Two hot topics in top physics

Marcel Vos (IFIC, CSIC/UV, Valencia, Spain)

Particle Physics Seminar

University of Vienna

18 November 2014

CAVEATs: not an overview talk, discarding a lot of interesting (top) physics, not respecting any ATLAS/CMS balance

Two hot topics in top phyiscs

This is not a review, find good top quark physics reviews here:
Bernreuther on LHC top quark theory (before the start of the LHC):
http://arxiv.org/abs/arXiv:0805.1333
An experimentalist's review of the first two years,
Int. J. Mod. Phys. A27 (2012) 1230016

Top quark mass: how can we make further progress?
Determination of the top quark mass circa 2013: methods, subtleties, perspective,
arXiv:1310.0799
A new observable to measure the top quark mass at hadron colliders,
EPJC 73 (2013) 2438
ATLAS top quark pole mass measurement
ATLAS-CONF-2014-053

Boosted top quark production: a new window
Boosted objects: a probe of new physics,
EPJC71 (2011) 1661
Boosted top quarks and jet structure,
arXiv:1403.5176
ATLAS differential cross-section measurement
ATLAS-CONF-2014-057

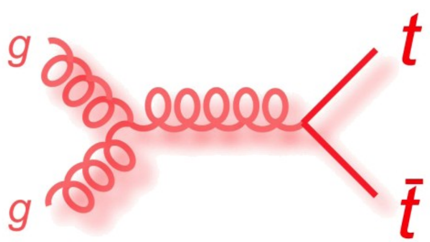
What do we really know about the top quark?

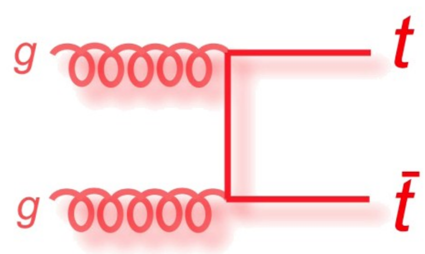
quantity	CDF/DØ		ATLAS/CMS	
$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$	11% with 1 fb^{-1}	[554]	5%–10% luminosity systematics dominated	[286, 288]
$\Delta\sigma_{\text{single-top}}/\sigma_{\text{single-top}}$	26% with 1 fb^{-1}	[554]	10% ($<$ 2% stat. error with 10 fb^{-1}	[288])
$B(t \to Wb)$	3.3% with 1 fb^{-1}	[554]		
V_{tb} from $\sigma_{\text{single-top}}$	14% with 1 fb^{-1}	[554]	6.5%	[528]
V_{tb} from $B(t \to Wb)$	>0.22 with 1 fb^{-1}	[554]	0.2% (stat. only)	[286]
single-top polarisation	–		1.6% with 10 fb^{-1}	[288]
$\Delta m_{\text{top}}/m_{\text{top}}$	$\leq 2\,\text{GeV/c}^2$	Sect. 7	$\approx 1\,\text{GeV/c}^2$	[286, 288]
spin correlation θ	40% (2 fb^{-1})	[538]	7% ($\ell\ell \oplus \ell+$jets) for 10 fb^{-1}	[538]
spin correlation ϕ	–		4% ($\ell\ell \oplus \ell+$jets) for 10 fb^{-1}	[538]
W-helicity $\mathcal{F}_0$	6.5% with 1 fb^{-1}	[554]	2%–5% with 10 fb^{-1}	[527, 537, 538]
W-helicity $\mathcal{F}_+$	2.6% with 1 fb^{-1}	[554]	1% with 10 fb^{-1}	[538]
electric charge q_t	distinguish $\frac{2}{3}$ and $\frac{4}{3}$ cases with 1 fb^{-1}	Sect. 7.2	distinguish $\frac{2}{3}$ and $\frac{4}{3}$ cases with 10 fb^{-1}	[536]
Yukawa coupling y_t	–		4.8σ, 16% (12%) with 30(100) fb^{-1}	[548, 549]
FCNC $B(t \to gq)$	$< 1.9 \times 10^{-2}$ with 2 fb^{-1}	[288, 555]	$< 1 \quad \times 10^{-5}$ - $< 1.4 \times 10^{-3}$ (10 fb^{-1})	[288, 556]
FCNC $B(t \to Zq)$	$< 1.5 \times 10^{-2}$ with 1 fb^{-1}	[554]	$< 6.5 \times 10^{-4}$ - 1.3×10^{-3} with 10 fb^{-1}	[286, 288, 556]
FCNC $B(t \to \gamma q)$	$< 3.0 \times 10^{-3}$ with 1 fb^{-1}	[554]	$< 8.6 \times 10^{-5}$ - 1.9×10^{-4} with 10 fb^{-1}	[286, 288, 556]
FCNC $B(t \to WbZ)$	–		$< 10^{-7}$ with 100 fb^{-1}	[553]
$\Delta\sigma^{M_{Z'}=1\,\text{TeV/c}^2}$ $B(Z' \to t\bar{t})$	100 fb with 1 fb^{-1}	[554]	700 fb with 30 fb^{-1}	[286, 288]
anom. coupling	$F_{2L}{}^{>+0.55}_{<-0.18}$	[553]	$F_{2L}{}^{>+0.097}_{<-0.052}$	[553]
	$F_{2R}{}^{>+0.25}_{<-0.24}$	[553]	$F_{2R}{}^{>+0.13}_{<-0.12}$	[553]
$\Delta F^Z_{1V,A}$	–	[542]	15%–85% (300 fb^{-1})	[542]
$\Delta F^\gamma_{1V,A}$	${}^{<+1.03\ldots+2.60}_{>-1.17\ldots-1.88}$ (8 fb^{-1})	[542]	15%–50% (30 fb^{-1}), 4%–7% (300 fb^{-1})	[542]
$\Delta F^\gamma_{2V,A}$	–	[542]	35% (30 fb^{-1}), 20% (300 fb^{-1})	[542]
$\Delta F^Z_{2V,A}$	–	[542]	55% (300 fb^{-1})	[542]

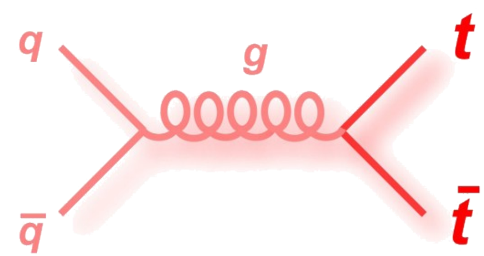
A. Quadt, Top quark physics at hadron collilders, Springer Verlag, 2007

The top quark: production

Pair production at hadron colliders (primarily) through QCD processes







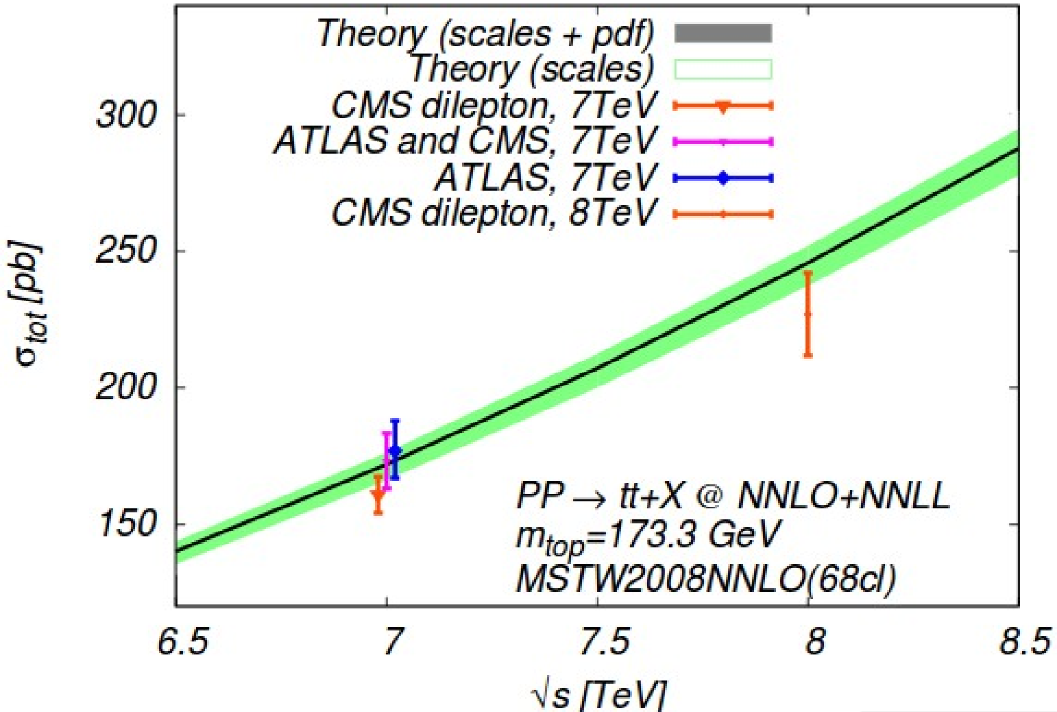
Collider (energy)	process	approx σ	lumi (deliv/on tape)	# of ev
Tevatron $p\bar{p}$ (run II 1.96 TeV)	$t\bar{t}$	~7 pb	12/10 fb^{-1}	~70 K
LHC pp (7 TeV)	$t\bar{t}$	~165 pb	5.7/5 fb^{-1}	~800 K
LHC pp (8 TeV)	$t\bar{t}$	~235 pb	23/22 fb^{-1}	~5 M

Collider	**$q\bar{q}$**	**gg**
Tevatron $p\bar{p}$ (1.96 TeV)	~85%	~15%
LHC pp (7 TeV)	~20%	~80%

Complementary sensitivity to gluon and quark-initiated processes

100.000 (Tevatron) + 5 million (LHC – phase I) + 2 million single top

How well can we predict top quark production?



Theory milestone:

full NNLO and NNLL result for top quark pair production at hadron colliders

K-factor (NLO → NNLO) ~ 10%

Scale stability ~ 5 %

Series seems to converge...

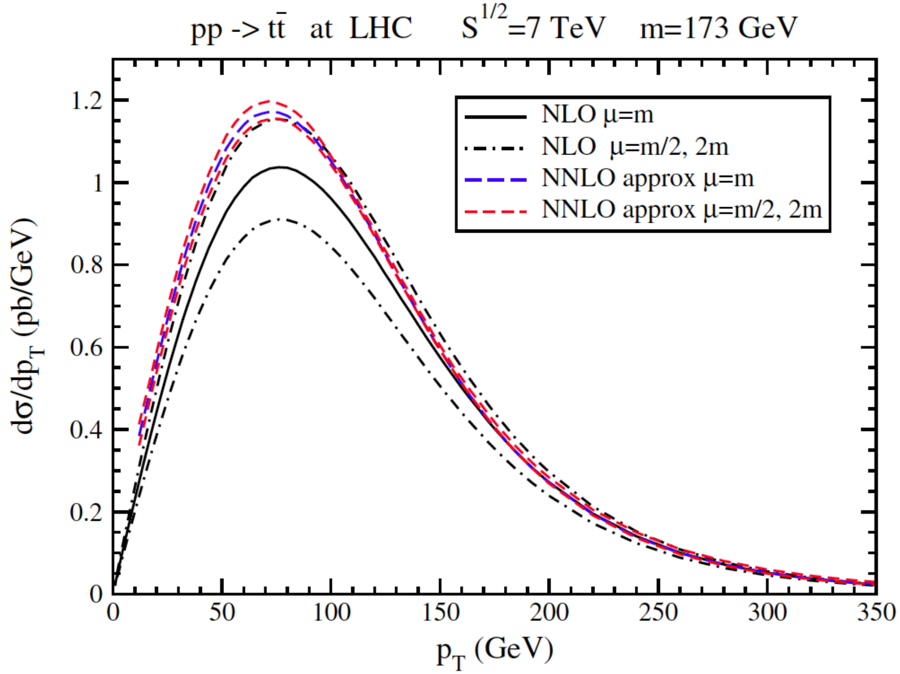
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

How good are the predictions beyond the inclusive rate?

Differential in p_T, η, m_{tt}

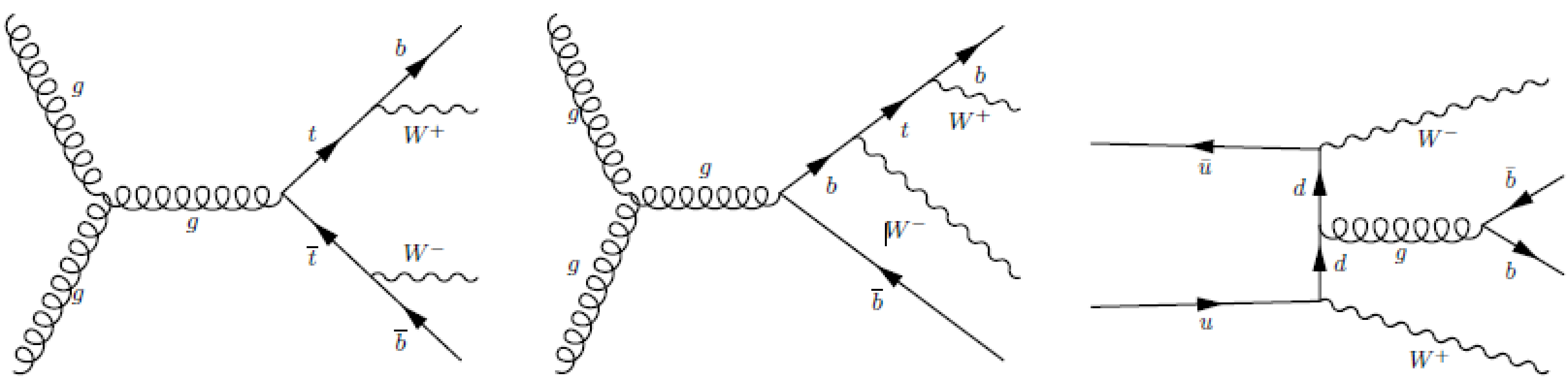
Kidonakis
PR D82 (2010) 114030

Now also differential NNLO!
Czakon, Fiedler, Mitov, , arXiv:1411.3007
focus on Tevatron, but LHC is expected soon



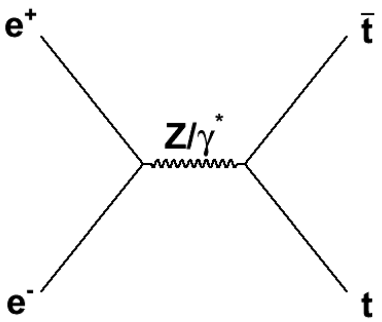
Including top decay

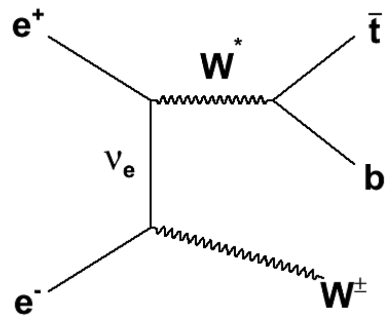
Dittmaier, Czakon
See, eg. Heinrich et al.
arXiv:1312.6659



In fiducial region?

Compare to top quark production at lepton colliders





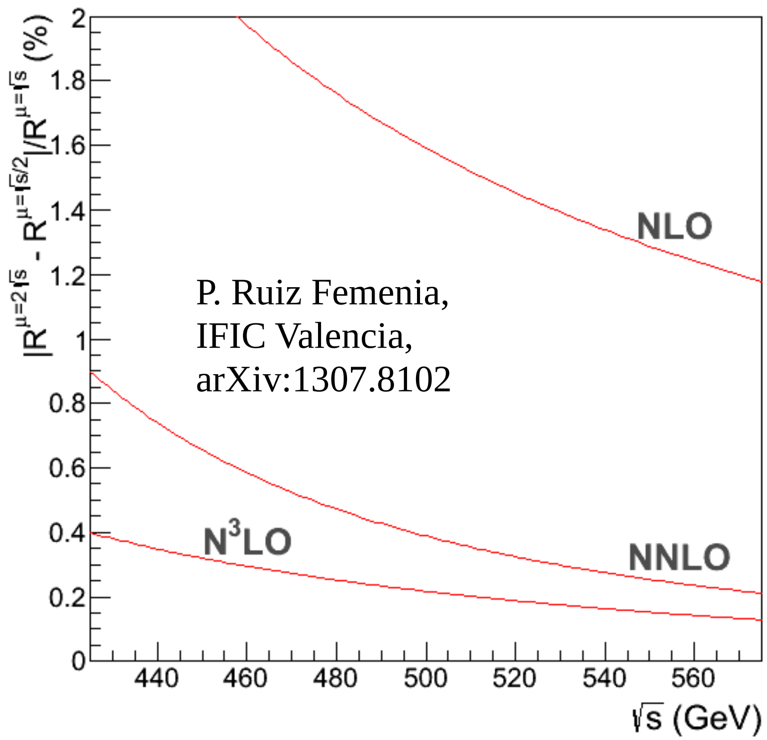
Careful with single top
arXiv:1411.2355
Key for mass determination and study of ttZ and ttγ vertices
arXiv:1307.8102

Pair production ~0.6 pb above threshold
300.000 pairs after 4 years at 500 GeV

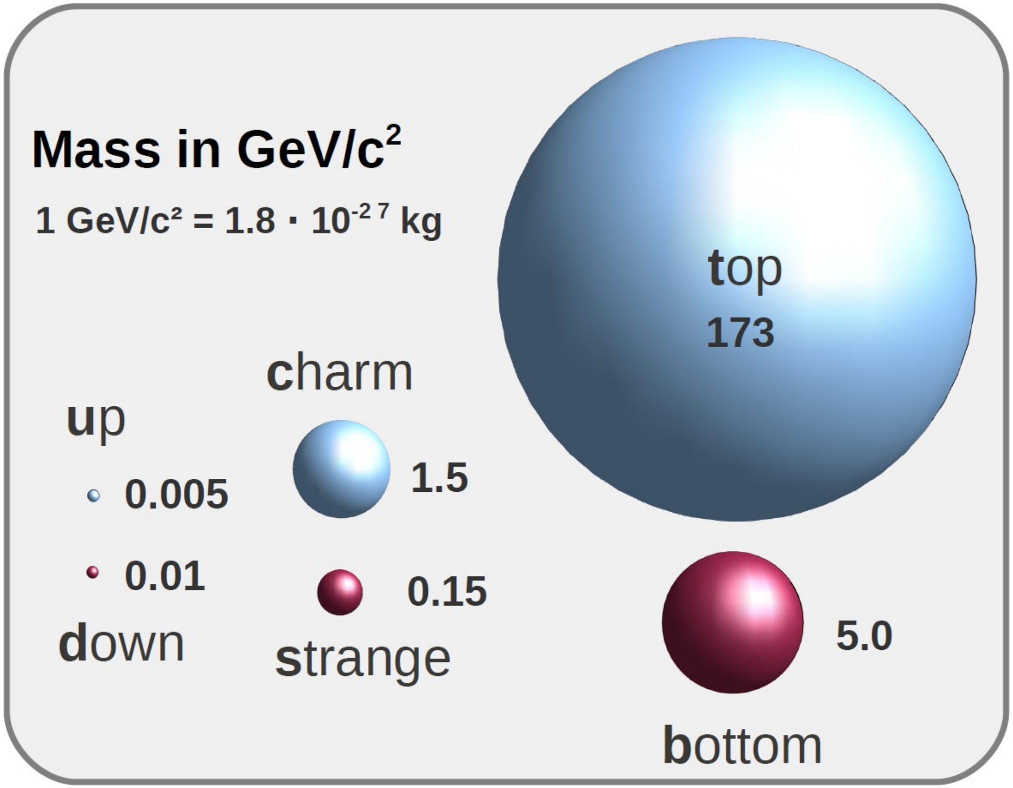
Monochromatic boosted top quark samples from CLIC/μ–Collider

For precision there is nothing like e^+e^-
QCD corrections calculated to N^3LO, scale variations ~ 0.3%. Electroweak corrections are sizable, though.
Calibrate center-of-mass-energy to 1 in 10^4 and luminosity to 0.1%

Variation in x-section due to scale variations



The top quark mass



The heaviest particle in the Standard Model

We don't know why the SM fermions have the masses they have. The top quark has a mass of ~173 GeV. What does that number come from? In the SM it's the result of the Yukawa coupling of the top quark to the Higgs boson. But what does the number come from? We have been worrying about this for 45 years and we haven't made any progress!

Steve Weinberg, public lecture UTA, 24/10/2012

Top quark mass

Precision test of the SM

Enter in all loop corrections

Reduce parametric uncertainty

SM relation H, W, t mass → EW fit

Currently limited by m_W, must improve α_s, $\sin^2\theta$, m_Z

Driving the Higgs potential negative

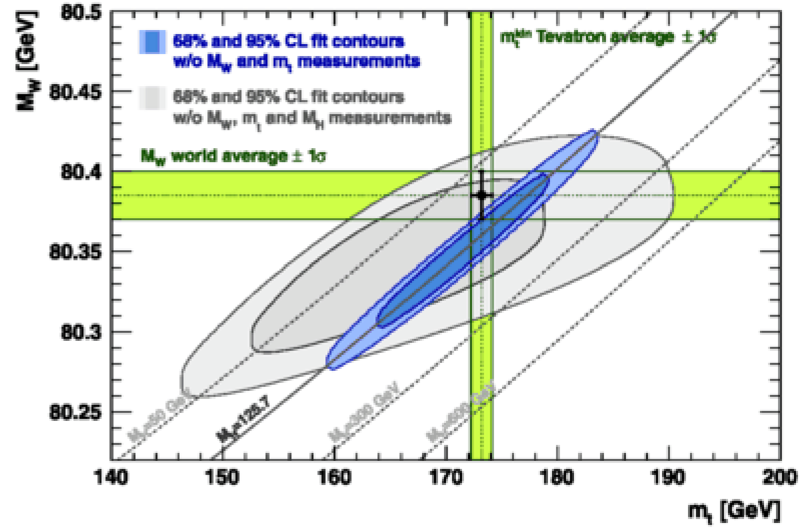
But universe not likely to decay any time soon

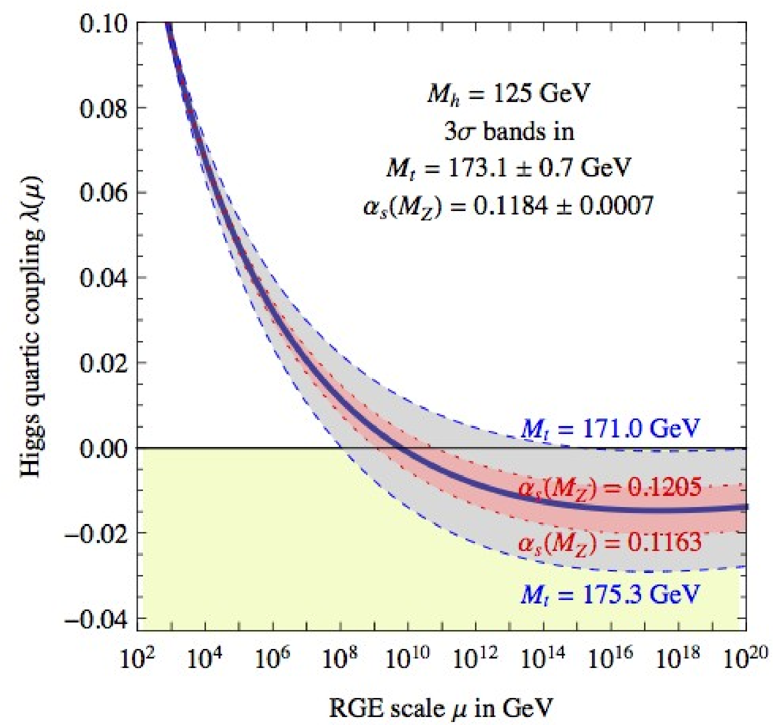
A particle and parameter we can (and must) characterize well

Top escaped scrutiny at LEP

Produced by the millions at the LHC

Charge, polarization accessible

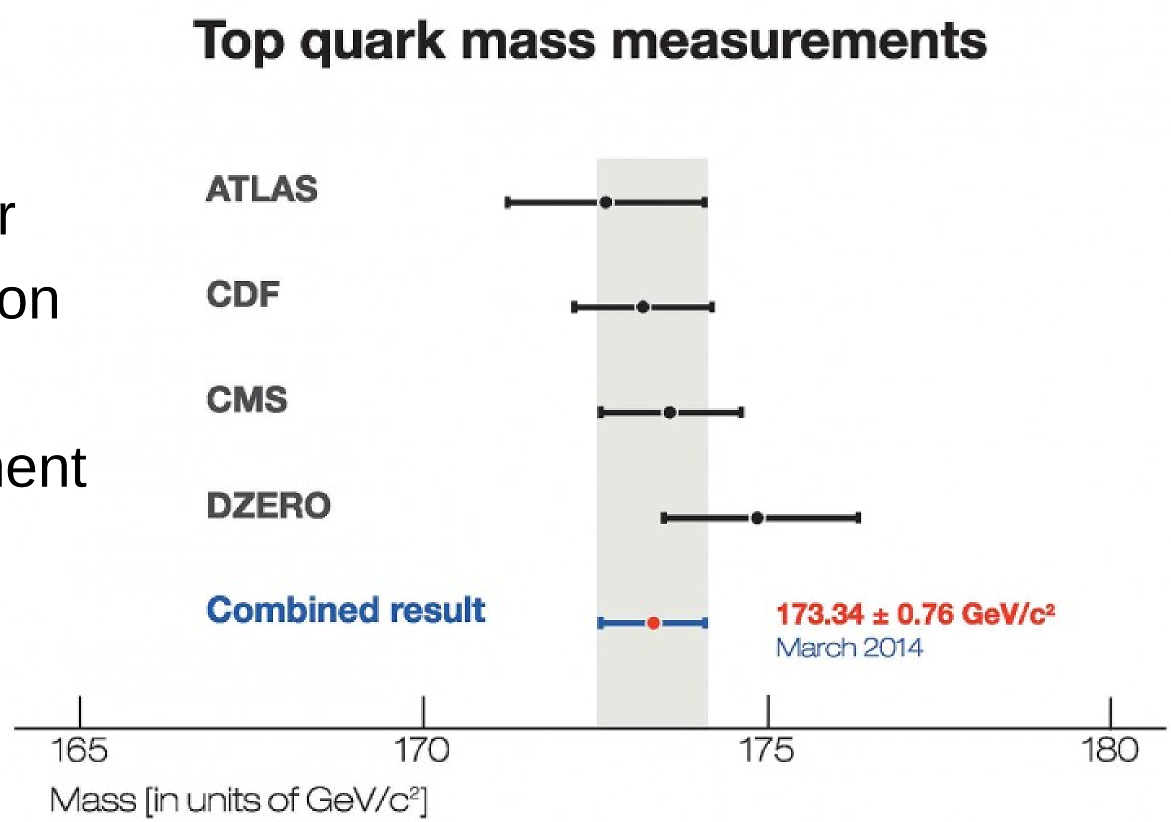




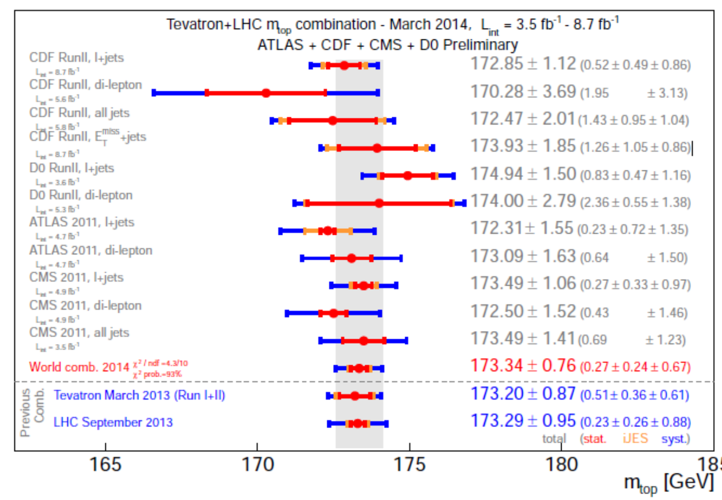
Top quark mass

Historical result, first ever LHC/Tevatron Combination *arXiv:1403.4427*

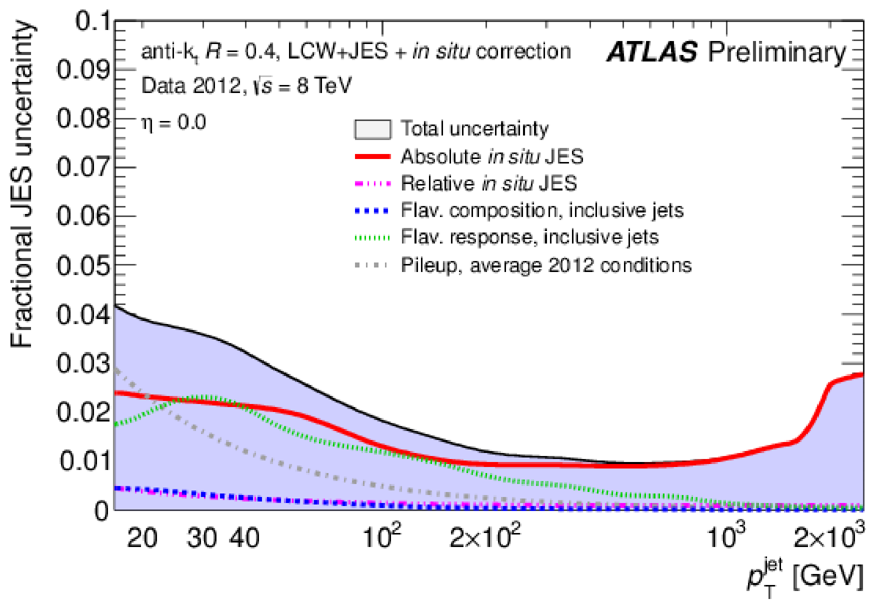
A quark mass measurement to better than 0.5%

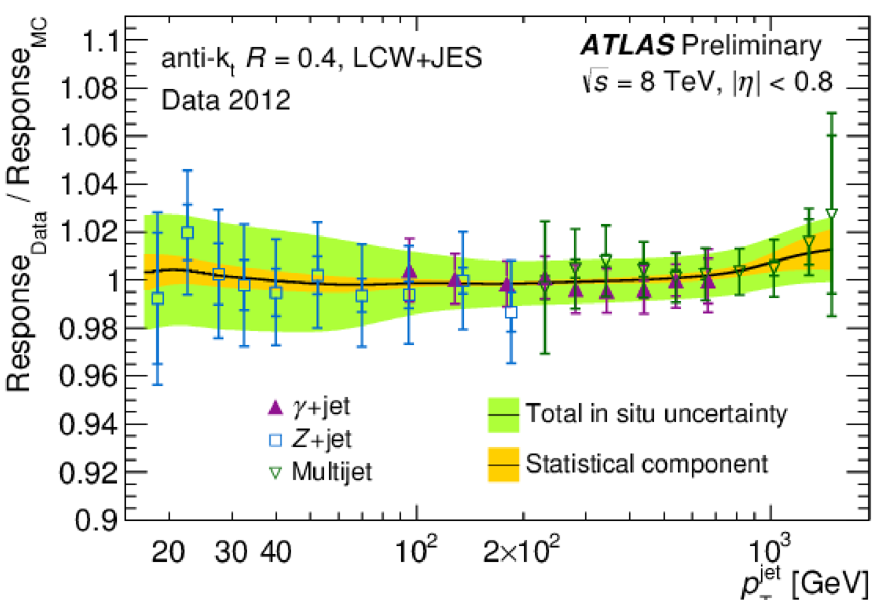


Consistent result in different experiments, continents, initial and final states and kinematic regimes (in fact, agreement was a bit too good at this point; tension has increased a bit since)



Perspective for improvement – systematics on combination





Break-down of uncertainties on March '14 world average:

Jet energy scale:

in situ JES (240 MeV),
standardJES (200 MeV),
flavourJES (120 MeV)
and b-JES (250 MeV)

Statistics:

already < 300 MeV

Modelling:

(strongly correlated even between experiments):
Monte Carlo (380 MeV)
radiation (210 MeV)
colour reconnection (310 MeV)

Top quark mass - alternatives

Endpoint measurement

CMS, arXiv:1304.5783, currently 2 GeV uncertainty)

CMS estimate 600 MeV precision after the complete LHC programme

Move away from jets

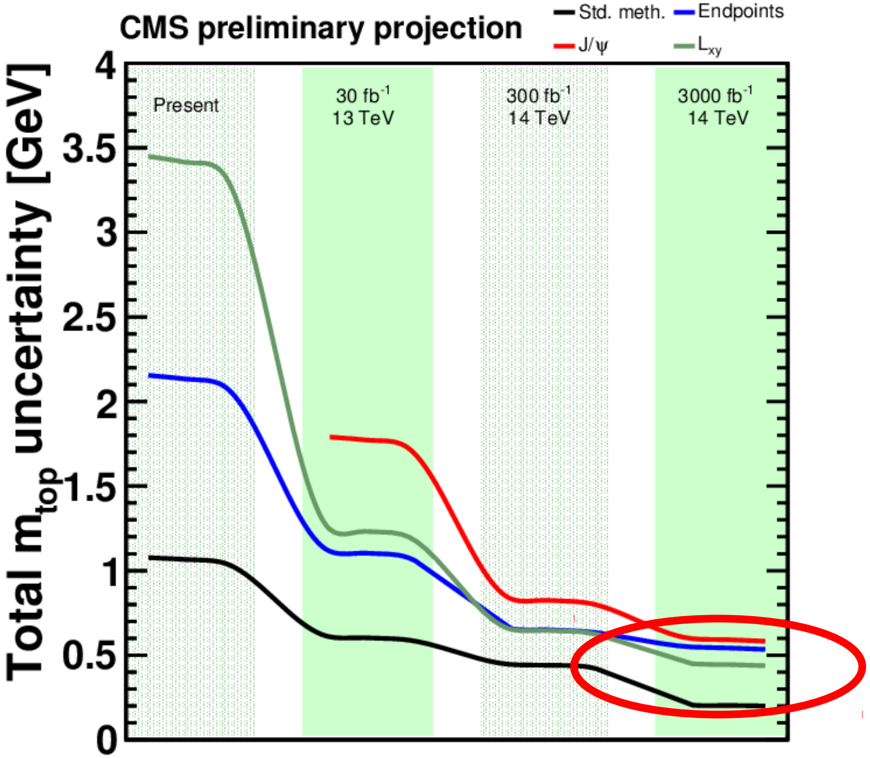
(reduced dependence on shower modelling and JES)

- Extraction from m_{bl}
- Extraction from J/psi spectra $t \rightarrow Wb \rightarrow l\nu b \rightarrow l\nu J/\varphi \rightarrow l\nu ll$

Prospects for precision

For a long time we claimed an LHC precision of 1 GeV

Prospect studies for top quark mass precision at Snowmass reported in arXiv:1310.0799, that I sign, concluded: *"We estimate that [...] might lead to a top mass extraction with uncertainty as low as 500-600 MeV"*



CMS-FTR-13-017-PAS claims the ultimate reach of the "conventional method is 200 MeV, based on "assumptions [that] are optimistic but not unrealistic."

Clearly, the 200 MeV require a lot of work on JES and generators. Time will tell...

The relation between the pole mass and the MC top-quark mass as "not an experimental problem, but a theoretical (or phenomenological) issue."

Serious attempts to discover the relation (provided there is one) between MC mass and pole mass are encouraged! (see for instance: A. Hoang, LCWS14)

The top quark mass combination, small print

all measurements considered in the present combination, the analyses are calibrated to the Monte Carlo (MC) top-quark mass definition. It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV (see Refs. [19, 20] and references therein).

to jet calibration and modelling of the $t\bar{t}$ events. Given the current experimental uncertainty on m_{top}, clarifying the relation between the top quark mass implemented in the MC and the formal top quark pole mass demands further theoretical investigations. The dependence of the result on the correlation assumptions between mea-

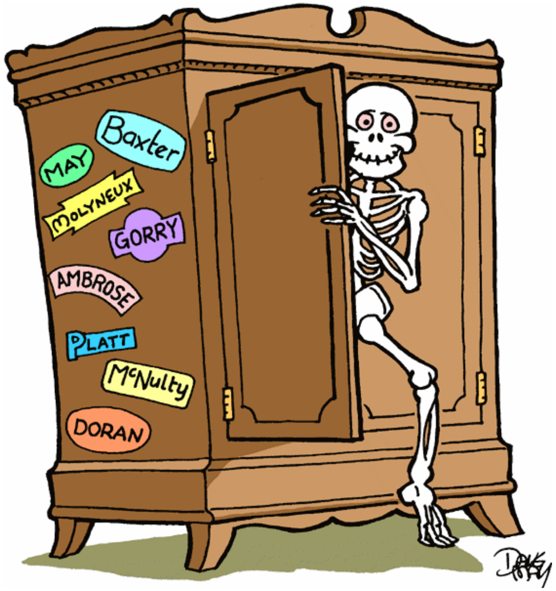
[19] General-purpose generators for particle physics

$$m_t^{pole} = m_t^{MC} + Q_0[\alpha_s(Q_0)c_1 + \ldots]$$

With Q_0 ~ 1 GeV (Parton Shower infra-red cut-off)

And C1 a constant of order 1 (and positive)

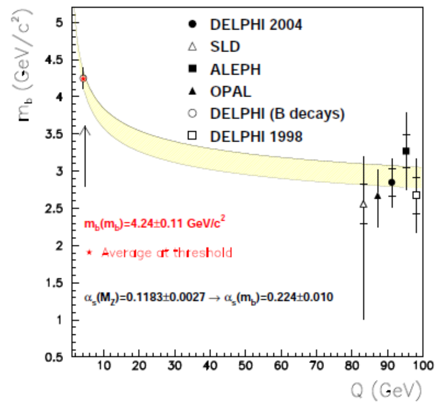
At least partially accounted for in current modelling uncertainty

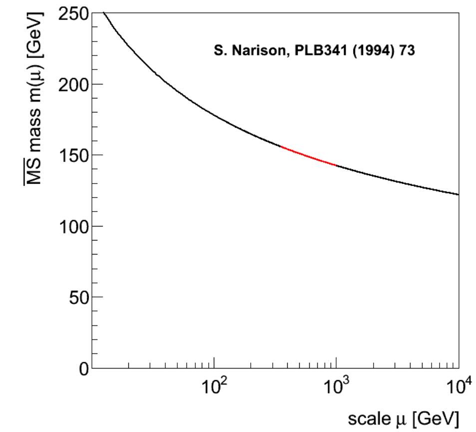


Scheme dependence – an old debate

Even if it decays (rather than hadronizes) the top is a quark, a coloured object. Mass is not an observable, but must be inferred from measurements.

The scheme makes a difference:
For a top pole mass of 173 GeV,
the $\overline{\text{MS}}$ mass is ~167 GeV





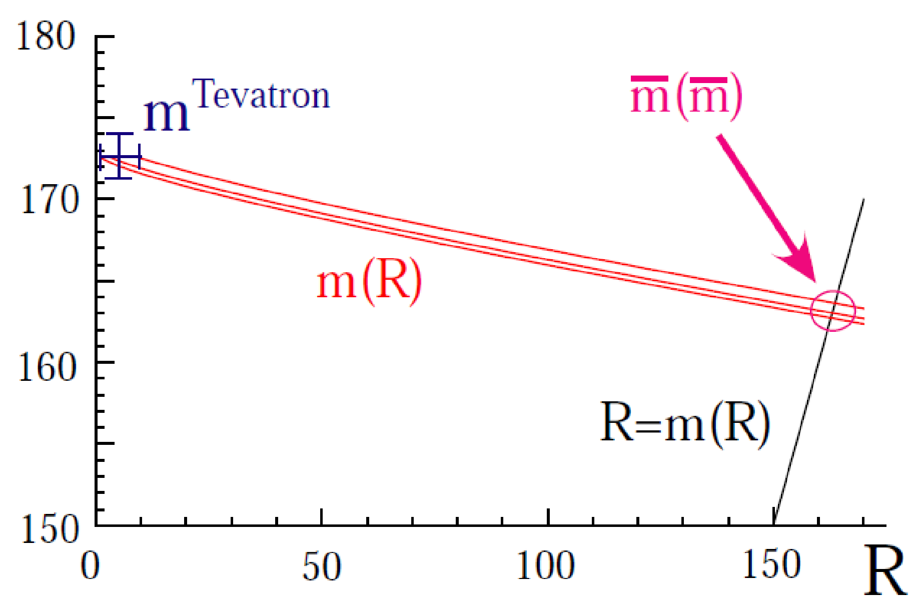
Quantify the difference between pole and MC mass
Hoang & Stewart, Nucl.Phys.Proc.Suppl. 185 (2008) 220-226

$$m_t^{pole} = m_t(R,\mu) + R\,\Sigma_k \Sigma_n a_{nk} \left[\frac{\alpha_s(\mu)}{4\pi}\right]^n \ln^k\left(\frac{\mu}{R}\right)$$

R is the scale chosen the scheme (dial m for MS, 0 for pole mass)

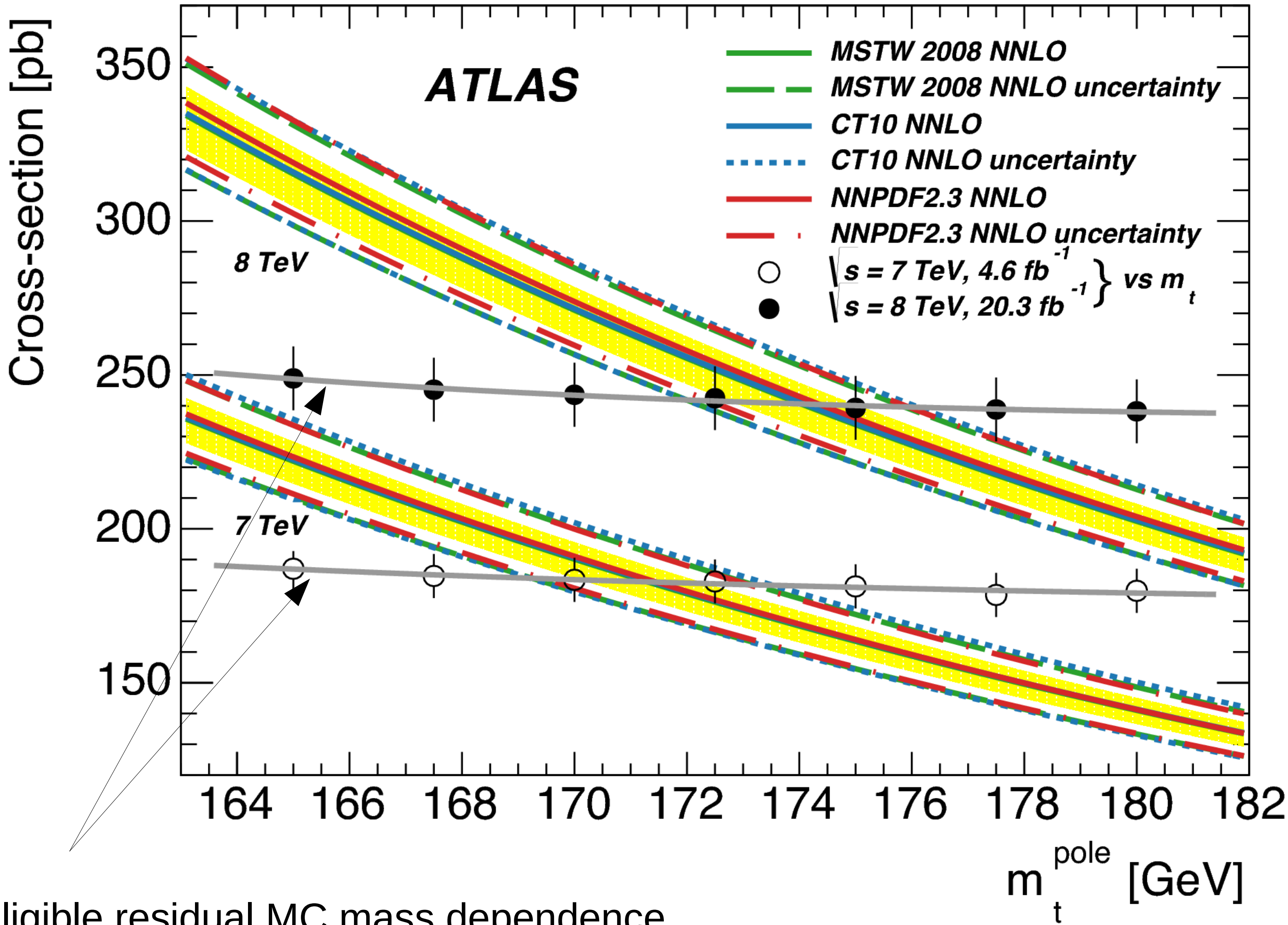
MC mass: R~Γ_t~ PS cut-off and:

$$m_t^{pole} = m_t^{MC}(R) + R\,\alpha_s \frac{(\mu)}{4\pi}$$



Alternative: top mass from cross-section

$\Delta m_t^{pole} = 2.5$ GeV



Nearly flat, negligible residual MC mass dependence

Top quark mass

Extraction from cross section - revisited

Well-defined mass scheme (pole mass, $\overline{\mathrm{MS}}$ mass)

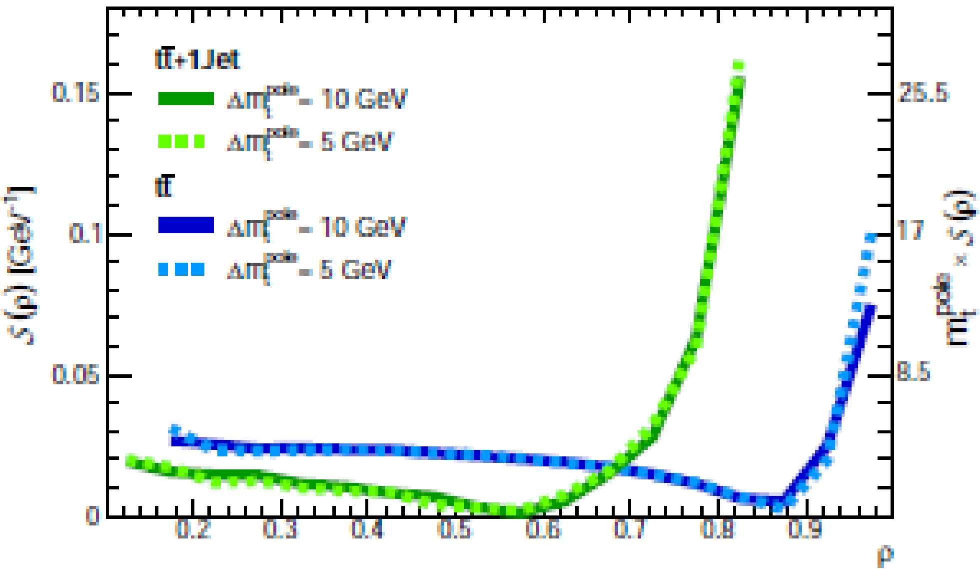
Limited by poor sensitivity: $\Delta m/m \sim 0.2\ \Delta\sigma/\sigma$

$t\bar{t}$ threshold has better sensitivity, but requires theory progress (bound states)

currently ~4 GeV uncertainty, PLB728 (2014) 496-517

Now consider the $t\bar{t}g$ cross-section

Alioli, Moch, Uwer, Fuster, Irles, Vos, EPJC73 (2013) 2438, arXiv:1303.6415



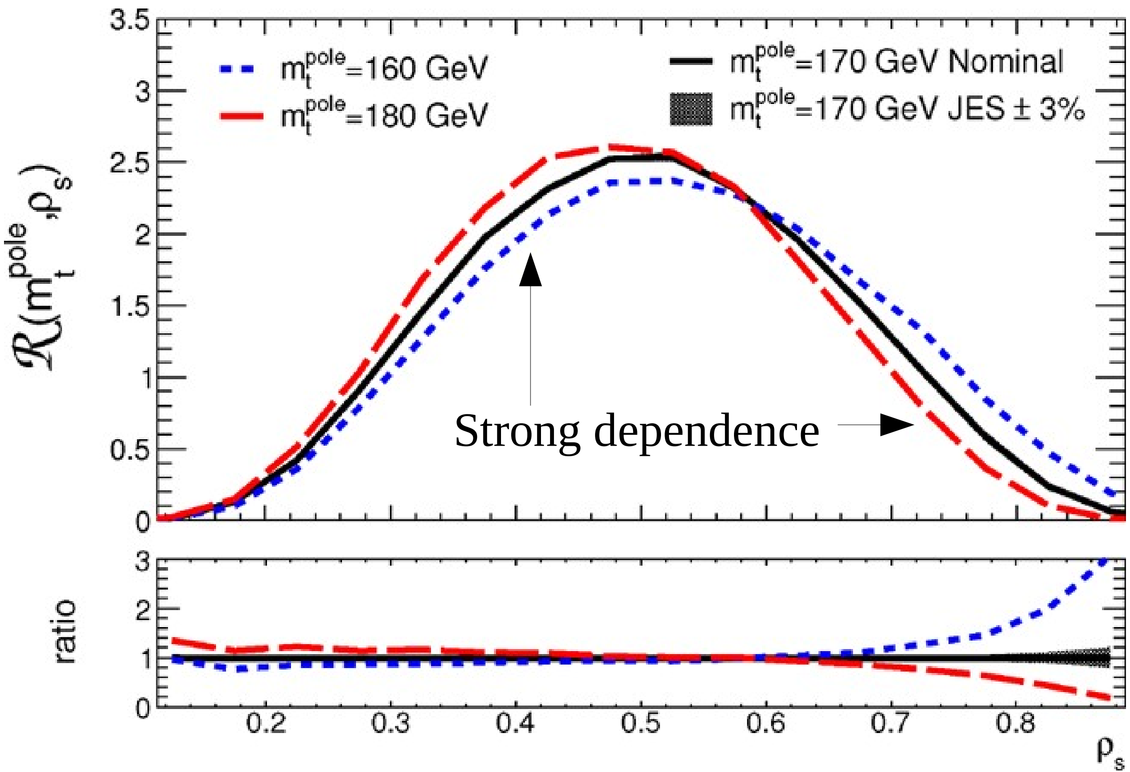
Top quark mass

Measure the normalized differential tt+1jet production cross-section vs. Invariant mass of the tt+1jet system.

Extract the mass in any (well-defined) scheme. Currently: pole mass

Theory uncertainty (due to scale and PDF) < 1 GeV

Experimental uncertainties can be controlled to same level

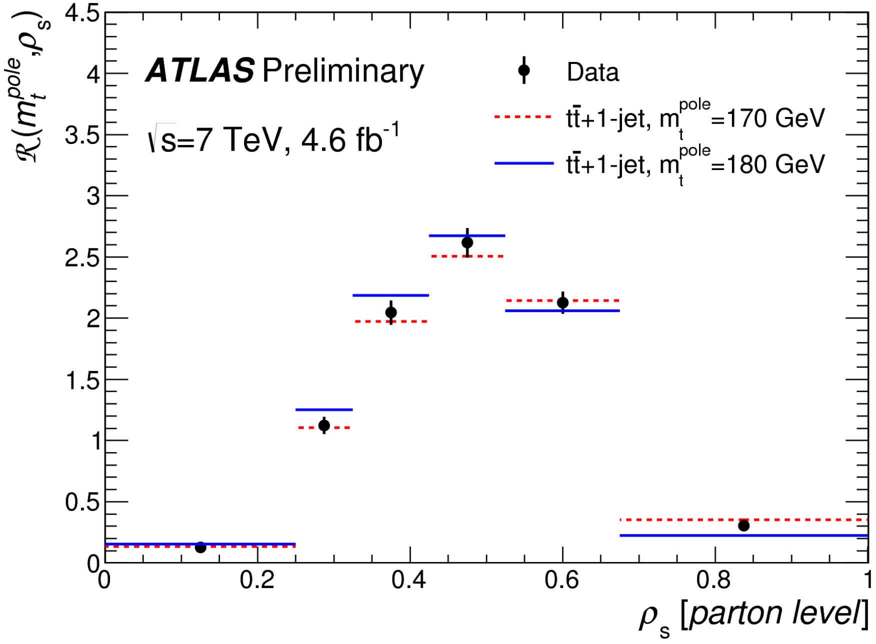


ρ_s μ 1/m($t\bar{t}j$)

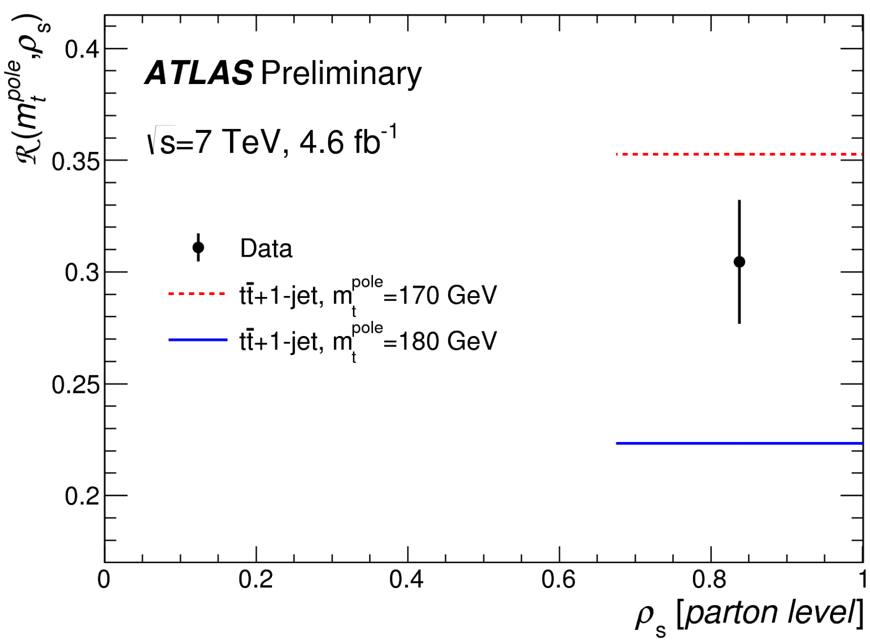
→ *1 at threshold*

→ *0 for boosted production*

Top quark mass from tt + 1 jet events



ATLAS-CONF-2014-053



Correct normalized differential cross-section to parton-level

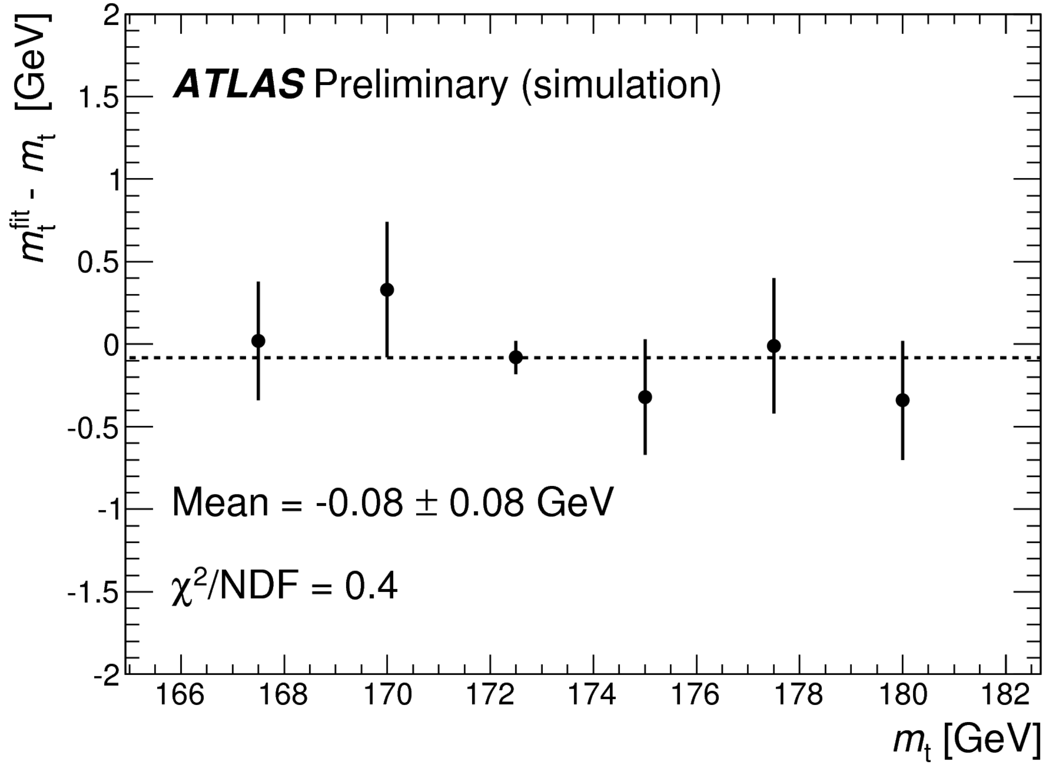
Fit with tt+jet NLO+PS theory

Is this the pole mass? Yes!
Scheme fixed in NLO calculation
(difference NLO vs. NLO+PS ~ 300 MeV)

Top quark mass

Don't you run into a MC mass dependence in the correction of the normalized differential cross-section?

No, compatible results are obtained for a large range of MC mass values.



Top quark pole mass

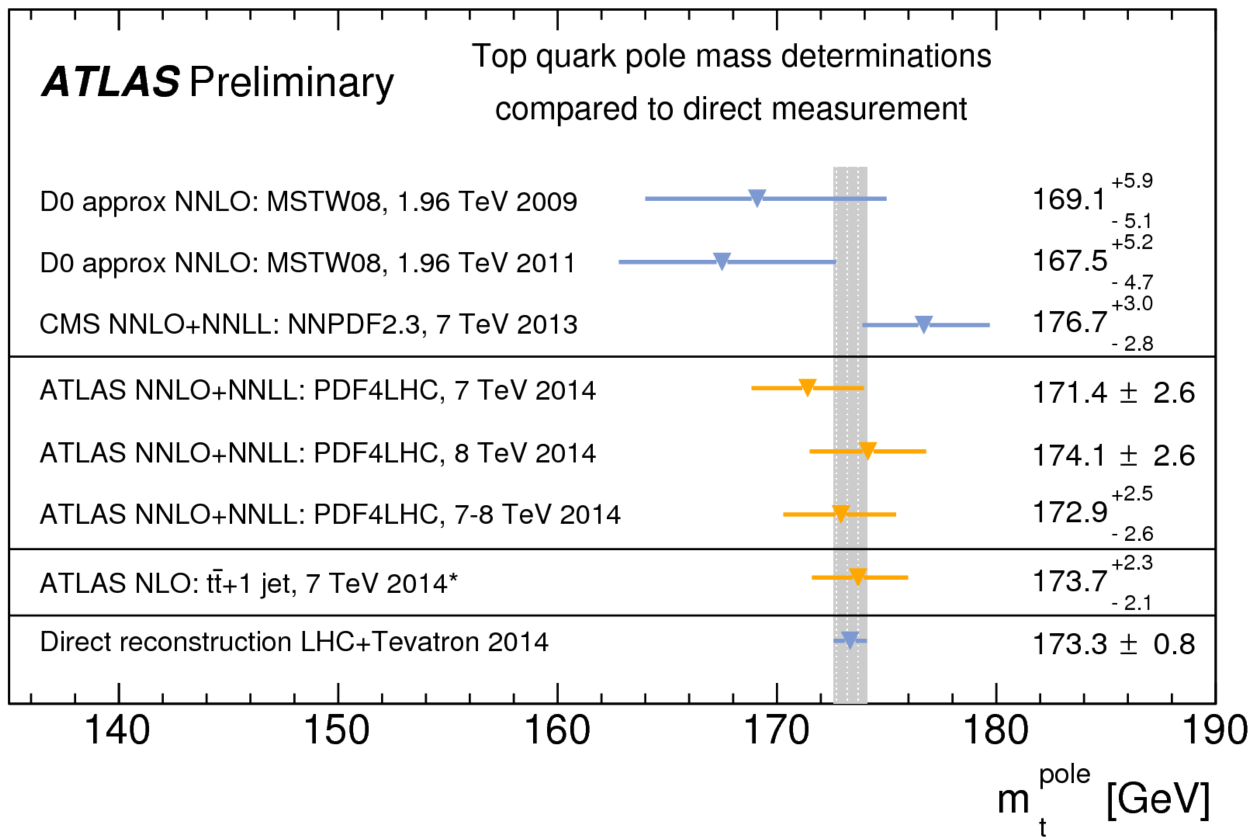
M_t^{pole}=173.7 +2.3 -2.1 GeV

→ *currently the most precise top quark pole mass*

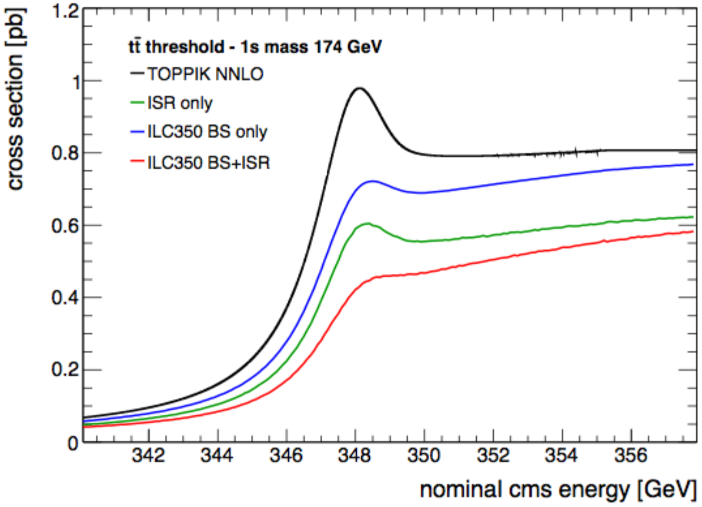
1.5 (stat.), 1.4 (syst.), +1.0/-0.5 (theo.)

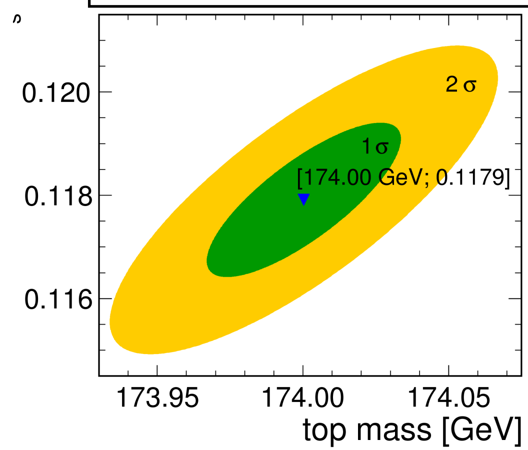
→ *room for improvement, even with 2012 data set (ongoing)*

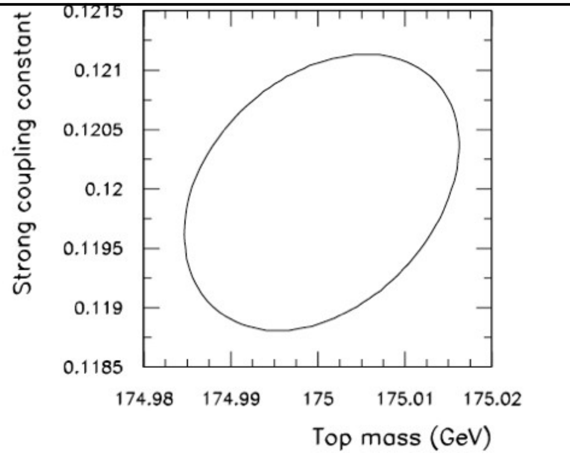
→



Top quark mass at an LC







No dependence on location of scan energy
5% uncertainty non-tt bkg → 18 MeV
10^{-4} precision on √s → 30 MeV
uncertainty on lumi-spectrum → ~10 MeV

1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

A precise measurement ($\Delta\, m_t$ < 100 MeV) can be achieved
+ $\Delta\, \alpha s$ < 0.001 (+ $\Delta\, \Gamma_t$ < 30 MeV) (+ $\Delta\, y_t/y_t$ ~ 35% *)

Top quark mass: a program for 3 decades

Tevatron: discovery (1995) and first characterization

- Legacy δm_t < 1 GeV

LHC: new methods based on kinematical observables

- *B hadron decay length*
- *lepton p_T*
- *J/ψ+lepton from W*
- *Endpoints*

LHC: extract top mass from measured cross-section

- *Achieved 3% precision, with a rigorous interpretation*
- *Increase sensitivity: differential tt+jet x-section yields ~GeV precision*

Future LC: threshold scan + …

- *100 MeV precision!**

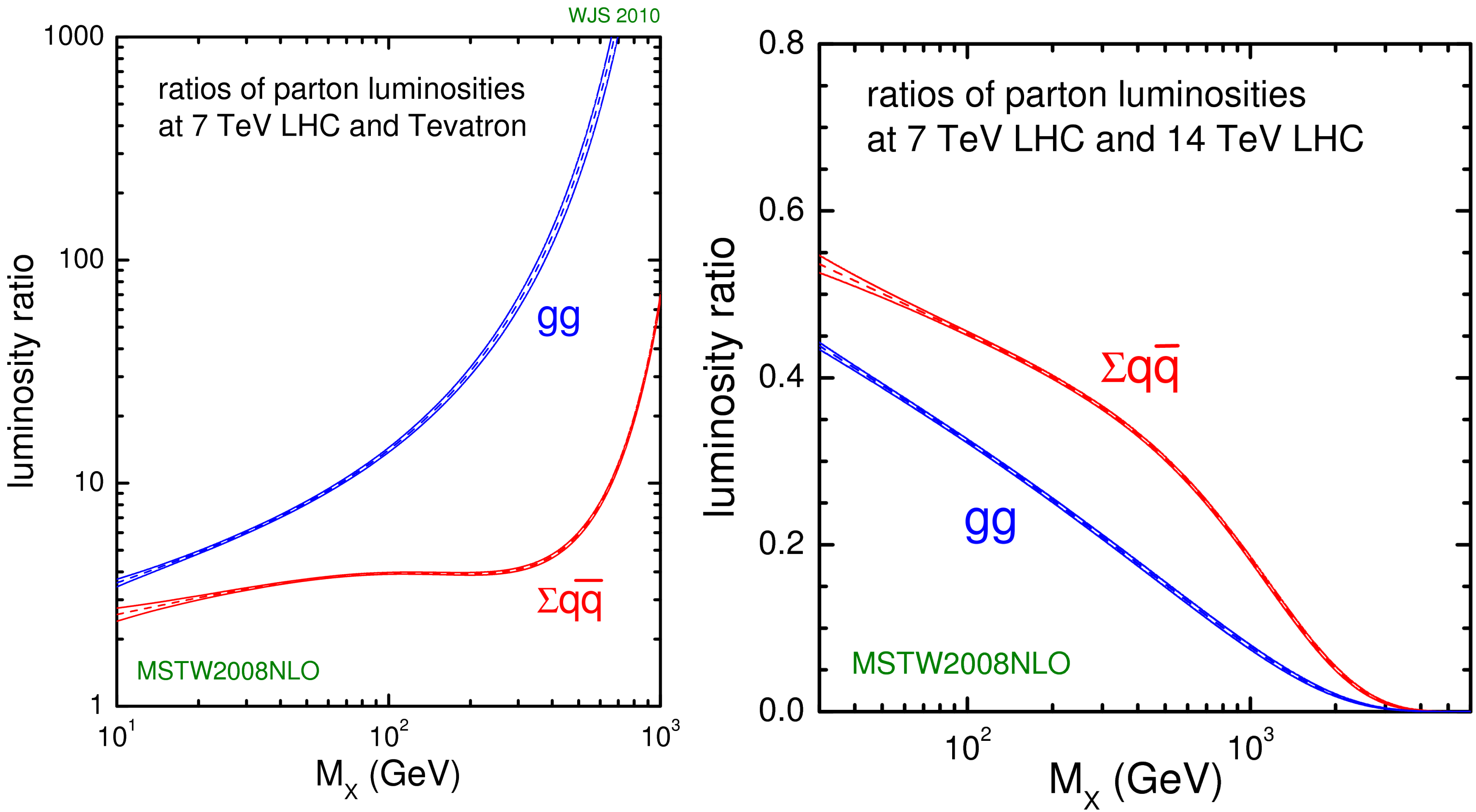
marcel.vos@ific.uv.es

The top quark

Measurement of top quark differential cross-sections

- Lepton + many jets background important for searches
- Search for new physics decaying to top quarks
- Charge asymmetry (sort out the Tevatron puzzle)
- Boosted top quark production probes the internal structure of the top quark (Englert et al., PLB 721)

Parton luminosity!



For 1-2 TeV states, the luminosity increase wrt Tevatron is spectacular
Prepare to leap well into the multi-TeV regime in the next runs!

Boosted top quark production

	Tevatron rII (1994-2012) **10 fb-1 @ 1.96 TeV**	**LHC fase I** (2012) **20 fb-1 @ 8 TeV**	**LHC design** (2015 – ...) **300 fb-1 @ 13 TeV**	**VLHC** (>2030) **3000 fb-1 @ 33 TeV**	**VHE-LHC** (>2030) **3000 fb-1 @ 100 TeV**
Boosted: M_{tt} > 1 TeV	25	30.000	3.000.000	46.000.000	820.000.000
Highly so: M_{tt} > 2 TeV	-	300	47.000	23.000.000	450.000.000
Extreme: M_{tt} > 5 TeV	-	0	30	150.000	9.500.000

Indicative numbers based on MCFM NLO calculation.

Enormous increase in available data:

Tevatron harvest of top quark pairs: 100.000

LHC top quark factory: 5 M/year in run I

→ can we (ever) control the systematics to match the statistical error?

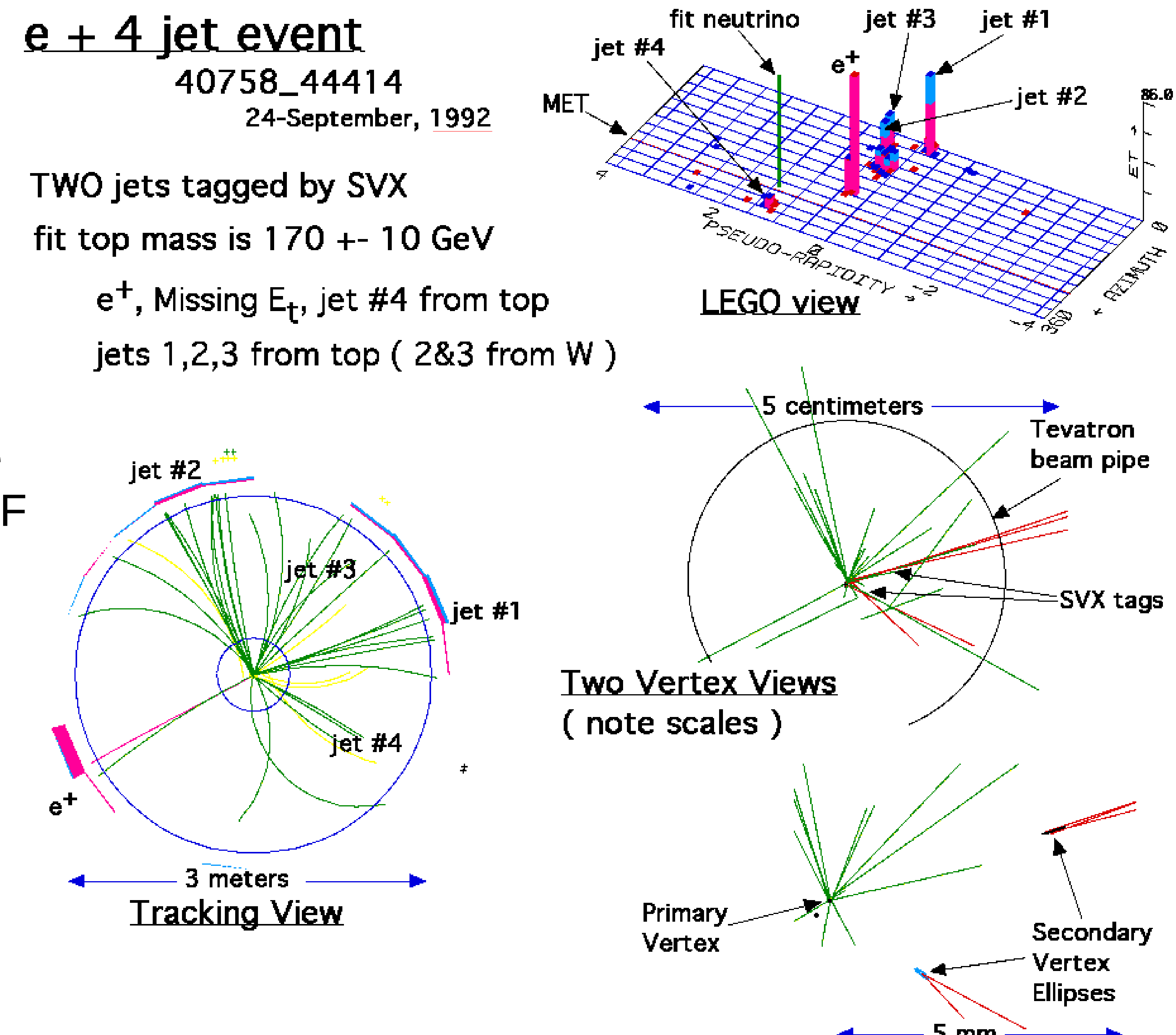
First useful sample of boosted top quark has been collected

Be ready to handle millions in next phase of operation

→ not just for searches in extreme corners of phase space

→ be ready to repeat bread and butter SM measurements with boosted objects

An old example from CDF

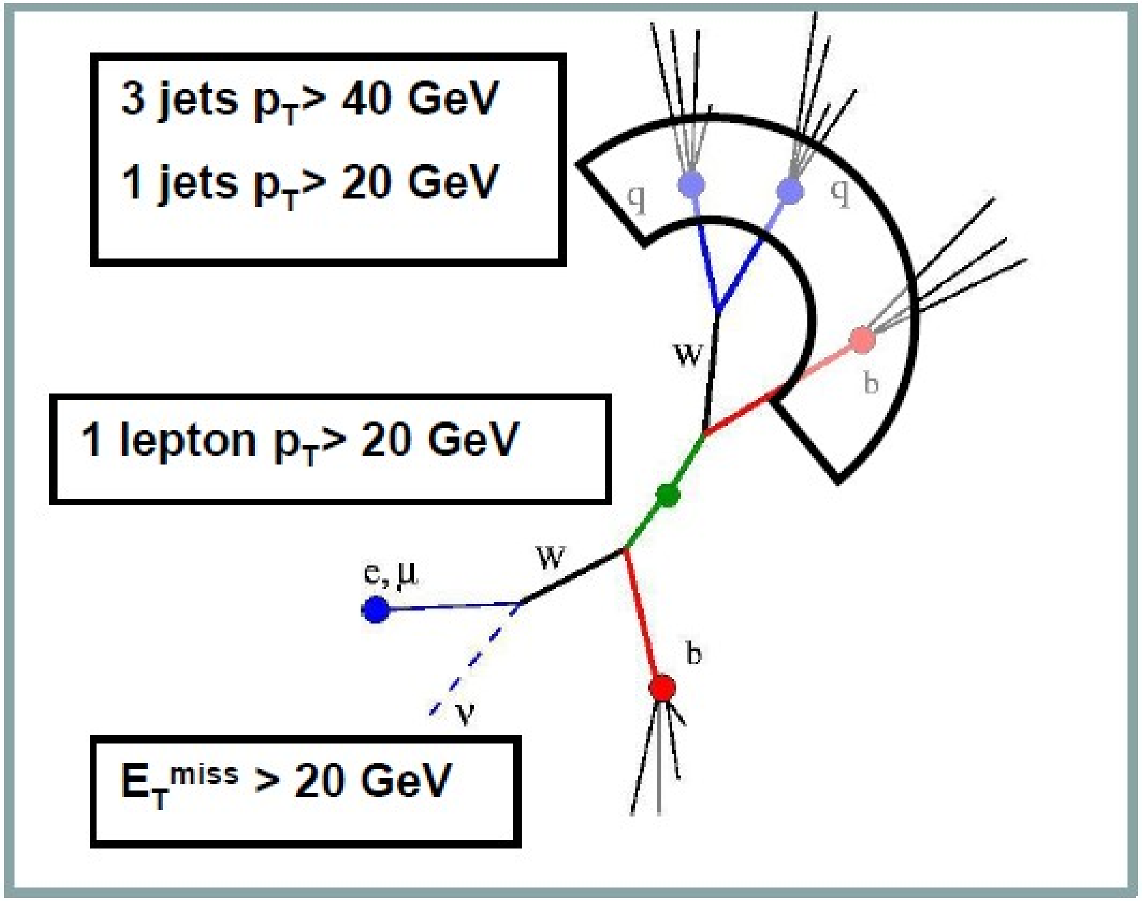


Top quark pairs: reconstruction

B-tagging distinguishes **b-jets** from W-decay jets and gluon radiation

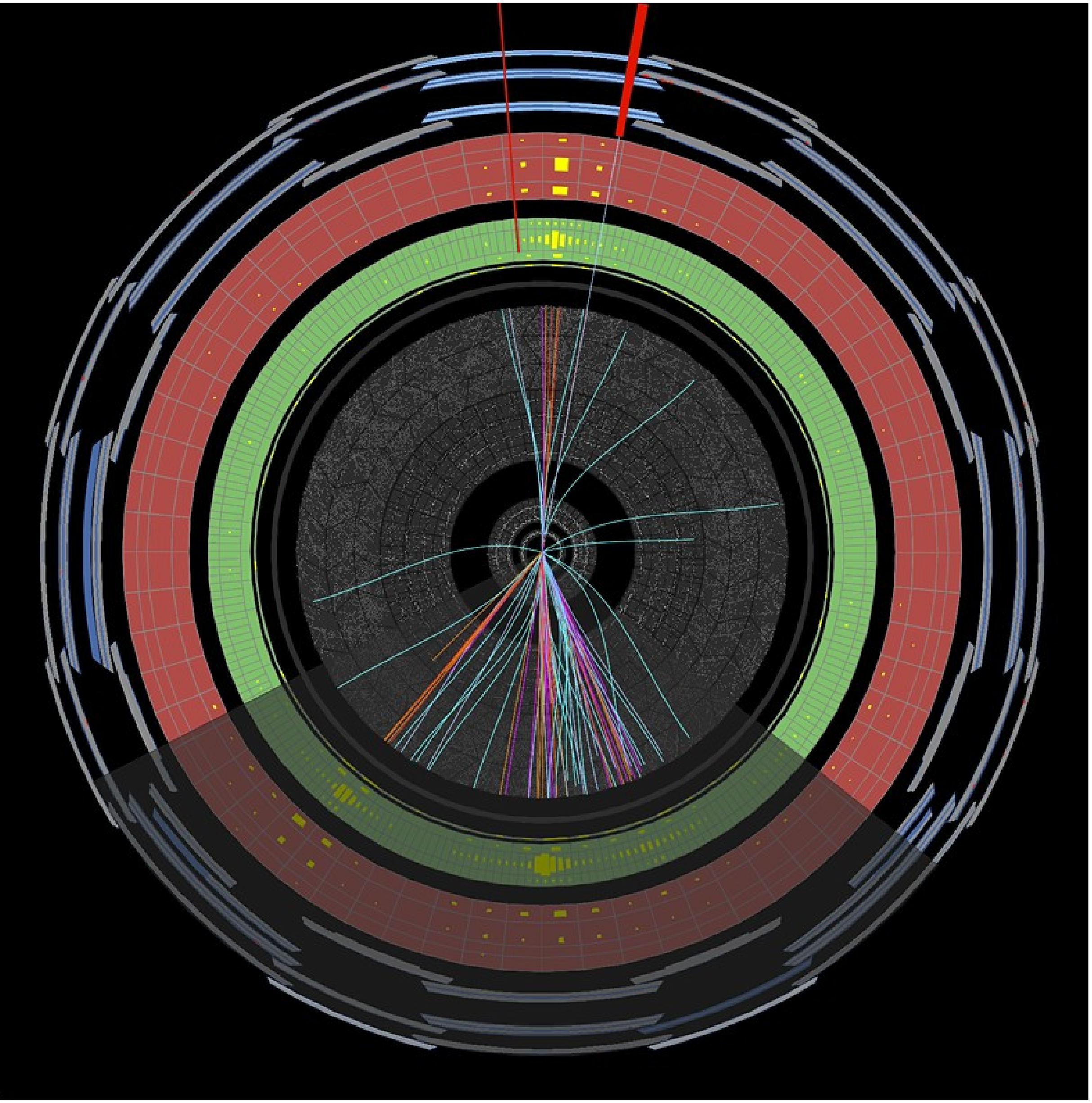
The **neutrino:** $\mathbf{p_T} = - \mathbf{p_T^{miss}}$, p_z from W-mass constraint, resolve 2-fold ambiguity in some ad hoc way

Pick the two with highest $\mathbf{p_T}$ among the **remaining jets**



tt -> Wb Wb -> ℓνb qqb

Try to apply that to this event!



LHC data

Likely $t\bar{t}$ (purity ~70%)

But, m ~ 2.5 TeV

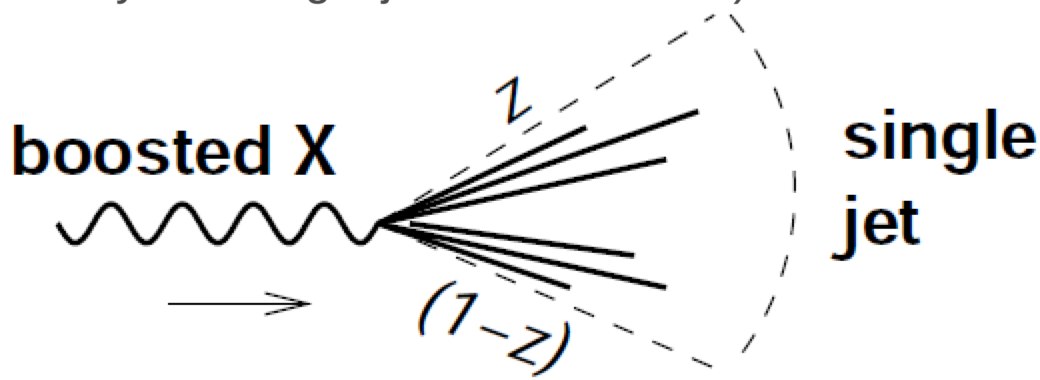
Boosted objects

Let's define "boosted object" by comparing the standard approach (reconstruct components and combine) **to Mike Seymour's alternative** (find composite object and decompose).

Rules of thumb for maximum jet radius parameter for 2-body decay:

$R < 2m/p_T$ (always resolve two jets)

$R > 3m/p_T$ (capture full decay in a single jet 75% of cases)



W boson at rest → use resolved approach

$p_T \sim 240$ GeV → coexisting algorithms,

can resolve with R=0.4, or contain in R=1

$p_T \sim 400$ GeV → boosted regime

cannot (always) resolve even with R=0.4

BOOST2010 report: Boosted objects: A Probe of beyond the Standard Model physics.

Jet mass

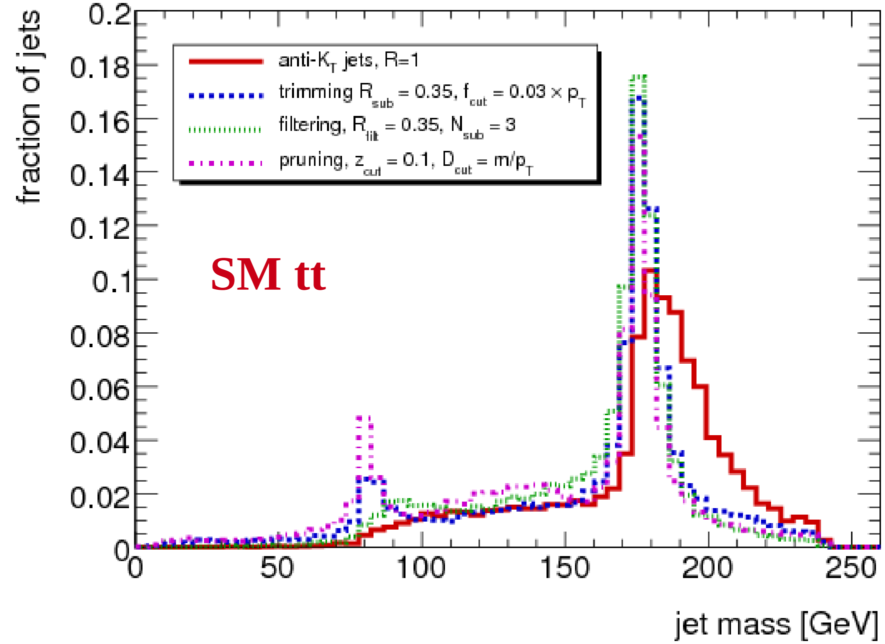
Pythia: $500 < p_T < 600$ GeV
Anti k_T (R=1.0) particle-level

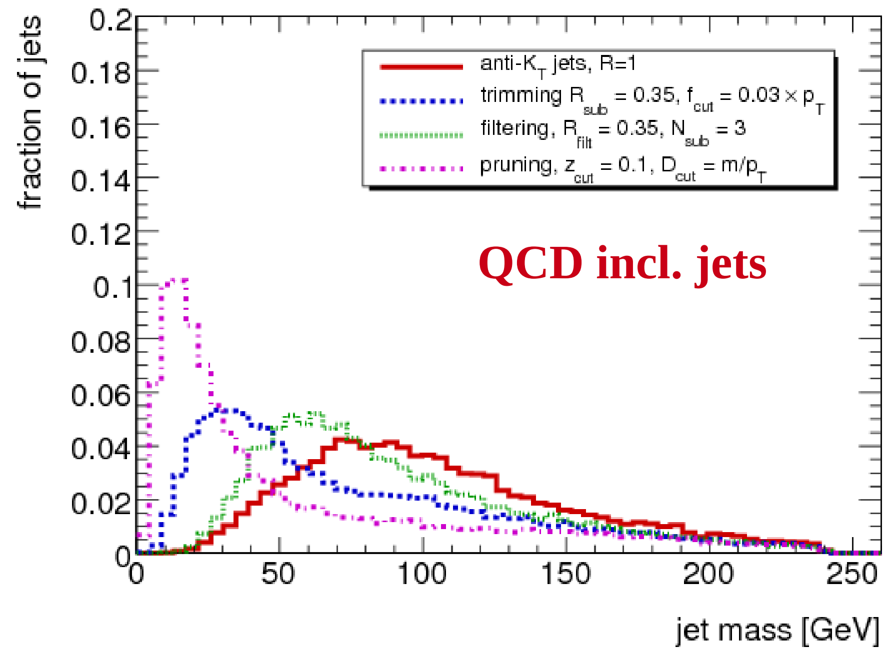
Top jet → $m_j \sim m_t$

Background → $m_j\, \mu\ \alpha_s\, p_T\, R$

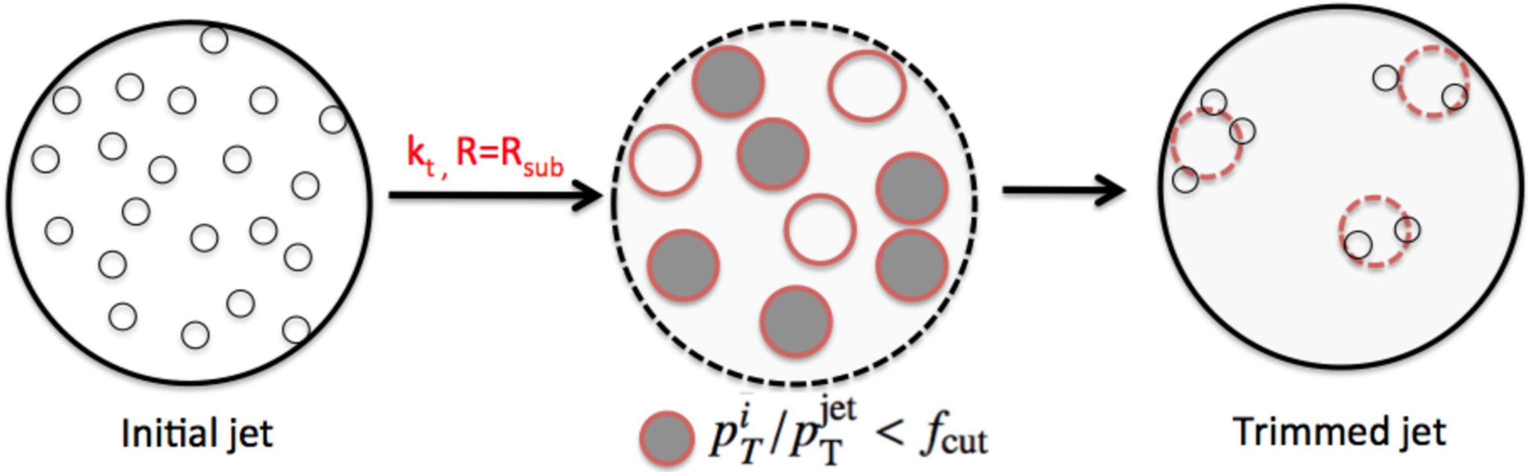
Jet grooming improves performance:

- Resolution
- Background rejection
- Pile-up resilience





Tools and Techniques: grooming & area subtraction



Jet substructure is often hidden:

- ✓ Soft emissions inside the jet
- ✓ Underlying event
- ✓ Pile-up

Jet grooming techniques to remove the "softest" parts of the jet:

- ✓ **Trimming:** construct subjets on scale R_{trim}, retain those with $p_{T,sub} > \varepsilon_{trim} p_{T,jjet}$ Krohn, Thaler & Wang '09
- ✓ **Pruning:** **during clustering** discard softer subjet if $R > R_{prune}$ and min(pt1, pt2) < ε_{prune} ($p_{T1} + p_{T2}$). Ellis, Vermilion & Walsh '09
- ✓ **Filtering:** construct subjets on scale R_{filt} , take n_{filt} hardest subjets Butterworth, Davison, Rubin & Salam '08

Area subtraction, determine the event-by-event pile-up activity and subtract a contribution proportional to jet area, Cacciari, Salam, PLB659 (2008!)

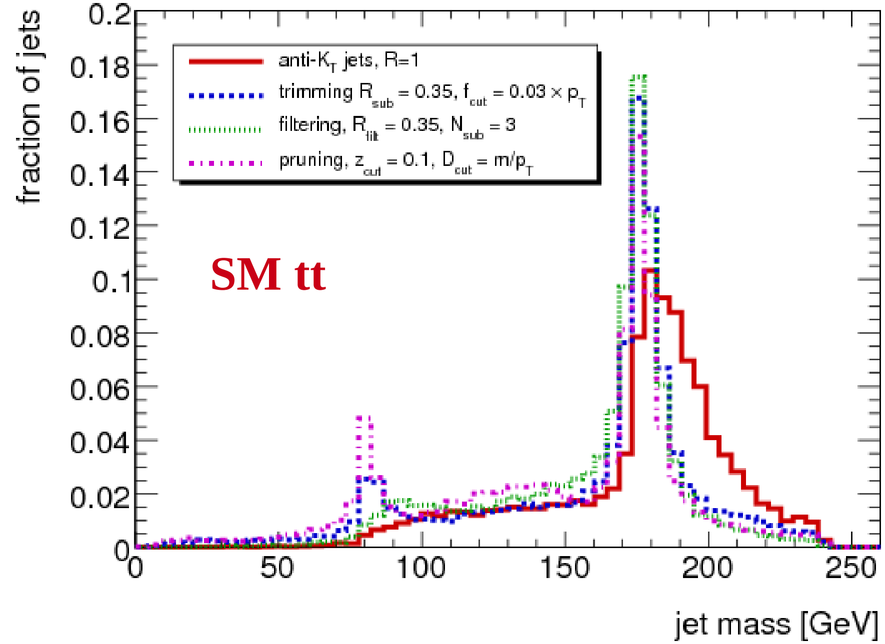
Jet mass

Pythia: 500 < p_T < 600 GeV

Anti k_T (R=1.0) particle-level

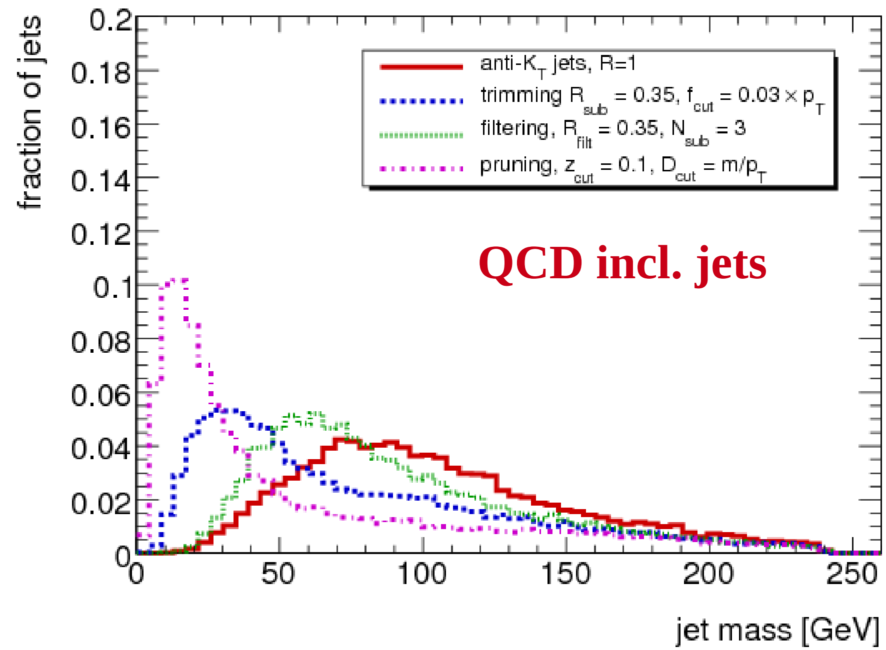
Top jet → $m_j \sim m_t$

Background → $m_j\ \mu\ \alpha_s\ p_T\ R$



Jet grooming improves performance:

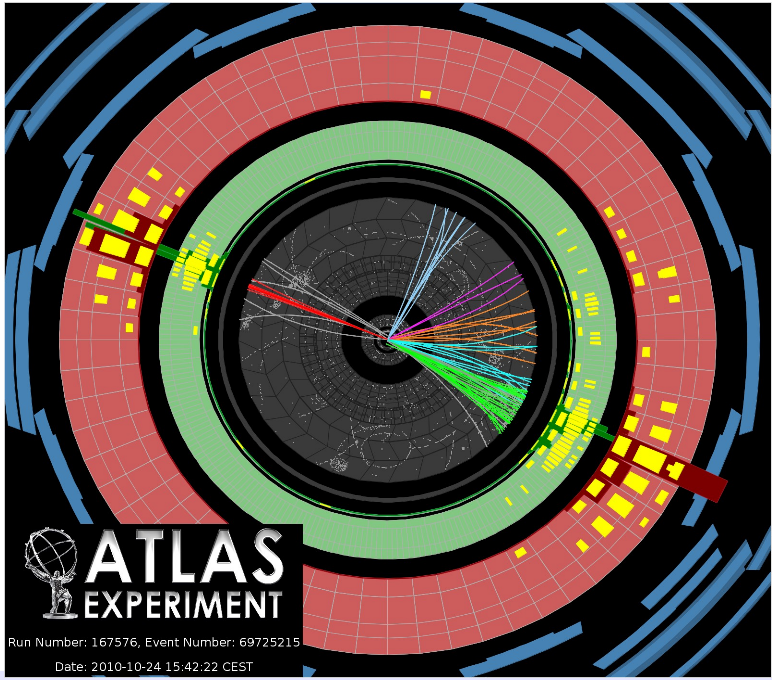
- resolution
- background rejection
- Pile-up resilience

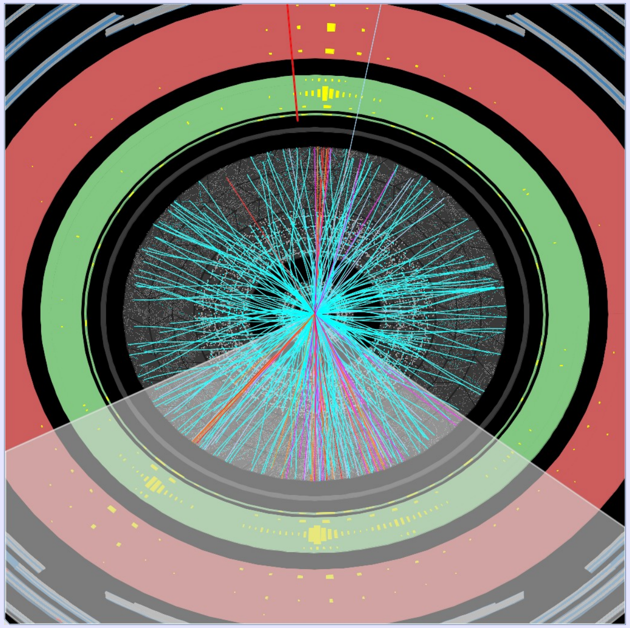


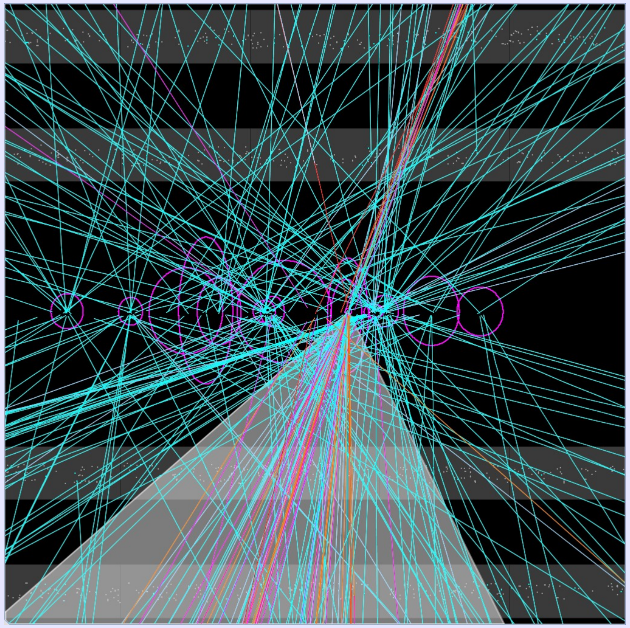
Detector response

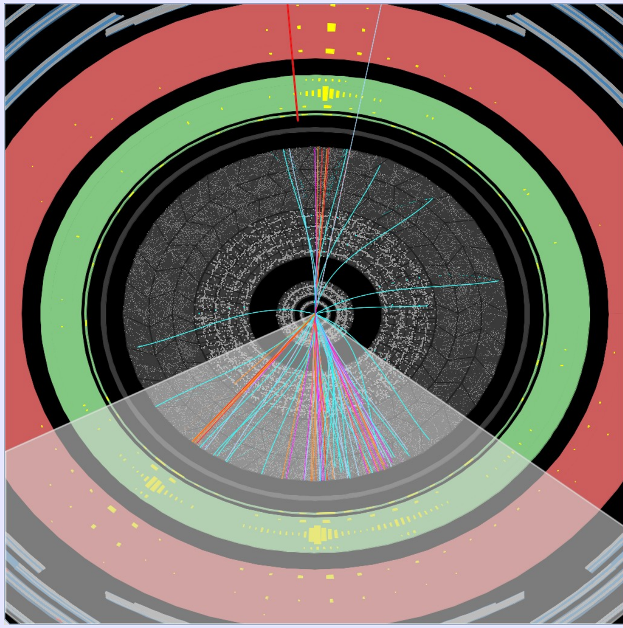
Can we measure jet substructure precisely and reliably?

Under these conditions?







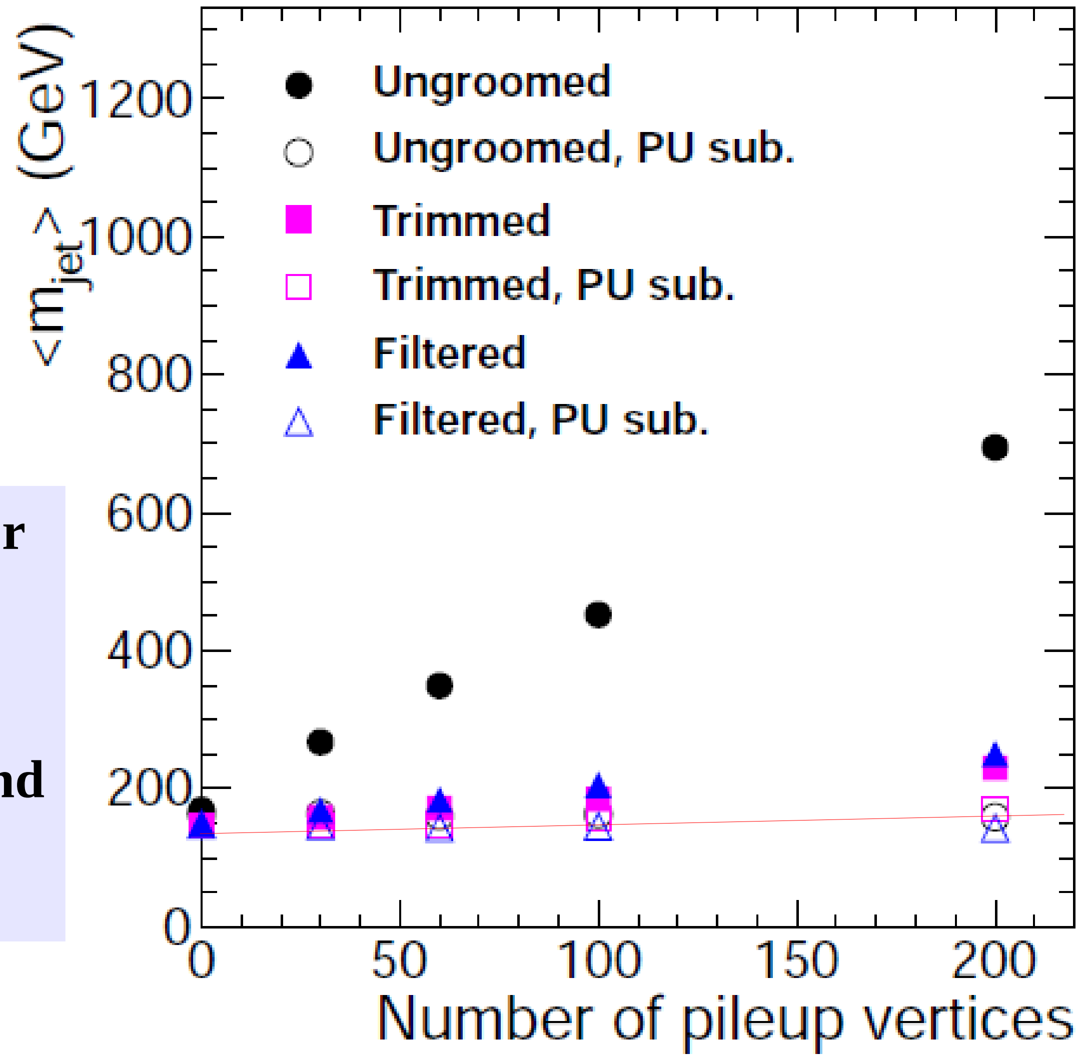


Measuring jet mass

BOOST2012 report,
EPJC74 (2014)

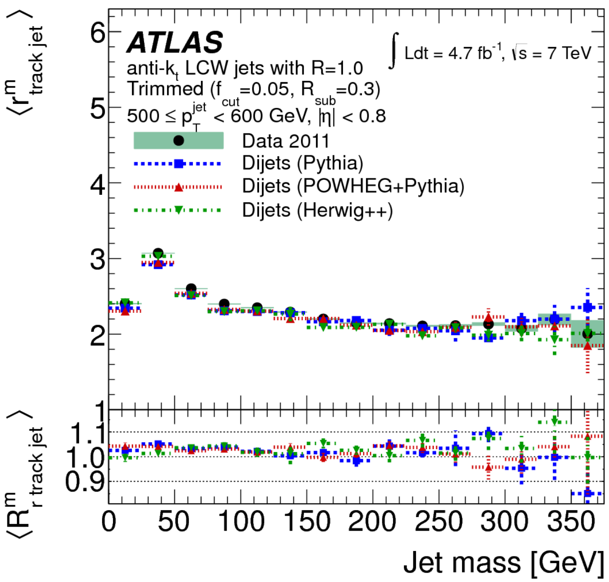
Simulation: jet mass scale for boosted top quarks verus number of pile-up vertices

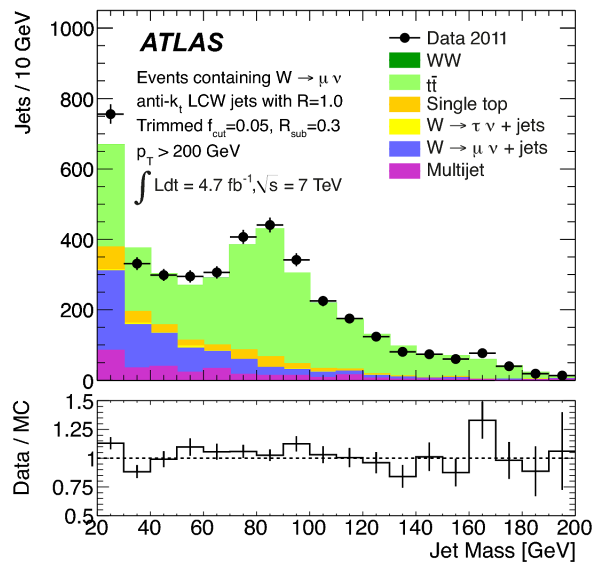
Combination of grooming and pile-up subtraction restores the scale

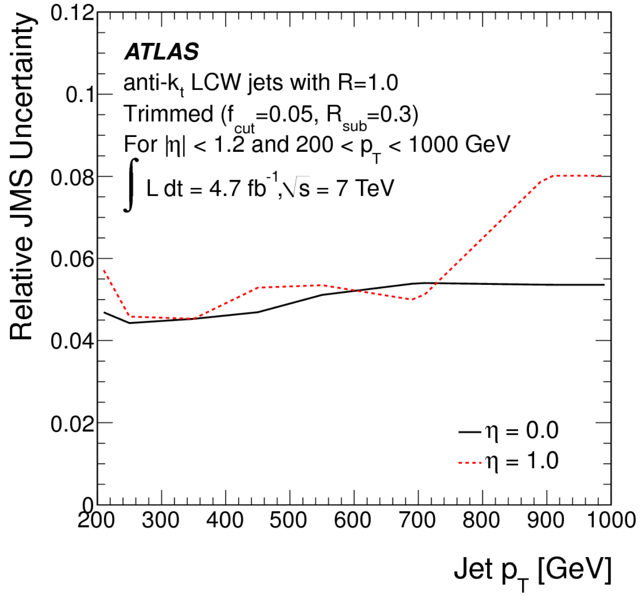


OK! This works for foreseeable future

Large-R jet and substructure performance







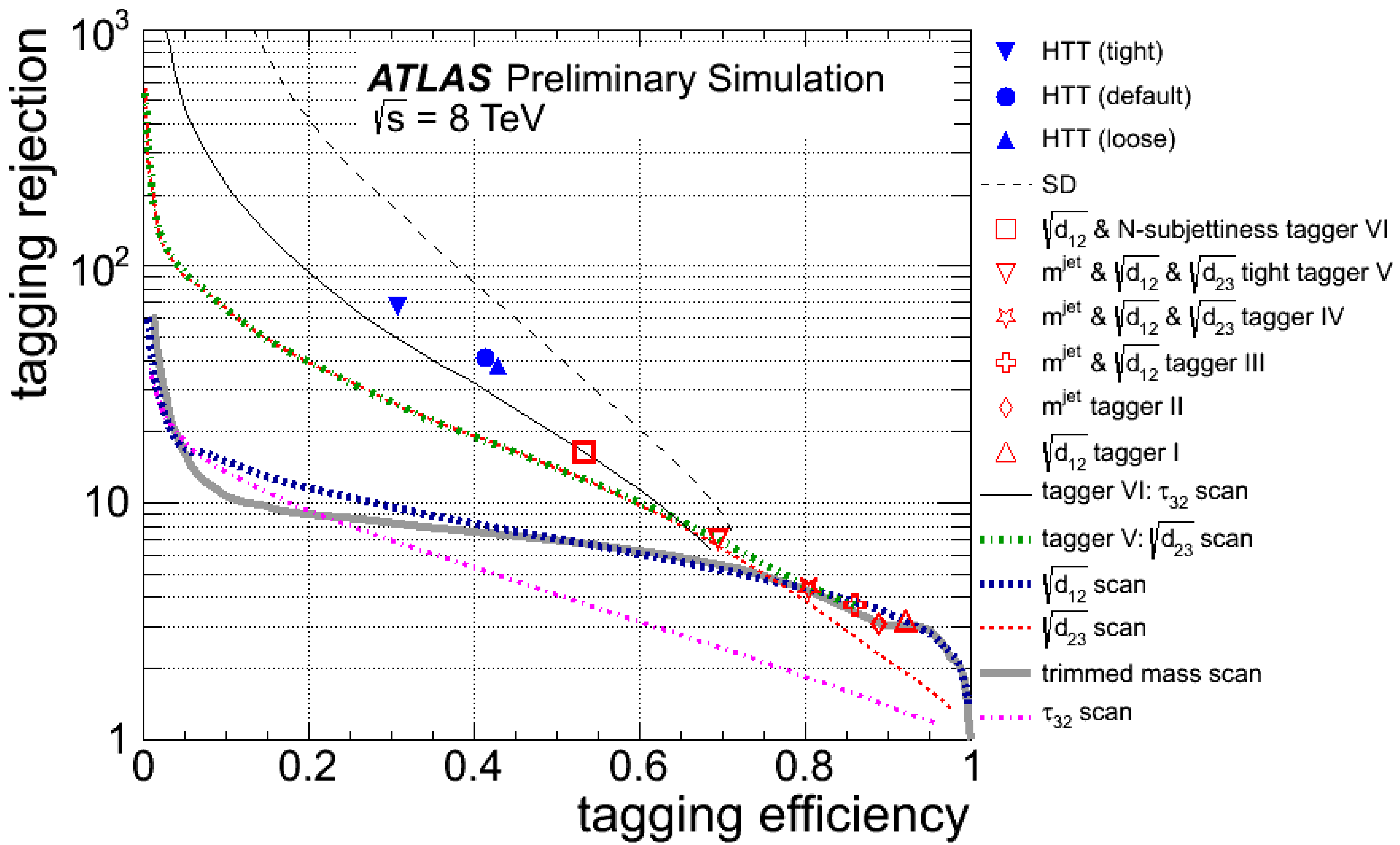
Use in-situ methods to constrain response for large jets, JHEP09 (2013) 076

Initially MC-based + track/calo ratio

Energy response: use γ+jets for energy response

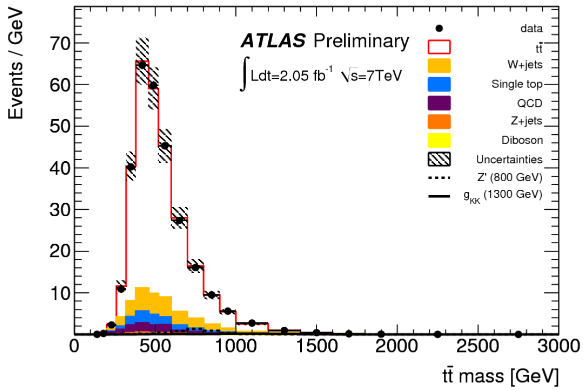
Jet mass scale uncertainty is harder to constrain: use W-peak, top-peak...

Boosted top quark tagging



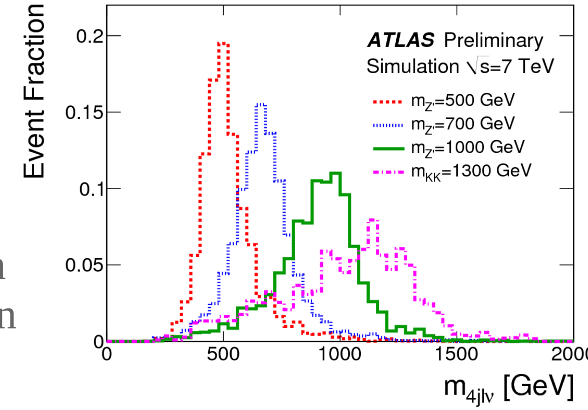
From ATLAS-CONF-2014-003

tt resonances

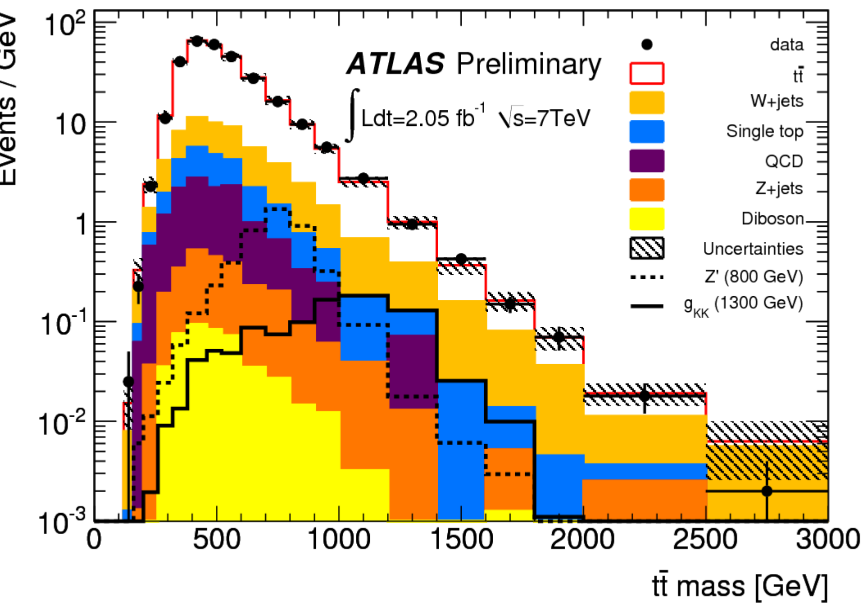


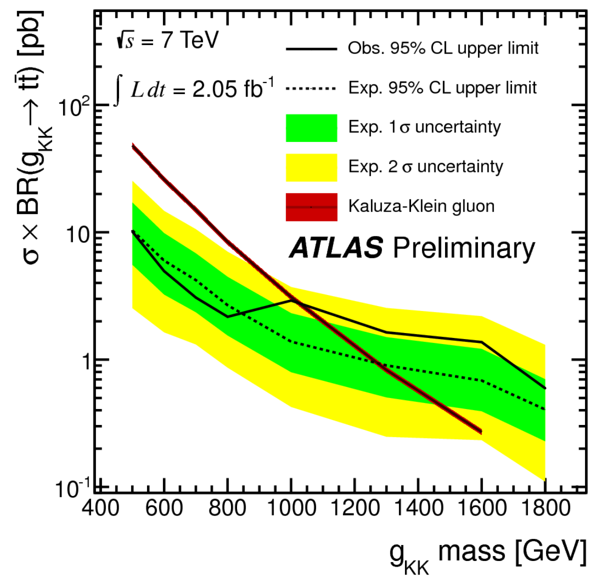
Expect 80% SM population of the Signal Region is due to tt pair production

tt system reconstruction
10% mass resolution



Full Signal Region



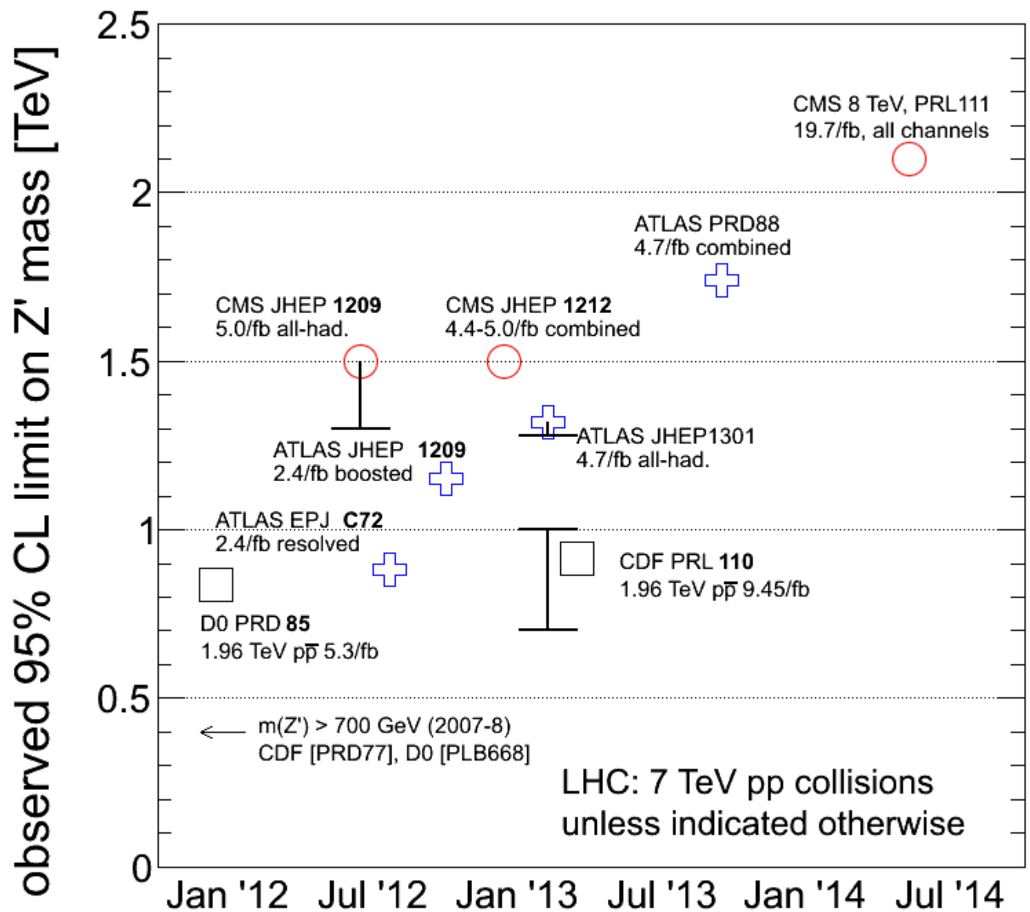


JHEP1209 demonstrated feasibility of boosted selection for lepton+jets
JHEP1310 showed the same for fully hadronic final state

Resonance searches

Use Z' limits as a benchmark to monitor progress

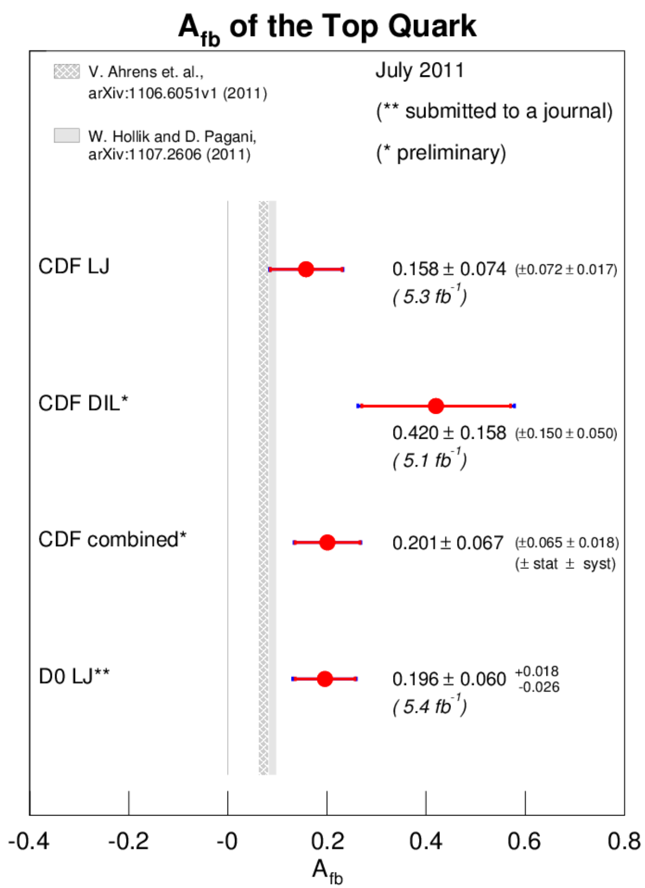
l+jets analyses only. Searches in fully hadronic events are close behind!

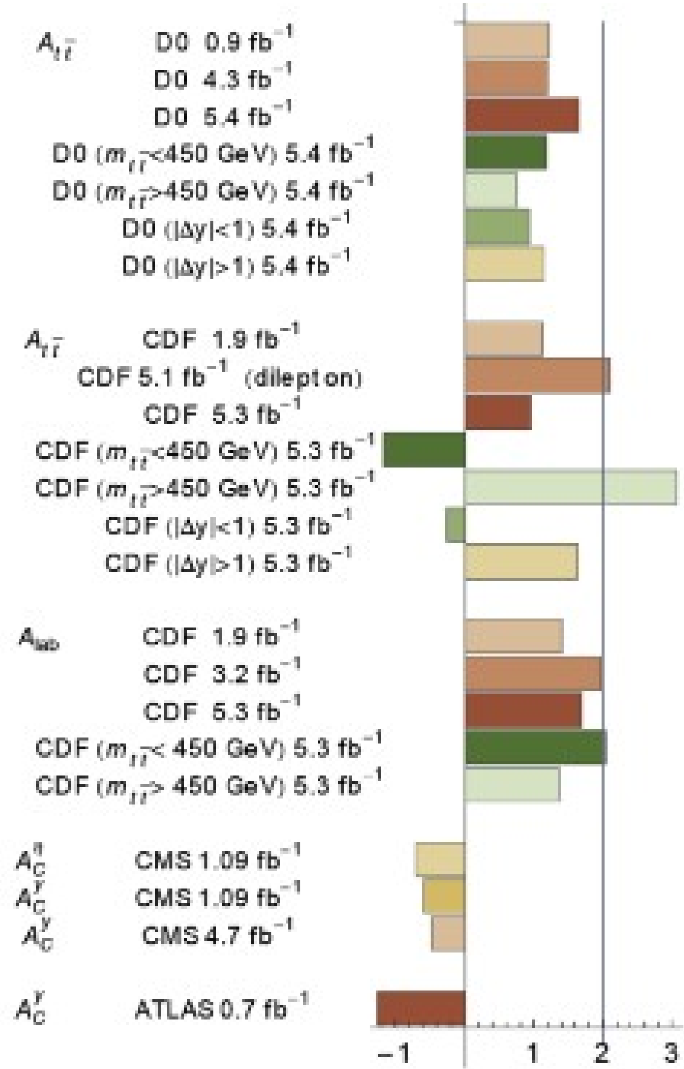


marcel.vos@ific.uv.es

Charge asymmetry

It all started with one paper... (CDF, PRD83)
But, then again, it did have "evidence" in the title and a 3 σ effect inside...



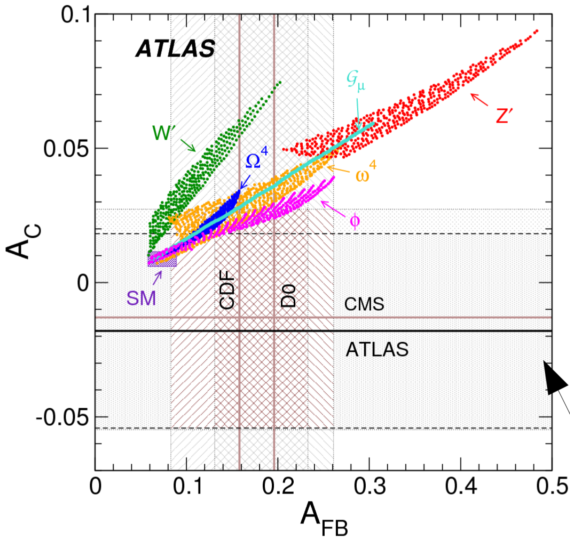


This triggered a lot of experimental scrutiny
And a zoo of new physics models
Better calculations (EW corrections, NNLO) are bridging the gap
First LHC results not very encouraging

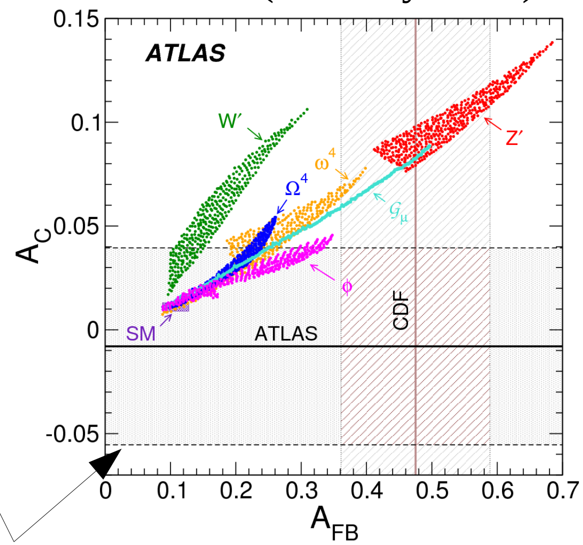
Charge asymmetry

Let's analyze possible LHC measurements in terms of their Impact on model zoo

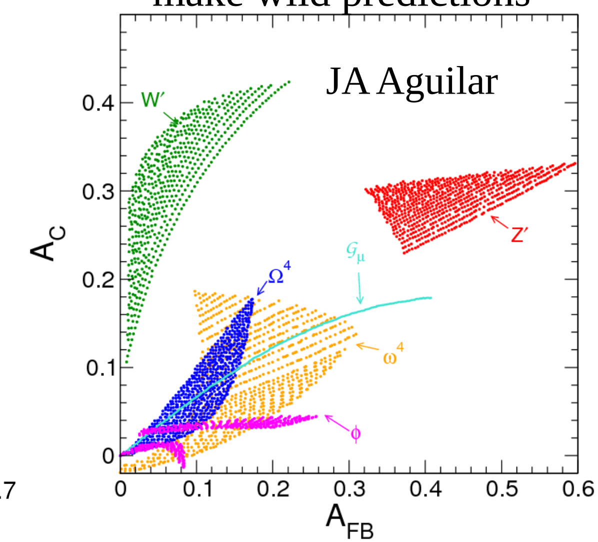
Inclusive, good,
Z' mostly dead



m_{tt} > 450 GeV (Tev & LHC)
Better! (look at y-scale)



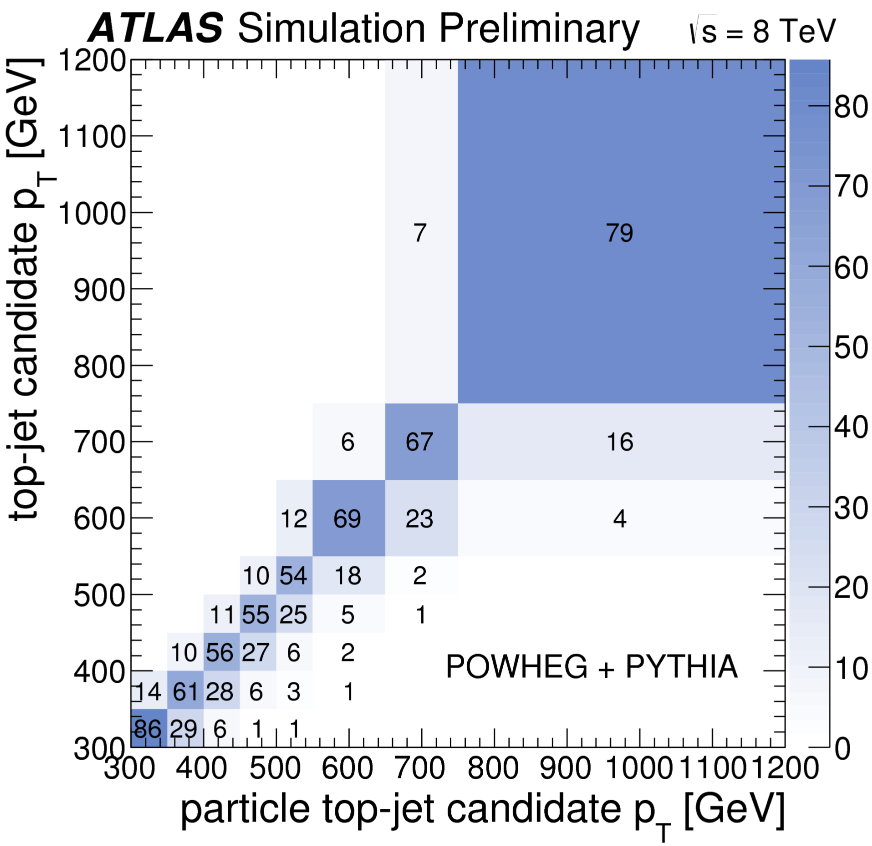
M_{tt} > 800 GeV (LHC only)
Best! Forces most models to make wild predictions

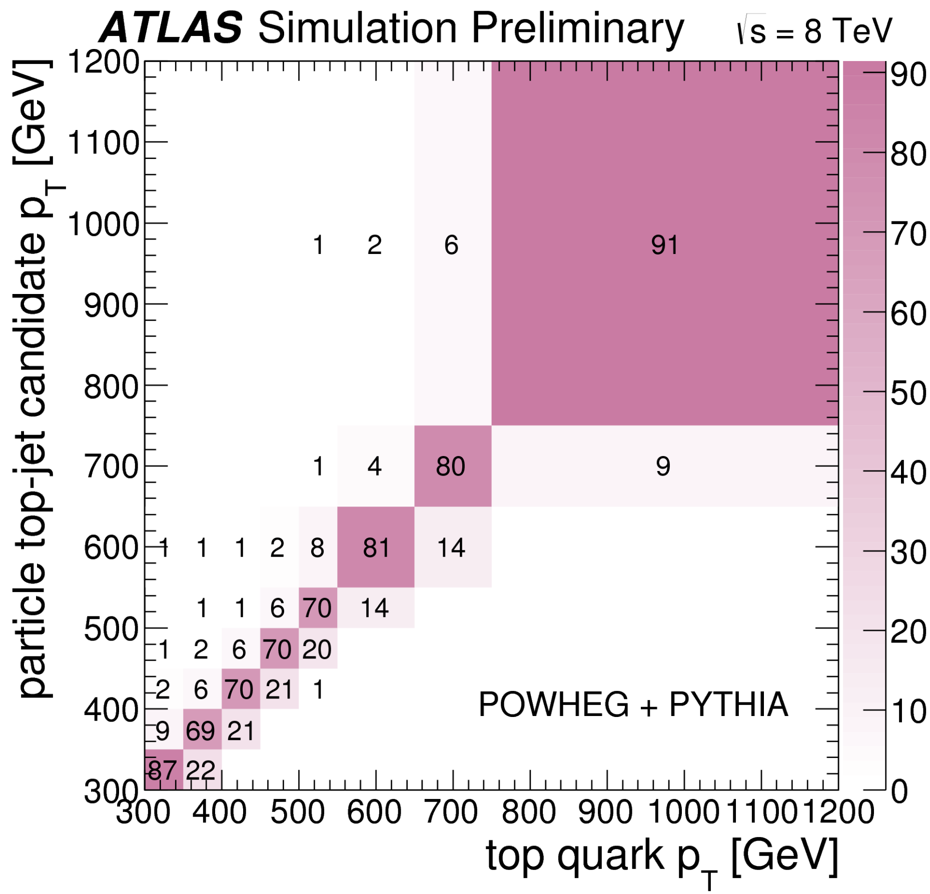


1 σ bands!

A charge asymmetry measurement for boosted top quark pair production with 5% precision may be worth more than a 1% measurement of the inclusive charge asymmetry → ongoing (V. Sánchez)

One step further: differential x-section



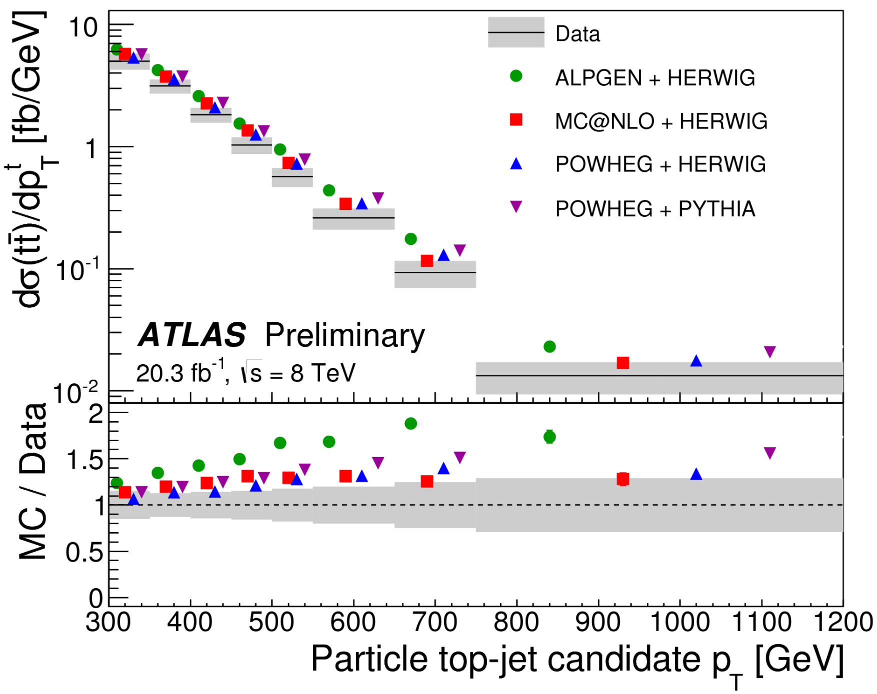


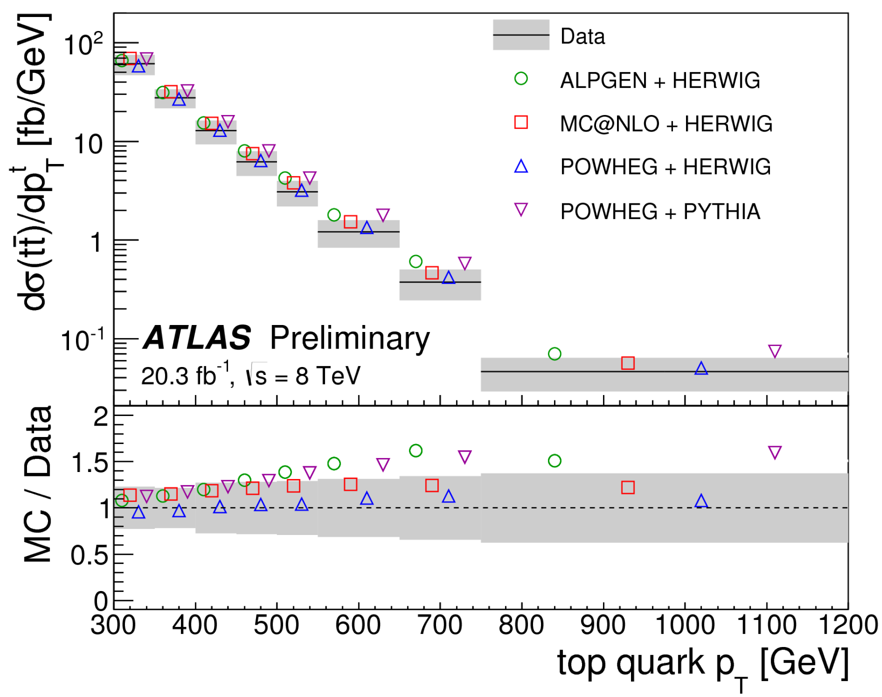
A differential cross-section based on the novel selection for boosted top quarks with a lepton+jets final state.

Better acceptance at very high transverse momentum: now beyond 1 TeV!

Good mapping of reconstructed top quarks on MC candidates.

Results



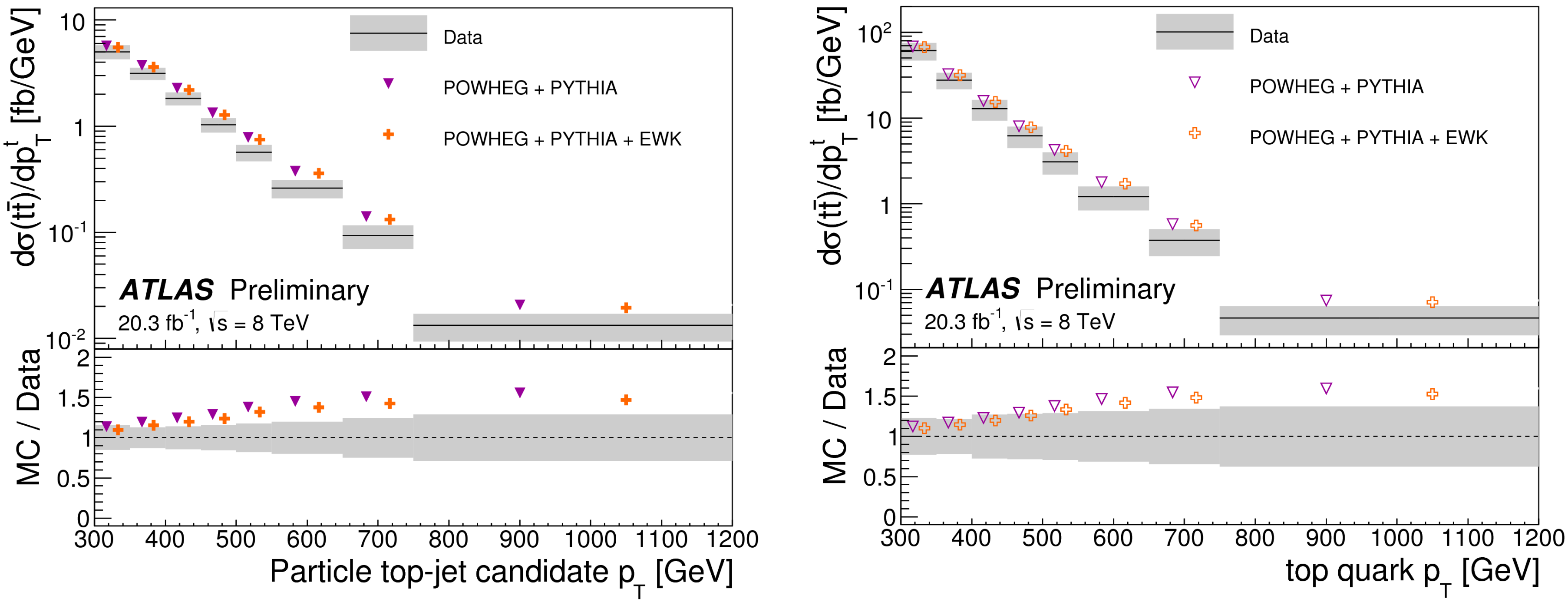


Result is presented as cross-section versus p_T of the:

- top quark (parton-level)
  - → *comparison to NLO (and soon NNLO)*
- particle-level top-jet candidate (~pseudo-top).
  - → *smaller modelling uncertainties, more precise comparison in future*

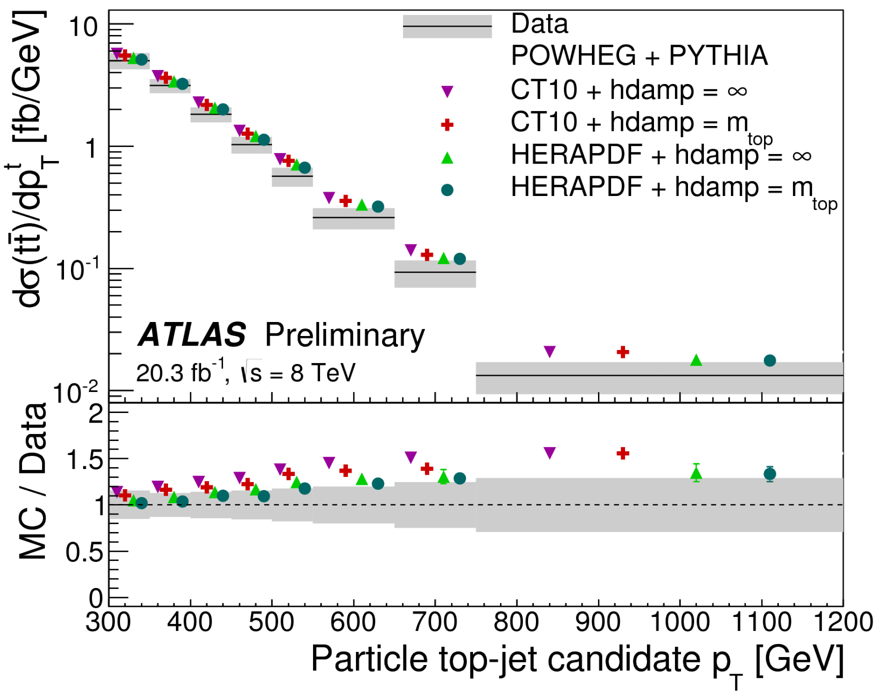
Don't assume blindly that extreme phase-space corners of this "bread-and-butter" physics is modelled flawlessly by (envelope of) MC → SUSY & Exotics

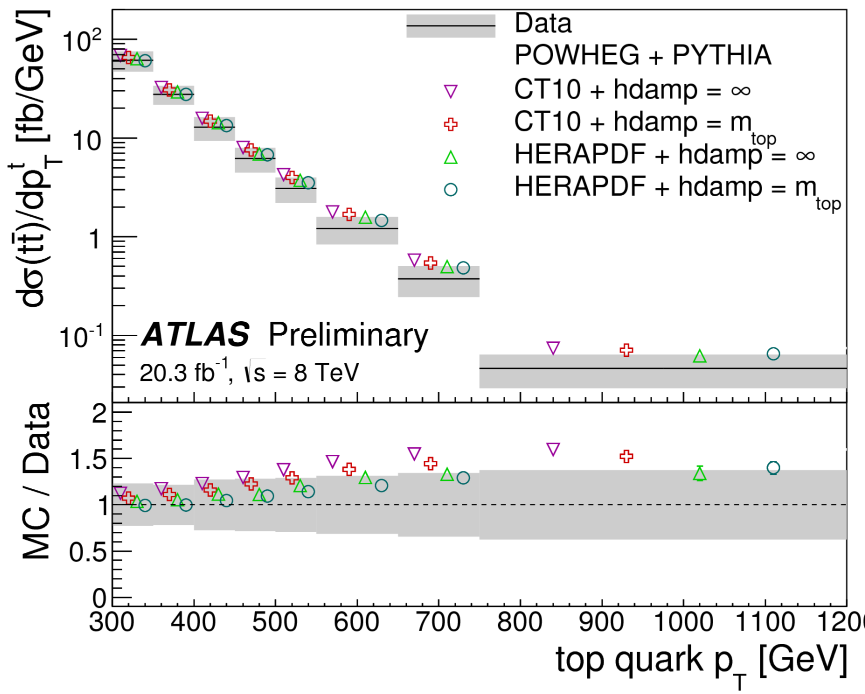
Missing electroweak corrections?



Electroweak corrections known to be sizable. And with the right sign!

PDF + HDAMP





Reconsidering the choice of the PDF and MC parameters helps!

Bringing it all together

Can we extract the top quark mass from boosted top quark jets?

SCET to maintain rigorous interpretation, Hoang, Mantry and others...

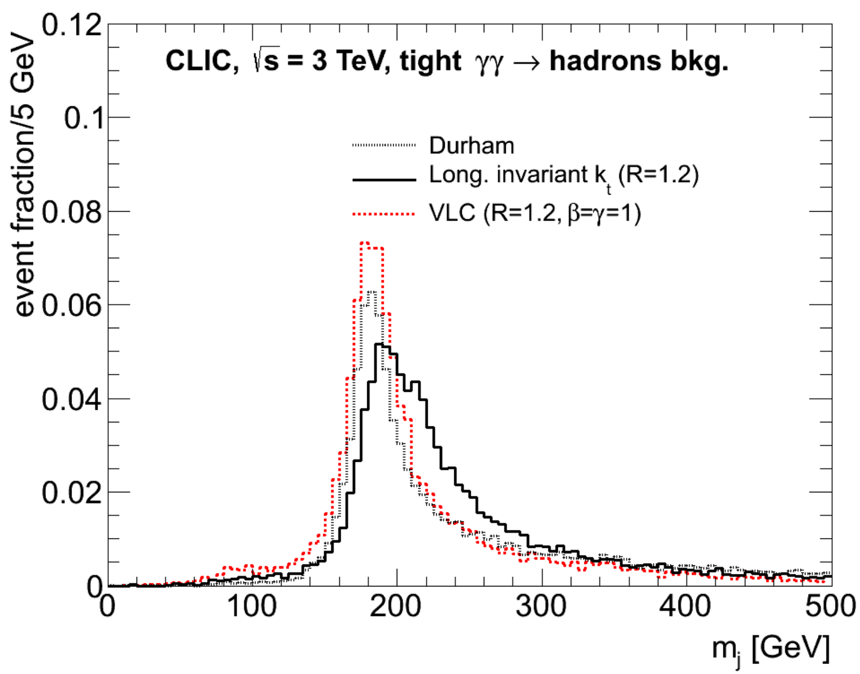
- 1 TeV e^+e^- collider

→ theory picture complete since several years

see Hoang, Mantry et al., PRD77 (2008) 074010 & 114003

→ experimental studies largely lacking so far, but...

ILC /CLIC top jet mass resolution, including realistic background
→particle flow response is excellent
→background mitigated by jet algorithm
arXiv:1404.4294



- Hadron collider

→ data already in hand, to grow strongly in next years

→ important experimental challenges (pile-up)

→ calculations much more complex, but tractable...

Two interesting topics in top physics

Discussed two interesting challenges on offer at the LHC:

New ideas needed to make progress on top quark mass

Rigorous interpretation, including theory uncertainty, less dependence on jet-related systematics

Standard method based on extraction using MC templates from invariant mass distribution of top decay products can go well below a GeV. Interpretation must be made more precise. Alternative methods are being developed, with (partly) orthogonal systematic uncertainties. Extraction from cross-section can attain GeV-level precision.

How can we extract the maximum information from boosted top quark production?

Techniques for boosted object tagging and reconstruction are mature; after deployment and proof-of-principle in $t\bar{t}$ resonance searches they are finding their way to:

Exotics (highlight: WIMP dark matter limits from boosted mono-W/Z analysis)

SUSY (highlight: multi-jet analysis with 'accidental' jet substructure)

Top (differential x-section, charge asymmetry at high mass)

Standard Model (boosted W cross-section, other measurements in preparation)

Higgs (H → bb in WH and ttH production)