Top quark physics at the LHC

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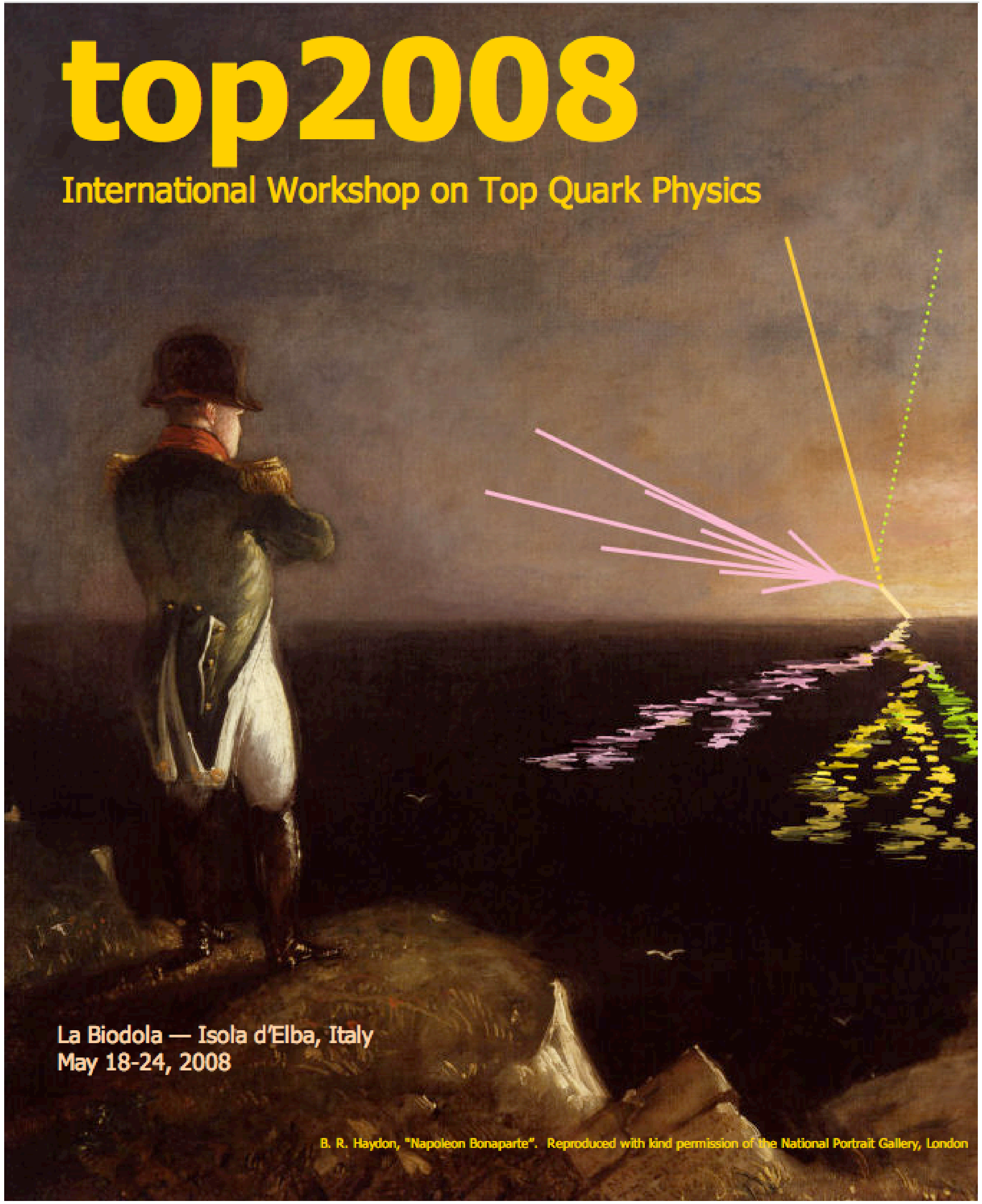
@ HCPS 2008

Last week...



More info on:

Conference agenda

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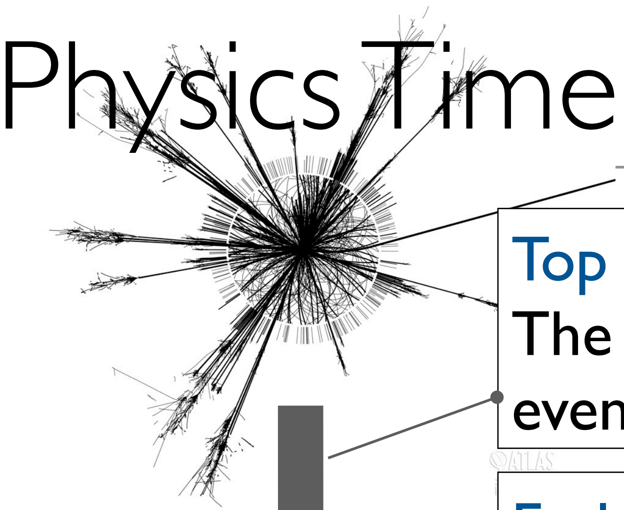
Top Physics Timeline at the LHC



10 pb^{-1}

Top for commissioning:
The first observation of the top quark is a landmark event for the initial detector commissioning.

Early Measurements:
tT cross section will be among the first top physics measurements to be made.

100 pb^{-1}

Top for calibration:
The top mass and the tT topology are strong tool for understanding the detector.

1 fb^{-1}

Top as background:
Good understanding of the top is crucial to the discovery of new physics.

10 fb^{-1}

Precision measurements:
Precision-measurement of top properties and single top can be performed with accumulated data.

100 fb^{-1}

Discovery through top:
Study of the top quark may itself lead to the discovery of new physics.

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Top-physics topics of interest

tT cross section :

- tT semileptonic (lepton + jets)
- tT dileptonic
- tT fully hadronic

Top mass:

- tT semileptonic (using hadronic jets)
- tT dileptonic (using leptons)

Top property:

- top charge
- top width
- tT spin correlation
- W helicity
- Yukawa coupling
- anomalous coupling
- resonance production

Single top measurement:

- s-, t-, Wt cross section
- Vtb measurement
- top polarization

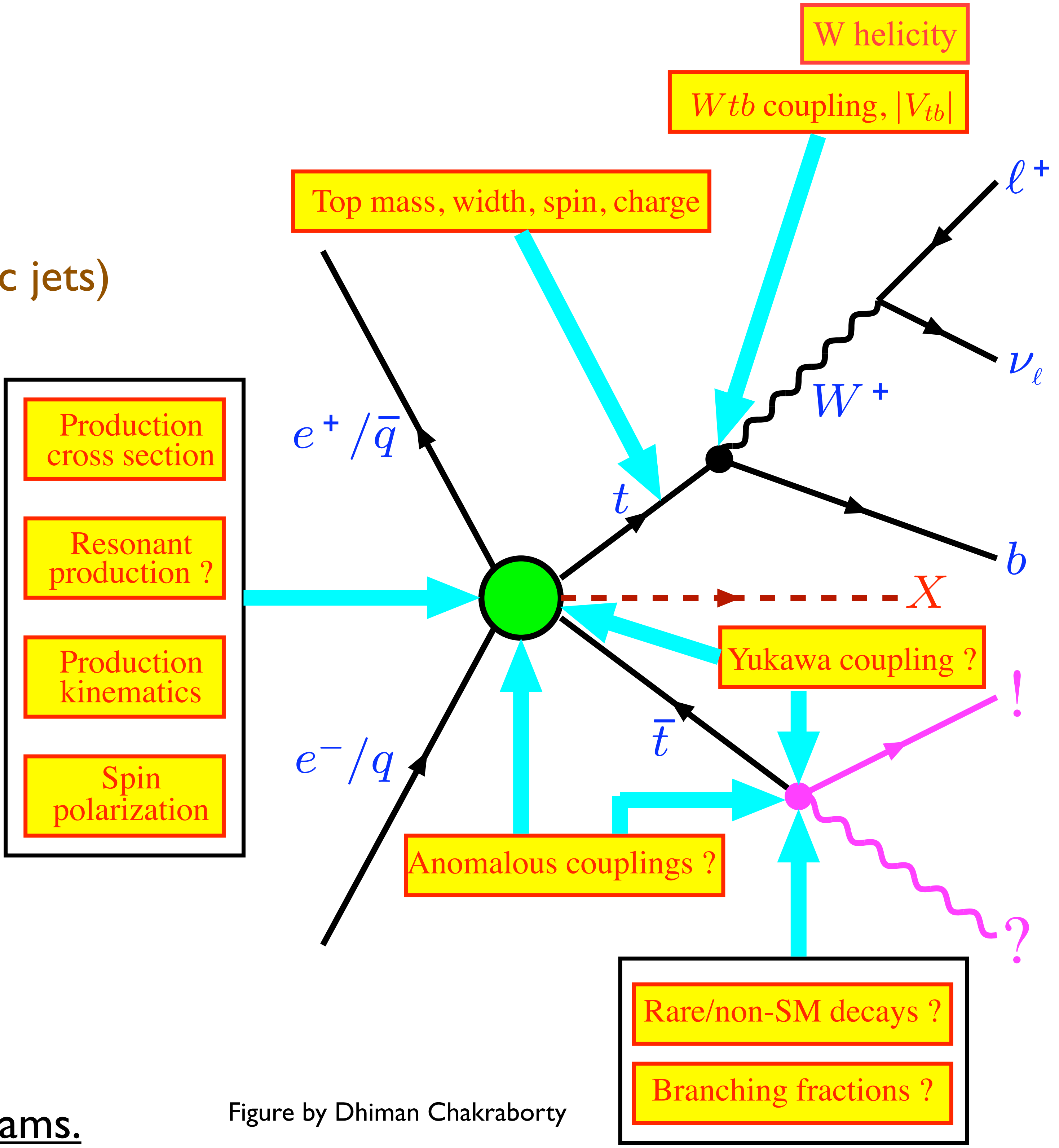


Figure by Dhiman Chakraborty

A rich collection of physics programs.

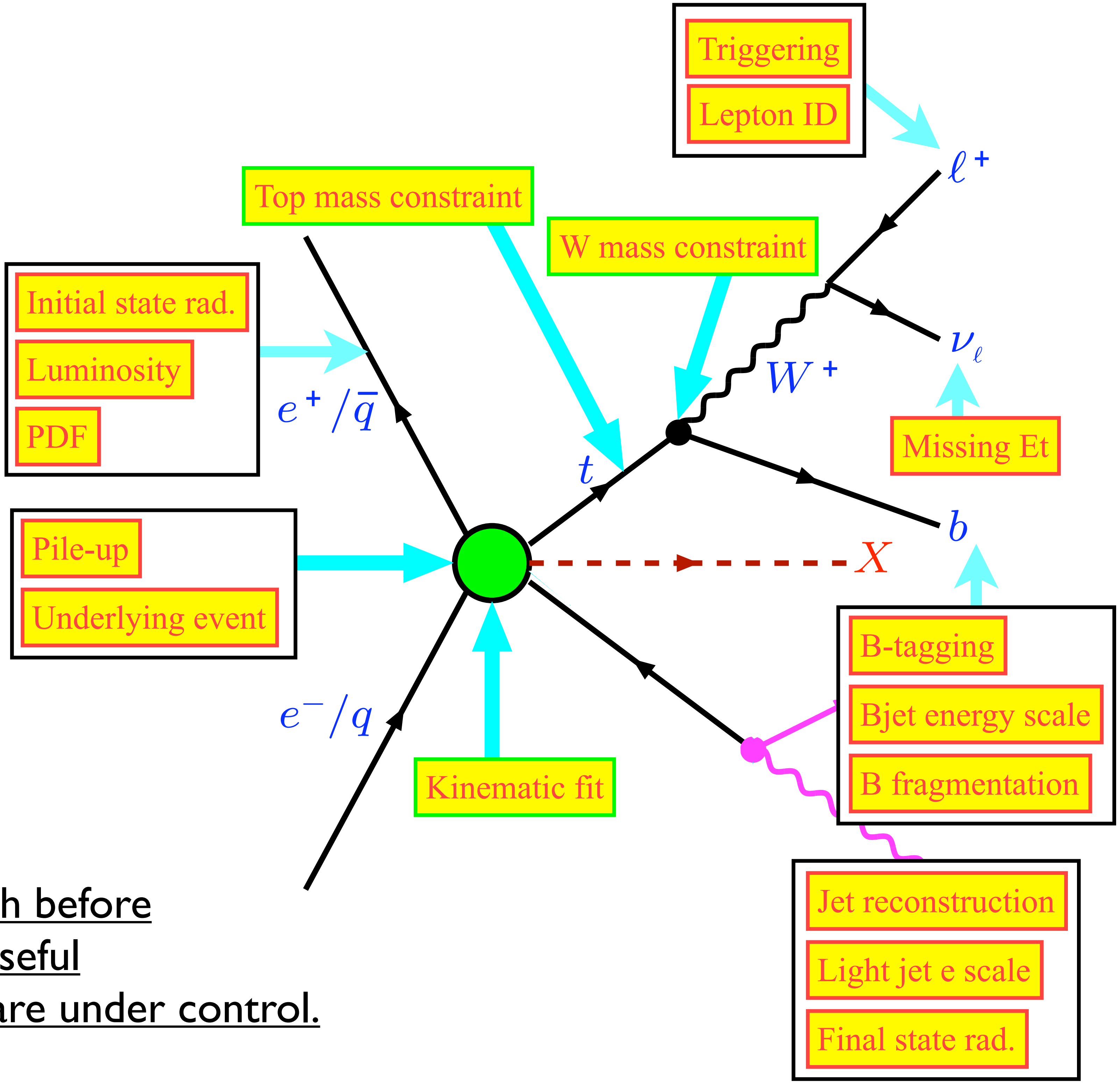
Experimental issues and known constraints

Uncertainties that affect measurements :

- Trigger efficiency
- Lepton identification
- Missing Et measurement
- B-tagging efficiency
- Light/b jet energy scale
- QCD activity (MI, ISR/FSR)
- Beam related issues (Pile-up, Luminosity, PDF)

Useful “known” constraints :

- W mass
- Top mass, branching ratio
- tT event topology



A number of issues to be dealt with before measurements. Also a number of useful experimental handles once things are under control.

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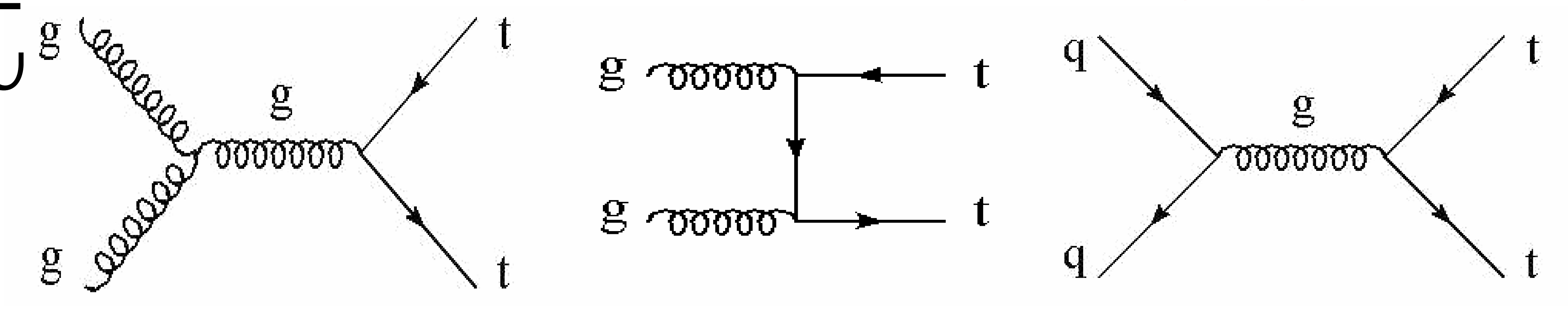
Top production, Tevatron to LHC

The bigger the bang, the more exciting the result!

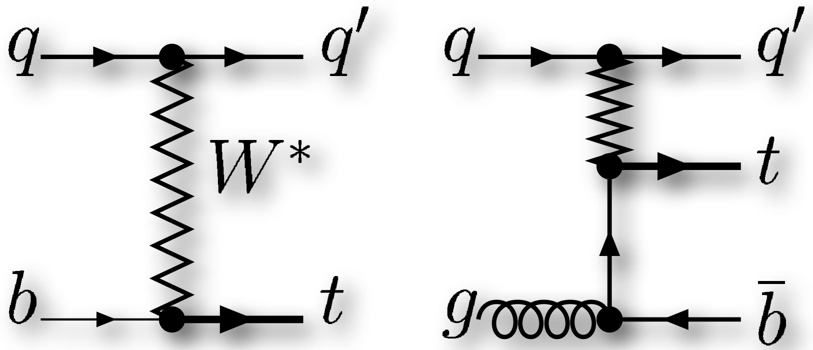
proton-antiproton vs proto-proton
$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ vs $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (design)
1.96 TeV vs 14 TeV (design)

$t\bar{t}$

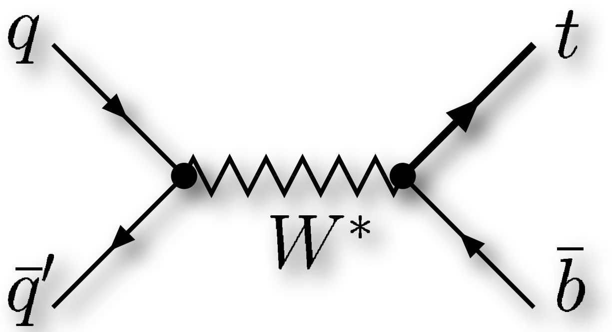


85% qqbar initial state (right) vs 90% gluon-gluon initial state (left)
10 tt pairs per day (6.77 pb) vs 1 tt pair per sec (833 pb)
>> ~1/2 wih 10 TeV

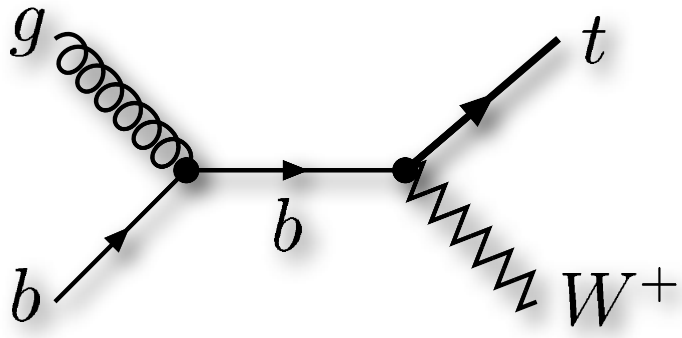
Single top



t-channel
1.72 pb vs 244.6 pb

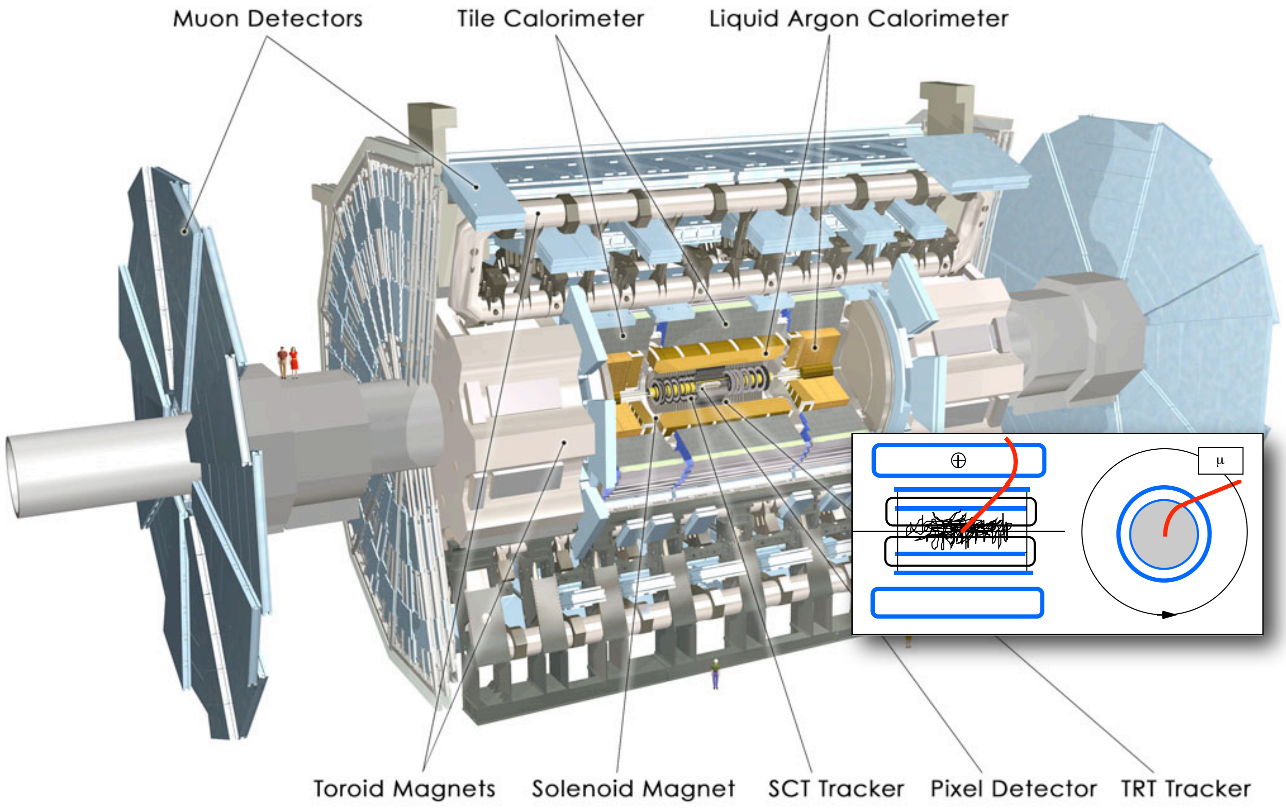


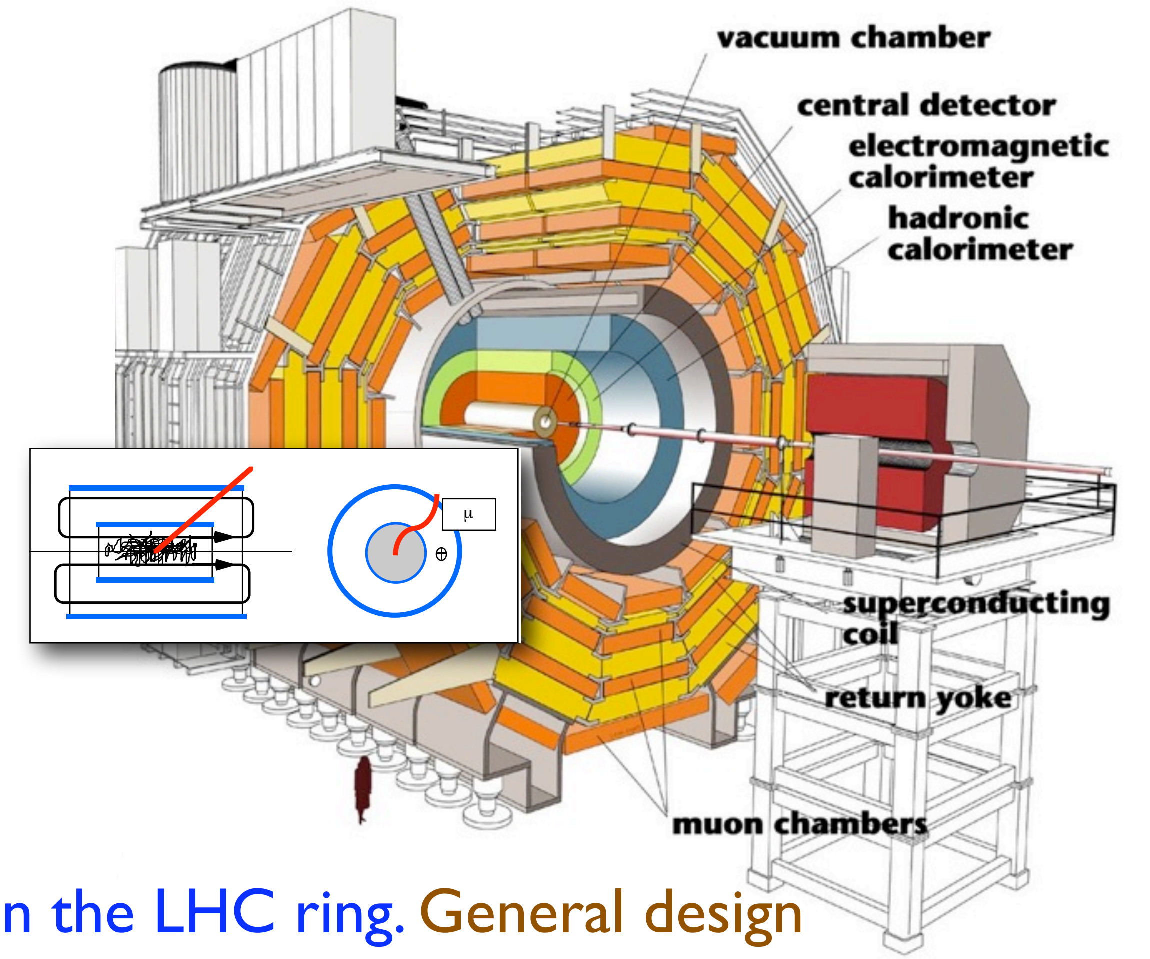
s-channel
0.82 pb vs 10.65 pb



Wt-channel
0.14 pb vs 62.1 pb

ATLAS vs CMS





- Two competing general purpose detectors on the LHC ring. General design concepts are similar: (from the center) inner tracking detectors, solenoid magnet, presampler, electromagetic calorimeter, hadronic calorimeter, toroid (ATLAS) / solenoid (CMS) muon magnet and muon spectrometers.
- Current "results" based on studies using Monte Carlo generators and detector simulation. CSC notes from ATLAS and TDR from CMS are the main source of this talk.
- Both experiments preparing for real data! Full Dress Rehearsal (ATLAS) and Computing, Software and Analysis Challenge (CMS) are stress testing their analysis facility.

What to expect with early data?

- Unknown unknown
  - Something unexpected, we might not have data as expected in 2008 :-(
- Known unknown
  - Jet calibration is off and with large uncertainty.
  - Poor inner detector performance - no useful b-tagging
  - Unreliable missing E_T
  - Efficiency (trigger/offline reconstruction) not well measured
  - Large uncertainty on luminosity
  - Lots of bad runs
- Known known
  - Top observation will not be the first publication but it will indicate the readiness of the "discovery machine".
  - Observability of top is high. Ten days of good run (at 10^{31} initial lumi = ~10 pb^{-1}) will provide enough data.

- Minimum requirements
  - ID, EM calo, Had calo to trigger and reconstruct leptons and jets.

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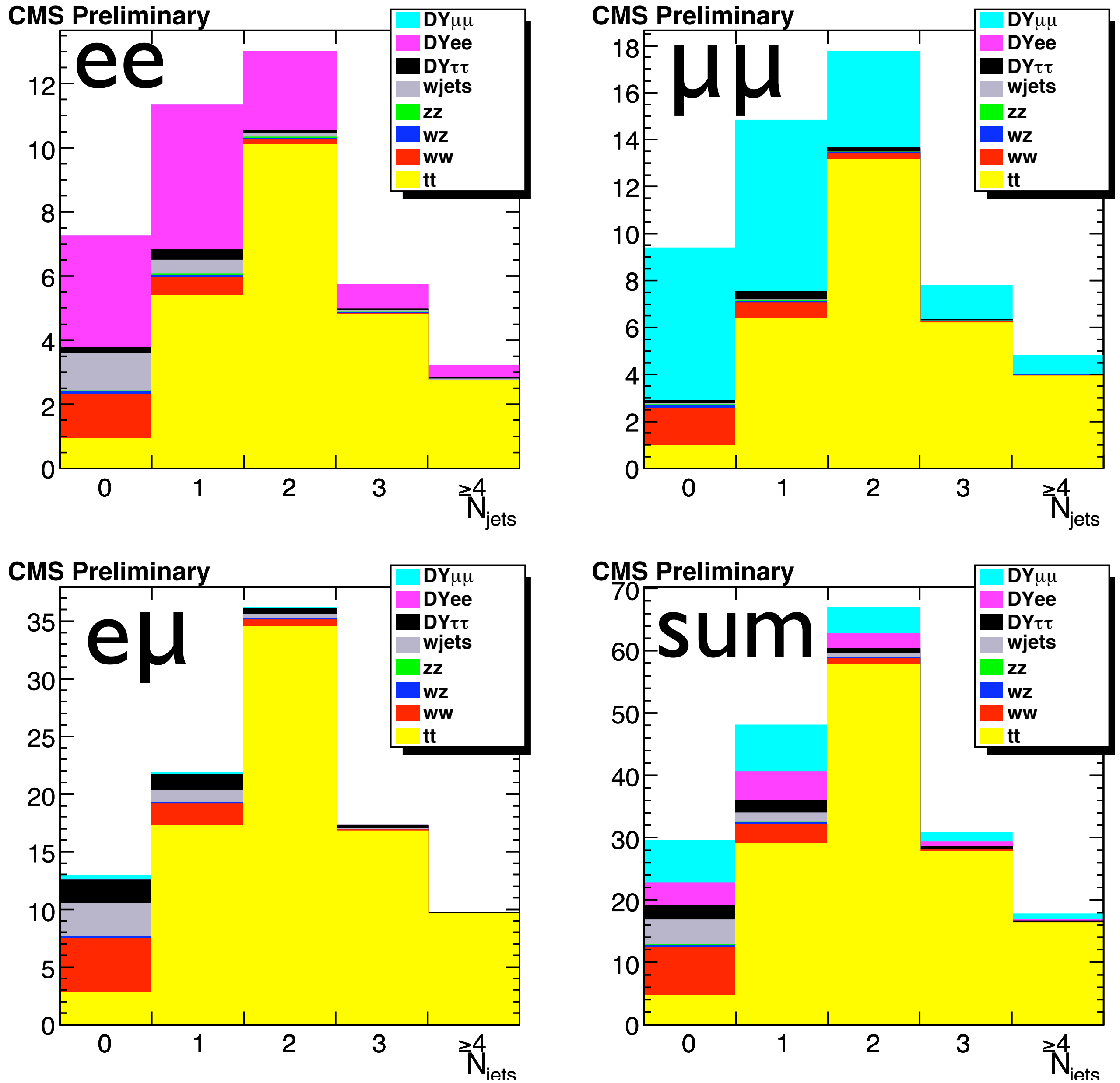
Early top measurements - Dileptonic

- Trigger
  - Single e ($p_T>16$ GeV) or single μ ($p_T>17$ GeV)
  - very high efficiency
- Lepton ID
  - Two opposite charge with $p_T>20$ GeV
  - isolated (calo/track)
- Missing Et
  - > 20 GeV for eμ
  - > 30 GeV for ee and μμ
  - Additional cuts for ee/μμ to remove fake from Drell-Yann
- Remove ee/μμ invariant mass within 15 GeV of M_Z

▶ Count the number of jets with $p_T>30$ GeV, no b-tag!

tT, Wj, Zj - Alpgen (NLO K fact. MCFM)
Dibosln - Pythia



Somewhat large DY in ee/μμ, clear advantage in eμ. Estimate bkg from 0/1 jet bins, count number of ≧2 jet events. At 10 pb’ combined Δσ/σ ~ 9%. ~13% with eμ only. Expect systematics of the same order.

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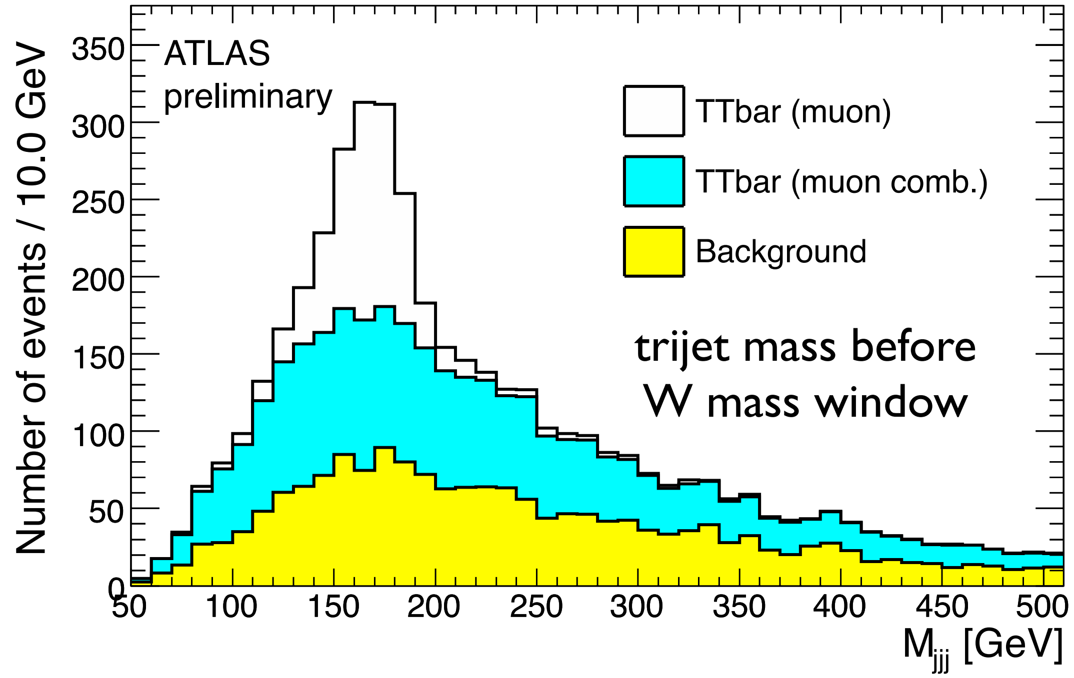
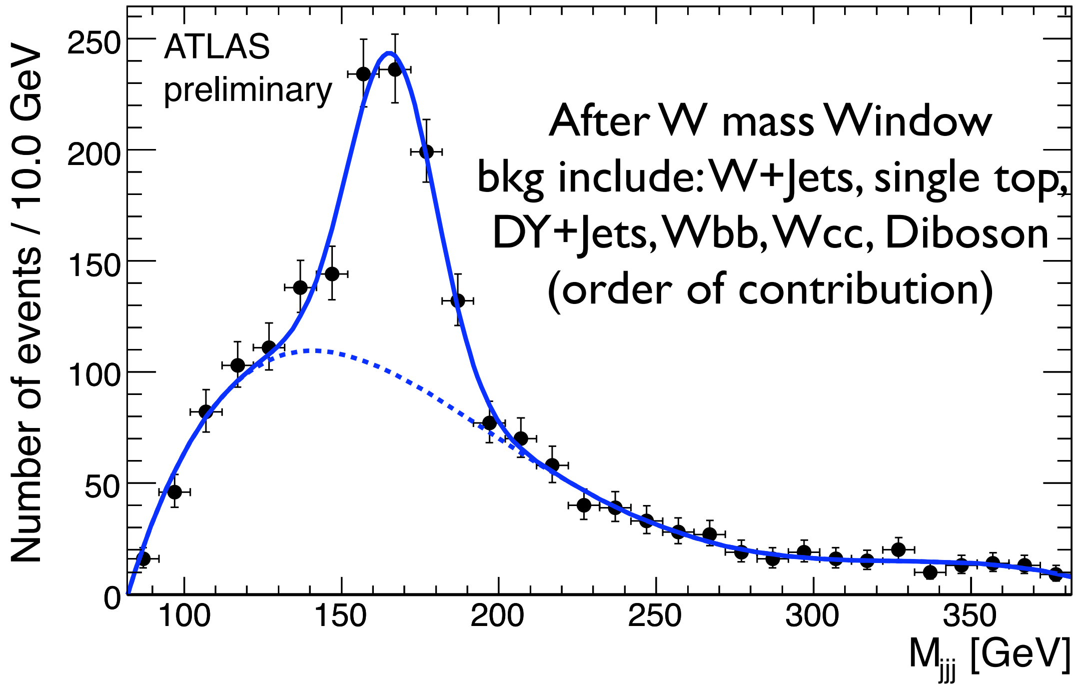
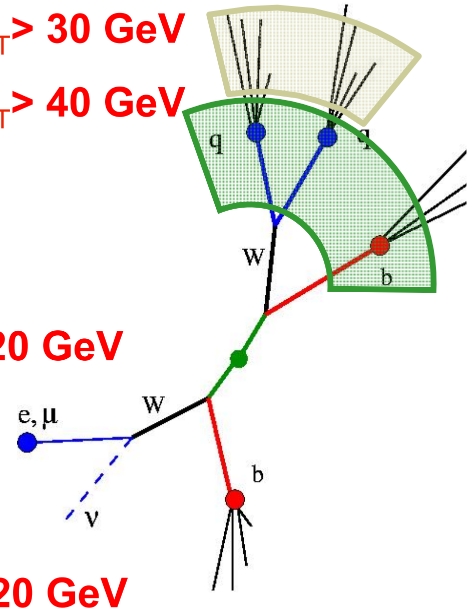
Early top measurements - Semileptonic

“Commissioning tT analysis”







4 jets p_T> 30 GeV

3 jets p_T> 40 GeV

P_T^{lep} > 20 GeV

E_T^{miss} > 20 GeV

No b-tagging

ε^e=18.2%
ε^μ=23.6%
Half with W
mass Window

- Algorithm
  - Take tri-jet comb. with highest p_T.
  - Remove events if no dijet has mass ~ M_W.
- Likelihood fit method
  - Fit Gaussian (peak) and Chebyshev polynomial (background).
  - Subtract background and correct for efficiency using MC.
- Counting method
  - More sensitive to bkg normalization.

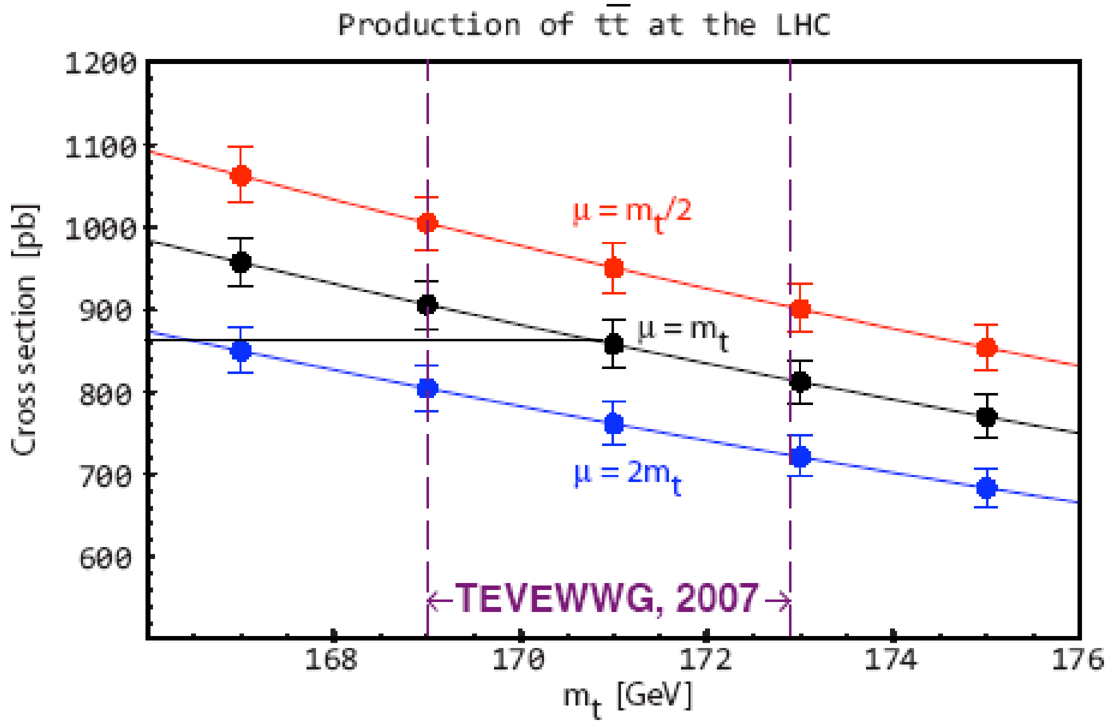
tT - MC@NLO and AcerMC (NLO K)
Wj,Zj - Alpgen (NLO K fact. MCFM)
Dibosln - Herwig

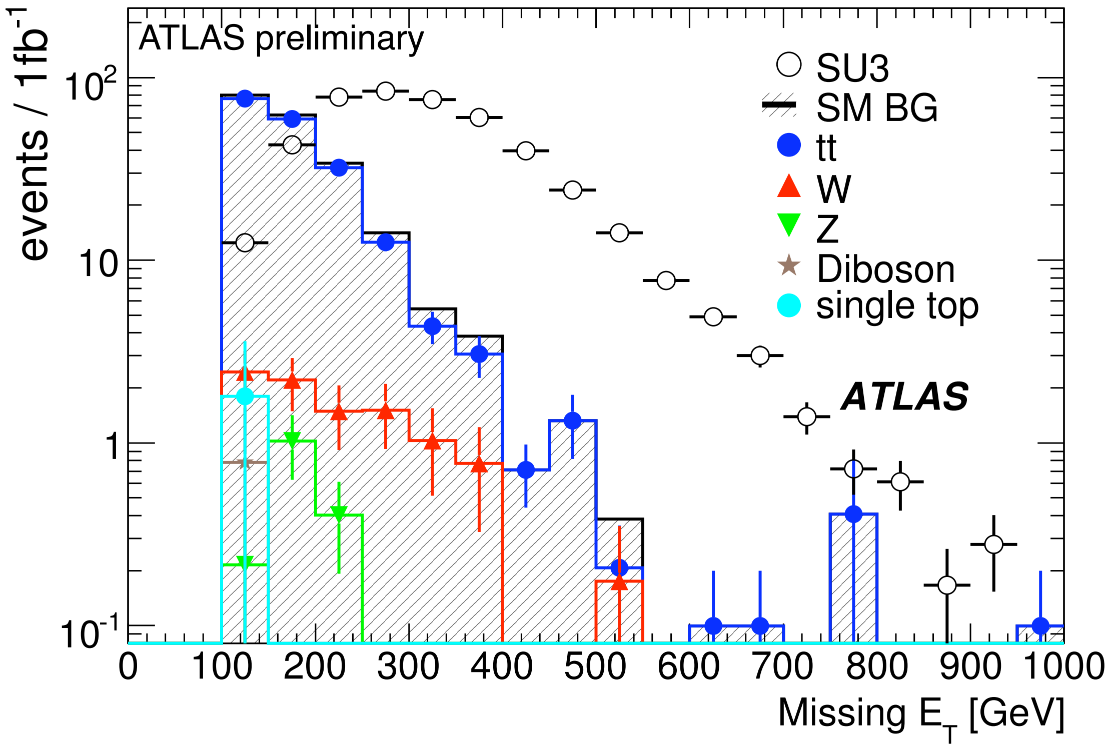
- Likelihood fit method: $\Delta\sigma/\sigma$ = 7(stat) ±15(syst)±3(pdf)±5(lumi)%
- Countingmethod: $\Delta\sigma/\sigma$ = 3(stat) ±16(syst)±3(pdf)±5(lumi)%

Top as background to new physics

Yesterday's discovery, today's background...

- Somewhat large theoretical uncertainty on tT production
  - Scale uncertainty ~12 % with NLO, may be reduced by half with full NNLO calculation (soon?)
  - Mass dependence ~6%, decreased with improved measurements.
  - Challenge at LHC to test.
- With lepton, jets and missing Et, top events are background to a number of other measurements
  - Higgs search (ttH, WH, H→ττ)
  - SUSY search (various signatures)
  - Twin Higgs Model (W_H->tb), etc, etc.
- MC based approach: use whatever generator and normalize to NLO.
  - Detector simulation in tail region is difficult and unreliable.
- Data driven tT background estimation is needed for new physics discovery.

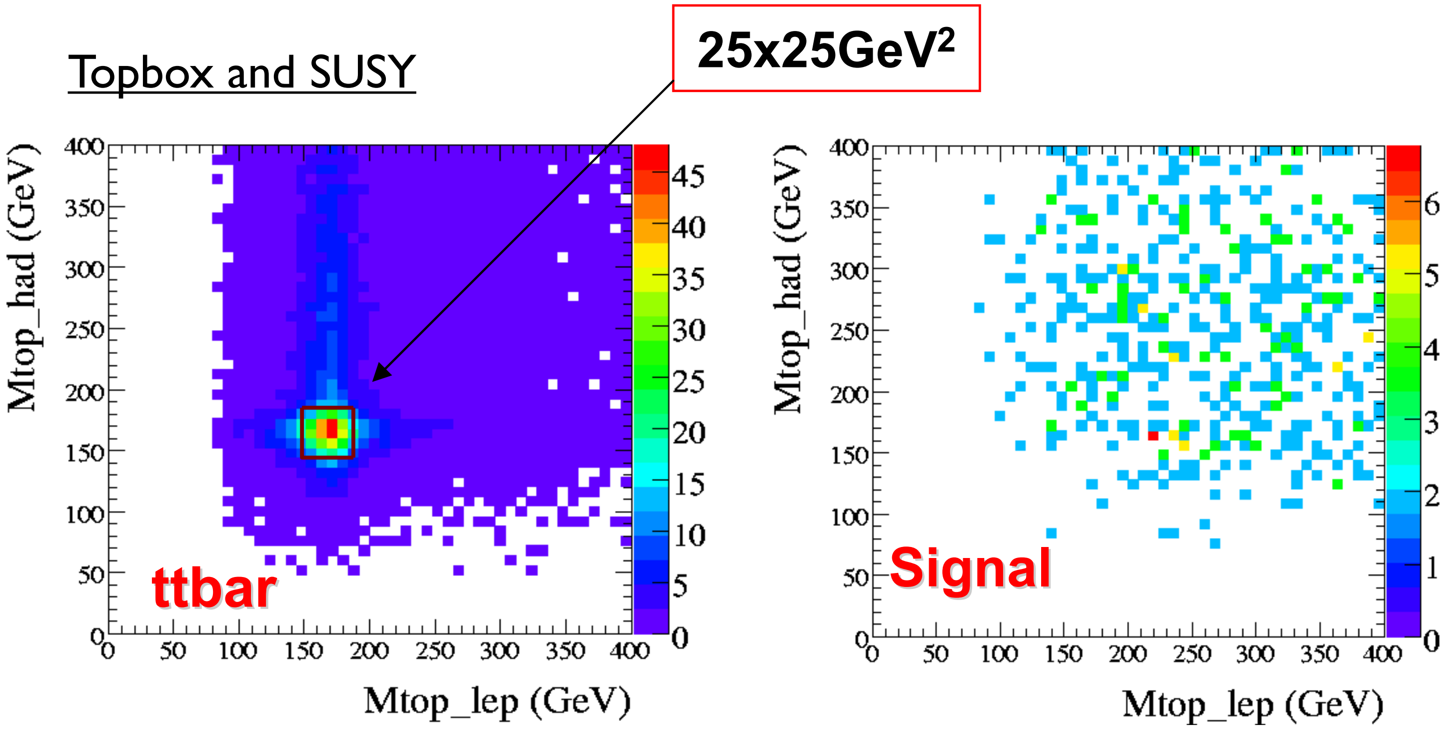




Top as background to new physics

or new physics as background to top?

Topbox and SUSY



SUSY contamination in ATLAS commissioning analysis

Event type	Electron analysis			Muon analysis		
	Trigger+Selection	W const.	m_t win	Trigger+Selection	W const.	m_t win
SU1	53	9	1	64	12	2
SU2	10	2	0.5	13	3	0.7
SU3	108	22	4	124	26	4
SU4	1677	541	155	2141	700	199
SU6	29	5	0.6	35	6	0.6
SU8	27	5	0.6	33	6	0.8

- Datad-driven background estimation needs a control region
  - Background-rich area (topbox, left) with little contamination from the signal is desirable.
  - May partially depend on MC (e.g. to estimate ratio between number in the box and outside.)
- Overlap between new physics and top can be large depending on signature.
  - SM top measurements can be contaminated with new physics.
- Crucial to compare measurements from all tT final states to verify global consistency.

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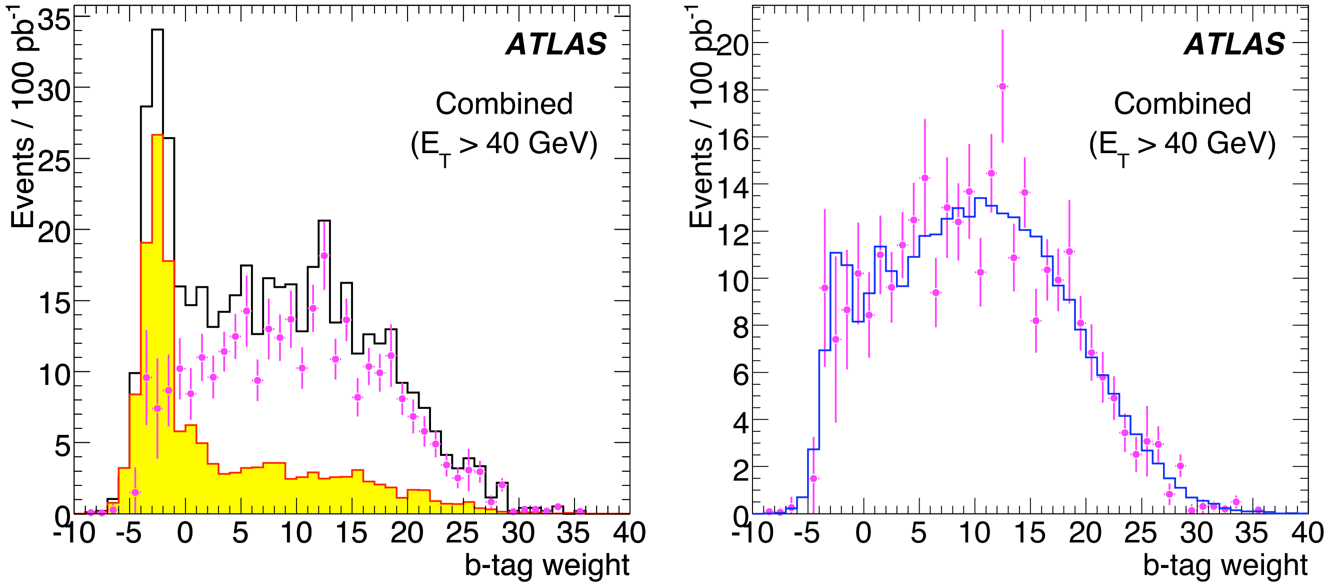
Top as a candle in the dark - B-tagging

		ε_b (%)		ε_c (%)		$\sigma_{t\bar{t}}$ (pb)
		true	meas.	true	meas.	
Lepton+jets	$w > 4$	72.1	71.7±0.7	22.3	21.9±1.5	841±9
	$w > 7$	60.4	59.8±0.8	12.8	13.8±1.3	844±10
	$w > 10$	48.1	47.4±0.9	6.7	8.2±1.4	832±13
Dilepton	$w > 4$	72.9	72.9±1.0	-	-	882±17
	$w > 7$	61.1	60.5±1.2	-	-	883±19
	$w > 10$	48.4	47.9±1.3	-	-	883±25

Estimated efficiency from counting method. 100 pb^{-1}

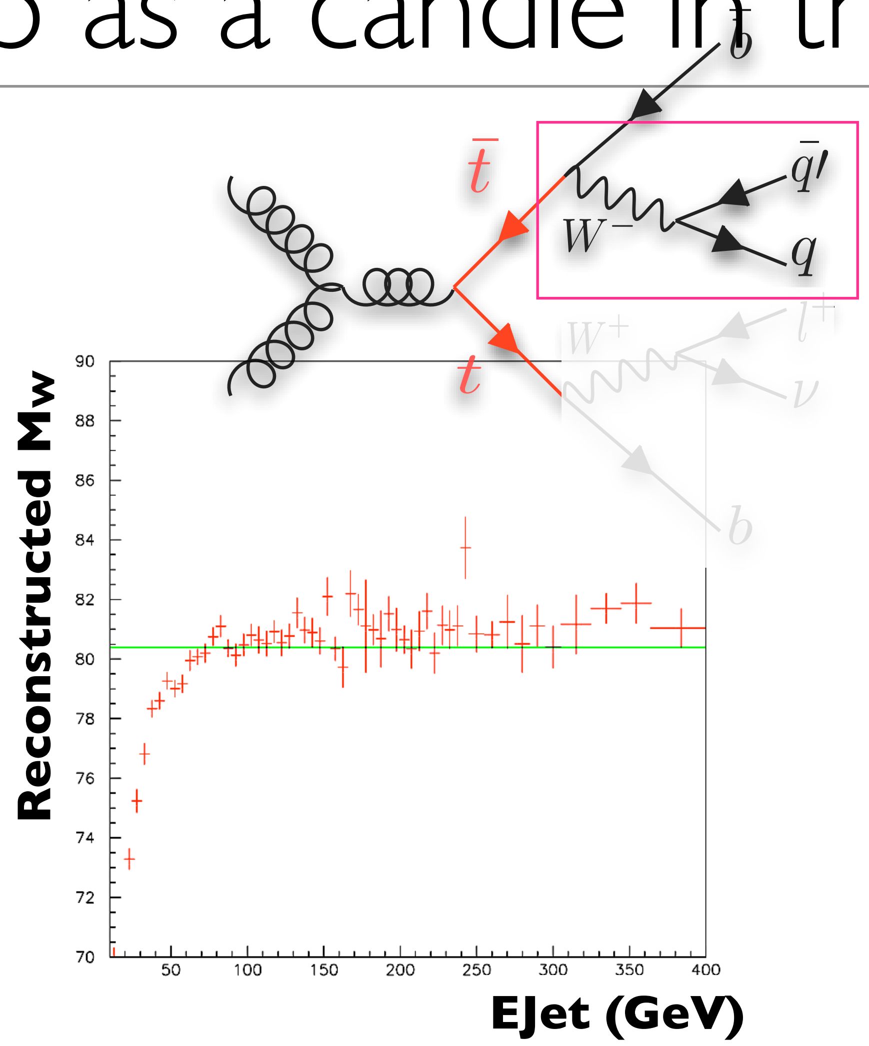


Estimated b-tag weight before and after background subtraction.
Kinematic fit was used to select the sample exploiting tT topology.

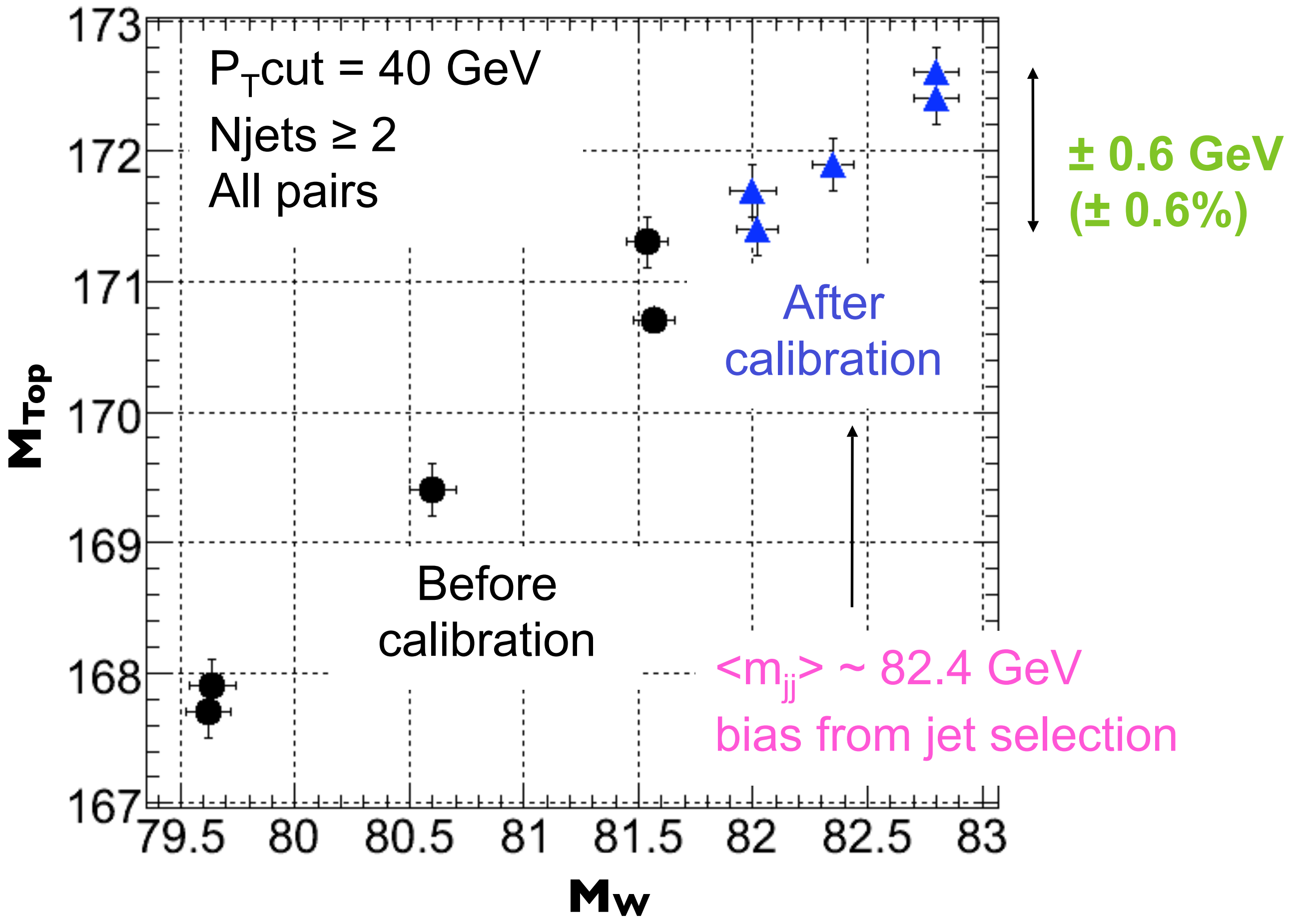
- Conventional b-tagging performance estimation
  - Measure rejection in inclusive jet samples
  - Measure efficiency using soft-lepton tagger
- An alternative method using tT
  - tT constraints can produce enriched b-jet sample.
  - Closer to the environment where b-tagging is used in physics studies.
- Methods proposed
  - Count number of events with different number of b-tagged jet. Only integrated efficiency measured.
  - Reconstruct tT to identify a pure sample of b-jets and measures efficiency as function of other variables.
  - Limited by background, statistically subtracted and the sample never completely pure.

▸ ~5% precision from counting method and ~10% from tT reconstruction method at 100 pb^{-1}. Very useful once enough data is available.

Top as a candle in the dark - JES



Ensemble test with scale variation



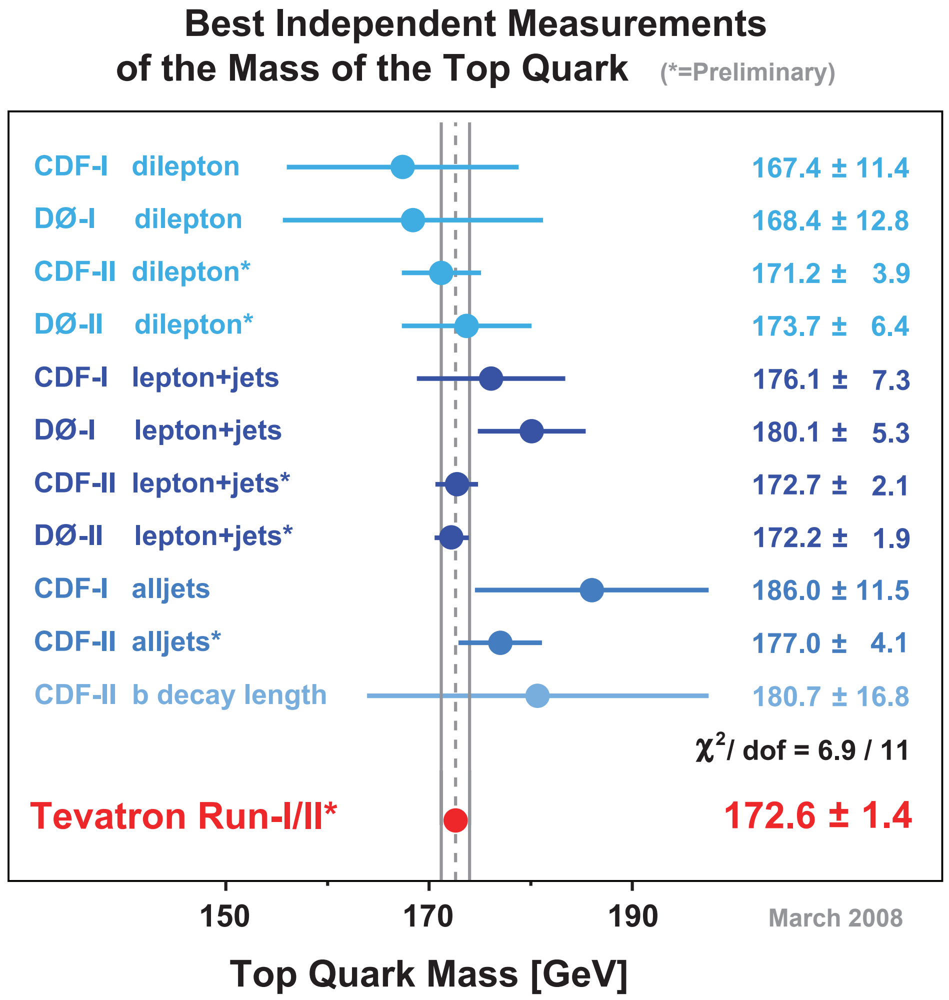
- Reducing dependency to the light jet energy scale by calibration using W hypothesis
  - Template fit for scale and resolution.
  - Important method to constrain quark-jet energy scale in general.
  - Simultaneous fit to JES and top mass stabilize measured top mass against jet energy scale uncertainty.
- Large out-of-cone energy at lower energy.
  - Even more of an issue with b-jets.
  - No good data-driven method to fix b-jet energy scale other than to fix top mass! (a method under development to extract b-jet energy scale independent of Mtop)

Top mass measurement

Top mass enters quadratically in loop corrections to the W mass, provides strong constraints on internal consistency of the Standard Model.

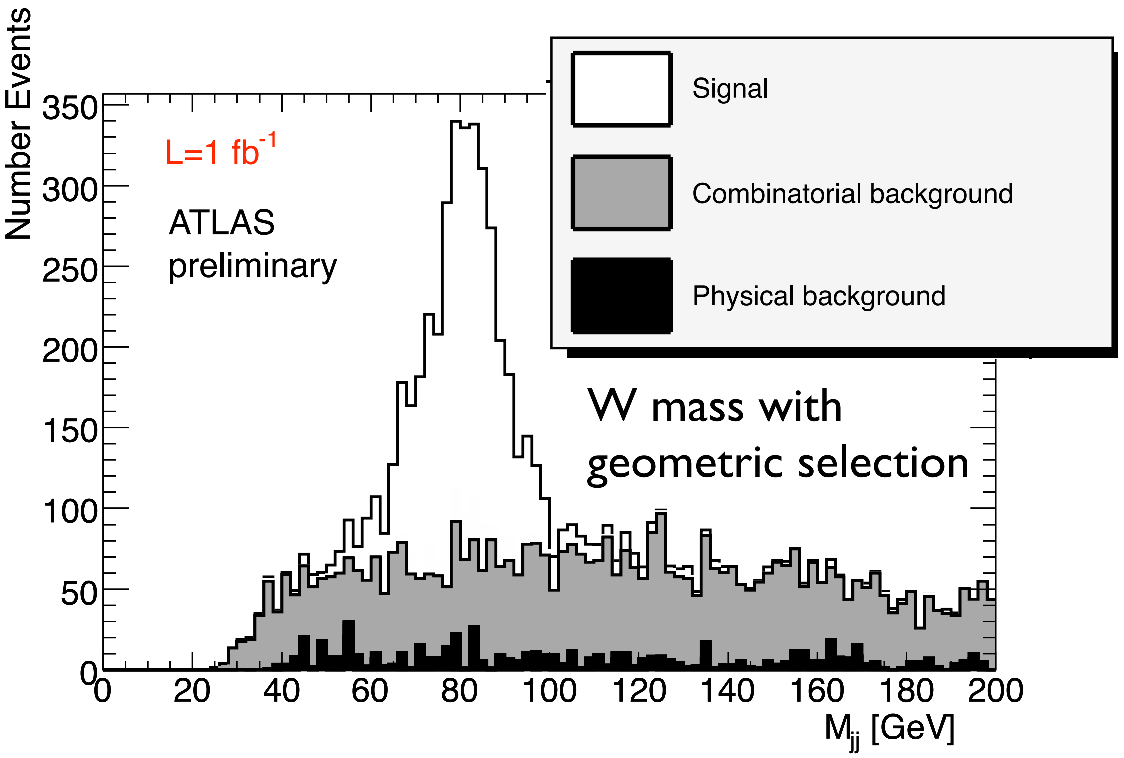
Methods

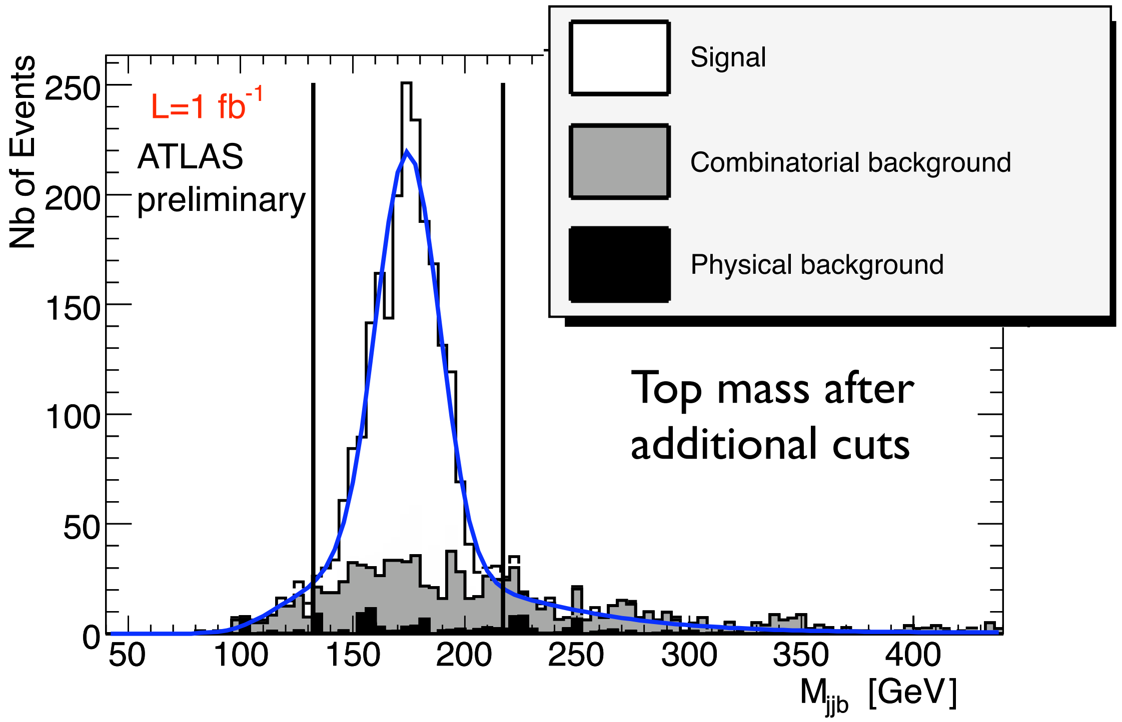
- Semileptonic channel
  - High branching ratio (~36/81)
  - Event over-constrained
  - Manageable background
- Dileptonic channel
  - Low background
  - Low branching ratio (~9/81)
  - Event under-constrained
- Fully hadronic channel
  - Event fully constrained
  - Huge QCD and comb. background
- “Pure leptons” tt->lvJ/Psi(l+l-)+X
  - No dependency on jet energy scale
  - Very small branching ratio (~$5.5*10^{-4}$)
  - Mass indirect using MC lookup
- Others
  - b quark decay length
  - lepton p_T



With ample statistics, possibility of competitive results from lepton based measurements, less sensitive to jet energy uncertainty. Aim for Δm_{top} < 1 GeV, a challenging goal.

Top mass in semileptonic channel





tT - MC@NLO and AcerMC (NLO K)
Wj,Zj - Alpgen (NLO K fact. MCFM)
Single Top - AcerMC

The “Golden” channel

- Trigger & Lepton ID & Missing Et > 20 GeV
    - Single e (p_T>25 GeV) or single μ (p_T>20 GeV)
    - Corresponding offline cut plus isolation (calo)
- ≧ 4 Jets p_T> 40 GeV, two of those are b-tagged
    - Tight cut to remove combinatorial bkg and sensitivity to scale issues including ISR/FSR.
- Geometric reconstruction (fit method also studied)
    - Select nearest (in ΔR) jet pair as W candidate. Select 2σ from pdg mass. Add b-tagged jet nearest to the W to form top.
- Additional cuts to reduce combinatorics
    - Mass of hadronic W + leptonic b-jet > 200GeV
    - Mass of lepton and leptonic b-jet < 160 GeV

- Purity 78% with 3σ of m_{top}. Efficiency is 0.82.
- Mass extracted from Gaussian + polynomial fit. 174.6 ±0.5 (stat 1fb^{-1}) ±0.2 (syst JES 1%) ±0.7 (syst B-JES 1%) ±0.4 (ISR/FSR and b-fragmentation) GeV
- JES extraction from W mass leads to 1% uncertainty at 1fb^{-1} but expect larger uncertainty on BJES.

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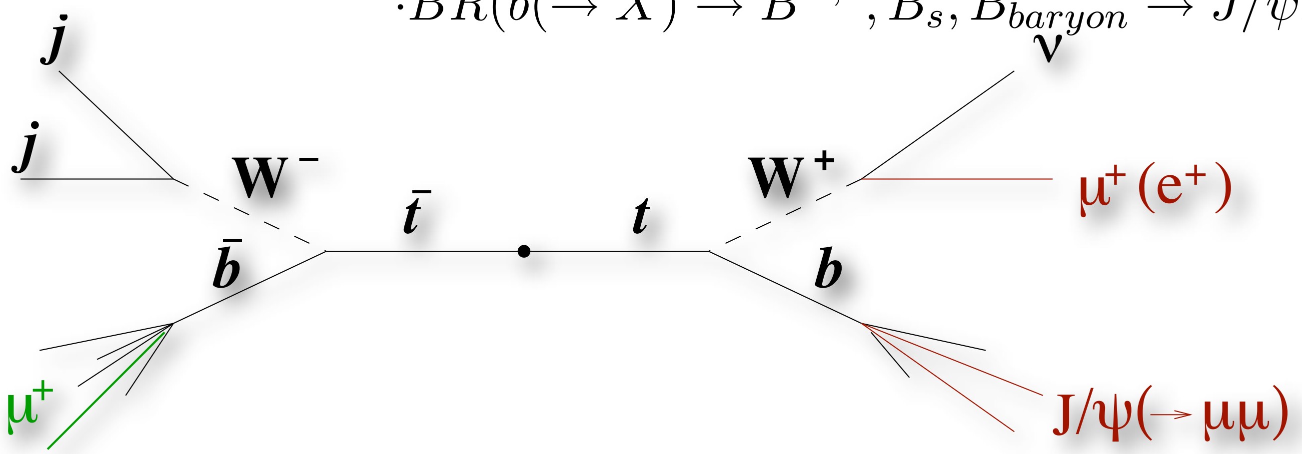
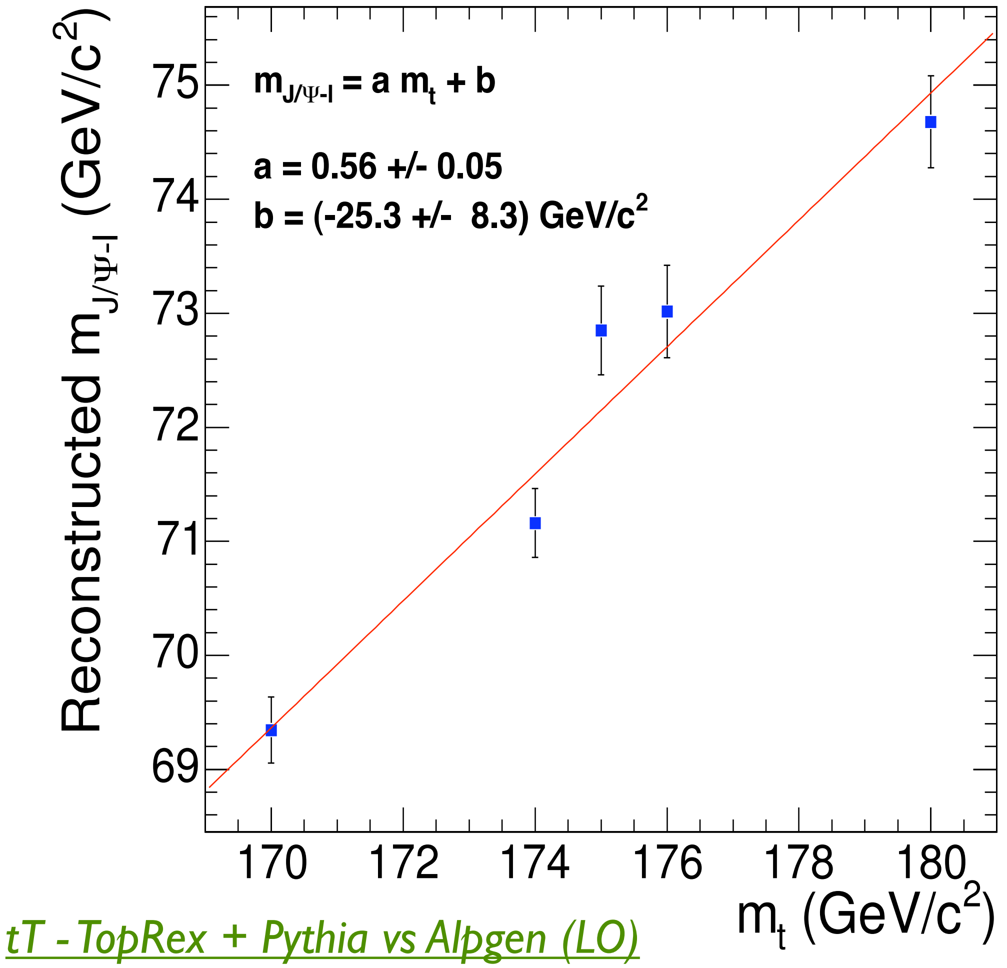
Top mass in J/ψ+l channel

$$BR(t\bar{t} \to (Wb)(Wb) \to (Xb)(\ell\nu J/\psi X)) \;=\; 2 \cdot BR(W \to \ell\nu)$$
$$\cdot BR(b(\to X) \to B^{\pm,0}, B_s, B_{baryon} \to J/\psi X) \cdot BR(J/\psi \to \ell\ell)$$

$=5.5*10^{-4}$



- Different systematics but extremely low BR
  - 4500 events at 10 fb^{-1} before trigger/ selection. ~400 after selection.
  - Difficult to reconstruct leptons (especially electrons) in jet.
- Event selection
  - Opposite-sign leptons (p_T>40 GeV)with invariant mass between 2.8-3.2 GeV
  - 35 > $\Delta\phi(l^+l^-)$ > 2 degrees
  - H_T jet momenta > 100 GeV
  - Z inv mass veto
- Peak of the invariant mass of the 3 leptons most correlated to the top mass
  - Non negligible combinatorial background with third lepton from wrong W.
- Statistical uncertainty ~1 GeV at 20 fb^{-1}. Systematics ~1.5 GeV and dominated by MC model to calculate correlation. NLO model may reduce systematics.



tT - TopRex + Pythia vs Alpgen (LO)
Wj, Wbb, Zbb - Alpgen

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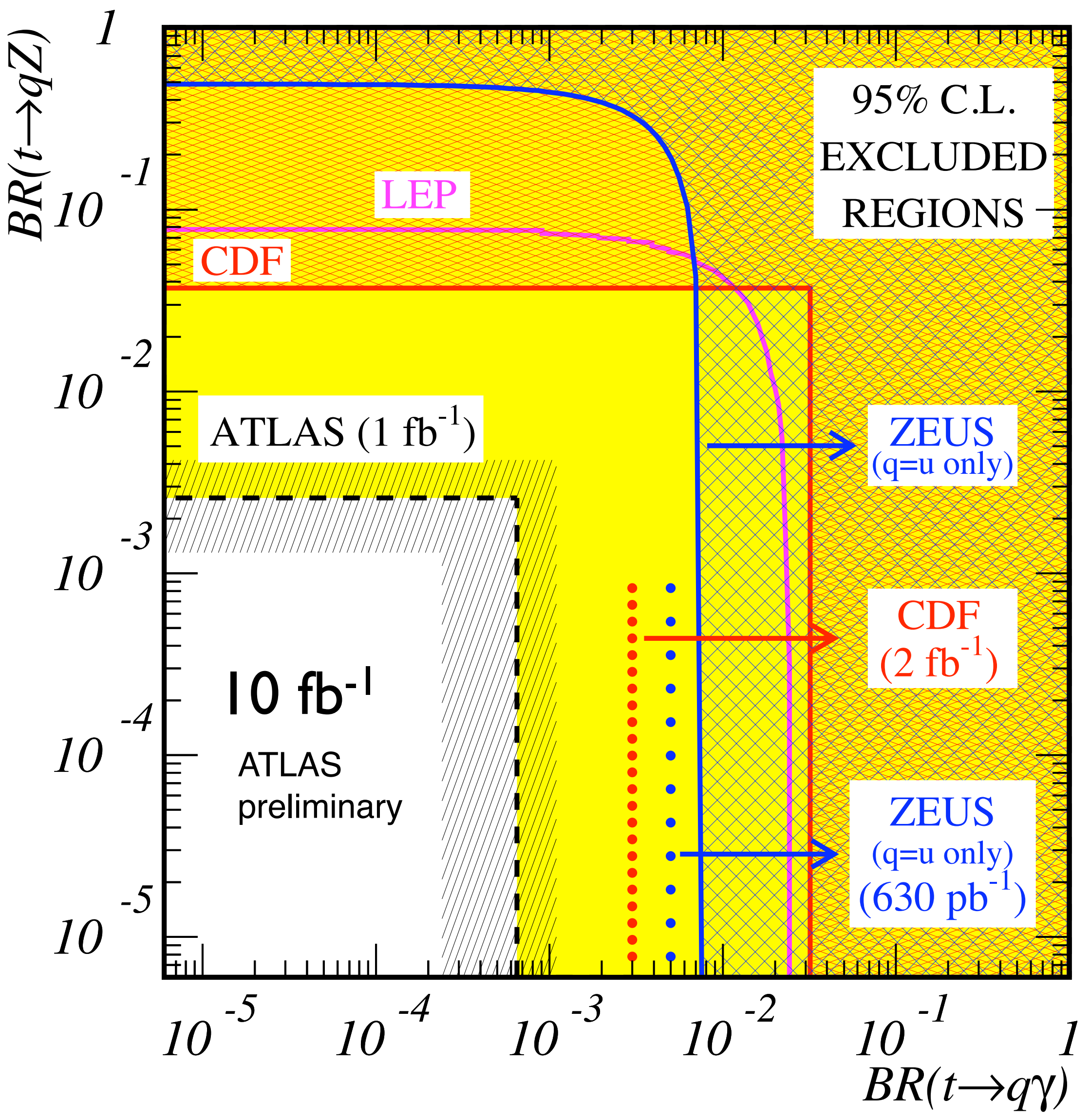
Top property - FCNC



- Study FCNC in top (t→qX, X=γ,Z,g)
  - Strongly suppressed in SM at tree level.
  - Excess may be seen from new physics such as SUSY, multi-Higgs doublet models.
- Event reconstruction
  - Study all lepton decay modes.
  - Lepton trigger and requirement on jet/lepton as appropriate. Additional cut specific to each channel.
  - Fit the event assuming tT topology and use χ^2 to resolve combinatorics.

$$\chi^2 = \frac{(m_t^{\mathrm{FCNC}} - m_t)^2}{\sigma_t^2} + \frac{(m_{\ell_a \nu j} - m_t)^2}{\sigma_t^2} + \frac{(m_{\ell_a \nu} - m_W)^2}{\sigma_W^2} + \frac{(m_{\ell_b \ell_c} - m_Z)^2}{\sigma_Z^2},$$

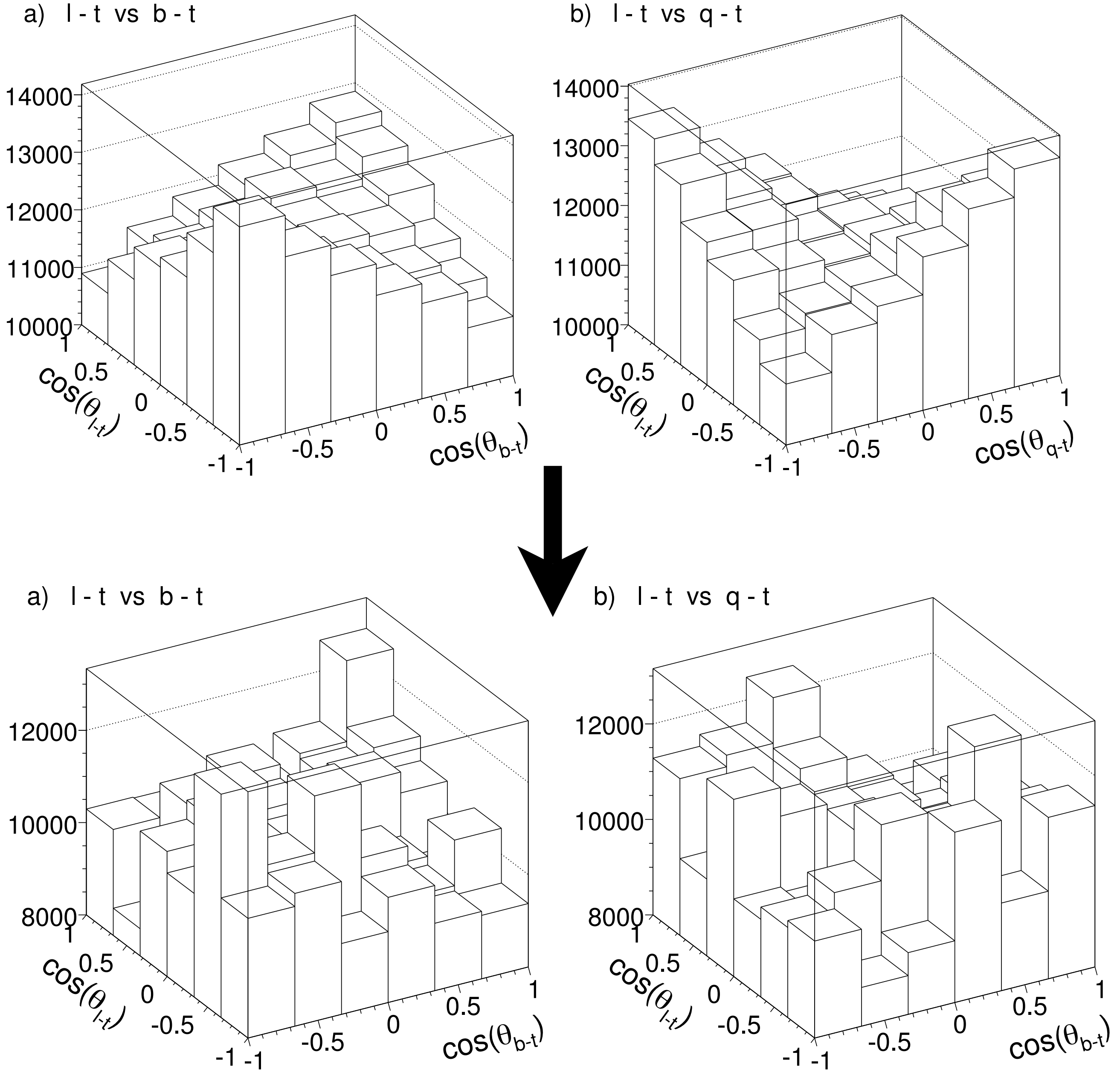
  - Additional selection based on likelihood discriminants.

- Extend the current limits by factor of 10^1-10^2 with 10 fb^{-1} of data (inc. systematics)

tT - t→qX TopRex + Pythia
Wj, Wbb, Zbb - Alpgen

Top property - tT spin correlation

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_l\, d\cos\theta_q} = \frac{1}{4}(1 - \mathcal{A}\kappa_l\kappa_q \cos\theta_l \cos\theta_q)\ .$$



tT - re-weighted Pythia
Wj - Alpgen (?)

- Top quark decays quickly, ~10^{-25}s
  - Leaves no time for hadronization
  - No gluon coupling to flip its spin
  - Daughter particles carry spin information
- Test SM prediction, anomaly may come from resonance
  - Use semileptonic tT, use $\theta_{l\text{-}t}$, $\theta_{q\text{-}t}$, $\theta_{b\text{-}t}$ (helicity basis) and fit for A (= 0.32 in SM).
- Apply event selection and correct
  - Selection similar to cross section measurement plus wide window on W and top mass.
  - Correct bin by bin for selection efficiency to remove bias. Also remove background using independent MC.
- ▸ Including systematics (M_{top}, JES, b-tag, x-sec, jet multip.), 27% uncertainty on $A_{b-t\ l-t}$ and 17% on $A_{q-t\ l-t}$ at 10 fb^{-1}.

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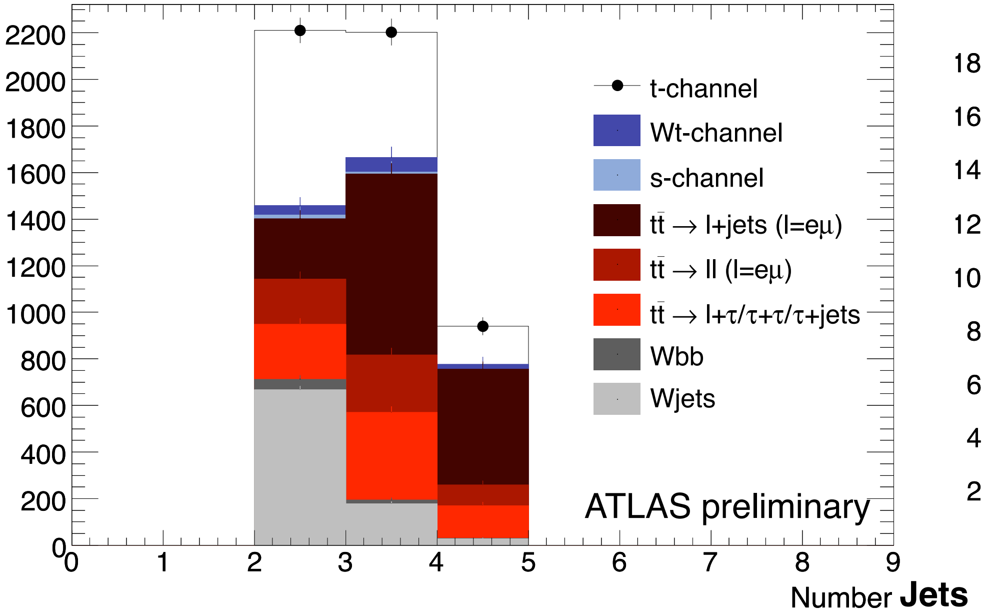
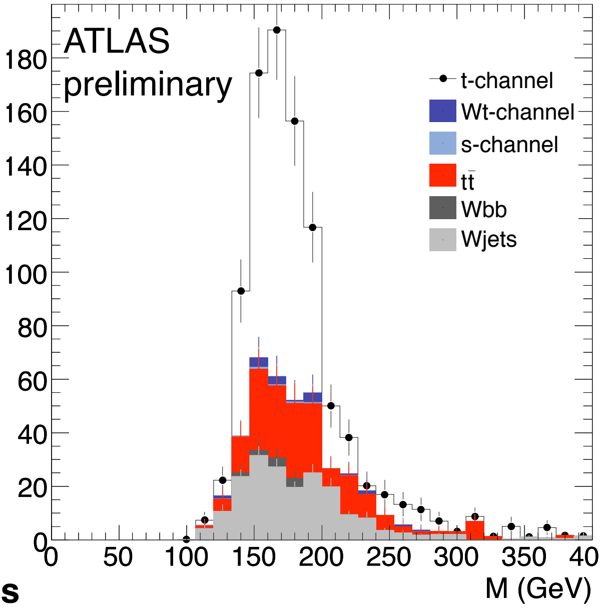
Single top measurement - t-channel

Selected events



After BDT



Source	Analysis in 1 fb^{-1}			Analysis in 10 fb^{-1}		
	Variation	Cut-based	BDT	Variation	Cut-based	BDT
Data Statistics		5.0%	5.7 %		1.6%	1.8 %
MC Statistics		6.5 %	7.9%		2.0 %	2.5%
Luminosity	5%	18.3 %	8.8%	3%	10.9 %	5.2%
b-tagging	5%	18.1 %	6.6%	3%	10.9%	3.9%
JES	5%	21.6%	9.9%	1%	4.4 %	2.0%
Lepton ID	0.4%	1.5 %	0.7%	0.2%	0.6 %	0.3%
Trigger	1.0%	1.7 %	1.7%	1.0%	3.6 %	1.7%
Cross section		22.9%	8.2%		6.9 %	2.5%
ISR/FSR	+7.2 -10.6%	9.8 %	9.4%	+2.2 -3.2%	2.7 %	2.5%
PDF	+1.38 -1.07%	12.3 %	3.2%	+1.38 -1.07%	12.3 %	3.2%
MC Model	4.2%	4.2 %	4.2%	4.2%	4.2 %	4.2%
Total		44.7 %	22.4%		22.4 %	10.0%

t-chan ST - AcerMC
tT - MC@NLO (NLO K)
Wj - Alpgen (NLO K fact. MCFM)

- Most promising single top channel
  - |Vtb| measurement and top polarization measurement. Also background to tT, SUSY, Higgs.
- Background rejection strategy
  - One isolated lepton, p_T>25 GeV
  - Veto dileptonic events (vs tT dilep)
  - ≧ 2 jets with p_T>30 GeV
  - veto >4 jets (vs tT semilep)
  - MET>20 GeV
  - 1 b-tag with p_T>50GeV
  - One jet in |η|>2.5
- Analysis dominated by systematics
  - Due to high level of tT background
  - Specifically trained BDT (12 variables) to reject tT.

▶ BDT very effective for single top.

▶ Lacking data driven bkg estimation: QCD estimation!

▶ 10% (Δ|Vtb|~5%) at 10 fb^{-1}, assuming very good understanding of detector.

Single Top Measurement - tW

Ratio method

$$\begin{aligned} S &= \frac{R_{t\bar{t}}(N_s - N_s^o) - (N_c - N_c^o)}{R_{t\bar{t}} - R_{tW}}, \\ B &= \frac{(N_c - N_c^o) - R_{tW}(N_s - N_s^o)}{R_{t\bar{t}} - R_{tW}} + N_s^o. \end{aligned}$$

Source	Uncertainty	$\Delta\sigma/\sigma$ (dilept.)	$\Delta\sigma/\sigma$ (semi-lept.)
Statistical uncertainty	—	8.8%	7.5%
Integrated luminosity	5%	5.4%	7.8%
$t\bar{t}$ cross-section	9%	*negligible*	*negligible*
t-channel cross-section	5%	*negligible*	0.8%
W+jets cross-section	10%	*not applicable*	3.1%
WW+jets cross-section	10%	1%	*not applicable*
Jet energy scale	5%-2.5%	19.7 %	9.4%
b tagging efficiency	4% - 5%	8.7 %	3.6%
PDF	1σ	+4%/-6.0%	1.6%
Pileup	30%	6.1 %	10.3%
MC statistics	—	9.9%	15.2%
Total uncertainty		±23.9%(syst.) ± 9.9%(MC)	±16.8%(syst.) ±15.2%(MC)

10 fb^{-1}

[t-chan ST - SingleTop/TopRex](#)
[tW - TopRex](#)
[tT - Pythia](#)
[Wbb - TopRex/MadGraph](#)
[Wj - CopHep/MadGraph](#)

- Severe background from tT
  - Extremely similar final state to tT. Just one b-jet less.
  - Dileptonic and semileptonic decay channels.
- Avoid heavy dependency on MC to estimate tT background
  - "Ratio method" uses ratio of efficiencies Rx=εx(control region)/εx(signal region), estimated with MC.
  - Cancels systematic uncertainties from PDF, JES and b-tagging to a large extent.
  - N^0, non tT background is estimated with MC.

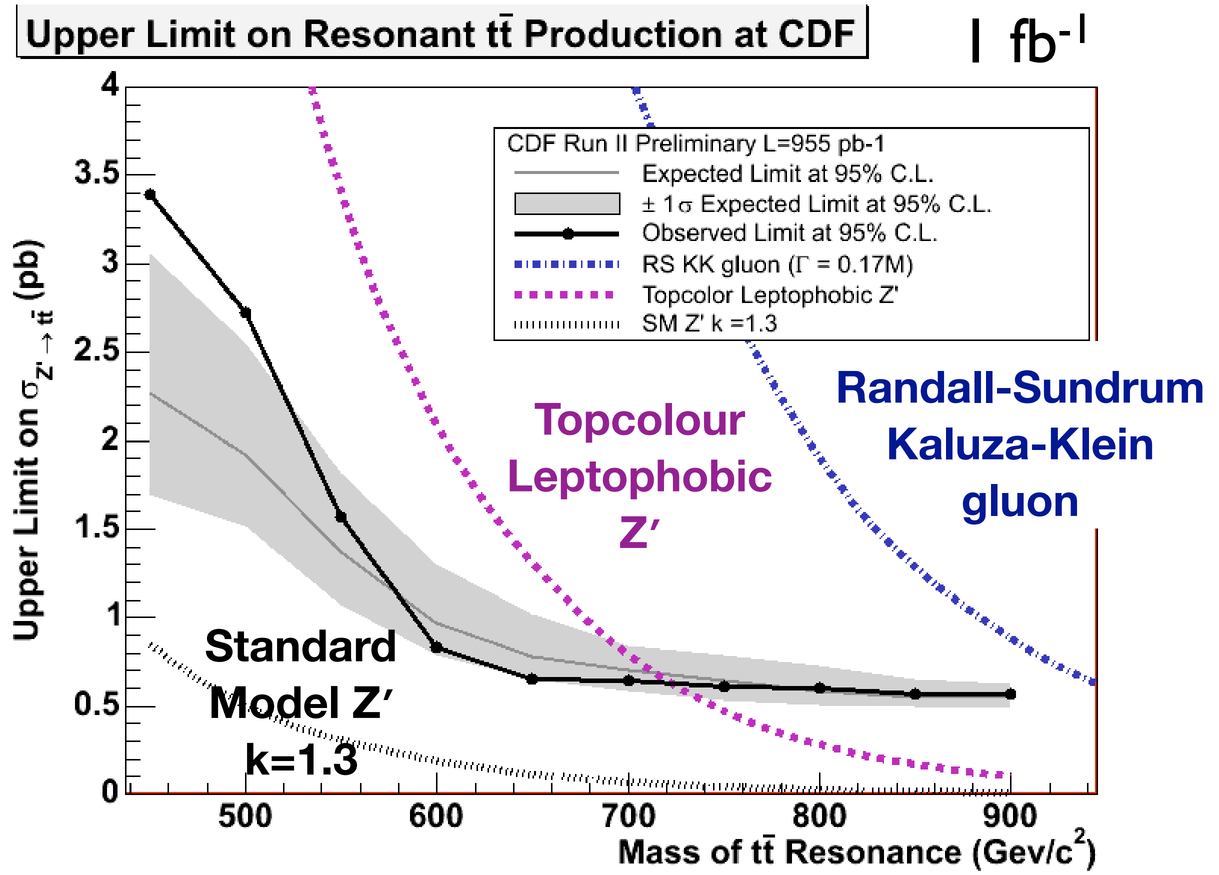
▸ tW cross section 2nd largest after t-channel but visibility is low.

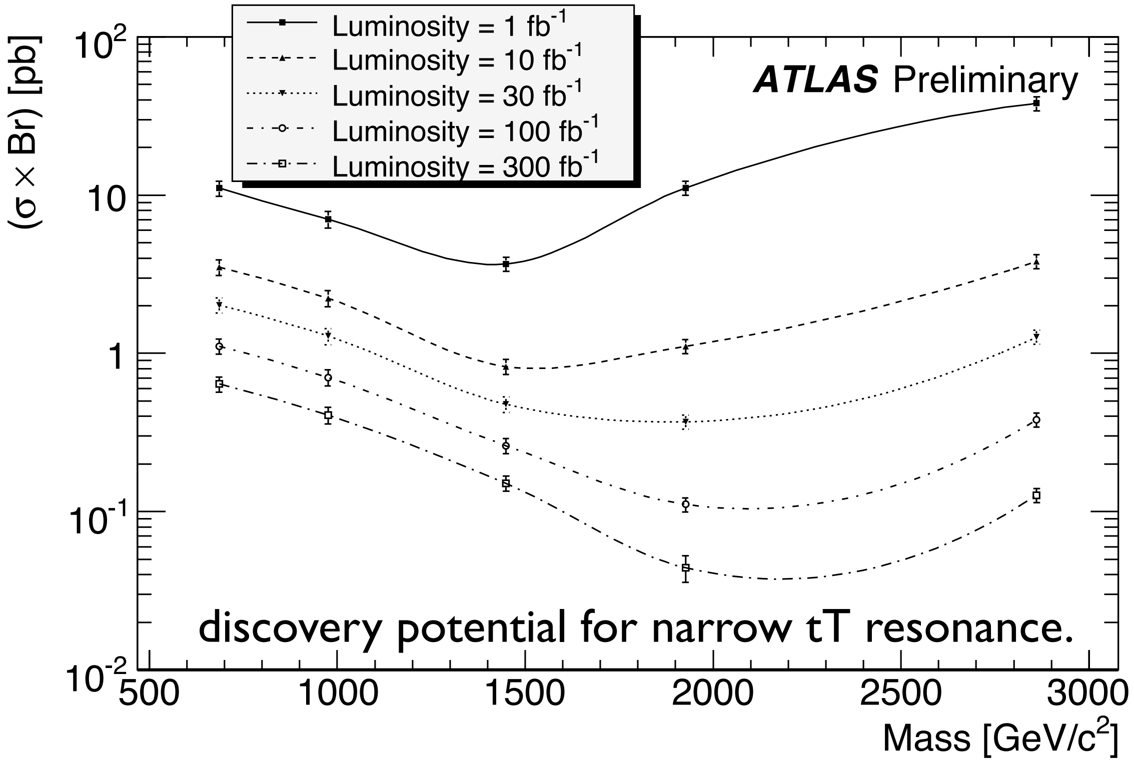
Top as new physics signature

- Top may be a signature for new physics
  - Alternative models to explain EWSB tend to couple strongly to the top quark (“best probe for EWSB”).
  - Top-color, extra dimension (ADD, RS), extra generation etc.

$$pp \rightarrow X \rightarrow t\,\bar{t}$$
$$pp \rightarrow b'\,\bar{b}' \rightarrow W^{-}t\,W^{+}\bar{t}$$
$$pp \rightarrow \tilde{g}\,\tilde{g} \rightarrow \tilde{g}t\,\tilde{g}\bar{t}$$

- Measurement of di-top system is itself interesting and may reveal resonance structure.
  - Can start as long as tT is fully reconstructed.
  - But improvement on resolution can take time.
  - Moreover, reconstruction of high-p_T top can be problematic.





discovery potential for narrow tT resonance.

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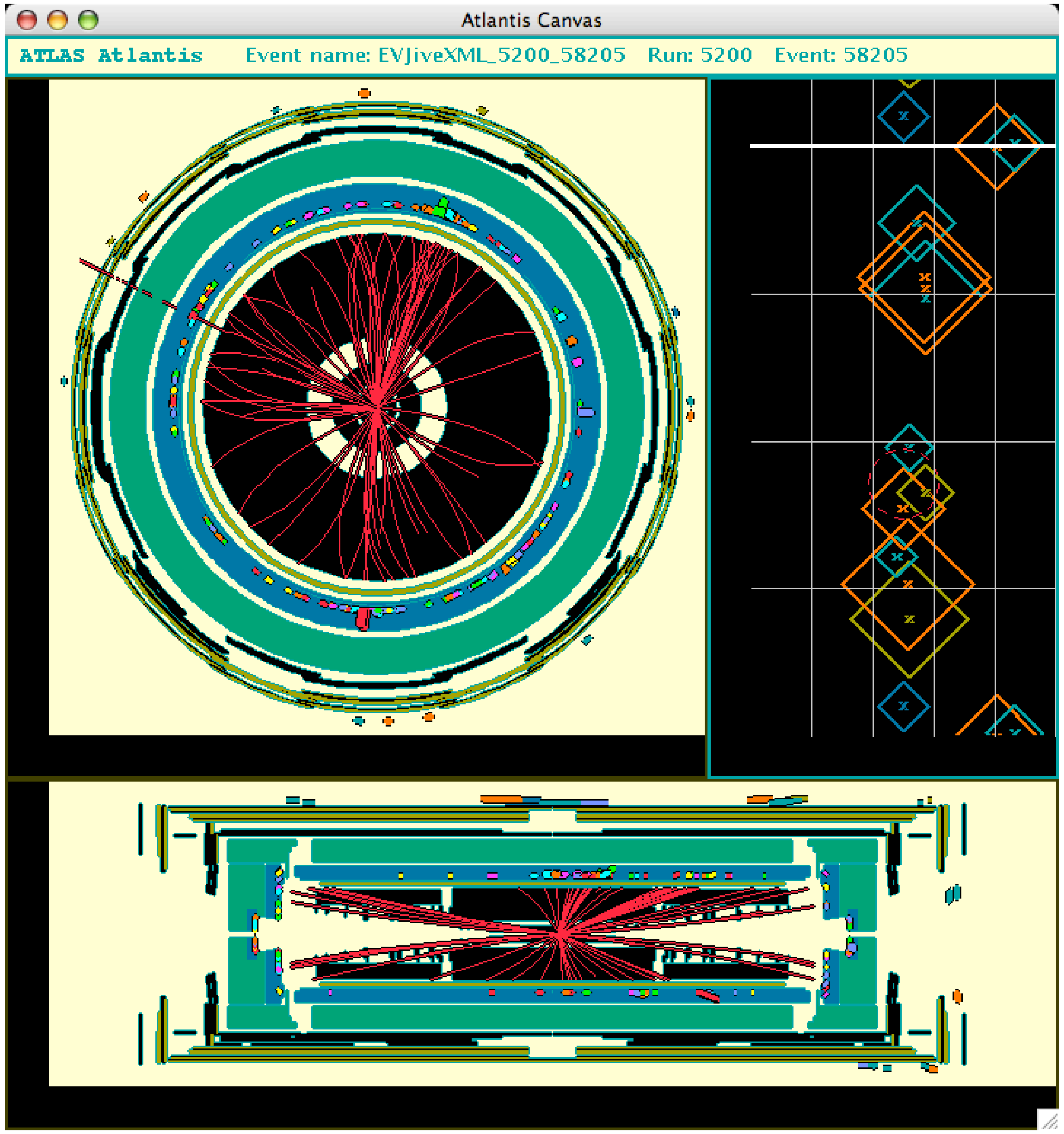
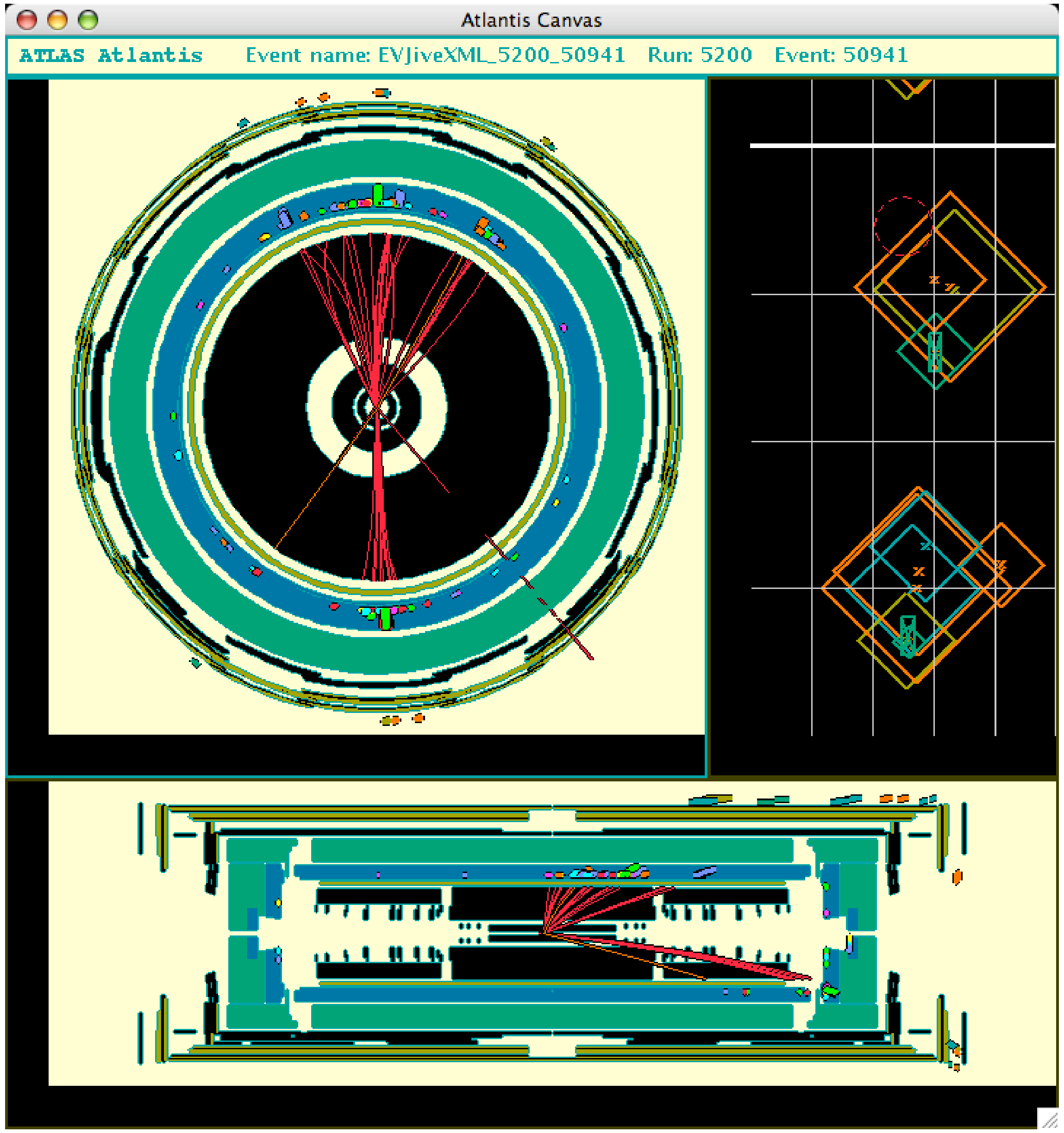
Higher end of the spectrum



$p_T^{top} = 150$ GeV

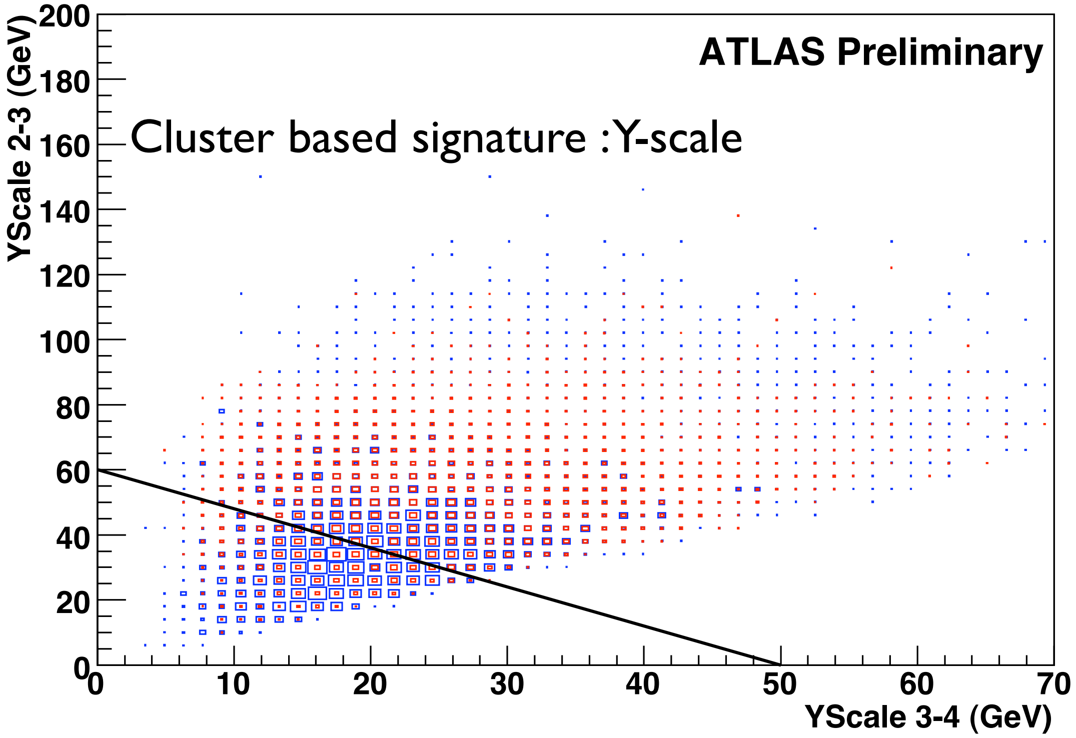


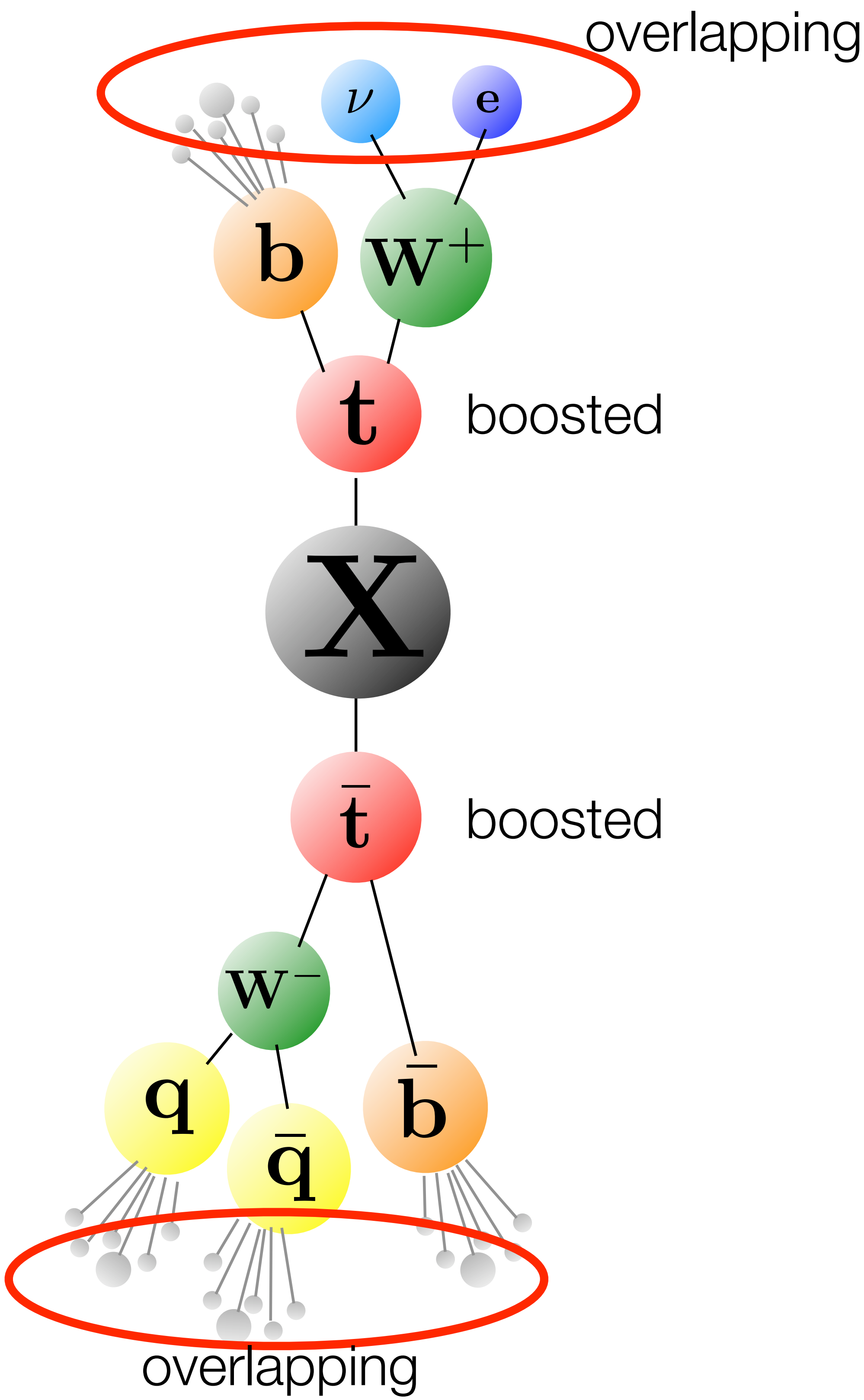
$p_T^{top} = 250$ GeV

- Large phase space available for highly boosted top quarks, may even come from resonance.

Reconstructing highly boosted top

- For top quarks with pt above ~400 GeV, the decay products start to merge due to high boost. A different approach in top reconstruction is required:
  - less jets
  - lepton not isolated
  - b-tagging performance changes
- Gradually lose the useful features of the top quark as they go harder.
  - Need study of jet substructure to distinguish high pt QCD jets from "topjet".





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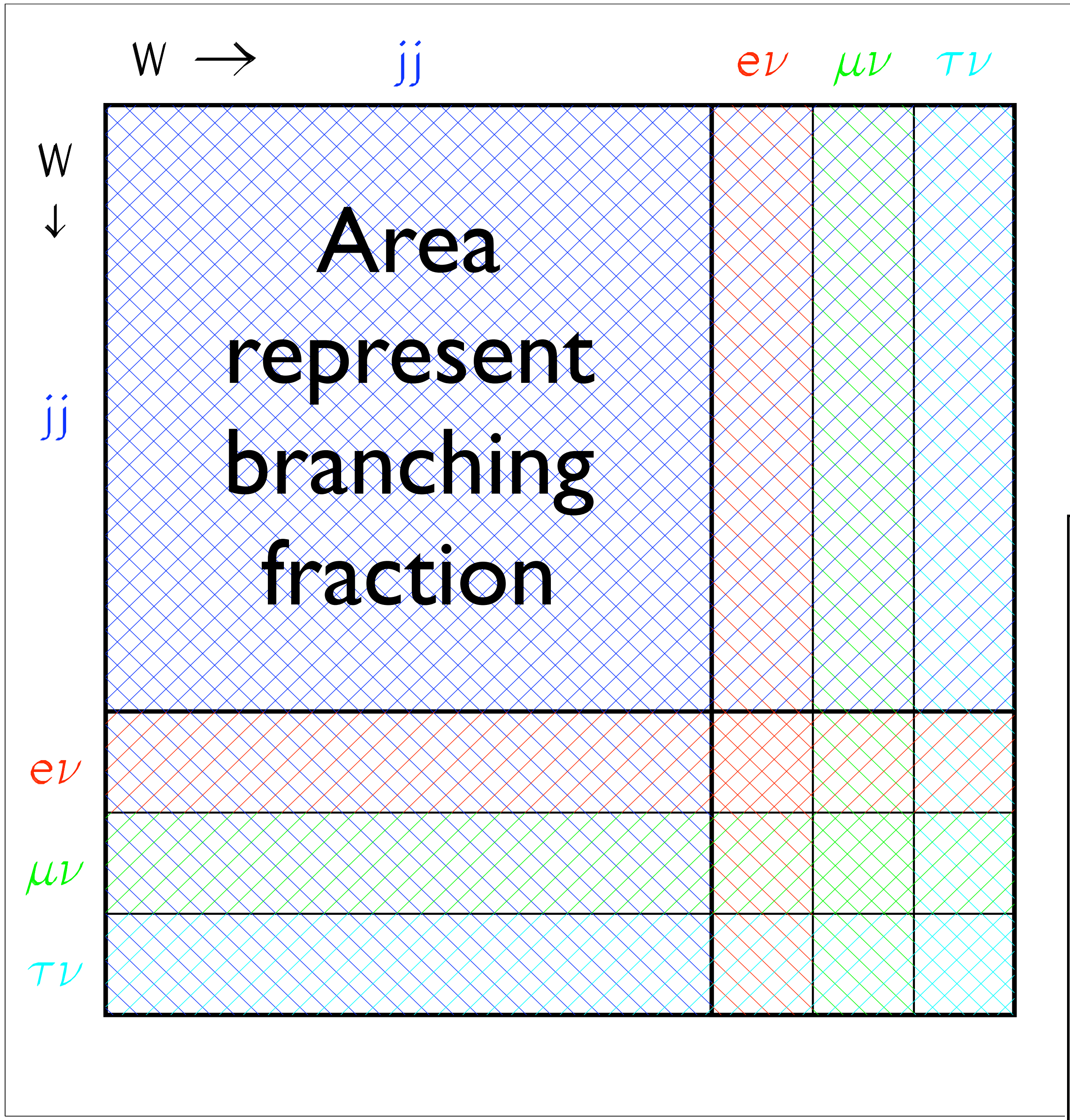
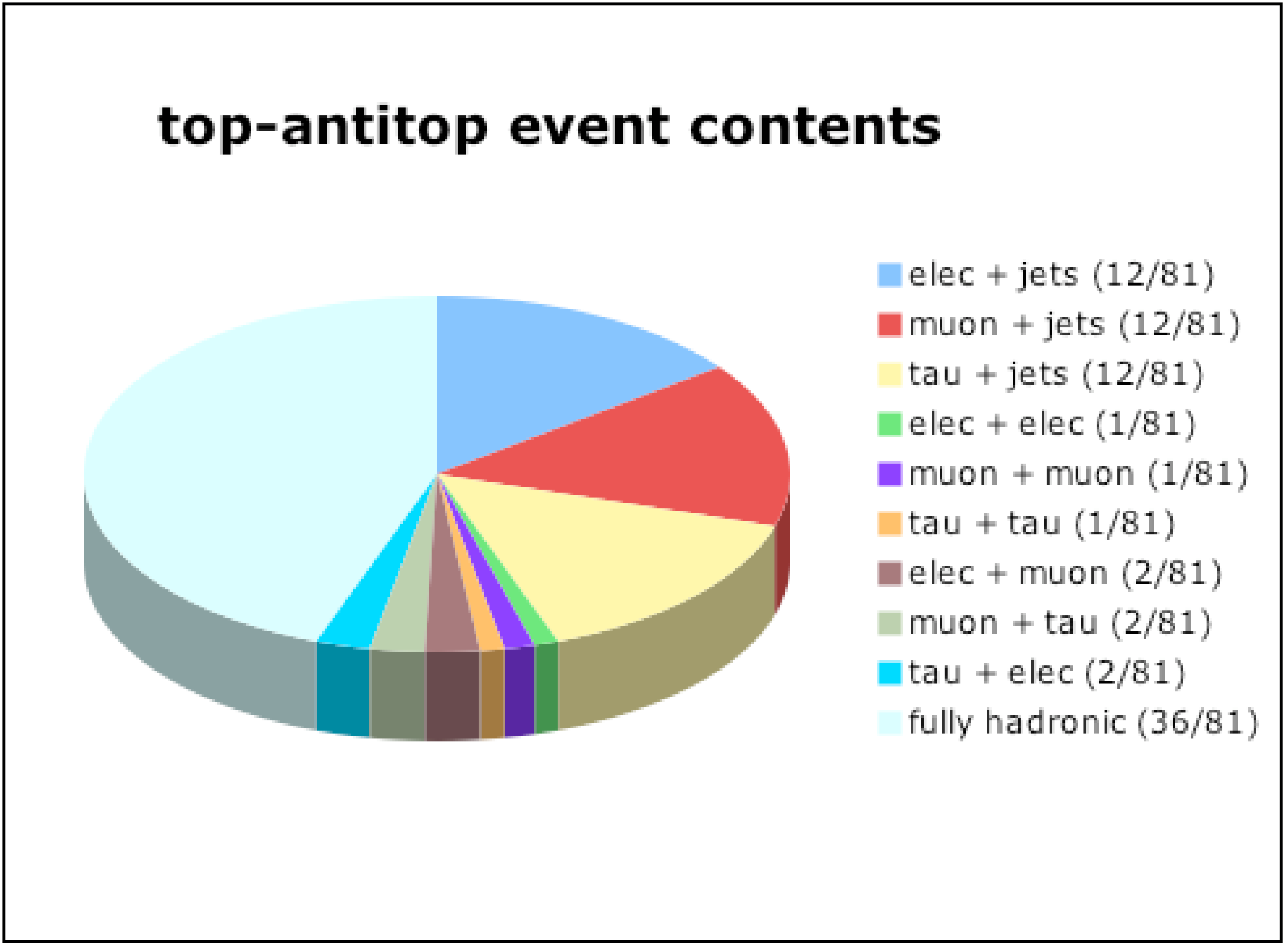
Appendix

tT branching fraction





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