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Top quark physics, including the top quark mass









- Previously
 - W and Z physics, precision electroweak measurements
 - Measurements with jets
- Lecture 3
 - Introduction to top quark physics, some history
 - Tagging jets with b-hadrons
 - Top cross-section measurements, comparisons with theory
 - The LHC beam energy measurement
 - Differential cross-section measurements
 - Single top production (briefly)
 - Measurements of the top quark mass
 - Direct measurements
 - The pole mass and how to measure it
 - Summary and conclusions





- Why is top quark physics interesting?
 - Top quark fits into the 3-generations of quark doublets
- But it is very heavy 40x bottom quark
 - Same mass scale as W, Z and Higgs bosons connection to EW symmetry breaking?
 - Now we know m_{H} =125 GeV, top Yukawa coupling is almost exactly 1... coincidence?

$$y_{\rm t} = \sqrt{2}m_{\rm t}/v \simeq 1$$

- SM could be valid up to Plank scale, meta-stable?
- Top decays quickly, as a bare quark: $t \rightarrow Wb$
 - Lifetime of ~10⁻²⁵ s too short to form hadrons (10⁻²⁴ s)
- Heaviest particle in SM, copiously produced
- Also shorter than spin decorrelation time (10⁻²¹ s) aviest particle in SM, copiously produced Cross-section 0.2-0.8 nb at LHC energies (7-13 TeV)
 - Laboratory for QCD studies at highest energies
 - Important background for BSM searches involving new heavy states 1st September 2017 **Richard Hawkings**









• Main production process: top-pair via gg or qqbar:





LO diagrams NLO, NNLO also very important

- Cross-section ~250 pb @ 8 TeV, 830 @ 13 TeV
 - C.f 7 pb in p-pbar production at Tevatron
- BR(t \rightarrow Wb)=99.8%, signatures depend on W decay
 - Dilepton channels (eevvbb, µµvvbb, eµvµbb) are cleanest, but only a few % of ttbar (tT) events
 - Especially $e\mu$, free of background from $Z \rightarrow ee/\mu\mu$
 - Lepton+jets (30%) e/μ νbbqq
 - Significant background from W+jets, single top, multijet
 - All-hadronic (46%): bbqqqq
 - Challenging final state hard to trigger, multijet b/g
 - Remainder: states involving at least one tau decay

<u>c</u> s	n+jets	I+jets	jets	alluhadrania	
ūd	electro	muon	tau+		
4 ¹	et	μτ	E1	tau+j	jets
Ľ,	eµ	10 ¹ 0	μτ	muon+jets	
U U	ő.	eμ	ет	electro	on+jets
W decay	e⁺	μ	τ	иd	<u>cs</u>





- First top-pair (tT) events at CDF and D0 in 1993
 - Clean signature with eµ+2 jets (including b-tags at CDF)







Mass measurements from ~1995 – the top quark is very heavy !





Top quark pair production at LHC



 Some early tT→eµ+b-tagged jets from ATLAS (early run-1 at 7 TeV) and CMS (early run-2 at 13 TeV)





Tagging b-jets

- B-jet tagging essential for top physics
 - Long lifetime, high mass and hard fragmentation of B-hadrons containing b quarks
 - Decay of B-hadrons several mm from primary vertex - resolved with silicon pixel detectors
 - Track impact parameters (d₀) inconsistent with primary vertex
 - Secondary (and tertiary $B \rightarrow D$) vertices
 - Muons from semileptonic decays $B{\rightarrow}\mu X$
 - Typically combined in a MVA (BDT or NN)
 - Rejection factor of >100 for light jets and 5-10 for charm jets for b-tagging efficiency 70-80%
- Top-pair events used to calibrate b-tag efi.
 - Two b-jets in a tT→llbbvv event tag and probe or more complex combinatorial approaches
 - Typically get b-tag efficiency to a few % precision for jet p_T of 50-100 GeV
 - Light and charm mistags more difficult ..
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Cross-section measurements in eµ channel



- Cleanest final state: $e\mu$ + b-tagged jet(s)
 - Main background from Wt (WWb(b) final state)
 - Z→II background only via Z→ $\tau\tau$ →e μ (+jets)
 - Small diboson background from WW $\rightarrow e\mu(+jets)$
 - Fake lepton background from same-sign eµ
- Count events with eµ and 1 or 2 b-tagged jets
 - Ignore light jets (from radiation)
 - Predict number of 1 and 2 b-tagged jets in terms of probability $\varepsilon_{\rm b}$ to select and b-tag a jet from top decay

 $N_1 = L\sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{bkg}$ $N_2 = L\sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_2^{\rm bkg}$

- Use 1 and 2 tag rates to obtain $\varepsilon_{\rm b}$ from data, along with tT cross-section σ_{tT}
- Correlation $C_{b} \approx 1$ accounts for kinematic correlations between two b jets from top decay **Richard Hawkings**

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	$\sqrt{s} =$	7 TeV	$\sqrt{s} = 8 \text{TeV}$	
Event counts	N_1	N_2	N_1	N_2
Data	3527	2073	21666	11739
Wt single top	326 ± 36	53 ± 14	2050 ± 210	360 ± 120
Dibosons	19 ± 5	0.5 ± 0.1	120 ± 30	3 ± 1
$Z(\rightarrow au au \rightarrow e\mu)$ +jets	28 ± 2	1.8 ± 0.5	210 ± 5	7 ± 1
Misidentified leptons	27 ± 13	15 ± 8	210 ± 66	95 ± 29
Total background	400 ± 40	70 ± 16	2590 ± 230	460 ± 130





- tT modelling uncertainties
 - $ε_{e\mu}$ fraction of leptons which pass selection cuts of p_T>25 GeV and |η|<2.5
 - Compare different generators, QCD scale settings, PDFs
 - No systematics from jets/b-tag as ε_b determined from data
- Background modelling
 - Wt modelling, cross-section, tT/Wt interference ambiguities
 - Wt→WWb with extra b-jet is same final state as tT→WbWb)
 - Different theoretical approaches diagram removal vs. diagram subtraction
- Lepton uncertainties mainly from Z→II
 - 'In-situ' measurement of isolation efi.
- Total analysis systs. ~2%, + lumi, +E_{beam}

Uncertainty	$\Delta \sigma_{ii}/c$	7 ₁₁ (%)
\sqrt{s}	7 TeV	8 TeV
Data statistics	1.69	0.71
$tar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and <i>b</i> -tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics $(\sigma_{t\bar{t}})$	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27

Beam energy uncertainty now 0.2%



How well do we know \sqrt{s} or E_{beam} at LHC?







LHC magnetic model and beam energy



Momentum depends on B-field integral along closed path-length s:

$$P = rac{Ze}{2\pi} \oint B(s) \, ds$$

- Bending mainly from the LHC dipoles, precisely mapped, reproducible etc.
 - 16% of dipoles mapped at 1.8K over full range
- Main uncertainty from iron saturation
 - Non-linearity of 1% at full-field
- Uncertainties in the path length
 - Tides, geological changes, compensated by radial feedback keeping beam centered
 - Effect of orbit correctors displacing the beams horizontally
- Total ⊿E/E of 0.1%, dominated by dipole transfer functions (c.f.0.002% at LEP)
 - $\Delta\sqrt{s}/\sqrt{s}=0.1\%$ corresponds to 0.2-3% on $\sigma(tT)$



Contribution	Error (%)
PC calibration	0.001
Slow radial changes	0.005
Earth tides	0.005
Orbit correctors	0.03
Transfer function	0.1
Sum	0.1





- tT→I ν b qqb lepton+≥4 jets (2 b-jets) and E_t^{miss}
 - Backgrounds from single top (t-channel), W+jets dibosons and multijets
- CMS 13 TeV analysis with 2.2 fb⁻¹ split data into many bins of (jet,b) mult.
 - Each with different fractions of tT signal and different backgrounds







- Extract tT yield from simultaneous fit to all event categories
 - Use a discriminating variable to separate signal and background in each category
 - Define fiducial region: ≥1i,1≥b-tag to maximise acceptance



Parameterise expected event count N_k in each bin of each distribution

 $\hat{N}_{k}(\mu,\Theta) = \mu \hat{S}_{k} \prod (1 + \delta_{1}^{S}\theta_{1}) + \hat{B}_{k} \prod (1 + \delta_{1}^{B}\theta_{2})$ i sources of signal, background

- tT signal strength μ (× expected x-sec) and nuisance parameters θ in each bin
 - θ parameterise effect of systematic in each bin, including correlations, constrained in fit

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σ (tT) lepton+jets - uncertainties



- Maximise likelihood over μ and θ
 - Define total uncertainty from ⊿In(L)=1
- Measurement for fiducial region:
 - $p_T(I)$ >30 GeV, ≥1 jet with p_T >30 GeV

 $\sigma_{
m t\bar{t}}^{
m vis}=208.2\pm0.4$ (stat) $^{+5.5}_{-4.9}$ (syst) \pm 4.8 (lumi) pb

- Uncertainty components estimated from $\pm 1\sigma$ variations in fitted θ parameters
 - Due to correlations, these do not correspond to an orthogonal set of uncertainties
- Largest uncertainties from
 - W+jets background normalisation
 - b-jet tagging efficiency
 - Lepton trigger and selection efficiencies
- Acceptance correction to go to inclusive x-sec measurement: A=23.5±0.4% (±1.6% relative) $\sigma_{t\bar{t}} = 888 \pm 2 \text{ (stat)} ^{+28}_{-26} \text{ (syst)} \pm 20 \text{ (lumi) pb}$
- Statistical error negligible, analysis systematic 3.0%, bit larger than eµ (2.3% at 7-8 TeV) 1st September 2017







Calculating $\sigma(tT)$

5 tot [pb]



- A challenge for QCD calculations
 - qq→tT : ~90% @ Tevatron, 10% @ LHC
 - gg→tT ~10% @ Tevatron, 90% @ LHC
- Many diagrams at NLO (including qg)
 - Many more at NNLO (including qq→qqtT)
- Also include soft-gluon terms via resummation approaches
 - Total uncertainties of around 5% for NNLO+NNLL result
 - Dominated by PDF and QCD scale choice
 - NLO result ~10% lower, with \pm 15% unc.
- Total cross-section only
 - Differential predictions (e.g. vs top p_T) becoming available in last years
 - Predictions including top decay only at NLO – NNLO just becoming available

For comparison to fiducial measurements
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Summary of tT cross-section measurements





•Experimental precision (e μ) ~3-4% per expt. at 7-8 TeV, 6-7% so far at 13 TeV

Typically dominated by luminosity and tT modelling uncertanties

Agreement at with theory at Tevatron, LHC run-1 and now run-2 energies

•Theory NNLO+NNLL 4-5% PDFs, 3% scales, \mp 3% for \pm 1 GeV on top mass

Some modest improvements may be possible – average expt. results, updated PDFs 1st September 2017 **Richard Hawkings** 17



[dd]



- Cross-section prediction depends on m_t
 - Here, m_t is the 'pole' mass corresponding to top propagator, value for electroweak fit
- Turn cross-section to mass measurement ^g
 - Find value which best fits measured x-sec
 - Depends on PDF used in calculation
 - Avoid PDFs which includes tT x-sec data
 - Account for measurement dependence on assumed m_t (e.g. through selection efi.)
- ATLAS results from 7/8 TeV eµ, using envelope of several PDFs:

 $m_t^{\text{pole}} = 171.4 \pm 2.6 \text{ GeV} (\sqrt{s} = 7 \text{ TeV})$ $m_t^{\text{pole}} = 174.1 \pm 2.6 \text{ GeV} (\sqrt{s} = 8 \text{ TeV}).$

- CMS result from 13 TeV I+jets, CT14 PDF $m_{\rm t} = 170.6 \pm 2.7 \,{\rm GeV}$
 - Similar uncertainty breakdown as ATLAS
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ATLAS m_t uncertainties:

$arDelta m_t^{ m pole}$ (GeV)	$\sqrt{s} = 7 \text{TeV}$	$\sqrt{s} = 8 {\rm TeV}$
Data statistics	0.6	0.3
Analysis systematics	0.8	0.9
Integrated luminosity	0.7	1.2
LHC beam energy	0.7	0.6
$PDF+\alpha_s$	1.8	1.7
QCD scale choice	+0.9 -1.2	<u>+0.9</u> <u>-1.3</u>
5		18



tT/Z cross-section ratios



Systematics cancel in tt/Z x-sec ratio



- Luminosity uncertainty (almost) cancels
- Use of Z→ee+µµ average cancels lepton efficiency systematics with tT→eµ
 - Except for different lepton p_T spectrum
- Need to ensure consistent tt and Z analyses
- Ratio of tt/Z at one energy sensitive to ratio of gluon over quark PDFs
 - ATLAS ep-WZ12 and HERAPDF do well,
 - Global PDF sets a bit high (too much gluon), ABM12 too low
 - Double ratio cancels more theoretical uncertainties on predictions (PDF, scales)
 - 13/8 TeV data agrees with all except ABM12



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tT/Z cross-section comparisons







- χ^2 comparison of measured and predicted tT and Z cross-sections at all energies (6 measurements)
 - Take into account uncertainties on predictions, including PDF errors and correlations

	ATLAS-epWZ12	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12
χ^2/NDF	8.3 / 6	15 / 6	13 / 6	17 / 6	10 / 6	25 / 6
p-value	0.22	0.02	0.05	0.01	0.11	< 0.001

- Similar pattern, with ABM12 excluded, and best χ² from ATLAS-epWZ12 PDF
- Profiling analysis to determine impact of new data on PDFs
 - Starting from epWZ12 PDF (HERA+ ATLAS 2010 WZ)
 - New data gives constraints on light quark sea (mainly strange component) and gluon PDF at x~0.1





- Measure cross-sections as function of top kinematics
 - p_T , |y| of top quark, p_T , m, |y| of tT system ...
 - Typically smaller uncertainties on normalised differential cross-sections - i.e. shapes
- Probe modelling of distributions by MC/QCD calcⁿs
 - Improve background modelling for searches / Higgs
 - Hints for BSM physics in tails?
- Possible in all tT decay modes, focus here on I+jets
 - Require lepton, E_T^{miss}, ≥4 jets, ≥2 b-tagged jets
 - Selection 90% pure in tT, b/g from W+jet and single top
 - Corresponding object selections at particle-level to define the fiducial region
 - Define leptonic top quark with b-jet closest to lepton
 - Hadronic top quark from other b-jet and the two untagged jets (from W→qq)
 - Same procedure applied on particle-level jets
 - No use of 'truth' information from top quark decay chain
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$$\frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^{i}} \equiv \frac{1}{\mathcal{L} \cdot \Delta X^{i}} \cdot \frac{f_{\mathrm{eff}}^{i}}{f_{\mathrm{eff}}^{i}} \cdot \sum_{i} \mathcal{M}_{ij}^{-1} \cdot \frac{f_{\mathrm{match}}^{j}}{f_{\mathrm{match}}^{j}} \cdot \frac{f_{\mathrm{acc}}^{j}}{f_{\mathrm{acc}}^{i}} \cdot \left(N_{\mathrm{reco}}^{j} - N_{\mathrm{bg}}^{j}\right)$$

- Matrix M_{ii} describes migration of events into wrong bin at detector level (reslⁿ)
- Efficiency f^{eff} correction for events passing particle- but failing detector-level selection
 - Dips at ~300 GeV as top quarks become boosted non-isolated leptons, merged jets
- Acceptance correction f^j_{acc} for events outside fiducial region which get reconstructed
- Matching correction f^j_{match} events with unmatched jets between particle/reco level







- Results for normalised p_T and |y| of hadronic top in fiducial regions
 - Uncertainties 1.3-11/5% for p_T/|y| strong cancellations in normalised distributions
 - Data is softer than all MC models for p_T, and more central when using CT10 PDF







- Extrapolate to full phase space to compare with NNLO calculations
 - Better agreement with data shows importance of NNLO corrections in differential distributions as well as inclusive cross-sections
 - Unfortunately not available in full Monte Carlos yet need to rely on reweighting





Single top production



Electroweak process involving the Wtb vertex – 3 sub-processes



- Cross-sections are proportional to |V_{tb}|² ≈1 can interpret as constraints on |V_{tb}|
 Cross-section values given for √s=13 TeV
- Typically look for semileptonic decay of W: $t \rightarrow b l v$
 - t-channel: additional forward 'spectator' jet from the outgoing light quark
 - Wt-associated production: additional $W(\rightarrow I\nu)$ like tT but with one fewer b-jet
 - Process interferes with tT production at NLO (Wtb \rightarrow WWbb vs. tT \rightarrow WWbb)
 - s-channel: Iv+2 high p_T b-jets, low x-sec at LHC due to sea antiquark in initial state
- Significant backgrounds from top-pair production, and W/Z+(b) jets
 - Sophisticated analysis techniques (multivariate, matrix element) needed

Only t-channel measurements reaching 'precision' at this point
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t-channel single top

- Multivariate techniques based on e.g.
 - Light jet rapidity, m(lvb), angular information
 - Control regions with extra jets, non-b-tagged jets to constrain tT and W+jets contribution
- Total x-sec measured to ~10%, c.f. ~5% predⁿ
 - Start to measure differentially , e.g. p_T(t)
 - Results so far agree with MC predictions
- Ratio $R_t = \sigma(t)/\sigma(t-bar)$ sensitive to u/d in proton
 - Many systematics cancel R_t stat-dominated







[GeV]



- Top quark is the heaviest fermion
 - Mass ~173 GeV compared with ~5 GeV for its partner b-quark is this 'natural' ?
- Predicted from the EW fit to ± 2.3 GeV
 - Direct measurements have <1 GeV precision
- Renewed interest after Higgs discovery

 $y_{\rm t}=\sqrt{2}m_{\rm t}/v\simeq 1$

- Top Yukawa coupling close to 1 coincidence?
- Relationship between m_t and m_H
 - If SM holds all the way up to the Planck mass, the scalar potential may be stable or meta-stable
- Stability condition on the value of m_t:

 $M_t < (171.53 \pm 0.15 \pm 0.23_{lpha_s} \pm 0.15_{M_h})\,{
m GeV}$

- Current values suggest larger m_t metastable
 - Strong assumption of SM validity up to m_{Planck} !
- The fate of the universe depends on m_t



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Many measurements in dilepton, I+jets and all-hadronic channels



- Tevatron combination: 174.30±0.65 GeV (0.4% rel.)
- ATLAS combination 172.84±0.70 GeV, CMS combination 172.44±0.48 GeV (0.3%)
 - No recent 'world' combination, some Tevatron vs. LHC tension

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- Select events with e/μ , E_T^{miss} and ≥4 jets, typically with 1 or 2 b-tags
 - Combinatorics from assignment of jets to top quark decay products $(t \rightarrow b, W \rightarrow qq)$
 - B-tagged jet information can help reduce the permutations
 - Kinematic fit to decay topology, assume equal masses for two top quarks in event
 - Choose best-fit combination (ATLAS), or weight combinations by probability (CMS)
- Template fit major systematic from jet energy scale JES (esp. for b-jets)
 - Changes in JES affect event-by-event reconstructed mass like changes in m_t
 - In-situ calibration using reconstructed W mass peak ($W \rightarrow qq$), should match m_W
 - Typically fit a global jet energy scale factor (JSF) along with m_t





Top mass from lepton+jets - continued



- But tends to concentrate remaining wrong and unmatched combinations under mass peak
 - Good MC modelling of extra jet multiplicity and kinematics is crucial for small systematic uncertainty
- Fit of m_t and JSF costs statistics, but reduces JES unc.
 - CMS has various approaches (2D, hybrid) to inclusion of prior information on JES from jet energy scale calibration
 - ATLAS also fits a separate b-jet JSF for b-jet scale









- Very low background, but cannot fully reconstruct tT→Ivb lvb kinematics (2 neutrinos)
 - System can be solved for an assumed top mass
 - CMS uses 'analytical matrix weighting technique'
 - Look at relative probabilities of the event kinematics
 X being compatible with different values of m_t, including proton PDFs F(x₁), F(x₂)

$$w(\vec{X}|m_{t}) = \begin{bmatrix} \sum F(x_{1})F(x_{2}) & p(E_{\ell^{+}}|m_{t})p(E_{\ell^{-}}|m_{t}) \\ p(E|m_{t}) &= \frac{4m_{t}E(m_{t}^{2}-m_{b}^{2}-2m_{t}E)}{(m_{t}^{2}-m_{b}^{2})^{2}+M_{W}^{2}(m_{t}^{2}-m_{b}^{2})-2M_{W}^{4}},$$

- Gives 'most-likely' mt value mt^{AMWT} for each event ਦੂੰ
- Alternative use recon. m(lb) as mass estimator
 - Gives a peak at m(lb)<m_t which can also be fitted to templates derived from simulation
- No JSF fitted in dilepton events no $W \rightarrow qq$







- Fully hadronic tT \rightarrow bqq bqq has at least 6 jets, and no leptons
 - Trigger using multi-jets (e.g. 4 with p_T>50 GeV), require two b-tagged jets
 - Large QCD multijet background needs to be assessed from non-b tagged data
 - Signal fraction only 13% before kinematic fit
 - Kinematic fit to find best assignment of jets to correct W, top (6 comb/event)
 - Also reduces QCD mutlijet background, still lots of wrong combinations
- Apply W mass constraint to fit JSF as in I+jets channel

arXiv:1509.04044





CMS top mass combination



 Final run-1 result from combination of dilepton, lepton+jets and fully-hadronic

- Careful treatment of correlations amongst systematics – between channels and years
- Result dominated by 2012 lepton+jets
- Largest systematics related to flavour dependence of JES calibration
 - Comparison of jet flavour composition predicted by Pythia and Herwig
 - Also B-jet modelling (fragmentation, b→I BR)
- Modelling uncertainties from choice of tT MC model and parameters
- Modelling of underlying event and colour reconnection
- Final result is systematics limited:

 m_t =172.44±0.13 (stat) ±0.47 (syst) GeV

New ideas needed to exploit run-2 statistics

Combined $m_{\rm t}$ result	$\delta m (C \circ V)$
	om _t (Gev)
Experimental uncertainties	
Method calibration	0.03
Jet energy corrections	
 – JEC: Intercalibration 	0.01
 – JEC: In situ calibration 	0.12
 – JEC: Uncorrelated non-pileup 	0.10
Lepton energy scale	0.01
$E_{\rm T}^{\rm miss}$ scale	0.03
Jet energy resolution	0.03
b tagging	0.05
Pileup	0.06
Backgrounds	0.04
Trigger	< 0.01
Modeling of hadronization	
JEC: Flavor	0.33
b jet modeling	0.14
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	0.10
ME-PS matching threshold	0.08
ME generator	0.11
Top quark $p_{\rm T}$	0.02
Modeling of soft QCD	
Underlying event	0.11
Color reconnection modeling	0.10
Total systematic	0.47
Statistical	0.13
Total Uncertainty	0.48



Top quark mass – what are we measuring?



- Experimentally, √(E²-p²) from final state particles (leptons, jets, E_T^{miss})
 - But we are measuring a coloured particle
- Colour reconnection to rest of the event
 - Transfer of 4-momentum, change effective m_t
 - Only phenomenological models, tuned to minbias and underlying event data
- And there are radiative corrections …
 - In principle accounted for in the NLO generators and the parton shower
 - And top quark-self energy corrections
- Need the pole mass for EW fit
 - Corresponding to propagation of free particle
 - O(1 GeV) diff. between pole and MC masses?
- Experimental precision now ~0.5 GeV
 - EW fitting groups add another ±0.5 GeV when using the results in the SM EW fit 1st September 2017
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Probing QCD effects



- Study m_t vs. kinematic variables with 8 TeV data
 - Look at m_t <m_t> to look for biases which are not modelled by the MC generators
 - Top kinematics (e.g. p_T(t)) and variables which might be sensitive to colour reconnection
 - E.g. ⊿R between jets
 - So far, no indications of mismodelling important to continue with higher statistics at 13 TeV





Simulation	χ^2	Standard deviations
MG + pythia 6 Z2*	17.55	0.10
MG + pythia 6 P11	37.68	1.73
MG + PYTHIA 6 P11noCR	31.57	1.15
POWHEG + PYTHIA 6 Z2*	19.70	0.20
POWHEG + HERWIG 6	76.48	4.84
MC@NLO + HERWIG 6	20.47	0.24
SHERPA	46.79	2.56





- Direct reconstruction template fits give 'MC mass'
 - Top mass parameter in MC which best describes the detector-level data
 - Sublties of mass definition 'hidden' in MC
- Alternative look for mass-sensitive distributions which can be rigorously calculated in QCD, and compare to unfolded data
 <u>arXiv:1507.01769</u>
- E.g inclusive tT production cross-section
- E.g. top mass from m(ttj) in tT+1 jet events
 - Diff. x-sec shape $R(\rho_s)$ with $\rho_s \sim 1/m(ttj)$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1-jet}}} \qquad \mathcal{R}(m_t^{\text{pole}},\rho_s) = \frac{1}{\sigma_{t\bar{t}+1-jet}} \frac{\mathrm{d}\sigma_{t\bar{t}+1-jet}}{\mathrm{d}\rho_s} (m_t^{\text{pole}},\rho_s),$$

- Mass m_t here corresponds to pole mass
- Measure $R(\rho_s)$ distribution and unfold to parton level
- Compare to NLO(+parton shower) predictions calculated for different top masses

$$m_t^{\text{pole}} = 173.7 \pm 1.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)}_{-0.5}^{+1.0} \text{ (theory) GeV}$$

 Result from 7 TeV data consistent with direct reconstruction, but large uncertainties

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- Exploit progress in calculating inclusive differential distributions at NNLO
 - E.g. p_T(top), p_T(tT), m(tT) etc these quantities are sensitive to top mass in a welldefined renormalisation scheme – e.g. fixed order NNLO
- E.g. D0 extraction of pole mass using measured p_T(top), m(tT)

Exploits both absolute normalisation and shape of kinematic distribution

- Combine $p_T(tT)$ and m(tT) extractions: ~2 GeV expt. and 0.8 GeV theory error
- Theoretical error dominated by QCD scale variations (factor 2 up/down around m_t)
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1/σ dσ/dp_T [1/GeV

10⁻²

 10^{-3}

ATLAS Preliminary

 $\sqrt{s} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

Powheg+PY6
 MC@NLO+HW

• Data 2012

..... Alpgen+HW

ATLAS-CONF-2017-044

- Decay leptons also carry information on m_t
 - Extension of the tT→eµbbvv cross-section analysis measuring lepton kinematic distributions
 - 1-2% precision in some phase space regions
- Several distributions sensitive to m_t
 - Lepton p_T, dilepton p_T and mass, sum of lepton p_T, sum of lepton energies
 - Also affected by PDF uncertainties and modelling of top quark p_T

- Results from different distributions consistent within uncertainties of 2-5 GeV
- Fit several lepton and dilepton distributions simultaneously
 - Constraining m_t, PDF uncertainties and QCD scale uncertainties (affecting top p_T)
 - Final result $m_t = 173.2 \pm 0.9$ (stat) ± 0.8 (syst) ± 1.2 (theory) GeV

Results from various inclusive and differential cross-section measurements

- So far, all consistent with mass measurements from direct reconstruction, but precision not sufficient to address potential differences of O(1 GeV)
- Need theoretical progress (e.g. more NNLO calculations) to match Run-2 data

- LHC run-2 is underway, with ~50 fb⁻¹ delivered at 13 TeV so far
 - Hope for ~100+ fb⁻¹ before next LHC shutdown (LS2) 15x more tops than run-1
- Full program of measurements ahead
 - With present techniques, many measurements will be systematically limited
 - Harsher environment (pileup) than run-1 new ideas and analysis strategies will be needed to fully exploit this sample
 - At 13 TeV, **boosted** techniques (e.g. tagging top jets) will become more important
- Looking further ahead to HI-LHC: 1-3 ab⁻¹ sample another jump in statistics
 - Ultimate precision on top mass: ~0.3 GeV in well-defined scheme ?
 - Precise measurements of top couplings (g, γ , W, Z, H) possible BSM contribⁿs
 - Extending reach of rare decay searches (e.g. FCNC)
 - Very challenging experimental environment for precision measurements, and large statistics in boosted topologies...
- Exciting challenges ahead in top physics...

- An overview of some precision top physics measurements
 - Inclusive cross-sections and comparison with theory
 - Applications to the top quark mass and PDFs
 - Differential cross-section measurements
 - Testing QCD calculations and event generators
 - Single top production
 - Top mass measurements
 - Already systematics limited with run-1 data
 - The top pole mass and ways of measuring it
- Much more to top physics
 - Measurements with boosted tops merged topologies
 - Coupling of the top quark to W, Z and H
 - Tops produced in BSM searches (e.g. tT resonances, vector-like quark decays)
 - Spin correlations and polarisation measurements
 - Rare top decays (e.g. flavour changing neutral currents $t \rightarrow Zq$)
- The end …

The future is yours...where will you contribute?

SUSY phenomenology papers'

Richard Hawkings