Boosted Tops at ATLAS

(a summary of public ATLAS prospects and results)

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for ATLAS collaboration

IoP Half-Day

QMUL

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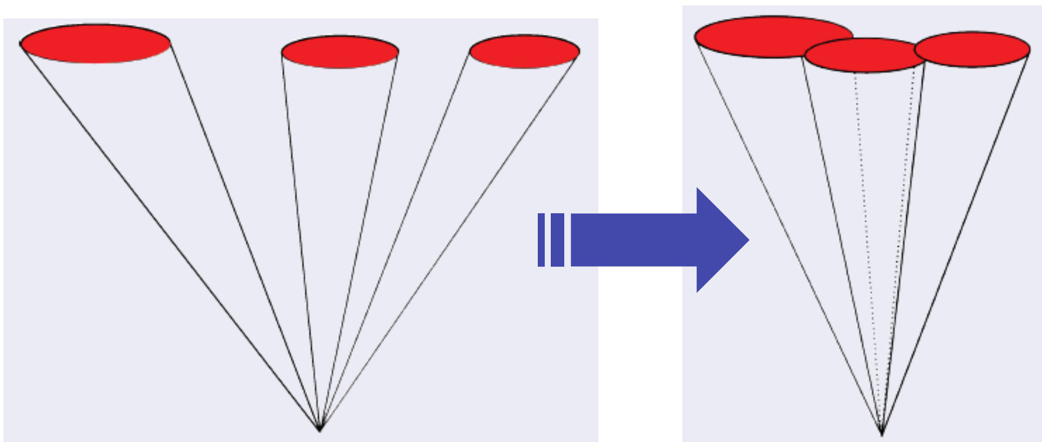
Outline

- Why boosted tops?
  - An introduction
- Boosted top prospects at ATLAS
  - MC studies for resonances (ATL-PHYS-PUB-2010-008, 16/7/10)
- Where we are with current data?
  - Jet substructure (SM note out just today, so plots from Twiki: AtlasPublic/JetEtmissApproved2010JetPropertyPlots, 5/2/11)
  - Resolved ttbar resonances (ATLAS-CONF-2011-070, 6/5/11)
- Conclusion
- Backup
  - CDF boosted top search
  - CMS jet substructure for top-tagging
  - CMS ditop search in 2010 data

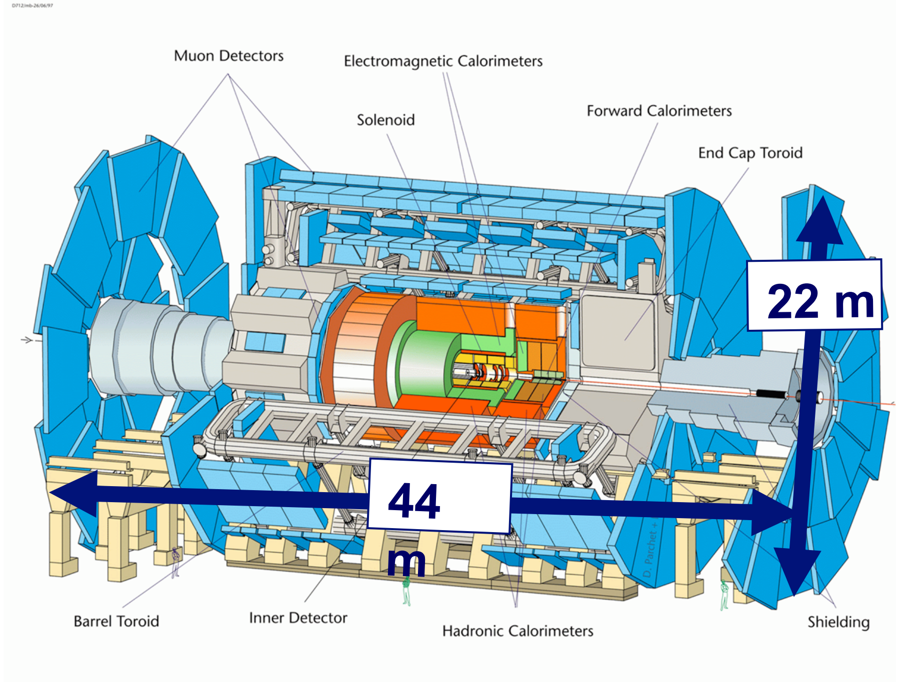
What is Boost?

- LHC is a heavy and boosted object factory!
- Sources and reasons:
  - Something heavy (e.g. Z') decays to something lighter (t,W/Z,H,. . .), which is then naturally boosted
  - A new light particle (H, χ^0, . . .) emerges more clearly above backgrounds when produced boosted
- Signatures:
  - Merged/collimated decay products, large displaced vertices, ...
- Concerns:
  - Standard algorithms may fail, background estimation



Boosted Objects in the ATLAS Detector

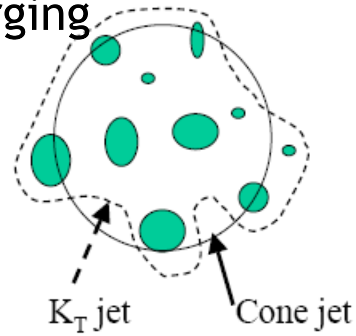
- ATLAS is well-prepared for boosted objects
  - High granularity calorimeter and precision tracking to exploit new techniques for efficient reconstruction
- An interplay between BSM (massive objects) and SM (jet substructure and QCD) groups -> QCD for BSM
- ATLAS has a boosted objects group



Boosted Jet Techniques

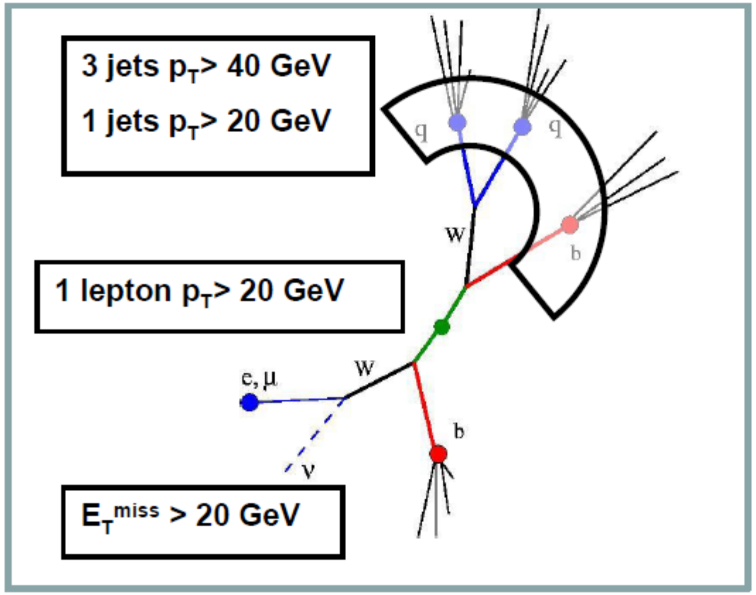
- Reminder: ATLAS jet finding default is anti-k_T (R=0.4 or 0.6)
  - Infra-red safe and considered robust against noise, etc..
- For a parent with m and p_T, merging starts showing at $R > 2m/p_T$
  - Use **jet mass** for parent and **jet substructure** to resolve merging
  - Apply further **tagging** criteria
- Recombination algorithms favoured for jet substructure
- k_T algorithm:
  - recombination intrinsically **ordered in p_T** scale:

    $d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) * \Delta R_{ij}^2/R^2$
  - For subjet analysis, undo last merging:
  - Define y-value $y_n = d_{ij} / p_T^2$ (sometimes m^2) where d_{ij} is the k_T splitting level from the last (n-th last) merging
  - Get the y-scale at which the jet would split into 2 subjets.
- Cambridge/Aachen algorithm (C/A):
  - Similar to k_T but **ordering is in angles**, not p_T.
  - Clustering stops when all jets separated by a prescribed η-φ distance R

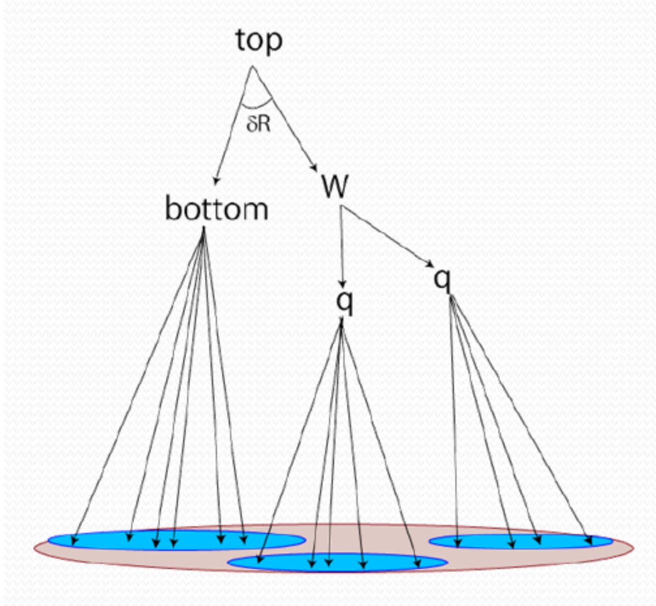


Boosted Top Quarks

- Top quark plays a special role in many EWSB BSM, due to $m_{top} \sim M_{EWSB}$
- LHC energy and luminosity: physics involving energetic tops in the final state possible
- ~15 % of pp -> tt events has at least one top quark with $p_T > m_{top}$
- At high top p_T, top may get reconstructed as one fat-jet (~75% within dR<0.4 for 1TeV top)



Standard semileptonic ttbar selection



Merged top jet in a single cone

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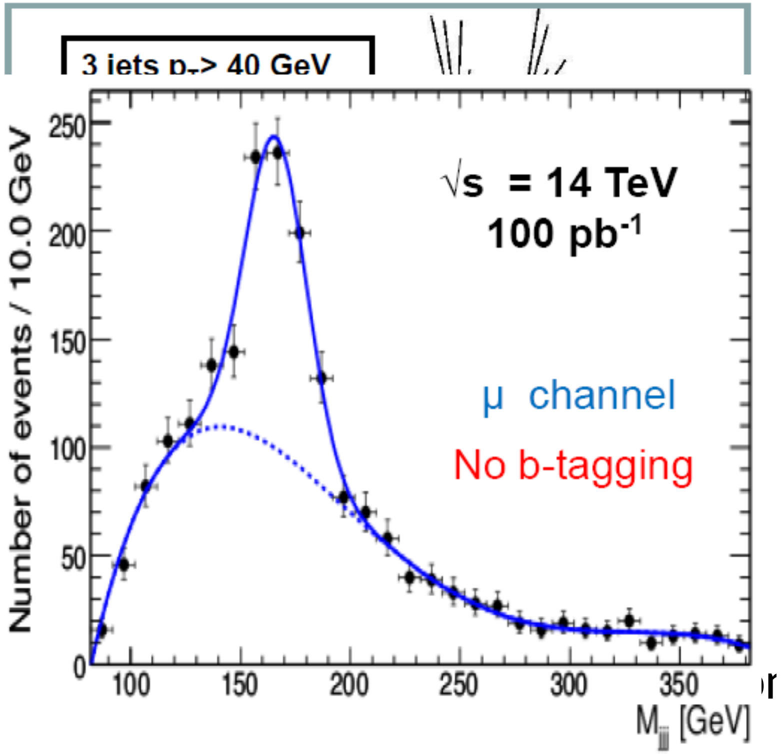
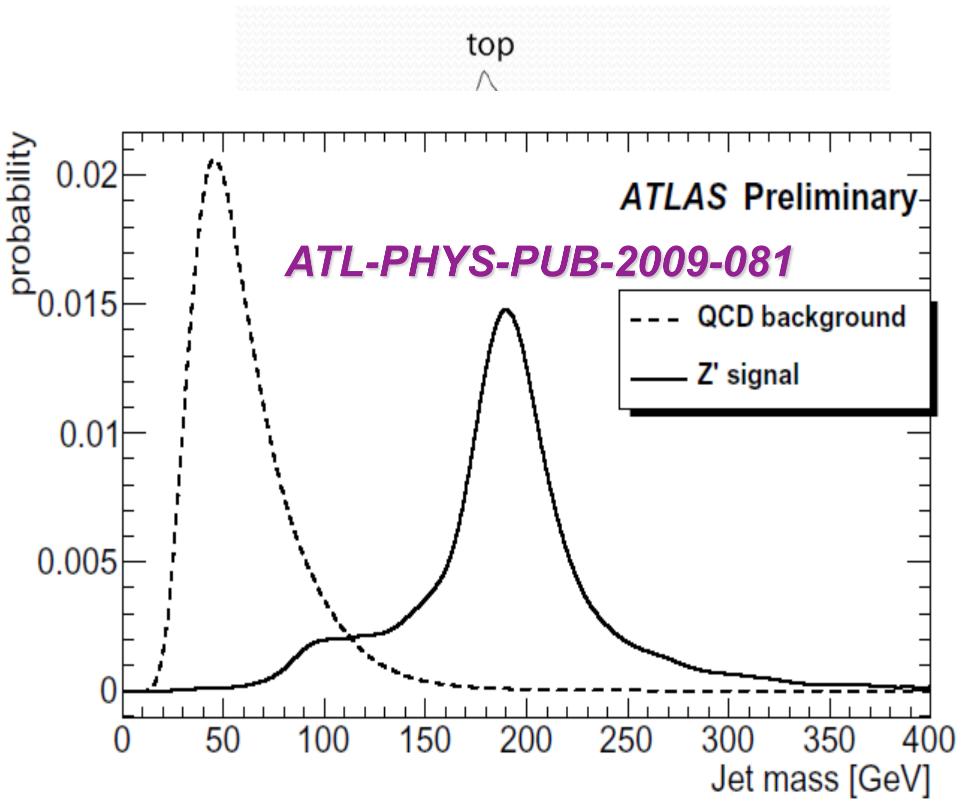
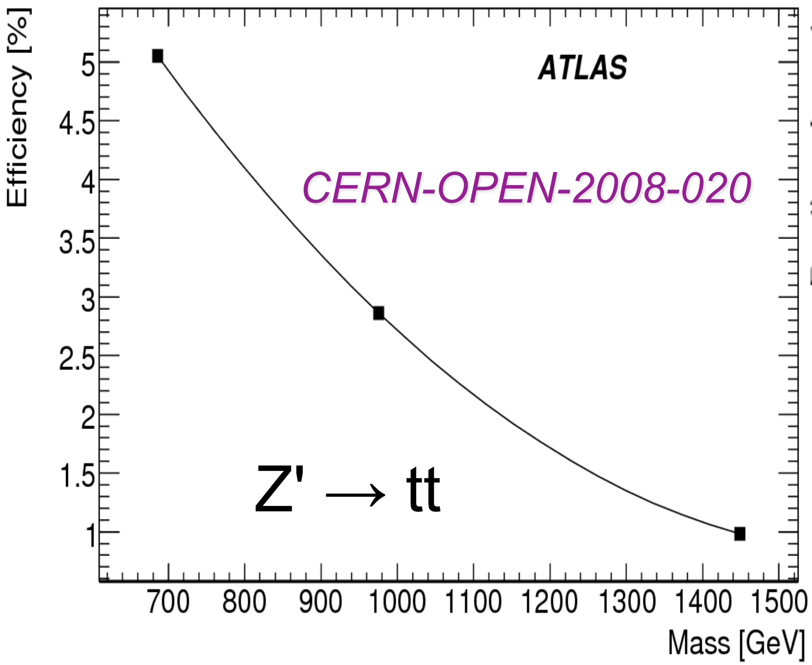


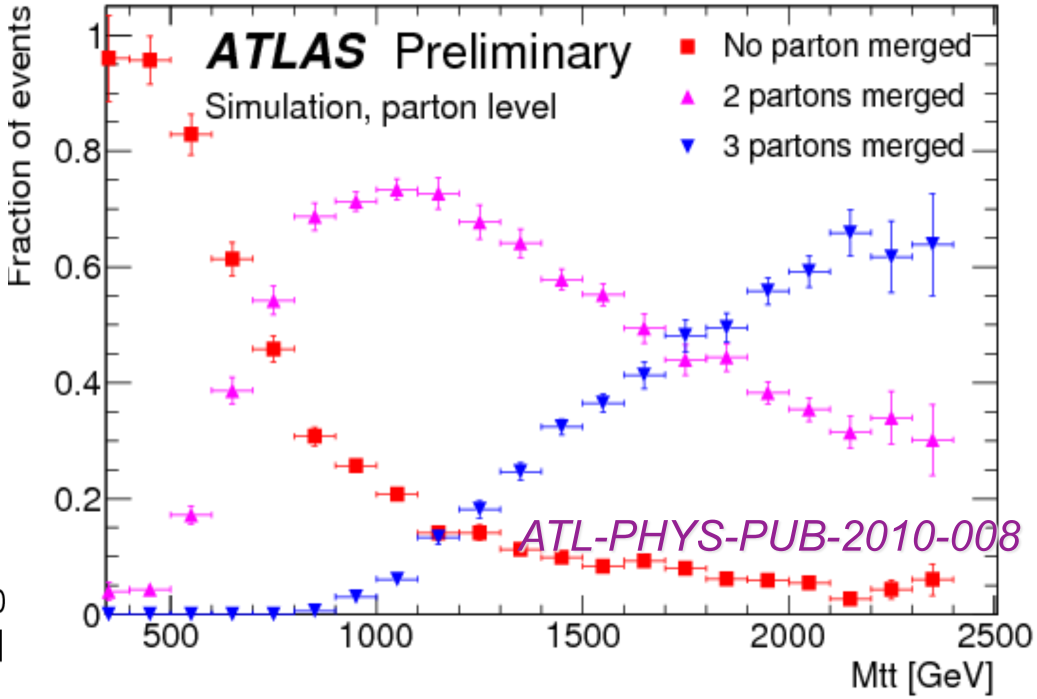
three jet mass



Why top-tagging?

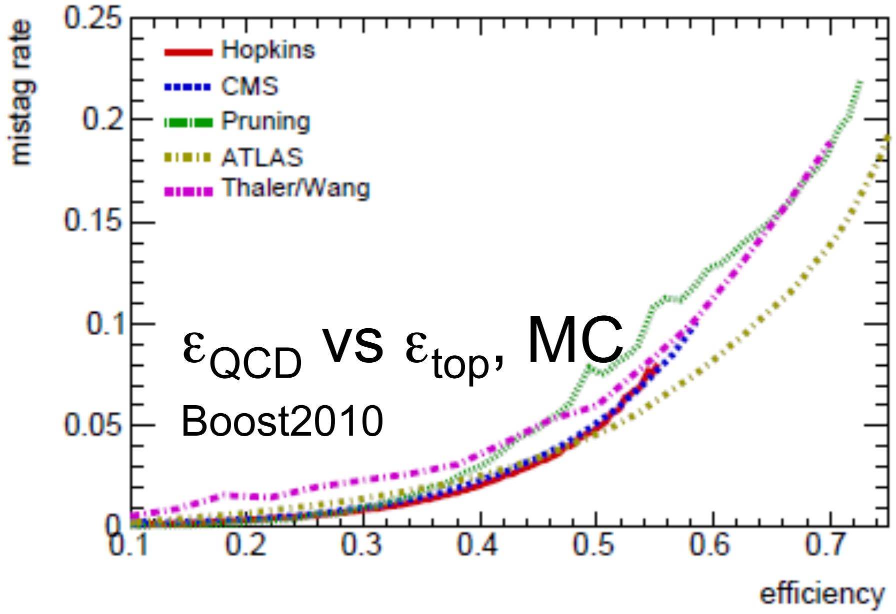
- A reason: In resolved approach (no partons merged) signal efficiency drops drastically at high mass.
- Restore this by using merged approach, i.e, looking for top fat mono-jets





Top-tagging

- Various "top-tagging" techniques developed
- Boost2010 report for a performance comparison of most widely-used taggers and provide benchmarks.
  - Configure a number of popular taggers for optimal hadronic top-tagging performance at given target efficiency



(a) all p_T samples

For more on boosted tops, see Boost2010 report ***arXiv:1012.5412***

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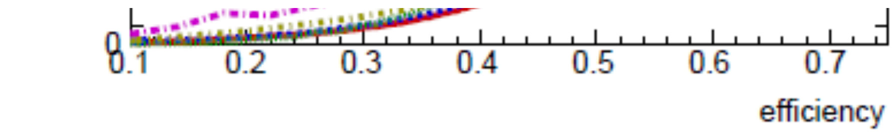
G. Salam (2010)

Rough results for top quark with $p_t \sim 1$ TeV

	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans '08	3,4 k_t subjets, d_{cut}	45%	5%
Thaler & Wang '08	2,3 k_t subjets, z_{cut} + various	40%	5%
Kaplan et al. '08	3,4 C/A subjets, $z_{cut} + \theta_h$	40%	1%
Ellis et al. '09	C/A pruning	10%	0.05%
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%
Chekanov & P. '10	Jet shapes	60%	10%
Almeida et al. '08–'10	Template + shapes	13%	0.02%
Plehn et al. '09–'10	C/A MD, θ_h/Dalitz [busy evs, $p_t \sim 300$]	35%	2%

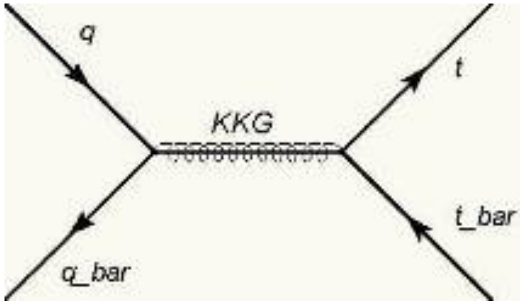


(a) all p_T samples

*For more on boosted tops, see Boost2010 report **arXiv:1012.5412***

Example BSM Boosted Top Quarks

- Resonance production
  - KK gluon from RS ED(M < 4 TeV)
    - advantage due to higher rates from strong coupling :σ=O(10pb), for M_{KKg} = 1 TeV
    - enhanced BR to tops → source of boosted tops
    - Broad resonances (width ~20% of mass)



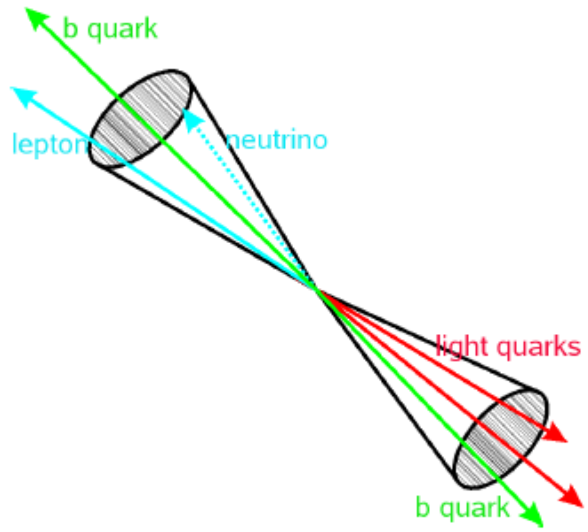
Les Houches 2009 BSM review
arXiv:1005.1229

- Also single t production with t,b,g ... association from W', excited strings, technicolor, ...

Resonances in semileptonic ditops - I

(ATL-PHYS-PUB-2010-008)

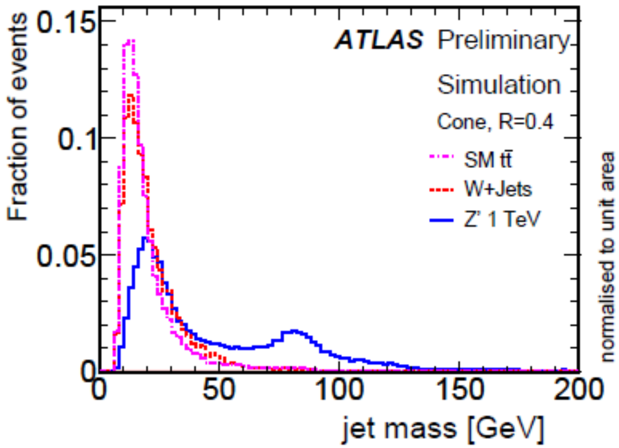
- Top pair resonances in semileptonic channel for fully-resolved, partially-merged and fully merged (mono-jet) events
- Here, concentrate on mono-jets, expected at M_{ditop} > 1.5 TeV
- Resonance signals (1 ≤ M ≤ 2 TeV):
  - Z': narrow, spin 1, colour singlet
  - RS graviton: narrow, spin 2, colour singlet
  - RS gluon: wide, spin 1, colour octet
- Use "top-tagging" for background discrimination
  - Hadronic top: a 3- prong fat jet with substructure
  - Leptonic top: a merged lepton + a b-quark



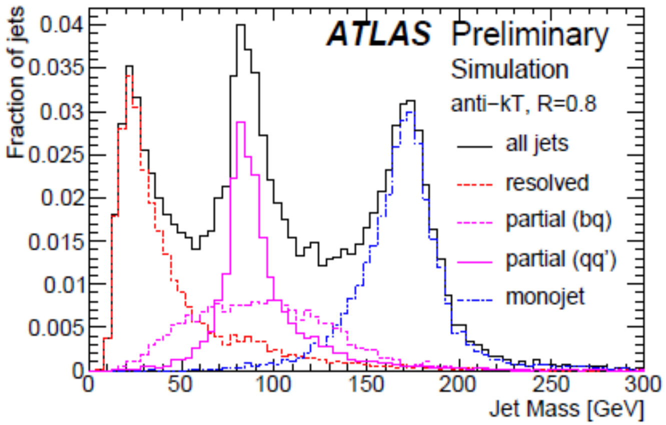
Resonances in semileptonic ditops - II

(ATL-PHYS-PUB-2010-008)

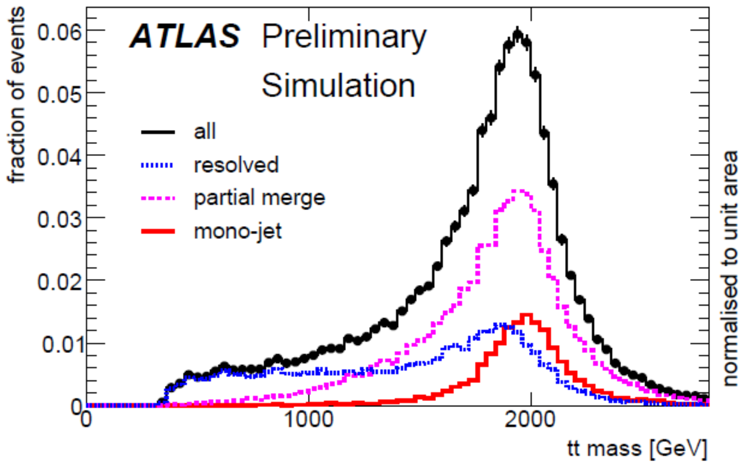
- Use a fat "mono-jet" to increase the yield of top quarks and resolution of resonances



(b)



(b) jet mass



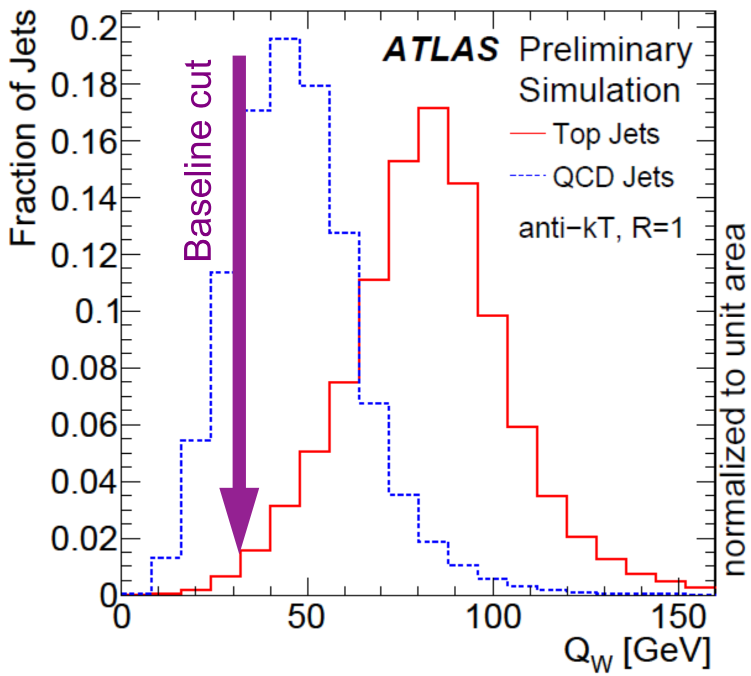
Resonances in semileptonic ditops - III

(ATL-PHYS-PUB-2010-008)

Hadronic top mono-jet reconstruction

- Anti-k_T jet algorithm (a large jet size of R =1.0)
- Procedure: Start with a fat-jet, split it and explore tagging variables for 3 subjet structure
  - Techniques avoid combinatorics, increase sensitivity and provide good performance down to ~ 1 TeV reach

- Tagging variables used:
  - Q_{jet} : mass of the hadronic top jet
  - z_{cut} : energy sharing between subjects
  - Q_W : invariant mass of the subjet pair with lowest mass, after splitting into 3 subjets



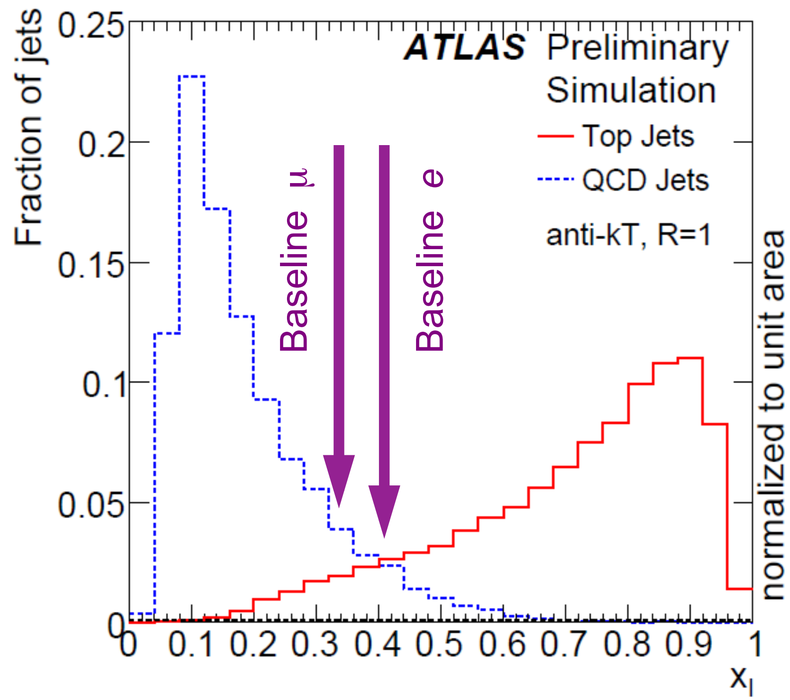
Resonances in semileptonic ditops - IV

(ATL-PHYS-PUB-2010-008)

Leptonic top reconstruction

- Search for a lepton (e or μ) and a jet (b-quark)
- Leptons define the trigger path
- Selection exploring variables for leptonic top structure

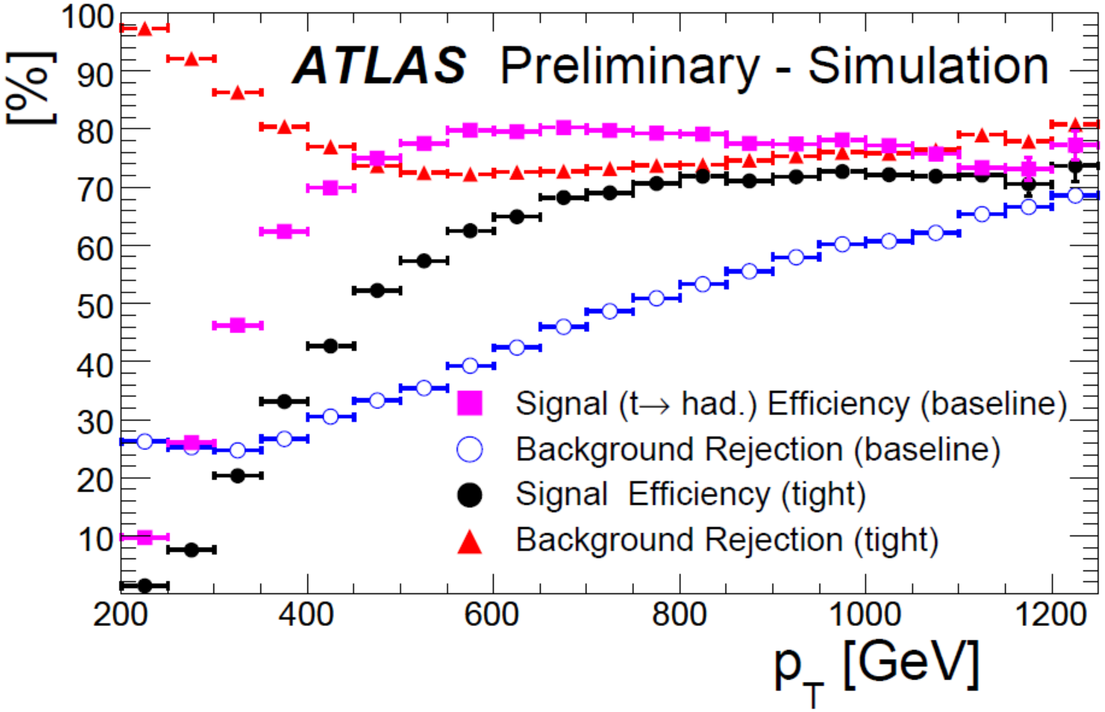
- Tagging variables used:
  - Q_{vis} : mass of the leptonic top jet
  - DR (l,j)
  - x_l: invariant mass carried by leptonic activity
  - $z_l = E_l / E_j$
  - iso - relative energy in a 0.2 cone around the lepton



Resonances in semileptonic ditops - V

(ATL-PHYS-PUB-2010-008)

Overall efficiency and rejection rates



Signal reconstruction efficiency & (QCD dijet) background rejection (*R* = 1−e) for hadronic top decay

Resonances in semileptonic ditops - VI

(ATL-PHYS-PUB-2010-008)

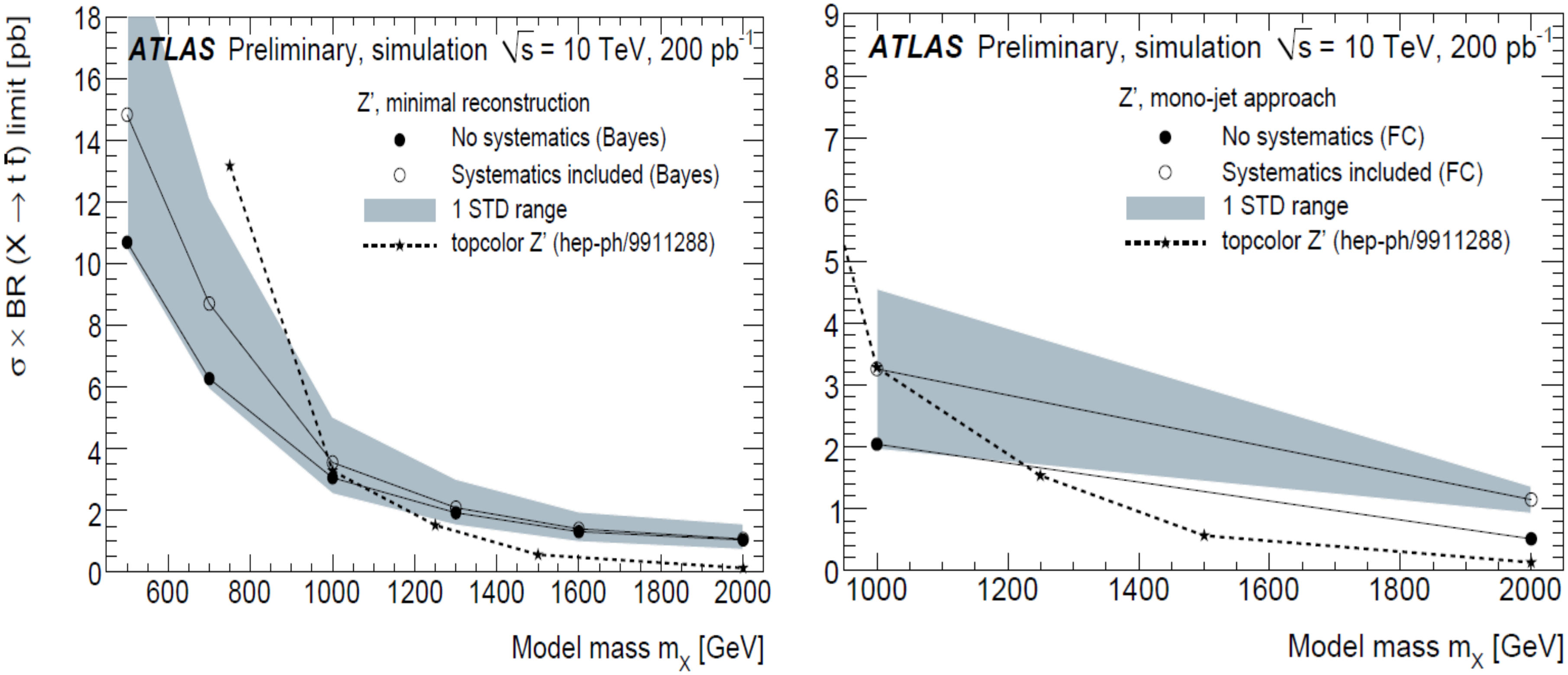
Benchmark signal efficiencies per reconstruction method

Table 5: Expected number of signal and background events, normalised to 200 pb^{-1} at 10 TeV. Events are counted in a ± 1 RMS range around the reconstructed signal mass peak. Reducible backgrounds include W+jets, Z+jets, single top and QCD di-jet production. For the full reconstruction approach, including b-tagging, the contribution from $Wb\bar{b}$ is taken into account. For the mono-jet approach, single top and Z+jets were ignored after earlier studies established that their contribution is negligible.

	minimal reconstruction					full reco.	mono-jet approach	
	3-jet low m_j	3-jet high m_j	4-jet	≥ 5 jets	all		baseline	tight
Z', $m = 1$ TeV, $\Gamma/m \sim 3.3$ %, $\sigma \times BR(X \to t\bar{t}) = 0.634$ pb								
$t\bar{t}$	322.8	41.3	442.4	215.5	1022	214.3	88.8	29.2
reducible bkg.	858	28	272	59	1217	9.9	22.5	2.8
Z'	4.13	2.26	4.18	1.92	12.5	3.36	6.4	2.9
signal eff.	6.0 %	3.3 %	6.1 %	2.8 %	18.2 %	4.9 %	9.3 %	4.3 %
S/B	0.003	0.033	0.006	0.007	0.006	0.015	0.049	0.091
Z', $m = 2$ TeV, $\Gamma/m \sim 3.3$ %, $\sigma \times BR(X \to t\bar{t}) = 0.0214$ pb								
$t\bar{t}$	51.2	6.11	38.3	25.3	121	15.6	9.7	4.4
reducible bkg.	278	16.7	66	22.2	394	3.0	14.2	1.6
Z'	0.046	0.14	0.13	0.0825	0.40	0.12	0.36	0.29
signal eff.	2.0 %	6.0 %	5.6 %	3.6 %	17.2 %	5.2 %	15.5 %	12.5 %
S/B	1.4×10^{-4}	0.006	0.001	0.002	8×10^{-4}	0.006	0.015	0.04

Prospective Limits on Z' from ditops

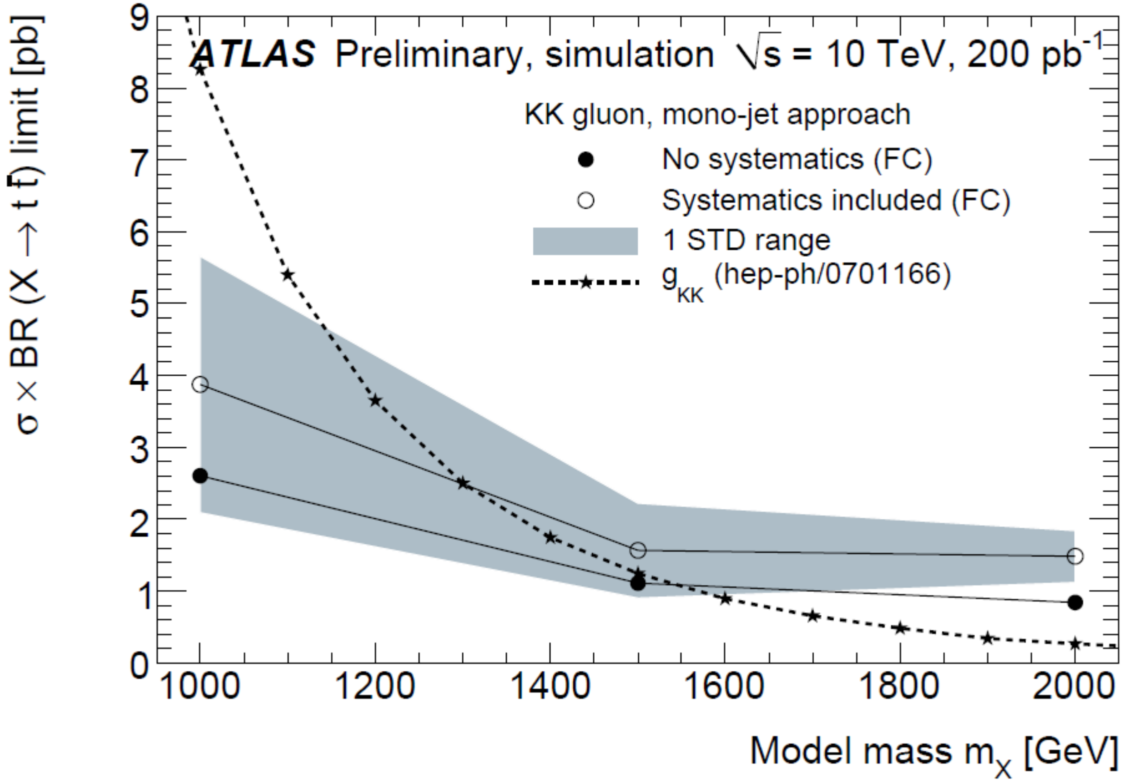
(ATL-PHYS-PUB-2010-008)



- New cross section limits for Z'-like resonances ~3 pb for M =1 TeV. Slightly better limits for spin-2 RS KK Gravitons
- A factor of ~2 increased sensitivity with mono-jets wrt minimal (ie no top reconstruction) for M= 2 TeV

Prospective Limits on KK Gluons from ditops

(ATL-PHYS-PUB-2010-008)

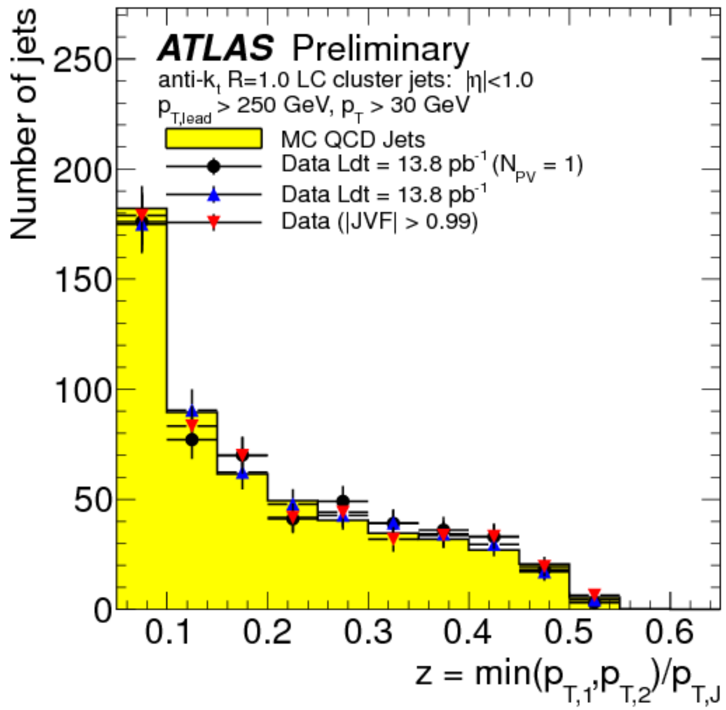


- Exclusion possible with 200 pb^{-1} @ 10 TeV for KK gluon at ~ 1 TeV mass.
  - compatible with 1 fb^{-1} @ 7 TeV

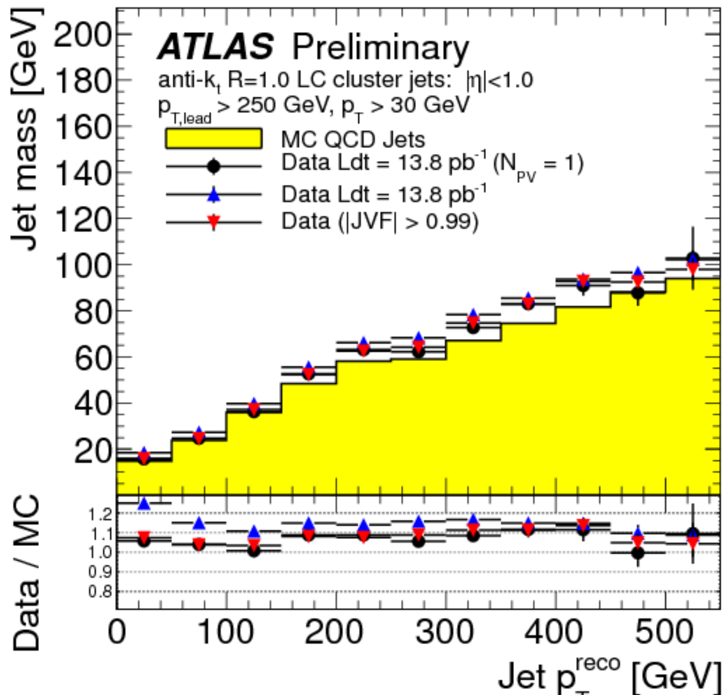
ATLAS Jet Substructure Measurements

(AtlasPublic/JetEtmissApproved2010JetPropertyPlots)

- Measure mass and substructure related quantities in QCD
- Crucial to get ready for boosted BSM analyses
- Jet mass sensitive to pile up (use track information)



pT ratio of 2nd hardest sub-jet (kT with R=0.3) to the parent jet (anti-kt with R=1.0) . Crucial parameter in “pruning”.



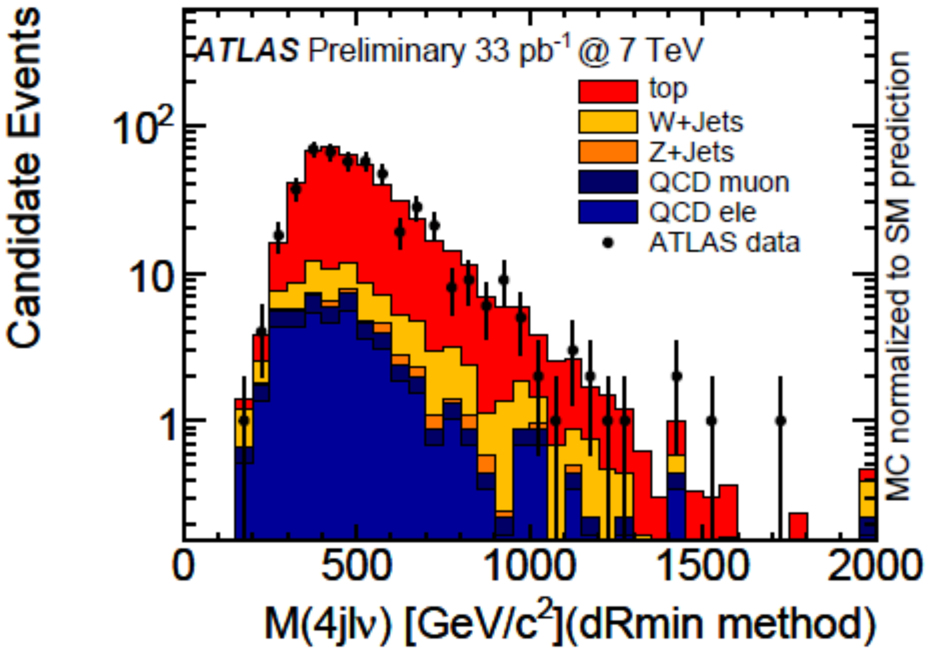
Mean jet mass as a function of pT. Prior to pile-up filtering using jet-ver tex fraction, mass ~ 10% higher than events with Npv=1. After JVF, agreement with Npv=1 events is < few %

Resolved ditop searches in 2010 data- I

(ATLAS-CONF-2011-070)

- ATLAS looked for anomaly in ditop spectrum in 2010 data with 33 pb^{-1}
- Simple whole mass reconstruction from semi-leptonic ditop products
- Follow top observation paper recipe

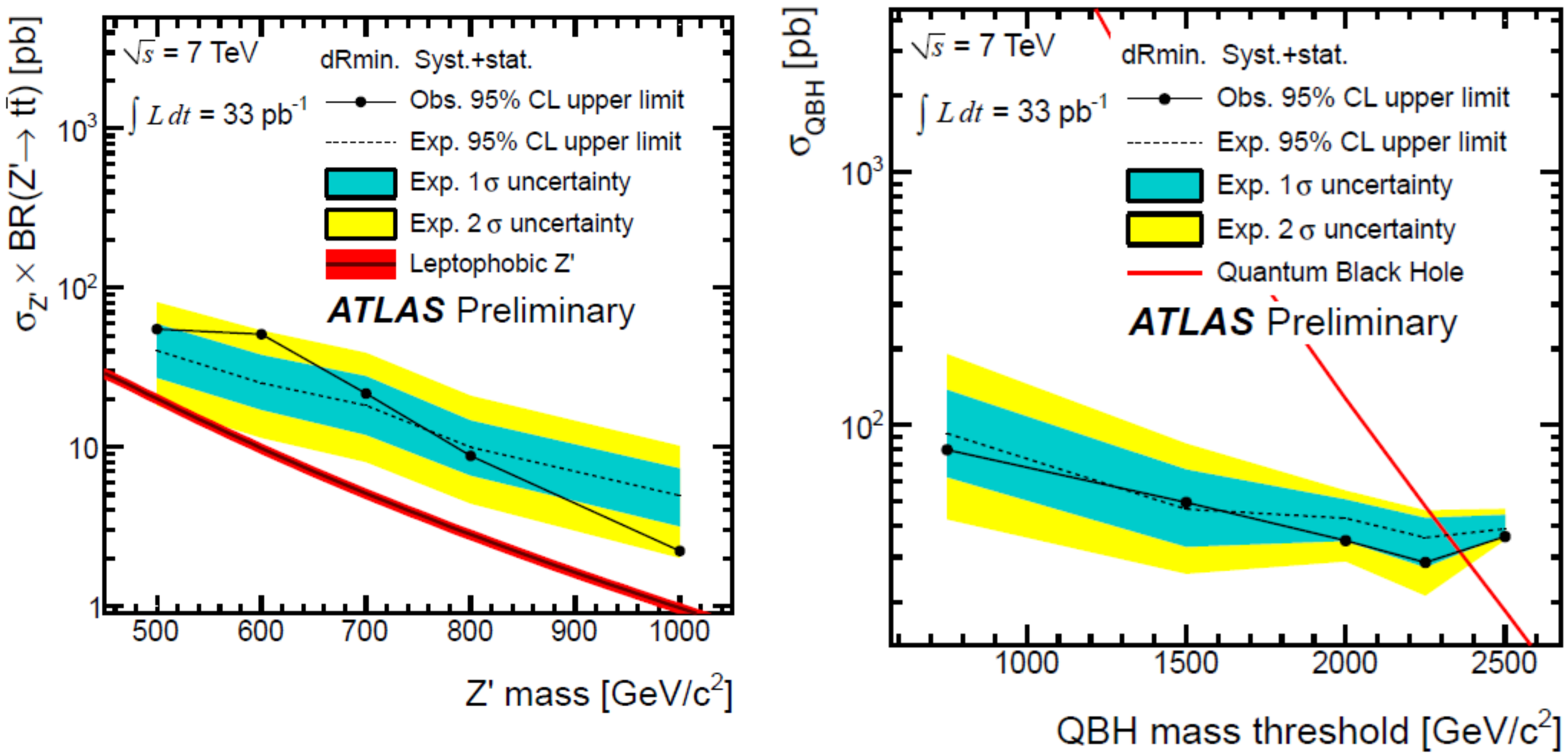
- ~ 500 events observed
- Highest mass at 1.7 TeV
  - Well above Tevatron
  - Getting into boosted regime!
- Use full shape of mass distribution for limits



Resolved ditop searches in 2010 data- II

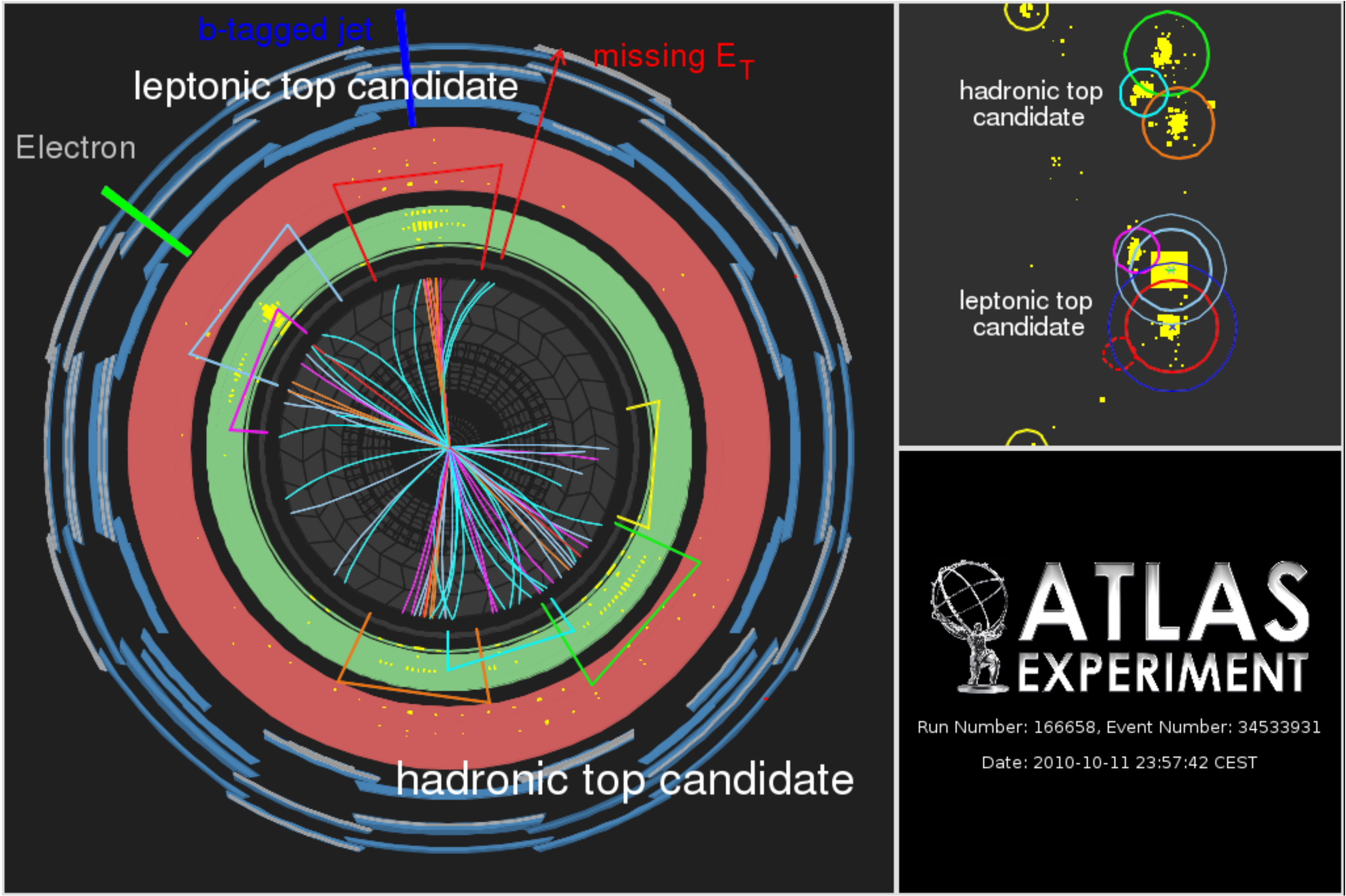
(ATLAS-CONF-2011-070)

- 95% C.L. Limits ~ 55 pb to 2.2 pb for m_Z = 0.5 TeV to 1.0 TeV.
- No sensitivity to benchmark leptophobic topcolor Z'
- Exclude m < 2.35 TeV for Quantum black holes
- Will improve with 2011 data (in approval)



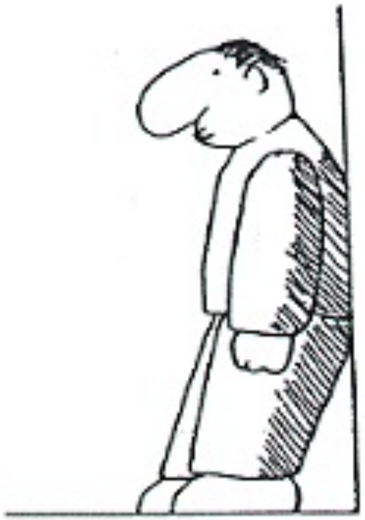
A high mass ttbar candidate (boosted)

High-mass event (714 GeV). Decay products collimated due to top quark boosts, but still distinguishable using standard reconstruction algorithms.



Conclusion & Outlook

- LHC energies open up new channels and signatures for BSM with top for which ATLAS has a very rich discovery potential.
- We have been exploiting techniques to efficiently reconstruct boosted tops and other particles
- Estimated prospects for BSM in ditop resonances.
- Looking at data for boosted particle identification and jet substructure to be used in analysis.
- Performed a search for resolved ditop resonances in lepton+jets channel in 33 pb^{-1}. No sensitivity to the leptophobic Z' from topcolor models yet but exclude quantum black holes with $m <$ 2.35 TeV @ 95% C.L.
- Boosted top resonance searches have started. Resolved ditop analysis is being repeated with 2011 data, using > 100 pb^{-1}.



BACKUP

Selection Criteria for boosted ditop search

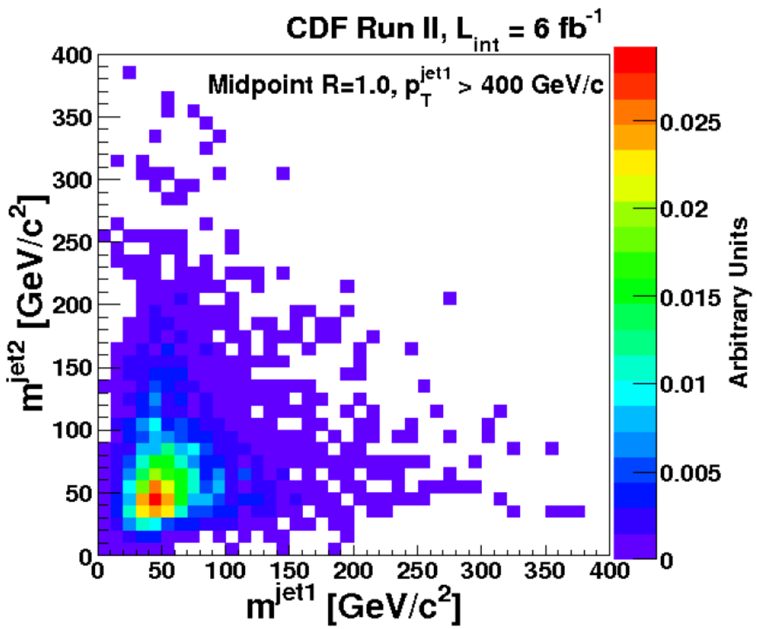
Table 2: The baseline and tight mono-jet selection. The tight selection does not include the baseline cuts.

selection	leptonic	hadronic
baseline, leading jet $E_T > 250$ GeV	$\Delta R_{lj} < 1$, $x_l < 1.2$, $z_l < 0.8$ muon: $I_{\mu}^{rel} < 0.5$, $Q_{vis}^{\mu} > 53$ GeV, $\Delta R_{\mu j} > 0.15$, $x_{\mu} > 0.35$, $z_{\mu} > 0.15$, electron: $I_{e}^{rel} < 0.1$, $Q_{vis}^{e} > 50$ GeV, $\Delta R_{ej} > 0.25$, $x_e > 0.4$	$z_{12} > 0.08$, $Q_W > 30$ GeV, $m_j > 100$ GeV
tight, leading jet $E_T > 250$ GeV	$\Delta R_{lj} < 1$, $\log y_l > 0$, $x_l > 0.3$, $I_{trk}^{mini} > 0.9$, $I_{calo}^{mini} > 0.8$	$z_{12} > 0.06$, $z_{23} > 0.042$, $z_{34} > 0.007$, $Q_W > 50$ GeV, $m_j > 140$ GeV

Boosted Jets and Tops at CDF

(Conf Note 10234)

- Boosted top search in high p_T jets in 6 fb^{-1}
- 58 candidate events in a sample when required two massive jets or one massive jet with significant missing transverse energy, with an estimated background of 44 +- 8 (stat) +- 13 (syst) events

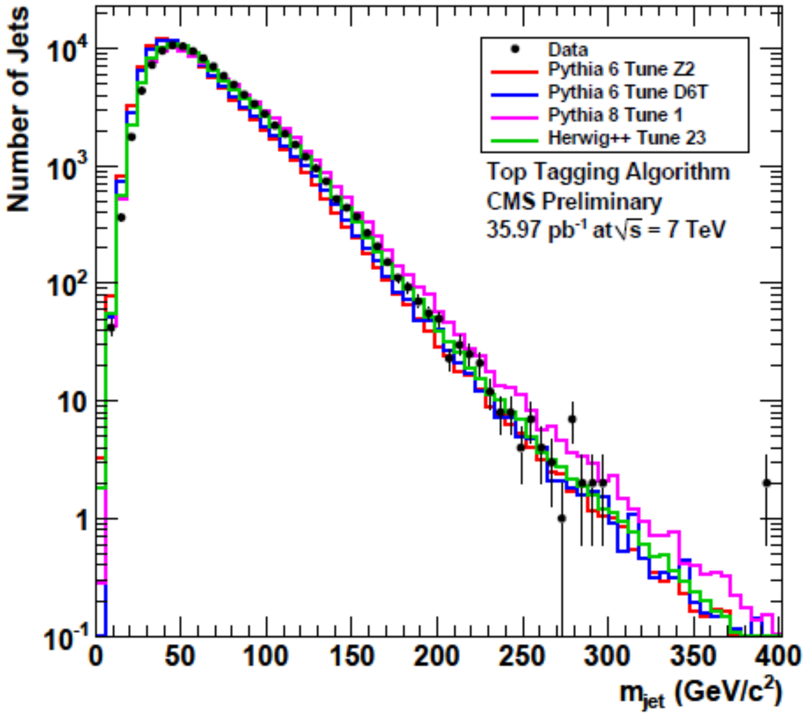


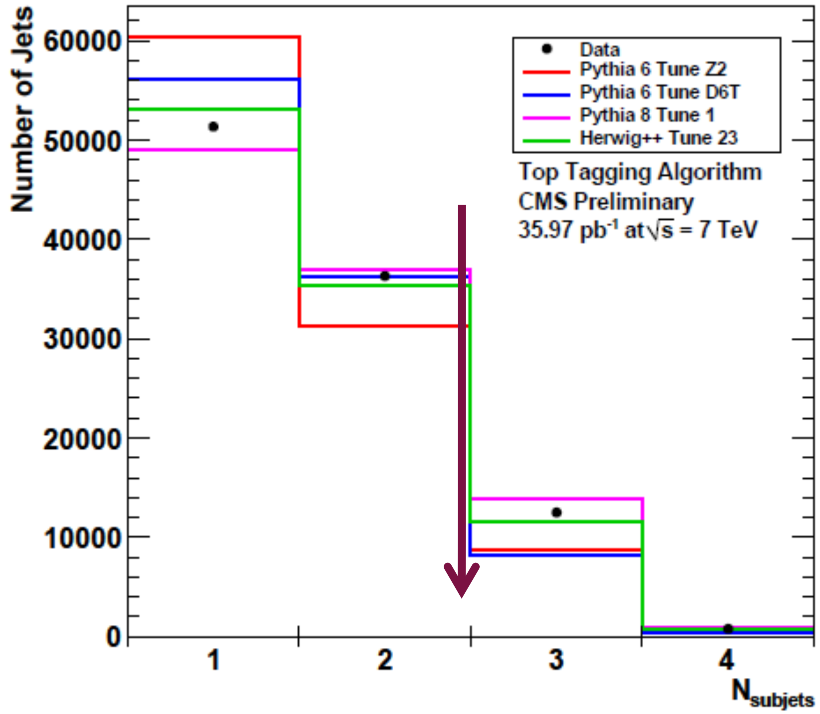
N_{top} > 0 with p_T > 400 GeV, σ < 40 fb at 95% CL (SM prediction 4.55 fb)

A pair of massive objects with p_T > 400 GeV, σ < 20 fb at 95% CL

CMS jet substructure for top-tagging in 2010 data *(CMS PAS JME-10-013)*

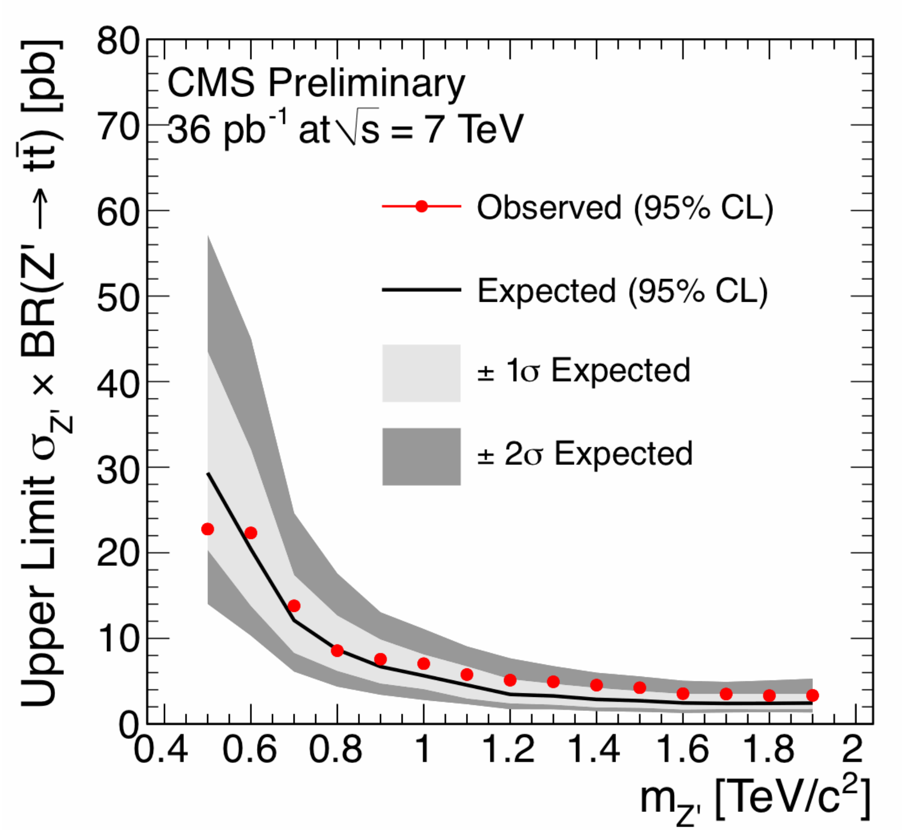
- Top and W tagging tested on 36 pb^{-1} of data during 2010.
- Cambridge-Aachen R = 0.8 jets, with 2 decomposition stages and 3 subjet variables for top-tagging.
- Three of two variables are shown





CMS ditop search in 2010 data

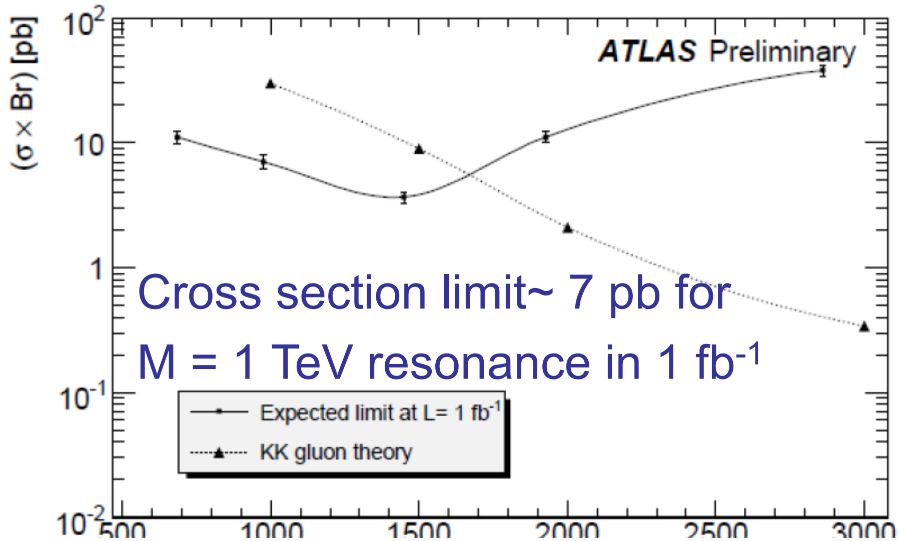
- Search for massive neutral bosons decaying via a top-antitop quark pair based on 36 pb^{-1} of data during 2010.
- Combined analysis of the muon plus jets and electron plus jets decay modes
- Observed limits range from approximately 25 pb at a Z0 mass of 500 GeV to approximately 7 pb at 1 TeV



Earlier ATLAS limits on top resonances

CERN-OPEN-2008-020 and ATL-PHYS-PUB-2009-081

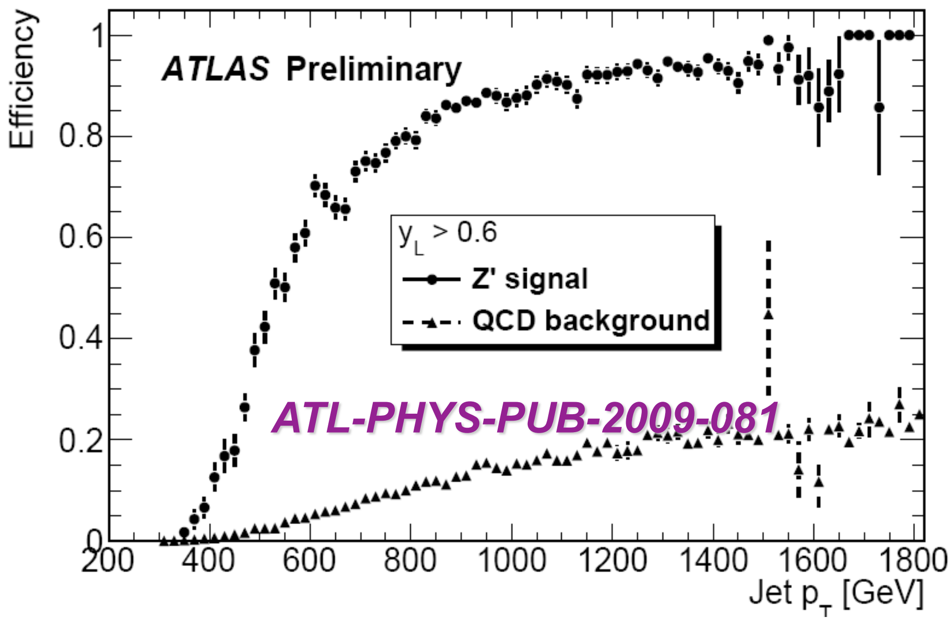
- Benchmark limit on narrow Z' ttbar resonance
- Standard M(ttbar) reconstruction in lepton+jets
- Worse sensitivity at higher mass due to drop in reconstruction efficiency



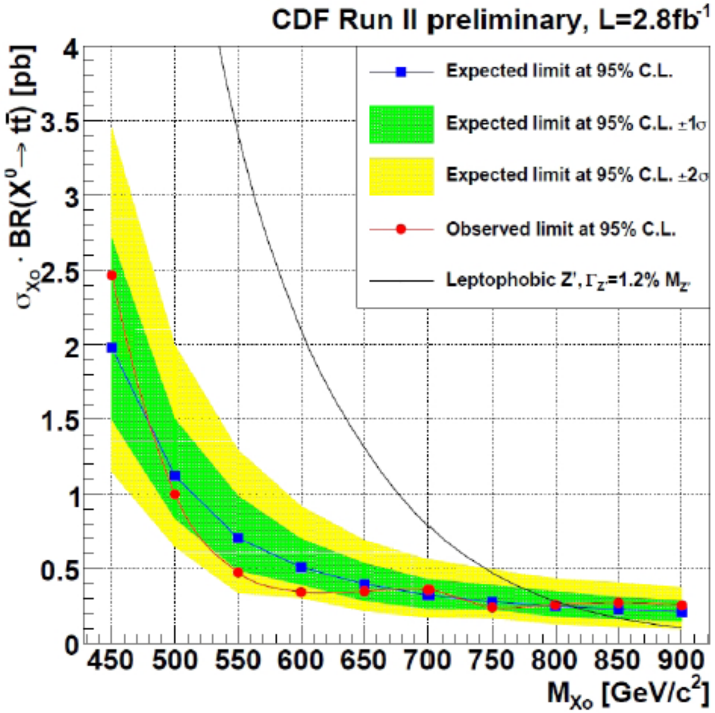
- Using subjet technique, possible to improve the limits at the interesting mass region

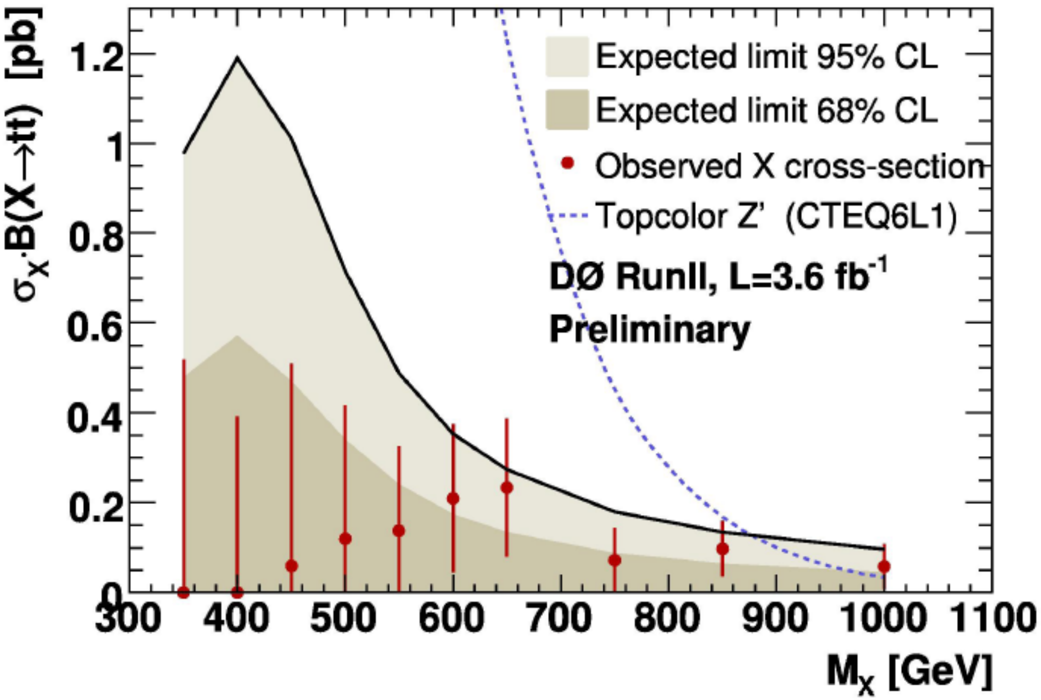
Limits for M = 2(3) TeV Z'

in 1 fb^{-1} ~ 550 (160) fb



Current status of resonance searches





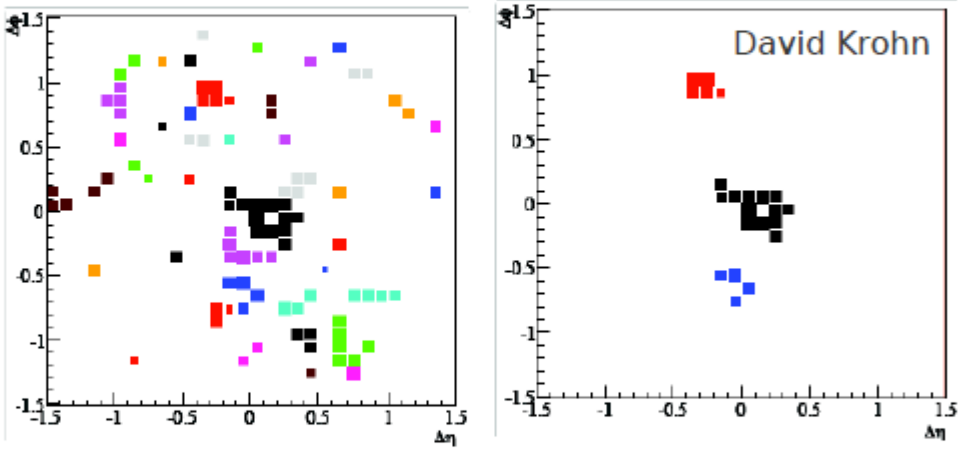
- no significant deviations from Standard Model prediction
- constraints on leptophobic $Z' \sim 820\ \mathrm{GeV}/c^2$ upper limit @ 95% CL

$\hookrightarrow$ large center-of-mass energy at LHC will extend Tevatron reach into multi-TeV region

Tools and Techniques: grooming

Jet substructure is often hidden:

- ✔ **Soft emissions inside the jet**
- ✔ **Underlying event**
- ✔ **Pile-up***



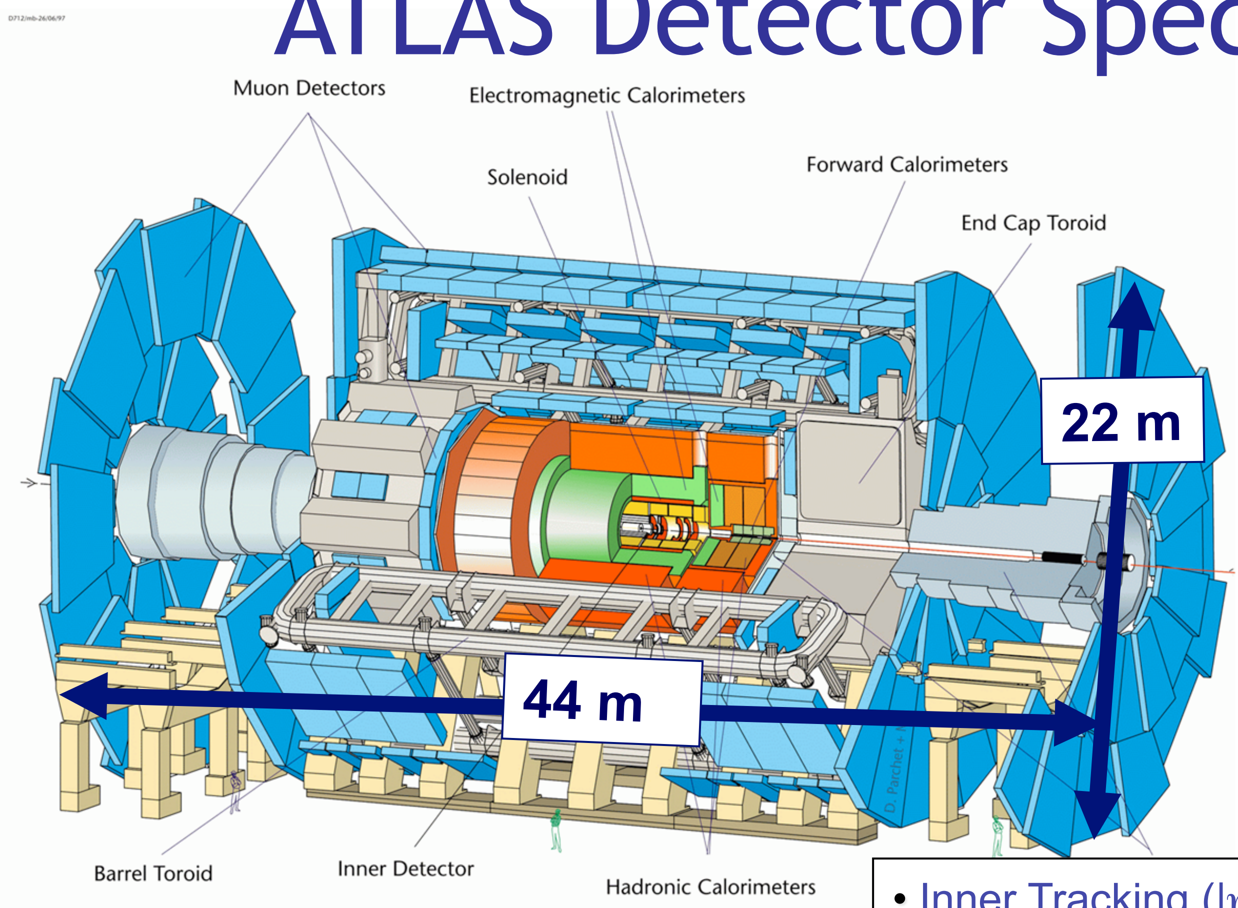
*Pile-up is identified and (partially) corrected for by associating jets or clusters to tracks and vertices

***Jet grooming techniques* to remove the "softest" parts (at large angle) of the jet:**

- ✔ **Filtering:** break jet into subjets on angular scale R_{filt} , take n_{filt} hardest subjets Butterworth, Davison, Rubin & Salam '08
- ✔ **Trimming:** break jet into subjets on angular scale R_{trim}, take all subjets with $p_{T,sub} > \varepsilon_{trim} p_{T,jjet}$ Krohn, Thaler & Wang '09
- ✔ **Pruning:** as you build up the jet, if the two subjets about to be recombined have $R > R_{prune}$ and $\min(pt1, pt2) < \varepsilon_{prune} (p_{T1} + p_{T2})$, discard the softer one. Ellis, Vermilion & Walsh '09

Boost2010 ignored the variable R option

ATLAS Detector Specifics



A toroidal LHC apparatus

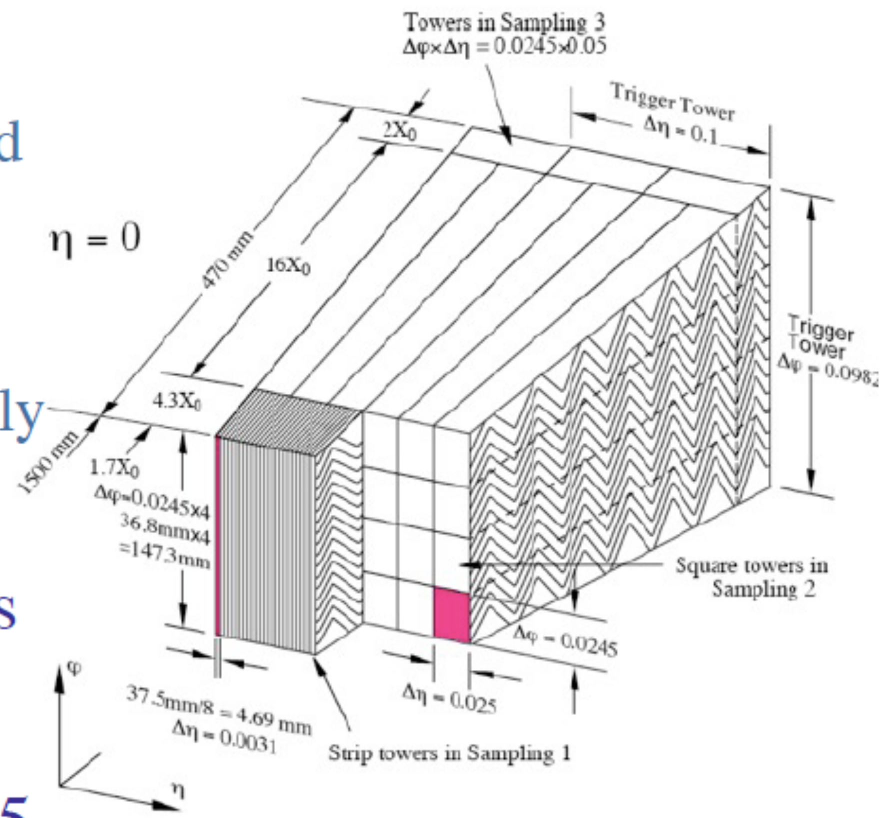
ID:	$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$
	$\sigma(d_0)$=15μm at 20GeV
ECAL:	$\sigma/E \approx 10\%/\sqrt{E(\text{GeV})} \oplus 0.7\%$
HCAL:	$\sigma/E \approx 50\% / \sqrt{E(\text{GeV})} \oplus 3\%$
Muon:	$\sigma/p_T \approx 10\%$ at 1 TeV/c

- Inner Tracking ($|\eta|<2.5$, 2T solenoid) :
  - Silicon pixels and strips
  - Transition Radiation Detector (e/π sep'n)
- Calorimetry ($|\eta|<5$) :
  - EM : Pb-LAr, Accordion shape
  - HAD: Fe/scint (central), Cu/W-LAr (fwd)
- Muon Spectrometer ($|\eta|<2.7$, 4T toroid) :
  - air-core toroids w/ muon chambers

Modern Calorimeters

- Jets often deposit ~50% of their energy in EM calorimeters
  - ATLAS has most finely segmented EM calorimeter in any hadron collider experiment!
  - (CMS has 0.0175 x 0.0175 but only one layer)
- Hadron ("tile") calorimeter has 0.1 x 0.1 segmentation
- CDF, DØ, H1, ZEUS have 0.05 as finest granularity, mostly 0.1

ATLAS EM Barrel

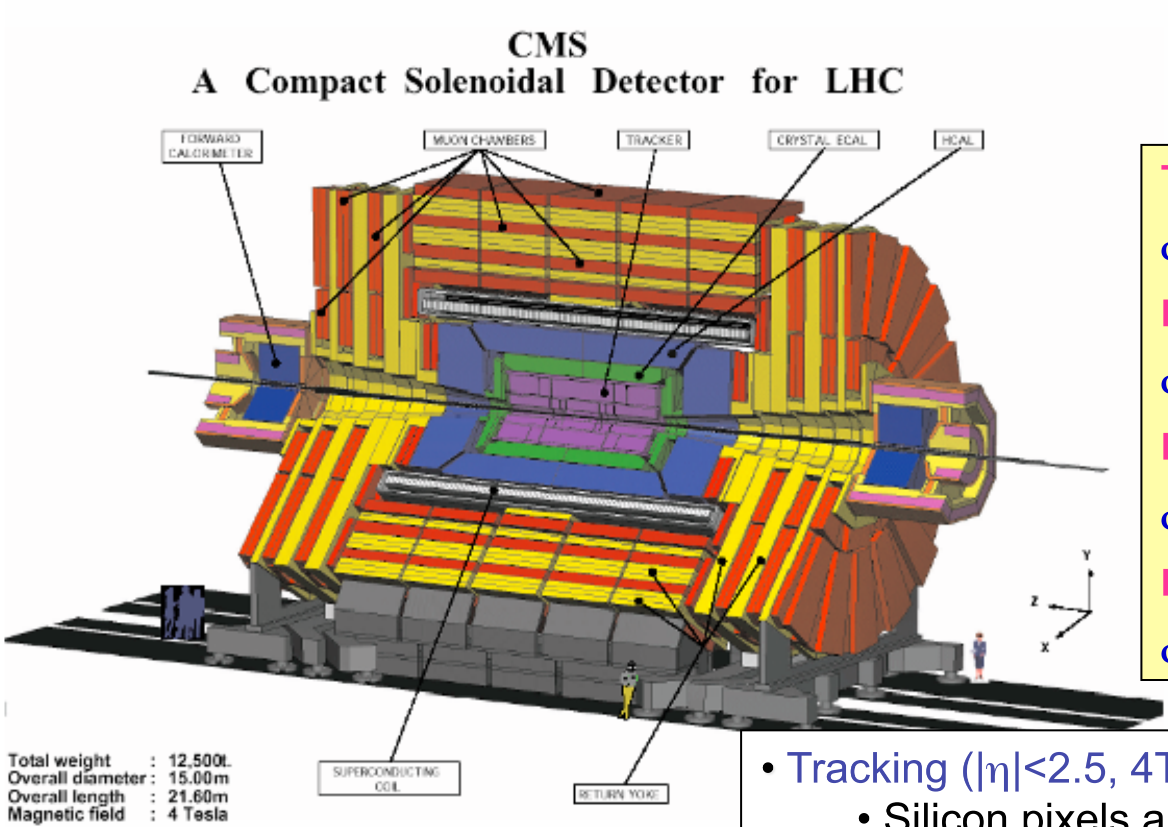


Comparison of detectors

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

F. Gianotti, Ichep06

the CMS detector



Tracker:

$\sigma/p_T \approx 1.5 \times 10^{-4}\ p_T \oplus 0.005$

EM Calorimeter:

$\sigma/E \approx 3\%/\sqrt{E(\mathrm{GeV})} \oplus 0.5\%$

Hadron Calorimeter:

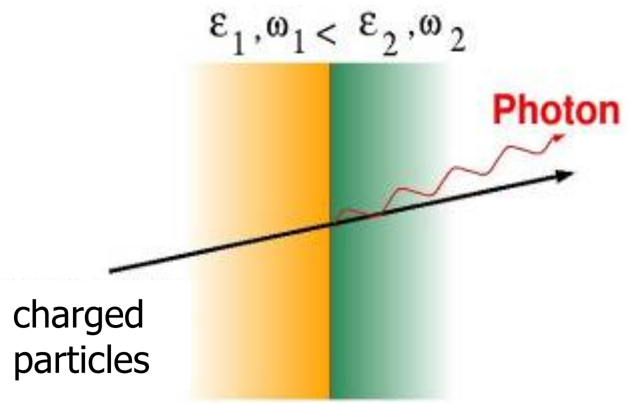
$\sigma/E \approx 100\% / \sqrt{E(\mathrm{GeV})} \oplus 5\%$

Muon Spectrometer:

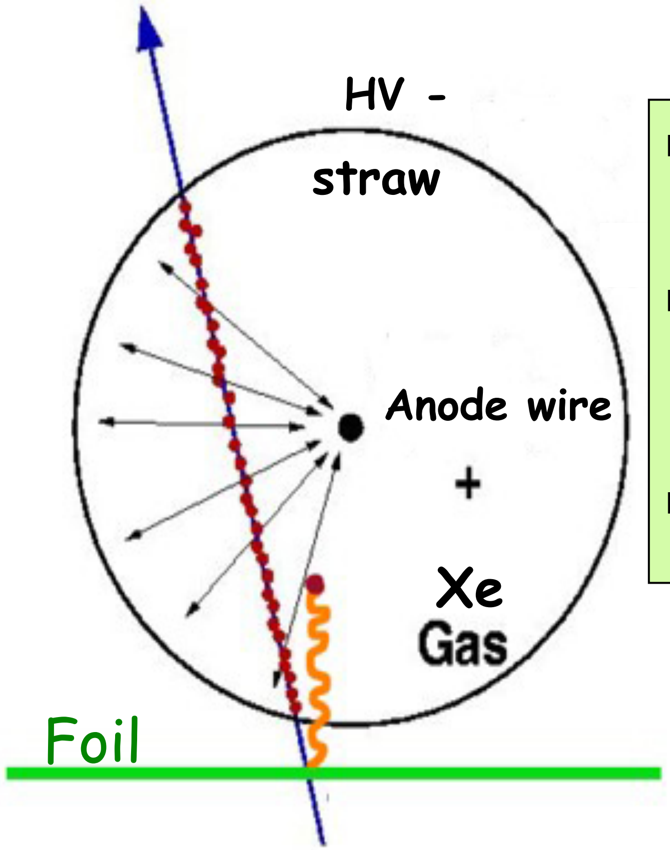
$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

- Tracking ($|\eta|<2.5$, 4T solenoid) :
  - Silicon pixels and strips
- Calorimetry ($|\eta|<5$) :
  - EM : $PbWO_4$ crystals
  - HAD: brass/scintillator (central+ end-cap), Fe/Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) :
  - return yoke of solenoid with muon chambers

The Transition Radiation detector (TRT)



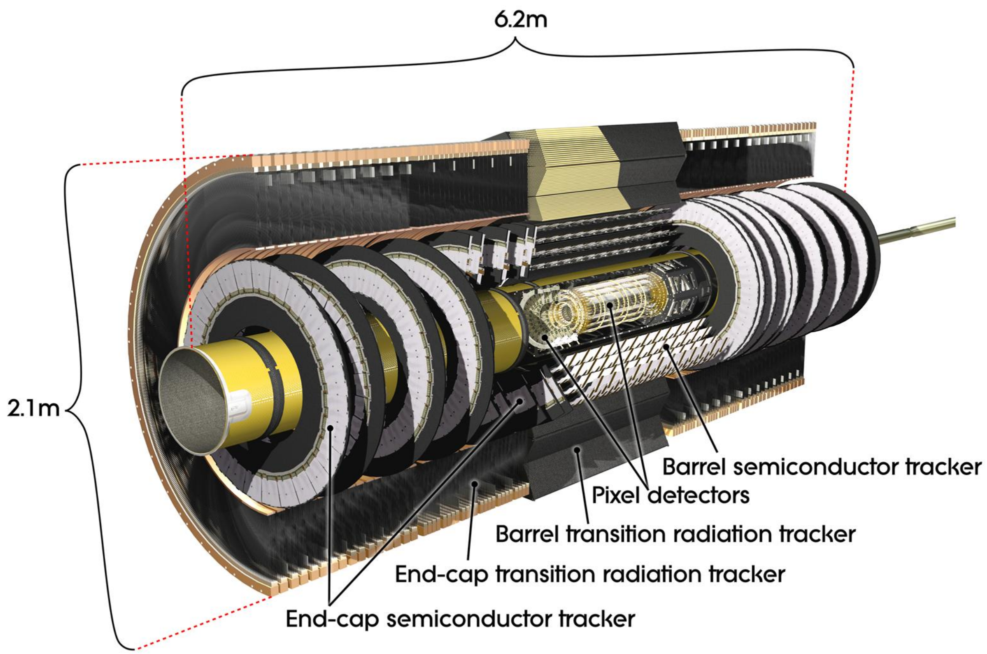
Transition radiation is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants.
TR intensity is proportional to the particle γ-factor
→ for a given particle momentum p, electrons emit more TR than pions → TR detectors used for particle identification



- Energy of TR photons (proportional to ε_1-ε_2): ~ 10-30 keV (X-rays)
- Many crossings of polypropylene foils (radiator) to increase TR photons
- Xenon as active gas for high X-ray absorption

Radiator: Polypropylen foils (15 μ) interleaved with straws

The Inner Detector (or inner tracker)



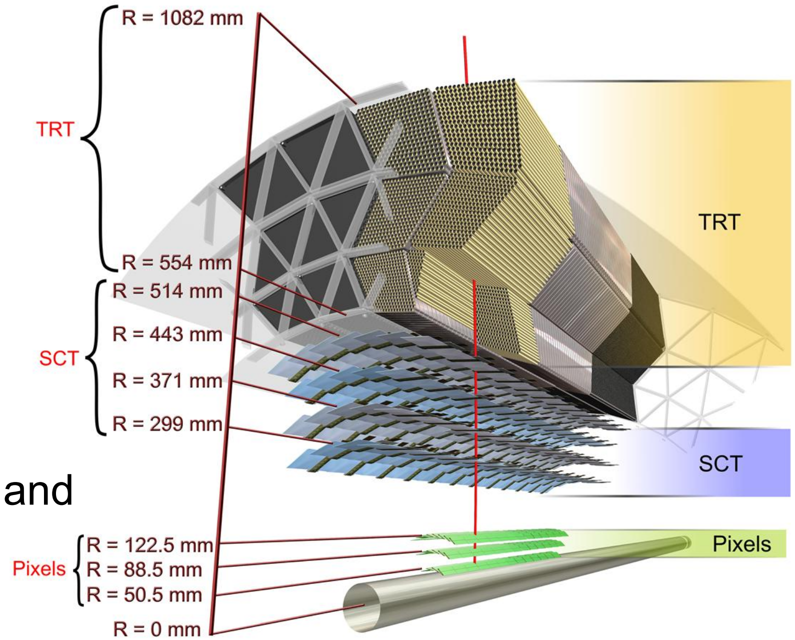
Immersed in a solenoid field of 2 Tesla measures the trajectories of charged particles.

The ID comprises 3 sub-detectors: (resolution)

Pixel :	10/115 μm in Rϕ/z
Silicon strip(SCT):	17/580 μm
Transition radiation tracker (TRT):	130μm in Rϕ

The ID covers : |η| < 2.5 (2.0 for TRT) with 3 Pixel measurements, 8 SCT and ~30 TRT.

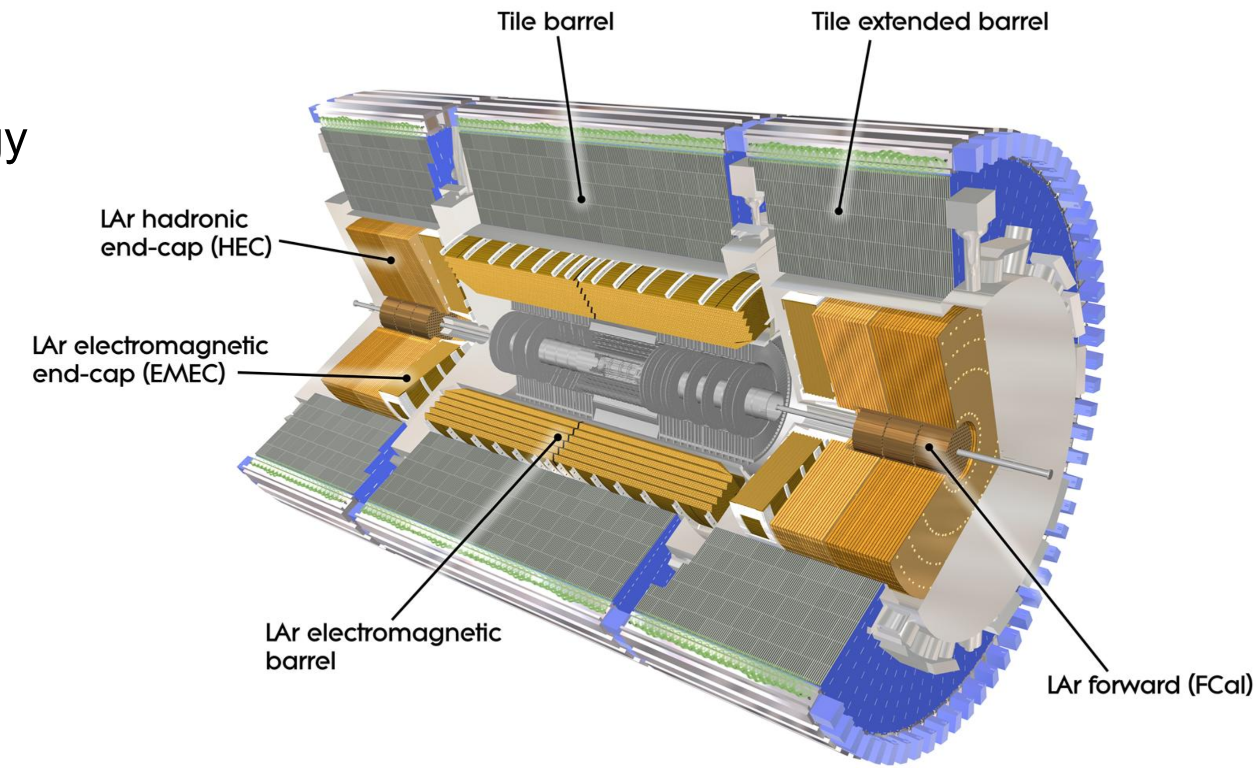
Designed for tracking efficiency >90% (π) and 99% (μ) , momentum measurement with $\sigma_{p_T} / p_T = 0.05\% \, p_T \oplus 1\%$ and impact parameter (at high p) = 10μm



The calorimeters

- Measure the energy deposit (therefore also the eventual inbalance = missing E_T)
- Electromagnetic calorimeter (LAr): $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
  - Precise measurement of the energy deposit of photons and electrons (and hadrons (HEC) outside the acceptance of the Tile)
  - coverage $|\eta| < 4.9$
- Hadronic calo (Tile):
  - Measurement of energy deposit of hadrons
  - coverage $|\eta| < 1.7$

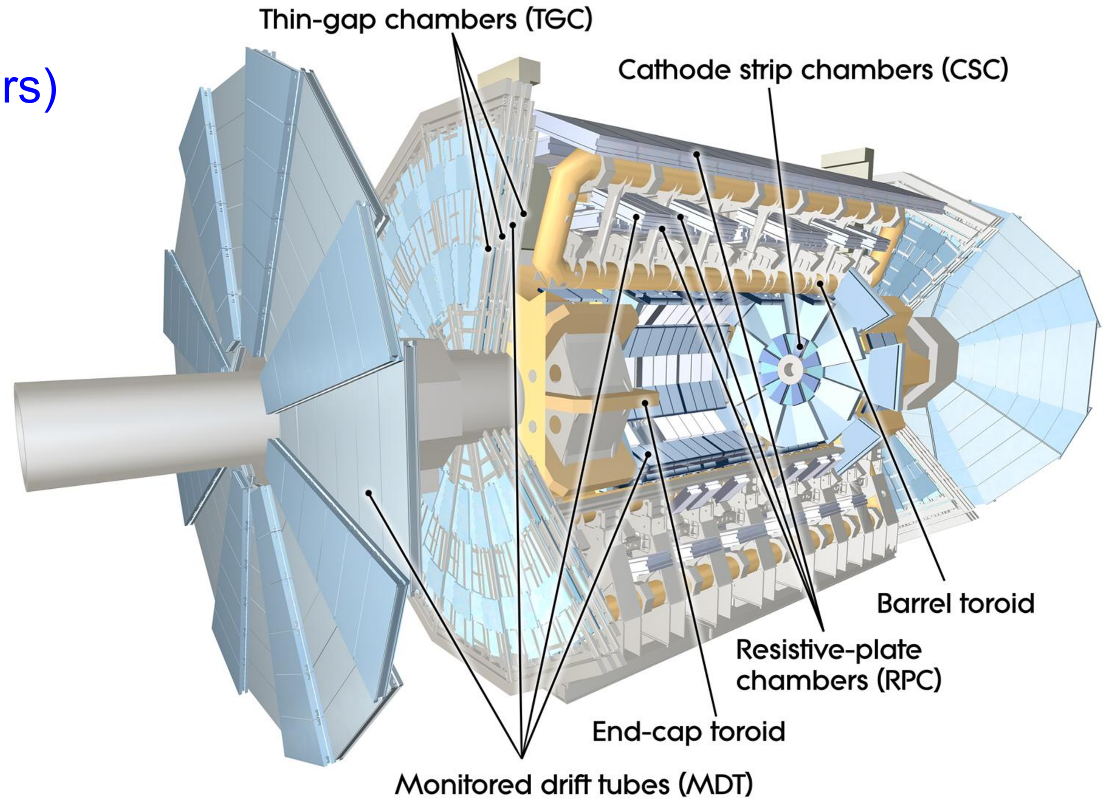
$$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$$



The muon spectrometer

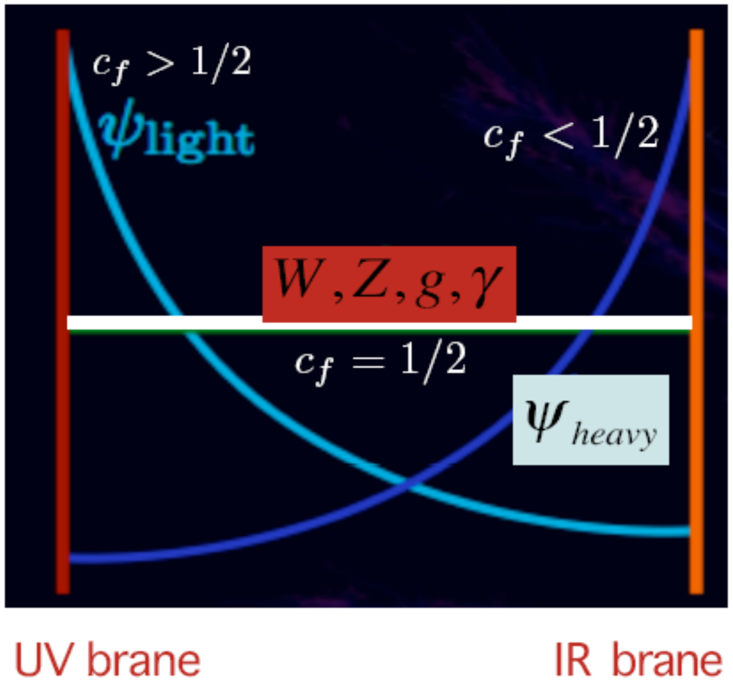
- Immersed in a toroidal magnetic field of ~ 0.5 T (3x8 superconducting toroids)
- Precision measurement chambers and trigger chambers
  - MDT (Monitored Drift Tubes)
  - RPC (Resistive Plate Ch.)
  - CSC (Cathode Strip Chambers)
  - TGC (Thin-Gap Chambers)
- coverage |η|<2.7

$$\sigma_{p_T}/p_T = 10\% \text{ at } p_T = 1 \text{ TeV}$$



Realistic RS Models: Bulk RS

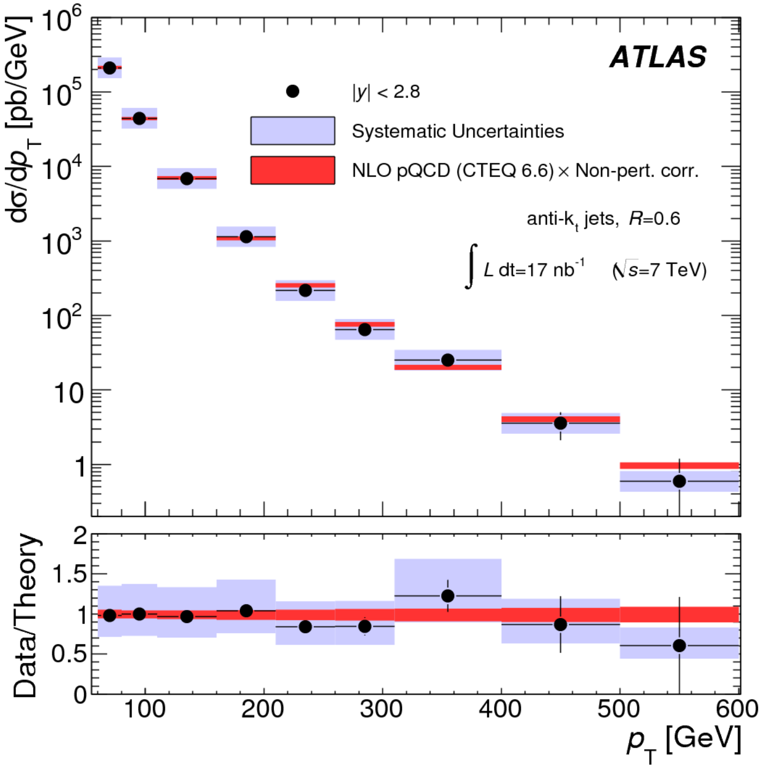
- Current favourite model building in RS
- EWSB with bulk matter fields & KK modes for SM particles
- Solves more than gravity hierarchy problem
  - Gauge hierarchy problem, Fermion mass hierarchy, Gauge Higgs Unification, ….
- New physics couples with stronger coupling to heavier SM particles (Top, H, V_L)
- Arrange zero modes (couplings) such that
  - Light fermions close to the UV brane to protect precision EW corrections
  - Top (t_R) near IR (TeV) brane (where Higgs resides) in order to produce its observed heavy mass



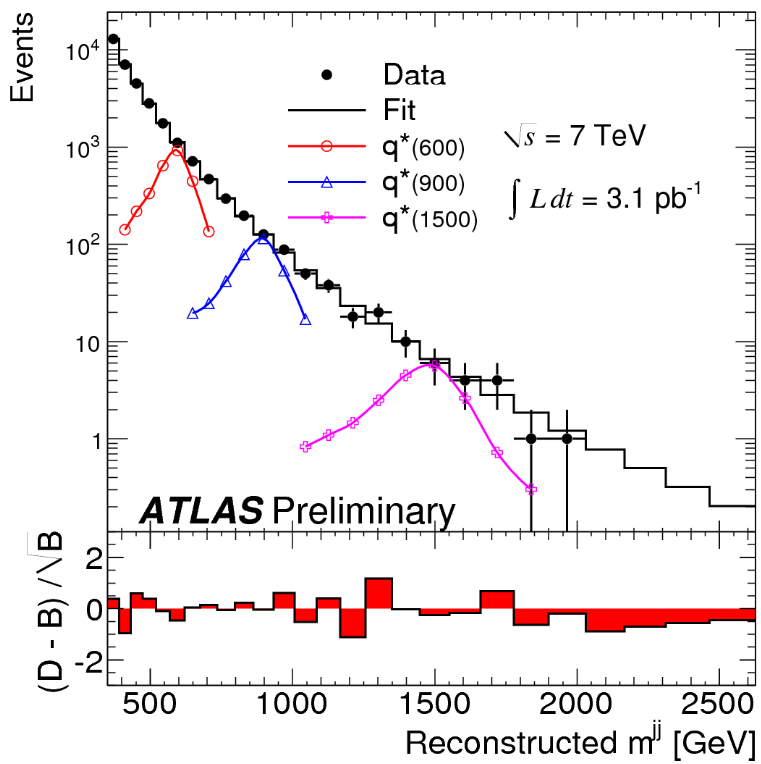
ATLAS Jet Measurements

(arXiv:1009.5908)

- High p_T jets are observed on a daily basis
- Start to make jet substructure/fat-jet analysis for boosted objects!



Inclusive jet differential cross section.
Luminosity uncertainty of 11% is not shown.



Dijet inv. Mass used to derive BSM limits
95% CL exclusion for 0.50< mq*< 1.53 TeV