Searches for new physics at the LHC outside the Higgs sector

Paris Sphicas
CERN & University of Athens
The Zurich phenomenology workshop: Higgs search confronts theory
Jan 09, 2012

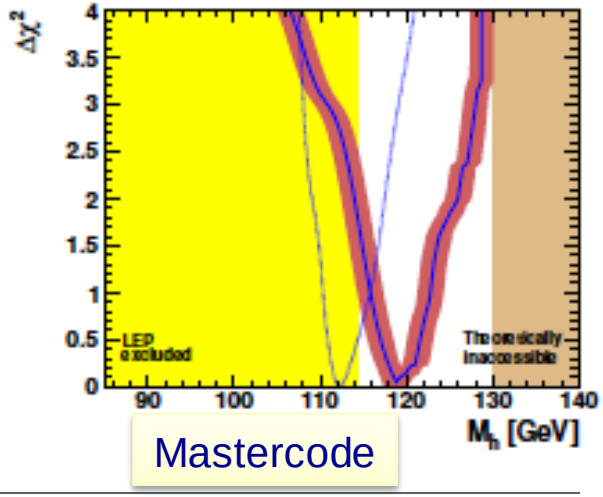
- **Prelude**
- **The foundations: a very quick tour of pp collisions at 7 TeV**
  - **Strong interaction physics (jets, QCD); Electroweak signals (W/Z production & properties); The top quark (still there)**
- **Searching for New Physics**
  - **Bread-and-butter searchers + Tevatron checks**
  - **Where is SUSY?**
- **The 2012 run.**
  - **More data (lumi?); higher energy?**
- **Summary**

In a nutshell (I)

- **At 95% CL:**
  - **ZPW participants are aware of the fact that the LHC has had a spectacular year, breaking luminosity records and all expectations**
  - **Most people are aware of the incredibly successful operation of ATLAS and CMS**
  - **Standard model (SM) of particle physics reigns supreme in pp collisions at 7 TeV**
  - **The mass of the SM Higgs boson is not in the ranges M_H<115 or M_H>128 GeV**
  - **R_P-conserv: gluinos, 1st/2nd-gen squarks, not lighter than ~0.5TeV**
  - **There exist no new resonances with mass <~2 TeV**
  - **There are no spectacular signatures from objects of mass ~few TeV decaying "democratically" to lots of jets, MET, leptons....**
  - **Most of the information in this talk is already well known**
  - **Standard model of human behavior reigns supreme in pp collisions at 7 TeV (some level of worry has set in; still in control)**

In a nutshell (II)

- **At 100% CL, all the reasons for building the LHC are still there, intact:**
  - **The WW cross section regulator is still missing. (S)he must be there before we explore fully the 1 TeV.**
    - **Old name: "LHC no-lose theorem"; new name: "not finding the Higgs is a major discovery"**
  - **Any (reasonable) M_H unnatural; Higgs needs its own regulator**
    - **Old name: SUSY; New name: SUSY; its main prediction is (so far) vindicated ☺**
    - **Old CW: SUSY around the corner; New CW: she's in the third generation (stop, sbottom)**
  - **Other stuff:**
    - **Extra-dimension physics, new gauge bosons, leptoquarks, fourth fermion Generation, quark substructure…**
      Still huge space of unexplored physics
- **The best has yet to come – read on.**



Mastercode

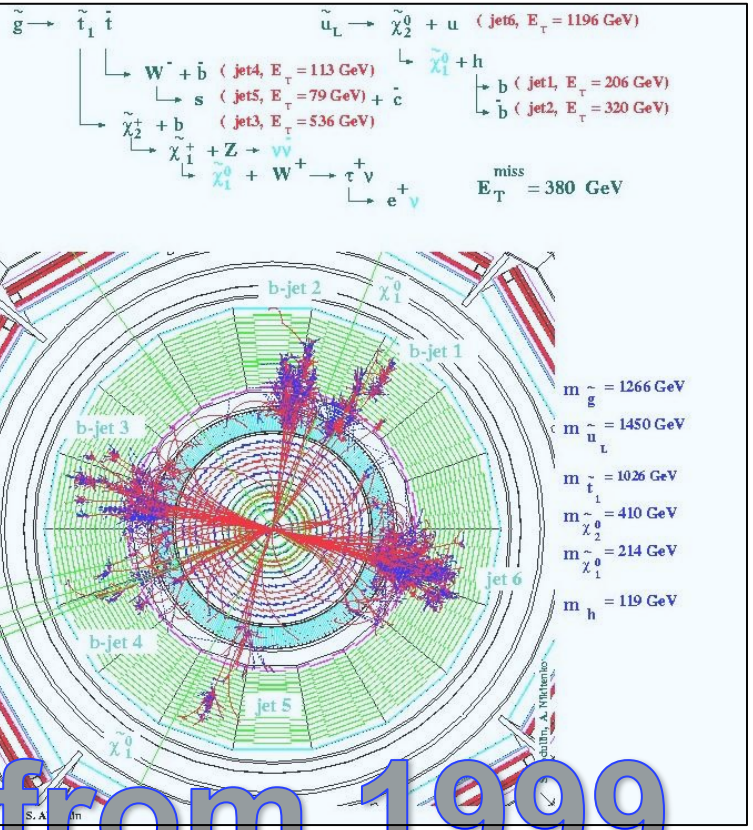
LHC(t_0):

Great expectations

"Turn on the LHC and find Higgs & SUSY"

- **ATLAS and CMS were designed to do this; they were "guaranteed" to find the Higgs – period; right away**
  - **In fact: SUSY is strongly produced, so will be observed first**
    - **For the "impatient": join SUSY physics group**

- **Many hard Jets**
- **Large missing energy**
  - **2 LSPs**
  - **Many neutrinos**
- **Many leptons**
- **In a word Spectacular!**

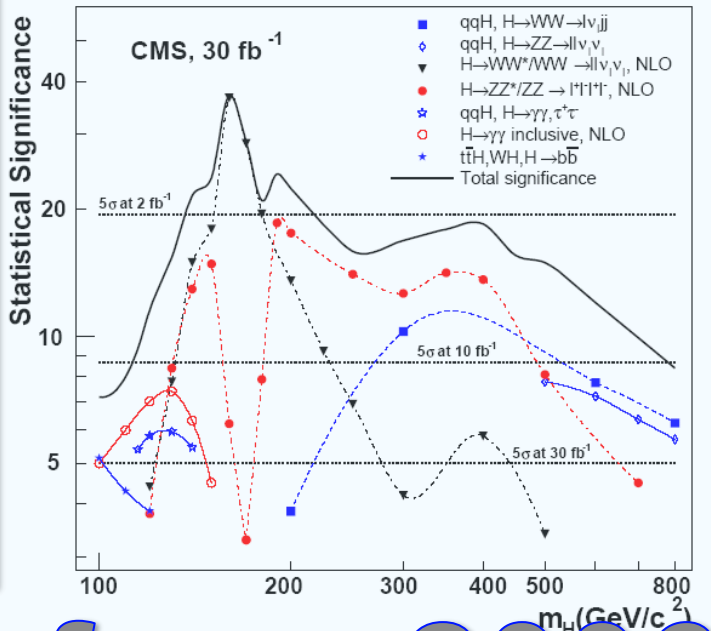


Text & simu from 1999

"Turn on the LHC and find Higgs & SUSY"

- **ATLAS and CMS were designed to do this; they were "guaranteed" to find the Higgs – period; right away**
  - **In fact: SUSY is strongly produced, so will be observed first**
    - **For the "impatient": join SUSY physics group**
    - **For the "patient" ones: join the Higgs group**

- **The LHC can probe the entire set of "allowed" Higgs mass values;**
  - **in most cases a few months at $10^{33}cm^{-2}s^{-1}$ are adequate for a 5σ observation**



Text & simu from 2006

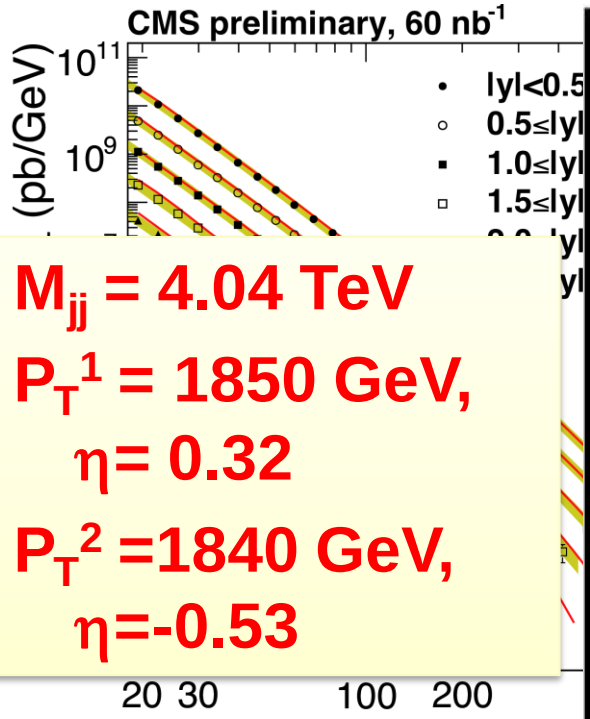
Turn on the LHC and find Higgs & SUSY

- **ATLAS and CMS were designed to do this; they were "guaranteed" to find the Higgs – period; right away**
  - **In fact: SUSY is strongly produced, so will be observed first**
    - **For the "impatient": join SUSY physics group**
    - **For the "patient" ones: join the Higgs group**
  - **For all others:**
    - **For those who like smaller analyses: join the Exotica group**
    - **For those who like finding *something*:**
      - **➔ QCD, EWK, B physics, …**

LHC(t_0+Δt=2yrs):

Foundations established
a “tour de force” of SM measurements

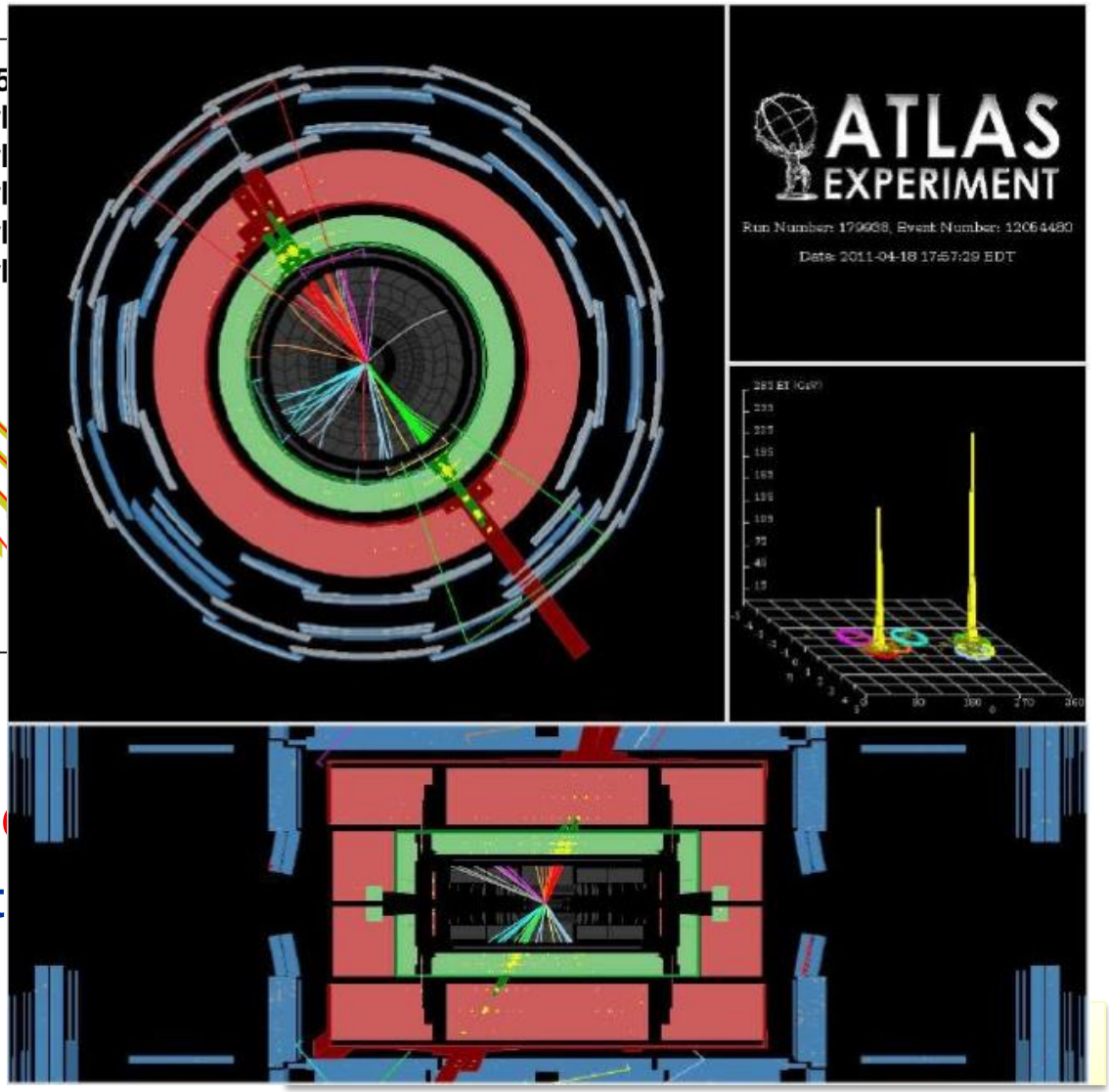
Jets



M_{jj} = 4.04 TeV

P_T^1 = 1850 GeV,
η= 0.32

P_T^2 =1840 GeV,
η=-0.53



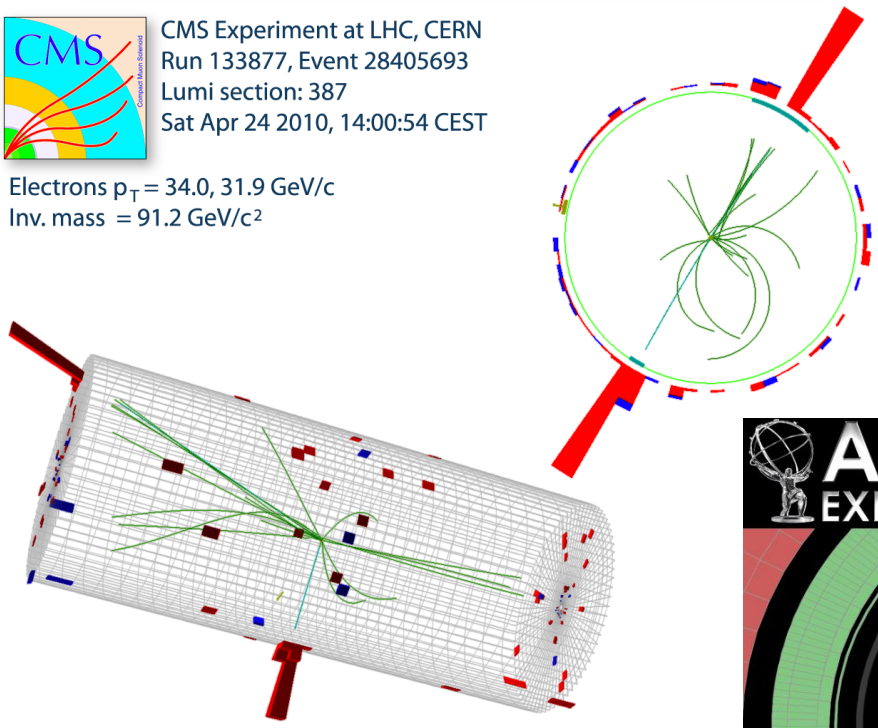
- To probe the hard s
  - The hard scatter: jet

W/Z at 7 TeV: (still) clean & beautiful

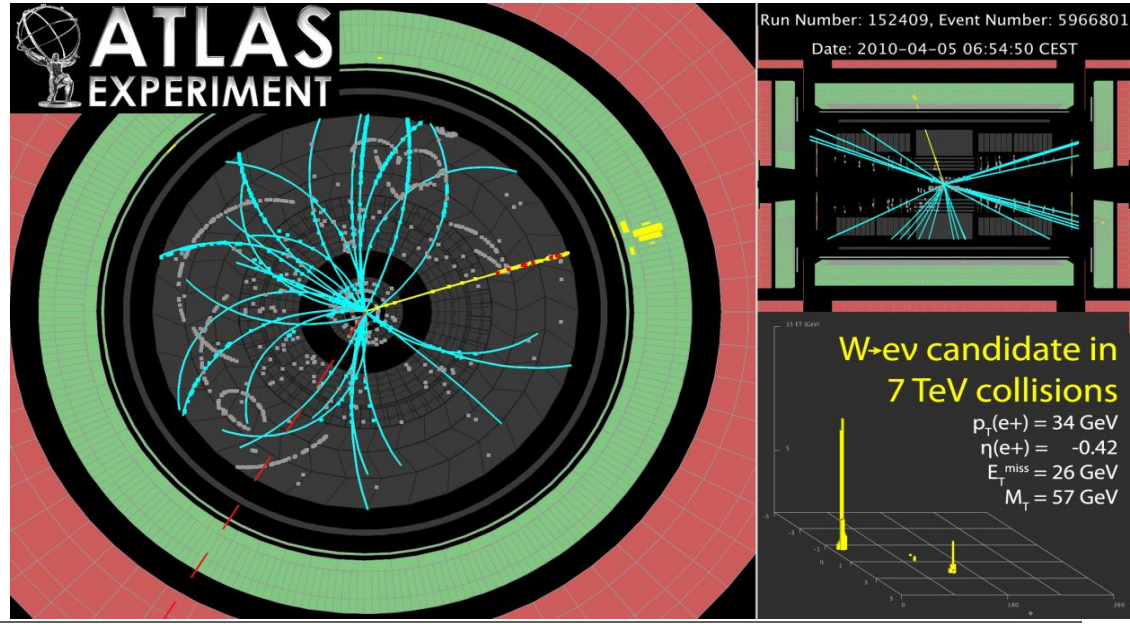
Z → electron + positron

CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

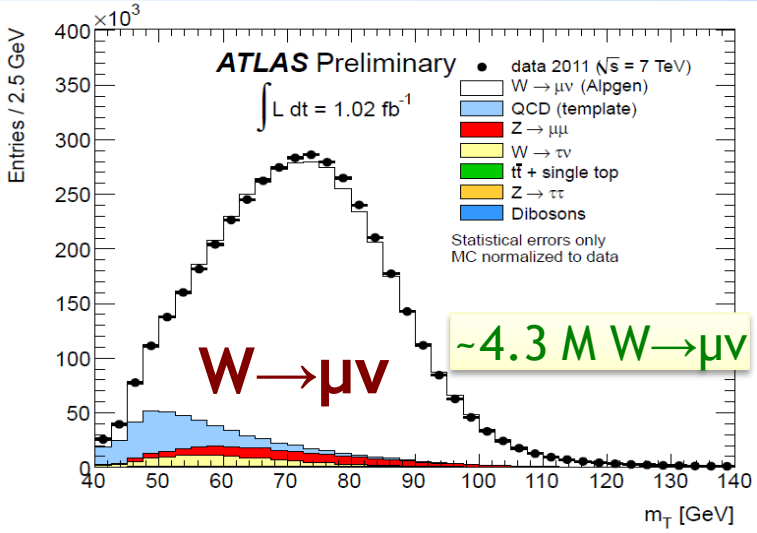
Electrons p_T = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/c^2

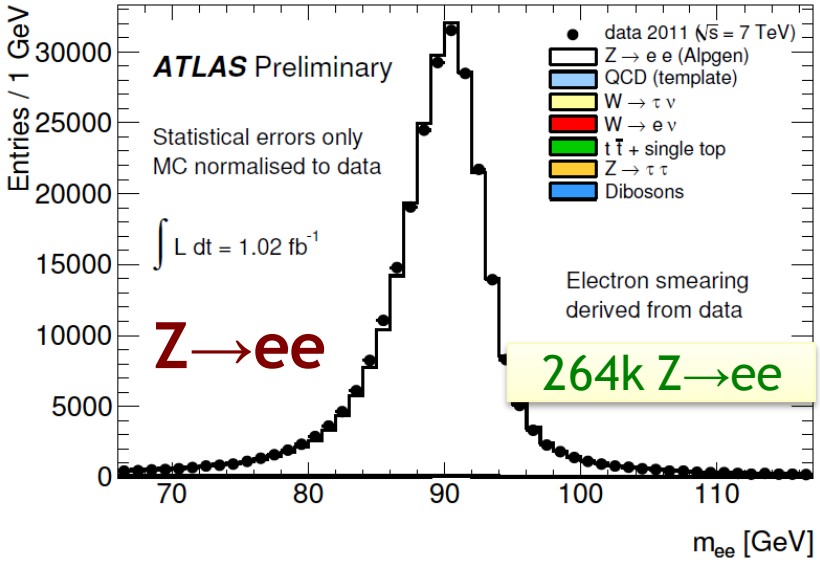


W → electron + neutrino

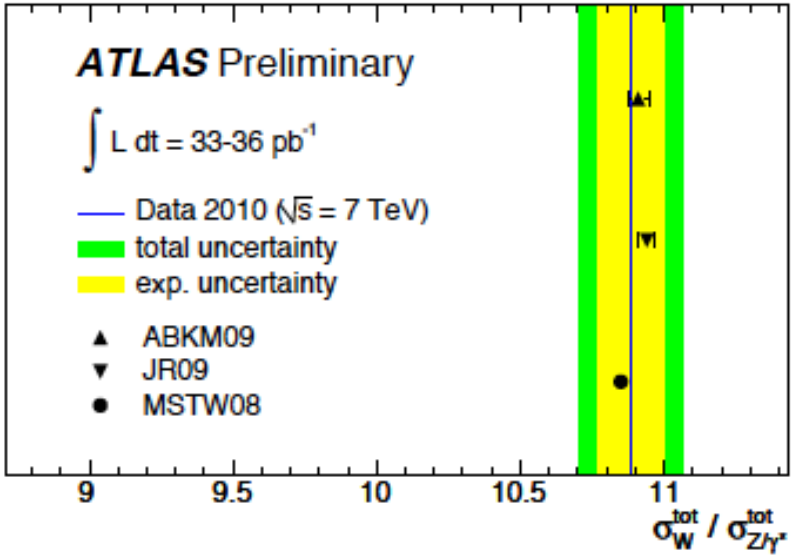


W/Z production (+LHC-specific obs)





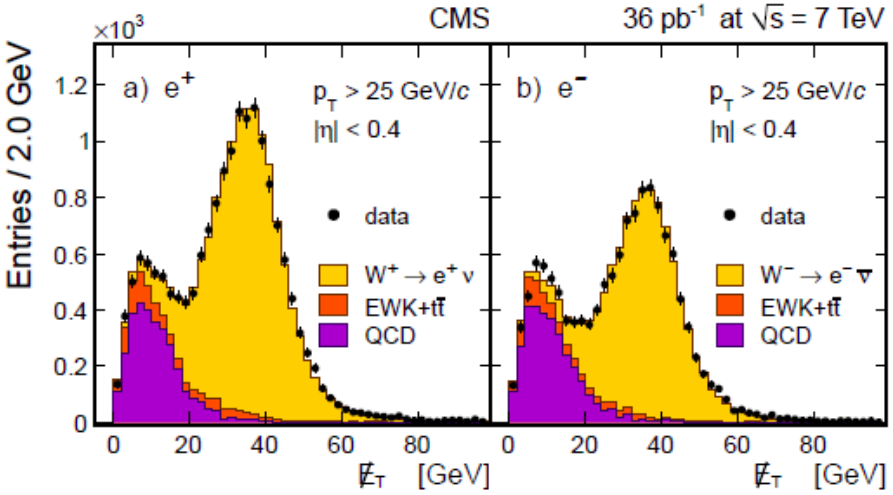
- **Excellent agreement between data and simulation**
- **Good agreement with NNLO+PDF theory predictions**



- **Move to "new environment":**
  - **σ(W⁺)≠σ(W⁻) (~1.4)**
  - **W polarization**

W production: charge asymmetry

- **Split samples in η; fit W^+, W^-.**



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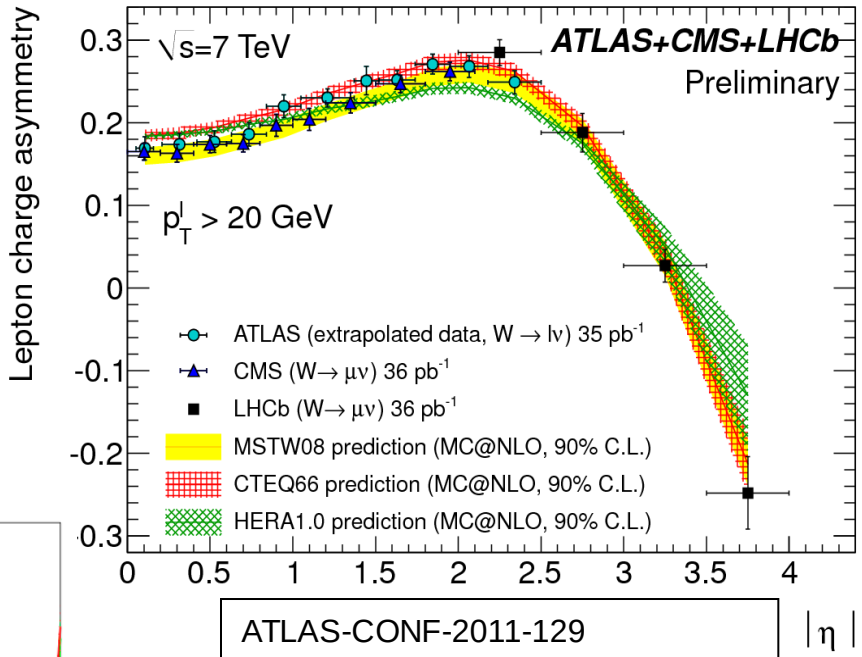
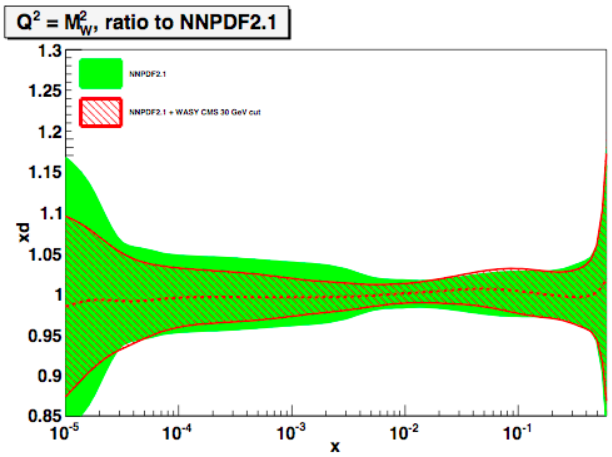


ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

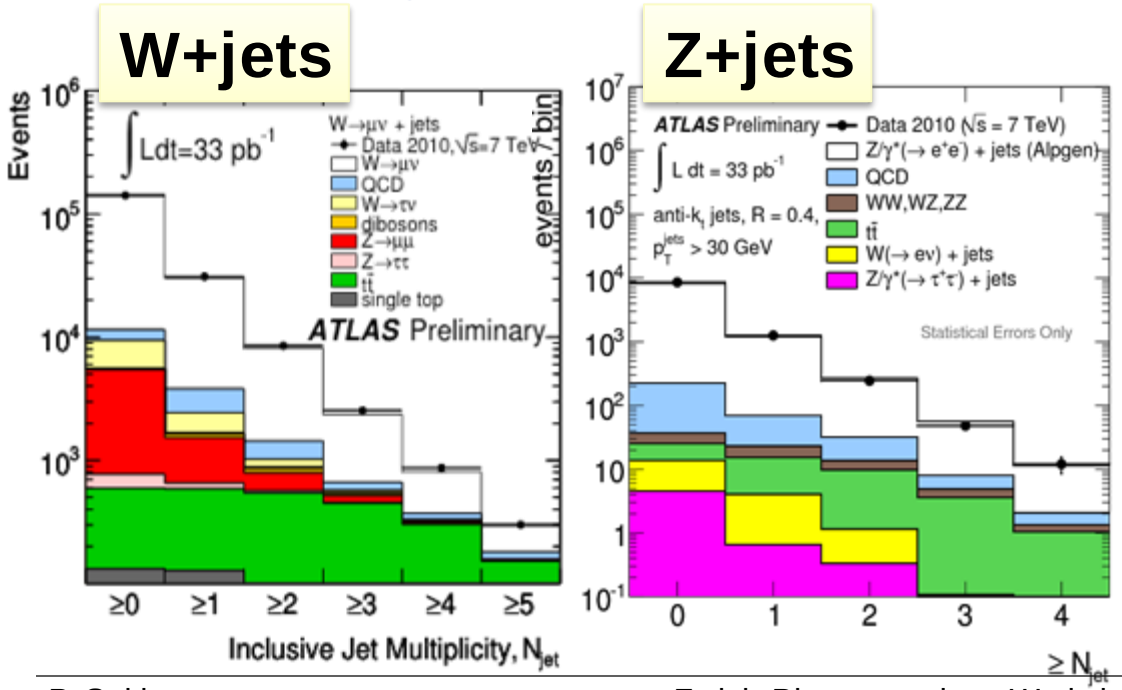
In $10^{-3} < x < 10^{-2}$:

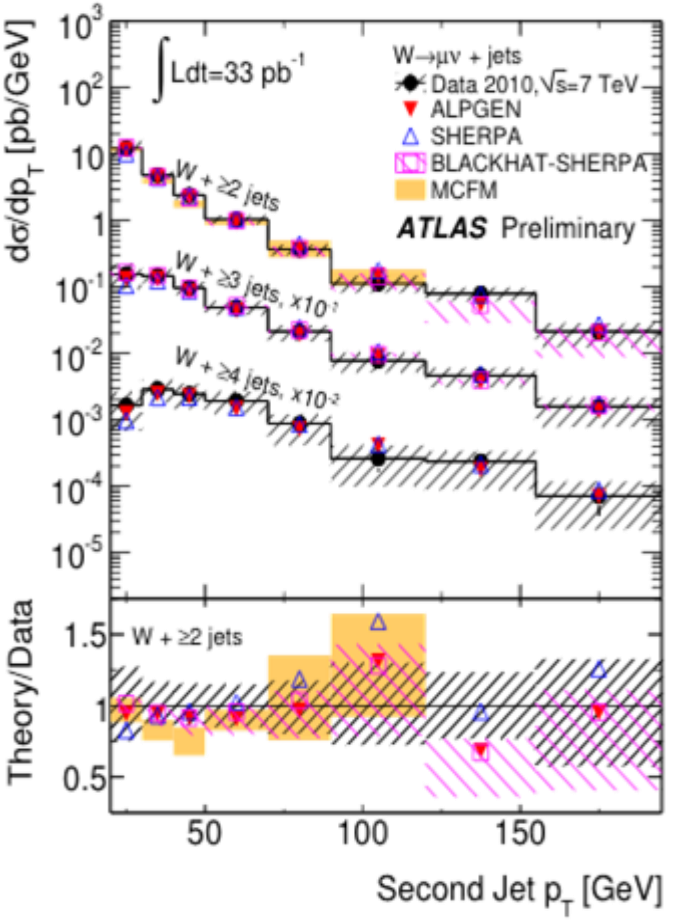
measurement already improves d,u,q-bar PDFs by >40%



W/Z + jets

- **Background for top and new physics; especially at high p_T(W/Z); each jet "costs" ~α_s**
- **Jet multiplicity and p_T distributions**
  - **Good description by state-of-the art QCD NLO calculations and LO multi-parton generators**





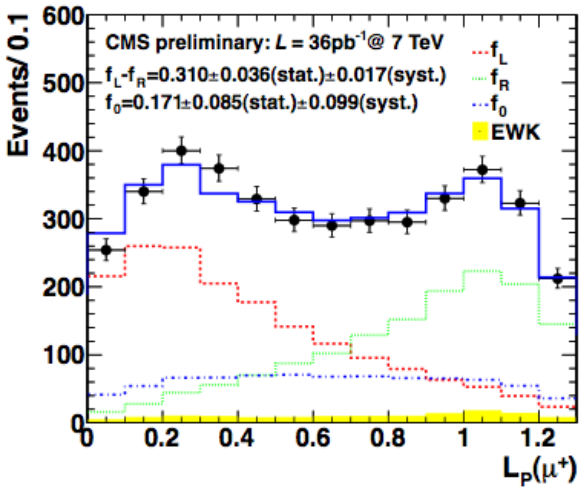
LHC-specific: W polarisation in pp

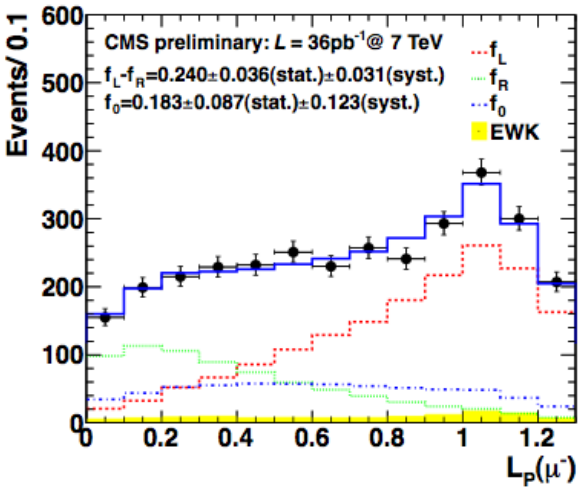
- **Produc**
  - Valen
    effect
  - Initial
    at *pp*

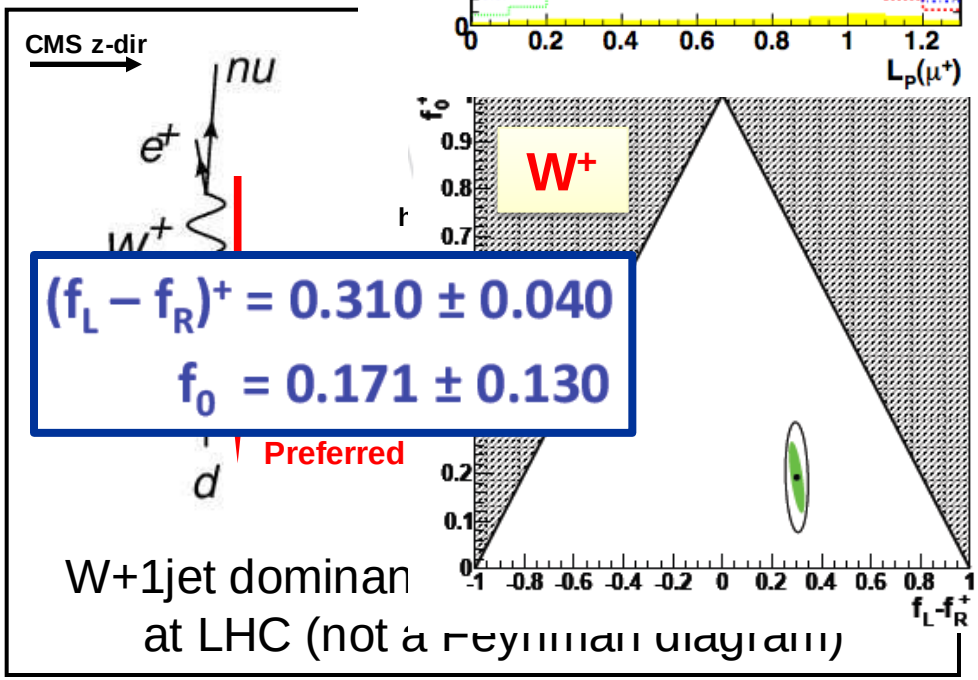
→ W's p

sation

amounts

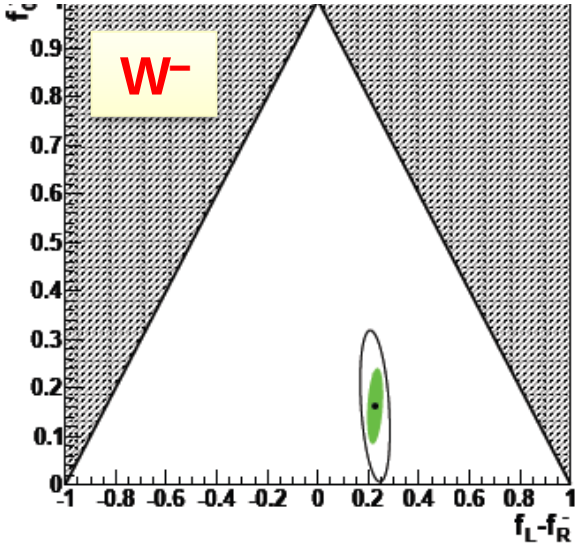


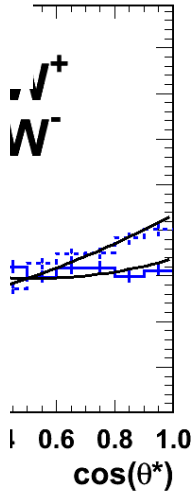




$(f_L - f_R)^+ = 0.310 \pm 0.040$

$f_0 = 0.171 \pm 0.130$





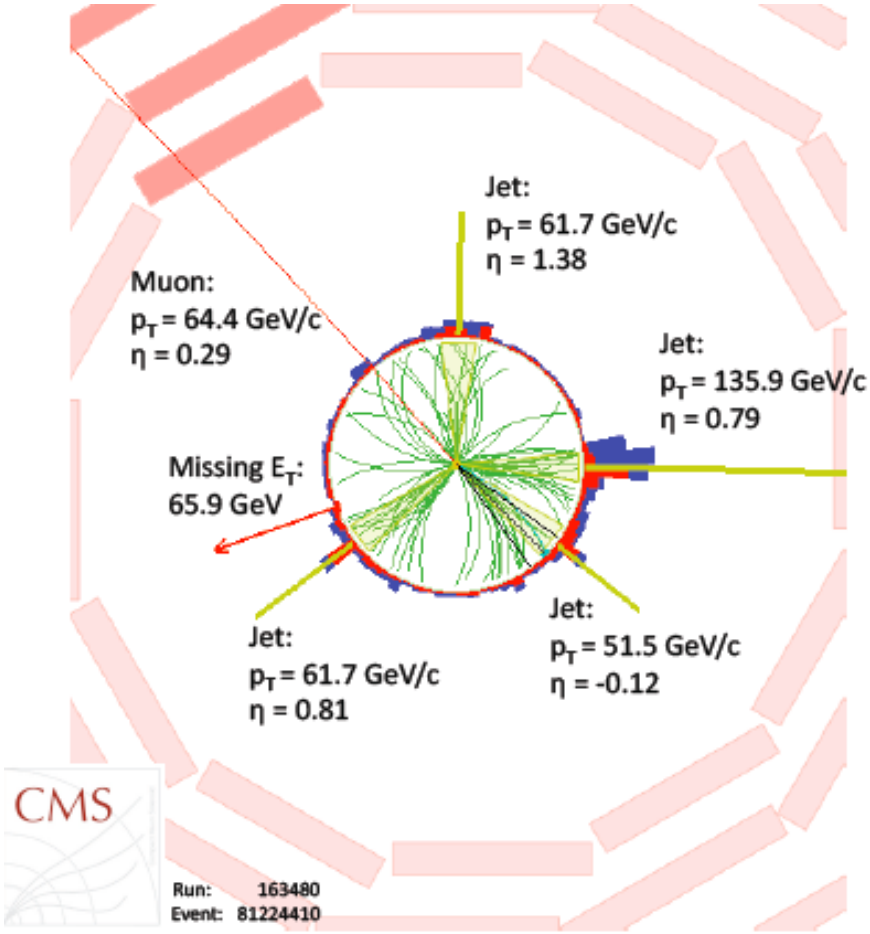
W+1jet dominan

at LHC (not a Feynman diagram)

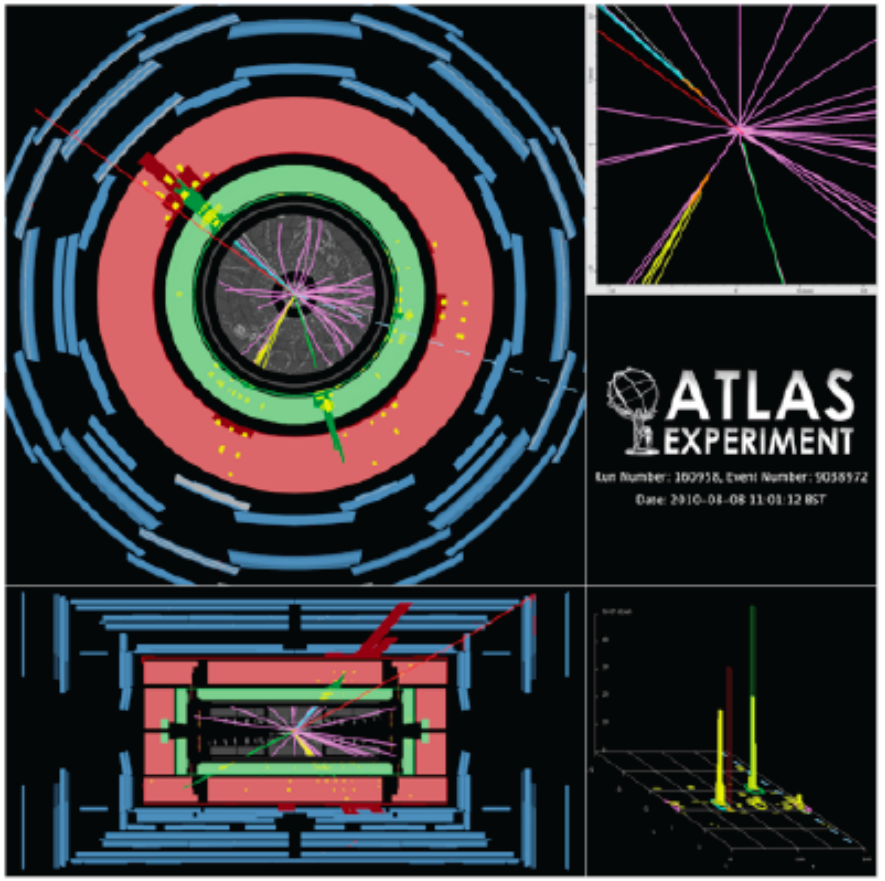
neasure

utrino)

The most complex SM signal: the top



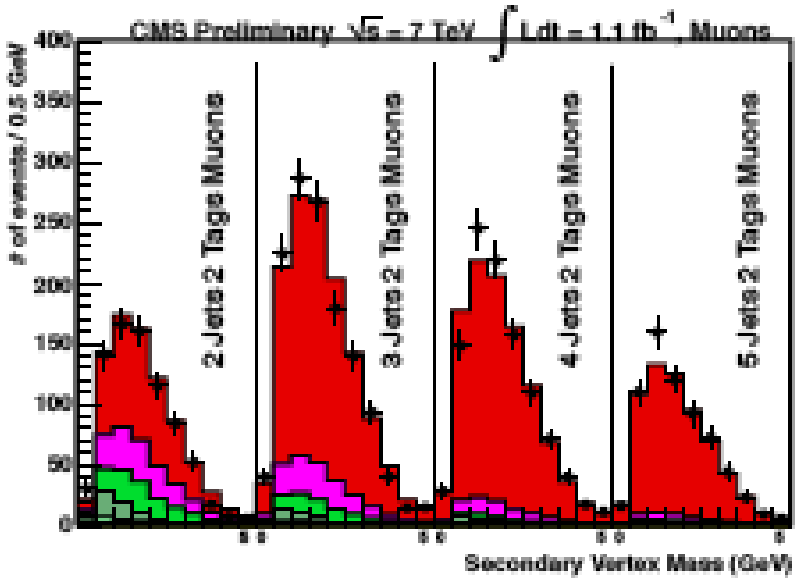
muon+jets event

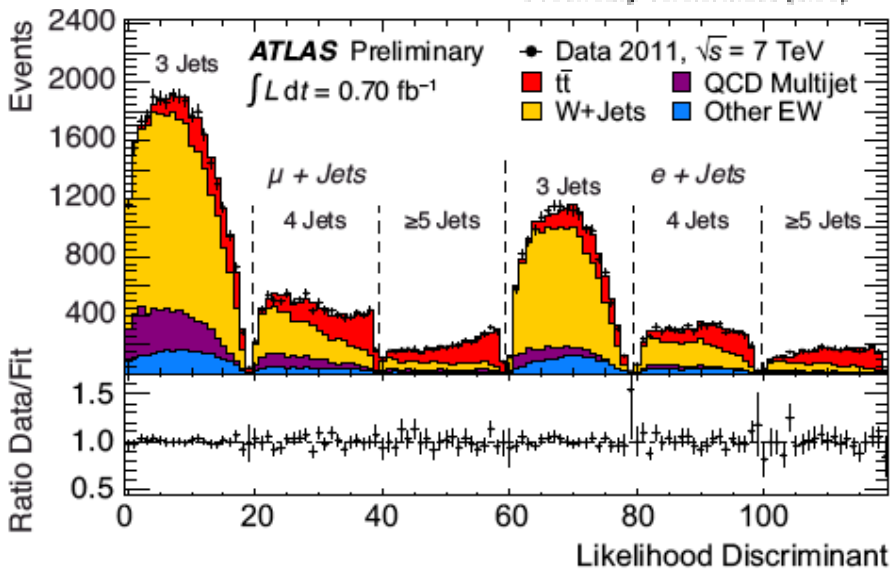


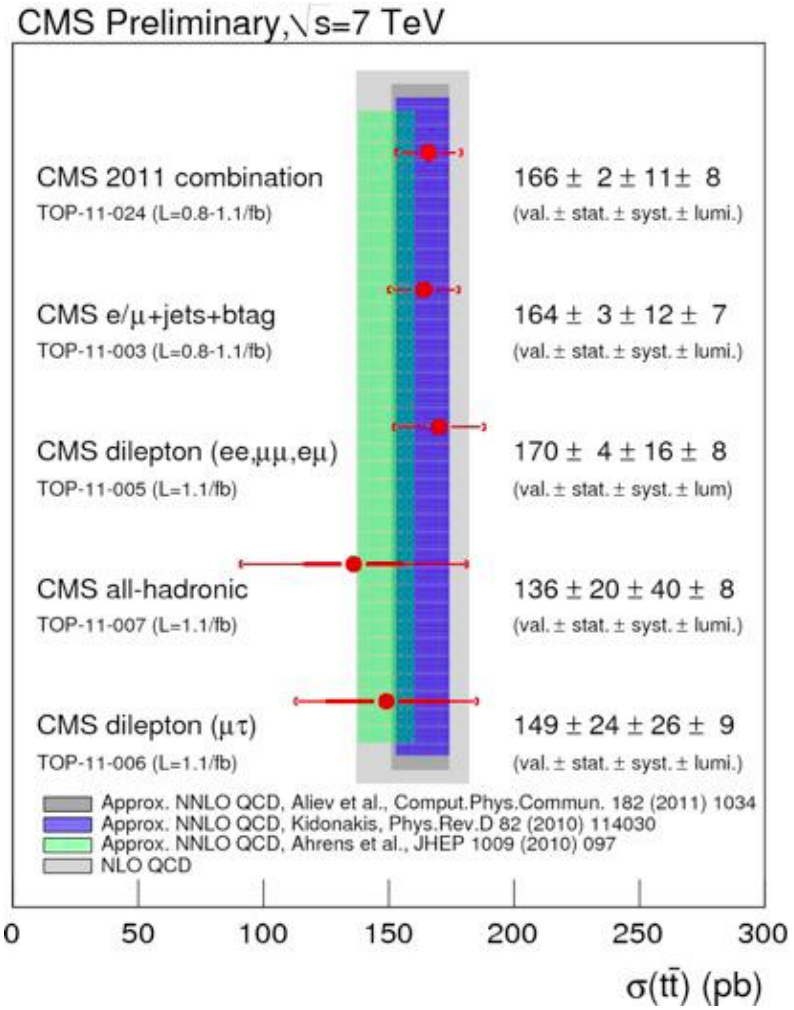
electron+muon event

HCP at Paris, 14/11/2011 3 Tae Jeong Kim

Top physics @ 7 TeV

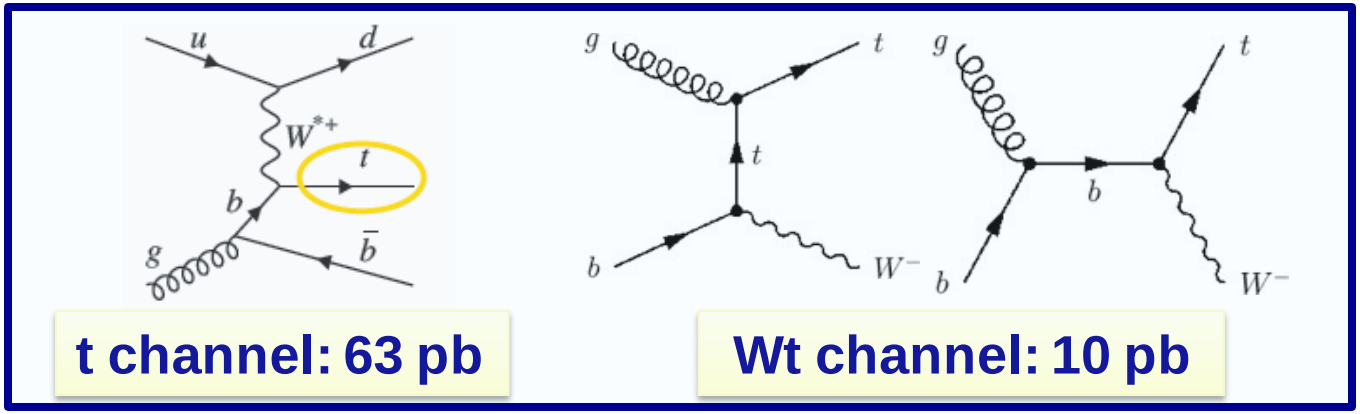






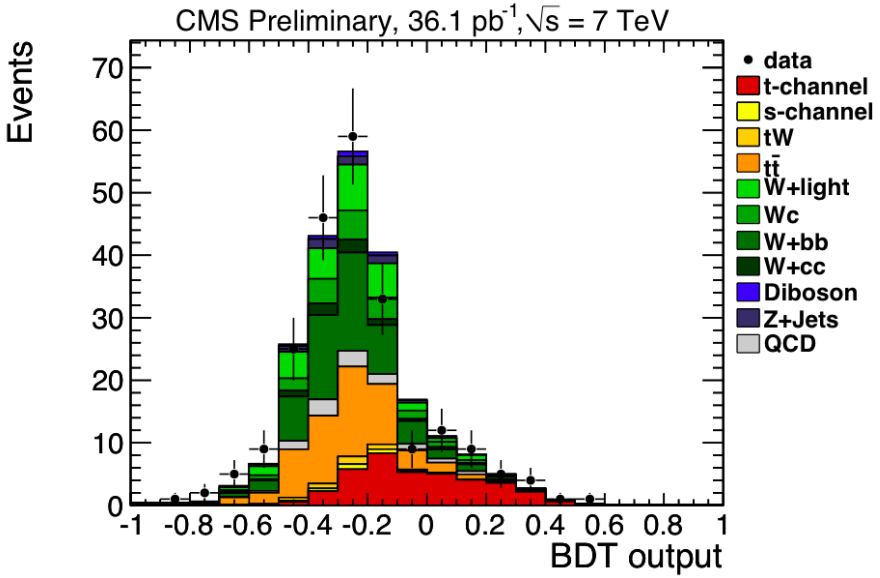
Small, tricky signals as well

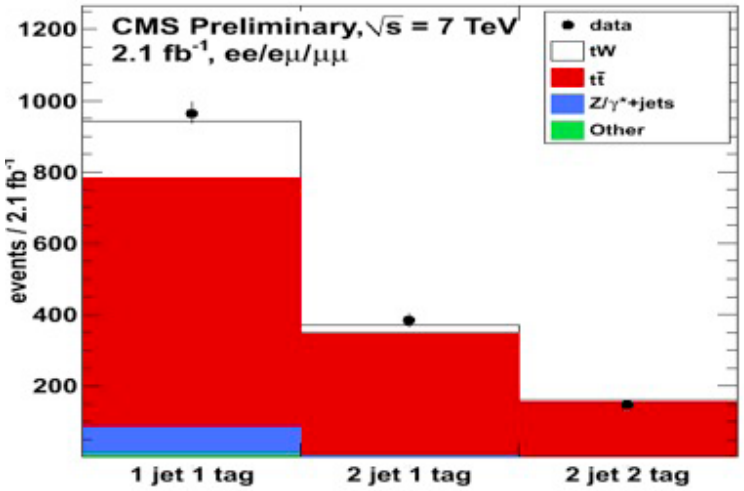
- **Single-top production**



t channel: 63 pb

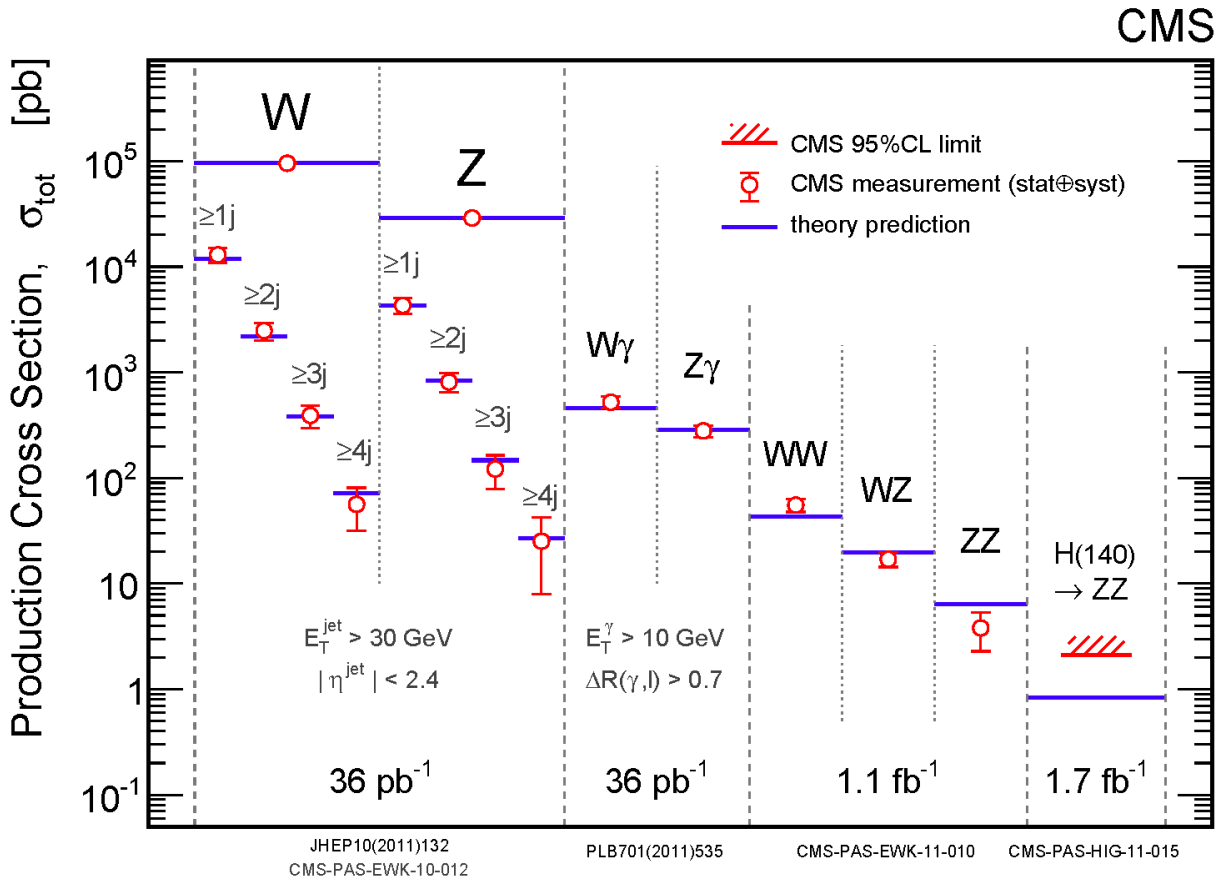
Wt channel: 10 pb





Standard model in pp collisions @ 7 TeV

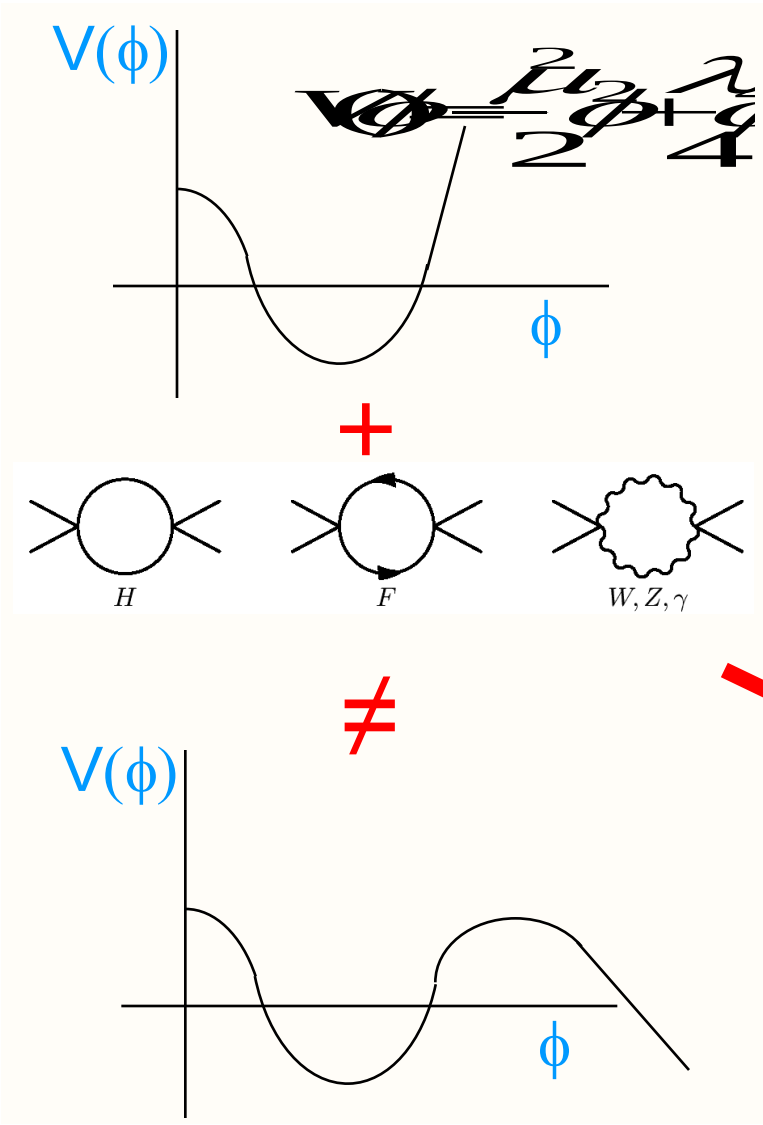
- **Understanding of SM processes at level of Tevatron experiments.**
  - **Let the search begin.**



LHC(t_0+Δt=2yrs):

What about new physics?
Good news from the Higgs
“Bad” news from the searches

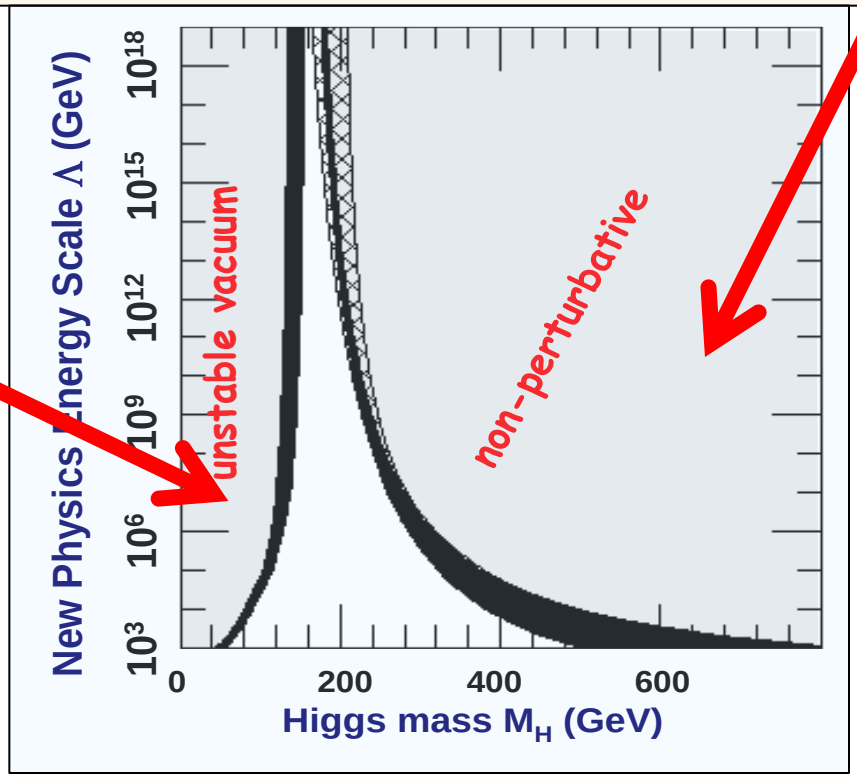
Scale of New Physics = F(M_H)



$$\lambda(Q^2) = \frac{\lambda(Q_0^2)}{1 - \lambda(Q_0^2)/16\pi^2 \log(Q^2/Q_0^2)}$$

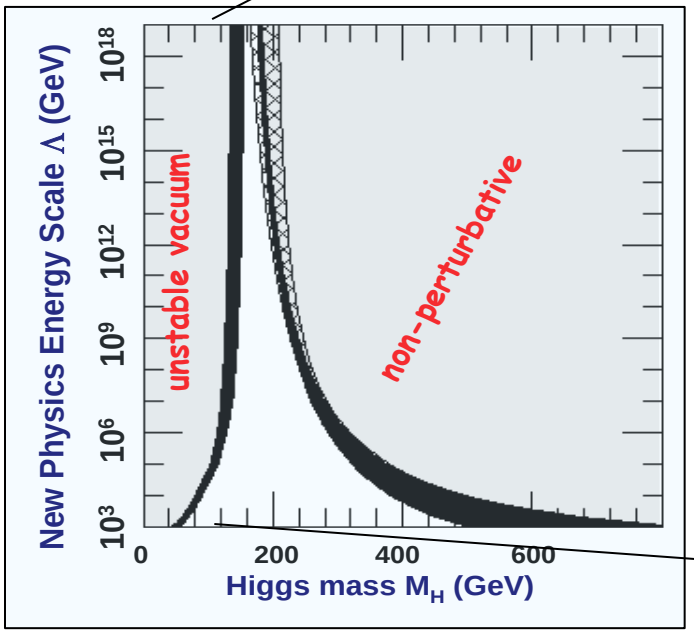
$Q^2 \to \infty,\ \lambda \to \infty!$

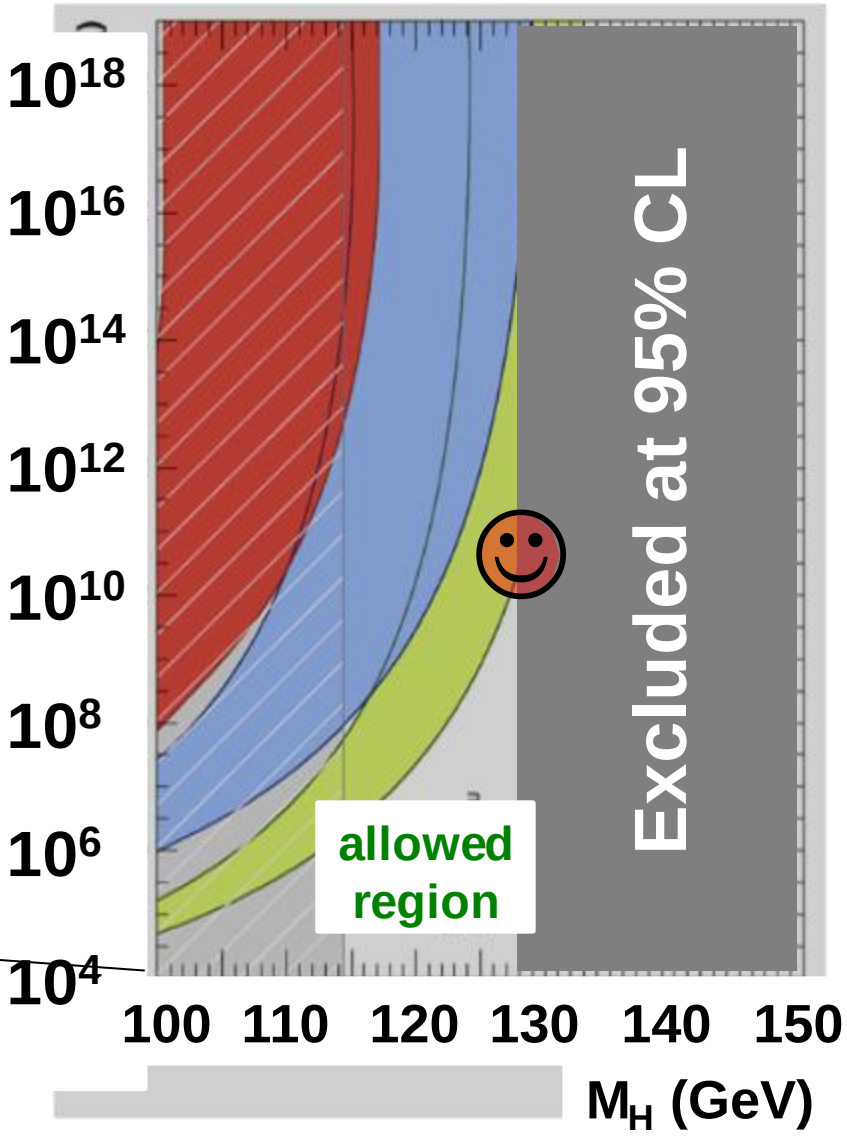
$$\Lambda \sim M_H \exp\left(\frac{4\pi^2}{3M_H^2}\right)$$



Zooming in: some good news

- **At 95% CL: there Is new physics at a scale below the GUT scale ☺**





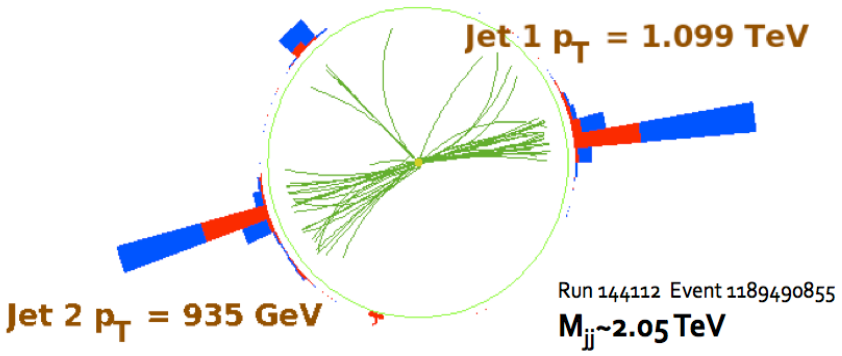
Where is the new physics?

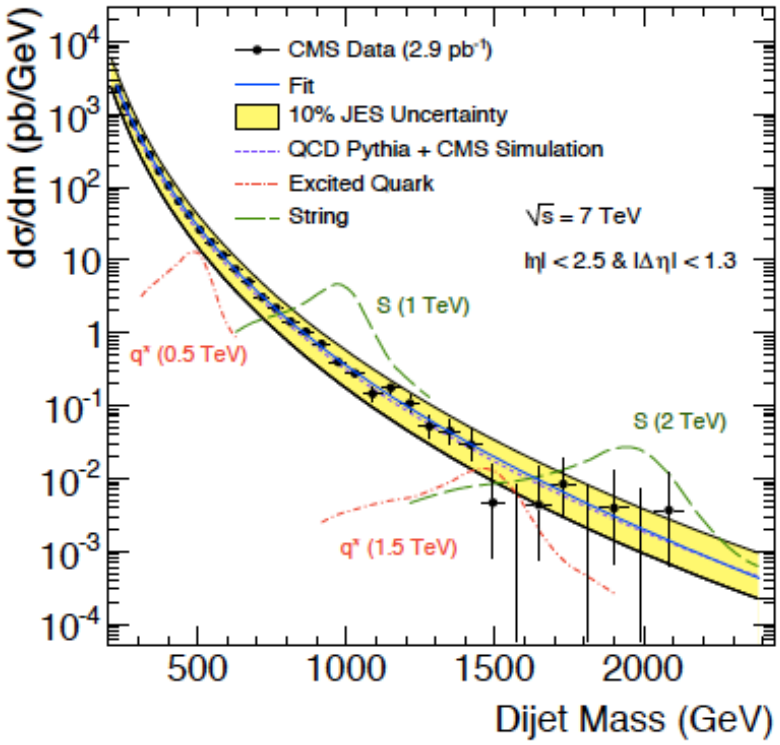
Searches for signs of exotic New Physics

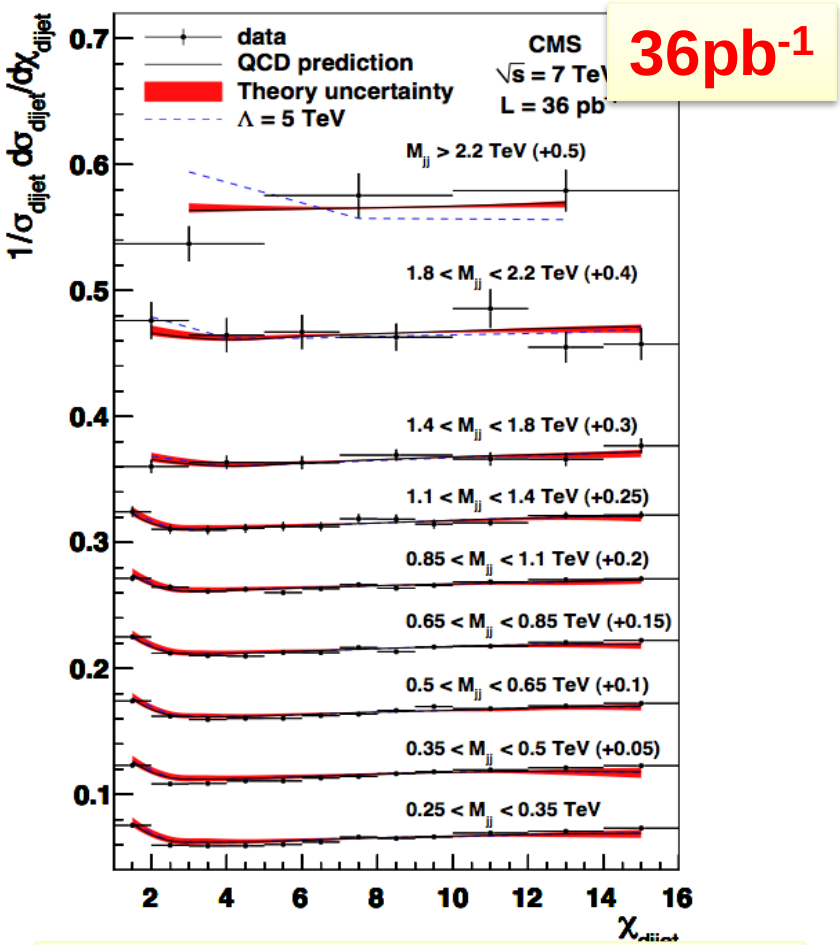
Many (many) possibilities

- **Compositeness; new contact interaction(s)**
- **Exotica:**
  - **Leptoquarks**
  - **New gauge bosons (W', Z') – or resonances**
  - **Fourth generation (b')**
  - **TeV-scale gravity: Black Holes; mono-jets; mono-photons; UED**
    - **Universal Extra dimensions (diphotons)**
- **Supersymmetry**
  - **Squarks and gluinos**
    - **Decays into jets and MET plus 0, 1 or 2 leptons**
    - **Decays into photons (GMSB)**
- **SUSY-based exotica**
  - **Long-lived particles**
- **The totally unexpected**

Jet searches (resonances, contact intrctn)







36pb^{-1}

Scale of contact interaction

Λ>5.6 TeV (95% CL)

(Null) search for W'

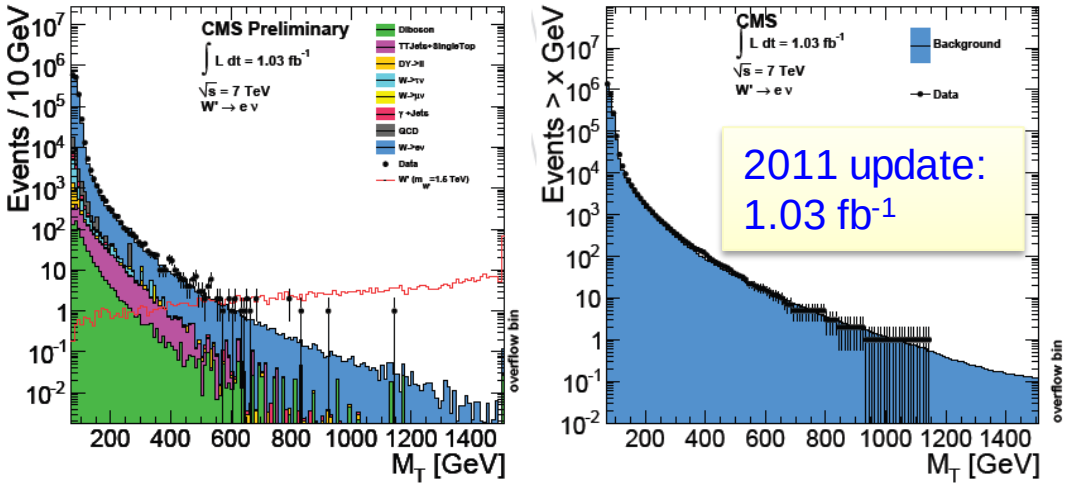
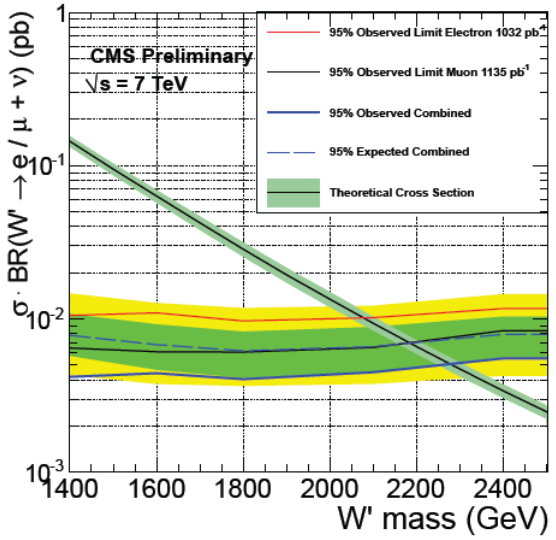


Figure 2: Transverse mass distribution (left) and cumulative distribution (right) for the electron channel.

2011 update:
1.03 fb^{-1}



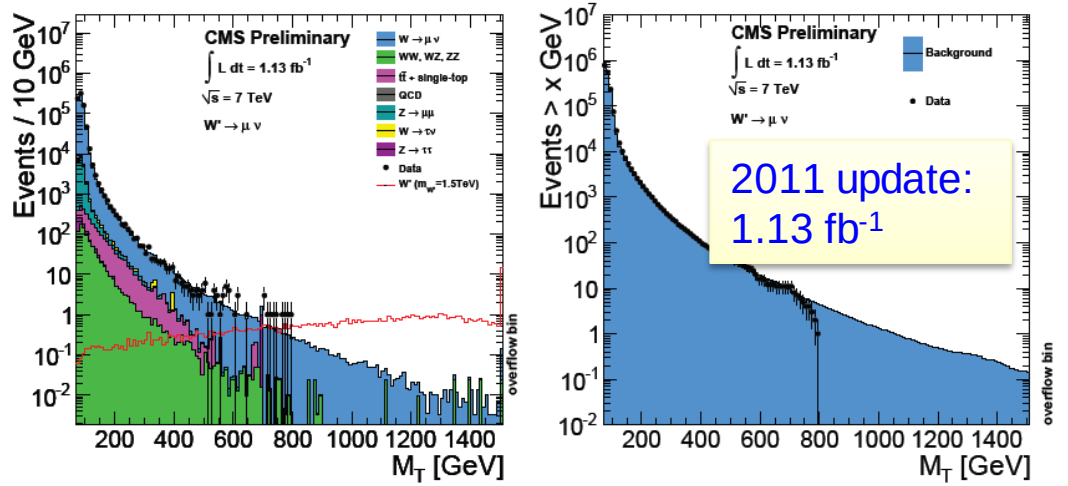


Figure 3: Transverse mass distribution (left) and cumulative distribution (right) for the muon channel.

2011 update:
1.13 fb^{-1}

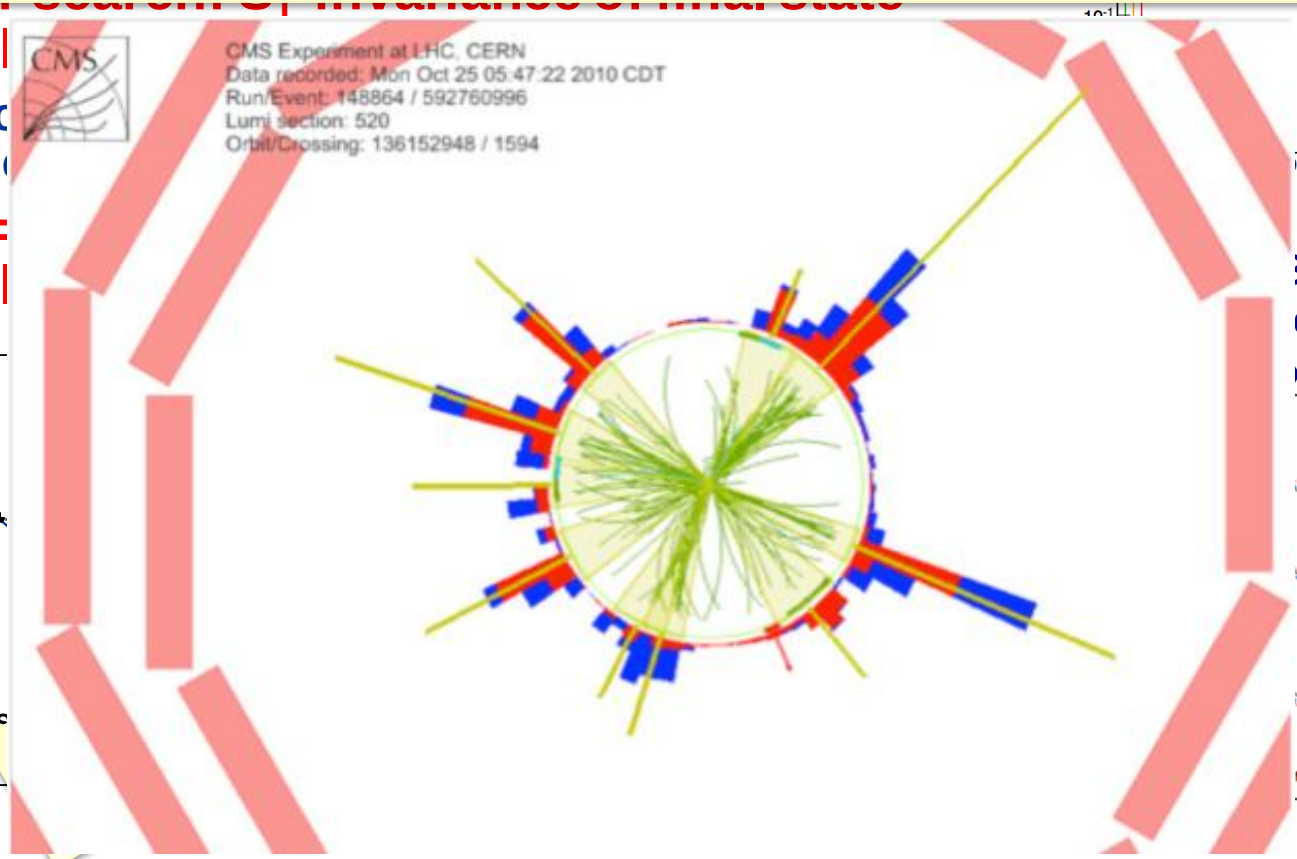
Combined (SSM) limit:
M(W')>2.20 TeV obs
M(W')>2.27 TeV exp

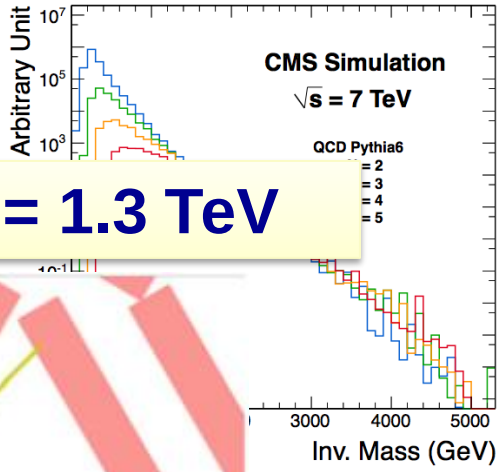
(Null) search for BHs

arXiv:1012.3375

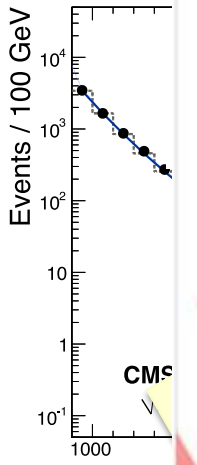
- **Expect lots of activity in the event, so**
  - **Use S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV.**
- **Key for search: invariant of final state multipl**
  - **A pc affe**
- **Use N= multipl**

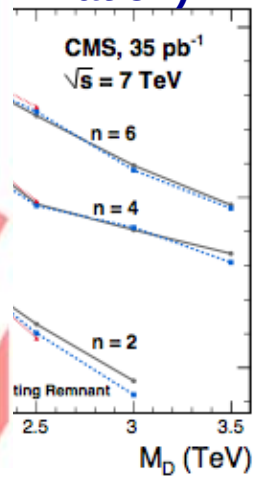
A candidate event with 10 jets and S_T = 1.3 TeV





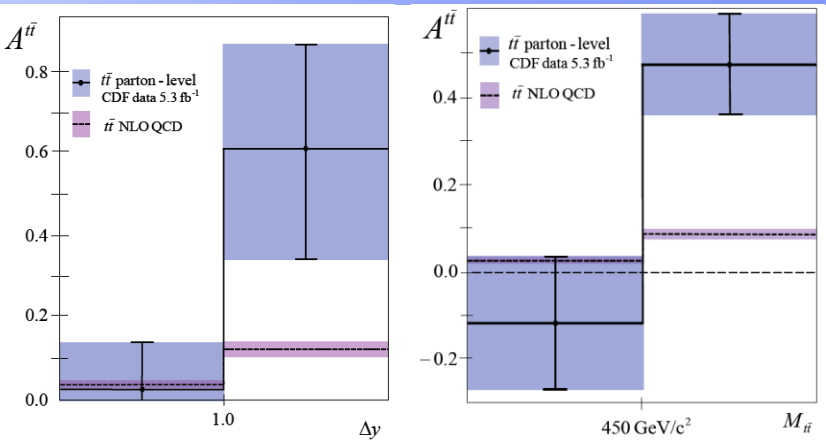
3.5-4.5 TeV
classical
ximation)

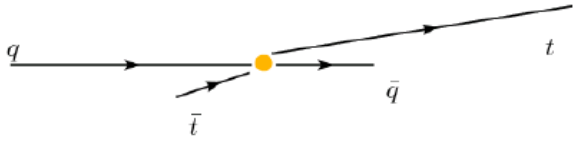


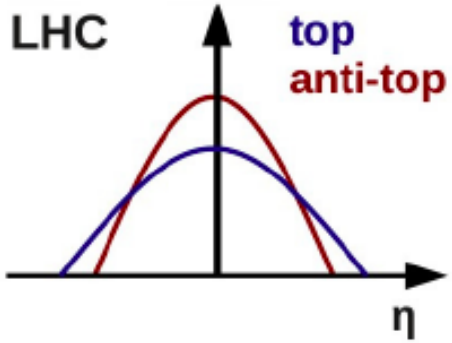


Top-antitop production

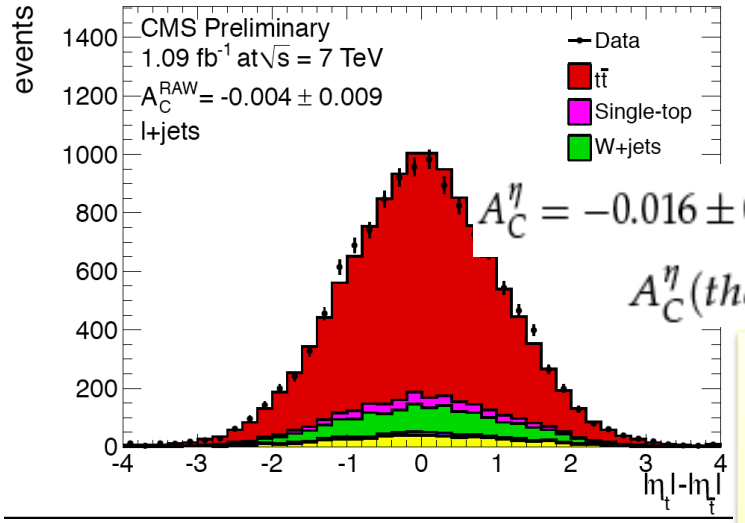
- **CDF/D0 measurement of forward-backward asymmetry : ~3σ deviation from SM expectation**
- **At the LHC:**







$$\mathcal{A}_\eta = \frac{N(|\eta_t| > |\eta_{\bar{t}}|) - N(|\eta_t| < |\eta_{\bar{t}}|)}{N(|\eta_t| > |\eta_{\bar{t}}|) + N(|\eta_t| < |\eta_{\bar{t}}|)}$$



$$A_C^\eta = -0.016 \pm 0.030\,(\text{stat.})^{+0.010}_{-0.019}(\text{syst.})$$

$$A_C^\eta(\text{theo.}) = 0.013 \pm 0.001$$

No asymmetry beyond SM observed

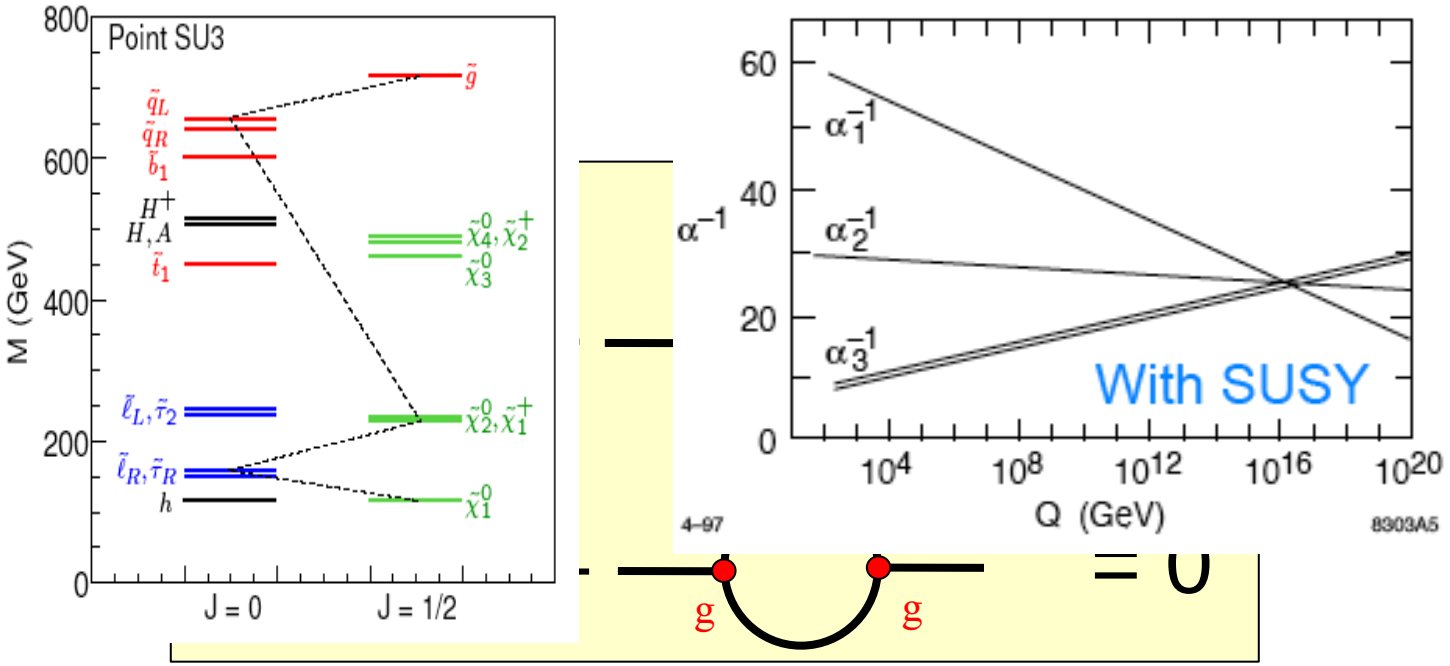
Supersymmetry

Supersymmetry: TO“E” at the Weak Scale

- **The beautiful part: minimal price (one new principle plus an unknown SB mechanism)**

Supersymmetry: TO“E” at the Weak Scale

- **The beautiful part: minimal price (one new principle plus an unknown SB mechanism) yet it achieves quite a lot:**
  - **No fine-tuning (large radiative corrections cancel)**
  - **If Lightest SUSY Particle stable: offers “natural” dark-matter**
  - **Equality of Strong, Weak and EM couplings at ~10^{16} GeV**



Supersymmetry: TO“E” at the Weak Scale

- **The facts: despite conventional wisdom, SUSY is quite predictive: it specifies spins & couplings of superpartners**
  - **At least as predictive as the SM (if one does not measure the CKM)**
- **The ugly part: one unknown SB but 500% increase in number of parameters (MSSM). Unfortunately, nothing about the masses**

$\tilde{u}_L, \tilde{d}_L$	$\tilde{u}_R$	$\tilde{d}_R$	$\tilde{e}_L, \tilde{\nu}_L$	$\tilde{e}_R$	$\tilde{h}^{\pm}, \tilde{h}^0_u, \tilde{h}^0_d$	$\tilde{b}^0$	$\tilde{w}^{\pm}, \tilde{w}^0$	$\tilde{g}$
Q	U	D	L	E	H	B	W	G
M_Q	M_U	M_D	M_L	M_E	M_H	M_B	M_W	M_G

  - **End result: large space of signatures, dependent on models**
- **Even MSSM-124 is tough. Hard work to study particular scenario. Reduce complexity: use model of dynamical SYSY breaking**
  - **mSUGRA (gravity-mediated)**
  - **GMSB (gauge-mediated)**
  - **AMSB (anomaly-mediated; studied in less detail)**

SUSY: what we do not know

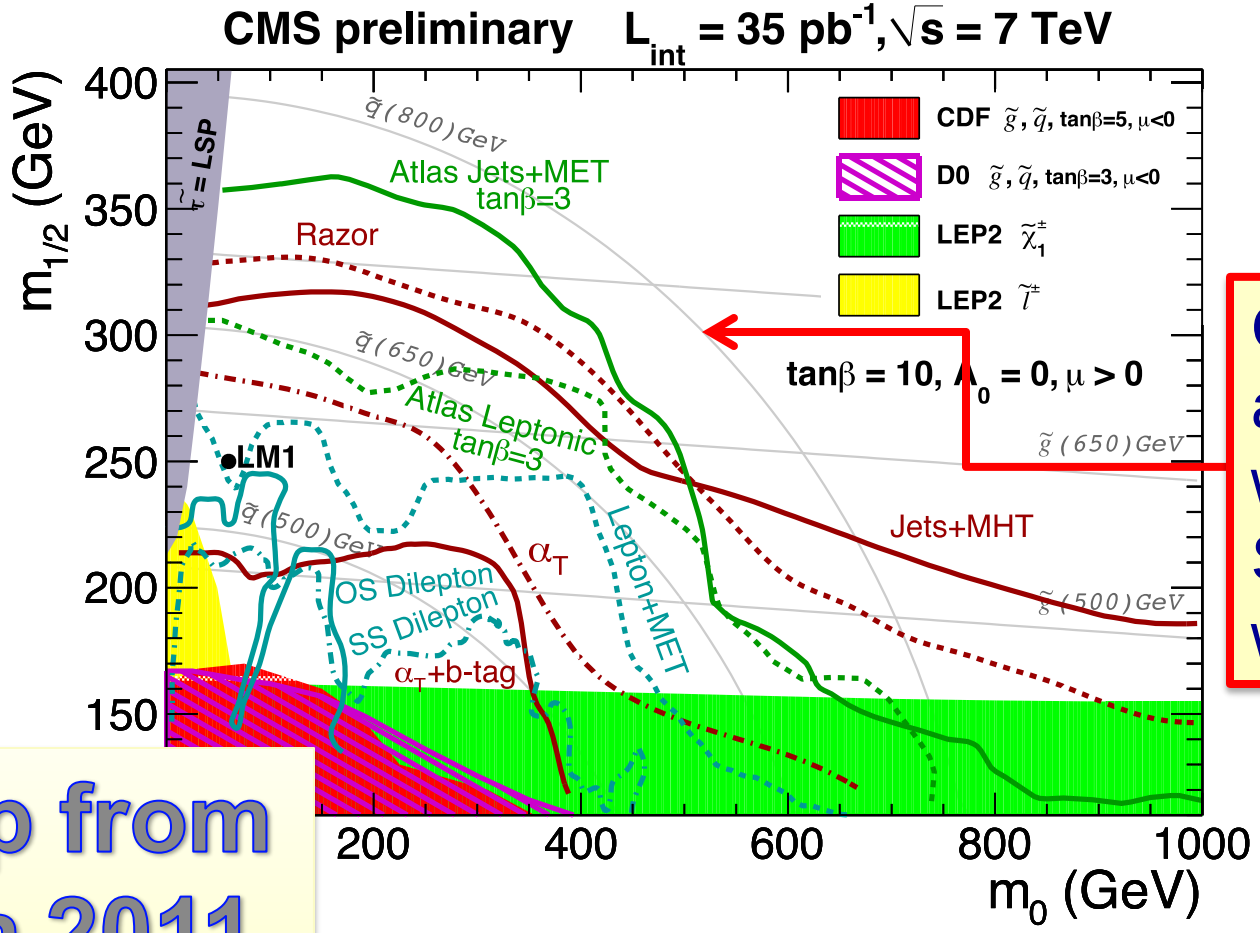
$\tilde{u}_L, \tilde{d}_L$	$\tilde{u}_R$	$\tilde{d}_R$	$\tilde{e}_L, \tilde{\nu}_L$	$\tilde{e}_R$	$\tilde{h}^{\pm}, \tilde{h}^0_u, \tilde{h}^0_d$	$\tilde{b}^0$	$\tilde{w}^{\pm}, \tilde{w}^0$	$\tilde{g}$
Q	U	D	L	E	H	B	W	G
M_Q	M_U	M_D	M_L	M_E	M_H	M_B	M_W	M_G

- **Agnostic approach: consider all possible mass hierarchies: there are 9! = 362880 of them**
  - **ME_T: 4x8! (161,280) cases, LSP=weakly-interacting, neutral particle; phenomenology depends crucially on mass hierarchy**
  - **CHAMPs: 8! (40,320) cases, LSP=e_R (charged, color-neutral); signature: CHAMP (independently of hierarchy)**
  - **R-hadrons: 4x8! (161,280) cases, LSP=colored object; again, independent of hierarchy**

arXiv:1008.2483: "How to look for supersymmetry under the lamppost at the LHC"; P.Konar, K.Matchev, M.Park, G.Sarangi

SUSY search with ME_T: summary of 2010

- **No signs yet. But all analysis methods in place; now need more data (2011!)**



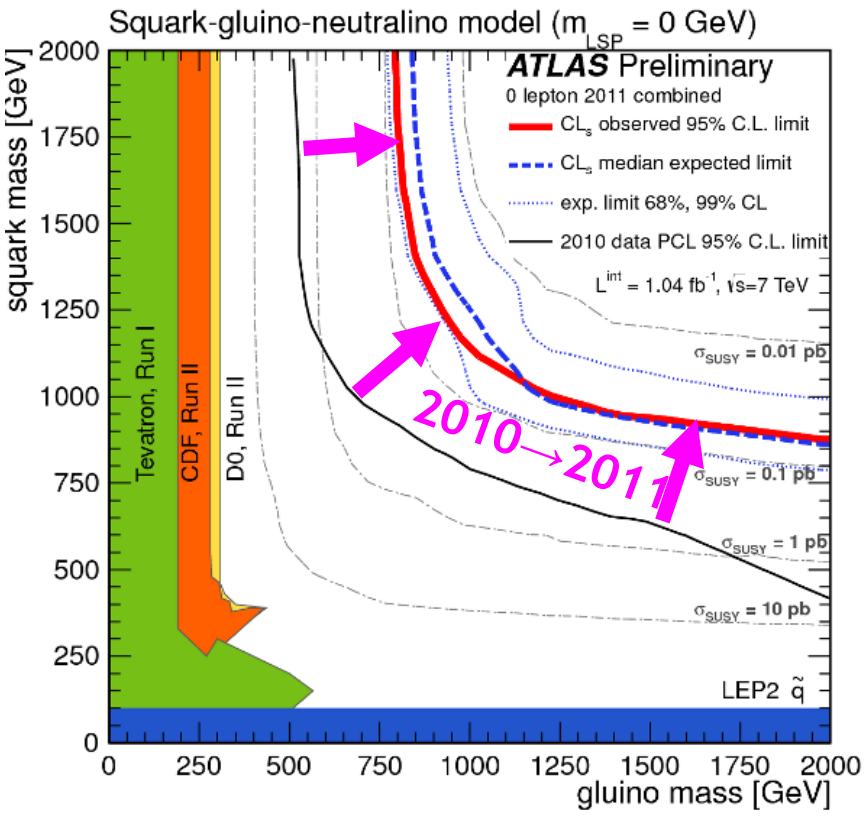
Corner around which SUSY would lie

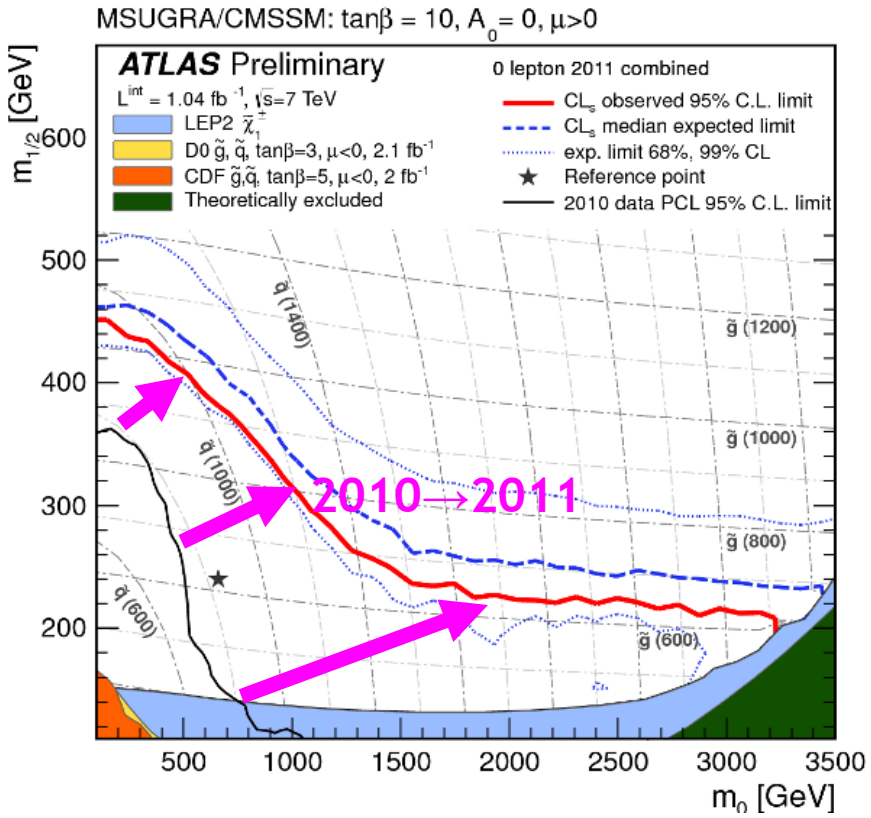
Transp from March 2011

In brief: SUSY moving further out

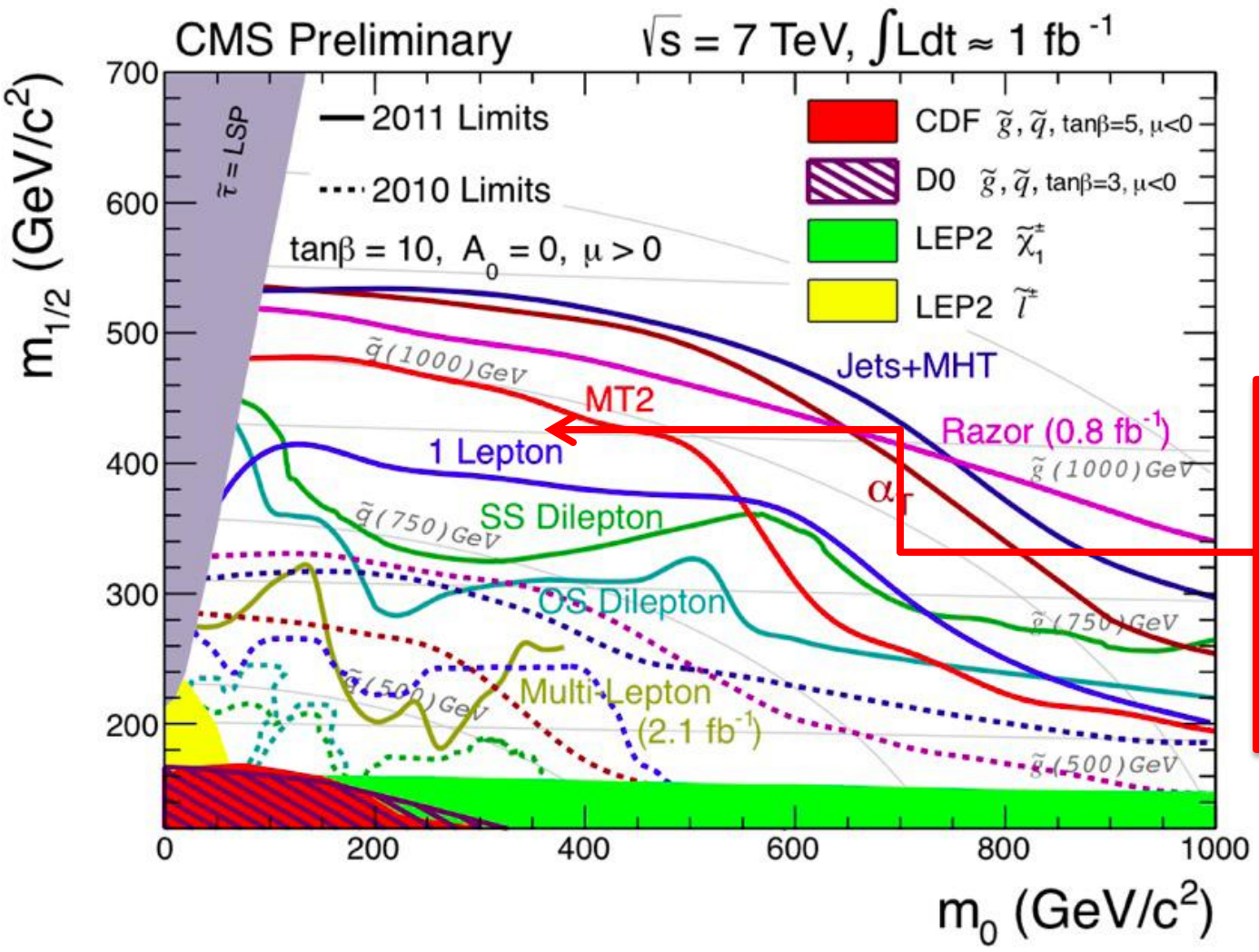
Simplified model: two squark (q) generations, m(χ_1^0)~0
m_g>800 GeV m_q>850 GeV
Equal mass case: m_g=m_q>1.075 TeV

MSUGRA/CMSSM:
tanβ=10, A_0=0, μ>0
Equal mass case:
m_q=m_g > 980 GeV





Constrained MSSM



Corner around which SUSY used to lie

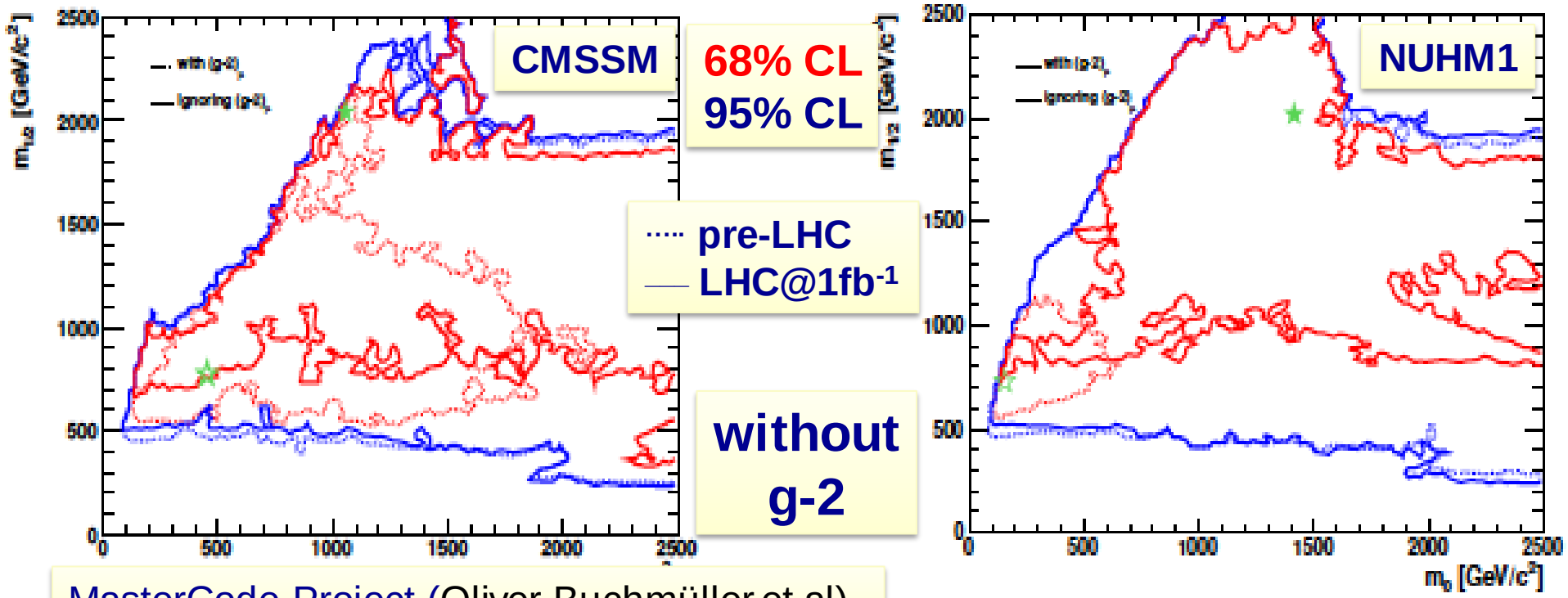
Then again…

- **A bit of a self-fulfilling prophecy; very early searches were guided by combination of "probability of success" and "obeying the rules":**
  - **Go after high cross section processes (i.e. accessible already with small integrated luminosity ~10-50 pb^{-1})**
  - **Do not rely on a perfectly working detector: seek robust signatures with good experimental control of "things"**
  - **Do not rely on Monte Carlo; "thou shall use the data" (well, ok, and some Monte Carlo)**
  - **Beat the competition: go after the simplest signatures**

- **We have followed these four guidelines extremely well**
  - **(another reason to rejoice – when we set to do sthng, we do)**
  - **(another reason to think that there is much, much more)**

What the LHC has done to/for the CMSSM

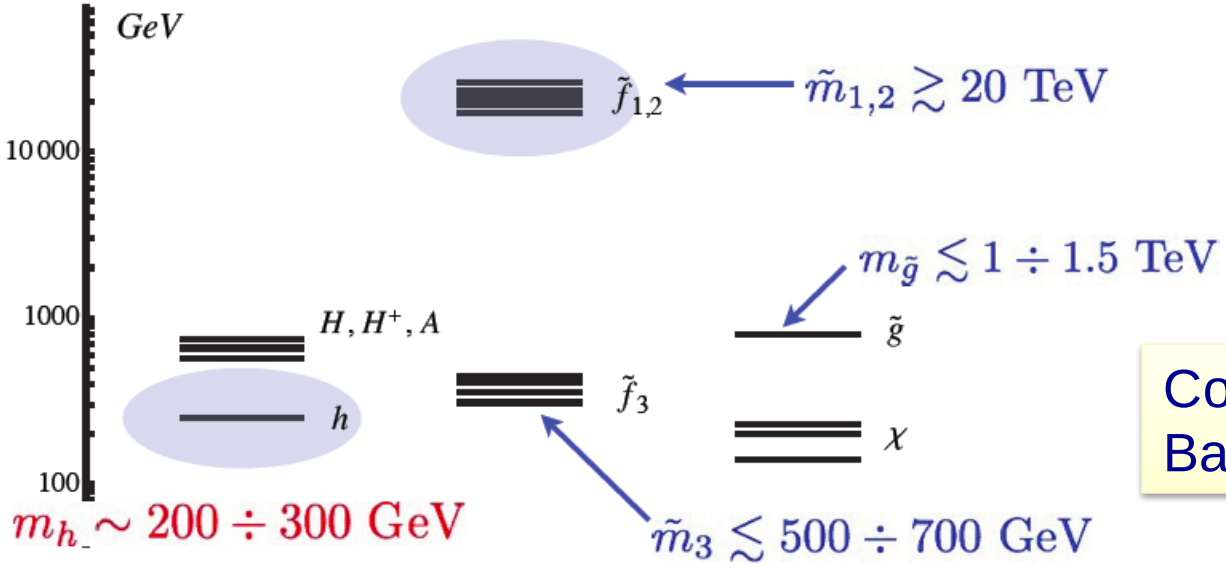
- **With 1fb^{-1} of data the amount of naturalness need has diminished to "unnaturally" small values [?!?!]**
  - **CMSSM being cornered. Not excluded [yet] but looking unlikely [e.g. "high fine-tuning price of the LHC" hep.ph/1101.2195]**
- **But: (a) effect of g-2 ?! (b) SUSY >> CMSSM**



MasterCode Project (Oliver Buchmüller et al)

SUSY is far from excluded (let alone dead)

- **Simple models (e.g. universal soft masses) being squeezed**
- **Numerous other scenarii still very much unprobed [thus very unconstrained]. Two examples:**
  - **Large flavor splitting: very heavy squarks [1st, 2nd gen], light 3rd gen (plus gluino at ~1-1.5 TeV)**
  - **Low ME_T: not only within R_p-violation; small mass splittings (would be equally lethal to ME_T signature)**
    - **Could even have all sparticles with mass < ~0.5 TeV…**



Cohen et al (96)
Barbieri et al (07)

SUSY: we will always have the stop

- **Only the stop (+sb) need be light** **[e.g. Barbieri @ HCP 2011]**

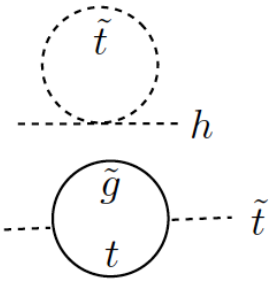
The key equations:

$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2$$

$$\delta m_u^2 \approx -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2)\log M/m_{\tilde{t}}$$

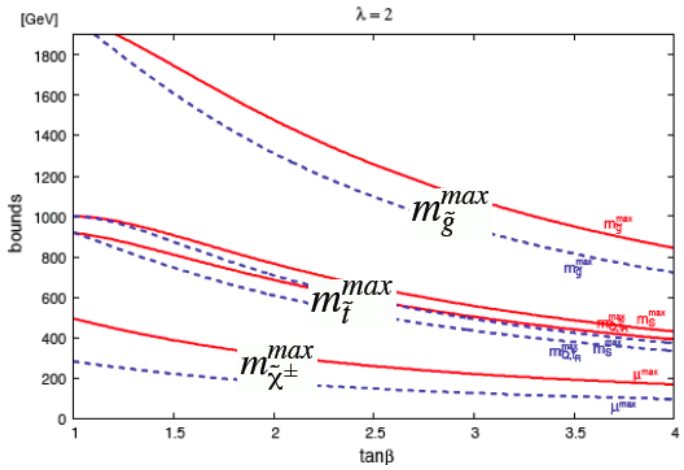
$$\delta m_{\tilde{t}}^2 \approx \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 \log M/m_{\tilde{t}}$$

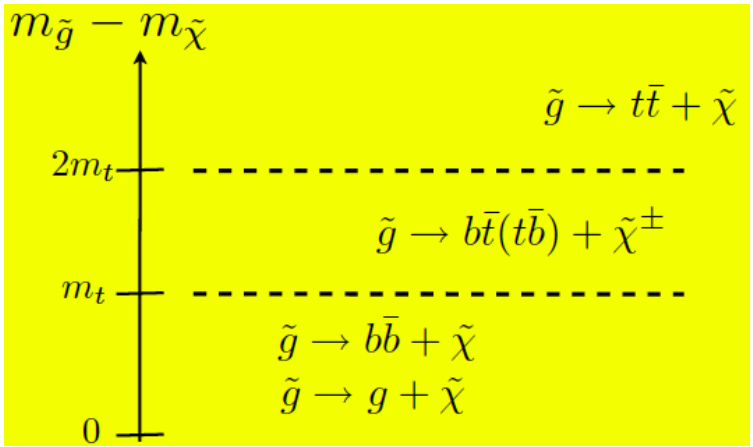
$m_{\tilde{h}}$, $m_{\tilde{b}_L}$



(to be made more precise in any given SB-mediation scheme)

see, e.g., Dimopoulos, Giudice for SUGRA-mediation, 1995





Some incredible signatures…

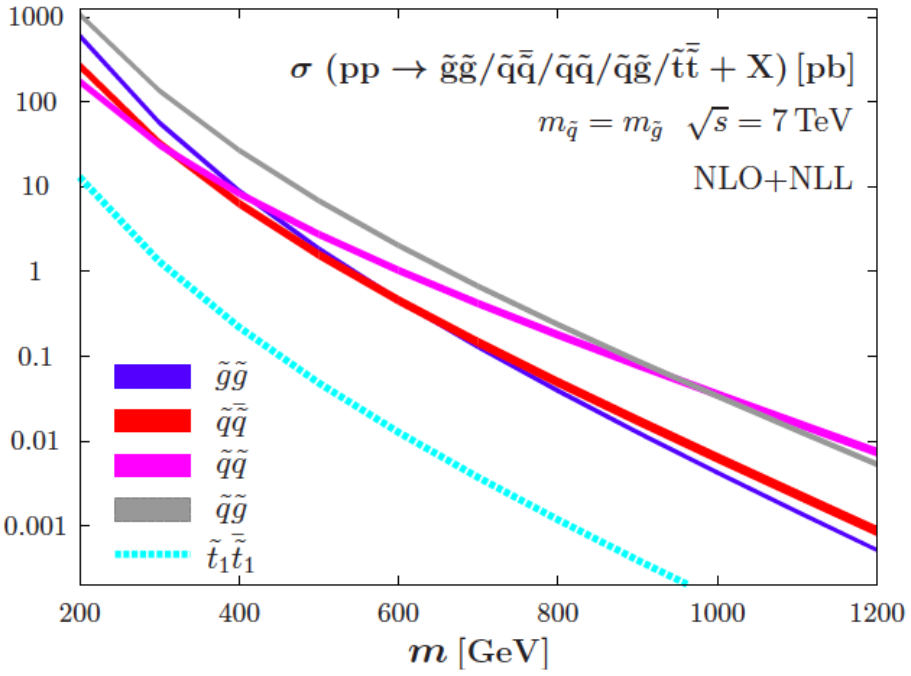
$$pp \to \tilde{g}\tilde{g} \to tttt + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to tt\bar{t}b(\bar{t}\bar{t}tb) + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to tt\bar{b}\bar{b}(\bar{t}\bar{t}bb) + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to t\bar{t}b\bar{b} + \chi\chi$$
$$\chi = \chi^\pm, \chi_1, \chi_2$$

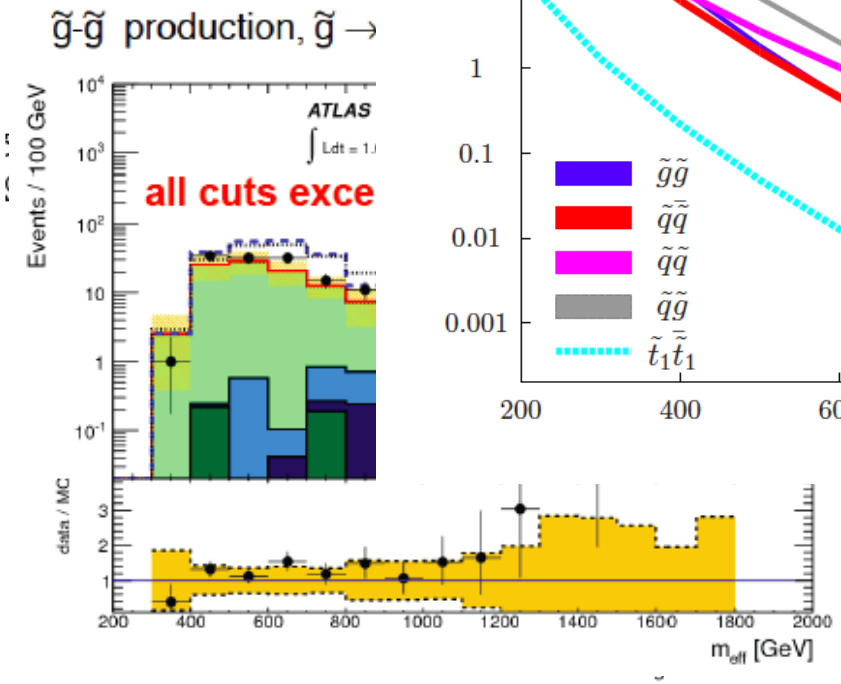
First stop searches (ATLAS)

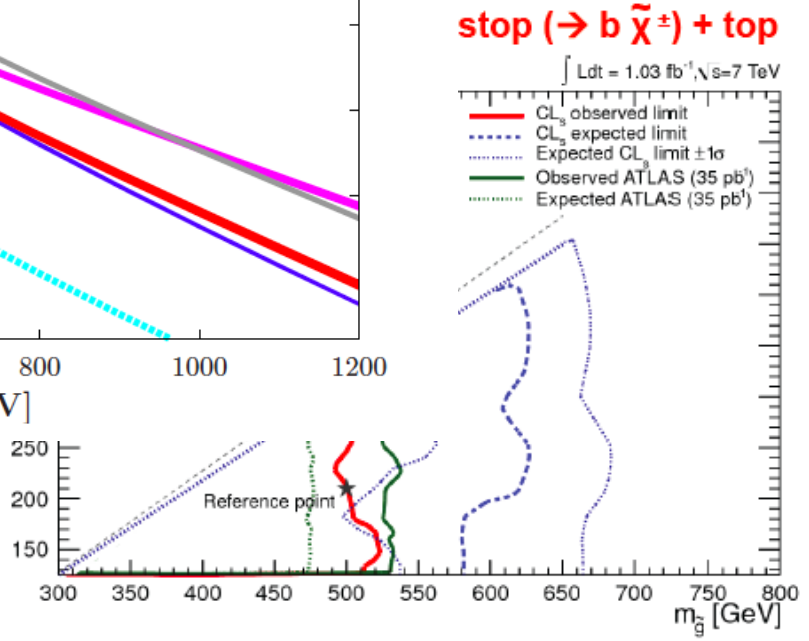
- **SUSY will be unnatural if m_{stop}>1 TeV: this is a real challenge for the LHC experiments!**

Cuts	m_{eff} > 600 GeV
SM (MC)	52 ± 28
SM (d-d)	54.9 ± 13.6
data	74

[Beenakker, Brensing, MK, Laenen, Kulesza, Niessen '09]







First sbottom searches

- **ATLAS, 2 b tags, MET 2fb^{-1}.**
  - **Uses co-transverse mass**

$$M_{CT}^2(v_1,v_2) \equiv [E_T(v_1)+E_T(v_2)]^2 - [\mathbf{p_T}(v_1)-\mathbf{p_T}(v_2)]^2$$

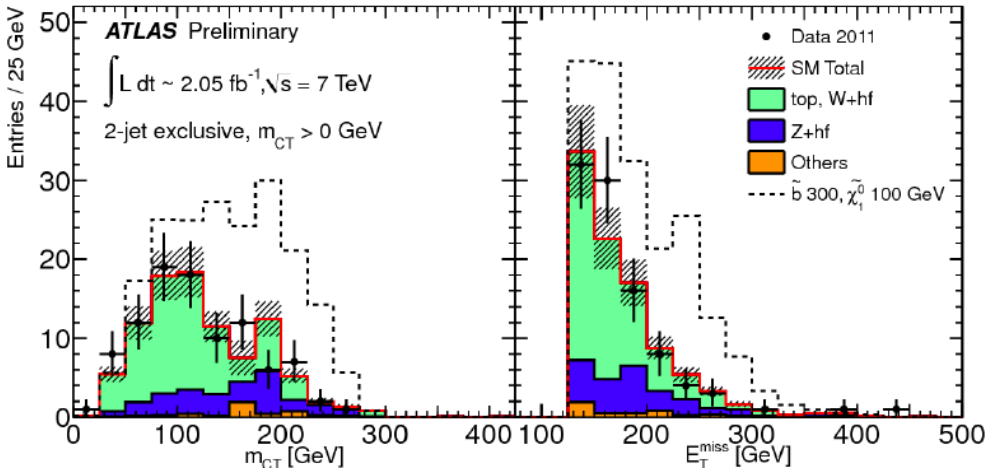
(JHEP 0804 (2008) 024,
JHEP 1003 (2010) 030)

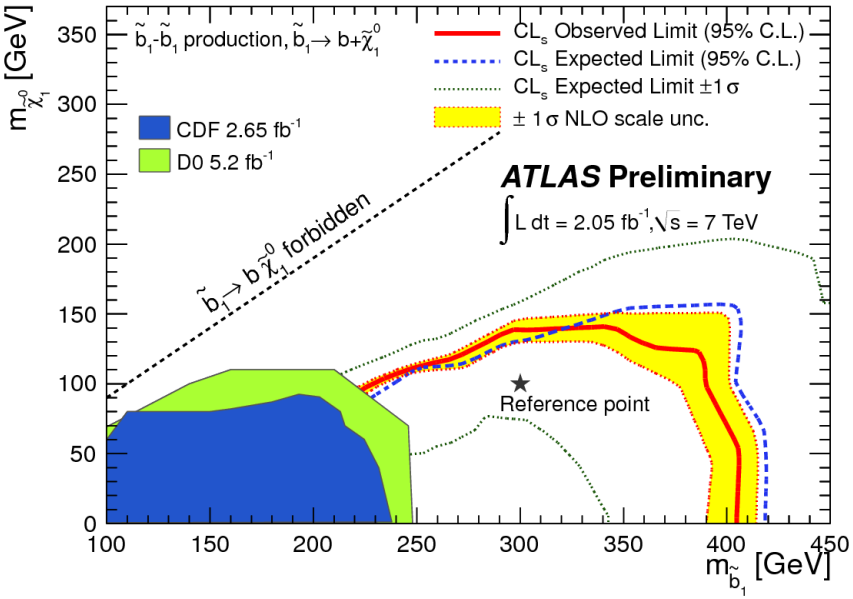
  - **End-point at**

$$(m(\tilde{b}_1)^2 - m(\tilde{\chi}_1^0)^2)/m(\tilde{b}_1)$$

$\tilde{b}_1$-$\tilde{b}_1$ production, $\tilde{b}_1 \rightarrow b+\tilde{\chi}_1^0$

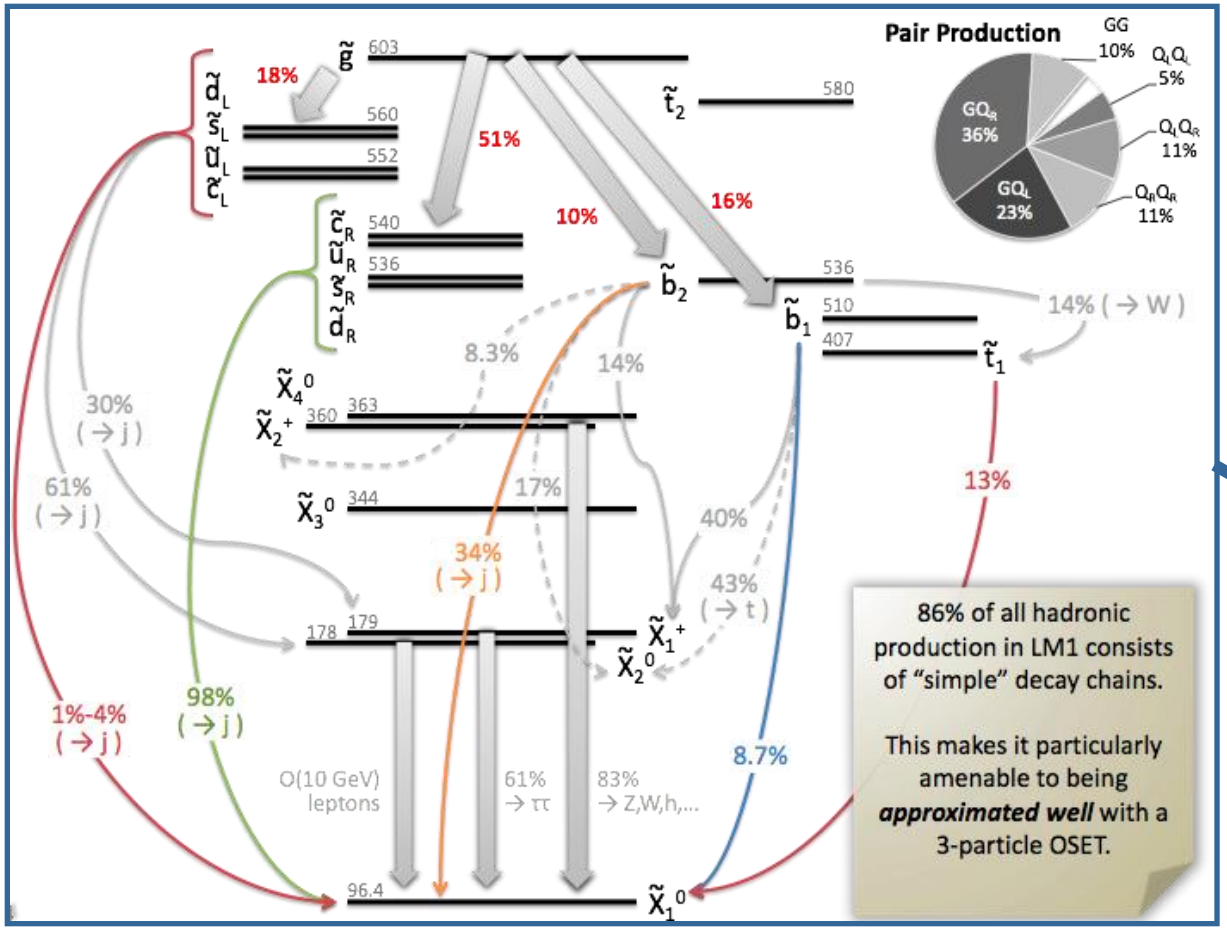
Selection: 2 b-jets, p_T > 130,50 GeV
E_T^{miss} > 130 GeV, E_T^{miss}/m_{eff} > 0.25
$\Delta\Phi$(jet,E_T^{miss})>0.4
Veto leptons and 3rd jet > 50 GeV



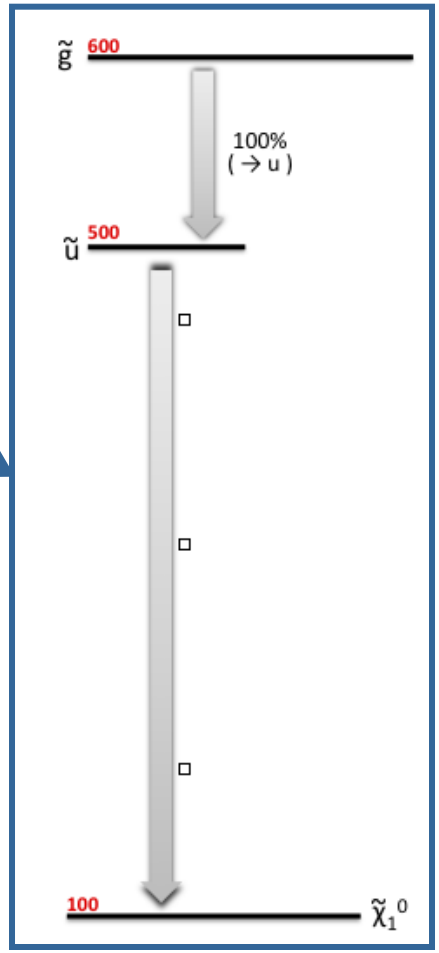


Recently: use of simplified models

CMSSM



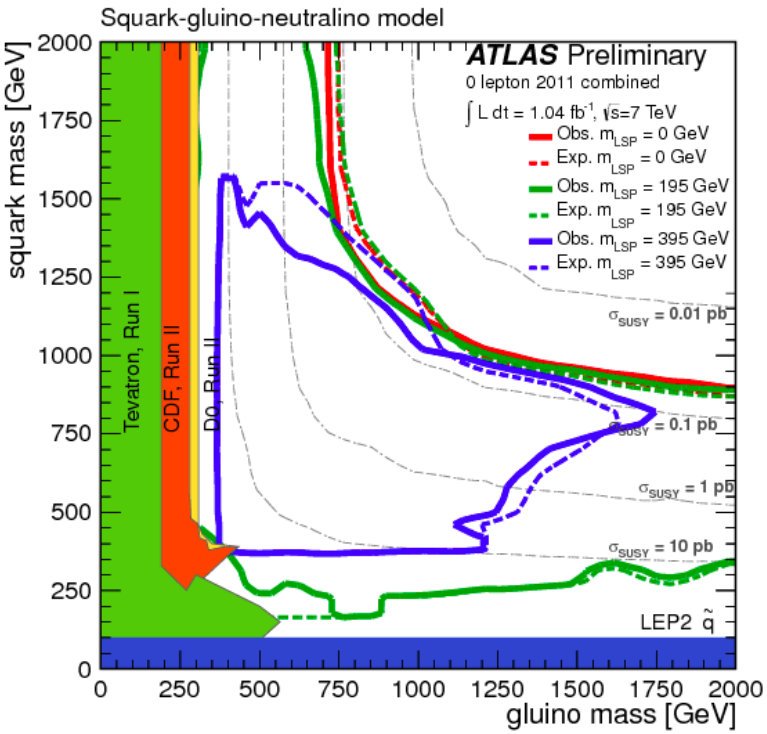
What we see: much simpler…

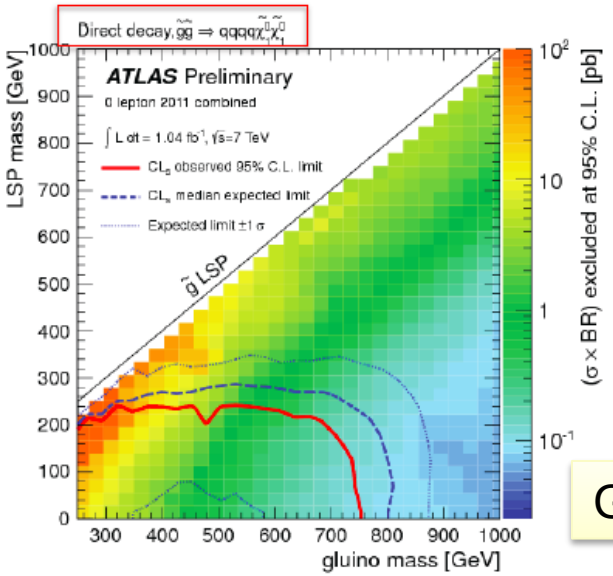


Simplified Model Spectrum (SMS) with 3 particles, 2 decay modes

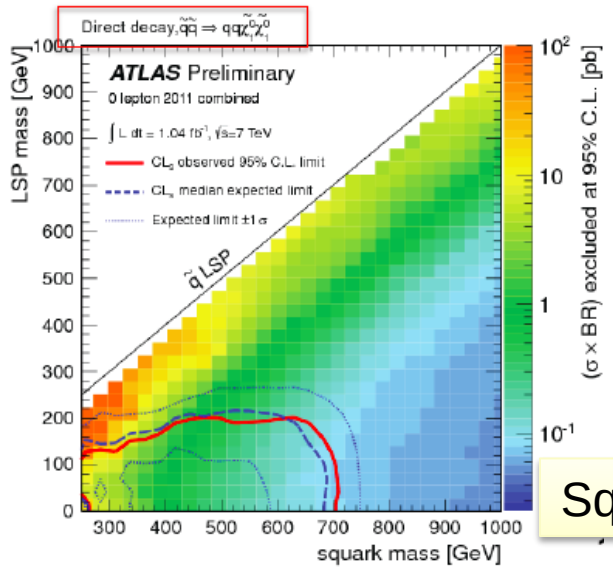
Simplified models

- **Effect of varying MLSP:**
  - **RED: M_{LSP}=0**
  - **Green: M_{LSP}=195 GeV**
  - **Blue: M_{LSP}=395 GeV**





Gluinos

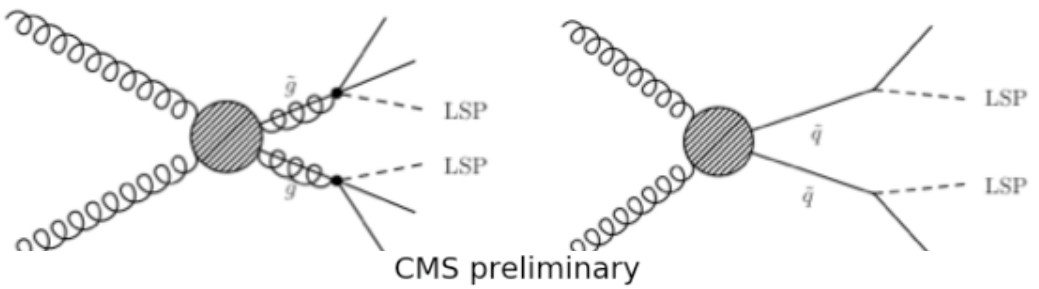


Squarks

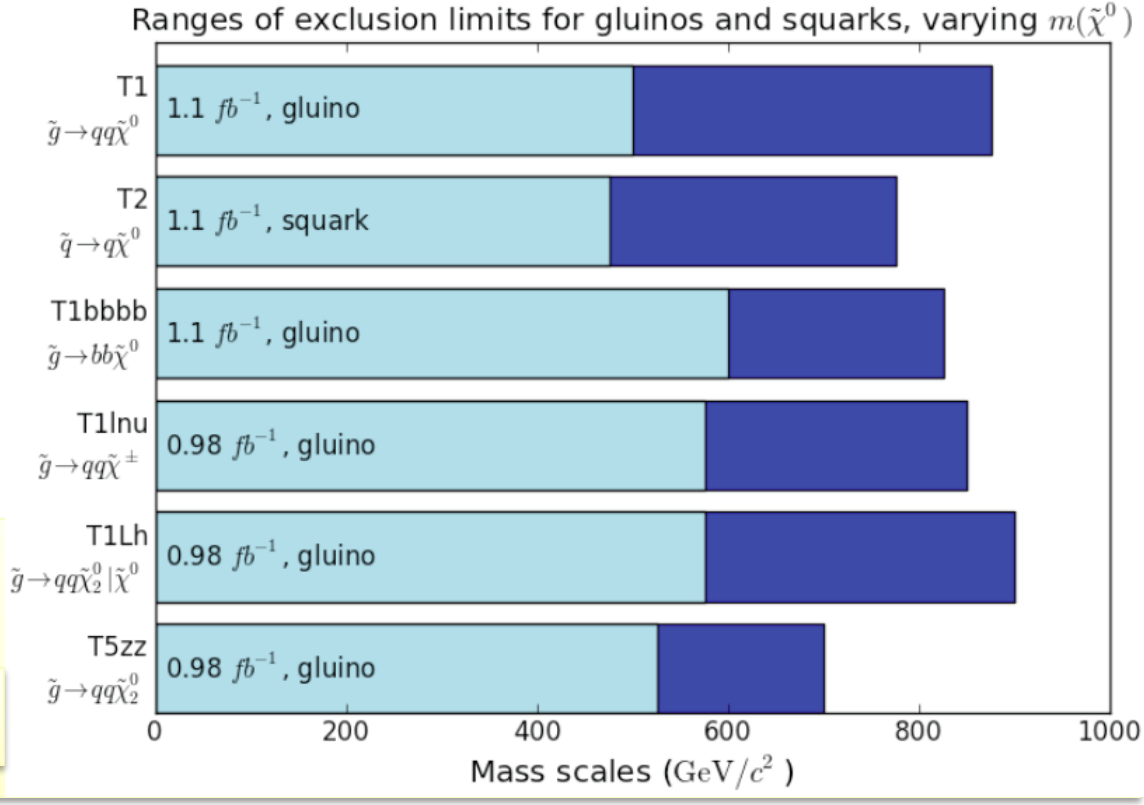
Simplified Model Spectra

- Started with squark and gluino pair-production topologies
- Limits are "best of N" searches (usually not a combination)
- Black lines are QCD-like cross sections
- Theoretical uncertainties like ISR simulation important (under study)

M(gluino)>0.4-0.5 TeV



CMS preliminary

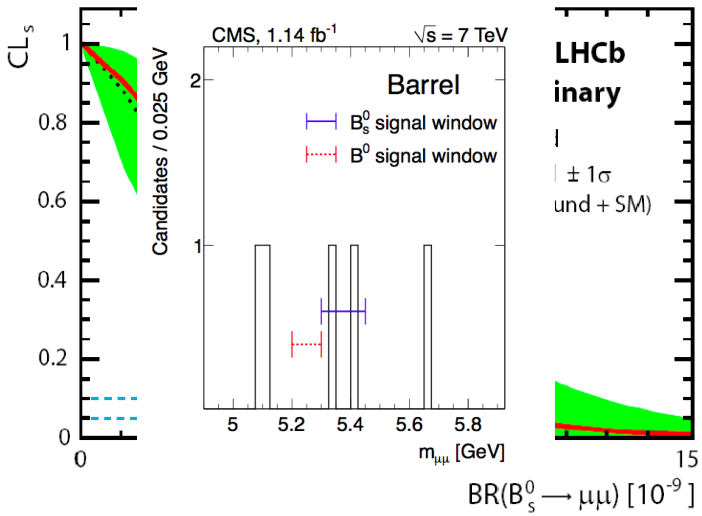


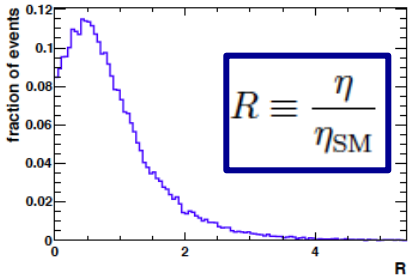
LHCb+CMS: $B_s \to \mu\mu$

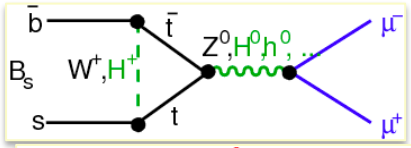
- **Power of the loop; + double ratio**

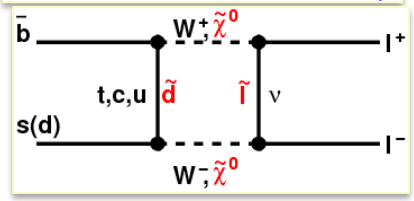
hep-ph:1108.3018

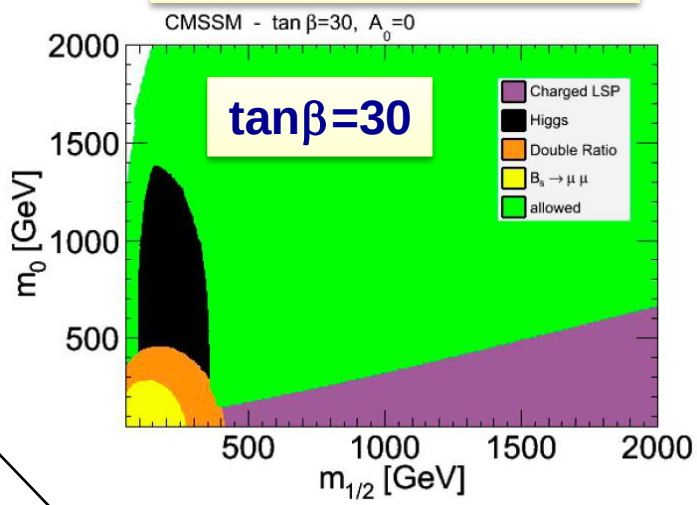
$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_u \to \tau\nu)} \Big/ \frac{\mathrm{BR}(D_s \to \tau\nu)}{\mathrm{BR}(D \to \mu\nu)} \sim \frac{|V_{ts}V_{tb}|^2}{|V_{ub}|^2} \frac{\alpha^2}{\pi^2} \frac{(f_D/f_{D_s})^2}{(f_B/f_{B_s})^2}$$

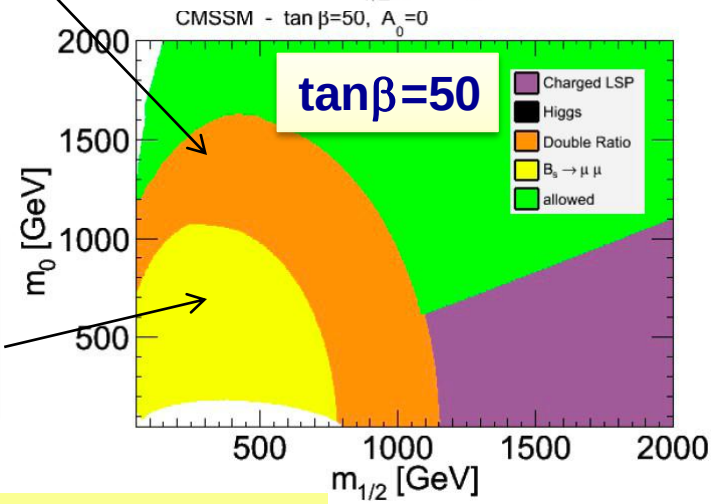












Observed limit: **BR($B^0_s \to \mu\mu$)<1.08 x 10^{-8}** @95%CL

Heavy Stable Charged Particles

- **Both in SUSY and other SM extensions:**
  - **SUSY (split SUSY: M(gluino)<<M(squark) → long lifetime; GMSB models: stau NLSP, decaying via gravitational coupling only…)**
  - **Other: hidden valleys; GUTs; …**
- **Two types of signatures: MIP & strongly-interacting**

MIP: HSCP passes through tracker & muon chambers

R-hadrons traversing material can flip Q or become neutral

dE/dx: Massive, charged particles traversing detector: highly ionizing tracks (tracker, possibly muon dets)

(Out-of-time) Jet: particles stopping in the detector and decaying – possibly out-of-time with the collisions

Heavily ionizing tracks

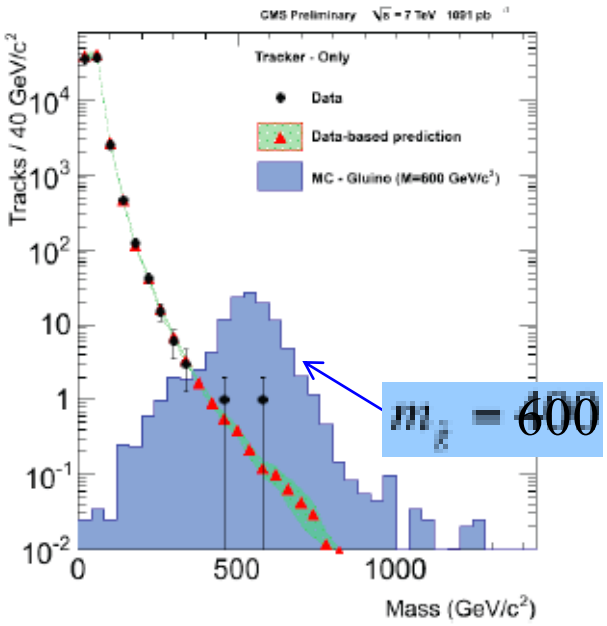
- **Mass estimate from approximate Bethe-Bloch:**
  - **K and C determined from proton data**
    - **Mass resolution: 12% at 300 GeV**

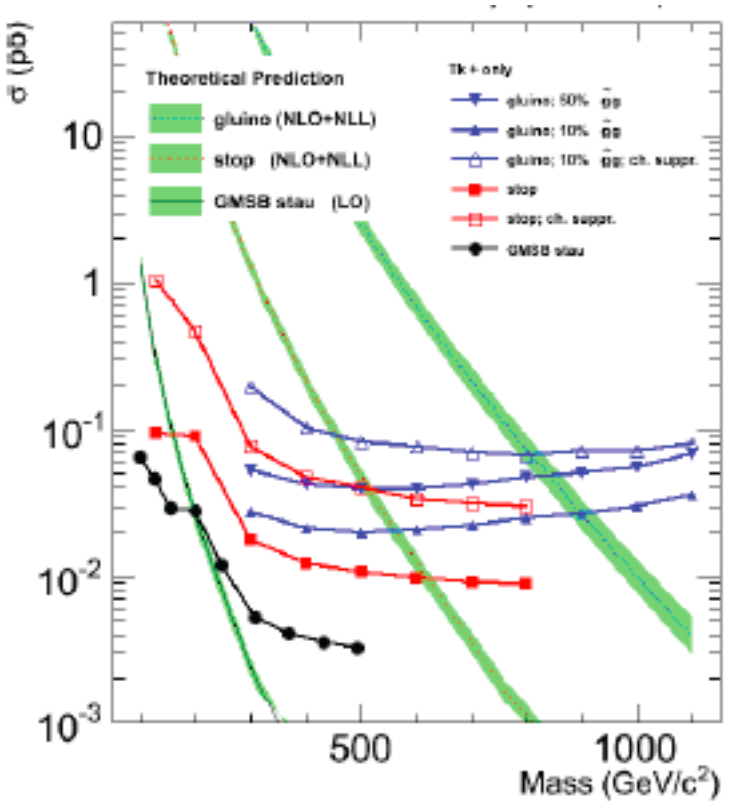
$$I_h = K\frac{m^2}{p^2} + C$$

K=2.58 MeV c²/cm
C=2.56 MeV/cm

- **Cut on I_{AS} (MIP compatibility) & p_T (I_{AS}, p_T: uncorrelated)**

Bkg $= \dfrac{(\#\text{pass } I_{AS} \text{ only})(\#\text{pass } p_T \text{ only})}{\#\text{Fail } I_{AS} \cap p_T}$



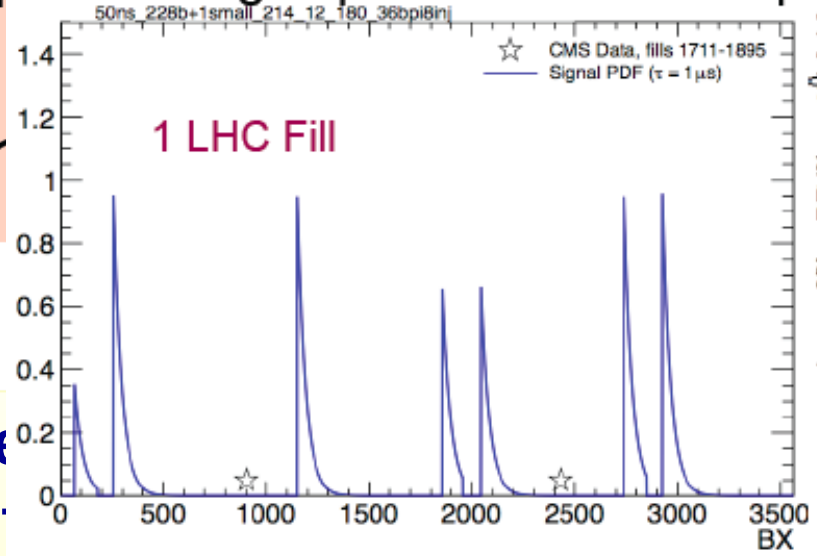


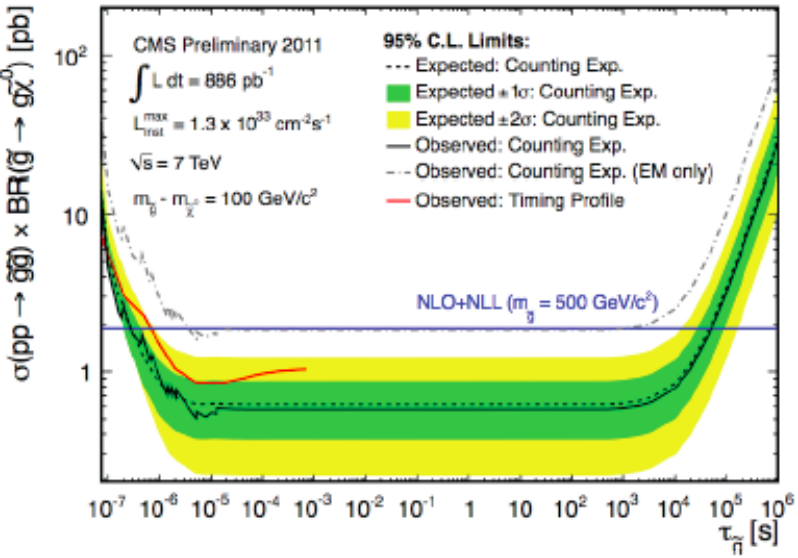
Stopped gluinos

- **Slow (β < 0.4) long-lived gluinos hadronize into and then stop in the dense material of the CMS detector**
  - **Their number builds up with luminosity:**

They then decay μs,

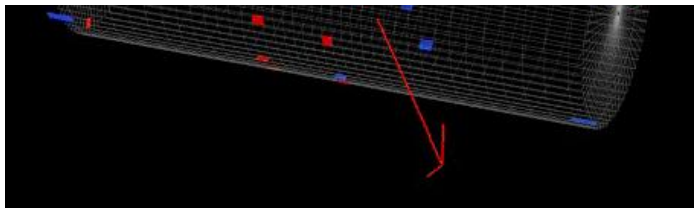
Counting experiment and time-profile analysis are performed

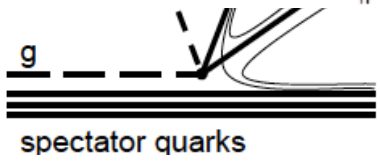




(uu)

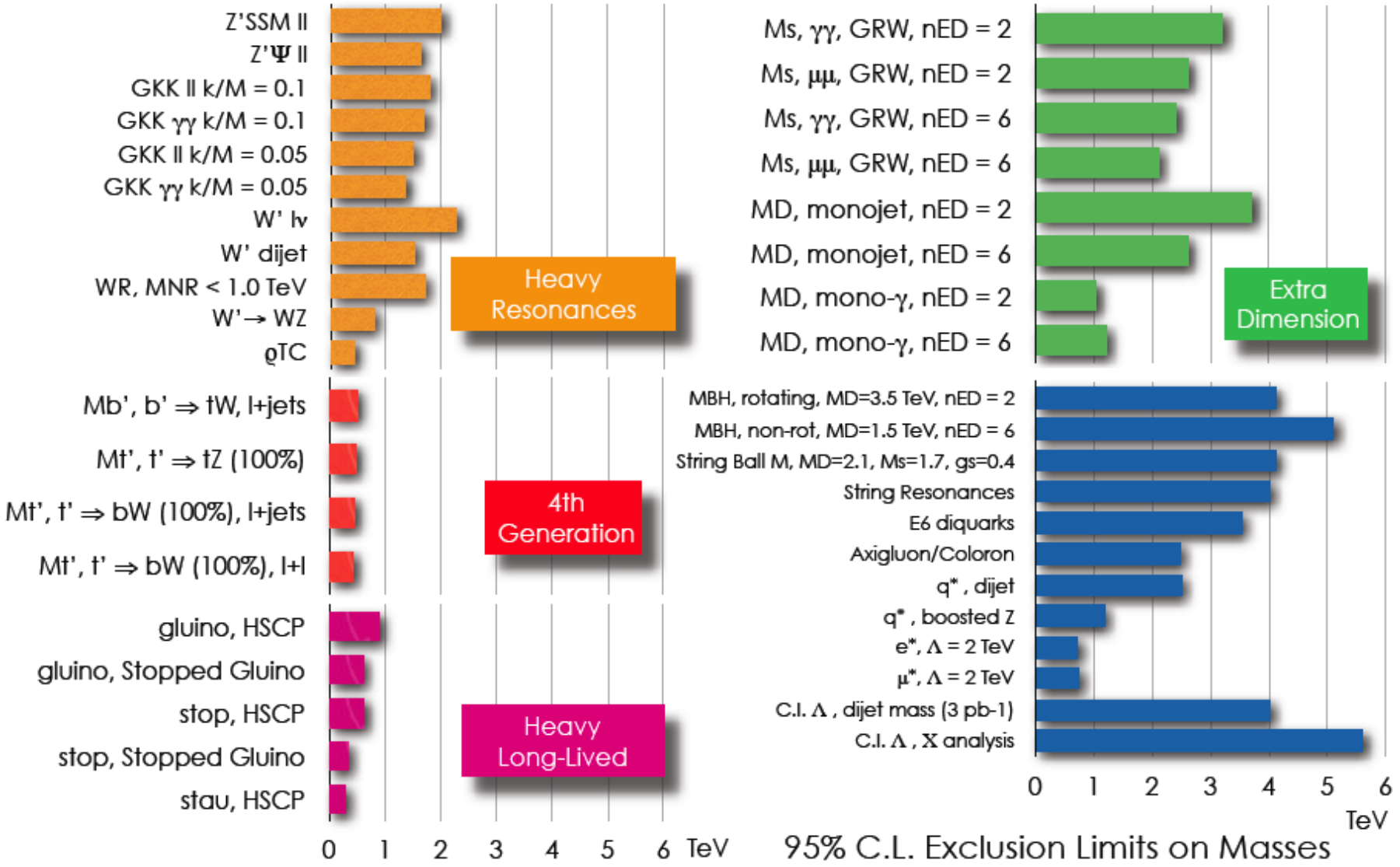
Spe… je… absence of beam





$$\Delta_{\tilde{g}}^{++} \rightarrow \tilde{g}\, u(uu) \rightarrow q\bar{q}\, \chi_1^0\, u(uu)$$

A dizzying array of (null) searches



2012

LHC running in 2012: 8 TeV [?]

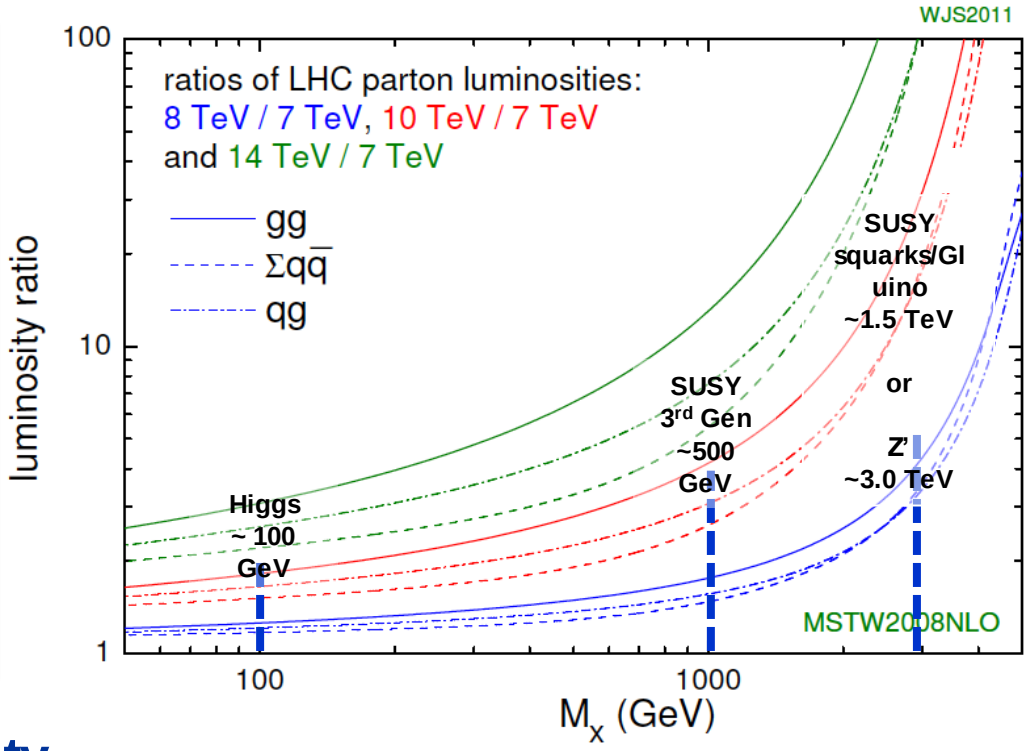
- **Enhances physics reach in two ways:**
  - **Higher cross sections for new physics over full mass range**

Higgs: pp → H, H→ WW, ZZ & γγ
mainly gg: Factor ~1.2

SUSY: 3rd Gen Mass ~ 0.5 TeV
qq and gg: Factor ~1.5

SUSY: Squarks/Gluino M~1.5TeV
qq,gg,qg: Factor ~4.0

Z′ : Mass ~ 3.0 TeV
qq: Factor ~3.5



  - **More integrated luminosity**
    - **@ 8 TeV: 10-16 fb^{-1} expected (25/50 ns bunch-crossing)**

Summary

Summary and Outlook

- **LHC and experiments' run at 7 TeV truly impressive**
  - **By now the detectors are fully functioning scientific instruments: physics-producing engines**
- **With ~40pb^{-1} the LHC observed all particles of the standard model (indirectly, even neutrinos)**
  - **Solid basis for understanding the "background" to searches at higher mass and transverse energy scales**
- **With 5 fb^{-1} we entered a true discovery era. With 10-15 fb^{-1}: discovery [no matter what]**
  - **"SUSY" explorable over very large area with 1 fb^{-1}; possible new resonances. Very large reach for other new physics.**
  - **But nobody said it would be easy. We have to start looking hard for the more complicated scenarios.**
  - **Perhaps unification should start in the physics [search] groups**
- **Thankfully, there is also always the anthropic principle.**
  - **Anthropically, history repeats itself ☺ → we should find something unexpected!**
- **The journey has only just started!**