Some Thoughts on Tops

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Motivation

Why is the Top Quark so Special?

(or carrying coal to Newcastle/owls to Athens/ sunshine to the Cote d'Azur)

- it decays before it hadronises:
  the only chance to inspect partons without having to deal with hadronisation: a great laboratory for perturbative QCD
- it has tight links to electroweak symmetry breaking:
  due to its large mass a dominant role in running of the Higgs boson mass: important for our understanding of the particle universe

  (a strange thing: $m_t/v \approx 1$, but still perturbation theory!)
- it is important as a signal or a part thereof – examples:
  - we need to check its Yukawa coupling $\longrightarrow t\bar{t}H$
  - we need to check $V_{tb} \approx 1$ $\longrightarrow$ single-top
- it is the dominant background for nearly every BSM search @ LHC

. . . and it is there . . .

Outline of the talk

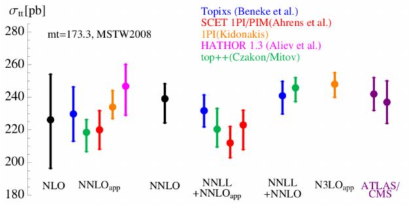
- some reflections on recent theory progress
  (most is outright amazing)
- some discussion on progress in tools
  (sorry, my personal bias)
- some thoughts on experimental progress
  (hmmmmm - I am slightly worried)

Status of Precision Calculations

for Top Physics

Inclusive Top–Pair Production

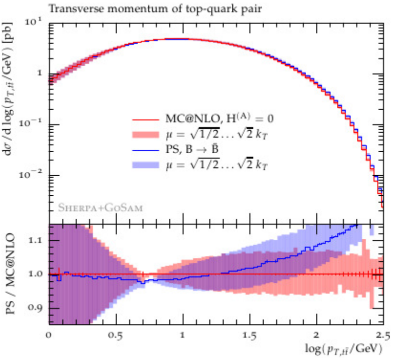
- NNLO results well known and available in public code
  - Top++ (NNLO+NNLL(soft)) by Czakon & Mitov, see talk by M.Czakon
  - HATHOR (NNLO) by Aliev at al.
  - TOPIXS (NLLO+soft+Coulomb) by Beneke et al.

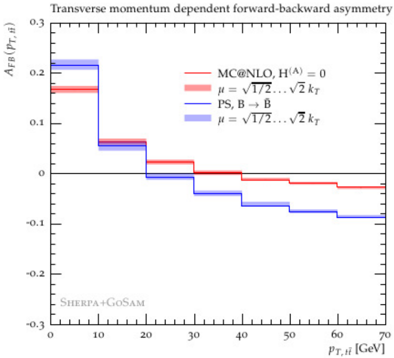


- top-mass from cross section now with error of $\pm 3\%$
  $\longrightarrow$ good cross check of kinematical methods

Aside: Is the $t\bar{t}$–asymmetry just QCD?

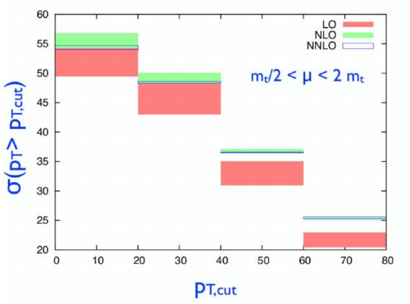
- effect of full colour treatment in Sudakov form factor, MC@NLO without **H**-part vs. parton shower with $\mathcal{B} \longrightarrow \tilde{\mathcal{B}}$
- take $t\bar{t}$ production (red = full colour, blue = “PS” colours)





Inclusive Single Tops

- look at t–channel single top production at LHC
- trivially: about 80% of single-top at LHC
- analysis: NLO K-factor is small (is this an accident?!)
  need to got to NNLO
  $\longrightarrow$ approximately achieved
  see talk by F.Caola



Top–Associated Higgs Boson Production

- one of the “big” measurements of LHC Run-II
- need to pin down top-Yukawa coupling
- NLO (QCD) corrections available in Monte Carlos
- NLO (EW) corrections available in Monte Carlos
- but: problem is that backgrounds look like signals
- becomes a counting experiment in $t\bar{t}b\bar{b}$
- figure of merit; $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
  big/dominant background from $g \to b\bar{b}$

  $\longrightarrow$ need to measure it!
- and, please, make it differential

  $\longrightarrow$ we need to check the parton showers

Tops plus Stuff

- NLO calculations for $t\bar{t} + V$, γ: no problem
  - funny backgrounds to BSM searches
  - and, yeah, probe of top-quark charge(s)

(I personally have some doubts on how conclusive this is)

- NLO calculations for $t\bar{t}+$ (≤ 2) jets: no problem
- both are available in Monte Carlos

aMC@NLO
SHERPA
use them & compare them

Boosted regime

- LHC is a factory for boosted stuff (and tops!)

Expected number of tt events in three different kinematical regimes	Tevatron run II 10 fb^{-1} @ 1.96 TeV	LHC 2012 20 fb^{-1} @ 8 TeV
Inclusive tt production	57.000	2.600.000
Boosted production: M_{tt} > 1 TeV	25	30.000
Highly boosted: M_{tt} > 2 TeV	0	300

Expected number of tt events in three different kinematical regimes	LHC 2012 20 fb^{-1} @ 8 TeV	LHC design 300 fb^{-1} @ 13 TeV
Inclusive tt production	2.600.000	155.000.000
Boosted production: M_{tt} > 1 TeV	30.000	3.000.000
Highly boosted: M_{tt} > 2 TeV	300	47.000

- lots of tools around:

  filtering, grooming, trimming, pruning, mass drop, shower deconstruction, . . .

  (very confusing, isn't it?)

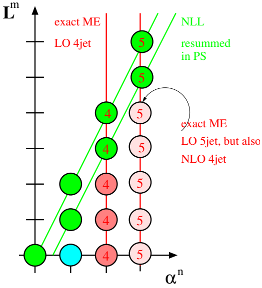
  see talk by M.Spannowsky

- but: do we understand similarities and differences?
- do we have a handle on systematics?
- how about backgrounds ($q \to qV$)?

Tools: Multijet Merging

Multijet merging: basic idea

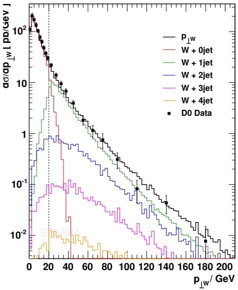
- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- combine ("merge") both:
  result: "towers" of MEs with increasing number of jets evolved with PS
  - multijet cross sections at Born accuracy
  - maintain (N)LL accuracy of parton shower



Separating jet evolution and jet production

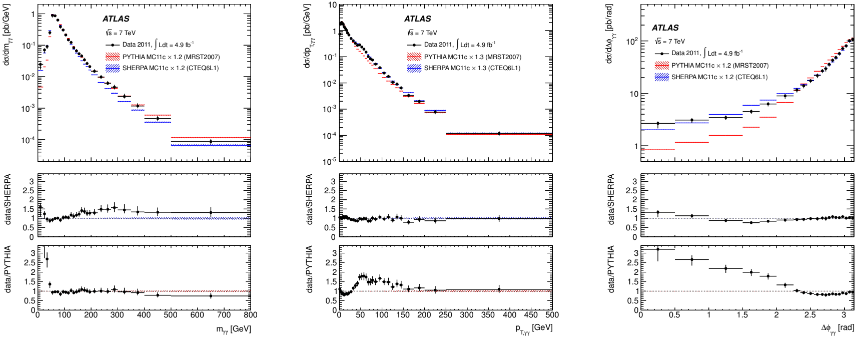
- separate regions of jet production and jet evolution with jet measure Q_J

  ("truncated showering" if not identical with evolution parameter)
- matrix elements populate hard regime
- parton showers populate soft domain

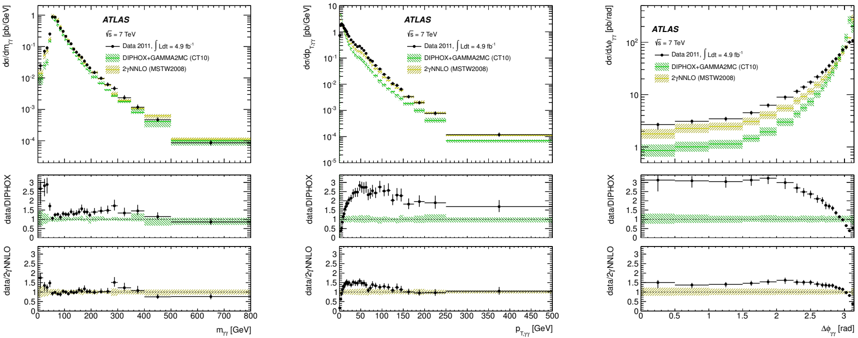


Example: Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$

(arXiv:1211.1913 [hep-ex])



(arXiv:1211.1913 [hep-ex])



Multijet-merging at NLO: MEPS@NLO

- basic idea like at LO: towers of MEs with increasing jet multi (but this time at NLO)
- combine them into one sample, remove overlap/double-counting

maintain NLO and LL accuracy of ME and PS

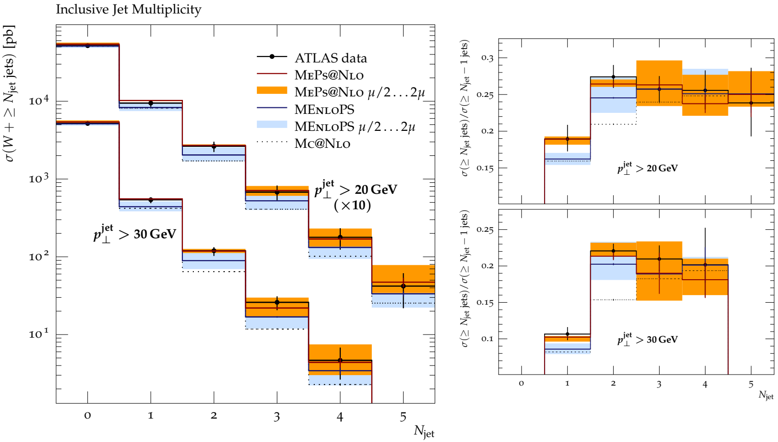
- this effectively translates into a merging of MC@NLO simulations and can be further supplemented with LO simulations for even higher final state multiplicities

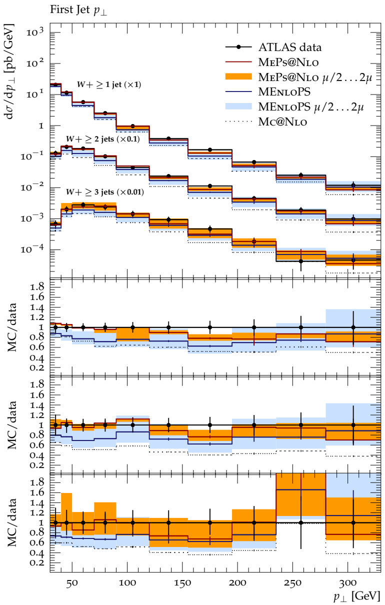
First emission(s), sketchy

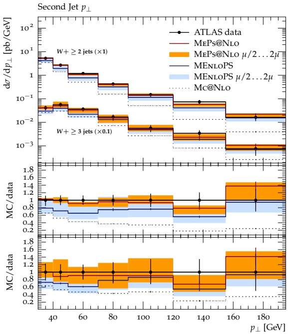
(just to remind you that these days Monte Carlo plumbing comes with some theory)

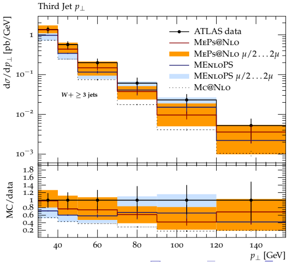
$$
\begin{aligned}
\mathrm{d}\sigma \;=\; & \mathrm{d}\Phi_N\,\tilde{\mathcal{B}}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0)+\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\right] \\
& +\mathrm{d}\Phi_{N+1}\,\mathcal{H}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1}) \\
& +\mathrm{d}\Phi_{N+1}\,\tilde{\mathcal{B}}_{N+1}\left(1+\frac{\mathcal{B}_{N+1}}{\tilde{\mathcal{B}}_{N+1}}\int\limits_{t_{N+1}}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\right)\Theta(Q_{N+1}-Q_J) \\
& \quad\cdot\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\cdot\left[\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_0)+\int\limits_{t_0}^{t_{N+1}}\mathrm{d}\Phi_1\,\mathcal{K}_{N+1}\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_{N+2})\right] \\
& +\mathrm{d}\Phi_{N+2}\,\mathcal{H}_{N+1}\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_{N+2})\Theta(Q_{N+1}-Q_J)+\dots
\end{aligned}
$$

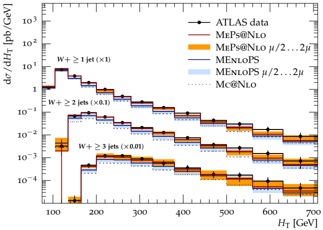
MEPS@NLO: validation in W+jets

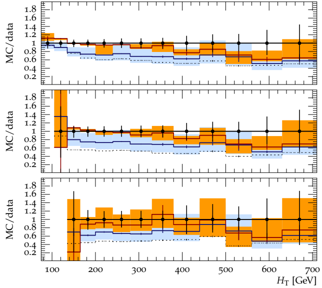


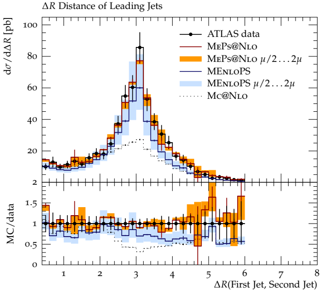

First Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times 1$)
$W+\geq 2$ jets ($\times 0.1$)
$W+\geq 3$ jets ($\times 0.01$)
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]

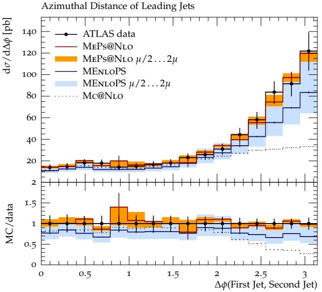

Second Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 2$ jets ($\times 1$)
$W+\geq 3$ jets ($\times 0.1$)
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]


Third Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 3$ jets
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]


ATLAS data
MEPS@NLO
MEPS@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
W+ ≥ 1 jet (×1)
W+ ≥ 2 jets (×0.1)
W+ ≥ 3 jets (×0.01)
dσ/dH_T [pb/GeV]
H_T [GeV]

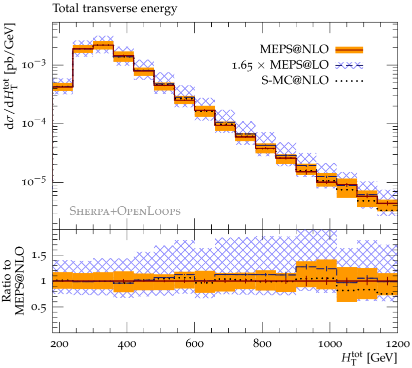

MC/data
MC/data
MC/data
H_T [GeV]

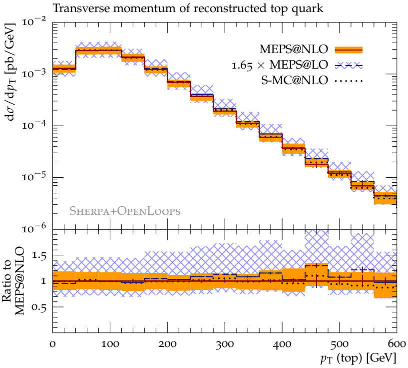

ΔR Distance of Leading Jets
ATLAS data
MEPS@NLO
MEPS@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
dσ/dΔR [pb]
MC/data
ΔR(First Jet, Second Jet)


Azimuthal Distance of Leading Jets
ATLAS data
MEPS@NLO
MEPS@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
dσ/dΔφ [pb]
MC/data
Δφ(First Jet, Second Jet)

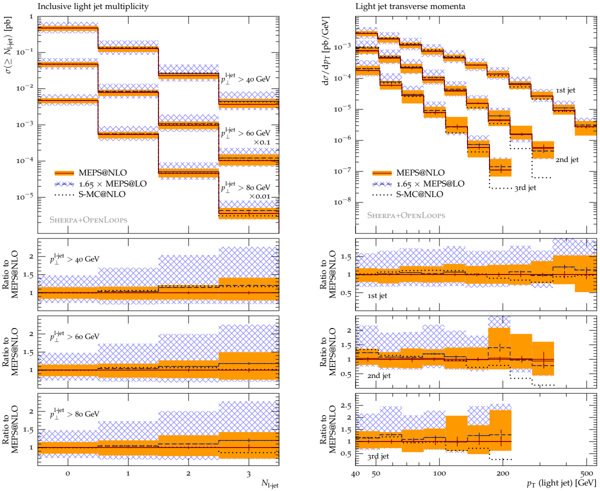
Inclusive observables in $t\bar{t}$ + jets

- multijet merging for $t\bar{t}$ + {0, 1, 2} jets





Light jet observables in $t\bar{t}$ + jets



Experimental Status

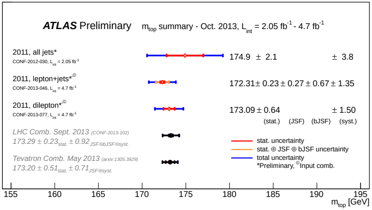
Experimental Status: Top Properties

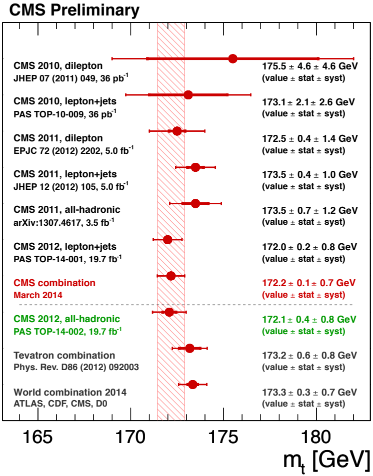
- lots of measurements at LHC @ Tevatron: concentrate on LHC
- but: somewhat too MC

  (do we measure PYMASS(6))

- extract $m_{\rm top}$ from:

  $\sigma_{t\bar{t}}$, $p_\perp^{\rm lep}$ or similar

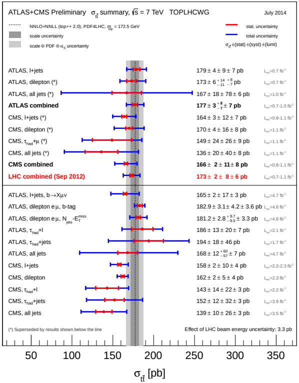


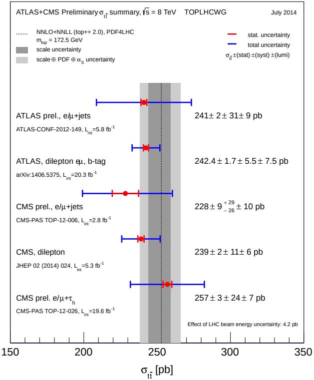


Experimental Status: Inclusive Cross Sections

- lots of analysis from D0, CDF, ATLAS & CMS
- Tevatron is a bit of a few-numbers experiment

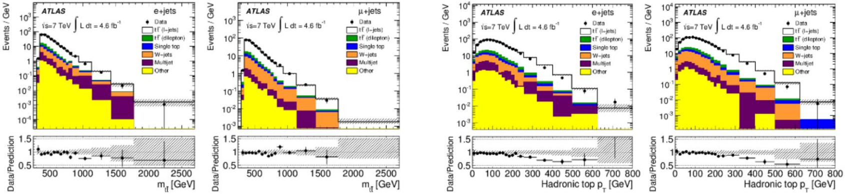
(will concentrate on LHC, sorry, folks!)





Experimental Status: Differential Cross Sections

- simple pattern: $m_{t\bar{t}}$ seems okay, $p_\perp^{(t)}$ a bit tricky

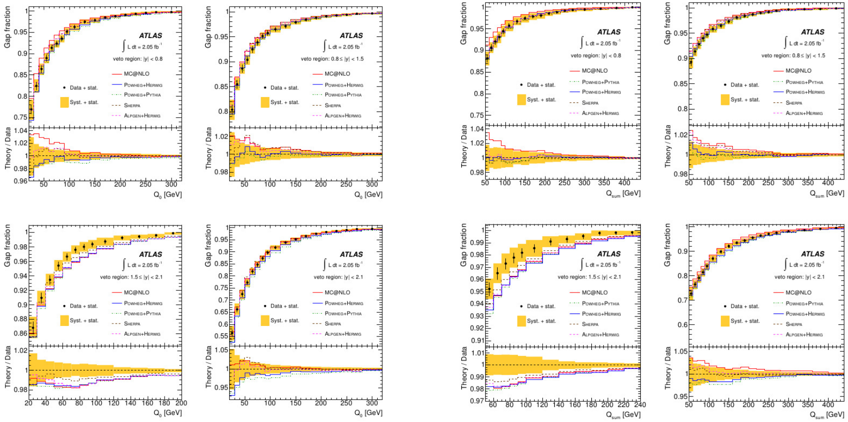


- this is where I start being worried . . .
- I would love to start checking things and try to find a solution

but I cannot

Experimental Status: Differential Cross Sections

- measurement of rapidity gaps in top events (arXiv:1203.5015 [hep-ex])



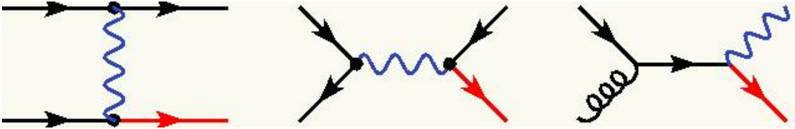
Experimental Status: A Critical Appraisal

- up to now, **nearly all** measurements on “parton–level”
- this is pretty awkward:
  - please, report your measurements based on **physical objects**

    (as an undergraduate I was told this was the most important bit!)
  - please, add your interpretation as an **important part** afterwards

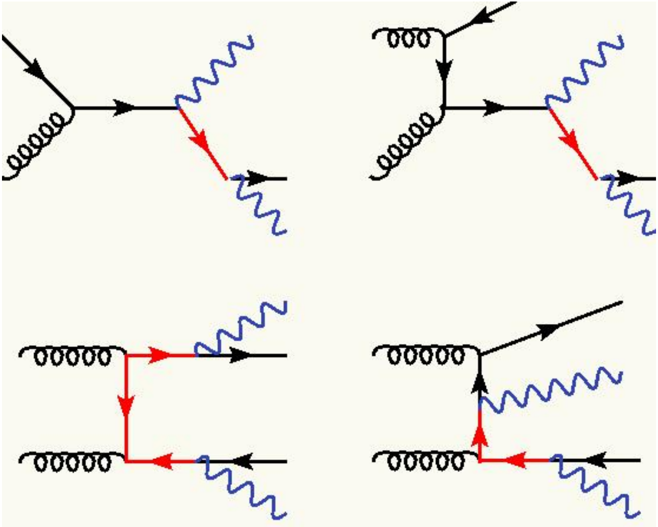
A Good example for Bad Science

- consider single-top production
- common lore: three channels: t-channel, s-channel, and Wt



- but: discrimination breaks down at higher orders

- look at NLO (for Wt):



- already at NLO overlap between Wt and $t\bar{t}$
- differentiation between them makers sense at LO level only
  LO level is about $\mathcal{O}(20\%)$
  do you really want to waste time on this?
- alternative: define physical objects in $b\bar{b}W^+W^-$
  identify regions of double-, single- or non-resonant top production
- report measurements based on fiducial cross sections

  (and, if you feel like it, interpret in different channels . . .)
- anything else feels like particle physics based on classical physics – do you really want to "know" through which slid your electron went?

Lessons to be learnt

(sorry, private take)

- LHC is a new environment

  (Tevatron was a few-numbers experiment)

  differential cross sections are meaningful here!
- make sure we can compare with theory at **all** orders of PT
- means:
  - define physical objects (jets, isolated leptons, etc.)
  - must hold water on particle level and – in best world – allow extrapolation to parton level
  - report measurements in fiducial region of objects

    this is your most noble job!
  - only extrapolate to 4π afterwards

Why am I so fundamentalist about it?

- consider the possibility of LHC being the last experiment for 50 years
- how can we make our results reproducible for future generations?
  - make sure we can understand the conditions of the measurement

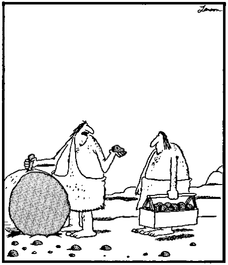
    (to be honest, I get a headache reading most of the experimental papers)
  - implement cuts etc. in simple code $\longrightarrow$ RIVET
  - link the results to *H*EP*D*ATA
  - allow tracing the Monte Carlos

    (only publicly available code, versioned, and tagged run-cards)
- this is – probably – THE experiment of our life

  let's make it count!
- code migration should be simpler than re-design/re-learn ...

Summary

- the reign of NNLO has arrived:
  cross sections for inclusive production start to become available and to be routinely used
  - $t\bar{t}$, t–channel single-top
  - other processes: DY, dijets etc., which input to PDFs
- the "NLO" revolution is over:
  NLO calculations are the new standard, available in event generators
  - as NLO matching ("POWHEG", "MC@NLO")
  - in multijet merging ("MEPS@NLO", "UNLOPS", "MINLO", "FxFx")



"So what's this? I asked for a *hammer*! A hammer! *This* is a crescent wrench! ... Well, maybe it's a hammer. ... Damn these stone tools."

Outlook

- get ready for the ride in Run-II:

  more statistics
  more energy
  more channels
  more precision
  more extreme kinematics
  more tops
  more fun

- it is time to take full advantage of all the tools and all data:
  we need to turn LHC into a high–precision experiment
- top-physics plays an important role
  we cannot leave any stone unturned or any avenue unexplored
  and we cannot be naive