Review of the High Energy Frontier Parallel Sessions

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CIPANP 2012
St. Petersburg, Florida
May 28th – June 3rd 2012

Outline

Parallel Session Topics and Convenors

High Energy Frontier:

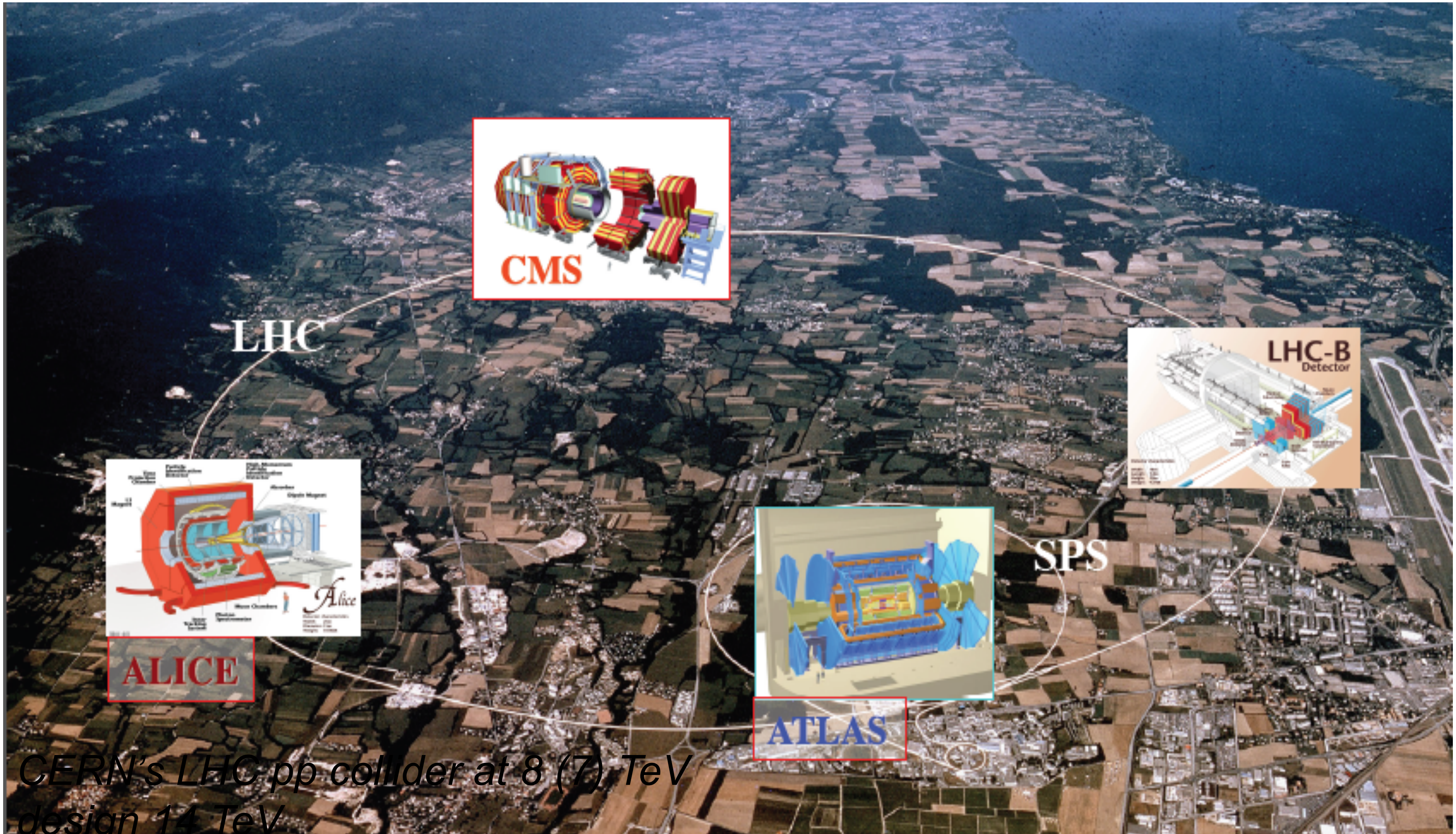
Oliver Stelzer-Chilton [TRIUMF]

Roni Harnik [FNAL]

Direct Searches for Higgs, SUSY, Exotics, Extra Dimensions
(Collider results from the LHC and Tevatron and theoretical interpretations)

- Total of 31 talks, of which 12 were invited
- Six sessions, broadly themed on a topic
- Searches for the Higgs boson
  Tuesday and Wednesday
- Beyond the Standard Model Searches: SUSY
  Wednesday
- Beyond the Standard Model Searches: Exotics
  Thursday
- Beyond the Standard Model Searches: Involving top quarks
  Saturday

The LHC



CERN's LHC pp collider at 8 (7) TeV
design 14 TeV

2011: 5.6 fb^{-1} delivered by LHC
5.2 fb^{-1} recorded by ATLAS and CMS experiments
2012: already ~3 fb^{-1} delivered

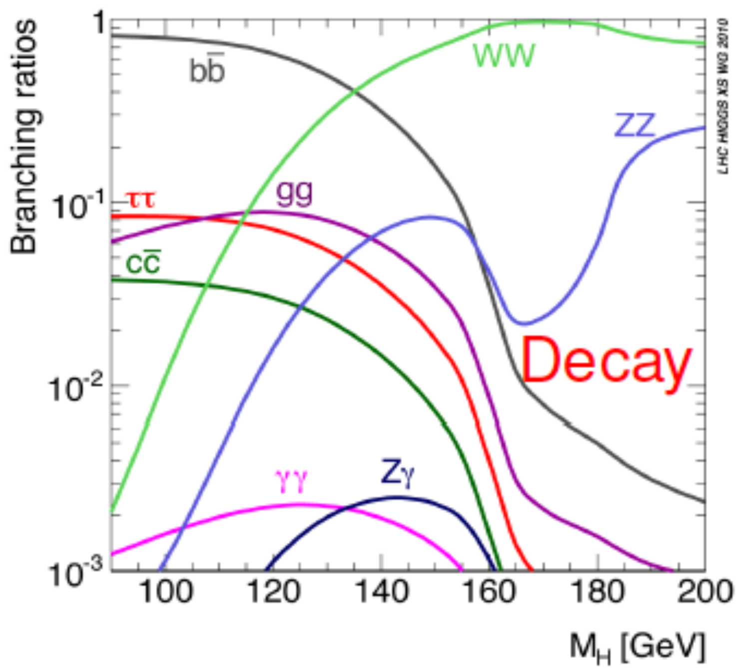
Searches for the Higgs Boson

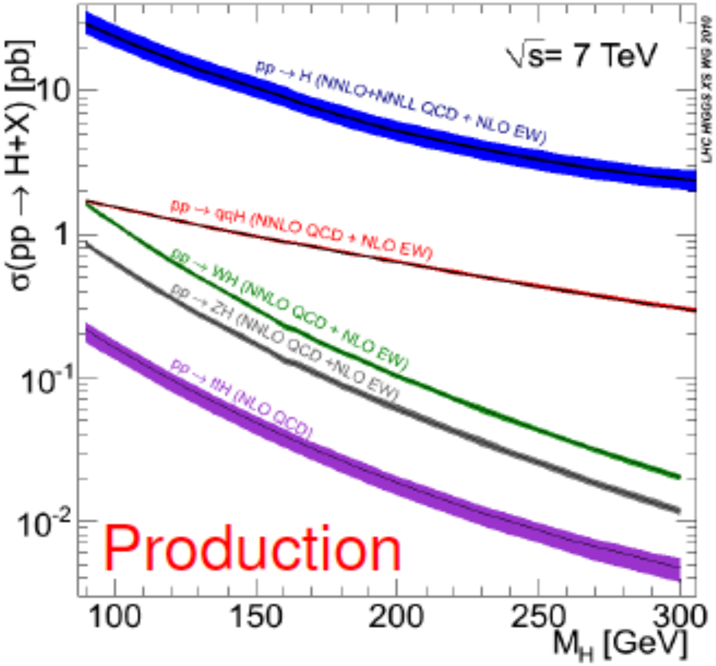
Standard Model Higgs Searches at the LHC

Chris Palmer

Previous Higgs' Constraints

- Indirect constraints
  - EW precision measurement - $M_H < 143$ GeV favored [GFitter, 2011]
- Direct search exclusions at 95% CL
  - LEP - $M_H < 114.4$ GeV
  - Tevatron - $147 < M_H < 179$ GeV





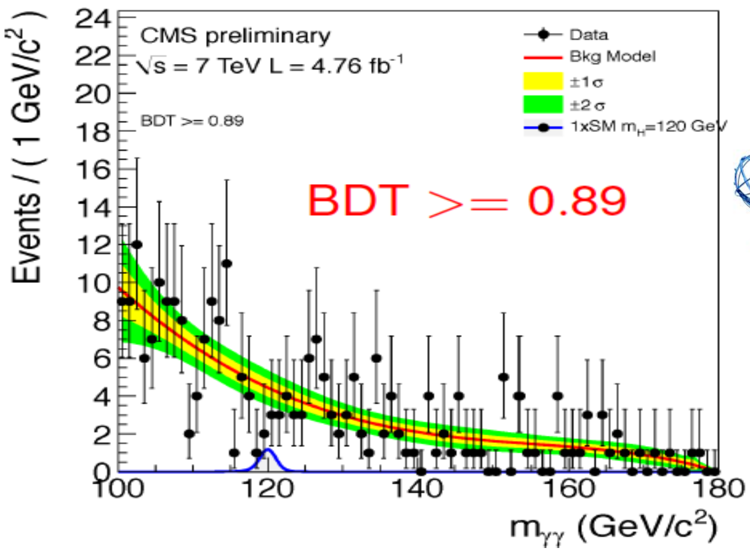
Higgs' Production

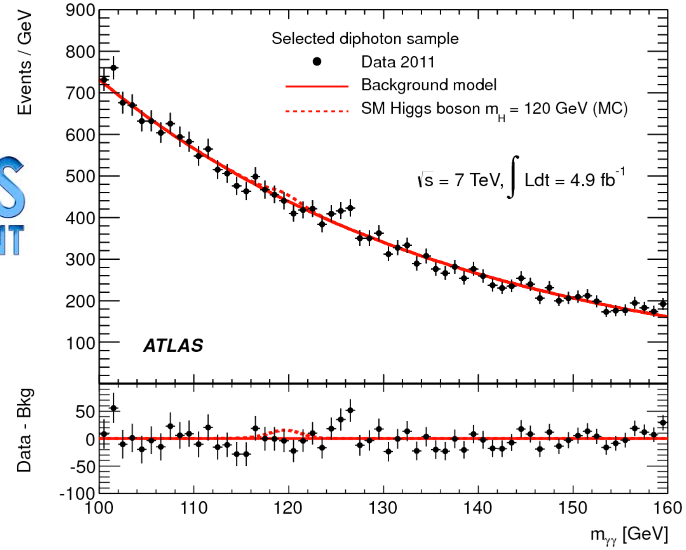
- Gluon fusion dominates Higgs' production at LHC
- Other channels provide extra final state tags

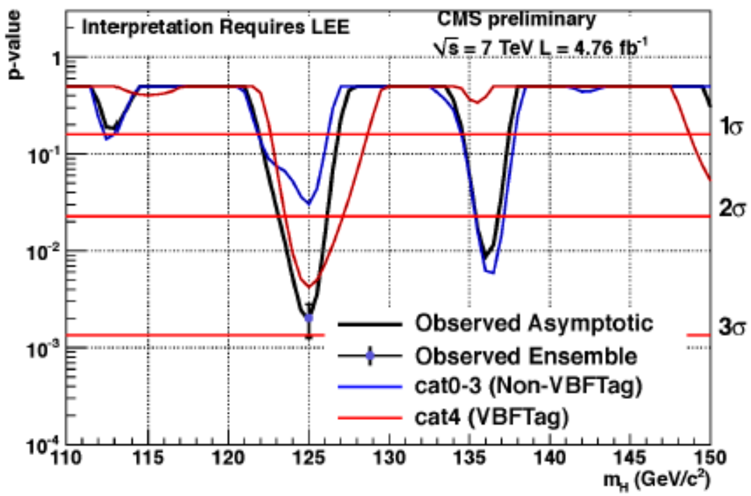
Most sensitive channels at low mass: *H→γγ, H→WW, H→ZZ*

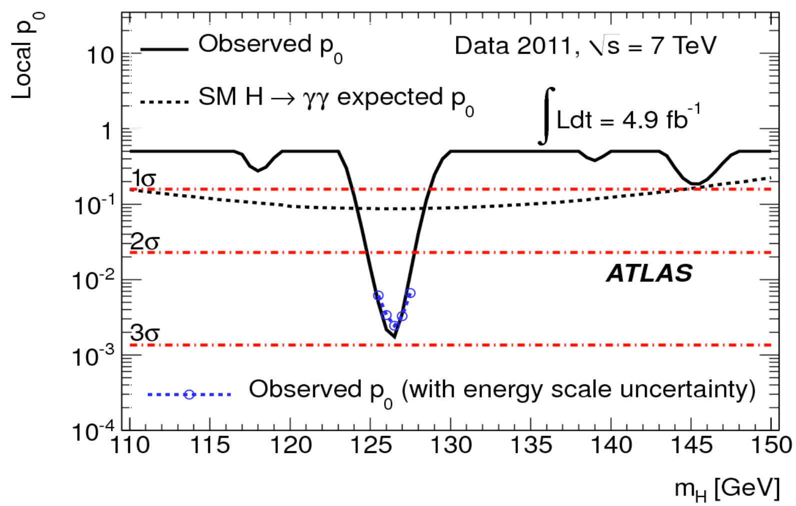
Higgs→γγ

Two high p_T photons, reconstruct invariant mass, good mass resolution









Higgs→γγ

Two high p_T photons, reconstruct invariant mass, good mass resolution

Chris Palmer

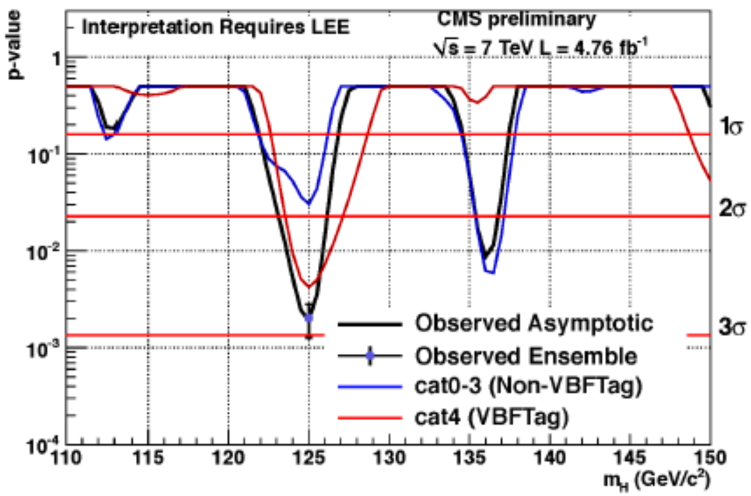
Excess

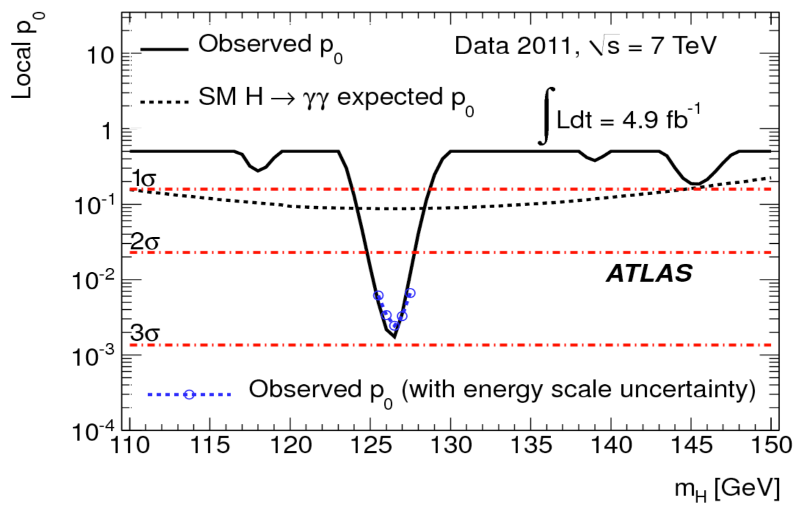
- P-value minimum at 125 GeV
- Local significance 2.9σ
- With look elsewhere effect (LEE) global significance 1.6σ

Bertrand Laforge

- First exclusion with this channel alone:
  - 113-115 GeV
  - 134.5-136 GeV
- Excess visible on the inclusive distribution
- Local excess of 2.8 σ down to 1.5 σ with a Look Elsewhere Effect in range 110-150 GeV

Both experiments see similar "small" excess in this channel near 125 GeV



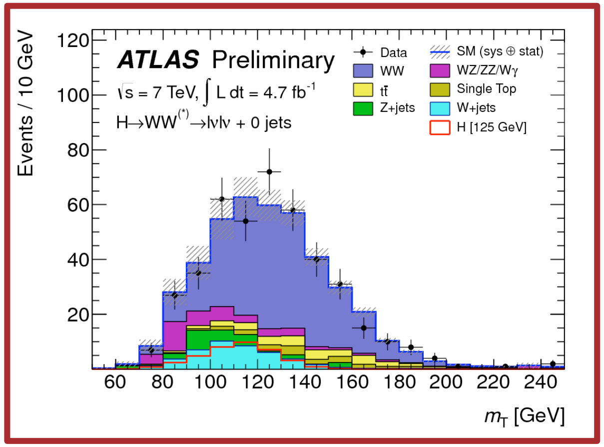


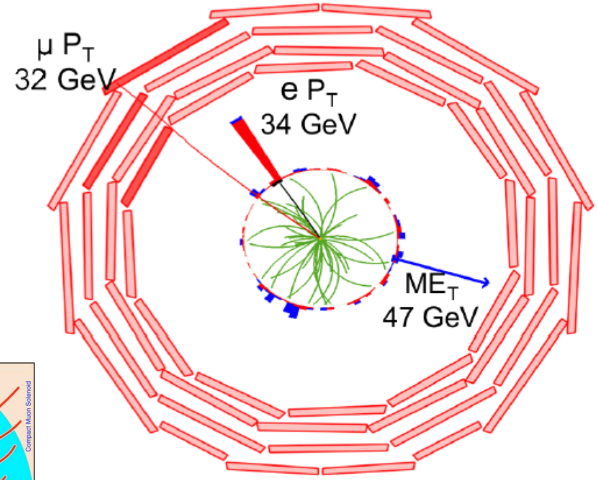
Higgs→WW*

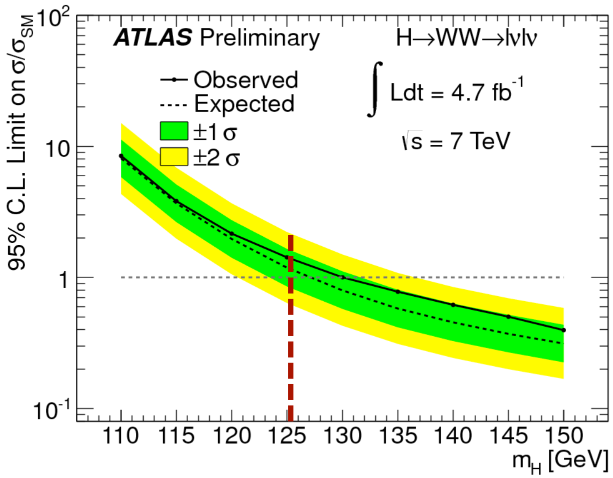
Most sensitive channel in broad range ~125-180 GeV

No mass reconstruction due to presence of two neutrinos

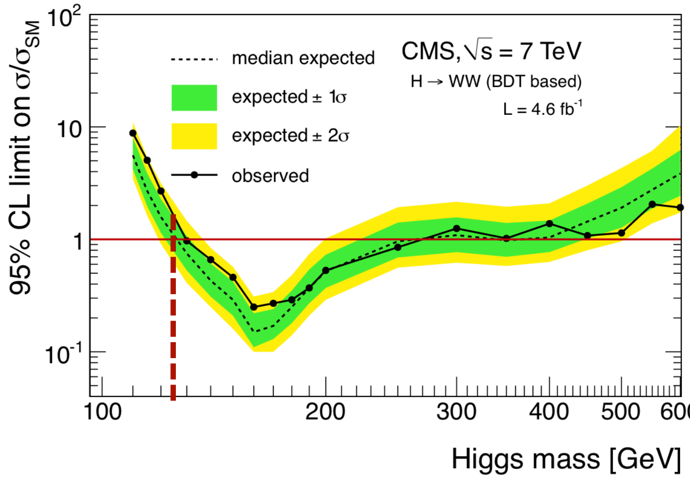
Transverse mass $m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss}\right|^2}$





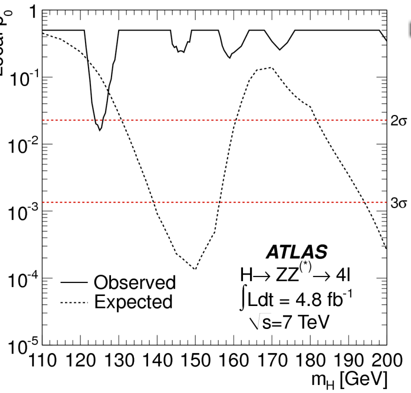


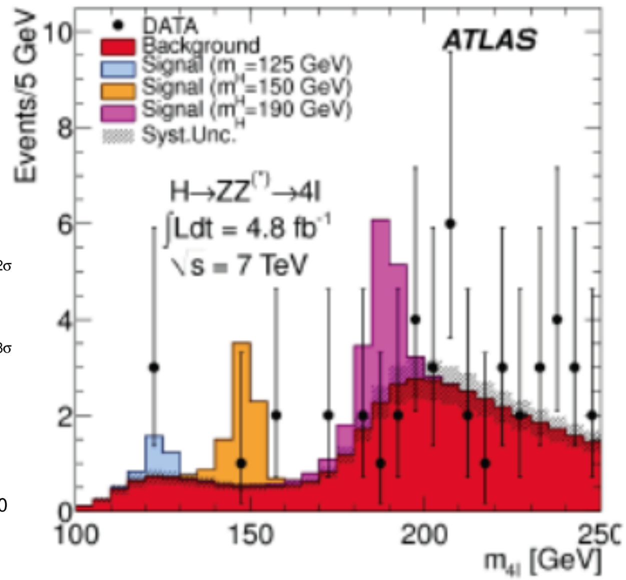
No excess in this channel

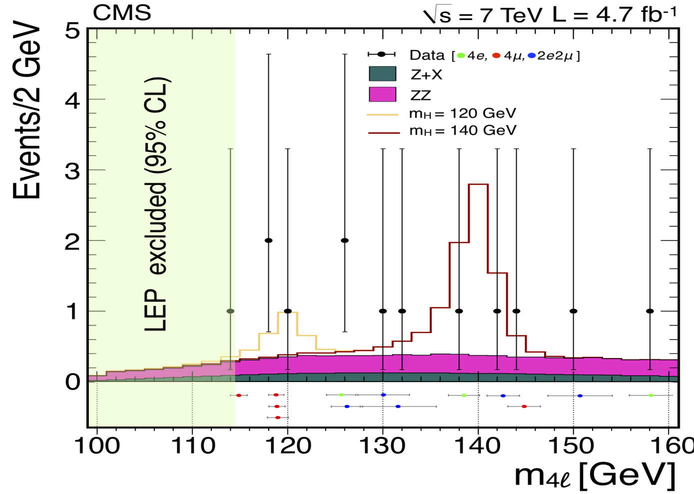


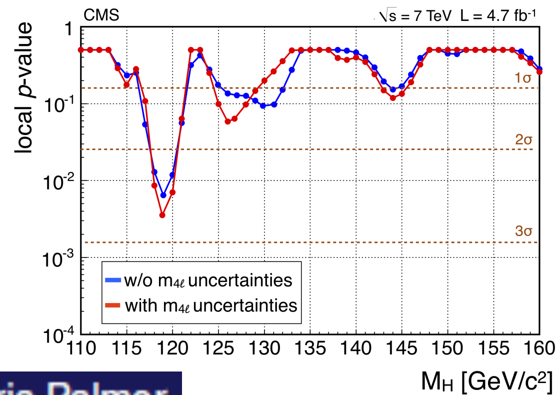
Higgs→ZZ*→4 leptons

Golden Channel, Best Signal/Background, good mass resolution









Bertrand Laforge

Small excesses observed around 3 mass values.

Local significance:

$m_{4\ell}$	125 GeV	244 GeV	500 GeV
Exp. w. signal	1.3σ	3.0σ	1.5σ
Observed	2.1σ	2.2σ	2.1σ

Chris Palmer

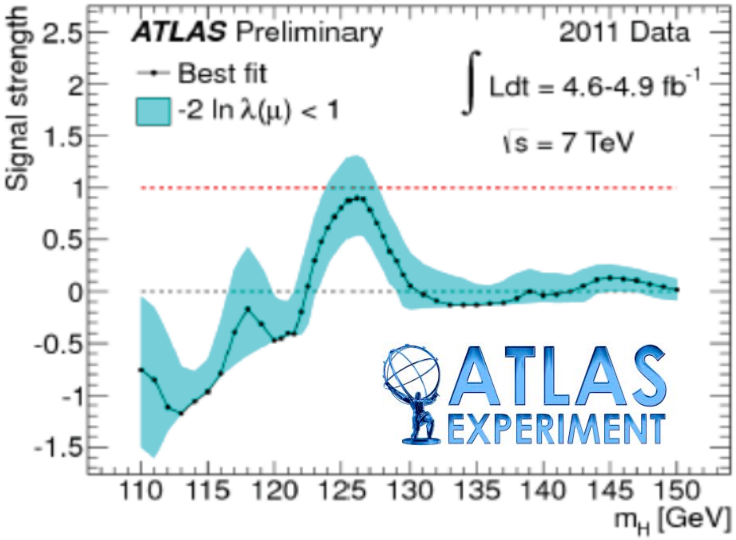
- Minimum p-value at 119.5 GeV
- Global significance 1.0σ (local 2.5σ)

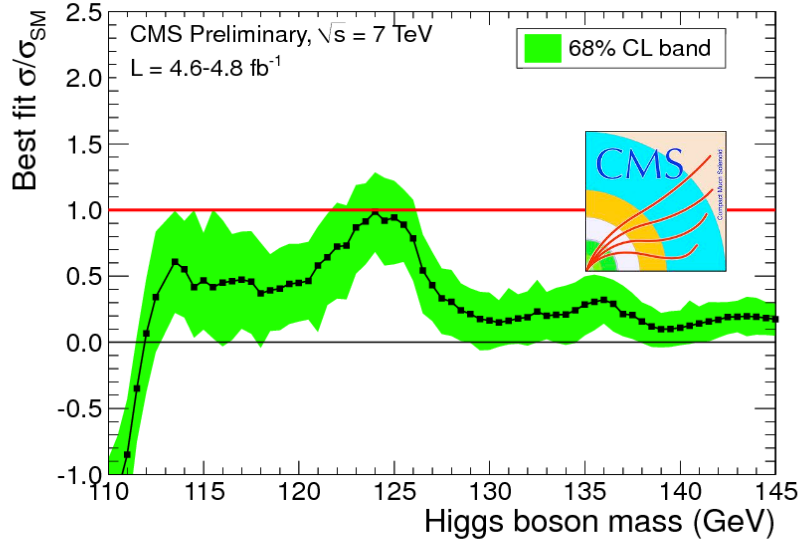
Local significance at ~120 GeV diluted in combination

Combination

Fit for observed signal strength (all channels) vs mass

Best fit signal strength $\mu = \sigma/\sigma_{SM}$:





Bertrand Laforge

Excess of events observed at 126 GeV:

- Observed local significance 2.5σ (expected 2.9σ).
- Best-fit signal strength at 126 GeV: $\hat{\mu} = 0.9^{+0.4}_{-0.3}$.
- Global probability of such a background fluctation : 10%. in the mass range (110-146 GeV)

Chris Palmer

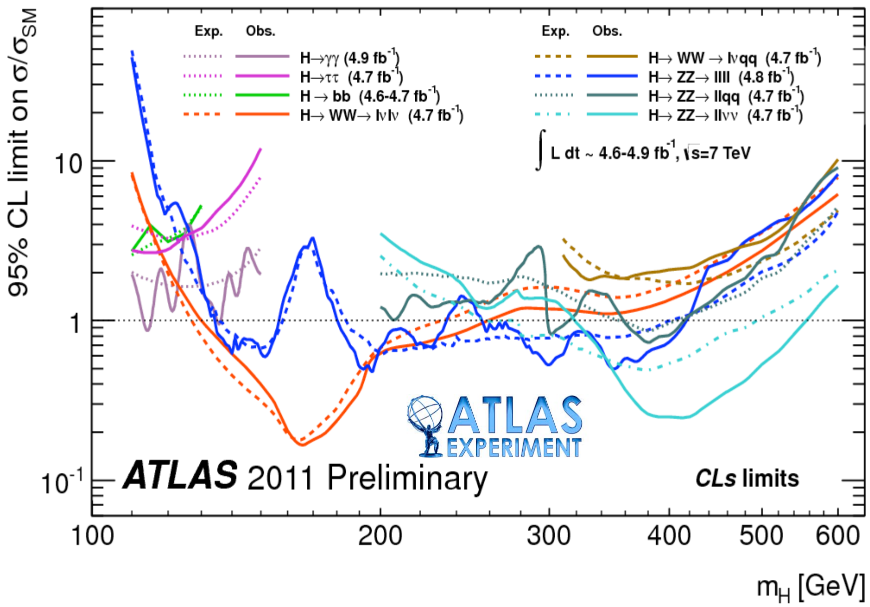
- Minimum pvalue at 125 GeV
- Local significance: 2.8σ
- Global significance with LEE
  - 2.1σ in 110-145 GeV
  - 0.8σ in 110-600 GeV

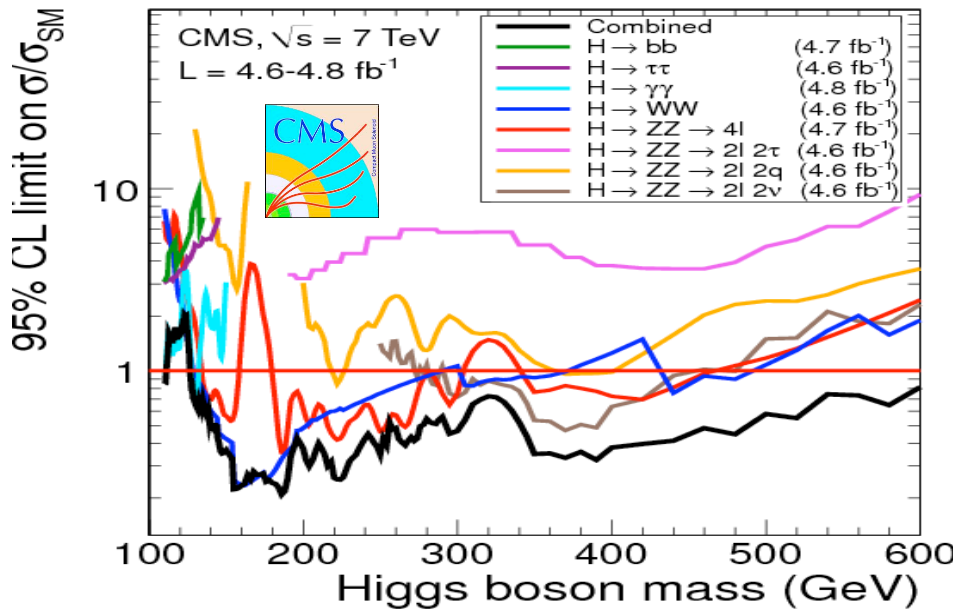
More Data from 2012 will tell if trend continues!

Full Mass Range Combined Exclusions

Many channels over full mass range

At high mass all sensitivity from *H→ZZ, H→WW in various final states*





Main result: **Olivier Simard**

Main Result

- Observed exclusion (95% CL):
  - Low mass: 110-117.5, 118.5-122.5 GeV
  - **High mass: 129-539 GeV**
- Expected exclusion: 120-555 GeV

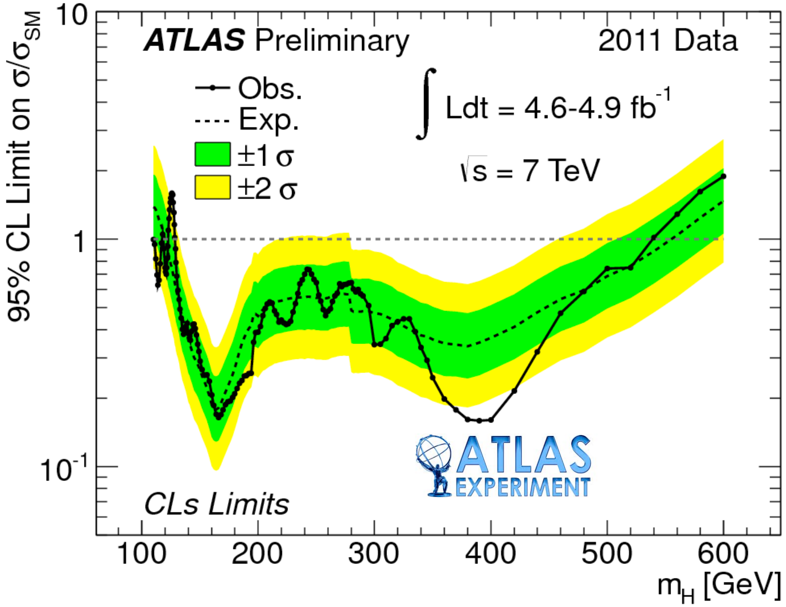
Alexey Drozdetsky

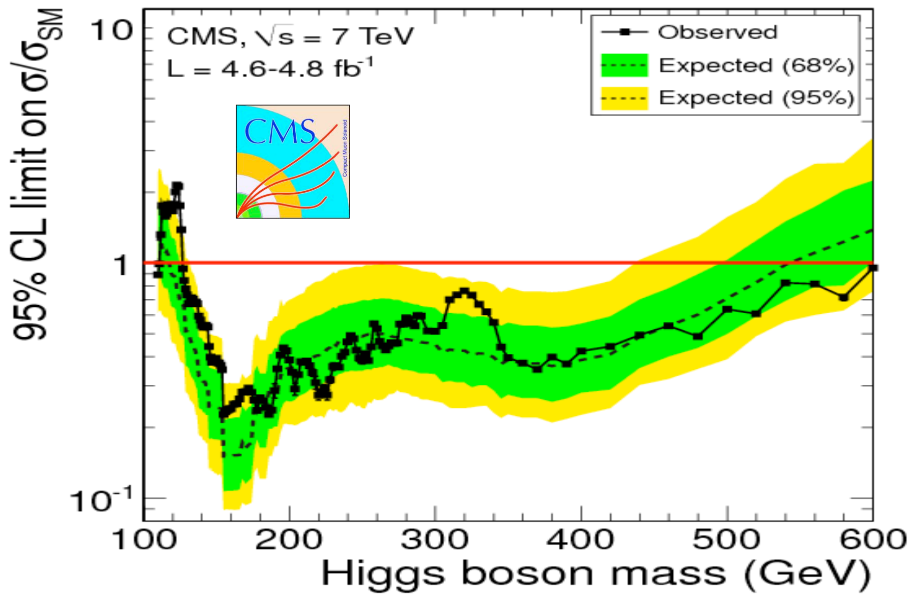
The SM Higgs boson is excluded at 95% confidence level in the mass range 127.5..600 GeV (expected: 114.5..543 GeV)

Full Mass Range Combined Exclusions

Many channels over full mass range

At high mass all sensitivity from *H→ZZ, H→WW in various final states*





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Olivier Simard

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Alexey Drozdetsky

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Chris Palmer **Fermiophobic Combination**

No fermionic coupling allowed

- No gluon fusion production
- Higgs decay only to gauge bosons ($\gamma\gamma$, ZZ, WW)

Observed 95% CL limit: 110-192 GeV

Higgs at the Tevatron

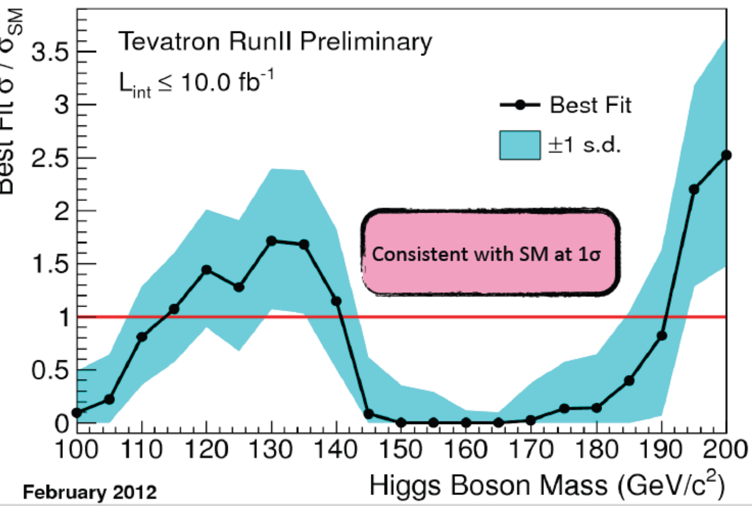
Long history for Higgs search, complementary to LHC, since associated production, WH, ZH contributes at low mass

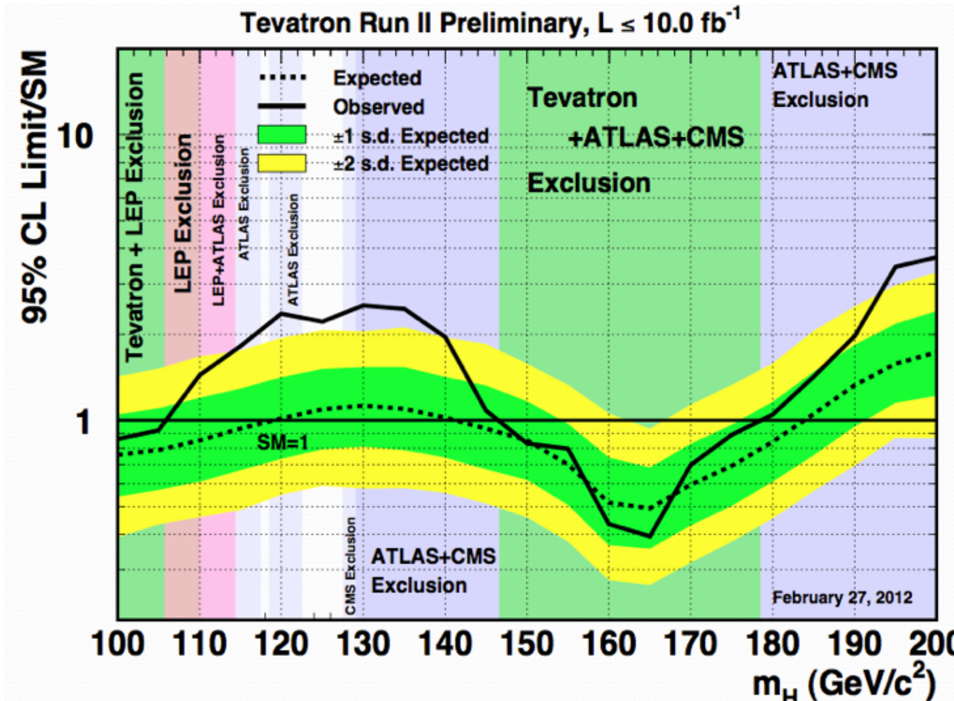
	Low mass	High mass
Production*	WH, ZH	gg→H
Decay	H→bb	H→WW
Main modes	bb+ℓν bb+ℓℓ bb+νν	ℓℓ+νν

Yuri Oksuzian

- Local 2.8σ
- Global 2.2σ(LEE of 4)

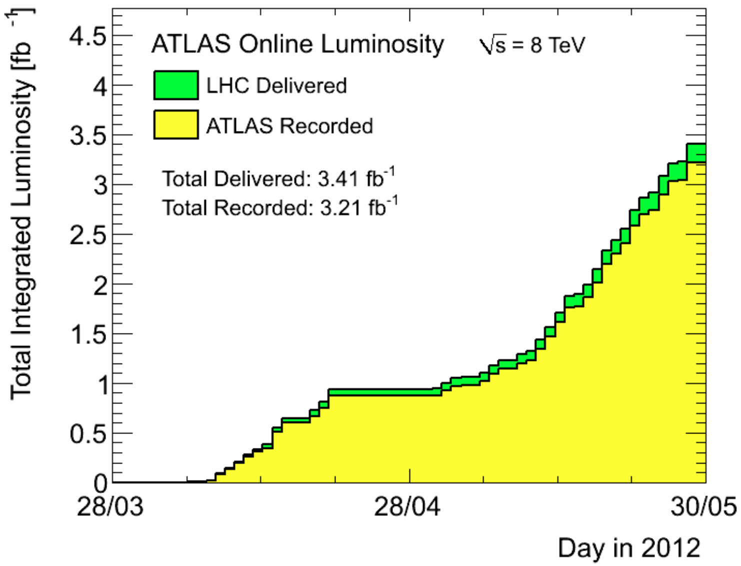
Sensitivity at M_H=125 GeV		
	Tevatron	Atlas, CMS
H→WW	~3.5xSM	1-2xSM
H→γγ	<10xSM	1.5-2xSM
H→bb	~2xSM	~4xSM



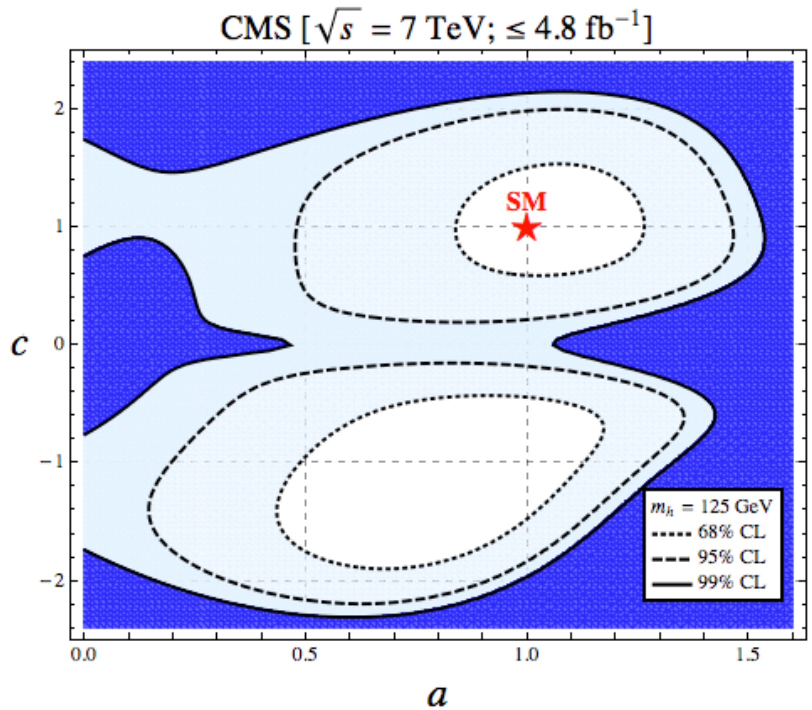


Higgs in 2012

LHC is confident to deliver 15-20 fb^{-1} this year (>3.4 fb^{-1} delivered)
Enough data to either exclude or discover Higgs



Jamison Galloway



In case of discovery important to determine if indeed SM Higgs
- spin, couplings…

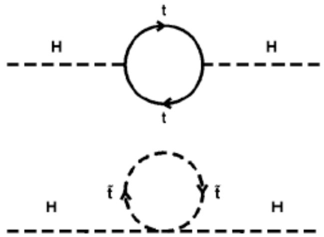
Higgs at 125 GeV would have the advantage to be accessible by many channels *H→WW*, *H→*γγ, *H→ZZ*, *H→*ττ, *H→bb*

Searches for SuperSymmetry

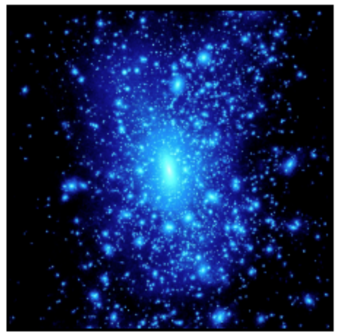
Supersymmetry

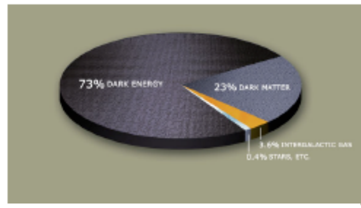
Alex Tapper

- The theory hypothesises a relationship between bosons and fermions
  - Leads to the prediction that every fermion has a bosonic super-partner and vice versa

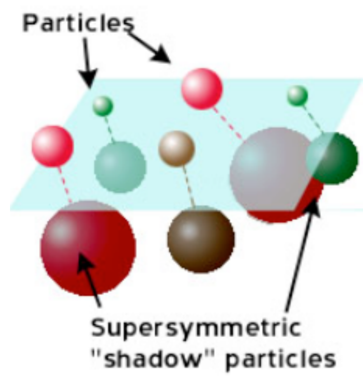


- Theorists love SUSY (@ TeV scale) because:
  - It provides a solution to the hierarchy problem
  - It allows unification of the gauge couplings at high scales and therefore a GUT?
  - It can provide a dark matter candidate





- Experimentalists love it because:
  - Plethora of new particles to discover and measure



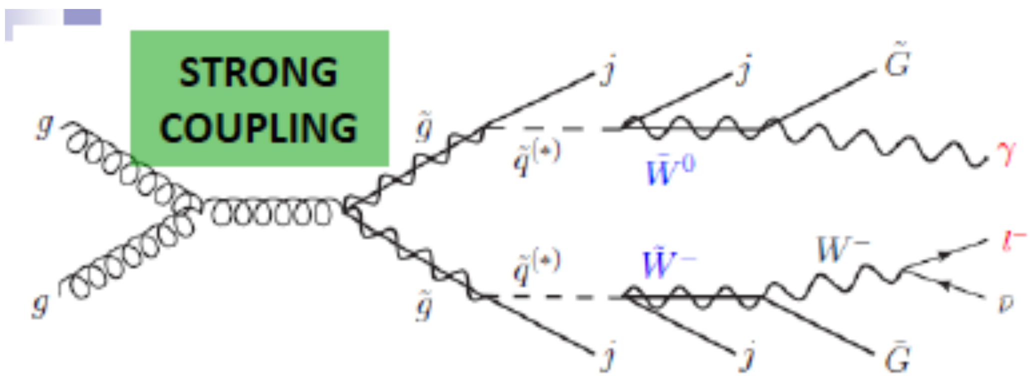
- Symmetry not exact
  - SUSY and Standard Model particles have different masses
  - SUSY is broken → what does it look like and how do we search?

Supersymmetry

Alex Tapper

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

- Generic missing energy signatures
- Categorised by numbers of leptons and photons
- Many include jet requirement ➔ strong production
- Transition from simple counting experiments to shape-based analyses



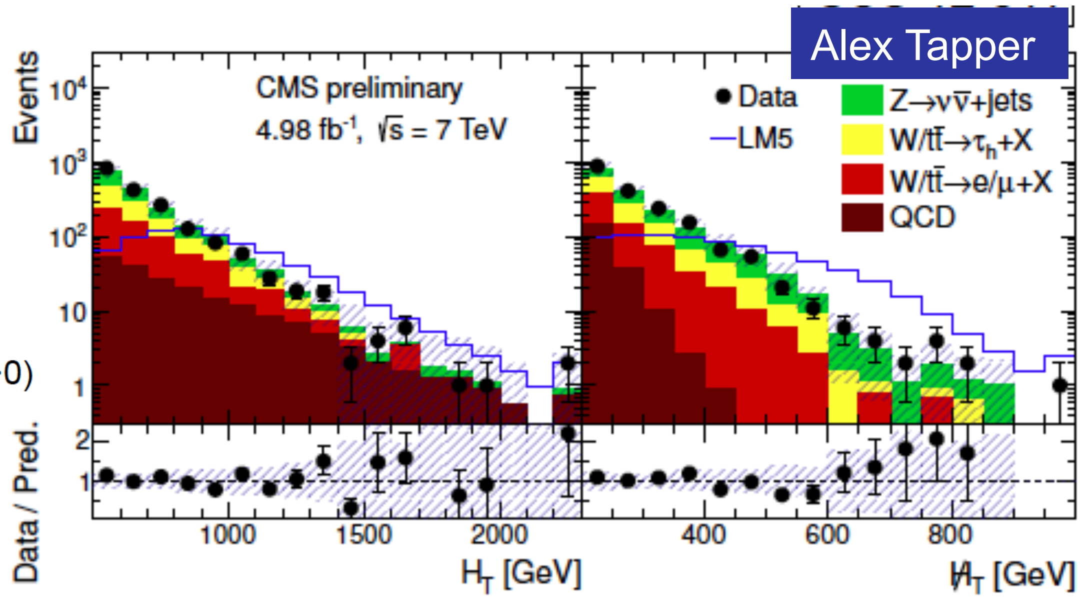
Bruce Schumm

High cross-sections probe high mass scale
beam energy vs. luminosity
“scale chasing”

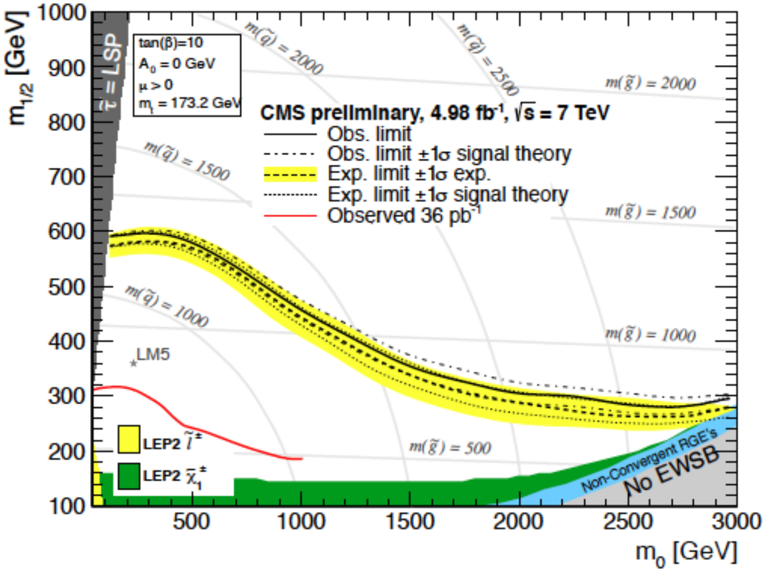
Signature: Jets and E_T^{miss}

Alex Tapper

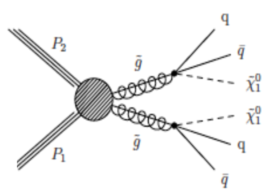
- No leptons (e or μ)
- At least 3 jets > 50 GeV
- Δφ between jets and MET
- Examine data in bins
  - H_T^{miss} (MET from Jets)
  - H_T ($\sum$ of jet p_T)

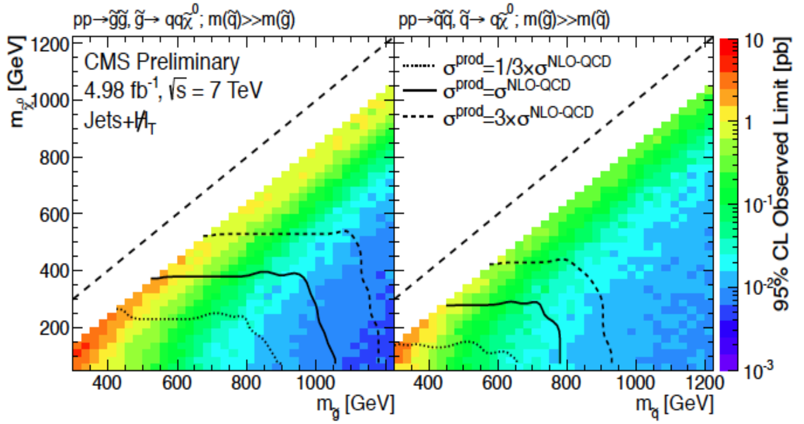


- Limit in the usual CMSSM plane (tanβ=10, A_0=0, μ>0)



- Simplified Model Spectra
  - Limited set of hypothetical particles and decays
  - Less specific mass patterns and signatures



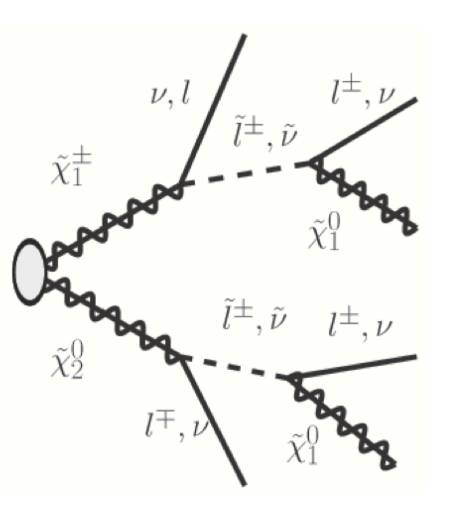


- Clean way to communicate results of our searches and compare different channels ➔ no hidden theory dependence
- Reference cross section scaled by 1/3 and 3 to demonstrate differences from spin or branching ration assumptions
- Areas of small mass splittings removed to reduce sensitivity to signal modelling

Limit reach: gluino ~1 TeV

Electroweak SUSY

Bruce Schumm



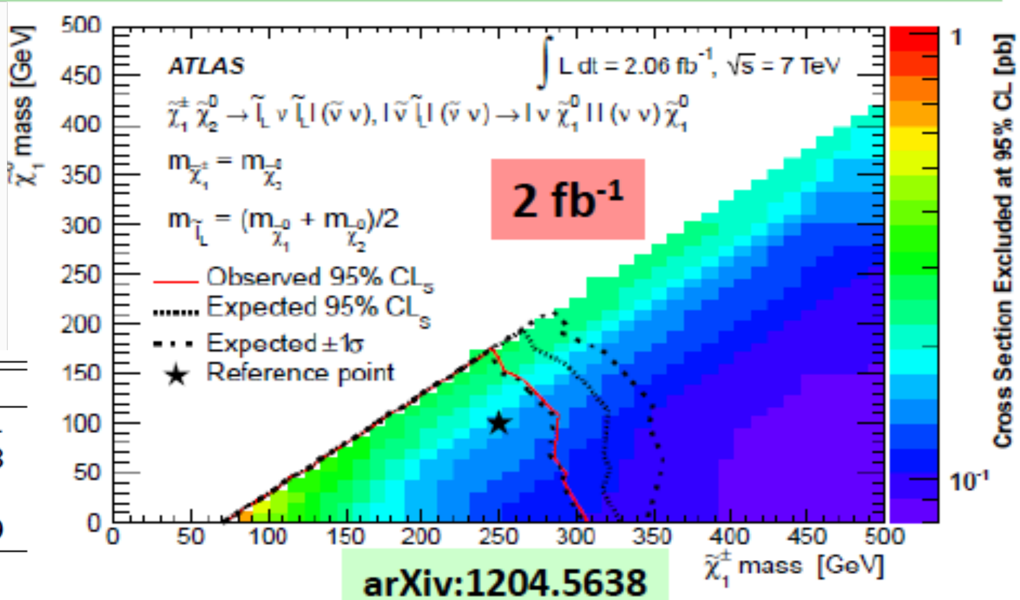
Few-hundred GeV gauginos, decoupled colored sparticles "natural".

- Multi-lepton signals
- E_T^{miss} from ν and χ_1^0
- Simplified model, only gauginos and sleptons light

3-Lepton (e,μ) + E_T^{miss} Search

- Require one opposite-sign, same flavor pair ($\chi^0 \rightarrow l^+l^-$)
- E_T^{miss} > 50 GeV

Selection	VR1	VR2	SR1	SR2
$t\bar{t}\,W^*/Z^*$	1.4±1.1	0.7±0.6	0.4±0.3	2.7±2.1
ZZ^*	6.7±1.5	0.03±0.04	0.7±0.2	3.4±0.8
WZ^*	61±11	0.4±0.2	11±2	58±11
Reducible Bkg.	56±35	14±9	14±4	7.5±3.9
Total Bkg.	125±37	15±9	26±5	72±12
Data	122	12	32	95

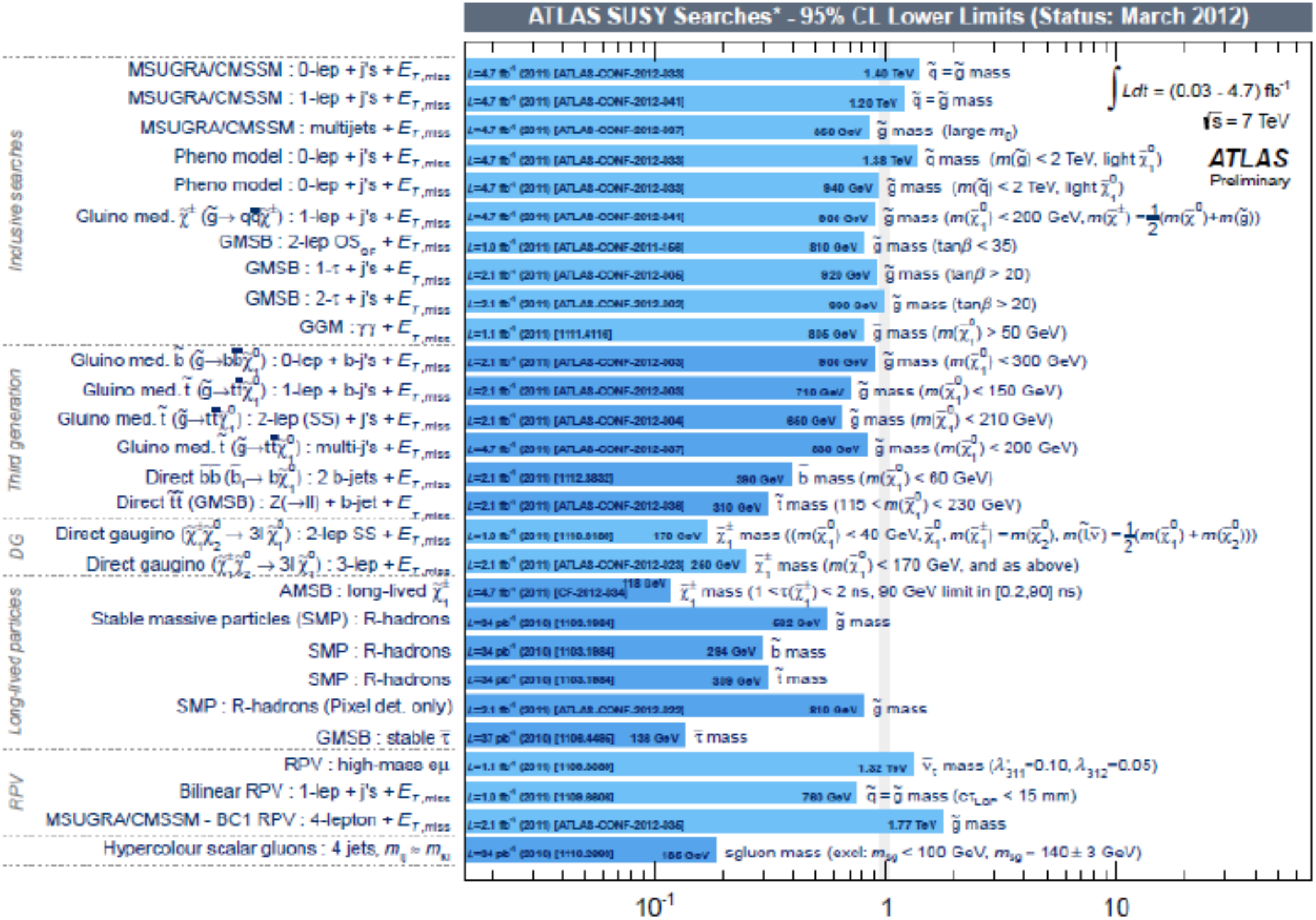


2 fb^{-1}

arXiv:1204.5638

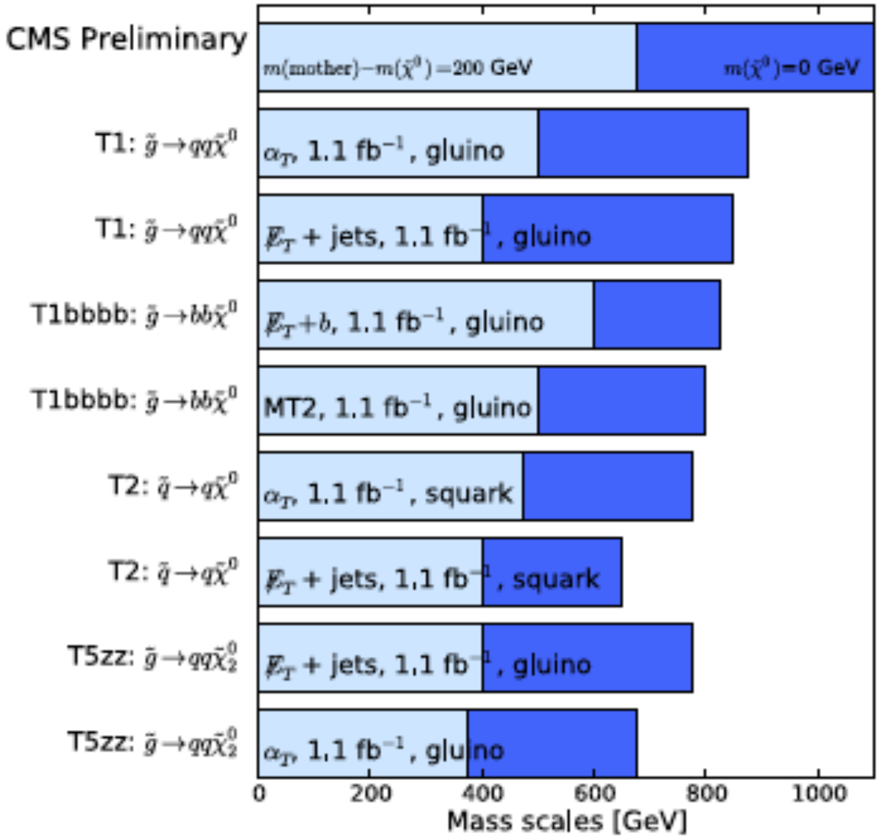
Limit reach: chargino ~300 GeV

Results ATLAS

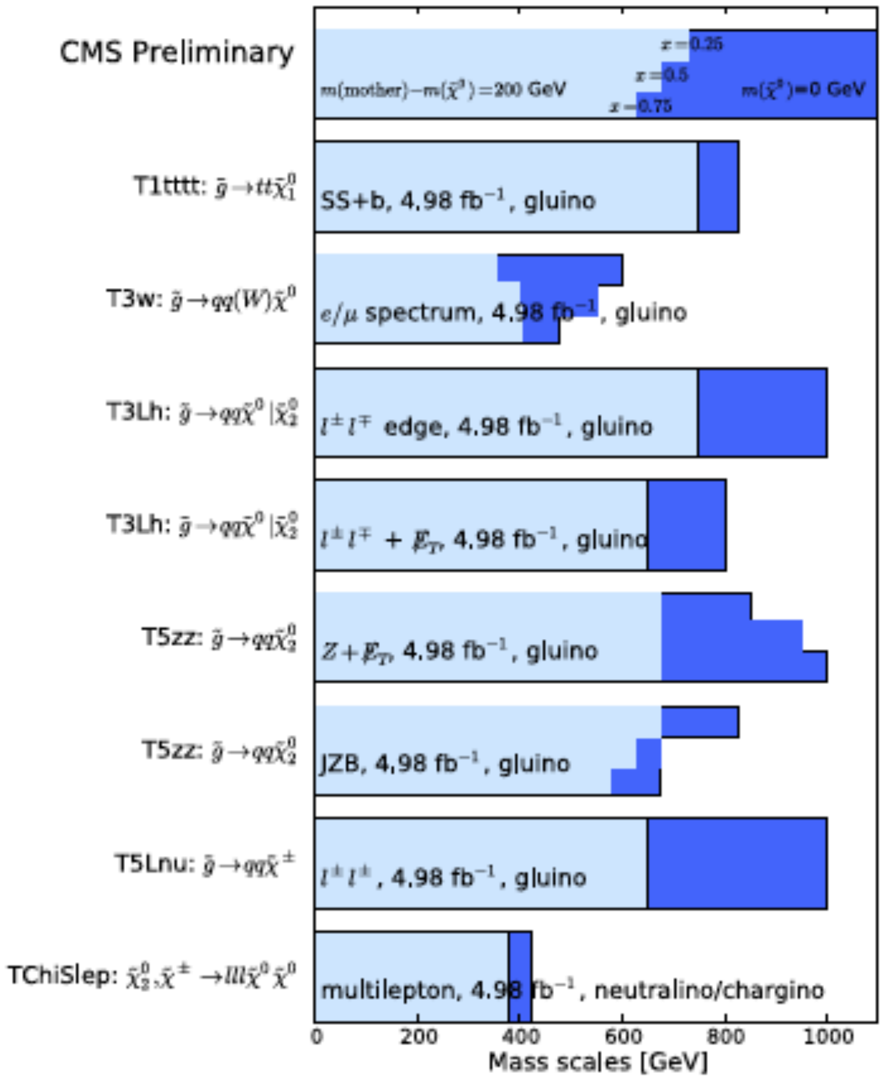


Results CMS

Hadronic searches



Leptonic searches



SUSY Summary

Strongly produced SUSY nearing ~TeV exclusion for gluinos and 1st and 2nd generation squarks

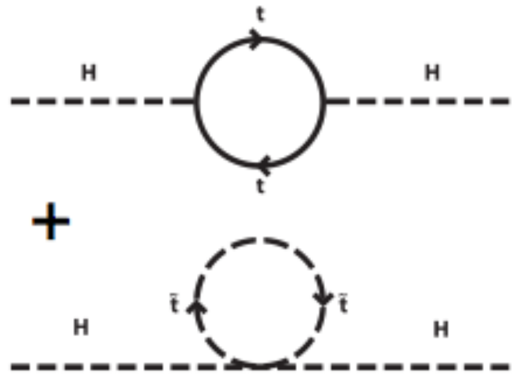
With larger luminosity becoming sensitive to electroweak SUSY production

New focus on natural SUSY

Theoretical motivation ("Naturalness")

- SUSY can ***cancel top loop corrections to the Higgs mass*** with 1-loop stop contribution ***if the stop is light enough***

Alfredo Gurrola



≈ 0 (if $\tilde{t}$ is light)

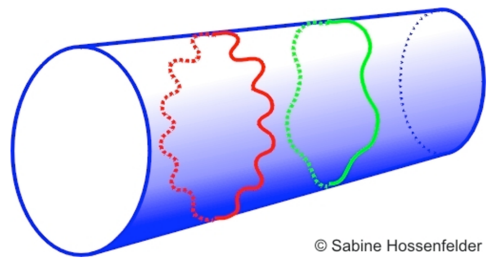
Wide range of SUSY searches involving third generation squarks and sleptons taking shape

Direct search for stop quarks anticipated for both experiments

Exotics Searches

Exotics

Large difference between electroweak scale and gravity could be explained by extra dimensions (ADD, Randall-Sundrum, UED…)



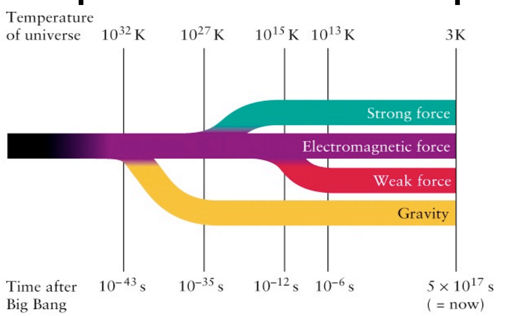
Neutrinos have mass, where are the right handed neutrinos?

Is there a fourth generation of quarks?

Are quarks and leptons fundamental particles or composites?

What is dark matter?

Can all forces be unified?



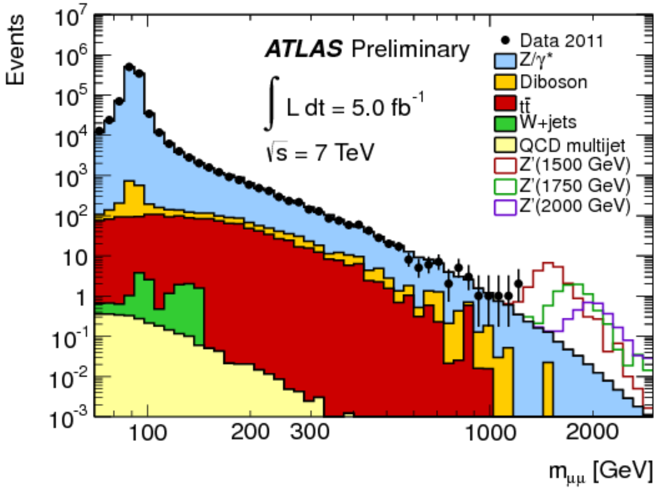
In Exotics searches, cast a wide net for signs for new physics

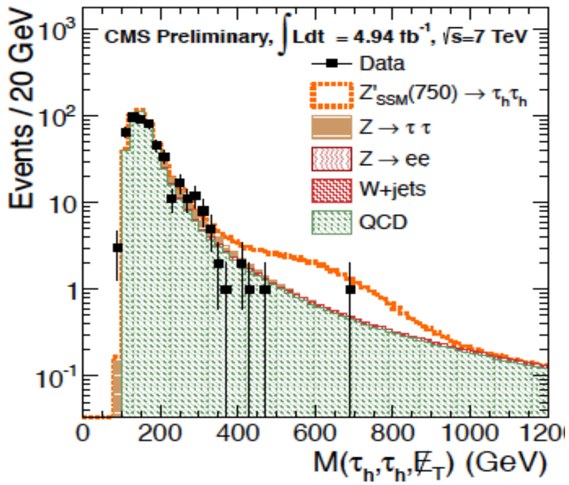
Combine physics objects: electrons, muons, photons, jets, b-jets, top quarks missing energy and interpret in benchmark models

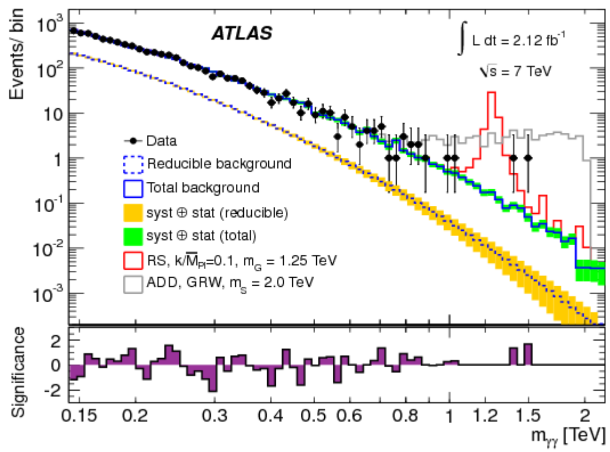
Classic Resonance Searches

Look for resonances in dijet, dilepton, lepton-neutrino, diphoton, multijet, photon-jet, diboson, di-tau, di-top, top-bottom… final states

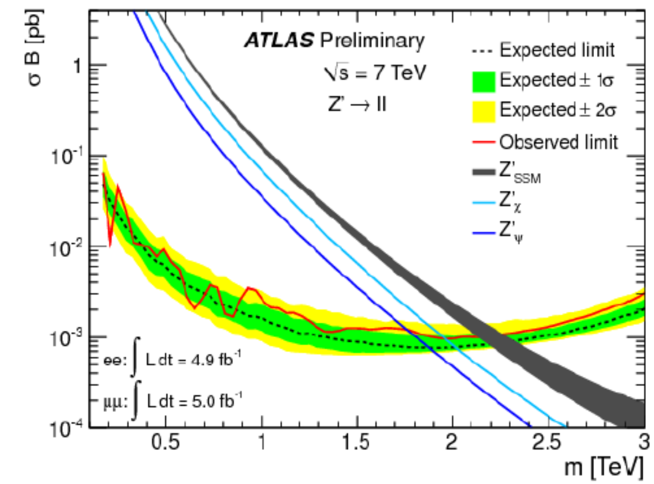
Sarah Heim | Eduardo Luiggi

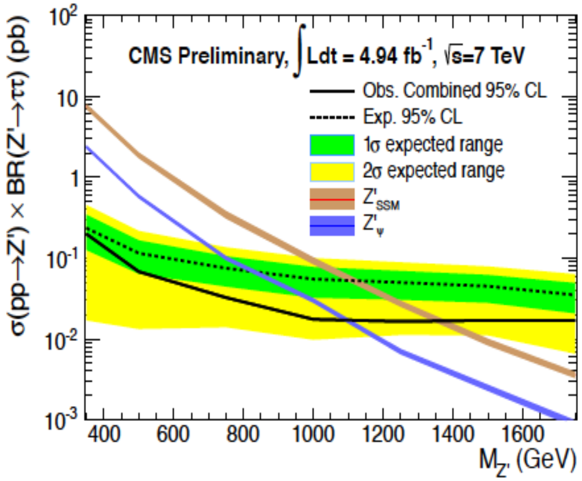


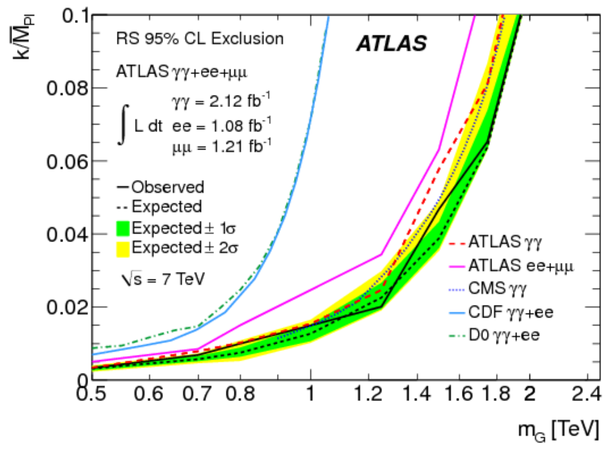




Interpret in various models, sequential SM, E6, RS Gravitons, ADD





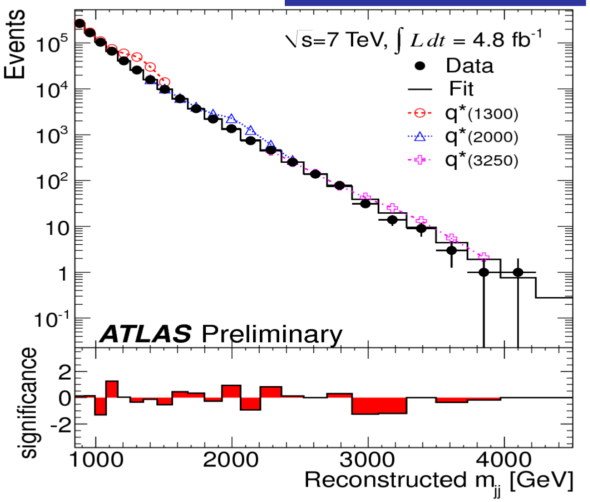


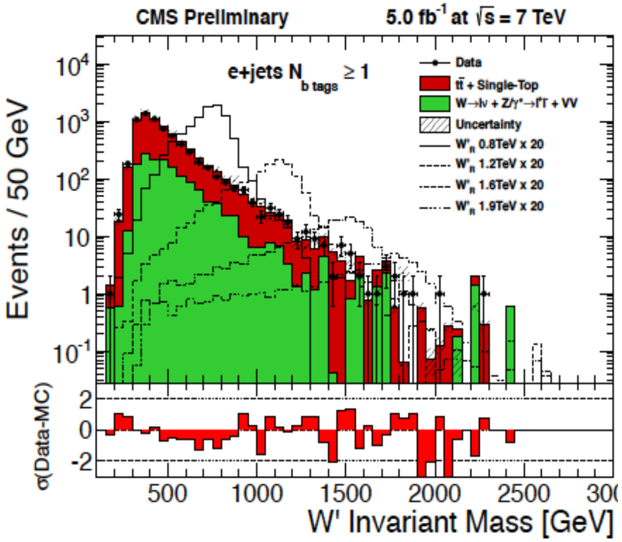
Resonance Searches

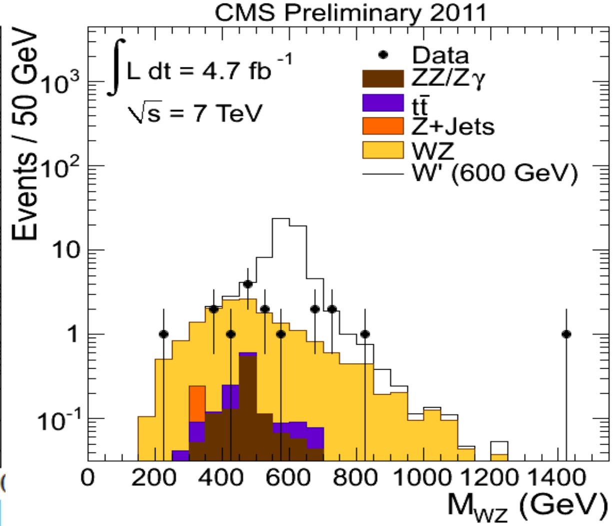
Look for resonances in dijet, dilepton, lepton-neutrino, diphoton, multijet, photon-jet, diboson, di-tau, di-top, top-bottom… final states

Eduardo Luiggi

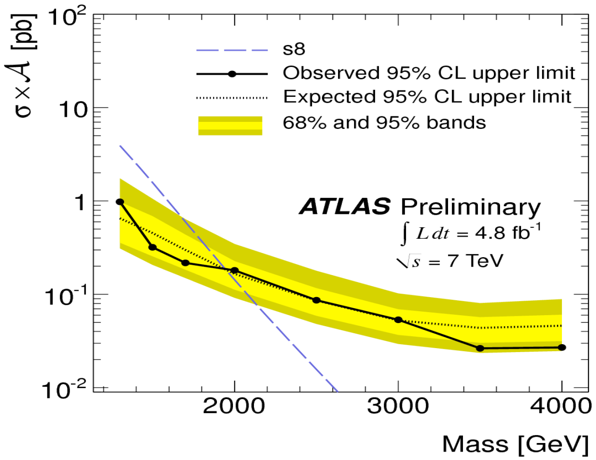
Sarah Heim

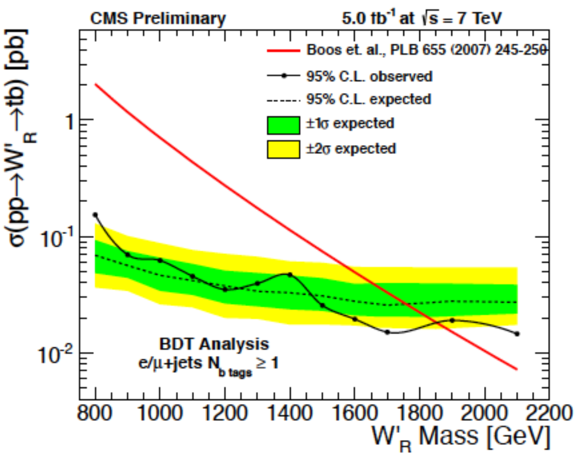


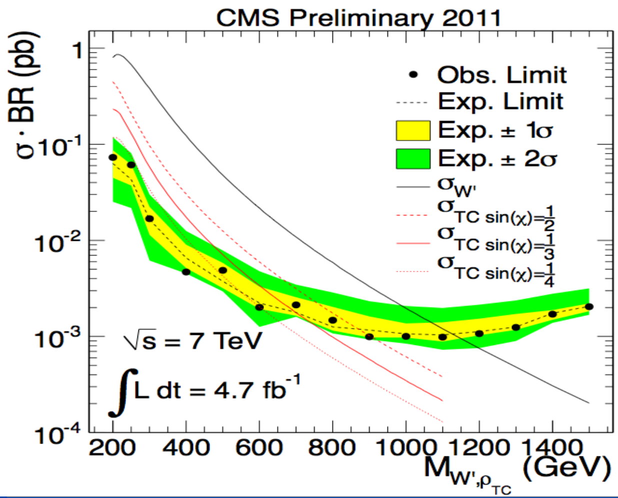




Interpret in various models, axigluons, sequential SM, technicolor



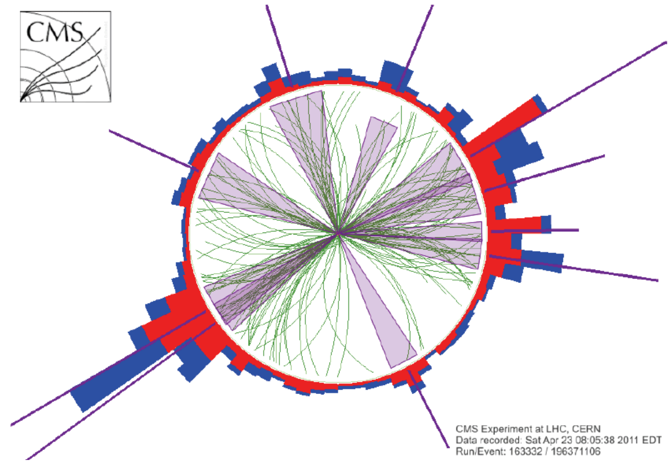




Black Holes

Emanuela Barberis

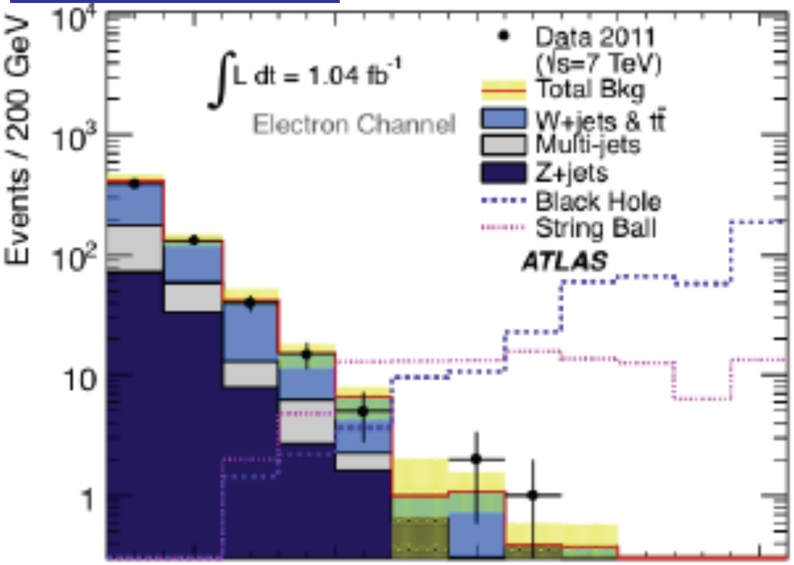
Signature of TeV scale gravity: characterized by democratic decay via Hawking radiation into high multiplicity, isotropic, energetic, final states of jets, electrons, photons, and muons.



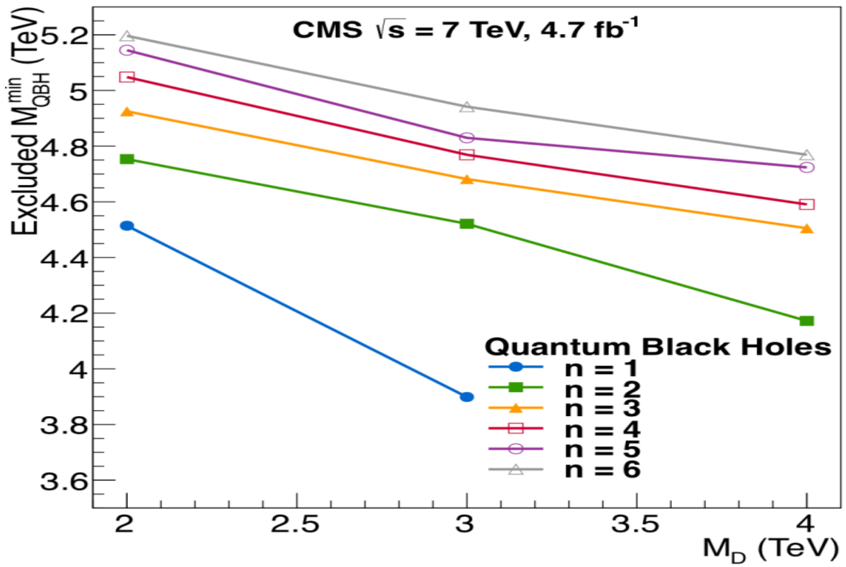
Analysis strategy: search for deviations in $S_T = \Sigma$ jets + γ's + l's+ E_T^{miss} distribution in bins of N objects

Similar search in ATLAS

Joseph Tuggle



Minimum QBH mass vs M_D for n extra-dimensions:
3.8-5.2 TeV range for M_D up to 4 TeV



Heavy Neutrinos

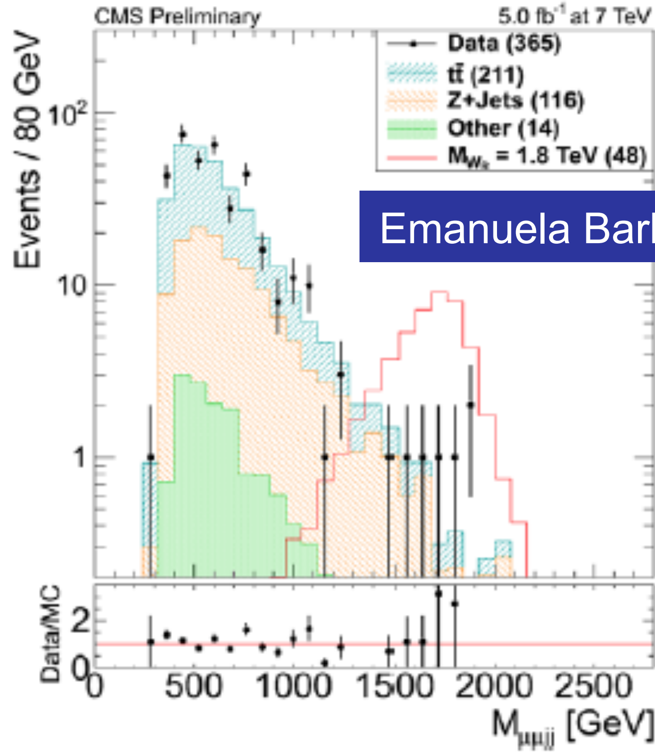
Right-handed W_R bosons and heavy neutrinos N(e or μ) arise in Left-Right Symmetric extensions of the Standard Model:

$$qq \rightarrow W_R \rightarrow N\ell \rightarrow W_R^{*}\ell\ell \rightarrow \ell\ell jj$$

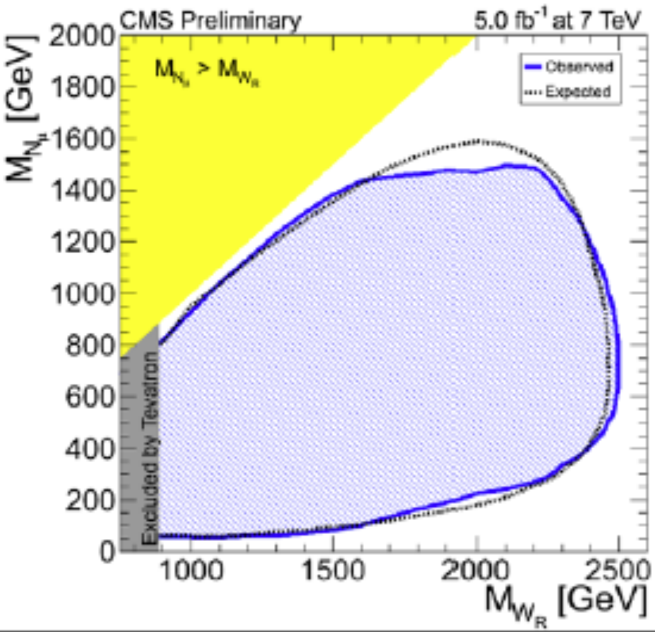
characterized by mass resonances both in ℓjj and $\ell\ell jj$

Analysis strategy: (5 fb^{-1})

- ✓final states with two muons and two jets.
- ✓Lead μ p_T> 60GeV, $M_{\mu\mu}$>200GeV, $M_{\mu\mu jj}$>600GeV



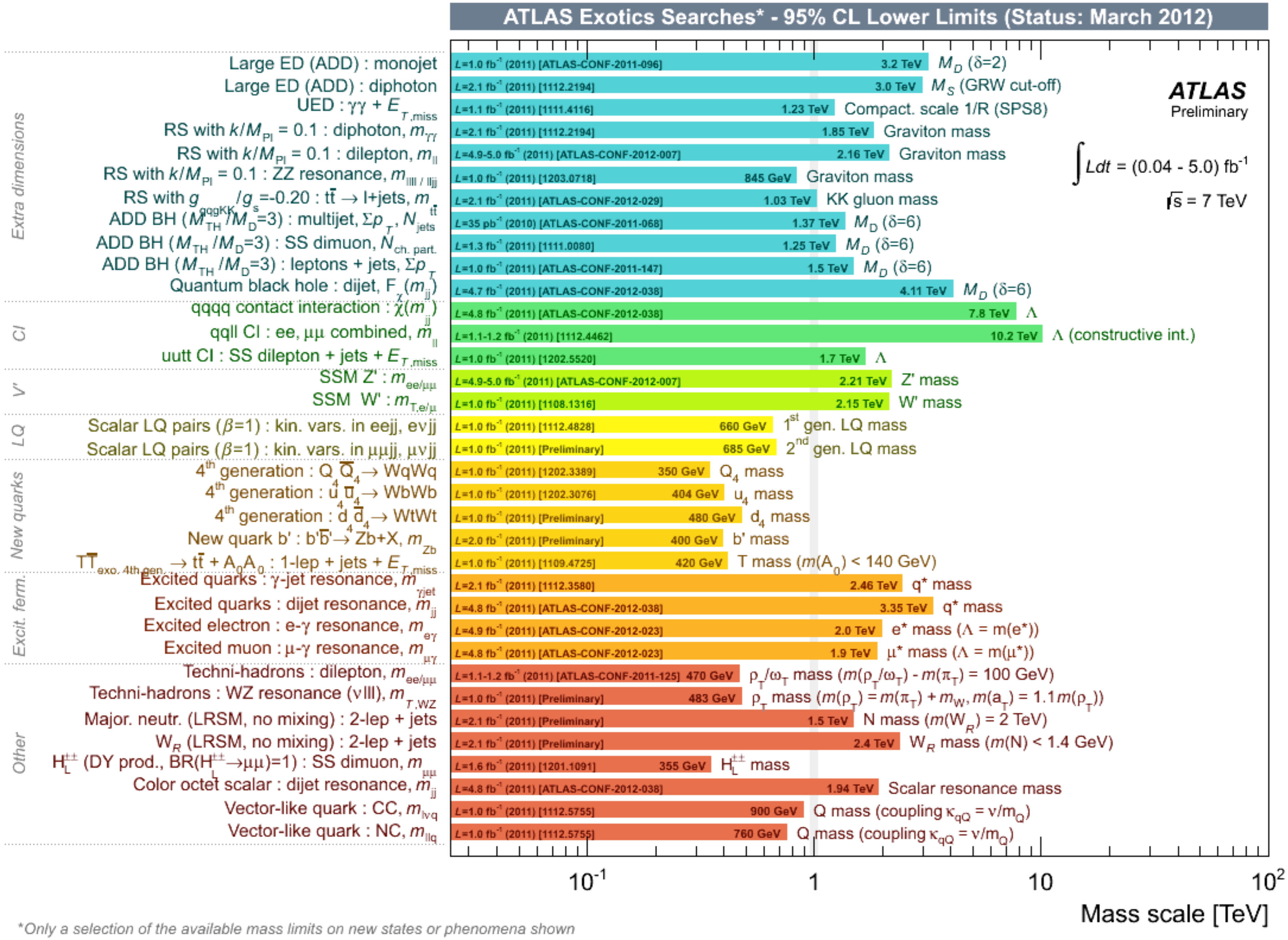
Emanuela Barberis



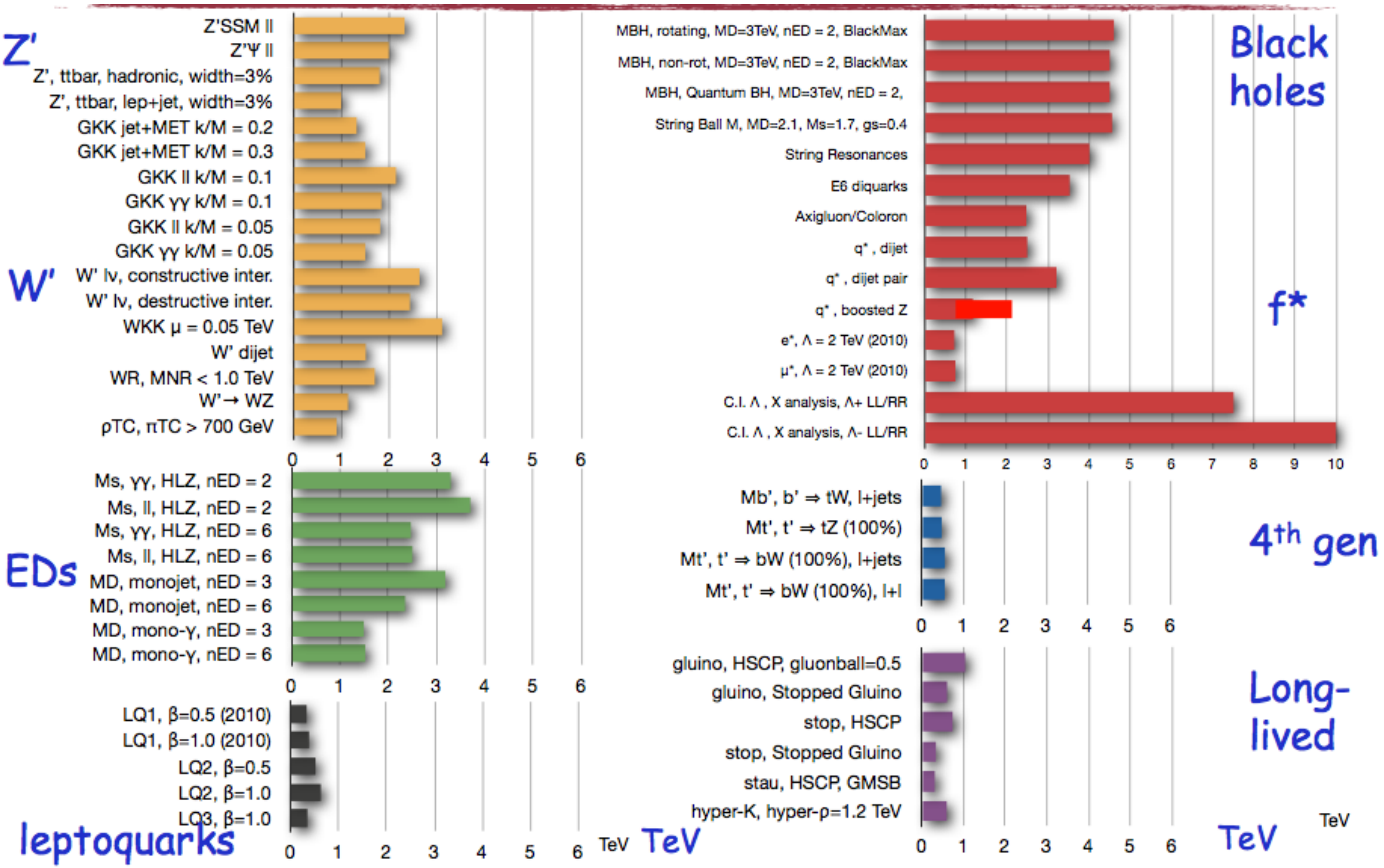
95% C.L. limits exclude a region in the (M_N, M_{W_R}) space that extends to M_{W_R} = 2.5 TeV.

CMS EXO-11-091

ATLAS Exotics Summary

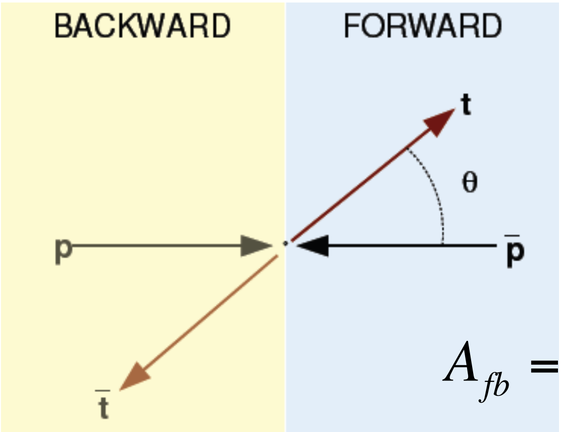


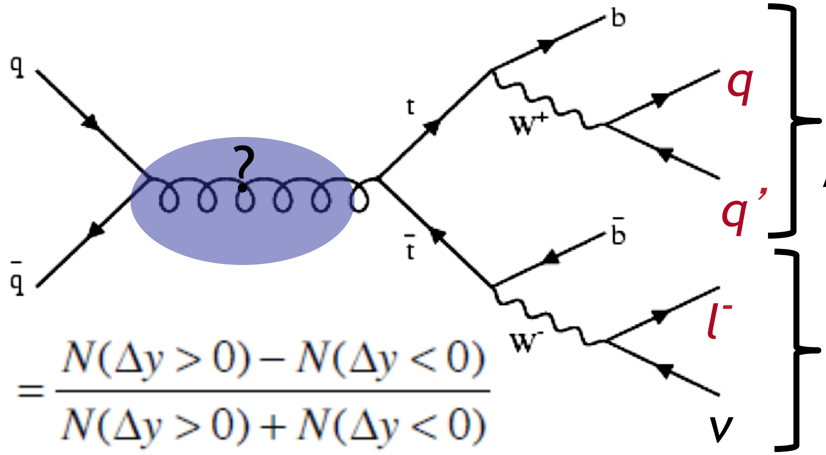
CMS Exotics Summary



Searches Involving Top Quarks

Forward Backward Asymmetry





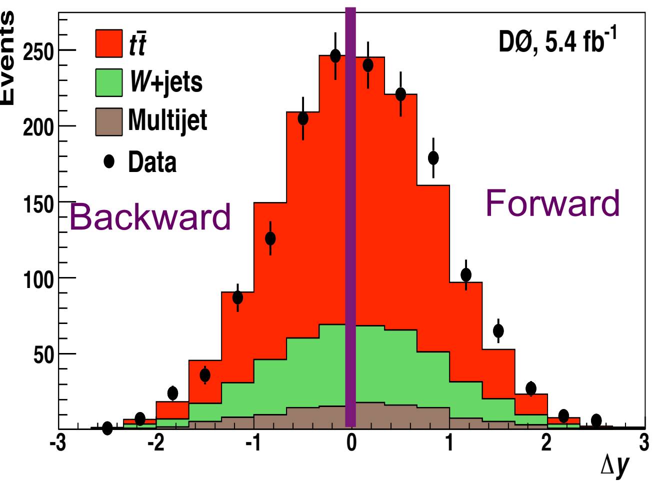
$$\Delta y = q_l(y_l - y_h) = y_t - y_{\bar{t}}$$

$$A_{fb} = \frac{F - B}{F + B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

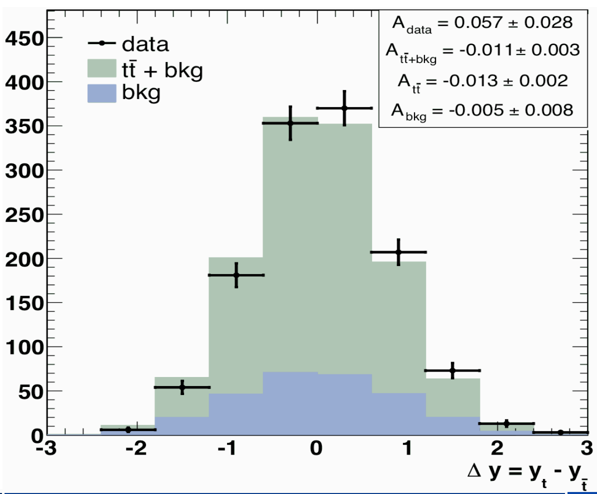
- SM predicts small asymmetry at NLO QCD: A_{fb}=0.066
- New physics could enhance observed A_{fb}

Powheg + EW Corrections:
JHEP **0709**, 126 (2007),
Phys. Rev. D **84**, 093003 (2011);
JHEP **1201**, 063 (2012)

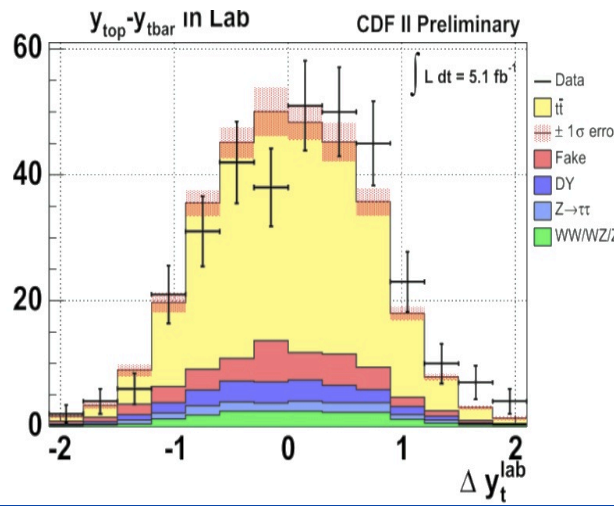
D0 Lepton + jets



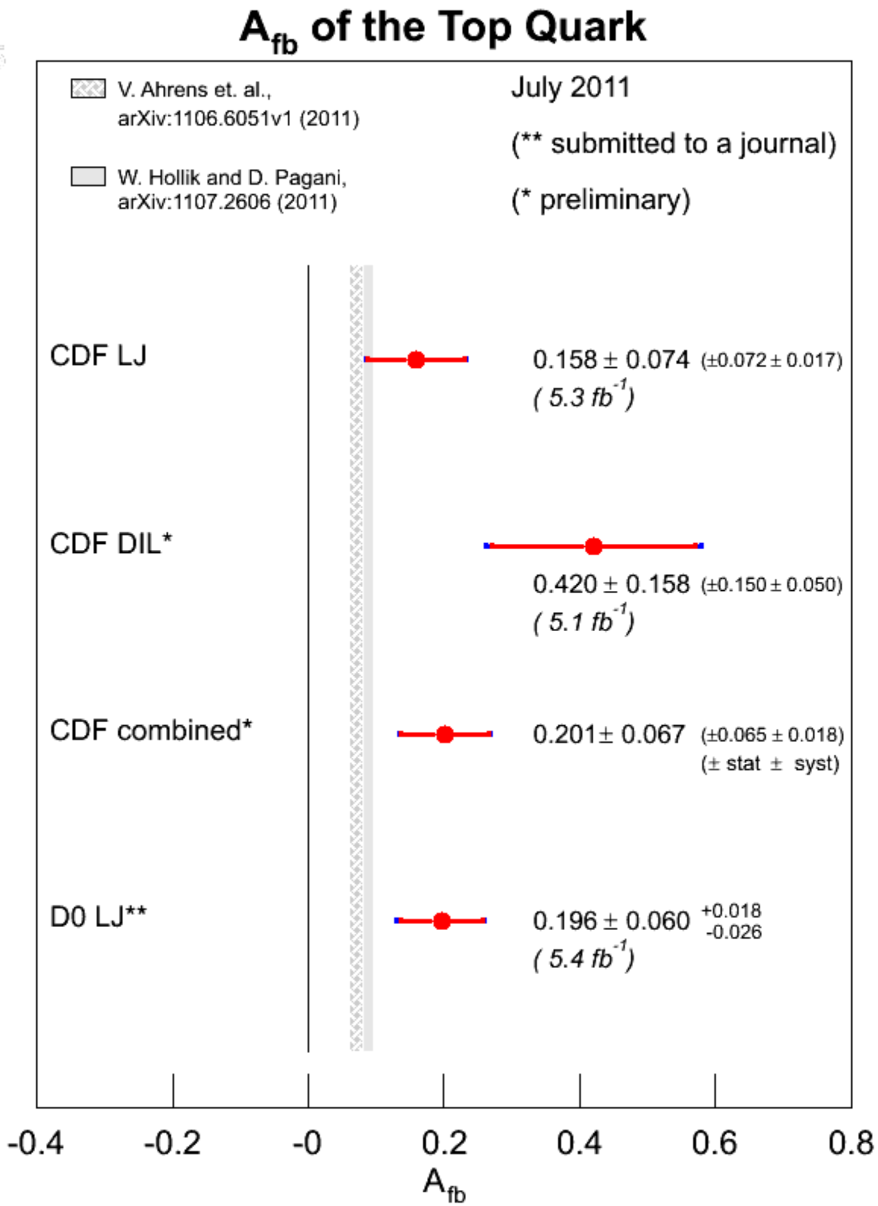
CDF Lepton + jets



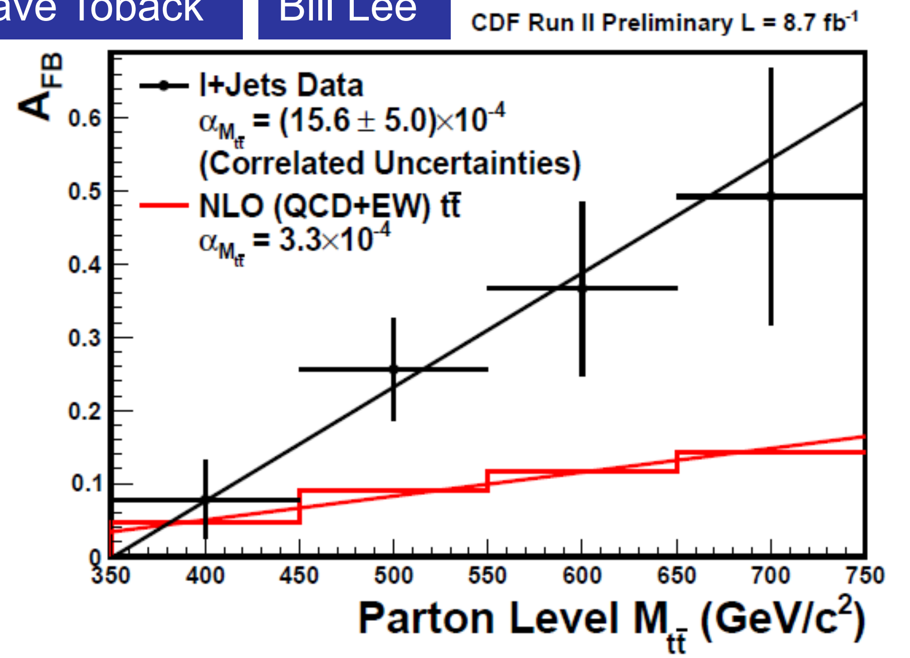
CDF Dilepton



Forward Backward Asymmetry



Dave Toback | Bill Lee



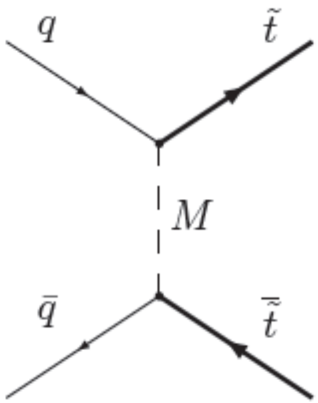
- A_{FB} vs mass of the ttbar system
- NLO A_{FB} dependence on $\mathbf{M_{ttbar}}$ is more shallow than observed data

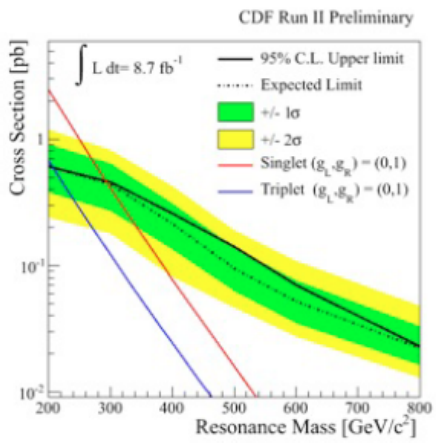
Slope	**A_{FB} vs. M_{tt}**
Data	$(15.6 \pm 5.0)\times10^{-4}$
SM	3.3×10^{-4}

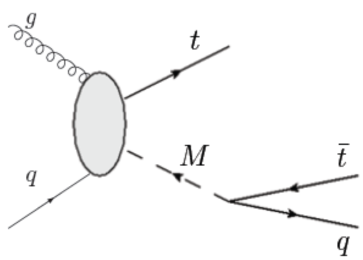
Forward Backward Asymmetry

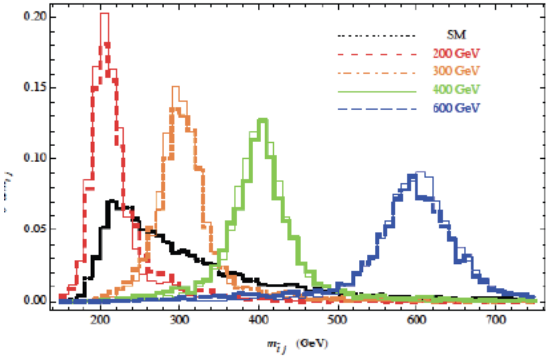
- Possible explanations: Ian-Woo Kim
  - t-channel exchange

Top-jet resonance signature



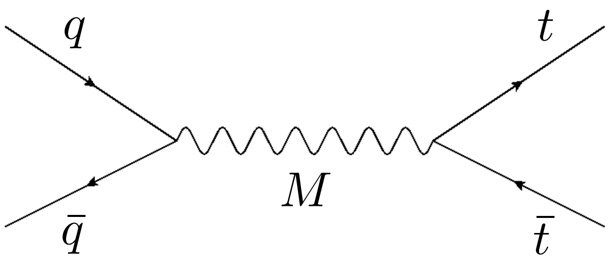






  - s-channel resonance

LHC results expected soon

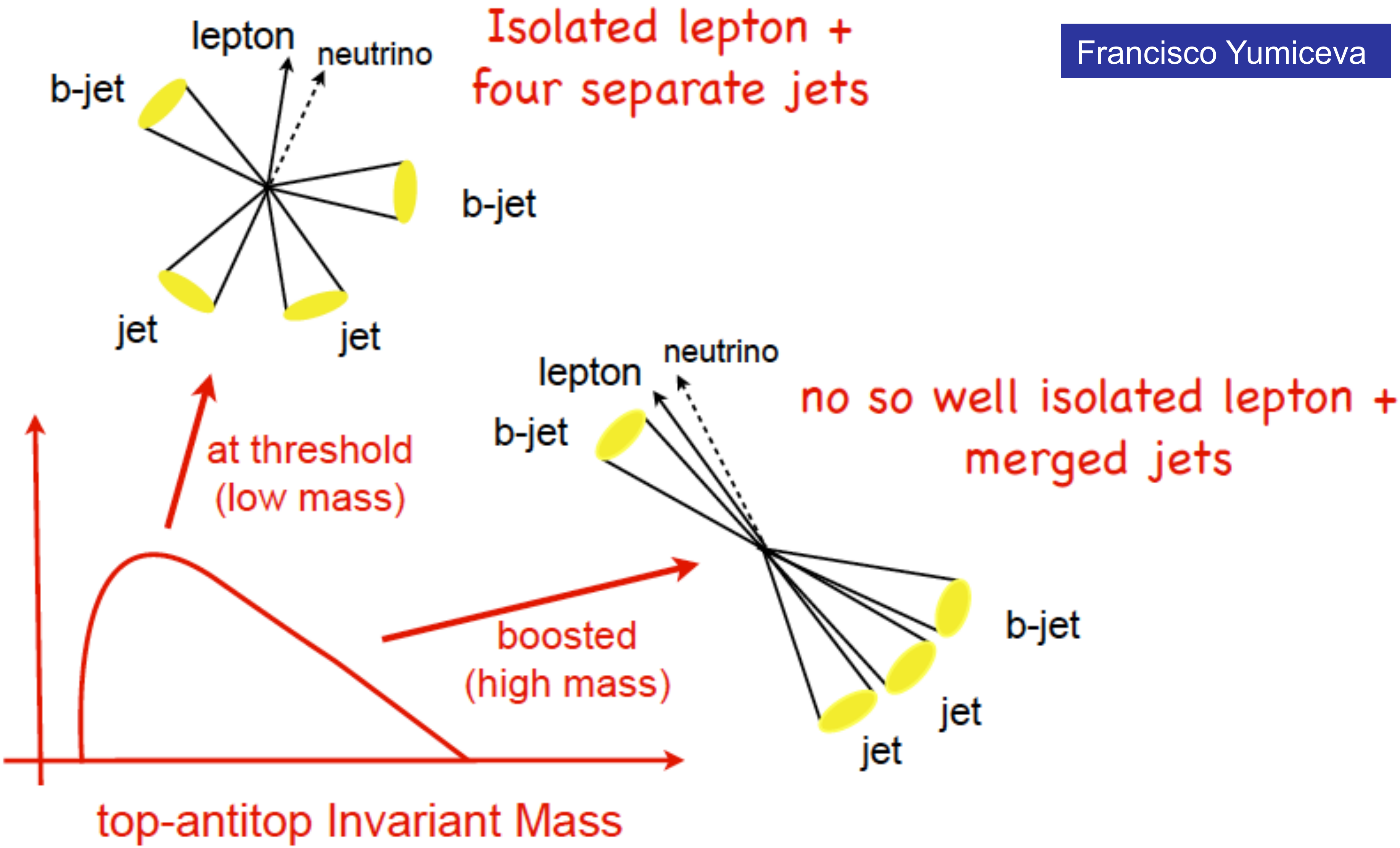


If at high mass (>2 TeV) and large coupling

  - tt cross-section measurements at Tevatron and LHC constrain both explanations
  - Atomic parity violation constraints important for t-channel explanation

Searches for Top Resonances

Francisco Yumiceva



Searches for Top Resonances

Emanuela Barberis

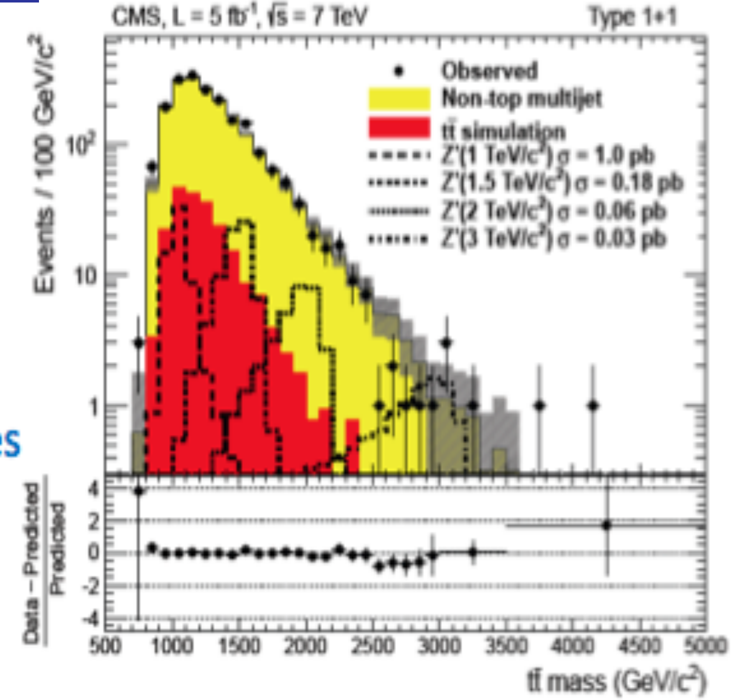
Z'→ttbar search (5fb^{-1}) :

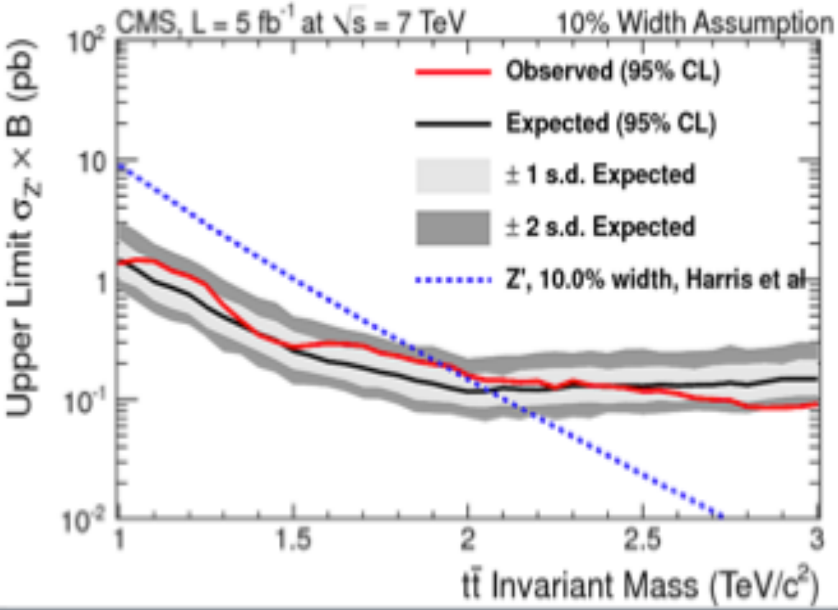
Analysis strategy: all-jets final state

✓high mass (> 1 TeV), highly boosted objects

✓uses novel jets substructure algorithms, (1+1) or (1+2) merged jet topologies

✓p_T, m_{jet}, and $\mu = m_{sub}/m_{jet}$ selected to be consistent with top and W merged jet topologies





95% C.L. limits (in the 1-2 TeV range) on Topcolor Z' (small/large width), and KK gluons. Constraints on enhancements of the SM ttbar cross-section for m_{tt} > 1 TeV

13

arXiv:1204.2488

Conclusions

- **Outstanding performance** of the LHC in first two years of Physics (*with rapid turn around from data taking to quality physics*)
- Doubled dataset size within weeks and months, 8 TeV results coming soon!
- New Physics was not just "around the corner"
- Good news:
  - Stringent/significantly improved limits on new Physics
  - Keep excluding parameter space or make a grand discovery!
- Higgs Search is finally coming to an end
  - Almost full Higgs mass range is excluded - The most likely region has been narrowed down to m_H=117-127 GeV
  - Some hints of a signal in the region m_H=125 GeV, not significant, yet!
  - 2012 will be the year of the Higgs: Either with a conclusive observation or with an exclusion
- Entered New territory at the Energy Frontier - *This is only the beginning*!
- LHC expects to deliver ~1000 x data over it's lifetime

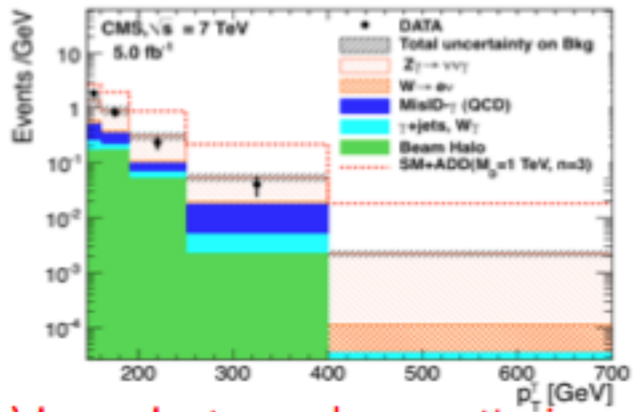
Dark Matter/Extra Dimensions

Emanuela Barberis

Search for Dark Matter or for Graviton production in association with a γ (5 fb^{-1}):

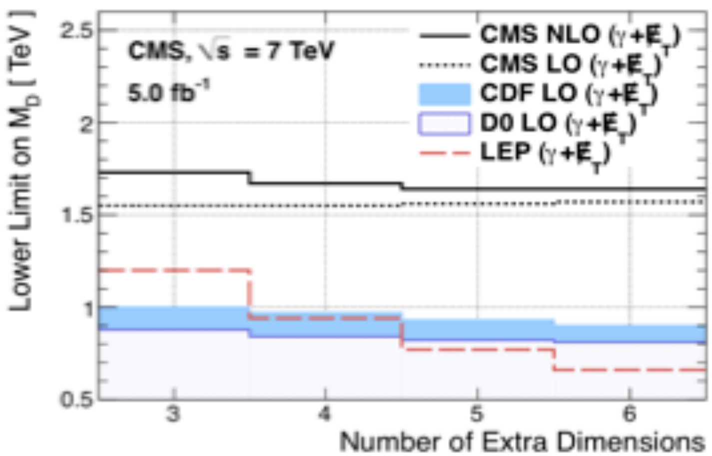
✓Dark Matter process: $qq \rightarrow \chi\chi\gamma \rightarrow \gamma + E_T^{miss}$

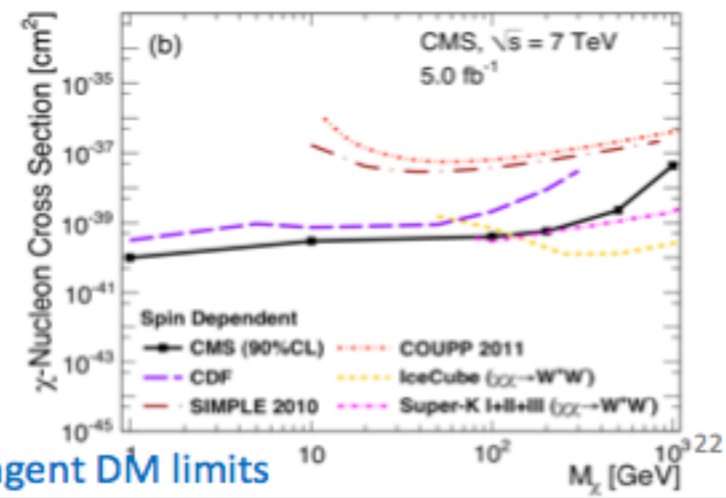
✓ADD process: $qq \rightarrow G\gamma \rightarrow \gamma + E_T^{miss}$



Analysis strategy: central, isolated high p_T photons ($p_{T\gamma}$>145 GeV) + large E_T^{miss} (>130 GeV)

95% C.L. limits on the modified Planck scale, M_D, in ADD models between 1.65-1.71 TeV (for n = 3-6), and 90% C.L. upper limits for spin-(in)dependent χ-nucleon scattering:





arXiv:1204.0821

most stringent DM limits

Orin Harris

Long-lived particle ATLAS Analyses

- Neutral massive particles
  - Hidden Valley: displaced vertex — arXiv:1203.1303v2
  - RPV LSP decay: displaced vertex — arXiv:1109.2242v2
- Charged massive particles
  - R-hadrons: dE/dx, β — ATLAS-CONF-2012-022, arXiv:1103.1984v1
  - Stable stau: β — arXiv:1106.4495v2
  - HIP: high-threshold TRT hits — arXiv:1102.0459v3
- Stopped R-hadron
  - Jets in empty/unpaired bunch crossings — arXiv:1201.5595v2
- Anomaly-Mediated SUSY-breaking
  - Truncated tracks: missing TRT hits — ATLAS-CONF-2012-034