Searches for Supersymmetry and Dark Matter with CMS

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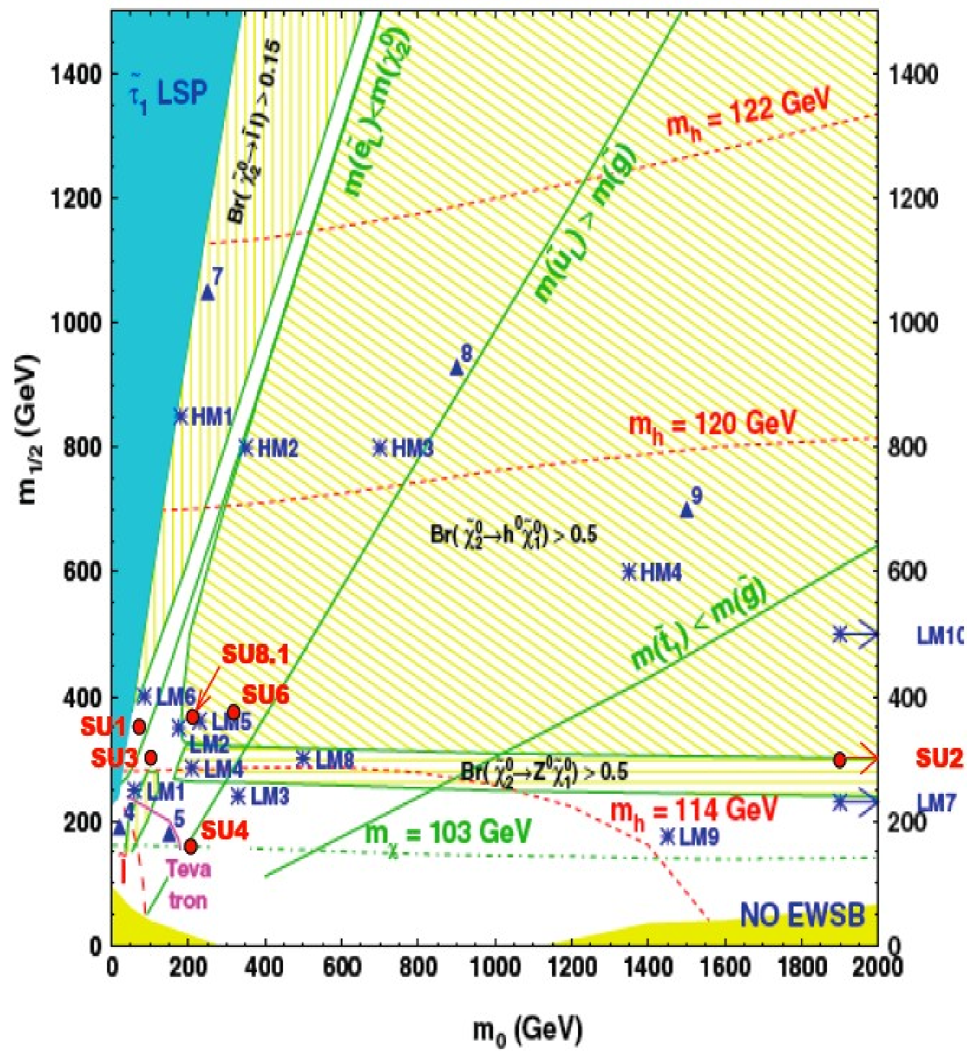
19 December 2013
IAP meeting Fundamental Interactions – UCL, Louvain-la-Neuve

Vrije Universiteit Brussel

A brief history of time

Back in 2006…

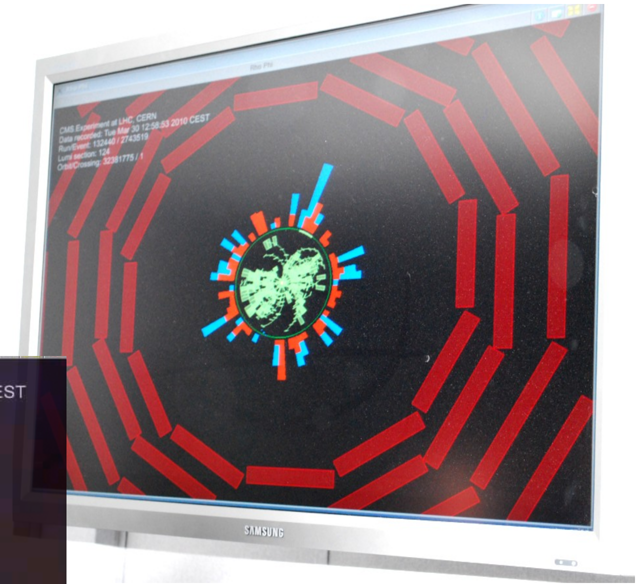
J. Phys. G: Nucl. Part. Phys. 34 995-1579

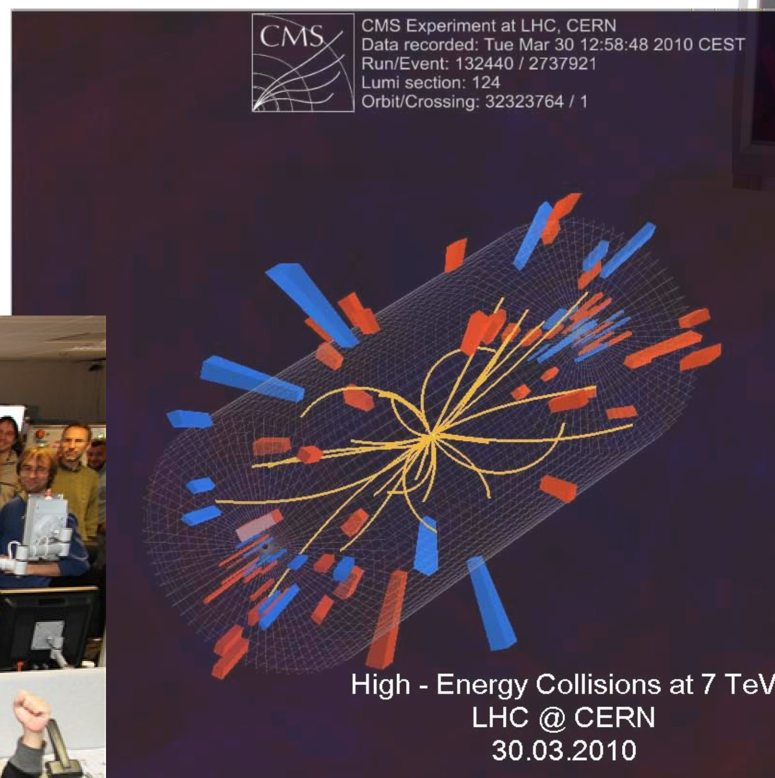


- CMS Physics TDR
  - grand 600-page overview of the CMS physics programme
- what concerns supersymmetry, only mSUGRA/CMSSM considered
  - reduction of MSSM to 5 parameters
- no mention of dedicated searches for dark matter...

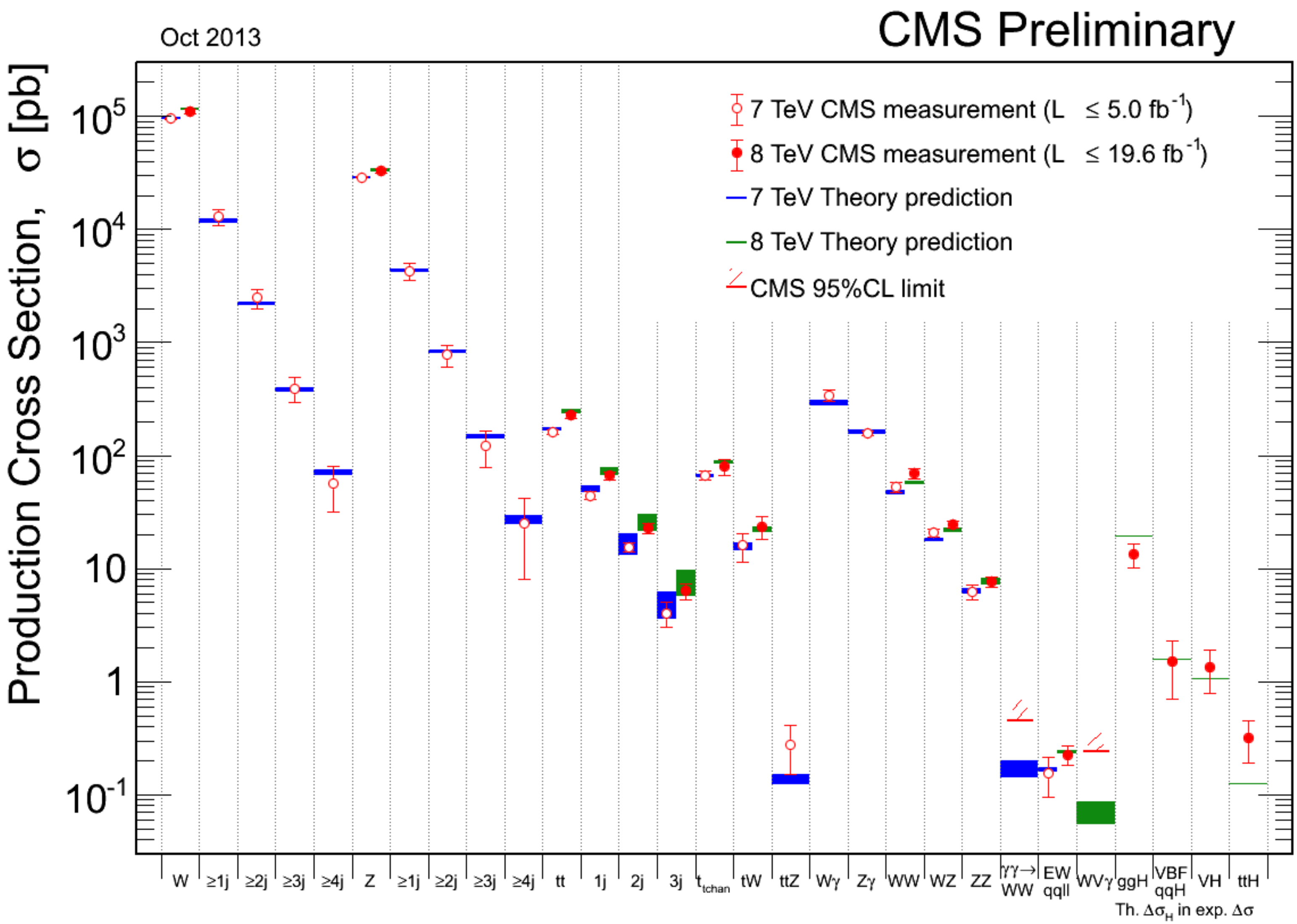
Finally, 2010 brought collisions…

- at 7TeV c.o.m. energy
- after 900 and 2360GeV collisions in 2009
- 8TeV in 2012





...and impressive results!



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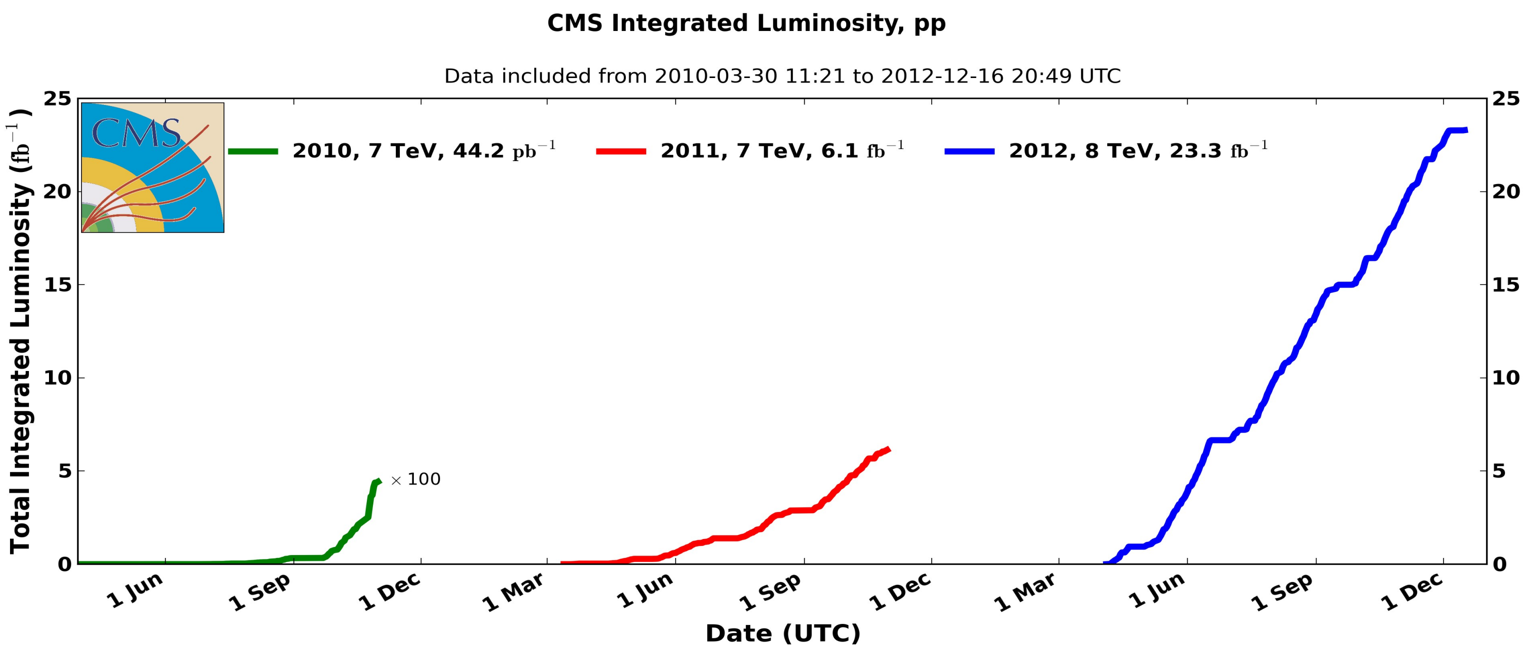

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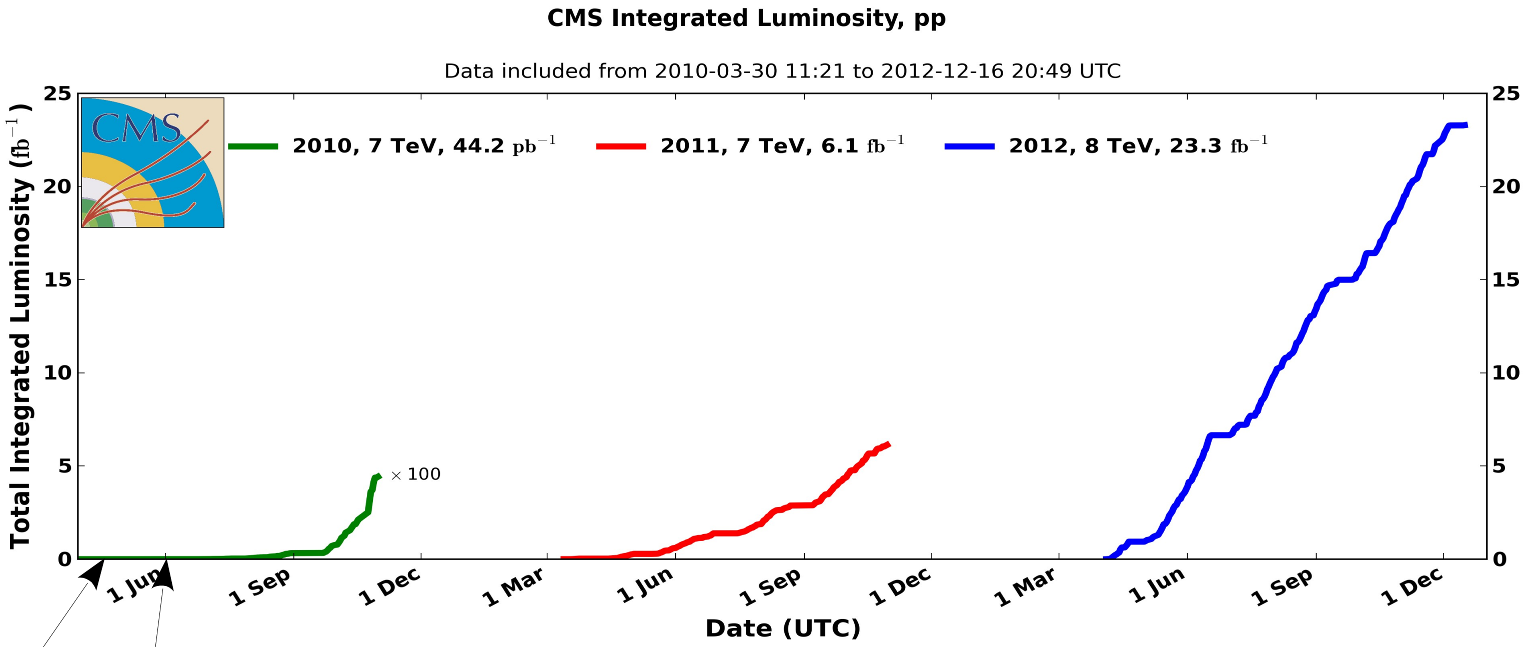
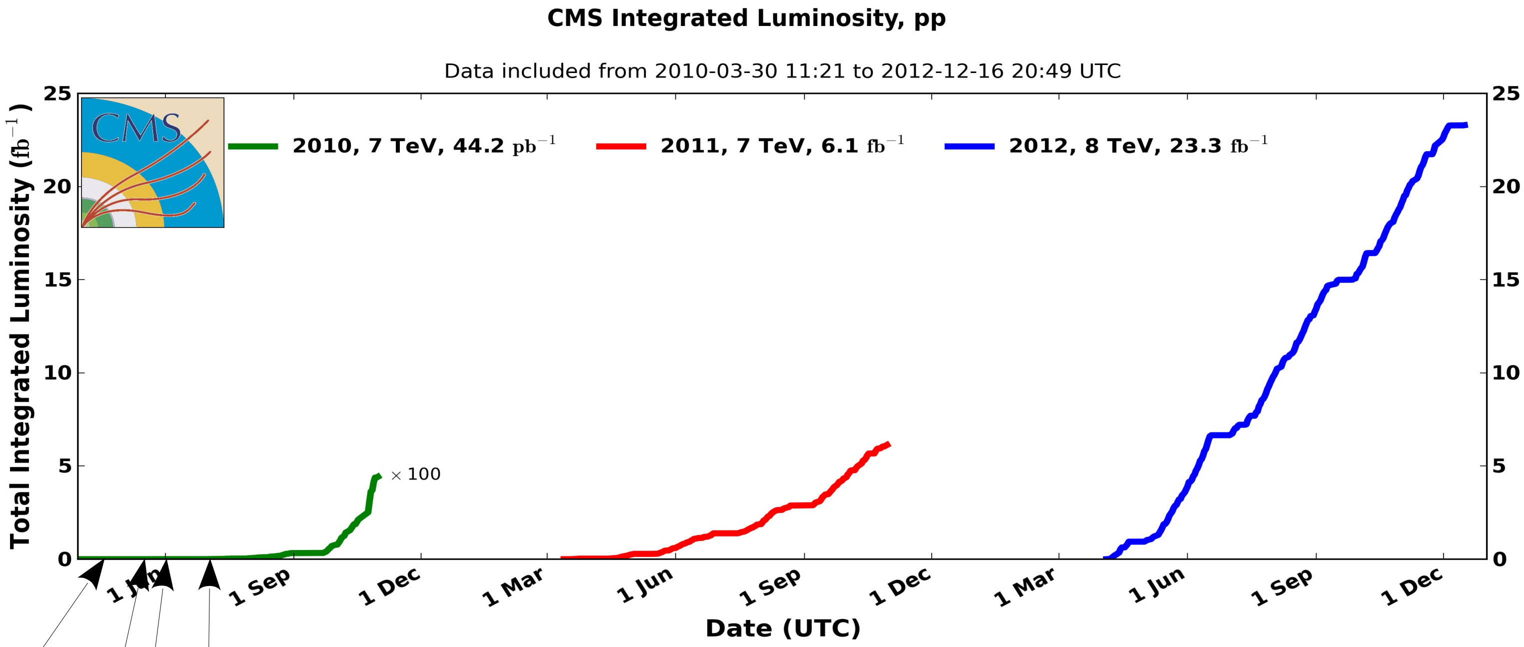


first MinBias / UE studies, particle multiplicities

first incl. jet x-sec, PF jets
60/nb   δ ~ 20-30%

adapted from G. Dissertori

A brief history of time



first MinBias / UE studies, particle multiplicities

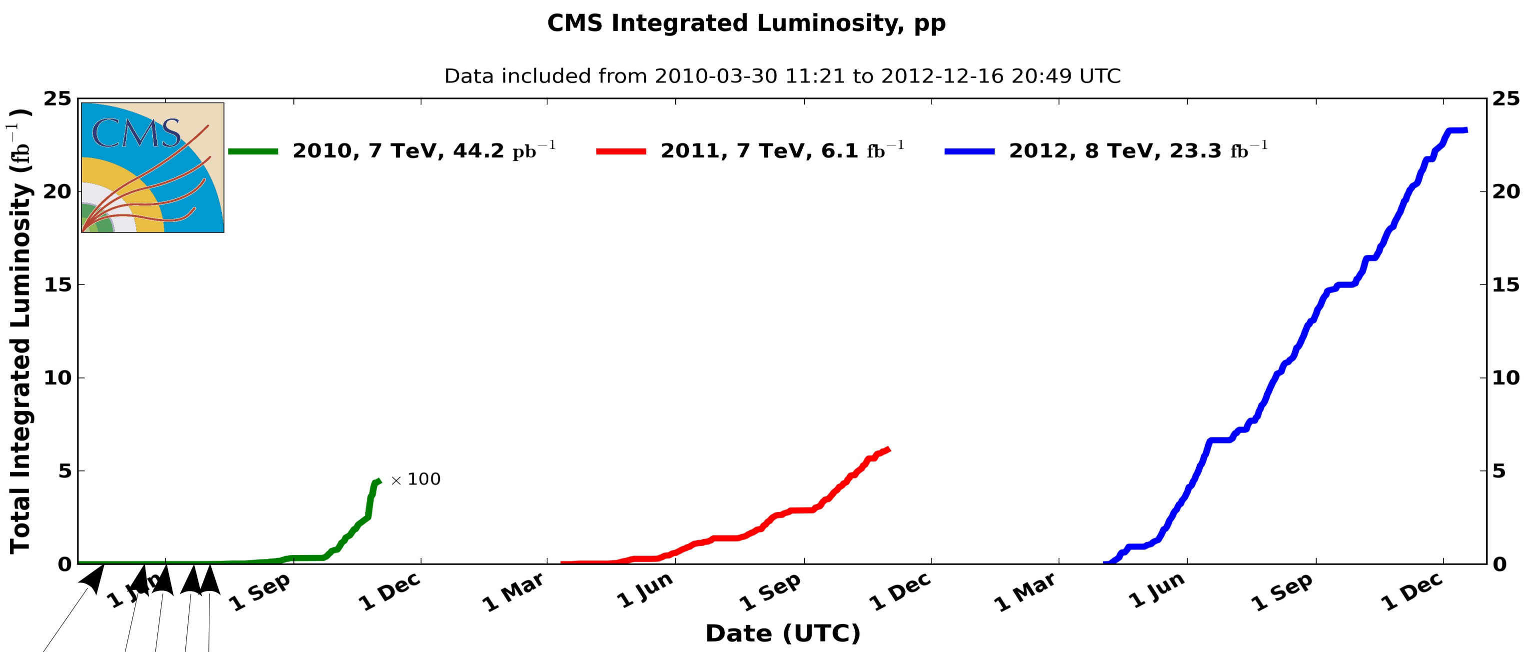
first incl. b x-section
8/nb δ ~ 15%

first incl. jet x-sec, PF jets
60/nb δ ~ 20-30%

first incl. J/ψ x-section
100/nb δ ~ 20%

adapted from G. Dissertori

A brief history of time



first MinBias / UE studies, particle multiplicities

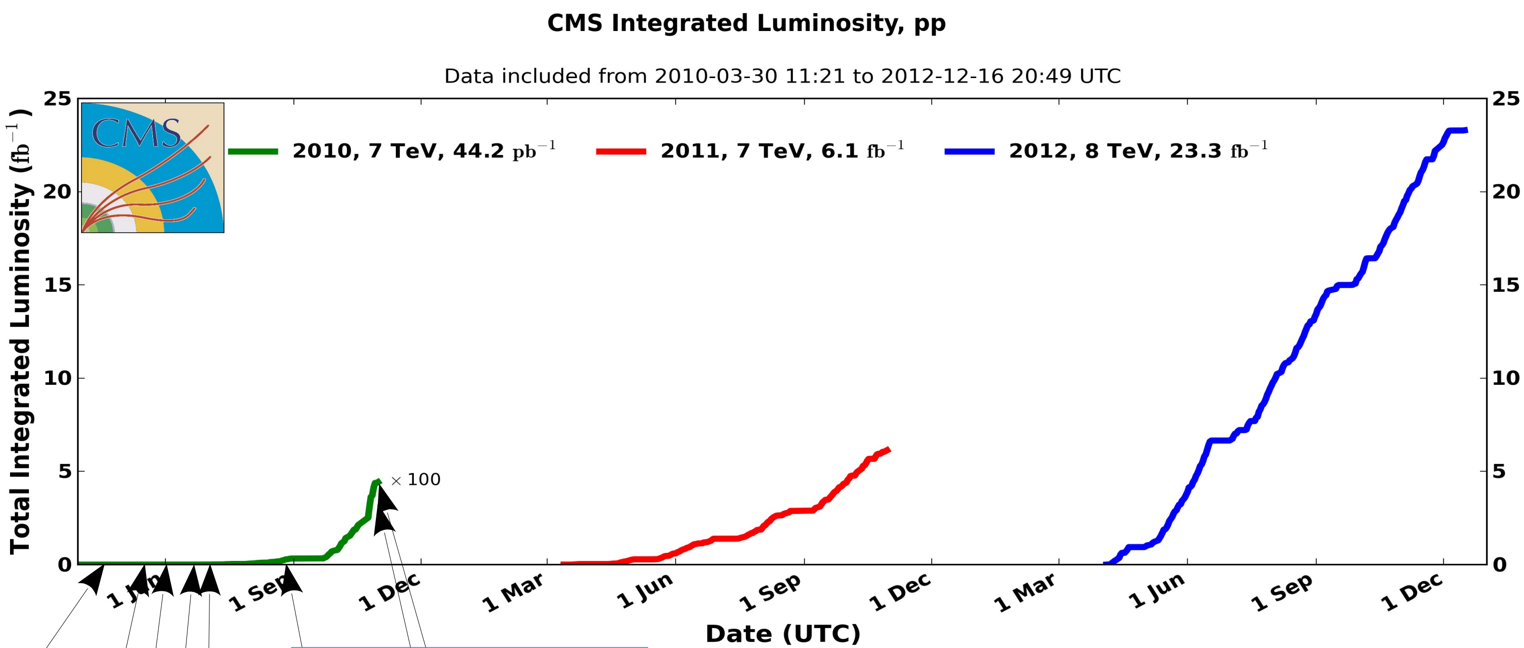
first incl. b x-section
8/nb   δ ~ 15%

first incl. jet x-sec, PF jets
60/nb   δ ~ 20-30%

first incl. W/Z x-sections
200/nb   δ ~ 4-6% + 11% lumi

first incl. J/ψ x-section
100/nb   δ ~ 20%

adapted from G. Dissertori



first top x-sec
3/pb δ ~ 40%

first MinBias / UE
studies, particle multiplicities

first incl. b x-section
8/nb δ ~ 15%

first single top x-sec
t-chan 36/pb δ~36%

first incl. jet x-sec, PF jets
60/nb δ ~ 20-30%

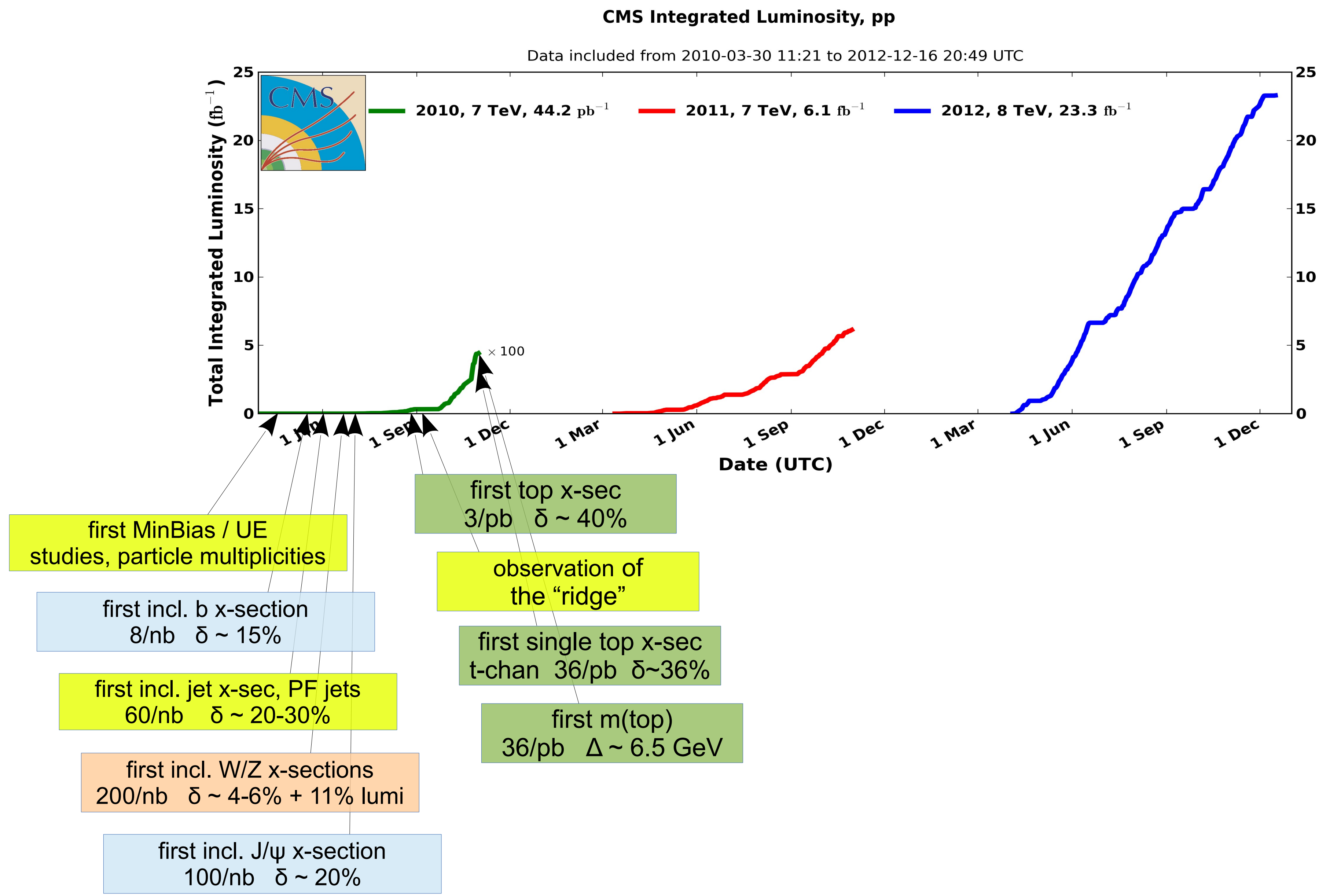
first m(top)
36/pb Δ ~ 6.5 GeV

first incl. W/Z x-sections
200/nb δ ~ 4-6% + 11% lumi

first incl. J/ψ x-section
100/nb δ ~ 20%

adapted from G. Dissertori

A brief history of time



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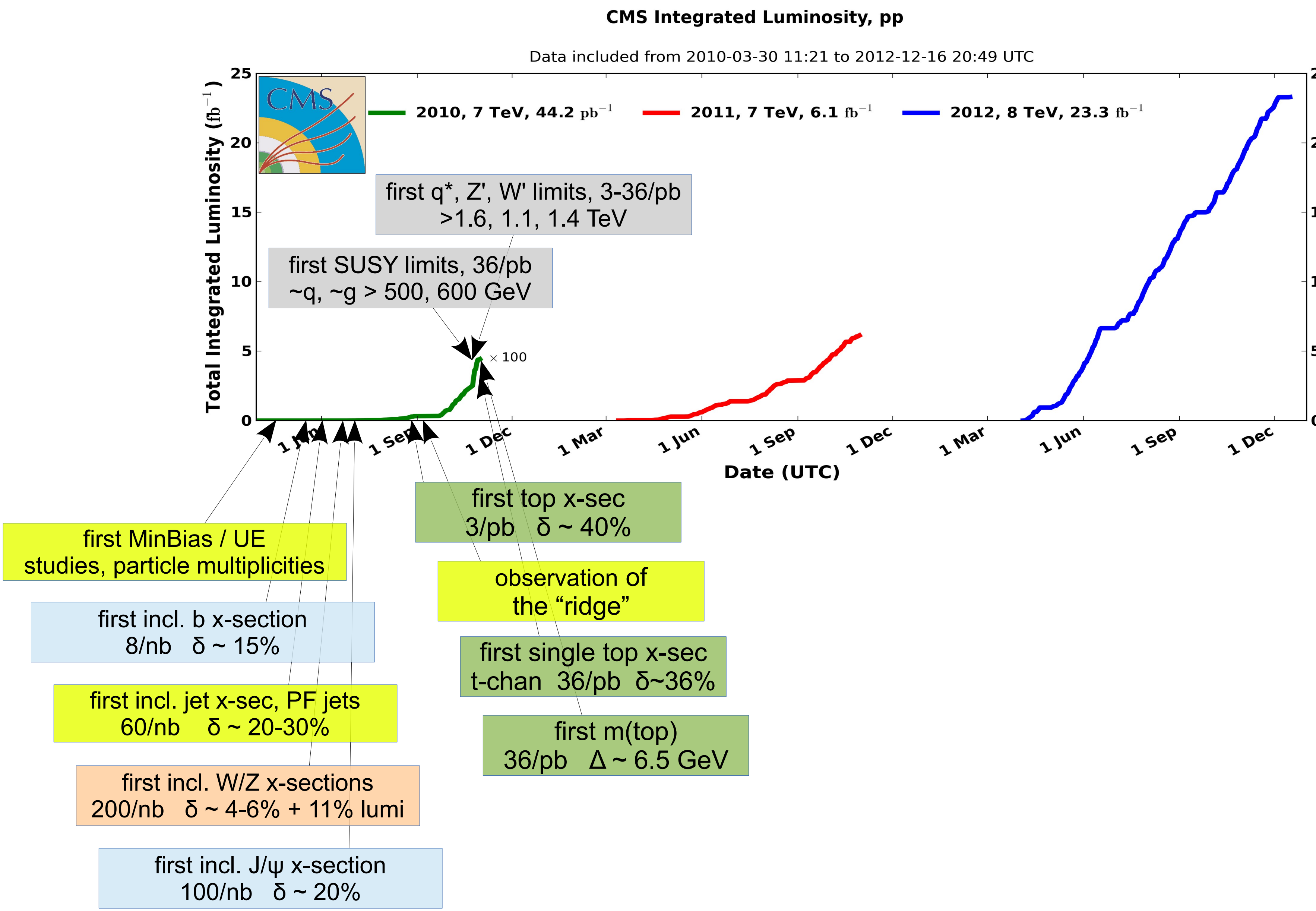

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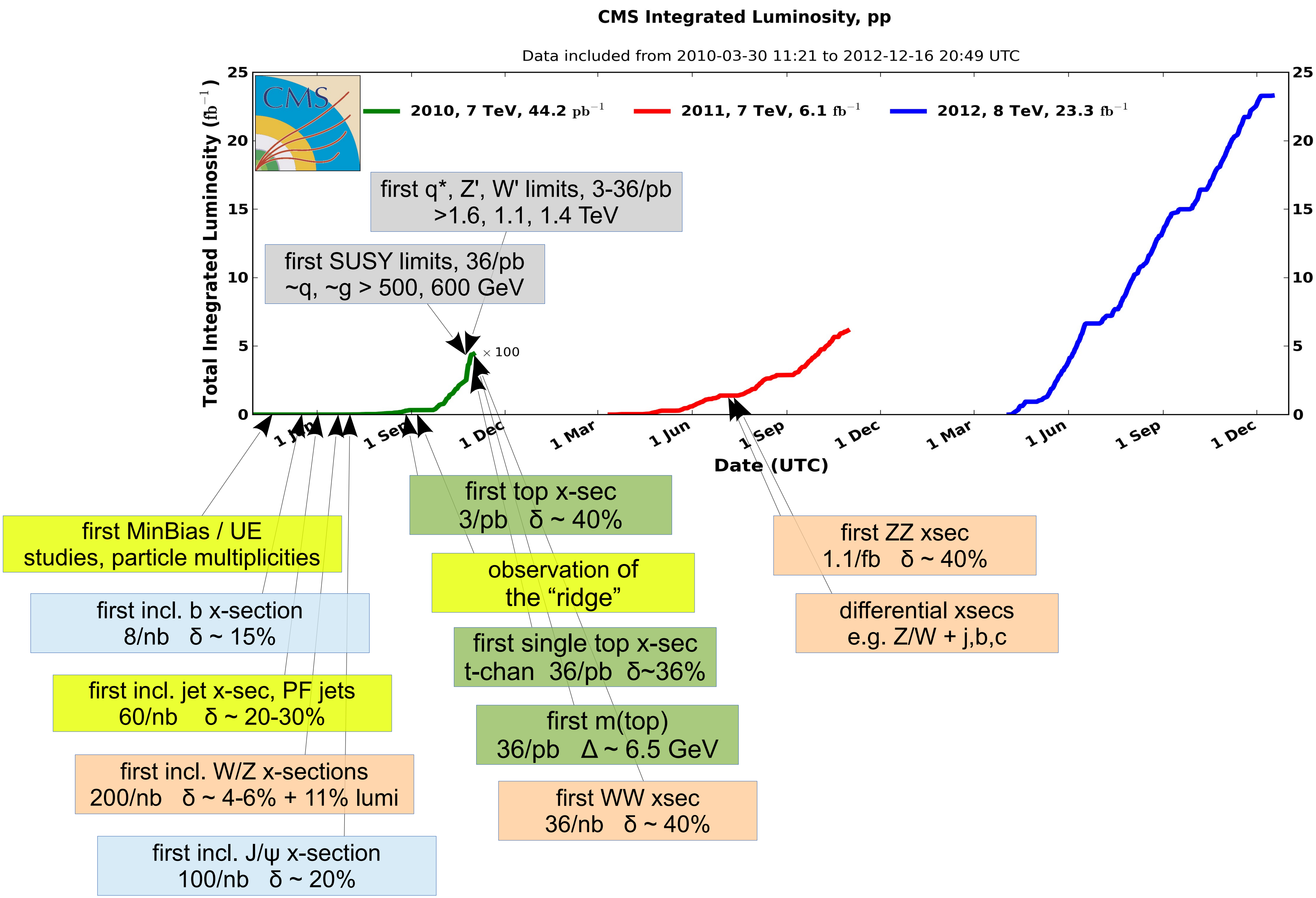

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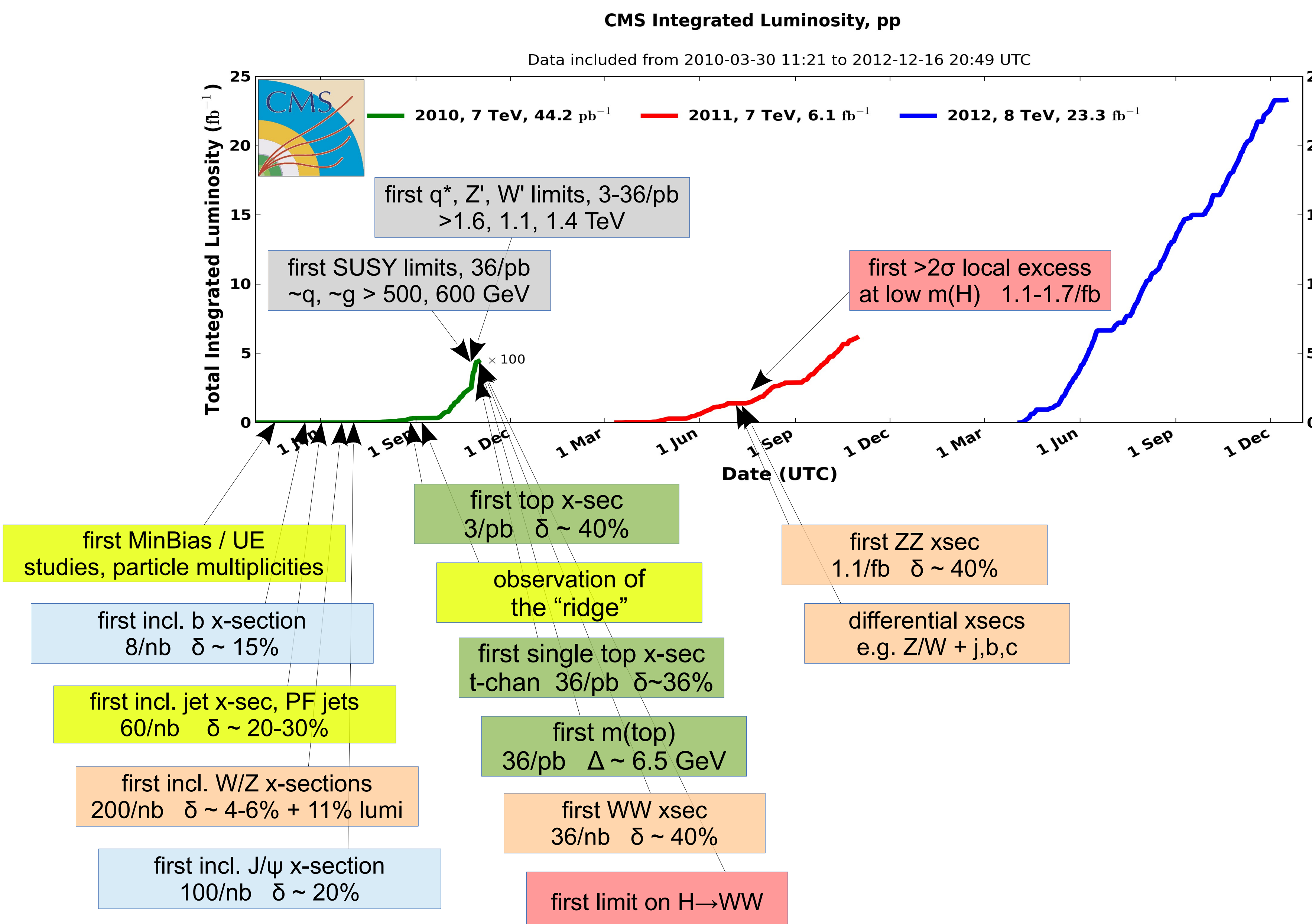

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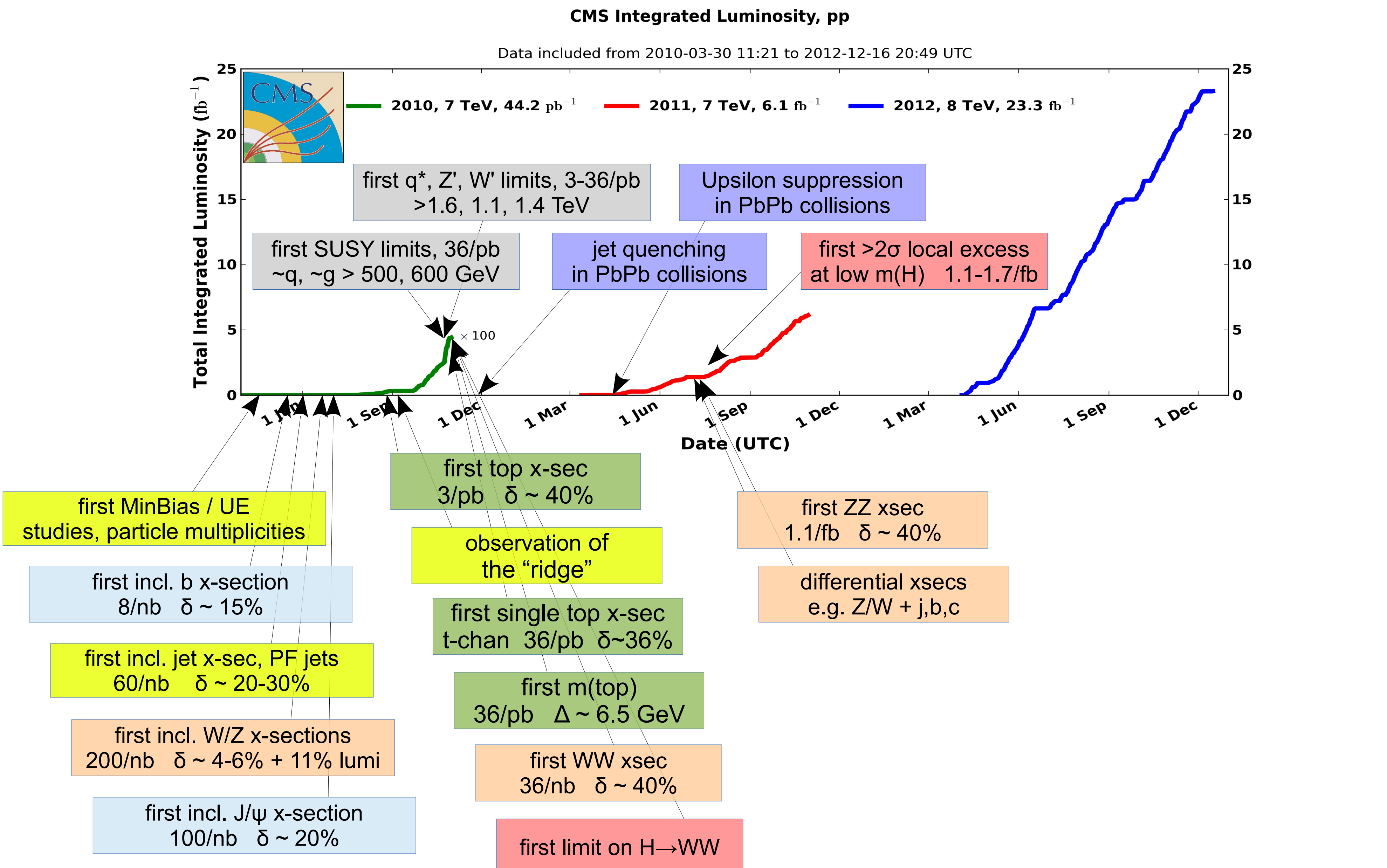

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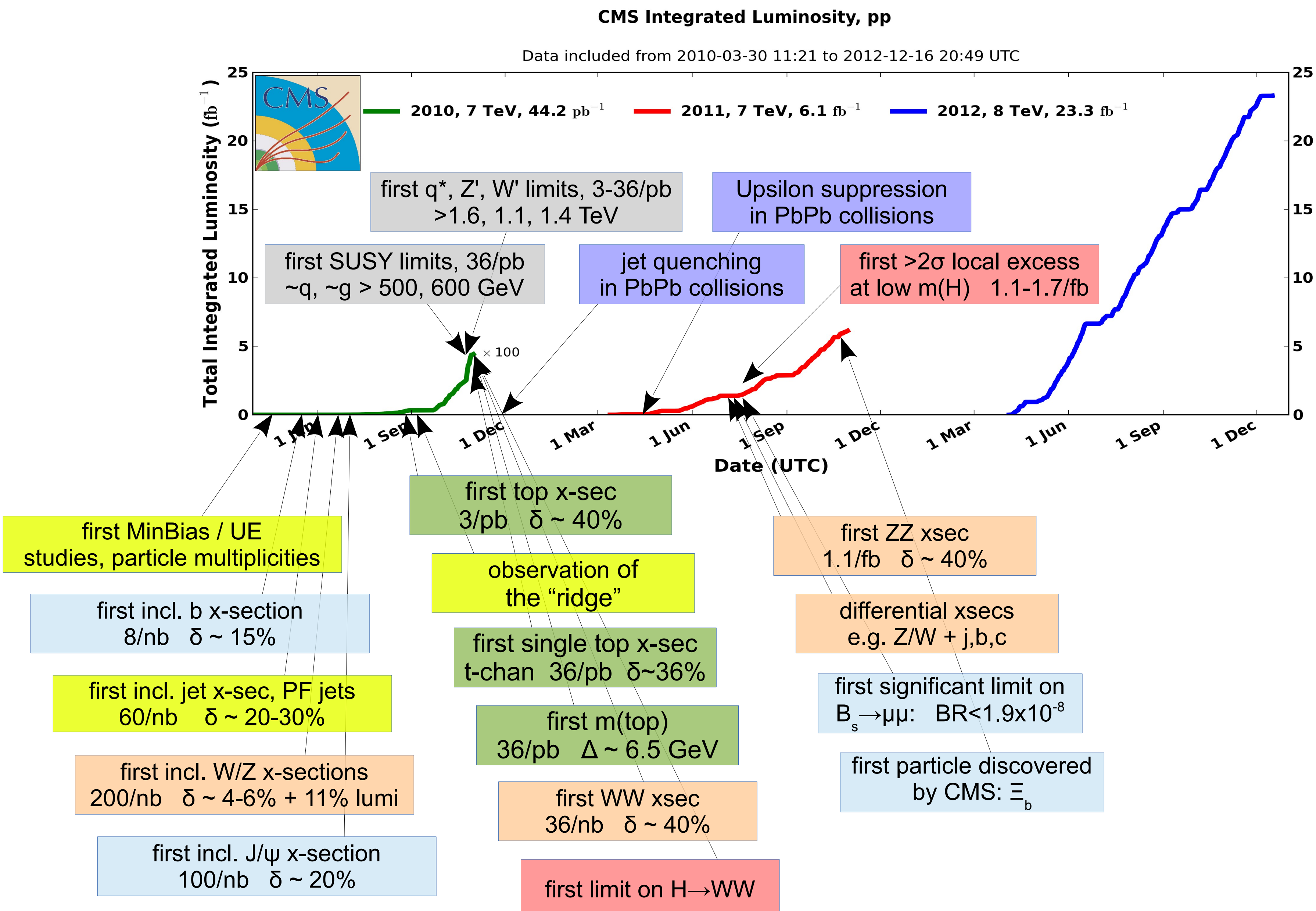

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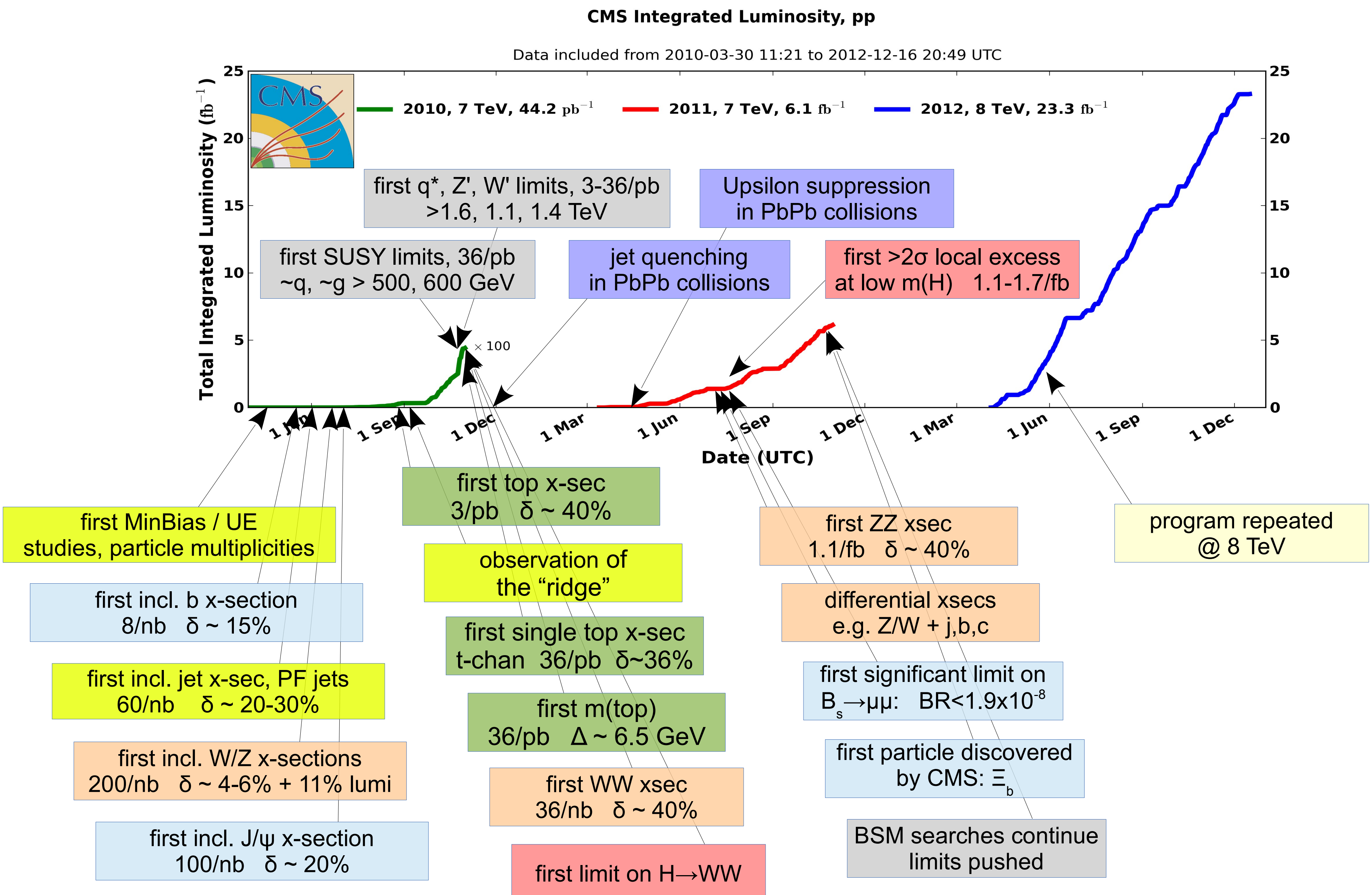

adapted from G. Dissertori

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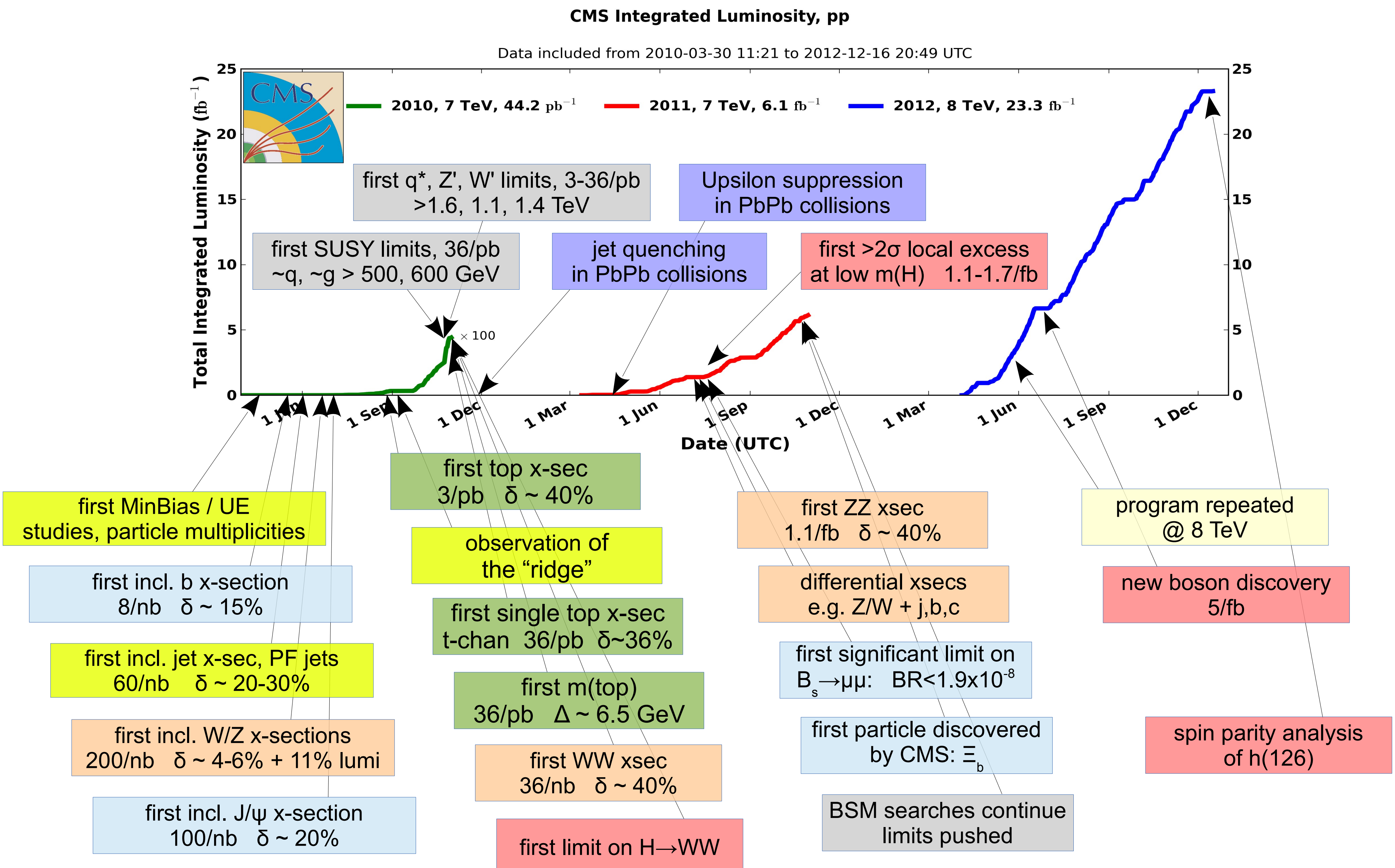

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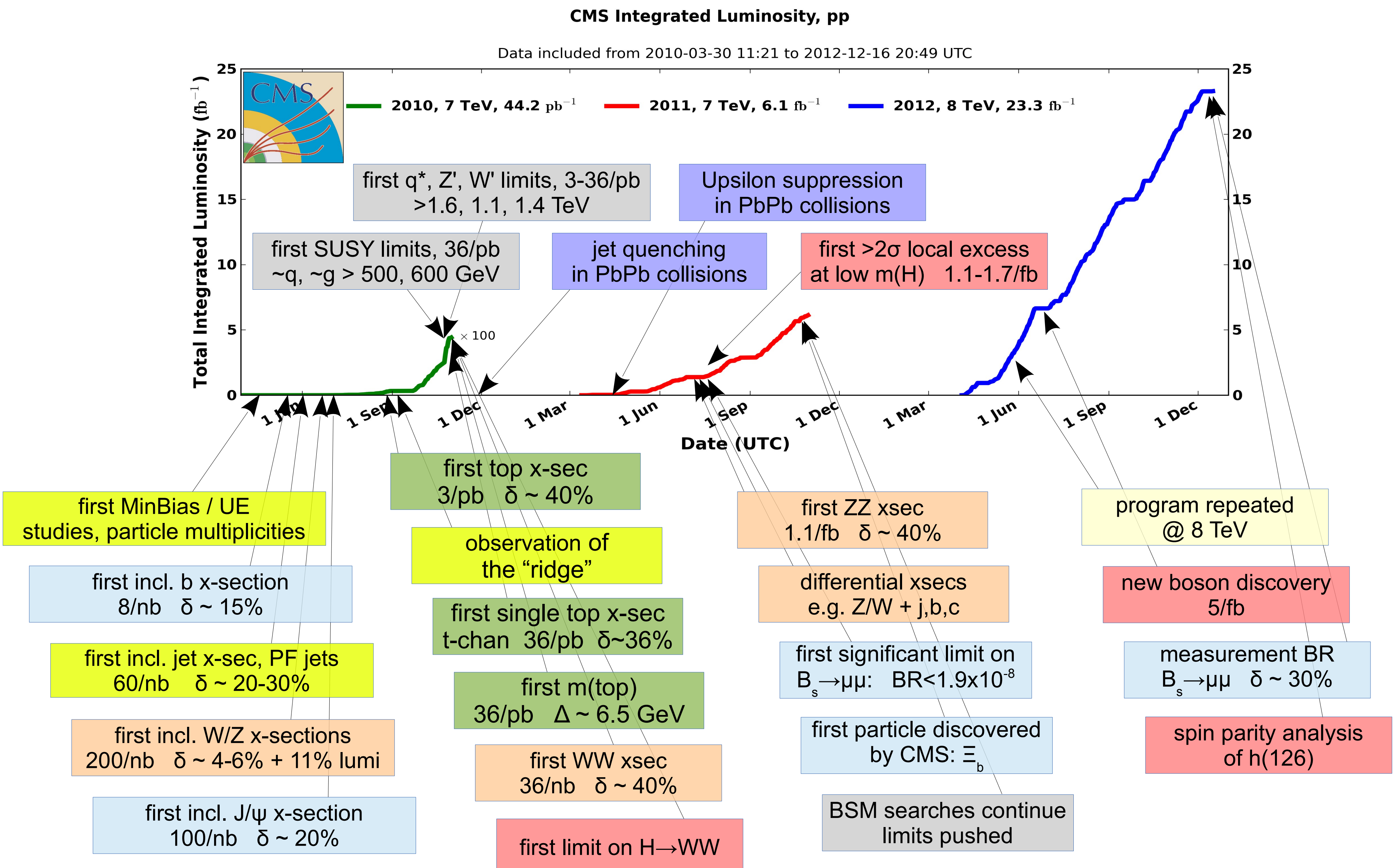

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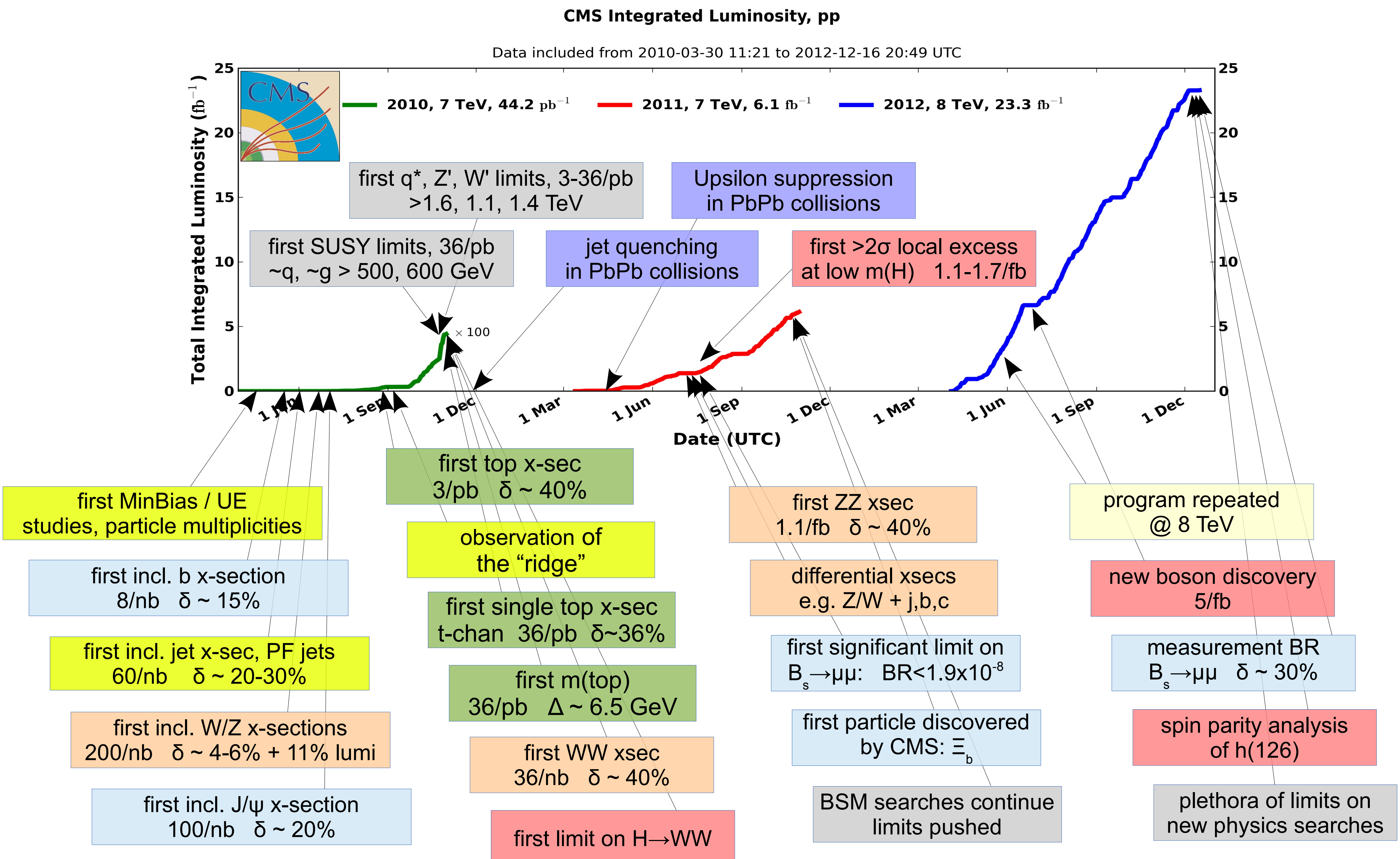
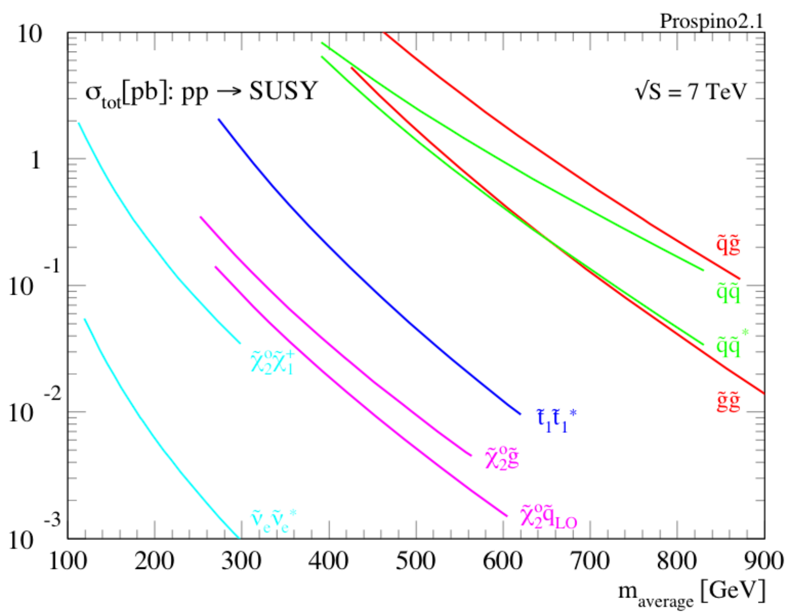


adapted from G. Dissertori

Inclusive searches

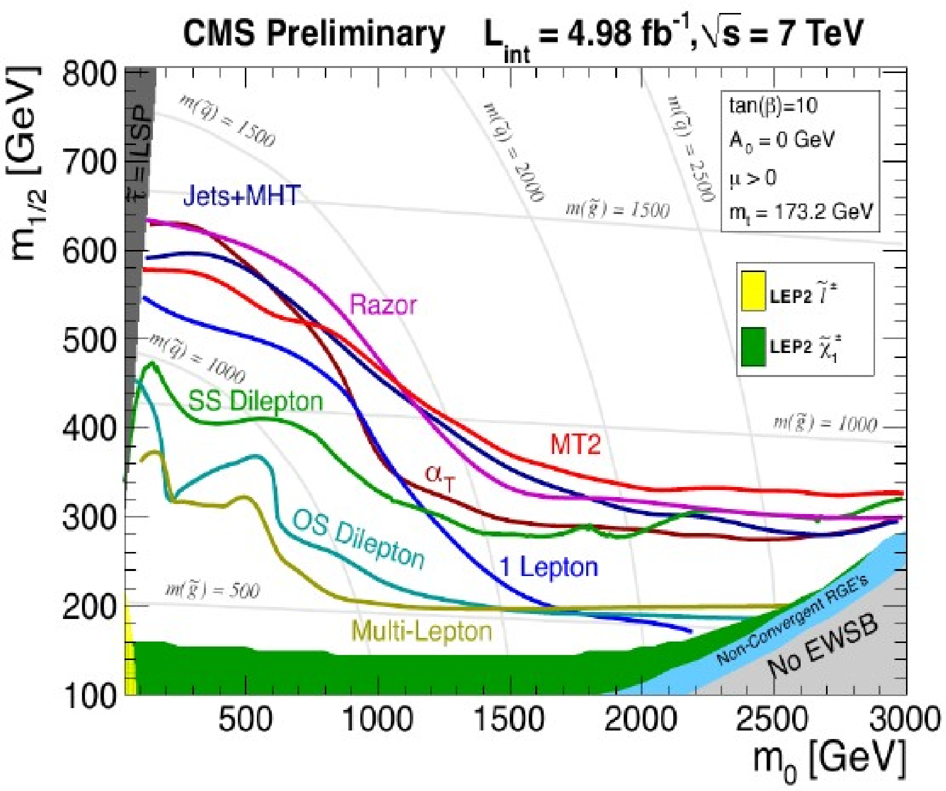
- quickly analyse the unknown territory with signature-based inclusive searches
- commonality missing energy (MET)
  - from LSP as DM candidate (R-parity conservation)
- emphasis on strong squark and gluino pair production
  - other production modes too low in cross section at first
  - coloured production, so jets expected



0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

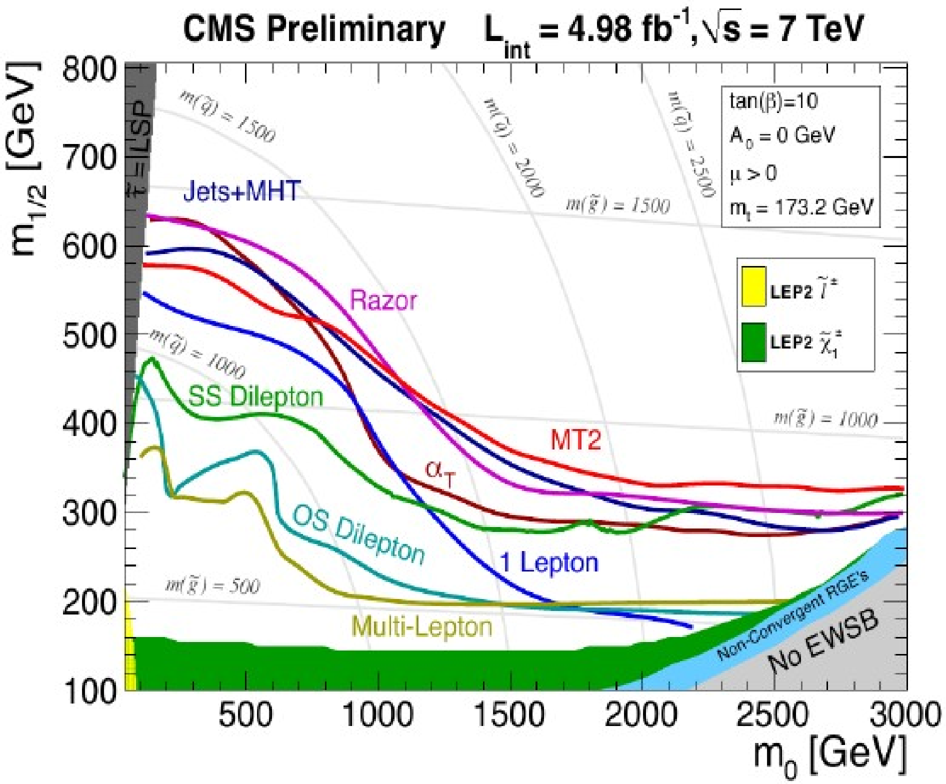
SUSY in the CMSSM

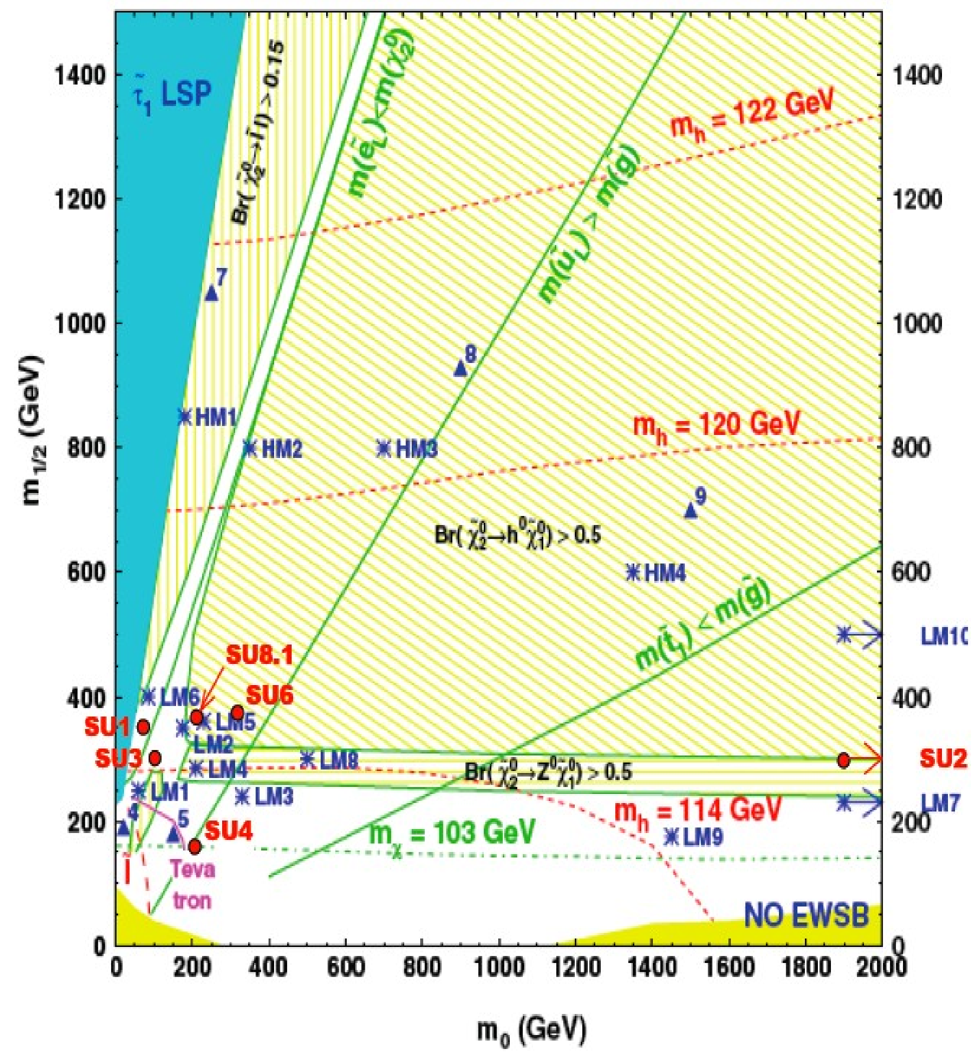
Limits beyond expectations



SUSY in the CMSSM

Limits beyond expectations



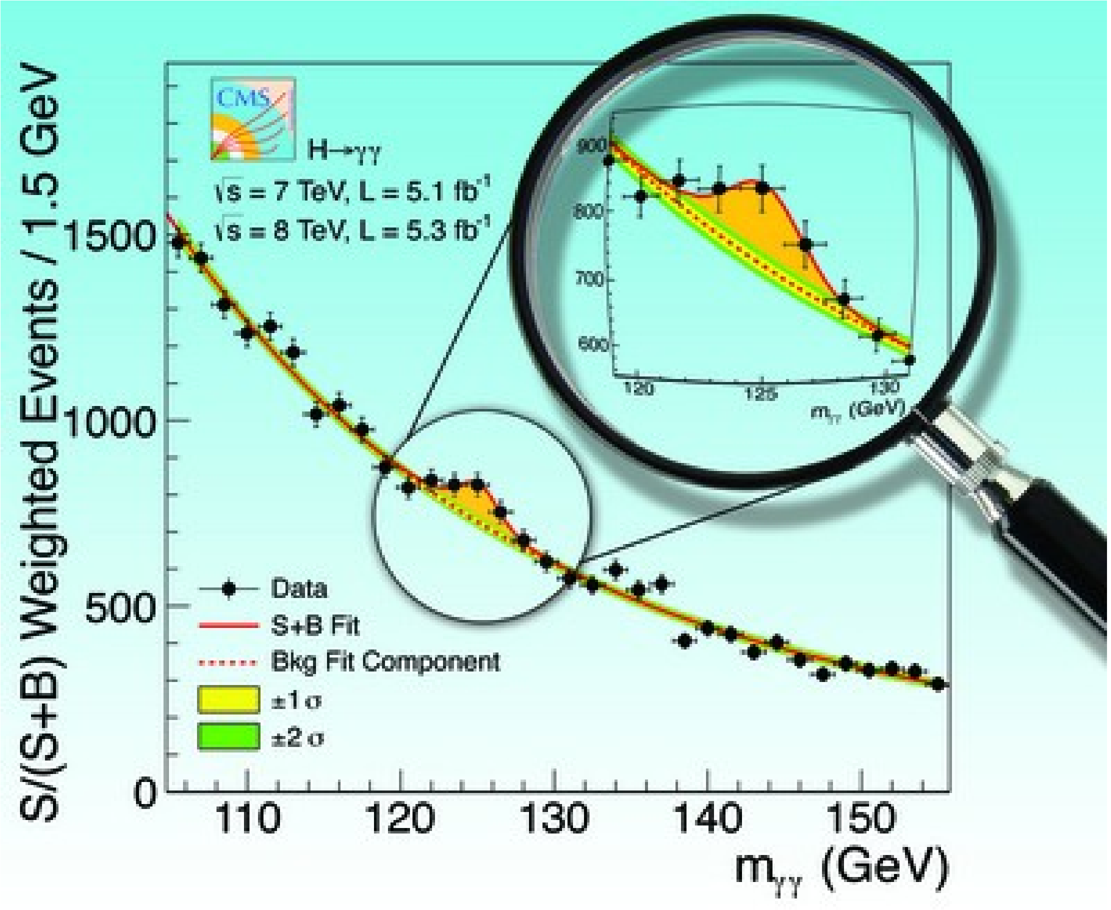


SUSY in the CMSSM

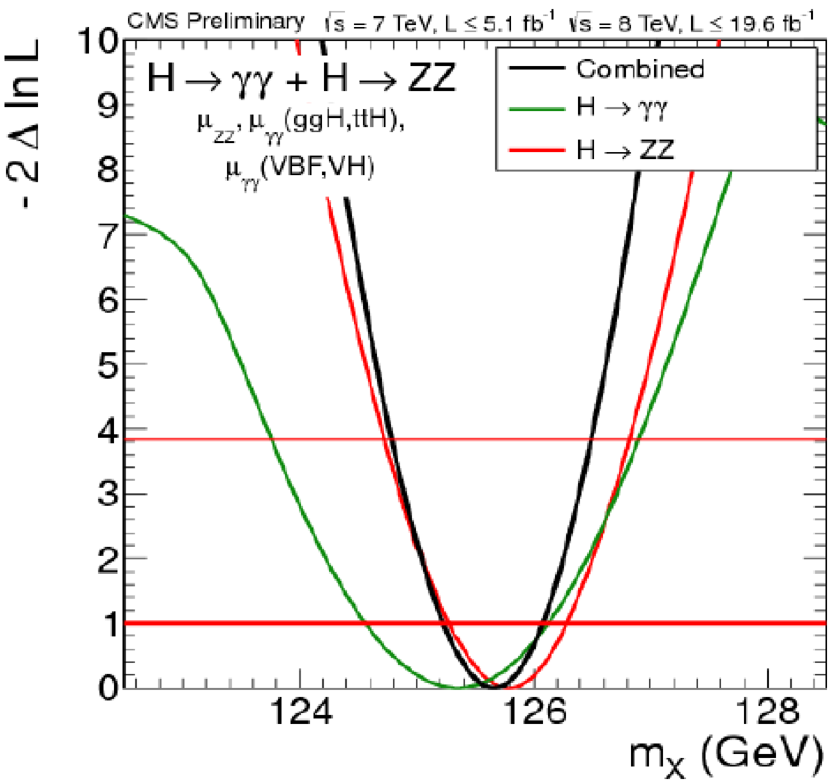
The most powerful SUSY search on the market…

The most powerful SUSY search on the market...

Phys. Lett. B 716 (2012) 30



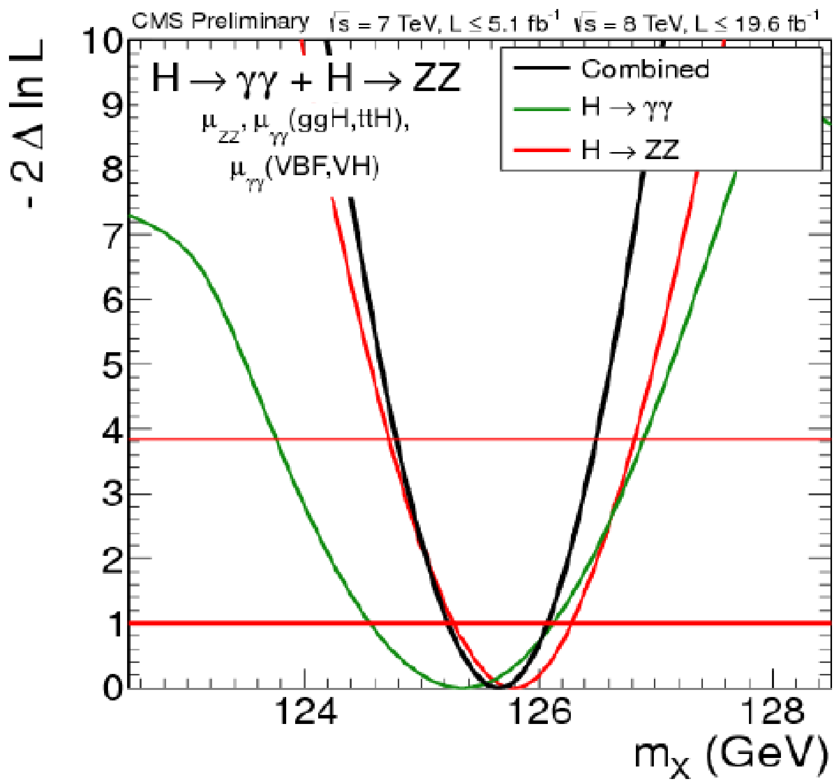
The constrained CMSSM



CMS-PAS-HIG-13-005

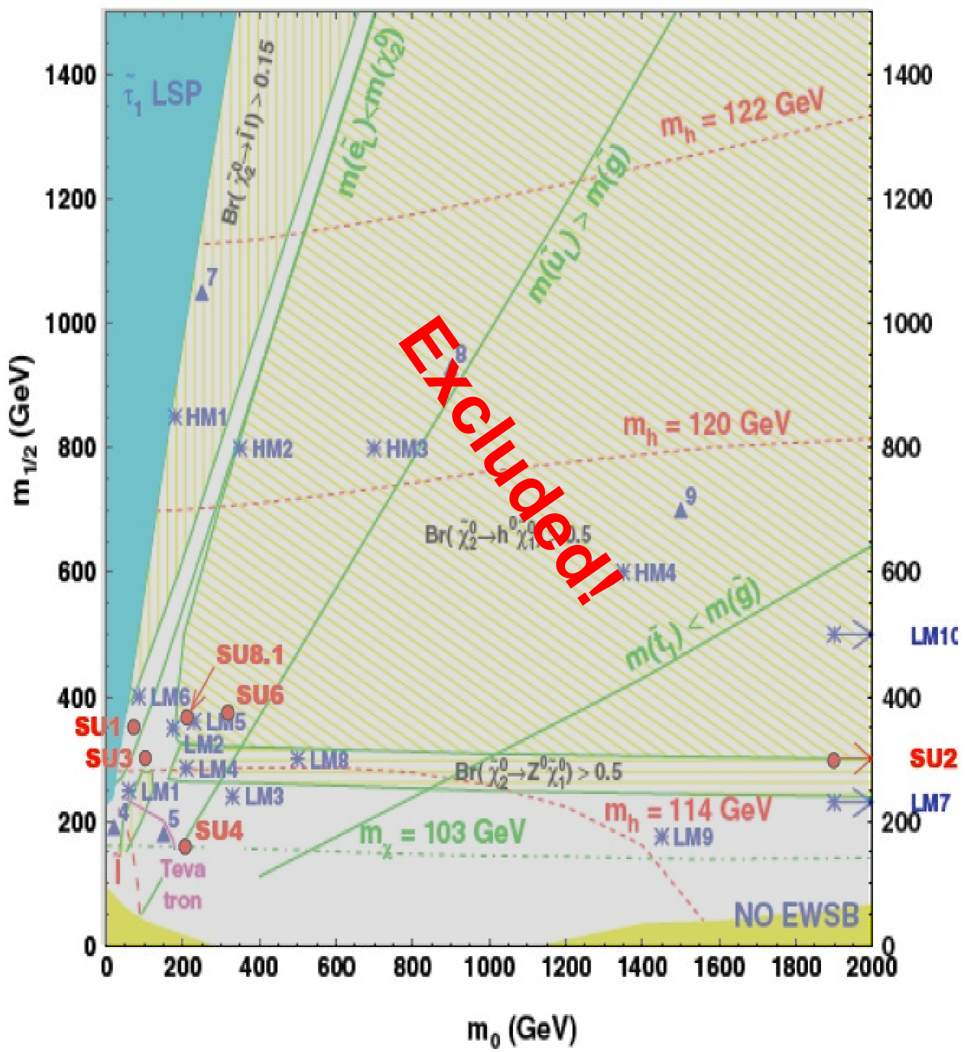
$m_H = 125.7 \pm 0.3\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst})$ GeV

The constrained CMSSM



CMS-PAS-HIG-13-005

m_H = 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

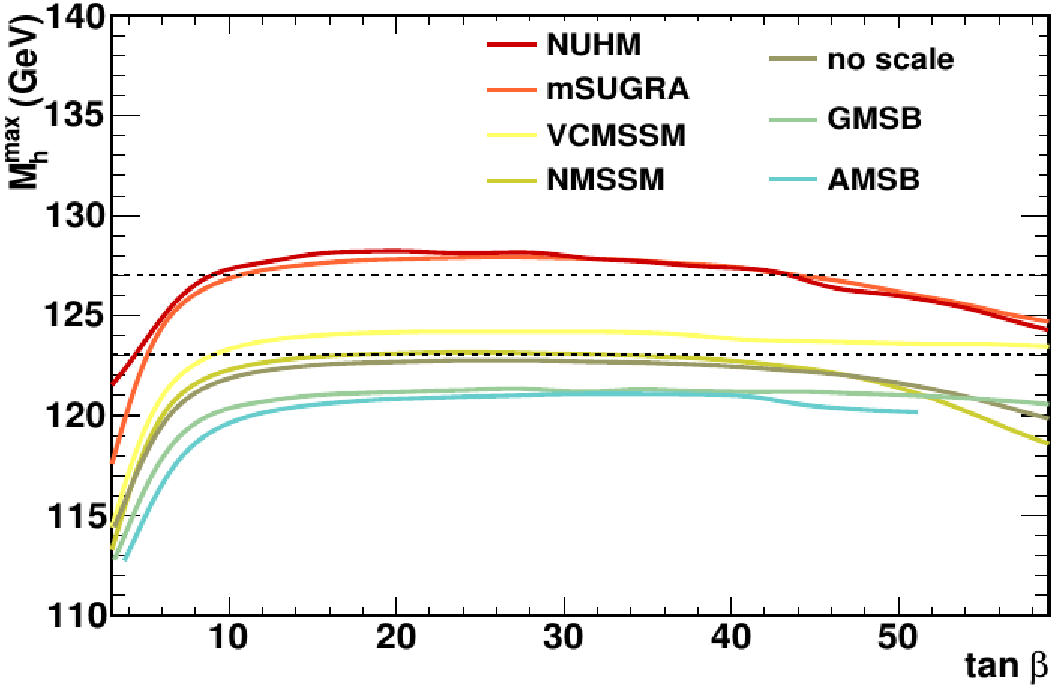


SUSY under pressure

Phys.Lett. B708 (2012) 162-169

Also other models have a hard time

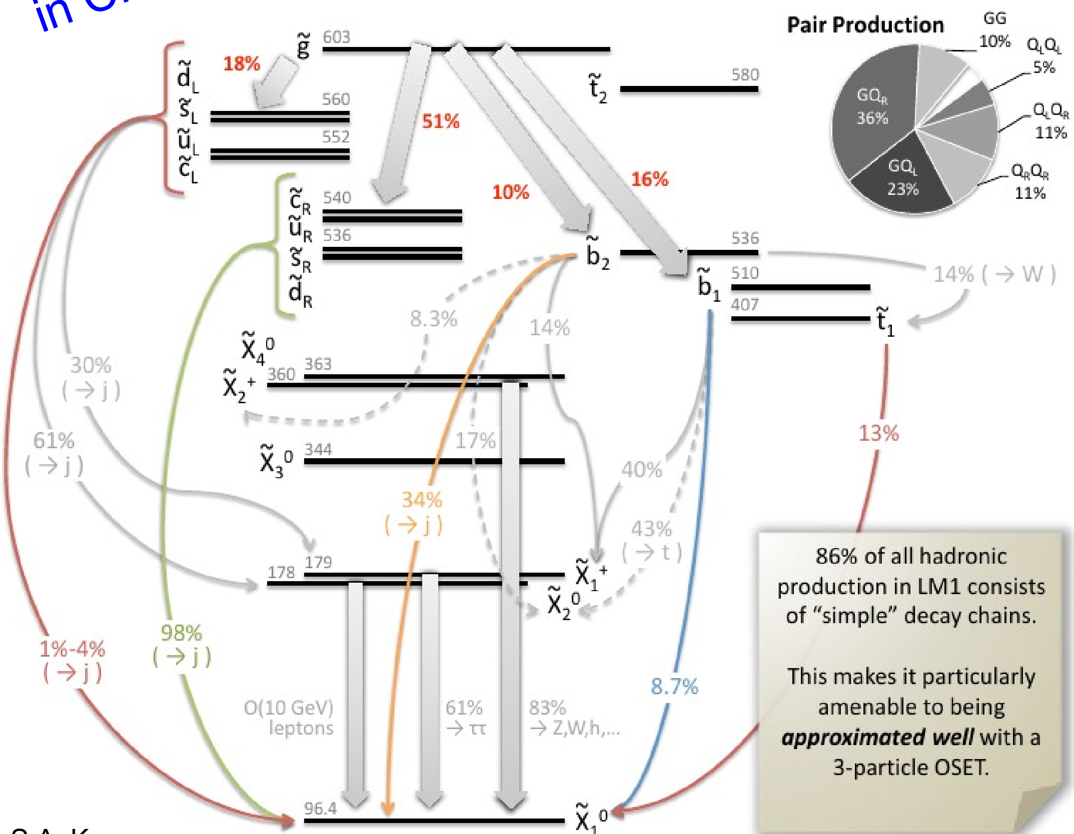
- in MSSM at tree level: $m_h \le m_Z\,|\cos(2\beta)|$
- a higher Higgs mass can arise from higher-order corrections
  - in particular from high stop mass
  - but still 130 GeV is about the maximum you can reach



99% probed models have m_h below the lines...

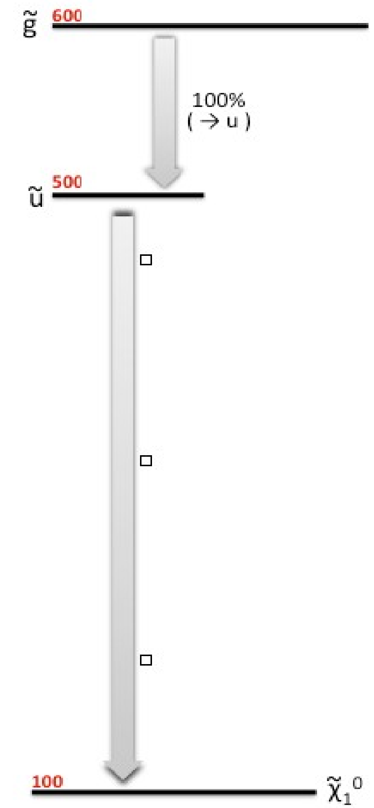
One way forward: ignore Higgs mass constraint

sparticle spectrum
LM1 benchmark
in CMSSM



credits: S.A. Koay

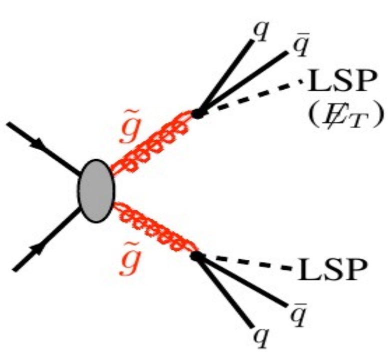
sparticle spectrum
yielding equivalent
hadronic observables

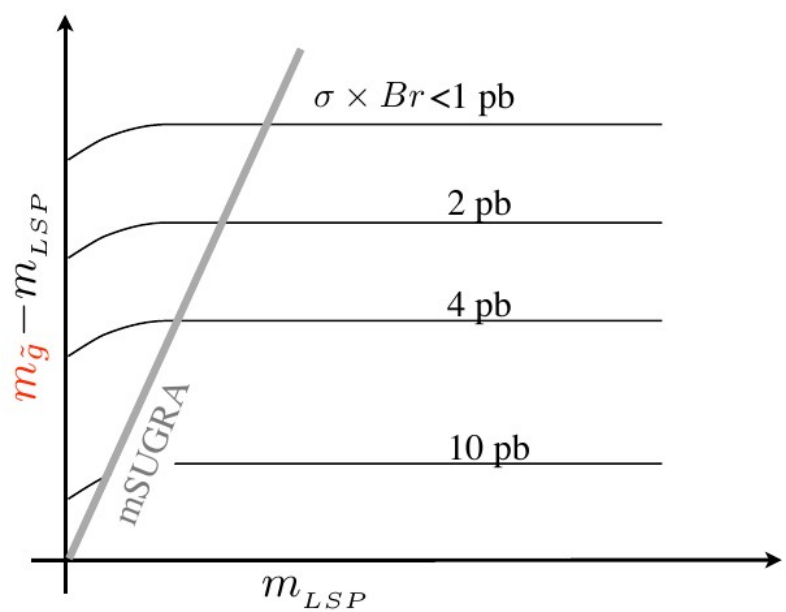


Simplified Model Spectra

- aim to capture typical signatures of what can be expected in full models
- consider a few sparticles only in the spectrum
- allow a few decays only

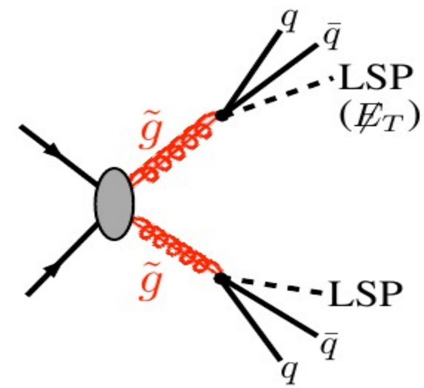
- this is actually expanding the phase space, rather than limiting it
  - example: in CMSSM/mSUGRA, the ratio of the gluino and LSP mass is approximately fixed (~7 to 1)
  - so CMSSM only explores a line on the gluino-LSP-mass plane!

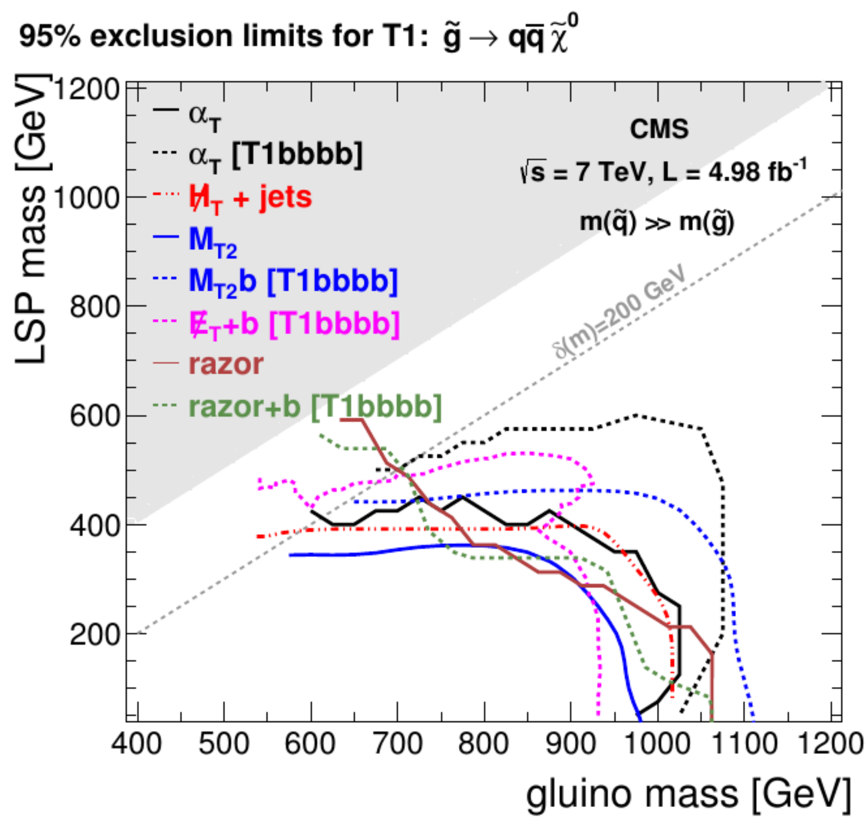




SMS Search strategy

- build analysis around a chosen signature
    - eg. jets+MET, SS dileptons, etc
- optimize for different SMS assumptions
    - avoid using assumptions, like σ x BR, only channel, etc
- interpret possibly in other SMS's
- publish maps of acceptance and cross-section upper limits
    - or even better, efficiency parametrizations

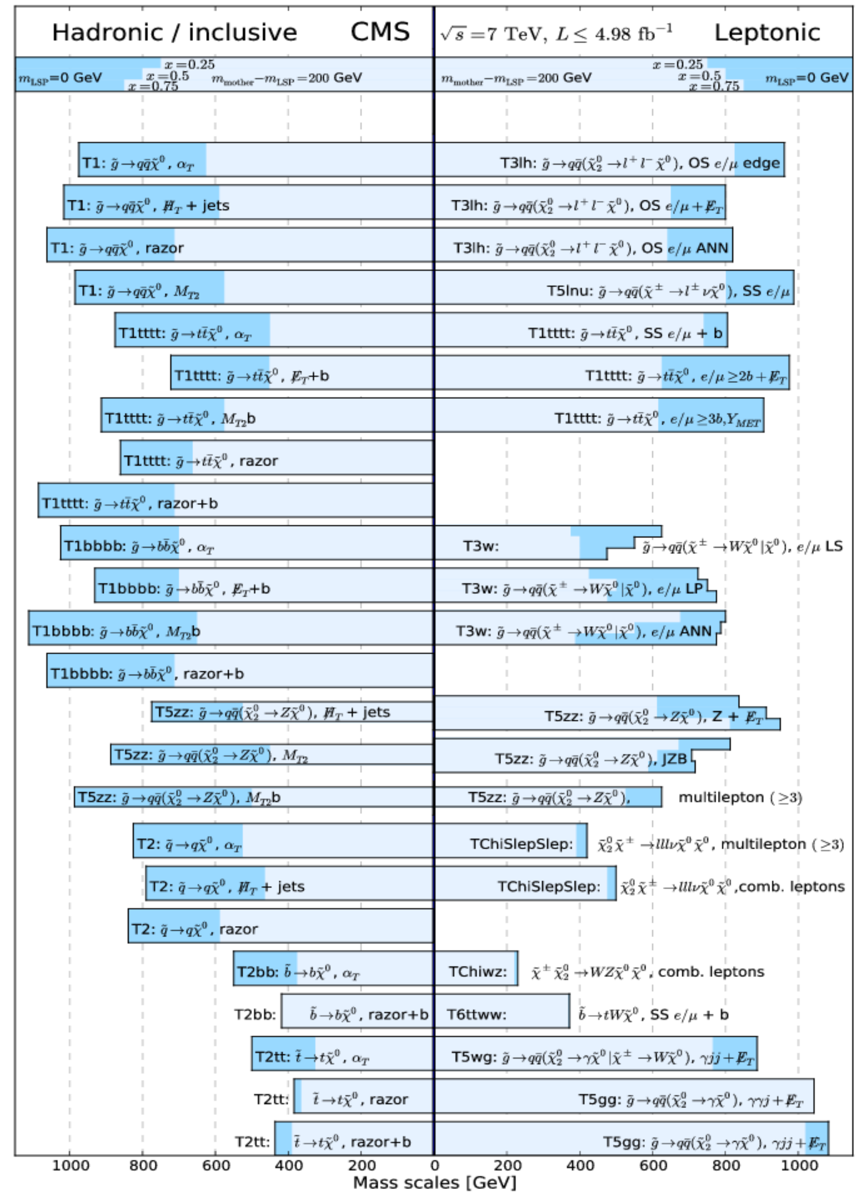




SUSY further under pressure

Limits, and more limits

- 2011 was a very rich year for limits on SUSY
- most limits from inclusive search program
  - adding b's, τ's,...

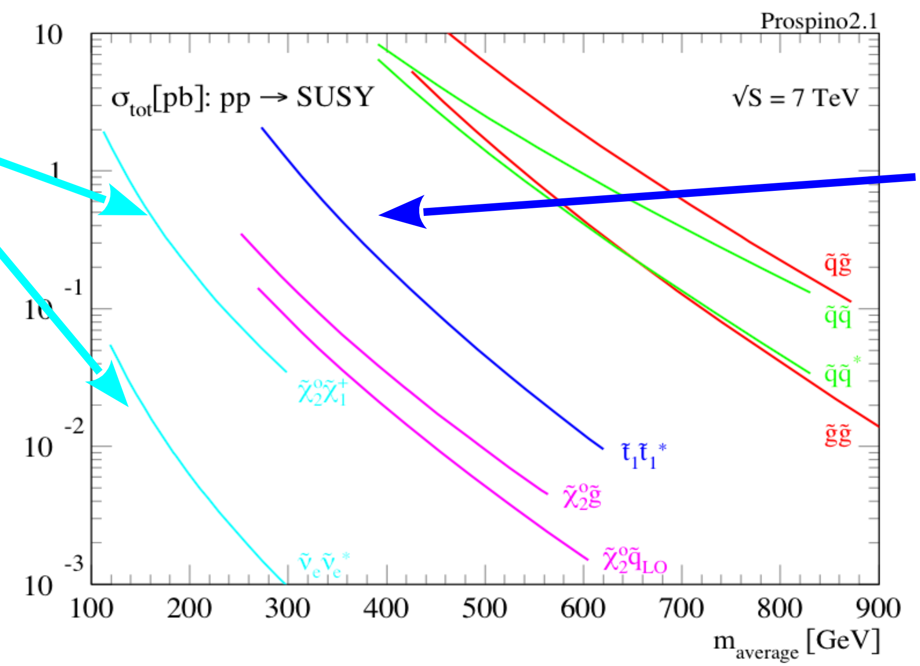


Onwards to exclusive searches

- with large luminosity, rarer SUSY production modes come available
- need new, dedicated, exclusive strategies

direct neutralino/ chargino/slepton production

- (multi)lepton signatures
- possibly very clean, without hadronic activity (jet veto)



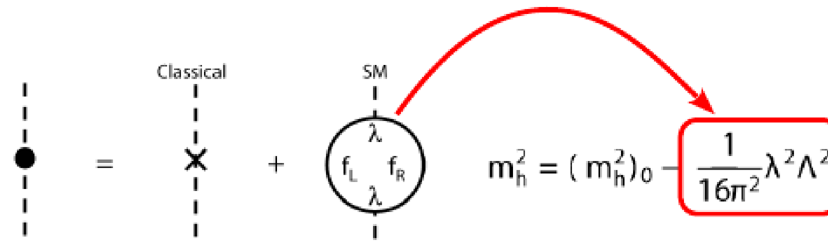
direct stop or sbottom production

- look for b quarks
- top reconstruction

Natural SUSY

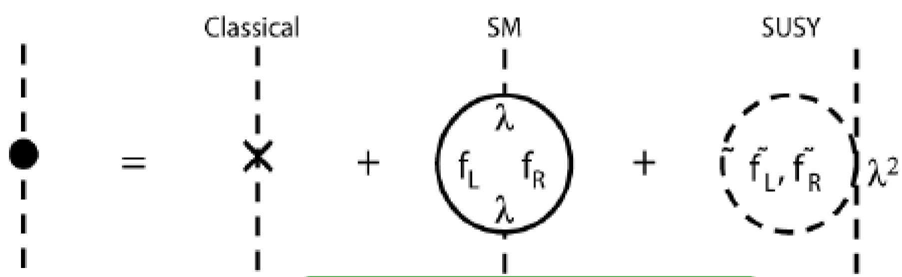
Why the interest in stop (and sbottom) squarks?

- since a good year, we have a hierarchy problem to solve
- need fine-tuning over 30 orders of magnitude to stabilize the Higgs mass
  - problem of naturalness



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots$$

- supersymmetry solves this in a natural way
  - superpartners cancel terms proportional to Λ^2, leaving terms in $\log(\Lambda)$

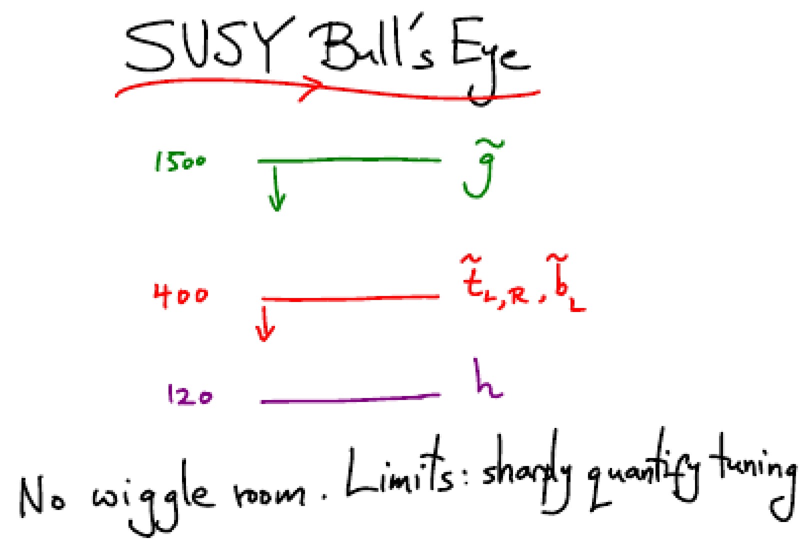


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots \quad \textbf{cancels}$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}), \quad \textbf{small}$$

Natural SUSY

- well... natural... supersymmetry is broken
  - if SUSY scale large enough, then terms in log(Λ) will create new fine tuning
- to keep the theory natural
  - need light Higgsinos
  - need m(gluino) < ~ 1500 GeV
  - need m(stop [sbottom]) < ~ 500 GeV



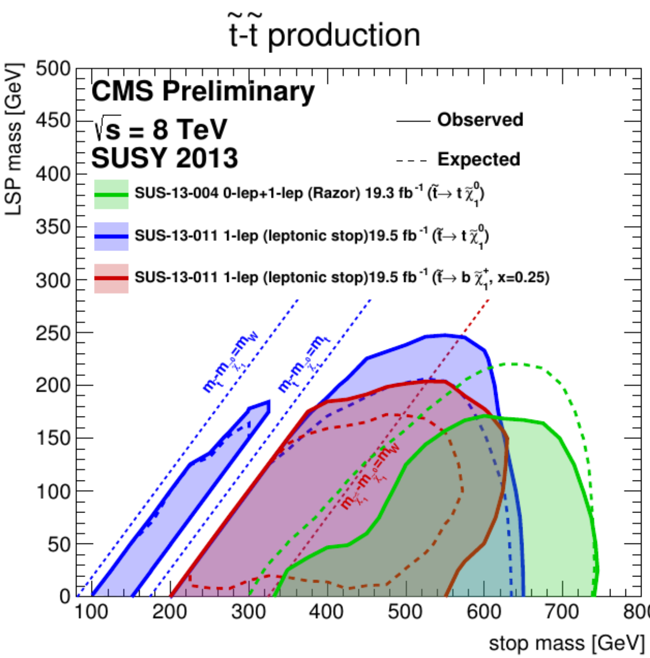
N. Arkani-Hamed at LPCC workshop, Oct. 2011

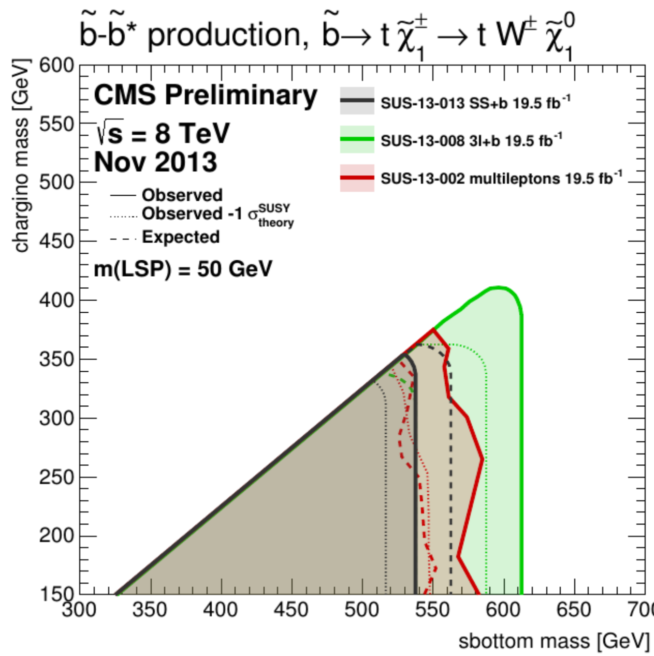
- a new dedicated search program was developed at the LHC around naturalness
  - search for direct stop and sbottom pair production
  - gluino searches, decaying through stop/sbottom

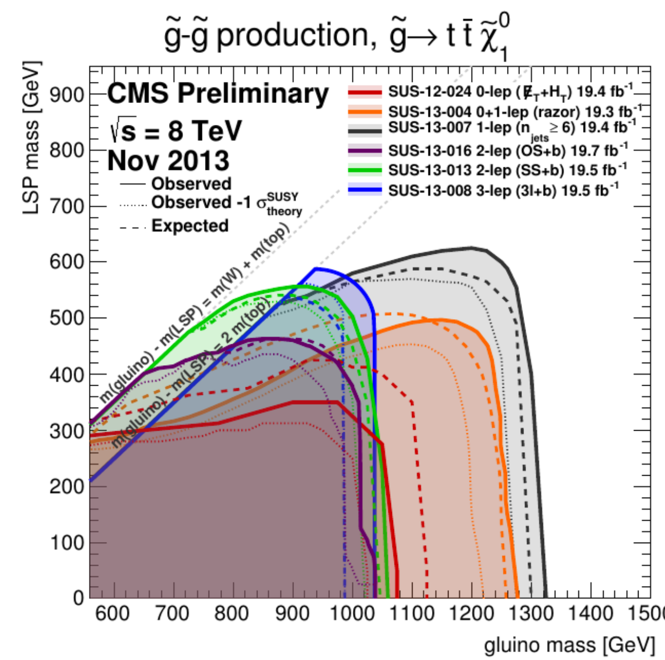
Natural SUSY searches

After 2 years of dedicated efforts…

- stringent limits on naturalness
  - with some caveats

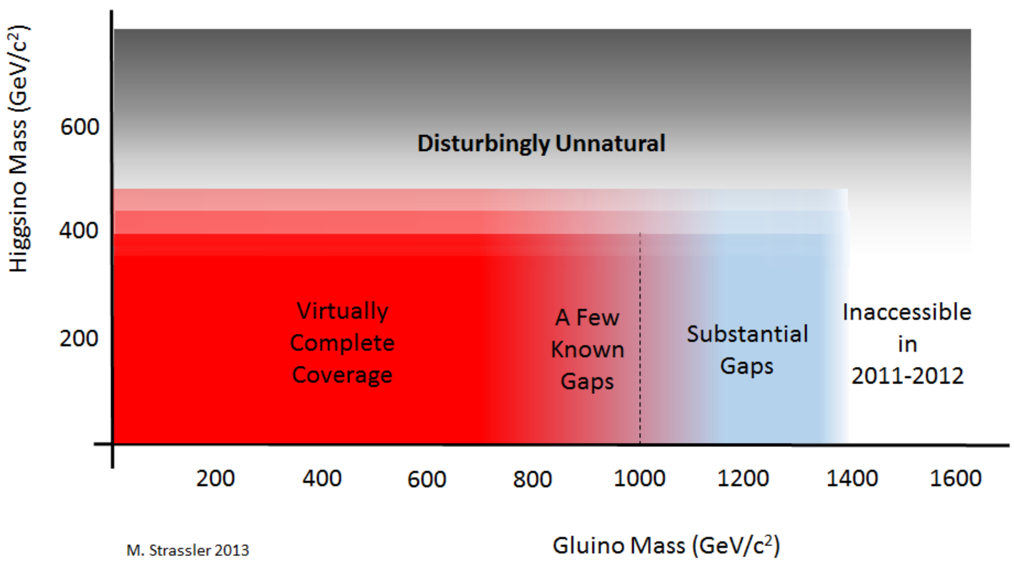


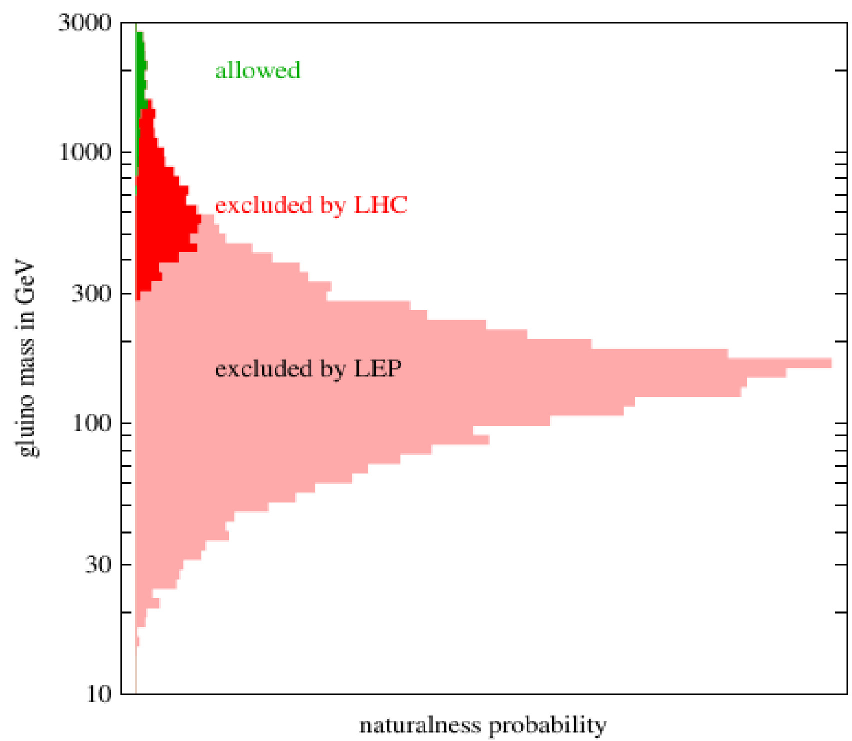




Natural SUSY under pressure

- Oct 2011: "Natural SUSY endures"
  (arXiv:1110.6926 [hep-ph])
- Oct 2013: "Toward Full LHC Coverage of Natural Supersymmetry"
  (arXiv:1310.5758 [hep-ph])

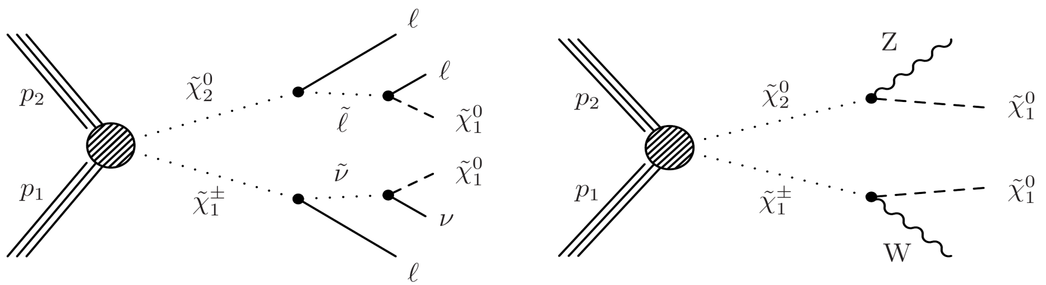




JHEP 1104 (2011) 073

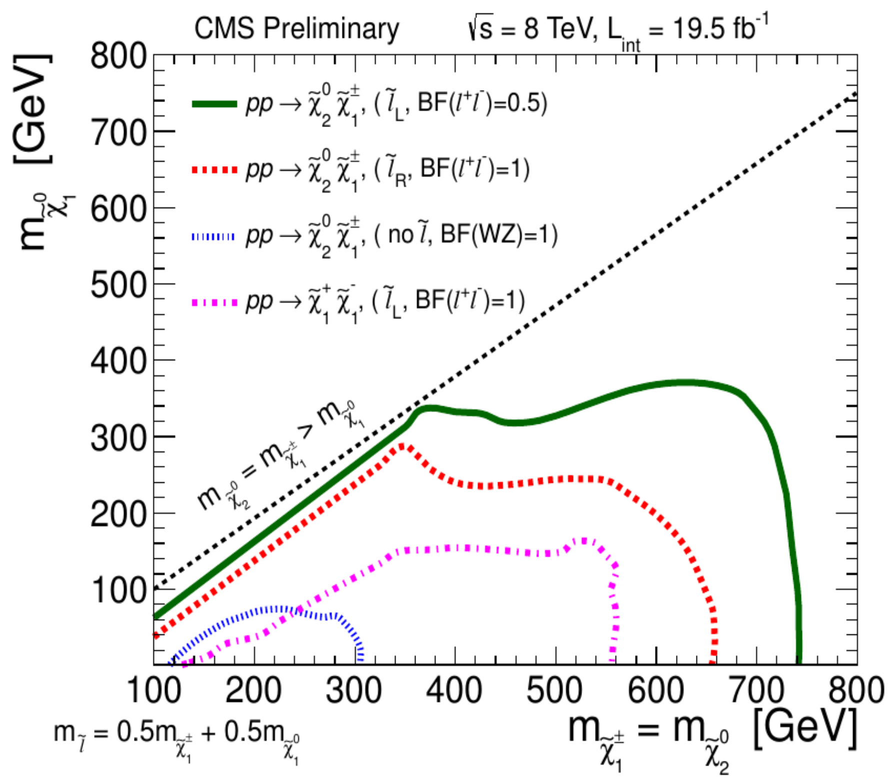
Searches for electroweak SUSY production

- without naturalness, all coloured sparticles could be out of reach
- other sparticles have low production cross sections (EWK production)
  - neutralinos, charginos, sleptons
- decay to leptons, from sleptons or from W/Z decays
  - no or little jet production
  - searches with 2 leptons (same charge or opposite charge), 3 and 4 leptons
  - example diagrams:



  - caveat: assumptions on BR's

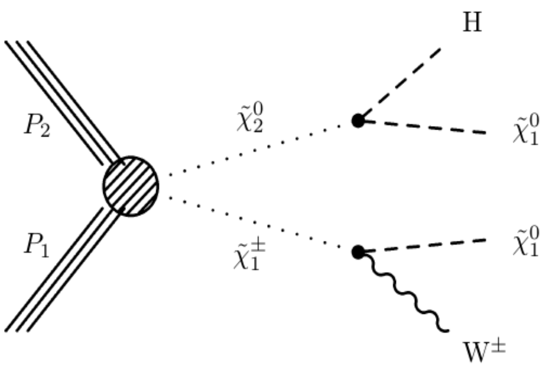
CMS-PAS-SUS-12-022



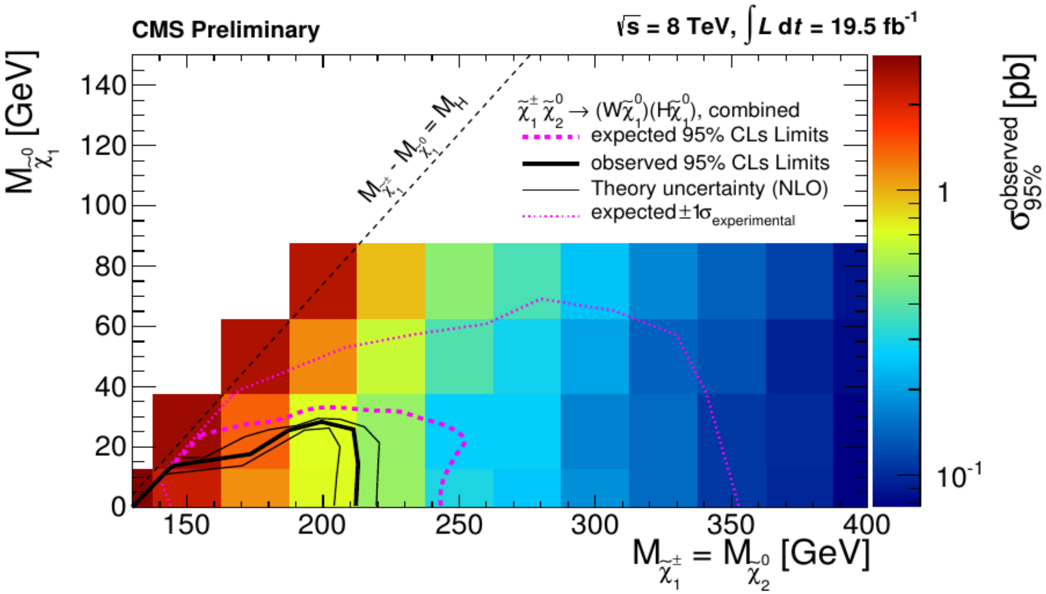
Welcome back, H(125)

Finally, we stopped ignoring our scalar boson

- it is possible to have scalar bosons produced in neutralino decays
- we know the mass now, and also couplings
- and we start to have enough data to be sensitive to these rare processes



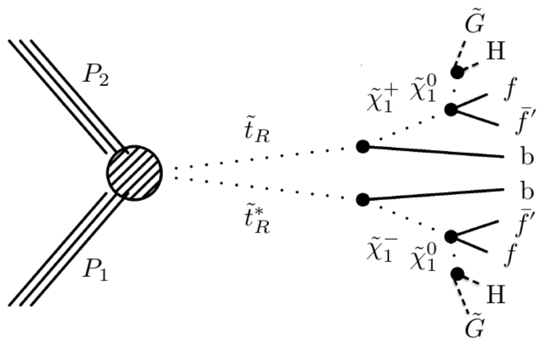
- search performed in all H → bb, ττ, WW, and ZZ decay modes
  - most sensitive in the single-lepton search where H → bb

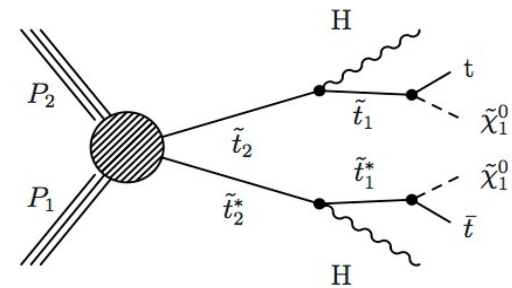


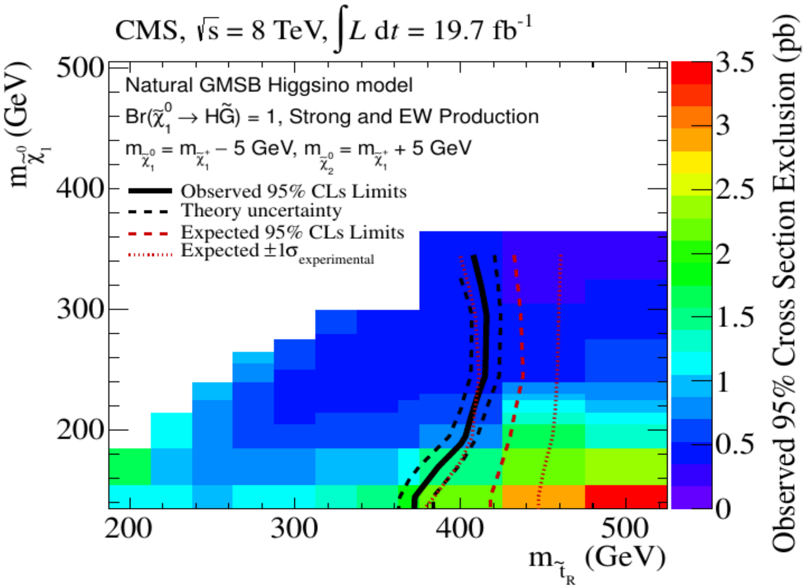
CMS-PAS-SUS-13-017

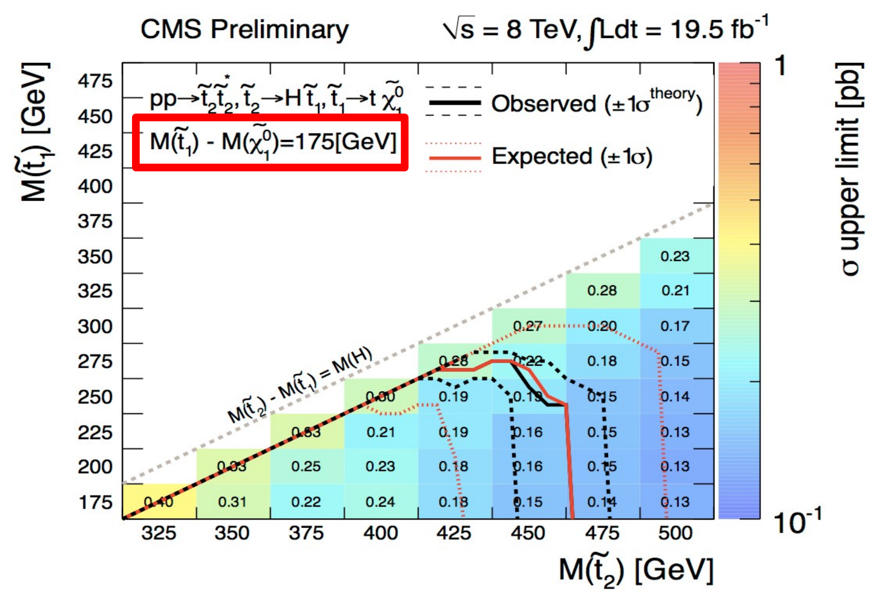
Other examples with H in cascades

- stop search in GMSB scenario
- stop2 → stop1 search





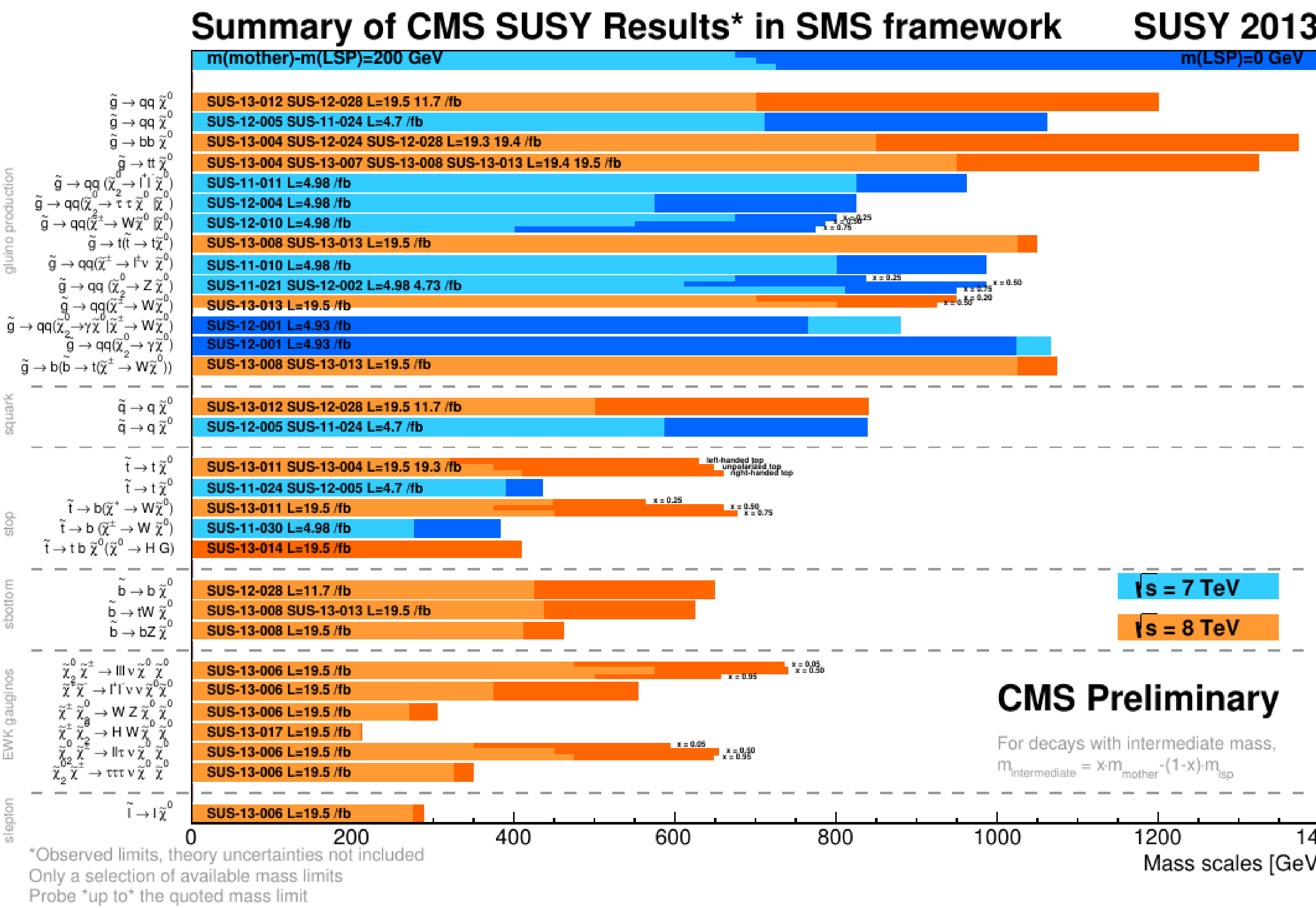




arXiv:1312.3310 [hep-ex]

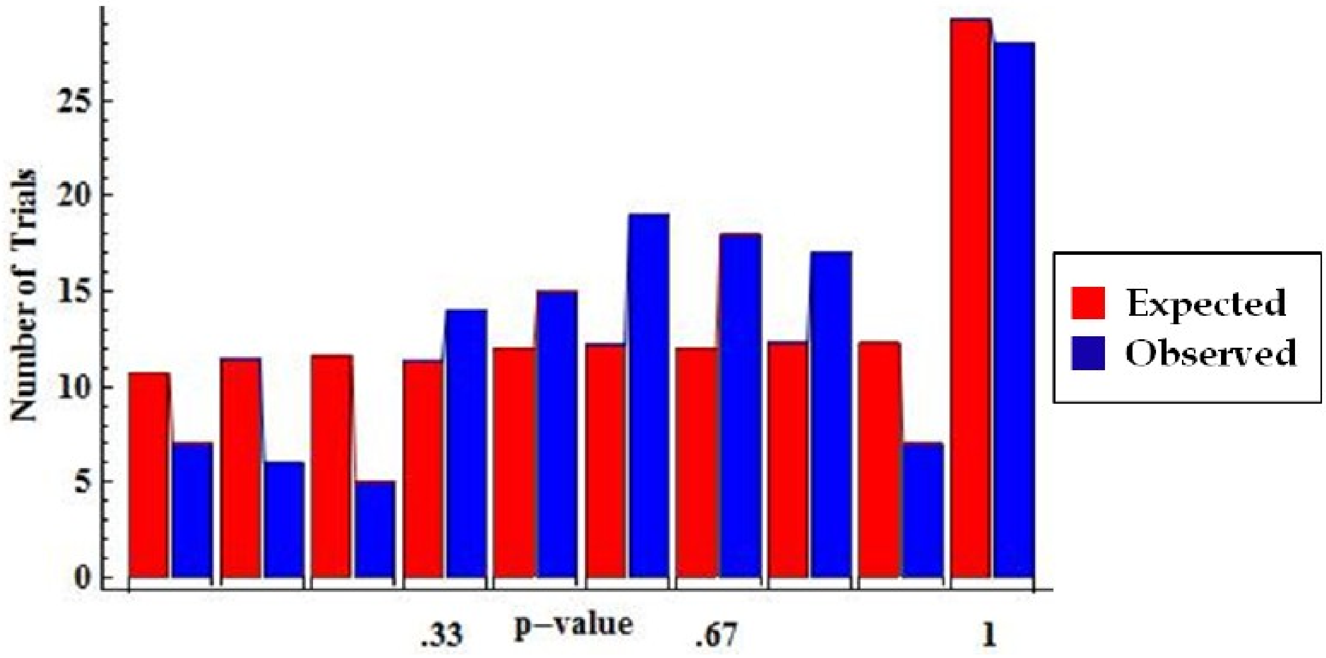
CMS-PAS-SUS-13-021

SUSY: nothing but limits



EPJ Plus, 127 12 (2012) 157

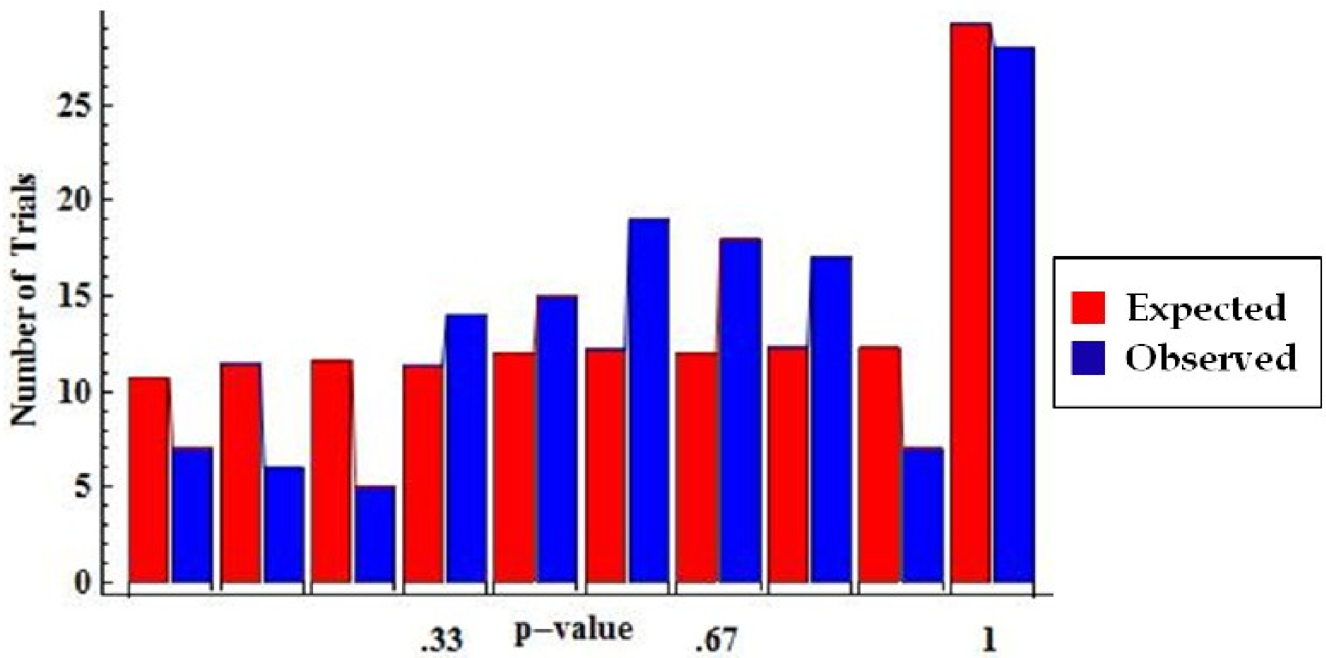
Evidence for … in LHC SUSY Searches



No evidence?

EPJ Plus, 127 12 (2012) 157

Evidence for conservatism in LHC SUSY Searches



- conservative uncertainties translate in too few observed excesses
- better uncertainties could still reveal something

SUSY under pressure?

“You can never exclude SUSY, you can only find it”

- however, the appeal is weakening
- it looks like we have to give in on one of the following
  - naturalness: with a higher SUSY scale, everything is possible again
  - RPC: don't try to solve dark matter, but make sure to keep proton stable
  - lack of fine-tuning: SUSY at low scale, but with compressed spectrum
  - minimal SUSY
  - …
- or maybe we need revolutionary (crazy?) ideas?
  - eg. H(126) is the superpartner of the neutrino (arXiv:1211.4526 [hep-ph])

First years LHC Run II will be crucial

- last energy increase for a while...

SUSY as a DM model

- many RPC SUSY searches at the LHC are searches for dark matter produced in decays of higher-mass particles
  - dark matter has more experimental backing than SUSY...
- eg. jets + MET is a very generic signature of a strongly produced particle decaying to a DM candidate

arXiv.org > hep-ex > arXiv:1106.4503

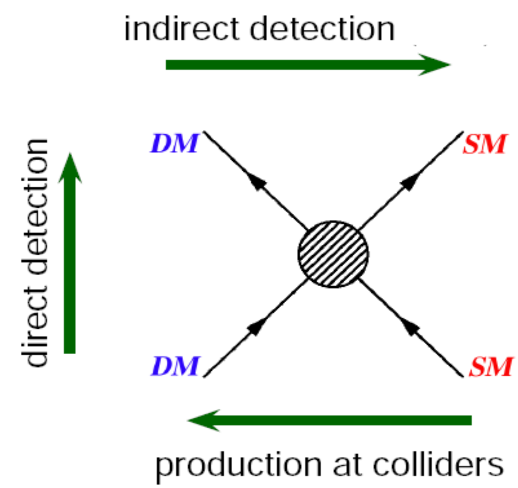
High Energy Physics - Experiment

Search for New Physics with Jets and Missing Transverse Momentum in pp collisions at sqrt(s) = 7 TeV

CMS Collaboration

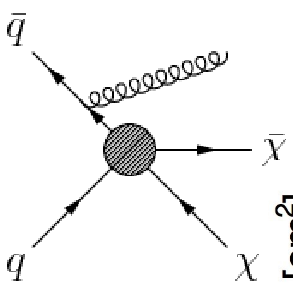
(Submitted on 22 Jun 2011)

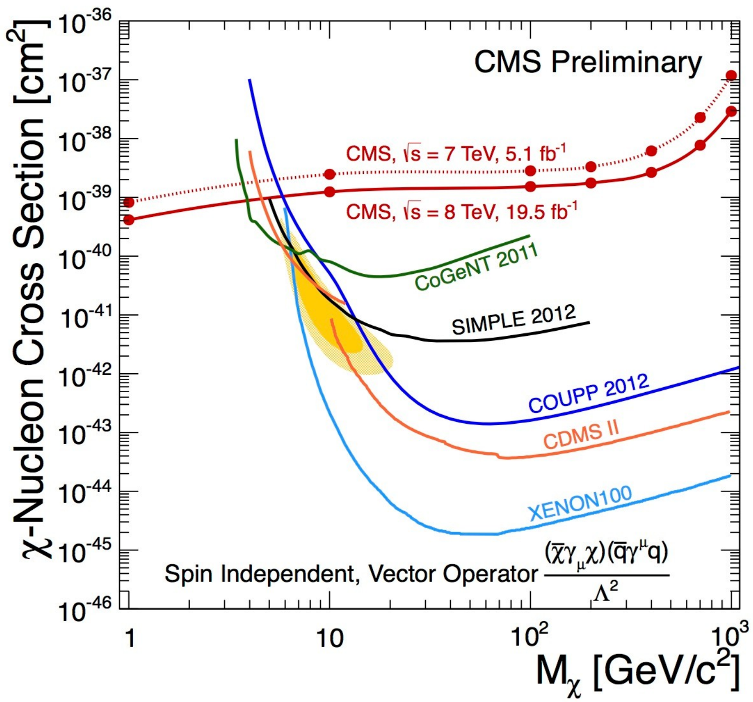
- if we're not seeing the higher-mass state, then maybe we can search for directly-produced dark matter?

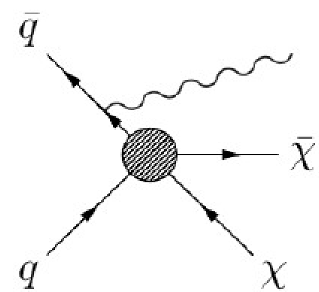


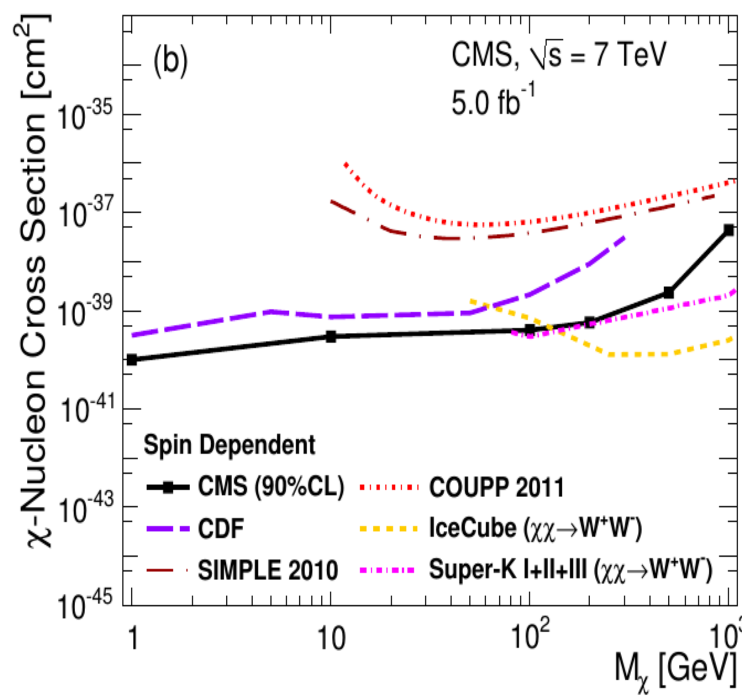
"Traditional" DM collider searches

- use initial-state gluon or photon radiation as a probe recoiling against a pair of DM particles
  - production vertex approached assuming couplings in an effective theory



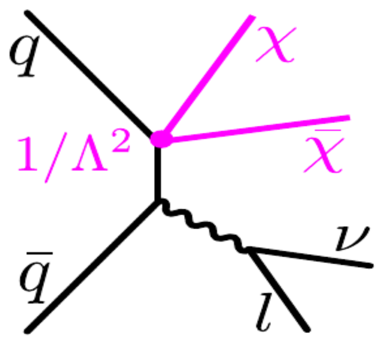


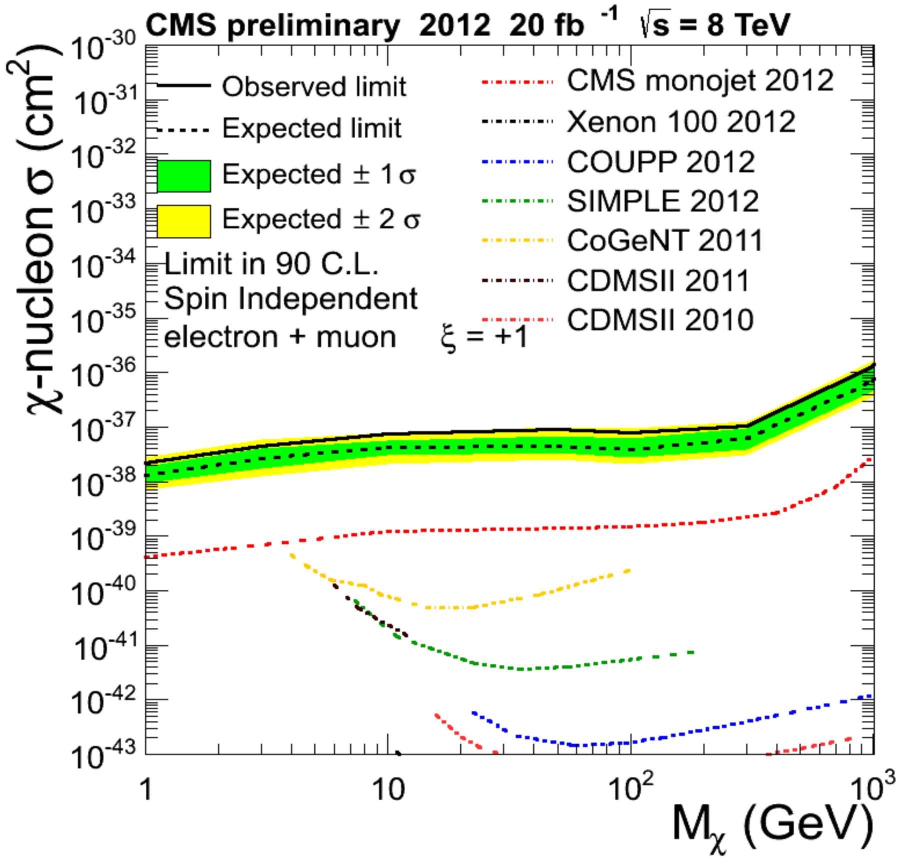




Mono-something

- other particles can be considered initial-state radiation, or produced in the DM interaction vertex
  - mono-W, mono-Z, monotop, monohiggs
- recent new result: mono-W with leptonic decay → monolepton

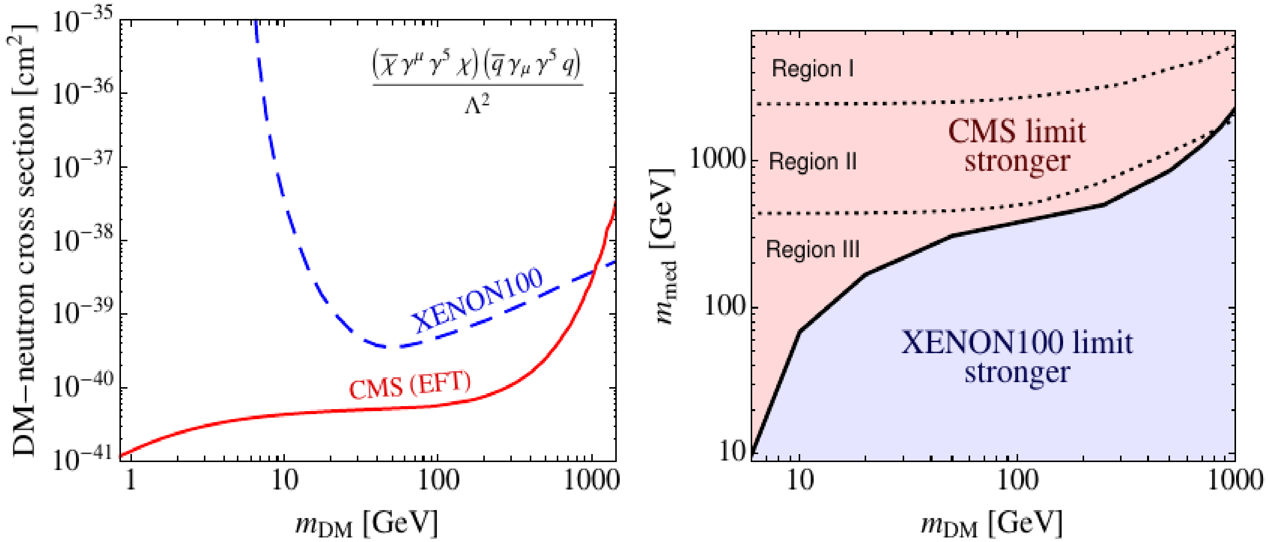




DM search interpretation can be tricky

- effective field-theory approach comes with caveats
  - mediator mass should be “sufficiently heavy” in order to treat the DM production as a contact interaction
- using EFT beyond its applicability can lead to overly optimistic limits

CMS monojet analysis compared to same limits with explicit Z' mediator



arXiv:1308.6799 [hep-ph]

- also here, a simplified model approach starts to be considered to scan the parameter space more systematically
- very active research area!

Quite a story for SUSY in LHC Run I

- from CMSSM to SMS descriptions
- the naturalness saga
- rare processes with electroweak production and H(126) in cascades
- run II will be crucial!

Dark Matter as a new motivator

- mono-something searches setting strong limits already
  - in particular on low-mass DM particles
- need to be careful with EFT approach