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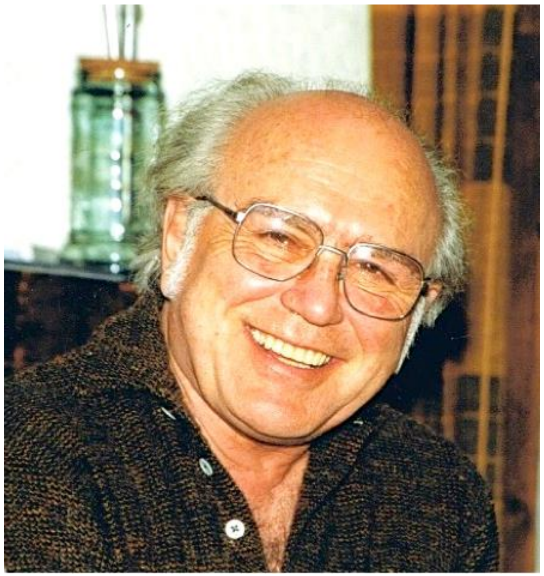
The search for Supersymmetry at the LHC

Zumino Memorial

CERN, 27 April 2015



Tejinder S. Virdee,
Imperial College, London

LHC Vista circa MCMXC's: Sergio da Vittorio Veneto aka Sergio Cittolin

2015 The Year of Light

The United Nations decided to proclaim 2015 the International Year of Light and Light based technologies.

1015: Ibn Al-Haytham - the works on optics,

1815: Fresnel - the notion of light as a wave

1865: Maxwell -the electromagnetic theory of light propagation,

1905: Einstein - theory of the photoelectric effect and of the
1915: Einstein - embedding of light in cosmology through general relativity,

1965: Penzias and Wilson - the discovery of the cosmic microwave background

1965: Kao - transmission of light in fibres for optical communication.

INTERNATIONAL YEAR OF LIGHT 2015

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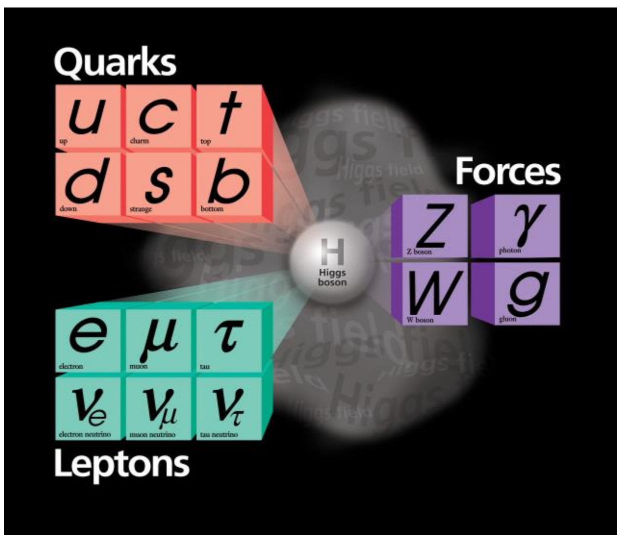
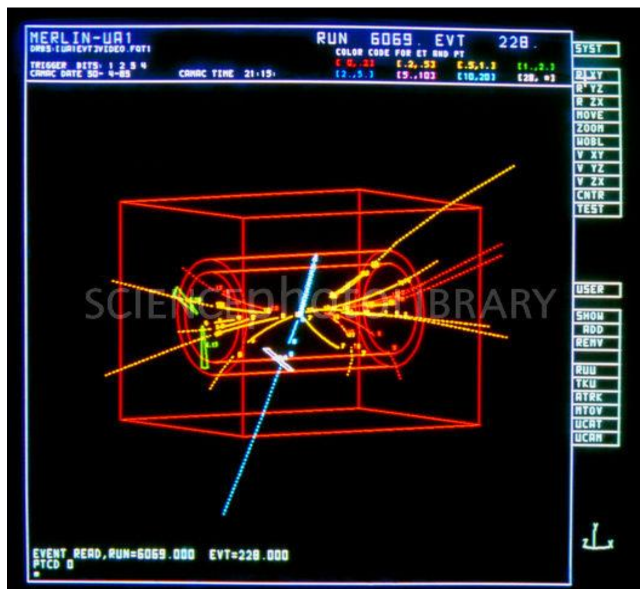
Electroweak Unification

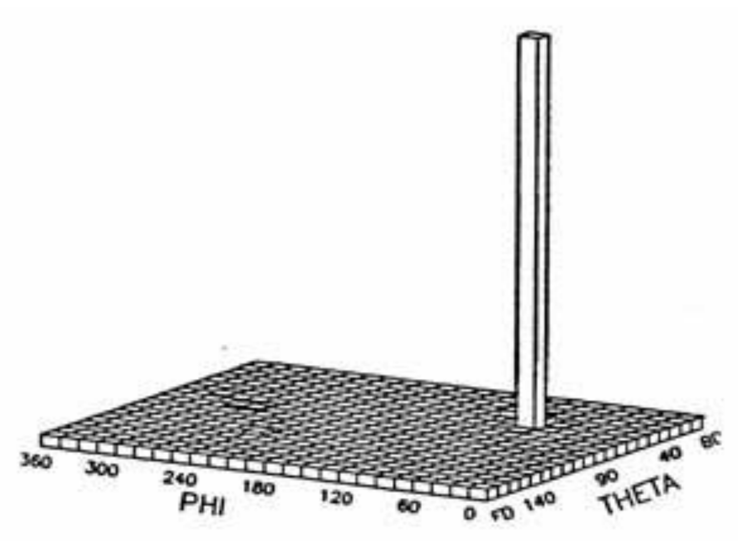
A key feature in the theory of electroweak unification of Salam and Weinberg (1967) (and earlier work of S. Glashow) was the prediction of the Z boson and the existence of neutral current interactions.

In 1973, the existence of neutral current interaction was confirmed at CERN.
(In 1974, the Wess-Zumino paper "Supergauge transformations in 4D") appeared

In 1983, the *W* and *Z* particles were discovered at CERN (UA1 and UA2)
***then* the Higgs boson became the last important missing piece of SM!**
Setting the scene for the LHC.







Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found 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)**

5. 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 ?

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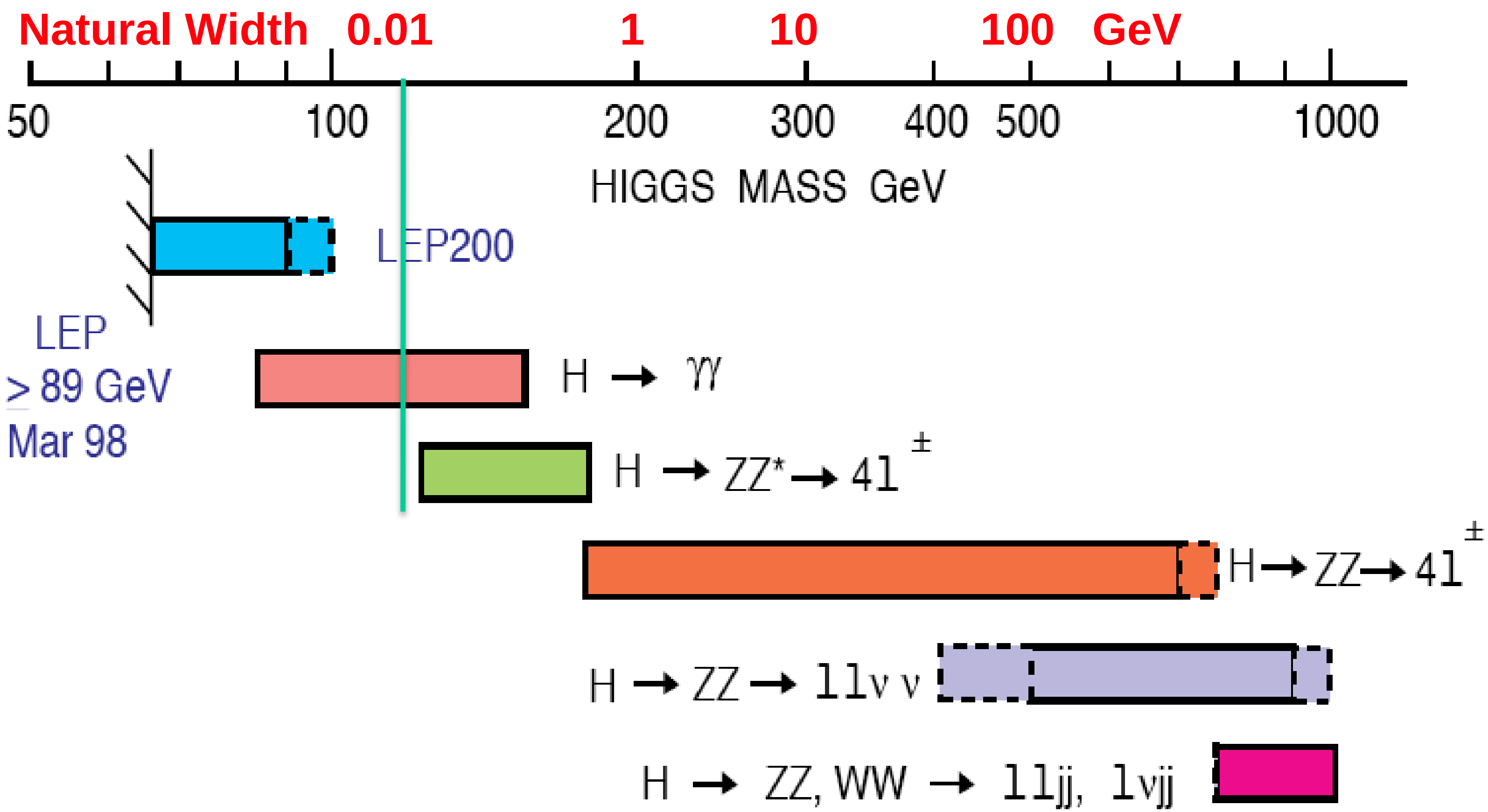
SM Higgs Boson as a Physics Benchmark For Detector Design



Theory does not predict m_H
The favourable decay modes change with mass

Transparency from the 90's

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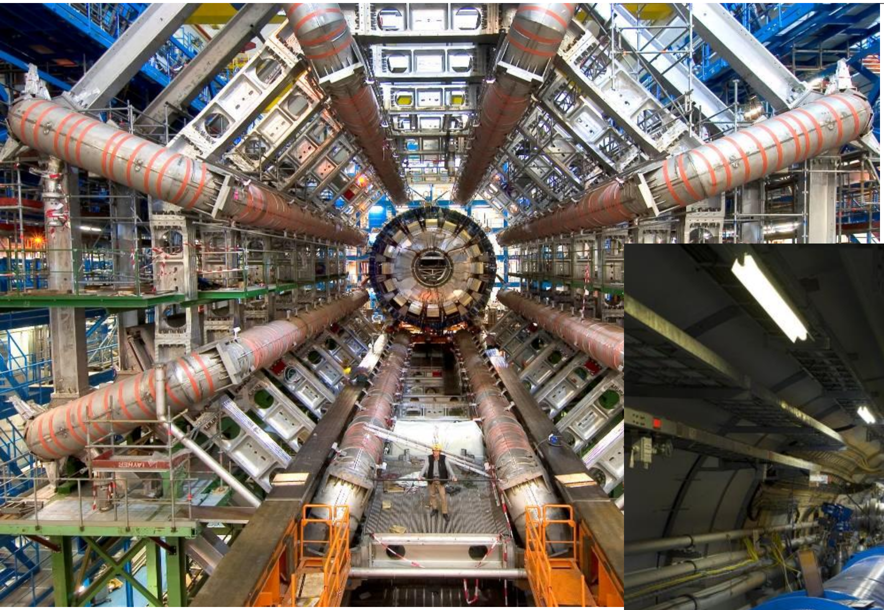
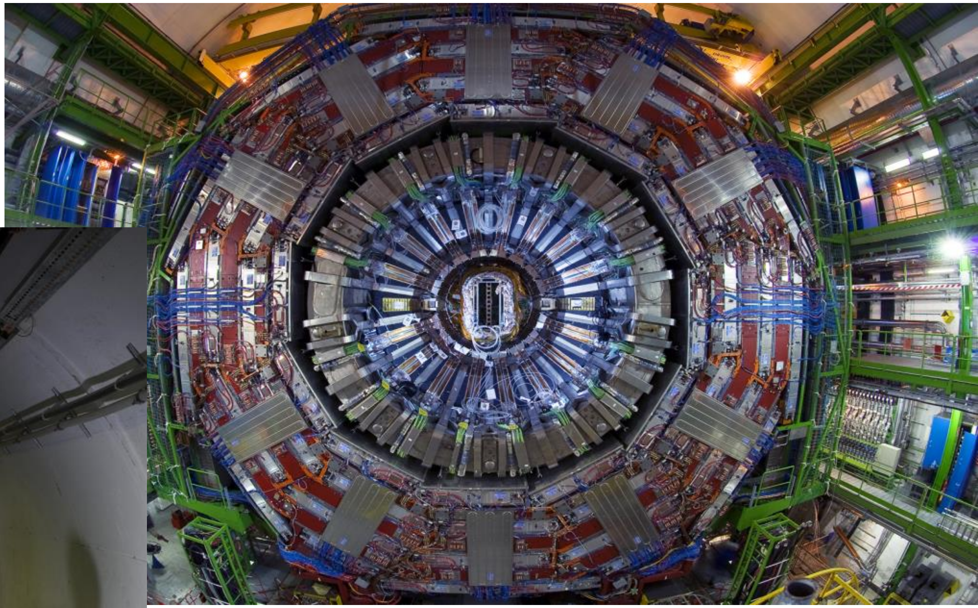
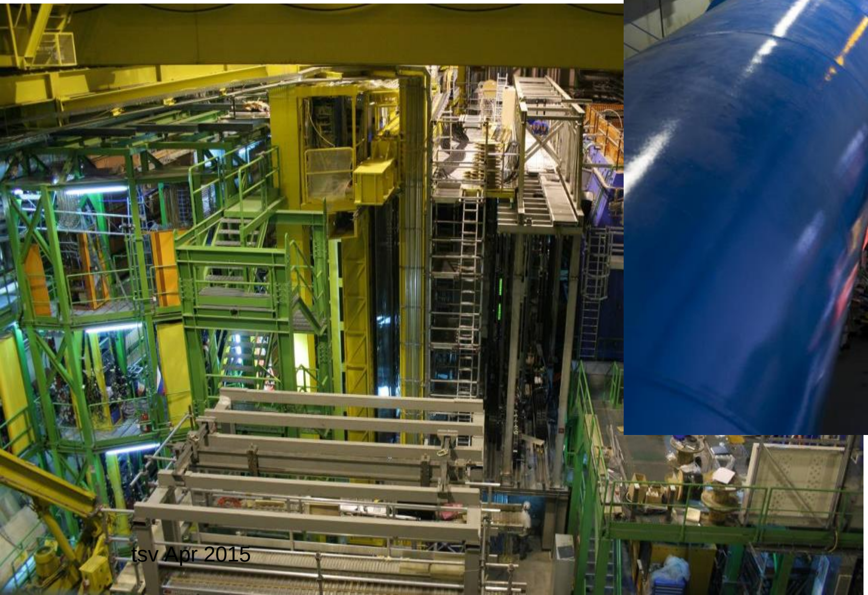
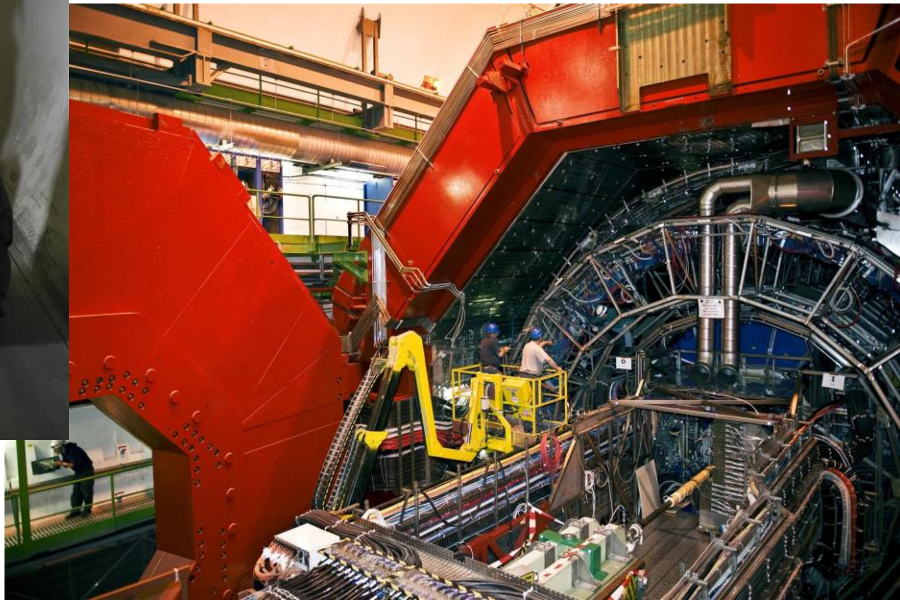
The LHC Accelerator and Experiments Have Performed Exceedingly Well



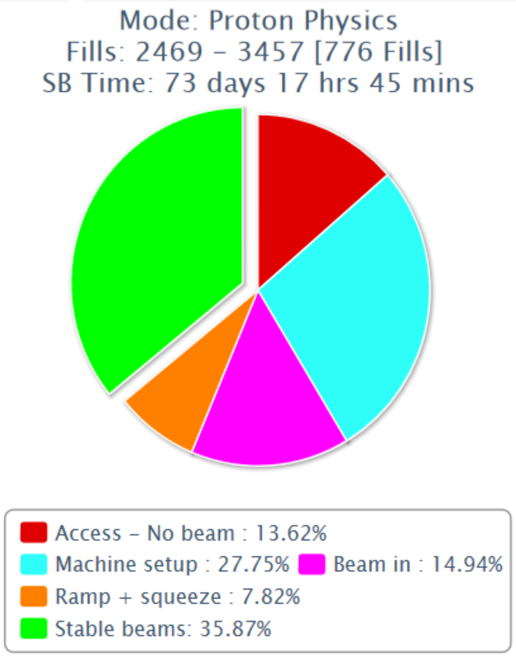


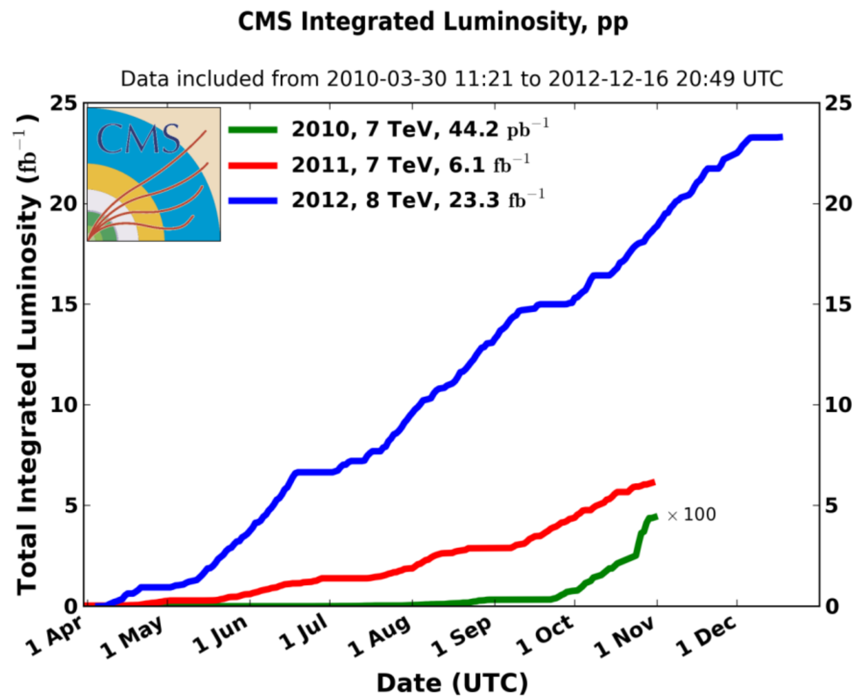




The LHC Accelerator and Experiments Have Performed Exceedingly Well

2012 **Stable beams 36%**





ATLAS

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

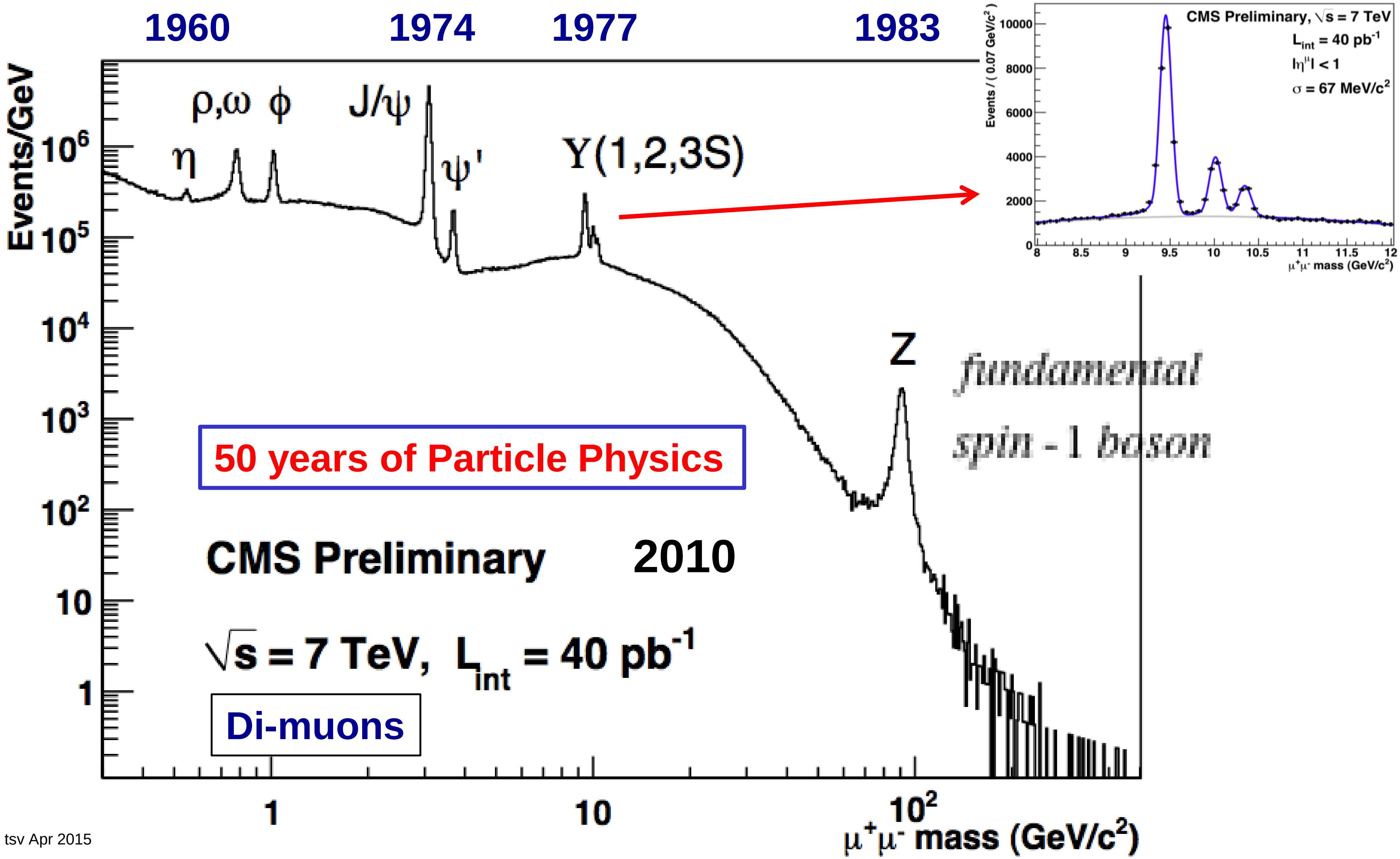
Luminosity weighted relative detector uptime. **Used for Physics > 90% of recorded data.**

1. Do the experiments perform as designed?
2. Is known physics correctly observed?
3. Then look for new physics

We can only claim signals of new physics after having made measurements of already known physics that are consistent with the precise predictions of the Standard Model.

1. Performance of the Experiments

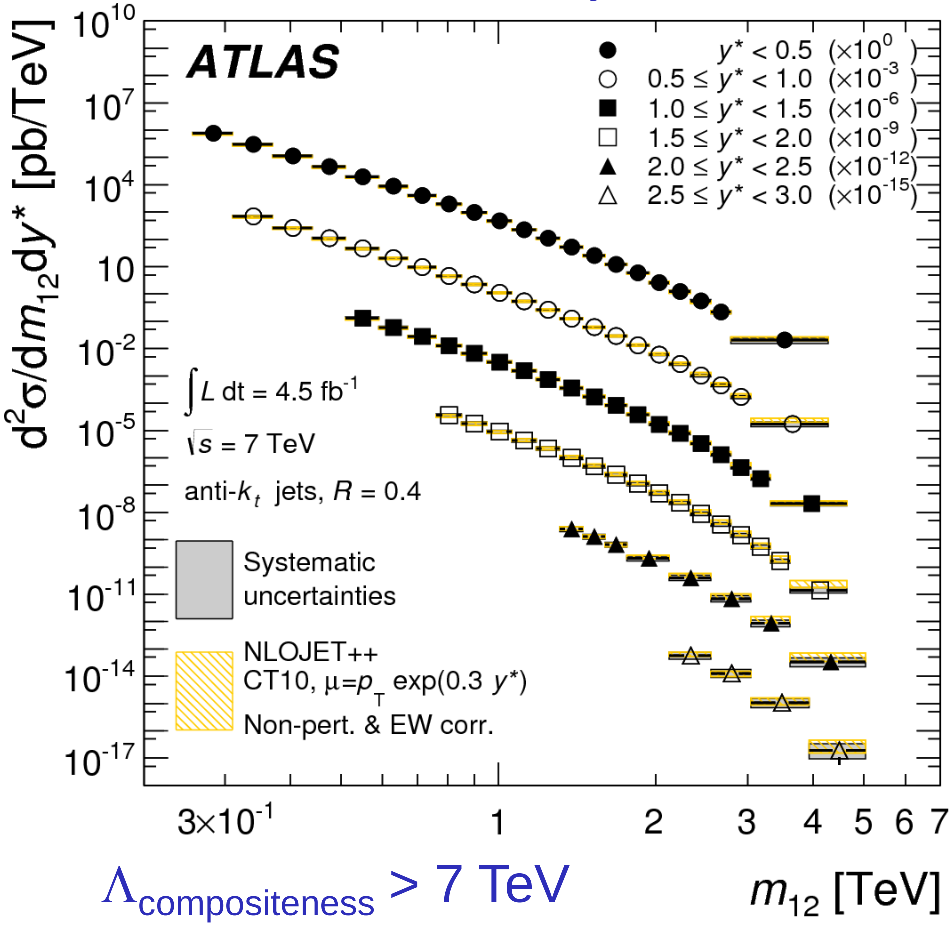
50 years of Particle Physics: The First Month at LHC Run I



2. LHC and Testing QCD

Routinely and successfully analyse physics at the high energy frontier in terms of quarks and gluons!

Double Differential Di-jet cross section

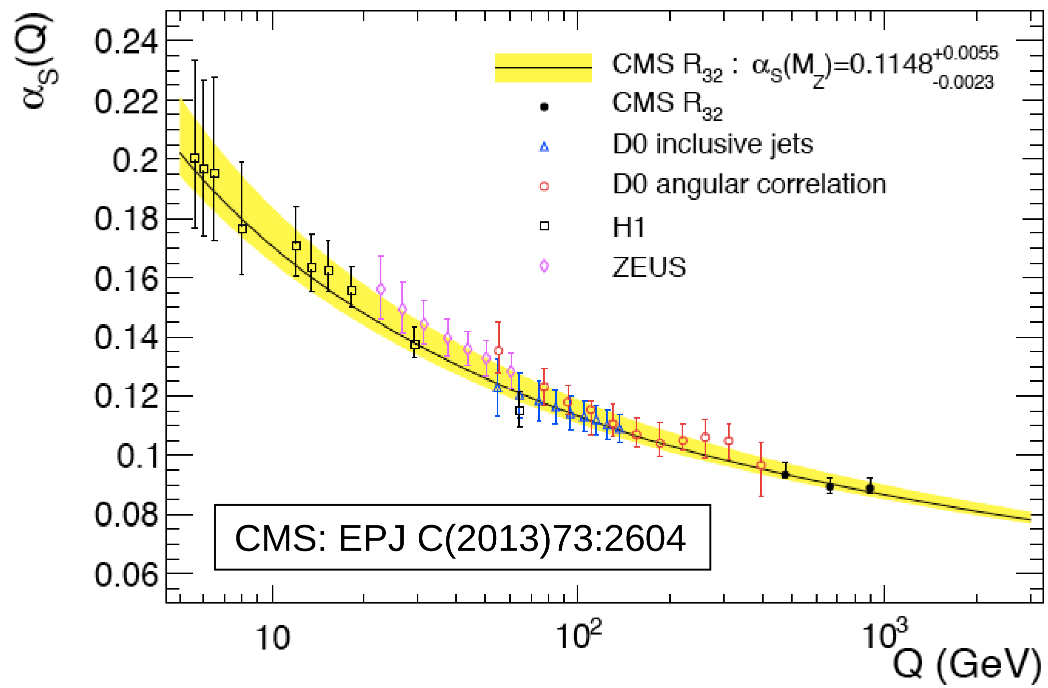


$\Lambda_{compositeness} > 7$ TeV

JHEP05(2014)059

Asymptotic freedom

Coupling "constants" run



$\alpha_S(M_Z)=0.1148\pm0.0014(\mathrm{exp})\pm0.0018(\mathrm{PDF})$
$^{+0.0050}_{-0.0000}(\mathrm{scale})$

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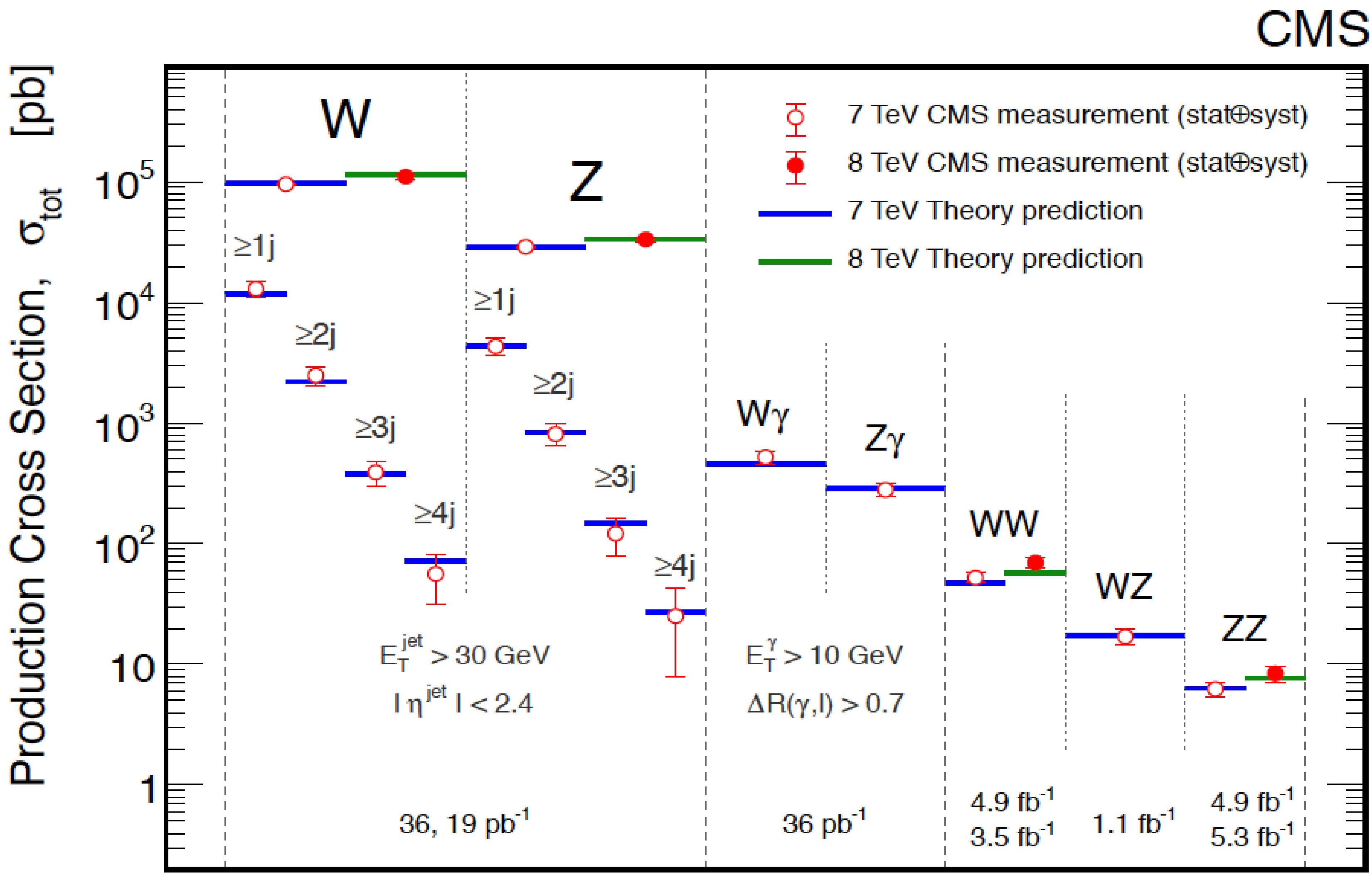
2. Electroweak Physics



JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

PLB701(2011)535

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

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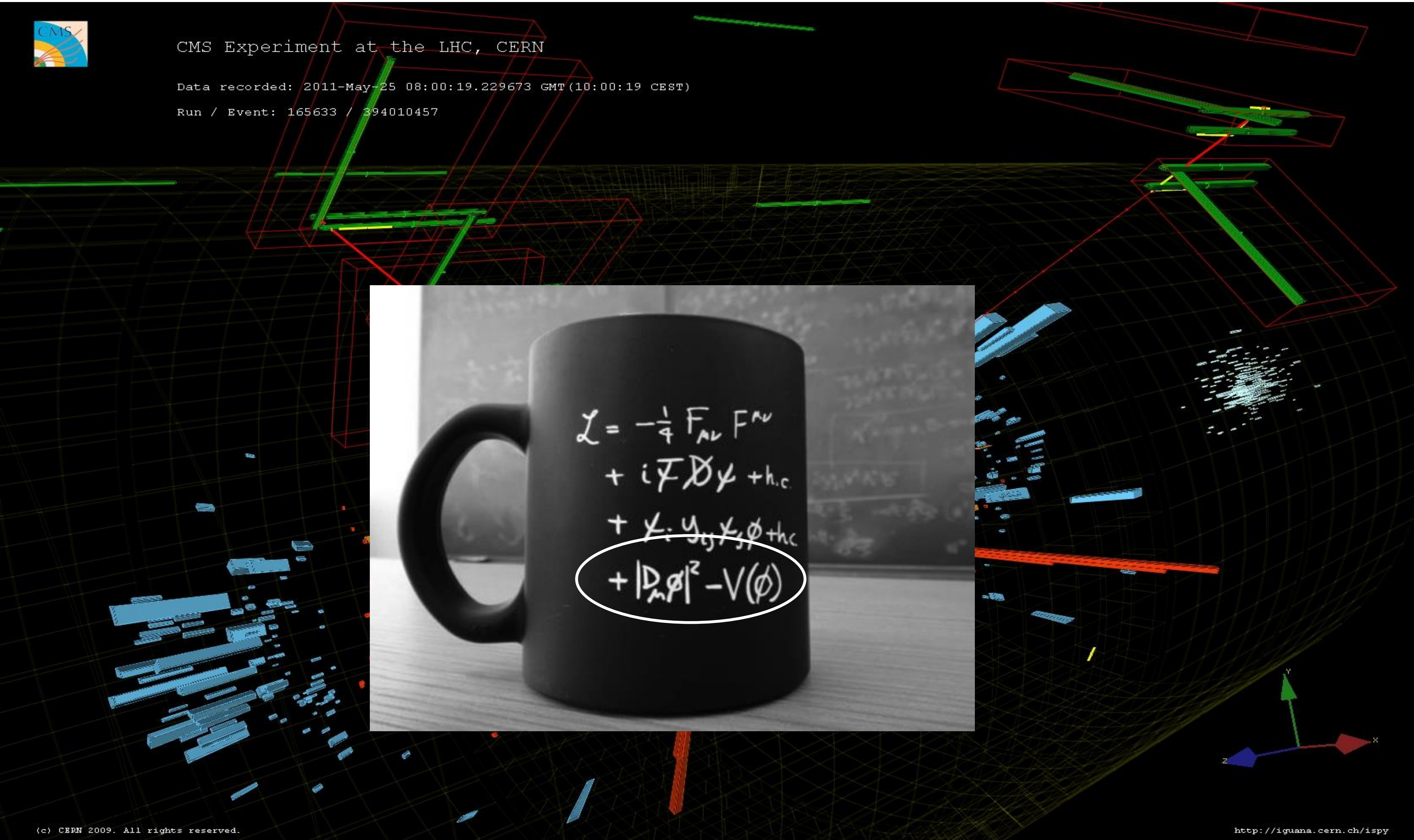
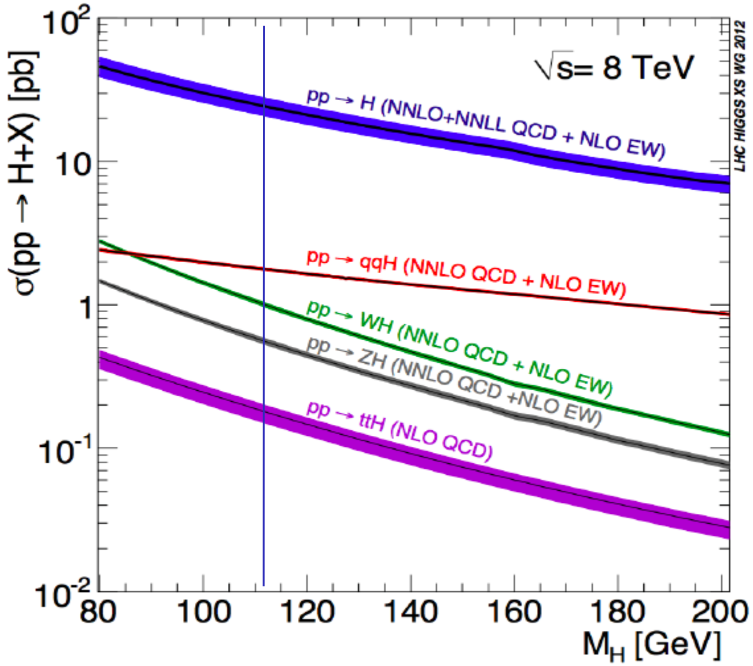
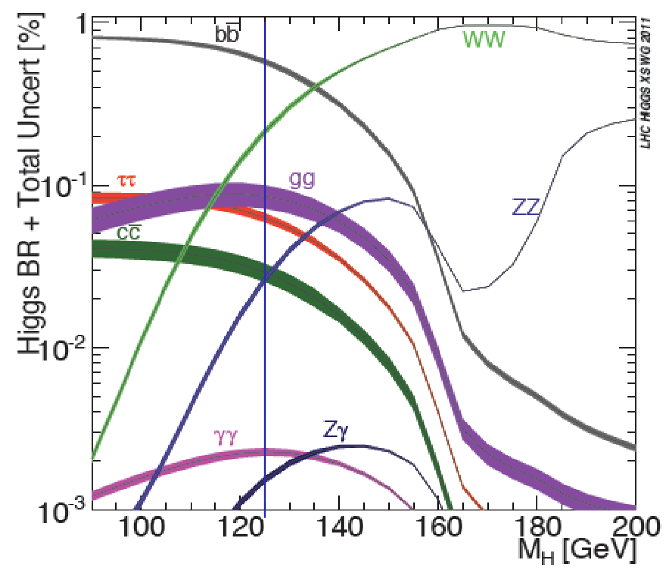
Search for the Higgs boson



SM Higgs Boson: Production Cross-section



decay branching fraction



- Natural Width: Γ_{H_125} ~ few MeV
- The best instrumental mass resolution achievable is ~1GeV in only two channels with decay Branching Fractions:

$H \rightarrow \gamma\gamma$ is 2 per mille

$H \rightarrow ZZ \rightarrow 4l$ is $\sim 10^{-4}$

Integrated Luminosity

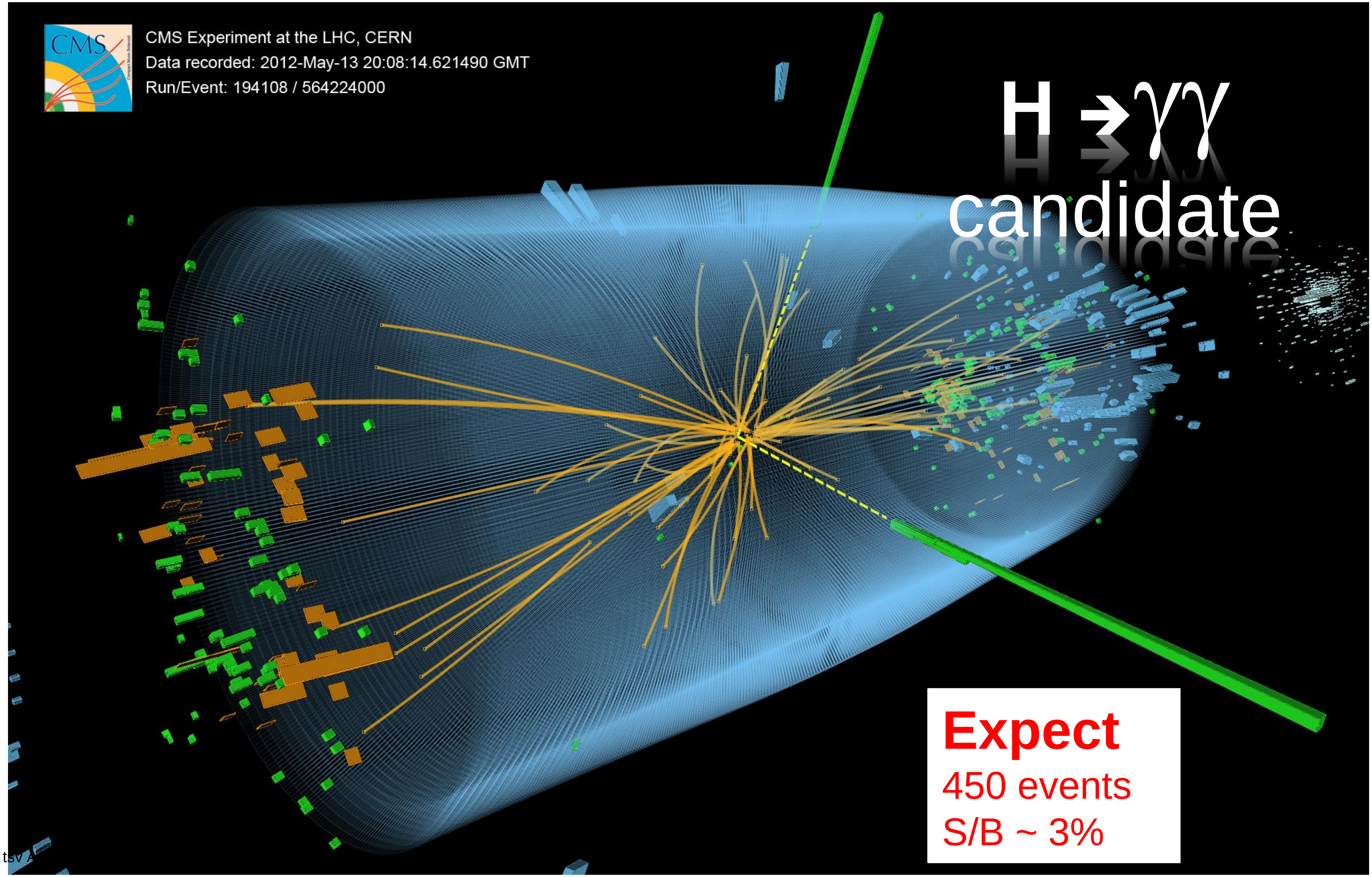
~5 fb^{-1} at $\sqrt{s}$=7TeV and ~ 20fb^{-1} at $\sqrt{s}$=8TeV

2000 trillion pp collisions examined/Expt

And potentially produced

~ 600k SM Higgs bosons (m_H=125 GeV)

H⟶ 2γ Channel


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate
Expect
450 events
S/B ~ 3%

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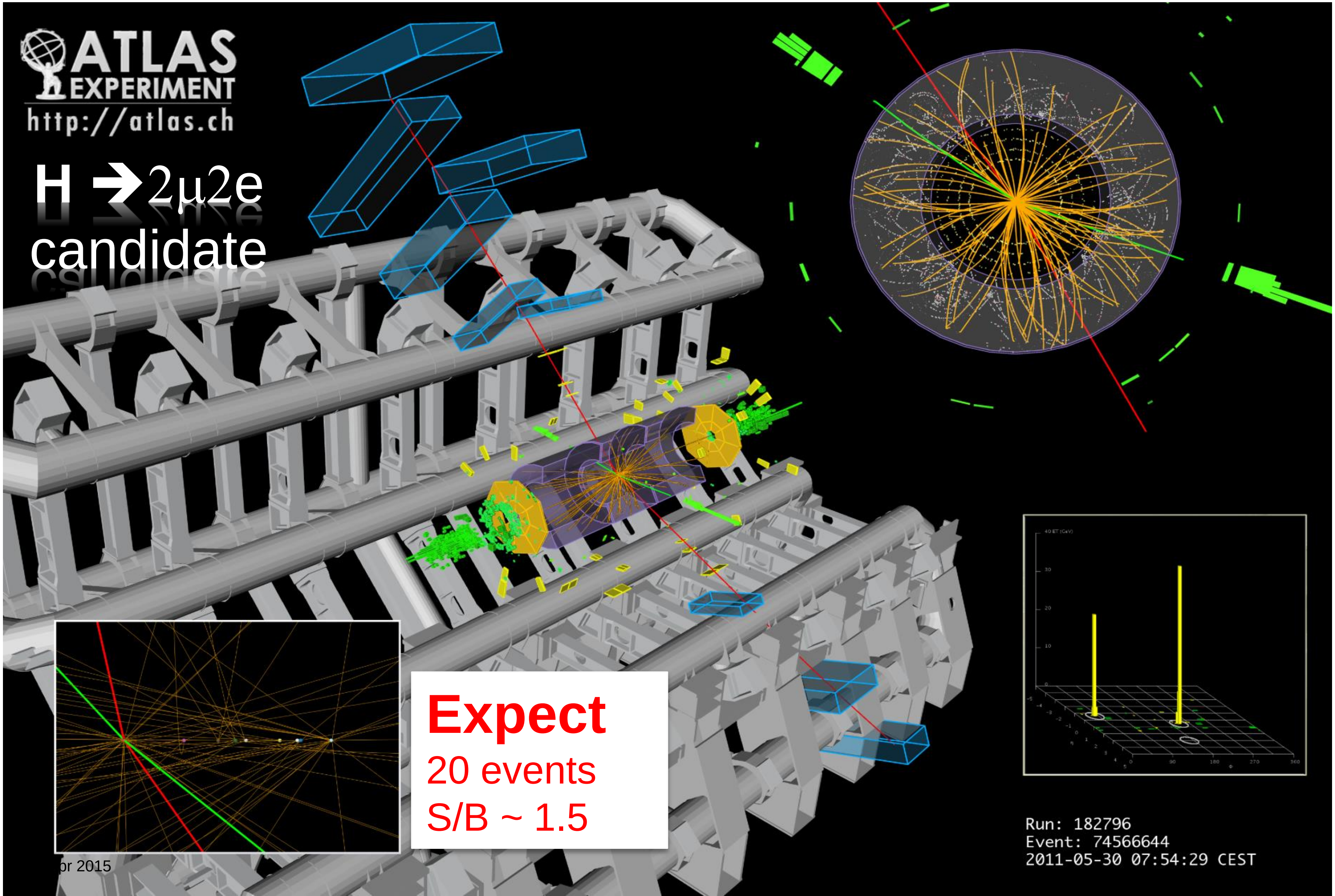
H→ ZZ$^{(*)}$ → 2μ2e Channel



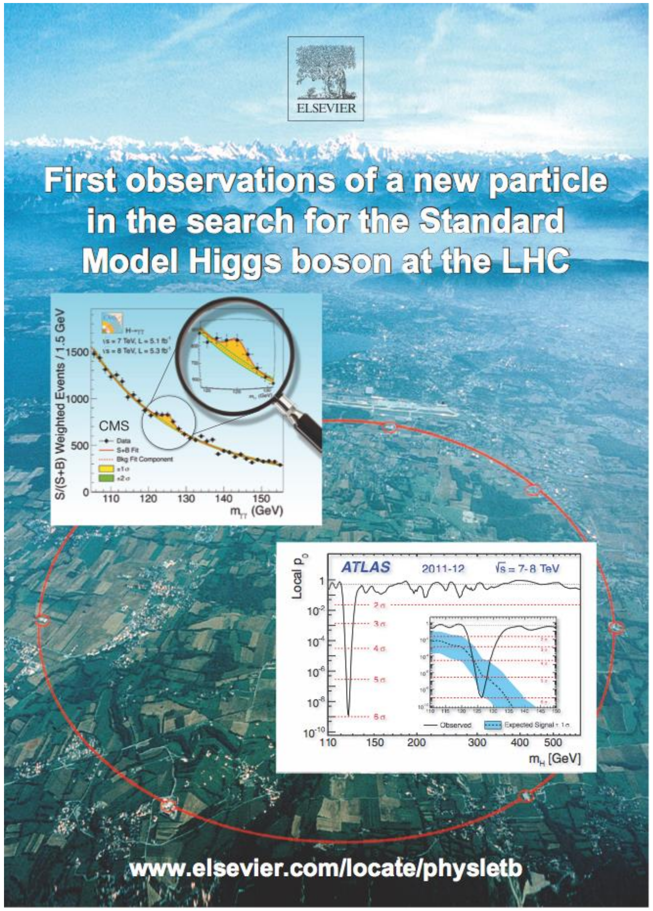
Expect

20 events

S/B ~ 1.5

Completing the SM: A Higgs boson is born

Born on the 4th of July 2012

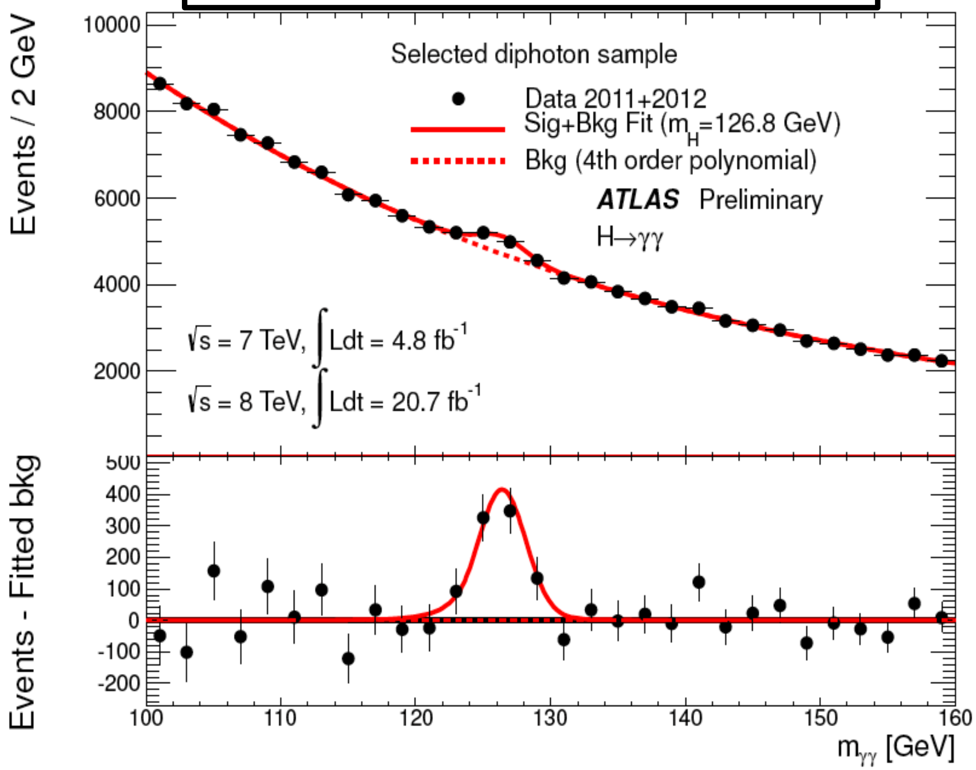


PLB 716(2012)1, 30

Situation Today: Higgs boson Decays to bosons

ATLAS: H→ 2γ Channel

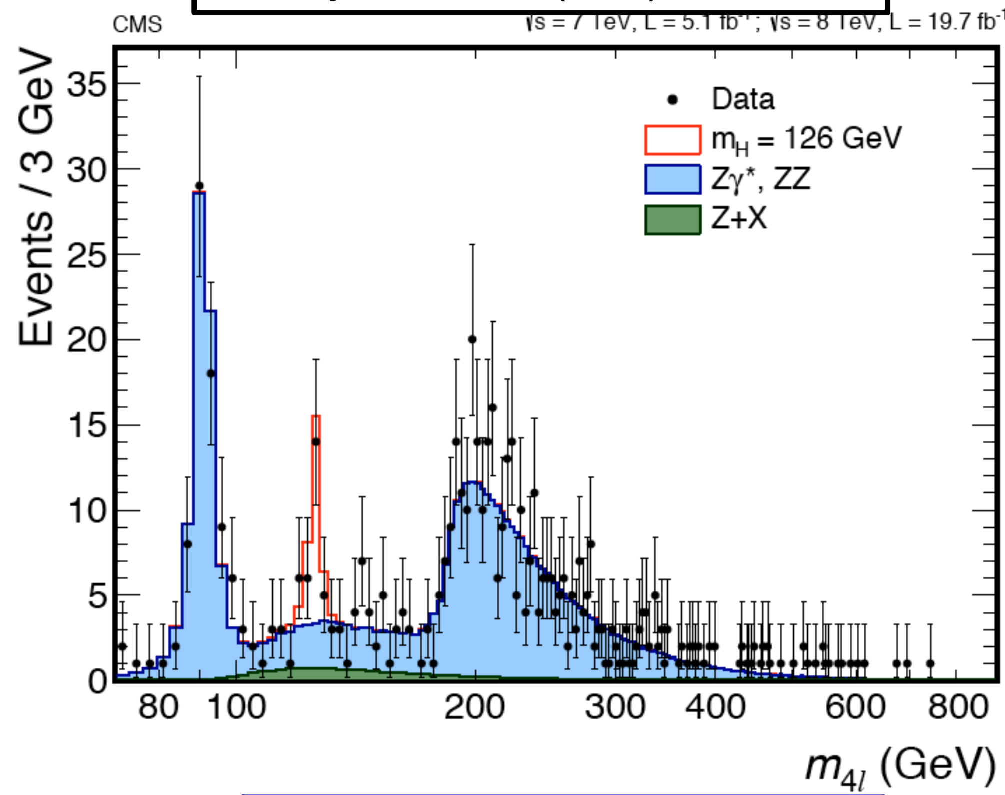
Phys. Rev. D90 (2014) 112015.



Sign/Exp	Exp	Obs
ATLAS	4.6 σ	5.2 σ
CMS	5.3 σ	5.6 σ

CMS: H→Z→4*l* Channel

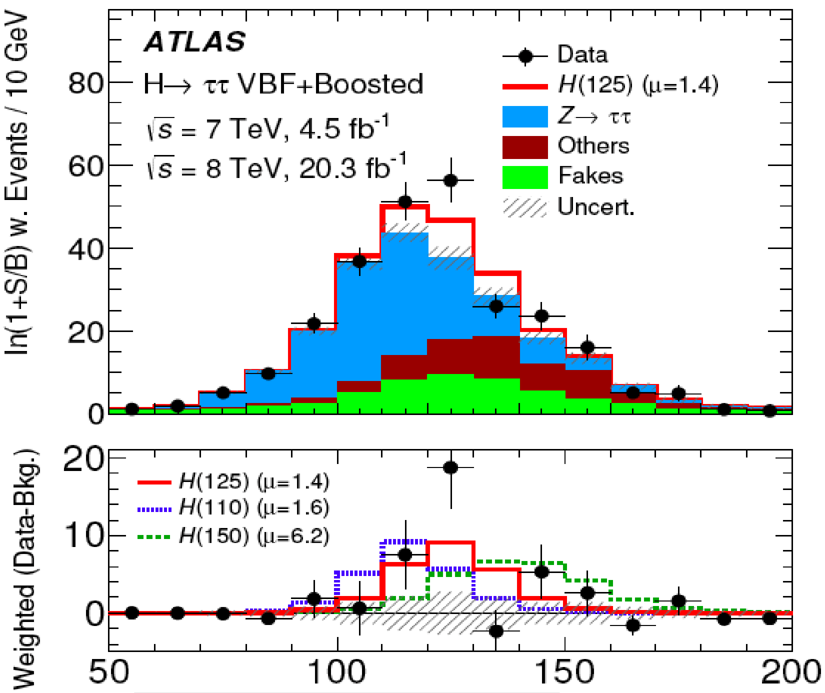
Phys. Rev. D89 (2014) 092007



Sign/Exp	Exp	Obs
ATLAS	6.2 σ	8.1 σ
CMS	6.3 σ	6.5 σ

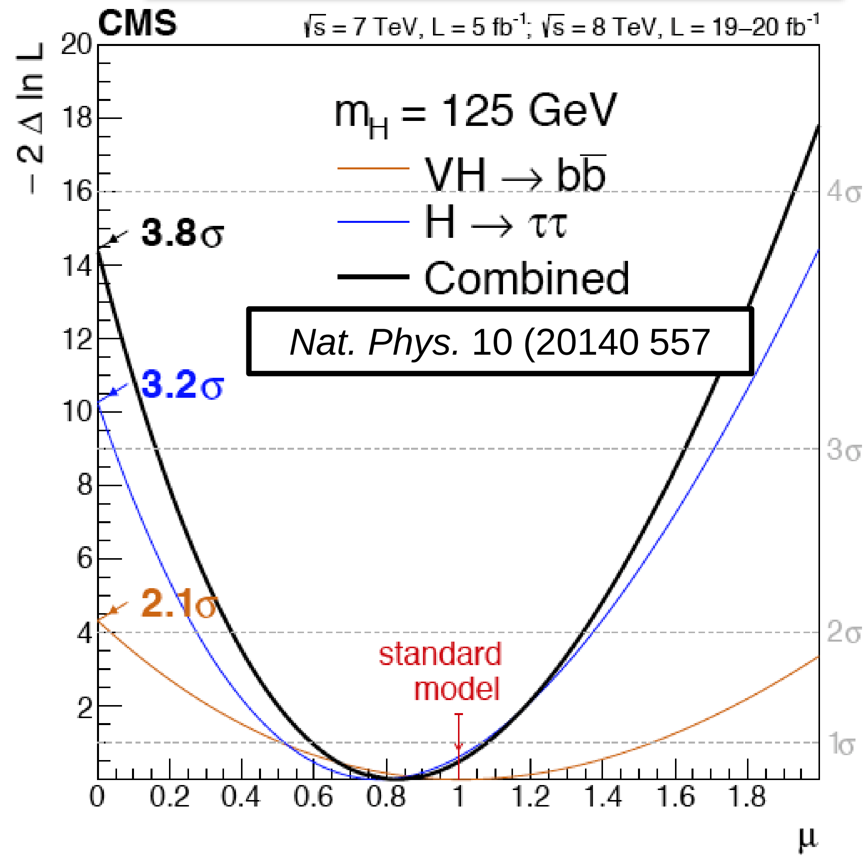
Situation Today: Higgs boson Decays to Fermions

ATLAS: H→ ττ Channel



arXiv: 1501.04943

CMS: H→ ττ, bb Channels



Nat. Phys. 10 (20140 557

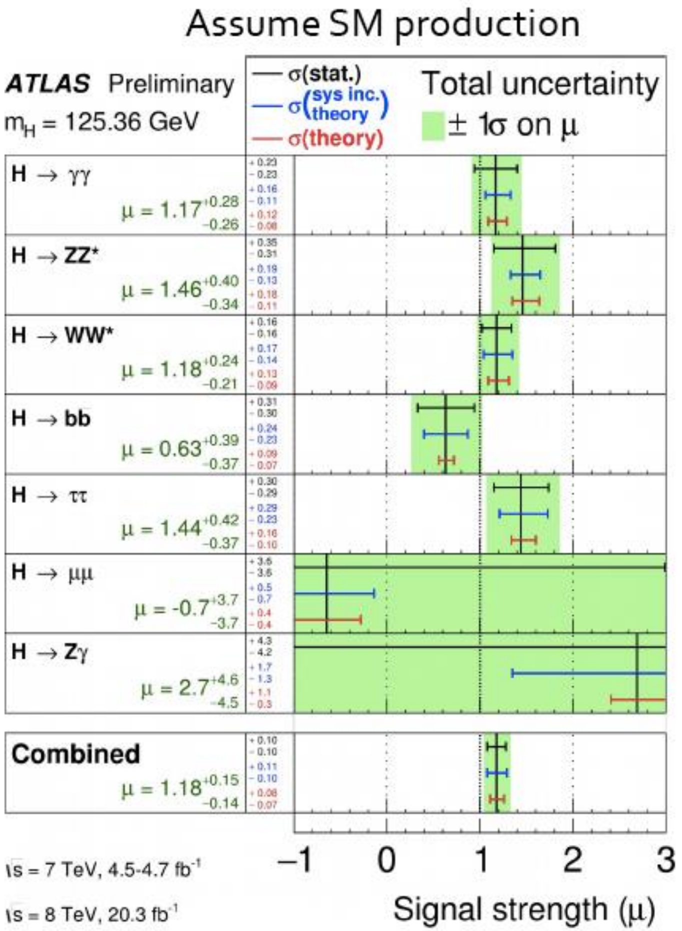
Significance	Exp	Obs
ATLAS (ττ)	3.4 σ	4.5 σ
ATLAS (bb)	2.6 σ	1.4 σ

Tevatron: exp (2.1σ), obs (3.0σ)

Significance	Exp	Obs
CMS (ττ)	3.9 σ	3.8 σ
CMS (bb)	2.6 σ	2.0 σ

Putting it all together: Signal Strength

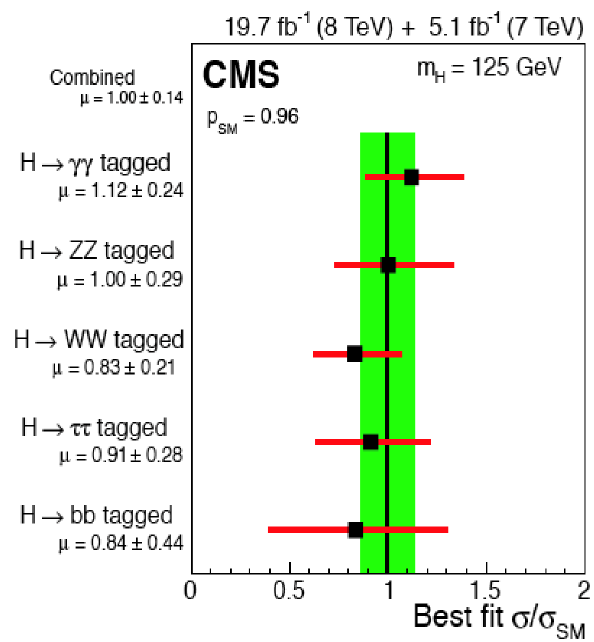
Signal strength and comparison to SM Higgs boson: $\mu = \sigma/\sigma_{SM}$

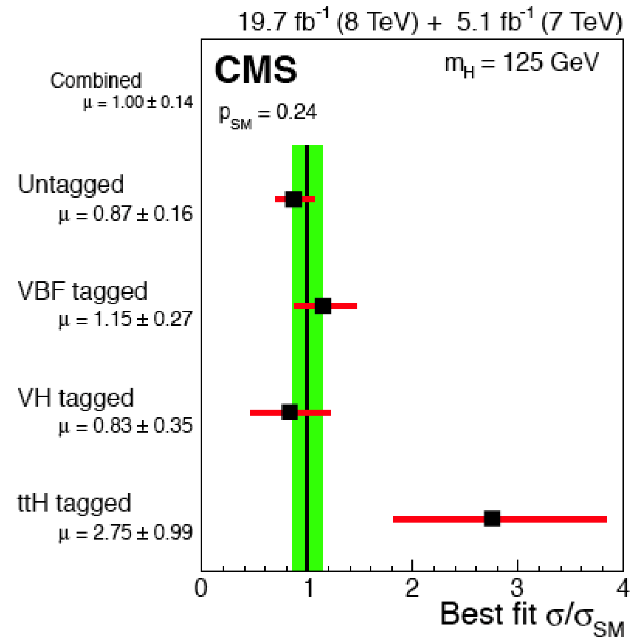


ATLAS
CERN Seminar
17 Mar

ATLAS
$\mu = 1.18 \pm 0.15$

CMS: arXiv: 1412.8662



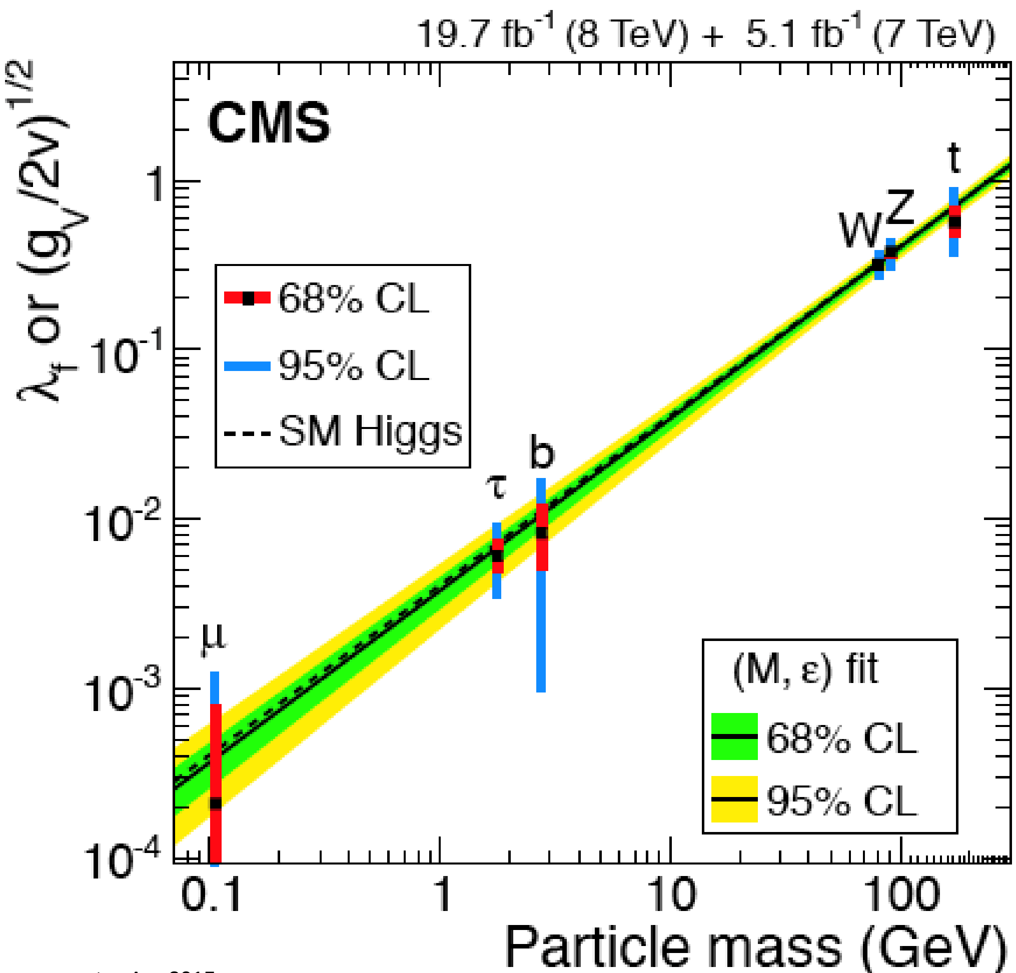


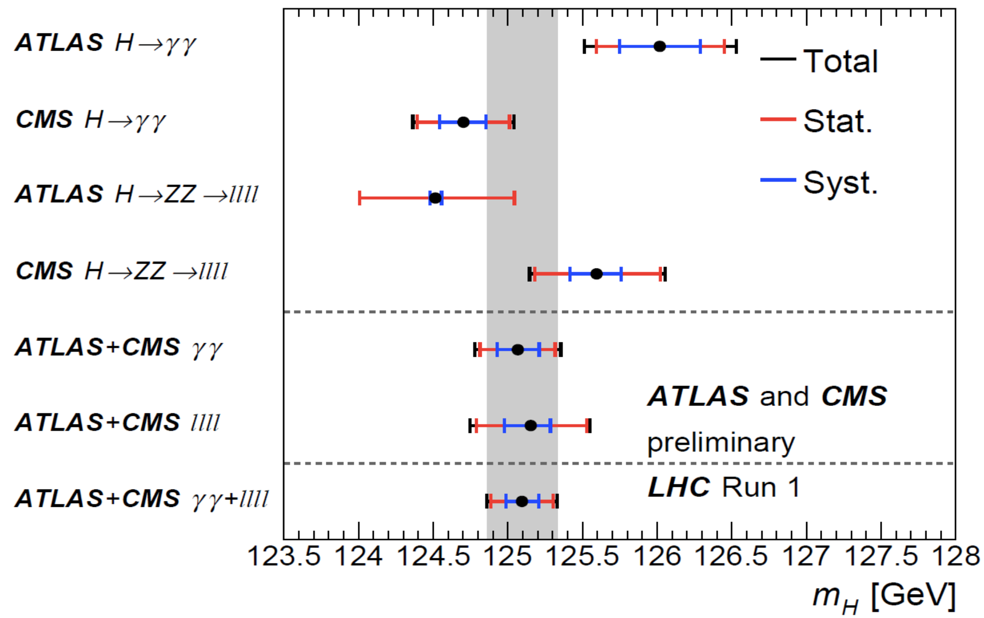
CMS
$\mu = 1.00 \pm 0.14$

Putting it all together: Mass and Couplings

arXiv: 1412.8662

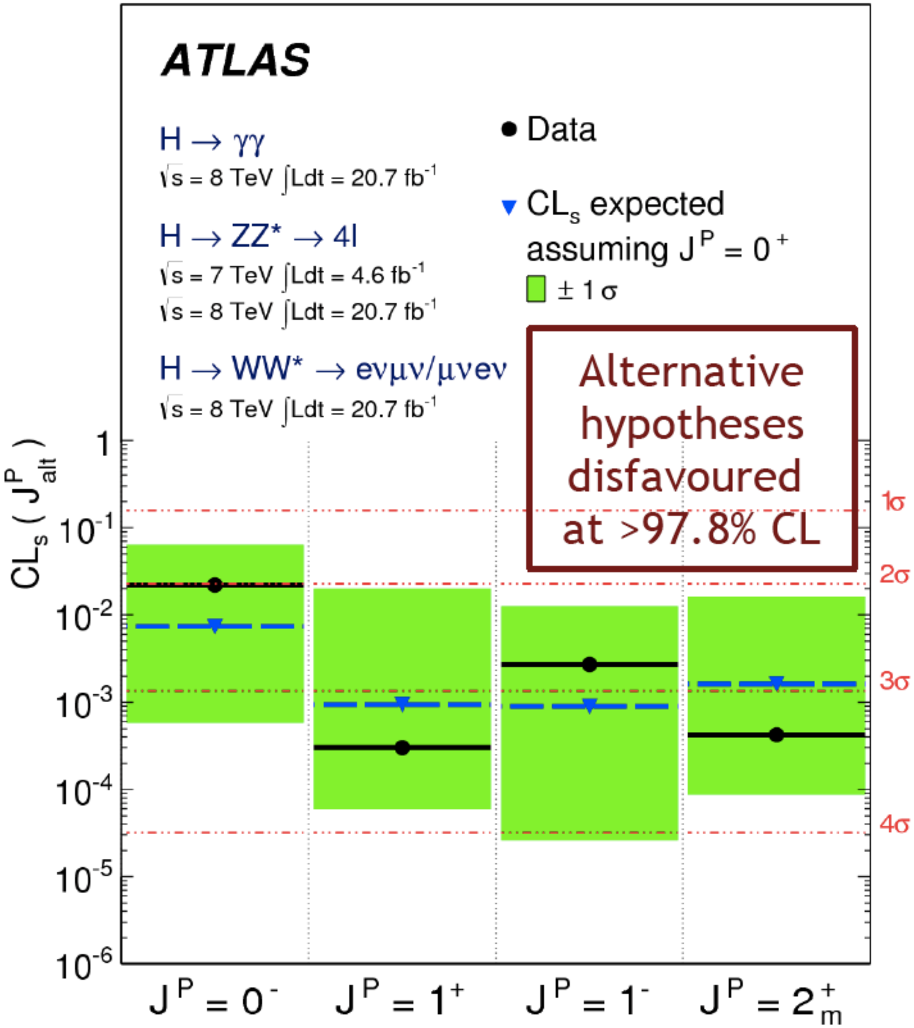
M_H = 125.09 ± 0.21 (stat) ± 0.11 (sys) GeV
ATLAS and CMS: H→γγ *and* H→ZZ$^{(*)}$ → 4*l*





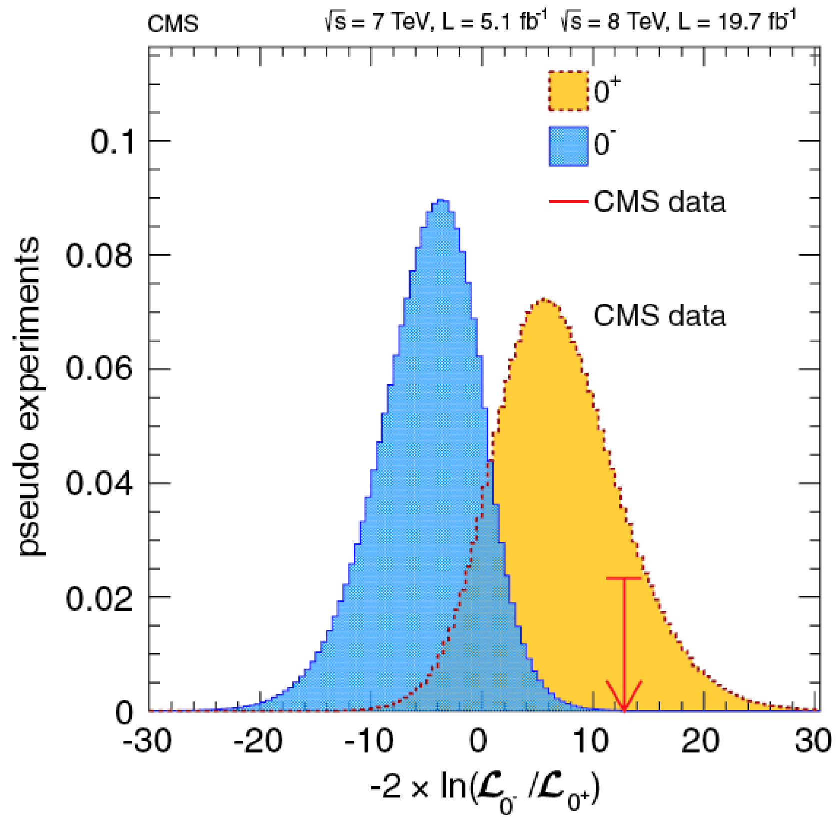
Moriond 2015
17 March

Properties: Spin-Parity – 0^+ Favoured



ATLAS: PLB726(2013)120

CMS: H→Z→4*l* Channel



All alternative spin-1 (spin-2) hypotheses tested are excluded at 99% (95%) CL or higher

PR D89(2014)092007


·IS·THIS·IT·

What about new physics?

In a world of a SM Higgs boson, is there any room for new physics?

We believe there must be new physics

Some real and some virtual reasons to believe in new physics

Real reasons: dark matter & ν masses
Virtual reasons: naturalness

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SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found 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)**

5. 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 ?

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Searching for New Physics

Should we really expect new physics ?

Ample observational evidence for physics Beyond the SM.

Neutrino masses (oscillations), dark matter, matter-antimatter asymmetry, (Low Higgs boson mass?)

Previously theory "always" showed a nearby new physics scale

Next scale could be anywhere between 1 TeV and very high scale (10^{12}-10^{15} GeV)

The new physics scale can be much lower than the scale Λ that we measure through precision physics

Flavour violation	1 – 10^5 TeV
EDMs	1 – 100 TeV
Neutrino masses	1 – 10^{12} TeV

Precision BEH boson physics is particularly interesting and promising:

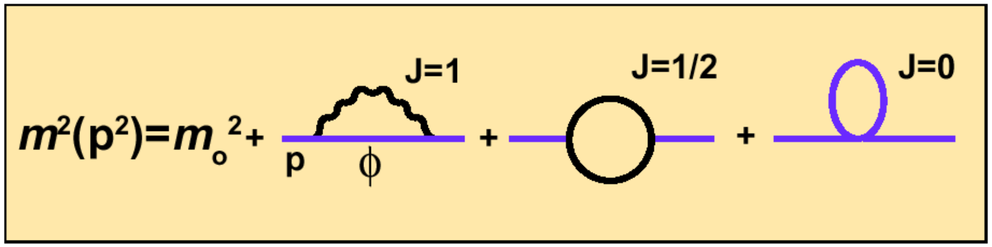
This is a new world.

Excellent portal to new physics.

How can the mass of Higgs boson be anything small?

It should “resist” itself (since it couples to mass, it should couple to itself as well)

Then it’s mass should be “almost infinite” through quantum corrections.



$M_H^2 \rightarrow M_H^2$ (bare) + c Λ^2 (quadratic divergence in the mass!)

Λ is the scale of the underlying theory (could be $M_{GUT} \sim 10^{15}$ GeV !)

Requires incredibly unnatural fine tuning to keep M_H small !!

What can be done ?

L_{SSB} does not contain an elementary Higgs boson (now unlikely)

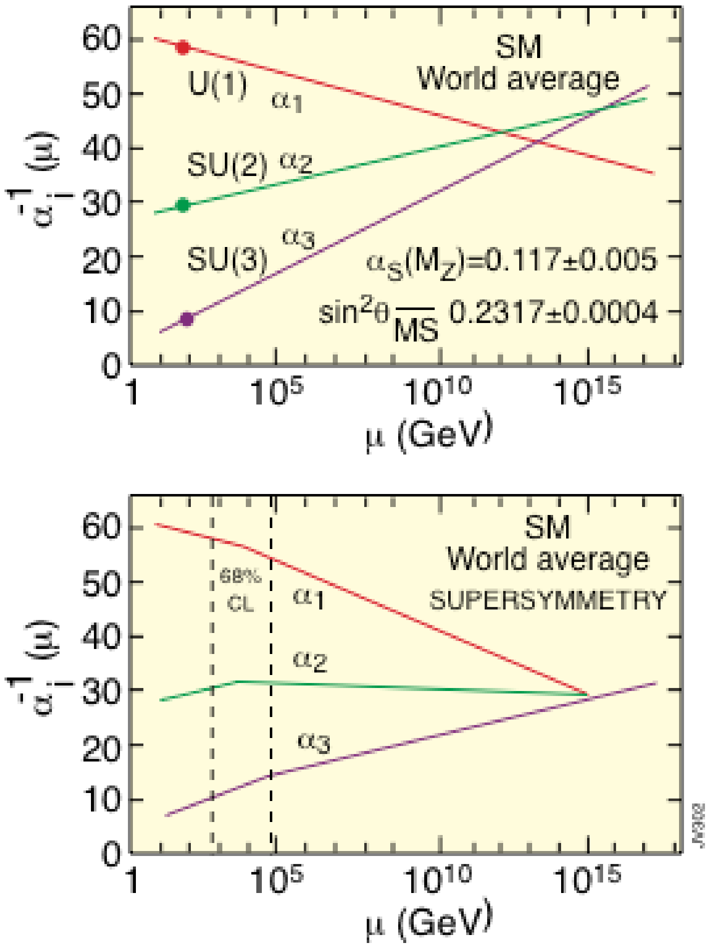
OR

Somehow cancel quadratic divergences (invoke another symmetry – SUSY?)

OR

Accept fine tuning!

Features of Supersymmetry



$M_S = 10^{3.7\pm0.8+0.4}$GeV $M_U = 10^{15.9\pm0.2+0.1}$GeV

Supersymmetry can play an important role in:

Grand unification (strong + EW forces)

Proton decay

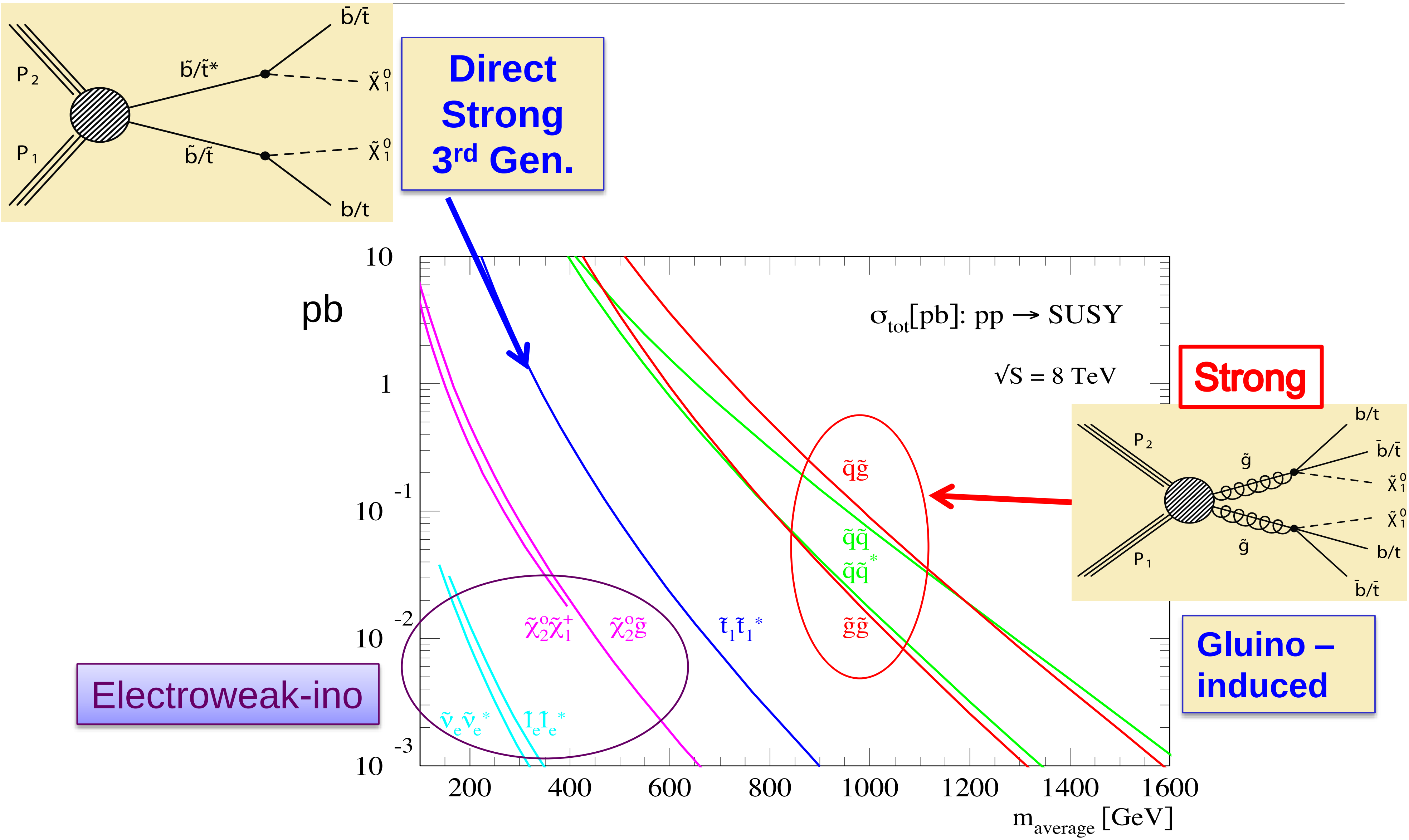
Heirarchy problem - why is the Higgs mass so low

Candidate for dark matter - lightest neutral sparticle

String theory requires supersymmetry (towards reconciling gravity and QM)

Is SUSY expected to do too much?

SUSY “production”

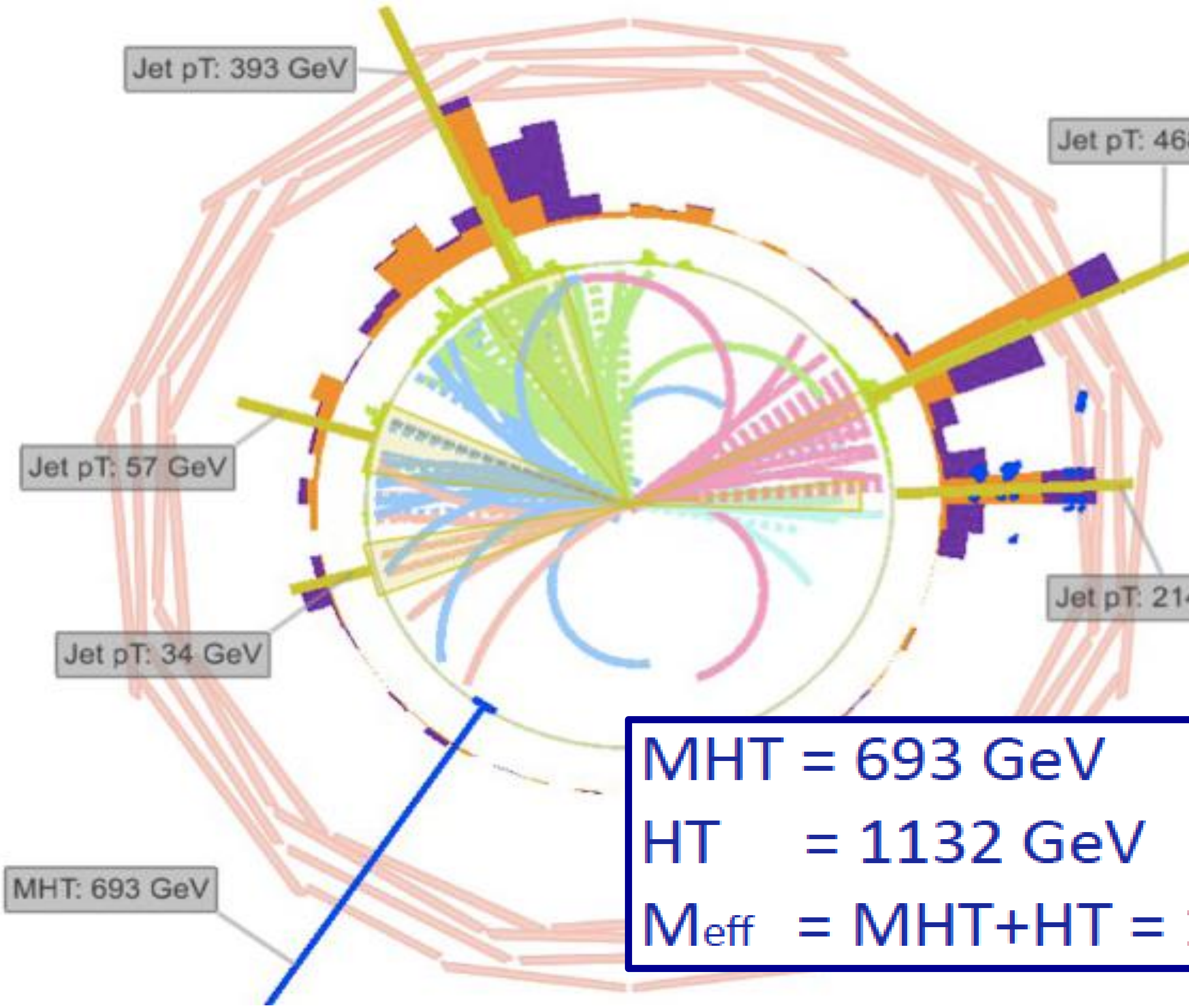


Experimentally: signatures

- **R_P conservation:**
  - Stable LSP, weakly interacting, "missing transverse energy" (E_T^{miss})
  - Mostly strong production – rich cascades; many jets, a few leptons
  - When going after the stop: b-tagging
- **R_P violation:**
  - The dreaded possibility (harder, except in corners of possibility space)
  - Hadronic modes: to first order, no ME_T (very hard); Leptonic modes more promising
  - Strong production, but several interesting new EWK-ino production mechanisms; even more jets and leptons
- **Prompted by R_P violation, but still possible with R_P conservation: exotic SUSY particles**
  - Long-lived particles (some are even "stable")

P. Sphicas, Latsis Symposium 2013

What it [could look/looks?] like. Spectacular!



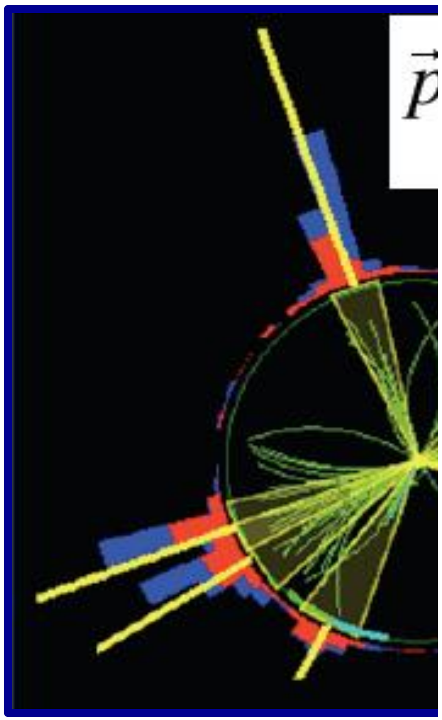
MHT = 693 GeV

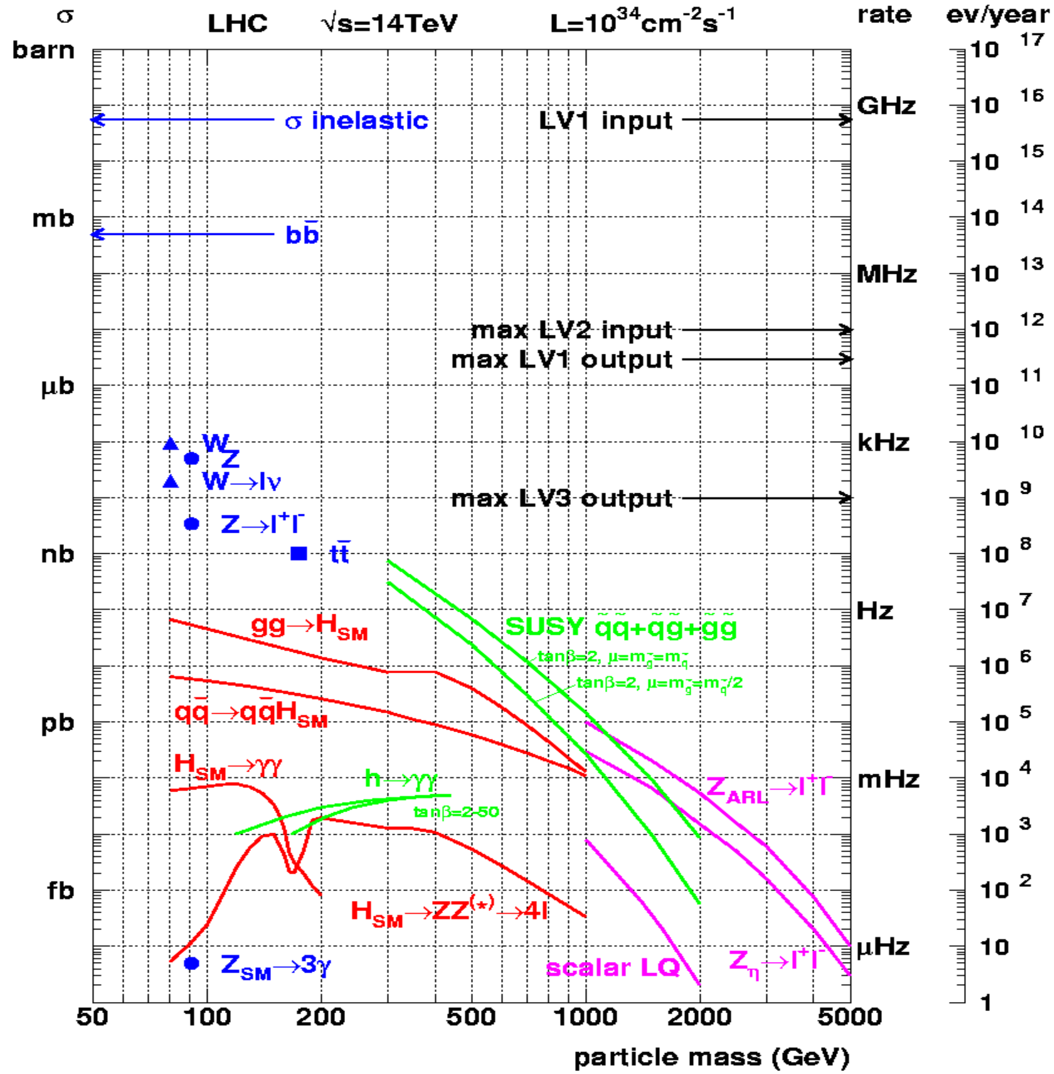
HT = 1132 GeV

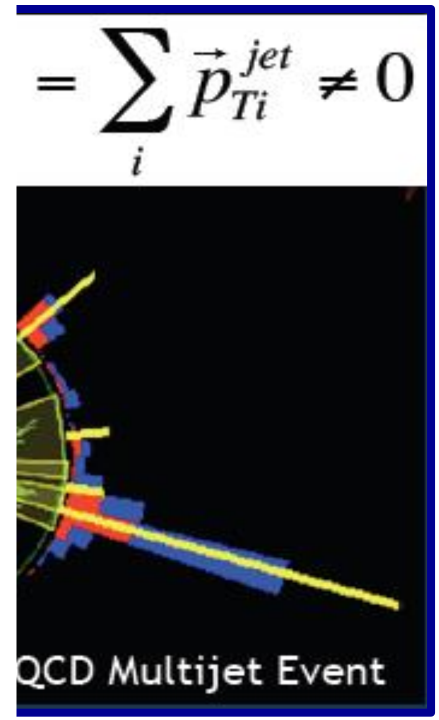
M_{eff} = MHT+HT = 1.83 TeV

The challenge from the Standard Model

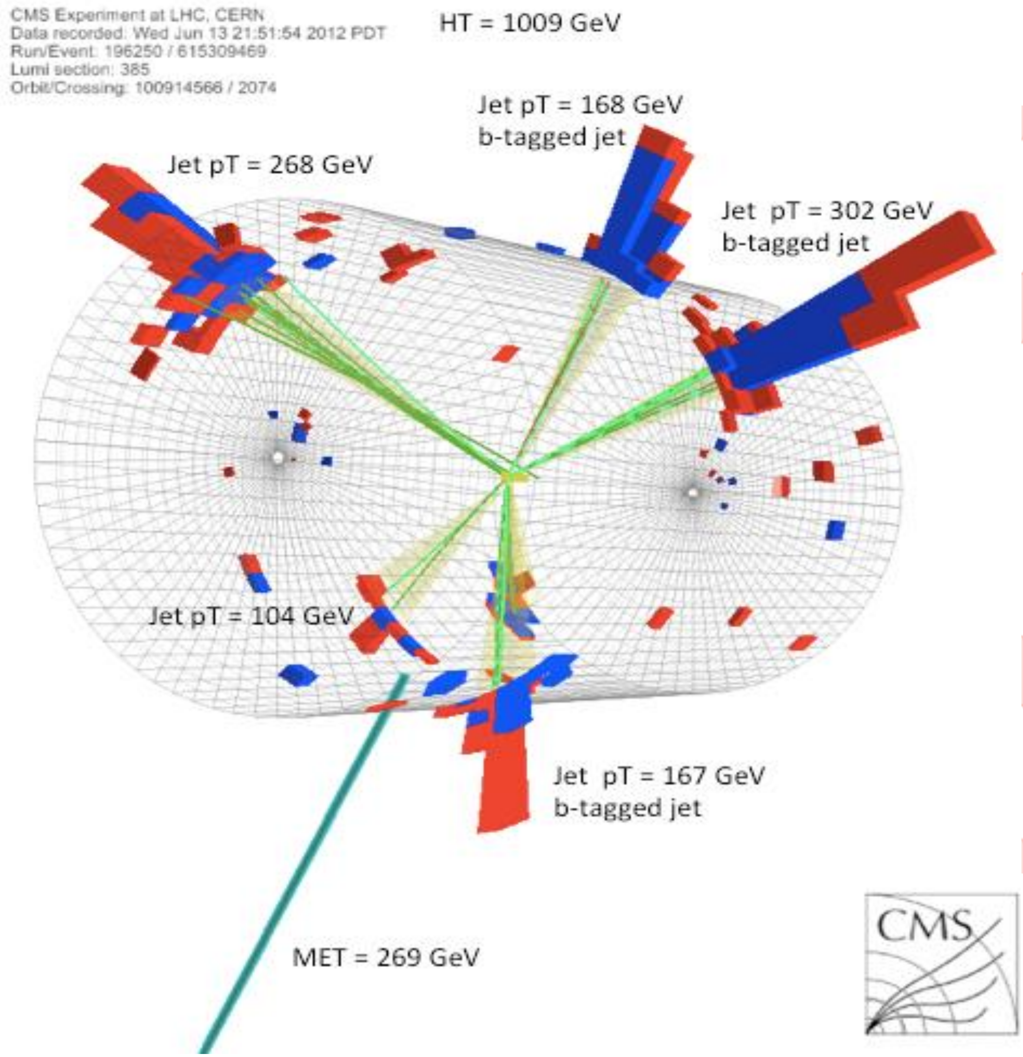
- **Understatement: the problem with jets – the huge production rate**

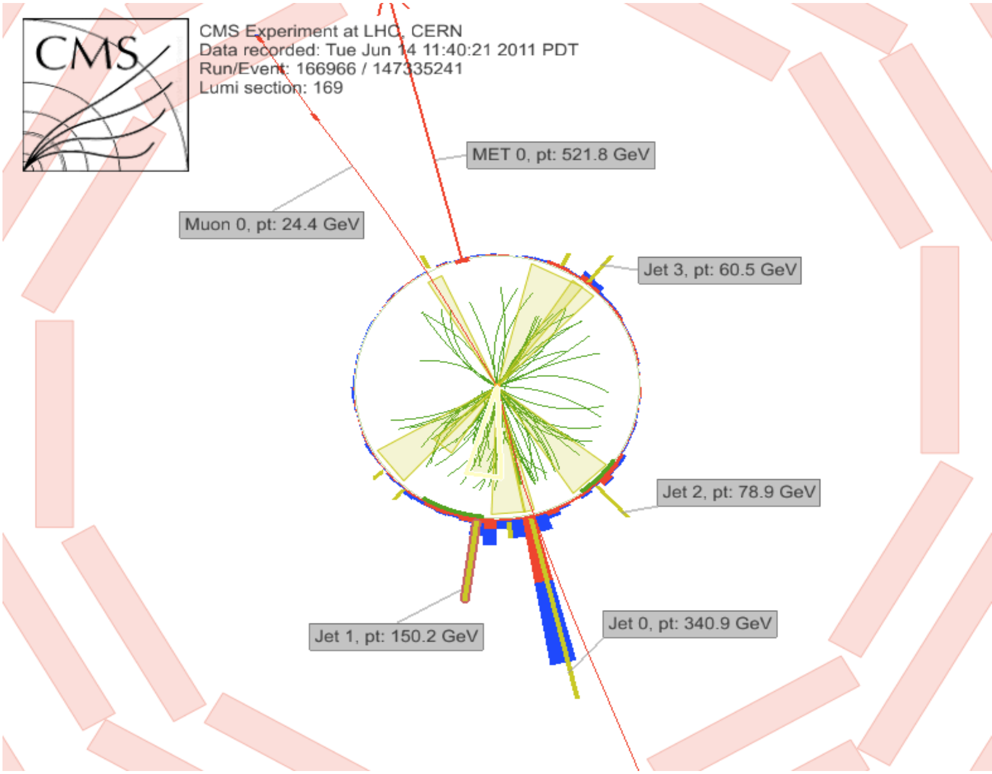




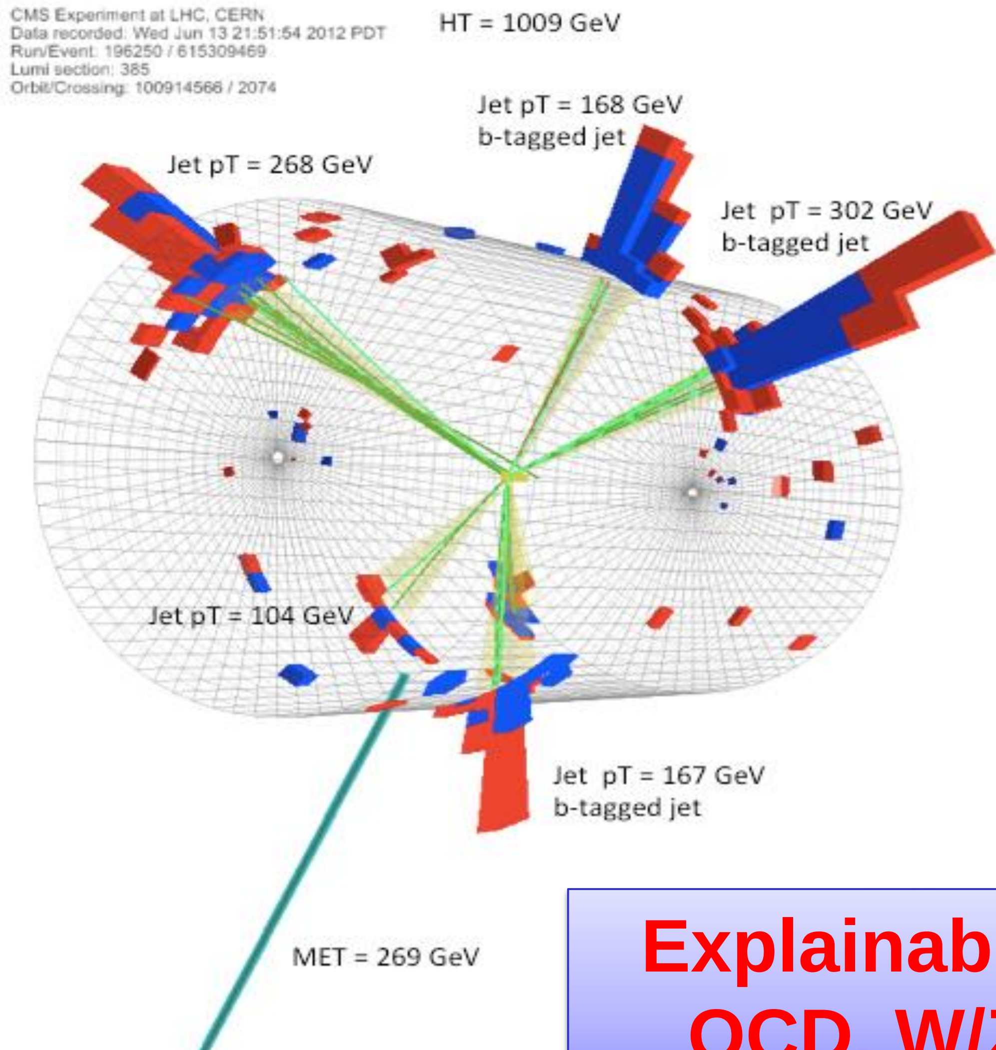


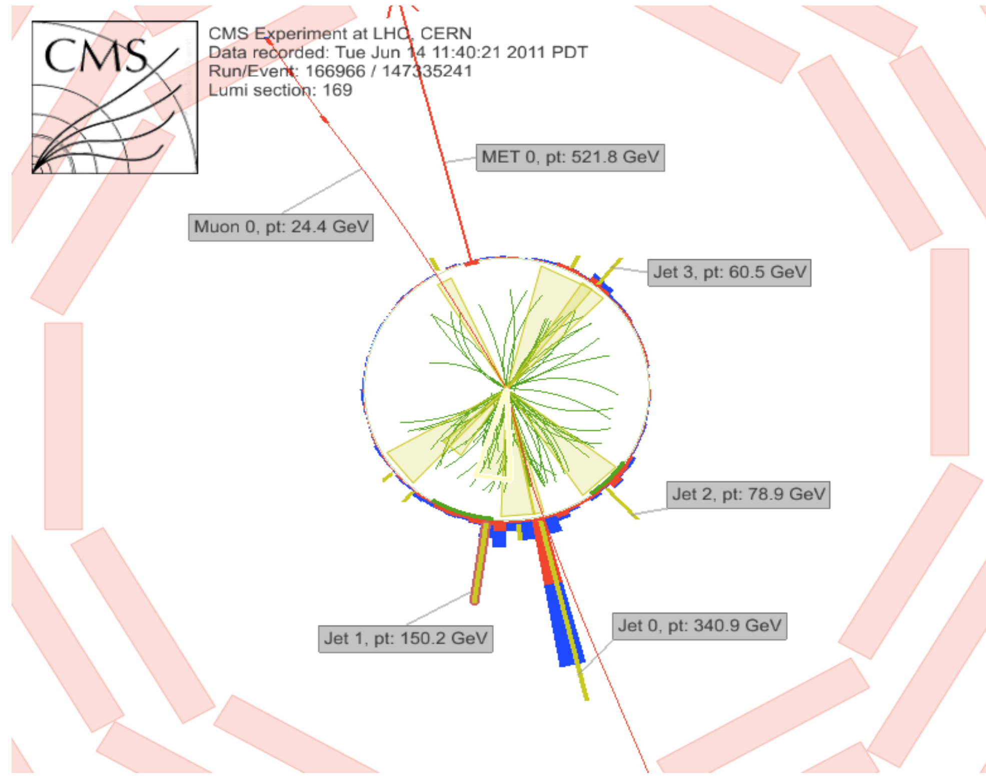
What we have been looking for





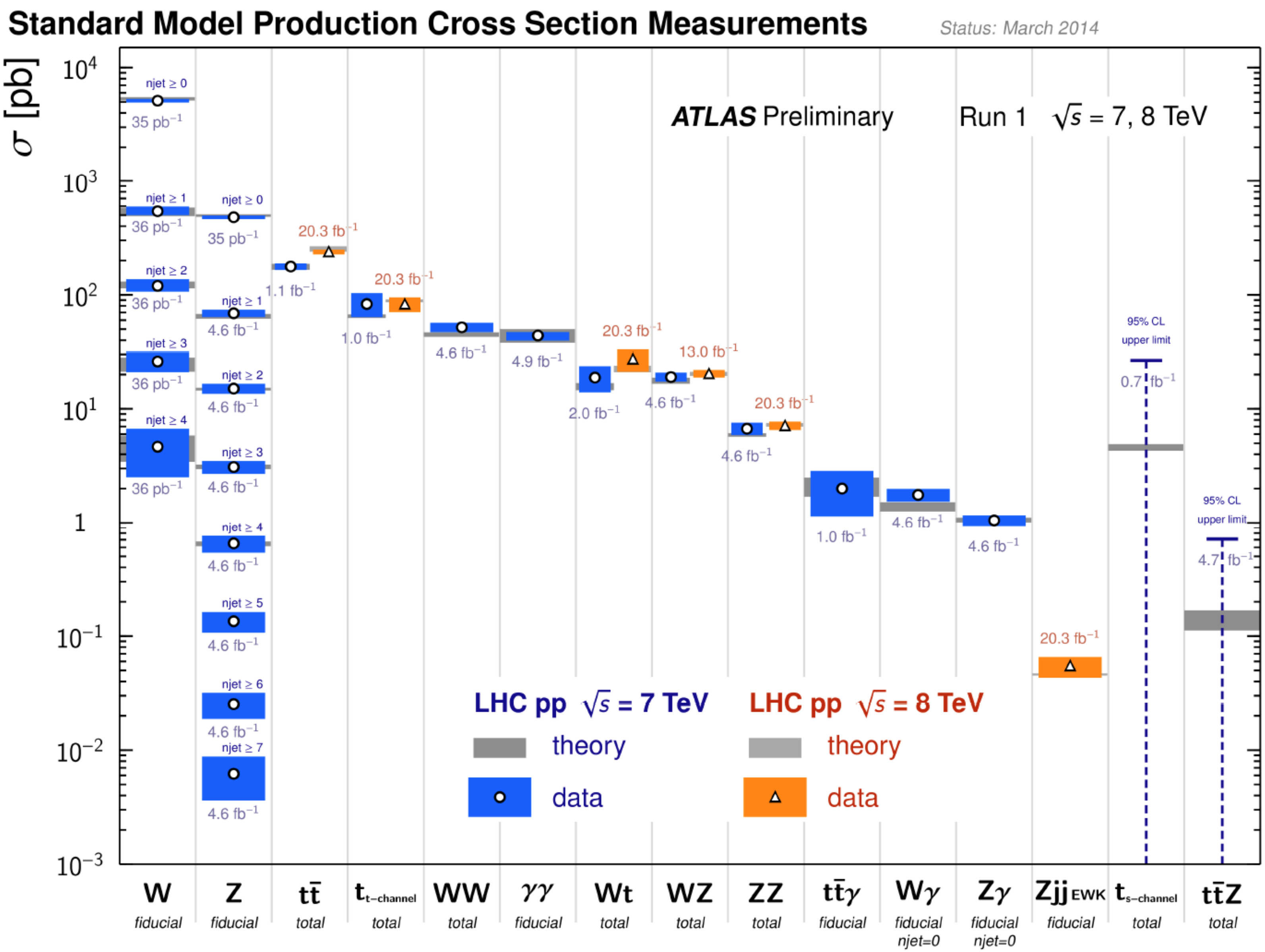
What we have found





Explainable in terms of: QCD, W/Z+jets, t-tbar

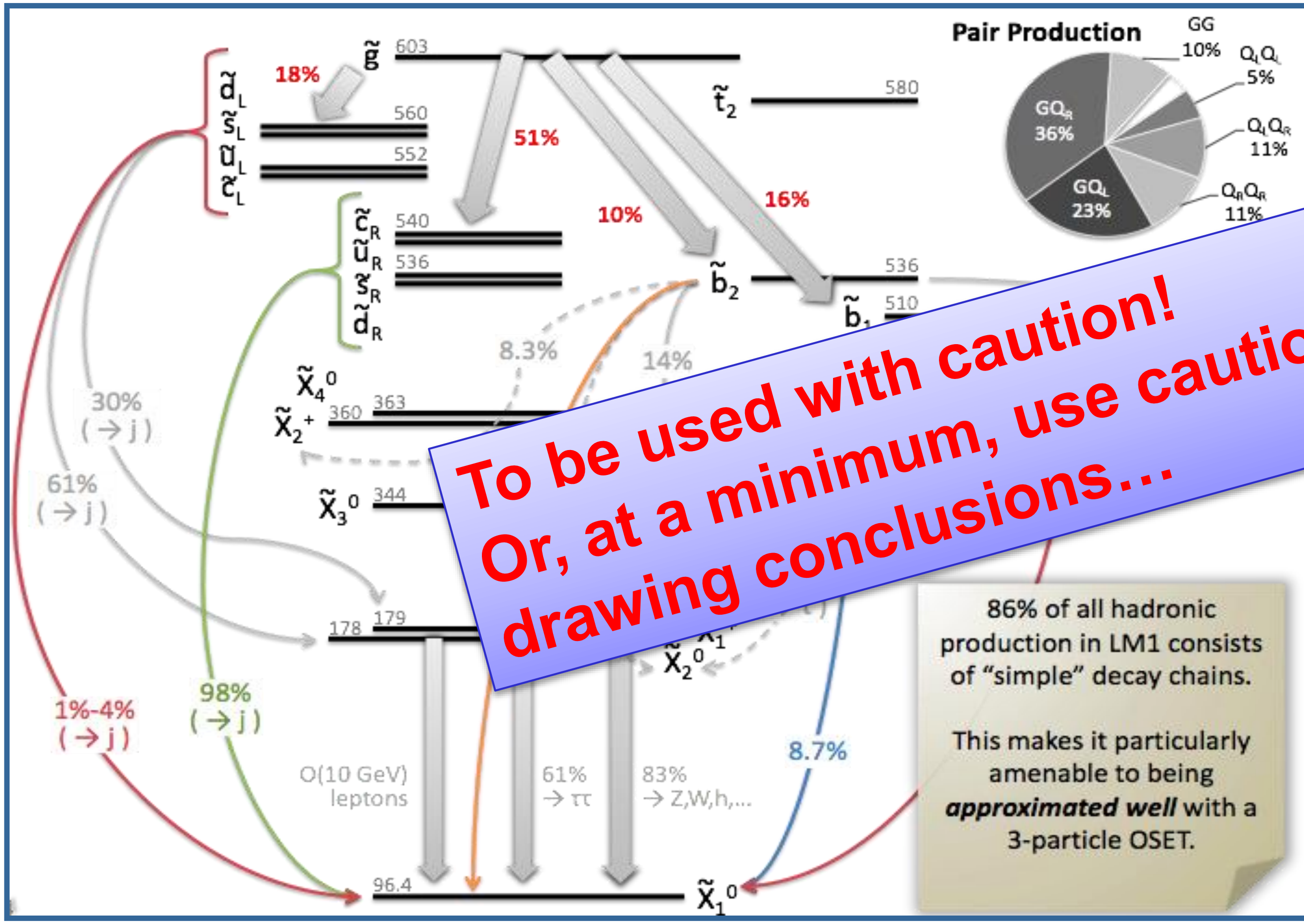
Understand SM Backgrounds: W/Z+jets; ttbar



Interpreting SUSY searches

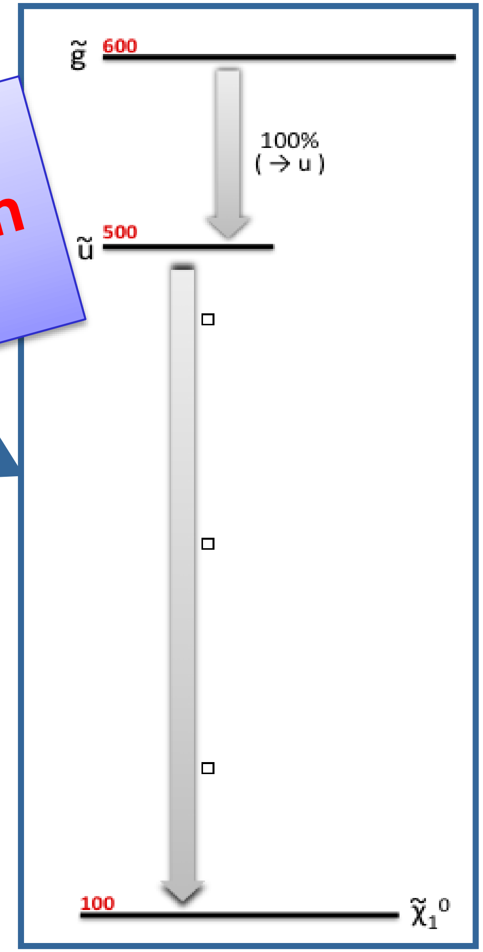
R_P Conservation: Simplified Model Spectra

CMSSM



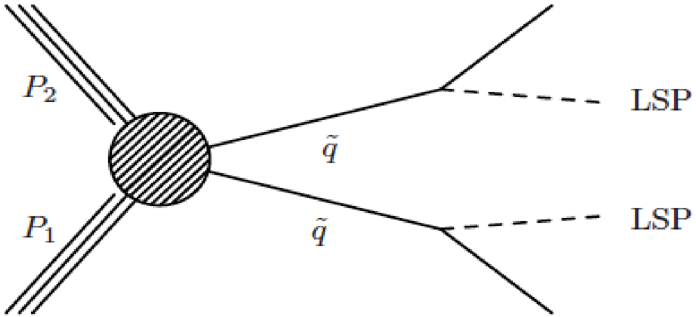
To be used with caution!
Or, at a minimum, use caution when drawing conclusions…

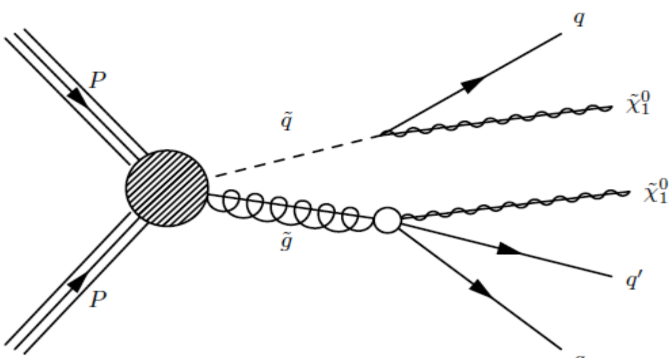
What we put in: much simpler…

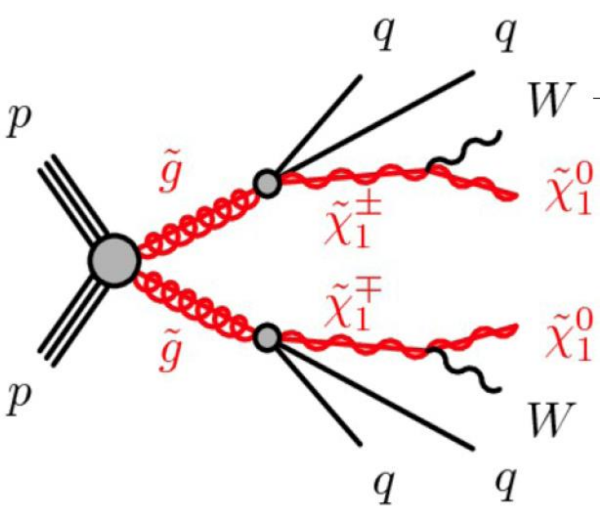


Simplified Model Spectrum (SMS) with 3 particles, 2 decay modes

ATLAS: R_P Conservation: 0- and 1-lepton+Jets+MET







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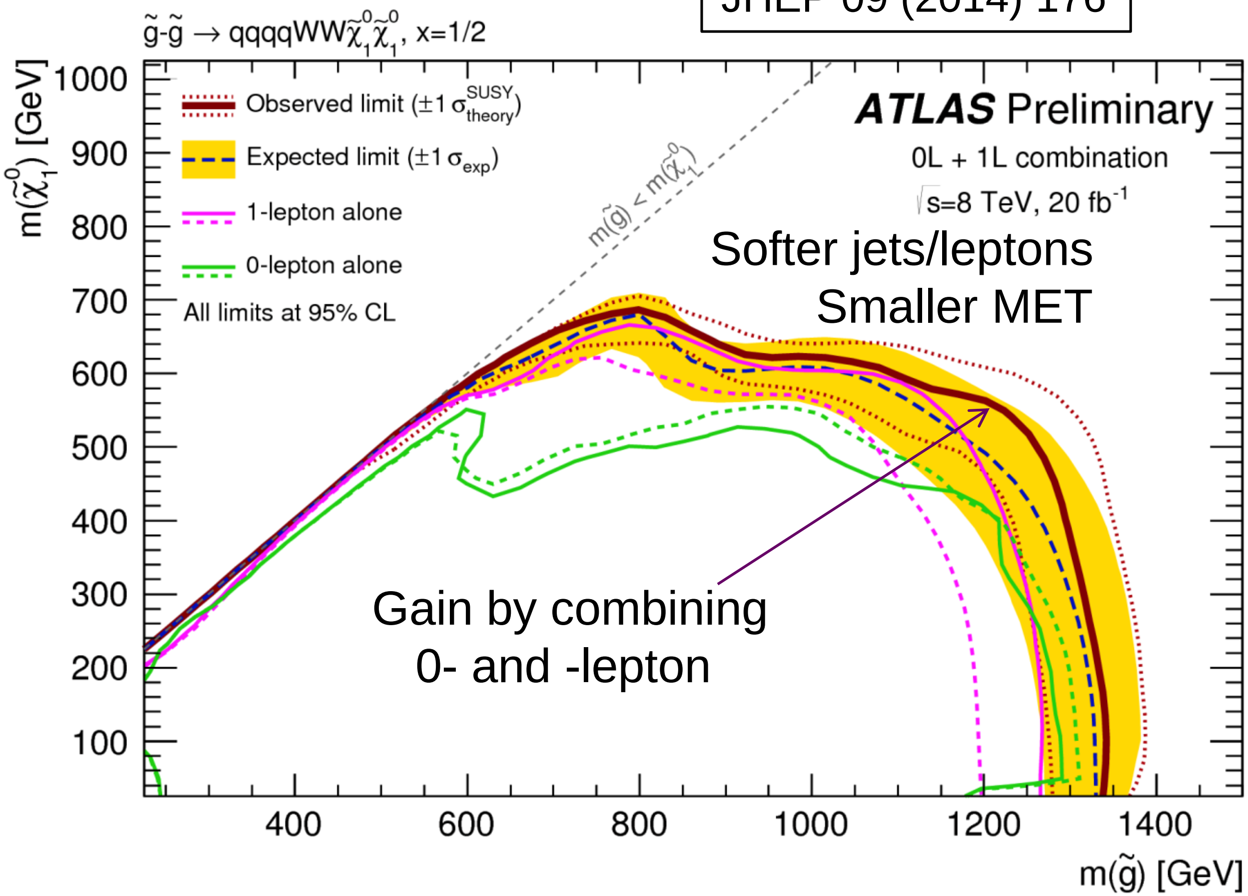
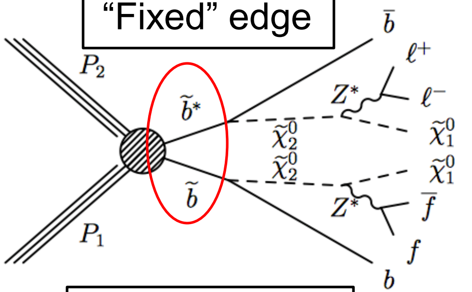
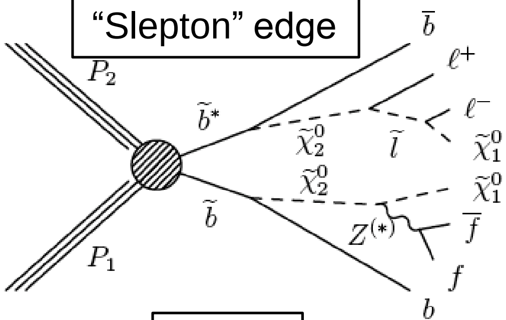


CMS: R_P Conservation: (SFOS) di-lepton+Jets+MET

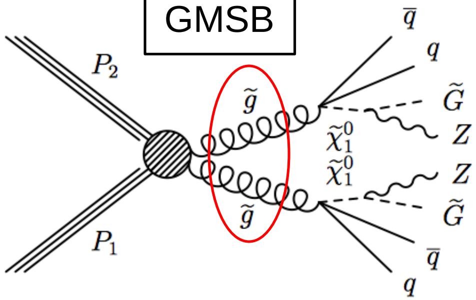
"Fixed" edge

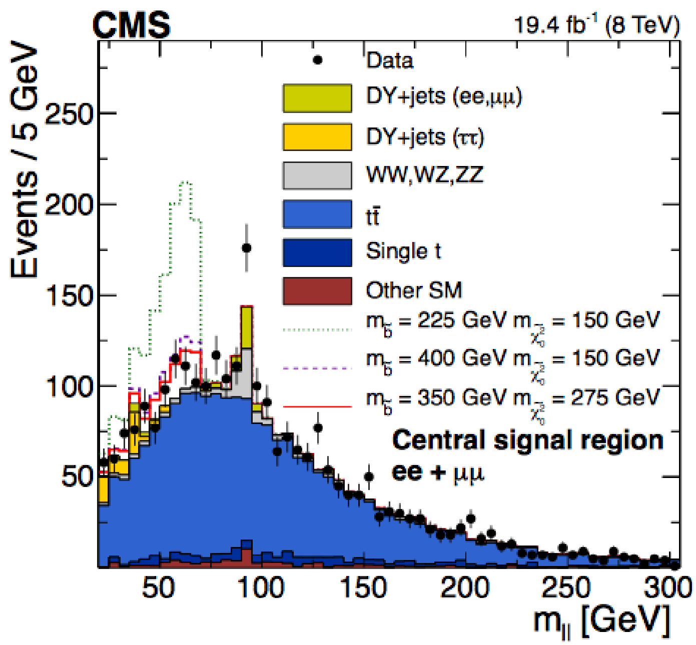


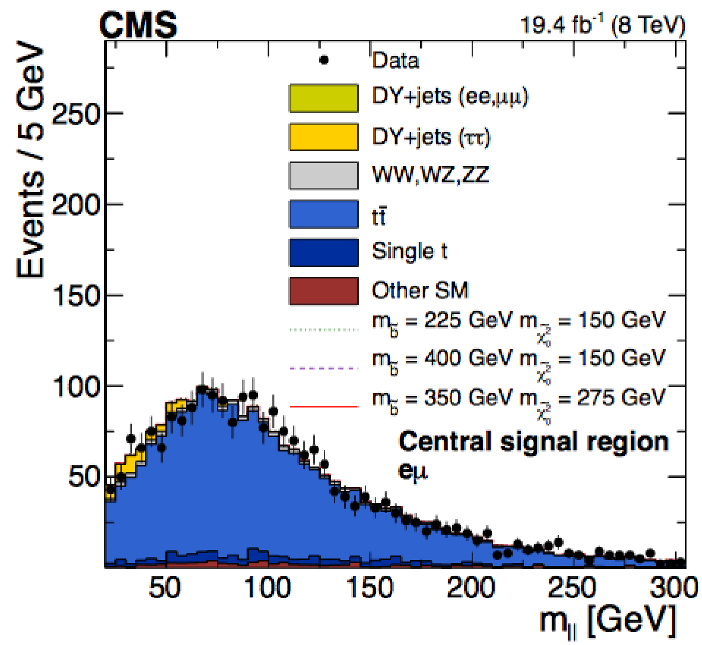
"Slepton" edge



GMSB





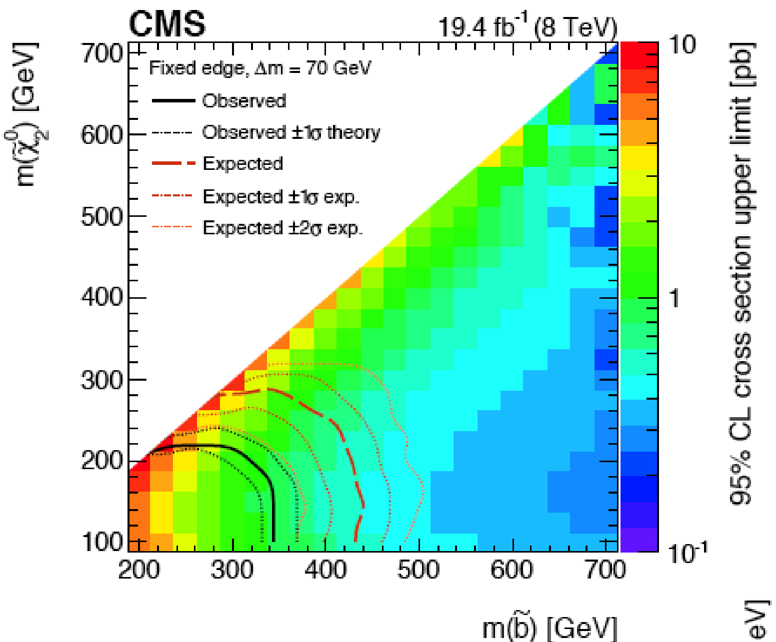


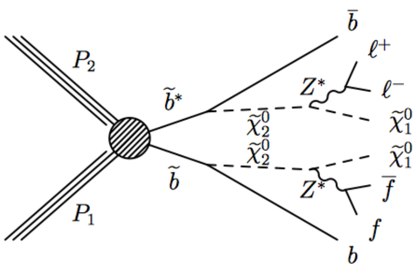
	Low-mass		On-Z		High-mass	
	Central	Forward	Central	Forward	Central	Forward
Observed	860	163	487	170	818	368
Flavor-symmetric	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$	$355 \pm 19 \pm 14$	$131 \pm 12 \pm 8$	$768 \pm 28 \pm 31$	$430 \pm 22 \pm 27$
Drell–Yan	8.2 ± 2.6	2.5 ± 1.0	116 ± 21	42 ± 9	2.5 ± 0.8	1.1 ± 0.4
Total estimated	730 ± 40	158 ± 16	471 ± 32	173 ± 17	771 ± 42	431 ± 35
Observed − estimated	130^{+48}_{-49}	5^{+20}_{-20}	16^{+37}_{-38}	-3^{+20}_{-21}	47^{+49}_{-50}	-62^{+37}_{-39}
Significance	2.6σ	0.3σ	0.4σ	$<0.1\sigma$	0.9σ	$<0.1\sigma$

arXiv:1502.06031

To be followed in Run 2!

CMS: R_P Conservation: (SFOS) di-lepton+Jets+MET



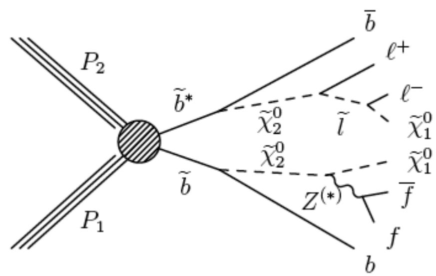


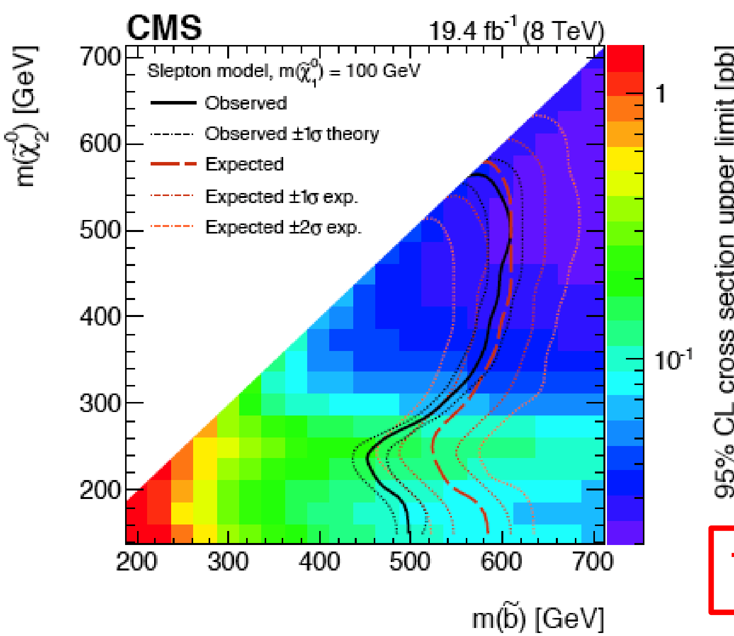
“Fixed” edge

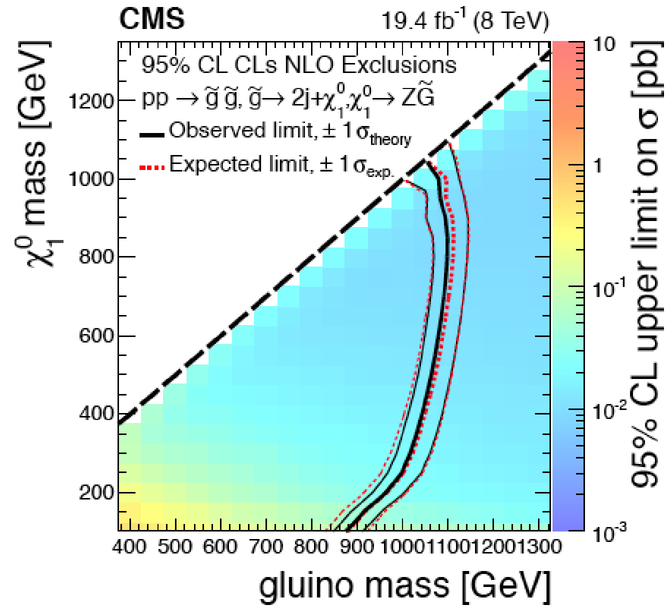
arXiv:1502.06031

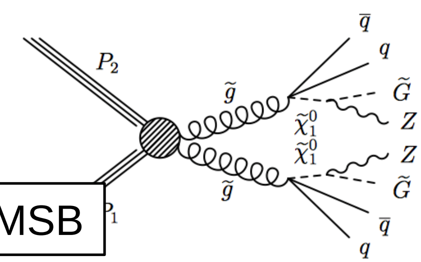
Interpretation
simplifed models

“Slepton” edge







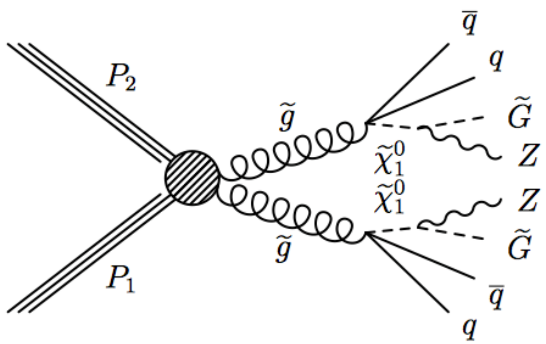


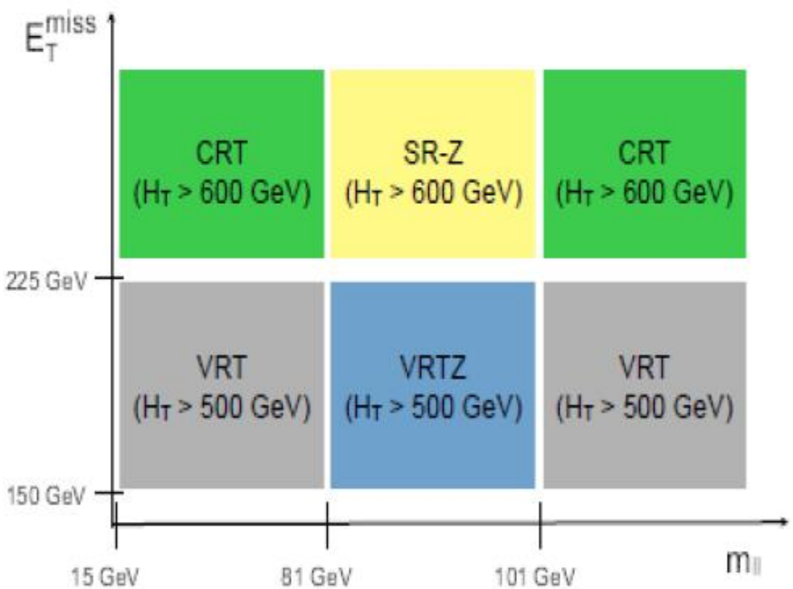
GMSB

To be followed in Run 2!

ATLAS: R_P Conservation: (SFOS) di-lepton+Jets+MET

arXiv:1503.03290

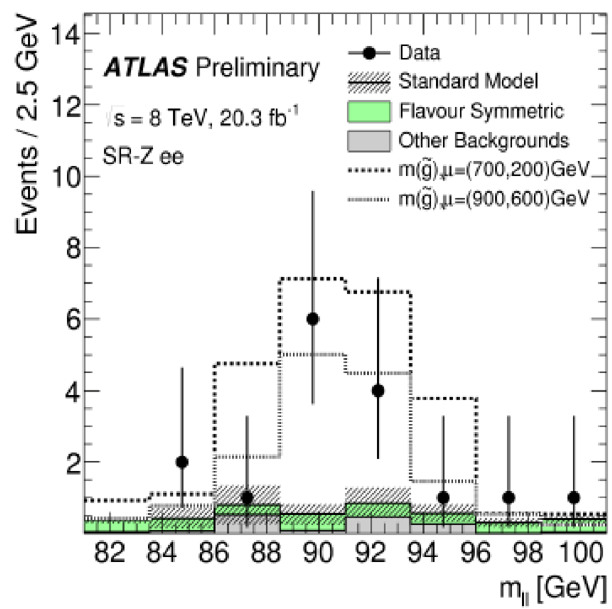


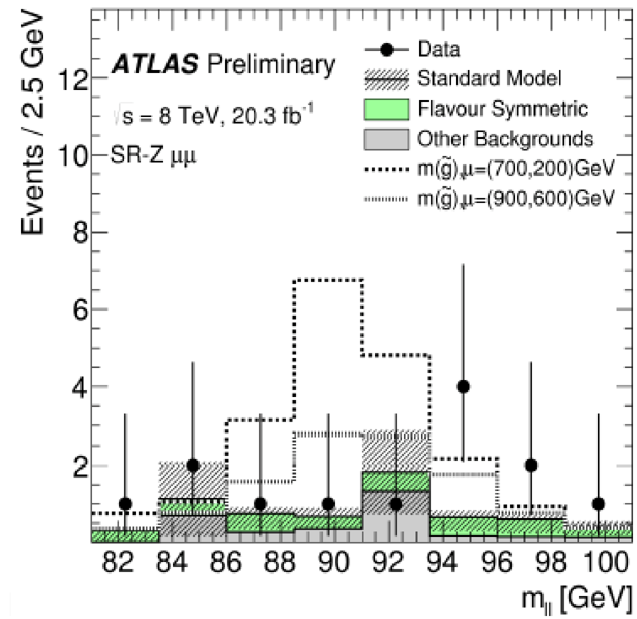


Electron
Data: 16
Bkgd: 4.2±1.6
p-value: 3.0σ

3σ combined

Muon
Data: 13
Bkgd: 6.4±2.2
p-value: 1.7σ

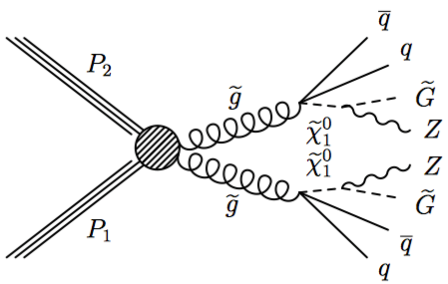


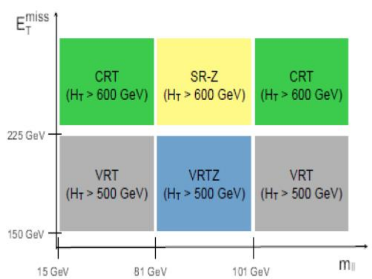


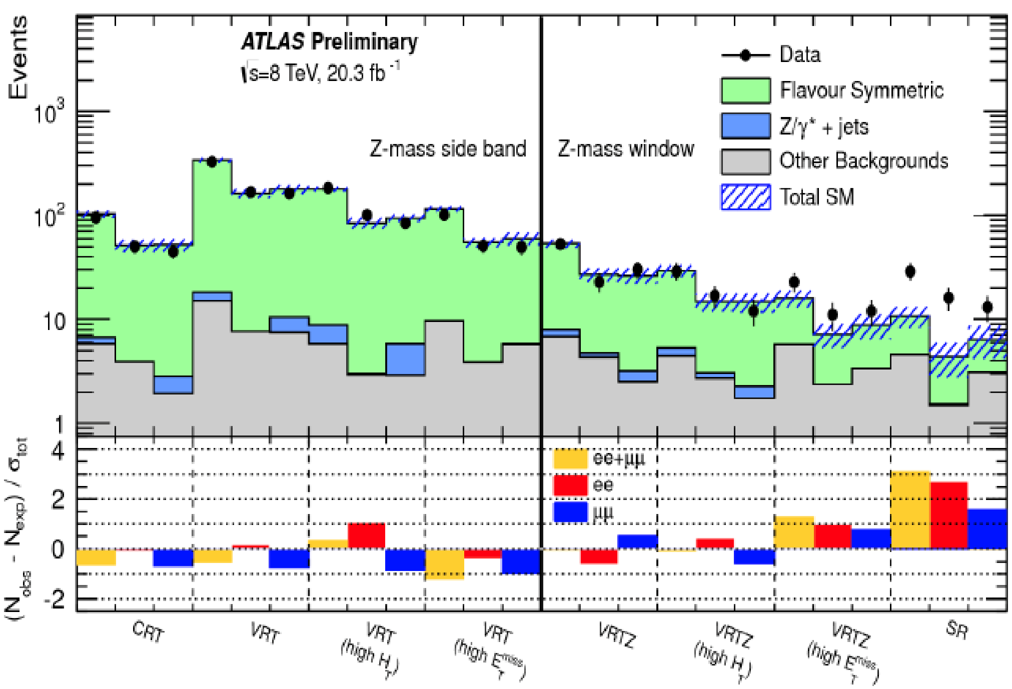
Signal region: H_T>600 GeV, MET>225 GeV

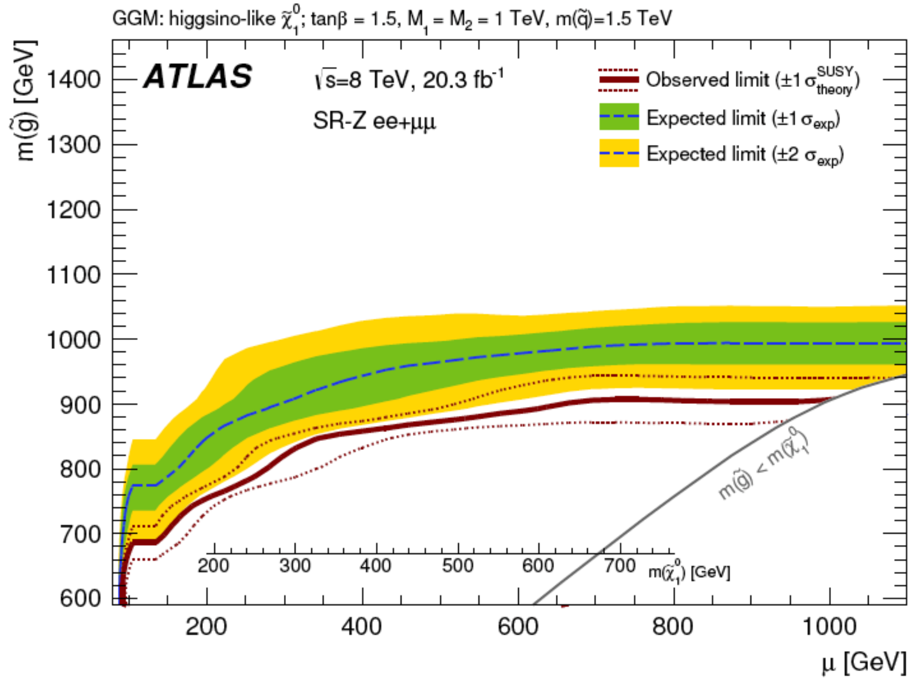
R_P Conservation: (SFOS) di-lepton + Jets + MET

arXiv:1503.03290









3σ combined

To be followed in Run 2!

Remarkable agreement: Data–SM

Multi Jets + MET

Interpret in context of Simplified Models

Gluino and squark production

H_T > 500 GeV
MH_T > 200 GeV
Jets with E_T >50 GeV

Veto on isolated leptons (p_T>10 GeV)

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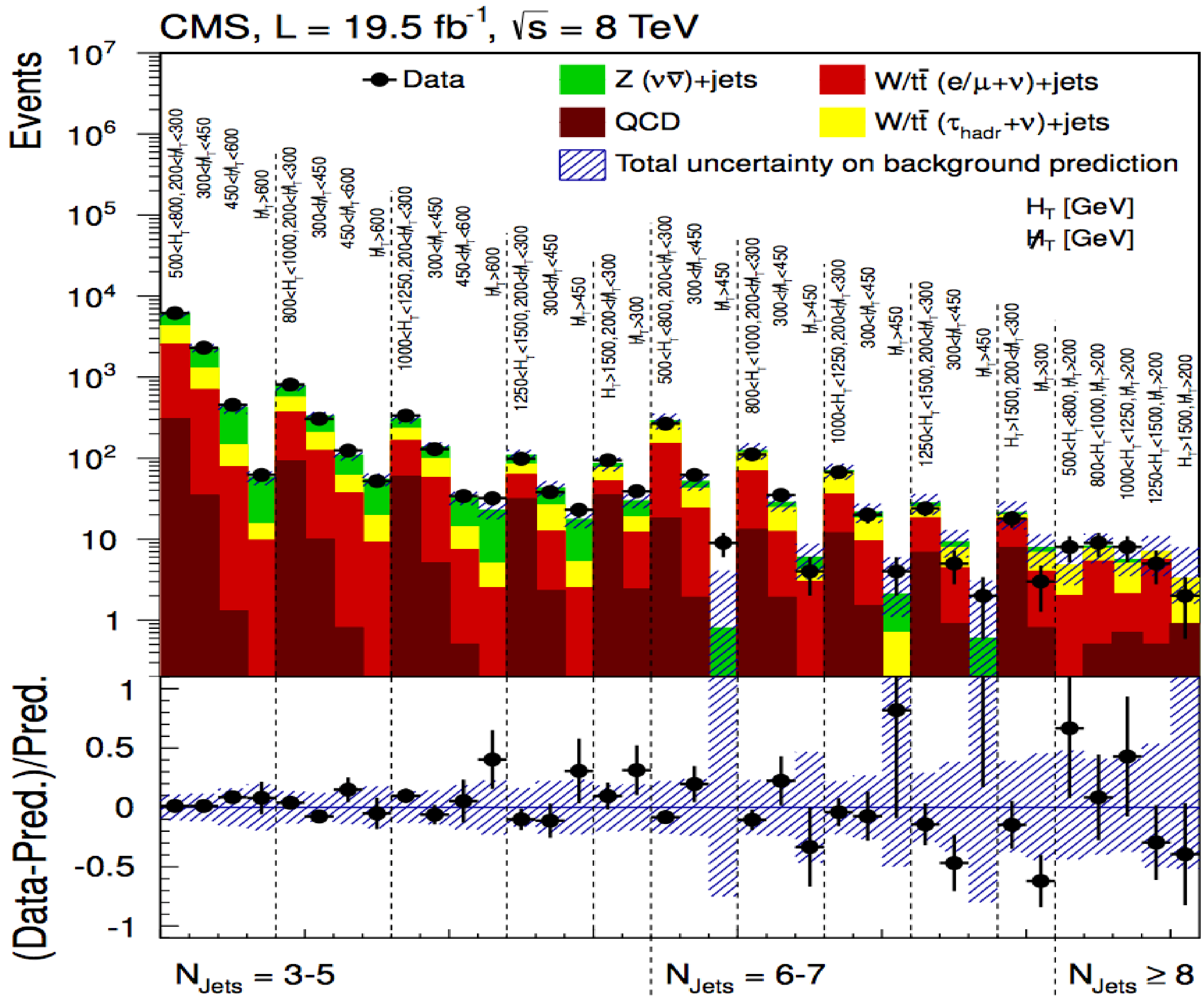
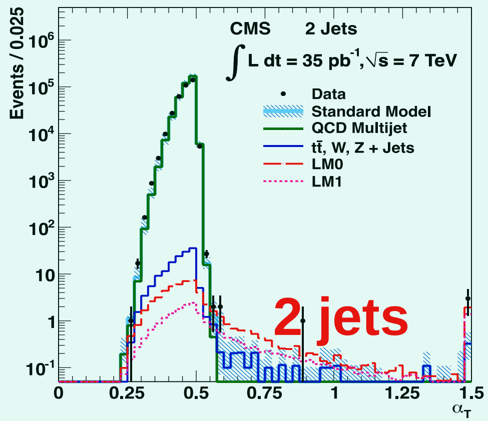


Considerable ingenuity in developing new methods; e.g. event-topology variables

α_T ("QCD killer")

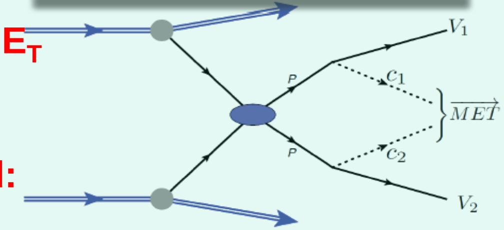
$$a_T = \frac{E_T(j_2)}{M_T(j_1 j_2)} = \sqrt{\frac{E_T(j_2)}{E_T(j_1)}}\,\frac{1}{\sqrt{2(1-\cos\Delta\phi)}} \le \frac{1}{2}$$



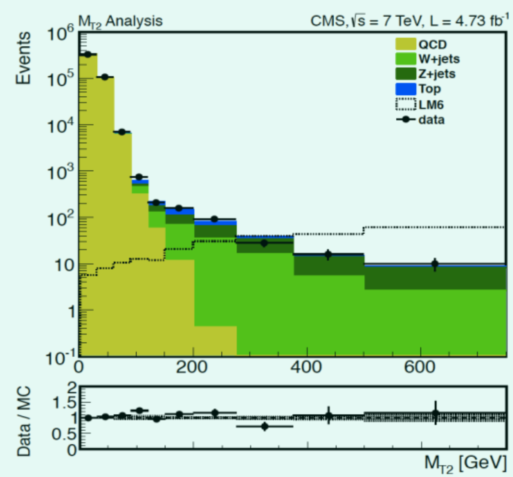
M_{T2}, etc – extensions from $W \rightarrow e\nu$ decays; TWO LSPs

Lesters & Summers, hep-ph/9906349

Signal: $M_{T2} \sim ME_T$;
Bkg: $M_{T2} \sim 0$
Mis-measured: $M_{T2} < ME_T$



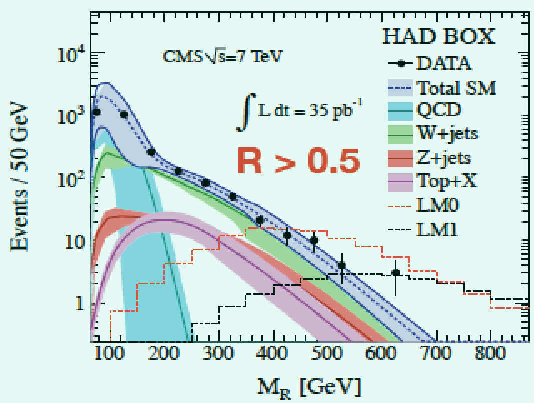
$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not{p}_T}\left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$



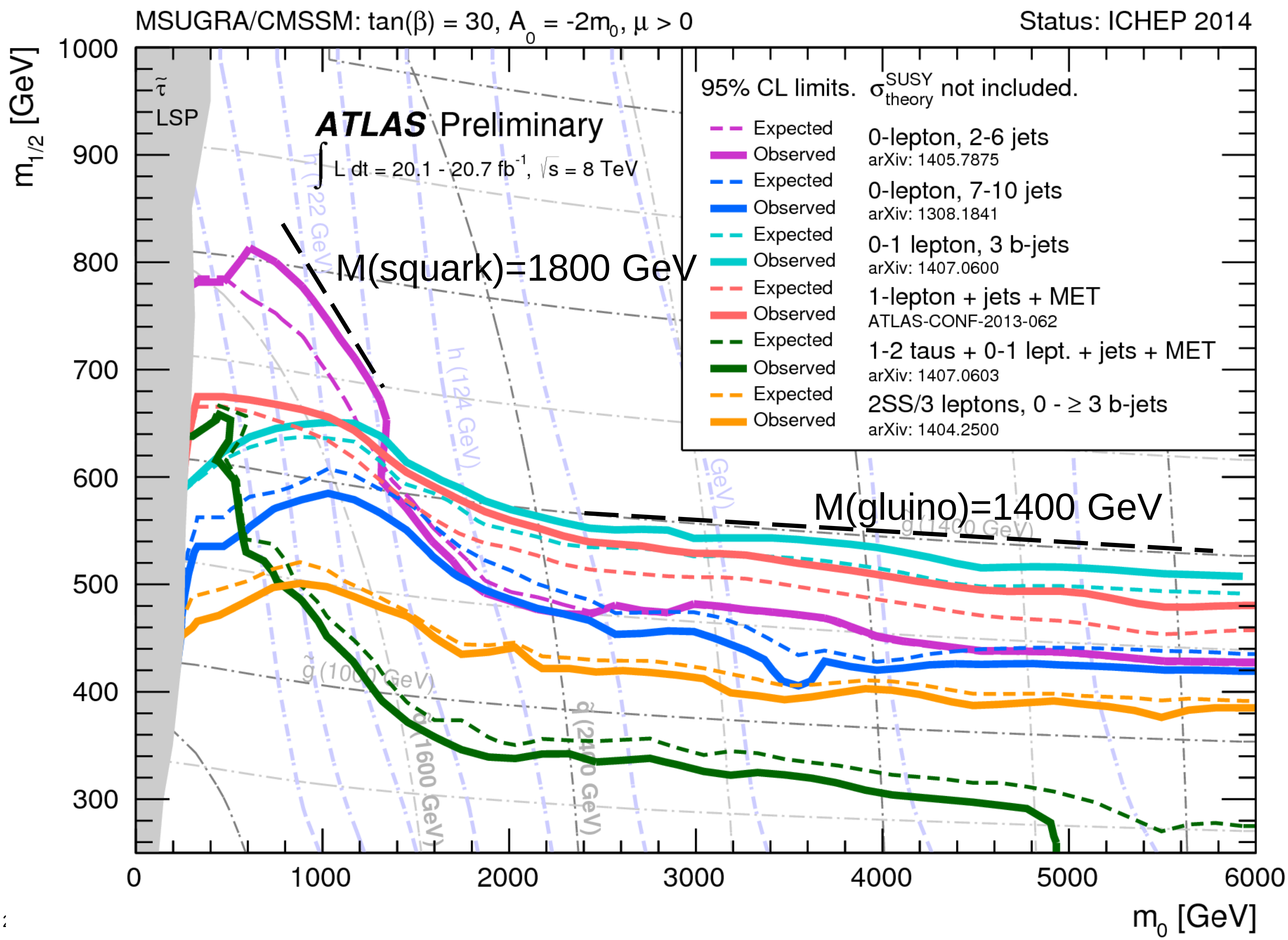
Razor (hunt for mass bump)

$$R \equiv \frac{M_T^R}{M_R}$$

For $\gamma_{CM} \rightarrow 1$; $M_R \rightarrow M_\Delta$
M_T^R has endpoint: $M\Delta$
$M_\Delta = M_{sq}^2 - M_\chi^2 / M_{sq}$



R_P Conservation: Summary of inclusive searches



Do [should] we still believe in SUSY

P. Sphicas, Latsis Symposium 2013

1. SUSY no-lose theorem: so many new parameters ($N_{MSSM} = N_{SM} + 105$) that it can never be declared dead (even the CMSSM); unless naturalness arguments used

2. Can it be that nature has missed opportunity to solve three major pending issues (M_H; Dark Matter; couplings) in one swoop?
   - **Three goods for the price of two** [one new principle (B→F; F→B) and one unknown symmetry-breaking mechanism]

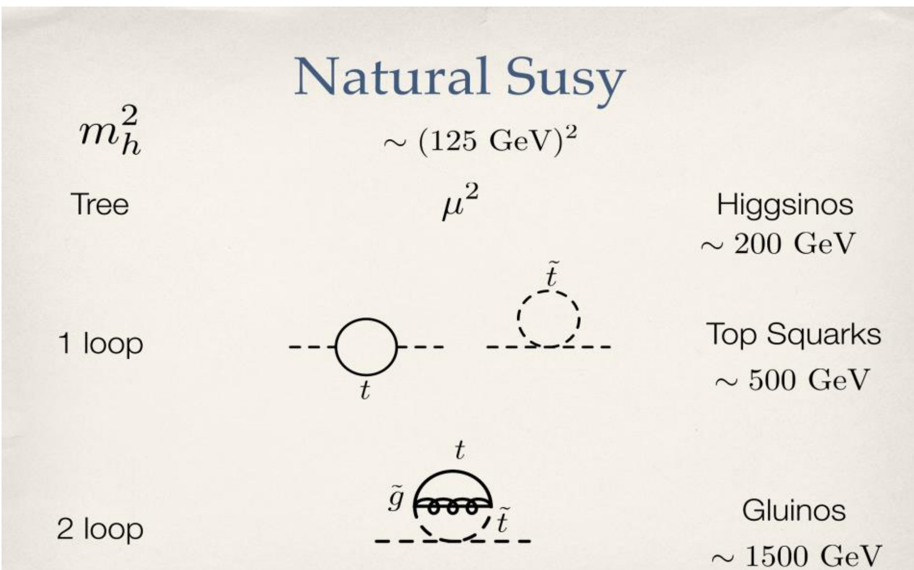
3. Alternative theories solve only one or two of these issues – so it allows consideration of less “powerful” versions of SUSY

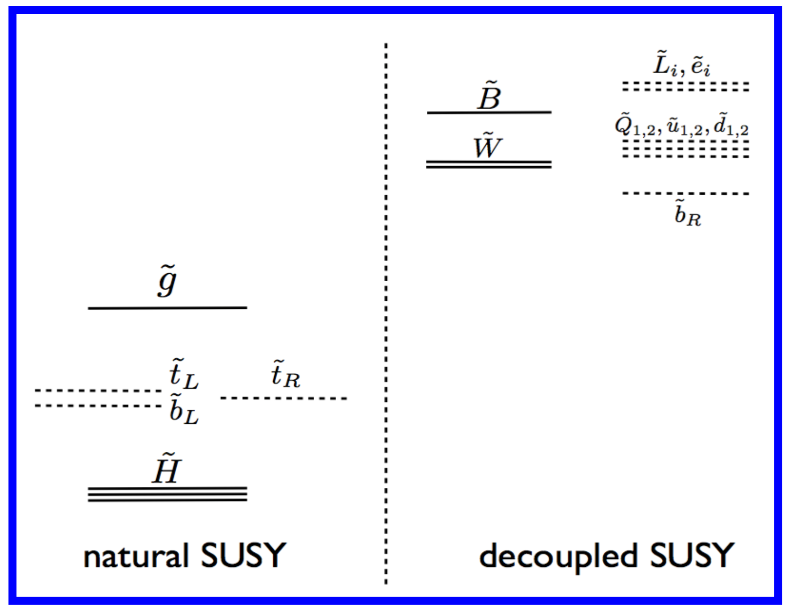
   As long as it solves the naturalness issue (which conveniently implies weak-scale SUSY)

- **Assuming it’s there, but it has escaped. How?**

Natural relationship between Higgs & SUSY

- Previous limits not applicable when ME_T is small (Compressed spectra; R_P violation?!?)
- Other signatures that would have (easily!) escaped?
- **A light top squark (stop) would suffice!**

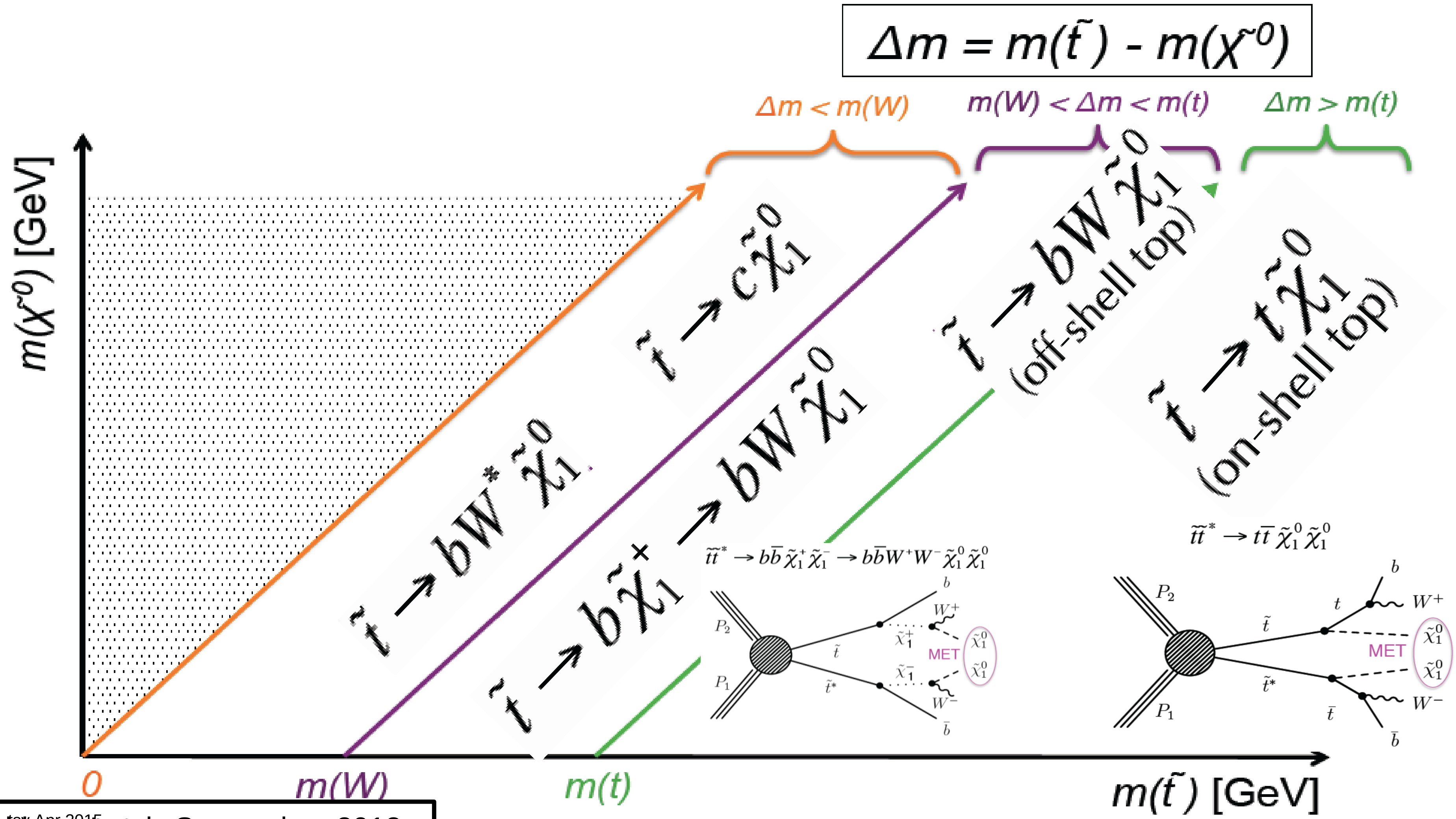




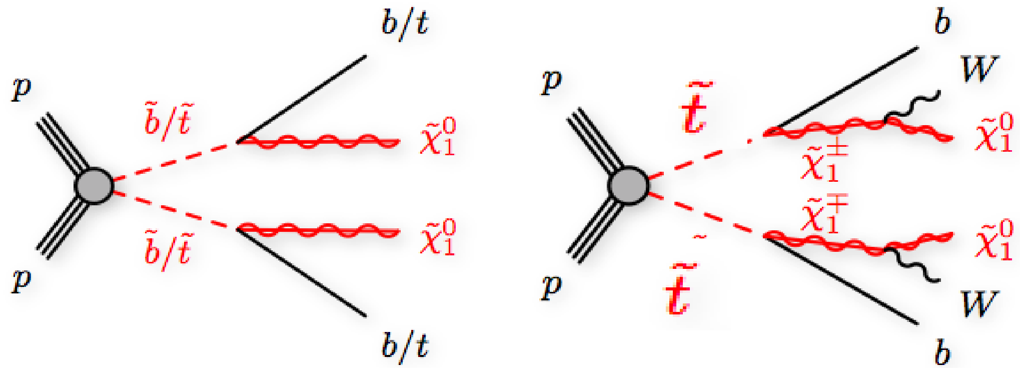
- Previous limits not applicable, due to (expected) different decays of the stop

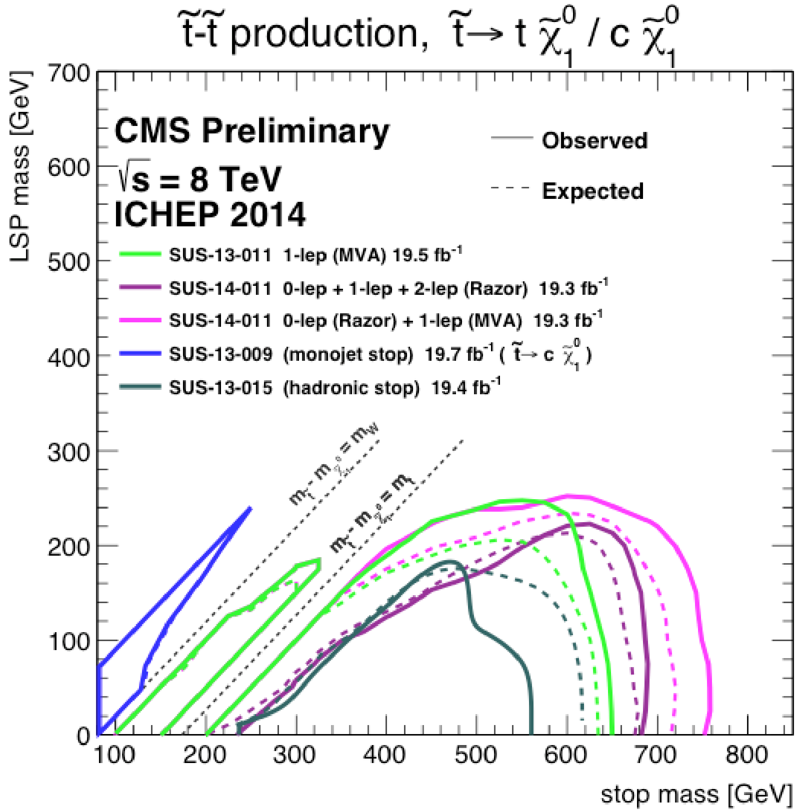
R_P Conservation: Direct stop search

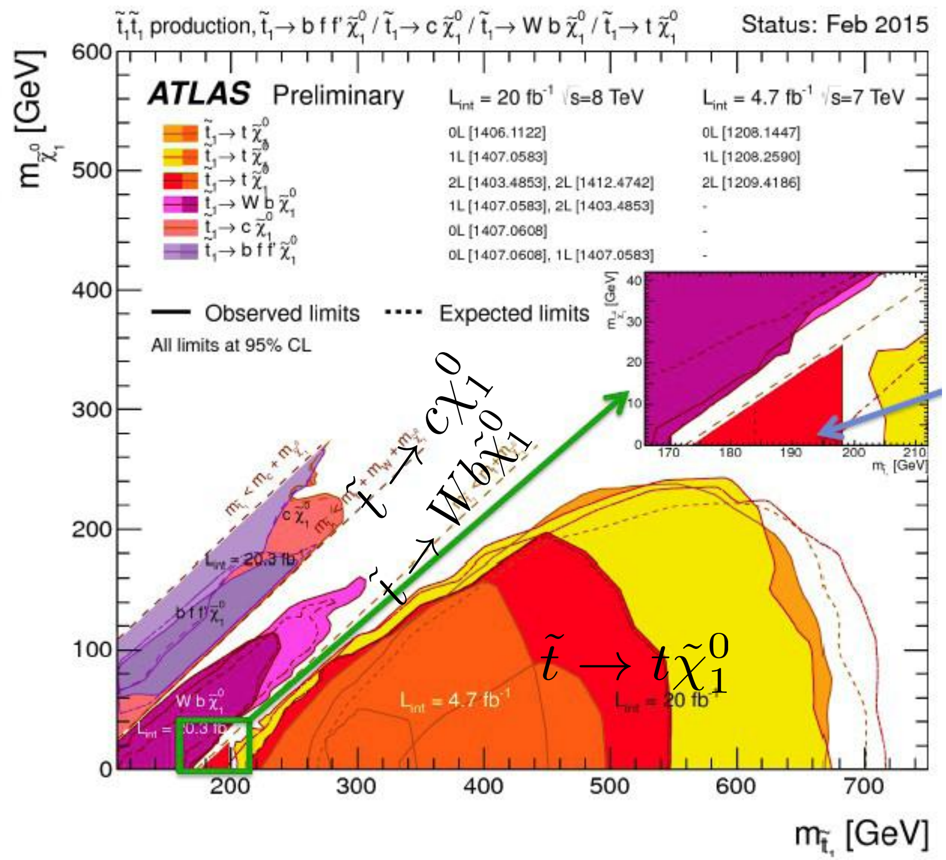
- Top squark decays: in large region, ~ "top+ME_T"



R_P Conservation: Dedicated searches for direct stop-pair production







- In the gaps, even after significant effort we are still not able to go beyond stop masses above 300 GeV!!!
- Analyses mainly rely on ISR to trigger the events.

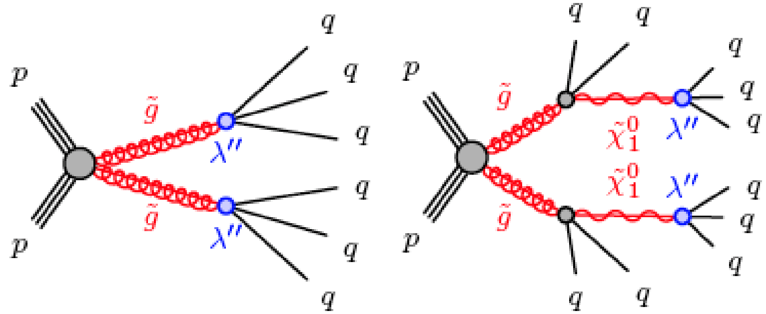
R_P violating SUSY

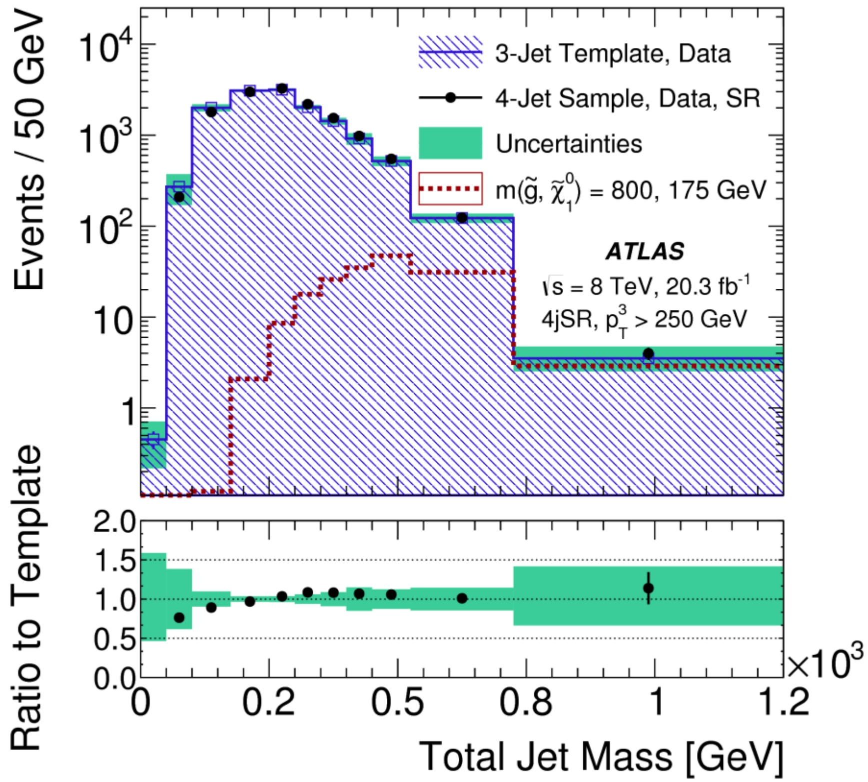
$$\Delta L = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

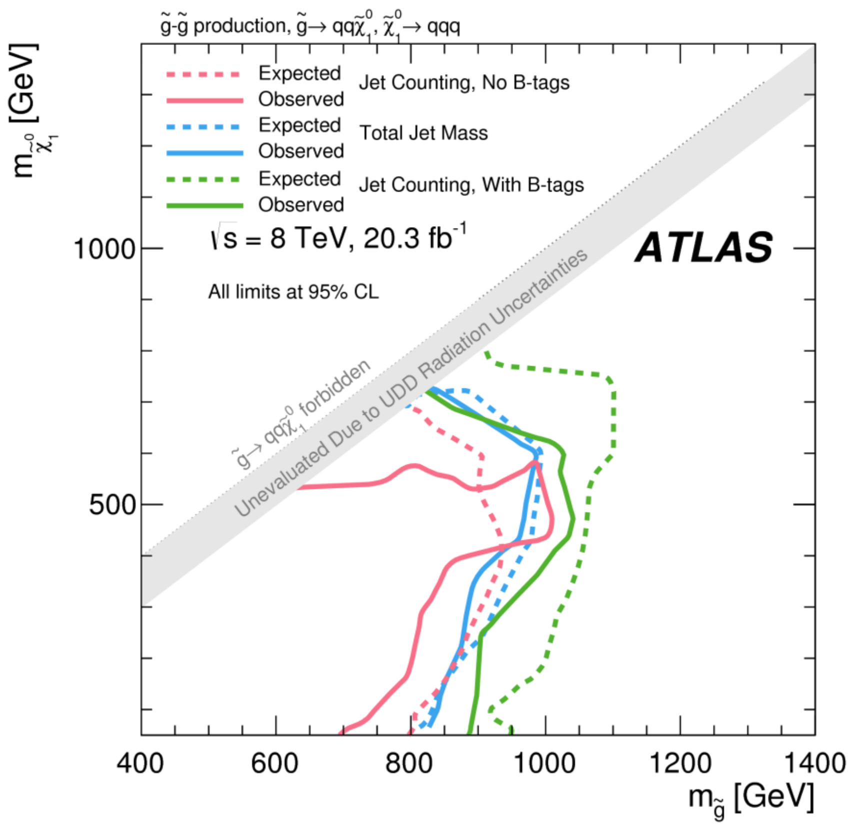
A test of RPV: with hadrons only

Hard… gluino → multi- jets (no MET)

- Search for excess in
  ≥ 6,7 jets or large total (Fat-)jet mass
- **Gluino excluded ≤ 900 GeV**.



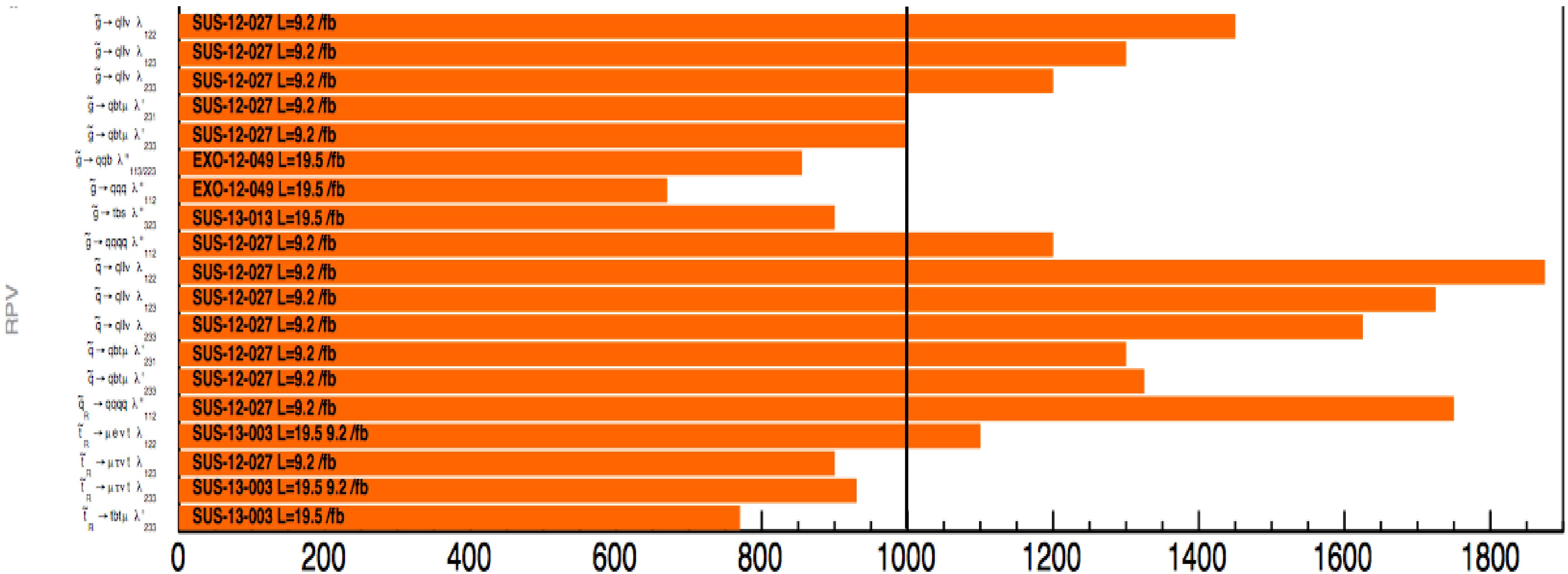




arXiv:1502.05686

Summary of RPV (with leptons) (e.g. CMS)

Summary of CMS RPV SUSY Results*

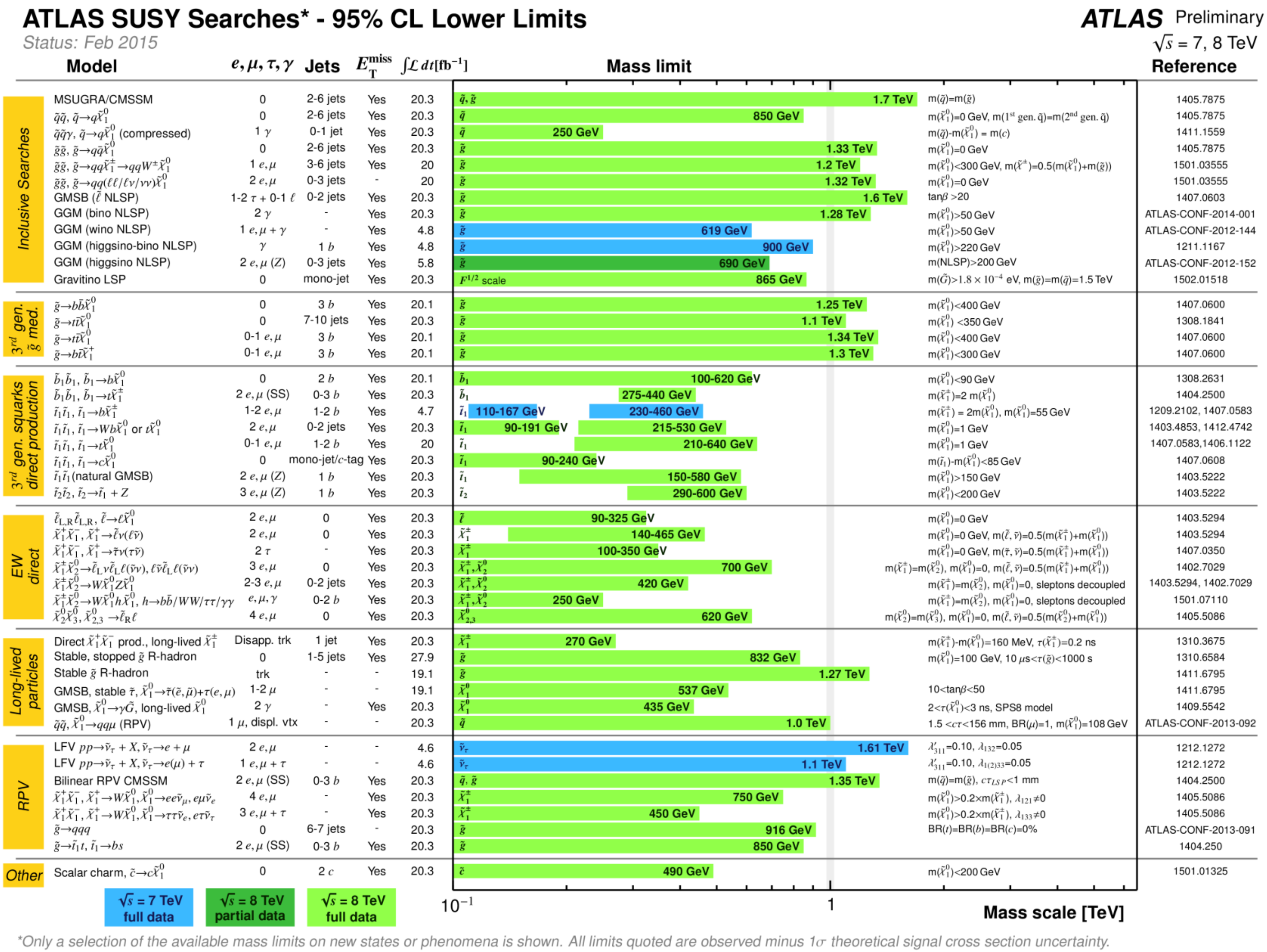


*Observed limits, theory uncertainties not included

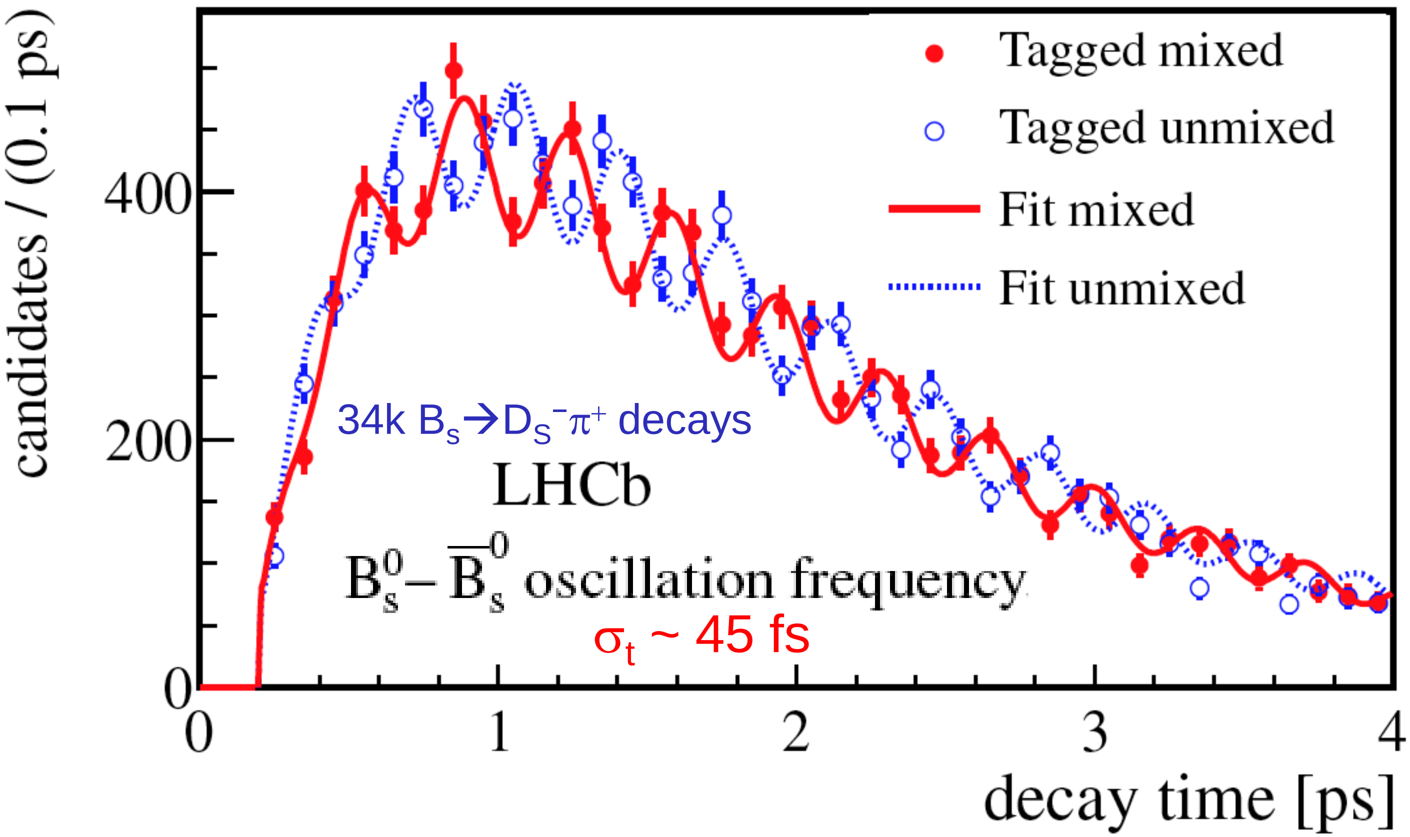
Only a selection of available mass limits

Probe *up to* the quoted mass limit

A dizzying exclusion map



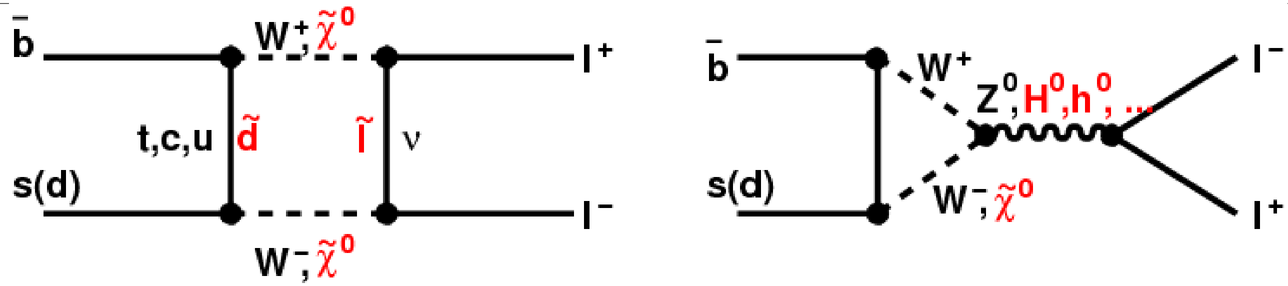
LHCb and Rare Decays



Δm_S = 17.768±0.023(stat)±0.006(syst) ps^{-1}

NJP 15 (2013) 053021

Supersymmetry and Rare B Decays: B → μμ



Sensitive to New Physics, can be strongly enhanced in SUSY with scalar H exchange

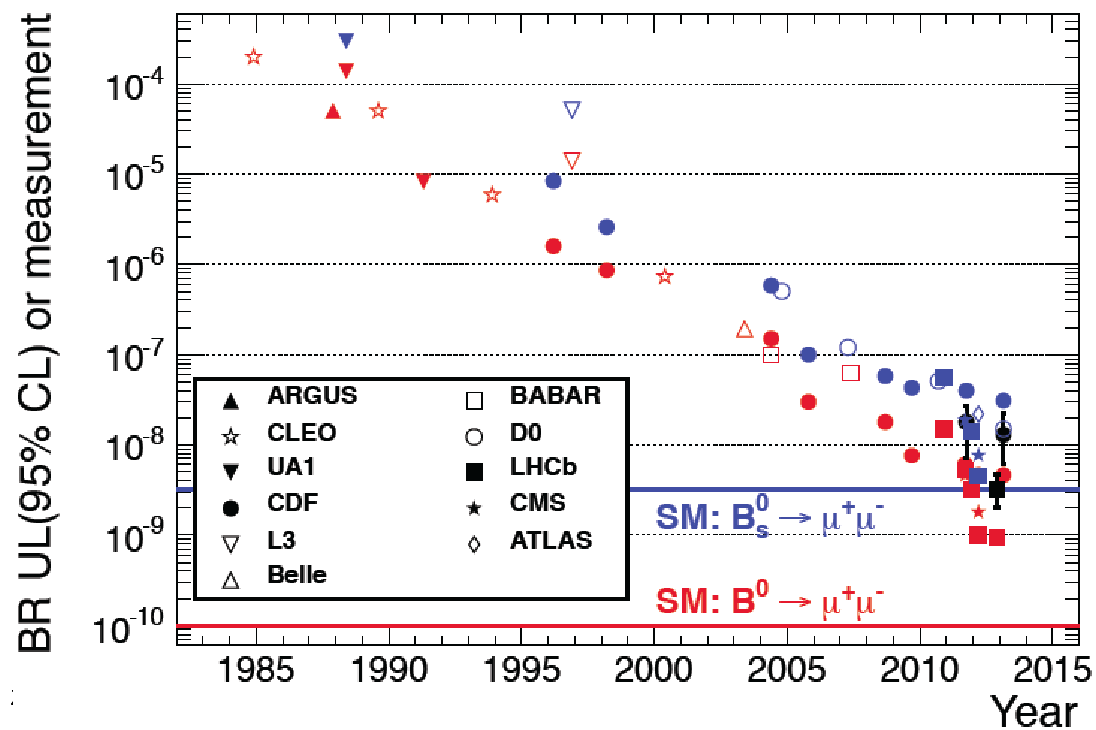
Sensitive probe for MSSM with large tanβ: $B(B_S \to \mu^+\mu^-) \sim \tan\beta^{\,6} / M_A^{\,4}$

In Standard Model:

$B(B_d \to \mu\,\mu) = (0.10 \pm 0.01)\times 10^{-9}$

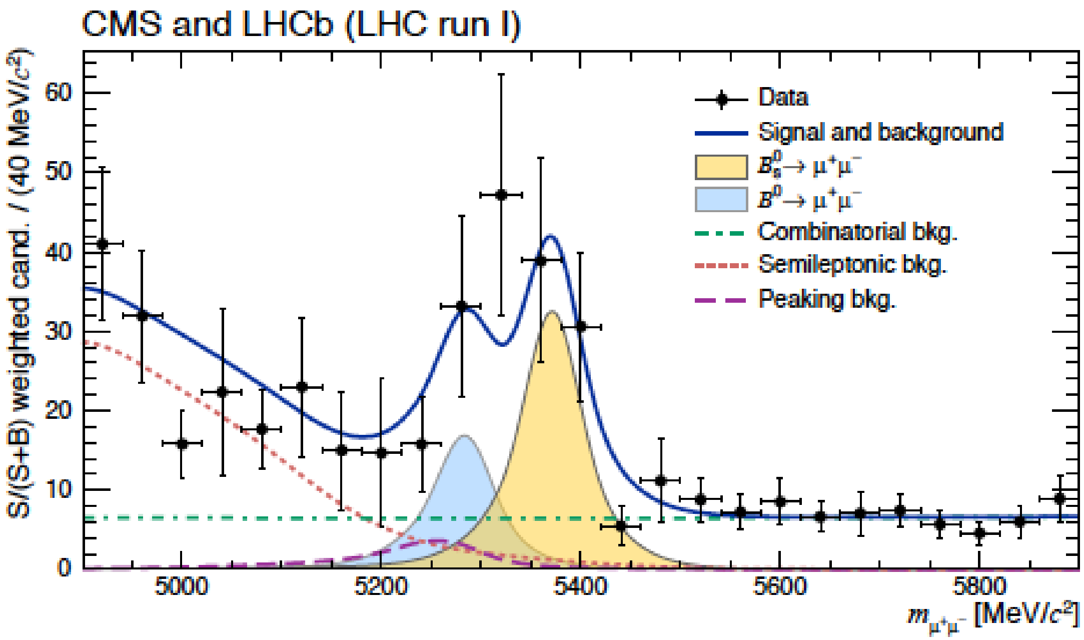
$B(B_s \to \mu\,\mu) = (3.2 \pm 0.2)\times 10^{-9}$

[A.J.Buras: arXiv:1012.1447]



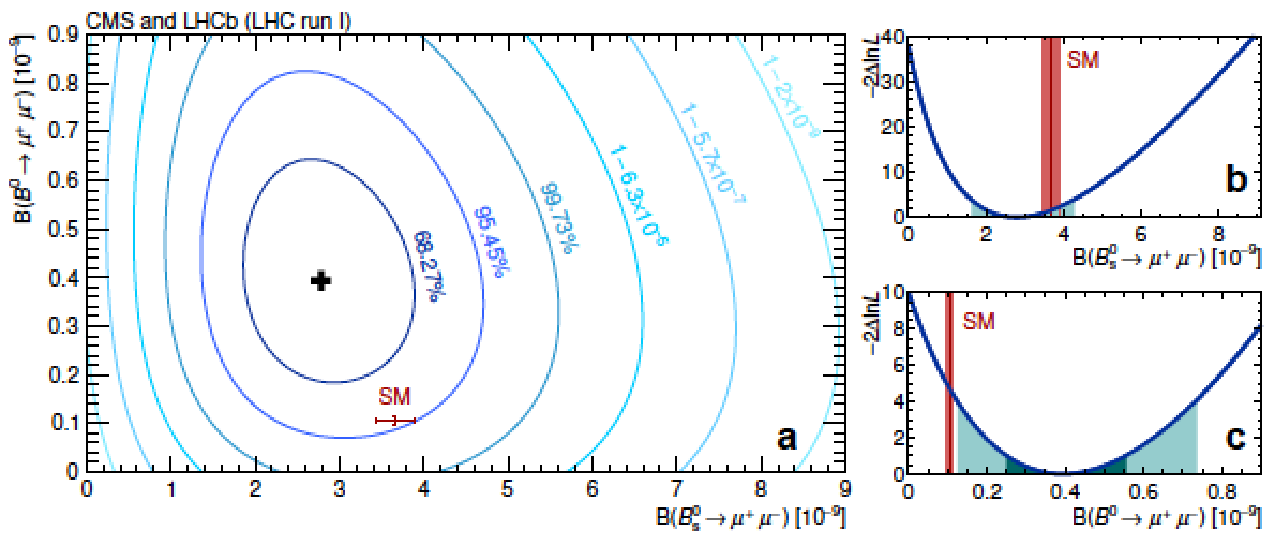
Imperial College London

Observation of $B_s \to \mu\mu$



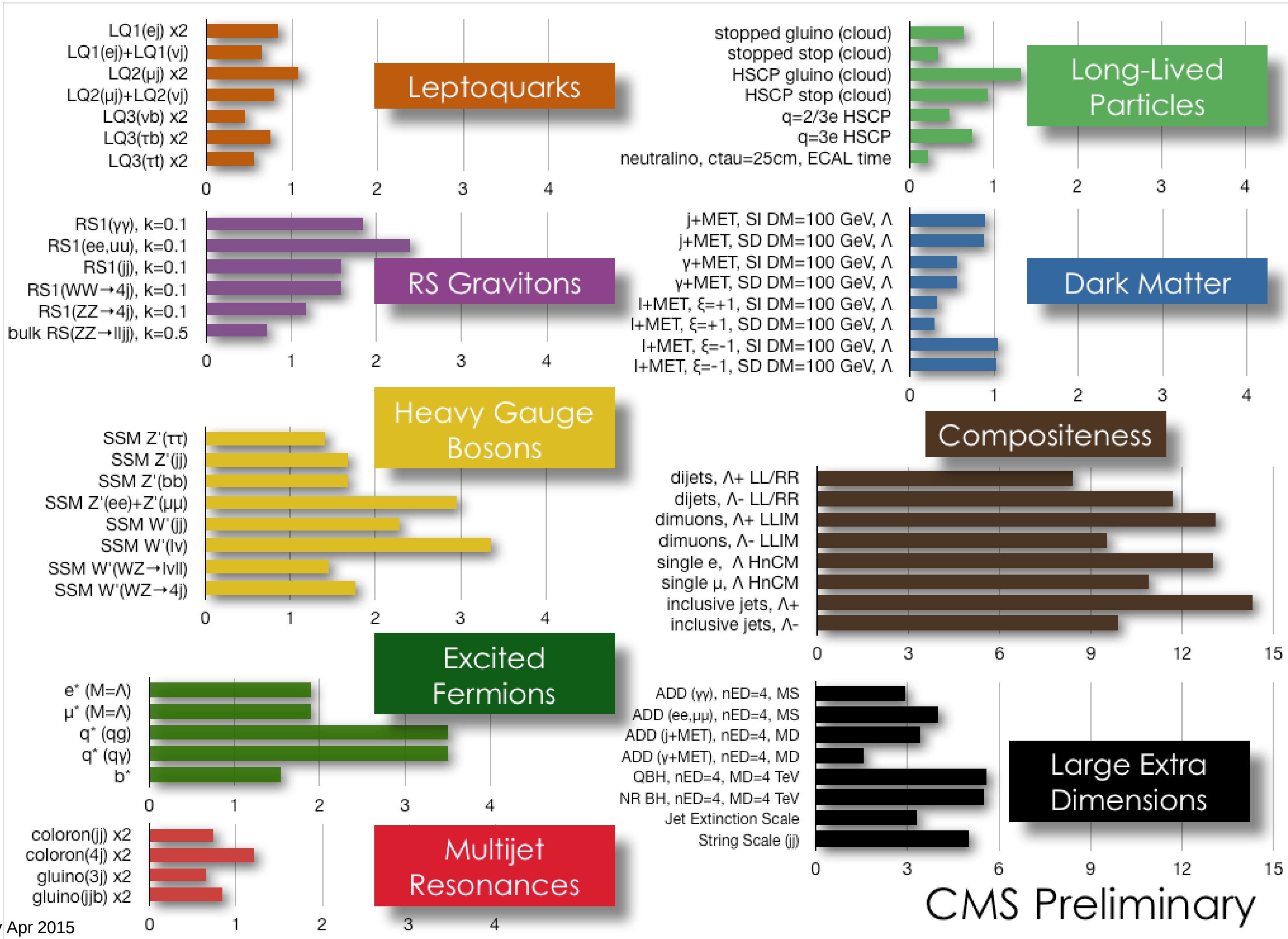
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

arXiv: 1411.4413



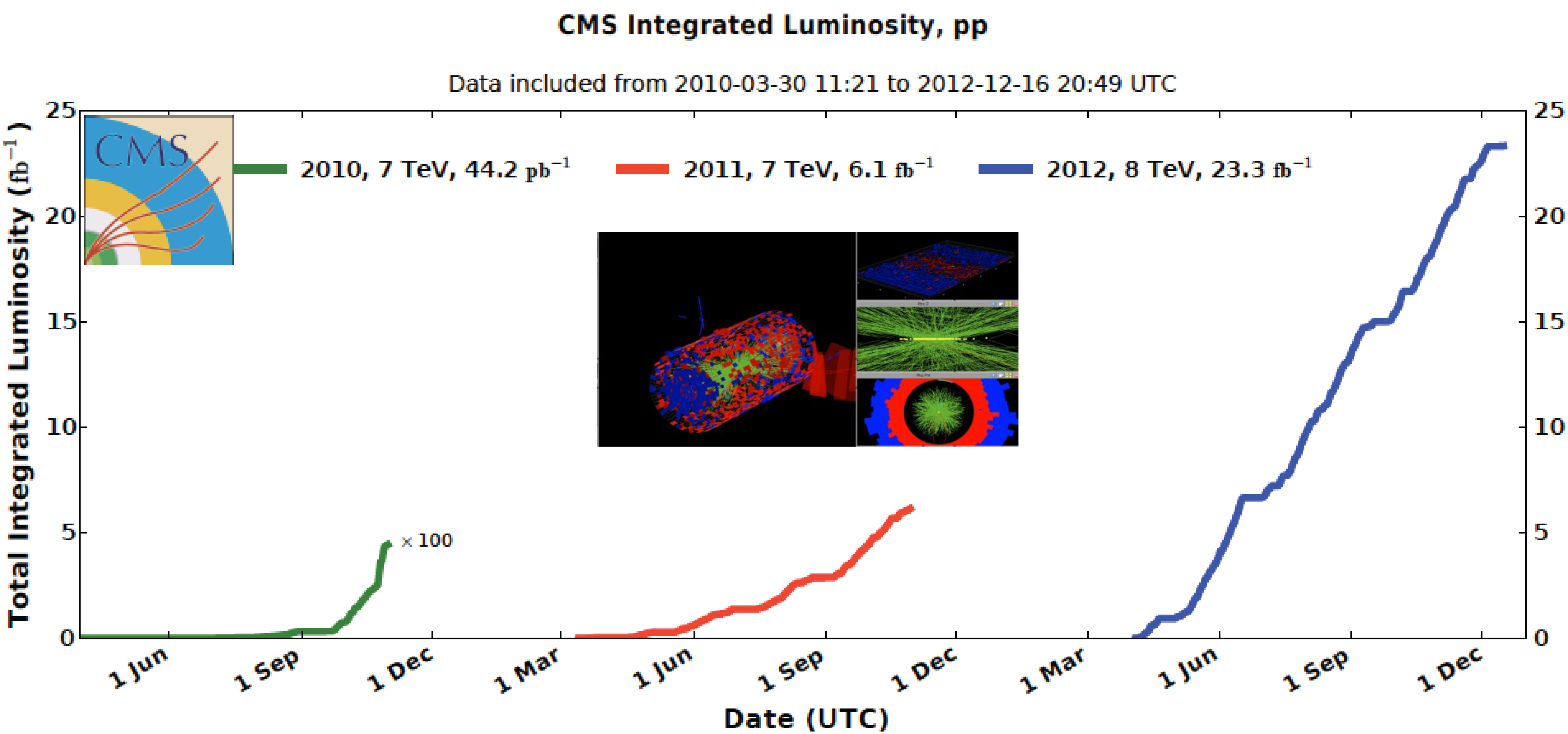
To be followed in Run 2!

Another dizzying exclusion map



Outlook

An amazing three years



LHC roadmap to achieve full potential

Last update: December 2013

Year	Period	Milestone	Run / integrated luminosity
2009		LHC startup, √s 900 GeV	
2010–2012		√s=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns	Run 1, ~25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity - Phase 0	
2015–2018		√s=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 2, ~75-100 fb^{-1}
2018–2019	LS2	Injector + LHC Phase I upgrade to ultimate design luminosity	
2020–2022		√s=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 3, ~350 fb^{-1}
2023–2025	LS3	HL-LHC Phase II upgrade: Interaction Region, crab cavities?	
2025 … 2035?		√s=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling	~3000 fb^{-1}

14 TeV vs 8 TeV – Gain Factors

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: Factor ~2

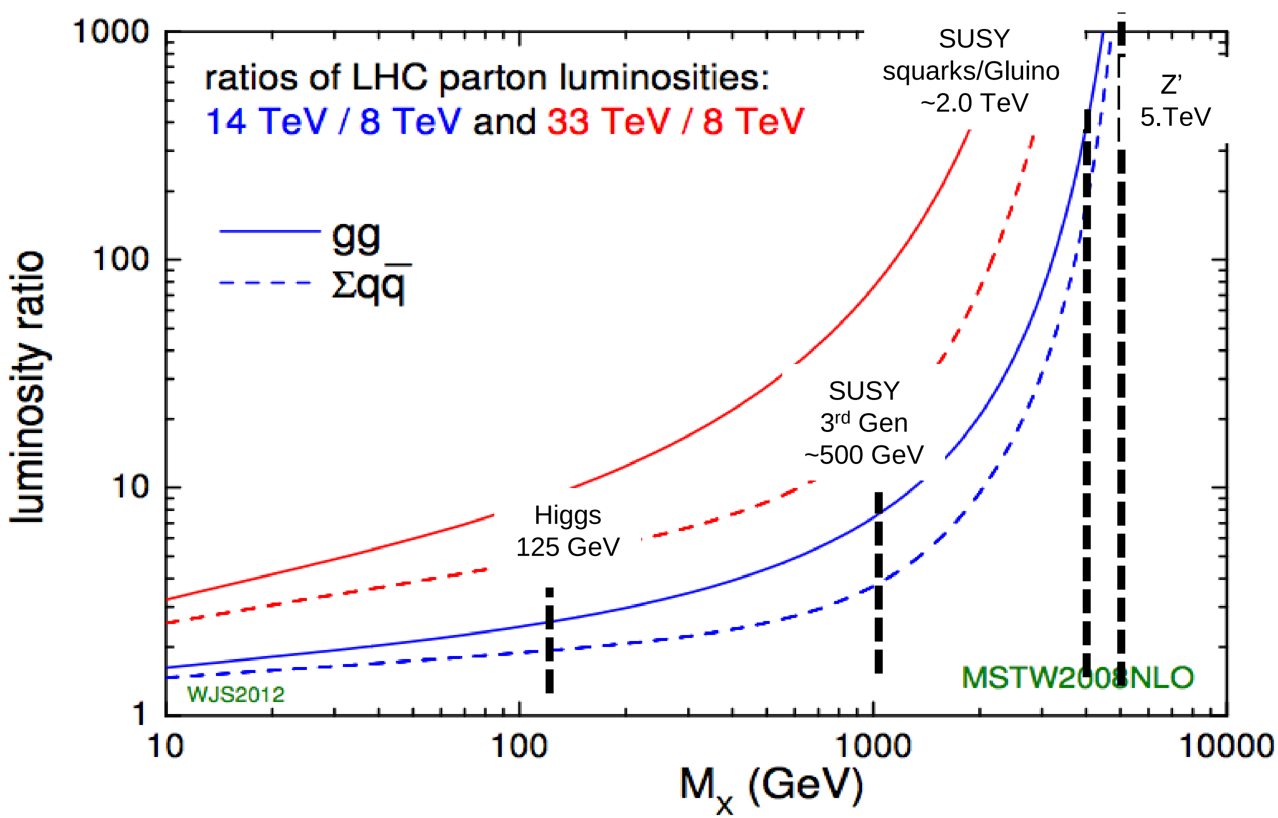
SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: Factor ~ 8

SUSY – Squarks/Gluino:
Mass scale ~ 2.0 TeV
qq,gg,qg: Factor ~300

Z' :
Mass scale ~ 5 TeV
qq: Factor ~1000

O. Buchmuller

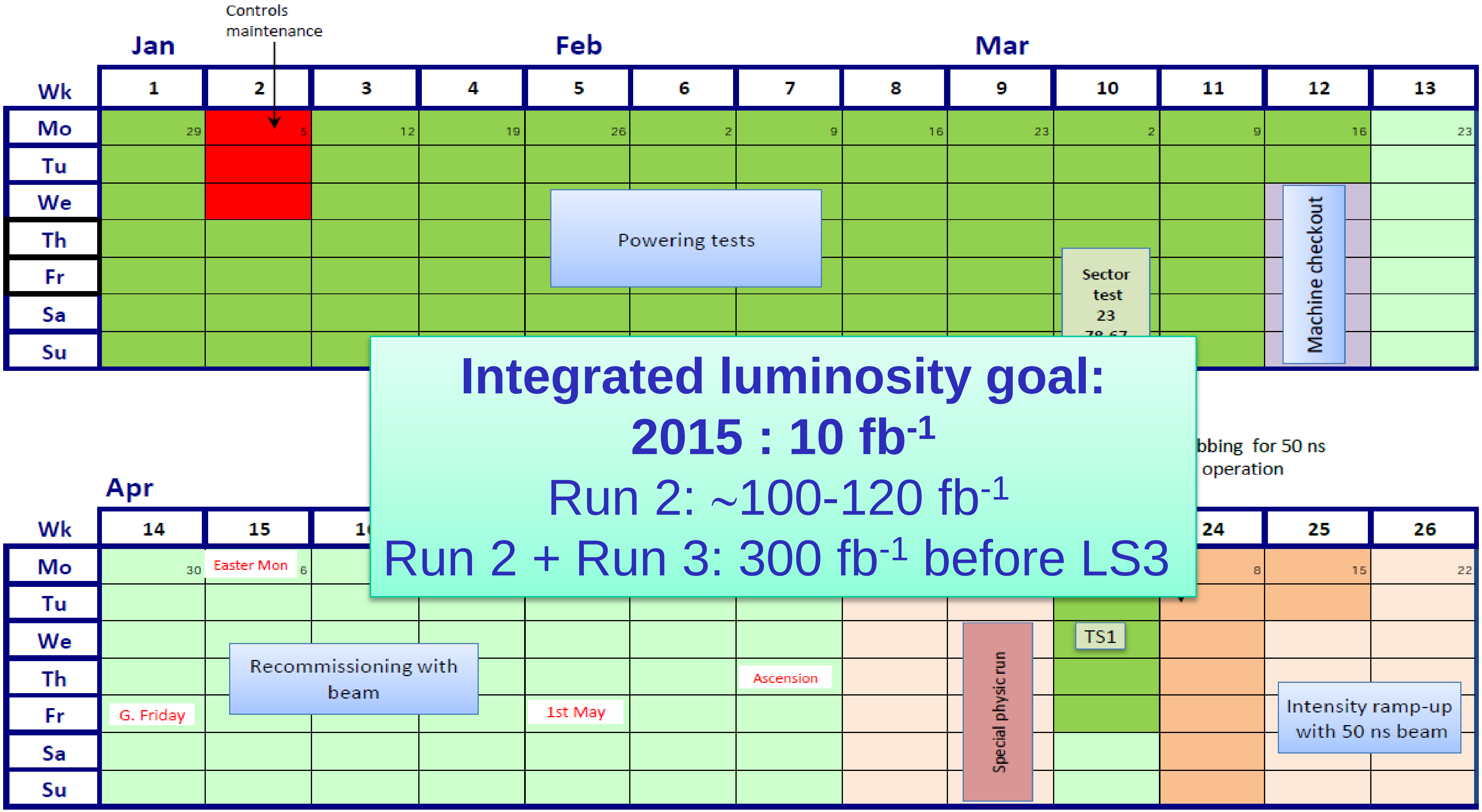
J. Stirling



For the searches increase in energy will help a lot!

Imperial College London

Restarting the LHC at 13 TeV



Integrated luminosity goal:

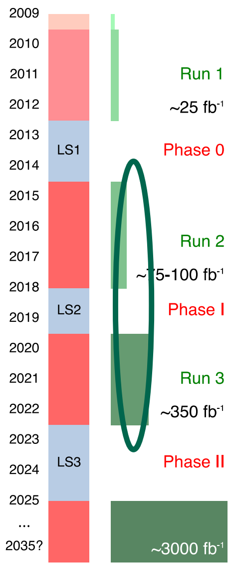
2015 : 10 fb^{-1}

Run 2: ~100-120 fb^{-1}

Run 2 + Run 3: 300 fb^{-1} before LS3

Looking Ahead to Phase 1

Runs 2 and 3



- **Conduct detailed studies of the properties of the found Higgs boson.** Run II will produce > 5M Higgs bosons
- Search for exotic decays of Higgs boson?

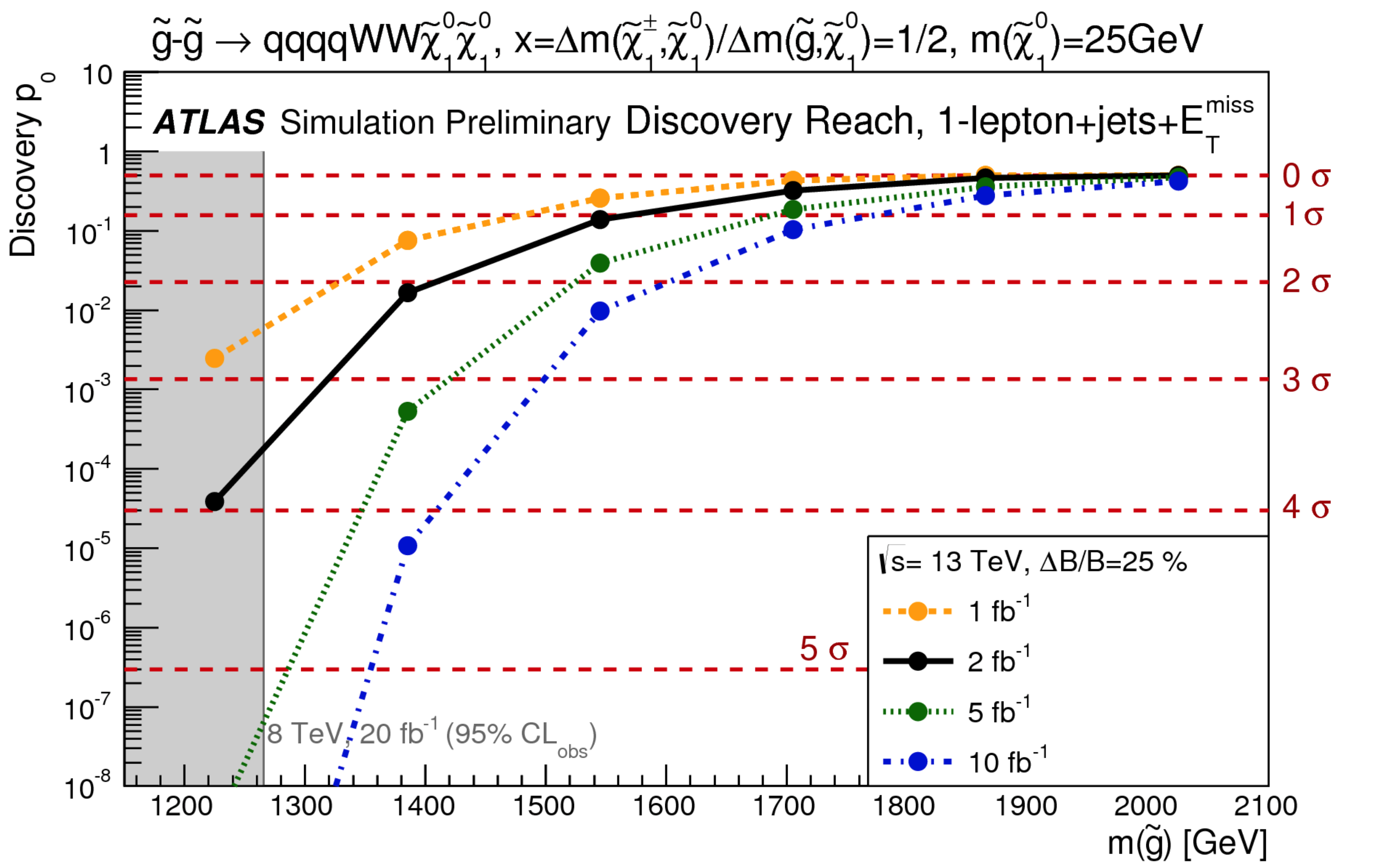
Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ
ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]
CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]

- **Couplings Precision ~ 5-15%** 300 fb^{-1}

- **Search for new physics: resonances, supersymmetry, exotica, yet unknown.**

It is conceivable that we find new heavy particle(s) in Phase 1.

- **Look for deviations from the standard model – precision SM measurements** (e.g. tens of millions of top pairs produced/yr)



ATL-PHYS-PUB-2015-005

Looking Further Ahead to Phase 2 (HL-LHC)

Topmost Priority – exploitation of the full potential of the LHC
High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

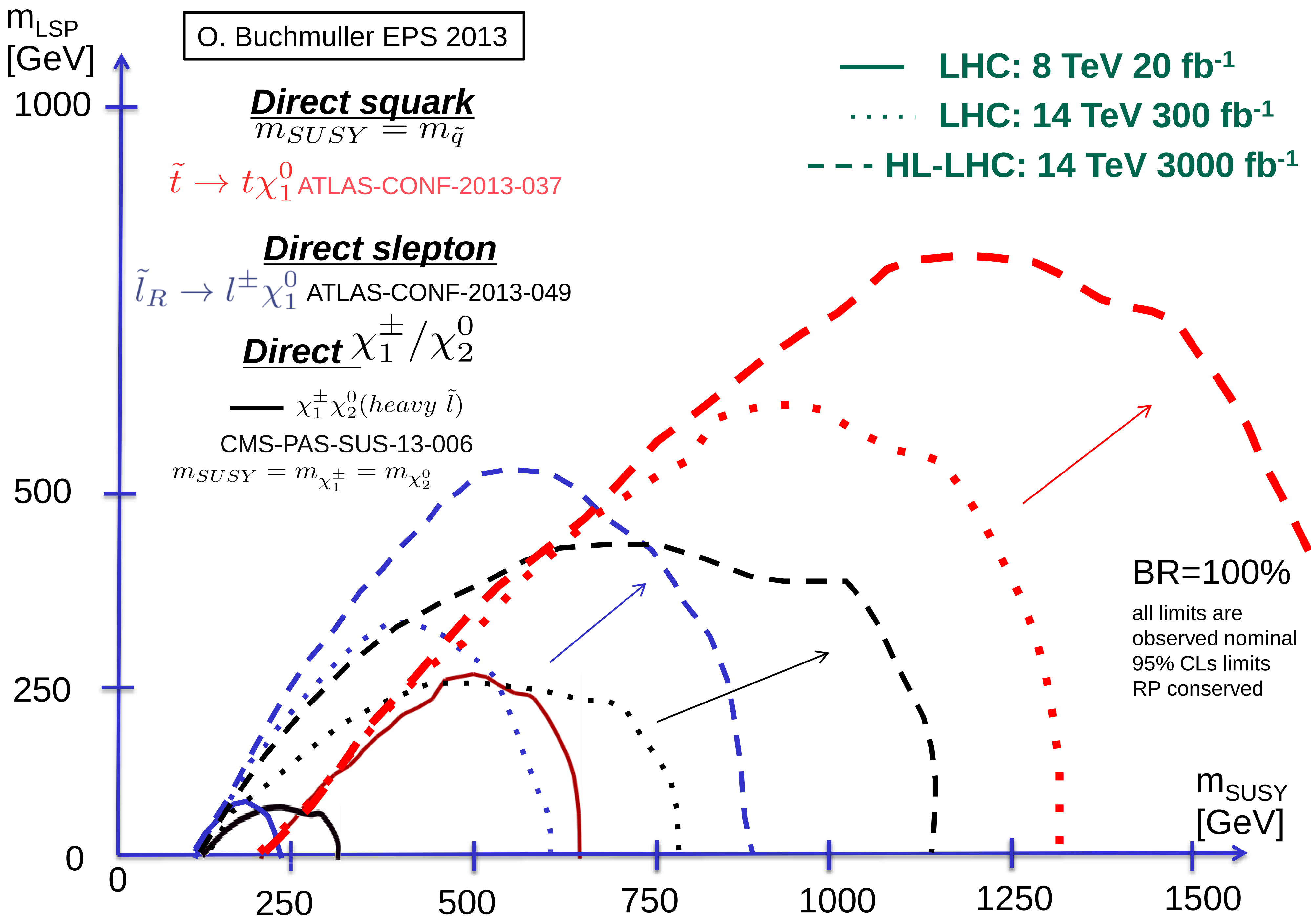
Conduct detailed studies of the properties of the found Higgs boson.
How much does it contribute to restoring unitarity in VBF (closure test of SM), exotic decays, rare decays (e.g. $H \rightarrow \mu\mu$)

LHC → HL-LHC - a Higgs factory! 100M produced $3ab^{-1}$

$L(fb^{-1})$	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

Couplings Precision ~ 2-10%, H self coupling ~30% (needs study)

Continue searching for new physics. If new physics has been found by the end of Phase 1, associated particle(s) will be heavy.
Then conduct detailed studies in Phase 3 (HL-LHC).



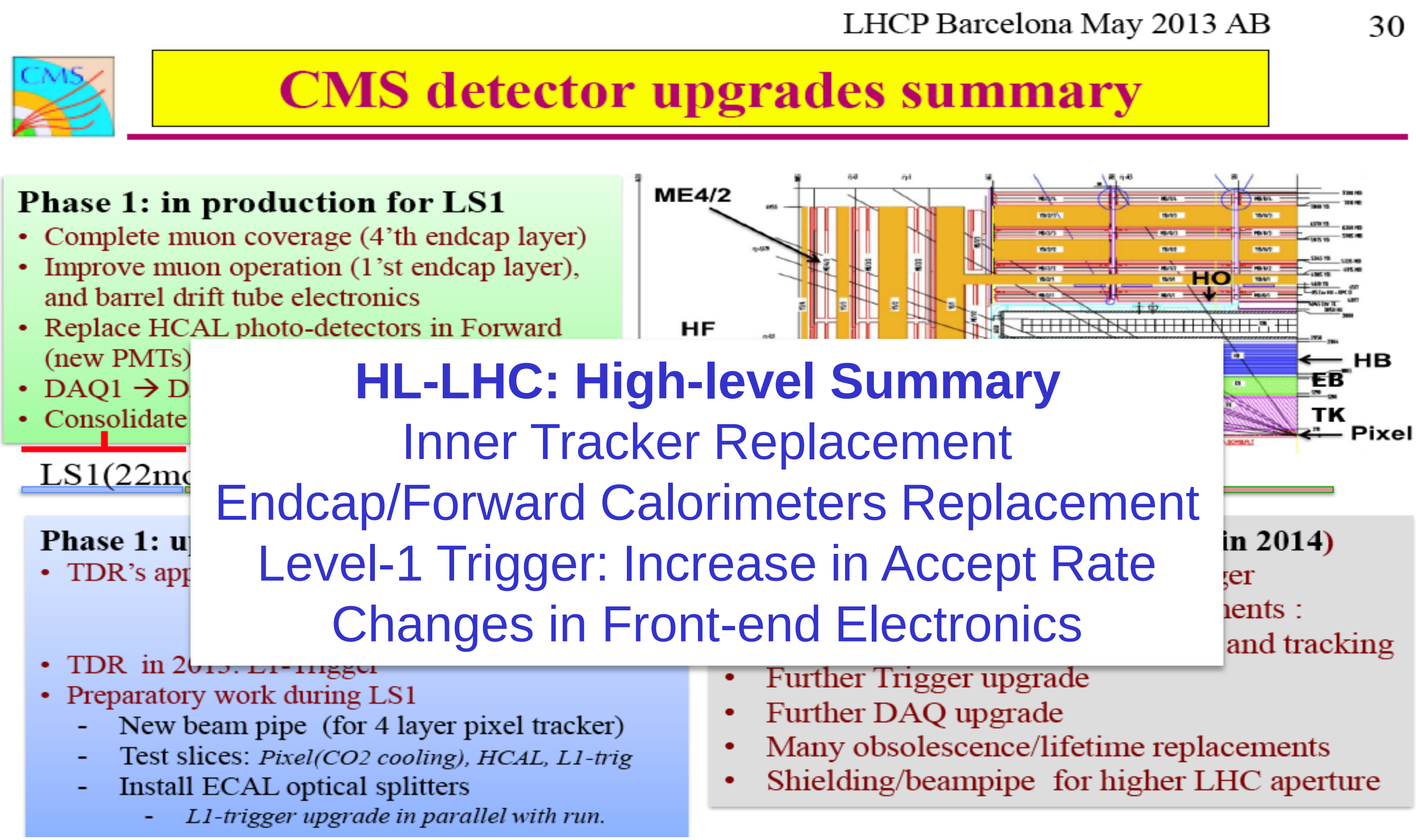
O. Buchmuller EPS 2013
m_{LSP} [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb-1
LHC: 14 TeV 300 fb-1
HL-LHC: 14 TeV 3000 fb-1
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

The Detector Challenge: Phase II

Detector Challenge: Maintain/improve on detector performance achieved in Run I, under more hostile conditions.

Apply lessons from the past – a directed programme of R&D and prototyping before starting construction.

Example:



HL-LHC: High-level Summary

Inner Tracker Replacement

Endcap/Forward Calorimeters Replacement

Level-1 Trigger: Increase in Accept Rate

Changes in Front-end Electronics

Summary/Outlook - Supersymmetry

- **Supersymmetry remains, to this date, a well-motivated, much anticipated extension to the Standard Model of particle physics**
  - **Advent of the LHC: huge new ground within reach**
  - **A search is defined by its signature and by its background estimation method. Need to be data-driven AMAP**
- **By now in all searches we are carrying out third-generation analyses (typically, second-gen and 8 TeV)**
  - **A huge number of analyses have been carried out**
  - **In some cases we are looking at third-generation analyses (both in terms of evolution and family ☺)**
  - **Nothing has turned up yet.**
    - **But there are grand hopes that something new is there!**
  - **There is Run 2 starting soon !**
- **And of course, if history is a guide, we will find the unexpected.**

Summary

- **The construction of the Standard Model is a towering intellectual achievement of humankind**
- **Magnificent interplay between theory and experiment**

- **After 25 years of design, construction (LHC+Xpt) we are firmly in the 2nd half of the journey – that of exploitation of the full scientific potential.**
- The accelerator and the experiments have operated very well.
- The LHC experiments are physics producing engines!

- **A "massive" discovery has been made – a Higgs boson.** The boson appears just to be the one predicted by the SM.

- **No evidence found yet of physics BSM.** The Standard Model with a single "elementary" scalar doublet seems to work well (too well)

- **The discovery of Higgs boson is just the start of the exploration of the Terascale. Lying ahead is an exciting programme - in equal parts:**
  - Precision measurements (not only of the new boson)
  - Searches for new particles and phenomena
- **We hope new physics will appear in Run II at 13-14 TeV.**