b-tagging commissioning strategy at ATLAS

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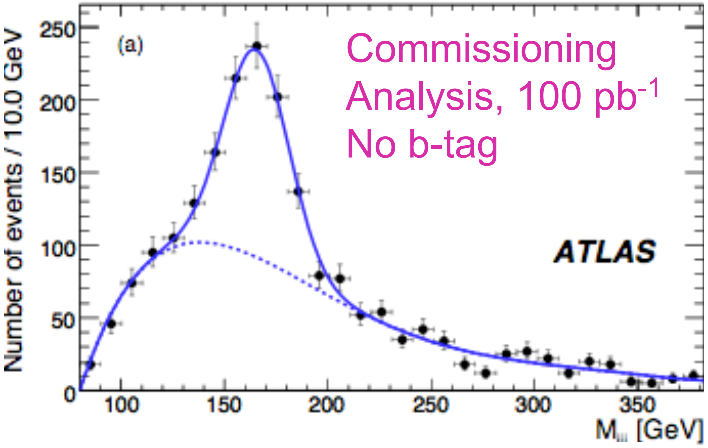
Top workshop @ Grenoble 23/10/08

- Introduction: b-tagging for top at LHC
  - What is required of b-tagging algorithms?
- Tagging b-jets
  - Lifetime-based b-tagging algorithms
  - Soft lepton-based b-tagging algorithms
- Commissioning b-tagging
  - Track selection and alignment
  - Measuring light quark tagging rates
  - Measuring b-tagging efficiency with di-jet and ttbar events
  - Towards the ultimate peformance
- Conclusions

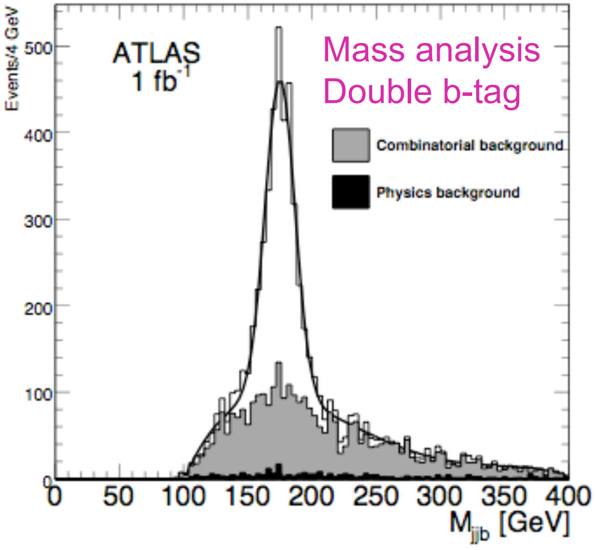
[Results taken from ATLAS CSC book (tracking performance, flavour tagging and top)]

Introduction - b-tagging for top physics at LHC

- B-tagging important tool for top physics at LHC
  - BR(t→W**b**)=100% in Standard Model - 1 t ⇒1 b
    - One of the most important signatures of top
- But not **essential** to see top-pair production
  - ‘Commissioning’ analyses can see top peak without b-tagging … before b-tag is commissioned
    - B/g is mixture of W+jets, QCD, ttbar combinatorial
- B-tagging for top-pair events brings
  - Reduction in non-ttbar background without b-jets
  - Help in dealing with ttbar combinatorial background - assigning jets to tops
    - Important for top reconstruction and top mass
  - B-tagging essential for single top (smaller S/B)
    - … but does not help with irreducible ttbar background
  - Ultimate b-tag performance (R_{uds}>100) not crucial, but will need to know R_{uds} and ε_b well
    - Good understanding of efficiency in top environment vital for x-section analysis ($\Delta\sigma \sim \Delta\varepsilon_b$ or $2\Delta\varepsilon_b$)



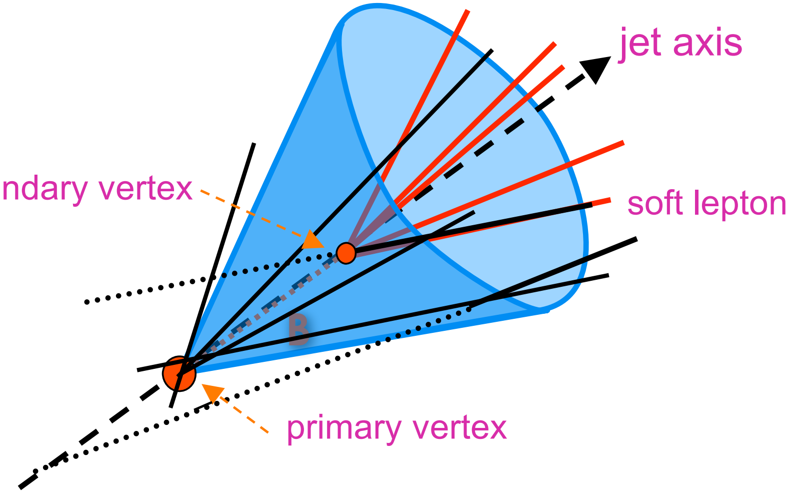
Commissioning Analysis, 100 pb^{-1}
No b-tag



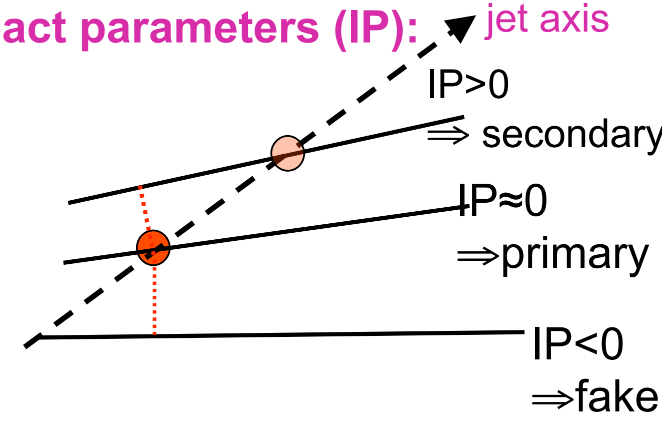
Mass analysis
Double b-tag

Tagging b-jets at LHC

- Properties of b-jets useful for tagging
  - B-hadron flies ~few mm before decaying
    - Tracks inconsistent with primary vertex
    - Tracks form a secondary vertex with high multiplicity, high energy fraction and high invariant mass
  - In ~40% of cases, B hadron decays include a soft lepton (e/μ) from b→l or b→c→l
- Complications …
  - Dense jet environment - patrec is difficult, hard to find (non-isolated) soft leptons
  - Pileup confuses primary vertex finding
  - Fake signatures from K_S, Λ, hyperons, and gluon splitting to heavy quarks in light jets
  - Charm quarks, midway between light and b-jets
- Combine information to get maximum performance…
  - But don't lose understanding, calibrate on data and with imperfect Monte Carlo

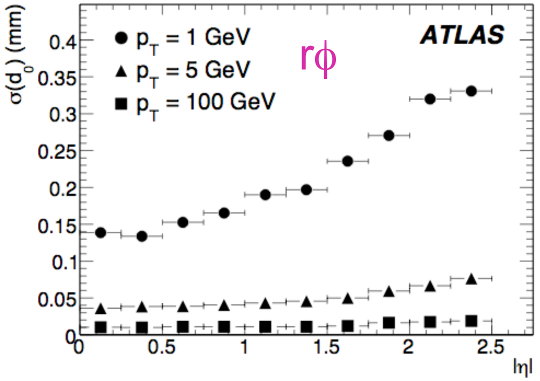


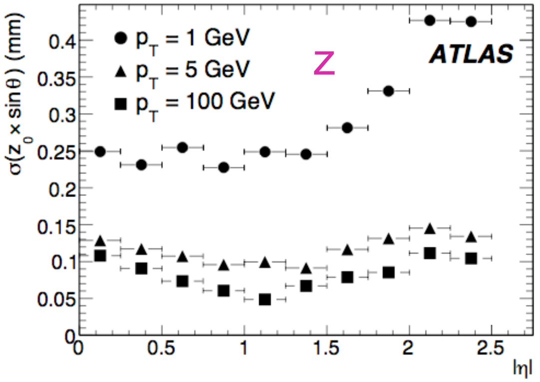
Impact parameters (IP):

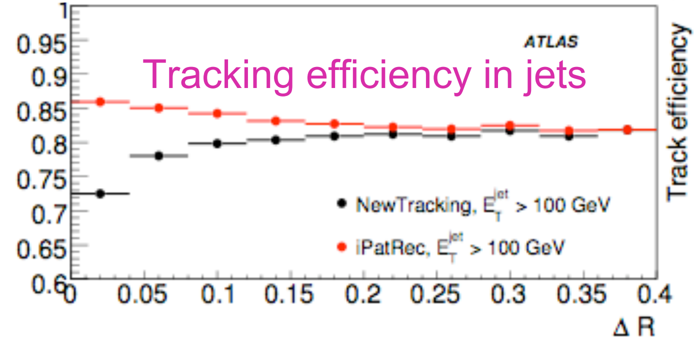


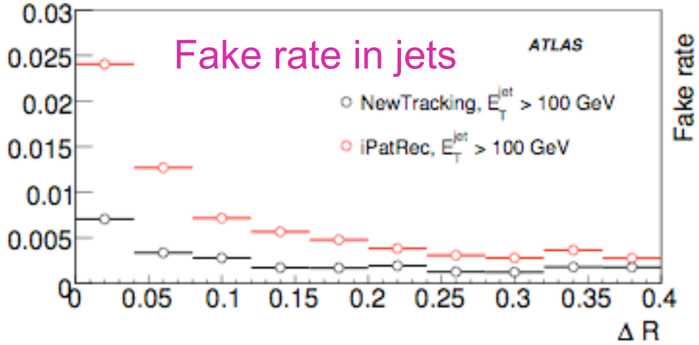
Tracking performance

- Keys to b-tagging performance
  - Pixel detector determines impact parameter resolution
  - Low p_T tracks (~ 5 GeV)
    - Resl^n ~40μm in rϕ (dominated by multiple scattering)
    - ~100μm in z (mult-scat/resl^n)
  - Reasonable track-finding efficiency (~80%) and low fake rate (~0.5%) in dense jet environment
    - Trade-off between two in pat-rec algorithms
  - Particularly difficult for high p_T (> 200 GeV) b-jets
- b-tagging algorithms make **quality cuts**
  - Relatively small impact parameters wrt PV (~mm)
  - p_T>1 GeV, hit required in b-layer + 1 other pixel
  - Removal of tracks consistent with material interactions/photon conversion (e.g. beampipe)



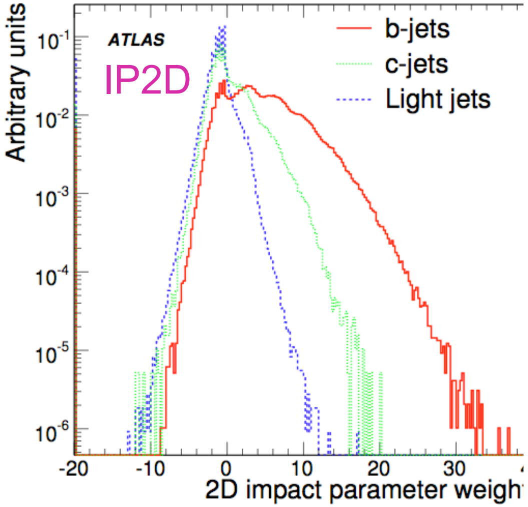




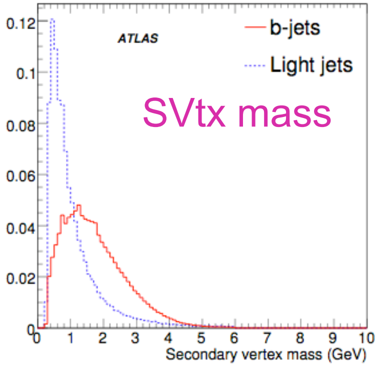


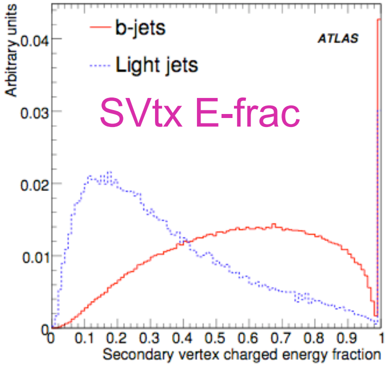
Lifetime-based b-tagging algorithms

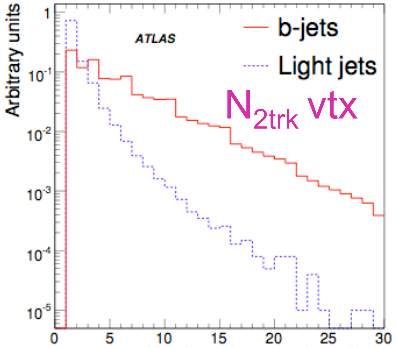
- Algorithms based on track impact parameters
  - Form track-by-track likelihood (b vs uds) using track IPs, then combine into a likelihood weight for the jet
    - IP2D likelihood combines transverse IPs, IP3D uses transverse and longitudinal IPs, including correlations
    - Final output is a weight w: small w=uds-like, large w=b-like

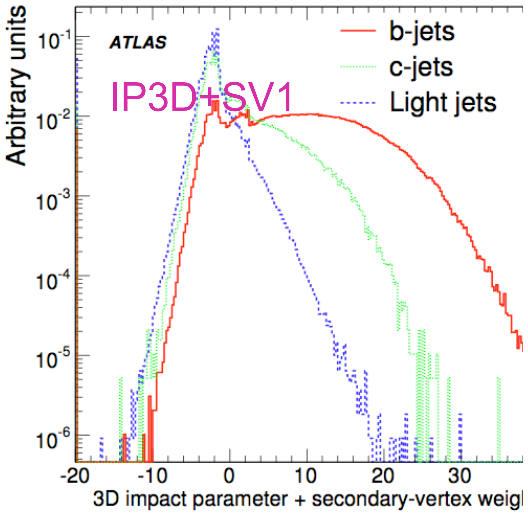


- Algorithms based on secondary vertex finding
  - Seed a secondary vertex using tracks with large IP, collect all tracks compatible with this vertex and fit it
    - SV1 uses vertex mass, energy fraction and N-2track as variables to form a likelihood - again for b vs uds jets





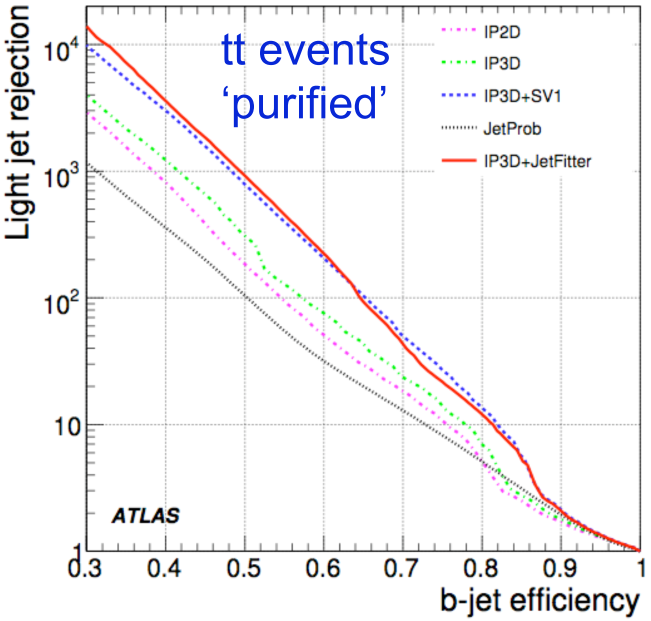


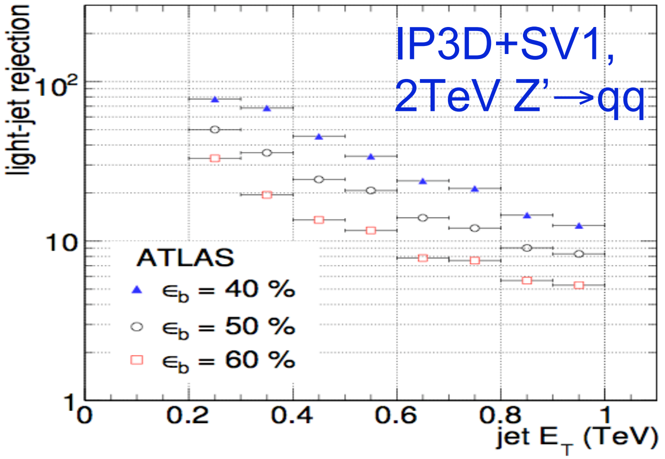


- Combine IP3D and SV1 to get best overall performance

Performance of lifetime-based b-tagging

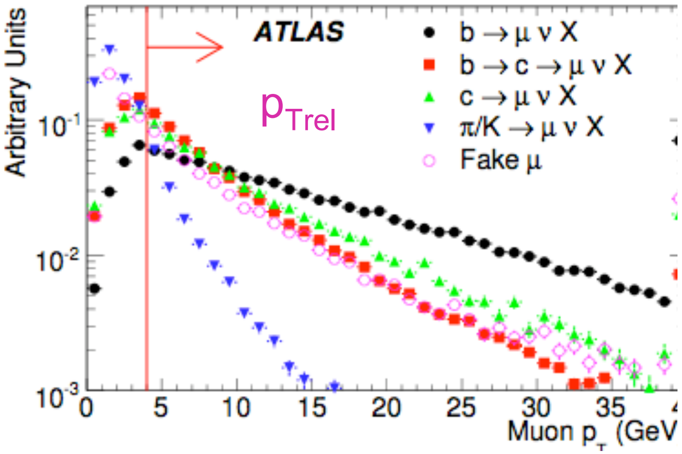
- Measure performance on tt Monte Carlo events
  - Efficiency for tagging b-jets vs rejection of light (uds) jets - charm jets from W→cs,cd ignored
  - When testing algorithms, 'purify' light jets - remove one close to b or c (gluon splitting, overlapping jets)
  - IP3D+SV1 achieves rejection 10^2-10^3 for ε_b=50-60%
- In real life, things are more complex
  - Strong dependence of performance on:
    - Jet E_T - best around 100 GeV, falls above and below
    - Jet η - tracking performance degrades at high η
    - Jet environment - presence of other jets nearby
    - .. Different results achieved on e.g. WH, tt, ttH Monte Carlo samples - need to be analysis-specific
  - Algorithms lose performance for jet E_T>300 GeV
    - Jets become narrower, more fragmentation tracks, pat-rec problems, some B hadrons decay after b-layer
    - Optimisation needed (see talks of Vos, Brooijmans)

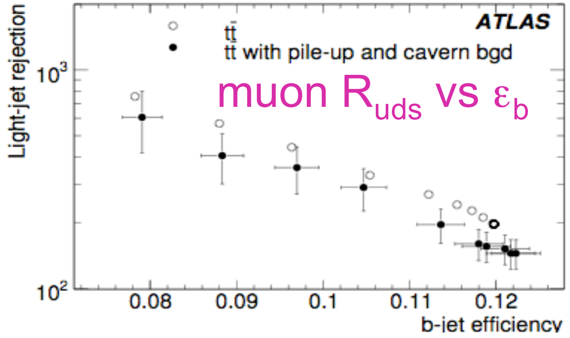

tt events
'purified'

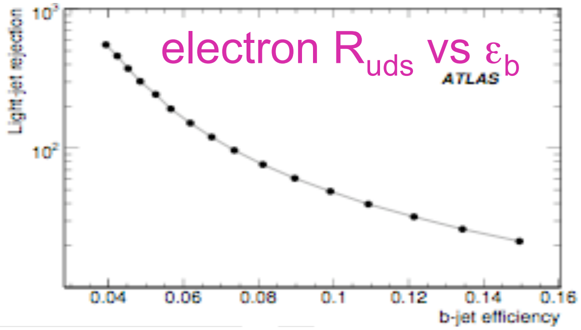

IP3D+SV1,
2TeV Z'→qq

Soft-lepton tagging algorithms

- ~40% of b-jets contain soft e/μ from $b \rightarrow l$, $b \rightarrow c \rightarrow l$
  - Can be exploited for b-tagging, limited by BR
    - Low correlation with lifetime-based taggers - can add to performance, and very useful for calibration
    - Also useful to identify b-jets with large neutrino energy component $\Rightarrow$ energy-scale corrections
- Require identification of **soft** leptons in jet cone
  - Muon background from π/K decays in flight, punch through calorimeter material, and 'neutron gas' in cavern ('cavern background')
  - Electron background from π in jet, photon conversions, Dalitz decays
  - Final discrimination using e.g. p_{Trel} of lepton wrt jet and lepton impact parameter wrt primary vertex
- Performance (μ/e): ε_b=10%/7% for R_{uds}=400/110
  - Expect degradation of 10-15% in R_{uds} with pileup background at 2 10^{33} cm^{-2}s^{-1}





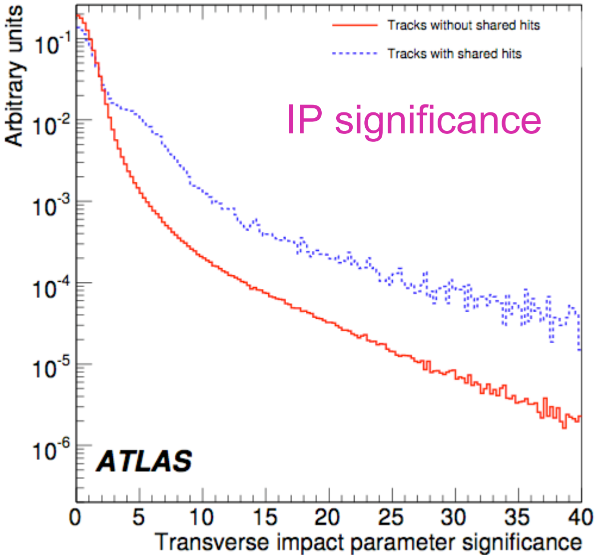


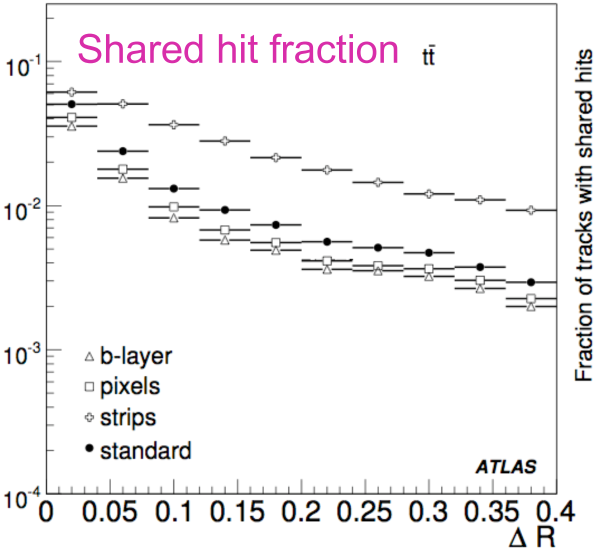
Commissioning b-tagging algorithms for physics

- Have sophisticated algorithms giving excellent performance on Monte Carlo … but what about data?
- Commissioning tracking, primary vertexing, lepton-ID
  - Starting to achieve separation between b and light quark jets - start with simple algorithms, and gradually add sophistication as calibration/performance improves
  - For tracking calibration, already made a start using O(1M) ID-cosmics from 2008
- Measuring the performance of what we have
  - Determining light jet rejection - tracking studies, simple taggers, MC extrapolation
- Measuring b-tagging efficiency in data
  - Using di-jet events (Tevatron-inspired methods, e.g. '$p_T$rel,' 'System8')
    - Needs dedicated trigger, environment rather different from tt events
  - Using top events themselves - unlike at Tevatron, we should have plenty
    - Well-identified topologies: use fractions of events with 1, 2, 3 tags
    - Or selections designed to isolate unbiased b-jet samples
  - Transporting the results to the analyses which need them (jet E_T, η, environment)
- Many tools will be needed to build a consistent picture, ready for analysis

Selecting good tracks and vertices

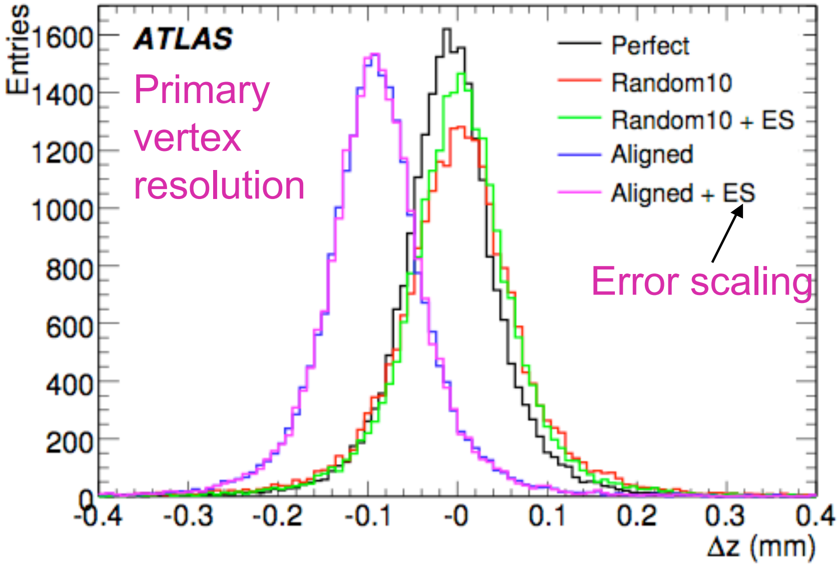
- Understanding track-by-track resolution critical
  - ‘Missing’ hits degrade the tracking resolution
    - Missed due to dead module, or pat-rec error?
    - Need link to conditions database
  - Tracks with ‘shared’ hits (assigned to >1 track) have worse resolution, larger tails
    - Signal of dense environment, pat-rec ambiguities
  - About 2% of tracks in top-event jets have shared hits, rises strongly with jet and top p_T
    - Important to treat these tracks correctly
- Primary vertex finding also important
  - Beamsize of 15μm dominates in transverse plane, vertex finding in z gives resolution of ~40 μm
  - Vertex z-position resolution strongly affected by pileup: with 5 events/crossing, 10% wrong PV
    - With e.g. 75ns bunch spacing running, pileup becomes important well below L=10^{33} cm^2s^{-1}





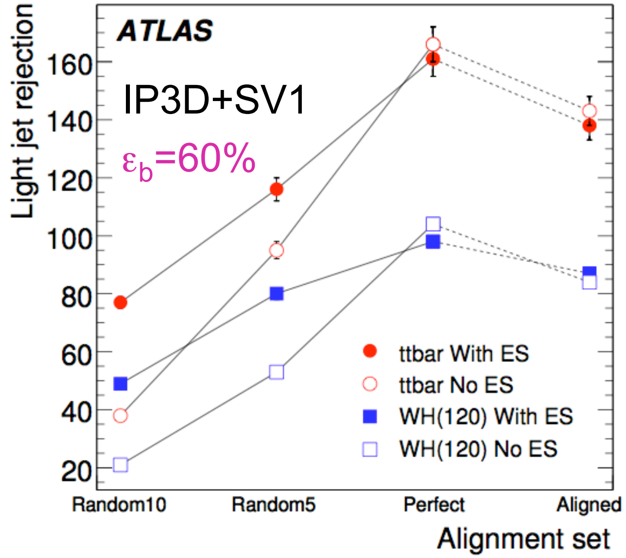
Sensitivity to detector alignment

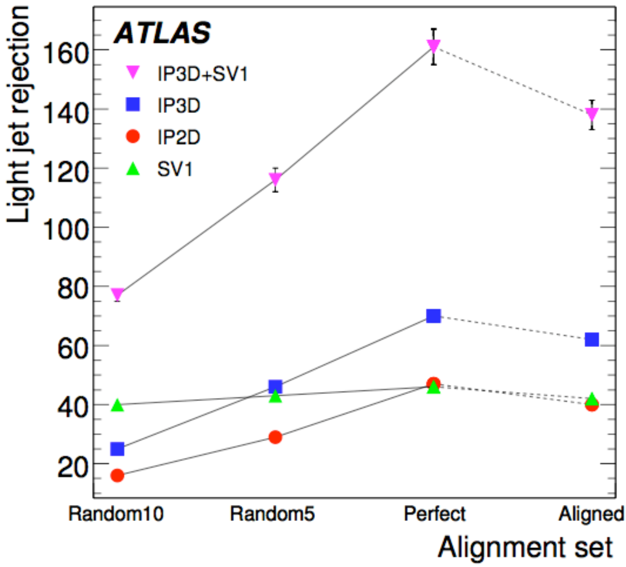
- Alignment precision (pixels most important for b-tagging) depends on:
  - As-built / as-installed precision of detector mechanics (10-20 μm module-module)
  - Ability of track-based alignment to find and follow real module positions
  - Sensitivity to **'weak modes'** - distortions in directions not well-constrained by tracks - e.g. clocking rotations of one barrel wrt next, 'breathing' of cylinders
- B-tagging sensitivity to alignment studied with various scenarios in MC:
  - 'Random10' - 10/30/30 μm random module displacements in rφ/z/r
  - 'Random5' - 5/15/15 μm random
  - 'Aligned' - 1st results of applying track-based alignment procedures to MC of 'realistic as-built' detector
    - Including O(mm) scale movements between detector parts
- **Error scaling** can also be applied
  - Parameterise residual misalignment - scales to be determined on data
    - By analysing track pulls



Alignment effect on b-tagging

- Compare uds-jet rejection with different alignments at constant b-tagging efi, for tt (and WH) events
  - Small degradation (10-15%) from perfect→aligned
    - Error scaling does not make much difference
    - Track-based alignment determines alignment parameters crucial to b-tagging well
    - Macroscopic distortions not important (c.f. z-vtx resl^{n})
  - Large degradation (~x4) from perfect →Random10
    - Error scaling is important for these significant mis-alignments - helps to partially recover performance
    - … both good resolution and good description important
- Sensitivity of different algorithms to alignment
  - Impact parameter-based tags (IP2D,3D) much more affected (factor 2-3) than SV1 (after error rescaling)
    - Performance depends directly on tracking resolution
- In principle, should recalibrate likelihood refs
  - In practice, this produces only a small change in rej^{n}



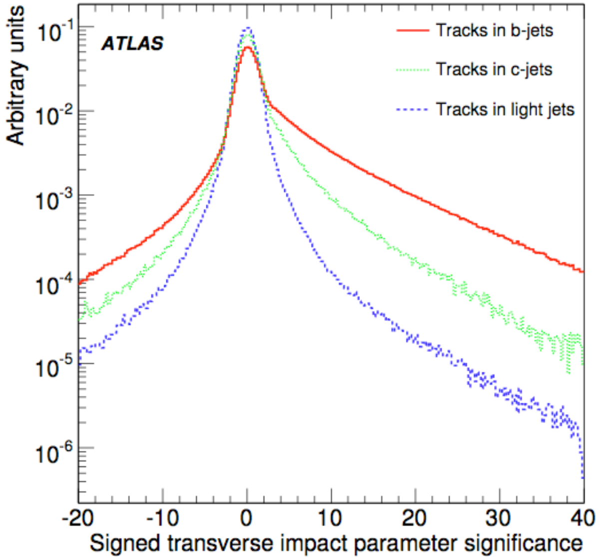


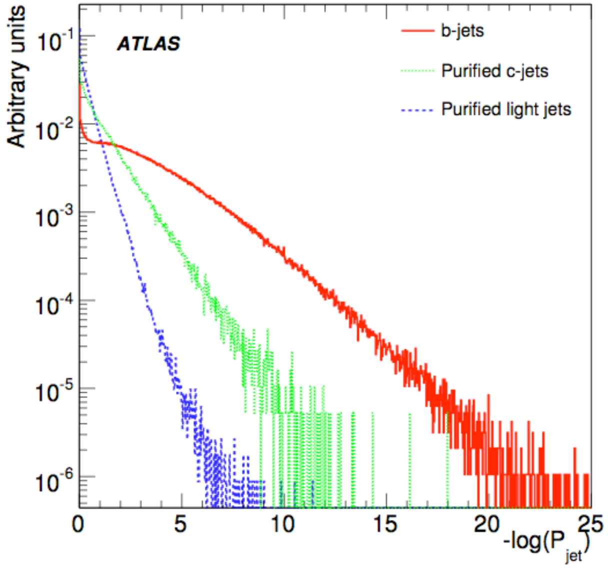
Measuring the light jet rejection

- Light jet rejection depends on
  - Intrinsic tracking resolution
  - Presence of long-lived decays (K_s, Λ, hyperon)
    - g→bb,cc in light jets (in MC, remove by ‘purification’)
- Extract the first from data - most transparently with simple JetProb tag (pioneered by ALEPH at LEP)
  - Resolution function gives track consistency with PV

$$\mathscr{P}_i = \int_{-\infty}^{-|d_0^i/\sigma_{d_0}^i|} \mathscr{R}(x)dx$$

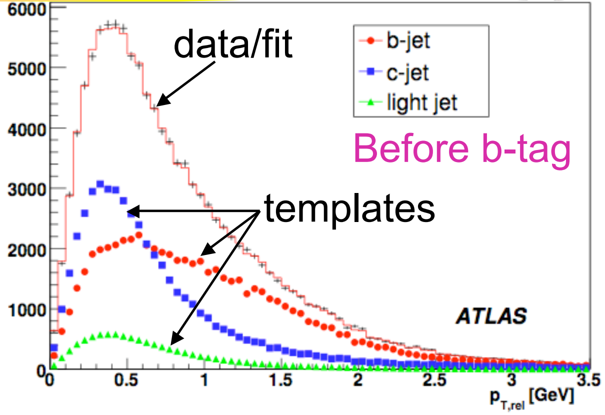
  - P_i can be measured from inclusive negative d_0/σ tail
  - Combine P_i for all tracks in jet, get JetProb P_{jet}
    - Can calculate P_i in categories of track quality
    - Performance is inferior to more sophisticated taggers, but easier to calibrate at start
  - Correct for long-lived decays and negative tail flavour dependence using scale factors from MC
    - Once understood, extend to more complex taggers



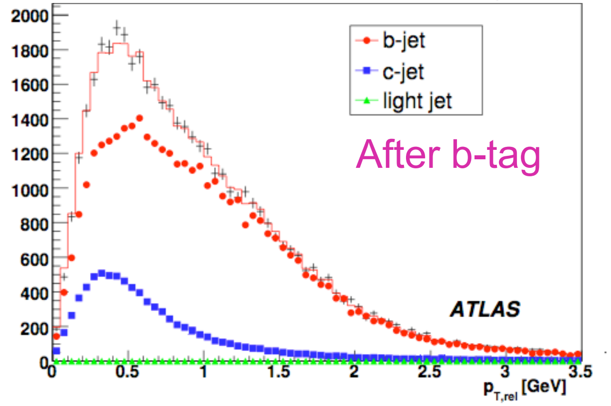


Measuring ε_b with di-jet events - $p_T$rel method

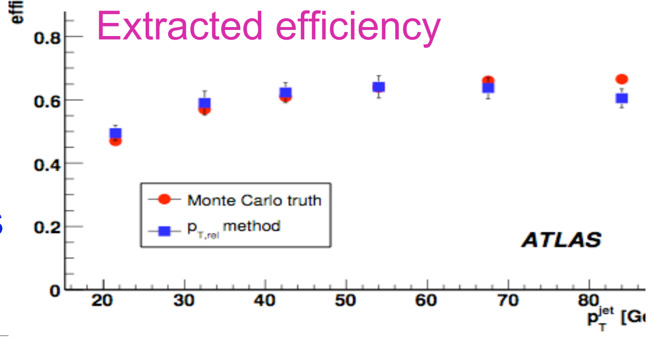
- Select a sample of events with jets containing muons
  - Majority from b,c decays - transverse momentum of muon wrt jet axis (p_{Trel}) larger in b-decays
  - Take templates of muon p_{Trel} from MC b- and c-jets, and data uds, and fit samples before/after lifetime b-tag
    - Derive number of b-jets in each sample, extract ε_b
    - Can be done as a function of jet p_T and η
- Complicating factors …
  - Need to take b/c templates from MC - modelling syst
  - Take uds templates from QCD di-jet data - need to remove b,c contamination (heavy flavour prod, g→bb)
  - Little p_{Trel} discrimination above 80 GeV, method breaks
  - … Expect systematic error controlled to ~6% abs
  - Statistical error determined by trigger bandwidth devoted to muon-jet sample
    - Need online selection and prescaling as function of E_T
  - Additional MC correction for jets w/**hadronic** b-decays



Before b-tag



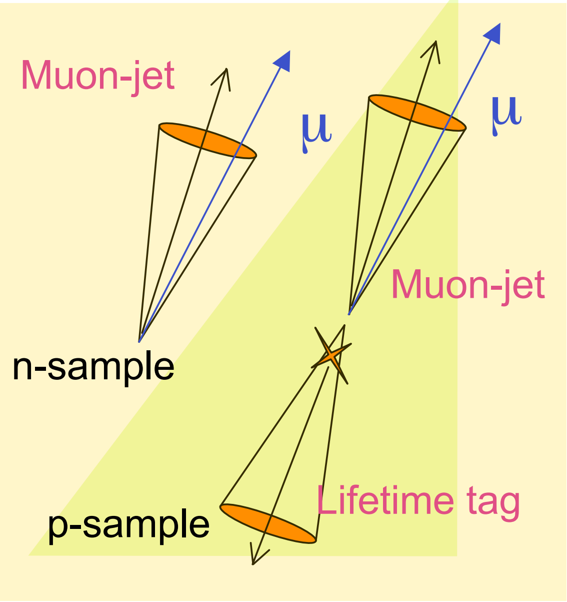
After b-tag

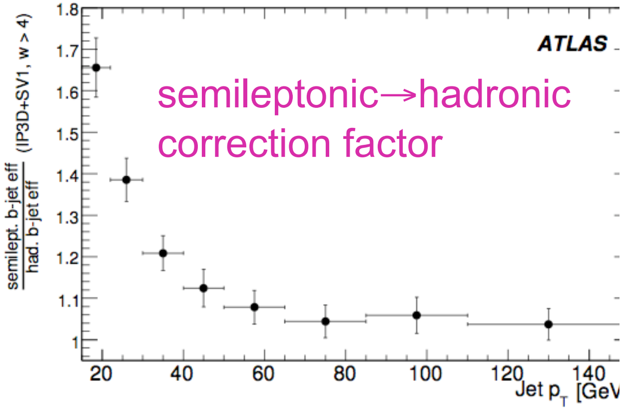


Extracted efficiency

Measuring ε_b with di-jet events - System8

- Again, exploits two samples with different b-fractions
  - Muon-jet sample (n), and sample (p) with additional requirement of a lifetime tag on opposite jet
  - Then measure fraction of muon-jets tagged by:
    - Muon with signifcant $p_T$rel
    - Lifetime tagger under test (~uncorrelated to muon-tag)
  - Measure n, p, n^{μ}, p^{μ}, n^{LT},p^{LT},n^{both},p^{both}, and solve 8 equations for unknowns including ε_b of LT tagger
- Complicating factors
  - Tags are not quite uncorrelated, and n/p samples do not have same ratio of charm to uds jets
    - Correction for this requires large MC samples…
  - Muon p_{Trel} tag has limited performance for E_T>80 GeV
  - Expect systematics to be around 6% as for p_{Trel} method
    - Can perform measurement as fn of E_T and η, given stats
  - Have to correct efficiencies to apply them to **hadronic** b-decays - correction factor is large below 40 GeV

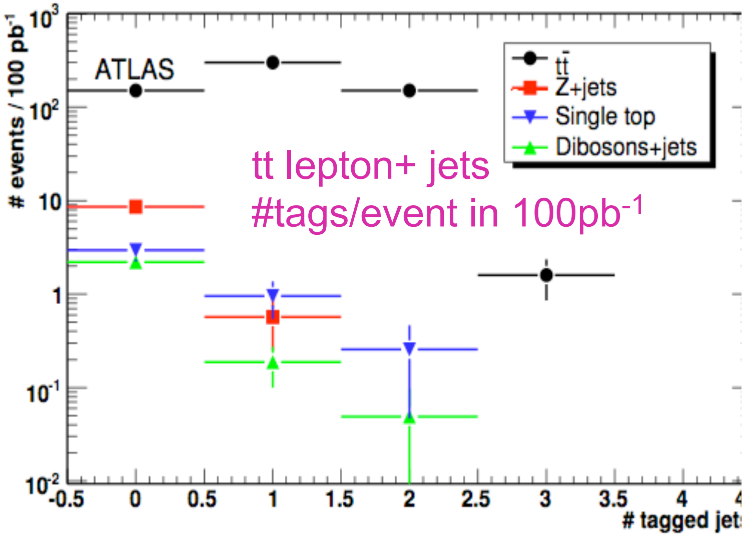




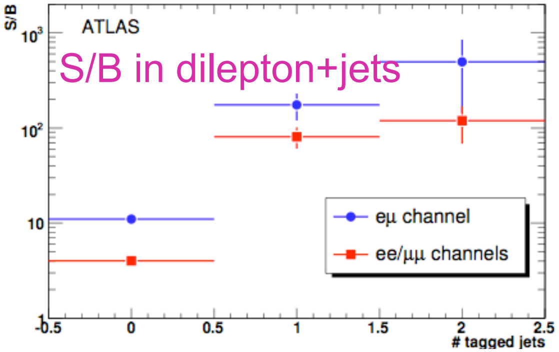
semileptonic→hadronic correction factor

Counting b-tags, rediscovering top

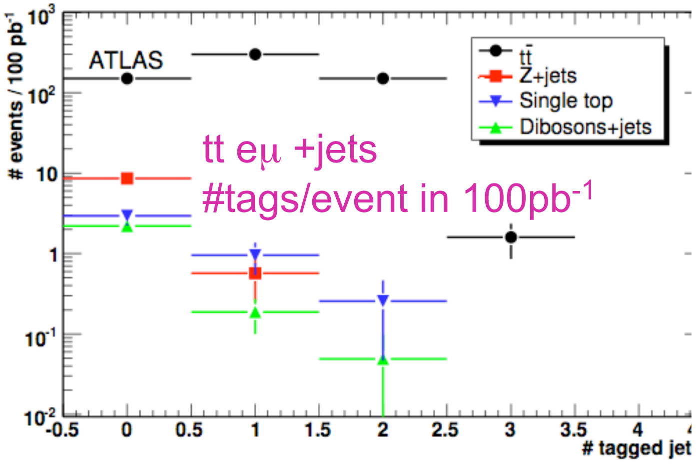
- ‘Classical’ top discovery analysis …
    - Select events with lepton (p_T>20 GeV), missing-E_T>20 GeV, 4 jets E_T>30 GeV
        - Count number of jets which are b-tagged, excess signals presence of ttbar events
    - Assuming kinematic acceptances and ε_{uds} from Monte Carlo, fit to extract ε_b, ε_c and σ_{tt}
        - Can get ε_b to ±3% (stat) ±3% (syst) in 100 pb^{-1}
        - Systematics dominated by knowledge of ISR/FSR
- Can also use dilepton events ee/μμ/eμ
    - Veto dilepton mass around Z resonance
        - Can get ε_b to ±4% (stat) ±4% (syst) in 100 pb^{-1}
- Mixed di-lepton mode could be source of pure b-jets
    - Tag one b-jet … other should have very high probability to be b
    - … to be studied



tt lepton+ jets
#tags/event in 100pb^{-1}



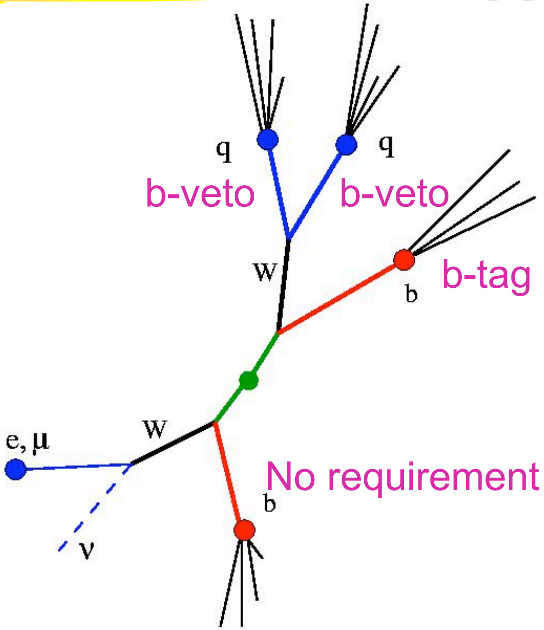
S/B in dilepton+jets

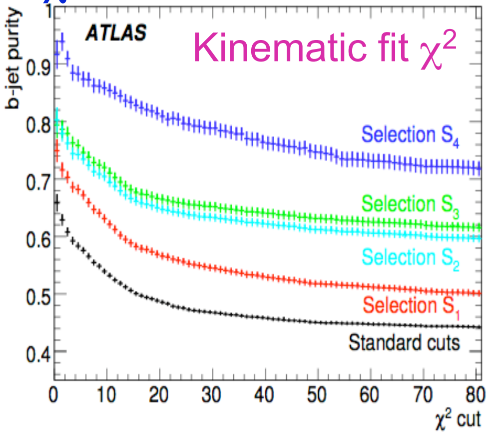


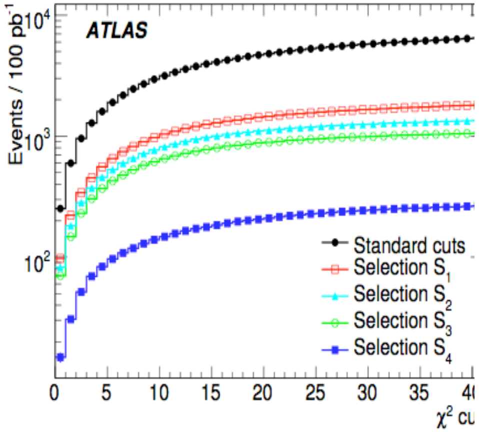
tt eμ +jets
#tags/event in 100pb^{-1}

Selecting ‘pure’ samples of b-jets

- Exploit topology / kinematics of semileptonic tt events
  - Standard lepton+4 jets selection, assign jets to tops
    - Typically tag **one** b-jet (associated to hadronic top), but do not look at b-tagging info on other b-jet (leptonic top)
  - Many jet permutations to be considered
    - Especially in events with >4 jets (ISR/FSR jets)
- Choose the ‘correct’ combination in various ways:
  - **Topological** selection based on recon top masses
  - **Likelihood** selection using jet/lepton p_T and angles
  - **Kinematic** fit-based selection, using fit χ^2 for each comb^n
- Select samples of ~few 100 jets in 100 pb^{-1}, purity 70-90%
  - Higher purity (but lower statistics) as jet E_T increases
  - Trade off between b-jet sample purity and data statistics … only a few % of the tt sample is used

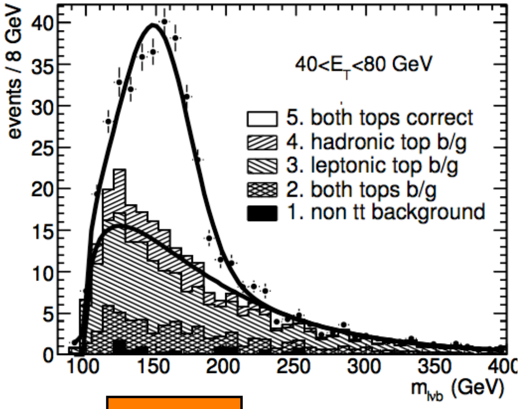


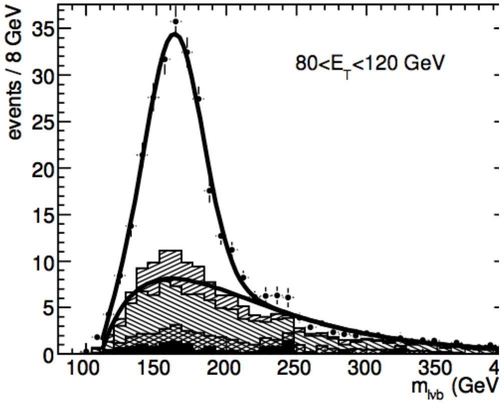




Measuring b-tagging efficiency

- Various ways to subtract background from b-jet sample
  - Define a control region with similar b/c/uds flavour mixture in data
  - Use Monte Carlo templates to fit contamination
- End up with a subtracted sample which is ‘statistically’ pure in b-jets
  - Then can study distribution of b-tag weights on this ‘unbiased’ sample to determine efficiency - to around 5% in 100-200 pb^{-1}
  - Have to determine ε_b in bins of jet E- due to changing sample purity
  - With enough statistics, can look at other variables (η, jet environment)
    - To be further developed …

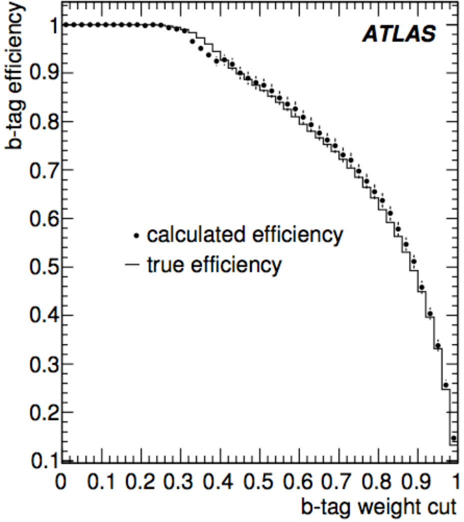




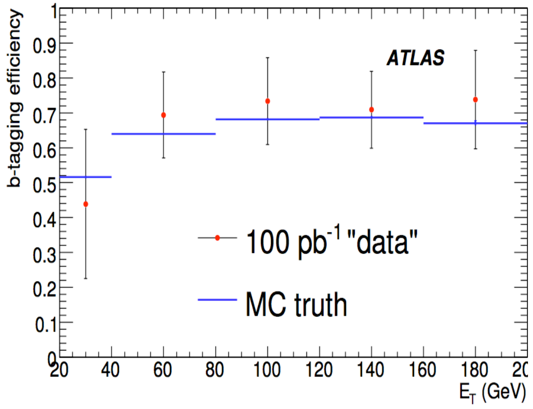
signal

sideband

Topological selection

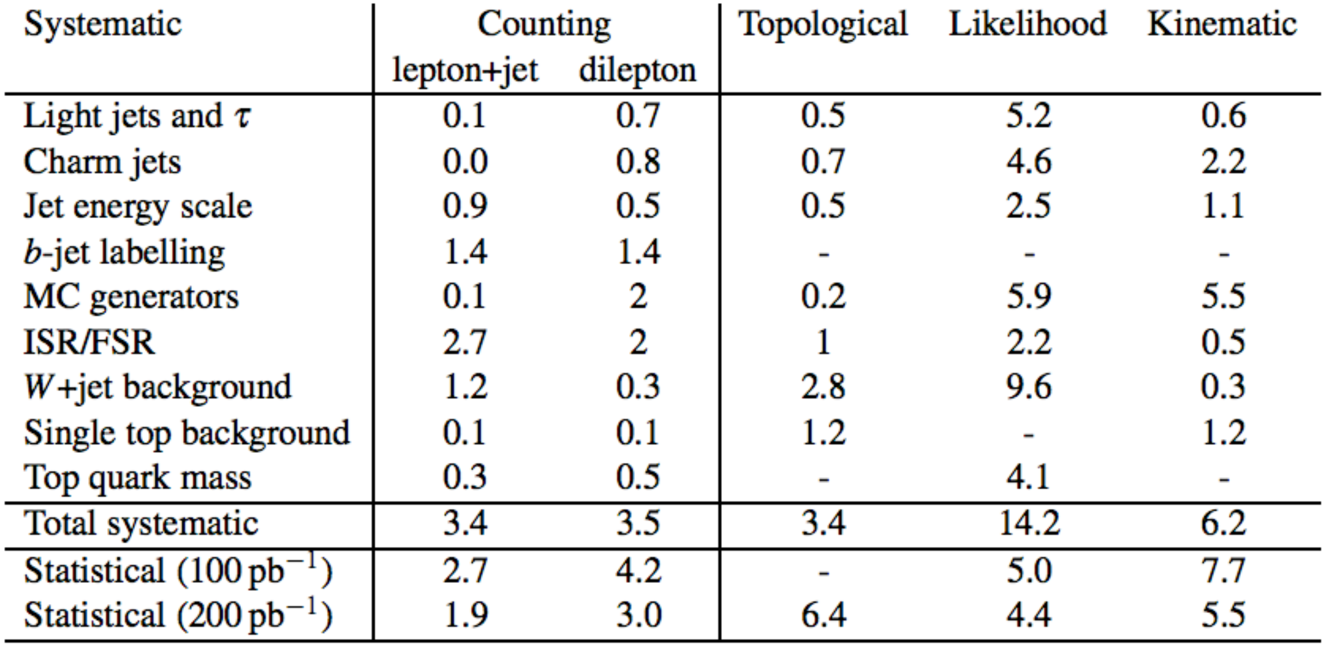


Likelihood selection



B-tagging efficiency results with top

- Systematic uncertainty summary for counting and b-jet selection methods
  - Relative errors in %, for a b-jet efficiency working point of ε_b=0.6

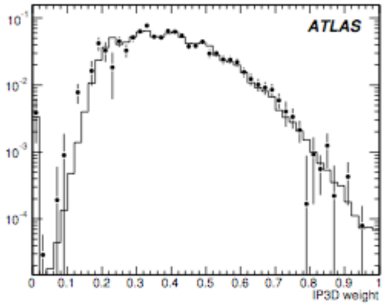


Systematic	Counting		Topological	Likelihood	Kinematic
	lepton+jet	dilepton			
Light jets and τ	0.1	0.7	0.5	5.2	0.6
Charm jets	0.0	0.8	0.7	4.6	2.2
Jet energy scale	0.9	0.5	0.5	2.5	1.1
b-jet labelling	1.4	1.4	-	-	-
MC generators	0.1	2	0.2	5.9	5.5
ISR/FSR	2.7	2	1	2.2	0.5
W+jet background	1.2	0.3	2.8	9.6	0.3
Single top background	0.1	0.1	1.2	-	1.2
Top quark mass	0.3	0.5	-	4.1	-
Total systematic	3.4	3.5	3.4	14.2	6.2
Statistical (100 pb^{-1})	2.7	4.2	-	5.0	7.7
Statistical (200 pb^{-1})	1.9	3.0	6.4	4.4	5.5

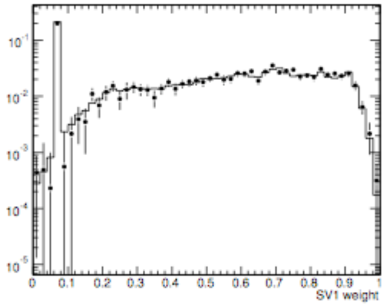
- Counting method is most precise, but cannot study dependencies (jet E_T, η)
  - Other methods will become more useful as luminosity increases
- All studying performance in top event environment - complementary to di-jet

Towards ultimate performance

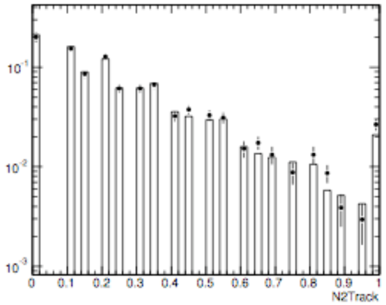
- As integrated luminosity increases:
  - Commission more complex taggers
    - Need to understand input distributions, check data/Monte Carlo distributions
  - Feedback discrepancies to tune MC
  - Study dependence of tagging on environment (e.g. jet multiplicity)
  - Extend to higher jet energies
- Selecting b-jet samples can help
  - Cross-check Monte Carlo predictions
    - Use background-subtracted data distributions to check against MC prediction
  - Eventually use likelihood references based on real data distributions
    - Needs large statistics for n-dimensional distributions where correlations need to be taken into account



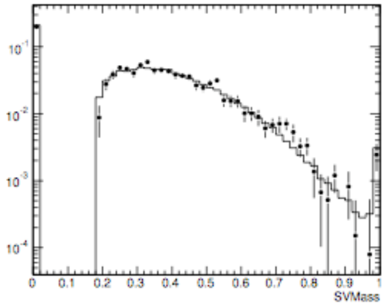
IP3D weight



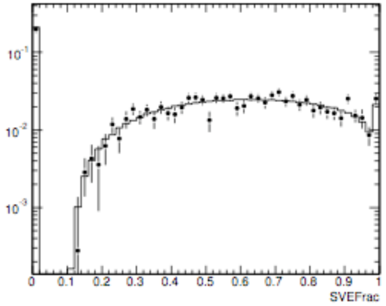
SV1 weight



N2Track vtx



SVtx mass



SVtx Efrac

Input variables for IP3D+SV1, for b/g-subtracted b-jet ‘data’ and MC for ~1 fb^{-1} (topological selection)

Conclusions

- B-tagging is very important for the ATLAS top physics program
- An enormous amount of work on b-tagging algorithms
  - Sophisticated multivariate lifetime-based algorithms to extract ultimate performance
    - Need to focus now on simpler algorithms for startup (e.g. JetProb with ‘symmetric’ performance on jets without lifetime)
  - Lepton-based taggers also well-developed
    - Less performant, but small-correlation with lifetime-based algorithms, essential for calibration and cross-checks during commissioning
- Commissioning requires
  - Good understanding of detector performance, in particular tracking
  - Rapid progress in alignment - especially track-based alignment
  - Methods to measure mistag rate from data
  - Methods to measure efficiency from data
    - Di-jet events with dedicated trigger
    - ttbar for ‘in-situ’ measurement of performance in the environment where it will be used
- Eventually use ttbar events to improve MC simulation of b-jets and tune the b-tagging performance on data