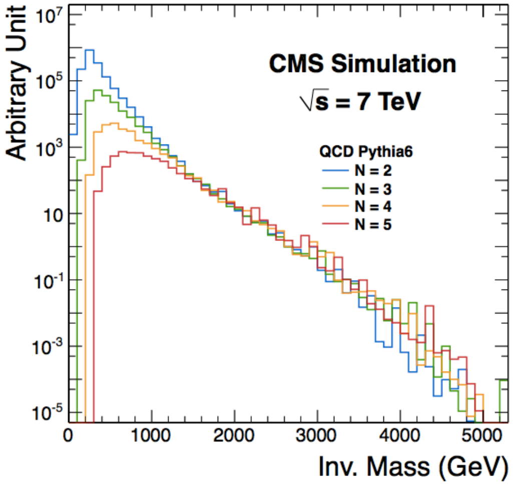
Expect lots of activity in the event, so
Use S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV
(good for avoiding pileup)

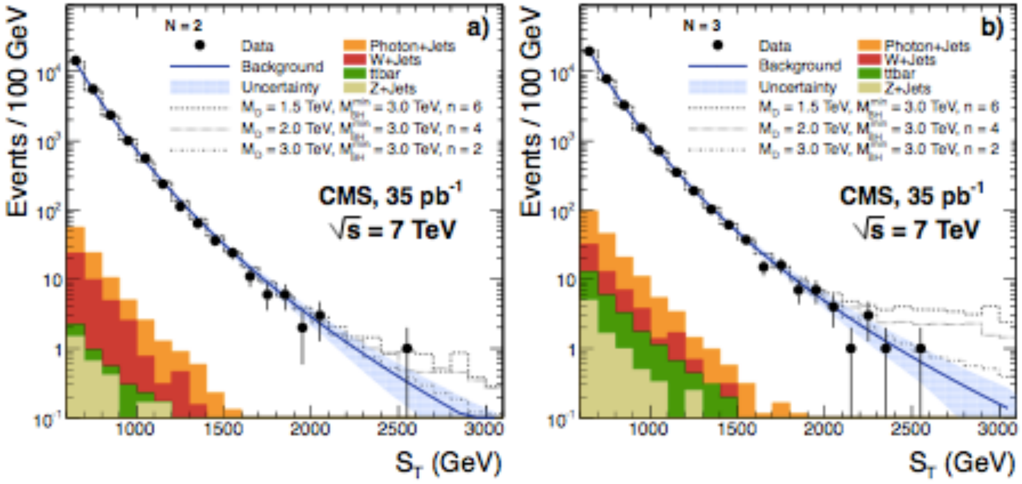


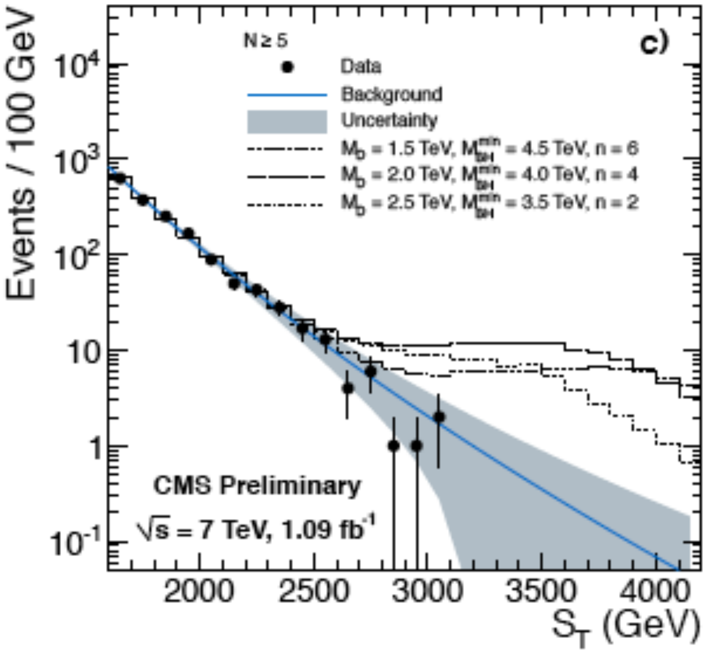
CMS Experiment at LHC, CERN
Data recorded: Mon May 23 21:46:26 2011 EDT
Run/Event: 165567 / 347495624
Lumi section: 280
Orbit/Crossing: 73255853 / 3161

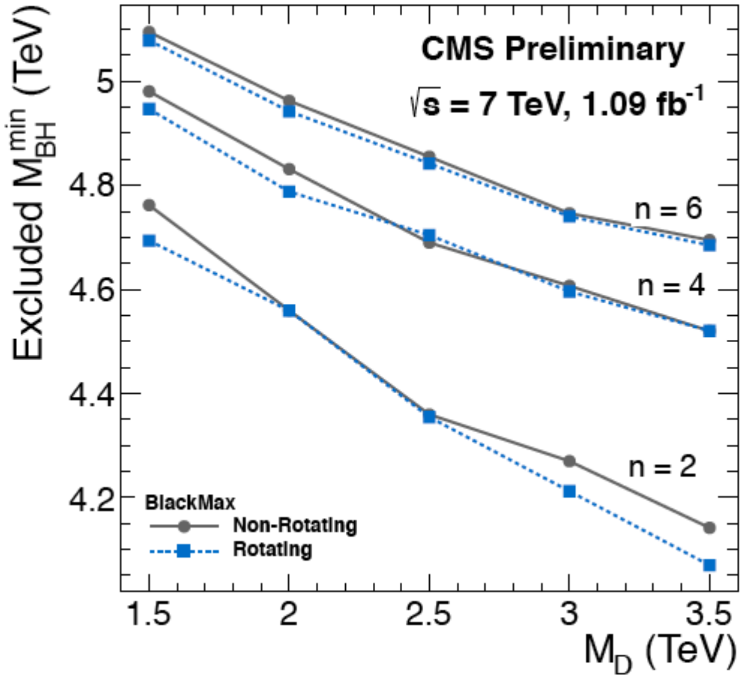
Search for Microscopic Black Holes

The shape of the S_T distribution is expected to be independent of event object multiplicity N



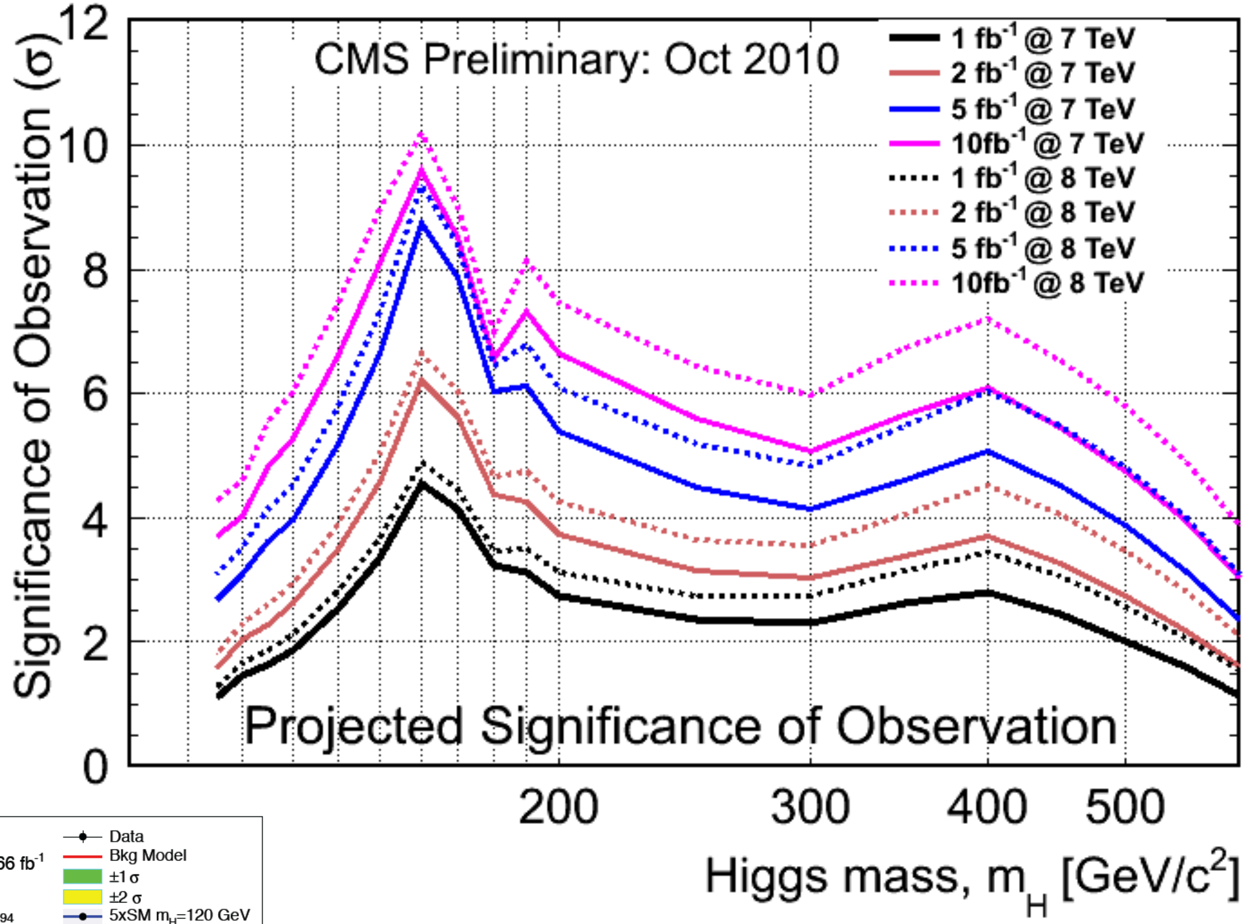


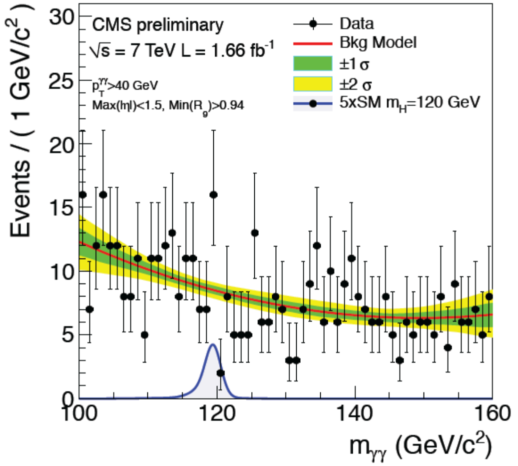


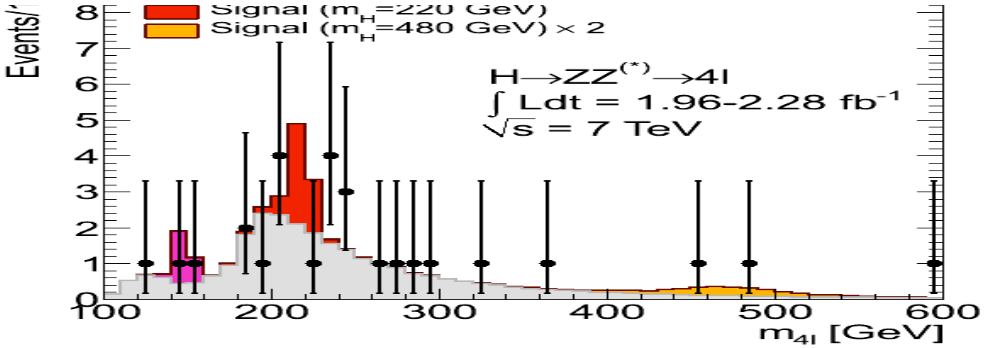


No excess, so set limits $M_{BH} > 4$ TeV

Standard Model (like) Higgs: LHC at 7/8 TeV







Wiki Loves Monuments: Photograph a monument, help Wikipedia and win!

John the Evangelist (20th-21st Century AD) is an itinerant preacher[1] and a major supersymmetric[2] figure who leads a movement of Susyites[3] at the Geneva Lake. Some scholars maintain that he is influenced by the Grand Unifiers[14]. Susyites expect a deluge of particles although there is no direct evidence to substantiate this. John is regarded as a prophet in the Cosmo[5], AstroPi[6] and PiPi[7] faiths.

John the Evangelist

St. John the Baptist Preaching by Anton Raphael Mengs (c. 1775)

Prophet, Preacher, Forerunner, Martyr

Image a la Sergio da Vittorio Veneto

We experimentalists owe you great thanks.

So just continue in the same vein
which you are intending to do