Discovery reach of the LHC with the first data

(selected topics)

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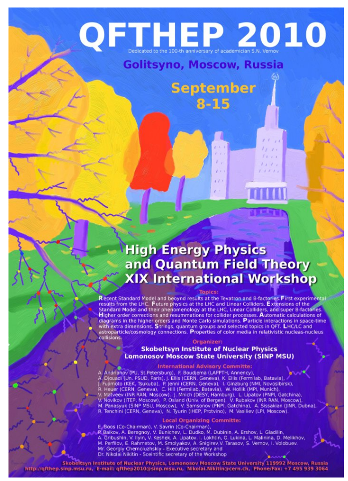
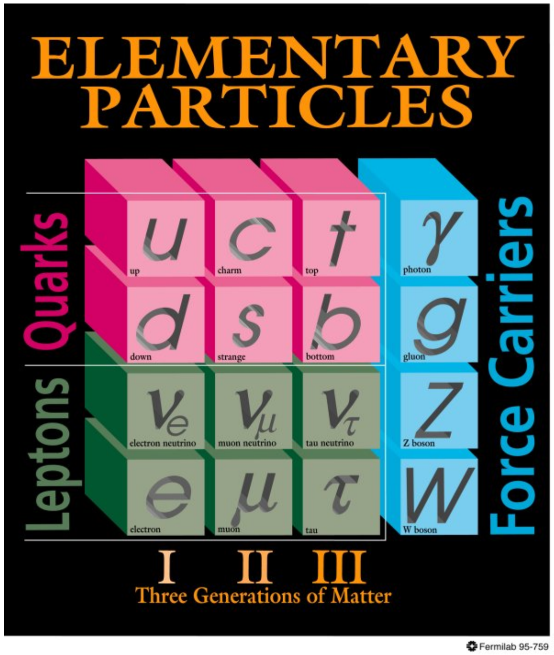


XIXth International Workshop QFTHEP 2010
Golitsyno, Moscow, Russia, September 2010

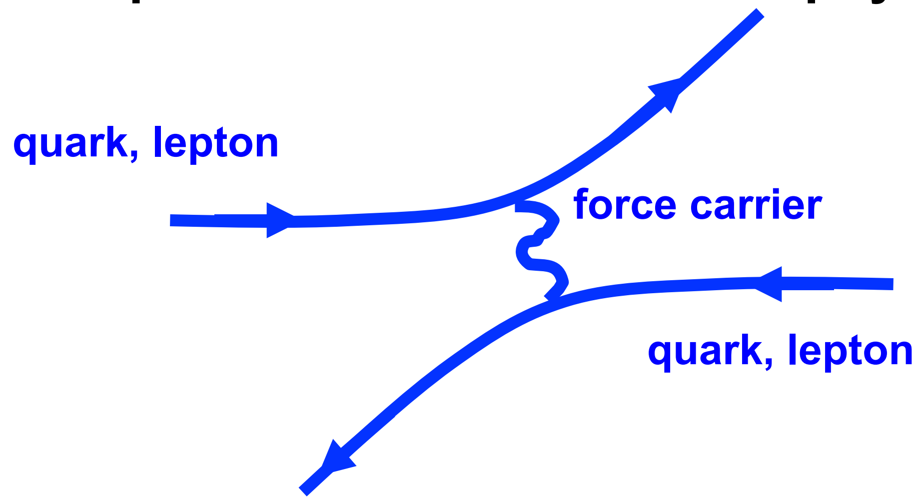
Outline

- **Exciting times for Particle Physics**
- **The LHC and prospects**
- **The CMS/ATLAS detectors**
- **Higgs searches**
  - **The SM Higgs with H→WW,ZZ,γγ and MSSM**
- **SUSY Searches**
  - **Search strategy**
  - **Background Studies**
- **Other Searches Beyond SM**
  - **New Physics with Dijets**
  - **Heavy W'**
  - **Other searches and prospects**
- **Outlook and Conclusions**

Standard Model of Particle Physics



- **The Standard Model gives an excellent description of the wealth of experimental data in collider physics**



Force	Carrier
Strong	Gluons (g)
Electro-Weak	Electro-weak bosons (γ,W,Z)
Gravitation	?

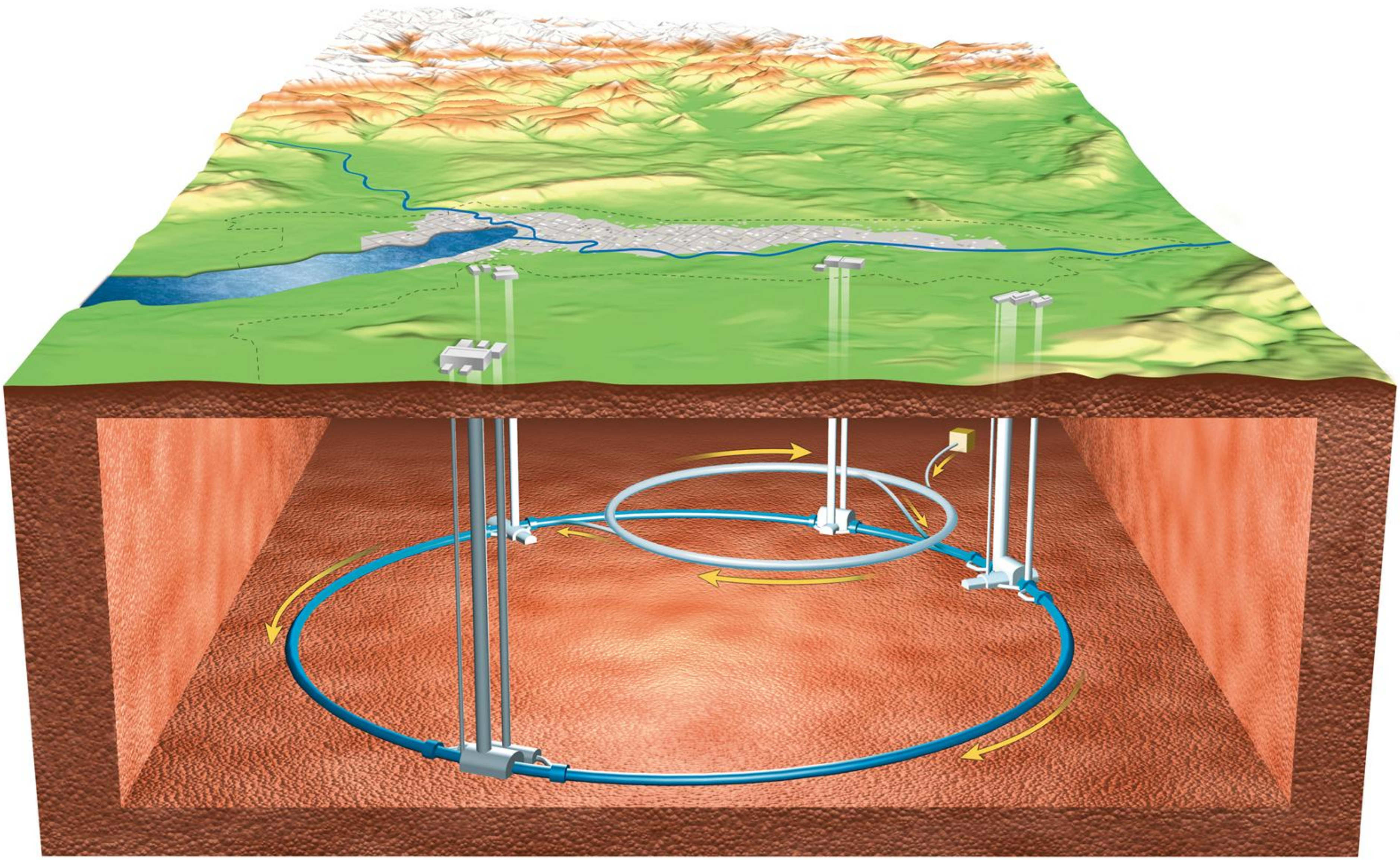
A Higgs boson is predicted and required to give mass to particles

Are We happy with the SM?

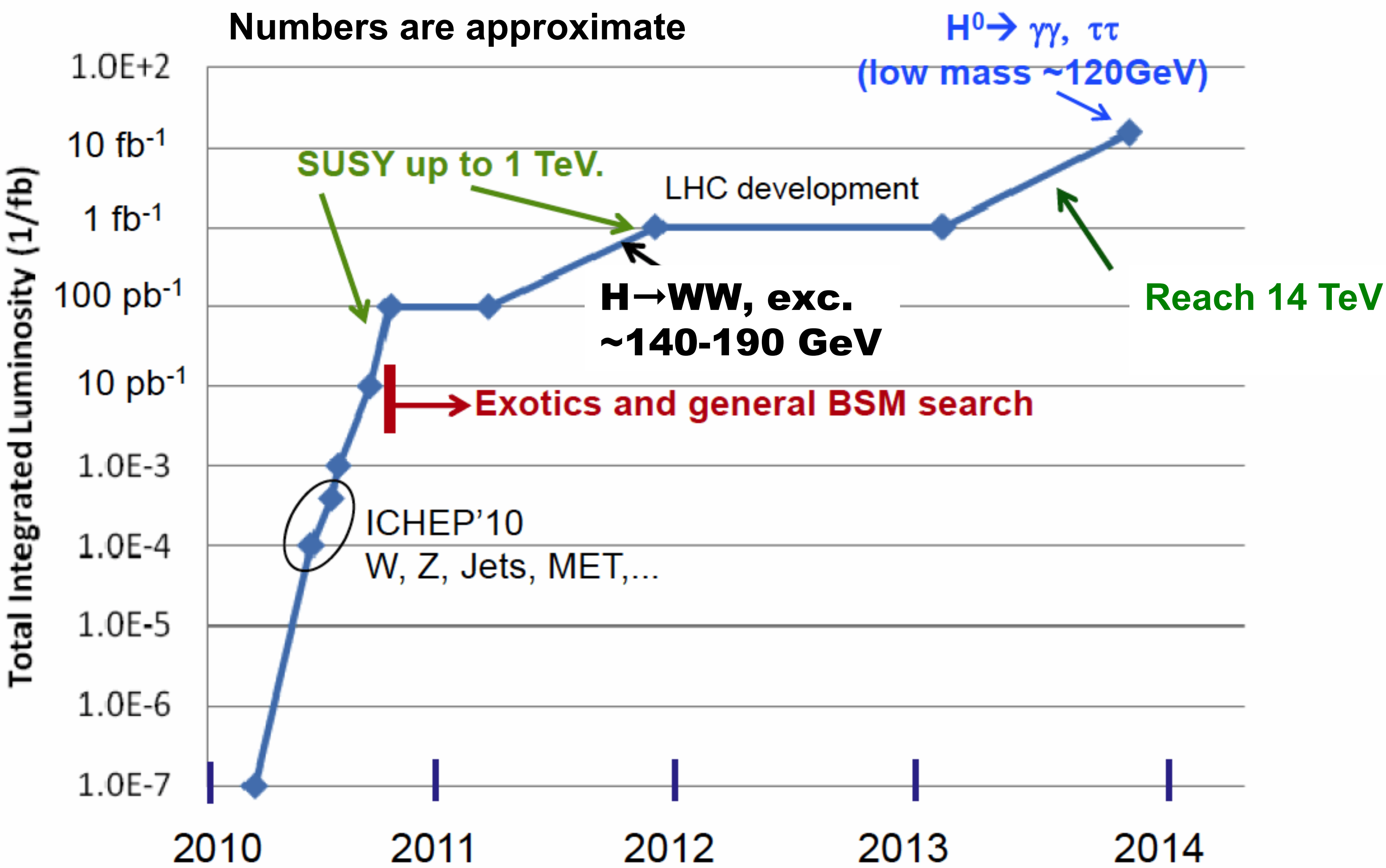
- The SM as it is does not solve a number of fundamental questions/problems
  - Quadratic divergences of the Higgs mass
    - Higgs mass grows with scale of new physics
  - Does not explain the origin of the neutrino mass
  - Does not explain dark matter in the universe
  - Does not explain dark energy in the universe
    - The universe expanding at an accelerated rate
  - How about gravity?
  - Unification of fundamental interactions
    - This is probably more of a philosophical issue
  - Why three generations?
  - Etc...

The LHC provides the energy frontier in collider physics giving a unique opportunity to address some of these fundamental questions

The Large Hadron Collider at CERN

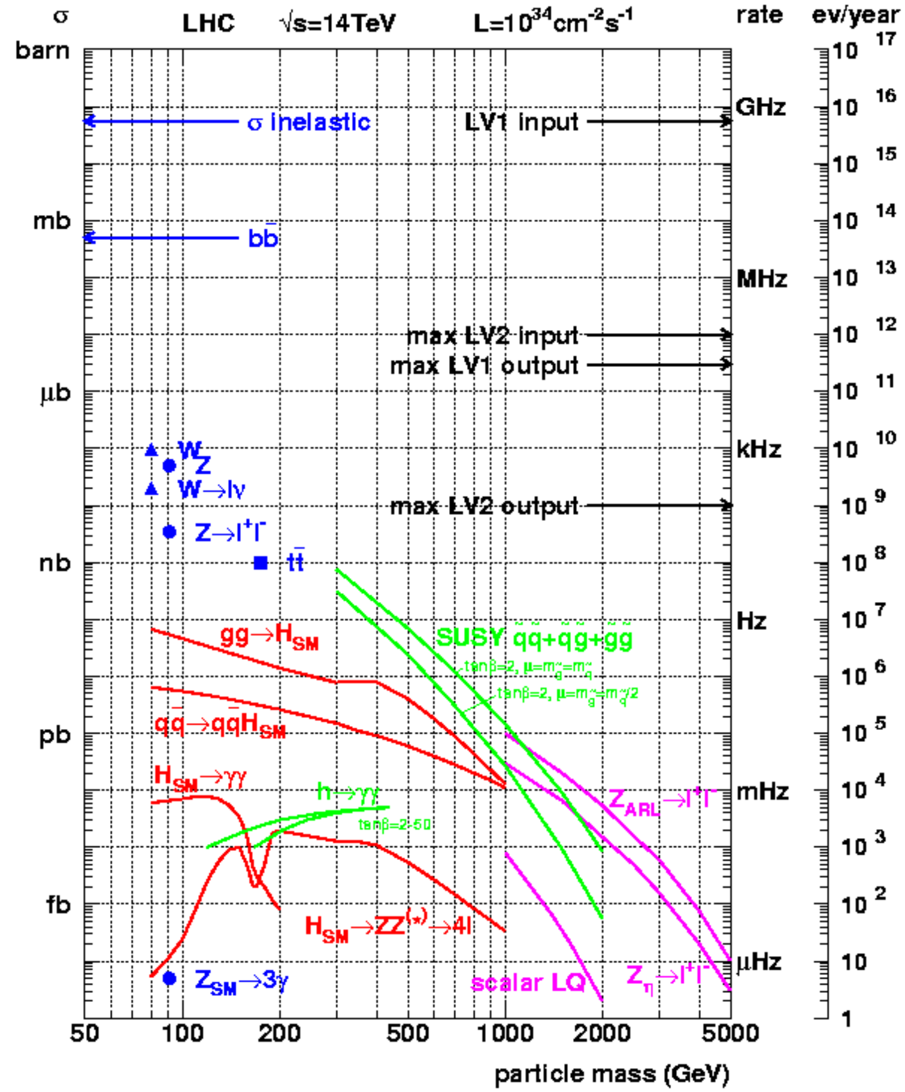


The LHC Schedule (next 3-4 years)

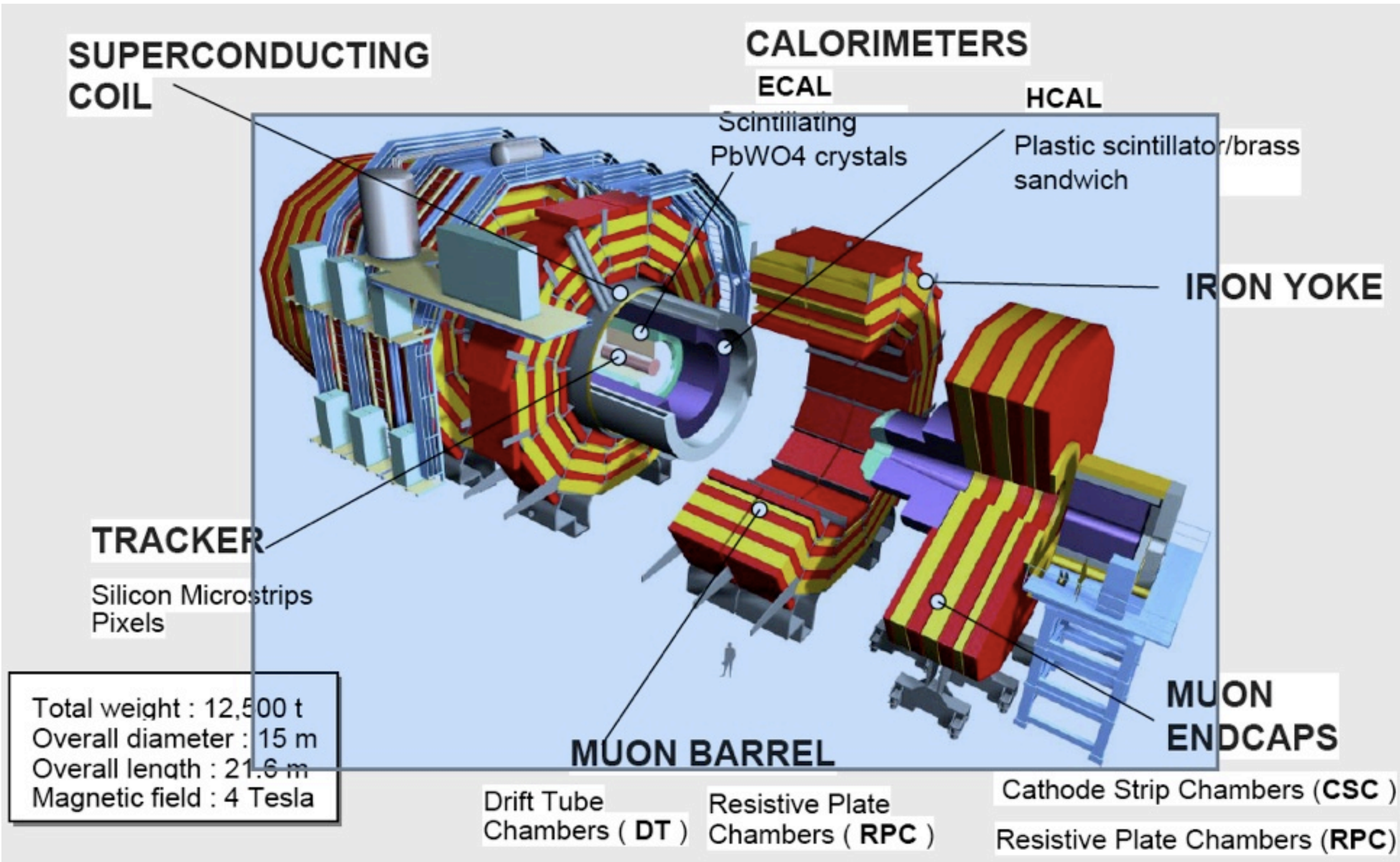


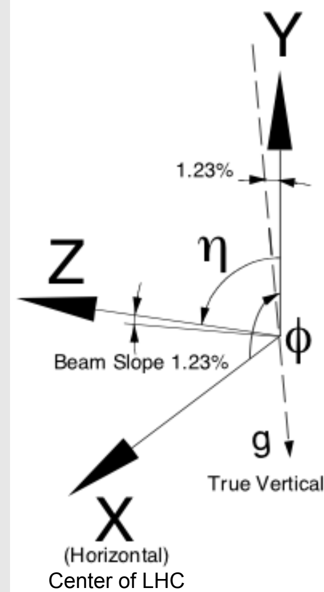
Cross-Sections at the LHC

- Search for Higgs and new physics hindered by huge background rates
  - Known SM particles produced much more copiously
- Need to rely on
  - Narrow resonances
  - Complex signatures
    - Leptons, jets, MET
- First, need to establish SM signatures
  - See Roberto's talk

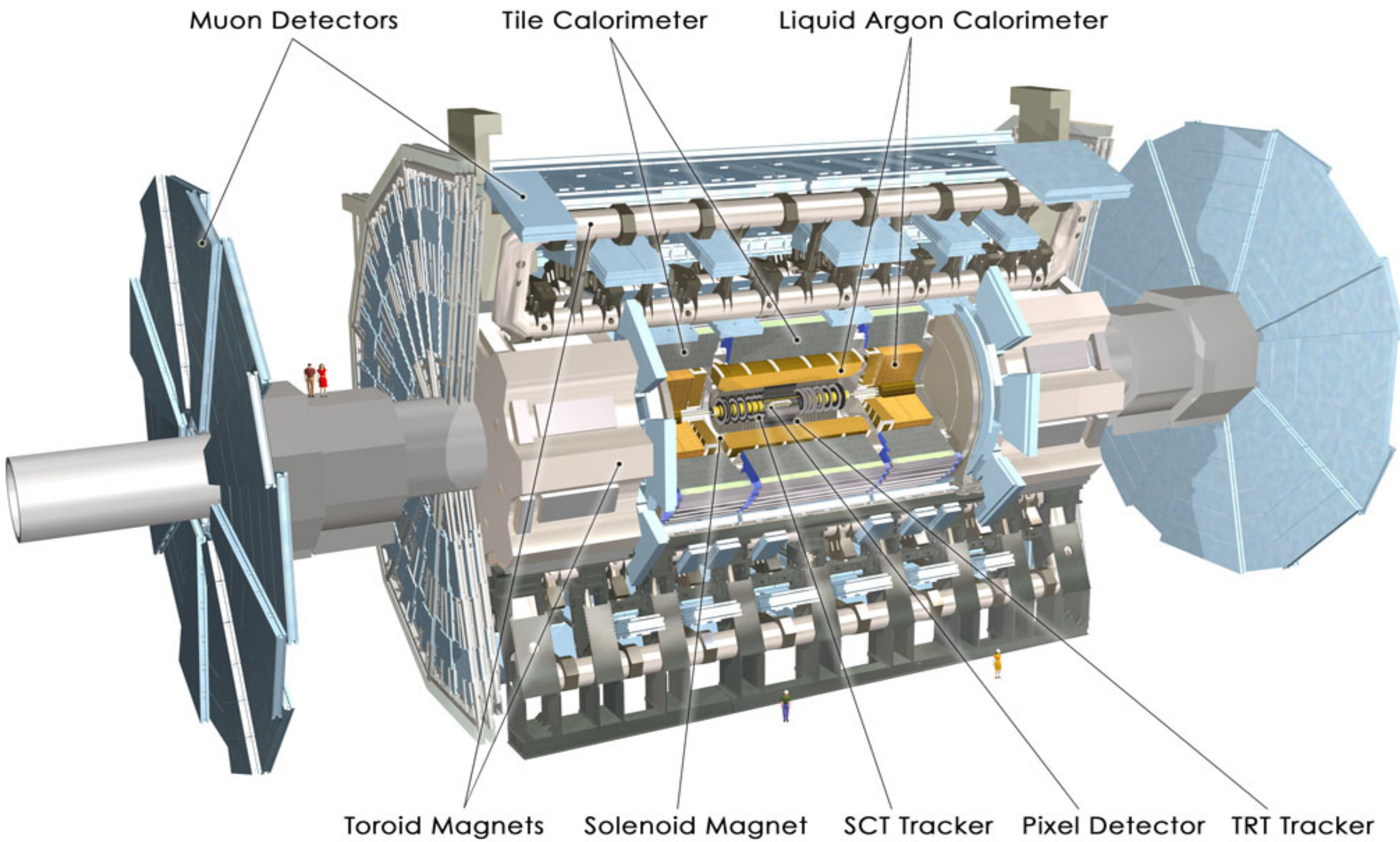


The CMS Detector



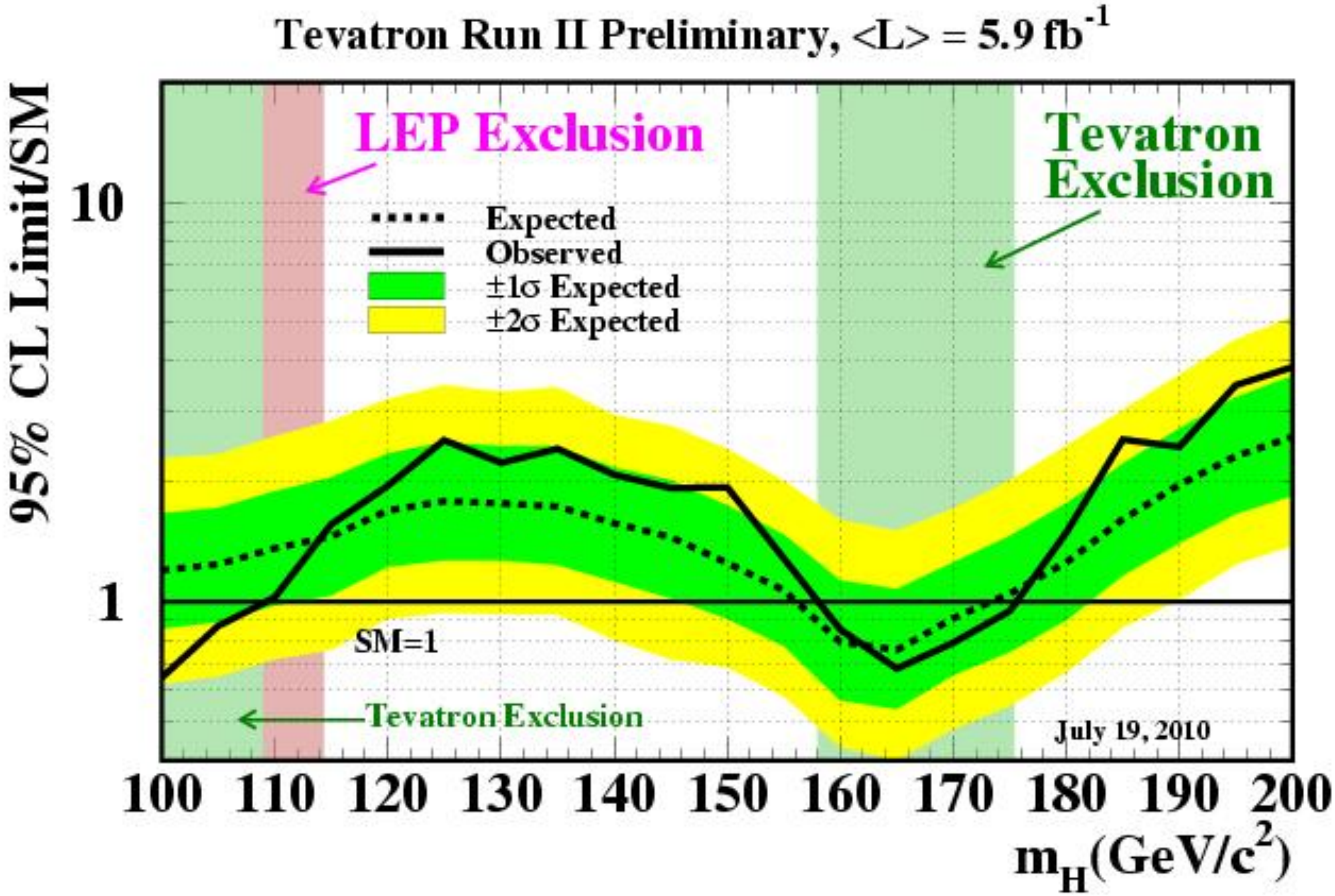


The ATLAS Detector



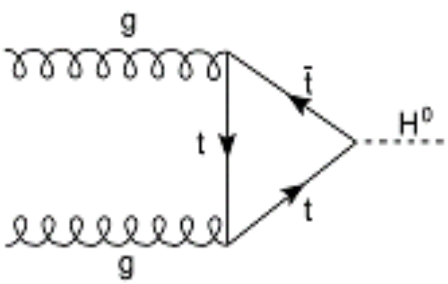
Higgs Searches

The Tevatron is making a lot of progress in the search for the Standard Model Higgs. Region around LEP limit remains a challenge

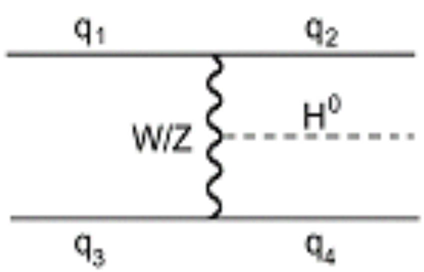


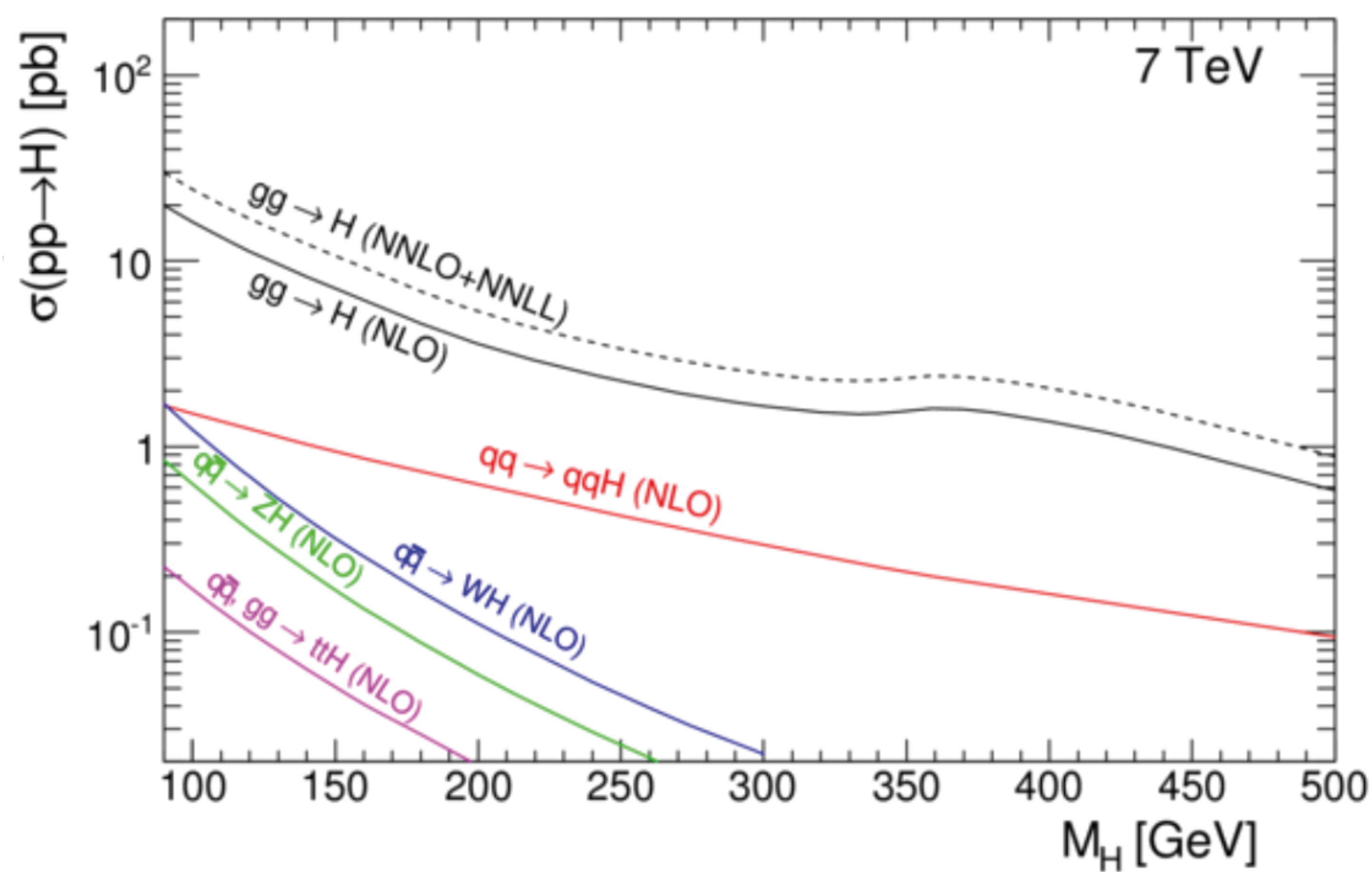
Higgs Production at LHC

Leading Process (gg fusion)



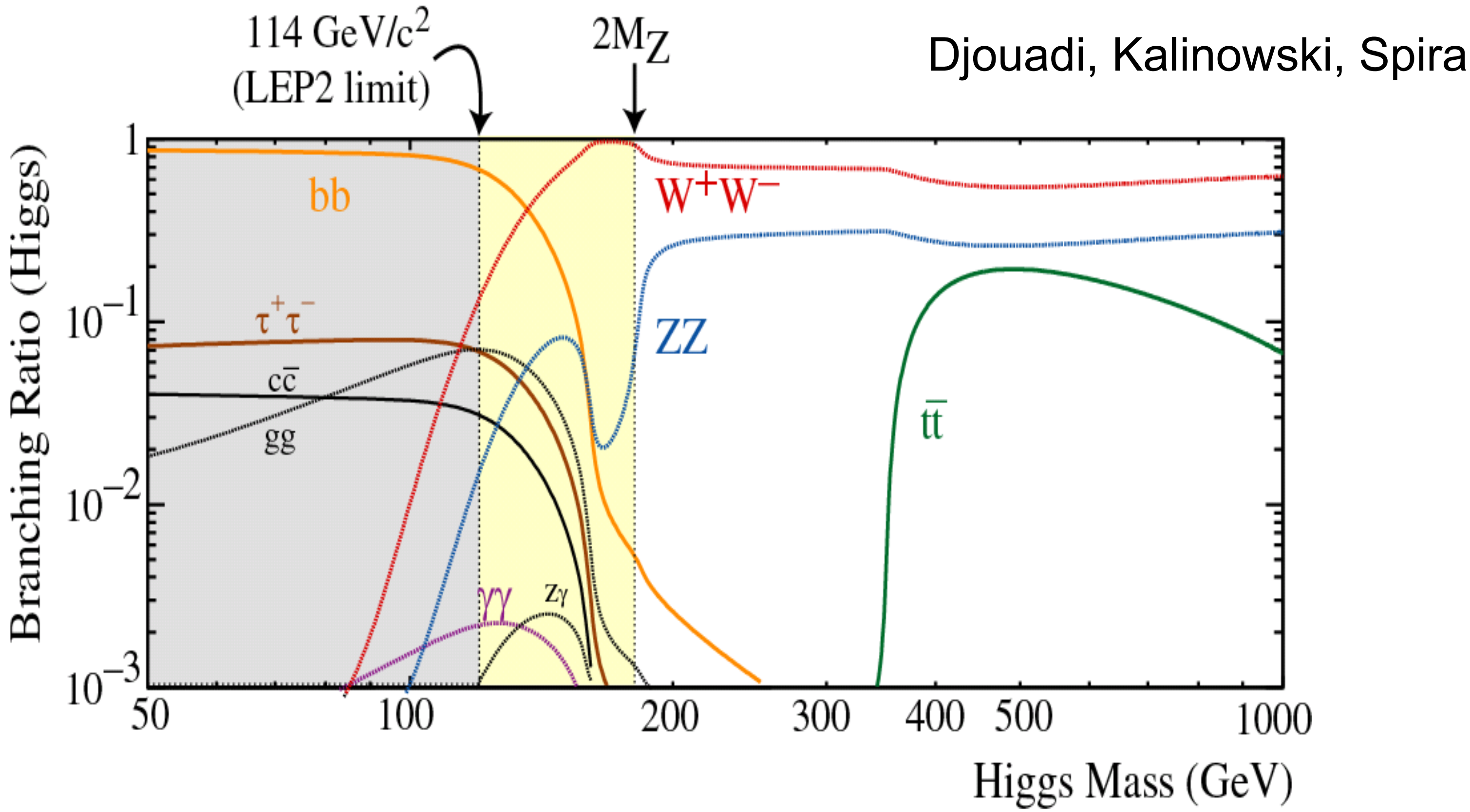
Sub-leading Process (VBF)





The Vector Boson Fusion (VBF) process plays and important role at the LHC

Main Decay Modes



Close to LEP limit:
H→γγ,ττ (most powerful)

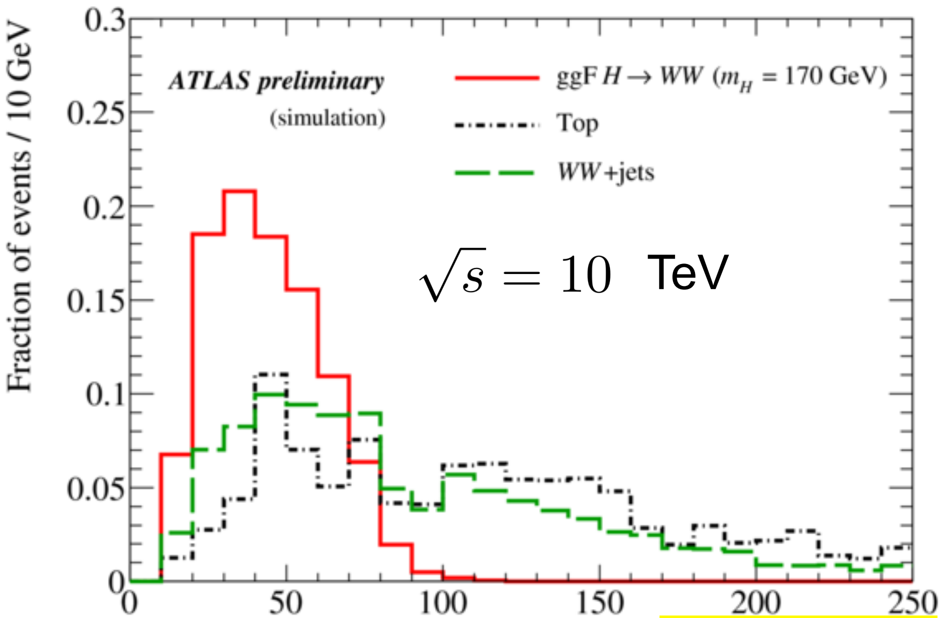
For M_H>140 GeV:
H→WW$^{(*)}$,ZZ$^{(*)}$

Significant potential with the first data

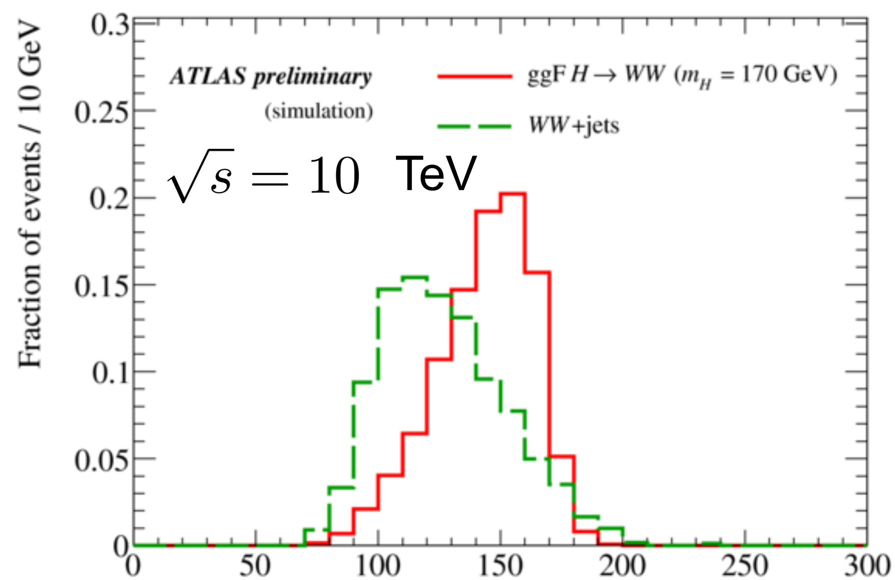
SM Higgs $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$

- Strong potential due to large signal yield, but no narrow resonance. Left basically with event counting experiment
  - **Role of lepton ID, QCD rejection, jet vetoing/tagging, MET reconstruction for different jet multiplicities, top background rejections are crucial for this analysis**

$H \rightarrow WW$+0j



M_{ll} (GeV)

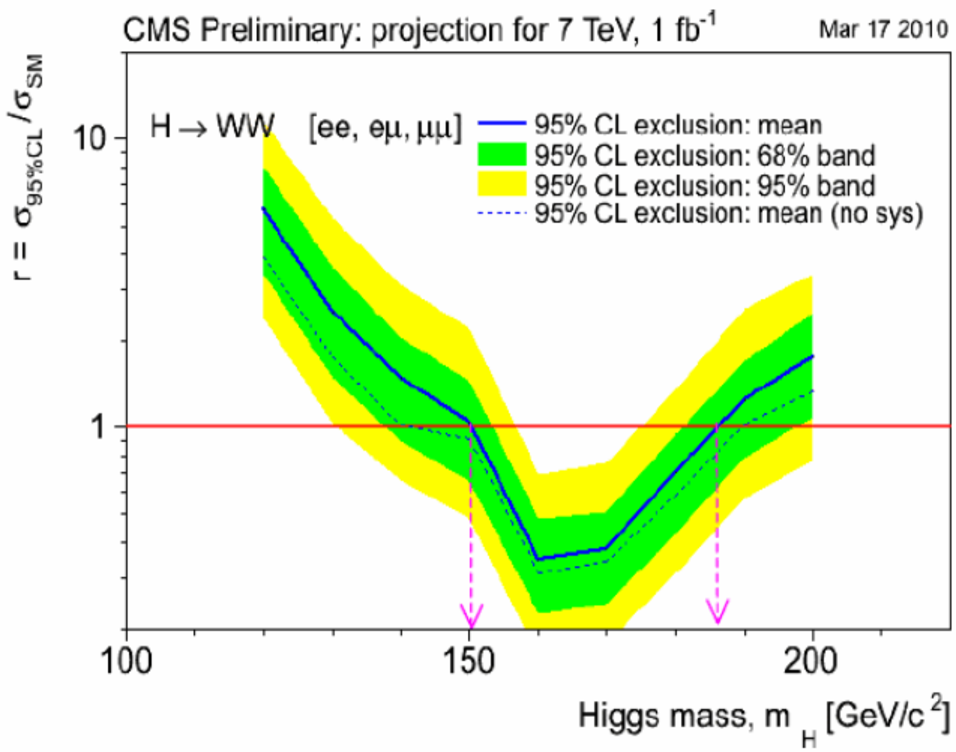


Transverse Mass (GeV)

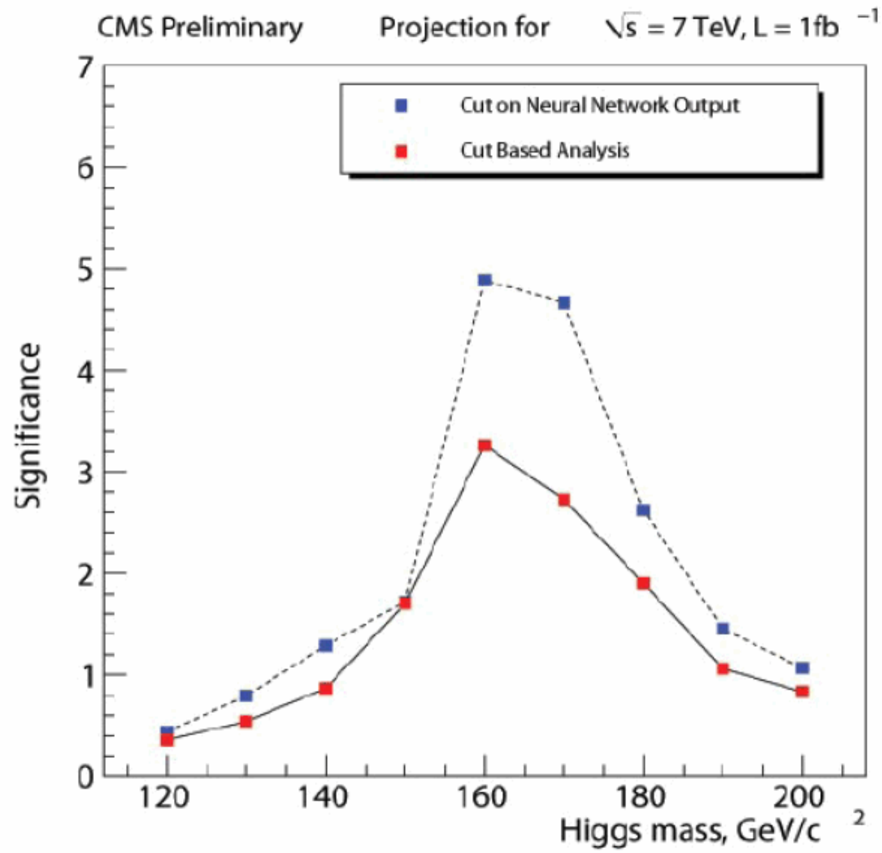
ATLAS classifies events according to jet multiplicity: H+0j, H+1j, H+2j

SM Higgs $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$ (CMS) (projection)

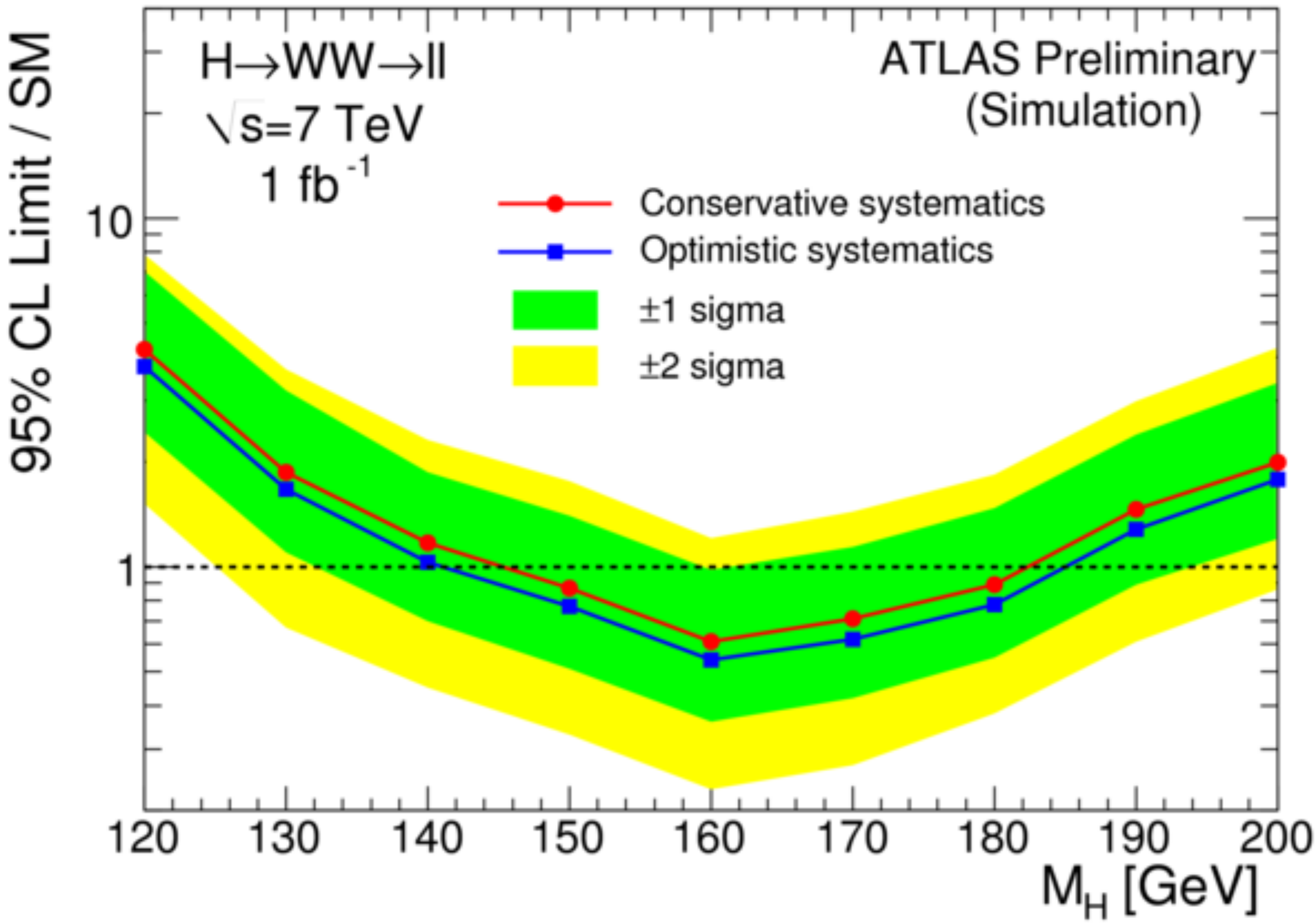
Expected exclusion range: 150-185 GeV



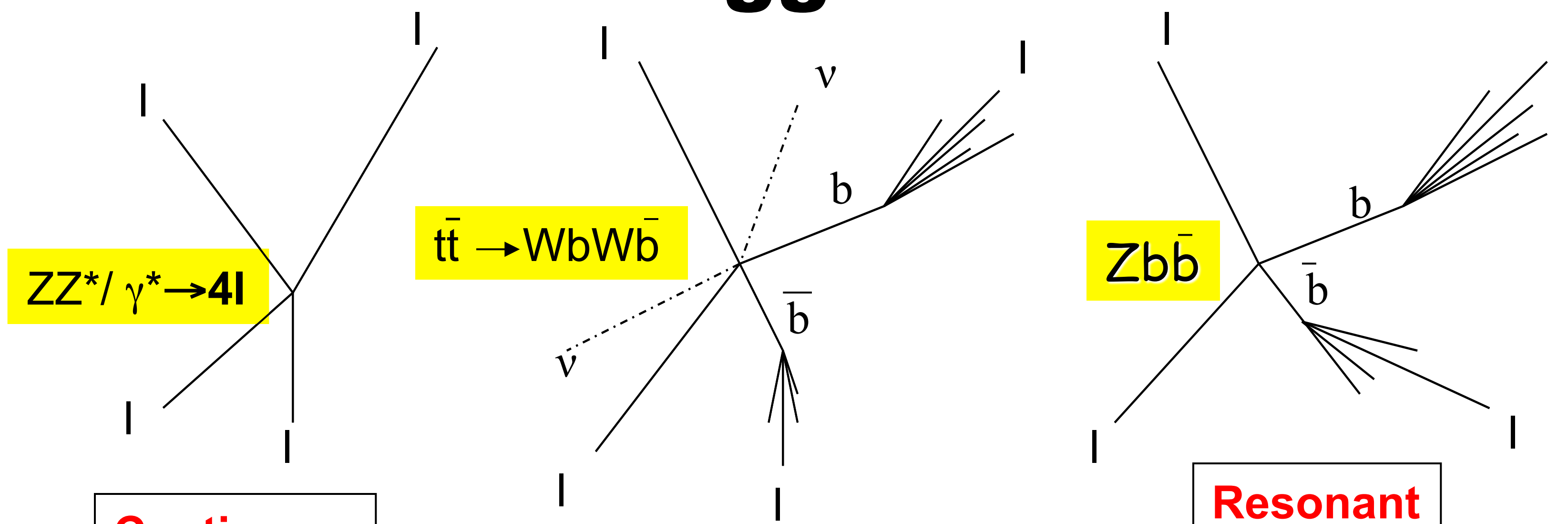
Discovery sensitivity ~160 GeV



SM Higgs $H \to WW^{(*)} \to 2l2\nu$ (ATLAS) (projection)



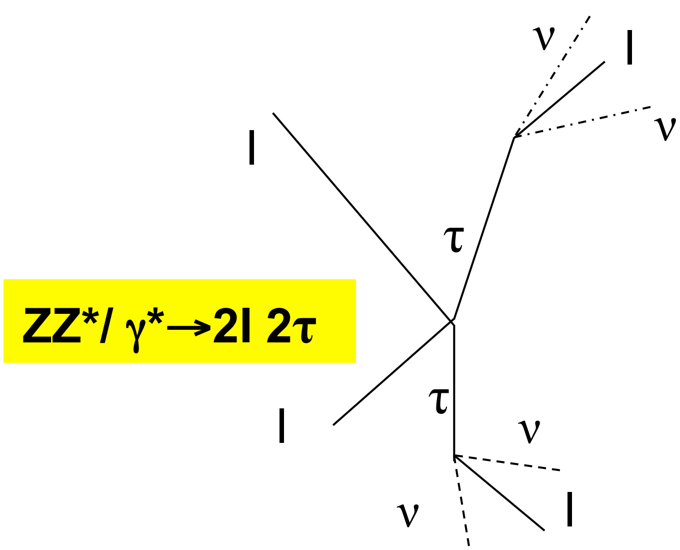
SM Higgs→ZZ(*)→4l



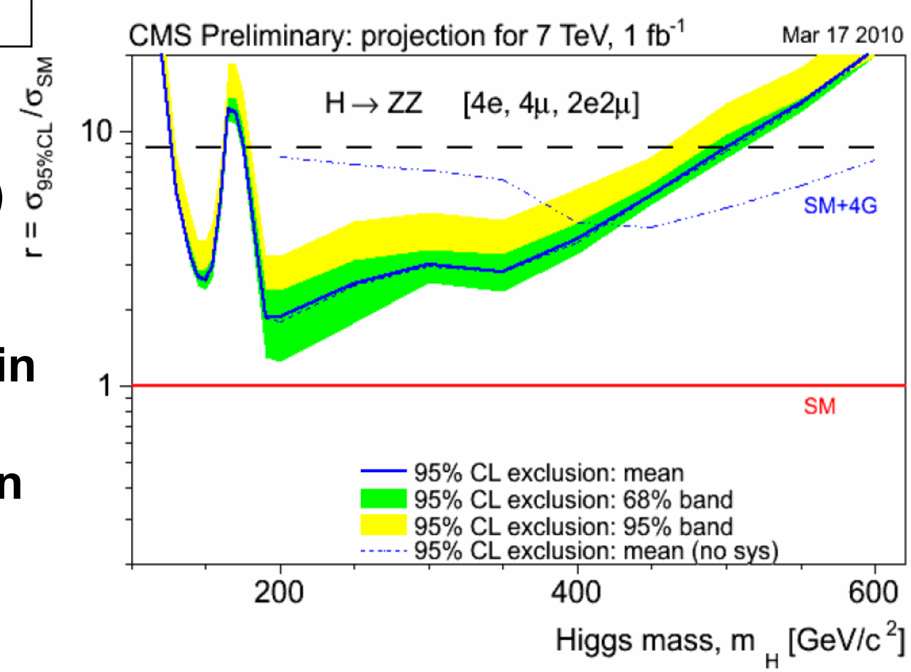
Continuum Irreducible

Non-Resonant reducible

Resonant reducible

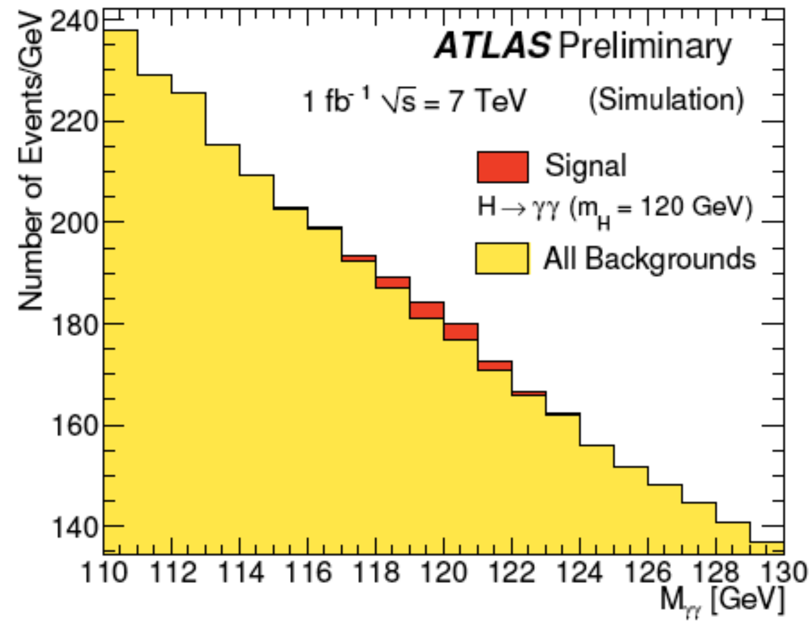


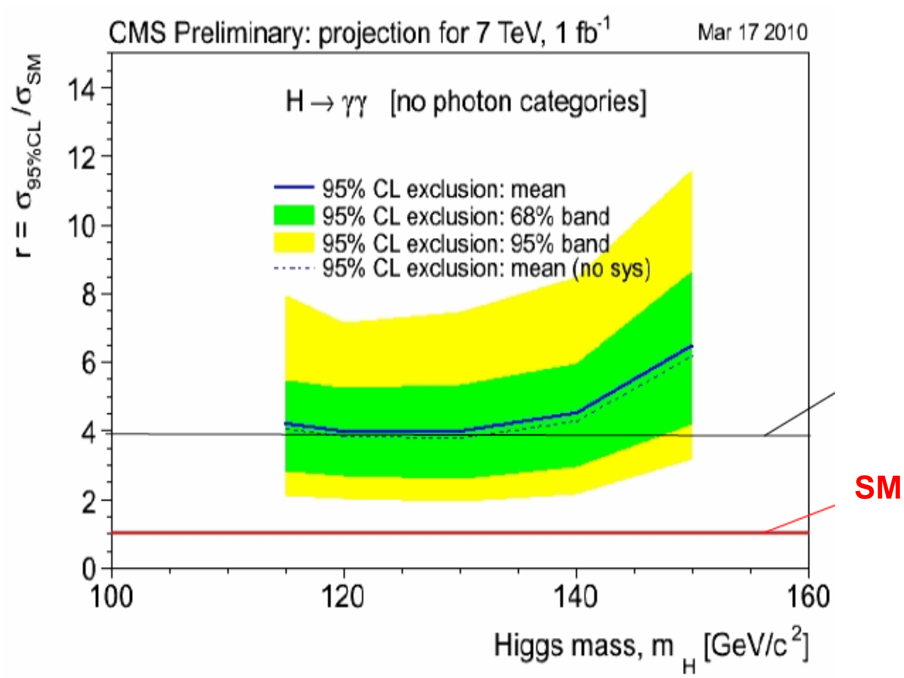
H->ZZ-> (4l,llvv,llbb) is the key channel for the search in the high-mass region above ~200 GeV

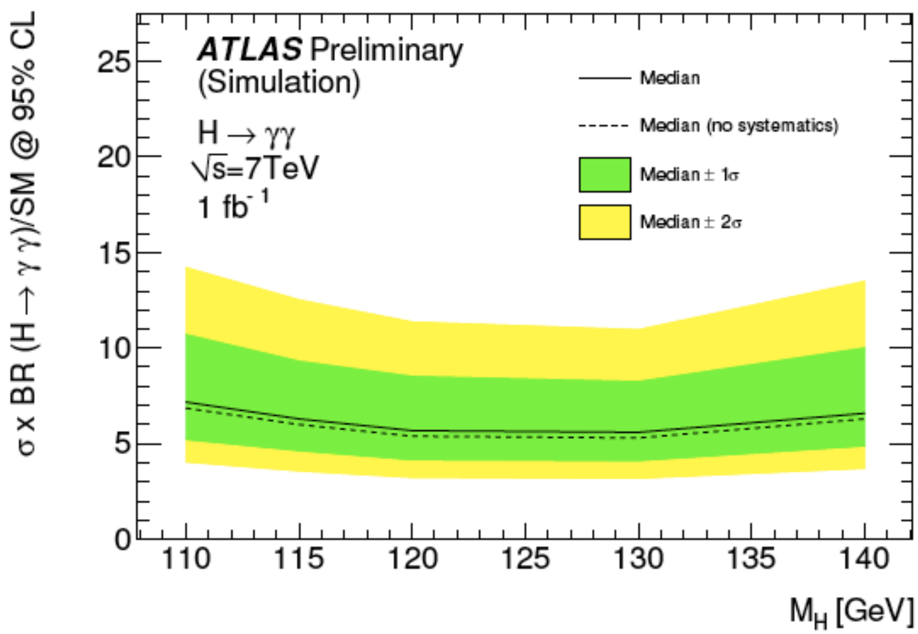


SM Higgs→γγ

Expected upper limit of ~4-5xSM between 110-140 GeV for 7 TeV and 1 fb^{-1}. Sentitive to fermiophobic Higgs, though.

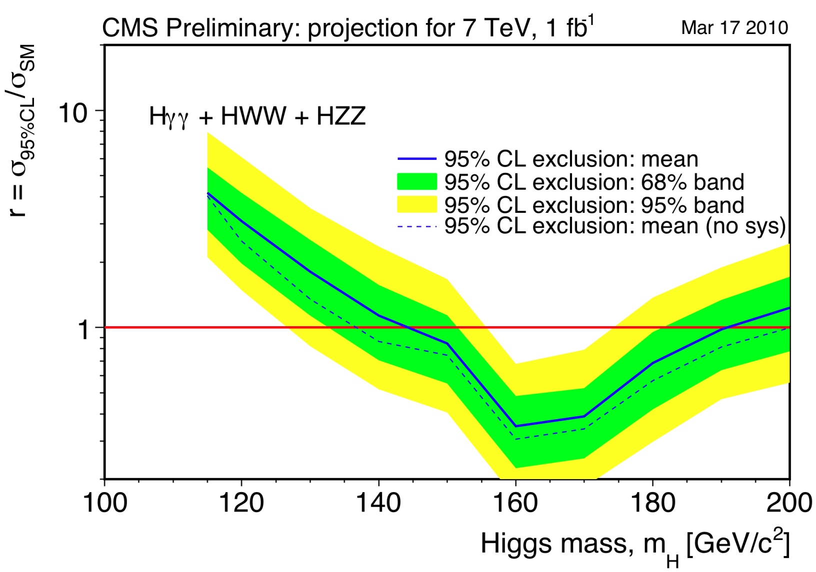


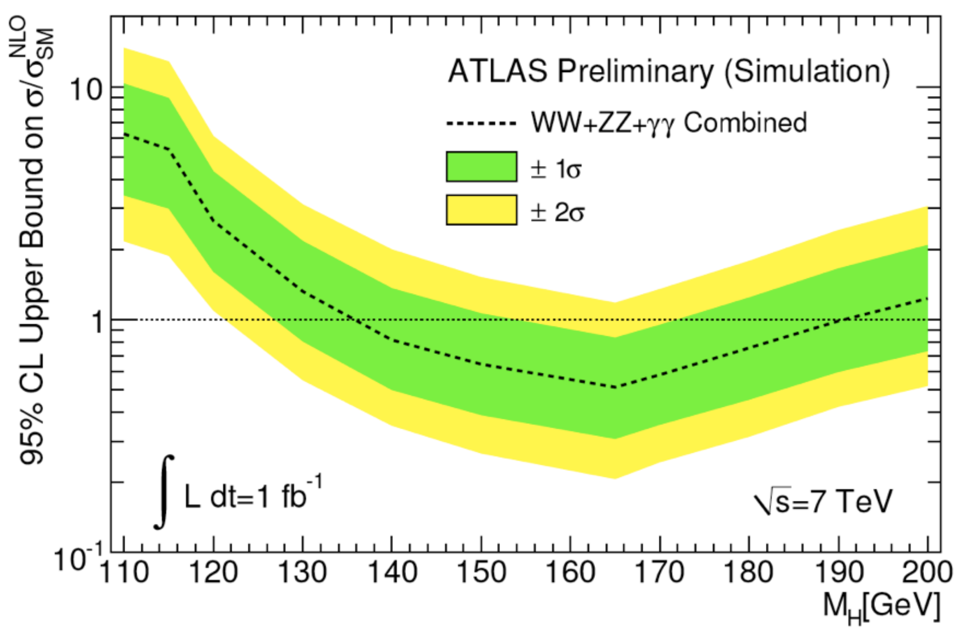




Standard Model Combined Limit

- Current feasibility studies include H→WW, H→γγ, H→ZZ
- Dominant contribution is H→WW
- Complete set of realistic systematics included
- Should be able to exclude at 95% C.L. the Higgs within ~140-190 GeV with 1 fb^{-1} of data (one experiment)
- Improvement expected by the ATLAS/CMS combination

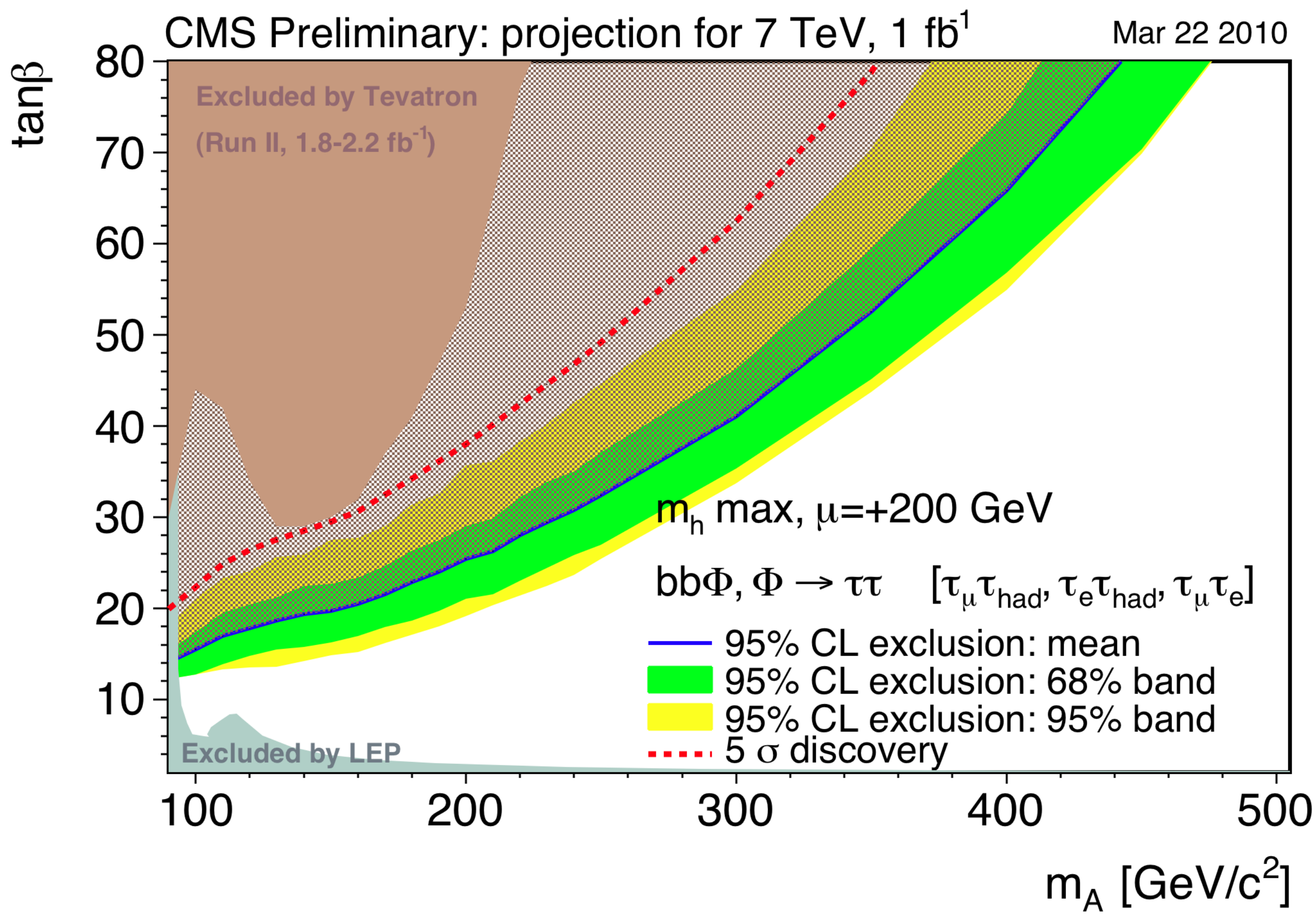




MSSM Higgs in pp→bbΦ; Φ→ττ (CMS)

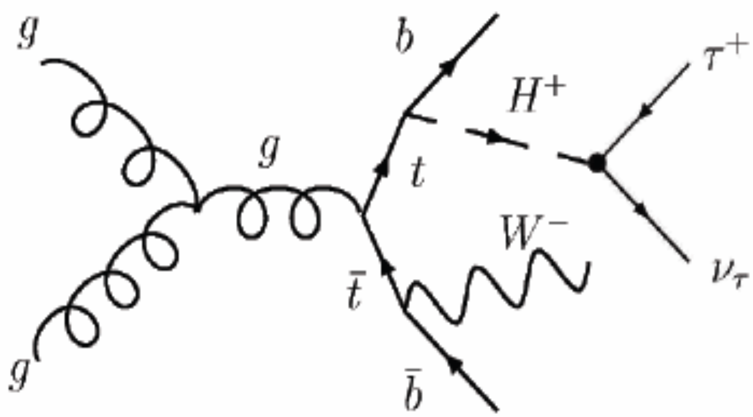
H→μμ channel will also be studied

Isolated pairs of taus (leptonic and hadronic decays)
MET, at least one b-jet and veto on extra jets
Using the collinear approximation to reconstruct di-τ invariant mass
Backgrounds from tt and Z+jets obtained with data-driven methods
At low mA: exclusion limit down to tanβ~15 and discovery down to tanβ~20



Searches for Charged Higgs ($M_{H\pm}$<M_t)

Signal Final State



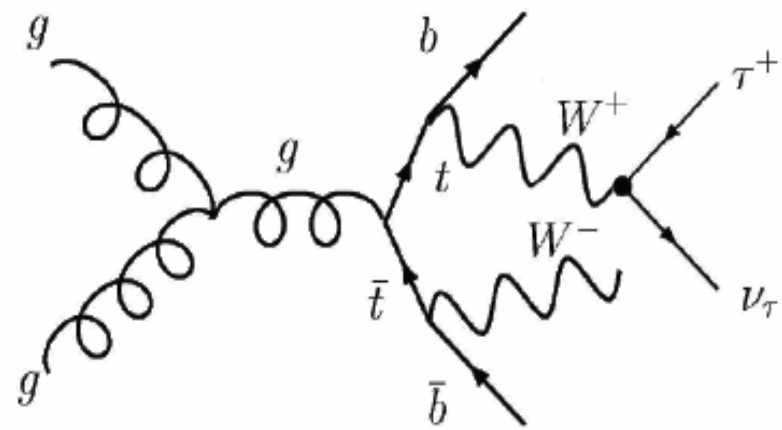
$$H^+ \to \tau_H \nu;\ W \to qq$$

$$H^+ \to \tau_L \nu;\ W \to qq$$

$$H^+ \to \tau_L \nu; W \to \ l\nu$$

$$H^+ \to \tau_H \nu;\ W \to l\nu$$

Dominant Background



$$W \to \tau_H \nu;\ W \to qq$$

$$W \to \tau_L \nu;\ W \to qq$$

$$W \to \tau_L \nu; W \to \ l\nu$$

$$W \to \tau_H \nu;\ W \to l\nu$$

MSSM $H^{+} \rightarrow \tau\nu$ in Di-Lepton ttbar (ATLAS)

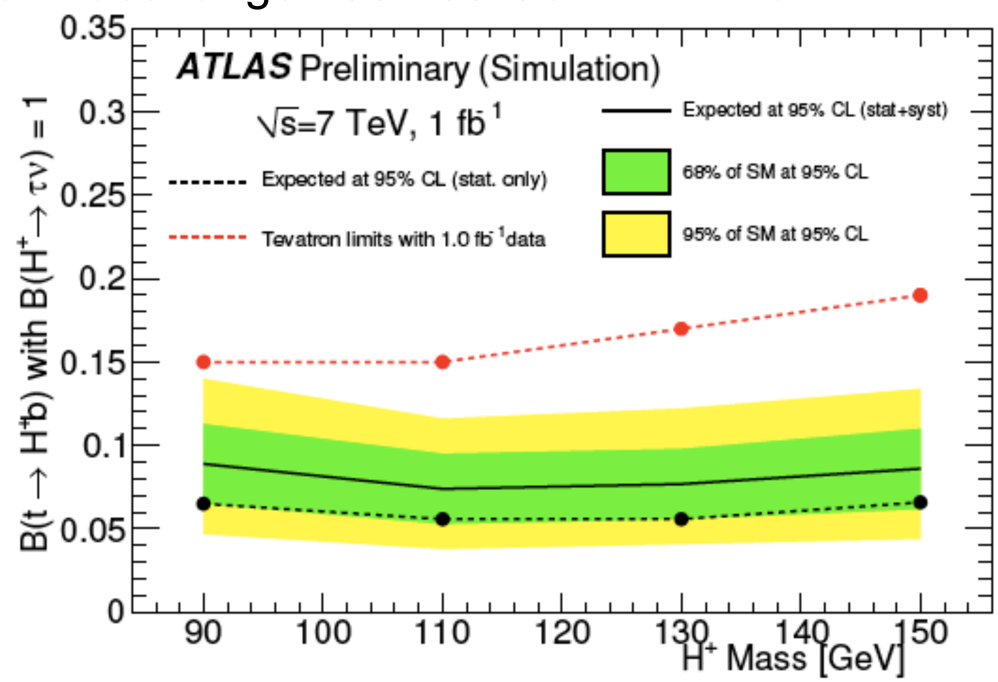
H→cs channel will also be studied

- Di-Lepton+MET+2jets
- Event Selection:

i. Two oppositely charged leptons
ii. Two jets with the highest likelihood of being b-jets are assumed to be daughters of the top and anti-top quarks
iii. Missing Transverse Energy
iv. Transverse mass of charge Higgs candidate
v. Lepton helicity angle

- Main background is: ttbar (~90%)
- Expected exclusion $Br(t \rightarrow H^{+}b)>10\%$ for mass range ~90-150 GeV with 1 fb^{-1}

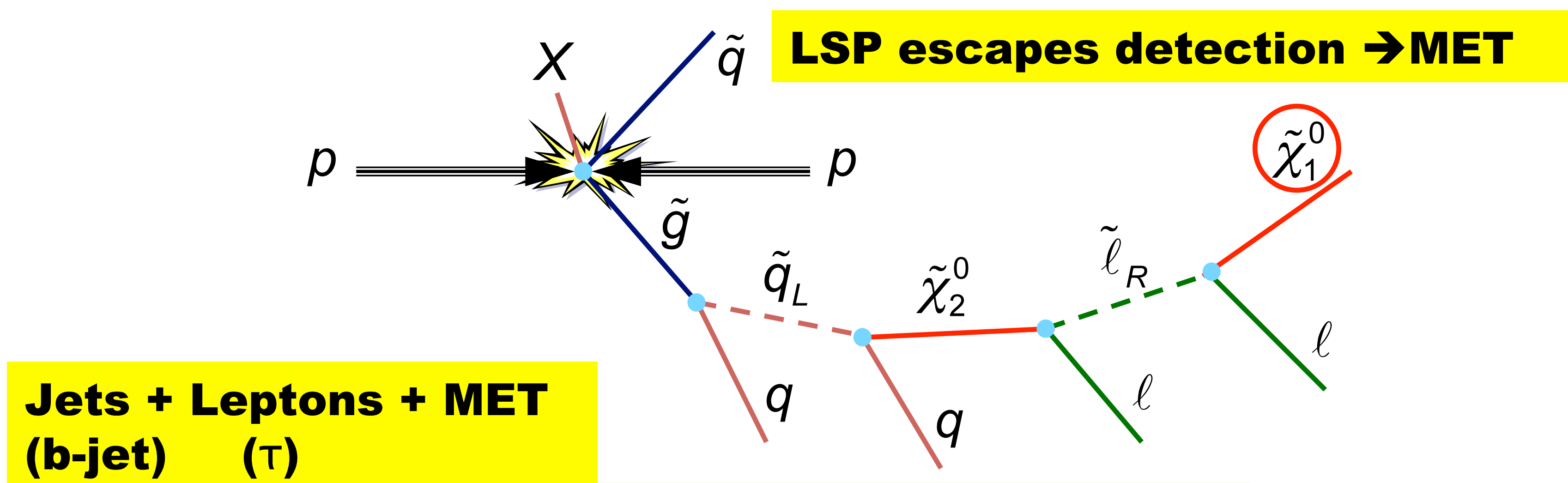
Process	Number of events after no cut	Number of events after all cuts
Signal $m_{H^+} = 90$ GeV	2.5×10^3	282
Signal $m_{H^+} = 110$ GeV	2.5×10^3	330
Signal $m_{H^+} = 130$ GeV	2.5×10^3	326
Signal $m_{H^+} = 150$ GeV	2.5×10^3	284
SM $t\bar{t}$ not hadronic	87.3×10^3	1194
Single top Wt-channel	5.7×10^3	55
Single top t-channel	20.4×10^3	43
Single top s-channel	0.9×10^3	3
$Z \rightarrow ll$ + jets	3.1×10^6	4
$W \rightarrow l\nu$ + jets	3.2×10^7	42
Wbb + jets	8.7×10^3	12
Zbb + jets	2.8×10^4	11



SUSY Searches

Characteristic SUSY "Cascades" at the LHC

- **Long decay chains and large mass differences between SUSY states**
  - **Many high P_T objects observed (leptons, jets, b-jets)**
- **If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced → requires energy 2 × SUSY mass**
  - **Since no exotic strong or EM bound states have been observed, the LSP should be neutral and colourless. LSP, like heavy neutrino**
  - **Large MET signature (c.f. W→lν)**
- **Closest equivalent SM signature t-tbar decay (t→Wb)**



"Typical" SUSY decay chain at the LHC

Experimental Strategy

Inclusive Searches

Search for deviations from the Standard Model

Fully hadronic channel
Lepton veto

1 lepton + Jets

2 lepton + Jets
Same Sign + Opposite sign

3 lepton
Jet veto and jets

Etc…

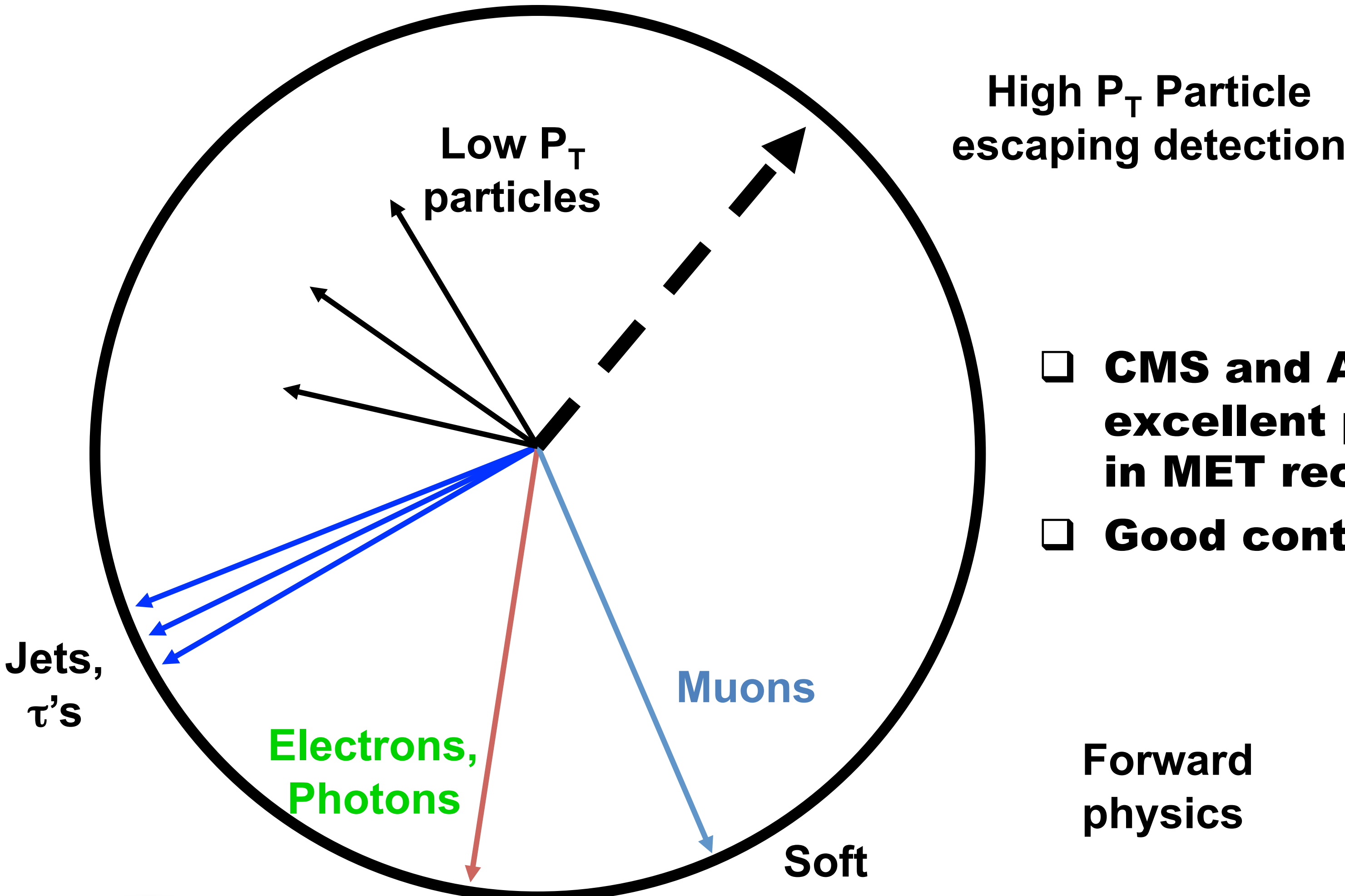
Assume $1fb^{-1}$ of data and 7 TeV

Great progress in defining data-driven methods to extract SM backgrounds in interesting corners of the phase-space

Exclusive Search

Understand properties like mass
Limited in pp-collisions

First steps: background studies



- CMS and ATLAS show excellent performance in MET reconstruction
- Good control of tails

Jet resolution

Lepton resolution

Soft depositions

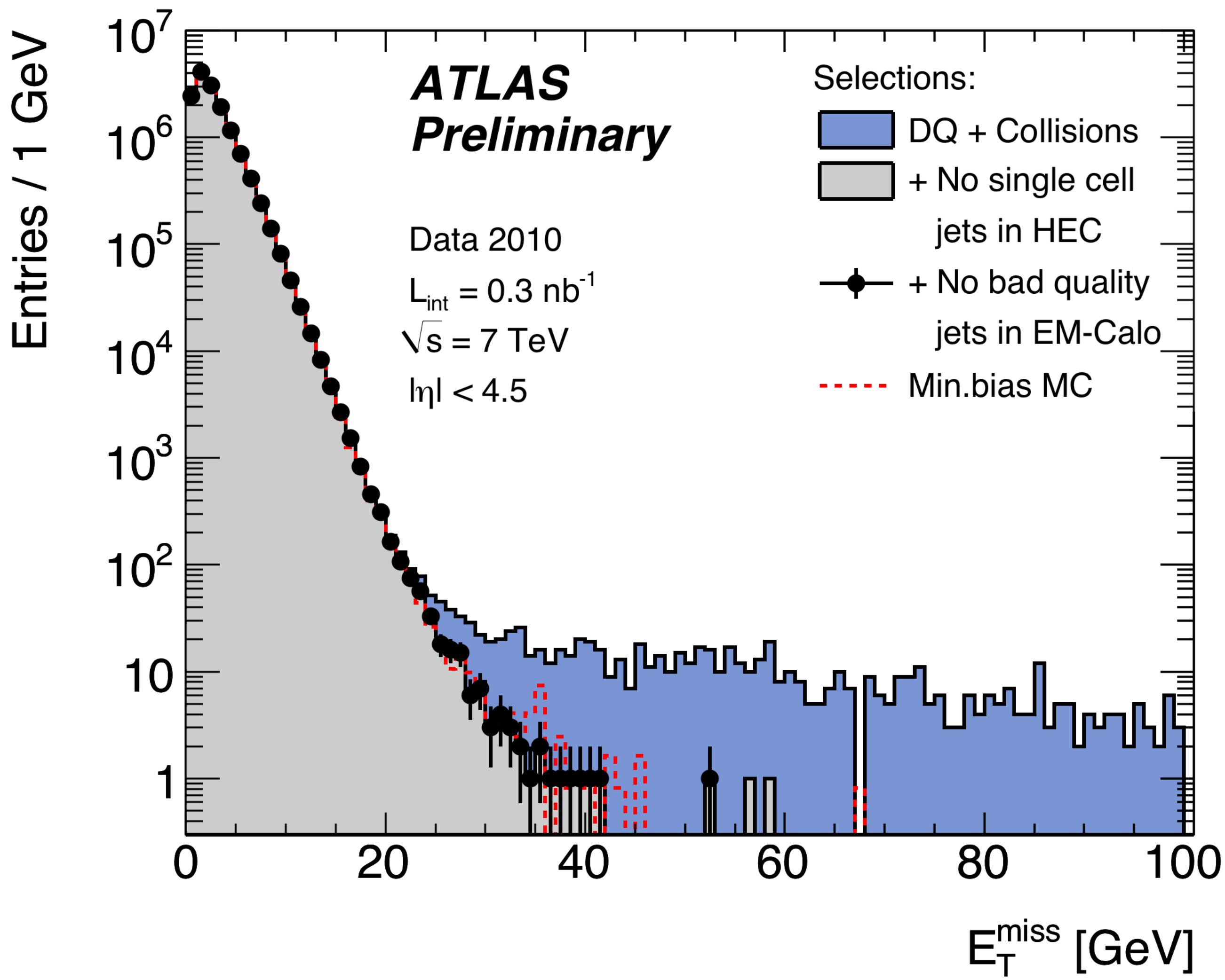
Forward physics

Intrumentals
Calo noise
Beam related
etc…

$$\sigma(MET) \approx \sigma^{Jet} \oplus \sigma^{Lep} \oplus \sigma^{Soft} \oplus \sigma^{Forw} \oplus \sigma^{Other}$$

MET Cleaning (ATLAS)

MET distribution for 14.4 million collision events from 7 TeV data, after successive jet cleaning selections. The corresponding distribution from the Monte Carlo simulation is overlaid and normalized to the number of events in data.

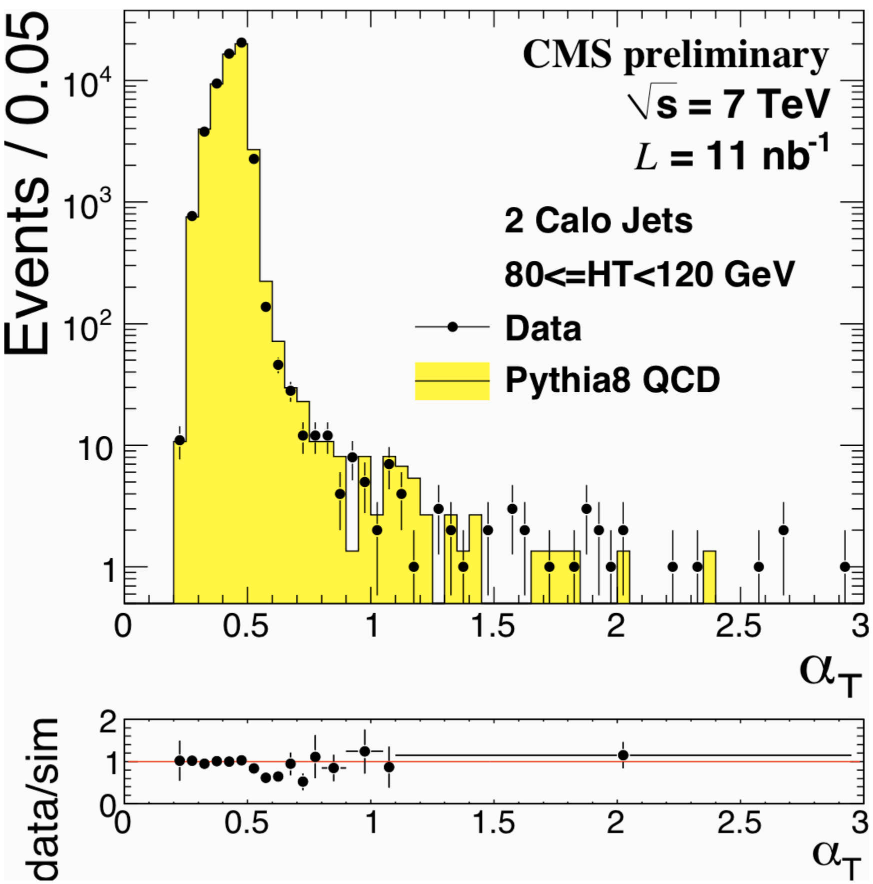


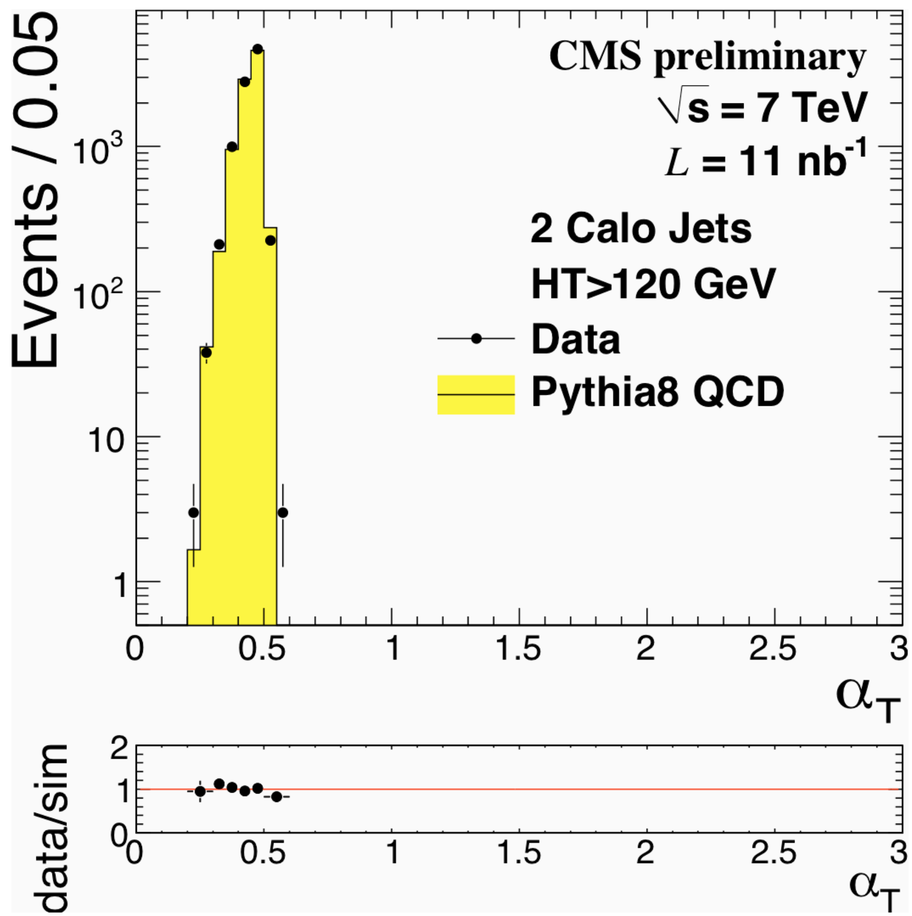
Suppression of Fake MET (CMS)

- CMS uses a variable (α_T) to suppress fake MET

$$\alpha_T = \sqrt{p_{T2}/p_{T1}}/\sqrt{2(1-\cos\Delta\phi)}$$

- Also looked at azimuthal angular correlations of jets and MET. Good description of data by MC

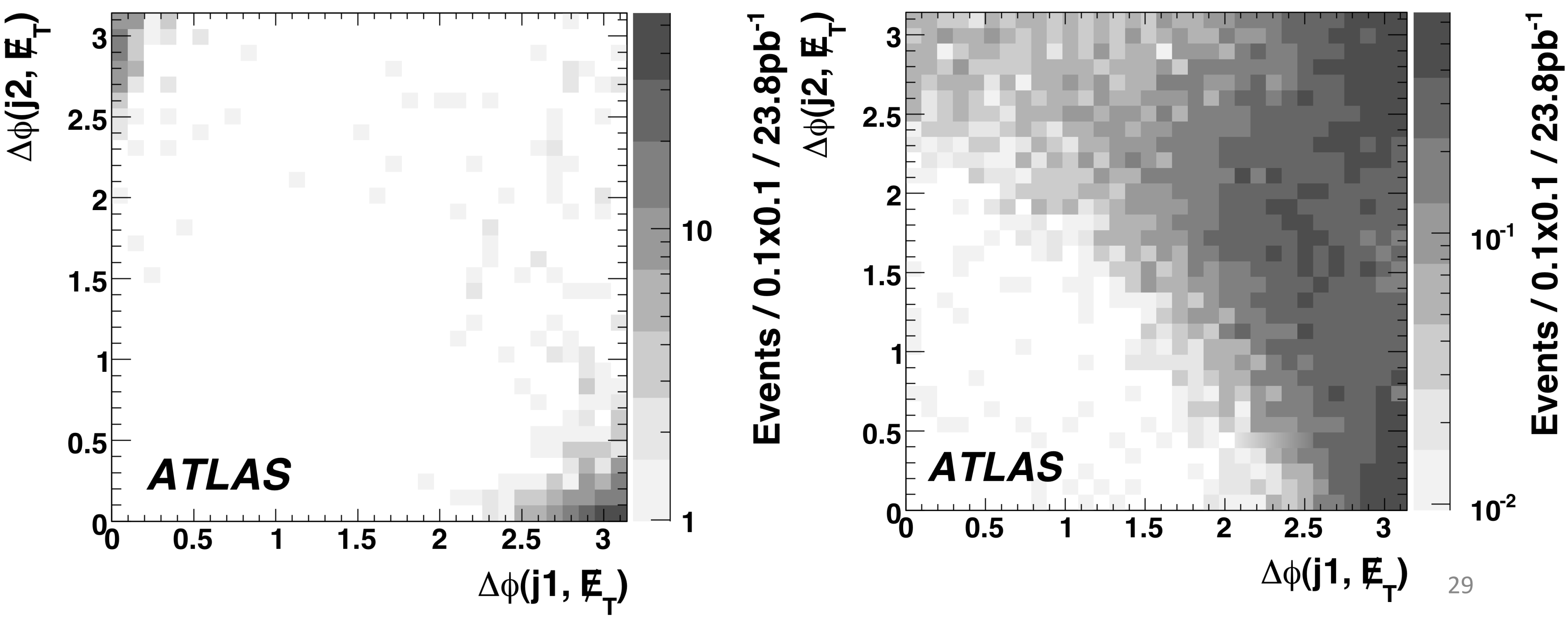




Suppression of Fake MET
(ATLAS)

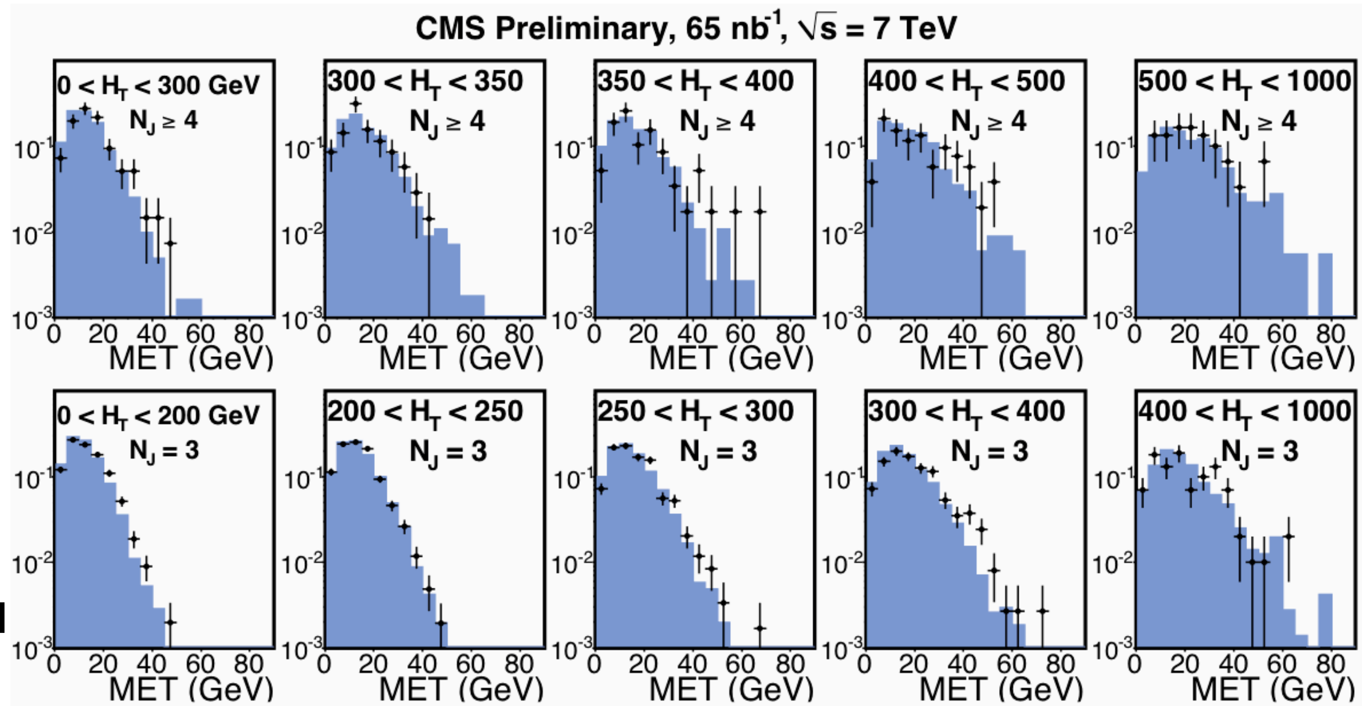
- Fake MET due to Jet resolution effects tends to point along the direction of the jet. Cuts on the opening angle between the jets and the MET are very effective in fake MET in multi-jet topologies, corresponding to SUSY searches
- Plots shown are obtained wit MC

QCD multi-jets MET>100 GeV SUSY SU3

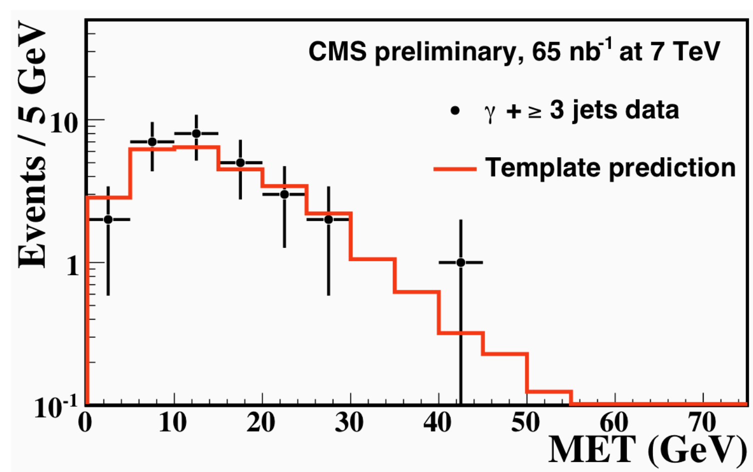


MET Templates (CMS)

Templates from data describing MET from jet resolution and mismeasurement effects. The data are shown by points with error bars and the Pythia6 QCD MC by the histograms. Each template corresponds to a sample with a specific number of jets (rows) and a range in H_T (columns).

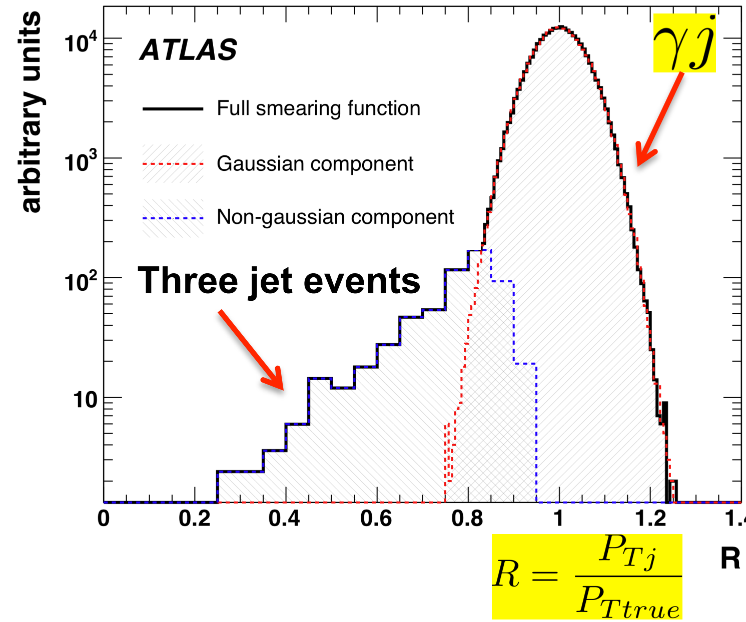


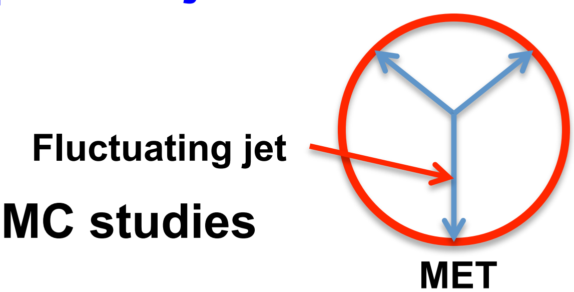
MET predictions, based on templates, compared to the observed MET in γ+ ≥ 3 jet events. The data are shown by points with error bars and the predictions are shown by histograms. Particle-flow reconstruction is used.



Data Driven Background Extraction

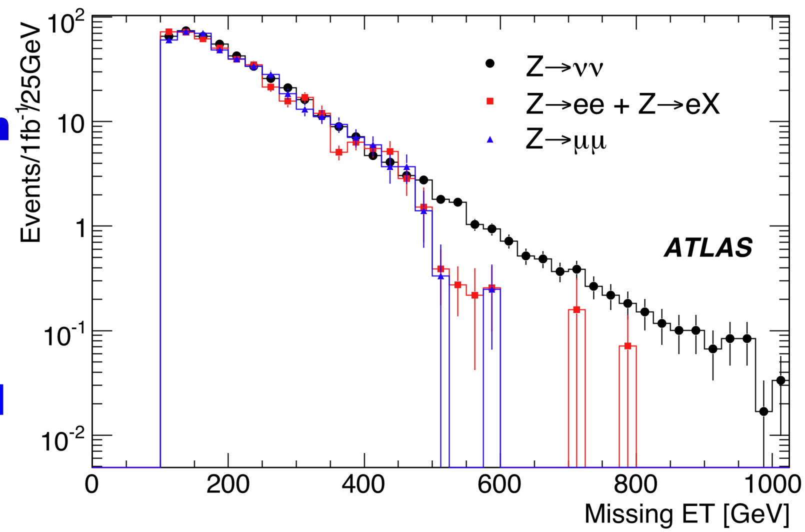
- **QCD extraction:**
  - **Get Gaussian resolution from γjet**
  - **Get non-Gaussian response from three jet events with only one jet parallel to the vector of the reconstructed MET**
  - **Smear jet P_T in four jet events with small MET**





Results are from MC studies

- **Z(→νν)+jets with Z(→ll)+jets:**
  - **Select Z(→ll) events with same cuts on jets as those for the SUSY analysis**
  - **Correct for difference in acceptance due to tagging leptons and the different branching ratios**
  - **Low statistics, which can be remedied by fitting MET shape**



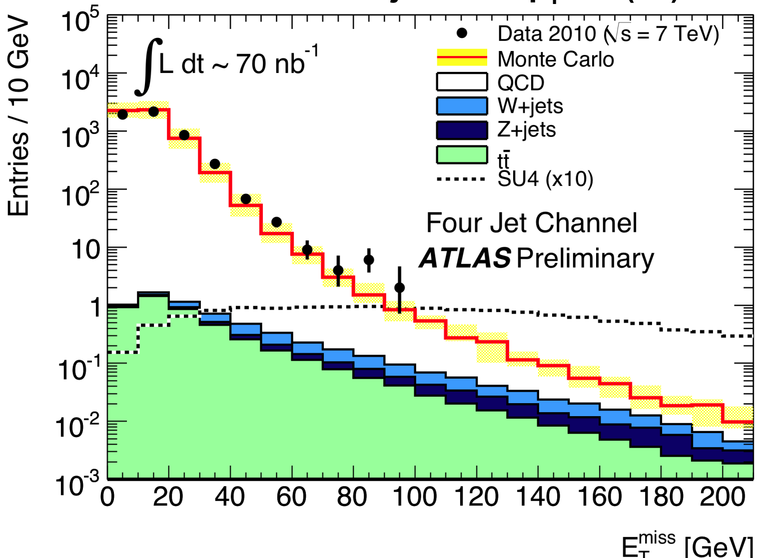
Early Searches (ATLAS)

ATLAS is exploring susy-sensitive variables with jets MET, lepton veto, one or more leptons, b-jets… Good description of Data by MC. MET tails under control

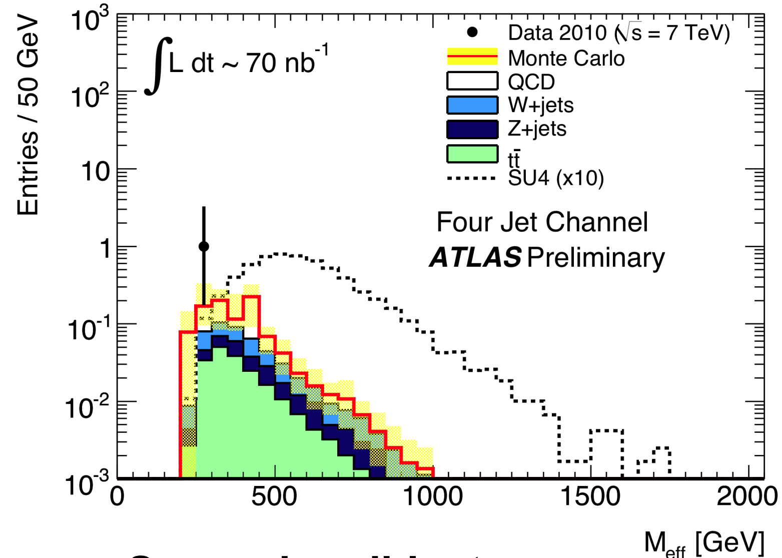
Four jet analysis

QCD MC normalized to di-jet sample in data

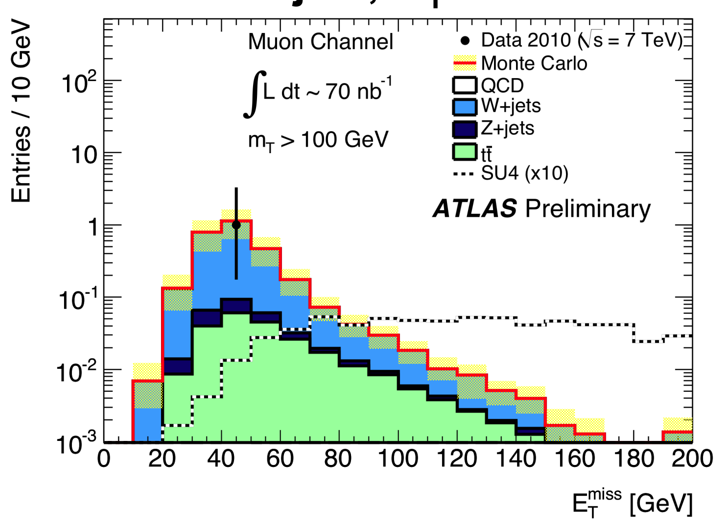
≥4 jets with p_T>70 (30) GeV



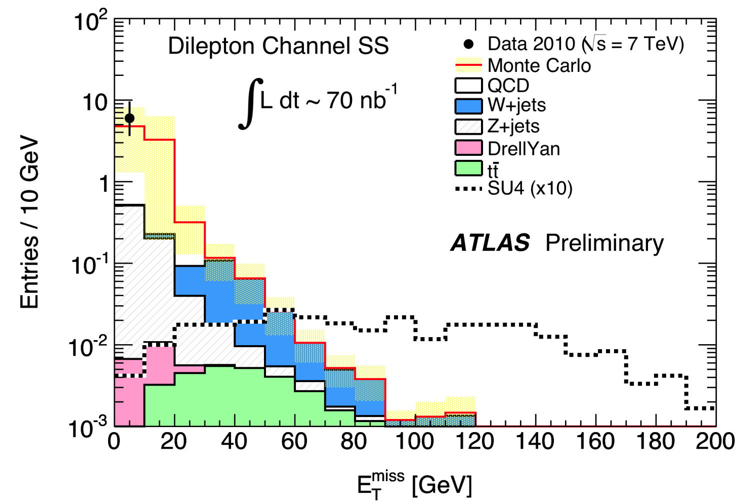
MET>40GeV, ΔΦ(ji, MET)>0.2, MET/M_{eff}> 0.25



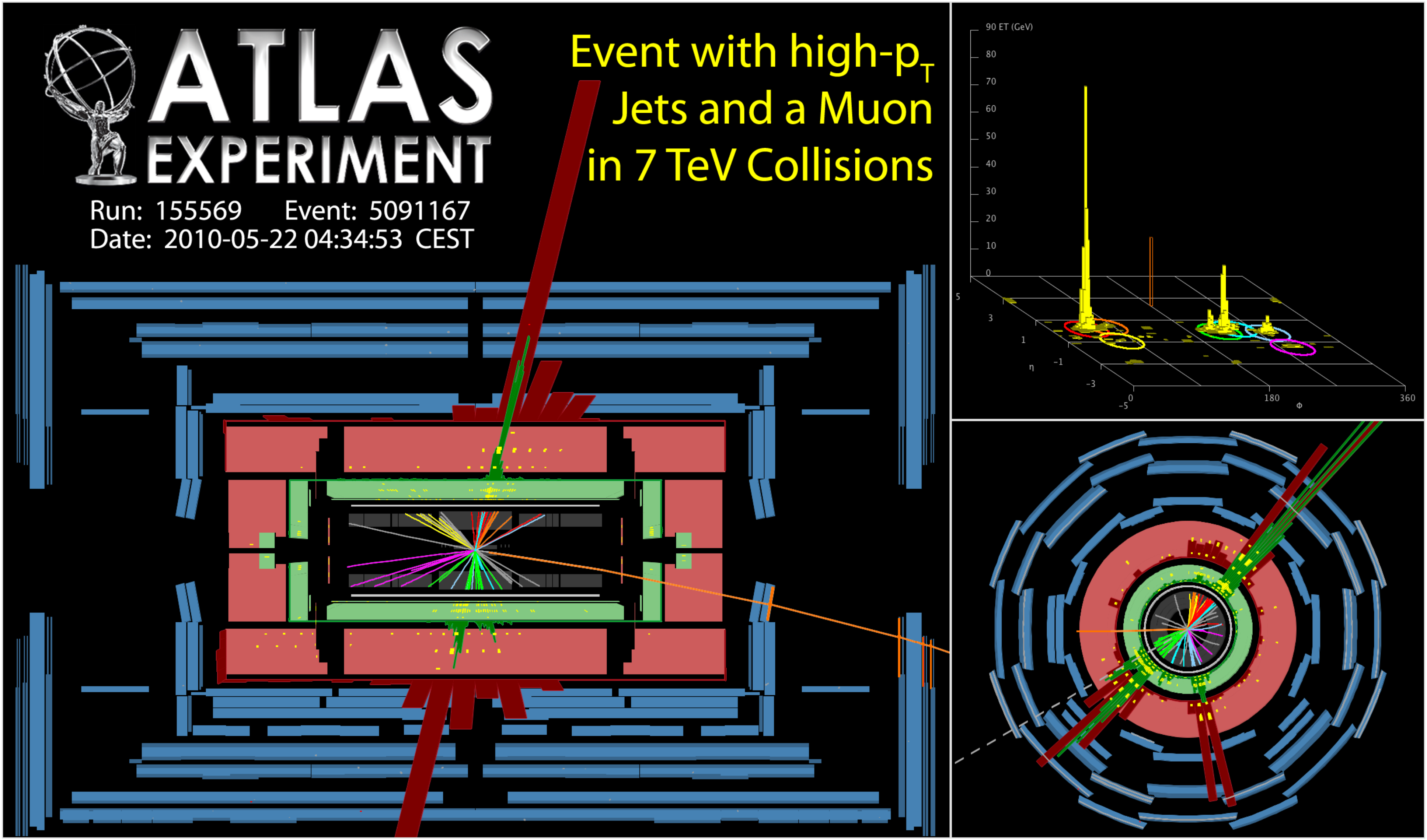
Muon + jets, M_T>100 GeV



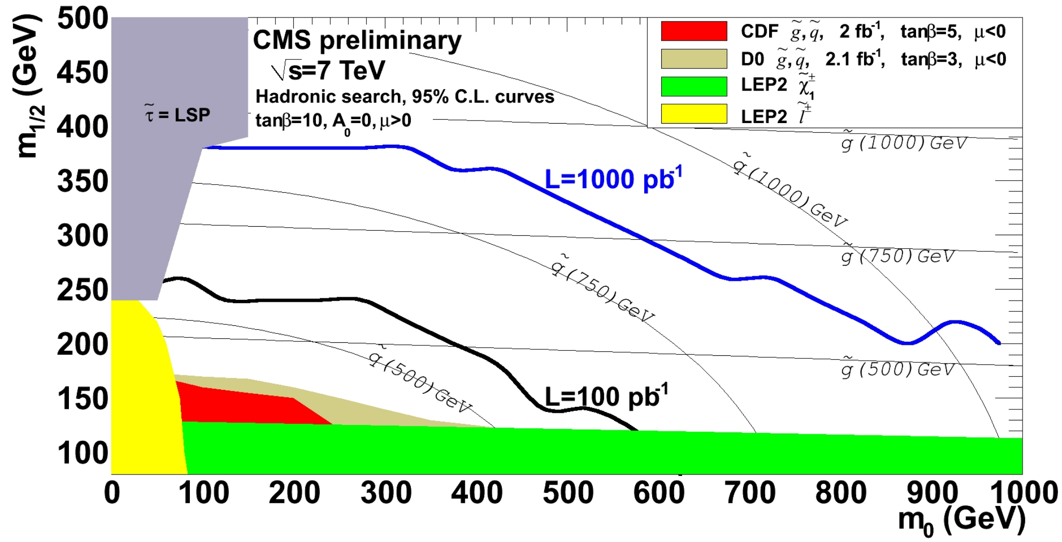
Same-sign di-leptons



With M_{eff} of 915 GeV when only the leading two jets are included in the scalar sum increasing to 1156 GeV if all jets are included. There are a total of 145 tracks associated with the primary vertex; no second vertex is reconstructed. The missing transverse momentum is 118 GeV. There is one well isolated positively charged muon with p_T of 25 GeV, and eta=2.33.



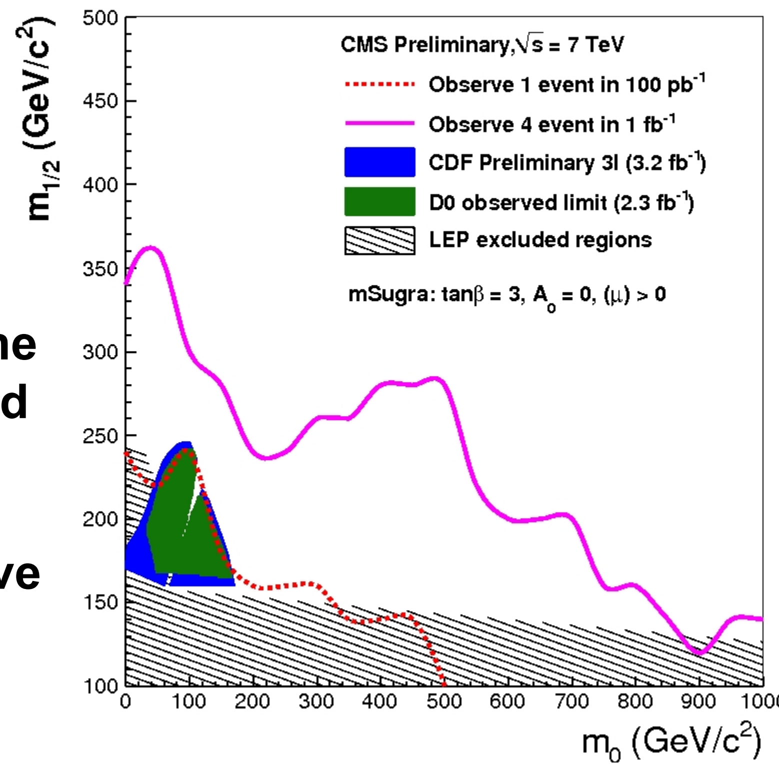
CMS Sensitivity



Estimated 95% C.L. upper limit contours for the all-hadronic search at two values of the integrated luminosity

The gluino mass is roughly given by $m(\tilde{g}) \approx 2.3 m_{1/2}$.

Surpasses sensitivity of Tevatron:
- ♣ m(squark) > 280 GeV
- ♣ m(gluino)> 340 GeV



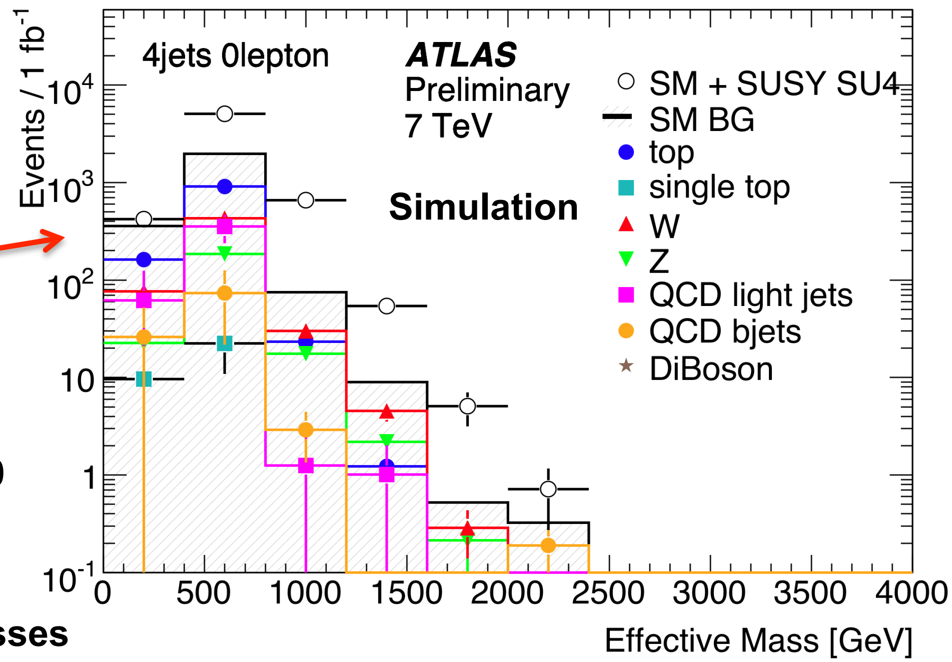
Estimated 95% C.L. exclusion limits for the like-sign dilepton SUSY search, expressed in mSUGRA parameter space. The expected standard model background at 100 pb^{-1} (1 fb^{-1}) is 0.4 (4.0) events; we have assumed an observed yield of 1 event (4 events) for the purpose of setting these exclusion limits

ATLAS Sensitivity

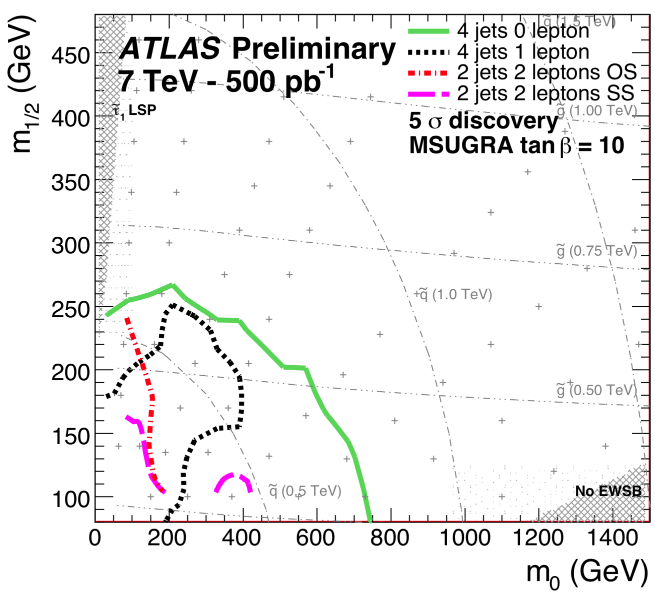
"ETmiss + 4 jets + 0 lept"
Best discovery potential
Dominant backgrounds:
- **Top production (pair, single)**
- **Vector Bosons + jets**

Shown is the SU4 benchmak (m_0=200 GeV, $m_{1/2}$ =160 GeV, A0=-400 GeV, tanβ=10 and μ>0, strongly interacting particle masses in 410-420 GeV range)

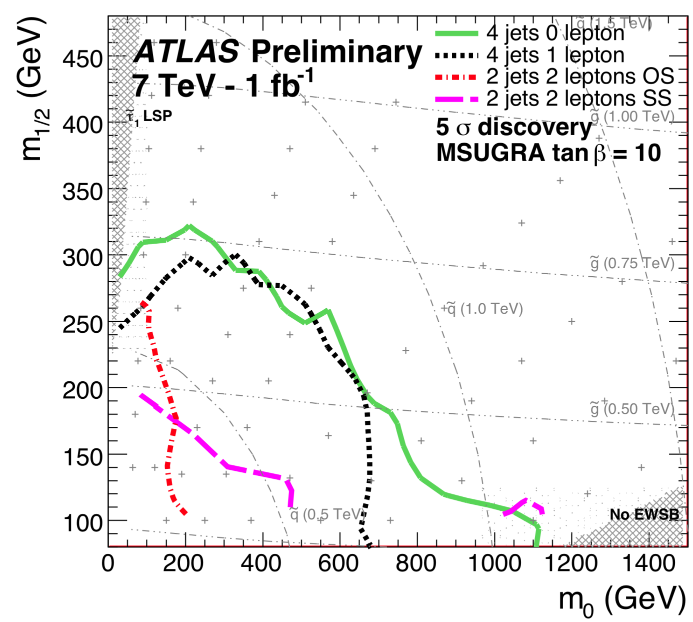
Effective mass distribution for 4 jet 0 lepton channel



5σ discovery reach as a function of m_0 and $m_{1/2}$ masses for tanβ = 10 mSUGRA scan for channels with 0, 1 and 2 leptons. The integrated luminosity is 0.5 fb^{-1}.



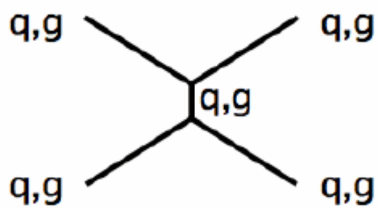
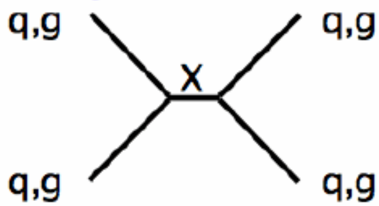
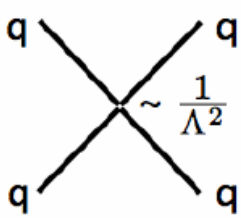
Same for 1 fb^{-1}



Other Searches Beyond the Standard Model

New Physics with Dijets

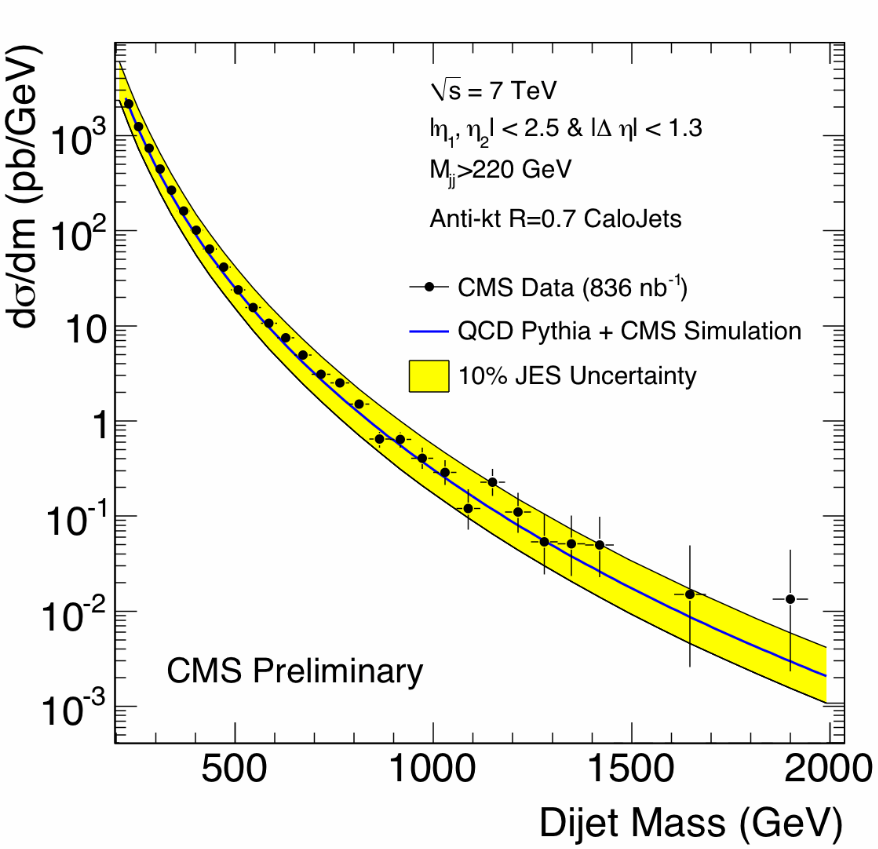
Study invariant mass and centrality ratio as sensitive observables

<table>
<tr><th></th><th>Mass Spectrum</th><th>Centrality Ratio</th></tr>
<tr><td>QCD

</td><td>simple test of cross section vs dijet mass from QCD and PDFs</td><td>detailed measure of QCD dynamics from angular distribution</td></tr>
<tr><td>Dijet Resonance

</td><td>provide most sensitive “bump” hunt for new particles decaying to dijets</td><td>less sensitive to dijet resonances, but important confirmation that “bump” is not QCD fluctuation</td></tr>
<tr><td>Contact Interaction

</td><td>because of experimental uncertainties, less sensitive to quark compositeness</td><td>sensitive search for quark compositeness</td></tr>
</table>

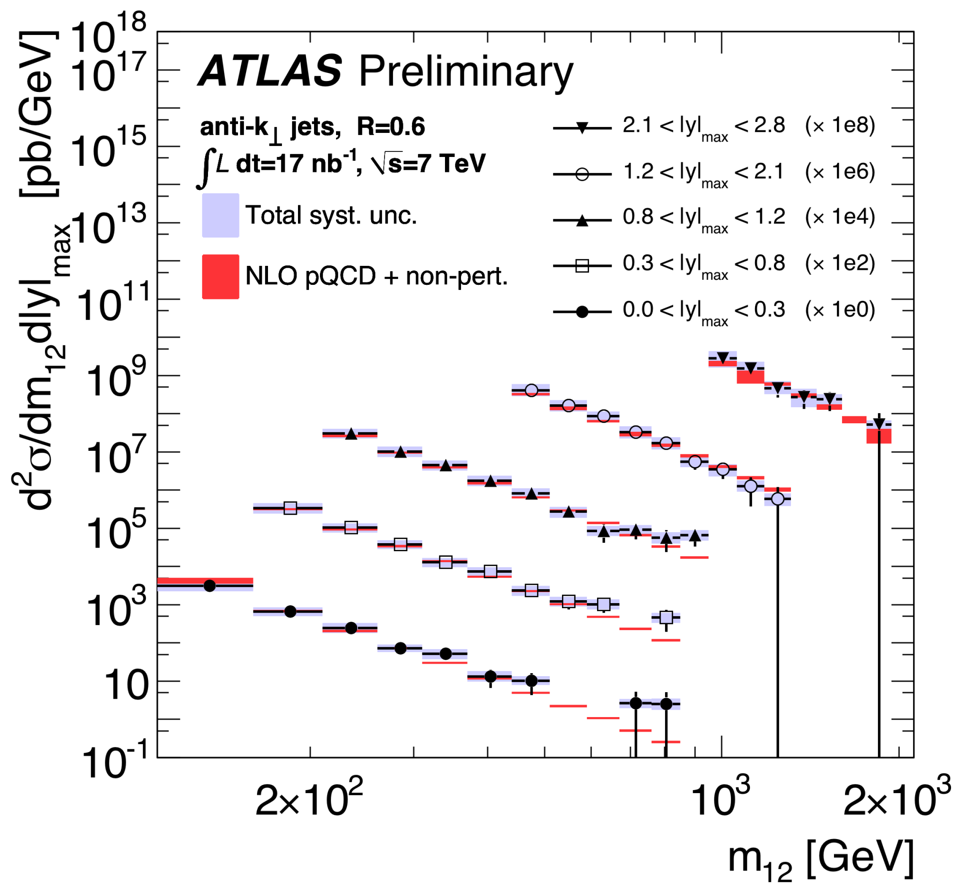
Slide from Sung-Won Lee

Dijet Invariant mass Spectrum

The measured differential cross section data (points) in dijet mass are compared to a QCD MC prediction (black line). The yellow band shows the sensitivity to a 10% systematic uncertainty on the jet energy scale

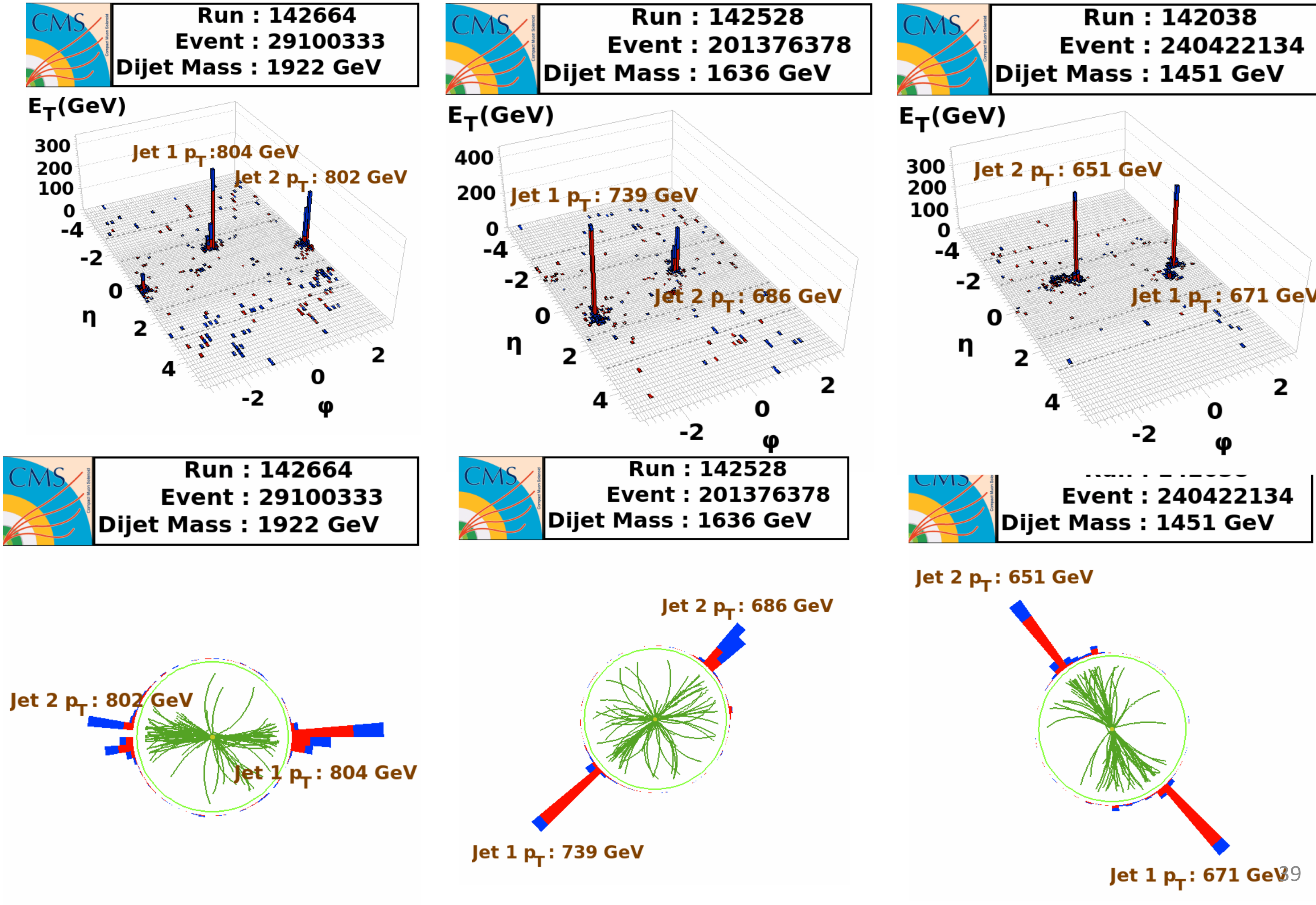


Dijet double-differential cross section as a function of dijet mass, binned in the maximum rapidity of the two leading jets, |y|_max = max(|y_1|, |y_2|). This is shown for jets identified using the anti-kT algorithm with R=0.6. The data are compared to NLO QCD calculations to which soft QCD corrections have been applied.



Good agreement between Data and theory predictions

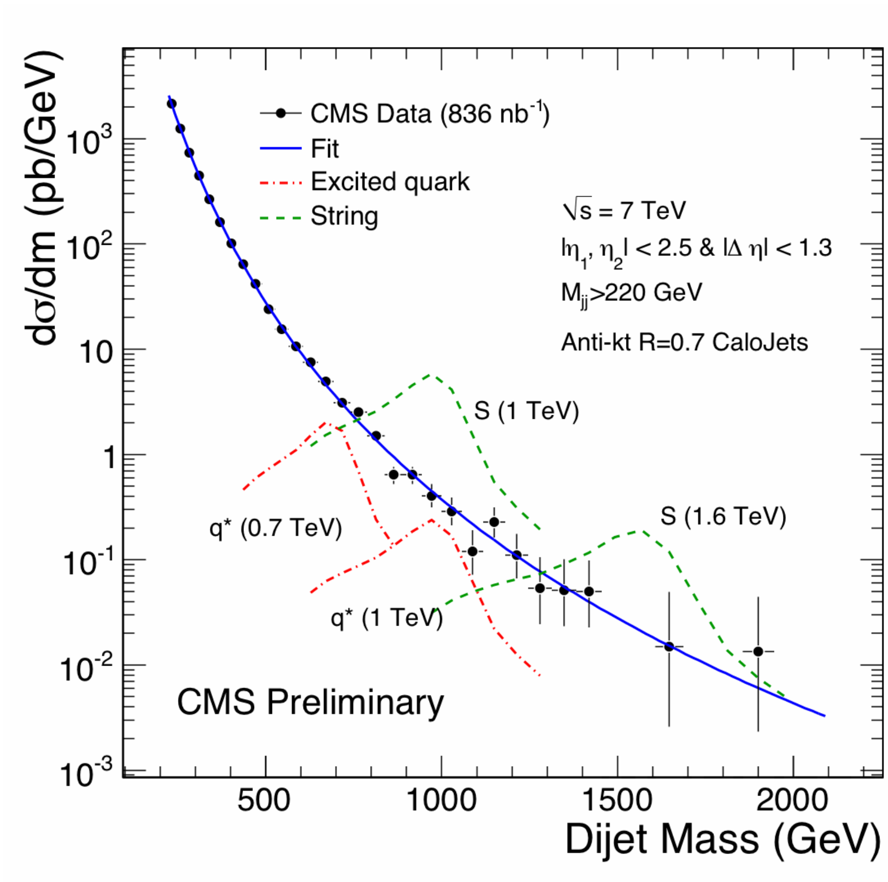
Highest Mass Dijet Events (CMS)



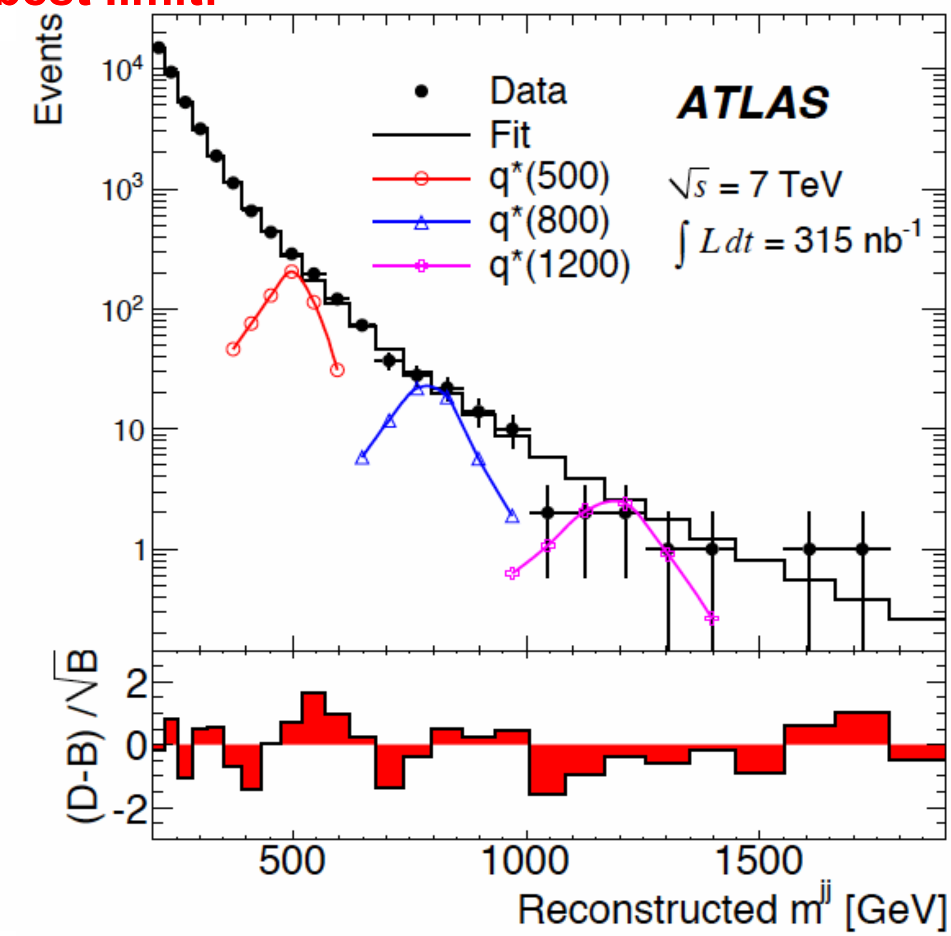
Fits to Mass Spectrum

Simultaneous fit of background and signal
Systematic uncertainties: Jet energy scale (dominant), Background fit parameters, Integrated luminosity, Jet energy resolution (small)

First LHC result surpasses the world's best limit!



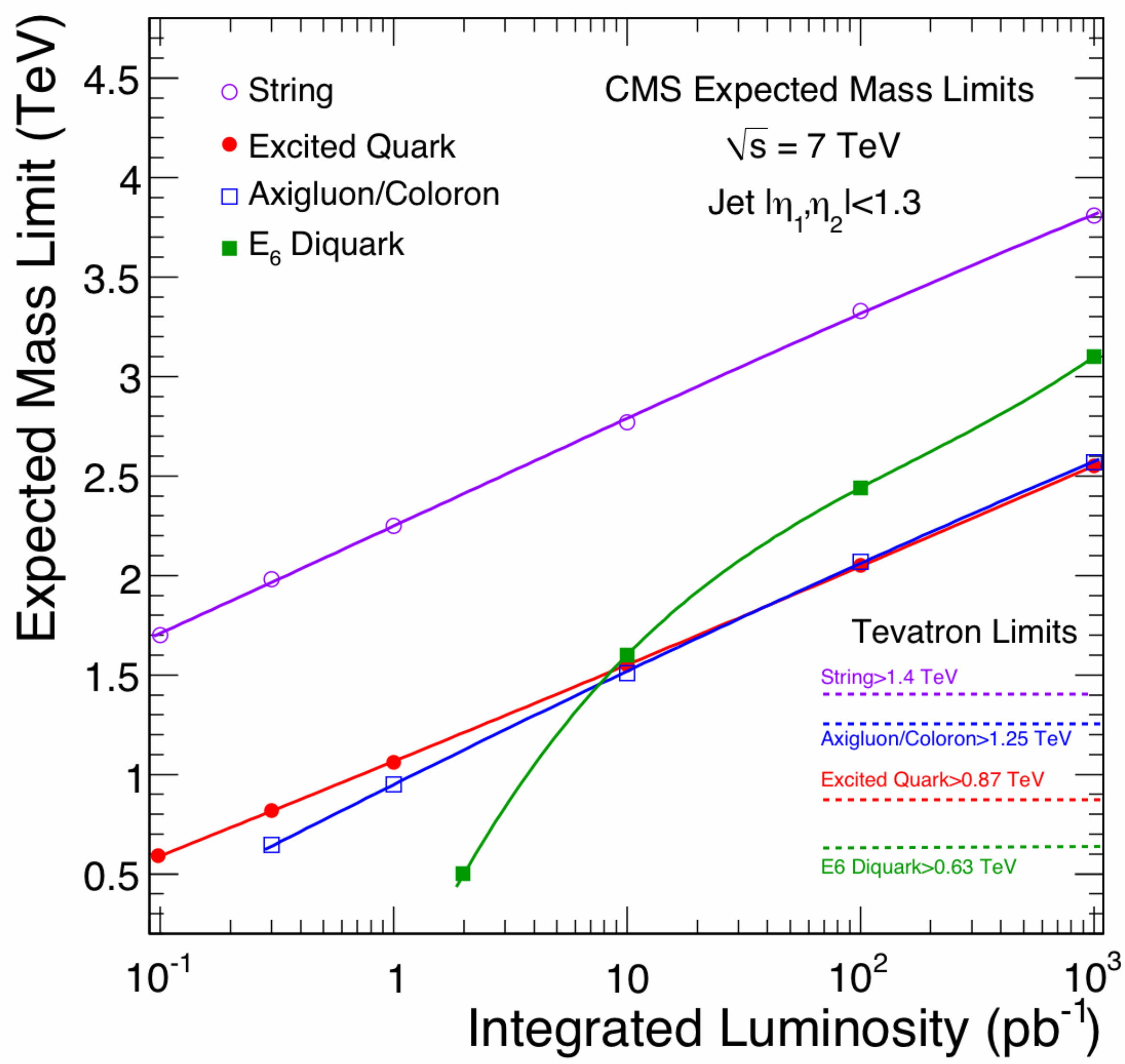
$$\frac{P_0 \cdot \left(1 - m/\sqrt{s} + P_3 \cdot (m/\sqrt{s})^2\right)^{P_1}}{m^{P_2}}$$



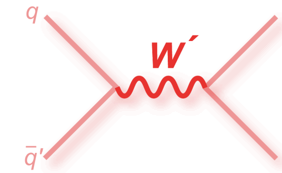
$$f(x) = p_0 \frac{(1-x)^{p_1}}{x^{(p_2 + p_3 \ln(x))}} \qquad x \equiv m^{jj}/\sqrt{s}$$

Projected Sensitivity (CMS)

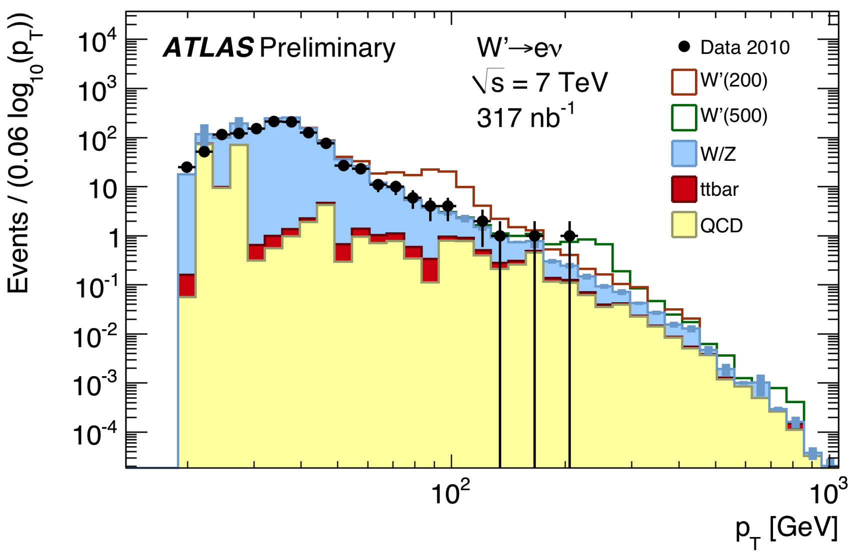
The expected mass limits for String, Excited Quark, Axigluon/Coloron and E6 Diquark models of dijet resonances are plotted versus integrated luminosity and fit with a smooth curve.

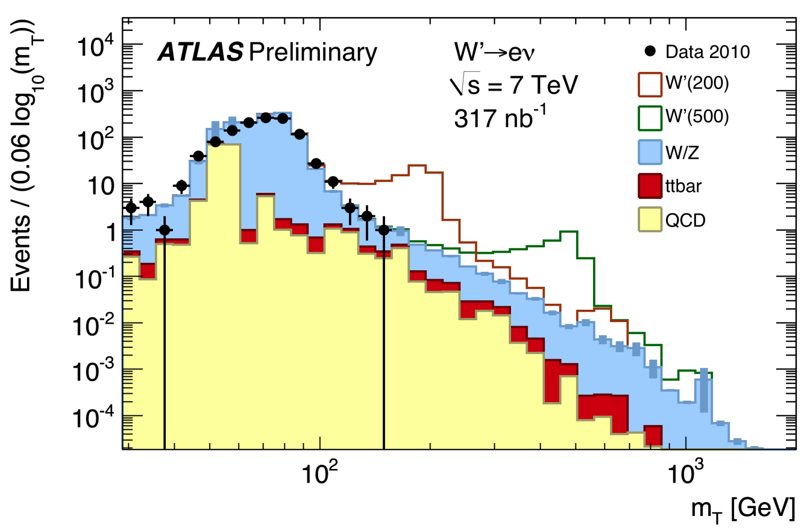


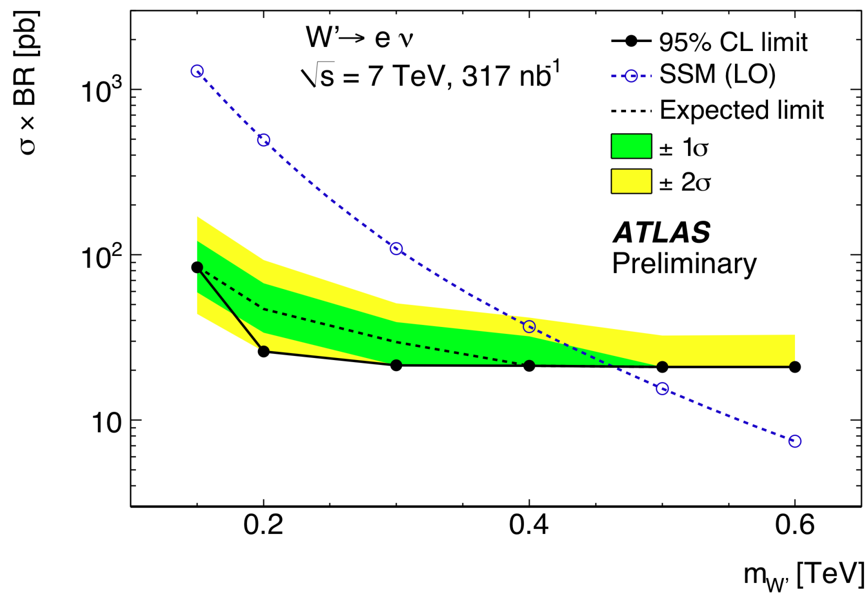
Search for W'(→eν) (ATLAS)

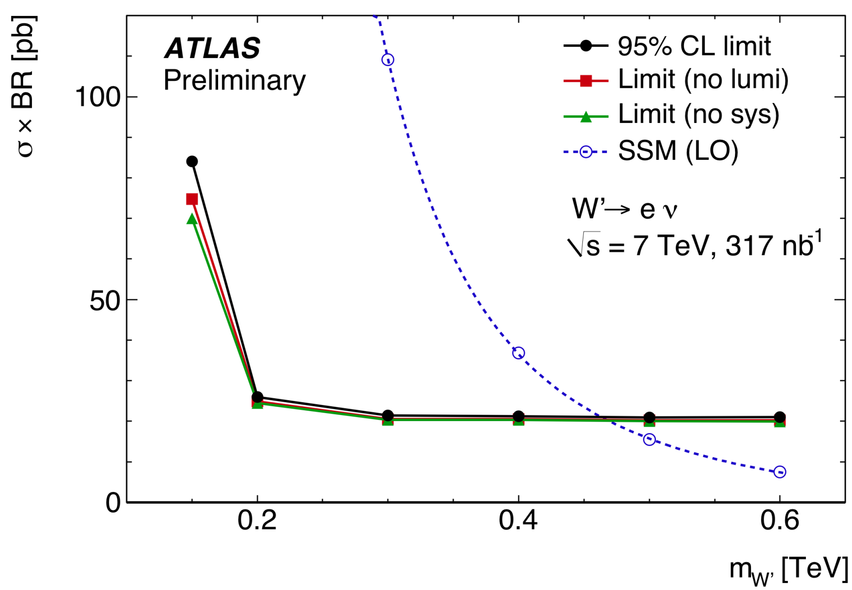


Transverse momentum and MET spectra after the final selection.







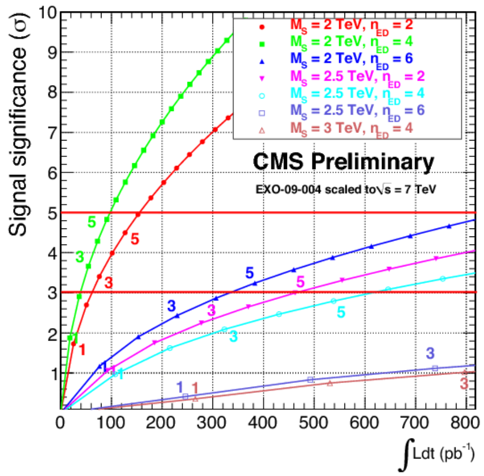


Other Topics beyond SM

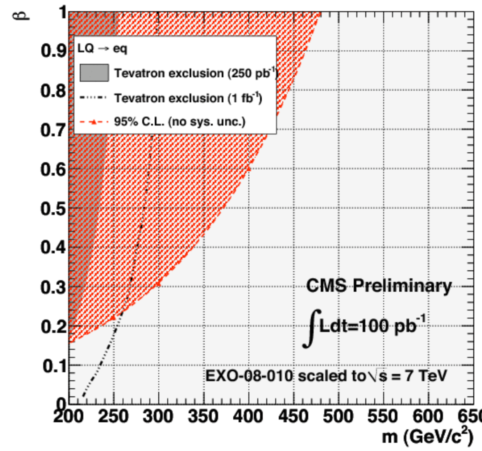
- **First Results on the Search for Stopped Gluinos (CMS PASEXO-10-003)**
- **Search for Heavy Stable Charged Particles (CMS PASEXO-10-004)**
- **Search for new physics in multi-body final states at high invariant masses (ATLAS-CONF-2010-088)**
- **High-pT dijet angular distributions (ATLAS-CONF-2010-074)**
- **Background studies to searches for long-lived stopped particles decaying out-of-time with LHC collisions (ATLAS-CONF-2010-071)**

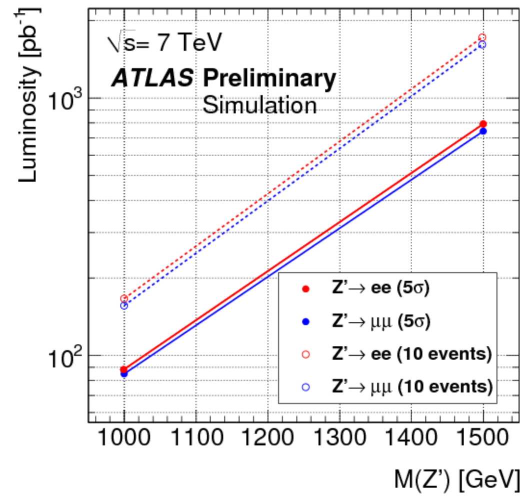
Projected Sensitivity for Exotica

large extra dimensions in the diphoton channel

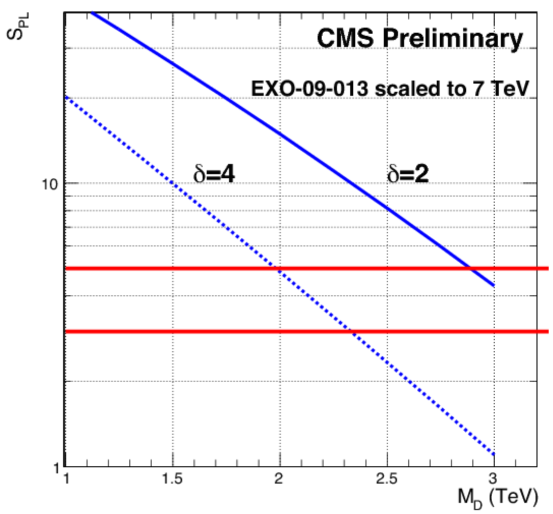


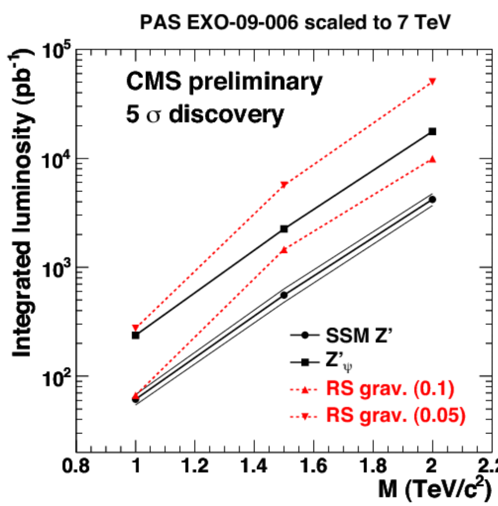
Discovery potential for first generation leptoquarks as a function of their branching fraction into a charged lepton

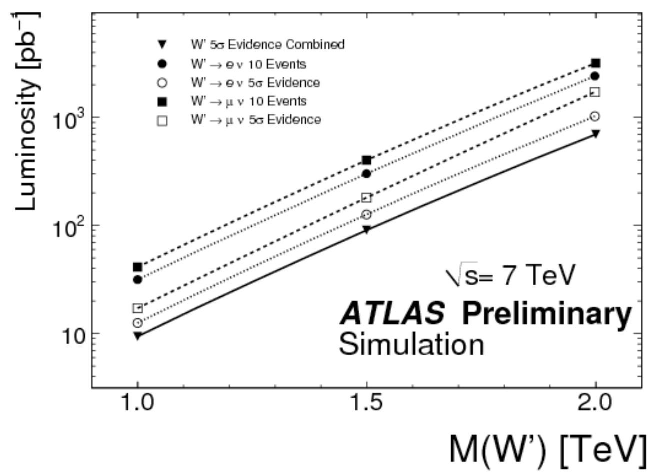




Discovery potential for an integrated luminosity of 200 pb^{-1} for large extra dimensions in the monojet channel







Outlook and Conclusions

- The physics potential of the LHC is breath taking
- First searches for the SM Higgs boson with ZZ,WW decays
  - A Single experiment should exclude the SM Higgs in the range $\sim 140<M_H<190$ GeV with 1 fb^{-1}
- Significant discovery potential for MSSM Higgs
- Inclusive SUSY searches give sensitivity to beyond that of the Tevatron with less 1fb^{-1} of data
  - Complex signatures that will require a good understanding of the detector performance and SM backgrounds
  - CMS/ATLAS defined control samples and data-driven methods for the extraction of SM backgrounds and different signatures
- Searches for other physics beyond the SM yield strong potential with 1pb^{-1}-1fb^{-1} of data
  - Searches for heavy boson, Majorana neutrinos, Leptoquarks, Black Holes, gravitons, excited quarks, etc…
- **Stay tuned for a very exciting 2011!**

Готов как пионер!

CMS and ATLAS are ready for a bright future of discoveries!

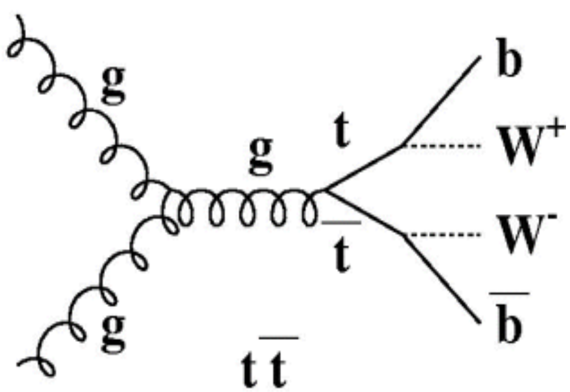
Extra Slides

Background Suppression and Extraction

- **Not able to use side-bands to subtract background. This makes signal extraction more challenging. Need to rely on data rather than on theoretical predictions**
- **Definition & understanding of control samples is crucial**
  - **Use large $\Delta\phi_{ll}$ and M_{ll} regions to extrapolate to signal-like region**
    - **Minimize theoretical uncertainties**
    - **Working on more methods minimize further dependence on MC**

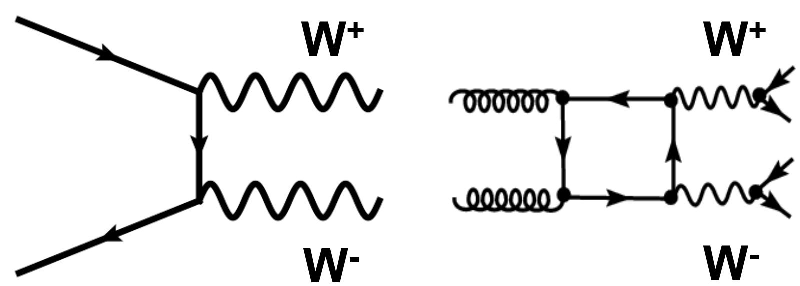
ttbar suppression

- Jet veto (understand low P_T jets)
- B-tagging for control samples
  - Working on methods that don't need the use of b-tagging



Non-resonant WW suppression

- $\Delta\phi_{ll}$ and M_{ll} very important variables
- Transverse momentum of WW system
  - Higgs production is harder. Missing E_T reconstruction plays a significant role here



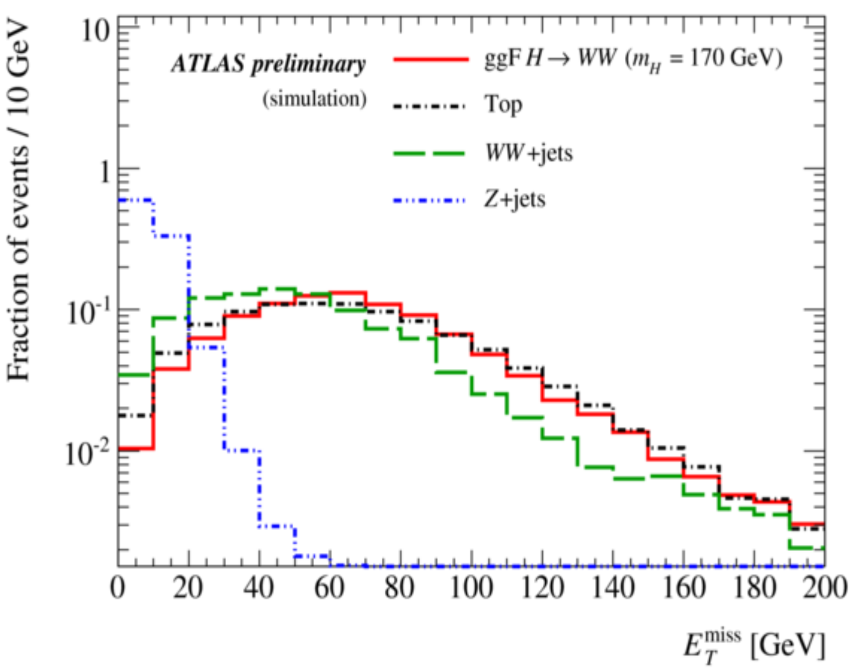
Feasibility for First Data
(200 pb^{-1})

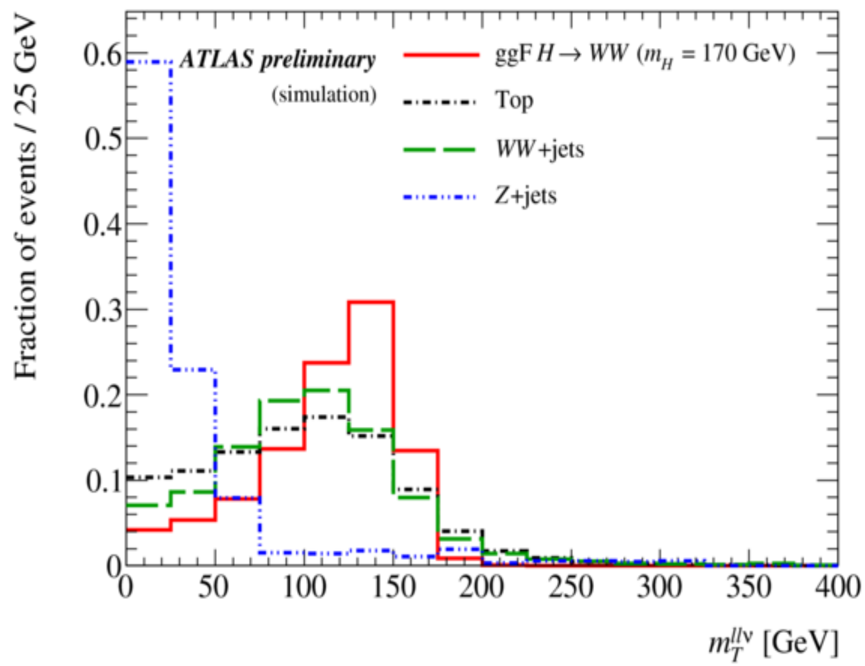
- ATLAS has recently released a complete study of $H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$ with 200 pb^{-1} at 10 TeV
  - Includes detailed evaluation of data-driven methods and systematics: ATL-PHYS-PUB-2010-005
    - http://cdsweb.cern.ch/record/1270568?ln=en
  - The analysis includes separation of events according to jet multiplicity and the addition of H+1j (Phys.Rev.D76:093007,2007)
  - Reanalysis for 7 TeV shown in ICHEP on the basis of re-scaling of the signal and background cross-sections

Analysis starts with preselection to isolate ll+MET events

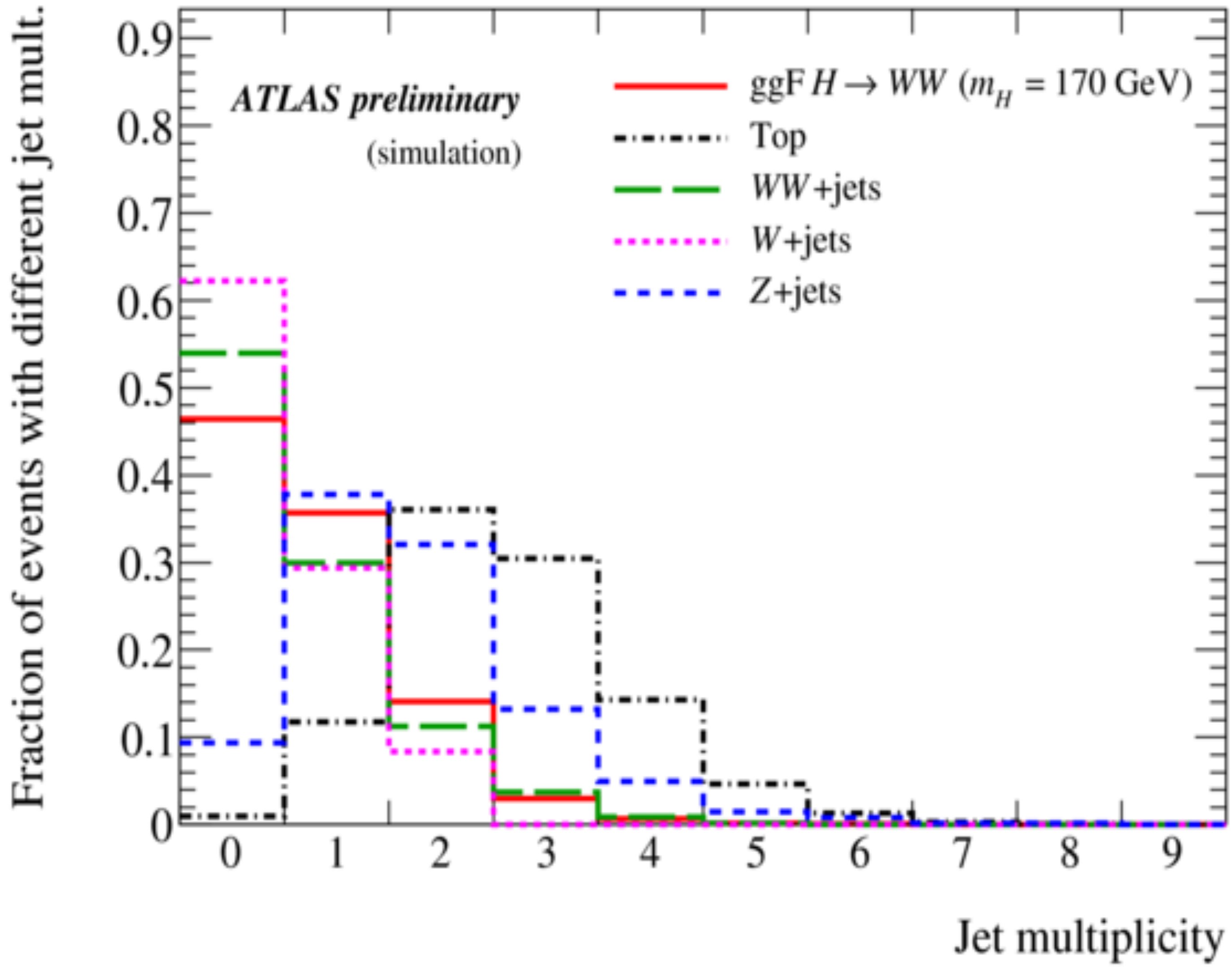
Cross-sections in fb

		Signal σ (fb)		Background σ (fb)					
		ggF	*VBF*	*WW*+jets	$t\bar{t}+Wt$	*W*+jets	Z/γ^*+jets	dijets	*total*
"tight" electrons - for $H+0j$ and $H+1j$ analyses									
Ia.	lepton requirement	187	27.7	1310	8830	785	$7.28{\cdot}10^5$	381	$7.40{\cdot}10^5$
Ib.	$m_{\ell\ell}$ cuts	175	26.1	1200	8110	175	$1.27{\cdot}10^5$	349	$1.37{\cdot}10^5$
Ic.	$E_T^{miss} > 30/40$ GeV	151	22.2	761	6570	84.6	447	–	7860
Id.	$m_T^{\ell\ell\nu} > 30$ GeV	148	21.0	722	5770	81.6	195	–	6770
"medium" electrons - for $H+2j$ analysis									
Ia.	lepton requirements	205	30.2	1360	9630	1670	$9.49{\cdot}10^5$	428	$9.62{\cdot}10^5$
Ib.	$m_{\ell\ell}$ cuts	192	28.4	1250	8850	927	$1.32{\cdot}10^5$	391	$1.43{\cdot}10^5$
Ic.	$E_T^{miss} > 30/40$ GeV	165	24.2	786	7170	472	769	–	9190
Id.	$m_T^{\ell\ell\nu} > 30$ GeV	163	22.9	744	6300	457	283	–	7780



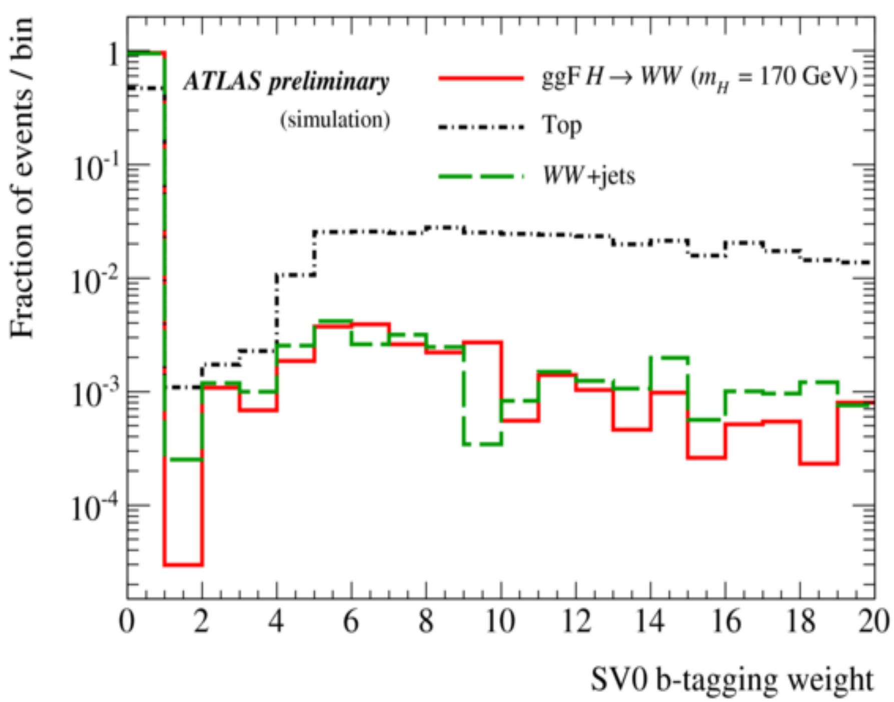


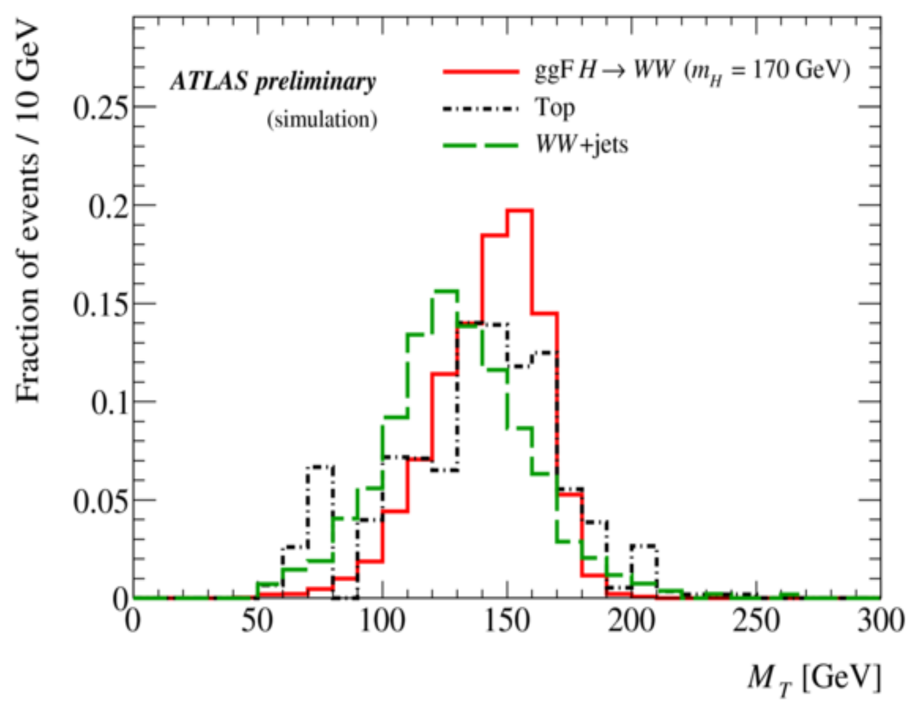
Events are classified according to jet multiplicity
In Case of H+2j analysis "VBF" topological cuts are applied



In the H+1j analysis the requirement of a b-jet veto plays an important role in suppressing top backgrounds

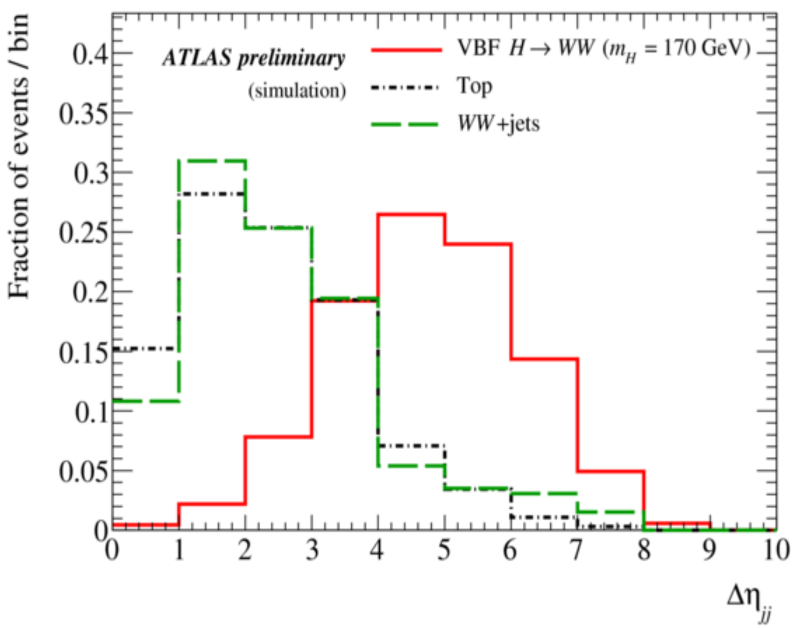
		Signal σ (fb)		Background σ (fb)				
		ggF	VBF	WW+jets	$t\bar{t}+Wt$	W+jets	Z/γ^*+jets	*total*
Preselection		148	21.0	722	5770	81.6	195	6770
1ja.	jet requirements	50.5	9.79	207	701	41.0	66.1	1020
1jb.	b-jet veto	49.0	9.30	199	315	40.3	55.8	609
1jc.	$p_T^{tot} < 30$ GeV	40.9	4.37	174	199	36.2	39.0	448
1jd.	$Z \to \tau\tau$ rejection	40.7	4.31	166	187	32.1	18.2	403
Ta.	$m_{\ell\ell} < 50$ GeV	25.8	2.71	39.1	36.1	7.00	11.3	93.5
Tb.	$\Delta\phi_{\ell\ell} < 1.3$ rad	23.1	2.42	27.6	29.6	4.27	2.19	63.7
Tc.	$M_T < m_H$	21.5	2.26	25.5	25.8	4.27	2.14	57.7

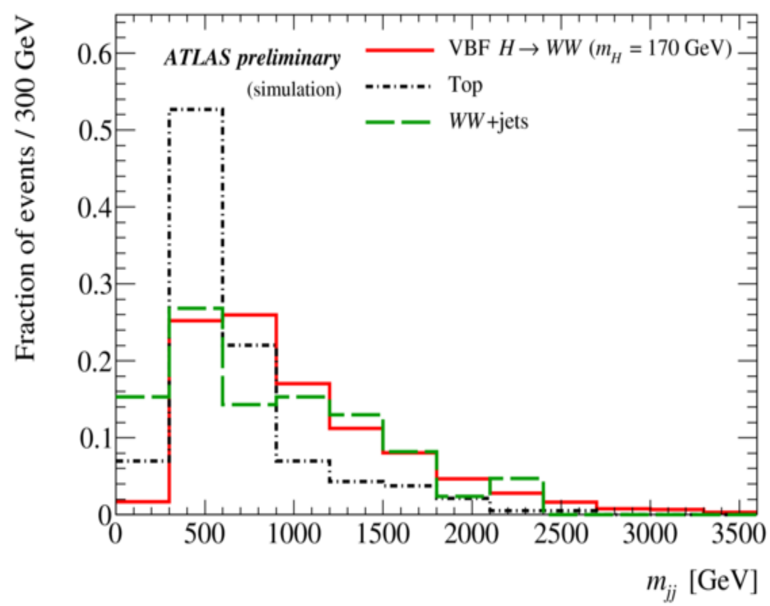




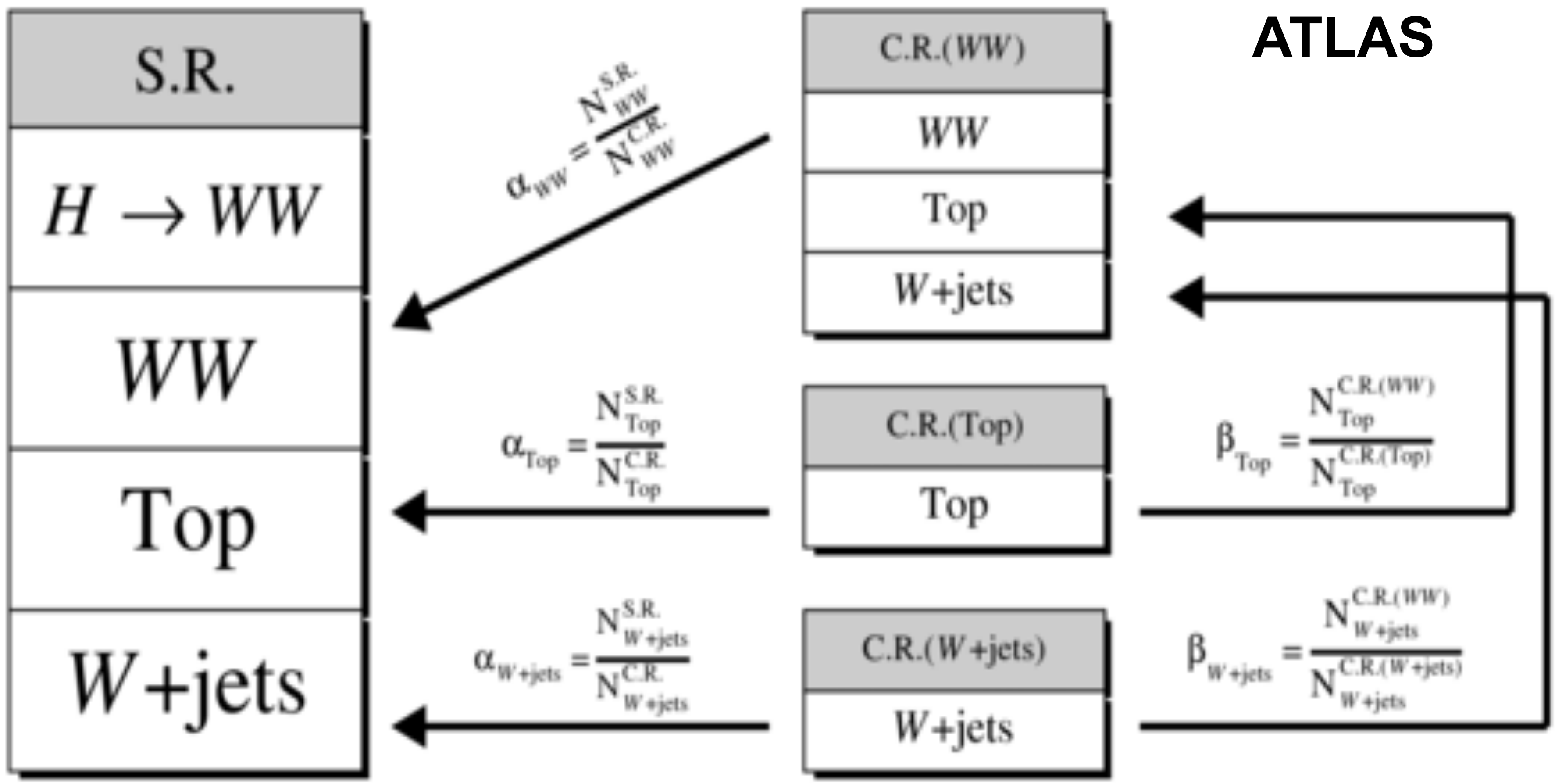
In the H+2j analysis the application of a b-jet veto and the "VBF" topological cuts are applied provide good S/B

		Signal σ (fb)	Background σ (fb)				
		VBF	WW+jets	$t\bar{t}+Wt$	W+jets	Z/γ^*+jets	total
Preselection		22.9	744	6300	457	283	7780
2ja.	jet requirements	14.4	117	2300	41.7	87.6	2540
2jb.	b-jet veto	13.4	108	562	39.0	73.1	782
2jc.	$\eta_{j1} \cdot \eta_{j2} < 0$	11.8	45.5	237	14.0	28.5	325
2jd.	$p_T^{lead.jet} > 40$ GeV	10.7	32.9	199	8.38	26.3	267
2je.	$\Delta\eta_{jj} > 3.8$	8.01	5.07	29.4	0.12	3.52	38.1
2jf.	$m_{jj} > 500$ GeV	6.67	3.07	14.9	–	2.42	20.4
2jg.	$p_T^{tot} < 30$ GeV	6.35	2.49	10.1	–	2.42	15.0
2jh.	$Z \to \tau\tau$ rejection	6.21	2.23	8.93	–	1.18	12.4
Ta.	$m_{\ell\ell} < 80$ GeV	6.03	0.75	2.38	–	1.18	4.30
Tb.	$\Delta\phi_{\ell\ell} < 1.3$ rad	4.55	0.51	0.88	–	1.18	2.57
Tc.	$M_T < m_H$	4.22	0.38	0.74	–	–	1.12





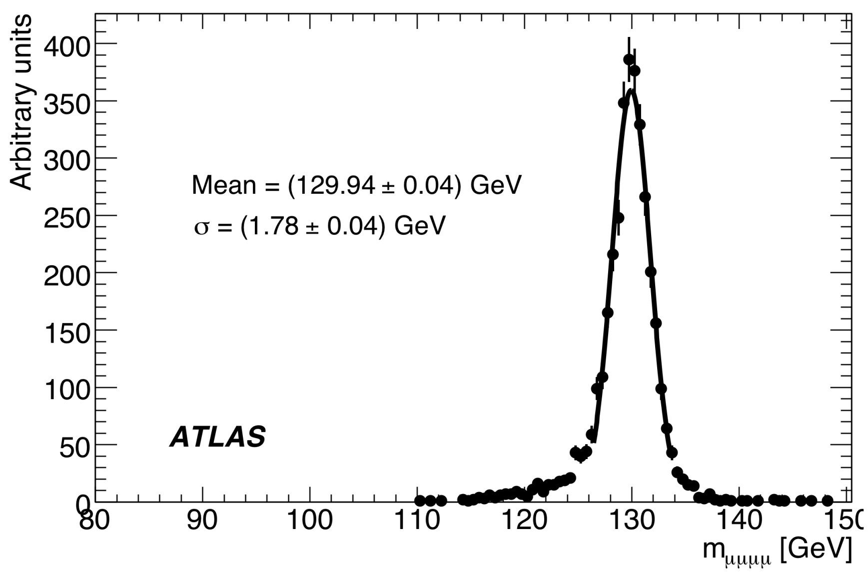
Backgrounds extracted with control samples using pseudo-data. Extrapolation coefficients taken from MC. Data-driven techniques exist for crucial processes



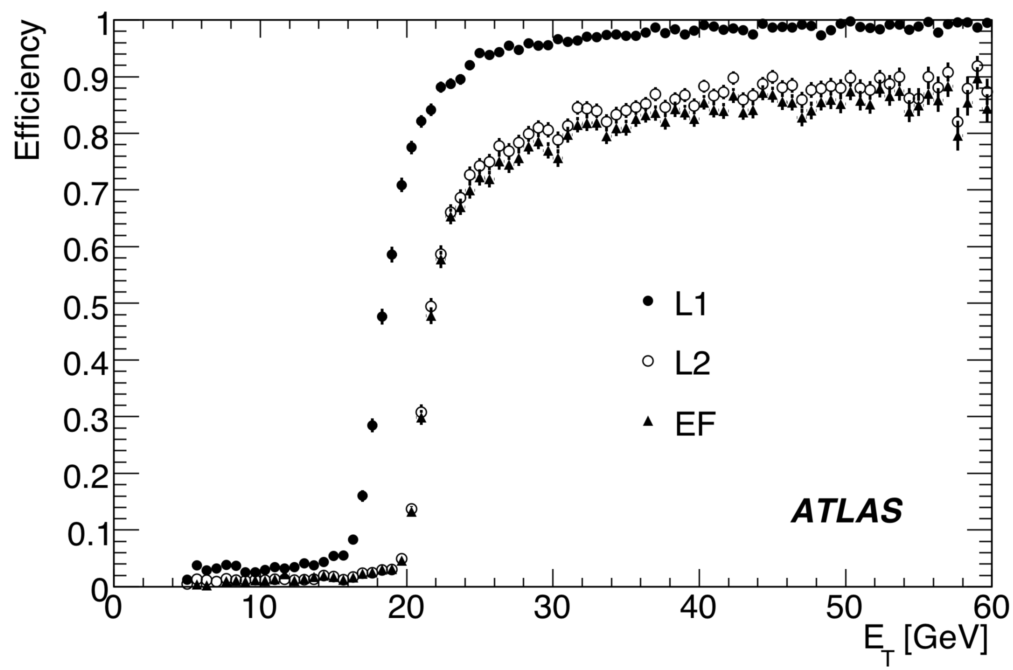
SM Higgs→ZZ$^{(*)}$→4l

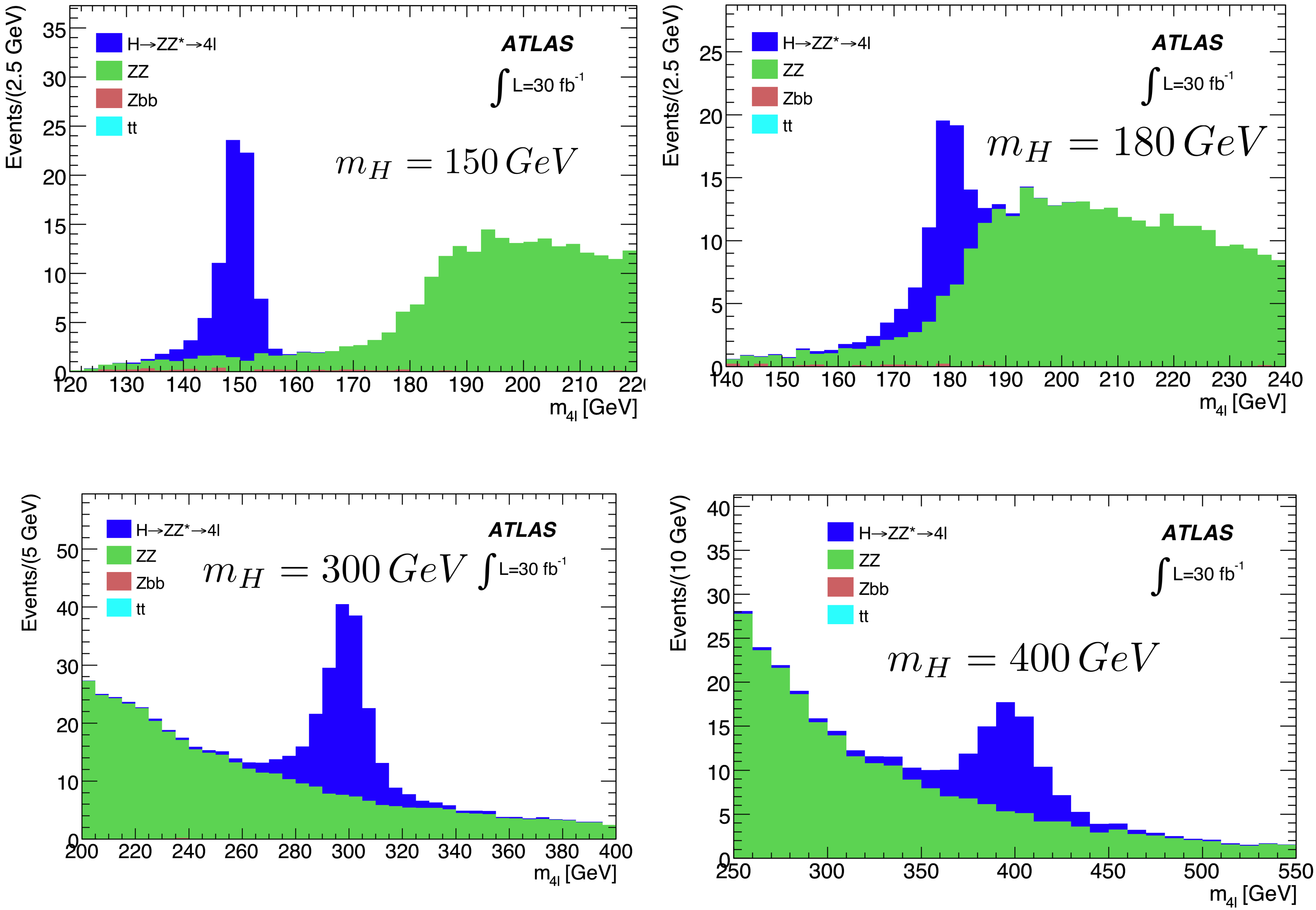
- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background > 1
  - **Major issues: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background Zbb,tt→4l**

H[**130** GeV]→4μ

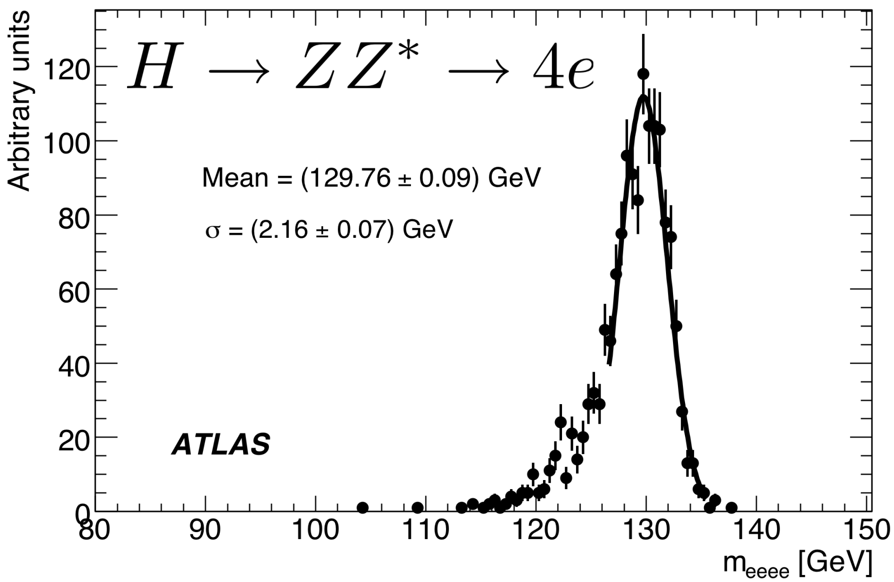


Electron efficiency

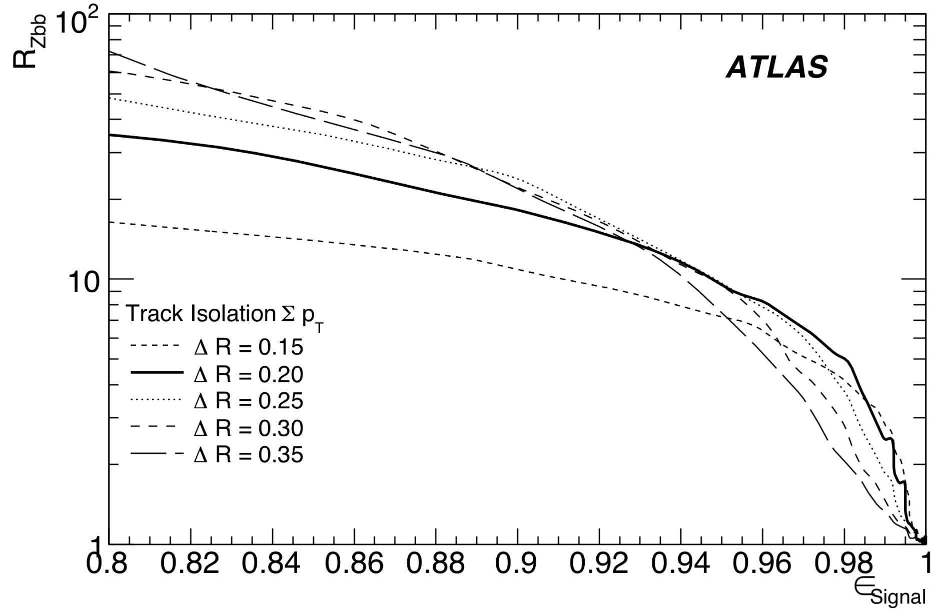




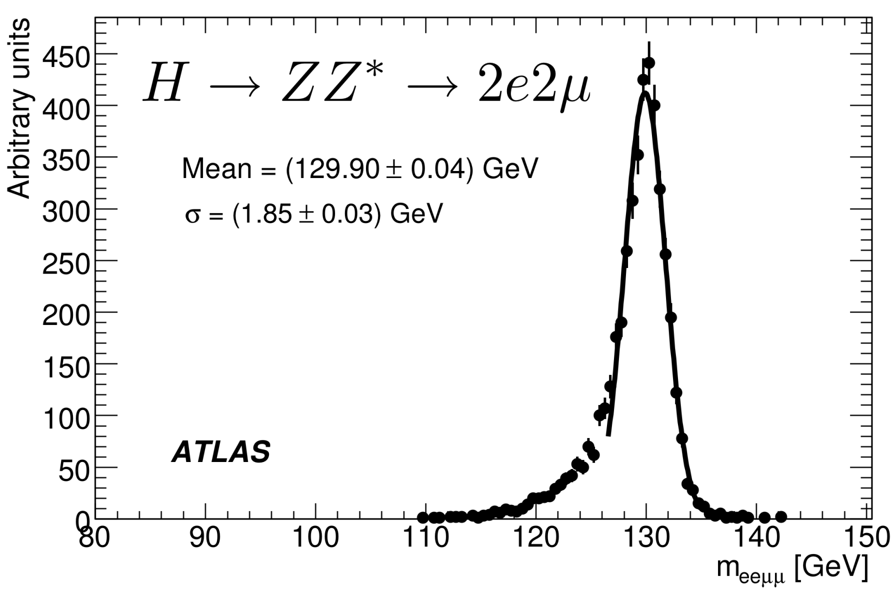
Events/(2.5 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
∫L=30 fb⁻¹
$m_H = 150\,GeV$
m4l [GeV]
Events/(2.5 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
∫L=30 fb⁻¹
$m_H = 180\,GeV$
m4l [GeV]
Events/(5 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
$m_H = 300\,GeV$
∫L=30 fb⁻¹
m4l [GeV]
Events/(10 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
∫L=30 fb⁻¹
$m_H = 400\,GeV$
m4l [GeV]



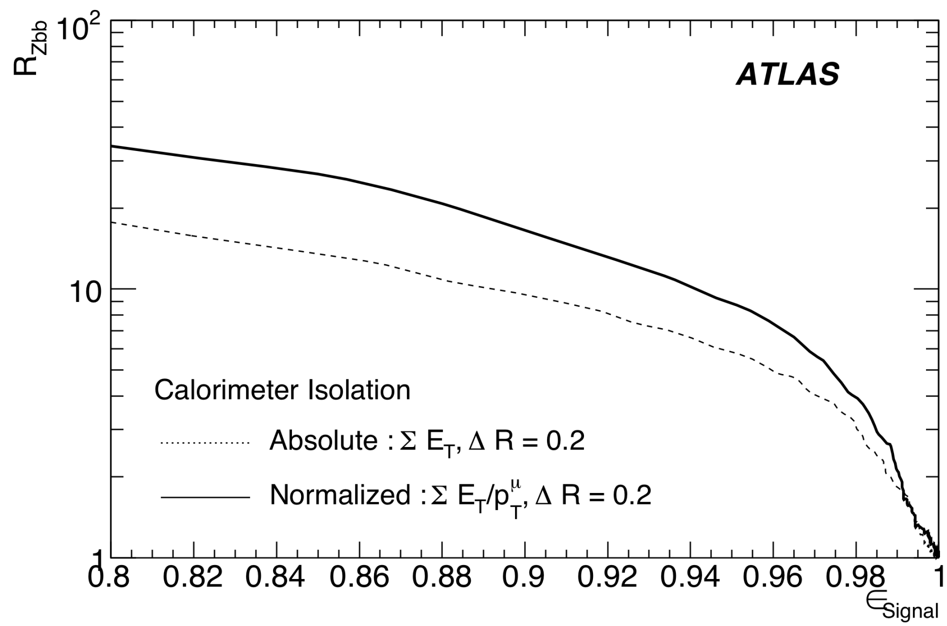
$H \rightarrow ZZ^* \rightarrow 4e$
Mean = (129.76 ± 0.09) GeV
σ = (2.16 ± 0.07) GeV
ATLAS
Arbitrary units
m_{eeee} [GeV]



ATLAS
Track Isolation Σp_T
$\Delta R = 0.15$
$\Delta R = 0.20$
$\Delta R = 0.25$
$\Delta R = 0.30$
$\Delta R = 0.35$
R_{Zbb}
ϵ_{Signal}



$H \rightarrow ZZ^* \rightarrow 2e2\mu$
Mean = (129.90 ± 0.04) GeV
σ = (1.85 ± 0.03) GeV
ATLAS
Arbitrary units
$m_{ee\mu\mu}$ [GeV]



ATLAS
Calorimeter Isolation
Absolute : ΣE_T, $\Delta R = 0.2$
Normalized : $\Sigma E_T/p_T^{\mu}$, $\Delta R = 0.2$
R_{Zbb}
ϵ_{Signal}

Normalizing VV with $Z^{(*)}$

- Strong similarities of diagrams since dominant cross-section comes from qq->V(V) via EW couplings
- Ratios VV/V expected to reduce pdf and a significant portion of the scale uncertainty
  - This is an asset especially at the very beginning of data taking when global pdf fits will not be available

Prediction | Theory | Experimental efficiencies | Observed

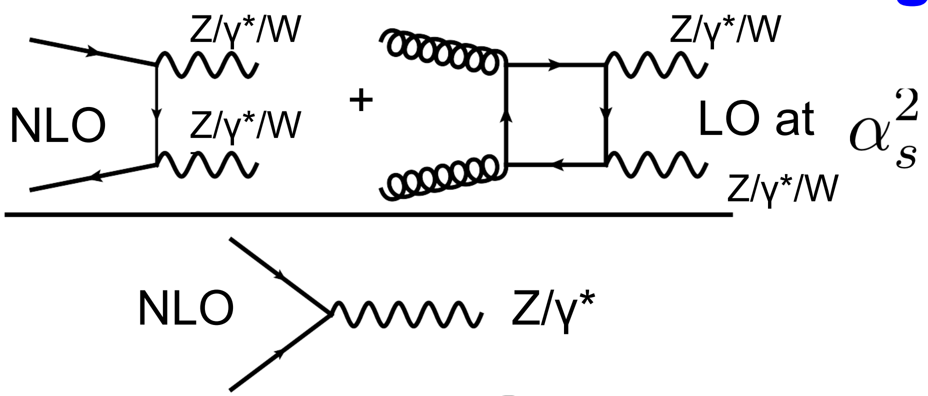
$$N(VV) = \left(\frac{\sigma(pp \to VV)}{\sigma(pp \to Z^{(*)})}\right)_{Th} \cdot \epsilon(ll \to Nl) \cdot N_{Obs}(Z^{(*)})$$

M. Dittmar, F. Pauss, and D. Zurcher, Phys. Rev. **D56**, 7284 (1997)

Abdullin et al. in hep-ph/0604120 computed the ratio ZZ/Z to NLO

Ratio ZZ(WW)/Z$^{(*)}$

- **The production of ZZ and WW is enhanced by large contributions from gg->VV with gluons in the initial state**
  - **Formally a part of the NNLO contribution, but enhanced due to the large gluon flux**



Phys.Rev.D80:054023,2009

Including decays into leptons

$$R = \frac{\sigma^{NLO}_{q\bar{q}\to ZZ,WW} + \sigma^{LO}_{gg\to ZZ,WW}}{\sigma^{NLO}_{q\bar{q}\to Z^{(*)}}}$$

Nominal Values of ZZ/Z*

- Ratios are constructed such that the invariant mass of Z* and ZZ are in the same bin
  - Contribution from gg->ZZ increases sigma by ~13%
  - Ratio depends weakly with Mass (nice surprise!)

Cross-sections in fb

Mass Range	$\sigma^{NLO}_{q\bar{q}\to Z^*}$	$\sigma^{NLO}_{q\bar{q}\to ZZ}$	$\sigma^{LO}_{gg\to ZZ}$	$\frac{\sigma_{ZZ}}{\sigma_{Z^*}} \times 10^3$
200 - 250	1773.7	7.99	1.182	5.17
250 - 300	753.2	3.65	0.530	5.54
300 - 350	372.4	1.86	0.246	5.66
350 - 400	205.7	1.07	0.131	5.83
400 - 450	121.0	0.64	0.082	5.94
450 - 500	76.0	0.40	0.055	6.01
500 - 750	143.9	0.74	0.114	5.92
750 - 1000	27.4	0.16	0.033	6.88

Ratio WW/Z$^{(*)}$

- Scale-related uncertainties arise from changing scales by factors of 4 (*4,/4)
  - **Pick biggest deviation of changing at the same time and in opposite directions**

M_{Z^*} >185 GeV

	$\sigma^{NLO}_{q\bar{q}\to Z}$	$\sigma^{NLO}_{q\bar{q}\to Z^*}$	$\sigma^{NLO}_{q\bar{q}\to WW}$	$\sigma^{LO}_{gg\to WW}$	$\frac{\sigma_{WW}}{\sigma_Z}\cdot 10^3$	$\frac{\sigma_{WW}}{\sigma_{Z^*}}$
Nom.	785.3	2256	636.0	31.04	0.85	0.296
Max.	6.2	4.6	11.5	62.1	16.1	9.4
Min.	-15.7	-9.9	-13.4	-36.0	-8.6	-5.3

Same as above after multiplying σ(gg->WW) by two

	$\sigma^{NLO}_{q\bar{q}\to Z}$	$\sigma^{NLO}_{q\bar{q}\to Z^*}$	$\sigma^{NLO}_{q\bar{q}\to WW}$	$\sigma^{LO}_{gg\to WW}$	$\frac{\sigma_{WW}}{\sigma_Z}\cdot 10^3$	$\frac{\sigma_{WW}}{\sigma_{Z^*}}$
Nom.	785.3	2256.4	636.0	62.08	0.89	0.309
Max.	6.2	4.6	11.5	62.1	19.2	12.0
Min.	-15.7	-9.9	-13.4	-36.0	-10.6	-6.7

MSUGRA - Parameters

The MSSM has 105 masses, phases and mixing angles. This is a reflection of us not knowing how SUSY is broken – we just put in the most general set of masses and soft SUSY breaking terms into the Lagrangian. This makes things rather hard for experimental (pre-data) analysis, so normally one assumes some well motivated model of SUSY breaking.

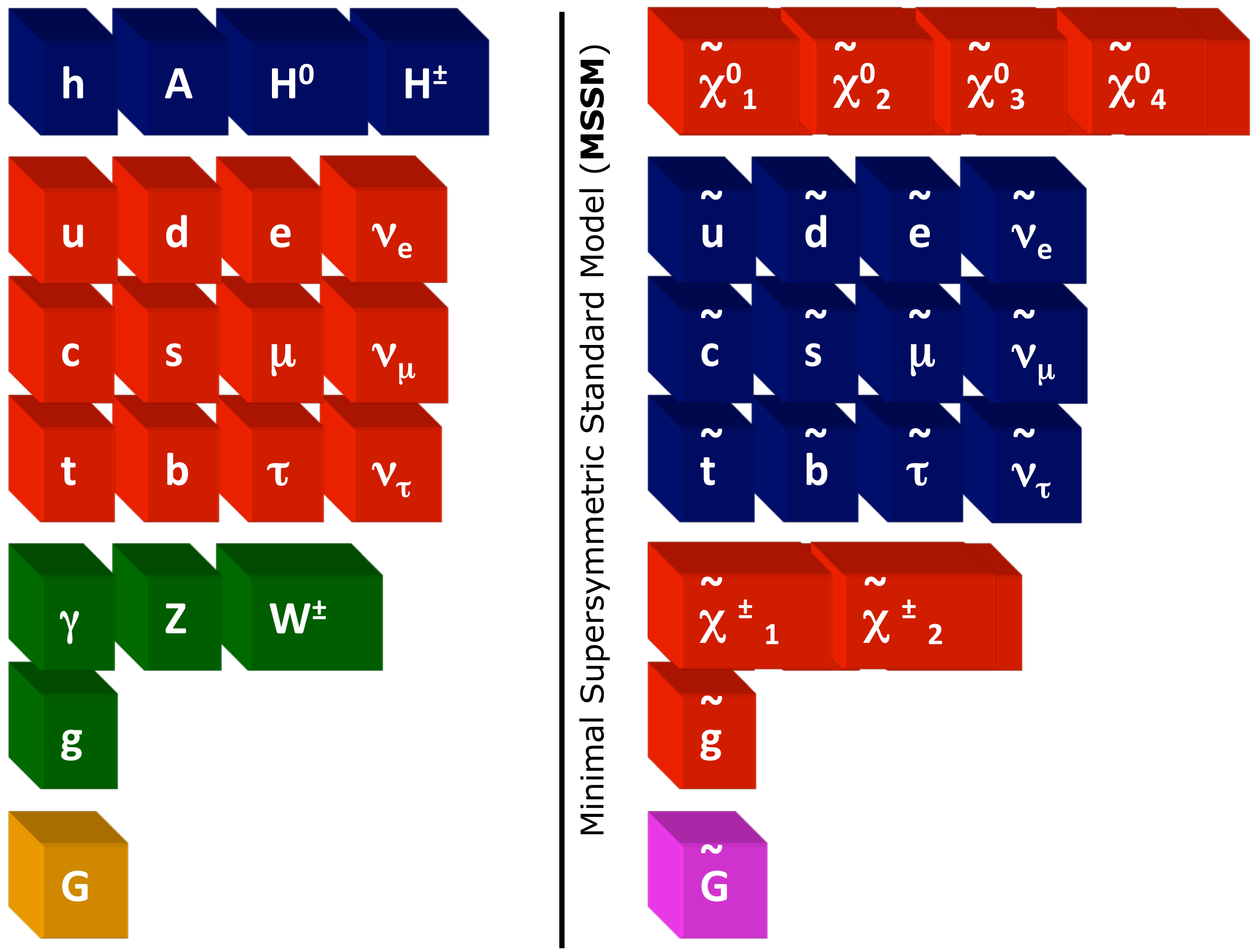
A popular choice is mSUGRA, which is useful for analysis

- **m_0 : universal scalar mass at GUT scale**
- **$m_{1/2}$: universal gaugino mass at GUT scale**
- **tan β : ratio of Higgs vacuum expectation value**
- **sgn μ: sign of Higgsino mass parameter**
- **A_0 : universal s-fermion mass mixing parameter**
- **M(SUSY) < 1 TeV for LSP**
- **Take account of limits from LEP and TEVATRON**

MSUGRA Particles

- SUSY gives rise to partners of SM states with opposite spin-statistics but otherwise same Quantum Numbers.

- **Expect SUSY partners to have same masses as SM states**
  - **Not observed!**
  - **SUSY must be a broken symmetry at low energy**
- **Higgs sector also expanded**
- **Colour-code**
  - **Spin-0**
  - **Spin-1/2**
  - **Spin-1**
  - **Spin-2**
  - **Spin-3/2**



Note: all scalar particles with same *e*-charge, *R*-parity and colour quantum number can mix !

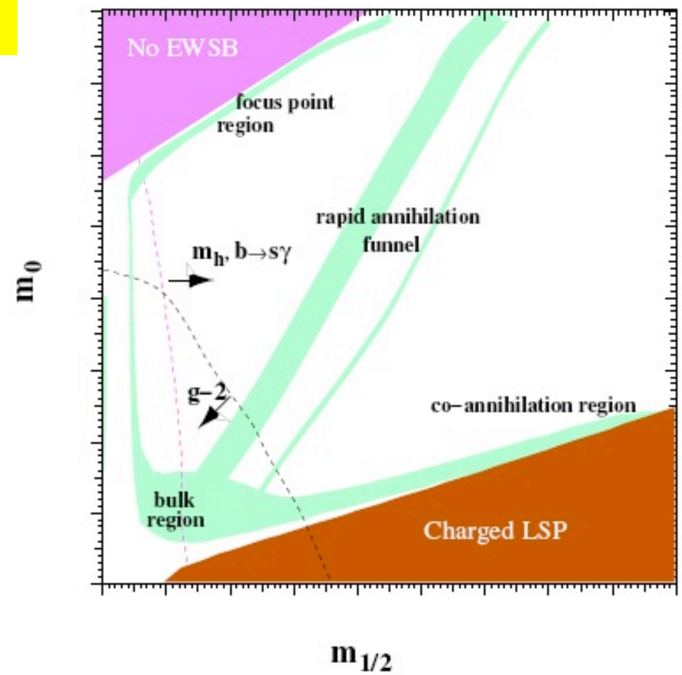
G.Polesello

ATLAS mSUGRA Benchmarks

Large annihilation sross-section required by WMAP data

Boost annihilation via quasi-degeneracy of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

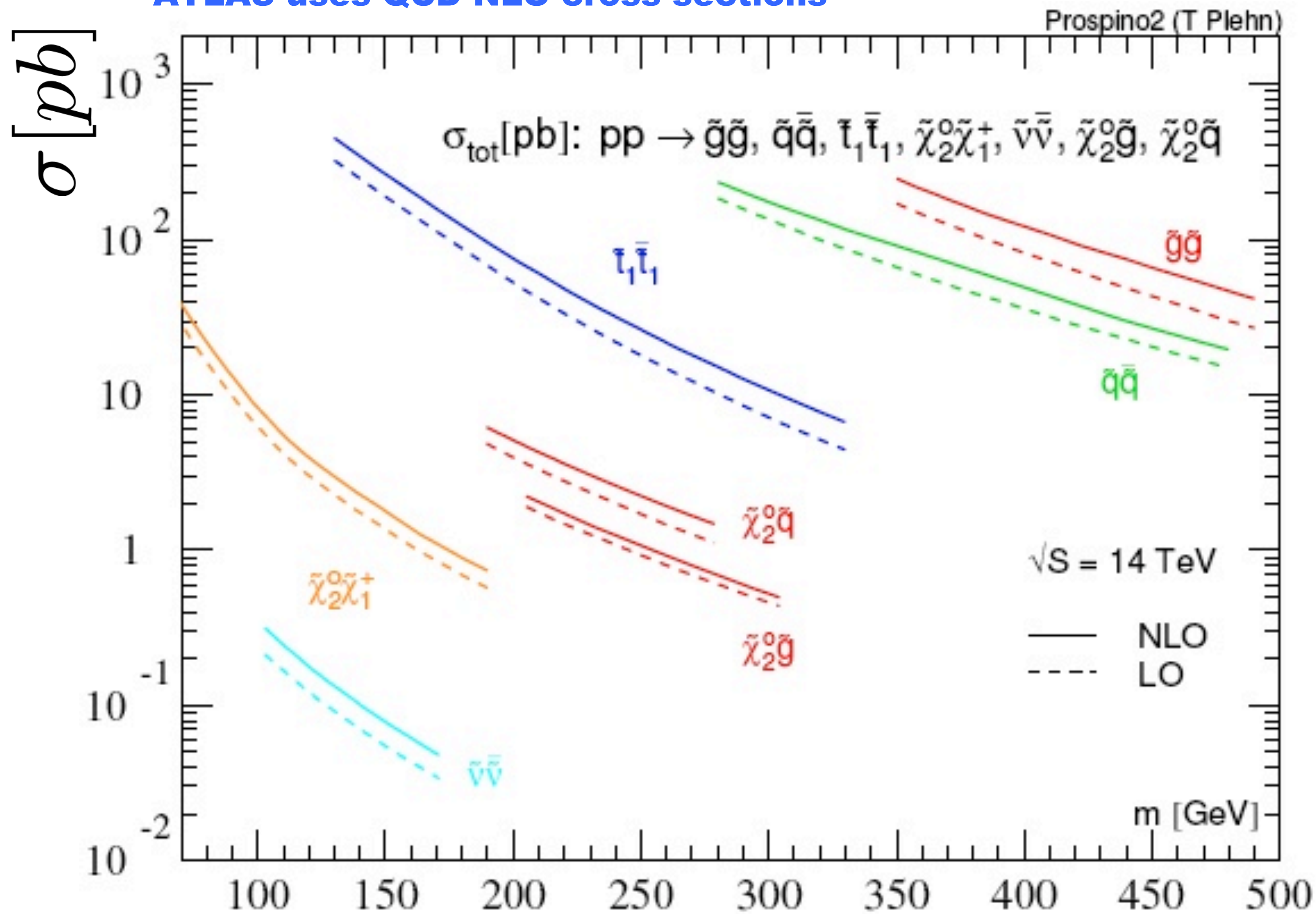
Regions in mSUGRA $(m_{1/2}, m_0)$ plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):



- SU3: Bulk region. Annihilation dominated by slepton exchange, easy LHC signatures fom $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$
- SU1: Coannihilation region. Small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev). Dominant processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$ Similar to bulk, but softer leptons!
- SU6: Funnel region. $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$ at high $\tan\beta$ Annihilation through resonant heavy Higgs exchange. Heavy higgs at the LHC observable up to ∼800 GeV
- SU2: Focus Point high m_0, large higgsino content, annihilation through coupling to W/Z Sfermions outside LHC reach, study gluino decays.
- SU4: Light point. Not inspired by cosmology. Mass scale $\sim$ 400 GeV, at limit of Tevatron reach

mSUGRA Cross-sections

- Strongly interacting sparticles (squarks, gluinos) dominate production
  - Cross-sections driven by sparticle masses
    - ATLAS uses QCD NLO cross-sections



Generic SUSY Signatures

(A) Light sneutrinos/sleptons

$\tilde{q}_L \to \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \to \tilde{\nu}+l / \tilde{l} + l$

>>Lepton enriched

(B) Direct decay

$\tilde{q}_R \to \tilde{\chi}_1^0 + q$

>> Lepton depleted

(C) Light Stop/Sbottom

$\tilde{g} \to \tilde{t}+t \to \tilde{\chi}_2^+ + b \to \tilde{\chi}_2^0 + W / \tilde{\chi}_1^+ + Z$

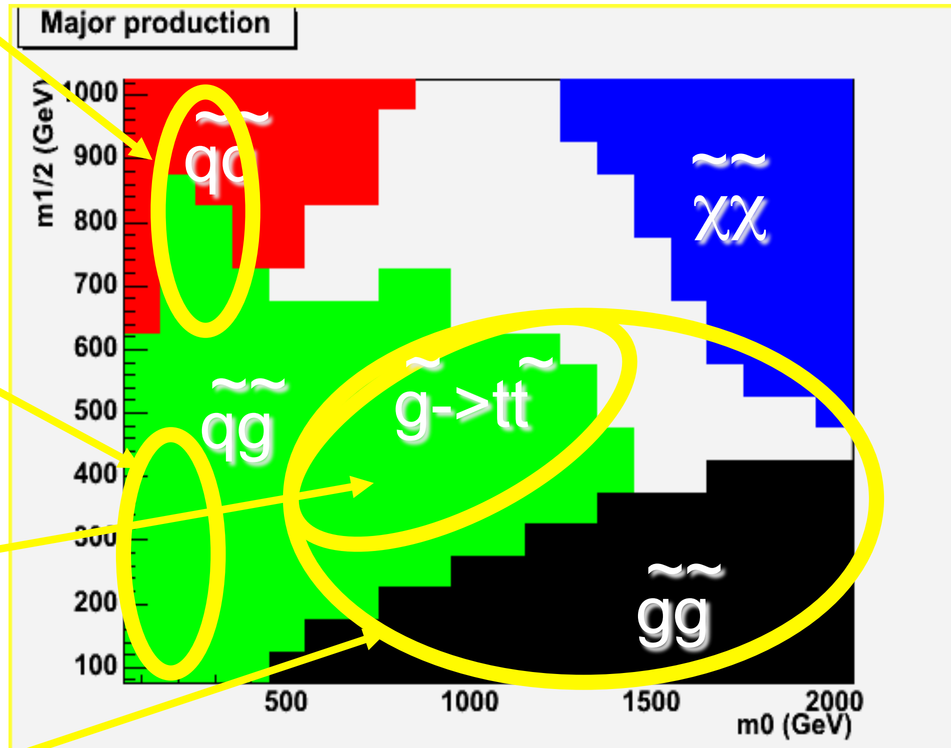
>> Lepton/b-jet enriched

(D) gluino production/decay

$\tilde{g} \to \tilde{\chi}_n^+ / \tilde{\chi}_n^0 + qq$

>> Multi-jets

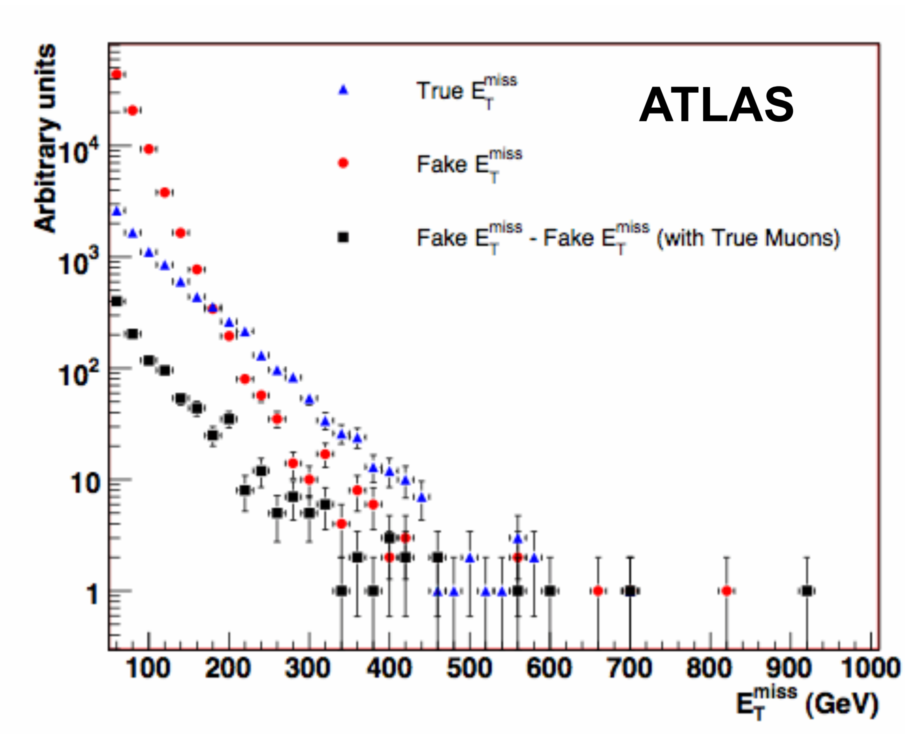
Leading Production

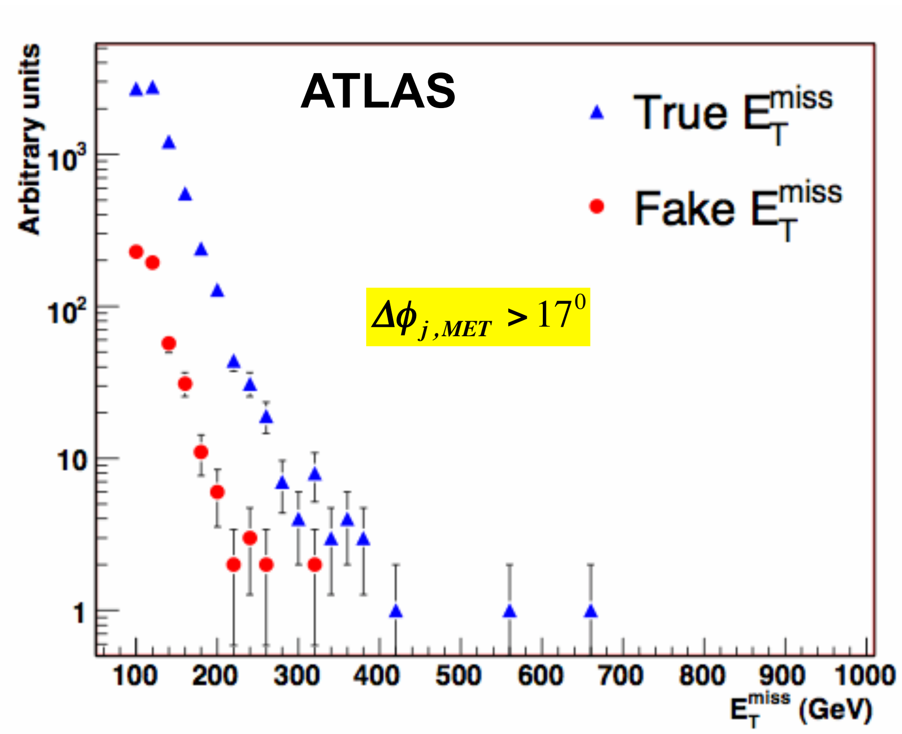


Fake MET

- The identification, suppression and prediction of fake MET is one of the most complex problems for experimentalists, even after the event clean up. This has strong implications on SUSY searches

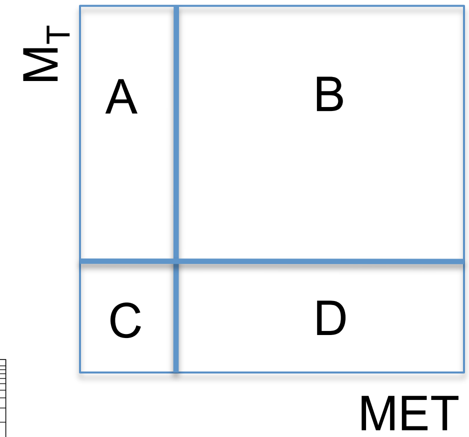
Study with QCD di-jets with 560<E_T<1120 GeV



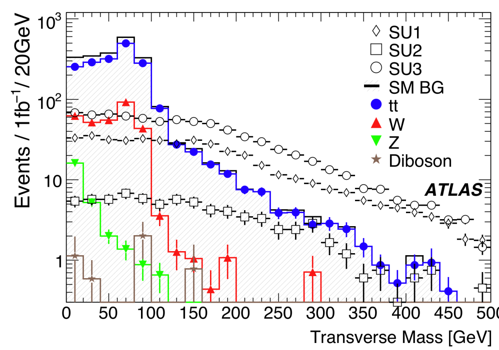


Inclusive Search with one Lepton

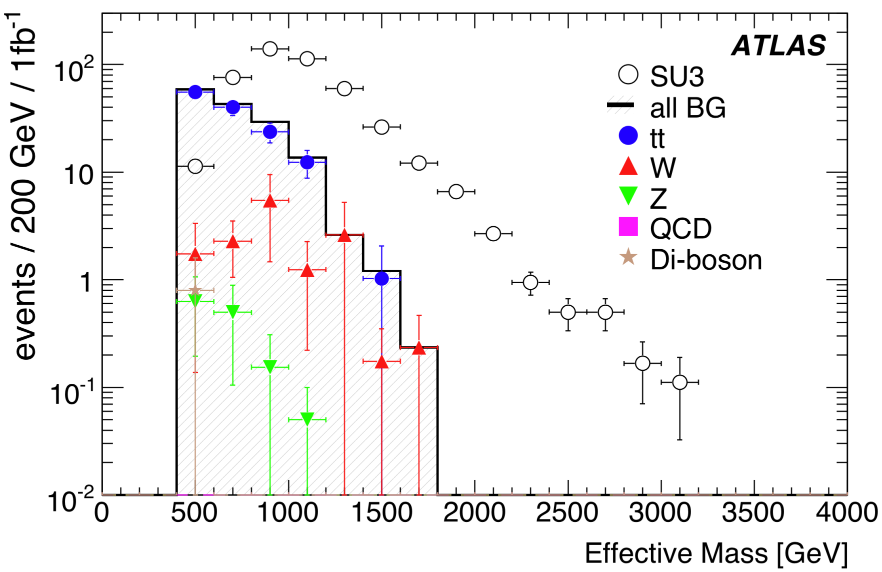
- **Zero lepton signature is the least model dependent. However, backgrounds in Lepton +jets+MET may be easier to control**
  - **tt+jets is the dominant background, QCD negligible**
  - **Need to use data-driven techniques to extract backgrounds**
    - **Use weakly correlated variables**

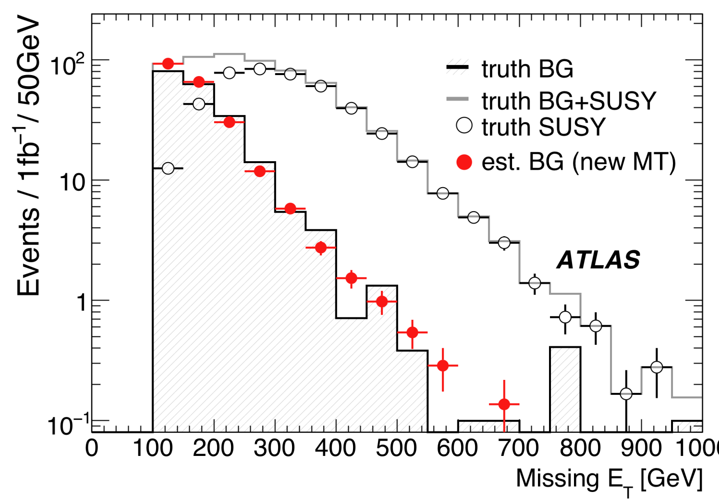


$$N(B) = N(D) \times \frac{N(A)}{N(C)}$$



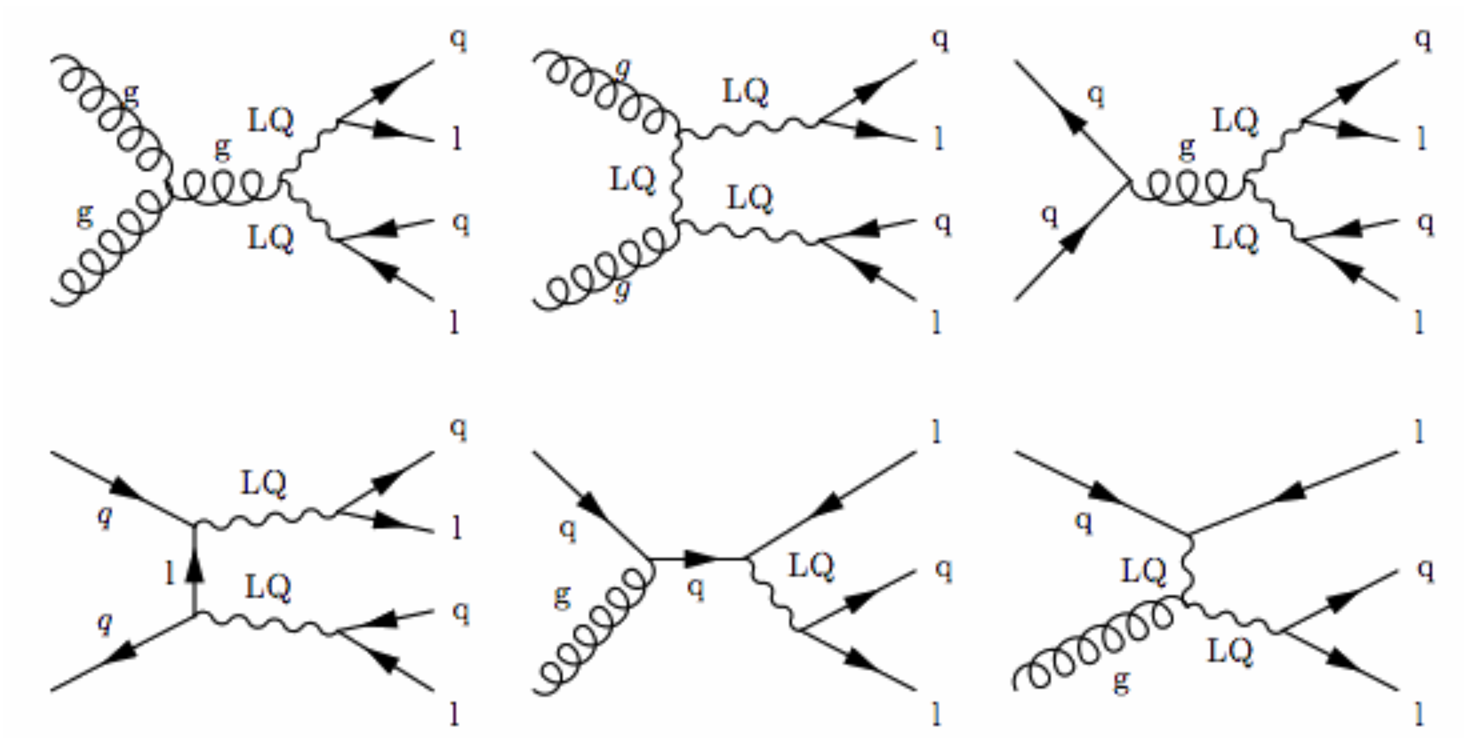
- **Results below after application of same cuts at in the 0-lepton analysis**





Searches for Lepto-Quarks

The symmetry between leptons and quarks impels some to consider bosons carrying both lepton and quark quantum numbers. This includes a fractional electric charge.
At proton-proton colliders leptoquarks can be produced doubly(via the strong interaction) or singly (via the lepton-quark coupling). Usually experiments consider decays into electrons and muons

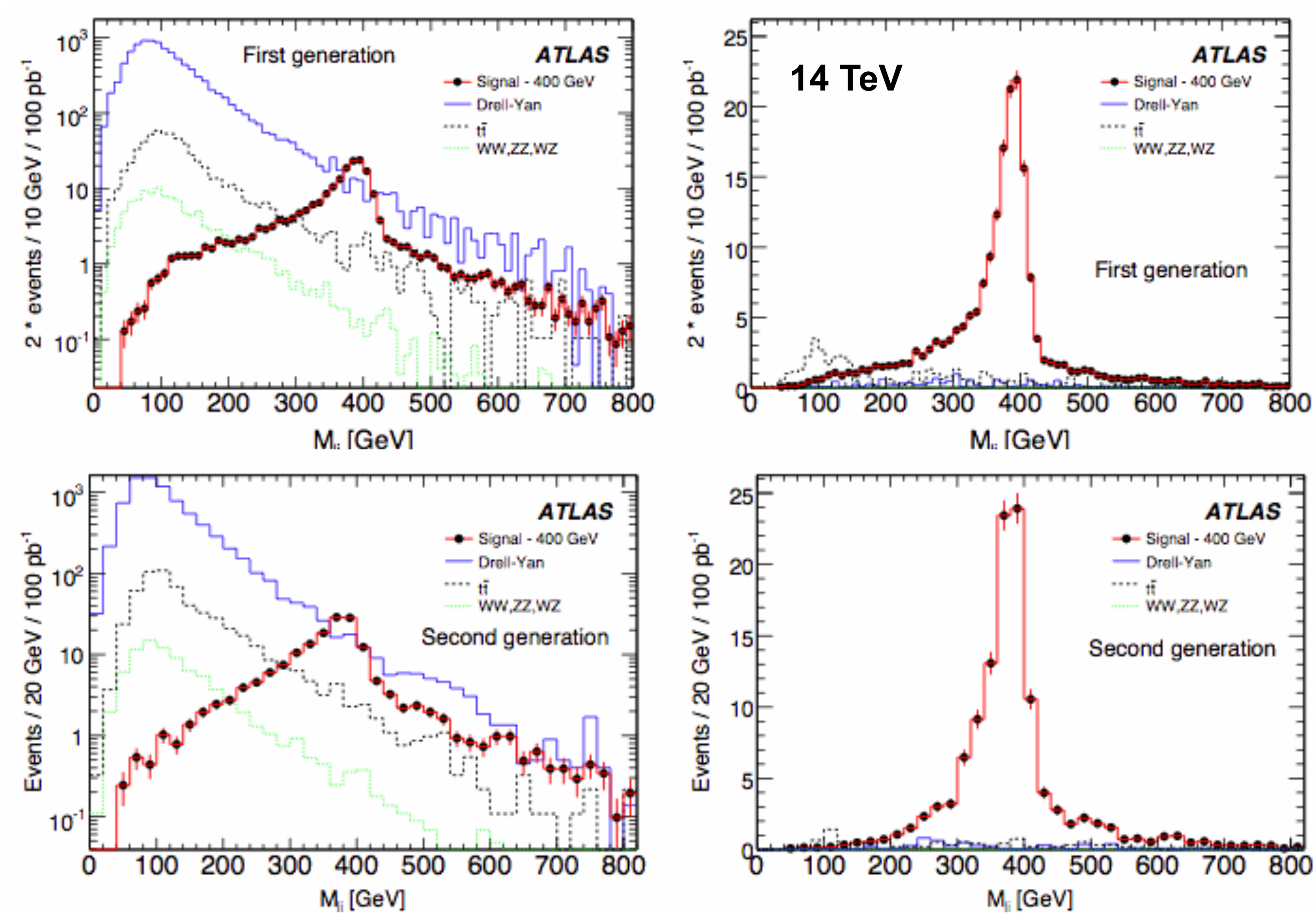


Search for Lepto-Quark pair production

Before tight selection criteria | **After tight selection criteria**

Electrons

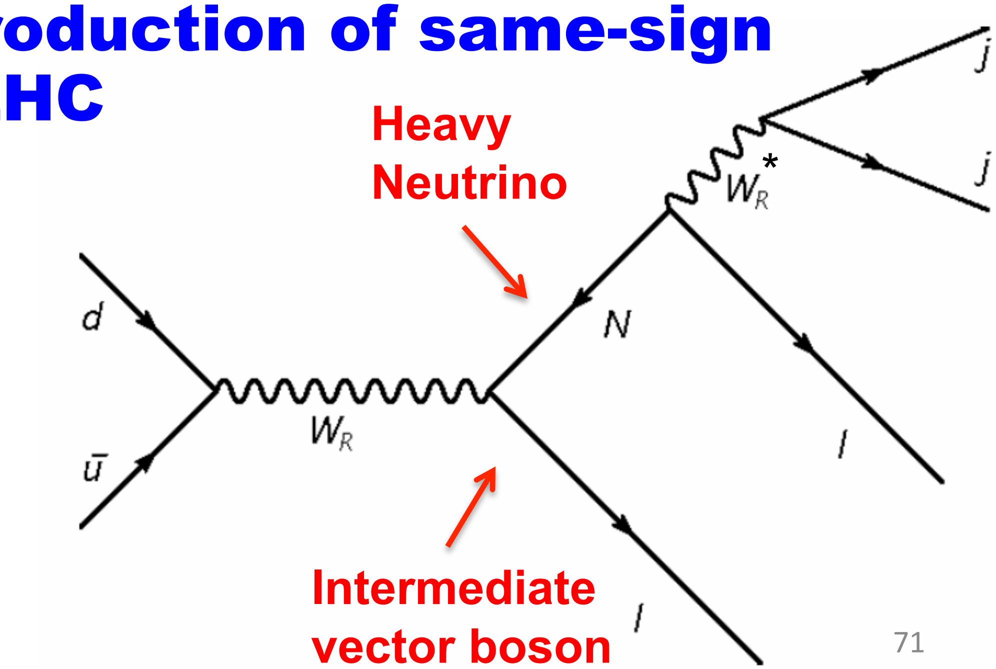
Muons



Left-Right Symmetric Models

- LRSM conserve parity at high energies by introducing three new heavy right-handed Majorana neutrinos. The masses of the left-handed neutrinos are explained by the see saw mechanism
  - The lepton number L is violated (ΔL=2)
  - This leads to the production of same-sign lepton pairs a the LHC

The most generic way of producing same-sign lepton pairs within LRSM models



Analog to neutrino-less beta decay