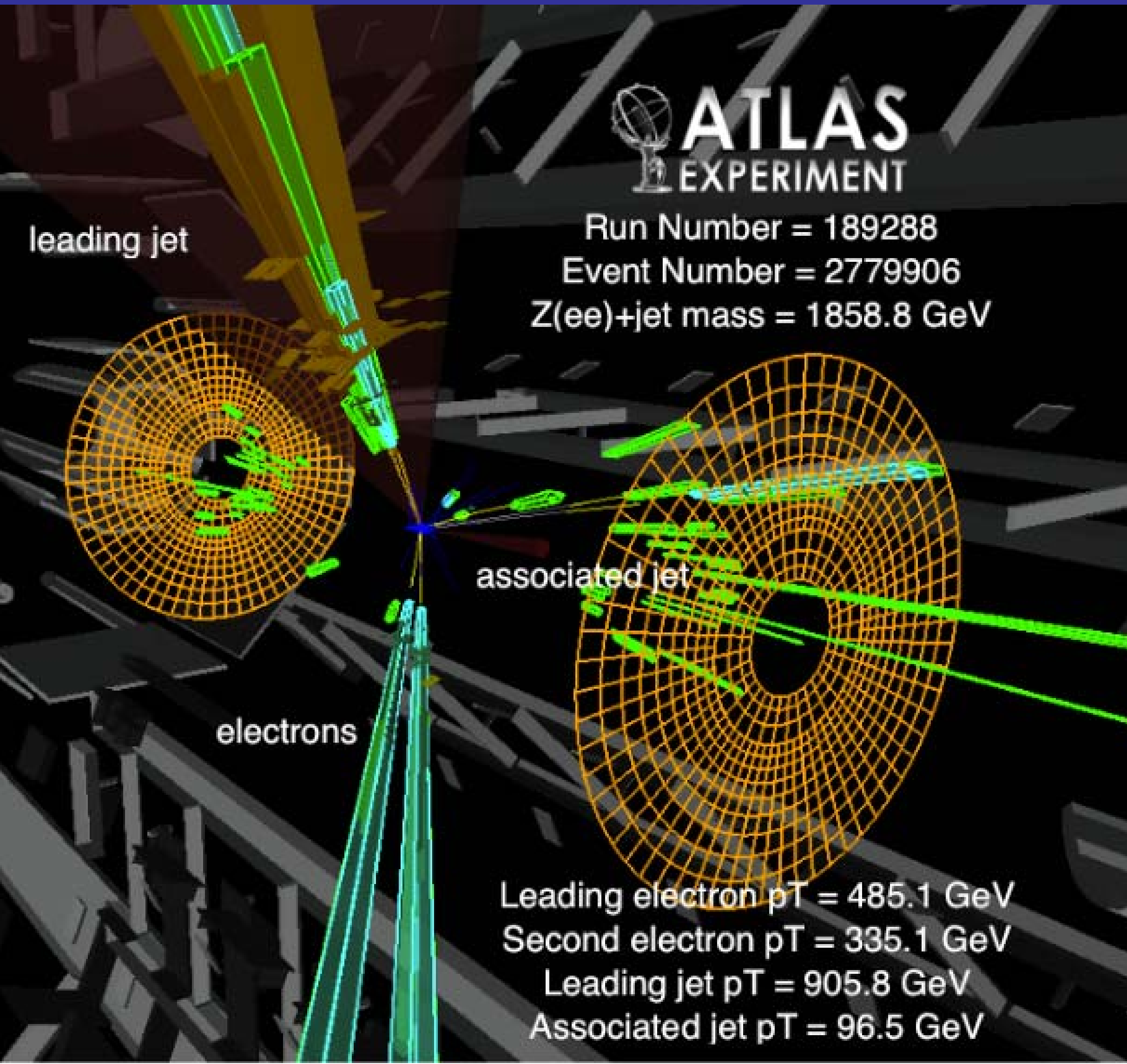
Beyond Supersymmetry



Cigdem Issever
University of Oxford

Wilhelm und Else Heraeus-Seminar
9.-12. December 2012
Physikzentrum Bad Honnef

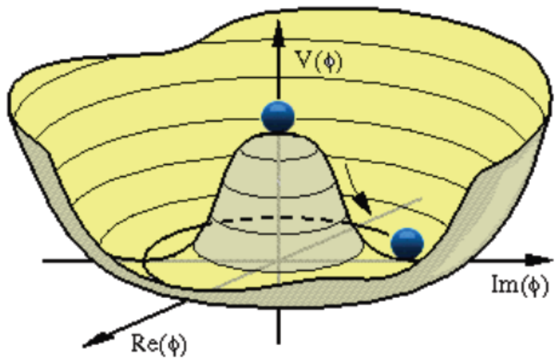
Why look beyond Supersymmetry (SUSY)?

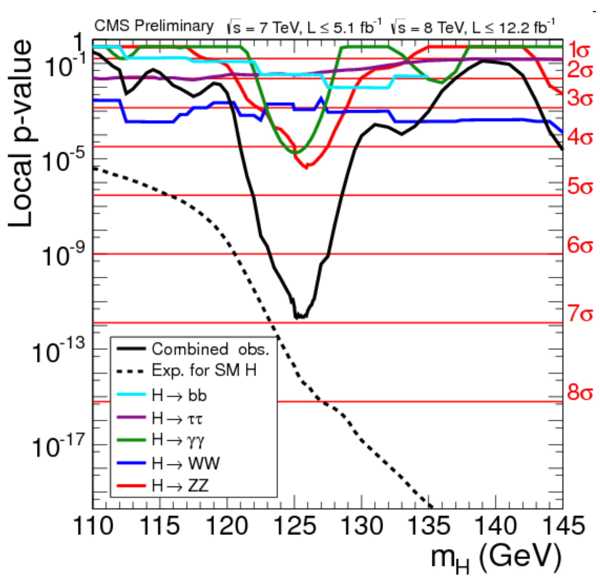
- SUSY is only one possible model among many others.
  - Many more ways to solve problems with Standard Model
  - What if nature has not chosen SUSY?
  - Make sure to cover every feasible corner…

- SUSY mass limits pushed to 1 TeV
  - SUSY becoming more “Exotic” the higher the mass limits get.

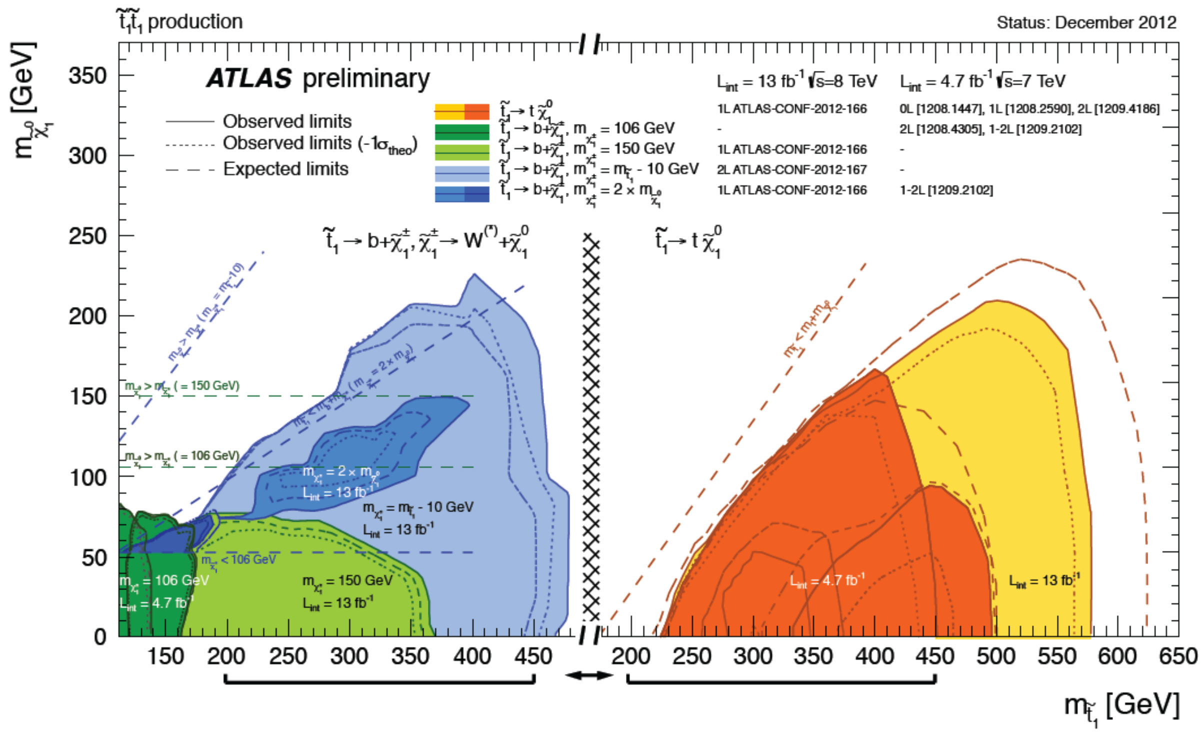
What Characterizes Exotics Searches?

- No specific Model to guide us.



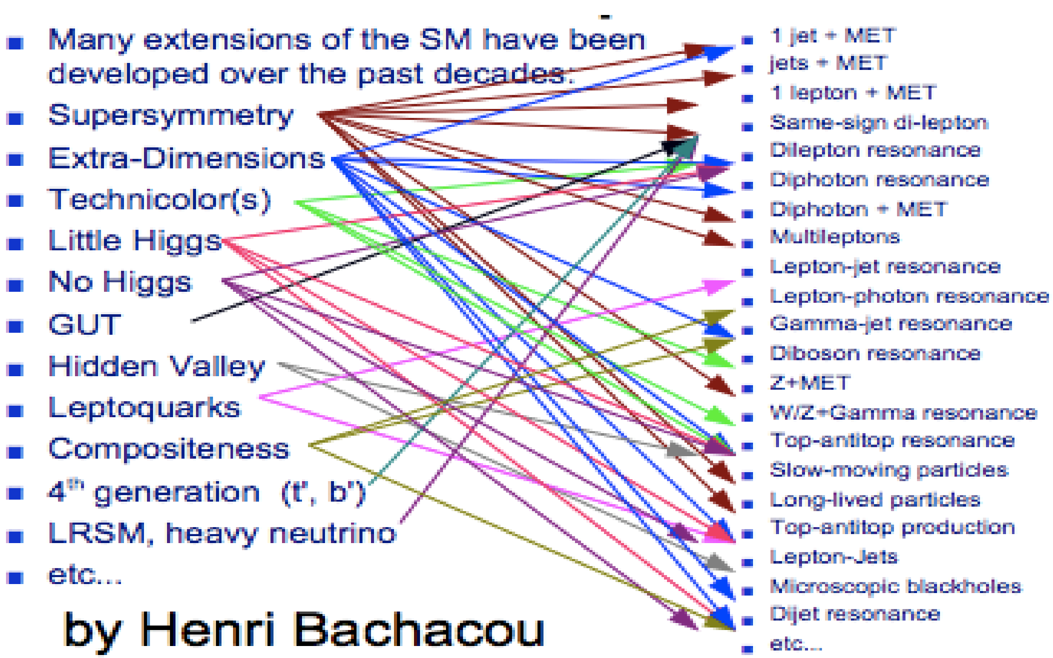


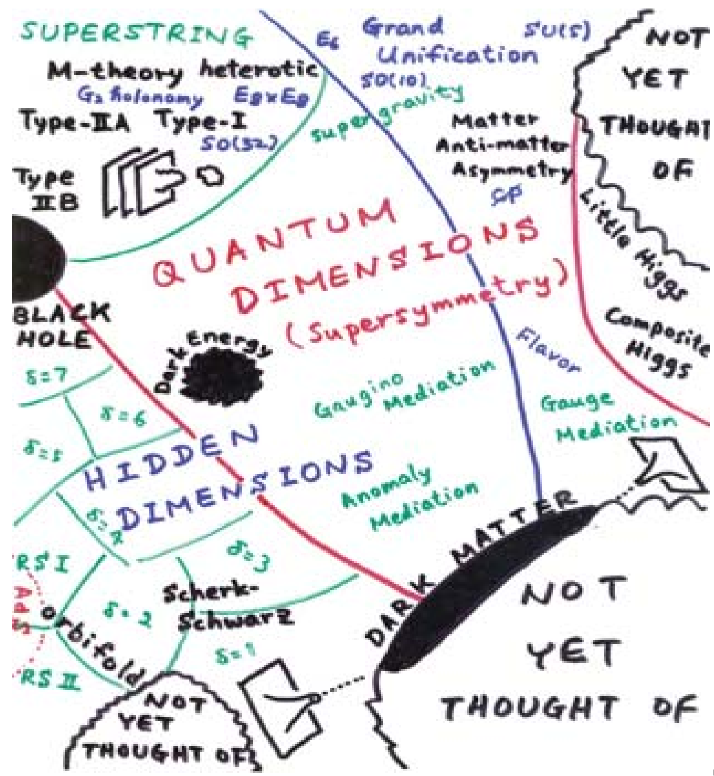
- No unified parameter phase space to map results



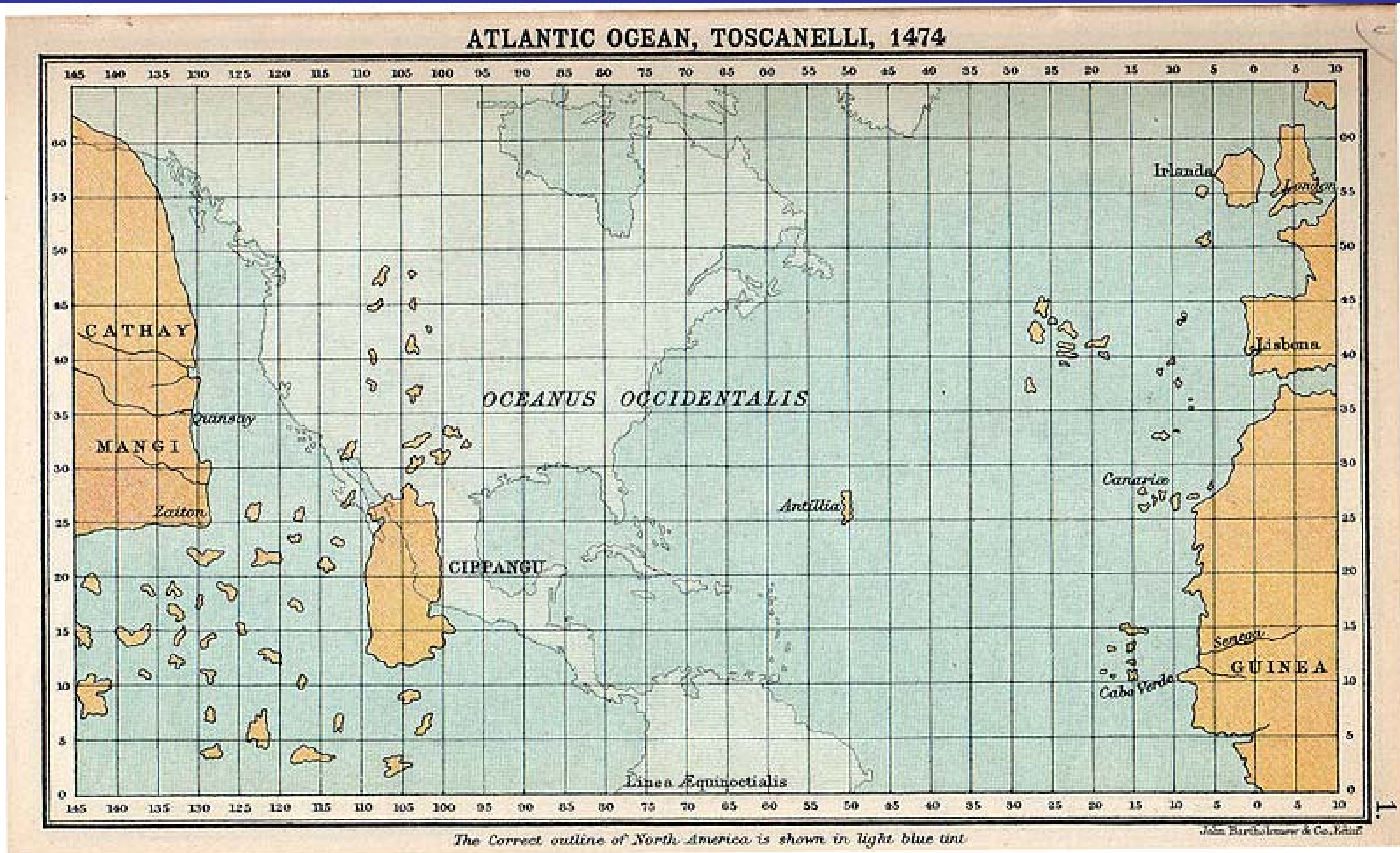
What Characterizes Exotics Searches?

- Exotics Search Strategy
  - Cover wide range of final states
  - Largely Model independent → Poster: S. Beranek, et al.
    - Look for resonances
    - Look for any disagreement from expectations
  - Cover interesting new BSM models





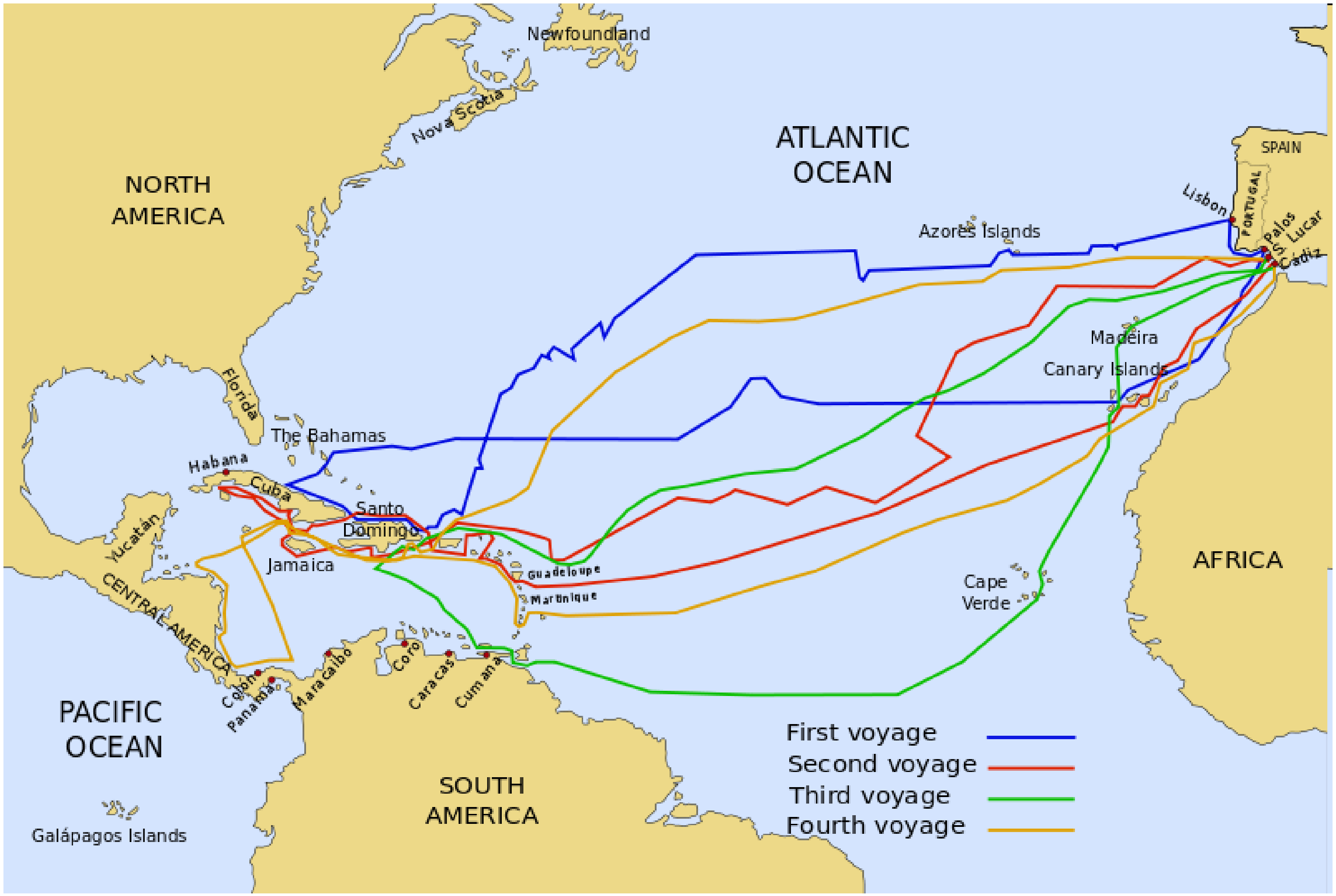
The Role of Models in "most" Exotics Searches



Toscanelli's model of the geography of the Atlantic Ocean, which directly influenced Columbus's plans

The Role of Models in "most" Exotics Searches

Columbus' voyages



The Role of Models in “most” Exotics Searches

- Models used to quantify our reach.
  - How far did we get?
  - How do we compare to previous searches?
- We use so called Bench Mark Models
  - Used before by other experiments
  - Add new features: wider widths
- Simplified Models or generic resonances

Basic Principles of a Search

- Most important: Robust background estimation!
  - Data-driven
  - Use background MCs
  - Use data to normalize in control regions MCs
- Biases ?
  - Fully blind not a realistic approach for Exotics searches
  - Need to think beforehand about control regions
  - Need to think beforehand about how to minimize bias.
- Trade-off between Signal and Background
  - Do NOT optimize towards a specific model
  - Selection cuts defined by triggers and background reduction.

Basic Principles of a Search

- You have a background estimate…what now?
- Check if data agrees with this expectation.
- If it does not agree…
  - Is the significance increasing with more data?
  - Look at time dependences...
  - Cross checks….
  - Discovery if significance is greater than 5 sigma.
- If it does agree….
  - How far did we explore the new physics phase?
  - Use Bench Mark models to quantify the search reach.
  - Make sure to publish also the acceptance for these models such that theorists can use your results to test other models.

Comment to Search Result Selection in this Talk

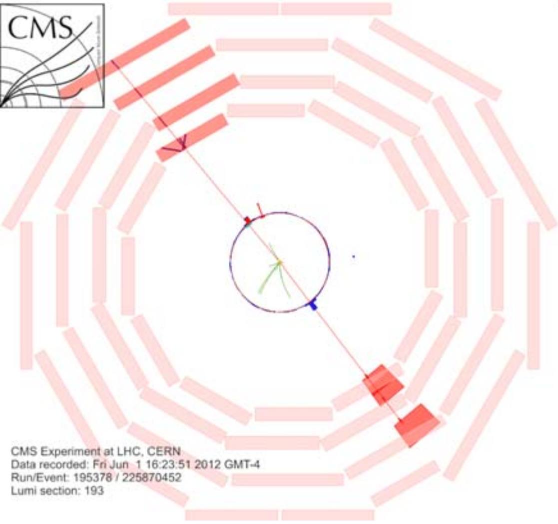
“What is the impact of the newly discovered boson on Exotics searches at the LHC?”

8 TeV Results

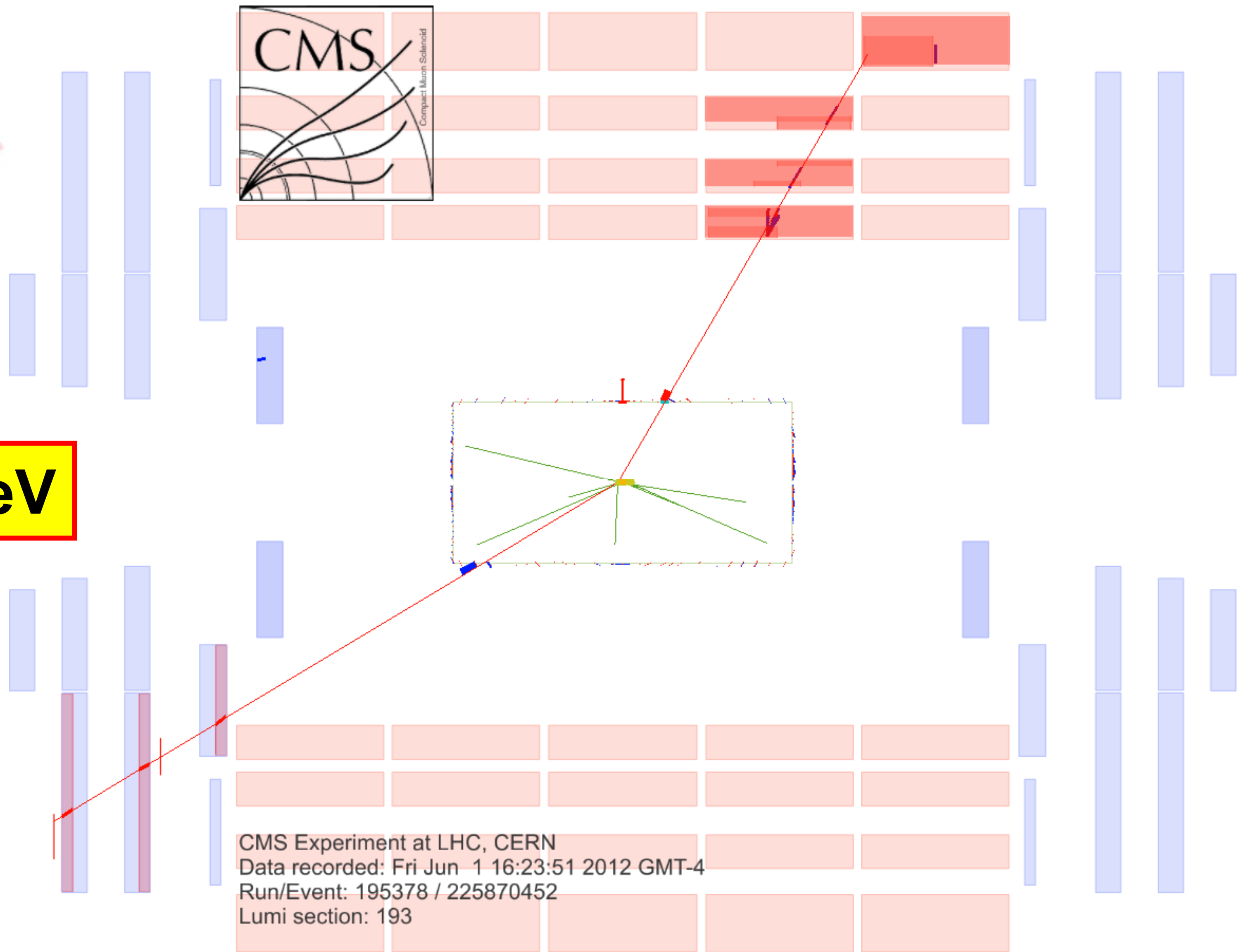
Exotics Searches

- **Heavy resonances**
  - **Dileptons**
  - **Dijets**
  - **Ttbar**
- **4^{th} gen quarks and vector-like quarks**
- **Dark matter and extra dimension**
- **Displaced muonic lepton jets from light higgs**

CMS Highest Dimuon Invariant Mass Event; 8 TeV



m_{inv} = 1418 GeV

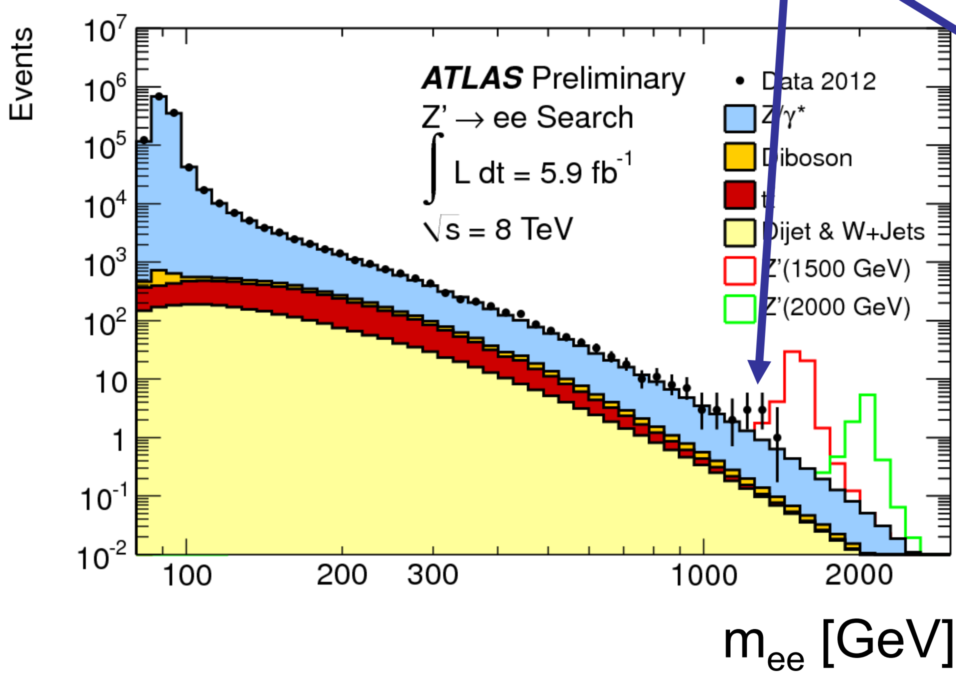


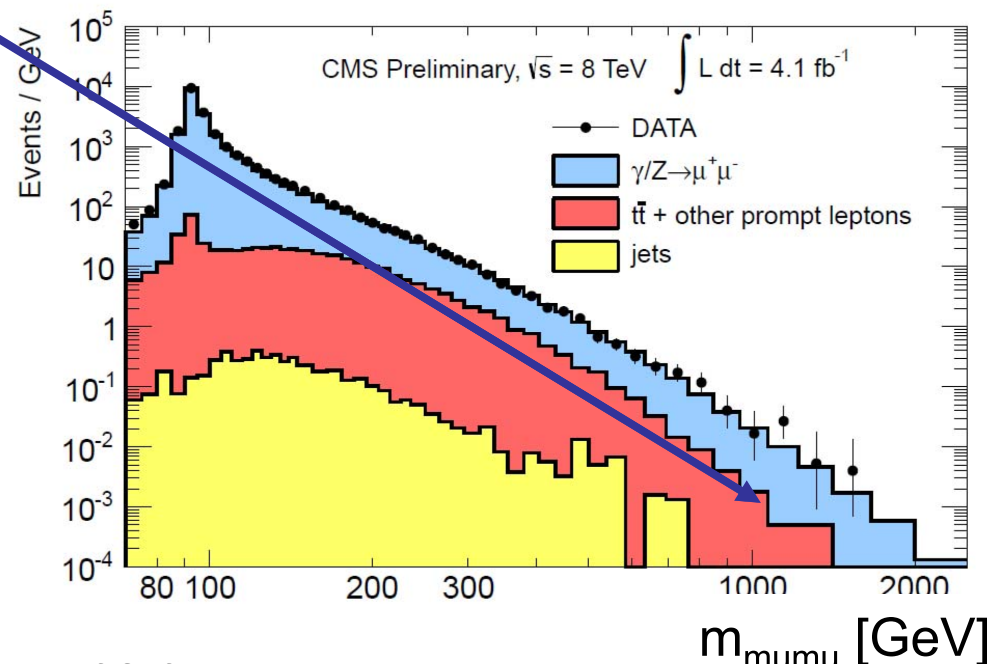
Heavy Resonances Search: 8 TeV Dileptons

ATLAS-CONF-2012-129
PAS EXO12015

- Models:
  - Randall-Sundrum ED → Kaluza-Klein graviton
  - GUT-inspired theories, Little Higgs → heavy gauge boson(s)
  - Technicolor → narrow technihadrons
- **Leptons reaching p_T ~ 1 TeV**

Poster: Sarah Heim





Heavy Resonances Search: 8 TeV Dileptons

ATLAS-Electron selection

- diphoton trigger
- E^1_T>40 GeV Use && E^2_T> 30 GeV
- $|\eta|<2.47$, excluding crack regions
- Cluster ID cuts
- Leading electron isolated
  - $(\sum E_T - E^1_T)\,|_{(\Delta R<0.2)} < 7$ GeV
  - Reject jets faking electrons
- Require pixel hit
  - Rejects photon conversions
- $A^*\varepsilon(Z\rightarrow ee$, m=2 TeV) ~ 70%

CMS-Electron selection

- Use dielectron trigger
- $E^{1,2}_T$>30 GeV
- $|\eta|<2.5$, excluding crack regions
- Cluster ID cuts
- Leading electron isolated
  - $(\sum P_T - P^e_T)\,|_{(\Delta R<0.3)} < 5$ GeV
  - $(\sum E_T - E^e_T)\,|_{(\Delta R<0.3)} < 3\%\ E^e_T$
  - $E_{Hcal}/E_{ECAL}\,|_{(\Delta R<0.15)} < 5\%$
- $A^*\varepsilon(Z\rightarrow ee$, p_T=100 GeV) ~ 90%

Heavy Resonances Search: 8 TeV Dileptons

Backgrounds

- SM Drell-Yan: $\gamma^*/Z \rightarrow l^+l^-$
  - shape taken from Monte Carlo
  - normalisation taken from Z peak in data
- t-tbar:
  - where tt goes to e+e-, mu+mu-
  - est. from MC, cross-checked in data
  - also includes Z->ττ, WW, WZ

ee and μμ

- Jet Background:
  - di-jet, W+jet events where the jets are misidentified as electrons/muons

ee

- Cosmic Ray Background:
  - muons from cosmic rays
  - estimated <0.1 event after vertex and angular difference requirements

μμ

Heavy Resonances Search: 8 TeV Dileptons
Backgrounds

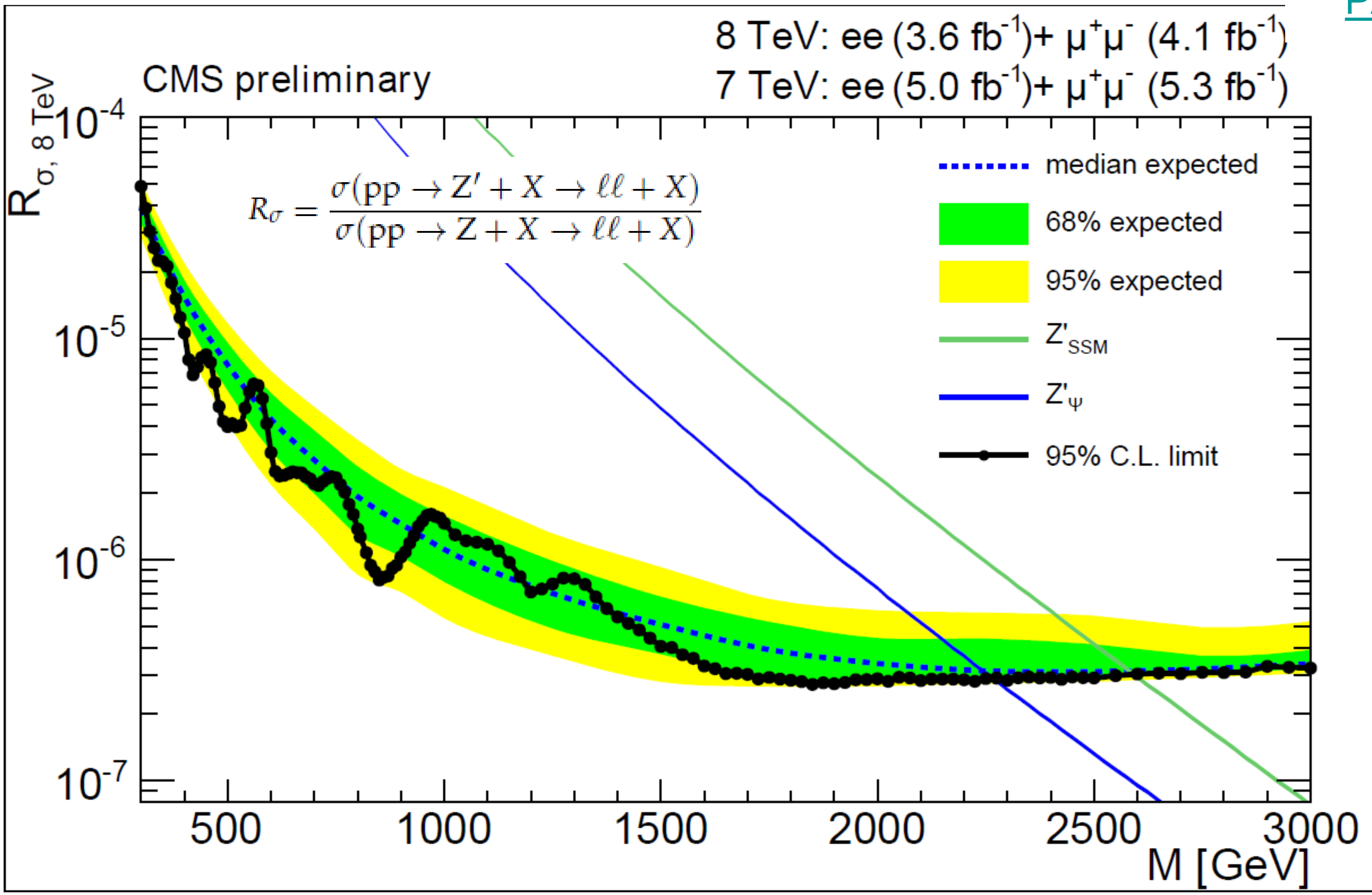
PAS EXO12015

Source	Number of events			
	Dimuon sample		Dielectron sample	
	(120 – 200) GeV	>200 GeV	(120 – 200) GeV	>200 GeV
Data	13831	3503	12030	2904
Total background	13007 ± 589	3627 ± 160	12241 ± 592	2968 ± 258
Z/γ^*	11703 ± 571	2919 ± 139	10657 ± 533	2198 ± 220
$t\bar{t}$ + others	1278 ± 146	698 ± 78	1222 ± 183	557 ± 84
jets	26 ± 3	10 ± 1	362 ± 181	213 ± 106

No deviation from expectation found.

Heavy Resonances Search: 7+8 TeV Dileptons

PAS EXO12015



m(SSM Z') > 2.59 TeV at 95% CL

Heavy Resonances Search: 8 TeV Dileptons

- No deviation from SM found → set limits

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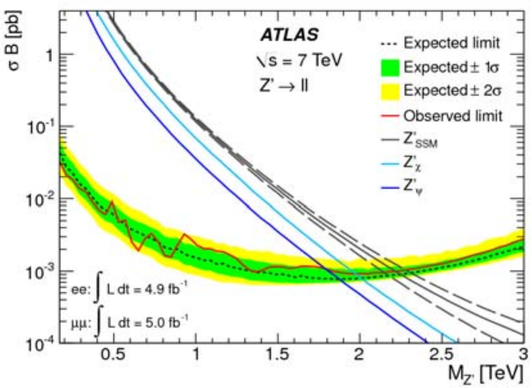
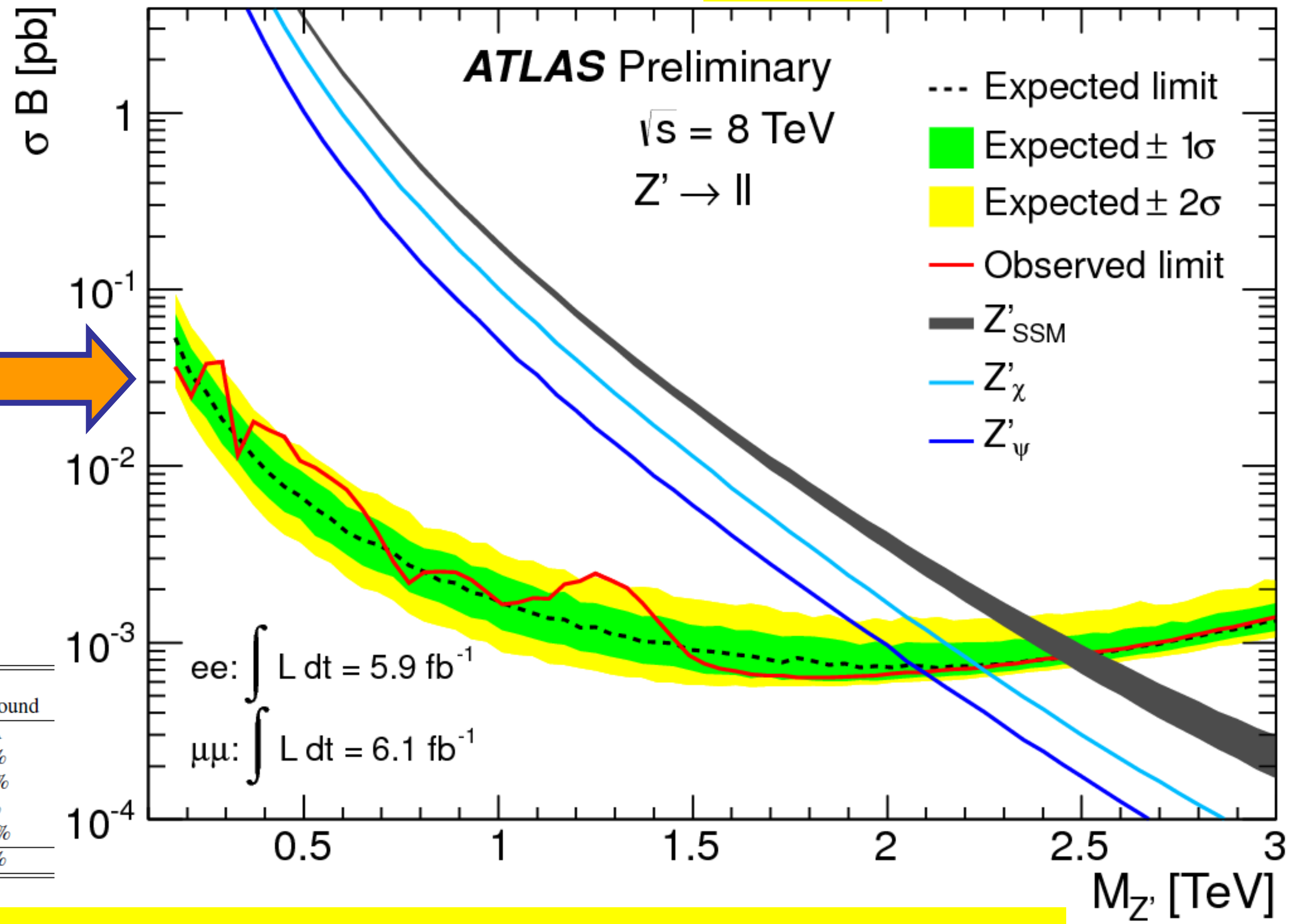
7 TeV



8 TeV



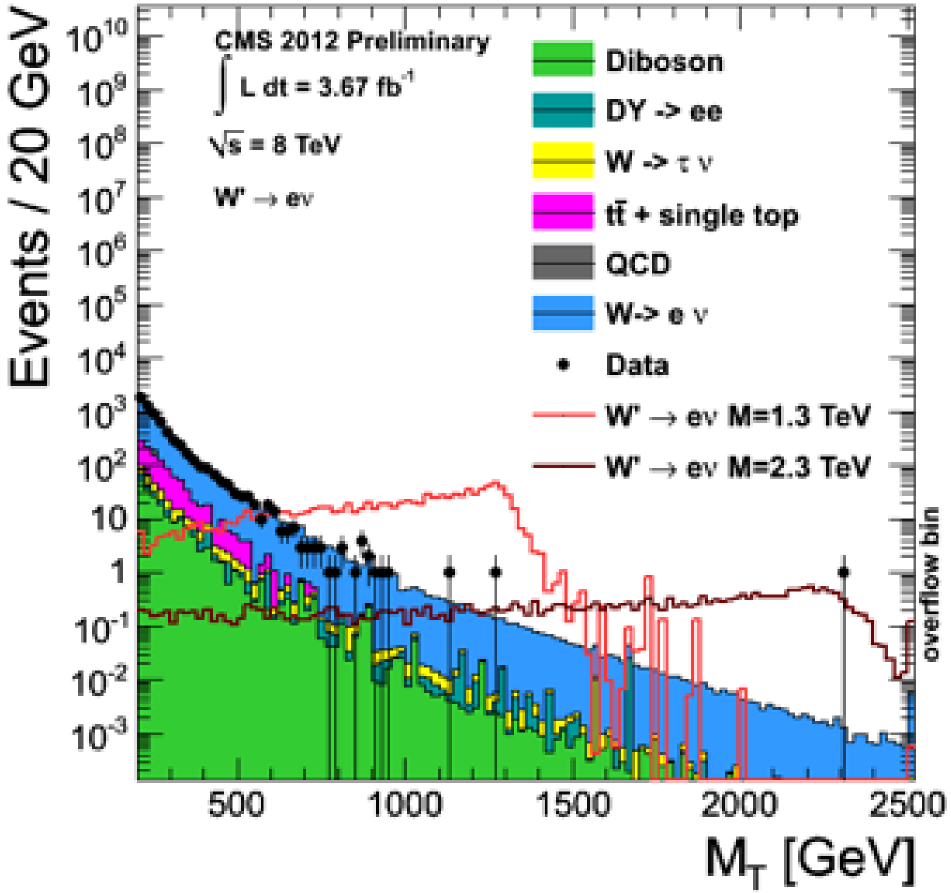
@ 2 TeV

Source	Dielectrons Signal	Dielectrons Background	Dimuons Signal	Dimuons Background
Normalization	5%	NA	5%	NA
PDF / α_s / α_{em} / scale	NA	20%	NA	20%
Electroweak corrections	NA	4.5%	NA	4.5%
Efficiency	< 3%	< 3%	6%	6%
Dijet and W + jets background	NA	21%	NA	< 3%
Total	5%	30%	8%	21%

m(SSM Z') > 2.49 TeV at 95% CL

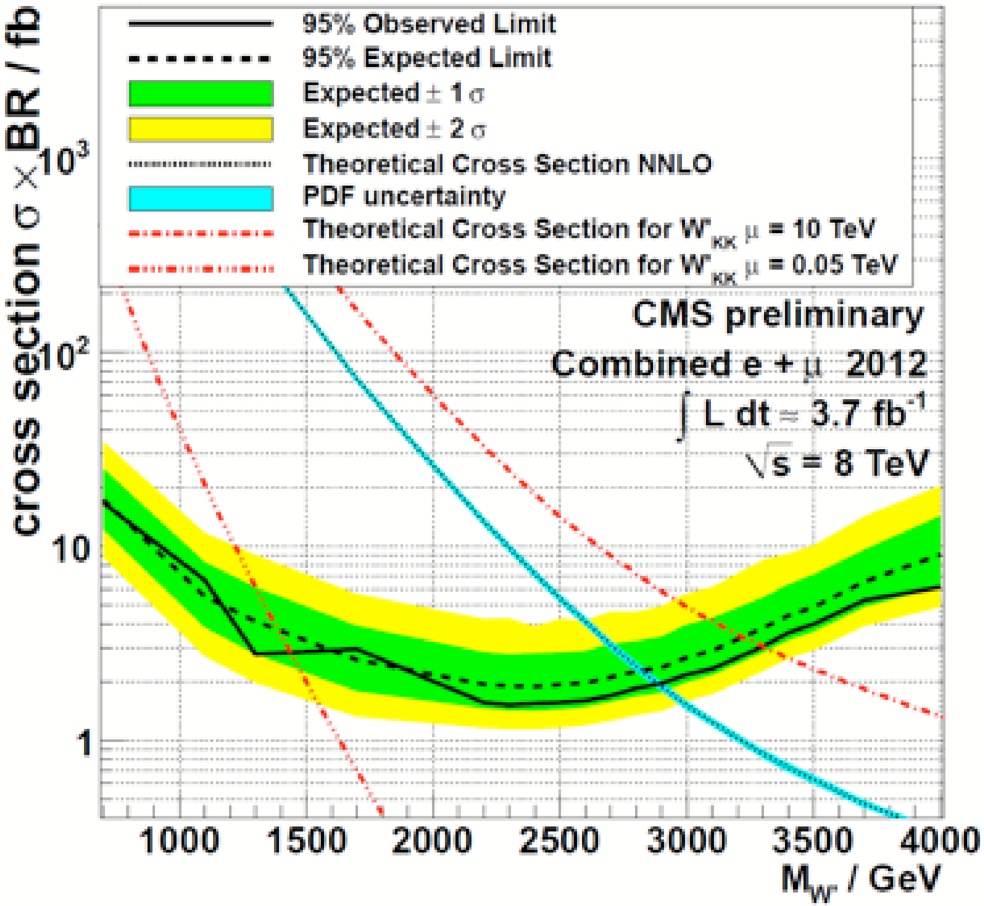
W' → lν in 8 TeV Data

- Many models possible
  - right-handed W' bosons with standard-model couplings
  - left-handed W' bosons including interference
  - Kaluza-Klein W'_{KK}-states in split-UED
  - Excited chiral boson (W*)
- Event Selection and Backgrounds
  - back-to-back isolated lepton and E_T^{miss}
  - Plot transverse mass of lν system
  - backgrounds from W, QCD, tt+single t, DY, VV from data



$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

W' → lν in 8 TeV Data

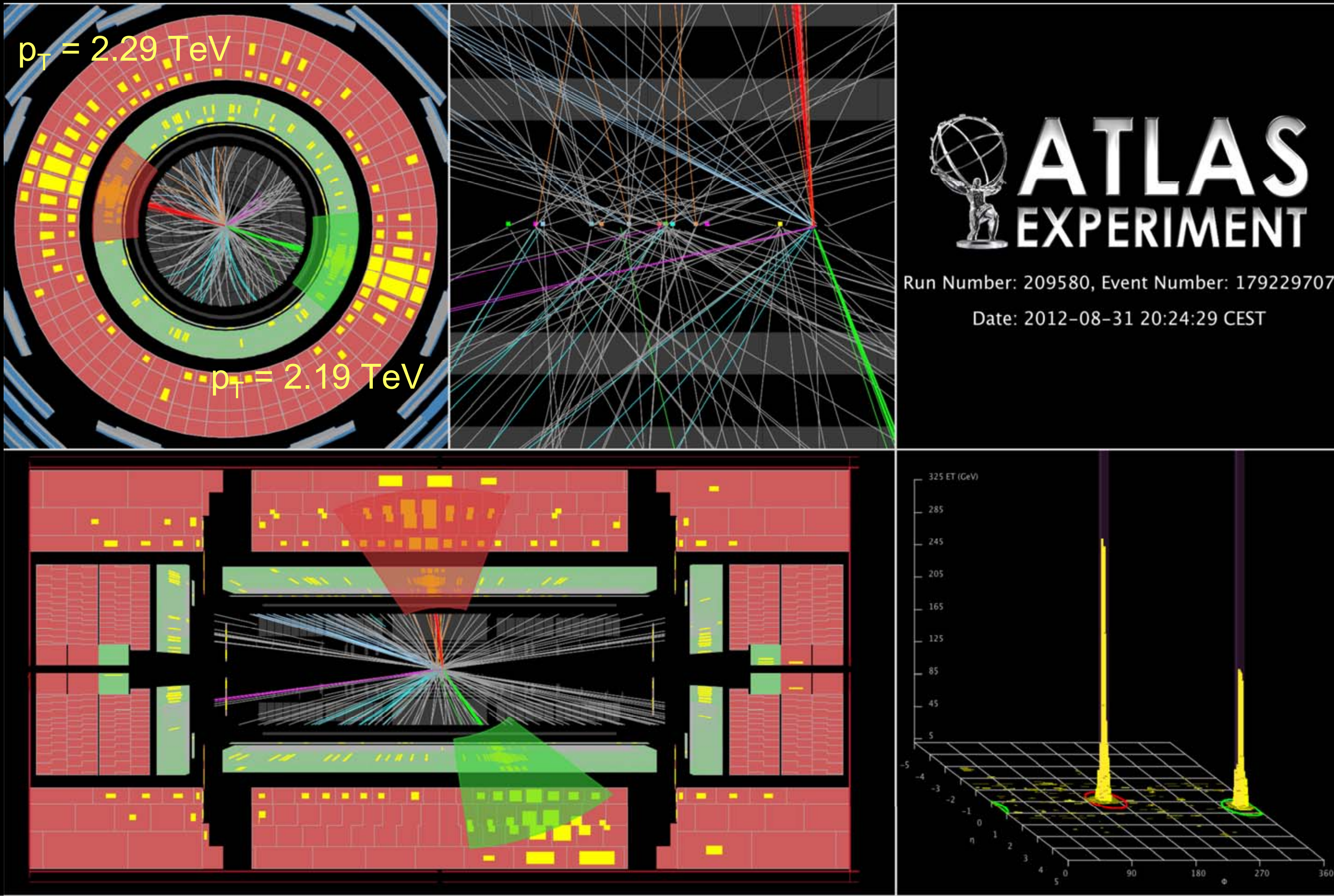


$M(W'_{SSM})$ 95% CL	Expected	Observed
ATLAS e+μ, 2011,4.7fb^{-1}	> 2.55 TeV	> 2.55 TeV
CMS e+μ, 2012, 3.7fb^{-1}	> 2.80 TeV	> 2.85 TeV
CMS e+μ, 2011+2012,5.0+3.7 fb^{-1}	> 2.85 TeV	> 2.85 TeV

$M(W'_{SSM})$ > 2.85 TeV 95% CL

[ATLAS hep-ex 1209.4446]
[CMS PAS EXO-12-010]

Dijet Event Display with m_{inv} = 4.69 TeV



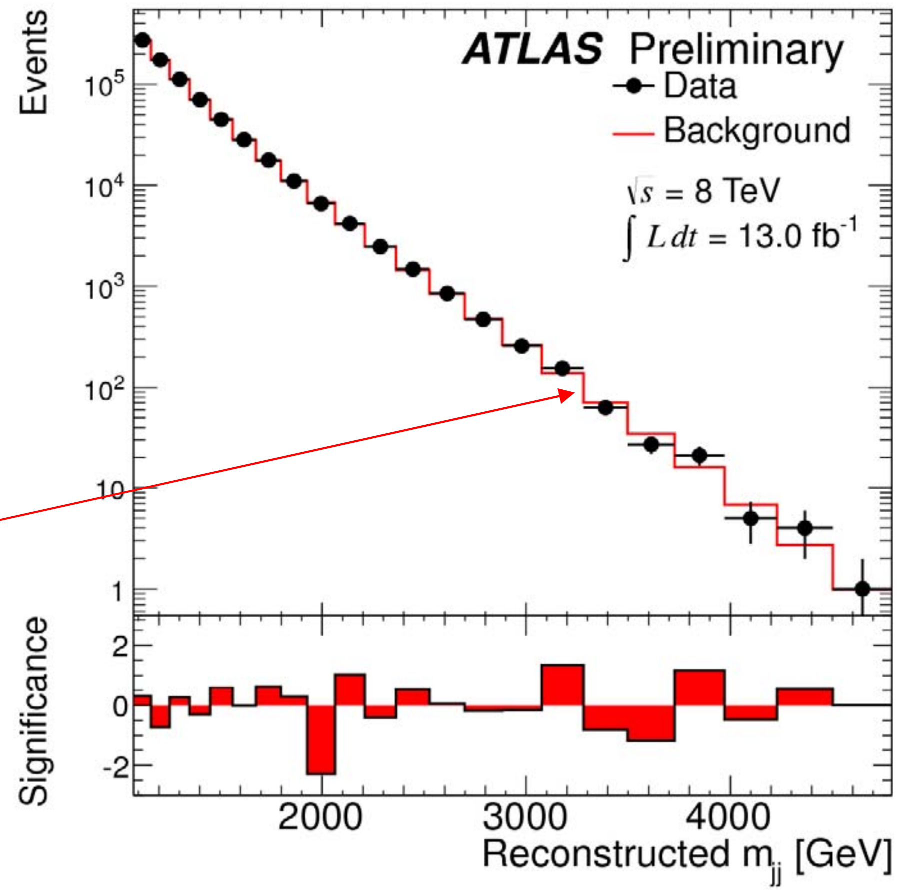
Heavy Resonance Search: 8 TeV Dijets

Probing quark structure ~ 5 TeV

- Strong gravity, excited quarks
- Selections
  - Two anti-kt 0.6 jets
  - $p^j_T > 150$ GeV && $m_{jj} > 1$ TeV
  - $|y| < 2.8$ && dijet CM rapidity $|y*| < 0.6$, $y^* = \pm 0.5 * (y_1 - y_2)$
- Look for resonance above phenomenological fit of data

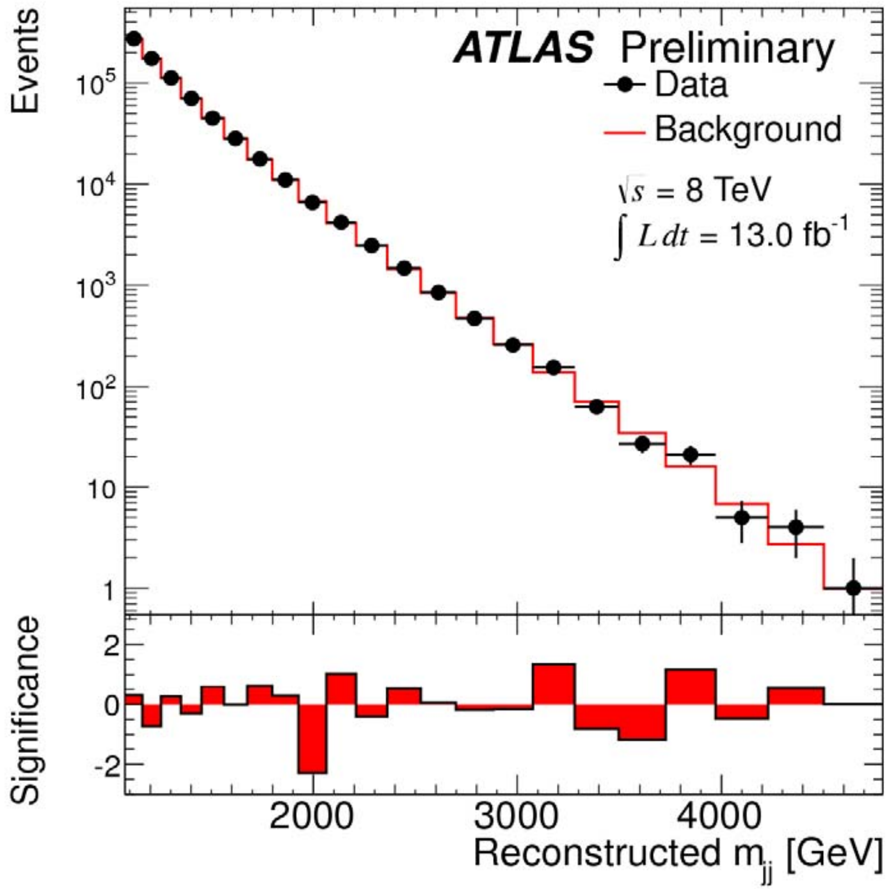
$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

$$x \equiv m_{jj}/\sqrt{s}$$



Heavy Resonance Search: 8 TeV Dijets

- Good agreement btw data and fit.
  - Global χ^2/NDF=15.5/18 = 0.86 → p-value = 0.61
  - good agreement btw data and fit
  - Bump Hunter

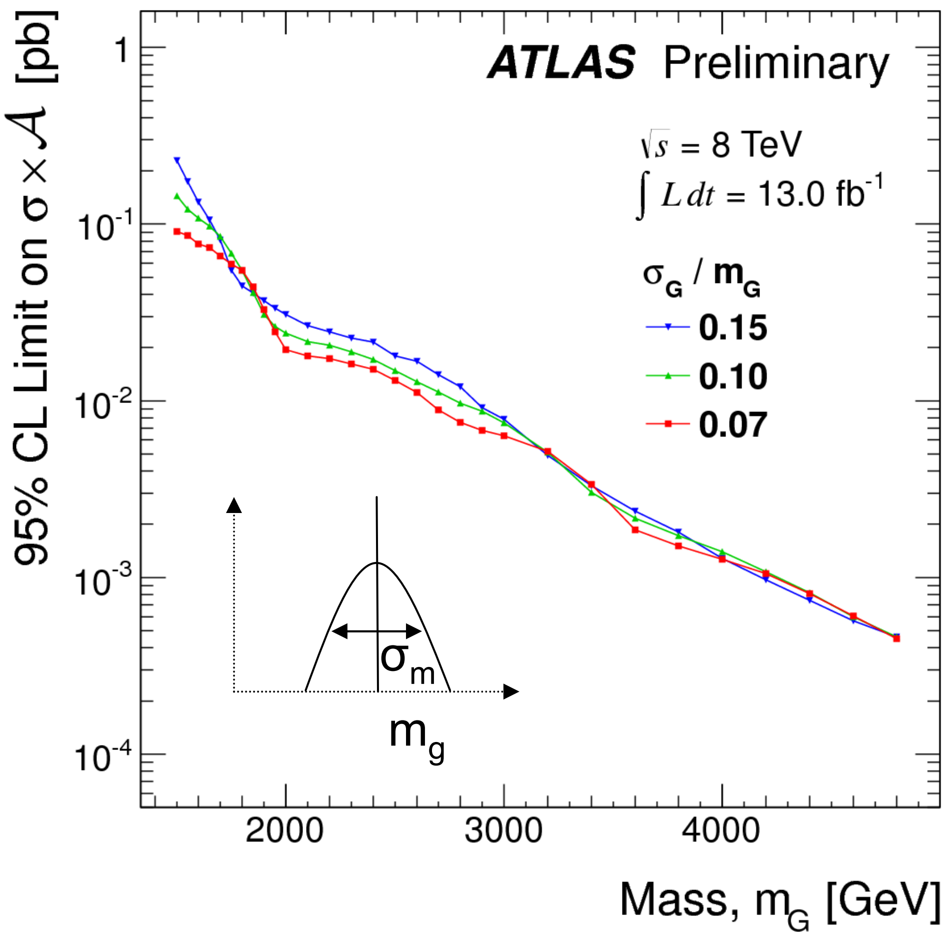


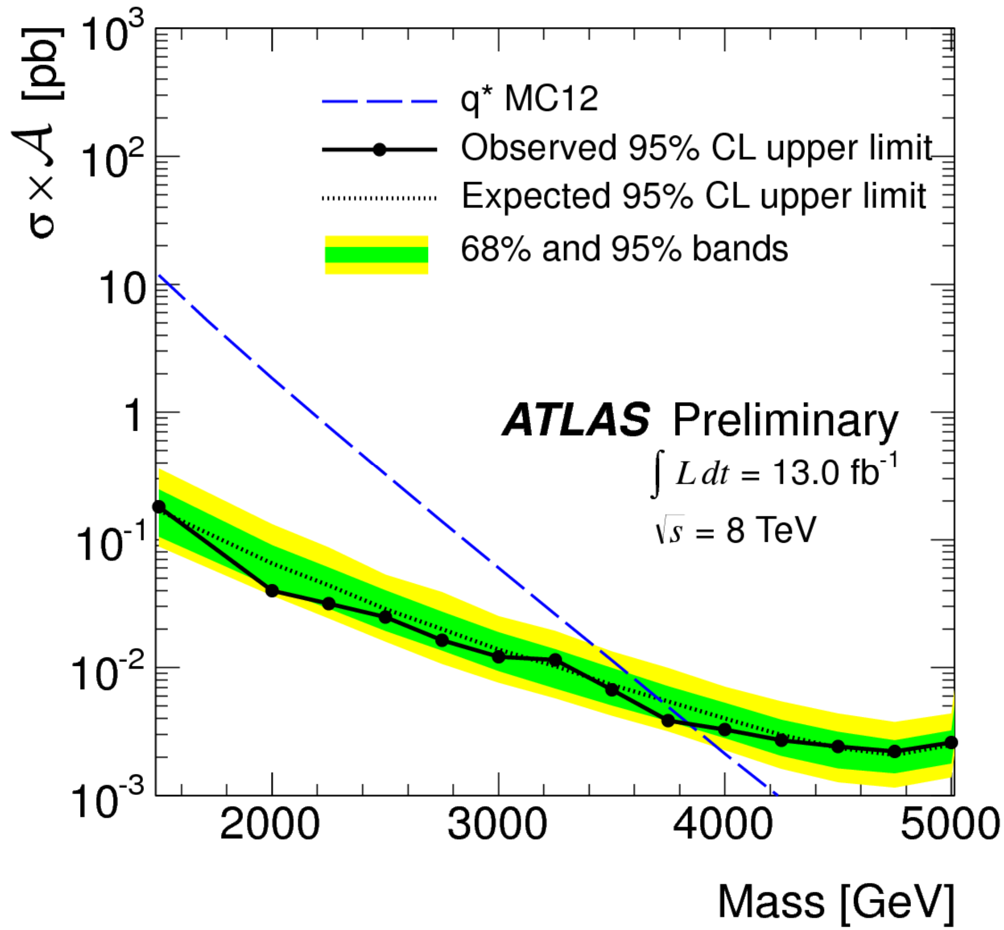
ATLAS-CONF-2012-148

Heavy Resonance Search: 8 TeV Dijets

Gaussian resonance limits:
mean mass, m_G, and 3 σ_G

Excited quark limit:
m > 3.84 TeV at 95% CL

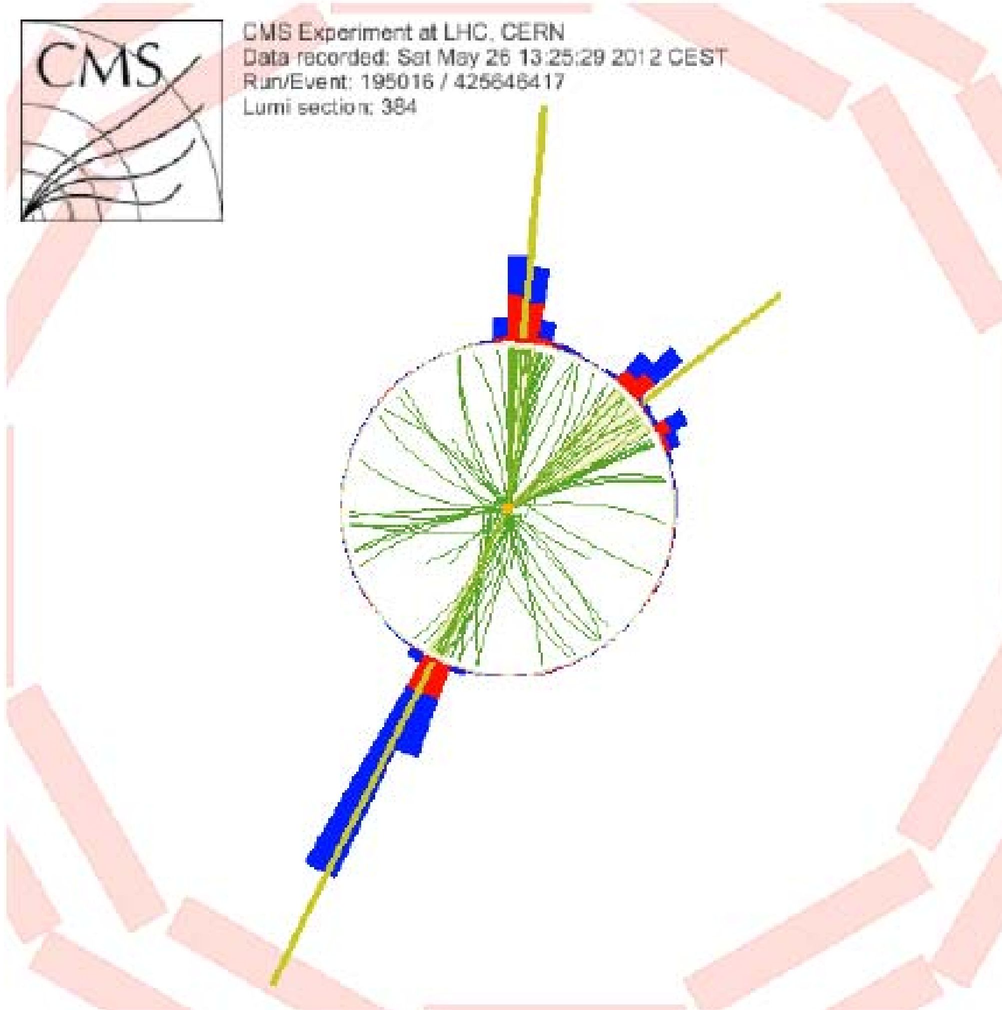




Heavy Resonance Search: 8 TeV Dijets

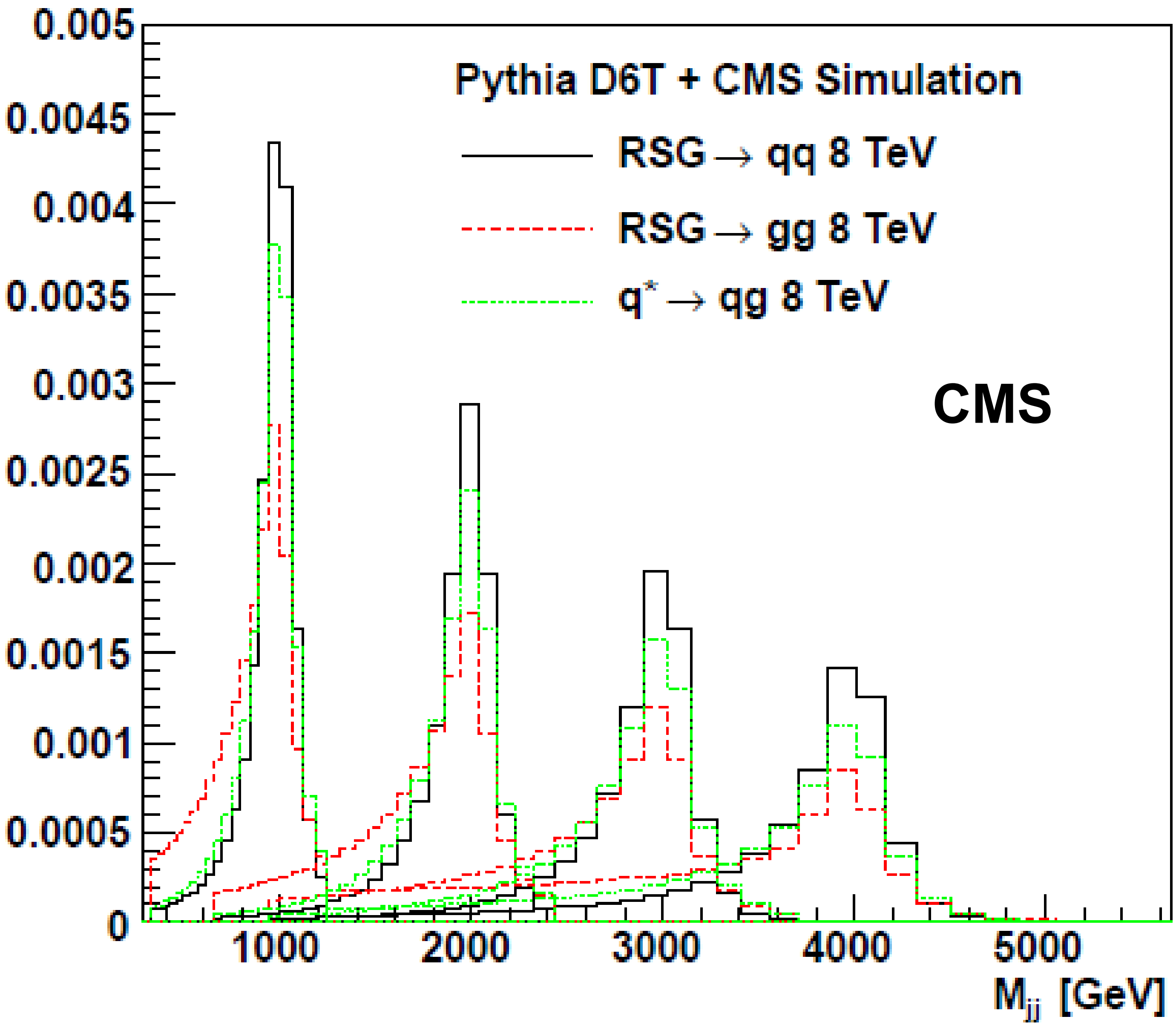
PAS EXO12016

- Uses particle flow jets R=0.5
- p_T > 30 GeV, $|\eta| < 2.5$
- combines particle-flow jets into ”wide jets” with R = 1.1
- two wide jets satisfy
  - $|\eta_{jj}| < 1.3$
  - $|\eta| < 2.5$
  - M_{jj}>890 GeV



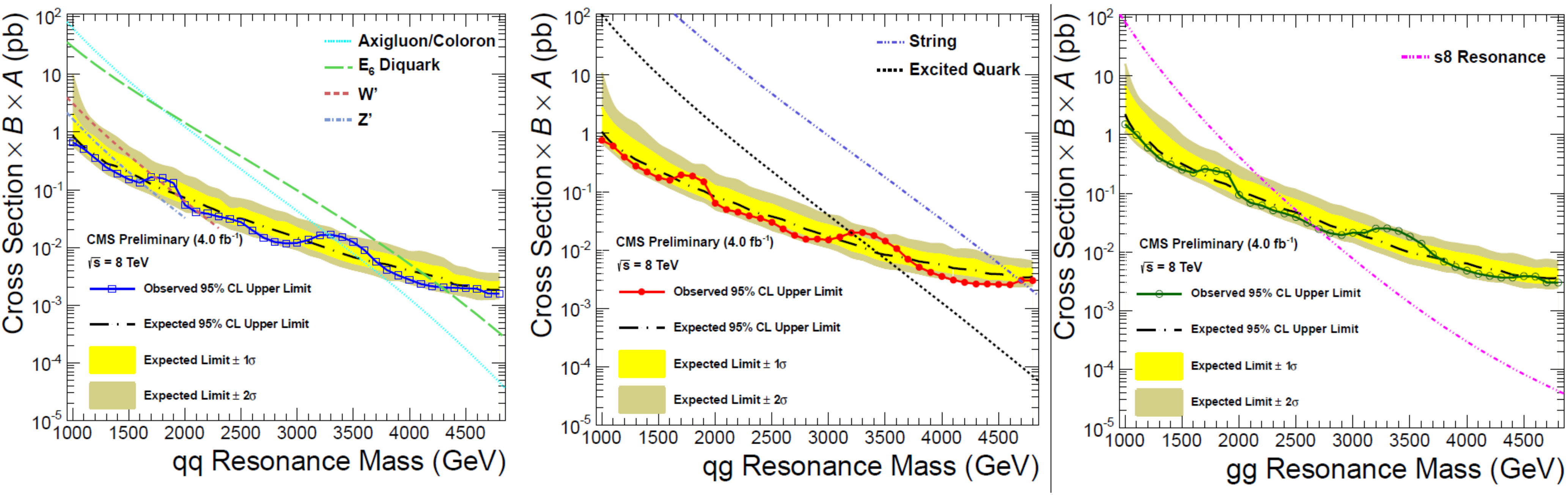
Heavy Resonance Search: 8 TeV Dijets

PAS EXO12016

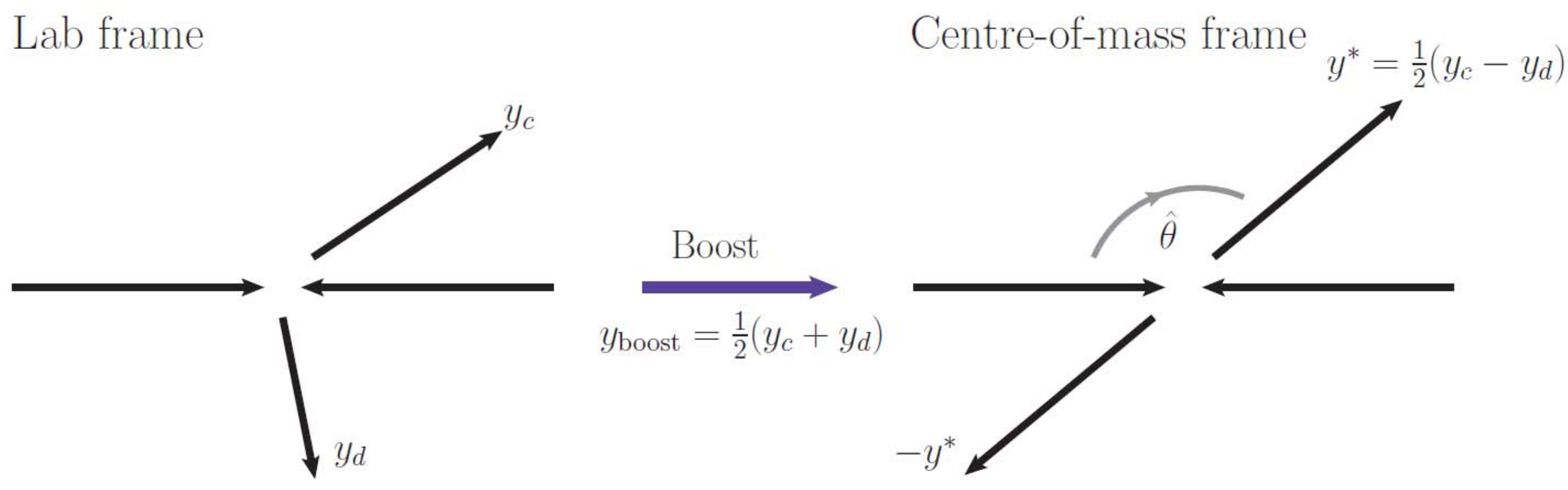


Heavy Resonance Search: 8 TeV Dijets

PAS EXO12016



Search for Heavy Resonance: Dijet Angular



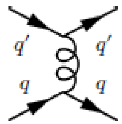
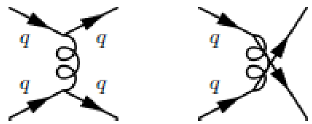
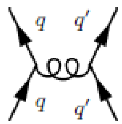
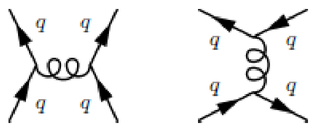
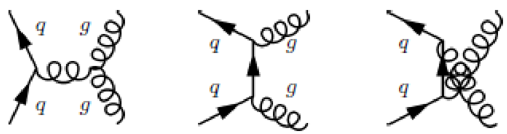
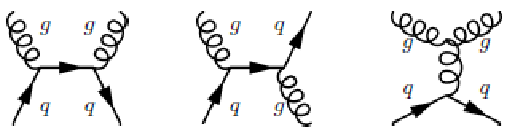
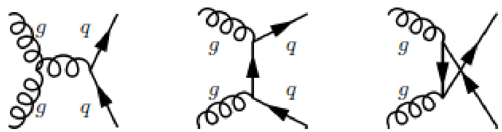
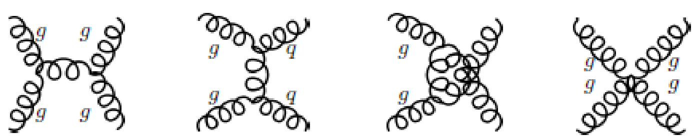
$$d\hat{\sigma}/d(\cos\hat{\theta}) \propto \sin^{-4}(\hat{\theta}/2)$$ t-channel Spin-1 exchange

$$\chi = \frac{1+|\cos\hat{\theta}|}{1-|\cos\hat{\theta}|} \sim \frac{1}{1-|\cos\hat{\theta}|} \propto \frac{\hat{s}}{\hat{t}}$$

$$\frac{d\hat{\sigma}}{d\chi} \propto \frac{\alpha_s^2}{\hat{s}} \quad (\hat{s}\ \text{fixed}) \quad \hat{s} = m_{jj}$$

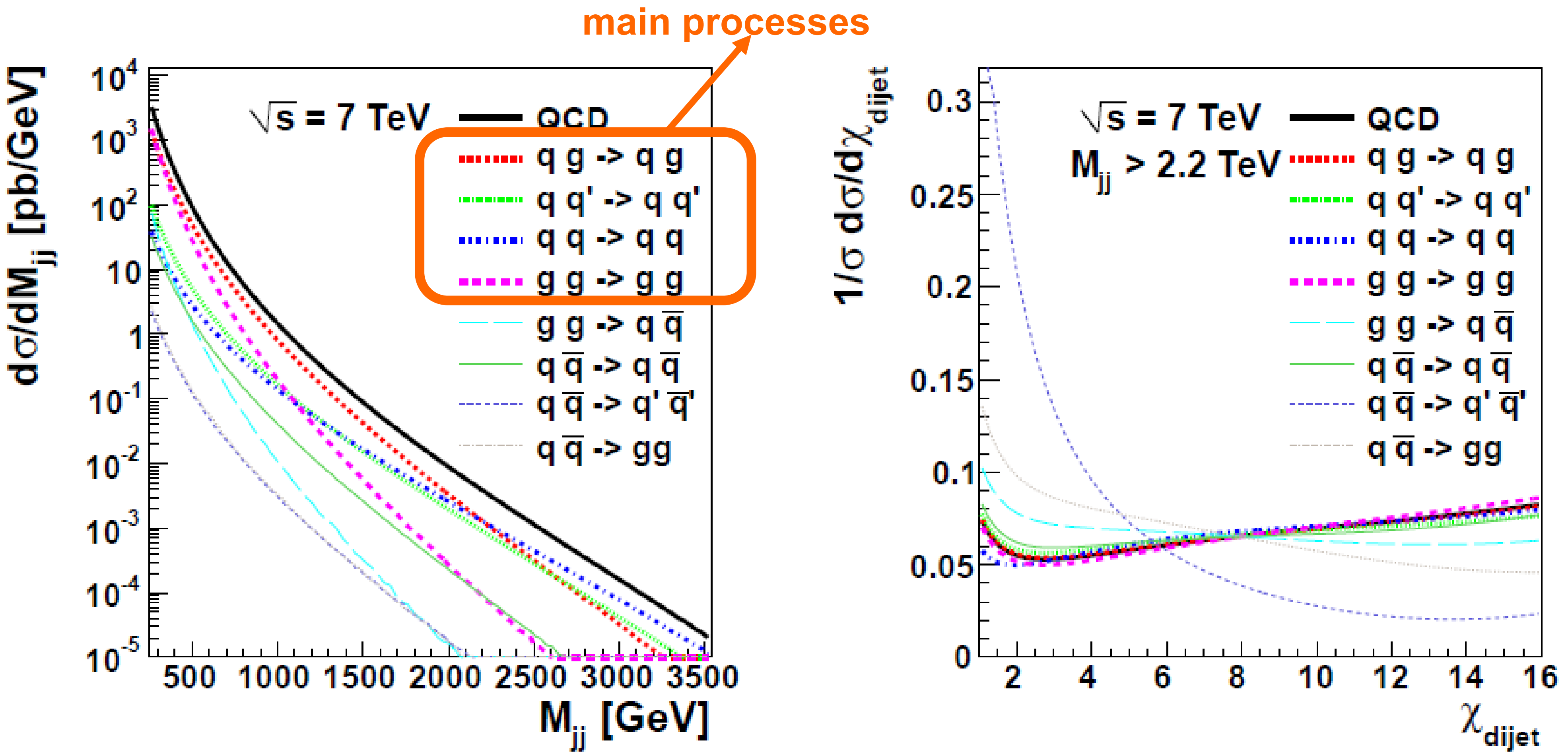
Constant in χ for fixed m_{jj}

Search for Heavy Resonance: Dijet Angular

$qq' \to qq' = q\bar{q}' \to q\bar{q}'$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)$	
$qq \to qq$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}-\frac{2}{3}\frac{\hat{s}}{\hat{u}\hat{t}}\right)$	
$q\bar{q} \to q'\bar{q}'$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$	
$q\bar{q} \to q\bar{q}$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}-\frac{2}{3}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right)$	
$q\bar{q} \to gg$	$\frac{128}{3}\alpha_s^2\left(\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$	
$qg \to qg$	$16\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}\right)$	
$gg \to q\bar{q}$	$\frac{8}{3}\alpha_s^2\left(\frac{1}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{4}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$	
$gg \to gg$	$72\alpha_s^2\left(3+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}+\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)$	

QCD is a bit more complicated…..

Search for Heavy Resonance: Dijet Angular



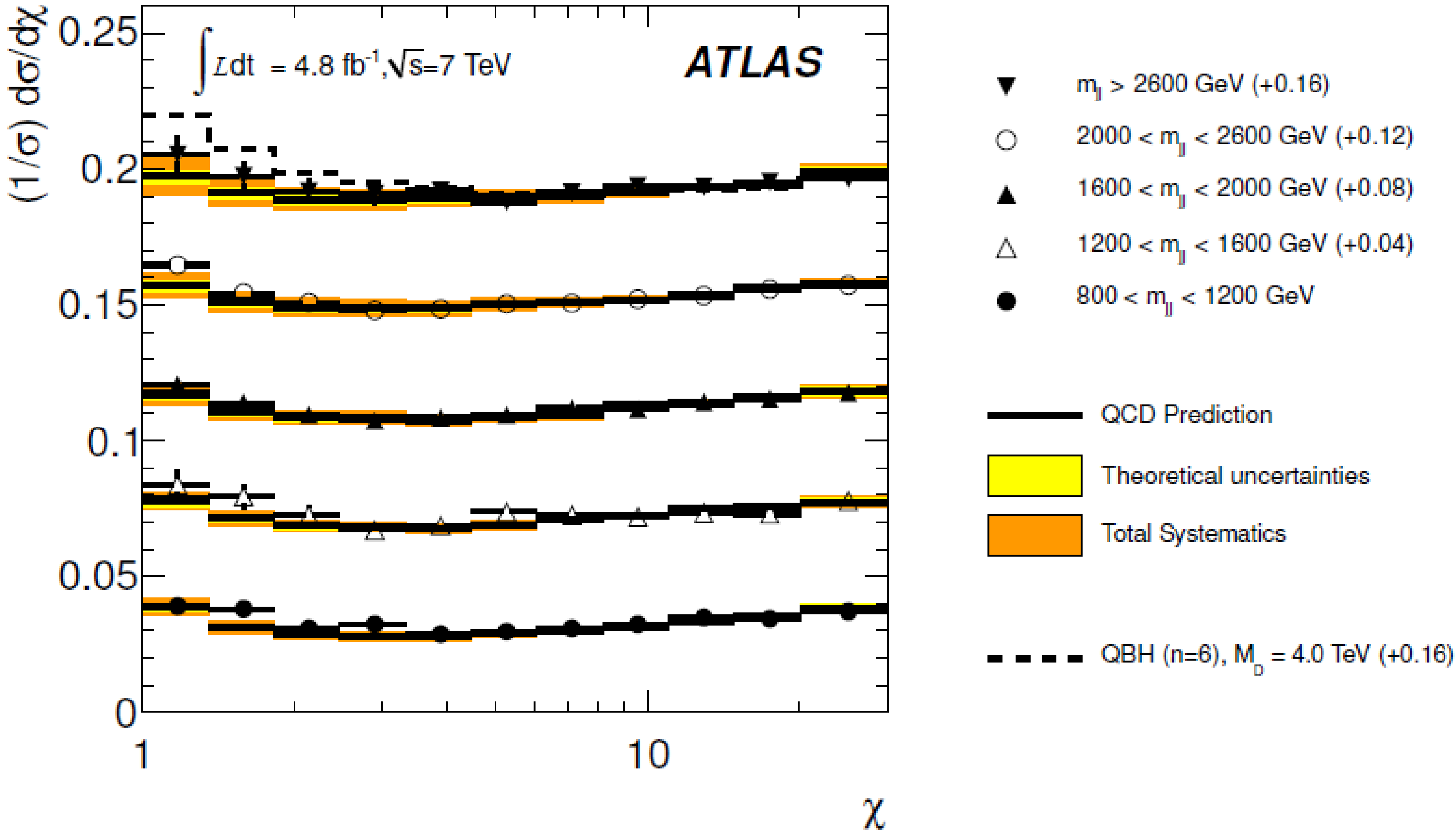
low M_{jj} gg and qg dominate
high M_{jj} qq dominate

QCD ~ flat in χ

Andreas Dominik Hinzmann

Search for Heavy Resonance: Dijet Angular

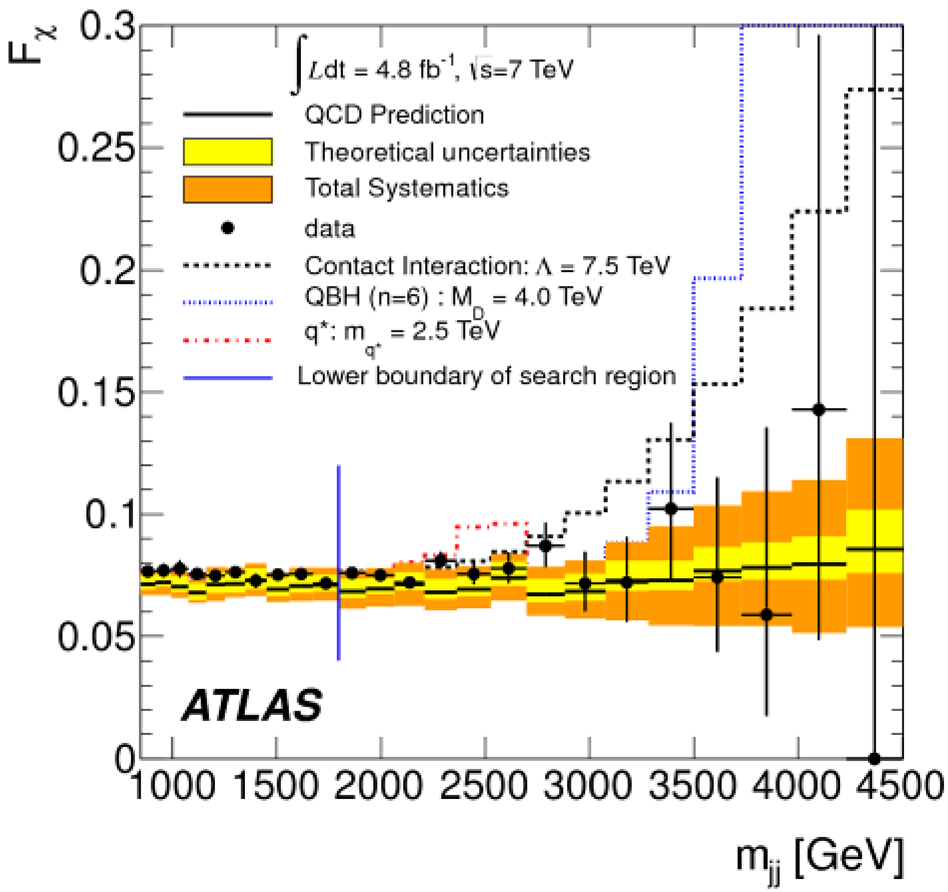
arXiv:1210.1718

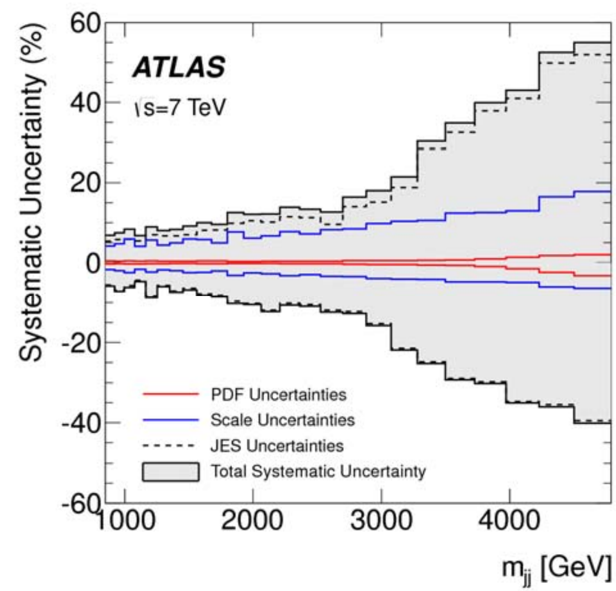


Search for Heavy Resonance: Dijet Angular

arXiv:1210.1718

$$F_\chi(m_{jj}) \equiv \frac{dN_{\mathrm{central}}/dm_{jj}}{dN_{\mathrm{total}}/dm_{jj}},$$

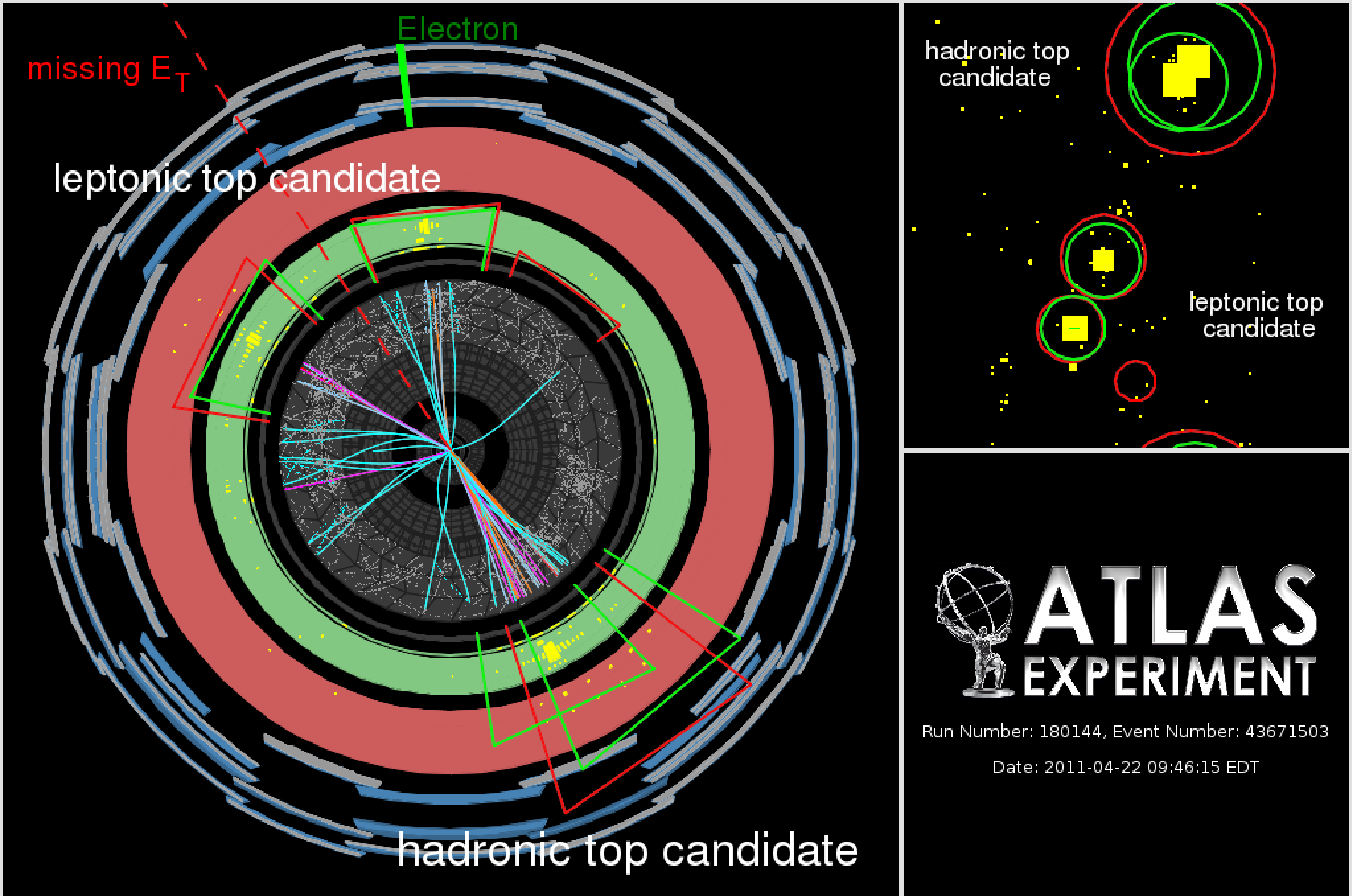




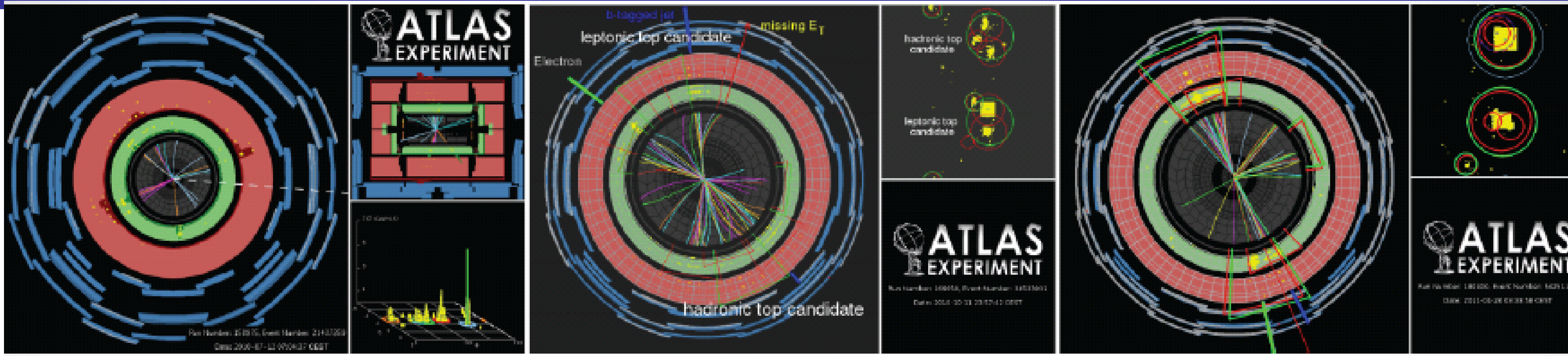
Models and Limits:

- Quark contact interaction (quark compositeness)
  - **Λ>7.6 TeV (7.7 TeV)**
- Quantum Blackholes
  - M_D>4.1 TeV (4.2 TeV) n=6

Boosted Top Event Candidate with m_{ttbar}=2.5 TeV



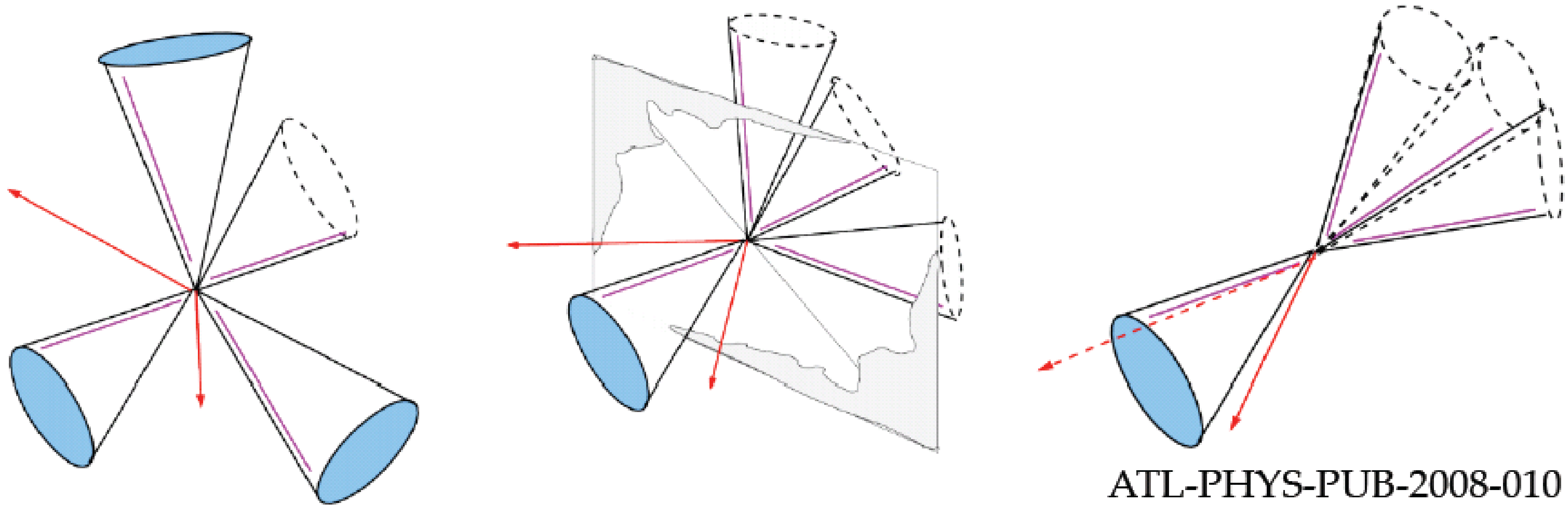
Top Reconstruction @ LHC: 3 Regimes



At rest: Mtt<500 GeV

Transition region: 500GeV<Mtt<700GeV

Mono-jet: Mtt>700GeV



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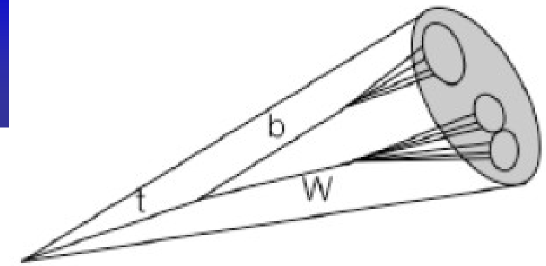
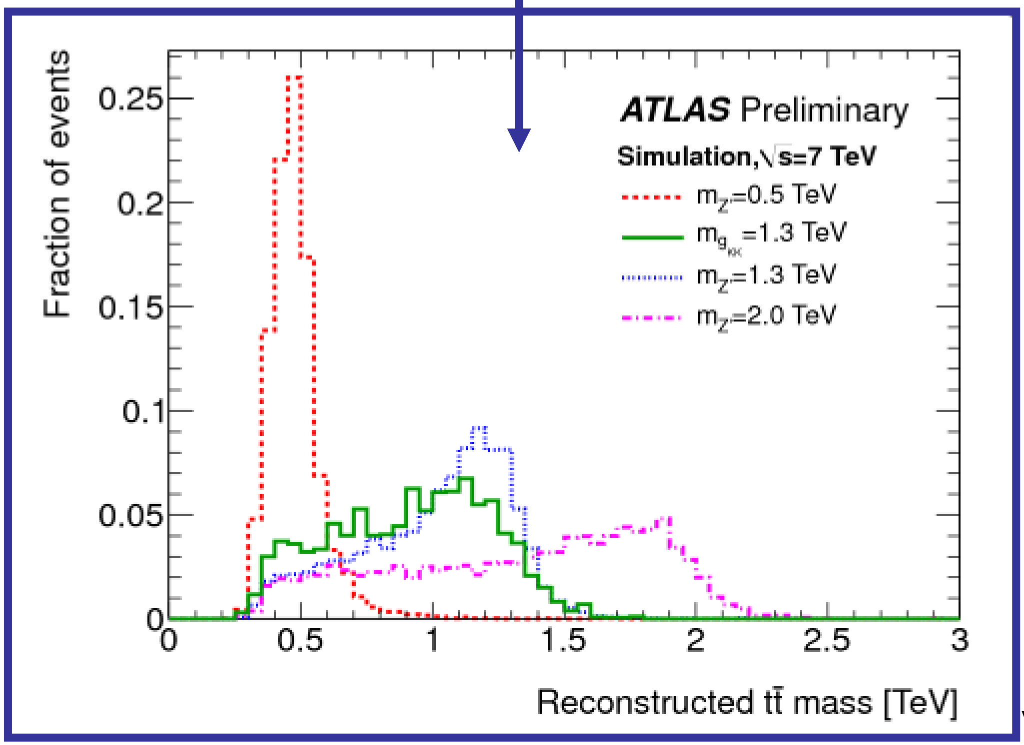
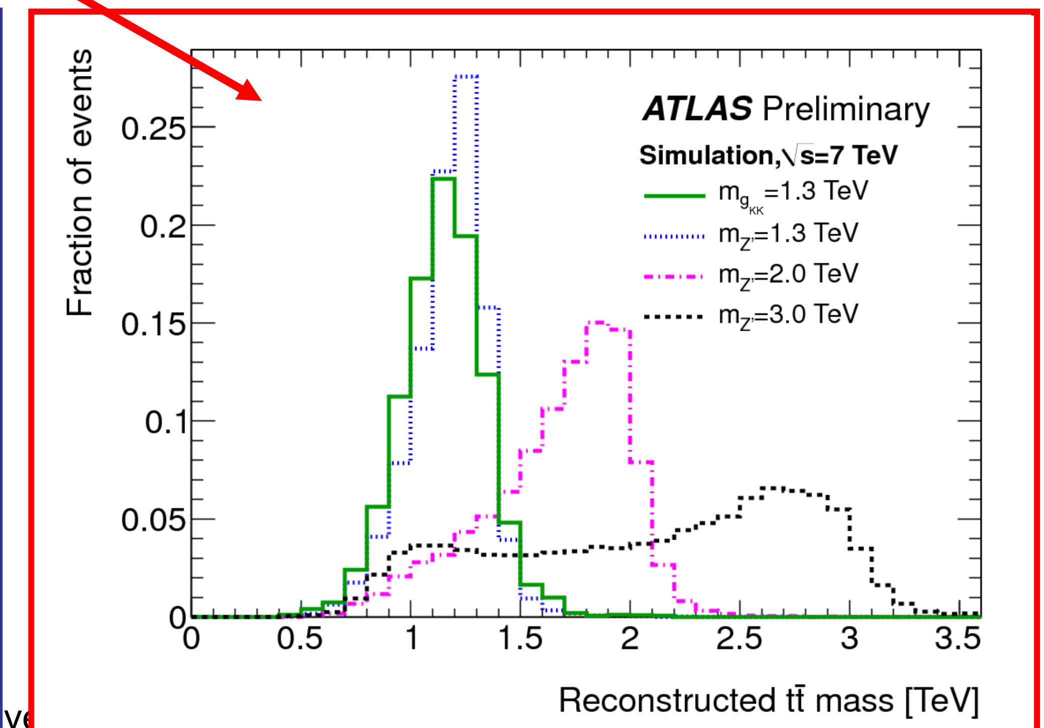
Heavy Resonances Search: Ttbar



ATLAS-CONF-2012-136

- Lepton+jets channel
- Models: e.g. bulk-RS (esp. KK gluons) and Leptophobic Z’
  - Large Branching Ratio to top-antitop
- Taking full advantage of boosted techniques
- Combining **resolved** and **boosted** reconstructions





Heavy Resonances Search: Ttbar

- Event Selection

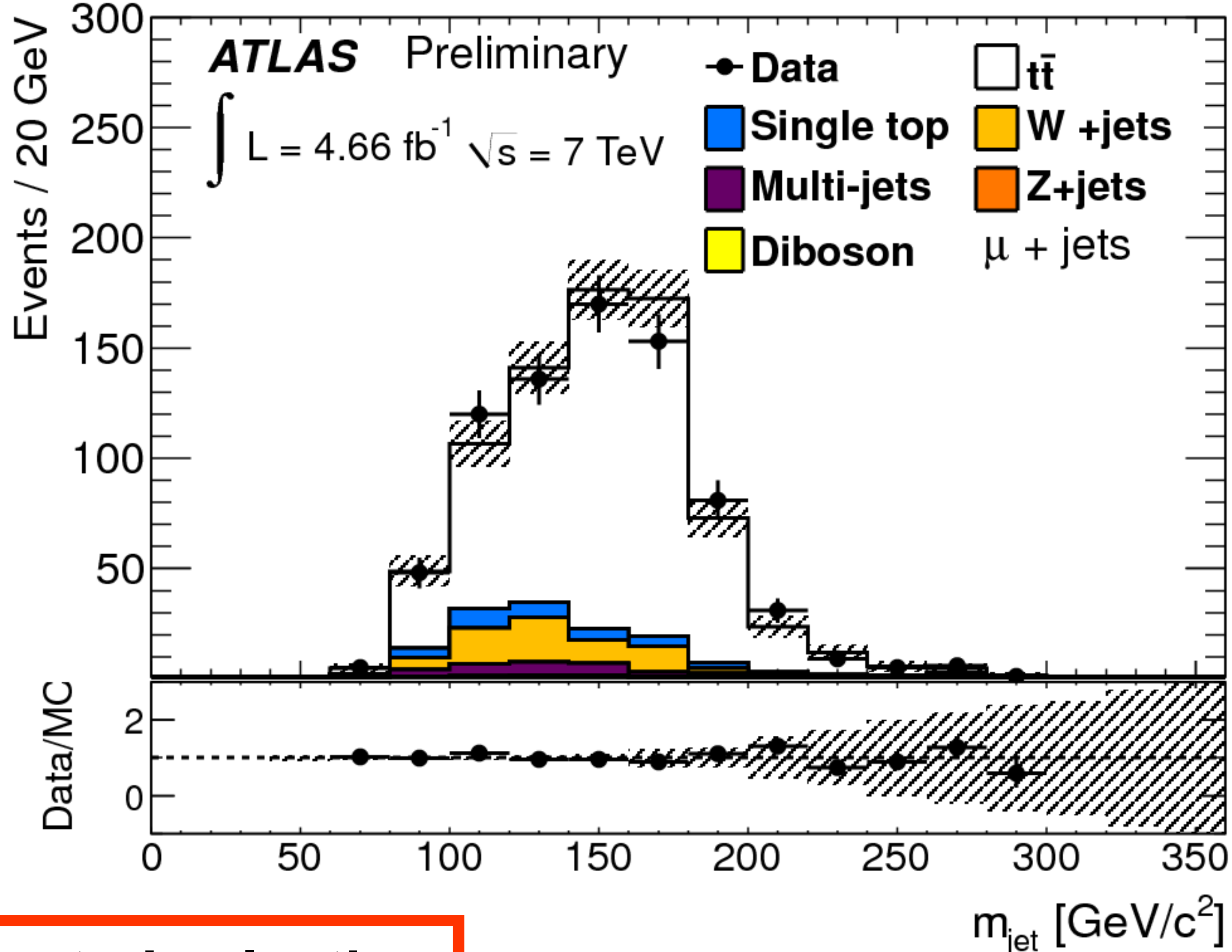
	resolved	boosted
trigger	single lepton trigger	fat jet (AKT10) trigger
leptons	1 lepton ($e^{\pm}$ or $\mu^{\pm}$), $p_T > 25\,\mathrm{GeV}$ additional lepton ($e^{\pm}$ or $\mu^{\pm}$) veto, $p_T > 20\,\mathrm{GeV}$	
	lepton trigger match	—
$\not{E}_T$	$e^{\pm}$: $\not{E}_T > 30\,\mathrm{GeV}$, $\mu^{\pm}$: $\not{E}_T > 20\,\mathrm{GeV}$	
m_T^W	$e^{\pm}$: $M_T(W) > 30\,\mathrm{GeV}$, $\mu^{\pm}$: $M_T(W) + \not{E}_T > 60\,\mathrm{GeV}$	
jets	$\geq 4(3)$ jets (if one jet $m_{\mathrm{jet}} > 60\,\mathrm{GeV}$)	"leptonic jet": AKT4 jet "hadronic jet": AKT10 jet
b-tag	≥ 1 b-tag using AKT4 jets ($\varepsilon_b = 70\,\%$)	

S. Fleischmann, Top2012

Heavy Resonances Search: Ttbar

- Improve efficiency at high t-tbar mass with:
  - Lepton “mini-isolation”:
    - cone shrinks at high momentum
  - Trigger:
    - use Fat Jet trigger (anti-kt jet R=1.0, pT>240 GeV)
    - Better efficiency than lepton trigger at high mass
  - Combine resolved and boosted selection:
    - If event is reconstructed by both methods, use the boosted one (better mass resolution)

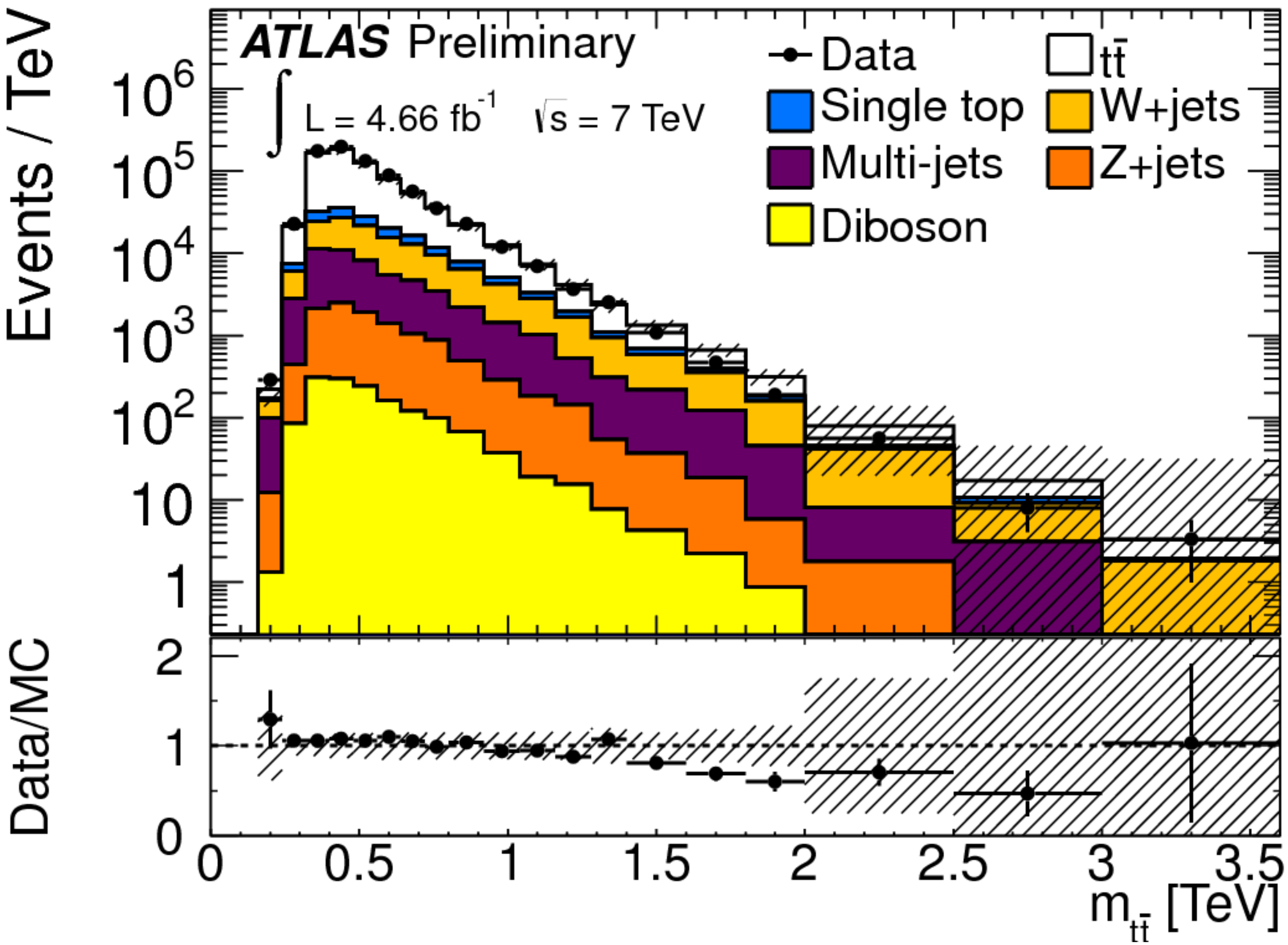
Heavy Resonances Search: Ttbar



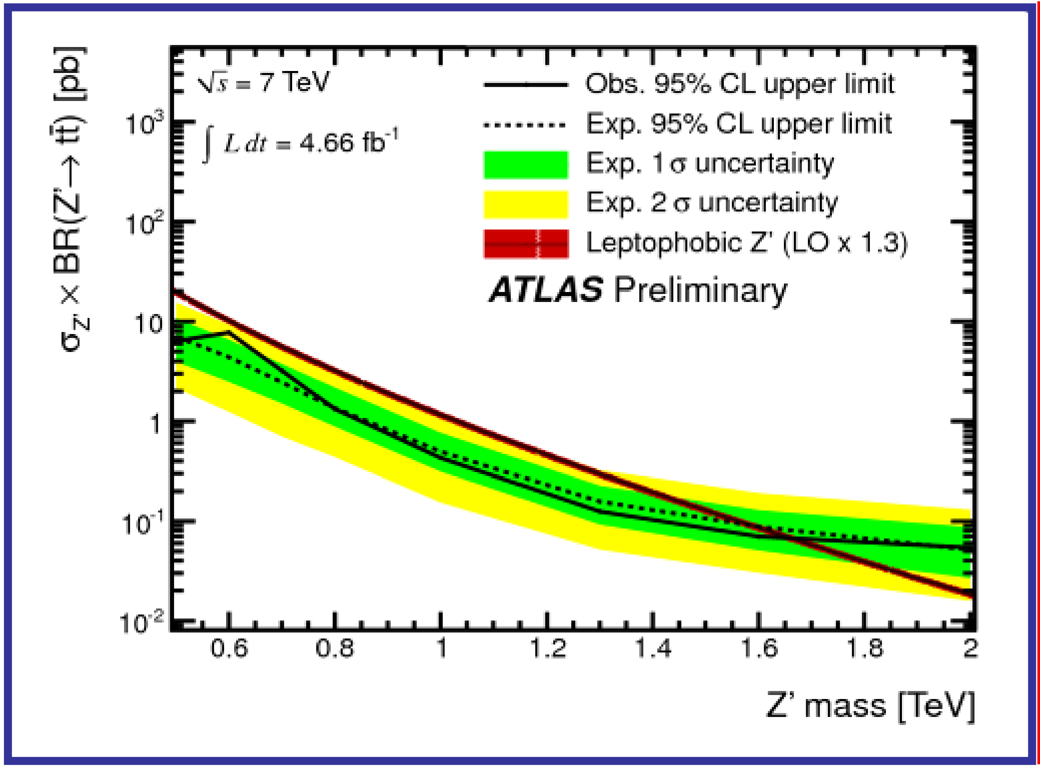
Boosted selection

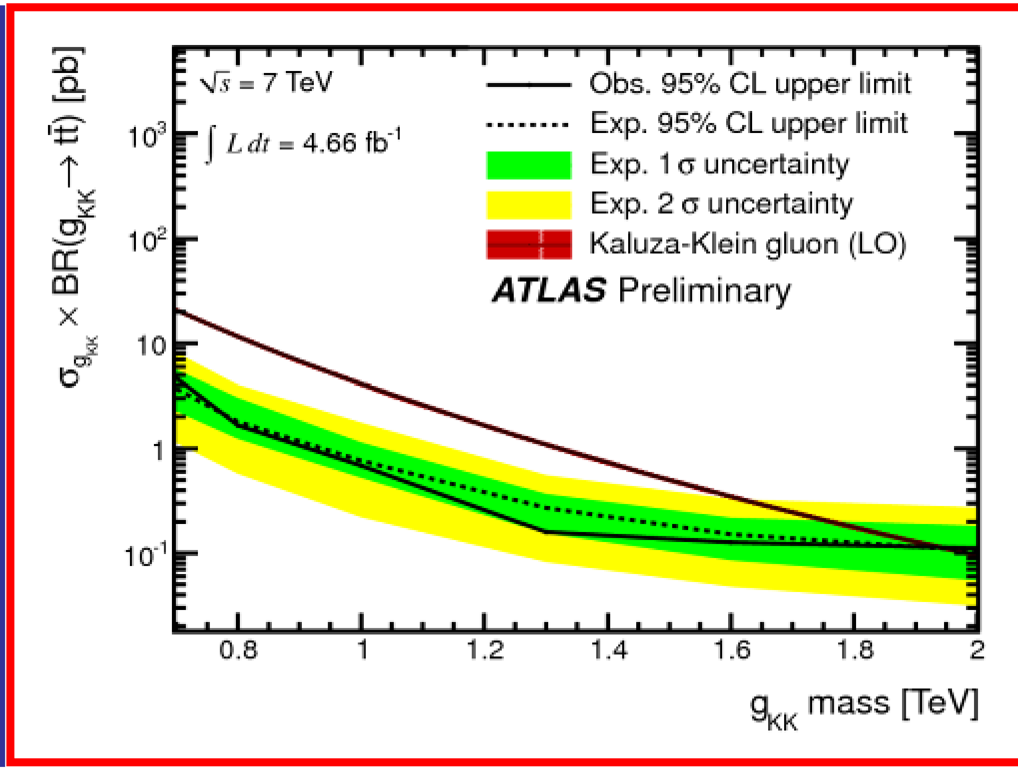
Heavy Resonances Search: Ttbar

- $m_{t\bar{t}}$ resolved + boosted in *e*+jets and *μ*+jets



Heavy Resonances Search: Ttbar

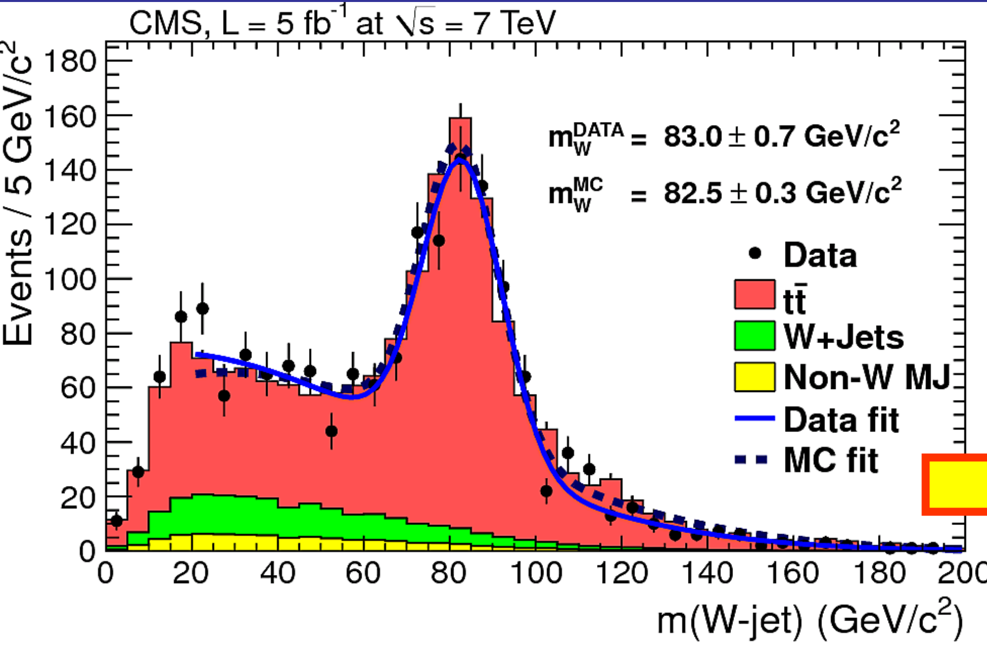


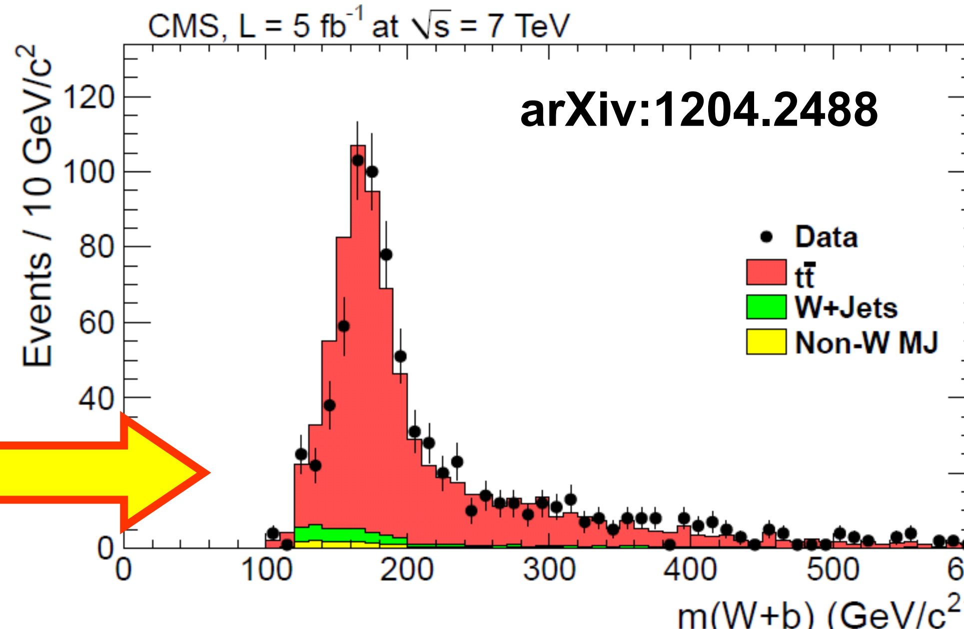


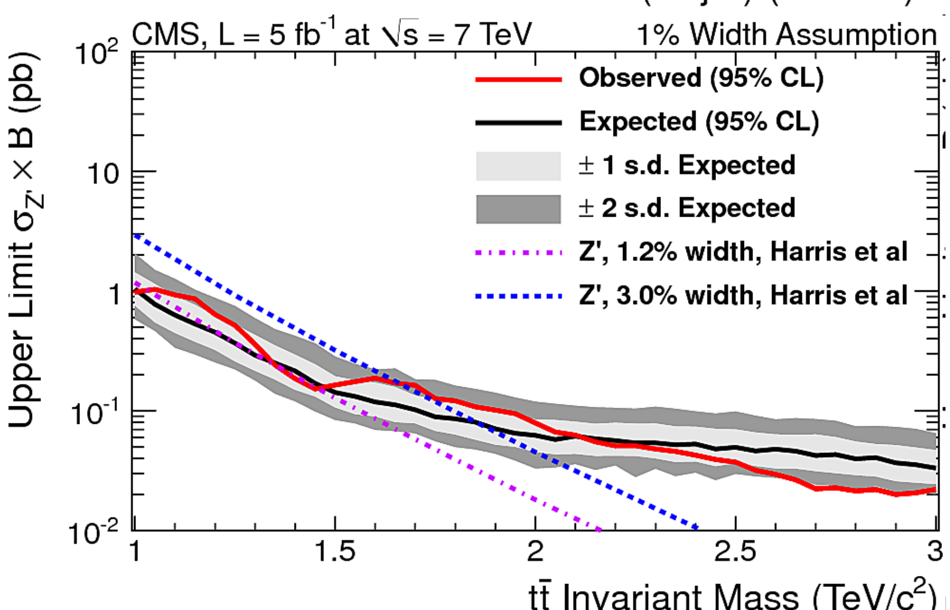
m(Z') > 1.7 TeV @95% CL
Γ/m(Z') = 1.2%

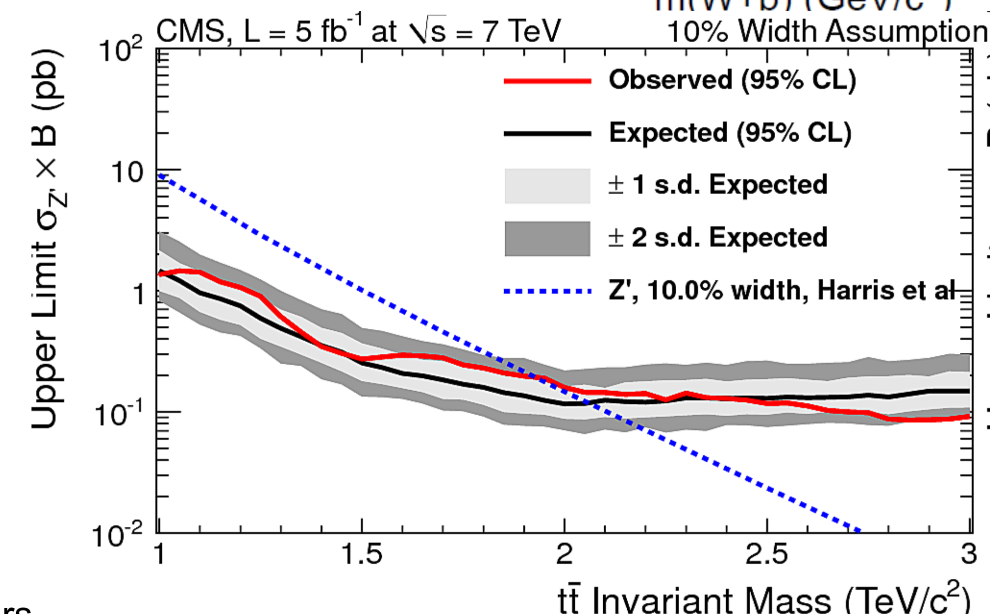
m(g_{KK}) > 1.9 TeV @95% CL
Γ/m(g_{KK}) = 15%

Heavy Resonance Search: ttbar hadronic channel

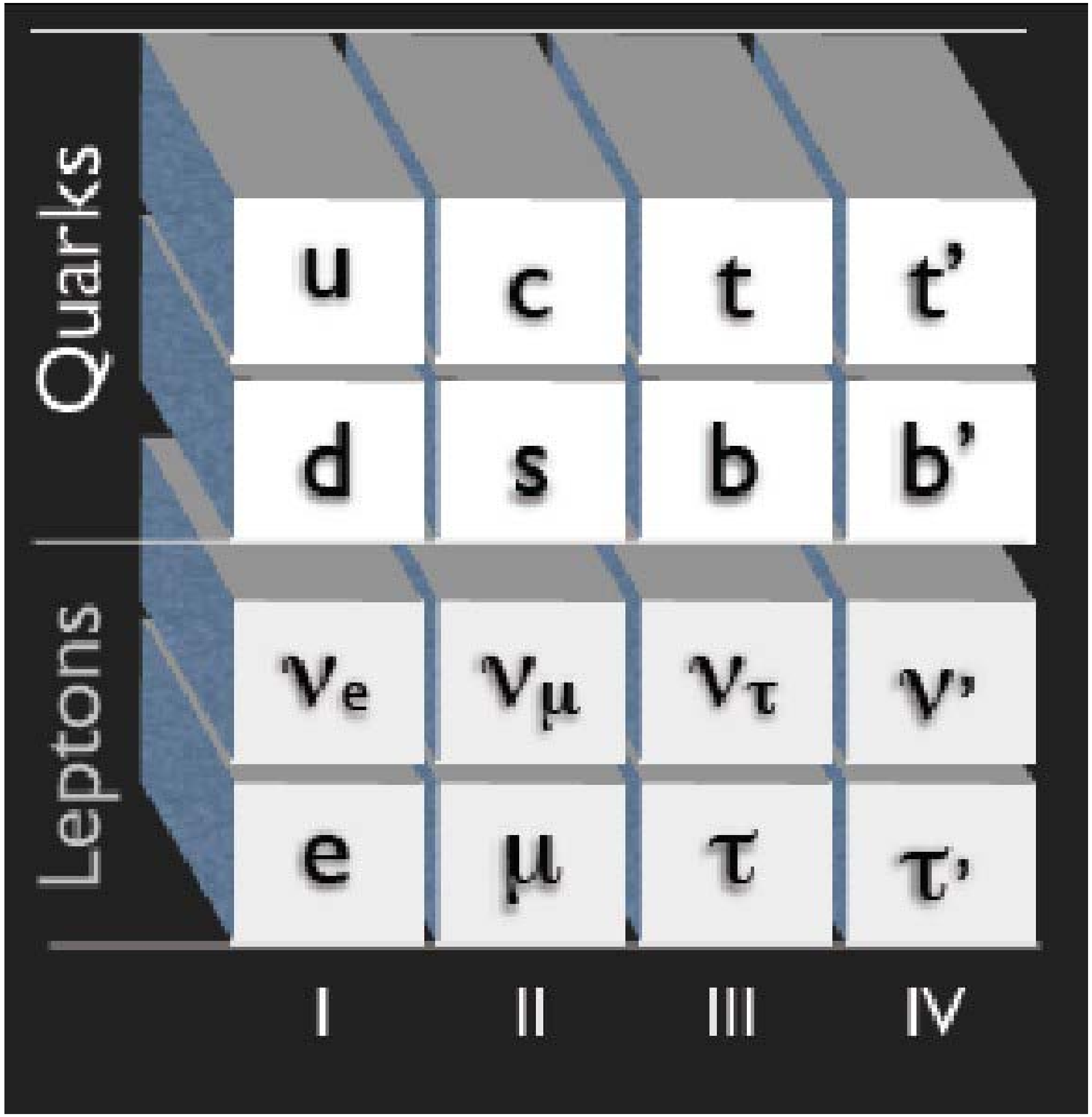








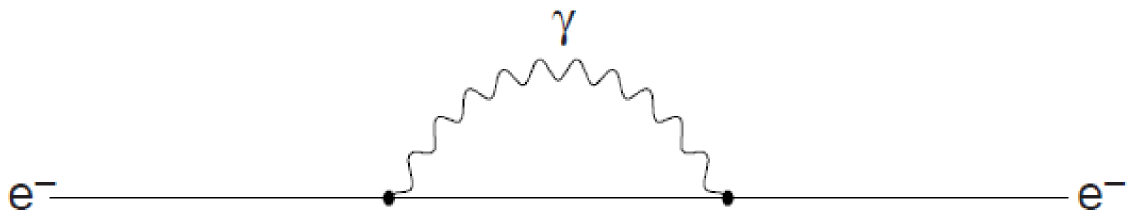
4th Generation and Heavy Quarks



Fine-Tuning Problem in Electromagnetism

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}$$

Coulomb self-energy



$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e},$$

$$r_e \lesssim 10^{-17}\ \text{cm} \quad \Longrightarrow \quad \Delta \text{E} \gtrsim 10\ \text{GeV}$$

$$0.511 = -9999.489 + 10000.000\ \text{MeV}$$

Fine tuning!

Murayama hep-ph/9410285

Fine-Tuning Problem in Electromagnetism

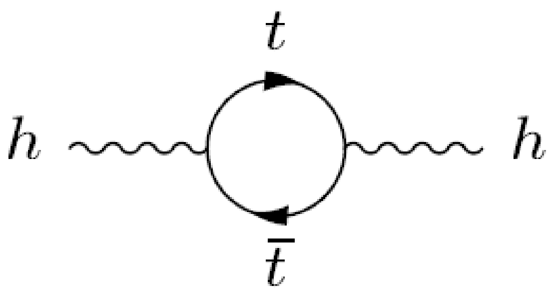
- Picture not complete:
  - Positron cancels $1/r_e$ term
  - New symmetry:
    - particle/anti-particle

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} \left[1 + \frac{3\alpha}{4\pi} \log \frac{\hbar}{m_e c r_e} \right]$$

    - Correction to bare mass becomes small

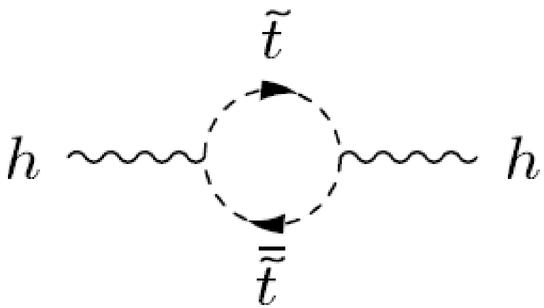
Supersymmetry

- Same problem with Higgs



$$\Delta\mu^2_{\text{top}} = -6\frac{h_t^2}{4\pi^2}\frac{1}{r_H^2}$$ ~ (100 GeV)^2

125 GeV = (huge number)-(huge number) even more fine tuned!

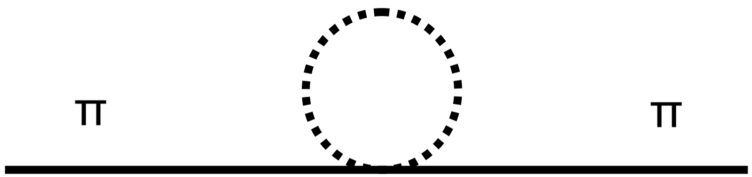


Add new particles (spin symmetry): SUSY

$$\Delta\mu^2_{\text{stop}} + \Delta\mu^2_{\text{top}} = -6\frac{h_t^2}{4\pi^2}(m_{\tilde{t}}^2 - m_t^2)\log\frac{1}{r_H^2 m_{\tilde{t}}^2}$$

Composite Higgs

- But there is another way….look at QCD

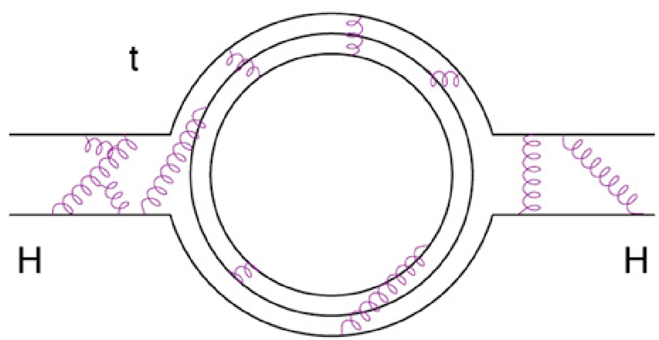


Pion mass is not divergent.

Why?

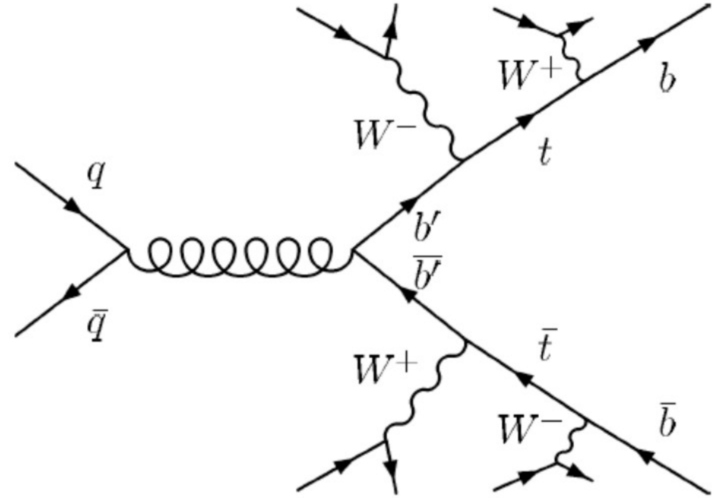
It is a composite particle!

- **Assume Higgs is a composite particle**
  - Changes couplings
  - Introduces new partners to top quarks
  - Vector-like quarks…
  - Solves fine-tuning problem….

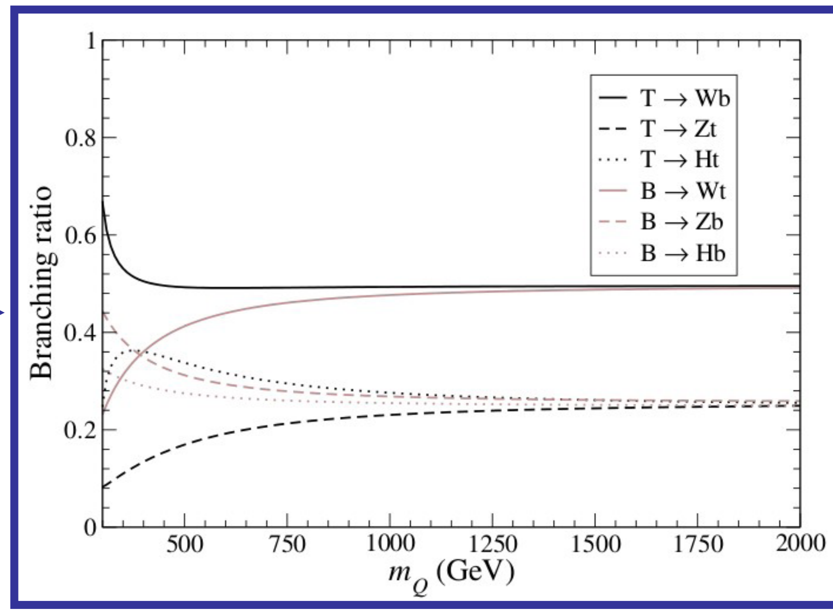


4th Generation and Heavy Quarks

- 4th generation would significantly enhance Higgs production cross section
  - (almost) excluded by observed Higgs cross-section
  - t't' → WbWb (100%): just like t-tbar but heavier
  - b’b’ →WtWt (100%): just like ttbar but messier



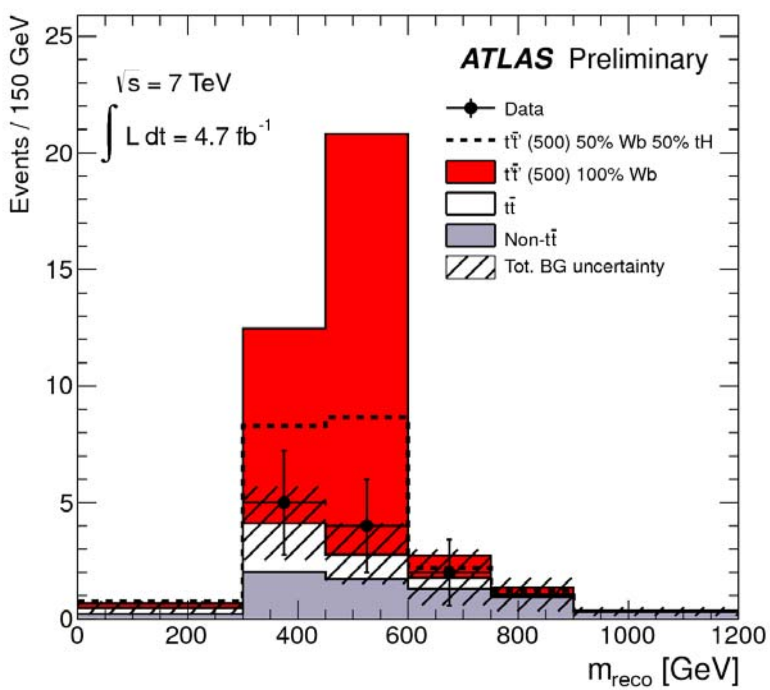
- Beyond 4th generation: **Vector-Like Quarks** in Composite Higgs theories
  - More diverse phenomenology
  - T': Decays to Wb, Zt, Ht
  - B': Decays to Wt, Zb, Hb
- Loose constraints on CKM4 → decays to light quarks possible!

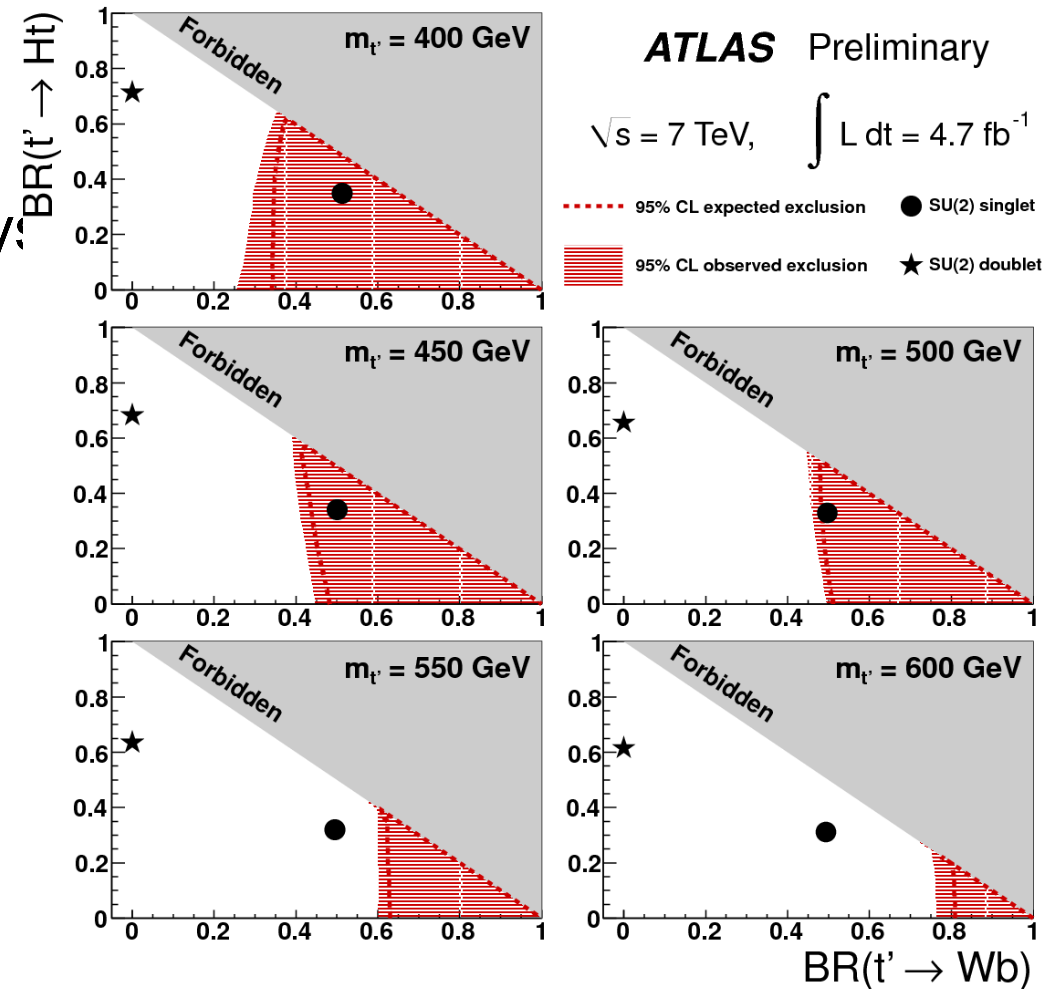


Search for Heavy Quarks

- Up-type heavy quark: t't' → WbWb
- l + ME_T + 4 jets (l=e,μ) + b-tagging
- Reconstruct boosted had. W decays

m(t')>656GeV at 95% CL (exp. 638GeV)



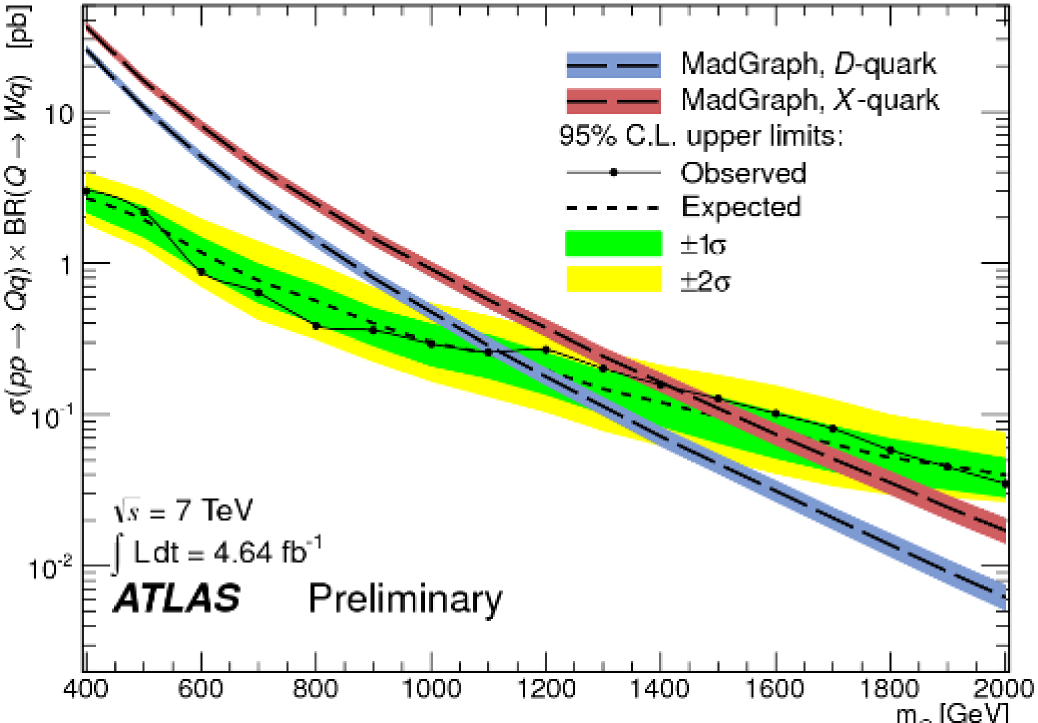


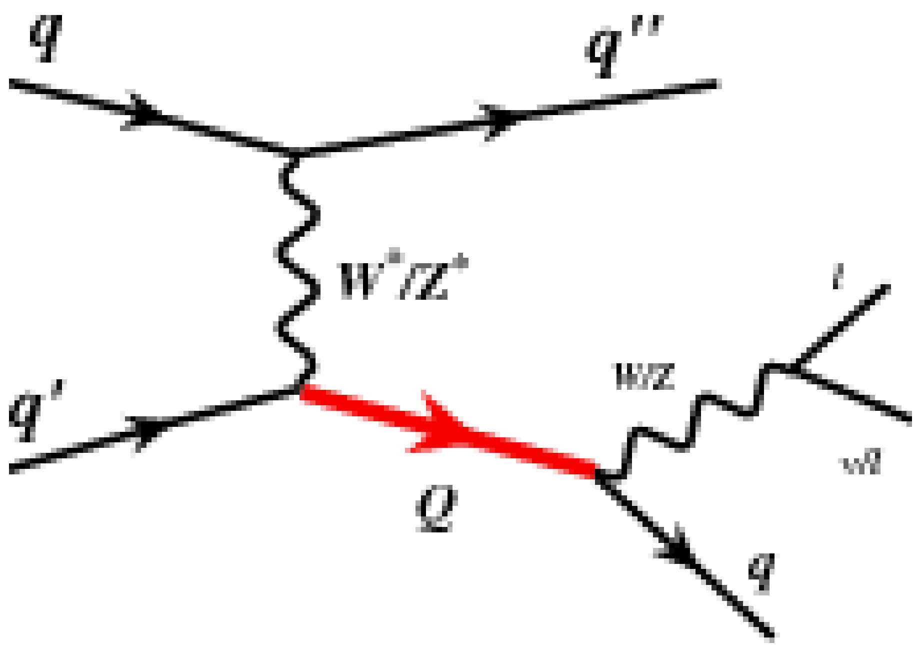
Vector-Like Quark interpretation: setting limits on branching ratios to Wb, tH, tZ

Vector-like Quarks Coupling to Light Generations

ATLAS-CONF-2012-137

- Mixing to first generations is not excluded
- Benchmark model: degenerate VLQ doublets ($U^{2/3}$,$Y^{2/3}$,$D^{-1/3}$,$X^{5/3}$)
- Single Production
- e and μ channel

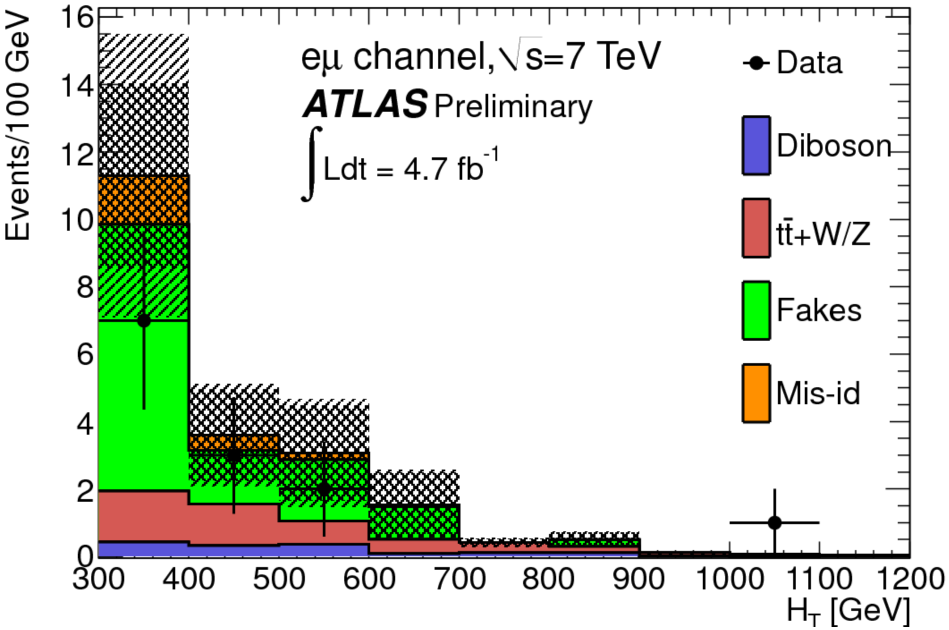


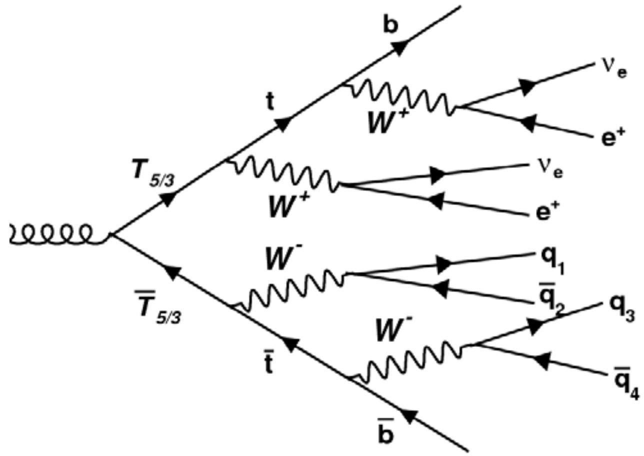


m($D^{-1/3}$)>1120GeV, m($X^{5/3}$)>1420GeV, m($U^{2/3}$)>1080GeV (not shown)

Exotic Same-Sign Dilepton Signatures: b', $T_{5/3}$

ATLAS-CONF-2012-130



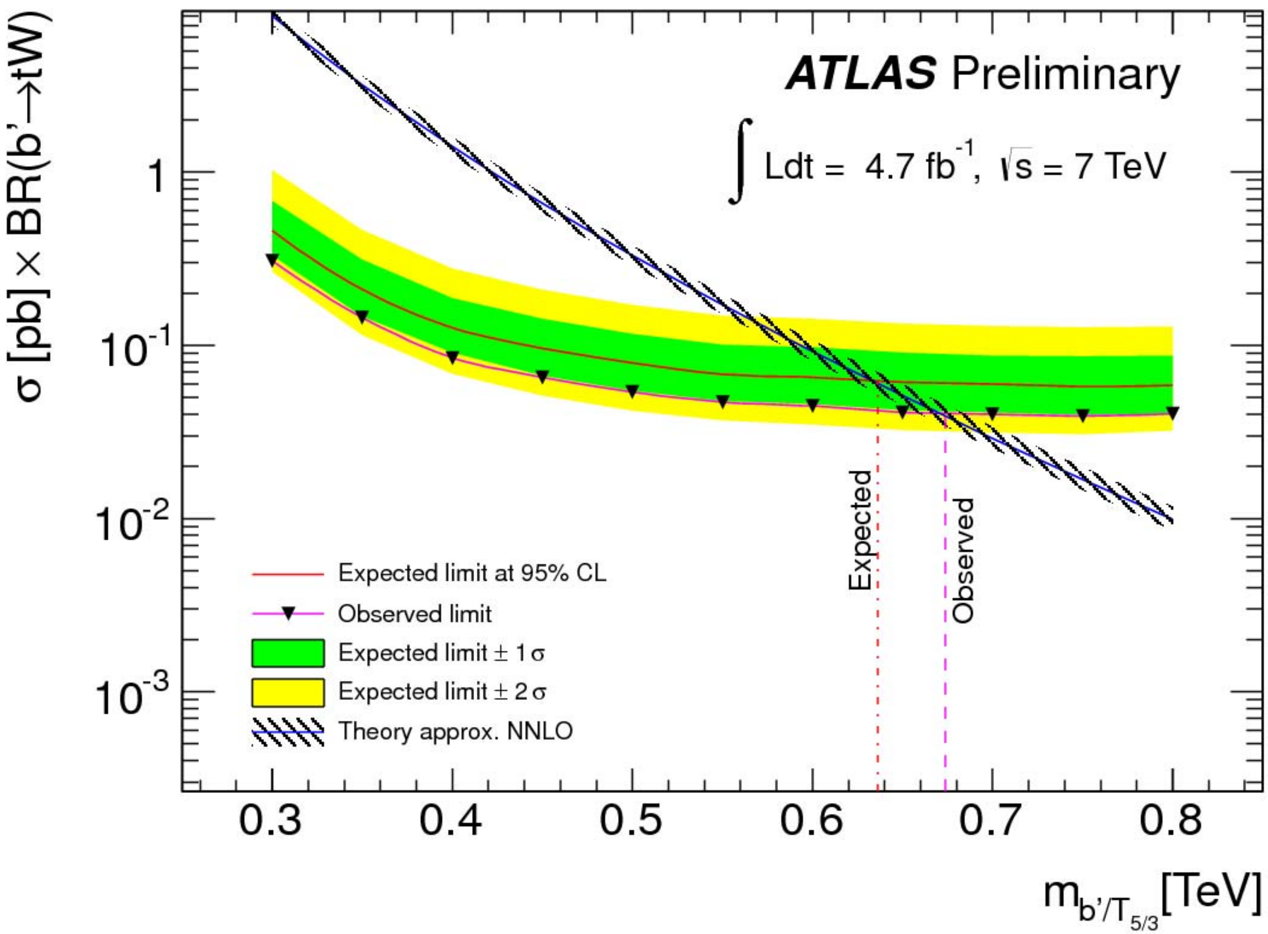


- 2 isolated same-sign leptons (*e* or μ)
- ME_T > 40 GeV
- ≥2 jets (≥1 b-tagged jet)
- large overall transverse momentum
  - H_T > 550 GeV

4 events observed
expected background of 5.6±1.7

Exotic Same-Sign Dilepton Signatures: b', $T_{5/3}$

ATLAS-CONF-2012-130



$m(b'/T_{5/3})$> 0.67 (0.64) TeV

at 95% confidence level, when produced in pairs

Inclusive Same-Sign Dilepton Search

1210.4538

- Model independent approach
  - Limit presented in terms of fiducial cross-section limit

$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{\varepsilon_{\text{fid}} \times \int \mathcal{L} dt}$$

95% CL upper limit on yield (given N_{obs} and N_{bkg})

Reconstruction and Selection efficiency
Within acceptance

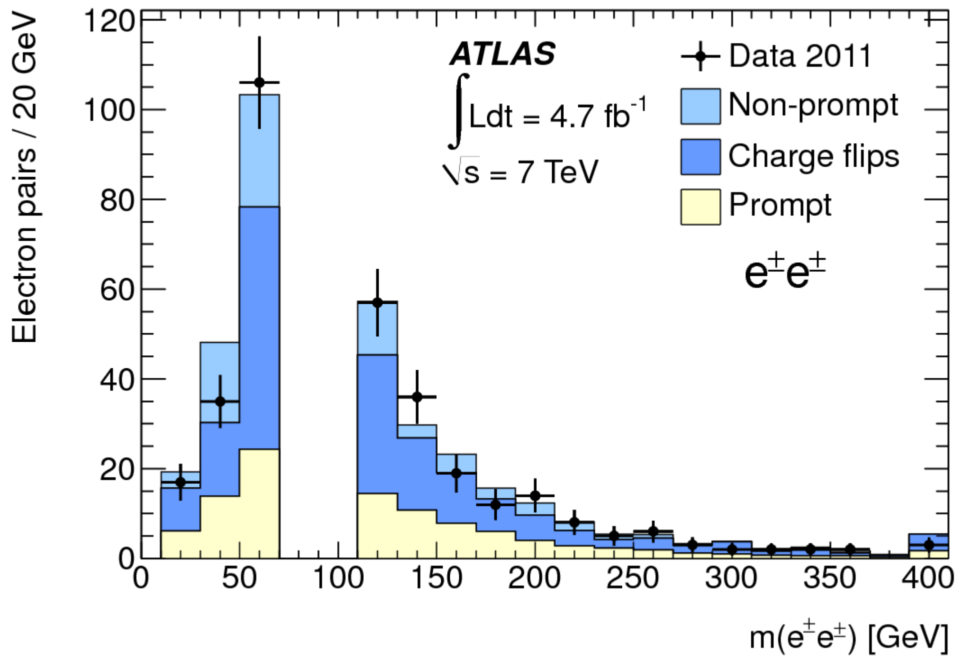
  - σ^{fid} is (almost) model-independent
  - Can turn σ^{fid} into σ^{total} with generator-level information only
  - Caveat: not exactly model-independent → must be conservative

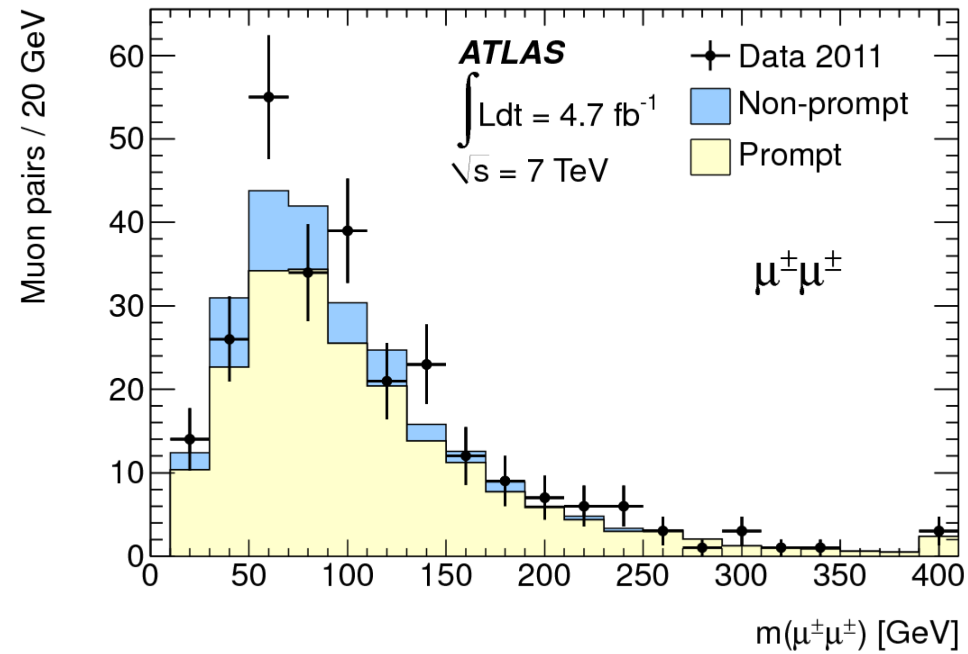
Particle-level definition of acceptance

	Electron requirement	Muon requirement
Leading lepton p_T	$p_T > 25$ GeV	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 20$ GeV	$p_T > 20$ GeV
Lepton η	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$
Isolation	$p_T^{\text{cone0.3}}/p_T < 0.1$	$p_T^{\text{cone0.4}}/p_T < 0.06$ and $p_T^{\text{cone0.4}} < 4\text{ GeV} + 0.02 \times p_T$

Inclusive Same-Sign Dilepton Search

1210.4538





Inclusive Same-Sign Dilepton Search

1210.4538

- 95% upper limits
  - 1.7 fb and 64 fb

Fiducial cross section upper limits

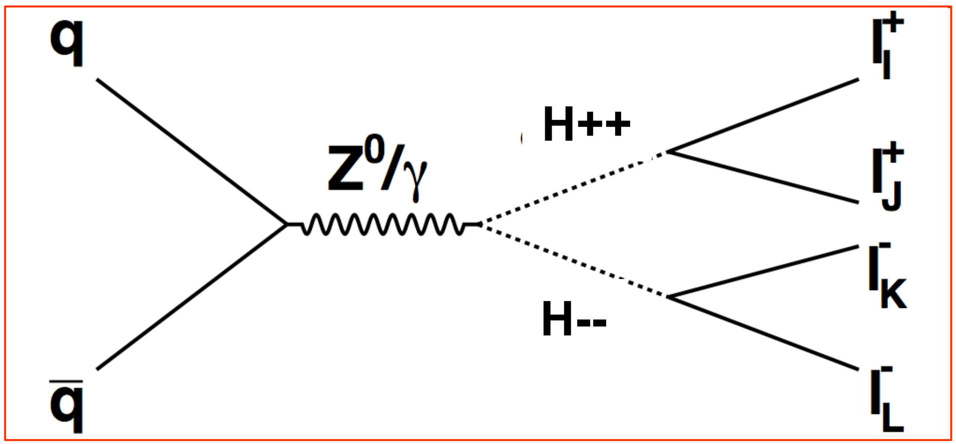
Mass | ee exp obs | eμ exp obs | μμ exp obs

Mass range	expected $e^\pm e^\pm$	observed $e^\pm e^\pm$	expected $e^\pm \mu^\pm$	observed $e^\pm \mu^\pm$	expected $\mu^\pm \mu^\pm$	observed $\mu^\pm \mu^\pm$
	95% C.L. upper limit [fb]					
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	e^+e^+		$e^+\mu^+$		$\mu^+\mu^+$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	e^-e^-		$e^-\mu^-$		$\mu^-\mu^-$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7	$11.5^{+4.2}_{-3.5}$	16.9	$6.0^{+2.3}_{-1.9}$	10.1
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0	$4.6^{+2.1}_{-1.2}$	4.5	$2.7^{+1.1}_{-0.7}$	4.4
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7	$2.7^{+1.1}_{-0.6}$	3.5	$1.5^{+0.8}_{-0.3}$	1.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3	$2.3^{+0.8}_{-0.5}$	2.5	$1.2^{+0.4}_{-0.0}$	1.2

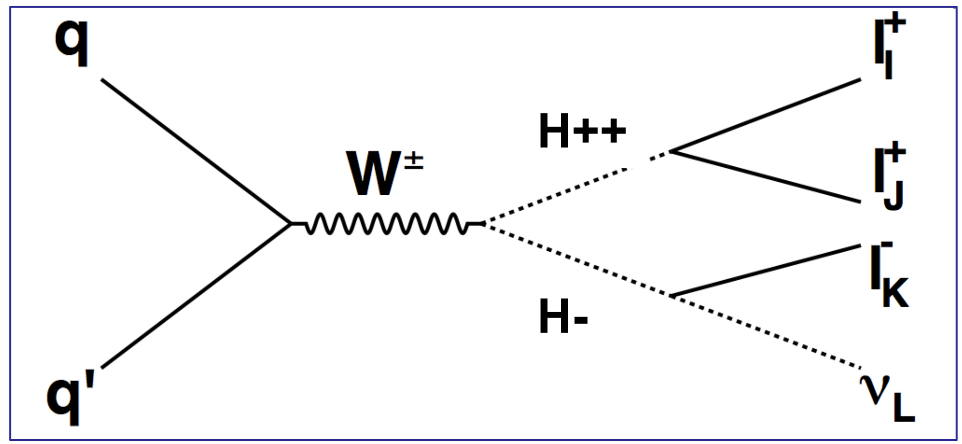
	e^-e^-	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3

Inclusive Same-Sign Dilepton Search: $H^{++/--}$ Limits

- Models explaining non-zero neutrino masses predict $H^{++/--}$
  - e.g. minimal type II seesaw model
    - additional scalar field
    - triplet (under $SU(2)_L$ with Y=2): $H^{++/--}$,$H^{+/-}$, H^0



pair production



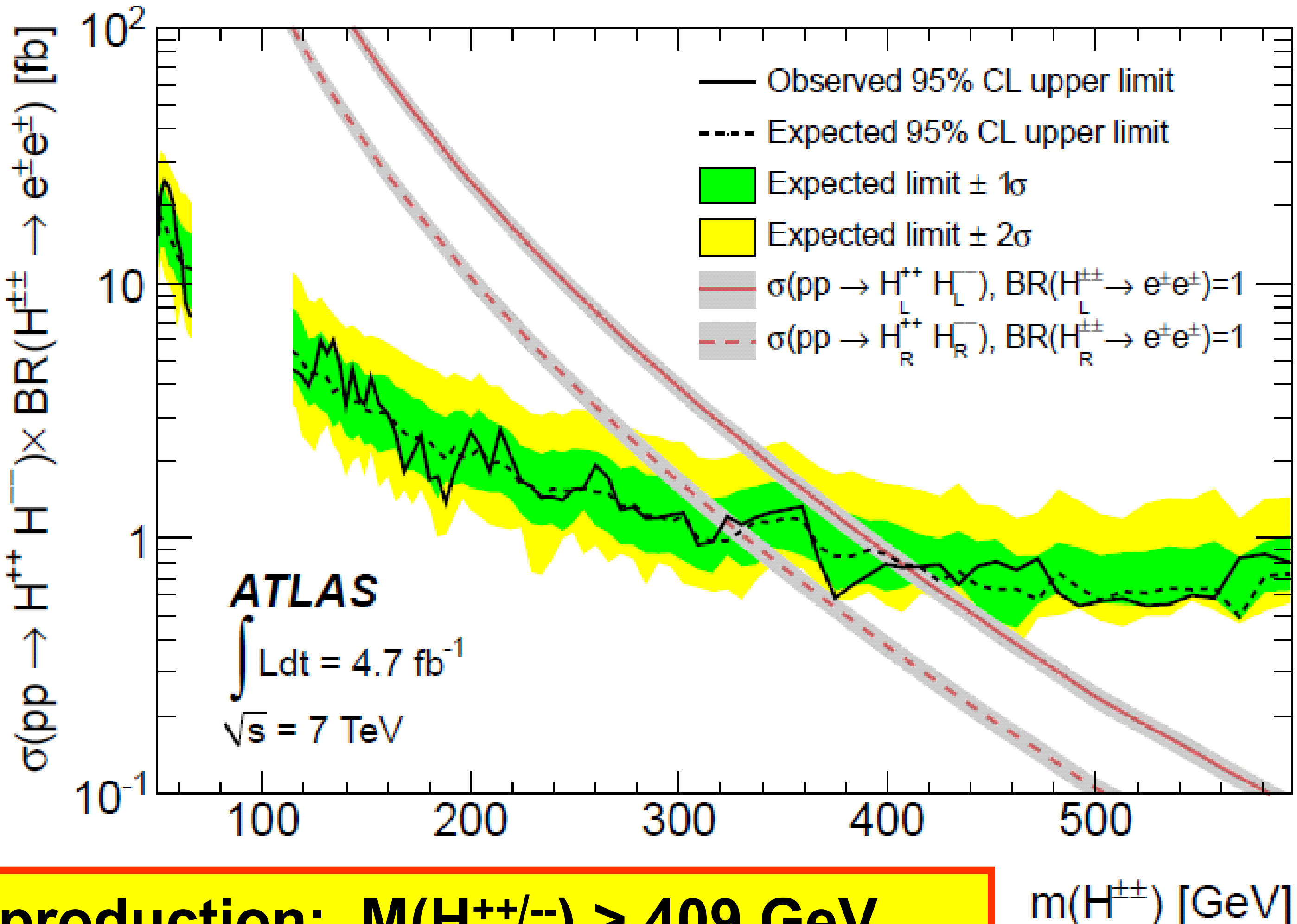
associate production

Signature: same-sign leptons

Doubly Charged Higgs Limits

arXiv:1210.5070

- Used e.g. limits on doubly charged Higgs



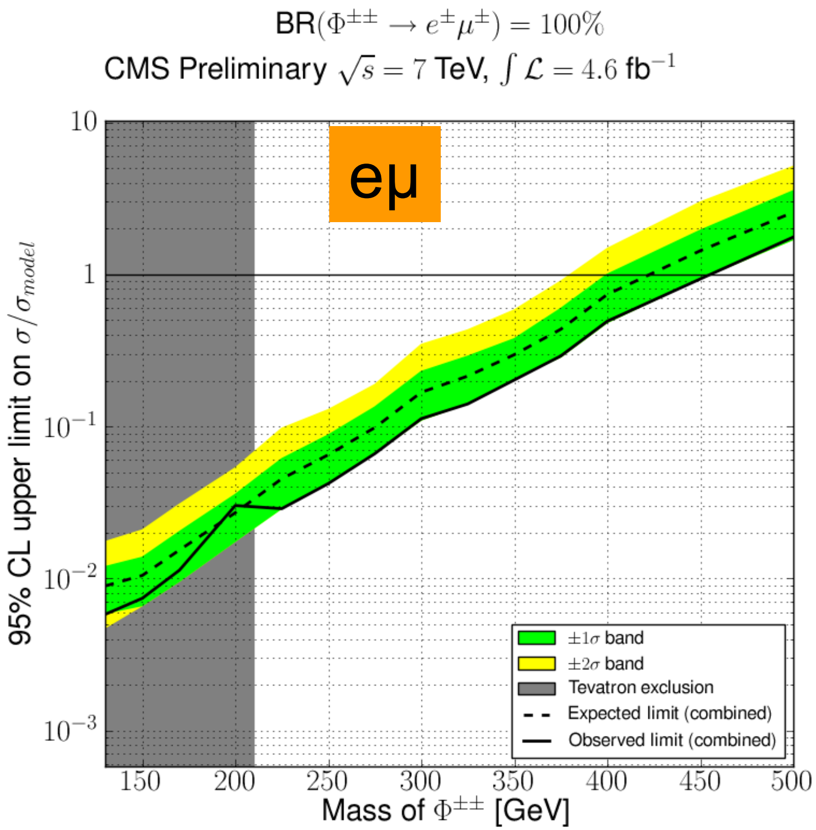
Pair production: $M(H^{++/--}) > 409$ GeV

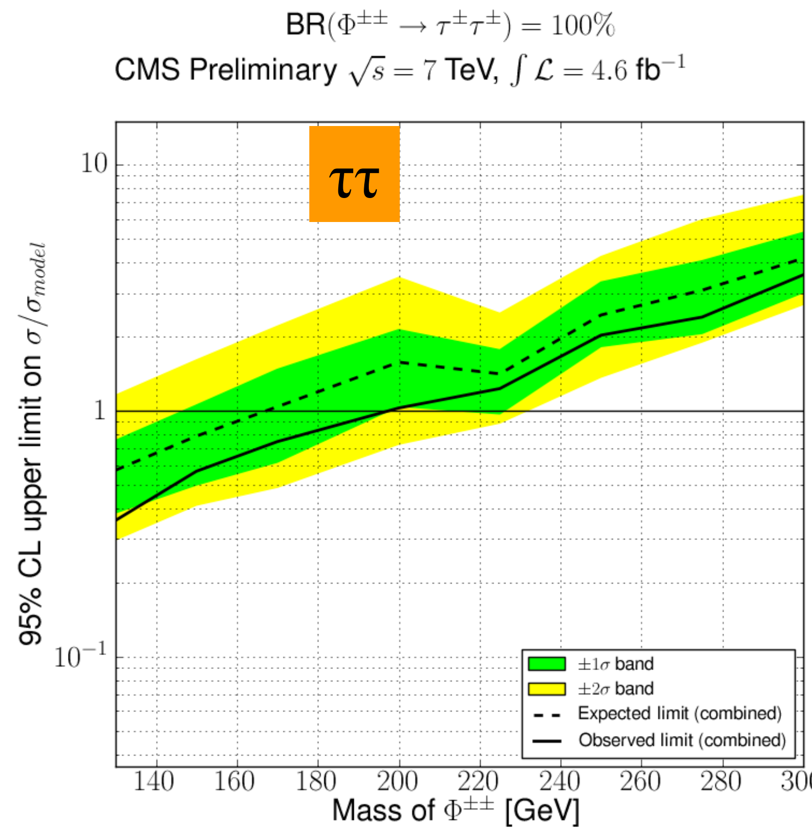
Doubly Charged Higgs Limits

- Example of more optimized search

arXiv:1207.2666

- Includes also τ-channel and associate production.



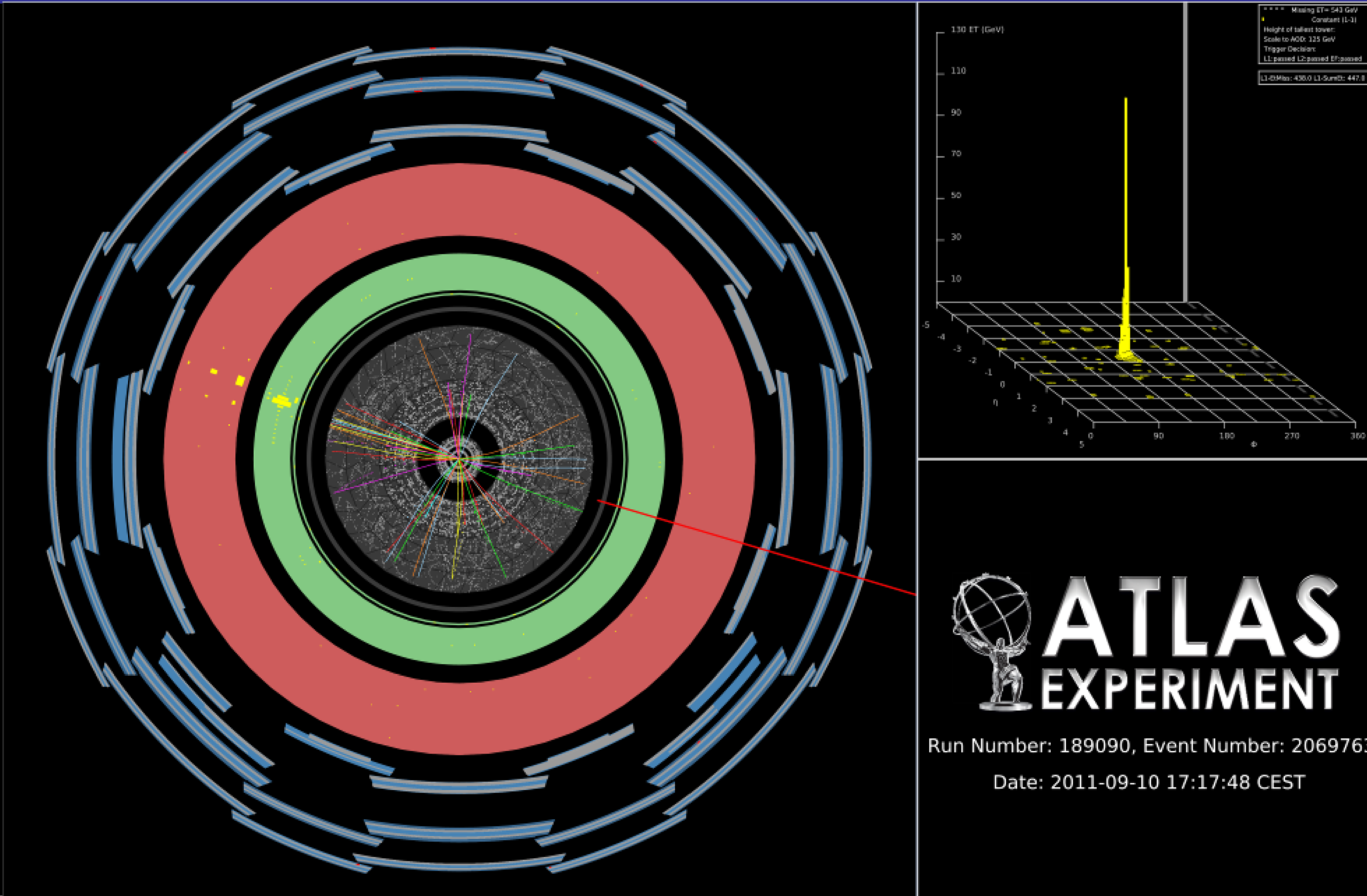


Combined eμ: M(H$^{++/--}$) > 455 GeV

Combined ττ: M(H$^{++/--}$) > 198 GeV

Poster: M. Kadastik, L. Rebane

Mono Jet Event Display

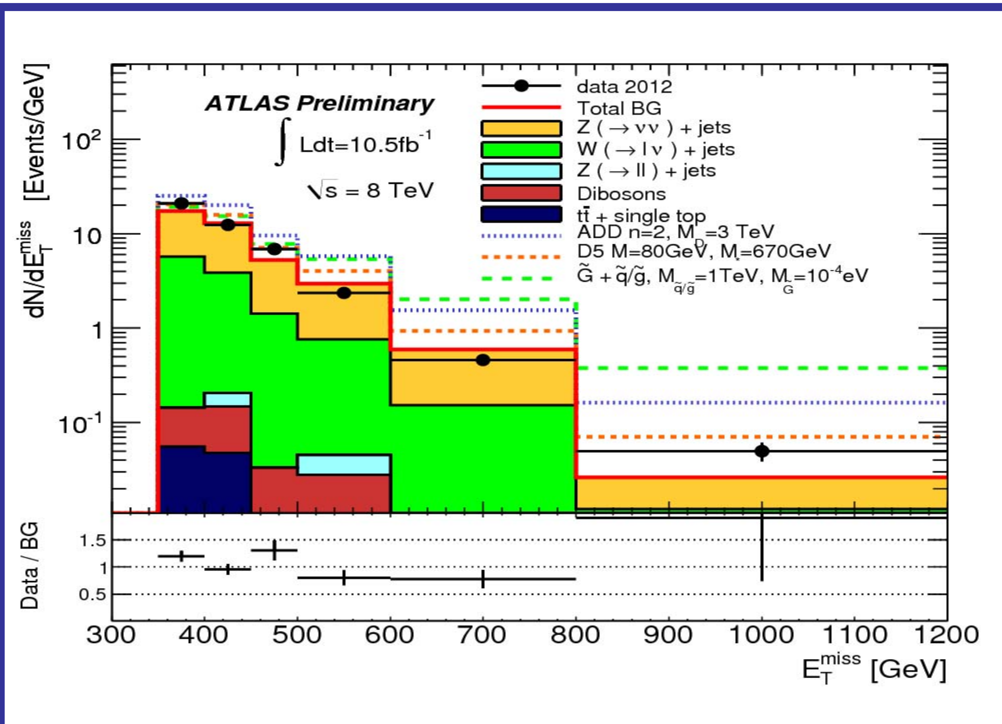


Search for Dark Matter and Extra Dimensions

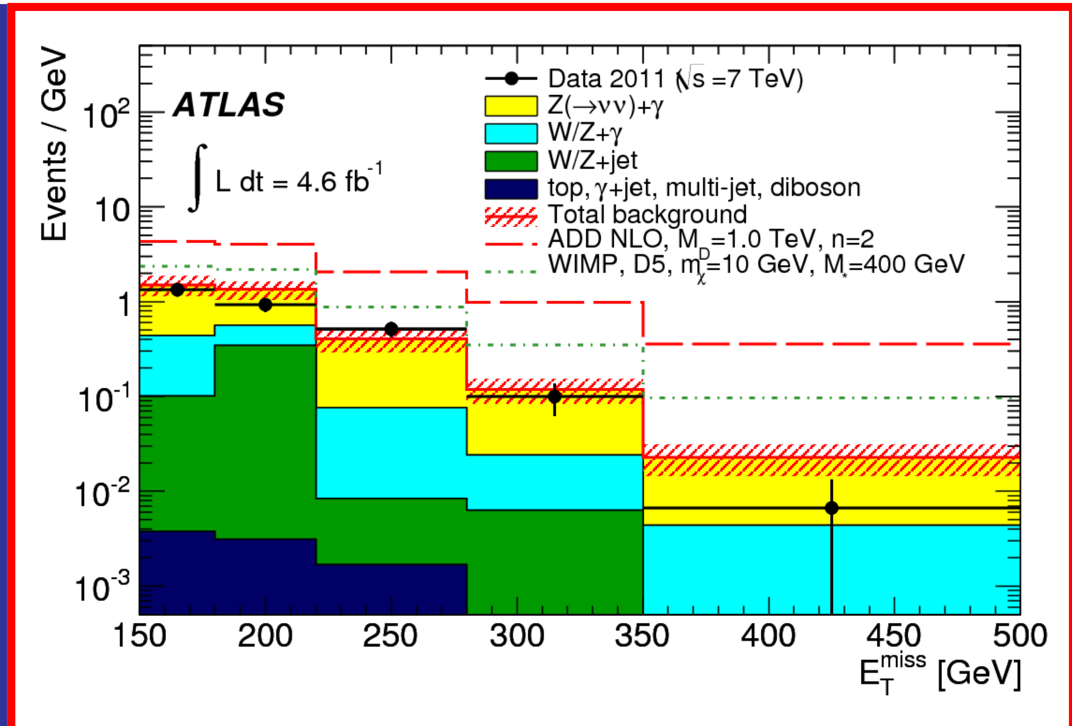
ATLAS-CONF-2012-147

arXiv:1209.4625

Mono jet



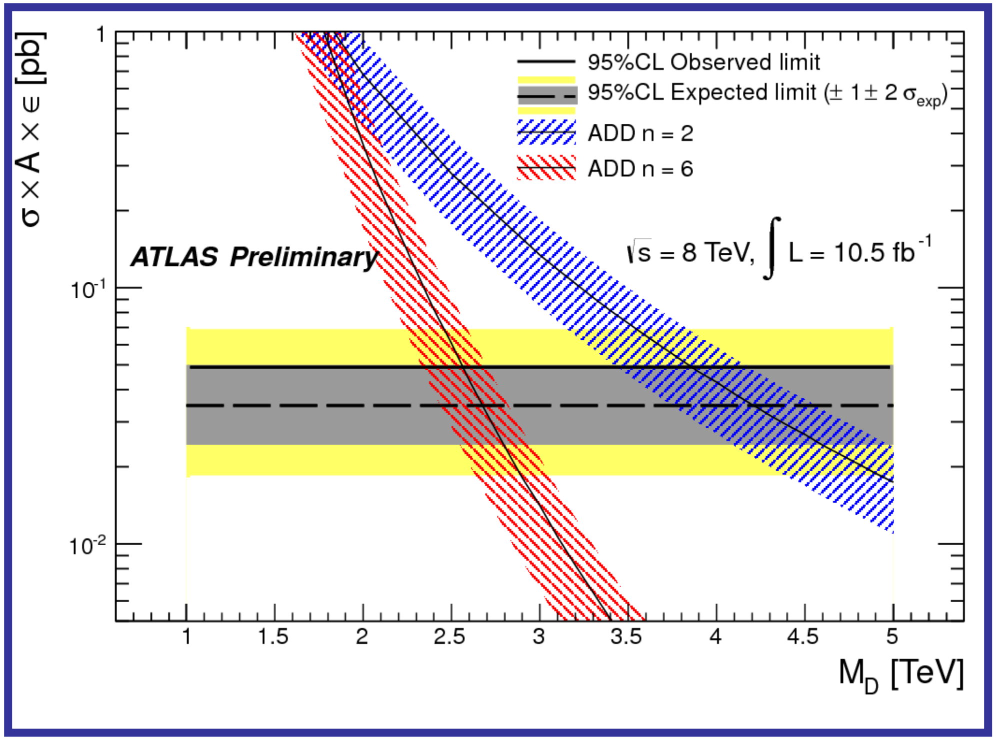
Mono photon



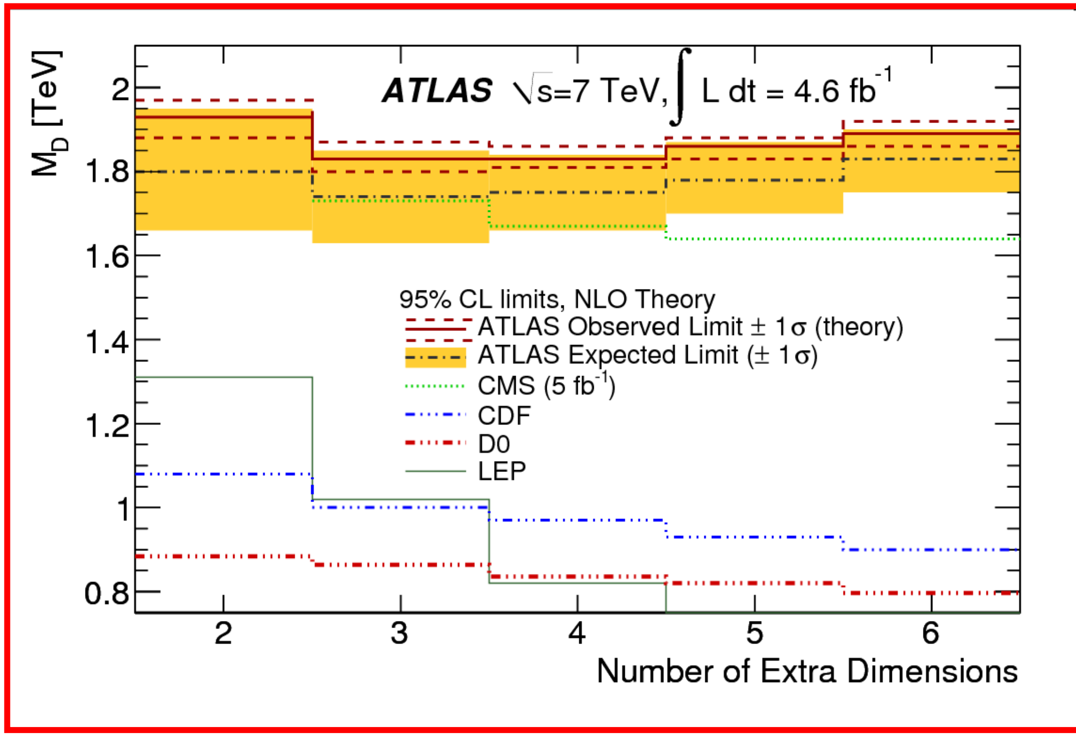
Analyses are not optimized for benchmark models

Mono jet & Mono Photon Limits on Extra Dimensions

Mono jet



Mono photon



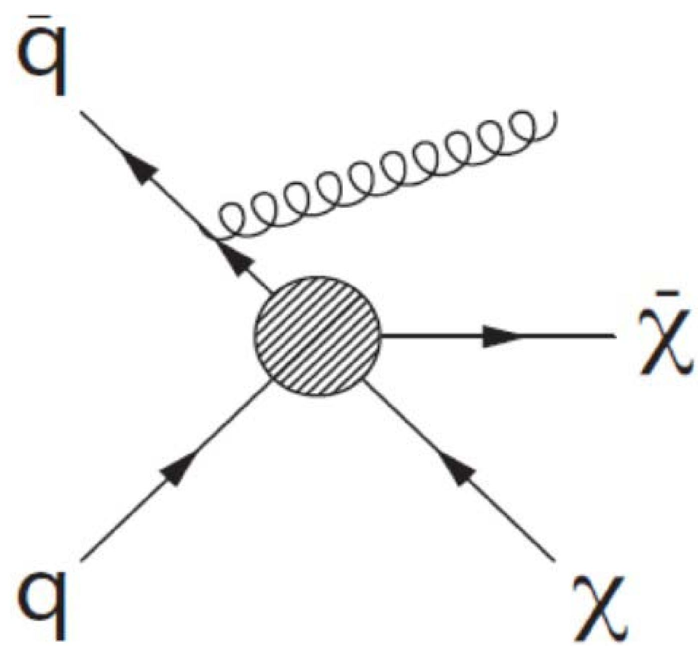
Limits on Dark Matter (DM)

$pp \rightarrow \chi\chi + X$

- Effective theory with only 2 parameters
  - M^* : characterize **interaction strength** of the interactions with SM particles
  - m_χ : mass of dark matter candidate

Effective interactions coupling DM to SM quarks or gluons

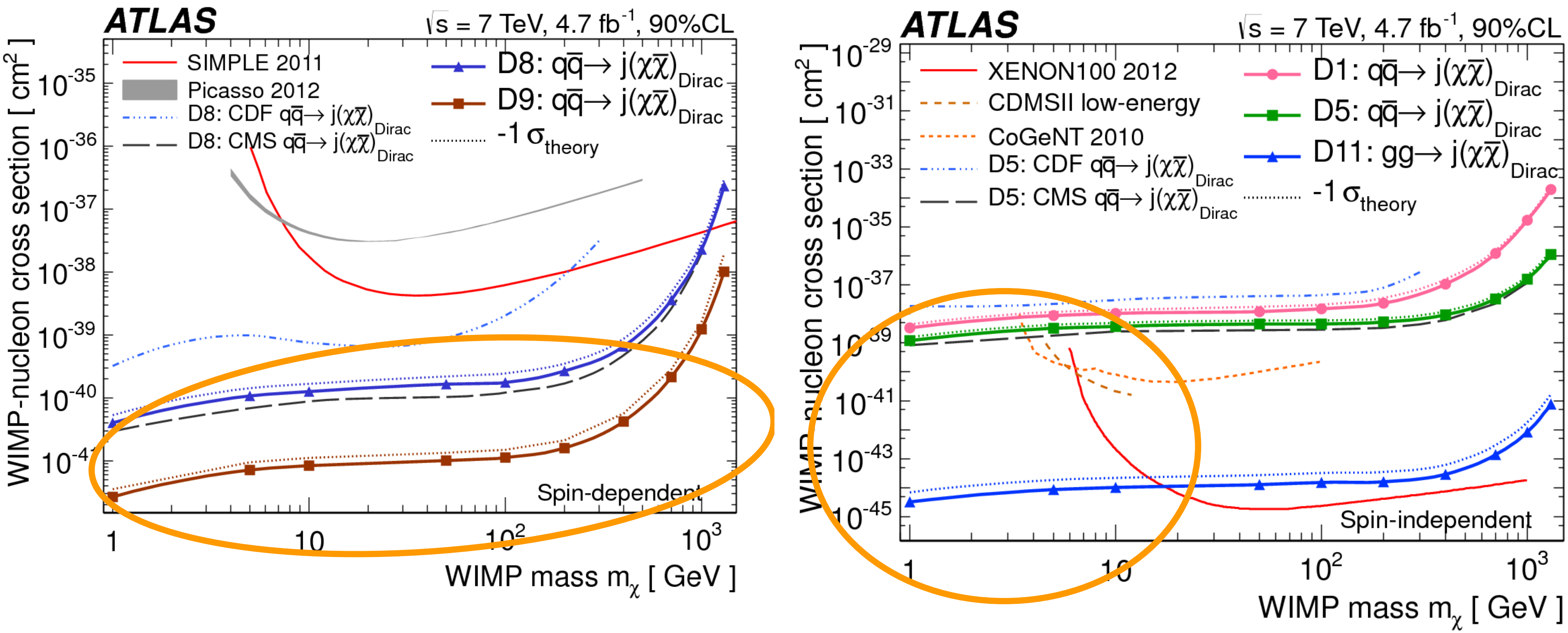
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



- Pair production of DM:
  - Events with ME_T, recoiling against additional hadronic radiation

DM-nucleon scattering cross sections

Mono jet analysis

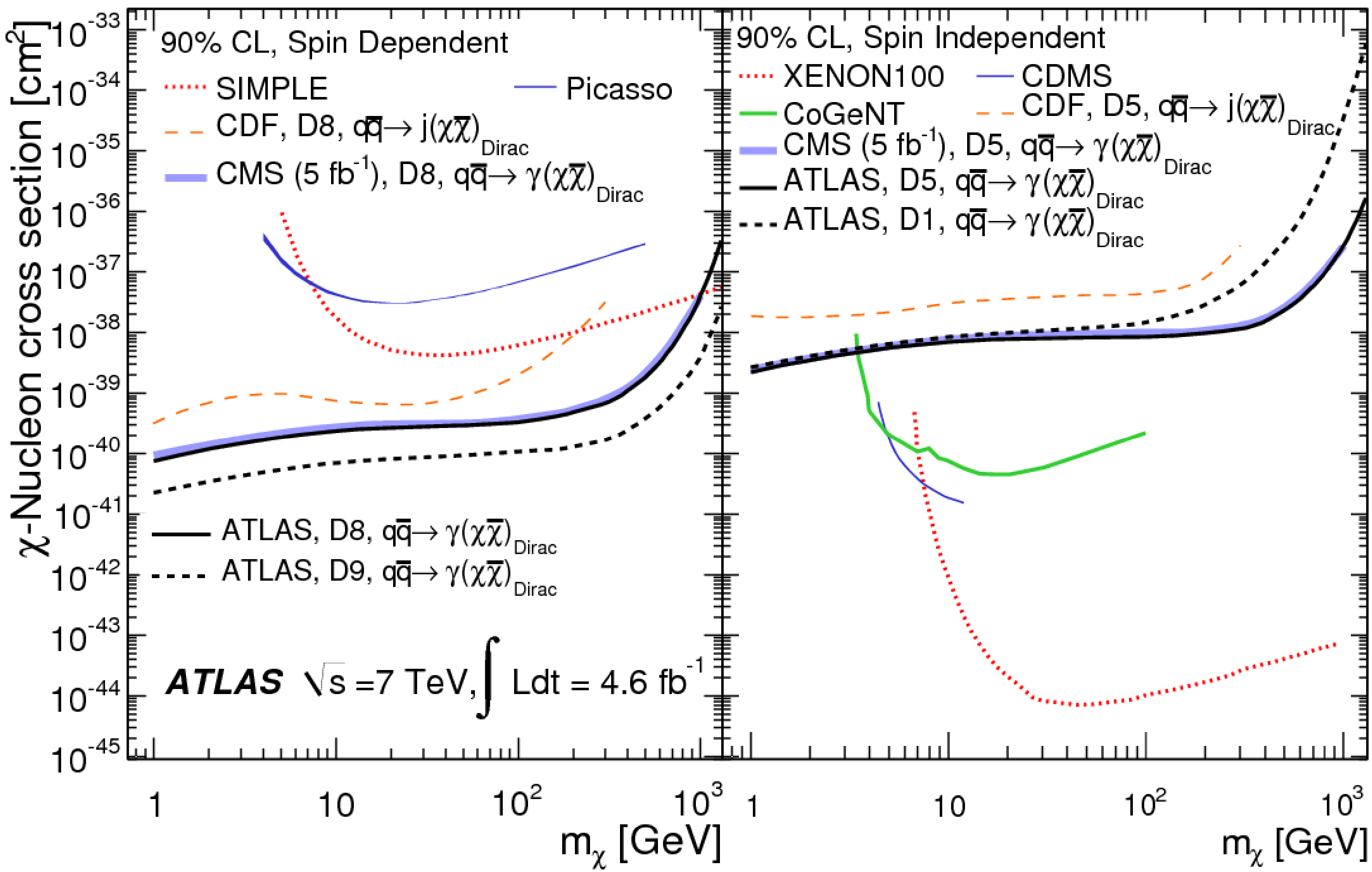


limits competitive with than limits by direct and indirect experiments

DM-nucleon scattering cross sections

arXiv:1209.4625

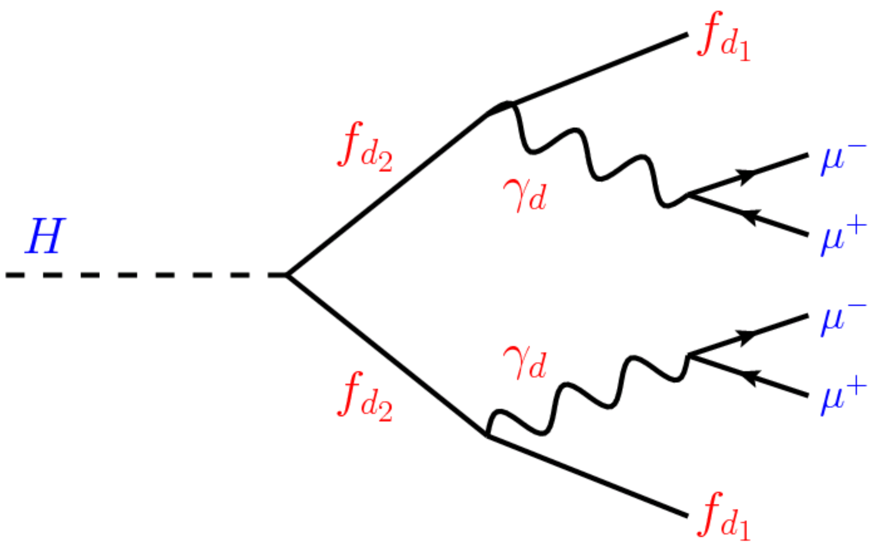
Mono photon analysis



Displaced Muonic Lepton Jets from Light Higgs

- Search for long-lived neutral particles
- Limits on
  - H → hidden-sector neutral long-lived particles
  - Focus on 100 GeV to 140 GeV mass range
    - Derive constraints on additional Higgs-like bosons
    - placing bounds on BR of discovered 126 GeV resonance into a hidden sector
- Relevant for other distinct models
  - heavier Higgs boson doublets,
  - singlet scalars
  - Z' that decay to a hidden sector

arXiv:1210.0435

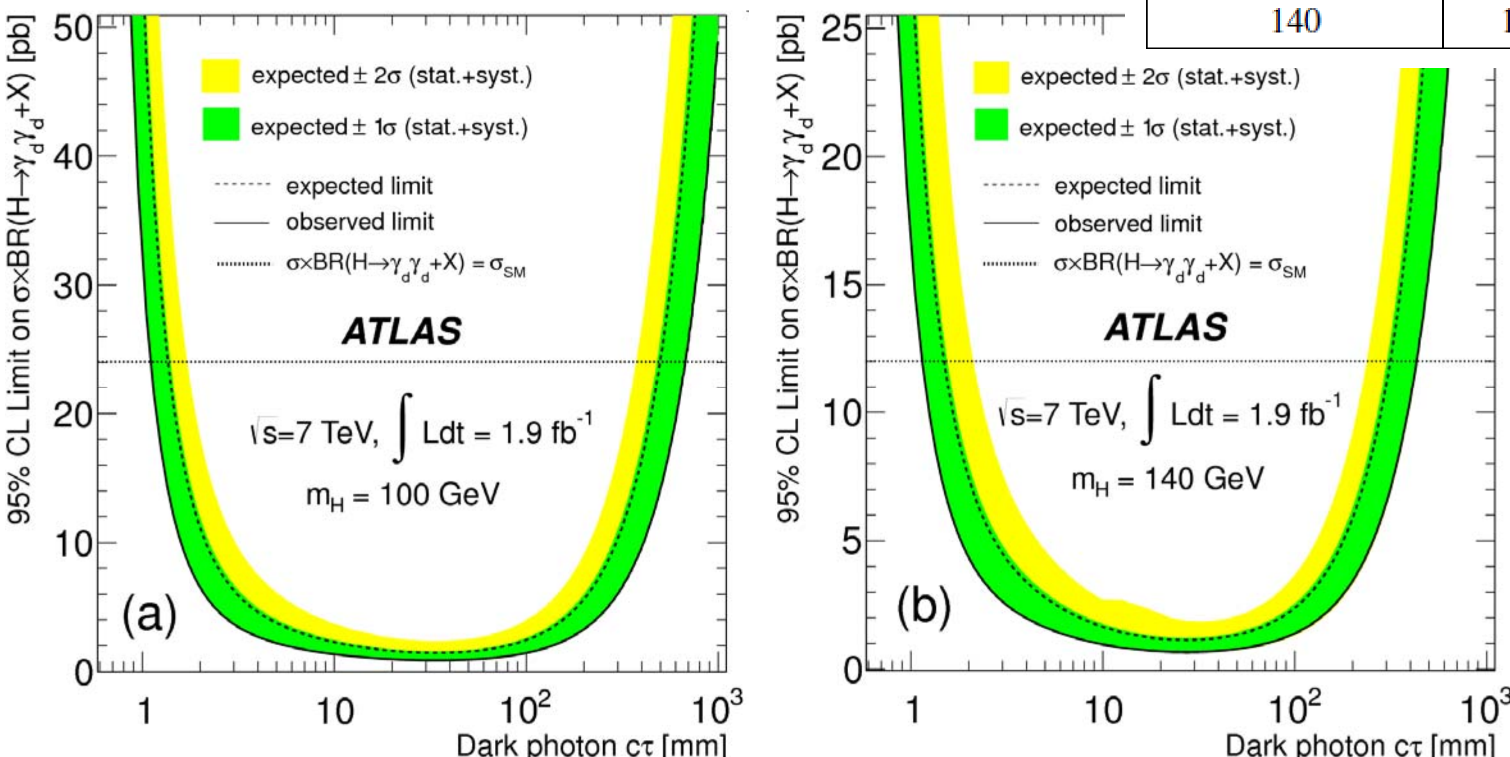


Displaced Muonic Lepton Jets from Light Higgs

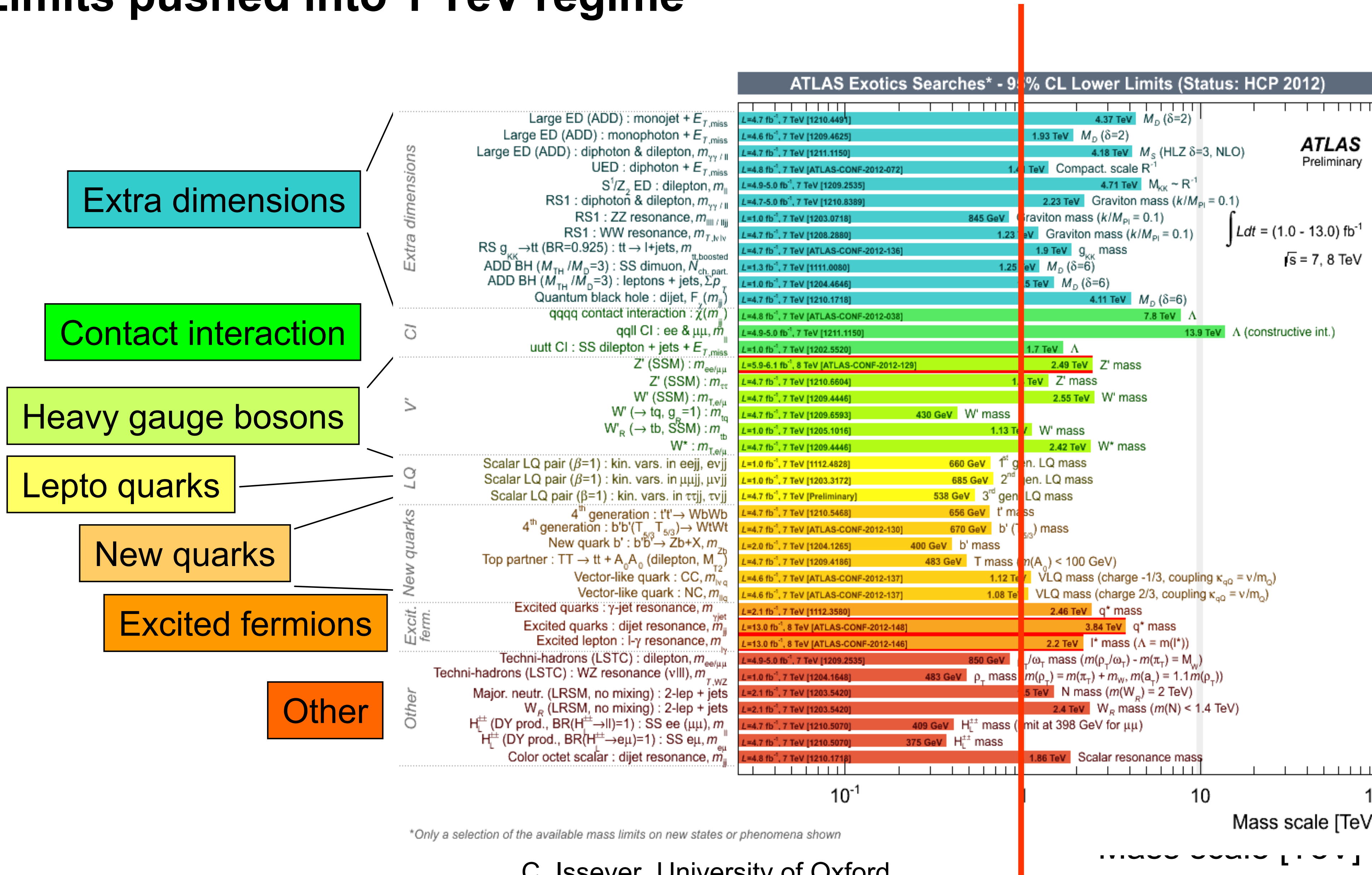
- Neutral particles
  - with large decay lengths
  - with collimated final states
  - challenge for the trigger and for the reconstruction

arXiv:1210.0435

Higgs boson mass [GeV]	excluded $c\tau$ [mm] BR(100%)	excluded $c\tau$ [mm] BR(10%)
100	$1 \le c\tau \le 670$	$5 \le c\tau \le 159$
140	$1 \le c\tau \le 430$	$7 \le c\tau \le 82$

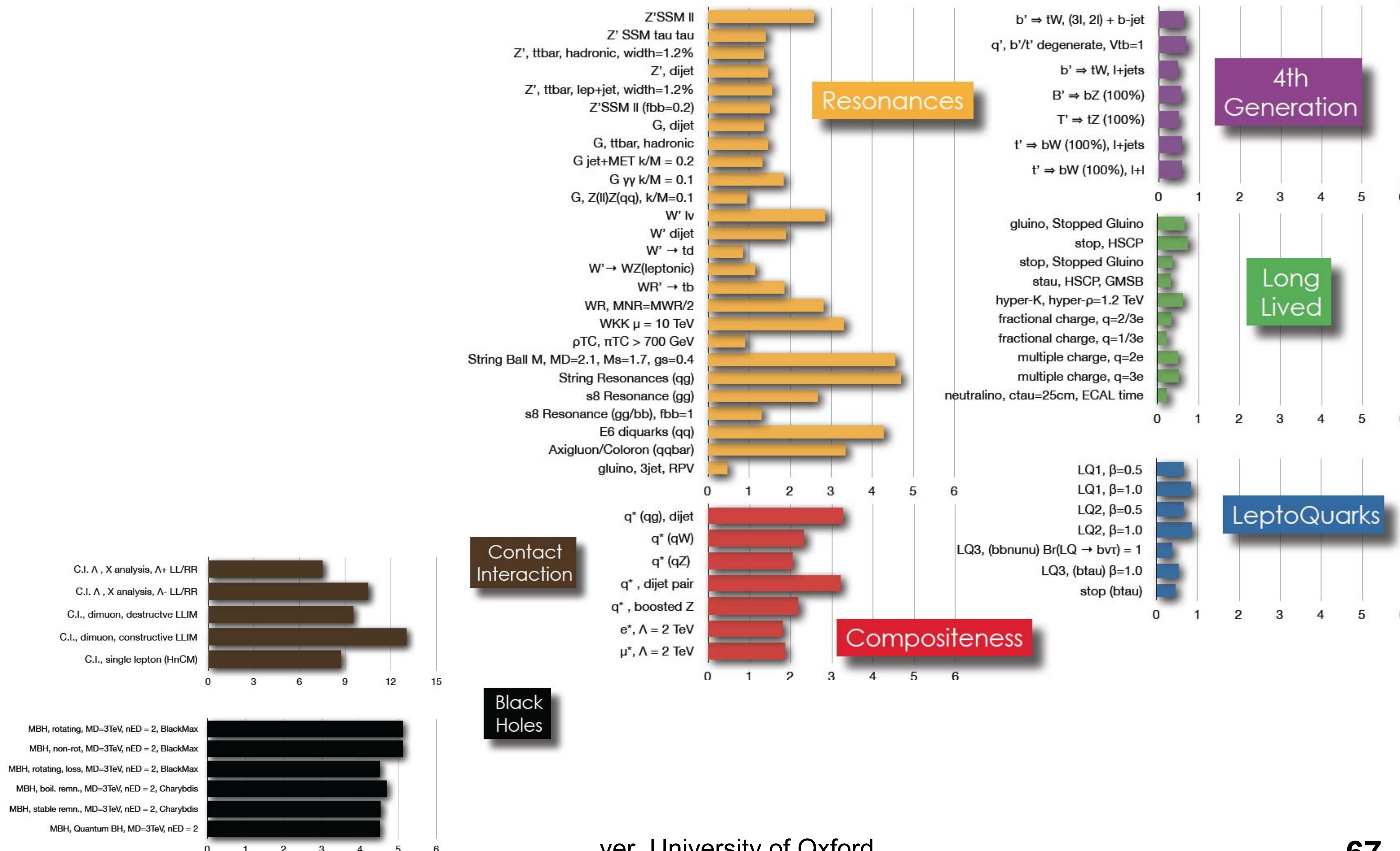


Limits pushed into 1 TeV regime



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

CMS Exotics Summary



Conclusion (1)

- New Physics BSM was not “around the corner”...

  … unless the Higgs is not a SM Higgs…

  - Continue exploration **beyond TeV regimes**
  - Push σ-limits at **low invariant masses** down.
- Role of models in Exotics
  - Models are used map our search reach
  - They give us some guidenance where to look
  - But, Exotics searches are mainly model-independent.
- Exotics searches coverage
  - Vast range of final states
  - Vast range of models

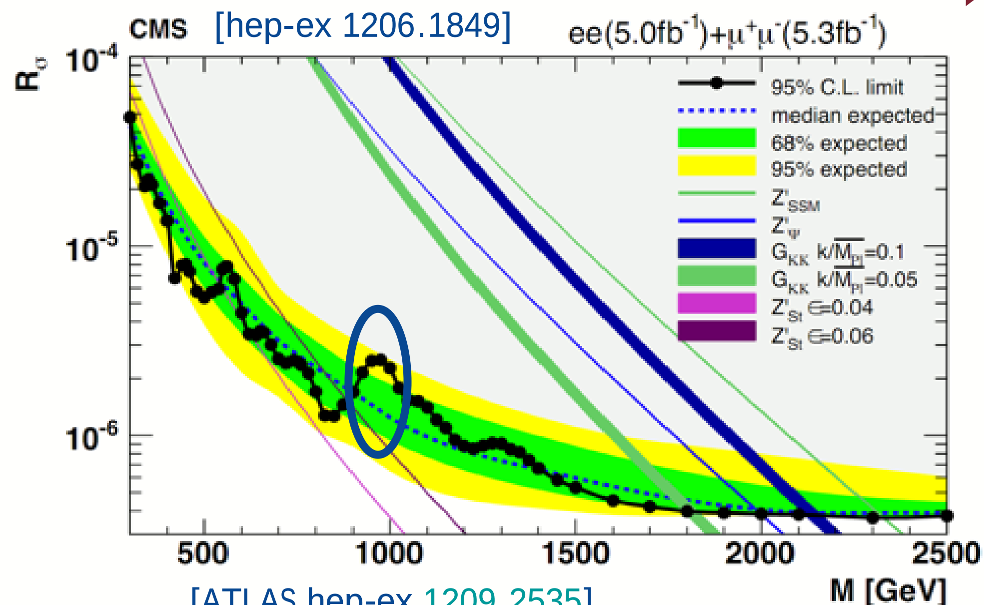
Conclusion (2)

- Exotics searches will continue broad range of searches
  - Technicolor and SM4 are in trouble.
  - Most other models live well with a light Higgs.
  - Interesting searches after Higgs boson discovery
    - Invisible Higgs : Higgs → LSP's (cf monojet analysis) interesting
    - Higgs to exotic objects.
      - E.g. Hidden Valley dark photon → LLP's or leptonjets arXiv:1210.0435
    - From now on we must consider heavy particle decays to Higgs systematically (esp. Heavy Quarks, e.g. t' → tH)

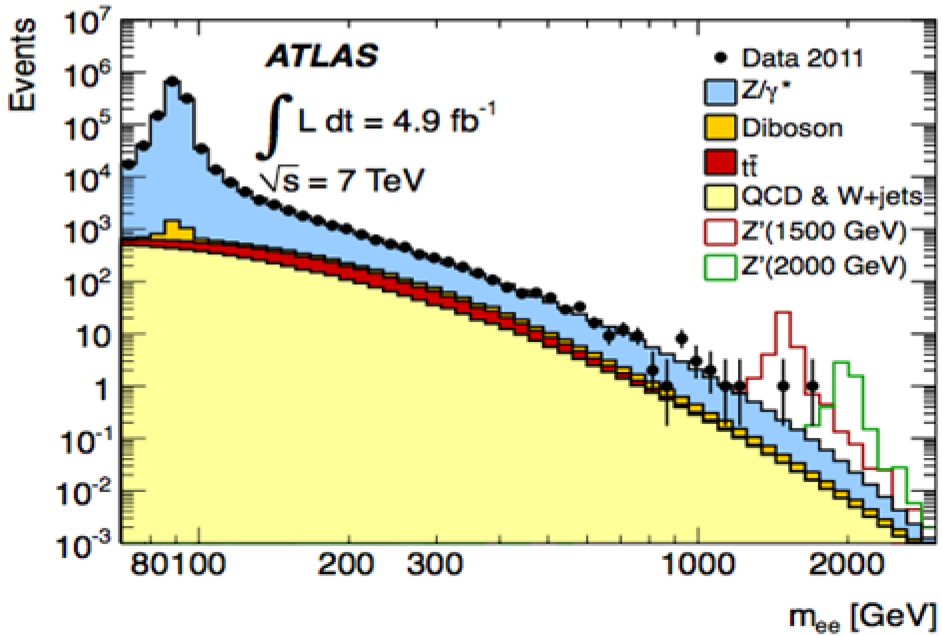
Backup Slides

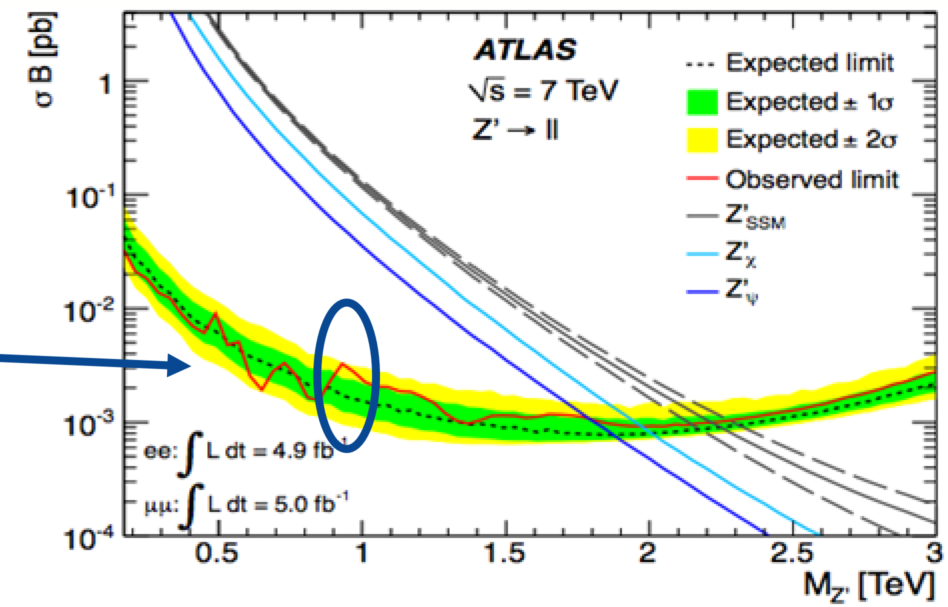
Z' in 2011 Data?

- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess



[ATLAS hep-ex 1209.2535]

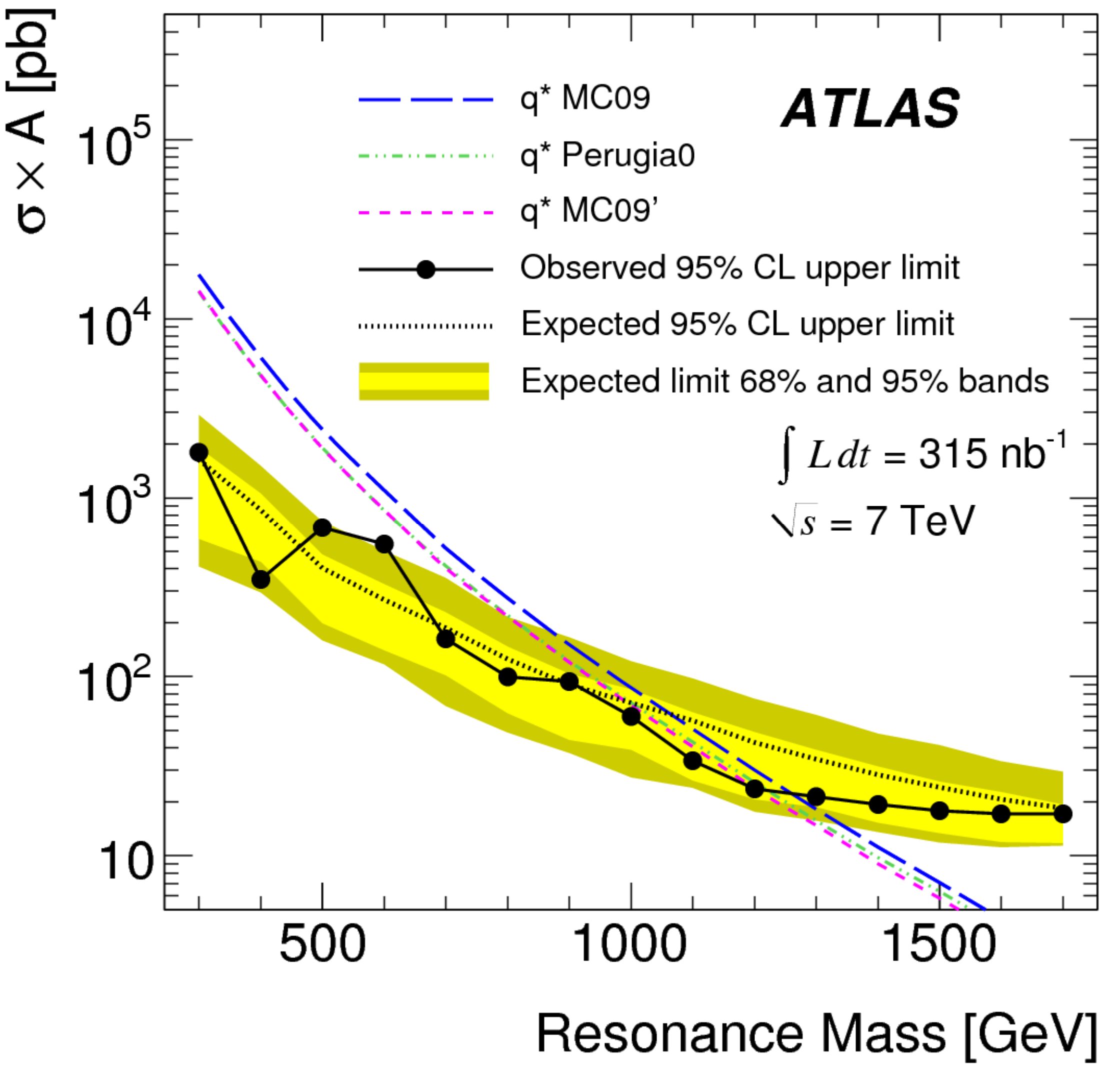




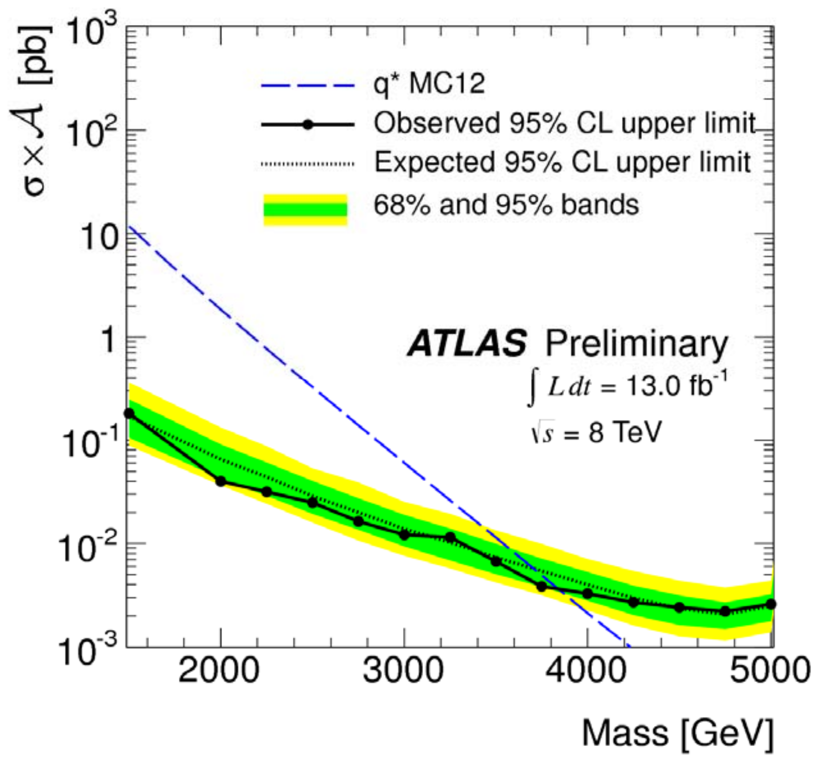
Mono Jet Signal Region Definions

Signal regions	SR1	SR2	SR3	SR4
Common requirements	Data quality + trigger + vertex + jet quality + $\|\eta^{\mathrm{jet1}}\| < 2.0$ + $\|\Delta\phi(\mathrm{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{p}_{\mathrm{T}}^{\mathrm{jet2}})\| > 0.5$ + $N_{\mathrm{jets}} \leq 2$ + lepton veto			
$E_{\mathrm{T}}^{\mathrm{miss}}$, $p_{\mathrm{T}}^{\mathrm{jet1}}$ >	120 GeV	220 GeV	350 GeV	500 GeV

"Although the results of this analysis are interpreted in terms of the ADD model and WIMP pair production, the event selection criteria have not been tuned to maximise the sensitivity to any particular BSM scenario. To maintain sensitivity to a wide range of BSM models, four sets of overlapping kinematic selection criteria, designated as SR1 to SR4, are defined (table 2)."

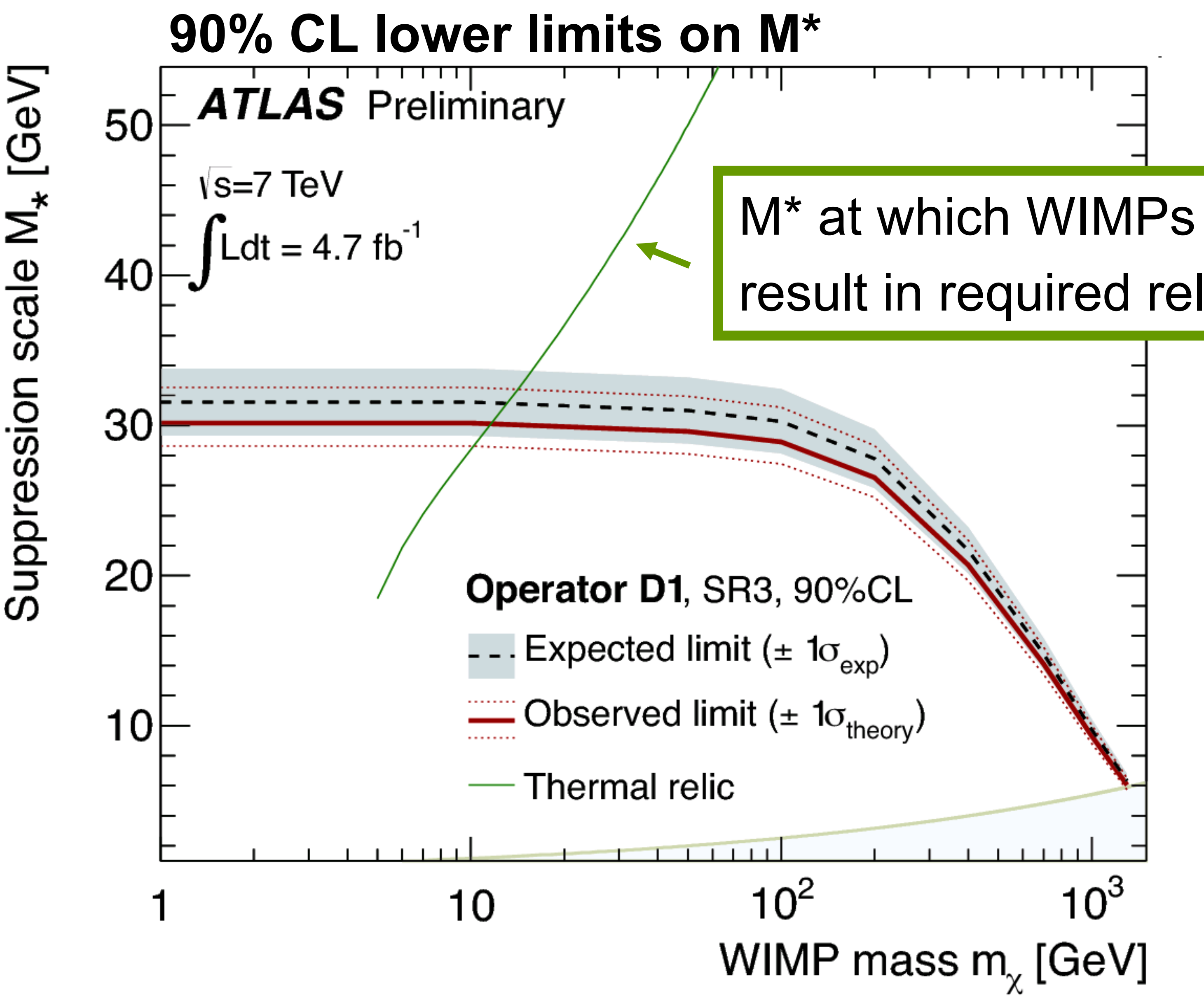


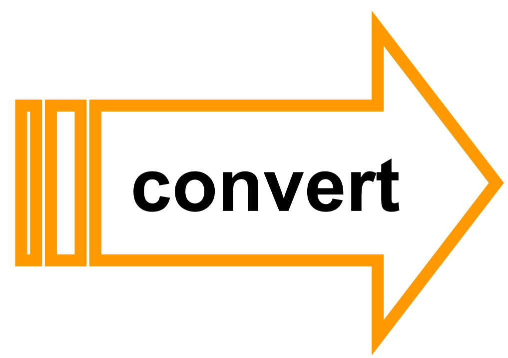
ATLAS
q* MC09
q* Perugia0
q* MC09'
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit 68% and 95% bands
$\int L dt$ = 315 nb^{-1}
$\sqrt{s}$ = 7 TeV
$\sigma \times A$ [pb]
Resonance Mass [GeV]



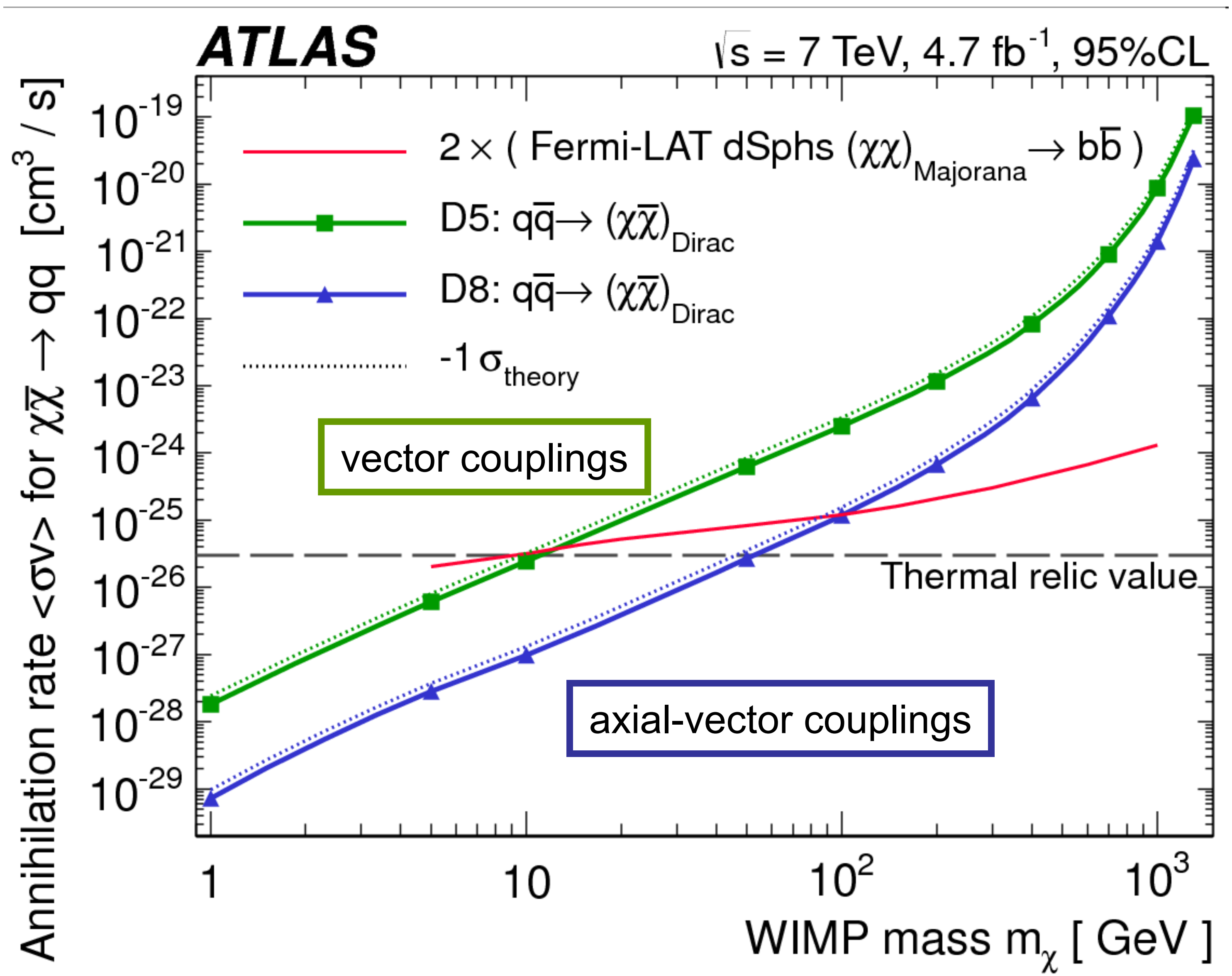
q* MC12
Observed 95% CL upper limit
Expected 95% CL upper limit
68% and 95% bands
ATLAS Preliminary
$\int L dt$ = 13.0 fb^{-1}
$\sqrt{s}$ = 8 TeV
$\sigma \times \mathcal{A}$ [pb]
Mass [GeV]

Limits on Dark Matter – Mono Jet





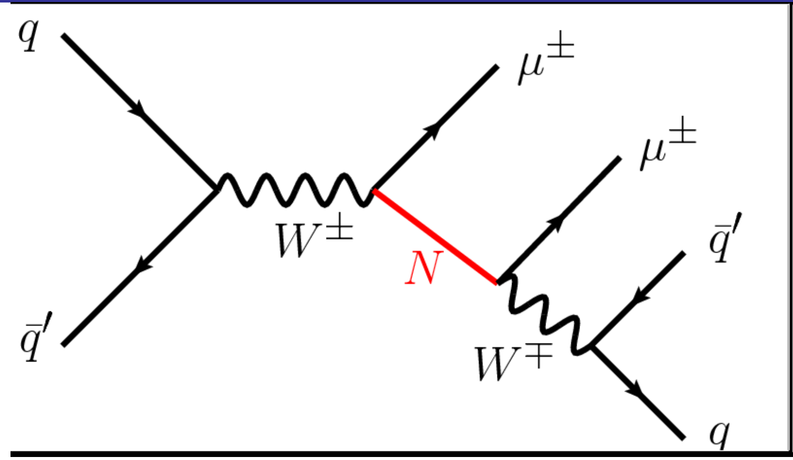
Limits on the annihilation rate of WIMPs

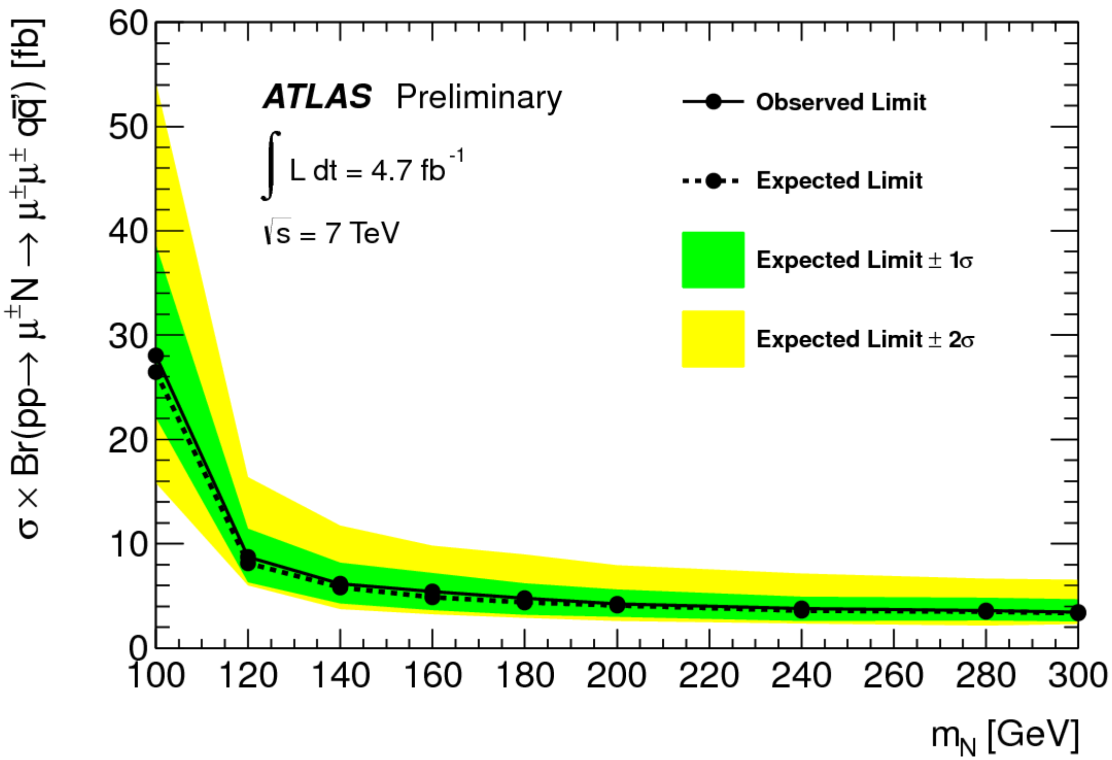


Majorana Neutrino Search in same-sign leptons

ATLAS-CONF-2012-139

- Two same-sign muons
- ≥2 jets and low ME_T





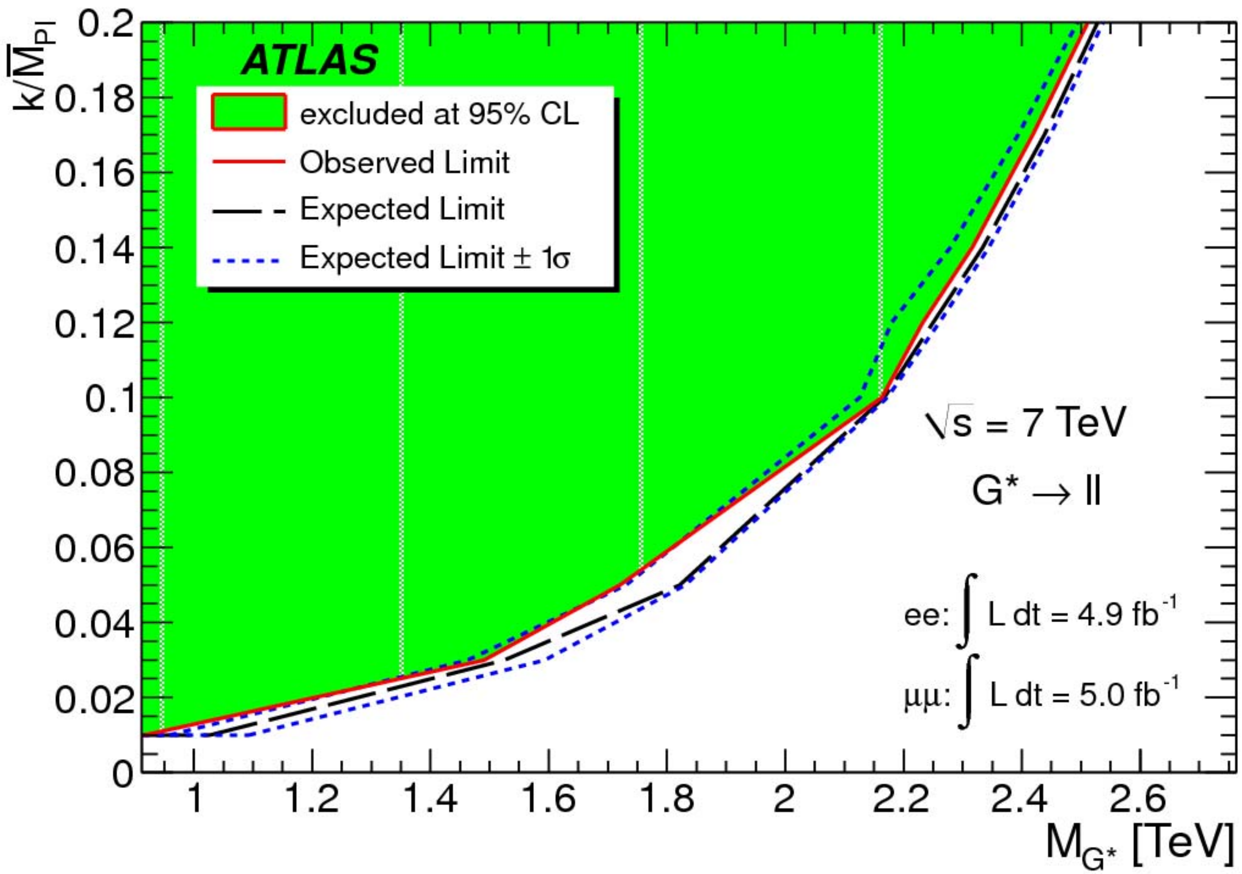
observed limits range from 28 to 3.4 fb for heavy neutrino masses between 100 and 300 GeV

)xford

Search for Heavy Resonance: dilepton channel

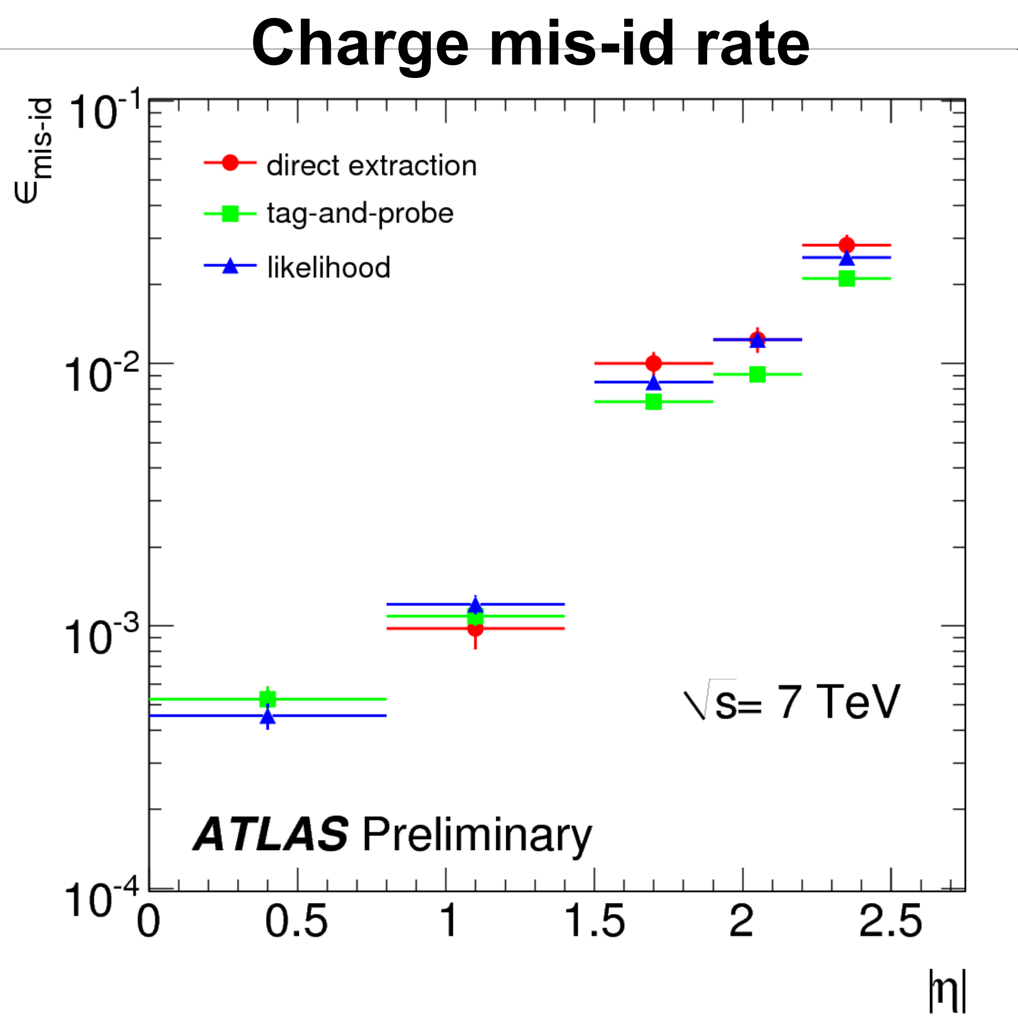
- Limits as a function of RS graviton mass and coupling

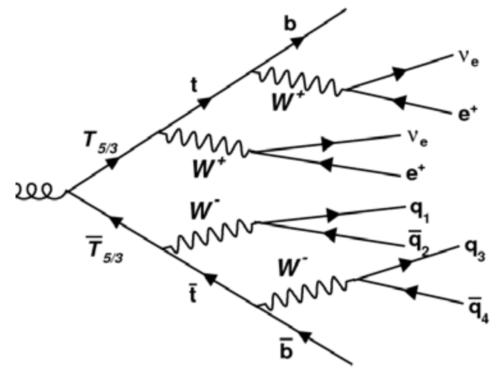
  m(RS graviton, k/MPl = 0.1) > 2.16 TeV at 95% CL



Exotic Same-Sign Dilepton Signatures: b', $T^{5/3}$

ATLAS-CONF-2012-130





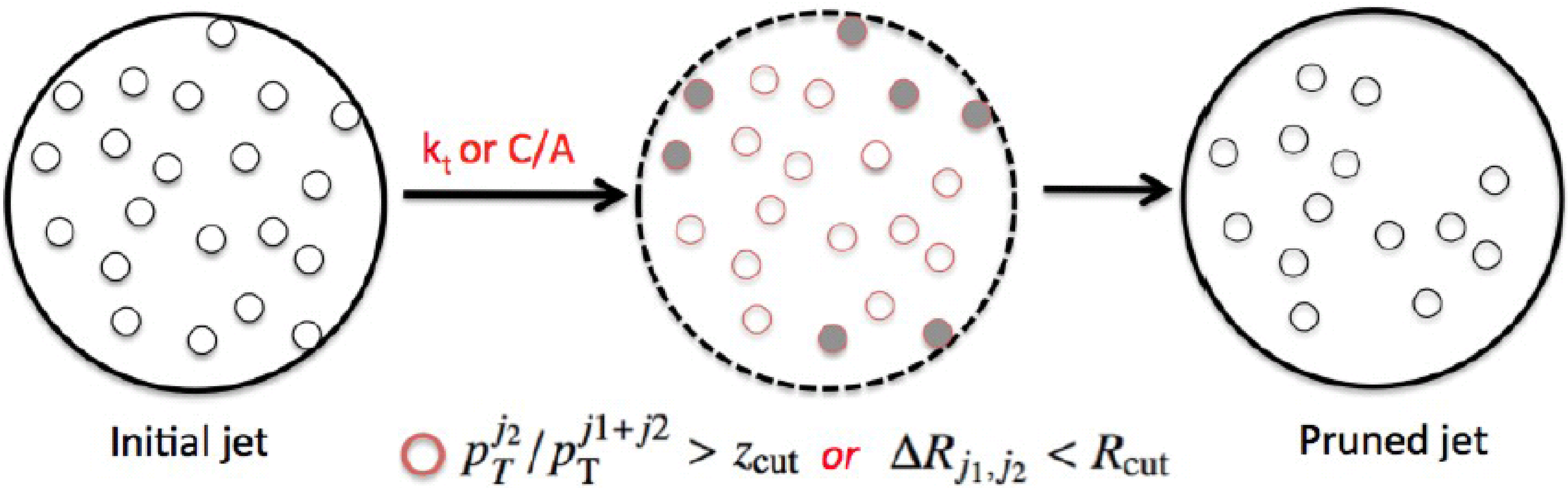
- 2 isolated same-sign leptons (*e* or μ)
- ME_T > 40 GeV
- ≥2 jets (≥1 b-tagged jet)
- large overall transverse momentum
  - H_T > 550 GeV

4 events observed

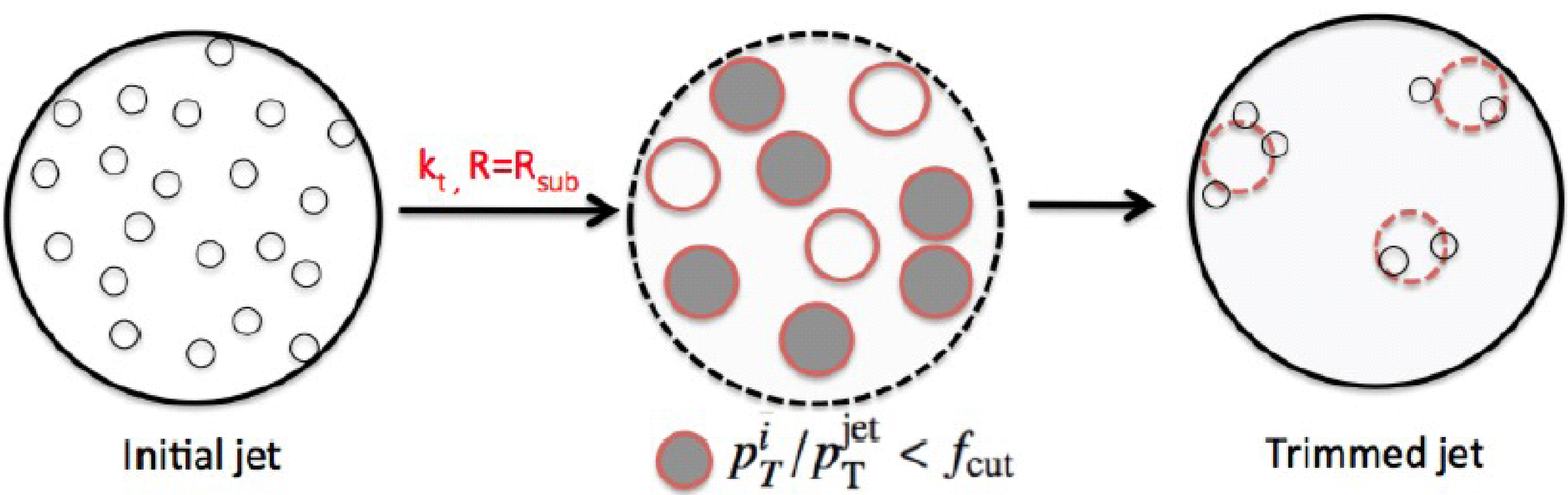
expected background of 5.6±1.7

Jet Grooming

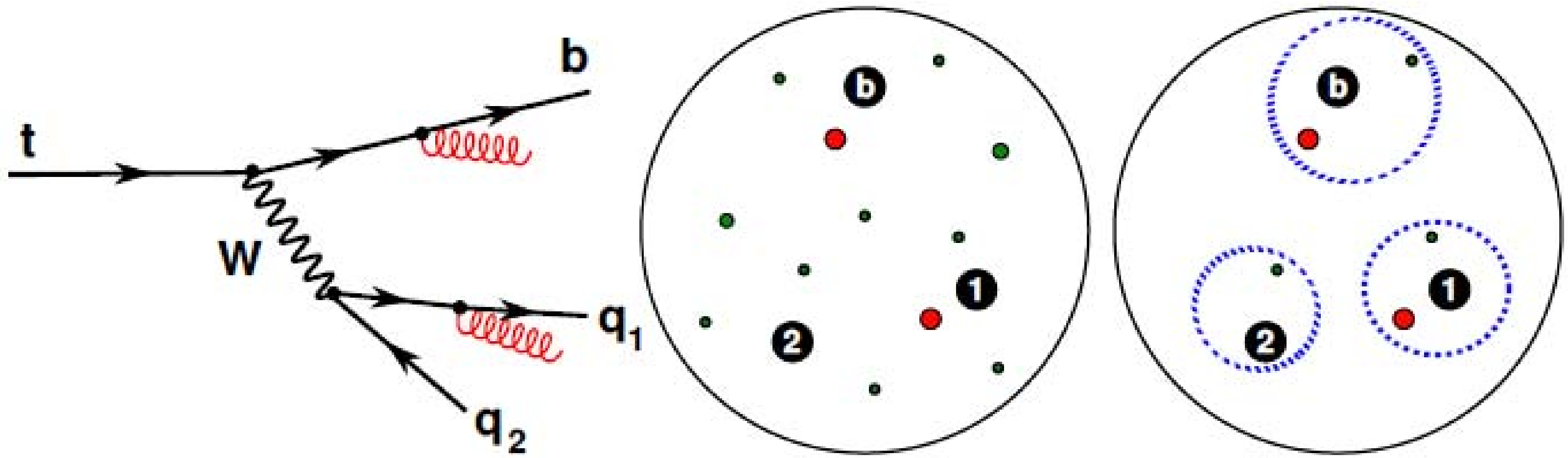
- "Pruning":
- Start with a fat jet (R ~ 1 or more)
- Run k_t or C/A algorithm on clusters within the fat jet
- At each step, if merging of two clusters fails, remove cluster with smallest pT



- "Trimming":
- Start with a fat jet (R ~ 1 or more)
- Run k_t algorithm on clusters within the fat jet
- Keep only jets with pT > pT(fat jet) . f_{cut}

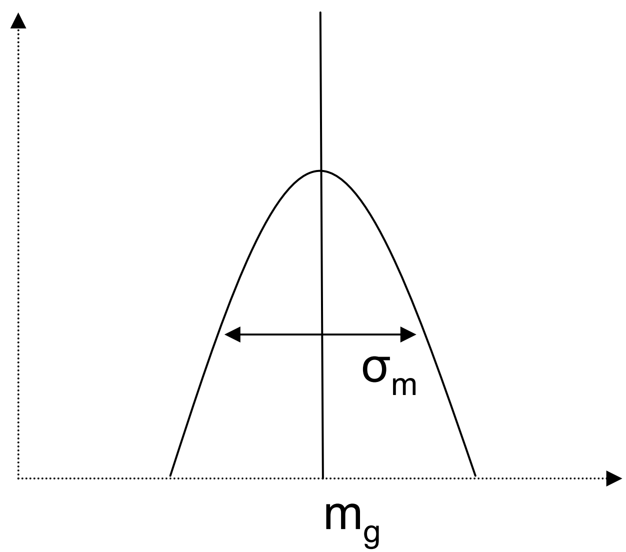


HEPTopTagger (Filtering)



1. Decompose until $m_{j_i} < 30\,\text{GeV}$ with mass drop requirement $m_{j_i} < \mu\, m_{\text{large jet}}$
2. Investigate 3 subjets and their constituents
3. Re-cluster using C/A with parameter $R = \min(0.3, \min_{ij} \Delta R(j_i, j_j)/2)$
4. Use only 5 hardest subjets of last step
5. Built exactly 3 subjets from the selected constituents

S. Fleischmann



σm
mg