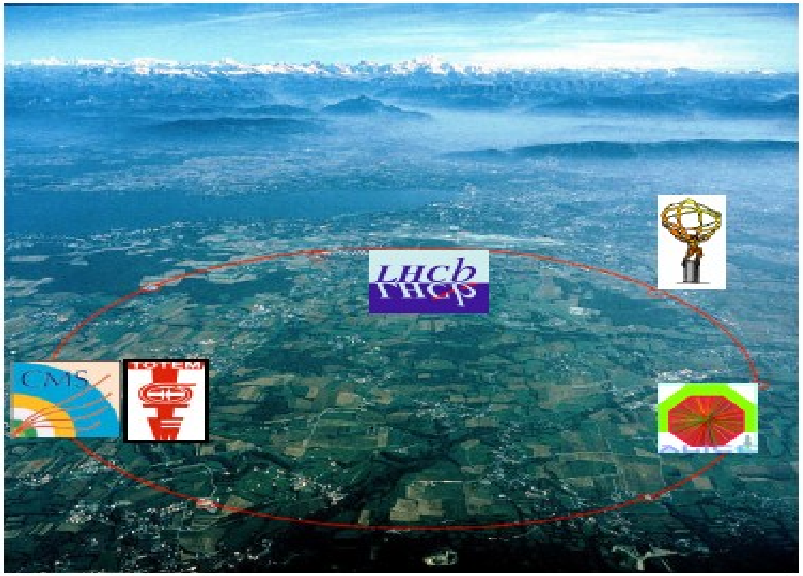
Physics Program

of the experiments at

Large Hadron Collider



Exotic models

End of pp RunI

Long list of models and signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

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A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

→ Practical

→ Less model-dependent

→ Important to cover every possible signature

Supersymmetry

Cascade ending with LSP
→ large MET

1 Jets+MET: Gluino and Squark prod. dominate

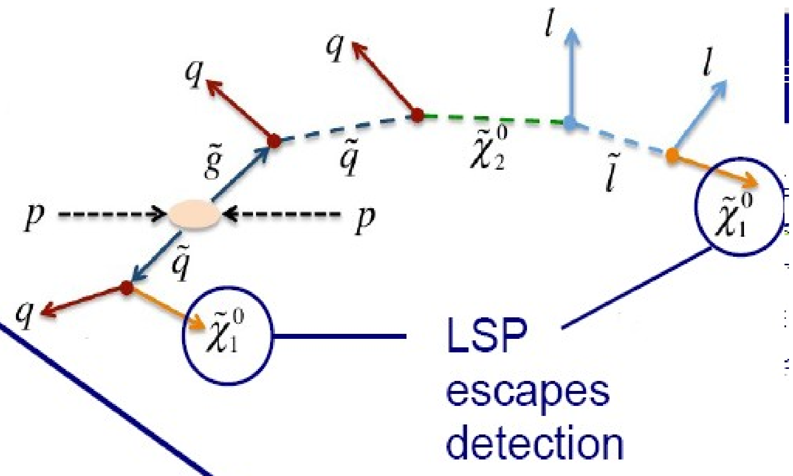
2 Leptons(+jets)+MET: lower branching ratio/cross-section but complementary

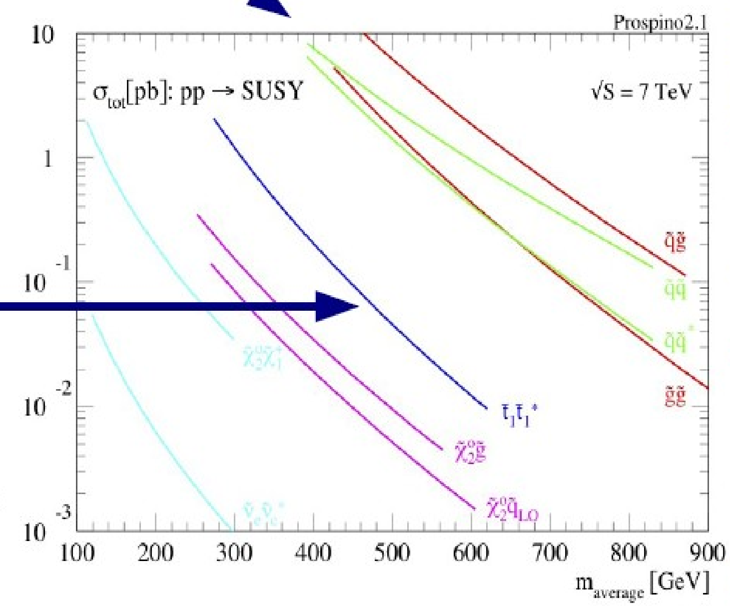
3 3rd generation (b or t)+MET:

- → in cascade
- → direct production requires > 1 fb^{-1}
  → coming soon

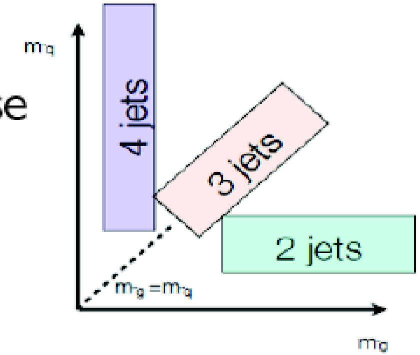
4 Photon(s)+MET: GMSB models

5 "Exotic" SUSY: long-lived, no MET

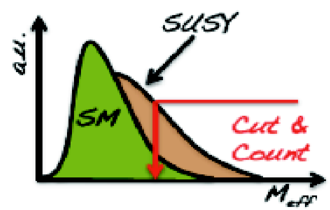


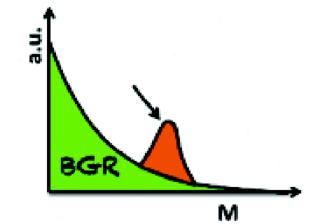


General search strategy



- Definition of **Signal Regions** (SRs) that maximise sensitivity to different models
  - → based on **discriminating variables**
- Identification and estimation of **SM backgrounds**
  - → different techniques (preferably data-driven)
- Search for **non-SM excess**
  - → cut & count
  - → resonances





- If no excess, **model independent limits** set
  - → different stat. methods
  - → different interpretations

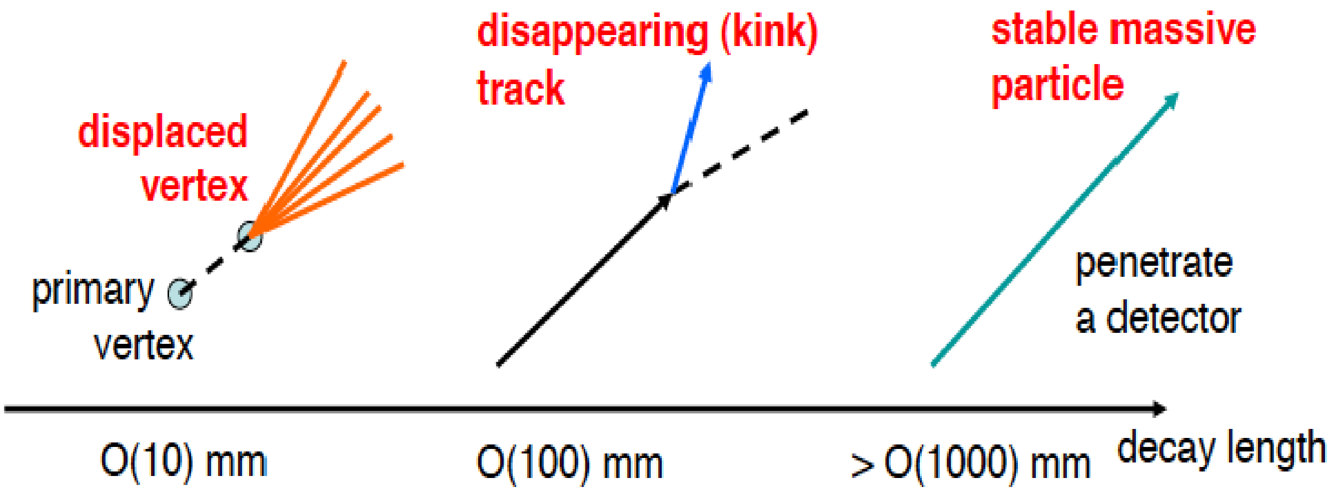
$$\sigma_{\rm BSM} \times \varepsilon \times A$$

Null searches so …

- Null searches also for any other BSM signal
- **What next…**
  - Generalize away from (over) constrained scenarios
  - Gaugino sector and sleptons: multi-leptons, photons
  - Stop (and sbottom and stau) sectors (major motivation for SUSY at low energies)
  - Non- “canonical” scenarios:
    - semi-stable SUSY particles, R-parity violation

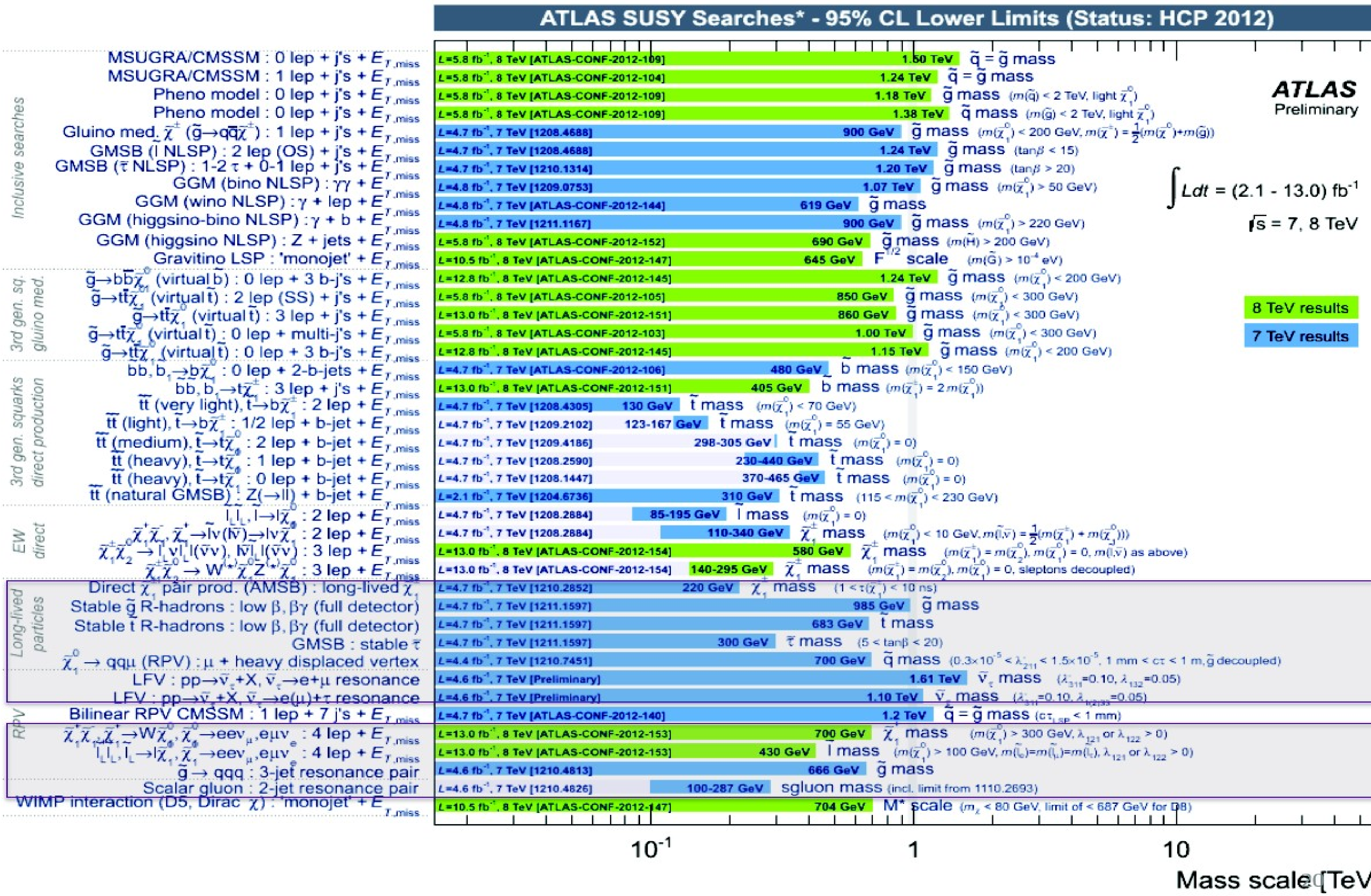
Special final states

Long-living supersymmetric particles: very well possible in SUSY!

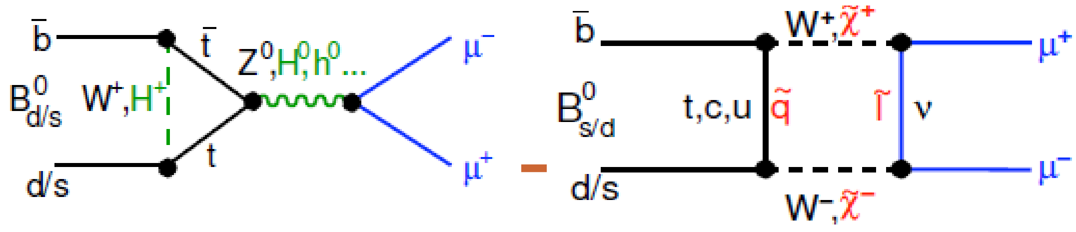


R-hadrons, R-parity violation, compressed spectra (AMSB)

Supersymmetry: search results



Rare decays



First observation of $B_s^0 \to \mu^+\mu^-$ LHCb-PAPER-2012-043

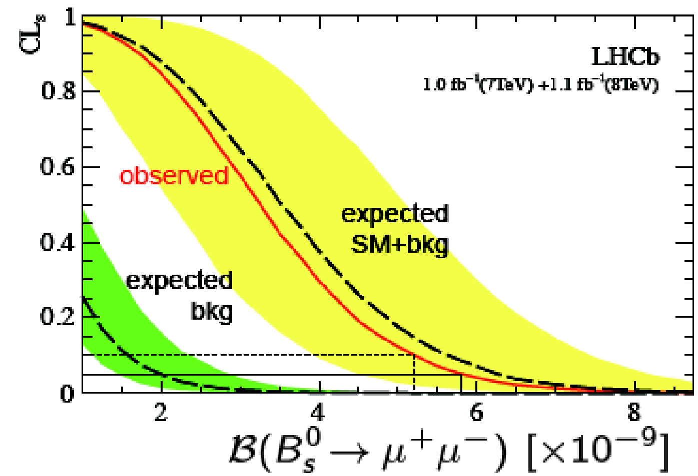
- In $1\,\mathrm{fb}^{-1}$ ($\sqrt{s} = 7\,\mathrm{TeV}$) + $1.1\,\mathrm{fb}^{-1}$ ($\sqrt{s} = 8\,\mathrm{TeV}$) of data, LHCb observes a signal for $B_s^0 \to \mu^+\mu^-$ that is **incompatible with the background only hypothesis at 3.5** σ. With:

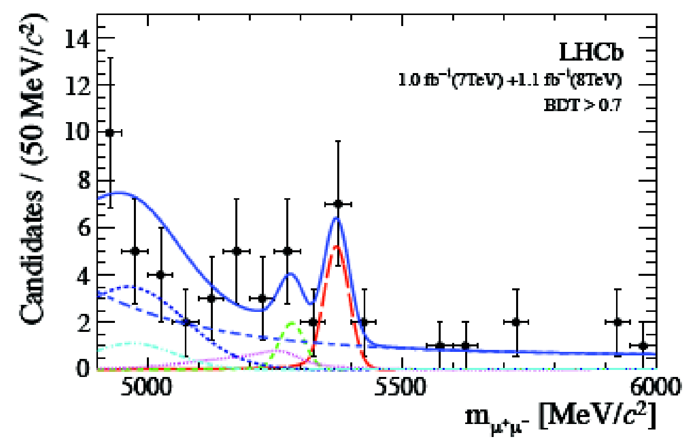
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.2\,^{+1.5}_{-1.2} \times 10^{-9}$$

c.f. a time integrated SM expectation of:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$$

[arXiv:1208.0934], [arXiv:1204.1735]



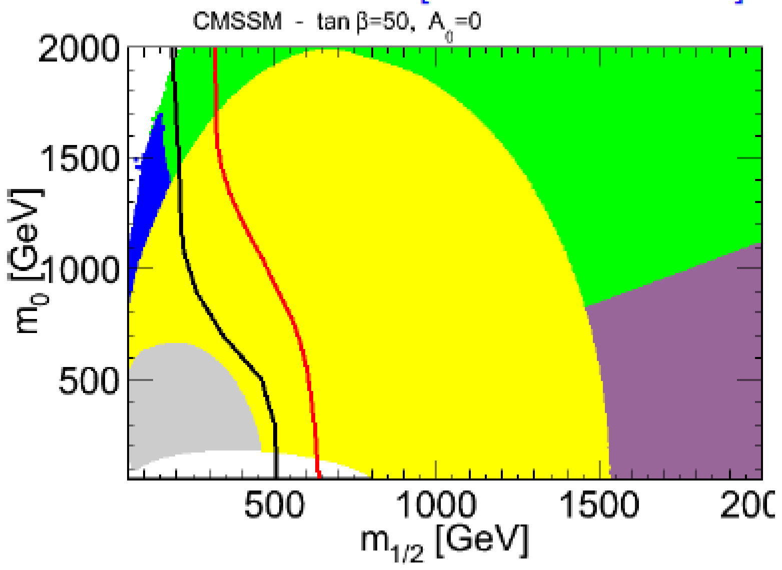


Constraints in CMSSM model

In general a SM-like $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ rules out CMSSM points with large $\tan\beta$.

Direct search results (CMS $5\,\mathrm{fb}^{-1}$), Charged LSP, $B \to \tau\nu$, $B_s^0 \to \mu^+\mu^-$, Allowed region.

F. Mahmoudi et. al. [arXiv:1205.1845]



At lower tanβ the relative importance of direct searches increases.

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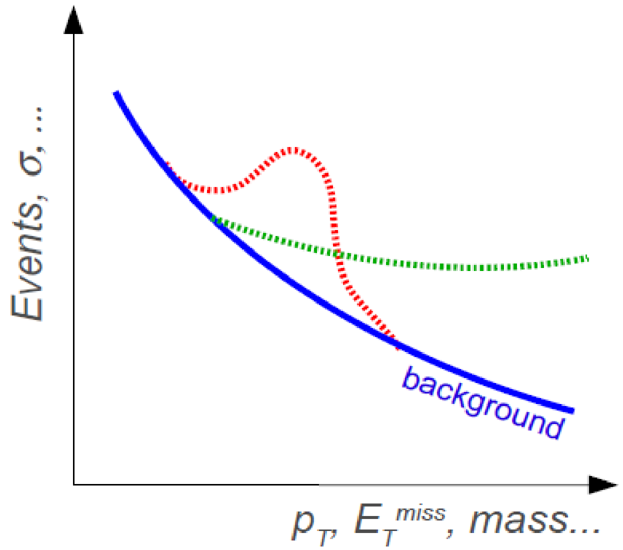
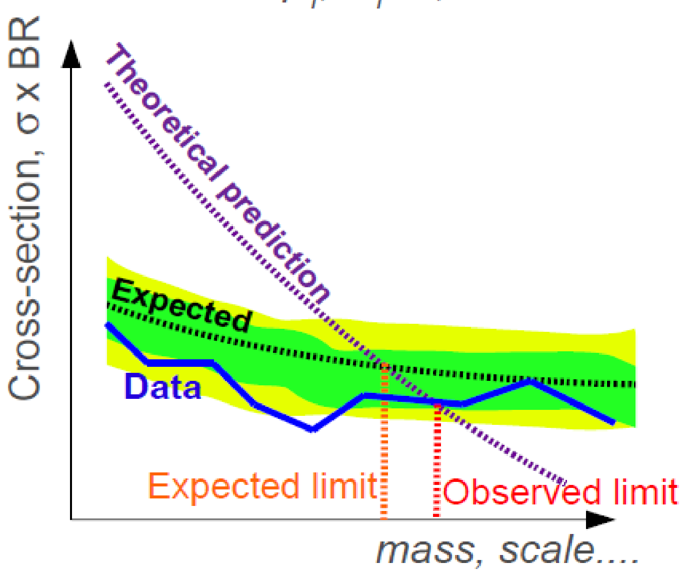
Typical exotic search topology





Search phase:

Search for deviations from known background,
in the spectra of reconstructed mass, sum(pT) etc...

Localized excess, bump, resonance

Non resonant phenomena

Limit setting

(do this for every point in the parameter space):

1) compute theoretical prediction

2) estimate acceptance $\mathcal{A}$, efficiency ε and luminosity $\mathcal{L}$ and their uncertainties

3) Pseudo-experiments

- *generate BG only pseudo experiments (PE).*

- *for each PE estimate the consistency between pseudo-data and signal+background hypothesis and get 95%CL limit on signal cross-section*

- *for all PE calculate the **median**, the **1 sigma RMS** and the **2 sigma RMS***

3) plot the σ(Data)

4) compute observed limits

5) compute expected limits

Heavy resonances

Predicted in many extensions of the Standard Model.
Examples:

→ Randall-Sundrum gravitons, *G* and G*bulk from warped extradimensions*
→ Technicolor → *narrow technihadrons, chiral bosons Z*, W**
→ GUT inspired theories → *Z', W' from a higher symmetry (E6)*
→ Composite models *for quarks, lepton with substructure scale* Λ
→ Quantum black holes, ADD, CI

	Signature	Model	Luminosity [fb^{-1}]	Publication
8TeV	$\ell^+\ell^-$	Z'	6	*ATLAS-CONF-2012-129*
	jj	q*	13	*ATLAS-CONF-2012-148*
	$ZZ(\ell\ell jj)$	G^*_{bulk}	7	*ATLAS-CONF-2012-150*
	$\ell\ell\gamma$	ℓ^*	13	*ATLAS-CONF-2012-146*
	jj	q*	5.8	*ATLAS-CONF-2012-088*
7TeV	$\ell^+\ell^-$	Z',G*,TC, KK,..	4.9	*arXiv:1209.2535*
	$\tau\tau$	Z'	4.6	*arXiv:1210.6604*
	$\ell\nu$	W',W*	4.7	*arXiv:1209.4446*
	jj	q*,QBH,W'	4.8	*arXiv:1210.1718*
	$WW(\ell\nu\ell\nu)$	G^*, G^*_{bulk}	4.7	*arXiv:1209.2880*
	$\gamma\gamma$	RS, ADD	4.9	*arXiv:1209.8389*
	$t\bar{t}$	LPTC Z', g_{KK},	4.7	*arXiv:1207.2409, arXiv1211.2202*

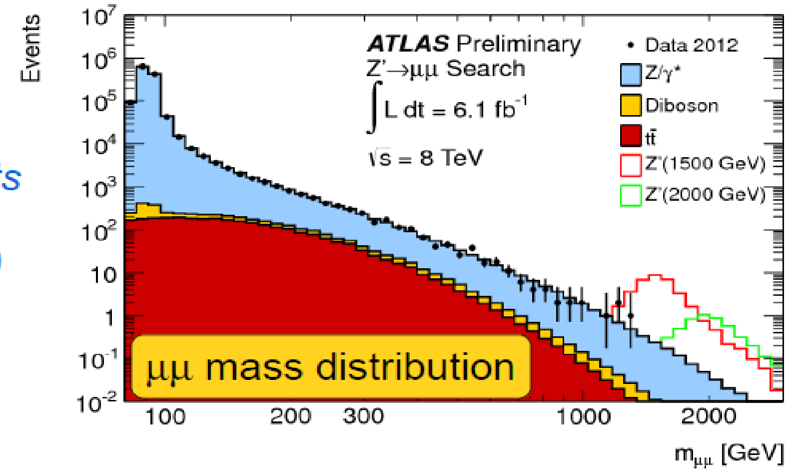
Dilepton resonance search

6 fb^{-1} 8TeV
ATLAS-CONF-2012-129

Well understood final states,
- → Isolated leptons (here ee, μμ)
- → main Background *Drell-Yan*

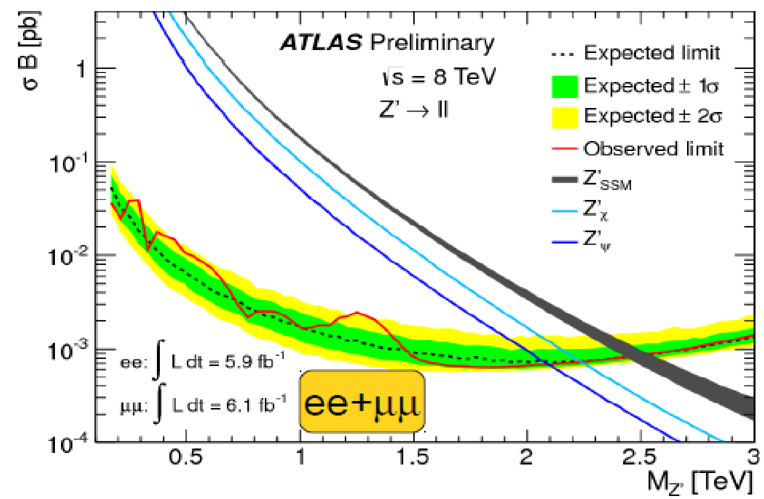
other background: dibosons, ttbar, multijets, W+jets
Sum of BG normalized to the Z-peak (70-110GeV)
Dominant uncertainties: 20%(theory), 21%(ee BG)

Experimental challenge
- no control sample at TeV level (like Z or W)
- understand efficiency and resolution
- confidence in alignment (μμ)



2 Benchmark models used here
Lower limit at 95%CL for 8TeV data:

Z'$_{SSM}$: m>2.49 TeV *(7TeV: 2.22 TeV)*
Z'$_{E6}$: m>2.09-2.24 TeV

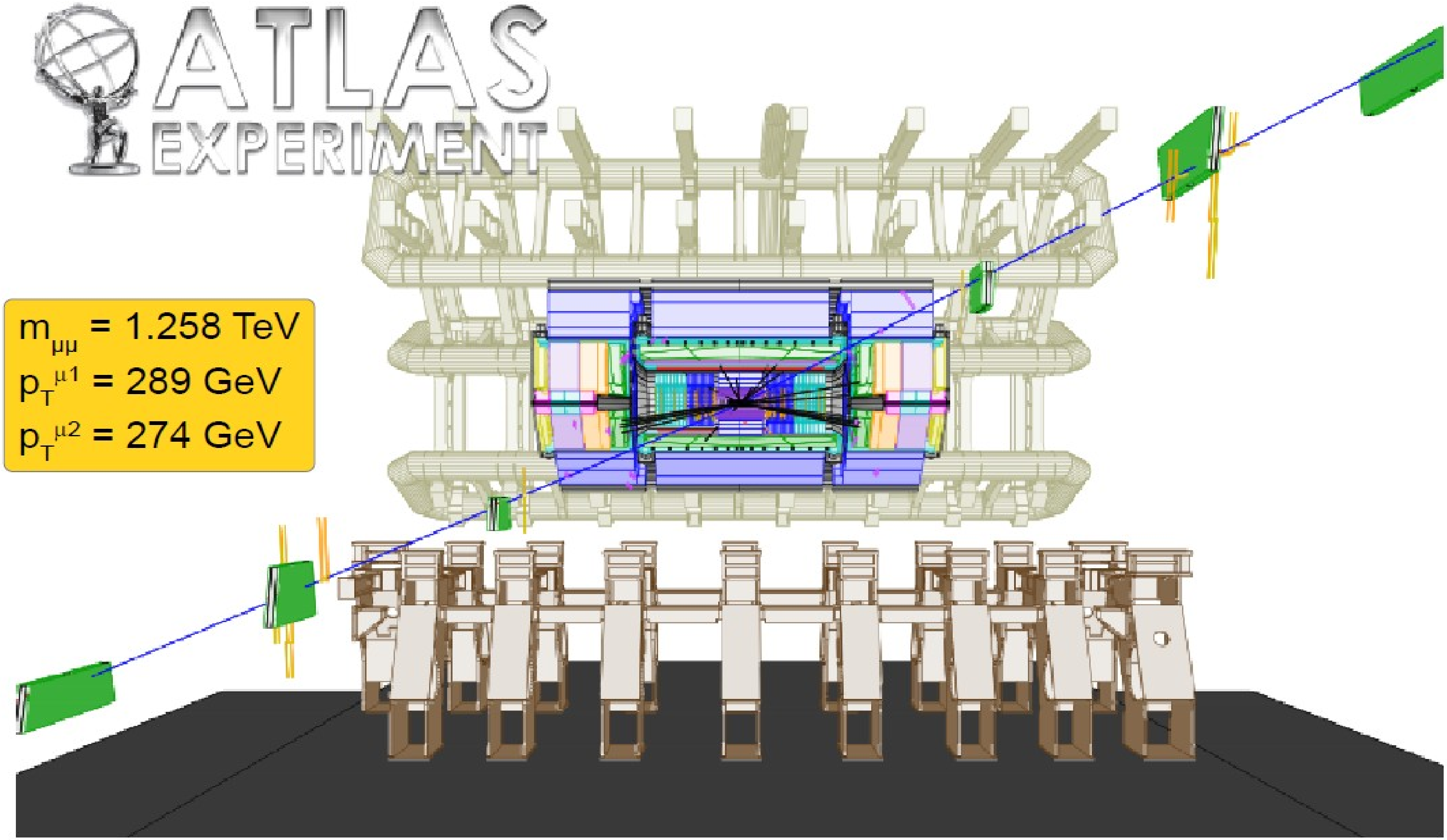


Mass limits E6 Z' 8TeV

Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
Observed mass limit [TeV]	2.09	2.10	2.15	2.14	2.18	2.24
Expected mass limit [TeV]	2.07	2.08	2.14	2.13	2.17	2.23

Other analysis probing ττ with 7TeV data: **Z'$_{SSM}$(ττ): m>1.40 TeV** *arXiv:1210.6604*

Highest $m_{\mu\mu}$ candidate

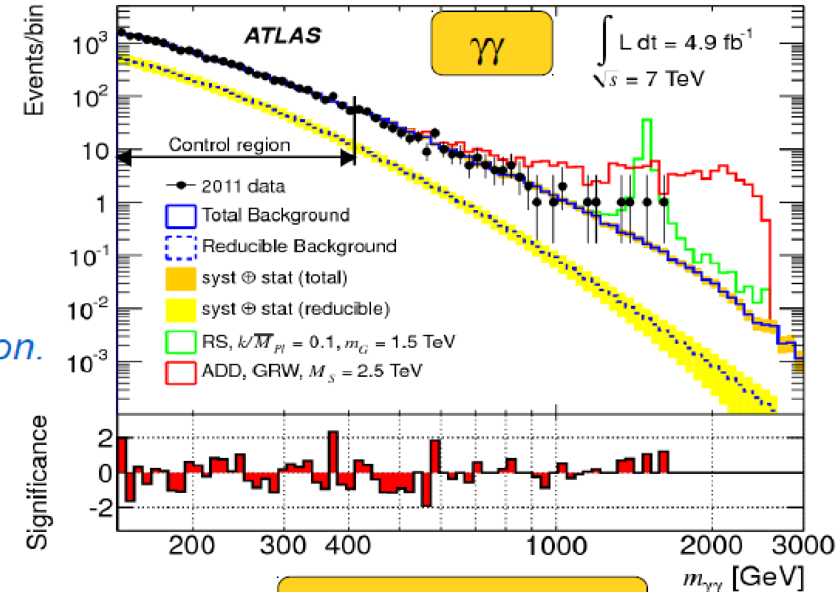


Diphoton

4.9 fb^{-1} 7TeV *arXiv:1209.8389*

Method:
Look invariant mass of two highest-E_T (>25GeV) isolated tight photons

Background:
- SM γγ (NLO, irreducible)
- γ+j, j+γ, jj with jet faking γ (data driven, reducible)
Background normalization in low mass control region.
Uncertainties: 9% (experiment), 5-15% (theory)

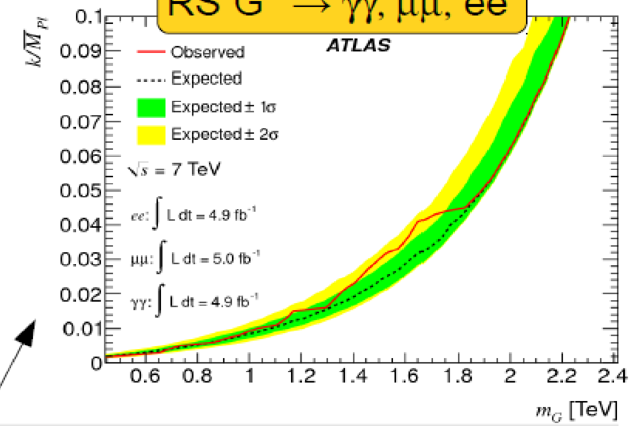


RS1 (search for bumps)
Example 95% CL limits:
RS G* ($k/\overline{M}_{Pl}$=0.1): m>2.06 TeV (γγ)
m>2.23 TeV (γγ+ee+μμ)

ADD Extra-dimensions (tail excess)

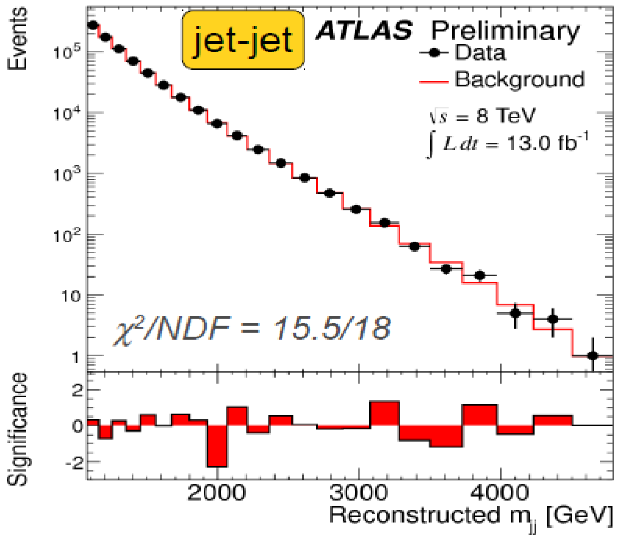
ADD: M_s>2.79 – 4.18 TeV (γγ+ee+μμ)
depending on number of EDs and theoretical formalism used.

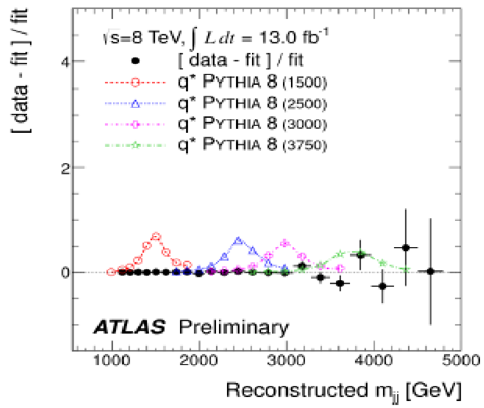
RS G* → γγ, μμ, ee



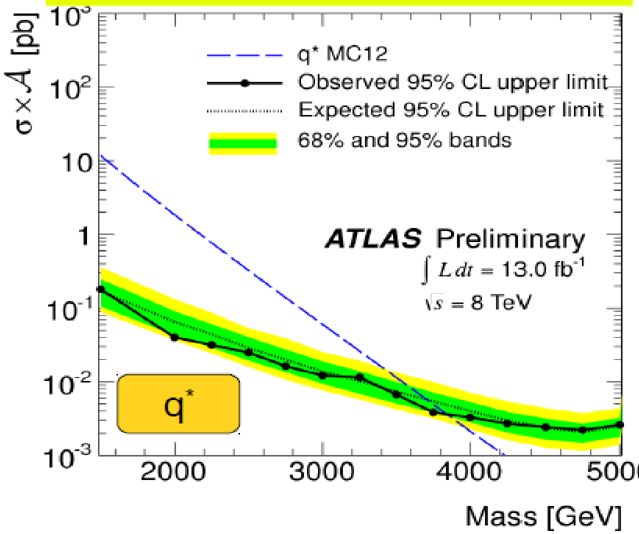
$k/\overline{M}_{Pl}$ dimensionless coupling to the SM fields

Dijet resonance search





13 fb^{-1} 8TeV *ATLAS-CONF-2012-148*



2 highest pT jets in an event

Fit m_{jj} data with smooth function and look for a bump

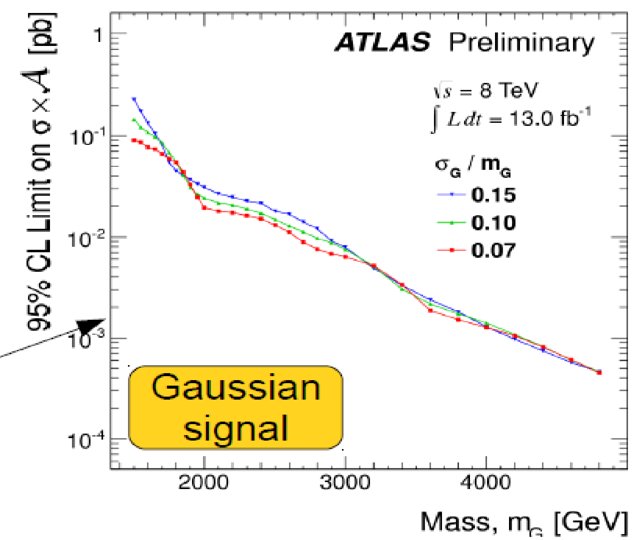
$$f(x) = p1(1-x)^{p2} x^{p3+p4\ln x} \quad with\ x = m_{jj}/\sqrt{s}$$

Uncertainties: 4% for p_T^{jet}>1TeV (JES), 3.6-3.9% luminosity

Two 8TeV benchmark models used (95%CL limits):

Excited quark: M_{q^*} > 3.84 TeV *(7TeV: 2.83 TeV)*

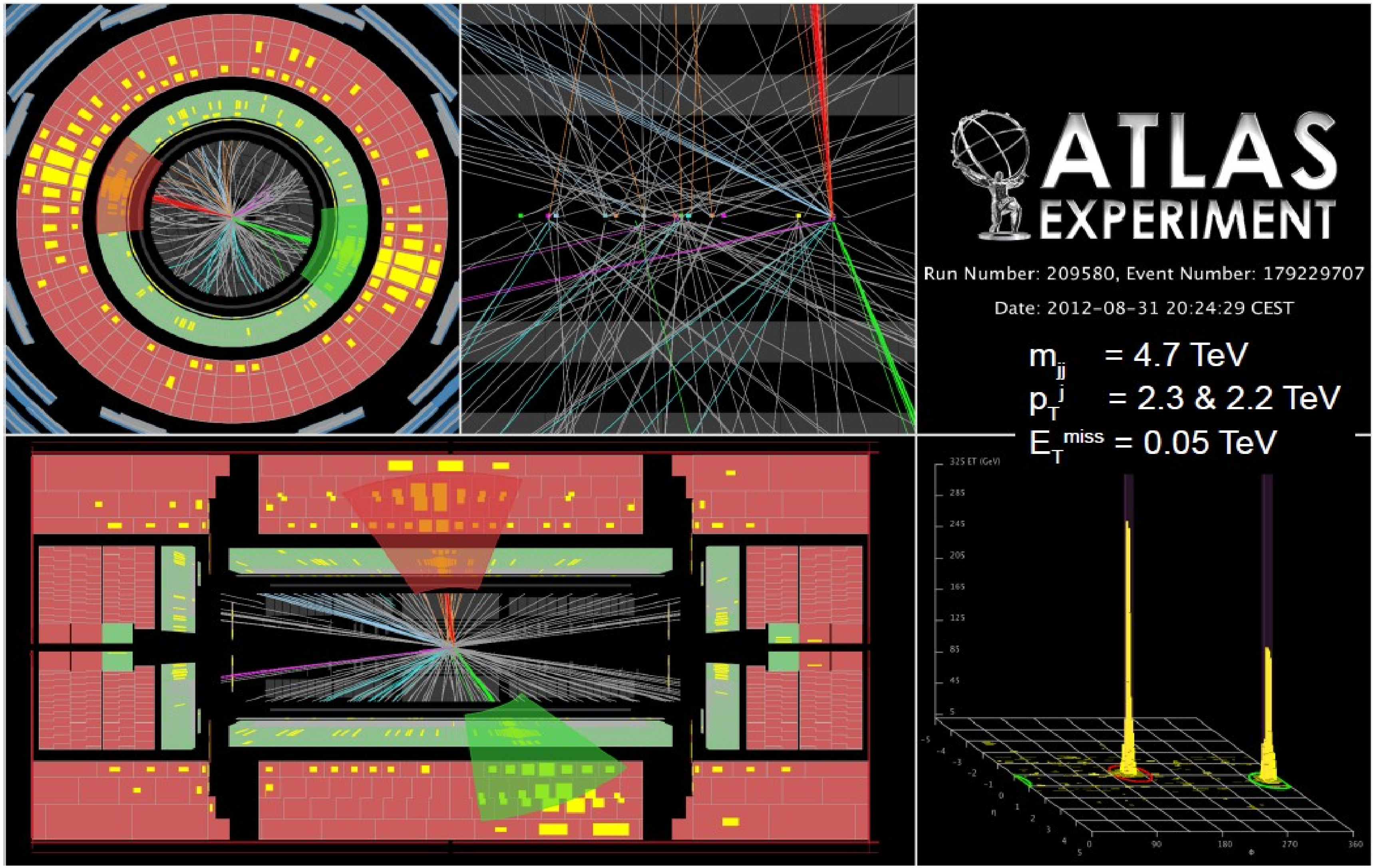
Model independent: Limit on generic Gaussian bumps



More models were tested with 7TeV:

CI, W'_{SSM}, Color octet scalar, string resonances

Dijet candidate event



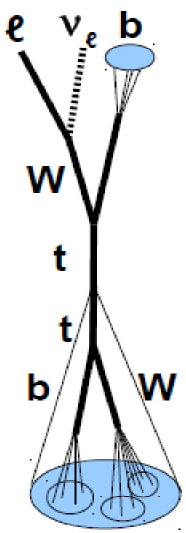
Top - antitop

Several BSM predict existence of heavy particles decaying to $t\bar{t}$.

Here: Lepton + jets channel

$t\bar{t} \rightarrow Wb\ Wb \rightarrow \ell\nu_\ell \bar{b}\ q\bar{q}b$ (~28% of $t\bar{t}$ events)

2 reconstruction scheme: resolved & boosted



Second jet:
Jet assignment relies on vicinity of charged lepton

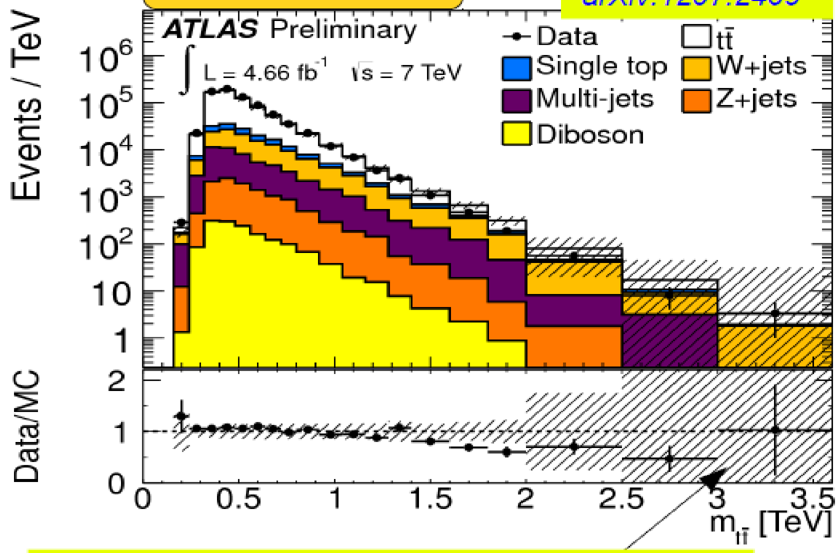
resolved: Kinematic fit on W and top mass to find best jet combination.

boosted *($m(t\bar{t})$> 1TeV)*
Specific boosted jets (single fat jet) reconstruction needed.
Disentangle substructures: light quarks from b jet.

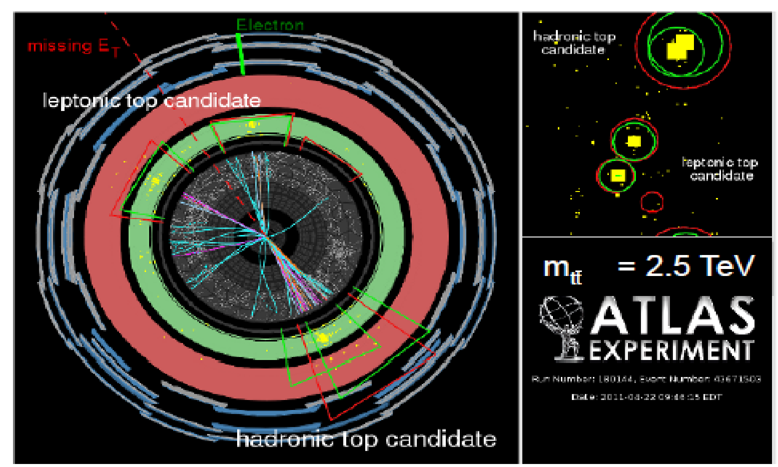
Background: SM $t\bar{t}$, single top, W+jets
BG determination of multijet and W+jets mostly data driven.

$t\bar{t}$ semi-leptonic

4.7 fb^{-1} 7TeV
arXiv:1207.2409



Hatched: total systematic uncertainty



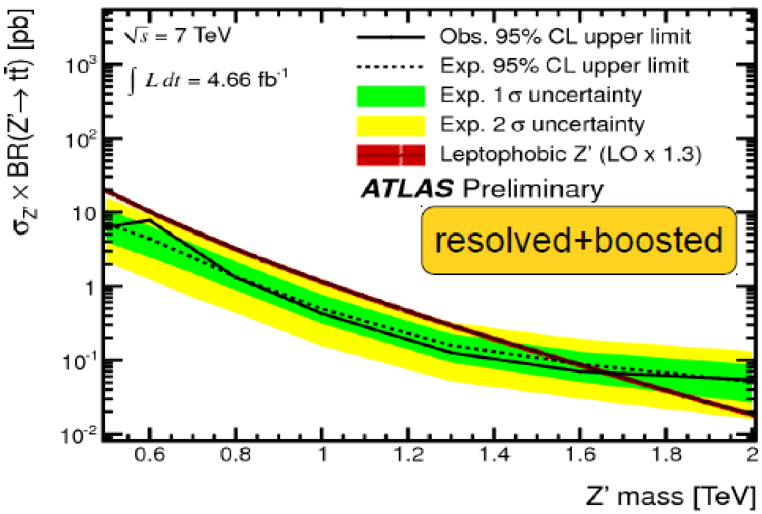
Top - antitop

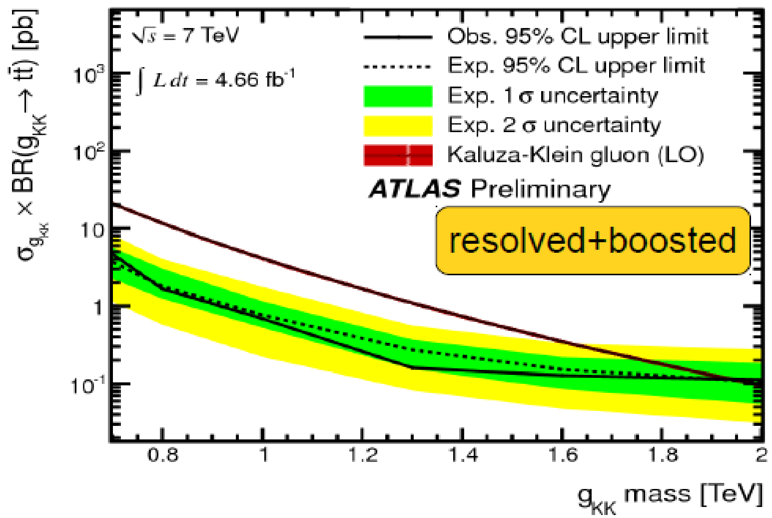
4.7 fb^{-1} 7TeV *arXiv:1207.2409*

95% CL for 2 benchmark models for **$t\bar{t}$ semi-leptonic**:

Leptophobic topcolor Z':
m(Z')> 1.7 TeV

RS KK gluon:
m(g_{KK})> 1.9 TeV





*An analysis using **fully hadronic $t\bar{t}$** has been done as well for Larger Branching ratio, but also larger multi-jet background:*

4.7 fb^{-1} 7TeV *arXiv1211.2202*

Leptophobic topcolor Z':
excludes 0.7<m(Z')< 1.0 TeV
& 1.28<m(Z')< 1.32 TeV

RS KK gluon:
excludes 0.7<m(Z')< 1.62 TeV

Large ED – dark matter

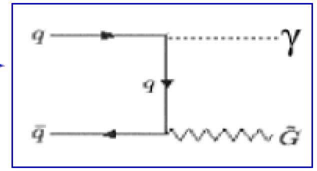
- Models:
  → Large Extra-dimensions → *ADD models*
  → Dark matter → *non renormalizable effective theory*

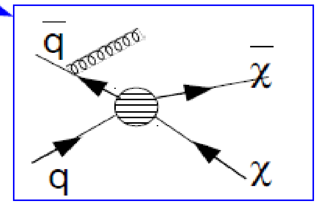
	Signature	Model	Luminosity [fb^{-1}]	Publication
8TeV	$j+E_T^{miss}$	ADD, DM	10.5	*ATLAS-CONF-2012-147*
7TeV	$\gamma+E_T^{miss}$	ADD, DM	4.6	*arXiv:1209.4625*
7TeV	$j+E_T^{miss}$	ADD, DM	4.7	*arXiv:1210.4491*

Monojet

10.5 fb^{-1} 8TeV *ATLAS-CONF-2012-147*

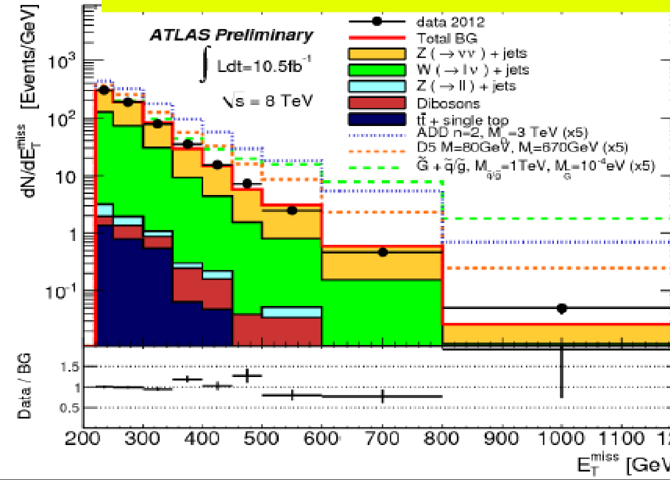
Sensitive to:
- Large Extradimension (ADD)
- Wimp (Dark Matter)
- Gravitino (SUSY)

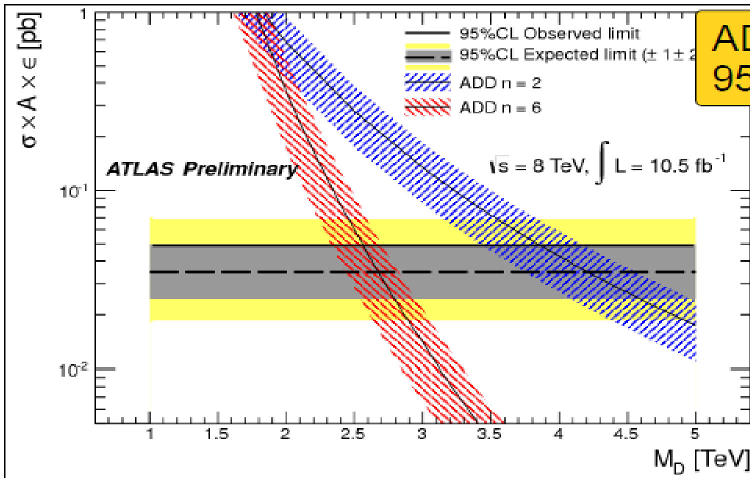




Look for a jet + E_T^{miss}
$\rightarrow$ 4 data samples

Challenge:
- instrumental background
- understand *($Z \rightarrow \nu\nu$) + jets background*

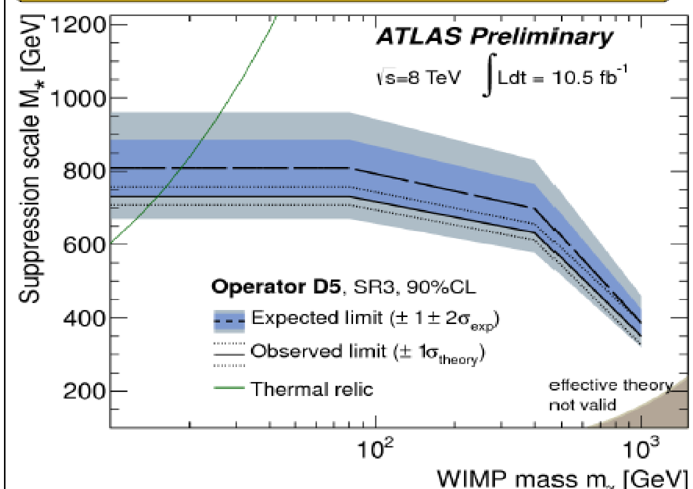




ADD 95% CL limits

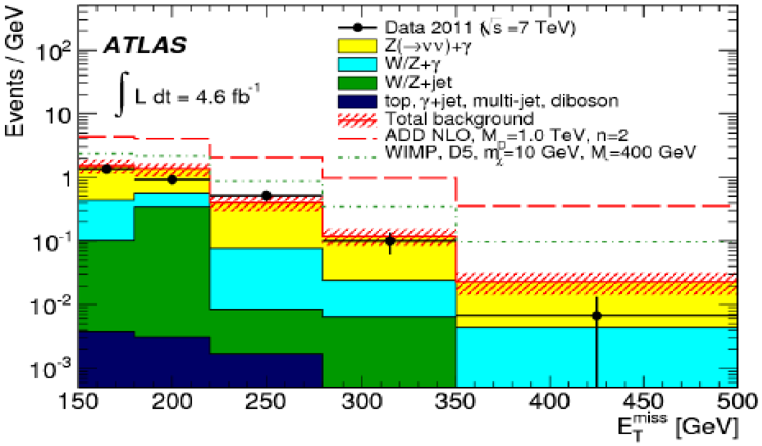
n_{ED}	2	3	4	5	6
M_D> [TeV]	3.88	3.16	2.84	2.65	2.58

Wimp 95% CL limits, operator D1, D5, D8, D9 of effective theory



Monophoton

4.6 fb^{-1} 7TeV *arXiv:1209.4625*

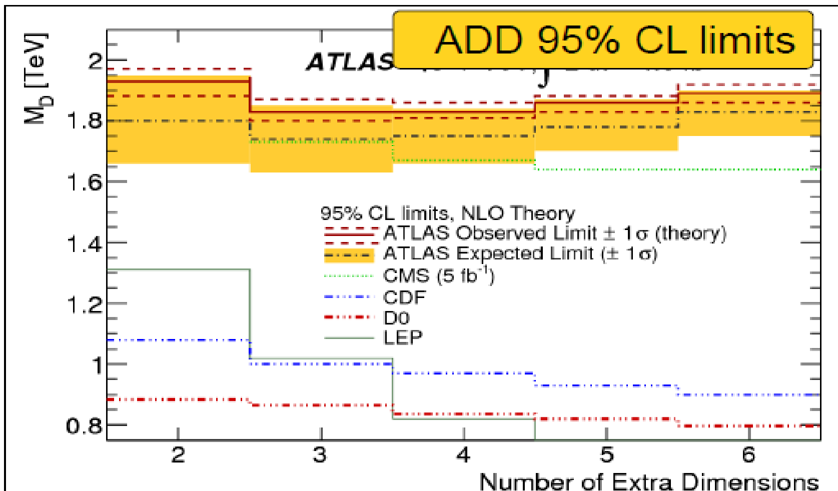


Sensitive to ADD and Dark matter candidates.

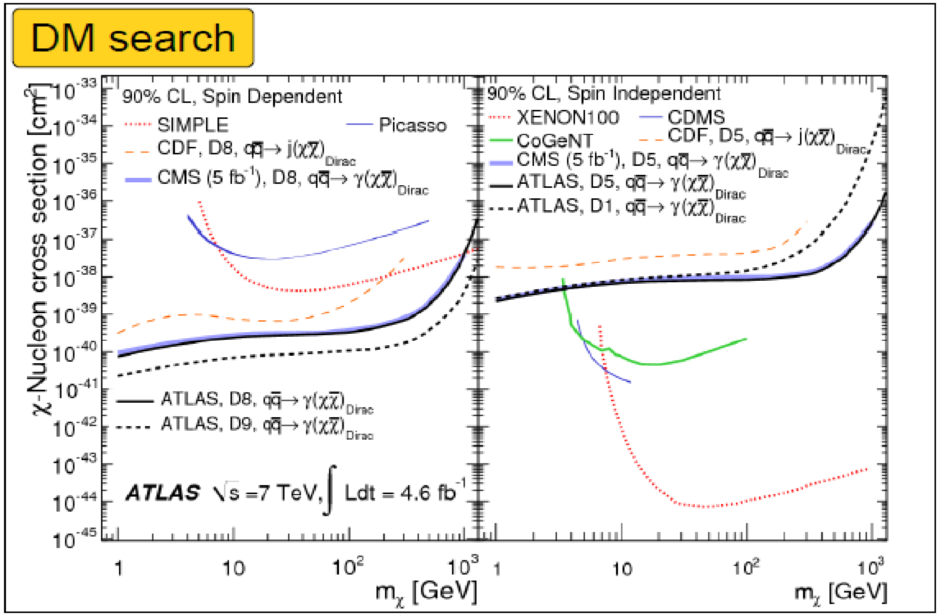
Look for a photon and nothing else.

E_t^{miss}>150GeV && $p_T(\gamma)$>150 GeV

Background: Z(νν)+γ, W/Z+γ, W/Z+j



n_{ED}	2	3	4	5	6
M_D>[TeV]	1.93	1.83	1.83	1.86	1.89



Very exotic signatures

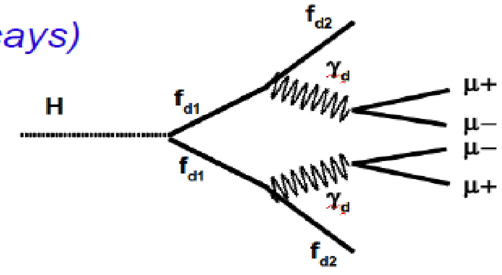
	Signature	Model	Luminosity [fb^{-1}]	Publication
7TeV	displaced μjet	hidden valley	1.9	arXiv:1210.0435
	monopole	monopole	2.0	arXiv:1207.6411

Displaced muonic jet

1.9 fb^{-1} 7TeV *arXiv:1210.0435*

Benchmark model: Hidden Valley
Messenger permits decay chains to cross between normal and dark sector.
In this analysis:

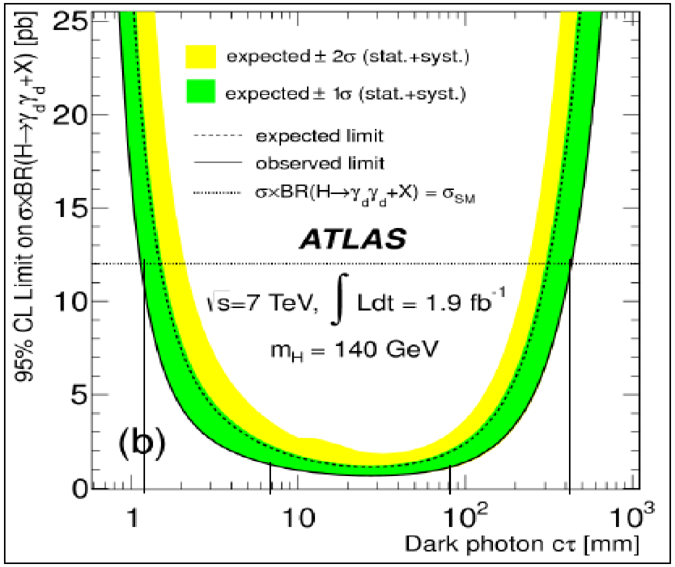
$H \rightarrow$ 2 hidden fermions $\rightarrow$ 2 dark photons $\rightarrow 4\mu$ + X (~20% of decays)



Difficulties:
- Boost of γ_d: 2 muon pairs each very collimated $\rightarrow \Delta R$<0,1
- γ_d neutral: displaced vertices, no ID information
- γ_D pair and thus f_{d1} pair, are back to back $\rightarrow$ E_T^{miss} unusable

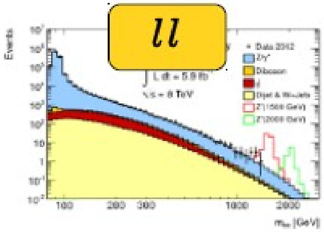
Challenge for Trigger and reconstruction.
Use of ATLAS standalone muon spectrometer capabilities
Simple clustering algorithm.

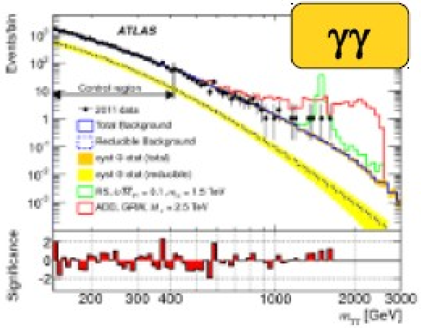
Main BG: K/π decays in flight, heavy flavor multijet, cosmics
Systematic uncertainty on reconstruction/trigger efficiency evaluated with J/ψ.

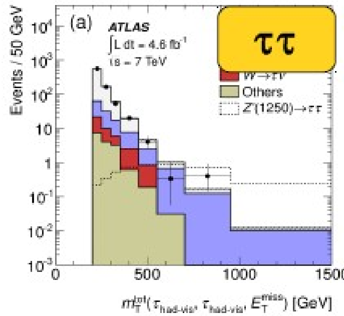


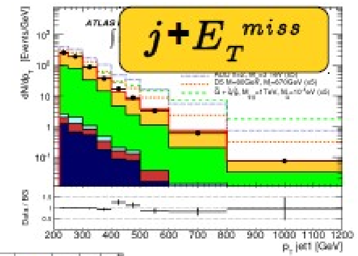
Constrains coupling of 126 GeV light Higgs to hidden sector

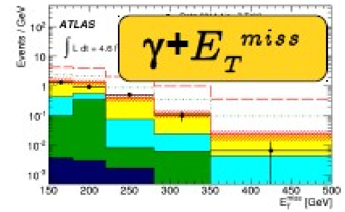
m_{higgs} [GeV]	cτ[mm] BR(100%)	cτ[mm] BR(10%)
100	$1 \leq c\tau \leq 670$	$5 \leq c\tau \leq 159$
140	$1 \leq c\tau \leq 430$	$7 \leq c\tau \leq 82$

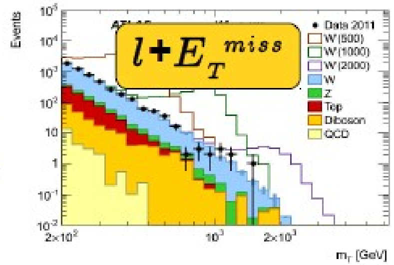


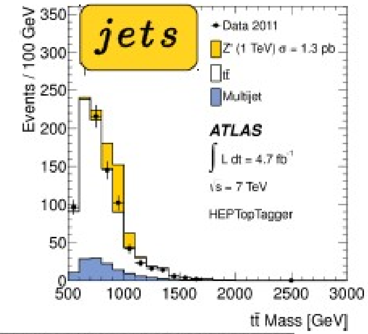










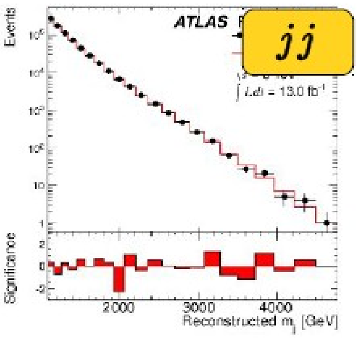


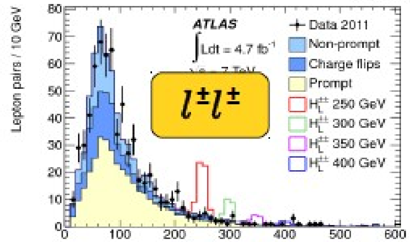
7 TeV analyses to be concluded soon
First results on 8 TeV data

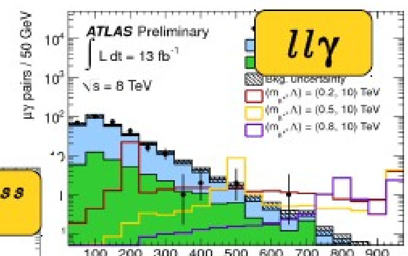
No sign of new physics so far

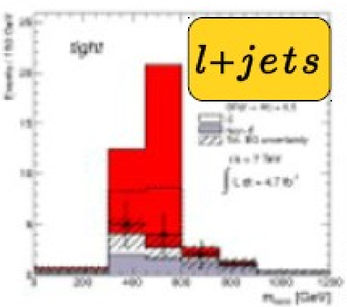
Lots of 8 TeV analyses in the pipeline...

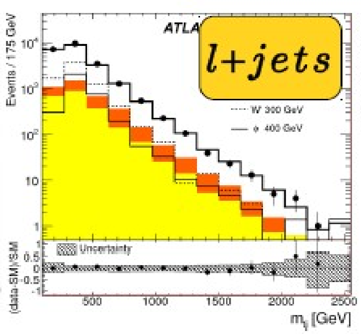
Surprise can be around the corner !!

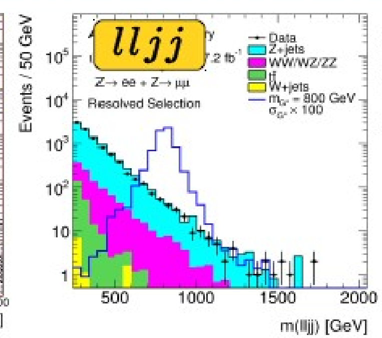


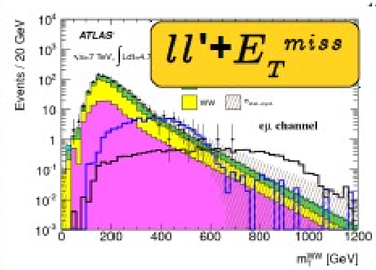


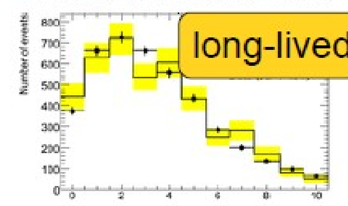




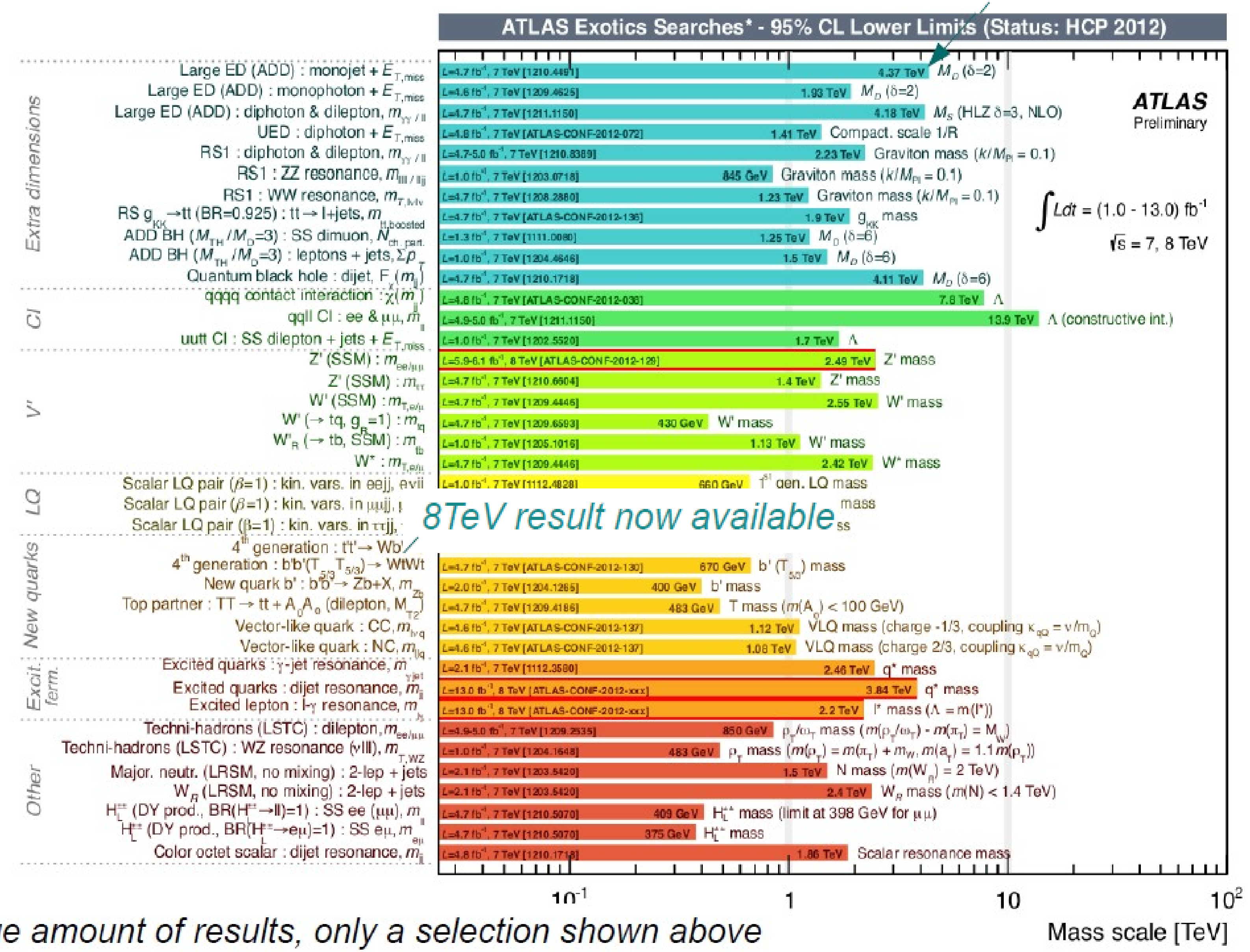








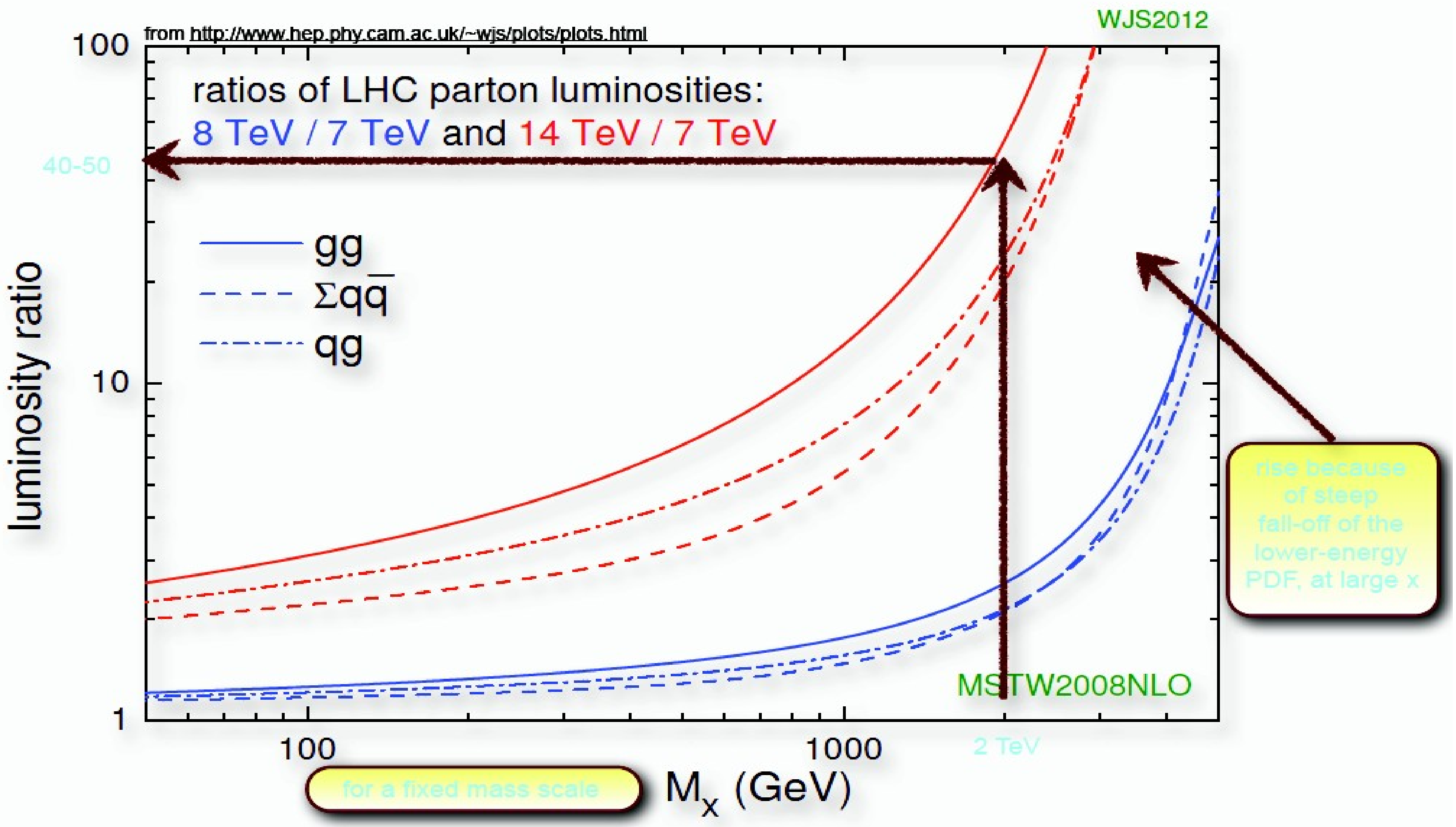
8TeV result now available



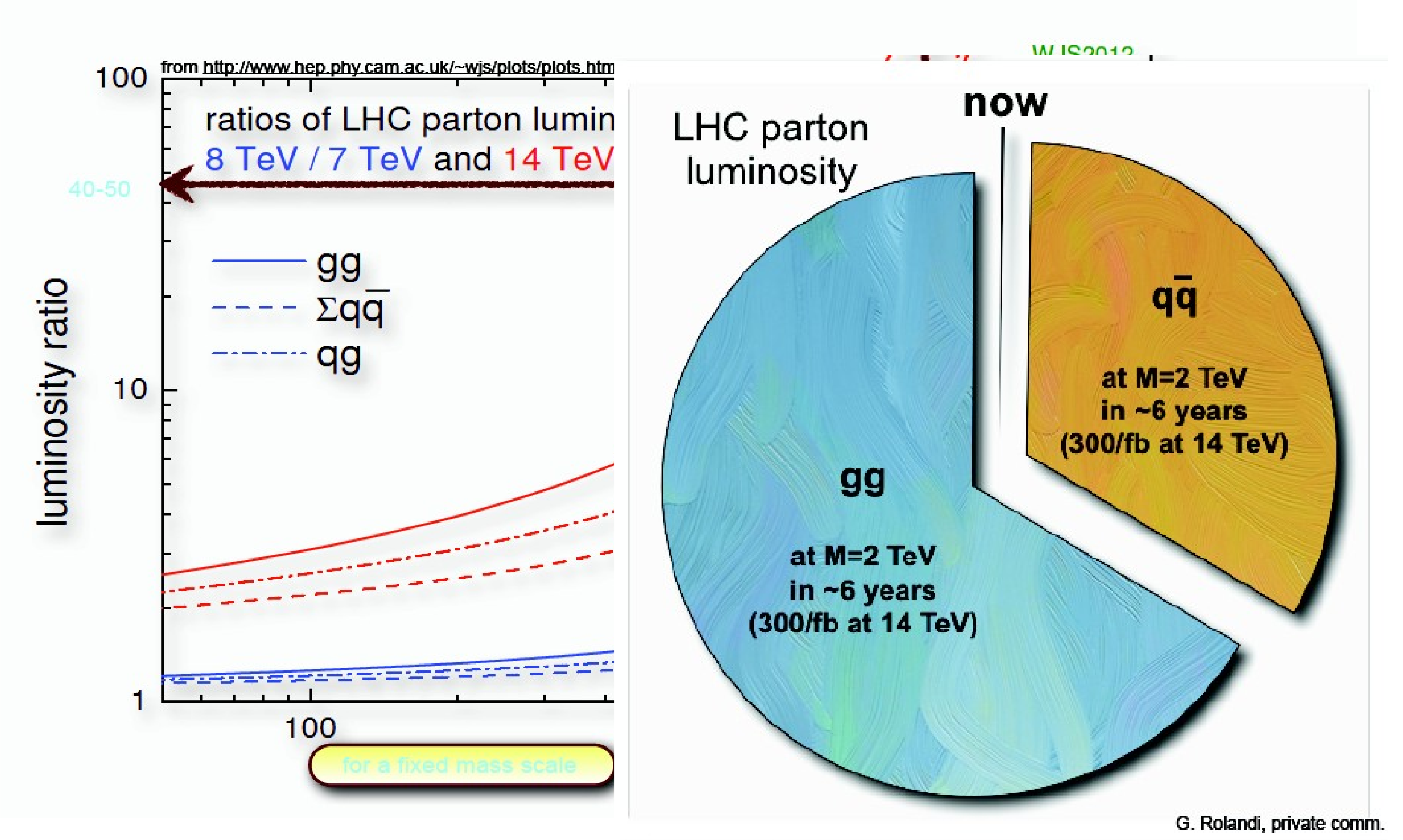
Huge amount of results, only a selection shown above

Red lines along a limit indicates 8TeV data

Parton luminosity



Parton luminosity

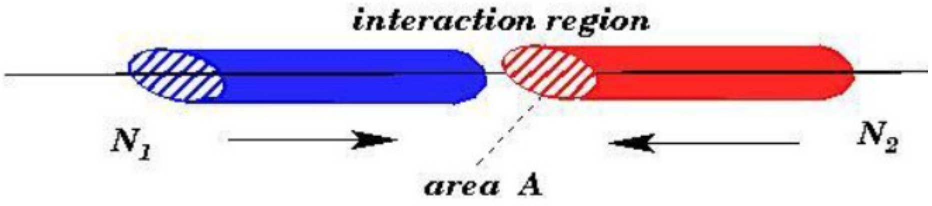


Luminosity: collider figure of merit

- The key parameter for the experiments is the event rate dN/dt. For a physics process with cross-section σ it is proprotional to the collider Luminosity L:

unit of L : 1/(surface × time)

$$dN/dt = L\sigma$$



- The luminosity can be expressed as (for equal particle populations and Gaussian profiles) :

$$L = \frac{k N_1 N_2 f}{4\pi\sigma^*_x \sigma^*_y} = \frac{k N_1 N_2 f \gamma}{4\pi \beta^* \varepsilon}$$

- σ^*_x, σ^*_y : transverse rms beam sizes.
- β^* betatron function
- ε beam emittance
- k : number of particle packets / bunches per beam.
- $N_{1/2}$: number of particles per bunch.
  - $k \times N_{1/2}$: total beam intensity
- f : revolution frequency = 11.25 kHz.

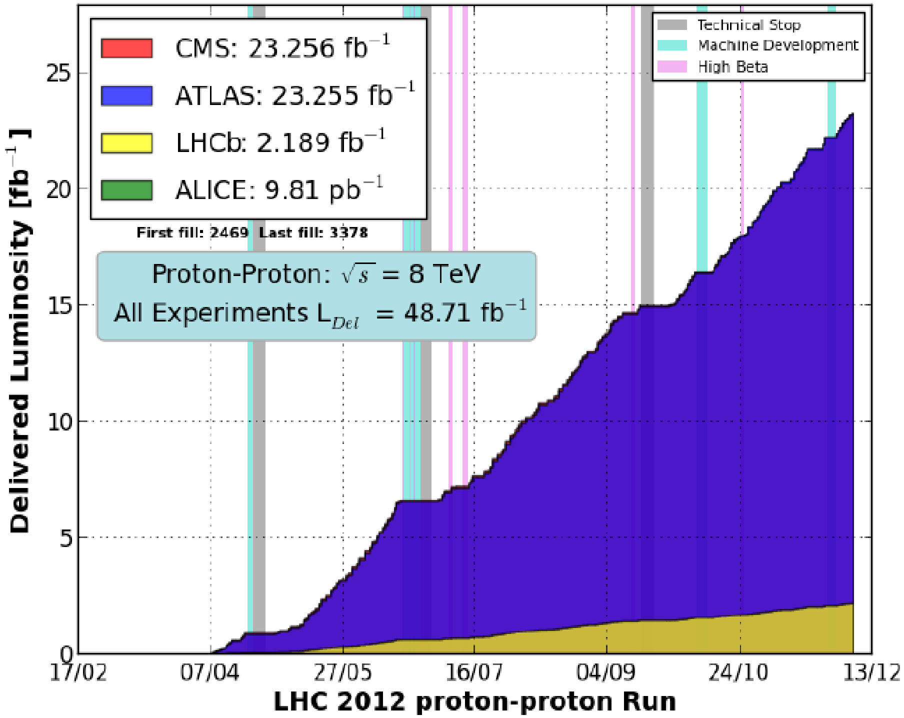
To maximize L we need:

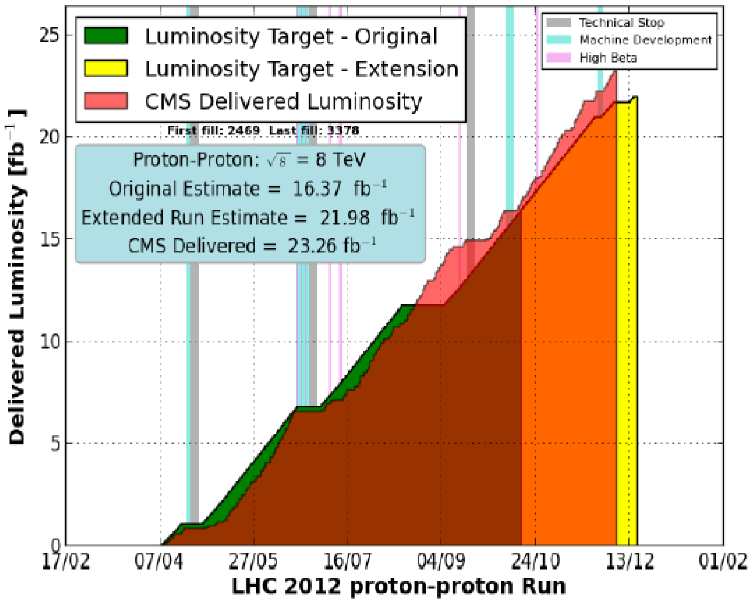
- Large N, large k,
- Smallest possible β^* or ε .

... or some optimum combination !

Luminosity production 2012

- 1 fb^{-1} on a good week; best week: 1.35 fb^{-1}
- Maximum integrated luminosity per day: 286 pb^{-1}
- Integrated luminosity 23.2 fb^{-1} (as of 05/12/2012)

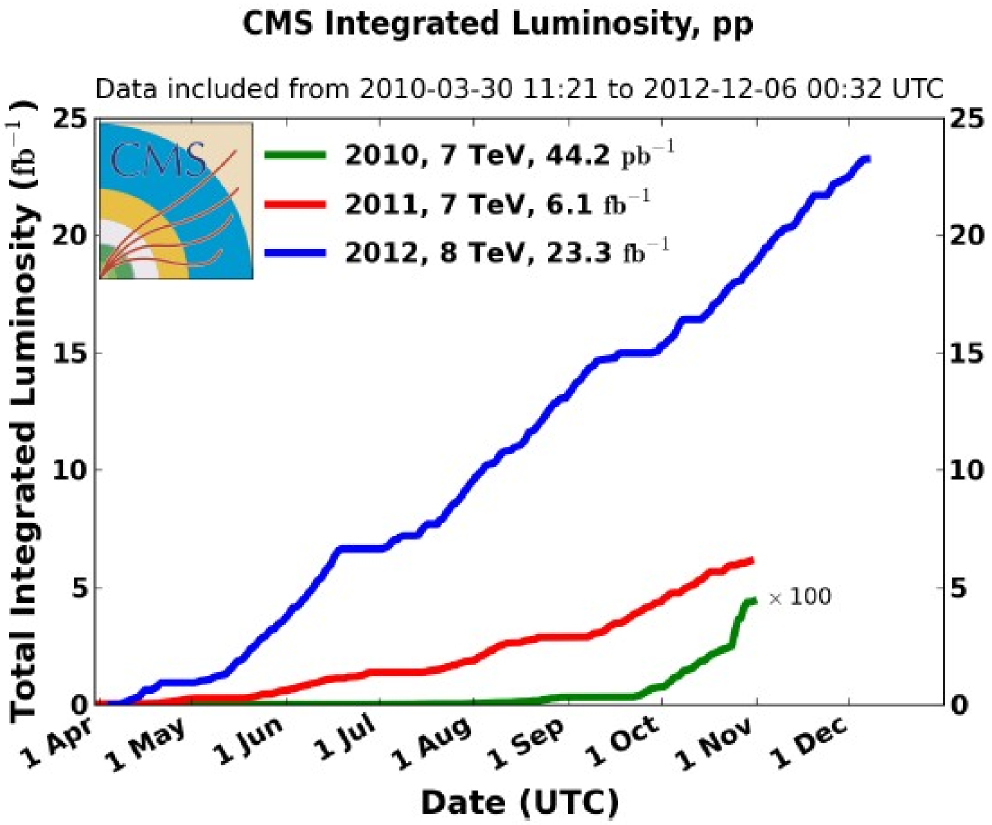


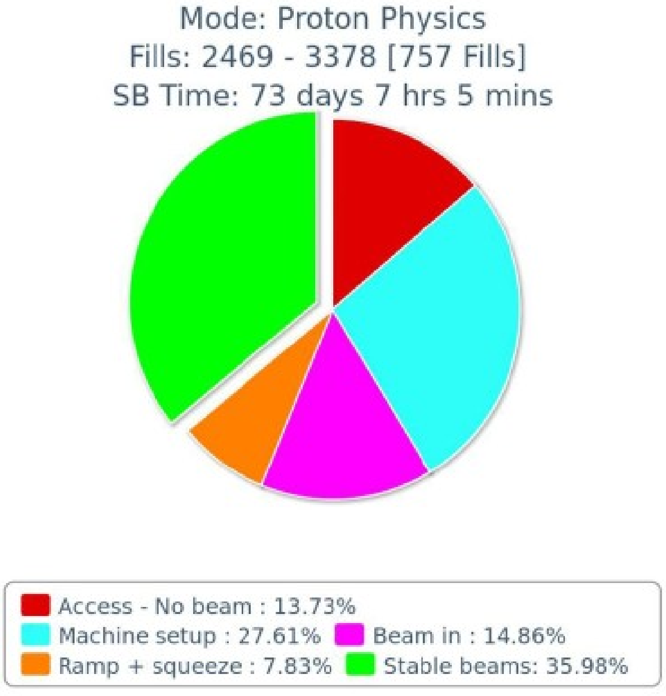


Luminosity production 2010-2012

Integrated luminosity for ATLAS/CMS reaches now ~ 28 fb^{-1}.

- *In 2012, we spent 37% of the scheduled time delivering collisions to the experiments ('stable beams'), compared to 33% in 2011*



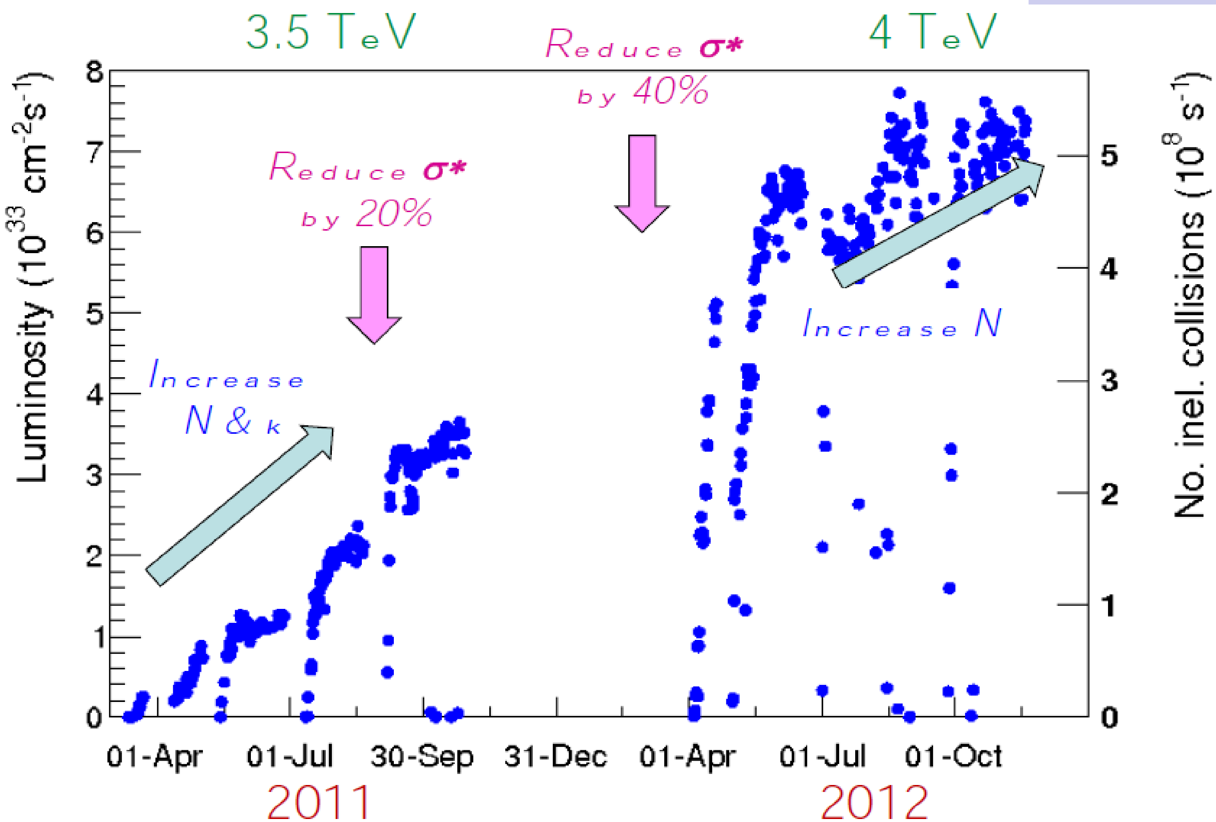


Peak luminosity 2011-2012

Over the last 2 years the peak luminosity was progressively increased:

- Through the beam intensity (mainly 2011),
- Through beam size reduction at the IP.
- Record Peak $L = 7.7 \times 10^{33}\ cm^{-2}s^{-1}$

75% of Design Luminosity @ Half design Energy and Half the number of bunches!!



LHC machine 2010-2012

Main changes in 2012:

- Beam energy: 4 TeV.
- Reduction of β^* ↔ tighter collimator settings.

Parameter	2010	2011	2012	Nominal	Constrained by
N (10^{11} p/bunch)	1.2	1.5	1.6-1.7	1.15	
k (no. bunches)	368	1380	1380/1374	2808	Bunch spacing
Bunch spacing (ns)	150	75 / 50	50	25	
ε (μm rad)	2.4-4	1.9-2.4	2.2-2.5	3.75	Injectors
β^* (m)	3.5	1.5 → 1	0.6	0.55	Aperture/ tolerance
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.5×10^{33}	7.6×10^{33}	10^{34}	
Pile-up	3	19	35	23	

Next topics

- 16.1 - B-physics programme
- 23.1 – heavy ion programme