Climbing the ladder: from $Z(\mu\mu)$ to $m_t$ and $\alpha_s$

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  - lepton reconstruction
  - b-tagging and gluon-jet discrimination
  - missing-\(E_T\) projection fraction (MPF)

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  - Underlying event: genRho
  - Jet flavor response: toyPF
  - Final/initial state radiation: \(\alpha\) and \(w_{PS}\)

- Application of "re-bJES" on D0 \(m_t\)
  - Shift in bJES
  - Shift in \(m_t\)

- Ideas for future and call for feedback from theory community
  - \(\alpha_s\) at NNLO from \(pT^{bal}\)?

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Caveat: I’m a CMS experimentalist, and as such not allowed to show unpublished results on data. To facilitate concrete discussion I will show results on representative stand-alone MC only.
Vacuum is metastable?

To know for sure, need more precise $m_t$ and $\alpha_s$ (from jets)

Experimental limitation in both cases is uncertainty in Jet Energy Corrections (JEC)

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Schwartz et al., arXiv:1707.08124
Measurement of $\alpha_s$

- At the LHC $\alpha_s$ best measured using jets (from quarks, gluons)
- Allows to probe running of $\alpha_s$ to high energy
- NNLO jet calculations now available, although theory scale uncertainty still an issue

CMS summary, TWiki

Climbing the ladder: from $Z(\ell\ell)$ to $m_t$ and $\alpha_s$
Experimental pre-requisites

- lepton reconstruction
- b-tagging and gluon-jet discrimination
- missing-$E_T$ projection fraction (MPF)
• Start calibration ladder from $Z(\ell\ell)$
• Leptons ($e, \mu$) calibrated with $m_Z$ wrt LEP
• Precision far **better than 0.10%**
  ▶ case in point: $\Delta m_H = 0.12\%$, still mostly statistics (syst. 0.07%)
**b-tagging**

- b-tagging in particular has benefited from Deep Learning explosion in HEP in Run 2
  - installation of fourth inner pixel layer (Phase 1) for 2017—2018 also helped

- Typical tight working point:
  - b (+g>bb) eff.: 70%
  - c (+g>cc) eff.: 3%
  - q+g (no g>HF) eff.: 0.1%

- Typical Z+jet, Z+b fractions:
  - b fraction: 5% => 90%
  - c fraction: 10% => 8%
  - uds fraction: 65% => 1.5%
  - g fraction: 20% => 0.5%

- By-product: deep methods can now also reasonably tag charm quarks vs b and uds
g

https://twiki.cern.ch/twiki/bin/view/CMSPublic/BTV13TeV2017FIRST2018
Quark-gluon likelihood

- Quark-gluon likelihood (QGL) discriminator based on: (i) number of particles (multiplicity), (ii) fragmentation from charged particles ($p_T D$), (iii) jet width on minor axis ($\sigma_2$)
- Quark/gluon efficiencies in data extracted by comparing $Z$+jet and dijet QGL shapes
- Pythia8 and Herwig++ bit agree after reweighing: quark eff. $\sim 0.7$, gluon eff. $\sim 0.3$
Estimate tagged sample purity by taking into account known fractions and efficiencies in MC.

Pure $Z+b$ and $Z+uds$ obtainable, gluon sample less easy on data.

Flavor-tagging in $Z+\text{jet}$

- **DeepJet**
  - 1(b): DeepBtight
  - 2(c): DeepCjme & !DeepBtight
  - 3(uds): QGL$\geq$0.5 & !DeepBtight & !DeepCjme
  - 4(g): QGL$<$0.5 & !DeepBtight & !DeepCjme

Flavor fraction

- Incl. jet
- $b$ jet
- $c$ jet
- $uds$ jet
- $g$ jet

Flavor and $p_T$ bin

Private Work
• Z and jet(b) balanced in transverse plane at leading order, **Z+recoil** at all orders

• Net recoil vector \( f_X = p_{T(x)}Z / p_{T,Z} \) split into three categories with different responses \( R_X \):
  - \( P_1 = R_1 f_1 \): leading jet (b) — \( R_1 \) calibrated up to data/MC difference (aka \( p_{T}^{\text{bal}} \) method)
  - \( P_n = R_n f_n \): subleading jets (2..n) of \( p_T > 15 \text{ GeV} \) — \( R_n \) calibrated up to residual (gluon) flavor
  - \( P_u = R_u f_u \): unclustered particles — \( R_u \) not calibrated

• Two identities:
  - \( R_{\text{MPF}} = P_1 + P_n + P_u \) (aka MPF method)
  - \( l = f_1 + f_n + f_u \) (momentum conservation)
Controlling leading biases

- Underlying event: genRho
- Jet flavor response: toyPF
- Final/initial state radiation: $\alpha$ and $w_{PS}$
Estimate underlying event offset density (genRho) by running FastJet GridMedianEstimator on **stand-alone particle-level MC** mixed with data-like pileup offset.

Method repeated with and without signal MC to extract underlying event offset:
- without data-like mixing median often zero for pure UE offset
- UE offset non-Gaussian so result depends on $N_{PU}$, although only weakly at $N_{PU}>10$

Heavy ion event, illustration only

http://inspirehep.net/record/1654912/plots
Underlying event

- Scanning a number of generators, tunes and final states for UE
- Detector-like level applies cuts of $p_T>0.3$ GeV on charged particles and photons, $p_T>3$ GeV on neutral hadrons
  - Ratio to particle level is effective response of UE
- CMS and ATLAS pileup offset corrections are based on $\rho$ so easy to add FullSim and data
- Difference of P8M1 (2016) and CP5 (2017–2018) tunes is $\sim0.3$ GeV => small, but relevant effect

### Diagram

Comparison of Simulation and Data for $\langle \rho \rangle$ - ZB (GeV)
- Private work-in-progress
- Particle level
- Detector-like level

Data: QCD_HS1, QCD_P8M1, QCD_CP5, TT_H7CH3, TTL+jets_CP5, DYJets_P8M1, DYJets_CP5

Ratio: QCD, ttbar, DY+jet

 CMS 2017DE (13 TeV)
• Understand jet response from first principles by approximating particle flow (PF)
  > \( p_{T,\text{raw}} = \sum_i R_i(p_{T,i}) \ p_{T,i} \)
  > \( R_i(p_{T,i})=1, \text{if } p_{T,i}>0.3, \text{else zero (for photon)} \)
  > \( R_i(p_{T,i})=1, \text{if } p_{T,i}>0.3, \text{else zero (for charged with tracking)} \)
  > \( R_i(p_{T,i})=c*(1-a*p_{T}^{m-1}) \) (for hadron without tracking)

• parameterise tracking efficiency + fakes from CMS papers
• apply PF hadron calibration and reconstruction thresholds on overlapping neutrals
Goal is to use toyPF to understand data/MC differences in flavour response in Z+f vs Z+q at 0.1% level

- High statistical precision with few events, more precise than FullSim
- Stand-alone mode allows to scan more MC generator tunes quickly
- Fewer knobs so maybe more transparent
**α extrapolation, \( w_{PS} \)**

- Pythia provides a set of event weights \( w_{PS} \) to vary \( \alpha_{S,ISR} \) and \( \alpha_{S,FSR} \) in parton shower
  - latest processing messed up the weights relative to nominal, but relative spread ok
  - future iterations split weights by process (\( gg>gg, gg>qq, qg, qq \))
- Sensitivity controlled by cutting on additional jets: \( \alpha = \frac{p_{T,jet2}}{p_{T,Z}} \)
  - Limit \( \alpha \to 0 \) used for jet energy corrections
  - MPF is stable at all \( \alpha \) cuts
  - \( p_{T,bal} \) slope at \( \alpha < 0.3 \) should be linearly proportional to \( C_F^*\alpha_s \) and \( C_A^*\alpha_s \)
- \( p_{T,bal} / MPF \) ratio at finite \( \alpha \) cut should be proportional to \( \alpha_s \)
Combined fit of MPF and $p_T^\text{bal}$ vs $p_{T,Z}$ enables to extract $\alpha_s$ sensitive observable

However, still needed to consider gluon fraction correction ($C_A=3$ vs $C_F=4/3$)

**Question to theorists:** could $q/Z$ ratio at NNLO compete with lattice QCD?

- loops cancel?
- $q/Z$ lower at each order?
- assuming very small expt. syst.
• Application of “re-bJES” on D0 $m_t$
  - Shift in bJES
  - Shift in $m_t$
Possible shift in D0 bJES thoroughly documented in MSc thesis of Toni Mäkelä

- https://aaltodoc.aalto.fi/handle/123456789/39024
- 1) could reproduce D0 results with their parameters
- 2) our Pythia6 fit suggested different global minimum with smaller flavor correction
- 3) our Herwig7 fit suggested yet different global minimum with even smaller flavor correction

D0 used $p_T^{\text{bal}}$ as input, sensitive to FSR+ISR differences in P6 and H7 => CMS will use MPF

D0 did not directly measure b-enriched sample => CMS will use $Z+b$ vs $Z+q$
Shift in $m_t$

- Hannu Siikonen carefully reverse engineered D0 $l+\text{jet}$ $m_t$ and back-propagated bJES change.
- Document detailing process to be submitted to arXiv any day.
- (Still) plan to follow up with a short paper summering shifts in bJES and $m_t$.

Then do better on CMS.

**Summary of Top Mass Measurements**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m_t$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (2018)</td>
<td>$172.69 \pm 0.25 \pm 0.41$ (0.48)</td>
</tr>
<tr>
<td>CMS (2016)</td>
<td>$172.44 \pm 0.13 \pm 0.47$ (0.49)</td>
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<td>CDF (2014)</td>
<td>$173.16 \pm 0.57 \pm 0.74$ (0.93)</td>
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<tr>
<td>D0 (2016)</td>
<td>$174.95 \pm 0.40 \pm 0.64$ (0.75)</td>
</tr>
<tr>
<td>D0 $l+\text{jets}$</td>
<td>$174.98 \pm 0.58 \pm 0.49$ (0.76)</td>
</tr>
<tr>
<td>D0 $l+\text{jets}$, P6-shifted (2020)</td>
<td>$173.17 \pm 0.58 \pm 0.49 \pm 0.06$ (0.76)</td>
</tr>
<tr>
<td>D0 $l+\text{jets}$, H7-shifted (2020)</td>
<td>$172.51 \pm 0.58 \pm 0.49 \pm 0.06$ (0.76)</td>
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<tr>
<td>D0 $l+\text{jets}$, H7-shifted (2020)</td>
<td>$171.85 \pm 0.58 \pm 0.49 \pm 0.07$ (0.76)</td>
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Summary

- $m_t$ and $\alpha_s$ largest uncertainties for SM vacuum stability
- Need robust calibration ladder starting from $Z(\mu\mu)+\text{jet}$ to $t\bar{t}$, preferably backed by solid theory
- Evaluating each step individually, and in connection to each other
Gluon jet response

- Current experimental limitation is gluon jet response (=parton shower + fragmentation)
- Dijets mostly gluons at $p_T \sim 100$ GeV ($gg \rightarrow gg$), $Z+$jet mostly quarks ($qg \rightarrow qZ$)
- Pythia and Herwig agree on quarks ($Z+$jet), but not on gluons (dijet)

CMS, arXiv:1607.03663
Constraints on UE

- **FastJet (GridMedianEstimator)**
  - Energy density $\rho$ is a proxy of UE
  - Pileup factorized out by comparing to Zero Bias data as a function of average number of pileup ($\mu$)

- **Very minimal dependence on event scale** (e.g. jet $p_T$, $Z$ $p_T$) above $p_T > 10$—20 GeV

- **Slight dependence on $\mu$ possible** from non-linear calorimeter scale

- **Present work**: defining $\rho$ for particle level MC, as it is designed to work better with pileup

\[
\text{UE} = \rho - \rho_{\text{ZB}}
\]
Constraints on FSR

- Jet corrections done with two methods
  - MPF, missing-$E_T$ projection fraction: response of hadronic recoil (mostly 1st jet)
  - $p_T^{\text{bal}}$, ratio of 1st jet $p_T$ to $Z$ $p_T$
- Latter is sensitive to additional jets in recoil, former much less so
  - MPF: $R_{\text{add'l}} \sim R_{\text{jet1}} \Rightarrow R_{\text{MPF}} \sim R_{\text{jet1}}$
  - $p_T^{\text{bal}}$: $R_{\text{add'l}} = 0 \Rightarrow R_{p_T^{\text{bal}}} << R_{\text{jet1}}$

Data / MC

$\alpha = \frac{p_T^{\text{extra jet}}}{p_T^{\text{ref}}}$
Constraints on FSR

- Actual data from 8 TeV vs MadGraph (right) and 7 TeV vs Pythia6 (bottom)
- Modelling of FSR has improved over time, but still requires close attention
• Besides Z+b, can use jet fragmentation and single particle response to predict $R_b$
  ▶ Main idea: $R_{\text{jet}} = \Sigma_i f_i \times R_i(E_i)$, where $f_i$ energy fraction, $R_i$ single particle response to be fitted

• Method pioneered by D0, but two known caveats:
  ▶ Input data uses $p_T^{\text{bal}}$ method to estimate $R_{\text{jet}}$, known to be biased for Pythia6 LO MC (ref. FSR)
  ▶ Input data uses gluon-rich EM+jet, and gluon $f_i$ known to be biased for Pythia6 LO MC (ref. QGL)

**Constraints on bJES**

**Combinations per experiment**

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**ATLAS**

**CMS Simulation**

**ATLAS, arXiv:1810.01772**

**CMS, arXiv:1607.03663**

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