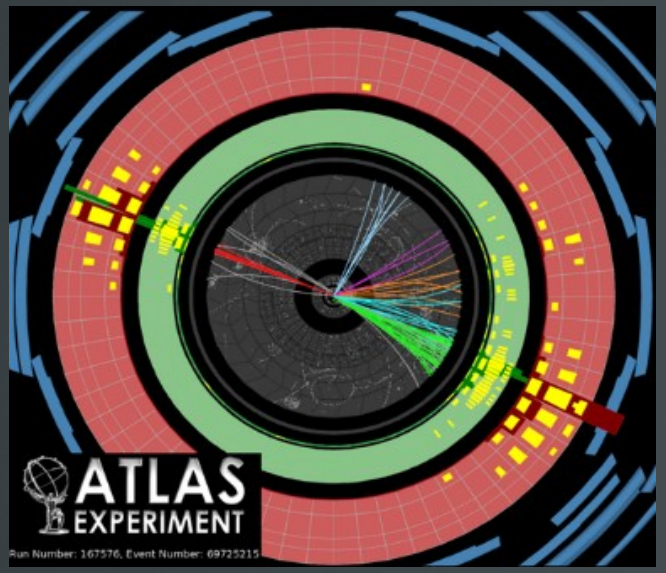


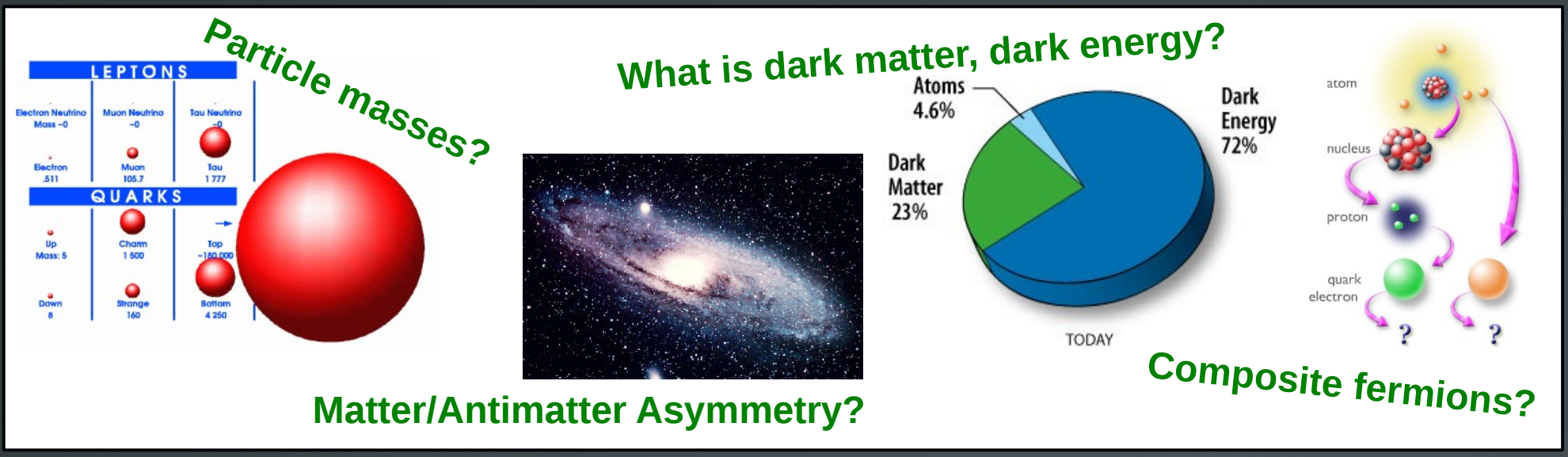
Searches for Exotic Physics with the ATLAS Detector

Emily Thompson
University of Massachusetts, Amherst
on behalf of the ATLAS Collaboration

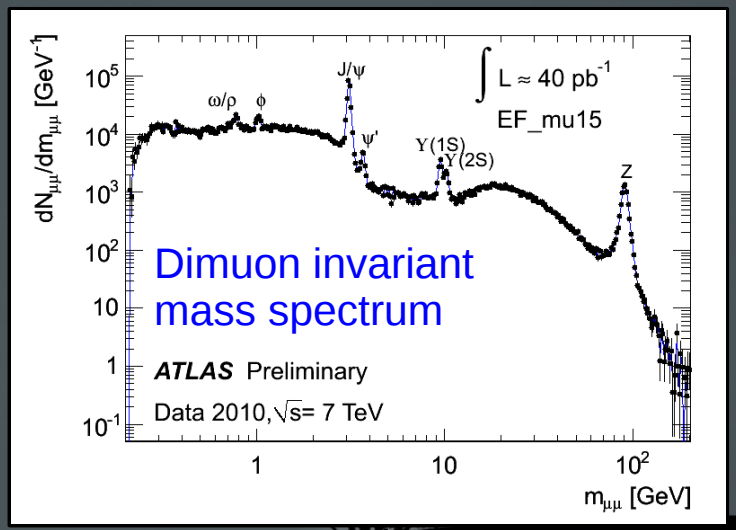
Rencontres de Moriond 2011
QCD and High Energy Interactions
March 21, 2011

New Physics Searches at ATLAS

- Even if the Higgs+SUSY are discovered, many questions left unanswered!



- LHC: Directly probe the Electroweak scale (~1 TeV interactions)
- ATLAS has rediscovered the Standard Model in ~7 months
- Poised and ready to discover new physics!



Measuring High Energy Objects

- Exotic signatures would exist at high p_T/E_T (> 100 GeV)...

...different detector-related issues for these kinds of objects!

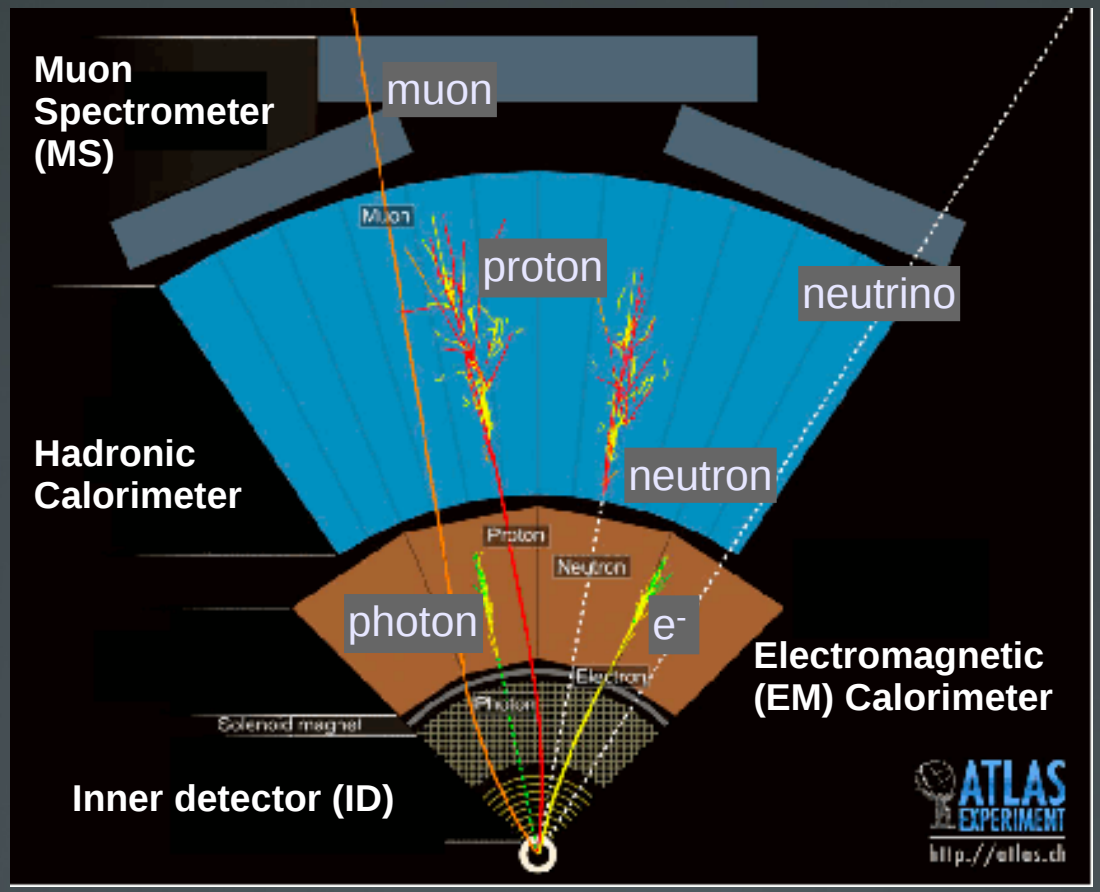
LEPTONS

Photons + Electrons: Isolated energy in EM Calorimeter

- QCD processes can mimic new physics signatures

Muons: Combined tracks from ID+MS

- Nominal p_T resolution: 10% for 1 TeV muon
- Uncertainty in alignment of Muon Spectrometer



JETS

Quarks/gluons: hadronize, deposit energy in the calorimeter

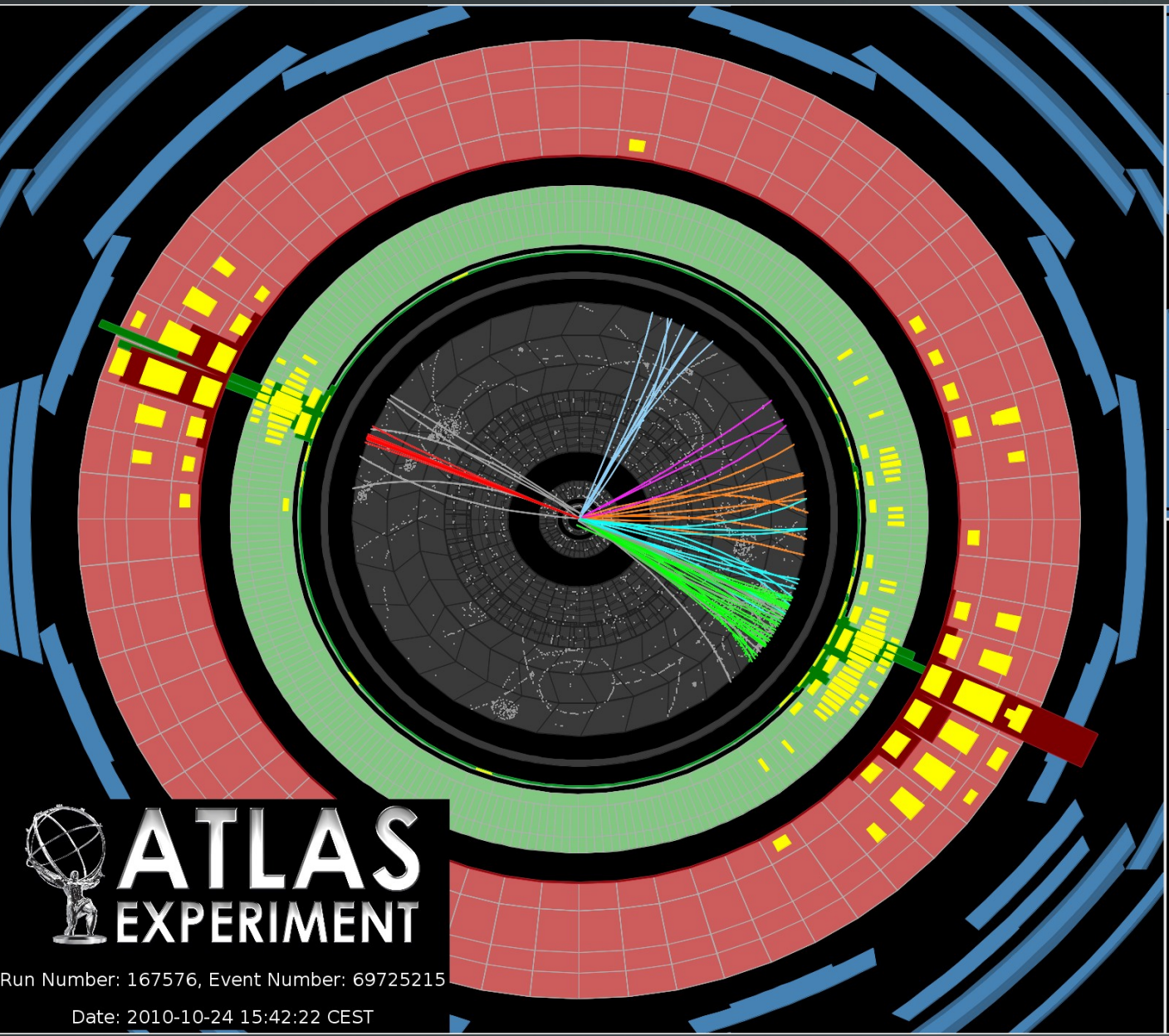
- Largest systematic from measuring the jet energy scale (JES)

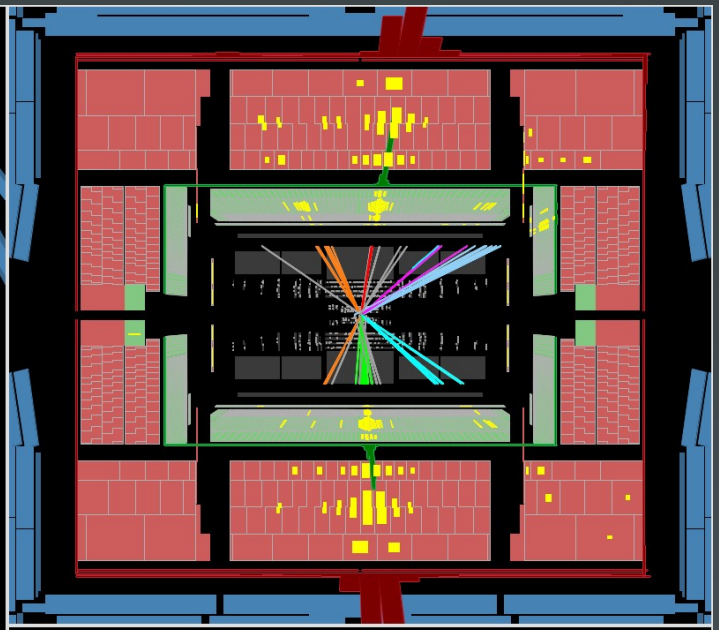
E_T MISS

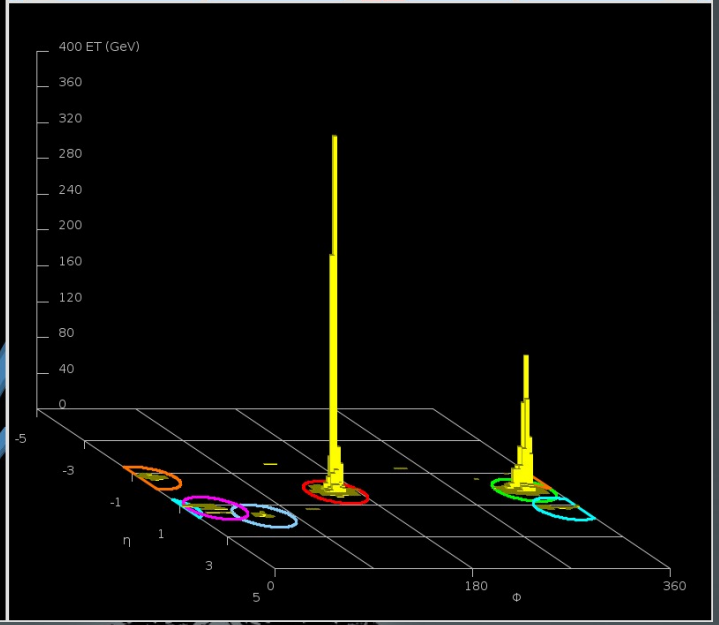
Neutrinos: (or possibly Dark Matter?)

- Total transverse energy of objects in calorimeter + muon corrections

Searches with Jets in ATLAS



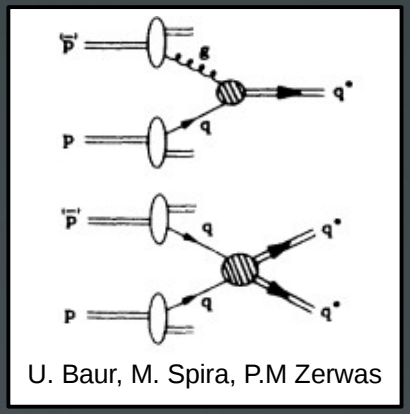




Two highest-p_T jets have invariant mass = 2.6 TeV

Searches with Dijets in ATLAS

- $2 \rightarrow 2$ scattering well understood in SM (QCD)...any deviation from expected behavior of dijet processes would indicate new physics



- Excited quarks (q*): result of quark compositeness

NEW!

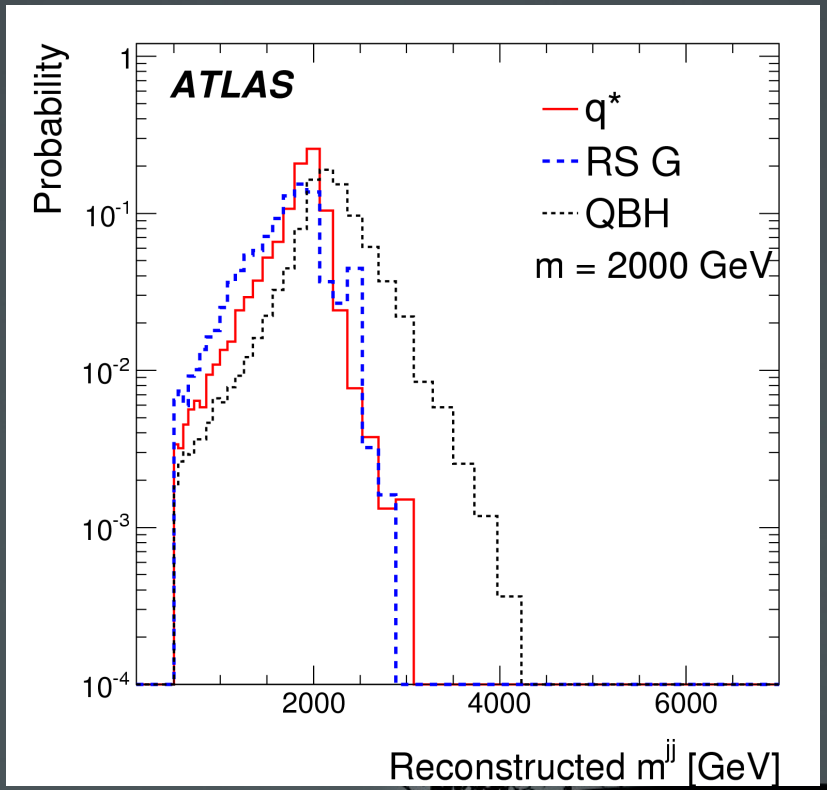
- Axigluons: would couple axially to quarks, arising from BSM extension of QCD including a chiral color gauge group

$$\mathcal{L}_{Aq\bar{q}} = g_{QCD}\bar{q}A_{\mu}^{a}\frac{\lambda^{a}}{2}\gamma^{\mu}\gamma_{5}\ q$$

NEW!

- Quantum black holes: Randall-Meade model with n=2 to 7 extra dimensions
- Contact interactions: effective scale Λ:

$$\mathcal{L}_{qqqq}(\Lambda) = \frac{\xi g^{2}}{2\Lambda^{2}}\bar{\Psi}_{q}^{L}\gamma^{\mu}\Psi_{q}^{L}\bar{\Psi}_{q}^{L}\gamma_{\mu}\Psi_{q}^{L}$$



All new dijets results with 36 pb^{-1}

Previous ATLAS publications:

Dijet resonance:

Phys. Rev. Lett. 105, 161801 2010 (315 nb^{-1})

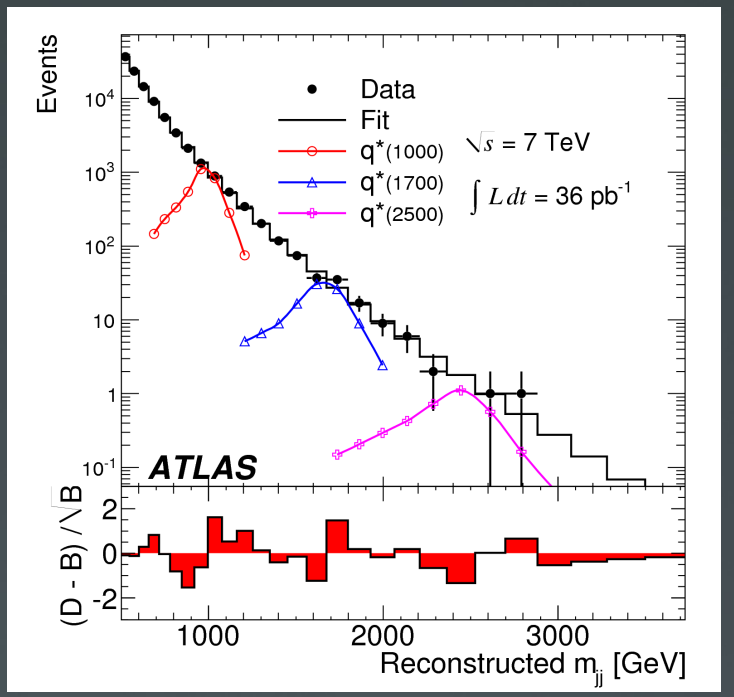
Quark Contact Interactions:

Phys. Lett. B694 327-345 2011 (3.1 pb^{-1})

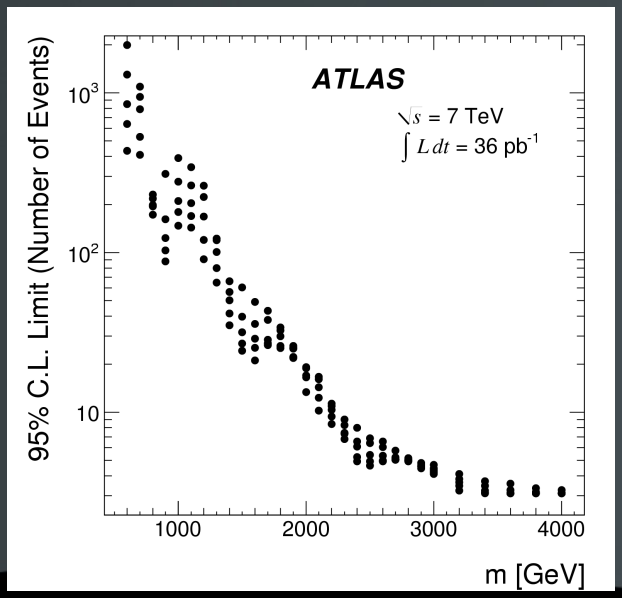
Dijet Resonances

- Look at invariant mass of two jets: $m_{jj} \equiv \sqrt{(E^{j_1} + E^{j_2})^2 - (\vec{p}^{j_1} + \vec{p}^{j_2})^2}$
- No evidence of a peak (p-value = 0.39 found with BumpHunter test)

95% C.L LIMITS Observed (Expected)
Excited quarks (q*): M > 2.15 (2.07) TeV
Quantum Black Holes: M > 3.67 (3.64) TeV
Axigluons: M > 2.10 (2.01) TeV



- Also can set limits on model-independent Gaussian resonances:



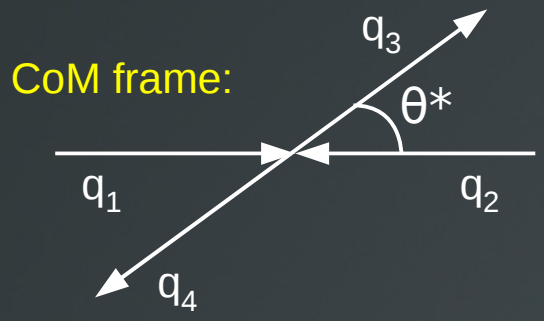
Using Gaussian with mean m, width σ:

Lower limits on N_{obs} (95% C.L.)

	σ/m				
Mean m (GeV)	0.03	0.05	0.07	0.10	0.15
1000	147	179	210	278	391
1500	24	27	32	40	60
2000	13	16	19	19	17
2500	4.6	4.9	5.4	6.4	6.9
3000	4.1	4.2	4.3	4.5	4.7

Angular Distributions of Dijets

- Can gain sensitivity by looking at rapidity



$$y^* = \frac{1}{2}\ln\left(\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}\right)$$

$$y^* = \frac{1}{2}(y_1 - y_2)$$

- Observable variable:

$$\chi \equiv \exp(|y_1 - y_2|) = \exp(2|y^*|)$$

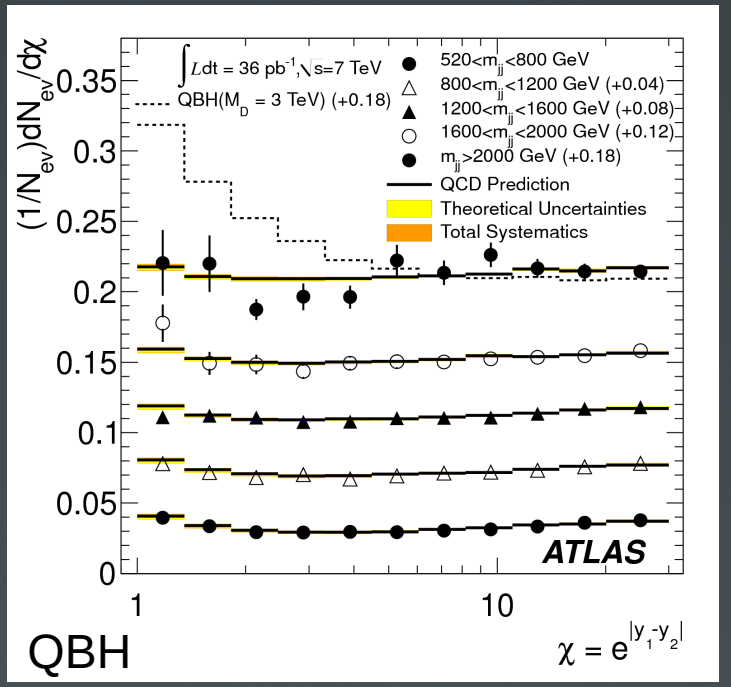
NEW!

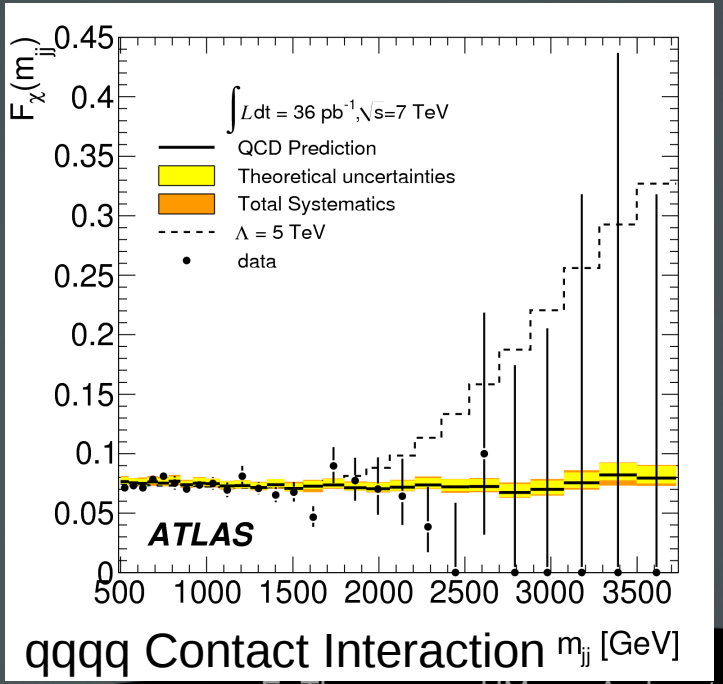
- Also “chi fraction”:

$$F_\chi(m_{jj}) = \frac{N_{events}(|y^*| < 0.6)}{N_{events}(|y^*| < 1.7)}$$

Reduced sensitivity to absolute JES

- Well suited for contact interaction search (non-resonance search)



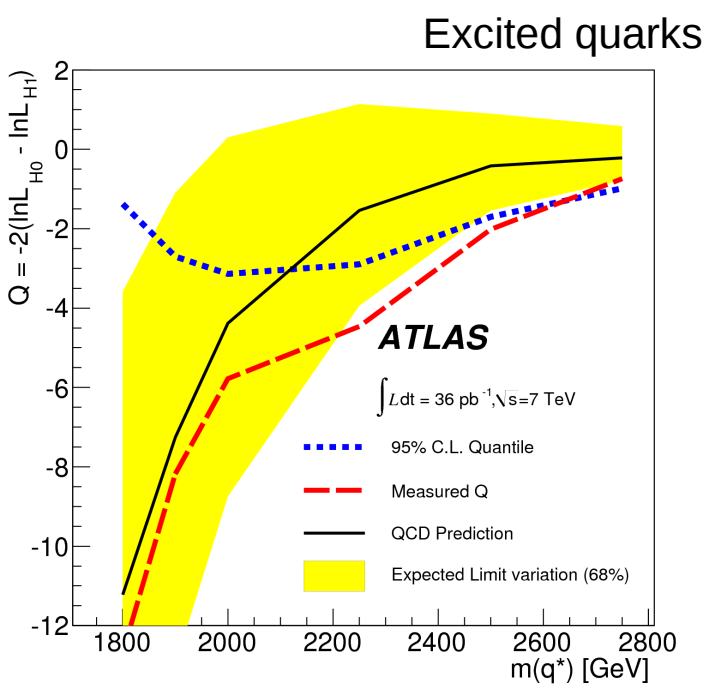


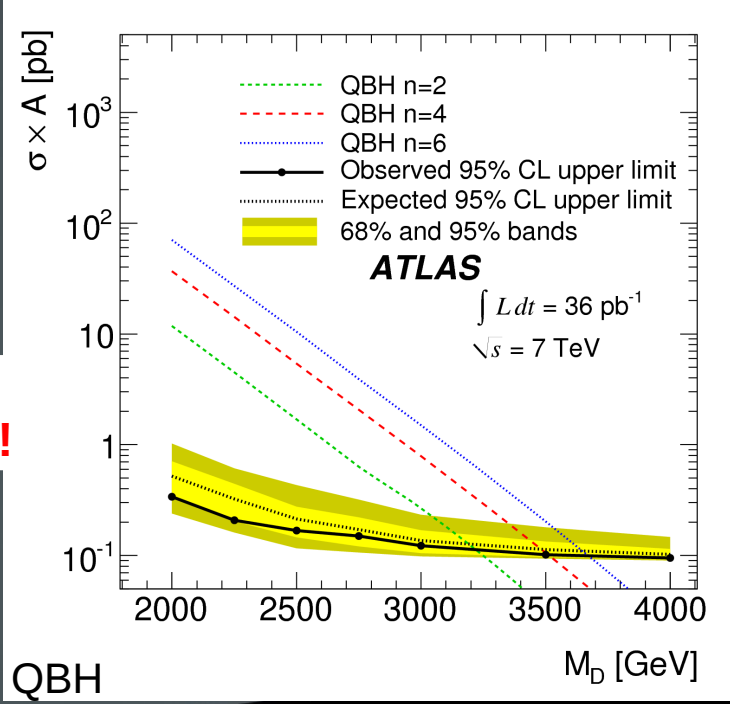
36 pb^{-1}

Dijets Limits

Summary of Dijet Limits:

Model and Analysis Strategy	95% C.L. Limits (TeV) Expected	Observed
Excited Quark q^*		
Resonance in m_{jj}	2.07	2.15
$F_\chi(m_{jj})$	**2.12**	**2.64**
Randall-Meade Quantum Black Hole for $n = 6$		
Resonance in m_{jj}	**3.64**	**3.67**
$F_\chi(m_{jj})$	3.49	3.78
θ_{np} Parameter for $m_{jj} > 2$ TeV	3.37	3.69
11-bin χ Distribution for $m_{jj} > 2$ TeV	3.36	3.49
Axigluon		
Resonance in m_{jj}	**2.01**	**2.10**
Contact Interaction Λ		
$F_\chi(m_{jj})$	**5.7**	**9.5**
F_χ for $m_{jj} > 2$ TeV	5.2	6.8
11-bin χ Distribution for $m_{jj} > 2$ TeV	5.4	6.6



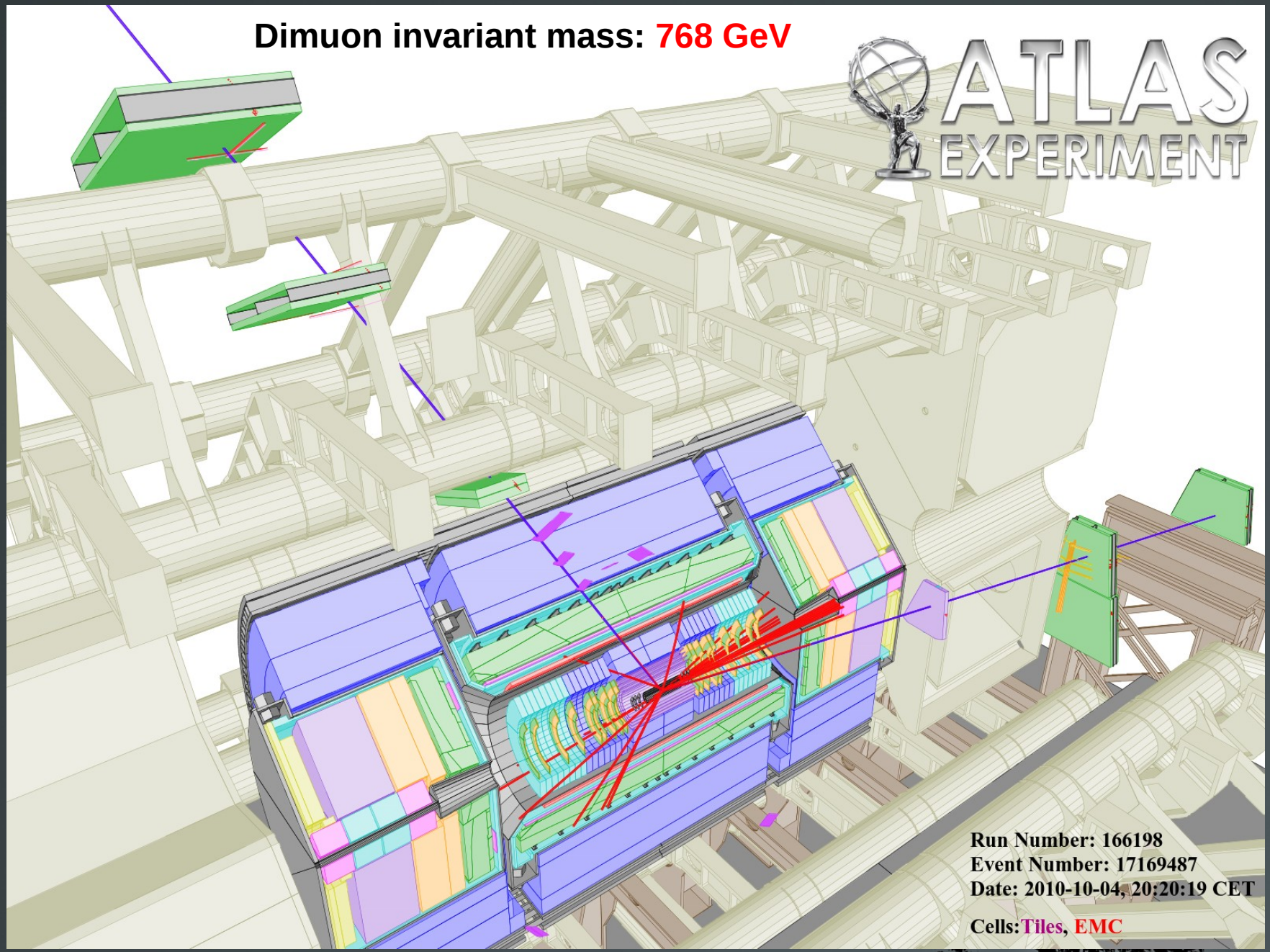


Submitted to arXiv and New Journal of Physics yesterday!

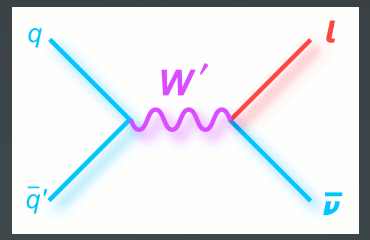
Previous Tevatron limits:

- Excited q*: **M > 0.870 TeV** (CDF 1.1 fb^{-1}) PRD79 112002, 2009
- Axigluons: **M > 1.250 TeV** (CDF 1.1 fb^{-1}) PRD79 112002, 2009
- Contact Int: **Λ > 2.9 TeV** (D0 0.7 fb^{-1}) PRL 103:191803, 2009

Searches with Leptons and Photons

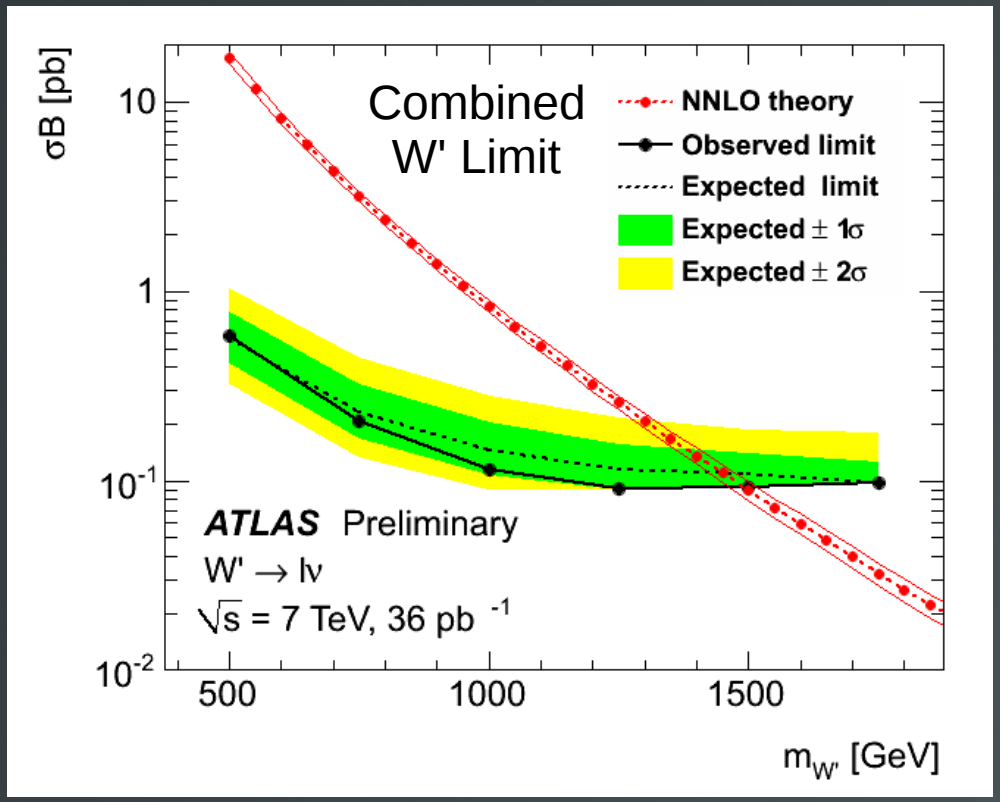


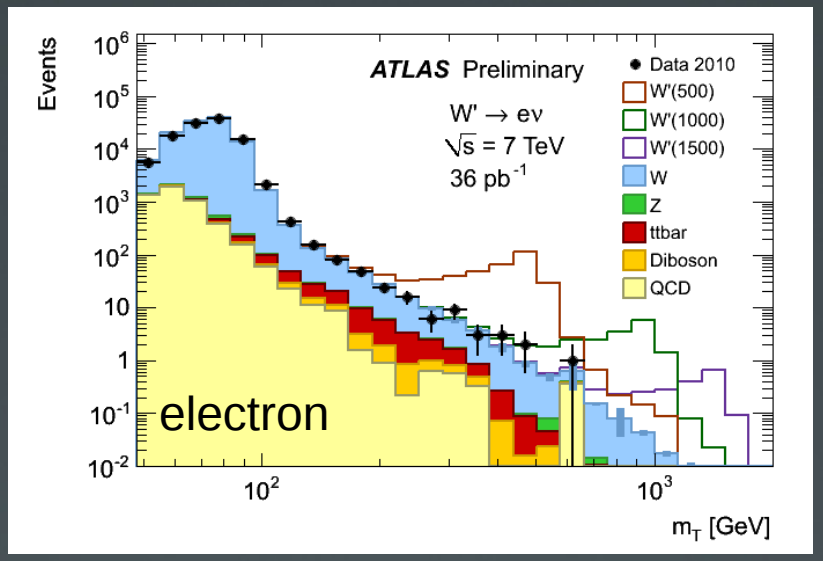
Extra Gauge Bosons

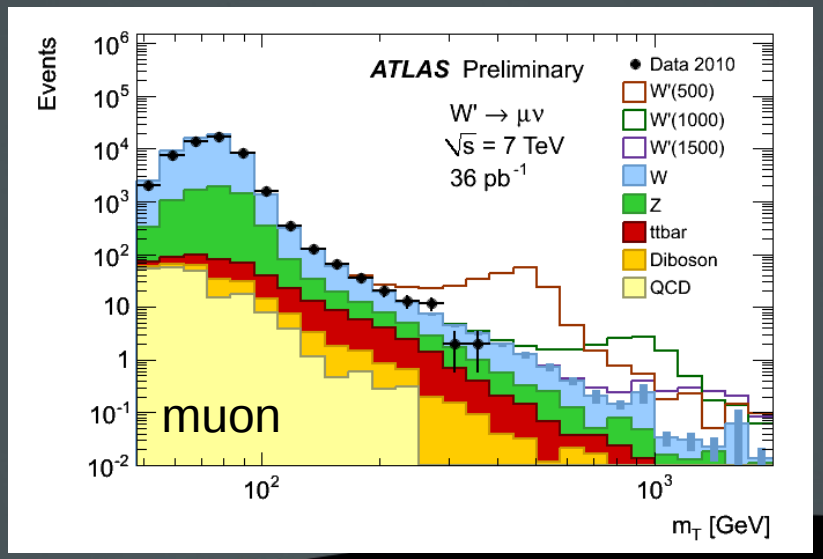


- W' → lν: Sequential Standard Model: Couplings same as SM bosons, width linearly scales with the mass
- Look for events in the transverse mass spectrum:

$$m_T = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos\varphi_{\ell\nu})}$$







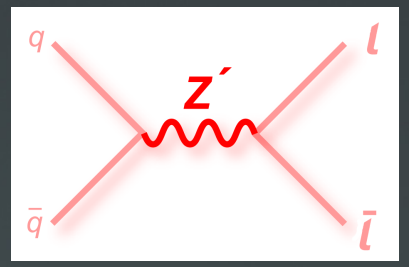
LIMIT 95% C.L. Observed (Expected): $M_{W'}$ > 1.490 (1.450) TeV

Previous Tevatron Limit: $M_{W'}$ > 1.100 TeV
(CDF public note 10303, 2010, 5.3 fb^{-1})

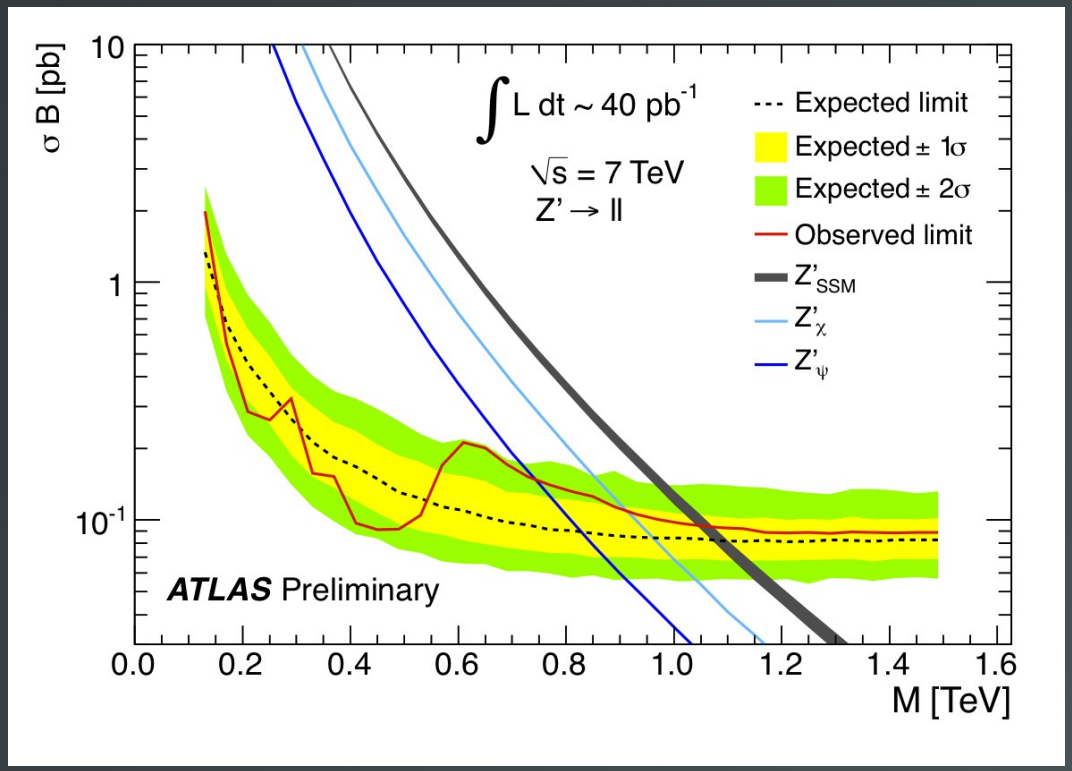
~40 pb^{-1}

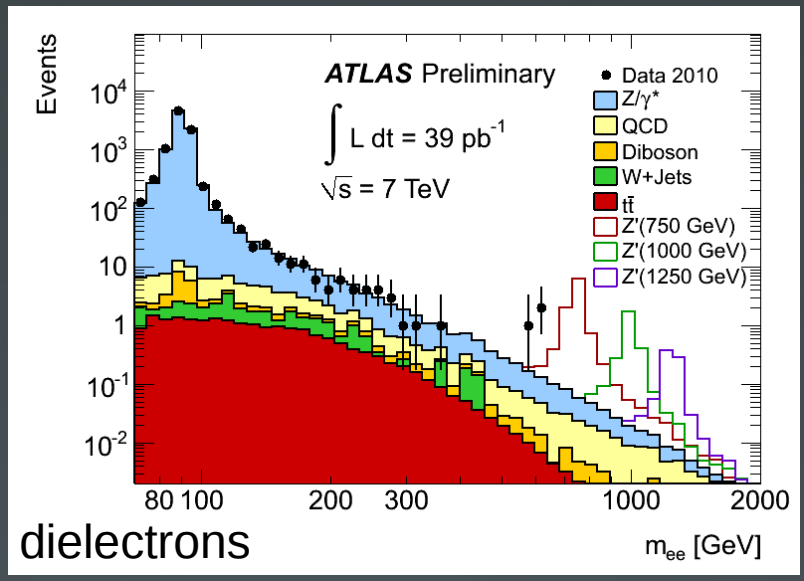
NEW!

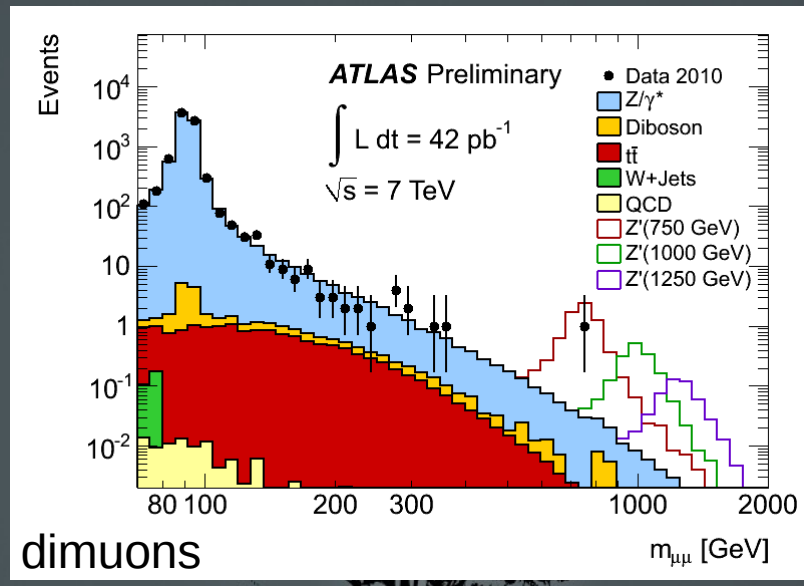
Extra Gauge Bosons



- Dilepton resonances (Z'), invariant mass spectrum
- Z' SSM as well as string-theory-inspired E6 models







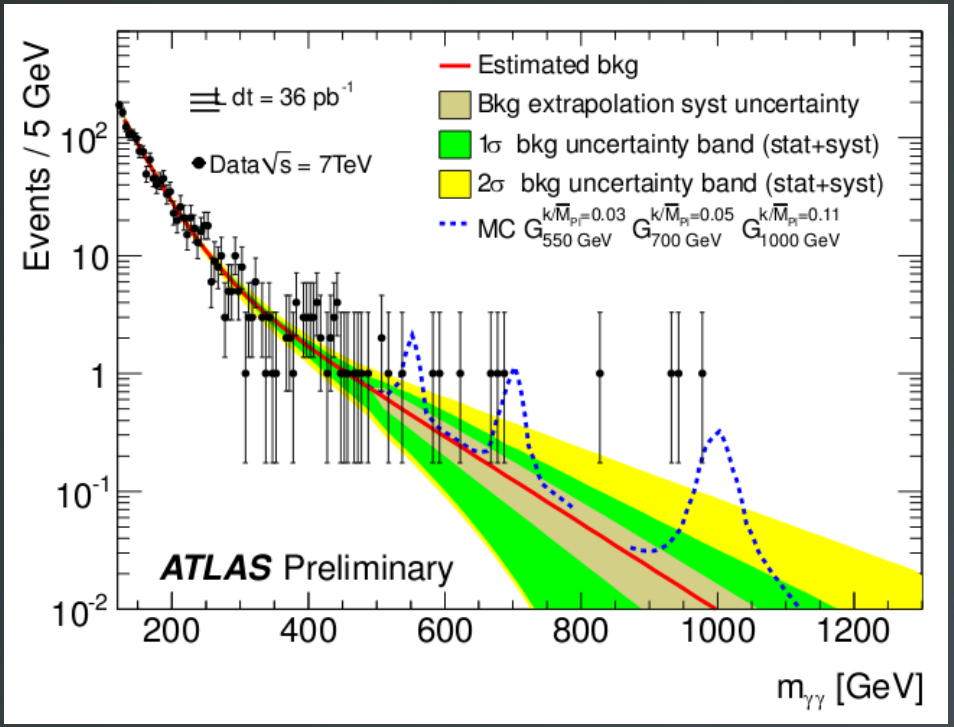
LIMITS 95% C.L. Observed (Expected):
$M_{Z' SSM}$ > 1.048 (1.088) TeV

E6: [TeV]

Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
0.738	0.763	0.771	0.842	0.871	0.900
(0.837)	(0.860)	(0.866)	(0.922)	(0.945)	(0.965)

Previous Tevatron Limit: $M_{Z'SSM}$ > 1.071 TeV
(CDF 4.6 fb^{-1} arXiv:1101.4578, 2011)

Searches with Di-Photons



- RS Gravitons (36 pb^{-1}) NEW!
- Plank scale ↔ TeV scale $\Lambda_\pi = \overline{M}_{\rm Pl}\exp(-k\pi r_c)$
- Predict a spin 2 graviton as lightest state of Kaluza-Klein (KK) tower with mass M_G
- R = compactification radius, k = curvature, coupling defined by k/M_{PL}

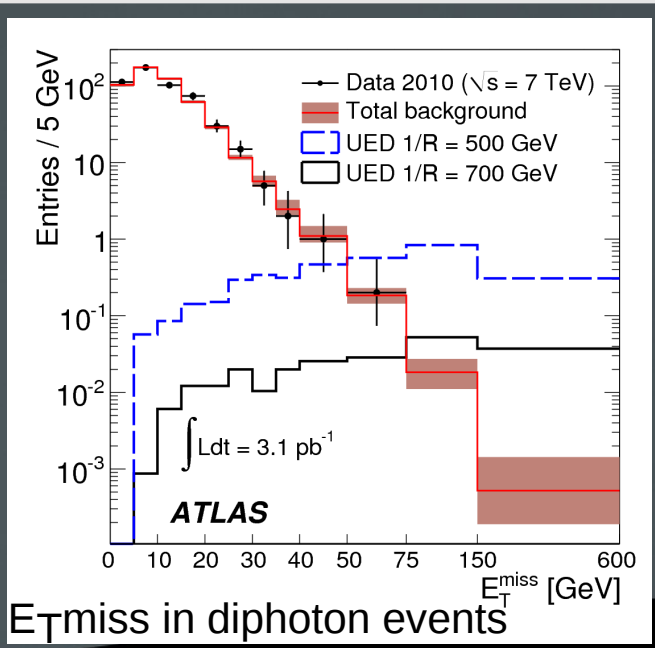
LIMITS M_G > 545 GeV (k/M_{PL} = 0.02)
95% C.L.: M_G > 920 GeV (k/M_{PL} = 0.1)

Previous Tevatron limit (D0): M_G > 1.050 GeV (k/M_{PL}=0.1) (Phys Rev Lett 104, 241802 2010, 5.4 fb^{-1})

- Universal Extra Dimensions (3.1 pb^{-1})
- Masses of states in KK tower of gravitons separated by 1/r ...lightest KK particle: KK photon
- $\gamma^* \rightarrow \gamma$ + G (x2 per event)
  → observe: $\gamma\gamma$ + $E_T$miss (+ other SM)
- Signal in $E_T$miss > 75 GeV, observe 0 events

LIMIT: 1/R > 728 GeV (95% C.L.)

Previous Tevatron limit (D0): 1/R > 477 GeV (PRL 105, 221802, 2010, 6.3 fb^{-1})

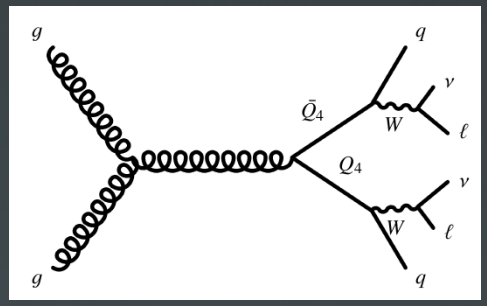


$E_T$miss in diphoton events

37 pb^{-1}

NEW!

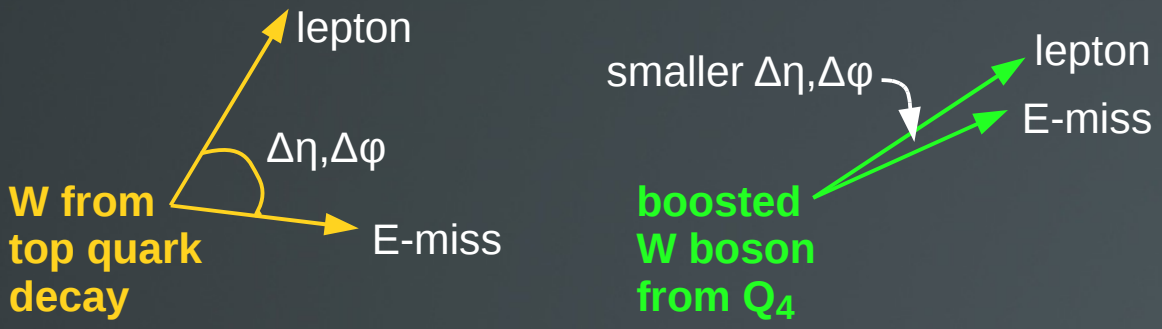
Leptons AND Jets!



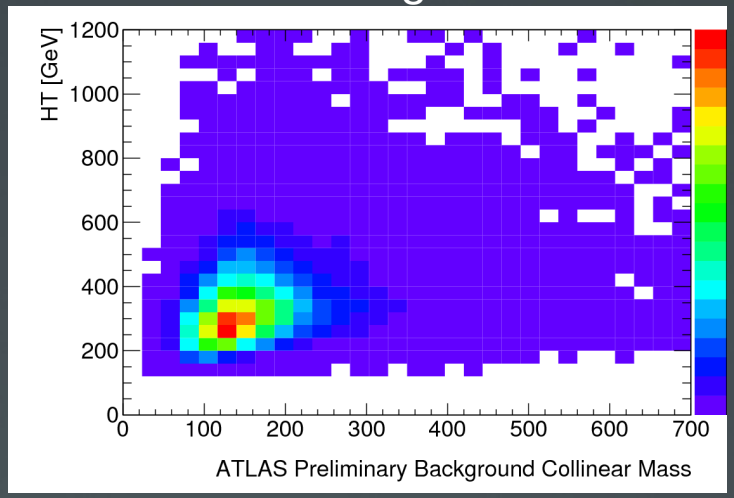
- 4th generation chiral quarks: 2 jets, 2 leptons, $E_T$miss

$$Q_4\bar{Q}_4 \rightarrow W^+qW^-\bar{q} \rightarrow \ell^+\nu q\ell^-\nu\bar{q}$$

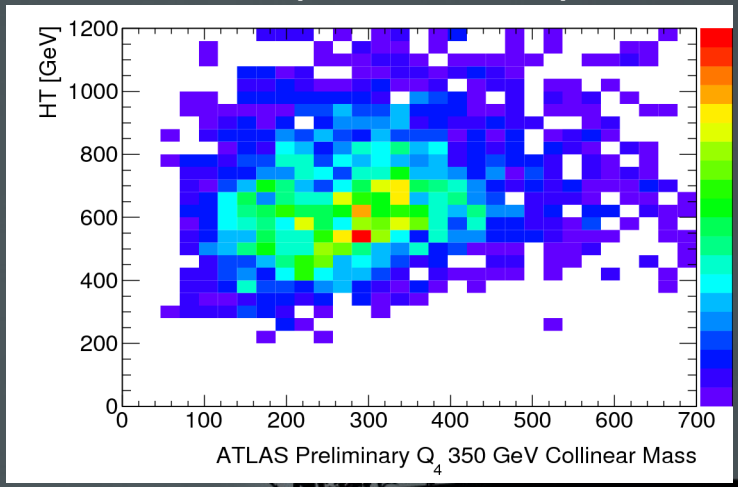
- $M_{collinear}$ vs H_T can be used as a discriminant against dominant ttbar background
  - H_T = scalar sum of E_T from leptons, jets and $E_T$miss
  - "Collinear Mass": Find best Δη,Δφ for each lν pair to minimize difference in the two Q_4 reconstructed masses ($M_{collinear}$)



SM background



Q_4 (M=350 GeV)



LIMIT 95% C.L. Obs (Exp): M_{Q4} > 270 (284) GeV

Limit with 5.6 fb^{-1} (CDF): M_{u4}> 356 GeV
Limit with 4.8 fb^{-1} (CDF): M_{d4}> 372 GeV
(CDFNote CDF/PUB/TOP/PUBLIC/10110, arXiv:1101.5728)

First dilepton u_4 search, and first search at the LHC!

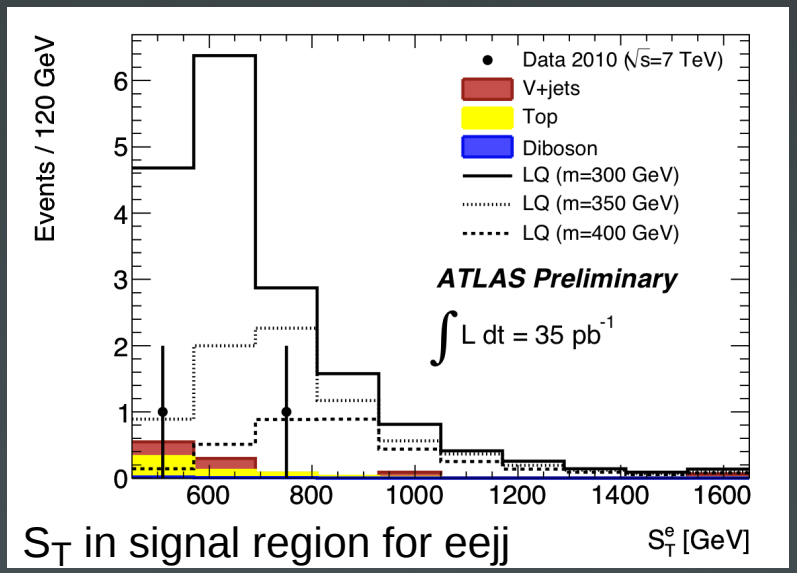
35 pb^{-1}

NEW! Leptoquarks

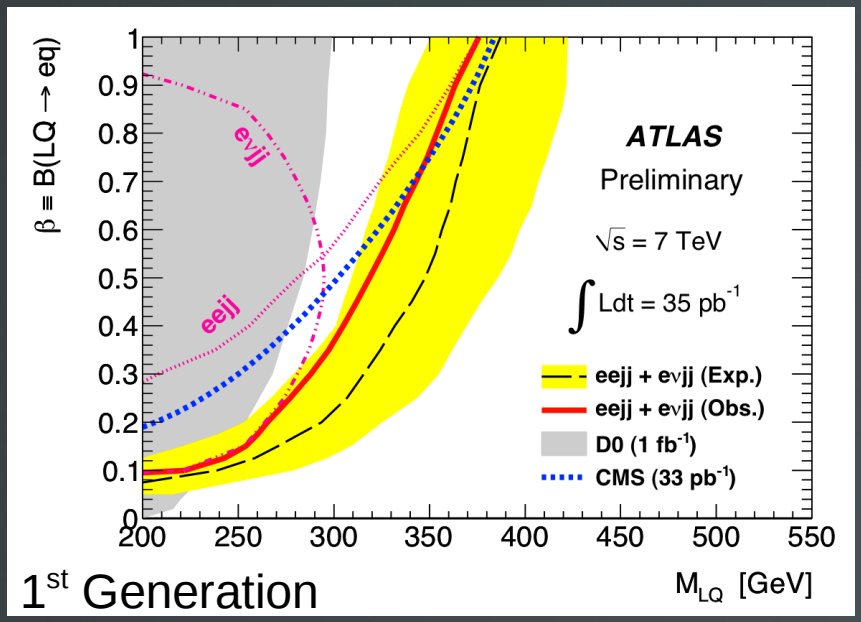
- Possess both lepton and quantum numbers
- Pair produced...search for charged lepton (qqll) or neutrino (qqlν) daughter
- High inv mass of lepton-jet pair has little bkgnd
- Also look at M_T and sum of transverse energy:

$$M_{\mathrm{LQ}}^{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{j}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\phi^{\mathrm{j}})} \qquad S_{\mathrm{T}}^{\ell} = p_{\mathrm{T}}^{\ell_1} + p_{\mathrm{T}}^{\ell_2} + p_{\mathrm{T}}^{\mathrm{j}_1} + p_{\mathrm{T}}^{\mathrm{j}_2}$$

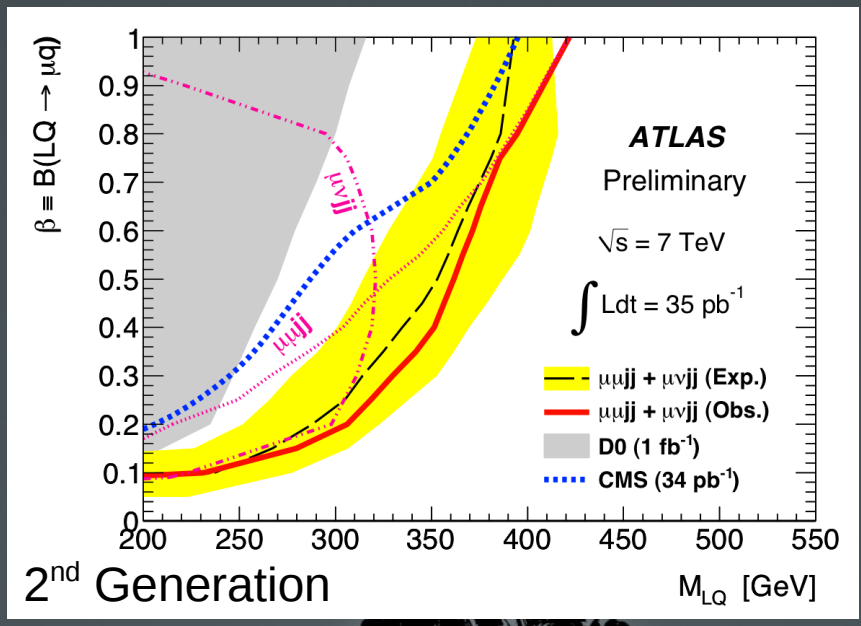
- β = BF for single leptoquark to decay to l±q



S_T in signal region for eejj



1st Generation



2nd Generation

95% C.L. LIMITS Observed (Expected) [GeV]

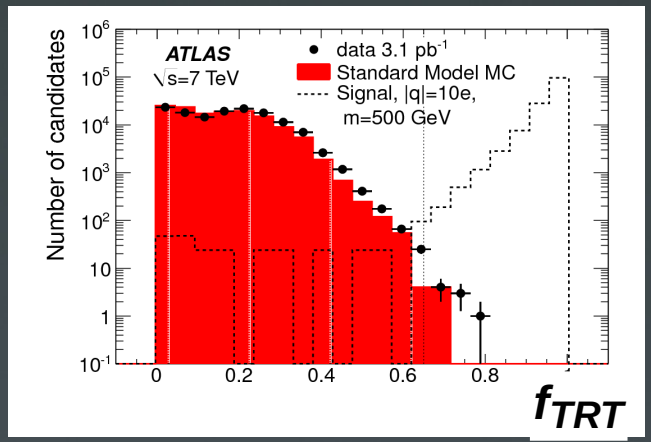
1st Generation: M > 376 (387)
2nd Generation: M > 422 (393)] β=1.0

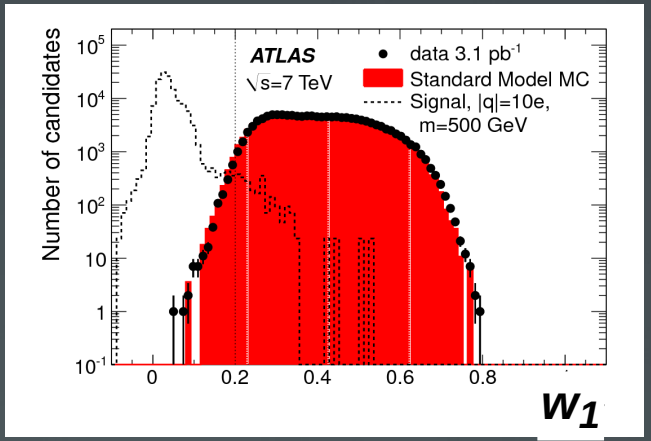
M > 319 (348)
M > 362 (353)] β=0.5

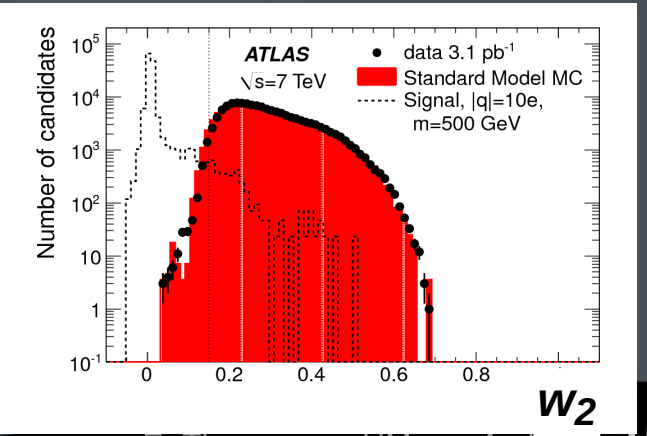
Limits with 1 fb^{-1} (D0)
(Phys Lett B 671 224, 2009)

Long-Lived Highly Ionizing Particles (HIPs)

- Q-balls, stable micro blackholes, magnetic monopoles, dyons 3.1 pb^{-1}
- Non-relativistically move through detector
- Charge (q) >> elementary charge (e)
- The presence of HIP can be found by measuring:
  - f_{TRT} – Fraction of TRT hits on the track which pass high-threshold (high-ionization hits)
  - w_1, w_2 – Fraction of energy deposited outside 3 most energetic cells first and second layers of the EM calorimeter
- Pair production assuming DY mechanism







Limits on production cross section: (95% C.L.)

m [GeV]	$\|q\| = 6e$	$\|q\| = 10e$	$\|q\| = 17e$
200	11.5	5.9	9.1
500	7.2	4.3	5.3
1000	9.3	3.4	4.3

Summary of Results

Mass limits (95% C.L.) [TeV]:

		Tevatron	**ATLAS**
Dijets	Excited quarks (q*)	0.87	**2.64***
	QBHs	-	**3.67***
	Axigluons	1.25	**2.10***
	Contact Int. Λ qqqq	2.9	**9.5***
Lepton +MET	W' SSM (e+μ)	1.100	**1.490**
Leptons +MET+ jets	4^{th} gen quark Q_{u4}	0.356	0.270
	1^{st} gen LQ (β=1.0)	0.299	**0.376**
	2^{nd} gen LQ (β=1.0)	0.316	**0.422**

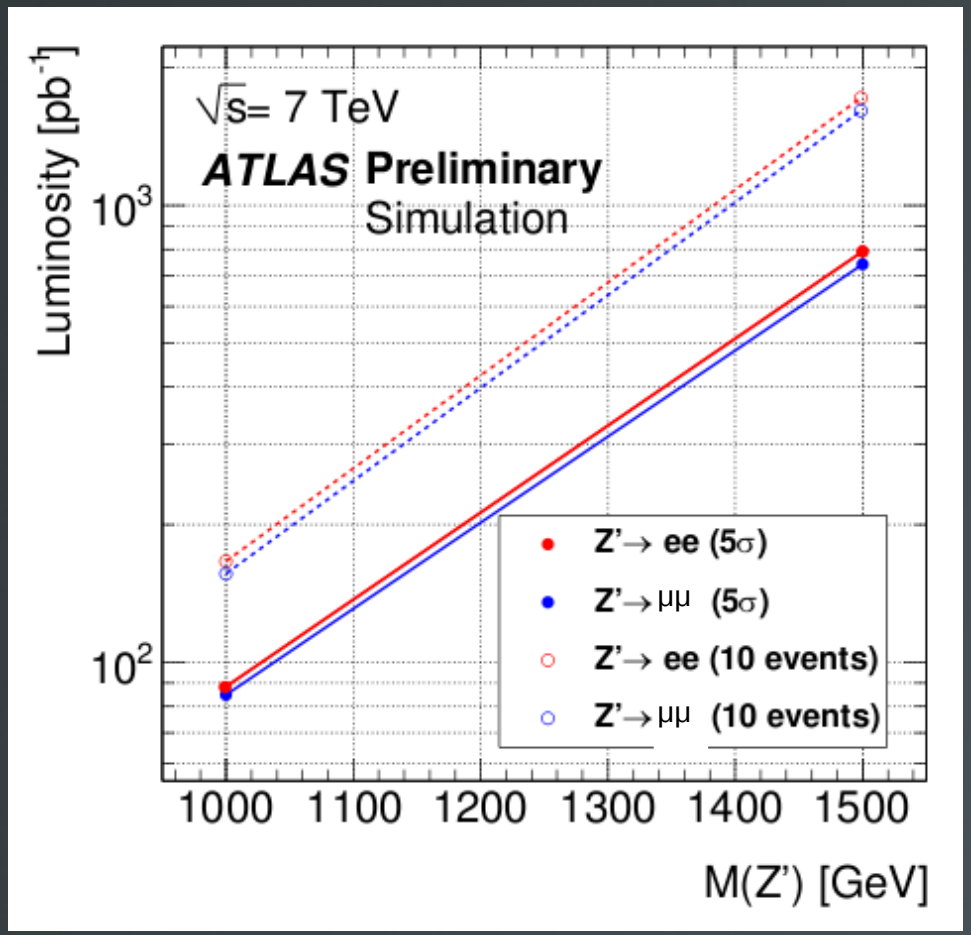
		Tevatron	**ATLAS**
Dileptons	Z' SSM (e+μ)	1.071	1.048
	E6 Z'_{χ} (e+μ)	0.930	0.900
	E6 Z'_{ψ} (e+μ)	0.917	0.738
	E6 Z'_{N} (e+μ)	0.900	0.763
	E6 Z'_{η} (e+μ)	0.938	0.771
	E6 Z'_{I} (e+μ)	0.817	**0.842**
	E6 Z'_{S} (e+μ)	0.858	**0.871**
γγ	RS Graviton	1.050	0.920
γγ+MET	UED (1/R)	0.477	**0.728***

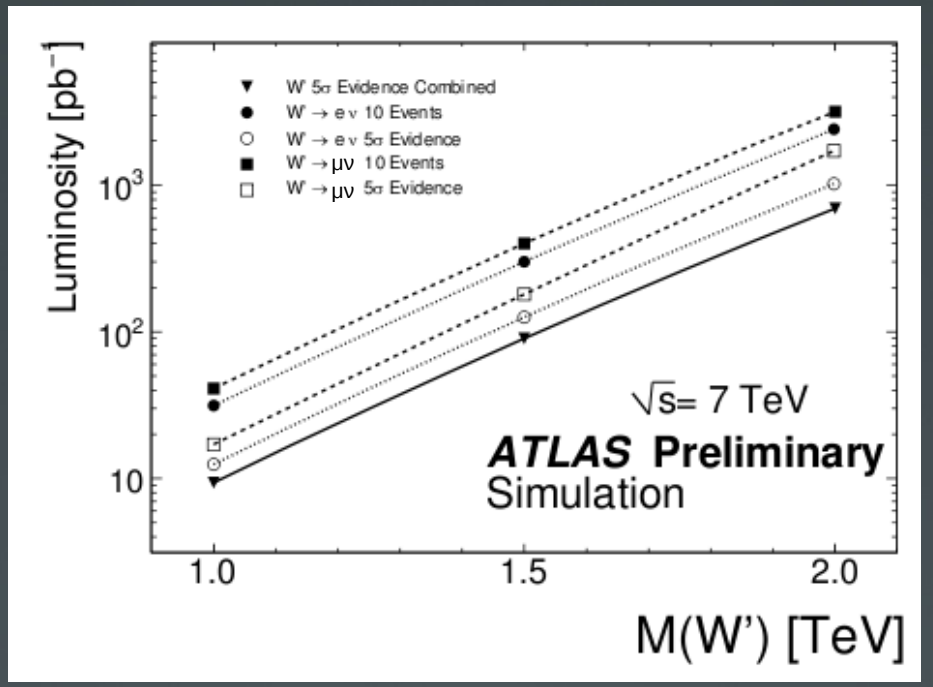
* world's best limit

With very little data, already able to push the reach to the TeV scale and set world's best limits!

Conclusions, Outlook

- ATLAS has already begun the search...first results came quickly after startup
- Expect LHC to deliver 1-3 fb^{-1} this year and more by the end of 2012





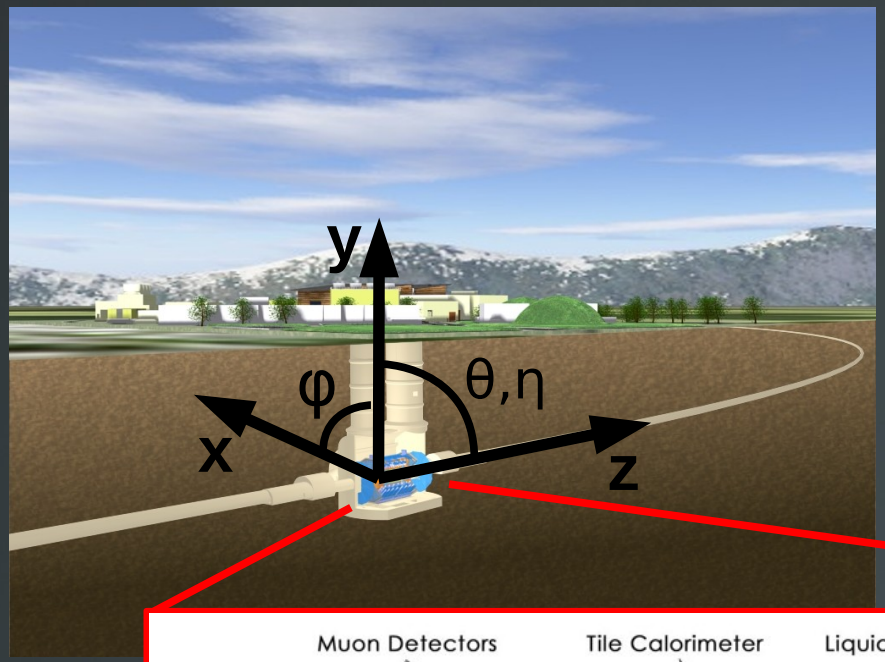
If it's there, we'll find it...
...expect discovery soon!!!

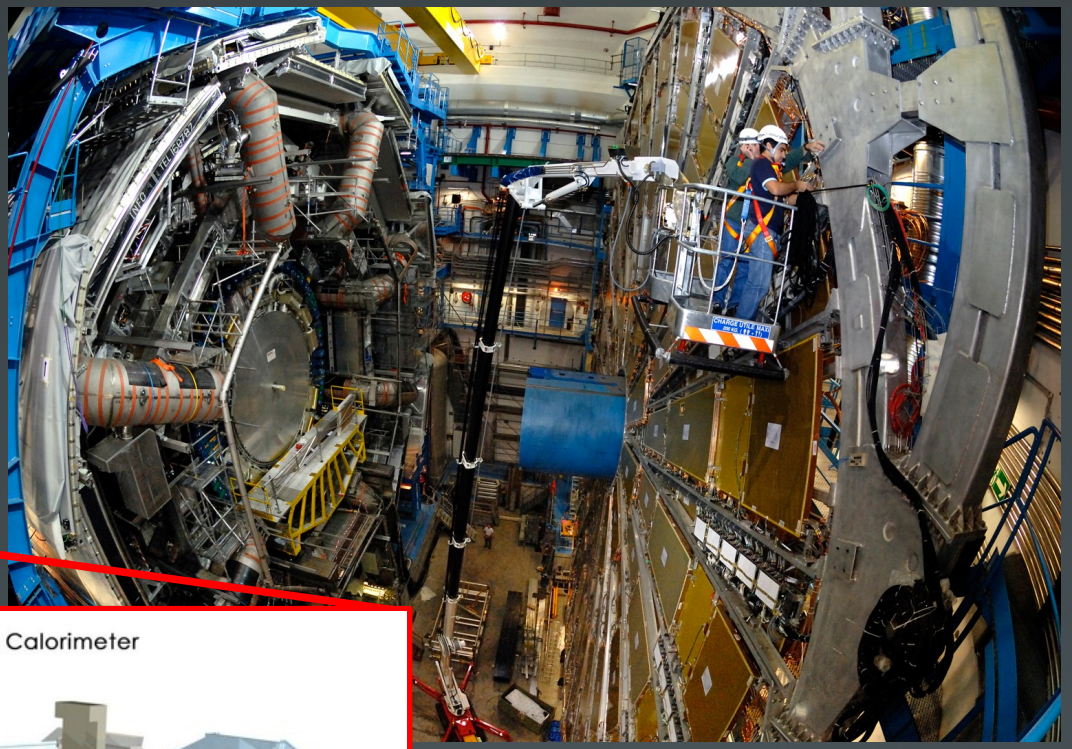
All ATLAS public results on Exotic Physics Searches:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

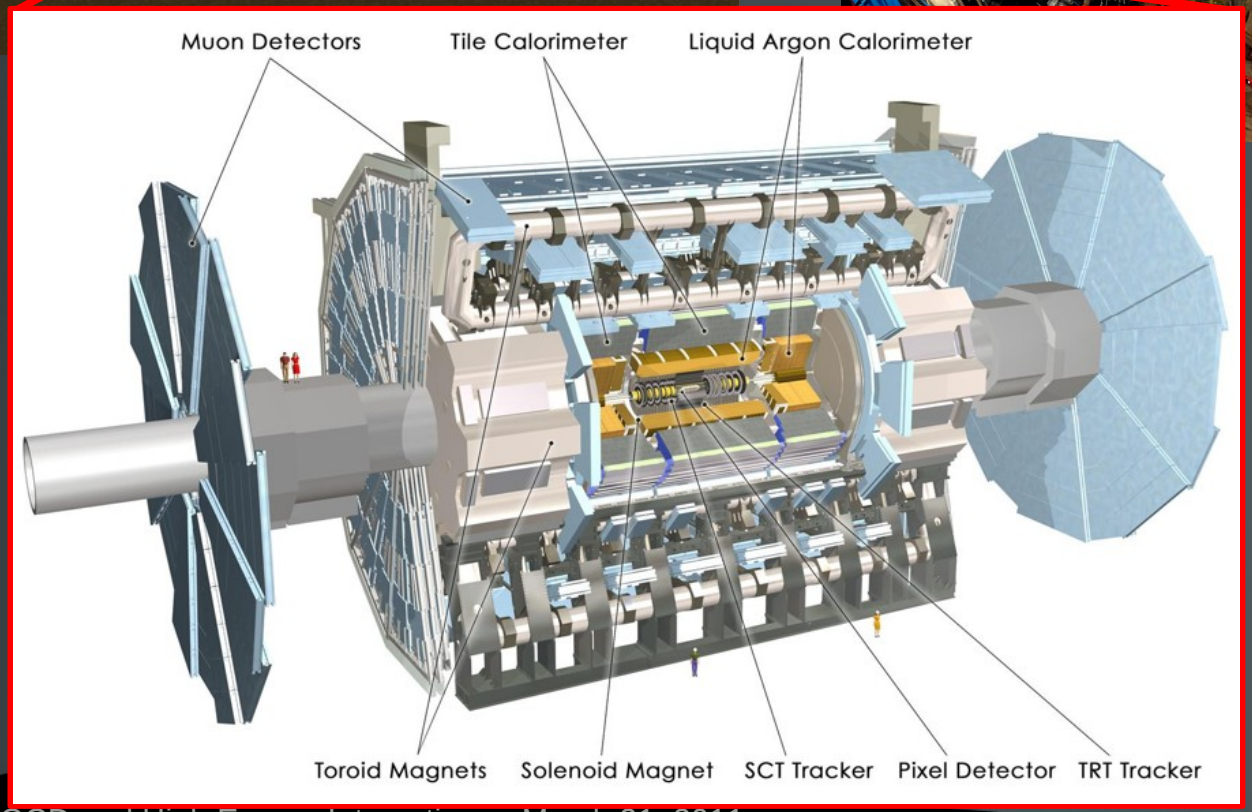
ATLAS EXPERIMENT
http://atlas.ch

Backup

The ATLAS Detector







Jet Reconstruction

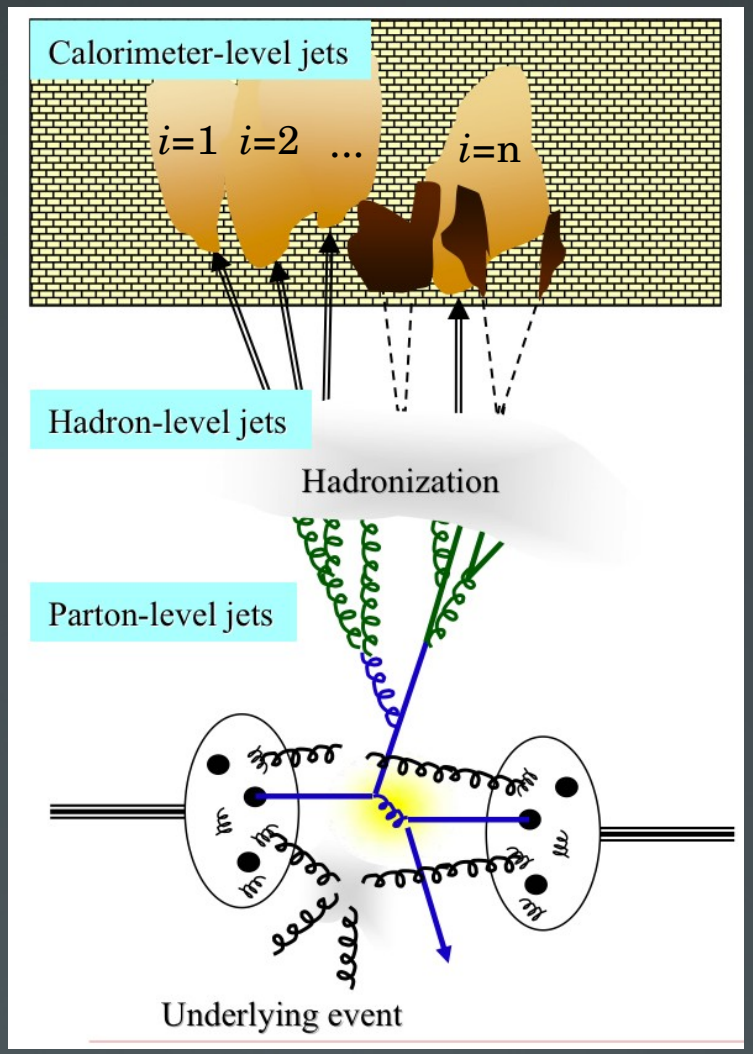
- Anti-kT algorithm:

Define: $k_{T,i}^2 = p_{T,i}^{-2}$

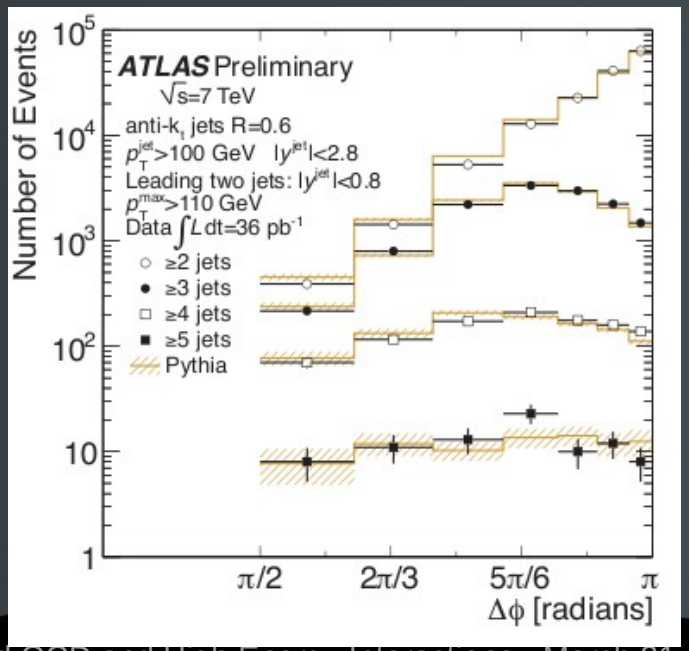
Pairs of "constituents": $k_{T,(i,j)}^2 = \min\left(p_{T,i}^{-2}, p_{T,j}^{-2}\right) \times \frac{\Delta R_{i,j}^2}{D^2}$

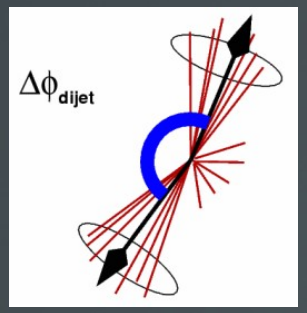
Combine pairs of constituents while:

$k_{T,(i,j)}^2 <$ min ($k_{T,i}^2$, $k_{T,(i,j)}^2$)



- Understanding jets in ATLAS:





Bayesian Analysis

- Likelihood: $$\mathscr{L}(\bar{n} \mid \theta, \bar{\nu}) = \prod_{i=1}^{N_{ch}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

- Integrate over nuisance parameters (Gaussian distributed):

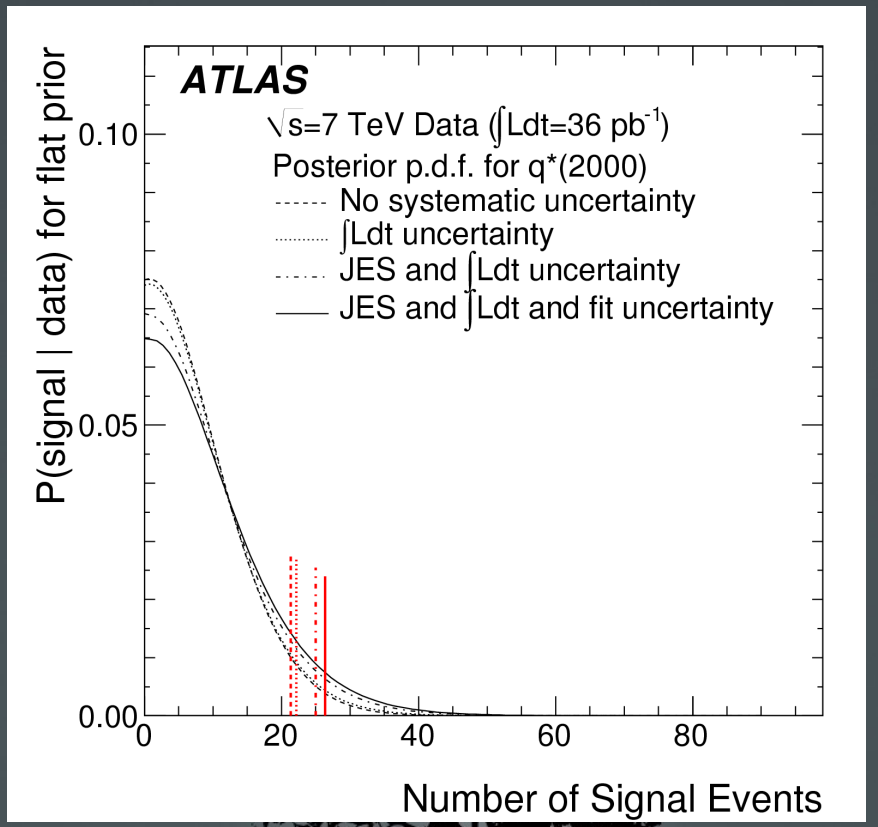
$$\mathscr{L}(\bar{n} \mid \theta, \nu) = \frac{1}{C} \int_0^{\infty} \frac{\mu'^n e^{-\mu'}}{n!} e^{-\frac{(\nu-\nu')^2}{2\sigma_\nu^2}} d\nu'$$

- Bayesian Posterior PDF:

$$\mathscr{P}(\theta \mid \bar{n}, \bar{\nu}) = \frac{1}{Z} \mathscr{L}(\bar{n} \mid \bar{\theta}, \bar{\nu}) P(\theta, \nu)$$

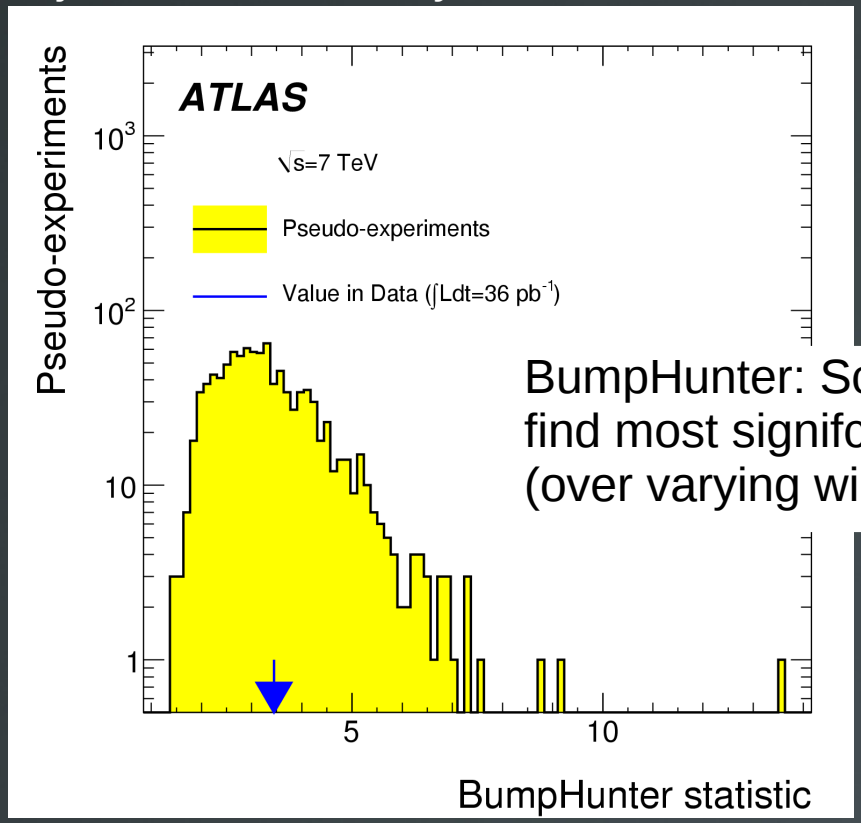
- Limit:

$$\int_0^{\theta_{lim}} \mathscr{P}(\theta' \mid \bar{n}, \bar{\nu}) d\theta' = 0.95.$$

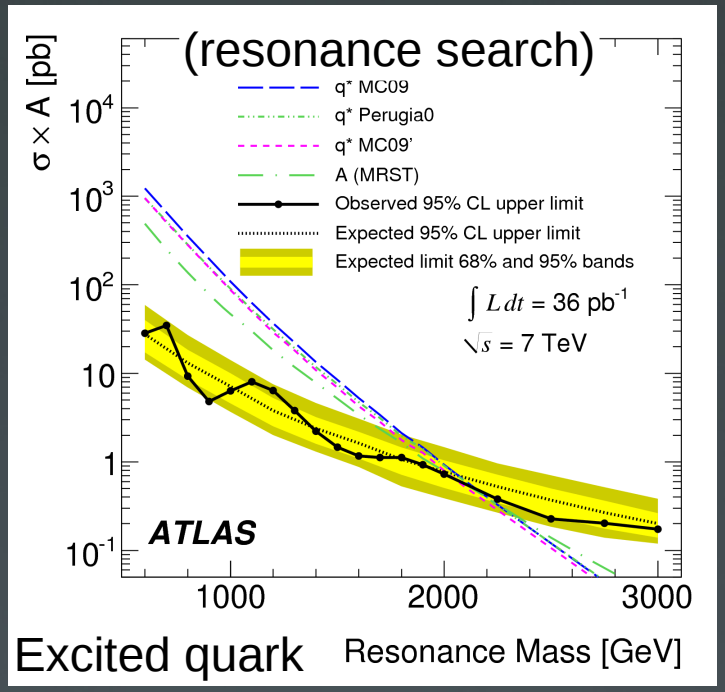


Dijets Resonance Searches

Dijet SM consistency test



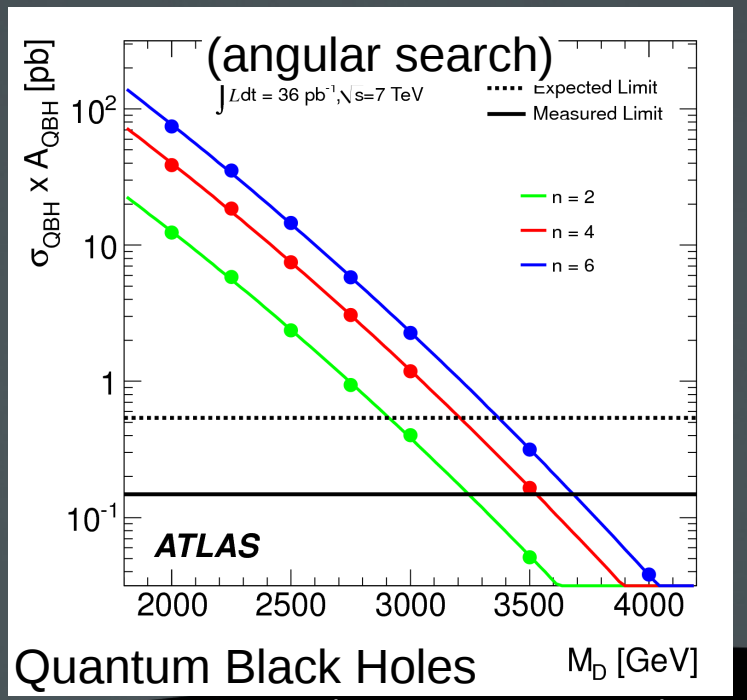
BumpHunter: Scans mass to find most signifcant excess (over varying window sizes)



Excited quark

Limits on QBH Mass (95% C.L.):

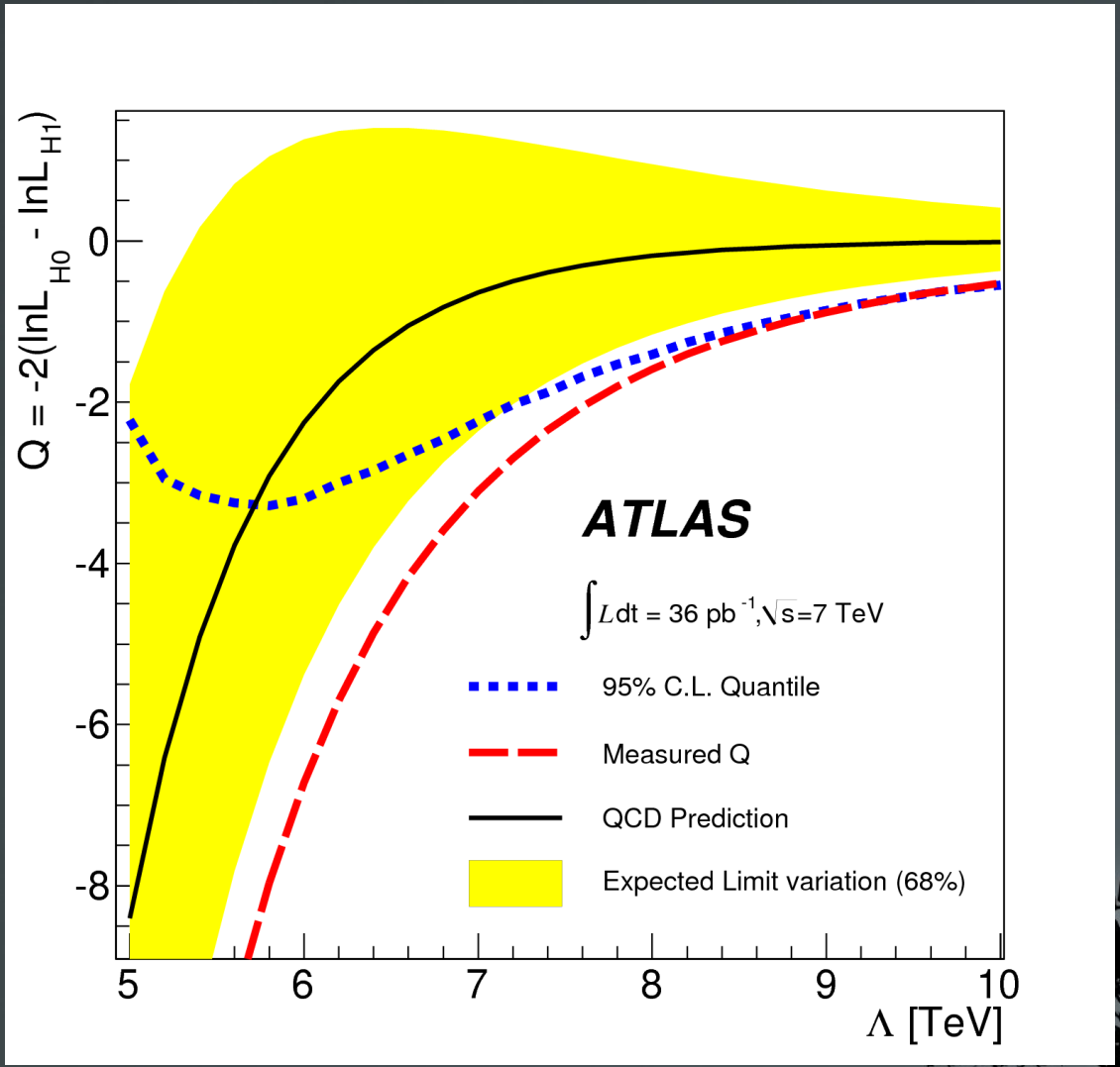
Number of Extra Dimensions	Observed M_D Limit [TeV] Stat. ⊕ Syst.	Stat. only	Expected M_D Limit [TeV] Stat. ⊕ Syst.	Stat. only
2	3.20	3.22	3.18	3.20
3	3.38	3.39	3.35	3.37
4	3.51	3.52	3.48	3.50
5	3.60	3.61	3.58	3.59
6	3.67	3.68	3.64	3.66
7	3.73	3.74	3.71	3.72



Quantum Black Holes

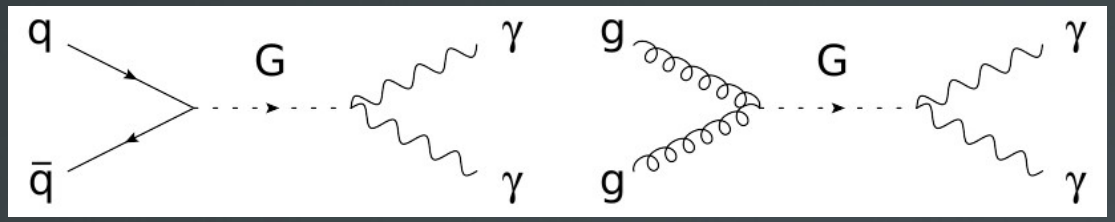
Dijets Contact Interaction Search

- Limit on contact interaction scale Λ
- Probability for limit to fluctuate upwards to 9.51 TeV: 8%

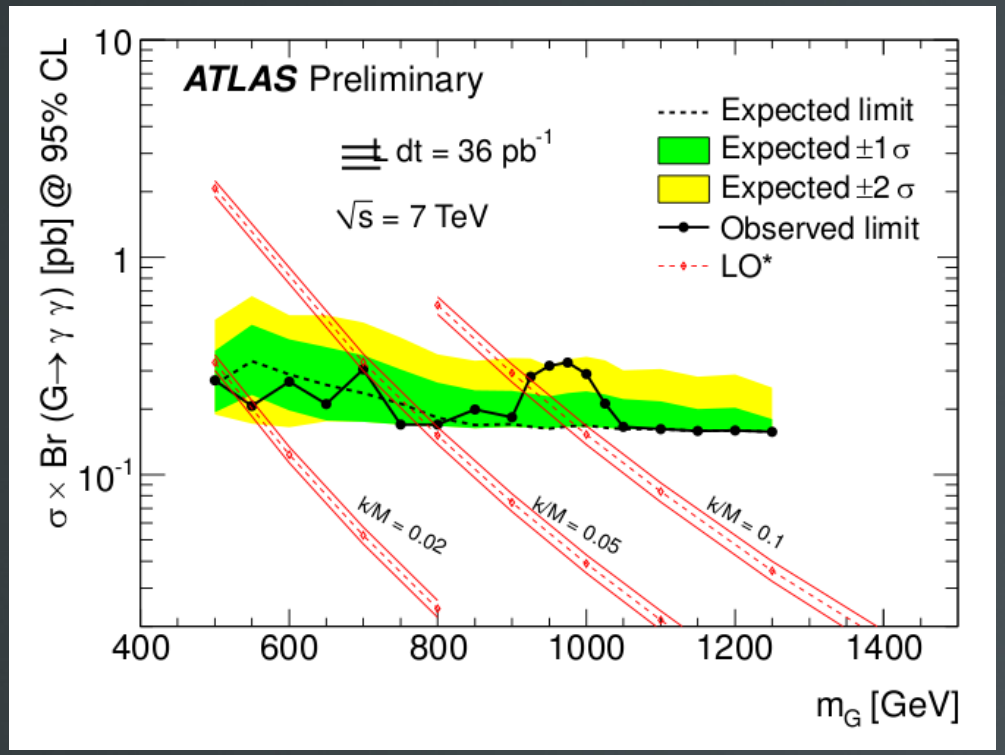


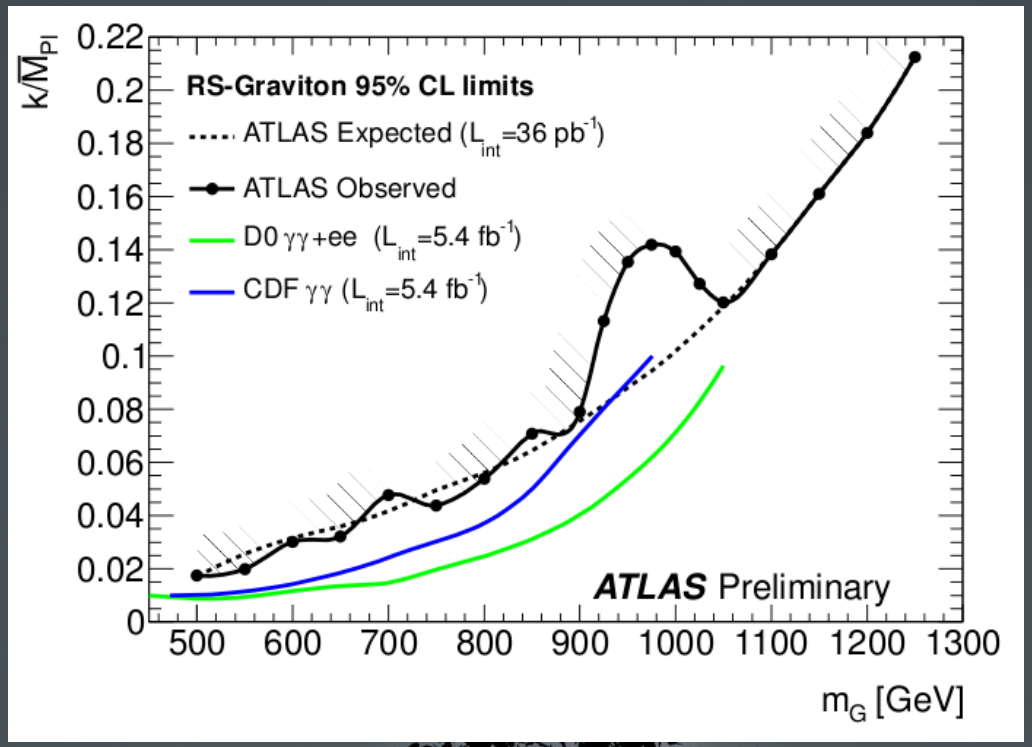
Di-Photons (RS Graviton)

- LO diagrams of graviton production:

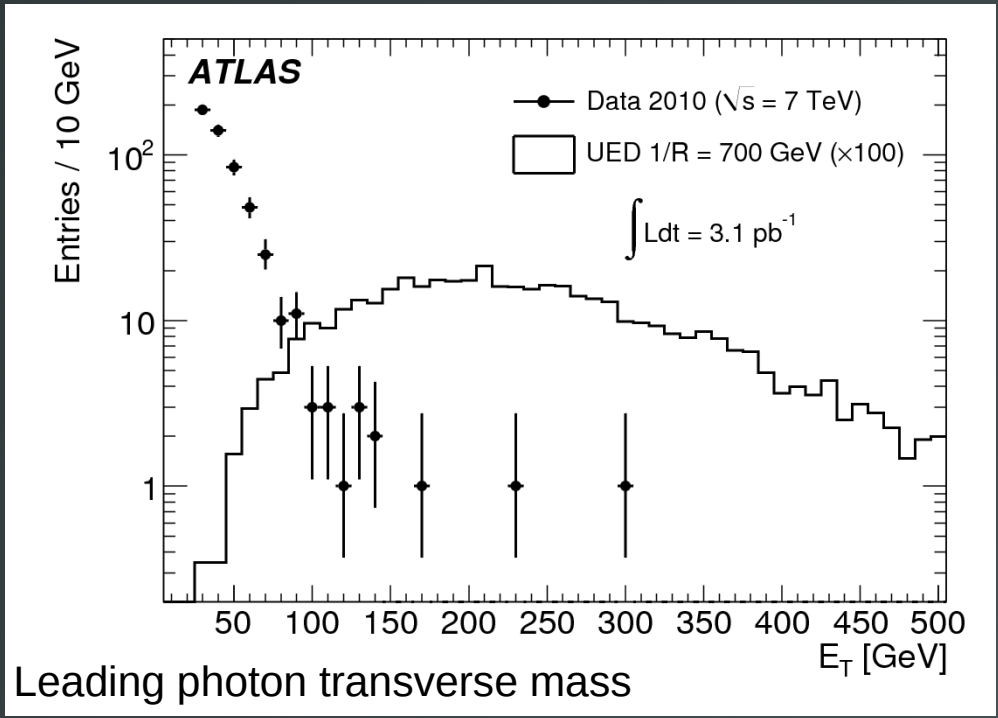


- p-value: 9% (BumpHunter)
- Limits:

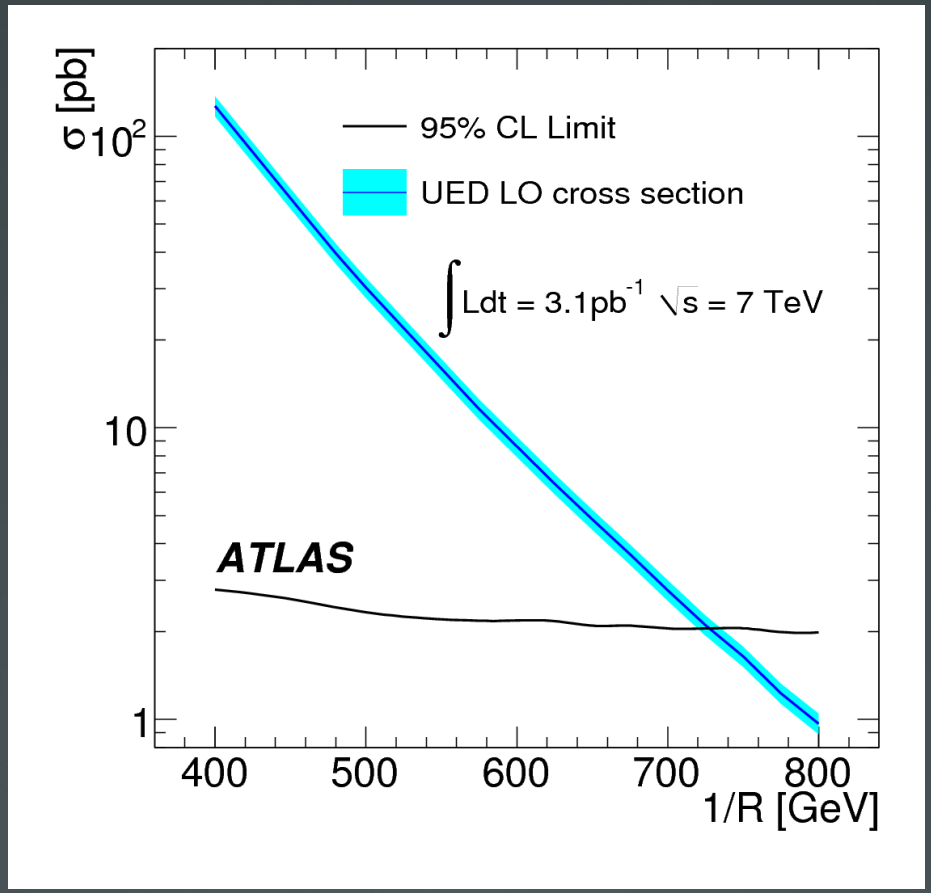




Di-Photons (UED)

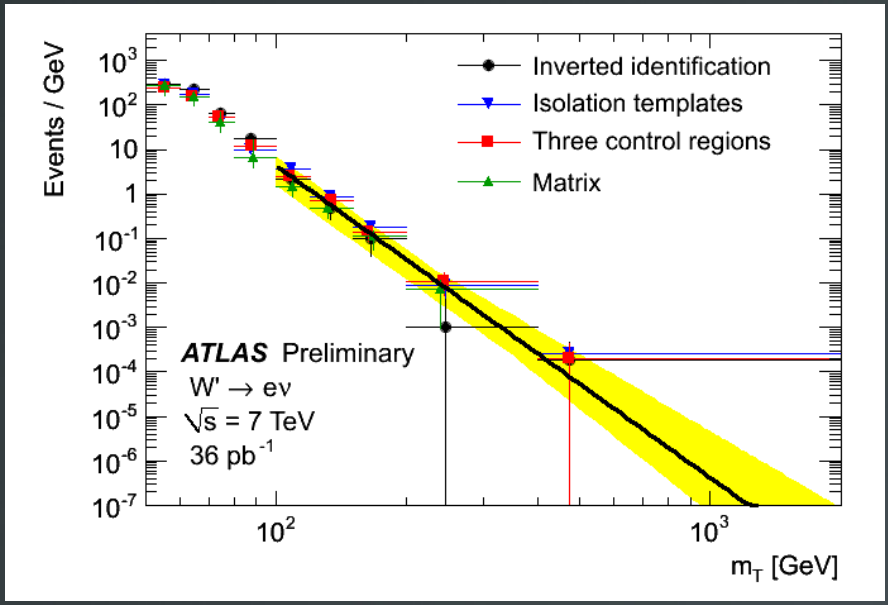


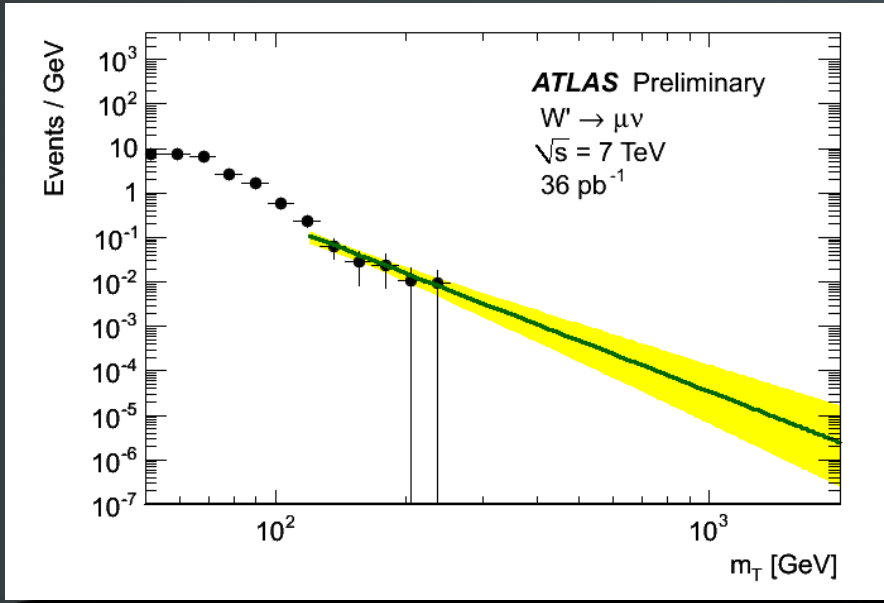
Leading photon transverse mass



W' Analysis

Data-driven QCD background estimates (electron and muon channels)

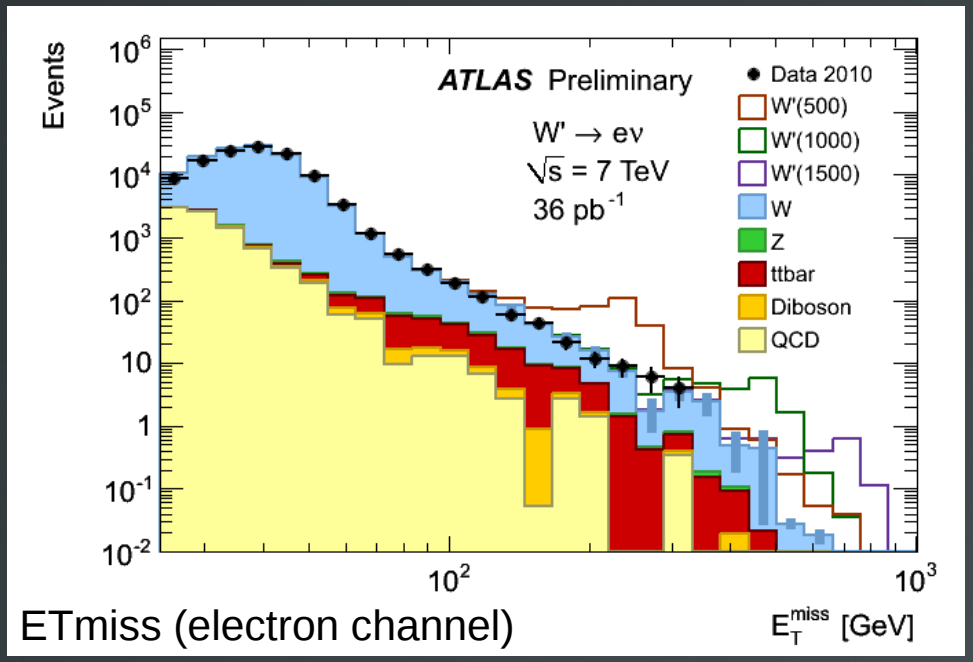




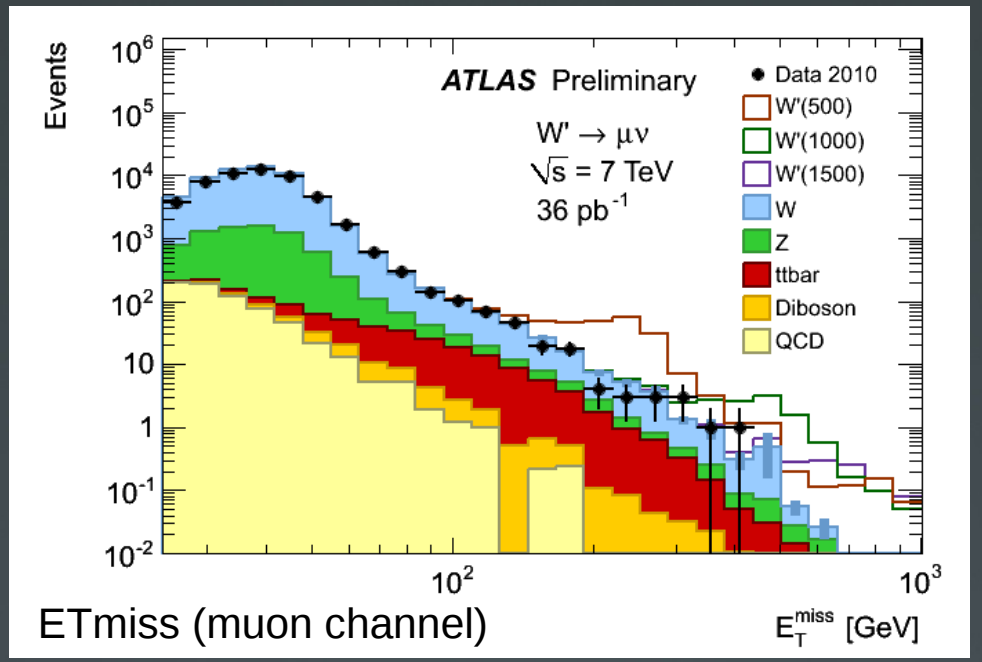
Uncertainty on efficiency and background estimation for W' with mass 1500 GeV

Source	$\varepsilon_{\mathrm{sig}}$ $e\nu$	$\varepsilon_{\mathrm{sig}}$ $\mu\nu$	N_{bg} $e\nu$	N_{bg} $\mu\nu$
Missing E_{T} scale	0.1%	0.1%	1.1%	**3.4%**
Trigger efficiency	**1.0%**	**0.7%**	1.0%	0.7%
Reco. and id. efficiency	**3.6%**	**1.6%**	**3.6%**	1.3%
Isolation leakage	**2.7%**		**3.4%**	
Energy/momentum resolution	0.1%	0.4%	2.4%	**3.1%**
Energy/momentum scale	**0.8%**	0.1%	**6.6%**	0.1%
Correlated misalignment		0.6%		**3.3%**
QCD background			2.2%	**7.7%**
Monte Carlo statistics	**1.7%**	**1.6%**	2.2%	**16.6%**
Cross section (shape/level)	**0.7%**	**0.7%**	**8.5%**	**7.7%**
Isolation	**1.5%**	**1.5%**	1.0%	1.0%
Other	0.2%	0.4%	0.4%	0.9%
All	5.3%	3.0%	12.6%	20.7%

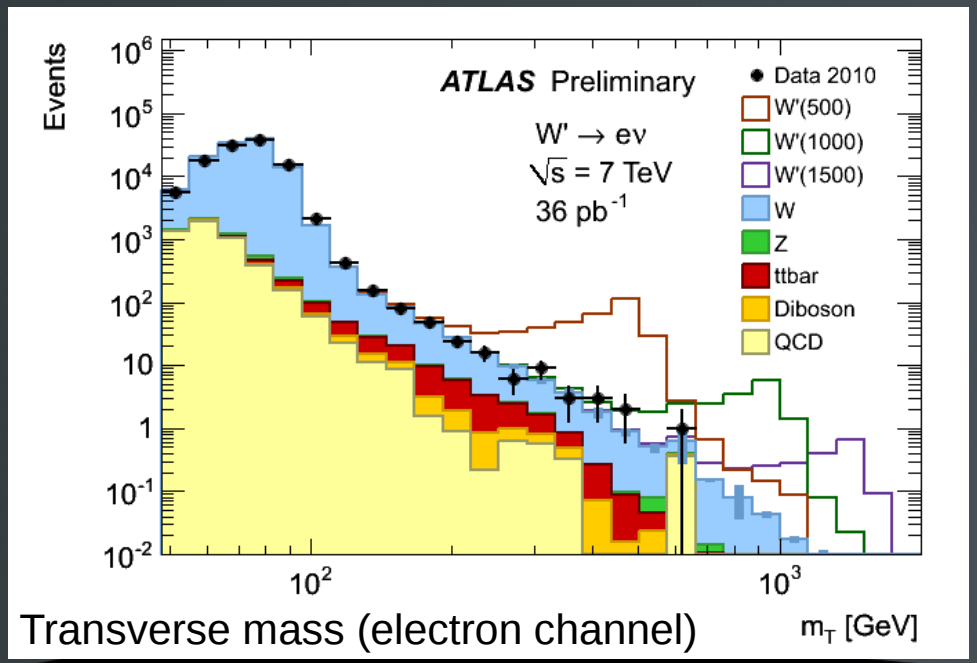
W' Analysis



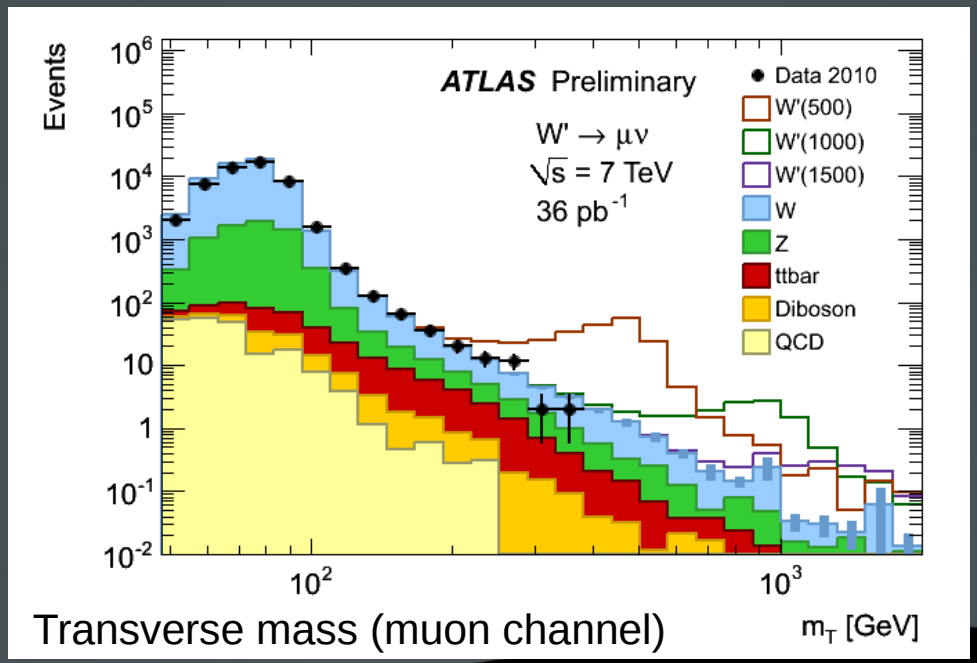
ETmiss (electron channel)



ETmiss (muon channel)



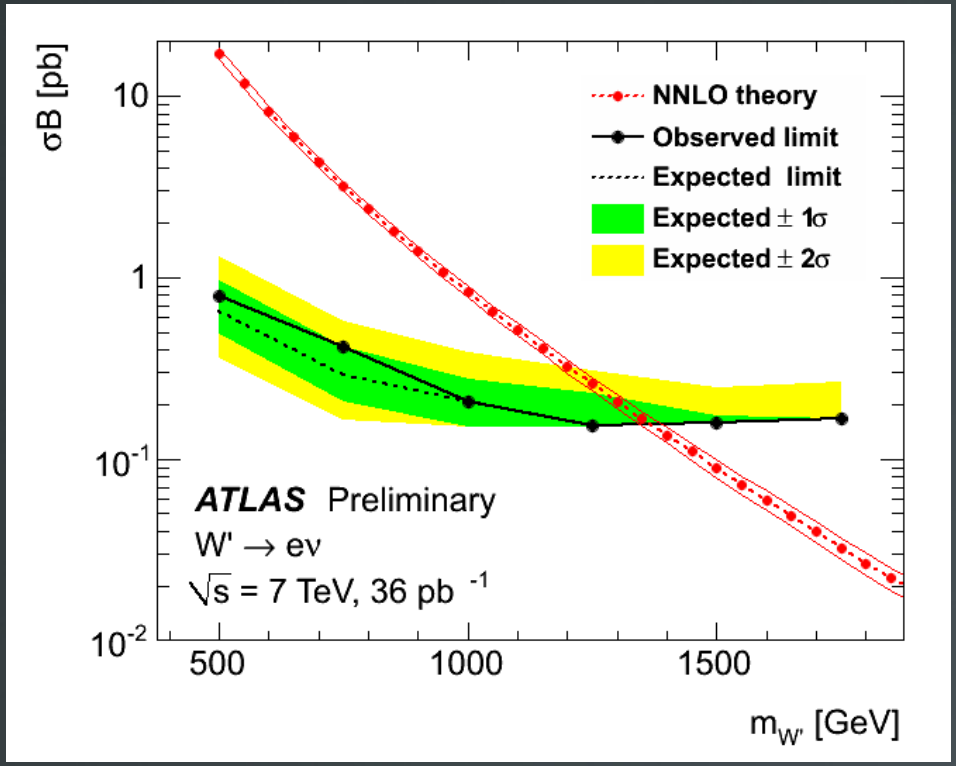
Transverse mass (electron channel)



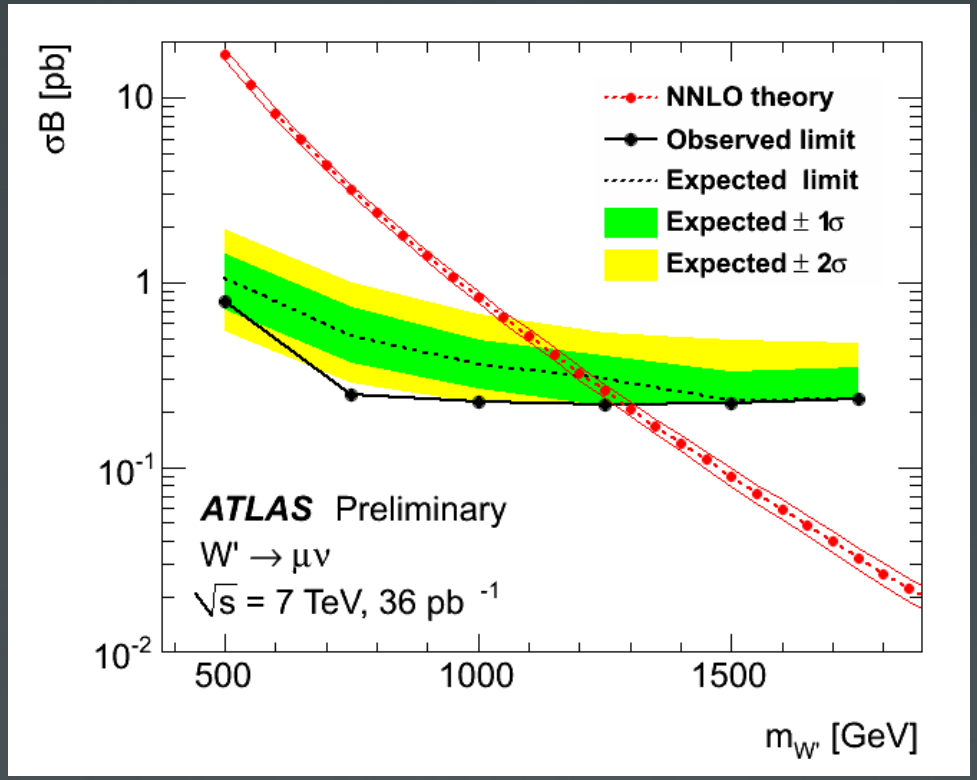
Transverse mass (muon channel)

W' Analysis

Limit on W' (electron channel)

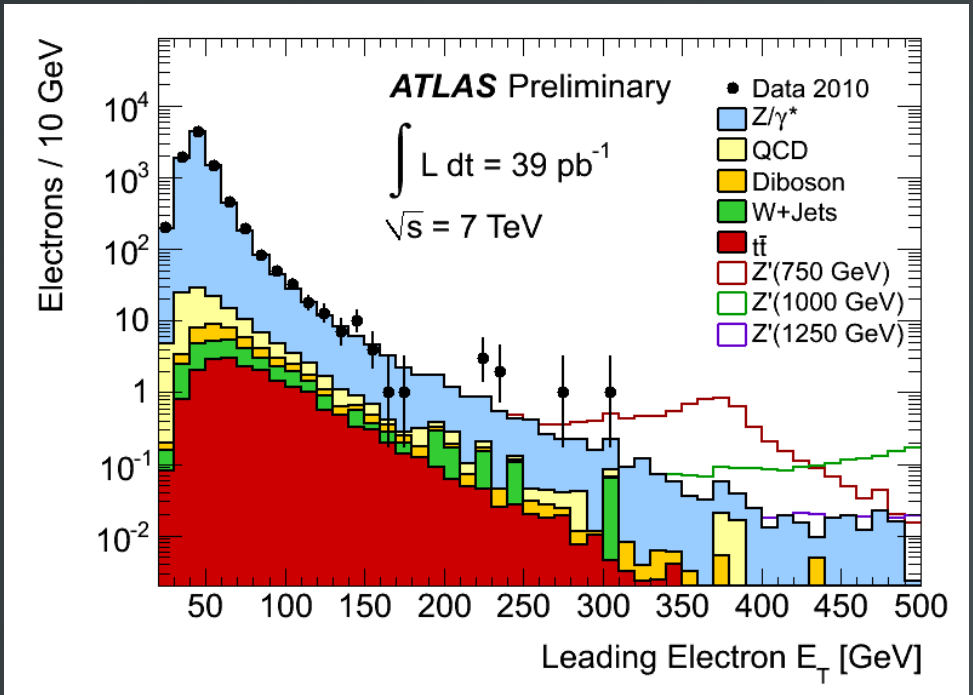


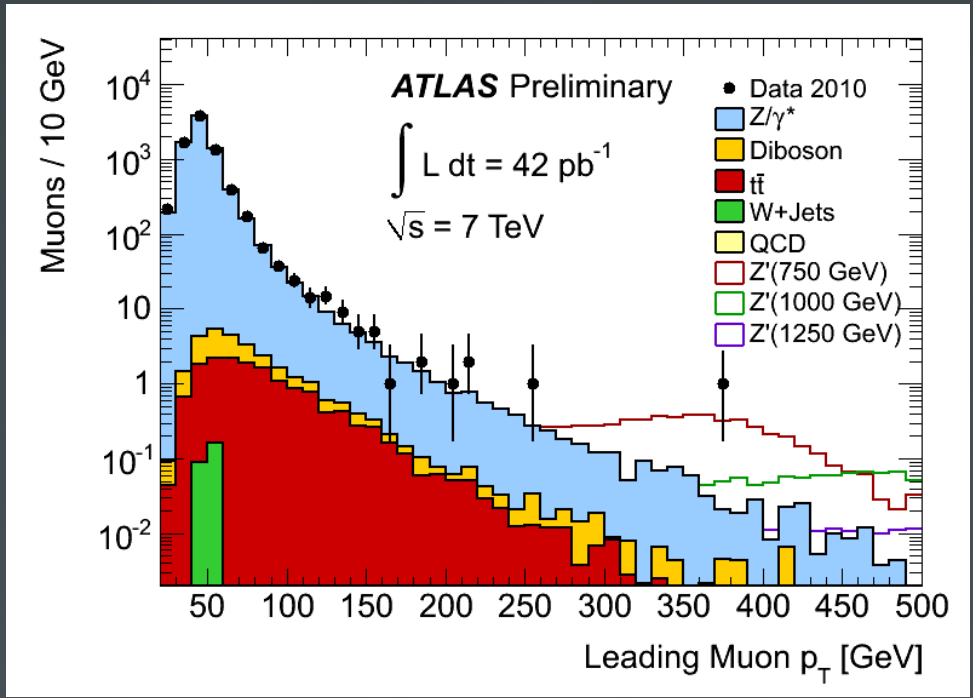
Limit on W' (muon channel)



Z' Analysis

- No evidence of peak: p-value = 0.08 (electron), 0.17 (muon)
- Kinematic variables:





Uncertainties as 1 TeV:

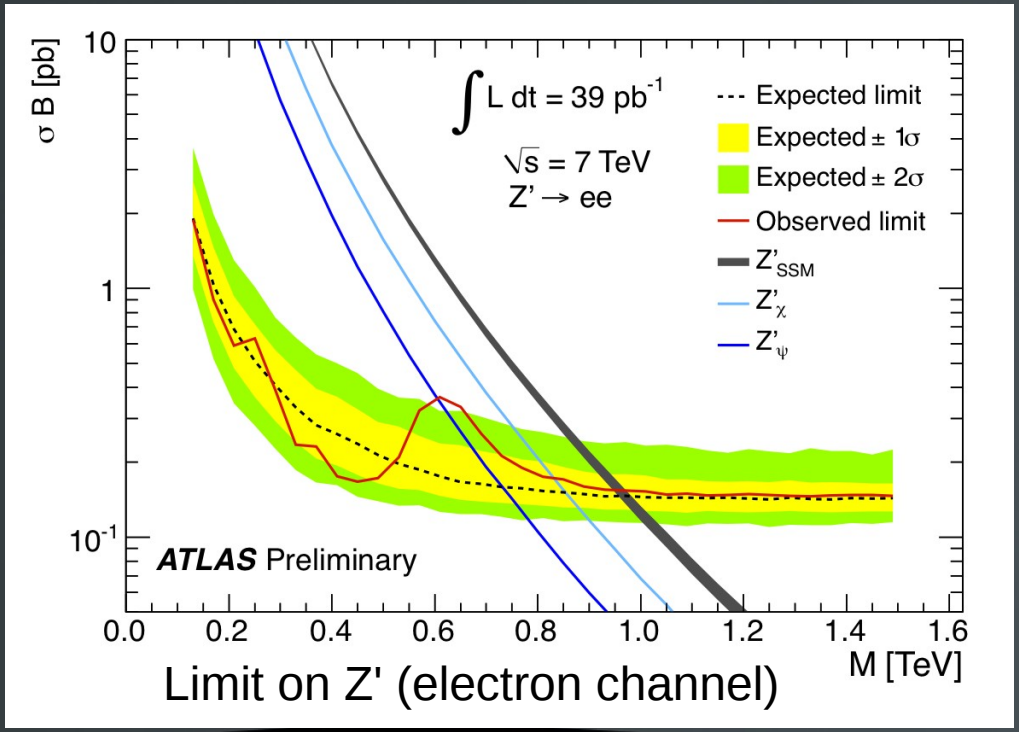
Source	dielectrons		dimuons	
	Z' signal	background	Z' signal	background
Normalization	5%	5%	5%	5%
PDFs	6%	6%	6%	6%
QCD K-factor	3%	3%	3%	3%
Weak K-factor	NA	4.5%	NA	4.5%
Efficiency	-	-	3%	3%
Resolution	-	-	3%	3%
Total	9.4%	9.5%	9.4%	10.4%

Z' Analysis

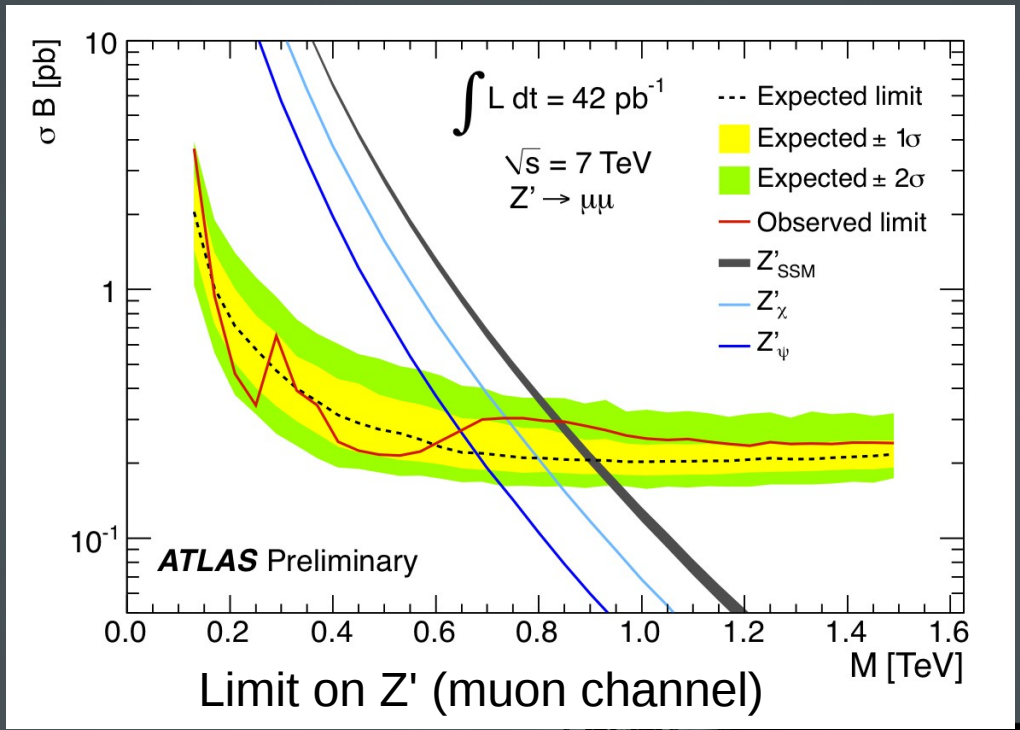
- E6 Model: $SO(10) + U(1)_\psi \rightarrow SU(5) + U(1)_\chi + U(1)_\psi$ … $Z'(\theta) = Z'_\psi \cos(\theta) + Z'_\chi \sin(\theta)$
  - θ = mixing angle in lightest linear combination between neutral bosons Z'_ψ and Z'_χ
  - 6 models lead to specific Z' states: Z'_ψ Z'_N Z'_η Z'_I Z'_S and Z'_χ

- Limits (95% C.L.):

	Observed limit		Expected limit	
	mass [TeV]	σB [pb]	mass [TeV]	σB [pb]
$Z'_{SSM} \rightarrow e^+e^-$	0.957	0.155	0.967	0.145
$Z'_{SSM} \rightarrow \mu^+\mu^-$	0.834	0.297	0.900	0.201
$Z'_{SSM} \rightarrow \ell^+\ell^-$	1.048	0.094	1.088	0.081



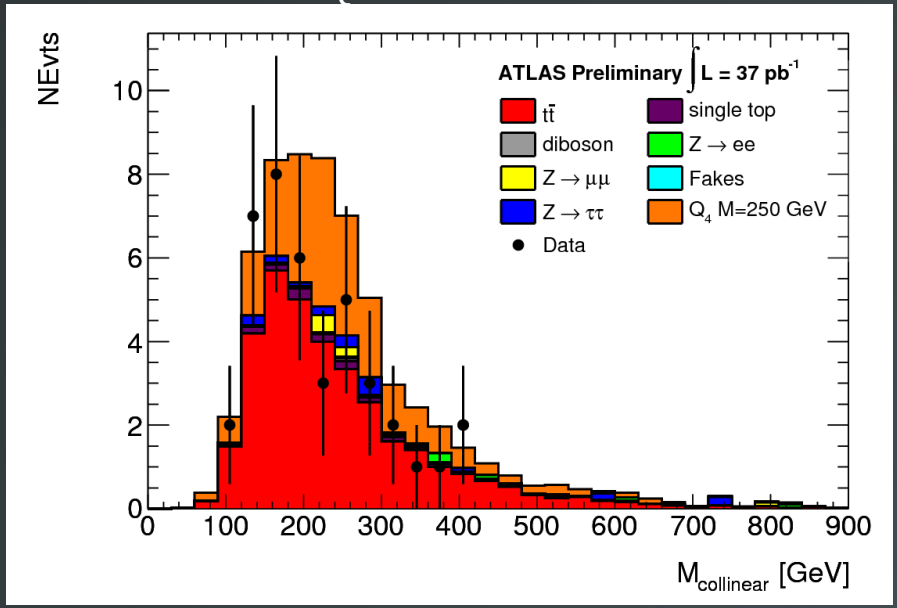
Limit on Z' (electron channel)



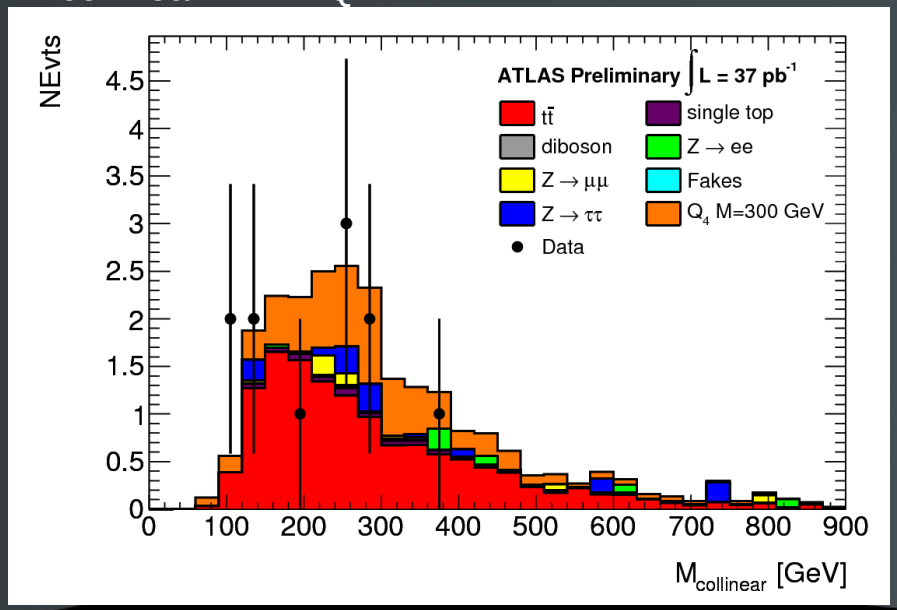
Limit on Z' (muon channel)

4th Generation Quark Search

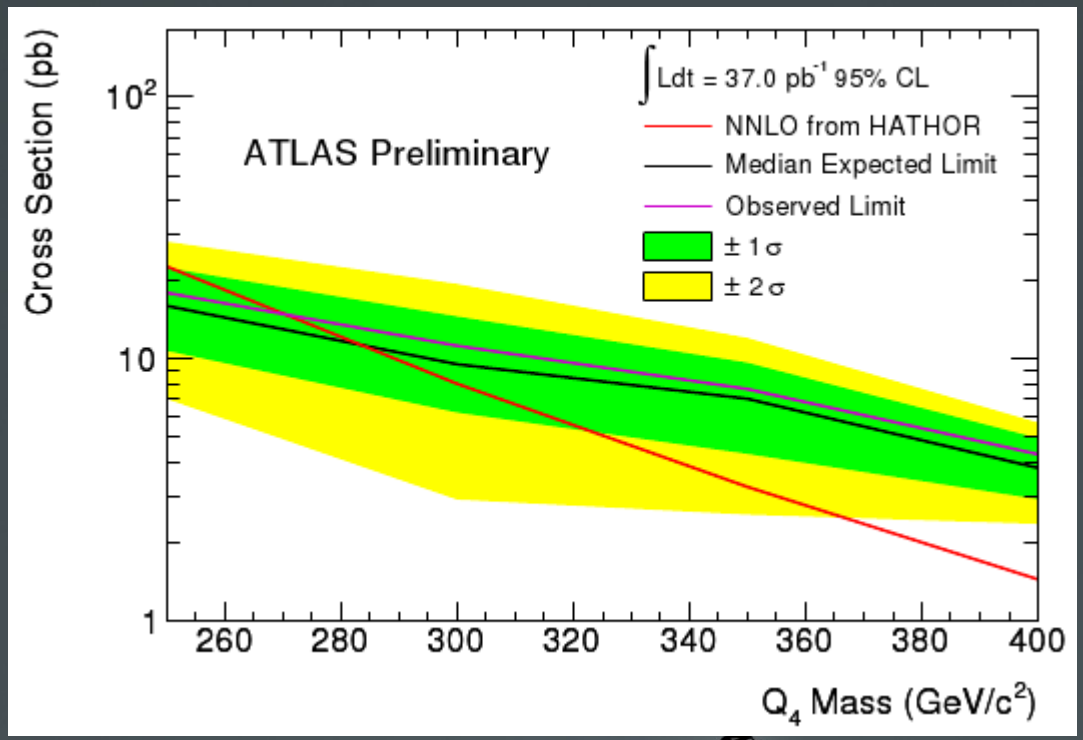
$M_{collinear}$ for M_{Q4} = 250 GeV



$M_{collinear}$ for M_{Q4} = 300 GeV



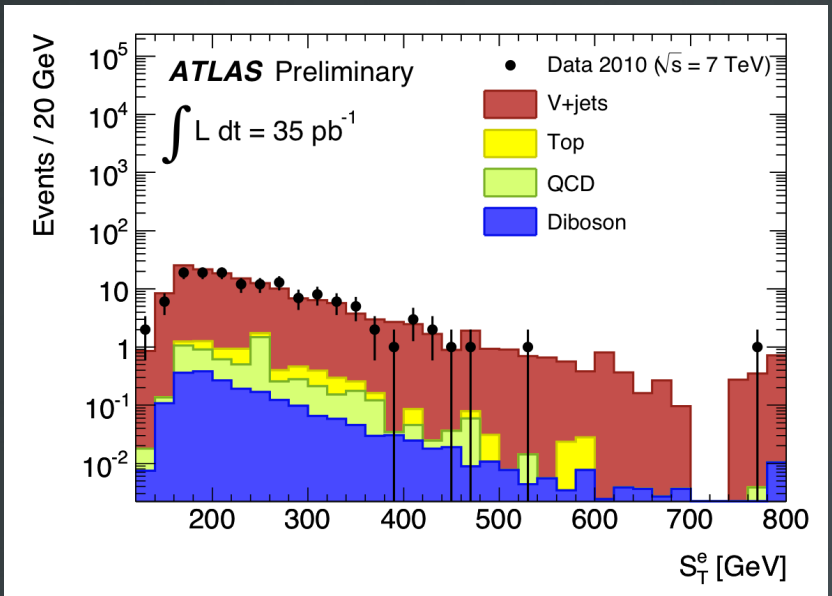
Limit on M_{Q4}:



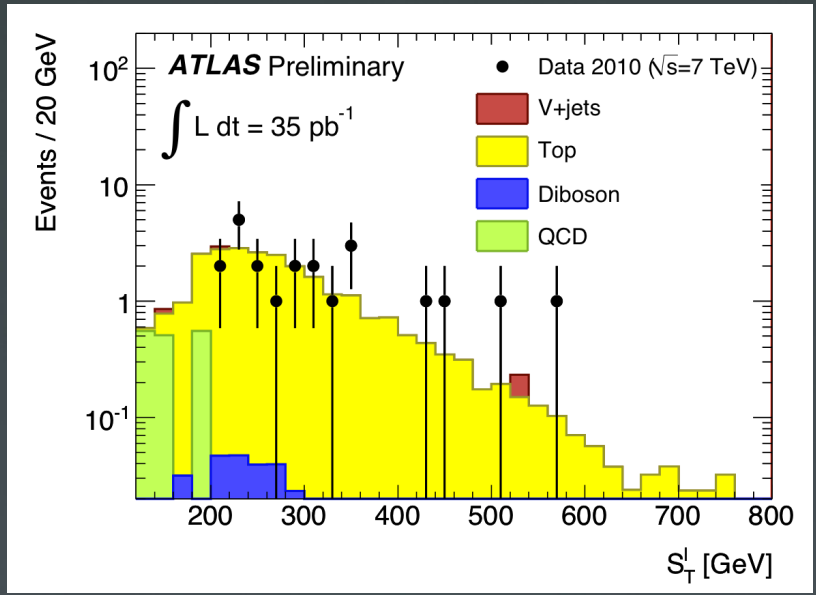
Background determination

Leptoquarks

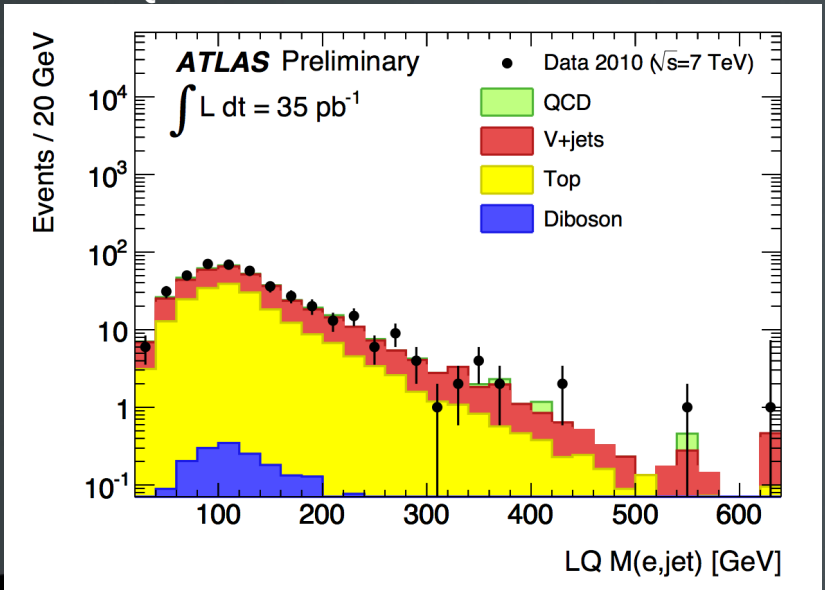
S_T distribution in the Z control region (e channel)

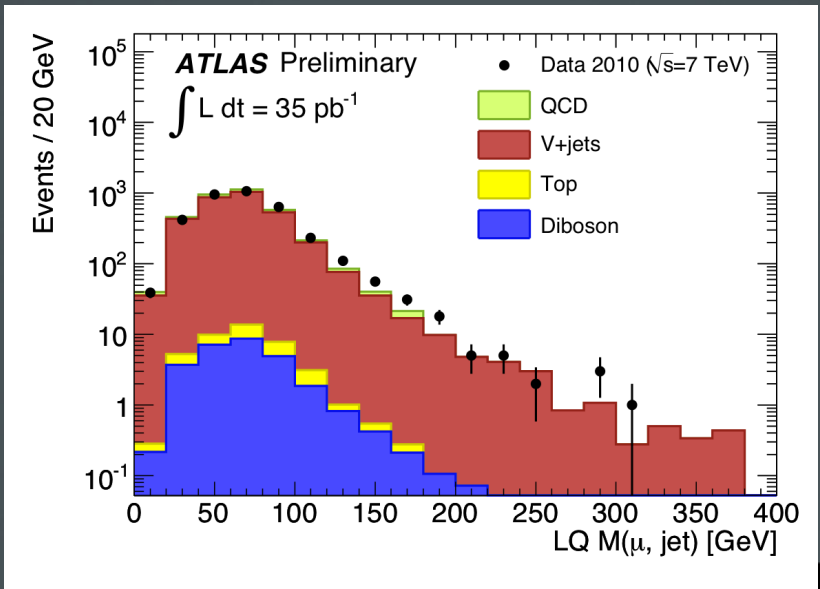


S_T distribution in the ttbar control region



M_{LQ} distributions in the W+j (e channel) and ttbar (mu channel) control regions



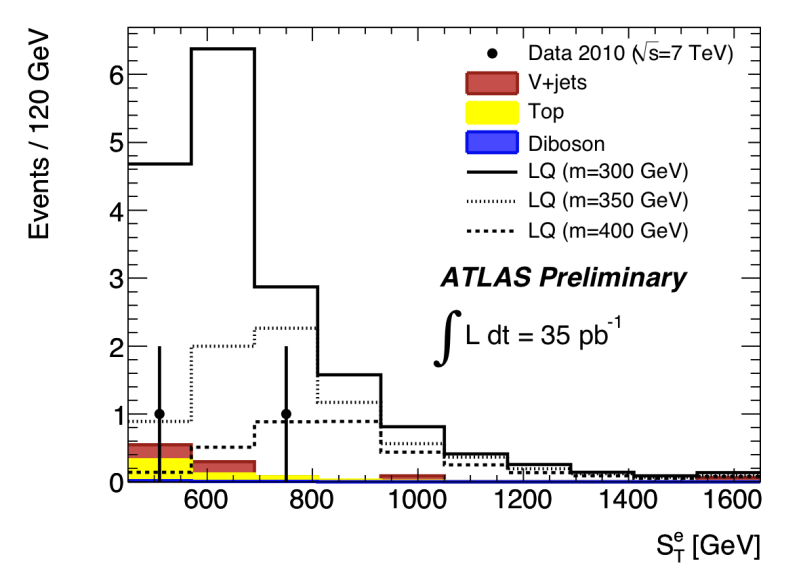


Leptoquarks

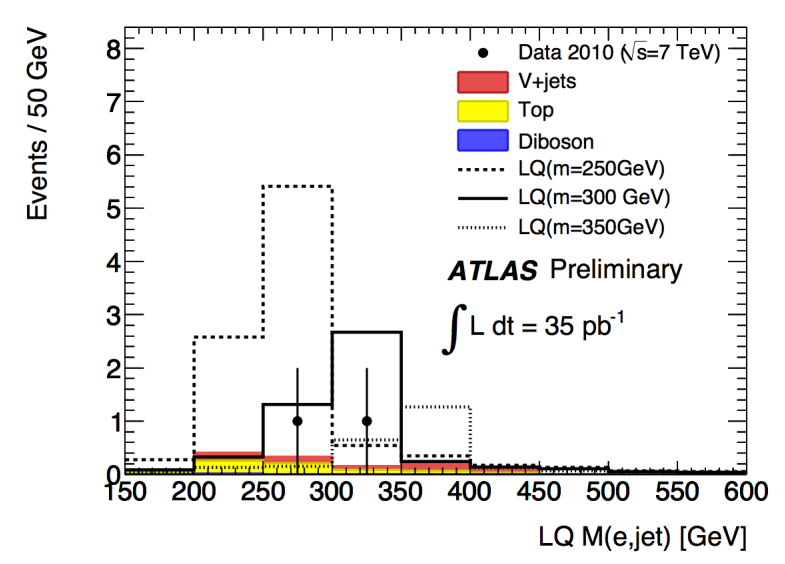
Signal regions:

1st Generation:

eejj

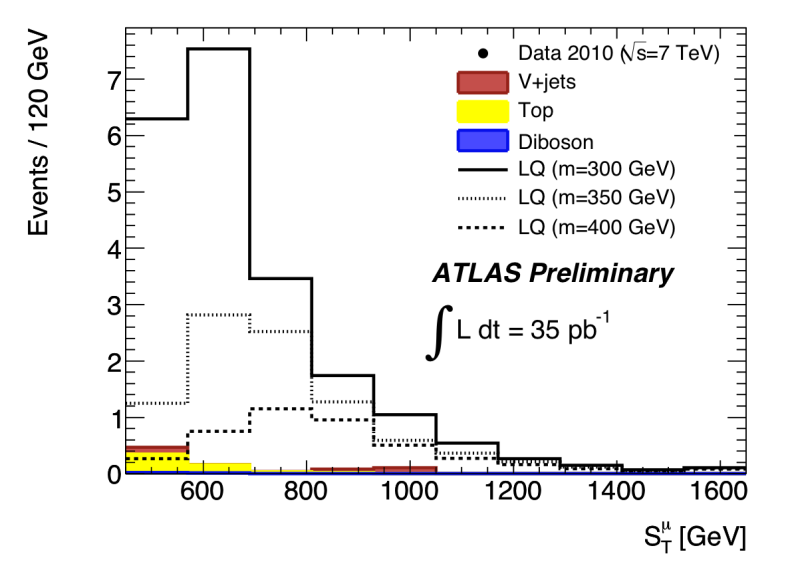


evjj

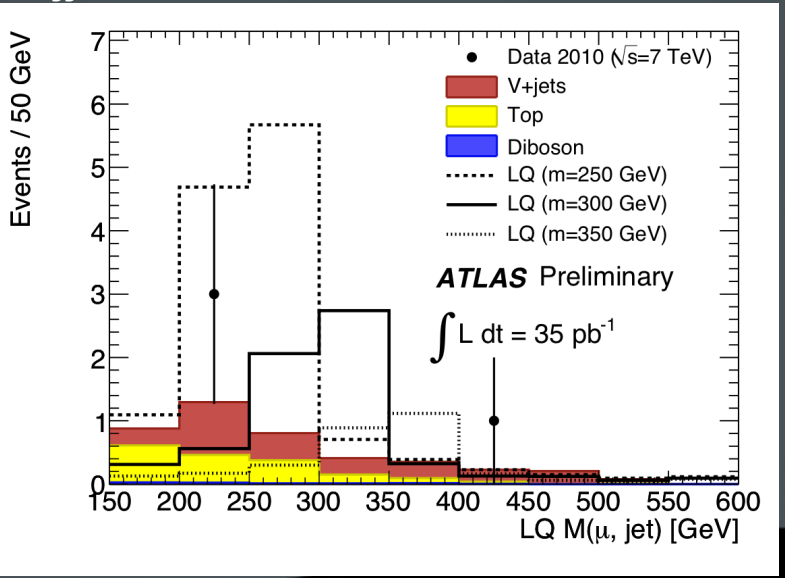


2nd Generation:

μμjj

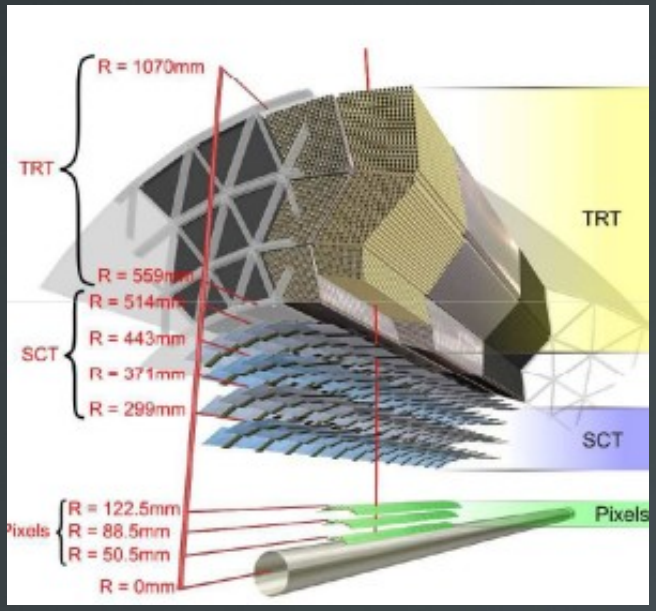


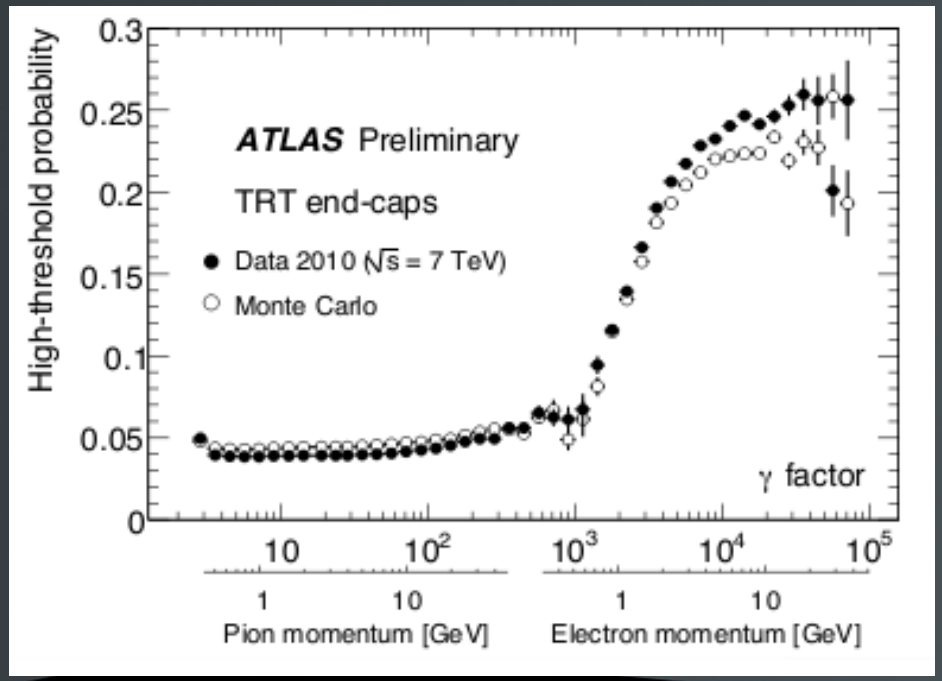
μνjj



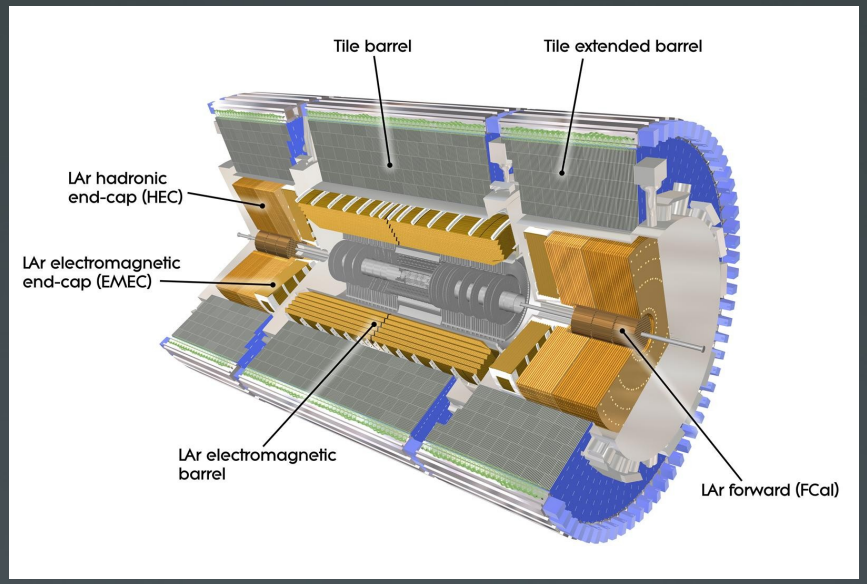
Long-Lived HIP Analysis

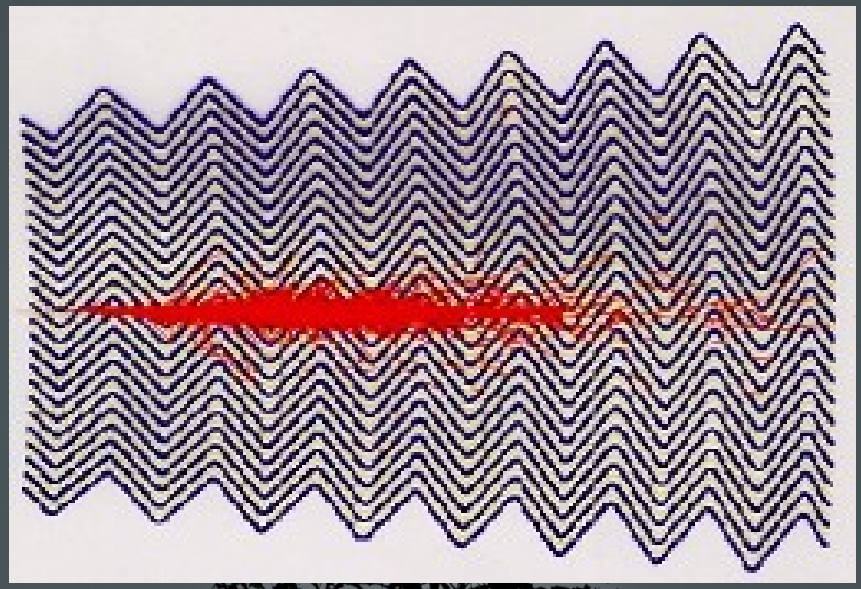
- Transition Radiation Tracker



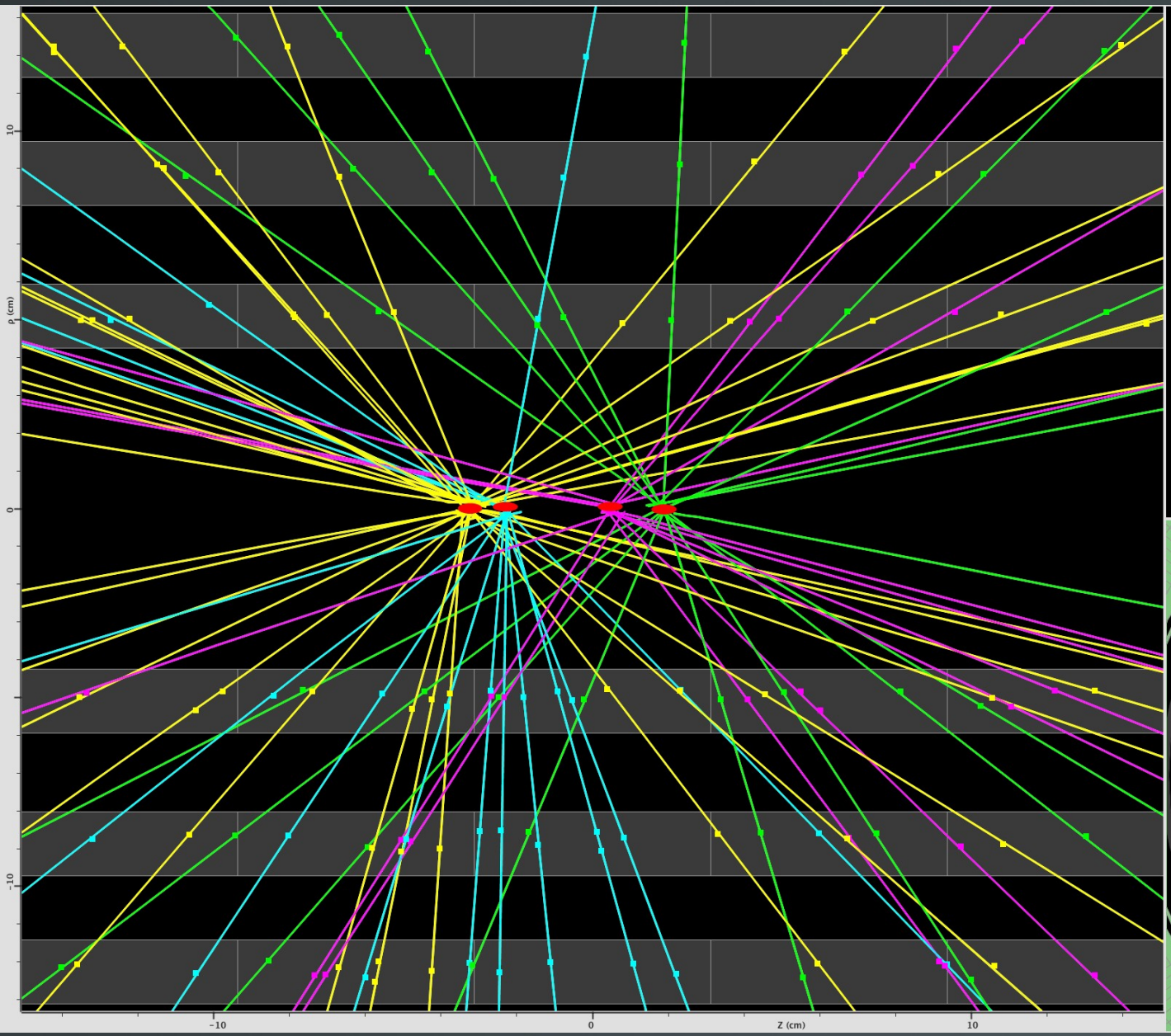


- EM Calorimeter





Pileup – Multiple Vertices



ATLAS EXPERIMENT

Run Number: 153565, Event Number: 4487360

Date: 2010-04-24 04:18:53 CEST

Event with 4 Pileup Vertices in 7 TeV Collisions